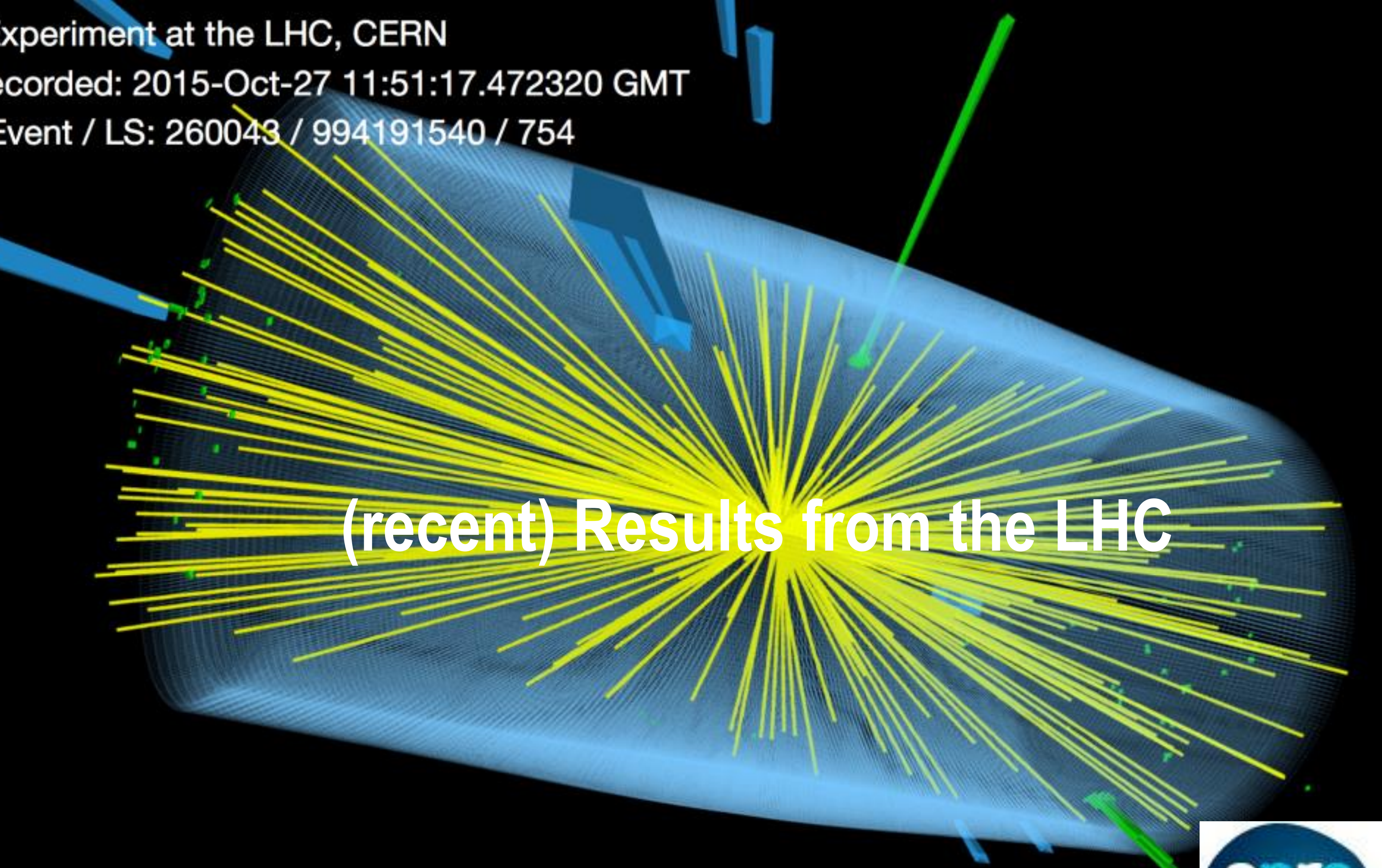


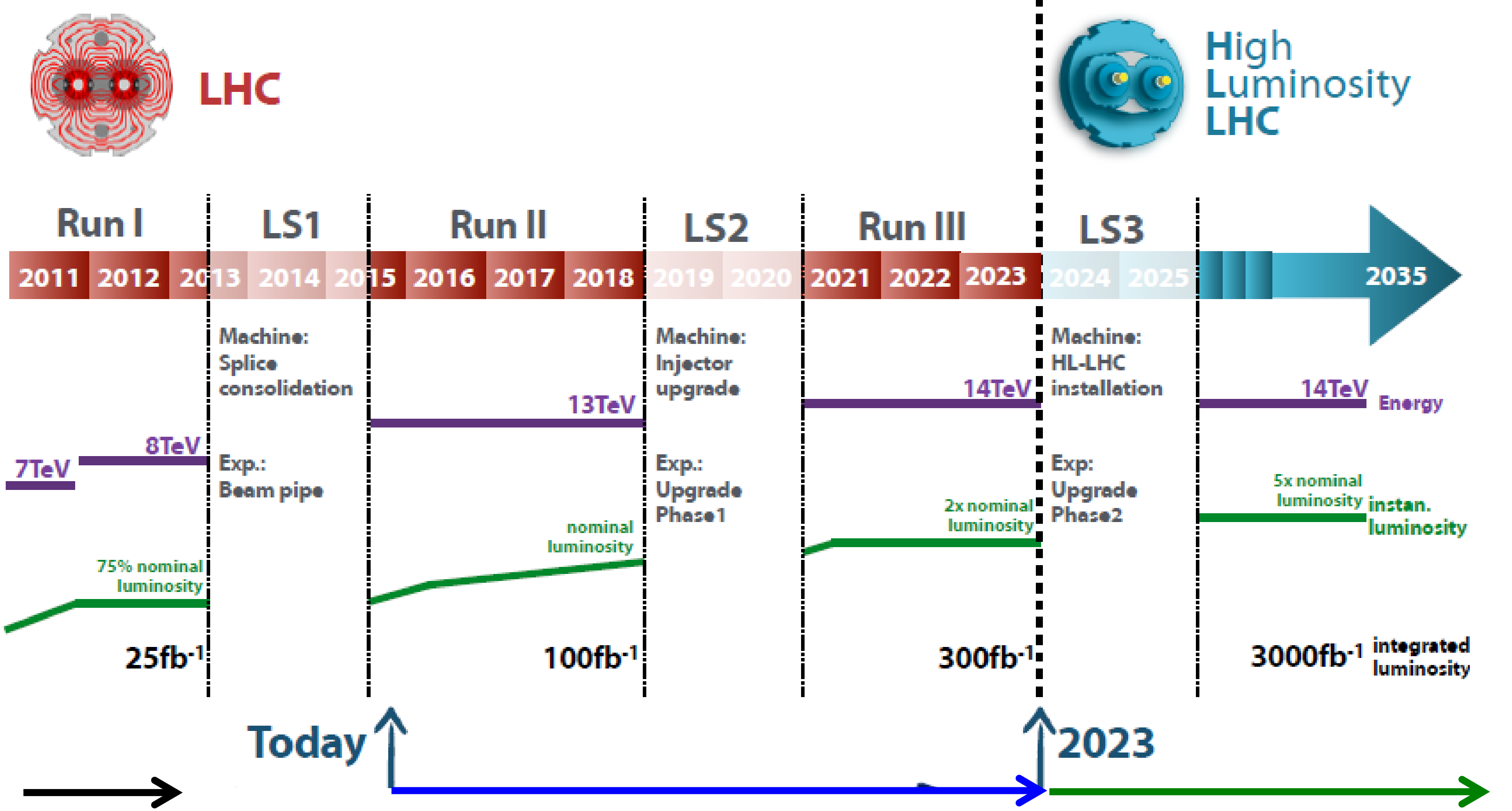
(recent) Results from the LHC

Christophe Ochando
(LLR/Ecole Polytechnique/CNRS)

March 24th 2016
4e Journée Collisionneur Linéaire

Introduction

- (short) Overview of (some) LHC results (top, Higgs, BSM)
- Obviously cannot cover everything…
- Focus on Run I (7-8 TeV, 25 fb-1) and Run II (13 TeV, 2-3 fb-1)
  + perspectives up to ~2018, where major decisions could occur for the future of HEP



"Phase 0"

Additional pp interactions (Pile-Up): <PU> ~20

Phase I

<PU> ~50

2x nominal lumi

x10 Run I statistics

Phase II (HL-LHC, >2025)

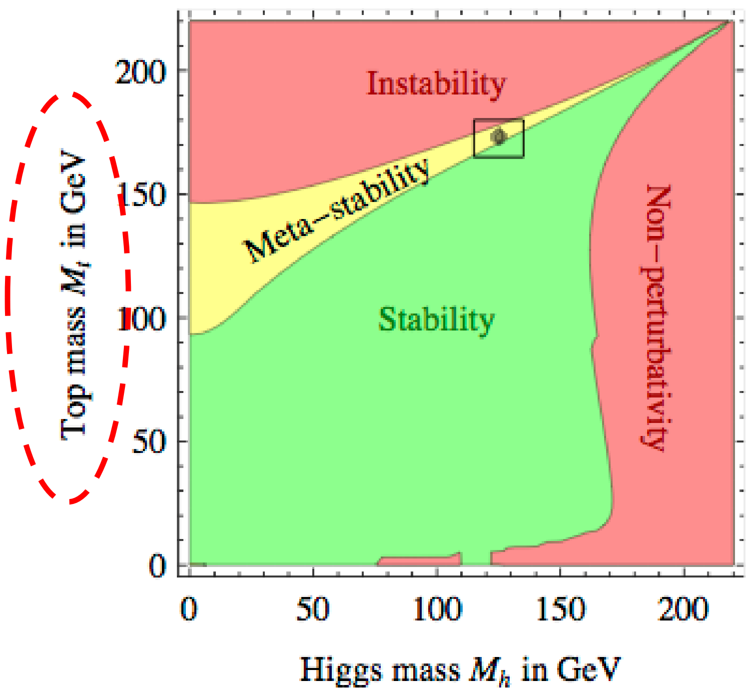
<PU> ~140-200

x100 Run I statistics

Top Physics at LHC

Top Quark

- Heaviest known fundamental particle,
- Privileged coupling to Higgs
- Critical role in EWSB, NP, …

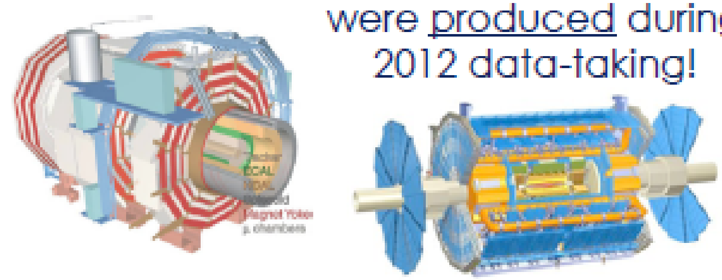


Era of Precision Top Quark Measurements

At peak instantaneous luminosities @ **ATLAS** & **CMS**:

~**2** top pairs/sec (per experiment)
~**1** single top/sec

were produced during 2012 data-taking!



Overall from **both** experiments combined:

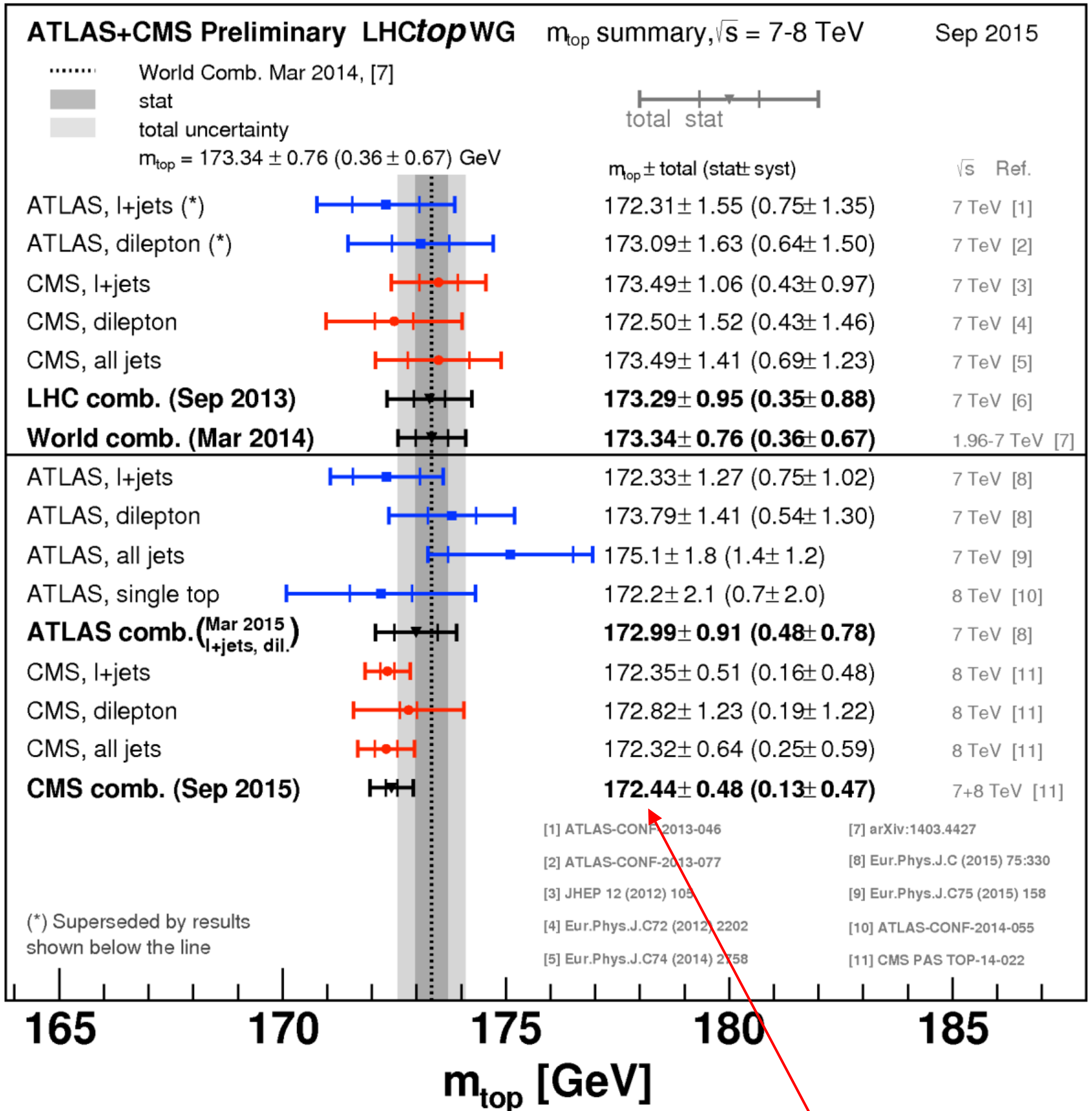
~**4M** top quarks produced in 2011 (**√s = 7 TeV**)
~**24M** top quarks produced in 2012 (**√s = 8 TeV**)
~**13M** top quarks produced in 2015 (**√s = 13 TeV**)

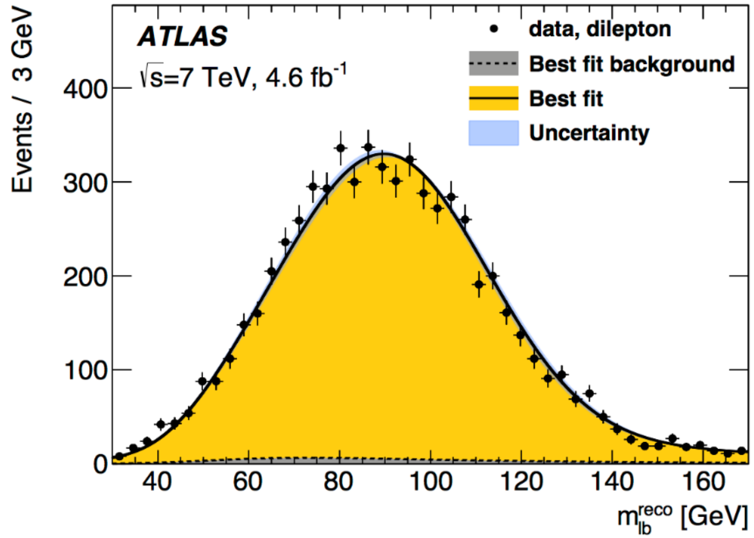
Cross-section values taken from:
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO

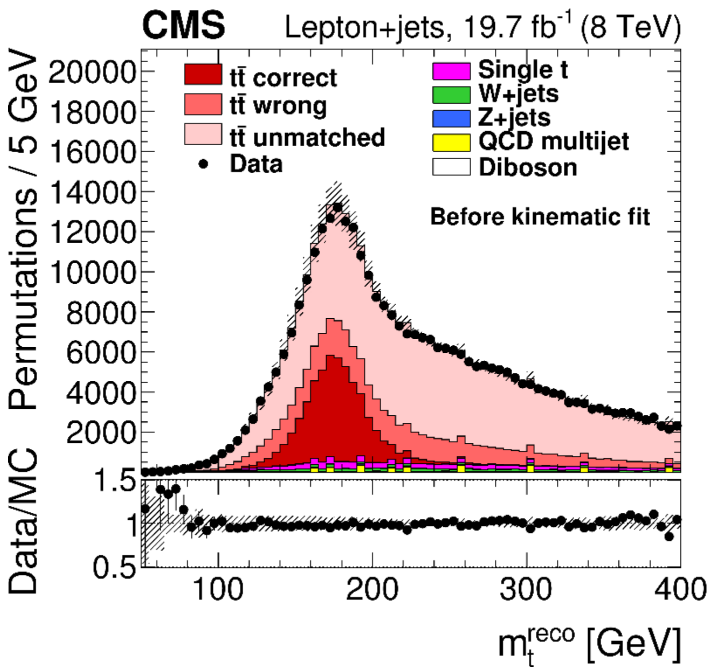
➢ **Very rich physics program:**
- Mass, (inclusive or differential) Cross sections,
- Spin correlations, polarization, charge asymmetry, FCNC, W helicity, …
- ttbar resonances
- tt+V

Search for NP (directly or not)

Top Quark Mass (LHC)



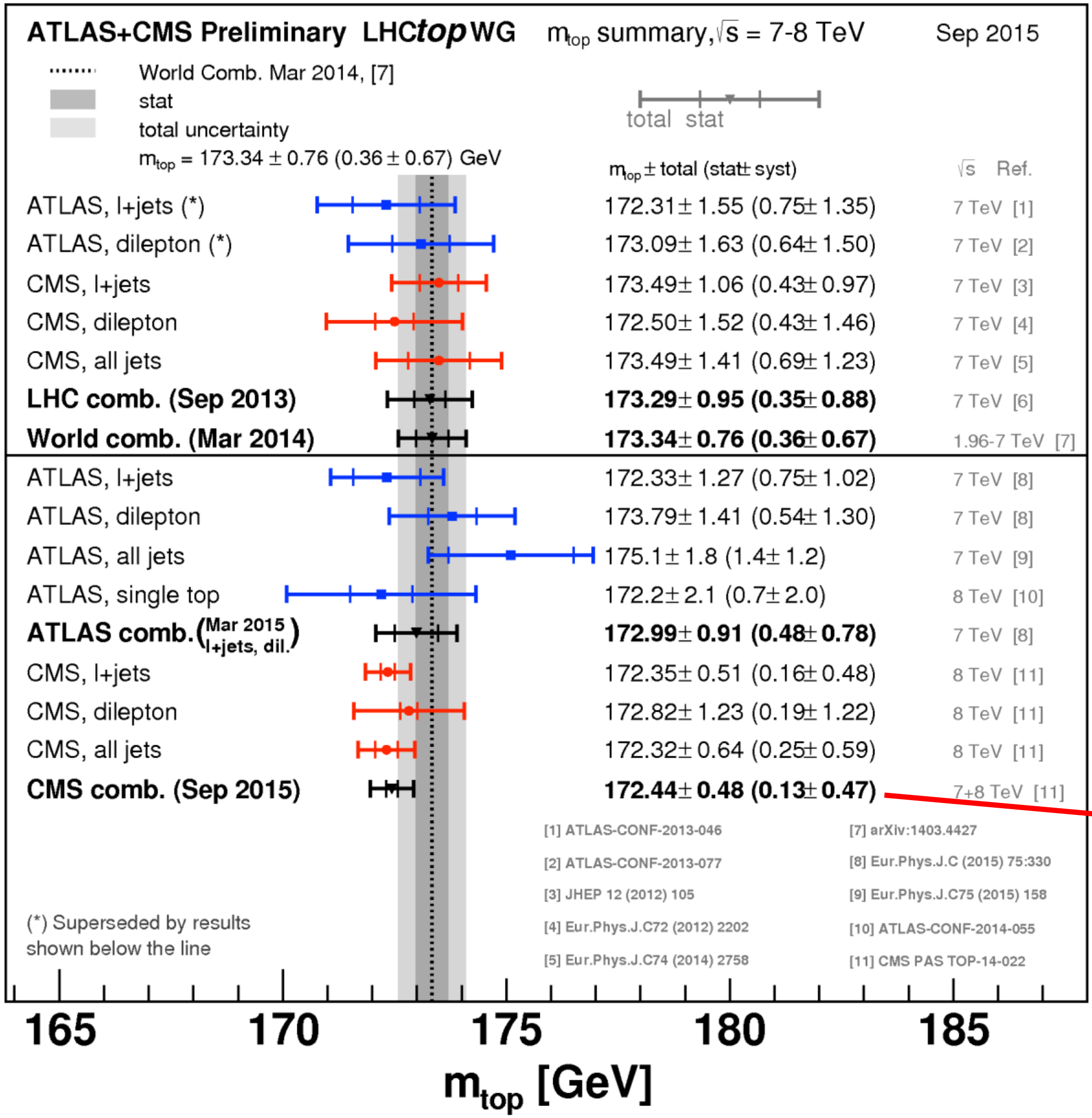


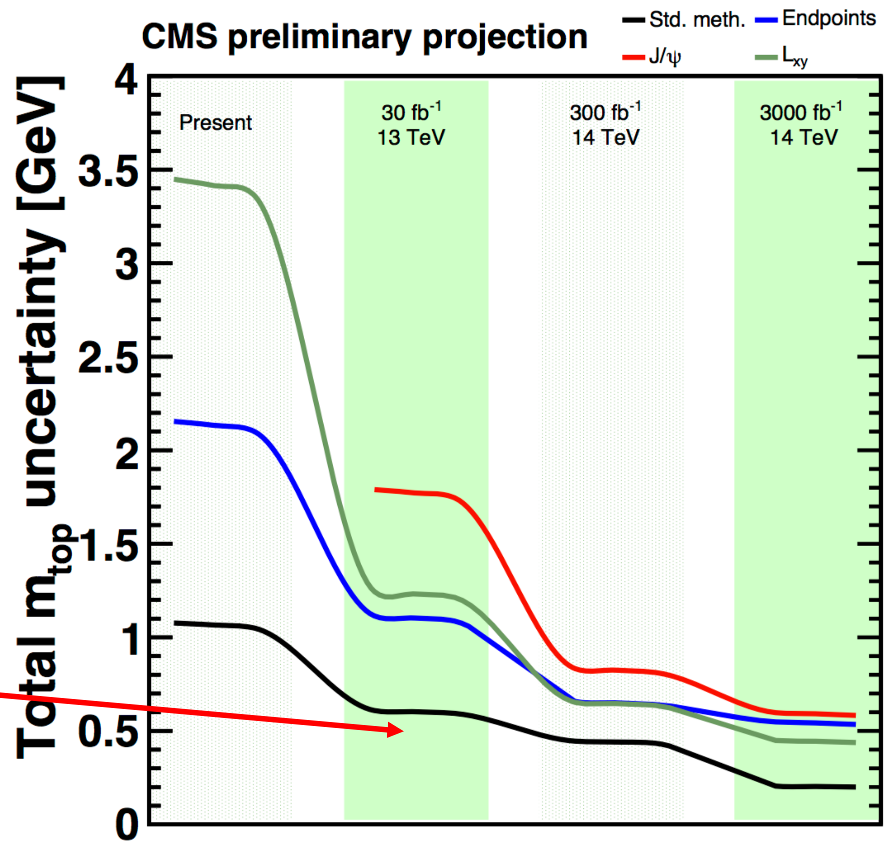


0.3% precision !

