Collider Phenomenology

Fabio Maltoni
Université catholique de Louvain
Università di Bologna

Multa novit vulpes, verum echinus unum magnum

Collider Phenomenology

I Basics of collider physics and QCD

II SM Pheno: the top quark

III Searching for New Physics with tops

Collider Physics

The purpose of collider physics is to test theoretical predictions experimentally in a controllable environment

Theory

- QFT
- Lagrangian
- Models:
  - SM
  - SUSY
  - ...
- Cross Sections

Collider (Accelerator)

Experiment

- Measurement of properties physical objects
  - momentum
  - energy
  - angles
  - ...
- Assess systematic uncertainties

Interpretation

- Signal/Background
- Statistics

Collider	Site	Initial State	Energy	Discovery / Target
SPEAR	SLAC	e^+e^-	4 GeV	charm quark, tau lepton
PETRA	DESY	e^+e^-	38 GeV	gluon
S$p\bar{p}$S	CERN	$p\bar{p}$	600 GeV	W, Z bosons
LEP	CERN	e^+e^-	210 GeV	SM: elw and QCD
SLC	SLAC	e^+e^-	90 GeV	elw SM
HERA	DESY	ep	320 GeV	quark/gluon structure of proton
Tevatron	FNAL	$p\bar{p}$	2 TeV	top quark
BaBar / Belle	SLAC / KEK	e^+e^-	10 GeV	quark mix / CP violation
LHC	CERN	pp	7/8/14 TeV	Higgs boson, elw. sb, New Physics
ILC		e^+e^-	> 200 GeV	hi. res of elw sb / Higgs couplings
CLIC		e^+e^-	3 - 5 TeV	hi. res of elw sb / Higgs couplings
FCC		pp	100 TeV	disc. multi-TeV physics

The reach of collider facilities

$A + B \to M$ production in 2-particle collisions: $M^2 = (p_1 + p_2)^2$

<u>fixed target:</u>

$$p_1 \simeq (E, 0, 0, E)$$

$$p_2 = (m, 0, 0, 0)$$

before after

$$M \simeq \sqrt{2mE}$$

root increase in M

- root E law: large energy loss in $E_{\rm kin}$
- dense target: large collision rate / luminosity

<u>collider target:</u>

$$p_1 = (E, 0, 0, E)$$

$$p_2 = (E, 0, 0, -E)$$

before after

$$M \simeq 2E$$

- linear E law: no energy loss
- less dense bunches: small collision rates

Collider characteristics

Energy: ranges from a few GeV to several TeV (LHC)

Luminosity: measures the rate of particles in colliding bunches

$$\mathcal{L} = \frac{N_1 N_2 f}{A}$$

$N_i =$ number of particles in bunches

$A =$ transverse bunch area

$f =$ bunch collision rate

$\mathcal{L}\sigma =$ observed rate for process with cross section σ

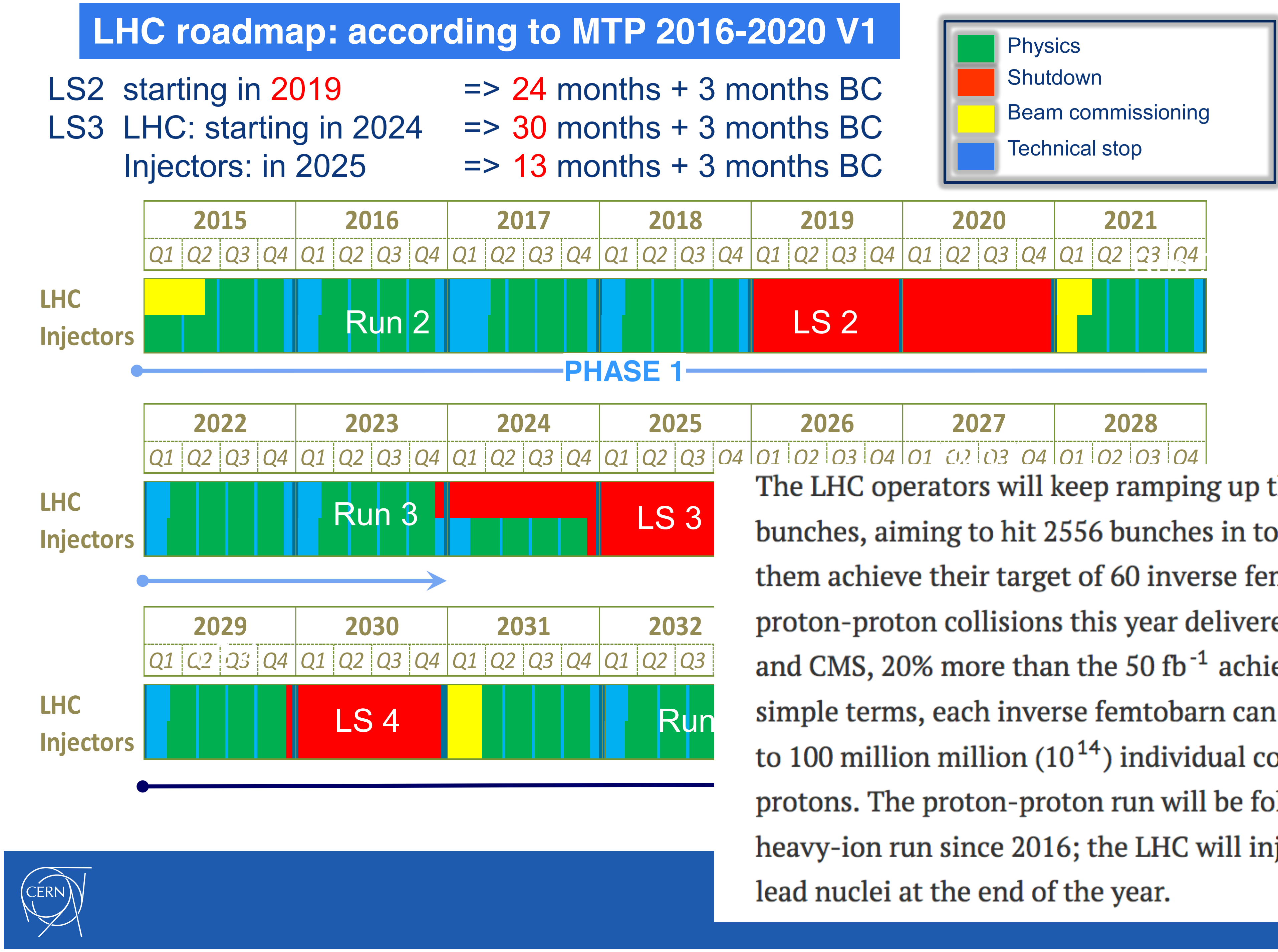
LHC (targeted): $\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1} \rightarrow 300\ \mathrm{fb}^{-1}$ in 3 years

Circular vs linear collider:

charged particles in circular motion: permanently accelerated towards center -> emitting photons as synchrotron light $\Delta E \sim E^4/R$

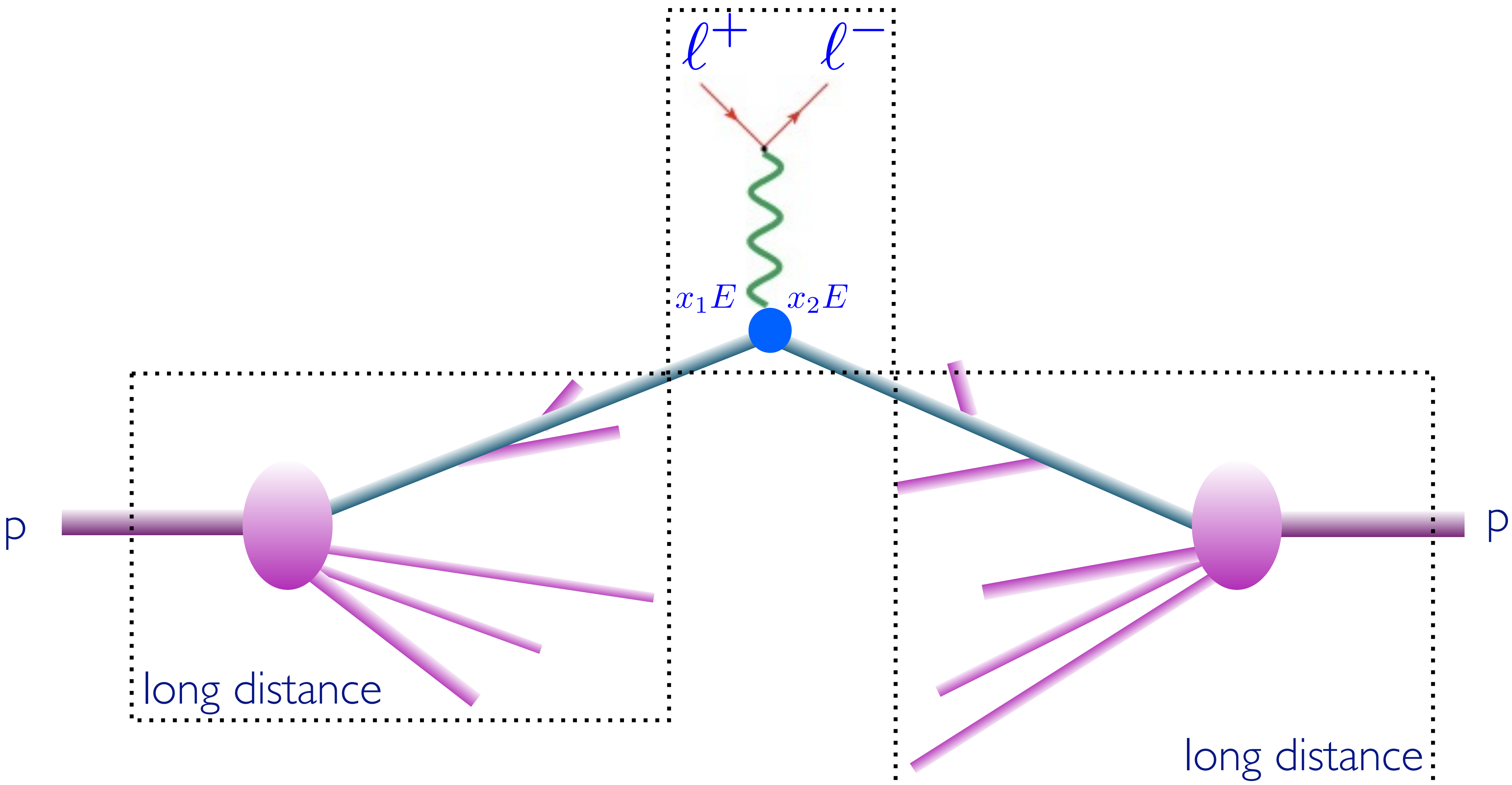
- large loss of energy [hypothetical TeV collider at LEP: $\Delta E \simeq E$ per turn]
- no-more sharp initial state energy

LHC schedule



The LHC operators will keep ramping up the number of bunches, aiming to hit 2556 bunches in total. This will help them achieve their target of 60 inverse femtobarns (fb^{-1}) of proton-proton collisions this year delivered to both ATLAS and CMS, 20% more than the 50 fb^{-1} achieved in 2017. In simple terms, each inverse femtobarn can correspond to up to 100 million million (10^{14}) individual collisions between protons. The proton-proton run will be followed by the first heavy-ion run since 2016; the LHC will inject and collide lead nuclei at the end of the year.

LHC master formula

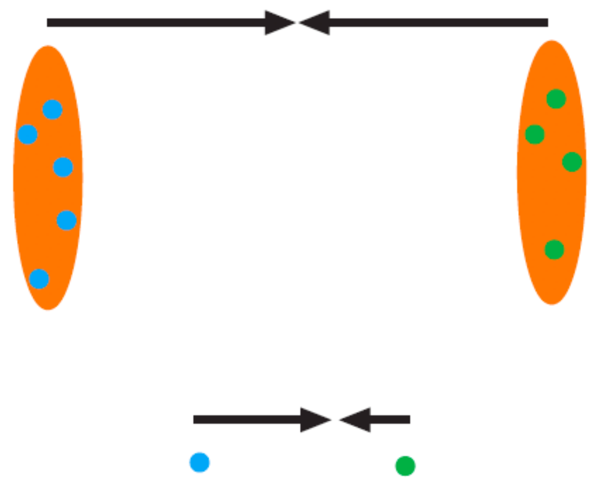


$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2) f_b(x_2, \mu_F^2) \times \hat{\sigma}_{ab \to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

pp kinematics

We describe the collision in terms of parton energies

$E_1 = x_1$ Ebeam
$E_2 = x_2$ Ebeam

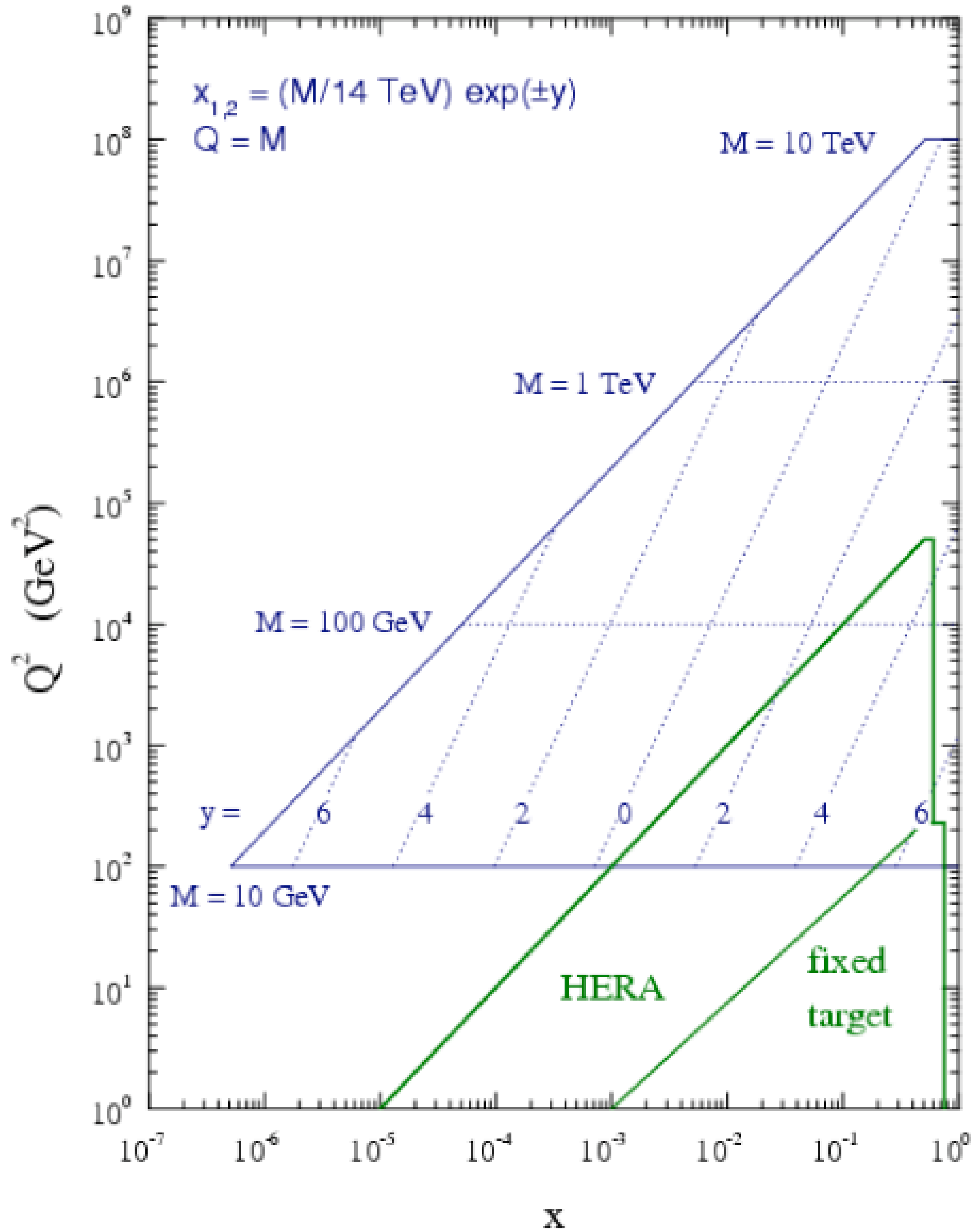


Obviously the partonic c.m.s. frame will be in general boosted. Let us say that the two partons annihilate into a particle of mass M.

$$M^2 = x_1 x_2 S = x_1 x_2 4E^2_{\text{beam}}$$

$$y = \frac{1}{2}\log\frac{x_1}{x_2}$$

$$x_1 = \frac{M}{\sqrt{S}}e^{y} \quad x_2 = \frac{M}{\sqrt{S}}e^{-y}$$



Rapidity and pseudo-rapidity

$$y = \frac{1}{2}\log\frac{E+p_z}{E-p_z} = \frac{1}{2}\log\frac{p^+}{p^-}$$

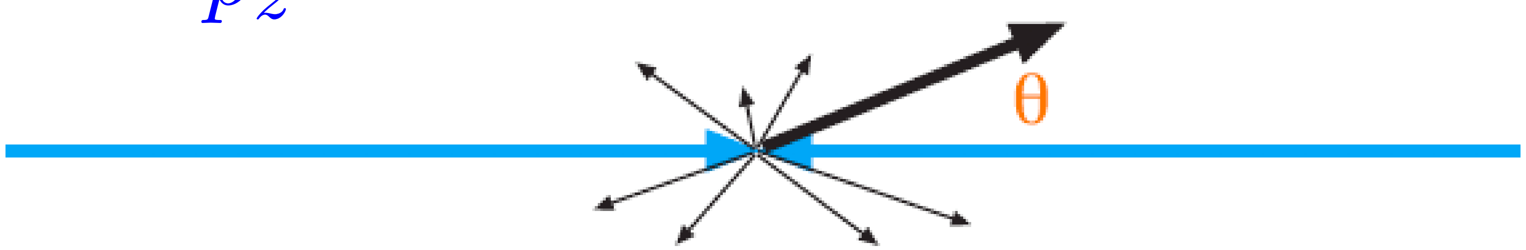
RAPIDITY

$$\eta = -\log(\tan(\theta/2))$$

PSEUDORAPIDITY

with

$$\tan\theta = \frac{p_T}{p_z}$$



1. Rapidity transforms additively under a Lorentz boost : $y \to y' = y + \omega$
2. Rapidity differences are Lorentz invariants : $\Delta y \to \Delta y'$
3. Pseudo rapidity has a direct experimental definition but no special properties under the Lorentz boosts.
4. For massless particles rapidity and pseudo rapidity are the same.

LHC master formula

More exactly

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

where the partonic cross section is calculated by

$$\hat{\sigma}_{a,b\to k} = \frac{1}{2s} \int \left[\Pi_{i=1}^{n} \frac{d^3\vec{q}_i}{(2\pi)^3 2E_i}\right] \left[(2\pi)^4 \delta^4 \left(\sum_i q_i^\mu - (p_1+p_2)^\mu\right)\right] |\mathcal{M}_{ab\to k}(\mu_F,\mu_R)|^2$$

[flux factor] × [phase space (LiPS)] × [squared matrix element]

Crucial pieces for the calculation of the hadronic cross section are the **parton distribution functions** $f_{i/p}$ and the **squared matrix element** $|\mathcal{M}|^2$

LHC master formula

$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \hat\sigma_{ab\to X}(x_1, x_2, \alpha_S(\mu_R^2), \frac{Q^2}{\mu_F^2}, \frac{Q^2}{\mu_R^2})$$

Two ingredients necessary:

1. Parton Distribution Functions (from exp, but evolution from th).

2. Short distance coefficients as an expansion in α_S (from th).

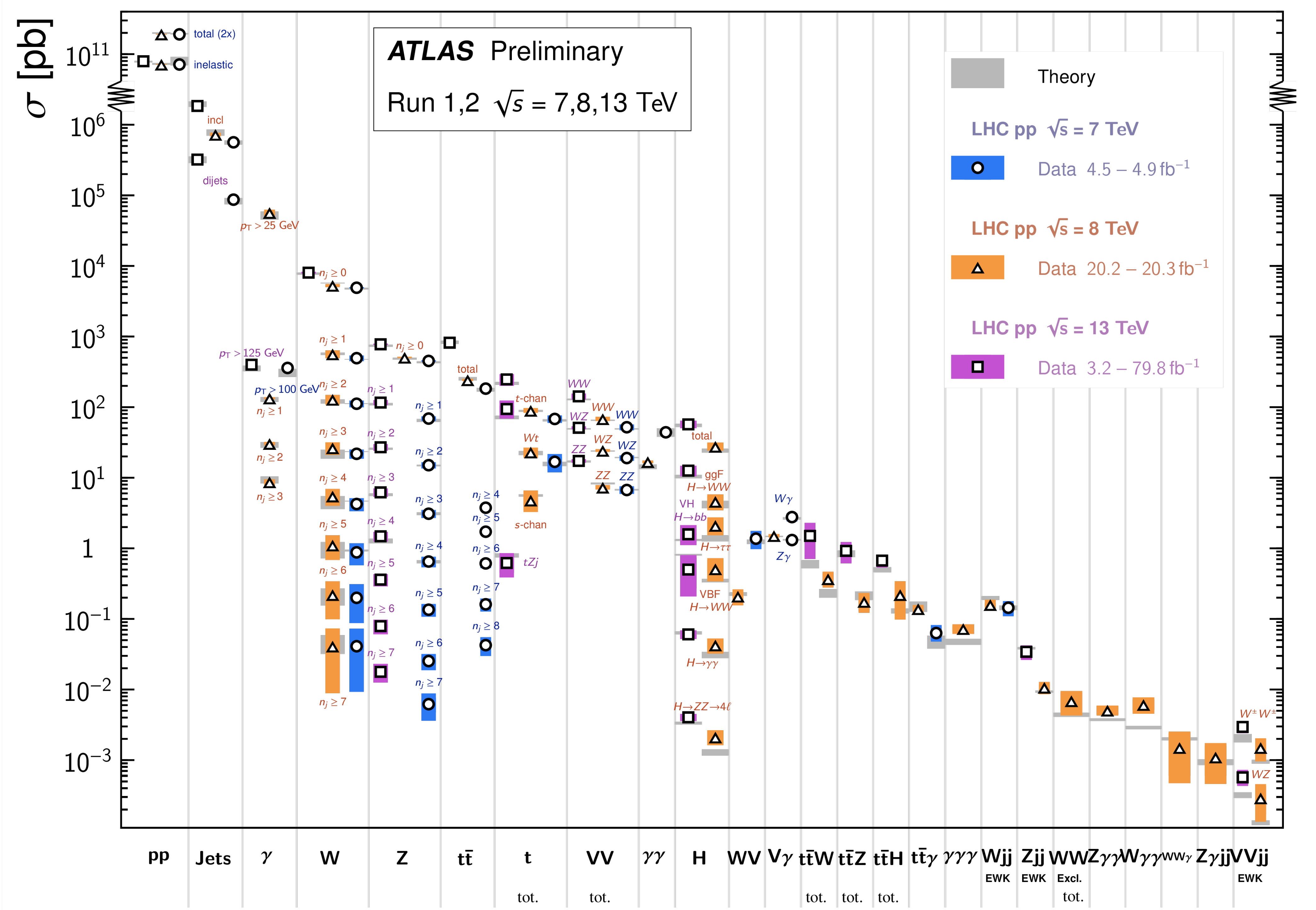
$$\hat\sigma_{ab\to X} = \sigma_0 + \alpha_S \sigma_1 + \alpha_S^2 \sigma_2 + \dots$$

Leading order

Next-to-leading order

Next-to-next-to-leading order

LHC Physics = QCD + ϵ



QCD basics #1 : Lagrangian

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} + \sum_f \bar{\psi}_i^{(f)} (i\partial\!\!\!/ - m_f) \psi_i^{(f)} - \bar{\psi}_i^{(f)} (g_s t^a_{ij} A\!\!\!/_a) \psi_j^{(f)}$$

Gauge Fields and their interact.

Matter

Interaction

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu - g f^{abc} A^b_\mu A^c_\nu$$

$$[t^a, t^b] = i f^{abc} t^c$$

→ Algebra of SU(N)

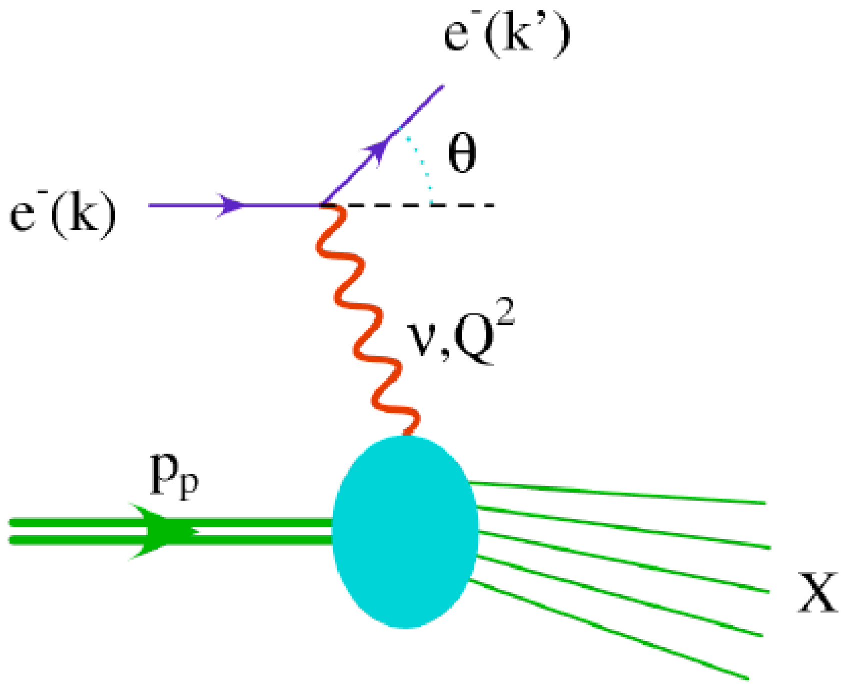
$$\mathrm{tr}(t^a t^b) = \frac{1}{2} \delta^{ab}$$

→ Normalization

QCD for the LHC in a nutshell

- Asymptotic freedom : UV property
- Universality : IR property

QCD Concept #1 : AF



$$s = (P+k)^2$$ cms energy^2

$$Q^2 = -(k-k')^2$$ momentum transfer^2

$$x = Q^2/2(P\cdot q)$$ scaling variable

$$\nu = (P\cdot q)/M = E - E'$$ energy loss

$$y = (P\cdot q)/(P\cdot k) = 1 - E'/E$$ rel. energy loss

$$W^2 = (P+q)^2 = M^2 + \frac{1-x}{x}Q^2$$ recoil mass

$$\frac{d\sigma_{\mathrm{elastic}}}{dq^2} = \left(\frac{d\sigma}{dq^2}\right)_{\mathrm{point}} \cdot F^2_{\mathrm{elastic}}(q^2)\,\delta(1-x)\,dx$$

$$\frac{d\sigma_{\mathrm{inelastic}}}{dq^2} = \left(\frac{d\sigma}{dq^2}\right)_{\mathrm{point}} \cdot F^2_{\mathrm{inelastic}}(q^2,x)\,dx$$

What should we expect for F(q^2,x)?

QCD Concept #1 : AF

Two plausible and one crazy scenarios for the $|q^2| \to \infty$ (Bjorken) limit:

1.Smooth electric charge distribution: (classical picture)

$$F^2_{elastic}(q^2) \sim F^2_{inelastic}(q^2) \ll 1$$

i.e., external probe penetrates the proton as knife through the butter!

2. Tightly bound point charges inside the proton: (bound quarks)

$$F^2_{elastic}(q^2) \sim 1 \text{ and } F^2_{inelastic}(q^2) \ll 1$$

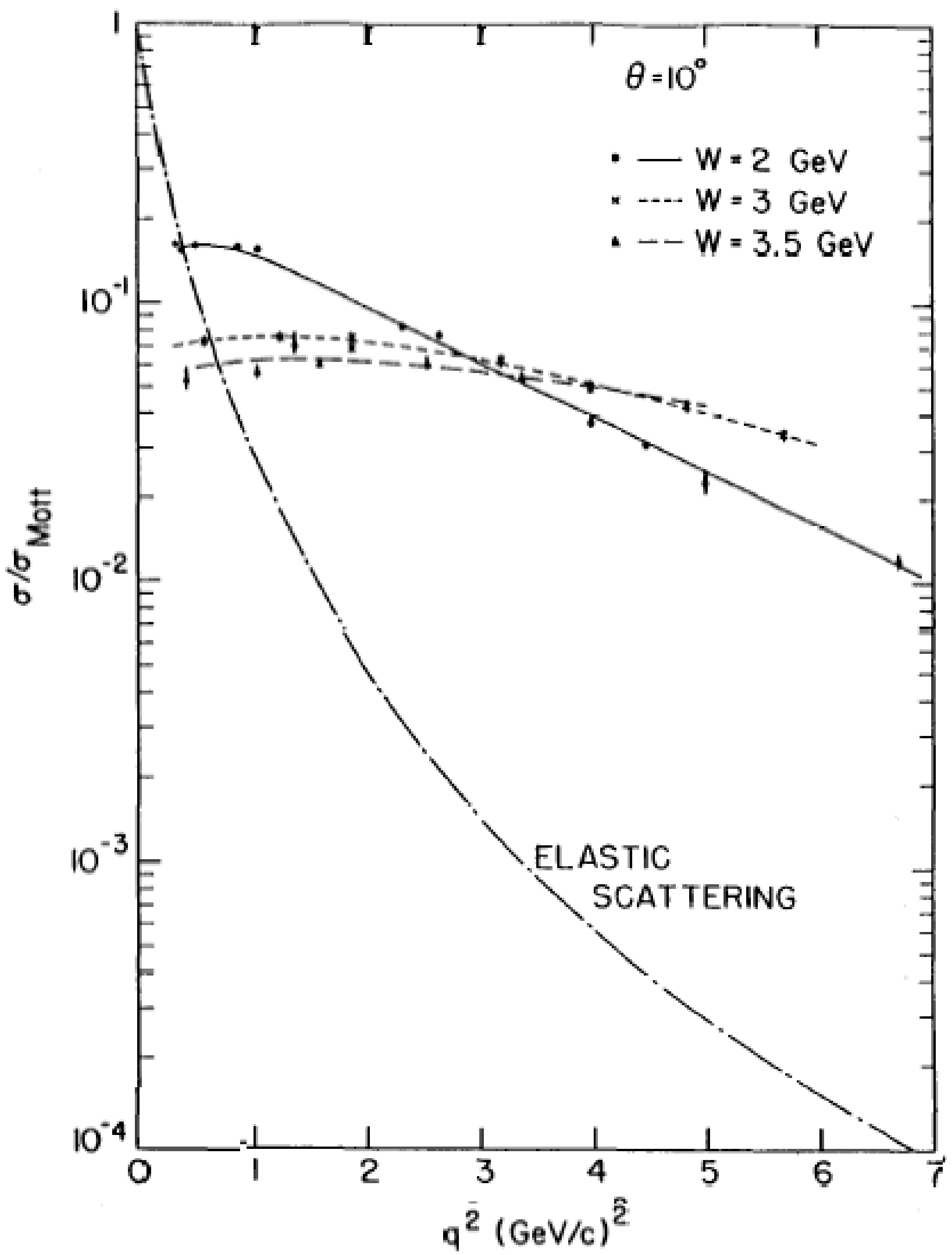
i.e., quarks get hit as single particles, but momentum is immediately redistributed as they are tightly bound together (confinement) and cannot fly away.

3. And now the crazy one: (free quarks)

$$F^2_{elastic}(q^2) \ll 1 \text{ and } F^2_{inelastic}(q^2) \sim 1$$

i.e., there are points (quarks!) inside the protons, however the hit quark behaves as a free particle that flies away without feeling or caring about confinement!!!

QCD Concept #1 : AF

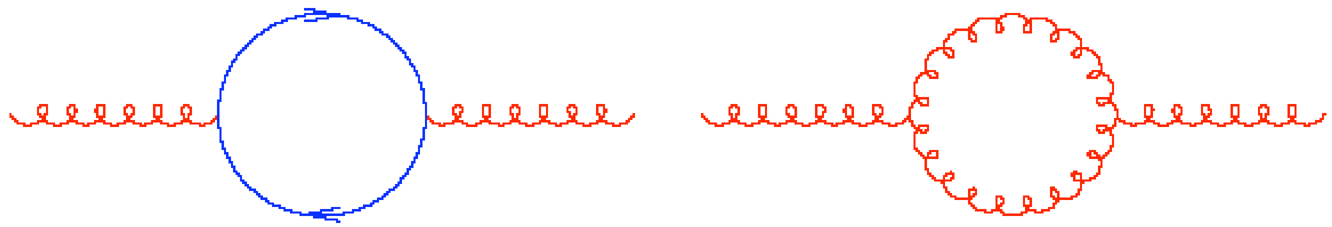


$$\frac{d^2\sigma^{\mathrm{EXP}}}{dx dy} \sim \frac{1}{Q^2}$$

Remarkable!!! Pure dimensional analysis!
The right hand side does not depend on Λ_S !
This is the same behaviour one may find in a renormalizable theory like in QED.

This motivated the search for a weakly-coupled theory at high energy!

QCD Concept #1 : AF



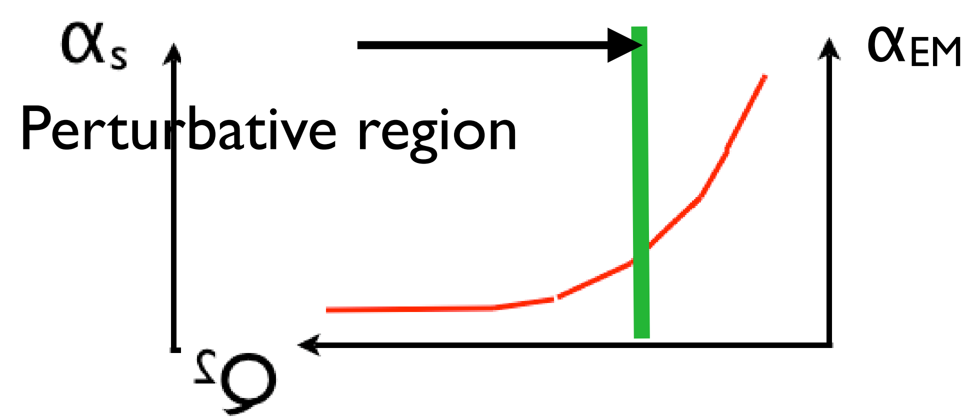
(a) (b)

Roughly speaking, quark loop diagram (a) contributes a negative N_f term in b_0, while the gluon loop, diagram (b) gives a positive contribution proportional to the number of colors N_c, which is dominant and make the overall beta function negative.

$$b_0 = \frac{11N_c - 2n_f}{12\pi} \quad > 0 \quad \Rightarrow \quad \beta(\alpha_S) < 0 \text{ in QCD}$$

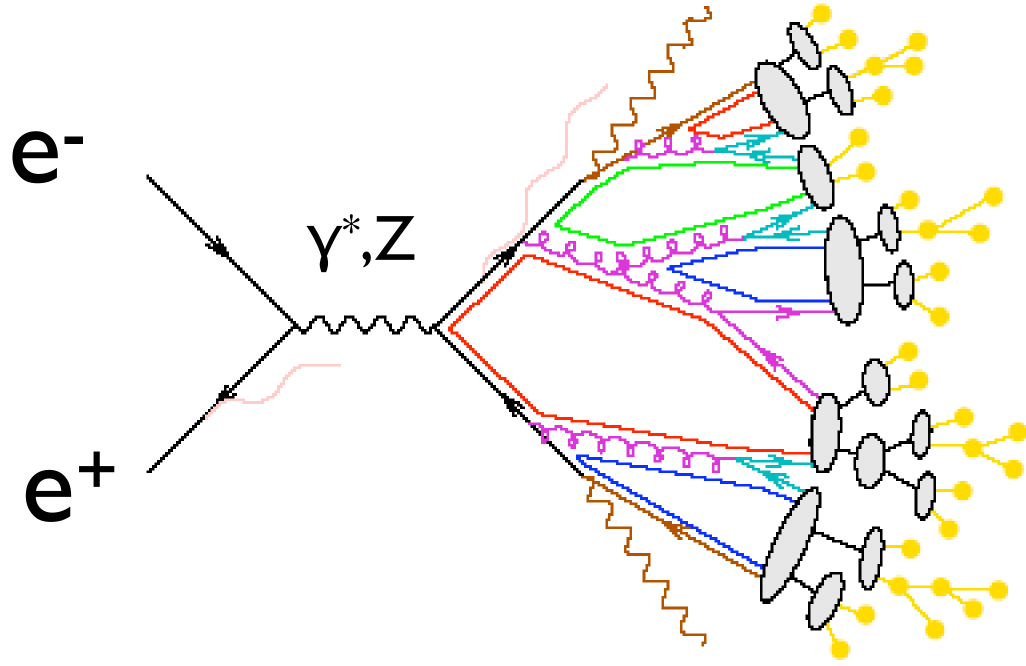
$$b_0 = -\frac{n_f}{3\pi} \quad < 0 \quad \Rightarrow \quad \beta(\alpha_S) > 0 \text{ in QED}$$

$$\alpha_{EM}(\mu) = \frac{1}{b_0 \log \frac{\mu^2}{\Lambda^2_{\mathrm{QED}}}}$$

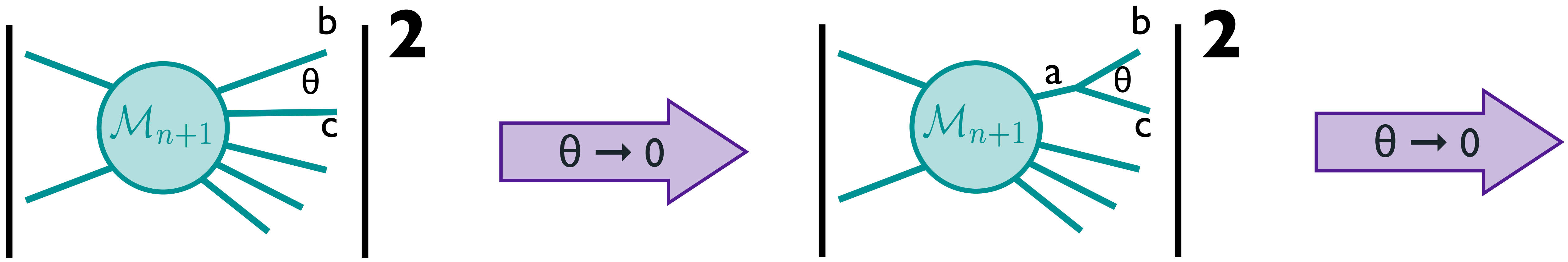


QCD Concept #2 : Universality

- We need to be able to describe an arbitrarily number of parton branchings, i.e. we need to ‘dress’ partons with radiation
- This effect should be unitary: the inclusive cross section shouldn’t change when extra radiation is added
- And finally we want to turn partons into hadrons (hadronization)....

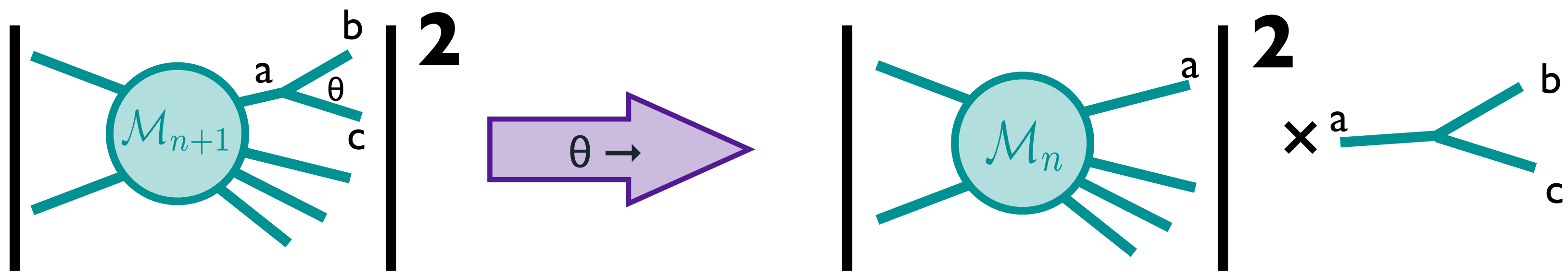


QCD Concept #2 : Universality



- Consider a process for which two particles are separated by a small angle θ.
- In the limit of θ → 0 the contribution is coming from a single parent particle going on shell: therefore its branching is related to time scales which are very long with respect to the hard subprocess.
- The inclusion of such a branching cannot change the picture set up by the hard process: the whole emission process must be writable in this limit as the simpler one times a branching probability.
- The first task of Monte Carlo physics is to make this statement quantitative.

QCD Concept #2 : Universality



- The process factorizes in the collinear limit. This procedure it universal!

$$|\mathcal{M}_{n+1}|^2 d\Phi_{n+1} \;\simeq\; |\mathcal{M}_n|^2 d\Phi_n \frac{dt}{t} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)$$

- z is the "energy variable": it is defined to be the energy fraction taken by parton b from parton a. It represents the energy sharing between b and c and tends to 1 in the soft limit (parton c going soft)

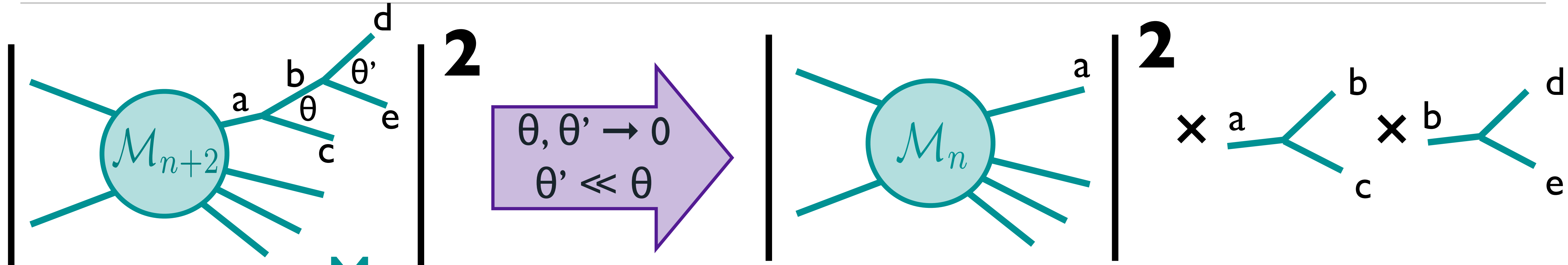
- Φ is the azimuthal angle. It can be chosen to be the angle between the polarization of a and the plane of the branching.

- $P_{a\to bc}$ are the Altarelli-Parisi splitting functions

$$P_{g\to qq}(z) = T_R\left[z^2 + (1-z)^2\right], \qquad P_{g\to gg}(z) = C_A\left[z(1-z) + \frac{z}{1-z} + \frac{1-z}{z}\right],$$

$$P_{q\to qg}(z) = C_F\left[\frac{1+z^2}{1-z}\right], \qquad P_{q\to gq}(z) = C_F\left[\frac{1+(1-z)^2}{z}\right].$$

QCD Concept #2 : Universality

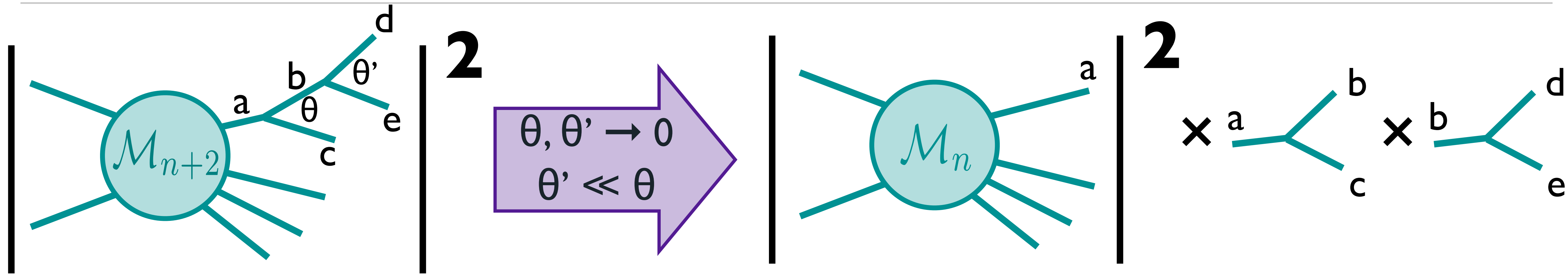


- Now consider M_{n+1} as the new core process and use the recipe we used for the first emission in order to get the dominant contribution to the (n+2)-body cross section: add a new branching at angle much smaller than the previous one:

$$|\mathcal{M}_{n+2}|^2 d\Phi_{n+2} \simeq |\mathcal{M}_n|^2 d\Phi_n \frac{dt}{t} dz \frac{d\phi}{2\pi} \frac{\alpha_{\rm S}}{2\pi} P_{a\to bc}(z)$$
$$\times \frac{dt'}{t'} dz' \frac{d\phi'}{2\pi} \frac{\alpha_{\rm S}}{2\pi} P_{b\to de}(z')$$

- This can be done for an arbitrary number of emissions. The recipe to get the leading collinear singularity is thus cast in the form of an iterative sequence of emissions whose probability does not depend on the past history of the system: a ‘Markov chain’. No interference!!!

QCD Concept #2 : Universality



- The dominant contribution comes from the region where the subsequently emitted partons satisfy the strong ordering requirement: θ ≫ θ' ≫ θ''...
  For the rate for multiple emission we get

$$\sigma_{n+k} \propto \alpha_S^k \int_{Q_0^2}^{Q^2} \frac{dt}{t} \int_{Q_0^2}^{t} \frac{dt'}{t'} \ldots \int_{Q_0^2}^{t^{(k-2)}} \frac{dt^{(k-1)}}{t^{(k-1)}} \propto \sigma_n \left(\frac{\alpha_S}{2\pi}\right)^k \log^k(Q^2/Q_0^2)$$

  where Q is a typical hard scale and Q_0 is a small infrared cutoff that separates perturbative from non perturbative regimes.

- Each power of α_s comes with a logarithm. The logarithm can be easily large, and therefore it can lead to a breakdown of perturbation theory.

Absence of interference

- The collinear factorization picture gives a branching sequence for a given leg starting from the hard subprocess all the way down to the non-perturbative region.
- The collinear picture completely misses the possible interference effects between the various legs. The extreme simplicity comes at the price of quantum inaccuracy.
- Nevertheless, the collinear picture captures the leading contributions: it gives an excellent description of an arbitrary number of (collinear) emissions:
  - it is a “resummed computation”
  - it bridges the gap between fixed-order perturbation theory and the non-perturbative hadronization.

Sudakov form factor

The differential probability for the branching $a \longrightarrow bc$ between scales t and $t+dt$ knowing that no emission occurred before:

$$dp(t) = \sum_{bc} \frac{dt}{t} \int dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)$$

The probability that a parton does NOT split between the scales t and $t+dt$ is given by $1-dp(t)$. Probability that particle a does not emit between scales Q^2 and t

$$\Delta(Q^2,t) = \prod_k \left[1 - \sum_{bc} \frac{dt_k}{t_k} \int dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)\right] =$$

$$\exp\left[-\sum_{bc} \int_t^{Q^2} \frac{dt'}{t'} dz \frac{d\phi}{2\pi} \frac{\alpha_S}{2\pi} P_{a\to bc}(z)\right] = \exp\left[-\int_t^{Q^2} dp(t')\right]$$

$\Delta(Q^2,t)$ is the Sudakov form factor

Parton shower algorithm

- The Sudakov form factor is the heart of the parton shower. It gives the probability that a parton does not branch between two scales
- Using this no-emission probability the branching tree of a parton is generated.
- Define dP_k as the probability for k ordered splittings from leg a at given scales

$$
\begin{aligned}
dP_1(t_1) &= \Delta(Q^2, t_1)\ dp(t_1)\Delta(t_1, Q_0^2), \\
dP_2(t_1, t_2) &= \Delta(Q^2, t_1)\ dp(t_1)\ \Delta(t_1, t_2)\ dp(t_2)\ \Delta(t_2, Q_0^2)\Theta(t_1 - t_2), \\
\ldots &= \ldots \\
dP_k(t_1, \ldots, t_k) &= \Delta(Q^2, Q_0^2) \prod_{l=1}^{k} dp(t_l)\Theta(t_{l-1} - t_l)
\end{aligned}
$$

- Q_0^2 is the hadronization scale (~1 GeV). Below this scale we do not trust the perturbative description for parton splitting anymore.
- This is what is implemented in a parton shower, taking the scales for the splitting t_i randomly (but weighted according to the no-emission probability).

Unitarity

$$dP_k(t_1, ..., t_k) \quad = \quad \Delta(Q^2, Q_0^2) \prod_{l=1}^{k} dp(t_l)\Theta(t_{l-1} - t_l)$$

- The parton shower has to be unitary (the sum over all branching trees should be 1). We can explicitly show this by integrating the probability for k splittings:

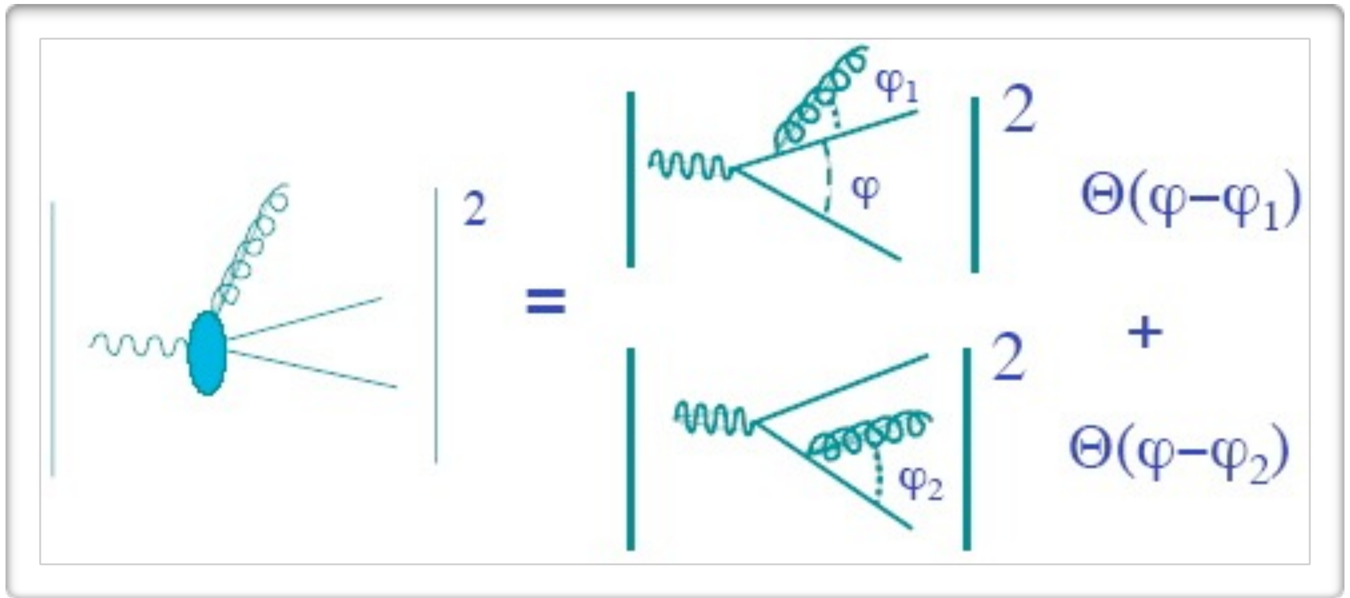
$$P_k \equiv \int dP_k(t_1, ..., t_k) = \Delta(Q^2, Q_0^2) \frac{1}{k!} \left[\int_{Q_0^2}^{Q^2} dp(t) \right]^k, \quad \forall k = 0, 1, ...$$

- Summing over all number of emissions

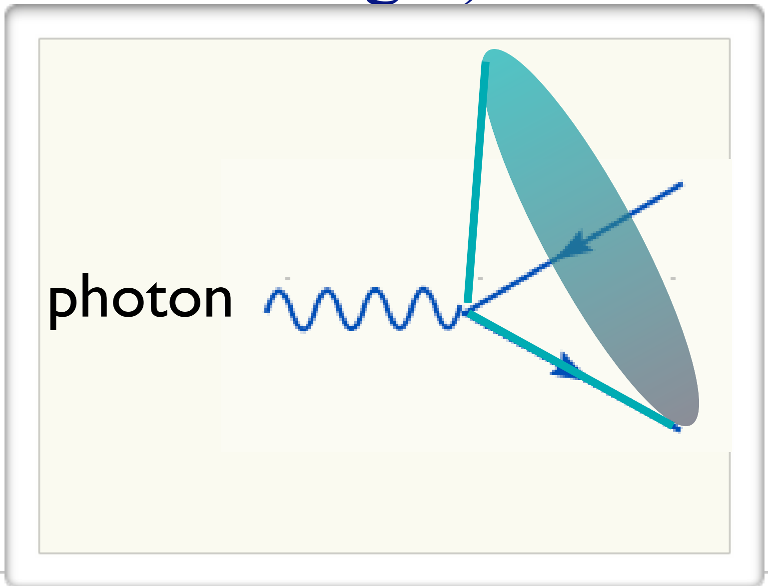
$$\sum_{k=0}^{\infty} P_k = \Delta(Q^2, Q_0^2) \sum_{k=0}^{\infty} \frac{1}{k!} \left[\int_{Q_0^2}^{Q^2} dp(t) \right]^k = \Delta(Q^2, Q_0^2) \exp \left[\int_{Q_0^2}^{Q^2} dp(t) \right] = 1$$

- Hence, the total probability is conserved

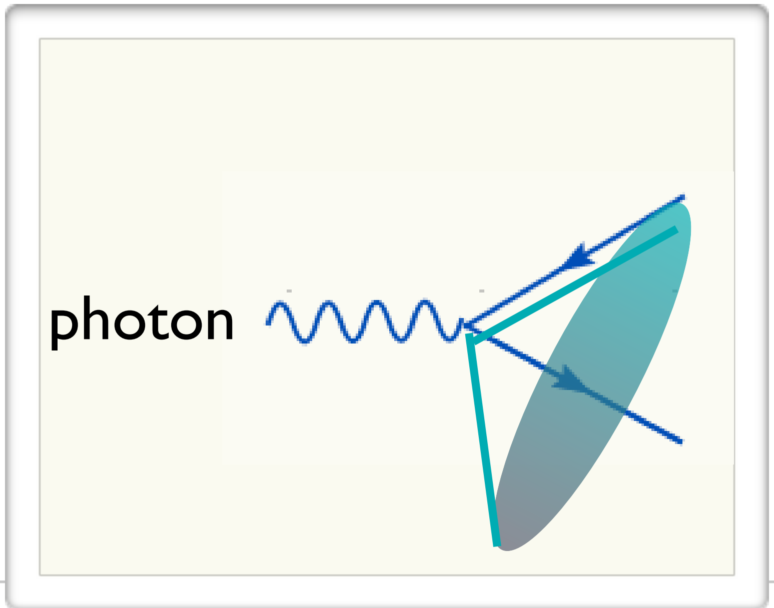
Reinstating the interference: Angular ordering



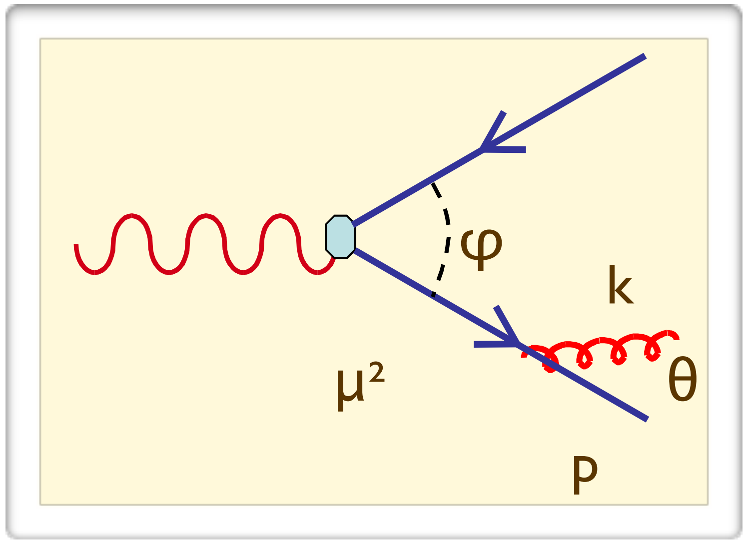
Radiation inside cones around the orginal partons is allowed (and described by the eikonal approximation), outside the cones it is zero (after averaging over the azimuthal angle)



+



Intuitive explanation



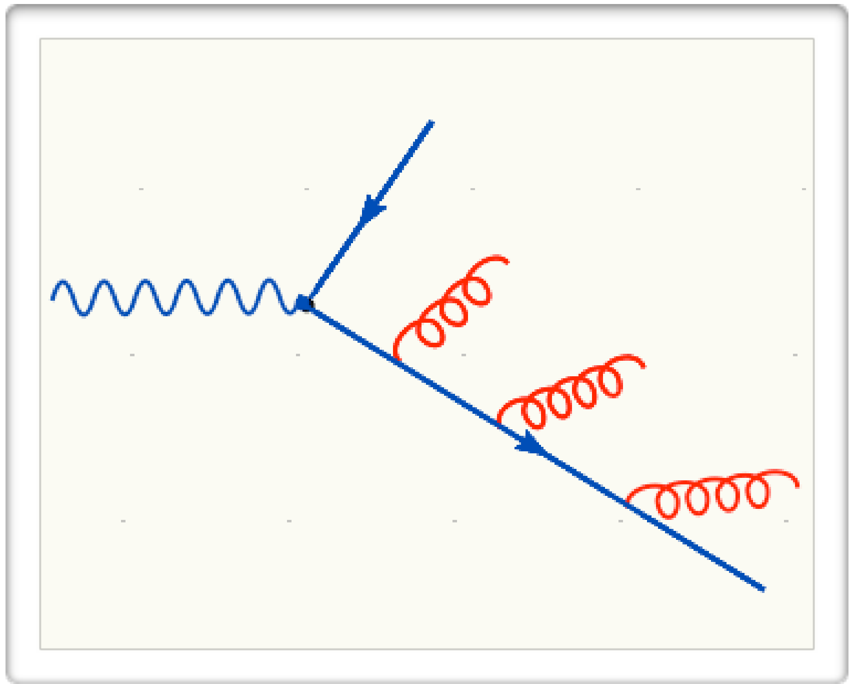
- Lifetime of the virtual intermediate state: $\tau < \gamma/\mu = E/\mu^2 = 1/(k_0\theta^2) = 1/(k_\perp\theta)$
- Distance between q and qbar after τ: $d = \varphi\tau = (\varphi/\theta)\ 1/k_\perp$

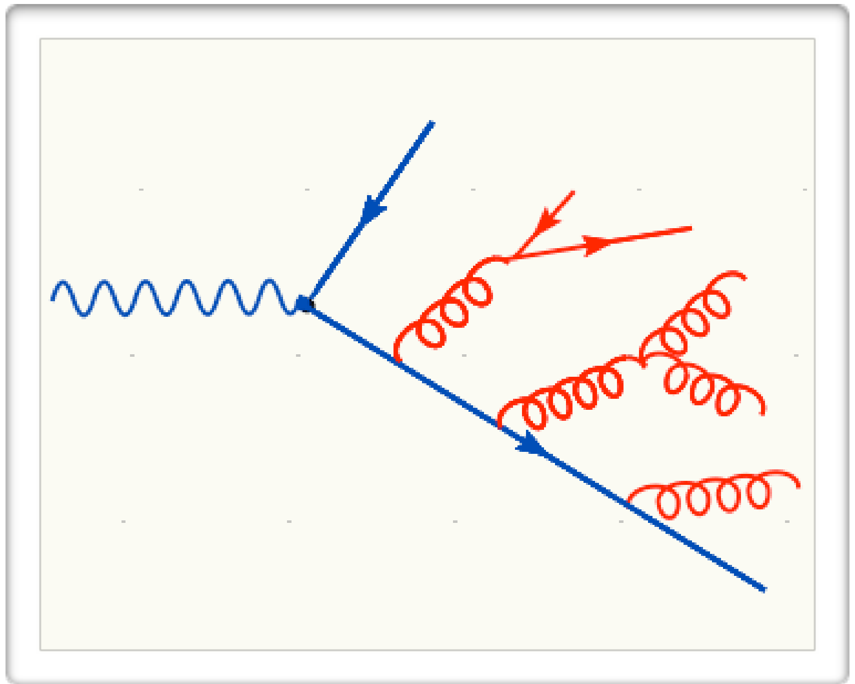
$$\mu^2 = (p+k)^2 = 2E\, k_0\, (1\text{-}\cos\theta)$$
$$\sim E\, k_0\, \theta^2 \sim E\, k_\perp\, \theta$$

If the transverse wavelength of the emitted gluon is longer than the separation between q and qbar, the gluon emission is suppressed, because the q qbar system will appear as colour neutral (i.e. dipole-like emission, suppressed)

Therefore $d > 1/k_\perp$, which implies $\theta < \varphi$.

Angular ordering

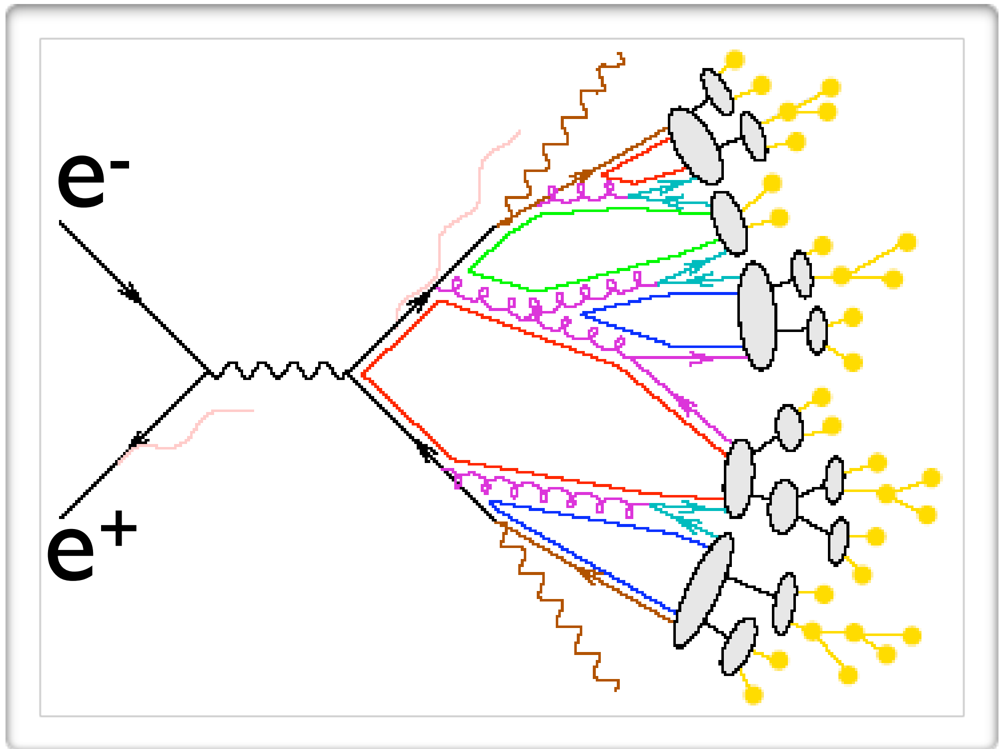


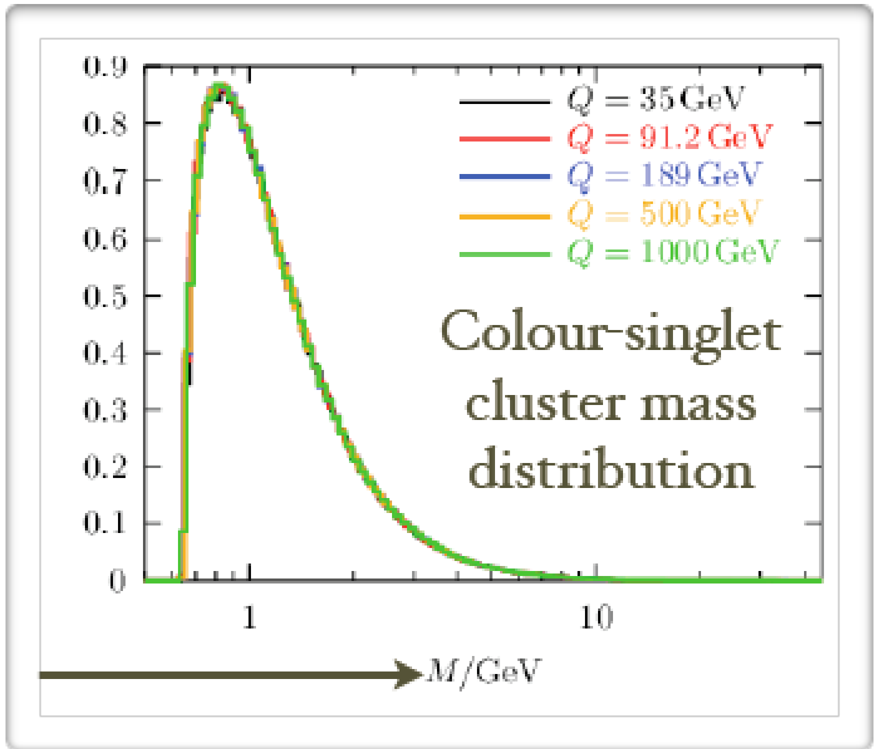


- The construction can be iterated to the next emission, with the result that the emission angles keep getting smaller and smaller.
- One can generalize it to a generic parton of color charge Q_k splitting into two partons i and j, $Q_k=Q_i+Q_j$. The result is that inside the cones i and j emit as independent charges, and outside their angular-ordered cones the emission is coherent and can be treated as if it was directly from color charge Q_k.
- KEY POINT FOR THE MC!
- Angular ordering is automatically satisfied in θ ordered showers! (and easy to account for in p_T ordered showers).

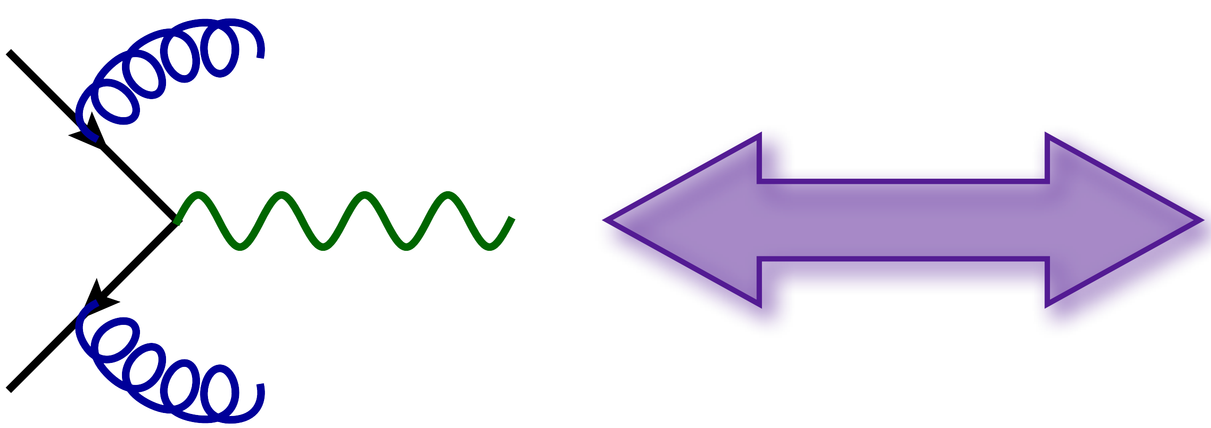
Hadronisation

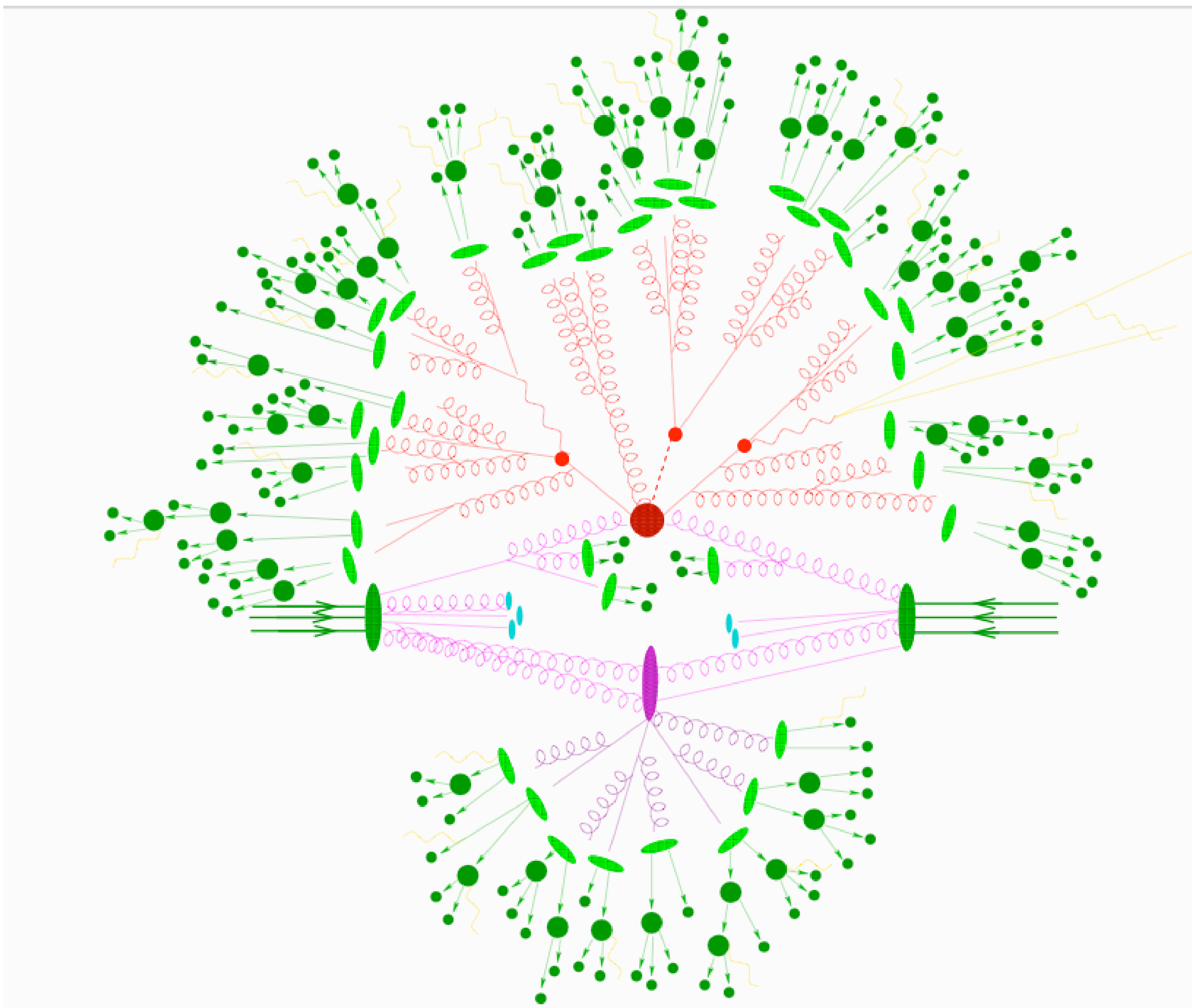
The structure of the perturbative evolution including angular ordering, leads naturally to the clustering in phase-space of color-singlet parton pairs (preconfinement). Long-range correlations are strongly suppressed. Hadronization will only act locally, on low-mass color singlet clusters.



