BEYOND STANDARD MODEL

Problems of the Standard Model. Search Strategy. Indirect search. Supersymmetry

Lecture 18

DIPARTIMENTO DI FISICA

SAPIENZA
UNIVERSITÀ DI ROMA

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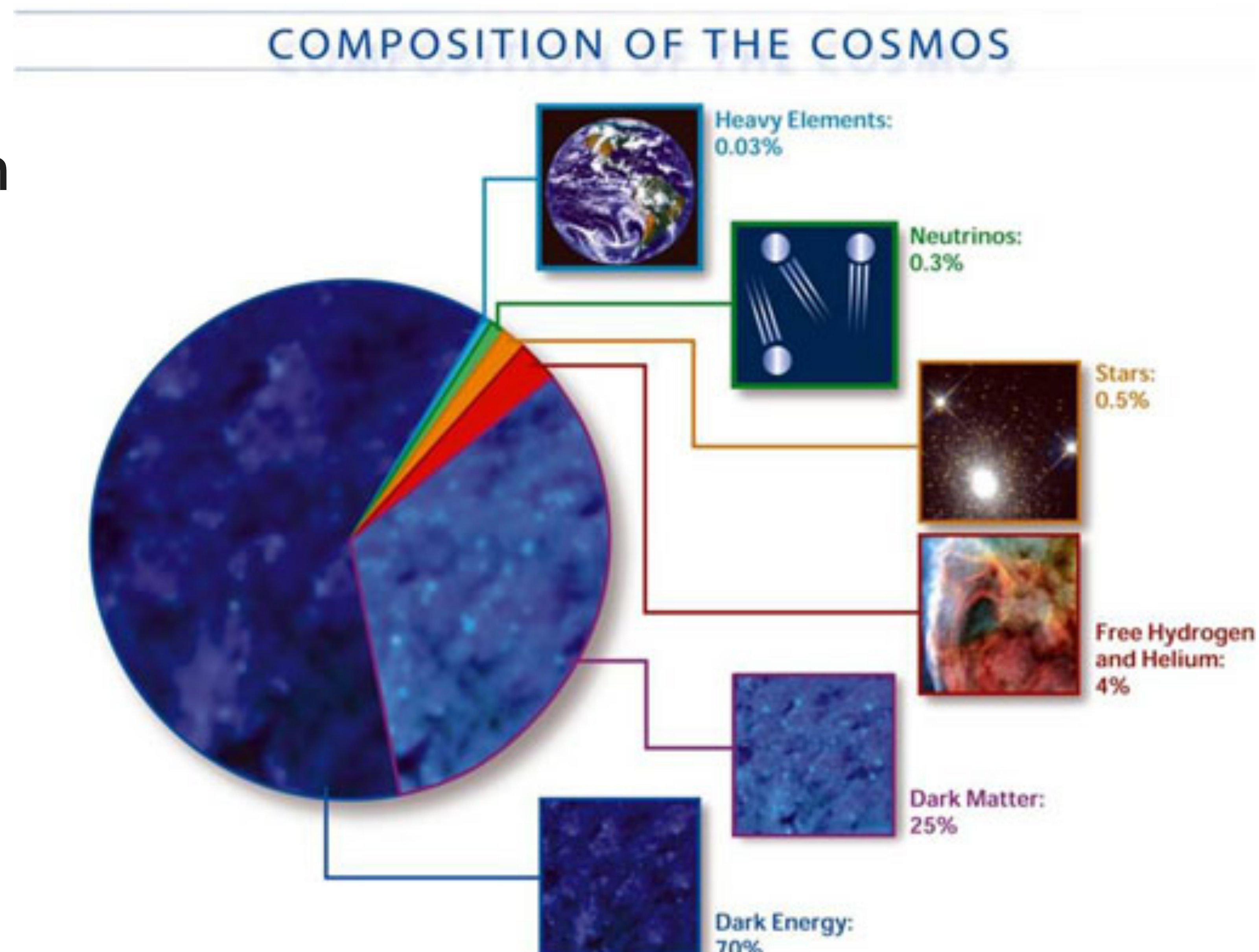
Success of Standard Model

- LEP Precisions measurements have proved SM to be reliable and correct in describing almost all phenomenology so far
- CP violation well described and verified experimentally
- Higgs discovered with mass ~125 GeV compatible with precision tests at LEP
- Neutrinos also integrated well within the Standard Model

- ***Shortcomings of the Standard Model***
  - cannot incorporate gravity
  - cannot survive any attempt at unification of all forces
  - cannot explain why all physics below TeV scale!
  - cannot explain why Higgs mass is so fine-tuned
  - cannot explain what happens up to Planck scale

Hints of New Physics

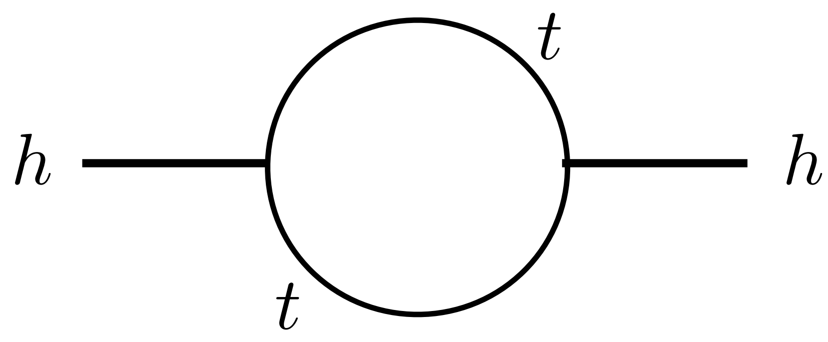
- Neutrinos have very small but non-zero mass
  - so far we have always assumed them to be massless
- Astrophysical proof of existence of cold dark matter and we also need a large amount of yet-to-be-understood dark energy



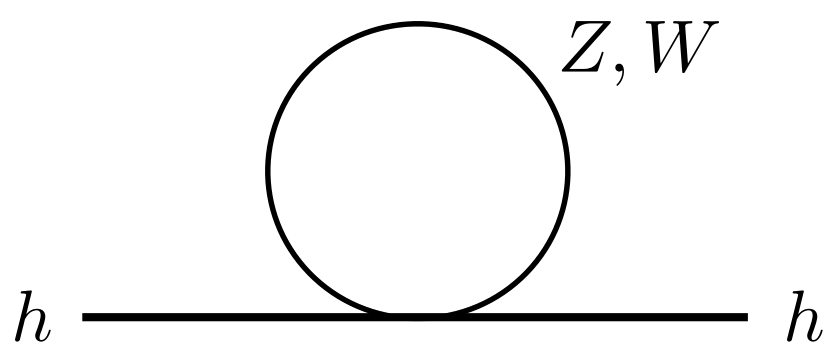
- Still no idea about origin of masses and mixing structure

Corrections To Higgs Mass

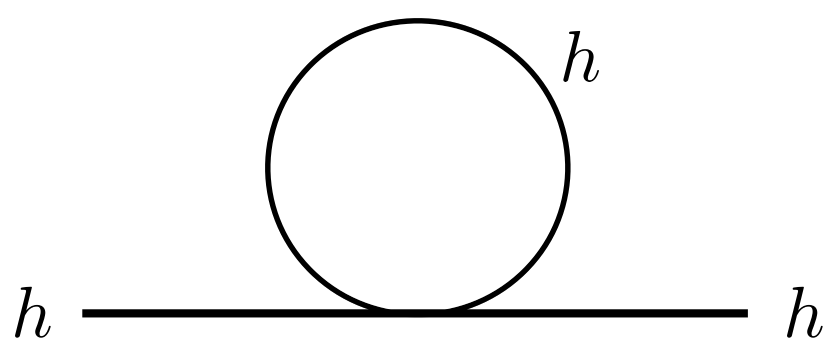
- Propagator of Higgs mass affected by higher order corrections



$$\delta m_h^2 \sim -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$$



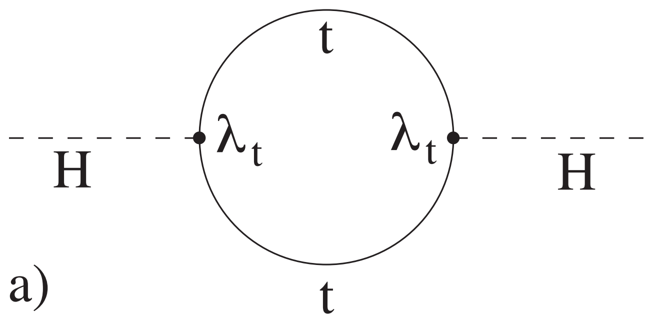
$$\delta m_h^2 \sim \frac{9}{64\pi^2}g^2\Lambda^2$$



$$\delta m_h^2 \sim \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

- Such terms change the bare Higgs mass. Regularization is needed to keep corrections finite

HIGGS PROPAGATOR



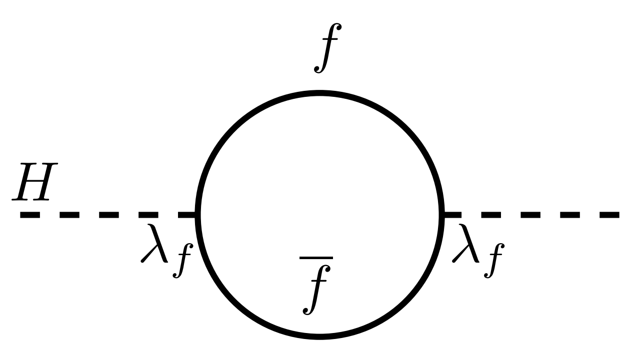
$$
\begin{aligned}
&= \int \frac{d^4p}{(2\pi)^4}(-)N_c \mathrm{Tr}\left[i\lambda_t \frac{i}{\not{p}}\, i\lambda_t \frac{i}{\not{p}}\right] \\
&= -N_c\lambda_t^2 \int \frac{d^4p}{(2\pi)^4} \mathrm{Tr}\left[\frac{1}{p^2}\right] \qquad \mathrm{Tr}\,[1] = 4 \\
&= -\frac{4N_c\lambda_t^2}{(2\pi)^4} \int \frac{d^4p}{p^2}
\end{aligned}
$$

- quadratic divergence with cutoff M_{UV}

HIGGS MASS CORRECTIONS

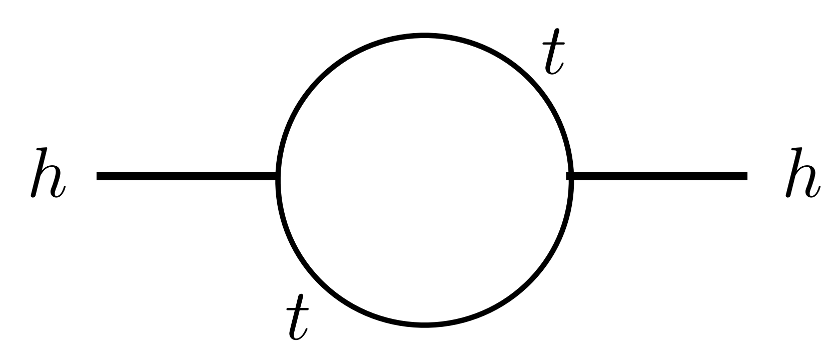
- High energy (UltraViolet) cutoff M_{UV} to regularize corrections
  - M_{UV} is highest energy accessible by known particles
  - For E > M_{UV} new particles enter the loop

- Fermionic corrections depend on fermion mass and coupling to Higgs
  - top contribution by far most dominant



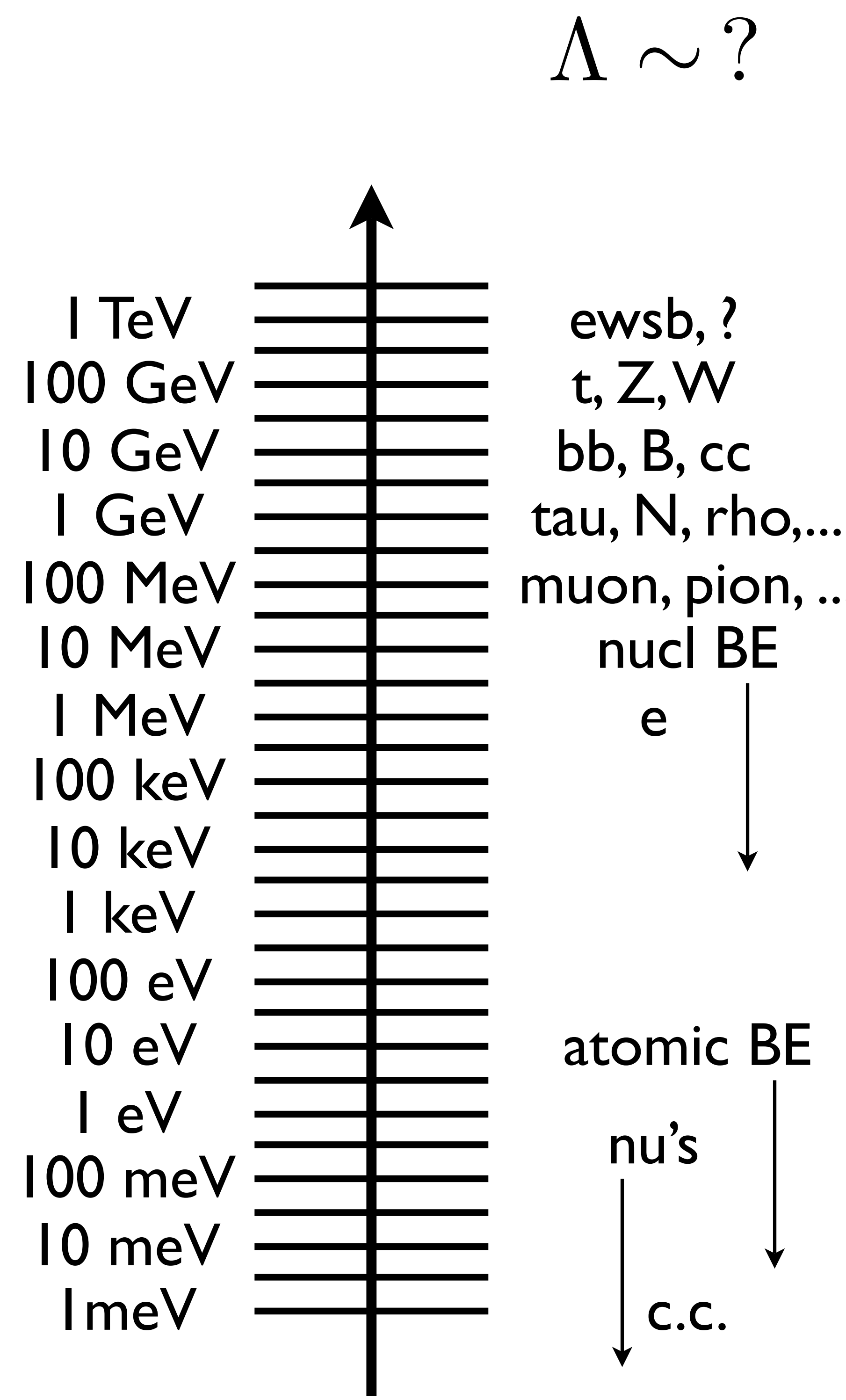
$$\Delta m_H^2 = \frac{\lambda_f^2}{16\pi^2}\left[-2M_{\mathrm{UV}}^2 + 6m_f^2 \ln\left(M_{\mathrm{UV}}/m_f\right) + \ldots\right]$$

- Higgs mass is sensitive to highest energy scale in the theory
- Divergences in Higgs mass if M_{UV} too large
- How can we determine the energy scale?