Dominated by systematics
(Jet Energy Scale, b-quark fragmentation)

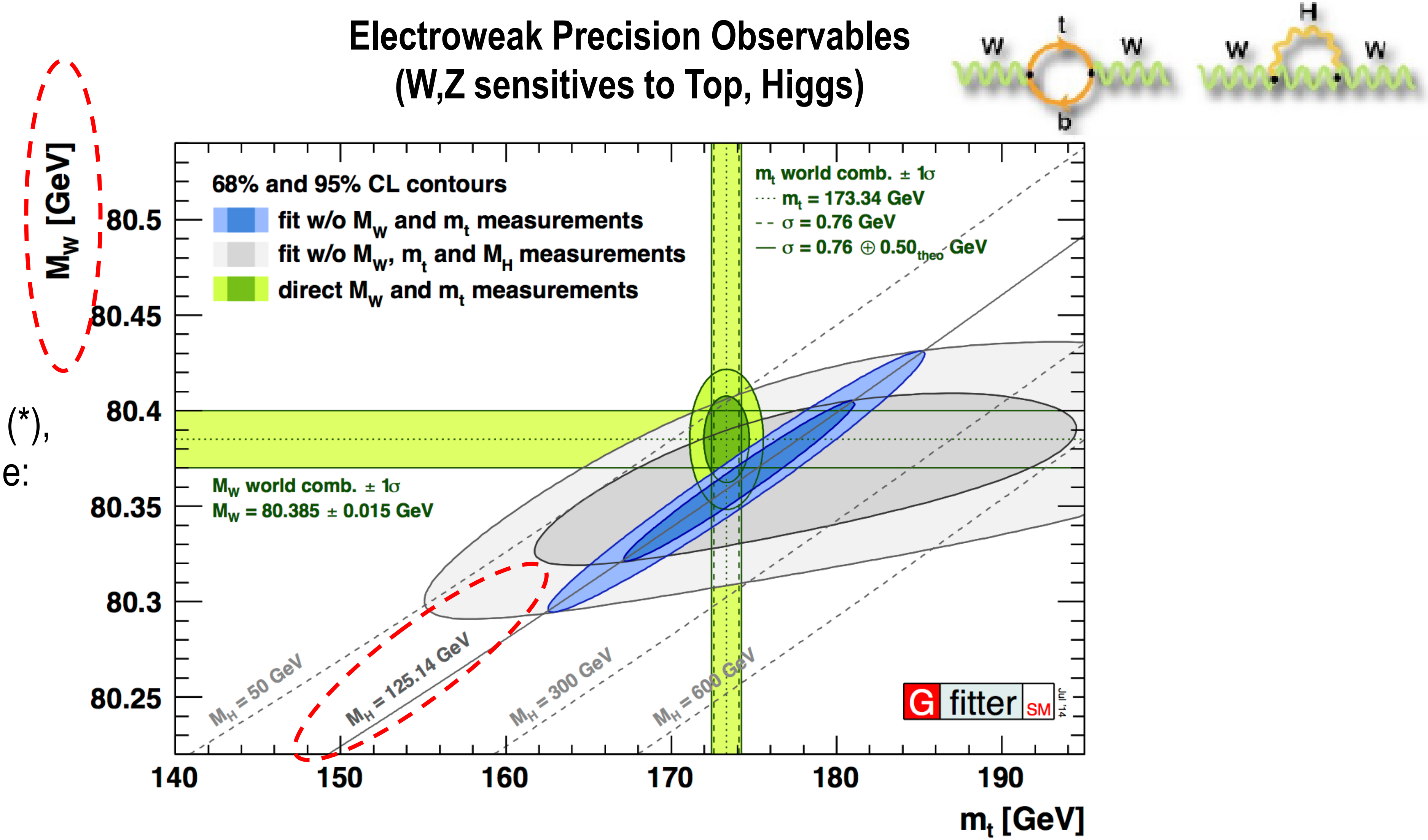
Top Quark Mass (LHC)





Already ahead of projections !

M_W vs M_{top}



- CDF 19 MeV (*),
- World average:
  15 MeV (**)

(*) Tevatron measurement with FULL dataset to come

(**) Indirect constraints now superior to some precise direct W, Z measurements

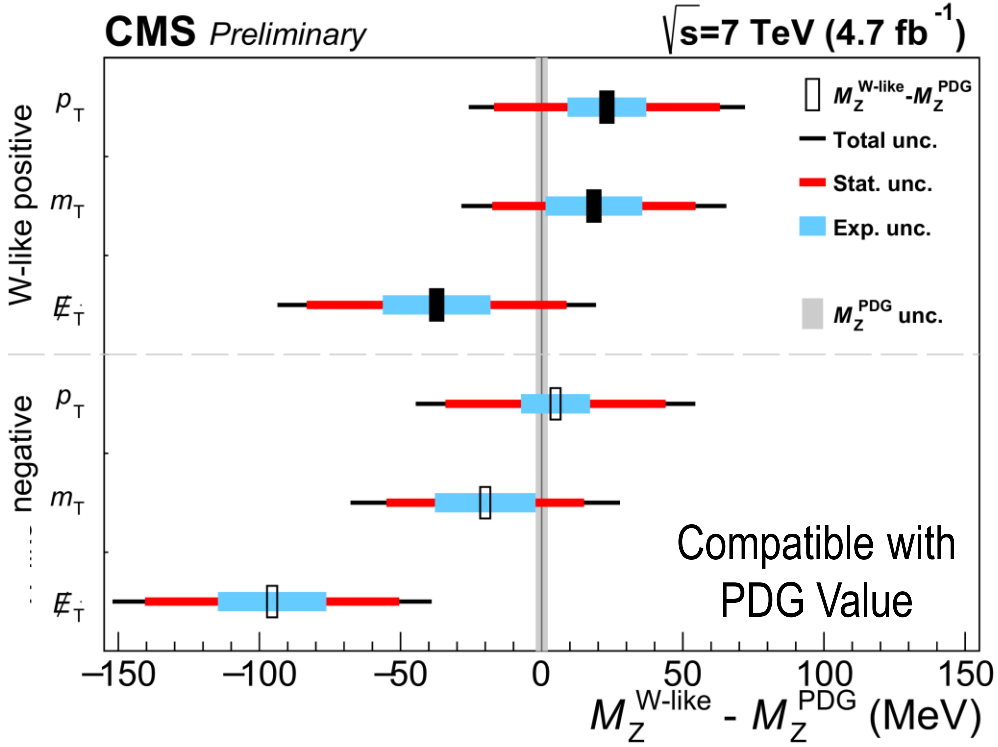
Indirect (EWK fit): $M_W = 80.359 \pm 0.011$

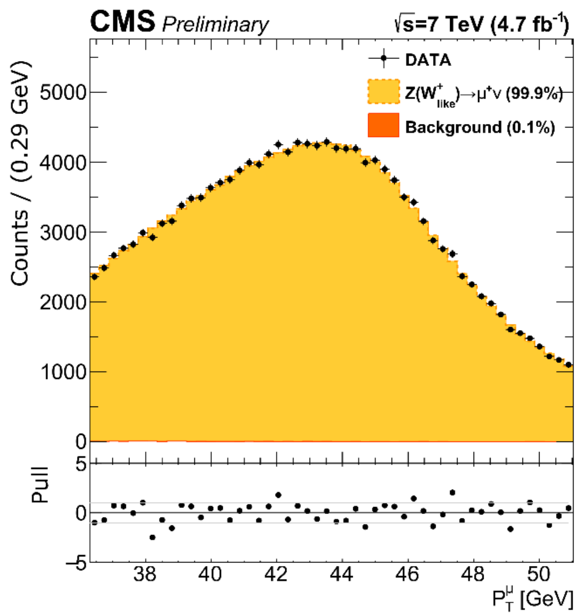
Direct (World average): $M_W = 80.385 \pm 0.015$

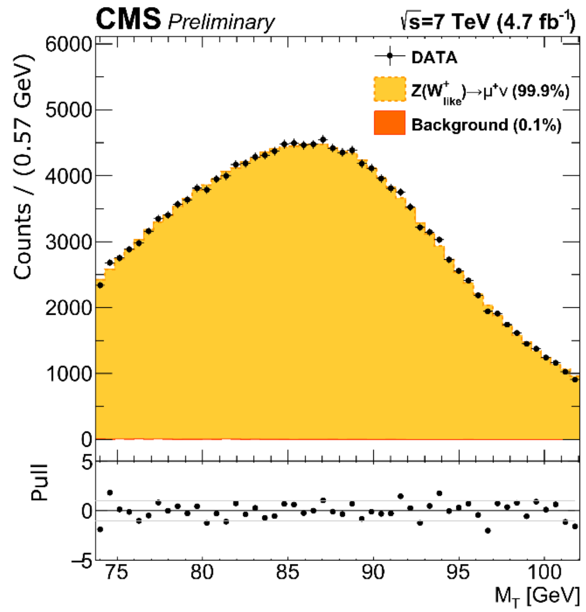
M_W: LHC enters the game !

Start with W-like measurement of the Z mass in muon channel
(replacing one muon by recomputed MET)

- Proof of principle analysis
- Quantitative validation of analysis techniques
  - 7 TeV dataset (low PU)
  - Scale/Resolution from low mass resonances
  - Several observables (pT_{μ}, M_T, MET)



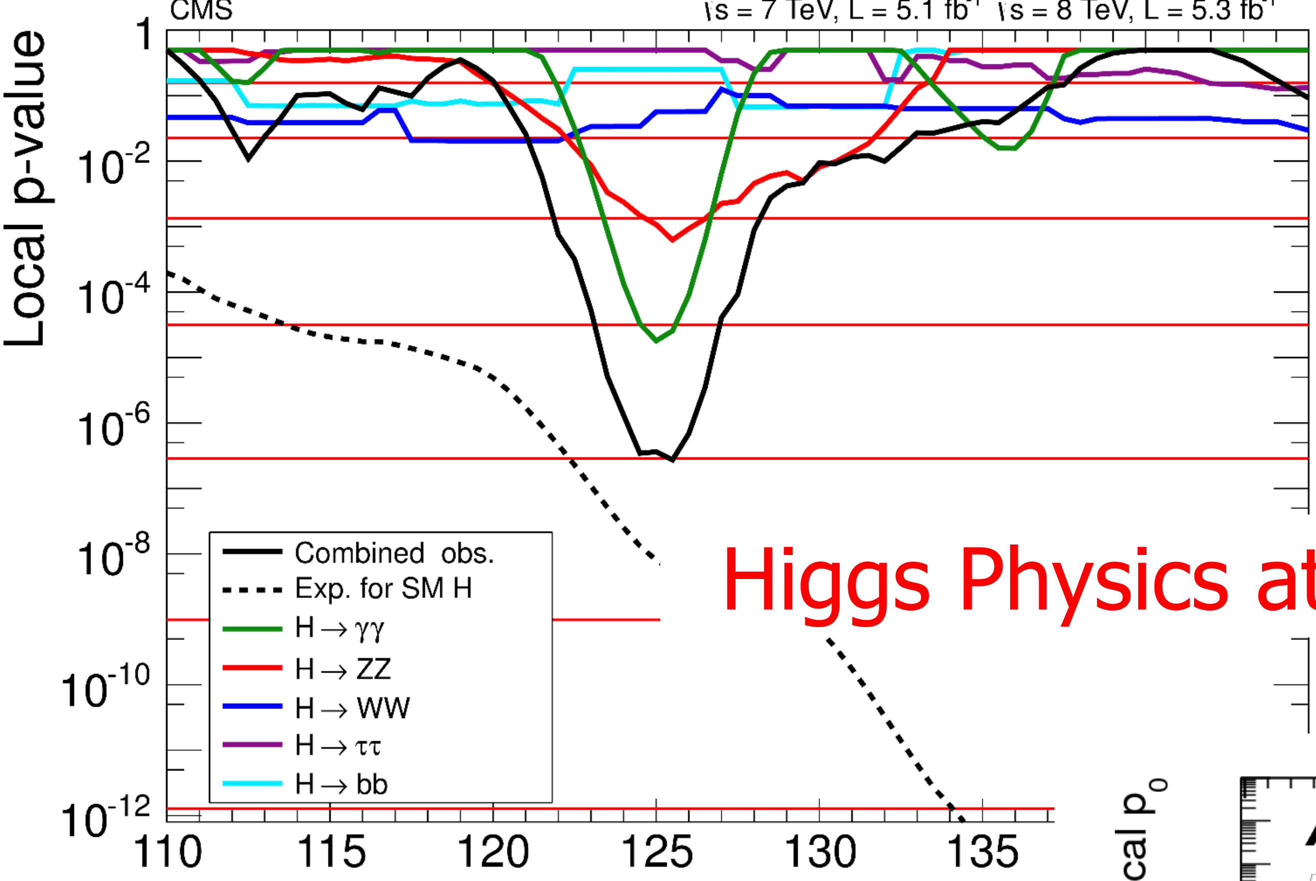


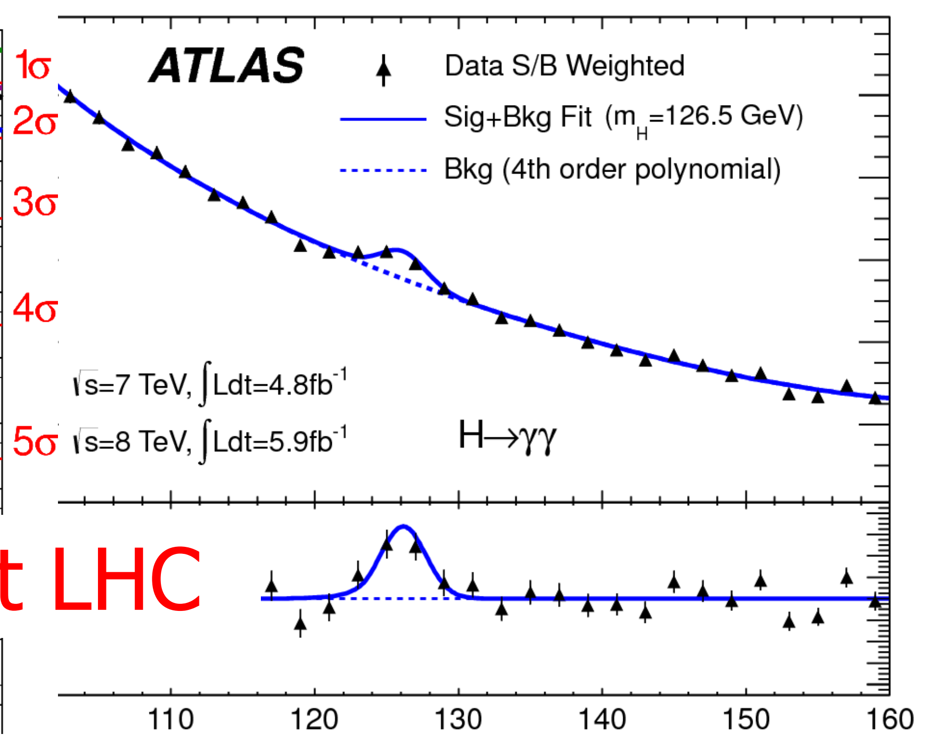


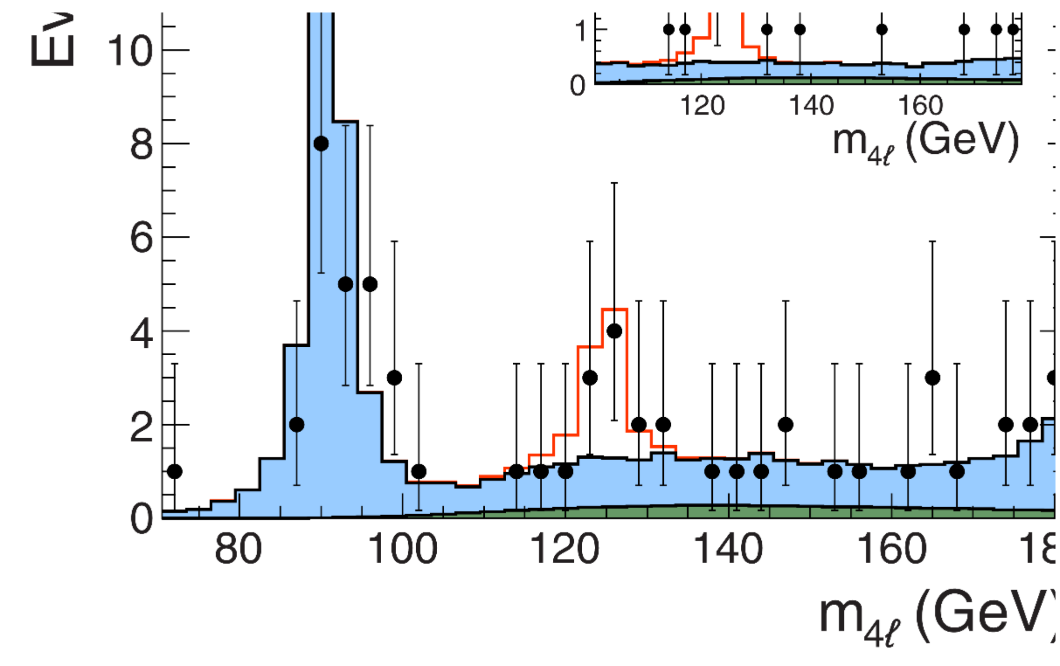
Results (depending on observable used):

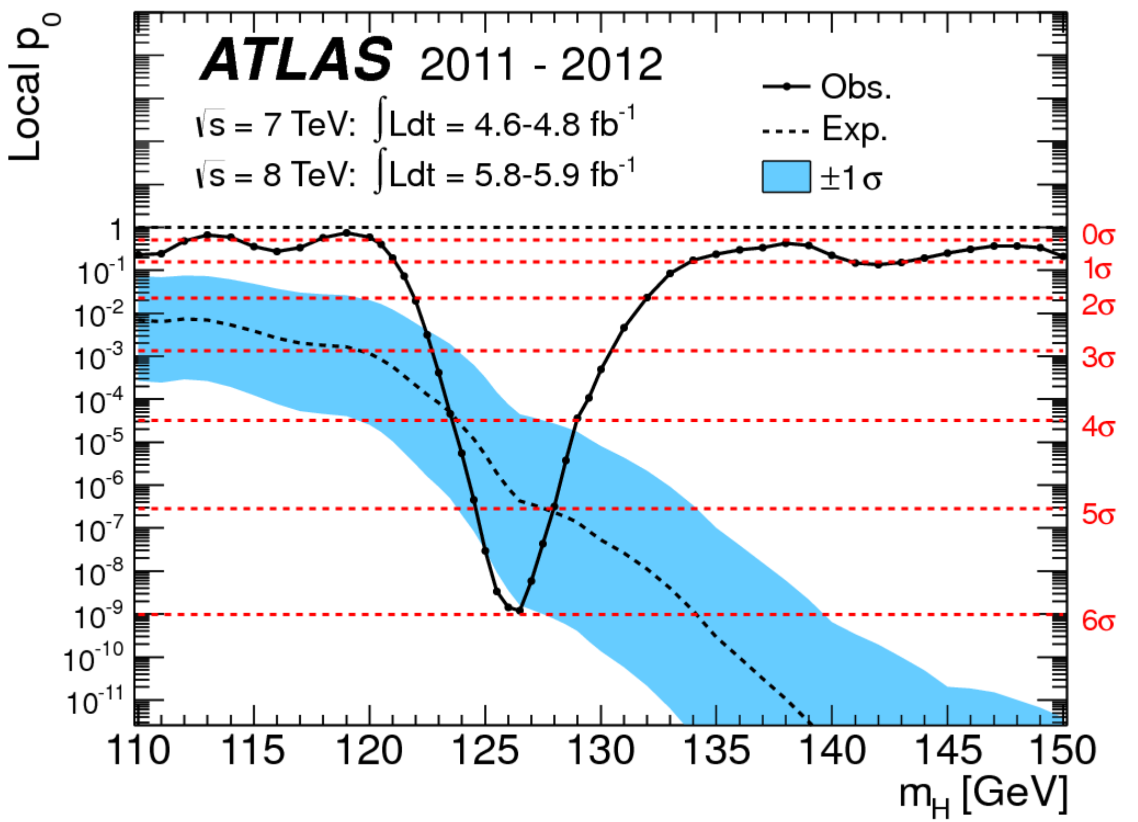
- Statistical errors: 35–46 MeV
- Total systematics: 28–34 MeV
- QED radiation: ~23 MeV (dominant)
- Lepton calibration: 12–15 MeV

Higgs Physics at LHC





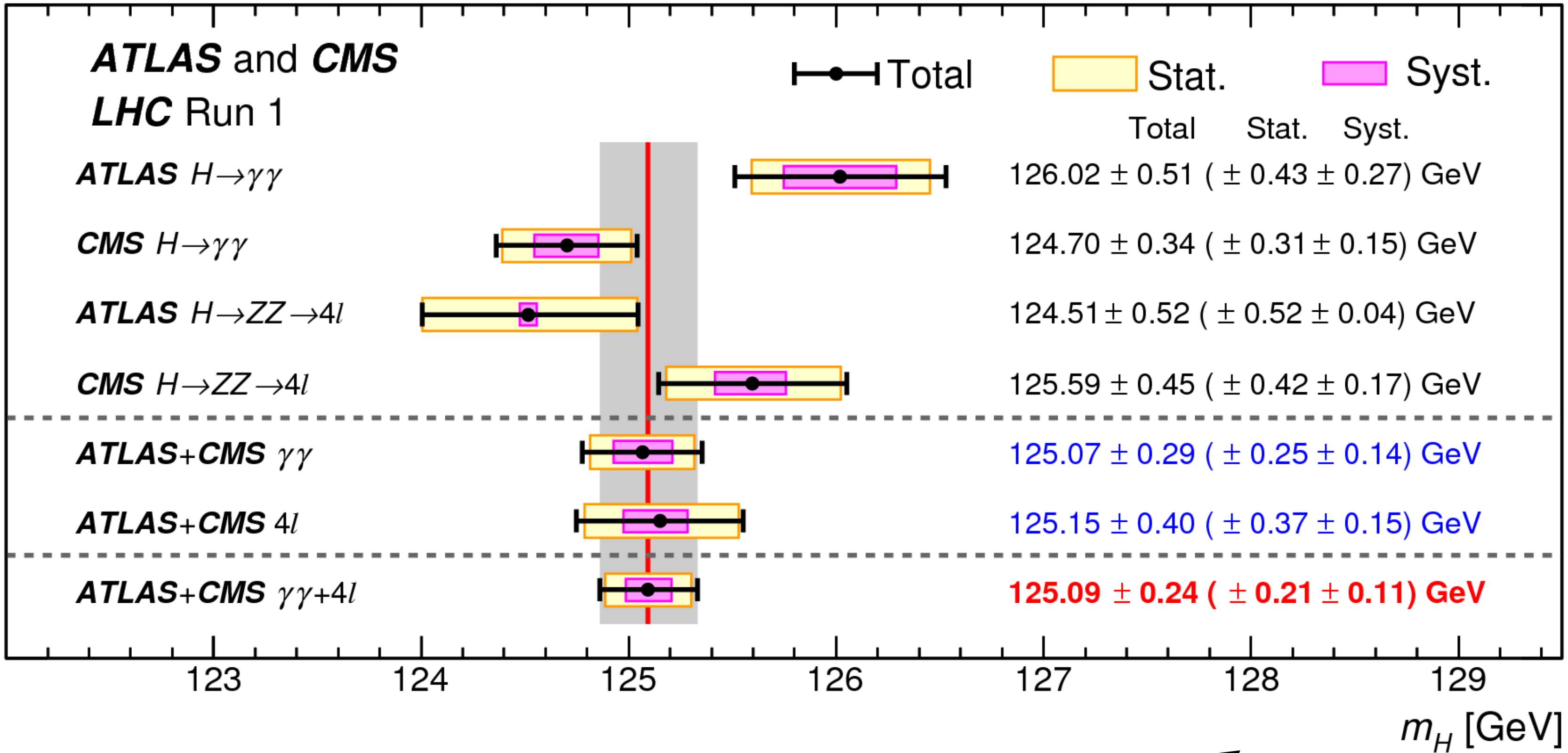




Higgs boson Run I Grand Summary (1)

- (light) Higgs boson,
- Pure CP even state (0+),
- narrow width

- m_H: Precise determination from $H \to \gamma\gamma$ and $H \to ZZ \to 4$ leptons (e, μ)



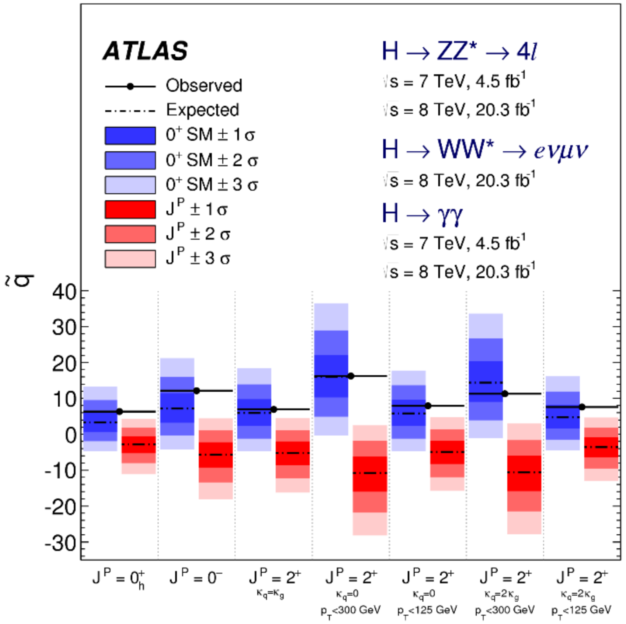
mH = 125.09 ± 0.24 GeV

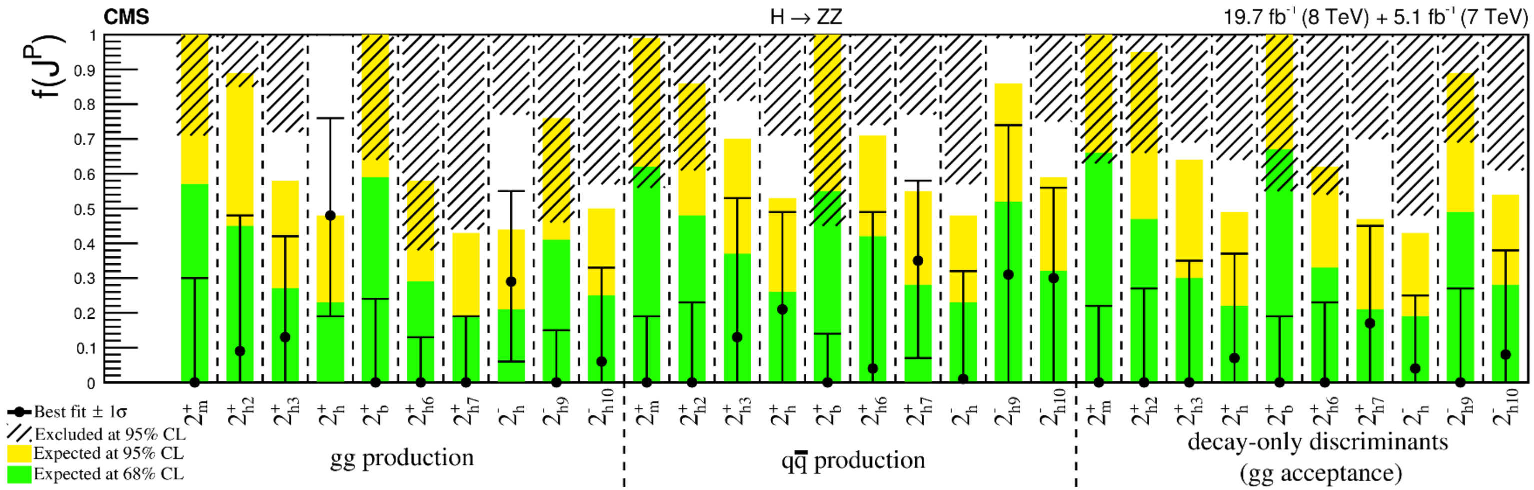
< 0.2 % precision !
(dominated by statistics !)