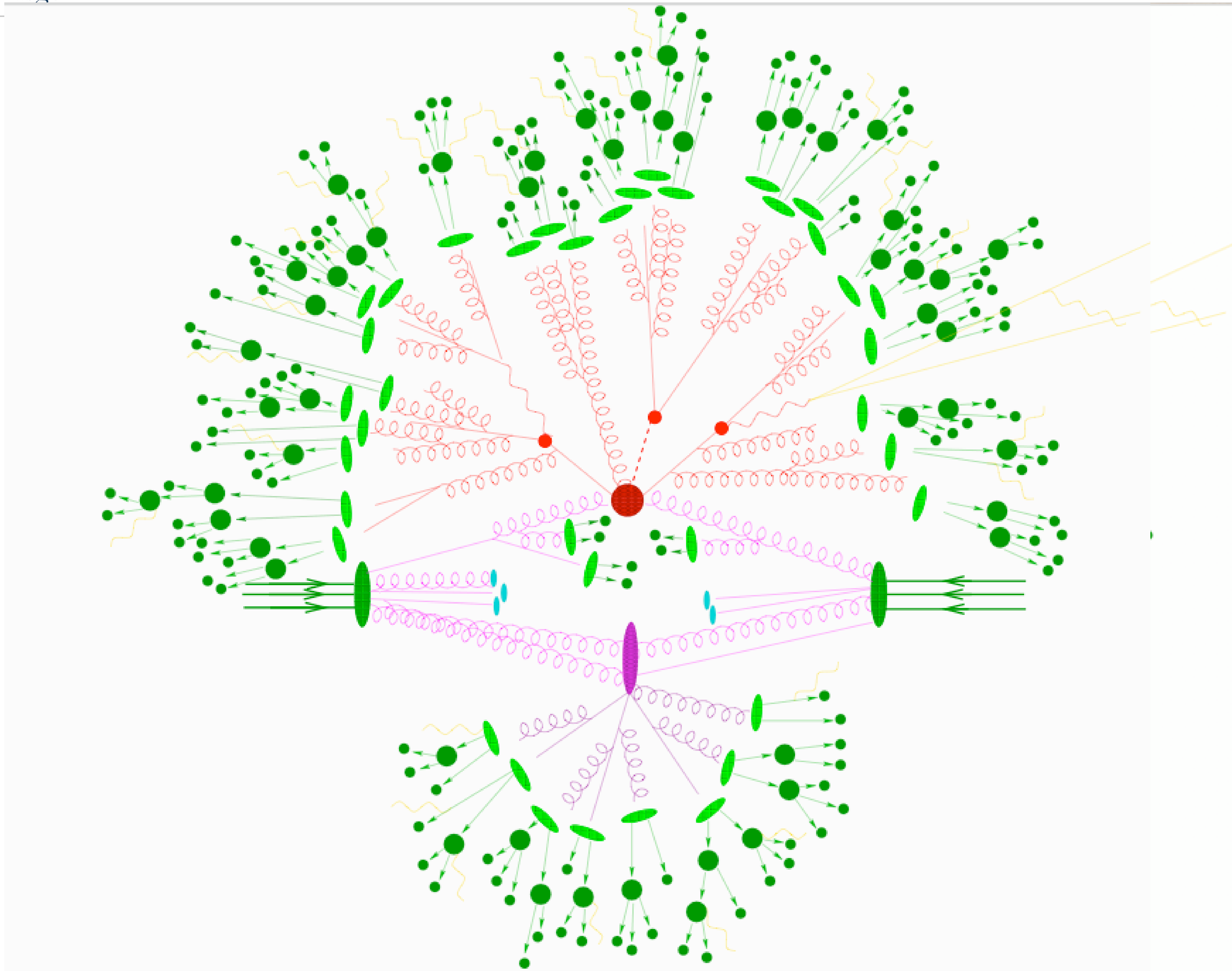


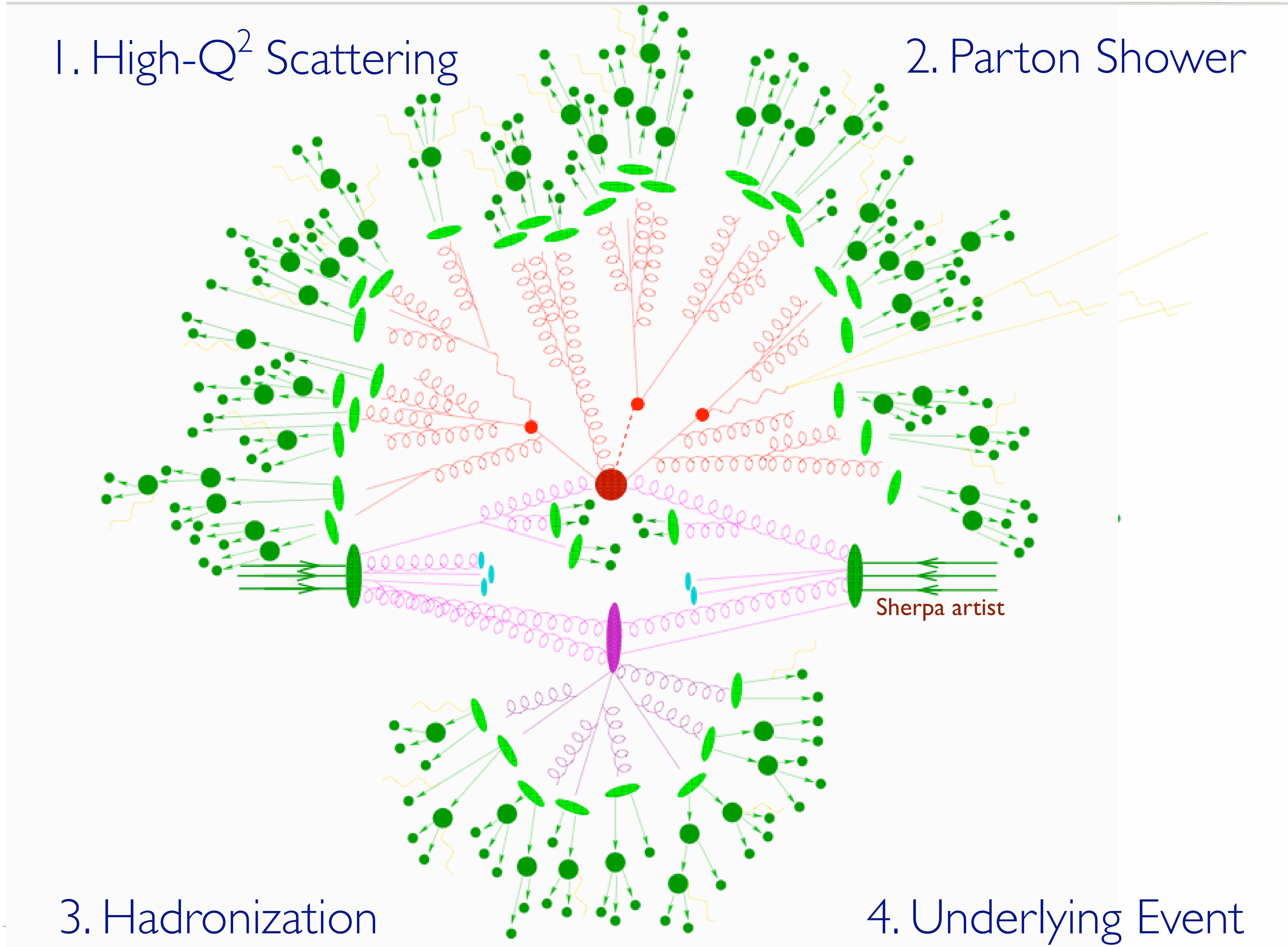
Event simulation





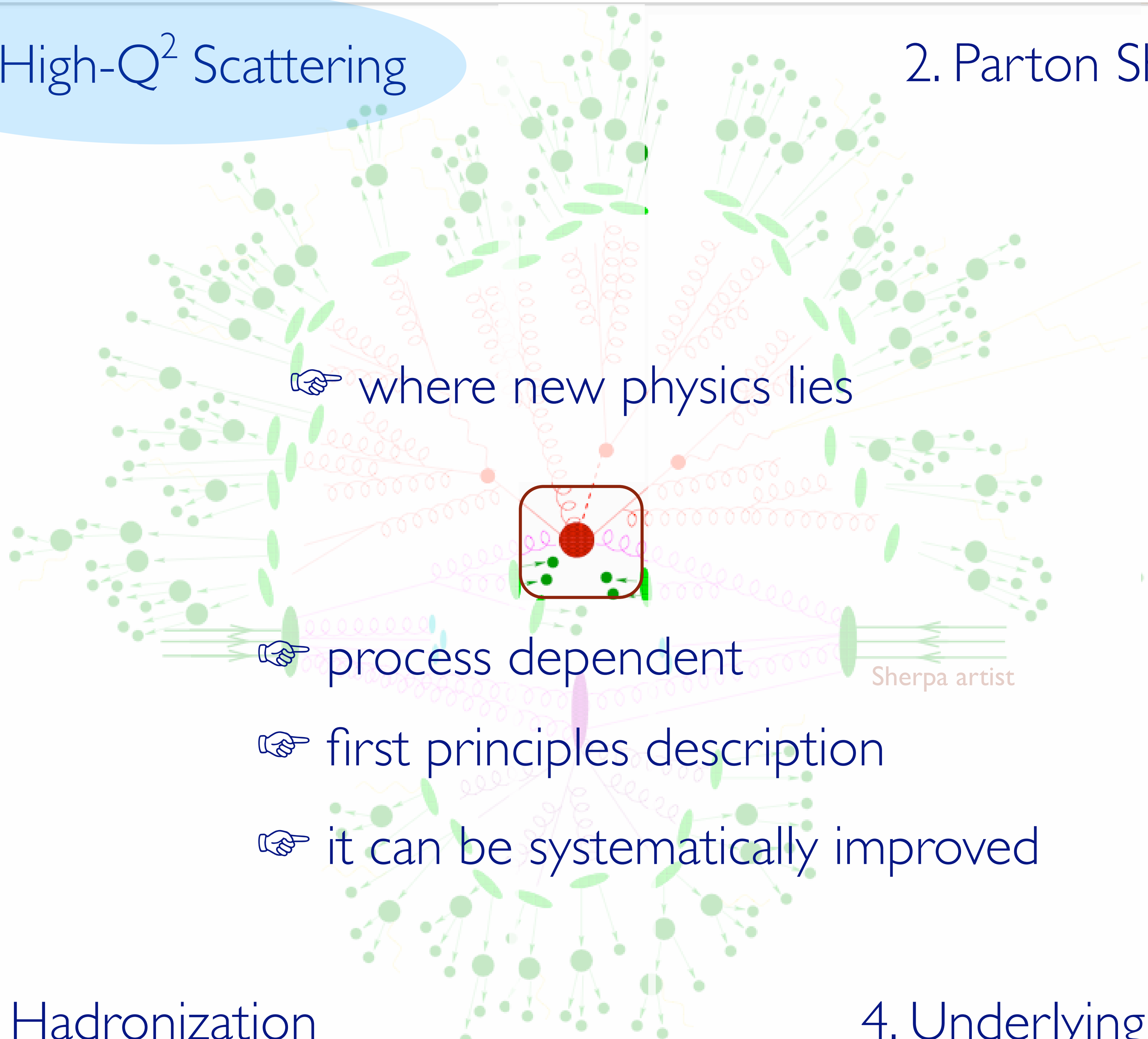
A parton shower program associates one of the possible histories (and pre-histories in case of pp collisions) of an hard event in an explicit and fully detailed way, such that the sum of the probabilities of all possible histories is unity.




1. High-Q^2 Scattering
2. Parton Shower
Sherpa artist
3. Hadronization
4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



☞ where new physics lies

☞ process dependent

☞ first principles description

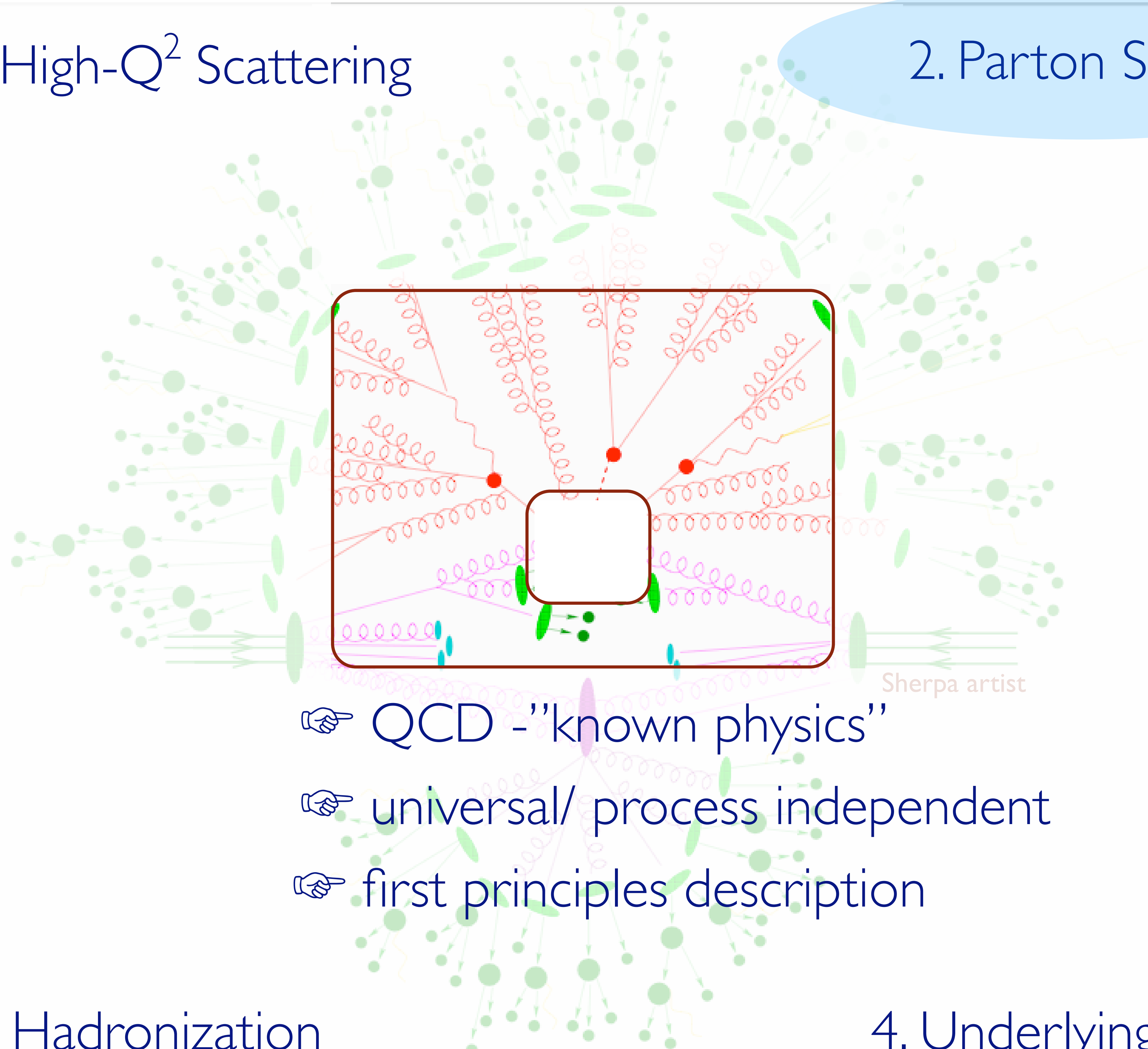
☞ it can be systematically improved

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



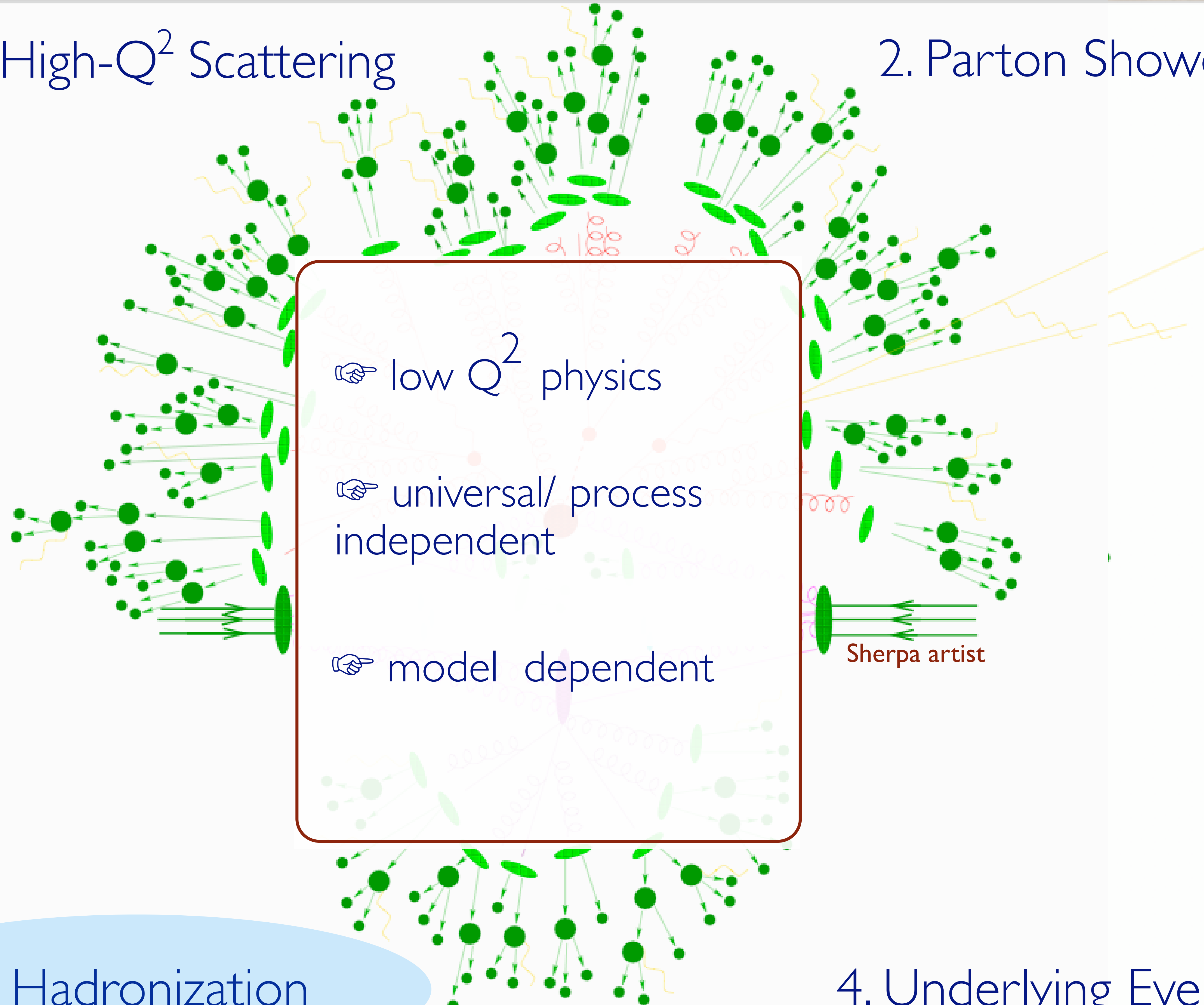
- ☞ QCD -"known physics"
- ☞ universal/ process independent
- ☞ first principles description

3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower



☞ low Q^2 physics

☞ universal/ process independent

☞ model dependent

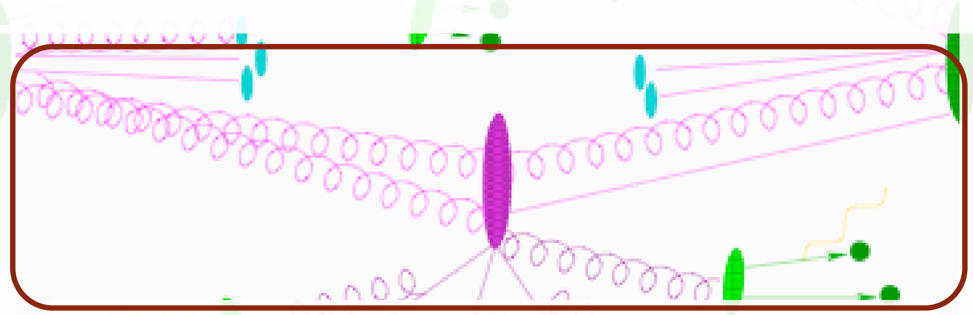
3. Hadronization

4. Underlying Event

1. High-Q^2 Scattering

2. Parton Shower

- ☞ low Q^2 physics
- ☞ energy and process dependent
- ☞ model dependent

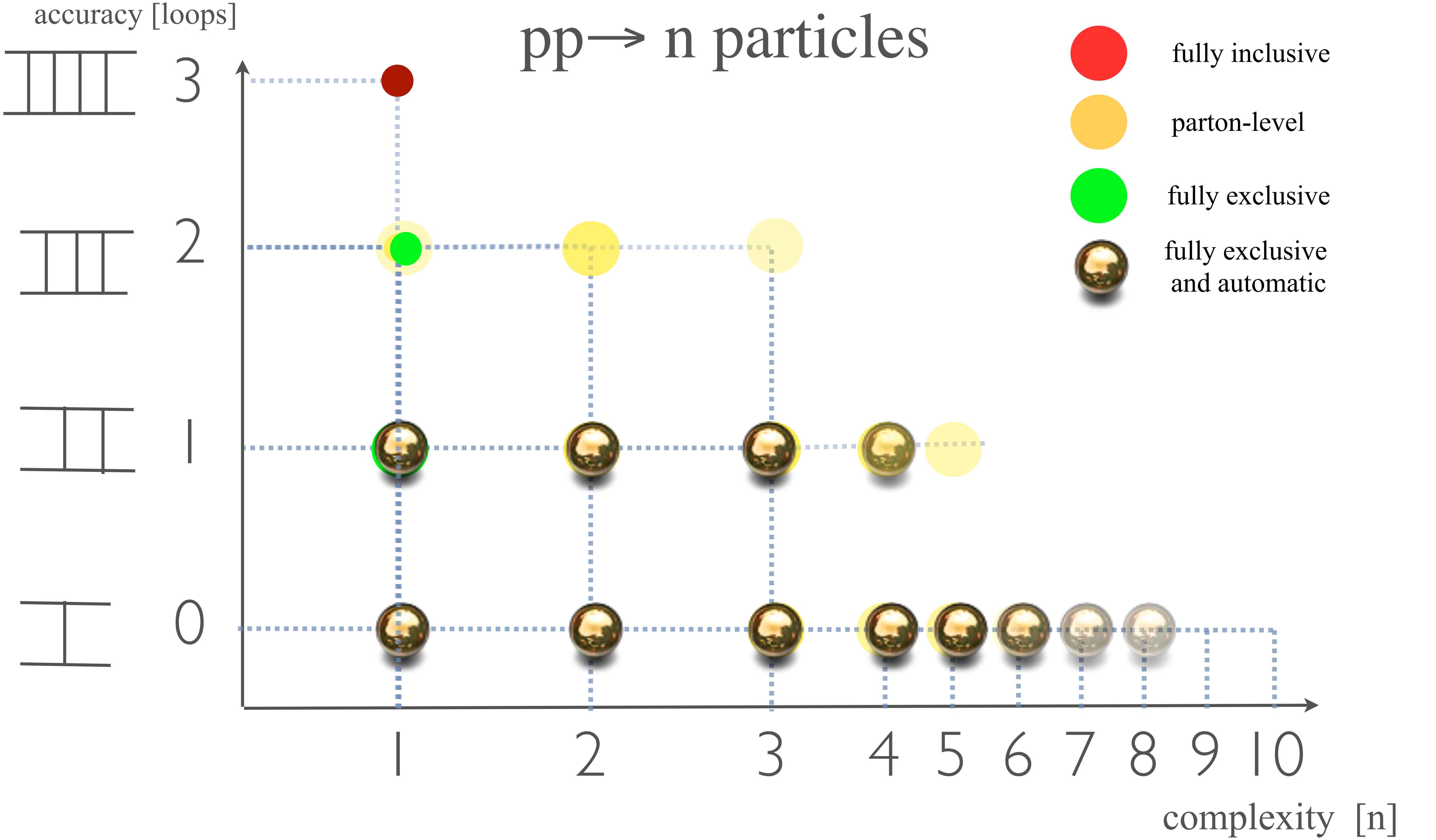


Sherpa artist

3. Hadronization

4. Underlying Event

SM : accuracy vs complexity



New generation of MC tools

Theory

Lagrangian
Gauge invariance
QCD
Partons
NLO
Resummation
...

Detector simulation
Pions, Kaons, ...
Reconstruction
B-tagging efficiency
Boosted decision tree
Neural network
...

Experiment

Fully automatic simulation chain

TH

EXP

Idea

Lagrangian

FeynRules//Sarah

ME Generator

Signal & Bkg

Events

PS+Had

Delphes/Sim

Data

- One path for all
- Physics and software validations streamlined
- Robust and efficient Th/Exp communication
- It works top-down and bottom-up

Complete automatization LO (and now NLO) calculations available, including merging with the parton shower in multi-jet final states, for SM as well as for BSM physics.

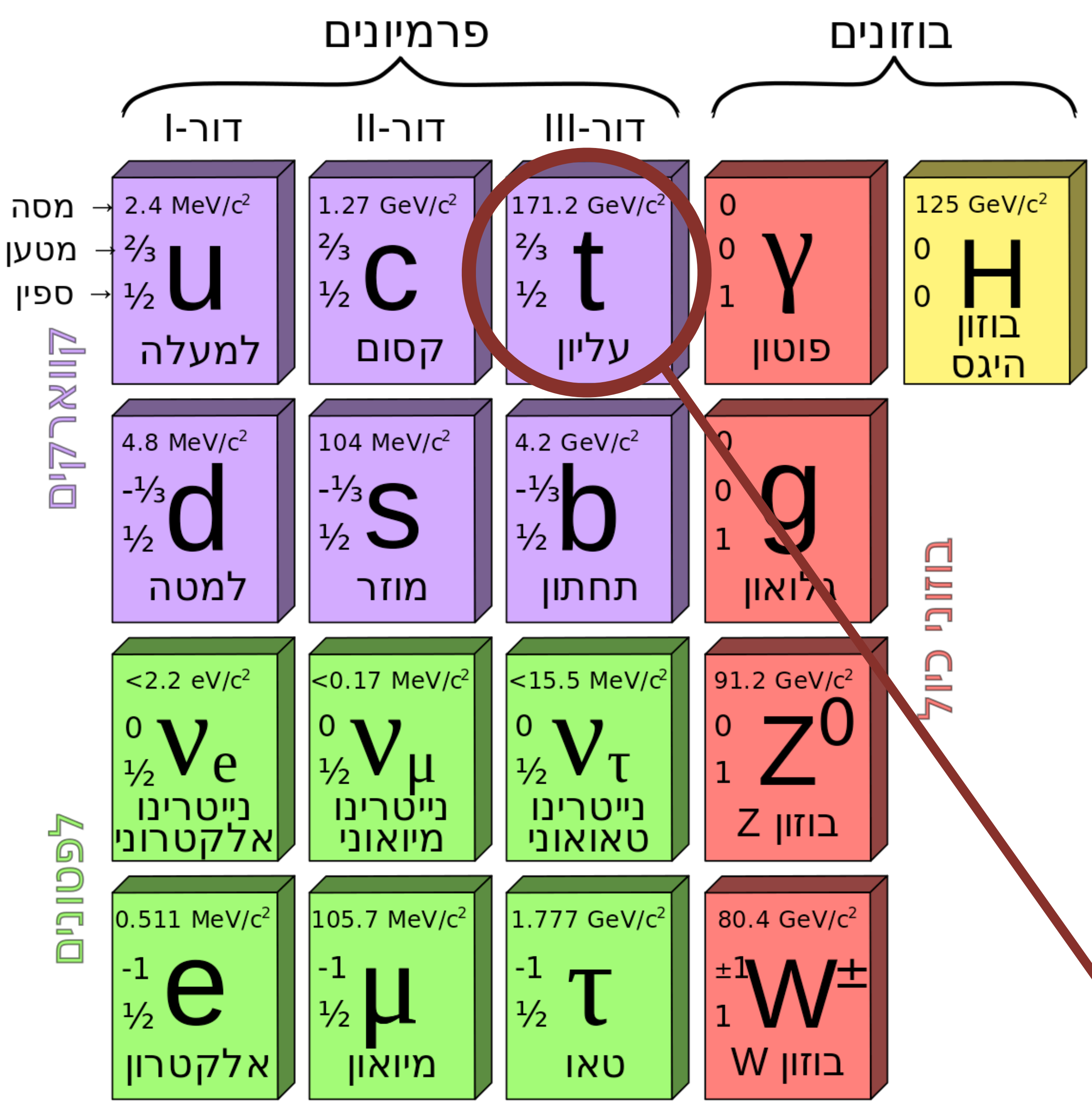
Collider Phenomenology

I Basics of collider physics and QCD

II SM Pheno: the top quark

III Searching for New Physics with tops

The SM in a nutshell

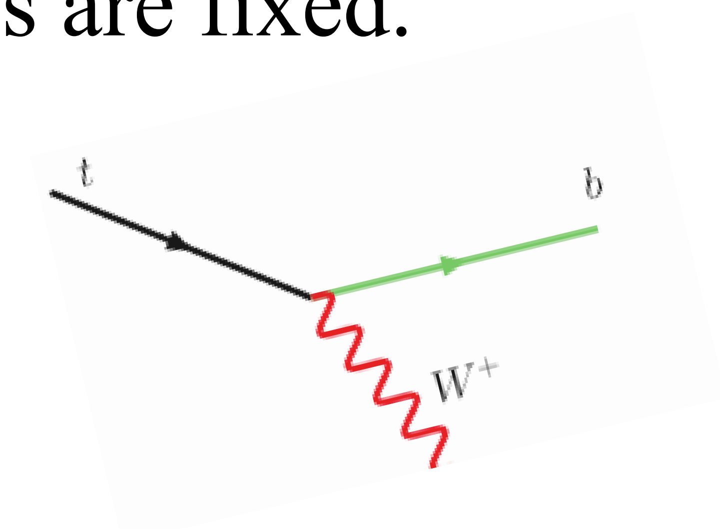


- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetries.
- Matter is organised in chiral multiplets of the fundamental representation of the gauge groups.
- The $SU(2) \times U(1)$ symmetry is spontaneously broken to EM.
- Yukawa interactions are present that lead to fermion masses and CP violation.
- Neutrino masses can be accommodated in two distinct ways.
- Anomaly free.
- Renormalisable = valid to "arbitrary" high scales.

Our guy!

The top quark

- It is the $SU(2)_L$ partner of the bottom.
- $t_L \Rightarrow T_3$=+1/2 , t_R singlet.
- Its mass is obtained in the EWSB.
- Q_t=+2/3 and is a color triplet.
- All gauge couplings are fixed.
- It decays weakly.




Charmonium is there, Bottomonium is there, what about Toponium?
Unfortunately, top decays too fast for bound states to form...
Radiation in top events? Everybody knows that top does not like to radiate a lot...
Measuring the top spin effects will prove that hadronization does not take place!
Have you heard of the latest top mass measurement?..
Which mass?
Vtb? I just measure it in top decays!
I think the top will become the gateway to a new world…
I don't understand why everybody gets so excited about Top: is just a quark like the others!

Truth or Myth #1 :

“The top is special”

The top is special

In the SM is the **only** quark with a “natural mass”:

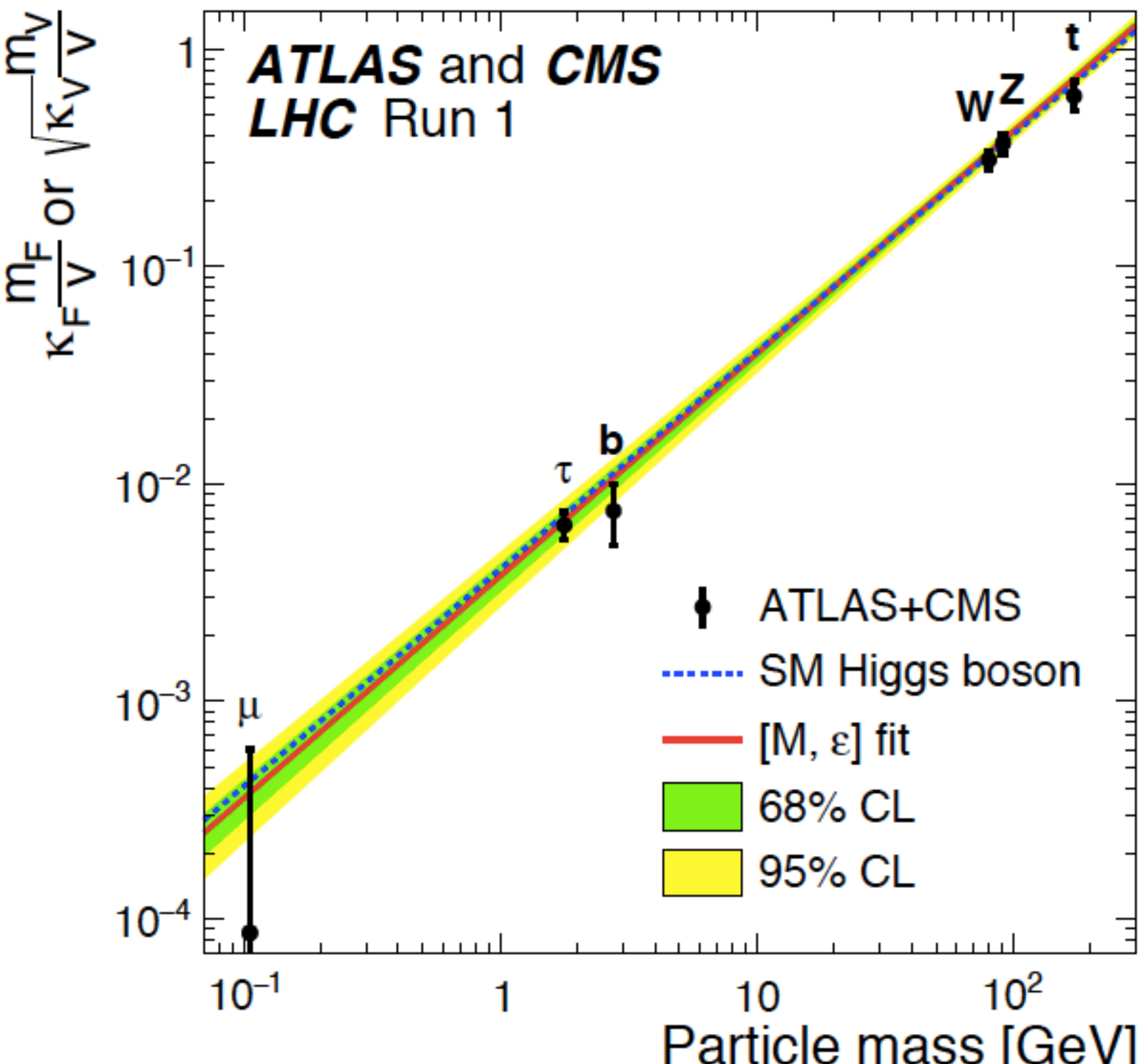
$$m_{top} = y_t\, v/\sqrt{2} \approx 174\ \text{GeV} \Rightarrow y_t \approx 1$$

i.e., it “strongly” interacts with the Higgs sector.

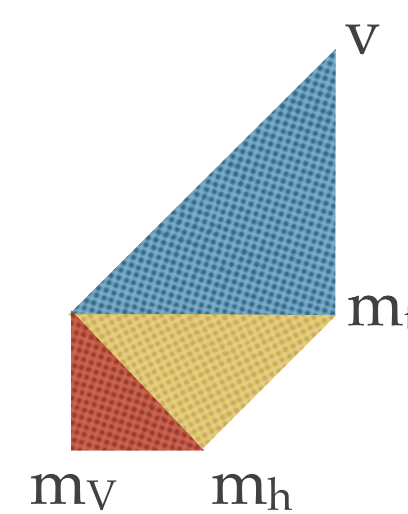
Therefore:

- It gives large corrections to EW observables.
- It points to a mass generation mechanism at low scales.
- It destabilises the Higgs mass.
- It deforms the Higgs potential at high energy.
- It decays semi-weakly.

Higgs couplings



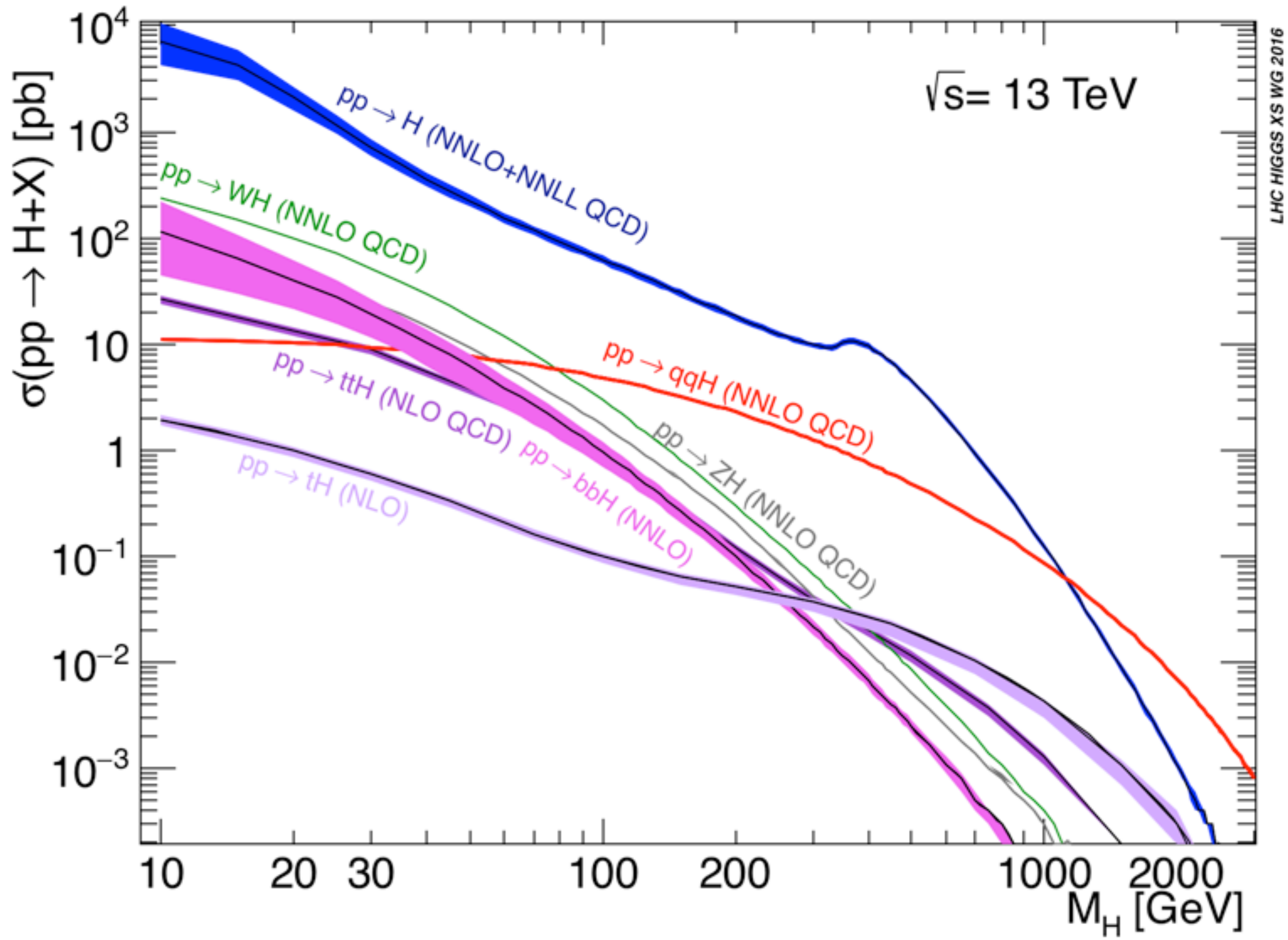
$$\frac{v}{m_t} = \frac{m_t}{m_h} = \frac{m_h}{\bar{m}_V} = \sqrt{2}$$

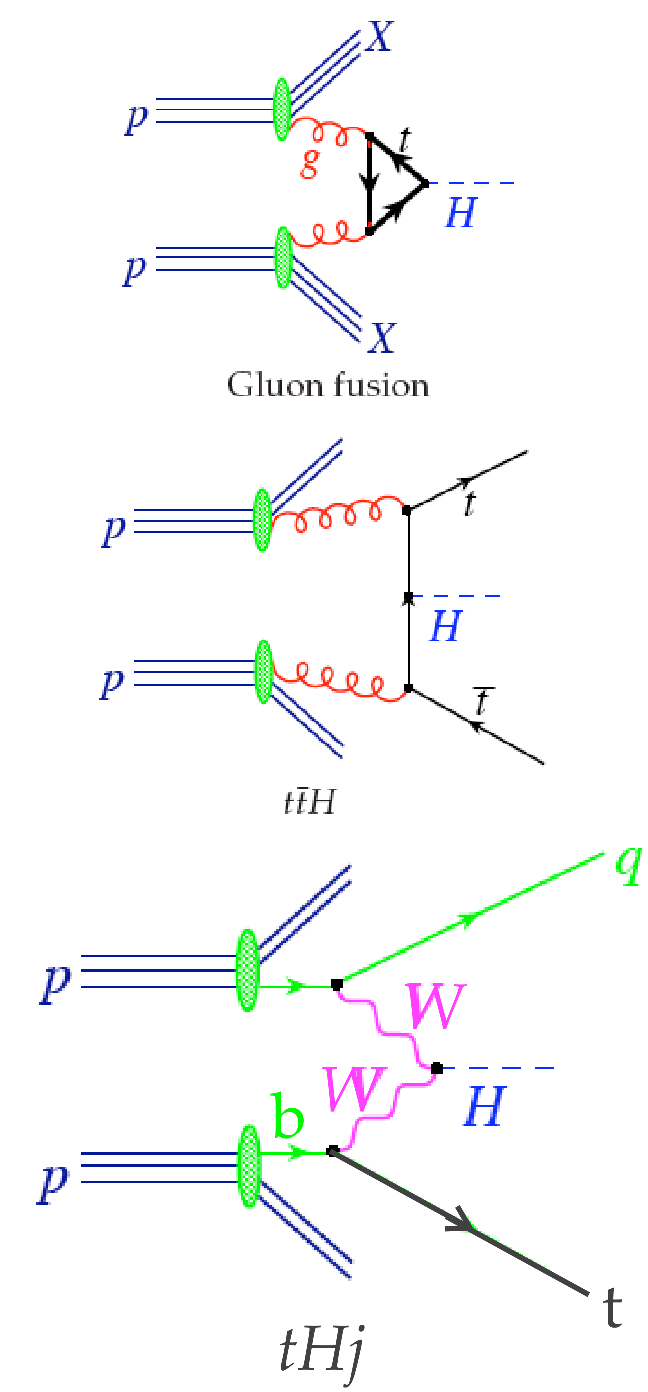


$$r = 2^{\frac{2\theta}{\pi}}$$

SM logarithmic spiral

Higgs production

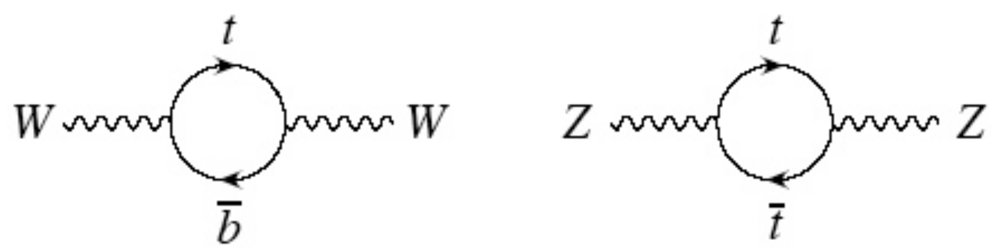




Precision EW measurements

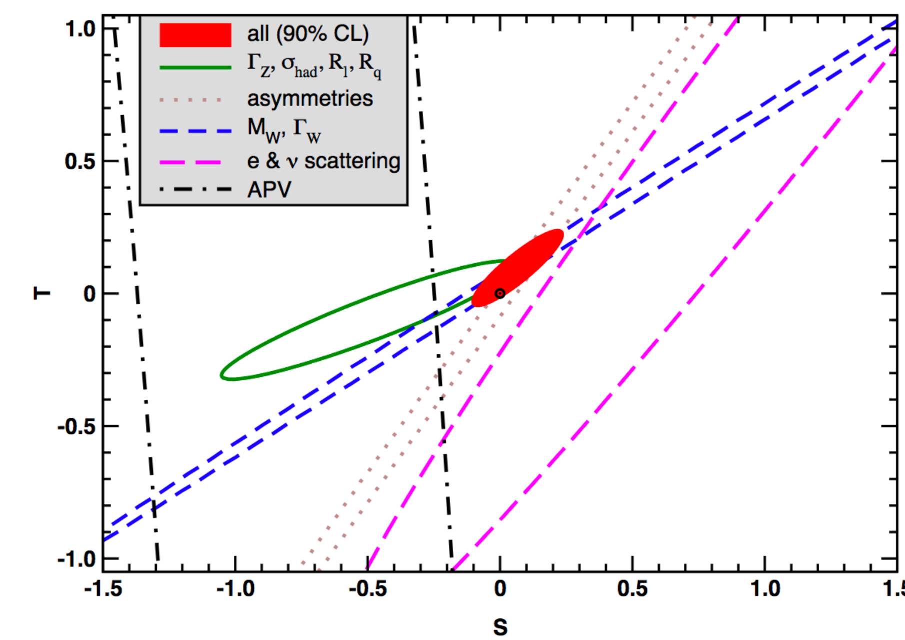
Indirect evidence for the existence of particles not yet detected can be inferred from quantum corrections. At tree level mW=mZ cos θ_W. At one loop:

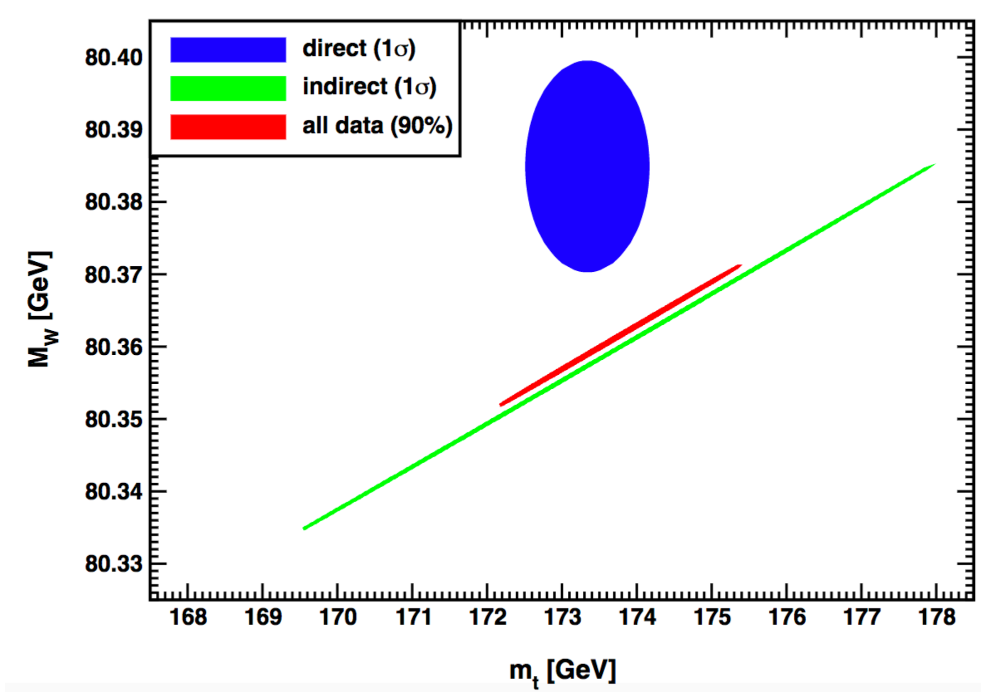
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



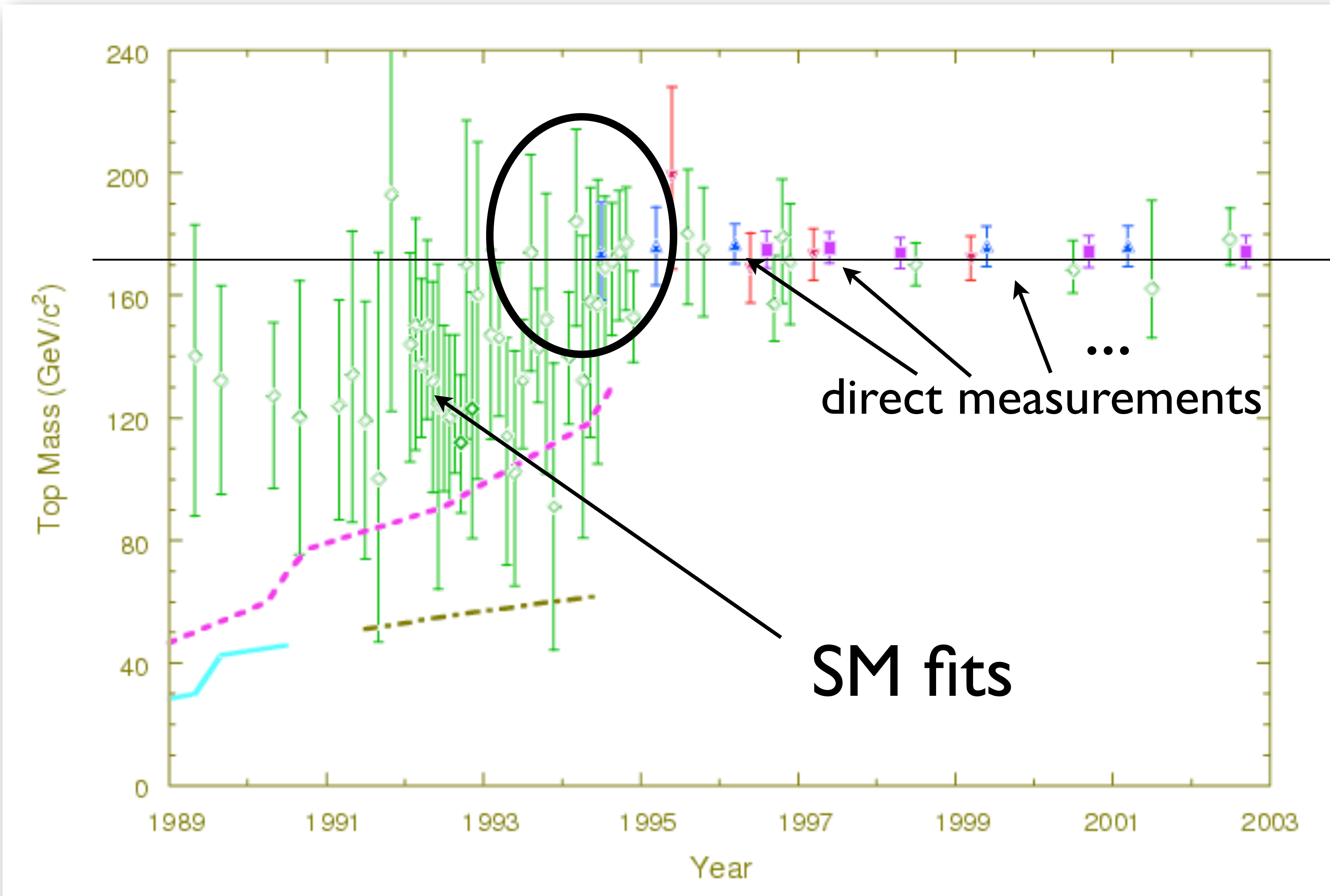
$$\Delta r_{\rm top}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$

$$\Delta r_{\rm Higgs}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$





Top mass history

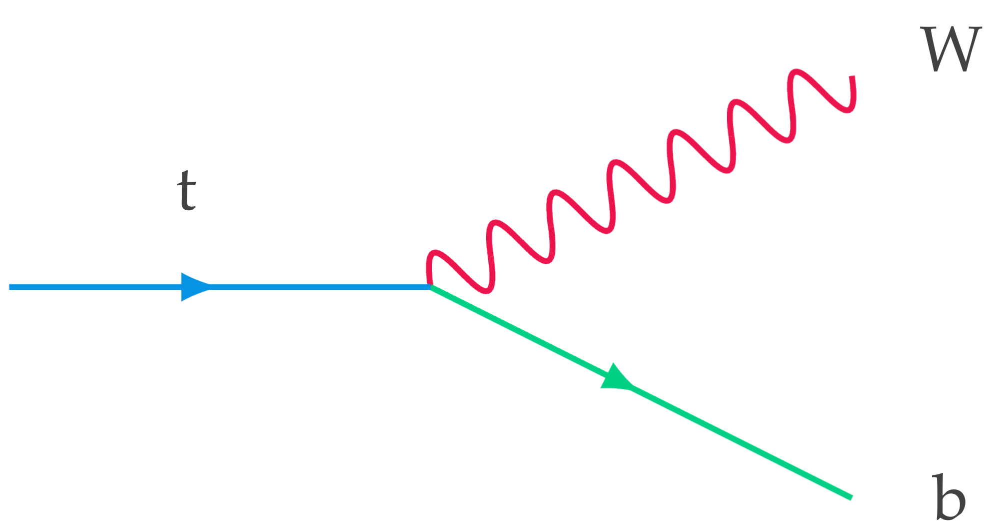


Quigg

Such a heavy top was a surprise. However, the lower limit had been increasing and there had been hints from analysis of electroweak data, where the top mass enters via loop corrections.

The top is special

Thanks to its large mass it is the only quark that decays before hadronising



b

$\tau_{had} \approx h/\Lambda_{QCD} \approx 2 \bullet 10^{-24}$ s
$\tau_{top} \approx h/\ \Gamma_{top} = 1/(GF\ m_t^3\ |Vtb|2/8\pi\sqrt{2}) \approx 5 \bullet 10^{-25}$ s
(with h=6.6 10^{-25} GeV s)

(Compare with $\tau_b \approx (GF^2\ mb^5\ |V_{bc}|^2\ )^{-1} \approx 10^{-12}$ s)

Truth or Myth #1 :

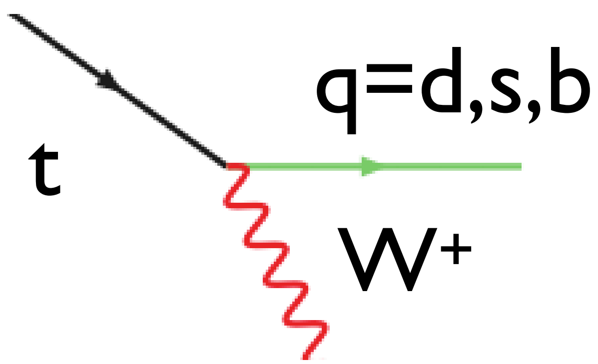
“The top is special”

Truth

Truth or Myth #2 :

“Vtb can be measured from the top decay”

Vtb can be measured from the top decay?



The argument goes as follows.

The number of events where the top decays into b jets is given by

$$N_{\text{events}} = (\mathcal{L}\cdot\epsilon)\sigma(t\bar{t})\cdot\frac{\Gamma(t\to Wb)}{\sum_q \Gamma(t\to Wq)} = (\mathcal{L}\cdot\epsilon)\sigma(t\bar{t})\cdot|V_{tb}|^2$$

where we have used unitarity of the CKM:

$$|V_{td}|^2+|V_{ts}|^2+|V_{tb}|^2=1$$

The top cross section depends only on QCD and top mass and can be given by theory. Lumi and efficiencies are exp. determined.

Do you agree?

Vtb intermezzo

Let's remind ourselves what the CKM matrix actually is

$$J_\mu^+ = \bar{u}_L \gamma_\mu d_L \quad \overset{\text{mass eigenstates}}{\Rightarrow} \quad J_\mu^+ = \bar{U}_L \gamma_\mu V_{\mathrm{CKM}} D_L$$

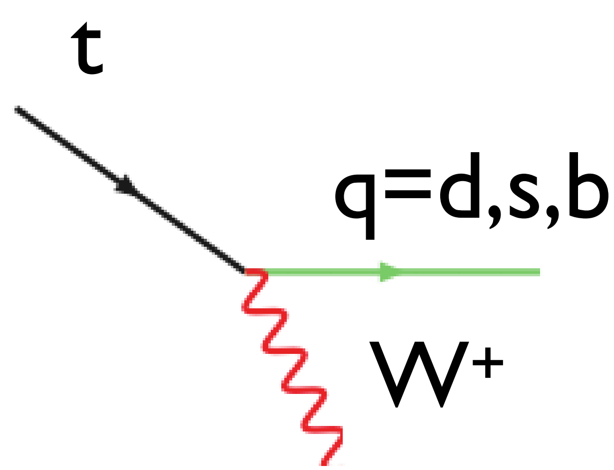
By fitting all the information we have available mostly from K0-$\overline{\text{K0}}$ mixing, B-physics:

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \Rightarrow \begin{pmatrix} 0.9730-0.9746 & 0.2174-0.2241 & 0.0030-0.0044 \ldots \\ 0.213\ \ -0.226 & 0.968\ \ -0.975 & 0.039\ \ -0.044\ \ \ldots \\ 0\ \ \ \ \ \ \ -0.08 & 0\ \ \ \ \ \ \ -0.11 & 0.07\ \ \ -0.9993 \ldots \\ \vdots & \vdots & \vdots \end{pmatrix}$$

However most of such information, does not tell us anything directly on the last row. It is the hypothesis of unitarity of the CKM which constraints the Vti matrix elements. For example the last measurements from CDF on Bs - Bs mixing gives

$$0.20 < |V_{td}/V_{ts}| < 0.22$$

Vtb can be measured from the top decay?



Counter arguments:

1. Assuming 3 generation unitarity leaves OUT the interesting BSM physics that this measurement explores (4th generation) In addition within 3 generation, Vtb = 0.999...!!!

2. Number of events is proportional to the Branching ratio,

$$R = \frac{\Gamma(t \to Wb)}{\sum_{light} \Gamma(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

where we already know that Vtd,Vts <<Vtb , so R~1 independently of the overall scale of Vtd,Vts ,Vtb and basically independent of Vtb.

Conclusion: Vtb cannot be measured from the decay of the top. From where then? You need quantities (almost) proportional to |Vtb|2 only. Two possibilities:

1. The width of the top
2. Single top cross section

Truth or Myth #2 :

“Vtb can be measured from the top decay”

Myth

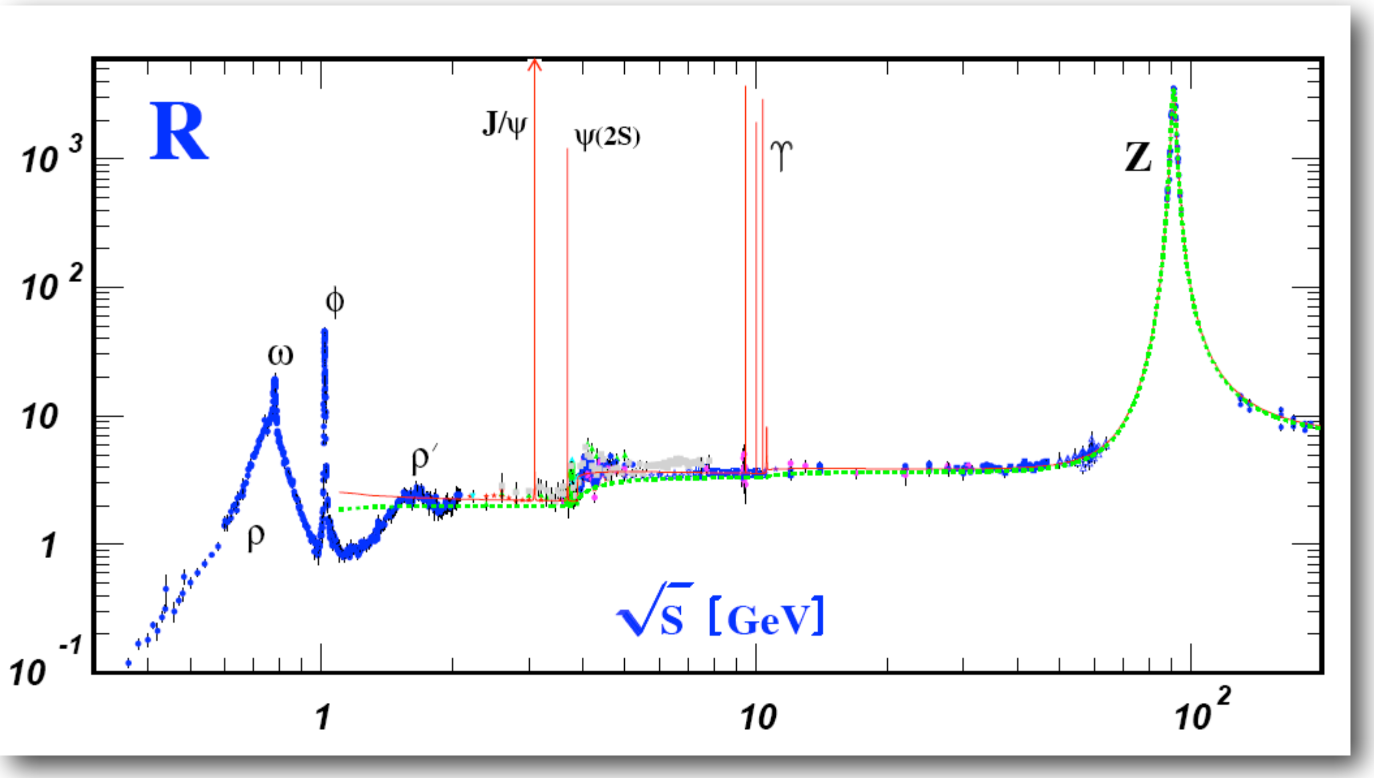
Truth or Myth #3 :

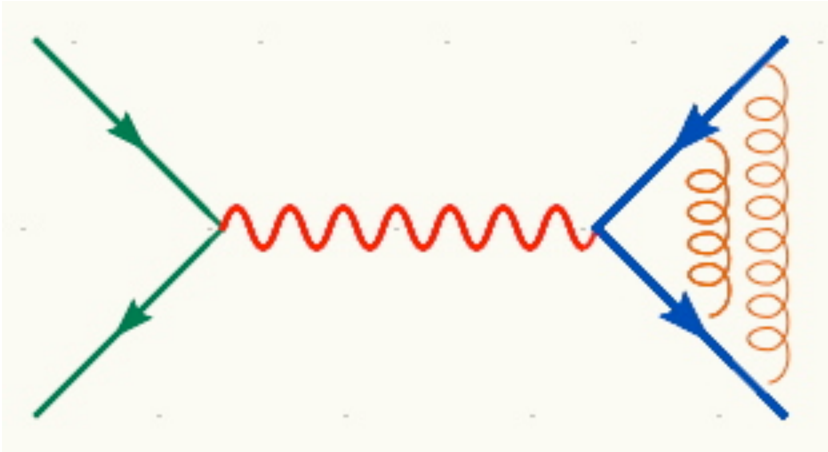
No hadronisation $\Rightarrow$ no resonance physics

What about toponium?

Consider how the charm and the bottom quarks were discovered:

$R \equiv \frac{\sigma(e^+e^- \to \text{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}$





$$^{2S+1}L_J^{[C]} = {}^3S_1^{[1]}$$

Very sharp peaks => small widths (~ 100 KeV) compared to hadronic resonances (100 MeV) => very long lived states. QCD is "weak" at scales >> ΛQCD (asymptotic freedom), non-relativistic bound states are formed like positronium!

The QCD-Coulomb potential is like $V(r) \simeq -C_F \frac{\alpha_S(1/r)}{r}$ $\qquad C_F = 4/3$

What about toponium?

Let analyse the scales which characterise the bound state. The scales can be found using the
the enegy of the ground state and the virial theorem:

$$E_0 = -\frac{1}{2}\frac{m_t}{2}(C_F\alpha_S)^2 \quad \text{with} \quad \langle T\rangle = -\frac{1}{2}\langle V\rangle \quad \text{gives} \quad v \simeq C_F\alpha_S(mv)$$

$$R_0 = 1/(C_F\alpha_S m_t/2)$$

Scale	Quantity	e+e-	toponium
m	annhilation time	0.5 MeV	172 GeV
mv	size p~1/R	3.7 KeV	15 GeV
mv^2	Formation time	25 eV	2 GeV

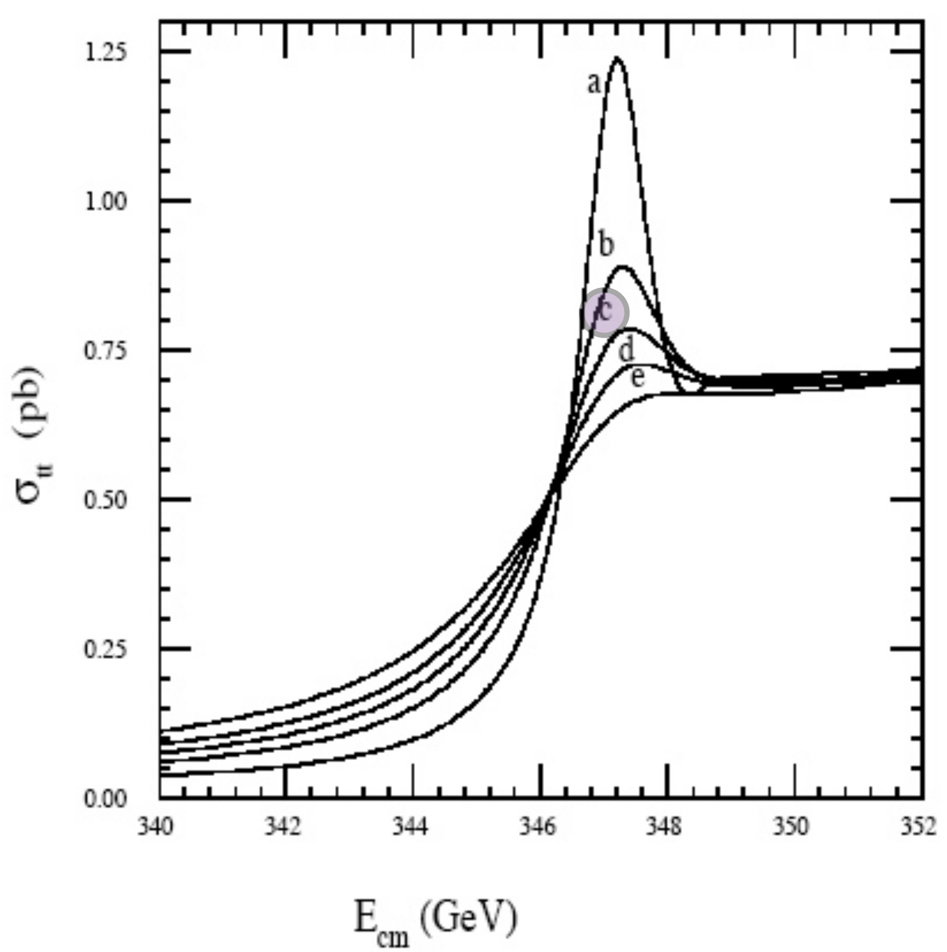
This equation can be solved iteratively and gives scales that are all perturbative and well separated.

"Unfortunately" the formation time for the bound state is

$\tau_{form} \approx$ size/v $\approx$ mv2 $\approx 1/(2$ GeV)

$\tau_{weakdecay} \approx \tau$top/2 $\approx 1/(3$ GeV) $< \tau_{form}$

What about toponium?



The time scales, formation and decay, are not so widely different (by chance!). Therefore if we perform a threshold scan in e+e- we should be able to see an enhacement of the cross section, due to Coulomb rescattering.

The width of the peak is proportional to the width (direct measurement) and the position of the peak would allow a very precise mass measurement.

Truth or Myth #3 :

No hadronisation ⇒ no resonance physics

Myth

Truth or Myth #4 :

“No hadronization $\Leftrightarrow$ Top spin effects”

“No hadronization ⇔ Top spin effects”

We have now very clear that most probably (if Vtb is indeed 1) top decays before hadronizing,

$$\tau_{had} \approx h/\Lambda_{QCD} \approx 2\cdot 10^{-24}\ s \ > \ \tau_{top\ dec} \approx h/\ \Gamma_{top}\ 5\cdot 10^{-25}\ s$$

Therefore non-perturbative effects (soft-gluons) don’t have the time to change the spin of the top which is then passed from the production to the decay. As a result the spin becomes a typical quantum mechanical quantity and correlation measurements can be performed (see tomorrow).

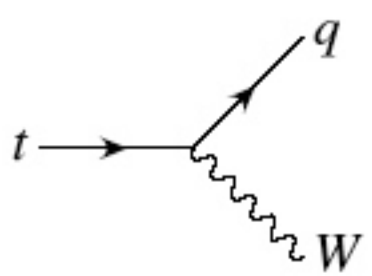
HOWEVER, one can also ask : Is the opposite true? if we see spin correlation effects do we automatically put an upper bound on the width and hadronization? NO!
Spin-flips are due to CHROMOMAGNETIC interactions, which are mediated by dimension 5 operators:

$$\mathcal{L}_{\rm mag} = \frac{C_m}{4m_t}\bar{Q}_v G_{\mu\nu}\sigma^{\mu\nu} Q_v \Rightarrow \tau_{\rm flip} \simeq h\left(\frac{\Lambda^2_{QCD}}{m_t}\right)^{-1} >> \tau_{\rm had}$$

If, for instance, Vtb ~ 0.3, then top would start hadronizing into mesons and still conserve its spin!

[Falk and Peskin, 1994]

W polarisation

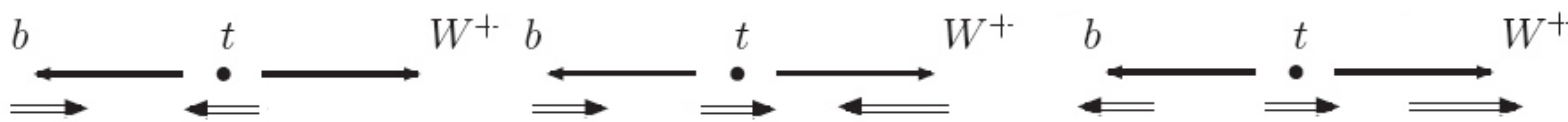


$-i\frac{g}{\sqrt{2}}V_{tq}\gamma^\mu\frac{1}{2}(1-\gamma_5)$

The SM vertex of the top decay implies that it's only the t_L that takes part to the interaction.

This has straightforward consequences on the possible helicity states of the on-shell W produced in the decay.

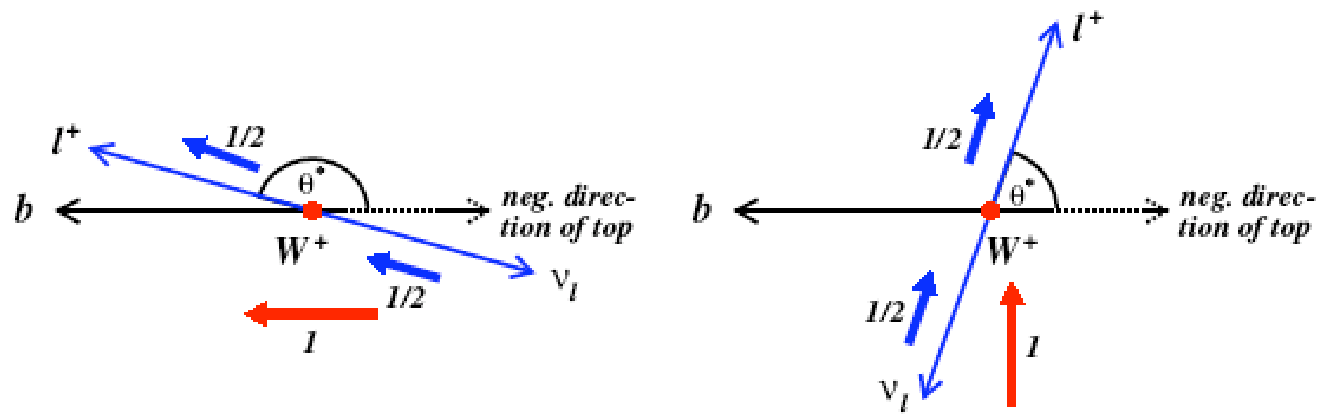
Neglecting mb, this implies that the W can be only either longitudinally polarised or with negative helicity. In general:



How do we measure it?? The W polarisation is inherited by its decay products, which "remember it" in their angular distributions.

