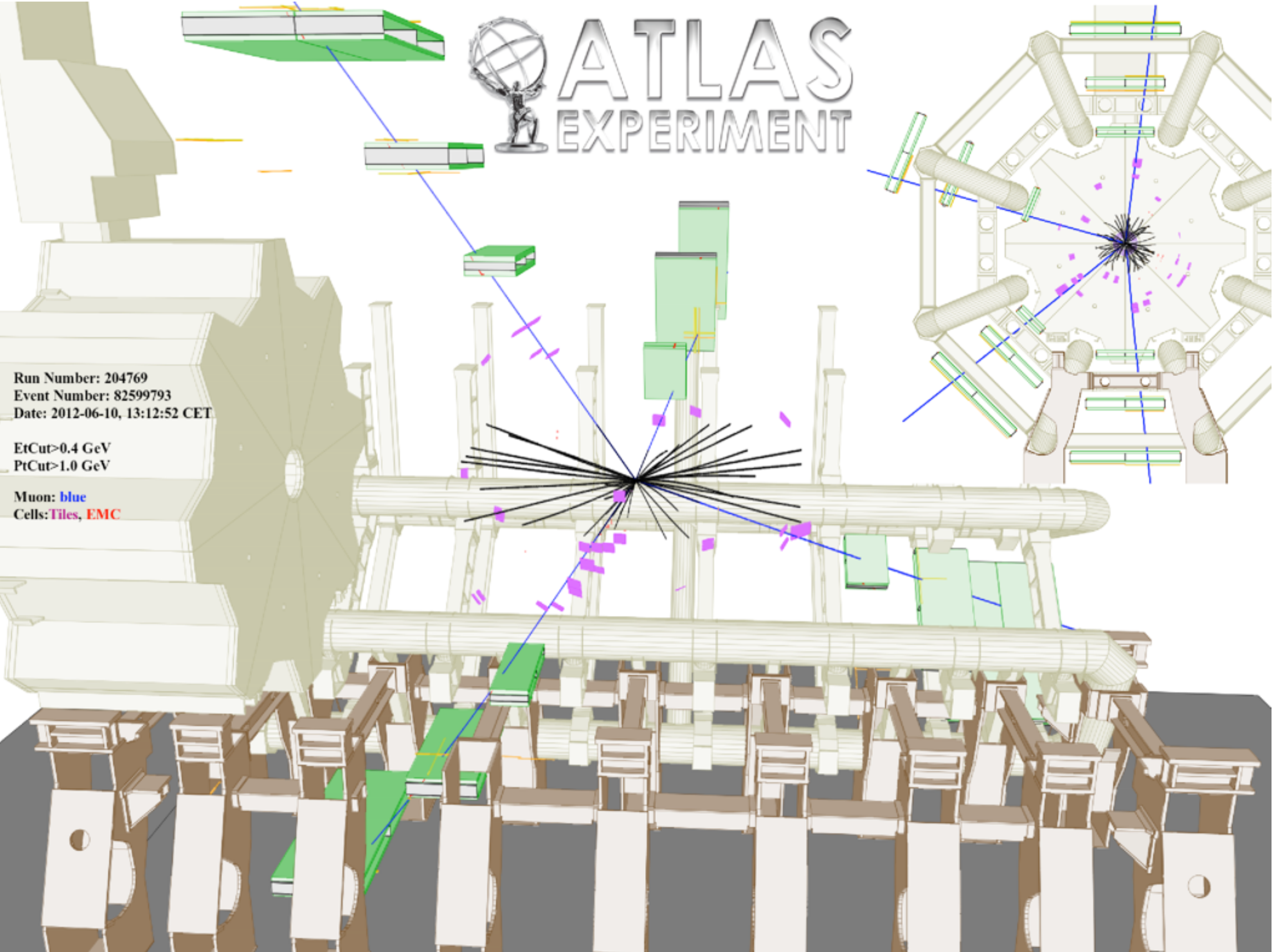


Status of the Higgs sector at the LHC

K. Nikolopoulos

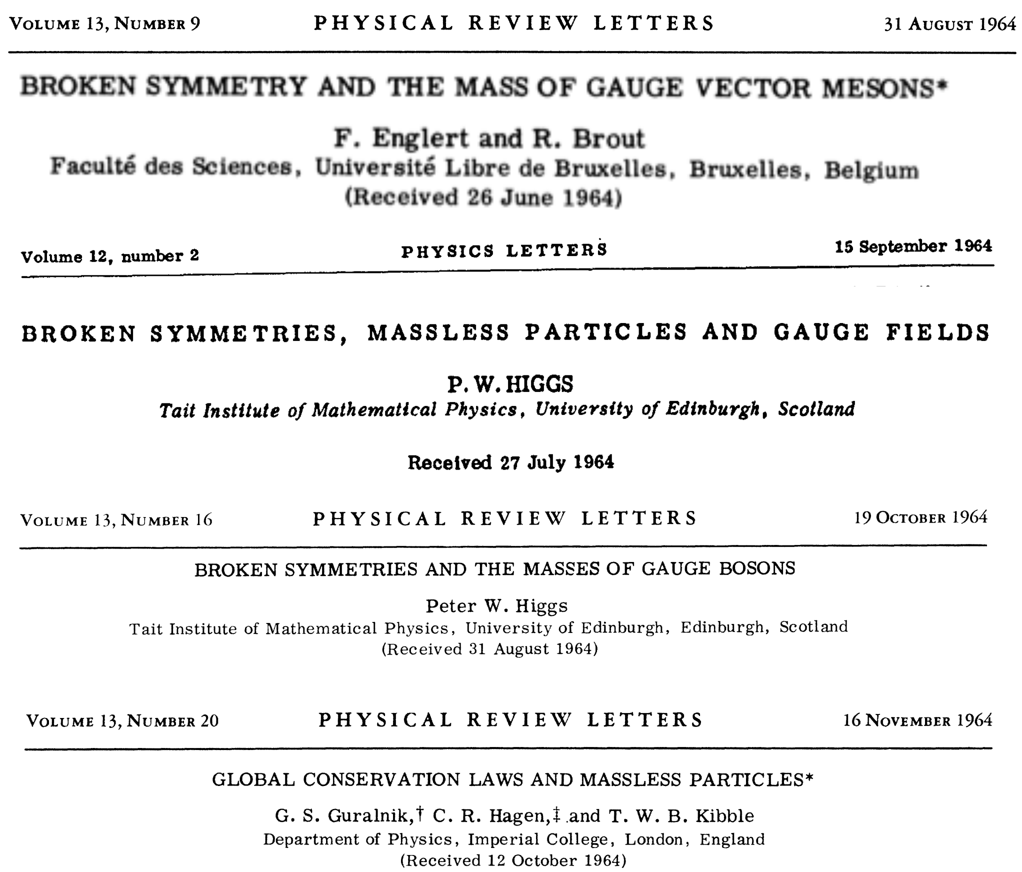
University of Birmingham

UNIVERSITY OF BIRMINGHAM

IoP Joint annual HEPP and APP conference

21st March 2016, University of Sussex, UK

The Higgs boson in the Standard Model



VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

Volume 12, number 2 PHYSICS LETTERS 15 September 1964

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

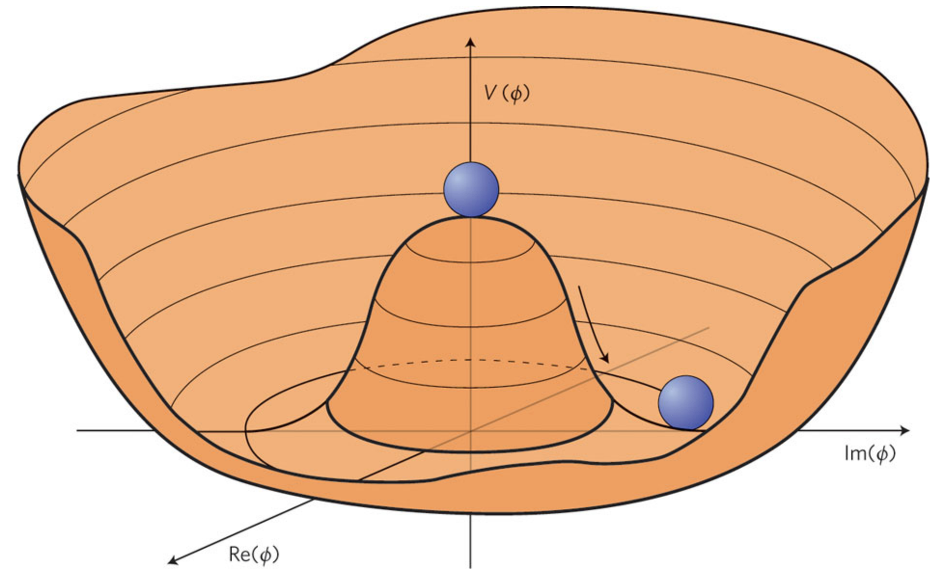
BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

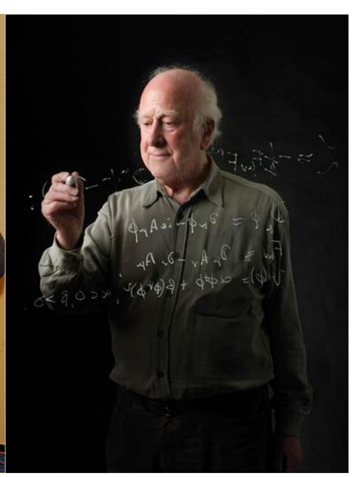
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

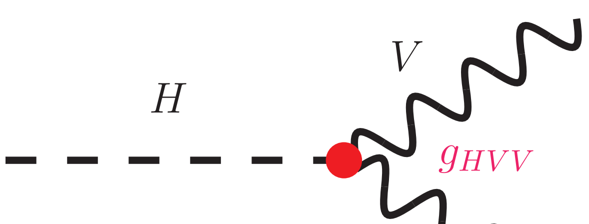


$$\varphi = \frac{1}{\sqrt{2}}\begin{pmatrix}\varphi^+\\ \varphi^0\end{pmatrix},$$

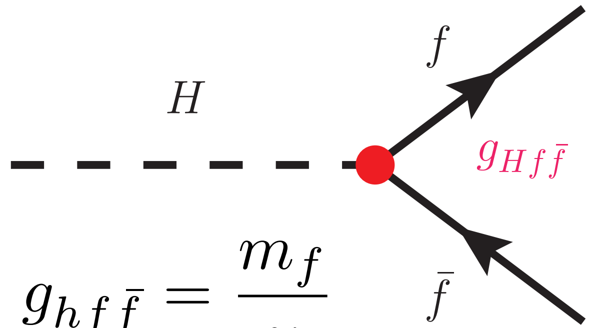
→ Unification of electromagnetic and weak interactions: $SU(2)_L \otimes U(1)_Y$ local gauge symmetry; massless carriers
→ Symmetry spontaneously broken via Higgs field's VEV≠0
→ 4 degrees of freedom of Higgs field
  → 3 become the vector bosons' longitudinal polarisations
  → the remaining is the Higgs boson
  → most economic way for EWSB



- h→VV defined by symmetry breaking
- h→ffbar is Yukawa coupling $\propto m_f$



$$g_{hVV} = \frac{2m_V^2}{v}$$



$$g_{hf\bar{f}} = \frac{m_f}{v}$$

How many Higgs bosons?

In the Standard Model (tree level) it is predicted that: $\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_w} = 1$

Measurement: $\rho_0 = 1.00040 \pm 0.00024$

LEP, SLD, Tevatron, …

The ρ-parameter constrains the structure of the scalar sector
In $SU(2)_L \otimes U(1)_Y$, ρ=1 at tree level for scalar sectors with:

→ singlets with Y=0
→ doublets with Y=±1
→ more complex arrangements…

$$\rho = \frac{\sum_{i=1}^{n}\left[I_i\left(I_i+1\right)-\frac{1}{4}Y_i^2\right]v_i}{\sum_{i=1}^{n}\frac{1}{2}Y_i^2 v_i}$$