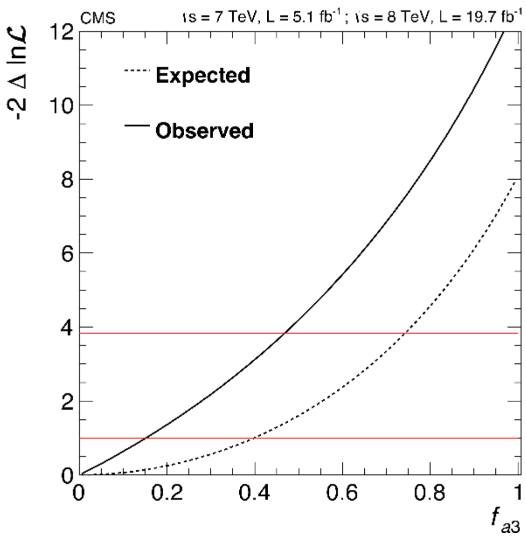
Higgs boson Run I Grand Summary (2)

- (light) Higgs boson,
- Pure CP even state (0+),
- narrow width

- Using kinematics in production and/or decay in H→γγ, H→ZZ→4 leptons (e, μ), H→WW





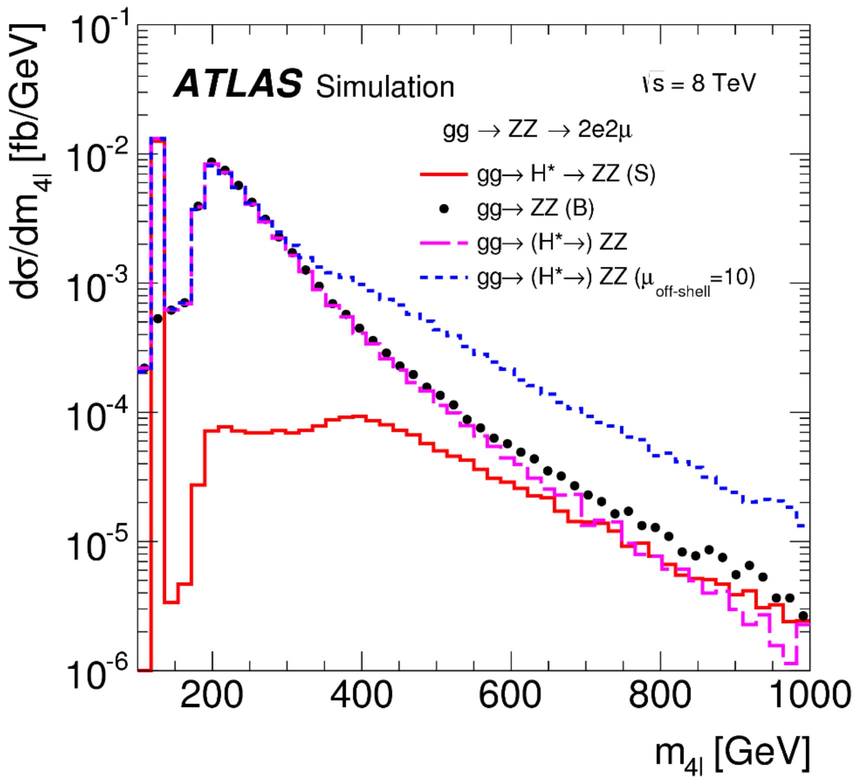


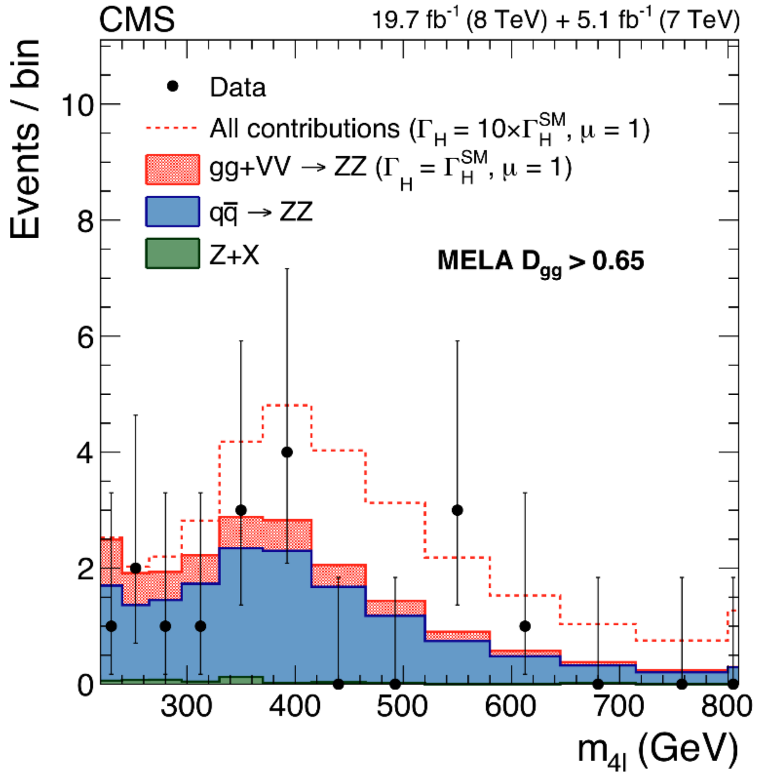
But weak constraints on HVV tensor structure (0+/0- mixture, …)

Higgs boson Run I Grand Summary (3)

- (light) Higgs boson,
- Pure CP even state (0+),
- narrow width

- Width (Γ_H): probed via analysis of on-shell/off-shell part of H→VV spectrum

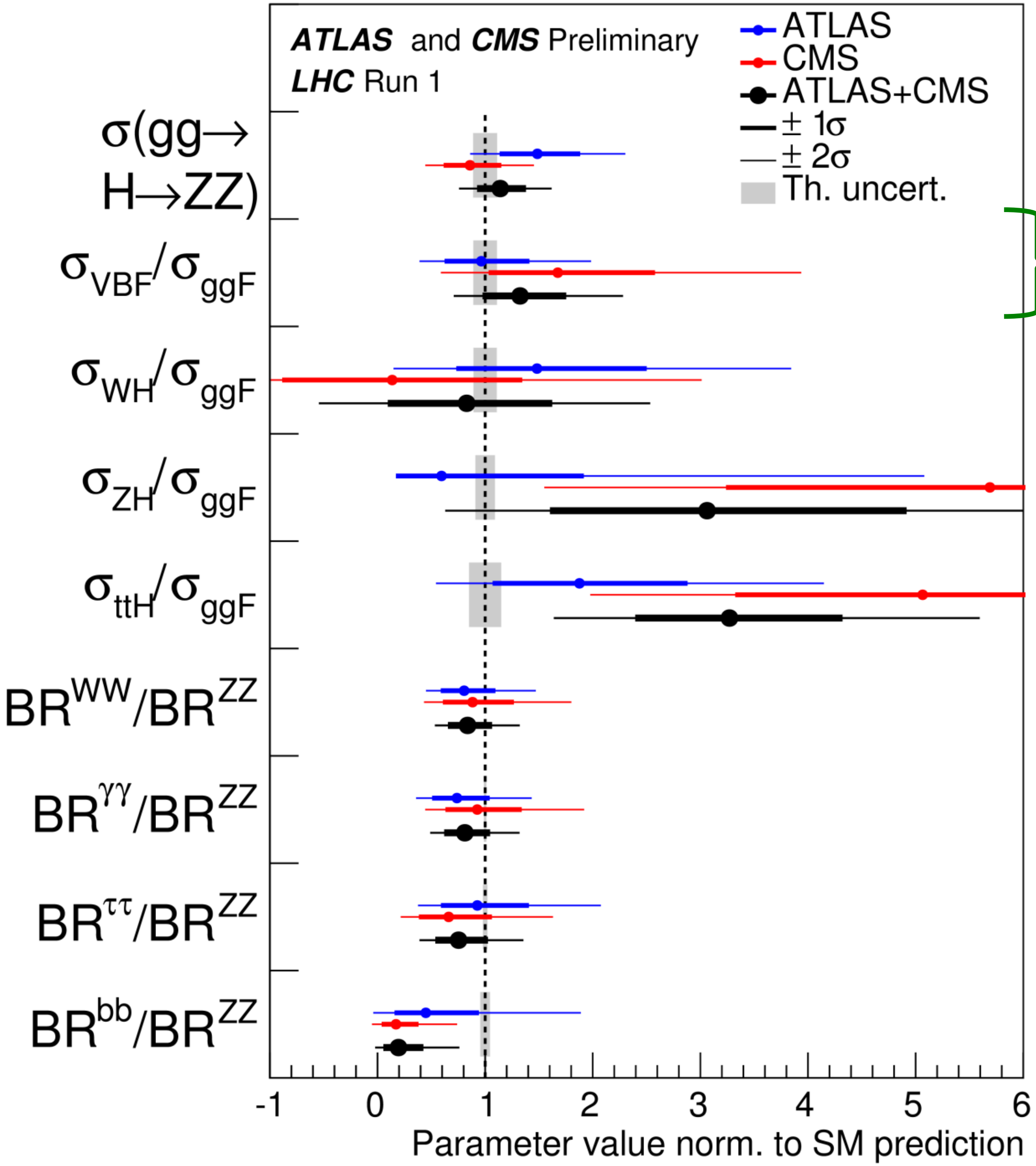




Γ_H < 23 MeV (ATLAS, VV), 26 MeV (CMS, ZZ)

+ $\Gamma_H > 3.5.10_{-9}$ MeV (lifetime)

Higgs boson Run I Grand Summary (4)

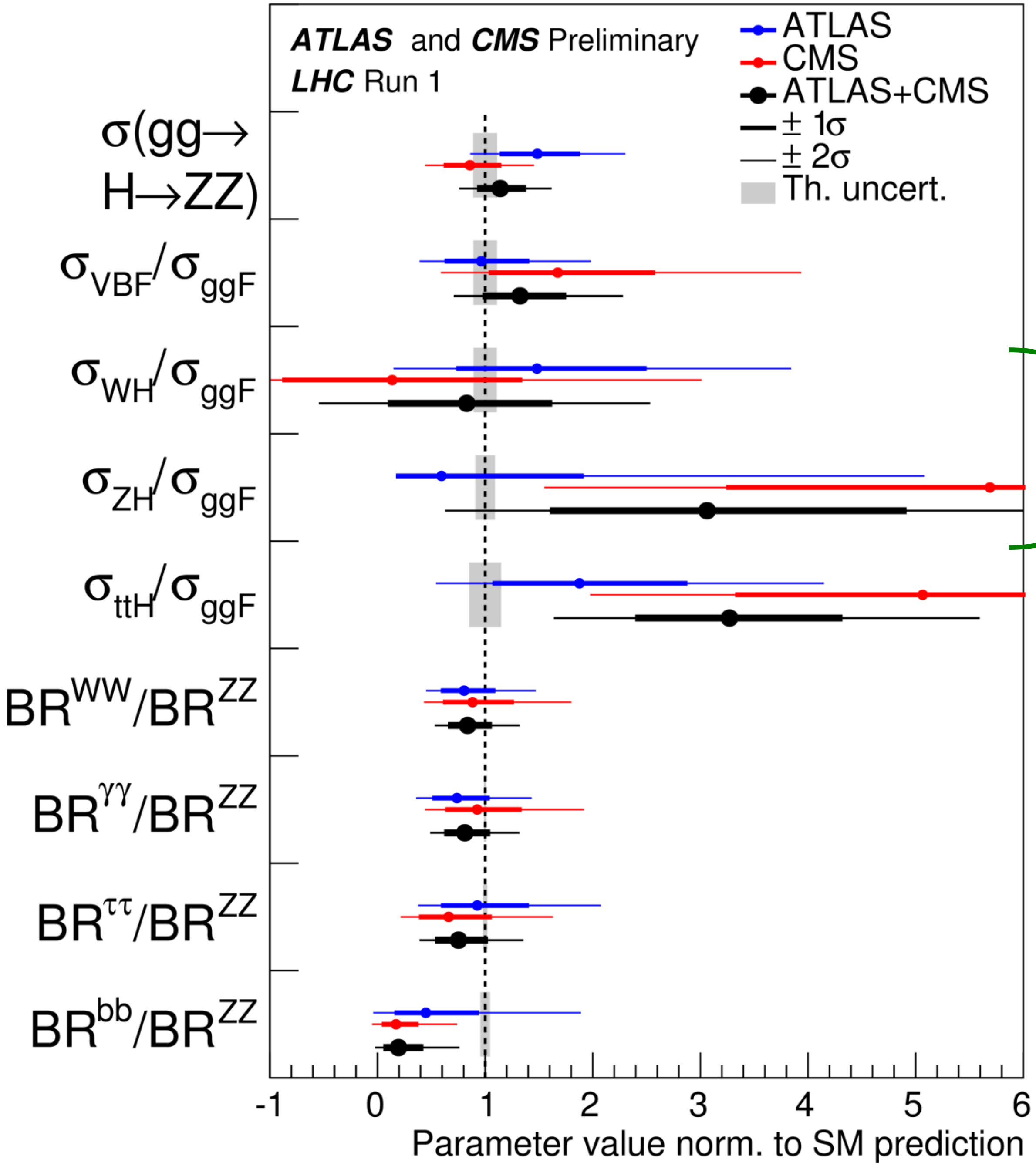


Using gg→H→ZZ as a reference:

$$(\sigma_i . BR_j) = \sigma(gg \to H \to ZZ) \; \frac{\sigma_i}{\sigma_{ggF}} \; \frac{BR^j}{BR^{ZZ}}$$

Observation of VBF Production at 5.5 σ (4.7 σ exp.)

Higgs boson Run I Grand Summary (5)

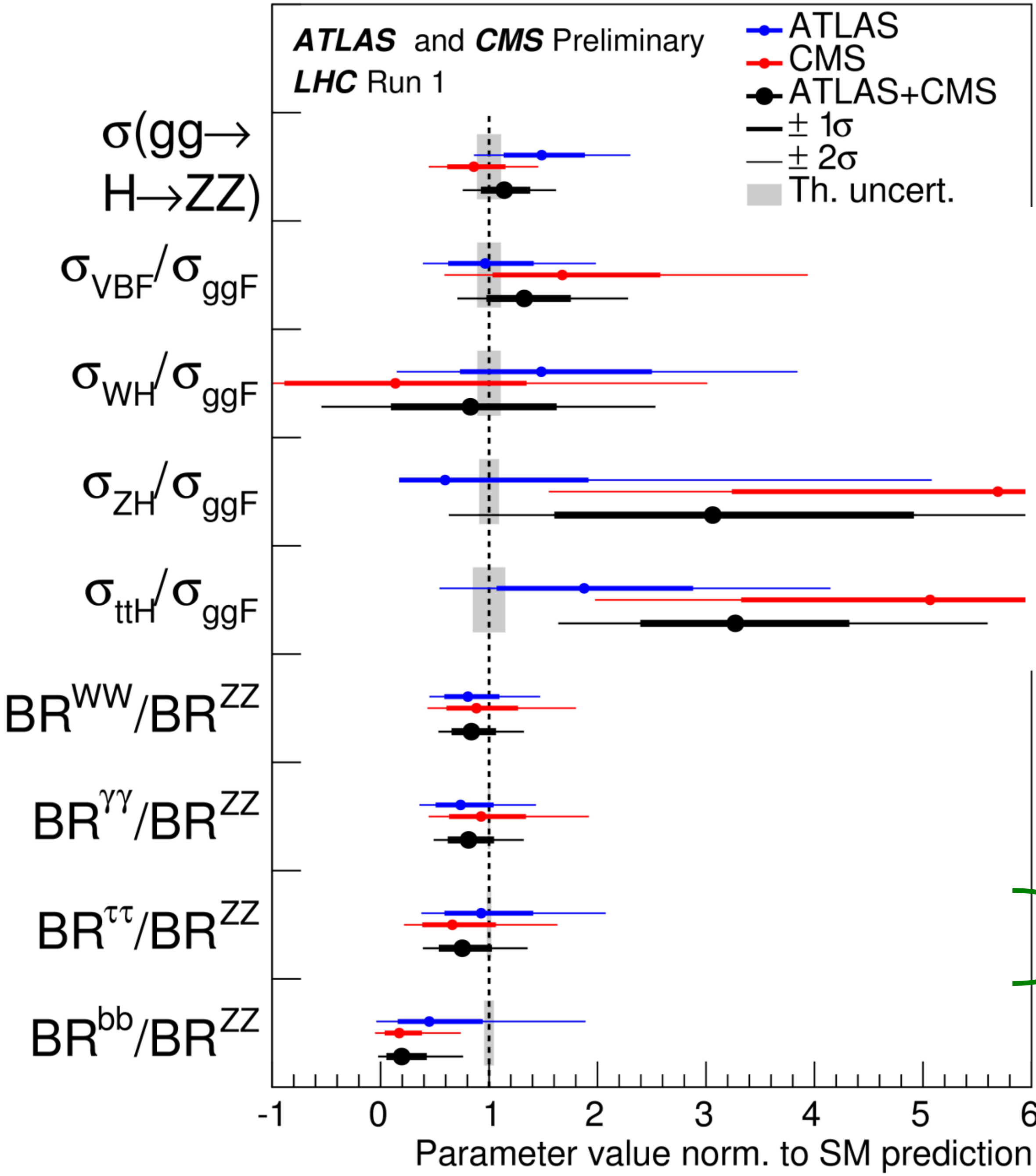


Using gg→H→ZZ as a reference:

$$(\sigma_i . BR_j) = \sigma(gg \rightarrow H \rightarrow ZZ) \; \frac{\sigma_i}{\sigma_{ggF}} \; \frac{BR^j}{BR^{ZZ}}$$

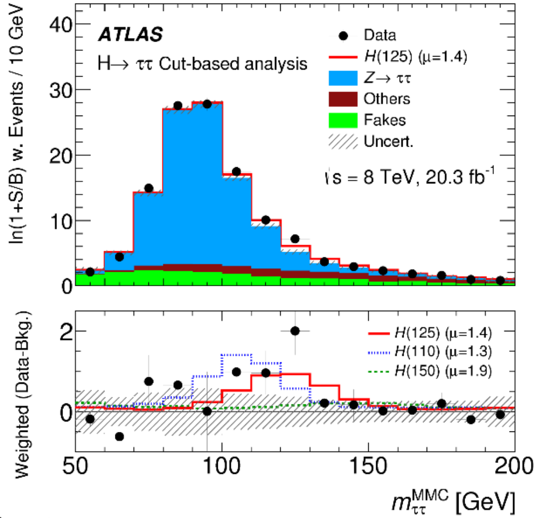
Evidence for VH Production at 3.5 σ
(4.2 σ exp.)

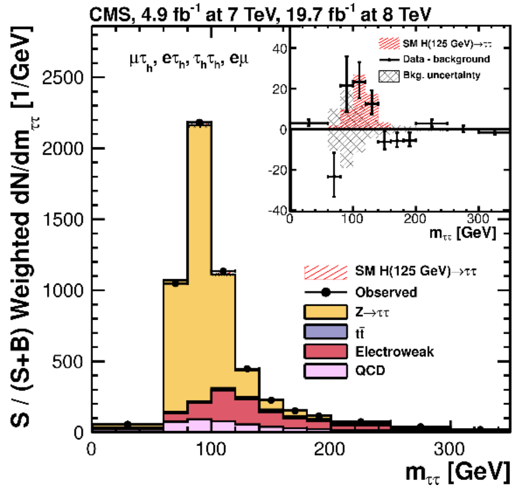
Higgs boson Run I Grand Summary (6)



Using gg→H→ZZ as a reference:

$$(\sigma_i . BR_j) = \sigma(gg \to H \to ZZ) \quad \frac{\sigma_i}{\sigma_{ggF}} \quad \frac{BR^j}{BR^{ZZ}}$$





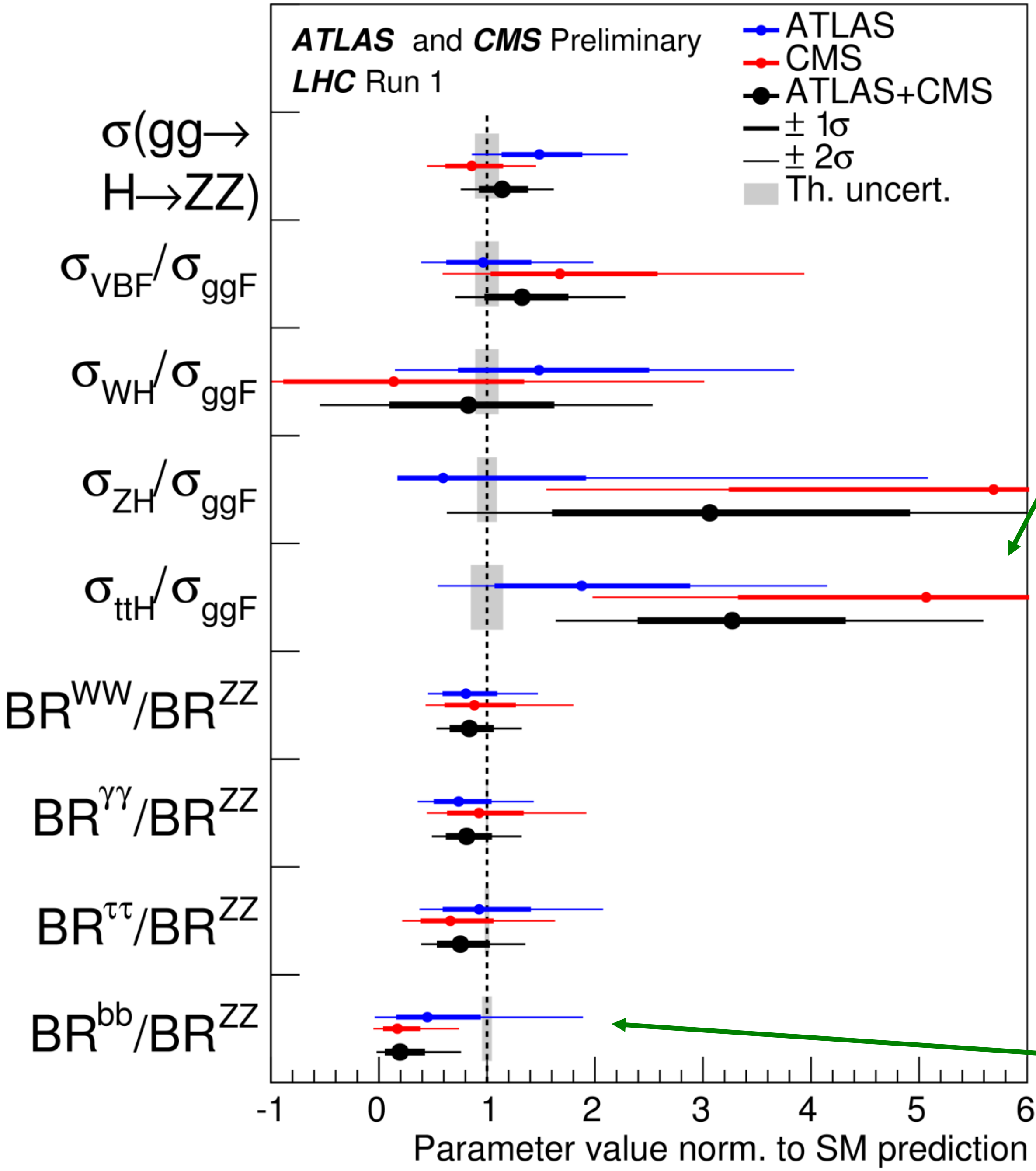
@ 125.09 GeV:

4.4 σ (exp. 3.3)

3.4 σ (exp. 3.7)

Observation of couplings to τ at 5.5 σ (exp 5.0)

