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Top Associated Higgs Production @ the LHC: Run2 and the horizon

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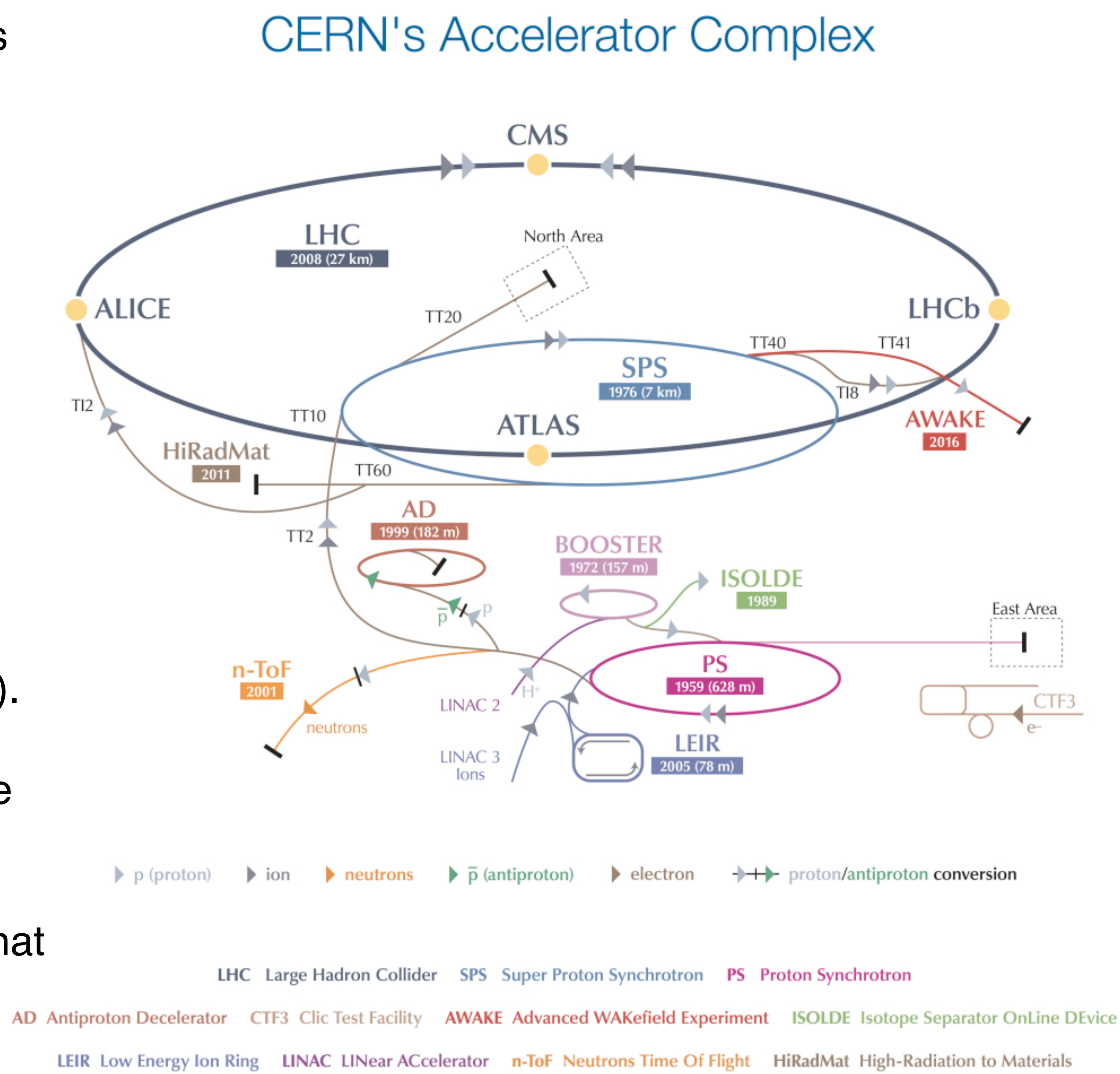
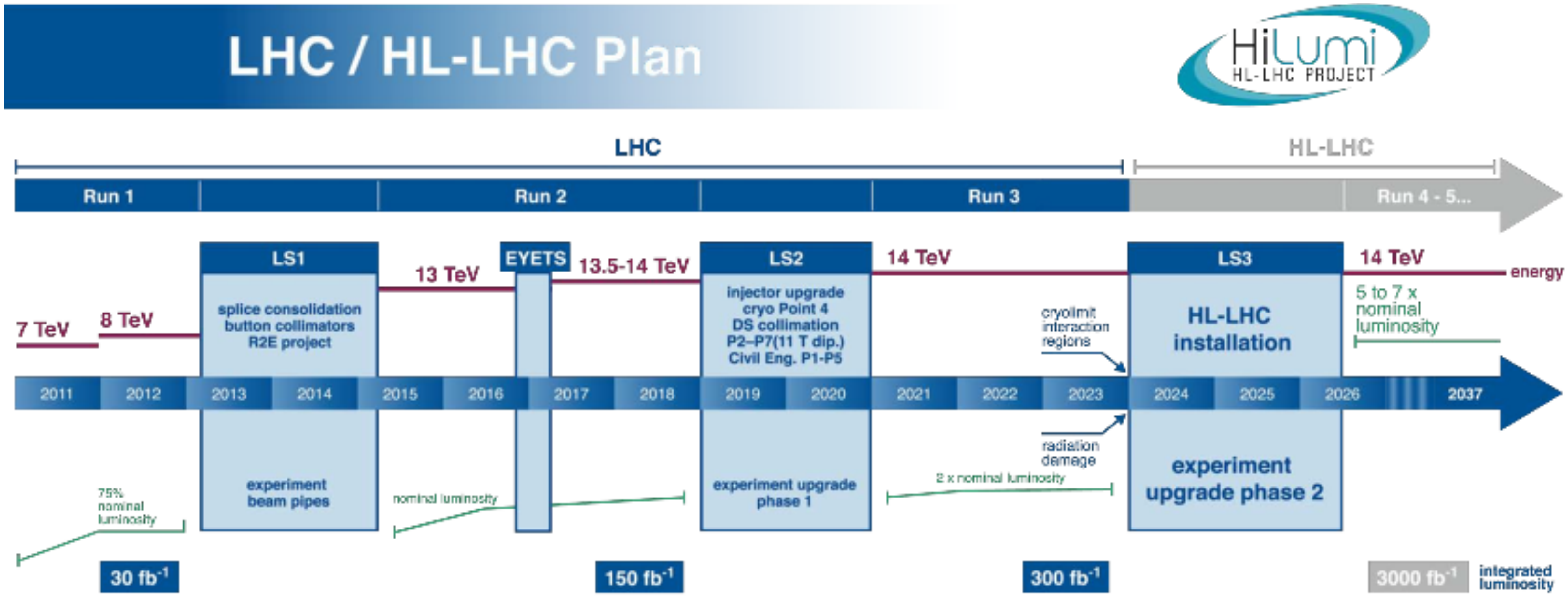
- Introduction to the LHC.
- The ATLAS and CMS detectors.
- Bit of background physics.
- Intro to and latest results from ttH searches.
- A few ideas for next steps.
- Summary.

- The LHC is a proton-proton / heavy ion particle collider.
- Accelerating structures generate electric fields to boost the particles energy.
- Magnetic fields to guide them.
- Accelerator complex - increase particles energy in stages.
- Particle beams travel in opposite directions round ring.
- Close to speed of light.
- Detectors @ interaction points (IP).
- Beams squeezed @ IP to increase probability of collision.
- Detectors record collision debris that looks interesting.

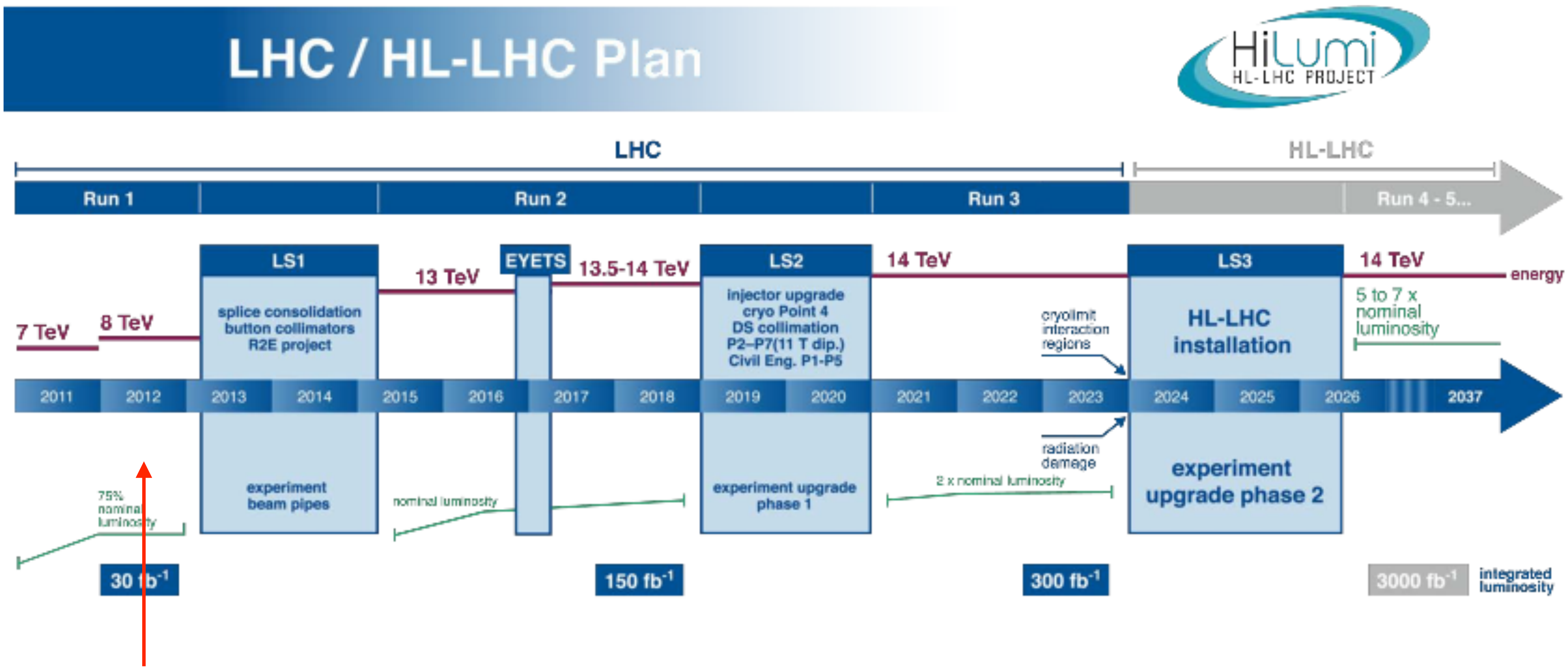


LHC Lifetime



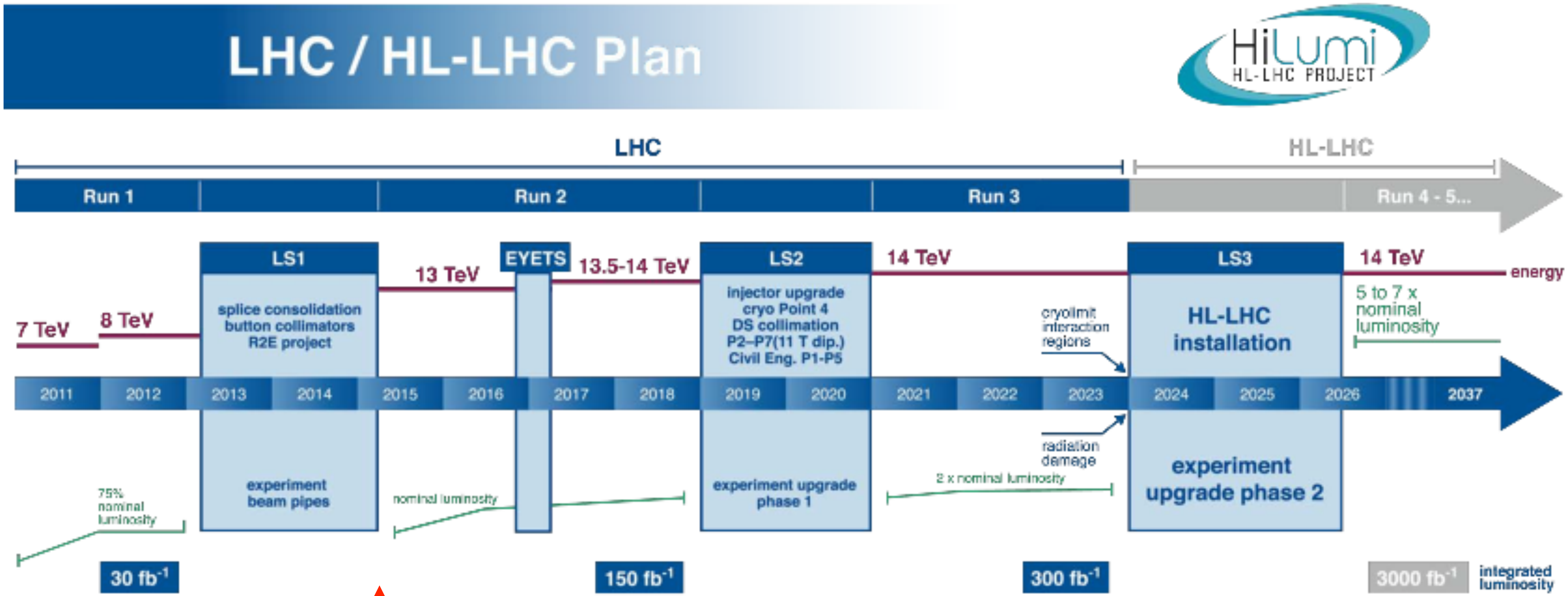
- 1st proton collisions at LHC in 2010.
- Ramp up to 3.5 TeV per beam in early 2010
- March = new high-energy collision record 7 TeV.
- November - December 2010 = first heavy ion collisions.

LHC Lifetime



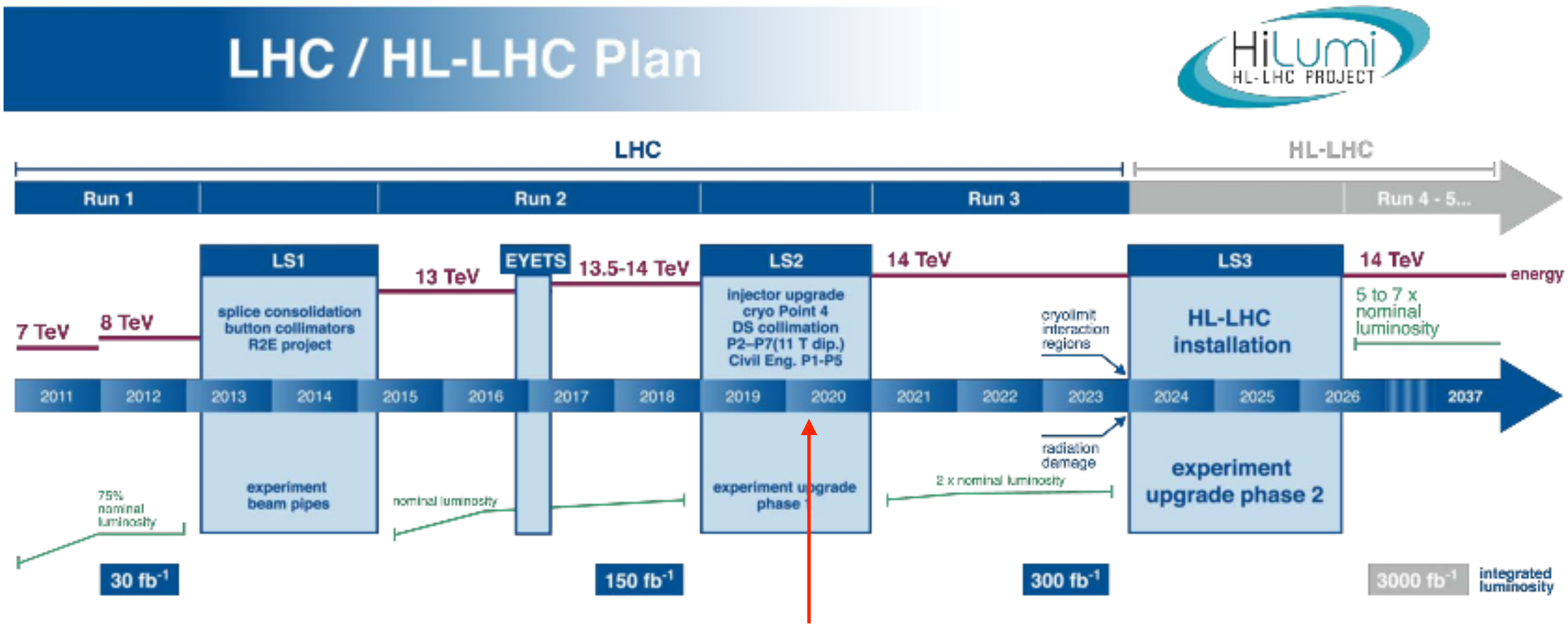
- July 2012: Higgs Discovery.
- Major physics objective for LHC.
- Delayed LS1 to collect more data.

LHC Lifetime



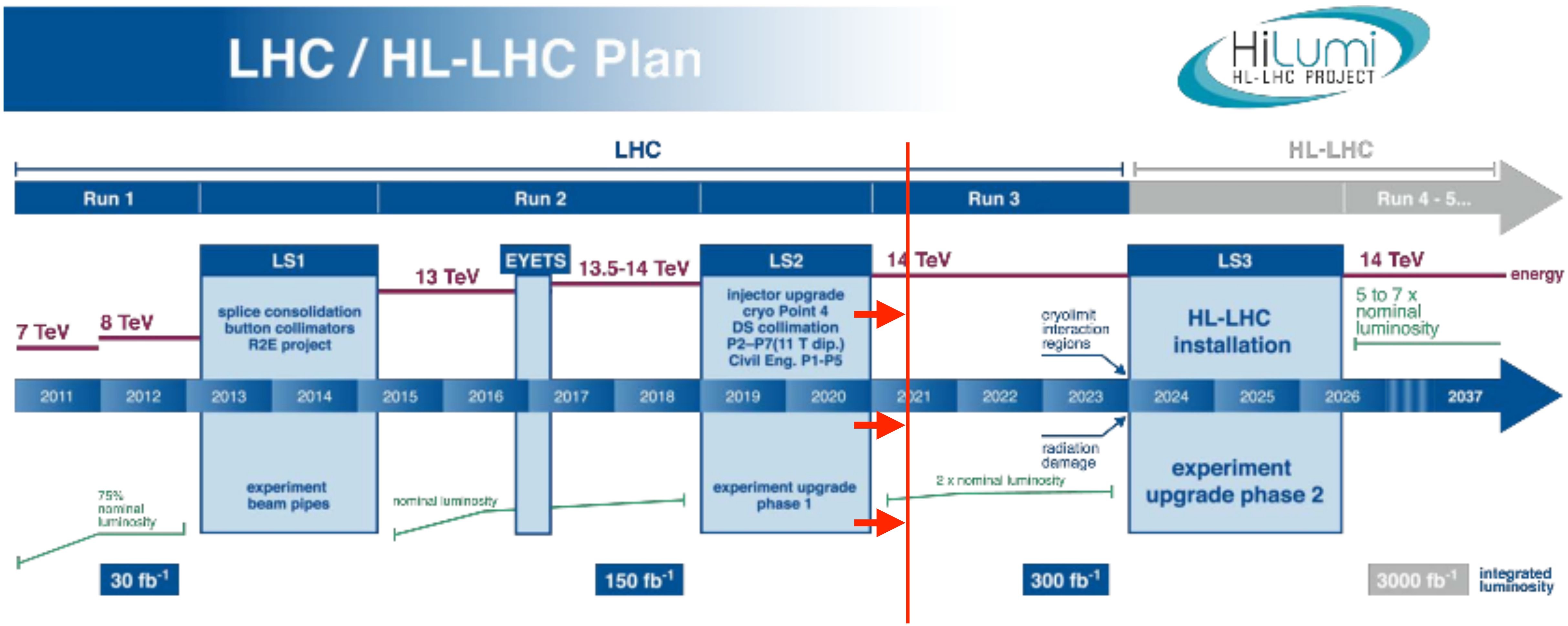
- April 2015: start of run 2.
- 6.5 TeV per beam =13TeV collisions.
- Increased luminosity.
- 2017, saw further increase to 2x design spec!

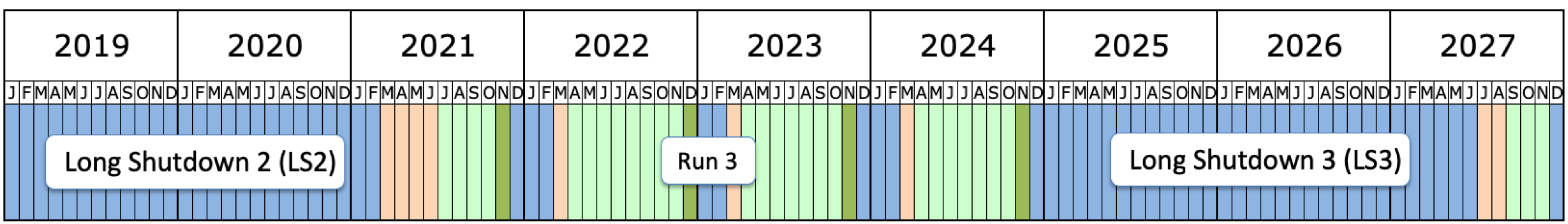
LHC Lifetime



- You are here.
- LS2 started in December 2018.
- Upgrades and repairs for Run 3.

LHC Lifetime





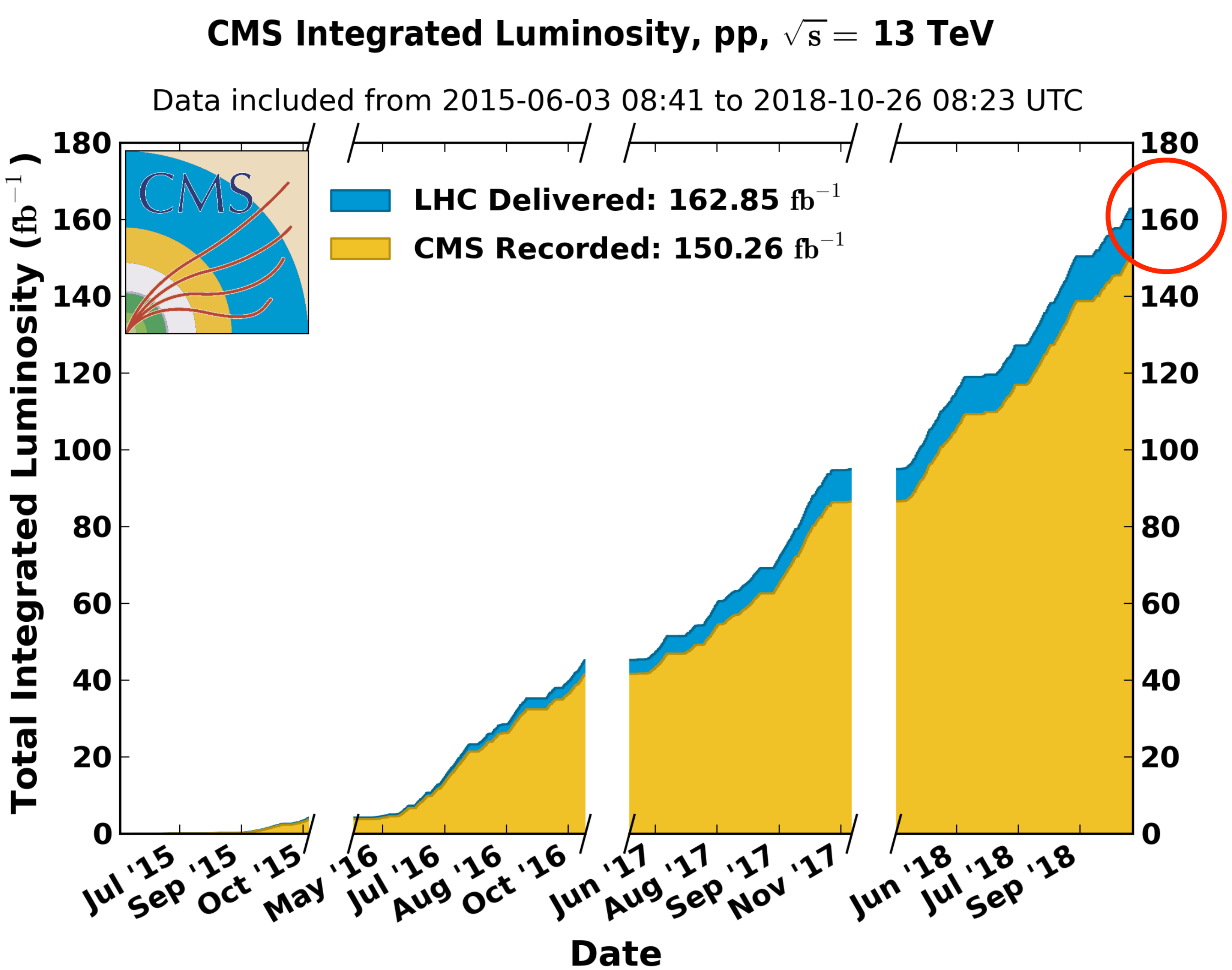
As of Jan 2020 (link)

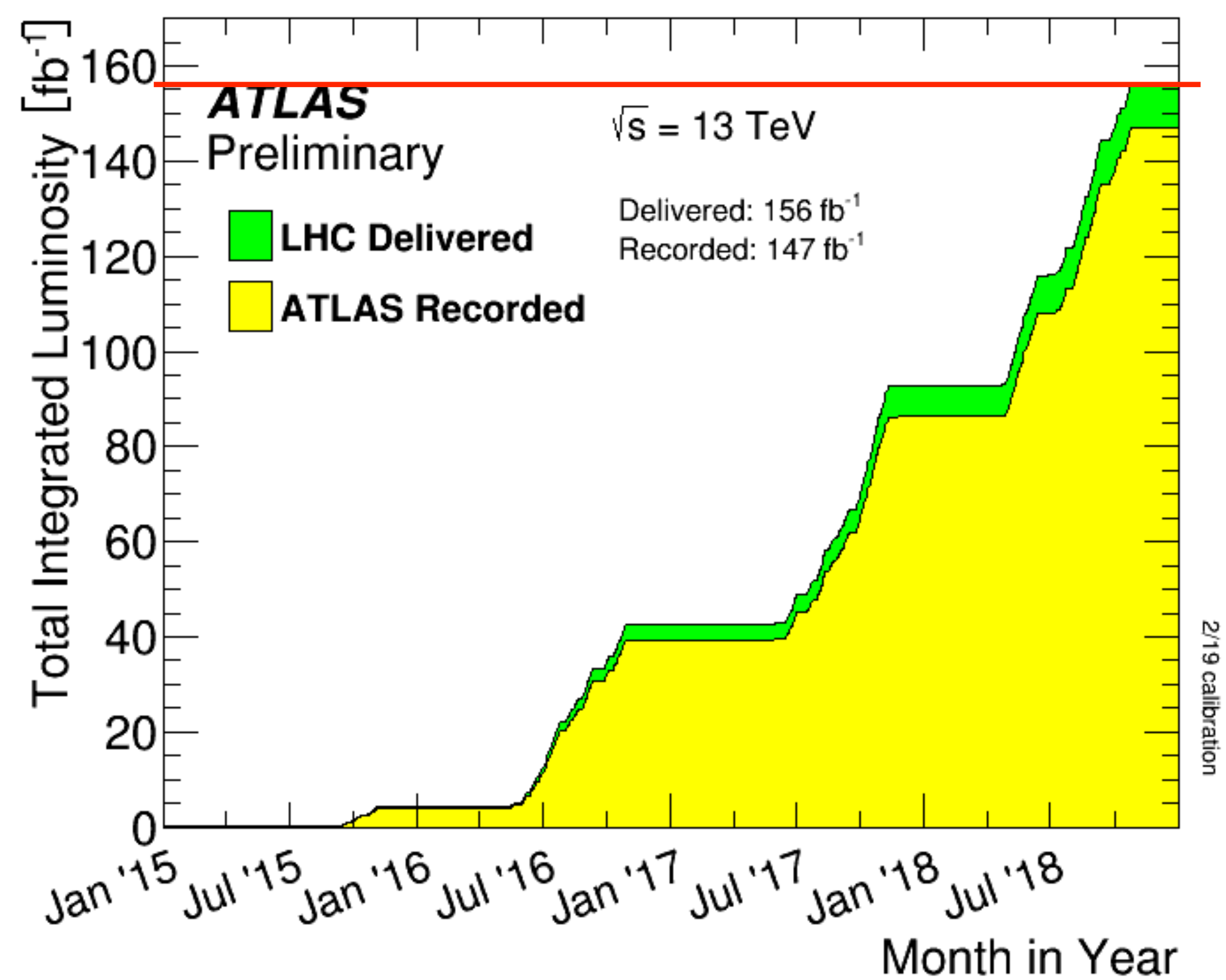
Shutdown/Technical stop
Protons physics
Commissioning
Ions

- Start of Run 3 pushed back due to the extensive upgrades and repairs needed for both the next run and the HL-LHC.

Run 2 Dataset

- ~ 160 /fb delivered to both experiments during stable beams.
- ~ 150 /fb recorded due to slight DAQ inefficiency and “warm start” i.e. when flag for stable beams is raised.
- ~ 140 /fb used for physics analysis: due to data quality monitored to ensure good data (all reconstructed objects are of good quality).





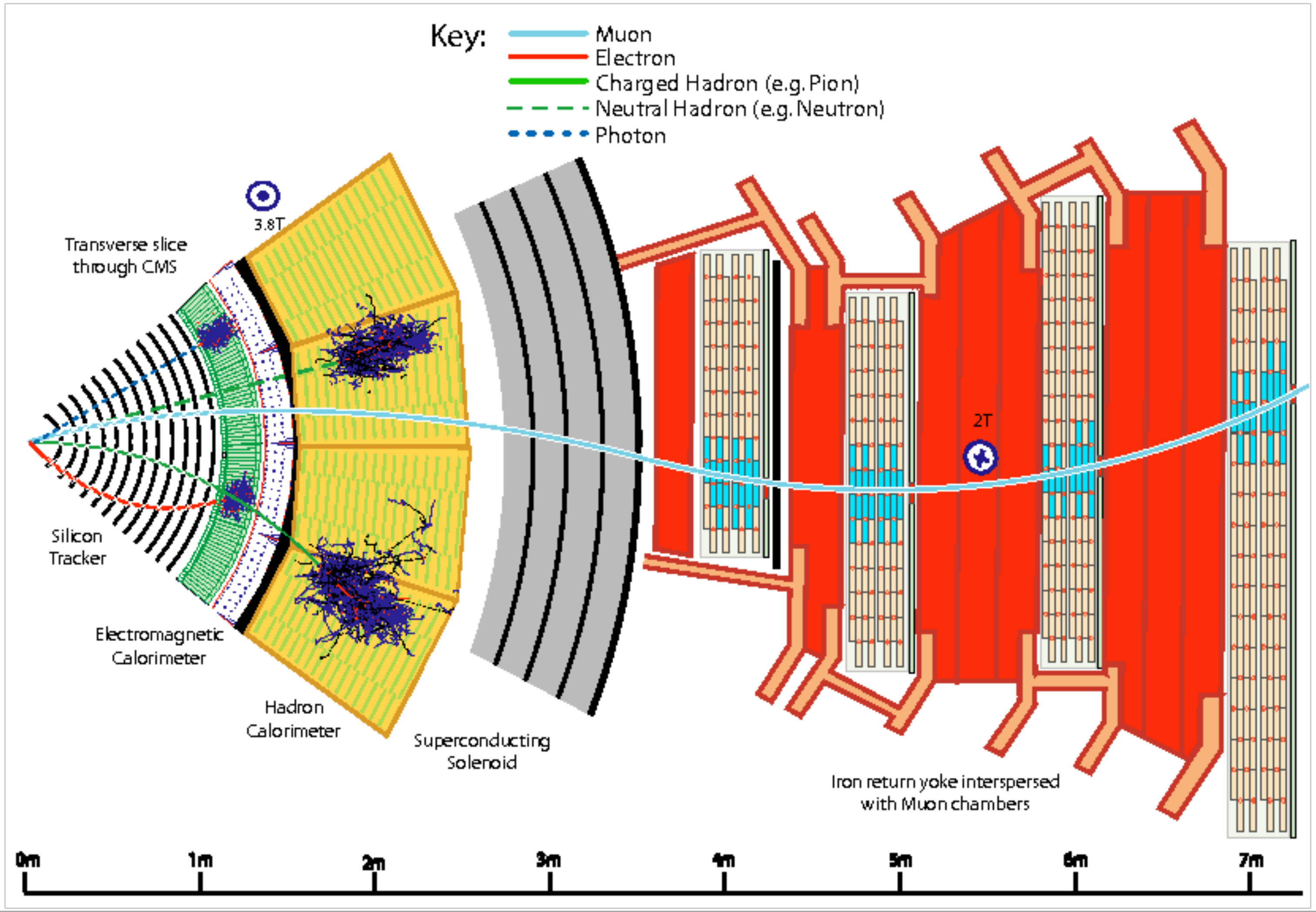
Run 2 dataset ~5.5x Run 1 data.

Much better precision for analyses.

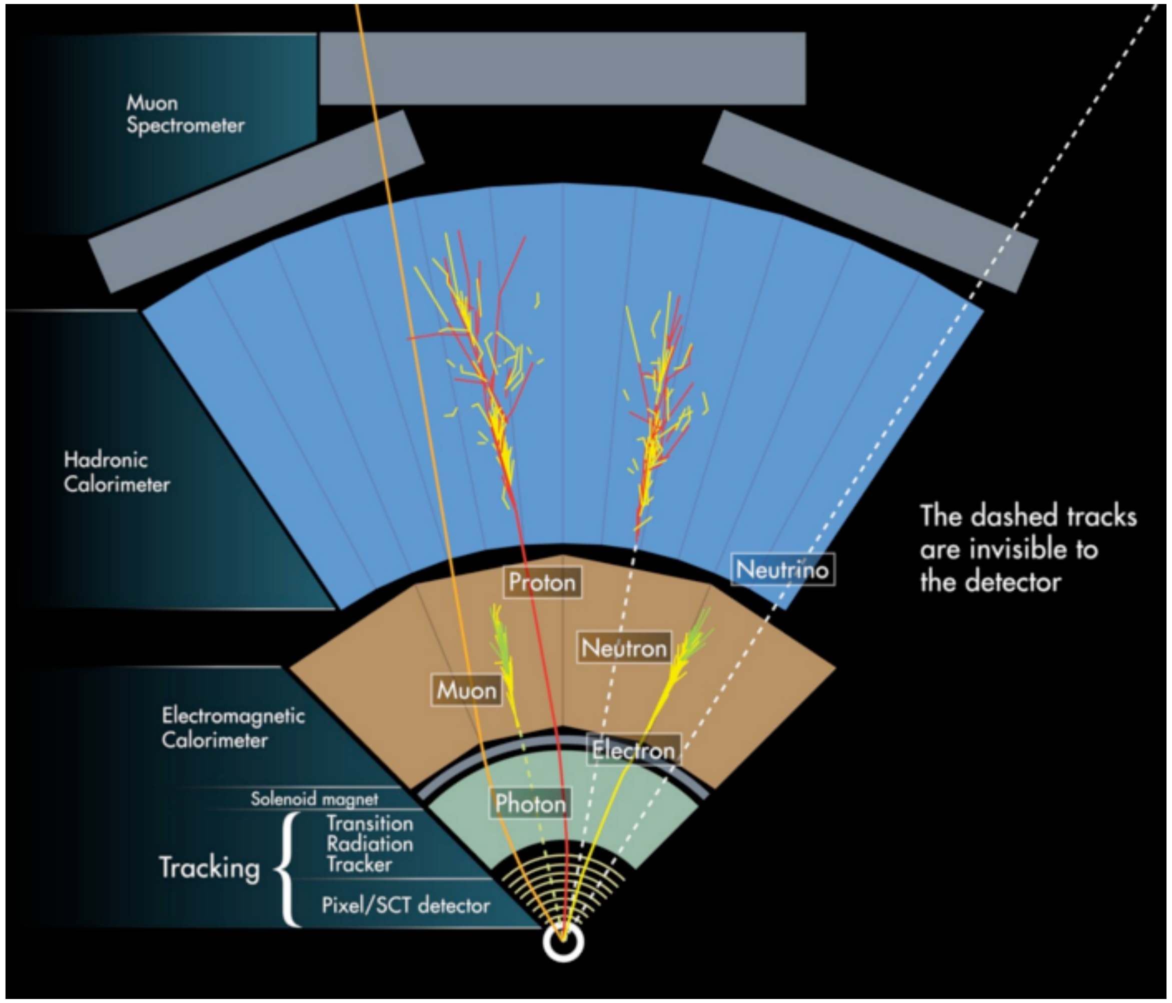
- General purpose detectors, broad physics programmes.
- Same scientific goals, different technical solutions particularly the magnet system designs.
- CMS based around 4T (=100,000 x earths magnetic field) solenoid magnet = cylindrical coil of superconducting cable.
- Improves tracking resolution in inner detector (ID).
- ATLAS solenoid just outside ID.

ATLAS	CMS
Larger, less dense	Smaller, denser
Liquid Argon EM cal.	PbWO4 crystal EM cal.
Better EM cal. space and energy res.	Better Hadronic cal. space and energy res.
2T B-field around inner detector	4T B-field around calorimeters

CMS (Compact Muon Solenoid)

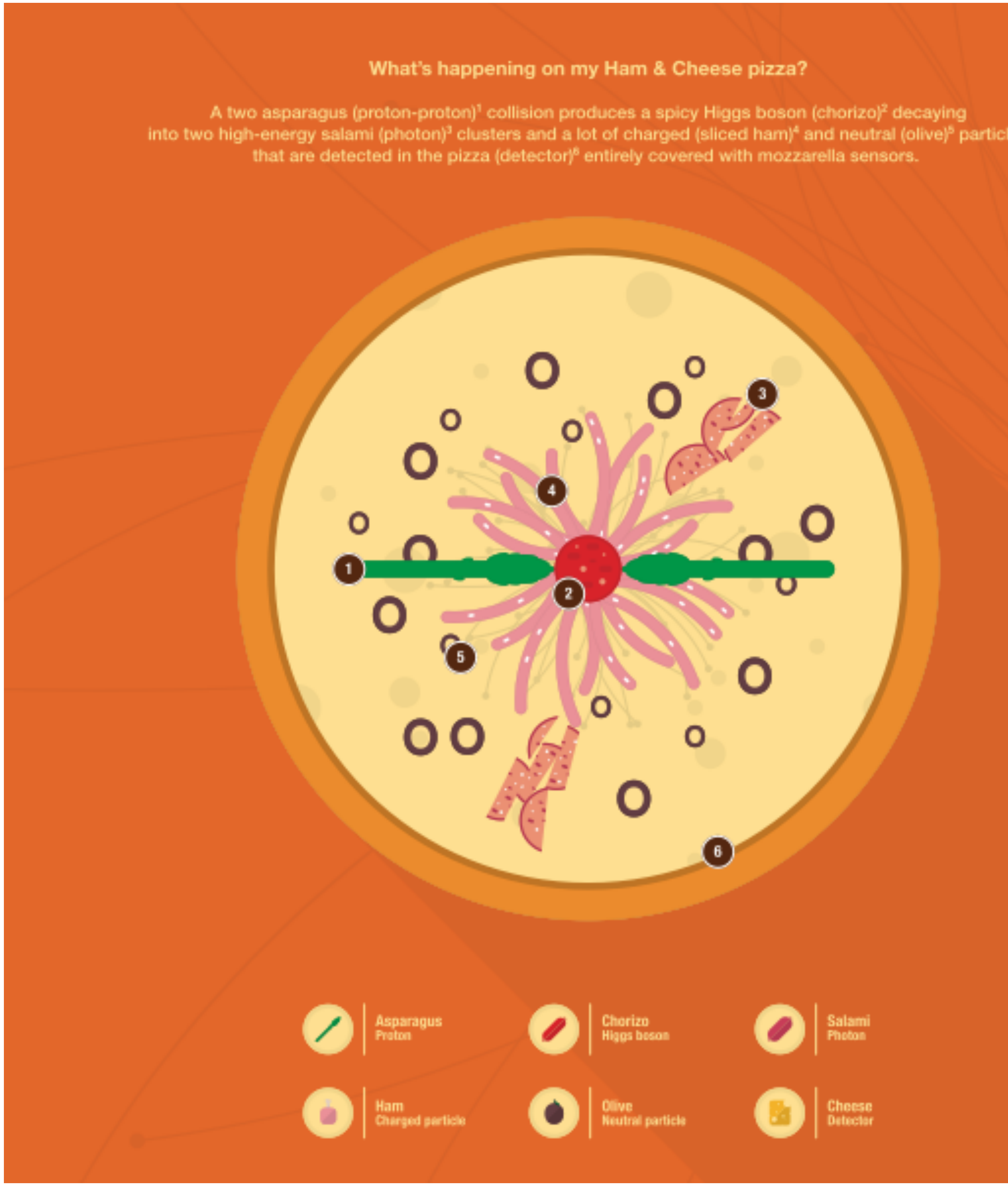


ATLAS (A Torroidal LHC ApparatuS)



Higgs physics: what's on the menu?

- Higgs observation in 2012.
- Whats the game now?
- Both experiments compare observed Higgs properties with SM predictions.
- Precise measurement of the mass.
- Cross-sections: inclusive, per decay/production channel, differential etc.
- Couplings to fermions and other bosons.
- Absence of new physics signals, testing SM is good gauge of scale of potential new physics.



Ms Iolanda Canale Higgs boson Pizza's for Art&Science exhibition, St Lucia, 2015

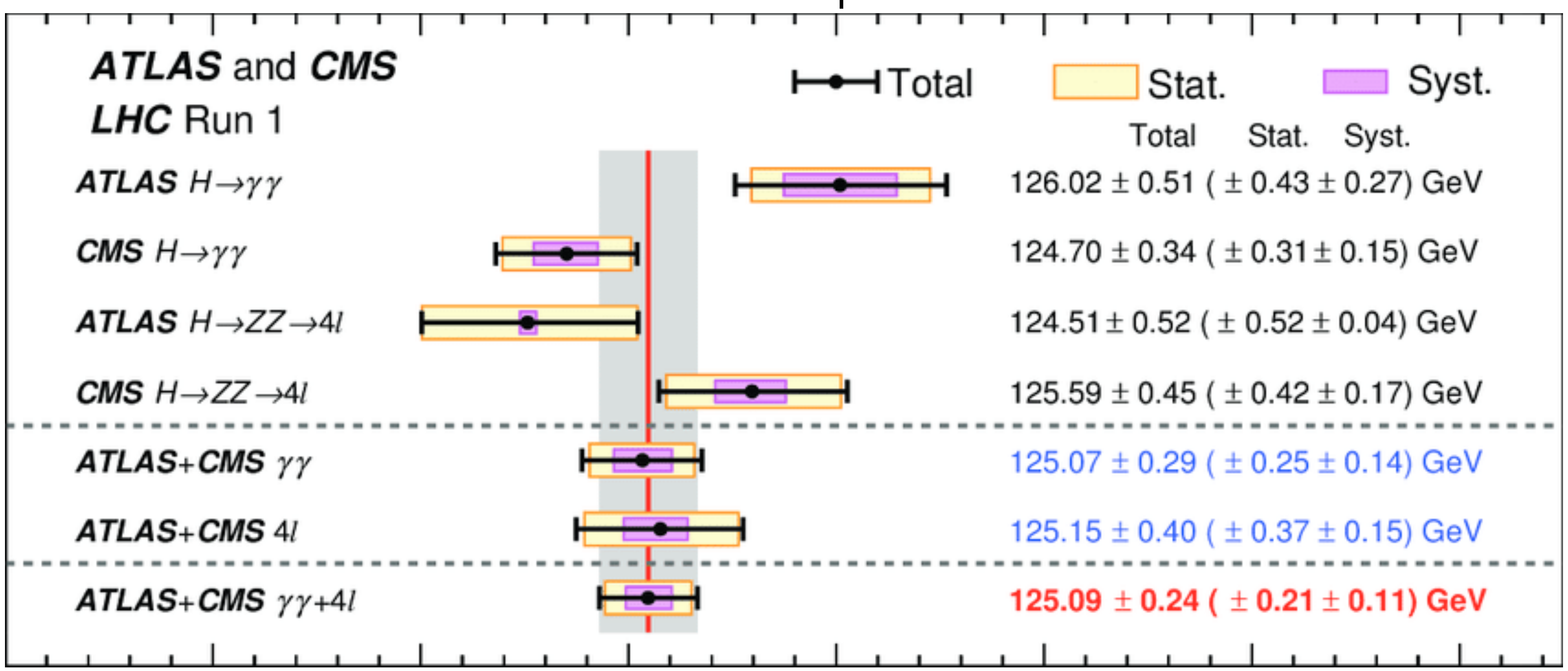
Putting things into place . . . .

The properties of fundamental particles and interactions encrypted in Lagrangian.

