Higgs production & decays

PIC 2017 Prague

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Deep Thought finally spoke : “The answer to the great question … of Life, the Universe, and Everything … is … is … 42. ”

So what is the question ?

the same thing happened in physics in 2012

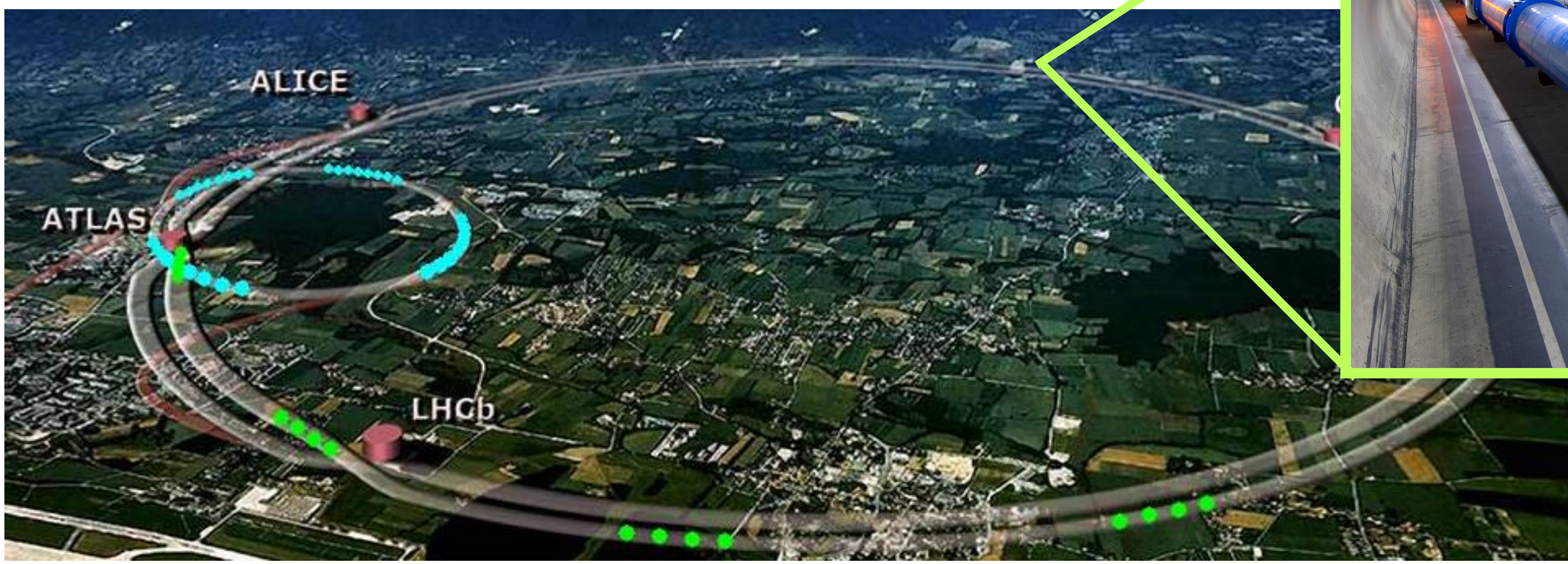
It started with a question

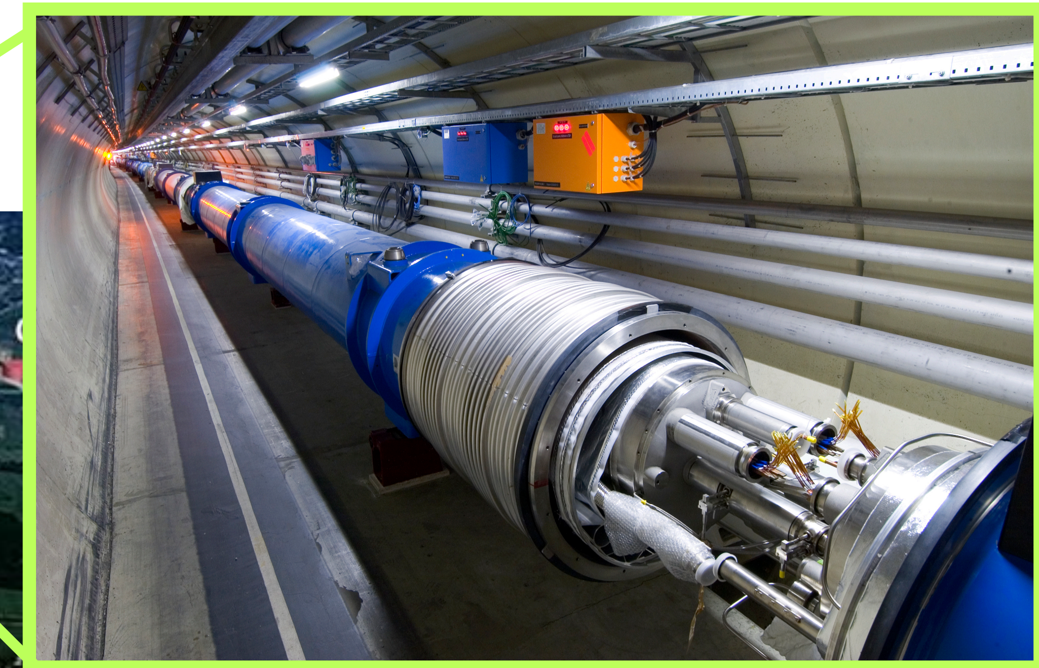
1964: How do particles get mass ?

Is there a physical Higgs boson ?

50 years later, we could answer this question

LHC



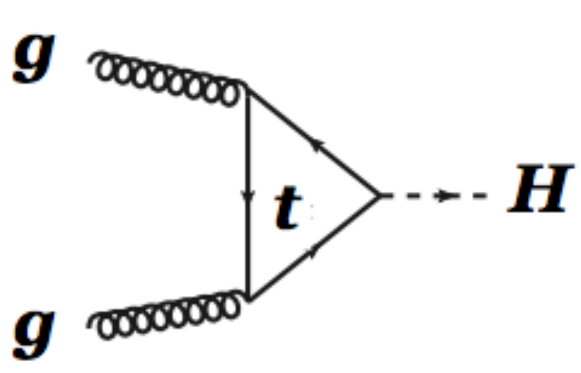


1200 superconducting dipoles
8-T field, 15-m long
11-kAmp current

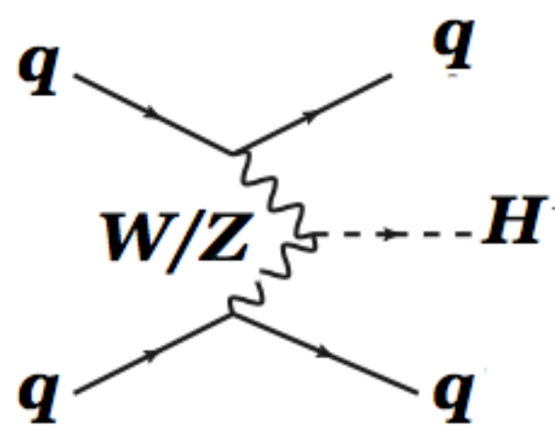
- **Delivering proton-proton collisions**
  - 2010-2011 : 7 TeV
  - 2012 : 8 TeV
  - 2015-2017 : 13 TeV

Higgs production — SM theory

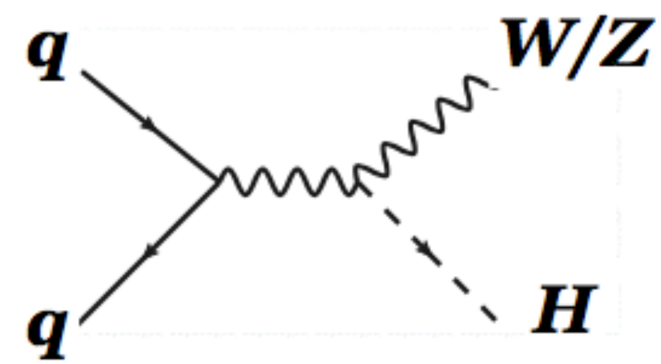
arXiv:1610.07922



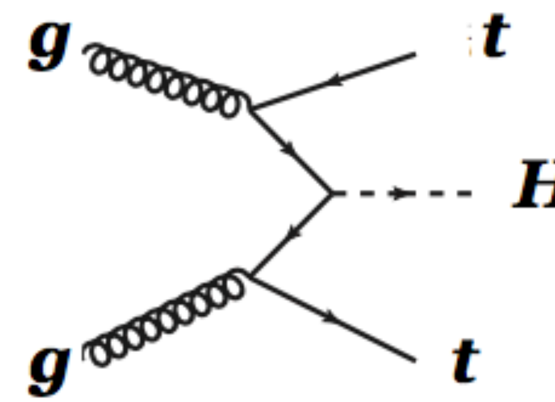
ggF: ~ 87%



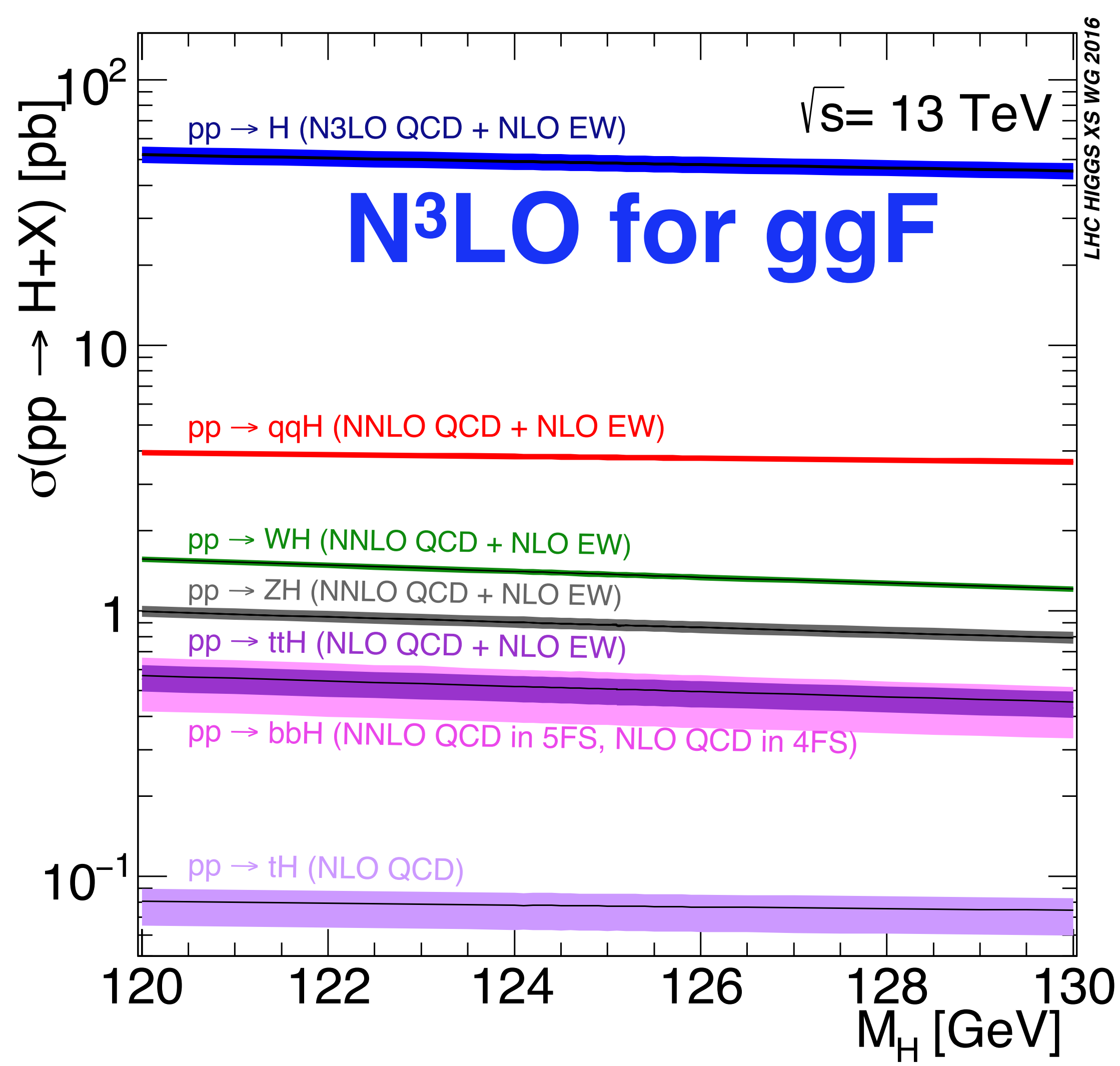
VBF: ~7.5%



VH ≡ WH or ZH: ~4.5%



ttH: ~1.0%



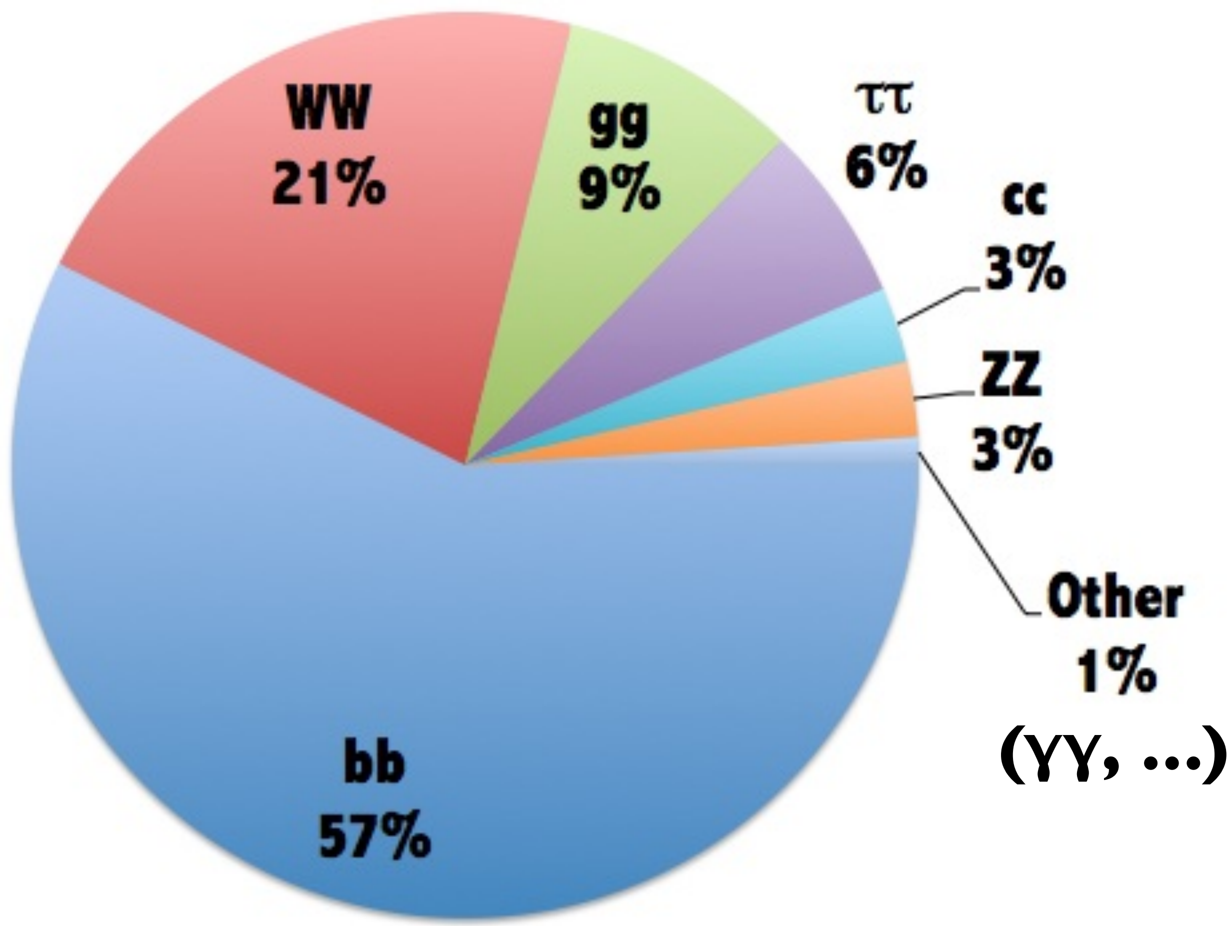
$$\sigma = 48.58\,\text{pb}^{+2.22\,\text{pb}\,(+4.56\%)}_{-3.27\,\text{pb}\,(-6.72\%)}\,(\text{theory}) \pm 1.56\,\text{pb}\,(3.20\%)\,(\text{PDF}+\alpha_s)\,.$$

δσ ~ 5.6% theory, 3.2% (PDF+ α_S)

48.58 pb =	16.00 pb	(+32.9%)	(LO, rEFT)
	+ 20.84 pb	(+42.9%)	(NLO, rEFT)
	− 2.05 pb	(−4.2%)	((t, b, c), exact NLO)
	+ 9.56 pb	(+19.7%)	(NNLO, rEFT)
	+ 0.34 pb	(+0.7%)	(NNLO, $1/m_t$)
	+ 2.40 pb	(+4.9%)	(EW, QCD-EW)
	+ 1.49 pb	(+3.1%)	(N^3LO, rEFT)

Higgs decay

Higgs decays at m_H=125GeV



Studying Higgs decays requires

- **Identifying :**
  - **Electrons**
  - **Muons**
  - **Photons**
  - **Taus**
  - **Jets**
  - **b-jets**
  - **Missing Energy from ν's**

} Precision needed (Electrons, Muons, Photons)

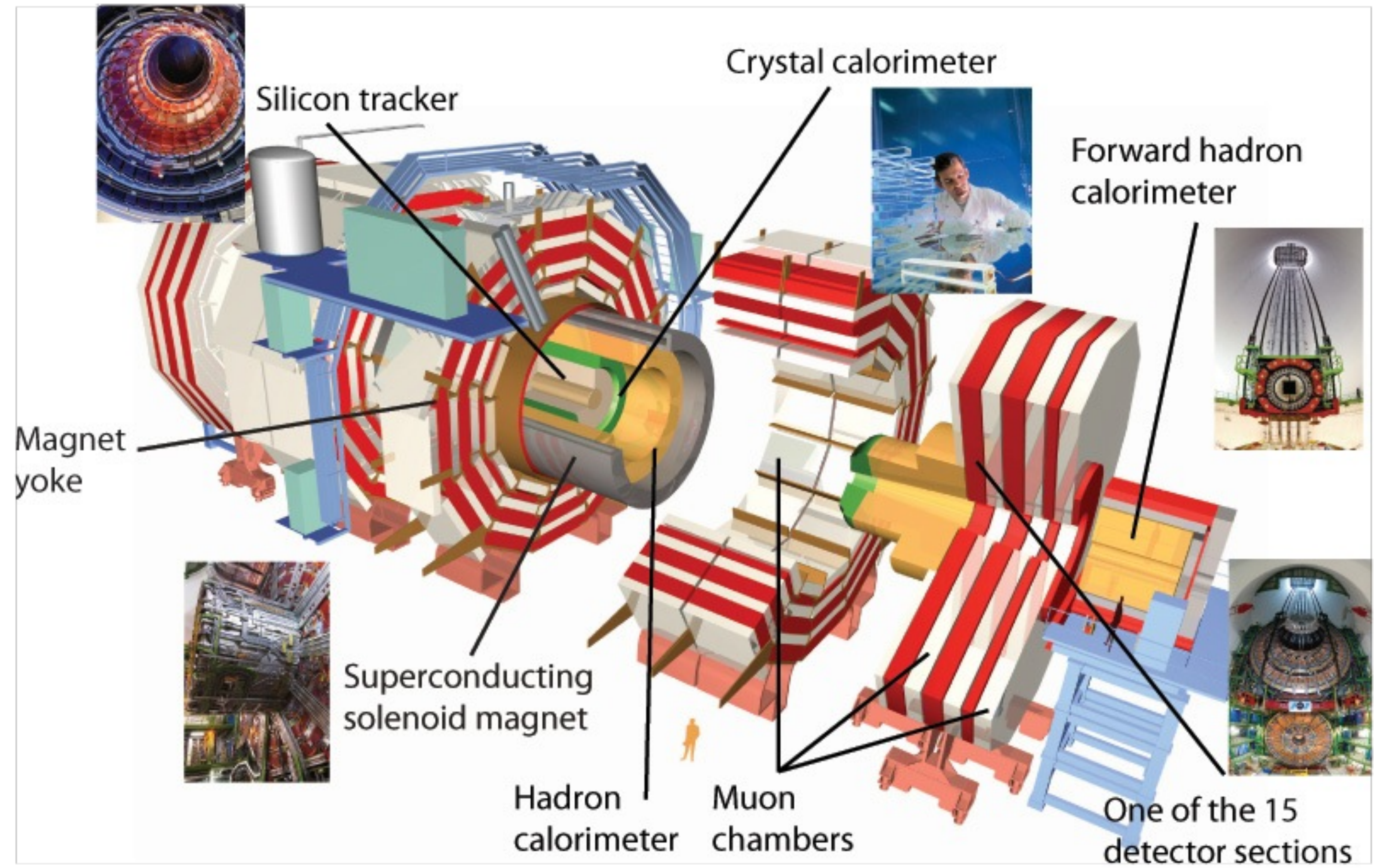
Precision Higgs boson mass measured from tiny fraction of Higgs decays :

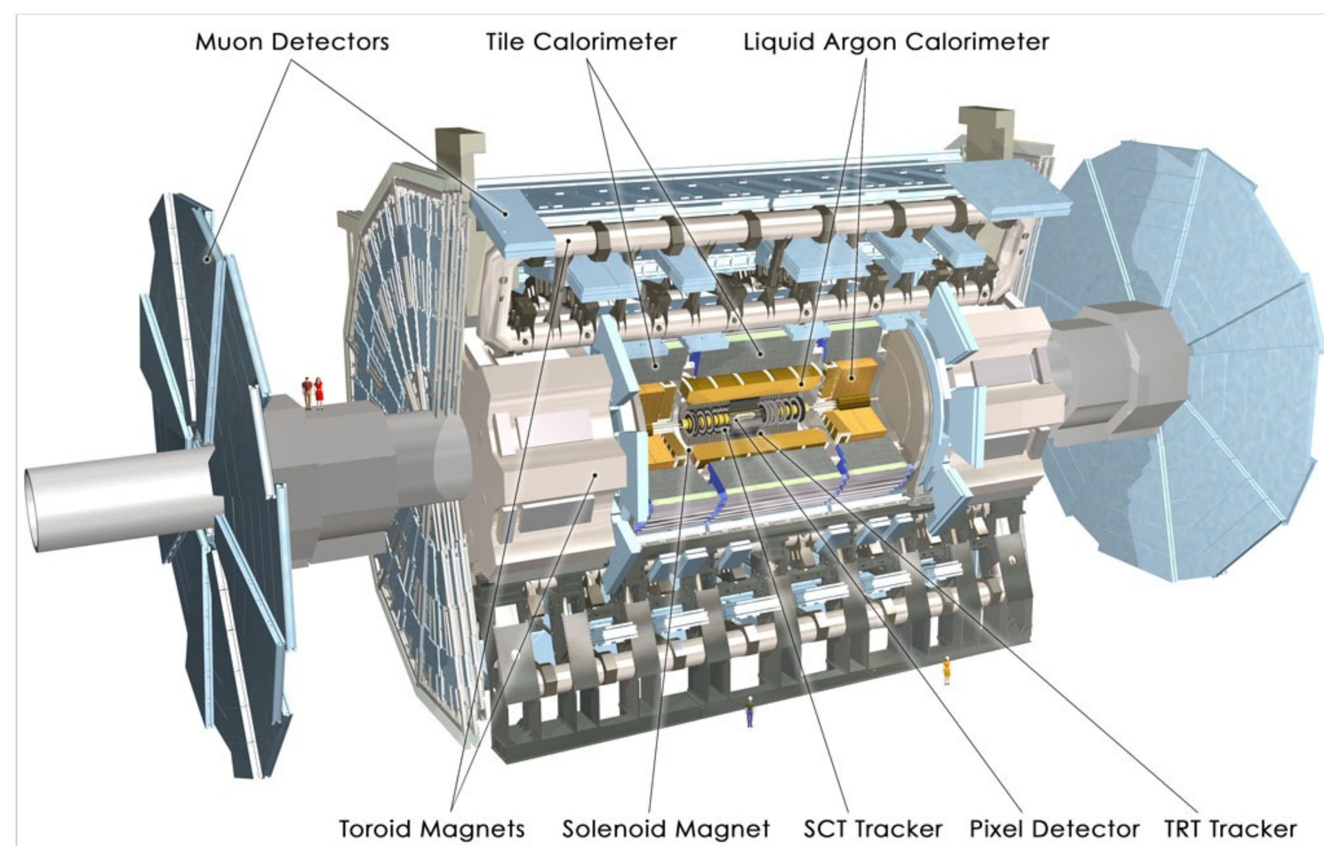
H→ZZ (3%) → eeee, eeμμ, μμμμ (0.01%)

H→γγ (0.2%)

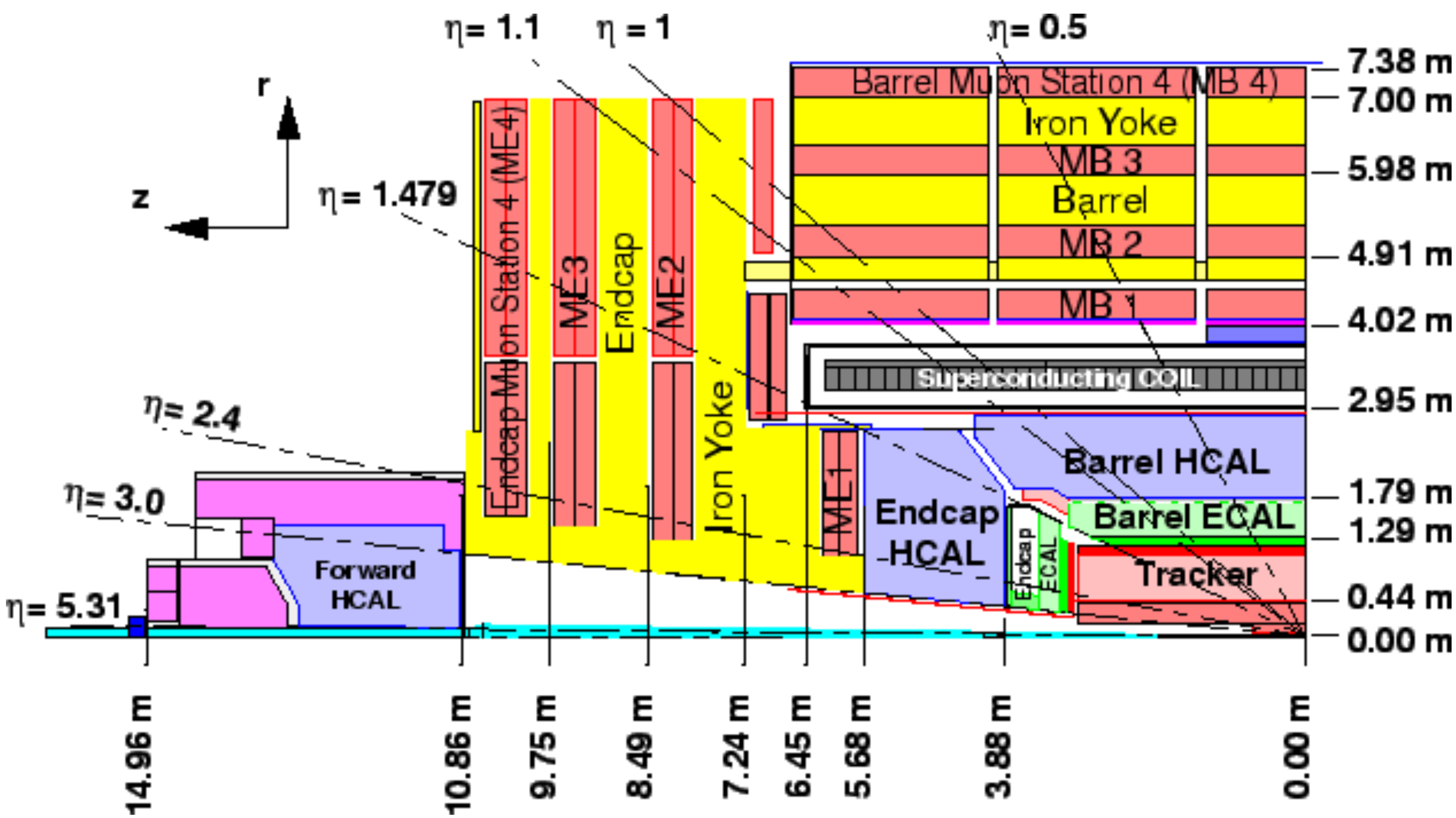
CMS
&
ATLAS

Multipurpose detectors designed for Higgs boson study





Coverage



	CMS	ATLAS
Tracking	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$
Muons	$\|\eta\| < 2.4$	$\|\eta\| < 2.7$
Electrons	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$
Photons	$\|\eta\| < 2.5$	$\|\eta\| < 2.5$
Jets	$\|\eta\| < 5$	$\|\eta\| < 4.5$
MET	$\|\eta\| < 5$	$\|\eta\| < 4.9$

~90% solid angle

~99%

	σ_M/M
• bb	10%
• ττ	10-20%
• WW	16%
• ZZ	1-2%
• γγ	1-2%

Oh great LHC, what is the answer to how particles get mass, and if there is a Higgs boson ?