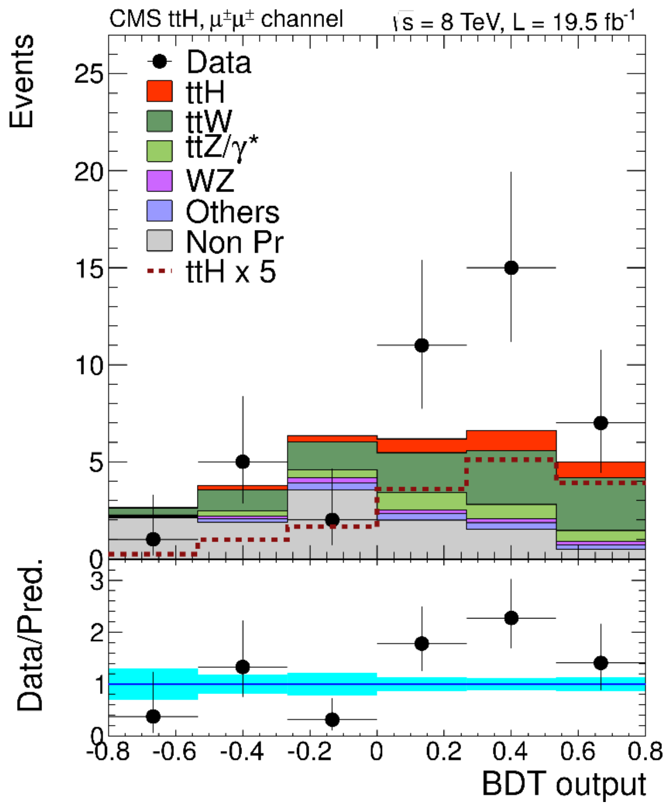
Higgs boson Run I Grand Summary (7)



Using gg→H→ZZ as a reference:

$$(\sigma_i . BR_j) = \sigma(gg \to H \to ZZ) \; \frac{\sigma_i}{\sigma_{ggF}} \; \frac{BR^j}{BR^{ZZ}}$$

2.4 σ excess in ttH…

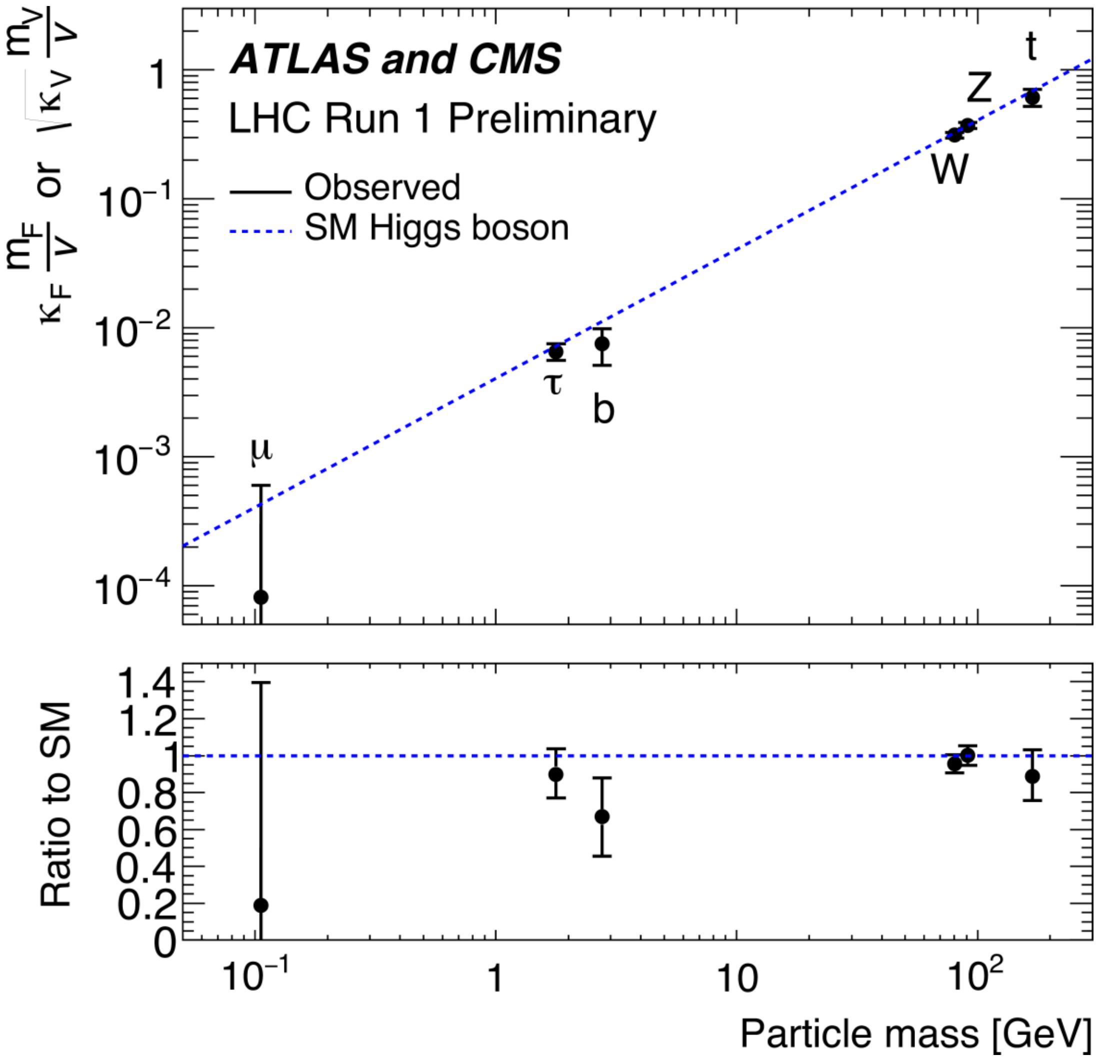


… and 2.5 σ deficit in Hbb.

Higgs boson Run I Grand Summary (8)

Constraints on tree-level Higgs boson couplings

- Assumptions:
  - Resolve loops with SM content
  - (good precision on top from loop induced gg rate)
  - $BR_{BSM}=0$



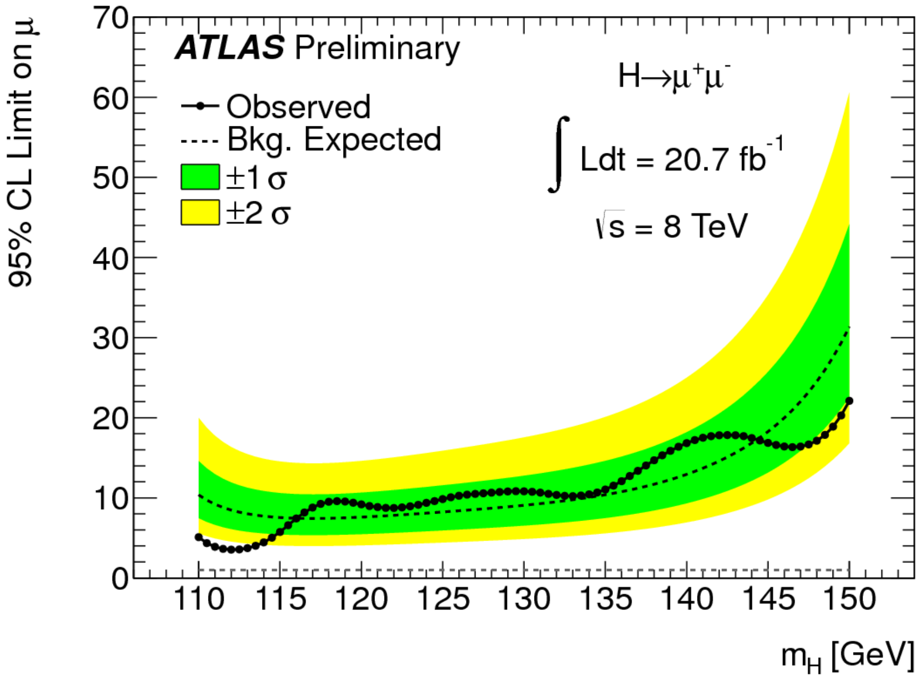
Higgs boson couplings to gauge bosons and fermions firmly established (10-20% accuracy).

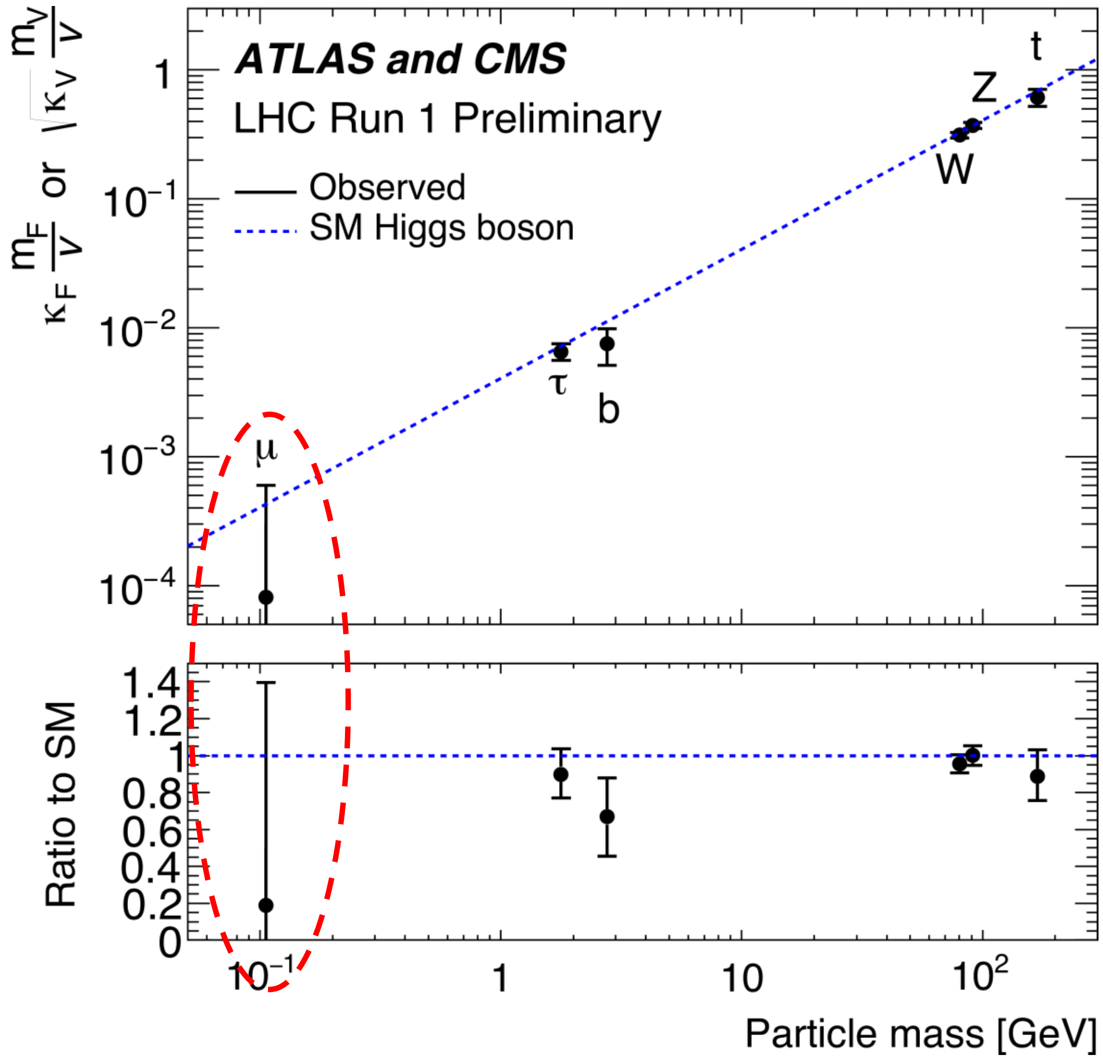
Compatible (within errors) with SM predictions:

$\mu = 1.09 \pm 0.07_{\text{stat}} \pm 0.04_{\text{exp syst.}} \pm 0.03_{\text{th. bkg}} +0.07-0.06_{\text{th. sigma}}$

Higgs boson Run I Grand Summary (9)

Constraints on tree-level Higgs boson couplings





- $H \to \mu\mu$ limits: ~7 x SM
- Observation/Measurement will require HL-LHC.

Higgs boson couplings to gauge bosons and ~~fermions~~ firmly established (10-20% accuracy)

3rd generation

A Higgs boson… so ?

With the discovery of the Higgs boson, **we have now a coherent theory of fundamental constituents of matter and their interactions:**

(forgetting about gravitation)

- Quantum Field theory based on Gauge symmetries (⇔ interactions)
- Valid up to very high energy (up to Planck scale ?)
- Leads to a meta-stable electroweak vacuum up to high scales
- Compatible with (almost) all precision data available so far

Is it the end of the story ?

Dark Matter, baryon asymmetry, arbitrary parameters (number of families, …), …
NOT explained by SM.

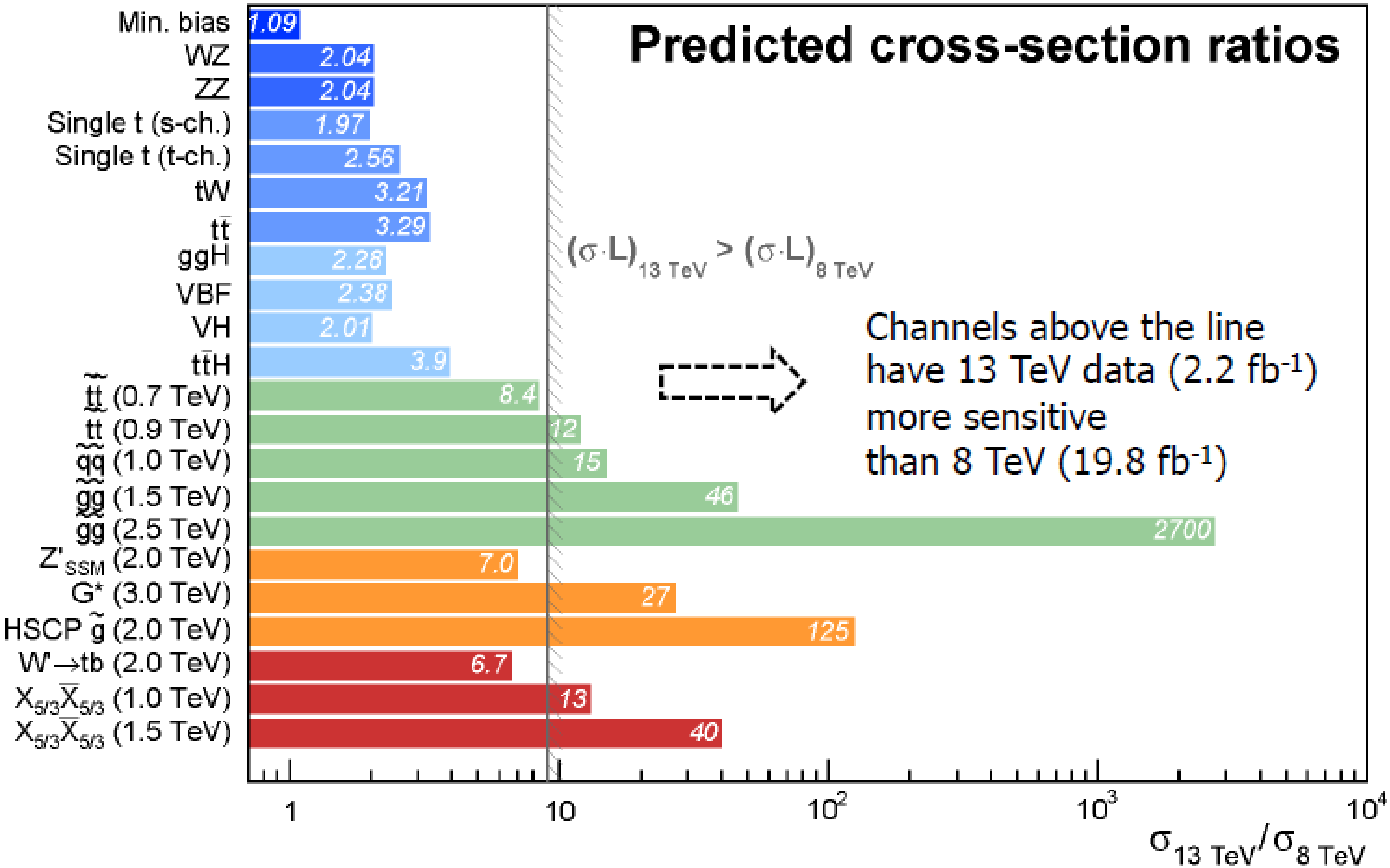
But scalar sector related to the deepest problems of HEP
(hierarchy, naturalness, vacuum energy cosmological constant, flavor puzzle & CP, …)

Very Rich program ahead !

- High precision Higgs couplings measurements
- Observe/Measure rare ($H\rightarrow Z\gamma$, $H\rightarrow\mu\mu$, $H\rightarrow cc$, …)
  or forbidden decay ($H\rightarrow$invisible, $H\rightarrow\mu\tau$.. ~2.5σ excess in Run I !)
- Di-Higgs production, Self-coupling.
- Unitarity (Vector Boson Scattering)
- Look at extended scalar sector (2HDM,…), new resonances, exotic matter….

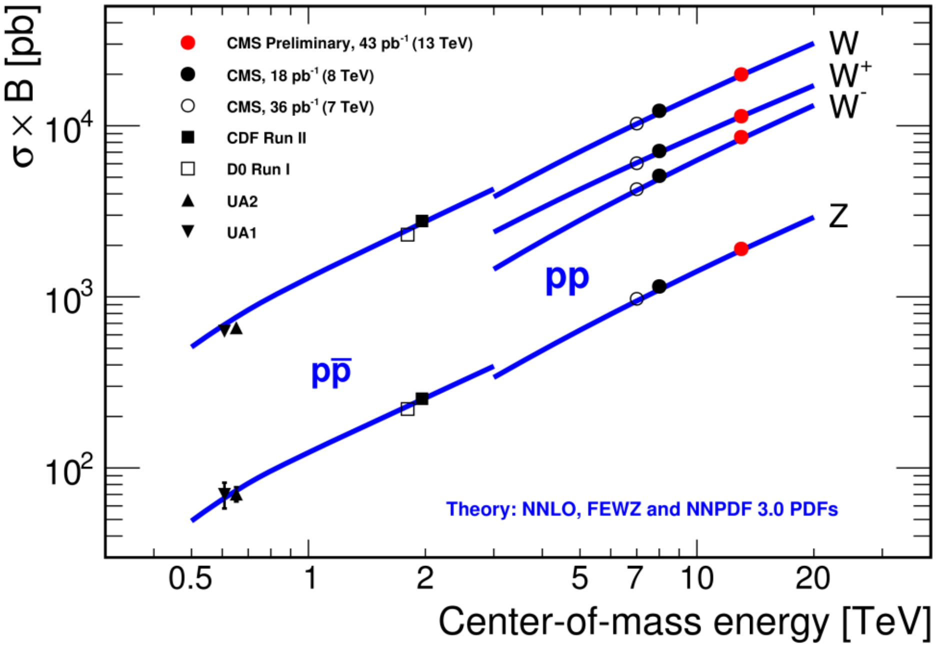

Exploring new territories…

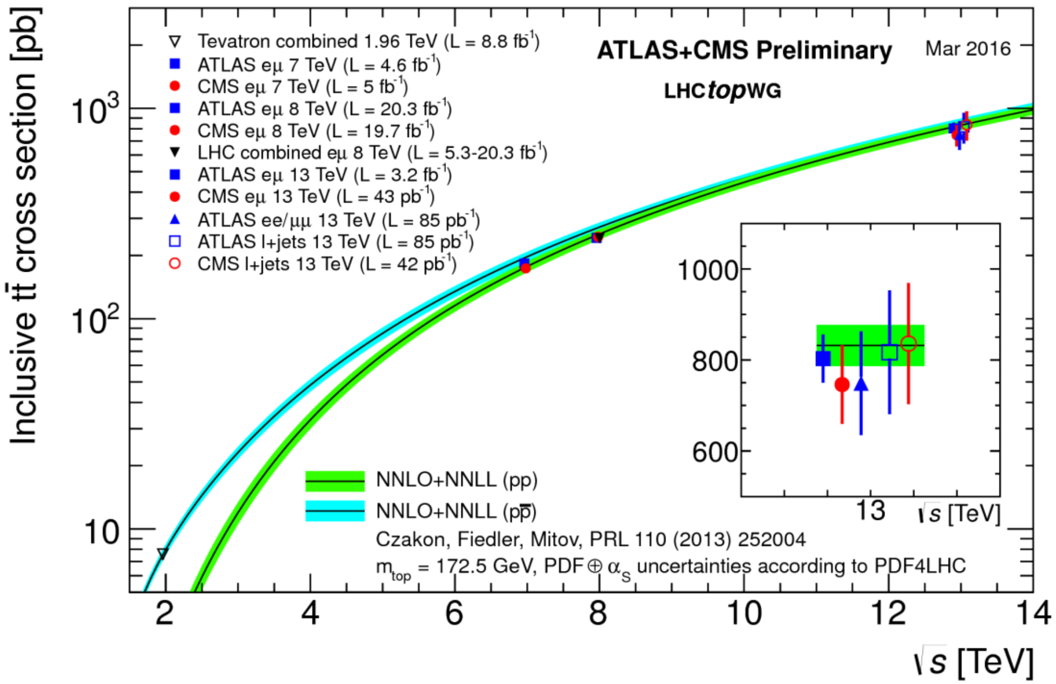
Increased potential in Run II

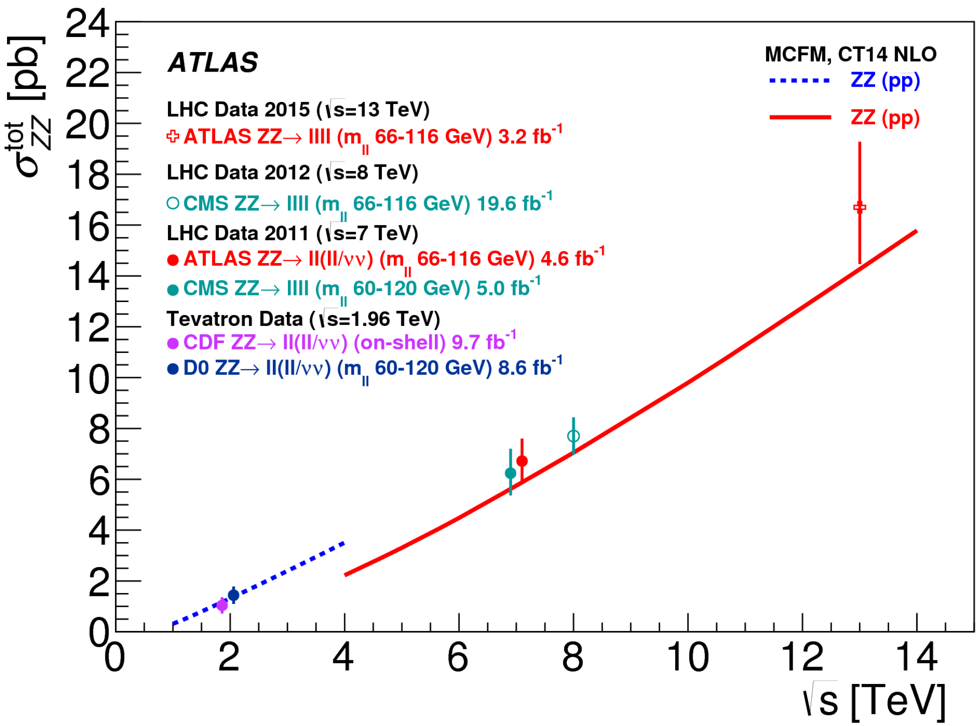


In 2015, with ~2-3 fb-1, only possible to ~re-observe Higgs, establish methods for future runs, …
But discovery potential of heavy particles get a tremendous kink

Re-discovering old friends (W, Z, top…)

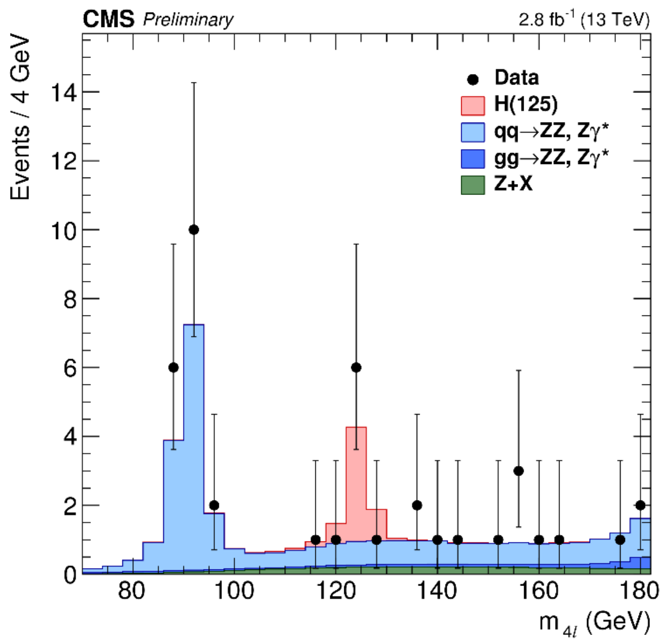




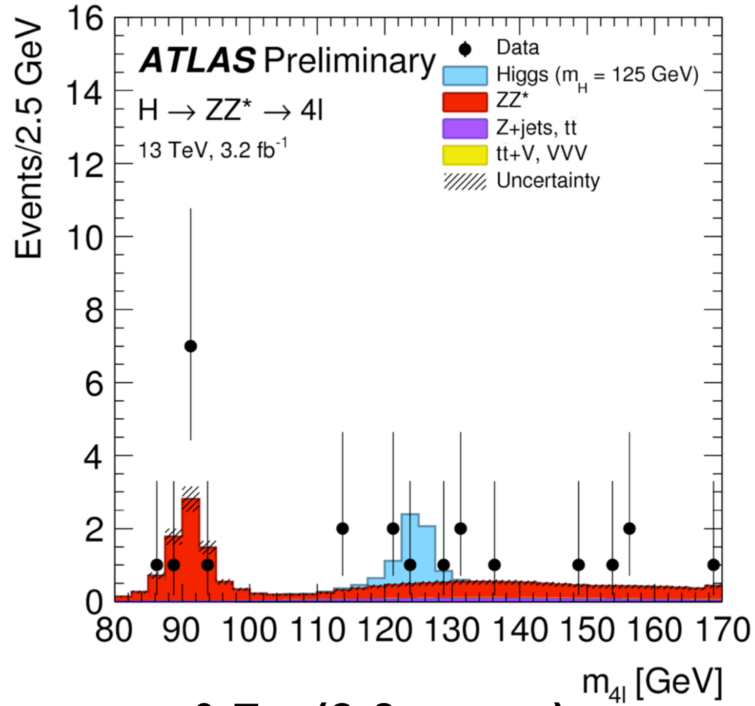


... and Higgs !