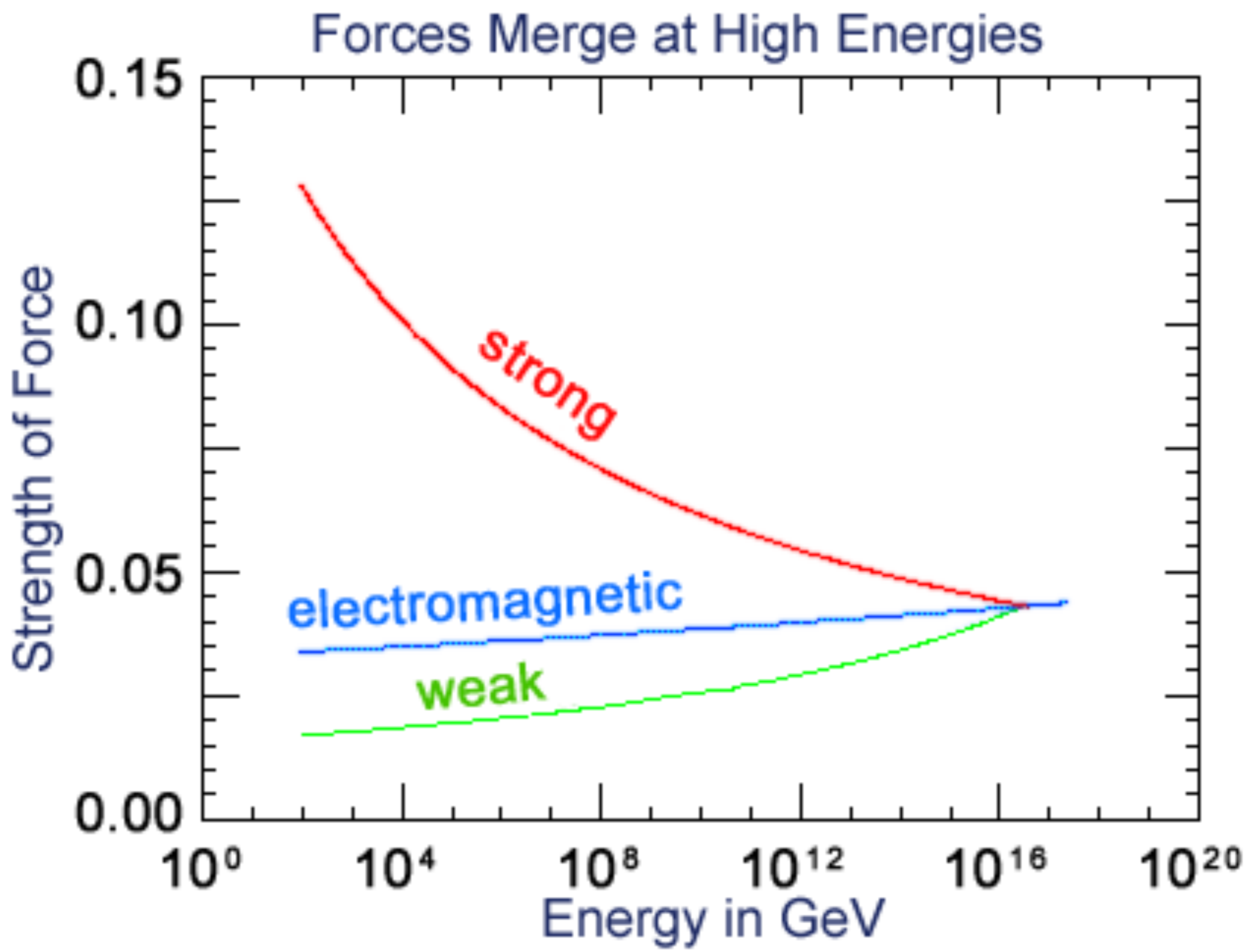


SCALE FOR NEW PHYSICS?

- Since birth of particle physics experiments have explored many orders of magnitude in energy
- Different phenomena have appeared at different scales
- Standard Model and EW breaking occurs up to TeV scale
- How to determine scale of new physics beyond SM ?



Grand Unification



- Running of coupling constants leads to unification of different forces at very high energy scale
- Gravity also can be included at Planck scale

Planck Scale

- Mass with same Compton wavelength and Schwarzschild radius
- Compton wavelength: defines length scale where quantum mechanics must be used
  - decreases with for lager mass
  - e.g. for a photon the corpuscular nature of light becomes relevant

$$E = mc^2 = \hbar\nu \to mc^2 = \frac{\hbar c}{\lambda_c} \to \lambda_c = \frac{\hbar}{mc^2}$$

- Schwarzschild radius is the radius in which a confined mass object becomes a black hole
  - classically radius such that escape velocity equal to speed of light
  - increases for larger mass

$$\frac{1}{2}\cancel{M}v^2 = \frac{G\cancel{M}m}{r} \to r_S = \frac{2Gm}{c^2}$$

- Planck mass or scale defines the scale at which quantum and gravitational effects are both relevant and comparable

$$m_P = \sqrt{\frac{c\hbar}{G}} = 1.2 \cdot 10^{19}\,\mathrm{GeV/c^2}$$

$$\ell_P = \frac{\hbar}{m_P c} = \sqrt{\frac{\hbar G}{c^3}} = 1.6 \cdot 10^{-35}\,\mathrm{m}$$

$$t_P = \ell_P / c = \sqrt{G\hbar / c^5} = 5.4 \cdot 10^{-44}\,\mathrm{s}$$

Naturalness or Fine-Tuning Problem

$$m_h^2 \sim m_{h0}^2 + \delta m_h^2$$

- We know that m_h = 125 GeV
- Nature sets m_{h0} at Planck scale and we observe the physical mass after all higher order correction terms
- For Higgs mass to be finite at EW scale, corrections must balance the bare mass over 16 order of magnitude
- This is not a consistency problem for the theory but **requires incredible fine-tuning of parameters** to achieve such precise cancellation
- Such accidental features although possible are extremely unlikely
- Nature generally prefers rules and symmetries to accidents

What is a Natural Scale?

- We could afford corrections of the order of the Higgs mass
  - fermion mass corrections are proportional to their mass
    - approximate chiral symmetry

- If M_{UV} = 1 TeV the Higgs mass fine tuning would be natural

- This implies that new particles and processes to be discovered at LHC!

Yet Another Headache: Hierarchy Problem

- Plank scale occurs 16 orders of magnitude higher than Standard Model
  - Λ_{pl} >> EW scale
- Almost all known phenomena so far occur within TeV scale
- Past experience tells us that going up in energy scale we find new phenomena
- Such a desert in energy scale is very unlikely and hard to explain
- This is known as the hierarchy problem
  - Huge energy gap between new physics scale and electroweak scale
- LHC will explore the gap by searching for signatures and phenomena not predicted by Standard Model at TeV scale

Search Strategies

- Indirect Searches
  - New physics by observing deviations from predictions
  - Enhanced decay and production rates due to new particles in loops
    - $B_s \rightarrow \mu\mu$ branching ratio
- Supersymmetry
  - complete theory with *few* free parameters
  - scan parameter space
  - Rich and well defined phenomenology
  - Well defined Higgs sector
- Direct search for exotic particles
  - kinematic observables or mass of new particles
  - Many models and many signatures
  - No comprehensive theory
  - very good signal to noise

$B_s \rightarrow \mu\mu$

B Production at Hadron Colliders

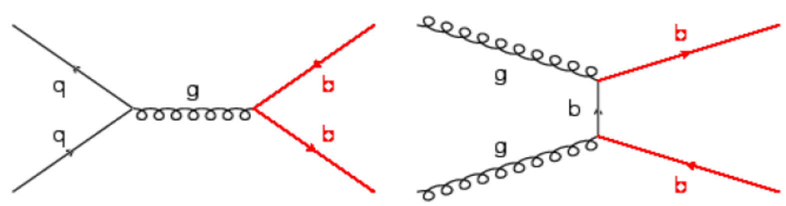
- At B factor xsec ~ 1 nb

$$\sigma = N_c Q_f^2 \frac{4\pi\alpha^2}{3s} = N_c Q_f^2 \frac{86.8\ \mathrm{nb}}{s\,(\mathrm{GeV}^2)}$$