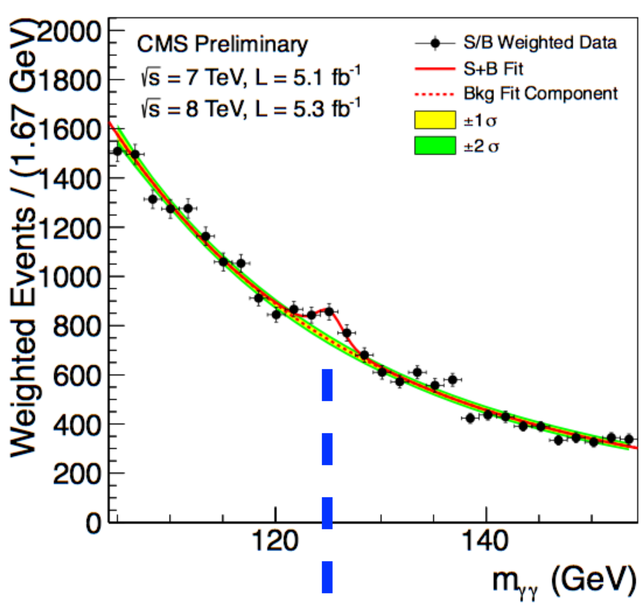
The answer is …
is …
125

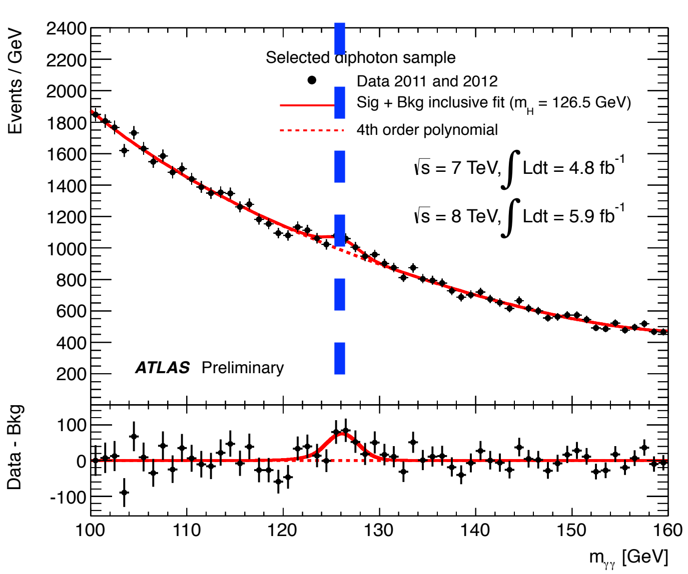
Higgs boson discovery 2012

ATLAS Higgs observation CMS Observation

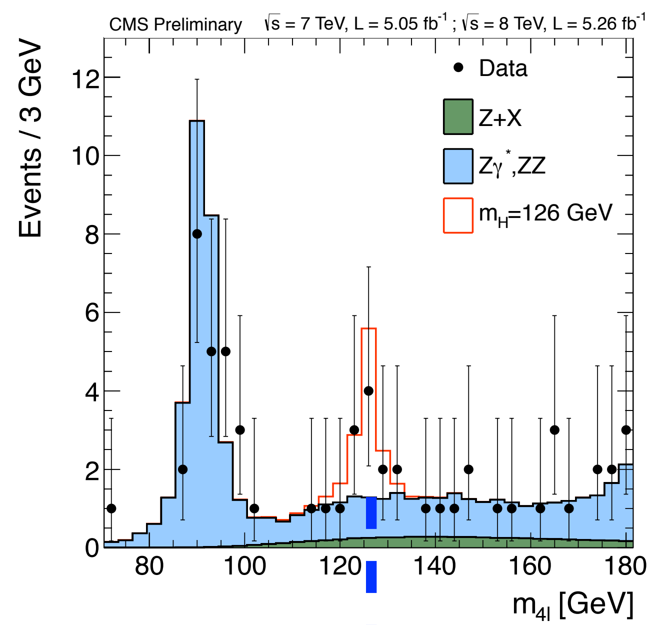
2 papers from CMS & ATLAS now with 15000 total citations

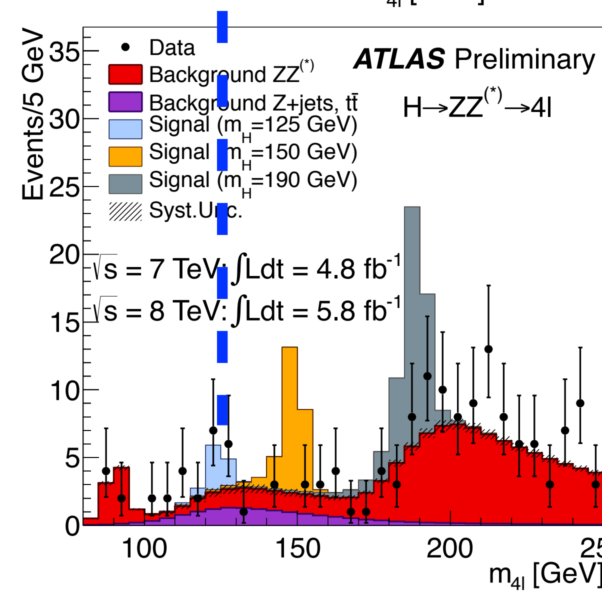
H→γγ





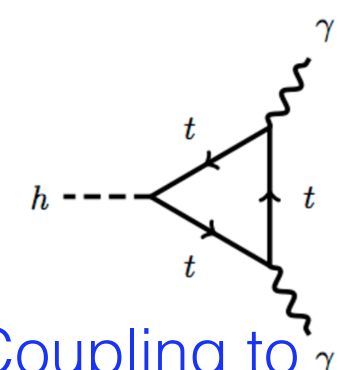
H→ZZ



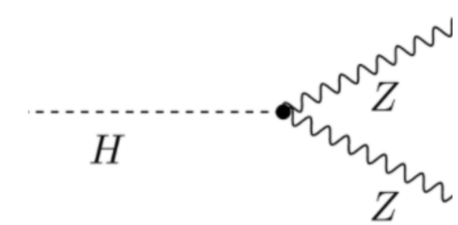


Clear observation :
2 different channels[1]
*****
2 different experiments
5.9σ (4.9σ expec.), 5.0σ (5.8σ)

Established :



Coupling to fermions (ggH/Hγγ)



Coupling to vector bosons

Mass combining H→γγ + H→ZZ→4l

ATLAS : 126.0 ± 0.4(stat) ± 0.4(sys) GeV
CMS : 125.3 ± 0.4(stat) ± 0.5(sys) GeV

δM/M ~ 0.5%

1: ATLAS H→WW also plays important role in constraining signal yield

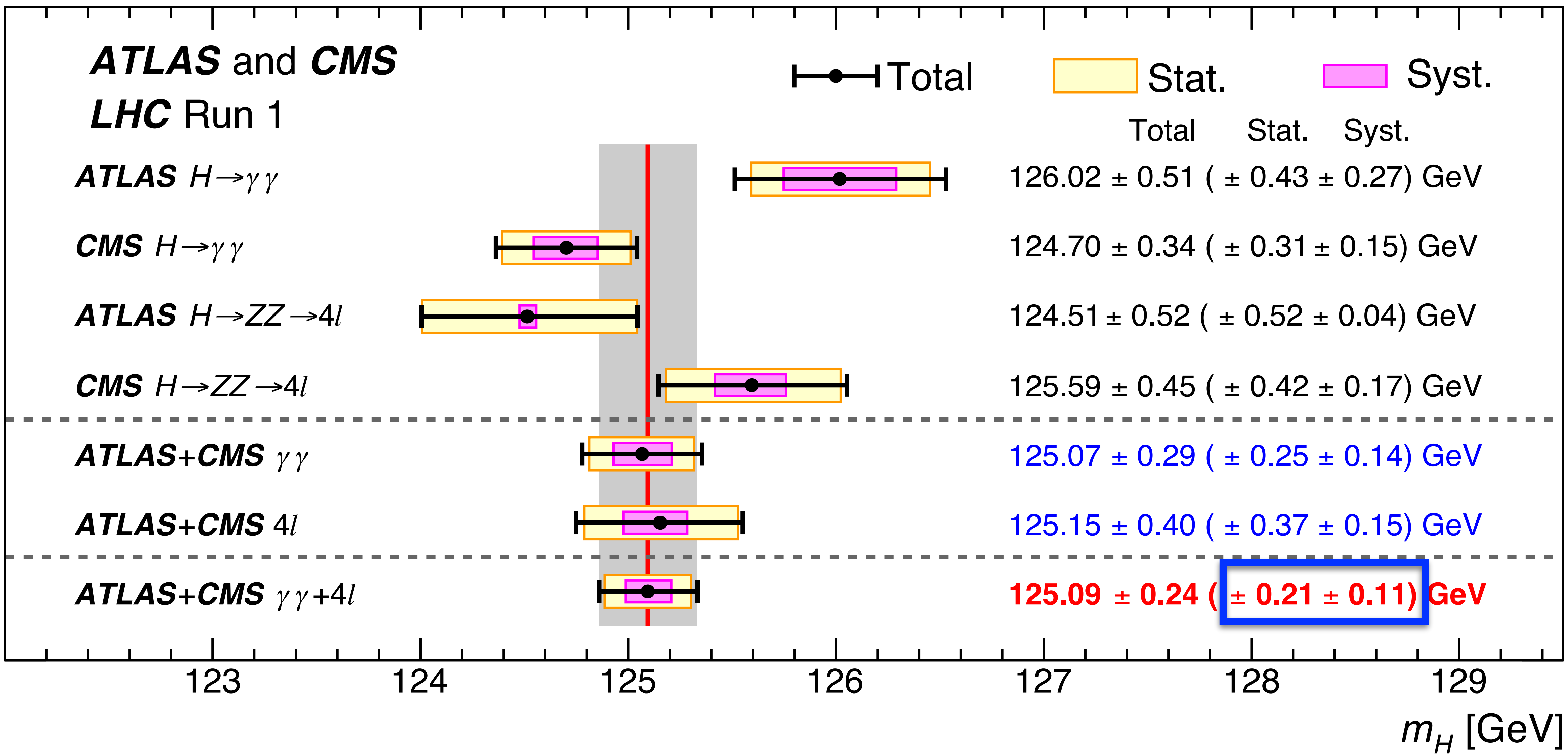
We checked quite carefully and we are quite certain the answer is 125

Run 1 combination

PRL 114 (2015) 191803

- **Higgs mass CMS+ATLAS end of Run 1**

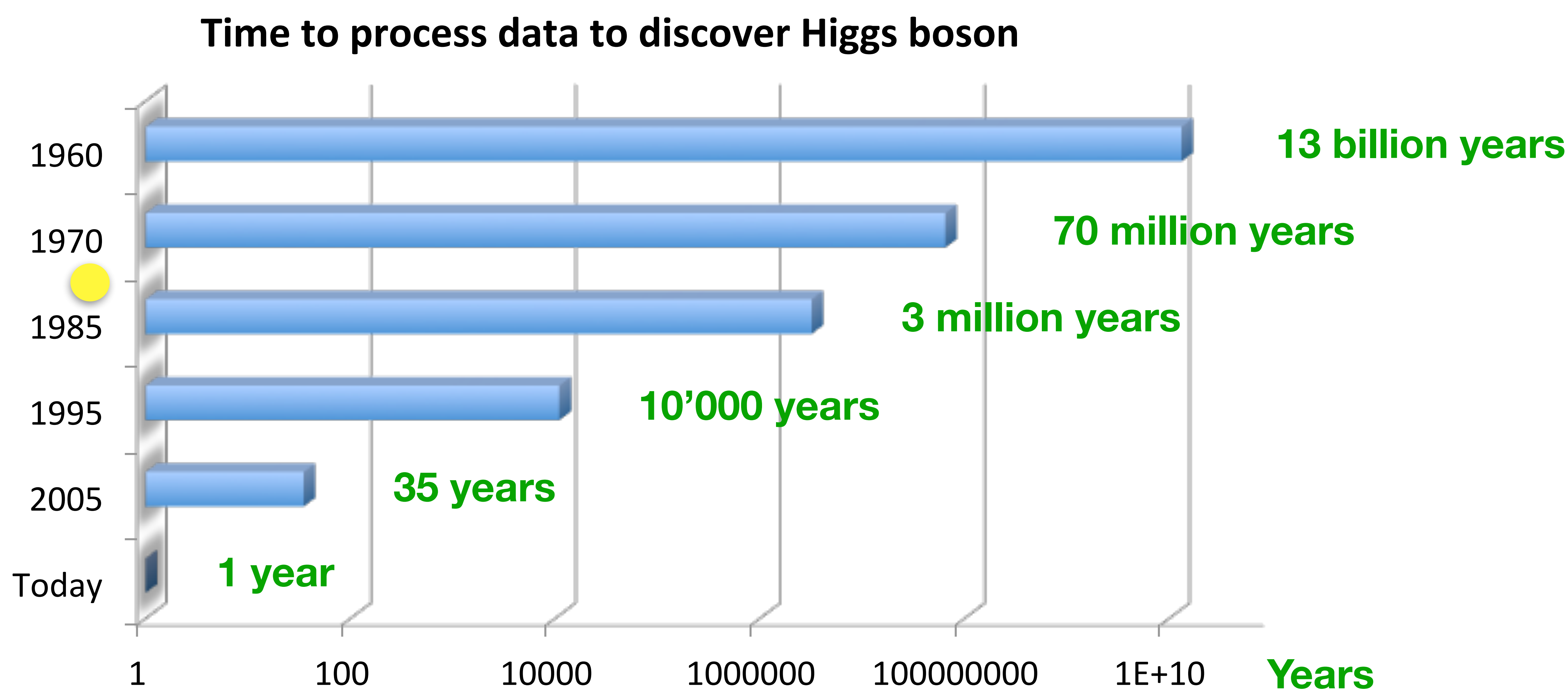
5fb-1@7TeV & 20fb-1@8TeV



δM/M ~ 0.2%

Measurement limited by statistics

Advances in computation



Douglass Adams wrote “Hitchhiker’s Guide to the Galaxy” in 1978

Indeed, with 1978 computers:
It would take about 7.5 million years to discover the Higgs boson
= same amount of time as Deep Thought !

But why is the answer 125 ?

- **Should be much larger unless there is new physics**

$$M_h^2 = M_{h,tree}^2 + c\frac{g^2}{4\pi^2}M_{pl}^2 \qquad (w/o\ SUSY)$$

$$M_h^2 = M_{h,tree}^2(1 + c'\frac{g^2}{4\pi^2}\ln(M_{pl}/M_W)) \qquad (with\ SUSY)$$

What is the question ?

Its always the same old story

- **Hitchhikers Guide to the Galaxy**
  - Build a super powerful computer
  - Ask it the answer to the universe
  - It calculates for over 7 million years
  - The answer is 42
  - Build another machine to calculate the question

- **Particle physics**
  - Build a huge experiment and a giant distributed computing system
  - Ask it how mass arises in the universe
  - It calculates in 1 year what used to take 7 millions years
  - The answer is 125
  - Build another machine (or upgrade to HL-LHC) to calculate why the answer is 125

Clearly, we need more measurements to help answer this

Higgs boson width

Phys.Lett.B 736 (2014) 64-85

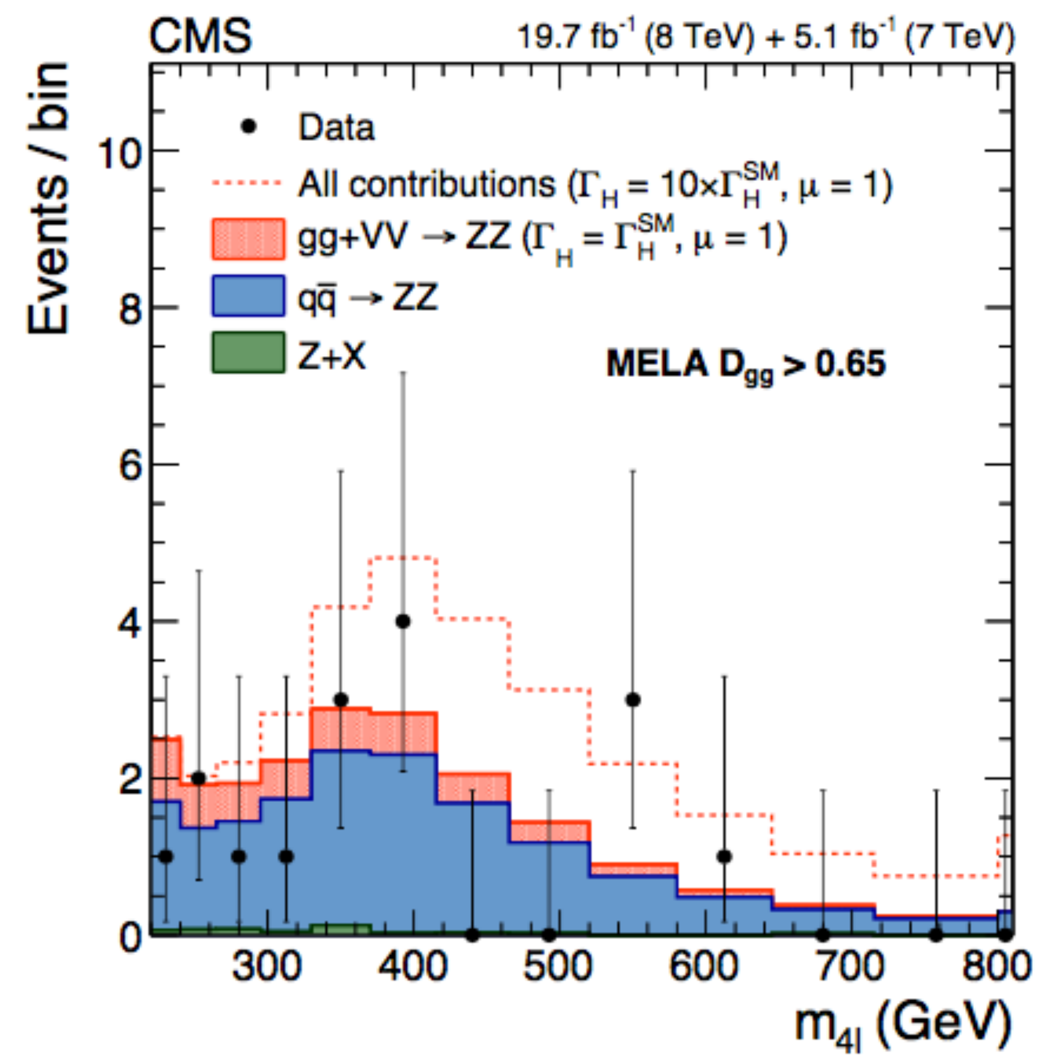
SM $\Gamma_H =$ 4 MeV   Far below experimental resolution ~ 1-2 GeV

- **MeV-level measurement of Higgs width possible using off-shell Higgs production**

$$\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}$$

$$\sigma^{\text{off-shell}}_{gg\to H\to ZZ^*} \sim \frac{g^2_{ggH}\, g^2_{HZZ}}{2m^2_H}$$

Therefore, $\Gamma_H \sim 2m_H\,(\sigma_{off} / \sigma_{on})$

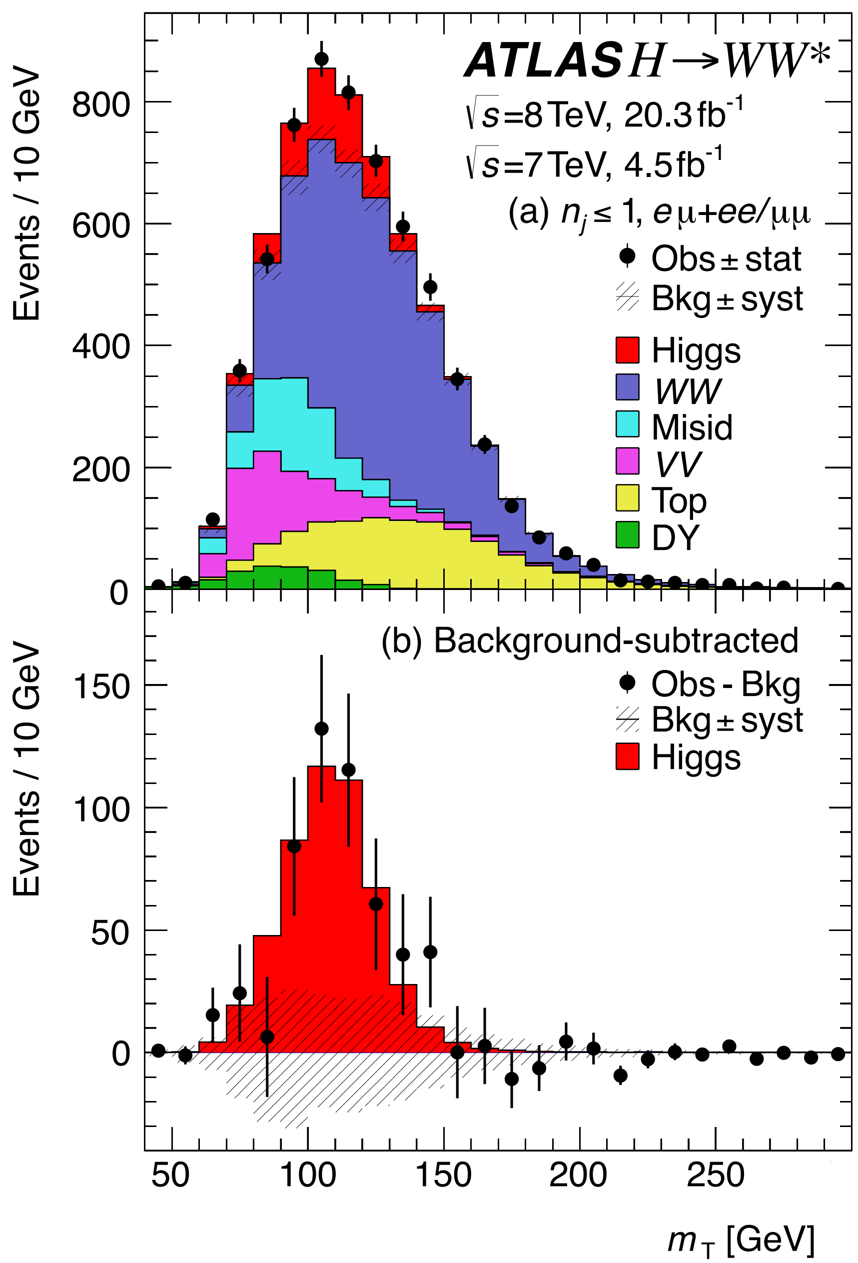


Measured $\Gamma_H < 22$ MeV @ 95% CL

(Indirect, assumes no new physics)

Other highlights from Run 1

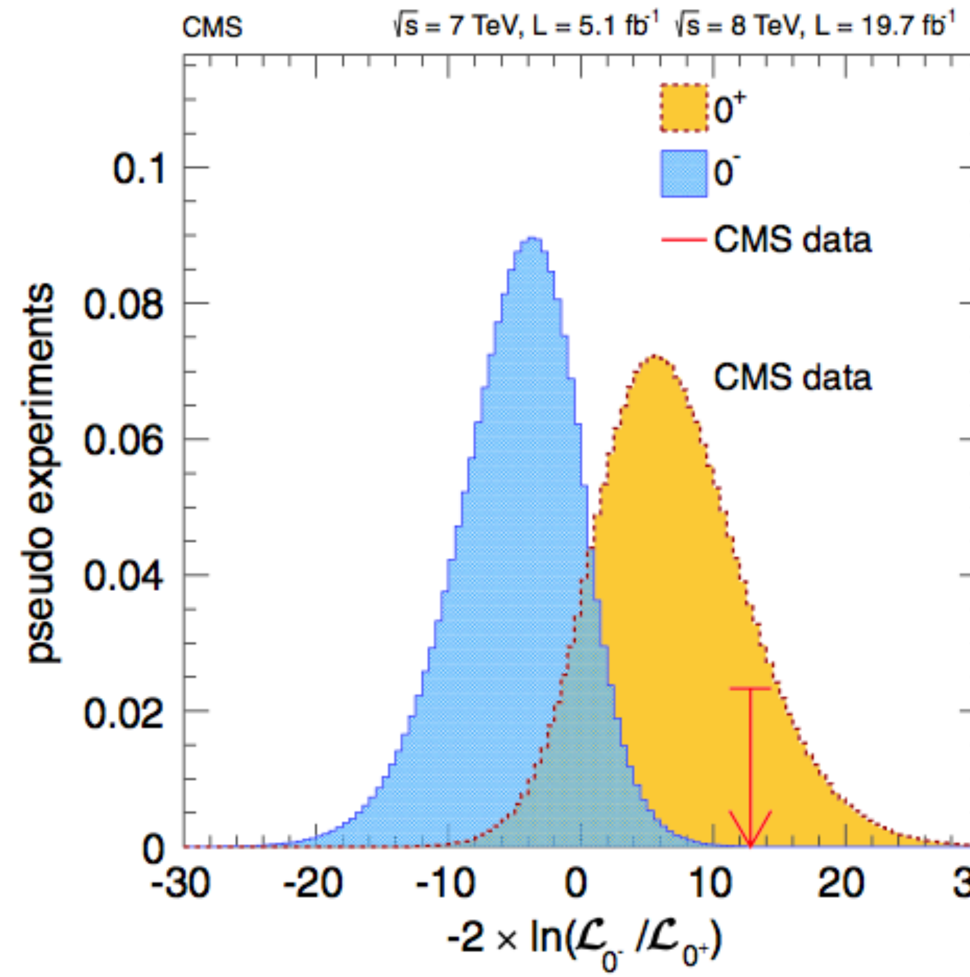
CMS PRD89 (2014) 092007 ATLAS HWW PRD

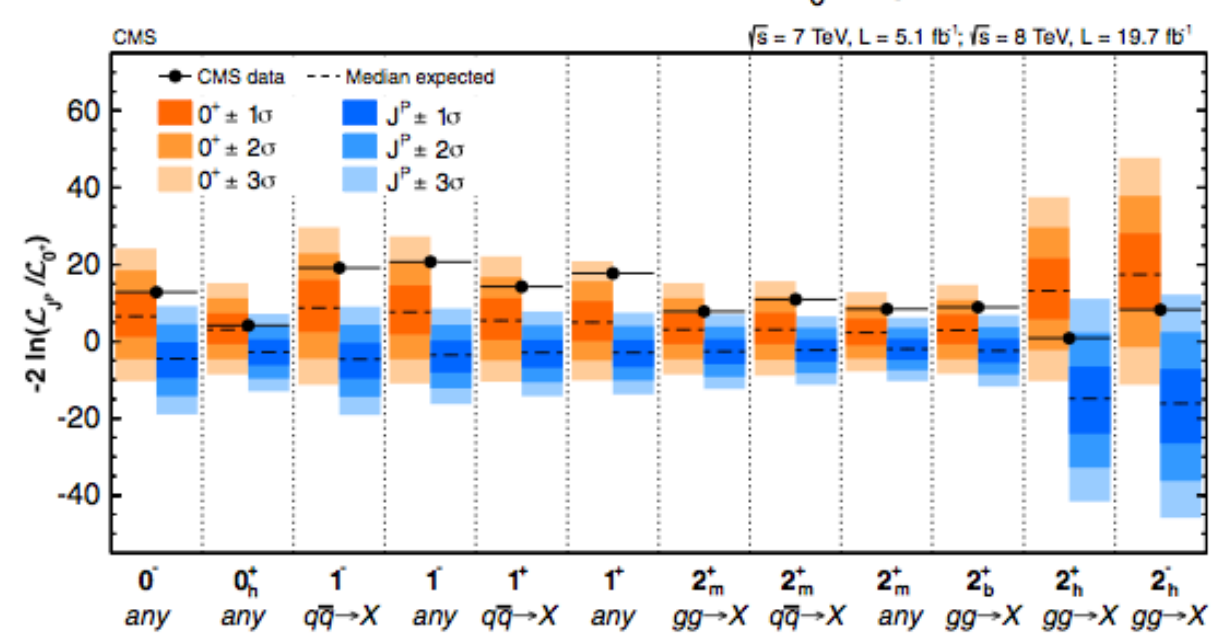


H➞WW observed :
ATLAS 6.1σ (5.8σ expec.)