H→ZZ→4 leptons (e, μ)

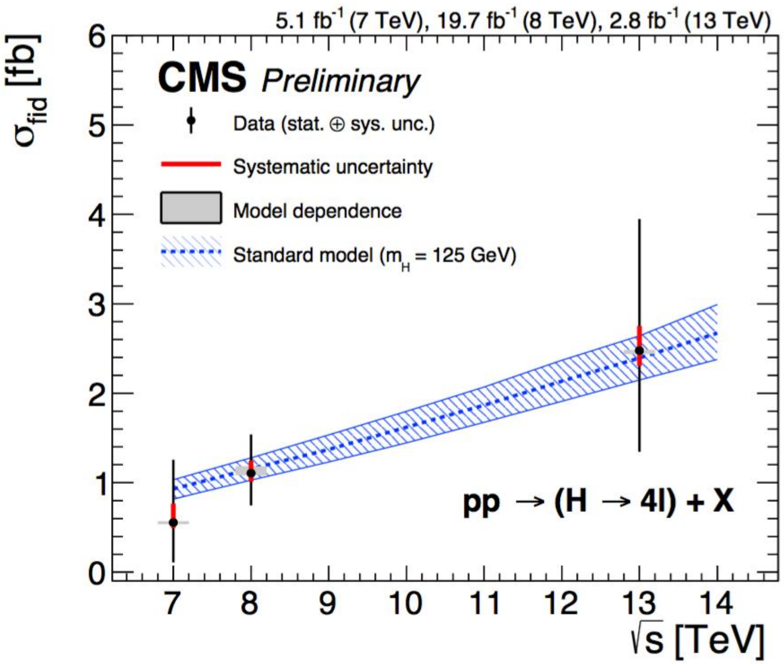


2.5 σ (3.4 σ exp.)



0.7σ (2.8 σ exp.)

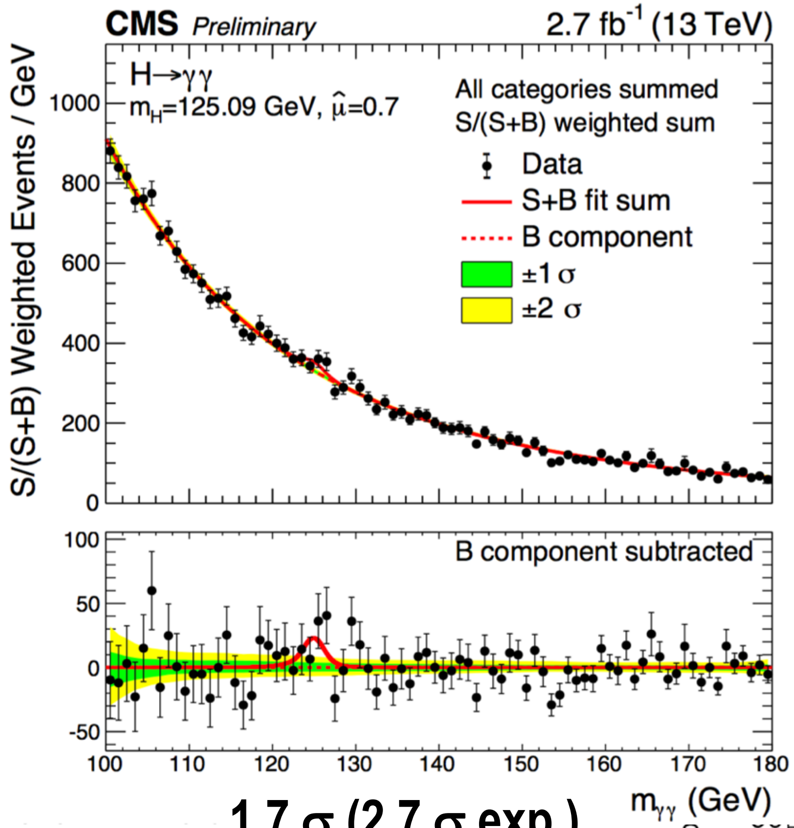
Fiducial cross-section

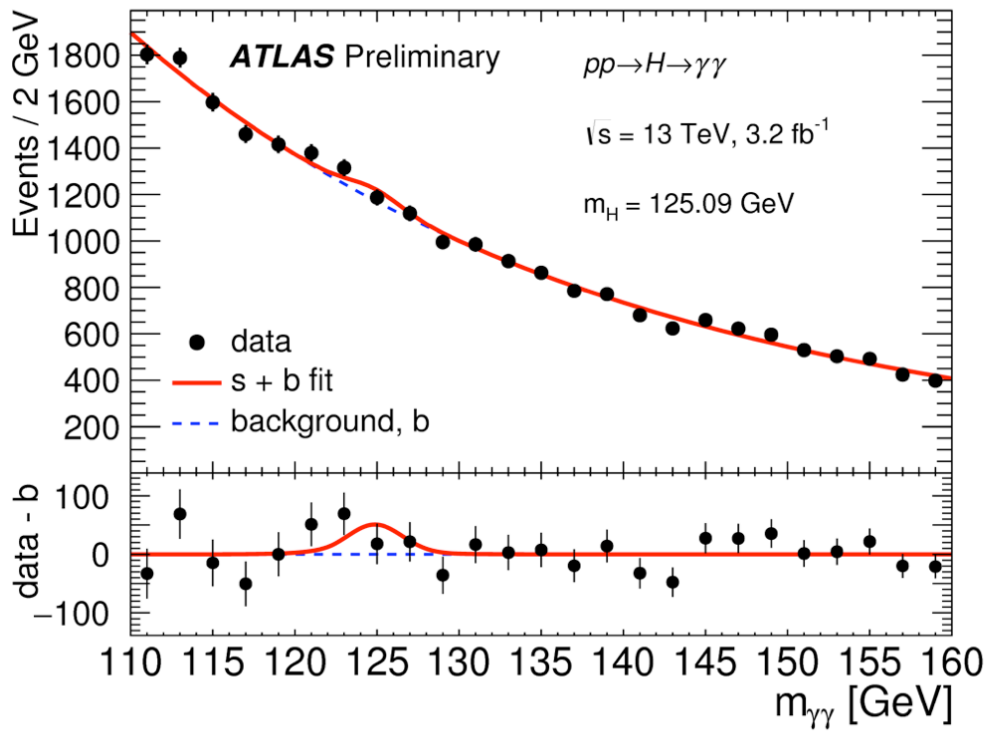


In good agreement with SM…

... and Higgs !

$H \to \gamma\gamma$

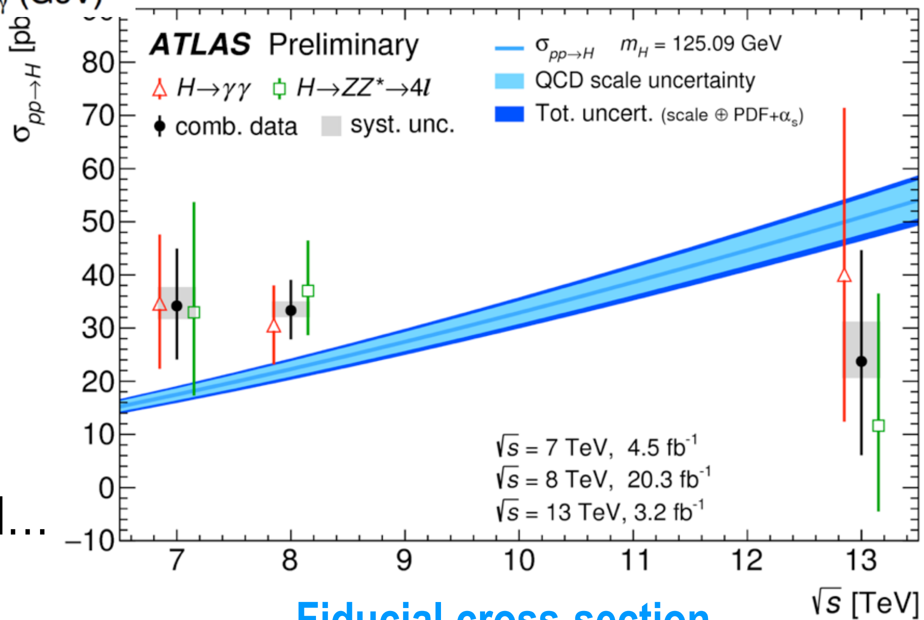




1.7 σ (2.7 σ exp.)

1.5 σ (1.9 σ exp.)

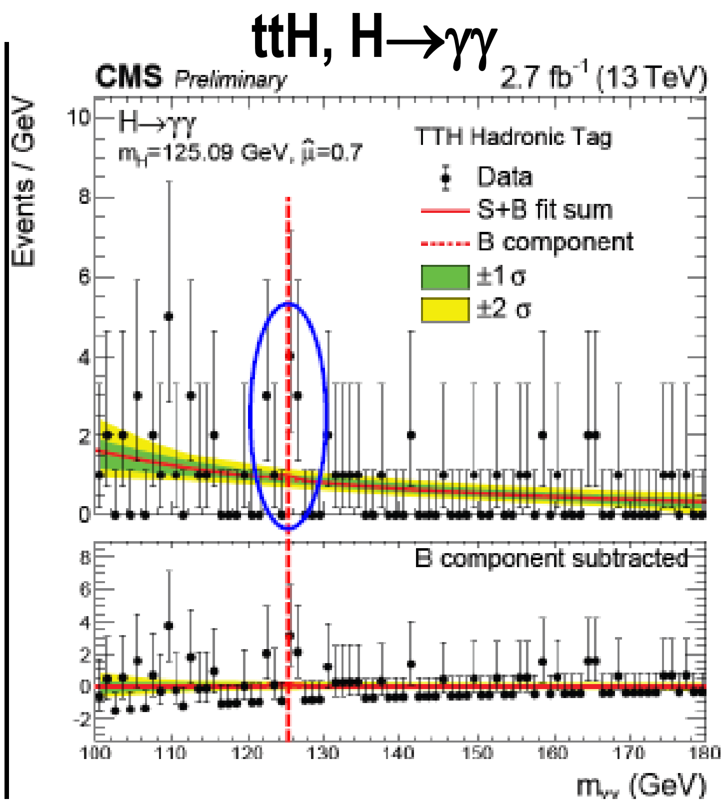
In good agreement with SM…

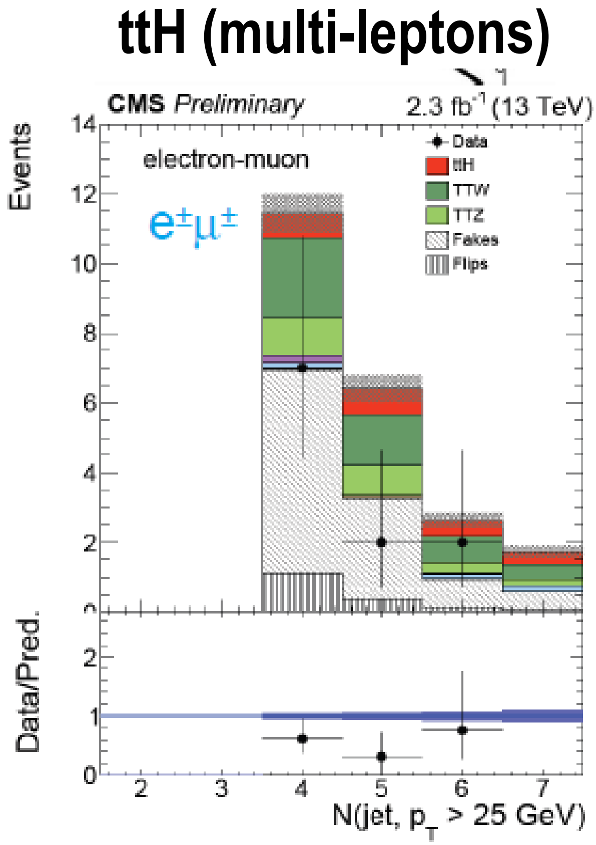


Fiducial cross-section

... and Higgs !

First look at ttH…





First 13 TeV measurements performed

- In γγ, multilepton and bb decay modes
- Similar sensitivity as Run 1 analysis
- Overall in agreement with SM

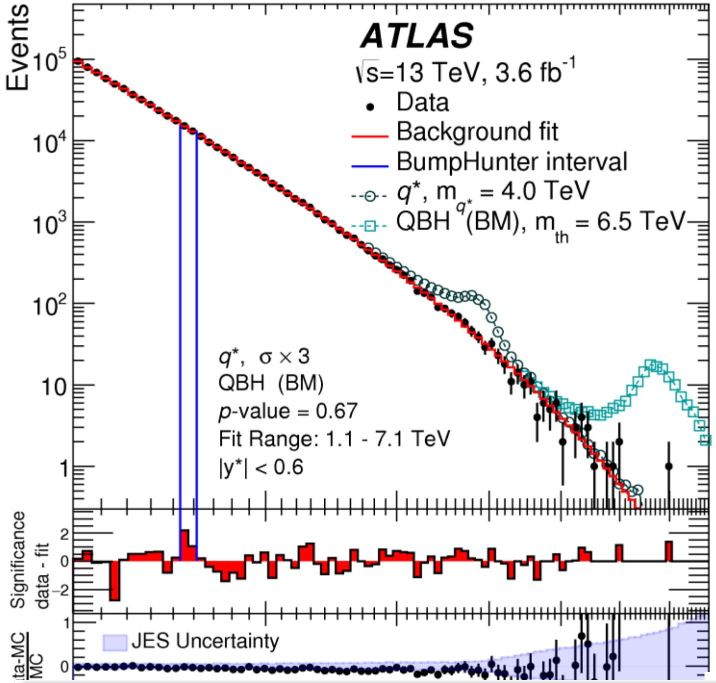
ttH(γγ) $\hat{\mu}_{obs} = 3.8^{+4.5}_{-3.6}$

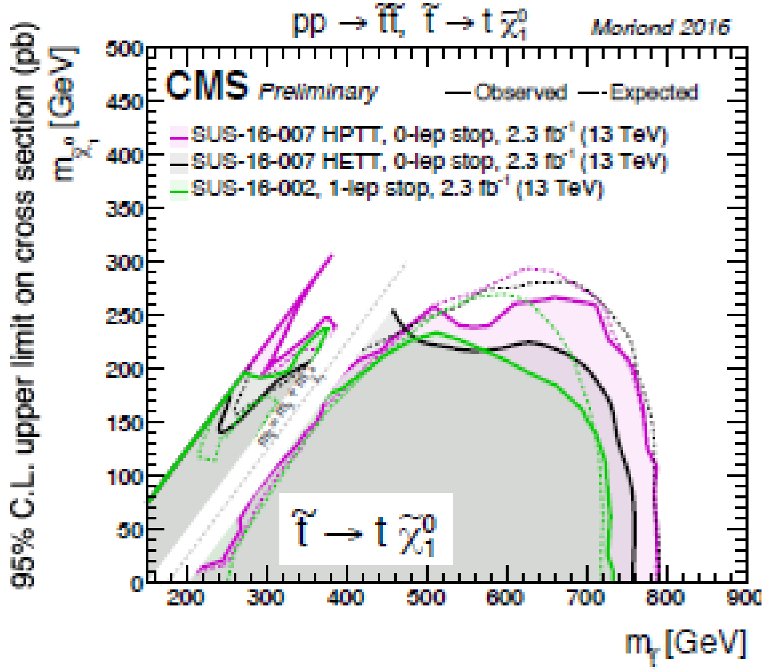
ttH(multilepton) $\hat{\mu}_{obs} = 0.6^{+1.4}_{-1.1}$

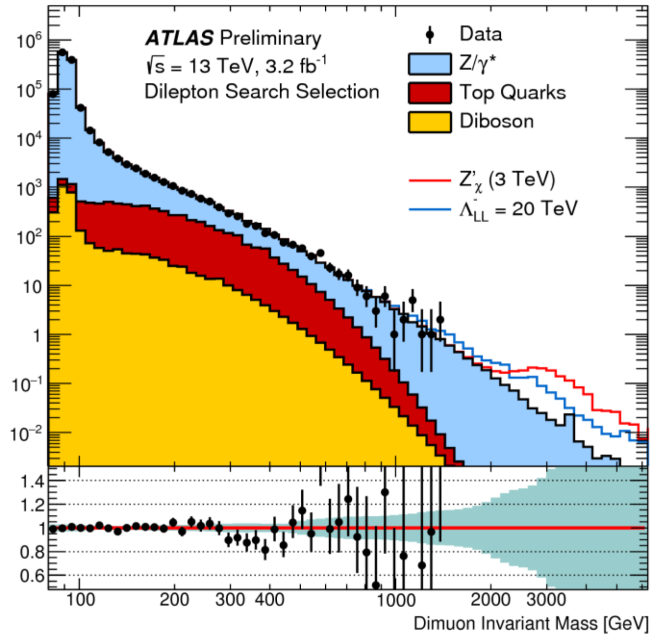
ttH(bb) $\hat{\mu}_{obs} = -2.0^{+1.8}_{-1.8}$

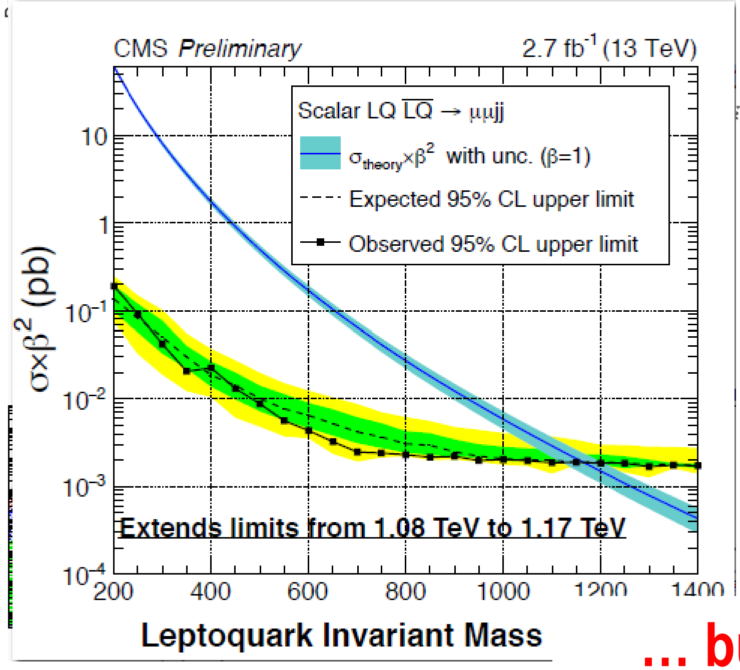
BSM Searches…

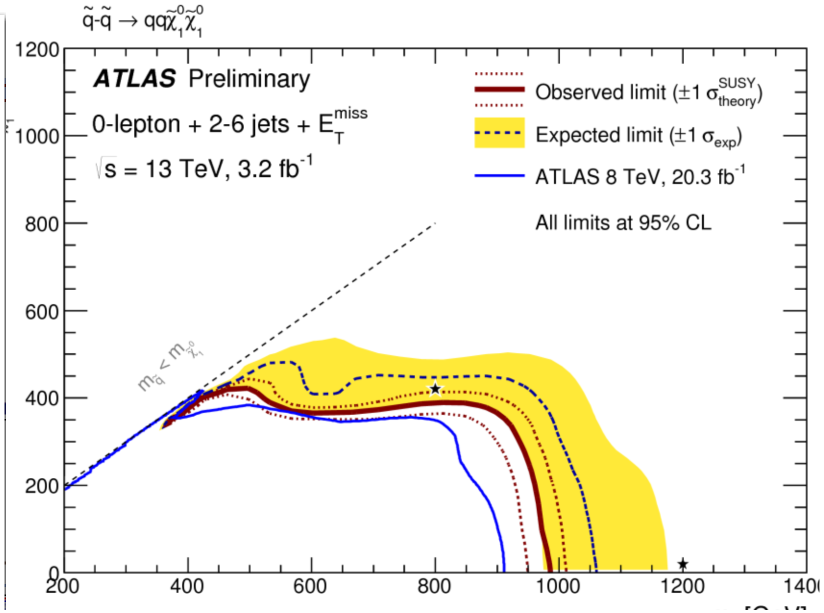
Search for sbottom, squarks, lepto-quarks, Z', W', Graviton,…

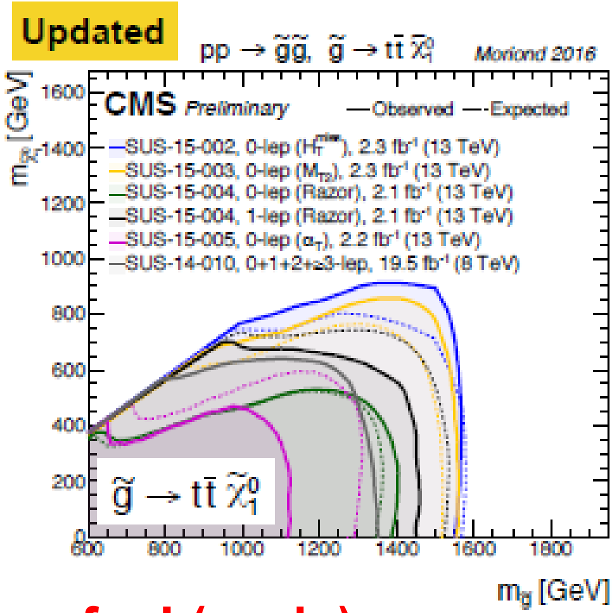










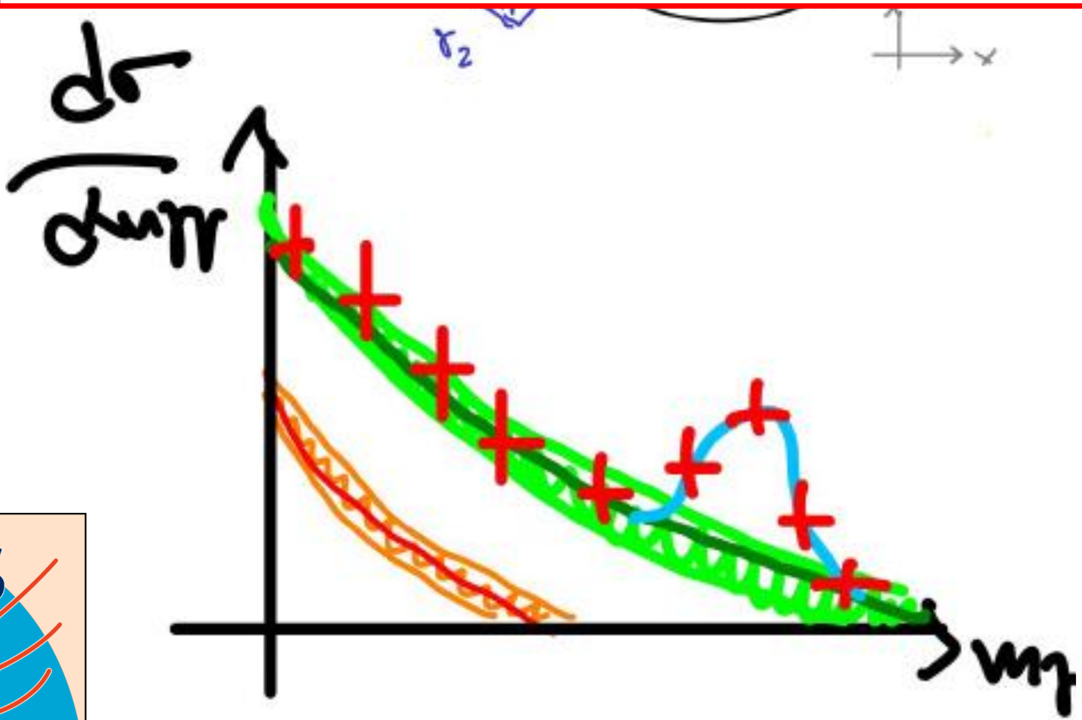


… but only found W, Z, top & QCD jets so far ! (again)


Are we crossing the desert ?

Unexpected Surprise ?