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\Psi}\not{D}\Psi + \boxed{\Psi_i y_{ij}\Psi_j\Phi} + \mathrm{h.c.} + \boxed{|D_\mu\Phi|^2} + \boxed{\mathrm{V}(\Phi)}$$

*Higgs potential (contains information on the **Higgs mass** + **trilinear** and **quartic** **self-coupling**)*

mass measured with precision of 0.2%

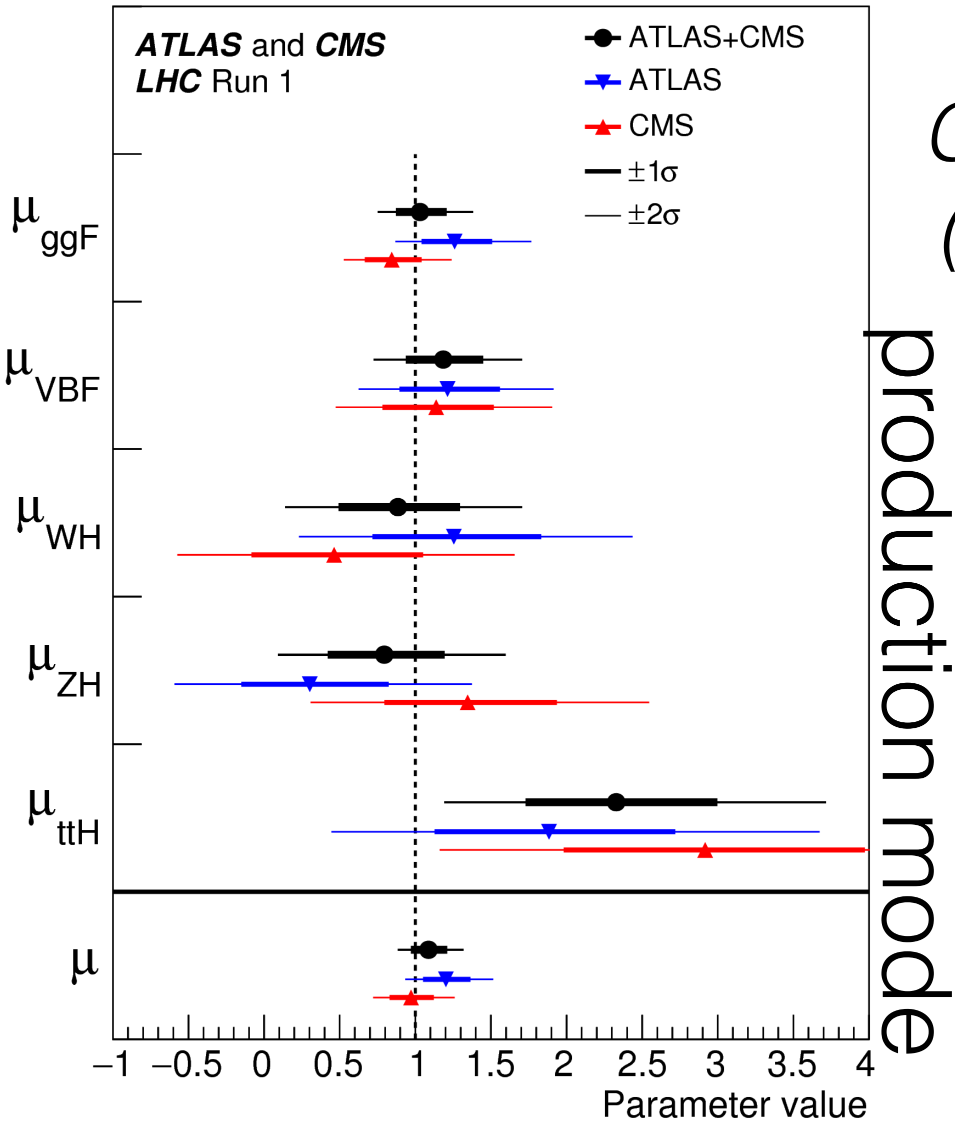


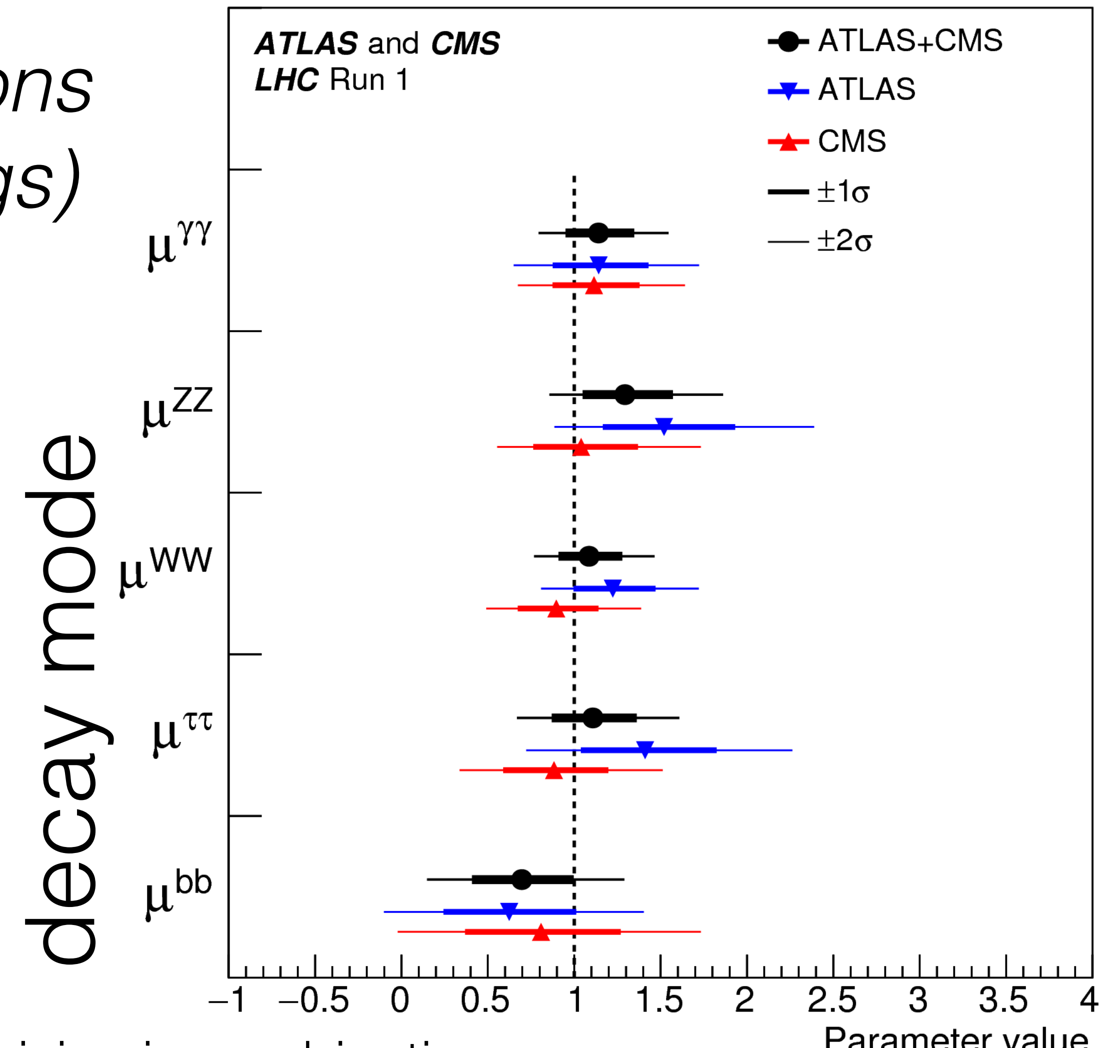
Putting things into place . . . .

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\overline{\Psi}\not{D}\Psi$$
$$+ \boxed{\Psi_i y_{ij} \Psi_j \Phi} + \mathrm{h.c.}$$
$$+ \boxed{|D_\mu \Phi|^2} + \mathrm{V}(\Phi)$$

Coupling to fermions (Yukawa couplings)

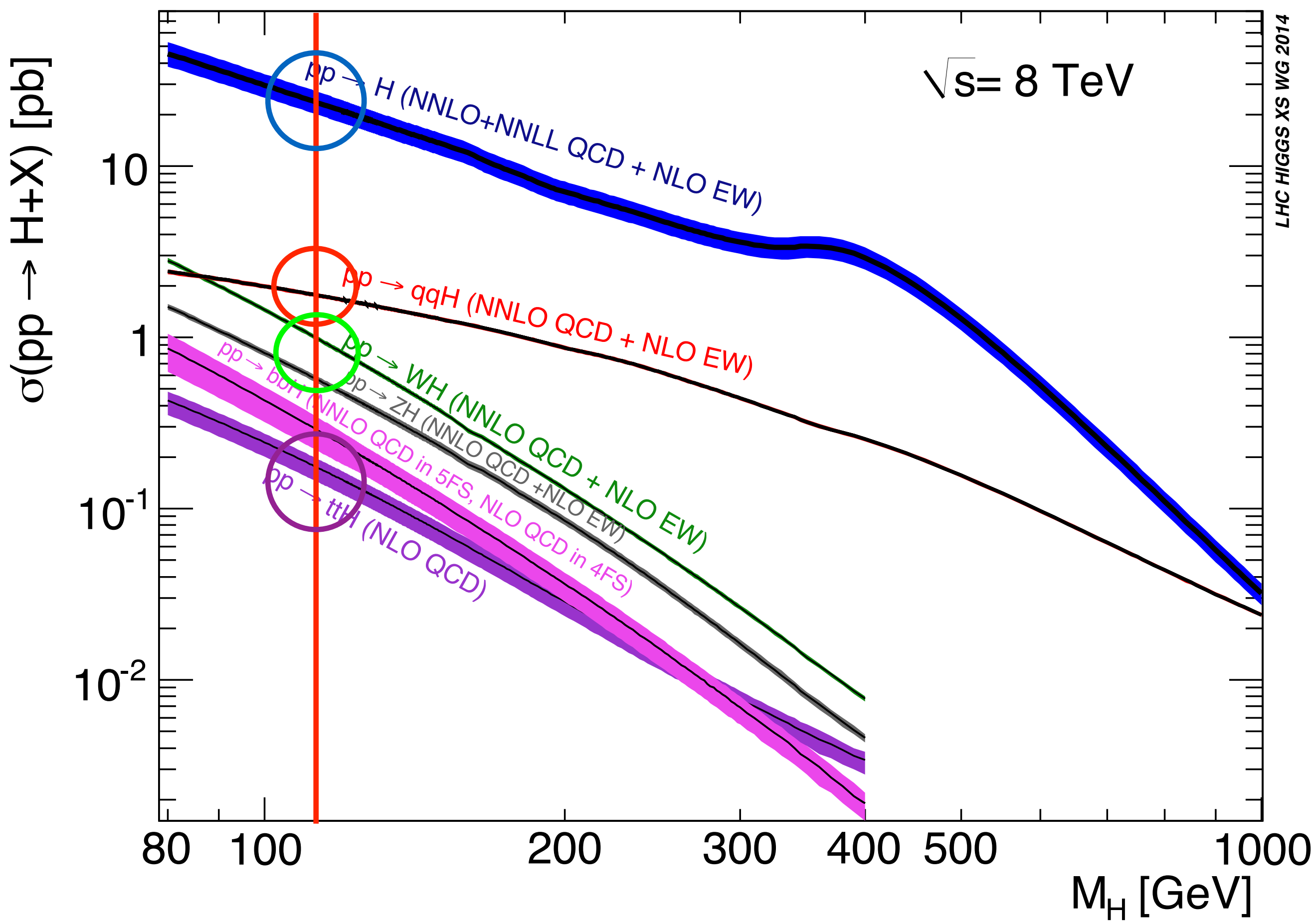
Coupling to bosons (Gauge couplings)

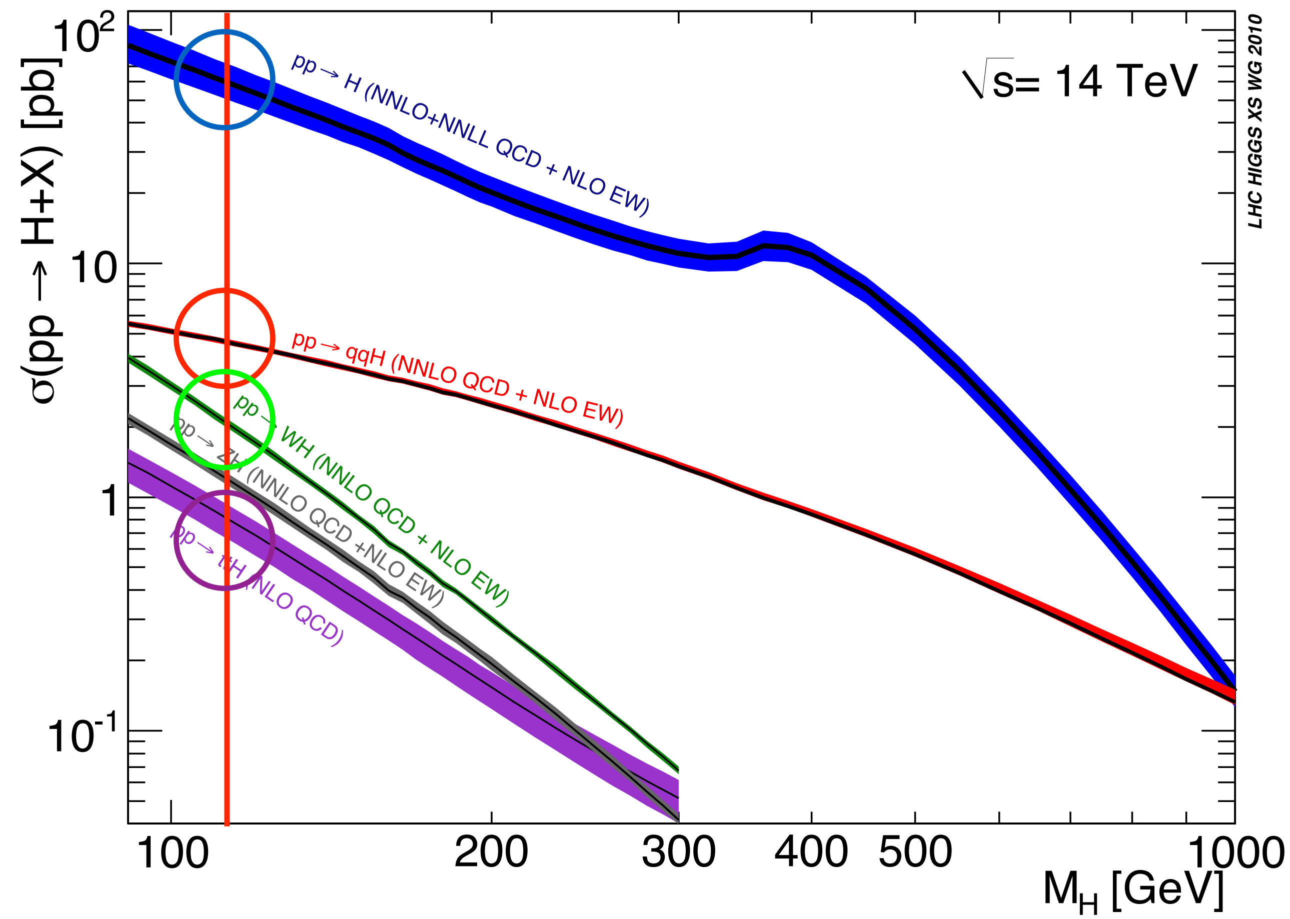




- Reasonably good precision in combination.
- Many channels individually statistically limited.

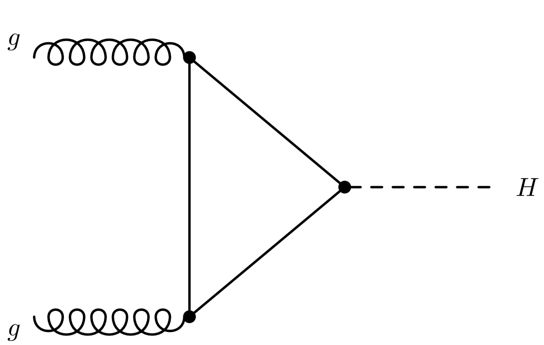
Comparison of Cross-sections



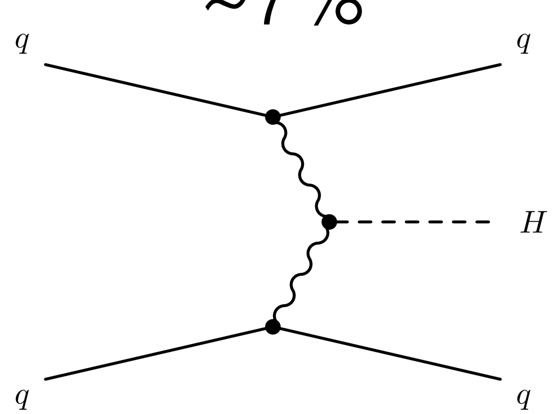


- Run 2 provided ~10 times increase in the Higgs production w.r.t Run 1.

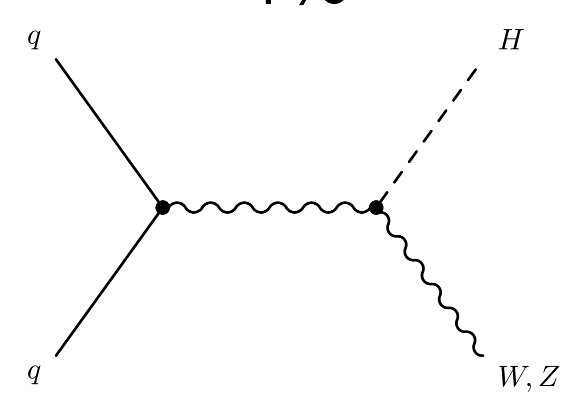
ggF
~87%



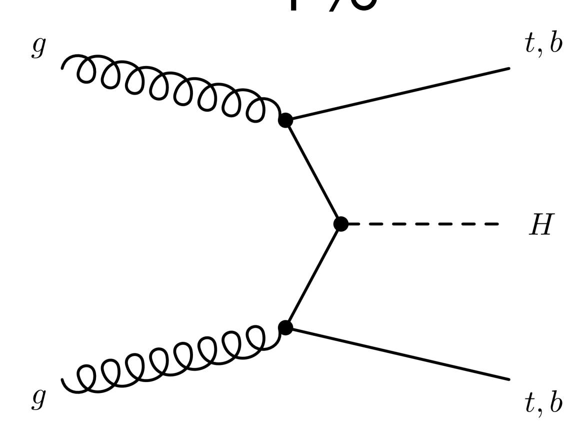
VBF
~7%



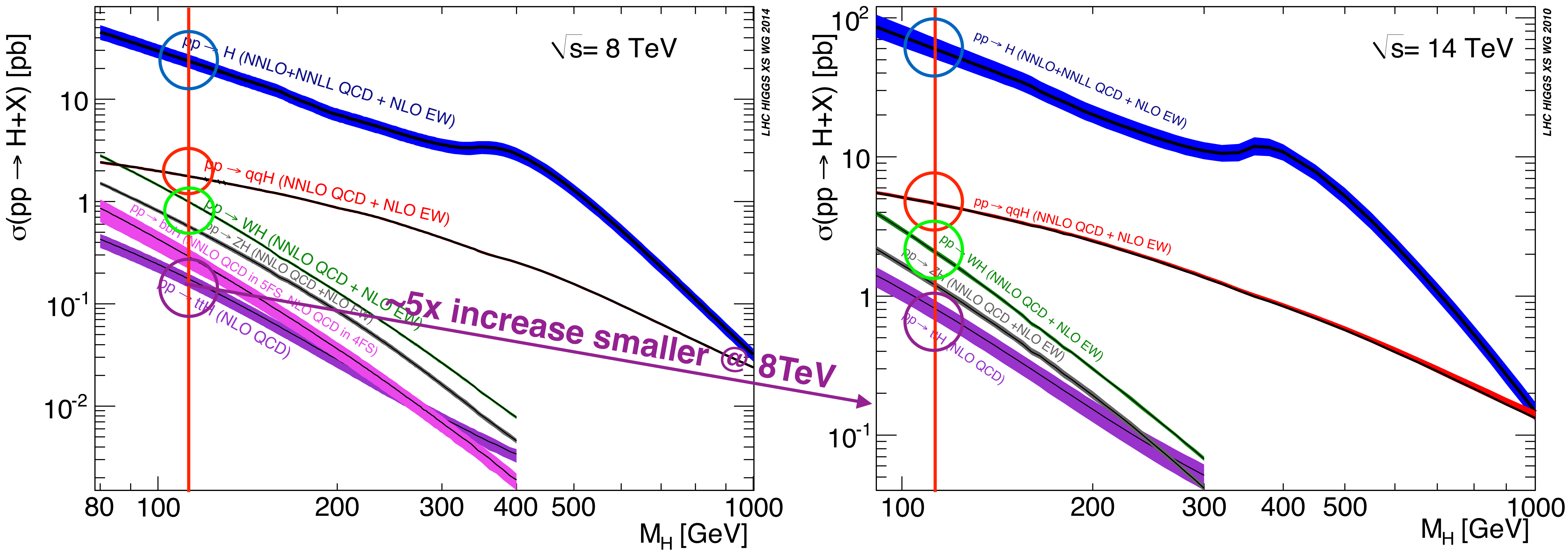
VH
~4%



ttH
~1%



Run 2 Dataset



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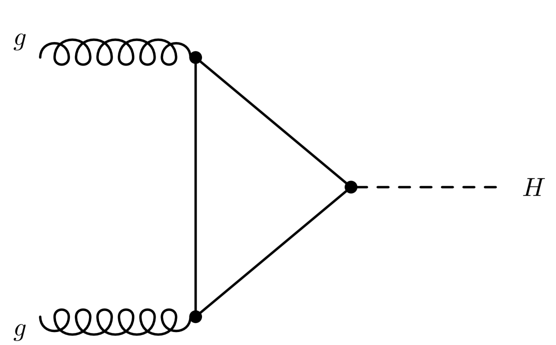
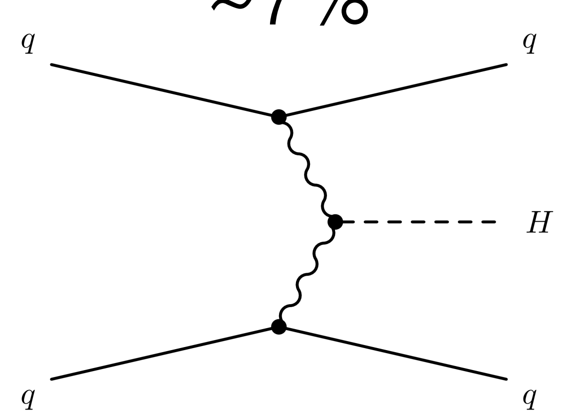


VBF
~7%



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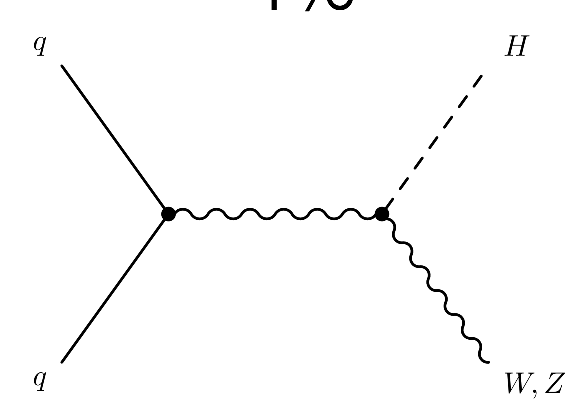
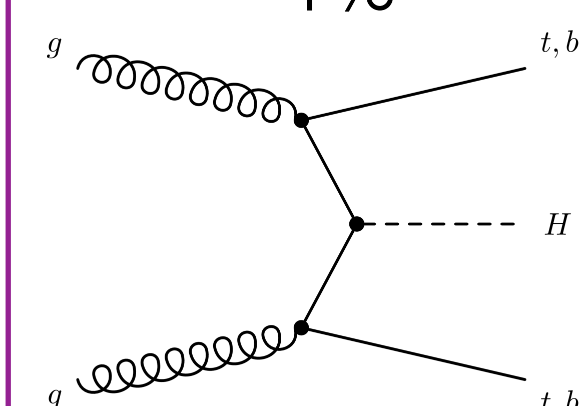
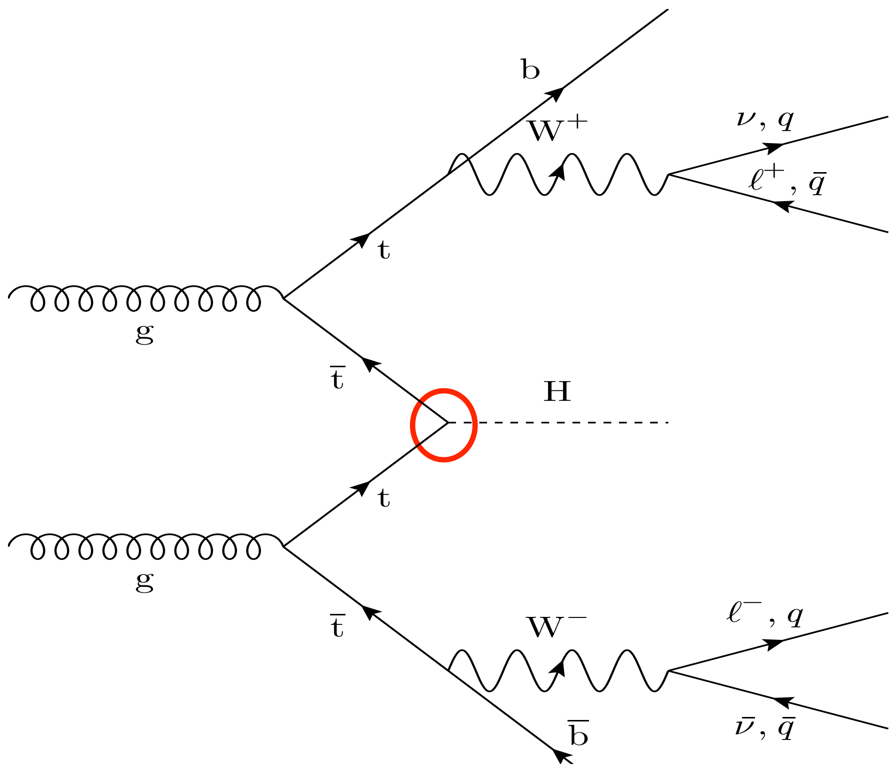


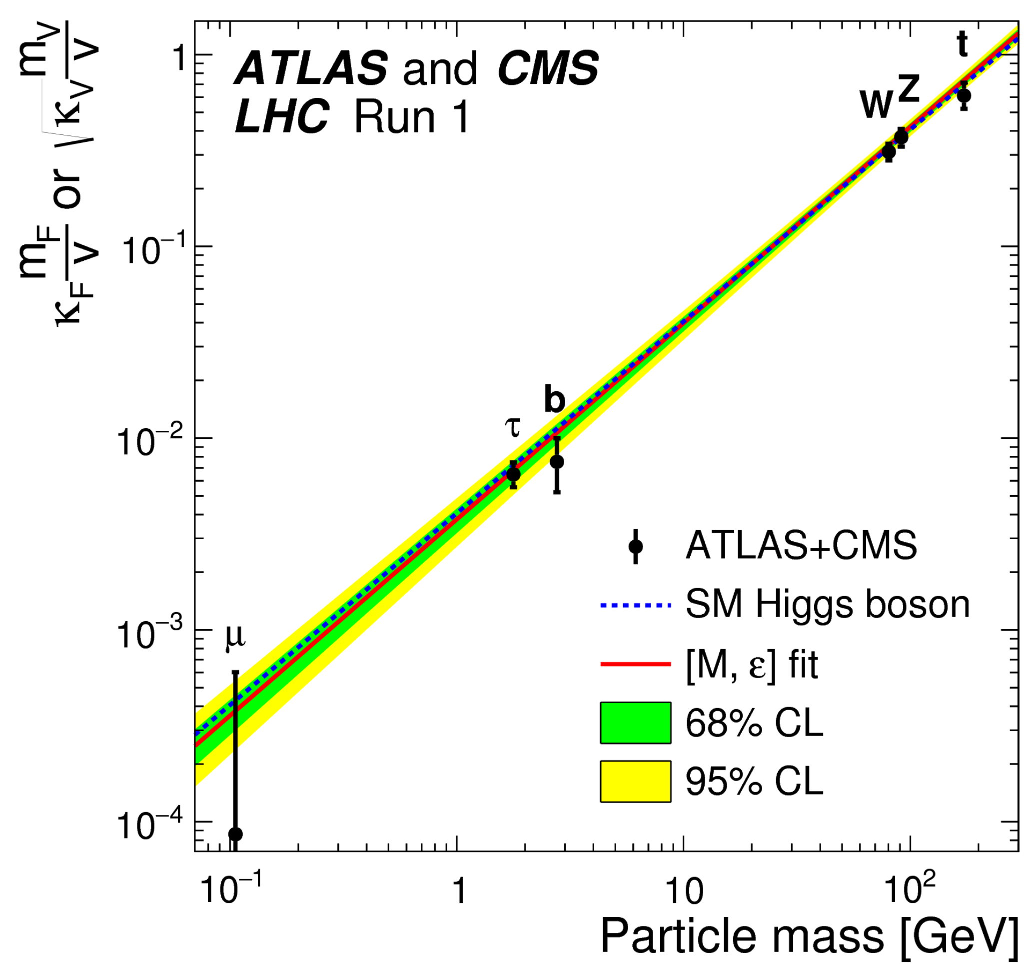
ttH
~1%



Importance of $t\bar{t}H$ Production

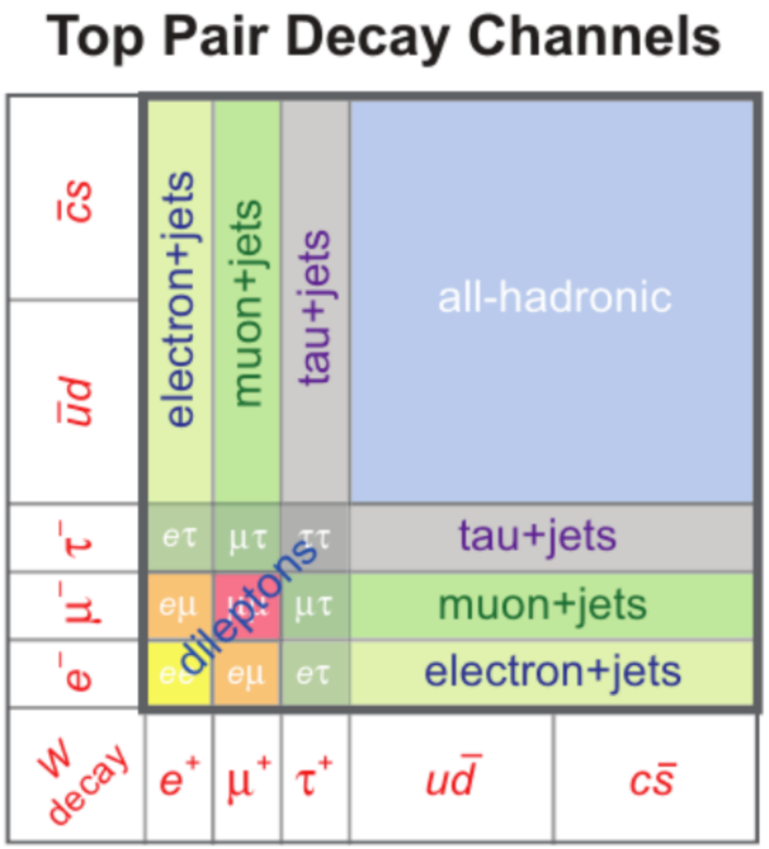
- In SM, Higgs Yukawa couplings proportional to mass.
- Top Yukawa coupling ($y_t \approx 1$).
- Measurement of $t\bar{t}H$ production:
  - Direct probe of y_t.
  - Deviation from SM - hint of energy scale for new physics.
  - May play a special role in EWSB?





How to hunt for $t\bar{t}H$

CMS $t\bar{t}H$ Observation **ATLAS $t\bar{t}H$ Observation**



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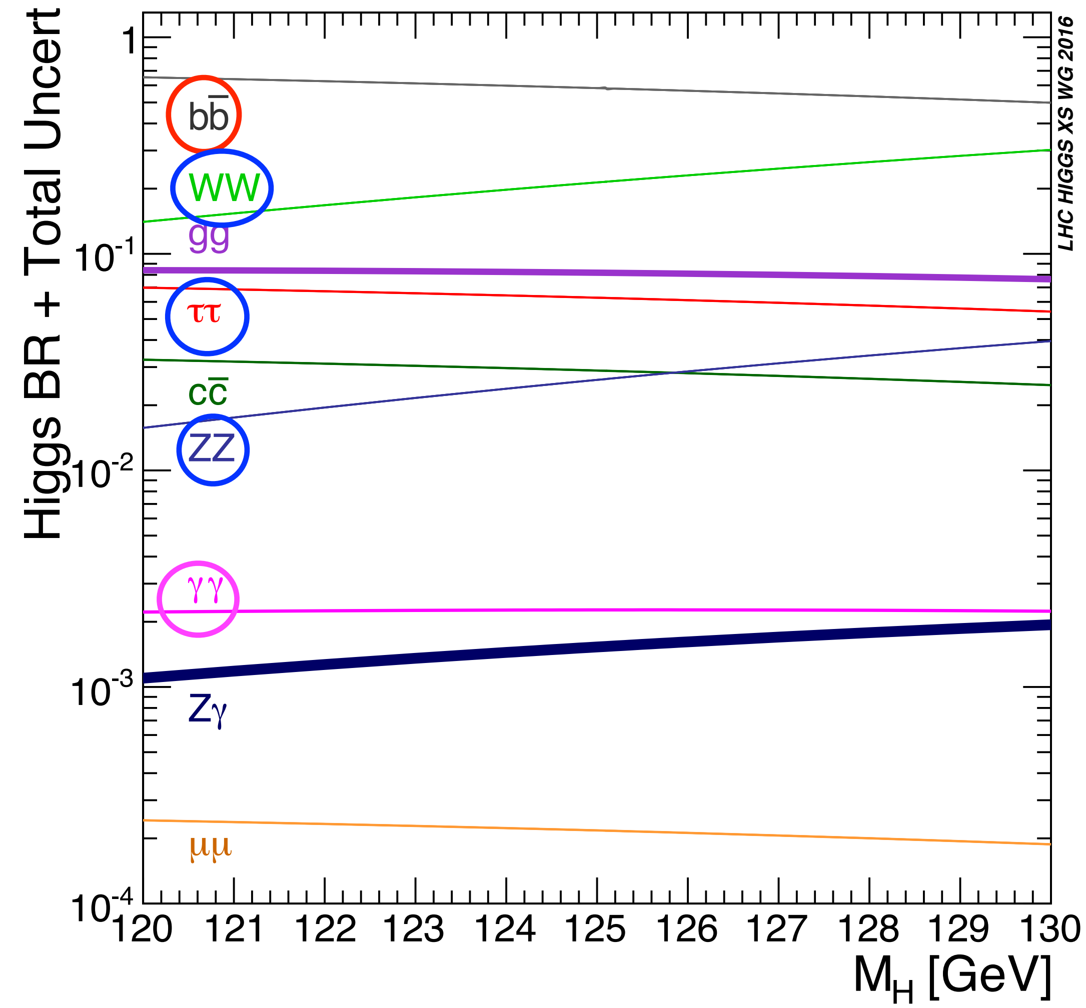
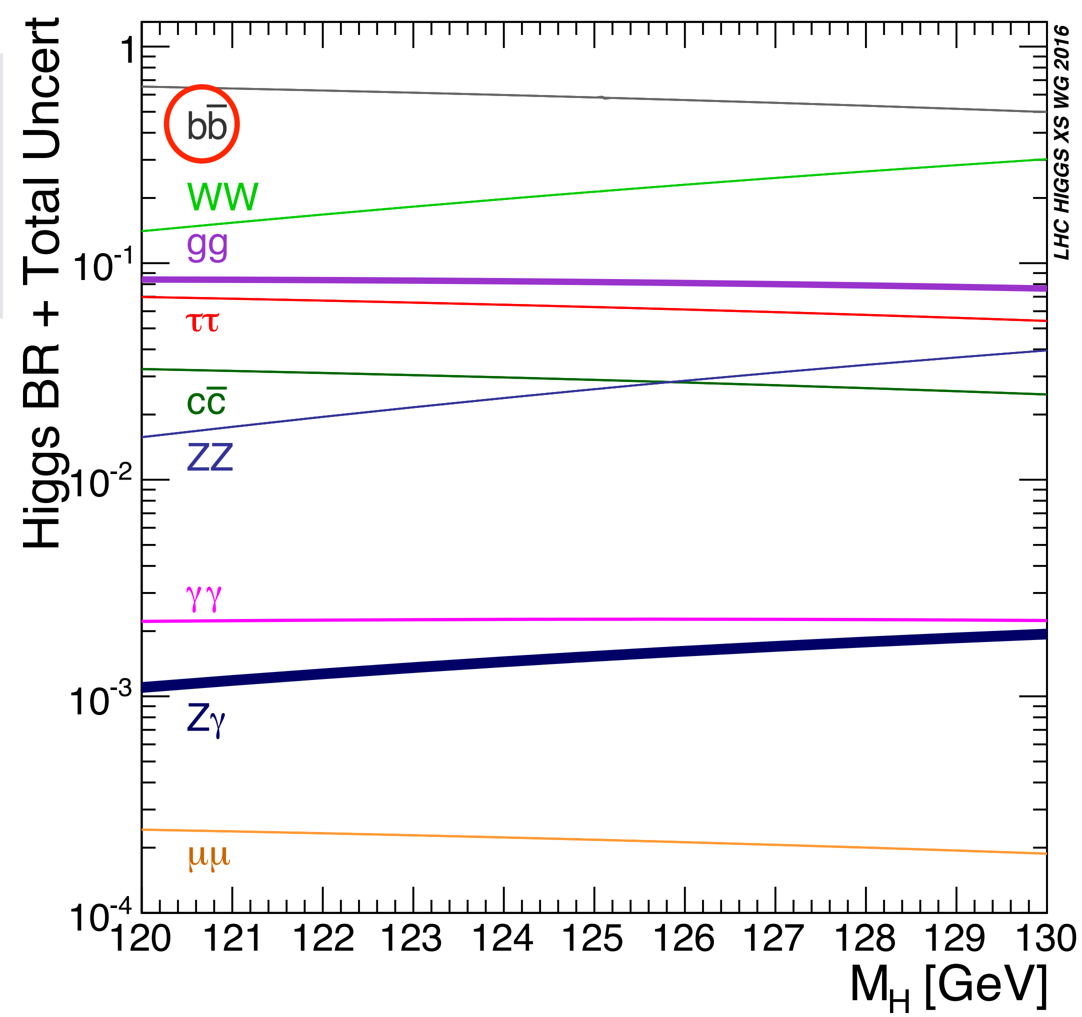


- $t\bar{t}H$ production has a **relatively low x-section** (~1% total Higgs production).
- Necessitates the combination of searches from multiple Higgs and top pair decay channels.
- Search channels in CMS and ATLAS: $t\bar{t}H(\gamma\gamma)$, $t\bar{t}H(bb)$, $t\bar{t}H(WW^*)$, $t\bar{t}H(\tau\tau)$,$t\bar{t}H(ZZ^*)$ (i.e. multilepton), $t\bar{t}H(ZZ^* \rightarrow 4l)$.

125 GeV Branching Ratio (%)				
H→bb	H→$\tau\tau$	H→ZZ	H→WW	H→$\gamma\gamma$
58.1%	6.3%	2.6%	21.5%	0.23%

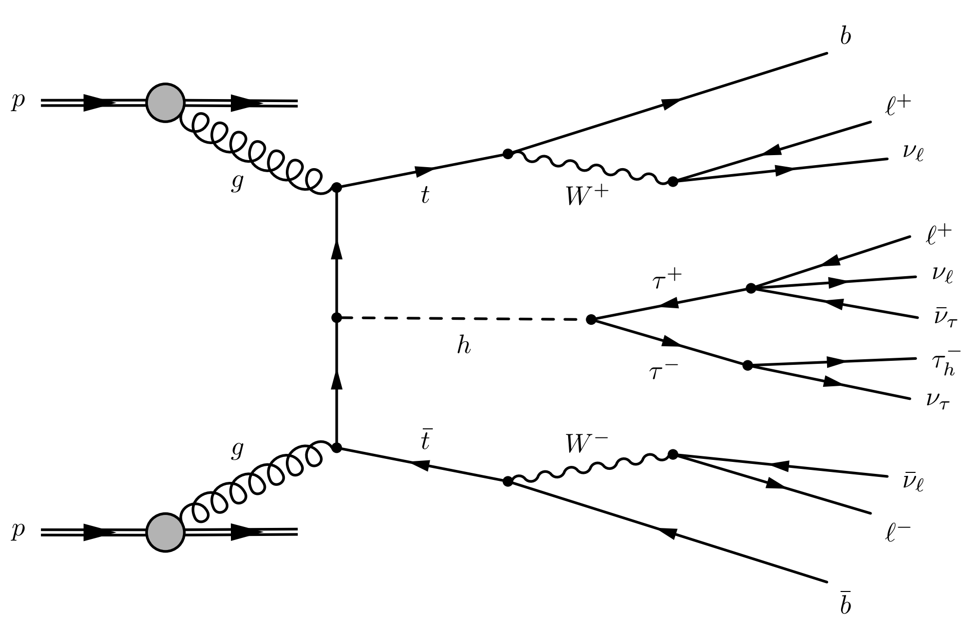
What does each channel bring?

Channel	Pros	Cons
$t\bar{t}H(bb)$	Largest branching fraction	Huge irreducible backgrounds from tt+HF

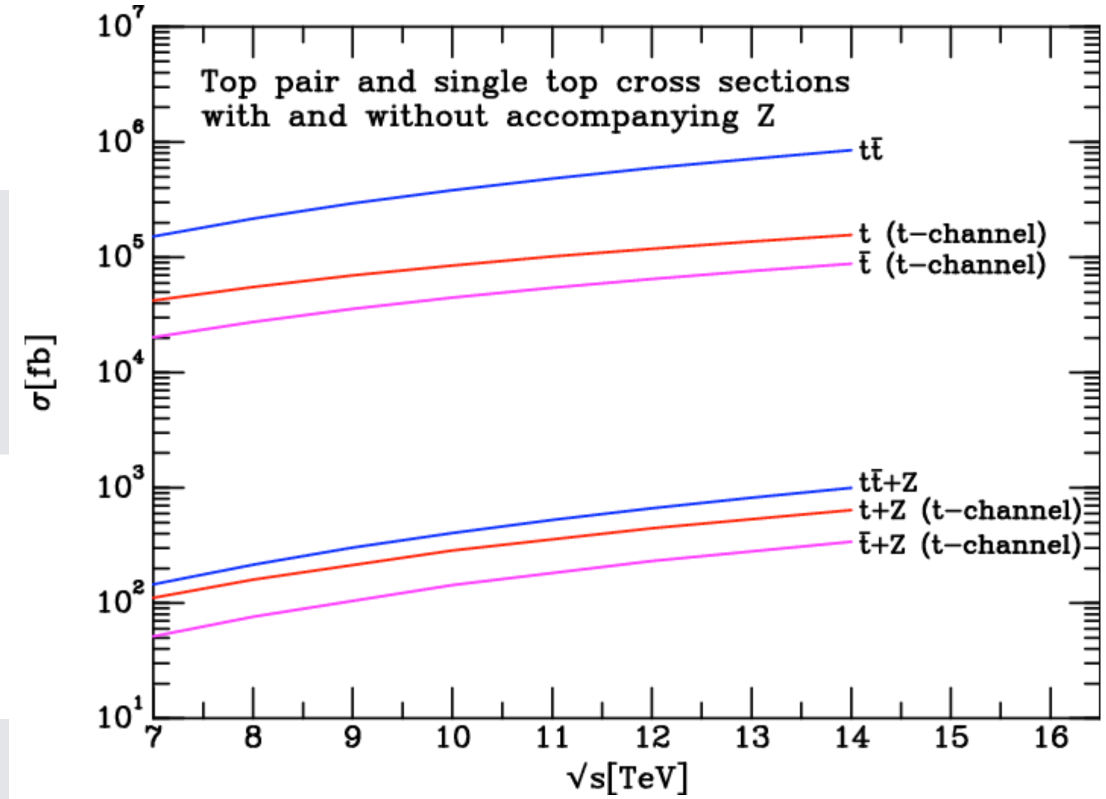


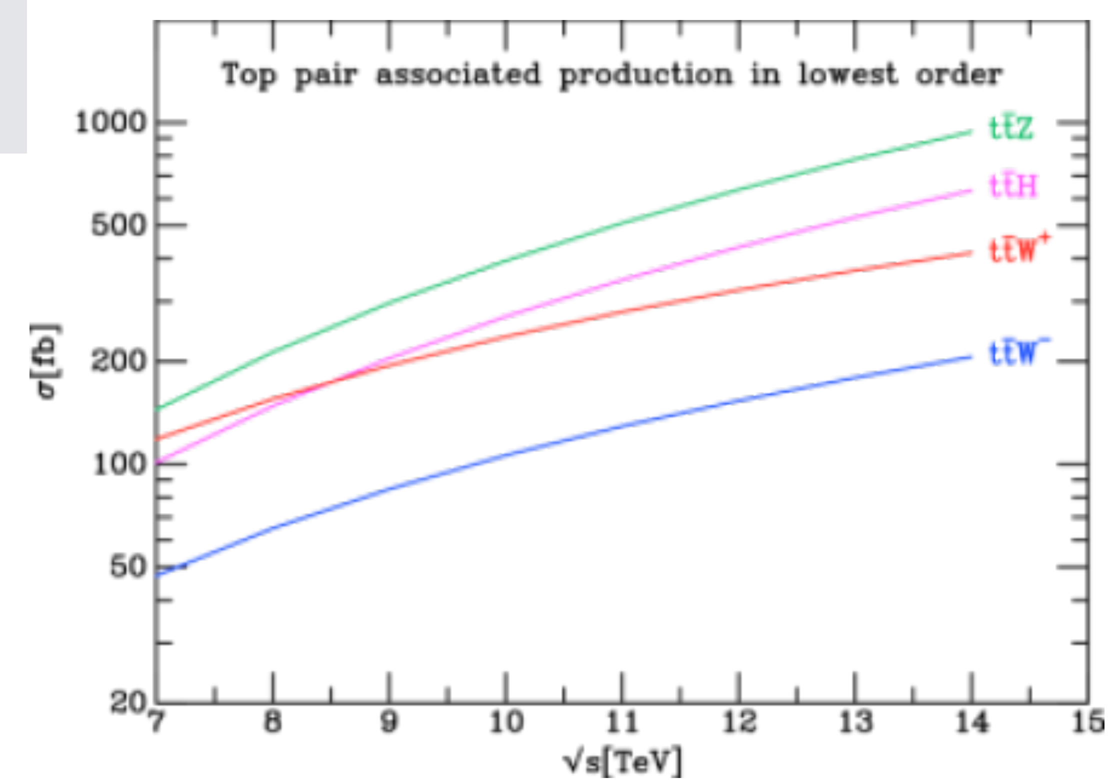
What does each channel bring?