Spin, C, P tested in H➞4l

$J^{PC} = 0^{++}$ preferred

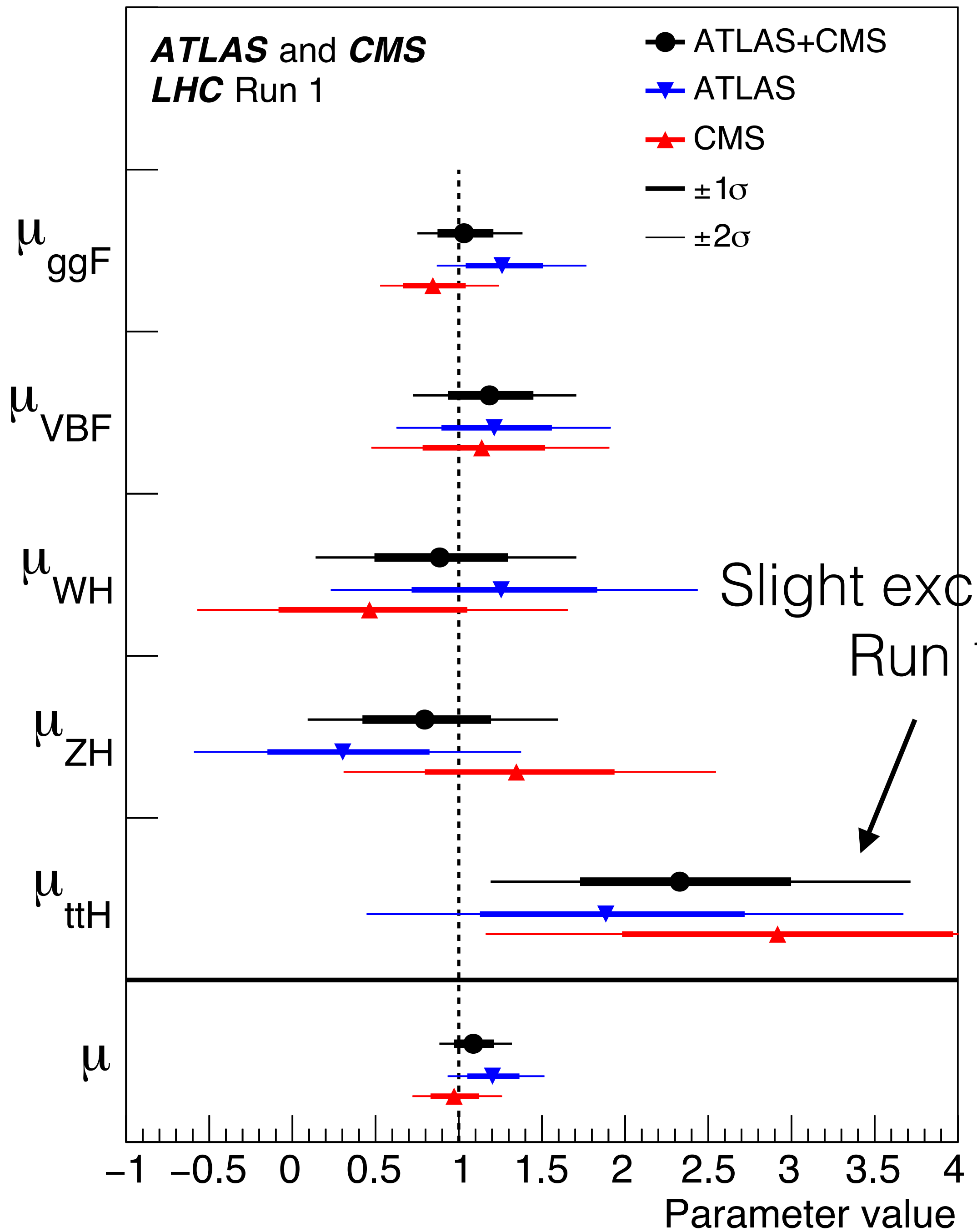


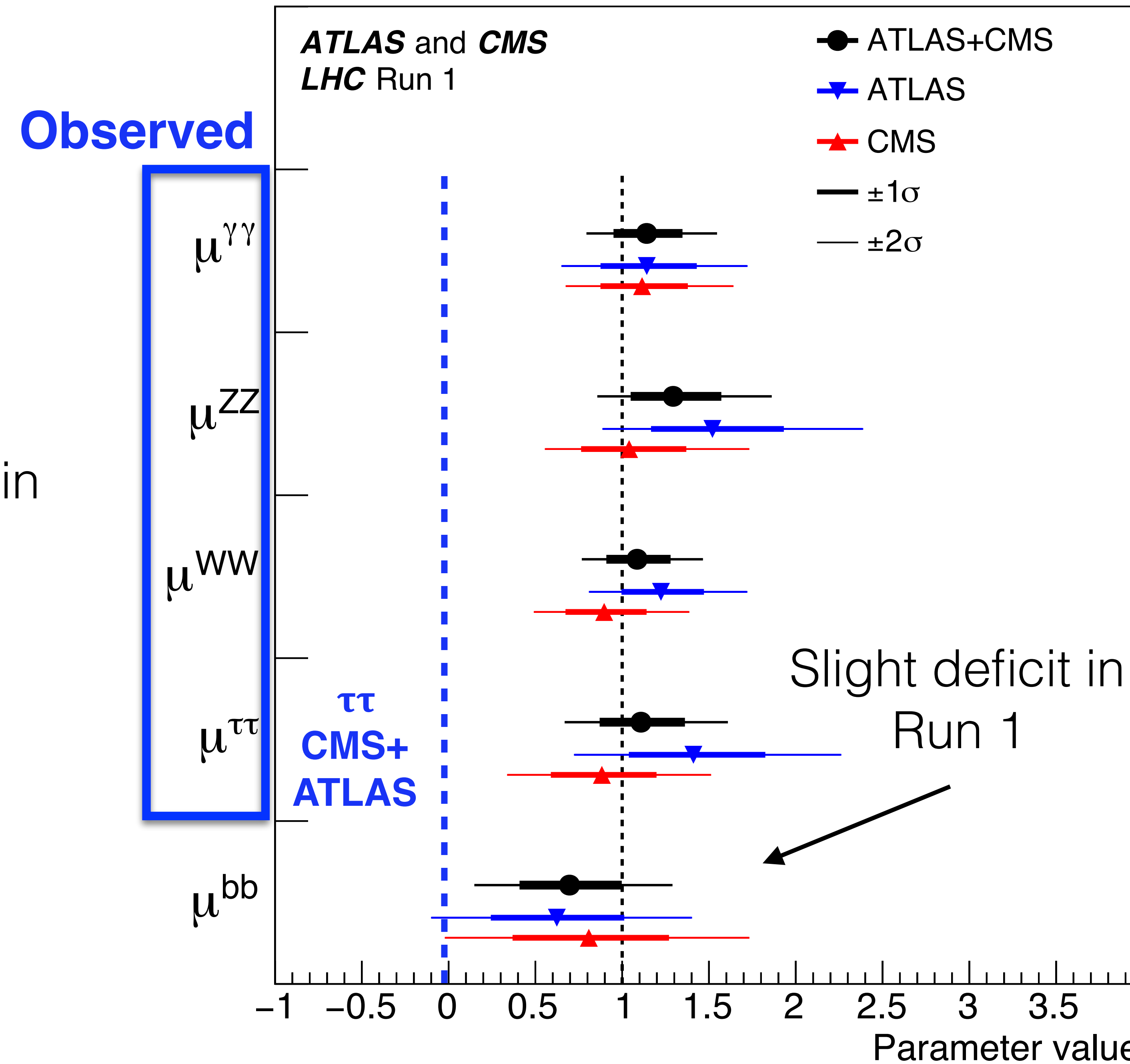


Production & decay

JHEP 08 (2016) 045

μ is ratio to SM expectation





Single global fit, relative to SM expectation

$$\mu = 1.09^{+0.11}_{-0.10} = 1.09^{+0.07}_{-0.07}\,(\text{stat})\,^{+0.04}_{-0.04}\,(\text{expt})\,^{+0.03}_{-0.03}\,(\text{thbgd})^{+0.07}_{-0.06}\,(\text{thsig})$$

Run 2

Move from 8 TeV (2012) → 13 TeV (2015)
Higher Energy : *1.6

2013-2014 : 10,000 superconducting splices reinforced

50 ns bunches (20 MHz) → 25 ns (40 MHz)
Higher instantaneous luminosity

Mechanism	$\sigma_{13TeV} / \sigma_{8TeV}$
gg→H	2.3
WH	2.0
VBF H+qq	2.4
ttH	3.9

ttH gets the most help

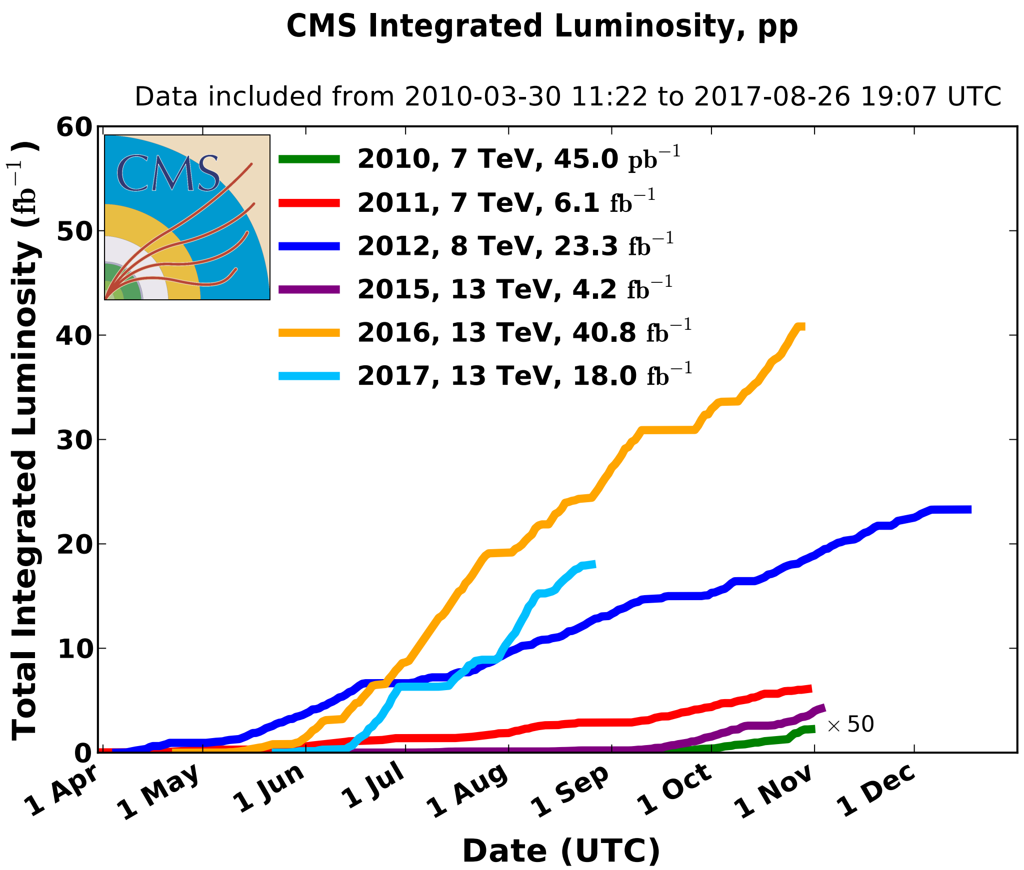
Why Higgs boson is still interesting

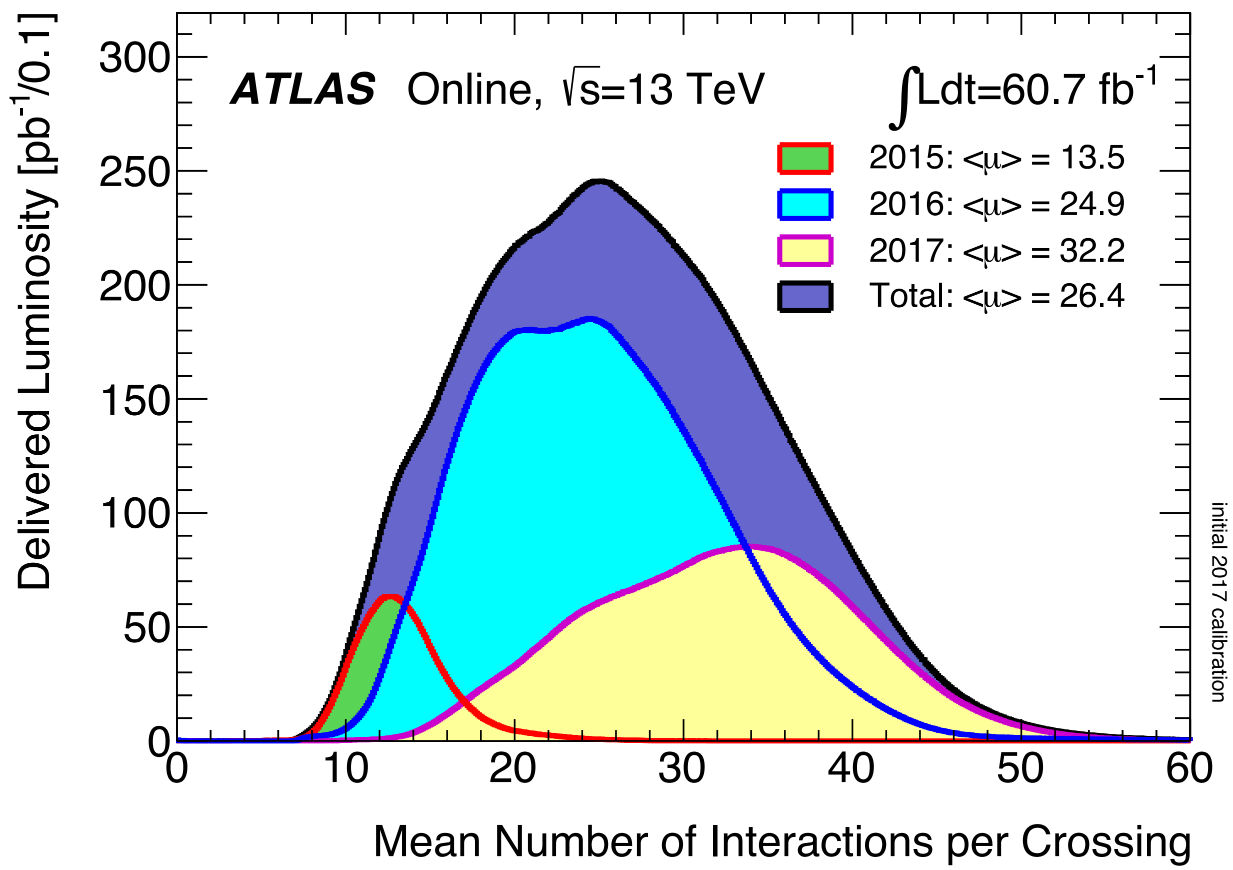
- **Higgs boson is manifestation of scalar field filling the universe**
  - **Field gives mass to (most?) fermions and W/Z bosons**
  - **Scalar field should be sensitive to fluctuations of higher energy scales**
    - In fact, if next scale is Planck scale, mass should naturally be 16 orders of magnitude bigger
- **Higgs boson is the only particle that can tell the difference between copies of particles**
  - **Tau (3rd gen.) and muon (2nd gen.) are heavy copies of electron**
  - **How does Higgs boson know which one is which ?**
  - **How does Higgs boson know what mass to give these particles ?**

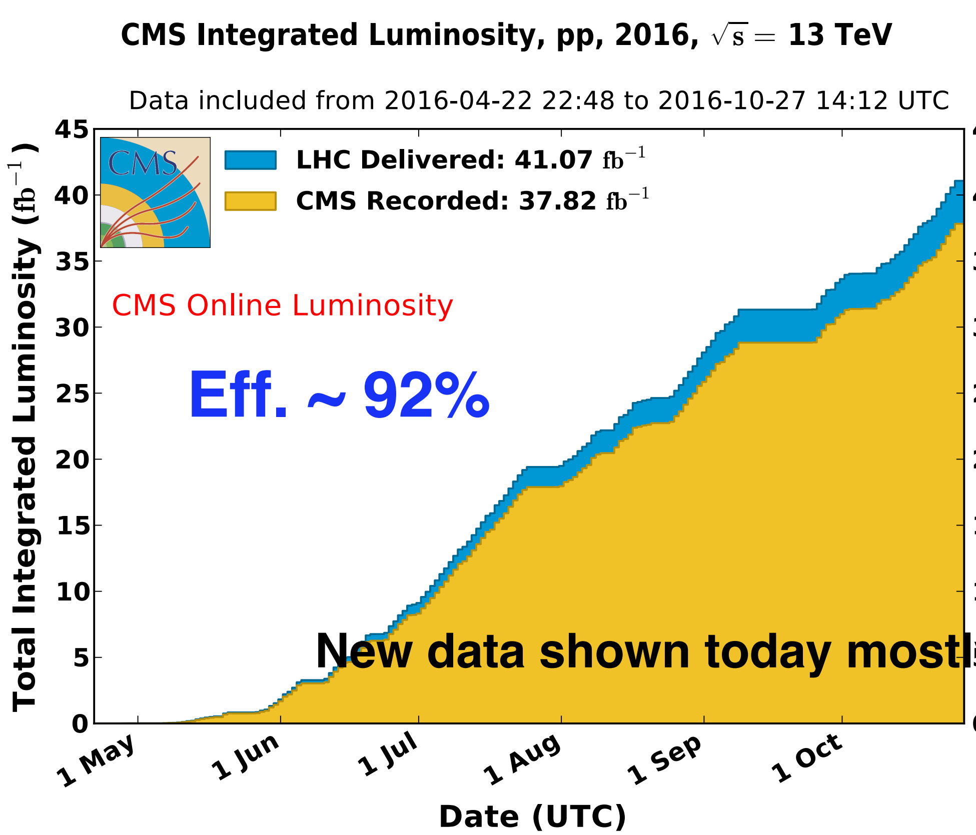
Goals for Run 2 Higgs program

- **Reestablish H→ZZ, H→γγ, H→WW**
- **Establish fermionic couplings**
  - **H→bb**
  - **H→ττ (not yet observed by a single experiment)**
  - **ttH**
- **More precise Higgs couplings**
  - **Coupling deviations from SM expectations ↔ new physics**
    - For a new mass scale of 1 TeV
      - Composite Higgs -> Couplings change ~3%
      - SUSY (tanβ=5) -> H→bb, H→**ττ** ~2%
      - Top partners -> ggH ~3%
- **Investigate rare decays that could be enhanced by new physics**
- **Reduce theory uncertainties by measuring in carefully constructed signal regions …**
  - **Identify signal regions more sensitive to new physics**
- **Differential cross-section measurements**

New 13 TeV data

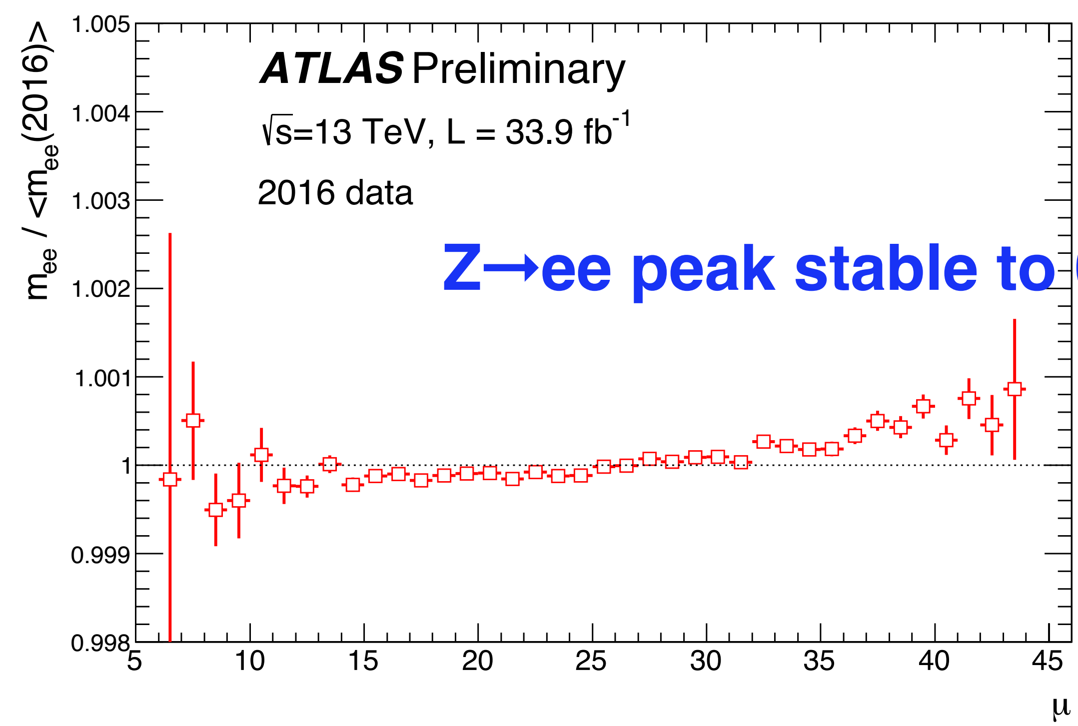






Eff. ~ 92%

New data shown today mostly from 2016

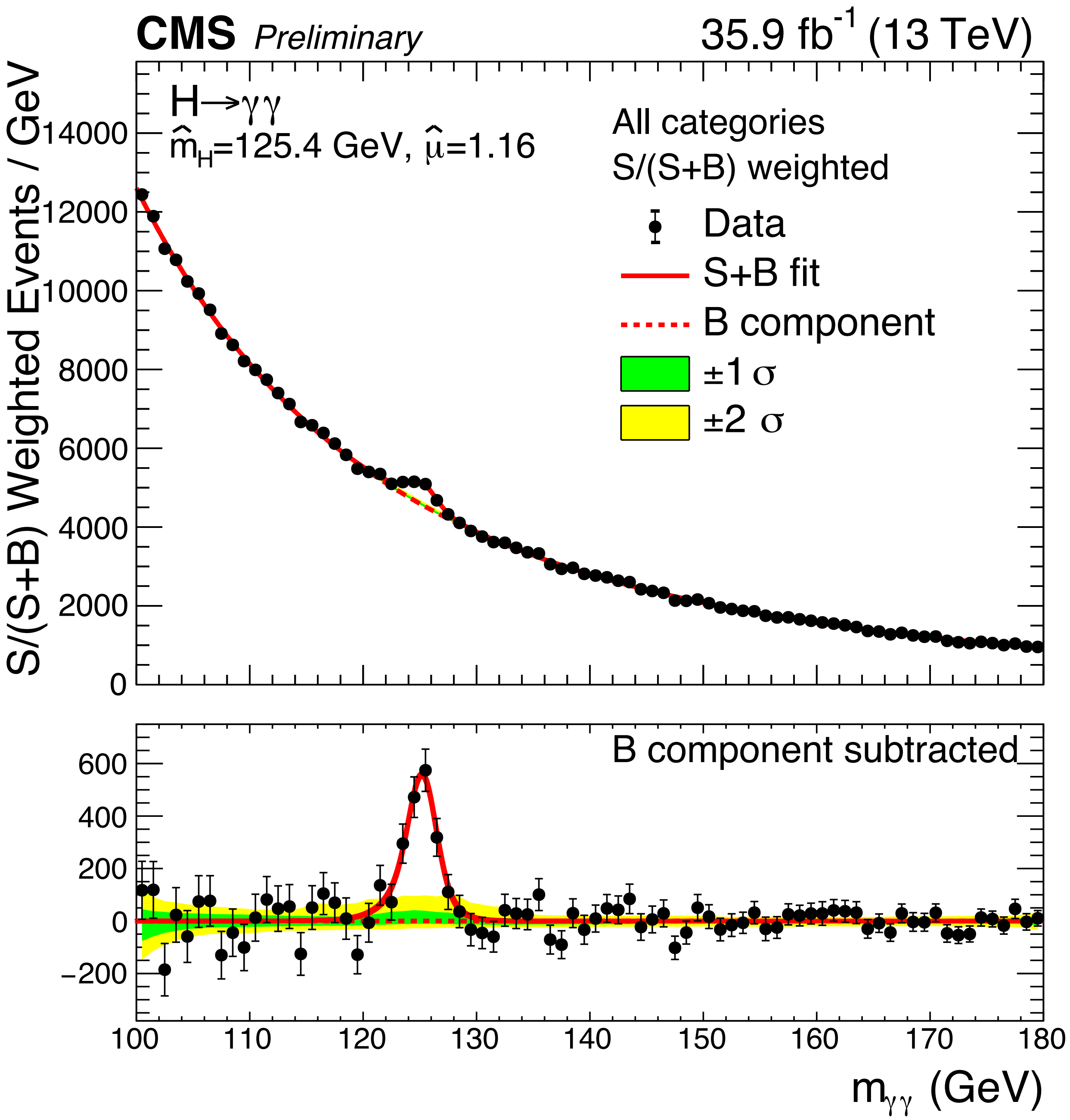


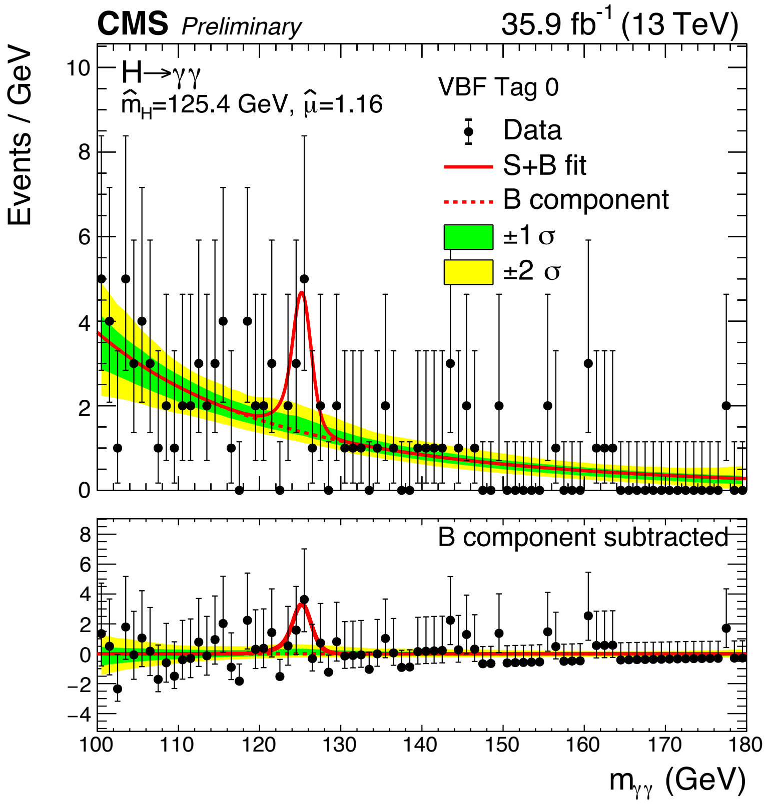
Z→ee peak stable to 0.5%

Precision measurements

[CMS HIG-16-040]