Simplest extensions of scalar sector

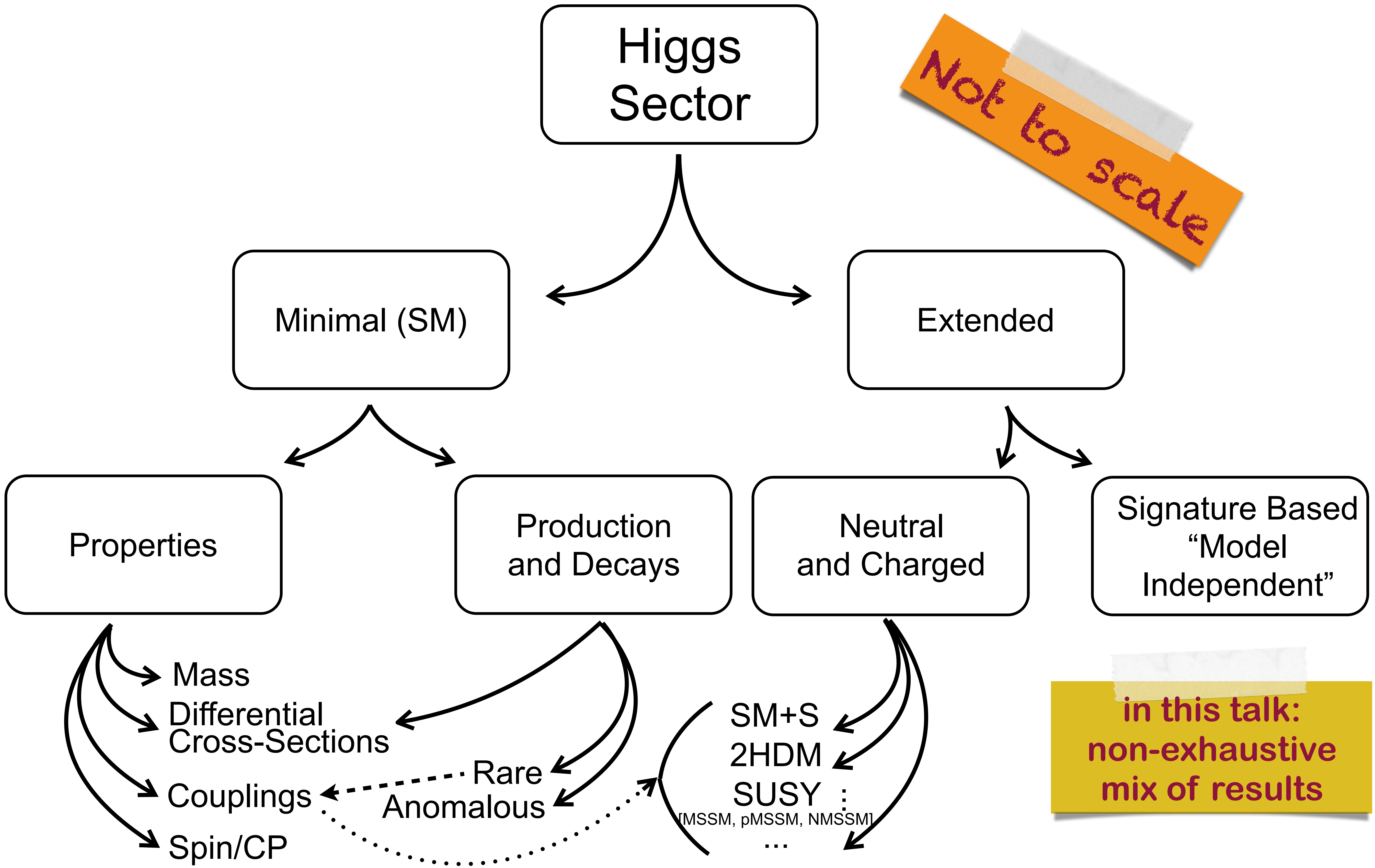
Higgs doublet + Singlet

singlet can be real or complex
real: h, s
complex: h, s, a

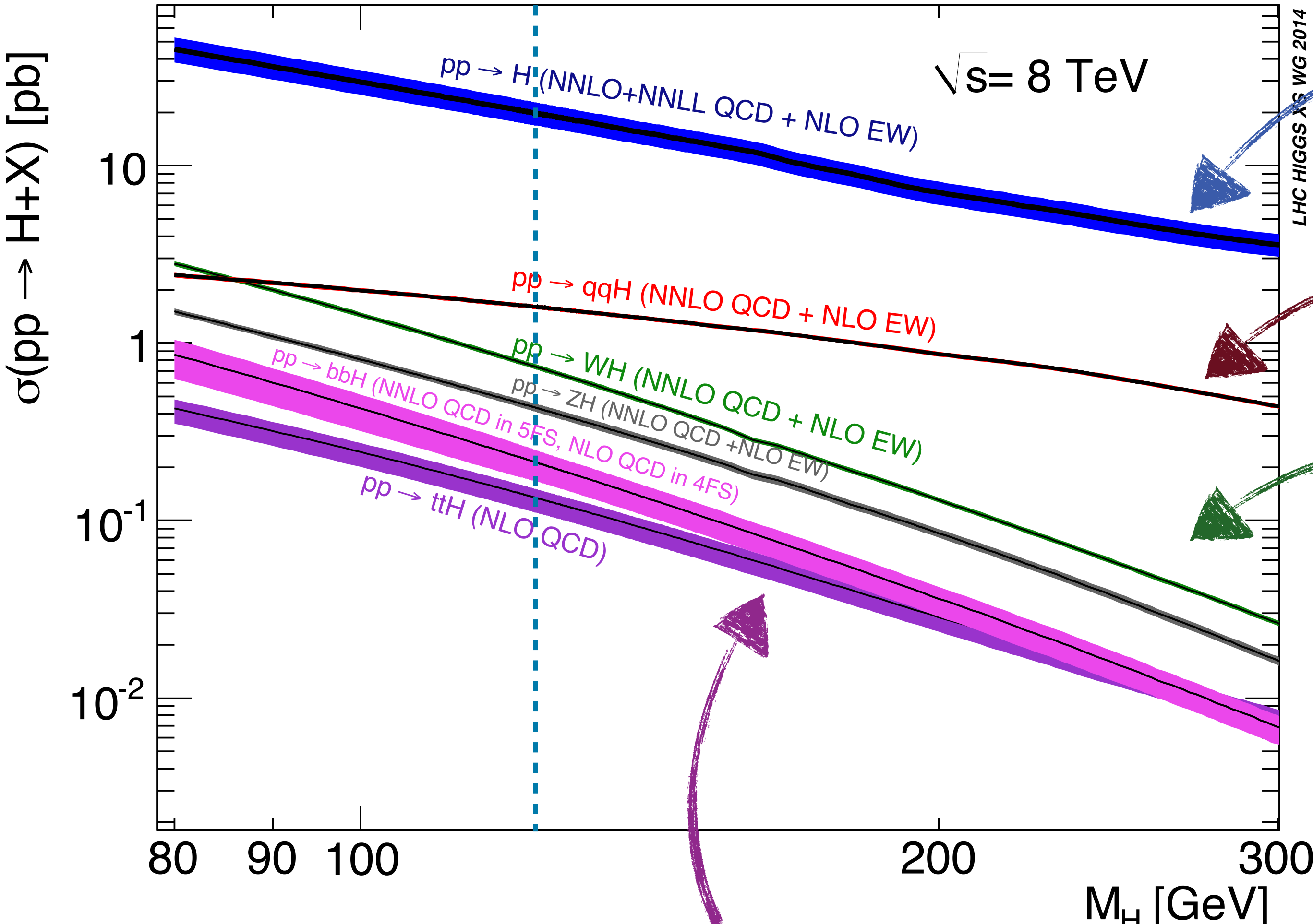
Two Higgs doublets

5 physical Higgs bosons
(CP-conserving scenario: h/H, A, $H^{\pm}$)