Channel	Pros	Cons
$t\bar{t}H(bb)$	Largest branching fraction	Huge irreducible backgrounds from tt+HF
$t\bar{t}H(WW,ZZ^*,\tau\tau)$	Small backgrounds	Requires good understanding of fake leptons



arXiv:1302.3856





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$t\bar{t}H(\gamma\gamma)$	Very clean final state	Small branching fraction

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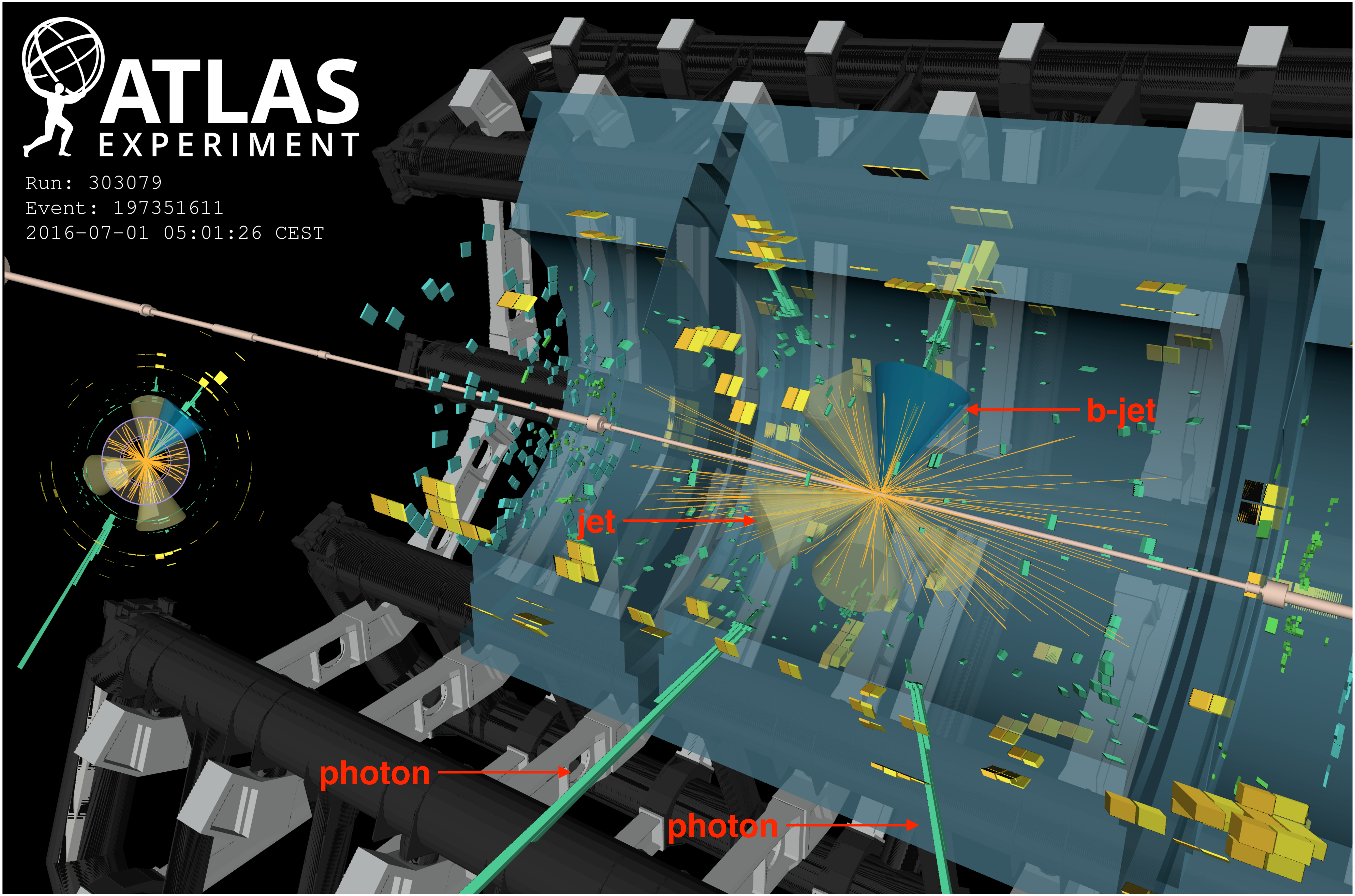
H→bb	**H→$\tau\tau$**	**H→ZZ**	**H→WW**	**H→$\gamma\gamma$**
58.1%	**6.3%**	**2.6%**	**21.5%**	**0.23%**

$t\bar{t}H(\gamma\gamma)$



Datasets Used in each Search

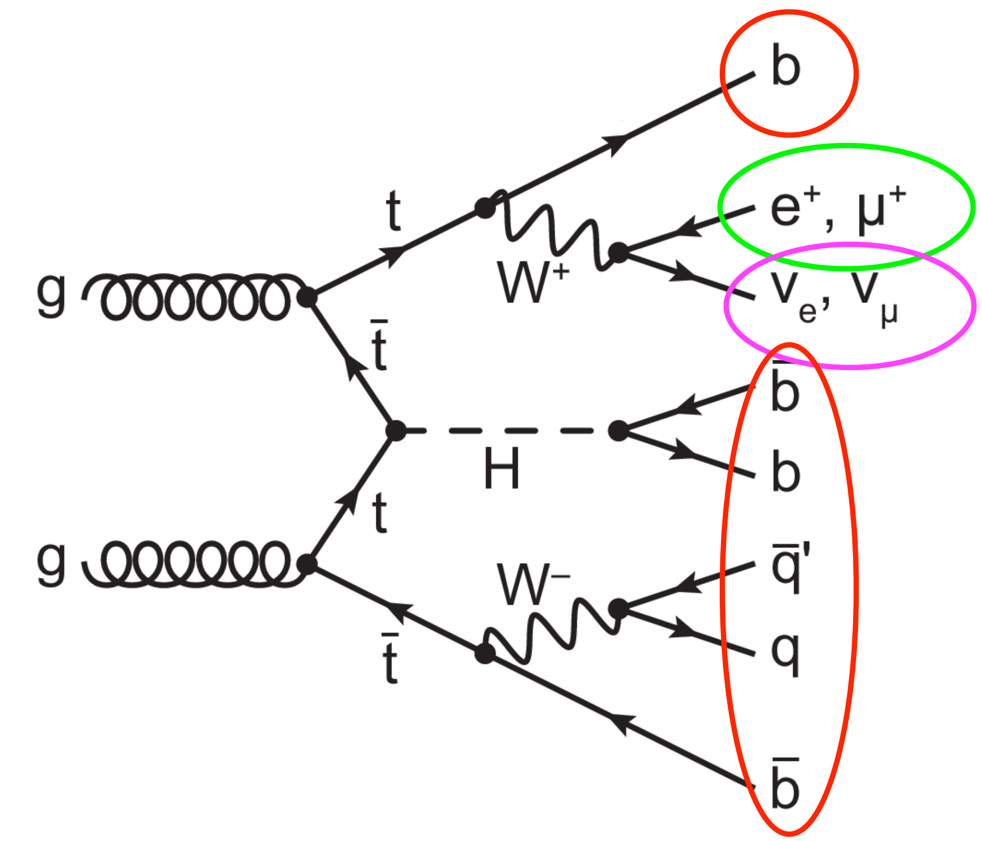
Channel	Pros	Cons	Datasets
$t\bar{t}H(bb)$	Largest branching fraction	Huge irreducible backgrounds from tt+HF	**CMS: 35.9 + 41.5 /fb** **ATLAS 36.1**
$t\bar{t}H(WW,ZZ^{*},\tau\tau)$	Small backgrounds	Requires good understanding of fake leptons	**CMS: 35.9 /fb** **ATLAS: 80 /fb**
$t\bar{t}H(\gamma\gamma)$	Very clean final state	Small branching fraction	**CMS: 35.9 + 41.5 /fb** **ATLAS: 139 /fb**

CMS ttH(bb) Leptonic

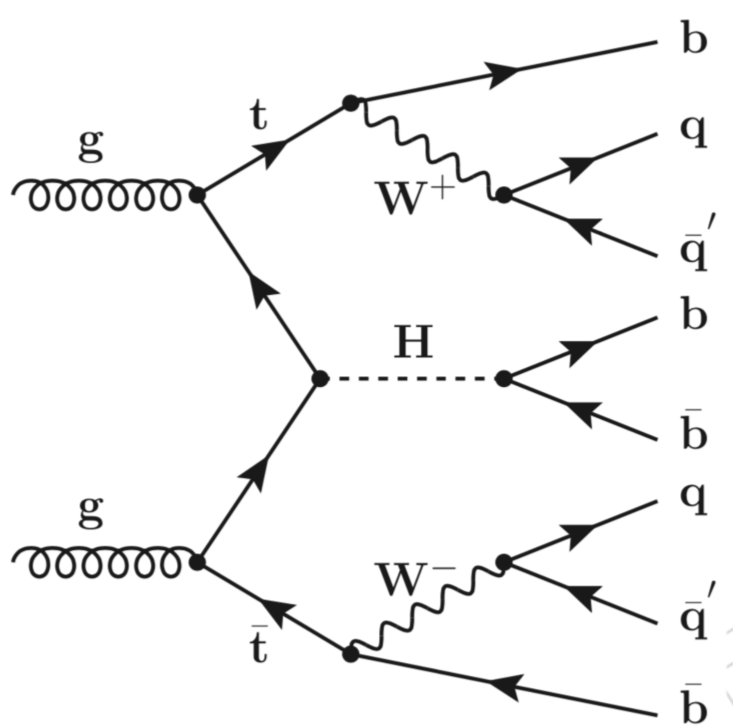
JHEP
HIG-18-030
41.5 /fb

- Largest branching fraction.
- Probes 3rd generation Yukawa couplings.
- Large and challenging $t\bar{t}$ background (irreducible $t\bar{t}$+≥1b). Large combinatorics in event reconstruction.
- **Single lepton: Lower purity, higher sensitivity.**
- **Dilepton: Higher purity, lower sensitivity.**
- **Fully Hadronic: Large QCD background, large statistics.**

Single lepton channel.

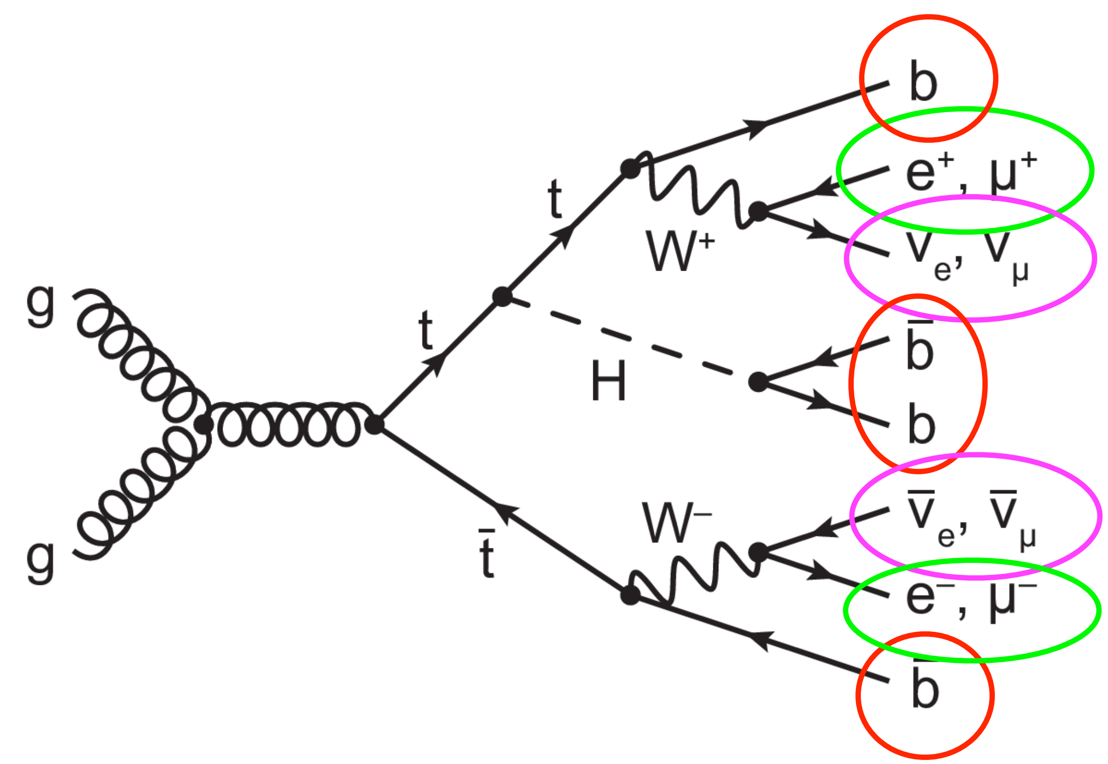


leptons == 1, MET > 20 GeV, ≥ 4 AK4 jets, ≥ 3 b-tags.



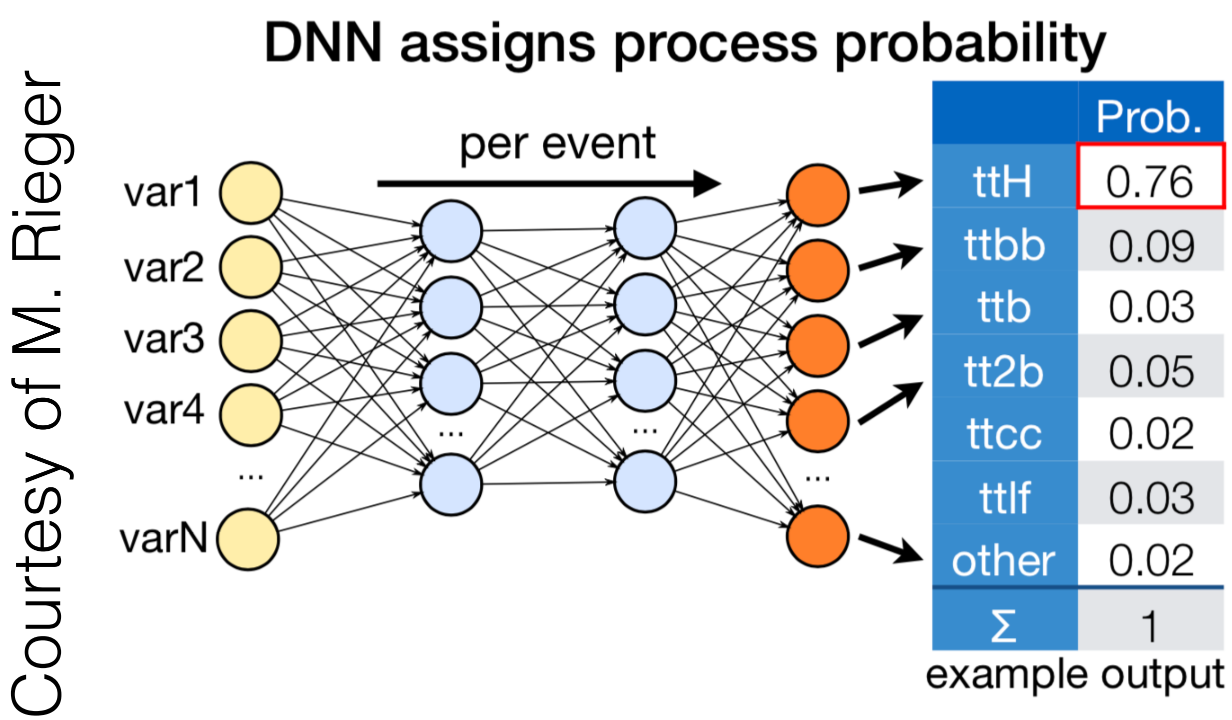
leptons == 0, ≥ 8 AK4 jets, ≥ 4 b-tags.

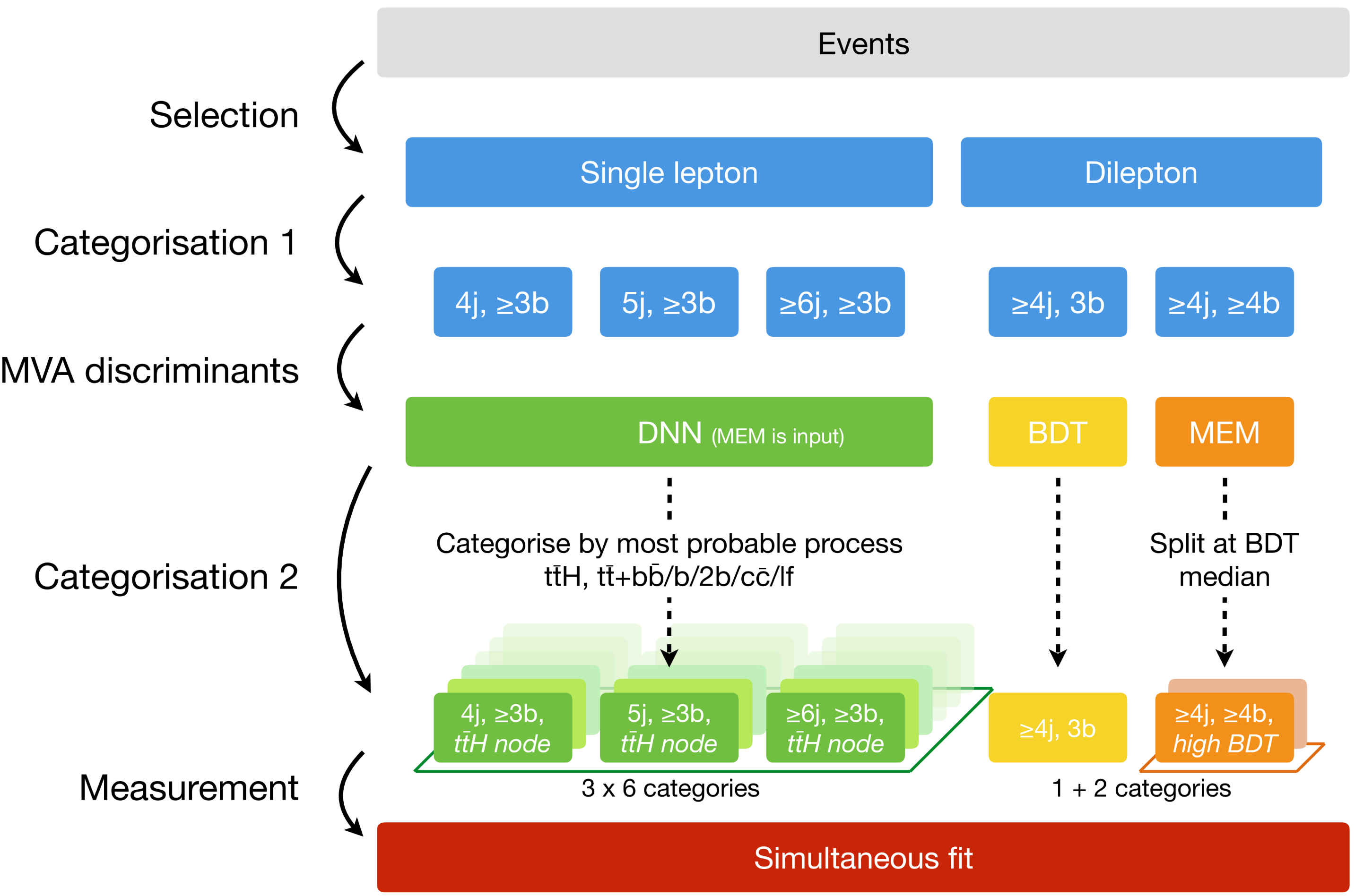
Dilepton channel.



#leptons == 2 OS, MET > 40 GeV, ≥ 4 AK4 jets, ≥ 3 b-tags.

Event Categorisation: Leptonic Channels

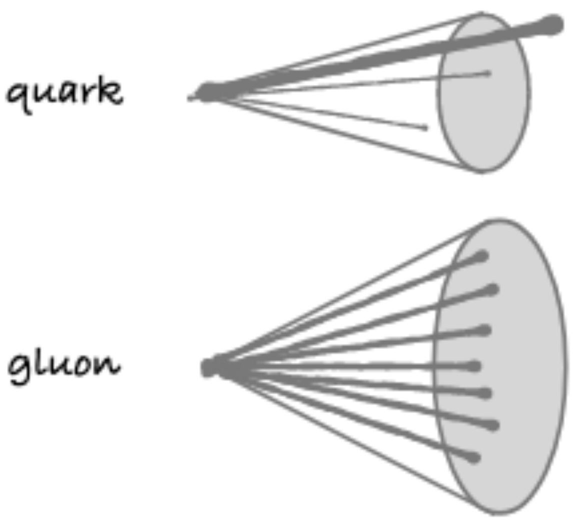




- MVA or MEM used in all channels.
- **Multi-class DNN** used for categorisation in Single lepton.
- Categorised according to highest process probability.
- Distribution of DNN output node values per category used in final fit.
- Generates analysis regions enriched in targeted process.

Event Categorisation: Fully Hadronic Channels

- Jets classified according to Quark-gluon likelihood (QGL) disc
- BDT discriminates light jets from W boson, from QCD/ISR jets.
- Evaluated for non-b jets only.
- QGLR = ratio constructed from likelihoods that encode the QGL disc. values and PDFs of when a jet originates from quark/gluon.



https://cds.cern.ch/record/2234117/files/DP2016_070.pdf

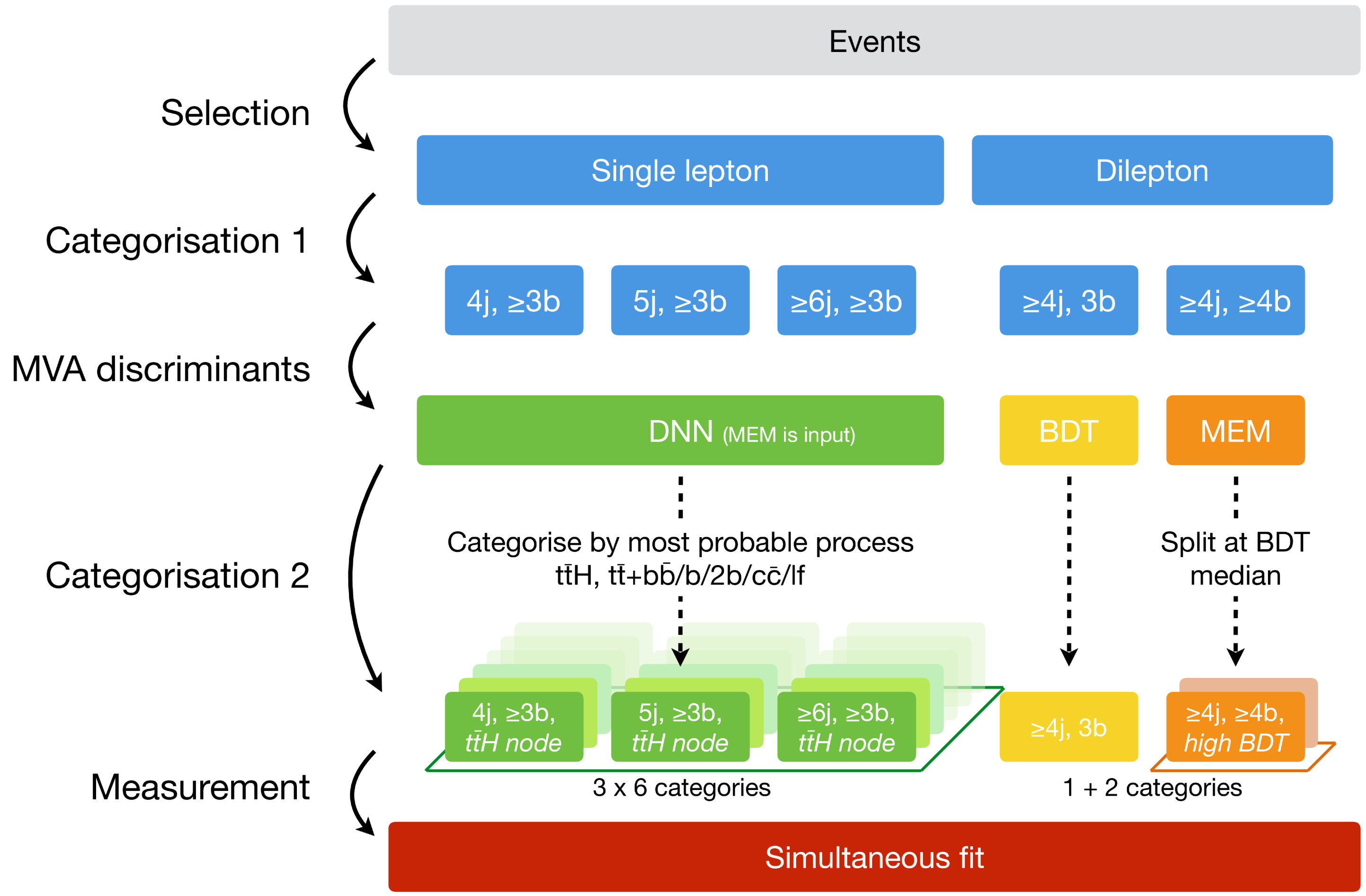
	$N_{\mathrm{b\ tag}} = 2$ $N_{\mathrm{b\ tag\ loose}} \geq 3$	$N_{\mathrm{b\ tag}} \geq 3$
QGLR > 0.5	CR (to extract distribution)	SR (final analysis)
QGLR < 0.5	Validation CR (to validate distribution)	VR (comparison with data)

Matrix element method used in fit to data.

Matrix Element Method (MEM)

Estimate of the probability of an event to be compatible with the signal hypothesis or one of the background hypotheses. MEM weights combined into a likelihood ratio for final discriminating variable.

Simultaneous Fit (very briefly)



e.g. this bit!

What do we measure?

Simultaneous fit of production XS * decay branching ratio.

Number of signal events:

$$\underbrace{}_{\text{}}$$

$$N_{sig} = \underbrace{L}_{\text{Luminosity}} \sum_i \sum_f \underbrace{\sigma_i}_{\text{Production XS}} \times \underbrace{\epsilon_i^f}_{\text{Signal efficiency}} \times \underbrace{A_i^f}_{\text{Signal acceptance}} \times \underbrace{B^f}_{\text{Branching fraction}}$$

Factorise out signal strengths for initial and final states for comparison with SM values:

$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}} \qquad \mu^f = \frac{B^f}{B^f_{SM}}$$

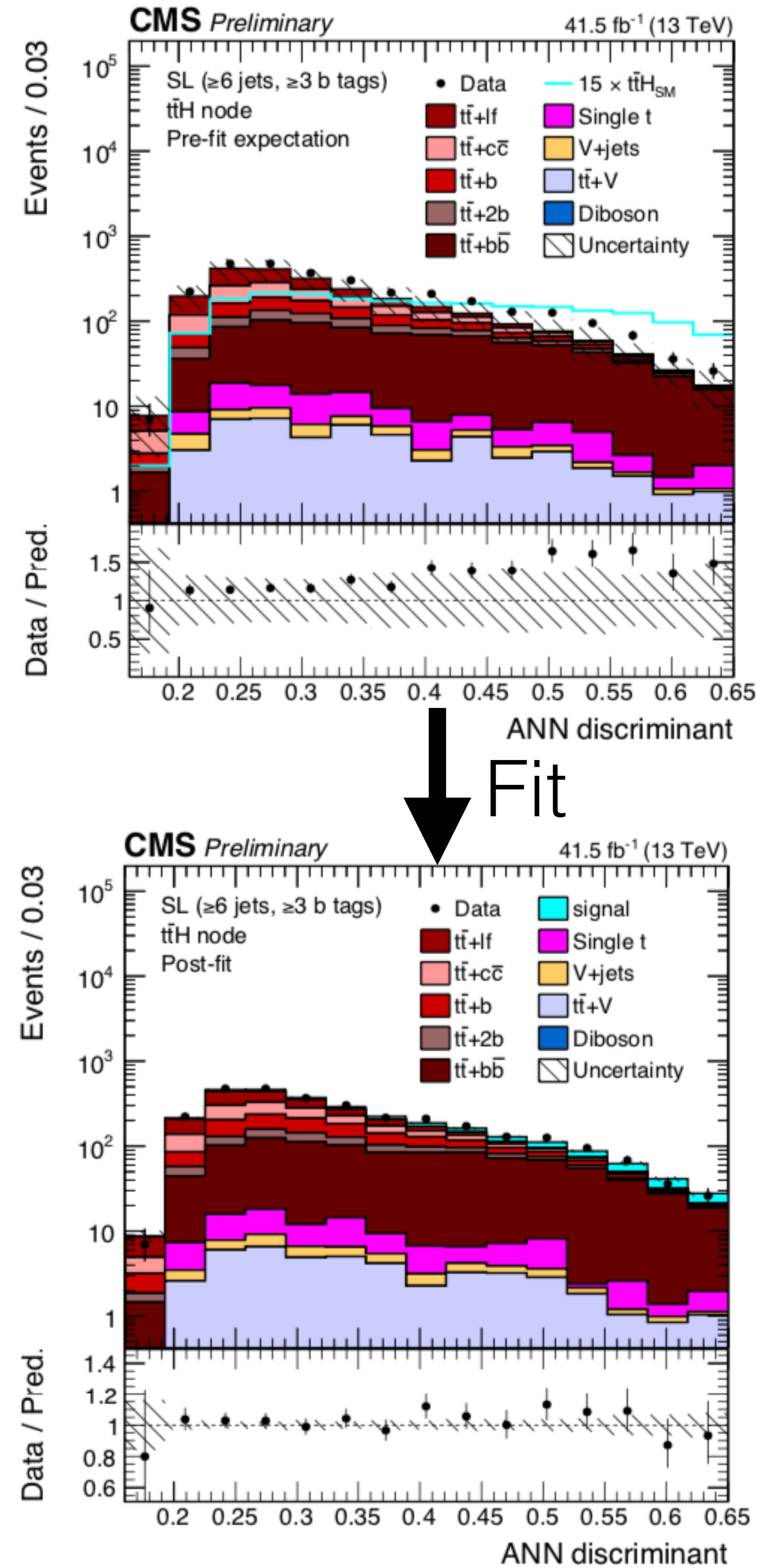
$$N_{sig} = L \sum_i \sum_f \mu_i \mu^f (\sigma_i^{SM} \times \epsilon_i^f \times A_i^f \times B^f_{SM})$$

Where signal strength of prod. XS * BR:

$$\mu_i \mu^f = \frac{\sigma_i B^f}{\sigma_i^{SM} B^f_{SM}}$$

Profile Likelihood Fit (PLF)

- Signal and background predictions depend on:
    - **Parameter of interest** (POI) e.g. signal strength.
    - **Nuisance parameters** (NPs) e.g. background normalisation.
- Build **likelihood function** from observables that encodes signal + background.
- Fit simulated distribution of observable to data.
- PLF includes systematic uncertainties in the likelihood.
- Principal: uncertainties in measurement of POI c.f. **imperfect knowledge** of the **parameters** of the signal+background of the **model**.
    - Systematics = **constrained nuisance parameters**.
    - **Modify background shapes and rates**.



Profile Likelihood Approach

- Define likelihood (binned):

μ = POI: signal strength parameter.
θ = nuisance parameters: inputs from subsidiary measurements.

$$\mathcal{L}(n;\overbrace{\mu,\theta}) = \prod_{i \in bins} \mathcal{P}(n_i|\mu \cdot S_i(\theta) + B_i(\theta)) \times \prod_{j \in syst} \mathcal{G}(\,\theta_j, \Delta\theta_j)$$

observed bin contents

Profile Likelihood Approach

- Define likelihood (binned):

$$\mathcal{L}(n;\mu,\theta) = \prod_{i \in bins} \underbrace{\mathcal{P}}_{\text{Poisson}}(n_i | \overbrace{\mu \cdot S_i(\theta) + B_i(\theta)}^{\text{S+B prediction in bin 'i'}}) \times \prod_{j \in syst} \mathcal{G}(\theta_j, \Delta\theta_j)$$

Profile Likelihood Approach

- Define likelihood (binned):

- Prior implemented as penalty term.
- Usually Gaussian (interpret $\pm\Delta\theta$ as Gaussian std dev).
- Define effect of systematic j on prediction n in bin i at $\pm\Delta\theta$ then interpolate and extrapolate to any value.

$$\mathcal{L}(n;\mu,\theta) = \prod_{i\in bins} \mathcal{P}(n_i|\mu\cdot S_i(\theta) + B_i(\theta)) \times \prod_{j\in syst} \mathcal{G}(\theta_j, \Delta\theta_j)$$

Profile Likelihood Approach

- N-dimensional likelihood maximisation problem (or **negative log-likelihood minimisation**).
- N-D fit result, yields POI value that maximises the likelihood.

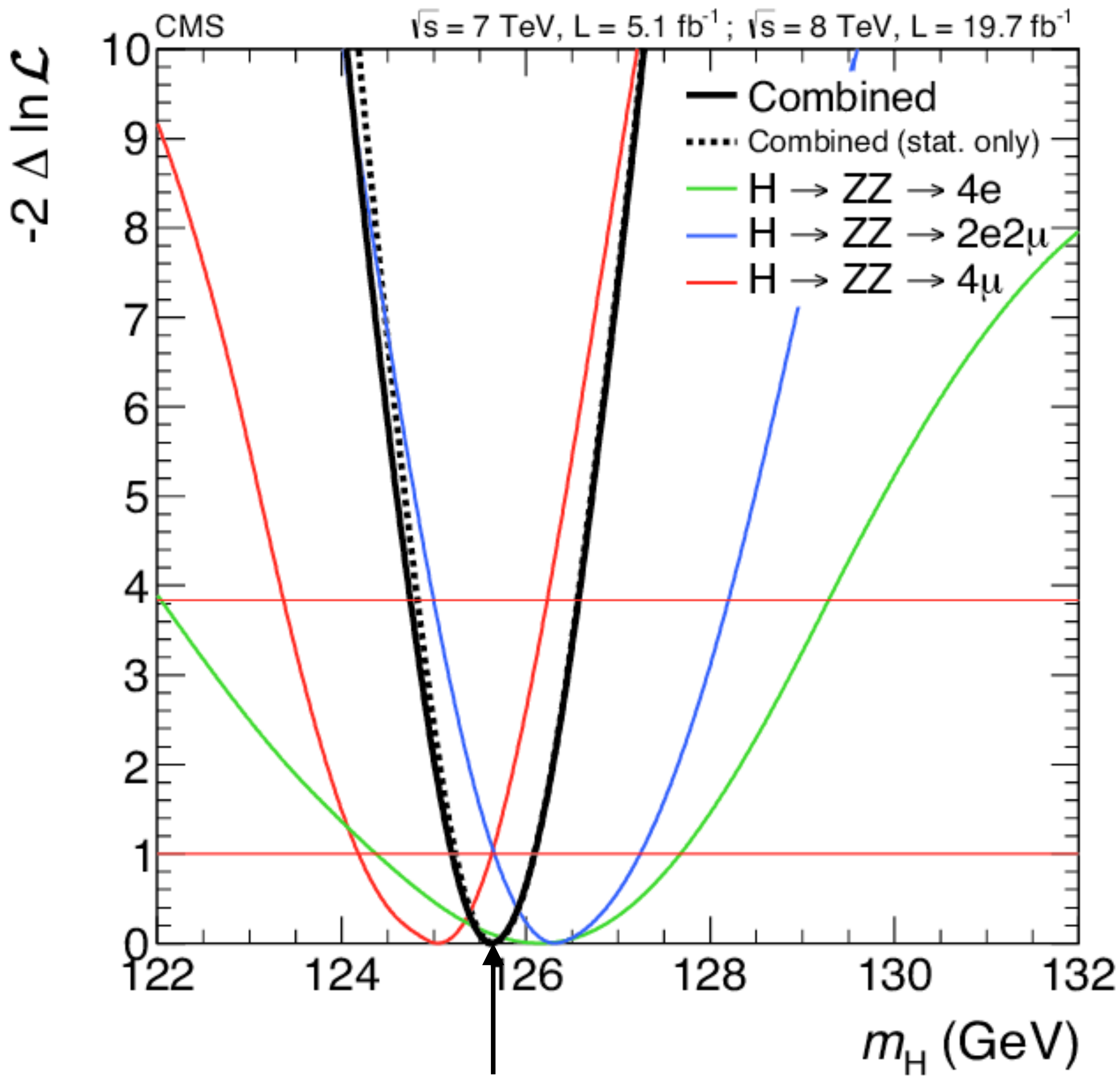
$$\mathcal{L}(n;\mu,\theta) = \prod_{i \in bins} \mathcal{P}(n_i|\mu \cdot S_i(\theta) + B_i(\theta)) \times \prod_{j \in syst} \mathcal{G}(\,\theta_j, \Delta\theta_j)$$

- Maximum likelihood fits performed on **all categories** in analysis **simultaneously** to extract POI.

Profile Likelihood Approach

- N-dimensional likelihood maximisation problem (or negative log-likelihood minimisation).
- N-D fit result, yields POI value that maximises the likelihood.

$$\mathcal{L}(n;\mu,\theta) = \prod_{i\in \ldots} \ldots \prod_{j \in syst} \mathcal{G}(\theta_j, \Delta\theta_j)$$



- Maximum likelihood … multaneously to extract POI.

Fit result = “best point” (μ, θ) : take value of POI and values of NP at minimum

Profile Likelihood Ratio

- **Neyman-Pearson Lemma** = optimal discriminator when testing a hypothesis is the likelihood ratio e.g. $L(H_0)/L(H_1)$ where **H_0 = no signal (μ=0)** and **H_1 = signal (μ>0)**.
- In case of PLR:

Maximise L for a given $\boldsymbol{\mu}$ '**conditional**' likelihood

Profile likelihood ratio only dependant on μ

$$\lambda(\mu) = \frac{\mathrm{L}(\mu, \hat{\hat{\theta}}_\mu)}{\mathcal{L}(\hat{\mu}, \hat{\theta})}$$

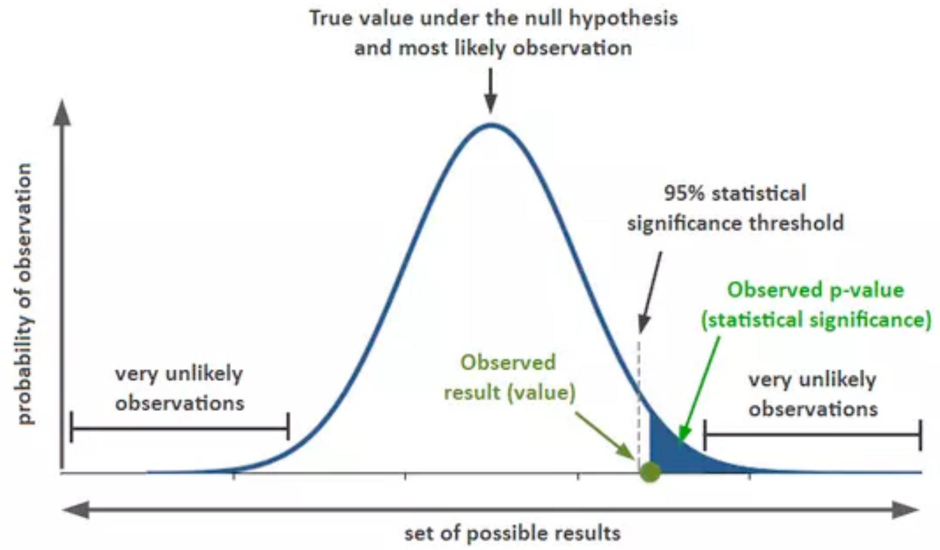
Maximise L '**unconditional**' likelihood

- Profile likelihood ratio ➞ used to define test statistic.

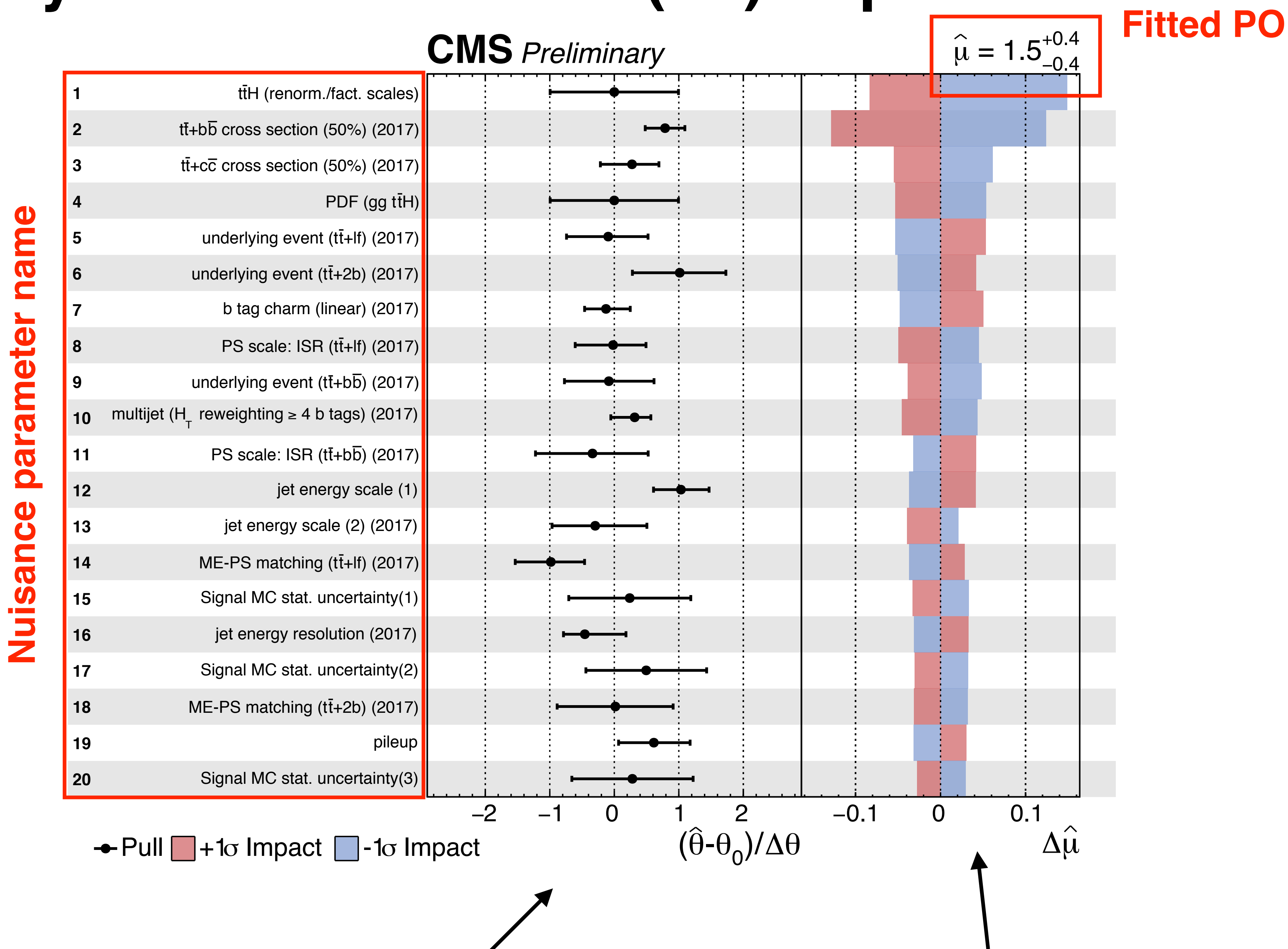
$$t_\mu = -2\ln\lambda(\mu) \qquad q_0 = \begin{cases} -2\ln\lambda(0) & ,\hat{\mu} \geq 0 \\ 0 & ,\hat{\mu} < 0 \end{cases}$$

- Distribution of test statistics used to build p-value and significance.

$$p_0 = \int_{q_0,obs}^{\inf} f(q_0|0)dq_0 \qquad Z_0 = \Phi^{-1}(1 - p_0)$$



Impact of Systematics CMS ttH(bb) Leptonic



Post-fit pull of nuisance parameters w.r.t pre-fit values θ_0 and uncertainties $\Delta\theta$.

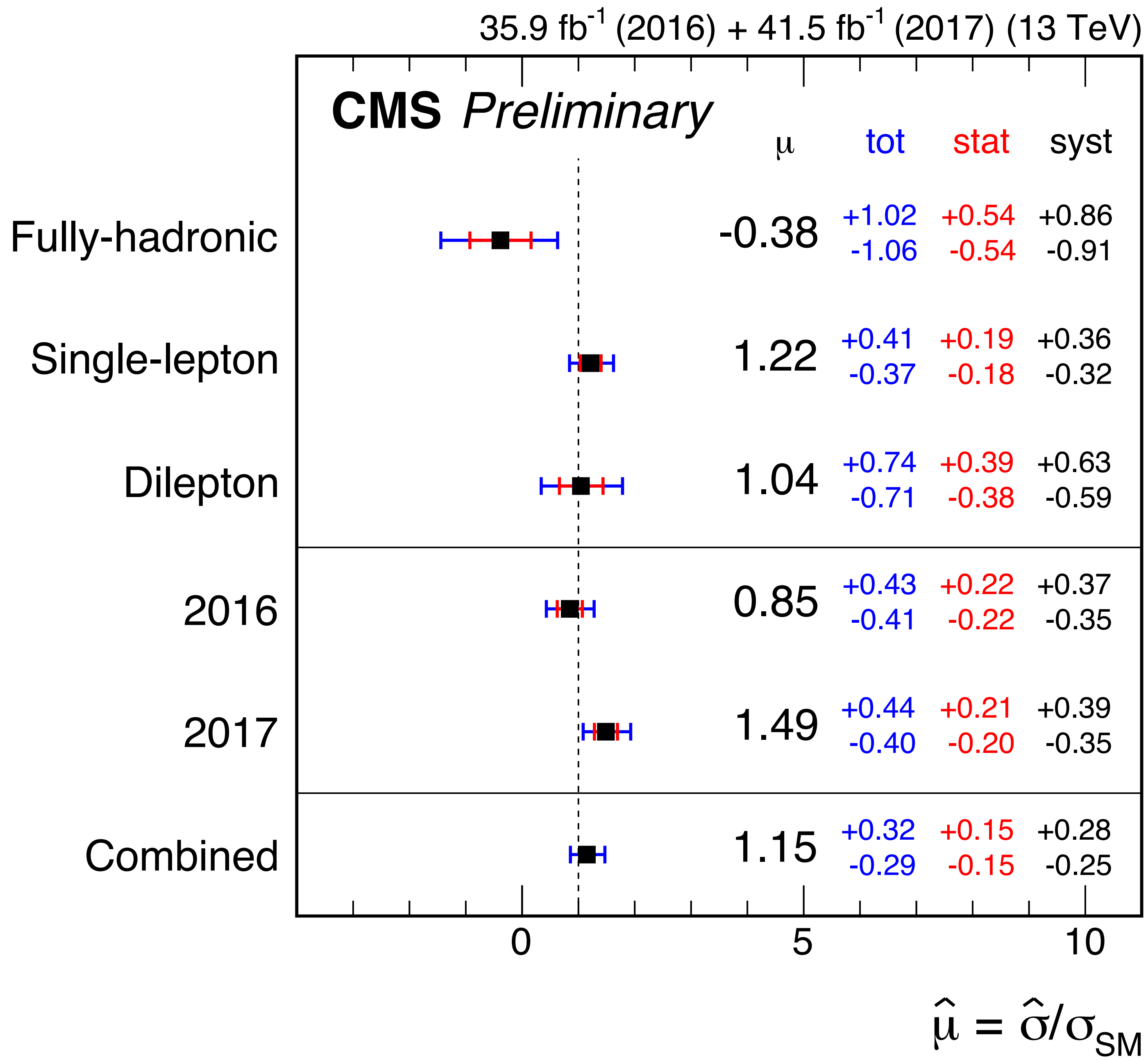
Impact on the signal strength is = coloured bars = diff. of nominal best fit value w.r.t best fit value when fixing NP to best fit value (θhat) ± post-fit uncertainty.

Impact of Systematics CMS ttH(bb) Leptonic

Uncertainty source	$\Delta\hat{\mu}$
Total experimental	$+0.15/-0.13$
b tagging	$+0.08/-0.07$
jet energy scale and resolution	$+0.05/-0.04$
Total theory	$+0.23/-0.19$
signal	$+0.15/-0.06$
$t\bar{t}$+hf modelling	$+0.14/-0.15$
QCD background prediction	$+0.10/-0.08$
Size of simulated samples	$+0.10/-0.10$
Total systematic	$+0.28/-0.25$
Statistical	$+0.15/-0.15$
Total	$+0.32/-0.29$

- Take home message:
  - **Limited by systematic uncertainties**.
  - Large contributions from theory uncertainty, mainly tt+HF modelling.
  - Age old problem and still a massive challenge.