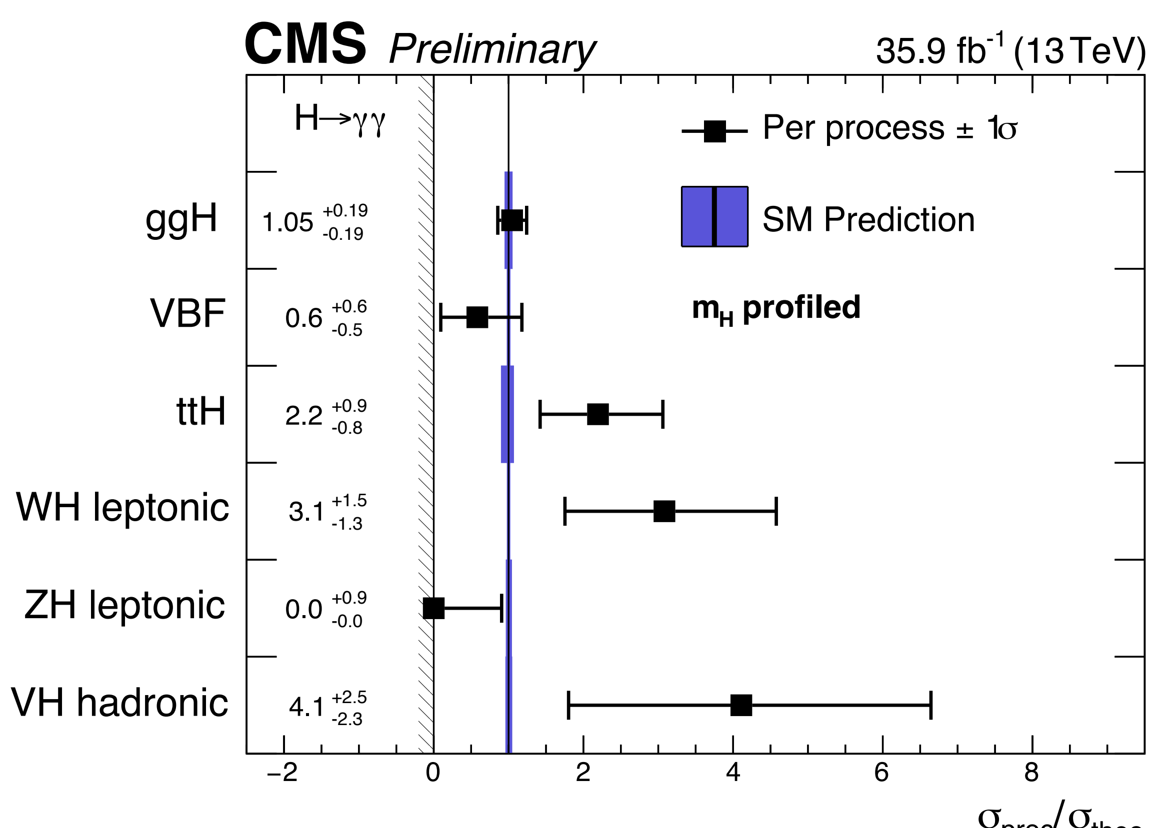
- **H→γγ**





VBF-tagged

Selection includes 2 jets with large Δη requirement



Differential measurements refine what we can learn

- Measuring Higgs P_T probes perturbative QCD modeling for the production mechanism
- Measuring Jet multiplicity sensitive to different relative production modes
- Angular observables (e.g., angle between Higgs and beam axis) sensitive to spin & charge conjugation
- Jet rapidity gaps can suppress color flow as in VBF production

New this year

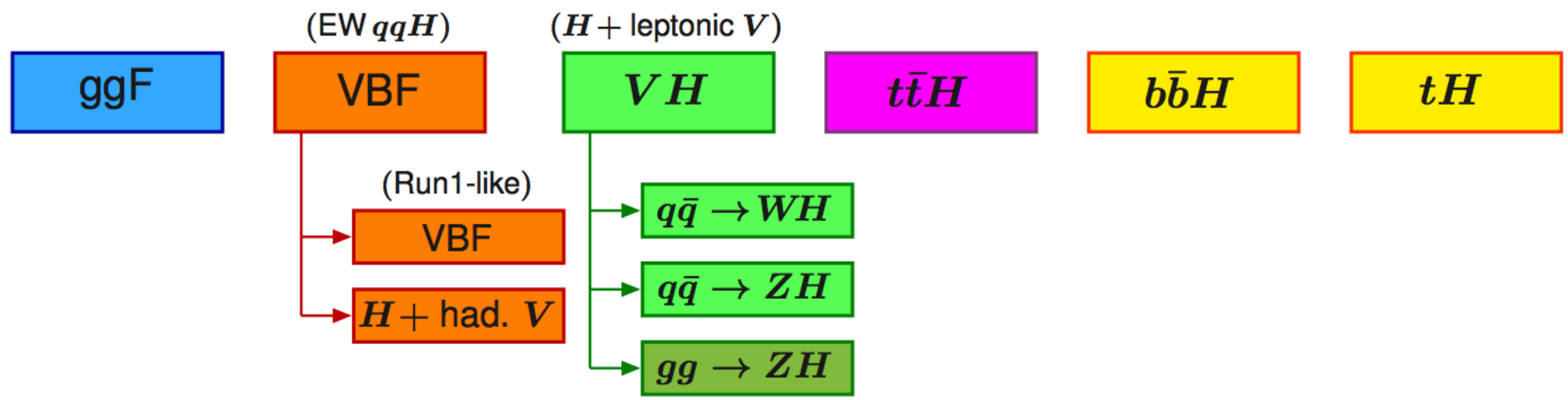
Simplified template cross section framework

arXiv:1610.07922

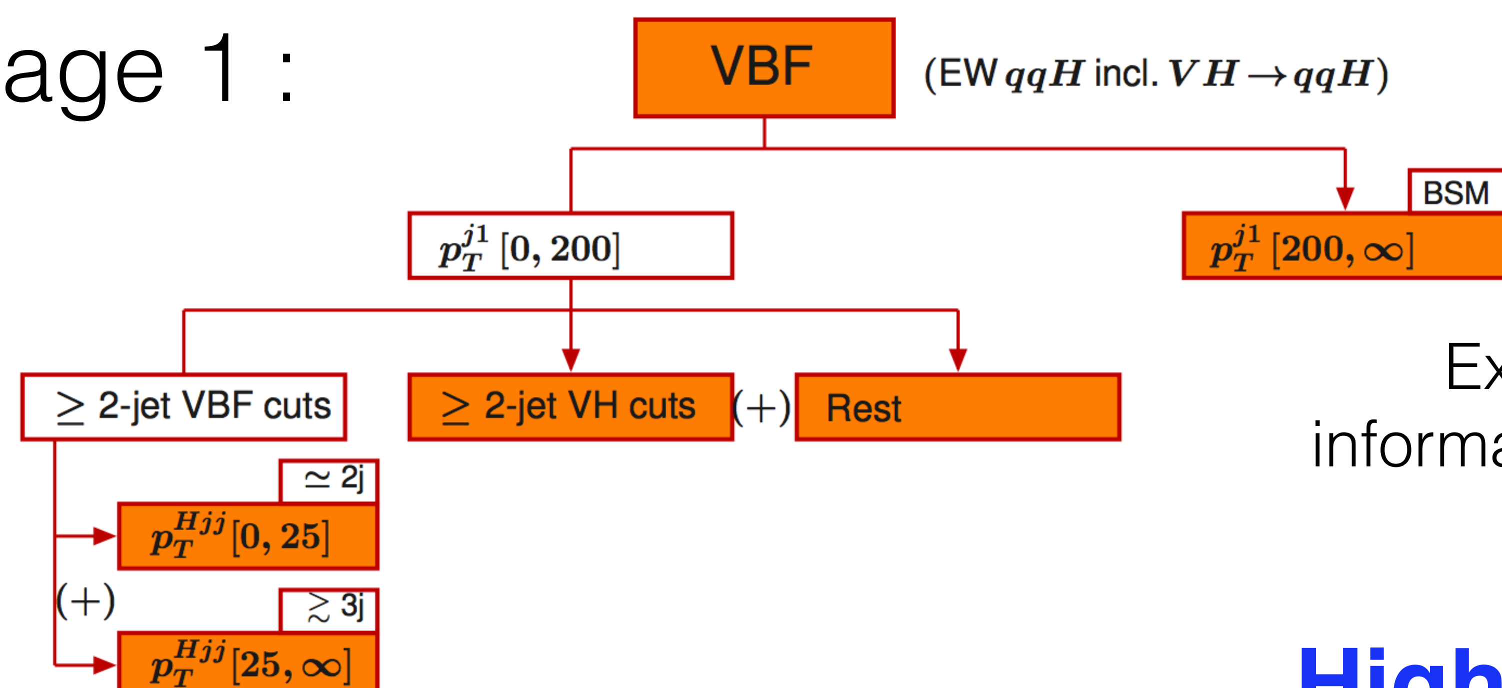
- **New framework established by LHC Higgs Cross section working group**
  - **Staged approach to factorize signal into truth-level regions of phase space**
    - Combination of all channels without overlap
    - Measure cross-sections instead of signal strengths, in mutually exclusive regions of phase space
    - Cross-section measured for specific SM production mode in simple fiducial volumes
  - **Goals**
    - Minimize dependence on theoretical uncertainties (extrapolations)
    - Maximize experimental sensitivity
    - Isolation of possible BSM effects
    - Minimize the number of bins without loss of experimental sensitivity

Example of simplified template bins

Stage 0 :
like Run 1



Stage 1 :

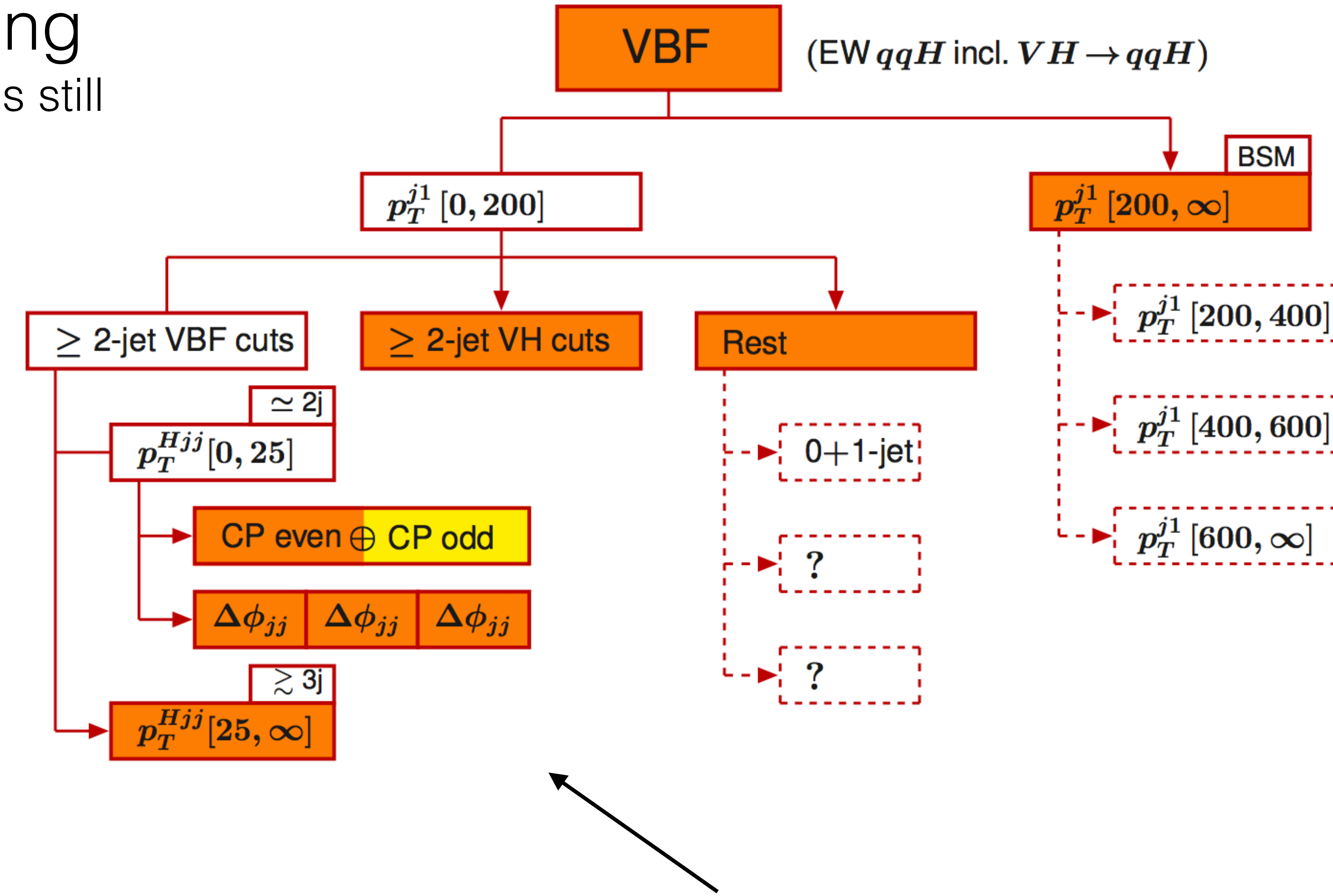


Exclusively split using truth-level information, to derive templates in fiducial regions

High P_T sensitive to BSM

Example of simplified template bins

Stage 2 :
Possible binning
since this approach is still
being developed



CP-odd contributions

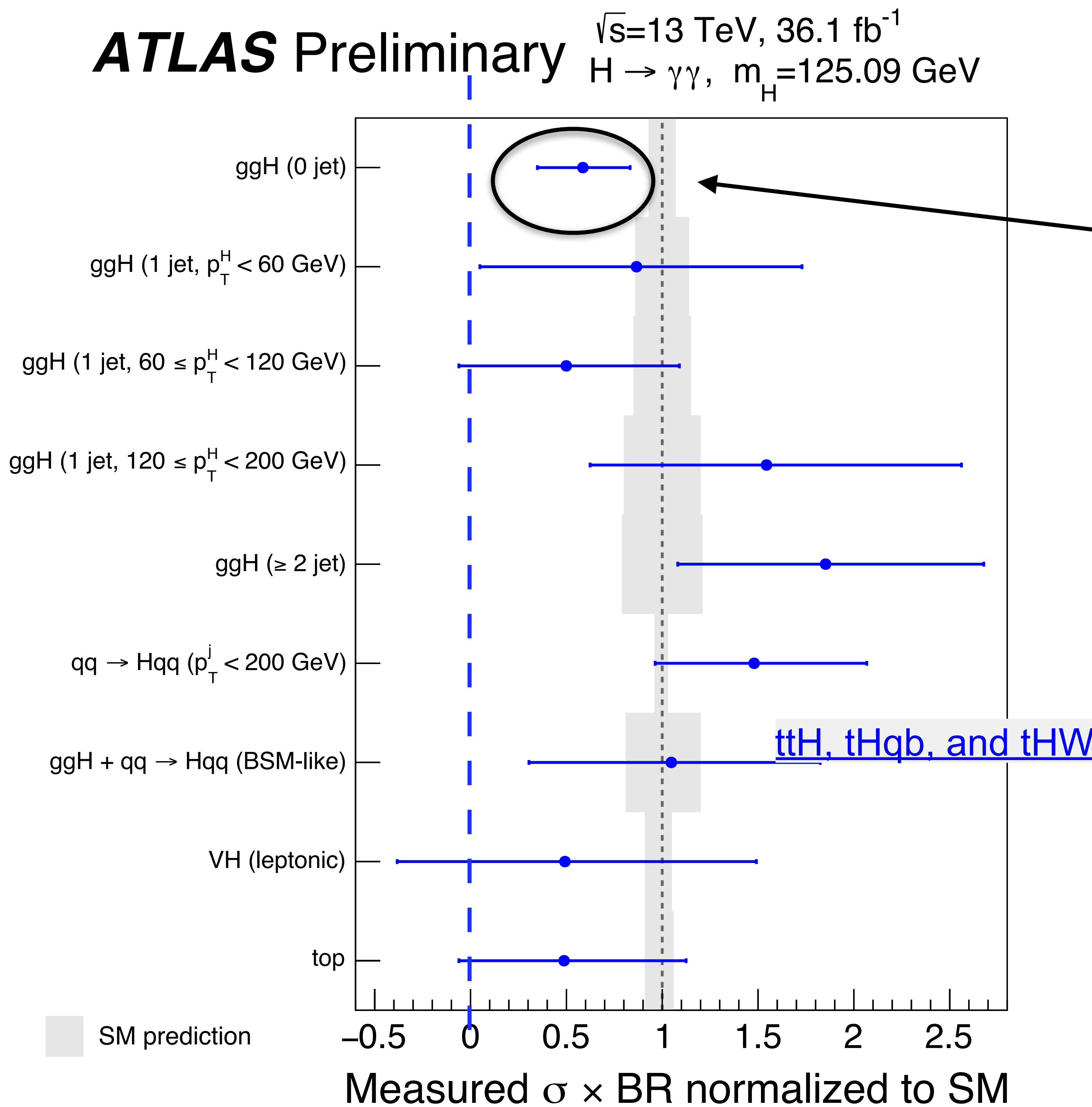
H→γγ in more detail

ATLAS-CONF-2016-067

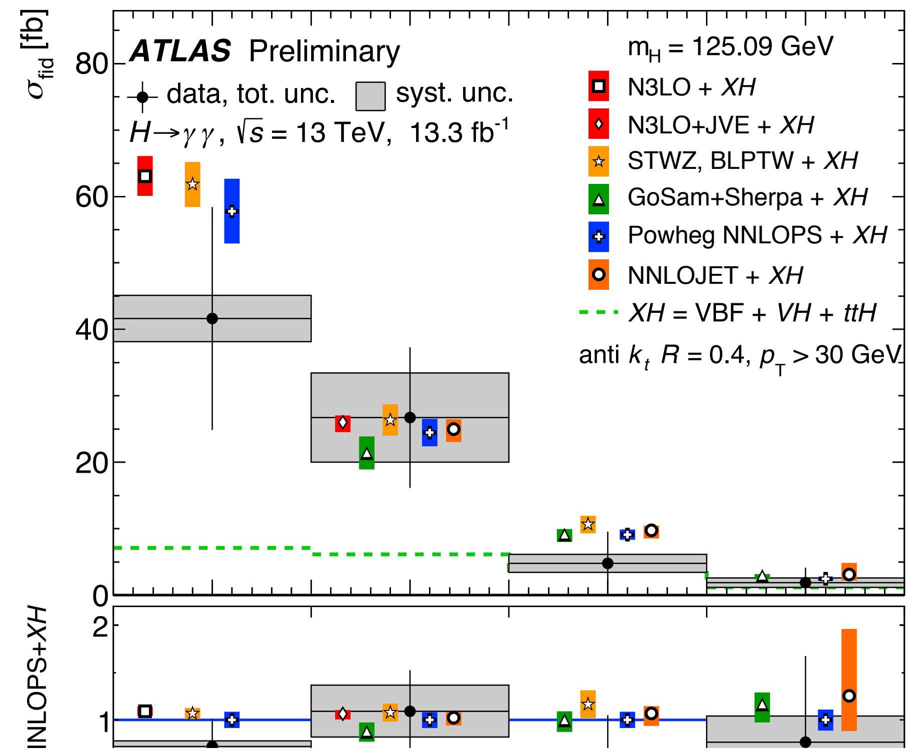
ATLAS-CONF-2017-045

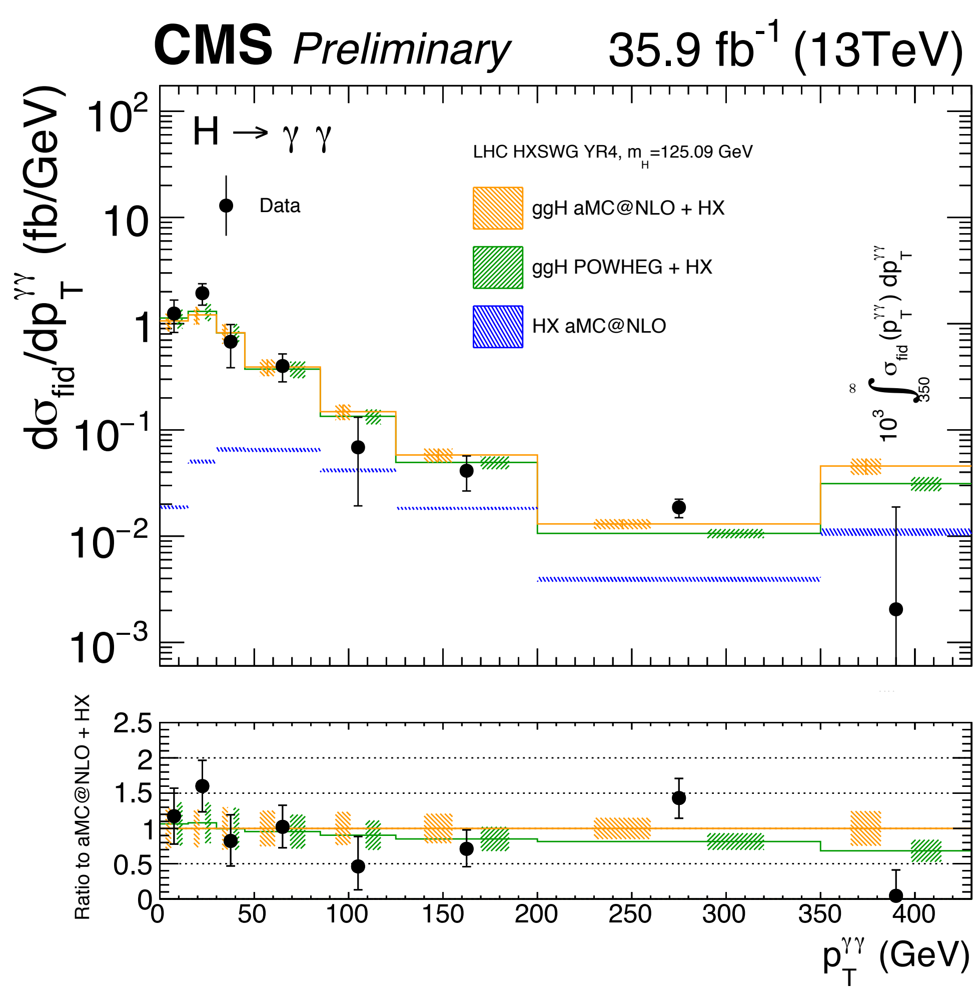
Simplified template cross section framework :

(factorize th. uncertainties or BSM-sensitivity)