Search for excess over di-photon continuum
(either spin 0 or spin2 resonance interpretation)

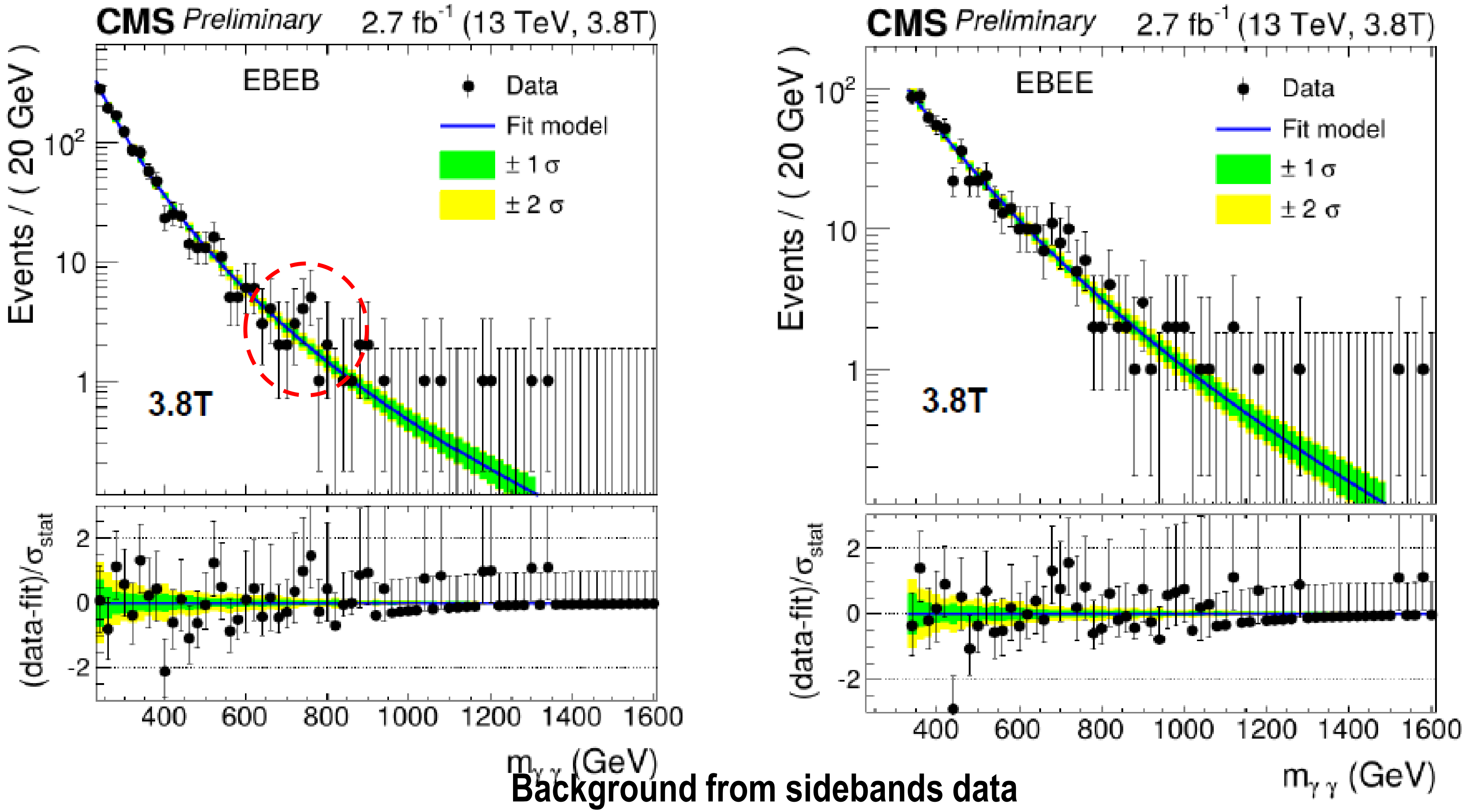


- Simple analysis
- Two high ET photons (> 75 GeV),
- At least one in barrel

- Two analysis (Spin0 or Spin2)
- ET1>0.4$m_{\gamma\gamma}$, ET2>0.3$m_{\gamma\gamma}$ (spin0)
- ET>55 GeV (spin 2)
- Different search range and width hypothesis depending on spin

~90% purity

CMS Di-photon spectrum (13 TeV)

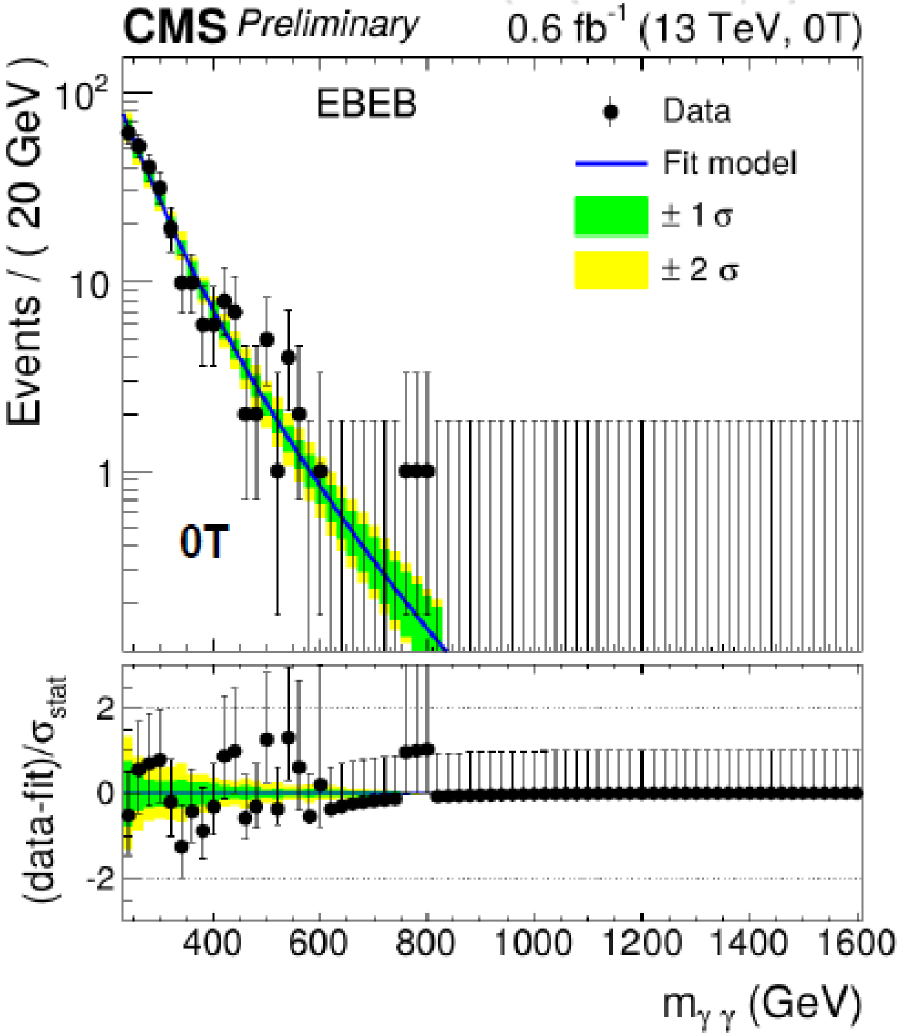


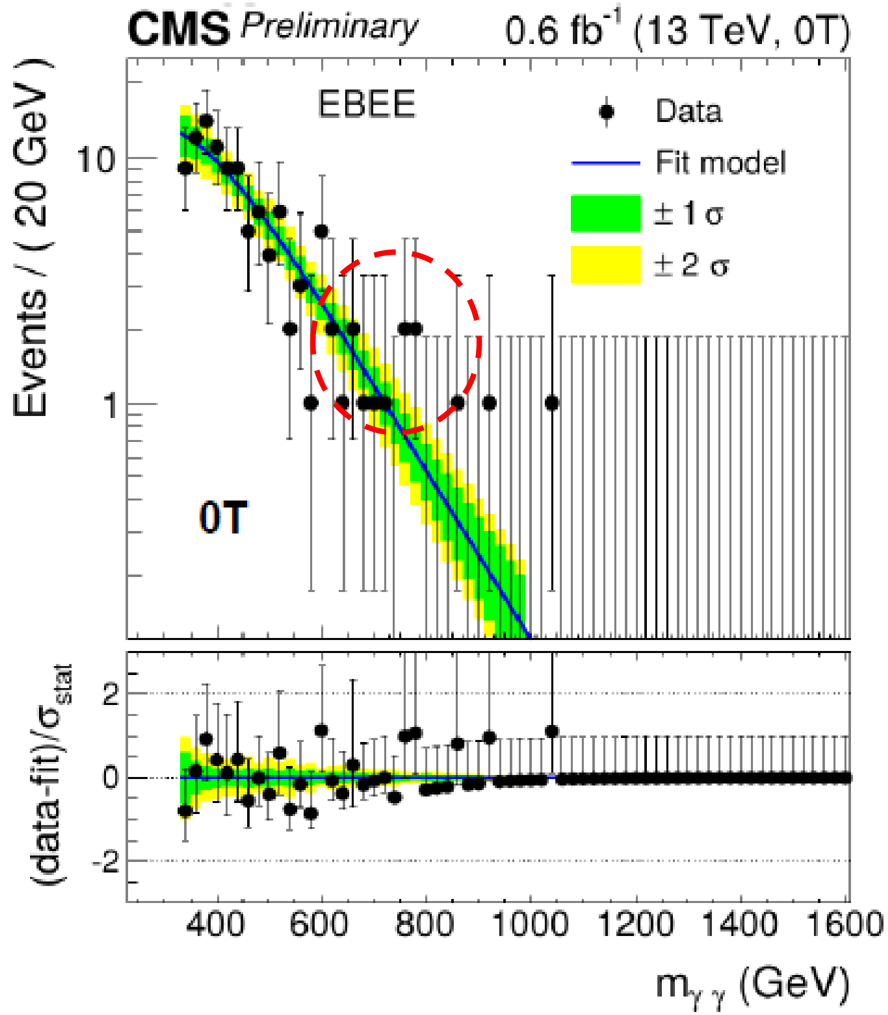
Background from sidebands data

NEW wrt December 2015:

- Data re-reconstruction, new ECAL channel-to-channel calibration
  - (30% improved resolution, 10% improved sensitivity)

CMS Di-photon spectrum (13 TeV)



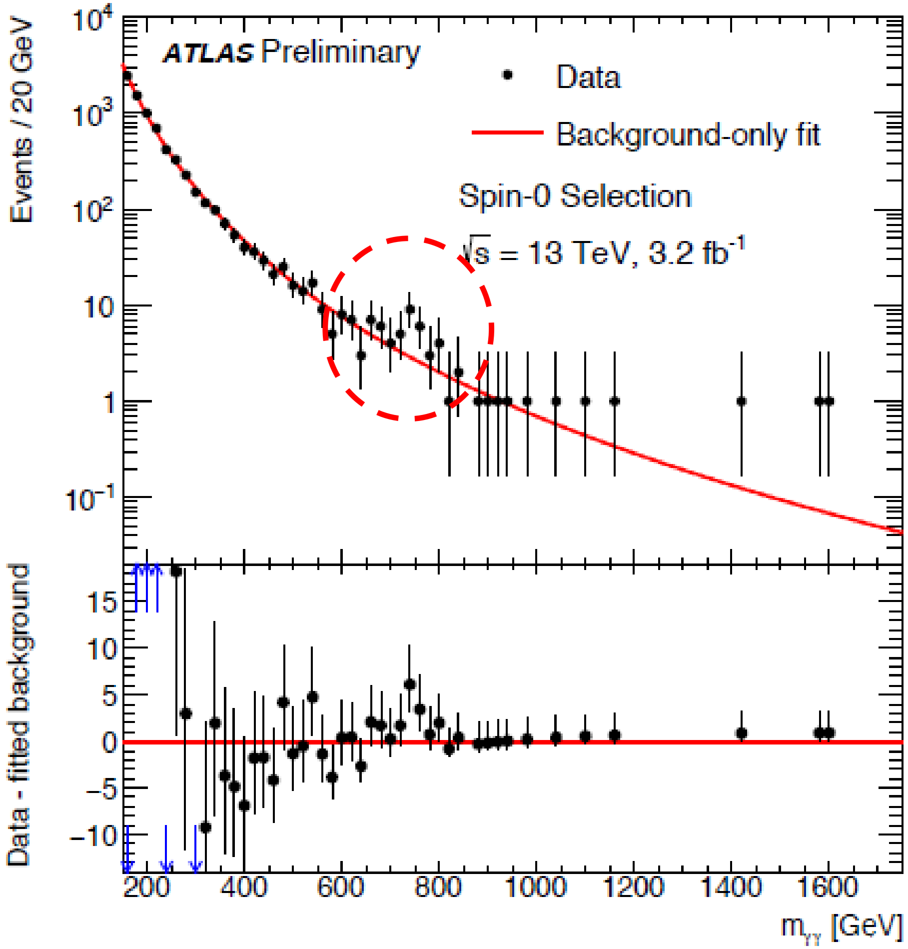


NEW wrt December 2015:

- Add 0 T data (0.6 fb-1), with dedicated calibration, photon ID, vertex ID.
  - 10% (additional) improved sensitivity

ATLAS di-photon spectrum (13 TeV)

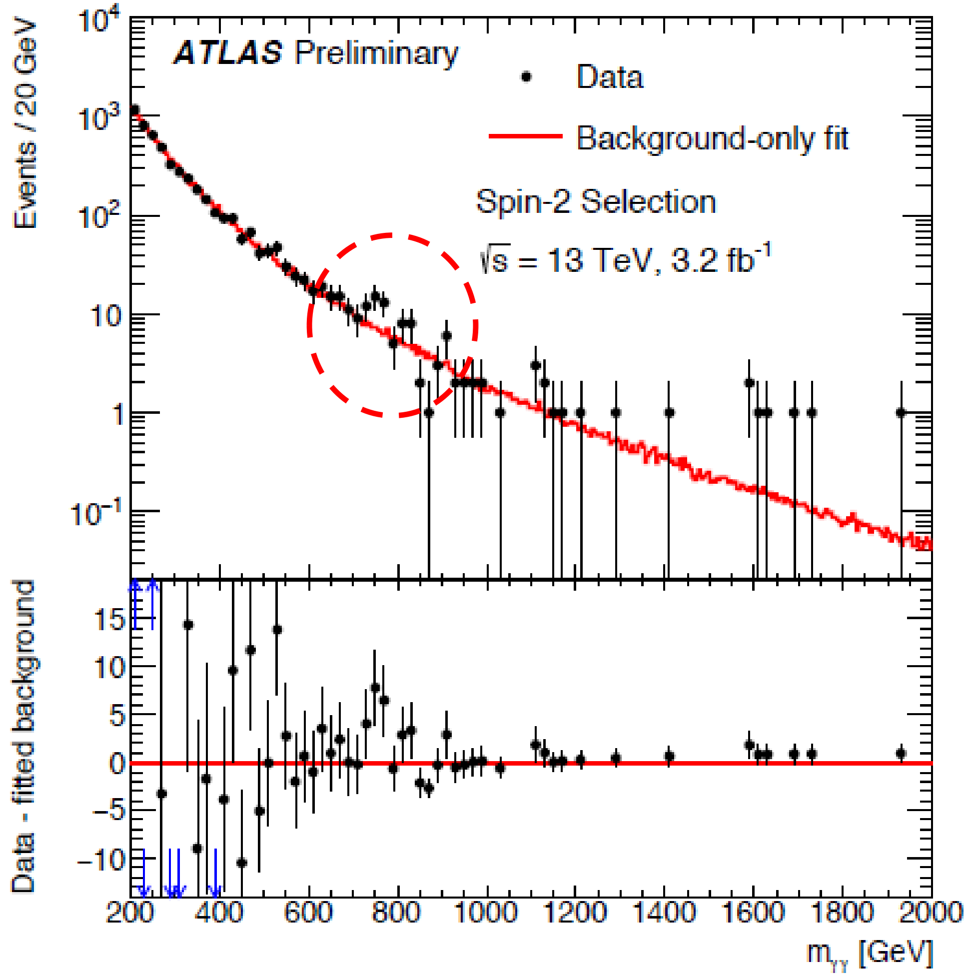
Spin 0



2878 events ($m_{\gamma\gamma}$ > 200 GeV)

Background from sidebands data

Spin 2



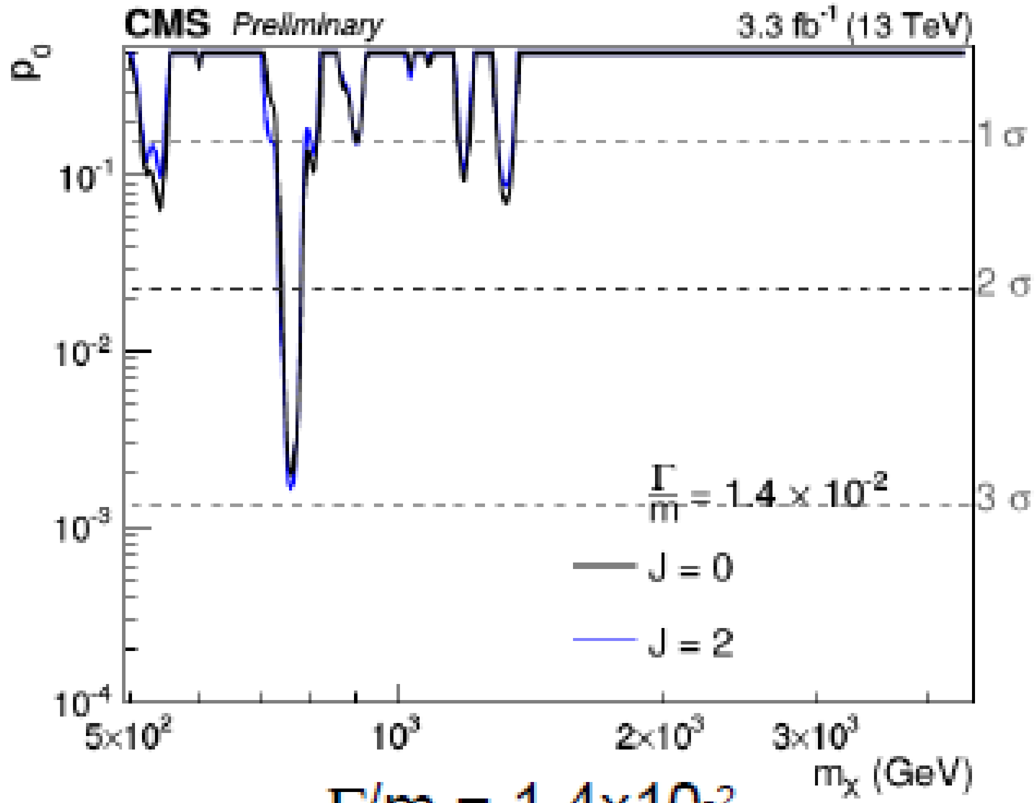
5066 events ($m_{\gamma\gamma}$ > 200 GeV)

Background from MC+data template

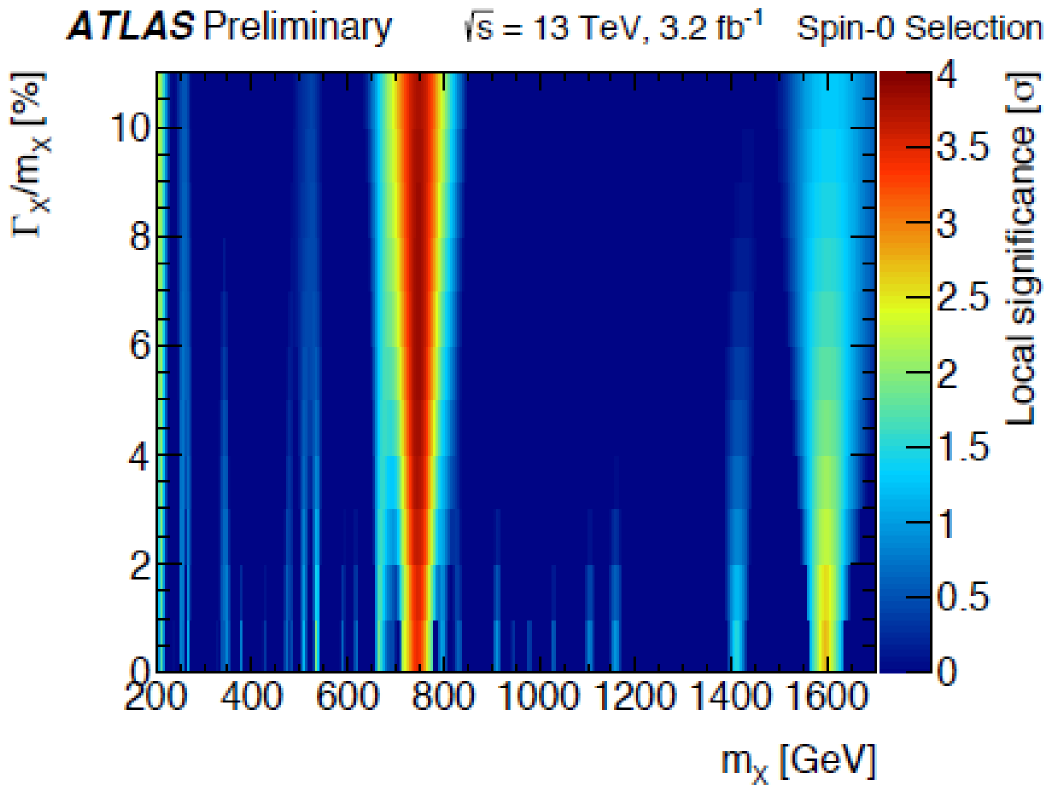
NEW wrt December 2015:

- 2 analysis, depending on spin hypothesis

Significance of the excess



$\Gamma/m = 1.4\text{x}10^{-2}$



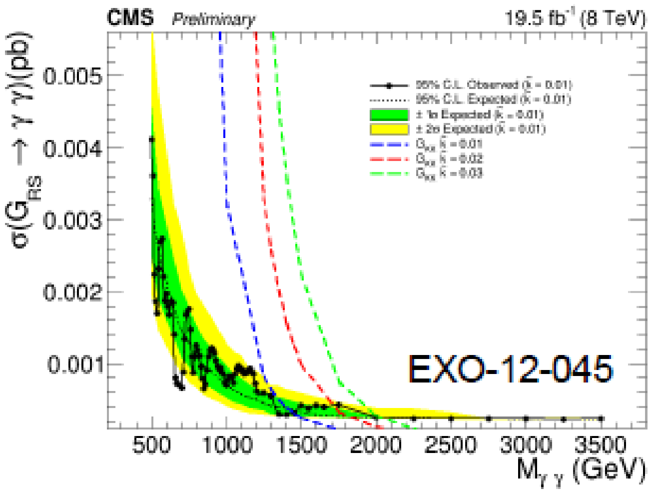
- Largest excess around 760 GeV and narrow width
- Local significance : **2.8-2.9 σ** (depending on spin hypothesis)
- Global: <1 σ

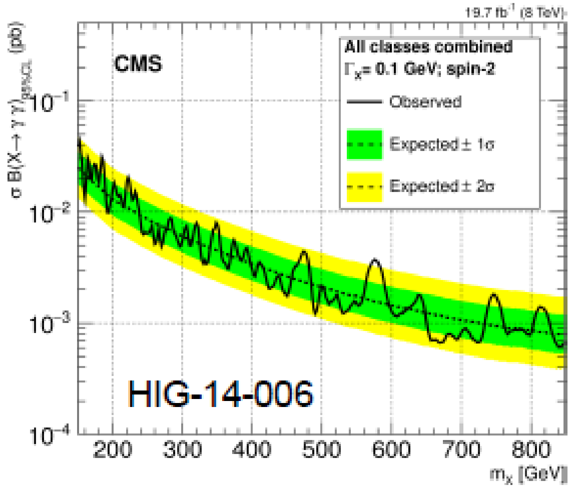
- Largest deviation from B-only hypothesis
  - ✓ m_X ~ 750 GeV, Γ_X ~ 45 GeV (6%)
  - ✓ Local Z = **3.9 σ**
  - ✓ Global Z = **2.0 σ**
    - m_X = [200 GeV - 2 TeV]
    - Γ_X/m_X = [1% - 10%]

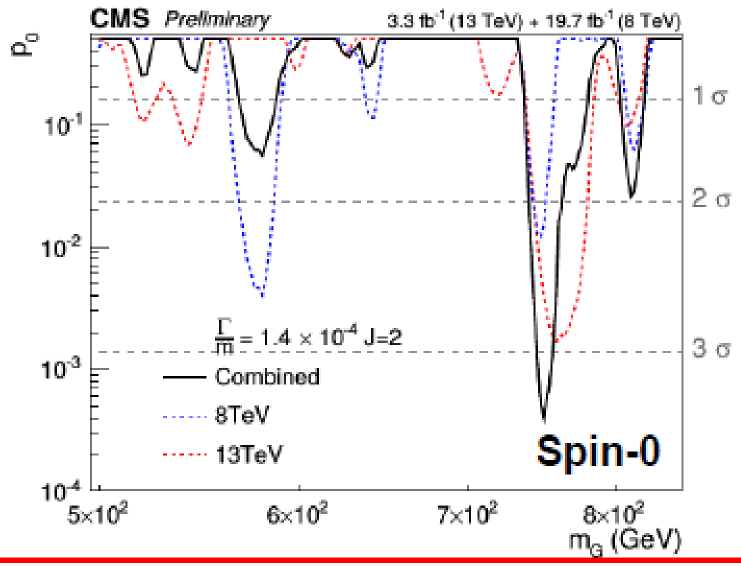
(3.6 σ for spin 2)

What about 8 TeV ?