CMS ttH(bb) Leptonic

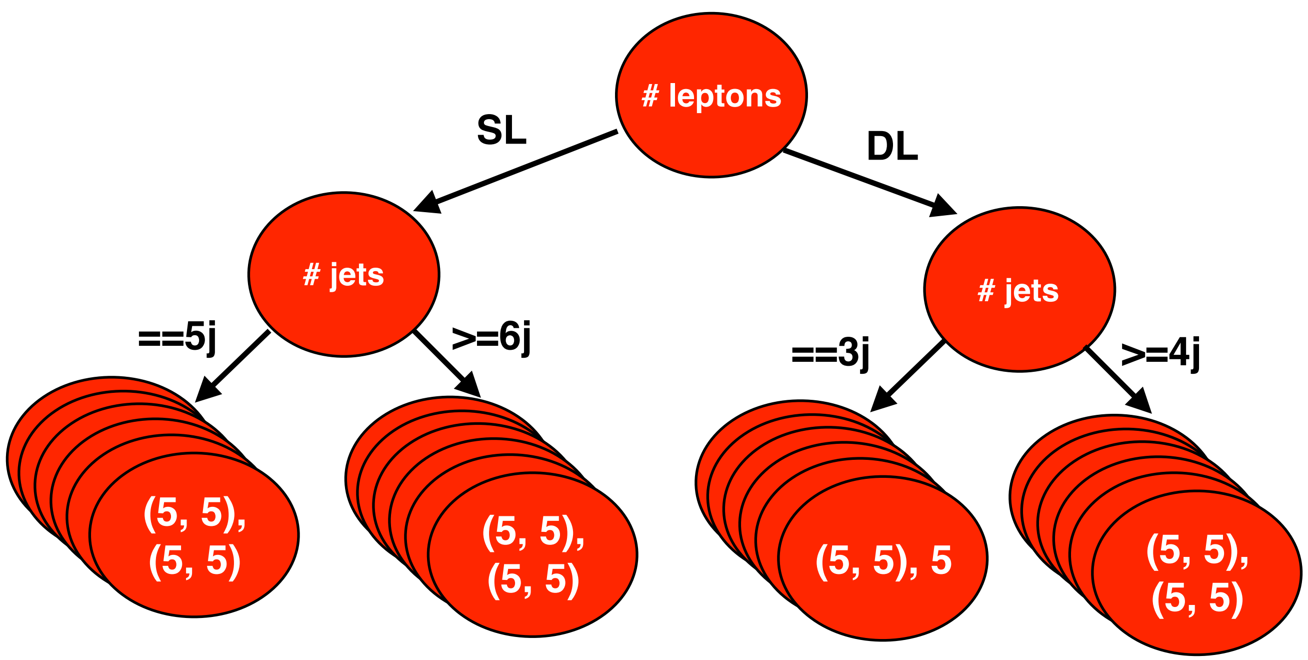


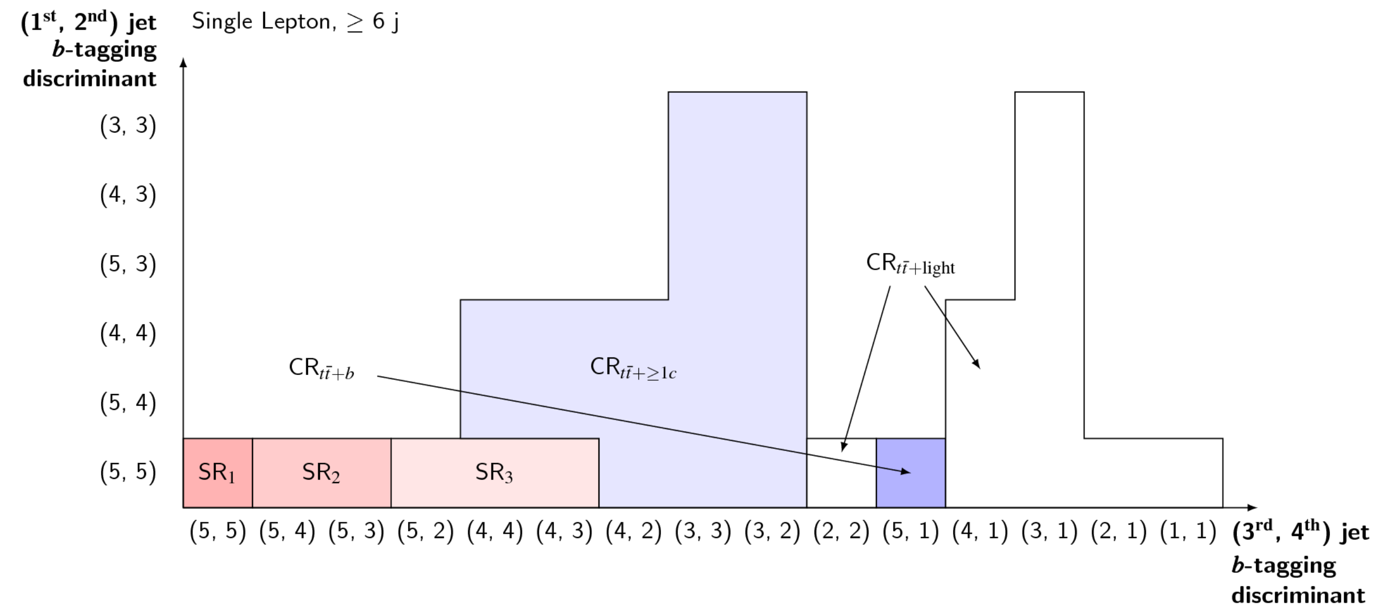
	$\hat{\mu}$ ± tot (±stat ± syst)	significance obs (exp)
FH+SL+DL combined 2016+2017	$1.15^{+0.32}_{-0.29}\left(^{+0.15}_{-0.15}\ ^{+0.28}_{-0.25}\right)$	$3.9\,\sigma$ $(3.5\,\sigma)$

ATLAS ttH(bb) Leptonic Strategy

CERN-EP-2017-291

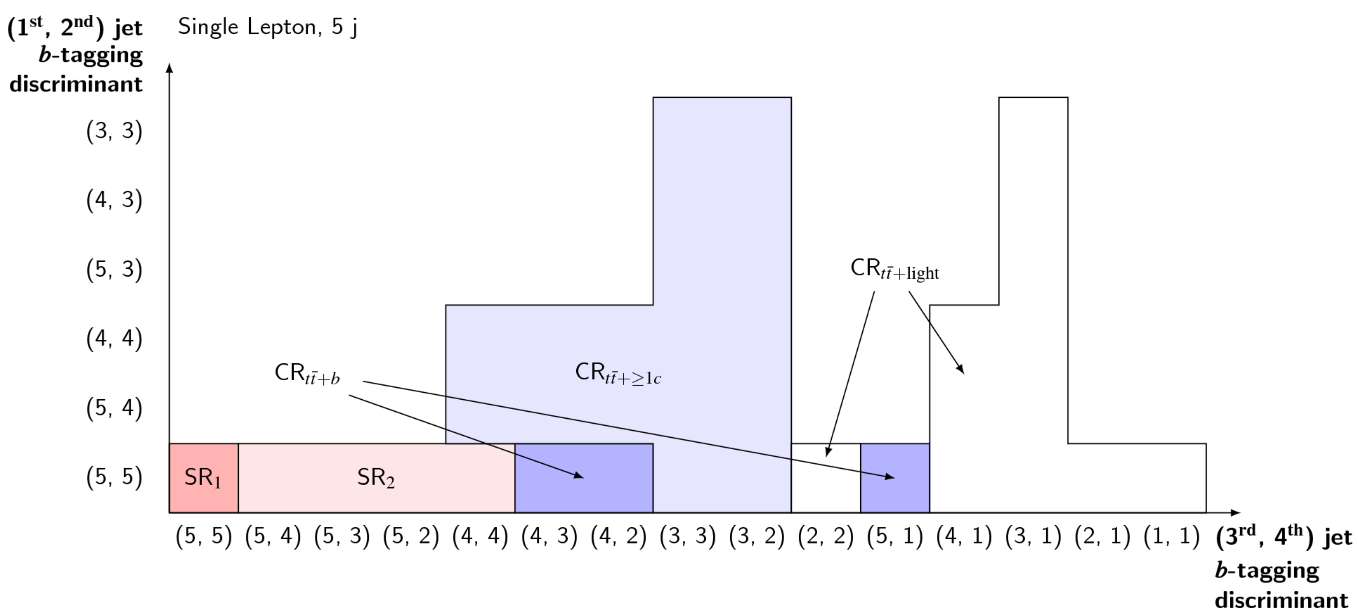
36.1 /fb





SR = MVA used to separate signal from bckg - $t\bar{t}H$, $t\bar{t}+b\bar{b}$ enriched.

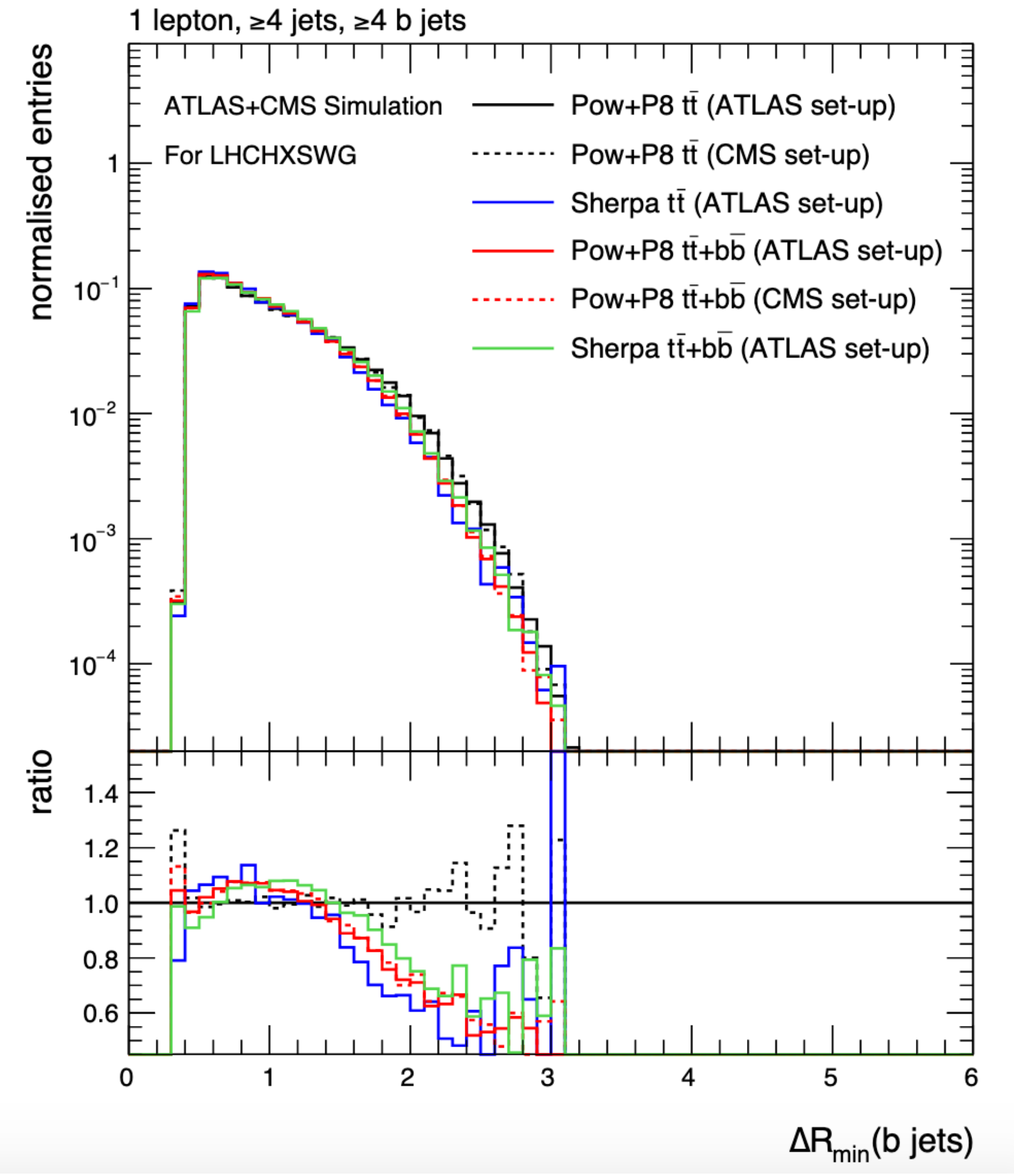
CR = Fit event yield (HT hadronic) - tt+light(tt+c) enriched.



- Discriminant value assigned to jet according to tightest WP it satisfies: 1=none, 2=loose, 3=medium, 4=tight, 5=very tight.
- Jets ordered by the value of b-tagging discriminant and used to categorise events.
- e.g. (5, 5) (5, 5) = 1st, 2nd, 3rd & 4th jets pass v. tight.

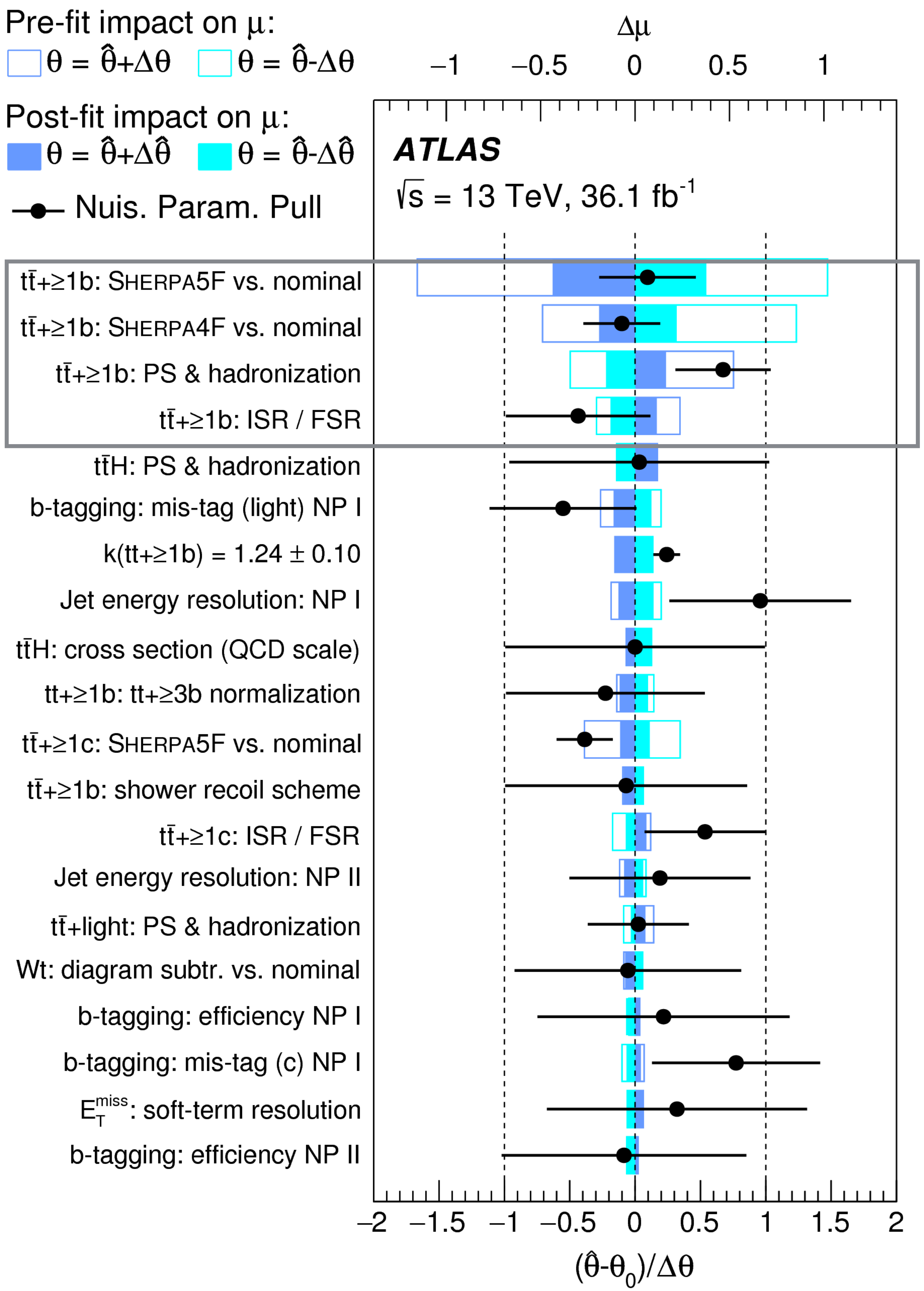
tt+jets Modelling

- **Largest background + major source of uncertainty.**
- **HF dominates signal-like regions.**
- Modelled using NLO matrix element generator + parton shower.
- Both CMS and ATLAS simulations generate additional b-jets (not from top decay) in parton shower.
- ATLAS simulation: scaled to sample additional b-jets generated with NLO precision.
- Understanding/comparisons of this background from the two collaborations is still ongoing.
- Uncertainties implemented that cover these differences in both collaborations.

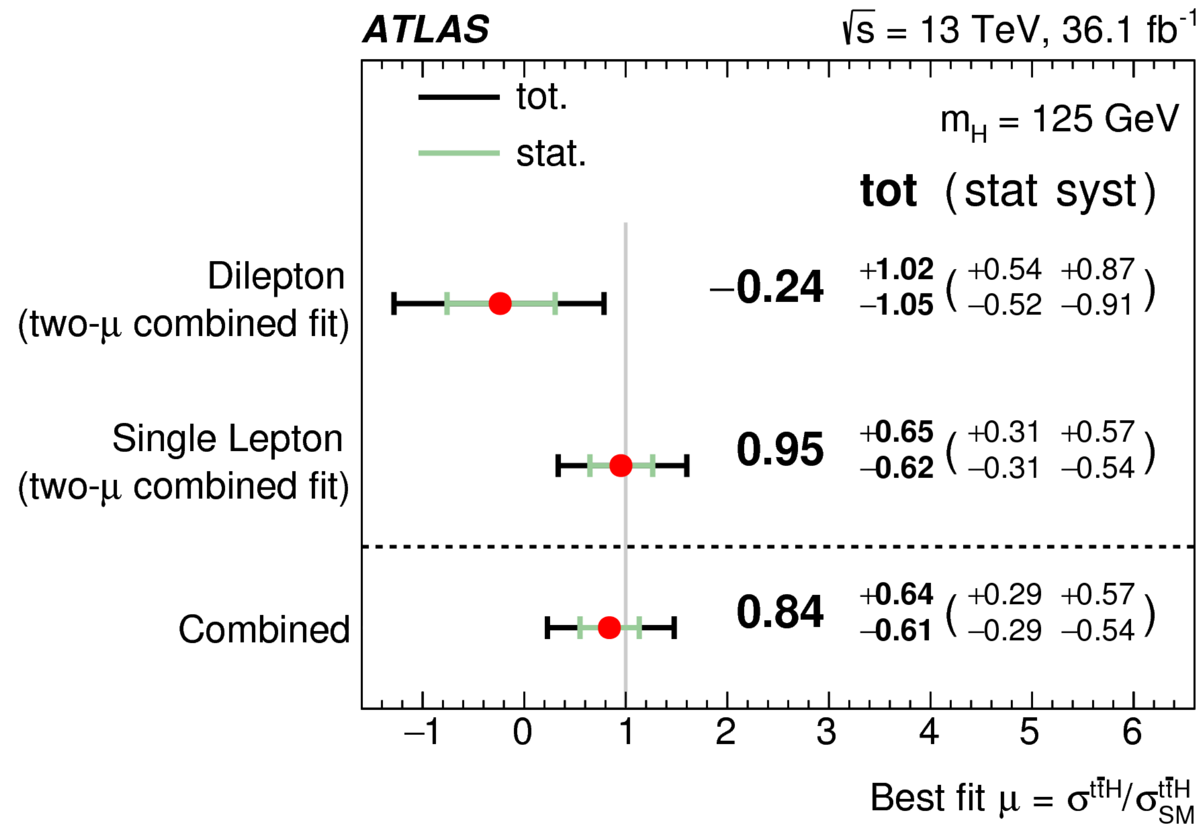


Nuisance Parameter Impacts

- **tt+jets modelling = dominant source of systematic** unc.
- Analyses very cautious, don't 'trust' MC - 17 independent NP's!
- Shape (kinematic) and normalisation uncertainties.
- tt+≥1b, tt+≥1c, tt+light affected by different sources of unc. due to availability of precision measurements in data, mass differences, difference in Feynman diagrams.

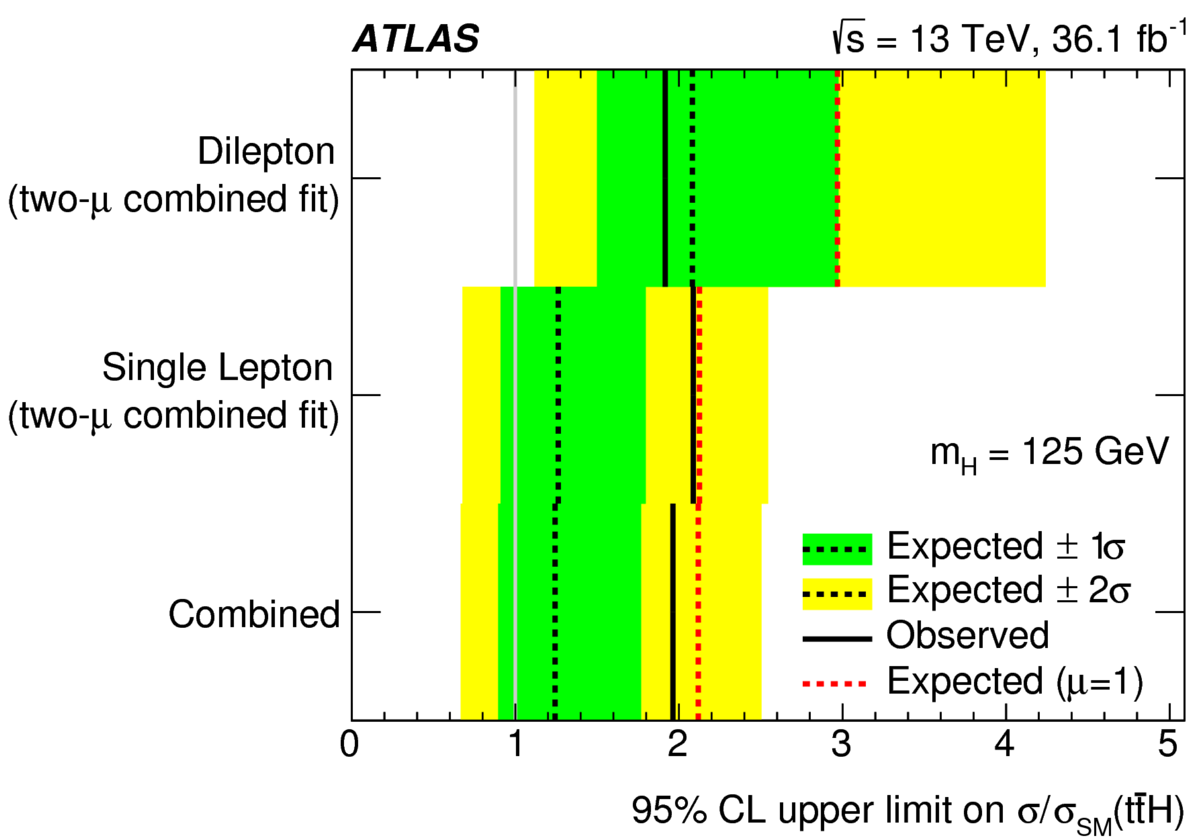


Results



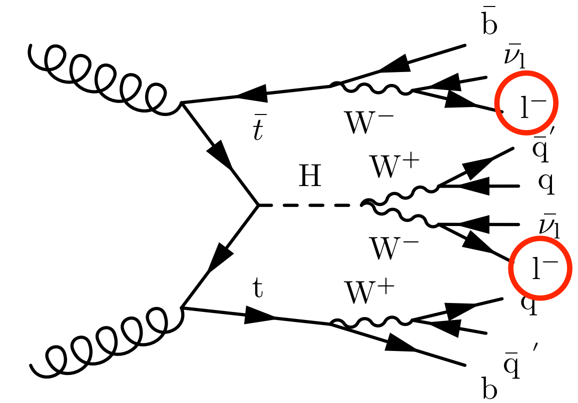
- Simultaneous fit in the two channels.
- Profile likelihood including data in both channels but with independent μ's.

- 95% CL upper limits.
- Expected B-only (black dashed), SM hypothesis (red dashed) & observed (solid black).
- Precision limited by systematic unc. on tt+≥1b simulation.



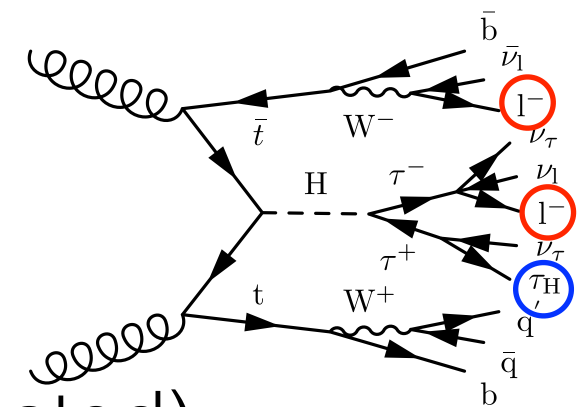
ttH(WW*, ZZ*, $\tau\tau$) aka 'multilepton'

2lSS



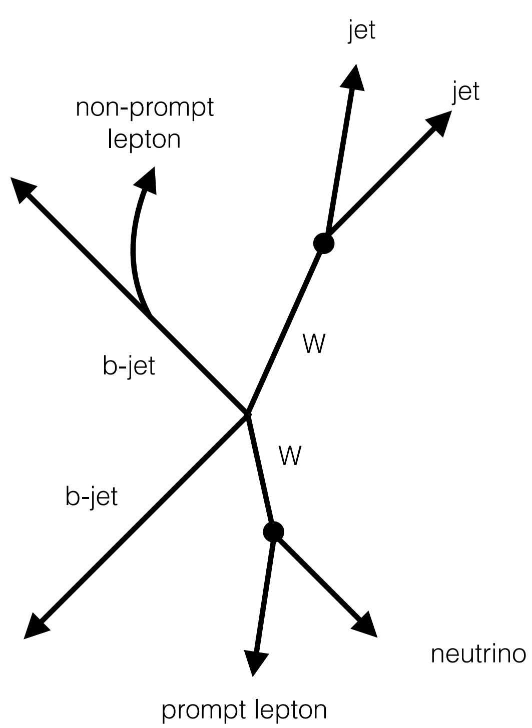
- Several multilepton signatures: Higgs decaying to either vector bosons or τ-leptons.
- Relatively clean signal.
- Major backgrounds: Fakes, $t\bar{t}W$, $t\bar{t}Z$, τ_{had} mis-reconstruction.

2lss+1τ_H

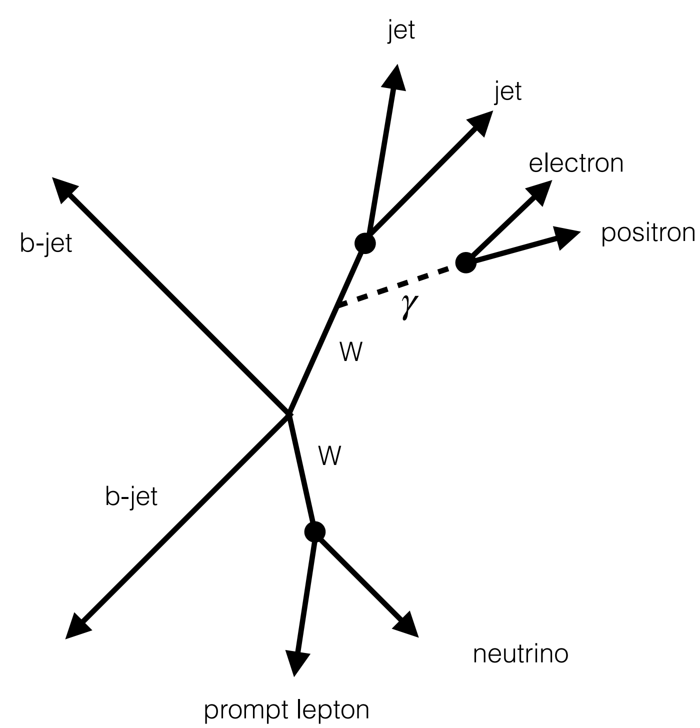


Sources of Fake leptons (tt+jets dominated)

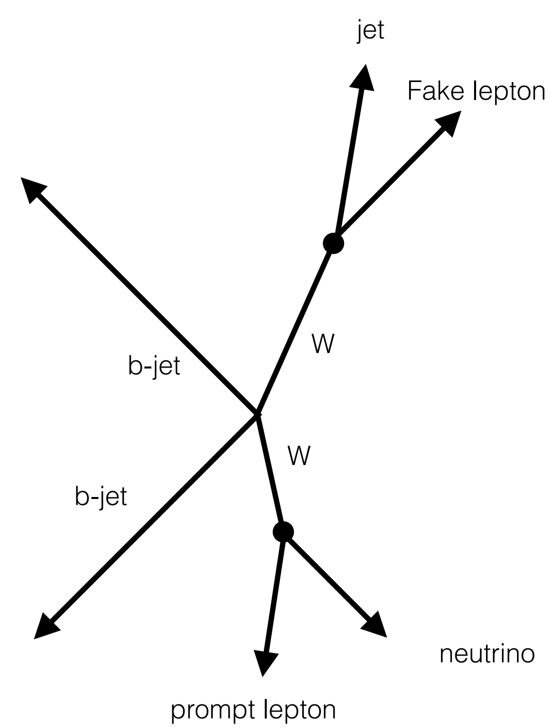
Semileptonic B hadron decay



Photon conversion

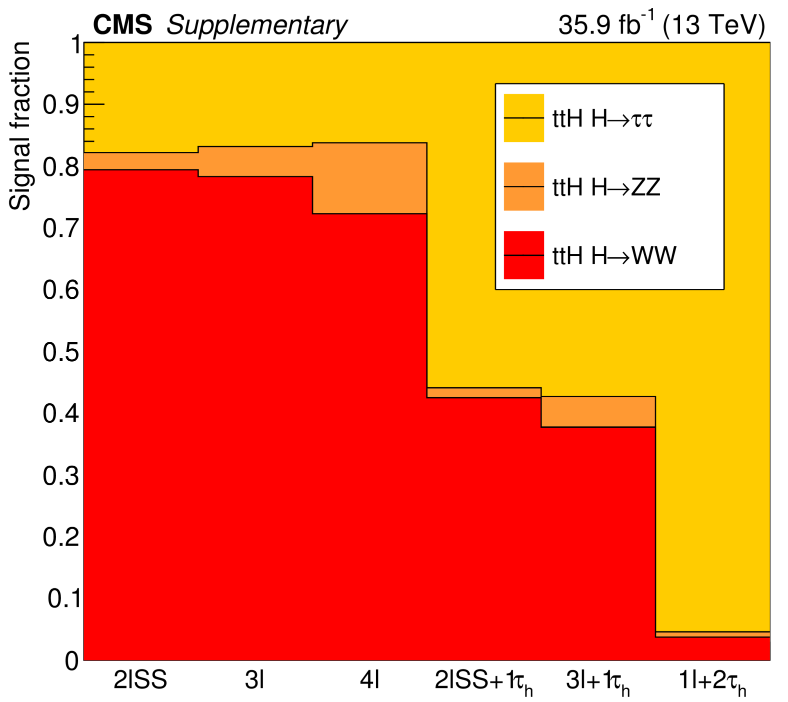


Mis-identified light jet



CMS ttH(WW*, ZZ*, $\tau\tau$) HIG-17-018 (35.9 + 41.5 /fb)

- Events categorised according to **# e/μ/hadronic tau's**.
- Dedicated lepton MVA discriminates prompt leptons (W,Z,leptonic τ) from non-prompt/fake.
- Prompt leptons required to pass 'tight' BDT working point.
- Leptons from relaxed selection used to estimate background processes/ vetos.



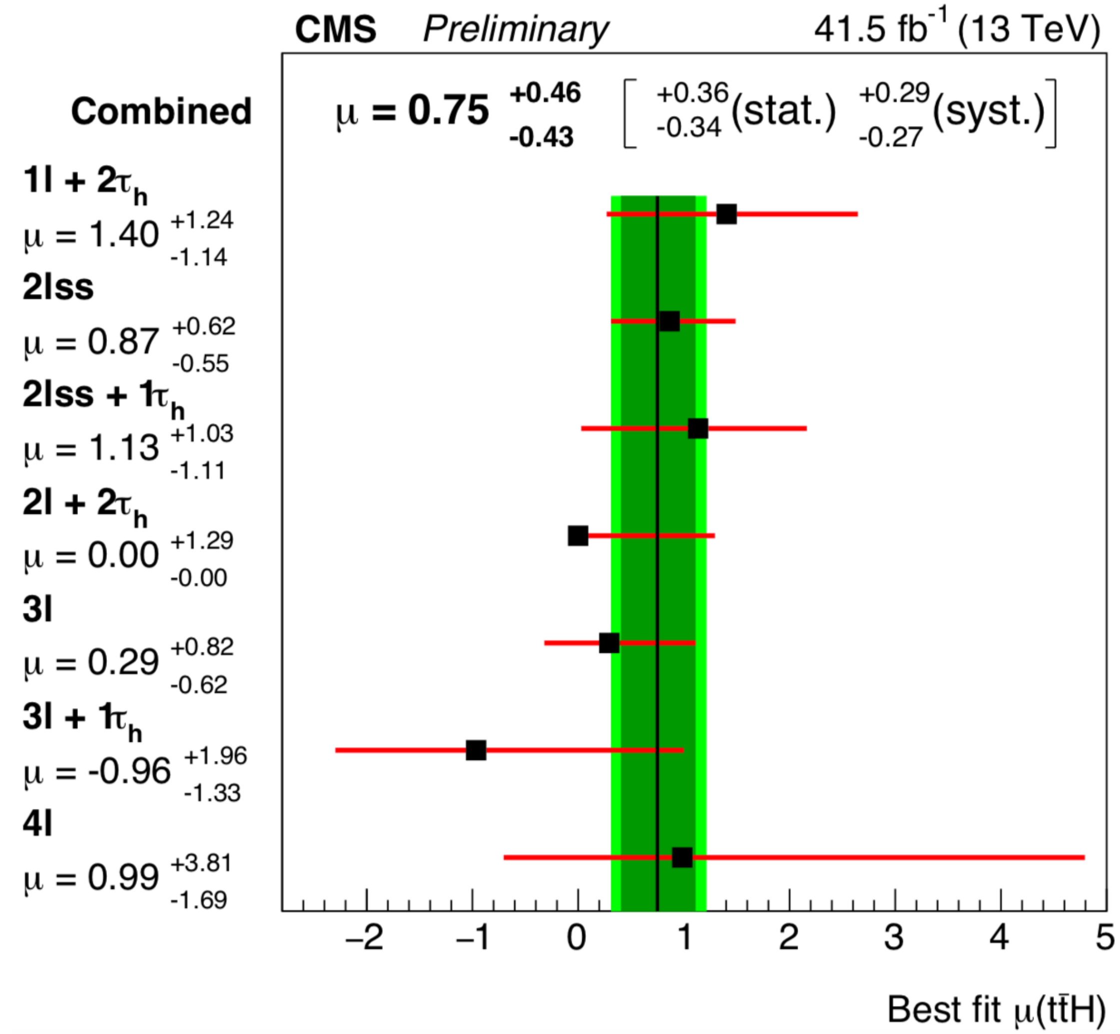
0τ Channels	2LSS+0τ	3L+0τ	4L+0τ
MVA	BDT	BDT	Cut & count

τ Channels	1L+2τ	2LSS+1τ	2L+2τ	3L+1τ
MVA	BDT	BDT	BDT	BDT

Results

- Results combined with 2016 result.

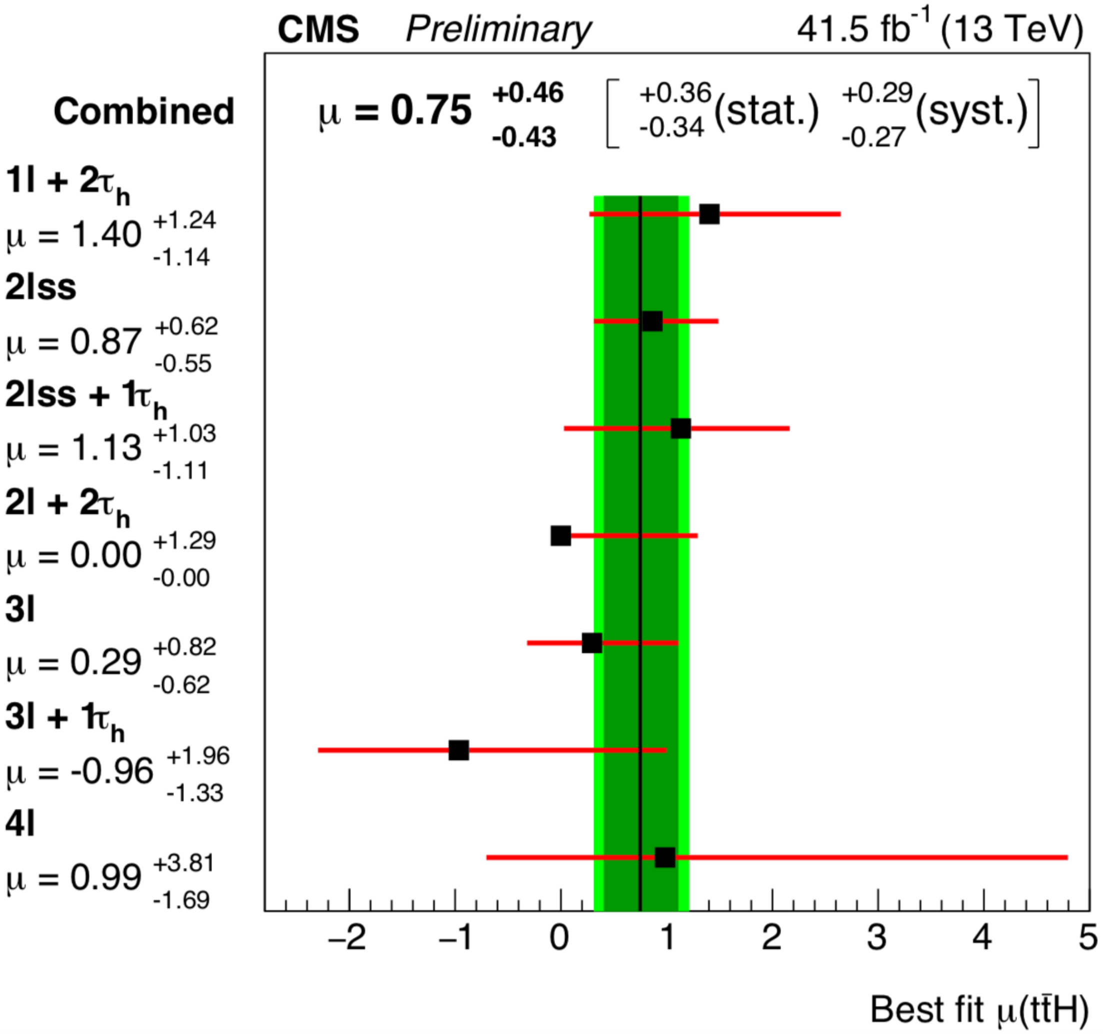
Dataset	μ_{ttH} (obs.)	μ_{ttH} (exp.)	Significance (obs.)	Significance (exp.)
2016 (35.9 /fb)	1.04 +0.50 -0.36	1.00 +0.42 -0.38	2.7σ	2.7σ
2017 (41.5 /fb)	0.75 +0.46 -0.43	1.00 +0.39 -0.35	1.7σ	2.9σ
2016+2017 (35.9+41.5 /fb)	0.96 +0.34 -0.31	1.00 +0.30 -0.27	**3.2σ**	4.0σ



Source	Uncertainty [%]	$\Delta\mu/\mu$ [%] (2017)	$\Delta\mu/\mu$ [%] (Comb.)	Correlations
Theoretical sources	$\approx$ 8	8	9	Correlated
e, μ selection efficiency	3–5	4	3	Correlated
τ_h selection efficiency	5	3	5	Correlated
τ_h energy calibration	1.2	1	2	Correlated
b tagging efficiency	2–15 [48]	10	5	Correlated
Jet energy calibration	2–15 [56]	3	3	Correlated
Fake background yield	$\approx$ 30–50	17	9	Un-correlated

Results

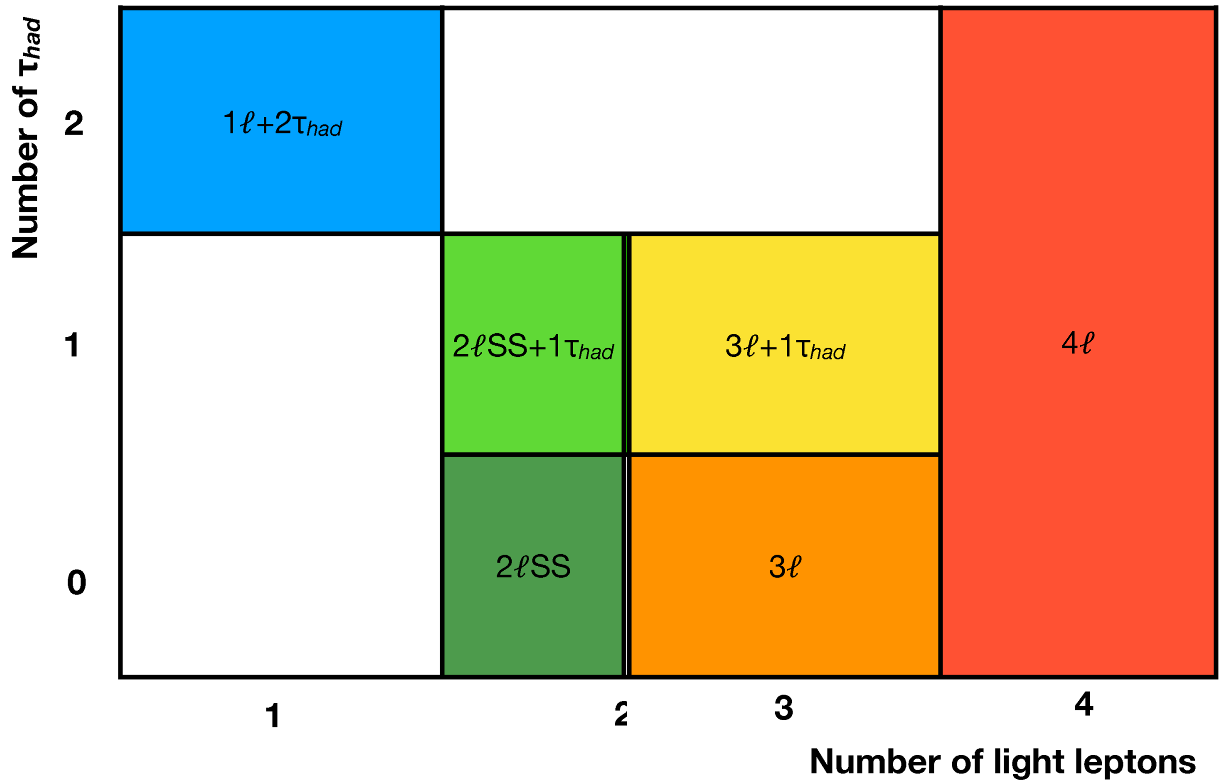
Dataset	μ_{ttH} (obs.)	μ_{ttH} (exp.)	Significance (obs.)	Significance (exp.)
2016 (35.9 /fb)	1.04 +0.50 -0.36	1.00 +0.42 -0.38	2.7σ	2.7σ
2017 (41.5 /fb)	0.75 +0.46 -0.43	1.00 +0.39 -0.35	1.7σ	2.9σ
2016+2017 (35.9+41.5 /fb)	0.96 +0.34 -0.31	1.00 +0.30 -0.27	**3.2σ**	4.0σ



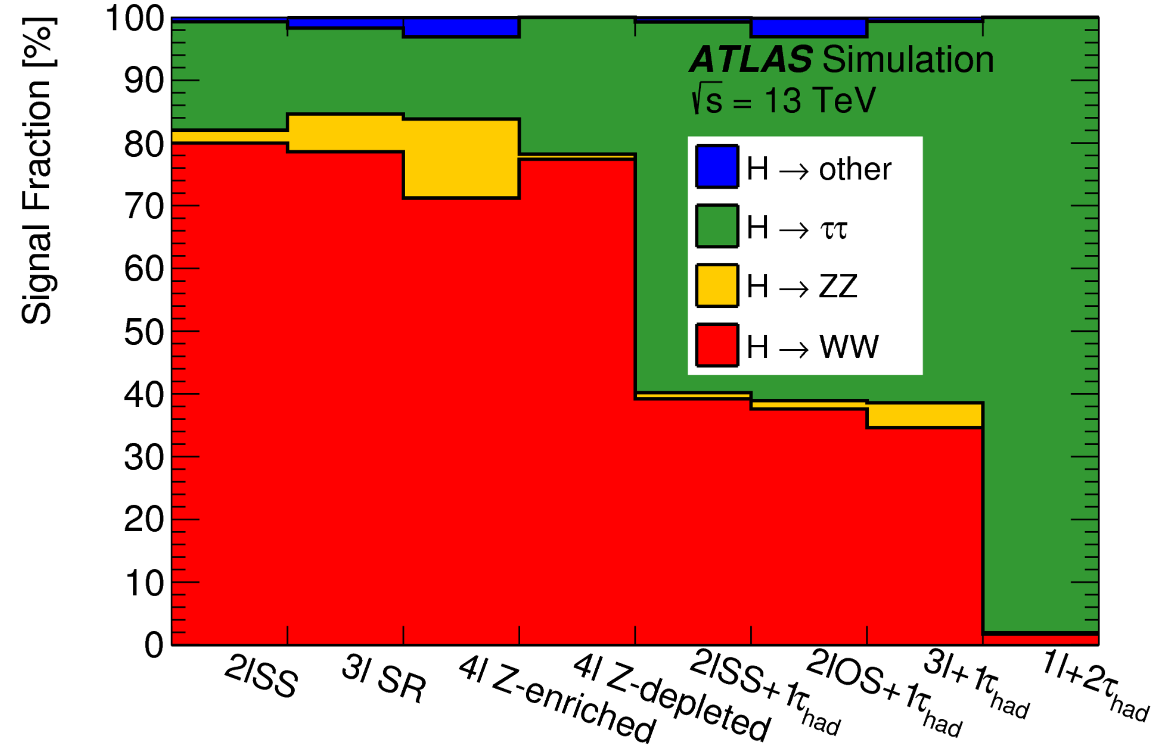
Source	Uncertainty [%]	$\Delta\mu/\mu$ [%] (2017)	$\Delta\mu/\mu$ [%] (Comb.)	Correlations
Theoretical sources	≈ 8	8	9	Correlated
e, μ selection efficiency	3–5	4	3	Correlated
τ_h selection efficiency	5	3	5	Correlated
τ_h energy calibration	1.2	1	2	Correlated
b tagging efficiency	2–15 [48]	10	5	Correlated
Jet energy calibration	2–15 [56]	3	3	Correlated
Fake background yield	$\approx$ 30–50	17	9	Un-correlated

ATLAS ttH(WW*, ZZ*, $\tau\tau$)

ATLAS-CONF-2019-045 (**80** fb^{-1})



Analysis regions organised by # light leptons and hadronic taus.



Z-enriched(depleted): presences(absence) of same-flavour opposite charge leptons. Background events in Z-enriched can c.f. off-shell Z* and y* → ll

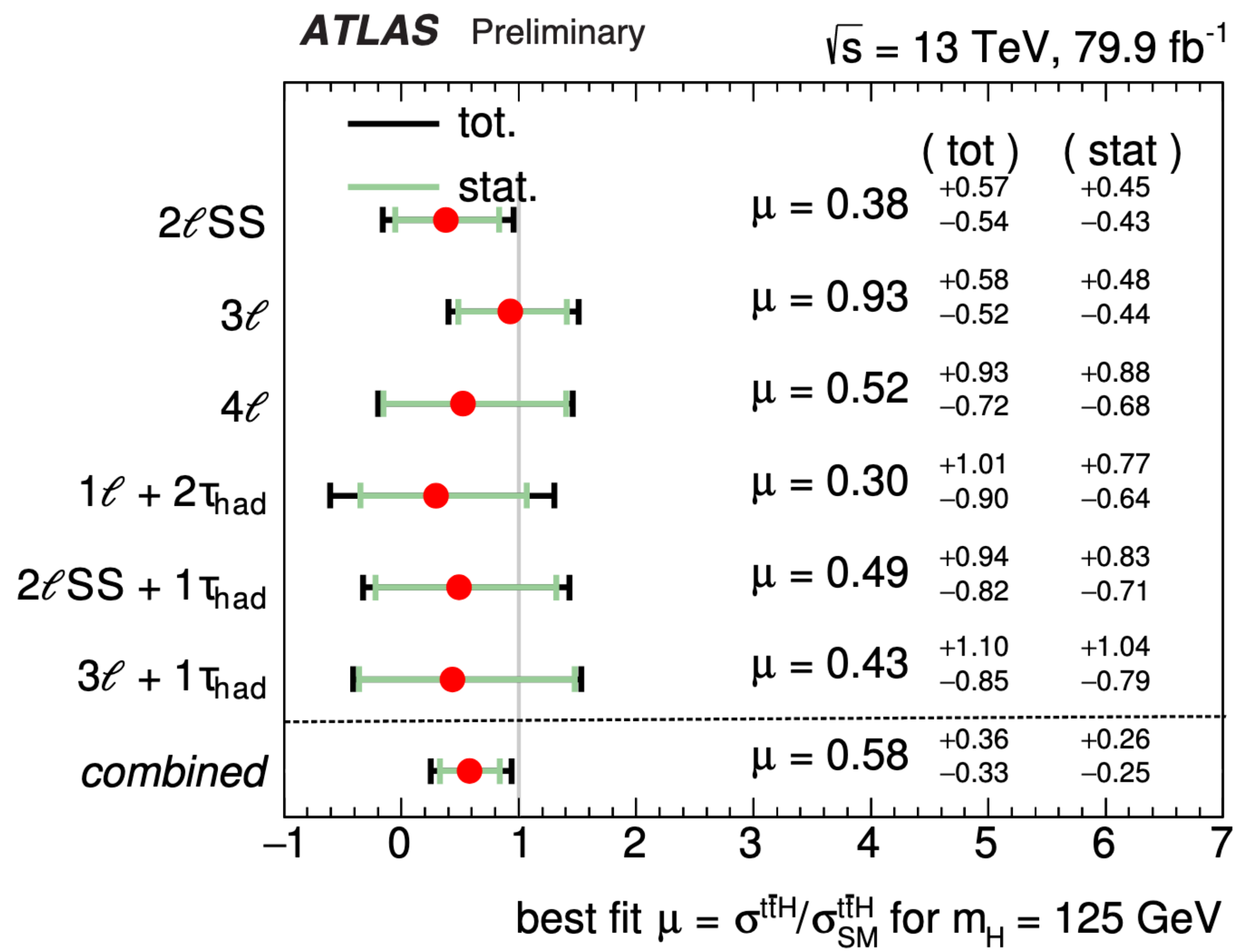
'other' = mostly H(μμ) and H(bb).