Differential measurement

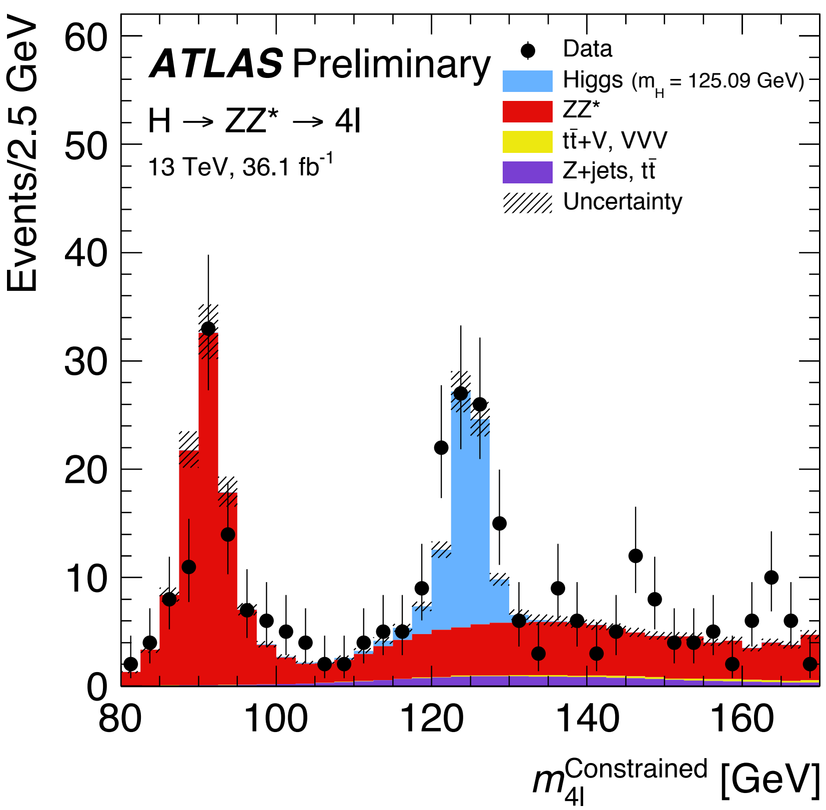




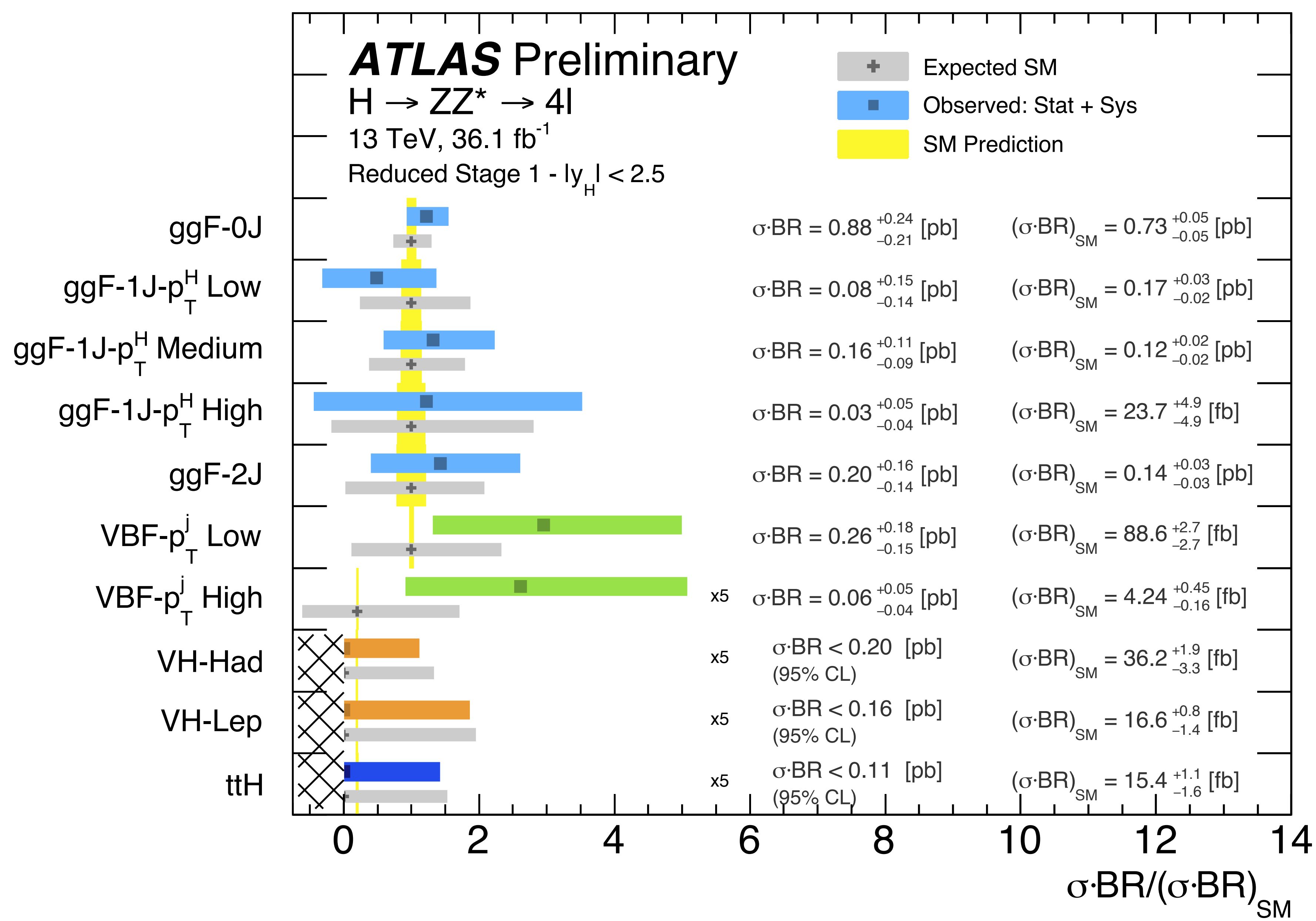
H→ZZ→4l

ATLAS-CONF-2017-043

Signal reestablished with c.m.=13 TeV



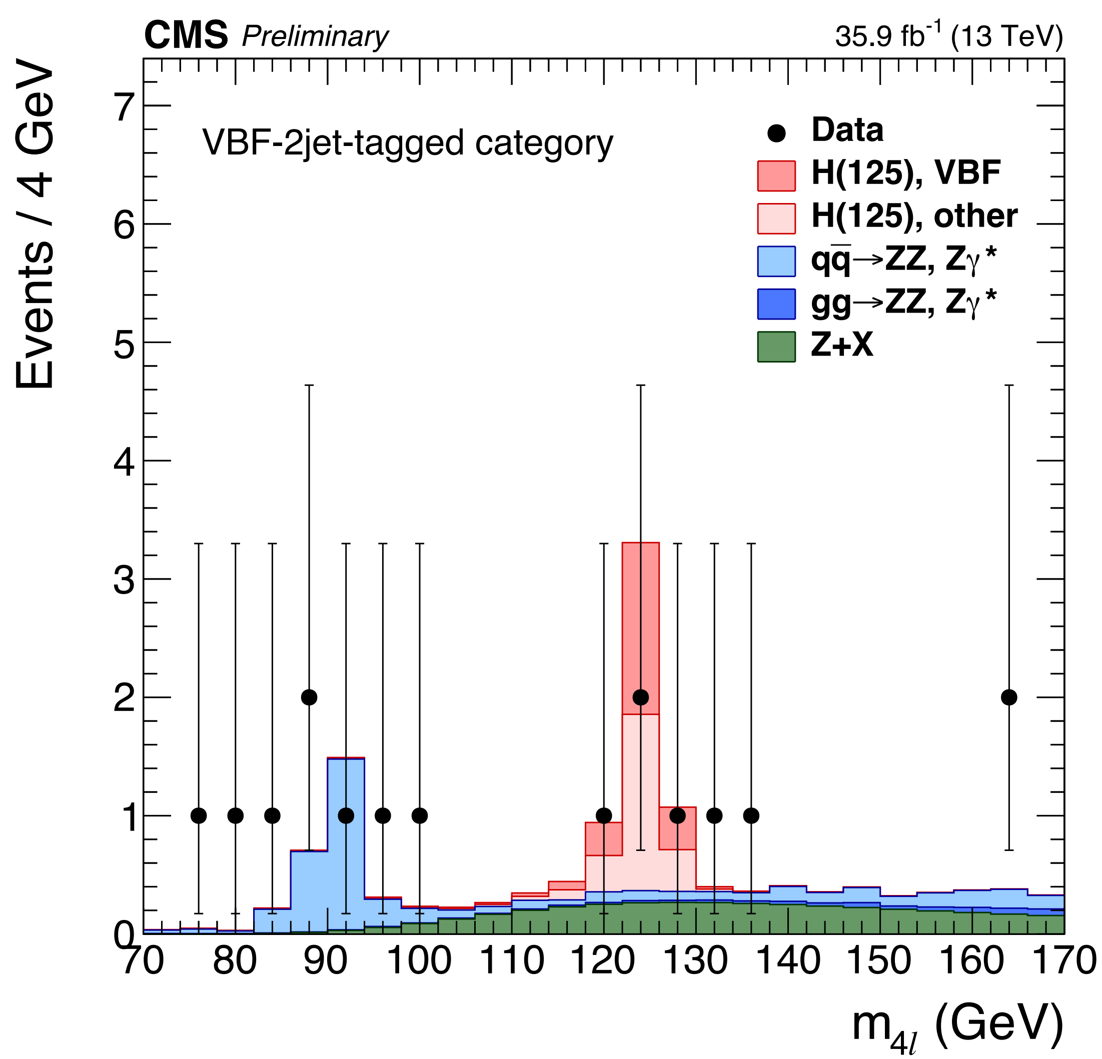
Simplified template cross-sections



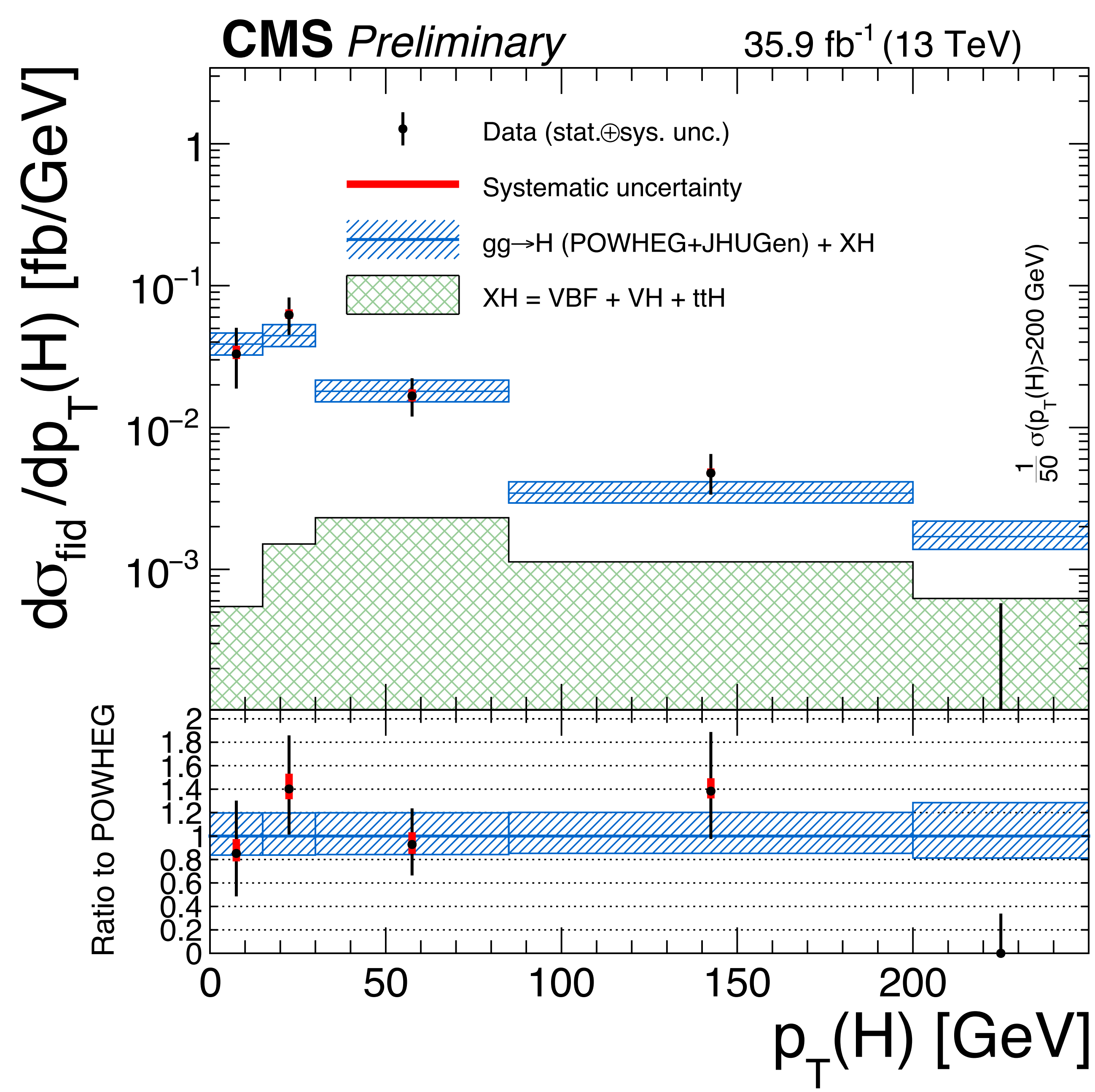
H→ZZ→4l in more detail

CMS arXiv:1706.09936

VBF-tagged



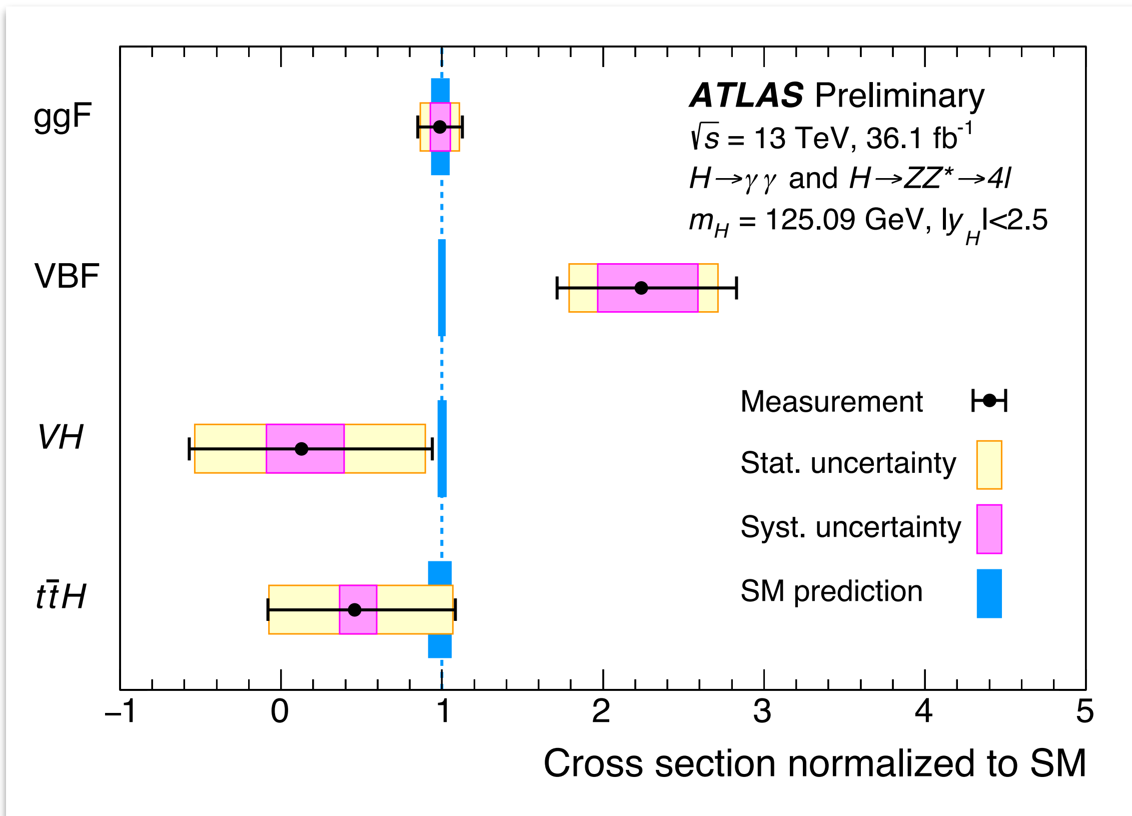
Differential in H P_T

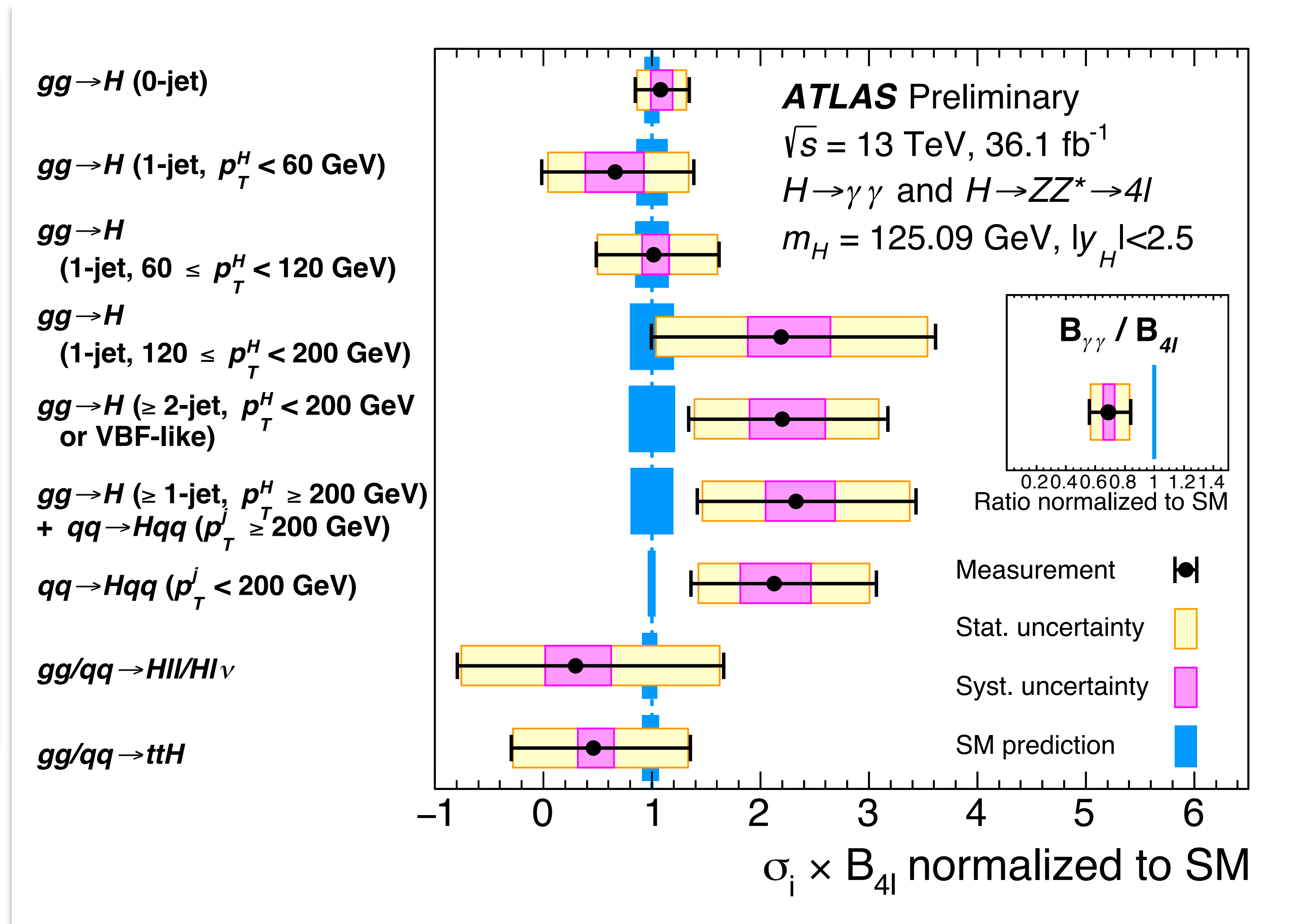


Precision production modes

ATLAS-CONF-2017-047

- ATLAS H→γγ + H→ZZ→4l combined





Effort to combine simplified template regions between different Higgs decays

Precision 13 TeV results in $H \to \gamma\gamma$ & $H \to ZZ$

ATLAS-CONF-2017-045
CMS HIG-16-040
ATLAS-CONF-2017-043
CMS arXiv:1706.09936
ATLAS-CONF-2017-046

	Measurement	CMS	ATLAS
15%	σ/σ_{SM} $H \to \gamma\gamma$	$1.16^{+0.11}_{-0.10}(\text{stat})^{+0.09}_{-0.08}(\text{exp})^{+0.06}_{-0.05}(\text{theo})$	$0.99\ ^{+0.12}_{-0.11}\ (\text{stat.})\ ^{+0.06}_{-0.05}\ (\text{exp.})\ ^{+0.06}_{-0.05}\ (\text{theory})$
~20%	σ/σ_{SM} $H \to ZZ$	$1.05^{+0.15}_{-0.14}\ (\text{stat})^{+0.11}_{-0.09}\ (\text{syst})$	$1.28^{+0.18}_{-0.17}(\text{stat.})^{+0.08}_{-0.06}(\text{exp.})^{+0.08}_{-0.06}(\text{th.})$
	Mass $H \to ZZ \to 4l$ [GeV]	125.26 ±0.20(stat) ± 0.08(sys) best measurement	124.88 ±0.37 ± 0.05
	Mass $H \to \gamma\gamma$ & $H \to ZZ$ [GeV]		124.98 ± 0.28

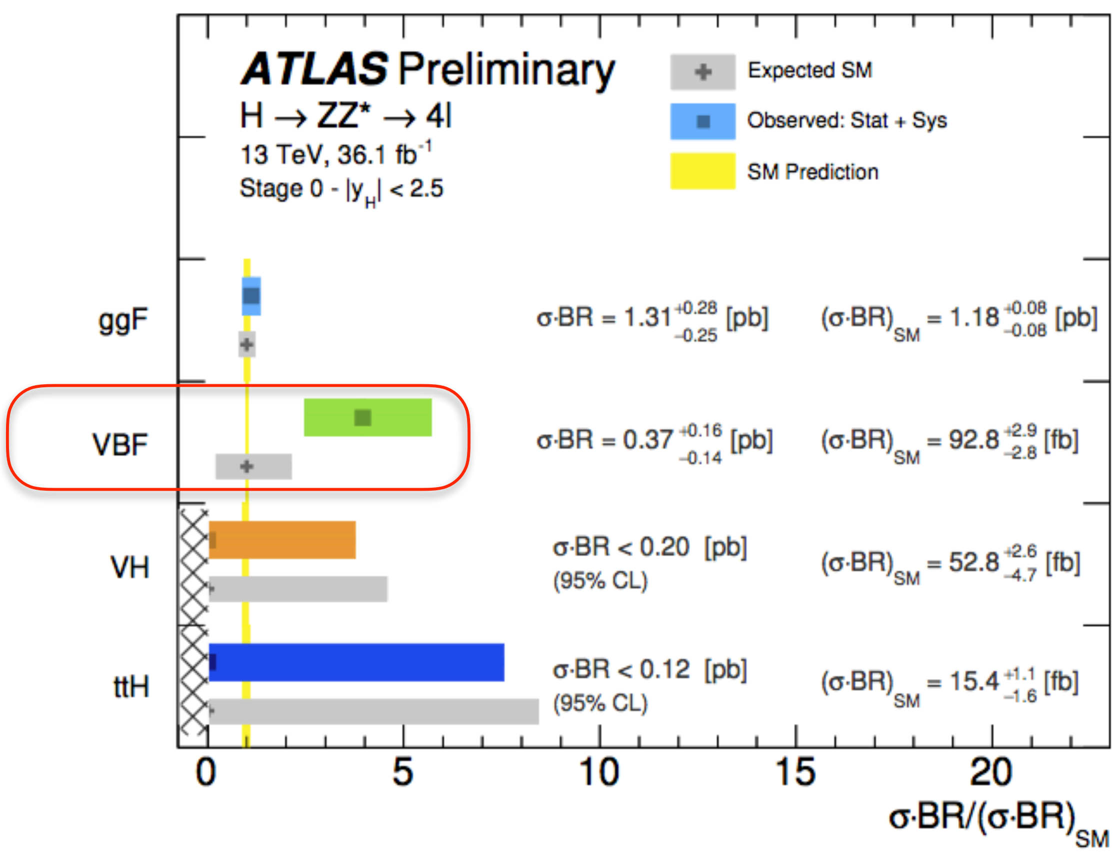
Compare to run 1 CMS+ATLAS combined mass : 125.09 ±0.24

Statistical uncertainties still dominate this page

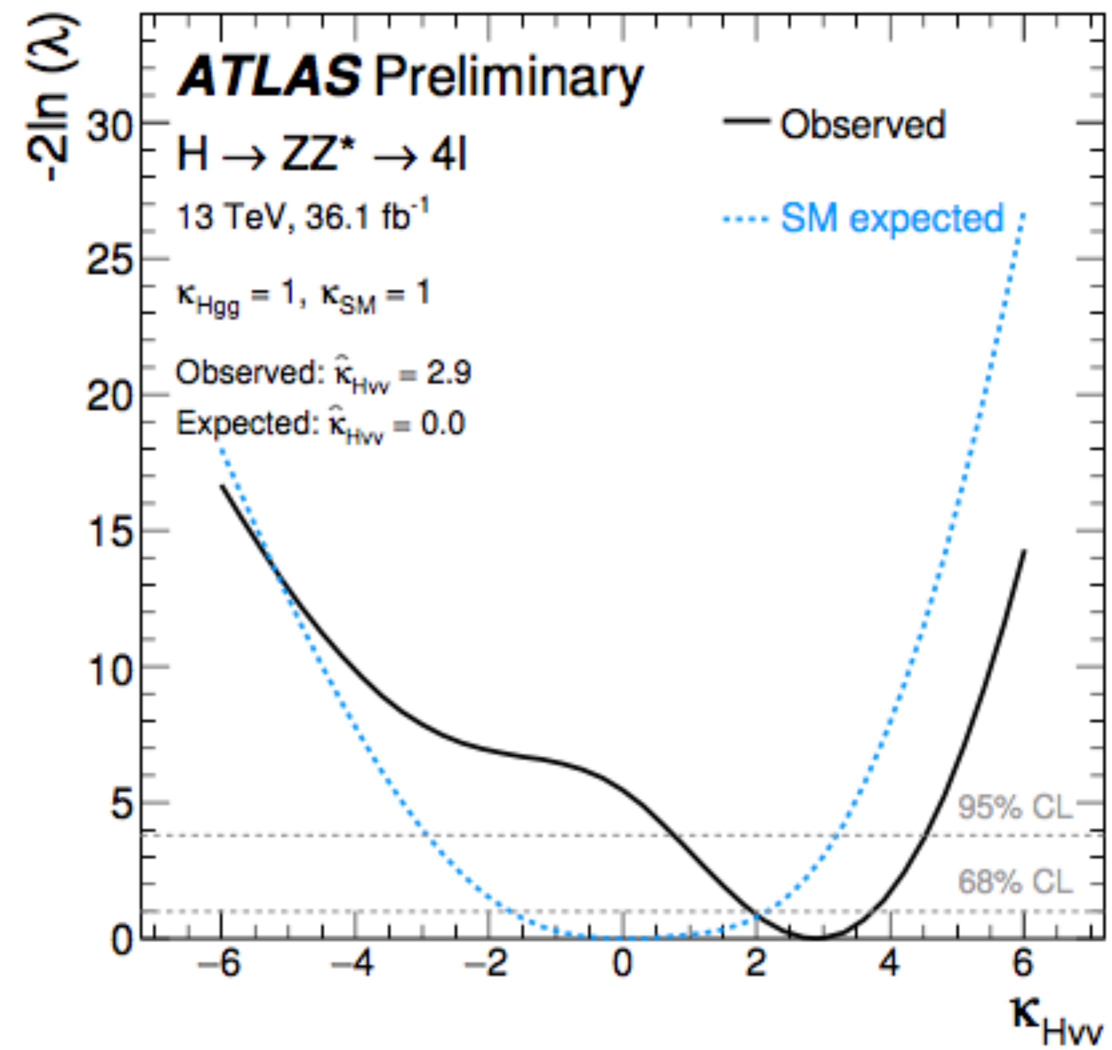
Searches for BSM

- **Tensor structure probed using effective Langrangian with no new physics below Λ = 1 TeV**

$$\mathcal{L}_0^V = \Big\{\kappa_{\rm SM}\left[\tfrac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right]$$
$$-\tfrac{1}{4}\left[\kappa_{Hgg}g_{Hgg}G^a_{\mu\nu}G^{a,\mu\nu} + \tan\alpha\,\kappa_{Agg}g_{Agg}G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right]$$
$$-\tfrac{1}{4}\tfrac{1}{\Lambda}\left[\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \tan\alpha\,\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right]$$
$$-\tfrac{1}{2}\tfrac{1}{\Lambda}\left[\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \tan\alpha\,\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\}X_0$$