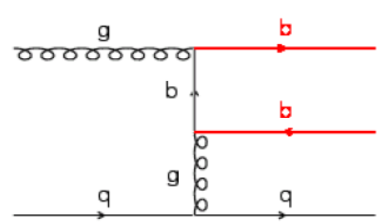
- At LHC @ 7 TeV xsec ~ 0.3 mb

$$\frac{d\sigma}{d\Omega}(q\bar{q}, gg \to q\bar{q}) \sim \frac{\alpha_s^2}{s}$$

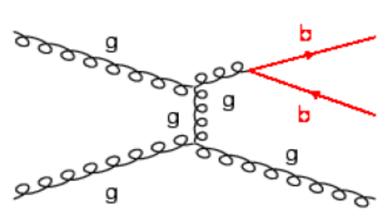
Lowest order

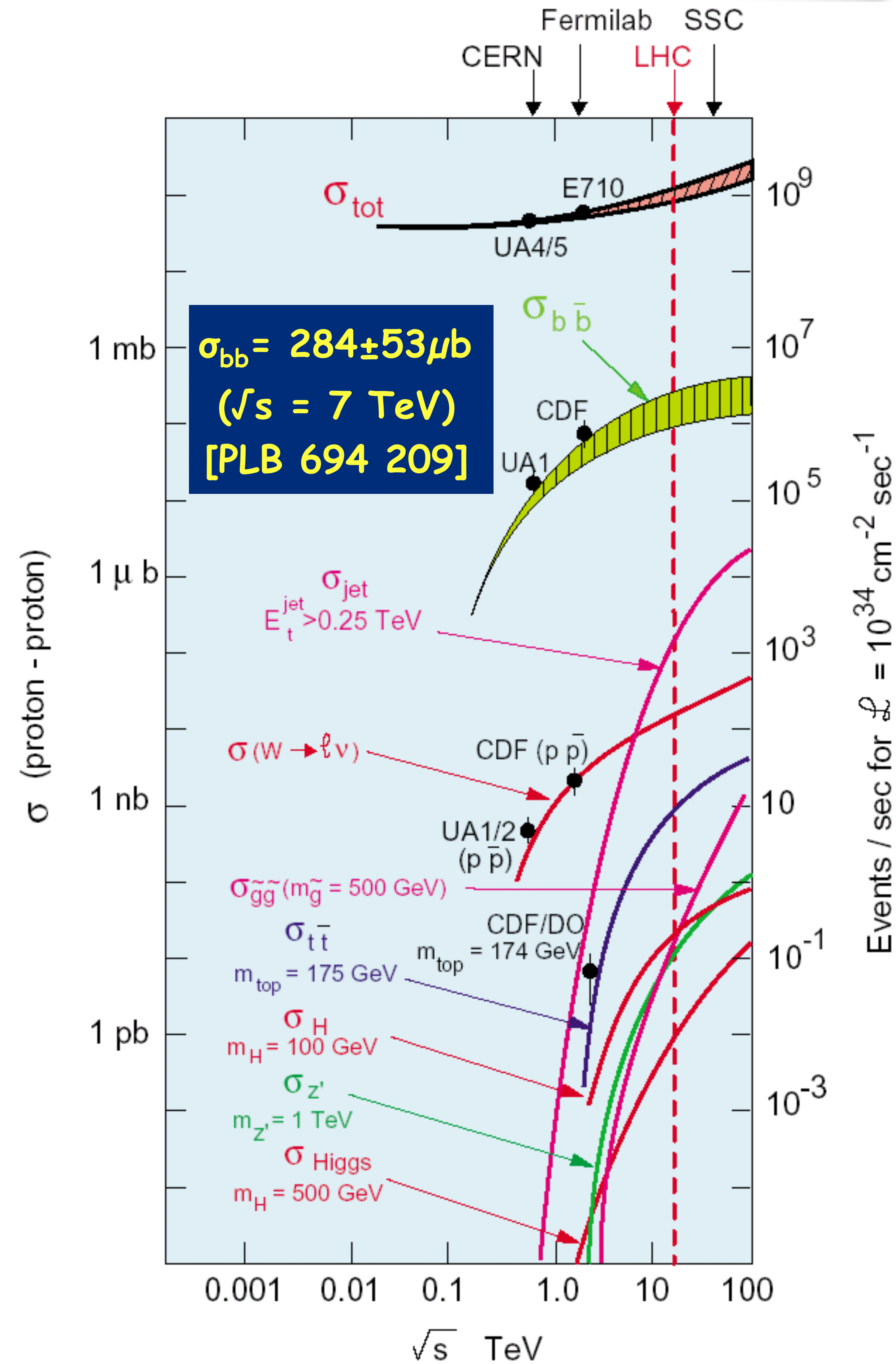


Flavor excitation

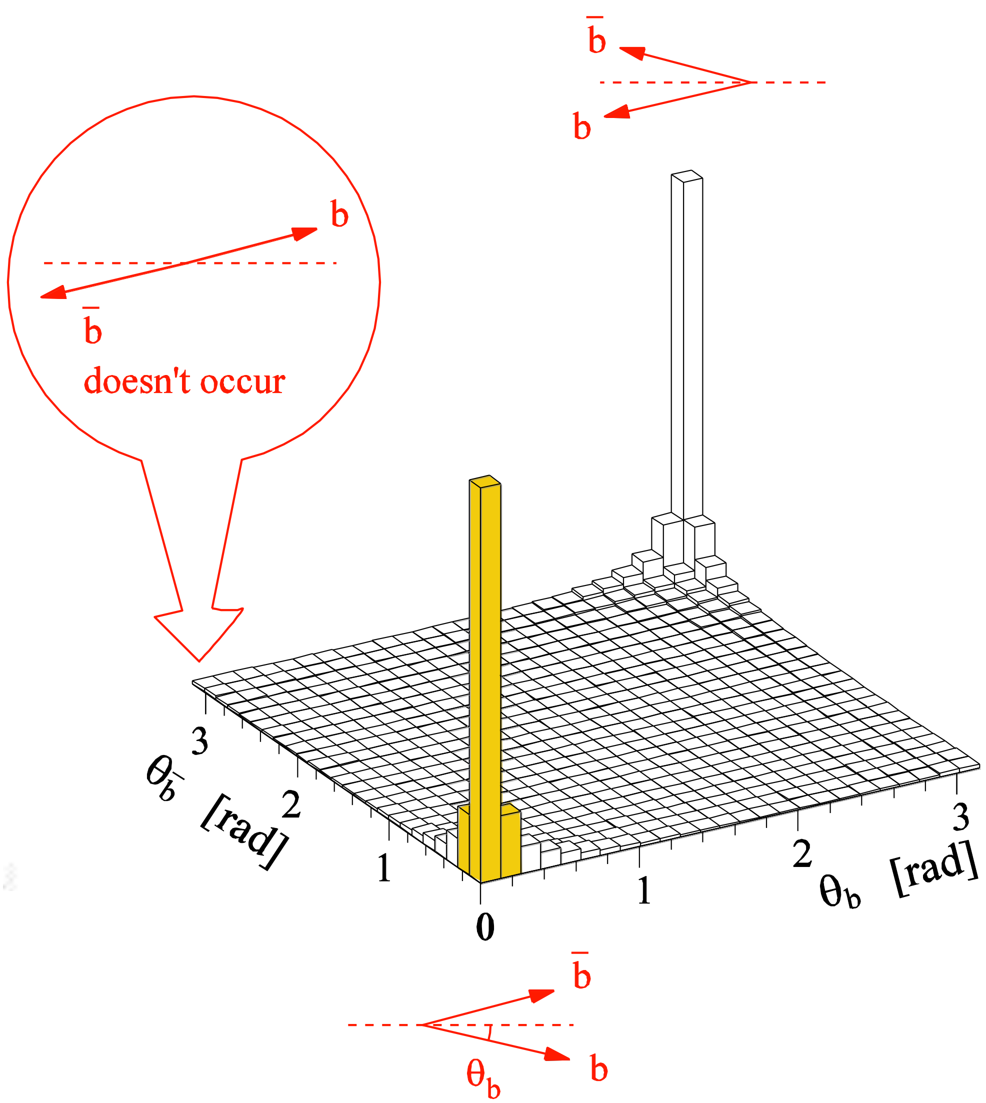


Gluon splitting



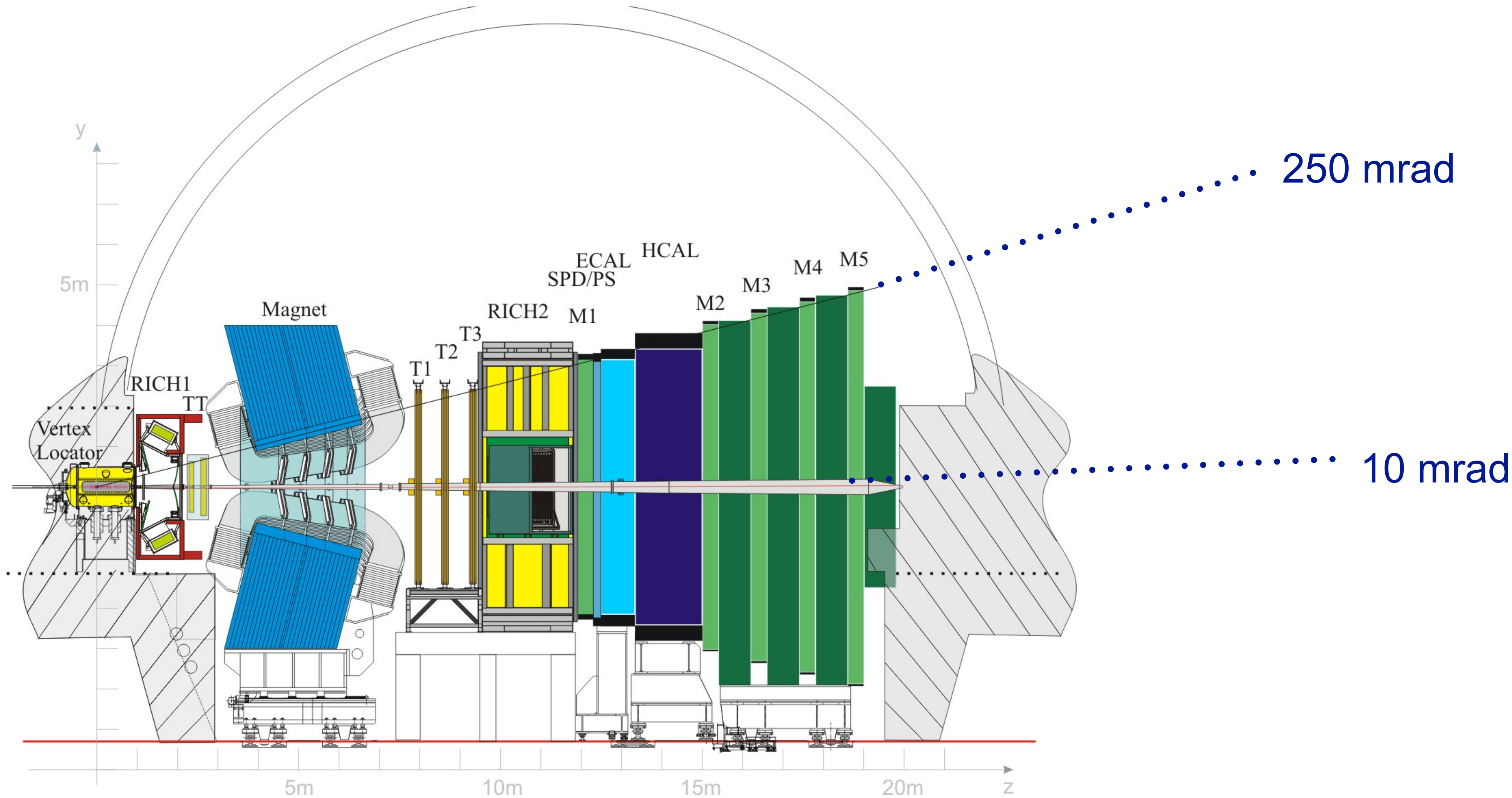


b Production Topology



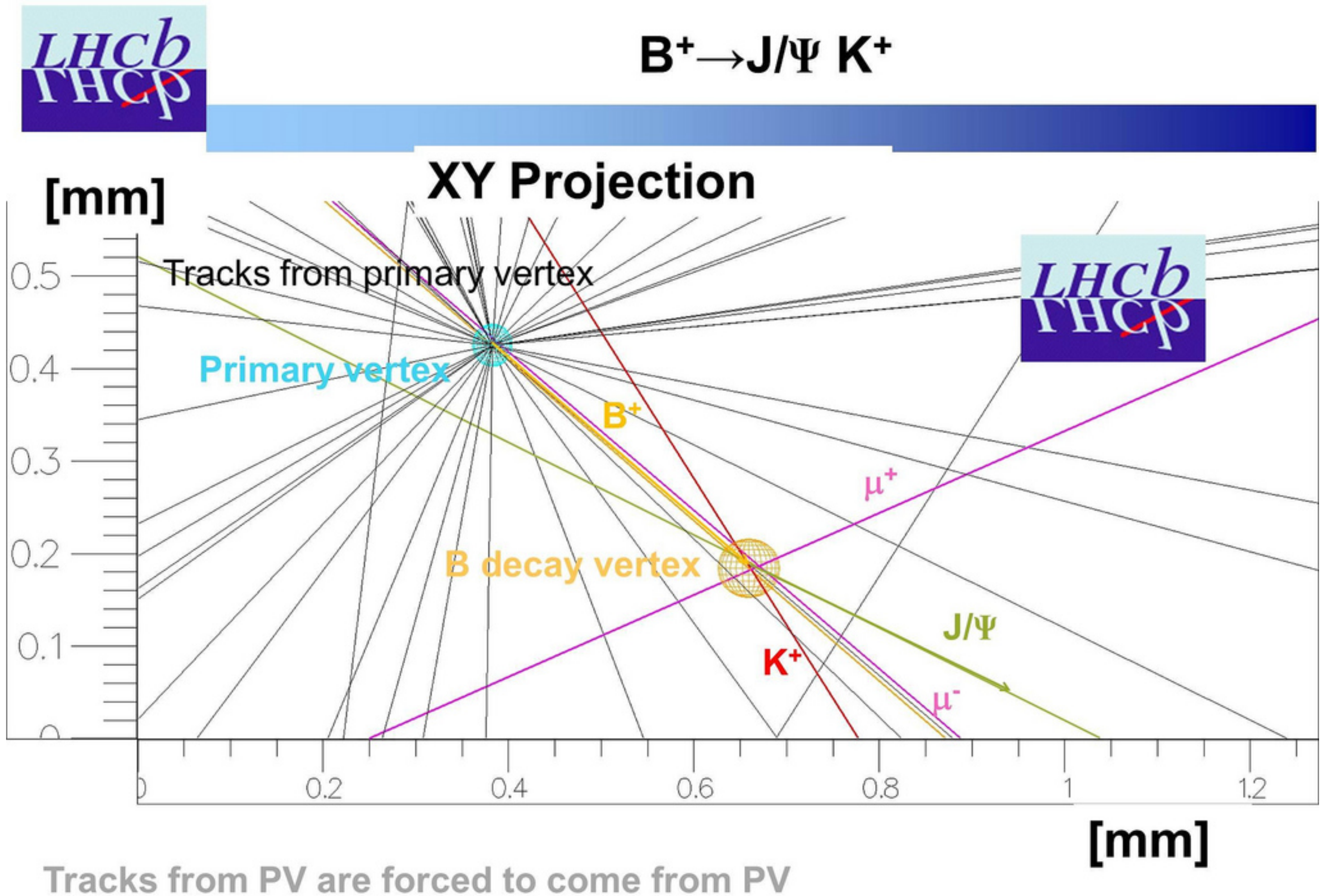
- Events of interest almost exclusively in forward region
  - Need excellent coverage at high η
- All flavors of b hadrons produced
  - Relative production ratio: $B_d/B_u/B_s/B_c$/b-baryons 4:4:1:0.01:1

LHCb Detector



- Dedicated detector covering 2< η < 5 region
  - Measurements also with ATLAS and CMS
- Extremely competitive for states with charged tracks but no access to neutrino
  - no semileptonic decays

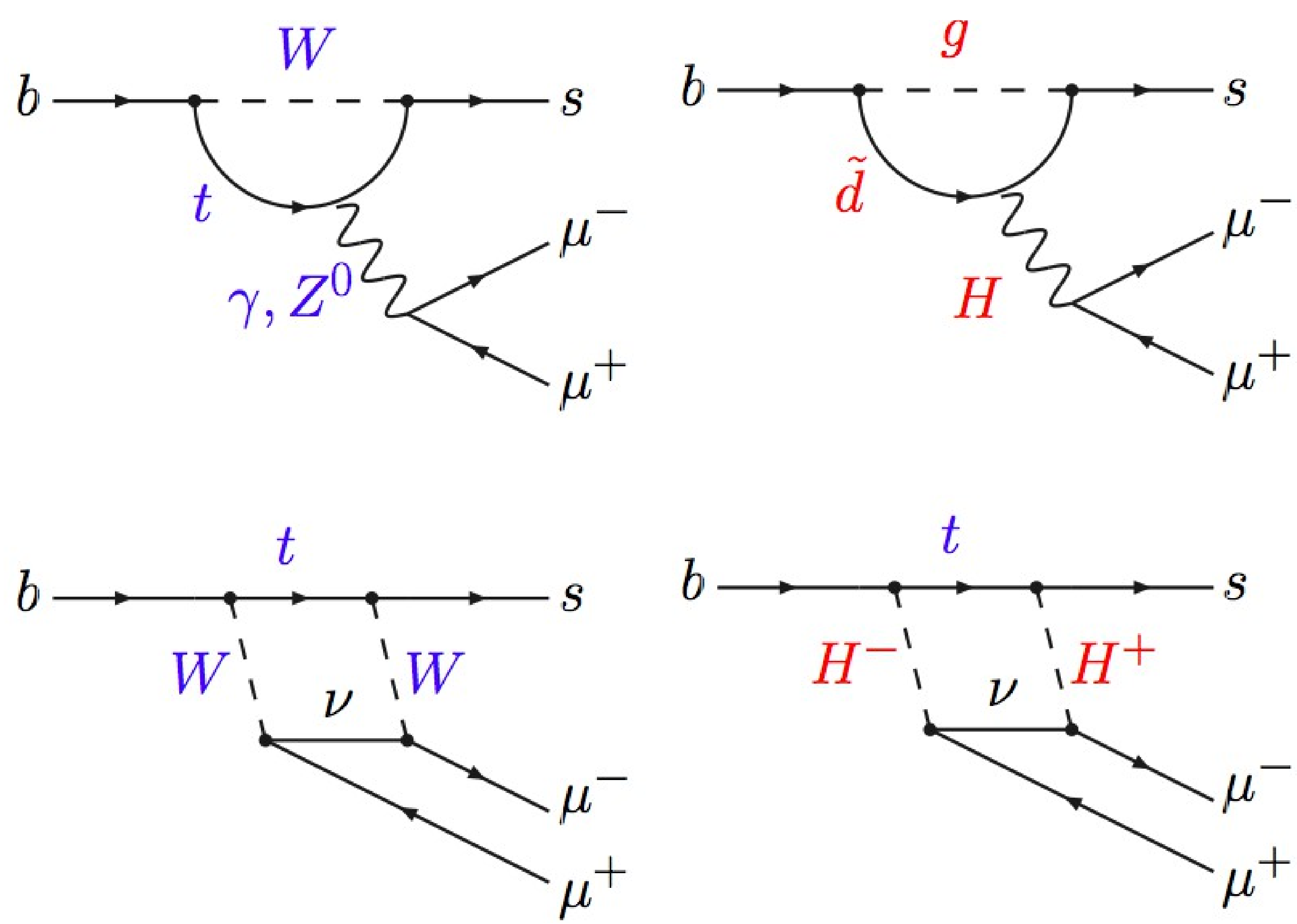
FLIGHT LENGTH



- Large impact parameters and very displaced secondary vertex
  - Large boost and flight length of ~ 1 cm
    - compare to 250 microns at B factory