- 6 main categories according to # light leptons / hadronic tau's.
- Dedicated lepton MVA - discriminate prompt leptons (W,Z,τ) from non-prompt/fake.
- Many subcategories enriched in various signal/bckg. - split by lepton flavour, charge, nJets …
- Several control regions to constrain backgrounds - targets .

	2ℓSS	3ℓ	4ℓ	$1\ell+2\tau_{\rm had}$	2ℓSS$+1\tau_{\rm had}$	2ℓOS$+1\tau_{\rm had}$	$3\ell+1\tau_{\rm had}$
BDT trained against	Fakes and $t\bar{t}V$	$t\bar{t}$, $t\bar{t}W$, $t\bar{t}Z$, VV	$t\bar{t}Z$ / -	$t\bar{t}$	all	$t\bar{t}$	-
Discriminant	2×1D BDT	5D BDT	Event count	BDT	BDT	BDT	Event count
Number of bins	6	5	1 / 1	2	2	10	1
Control regions	-	4	-	-	-	-	-

ATLAS ttH(WW*, ZZ*, $\tau\tau$)

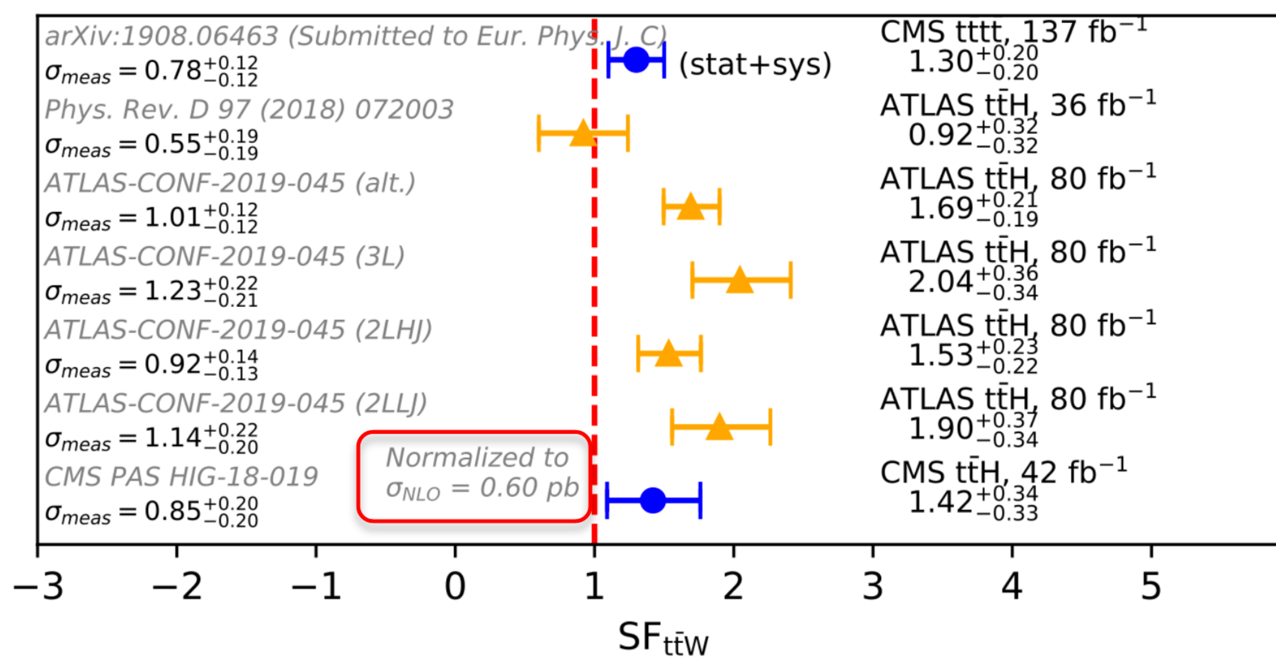
- Obs (exp) excess: **1.8 (3.1)**σ over SM background.
- JES, ttV and fake background modelling amongst largest uncertainties.
- Many categories still statistically limited.
- No prior on ttW and ttZ process normalisations.
- Simultaneously extract scale factors for these processes (next slide).
- Needs **improved description of the ttW background** to reach greater precision in the future.

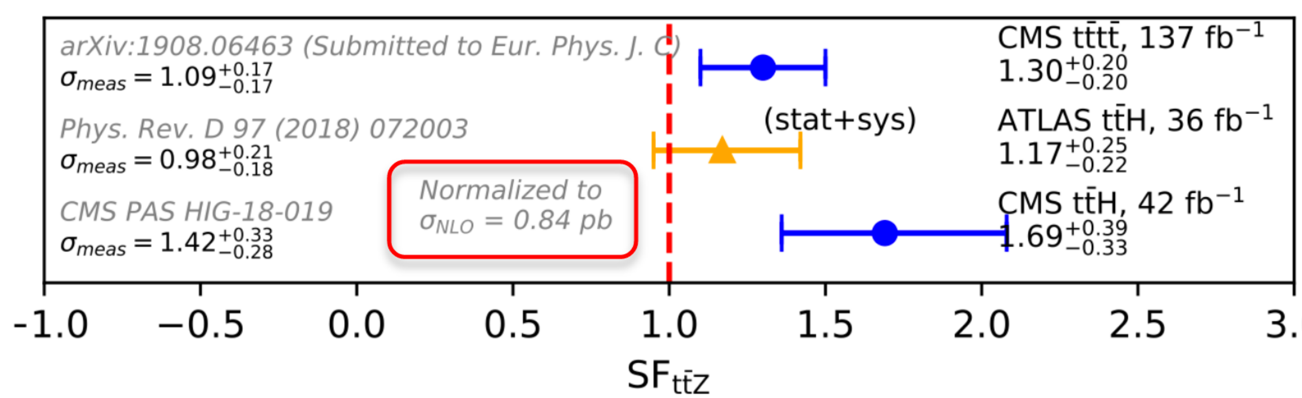


ttV Backgrounds

ttX free-floating parameters	ATLAS (80fb^{-1}; 2015-2017)		CMS	
	main result	alternative fit	2017	2016-2017
μ(*ttH*)	$0.58^{+0.36}_{-0.33}$	$0.70^{+0.36}_{-0.33}$	$0.75^{+0.46}_{-0.43}$	$0.96^{+0.34}_{-0.31}$
NF(*ttW*)	$1.56^{+0.30}_{-0.28}$ (2ℓSS0τ low NJets) $1.26^{+0.19}_{-0.18}$ (2ℓSS0τ high NJets) $1.68^{+0.30}_{-0.28}$ (3ℓSS0τ)	$1.39^{+0.17}_{-0.16}$	$1.42^{+0.34}_{-0.33}$ /1.2 *to compare with ATLAS: scale YR4 reference by 1.2*	--
NF(*ttZ*)	--	--	$1.69^{+0.39}_{-0.33}$	--

- Reducible backgrounds modelled using NLO ME + PS simulation.
- Unconstrained ttV cross-sections (freely float nuisance parameters).
- CMS added control regions for ttW, ttZ and WZ processes as cross-check result.
- ttW consistently high.
- Along with tt+bb, ttV modelling = **one of the largest theory systematics for ttH combination.**
- Cross-collab. + theorists attempt to understand this background better are ongoing.

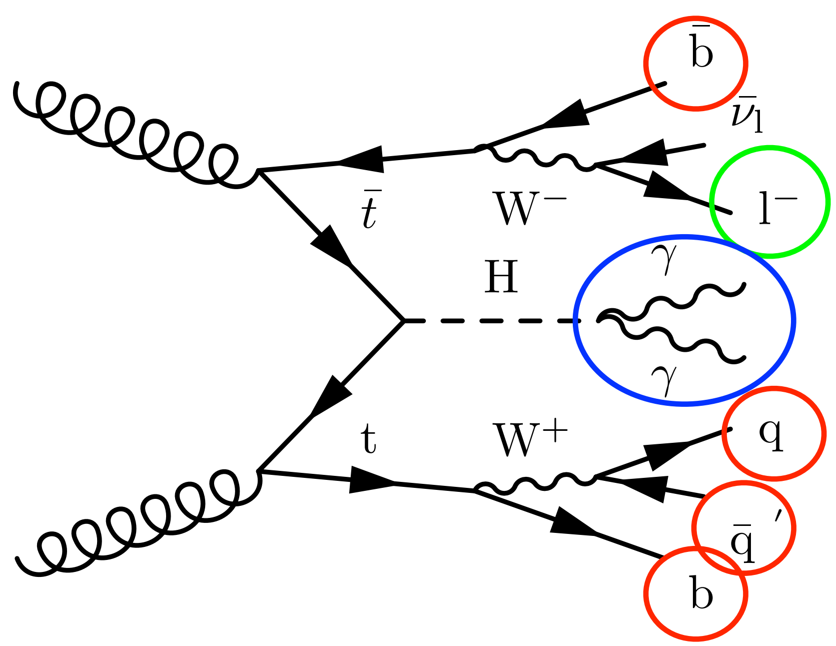




CMS $t\bar{t}H(\gamma\gamma)$ HIG-18-018 (35.9 /fb+ 41.5/fb)

- Small branching fraction but clean signal.
- Diphoton inv. mass peak can be reconstructed with excellent precision.
- Signal = narrow $m\gamma\gamma$ peak on smoothly falling bckg.
- Main background = non-resonant diphoton production and non-$t\bar{t}$H Higgs production.

Semi-leptonic Channel



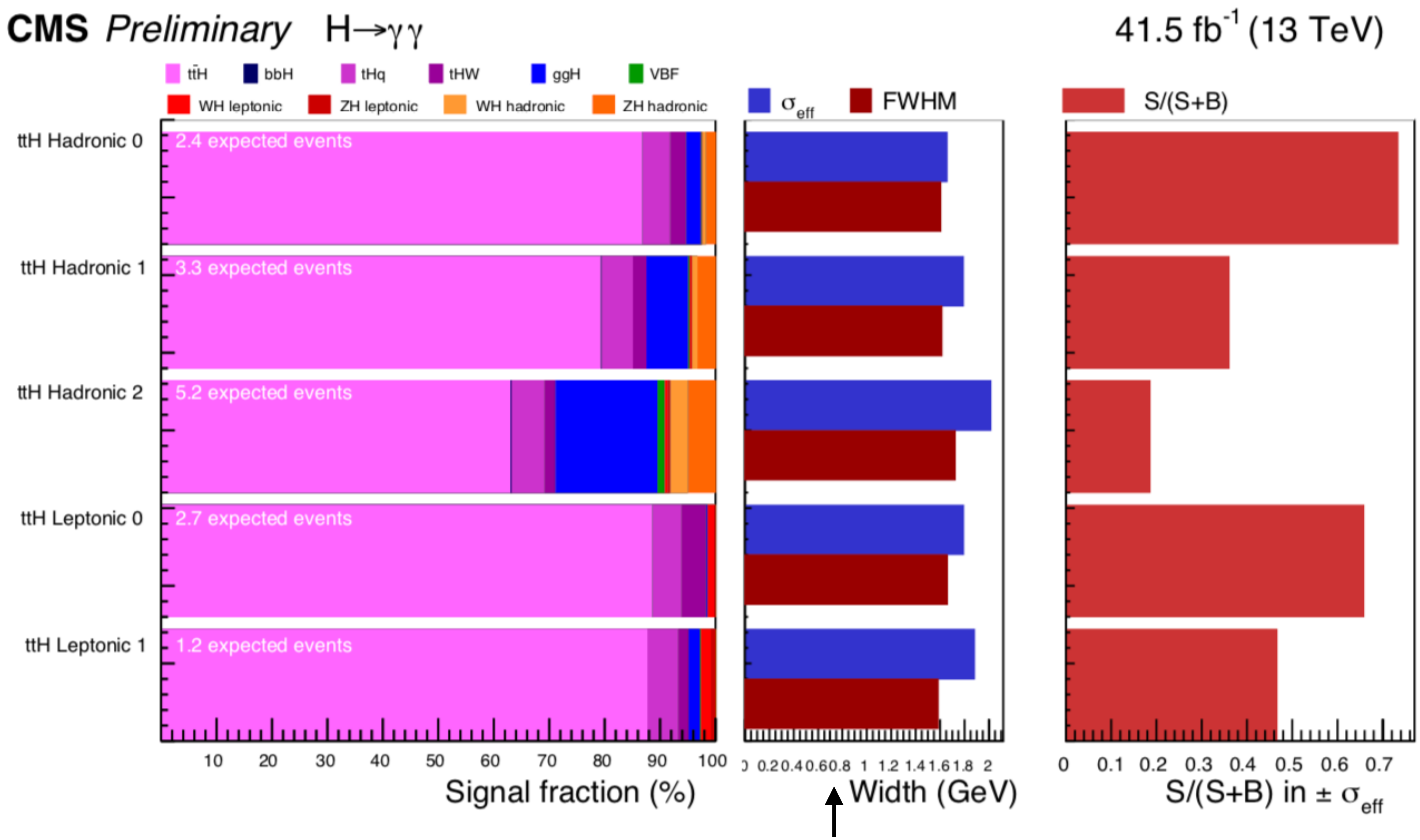
- # leptons ≥ 1

- Signal-like photon kinematics: Diphoton BDT > 0.11

- ≥ 2 jets, ≥ 1 b-tagged jet (CSV medium)

Channels

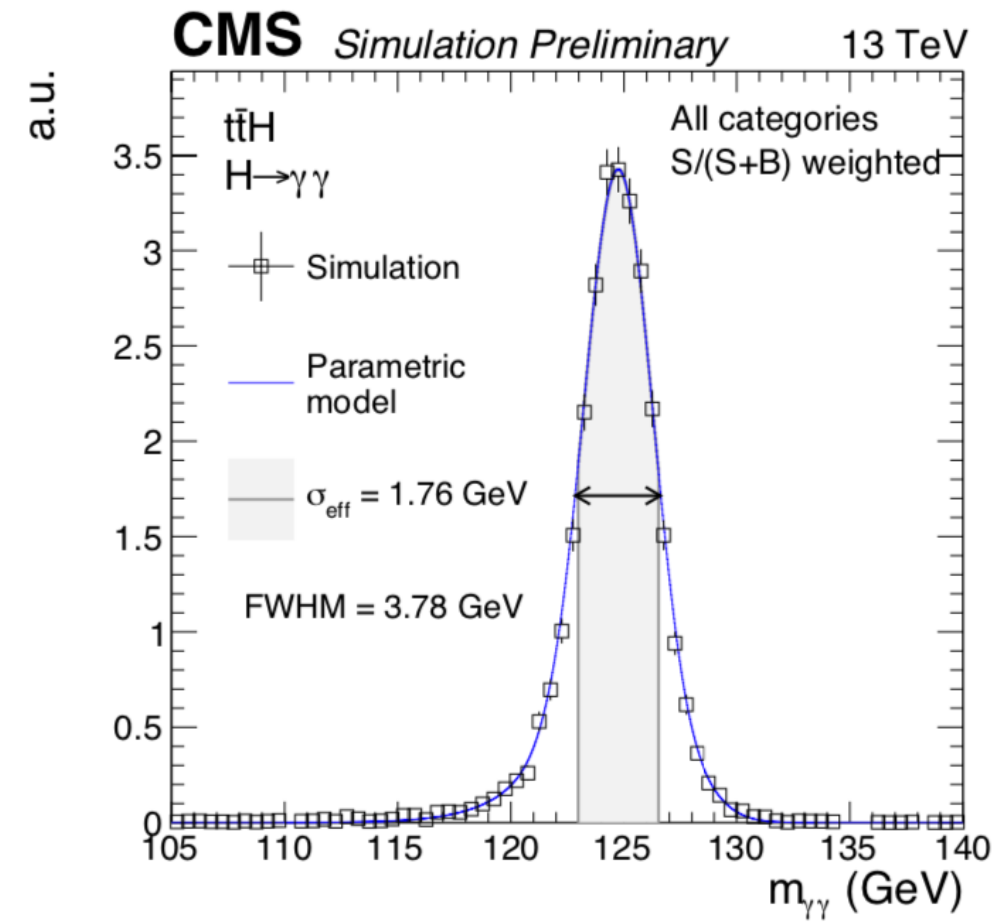
- 3 channels based on decay of the W bosons in the top pair system: fully leptonic, semi-leptonic, fully hadronic.
- Separate SvsB BDT trained in events with leptons and hadronic events.
- Leptonic categories required to pass BDT cut.
- Hadronic channel events categorised according to BDT score.



of signal model

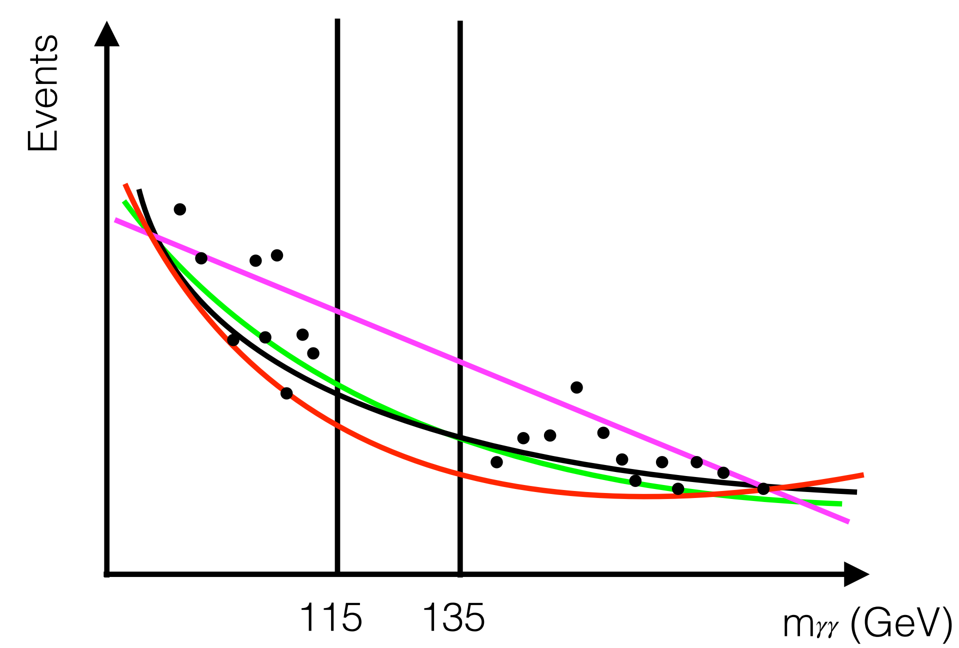
Signal Model

- Interpreting the data requires **description of expected signal** from SM Higgs.
- = # events in ε x acceptance as function of m_H + shape of $m_{\gamma\gamma}$ in each category.
- **Various m_H scenarios simulated - combined into single parametric model**.
- Simultaneous fit of different m_H samples performed - individual parameters of the functional form are polynomials of m_H.
- Floating parameters are the coefficients.
- Guarantees smooth behaviour as function of m_H.



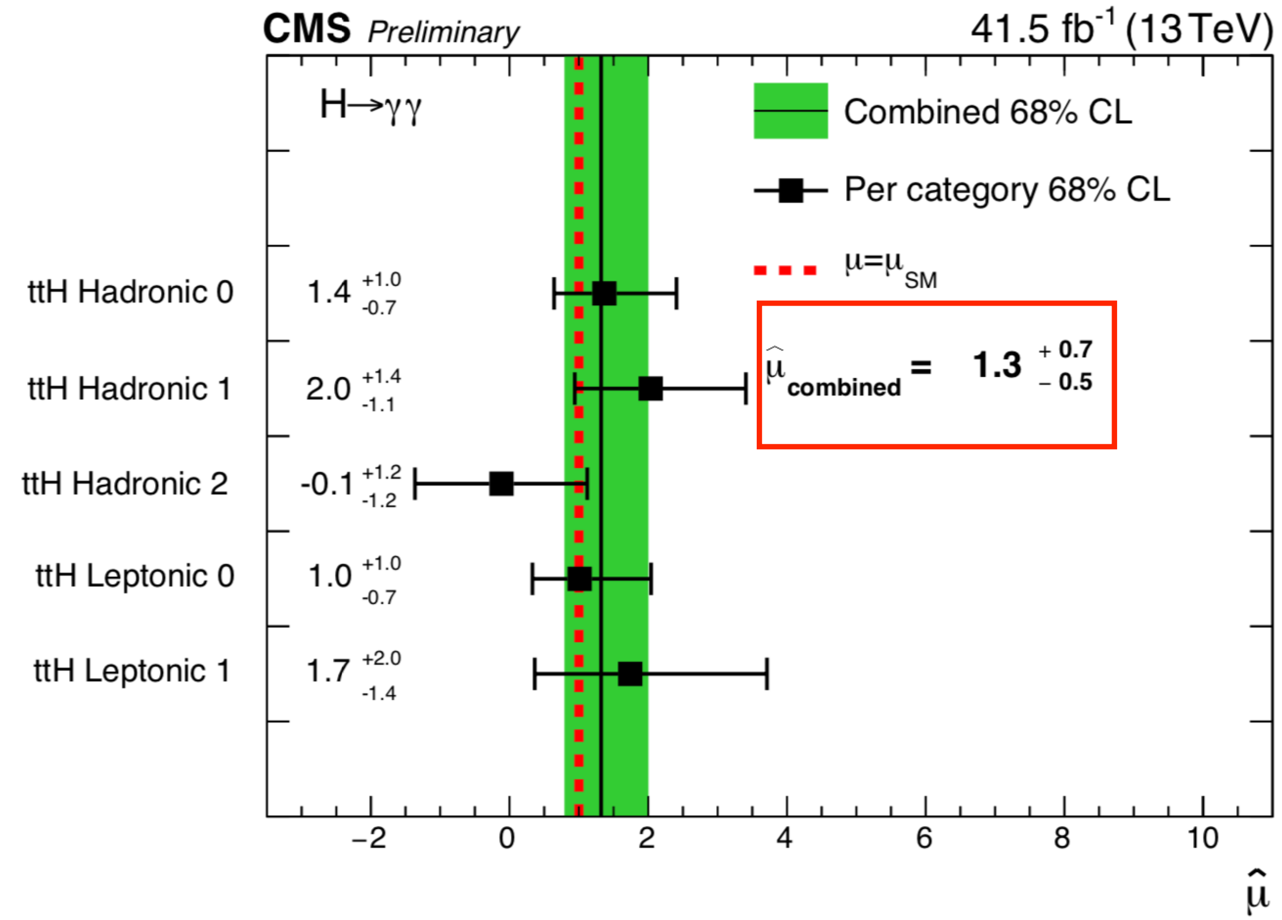
Background Model

- Fit various analytic functions to $m_{\gamma\gamma}$ distribution in sidebands.
- Choice of function describing background treated as a nuisance parameter in final likelihood fit.

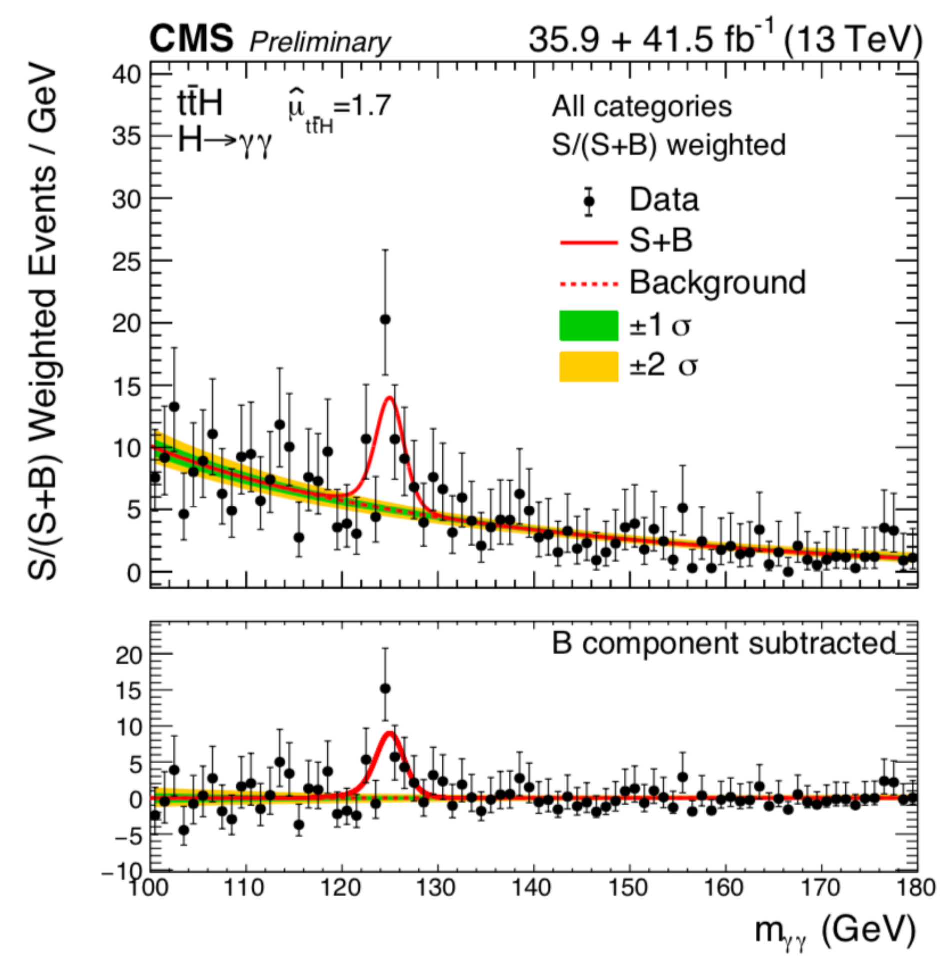


CMS $t\bar{t}H(\gamma\gamma)$

- Maximum-likelihood (un-binned) is performed on $m_{\gamma\gamma}$ distributions.
- Signal strength μ and m_H freely floating.
- Uncertainty is largely statistically dominated.
- Combined with 2016 dataset.

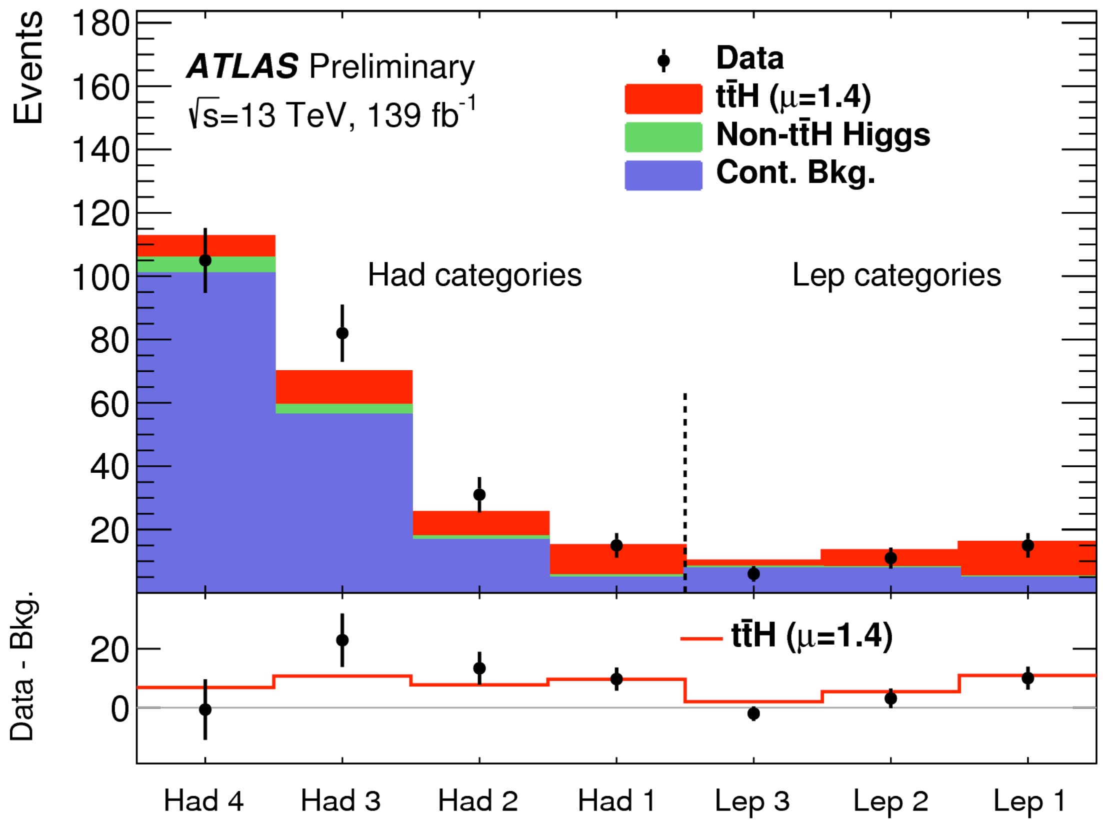


Dataset	Signal strength	Significance
2017	1.3 +0.7 -0.5	3.1σ
2016+2017	1.7 +0.6 - 0.5	4.1σ



ATLAS $t\bar{t}H(\gamma\gamma)$ ATLAS-CONF-2019-004 139 /fb

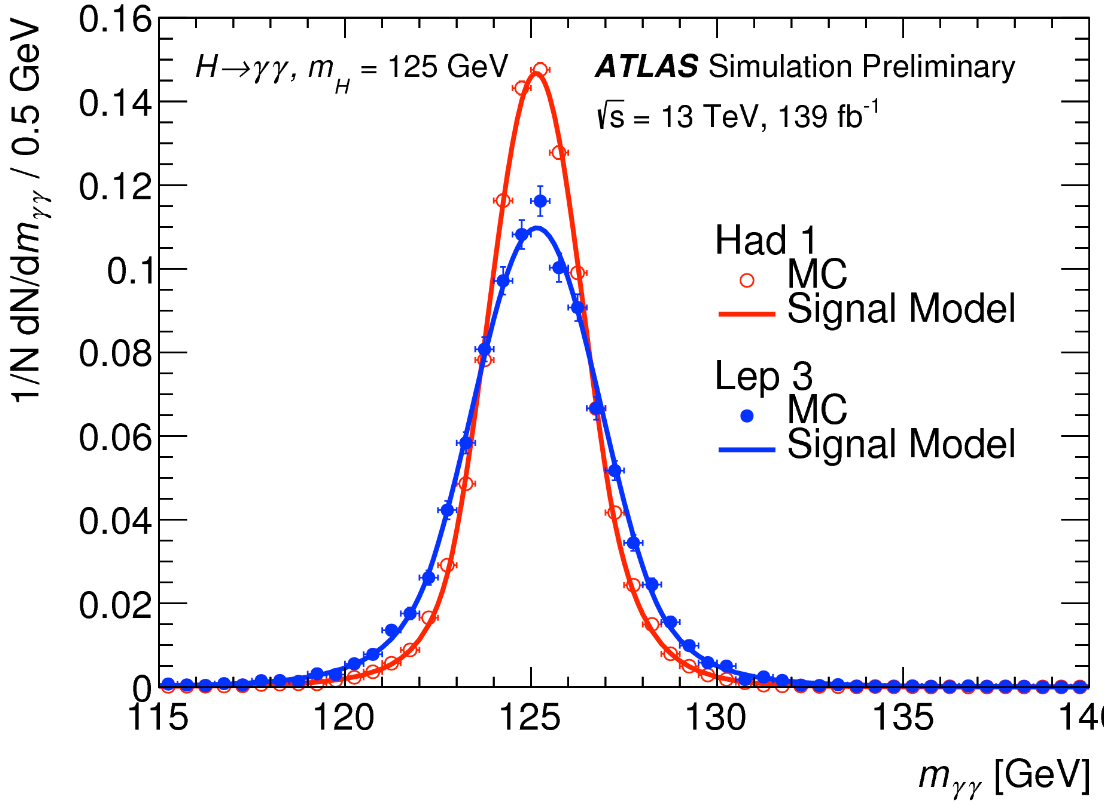
- Similar strategy, 2 signal regions (according to decay of W boson of top system):
    - **Leptonic category**: ≥ 1 lepton.
    - **Hadronic category**: ≥ 2 jets + 0 isolated leptons.
- SvsB **BDT** in each region used to sort the above regions into one of 4(3) hadronic(leptonic) categories based on BDT score.



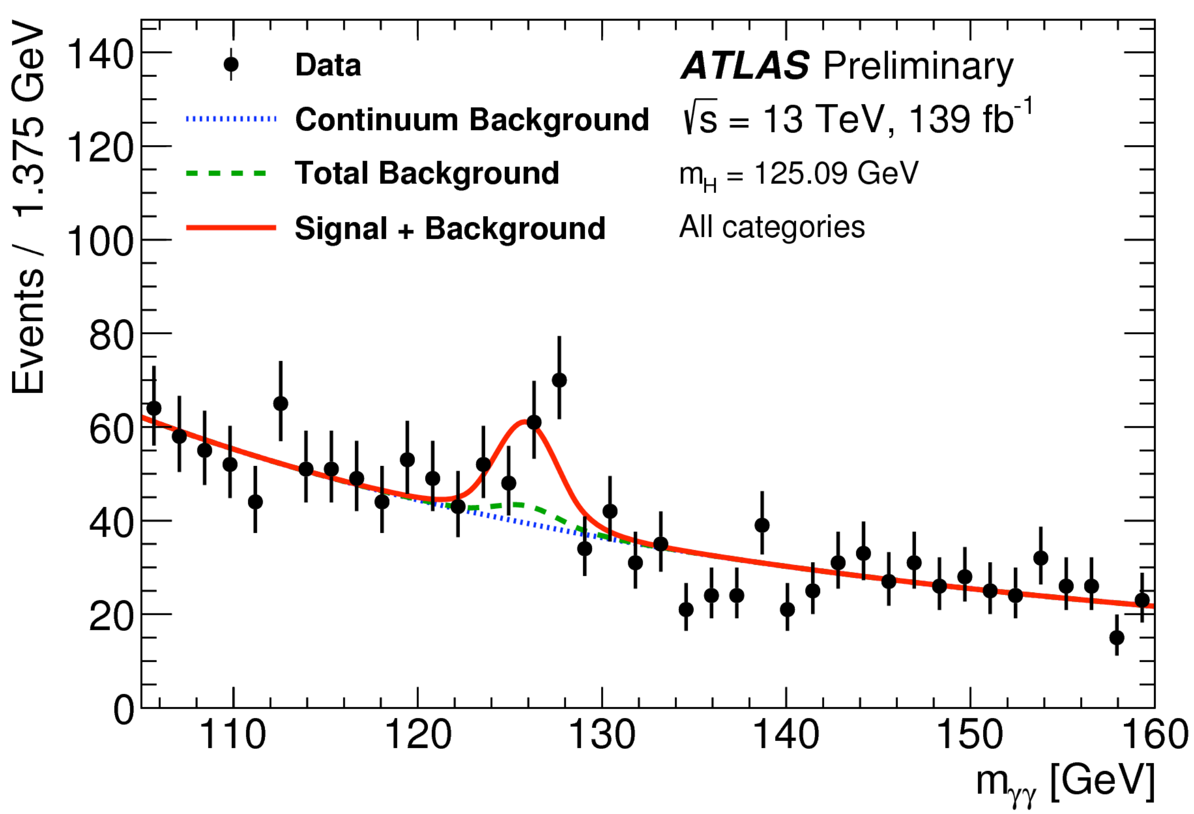
Category	$t\bar{t}H$ Signal	non-$t\bar{t}H$ Higgs	Continuum Background	Total (Expected)	Data
$t\bar{t}H$ "Lep" Category 1	7.9 ± 1.5	0.42 ± 0.12	4.6 ± 0.9	12.9 ± 1.8	15
$t\bar{t}H$ "Lep" Category 2	3.9 ± 0.6	0.43 ± 0.15	7.5 ± 1.2	11.8 ± 1.3	11
$t\bar{t}H$ "Lep" Category 3	1.45 ± 0.24	0.49 ± 0.19	7.5 ± 1.2	9.5 ± 1.2	6
$t\bar{t}H$ "Had" Category 1	6.9 ± 1.6	0.8 ± 0.5	4.5 ± 0.9	12.2 ± 1.9	15
$t\bar{t}H$ "Had" Category 2	5.6 ± 1.0	1.1 ± 0.8	16.5 ± 1.7	23.2 ± 2.3	31
$t\bar{t}H$ "Had" Category 3	7.7 ± 1.3	3.1 ± 2.2	56.0 ± 3.0	67 ± 4	82
$t\bar{t}H$ "Had" Category 4	4.9 ± 0.8	5 ± 4	101 ± 4	111 ± 6	105

Signal/Background Modelling

- **Signal** shape modelled analytically with double-sided crystal ball (central = gaussian, tails = power-law curves).



- **Background** shape either power-law or exponential function (one-parameter aside from normalisation due to low-stats) models continuum bckg.
- Bckg only sample = Data events where both photon candidates fail iso/ID requirements.
- Total background includes non-ttH production of Higgs.



ATLAS $t\bar{t}H(\gamma\gamma)$ Results

σ(ttH) x BR($\gamma\gamma$) (fb)	Significance
1.59 +0.38 -0.36 (stat.), +0.15 -0.12 (exp.), +0.15 - 0.11 (theo.)	4.9σ

Uncertainty source	$\Delta\sigma_{\text{low}}/\sigma$ [%]	$\Delta\sigma_{\text{high}}/\sigma$ [%]
Theory uncertainties	6.6	9.7
Underlying Event and Parton Shower (UEPS)	5.0	7.2
Modeling of Heavy Flavor Jets in non-$t\bar{t}H$ Processes	4.0	3.4
Higher-Order QCD Terms (QCD)	3.3	4.7
Parton Distribution Function and α_S Scale (PDF+α_S)	0.3	0.5
Non-$t\bar{t}H$ Cross Section and Branching Ratio to $\gamma\gamma$ (BR)	0.4	0.3
Experimental uncertainties	7.8	9.1
Photon Energy Resolution (PER)	5.5	6.2
Photon Energy Scale (PES)	2.8	2.7
Jet/$E_{\text{T}}^{\text{miss}}$	2.3	2.7
Photon Efficiency	1.9	2.7
Background Modeling	2.1	2.0
Flavor Tagging	0.9	1.1
Leptons	0.4	0.6
Pileup	1.0	1.5
Luminosity and Trigger	1.6	2.3
Higgs Boson Mass	1.6	1.5

Category	σ_{68} (GeV)	σ_{90} (GeV)
"Lep" Category 1	1.56	2.80
"Lep" Category 2	1.75	3.13
"Lep" Category 3	1.85	3.30
"Had" Category 1	1.39	2.48
"Had" Category 2	1.58	2.84
"Had" Category 3	1.65	2.96
"Had" Category 4	1.67	3.00

- Higgs boson signal resolution.
- Width of smallest window containing 68% and 90% of the inclusive Higgs boson events.
- Highest purity channel = lowest number.

CMS $t\bar{t}H(ZZ^* \rightarrow 4l)$

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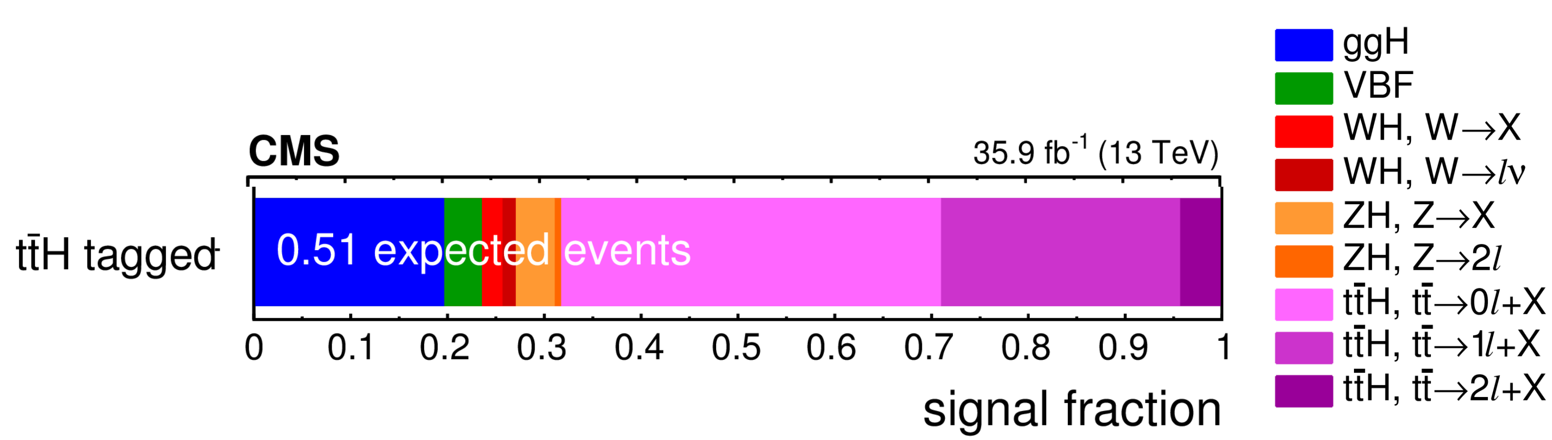
35.9 /fb

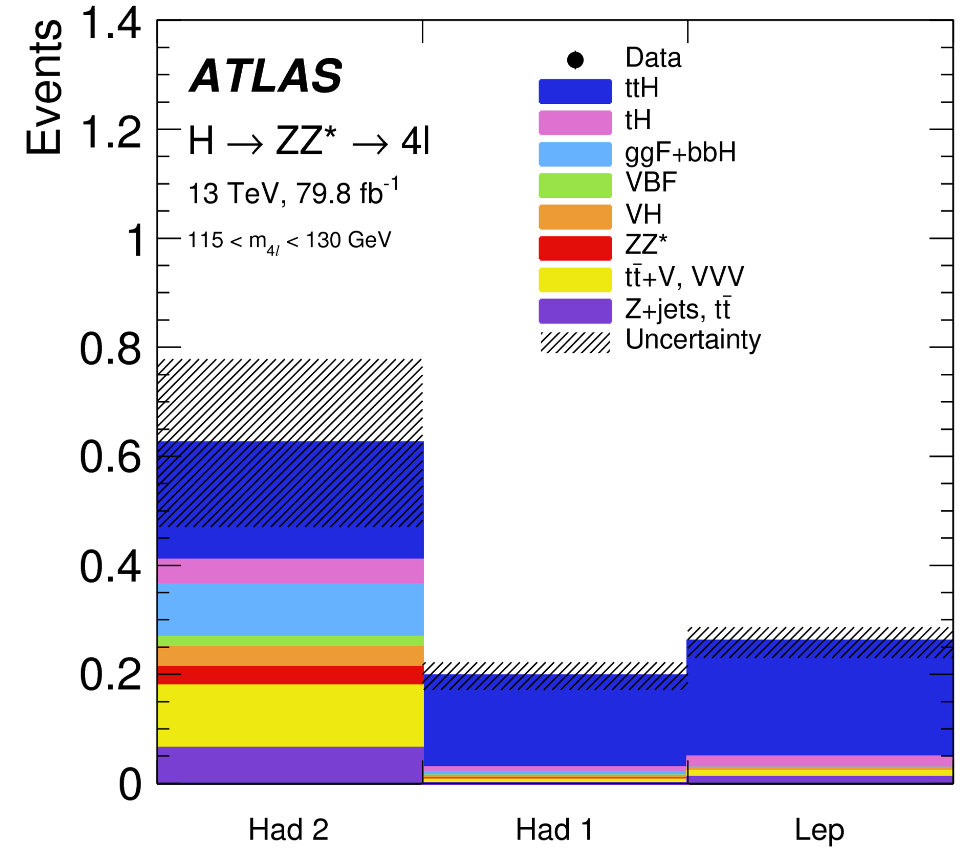
- Category in context of H(ZZ) analysis:
  - baseline selection = 4 isolated leptons (2 same-flavour, opposite charge pairs).
  - 'ttH tagged' category = ≥ 4 jets of which 1 is b-tagged or at least 1 additional lepton.
- Modelling of signal shape of a narrow resonance around m_H : central distribution = double-sided crystal ball function, non-resonant part = Landau function.
- Background contributions for ttH categories are ttW, ttZ and and non-ttH production.
- Irreducible qq/gg ➞ ZZ.
- Reducible fake leptons mostly from events w. HF jets producing secondary leptons.
- Also when HF jet, in-flight light meson within jet or charged hadrons overlap with π_0.
- Z+X = Z+jets (sub-dominant: tt+jets, Zγ+jets, WZ+jets, WW+jets) ➞ estimated from data in dedicated control regions (fake-factor method).



	$t\bar{t}H$
$q\bar{q} \rightarrow ZZ$	0.01
$gg \rightarrow ZZ$	<0.0
Z+X	0.27
Sum of backgrounds	0.28
$gg \rightarrow H$	0.10
VBF	0.02
WH	0.02
ZH	0.02
$t\bar{t}H$	0.35
Signal	0.51
Total expected	0.79
Observed	0

ATLAS $t\bar{t}H(ZZ^*\to 4l)$ 79.8 /fb

- 4 isolated leptons (2 same-flavour, opposite charge pairs).
- Baseline selection of ≥4 leptons, ≥ 1 b-tagged jet (70% WP).
- Then define 2 signal regions:
  - **Leptonic** (enriched in semi-leptonic top quark decays): 1 additional isolated lepton, ≥ 1 additional jet.
  - **Hadronic** (enriched in hadronic top quark decays): 0 additional isolated leptons, ≥ 3 additional jets.
- Hadronic category employs BDT to separate $t\bar{t}H$ - cut divides Had1/2.
- Observed events and expected background yields in both categories in mass window $115 < m_{4l} < 130$ GeV used as input to likelihood fit.
- Leading theory uncertainties: PS shower modelling (affecting acceptance) and XS unc. in Higgs+HF bckg.
- Leading experimental uncertainty: JES.