Fit to κ_{Hvv} is coupling of CP-even (scalar) BSM interaction with W/Z



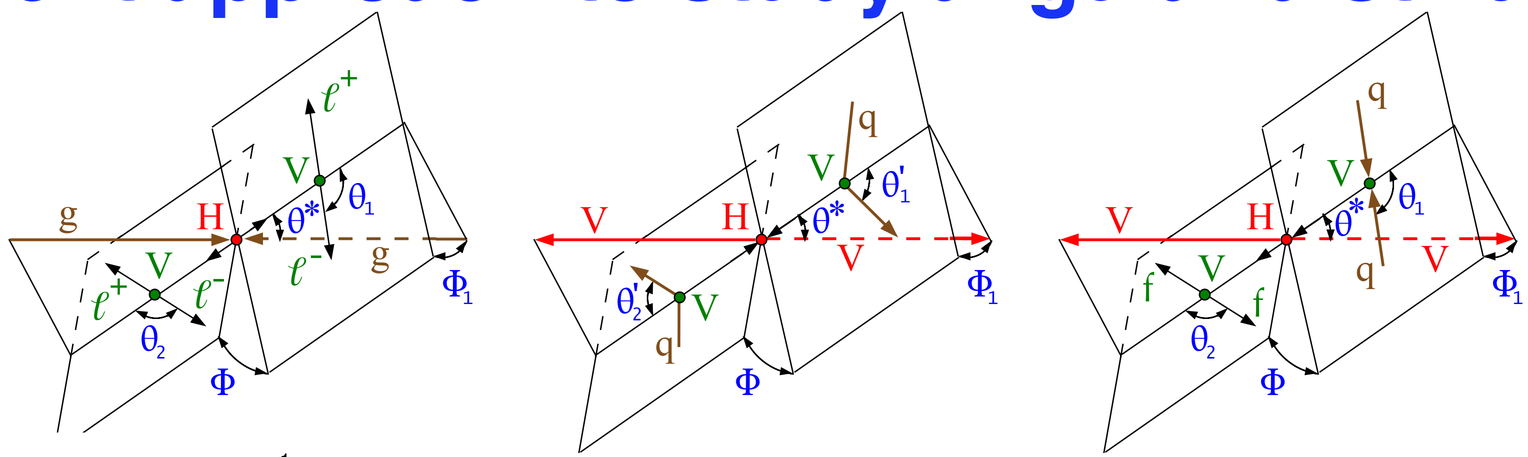
2.3σ deviation from SM is largest discrepancy

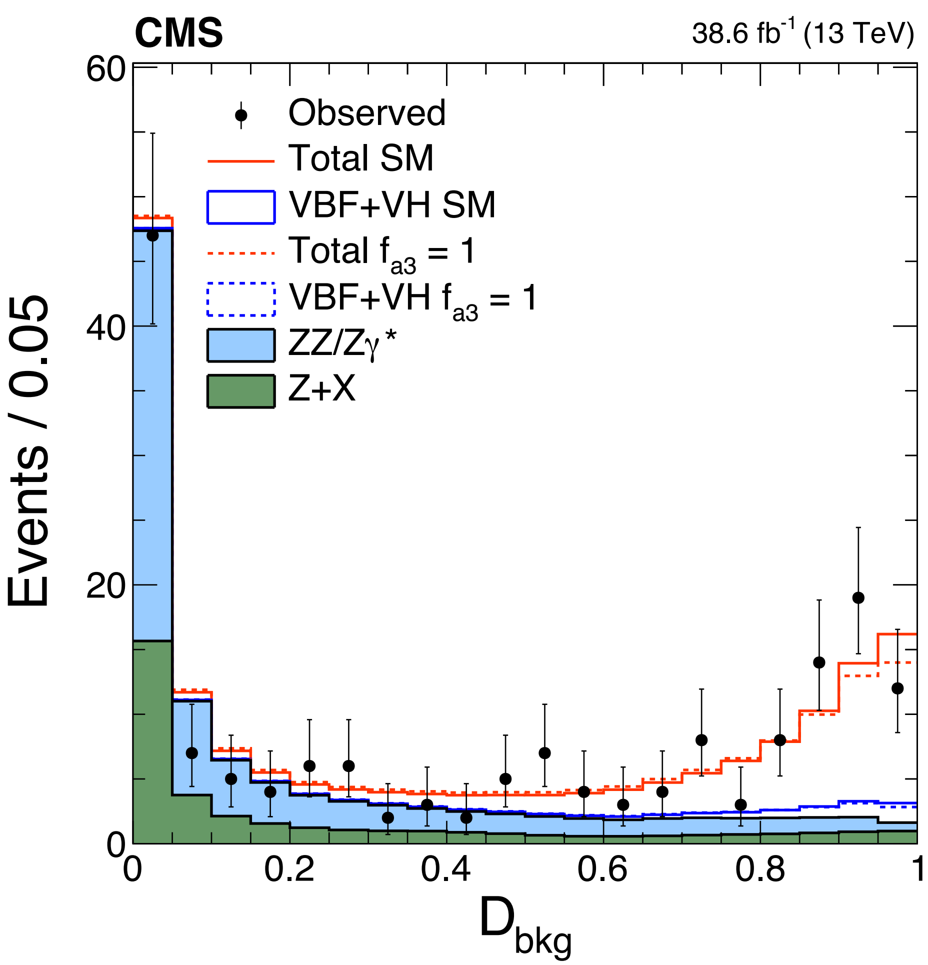
Due to excess in 2-jet event category

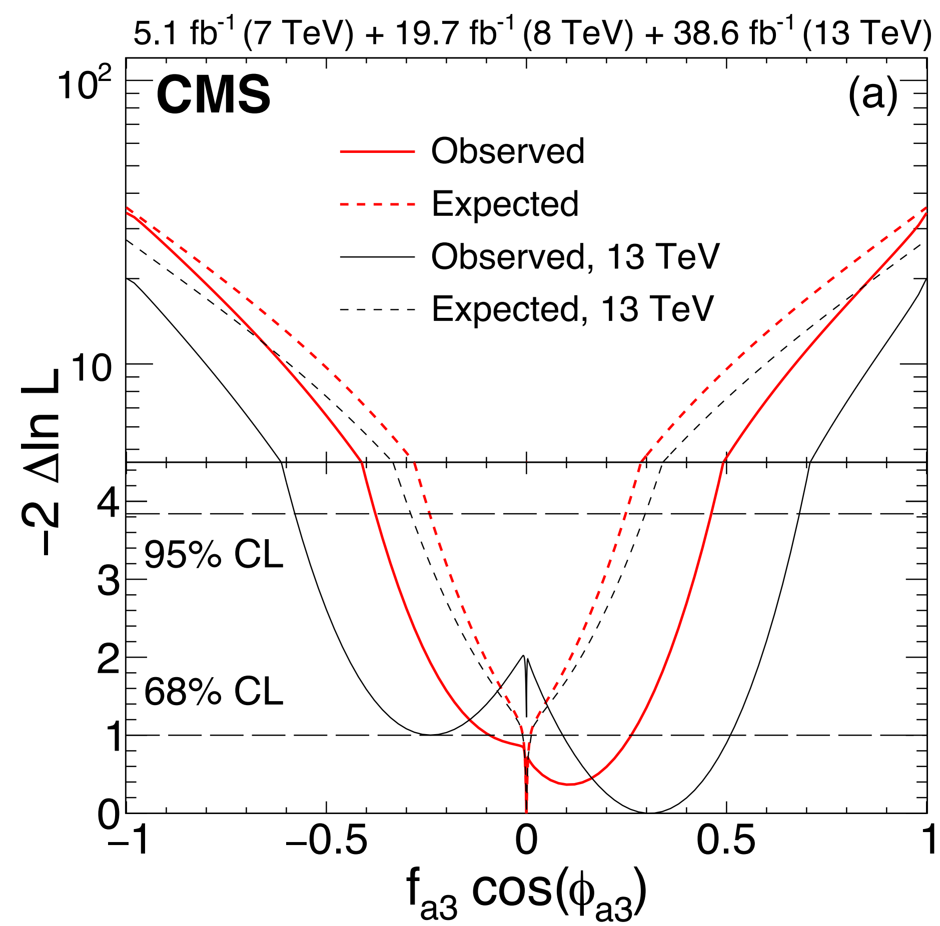
Decay-side BSM probes

arXiv:1707.00541

- **Search for anomalous interactions using matrix-element approach to study angular distributions**







f_{a3} is a CP-violation parameter, the fractional pseudoscalar cross section in the H → ZZ channel

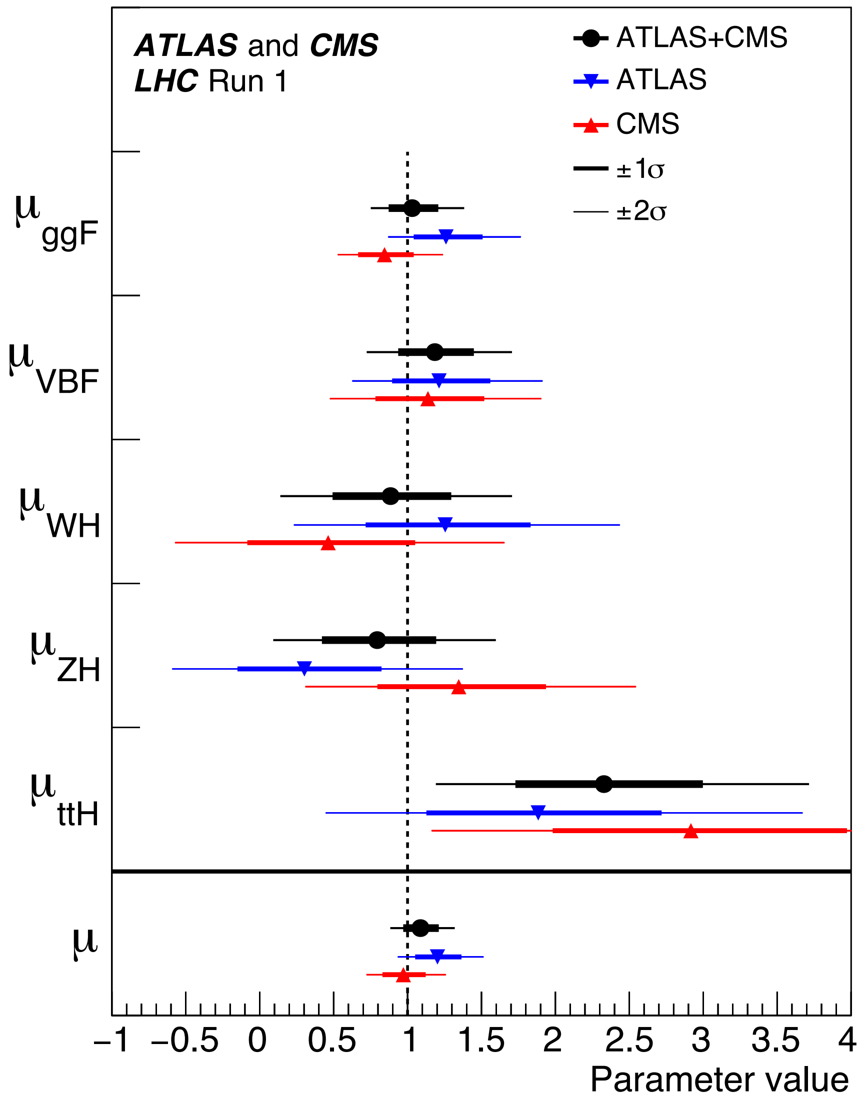
Small forward-backward asymmetry seen in $f_{a3}\cos(\phi_{a3})$ in 13 TeV

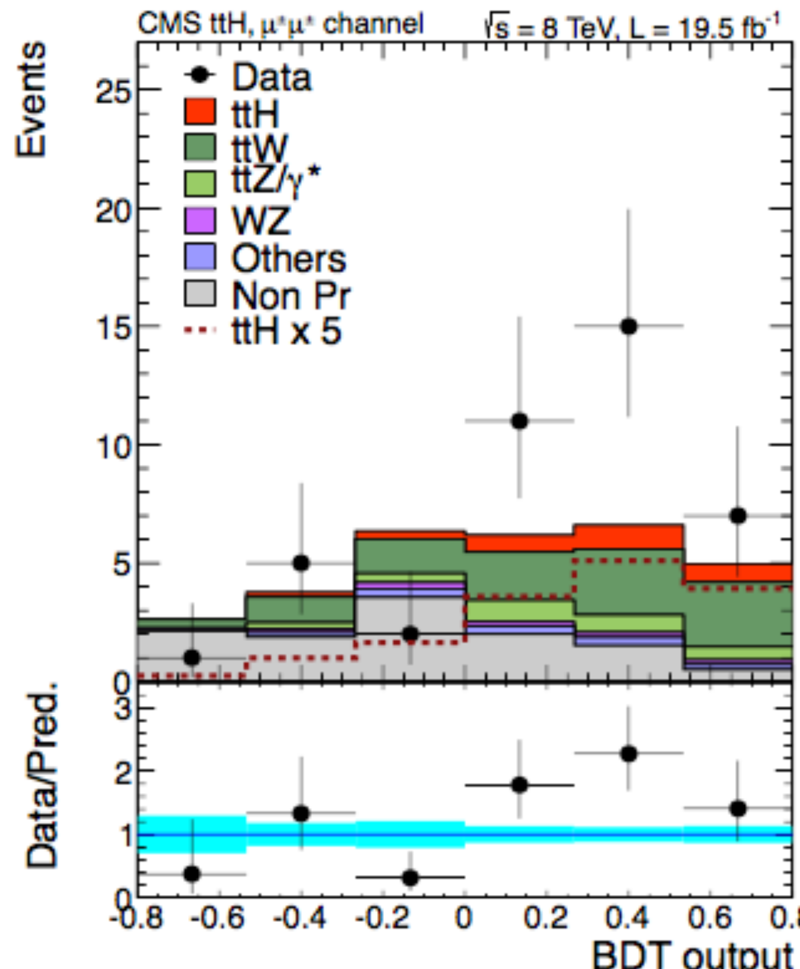
Coupling to fermions

ttH production

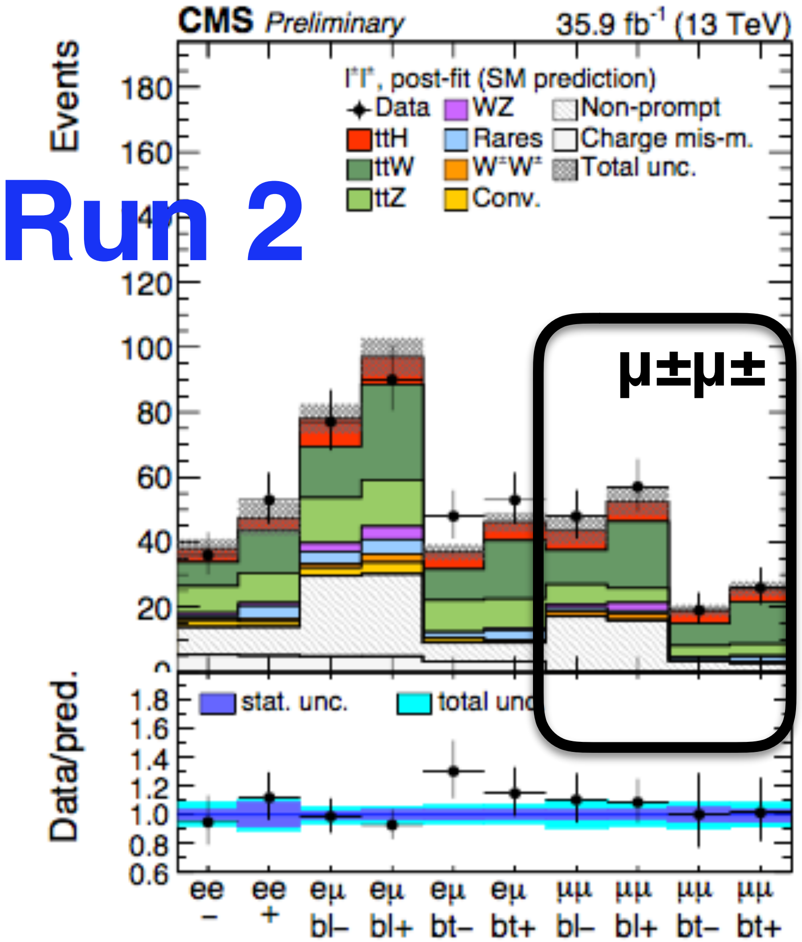
J. High Energy Phys. 08 (2016) 045

Run 1 slight excess in ttH



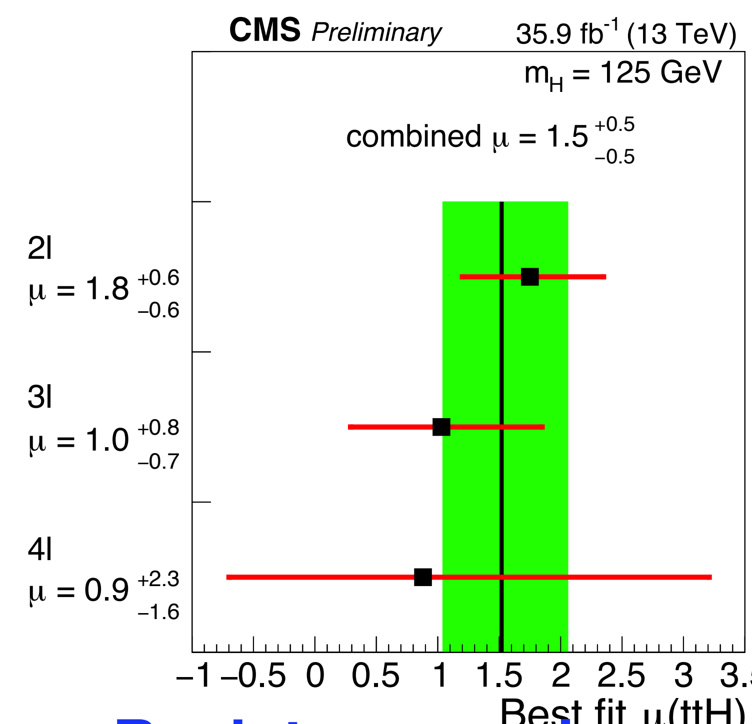


Run 2



Driven by ttH→ μμ+X

- (same-sign, μ from H→WW/ZZ, μ from t)



Back to normal …

Coupling to Taus

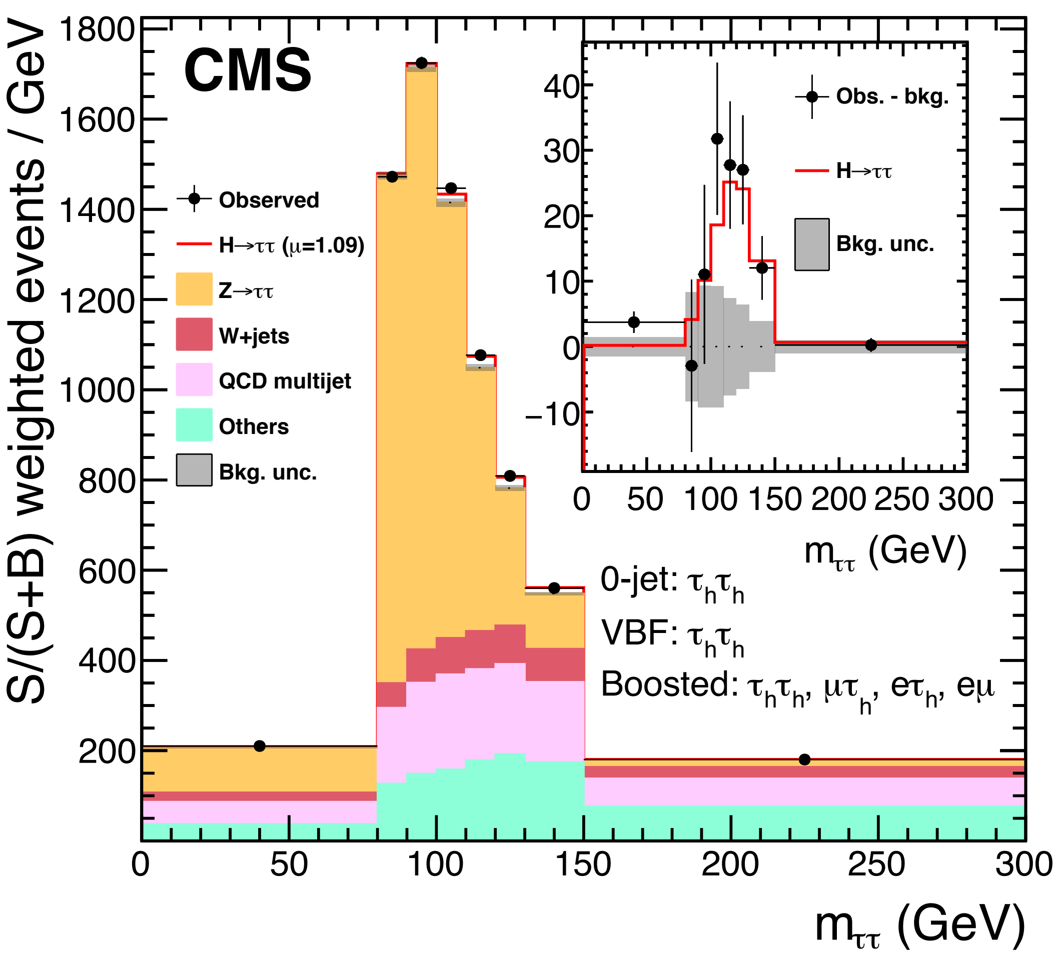
arXiv:1708.00373

JHEP 08 (2016) 045

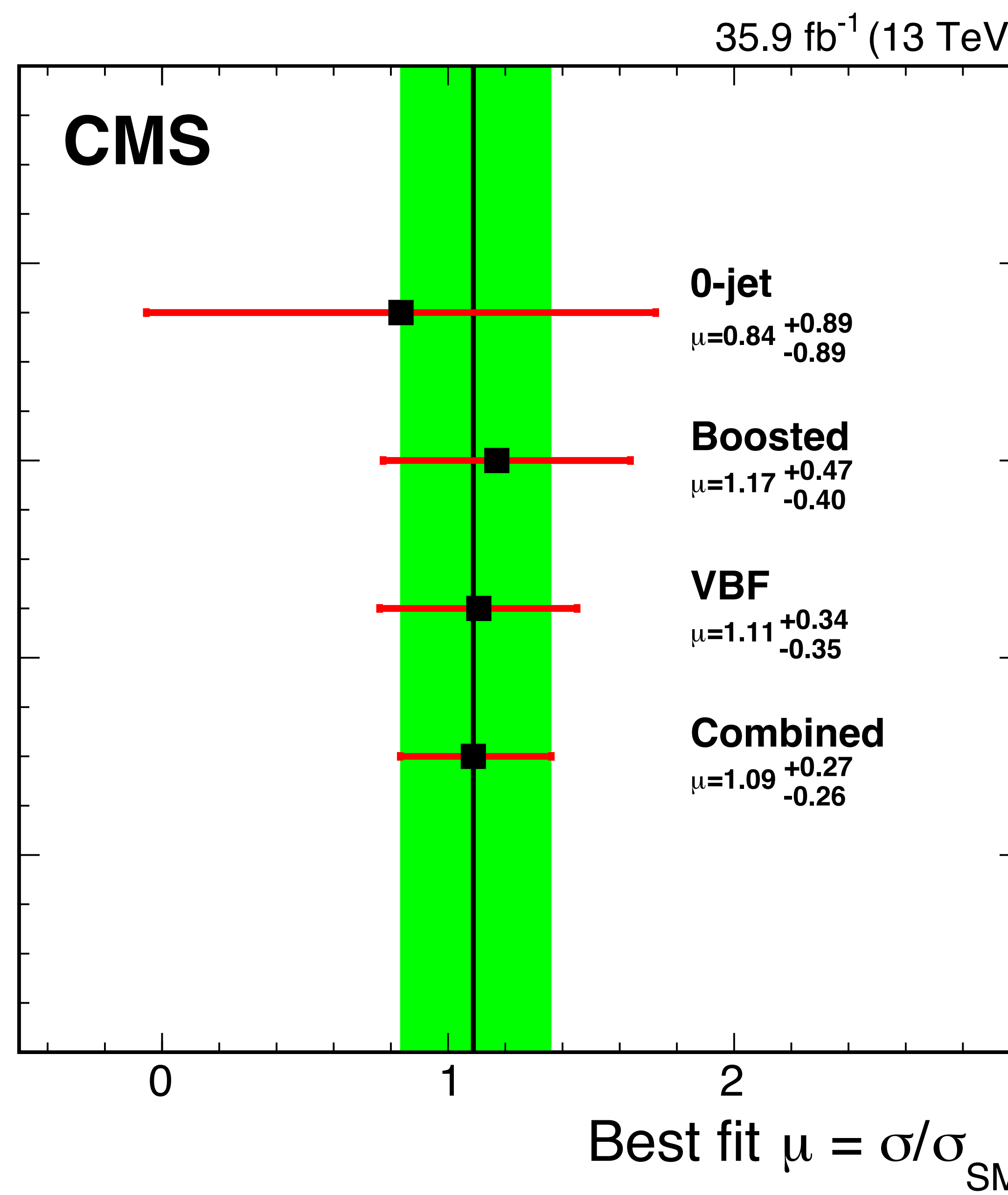
- **First single-experiment observation of H→ττ**

(previously, achieved with CMS+ATLAS combo)

4.9σ (expec. 4.7σ)



5.9σ significance 7/8/13TeV



Higgs coupling to leptons, directly to fermions, and 3rd generation firmly established

Dominant decay of H→bb

- **Tevatron 2 TeV ppbar by 2012**
  - **Tevatron data (2003-2011) 10 fb^{-1}**
    - Evidence for Higgs reported from CDF + D0
      - Local significance of **3σ at 125 GeV** (1.9 σ expected)
      - Dominated by H→bb channel
- **LHC as of 2016**
  - CMS & ATLAS each found only ~ 2σ significance
    - 5 fb^{-1} of 7 TeV 2011
    - 20 fb^{-1} of 8 TeV data 2012
    - 4 fb^{-1} of 13 TeV data 2015
- **Why so hard ?**

The search for H→bb

- **Differences between Tevatron & LHC**

Cross-sections fb	Tevatron	LHC	factor
gg→H	800	50000	*60
qq→WH (w/lepton)	40	150	*4

gg→H→bb impossible at both due to QCD bbX (cross-section is 500 000 000 pb at LHC)