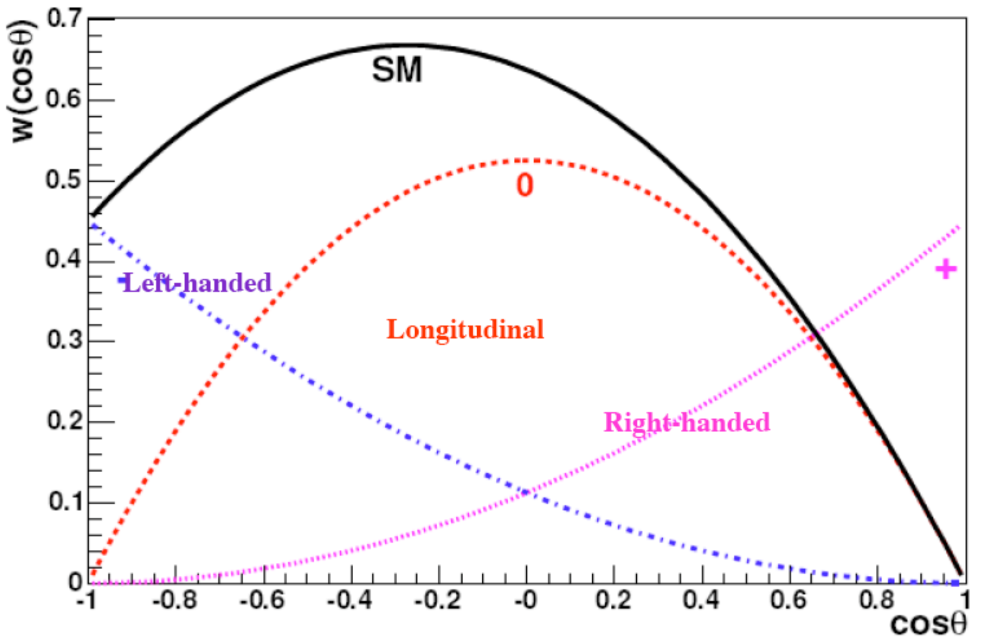
W polarisation

$$\frac{1}{N}\frac{dN(W\to l\nu)}{dcos\theta} = K\left[f_0\sin^2\theta + f_L(1-\cos\theta)^2 + f_R(1+\cos\theta)^2\right]$$



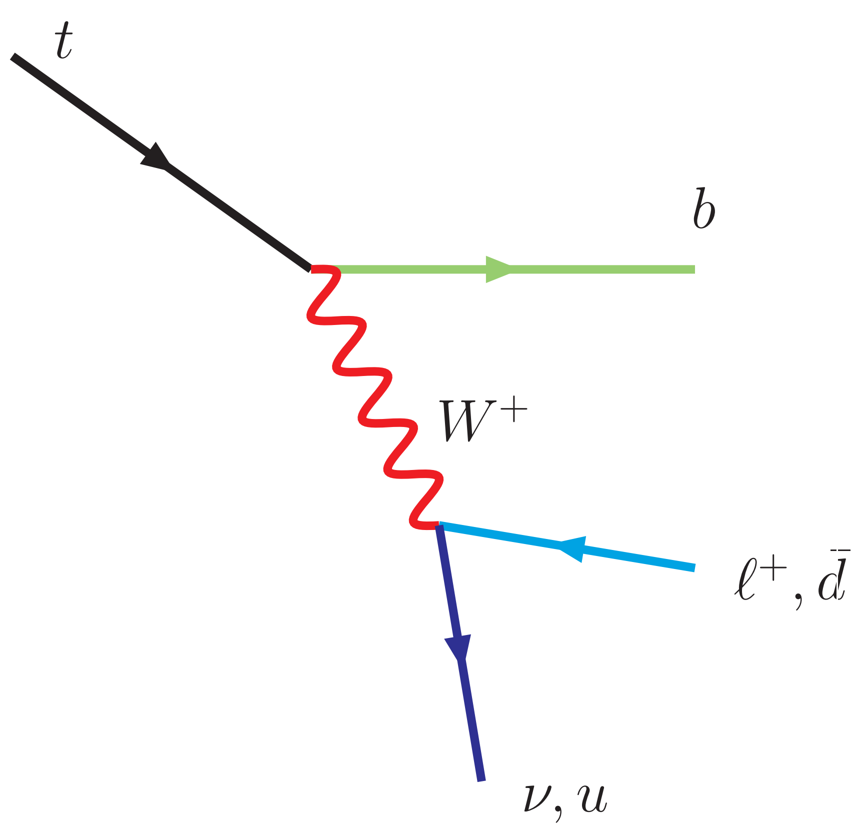
$$f_0 = \frac{m_t^2}{2m_W^2 + m_t^2} = 70\%$$

Fraction of longitudinal W's (basically the only ones we see in a pp collider!)



- The formula above is already not trivial since it says that W polarisations don't interfere! (This is true only for 1dim distributions!)
- Longitudinal polarisation come from the Higgs doublet (charged component).
- cos(θ), which is defined in a specific frame, can be related to m(lepton,bottom) or pt(lepton) , ergo
- no top momentum reconstruction necessary!
- Rather "easy measurement" .

Spin correlations



One can easily show that for the top, the lepton+ (or the d), in the top rest frame, tends to be emitted in the same direction of the top spin.

Note that this has nothing to do with W polarization! In particular one studies spin correlations between the top and anti-top in ttbar production and the spin of the top in single top.

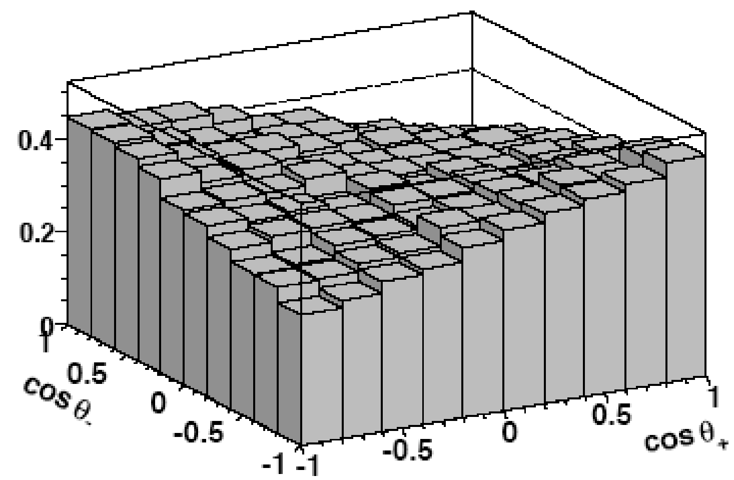
Results depend on the degree of polarization (p) of the tops themselves and from the choice of the "spin-analyzer" ki.

	ℓ^+	$\bar{d}$	u	b	$j_<$	$\mathbf{T}$	$j_>$
LO:	1	1	-0.32	-0.39	0.51	-0.32	0.2
NLO:	0.999	0.97	-0.31	-0.37	0.47	-0.31	

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = \frac{1 + p\, k_i \cos\theta}{2}$$

Spin correlations

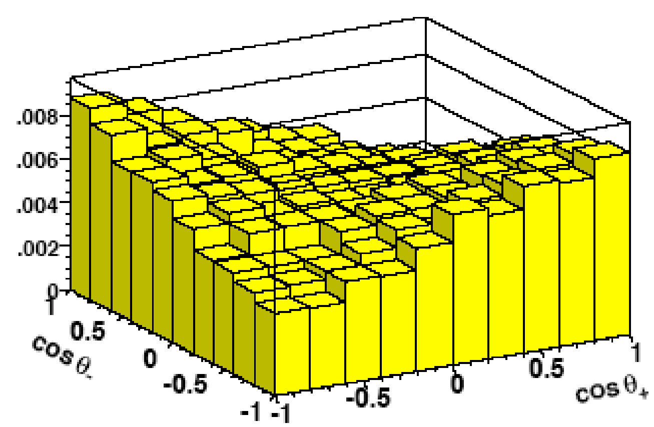
no cuts



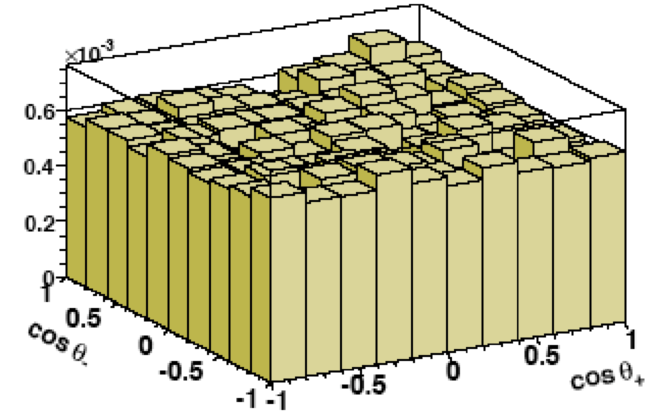
(a)

1S0 state at threshold!

low m(tt)



(b)

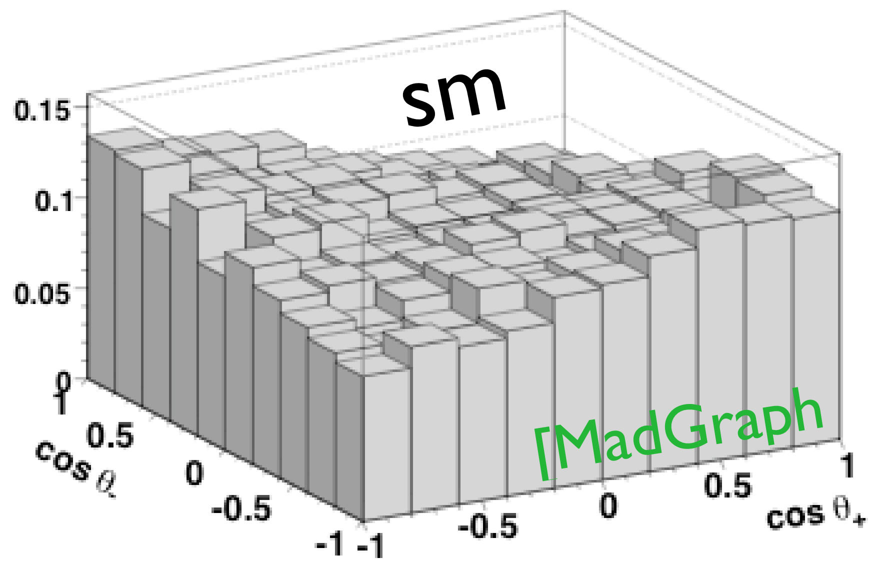


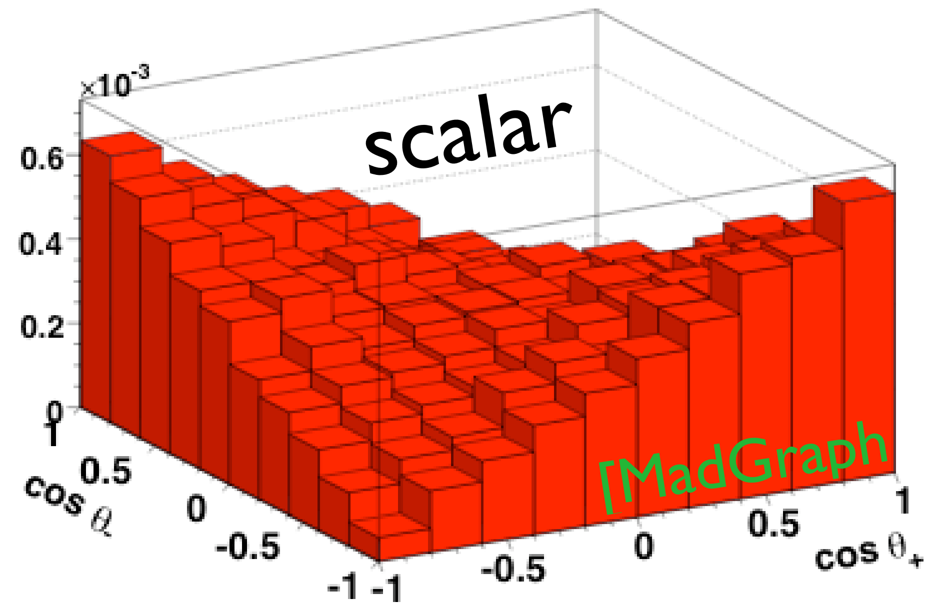
(c)

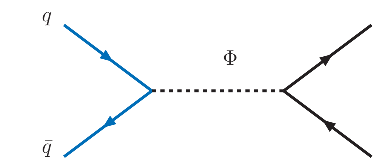
high m(tt)

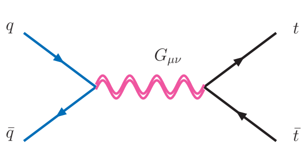
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\left(1 + \kappa_t\kappa_{\bar{t}} D\cos\theta_- \cos\theta_+\right)$$

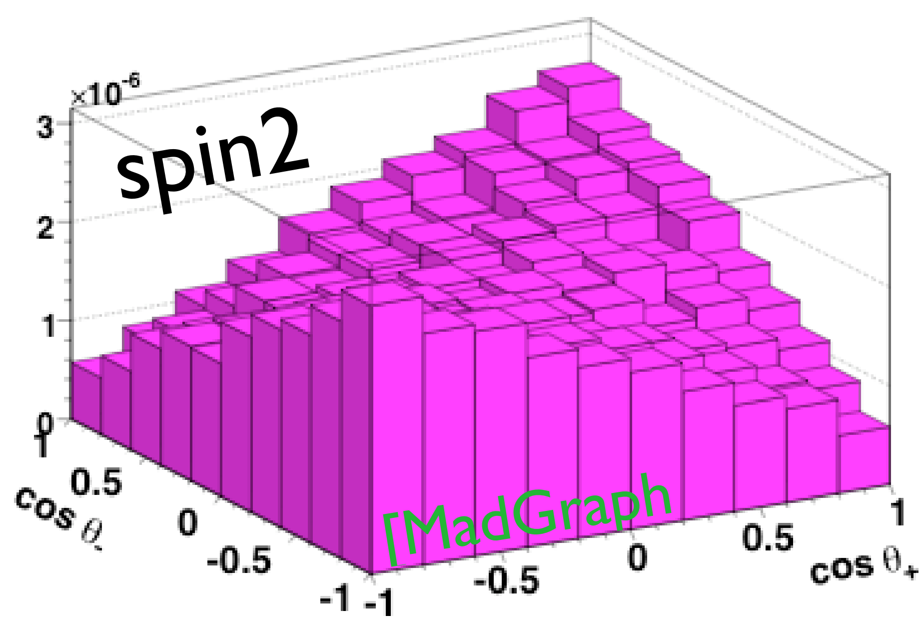
Spin correlations

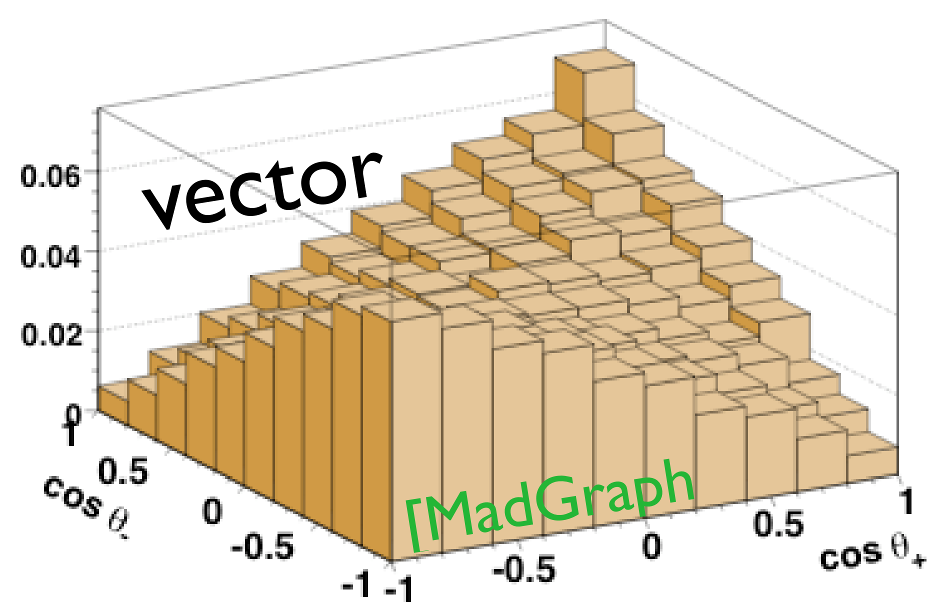


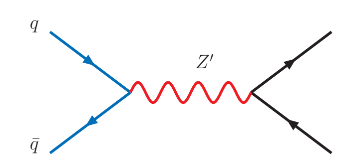


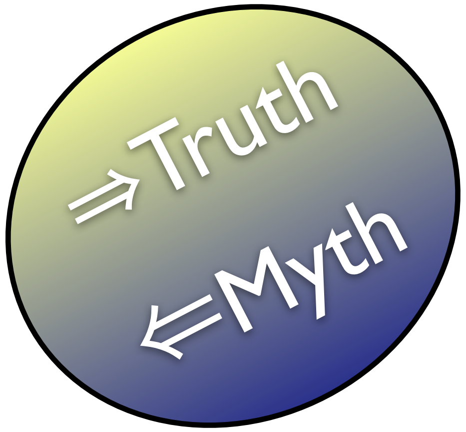












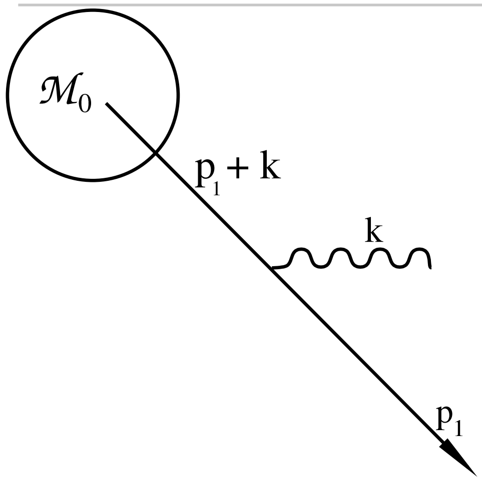
Truth or Myth #4 :

“No hadronization ⇔ Top spin effects”

Truth or Myth #5 :

“The top does not like to radiate much”

Radiation off the top



Consider gluon emission off a heavy quark using perturbation theory:

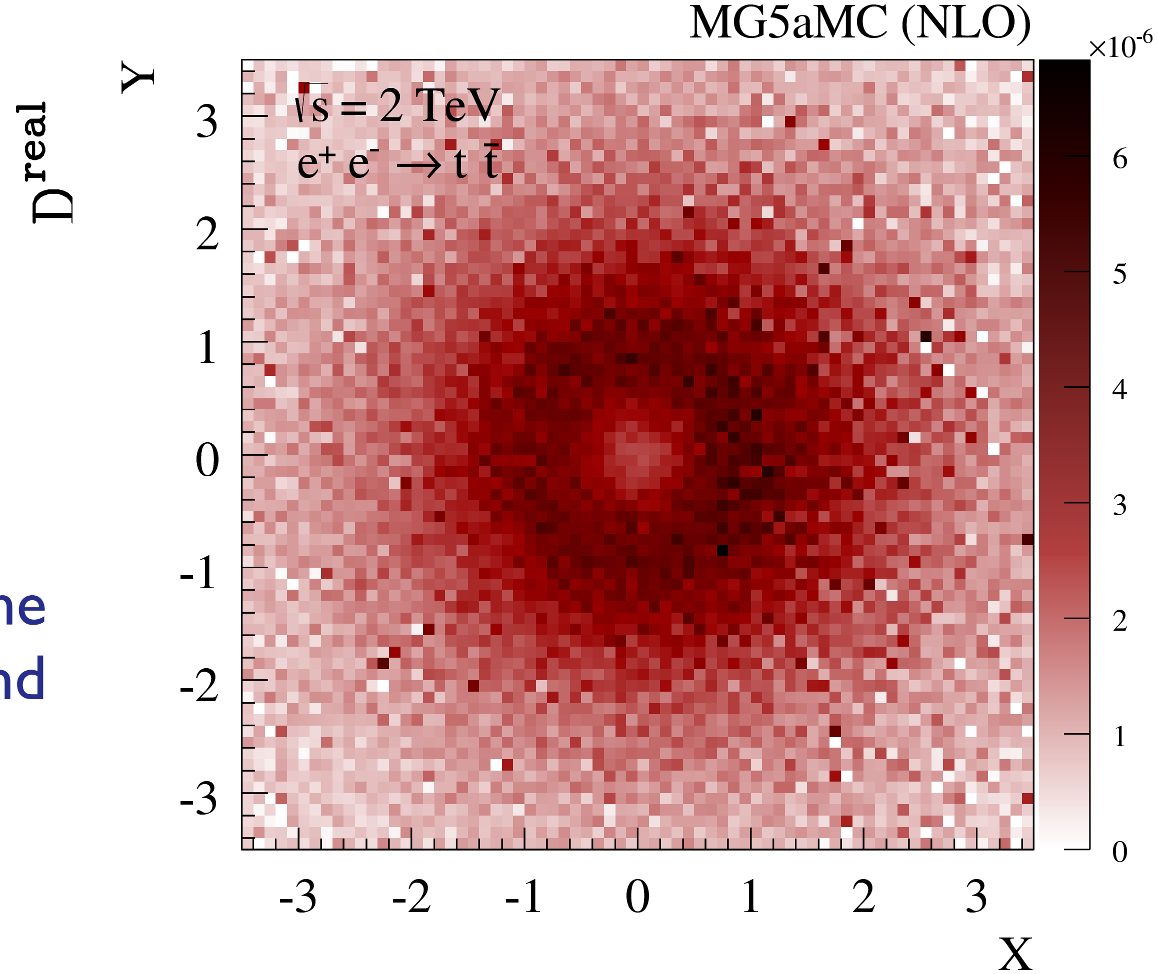
$$D^{\rm real}(x,k_\perp^2,m^2) = \frac{C_F\alpha_S}{2\pi}\left[\frac{1+x^2}{1-x}\,\frac{1}{k_\perp^2+(1-x)^2m^2} - x(1-x)\,\frac{2m^2}{(k_\perp^2+(1-x)^2m^2)^2}\right]$$

In the massless case (m=0) we have a non-integrable collinear singularity:

$$\int_0 D(x,k_\perp^2)dk_\perp^2 = \frac{1+x^2}{1-x}\int_0 \frac{dk_\perp^2}{k_\perp^2} = \infty$$

The presence of the heavy quark mass suppresses the collinear radiation at small transverse momenta and allows the integration down to zero.

Be careful because it's a frame dependent statement!



Truth or Myth #5 :

True

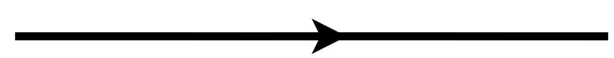
“The top does not like to radiate much”

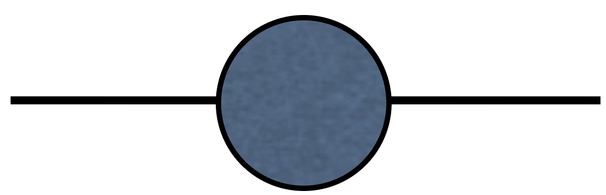
Truth or Myth #6 :

The top mass is a unique and well defined

Top mass definition

The top mass is so precisely measured (m_t=173.1 ± 1.0 GeV) that we have to worry about its definition.

Leading order:  $$\frac{1}{\not{p} - m}$$ (pole) mass = m

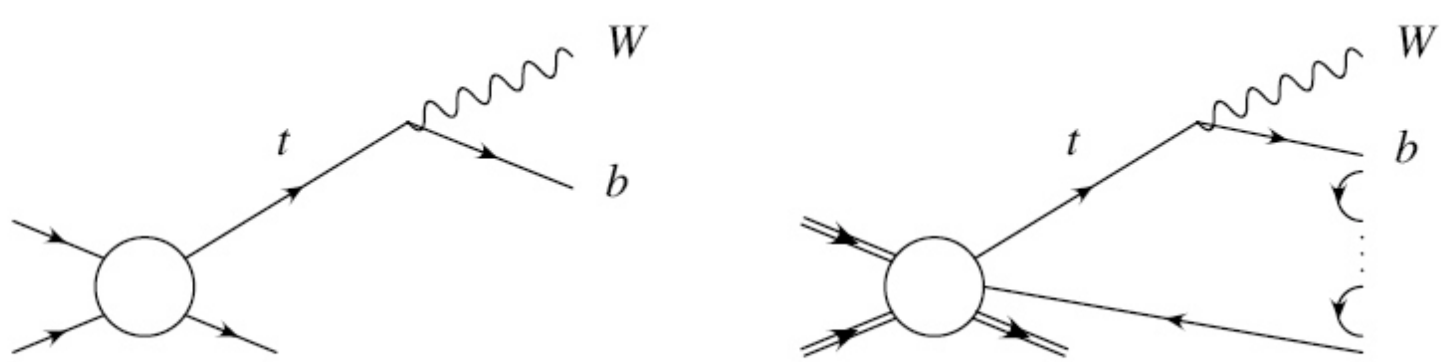
Higher orders:  $$\frac{1}{\not{p} - m_R - \Sigma(\not{p})}$$ mR = renor. mass

(At least) two possible renormalisation schemes: MSbar and on-shell, leading to to different mass definitions.

The MSbar mass is a fully perturbative object, not sensitive to long-distance dynamics. It can be determined as precisely as the perturbative calculation allows. The mass is thought as any other parameter in the Lagragian. It is the same as the Yukawa coupling.

Top mass definition

The pole mass would be more physical (pole = propagation of particle, though a quark doesn't usually really propagate -- hadronisation!) but is affected by long-distance effects: it can never be determined with accuracy better than ΛQCD.



The pole mass is closer to what we measure at colliders through invariant mass of the top decay products. The ambiguities in that case are explicitly seen in the modeling of extra radiation, the color connect effects and hadronization.
The two masses can be related perturbatively (modulo non-perturbative corrections!!):

$$m_{pole} = \overline{m}(\overline{m})\left(1+\frac{4}{3}\frac{\overline{\alpha}_s(\overline{m})}{\pi}+8.28\left(\frac{\overline{\alpha}_s(\overline{m})}{\pi}\right)^2+\cdots\right)+O(\Lambda_{\rm QCD})$$

Truth or Myth #6 :

The top mass is a unique and well defined

Myth

Truth or Myth #7 :

"The top decides the fate of the universe"

Vacuum stability

The one-loop renormalization group equation (RGE) for $\lambda(\mu)$ is

$$\frac{d\lambda(\mu)}{d\log\mu^2} = \frac{1}{16\pi^2}\left[12\lambda^2 + \frac{3}{8}g^4 + \frac{3}{16}\left(g^2+g'^2\right)^2 - 3h_t^4 - 3\lambda g^2 - \frac{3}{2}\lambda\left(g^2+g'^2\right) + 6\lambda h_t^2\right]$$

where

$$m_t = \frac{h_t v}{\sqrt{2}} \qquad\qquad m_H^2 = 2\lambda v^2$$

This equation must be solved together with the one-loop RGEs for the gauge and Yukawa couplings, which, in the Standard Model, are given by

$$\begin{aligned}
\frac{dg(\mu)}{d\log\mu^2} &= \frac{1}{32\pi^2}\left(-\frac{19}{6}g^3\right)\\
\frac{dg'(\mu)}{d\log\mu^2} &= \frac{1}{32\pi^2}\frac{41}{6}g'^3\\
\frac{dg_s(\mu)}{d\log\mu^2} &= \frac{1}{32\pi^2}\left(-7g_s^3\right)\\
\frac{dh_t(\mu)}{d\log\mu^2} &= \frac{1}{32\pi^2}\left[\frac{9}{2}h_t^3 - \left(8g_s^2 + \frac{9}{4}g^2 + \frac{17}{12}g'^2\right)h_t\right]
\end{aligned}$$

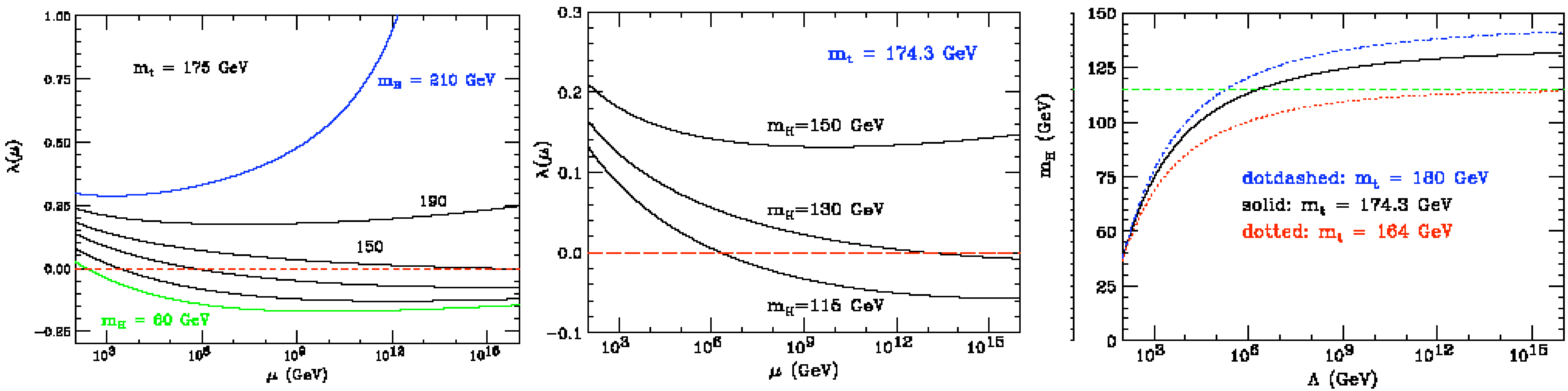
here g_s is the strong interaction coupling constant, and the $\overline{\mathrm{MS}}$ scheme is adopted.

Solving this system of coupled equations with the initial condition

$$\lambda\left(m_H\right) = \frac{m_H^2}{2v^2}$$

Vacuum stability

It can be shown that the requirement that the Higgs potential be bounded from below, even after the inclusion of radiative corrections, is fulfilled if $\lambda(\mu)$ stays positive, at least up to a certain scale $\mu \approx \Lambda$, the maximum energy scale at which the theory can be considered reliable (use effective action).

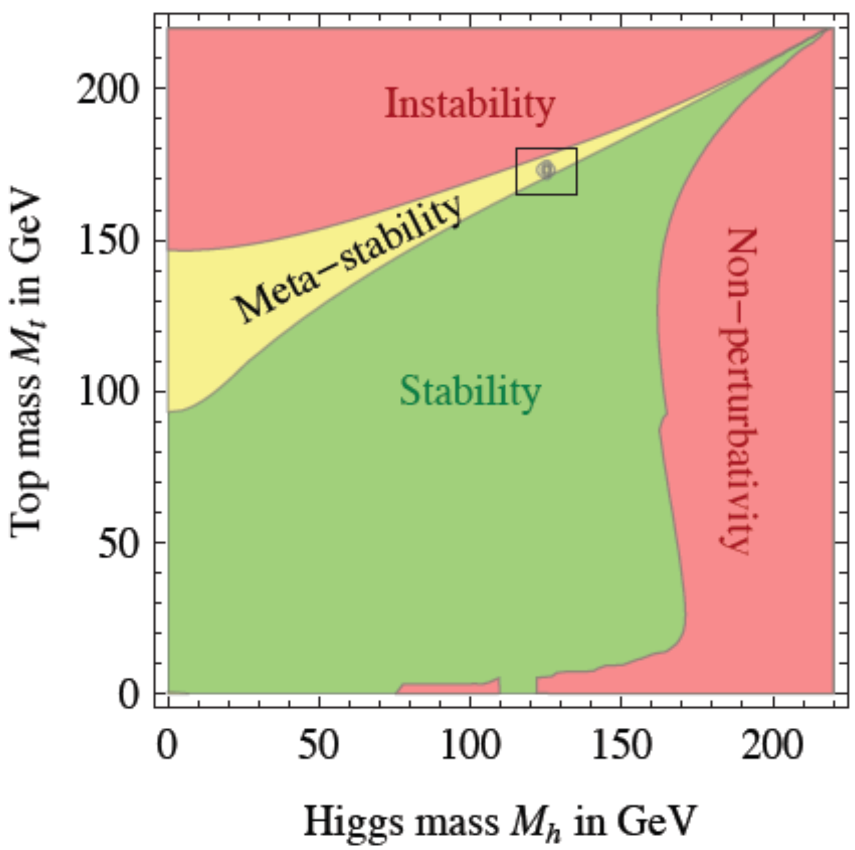


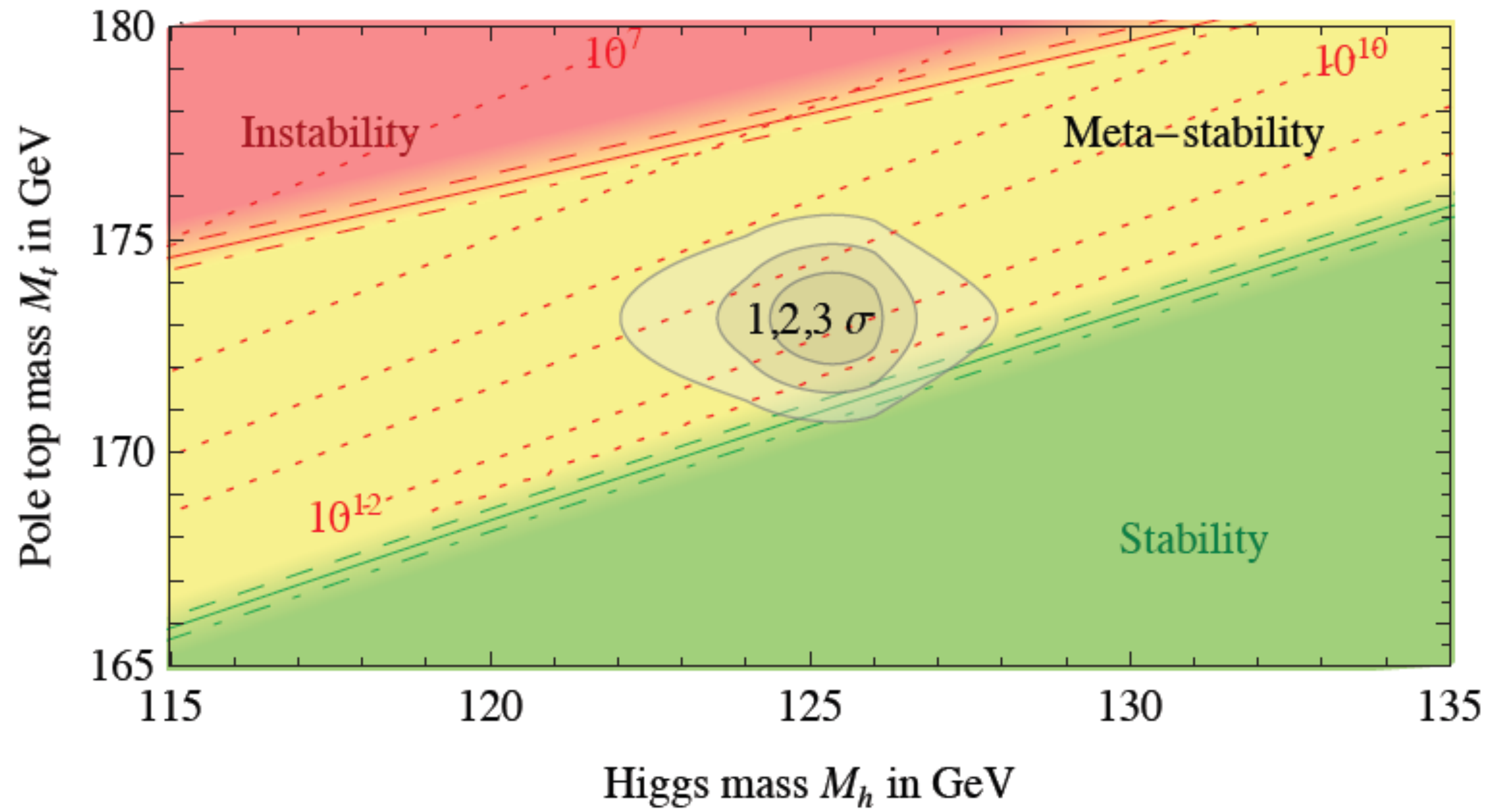
- ✗ This limit is extremely sensitive to the top-quark mass.
- ✓ The stability lower bound can be relaxed by allowing metastability

The future of the Universe

The fate of the Universe depends on 1GeV in m_t

[Degrassi, et al. ‘12]





$$y_t(M_t) = 0.93587 + 0.00557\left(\frac{M_t}{\text{GeV}} - 173.15\right)\ldots \pm 0.00200_{\text{th}}$$

It’s the Yukawa that enters in this calculation.

Truth or Myth #7 :

″The top decides the fate of the universe”

True
if no NP

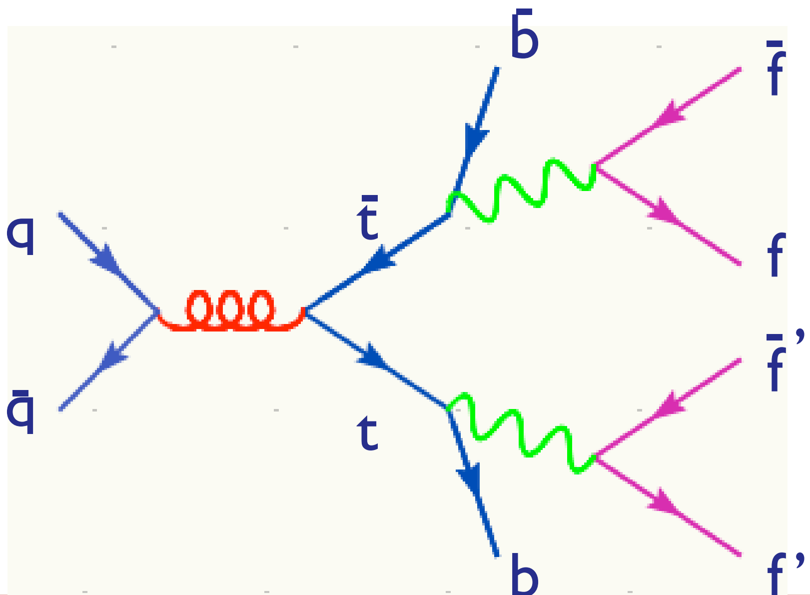
The top is special : summary

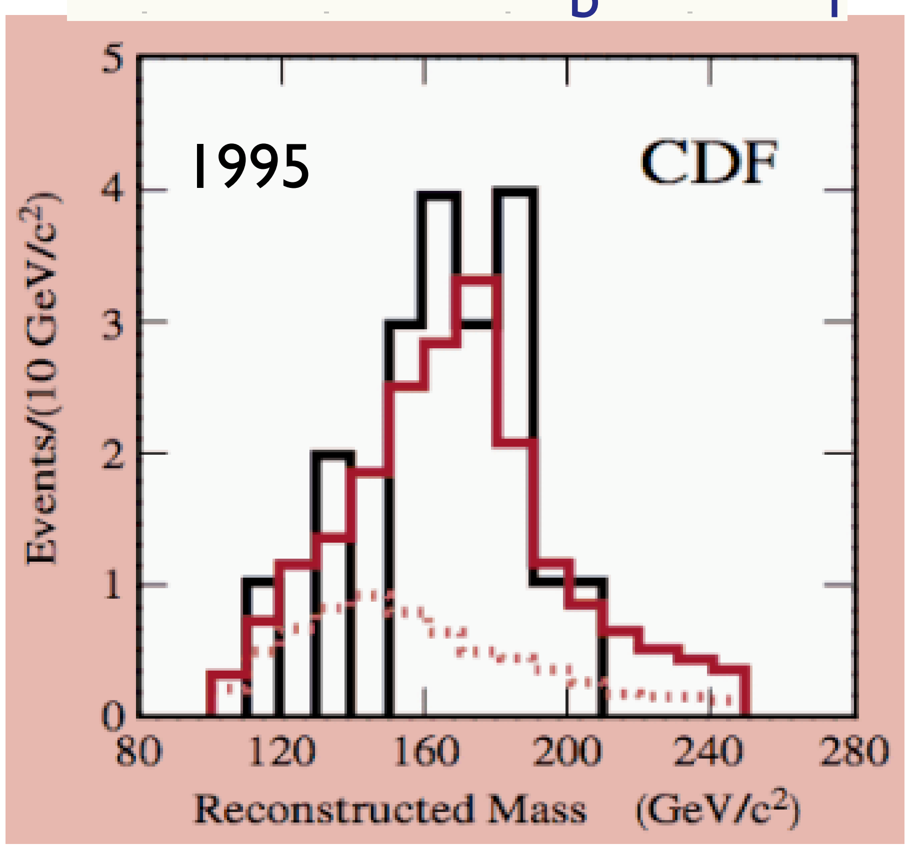
1. It is the only quark with a "natural mass" of order v. It is has a "large" weak width and therefore it is only quark that decays before hadronising.
2. Vtb is order 1 and can accessed through the width or single top.
3. Top-Antitop resonance physics is available.
4. Strong interactions cannot scramble its spin state. W polarisation is a good spin analyser for the top spin.
5. Tops do not like to radiate (QCD and QED) very much.
6. The top mass is a delicate quantity.
7. It can drive the Higgs potential unstable.

Review questions on top quark properties

1. How does the top width scale with the top mass?
2. Is there an upper bound to the top-quark mass?
3. Imagine the top quark mass were half of its value. What would be the consequences for the SM and the LHC phenomenology?
4. How would you look for a fourth generation? Why nobody talks about its existence lately?
5. Explain the difference between a short-distance mass and the pole mass.

The top story





The last quark to be discovered!

0. The only unknown was the top mass!

1.The experimentally easiest channel for triggering/reconstruction/background-control was chosen.

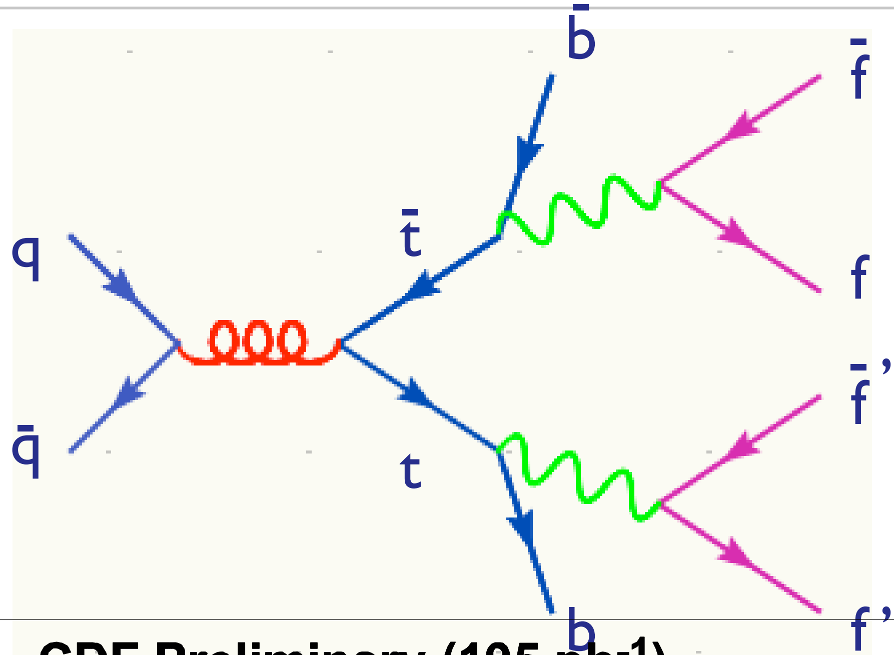
2. Mass reconstruction employed

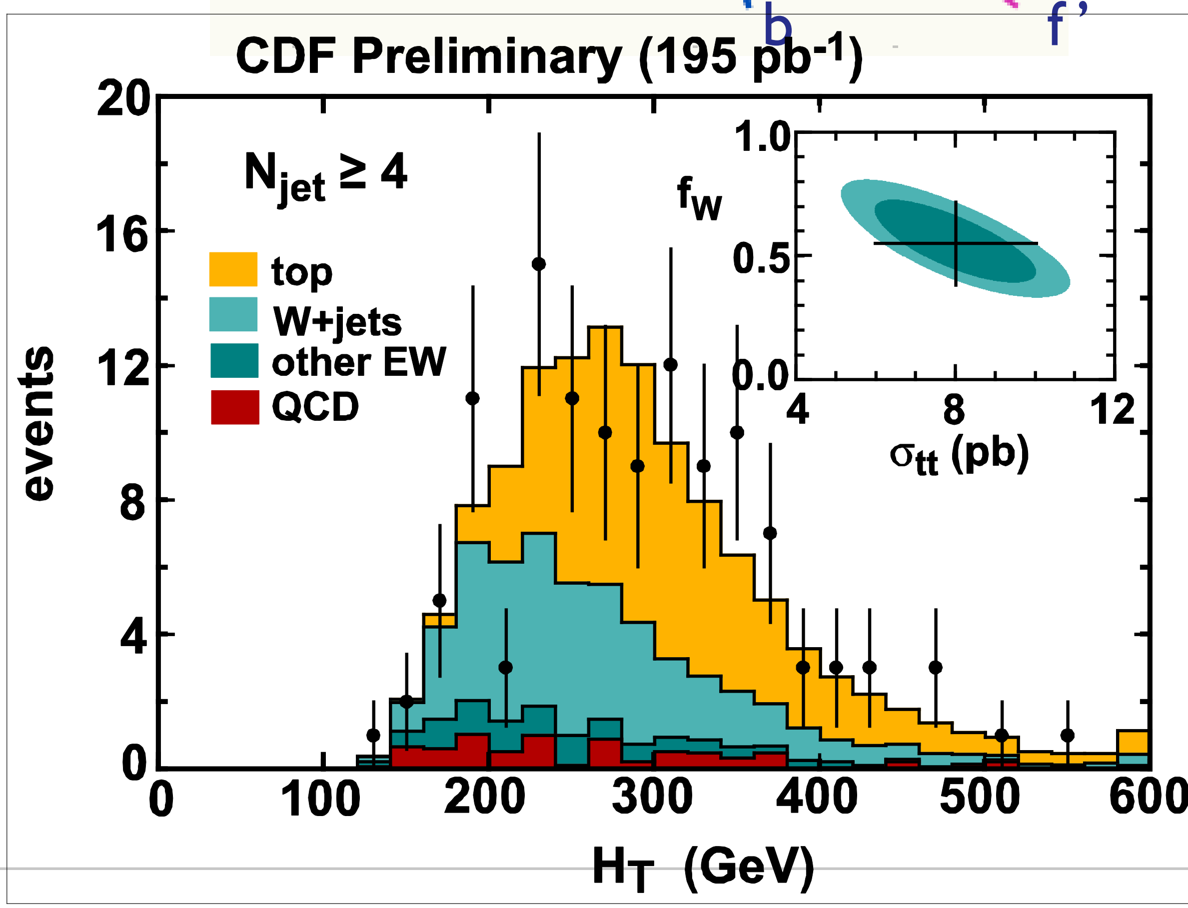
3. Backgrounds estimated via control samples with heavy flavors and also via MC ratio's.

4. Number of events consistent with the cross section expectation from QCD

Handful of events was enough!

The top story





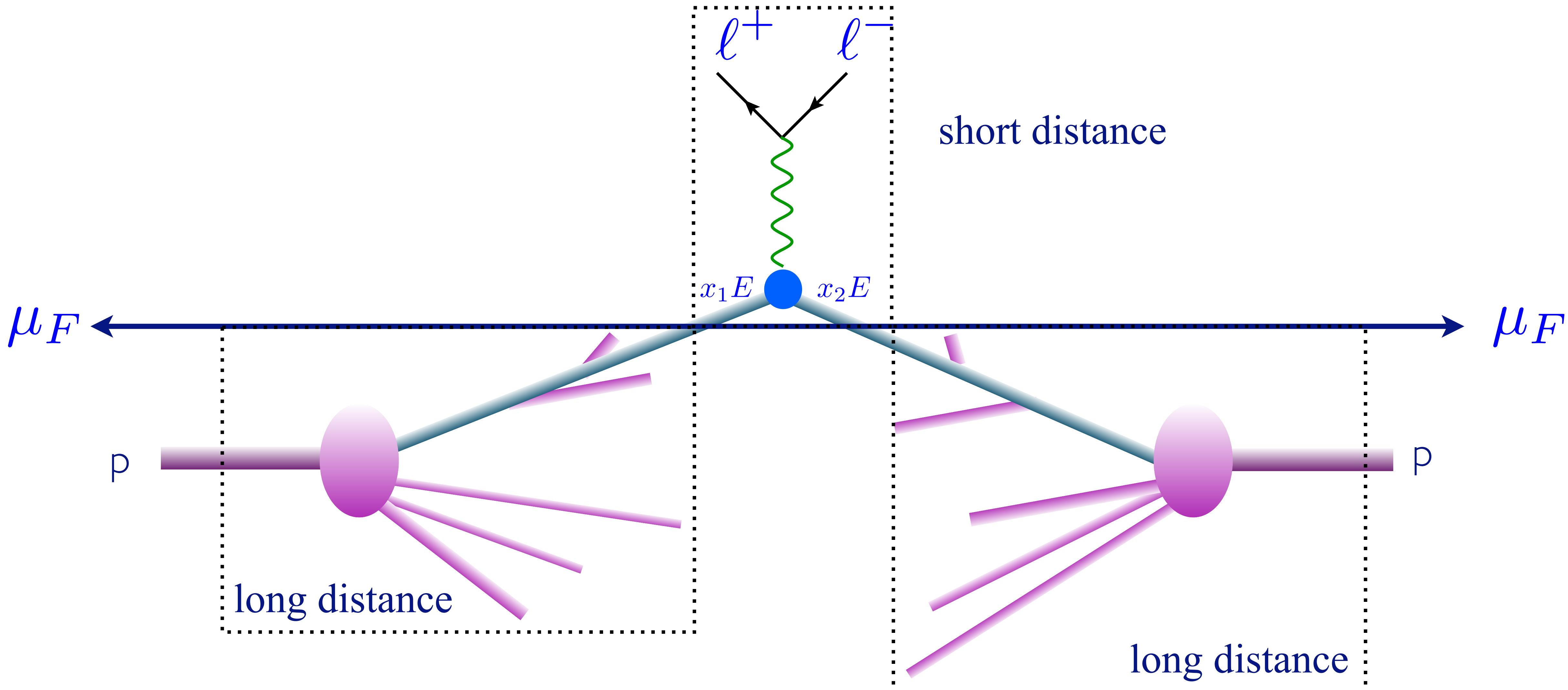
Immediately confirmed in Run II, also by the most inclusive measurements, HT.

Other channels start to be considered as the statistics increases to have a consistent picture.

Cleaner and cleaner samples more exclusive studies:

1. W Polarization
2. BR’s ratio’s
3. Top Quark charge
4. Differential mtt distribution
5. Search for new physics!!

Hadron colliders master formula



$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1,\mu_F^2) f_b(x_2,\mu_F^2) \times \hat{\sigma}_{ab\to X}(x_1,x_2,\alpha_S(\mu_R^2),\frac{Q^2}{\mu_F^2},\frac{Q^2}{\mu_R^2})$$

Example: t tbar production

Let's see how to calculate the cross section for a simple process such as pp → ttbar. There are two initial states possible, gg and qqbar. For gg (which will dominate at the LHC) we obtain:

$$\frac{d\sigma}{d\hat{s}} = \int_0^1 \int_0^1 dx_1 dx_2\, g(x_1,\mu_F) g(x_2,\mu_F)\, \hat{\sigma}(\hat{s}) \delta(\hat{s} - x_1 x_2 s)$$

We introduce the variable tau, that is proportional to x1 and x2:

$$\tau \equiv \frac{\hat{s}}{s} = x_1 x_2$$

and obtain

$$\frac{d\sigma}{d\tau} = \int_0^1 \int_0^1 dx_1 dx_2\, g(x_1,\mu_F) g(x_2,\mu_F)\, \frac{\hat{\sigma}(\hat{s})}{\tau} \delta\left(1 - \frac{x_1 x_2}{\tau}\right)$$

Example: t tbar production

$$\frac{d\sigma}{d\tau} = \frac{\hat\sigma(\hat s)}{\tau} \boxed{\int_\tau^1 \frac{dx_1}{x_1} g(x_1) g(\frac{\tau}{x_1})}$$

We define the dimensionless partonic luminosity Lgg:

$$\frac{dL_{gg}}{d\tau} \equiv \int_\tau^1 \frac{dx_1}{x_1} g(x_1) g(\frac{\tau}{x_1})$$

and calculate the total cross section as:

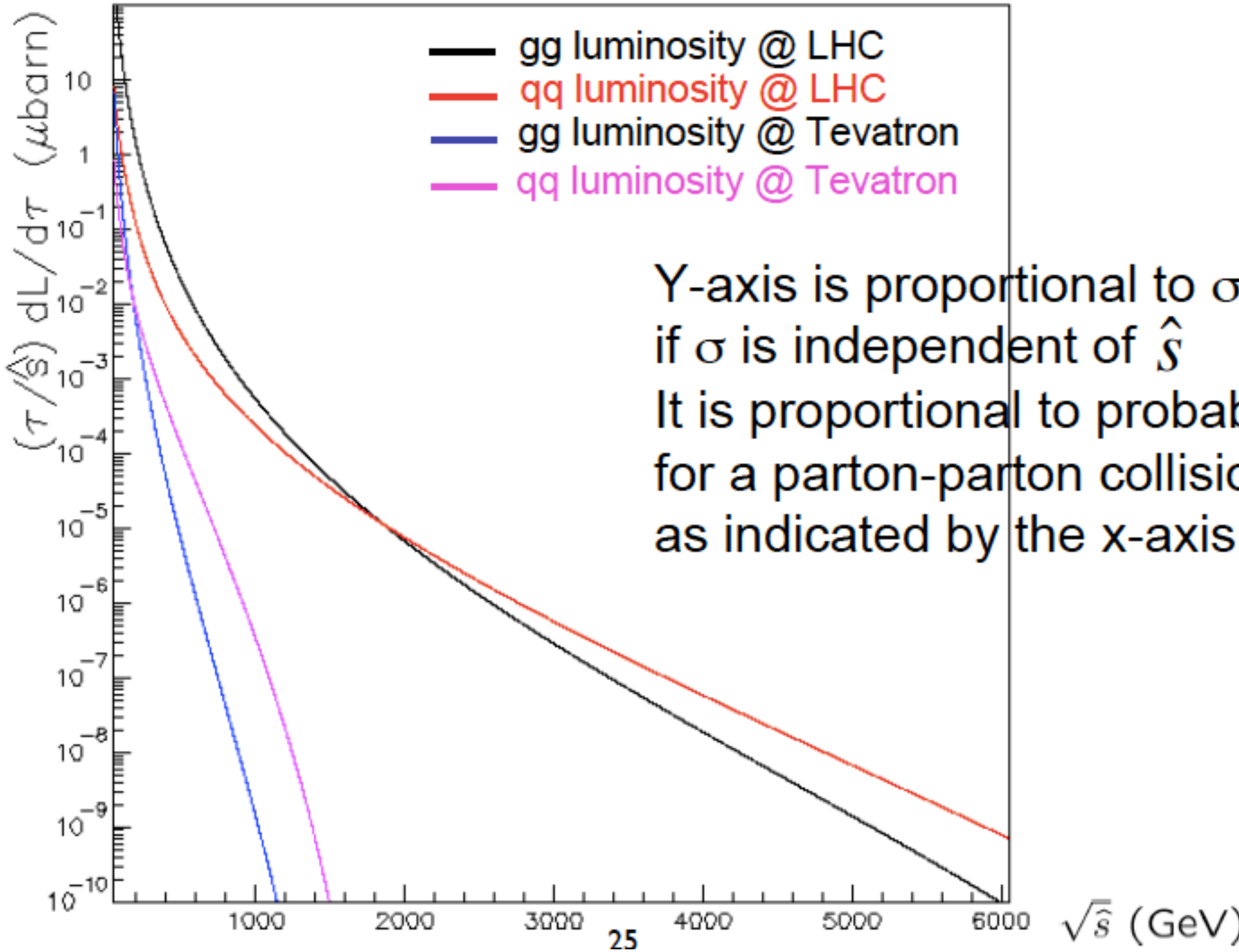
$$\sigma(pp \to t\bar t + X) = \int_{\tau_{\min}}^1 d\tau \cdot \hat\sigma_{gg\to t\bar t}(s\tau) \cdot \frac{dL}{d\tau}$$

$$= \int_{\tau_{\min}}^1 \frac{d\tau}{\tau} \cdot [\hat s \hat\sigma_{gg\to t\bar t}(\hat s)] \cdot \frac{\tau dL}{\hat s d\tau}$$

CLOSE TO A CONSTANT

"CROSS SECTION"

Example: t tbar production



Y-axis is proportional to σ if σ is independent of $\hat{s}$
It is proportional to probability for a parton-parton collision with $\hat{s}$ as indicated by the x-axis.

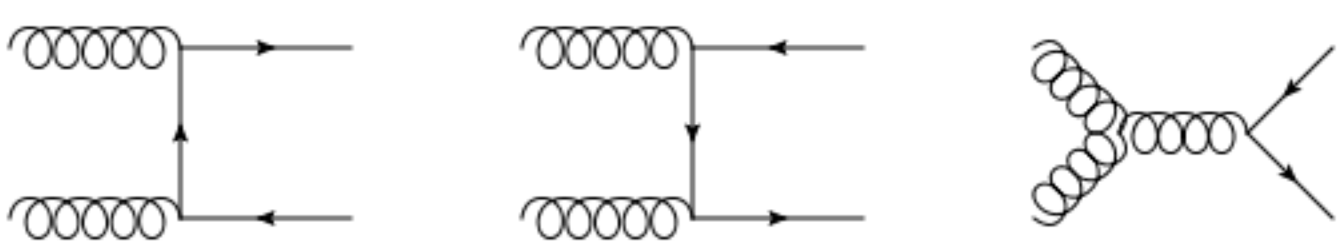
Example: t tbar production

$$\frac{dL_{gg}}{d\tau} \equiv \int_{\tau}^{1} \frac{dx_1}{x_1} g(x_1) g(\frac{\tau}{x_1})$$

If we take for simplicity $g(x) = \frac{1}{x^{1+\delta}} \Rightarrow \frac{dL_{gg}}{d\tau} = \frac{1}{\tau^{1+\delta}} \log \tau$

- Function of dimensionless quantity (Scaling).
- Note that the short distance coefficient depends on s

i.e. the total "cross section" will scale as a power of 1/mt1+delta Log Mt. The short distance coefficient can be easily calculated at LO via the feynman diagrams:



UCL Université catholique de Louvain

Example: t tbar production

$$
\begin{aligned}
\frac{1}{256}|M|^2 &= \frac{3g_s^4}{4}\frac{(m^2-t)(m^2-u)}{s^2} - \frac{g_s^4}{24}\frac{m^2(s-4m^2)}{(m^2-t)(m^2-u)} + \frac{g_s^4}{6}\frac{tu-m^2(3t+u)-m^4}{(m^2-t)^2} \\
&+ \frac{g_s^4}{6}\frac{tu-m^2(t+3u)-m^4}{(m^2-u)^2} - \frac{3g_s^4}{8}\frac{tu-2m^2t+m^4}{s(m^2-t)} - \frac{3g_s^4}{8}\frac{tu-2m^2u+m^4}{s(m^2-u)}
\end{aligned}
$$

3 diagrams squared + the interferences. This amplitude is integrated over the phase space at fixed shat:

$$
\hat{\sigma}_{gg\to t\bar{t}} = \frac{1}{2\hat{s}}\,\beta\,2\pi\int_{-1}^{+1} d\cos\theta^*\ |M|^2/256
$$

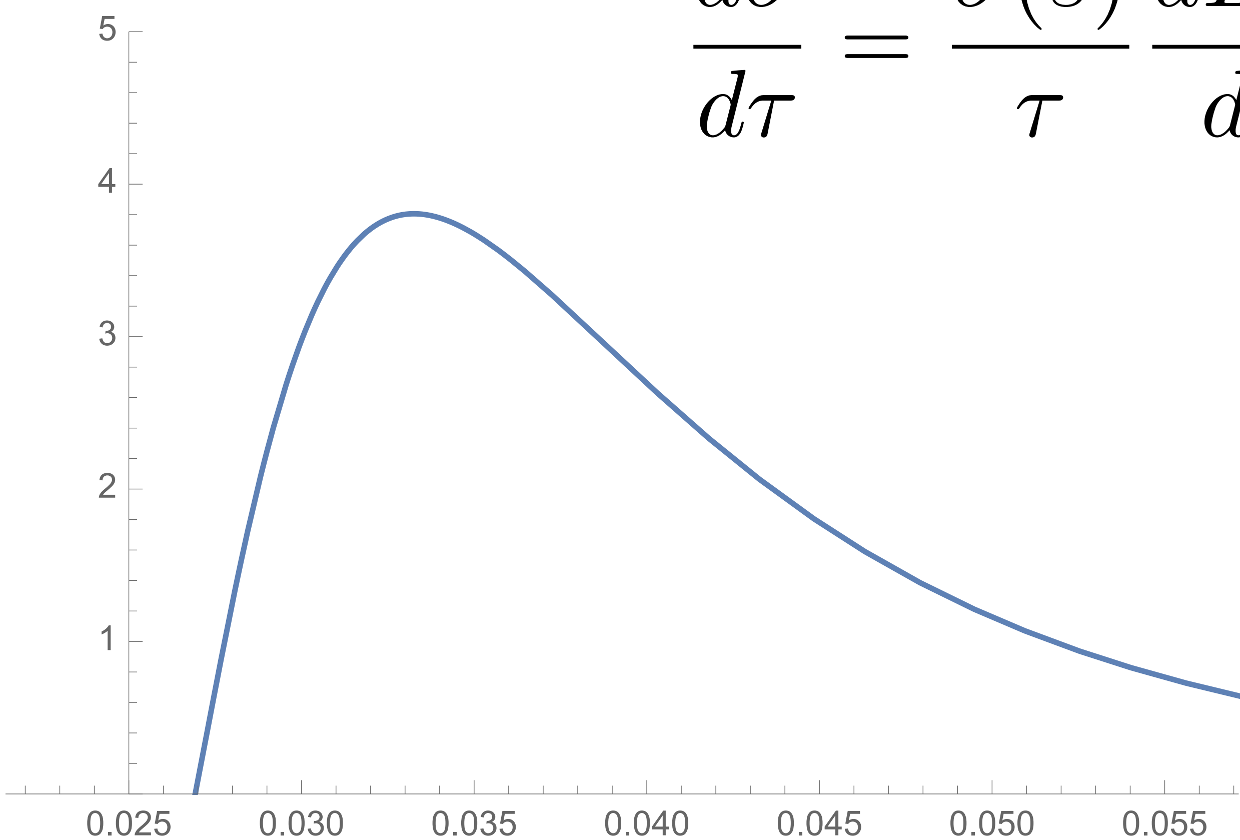
eventually giving:

$$
\beta = \sqrt{1-4m_t^2/\hat{s}}
$$

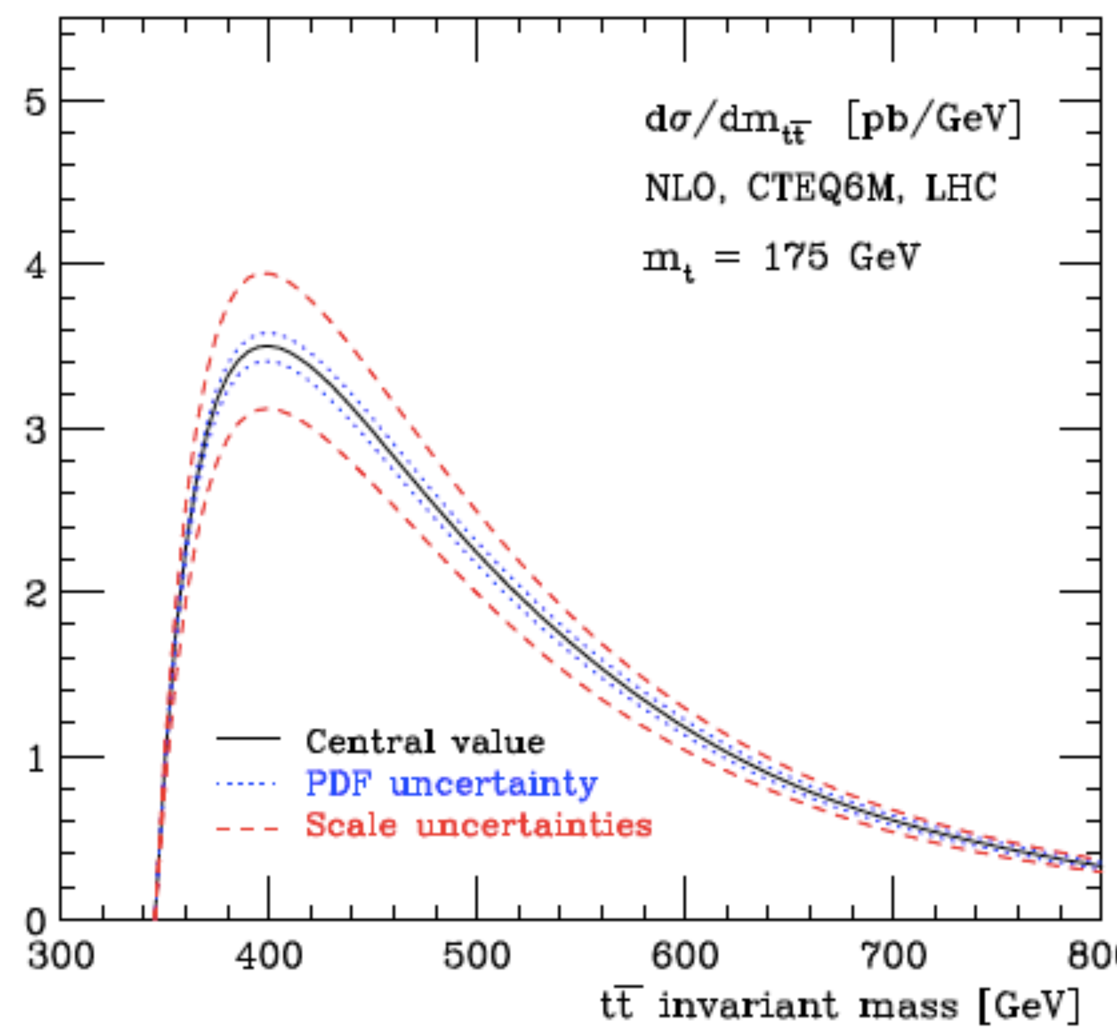
$$
\hat{\sigma}_{gg\to t\bar{t}} = \frac{\pi\alpha_s^2\beta}{48\hat{s}}\left(31\beta + \left(\frac{33}{\beta} - 18\beta + \beta^3\right)\ln\left[\frac{1+\beta}{1-\beta}\right] - 59\right)
$$

Example: t tbar production

$$\frac{d\sigma}{d\tau} = \frac{\hat{\sigma}(\hat{s})}{\tau}\frac{dL_{gg}}{d\tau}$$