$B_s \rightarrow \mu\mu$

- Rare B decay in Standard Model

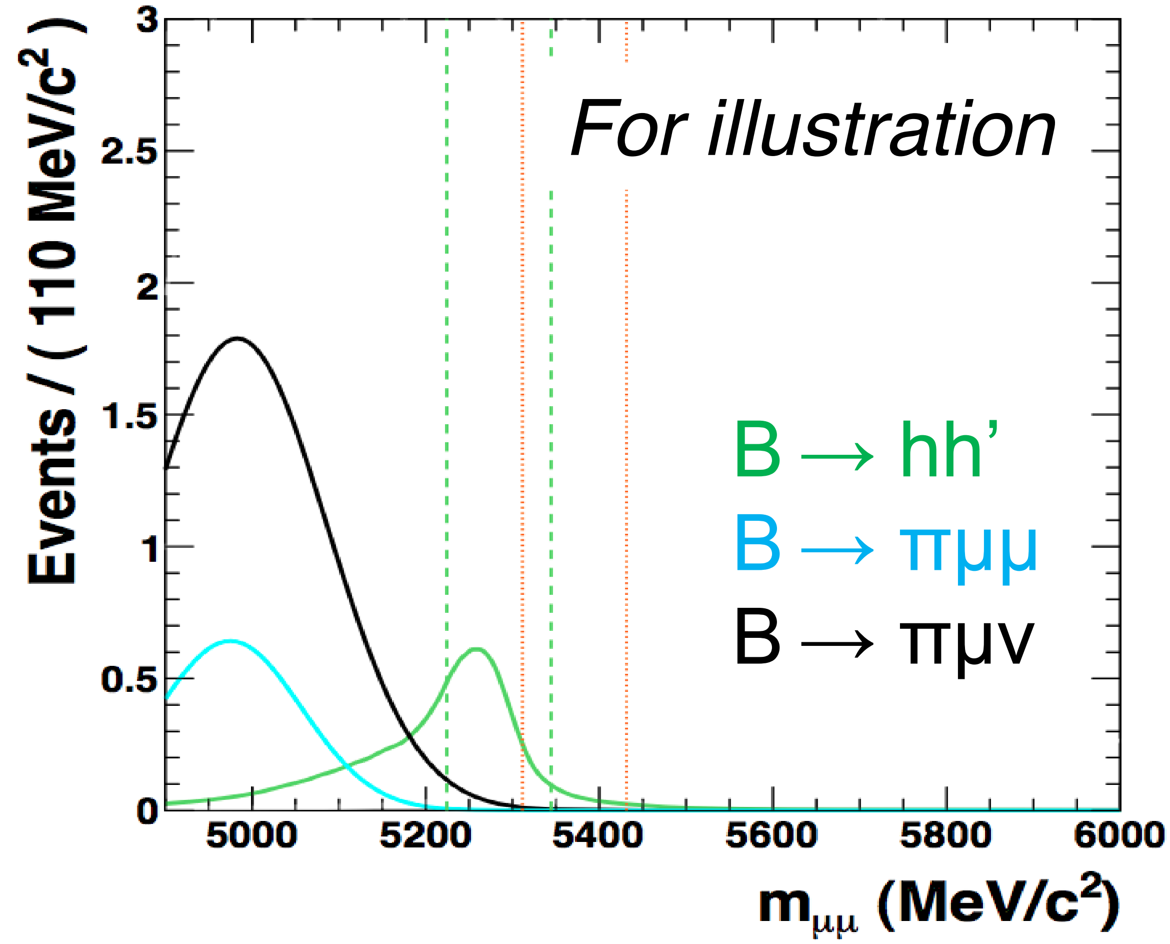


$$B_s \to \mu^+\mu^- = (3.2 \pm 0.2) \times 10^{-9}$$
$$B_d \to \mu^+\mu^- = (1.0 \pm 0.1) \times 10^{-10}$$

BACKGROUNDS

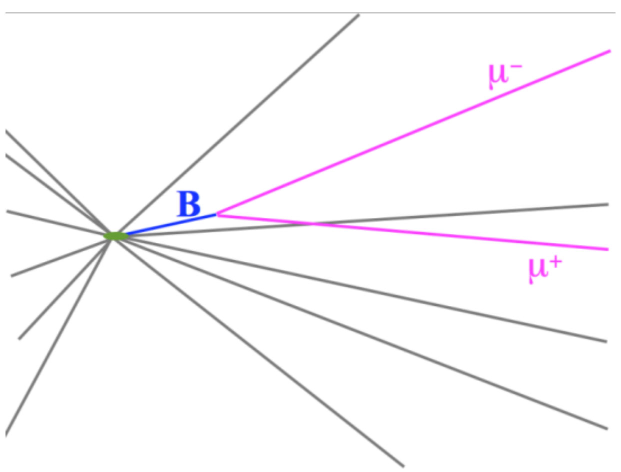
$B^0 \to \pi^- \mu^+ \nu$
$B_s \to K^- \mu^+ \nu$
$\Lambda_b \to p \mu \nu$

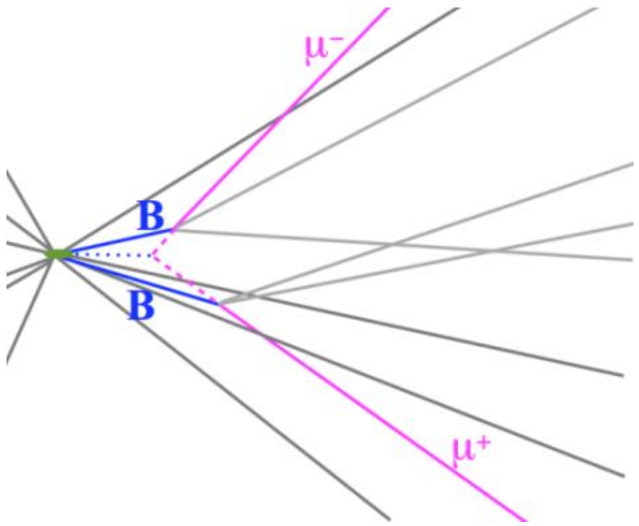
$B^{0/+} \to \pi^{0/+} \mu\mu$
$B_c \to J/\psi(\mu\mu)\, \mu\nu$



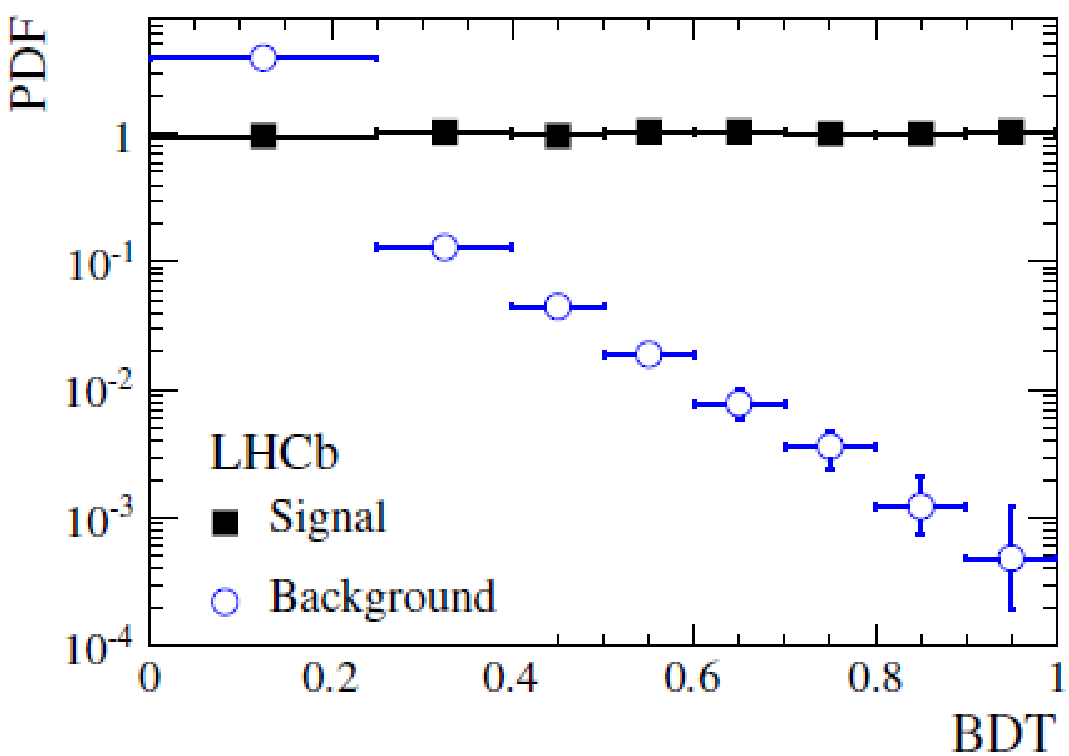
- 2 real muons
- 1 real muon and 1 fake muon
- But also two fake muons: very small BF for signal!