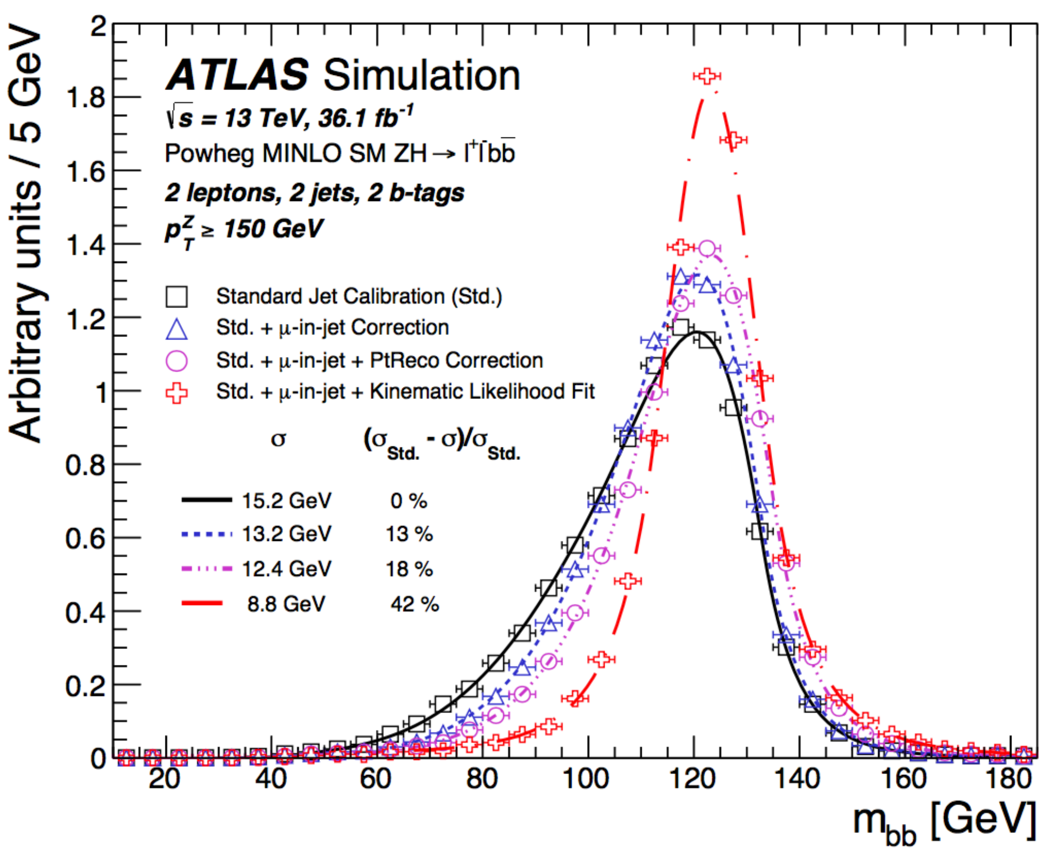
Signal bigger at LHC, but backgrounds much bigger

VH→V+bb

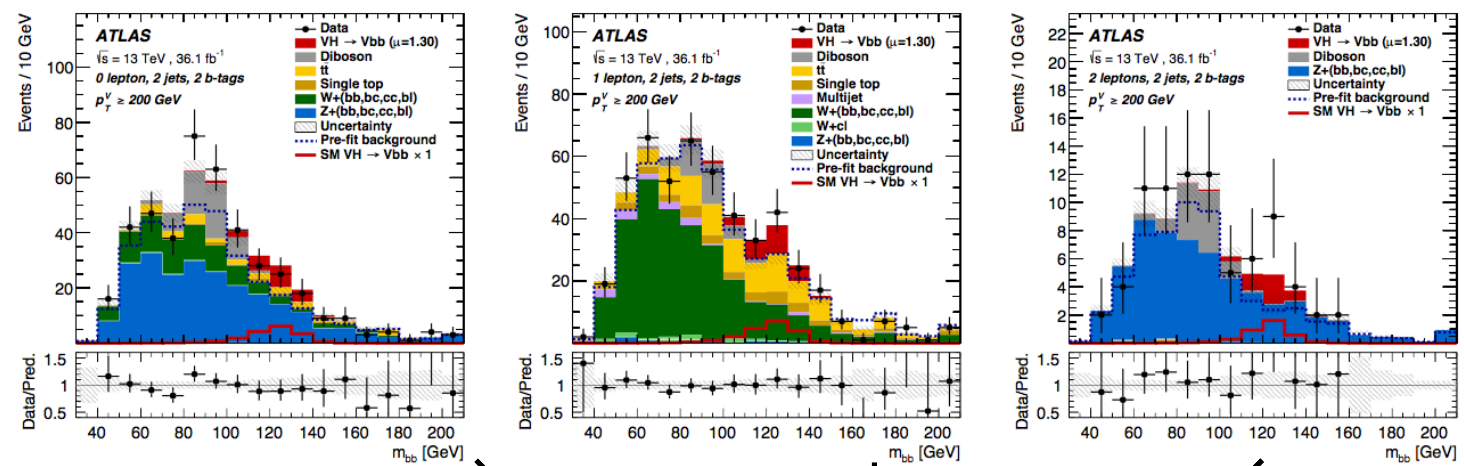
arXiv:1708.03299
10.1103/PhysRevLett.101.251803

Kinematic fit to get best Mbb mass for ZH→llbb

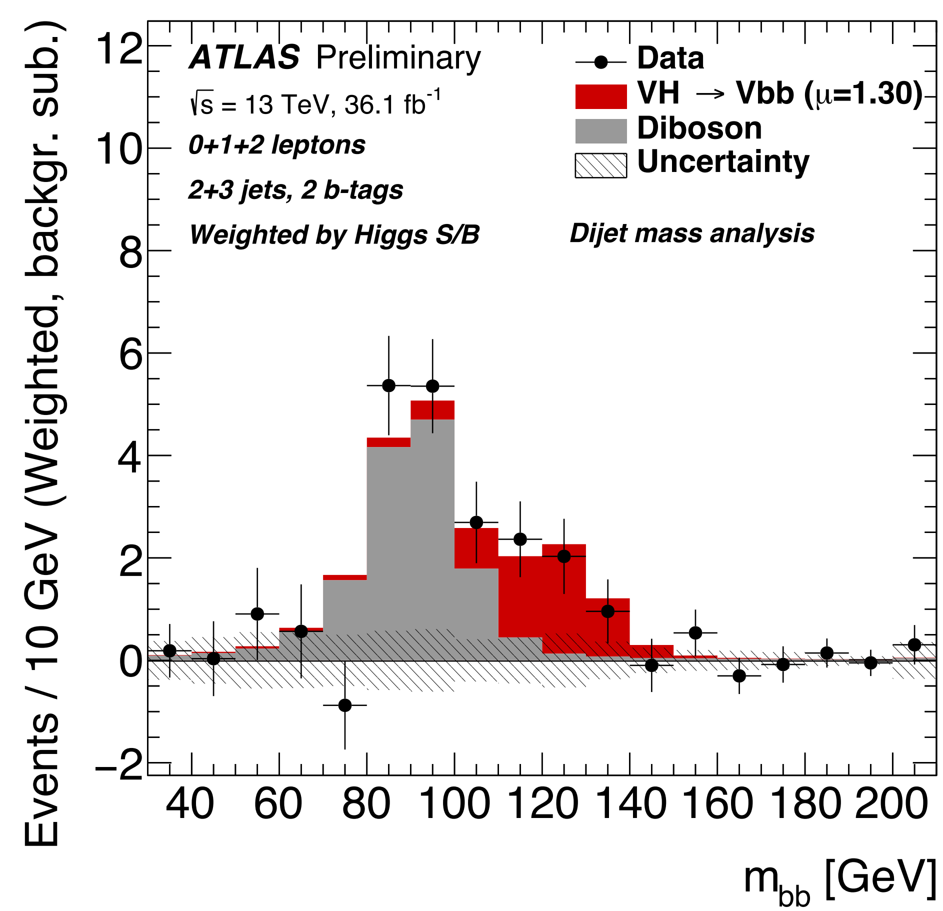
similar to technique developed at CDF



δM(bb)/M(bb) improved from 12% to 7% for ZH→llbb



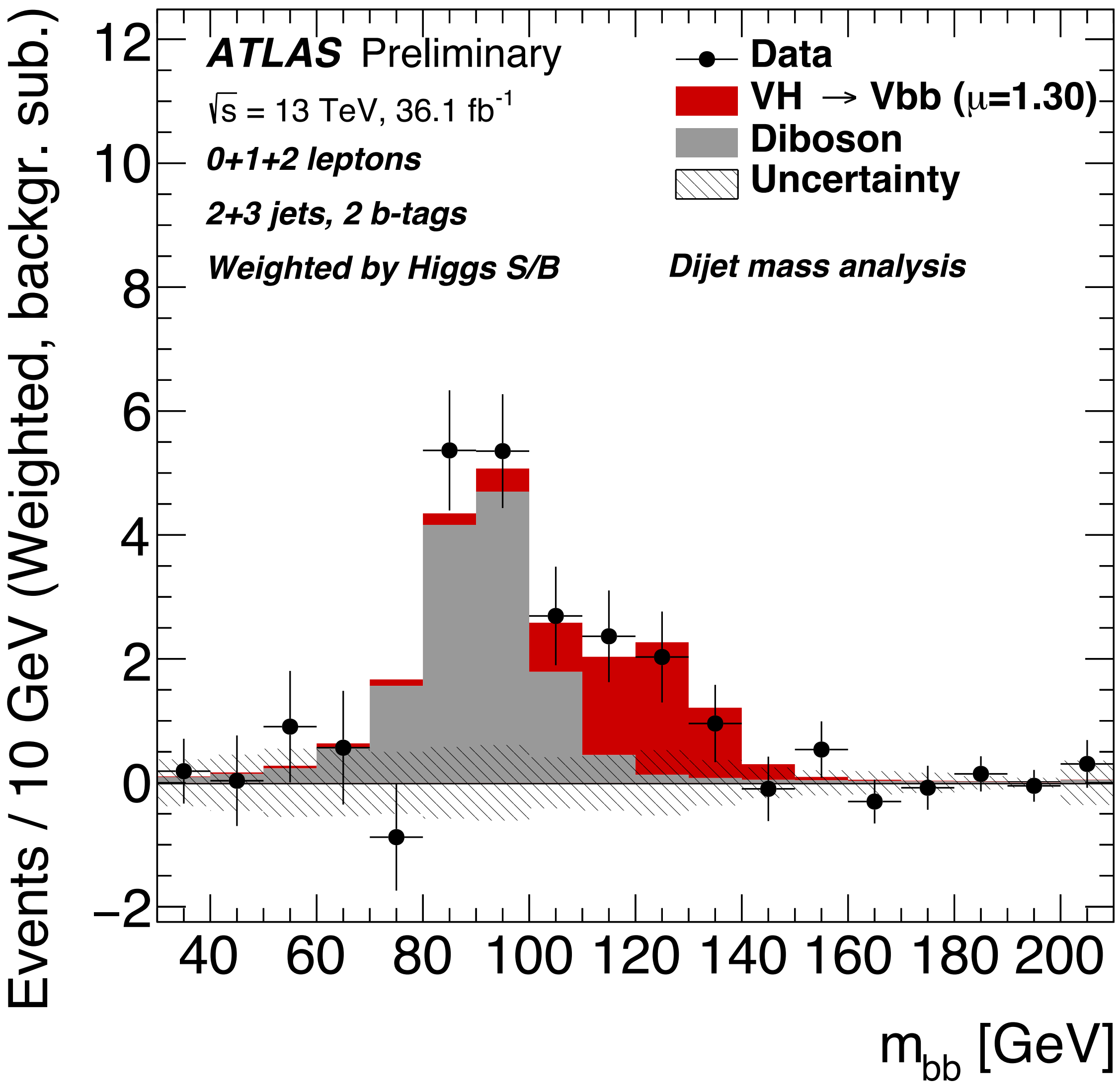
Combined, weighted M_{bb} after best fit



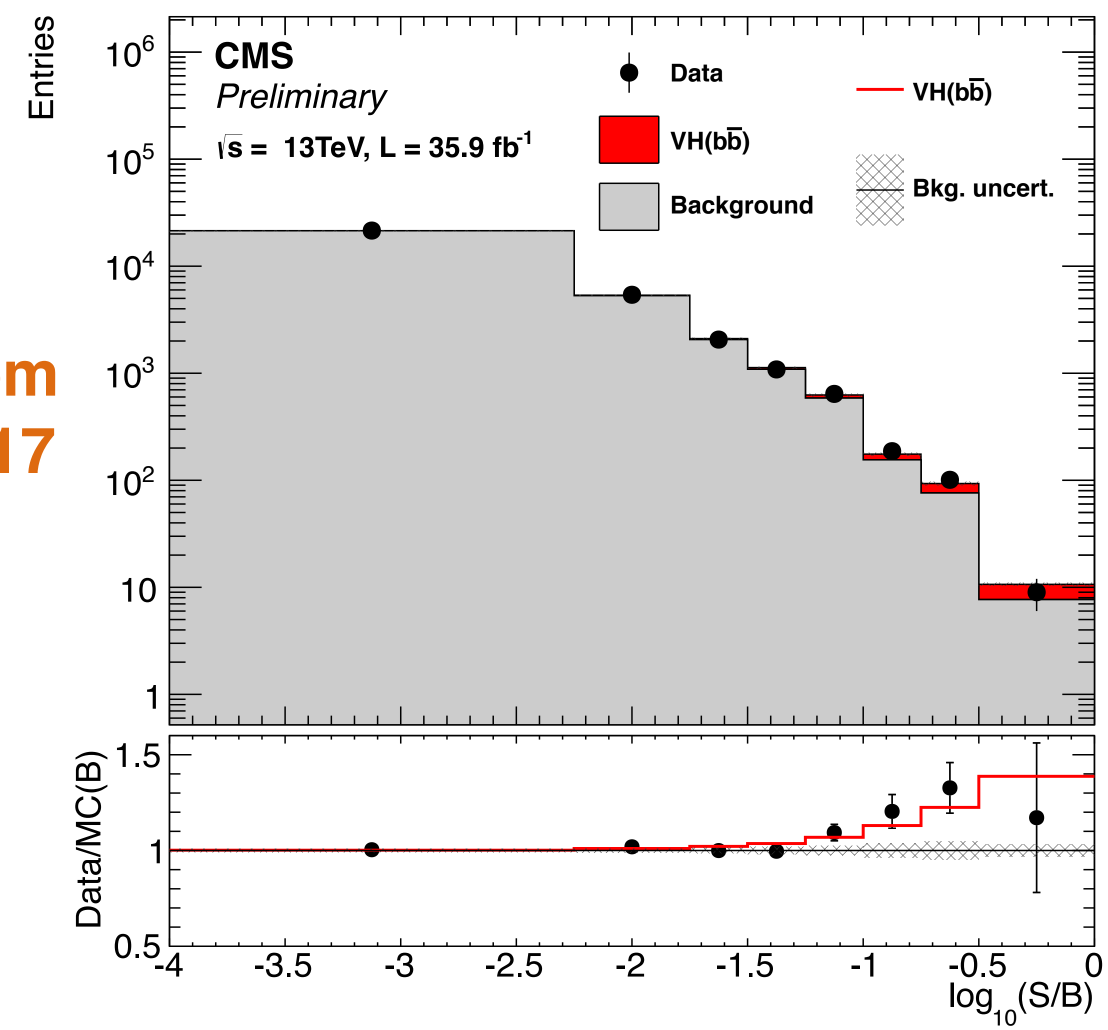
VH → V+bb

ATLAS_CONF-2017-041
CMS-PAS-HIG-16-044

- **2017 brought LHC evidence for H→bb finally**



Both from Aug. 2017



ATLAS : 3.5σ evidence observed (3.0 expected)

CMS: 3.3σ evidence observed (2.8 expected)

Run 1 + Run 2 : 3.6σ (4.0σ exp.)

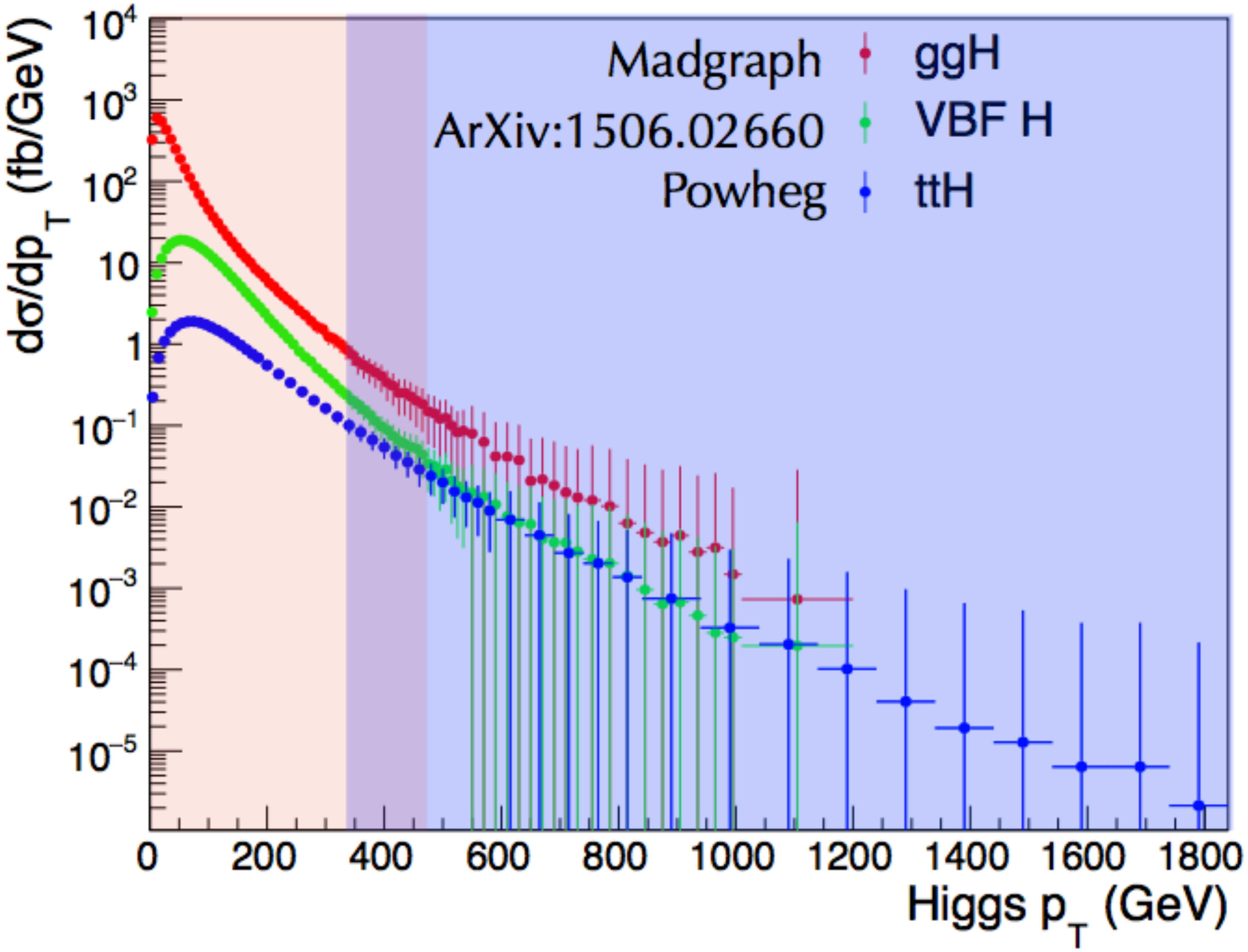
Run 1 + Run 2 : 3.8σ (3.8σ exp.)

>5σ ?

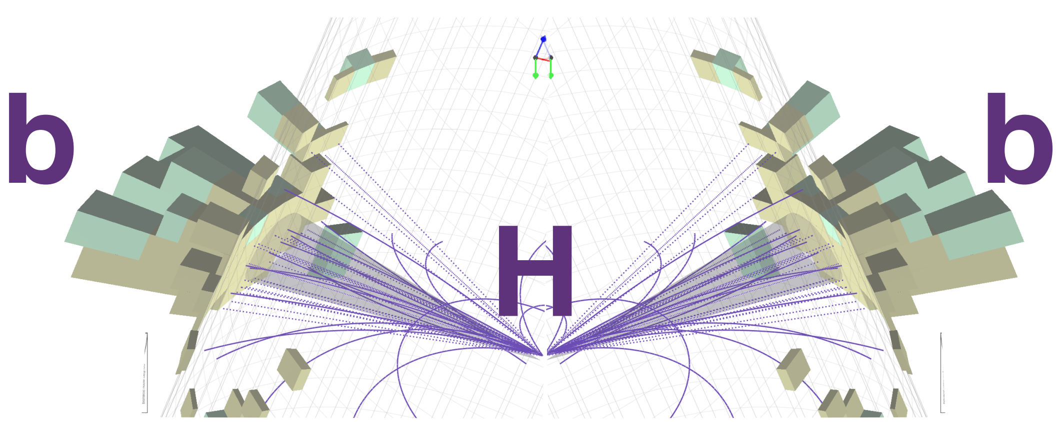
$gg \to H \to bb$

- Highest cross-section, highest branching ratio
  - $gg \to H \to bb$: $\sigma = 30\ 000$ pb
- However, highest background
  - QCD b prod. : $\sigma = 500\ 000\ 000$ pb
- And resolution is 5-10 times larger than for $\gamma\gamma$ & ZZ
  - $\delta M(bb)/M(bb) \sim 10\%$
- Conventional wisdom says impossible to find