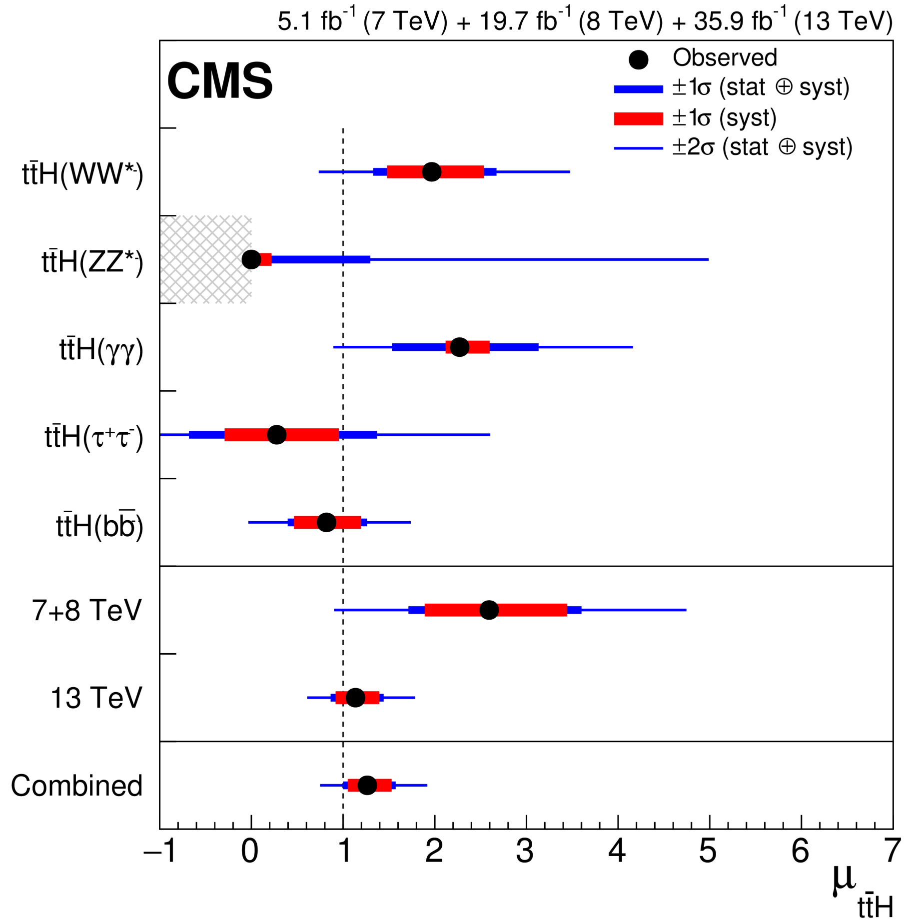
Bin	Expected $t\bar{t}H$ (signal)	Expected Non-$t\bar{t}H$ Higgs	Expected Non-Higgs	Expected Total	Observed Total
$H\to\gamma\gamma$					
Had 1	4.2(11)	0.49(33)	1.76(55)	6.4(13)	10
Had 2	3.41(74)	0.69(56)	7.5(11)	11.6(15)	14
Had 3	4.70(88)	2.0(17)	32.9(22)	39.6(32)	47
Had 4	3.00(55)	3.2(31)	55.0(28)	61.3(47)	67
Lep 1	4.5(10)	0.25(9)	2.19(59)	6.9(12)	7
Lep 2	2.23(39)	0.27(10)	4.59(91)	7.1(10)	7
Lep 3	0.82(18)	0.30(13)	4.58(91)	5.70(88)	5
$H\to ZZ^*\to 4\ell$					
Had 1	0.169(31)	0.021(7)	0.008(8)	0.198(33)	0
Had 2	0.216(32)	0.20(9)	0.22(12)	0.63(16)	0
Lep	0.212(31)	0.0256(23)	0.015(13)	0.253(34)	0

CMS Combination

- The results we looked at so far are the latest and greatest.
- **Some** of which **came after the latest combination**.
- The datasets analysed per channel that were used in the combination are listed below.
- Measurements using data from 2016 combine with those from 2011 and 2012.
- Consider the 5 Higgs decay modes with the largest expected event yields.
- Other production modes treated as backgrounds (normalised to SM values).

Channel	Pros	Cons	Datasets
$t\bar{t}H(bb)$	Largest branching fraction	Huge irreducible backgrounds from tt+HF	**5.1 + 19.7 + 35.9 fb^{-1}**
$t\bar{t}H(WW,ZZ^*,\tau\tau)$	Small backgrounds	Requires good understanding of fake leptons	**5.1 + 19.7 + 35.9 fb^{-1}**
$t\bar{t}H(\gamma\gamma)$	Clean signature, high signal-to-background ratio	Small branching fraction	**5.1 + 19.7 + 35.9 fb^{-1}**
$t\bar{t}H(ZZ^*)$	Clean signature, high signal-to-background ratio	Small branching fraction	**5.1 + 19.7 + 35.9 fb^{-1}**

CMS Combination

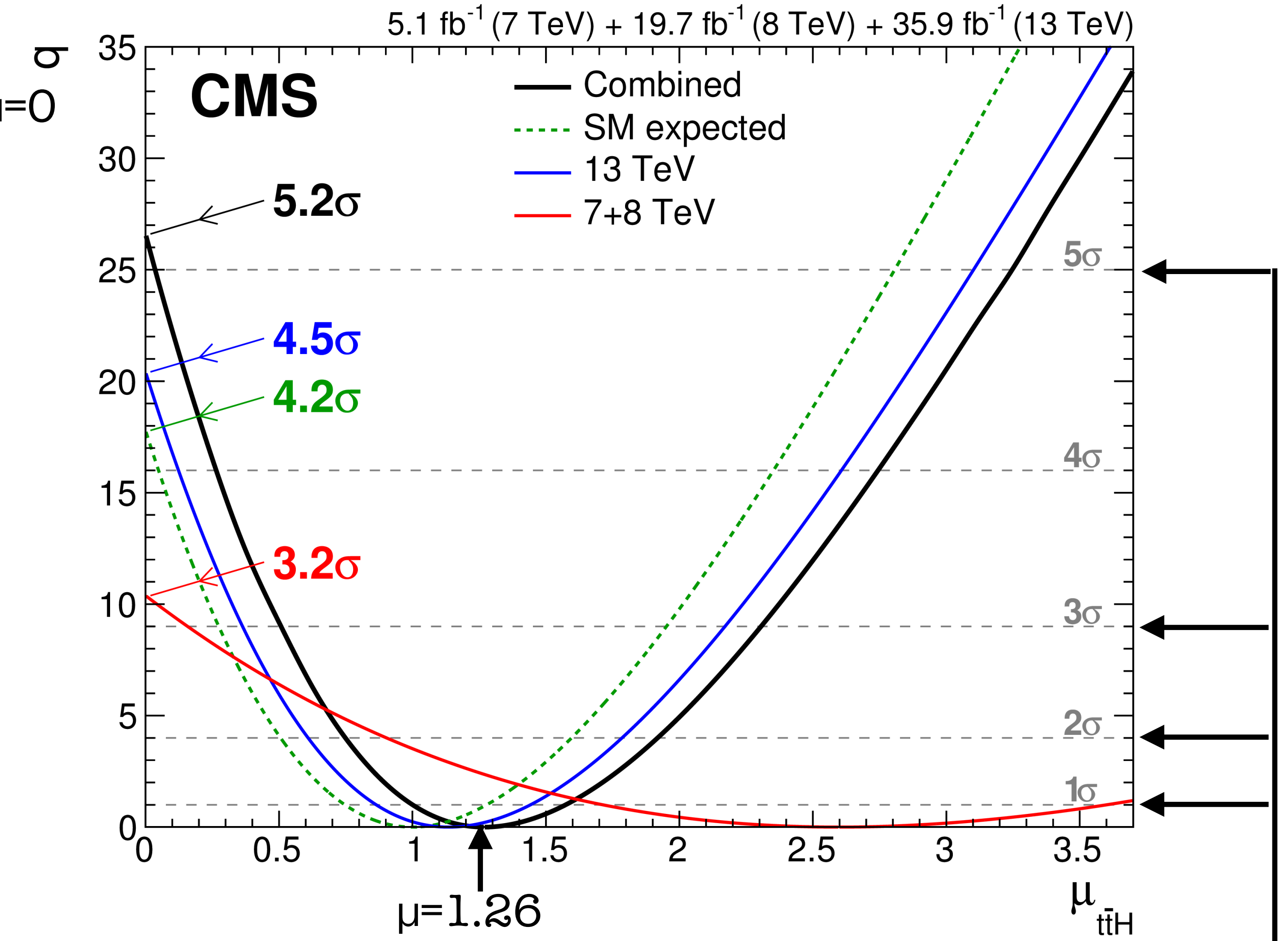


- Profile likelihood method.
- $\mu_{t\bar{t}H}$ = 1.26 +0.31/-0.26
- Agreement with SM expectation $\mu_{t\bar{t}H}$ = 1 within 1 s.d.

Uncertainty source	$\Delta\mu$	
Signal theory	+0.15	−0.07
Inclusive ttH normalisation (cross section and BR)	+0.15	−0.07
ttH acceptance (scale, pdf, PS and UE)	+0.004	−0.004
Other Higgs boson production modes	+0.002	−0.003
Background theory	+0.14	−0.13
tt + bb/cc prediction	+0.13	−0.11
tt + V(V) prediction	+0.06	−0.06
Other background uncertainties	+0.03	−0.03
Experimental	+0.17	−0.15
Lepton (inc. τ_h) trigger, ID and iso. efficiency	+0.08	−0.06
Misidentified lepton prediction	+0.06	−0.06
b-Tagging efficiency	+0.05	−0.04
Jet and τ_h energy scale and resolution	+0.04	−0.04
Luminosity	+0.04	−0.03
Photon ID, scale and resolution	+0.01	−0.01
Other experimental uncertainties	+0.01	−0.01
Finite number of simulated events	+0.08	−0.07
Statistical	+0.16	−0.16
Total	+0.31	−0.26

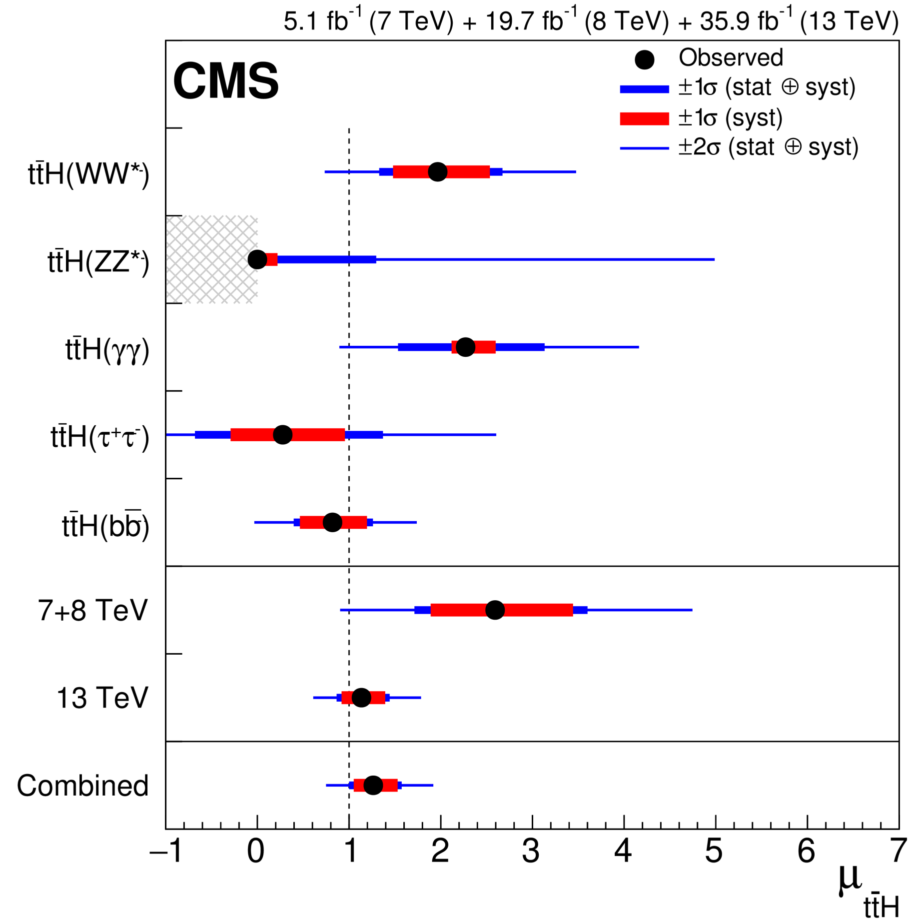
Test statistic as fn. of signal strength.

Test stat. for μ=0 using:



p-values for background only hypothesis expressed in units of s.d.'s

CMS Combination



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Photon ID, scale and resolution	+0.01	−0.01
Other experimental uncertainties	+0.01	−0.01
Finite number of simulated events	+0.08	−0.07
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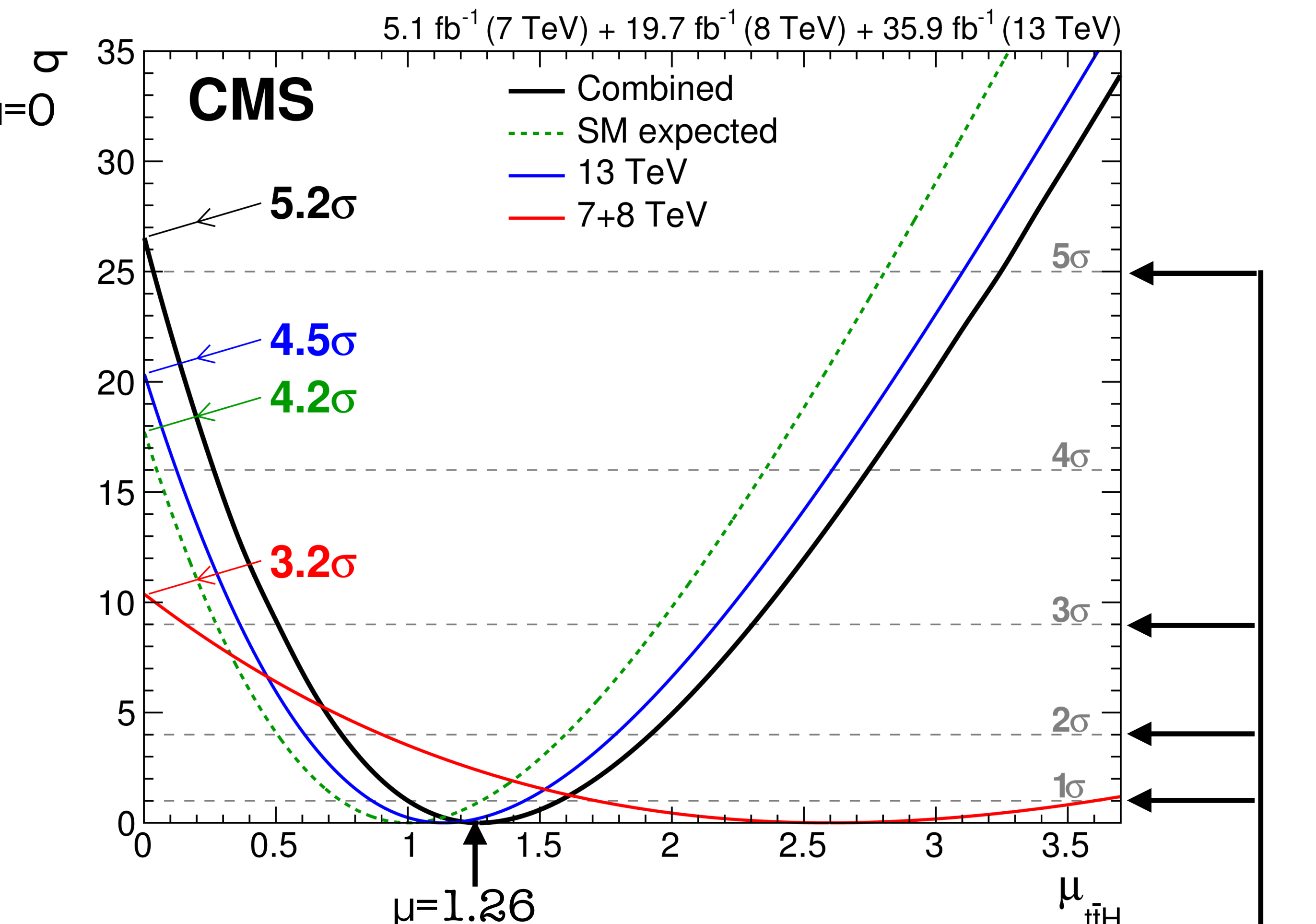
Total	+0.31	−0.26

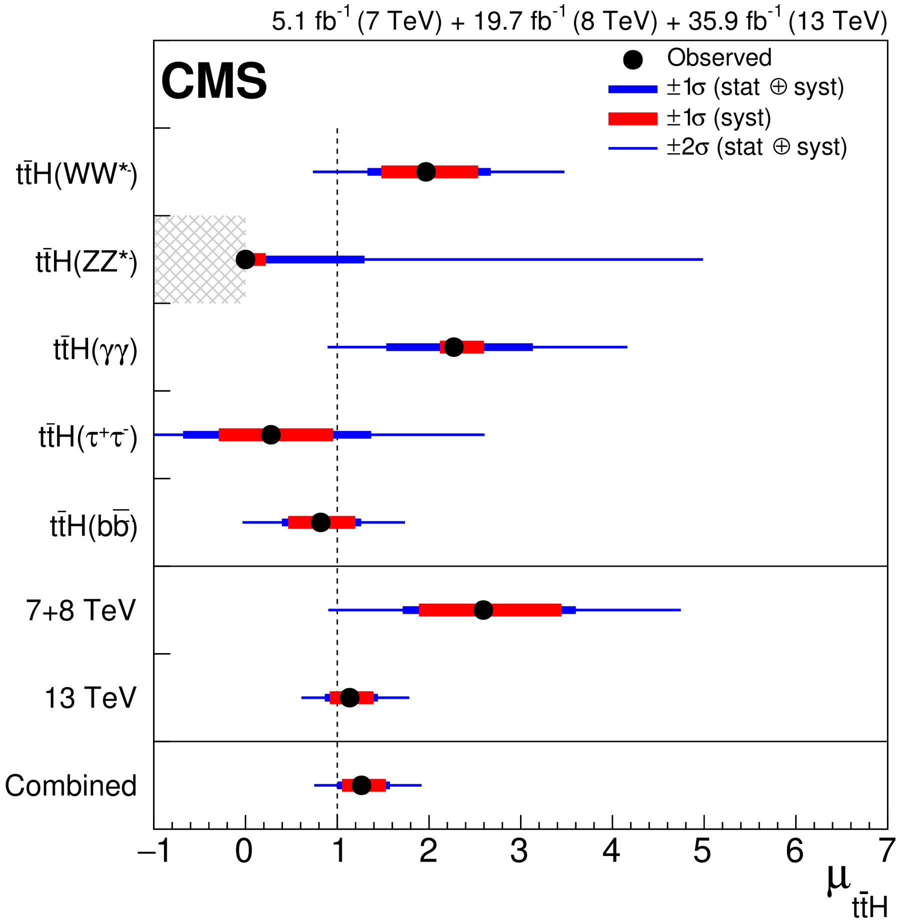
Test statistic as fn. of signal strength.

Test stat. for μ=0 using:



p-values for background only hypothesis expressed in units of s.d.'s

CMS Combination



- **First observation of tt̄H**: Phys. Rev. Lett. 120 (2018) 231801 4th June 2018.

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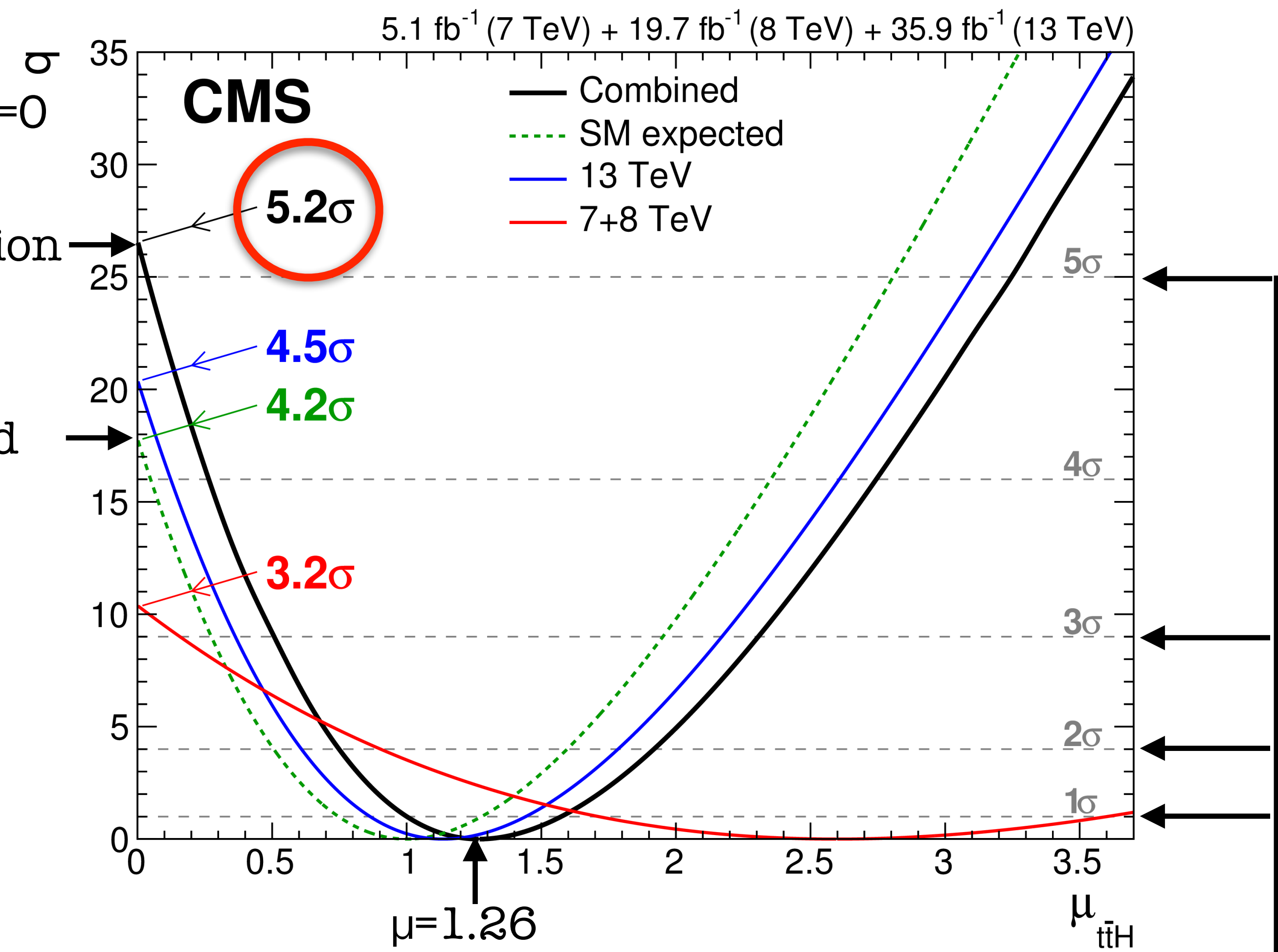
Total	+0.31	−0.26

Test statistic as fn. of signal strength.

Test stat. for μ=0 using:

Full Combination

SM Expected



p-values for background only hypothesis expressed in units of s.d.'s

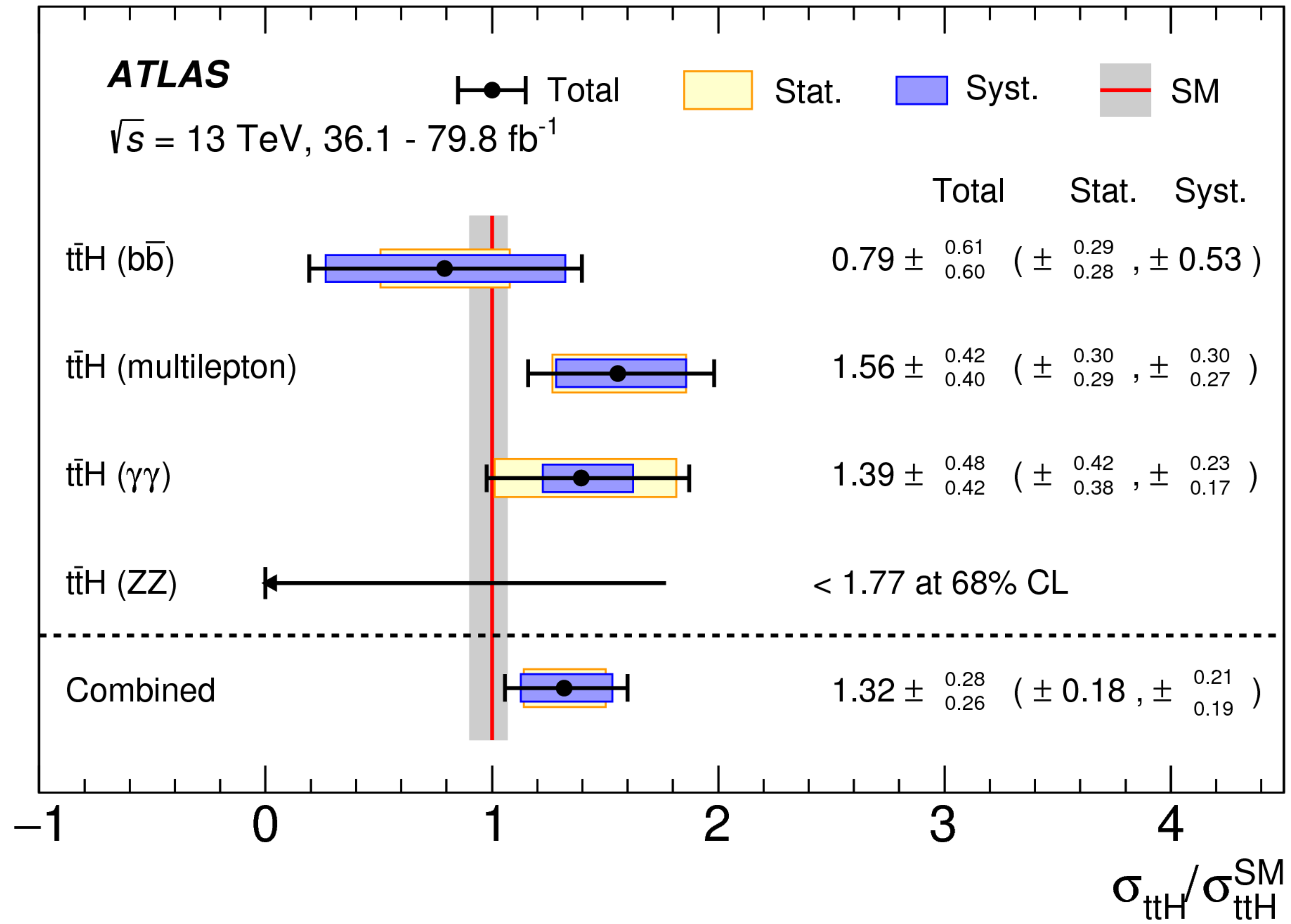
ATLAS Combination

- Measurements also using data from 2016 combine with those from 2011 and 2012.
- Consider the 5 Higgs decay modes with the largest expected event yields.
- $H \rightarrow ZZ^* \rightarrow 4l$ excluded in multilepton channel.
- Other production modes treated as backgrounds (normalised to SM values).
- $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ updated to include 2017 dataset (totals to 79.8 fb^{-1}).

Analysis	**Integrated luminosity [fb^{-1}]**	$t\bar{t}H$ **cross section [fb]**	**Obs. sign.**	**Exp. sign.**
$\boldsymbol{H \rightarrow \gamma\gamma}$	79.8	$710\,^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
$\boldsymbol{H \rightarrow}$ **multilepton**	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H \rightarrow b\bar{b}$	36.1	$400\,^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4σ	1.6σ
$\boldsymbol{H \rightarrow ZZ^* \rightarrow 4\ell}$	79.8	<900 (68% CL)	0σ	1.2σ

ATLAS Combination

- Profile likelihood method.
- Combination of $t\bar{t}H(b\bar{b})$, $t\bar{t}H(WW^*,ZZ^*,\tau\tau)$ analyses using 36.1 /fb with $t\bar{t}H(\gamma\gamma)$ & $t\bar{t}H(4l)$ using 79.8 /fb.
- $t\bar{t}H(b\bar{b})$, $t\bar{t}H(WW^*,ZZ^*,\tau\tau)$ analyses systematically limited, largest from theoretical uncertainties.
- $t\bar{t}H(\gamma\gamma)$ & $t\bar{t}H(4l)$ statistically limited.
- Run II combination observes $\mu_{t\bar{t}H}$ = 1.32 x SM = agreement with SM expectation $\mu_{t\bar{t}H}$ = 1 within 20%.



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$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)	0 σ	1.2 σ
Combined (13 TeV)	36.1−79.8	670 $\pm$ 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8 σ	4.9 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1−79.8	−	6.3 σ	5.1 σ

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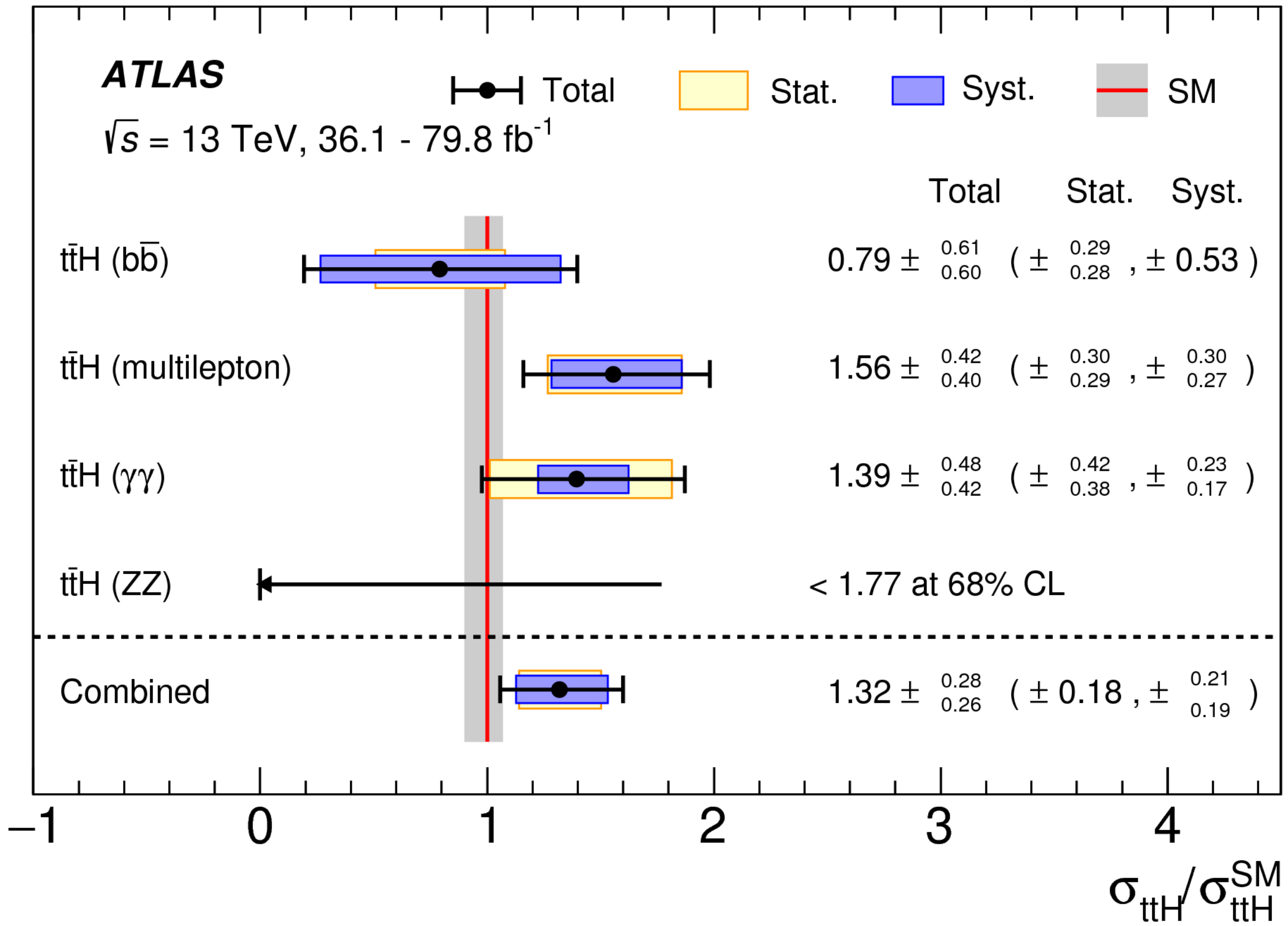

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Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3 σ	5.1 σ

Varying integrated luminosity across final states.

ATLAS Combination

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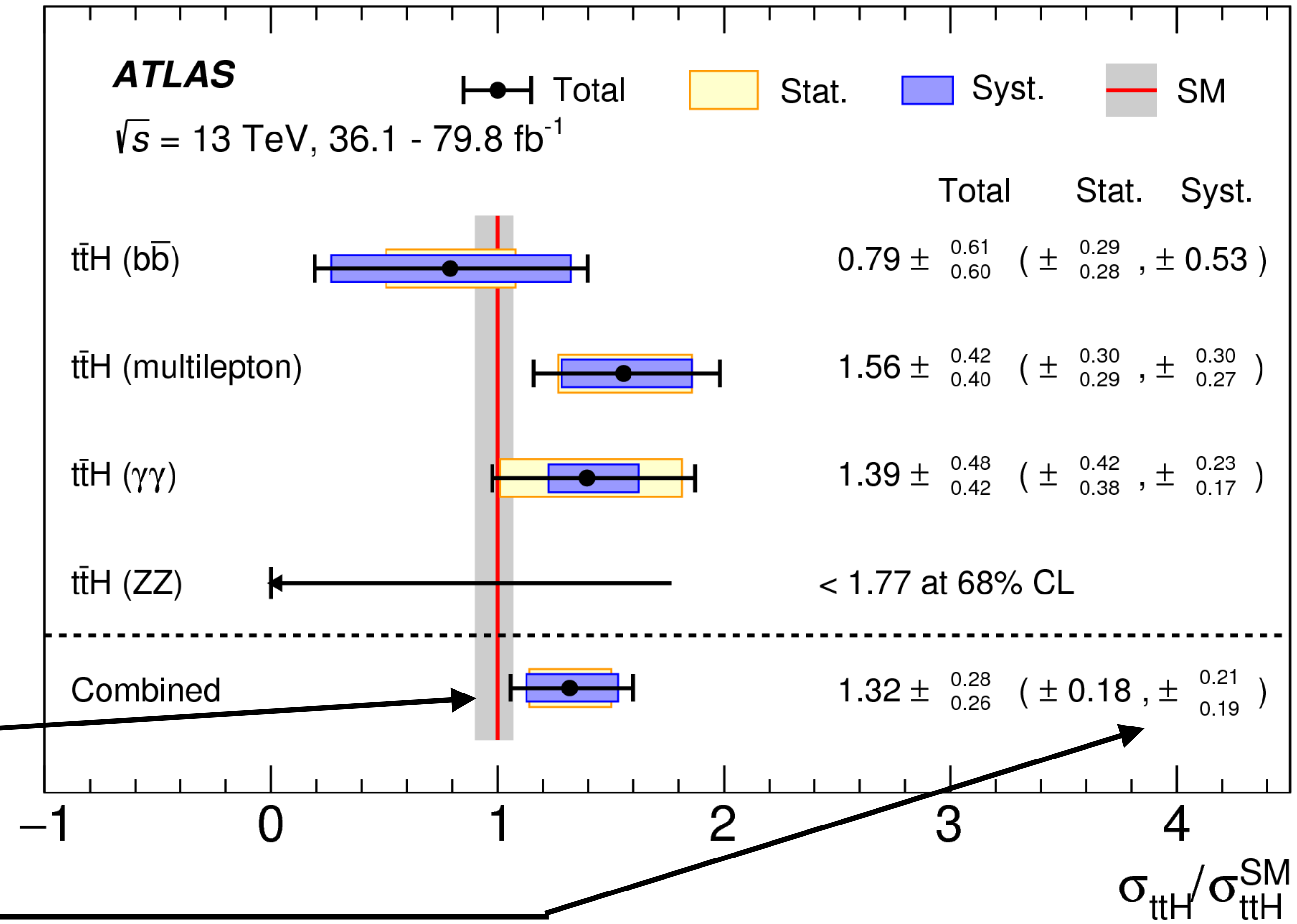

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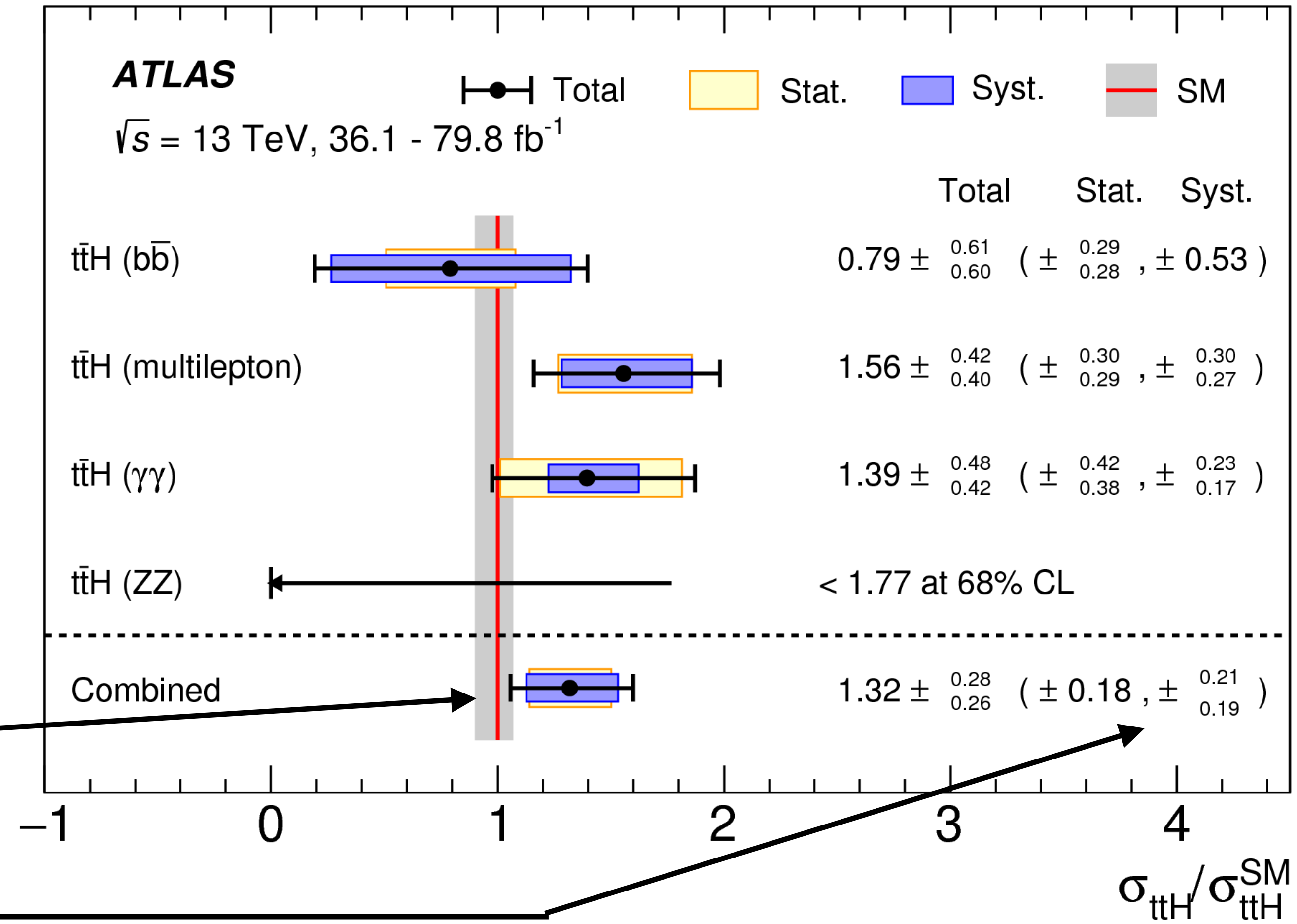

Uncertainty source	$\Delta\sigma_{t\bar{t}H}/\sigma_{t\bar{t}H}$ [%]
Theory uncertainties (modelling)	11.9
$t\bar{t}$ + heavy flavour	9.9
$t\bar{t}H$	6.0
Non-$t\bar{t}H$ Higgs boson production modes	1.5
Other background processes	2.2
Experimental uncertainties	9.3
Fake leptons	5.2
Jets, E_T^{miss}	4.9
Electrons, photons	3.2
Luminosity	3.0
τ-lepton	2.5
Flavour tagging	1.8
MC statistical uncertainties	4.4

ATLAS Combination

Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
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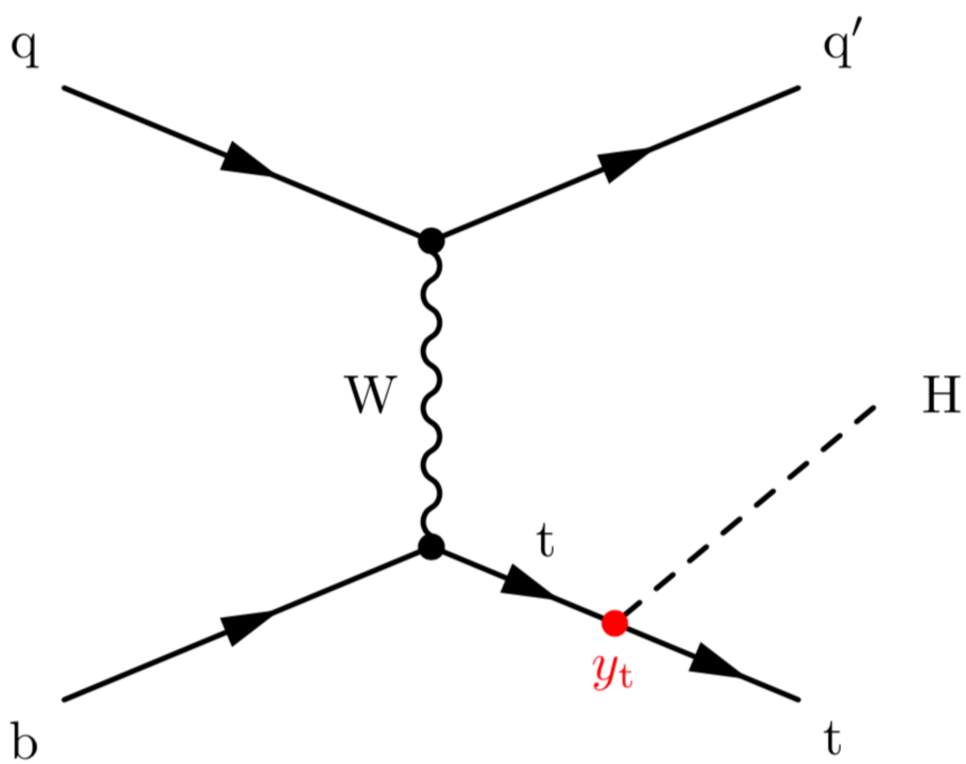
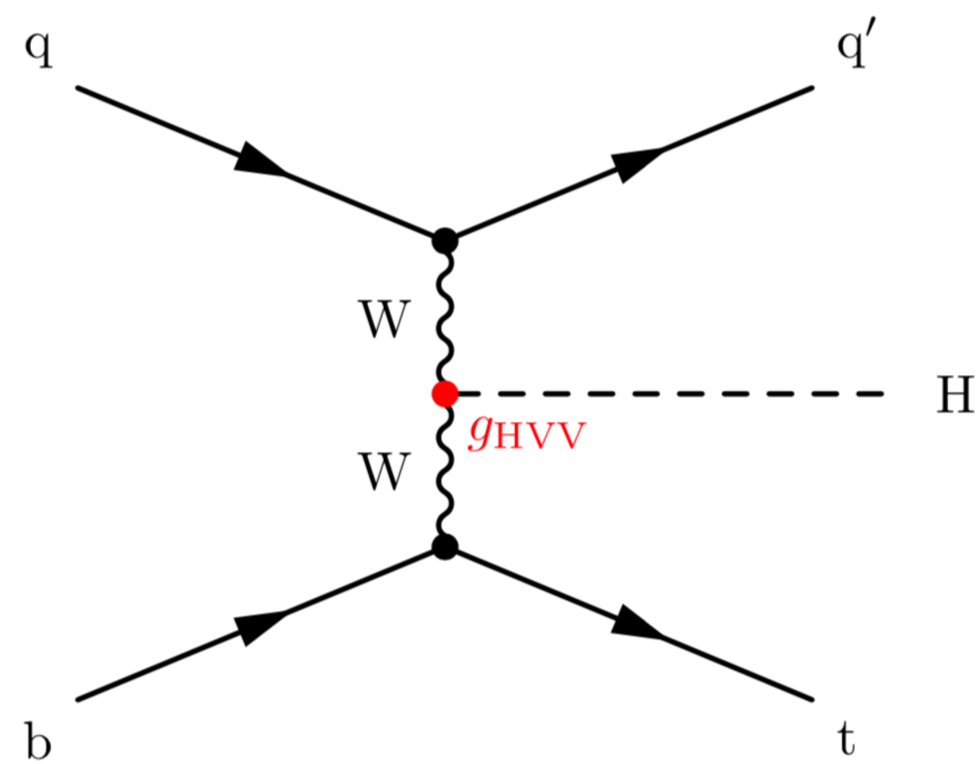
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3σ	5.1σ

ATLAS Observation!

tH Searches

- CMS and ATLAS have different approaches.
  - ATLAS consider **tH sensitive categories** of comprehensive analysis.
  - CMS design **dedicated tH analyses** to **test SM or inverted-top-coupling** (ITC) scenarios (bb,multilepton,diphoton).
- Tend to be **similar to the ttH searches** but lower yield.
- Production XS very sensitive to the t-H coupling modifier κ_t and vector boson coupling modifier κ_V. as well as their **relative signs**.