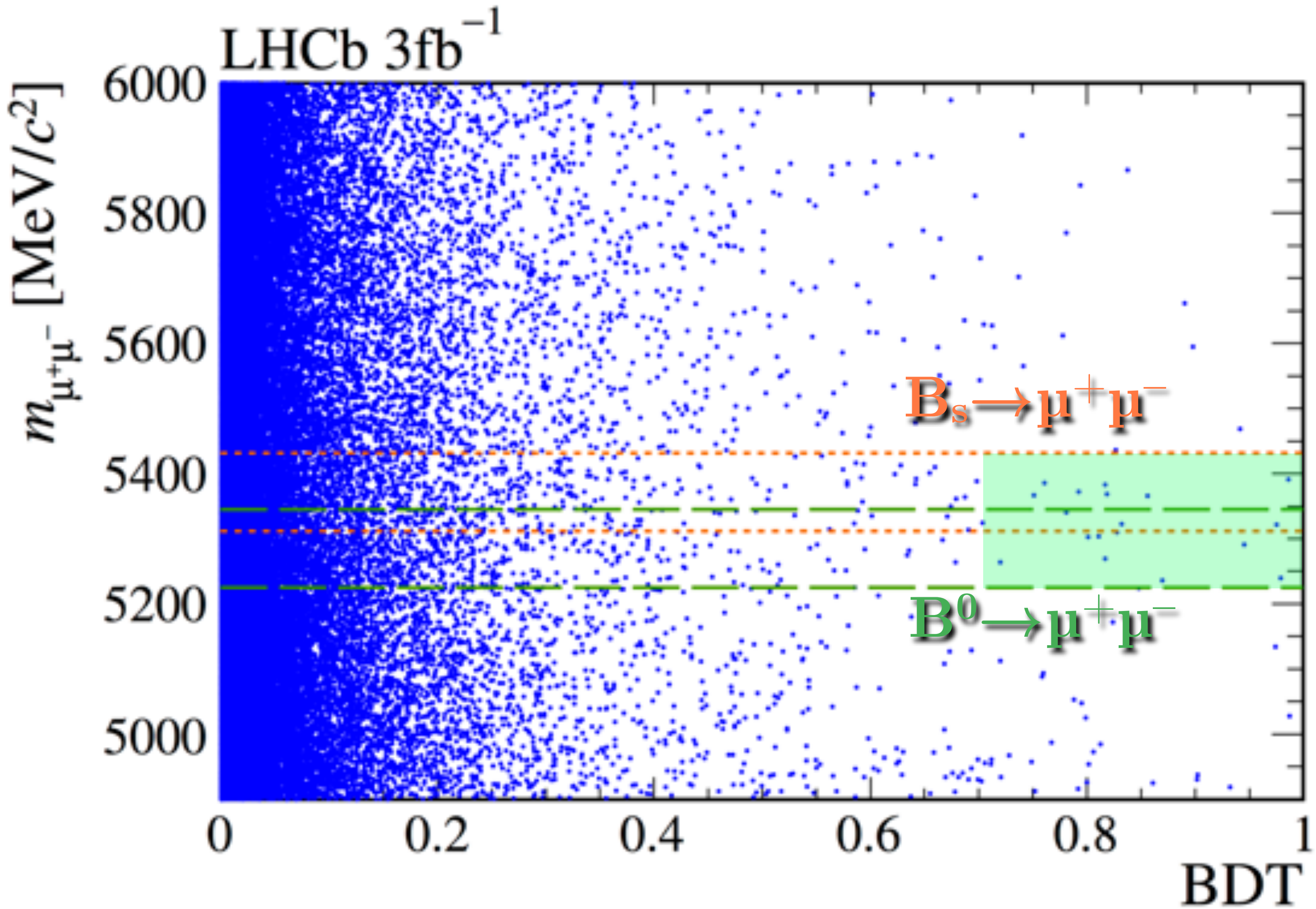
BACKGROUND REJECTION



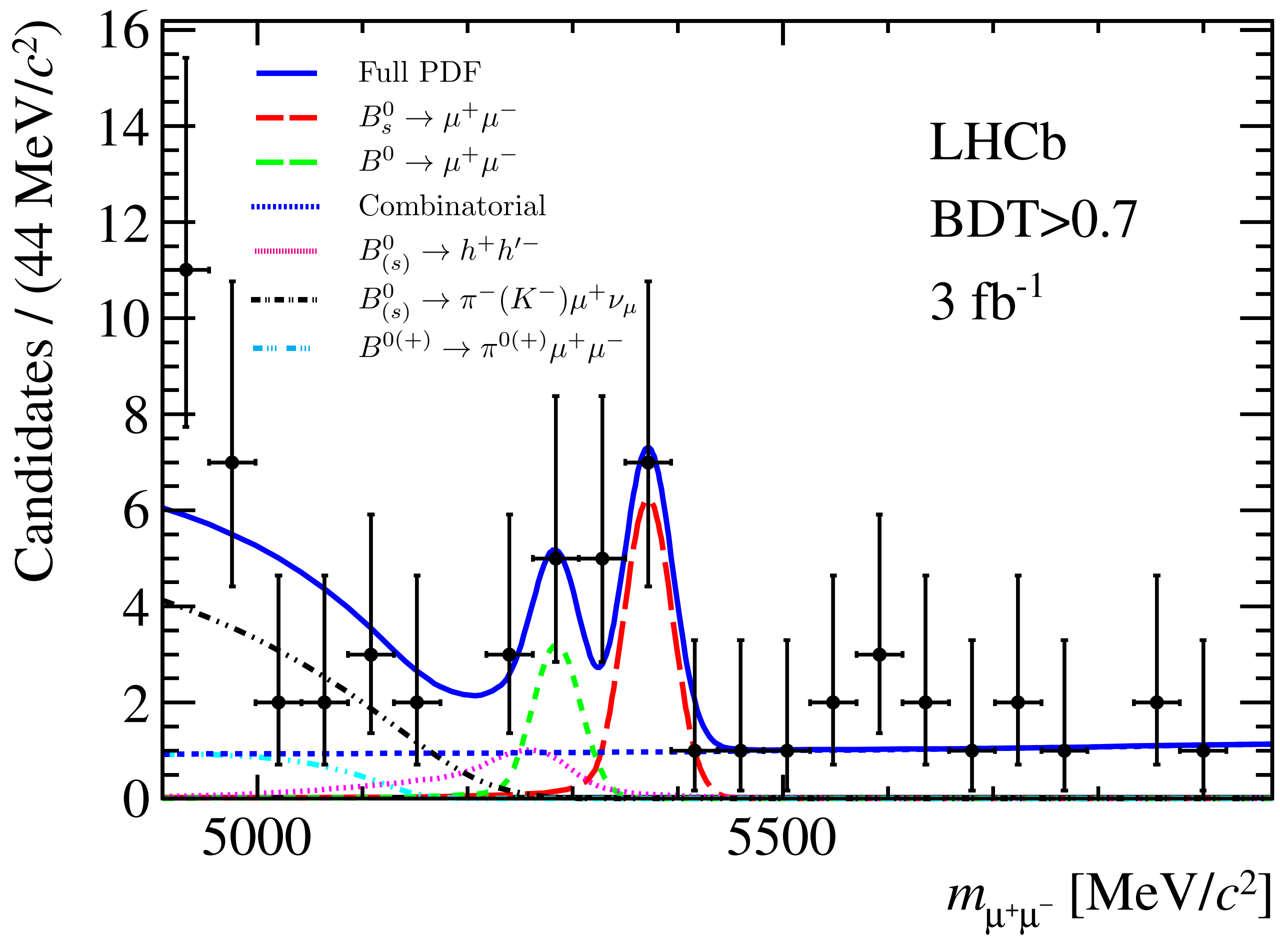


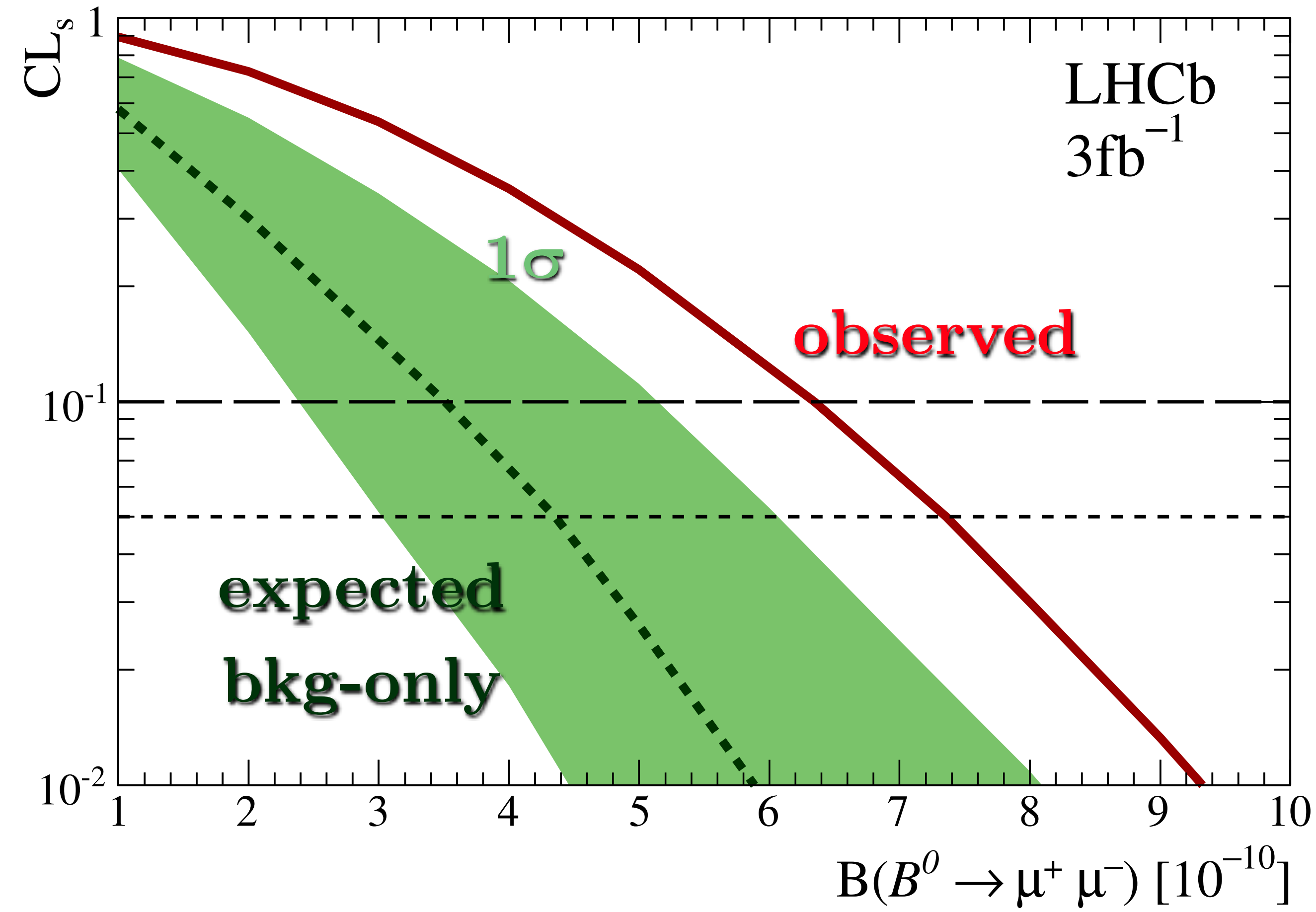
- Combination of two muons from different B mesons
- Multivariate tools to combine information and maximize background rejection
  - total of 12 B and muon variables
    - impact parameter of muon tracks
    - muon isolation
    - p_T of B
- Use each bin as a separate channel since different S/B
  - maximize power of each bin




LHCb 3fb^{-1}
$m_{\mu^+\mu^-}$ [MeV/c^2]
6000
5800
5600
5400
5200
5000
0
0.2
0.4
0.6
0.8
1
BDT
$B_s \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$