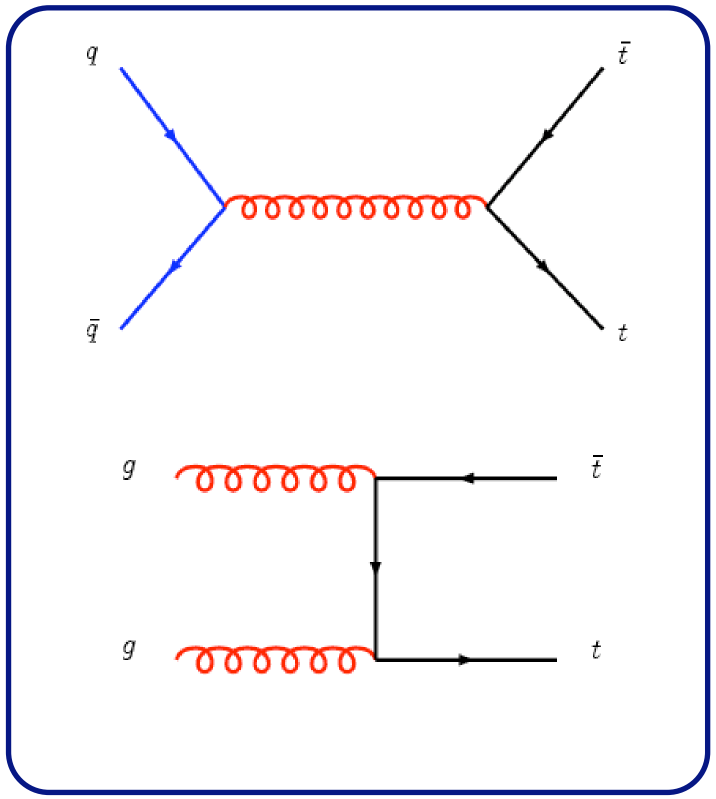
LO estimation with toy PDF



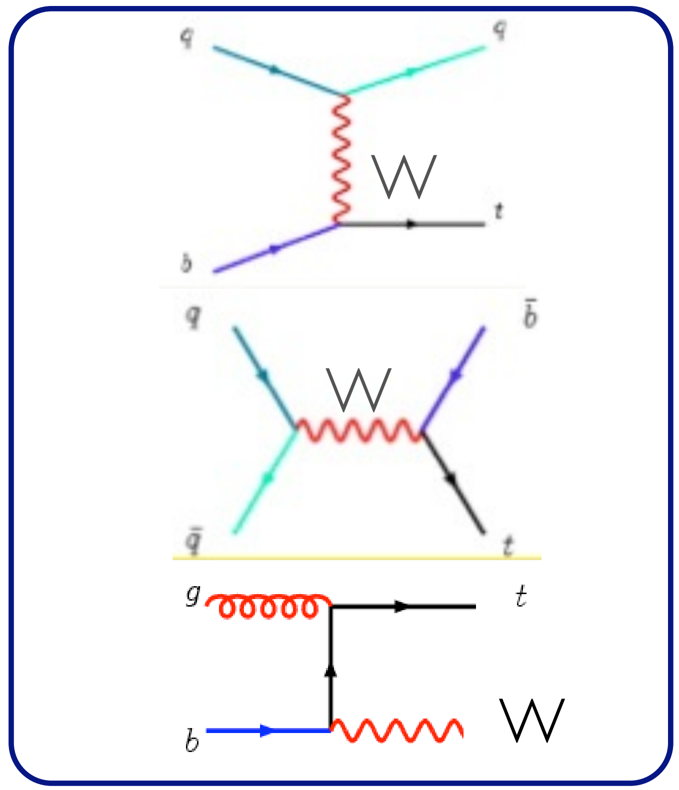
NLO result with proper MC

Top production at the LHC

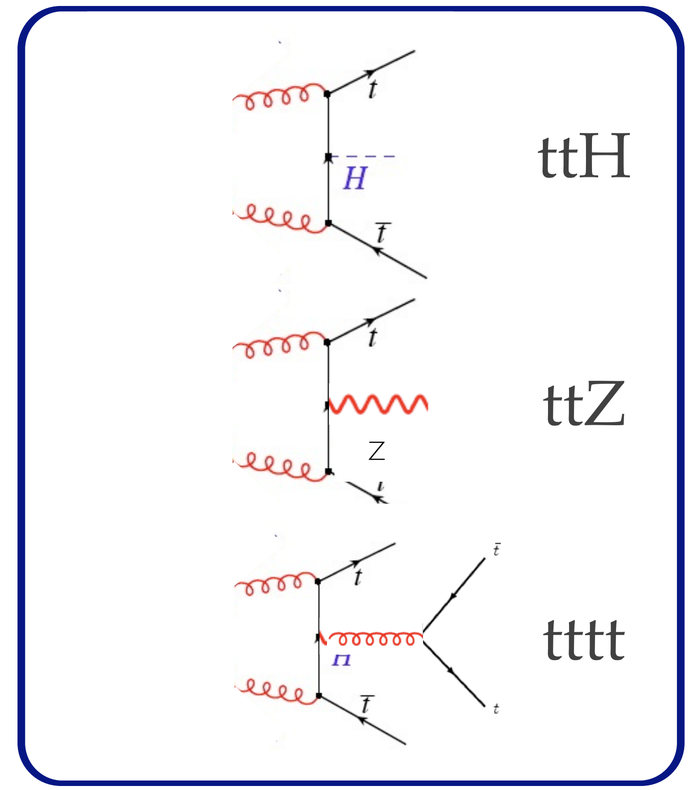
Strong



Weak



Associated



10^6

$250 \cdot 10^3$

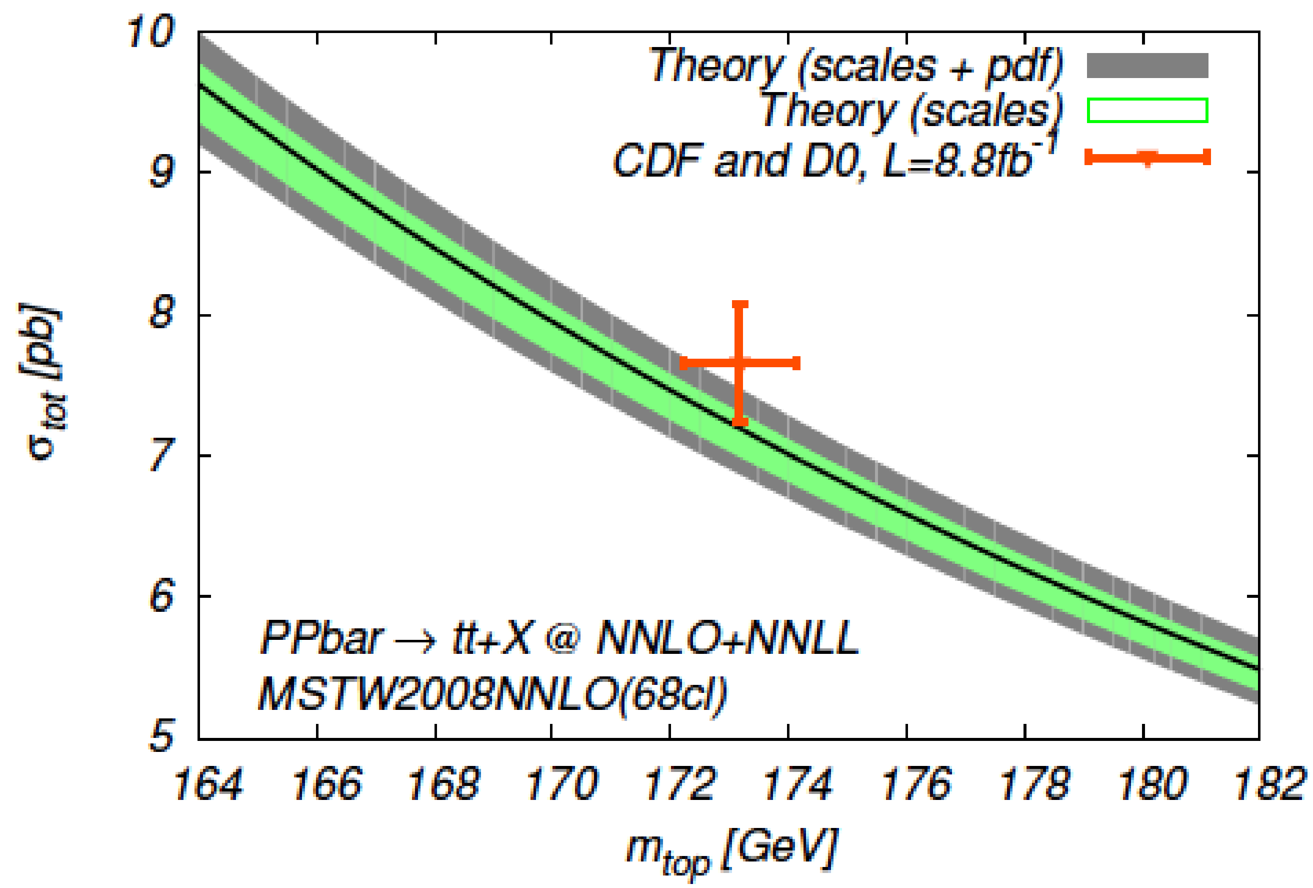
$< (2-3) \cdot 10^3$

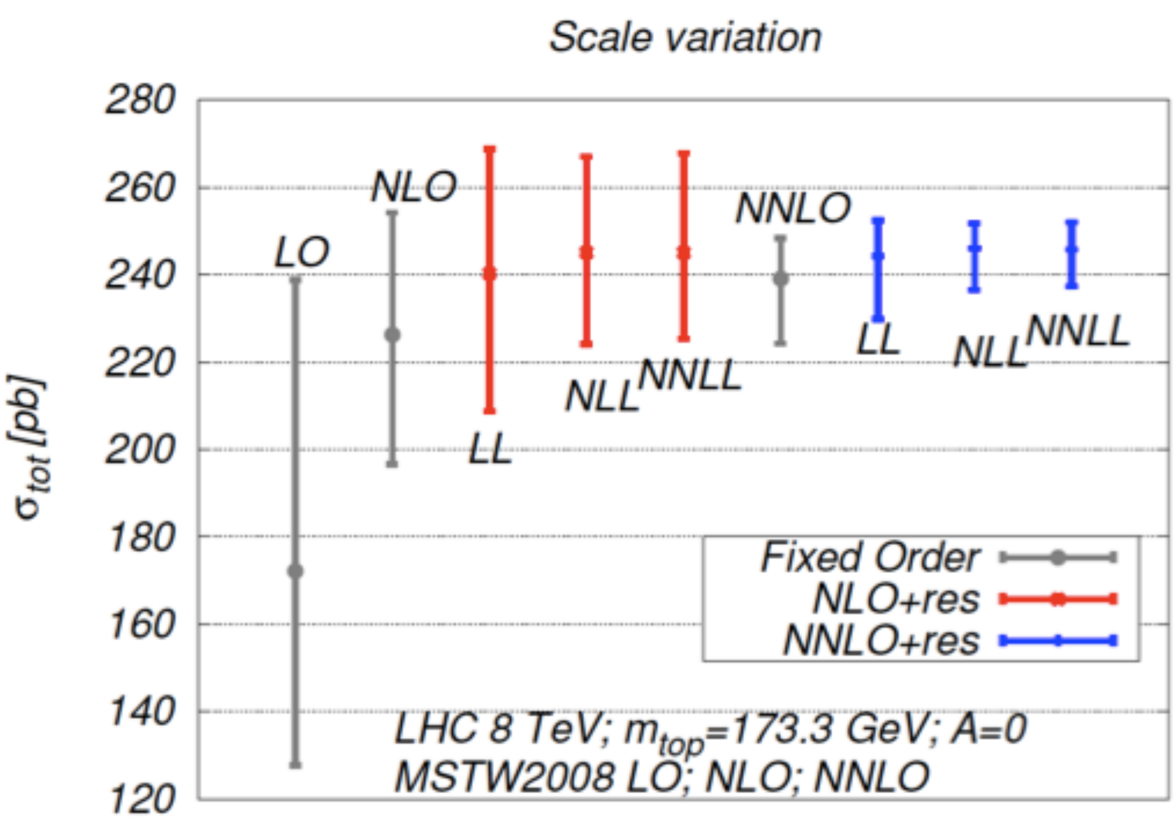
number of events @13TeV 1 fb^{-1}

$t\bar{t}$ cross section

Monumental MILESTONE in perturbative QCD:

[Bärnreuther, Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Fiedler, Mitov 2013]





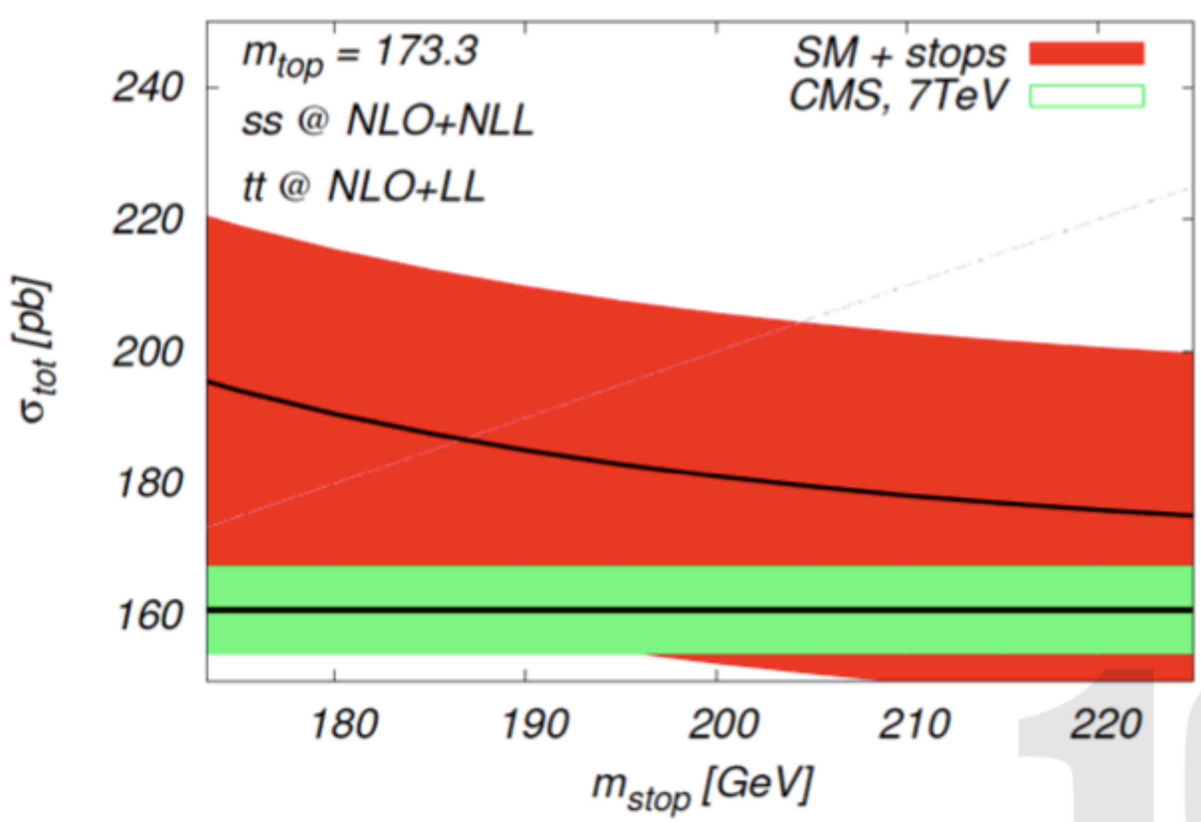
- Two loop hard matching coefficient extracted and included
- Very weak dependence on unknown parameters (sub 1%): gg NNLO, A, etc.
- ~ 50% scales reduction compared to the NLO+NNLL analysis

$t\bar{t}$ cross section

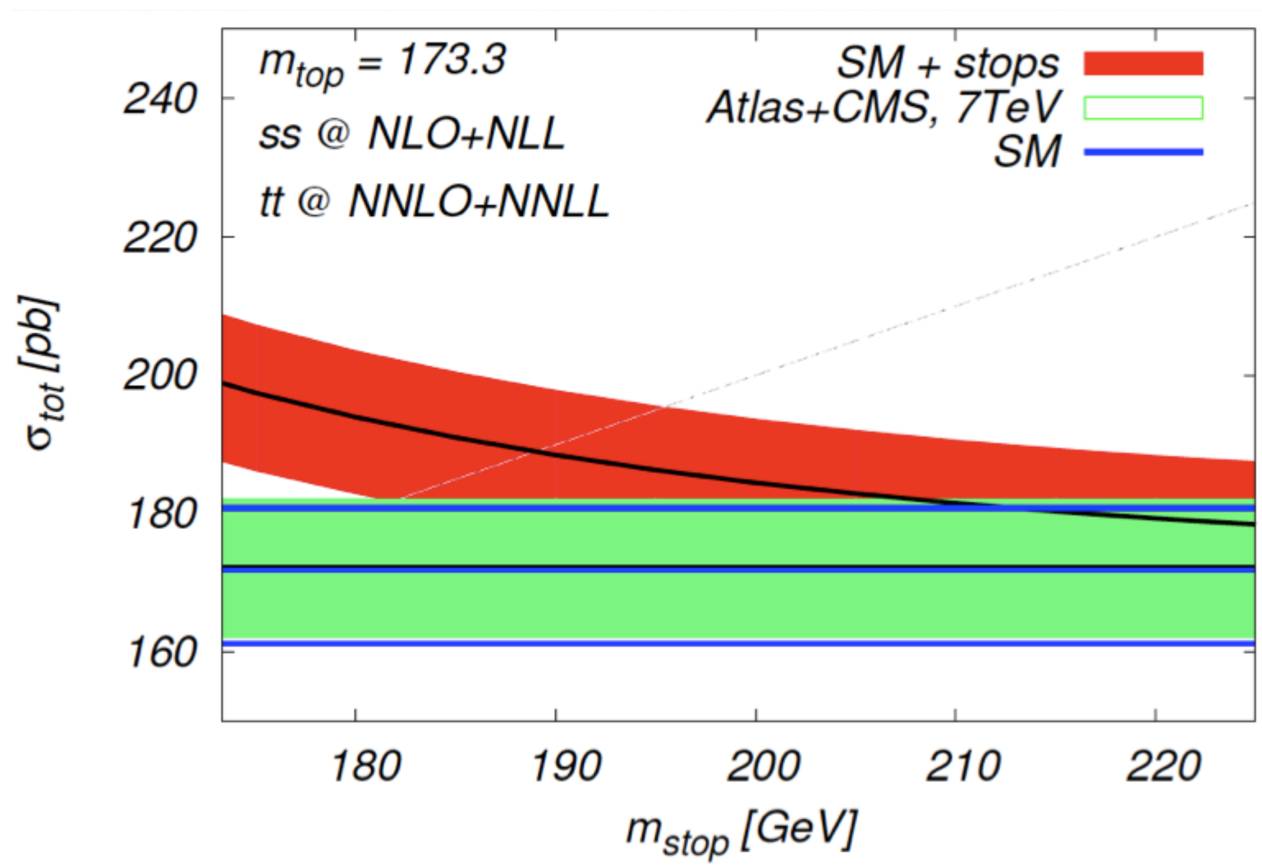
Having a NNLO prediction opens the door to new possibilities.

Consider the light stop window in a compressed spectrum, that mimicks the normal ttbar production:

[Czakon, Mitov, Papucci, Ruderman, Weiler,2014]

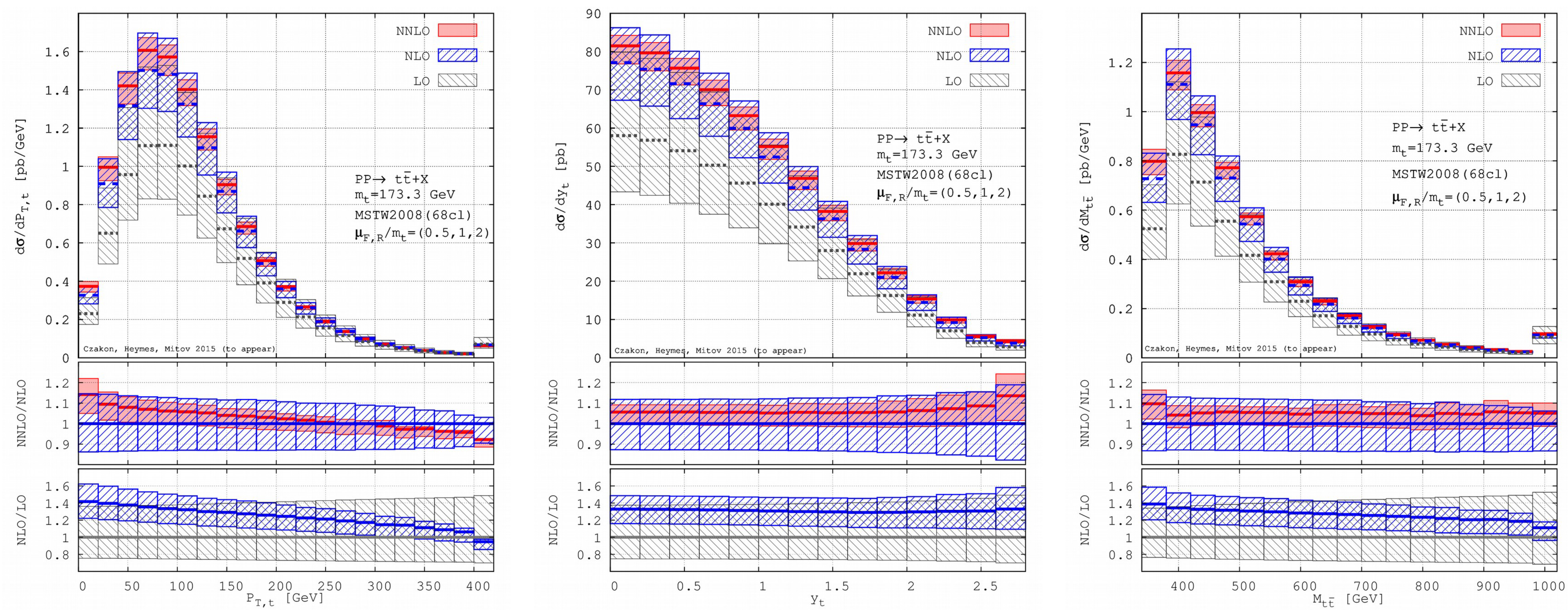


→



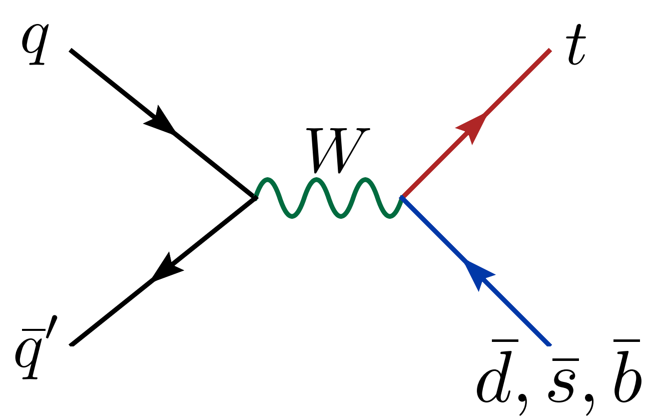
$t\bar{t}$ at NNLO : differential distributions

[Czakon, Fiedler, Heymes, Mitov.; in preperation]

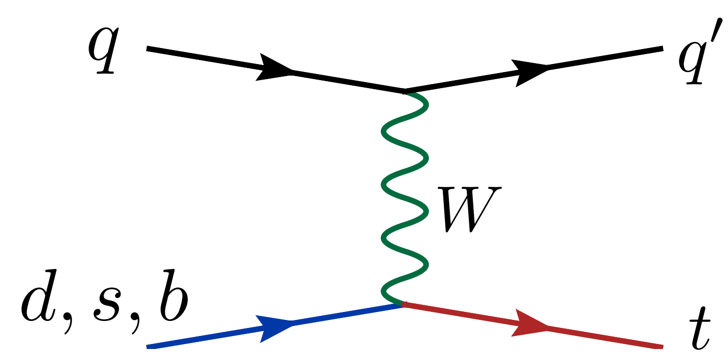


Good perturbative convergence. Improved precision.

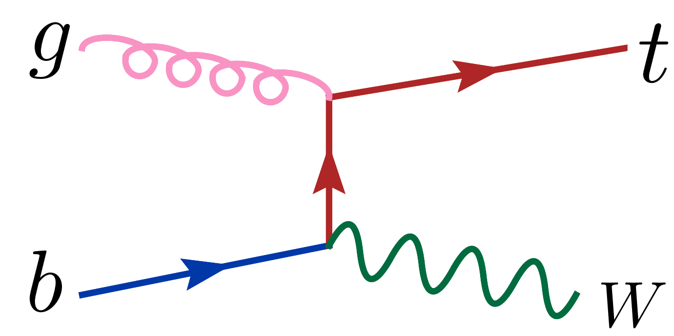
Single top



* "Drell-Yan" production mode.
* Tevatron is sizable (~1pb), quite small at the LHC14 (~10 pb).
* Fully inclusive x-sec known at NNLO (leading Nc).
* Channel to search for new charged resonances (H^+ or W'). Four-fermion interactions.
* Final State: 2 b's + W



* "DIS" production mode.
* Largest cross sections thanks to the t-channel W.
* Sensitive to FCNC involving top. Four-fermion interactions.
* b initiated
* Final State: 1 or 2 b's, W, forward jet



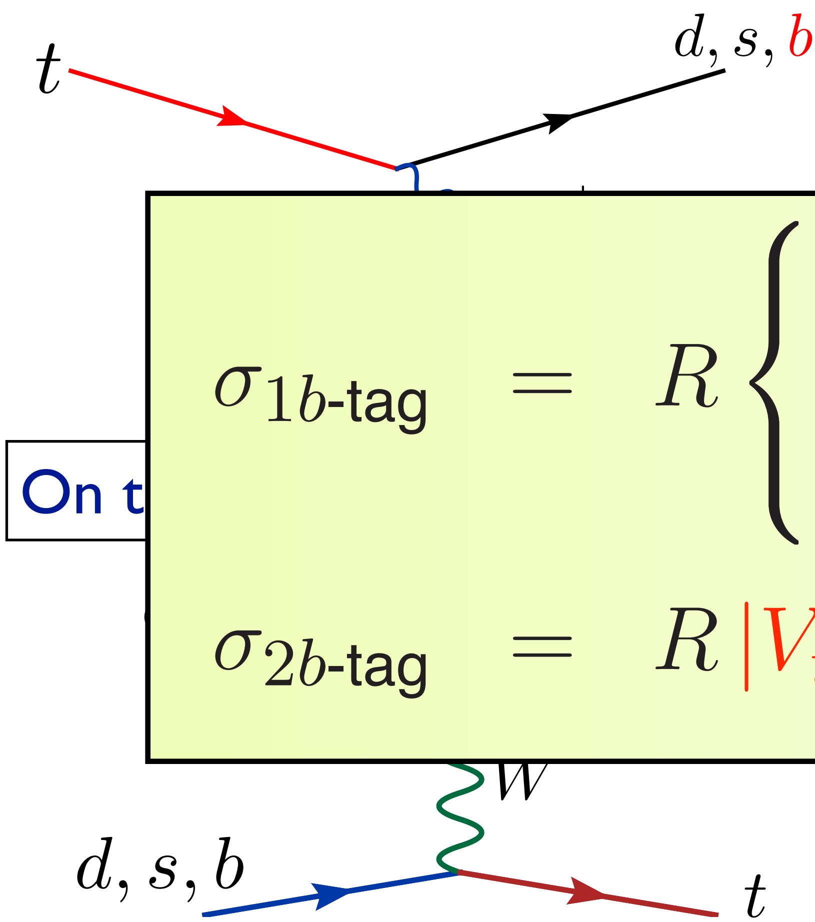
* Associated production
* Sizable cross section (60 pb) at LHC14, but difficult.
* Template for tH^+ production.
* b initiated
*Interferes with ttbar at NLO : subtle definition.
* Final State: 1b, 2W and jet veto

*

*Theorist's comments

Example: Direct constraints on the 3rd row of CKM

Remember that R is not so sensitive to V_{tb} as we already know that $V_{tb} > V_{ts}, V_{td}$



$$R = \frac{\Gamma(t \to Wb)}{\Gamma(t \to W(\ldots))} = \frac{|V_{tb}|^2}{|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2}$$

On t

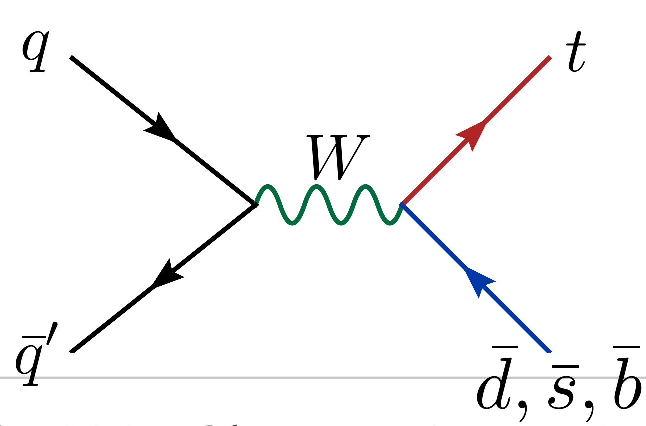
$$\sigma_{1b\text{-tag}} = R \left\{ \sum_{i=b,s,d} |V_{ti}|^2 \sigma_i^{\mathrm{t-ch}} + 2(|V_{td}|^2 + |V_{ts}|^2)\sigma^{\mathrm{s-ch}} \right\}$$

$$\sigma_{2b\text{-tag}} = R\,|V_{tb}|^2\,\sigma^{\mathrm{s-ch}}$$

n.b. : naive estimate

$$\sim |V_{td}|^2 \sigma_d^{\mathrm{t-ch}} + |V_{ts}|^2 \sigma_s^{\mathrm{t-ch}} + |V_{tb}|^2 \sigma_b^{\mathrm{t-ch}}$$

Enhancement due to large *d* and *s* densities

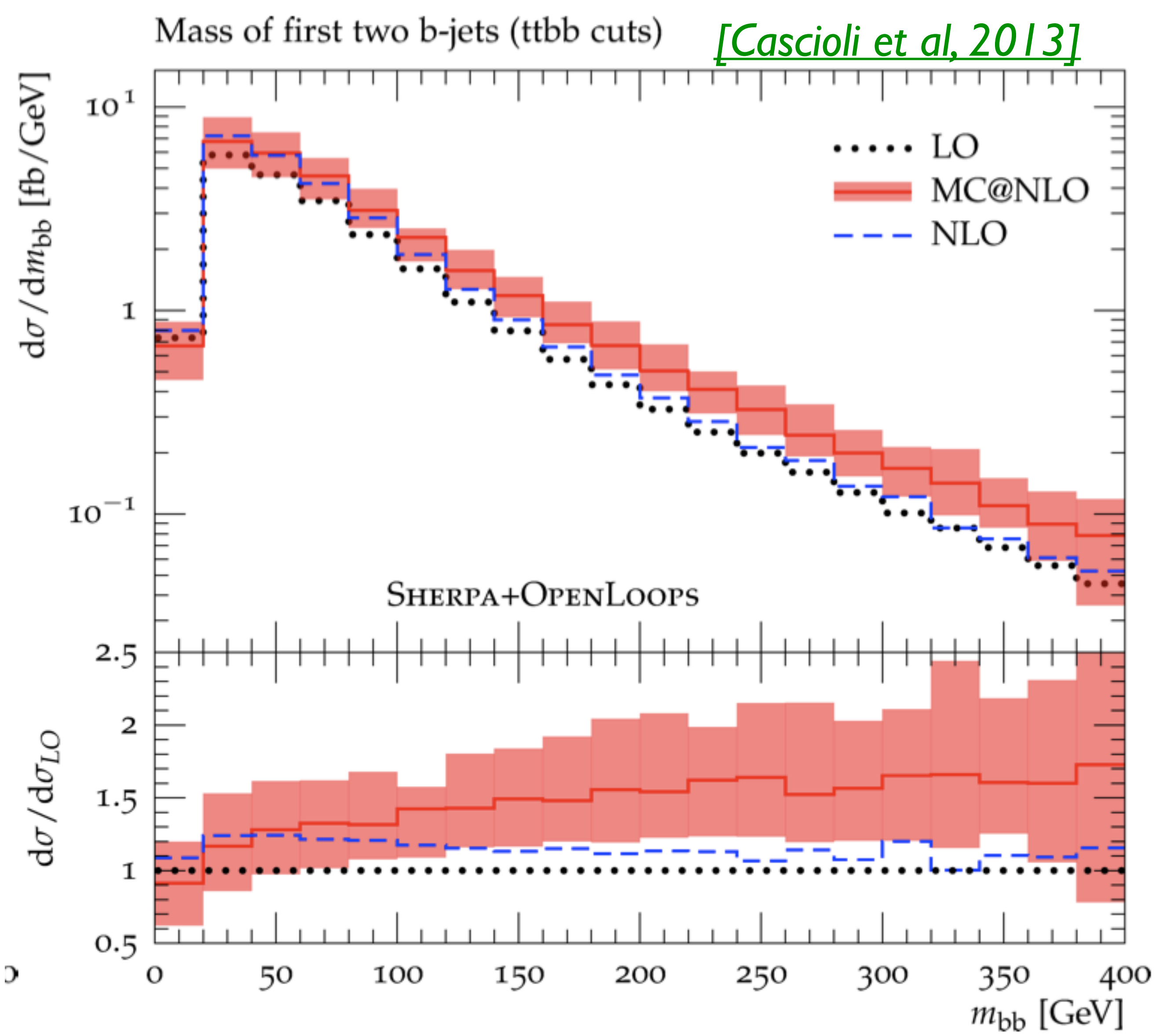


$$\sim (|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2)\sigma^{\text{s-ch}}$$

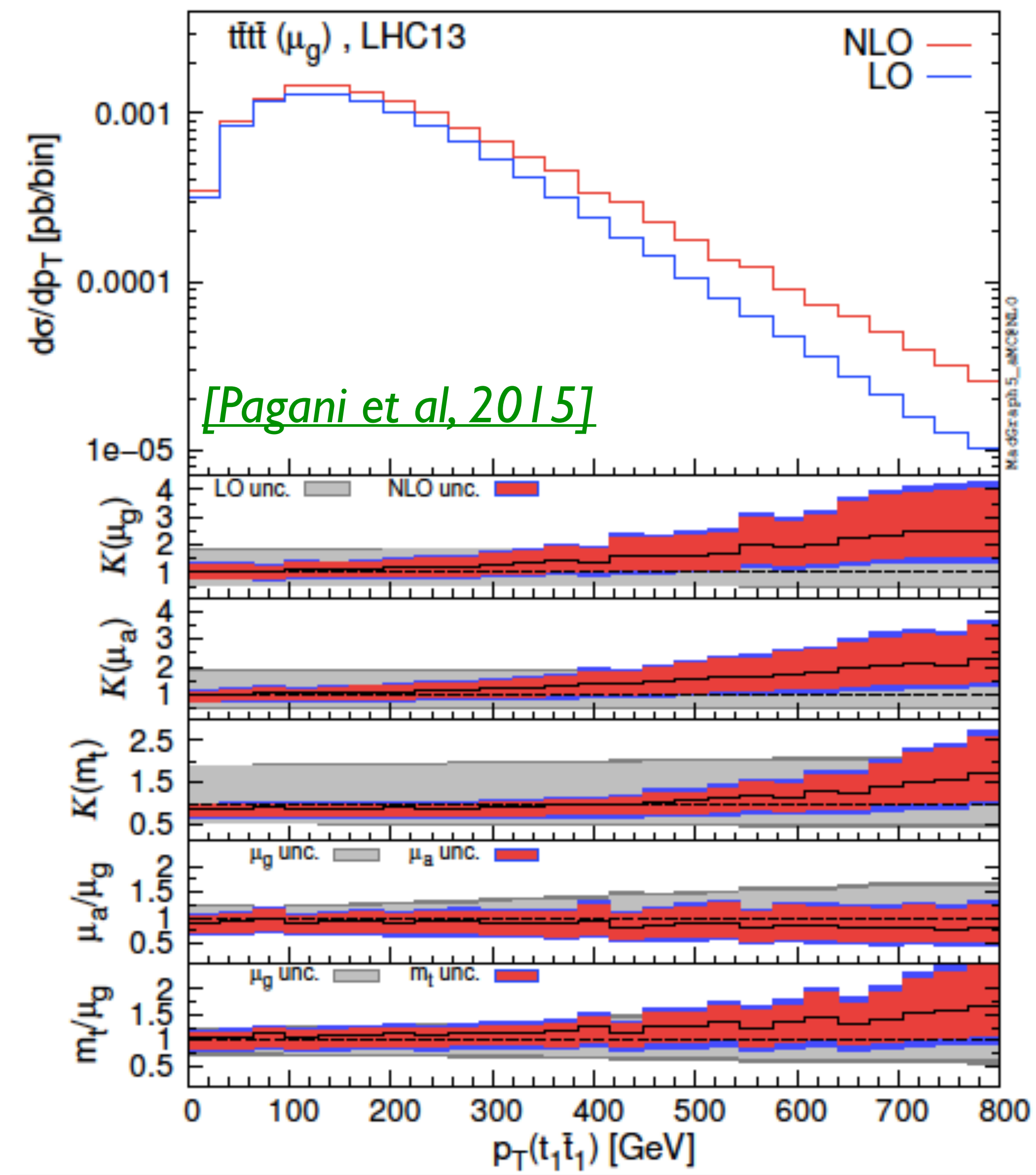
Signal becomes similar to t-channel (only 1 *b*-jet)

Associated production

$$pp \to t\bar{t}b\bar{b}$$

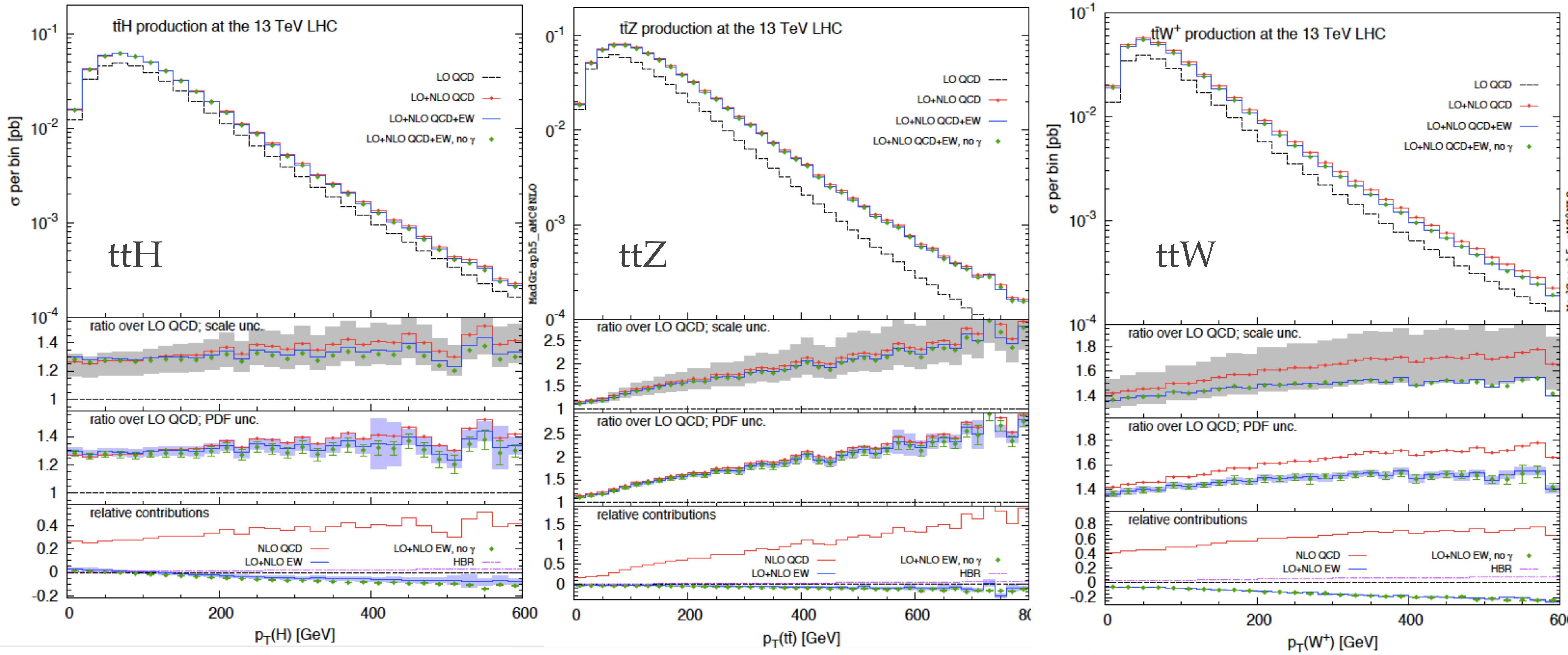


$$pp \to t\bar{t}t\bar{t}$$

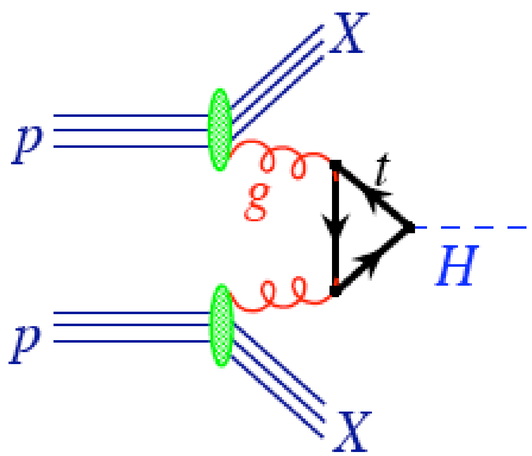


Associated production

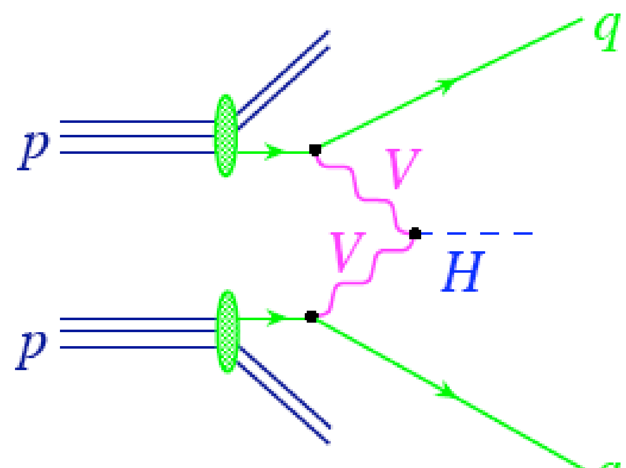
[Frixione et al, 2015]



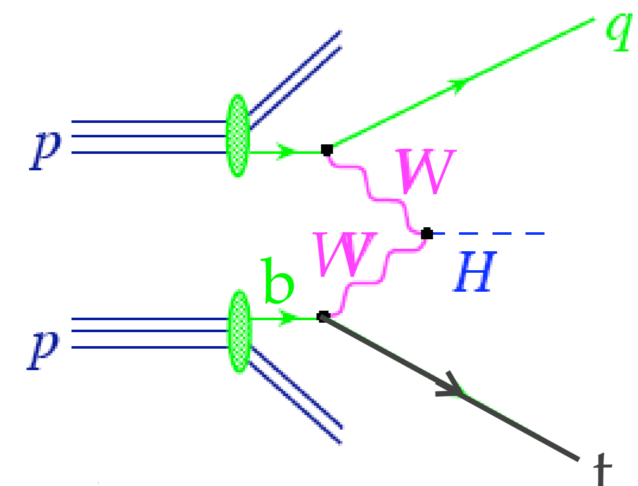
Higgs production channels



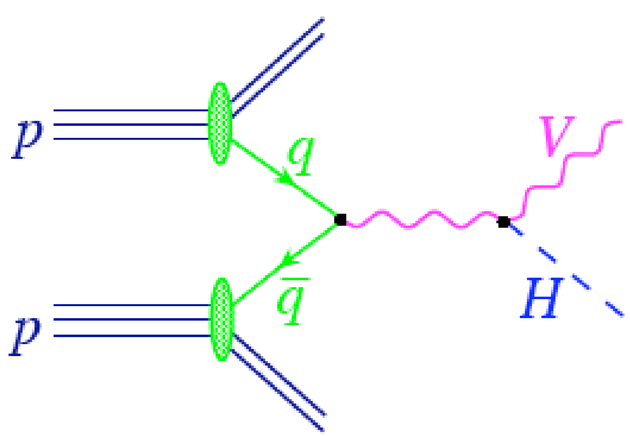
Gluon fusion



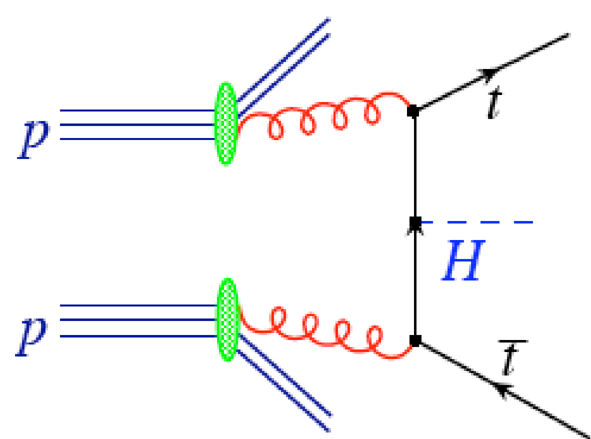
Weak-Boson Fusion



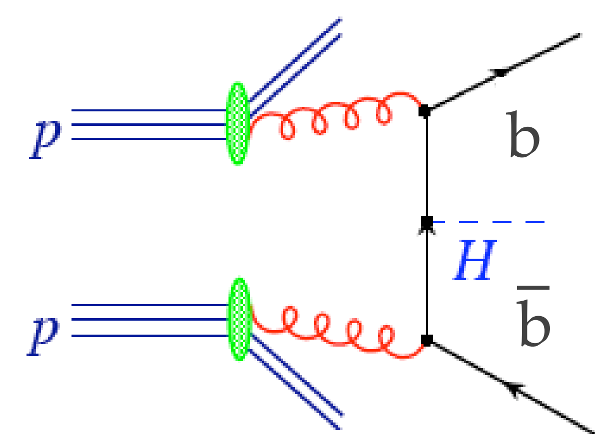
tHj



Higgs Strahlung

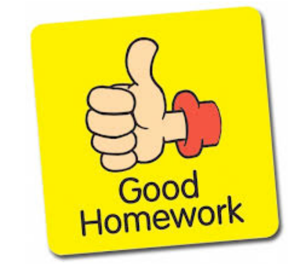


$t\bar{t}H$

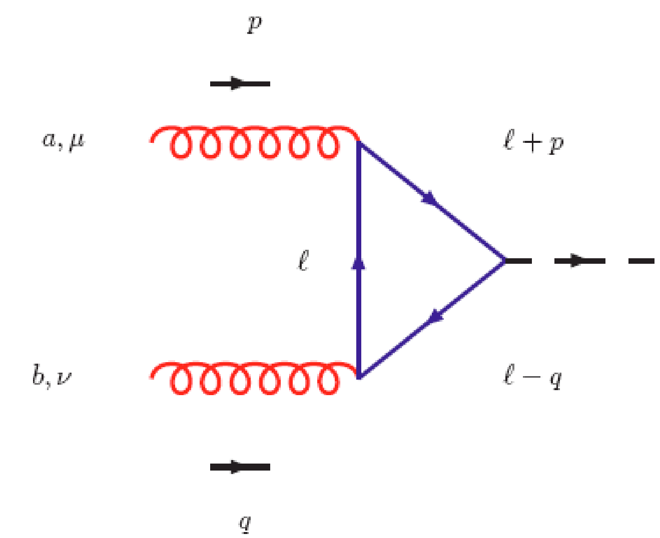


bbH

$\mathrm{H} \to gg$ at one loop



In this case, this means that the loop calculation has to give a finite result!



Let's do the calculation!

$$i\mathcal{A} = -(-ig_s)^2 \mathrm{Tr}(t^a t^b) \left(\frac{-im_t}{v}\right) \int \frac{d^d\ell}{(2\pi)^n} \frac{T^{\mu\nu}}{\mathrm{Den}} (i)^3 \epsilon_\mu(p) \epsilon_\nu(q)$$

where

$$\mathrm{Den} = (\ell^2 - m_t^2)[(\ell+p)^2 - m_t^2][(\ell-q)^2 - m_t^2]$$

We combine the denominators into one by using $\frac{1}{ABC} = 2\int_0^1 dx \int_0^{1-x} \frac{dy}{[Ax + By + C(1-x-y)]^3}$

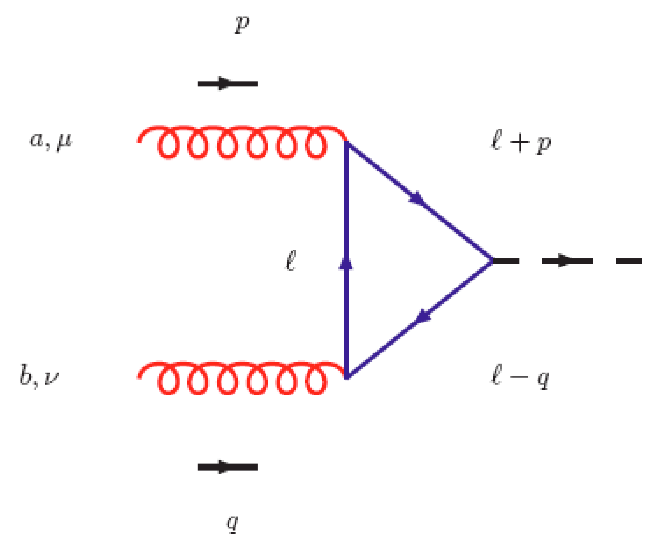
$$\frac{1}{\mathrm{Den}} = 2\int dx\; dy \frac{1}{[\ell^2 - m_t^2 + 2\ell\cdot(px - qy)]^3}.$$

$H \to gg$ at one loop

We shift the momentum:

$$\ell' = \ell + px - qy$$

$$\frac{1}{\text{Den}} \to 2\int dx\ dy \frac{1}{[\ell'^{\,2} - m_t^2 + M_H^2 xy]^3}.$$



And now the tensor in the numerator:

$$T^{\mu\nu} = \text{Tr}\Big[(\ell + m_t)\gamma^\mu(\ell + p + m_t)(\ell - q + m_t)\gamma^\nu)\Big]$$

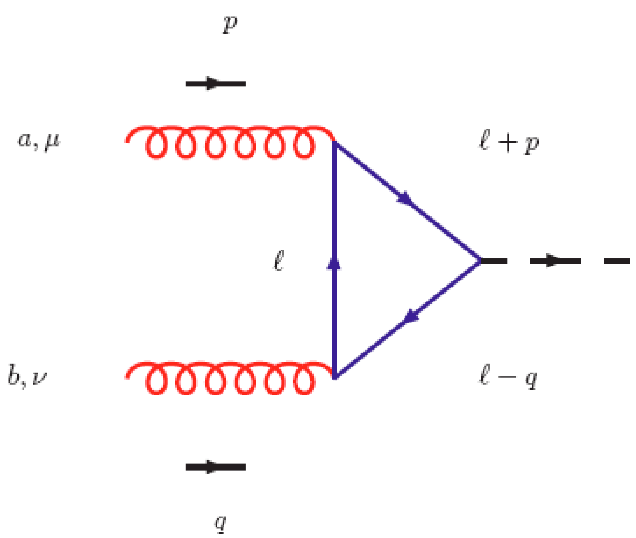
$$= 4m_t\left[g^{\mu\nu}(m_t^2 - \ell^2 - \frac{M_H^2}{2}) + 4\ell^\mu\ell^\nu + p^\nu q^\mu\right]$$

where I used the fact that the external gluons are on-shell. This trace is proportional to mt ! This is due to the spin flip caused by the scalar coupling.
Now we shift the loop momentum also here, we drop terms linear in the loop momentum (they are odd and vanish)

H → gg at one loop

We perform the tensor decomposition using:

$$\int d^d k \frac{k^\mu k^\nu}{(k^2 - C)^m} = \frac{1}{d} g^{\mu\nu} \int d^d k \frac{k^2}{(k^2 - C)^m}$$



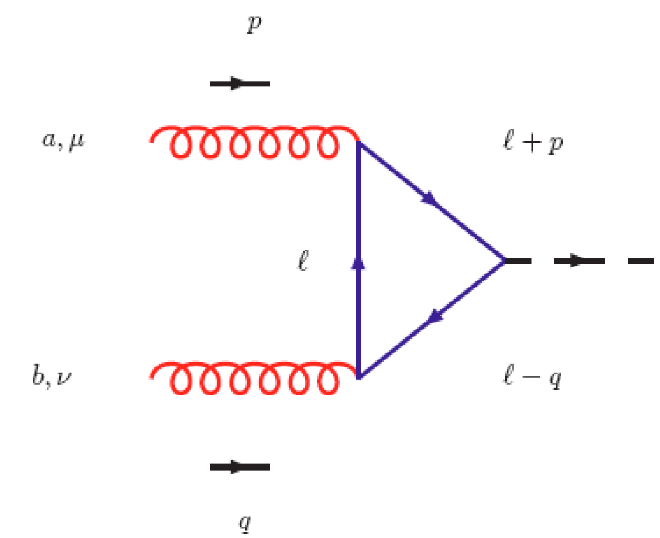
So I can write an expression which depends only on scalar loop integrals:

$$i\mathcal{A} = -\frac{2g_s^2 m_t^2}{v}\delta^{ab}\int \frac{d^d\ell'}{(2\pi)^d}\int dxdy\Big\{g^{\mu\nu}\Big[m^2 + \ell'^2\Big(\frac{4-d}{d}\Big) + M_H^2(xy - \frac{1}{2})\Big]$$
$$+p^\nu q^\mu(1-4xy)\Big\}\frac{2dxdy}{(\ell'^2 - m_t^2 + M_H^2 xy)^3}\epsilon_\mu(p)\epsilon_\nu(q).$$

There's a term which apparently diverges....??
Ok, Let's look the scalar integrals up in a table (or calculate them!)

H → gg at one loop

$$\int \frac{d^dk}{(2\pi)^d}\frac{k^2}{(k^2-C)^3} = \frac{i}{32\pi^2}(4\pi)^\epsilon \frac{\Gamma(1+\epsilon)}{\epsilon}(2-\epsilon)C^{-\epsilon}$$
$$\int \frac{d^dk}{(2\pi)^d}\frac{1}{(k^2-C)^3} = -\frac{i}{32\pi^2}(4\pi)^\epsilon \Gamma(1+\epsilon)C^{-1-\epsilon}.$$



where d=4-2eps. By substituting we arrive at a very simple final result!!

$$\mathcal{A}(gg\to H) = -\frac{\alpha_S m_t^2}{\pi v}\delta^{ab}\left(g^{\mu\nu}\frac{M_H^2}{2} - p^\nu q^\mu\right)\int dxdy\left(\frac{1-4xy}{m_t^2-m_H^2xy}\right)\epsilon_\mu(p)\epsilon_\nu(q).$$

Comments:

* The final dependence of the result is mt² : one from the Yukawa coupling, one from the spin flip.
* The tensor structure could have been guessed by gauge invariance.
* The integral depends on mt and mh.

pp→H at LO

$$\sigma^{\rm LO}(H+X) = \int_{\tau_0}^{1} dx_1 \int_{\tau_0/x_1}^{1} dx_2 f_g(x_1,\mu_F) f_g(x_2,\mu_F) \times \hat\sigma^{(0)}(gg \to H)\,,$$

where $\tau_0 = m_H^2/S$ and $s = x_1 x_2 S$. $\hat\sigma$ for a $2 \to 1$ process can be rewritten as

$$\begin{aligned}\hat\sigma &= \frac{1}{2s}\overline{|\mathcal{A}|^2}\frac{d^3P}{(2\pi)^3 2E_H}(2\pi)^4\delta^4(p+q-P_H)\\ &= \frac{1}{2s}\overline{|\mathcal{A}|^2}2\pi\delta(s-m_H^2)\,,\end{aligned}$$

where

$$\tau \equiv x_1 x_2 = \frac{S}{s}, \qquad \tau_0 = \frac{m_H^2}{S}\,.$$

Performing the change of variables $x_1, x_2 \to \tau, y$ with $x_1 \equiv \sqrt{\tau}e^{y}$, $x_2 \equiv \sqrt{\tau}e^{-y}$ (verify that the jacobian J is equal to 1) the change of the integration limits and the result becomes

$$\sigma^{\rm LO}(H+X) = \frac{\pi\overline{|\mathcal{A}|^2}}{m_H^2 S}\int_{\log\sqrt{\tau_0}}^{-\log\sqrt{\tau_0}} dy\, xg(\sqrt{\tau_0}e^{y})g(\sqrt{\tau_0}e^{-y})\,.$$

pp→H at LO

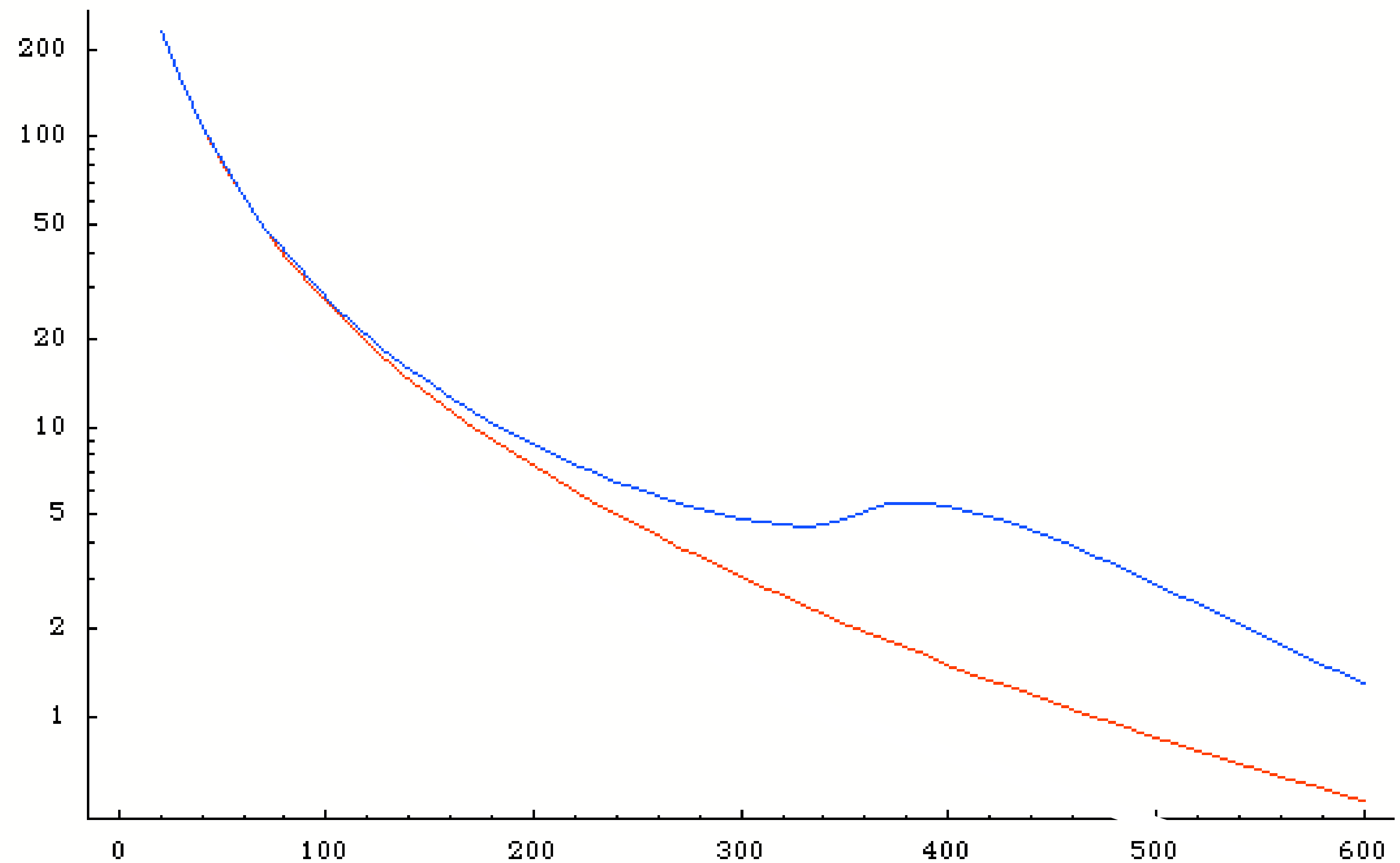
$$\sigma(pp \to H) = \int_{\tau_0}^{1} dx_1 \int_{\tau_0/x_1}^{1} dx_2\, g(x_1,\mu_f) g(x_2,\mu_f)\, \hat{\sigma}(gg \to H)$$

$$= \frac{\alpha_S^2}{64\pi v^2} \mid I\left(\frac{M_H^2}{m^2}\right) \mid^2 \tau_0 \int_{\log\sqrt{\tau_0}}^{-\log\sqrt{\tau_0}} dy g(\sqrt{\tau_0}e^y) g(\sqrt{\tau_0}e^{-y})$$

The hadronic cross section can be expressed a function of the gluon-gluon luminosity.

I(x) has both a real and imaginary part, which develops at mh =2mt.

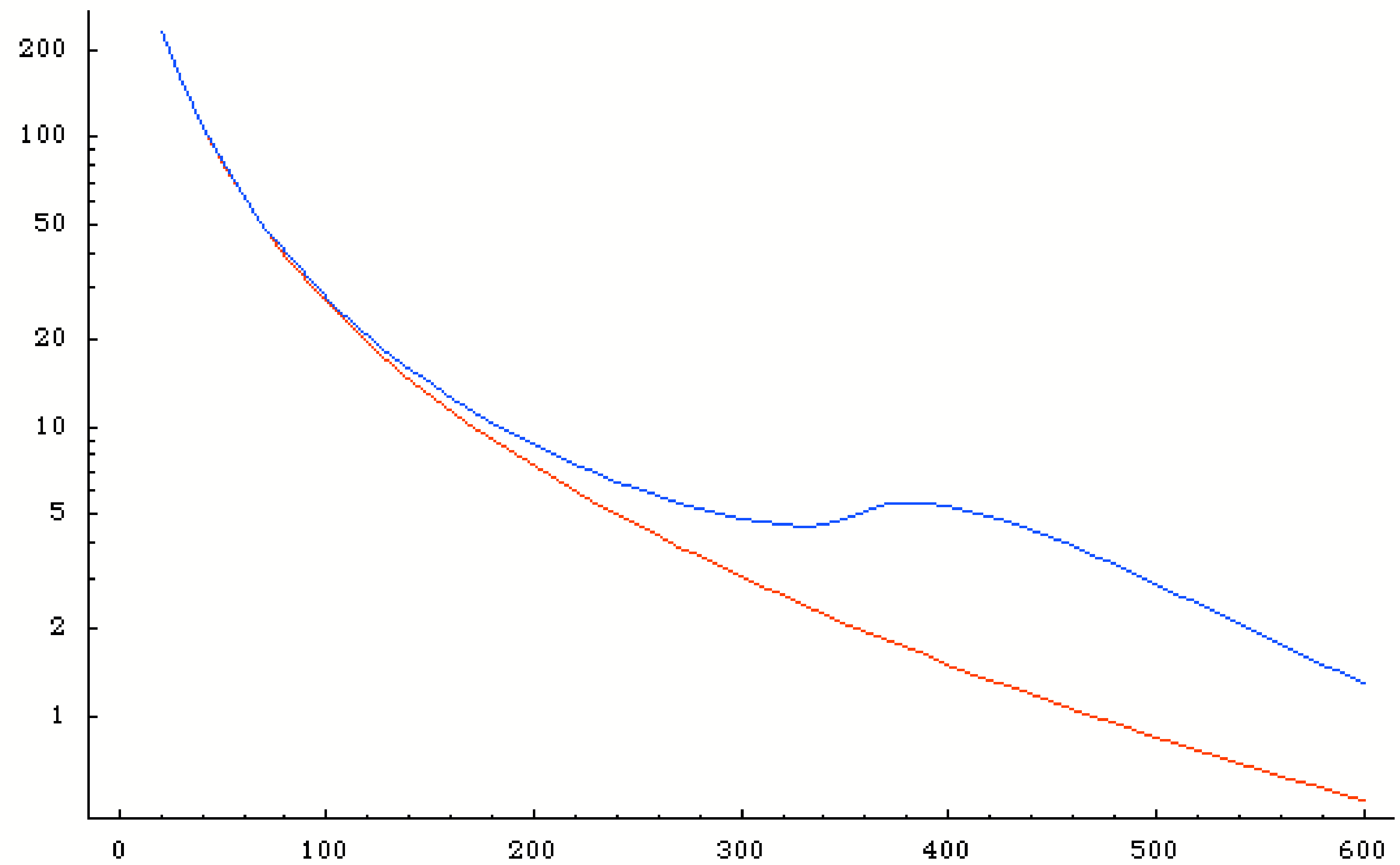
This causes a bump in the cross section.



pp→H at LO

The accuracy of the calculation in the HEFT calculation can be directly assessed by taking the limit m→∞.

For light Higgs is better than 10%.



So, if we are interested in a light Higgs we use the HEFT and simplify our life. If we do so, the NLO calculation becomes a standard 1-loop calculation, similar to Drell-Yan at NLO. We can (try to) do it!!

Collider Phenomenology

I Basics of collider physics and QCD

II SM Pheno: the top quark

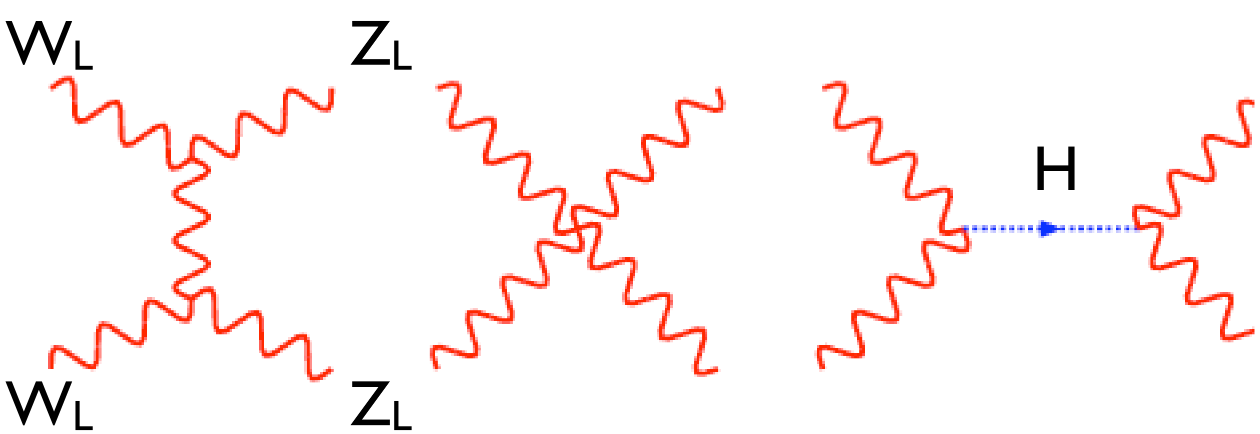
III Searching for New Physics with tops

BSM potential

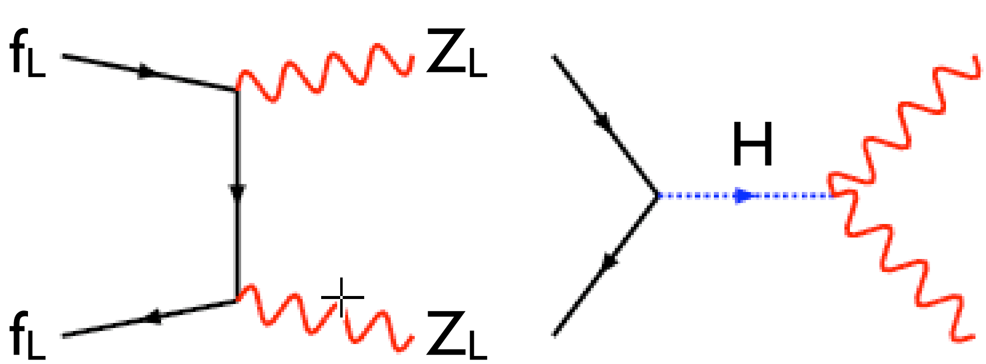
- It gives large corrections to EW observables.
- It points to a mass generation mechanism at low scales.
- It destabilises the Higgs mass.
- It deforms the Higgs potential at high energy.

The Higgs restores unitarity

Good Homework



$$a_0 \sim \frac{s}{v^2} - \frac{s}{v^2} \sim \frac{m_H^2}{v^2}$$



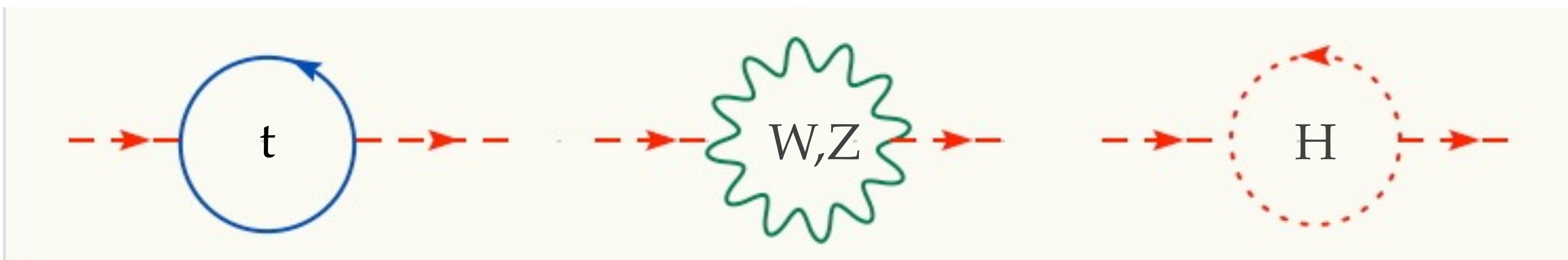
$$a_0 \sim \frac{\sqrt{s} m_f}{v^2} - \frac{\sqrt{s} m_f}{v^2} \sim \frac{m_f^2}{v^2}$$

SM is a linearly realised gauge theory which valid up to arbitrary high scales (if m_H<<1 TeV).