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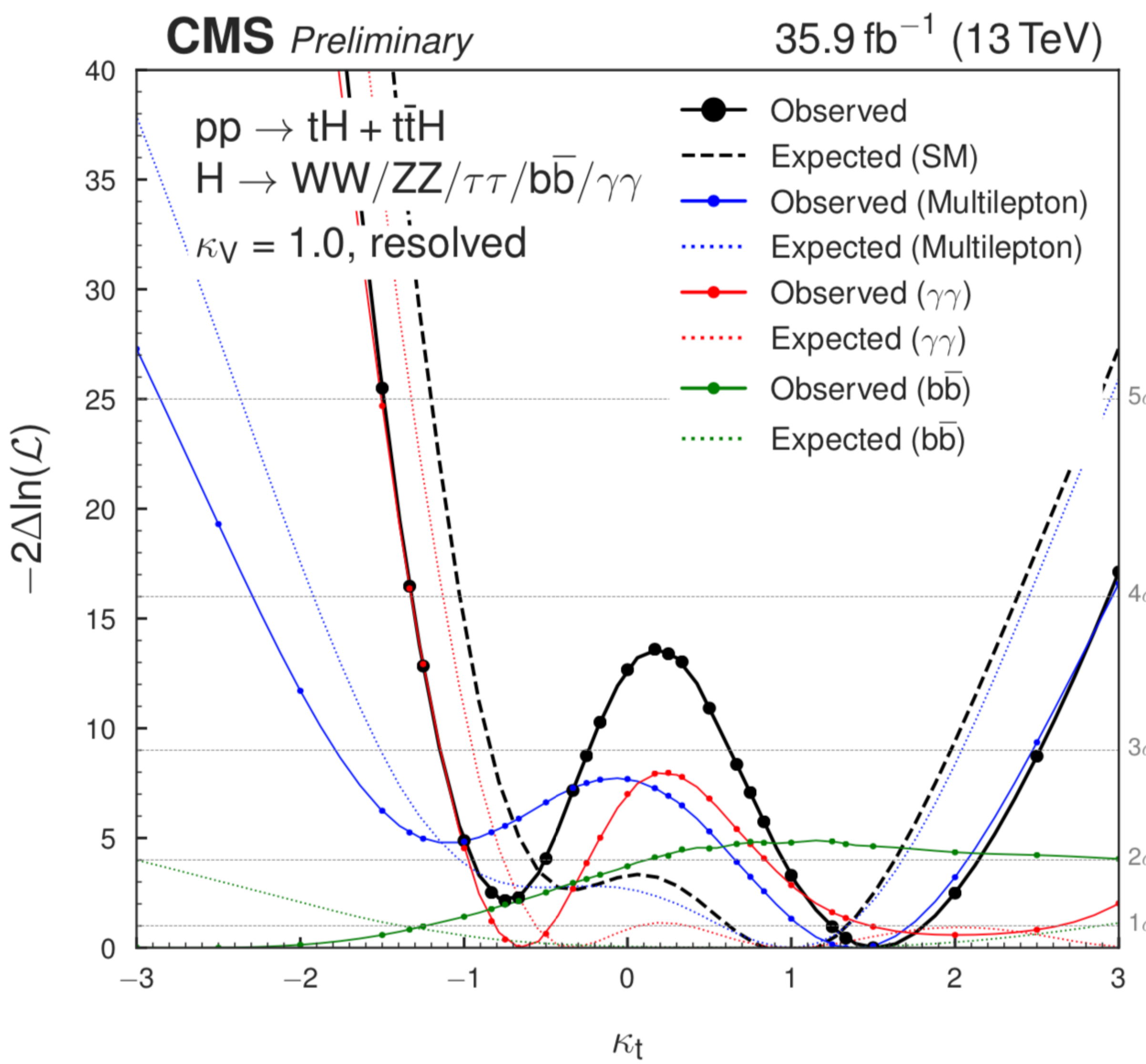
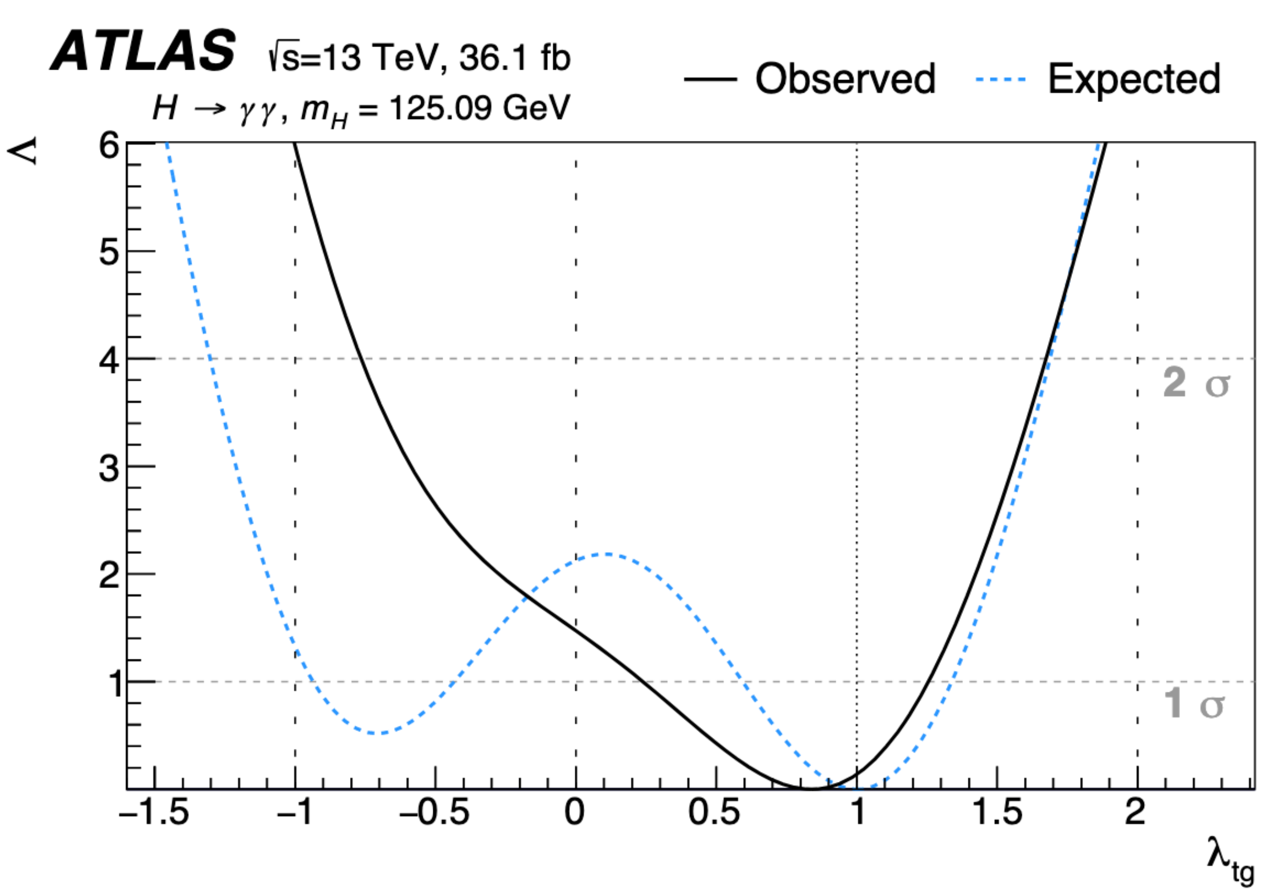
Λ profile of NLL

$$\lambda_{tg} = \kappa_t \kappa_g$$





Run 3 and Beyond

- **First direct observation of the top Yukawa coupling between the Higgs boson and a pair of top quarks**.
- Significant "evidence" already shown in several channels independently.
- Some still statistically limited - **inclusion of remaining data from run 2** should result in the observation of ttH in most sensitive channels e.g. ttH bb and multilepton (potentially even diphoton).
- **Precision measurements** - observations per channel: ~20% precision projected with integrated luminosity of 300 fb^{-1}.
- Improved analysis techniques and reduction in systematic uncertainty will improve this estimate.
- Picked a couple of measurements I think will be interesting in Run 3.
- Several others out there.

ttH/ttZ

- Measurement of the ttH cross-section - direct probe of top Yukawa.
- As we reduce systematic/statistical uncertainties, theoretical uncertainties on the ttH cross-section become more important.
- ttH(ZZ*) & ttZ differ in the final state through presence of neutrinos.
- ttH/ttZ measurement = greater precision.
- Should be able to get this for free in current ttH multilepton analyses.

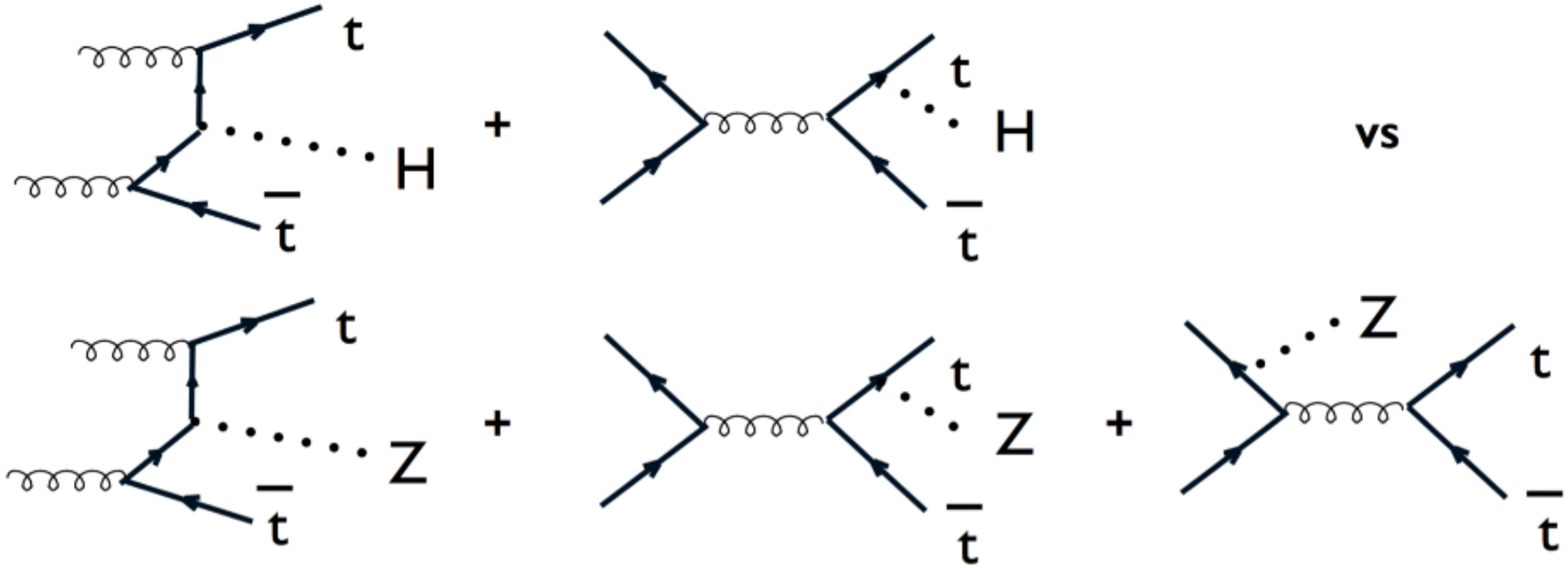
Process	XS	QCD Scale	α_S	PDF
ttH	507.2	+ 5.8 - 9.2	±2.0	±3.0
ttZ	839.3	+ 9.6% −11.3%	±2.8%	±2.8%

ttZ XS @ 13 TeV from LHC HXSWG

ttH (M_H = 125 GeV) @ 13TeV from YR4 table 231

ttH/ttZ

Diagram courtesy of K. Peters



qq→ttZ/H subdominant: Identical production dynamics

Correlated QCD corrections, correlated scale dependance.

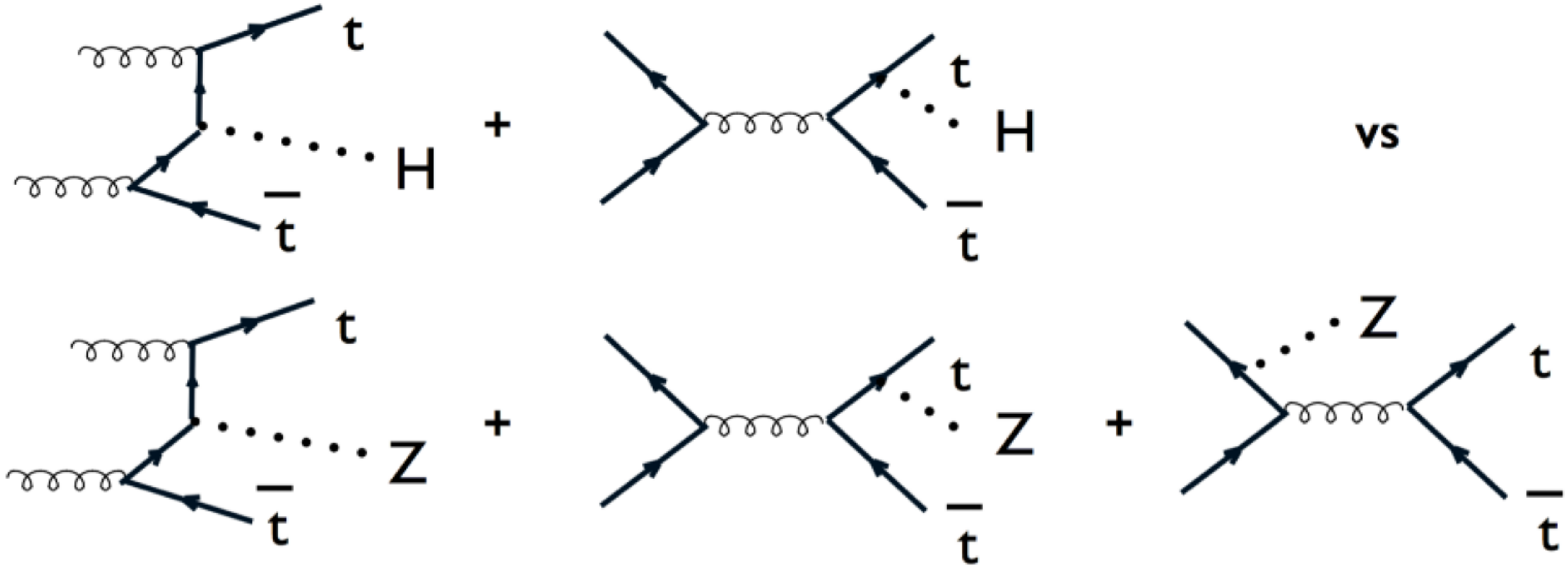
Process	XS	QCD Scale	α_S	PDF
ttH	507.2	+ 5.8 - 9.2	±2.0	±3.0
ttZ	839.3	+ 9.6% −11.3%	±2.8%	±2.8%

ttZ XS @ 13 TeV from LHC HXSWG

ttH (M_H = 125 GeV) @ 13TeV from YR4 table 231

ttH/ttZ

Diagram courtesy of K. Peters



qq→ttZ/H subdominant: Identical production dynamics

Correlated α_S syst.

Process	XS	QCD Scale	α_S	PDF
ttH	507.2	+ 5.8 - 9.2	±2.0	±3.0
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ttZ XS @ 13 TeV from LHC HXSWG

ttH (M_H = 125 GeV) @ 13TeV from YR4 table 231

ttH/ttZ

$m_Z \sim m_H$
very similar kinematics
PDF systematics correlated
m_{Top} systematics correlated

Process	XS	QCD Scale	α_s	PDF
ttH	507.2	+ 5.8 - 9.2	±2.0	±3.0
ttZ	839.3	+ 9.6% −11.3%	±2.8%	±2.8%

ttZ XS @ 13 TeV from LHC HXSWG
ttH (M_H = 125 GeV) @ 13TeV from YR4 table 231

ttH/ttZ

For a given value of top Yukawa, we expect the ratio to be predicted with great precision.

	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

Table 1: Total cross sections $\sigma(t\bar{t}H)$ and $\sigma(t\bar{t}Z)$ and the ratios $\sigma(t\bar{t}H)/\sigma(t\bar{t}Z)$ with NLO QCD corrections at 13 TeV and 100 TeV. Results are presented together with the renormalization/factorization scale and PDF+α_S uncertainties.

Magnano et al

Differential measurements of ttH

- Our understanding of the properties of the Higgs boson has improved dramatically.

- Fundamental property least understood = **Higgs potential**.

- It's due to the shape of the potential that EW symmetry is broken.

$$\boxed{V(\phi)} = V_0 + \frac{1}{2}\mu^2 h^2 + \frac{\mu^2}{v}h^3 + \frac{1}{4}\frac{\mu^2}{v^2}h^4 + ...$$

Potential of Higgs field ϕ → expand about its minimum (i.e. vev = ν) such that V(ϕ) becomes V(ν+h)

Differential measurements of ttH

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Potential minimum

Differential measurements of ttH

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$$V(\phi) = V_0 + \frac{1}{2}\boxed{\mu^2}h^2 + \frac{\mu^2}{v}h^3 + \frac{1}{4}\frac{\mu^2}{v^2}h^4 + ...$$

associated w. Higgs mass

Differential measurements of ttH

- Our understanding of the properties of the Higgs boson has improved dramatically.
- Fundamental property least understood = Higgs potential.
- It's due to the shape of the potential that EW symmetry is broken.

$$V(\phi) = V_0 + \frac{1}{2}\mu^2 h^2 + \frac{\mu^2}{\boxed{v}} h^3 + \frac{1}{4}\frac{\mu^2}{v^2} h^4 + \ldots.$$

Vacuum expectation

Differential measurements of ttH

- Our understanding of the properties of the Higgs boson has improved dramatically.

- Fundamental property least understood = Higgs potential.

- It’s due to the shape of the potential that EW symmetry is broken.

$$V(\phi) = V_0 + \frac{1}{2}\mu^2 h^2 + \frac{\mu^2}{v}\boxed{h^3} + \frac{1}{4}\frac{\mu^2}{v^2}h^4 + \ldots.$$

Trilinear coupling

Differential measurements of ttH

- Our understanding of the properties of the Higgs boson has improved dramatically.

- Fundamental property least understood = Higgs potential.

- It's due to the shape of the potential that EW symmetry is broken.

$$V(\phi) = V_0 + \frac{1}{2}\mu^2 h^2 + \frac{\mu^2}{v} h^3 + \frac{1}{4}\frac{\mu^2}{v^2} h^4 + ...$$

- Shape of the Higgs potential dictated by the relationship between the Higgs mass, VEV and trilinear/quartic couplings.

- At low energies, new physics could alter the trillinear coupling λ_3 thus altering the shape of the potential without affecting the value wither m_H or the vev.

- Differential effects particularly relevant in ttH (and VH).

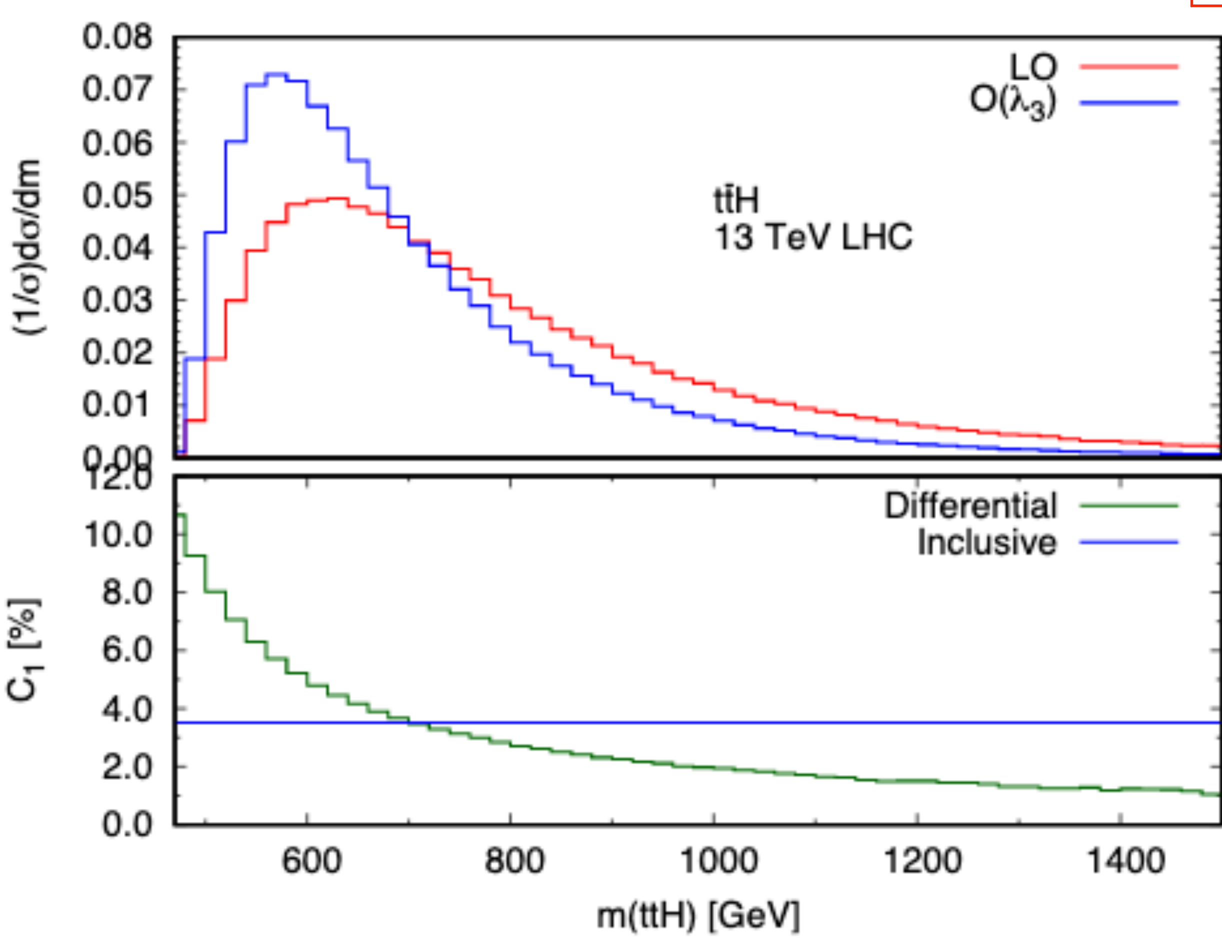
Differential measurements of ttH

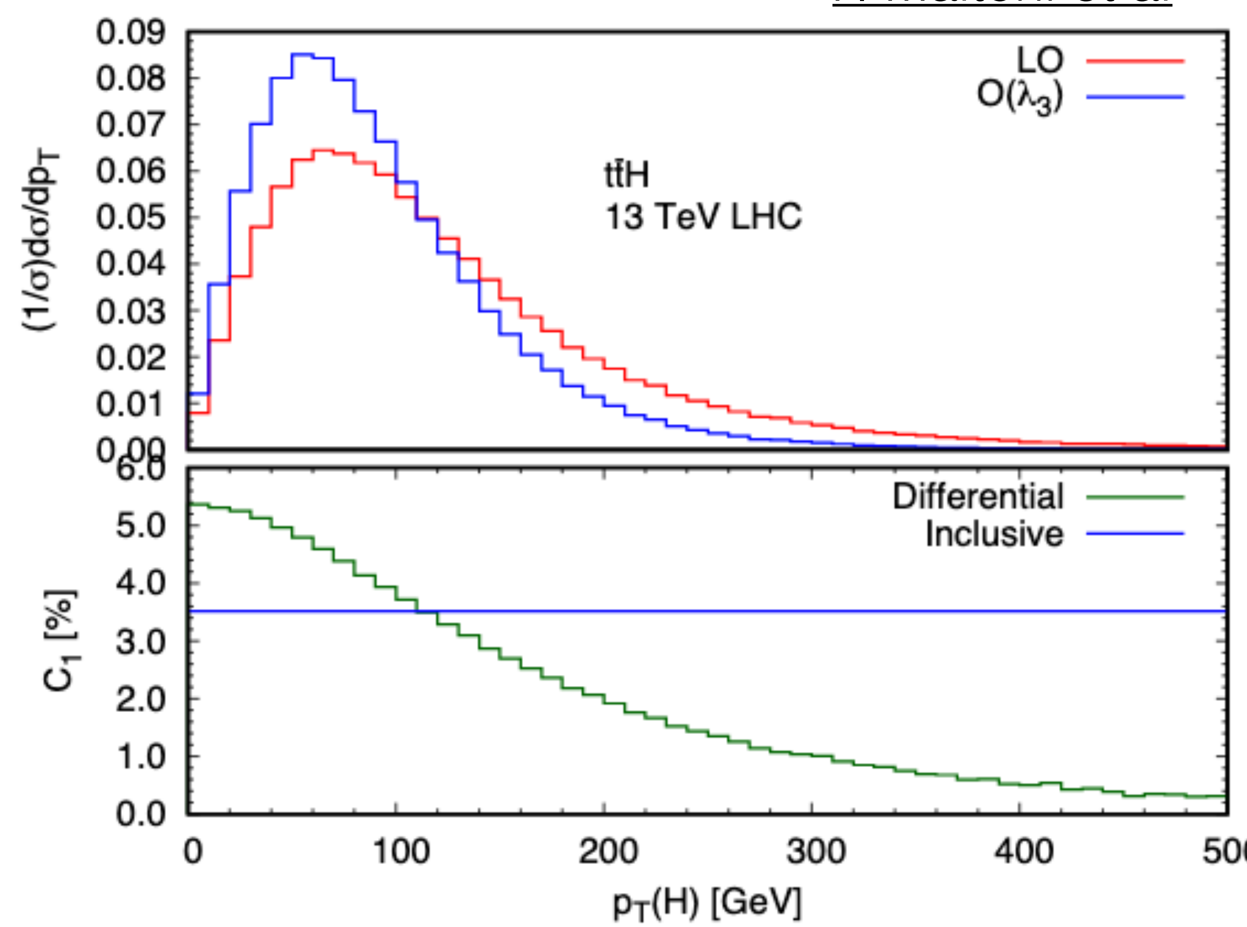
- Double Higgs production directly depends on trilinear self-coupling but low XS (observation more likely @ end of Run3/HL-LHC).
- Single Higgs production doesn't depend on λ_3 at LO or higher orders in QCD, it does depend on λ_3 via loop processes at NLO in EW interactions.
- Possible to have indirect measurement of λ_3 through impact of λ_3-dependant NLO EW 1-loop corrections have on Higgs observables.
- Potential sensitive variables: mass of ttH-system, transverse momentum of Higgs ….
- Relative corrections due to trilinear couplings:

change in generic observable Σ where $k_3 = \frac{\lambda_3}{\lambda_3^{SM}}$

$$\boxed{\delta\Sigma_{k_3}} \propto C_1$$

F. Maltoni et al





Summary

- Presented an overview of the measurements of Higgs boson production in association with a pair of top quarks at the LHC.
- Shown latest and greatest results using the (partial) Run 2 datasets from CMS & ALTAS.
- **ttH production observed by both collaboration in 2018** - combination of several decay channels.
- 'Evidence' of ttH production in specific decay channels also reported - close to observation.
- Many channels limited by lack of data.
- **Theoretical uncertainties of background modelling** starting to have a major impact on analyses - being addressed but work to be done.
- Full Run 2 dataset (+Run 3?) should provide enough data to observe ttH production per decay mode.

Summary

- Looking toward Run 3 and beyond the focus will become **precision measurements**.

- **Stringent test of the SM.**

- In **absence of direct measurement from di-Higgs** before end of Run 3 / HL-LHC, **differential measurements** provide an **indirect measurement** of the **trilinear self-coupling** of the Higgs.

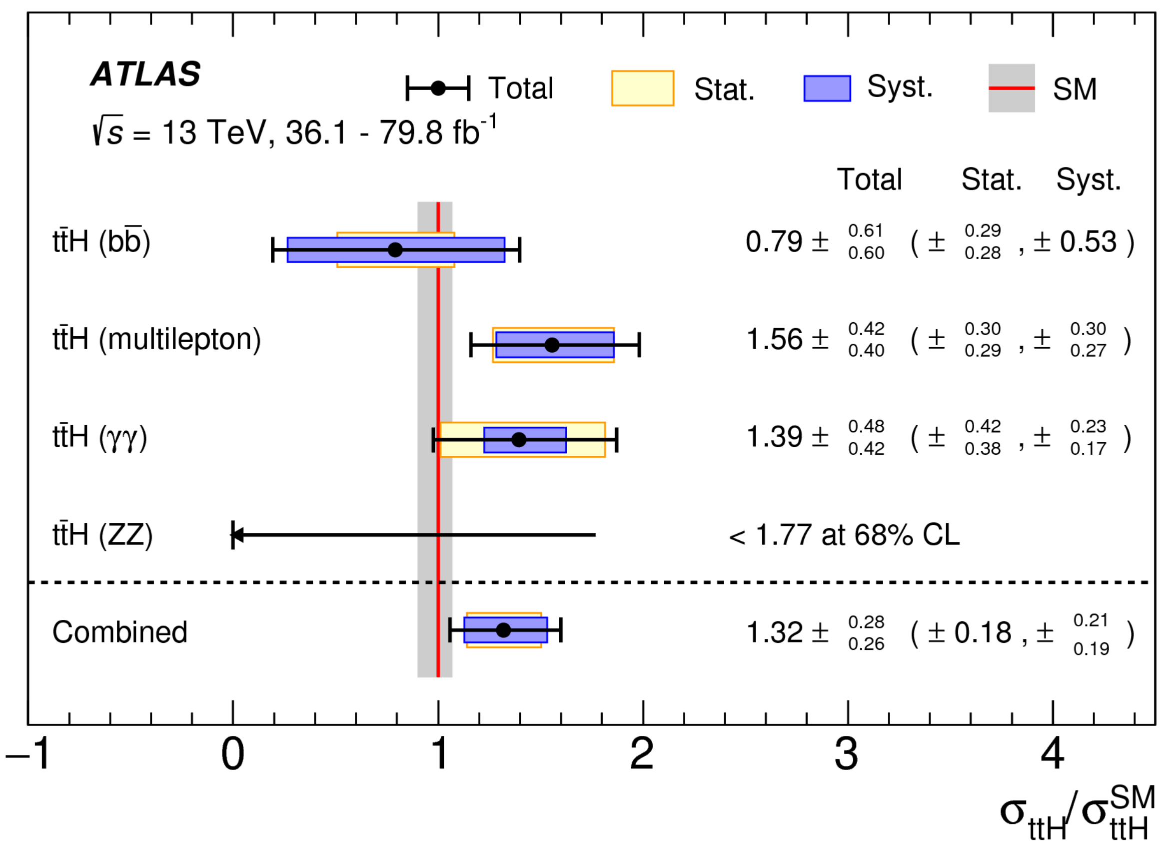
- Additional measurements to come: di-Higgs, rare decay channels etc.

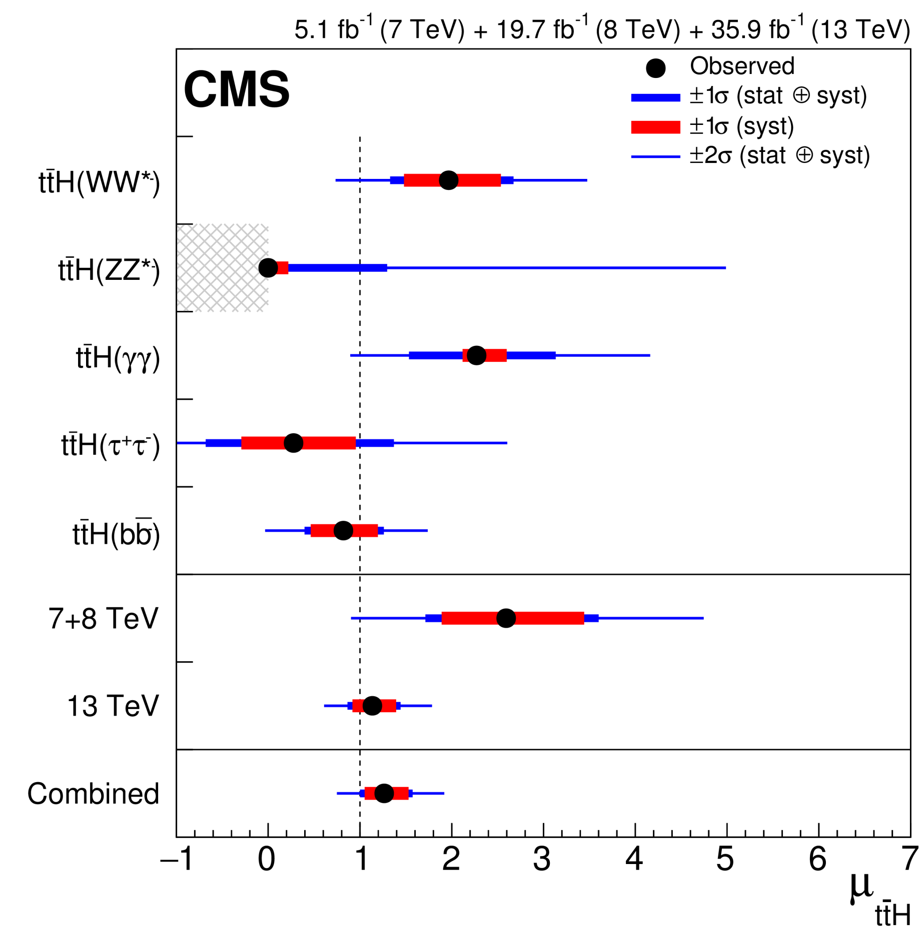
Backup

Comparison

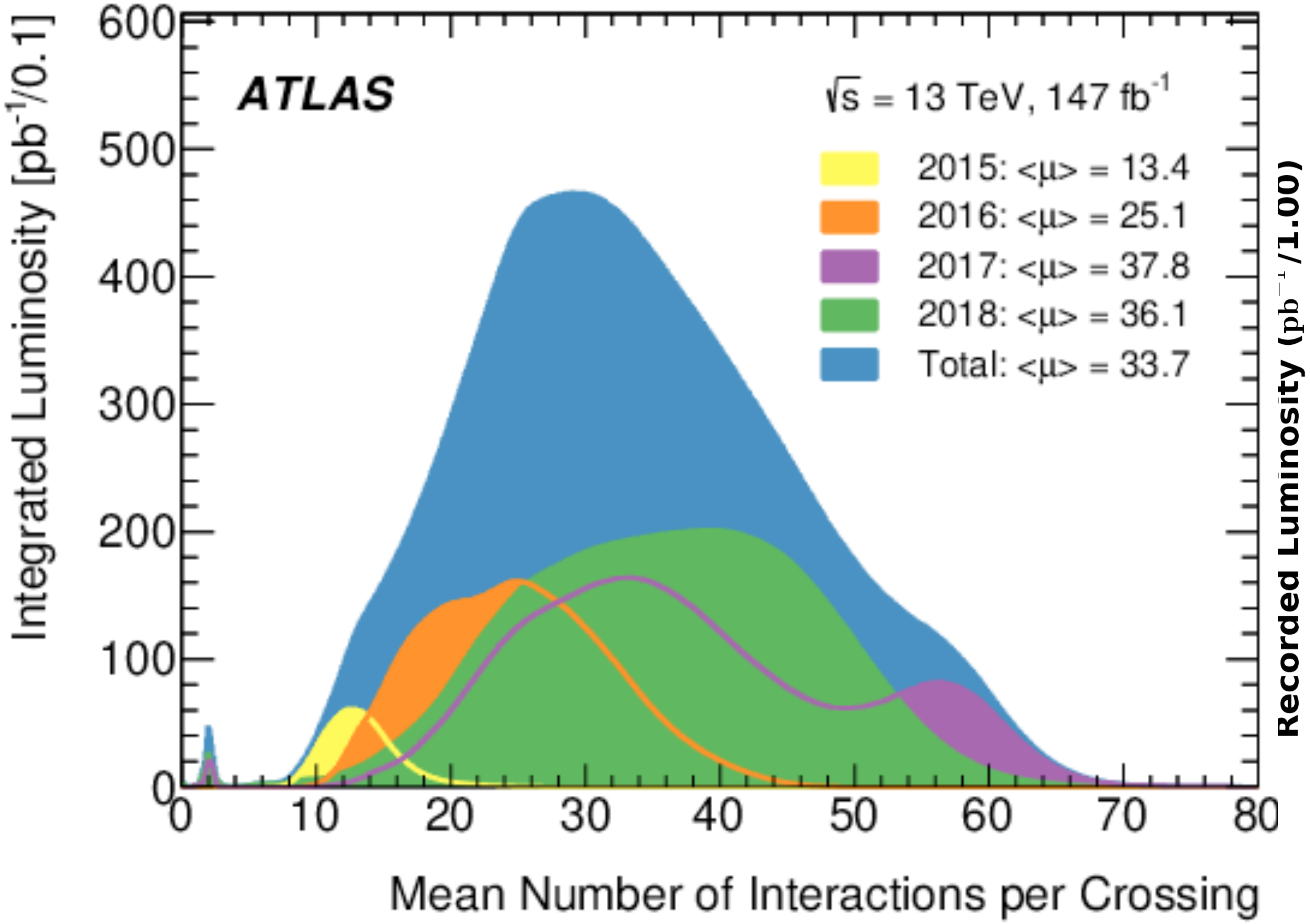
Analysis	Integrated luminosity [fb^{-1}]	$t\bar{t}H$ cross section [fb]	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	79.8	$710\ ^{+210}_{-190}$ (stat.) $^{+120}_{-90}$ (syst.)	4.1σ	3.7σ
$H \to$ multilepton	36.1	790 ± 150 (stat.) $^{+150}_{-140}$ (syst.)	4.1σ	2.8σ
$H \to b\bar{b}$	36.1	$400\ ^{+150}_{-140}$ (stat.) $\pm$ 270 (syst.)	1.4σ	1.6σ
$H \to ZZ^* \to 4\ell$	79.8	<900 (68% CL)	0σ	1.2σ
Combined (13 TeV)	36.1–79.8	670 ± 90 (stat.) $^{+110}_{-100}$ (syst.)	5.8σ	4.9σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	–	6.3σ	5.1σ

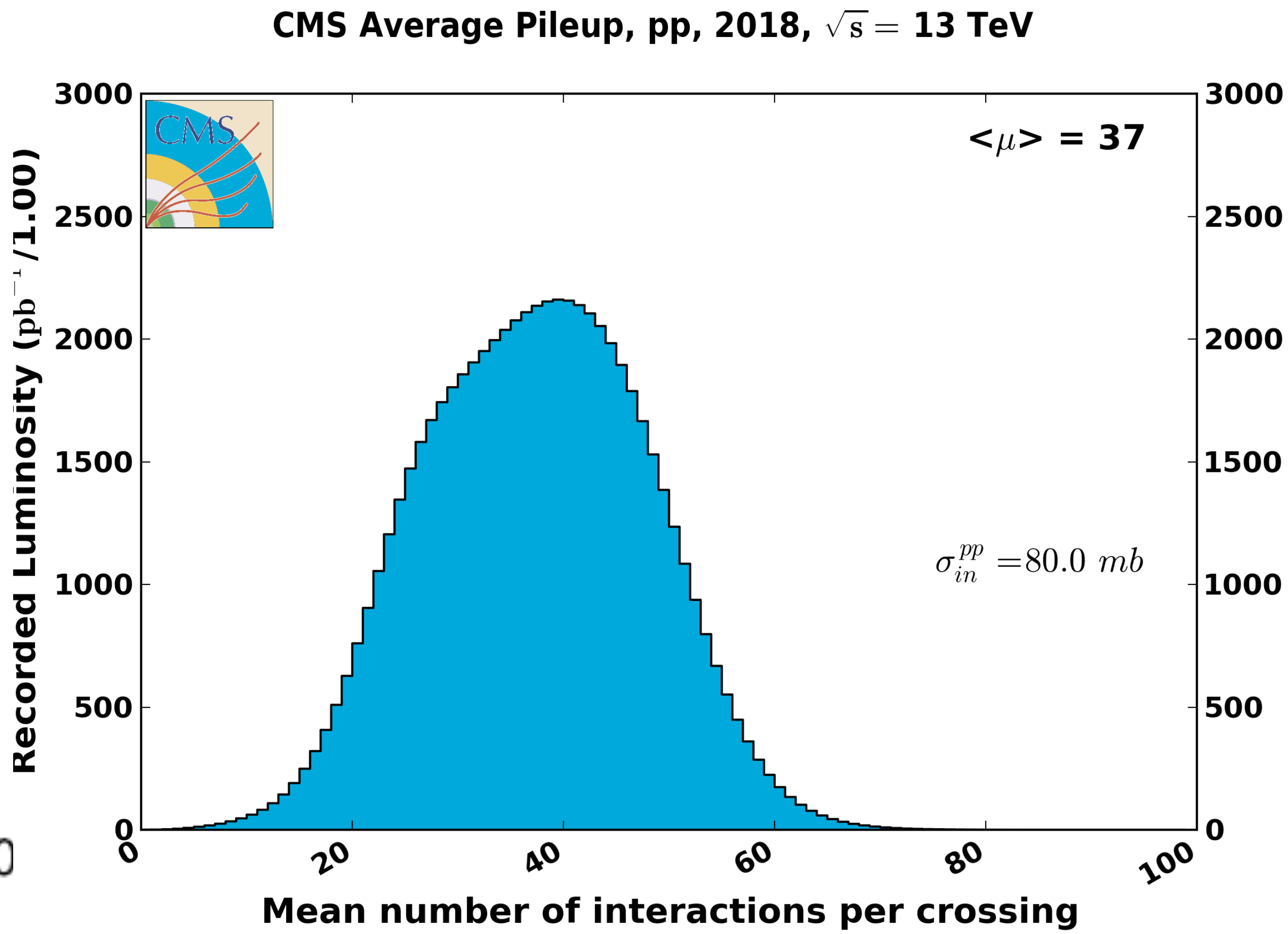
Parameter	Best fit	Uncertainty: Stat	Uncertainty: Expt	Uncertainty: Thbgd	Uncertainty: Thsig
$\mu^{\mathrm{WW}^*}_{\mathrm{t\bar{t}H}}$	$1.97^{+0.71}_{-0.64}$ $\left(^{+0.57}_{-0.54}\right)$	$^{+0.42}_{-0.41}$ $\left(^{+0.39}_{-0.38}\right)$	$^{+0.46}_{-0.42}$ $\left(^{+0.36}_{-0.34}\right)$	$^{+0.21}_{-0.21}$ $\left(^{+0.17}_{-0.17}\right)$	$^{+0.25}_{-0.12}$ $\left(^{+0.12}_{-0.03}\right)$
$\mu^{\mathrm{ZZ}^*}_{\mathrm{t\bar{t}H}}$	$0.00^{+1.30}_{-0.00}$ $\left(^{+2.89}_{-0.99}\right)$	$^{+1.28}_{-0.00}$ $\left(^{+2.82}_{-0.99}\right)$	$^{+0.20}_{-0.00}$ $\left(^{+0.51}_{-0.00}\right)$	$^{+0.04}_{-0.00}$ $\left(^{+0.15}_{-0.00}\right)$	$^{+0.09}_{-0.00}$ $\left(^{+0.27}_{-0.00}\right)$
$\mu^{\gamma\gamma}_{\mathrm{t\bar{t}H}}$	$2.27^{+0.86}_{-0.74}$ $\left(^{+0.73}_{-0.64}\right)$	$^{+0.80}_{-0.72}$ $\left(^{+0.71}_{-0.64}\right)$	$^{+0.15}_{-0.09}$ $\left(^{+0.09}_{-0.04}\right)$	$^{+0.02}_{-0.01}$ $\left(^{+0.01}_{-0.00}\right)$	$^{+0.29}_{-0.13}$ $\left(^{+0.13}_{-0.05}\right)$
$\mu^{\tau^+\tau^-}_{\mathrm{t\bar{t}H}}$	$0.28^{+1.09}_{-0.96}$ $\left(^{+1.00}_{-0.89}\right)$	$^{+0.86}_{-0.77}$ $\left(^{+0.83}_{-0.76}\right)$	$^{+0.64}_{-0.53}$ $\left(^{+0.54}_{-0.47}\right)$	$^{+0.10}_{-0.09}$ $\left(^{+0.09}_{-0.08}\right)$	$^{+0.20}_{-0.19}$ $\left(^{+0.14}_{-0.01}\right)$
$\mu^{\mathrm{b\bar{b}}}_{\mathrm{t\bar{t}H}}$	$0.82^{+0.44}_{-0.42}$ $\left(^{+0.44}_{-0.42}\right)$	$^{+0.23}_{-0.23}$ $\left(^{+0.23}_{-0.22}\right)$	$^{+0.24}_{-0.23}$ $\left(^{+0.24}_{-0.23}\right)$	$^{+0.27}_{-0.27}$ $\left(^{+0.26}_{-0.27}\right)$	$^{+0.11}_{-0.03}$ $\left(^{+0.11}_{-0.04}\right)$
$\mu^{7+8\ \mathrm{TeV}}_{\mathrm{t\bar{t}H}}$	$2.59^{+1.01}_{-0.88}$ $\left(^{+0.87}_{-0.79}\right)$	$^{+0.54}_{-0.53}$ $\left(^{+0.51}_{-0.49}\right)$	$^{+0.53}_{-0.49}$ $\left(^{+0.48}_{-0.44}\right)$	$^{+0.55}_{-0.49}$ $\left(^{+0.50}_{-0.44}\right)$	$^{+0.37}_{-0.13}$ $\left(^{+0.14}_{-0.02}\right)$
$\mu^{13\ \mathrm{TeV}}_{\mathrm{t\bar{t}H}}$	$1.14^{+0.31}_{-0.27}$ $\left(^{+0.29}_{-0.26}\right)$	$^{+0.17}_{-0.16}$ $\left(^{+0.16}_{-0.16}\right)$	$^{+0.17}_{-0.17}$ $\left(^{+0.17}_{-0.16}\right)$	$^{+0.13}_{-0.12}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.14}_{-0.06}$ $\left(^{+0.11}_{-0.05}\right)$
$\mu_{\mathrm{t\bar{t}H}}$	$1.26^{+0.31}_{-0.26}$ $\left(^{+0.28}_{-0.25}\right)$	$^{+0.16}_{-0.16}$ $\left(^{+0.15}_{-0.15}\right)$	$^{+0.17}_{-0.15}$ $\left(^{+0.16}_{-0.15}\right)$	$^{+0.14}_{-0.13}$ $\left(^{+0.13}_{-0.12}\right)$	$^{+0.15}_{-0.07}$ $\left(^{+0.11}_{-0.05}\right)$






2019
2020
2021
2022
2023
2024
2025
2026
2027
Long Shutdown 2 (LS2)
Run 3
Long Shutdown 3 (LS3)
2028
2029
2030
2031
2032
2033
2034
2035
2036
Run 4
LS4
Run 5
LS5
Shutdown/Technical stop
Protons physics
Commissioning
Ions


ATLAS
$\sqrt{s}$ = 13 TeV, 147 fb^{-1}
2015: <μ> = 13.4
2016: <μ> = 25.1
2017: <μ> = 37.8
2018: <μ> = 36.1
Total: <μ> = 33.7
Integrated Luminosity [pb^{-1}/0.1]
Mean Number of Interactions per Crossing


CMS Average Pileup, pp, 2018, $\sqrt{s} =$ 13 TeV
<μ> = 37
σ_{in}^{pp} =80.0 mb
Recorded Luminosity (pb^{-1}/1.00)
Mean number of interactions per crossing

Lagrangian

Force carrying gauge bosons.

Leptons, quarks and their interactions.

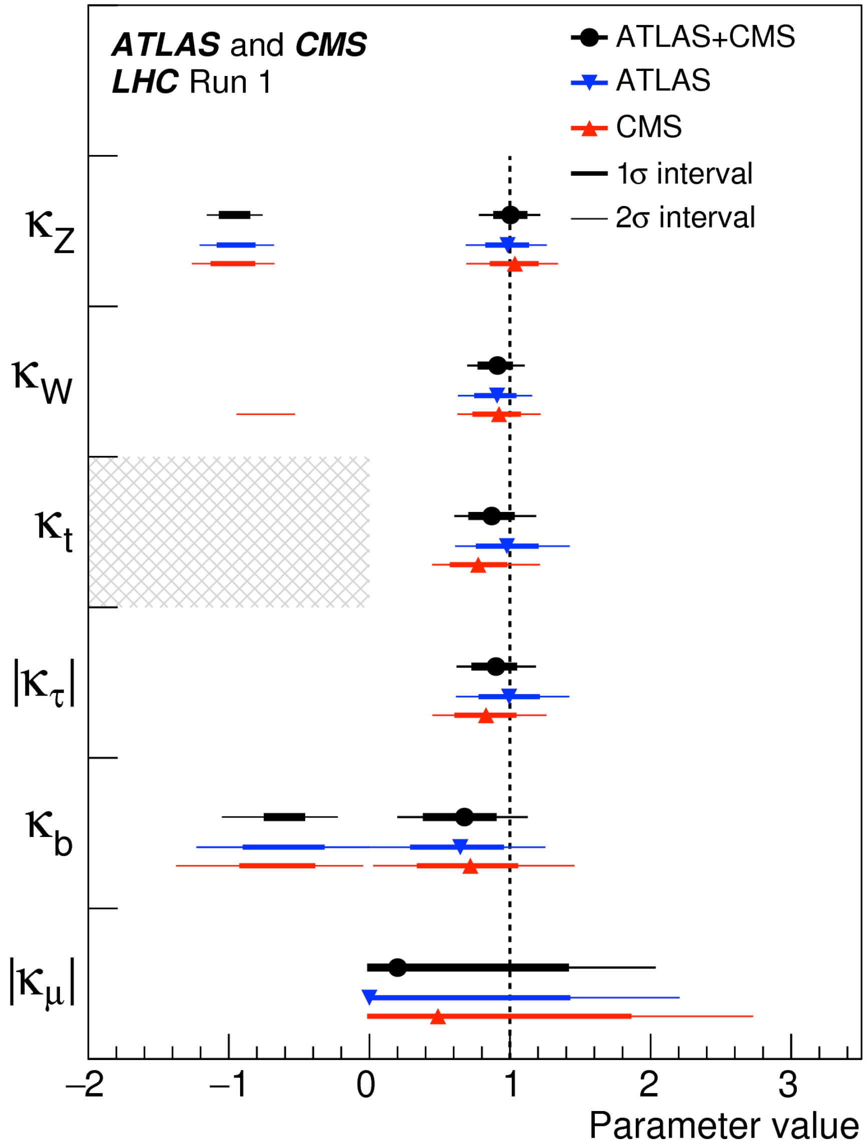
$$\mathcal{L} = \boxed{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}} + \boxed{i\overline{\Psi}\not{D}\Psi}$$
$$+\Psi_i y_{ij}\Psi_j\Phi + \mathrm{h.c.}$$
$$+|D_\mu\Phi|^2 + \mathrm{V}(\Phi)$$

Kappa Framework

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\overline{\Psi}\not{D}\Psi$$
$$+\boxed{\Psi_i y_{ij}\Psi_j\Phi} + \text{h.c.}$$
$$+\boxed{|D_\mu\Phi|^2} + \mathrm{V}(\Phi)$$

Coupling to fermions (Yukawa couplings)

Coupling to bosons (Gauge couplings)



- Fit coupling modifiers accessible at the LHC.
- Loop coupling signal strengths are resolved in expressions of tree-level couplings assuming SM.
- No BSM decays.
- All couplings compatible with SM.