- CMS performed 2 analysis in the past
- **Combination with 13 TeV with most sensistive 8 TeV analysis**

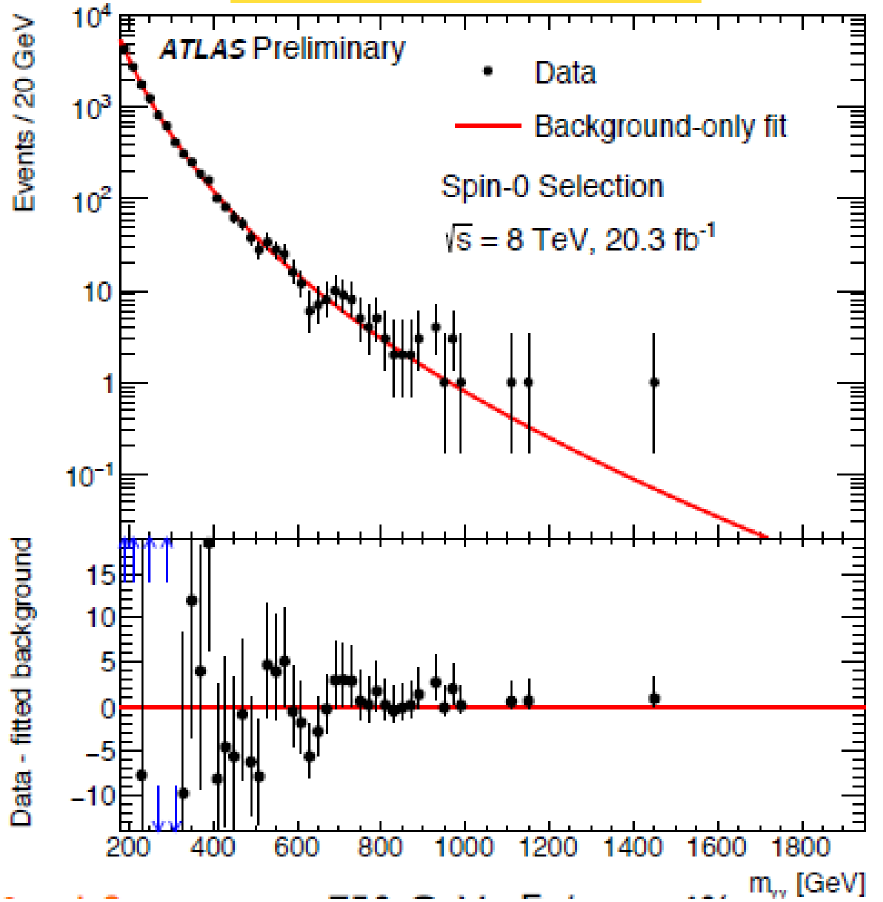






> Largest excess at 750 GeV and narrow width
>
> - **Local Z: 3.4 σ (RunI + RunII)**
> - (Global 1.6 σ)

- **ATLAS re-analyzed Run I data**
  (latest calib, Run I selections but Run II analysis methods)

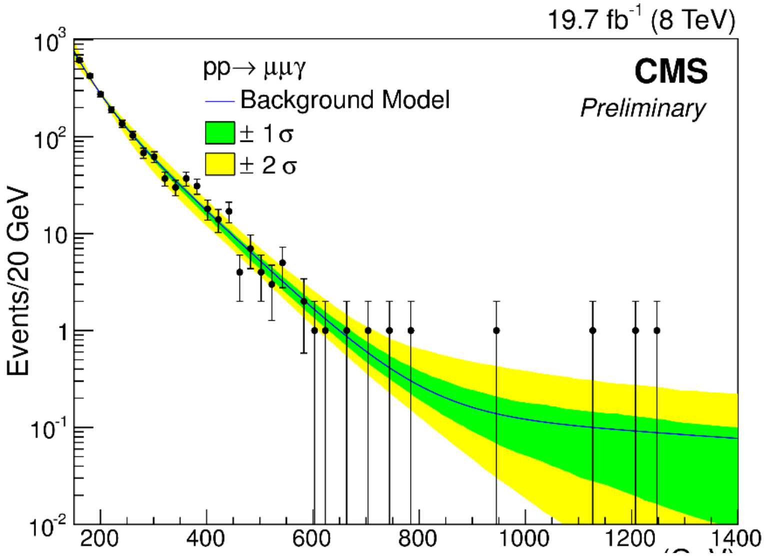


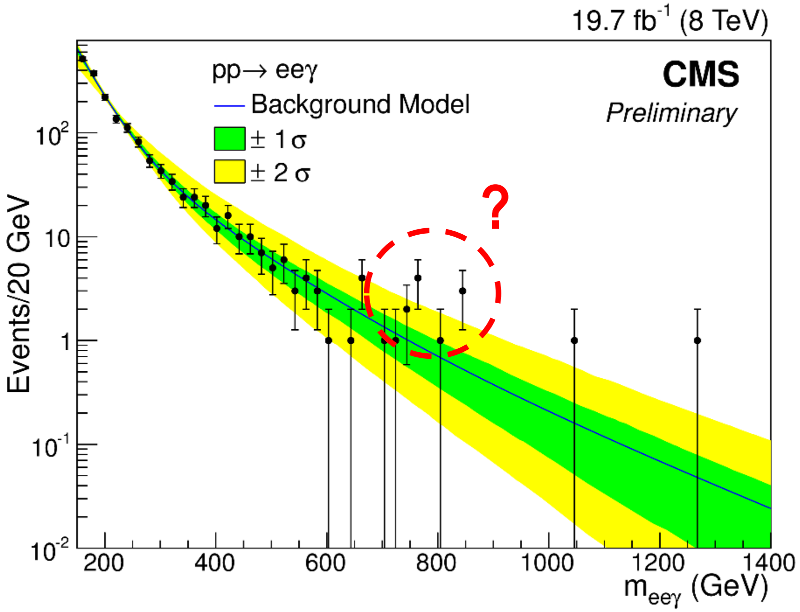
- $1.9\ \sigma$ at $m_X = 750$ GeV , $\Gamma_X/m_X = 6\%$
- Compatibility with 13 TeV scalar
  - ✓ gg (scaling: 4.7) → compatibility: $1.2\ \sigma$
  - ✓ qq (scaling: 2.7) → compatibility: $2.1\ \sigma$

(nothing for spin 2 analysis)

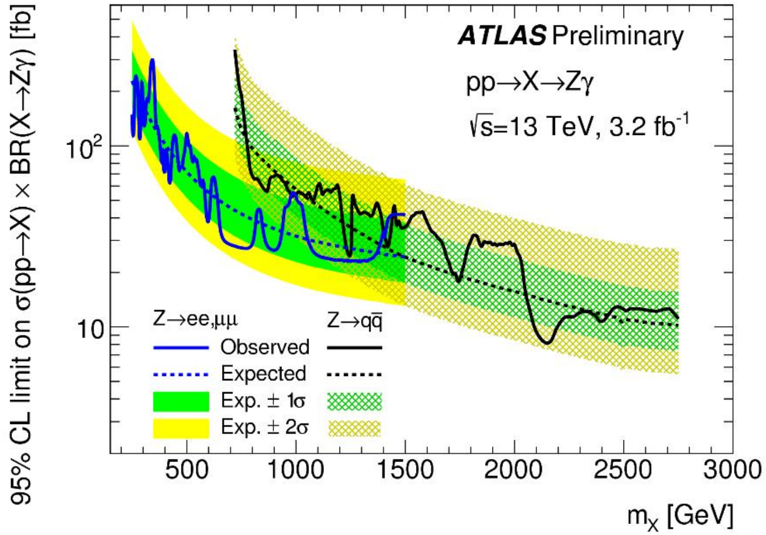
What about other decays ?

X→Z(→ll) γ (Run I)

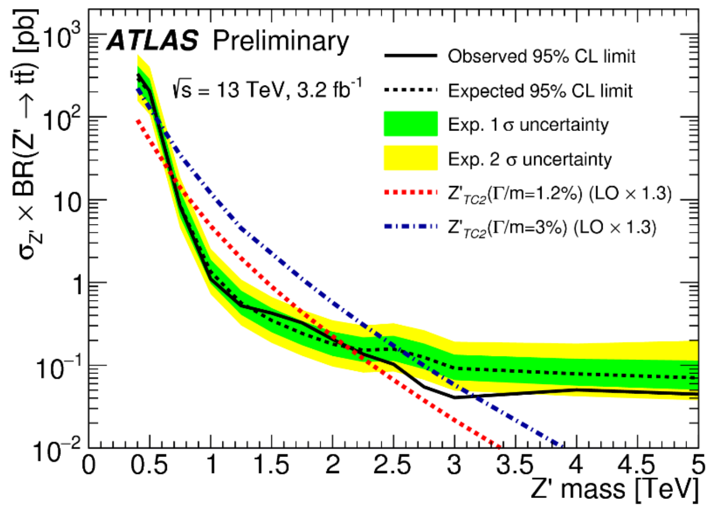




X→Z(→ll or qq) γ (RunII)



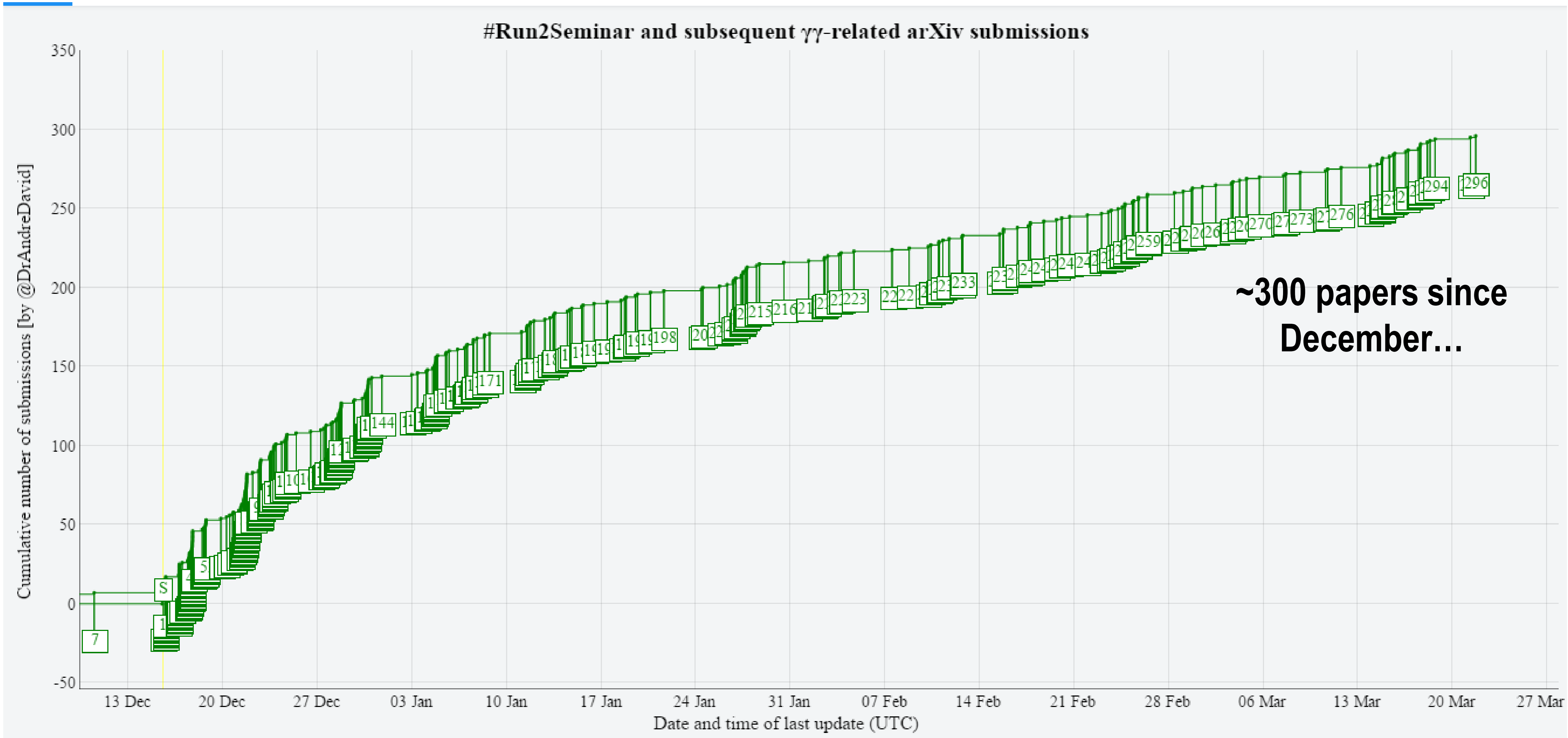
X→ttbar



Not conclusive yet…

What could it be ?!

(almost) 750 explanations…



~300 papers since December…

What could it be ?!

The Big Picture

- Spin 0 or Spin 2.
- Probably produced by gg. σ (gg→X→γγ) ~ 6 +/- 2 fb
- Couplings to gg/γγ induced by heavy fermions loop.

'Who ordered that?' 20th particle, 2nd massive parameter?
Naturalness? Will it kill anthropics? Too joung to tell what it will become.

If broad, new strong dynamics: theory can be predictive.

If narrow, just add weakly coupled extra scalar and extra charged states.

SUSY: S could be H, A, $\tilde{\nu}$, NMSSM, sgoldstinos + sparticles in the loop...

Extra dimensional radion or graviton.

String models often have extra states.

Unification could give extra light multiplets.

Extended gauge group can imply extra chiral fermions, need extra scalars:

G	extra ψ	diphoton	diboson
$\mathrm{SU}(3)_L \otimes \mathrm{U}(1) \otimes \mathrm{SU}(3)_c$	L, D	yes	no
$\mathrm{SU}(3)_L \otimes \mathrm{SU}(3)_R \otimes \mathrm{SU}(3)_c$	L, D	yes	yes
$\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1) \otimes \mathrm{SU}(3)_c$	–	ad hoc	yes

From A. Strumia

A mirage ?

(a.k.a., fluctuation !)

Theorist waiting for 30 years for new physics…

Perspectives

The discovery of the Higgs boson opens a new chapter in HEP.

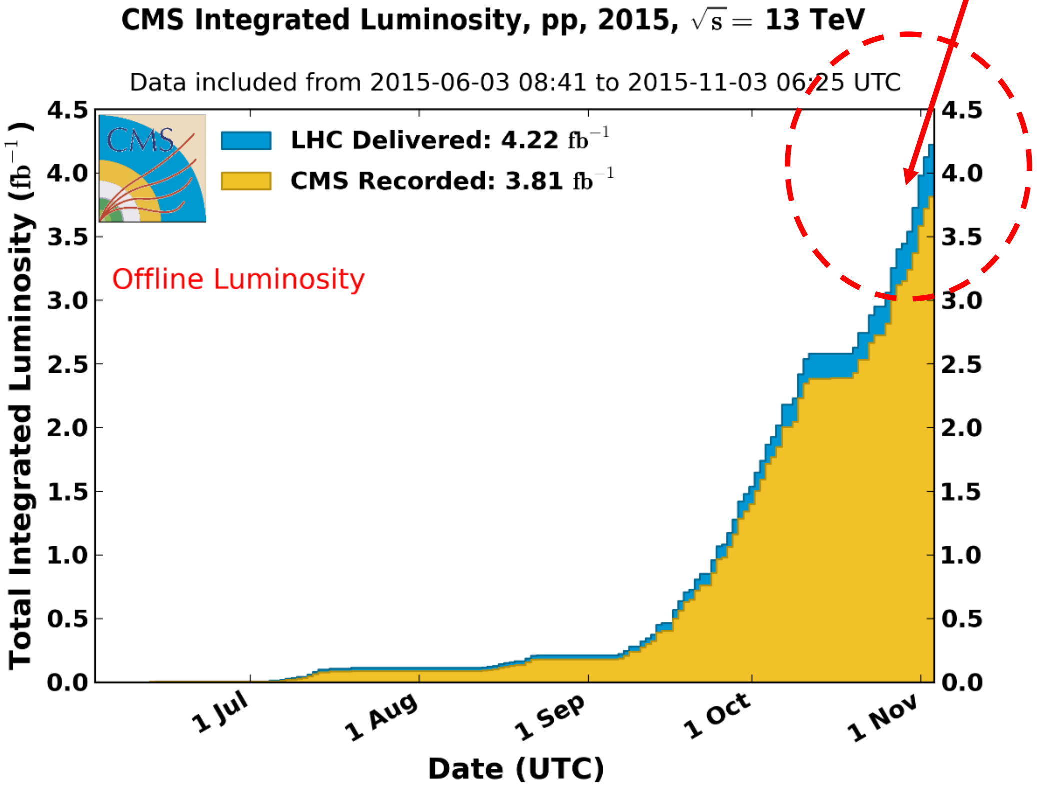
- **Physics is now at a turning point….**

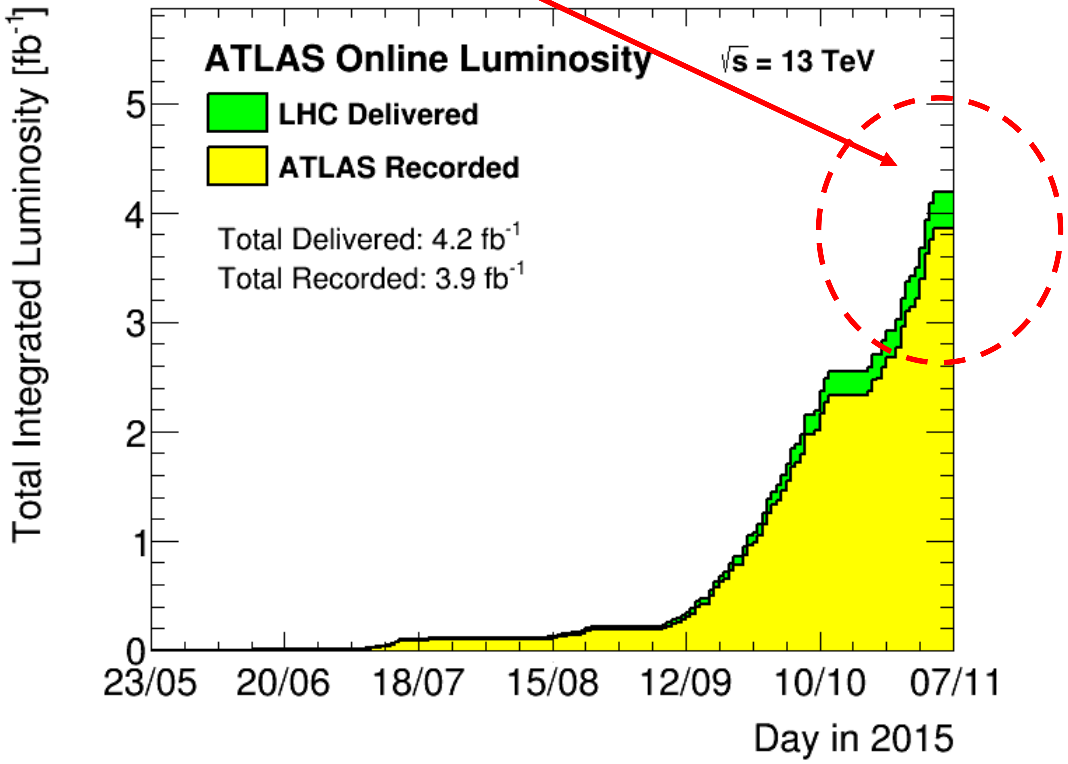
- **If nothing but the Higgs, are we ready to cross the desert ?**
  - Understanding EWSB & its consequences is the beginning of a long journey…
  - Irrespective of direct observation of physics at TeV scale, a rich program is ahead of us at (HL-)LHC and future colliders
    - Precision measurements, rare/forbidden decays, HH,…

- **On the other hand, are we ready for the unexpected ?**
  - Will it come from the 750 GeV excess ?
  - By ICHEP (August '16), we will have firm observation… or not !
  - By 2016 (30 fb^{-1}), confirmation (or not!) with other decay channels (Zγ, VV$\rightarrow$hadronic, …)

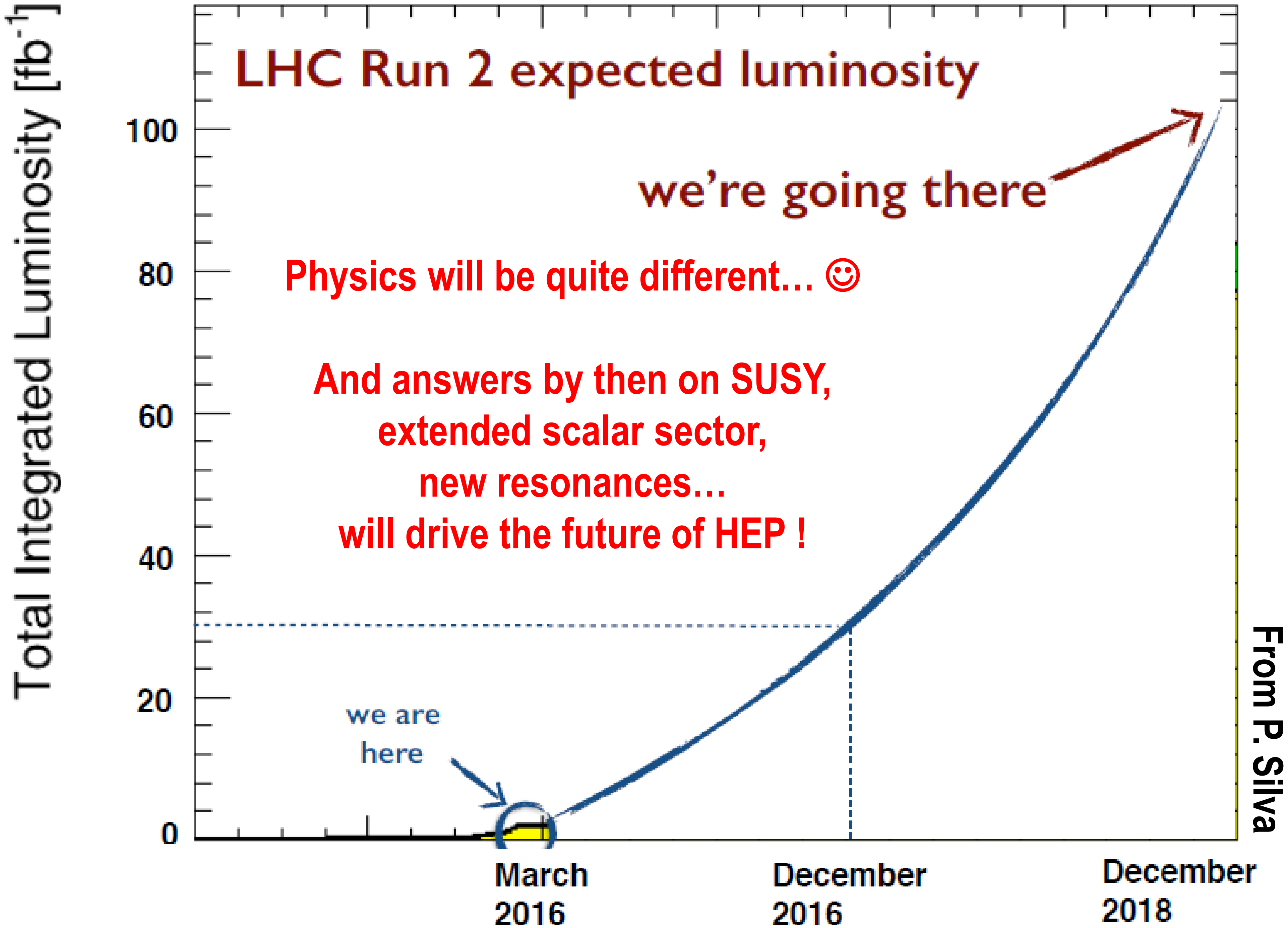
Towards 2018…

We are here





Towards 2018…



BACK UP SLIDES

$$\mathscr{L}_{\mathrm{SM}} = \underbrace{\mathscr{L}_{\mathrm{gauge}}(A_a, \psi_i)} + \underbrace{\mathscr{L}_{\mathrm{Higgs\ (Symm.\ Break.)}}(\phi, A_a, \psi_i)}$$

From G. Isidori

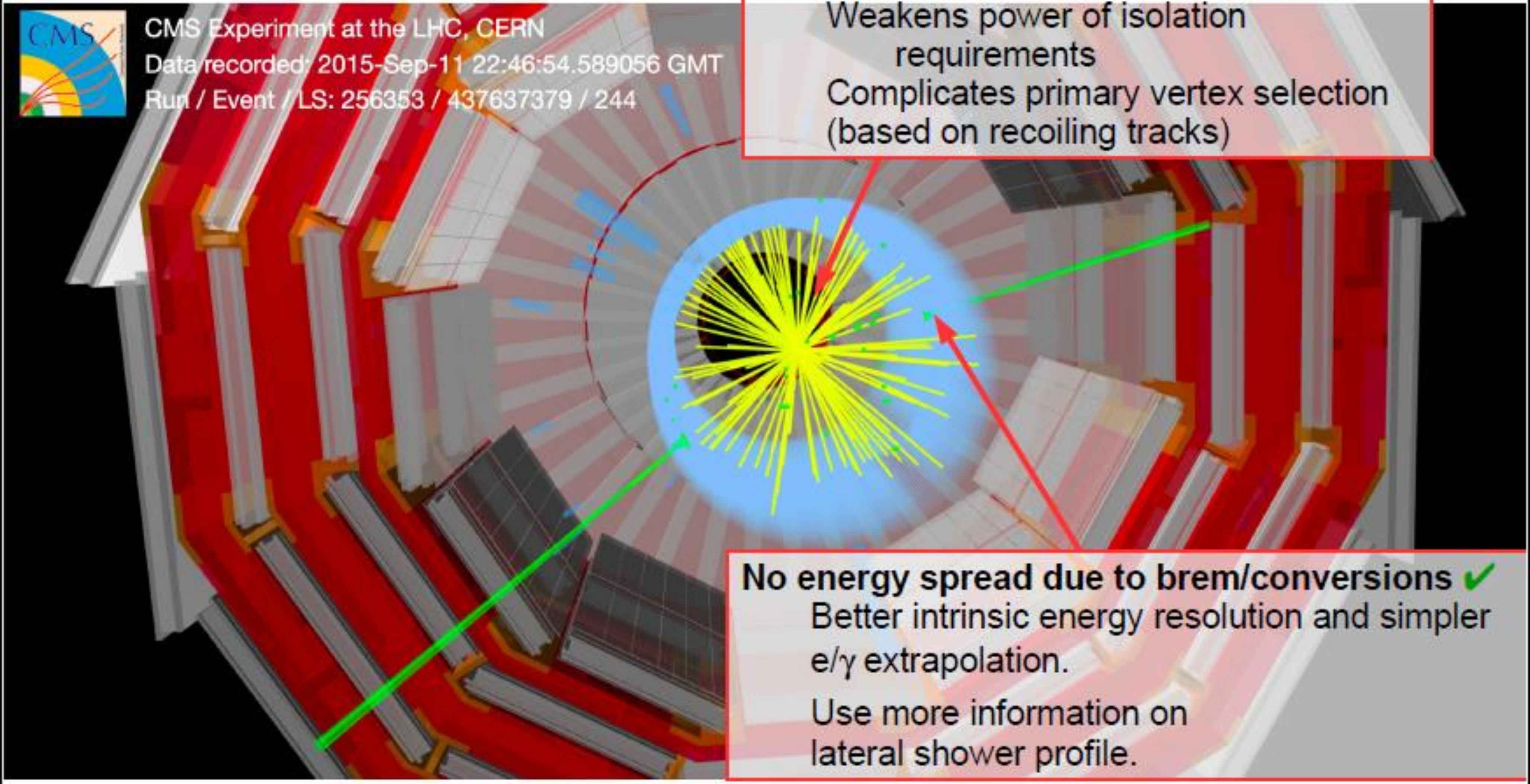
- Elegant, Based on symmetries
- Completely define all possible fundamental interactions (EW, strong)
- Massless particles

- **Ad-hoc…**
- … but necessary to describe reality !
- Related to the deepest problems of HEP (hierarchy, naturalness, vacuum energy cosmological constant, flavor puzzle & CP, …)

Analyzing B=0T data

NEW

- Significant re-thinking of the analysis needed to use data without magnetic field.