University of Glasgow

Naturalness in the SM

In the SM the radiative corrections to the Higgs mass can be written as



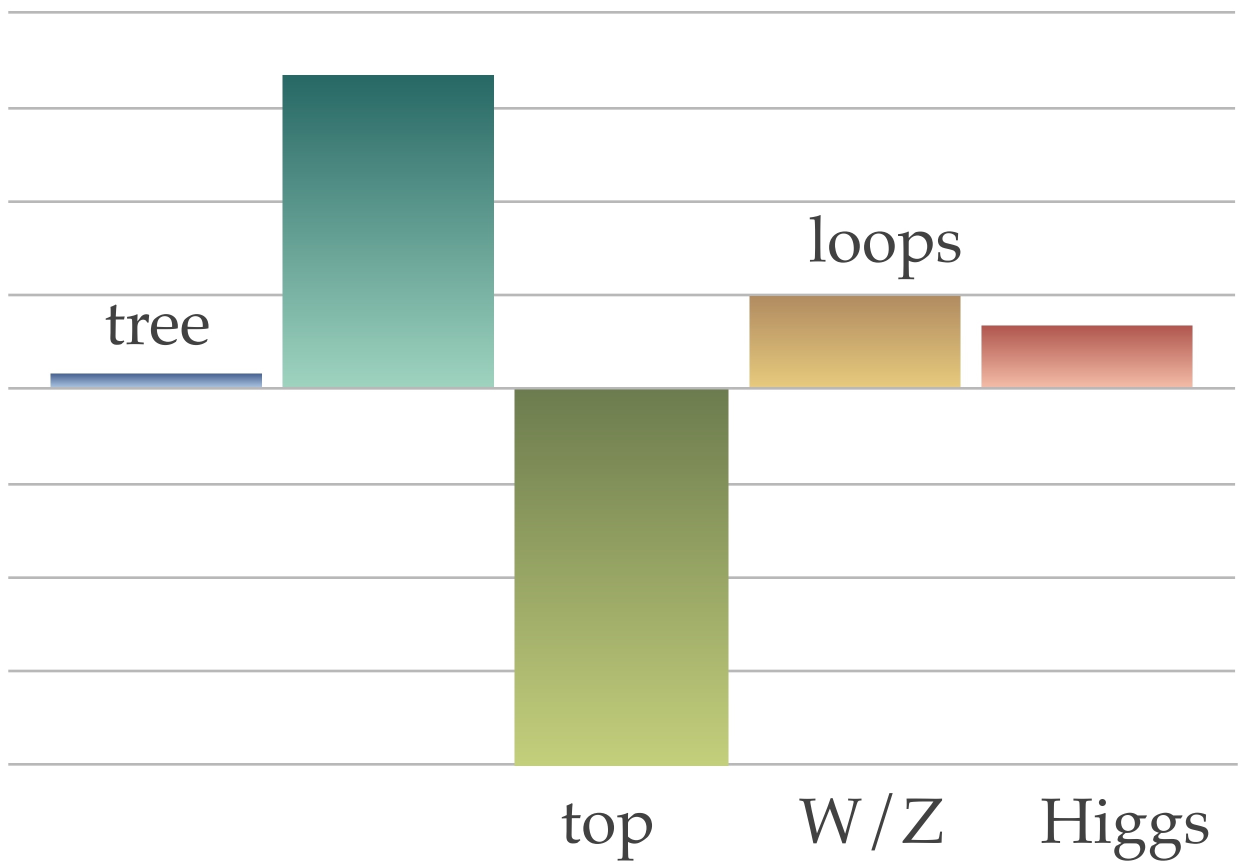
$$m_H^2 = m_{H0}^2 \qquad - \frac{3}{8\pi^2} y_t \Lambda^2 \qquad + \frac{1}{16\pi^2} g^2 \Lambda^2 \qquad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

Putting numbers, one gets:

$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right] \left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

Naturalness in the SM

mH² ~ (125 GeV)²

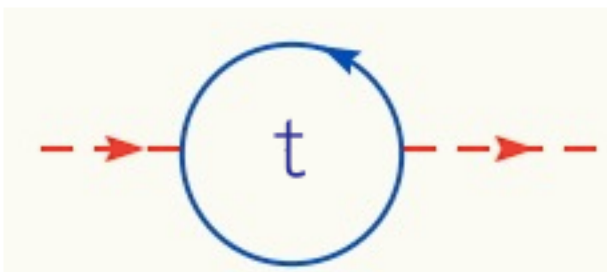


$$(125\,\mathrm{GeV})^2 = m^2_{H0} + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

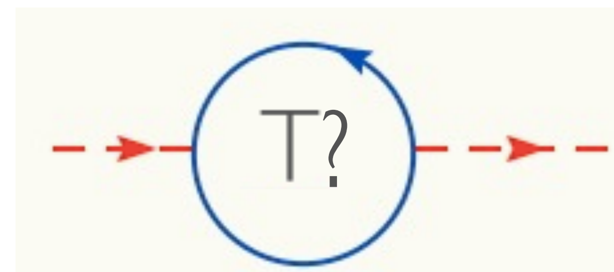
Definition of naturalness: less than 90% cancellation:

$\Lambda_t < 3\,\mathrm{TeV}$ $\Rightarrow$ top partners must be "light"

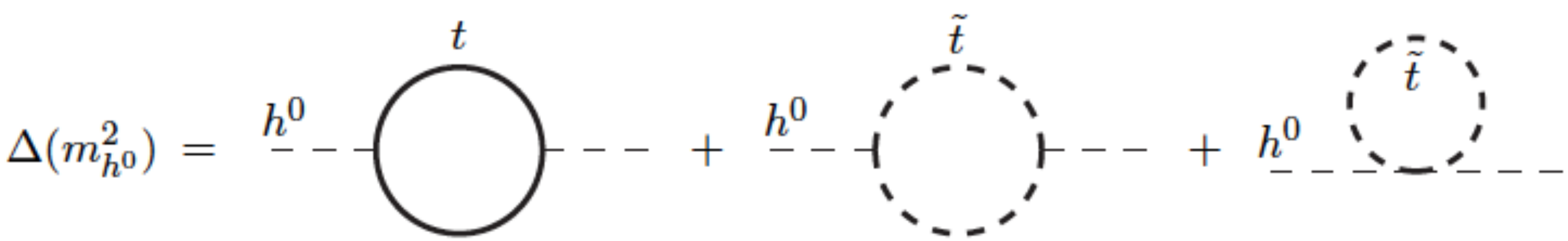
Model building inspired by naturalness



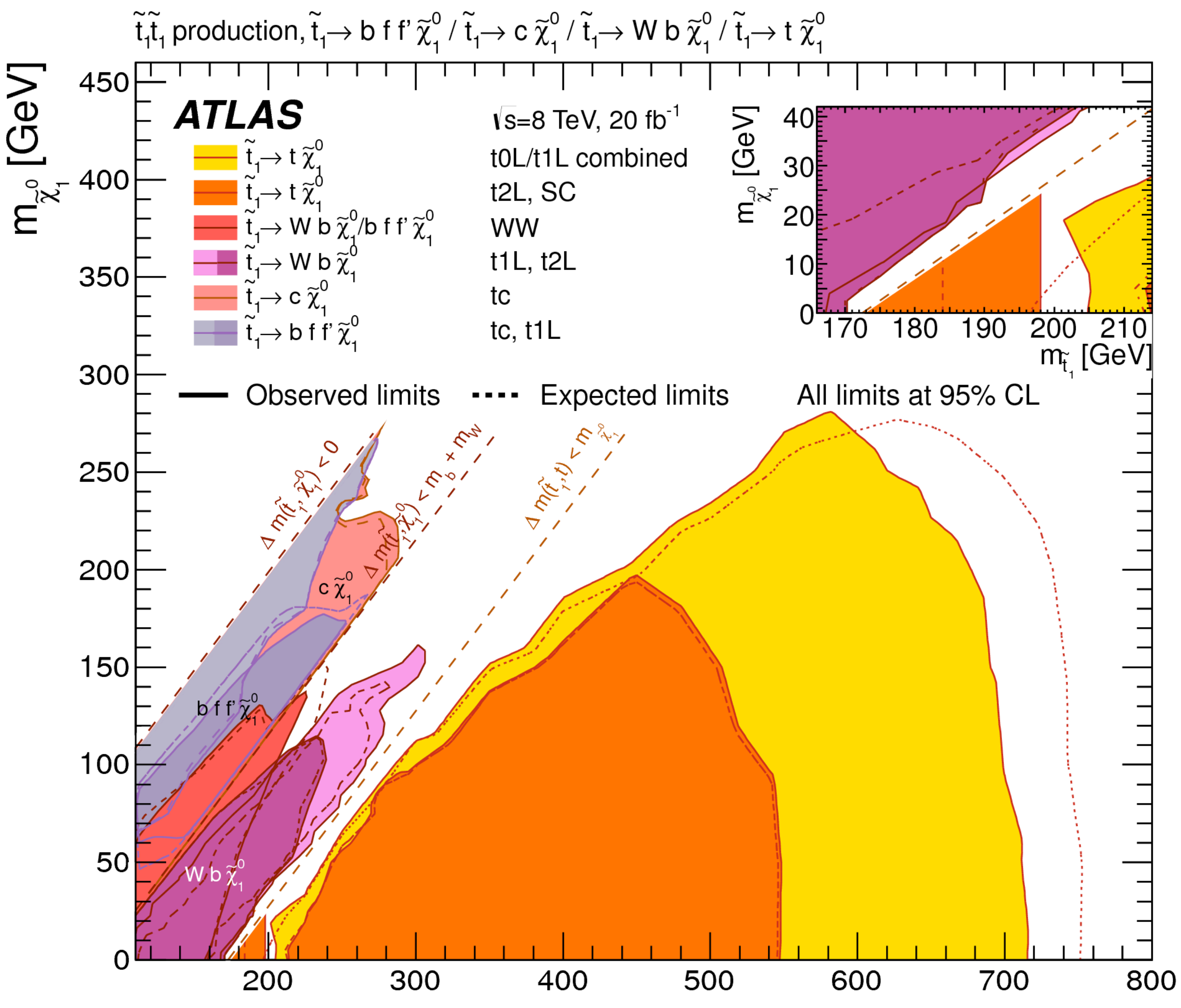
$+$



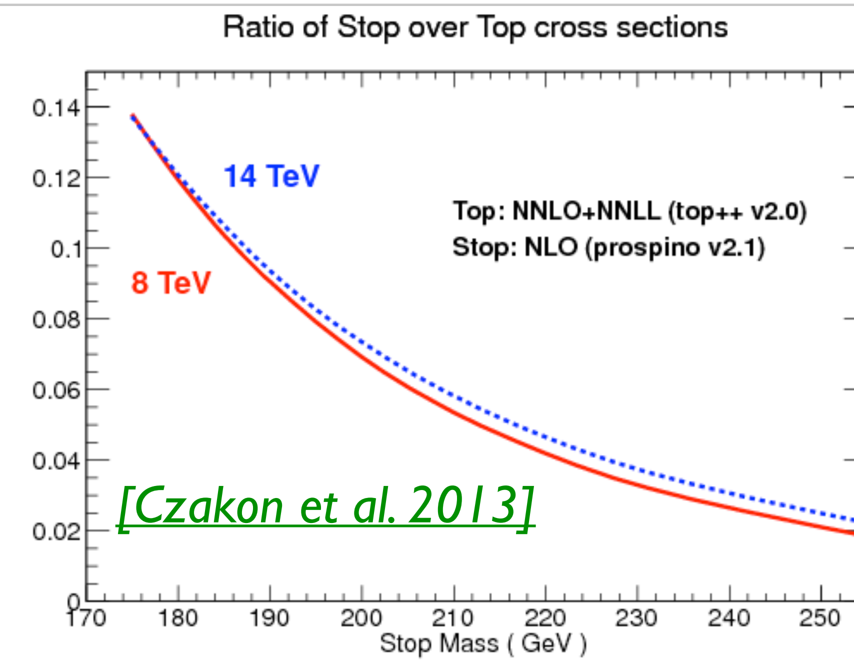
$$= \frac{8}{3\pi^2} m_T^2 \log \Lambda$$



Direct stop searches



[ATLAS 2015]

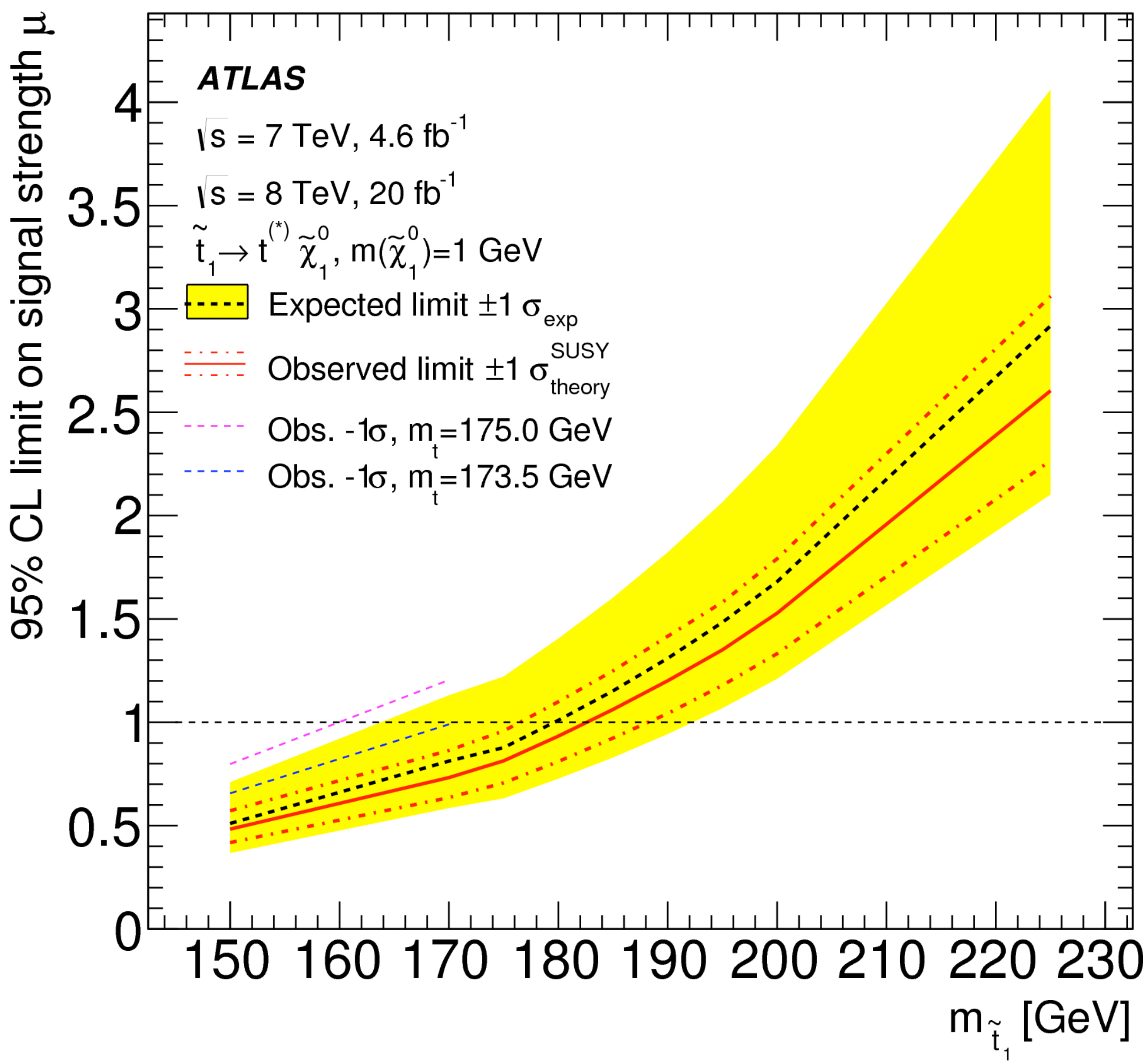


[Czakon et al. 2013]

- Stop direct searches based on four different final states:

1. stop → t+n1 (w/ stop1 mostly right),
2. stop → W+b+n1 (3-body decay for m(stop) < m(top) + m(ne1)),
3. stop → c + n1
4. stop → f+f'+b+n1 (4-body decay).

Precision stop searches



Expected and observed 95% CL limits on the signal strength μ (defined as the ratio of the obtained stop cross section to the theoretical prediction) for the production of $\tilde{t}$ pairs as a function of $m\tilde{t}$.

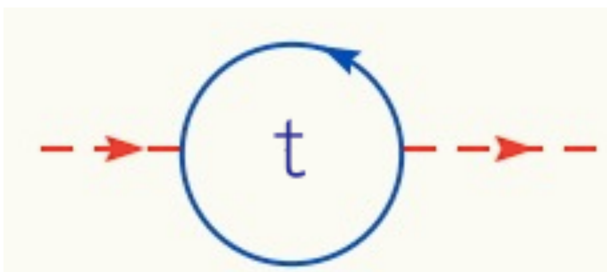
The stop is assumed to decay as $\tilde{t} \rightarrow t\tilde{\chi}$ or through its three-body decay depending on its mass. The neutralino is assumed to have a mass of 1 GeV.

The black dotted line shows the expected limit with ±1σ uncertainty band shaded in yellow, taking into account all uncertainties except the theoretical cross-section uncertainties on the signal.

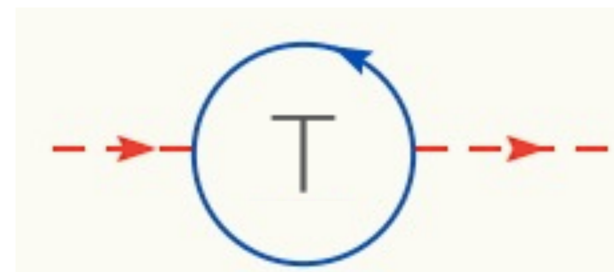
The red solid line shows the observed limit, with dotted lines indicating the changes as the nominal signal cross section is scaled up and down by its theoretical uncertainty.

The short blue and purple dashed lines indicate how the observed limits with the signal cross section reduced by one standard deviation of its theoretical uncertainty for $m\tilde{t}$ 1<mtop when the top quark mass is assumed instead to be 173.5±1.0 and 175.0±1.0 GeV.

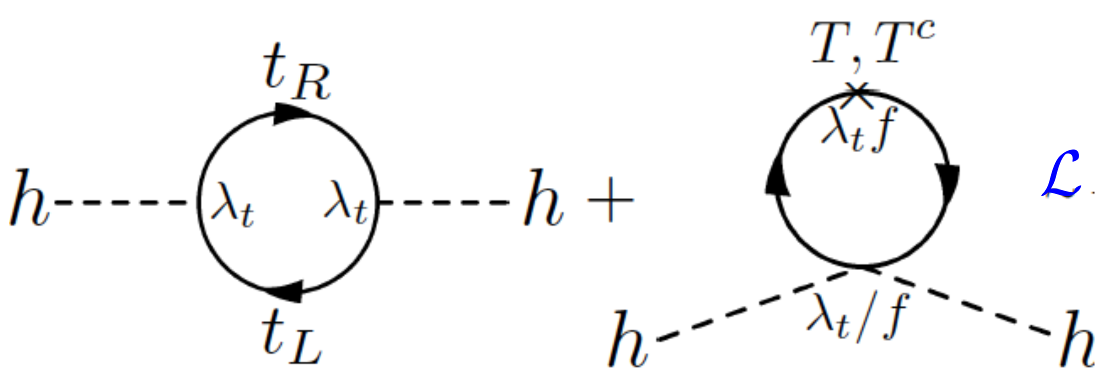
Model building inspired by naturalness



$+$



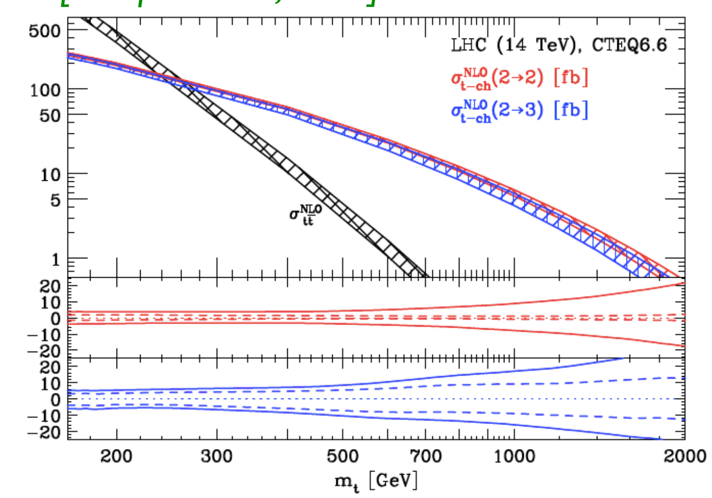
$$= \frac{8}{3\pi^2} m_T^2 \log \Lambda$$

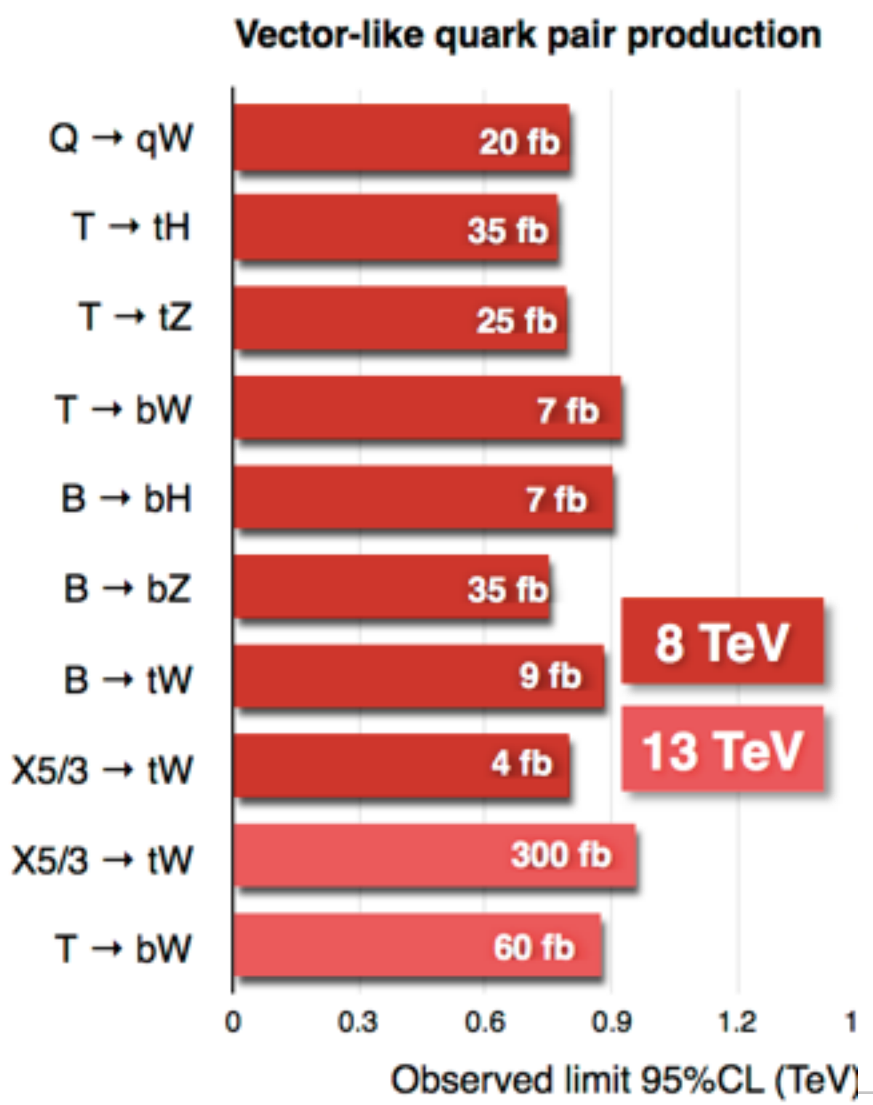


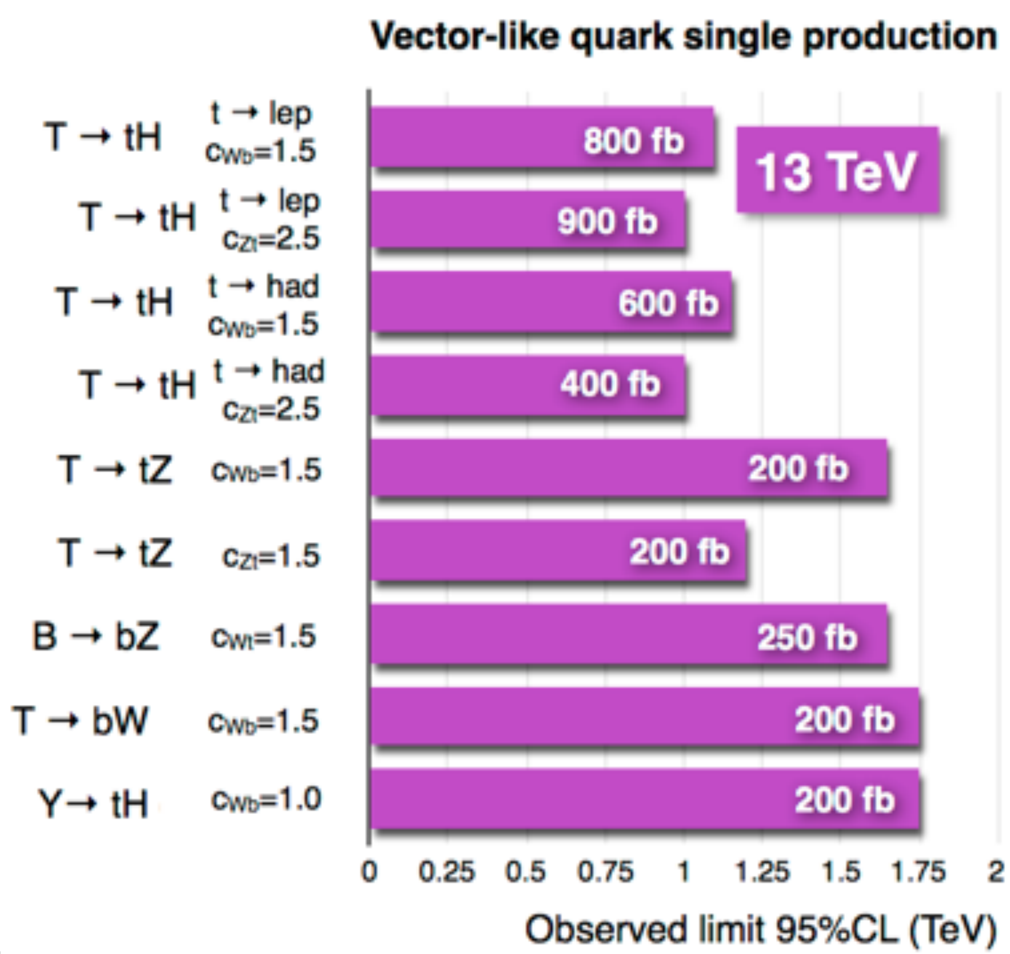
$$\mathcal{L} = y_t \left[iqht^c + f \left(1 - \frac{h^\dagger h}{2f^2} \right) TT^c + \ldots \right] + h.c.$$

Direct vector-like quarks searches

[Campbell et al, 2009]



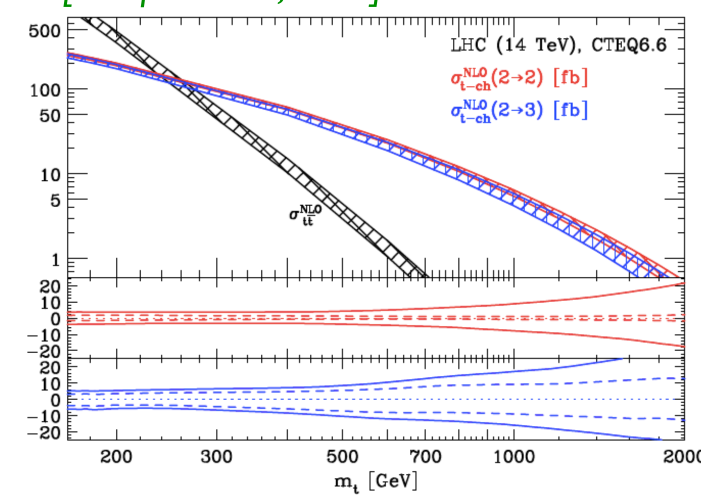


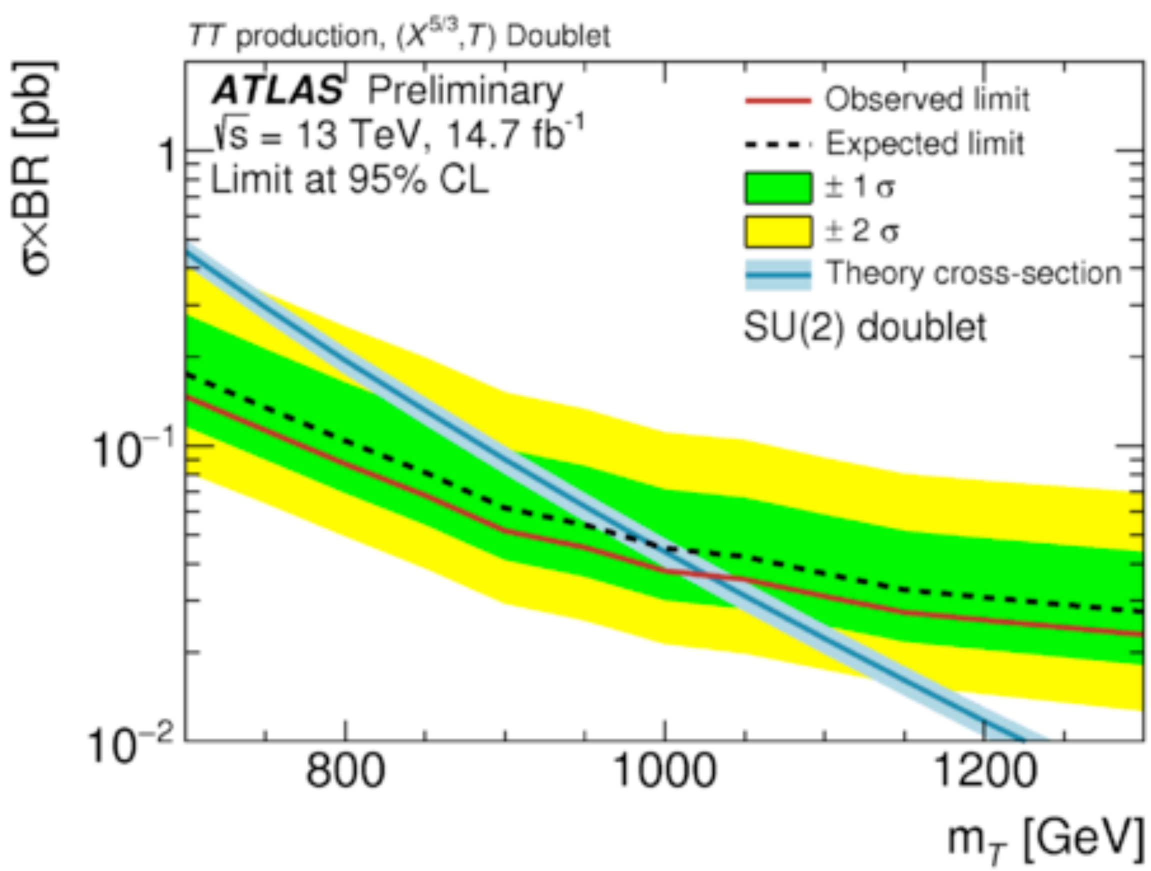


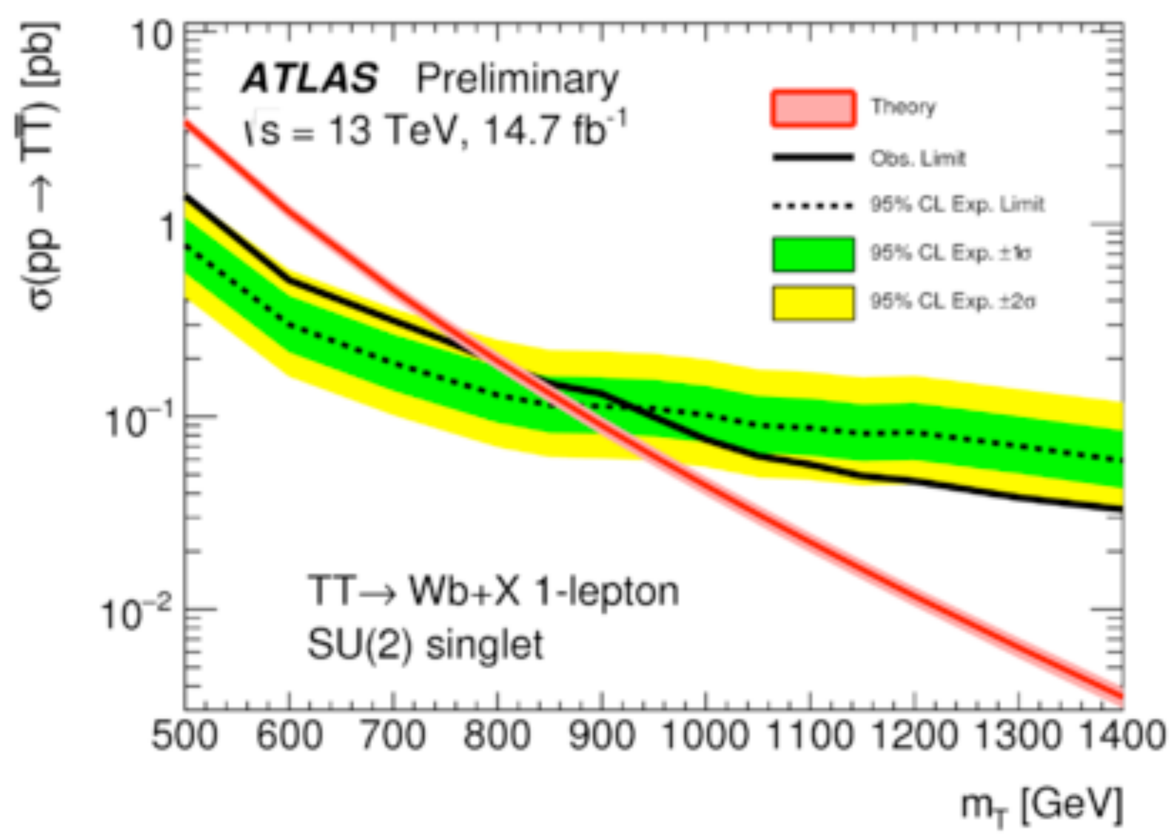
[CMS - B2G 2016]

Direct vector-like quarks searches

[Campbell et al, 2009]



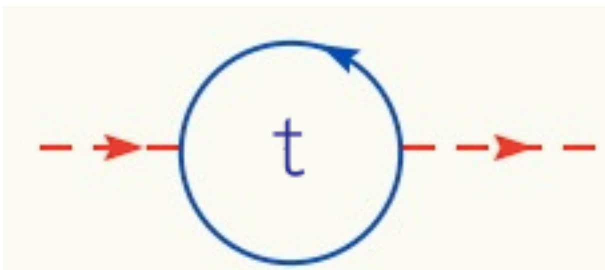




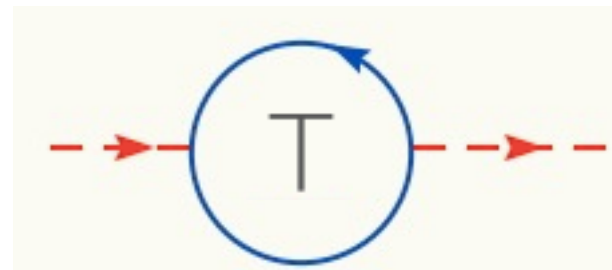
[ATLAS 2016]

[ATLAS 2016]

Model building inspired by naturalness



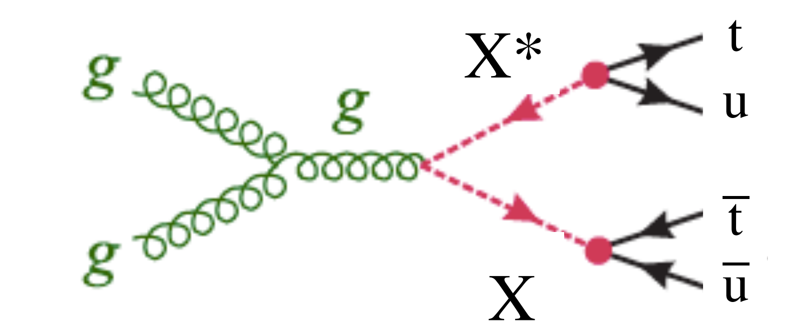
$+$

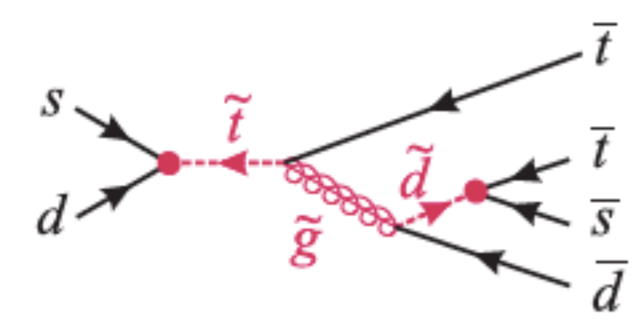


$$= \frac{8}{3\pi^2} m_T^2 \log \Lambda$$

Note that:

- Many variations exist of this mechanisms, such as for example partners that are not colored, or Hyperfolded SUSY.
- Such models typically entail other particles in the spectrum that couple to the top (such as extra scalars or DM candidates) and might lead to new top interactions at low energy (such as RPV).





Strategies

The fox and the hedgehog

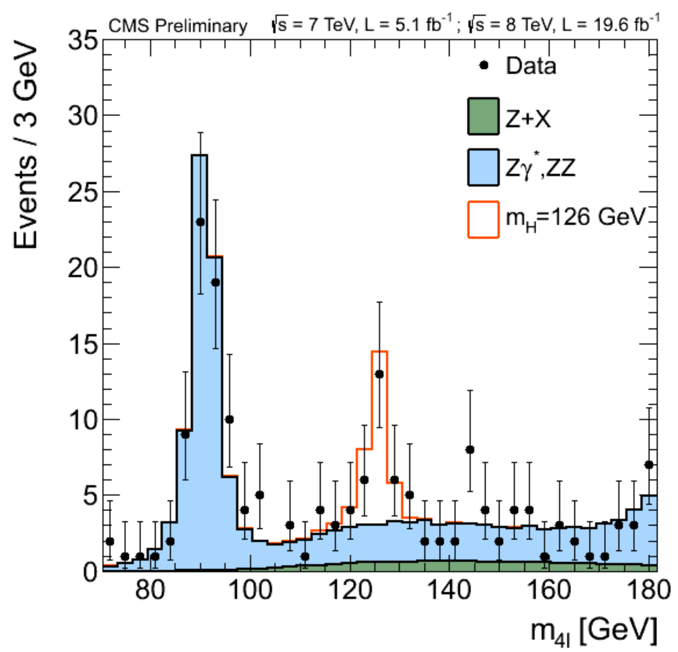
Searching for new physics

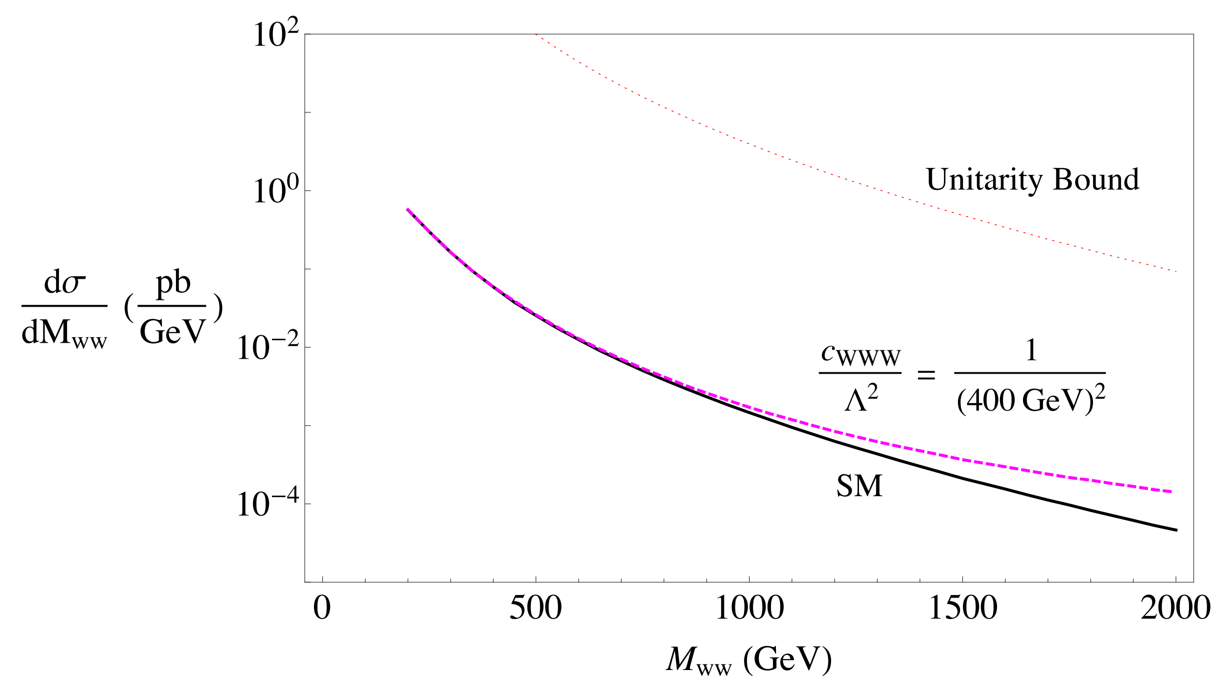
Model-dependent	⟷	Model-independent
SUSY, 2HDM, ED,…		simplified models, EFT, …
Search for new states	⟷	Search for new interactions
specific models, simplified models		anomalous couplings, EFT…
Exotic signatures	⟷	Standard signatures
precision measurements		rare processes

Search for New Physics at the LHC

Two main strategies for searching new physics

Search for new states ⟷ Search for new interactions





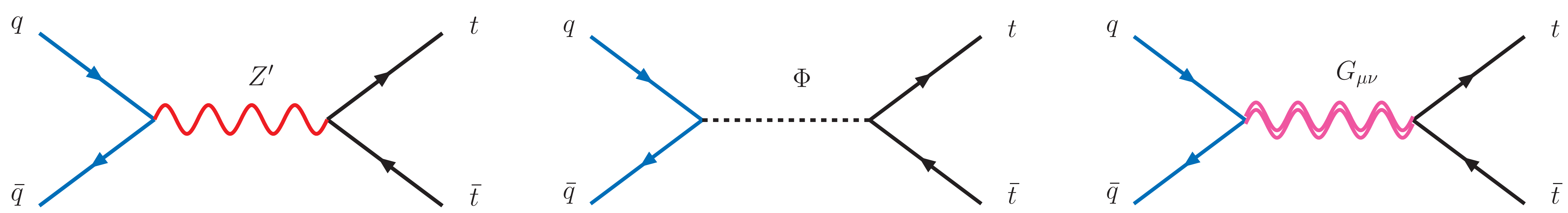
"Peak" or more complicated structures searches. Need for **descriptive MC** for discovery = Discovery is data driven. Later need precision for characterisation.

Deviations are expected to be small. Intrinsically a precision measurement. Needs for **predictive MC** and accurate predictions for SM and EFT.

Resonances in ttbar

Very interesting and rich history of searches for resonances in ttbar and many proposals and results since the first days of the LHC, see e.g., [Frederix, FM, 2007]. Higher masses can be reached by boosted top tagging techniques. I will make only two points here:

1. Limits on models that feature a clear BW peak (Z', coloron) with a fixed width are continuously improved by the increase in energy and luminosity:

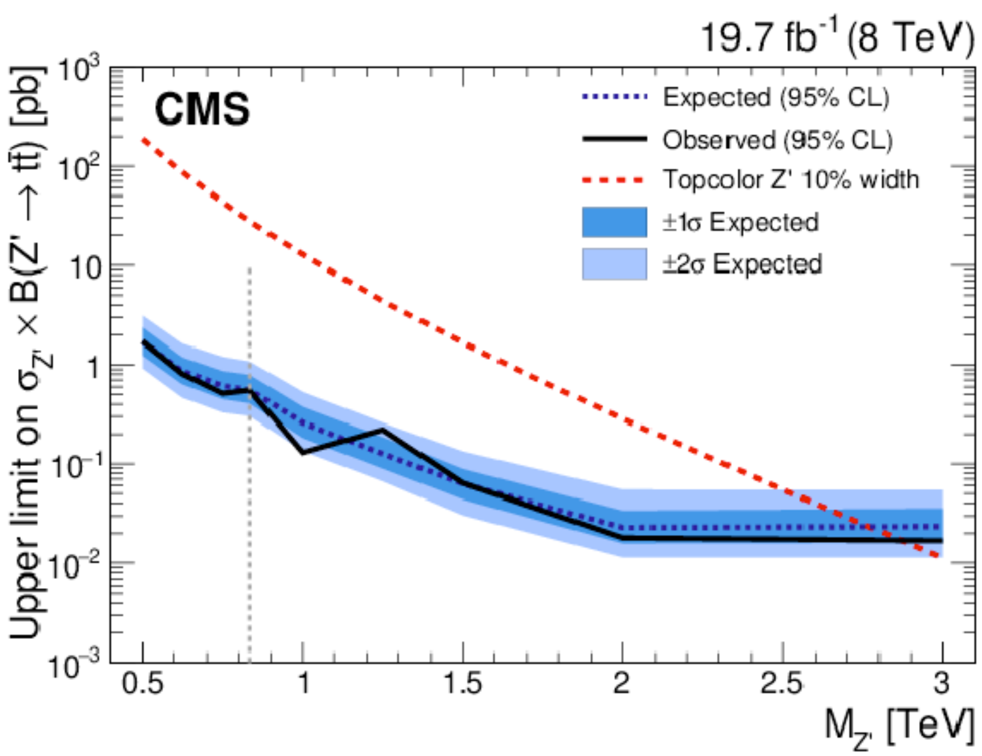


Resonances in ttbar

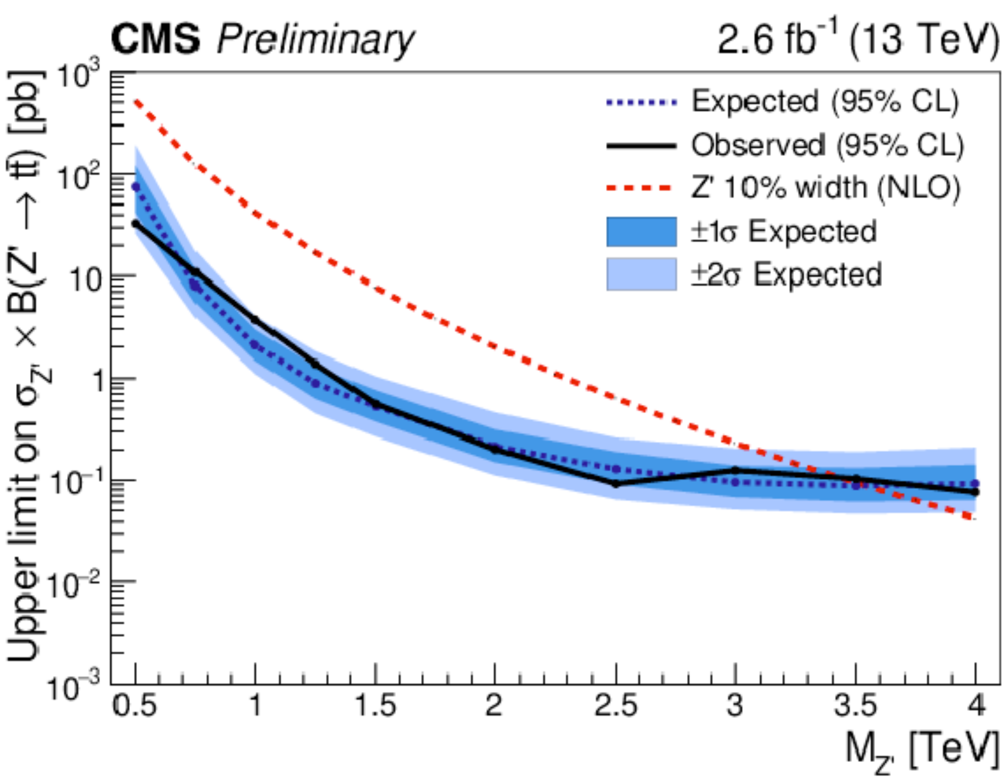
Very interesting and rich history of searches for resonances in ttbar and many proposals and results since the first days of the LHC, see e.g., [Frederix, FM, 2007]. Higher masses can be reached by boosted top tagging techniques. I will make only two points here:

1. Limits on models that feature a clear BW peak (Z', coloron) with a fixed width are continuously improved by the increase in energy and luminosity:

[CMS 2013]

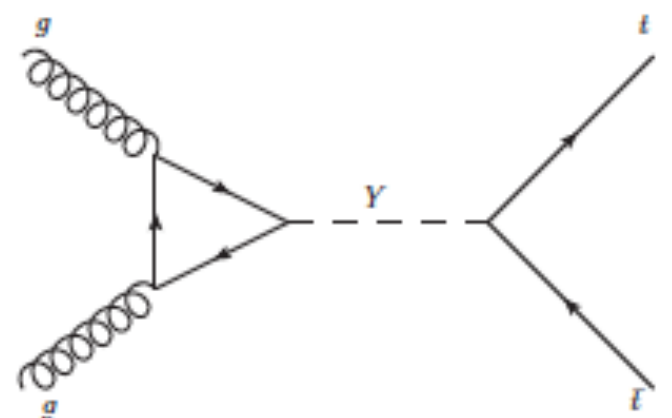


[CMS 2015]

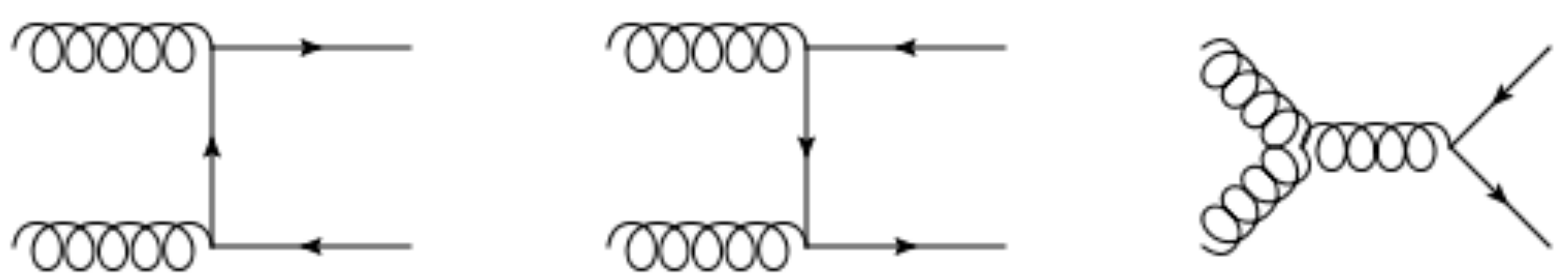


Resonances in ttbar

Imagine a new scalar exists which couples mostly to top quark, similar to the SM Higgs, but it is heavier than $2m_t$. It would be produced as the SM Higgs via gluon fusion and then mostly decay to top quarks:

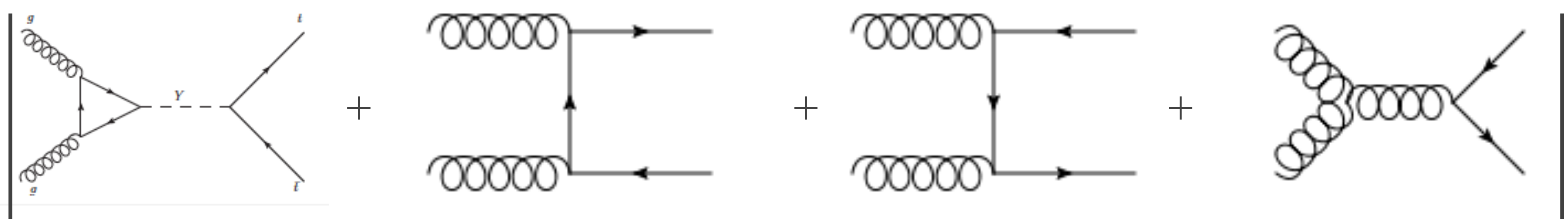


giving rise to a peak in the invariant mass distribution of m(tt). However, this process interferes with the QCD background:



Resonances in ttbar

| Amp | ^2=



2

Taking our previous calculation of the SM amplitude and adding the scalar production:

$$\hat{\sigma}(s) = \frac{\alpha_s^2 G_F^2 m^2 s^2}{768\,\pi^3}\beta^3 \left| \frac{N(s/m^2)}{s - m_H^2 + i m_H \Gamma_H(s)} \right|^2$$

BW resonance

$$-\frac{\alpha_S^2 G_F m^2}{48\pi\sqrt{2}}\beta^2 \ln\frac{1+\beta}{1-\beta}\ \mathrm{Re}\left[\frac{N(s/m^2)}{s - m_H^2 + i m_H \Gamma_H(s)}\right]$$

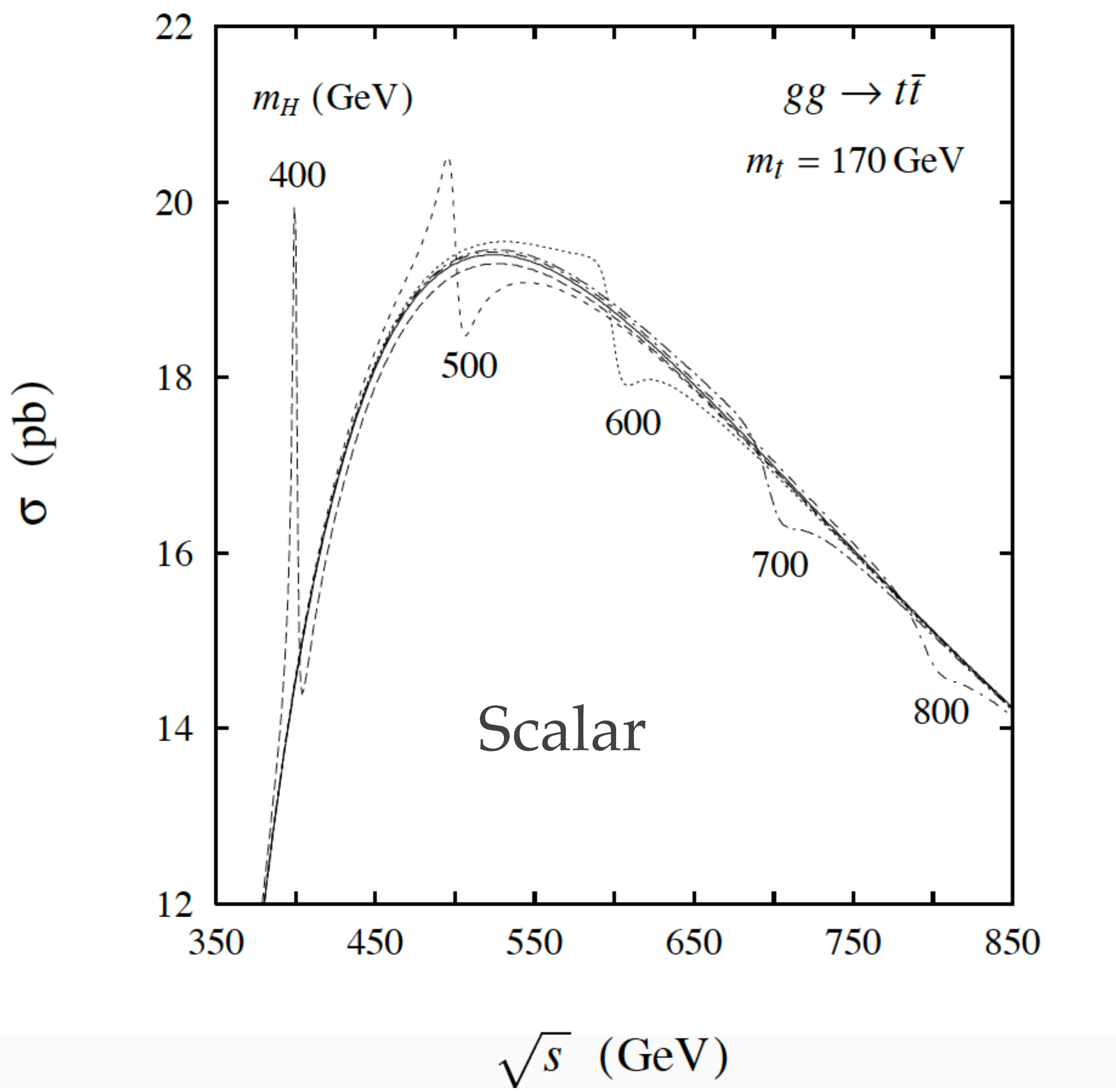
Interference

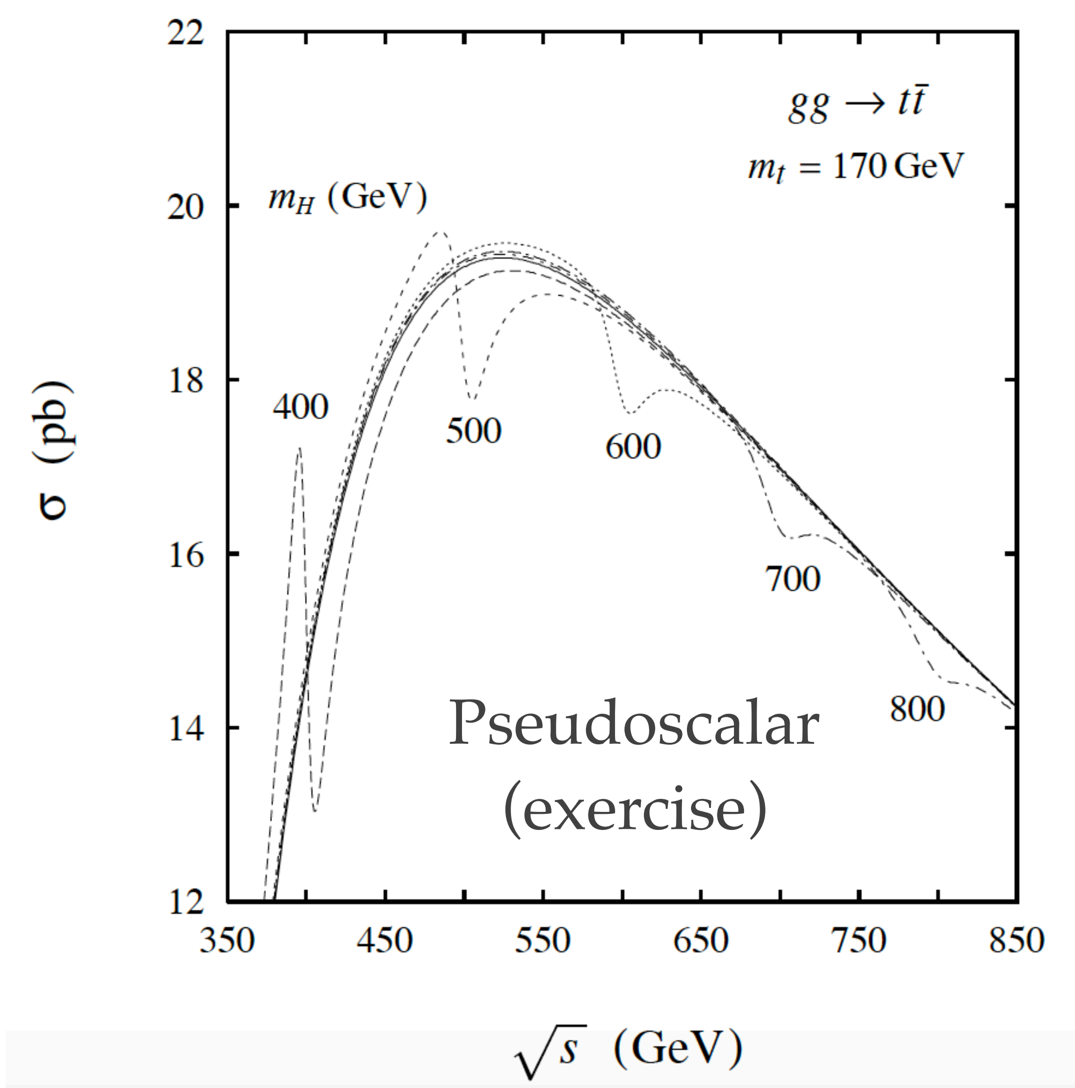
$$+\hat{\sigma}_{\mathrm{SM}}(s)$$

SM

$$N(s/m^2) = \frac{3}{2}\frac{m^2}{s}\left[4 - \left(1 - \frac{4m^2}{s}\right) I(s/m^2)\right] \quad I(s/m^2) = \left[\ln\frac{1+\beta}{1-\beta} - i\pi\right]^2 \quad (s > 4m^2)$$

Resonances in ttbar

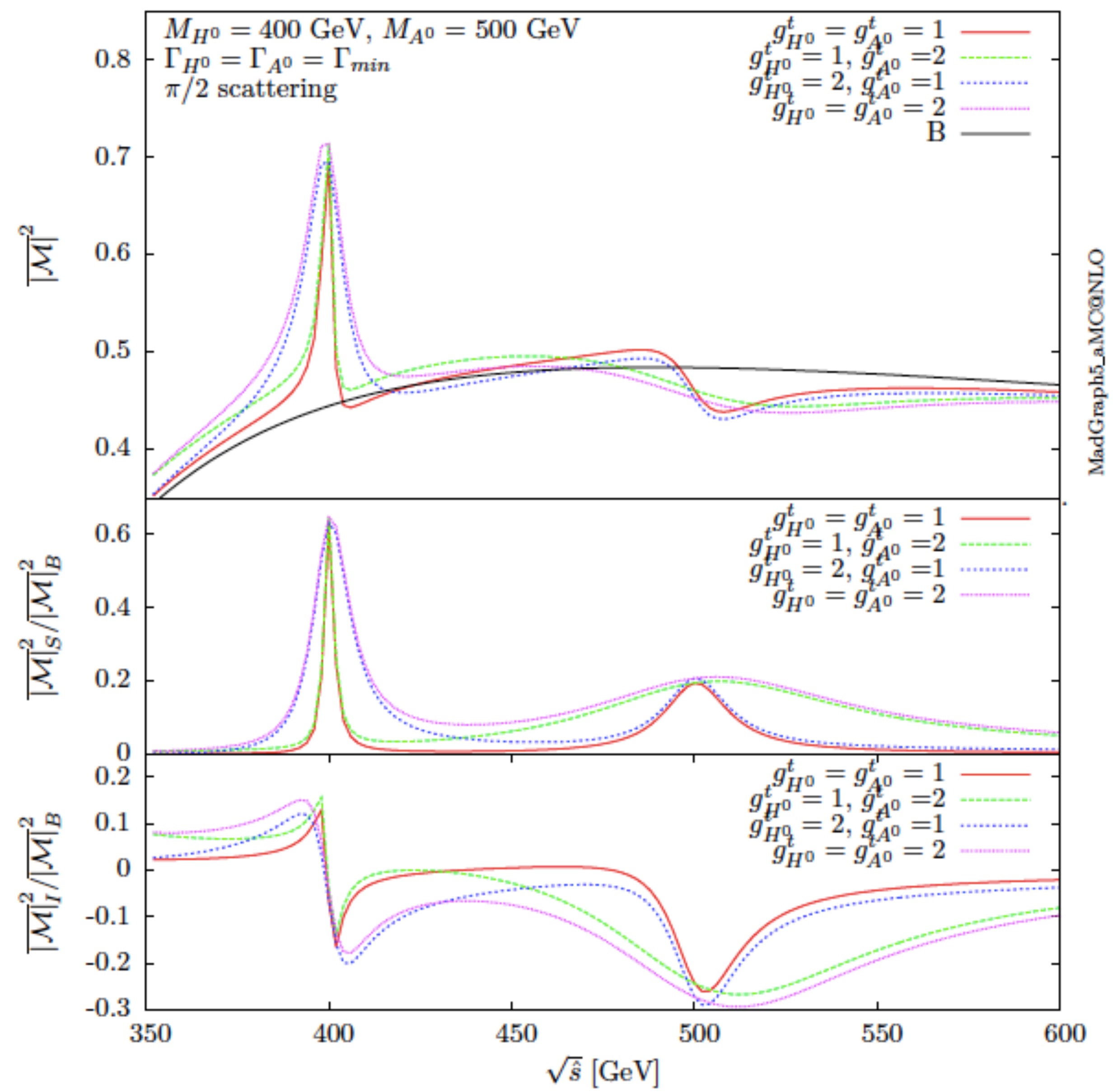




Peaks but also peak-dip and dip only structures. "Easy" to discover independently of the precise knowledge of the SM. However, needs accurate theory to characterise it.

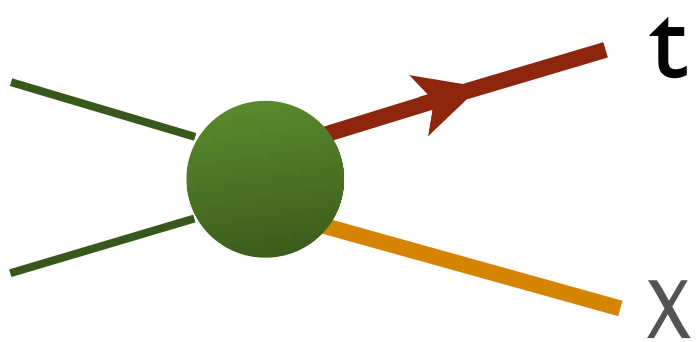
Resonances in ttbar

2. Analysis technology to look for BW peaks in place. Now it is time to consider more complicated situations, like peak-dip or even dips.



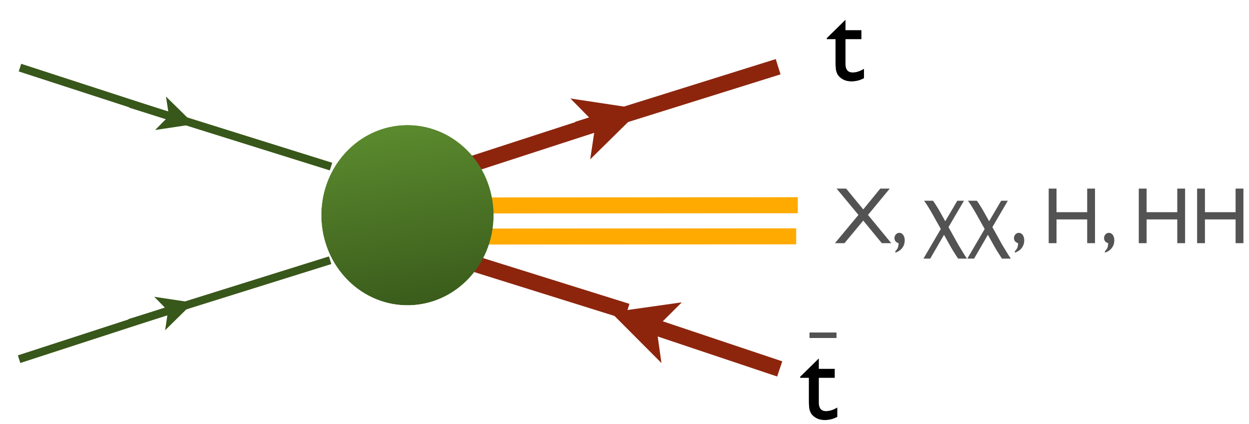
Exotic top-quark signatures

Searches for NP can be done in exotic or rare top signatures



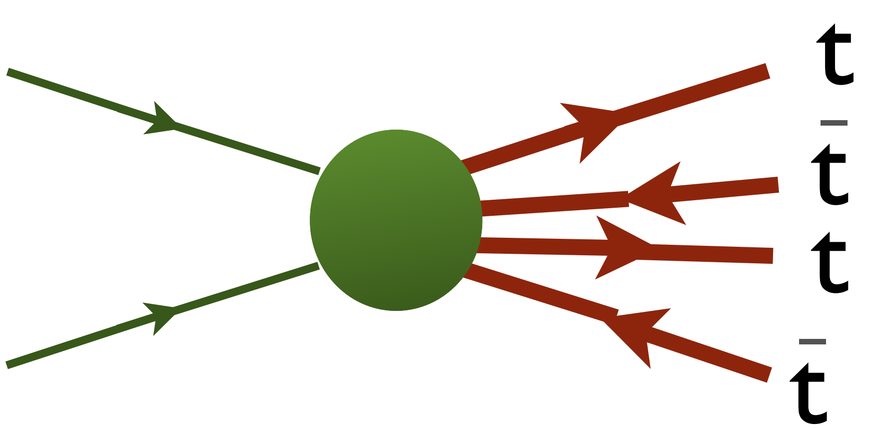
MONOTOPS

[Andrea et al. 2011]



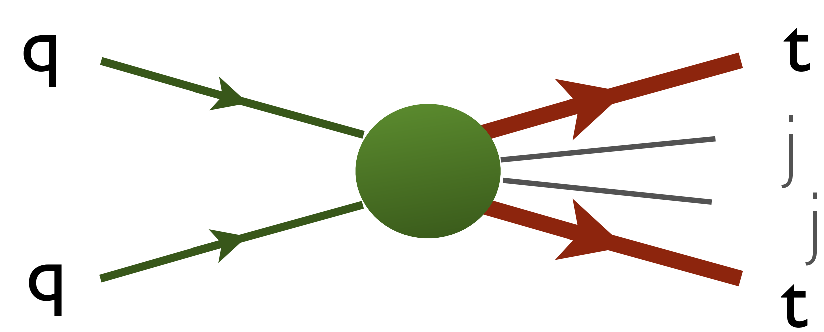
$t\bar{t} + \not{E}_T$, H,...

[Too long list here]



4 TOPS

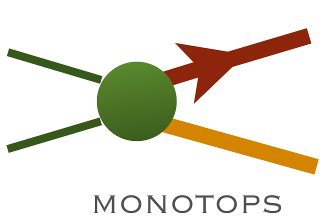
[Tait et al, 2008, Gregoire et al,, 2011, Servant et al. , 2010, Cacciapaglia et al. 2011, Degrande 2010 , ...]