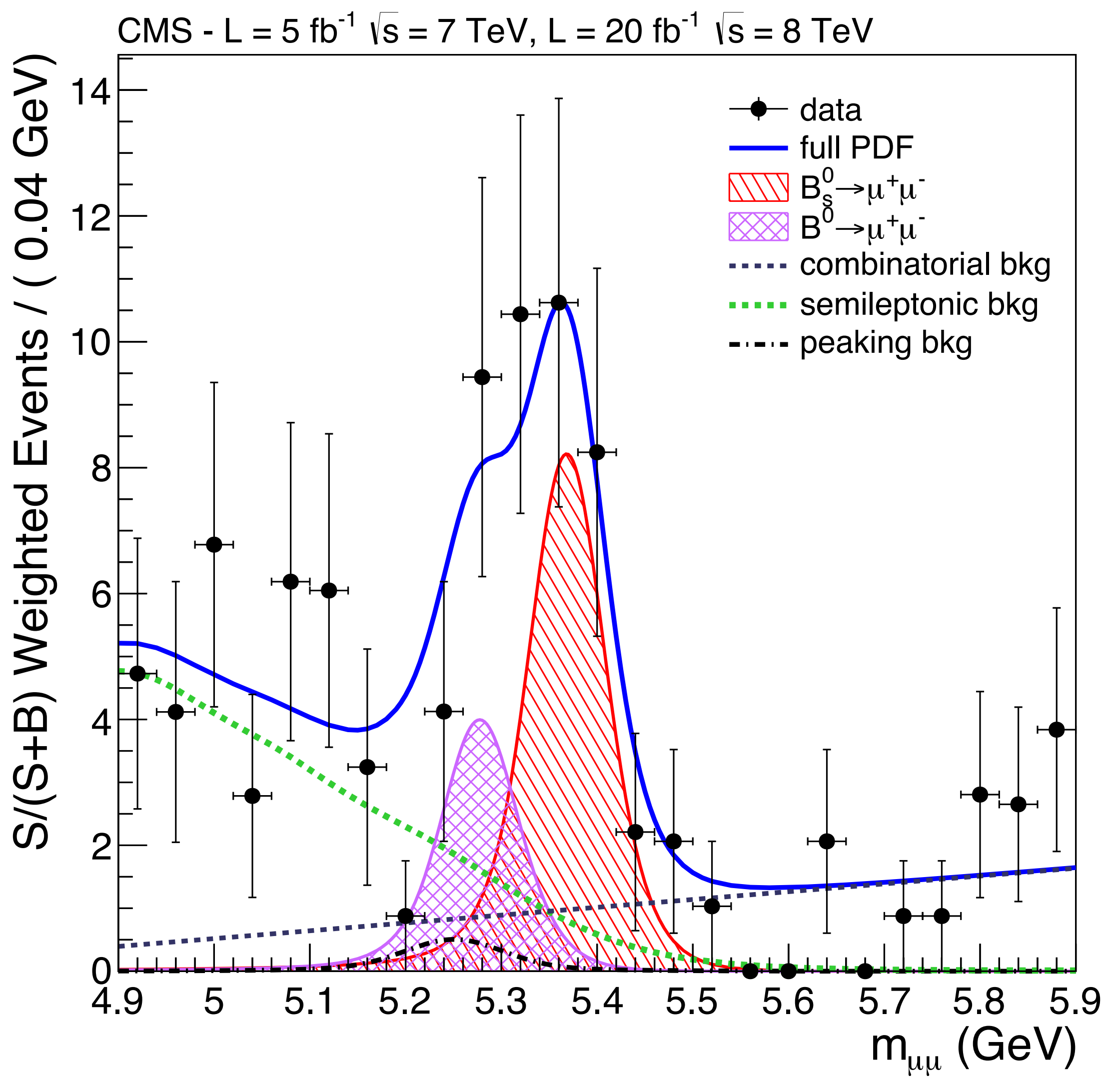
Evidence at LHCb

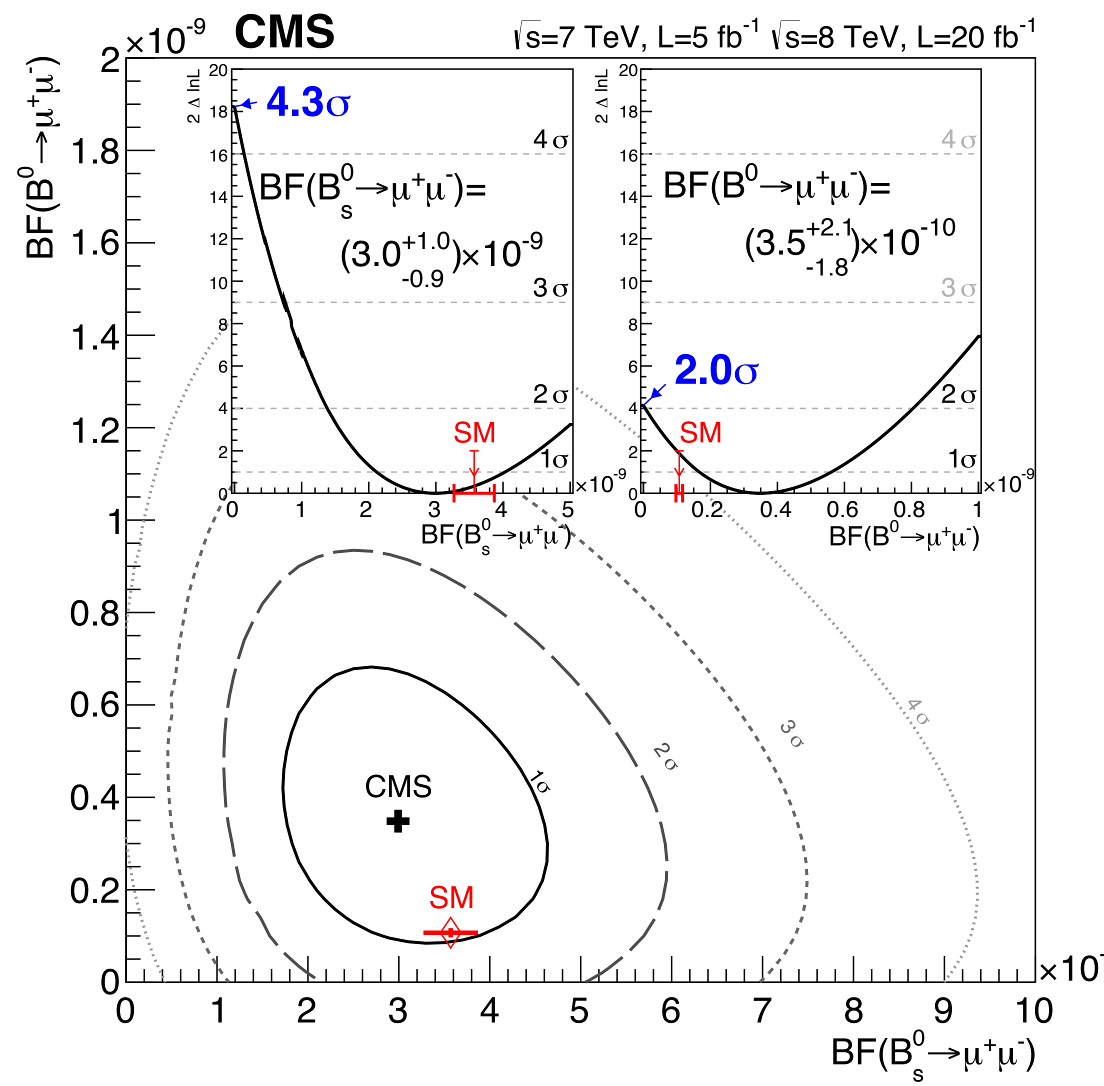




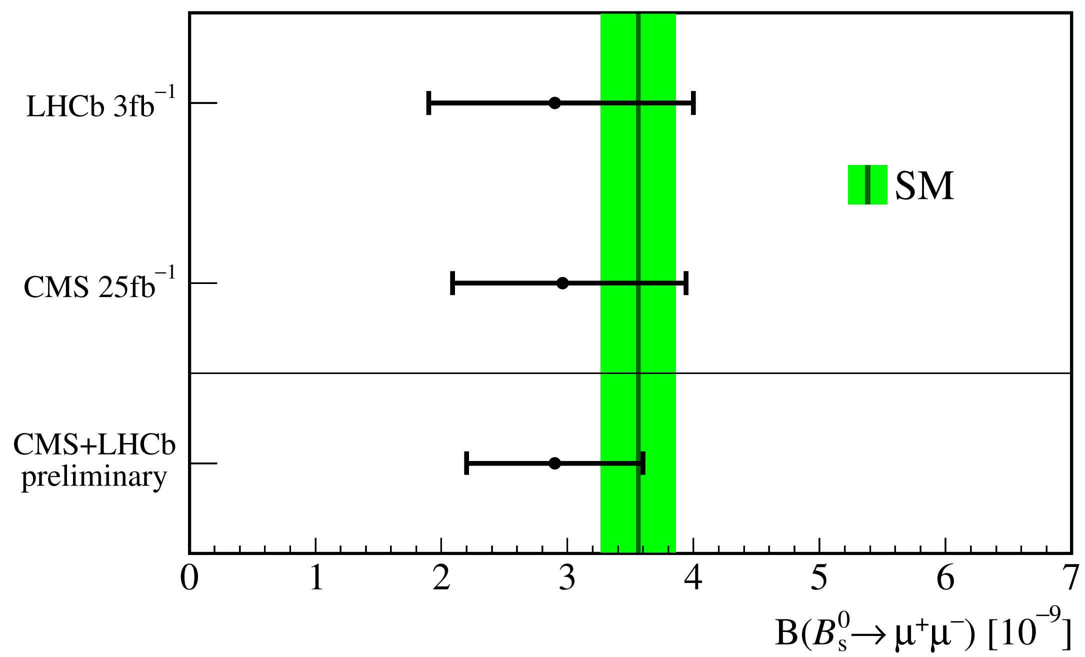
	90 % CL	95 % CL
Exp. bkg	3.5×10^{-10}	4.4×10^{-10}
Exp. bkg+SM	4.5×10^{-10}	5.4×10^{-10}
Observed	6.3×10^{-10}	7.4×10^{-10}

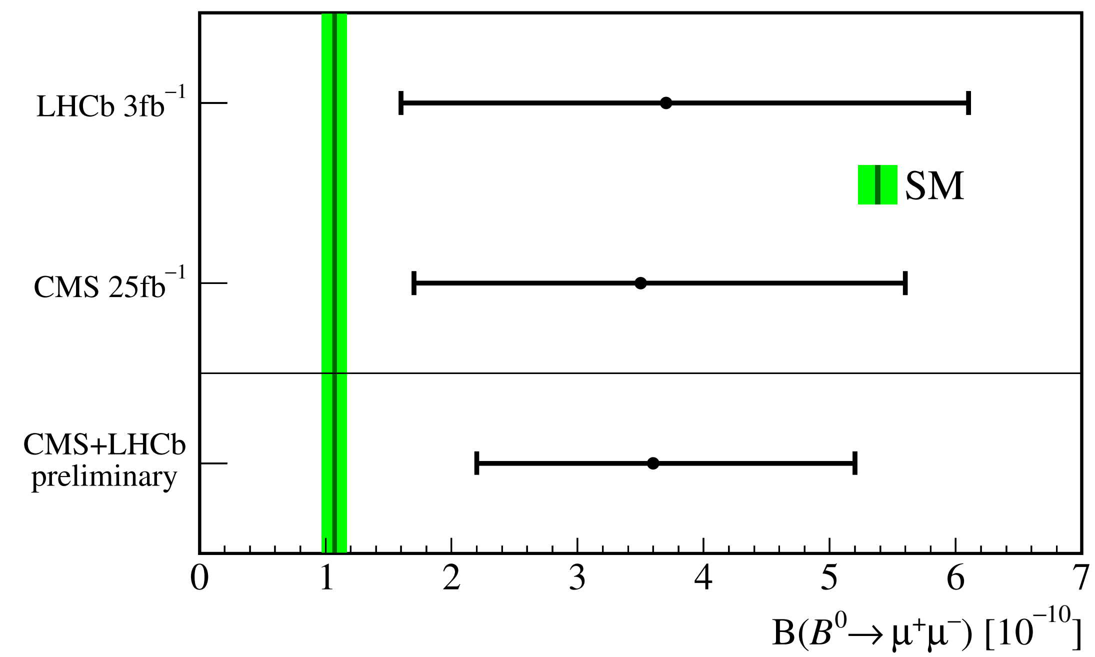
EVIDENCE AT CMS





ANOTHER TEST OF STANDARD MODEL



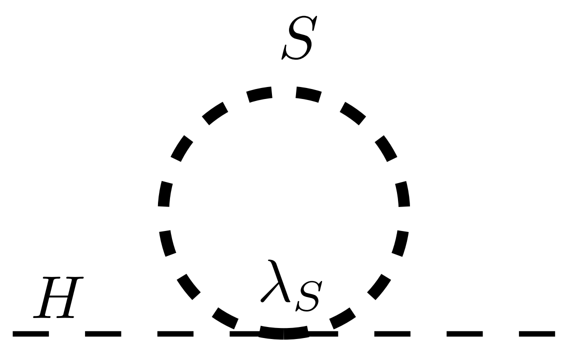


- Evidence at LHCb
  - http://arxiv.org/abs/1211.2674
- Evidence at CMS
  - http://arxiv.org/abs/1307.5025
- Combination of CMS and LHCb rare decays
  - http://cds.cern.ch/record/1564324

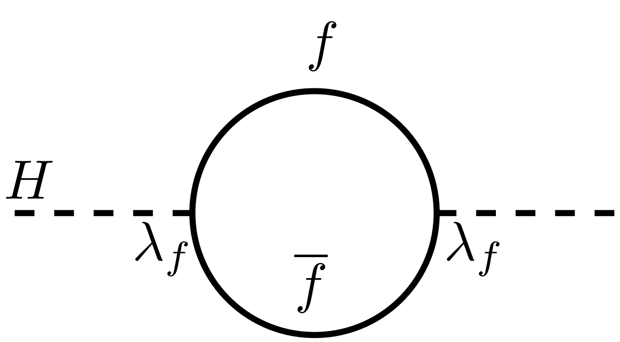
Supersymmetry

A Solution to Higgs Mass Divergence

- scalar particles contribution to Higgs mass also quadratically divergent with MUV
- Contribution with opposite sign compared to fermions



$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}\left[M_{\mathrm{UV}}^2 - 2m_S^2 \ln\left(M_{\mathrm{UV}}/m_S\right) + \ldots\right]$$



$$\Delta m_H^2 = \frac{\lambda_f^2}{16\pi^2}\left[-2M_{\mathrm{UV}}^2 + 6m_f^2 \ln\left(M_{\mathrm{UV}}/m_f\right) + \ldots\right]$$

- If such scalar particles existed, fermion and scalar contributions could cancel each other exactly and naturally without fine tuning
- Such conspiracy is generally known as a symmetry of the theory!

Origin of SUSY

- Before discovery of antimatter, electromagnetism had a problem

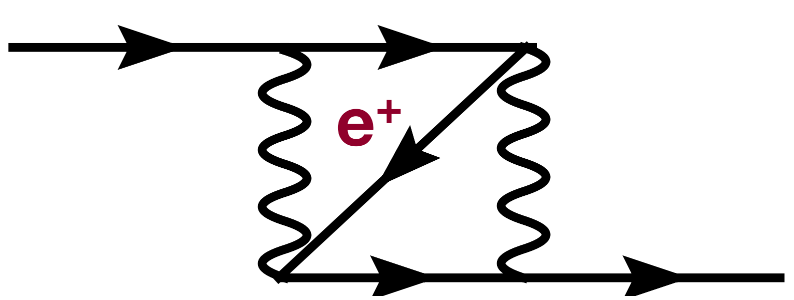
$$(m_e)^2 = (m_{e,0})^2 + \Delta E_{Coulomb}$$

$= 0.5$ MeV

$$\Delta E_{\text{Coulomb}} = \frac{1}{4\pi\epsilon_0}\frac{e^2}{r_e}$$

$r_e < 10^{-17}$cm → $\Delta E > 10$ GeV

- **Solution:** for every fermion, add an antifermion
  - Additional diagram that **cancels ΔE**!
  - Also **doubles** degrees of freedom of theory



SUPERSYMMETRY (SUSY)

- New symmetry of Lagrangian to cancel quadratic divergences of Higgs mass
- Create super partners for each fermion and boson of SM

$$Q^\dagger|\text{Boson}\rangle = |\text{Fermion}\rangle; \qquad Q^\dagger|\text{Fermion}\rangle = |\text{Boson}\rangle$$

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle; \qquad Q|\text{Fermion}\rangle = |\text{Boson}\rangle$$

- Q operator is a spinor: spin 1/2 and defined helicity
- Algebra of Q operator constrained when acting on chiral fermions

$$\{Q, Q^\dagger\} = P^\mu$$

$$\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0$$

$$[P^\mu, Q] = [P^\mu, Q^\dagger] = 0$$

- $P^\mu = (H, \vec{\mathbf{P}})$ is the momentum operator
- T^a are the gauge operators

Where Are SUSY Particles?

- Many SUSY particles have already been observed
  - leptons, quarks, W, and Z
  - same particles included in SM
- But no SUSY partner of SM observed yet!
- If SUSY is an exact symmetry, we should have seen SUSY partners of known particles with the same mass
- SUSY is certainly broken!
- Spontaneous SUSY breaking must be added by hand and still avoid divergences in Higgs mass corrections
- Different symmetry breaking mechanisms on the market
  - we'll see a short summary later

SUSY Breaking Mechanism

- Soft breaking means SUSY is not exact but still addresses the naturalness/hierarchy problem

$$\Delta m_H^2 = \frac{1}{16\pi^2}(\lambda_S - \lambda_F^2)M_{\rm UV}^2 + \ldots$$

- Add SUSY breaking term in Lagrangian $\mathcal{L} = \mathcal{L}_{\rm SUSY} + \mathcal{L}_{\rm soft}$

  $\mathcal{L}_{\rm SUSY}$ contains all of the gauge, Yukawa, and dimensionless scalar couplings, and preserves exact supersymmetry

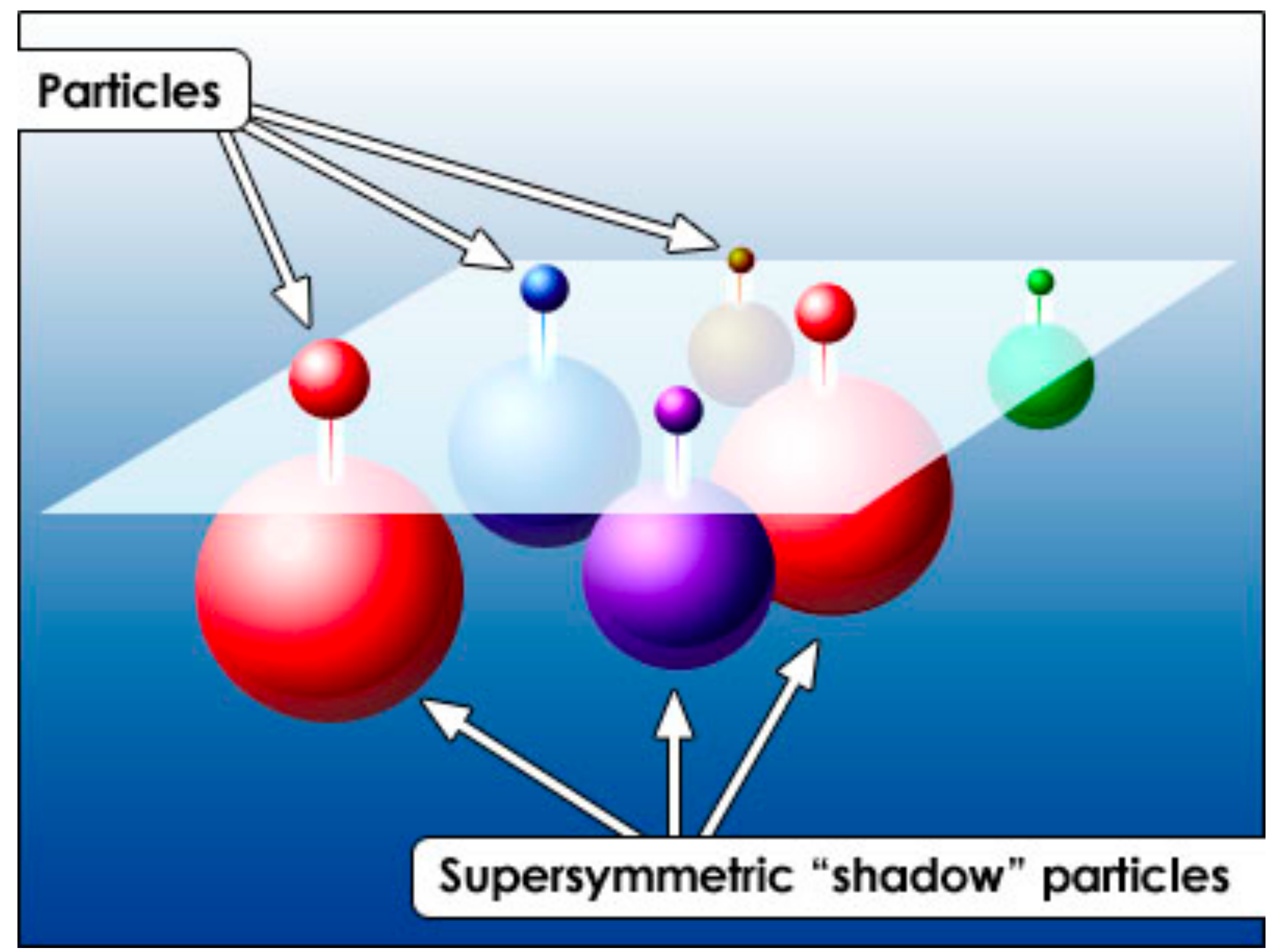
  $\mathcal{L}_{\rm soft}$ violates supersymmetry, and contains only mass terms and couplings with *positive* mass dimension.