No information on tracks momenta ✗

Weakens power of isolation requirements

Complicates primary vertex selection (based on recoiling tracks)

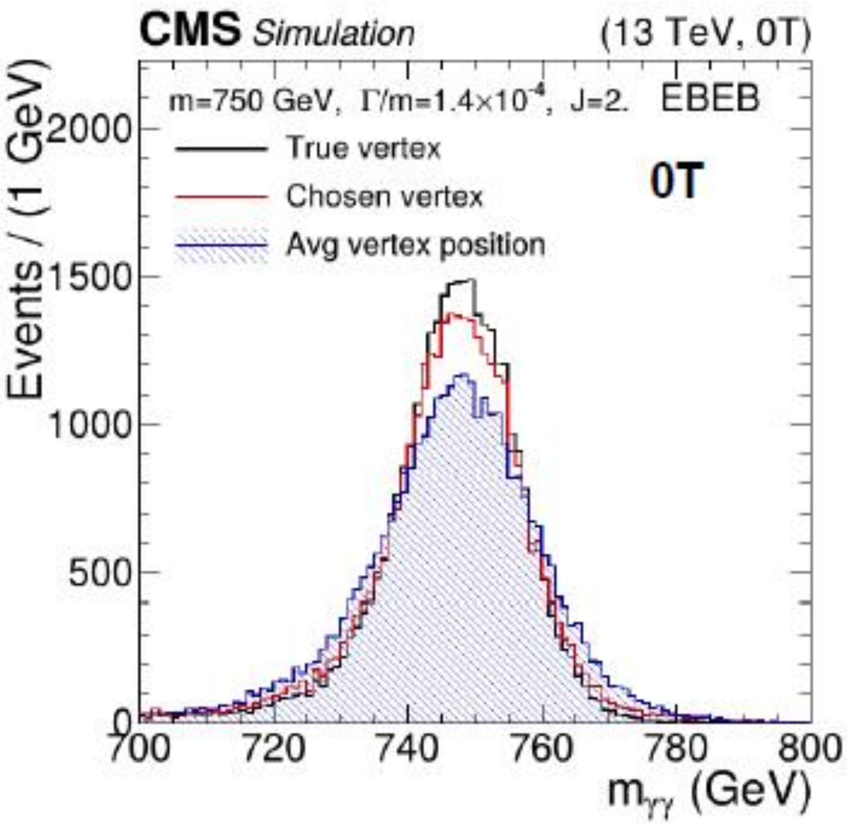
No energy spread due to brem/conversions ✓

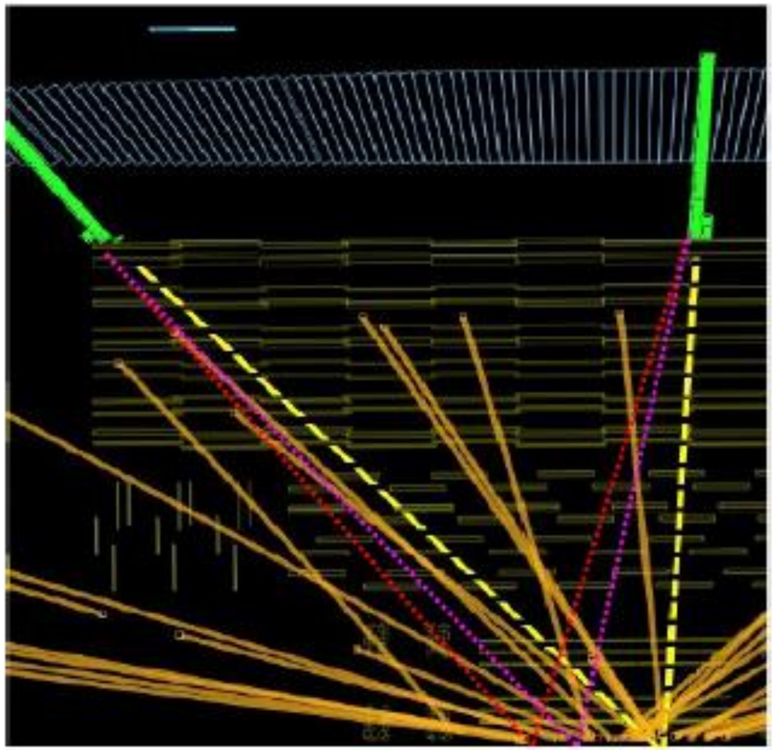
Better intrinsic energy resolution and simpler e/γ extrapolation.

Use more information on lateral shower profile.

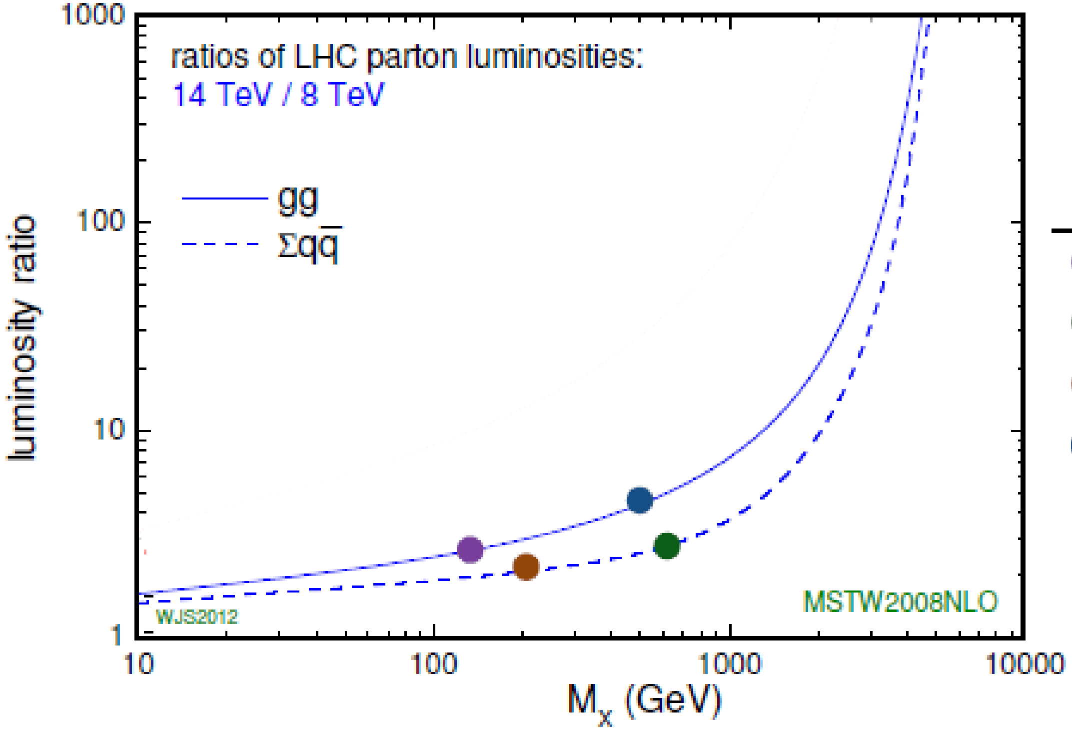
Vertex identification

- Vertex identification important to maintain good mass resolution.
  - For 3.8T: use BDT (using recoil and tracks p_T) trained for $H \rightarrow \gamma\gamma$. ***(see I.Kucker in Wed. YSF)***.
  - For **0T:** simpler algorithm based on **track-counting**.
  - **Correct** assignments: **90% at 3.8T**, **60% at 0T**





Higgs in Run II/III (13/14 TeV)



	$\sigma_{14TeV}/\sigma_{8TeV}$	σ_{14TeV} [pb]
● $gg \to h$	2.6(M_X=M_h)	49.5
● $qq \to qqh$	2.6(high M_X)	4.2
● $qq \to Vh$	2.1(M_X=M_V+M_h)	1.5/1
● $gg \to tth$	4.7(M_X=2M_t+M_h)	0.6

From R. Salerno

Higgs boson candidates for 300 fb^{-1} at 14 TeV:

ggF	VBF	Wh	Zh	tth	total
14M	1.3M	0.5M	0.3M	0.2M	17M

→ Access rare(r) Higgs boson production and decay modes

26K th candidates, 14K hh candidates

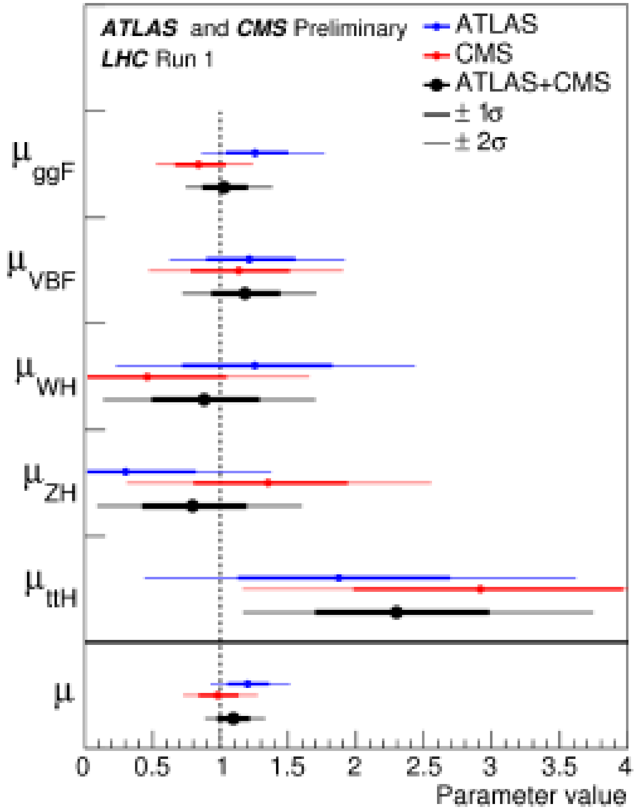
$BR_{h\to\mu\mu}$ = 0.021% $BR_{h\to Z\gamma}$ = 0.15% ($BR_{h\to Z\gamma\to ll\gamma}$ = 0.01%)

In 2015, with ~2-3 fb-1, only possible to ~re-observe, establish methods for future runs, …

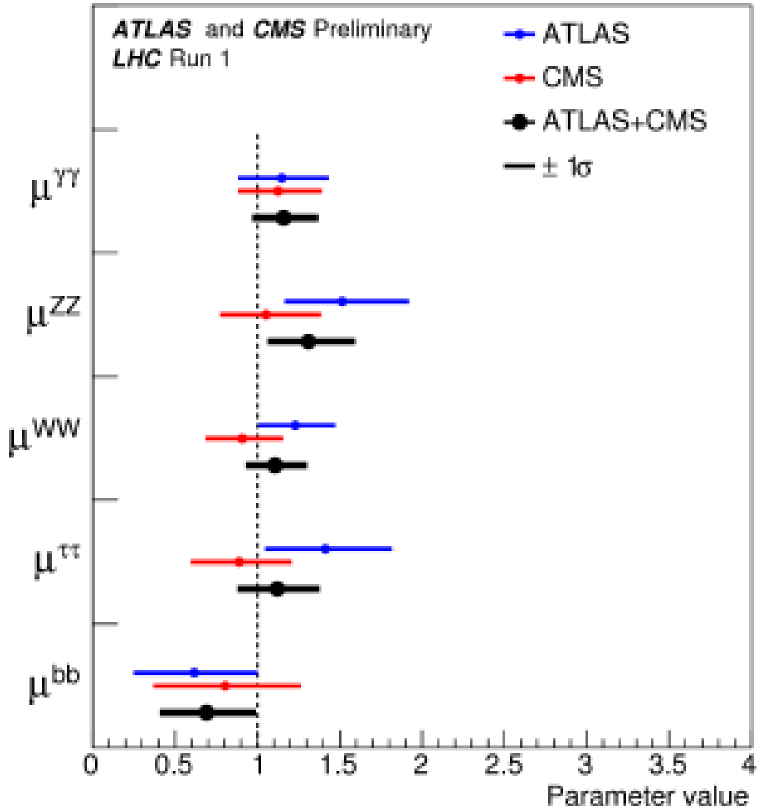
Channel	References for individual publications		Signal strength [μ]		Signal significance [σ]	
			from results in this paper (Section 5.2)			
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	[59]	[60]	$1.14^{+0.27}_{-0.25}$	$1.11^{+0.25}_{-0.23}$	5.0	5.6
			$\left(^{+0.26}_{-0.24}\right)$	$\left(^{+0.23}_{-0.21}\right)$	(4.6)	(5.1)
$H \to ZZ \to 4\ell$	[61]	[62]	$1.52^{+0.40}_{-0.34}$	$1.04^{+0.32}_{-0.26}$	7.6	7.0
			$\left(^{+0.32}_{-0.27}\right)$	$\left(^{+0.30}_{-0.25}\right)$	(5.6)	(6.8)
$H \to WW$	[63, 64]	[65]	$1.22^{+0.23}_{-0.21}$	$0.90^{+0.23}_{-0.21}$	6.8	4.8
			$\left(^{+0.21}_{-0.20}\right)$	$\left(^{+0.23}_{-0.20}\right)$	(5.8)	(5.6)
$H \to \tau\tau$	[66]	[67]	$1.41^{+0.40}_{-0.36}$	$0.88^{+0.30}_{-0.28}$	4.4	3.4
			$\left(^{+0.37}_{-0.33}\right)$	$\left(^{+0.31}_{-0.29}\right)$	(3.3)	(3.7)
$H \to bb$	[46]	[47]	$0.62^{+0.37}_{-0.37}$	$0.81^{+0.45}_{-0.43}$	1.7	2.0
			$\left(^{+0.39}_{-0.37}\right)$	$\left(^{+0.45}_{-0.43}\right)$	(2.7)	(2.5)
$H \to \mu\mu$	[68]	[69]	-0.6 ± 3.6	$0.9^{+3.6}_{-3.5}$		
			(± 3.6)	$\left(^{+3.3}_{-3.2}\right)$		
ttH production	[36, 70, 71]	[73]	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
			$\left(^{+0.7}_{-0.7}\right)$	$\left(^{+0.9}_{-0.8}\right)$	(1.6)	(1.3)

Signal strength $\mu_i^f = (\sigma_i.BR_f)meas / (\sigma_i.BR_f)theo = \mu_i \cdot \mu^f$

Cross-section per production mode (assuming SM BR) compared to theory prediction

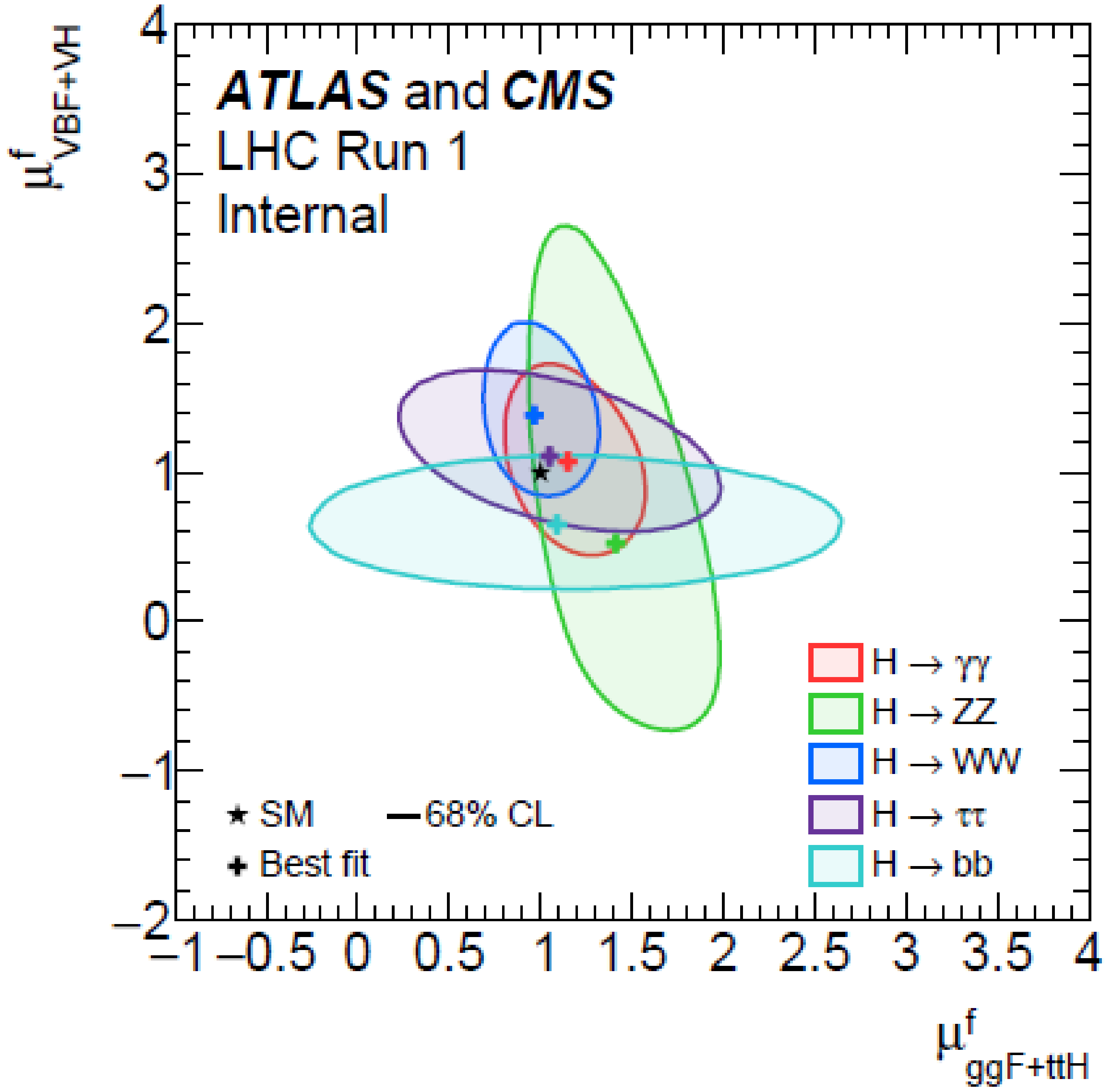


Branching ratio per decay mode (assuming SM cross-section) compared to theory prediction

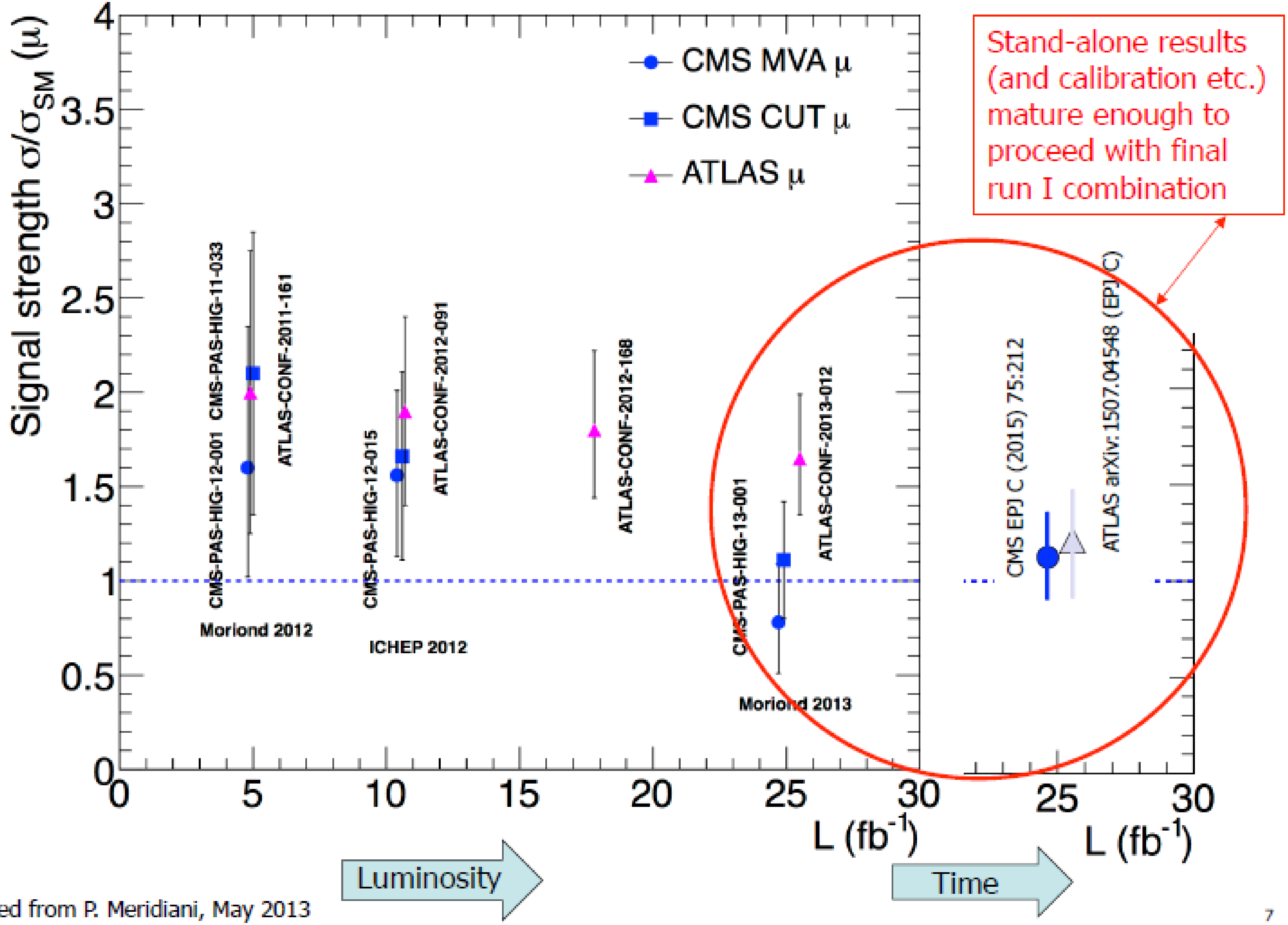


Global signal strength assuming SM ratio for all production and decay (~10% accuracy):

$$\mu = 1.09 \pm 0.07_{\text{stat}} \pm 0.04_{\text{exp syst.}} \pm 0.03_{\text{th. bkg}} {}^{+0.07}_{-0.06}{}_{\text{th. sigma}}$$


ATLAS and CMS
LHC Run 1
Internal
μ^f_{VBF+VH}
$\mu^f_{ggF+ttH}$
4
3
2
1
0
−1
−2
−1
−0.5
0
0.5
1
1.5
2
2.5
3
3.5
4
★ SM
✚ Best fit
— 68% CL
$H \to \gamma\gamma$
$H \to ZZ$
$H \to WW$
$H \to \tau\tau$
$H \to bb$

H → γγ signal strength – vs $\mathcal{L}$ and Time



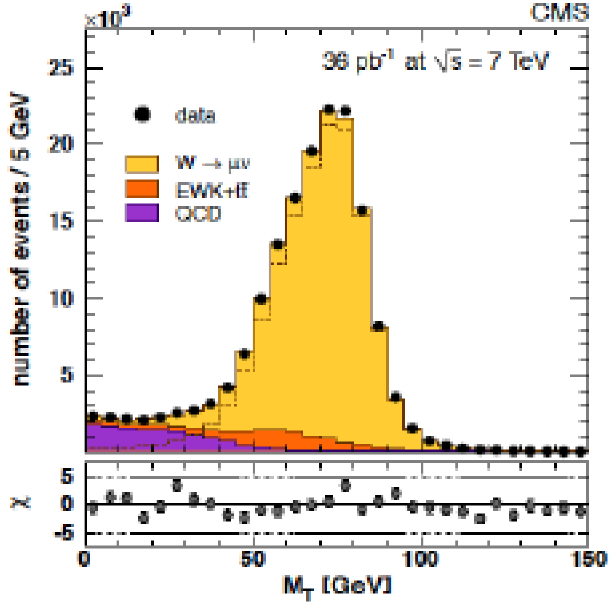
Adapted from P. Meridiani, May 2013

Decomposing the W events

What we see in the detector
→ We can calibrate

lepton

JHEP 10 (2011) 132, arXiv:1107.4789



recoil=(PU+UE+jets)

What we try to describe with MC

Boson production/decay

- proton PDF
- boson p_T (QCD and EWK, higher order)
- boson decay (polarization+ FSR)