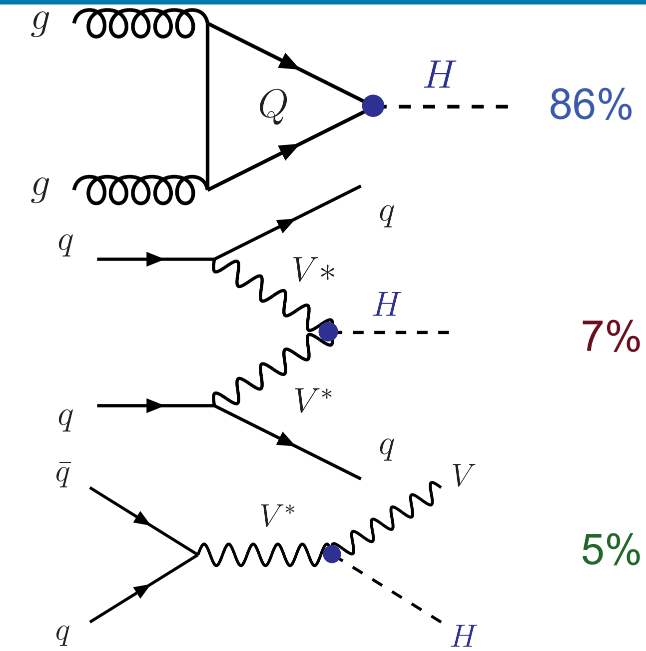
Landscape of studies in Higgs sector

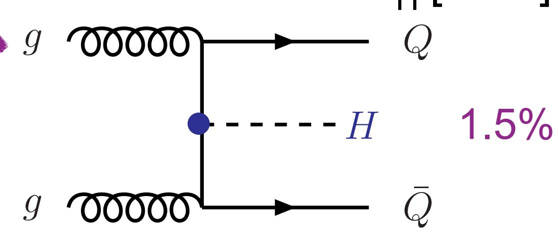


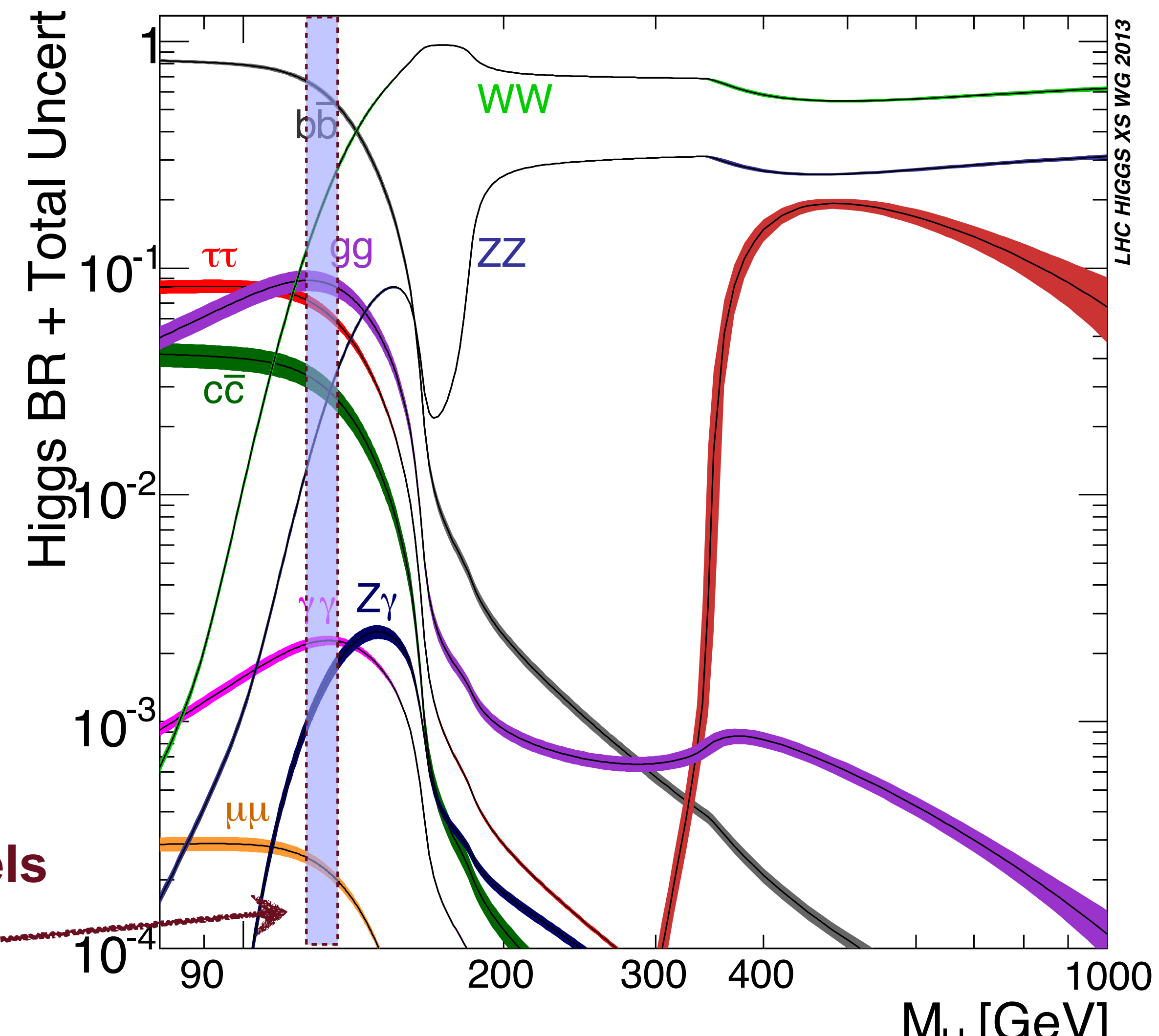
SM Higgs boson production and decay at the LHC