- Couplings of fermions and scalars are not identical but only slightly different so that corrections are logarithmically divergent

$$\Delta m_H^2 = m_{\rm soft}^2 \left[\frac{\lambda}{16\pi^2}\ln(M_{\rm UV}/m_{\rm soft}) + \ldots\right]$$

- Sufficient to have m_{soft} ~ TeV
- Such breaking saves the Higgs mass and opens up possibility of new phenomena at TeV scale to be tested now at LHC

MASS SCALE OF SUSY



- m_{soft} determines the scale of SUSY particles
- SUSY particles cannot be light or lighter than already known particles

Soft SUSY Breaking in MSSM

$$\mathcal{L}_{\text{soft}}^{\text{MSSM}} = -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B}\right) + \text{c.c.}$$
$$-\left(\widetilde{\bar{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\bar{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\bar{e}}\,\mathbf{a_e}\,\widetilde{L}H_d\right) + \text{c.c.}$$
$$-\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\bar{u}}\,\mathbf{m_{\bar{u}}^2}\,\widetilde{\bar{u}}^\dagger - \widetilde{\bar{d}}\,\mathbf{m_{\bar{d}}^2}\,\widetilde{\bar{d}}^\dagger - \widetilde{\bar{e}}\,\mathbf{m_{\bar{e}}^2}\,\widetilde{\bar{e}}^\dagger$$
$$-\,m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,.$$

first line gives masses to the MSSM gauginos (gluino $\widetilde{g}$, winos $\widetilde{W}$, bino $\widetilde{B}$)

second line consists of (scalar)^3 interactions.

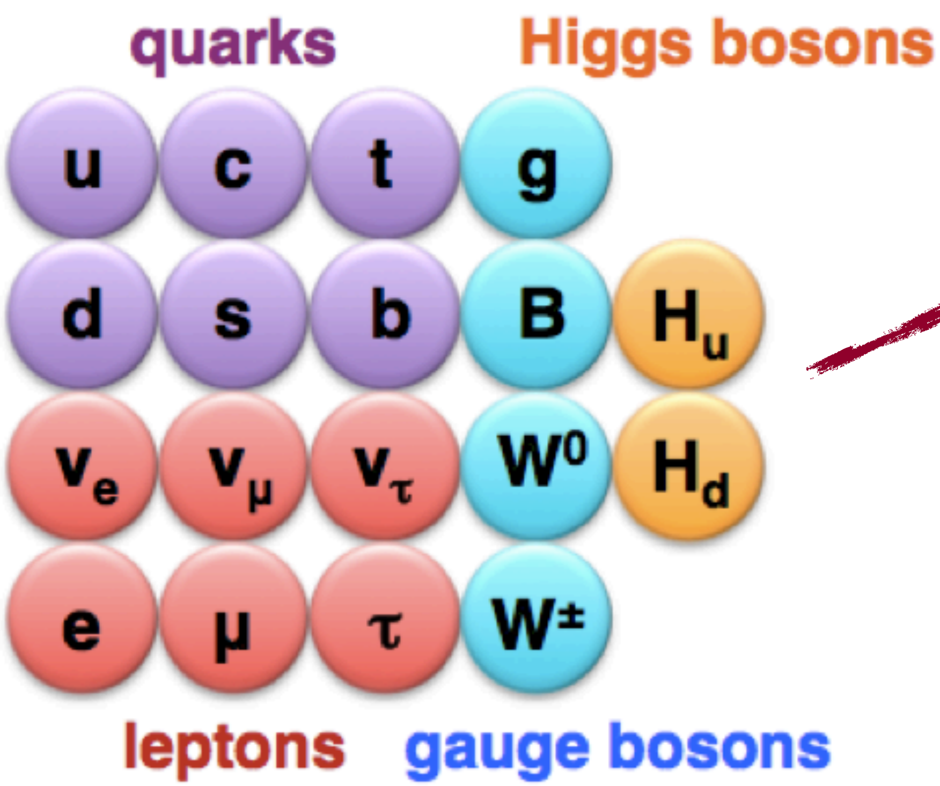
third line is (mass)^2 terms for the squarks and sleptons.

last line is Higgs (mass)^2 terms.

$$M_1,\ M_2,\ M_3,\ \mathbf{a_u},\ \mathbf{a_d},\ \mathbf{a_e}\ \sim\ m_{\text{soft}};$$
$$\mathbf{m^2_{\tilde{Q}}},\ \mathbf{m^2_{\tilde{L}}},\ \mathbf{m^2_{\tilde{\bar{u}}}},\ \mathbf{m^2_{\tilde{\bar{d}}}},\ \mathbf{m^2_{\tilde{\bar{e}}}},\ m^2_{H_u},\ m^2_{H_d},\ b\ \sim\ m^2_{\text{soft}}$$

- Total of > 100 parameters in the Lagrangian!
  - Different number of additional parameters for each type of SUSY breaking
  - In SM there are 27 parameters between masses, couplings, and CP violation parameters

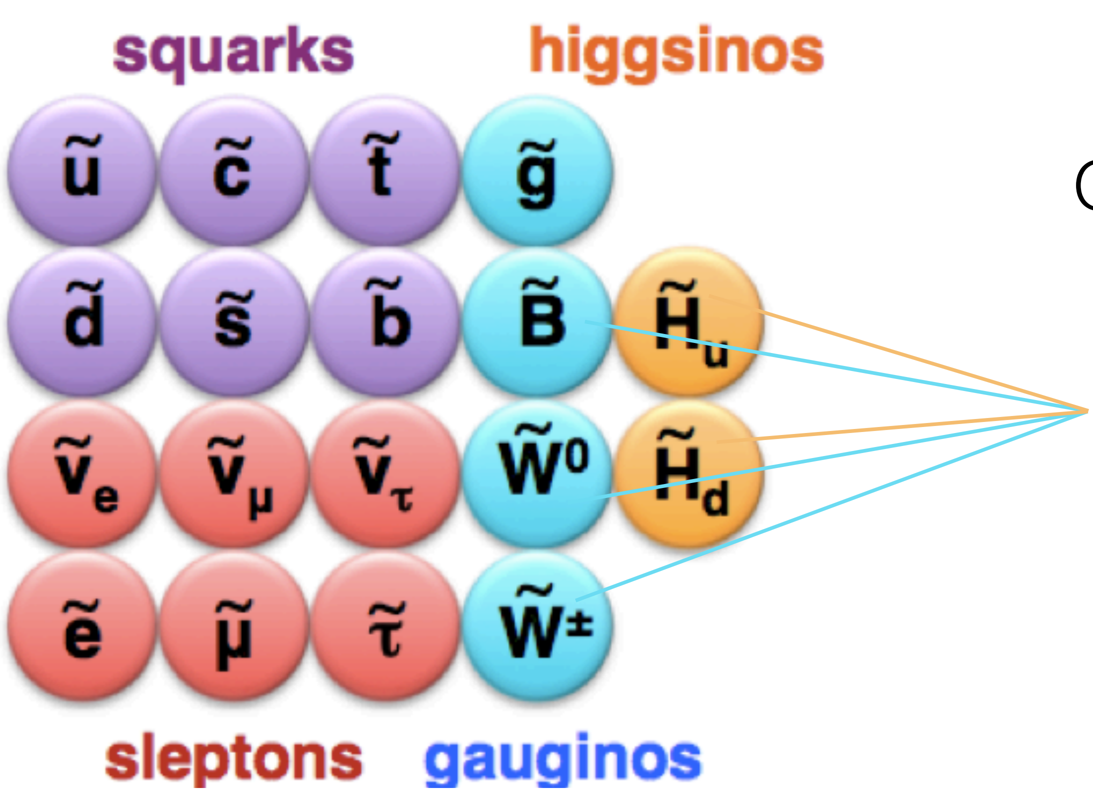
SUSY Zoo



Need to extend SM Higgs sector
Two doublets → **five** Higgs bosons

h, H, A, H^+, H^-

CP-even, light:
'our' 125 GeV Higgs



Gauginos and higgsinos mix:

$\chi_1^{\pm}$, $\chi_2^{\pm}$ — four charginos

χ_1^0, χ_2^0, χ_3^0, χ_4^0 — four neutralinos

Lightest Susy Particle (LSP):
stable if R-Parity is conserved

Dark Matter candidate

Undiscovered MSSM Zoology

Names	Spin	P_R	Mass Eigenstates	Gauge Eigenstates
Higgs bosons	0	$+1$	$h^0 \; H^0 \; A^0 \; H^\pm$	$H_u^0 \; H_d^0 \; H_u^+ \; H_d^-$
squarks	0	-1	$\widetilde{u}_L \; \widetilde{u}_R \; \widetilde{d}_L \; \widetilde{d}_R$	" "
			$\widetilde{s}_L \; \widetilde{s}_R \; \widetilde{c}_L \; \widetilde{c}_R$	" "
			$\widetilde{t}_1 \; \widetilde{t}_2 \; \widetilde{b}_1 \; \widetilde{b}_2$	$\widetilde{t}_L \; \widetilde{t}_R \; \widetilde{b}_L \; \widetilde{b}_R$
sleptons	0	-1	$\widetilde{e}_L \; \widetilde{e}_R \; \widetilde{\nu}_e$	" "
			$\widetilde{\mu}_L \; \widetilde{\mu}_R \; \widetilde{\nu}_\mu$	" "
			$\widetilde{\tau}_1 \; \widetilde{\tau}_2 \; \widetilde{\nu}_\tau$	$\widetilde{\tau}_L \; \widetilde{\tau}_R \; \widetilde{\nu}_\tau$
neutralinos	$1/2$	-1	$\widetilde{N}_1 \; \widetilde{N}_2 \; \widetilde{N}_3 \; \widetilde{N}_4$	$\widetilde{B}^0 \; \widetilde{W}^0 \; \widetilde{H}_u^0 \; \widetilde{H}_d^0$
charginos	$1/2$	-1	$\widetilde{C}_1^\pm \; \widetilde{C}_2^\pm$	$\widetilde{W}^\pm \; \widetilde{H}_u^+ \; \widetilde{H}_d^-$
gluino	$1/2$	-1	$\widetilde{g}$	" "

New Symmetry: R-Parity

$$R = (-1)^{3(B-L)+2S}$$

- Add new conservation law to protect against lepton and baryon number violation
- R-parity combines spin, baryon, and lepton quantum numbers
  - particles: R = +1
  - SUSY particles: R = -1
- Important phenomenological consequences
  - Lagrangian invariance requires all terms to be quadratic in negative R-parity
  - SUSY particles can only be produces in pairs
  - R = -1 particles must always decay in final states with at least one R = -1 particle
    - lightest SUSY particle (LSP) must be stable
  - Two R = -1 particles can annihilate and produce ONLY R = +1 particles
    - important for Dark Matter searches

Next Lightest Supersymmetric Particle (NLSP)

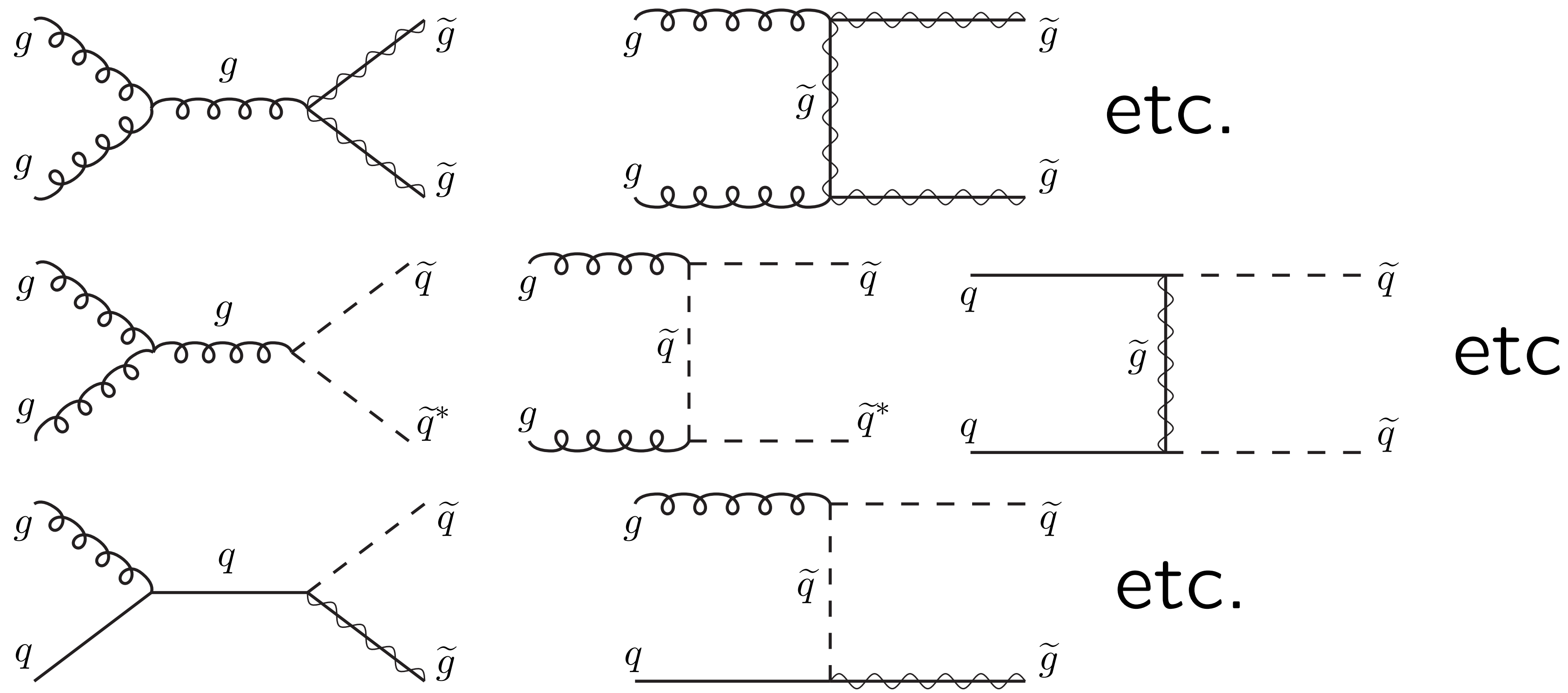
- Two particles play crucial role in SUSY searched
- Lightest supersymmetric particle must be stable and hence escape detection
  - missing energy in SUSY processes
  - SUSY masses are expected to be large therefore expect large missing energy
- Next to lightest supersymmetric particle (NLSP)
  - Because of R-parity conservation must always decay to LSP
    - two body decay of NLSP → X + LSP
  - X will always be an ordinary R = +1 particle
  - distinctive kinematic signature for X helps searching for NLSP