Kappa Framework

- Measurement of the coupling itself performed using the “Kappa Framework”.
- Assumes signals observed in different channels from single narrow resonance (NWA).
- Decompose signal XS as follows:

Prod. XS via initial state ii

Partial decay width into ff

$$(\sigma \cdot BR)(ii \to H \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_H}$$

Higgs total width

$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

$$\kappa_i^2 = \frac{\Gamma_i}{\Gamma_{SM}^i}$$

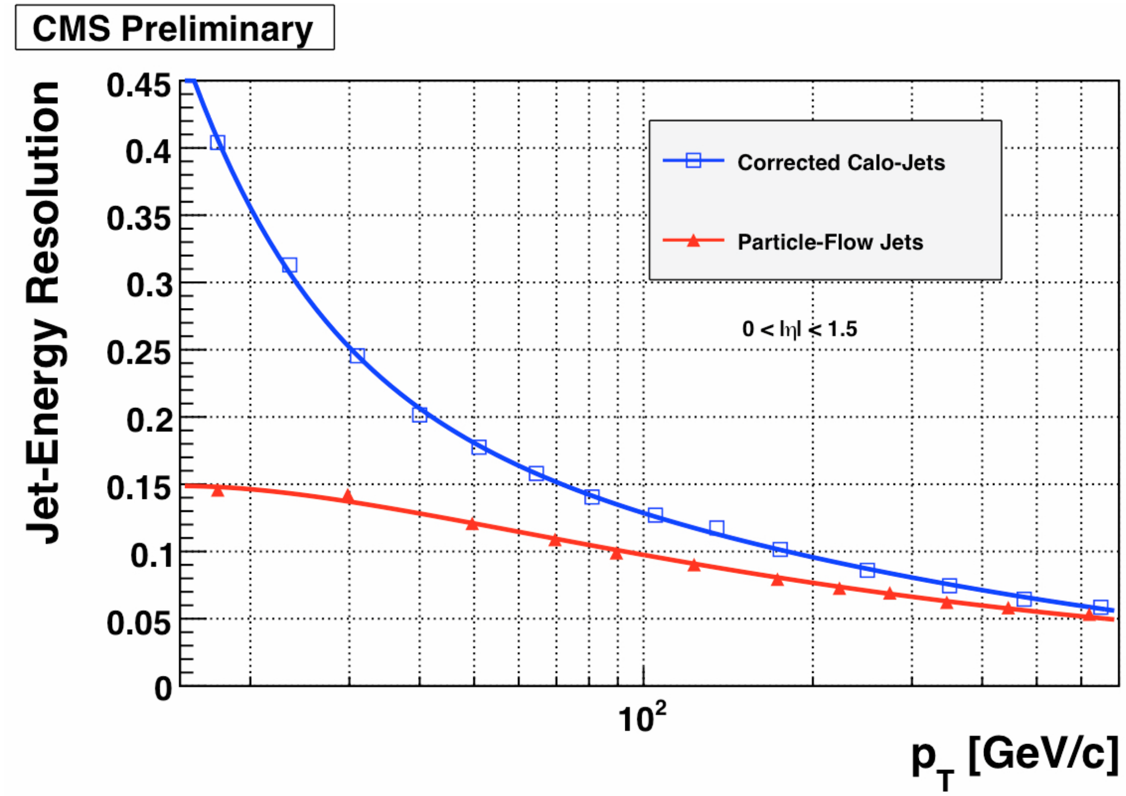
- Dresses SM Higgs XS and partial decay widths with scale factors κ_i.
- For tree-level LO process coupling modifiers: $\text{fermions}: \kappa_f \to \kappa_t, \kappa_b, \kappa_T$

$$\text{bosons}: \kappa_V \to \kappa_W, \kappa_Z,$$

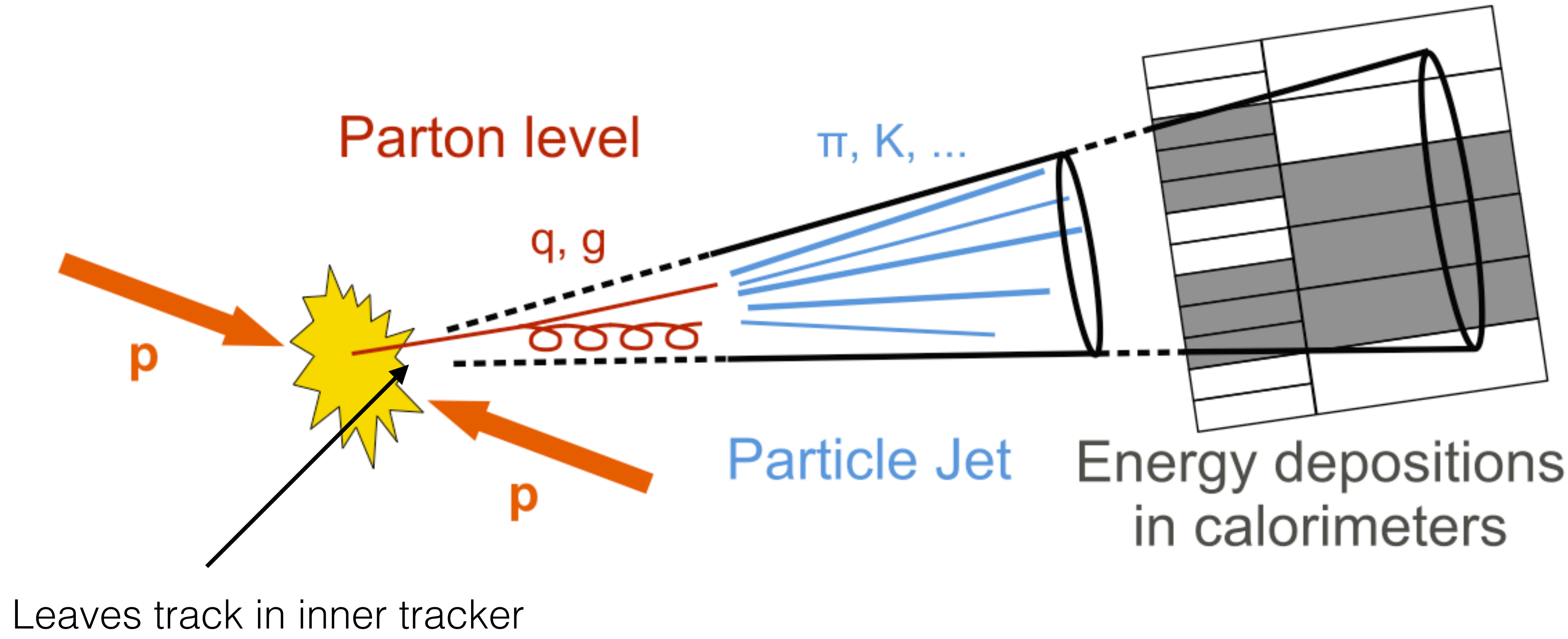
- Processes with loops at LO can be expressed as a polynomial of the above…..
- or an effective κ_i: $\kappa_g, \kappa_\gamma, \kappa_H$
- Although κ_i corresponds to LO degrees of freedom, usually multiplies SM cross-section NO or NNLO in QCD and EW.

CMS Particle Flow (PF)

- Information from inner tracking system typically ignored in jet reconstruction in @ hadron colliders.
- Presence of charged hadron (energy, direction, origin) signalled by a track connected to a calorimeter energy deposit.
- Key ingredients:
  - Excellent tracking efficiency (~90% in CMS) & purity (false tracks @ per cent level).
  - Ability to resolve calorimeter energy deposits from neighbouring particles: high granularity in ECAL, inside large B-field.
  - Unambiguous matching of charged-particle tracks to calorimeter deposits: Calorimeters are *inside* the magnet coil - minimises probability of charged particle generating a shower before calorimeters, facilitates matching.
- After PF, left with list of particles much like an event generator.
- Used to reconstruct jets, MET, tau decay ID, lepton isolation . . . . .



Jets



- Experimental signature of quarks and gluons.
- Cannot exist freely due to colour confinement so form colour neutral hadrons.
- Leads to collimated spray of hadrons.
- Clustered together we call them jets.

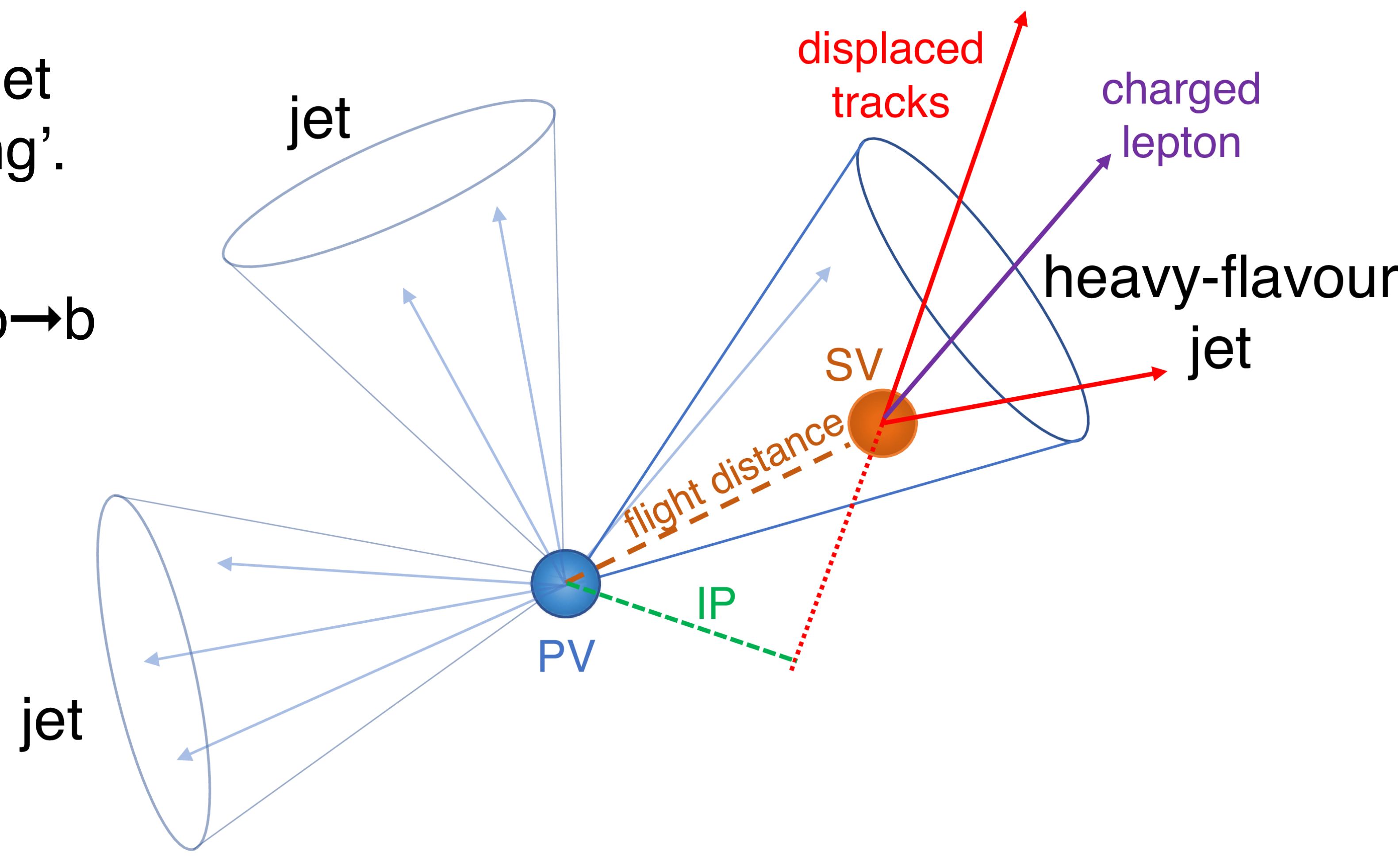
B-jets

- Jets formed from the hadronisation of a b-quark leave distinct signatures in the detector.

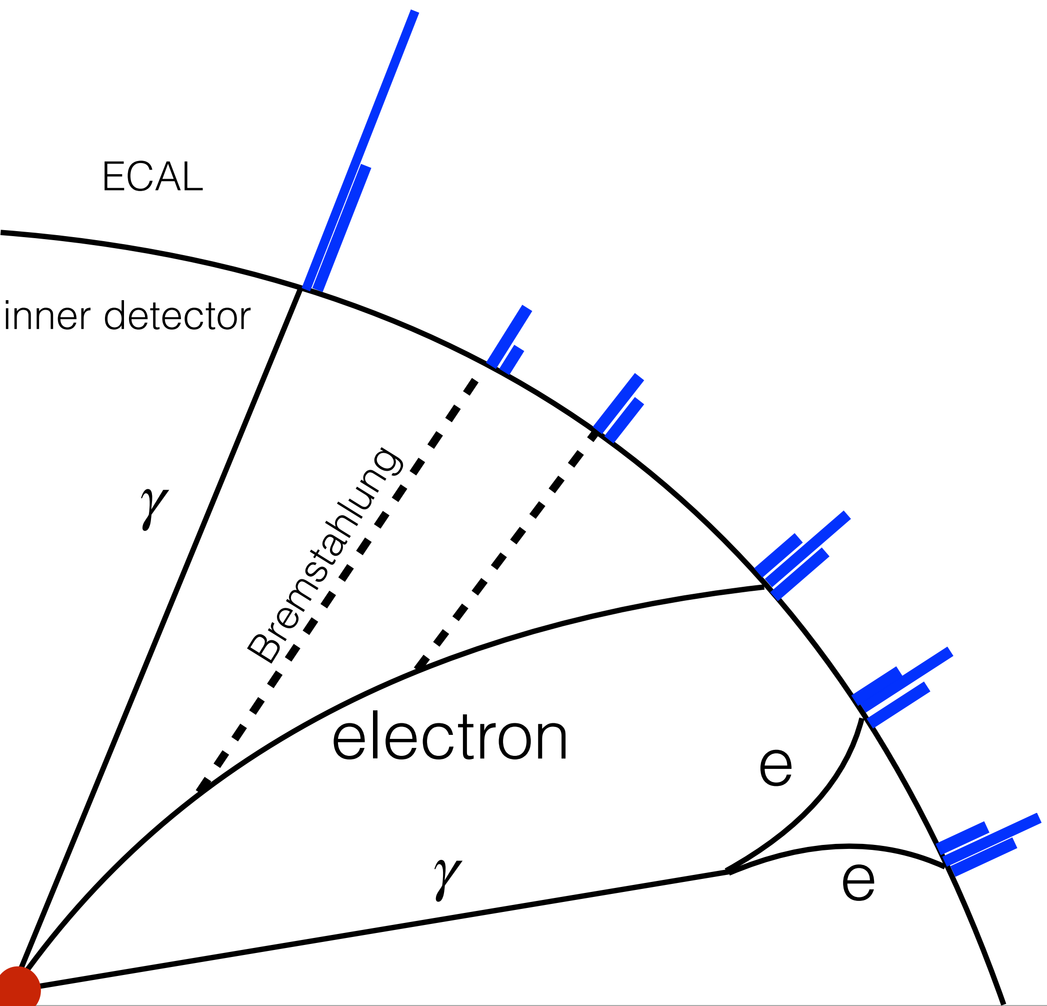
- Enabled by characteristics e.g. long lifetime, high mass.

- Relatively easy to identify using b-jet identification methods i.e. ‘b-tagging’.

- Very important in ttH due to the top➞b quark branching fraction ~ 97%.



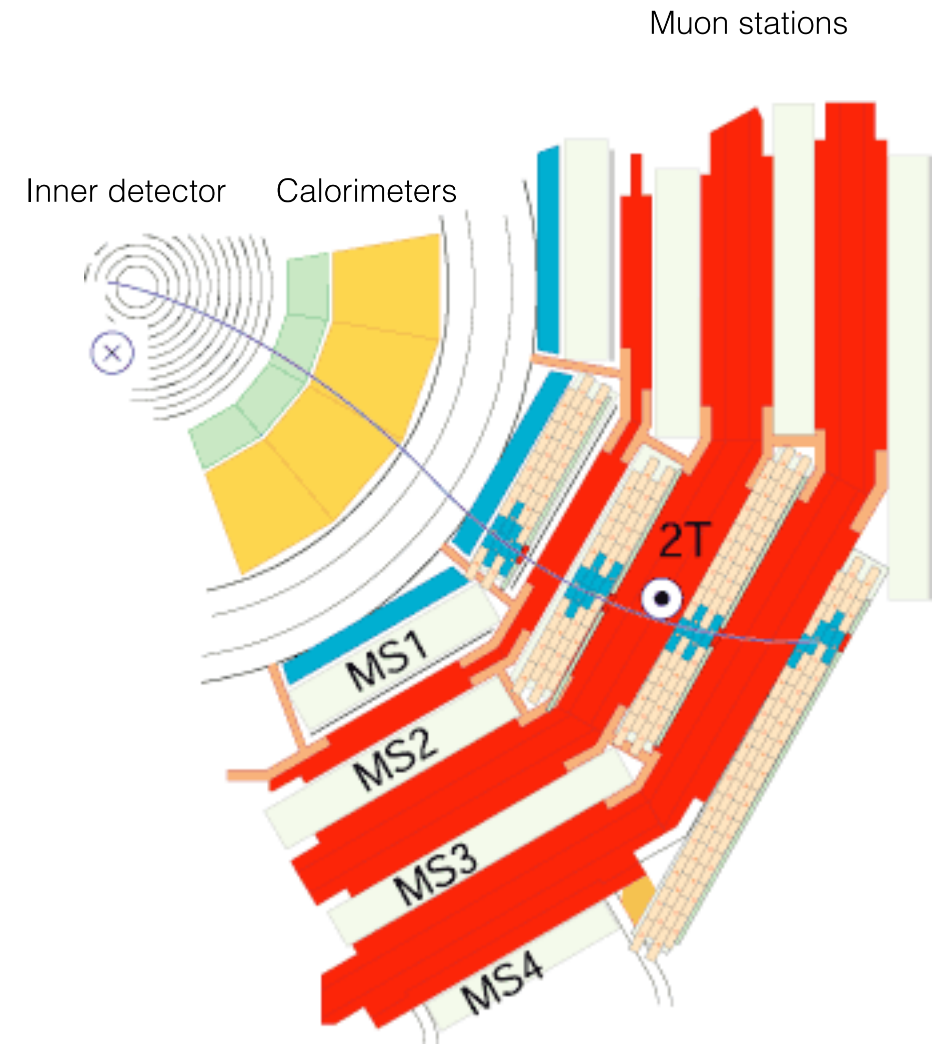
Electrons/photons



- Electrons:
  - Reconstructed tracks in inner detector.
  - Energy clusters in electromagnetic calorimeter.
  - Estimate of electron momentum.
  - Corrections for electron loss via Bremstrahlung.
- Photons:
  - Energy clusters in electromagnetic calorimeter.
  - Reconstructed tracks in inner detector for photons that converted in the tracker.

Muons

- 200 x mass of electrons - significant in the decay of a number of potential new particles.
- Penetrate several meters of iron, not stopped by calorimeters.
- Measured by fitting curve through it’s hits in 4 muon stations.
- Combined with tracker measurement to measure momentum.



τ_H jets

- Only lepton heavy enough to decay into hadrons.
- 1/3 leptonic decays → reconstructed and identified in a similar manner to other leptons.
- 2/3 Charged and neutral mesons with a tau neutrino.
- Two steps: reconstruction and identification.
- Tau-jets reconstructed using 'hadron plus strips' algorithm.
- Distinguish between real tau-jets and fake jets from quarks/gluons (can come from e/μ in some analyses).
- Typical features of a τ_H-jet:
  - Particles produced in τ_H decays are of lower multiplicity.
  - Deposit energy in narrower region.
  - Isolated wrt other particles in the event.
- Takes already reconstructed jets and searches for neutral pions and charged particles within the jet.
- Tau candidate is accepted into one of four categories depending on the number of pions and charged particles found.
- ID uses MVA techniques.

$t\bar{t}H(bb)$ All Hadronic - QGLR

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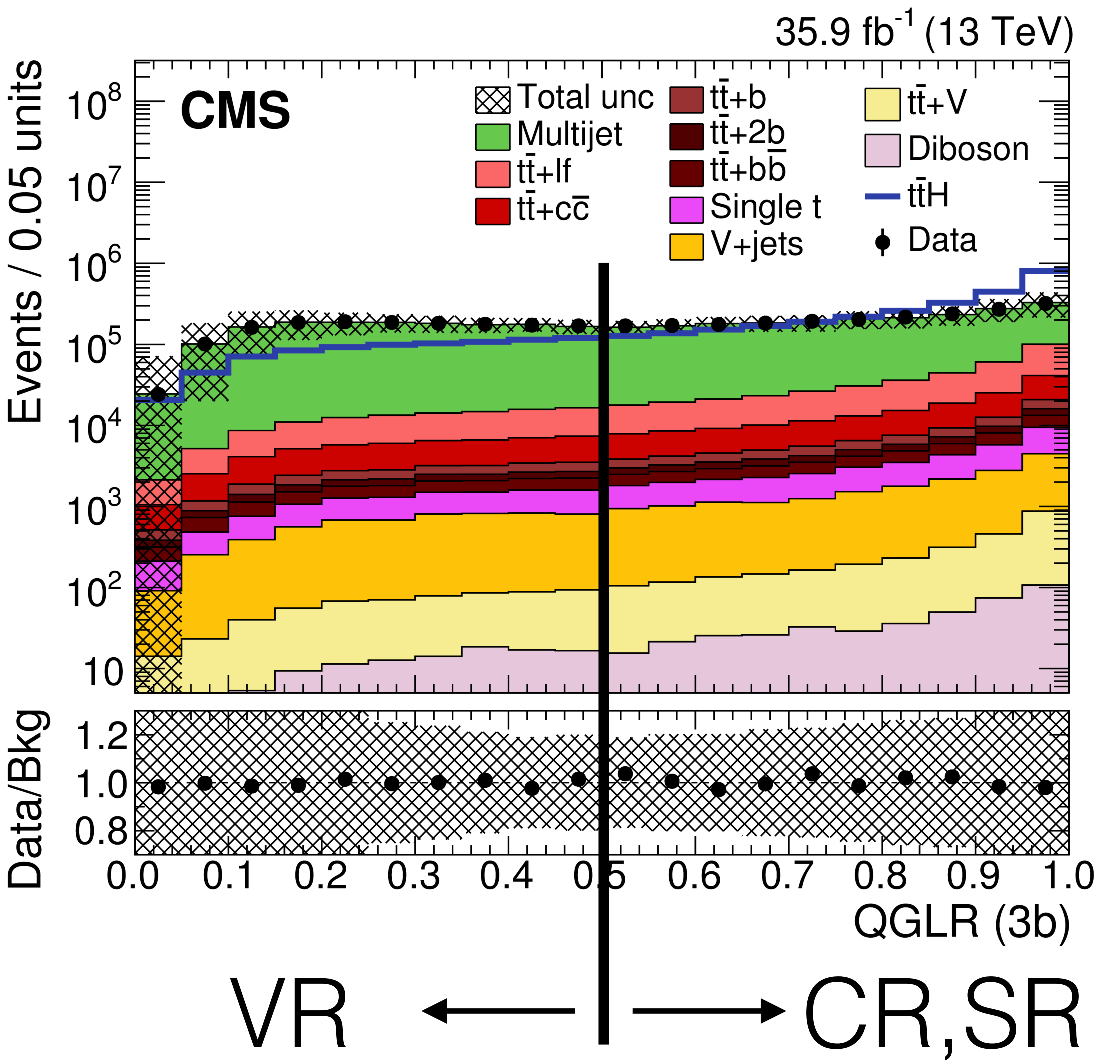
Chinese Academy of Sciences

- For a given variable, distribution of multi-jet events in SR estimated from low b-tag multiplicity CR.
- CR enriched in multijet.
- Other bckgs subtracted from data using MC.
- Kinematic properties of b-tagged and untagged jets differ in CR and SR due to HF composition.
- Corrections applied to CSVL jets in CR so kinematics match CSVM jets.
- Corrected multi-jet distribution from CR scaled to data in SR (multijet yield free-floating).
- Method validated in validation regions.

	$N_{\mathrm{CSVM}} = 2$, $N_{\mathrm{CSVL}} \geq 3$	$N_{\mathrm{CSVM}} \geq 3$
QGLR > 0.5	CR (to extract distribution)	SR (final analysis)
QGLR < 0.5	Validation CR (to validate distribution)	VR (comparison with data)



Courtesy of C. Perez

MEM weights

- **MEM** weights:

Permutations (assignment of reconstructed objects to parton-level objects)

Energy conservation (reduce integral dimensionality)

Hard-scattering **matrix element** (LO with MadGraph)

pp-collision

matrix element theory

detector

$$w_\Omega(\mathbf{y}) = \frac{1}{\sigma_\Omega} \sum_p \int d\mathbf{x} dx_a dx_b \frac{f_i(x_a, Q) f_j(x_b, Q)}{x_a x_b s} \delta^2(x_a P_a + x_b P_b - \sum p_k) |\mathcal{M}_\Omega(\mathbf{x})|^2 W(\mathbf{y}||\mathbf{x})$$

Normalization (cross-section * acceptance)

Numerical **integration** (VEGAS algorithm)

Parton distribution functions (LO with CTEQ6.6 and NNPDF3.0)

Transfer functions (from MC simulation)

- Can be used as final discriminating observable or combined into a **likelihood ratio** (LR):

$$\mathrm{LR}(\mathbf{y}) = \frac{w_{\mathrm{t\bar{t}H}}(\mathbf{y})}{w_{\mathrm{t\bar{t}H}}(\mathbf{y}) + \sum_{\mathrm{B}} \kappa_{\mathrm{B}} w_{\mathrm{B}}(\mathbf{y})}$$

κ_B coefficients derived to achieve the largest discrimination between the signal and single or combined backgrounds

$t\bar{t}H(WW^*, ZZ^*, \tau\tau)$ - Fake Factor

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- Analysis lepton definitions:
    - '**Loose**': preselected leptons (e.g. efficiency measurement, dilepton mass veto).
    - '**Fakeable**': Relaxed lepton BDT requirement (fake lepton background estimation).
    - '**Tight**': Selected using tightened lepton BDT requirement (event selection).
- Events pass all selection criteria except leptons pass 'fakeable' definition - 'Application region' (AR).
- Tight veto in AR.
- Apply weights to events in AR to estimate fakes background in signal region.
- Weights dependant on:
    - Probability 'f', that a fakeable object also passes the tight selection.
    - Multiplicity of fakeable objects and tultiplicity of tight objects in event.
- Probabilities derived in control regions defined as 'determination regions' (DR).

Kappa Framework

- Parametrisation of gg ➞ H ➞ $\gamma\gamma$.
- Production loop dominated by top quark with small correction from b quark loop.

$$\sigma(gg \to H) = \kappa_t^2 \sigma_{tt} + \kappa b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}$$

- Effective Hgg coupling:

$$\kappa_g^2 = \frac{\sigma(gg \to H)}{\sigma_{SM}} = \frac{\kappa_t^2 \sigma_{tt} + \kappa_b^2 \sigma_{bb} + \kappa_t \kappa_b \sigma_{tb}}{\sigma_{tt} + \sigma_{bb} + \sigma_{tb}}$$

$$\approx 1.06\kappa_t^2 + 0.01\kappa_b^2 - 0.07\kappa_t\kappa_b$$

- Decay channel mediated by top quark and W boson:

$$\kappa_\gamma^2 = \frac{\Gamma_{\gamma\gamma}^2}{\Gamma_{\gamma\gamma}^{SM}} = \frac{\kappa_t^2 \Gamma_{\gamma\gamma}^{tt} + \kappa_W^2 \Gamma_{\gamma\gamma}^{WW} + \kappa_t \kappa_W \Gamma_{\gamma\gamma}^{tW}}{\Gamma_{\gamma\gamma}^{tt} + \Gamma_{\gamma\gamma}^{WW} + \Gamma_{\gamma\gamma}^{tW}}$$

$$\approx 0.07\kappa_t^2 + 1.59\kappa_W^2 - 0.66\kappa_t\kappa_W$$

Kappa Framework

scales gg production mode

Scales $\gamma\gamma$ partial width

$$(\sigma \cdot BR)(gg \to H \to \gamma\gamma) = \sigma_{SM}(gg \to H) \cdot BR_{SM}(H \to \gamma\gamma) \cdot \frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}$$

Scales total width

Taken from LHC Higgs cross section WG for given Higgs mass hypothesis

Differential ttH

- Presence of modified trilinear couplings - can write the master formula for the $\lambda 3$ dependance of a generic observable Σ (total/differential XS) as:

$$\Sigma^{\mathrm{BSM}}_{\lambda_3} = Z^{\mathrm{BSM}}_{H} \Sigma_{\mathrm{LO}}(1 + \kappa_3 C_1 + \delta Z_H)$$

$$Z^{\mathrm{BSM}}_{H} = \frac{1}{1-(\kappa_3^2 - 1)\delta Z_H}$$

Process & kinematic dependant.

$$k_3 = \frac{\lambda_3}{\lambda_3^{SM}}$$

SM component is directly included at fixed NLO via δZHterm

Differential ttH

- Presence of modified trilinear couplings - can write the master formula for the $\lambda 3$ dependance of a generic observable Σ (total/ differential XS) as:

At limit:

$$\kappa_3 \to 1,\ Z_H^{\mathrm{BSM}} \to 1$$

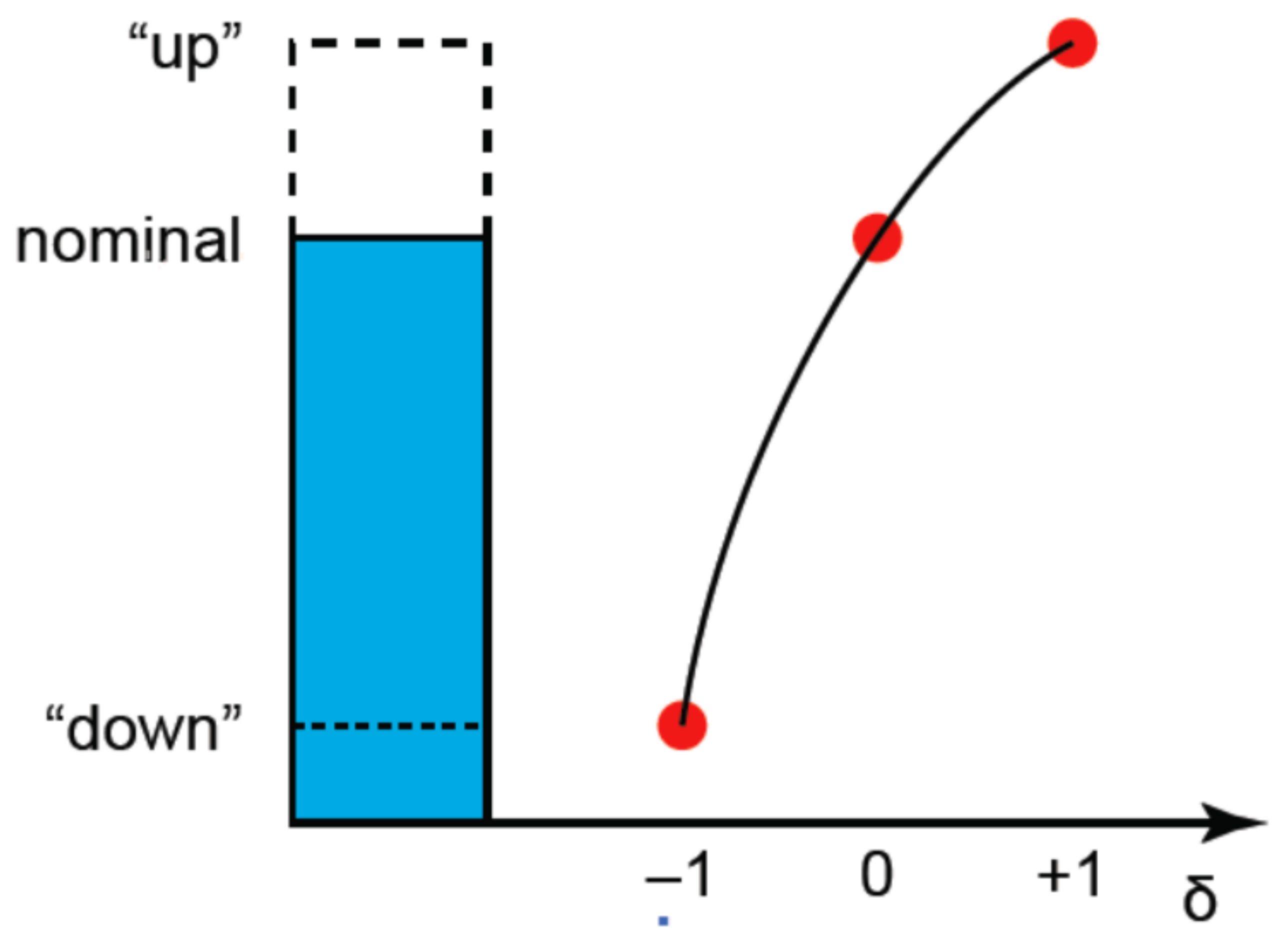
$$\Sigma_{\lambda_3}^{\mathrm{BSM}} \quad \to \quad \Sigma_{\lambda_3}^{\mathrm{SM}} = \Sigma_{\mathrm{LO}}(1 + C_1 + \delta Z_H)$$

H(ZZ)

- CMS:
  - ttH(ZZ*) in multilepton veto m4l < 140 GeV, outside signal mass range for H(ZZ*).
  - H(ZZ*) use m4l > 70 GeV, signal only really up to 140 GeV.
- ATLAS:
  - ttH(ZZ*) use 115 < m4l < 130 GeV, same as H(ZZ*).

Profiling

- We can reduce uncertainties in signal bin by profiling
- Constrain uncertainty in another bin, propagate this knowledge to signal bin



- Given: +1 sigma, nominal and -1 sigma of each systematic

- Assumption of interpolation of uncertainty between [-1,1] sigma
- Assume full correlation between bins

- What are we doing: Measuring the uncertainty in ***our*** dataset

95%Cl limit - tH XS * BR

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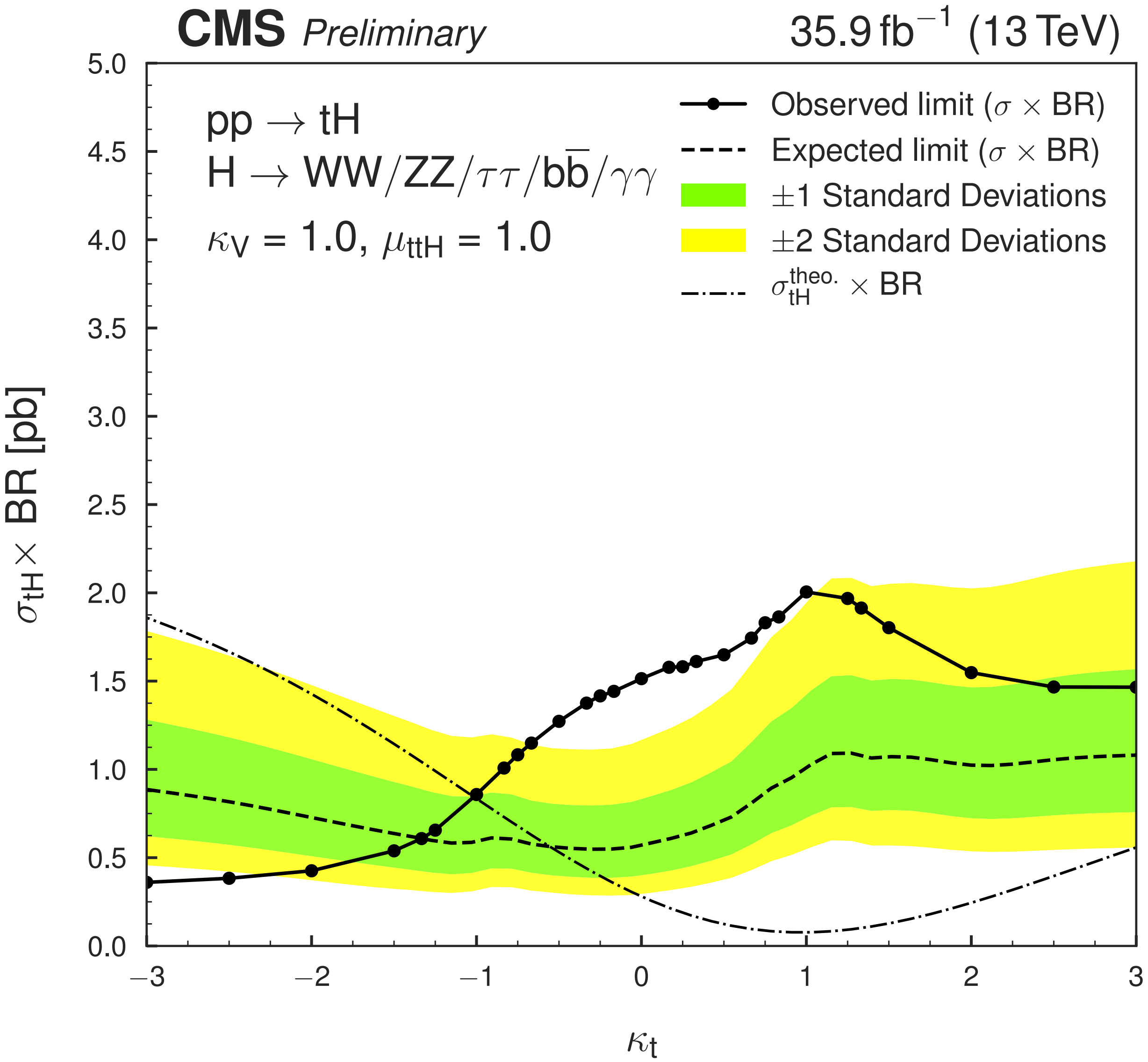
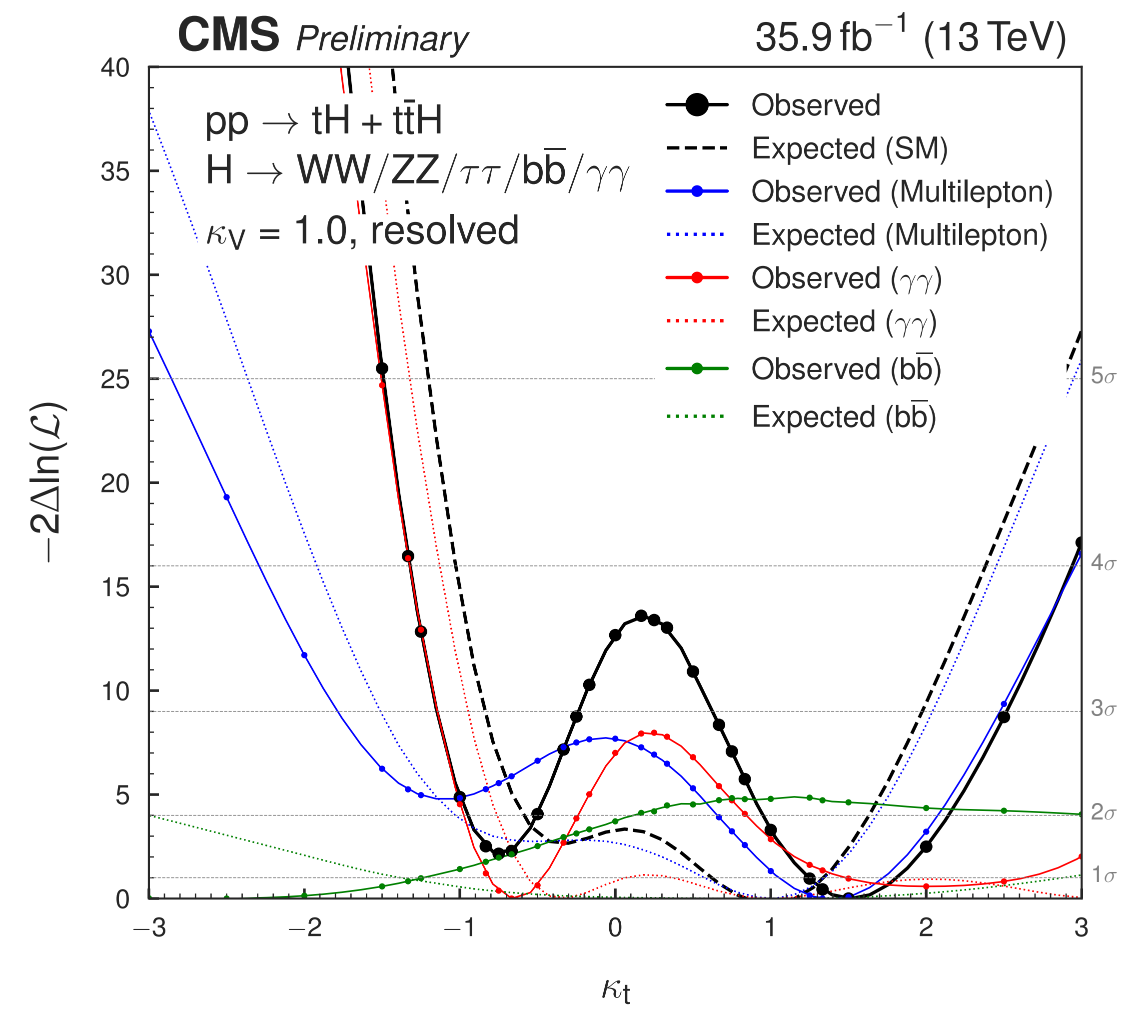
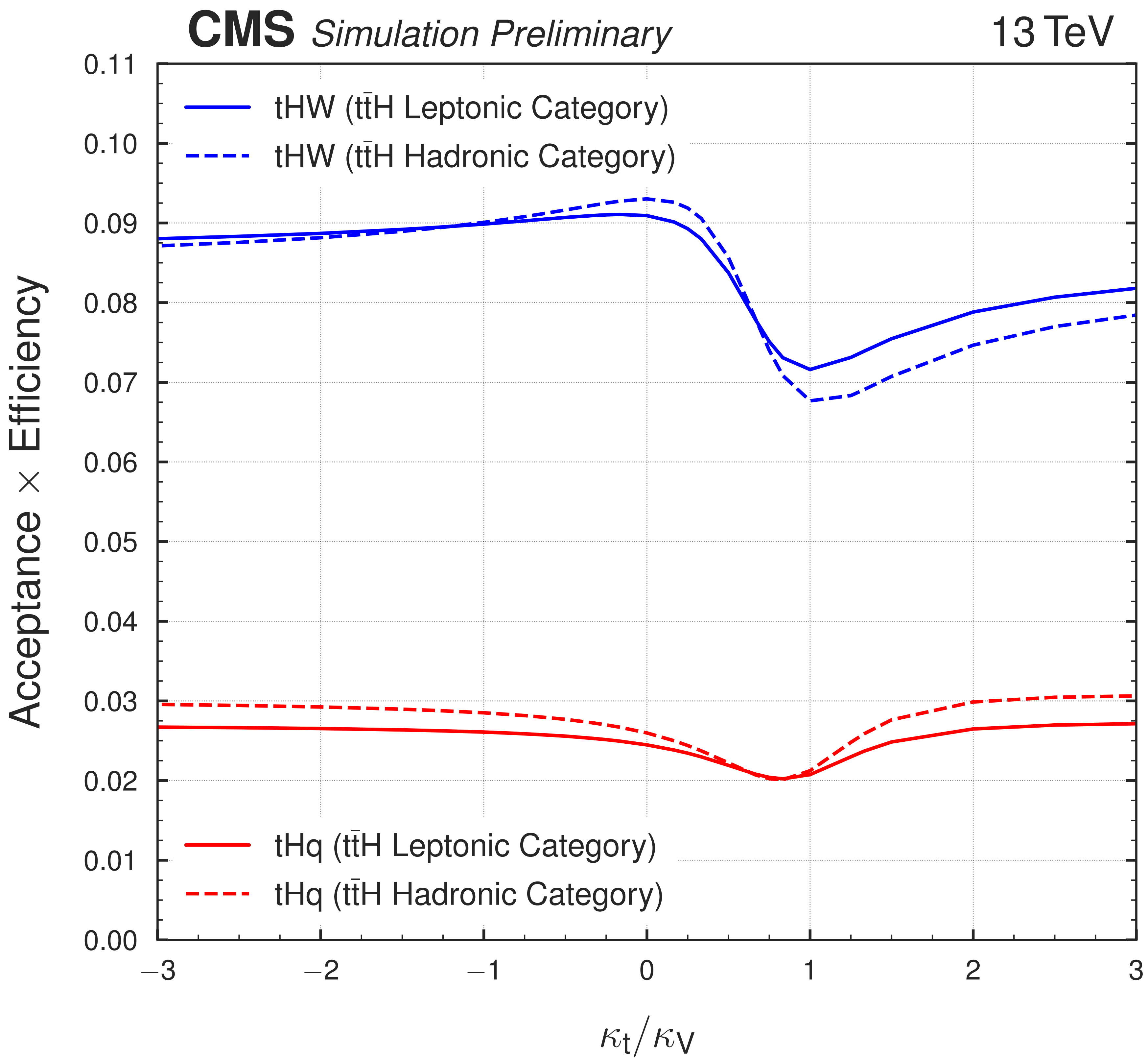




- Expected limit on B-only dataset (no tH contribution but includes a k_t dependant ttH contribution).
- ttH normalisation is fixed, tH signal strength floated.
- For SM-like Higgs coupling to Vector bosons - k_t values excluded [-0.9,-1]

- Scan of -2ΔLn(L) for combined fit of tH + ttH signal strength on data compared to Asimov dataset from SM expectation.


CMS Simulation Preliminary
13 TeV
tHW ($t\bar{t}H$ Leptonic Category)
tHW ($t\bar{t}H$ Hadronic Category)
tHq ($t\bar{t}H$ Leptonic Category)
tHq ($t\bar{t}H$ Hadronic Category)
Acceptance × Efficiency
κ_t/κ_V
0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
−3
−2
−1
0
1
2
3

CMS $t\bar{t}H(ZZ^* \rightarrow 4l)$

- Non-$t\bar{t}$H Higgs boson production (ggH) treated as background in ttH combination.
- **Full kinematic information extracted using MEM →** kinematic discriminants.
- Simultaneous fit in all regions of **2D likelihood function** composed from m_{4l} and background kinematic discriminant.
- Major theoretical uncertainties: Renormalisation and factorisation scale, PDF set, PS modelling.
- Major experimental uncertainties: Z+X background estimate, m_{4l} mass resolution.