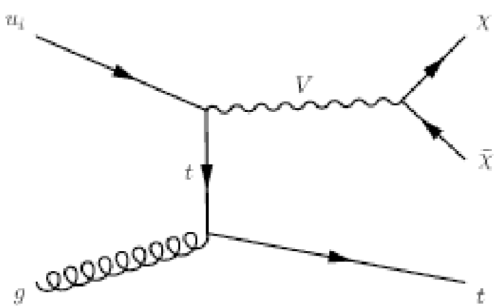
TT ($\bar{T}\bar{T}$) (+ JETS)

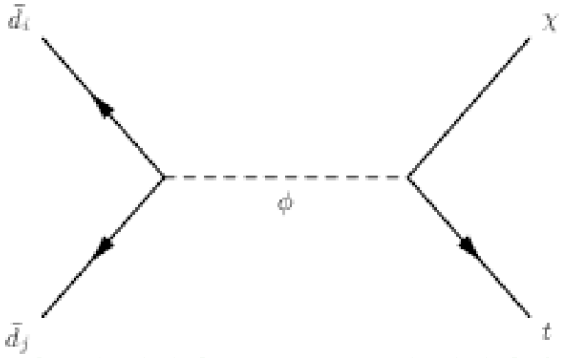
[Aguilar-Saavedra, 2011, Degrande et al. 2011, Kraml et al. 2006, Durieux et al. 2012,2013]

Exotic top-quark signatures

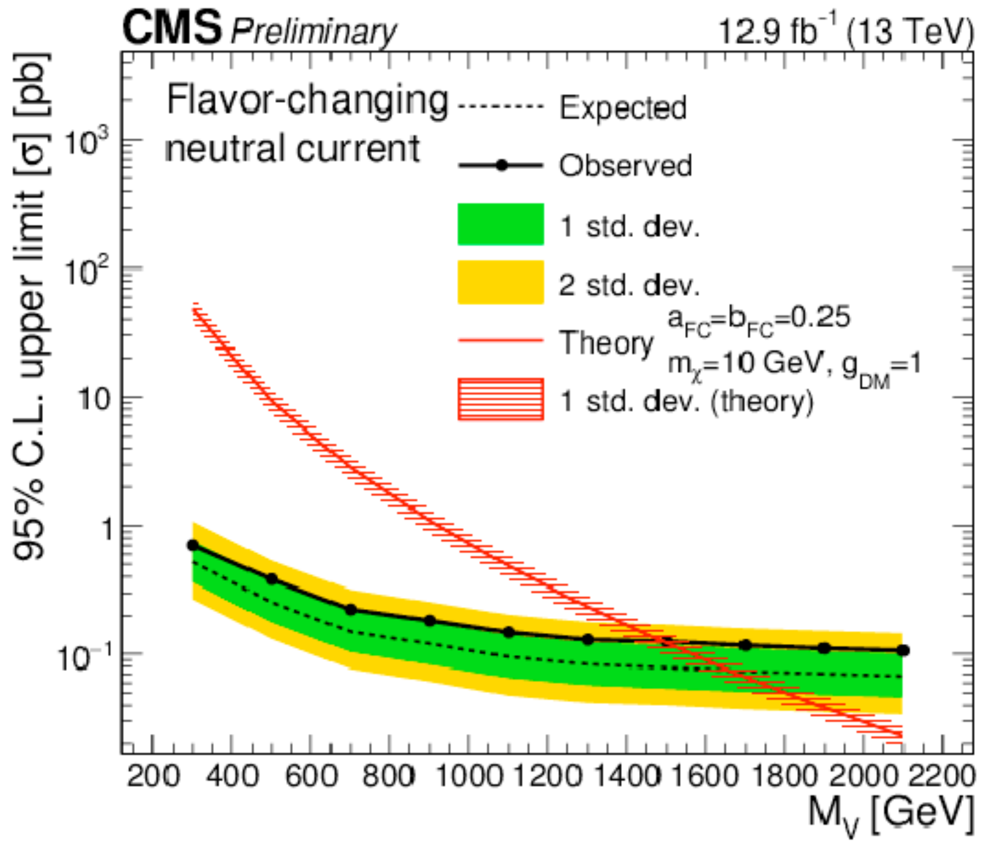


Several theoretical studies [Andrea et al. 2011], [Wang et al. 2011], [Alvarez, 2013] [Agram, 2013]…

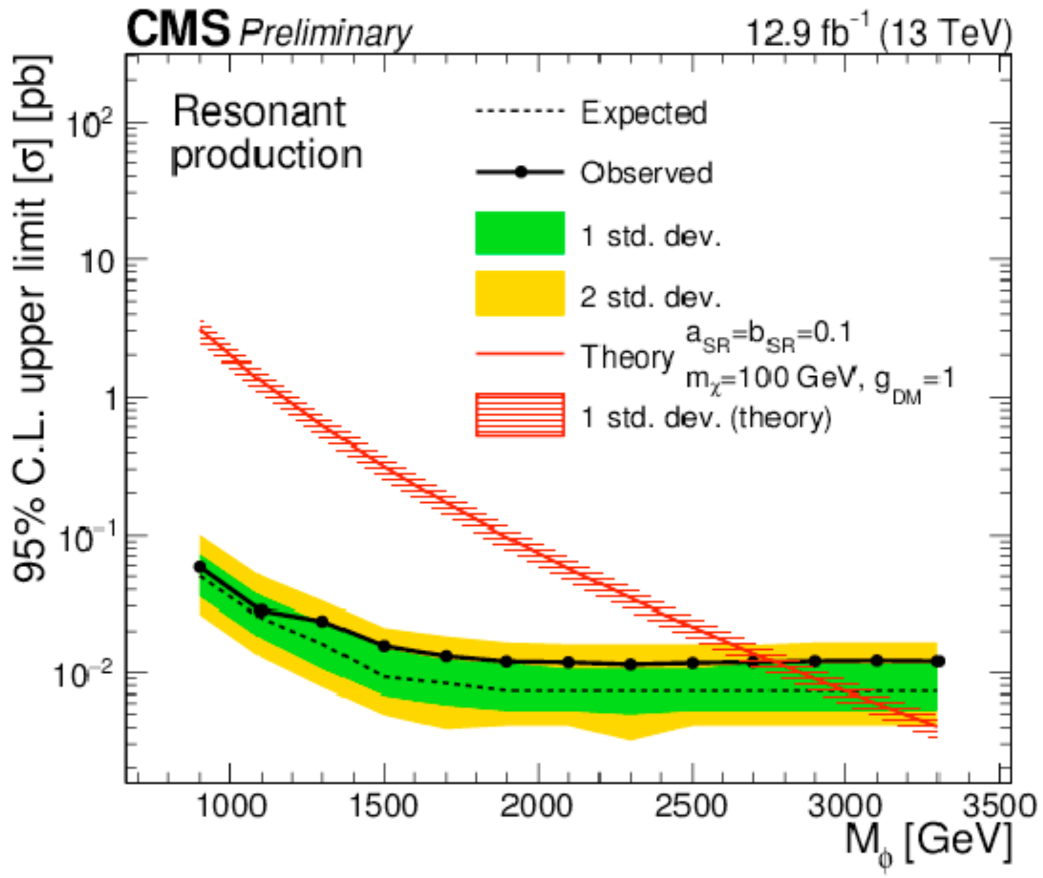




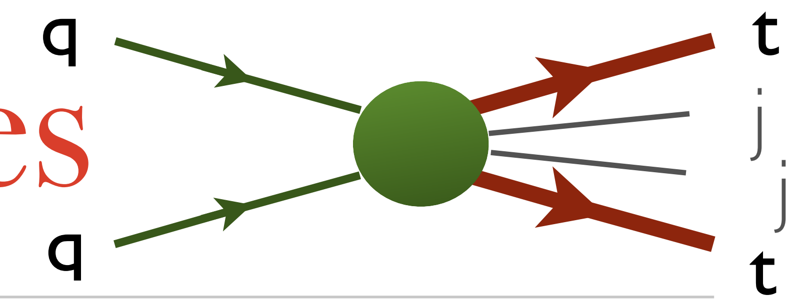
Several experimental analyses [CMS, 2015], [ATLAS, 2014]



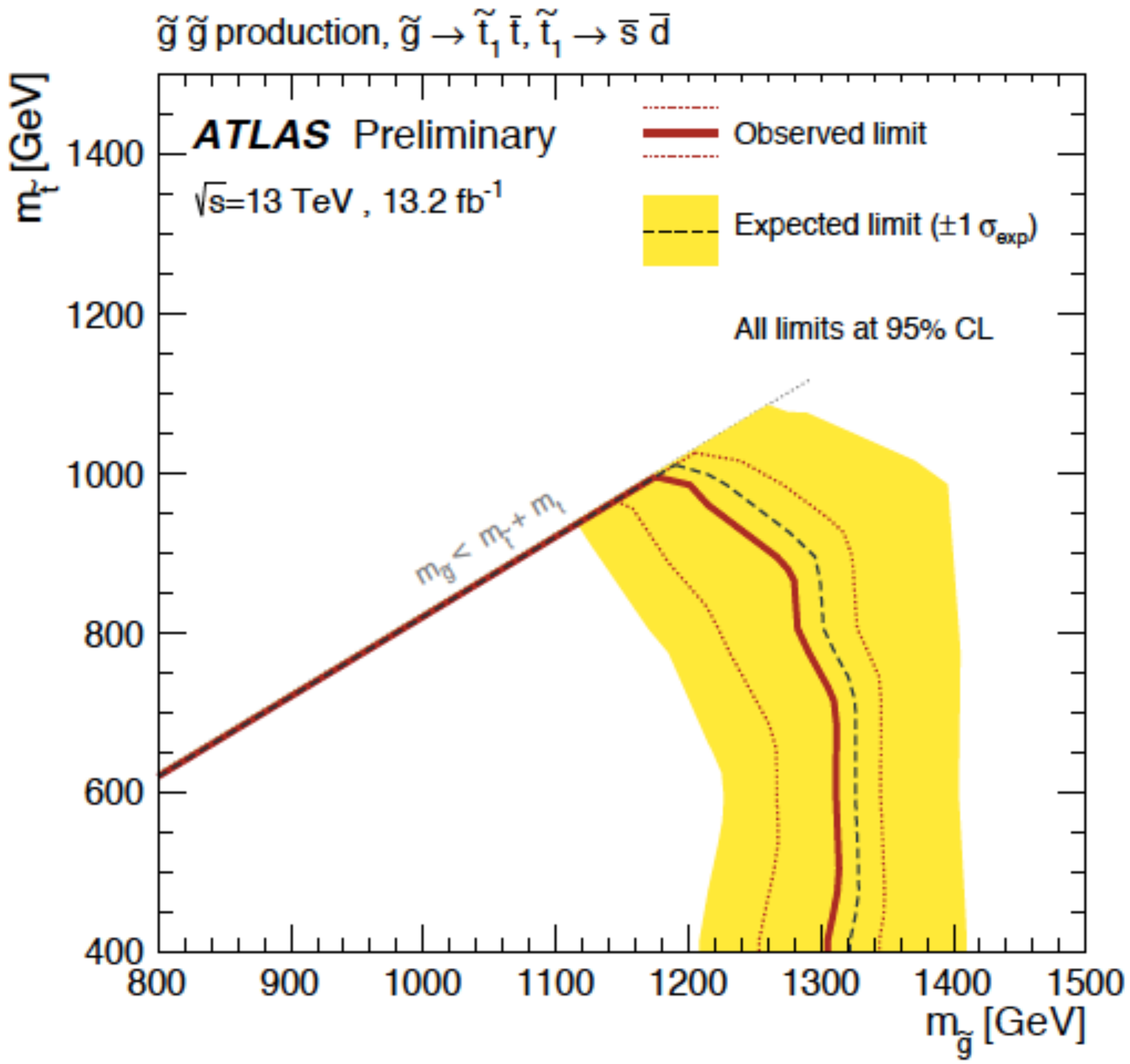
[CMS 2016]

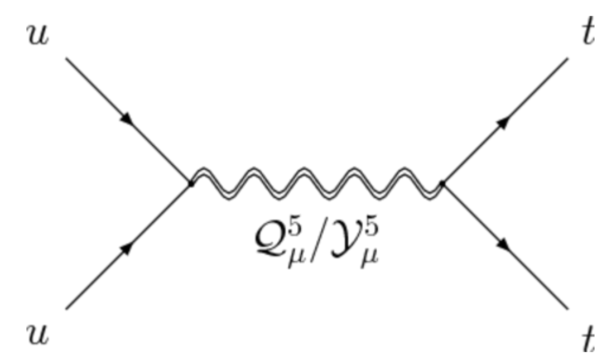


Exotic top-quark signatures

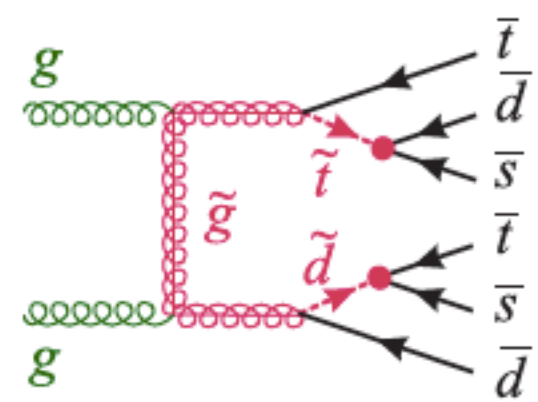


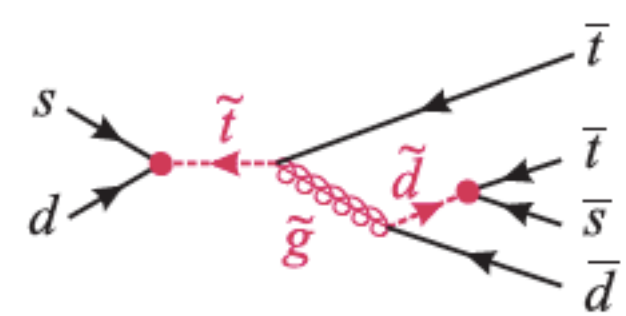
[ATLAS, 2016]





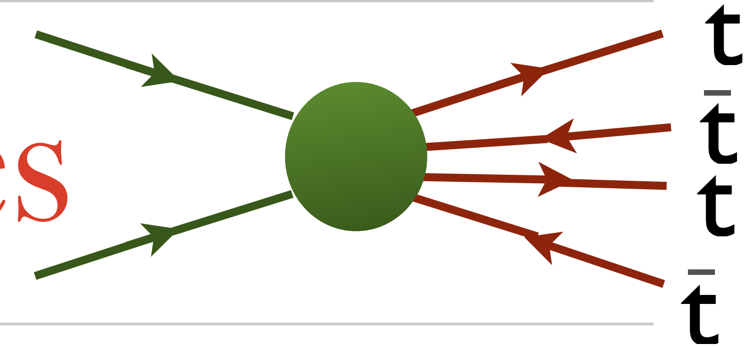
Signature that has attracted interest in the search of very exotic resonances, and more recently in interesting RPV scenarios. [Durieux and Smith, 2013]





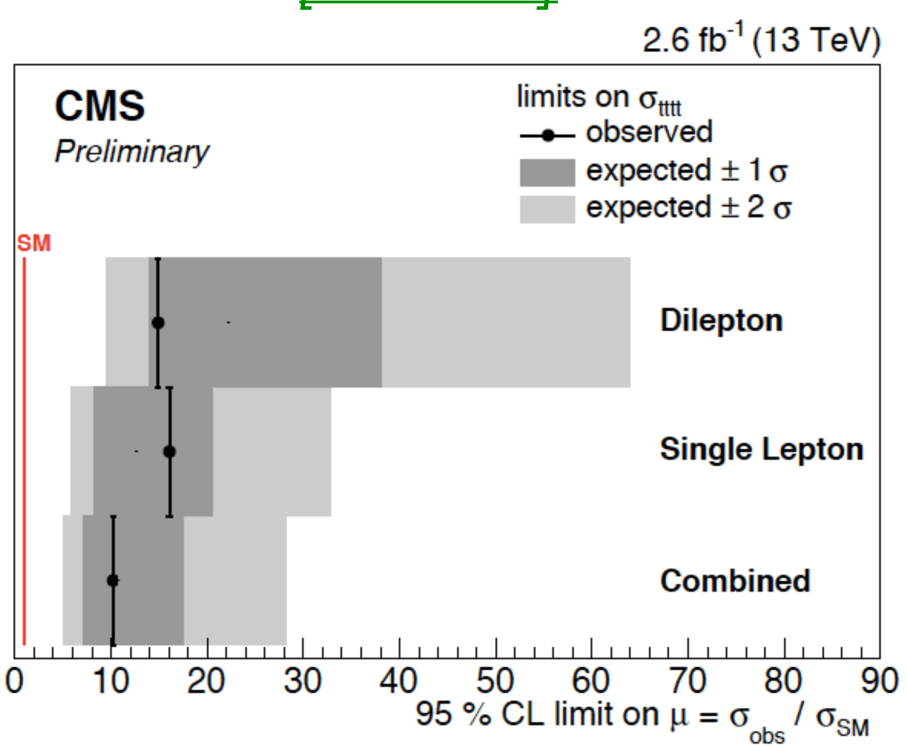
See also: [ATLAS, 2012], [CMS, 2013]

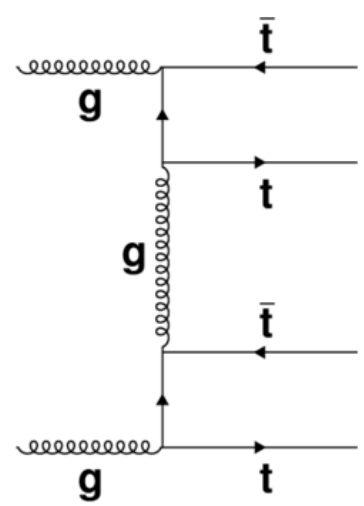
Exotic top-quark signatures

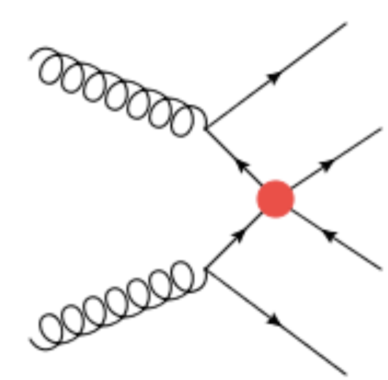


Four top signal has a long history, starting from [Tait et al, 2008]. SM signal known at NLO accuracy [Bevilacqua and Worek, 2012] and available NLO+PS [Maltoni et al. 2015]. BSM scenarios range from gluino gluino production and deca to 4t+Etmiss, to 4F interactions. Dedicated searches as well model independent ones have been undertaken.

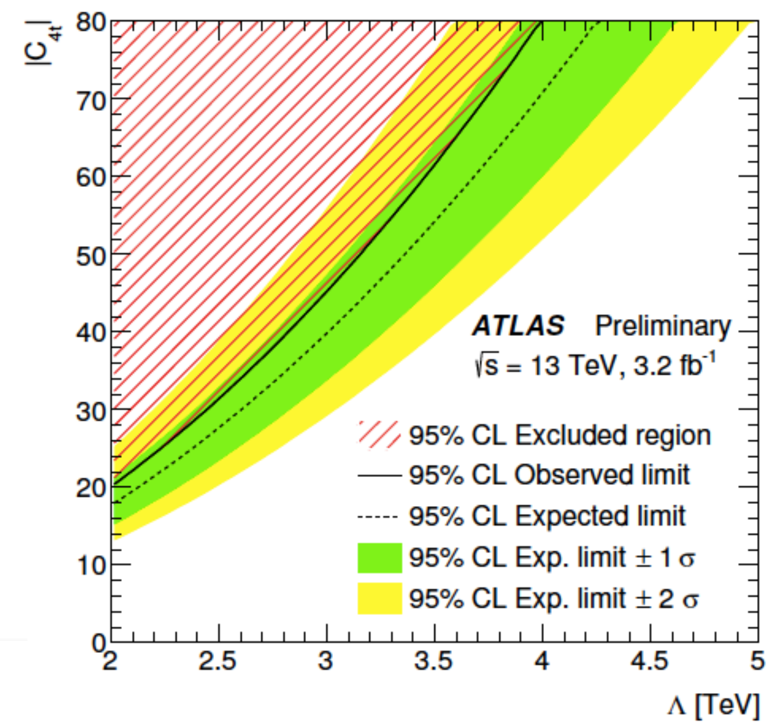
[CMS 2016]



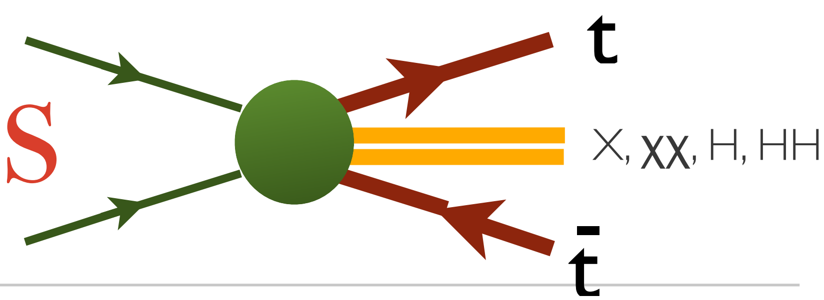




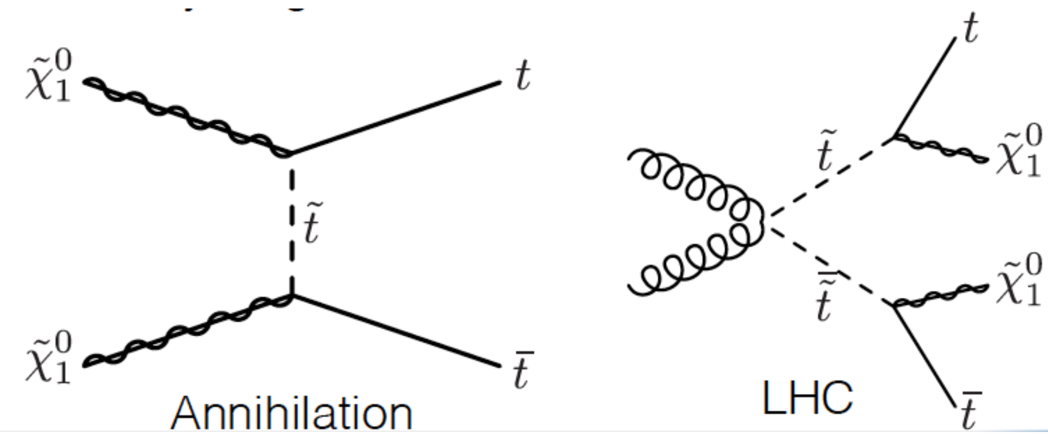
[ATLAS 2016]



Exotic top-quark signatures

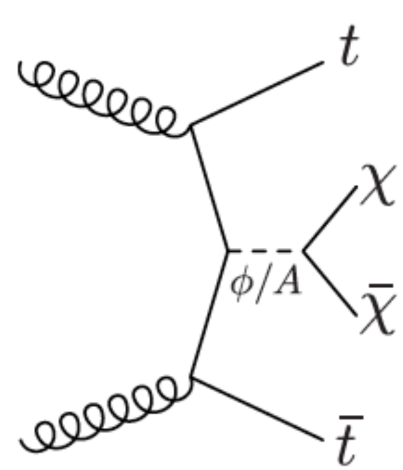


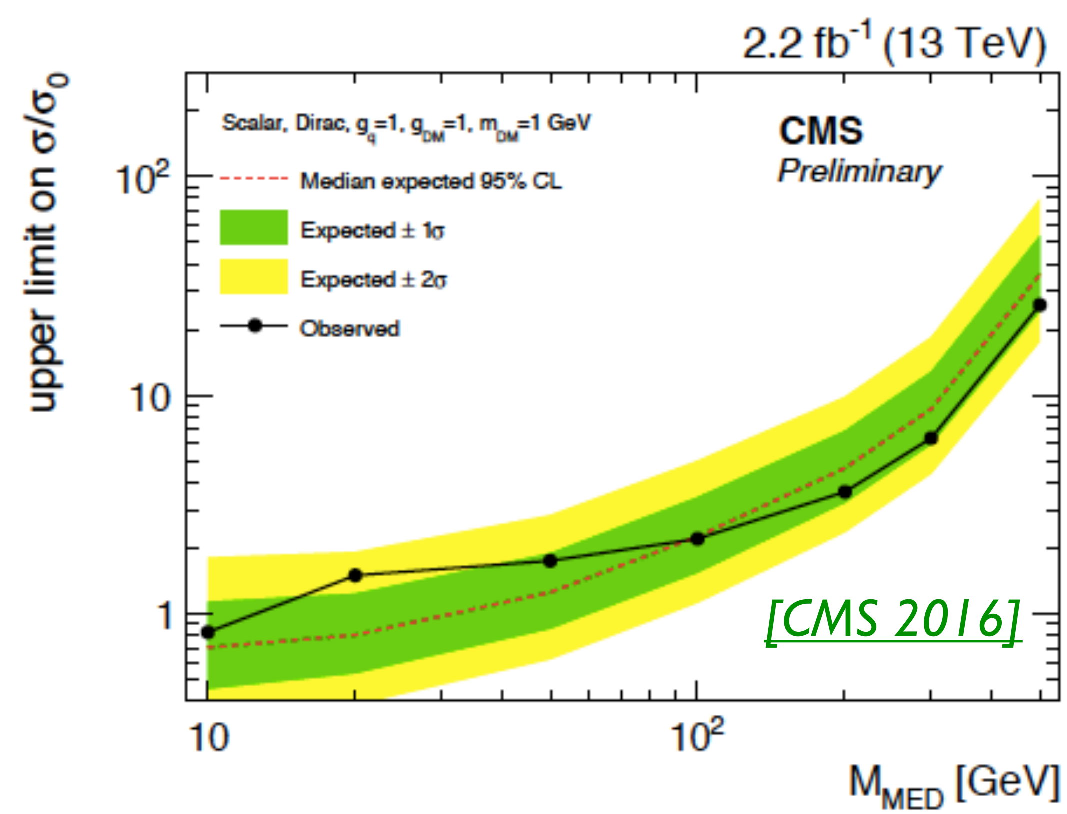
This signature is very popular, for SUSY and top-partner searches.



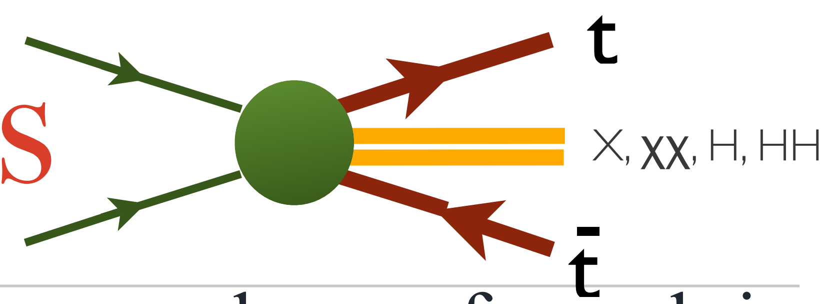
Lately also for DM searches in the s-channel.

$$\mathcal{L}_{t,X}^{Y_0} = -\left(g_t \frac{y_t}{\sqrt{2}} \bar{t}t + g_X \bar{X}X\right) Y_0$$



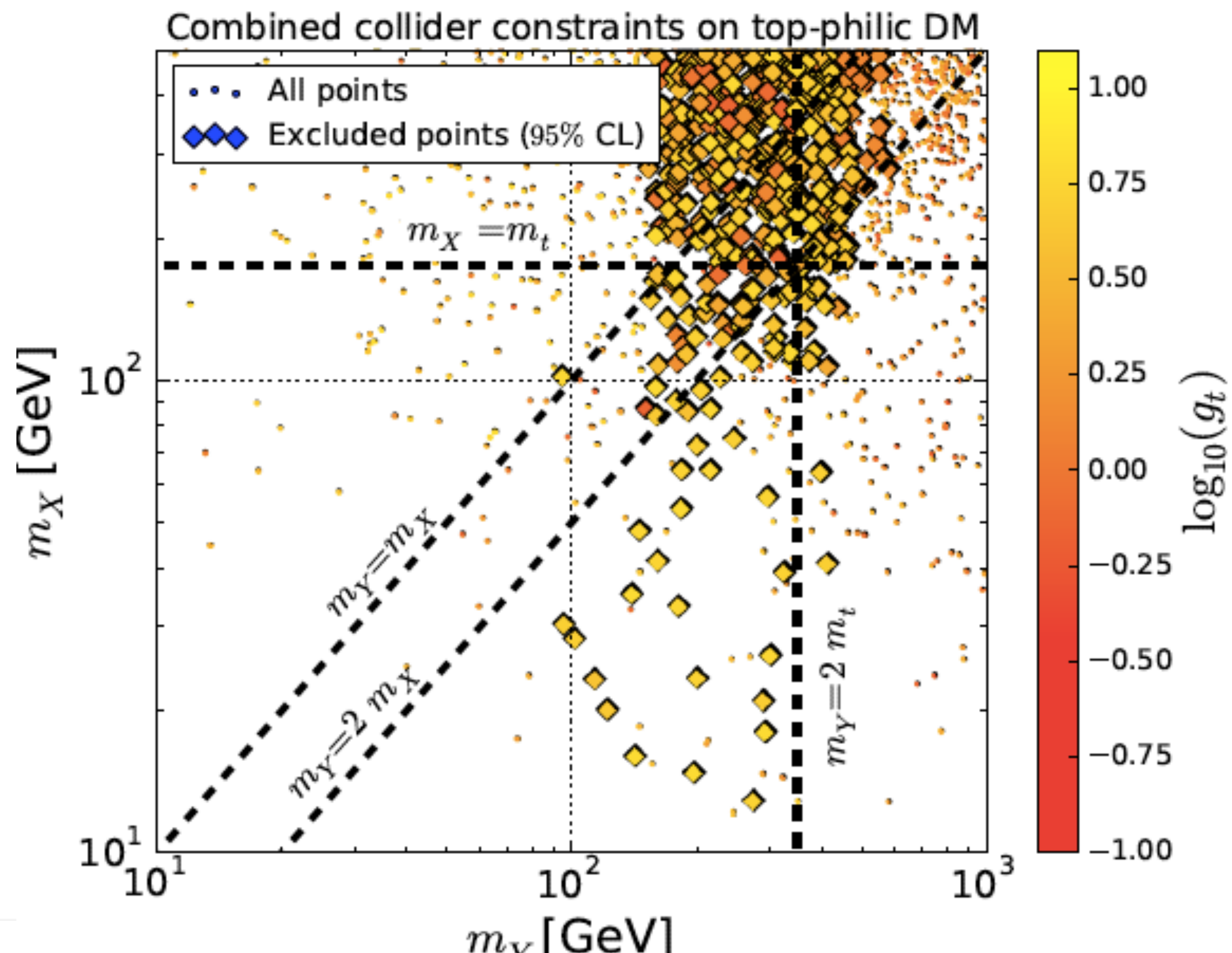


Exotic top-quark signatures



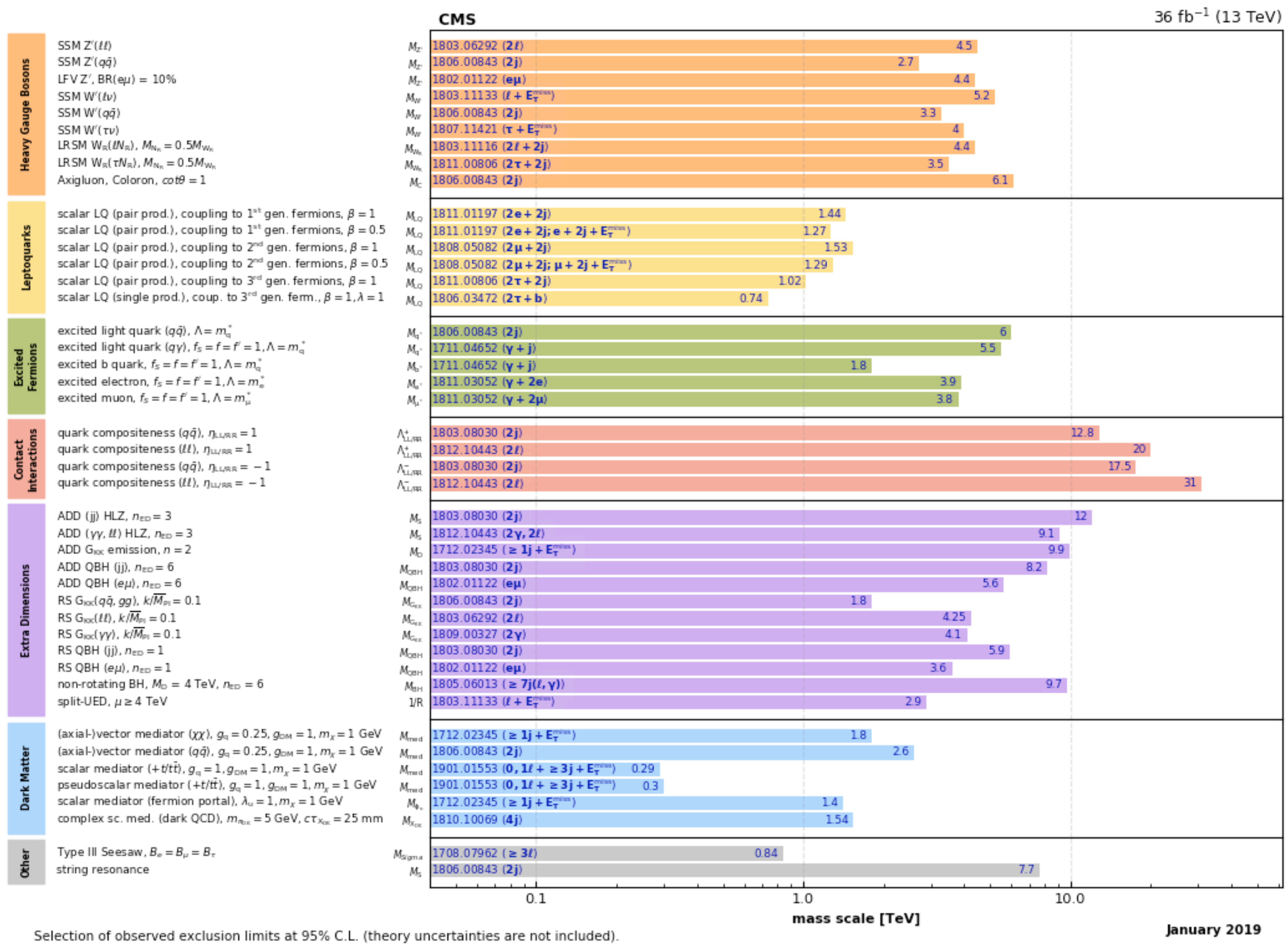
Simplified model searches for a top-philic mediator can be performed in different channels [Haisch et al., 2013] [Haisch et al., 2013] [Haisch et al., 2014] [Crivellin et al., 2015] [Haisch and Re, 2015] [Buckley and Gonsalves, 2015]

Cosmology	relic indirect	$m_X > m_t$	Planck, FermiLAT
		$m_X < m_t$	
Astrophysics		$m_X > m_Y$	
	direct	$m_X > 1$ GeV	LUX, CDMSLite
Colliders	$\not{E}_T$	$m_Y > 2m_X$	$+t\bar{t}$
		$m_Y > 2m_X$	$+j$, $+Z$, $+h$
	no $\not{E}_T$	$m_Y > 2m_t$	$4t$
		$m_Y > 2m_t$	$t\bar{t}$
		$m_Y < 2m_X, 2m_t$	jj, $\gamma\gamma$



[Arina et al., 2016]

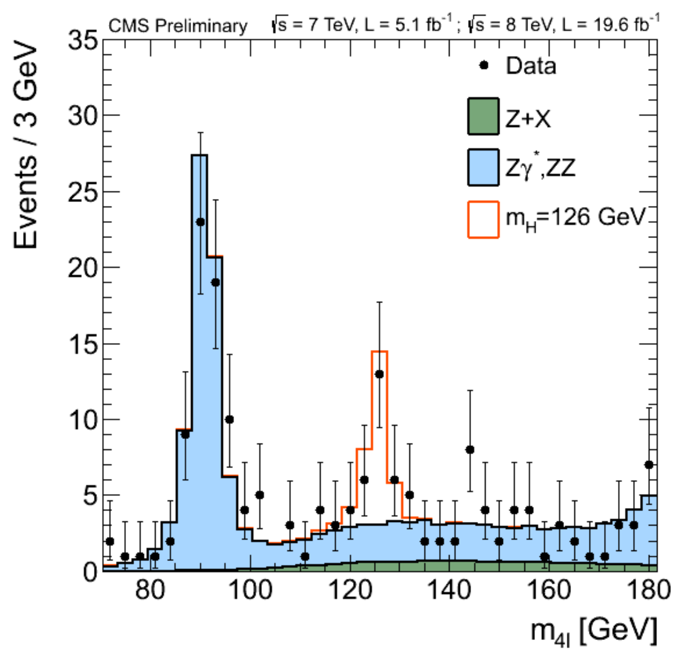
Beyond the SM at the LHC

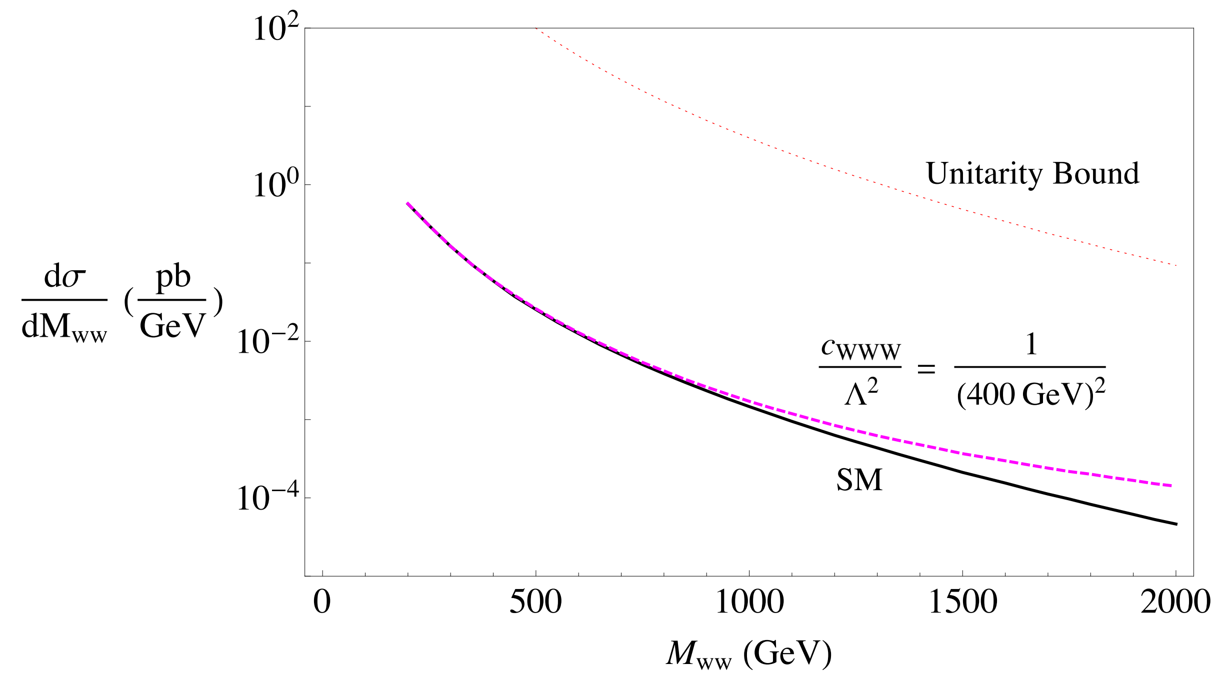


Search for New Physics at the LHC

Two main strategies for searching new physics

Search for new states ⟷ Search for new interactions





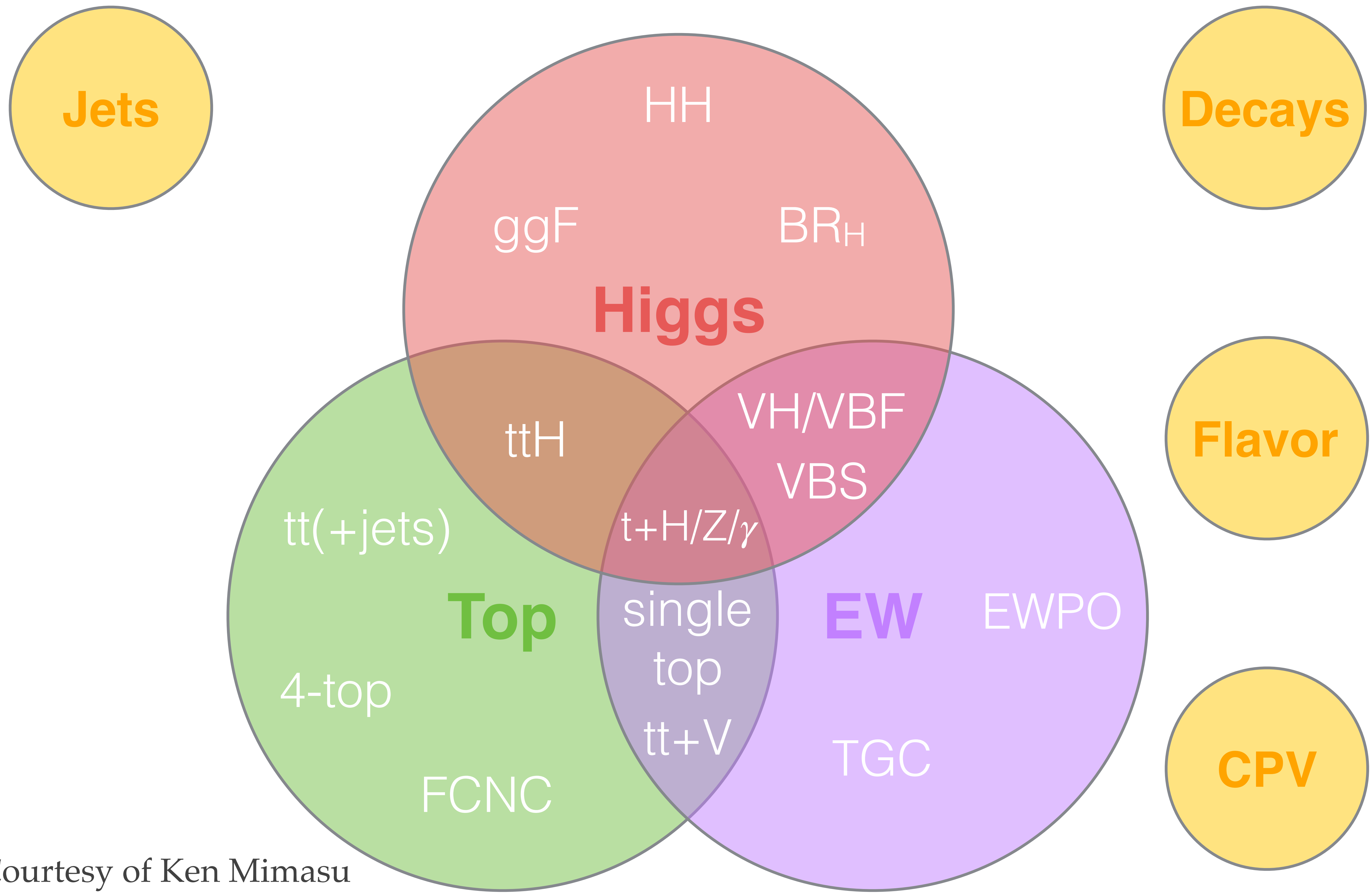
"Peak" or more complicated structures searches. Need for **descriptive MC** for discovery = Discovery is data driven. Later need precision for characterisation.

Deviations are expected to be small. Intrinsically a precision measurement. Needs for **predictive MC** and accurate predictions for SM and EFT.

Which interactions?

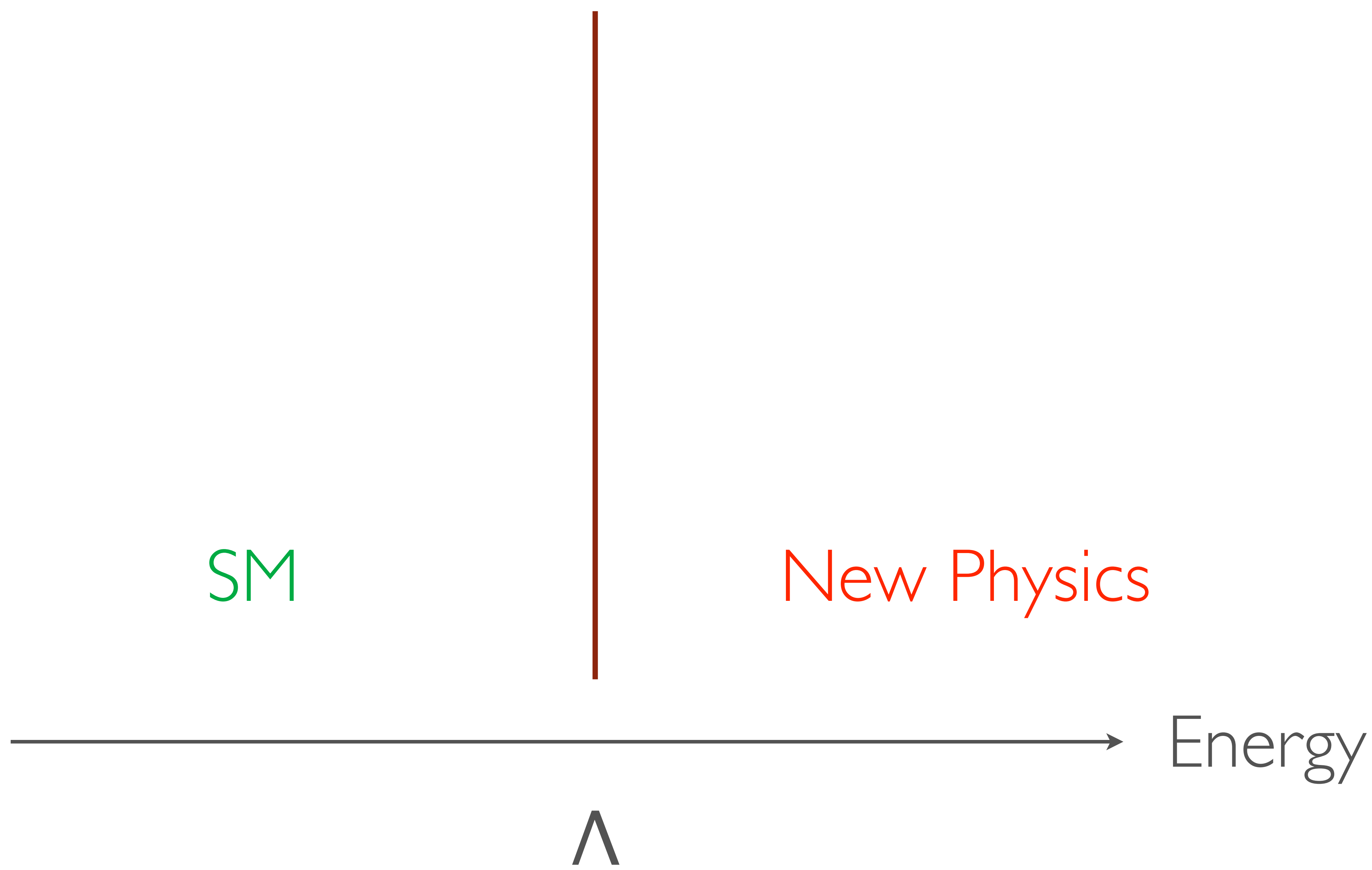
- Interactions between light fermions and gauge bosons tested at low energies and at LEP at below the per mill level.
- Self interactions of weak gauge bosons tested at LEP II High energy at the % level and can be competitive at the LHC
- Higgs interactions with gauge bosons constrained at 10% level.
- Top-quark interactions with gauge bosons and the Higgs at 10% level.
- Higgs self interactions unexplored
- Higgs interactions with light fermions unexplored.

t, H, W, Z

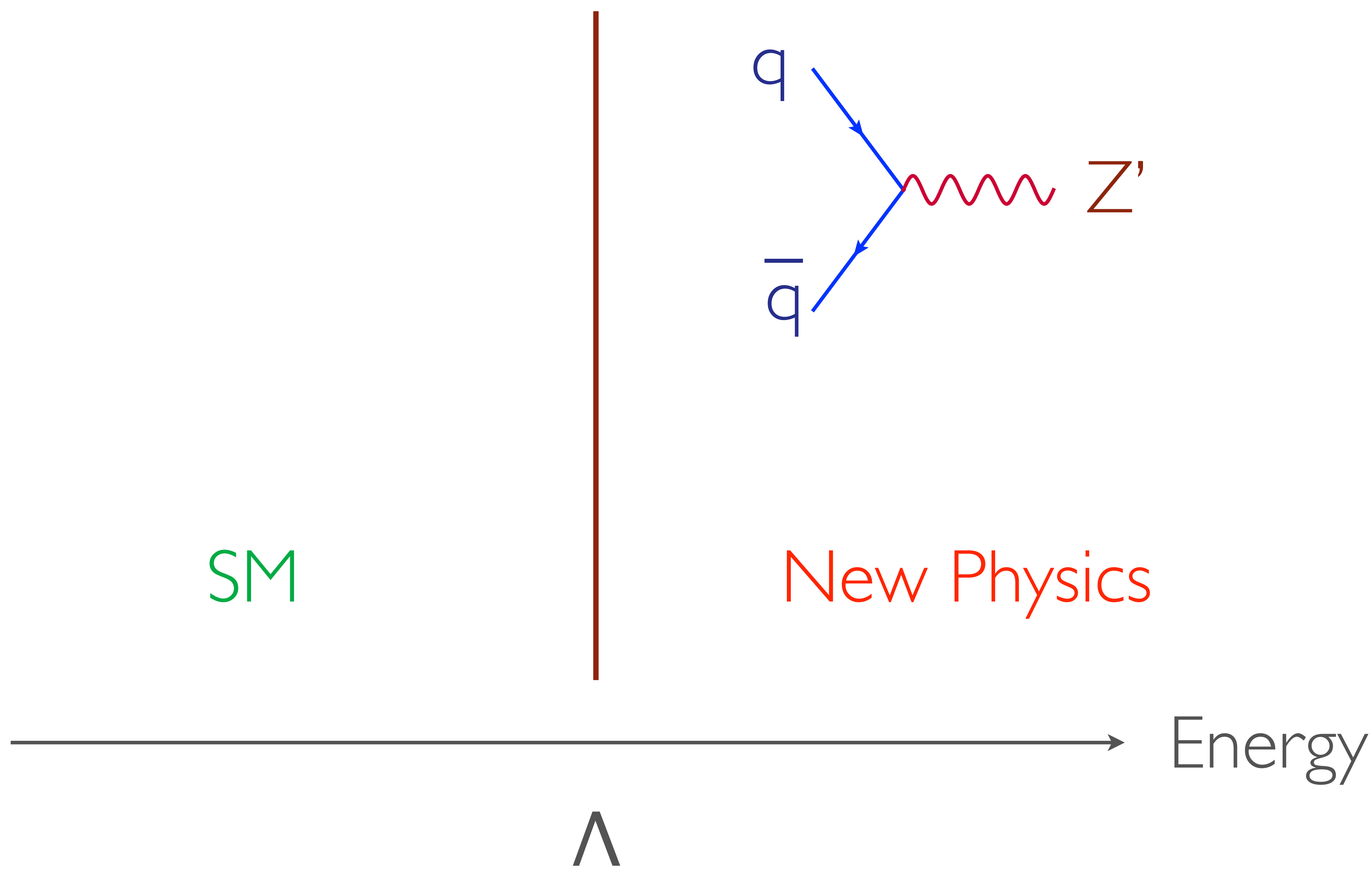


Courtesy of Ken Mimasu

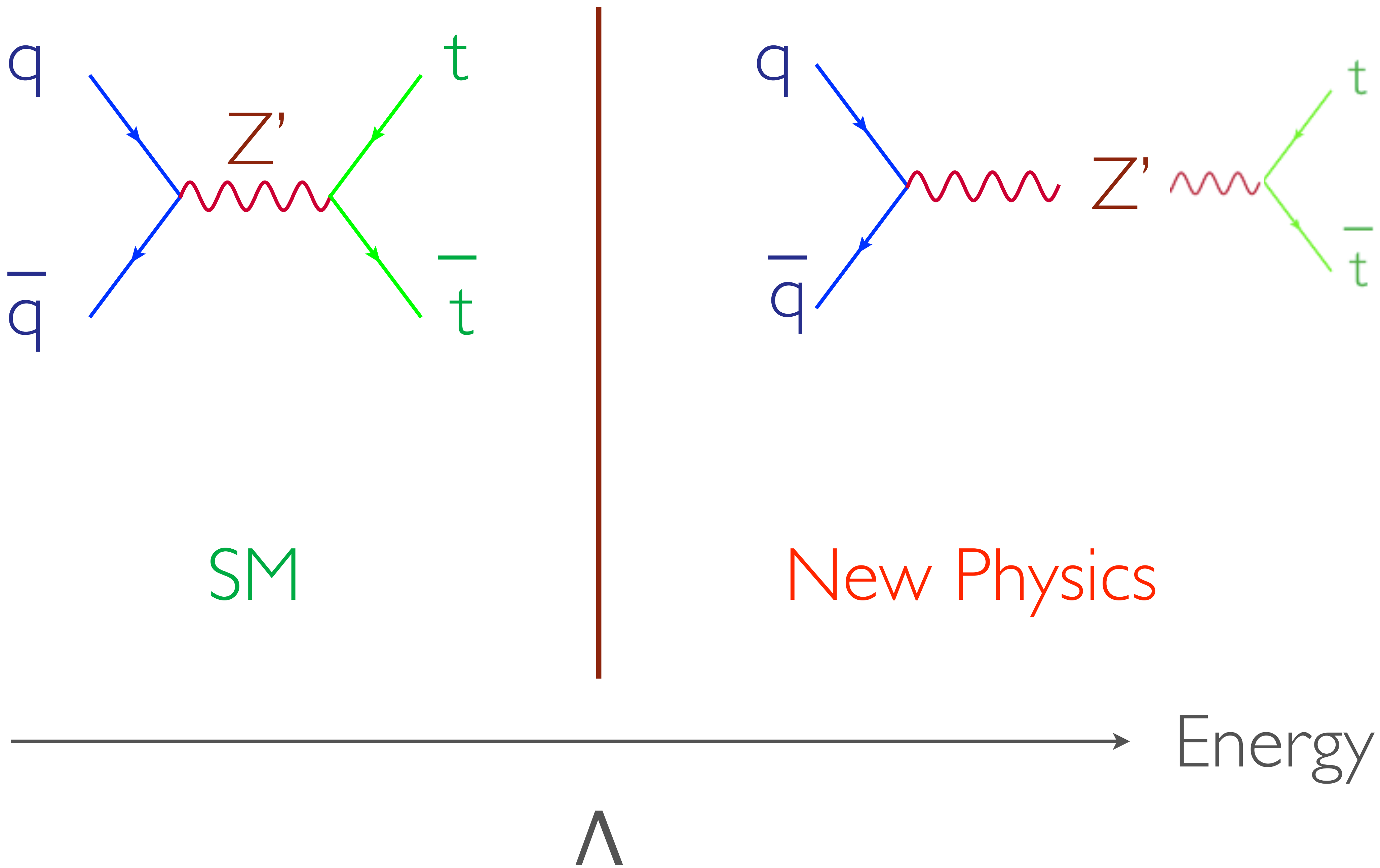
The idea of an EFT



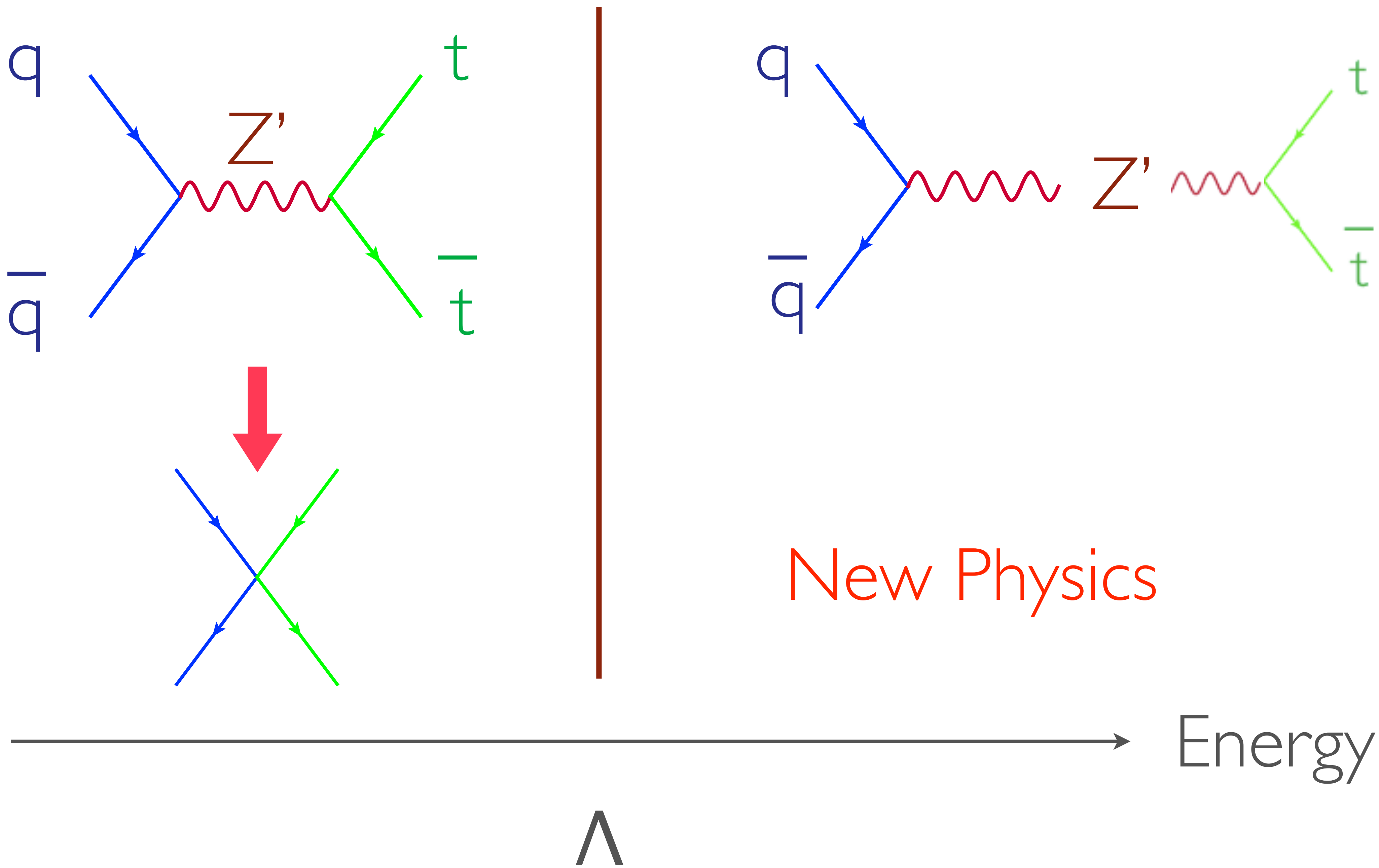
The idea of an EFT



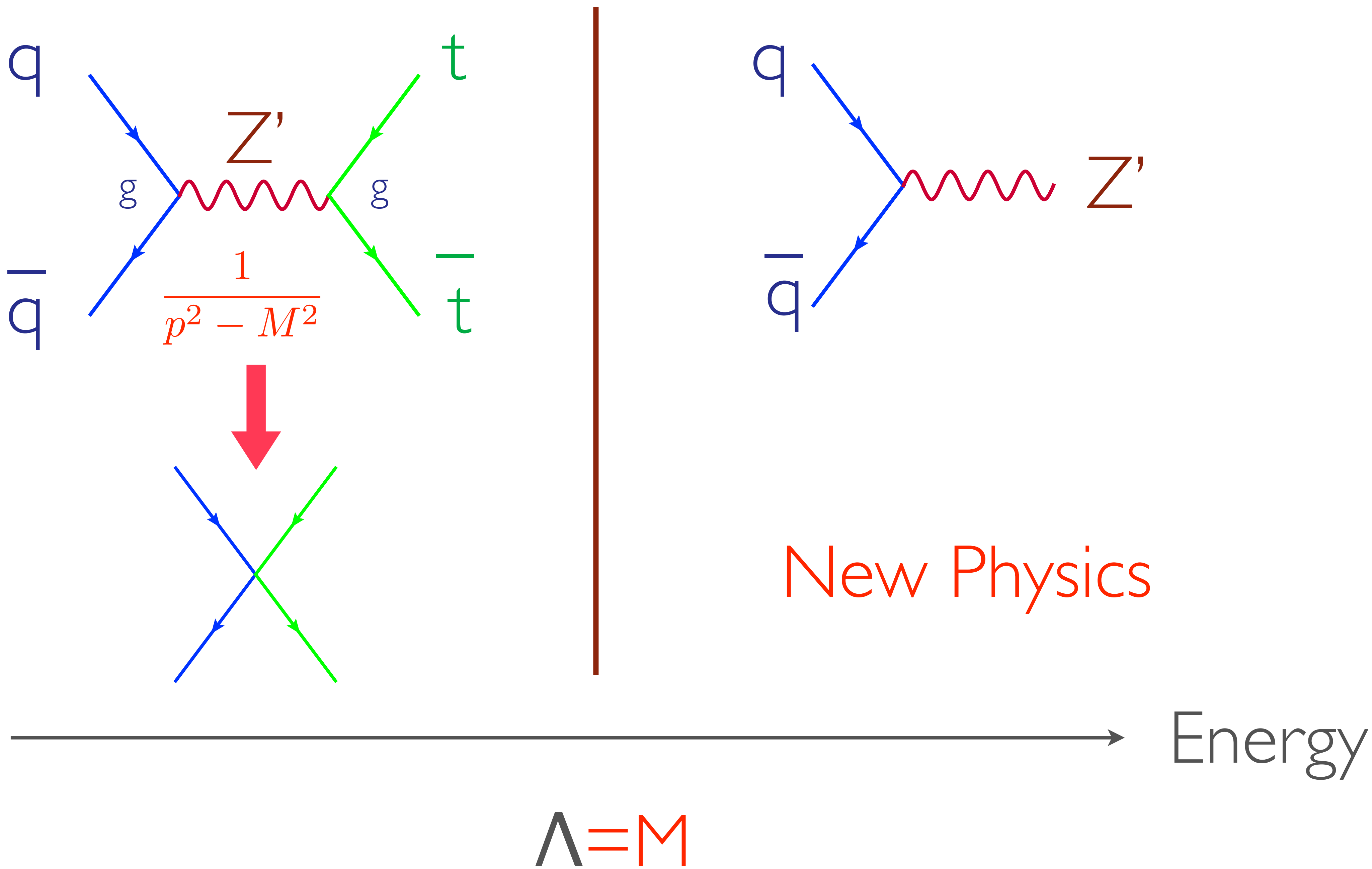
The idea of an EFT



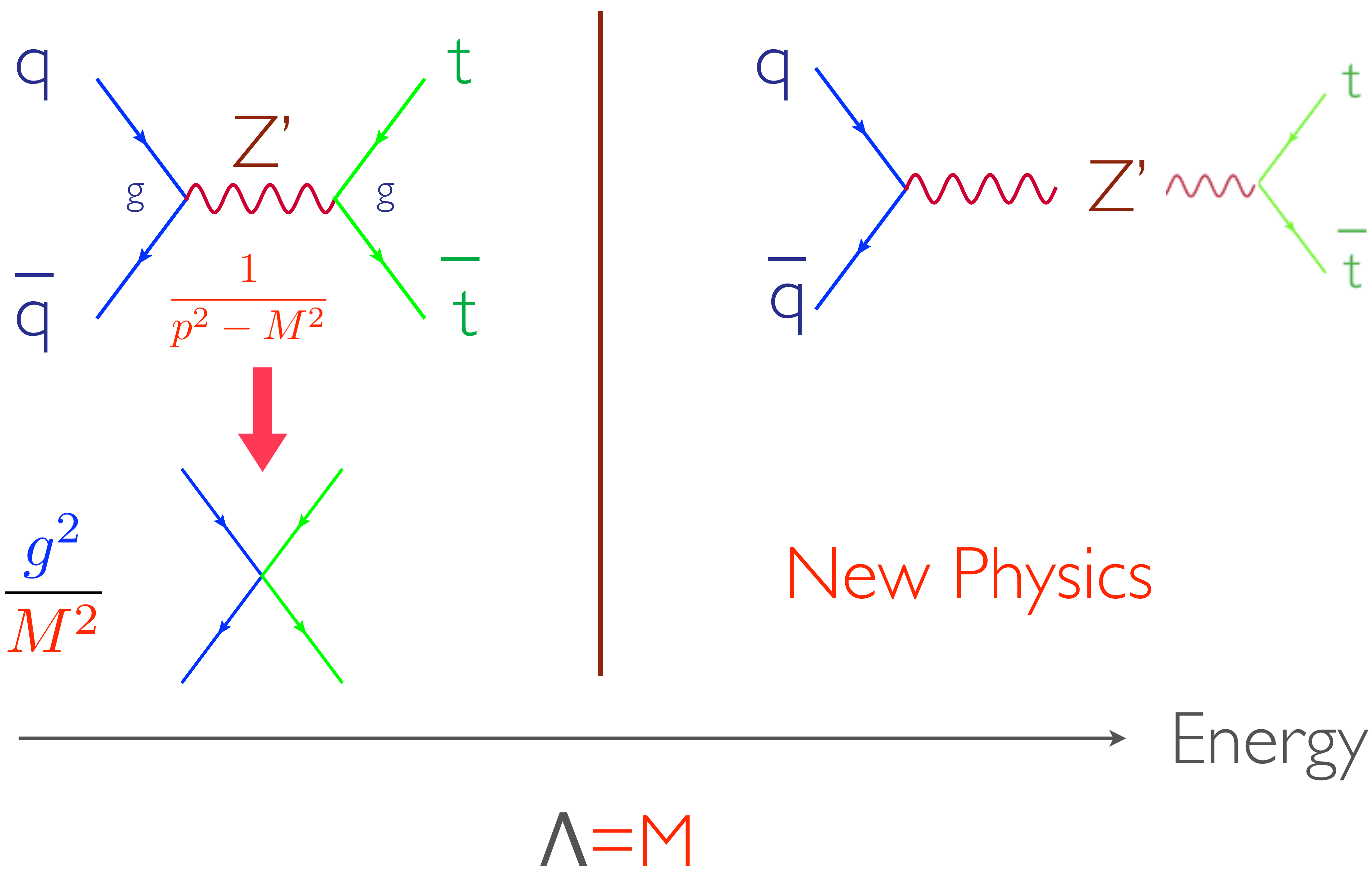
The idea of an EFT



The idea of an EFT

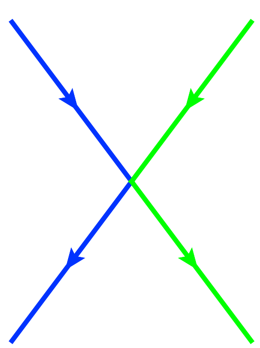


The idea of an EFT



The idea of an EFT

$$\frac{g^2}{M^2}$$



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{g^2}{M^2}\bar{\psi}\psi\bar{\psi}\psi$$

$$M^2 = g^2 v^2 \Rightarrow \Lambda = v$$

Λ is an upper bound on the scale of new physics

The idea of an EFT

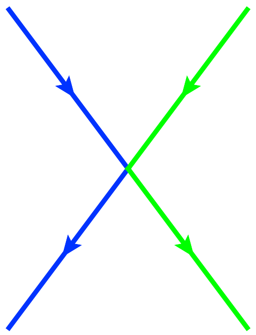
$$\hbar = c = 1$$

$$\dim A^\mu = 1$$

$$\dim \phi = 1$$

$$\dim \psi = 3/2$$

$$\frac{g^2}{M^2}$$



$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i^{\mathrm{dim}=6}$$

Bad News: 59 operators *[Buchmuller, Wyler, 1986]*
Good News : an handful are unconstrained and can significantly contribute to top phenomenology!

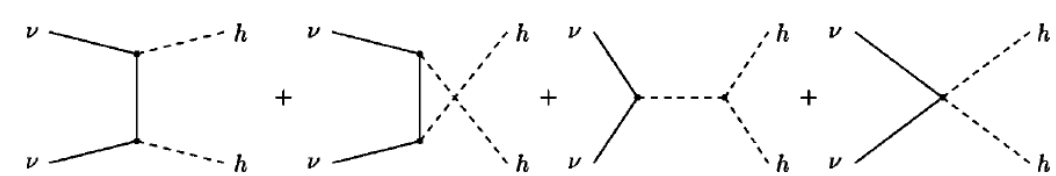
Majorana neutrinos

- Consider the SM@dim5. There is only one such operator that can be added:

$$\mathcal{L} = \frac{c}{\Lambda}(L^T \epsilon \phi) C (\phi^T \epsilon L) + h.c. \qquad \epsilon \equiv i\sigma_2$$

When the Higgs fields acquires a vev this term give rise to a Majorana neutrino mass

$$m_\nu = c\frac{v^2}{\Lambda}$$



If I now calculate the amplitude $\nu\nu \to hh$

$$a_0\left(\frac{1}{\sqrt{2}}\nu_\pm \nu_\pm \to \frac{1}{\sqrt{2}} hh\right) \sim \mp \frac{c\sqrt{s}}{16\pi M} \sim \mp \frac{m_\nu \sqrt{s}}{16\pi v^2} \quad \Longrightarrow \quad \text{grows with energy}$$

$= \text{unitarity violations}$

$$\Longrightarrow \quad \Lambda_{Maj} \equiv \frac{4\pi v^2}{m_\nu} \quad \Longrightarrow \quad \text{min mass for the neutrino} \quad \Longrightarrow \quad \text{upper bound for } \Lambda$$

Majorana neutrino mass implies New Physics before 10^{15} GeV

Majorana neutrinos

- An UV completion of the dim=5 operator (there are few) is well known: the see-saw model

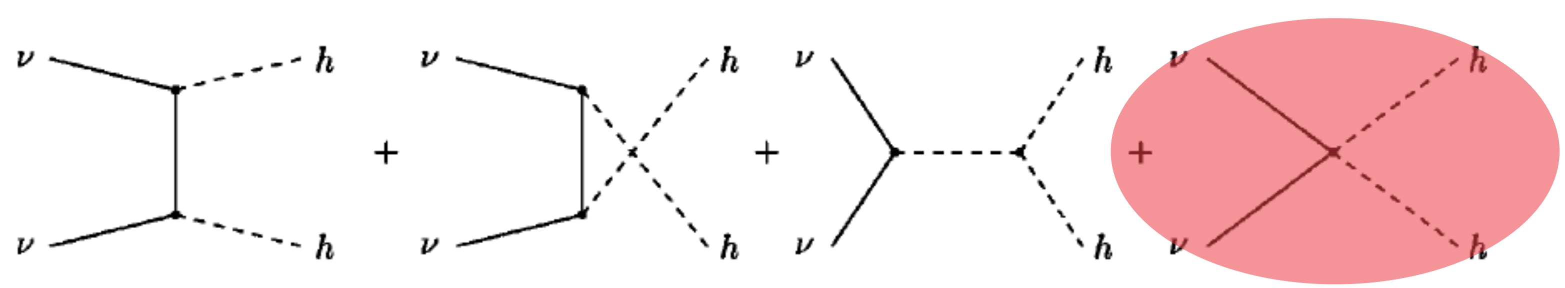
$$\mathcal{L} = -y_D \bar{L}\epsilon\phi^* \nu_R - \frac{1}{2} M_R \nu_R^T C \nu_R + \mathrm{H.c.}$$

with a Dirac mass term and a Majorana one (ν_R is a singlet of SU(2)). One can diagonalise the mass matrix and obtains two mass eingenstates

$$\nu \approx \nu_L \qquad m_\nu \approx m_D^2 / M_R$$

$$N \approx \nu_R \qquad M_R$$

and the amplitude $\nu\nu \to hh$ does not grow anymore because the last term is not present. anymore



SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

SMEFT Lagrangian: Dim=6

[Buchmuller and Wyler, 86] [Grzadkowski et al, 10]

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu \tau^I q_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu \tau^I l_r)(\bar{q}_s\gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

EFT picture: Matching and Running

$$\mathcal{L}_{\rm EFT}(\phi_{\rm SM}, \mu = \Lambda) \quad \overset{\rm M}{\longleftrightarrow} \quad \mathcal{L}_{\rm UV}(\phi_{\rm SM}, \phi_{\rm BSM})$$

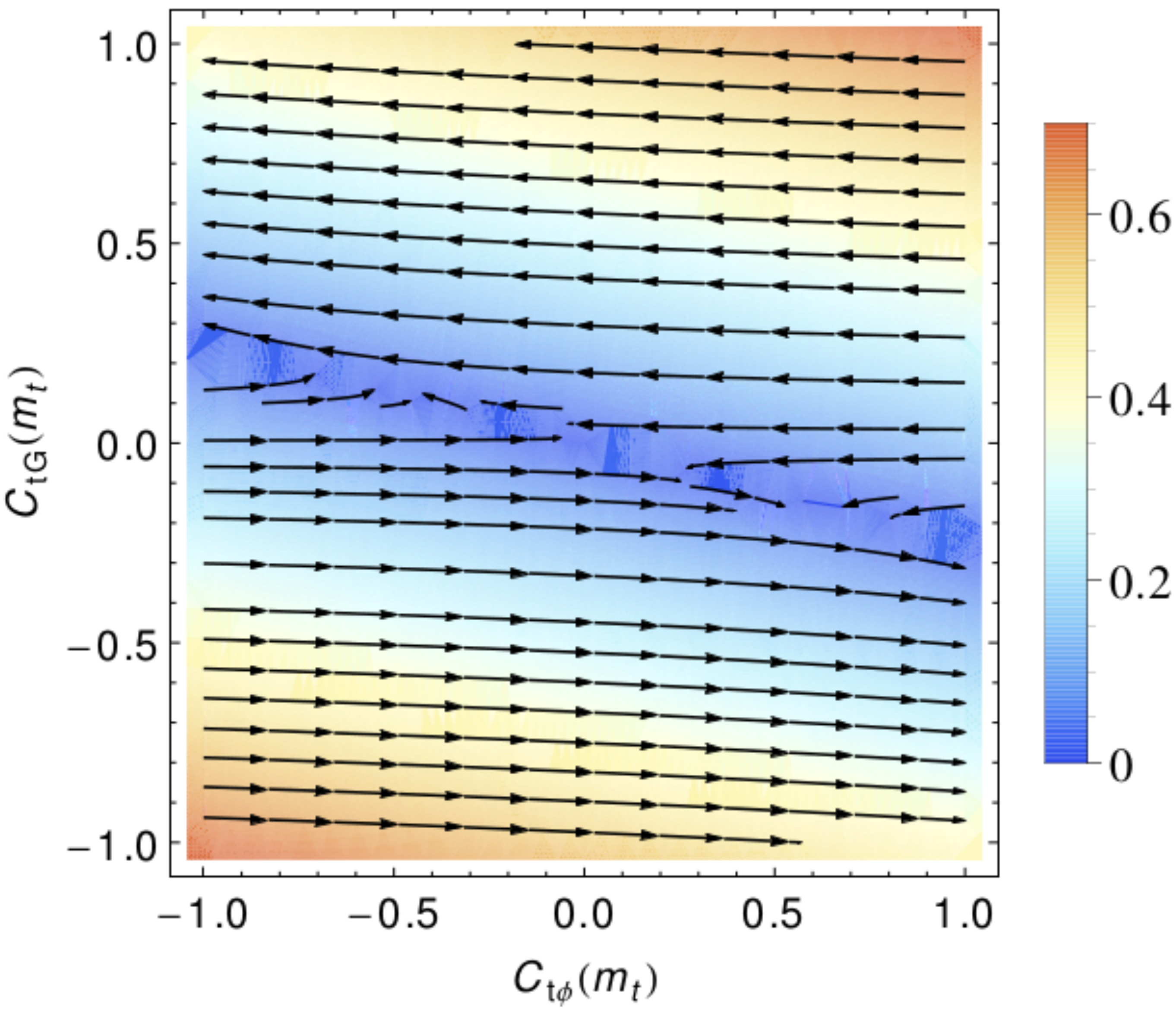
RGE $\downarrow$

$$\mathcal{L}_{\rm EFT}(\phi_{\rm SM}, \mu = v)$$

Energy

Running/Mixing

Operators run and mix under RGE



Scale corresponds to the change from mt to 2 TeV.

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}\,,$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}\,,$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}\,.$$

$$\frac{dC_i(\mu)}{d\log\mu} = \frac{\alpha_s}{\pi}\gamma_{ij} C_j(\mu), \qquad \gamma = \begin{pmatrix} -2 & 16 & 8 \\ 0 & -7/2 & 1/2 \\ 0 & 0 & 1/3 \end{pmatrix}$$

At = 1 TeV: $C_{tG} = 1$, $C_{t\varphi} = 0$;

At = 173 GeV: $C_{tG} = 0.98$, $C_{t\varphi} = 0.45$

SMEFT Lagrangian: Dim=6

- Based on all the symmetries of the SM
- New physics is heavier than the resonance itself : $\Lambda > M_X$
- QCD and EW renormalisable (order by order in $1/\Lambda$)
- Number of extra couplings reduced by symmetries and dimensional analysis
- Extends the reach of searches for NP beyond the collider energy.
- Valid only up to the scale Λ : $\sqrt{s} < \Lambda$

The EFT approach: managing unknown unknowns

- Very powerful model-indepedent approach.
- A **global constraining strategy** needs to be employed:
  - assume all* couplings not be zero at the EW scale.
  - identify the operators entering predictions for each observable (LO, NLO,..)
  - find enough observables (cross sections, BR's, distributions,…) to constrain all operators.
  - solve the linear (+quadratic)* system.
- Use to constrain UV-complete* models.
- The final reach on the scale of New Physics crucially depends on the THU.