SUSY Production via QCD

Gluino pairs

Squark pairs

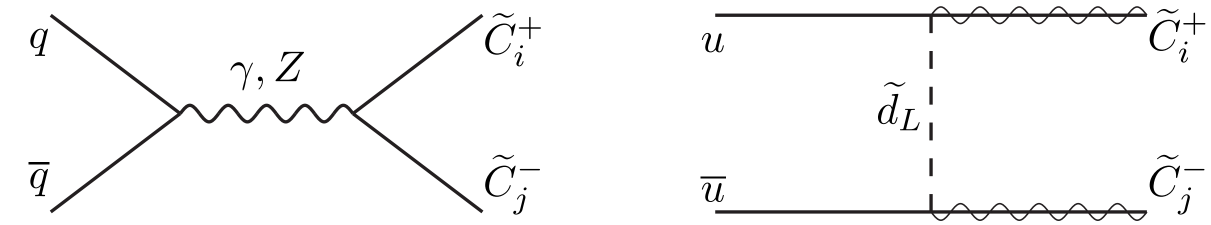
Squark + gluino



- QCD production dominates but given heavy mass for SUSY, cross section strongly depends on squark and gluino masses

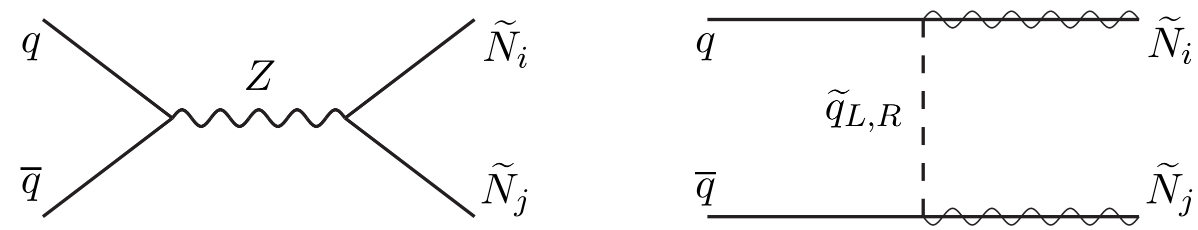
SUSY Production via Electroweak

Chargino pairs

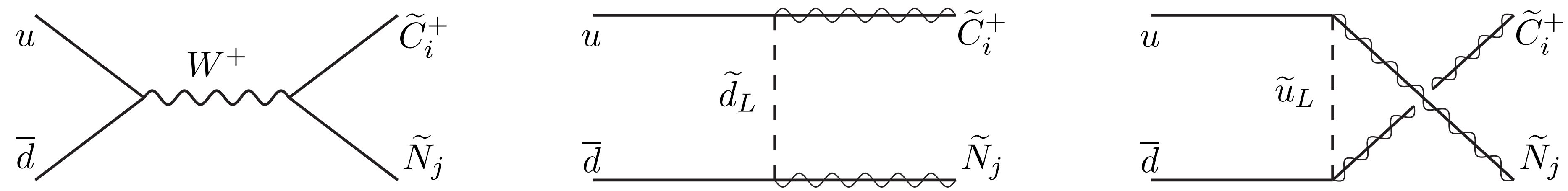


etc.

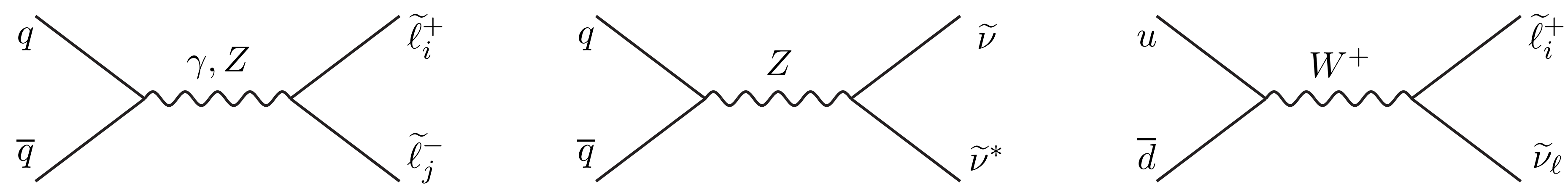
Neutralino pairs



Chargino + neutralino

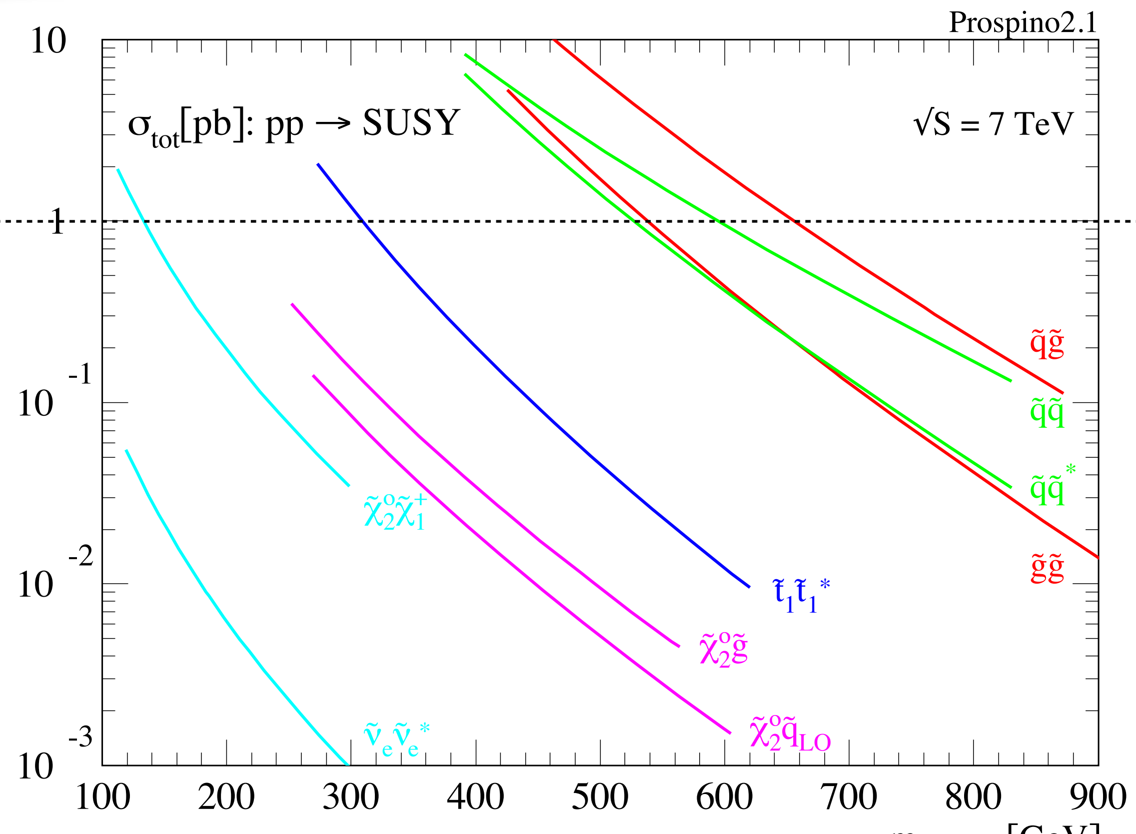


Slepton pairs

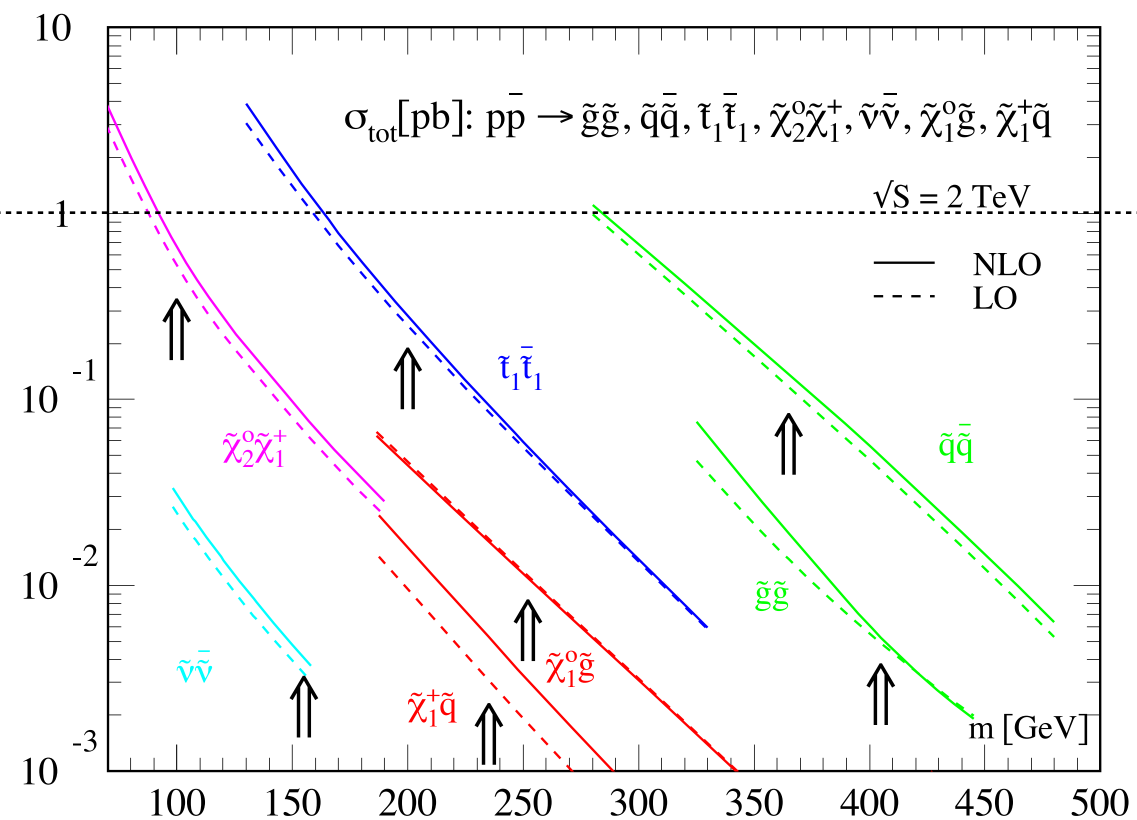


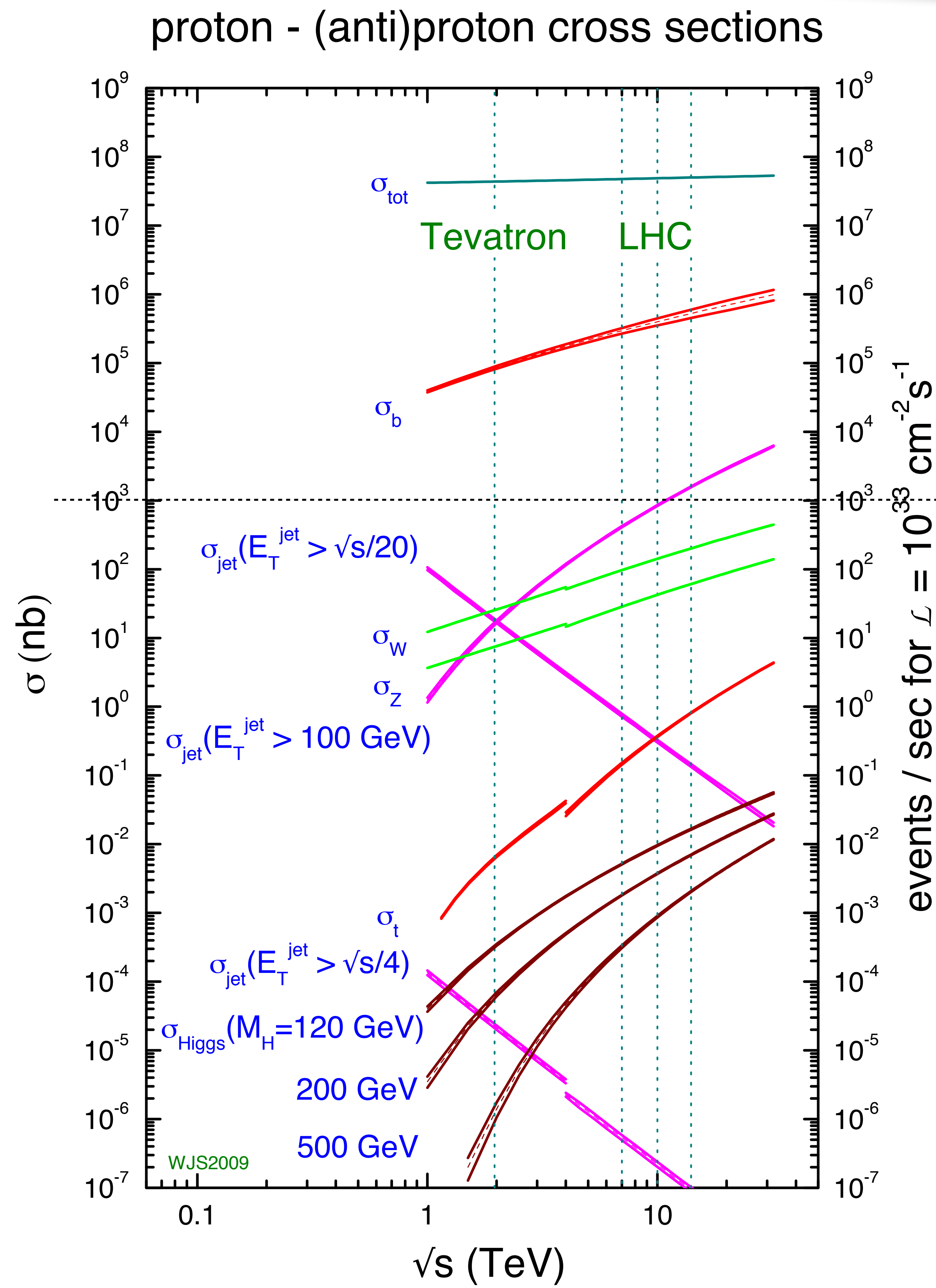
- Smaller cross section since EW coupling is smaller compared to QCD

SUSY Cross Section



http://www.thphys.uni-heidelberg.de/~plehn/prospino/





SUSY vs. Standard Model