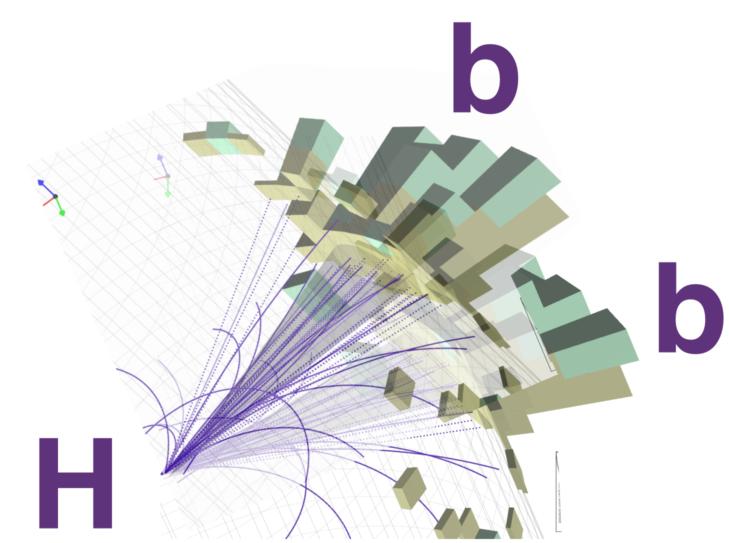
High-PT Higgs



High P_T Higgs bosons have boosted decay products



Low PT

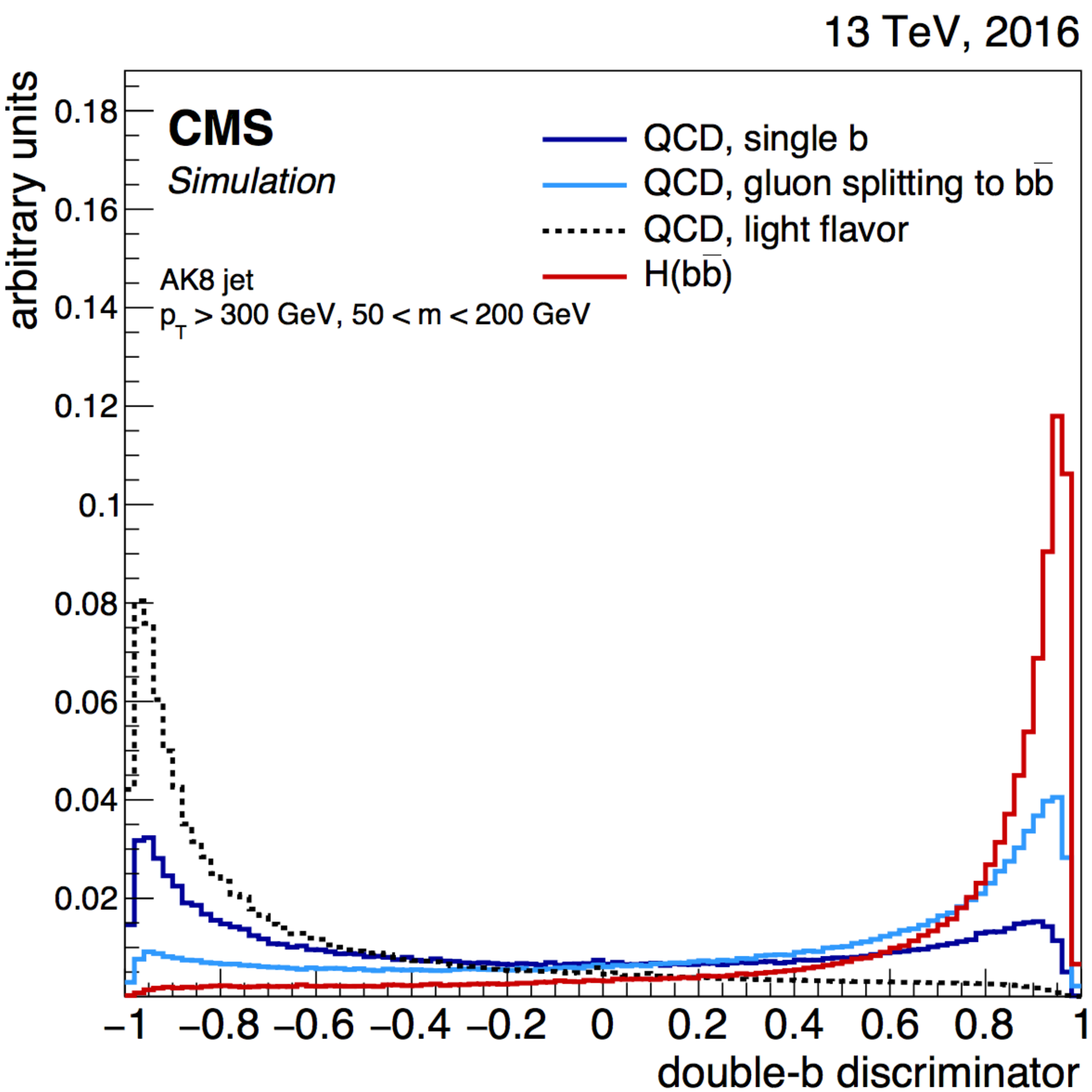


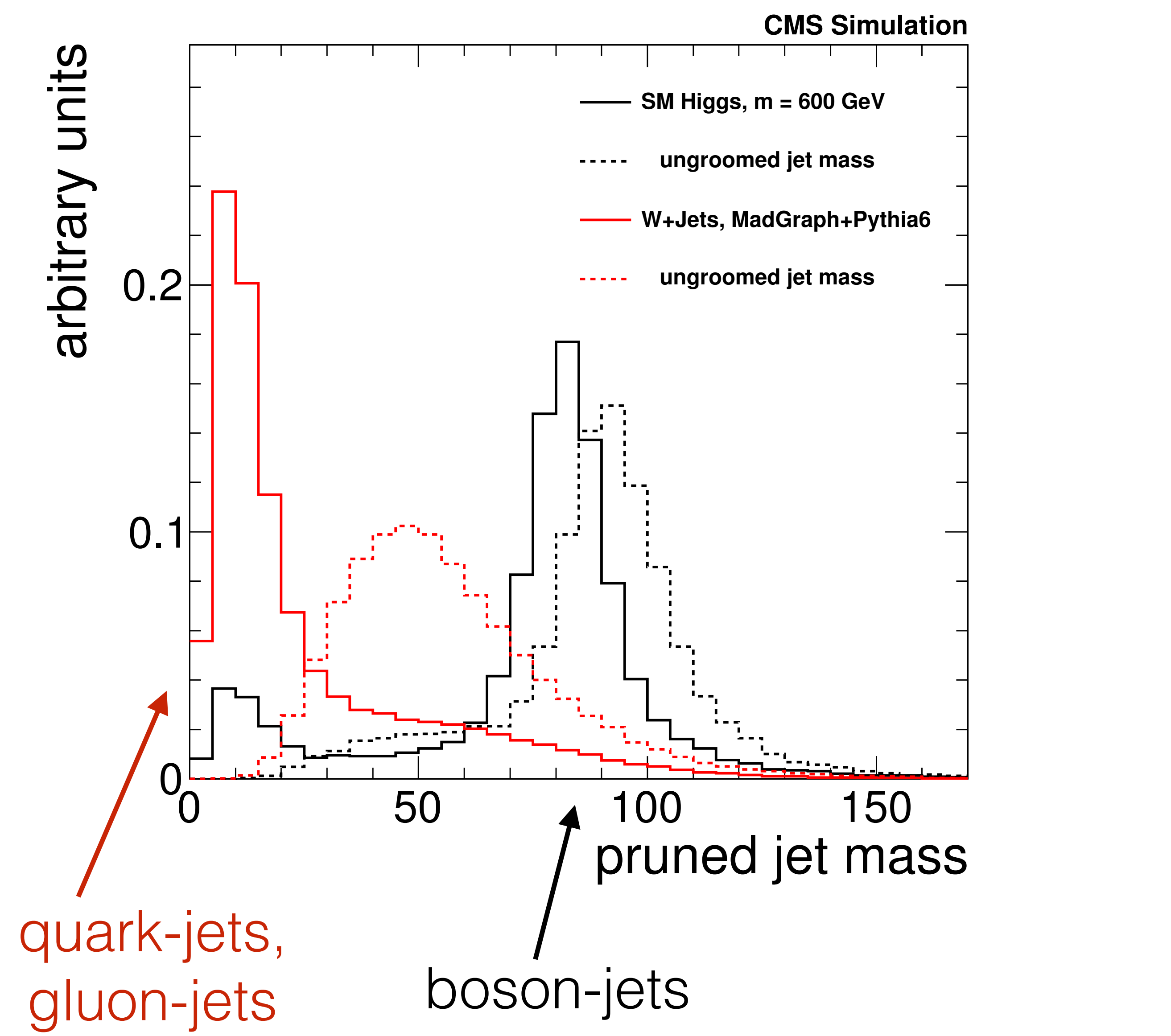
High PT

Identifying high P_T H→bb

JME-14-010

CMS-PAS-BTV-15-002





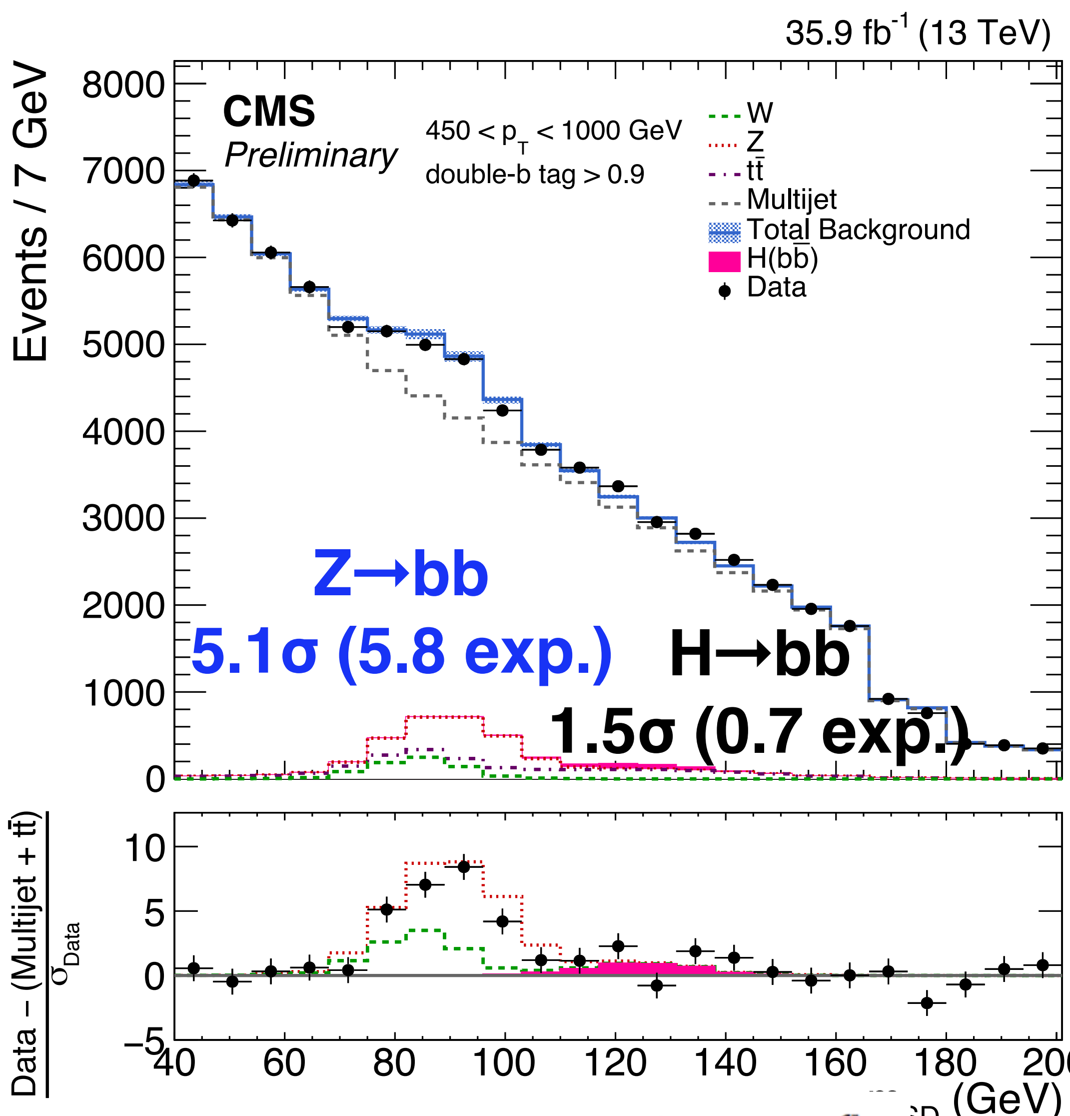
Tagging high P_T jets with two b's

Improving Mjj res. with softdrop algorithm

Search for gg→H→bb

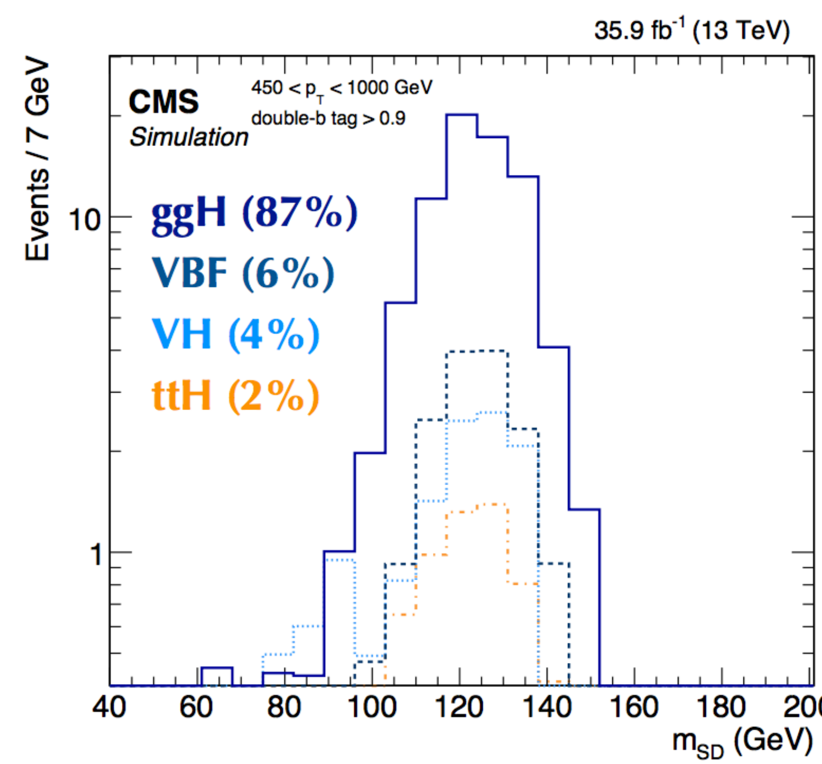
CMS-HIG-17-010

- **Selection keys on high-P_T (potential new physics) region**
  - **Trigger on high-PT ISR jet or high Σ(PT)**
  - **jets PT > 450 GeV, applying soft-drop mass, double-b tagger**



$\sigma_Z = 849 +257/-209$ fb

$\sigma_H = 74 +51/-49$ fb



Mostly gg→H→bb

Extrapolating … evidence could be possible with CMS+ATLAS by end of Run 3 !

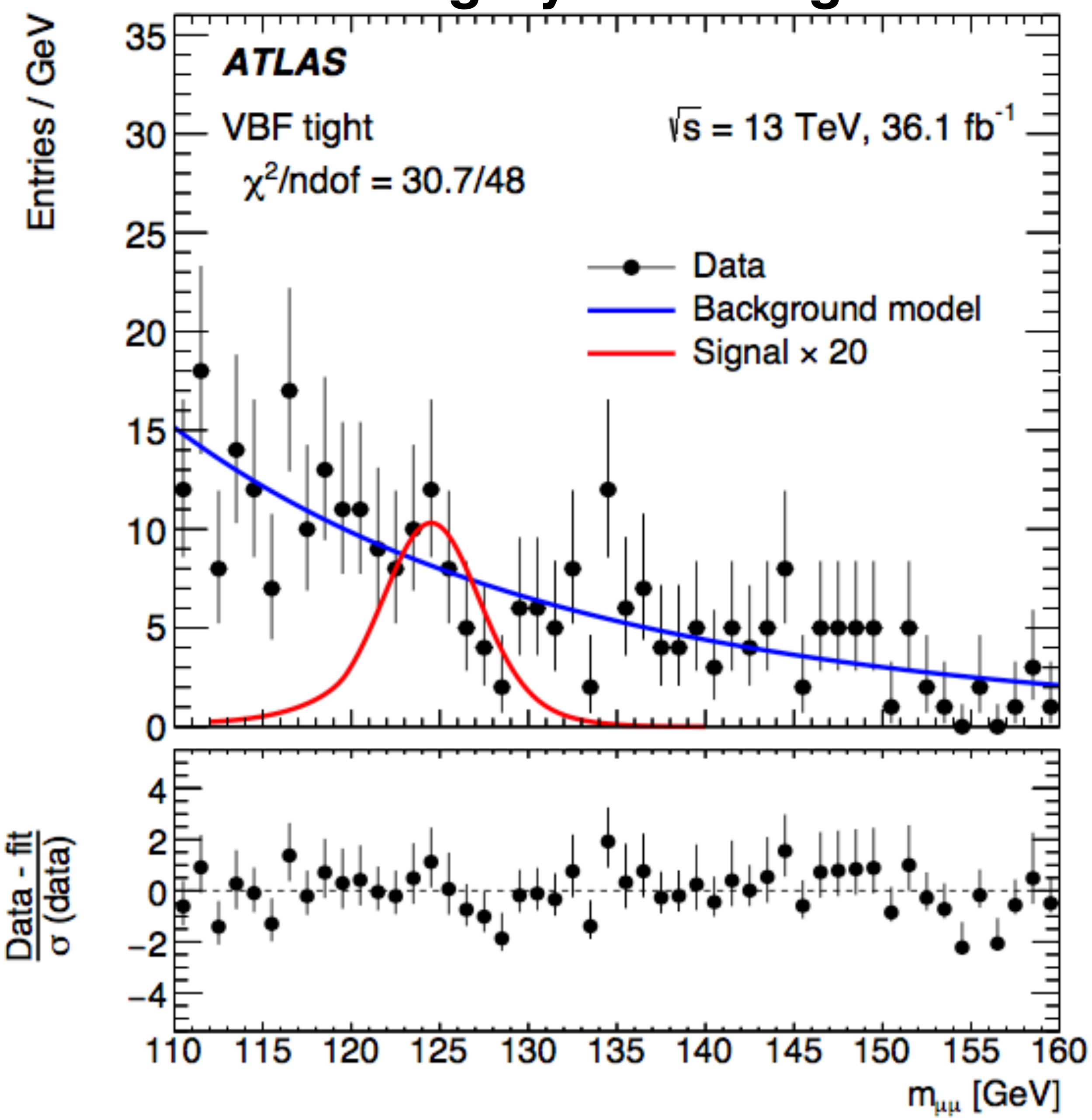
Coupling to 2nd generation

arXiv:1705.04582

- **SM BR(H→μμ) = 0.2%**
- **ATLAS analysis searches for all types of production modes**
  - Using all data : 5fb^{-1} 7 TeV, 20 fb^{-1} 8 TeV, 36 fb^{-1} 13 TeV
  - Split events into 8 categories, BDT to identify pure VBF category, then combined

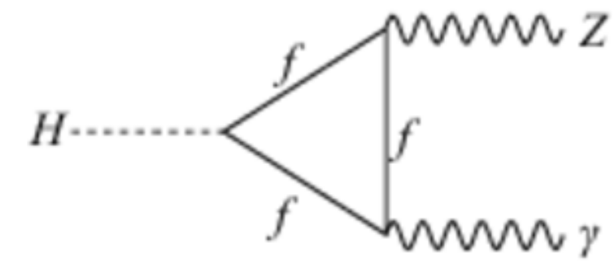
σ < 2.7*SM @ 95% CL

Highest-significance category : "VBF tight"



10X more data → 2σ significance → with CMS+ATLAS Run 2

Rare decays of the Higgs



Rare Higgs decay	CMS 95% CL limit	ATLAS 95% CL limit
$H \to Z\gamma$	< 9	< 6.6 NEW
$H \to J/\psi\gamma$	< 540	<540
$H \to ee$	$< 10^5$	
$H \to \rho\gamma$		< 52 NEW

Obtainable with < 1000 fb^{-1}

Probes 2nd generation quark couplings

Probes 1st generation couplings

Probes u,d,s quarks

Other possibilities :

VP mode	$\mathcal{B}^{SM}$	VP^* mode	$\mathcal{B}^{SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	2.2×10^{-6}

arXiv:1305.0663

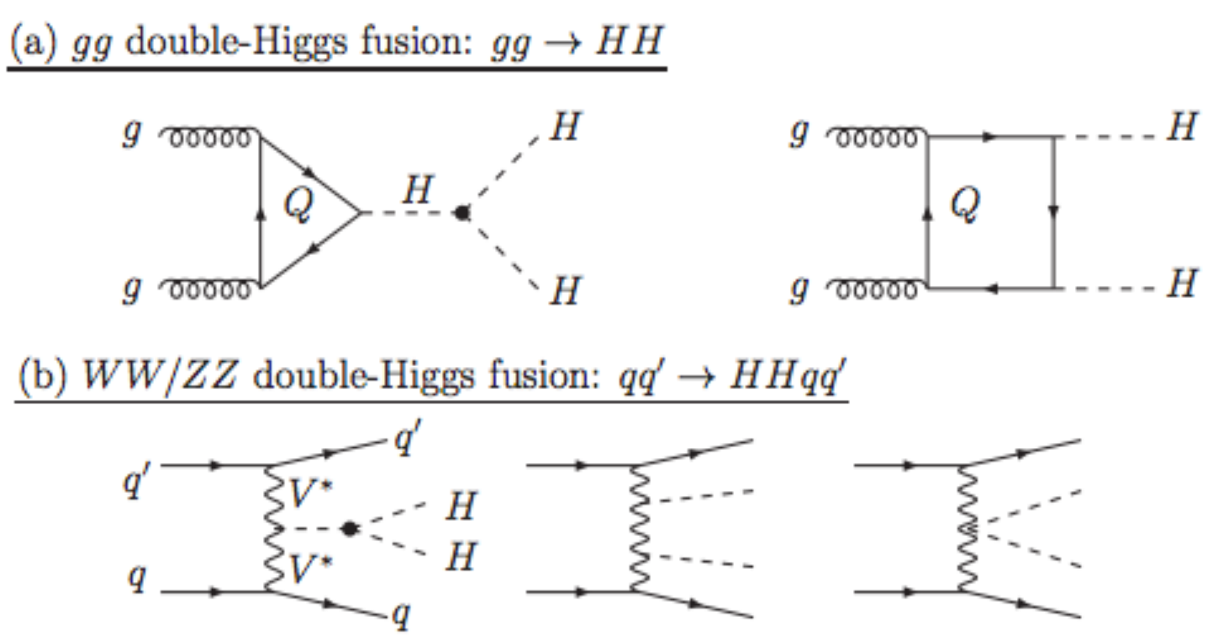
- **Observation in foreseeable future would mean new physics**

Double-Higgs production

Higgs potential with a physical Higgs boson

$$V(H) = \frac{1}{2}M_H^2 H^2 + \frac{1}{2}\frac{M_H^2}{v}H^3 + \frac{1}{8}\frac{M_H^2}{v^2}H^4 + \text{constant} \qquad \lambda_{HHH} = \frac{3M_H^2}{v}$$

Leading diagrams ~ 40 fb



120 000 HH with 3000 fb :

bb Channels	Nevts
bbbb	39,951
bbWW	14,886
bb2lep (e/mu)	85
bbtautau	4,375
bbZZ	1,827
bb4lep (e/mu)	9
bb2lep+X	131
bbgamgam	158

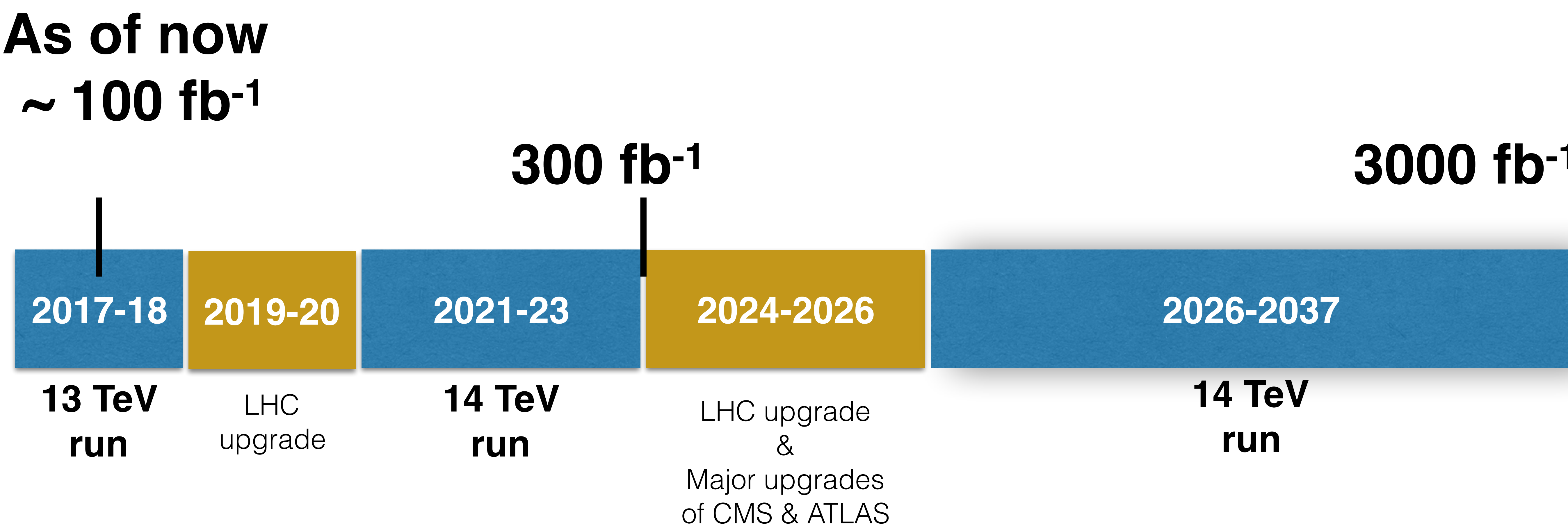
Considered so far by CMS+ATLAS

Best limit so far CMS with **19*SM** using 36 fb^{-1}

Score card

Channel	Result CMS and/or ATLAS
Decay	
H→ZZ	**Observed**
H→γγ	**Observed**
H→WW	**Observed**
H→ττ	**Observed**
H→bb	**Evidence**
H→μμ	95% CL - end of Run 2
Production	
gg→H	**Observed**
VBF	**Observed (in combination)**
ttH	Close to evidence
VH	**Evidence**
HH	end of Run HL-LHC
Global properties	
Uncertainty on global fit	**10%**
Mass	**0.2%**
Spin, parity	0^{++} strongly preferred

Future


As of now
~ 100 fb-1
300 fb-1
3000 fb-1
2017-18
2019-20
2021-23
2024-2026
2026-2037
13 TeV
run
LHC
upgrade
14 TeV
run
LHC upgrade
&
Major upgrades
of CMS & ATLAS
14 TeV
run

Goals for Run 2 Higgs program

- **Reestablish $H\to ZZ$, $H\to\gamma\gamma$, $H\to WW$**
- **Establish fermionic couplings**
  - **$H\to bb$**
  - **$H\to\tau\tau$ (not yet observed by a single experiment)**
  - **ttH**
- **More precise Higgs couplings**
  - **Coupling deviations from SM expectations ↔ new physics**
    - For a new mass scale of 1 TeV
      - Composite Higgs -> Couplings change ~3%
      - SUSY (tanβ=5) -> $H\to bb$, $H\to\tau\tau$ ~2%
      - Top partners -> ggH ~3%
- **Investigate rare decays that could be enhanced by new physics**
- **Reduce theory uncertainties by measuring in carefully constructed signal regions …**
  - **Identify signal regions more sensitive to new physics**
- **Differential cross-section measurements**

Conclusions

- **Reestablish H→ZZ, H→γγ, H→WW**

ZZ, γγ observed, WW on its way

- **Establish fermionic couplings**
  - **H→bb**
  - **H→ττ (not yet observed by a single experiment)**
  - **ttH**

bb evidence from both experiments, ττ observed, ttH close

- **More precise Higgs couplings**
  - **Coupling deviations from SM expectations ↔ new physics**
    - For a new mass scale of 1 TeV
      - Composite Higgs -> Couplings change ~3%
      - SUSY (tanβ=5) -> H→bb, H→**ττ** ~2%
      - Top partners -> ggH ~3%

Rare channels considered including (μμ, ργ)

- **Investigate rare decays that could be enhanced by new physics**
- **Reduce theory uncertainties by measuring in carefully constructed signal regions …**
  - **Identify signal regions more sensitive to new physics**

Implemented signal template cross section method

- **Differential cross-section measurements**

Differential ZZ, γγ measurements

Conclusions 2

- **We know the answer (125 GeV)**
- **Now we just need to know the question …**

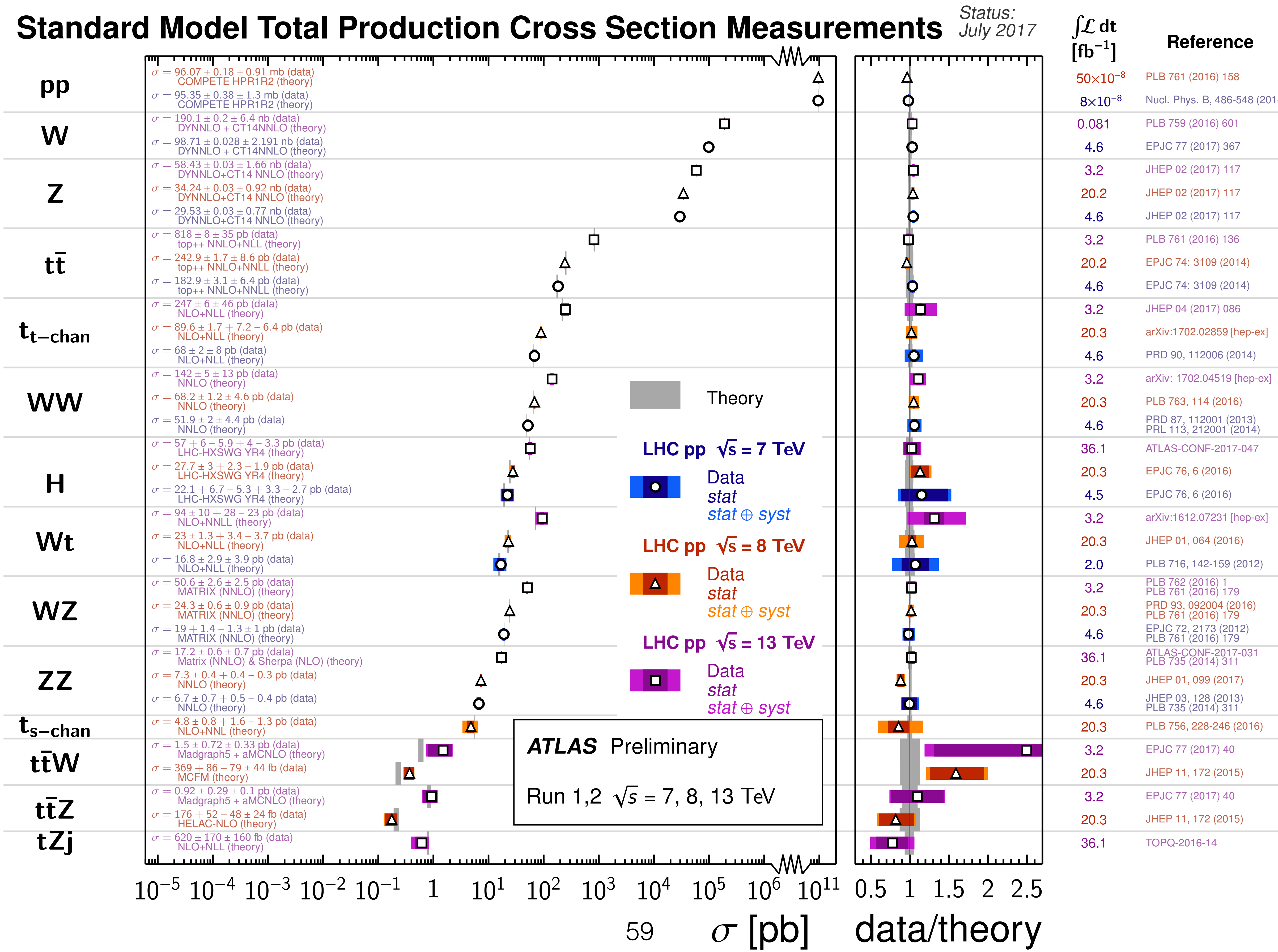
BACKUPS

Theory approximations

$$
\begin{aligned}
48.58\,\text{pb} = \quad & 16.00\,\text{pb} && (+32.9\%) && (\text{LO, rEFT}) \\
& +20.84\,\text{pb} && (+42.9\%) && (\text{NLO, rEFT}) \\
& -\ \ 2.05\,\text{pb} && (-4.2\%) && ((t,b,c),\ \text{exact NLO}) \\
& +\ \ 9.56\,\text{pb} && (+19.7\%) && (\text{NNLO, rEFT}) \\
& +\ \ 0.34\,\text{pb} && (+0.7\%) && (\text{NNLO},\ 1/m_t) \\
& +\ \ 2.40\,\text{pb} && (+4.9\%) && (\text{EW, QCD-EW}) \\
& +\ \ 1.49\,\text{pb} && (+3.1\%) && (\text{N}^3\text{LO, rEFT})
\end{aligned}
$$

- rEFT : approximation from EFT scaled by R_{LO} which scales to the exact LO cross-section
- t,b,c mass effects from top, bottom, charm quarks
- $1/m_t$: heavy top approximation with expansion in $1/m_t$

How do the SM measurements fit together ?



How does the SM **theory** fit together ?