m_H = 125 GeV

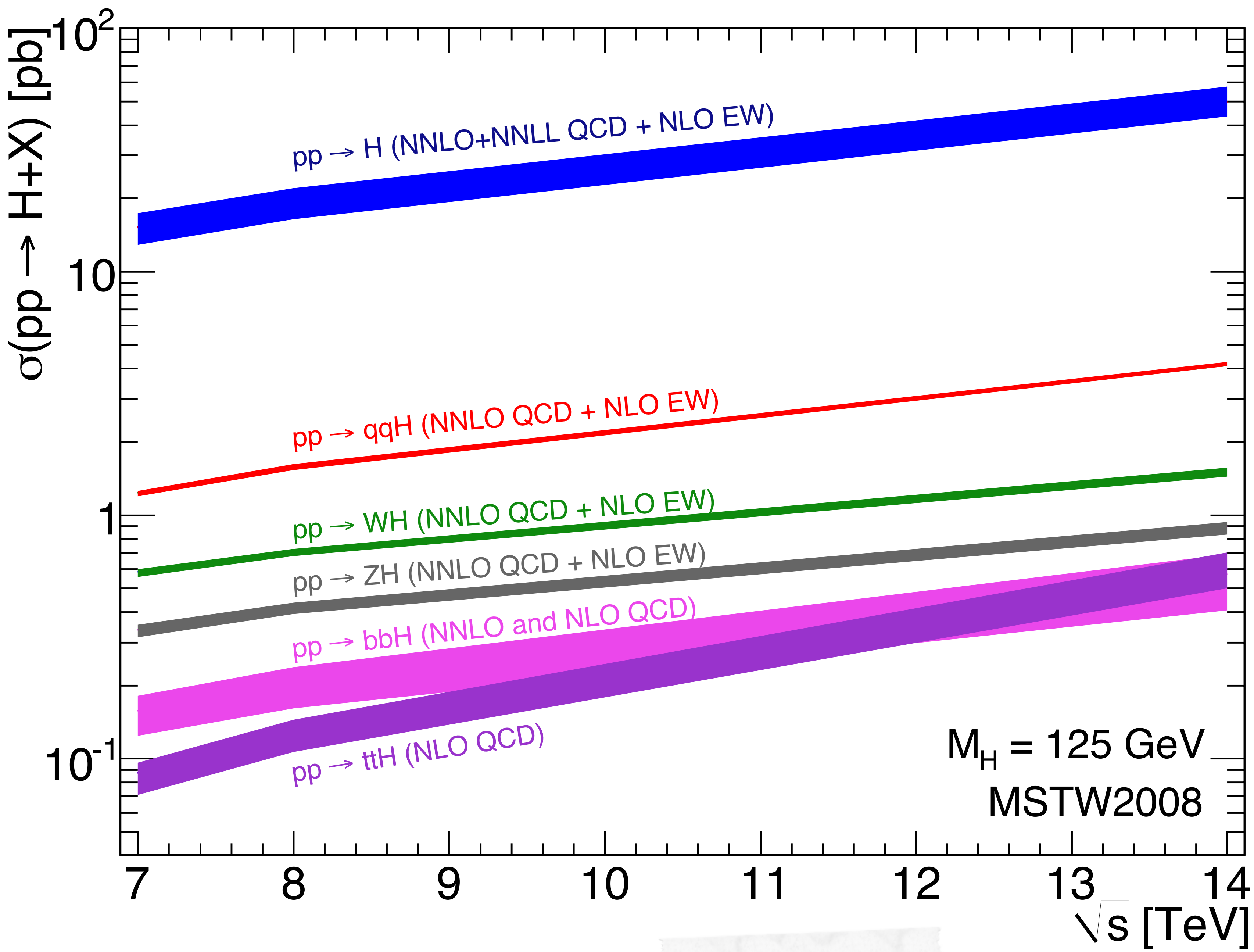


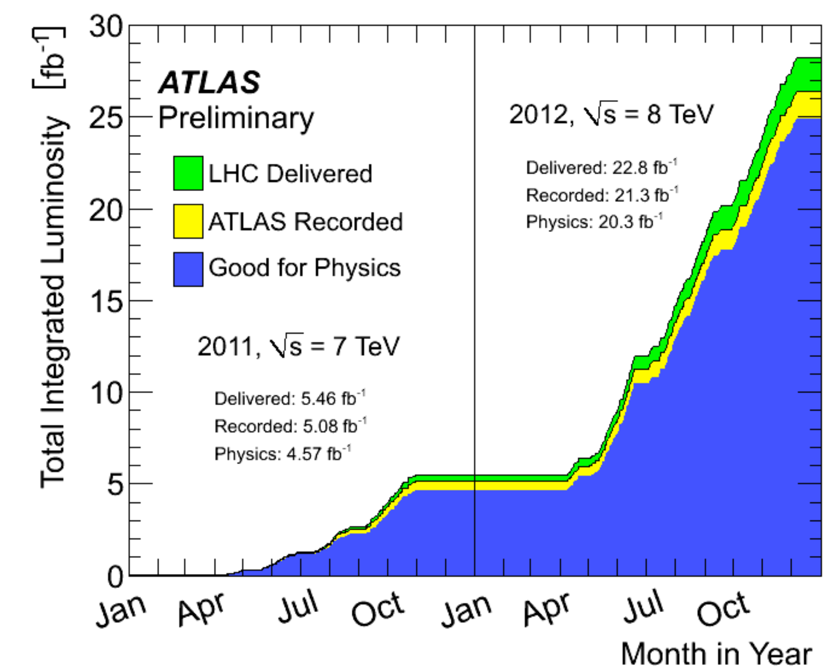


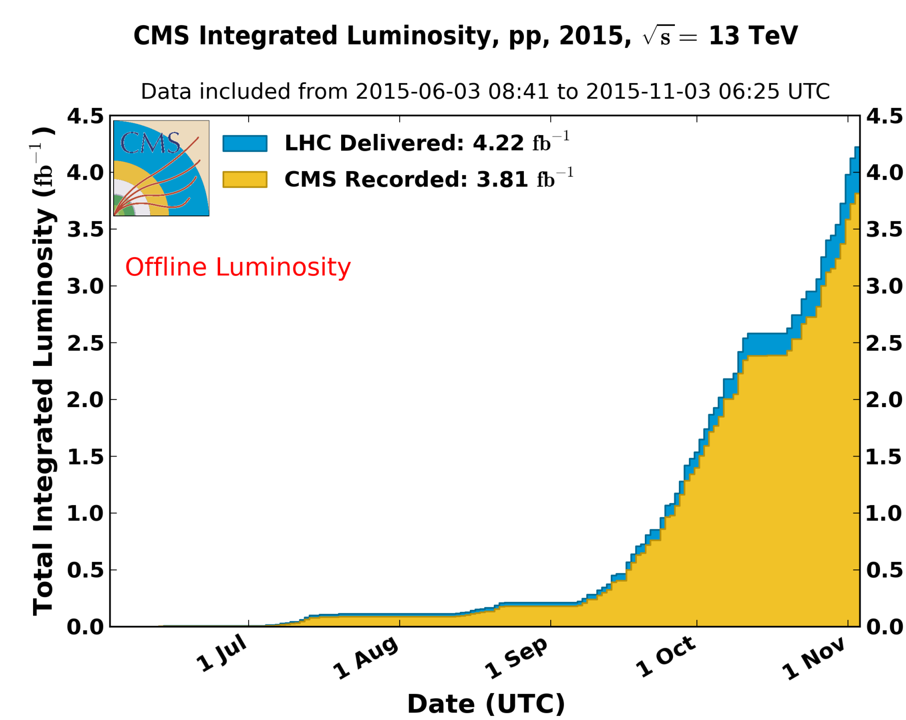


m_h~125 GeV gives access to several decay channels
Gauge bosons: γγ, ZZ*, WW*, Zγ
Fermions: bb, ττ, μμ

SM Higgs boson production versus √s







Production cross section

(m_H=125 GeV)

17.5 pb @ 7 TeV

22.3 pb @ 8 TeV

50.9 pb @ 13 TeV

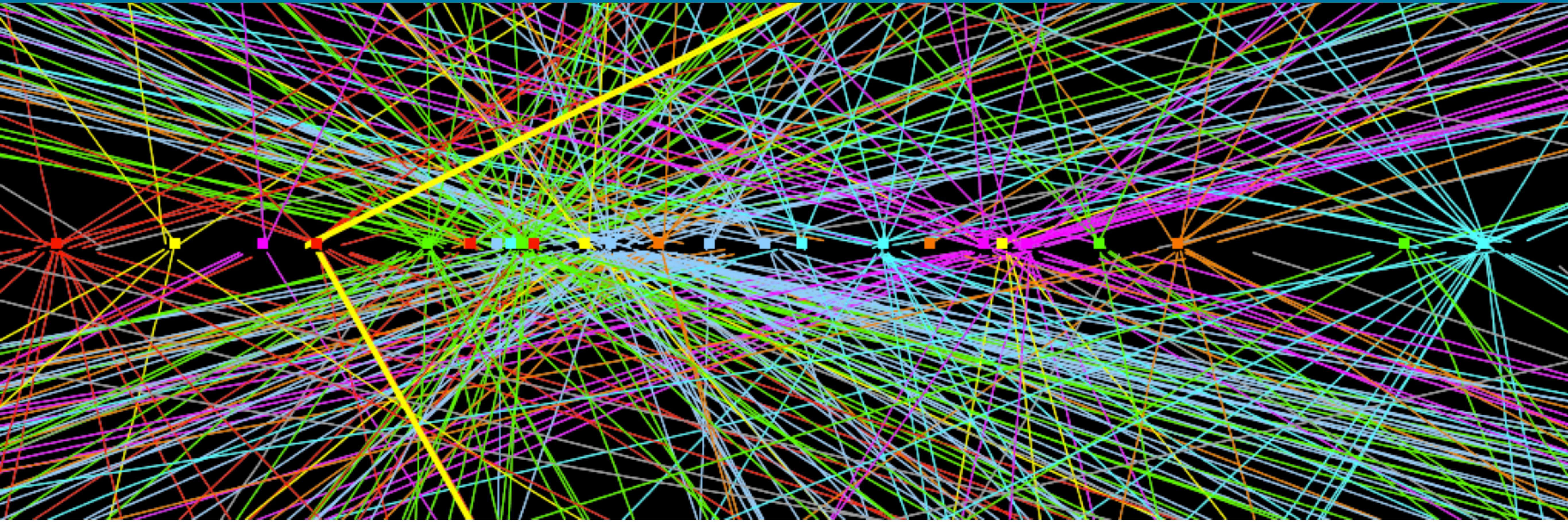
57.4 pb @ 14 TeV

8→13 TeV:

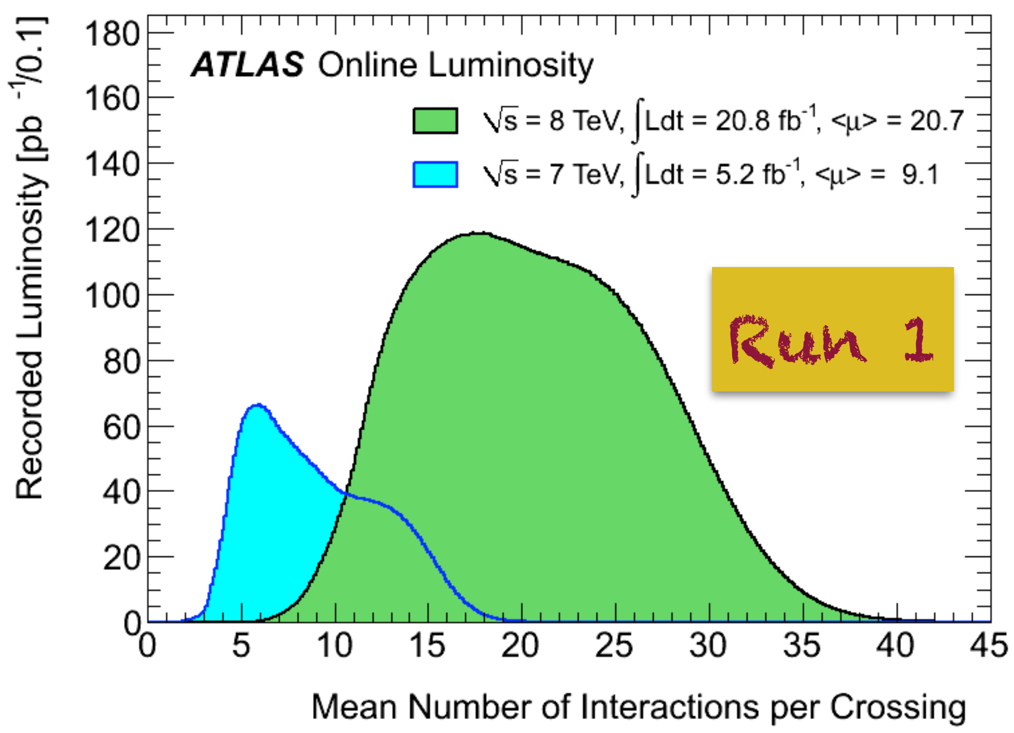
ggF: ×2.3

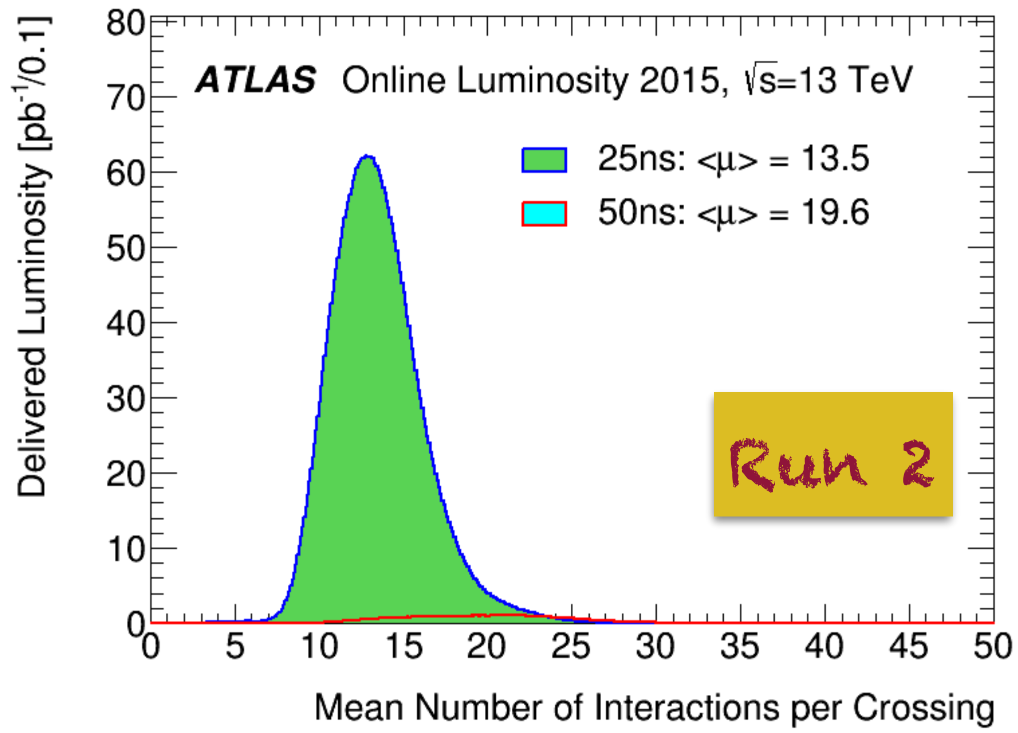
ttH: ×3.9

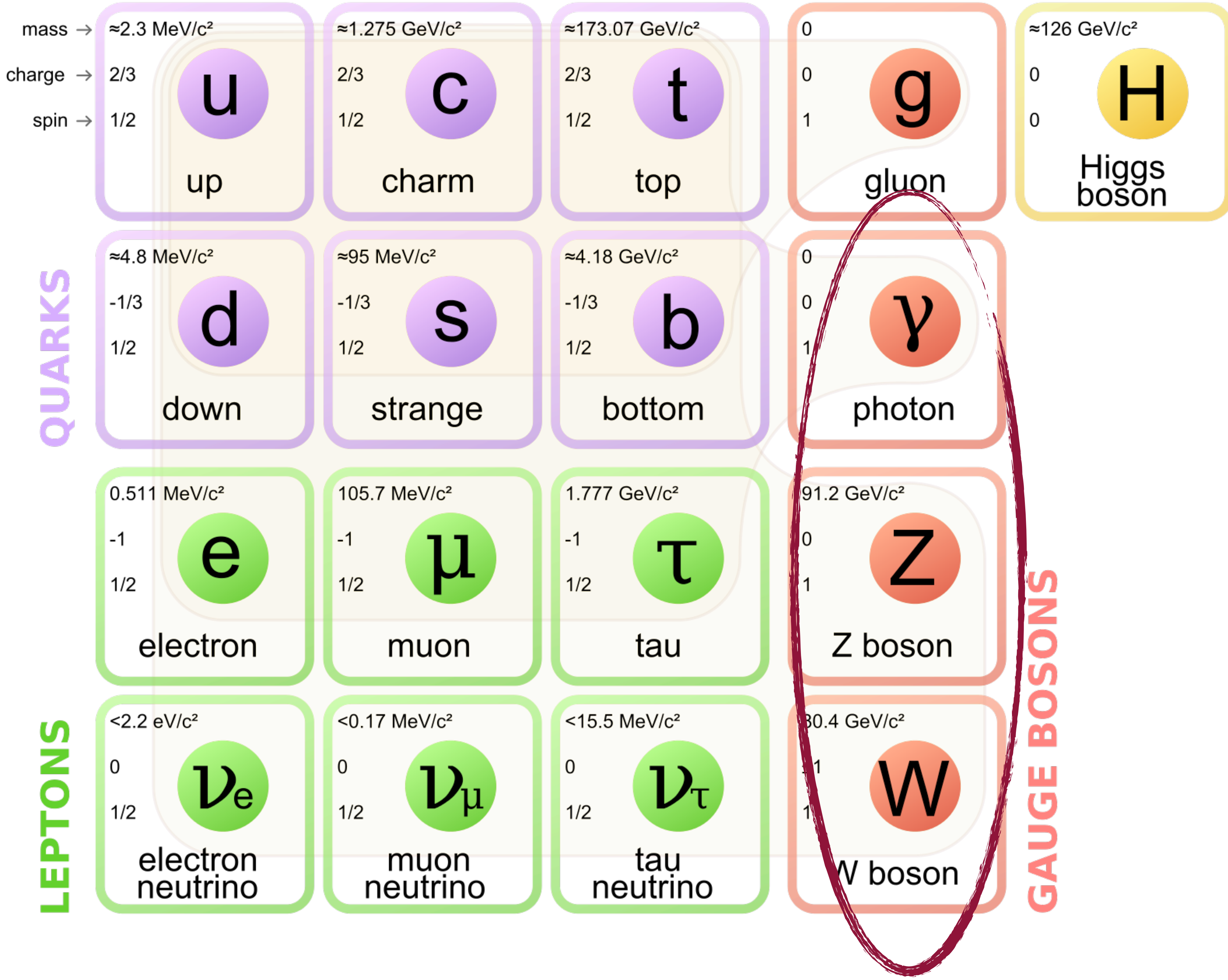
Pile-up



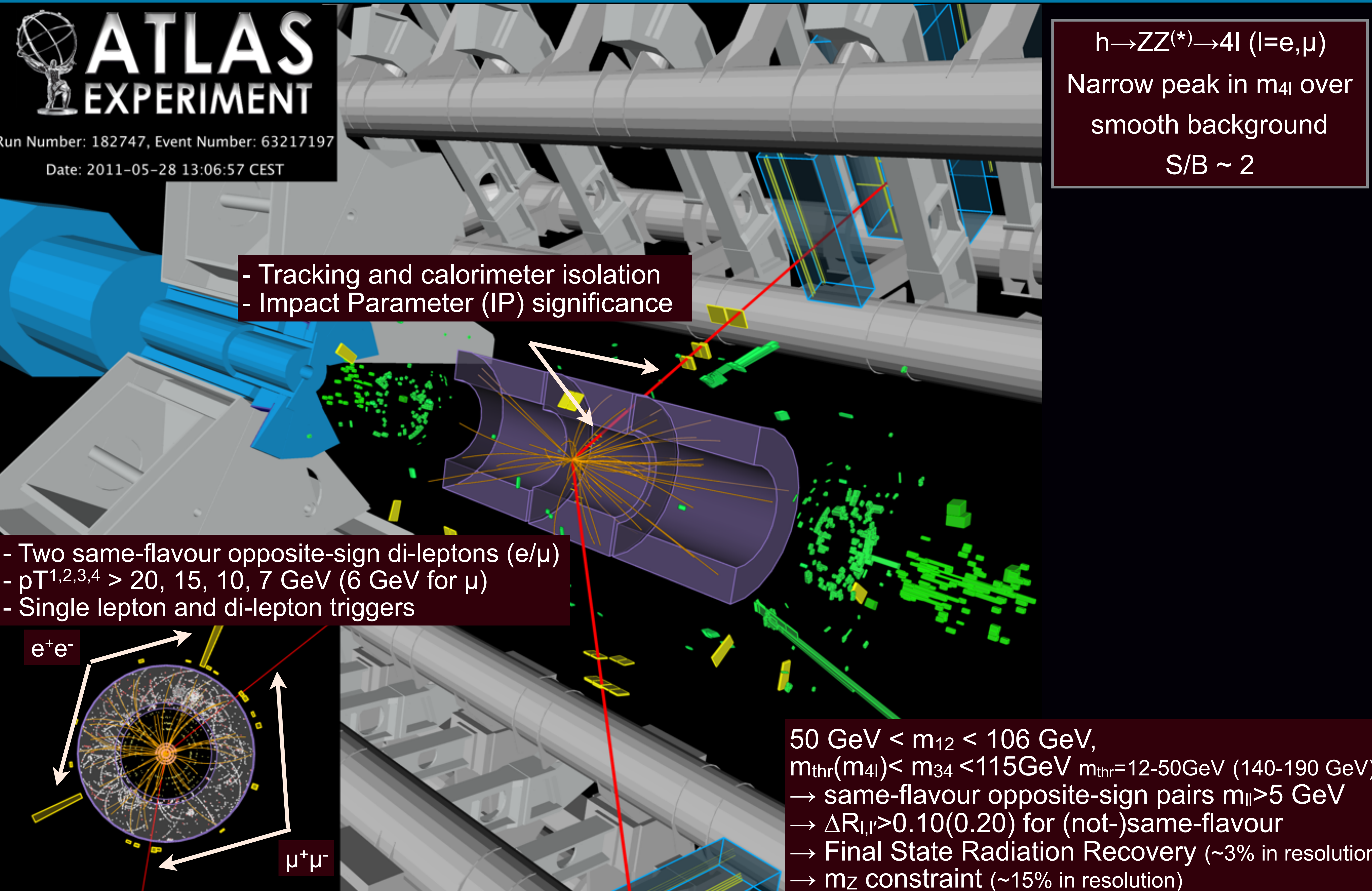
Z→μμ candidate with 25 reconstructed vertices (2012). Good quality tracks with pT>0.4GeV shown.






mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
W
boson
QUARKS
LEPTONS
GAUGE BOSONS

$h \rightarrow ZZ^{(*)} \rightarrow 4l$ ($l=e,\mu$)



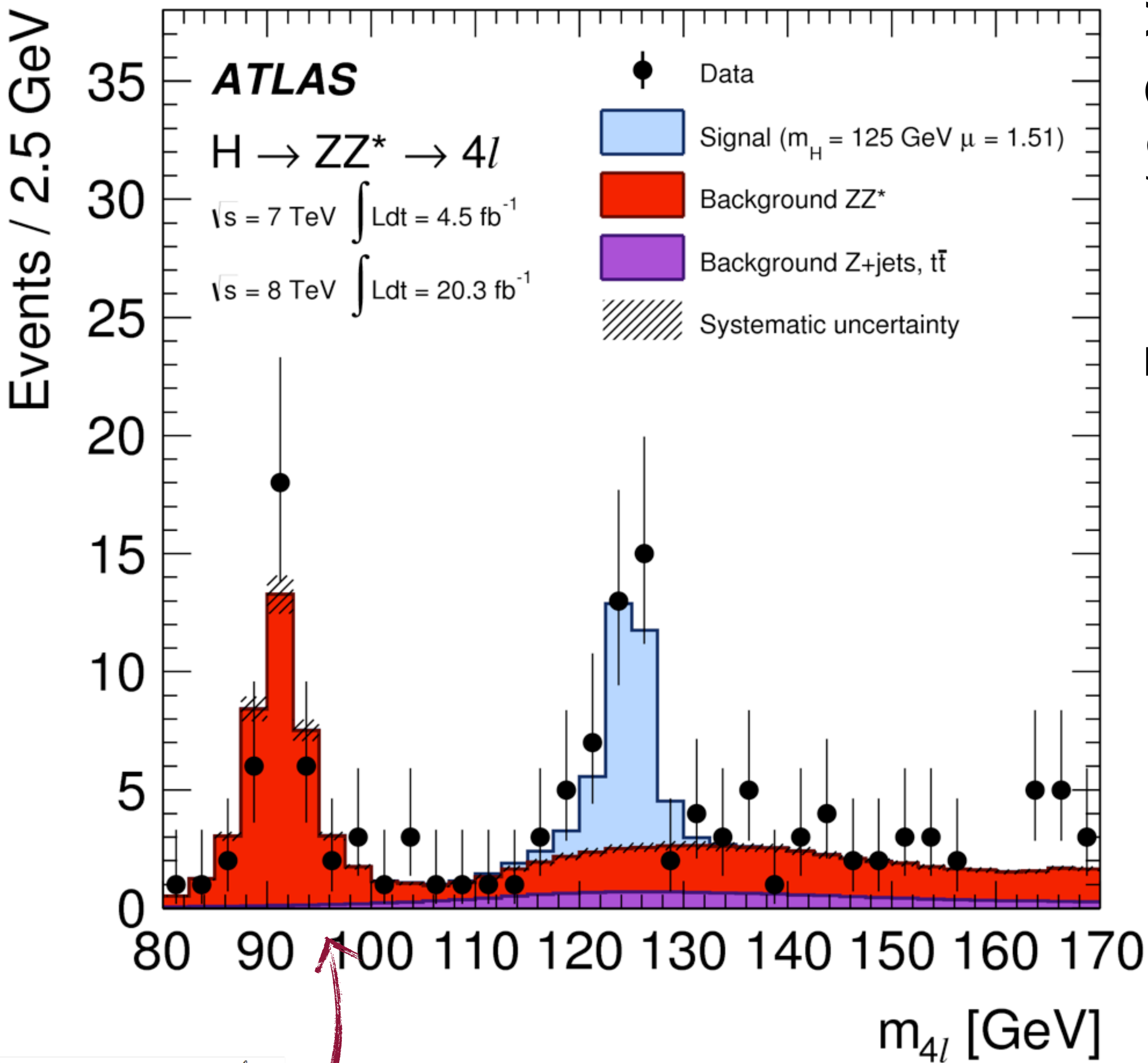
$h \rightarrow ZZ^{(*)} \rightarrow 4l$ ($l=e,\mu$)
Narrow peak in m_{4l} over smooth background
S/B ~ 2