SMEFT at the LHC

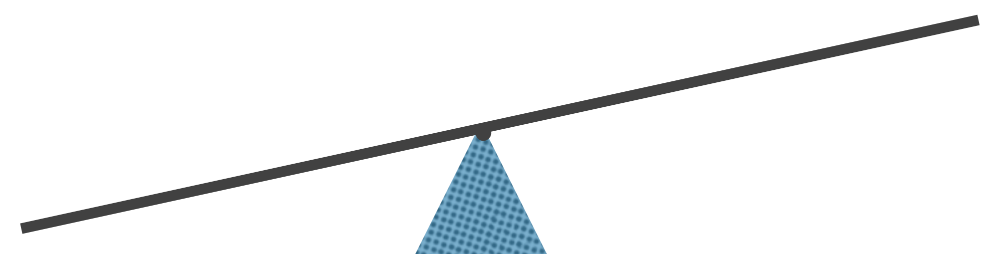
s is a generic scale, which is process and operator dependent

- Large number of operators, yet a plethora of observables and final states to measure.

$$\mathrm{Obs}_i = \mathrm{Obs}_i^{\mathrm{SM}} + M_{ij} \cdot \frac{s}{\Lambda^2}\, c_j$$

- Precision observables in the bulk of the distributions while tails provide sensitivity through the energy growth.

$$\Lambda > \sqrt{s}\sqrt{|c_i|/\delta}$$



$$|c_i| s/\Lambda^2 < \delta$$

- Validity issues arise, as well as for the interpretation in terms of models.

$$\sqrt{s} < \Lambda$$

Top-quark operators and processes

[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011,Degrande et al. 2011]

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

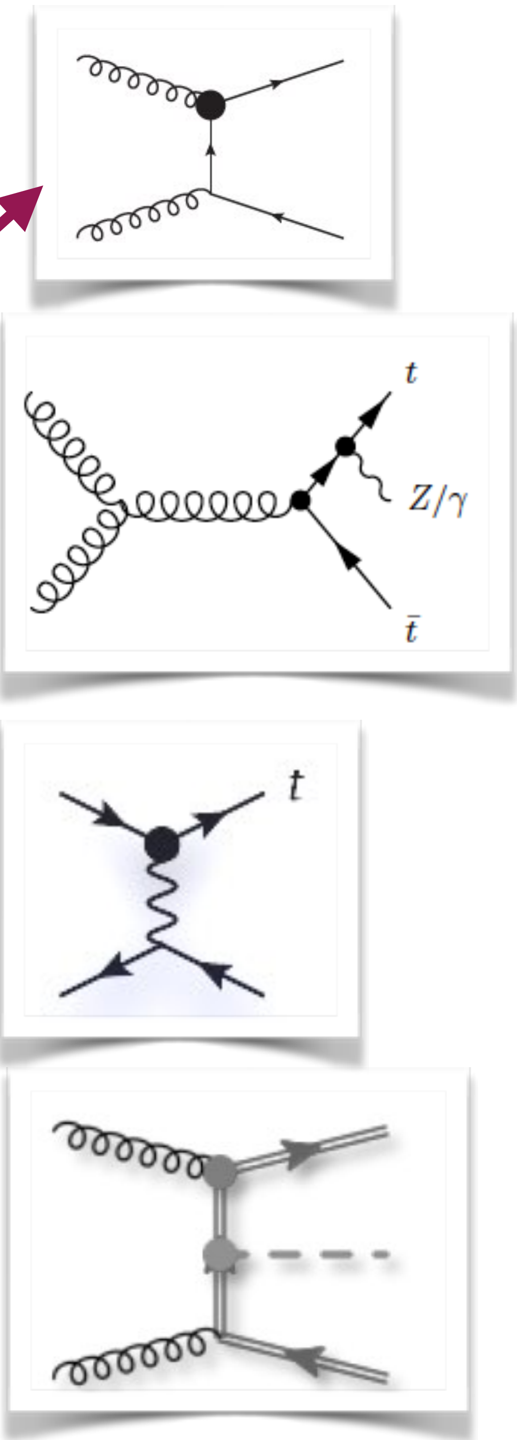
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu}$$

$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,$$

$$O_{t\varphi} = y_t^3(\varphi^\dagger\varphi)\bar{Q}\tilde{\varphi}t$$



+four-fermion operators

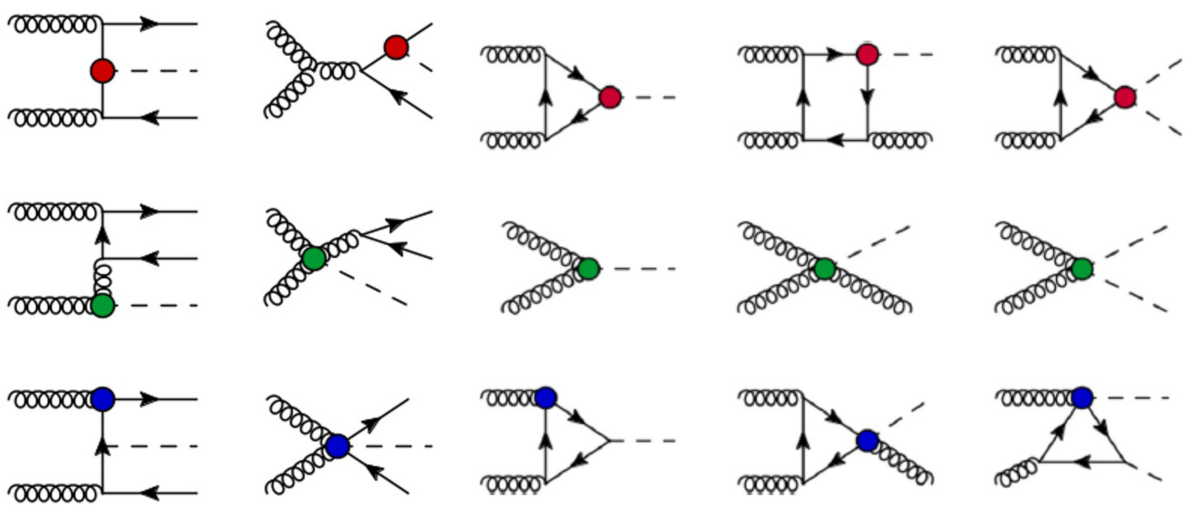
+ operators that do not feature a top, but contribute to the procs…

Top/Higgs operators and processes

Several operators typically enter each process at LO (or at LO²) and

NLO (no	Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
✓	$t \to bW \to bl^+\nu$	N		L	L				L²	L²	1L²		
✓	$pp \to tj$	N		L	L				L²	L²	1L		
✓	$pp \to tW$	L		L	L				L²	L²	1N	N	
✓	$pp \to t\bar{t}$	L									2L-4N	L	
✓	$pp \to t\bar{t}j$	L									2L-4N	L	
✓	$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
✓	$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
✓	$pp \to t\bar{t}W$	L								L	1L-2L		
✓	$pp \to t\gamma j$	N	L	L	L				L²	L²	1L		
✓	$pp \to tZj$	N	L	L	L	L	L		L²	L²	1L		
✓	$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
✓	$pp \to t\bar{t}H$	L						L			2L-4L	L	L
✓	$pp \to tHj$	N		L	L			L	L²	L²	1L		N
O ✓	$gg \to H$	L						L				N	L
O ✗	$gg \to Hj$	L						L				L	L
O ✗	$gg \to HH$	L						L				N	L
O ✗	$gg \to HZ$	L			L	L	L	L				N	L

Top/Higgs operators and processes



ttH H H+j HH

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

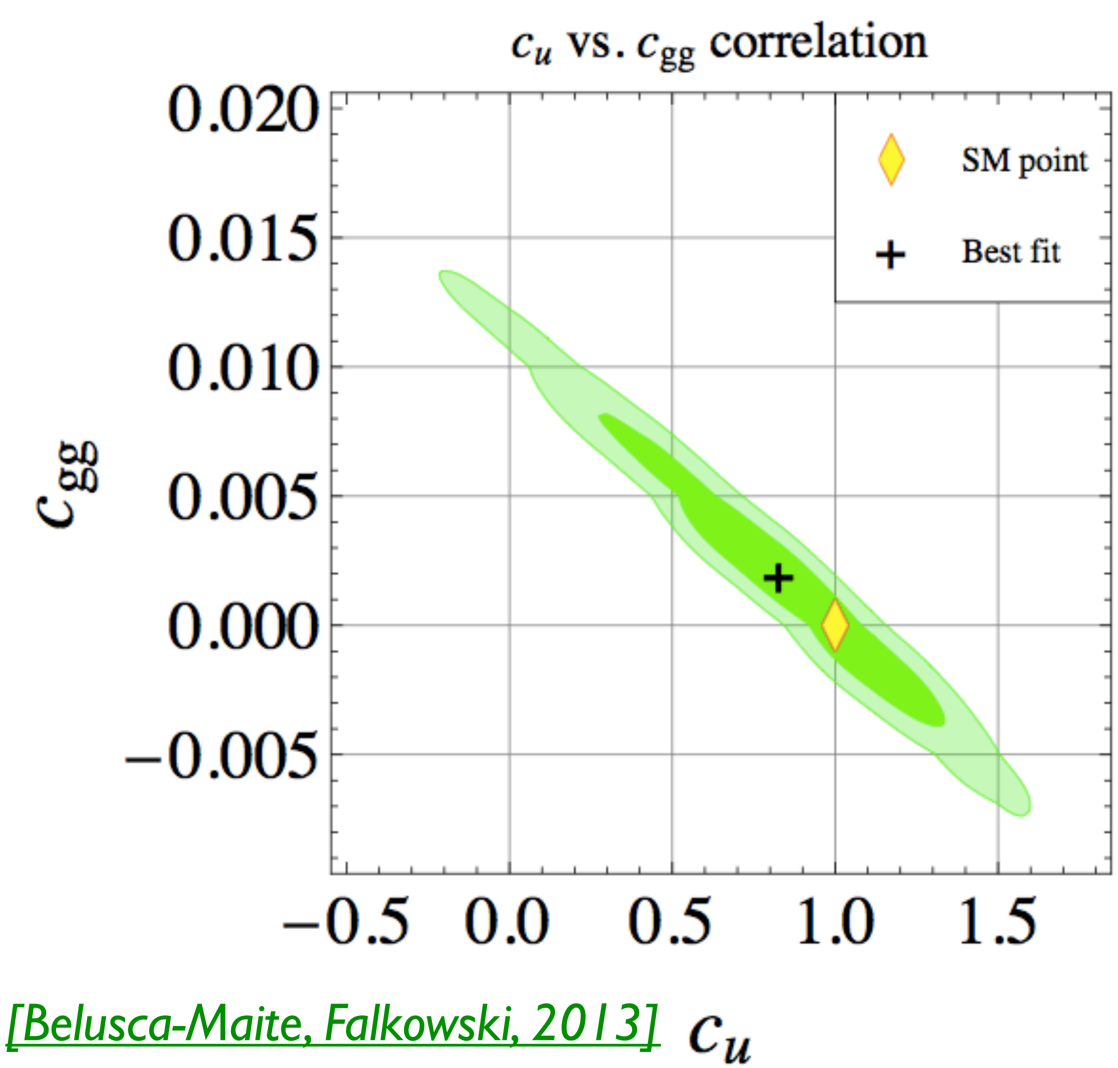
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

Top-Higgs interactions: constraints

From a global fit the coupling of the higgs to the top is poorly determined.

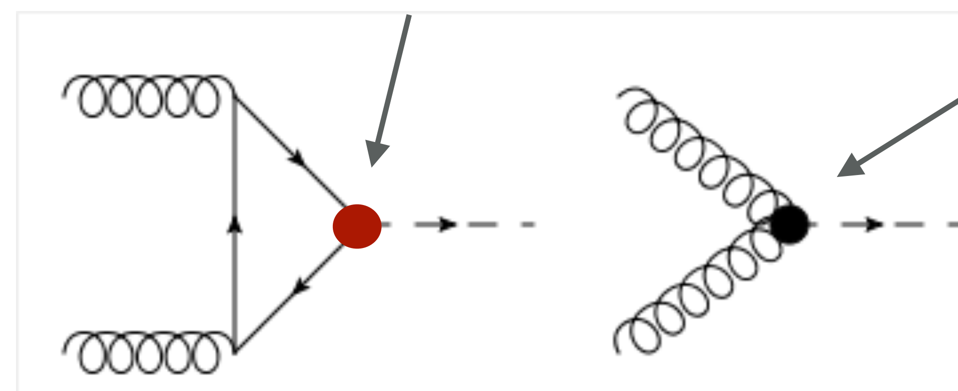
$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq \left|1+\frac{\hat{c}_{gg}}{c_{gg}^{\rm SM}}\right|^2$$

$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq 1 + 237 c_{gg} + 2.06\delta y_u - 0.06\delta y_d.$$



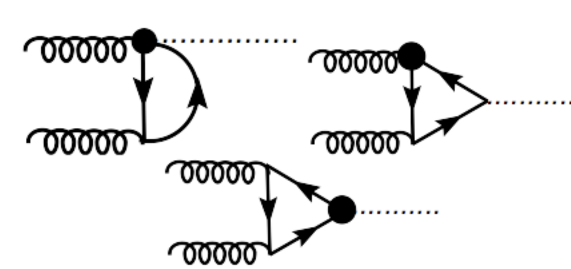
[Belusca-Maite, Falkowski, 2013]

$$\mathcal{O}_{Hy} = H^\dagger H \left(H \bar{Q}_L\right) t_R \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$



the loop could still be dominated by np.

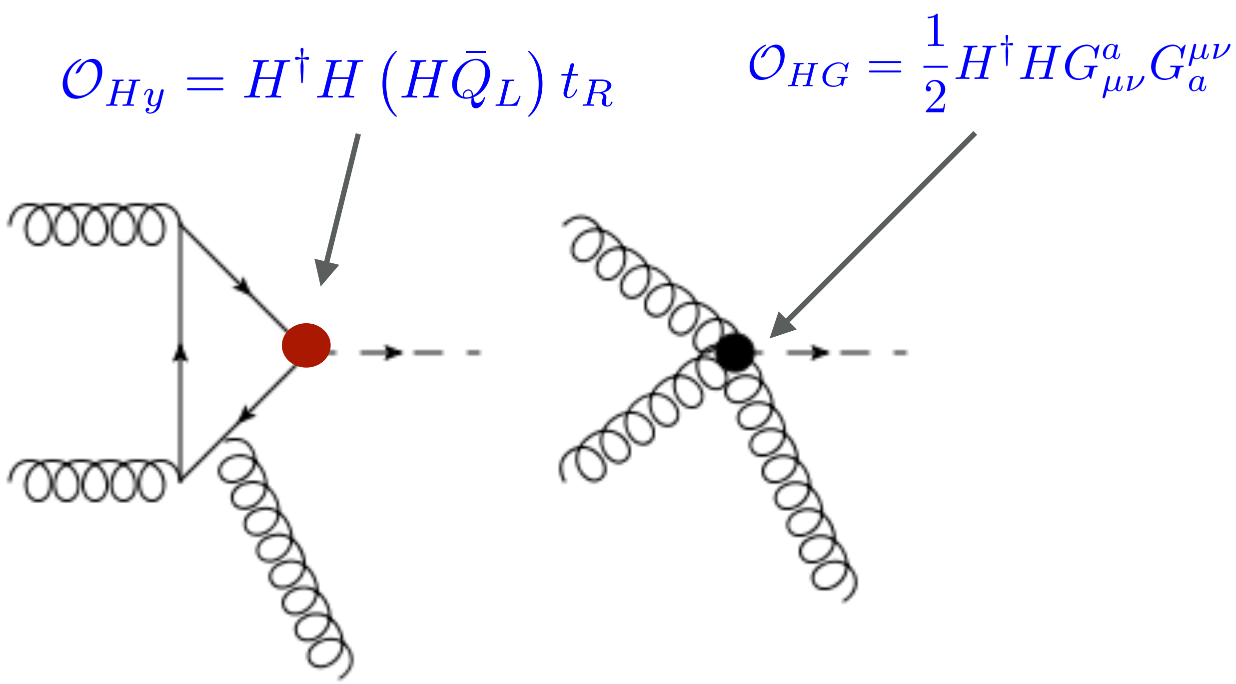
THE EFFECT OF THE CM OPERATOR NOT INCLUDED

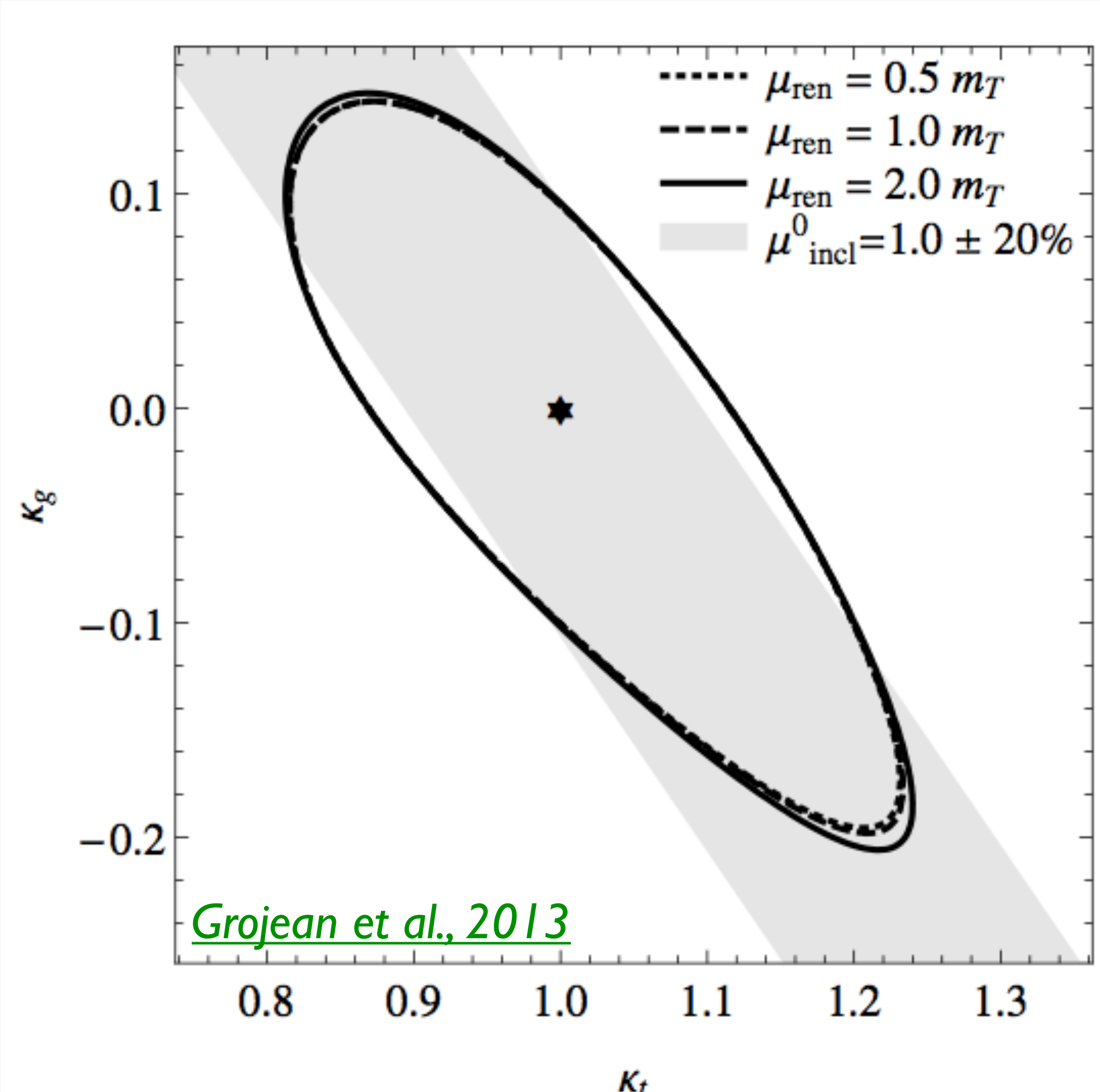


Top-Higgs interactions: high-pt

From a global fit the coupling of the higgs to the top is poorly determined: the loop could still be dominated by np.

[Grojean et al., 2013] [Banfi et al. 2014] [Buschmann, et al. 2014]

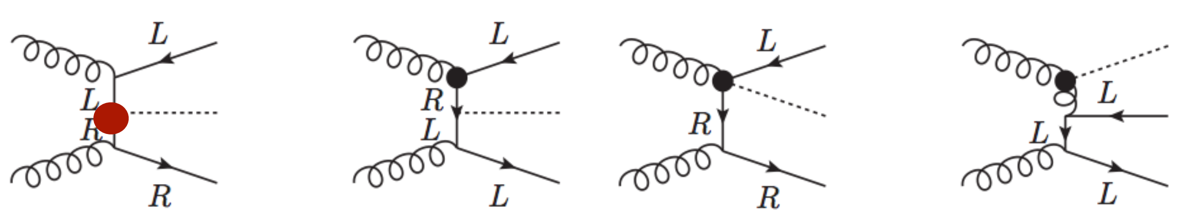




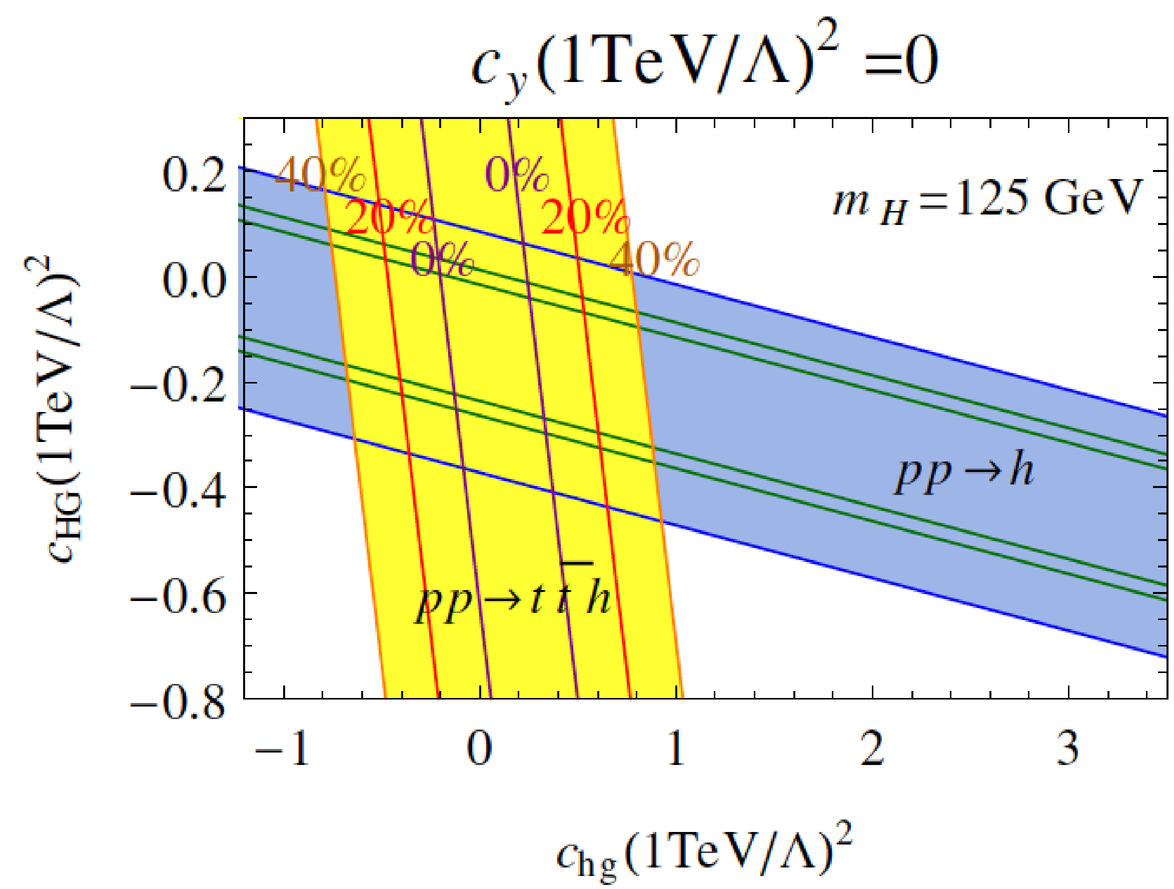
EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy and precision.

Top-Higgs interactions: ttH

[Degrande et al. 2012]



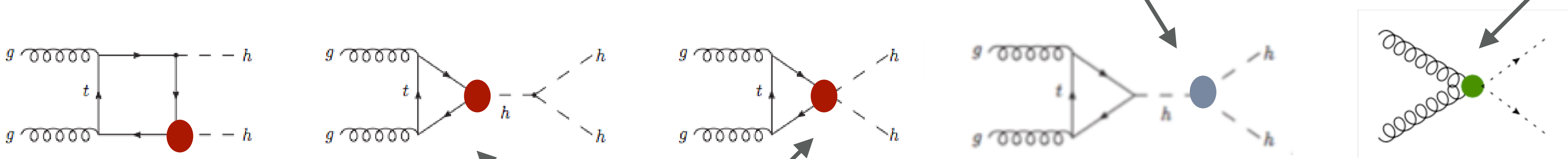
$$
\begin{aligned}
\frac{\sigma\,(pp \to t\bar{t}h)}{\text{fb}} = \; & 611^{+92}_{-110} + \left[457^{+127}_{-91}\Re c_{hg} - 49^{+15}_{-10}c_G \right.\\
& \left. + \; 147^{+55}_{-32}c_{HG} - 67^{+23}_{-16}c_y\right]\left(\frac{\text{TeV}}{\Lambda}\right)^2 \\
& + \; \left[543^{+143}_{-123}(\Re c_{hg})^2 + 1132^{+323}_{-232}c_G^2 \right.\\
& + \; 85.5^{+73}_{-21}c_{HG}^2 + 2^{+0.7}_{-0.5}c_y^2 \\
& + \; 233^{+81}_{-144}\Re c_{hg}c_{HG} - 50^{+16}_{-14}\Re c_{hg}c_y \\
& \left. - \; 3.2^{+8}_{-8}\Re c_{Hy}c_{HG} - 1.2^{+8}_{-8}c_Hc_{HG}\right]\left(\frac{\text{TeV}}{\Lambda}\right)^4
\end{aligned}
$$



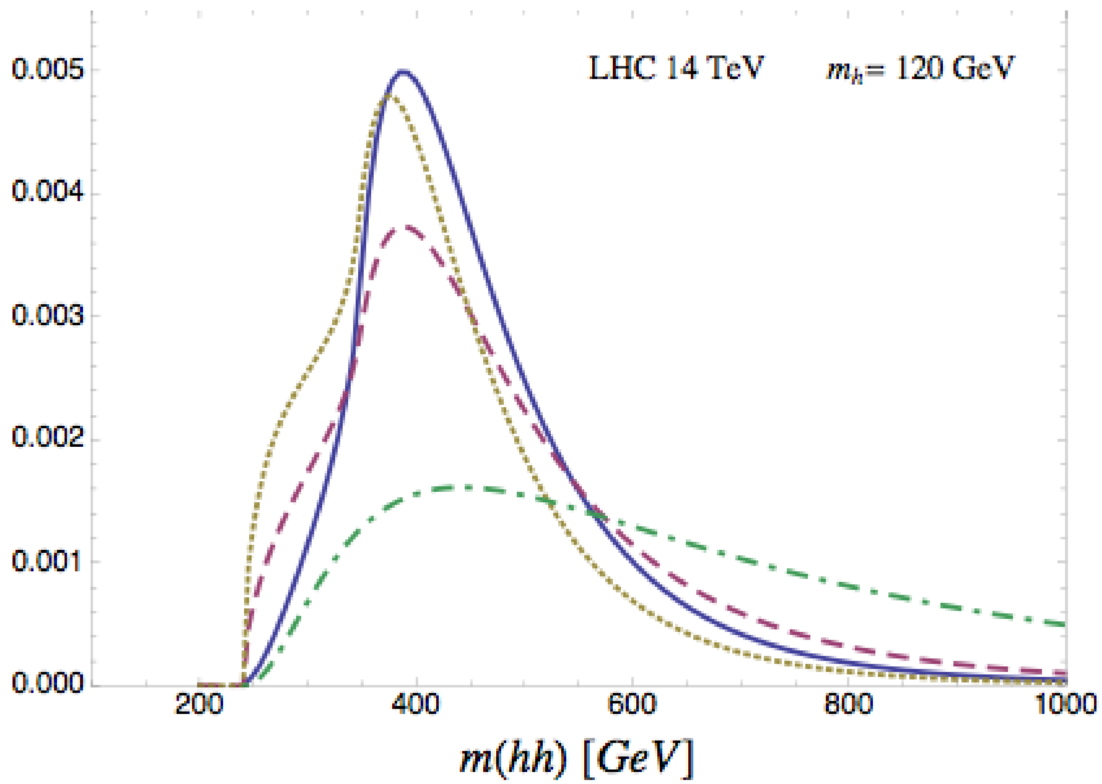
Top-Higgs interactions: HH

$$pp \to hh$$

$$\mathcal{O}_6 = (H^\dagger H)^3 \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$



$$\mathcal{O}_{Hy} = H^\dagger H \, (H \bar{Q}_L)\, t_R$$



[Contino et al. 2012]

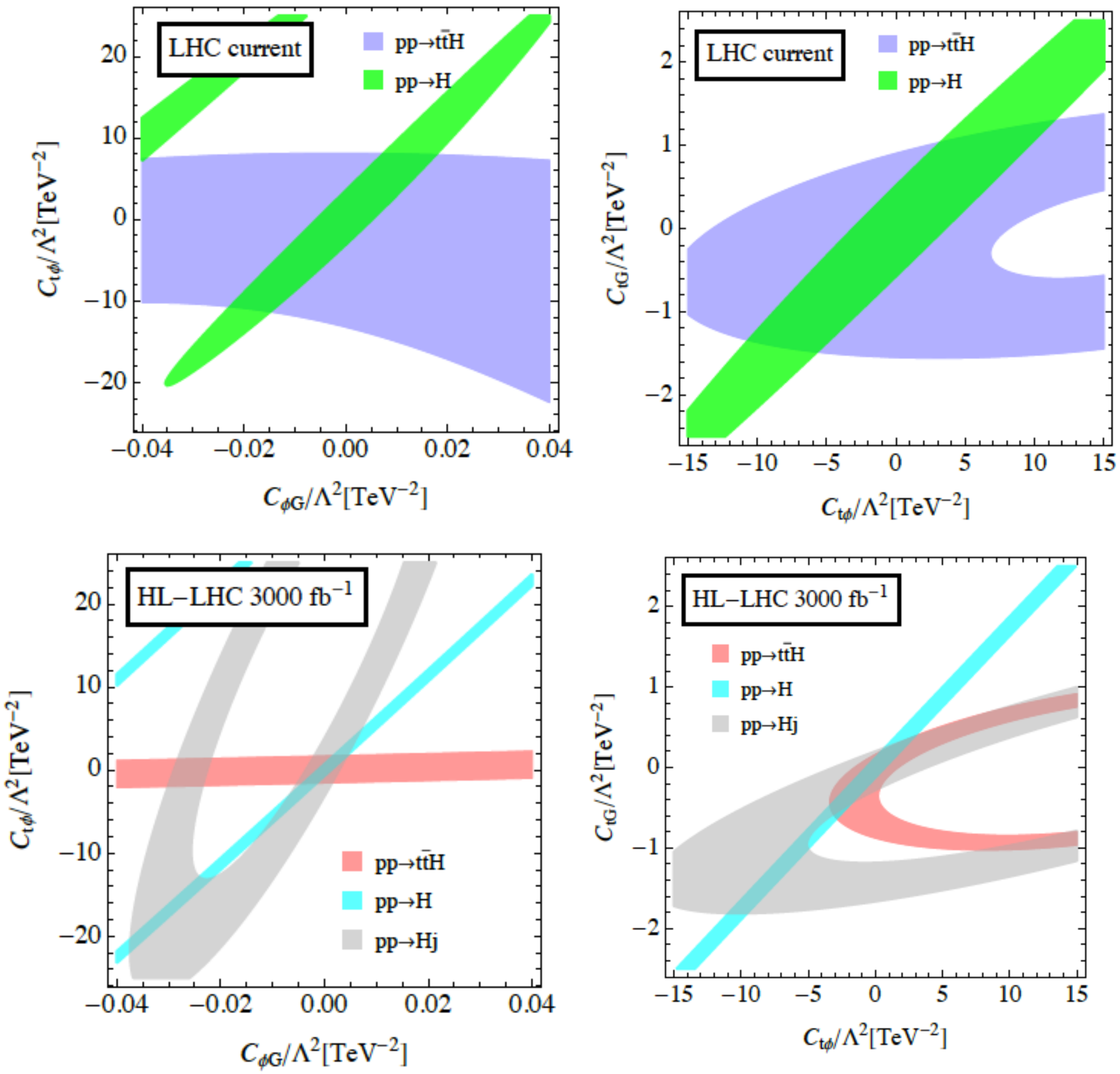
The strong destructive interference gives extra sensitivity of pp→HH to dim=6 operators.

The HHH coupling is modified by two operators of dim=6.

Only a global approach will allow to accurately measure the HHH coupling from HH.

Constraints from ttH and Higgs production

[FM, Vryonidou, Zhang, 16]



Current limits using LHC measurements

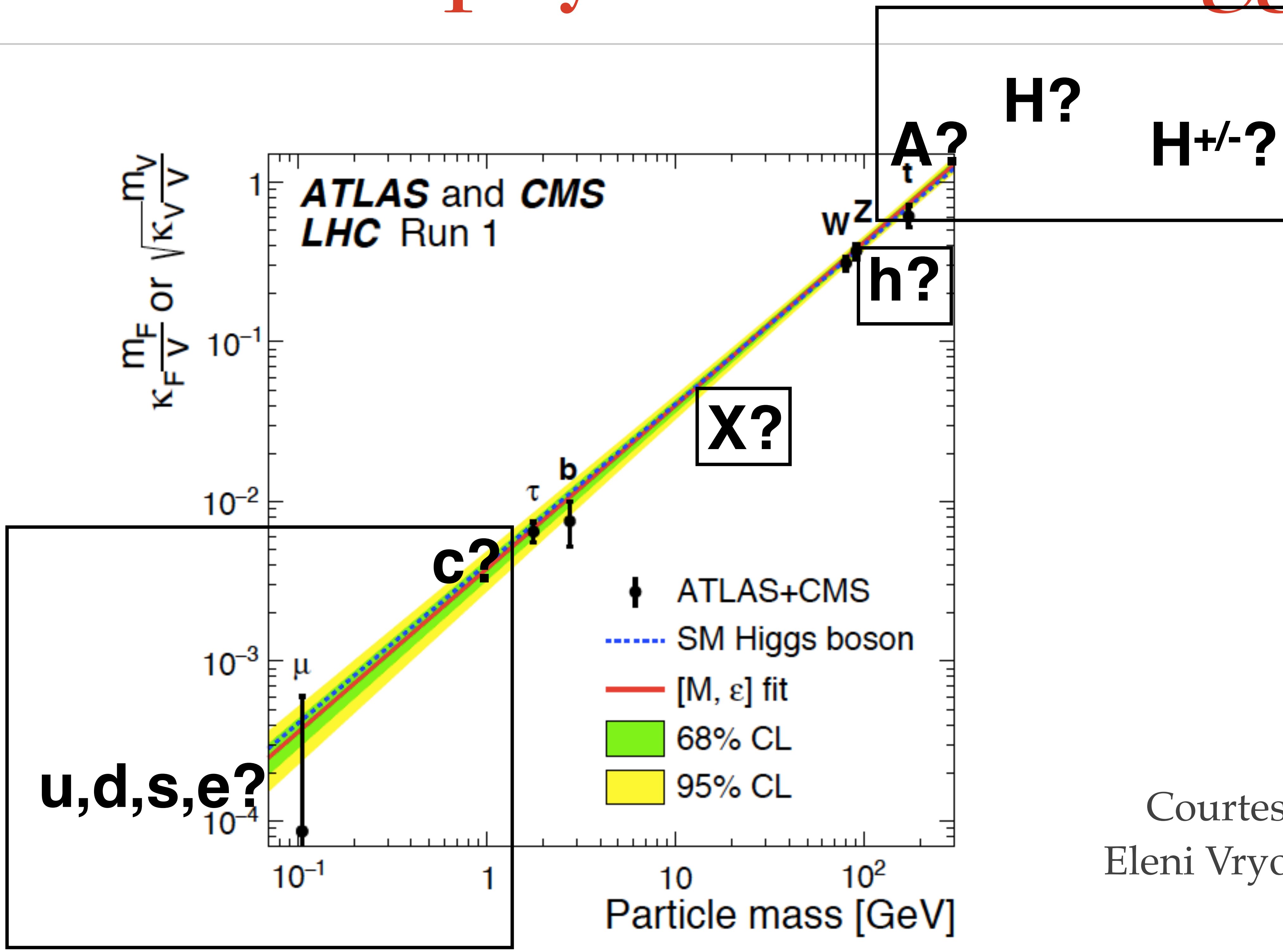
$$O_{t\phi} = y_t^3 \left(\phi^\dagger\phi\right)\left(\bar{Q}t\right)\tilde{\phi}$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger\phi\right) G^A_{\mu\nu}G^{A\mu\nu}$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\phi}G^A_{\mu\nu}$$

14TeV projection

3000 fb-1

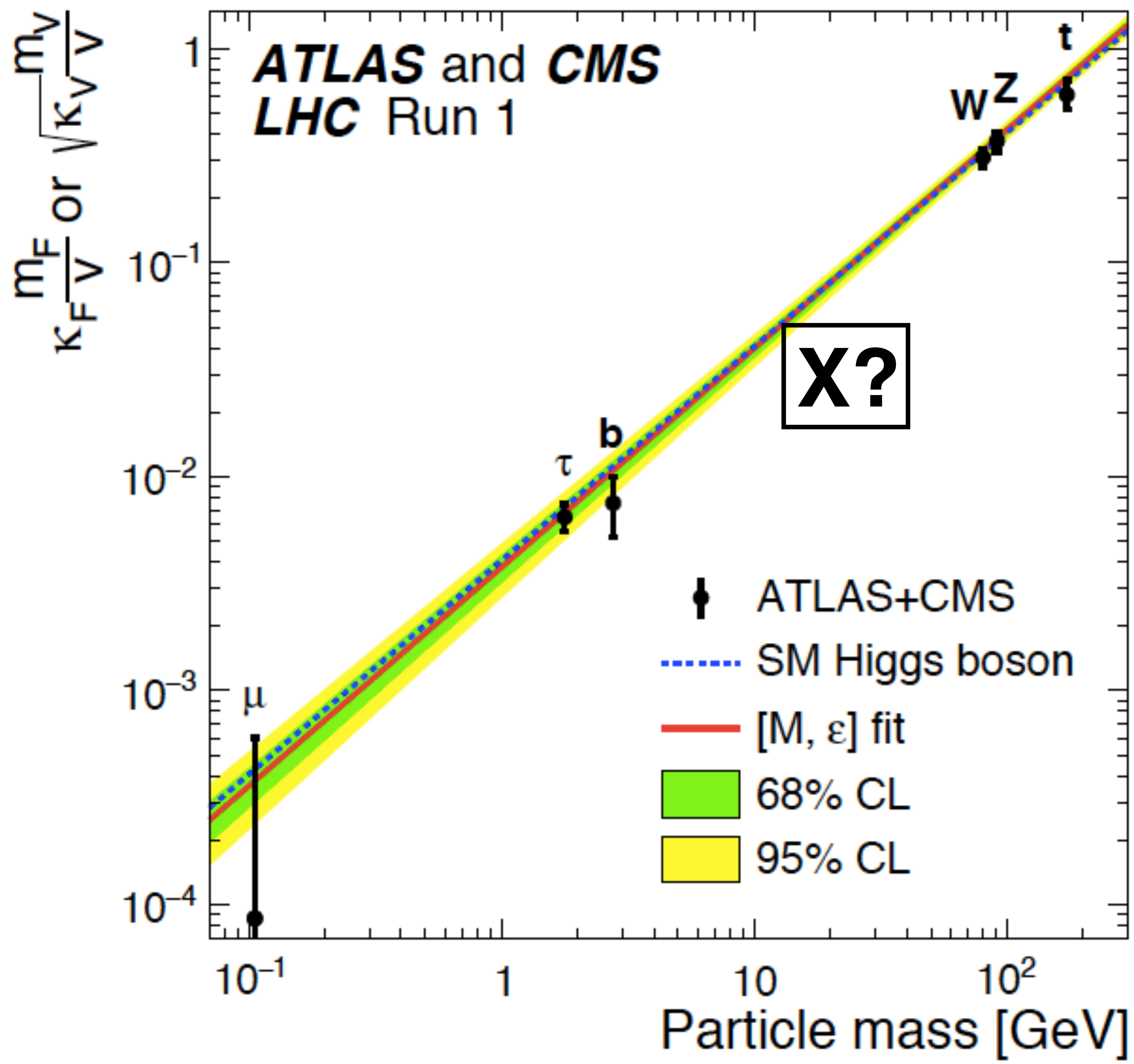

t
H

Search for new physics via the Higgs



Courtesy of
Eleni Vryonidou

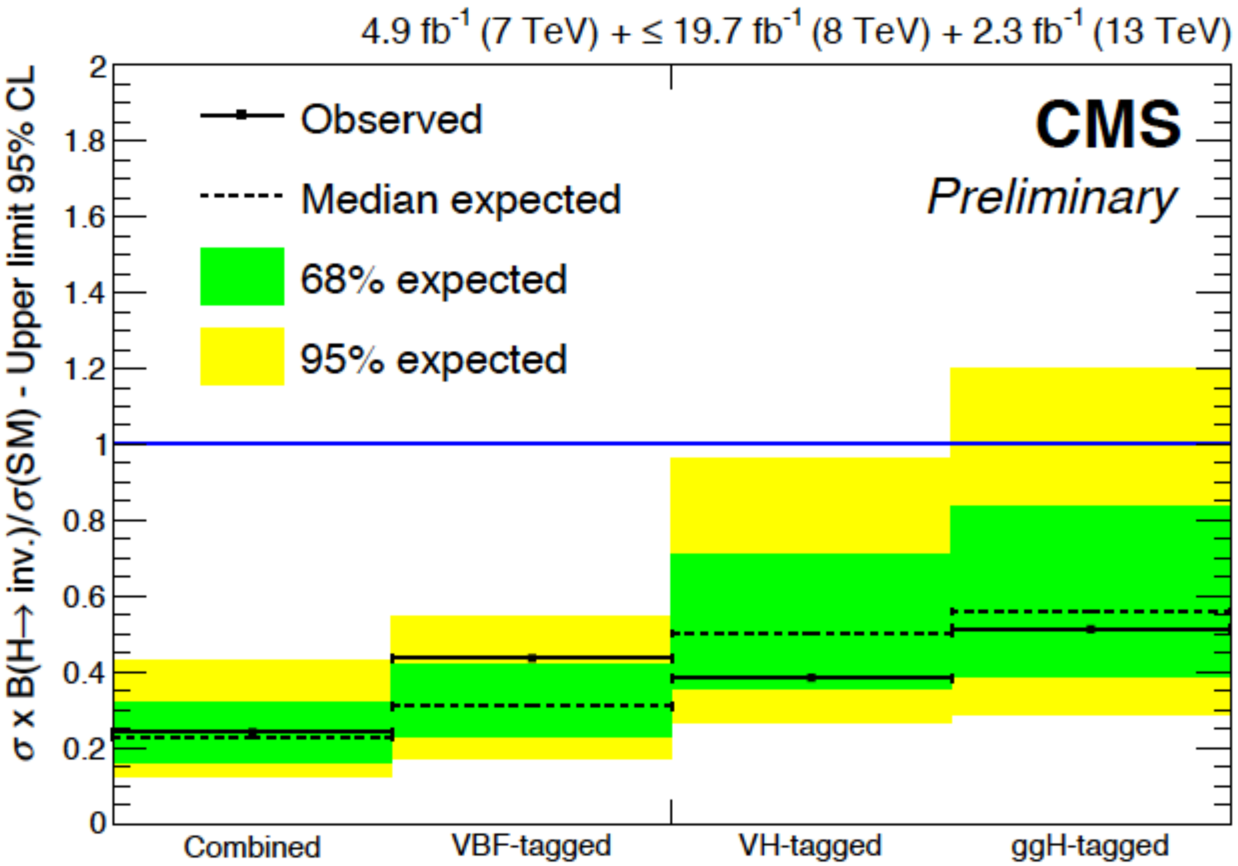
Search for new physics via the Higgs



SM Portals

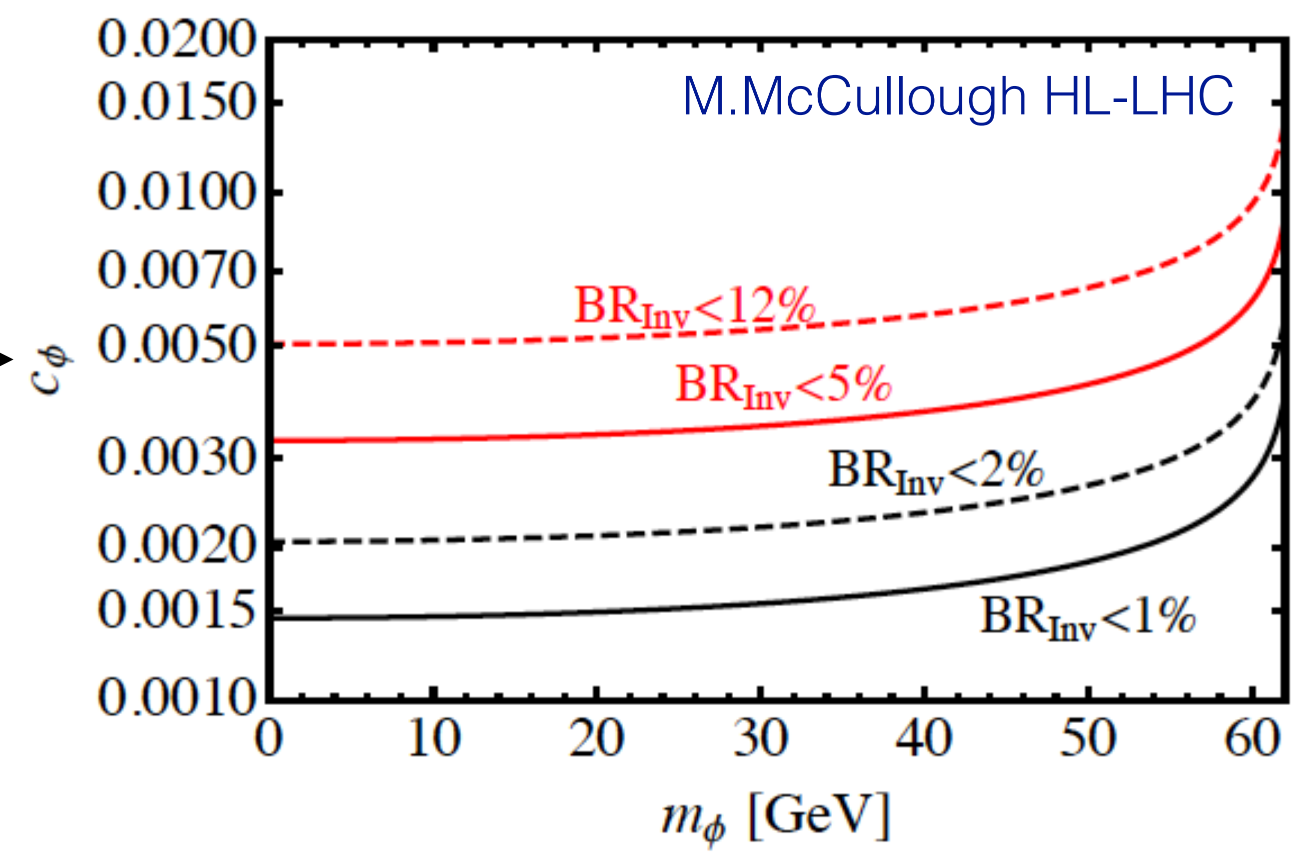
$(\Phi^\dagger \Phi)$	$(\bar{L}\Phi_c)$	$B^{\mu\nu}$
dim=2	dim=5/2	dim=2
Scalars and vectors	Sterile fermions	Dark photons

Searching for H to invisible



$B(H \to \text{inv.}) < 0.24\ (0.23)$ at a 95% CL

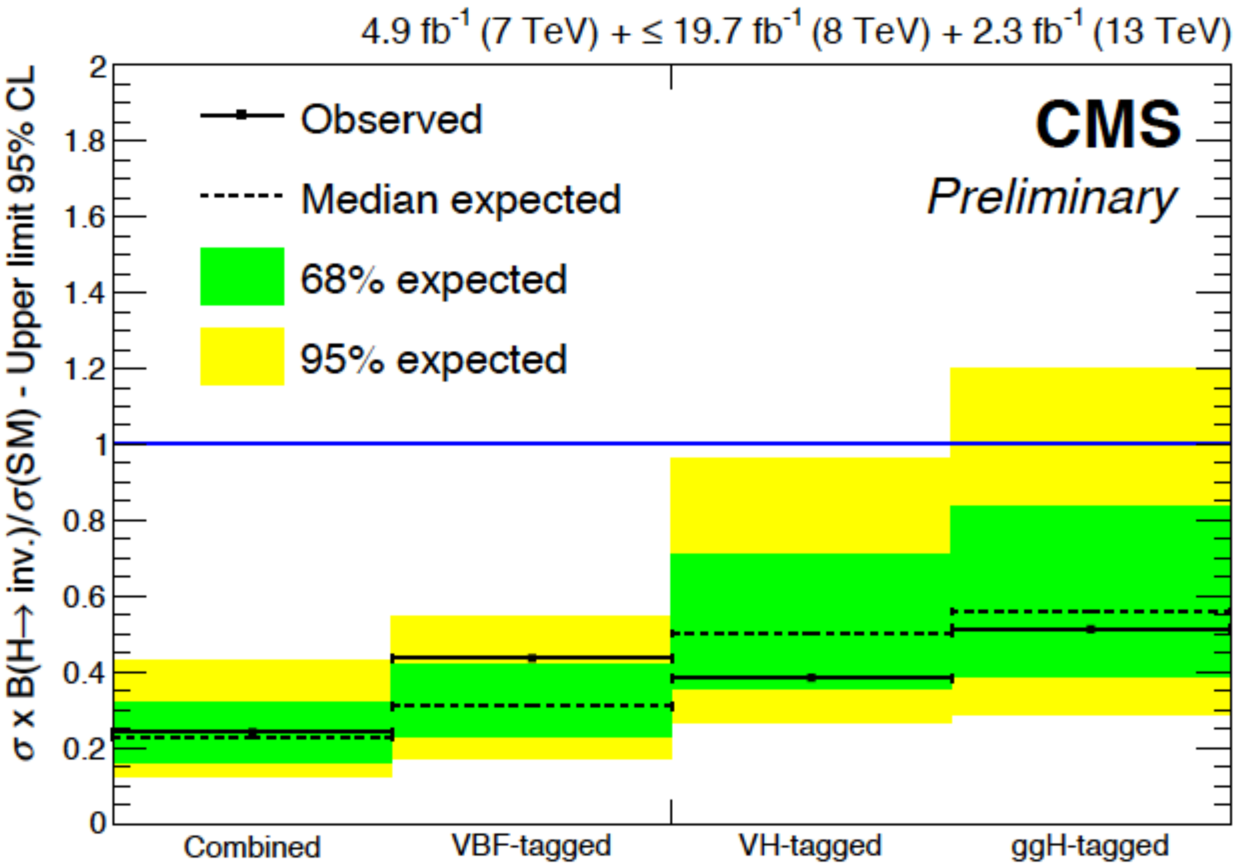
Immediate implications for any model with particles of mass $m<m_H/2$



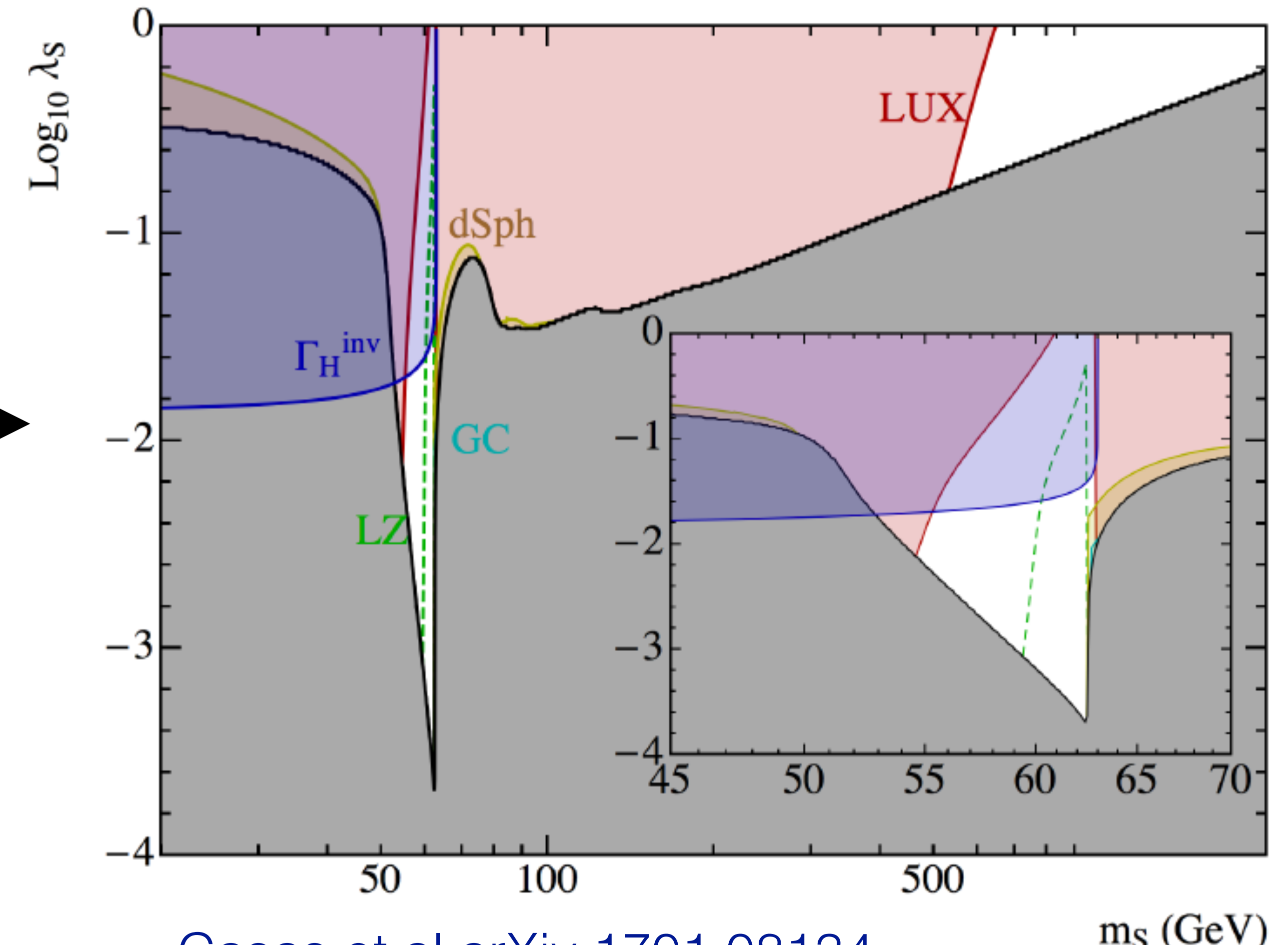
$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

Simplest extension of the SM: The Higgs portal

Searching for H to invisible



Important Dark Matter implications

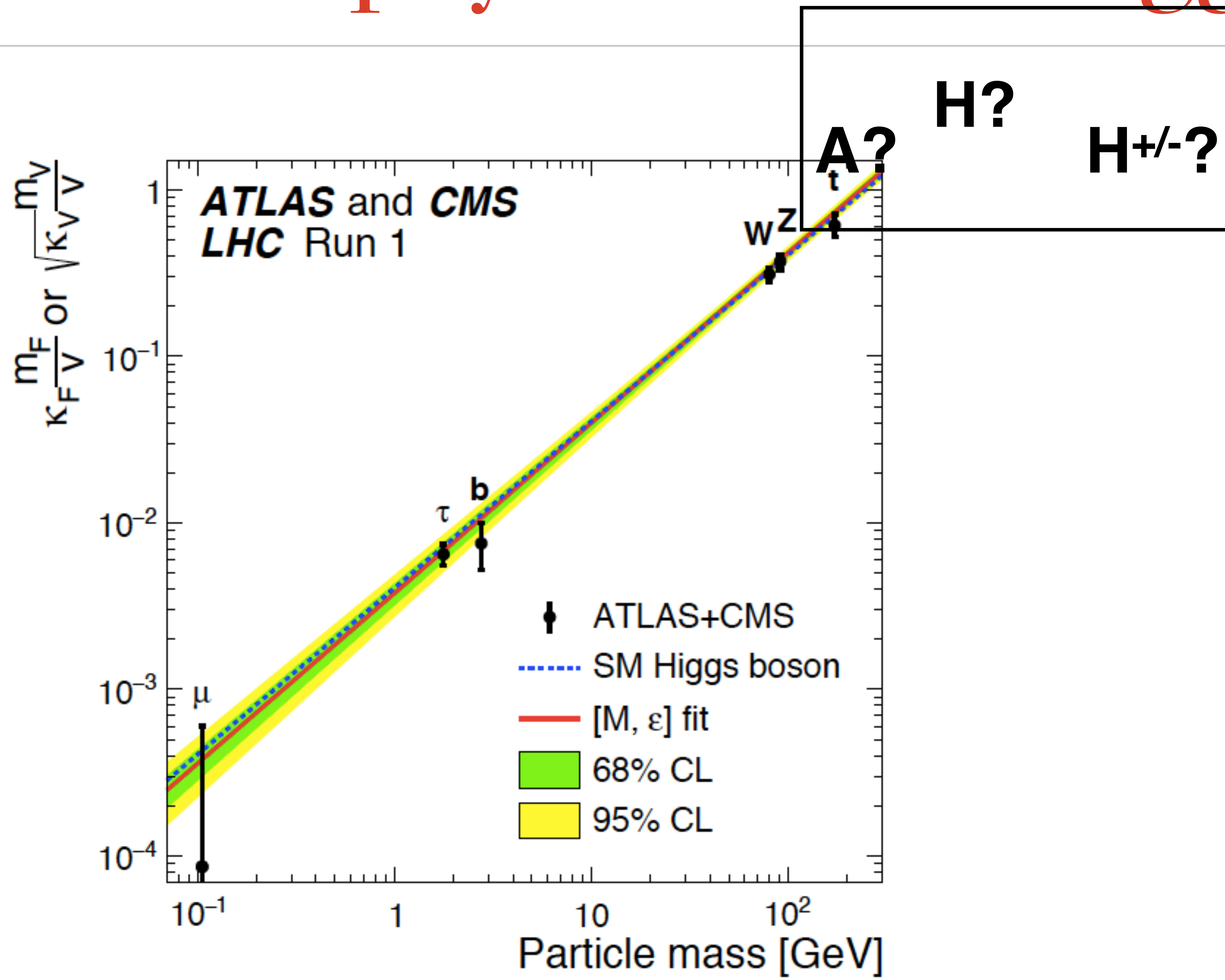


Casas et al arXiv:1701.08134

$B(H \to \text{inv.}) < 0.24\ (0.23)$ at a 95% CL

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}M^2\phi^2 - c_\phi|H|^2\phi^2$$

Search for new physics via the Higgs



Direct vs indirect searches

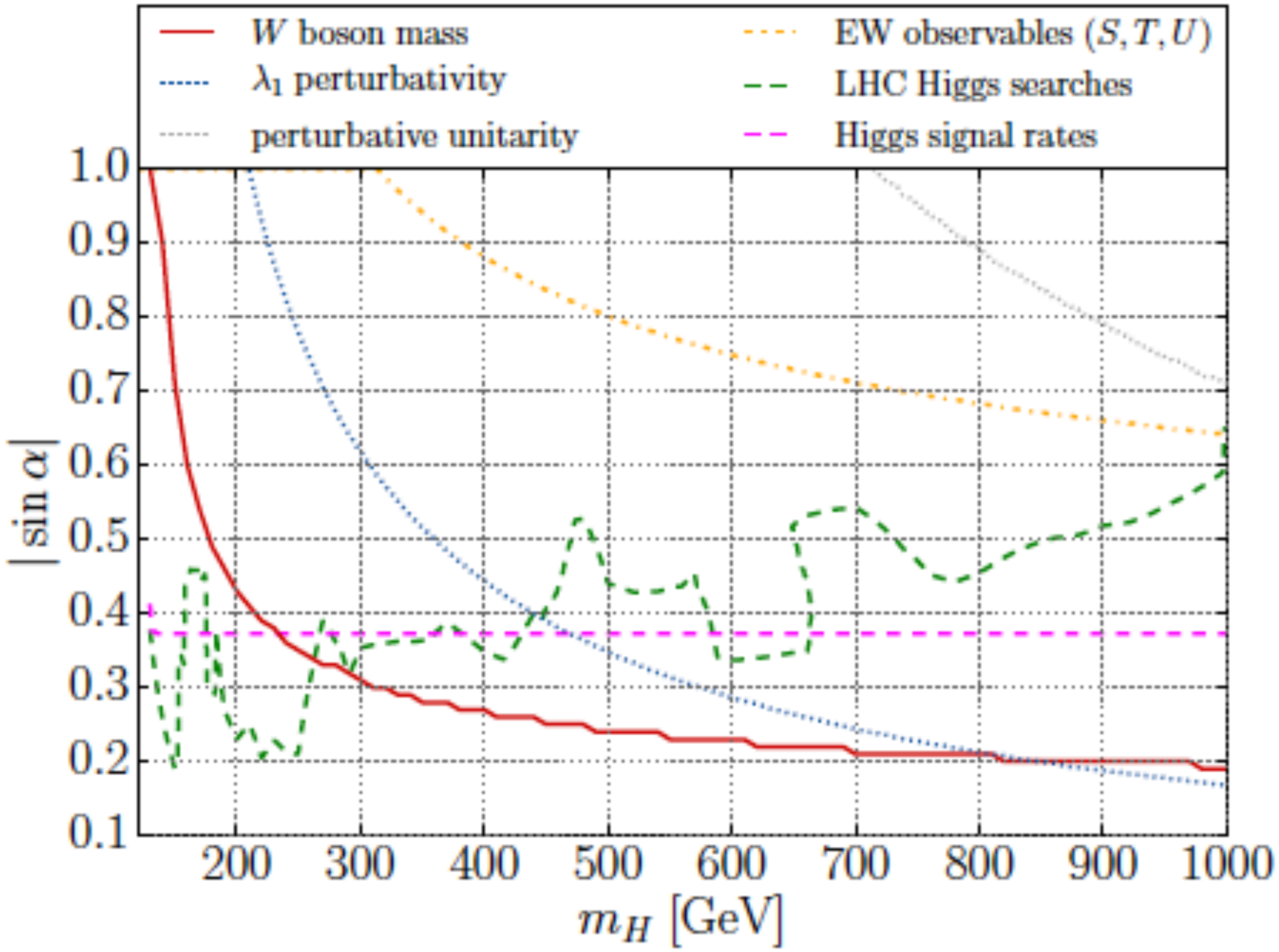
Adopting a simple model one can compare the reach for direct vs indirect measuremets:Again adding a singlet :

$$V(\Phi, S) = -m^2\Phi^\dagger\Phi - \mu^2 S^2 + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2 S^4 + \lambda_3\Phi^\dagger\Phi S^2 \qquad m_h,\, m_H,\, \sin\alpha,\, \tan\beta,\, v.$$

Heavy Higgs searches

vs

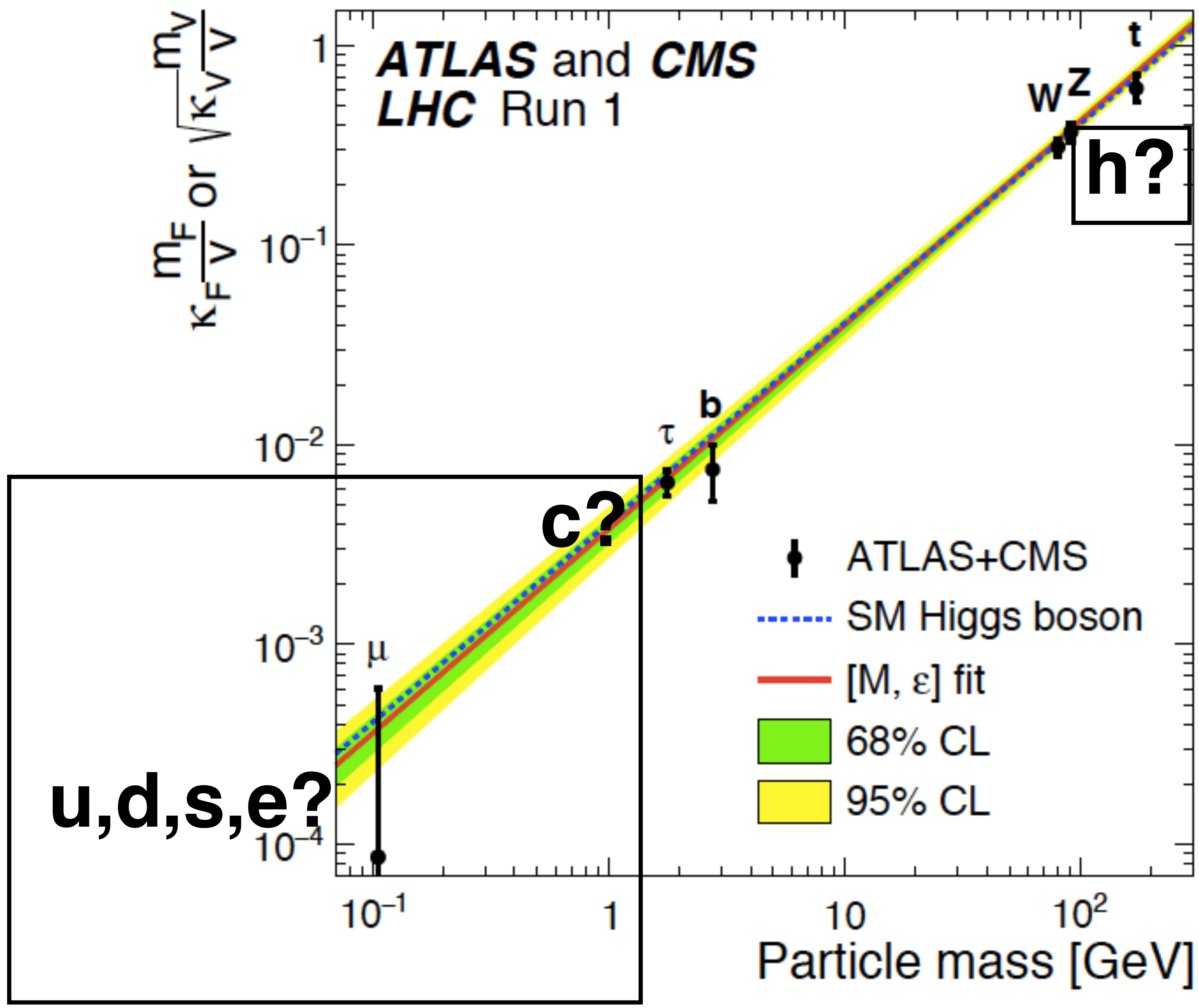
Light Higgs signal strengths



Search for new interactions

- Such a programme is based on large set of measurements, both in the exploration and in the precision phases:
    - **PHASE I (EXPLORATION):**
      Bound Higgs couplings
    - **PHASE II (DETERMINATION):**
      Stress test the SM: Look for deviations wrt dim=4 SM (rescaling factors)
    - **PHASE III (PRECISION):**
      Interpret measurements in terms the dim=6 SM parameters (SMEFT)
- Rare SM processes (induced by small interactions, such as those involving the Higgs with first and second fermion generations or flavour changing neutral interactions) are still in the exploration phase.
- For interactions with vector boson and third generation fermions we are ready to move to phase II.

Phase I (exploration) : examples



Phase I (exploration) : examples

COUPLINGS to SM particles

- H self-interactions
- Second generation Yukawas: ccH, μμH
- Flavor off-diagonal int.s : tqH, ll'H, …
- HZγ
- Top self-interactions : 4top interactions
- Top neutral gauge interactions
- Top FCNC's
- Top CP violation

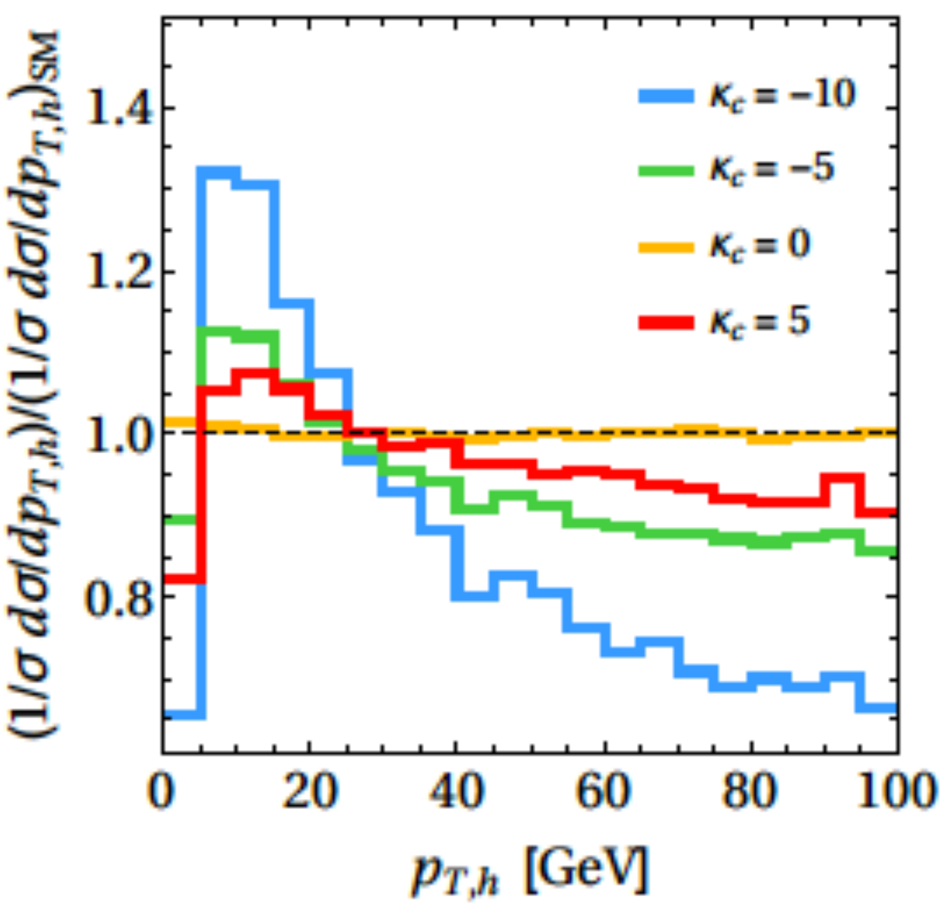
COUPLINGS to non-SM particles

- H portals

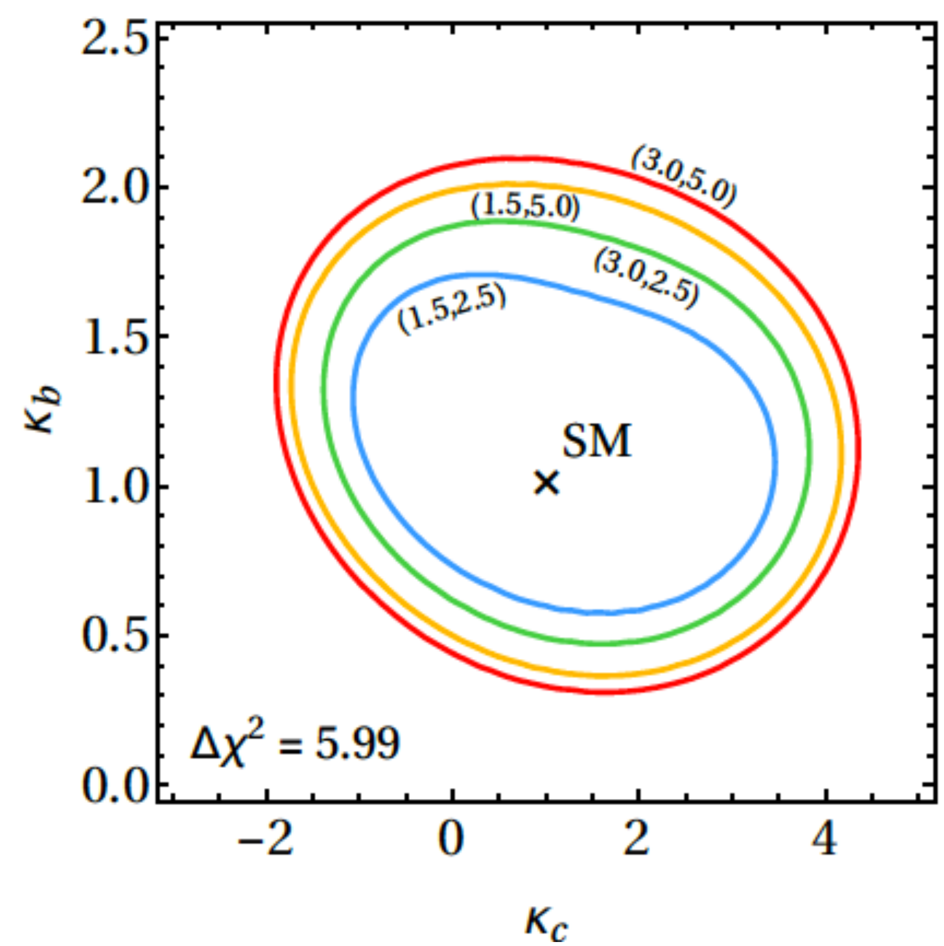
Second generation

Using kinematic distributions i.e. the Higgs pT

Bishara et al.1606.09253



Bishara et al.1606.09253



Inclusive Higgs decays i.e VH + flavour tagging (limited by c-tagging) gives a limit of 110 x SM expectation

$ZH(H \to c\bar{c})$

(for evidence of bottom couplings: ATLAS: arXiv:1708.03299 and CMS: arXiv:1708.04188)

Higgs potential 101

A low-energy parametrisation of the Higgs potential

$$V(H) = \frac{m_H^2}{2}H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4}H^4 + \ldots$$

In the Standard Model:

$$V^{\mathrm{SM}}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \quad \Rightarrow \begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases} \quad \begin{cases} \lambda_3^{\mathrm{SM}} = \lambda \\ \lambda_4^{\mathrm{SM}} = \lambda \end{cases}$$

i.e., fixing v and m_H, uniquely determines both λ_3 and λ_4.

That means that by measuring λ_3 and λ_4 one can test the SM, yet to interpret deviations, one needs to "deform it", i.e. needs to consider a well-defined BSM extension. Such extensions will necessarily depend on TH assumptions.

Higgs potential 101

To go Beyond the SM, one can parametrise a generic potential by expanding it in series:

$$V^{\mathrm{BSM}}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 + \sum_n \frac{c_{2n}}{\Lambda^{2n-4}}(\Phi^\dagger\Phi - \frac{v^2}{2})^n$$

so that the basic relations remain the same as in the SM:

$$\begin{cases} v^2 = \mu^2/\lambda \\ m_H^2 = 2\lambda v^2 \end{cases}$$

while the λ_3 and λ_4 are modified with respect to the SM values:

$$\begin{cases} \lambda_3 = \kappa_\lambda \lambda_3^{\mathrm{SM}} \\ \lambda_4 = \kappa_{\lambda_4} \lambda_4^{\mathrm{SM}} \end{cases}$$

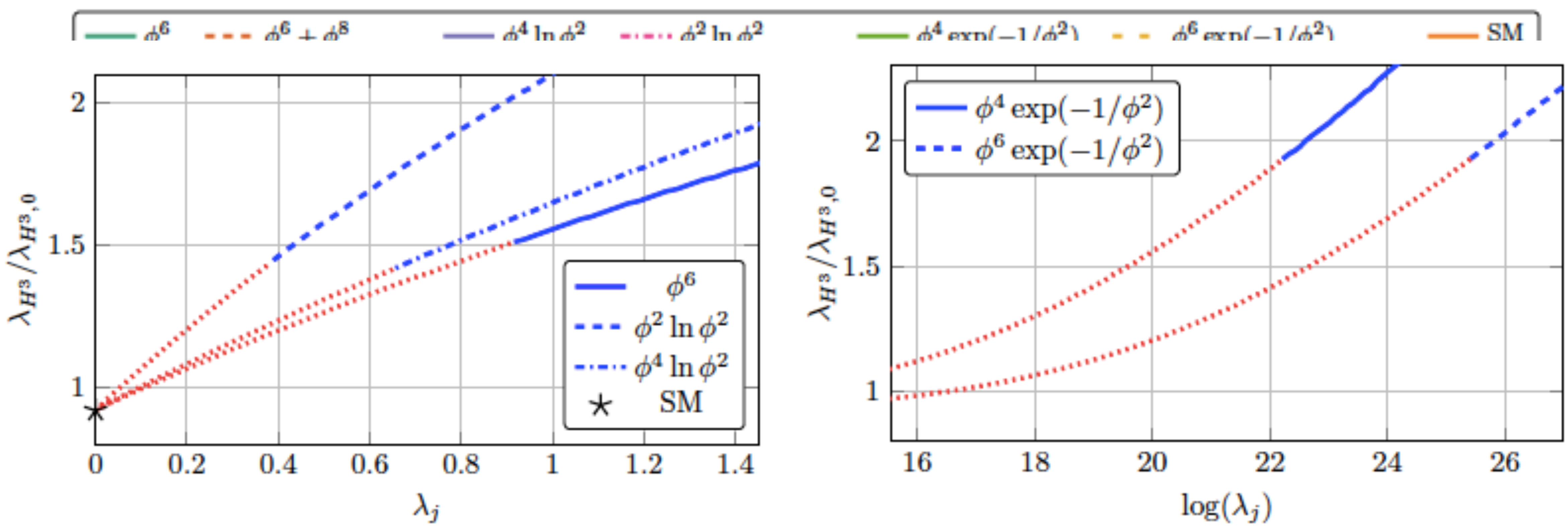
So for example: adding c_6 only

$$\begin{cases} \kappa_\lambda = 1 + \dfrac{c_6 v^2}{\lambda\Lambda^2} \\ \kappa_{\lambda_4} = 1 + \dfrac{6c_6 v^2}{\lambda\Lambda^2} = 6\kappa_\lambda - 5 \end{cases}$$

i.e., in this case λ_3 and λ_4 are related.

Baryogenesis

Remember that to generate a matter-antimatter asymmetry in the Universe the three Sakharov conditions have to be satisfied (B violation, first-order phase transition (out-of-equilibrium), C and CP violation). The SM potential leads to 2nd order phase transitions.

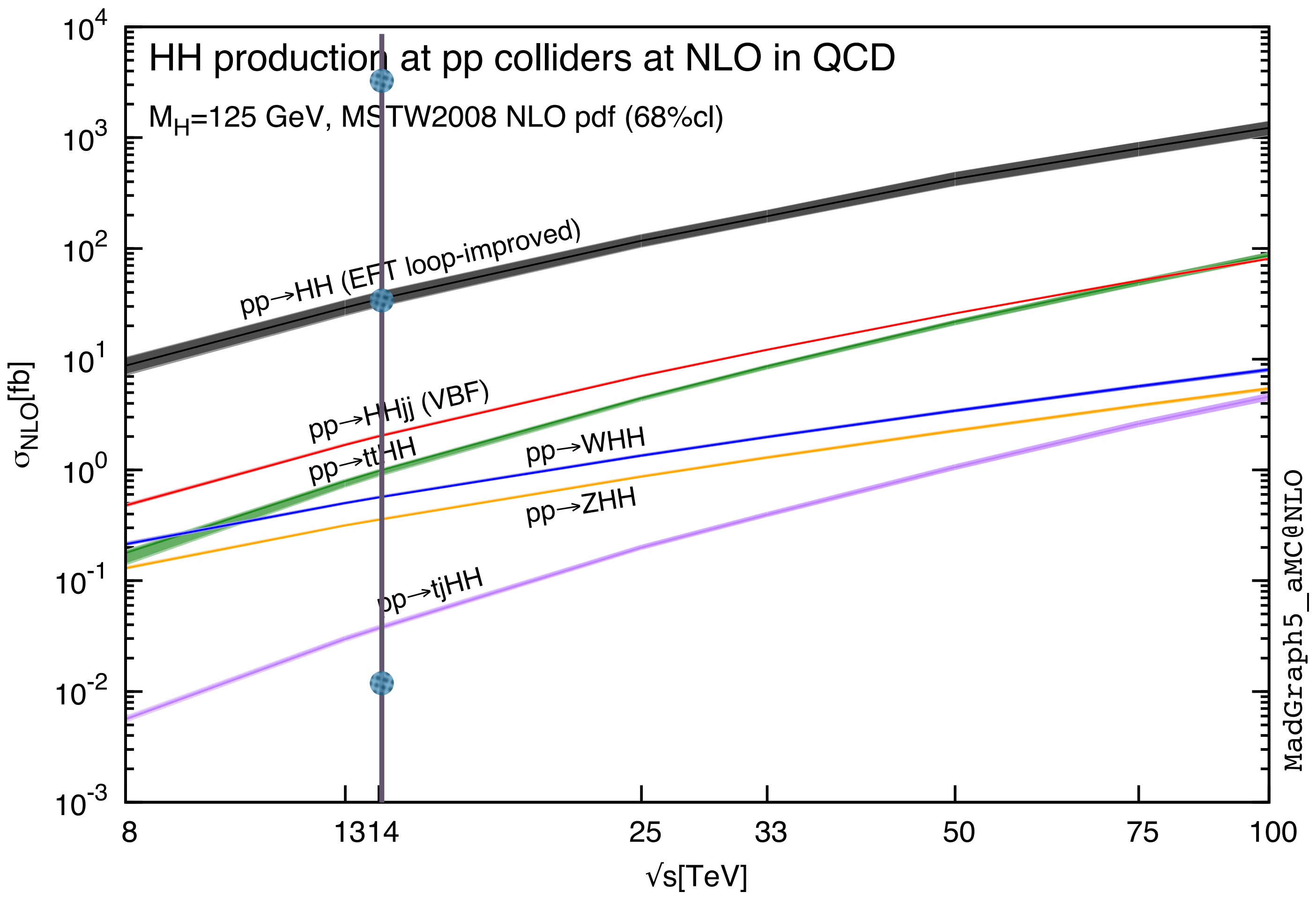


Reichert et al. 1711.00019

A trilinear coupling above 1.5*SM value allows a 1st order transition.

Phase I : Higgs self-coupling

[Frederix et al. '14]

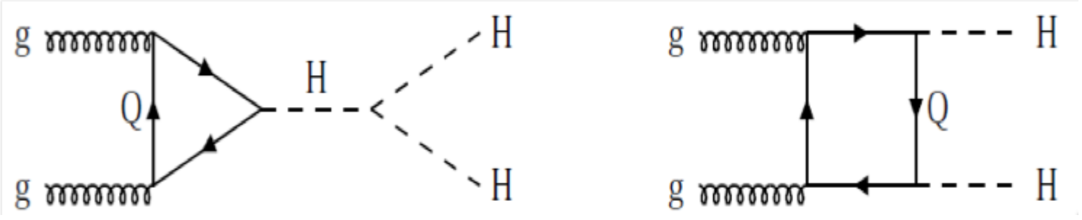


At 14 TeV from gg fusion:

$$\sigma_H = 55 \text{ pb}$$

$$\sigma_{HH} = 44 \text{ fb}$$

$$\sigma_{HHH} = 110 \text{ ab}$$

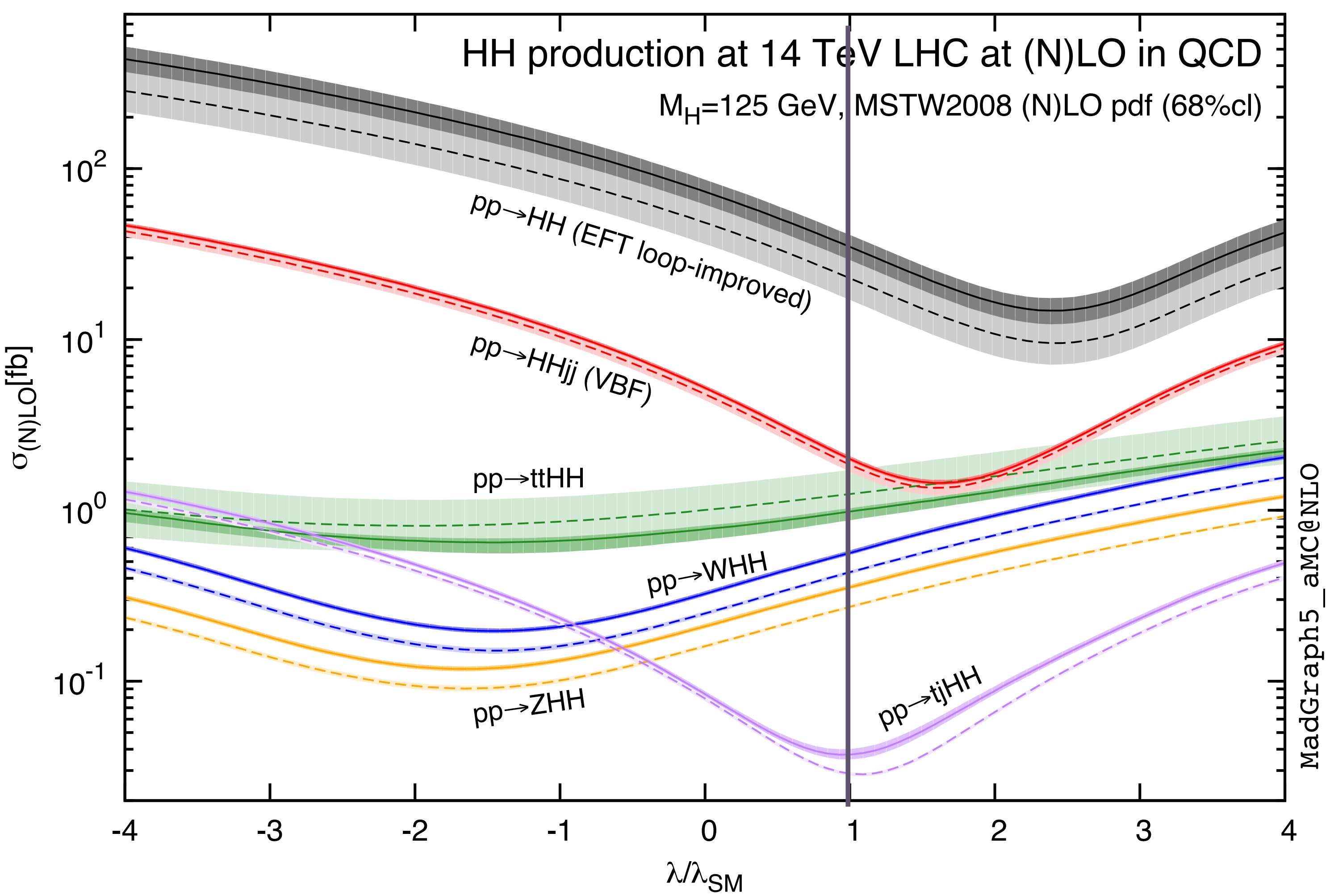


As in single Higgs many channels contribute in principle.

Cross sections for HH(H) increase by a factor of 20(60) at a FCC.

Phase I : Higgs self-coupling

[Frederix et al. '14]



Many channels, but small cross sections.

Current limits are on σ_{SM} (gg→HH) channel in various H decay channels:

CMS : $\sigma/\sigma_{SM} < 19$ (bbγγ) [EPS2017]
ATLAS : $\sigma/\sigma_{SM} < 13$ (bbbb). [Moriond18]

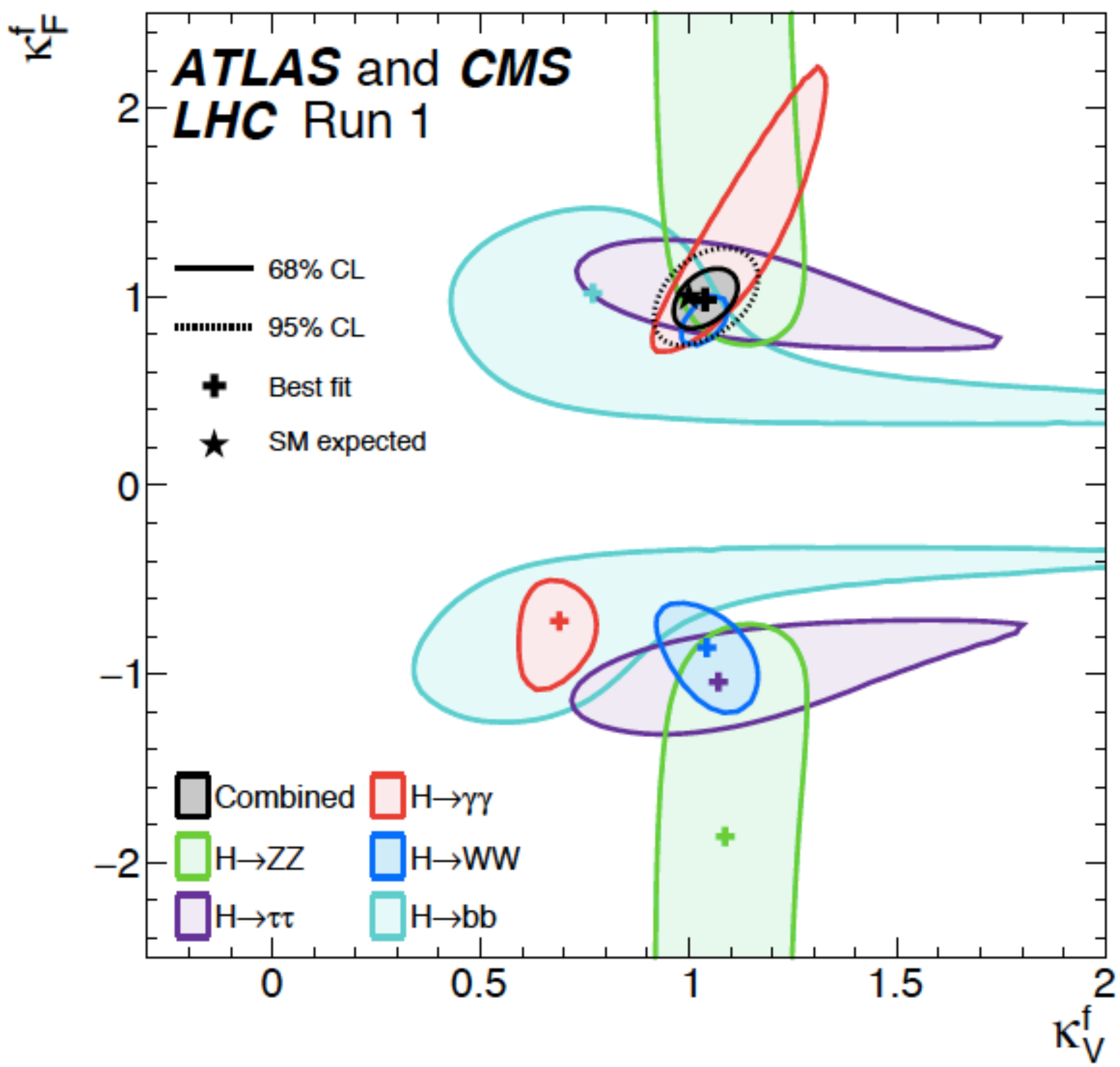
Remarks:

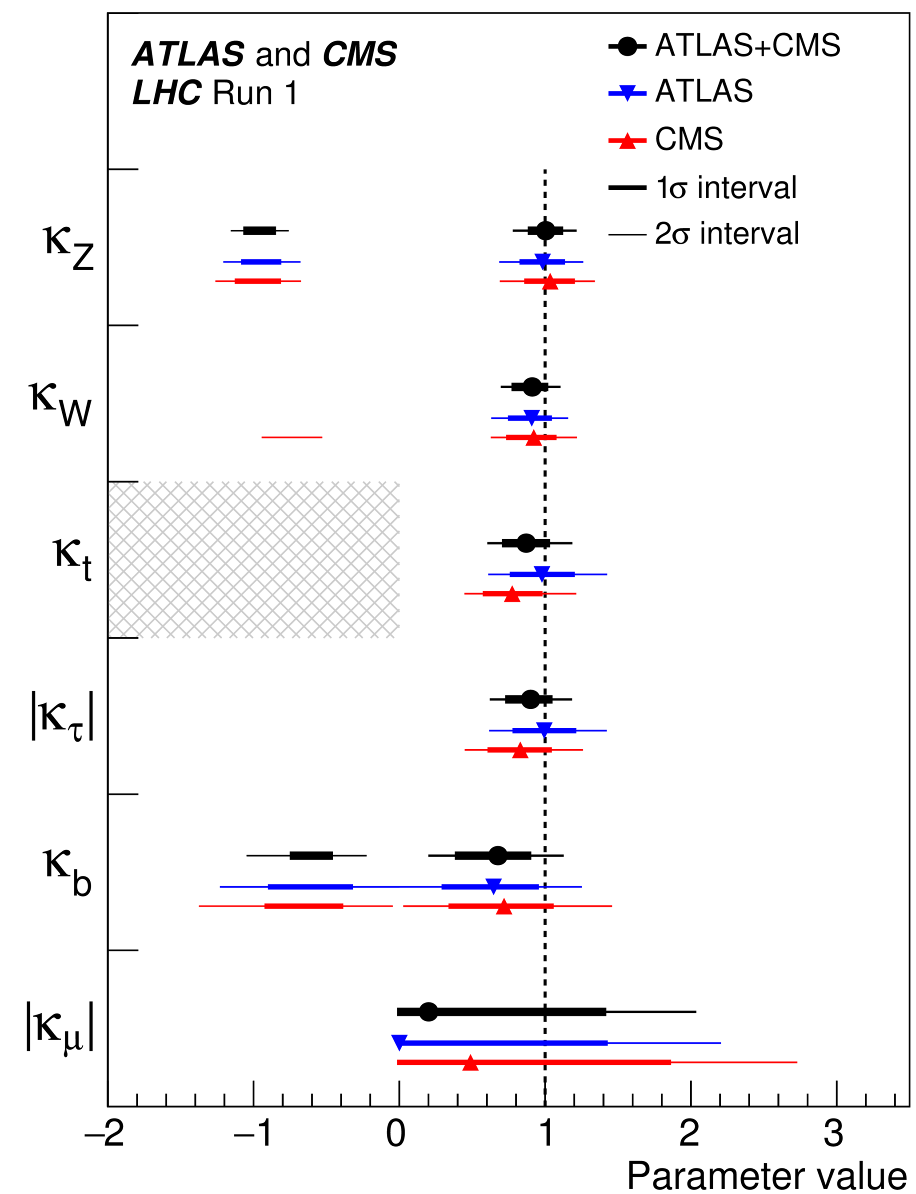
1. Interpretations of these bounds in terms of BSM always need additional assumptions on how the SM has been deformed.
2. The current most common assumption is just a change of λ_3 which leads to a change in σ as well as of distributions:

$$\sigma = \sigma_{\rm SM}[1 + (\kappa_\lambda - 1)A_1 + (\kappa_\lambda^2 - 1)A_2]$$

Note: due to shape changes, it is not straightforward to infer a bound on λ_3 from σ(HH), even when $\sigma_{BSM}=\sigma(\lambda_3)$ only is assumed.

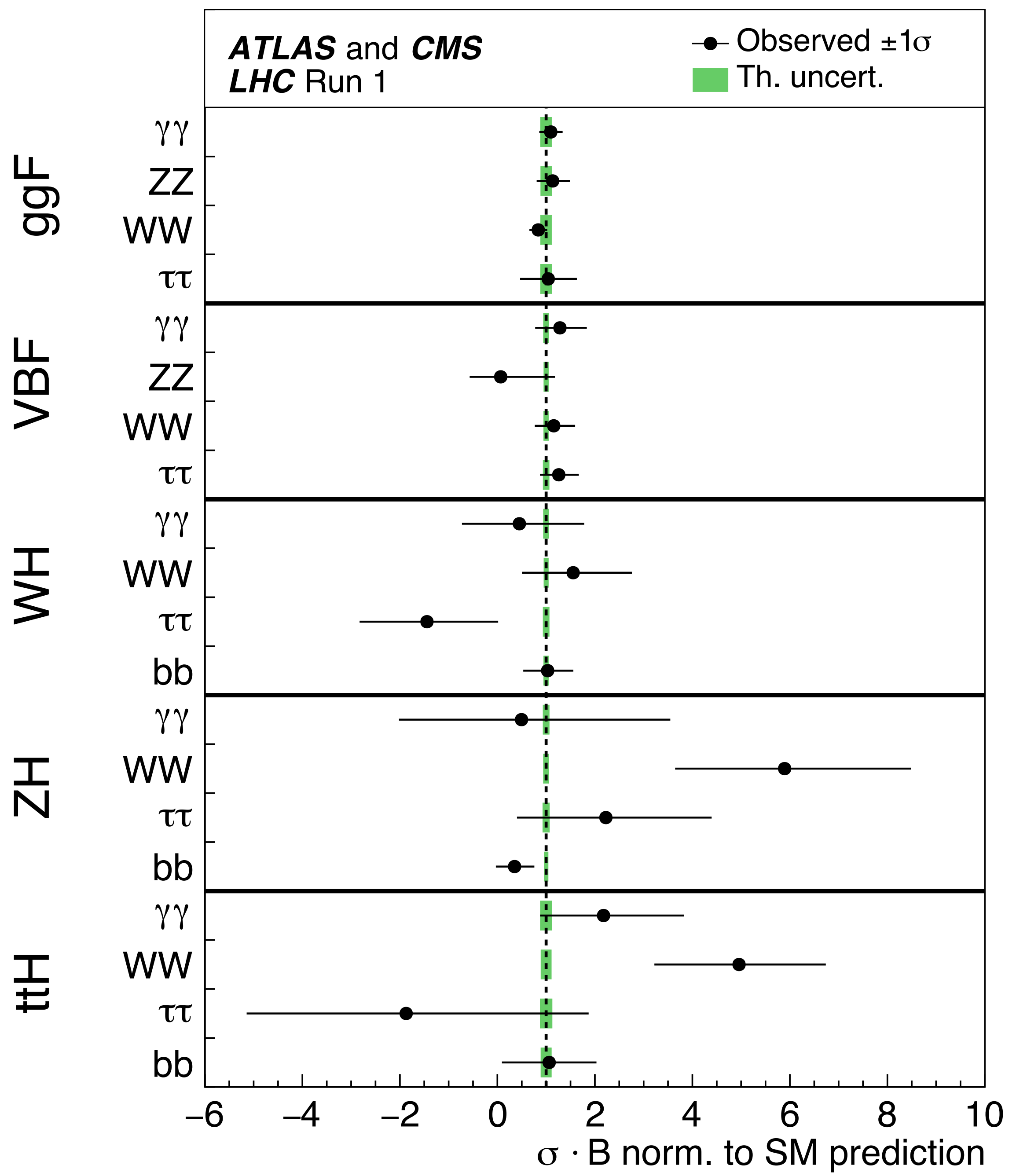
Phase II : CMS/ATLAS Higgs couplings combination





Data points agree with SM hypothesis at the 20-30% level

Phase II : CMS/ATLAS Higgs couplings combination



$$\mu_i^f = \frac{\sigma_i \cdot \mathrm{B}^f}{(\sigma_i)_{\mathrm{SM}} \cdot (\mathrm{B}^f)_{\mathrm{SM}}} = \mu_i \cdot \mu^f$$

$$\begin{aligned} \mu_i &= 1 + \delta\sigma_{\lambda_3}(i) \\ \mu^f &= 1 + \delta \mathrm{BR}_{\lambda_3}(f) \end{aligned}$$

This information can be used by anybody to test BSM scenarios that lead to different patterns of Higgs coupling changes.

Phase III : SMEFT

The matter content of SM has been experimentally verified and evidence for new light states has not yet emerged.

SM measurements can always be seen as searches for deviations from the dim=4 SM Lagrangian predictions. More in general one can interpret measurements in terms of an EFT:

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

the BSM ambitions of the LHC Higgs/Top/SM physics programmes can be recast in as simple as powerful way in terms of one statement:

"BSM goal" of the SM LHC Run II programme:

determination of the couplings of the SM@DIM6

Example: Gauge-Higgs operators

Focus on a subset of 10 operators:

arXiv:1803.03252

arXiv:1604.03105

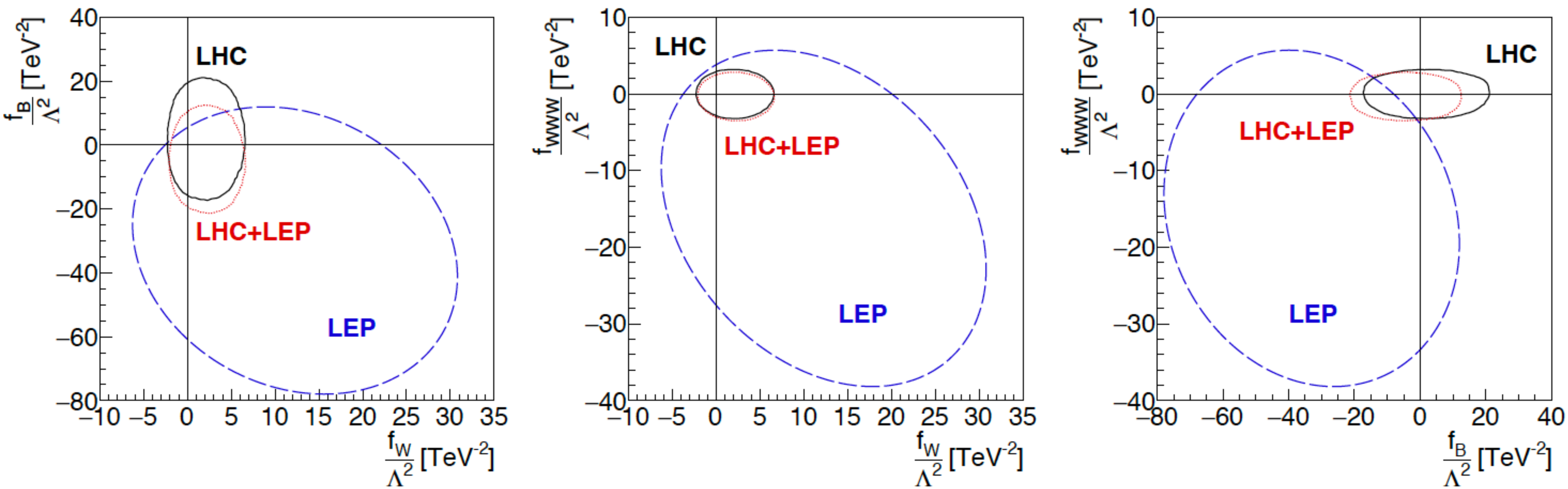
$$\mathcal{O}_{GG} = \phi^\dagger\phi\, G^a_{\mu\nu}G^{a\mu\nu} \qquad \mathcal{O}_{WW} = \phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi \qquad \mathcal{O}_{BB} = \phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\phi$$

$$\mathcal{O}_W = (D_\mu\phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\phi) \qquad \mathcal{O}_B = (D_\mu\phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\phi) \qquad \mathcal{O}_{\phi,2} = \frac{1}{2}\partial^\mu\left(\phi^\dagger\phi\right)\partial_\mu\left(\phi^\dagger\phi\right)$$

$$\mathcal{O}_{e\phi,33} = (\phi^\dagger\phi)(\bar{L}_3\phi e_{R,3}) \qquad \mathcal{O}_{u\phi,33} = (\phi^\dagger\phi)(\bar{Q}_3\tilde{\phi}u_{R,3}) \qquad \mathcal{O}_{d\phi,33} = (\phi^\dagger\phi)(\bar{Q}_3\phi d_{R,3})$$

$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^{\mu}_{\rho}\right) .$$

Constrain those modifying triple-gauge couplings by WW, WZ measurements

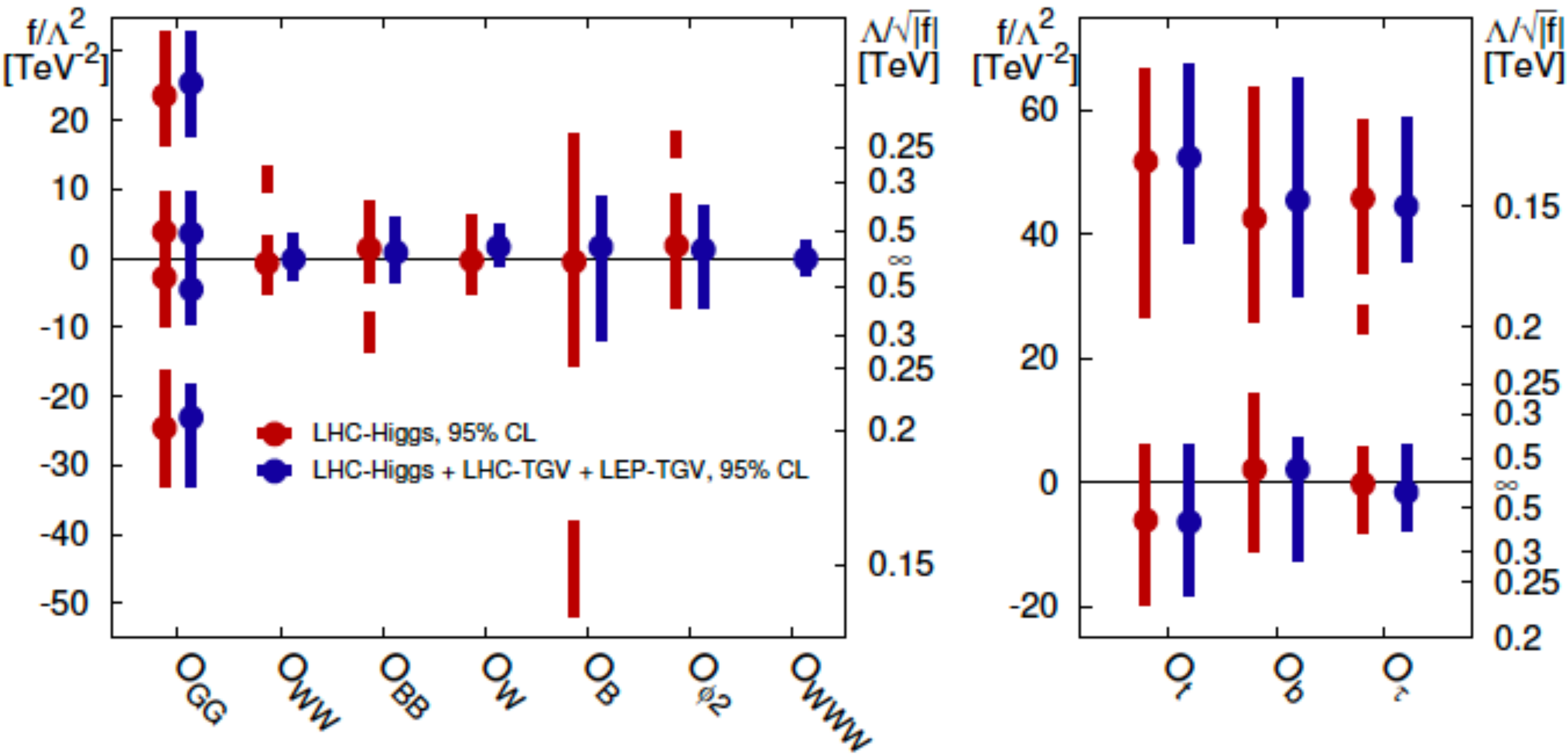


Example: Gauge-Higgs operators

arXiv:1803.03252

arXiv:1604.03105

Add the Higgs strengths constraints:



Top-quark operators and processes

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu \tau^I Q)$$

$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$

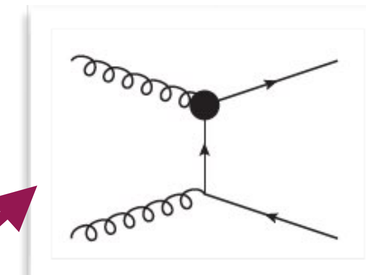
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$

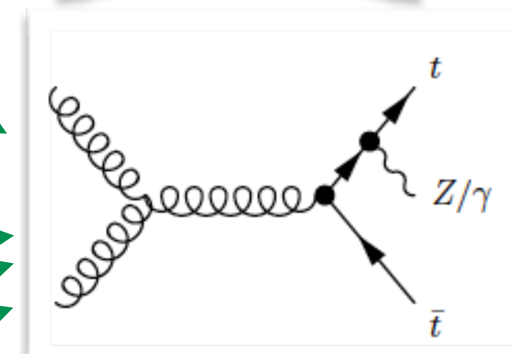
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi} W^I_{\mu\nu}$$

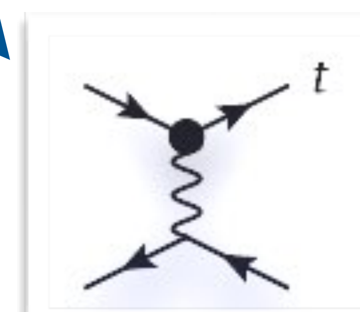
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi} B_{\mu\nu}$$

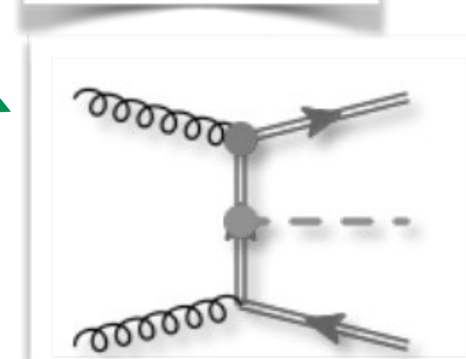
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\varphi} G^A_{\mu\nu}\,,$$

$$O_{t\varphi} = y_t^3 (\varphi^\dagger\varphi)\bar{Q}\tilde{\varphi} t$$









+four-fermion operators

+ operators that do not feature a top, but contribute to the procs…

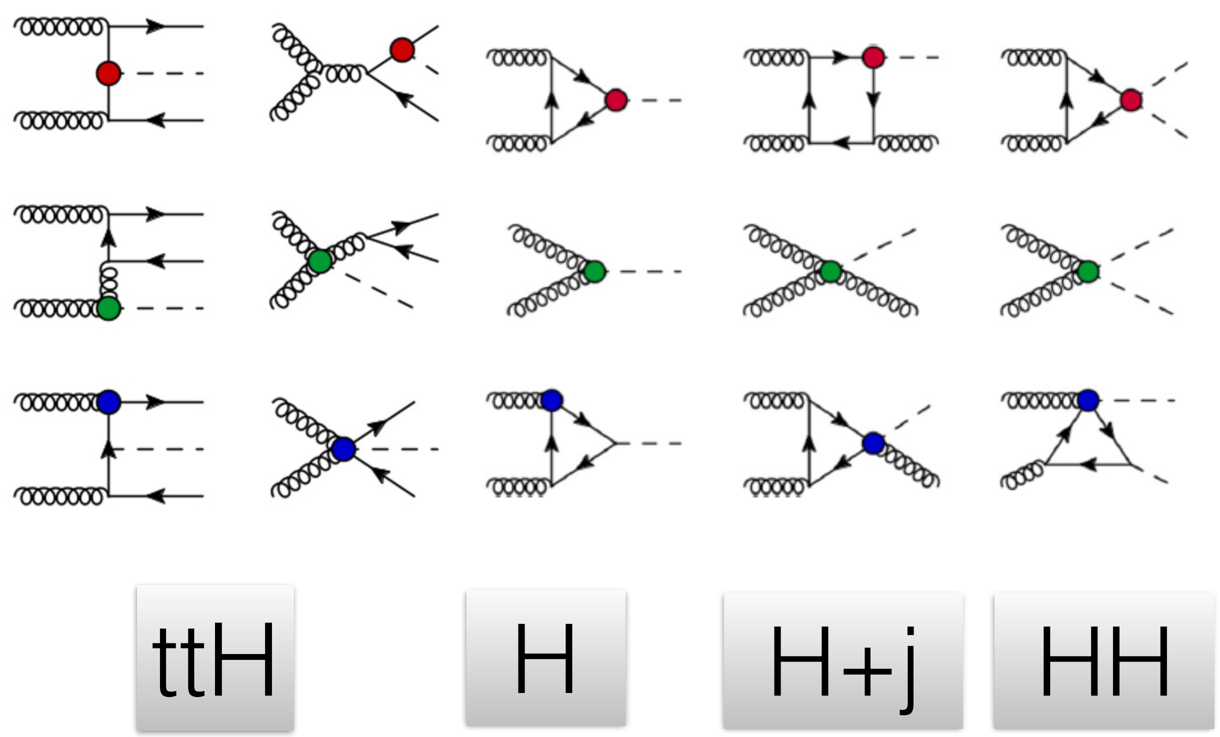
Top/Higgs operators and processes

Several operators typically enter each process at LO (or at LO^2) and

NLO (no	Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{bW}	$O_{\varphi tb}$	O_{4f}	O_G	$O_{\varphi G}$
✓	$t \to bW \to bl^+\nu$	N		L	L				L^2	L^2	1L^2		
✓	$pp \to tj$	N		L	L				L^2	L^2	1L		
✓	$pp \to tW$	L		L	L				L^2	L^2	1N	N	
✓	$pp \to t\bar{t}$	L									2L-4N	L	
✓	$pp \to t\bar{t}j$	L									2L-4N	L	
✓	$pp \to t\bar{t}\gamma$	L	L	L							2L-4N	L	
✓	$pp \to t\bar{t}Z$	L	L	L	L	L	L				2L-4N	L	
✓	$pp \to t\bar{t}W$	L								L	1L-2L		
✓	$pp \to t\gamma j$	N	L	L	L				L^2	L^2	1L		
✓	$pp \to tZj$	N	L	L	L	L	L		L^2	L^2	1L		
✓	$pp \to t\bar{t}t\bar{t}$	L									2L-4L	L	
✓	$pp \to t\bar{t}H$	L						L			2L-4L	L	L
✓	$pp \to tHj$	N		L	L			L	L^2	L^2	1L		N
O ✓	$gg \to H$	L						L				N	L
O ✗	$gg \to Hj$	L						L				L	L
O ✗	$gg \to HH$	L						L				N	L
O ✗	$gg \to HZ$	L			L	L	L	L				N	L

Top/Higgs operators and processes

Let's take a simple example, i.e. Higgs production via top interactions and consider the relevant subset of operators.



$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) (\bar{Q}t)\, \tilde{\phi}$$

$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$

$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu} T^A t)\tilde{\phi} G^A_{\mu\nu}$$

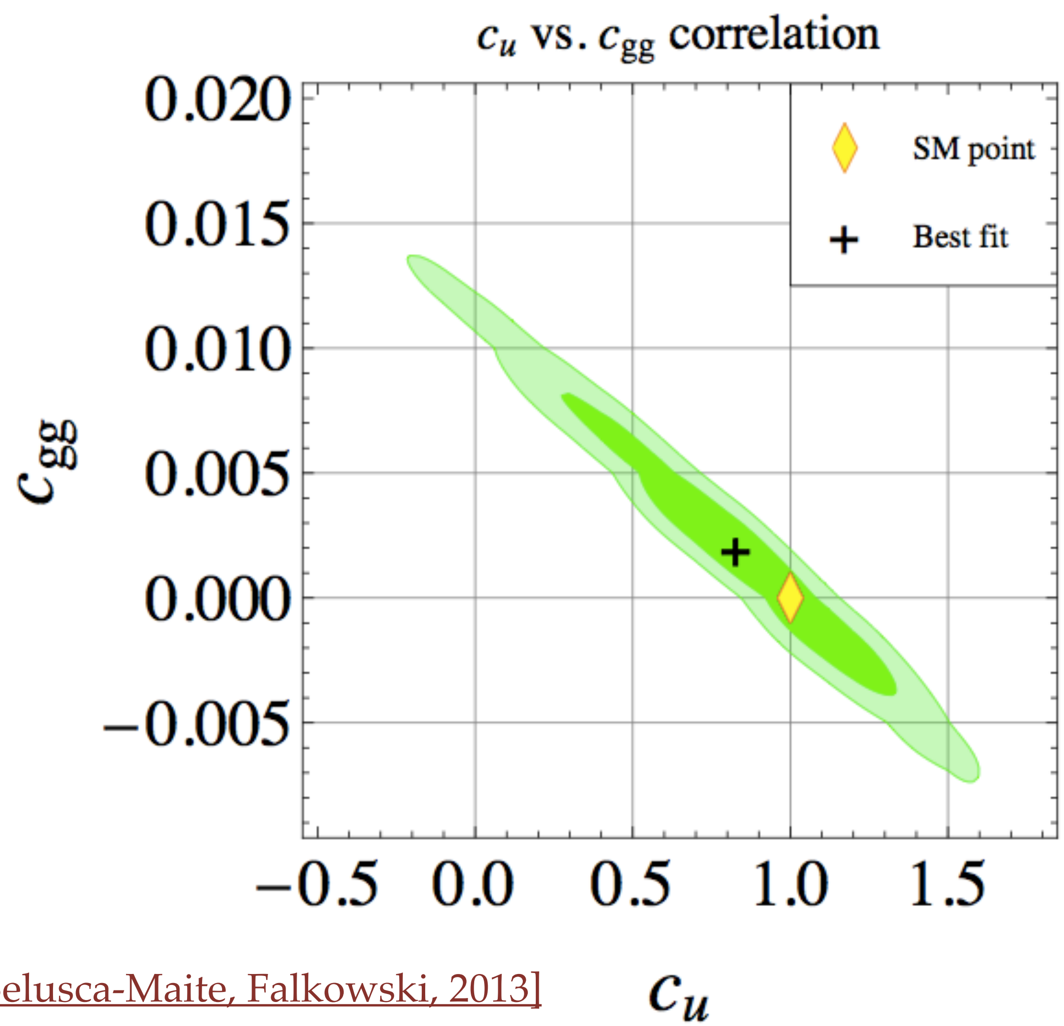
Note that these operators mix into each others and therefore they NEED to be considered together.

$$\gamma = \frac{2\alpha_s}{\pi} \begin{pmatrix} \frac{1}{6} & 0 & 0 \\ 4 & -1 & 4 \\ \frac{1}{4} & 0 & -\frac{7}{4} \end{pmatrix}$$

Top-Higgs interactions: constraints

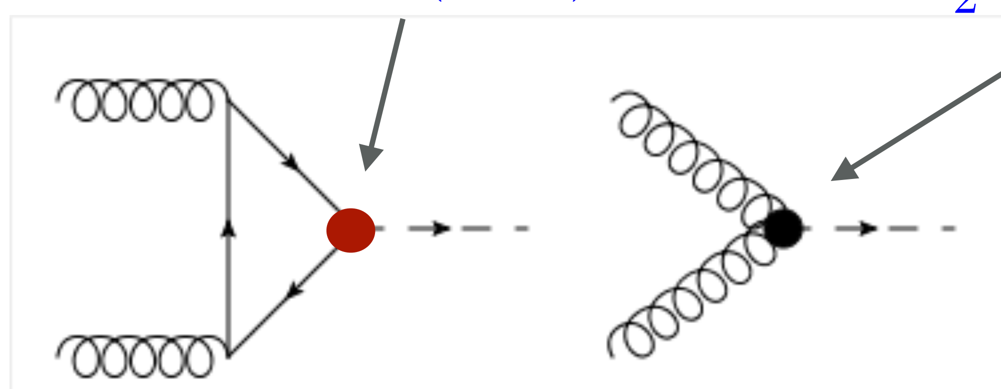
From a global fit the coupling of the higgs to the top is poorly determined.

$$\frac{\sigma_{ggh}}{\sigma_{ggh}^{\rm SM}} \simeq 1 + 237 c_{gg} + 2.06\delta y_u - 0.06\delta y_d.$$



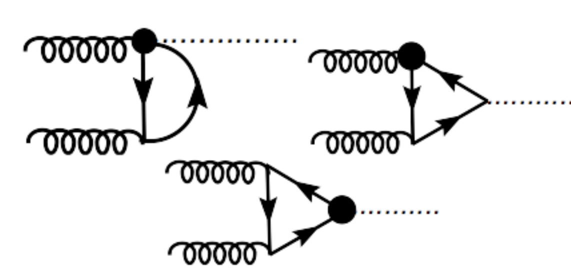
[Belusca-Maite, Falkowski, 2013]

$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R$ $\quad$ $\mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$



the loop could still be dominated by np.

THE EFFECT OF THE CM OPERATOR NOT INCLUDED

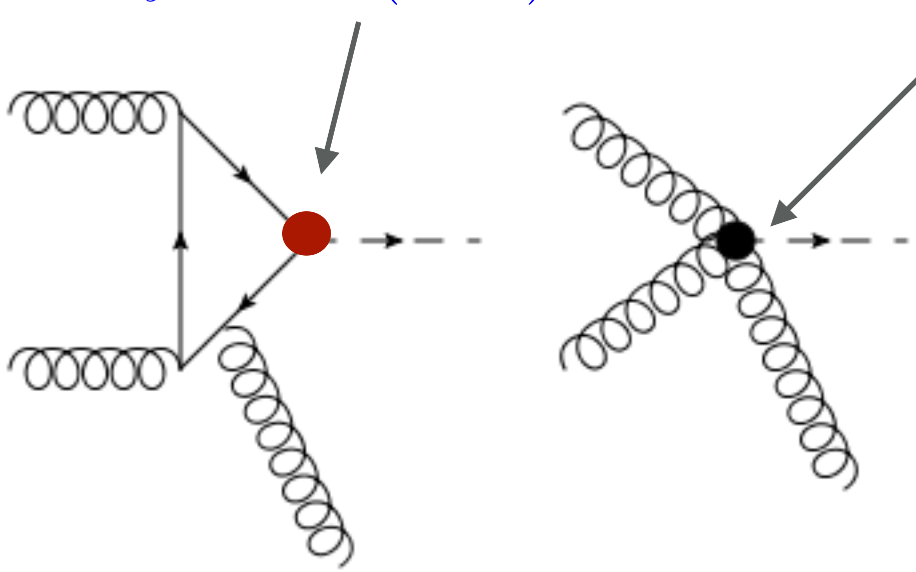


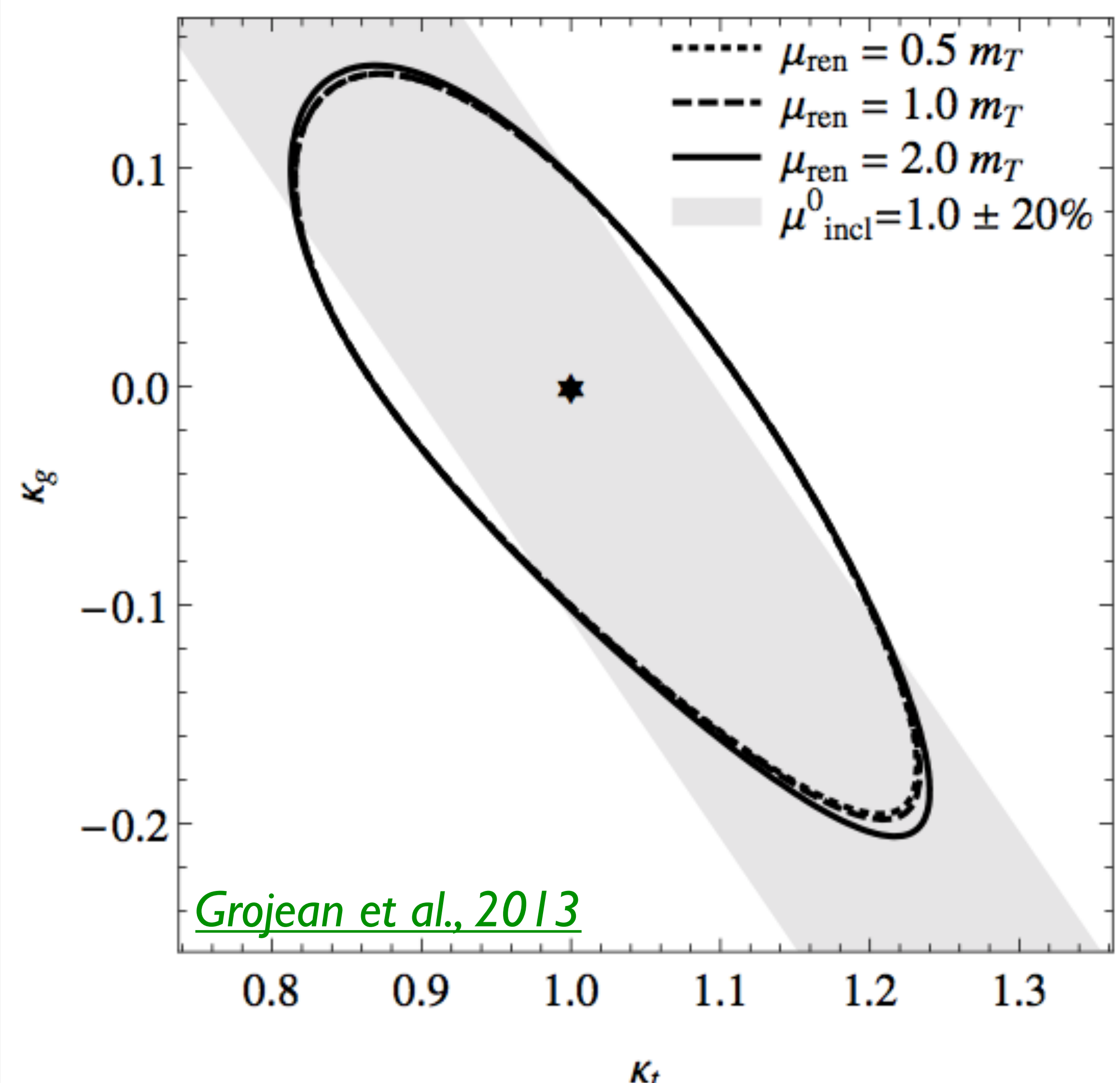
Top-Higgs interactions: high-pT

From a global fit the coupling of the Higgs to the top is poorly determined: the loop could still be dominated by NP.

$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R$

$\mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$

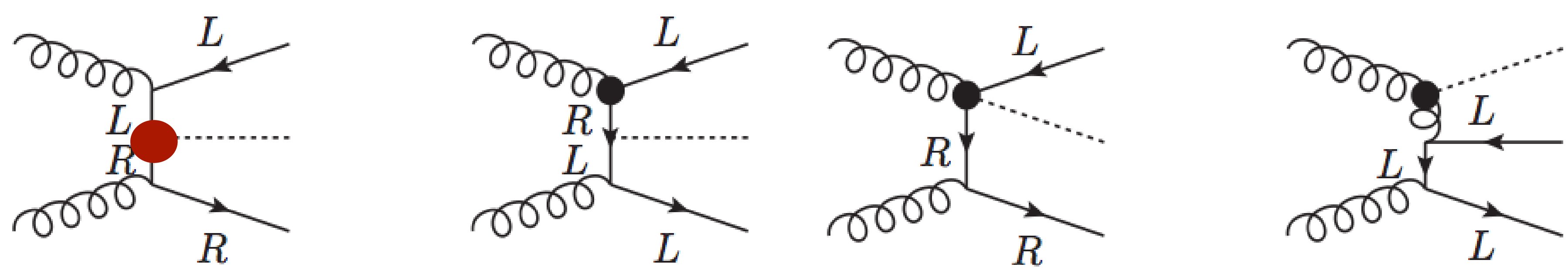




EFT at NLO predictions available, yet SM NLO predictions are needed to control accuracy a precision.

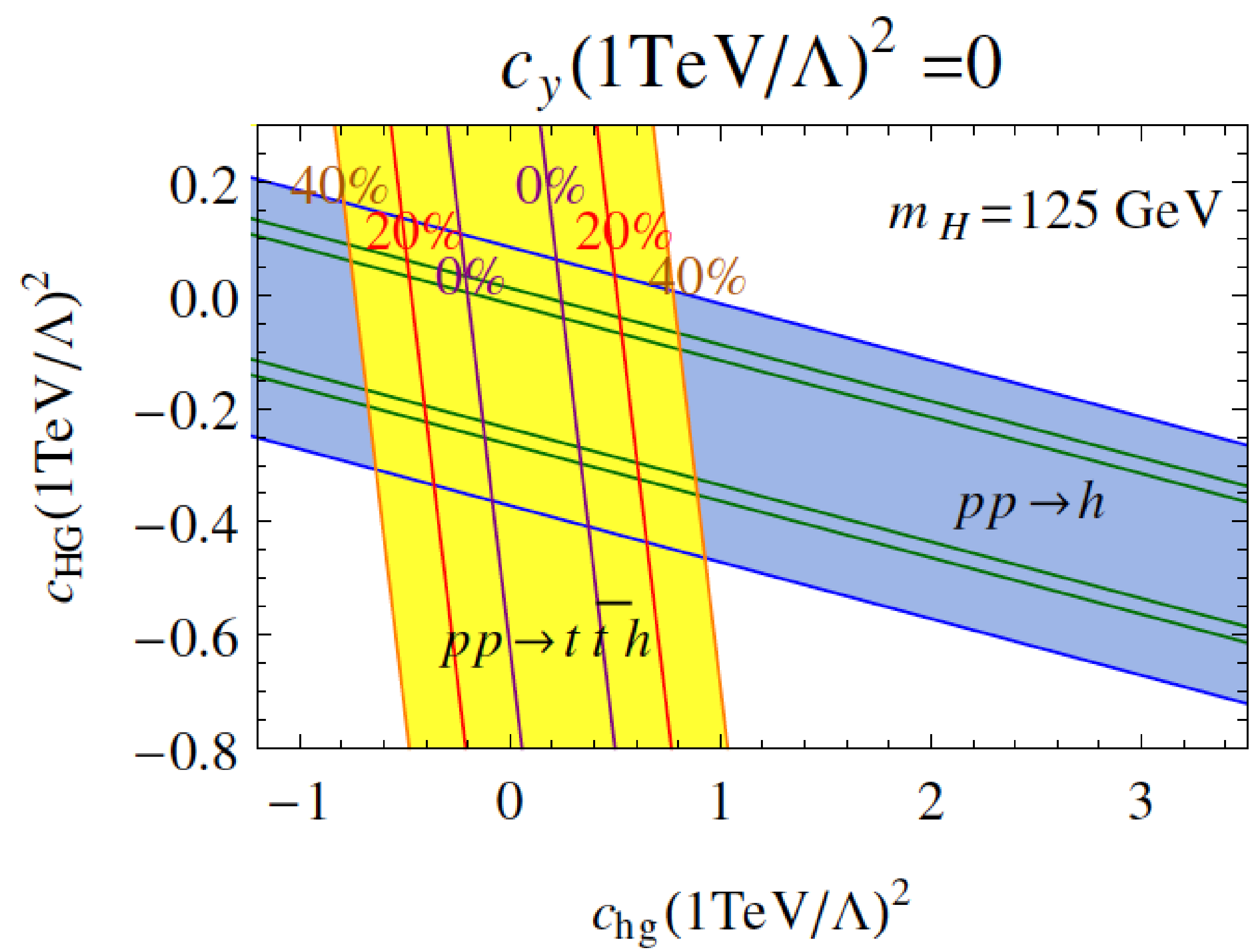
Top-Higgs interactions: ttH

$$pp \to t\bar{t}h$$



[Degrande et al. 2012]

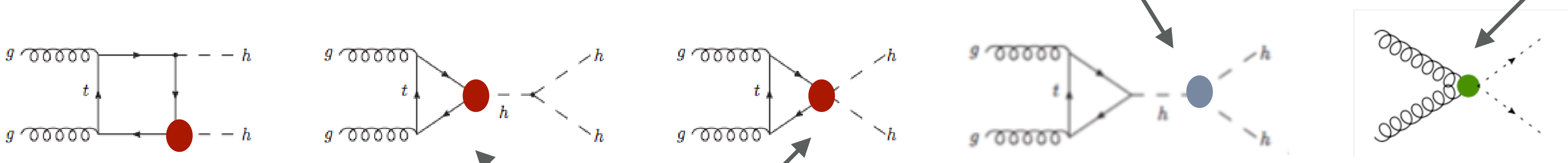
$$
\begin{aligned}
\frac{\sigma\left(pp \to t\bar{t}h\right)}{\text{fb}} = \; & 611^{+92}_{-110} + \left[457^{+127}_{-91}\,\Re c_{hg} - 49^{+15}_{-10}\, c_G \right.\\
& \left. + \, 147^{+55}_{-32}\, c_{HG} - 67^{+23}_{-16}\, c_y\right]\left(\frac{\text{TeV}}{\Lambda}\right)^2 \\
& + \left[543^{+143}_{-123}\,(\Re c_{hg})^2 + 1132^{+323}_{-232}\, c_G^2 \right.\\
& + 85.5^{+73}_{-21}\, c_{HG}^2 + 2^{+0.7}_{-0.5}\, c_y^2 \\
& + 233^{+81}_{-144}\,\Re c_{hg} c_{HG} - 50^{+16}_{-14}\,\Re c_{hg} c_y \\
& \left. - \, 3.2^{+8}_{-8}\,\Re c_{Hy} c_{HG} - 1.2^{+8}_{-8}\, c_H c_{HG}\right]\left(\frac{\text{TeV}}{\Lambda}\right)^4
\end{aligned}
$$



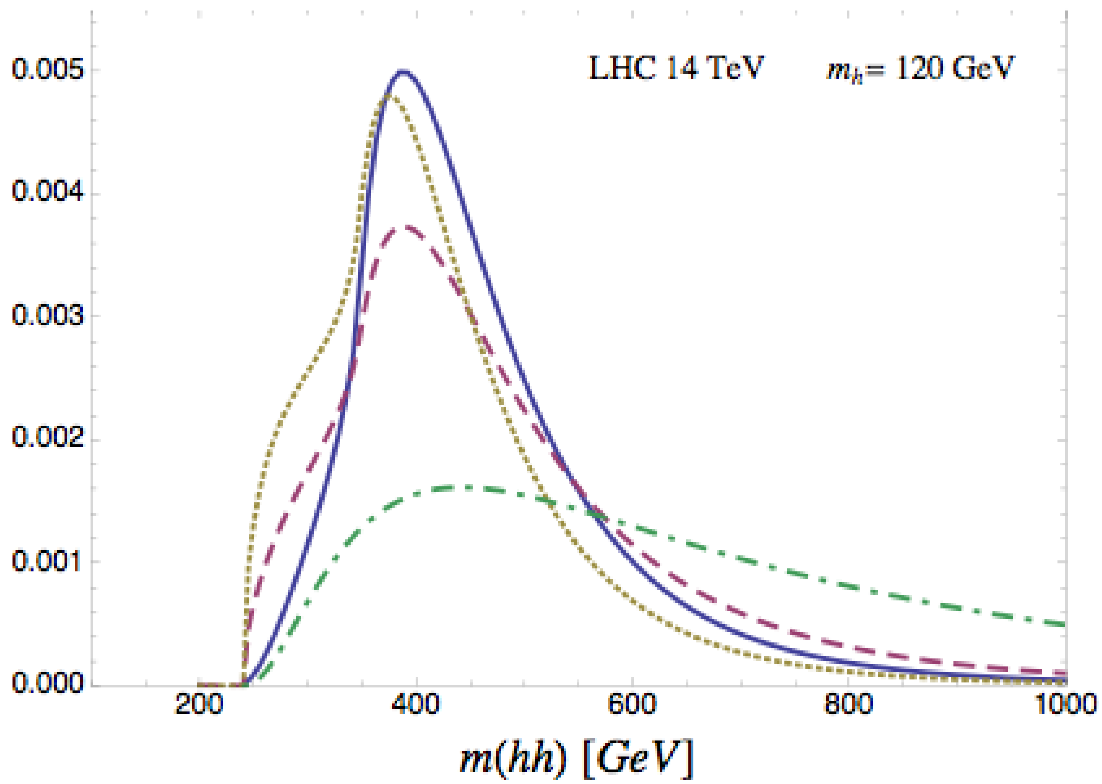
Top-Higgs interactions: HH

$$pp \to hh$$

$$\mathcal{O}_6 = (H^\dagger H)^3 \qquad \mathcal{O}_{HG} = \frac{1}{2} H^\dagger H G^a_{\mu\nu} G^{\mu\nu}_a$$



$$\mathcal{O}_{Hy} = H^\dagger H \left(H \bar{Q}_L\right) t_R$$



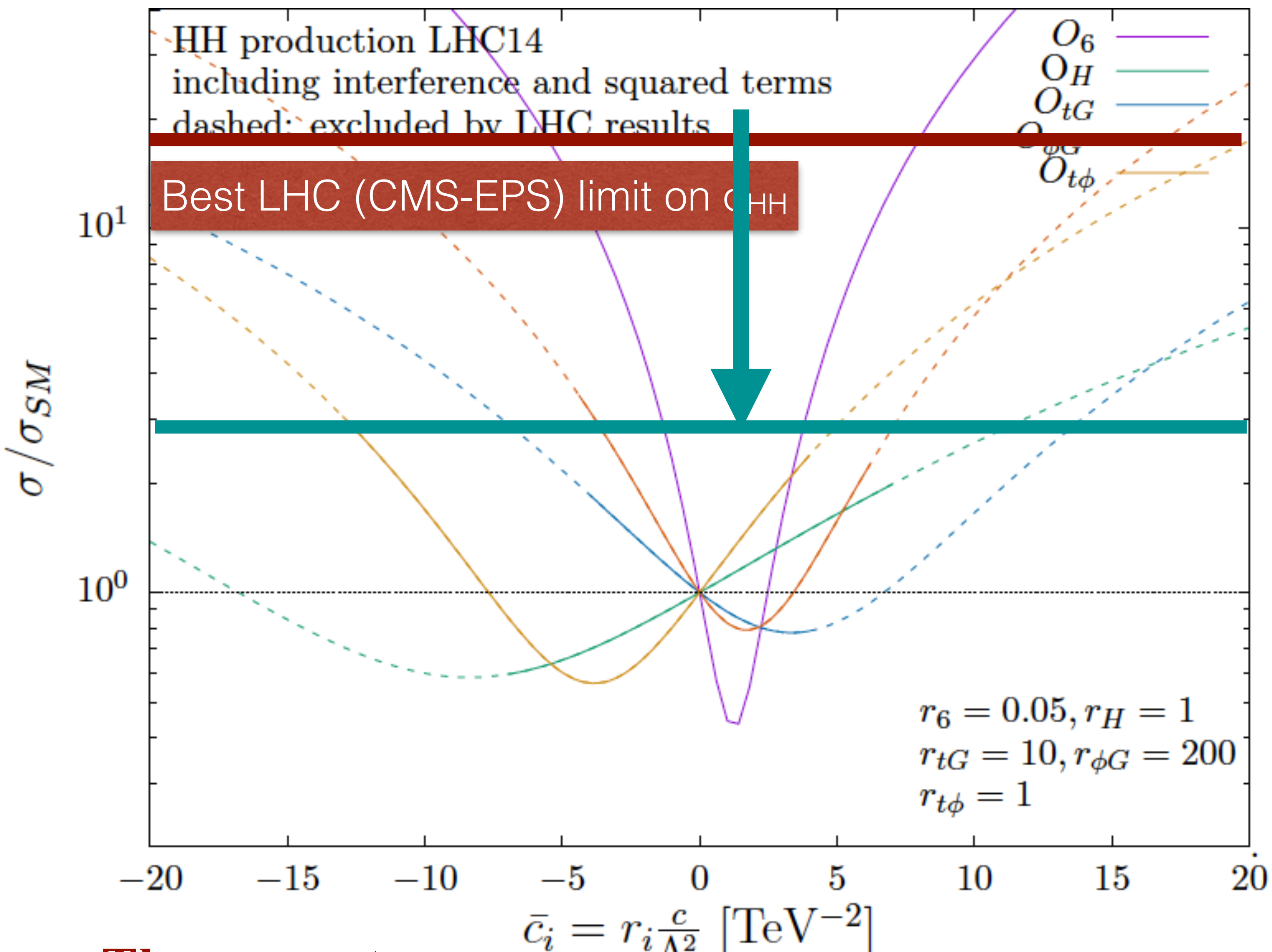
[Contino et al. 2012]

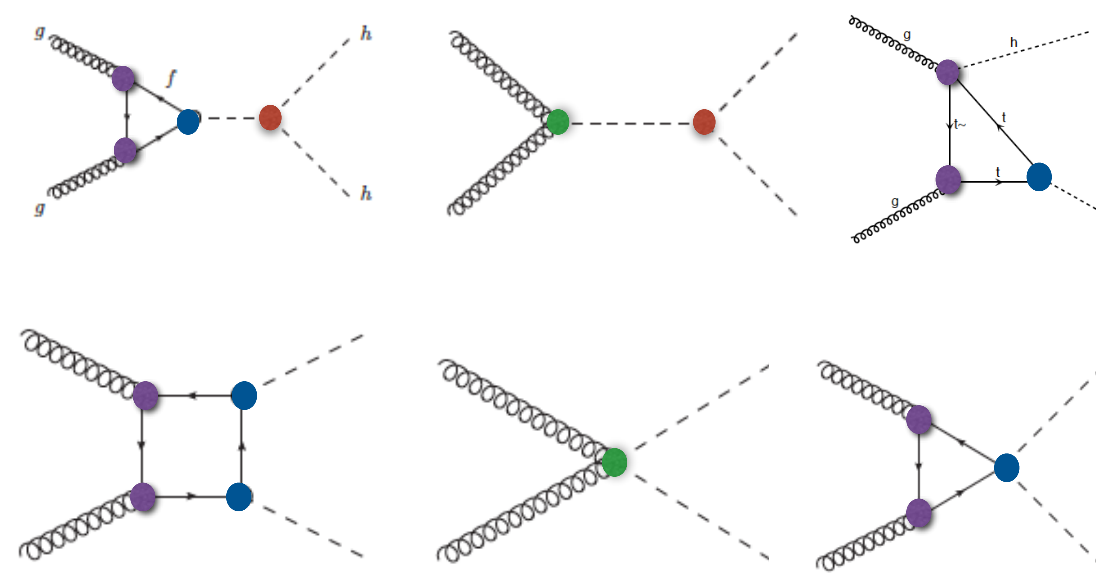
The strong destructive interference gives extra sensitivity of pp→HH to dim=6 operators.

The HHH coupling is modified by two operators of dim=6.

Only a global approach will allow to accurately measure the HHH coupling from HH.

How to extract λ_{HHH} from HH?





Other couplings enter in the same process: top Yukawa, ggh(h) coupling, top-gluon interaction

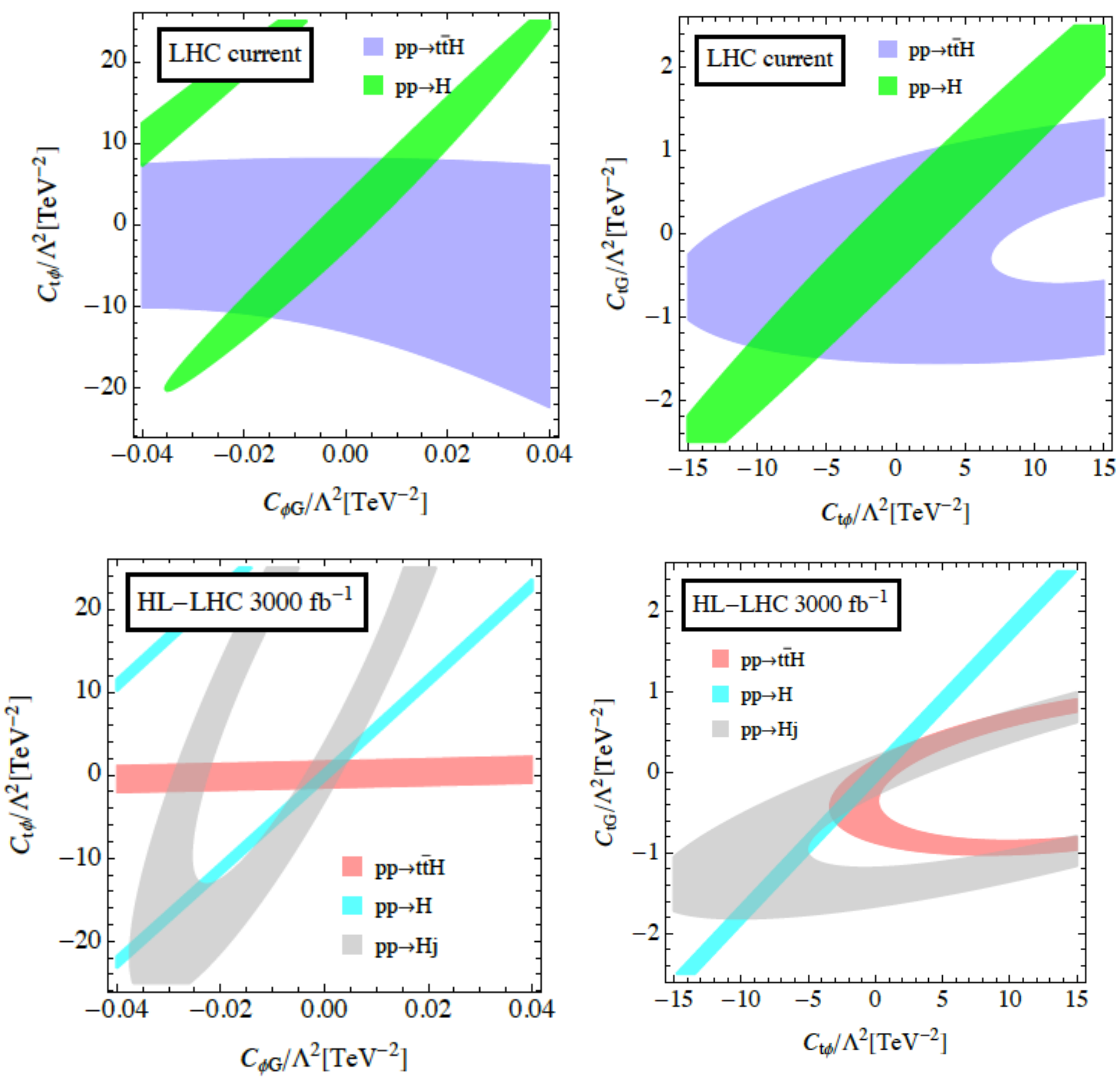
The present

Given the current constraints on σ(HH), σ(H) and the fresh ttH measurement, the Higgs self-coupling can be currently constrained "ignoring" other couplings

The future

Precise knowledge of other Wilson coefficients will be needed to bound λ as the bound gets closer to SM. Differential distributions will also be necessary

Constraints from ttH and Higgs production



Current limits using LHC measurements

$$O_{t\phi} = y_t^3 \left(\phi^\dagger \phi\right) \left(\bar{Q} t\right) \tilde{\phi}$$
$$O_{\phi G} = y_t^2 \left(\phi^\dagger \phi\right) G^A_{\mu\nu} G^{A\mu\nu}$$
$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\phi} G^A_{\mu\nu}$$

14TeV projection

3000 fb-1