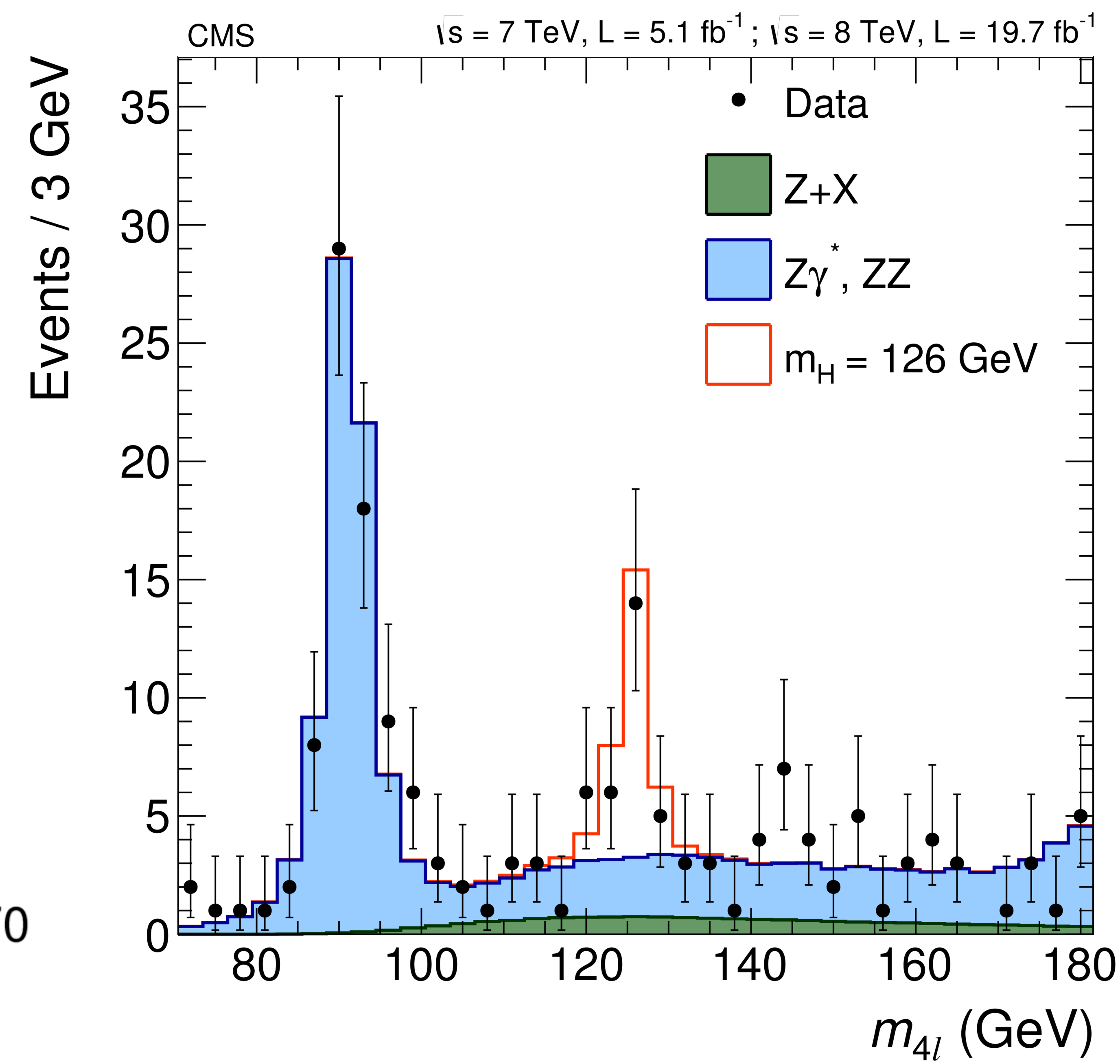
- Tracking and calorimeter isolation
- Impact Parameter (IP) significance

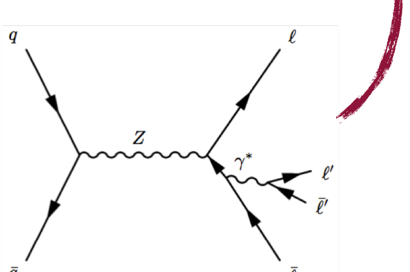
- Two same-flavour opposite-sign di-leptons (e/μ)
- $pT^{1,2,3,4}$ > 20, 15, 10, 7 GeV (6 GeV for μ)
- Single lepton and di-lepton triggers

50 GeV < m_{12} < 106 GeV,
$m_{thr}(m_{4l})$< m_{34} <115GeV m_{thr}=12-50GeV (140-190 GeV)
→ same-flavour opposite-sign pairs m_{ll}>5 GeV
→ $\Delta R_{l,l'}$>0.10(0.20) for (not-)same-flavour
→ Final State Radiation Recovery (~3% in resolution)
→ m_Z constraint (~15% in resolution)

$h\to ZZ^{(*)}\to 4l$

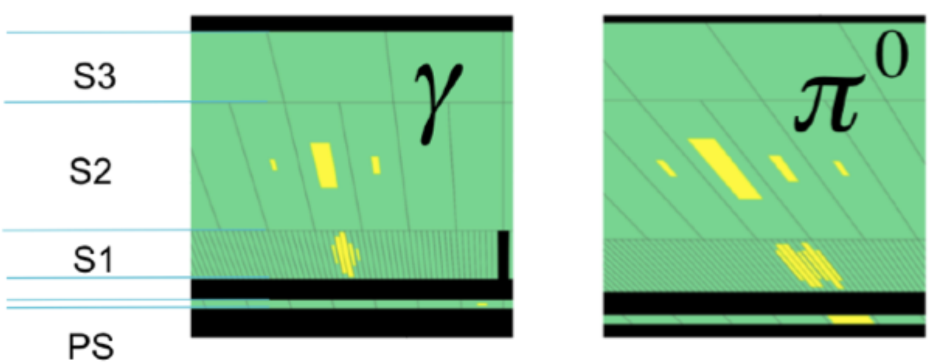

ATLAS
H → ZZ* → 4l
√s = 7 TeV ∫Ldt = 4.5 fb⁻¹
√s = 8 TeV ∫Ldt = 20.3 fb⁻¹
Data
Signal (m_H = 125 GeV μ = 1.51)
Background ZZ*
Background Z+jets, tt̄
Systematic uncertainty
Events / 2.5 GeV
m_4l [GeV]
0
5
10
15
20
25
30
35
80
90
100
110
120
130
140
150
160
170


CMS
√s = 7 TeV, L = 5.1 fb⁻¹ ; √s = 8 TeV, L = 19.7 fb⁻¹
Data
Z+X
Zγ*, ZZ
m_H = 126 GeV
Events / 3 GeV
m_4l (GeV)
0
5
10
15
20
25
30
35
80
100
120
140
160
180

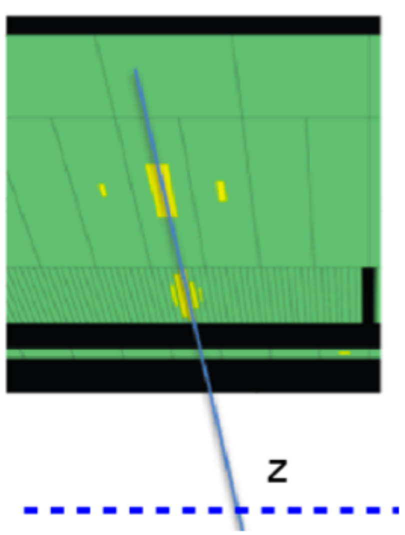

q
q̄
Z
γ*
ℓ
ℓ̄
ℓ'
ℓ̄'

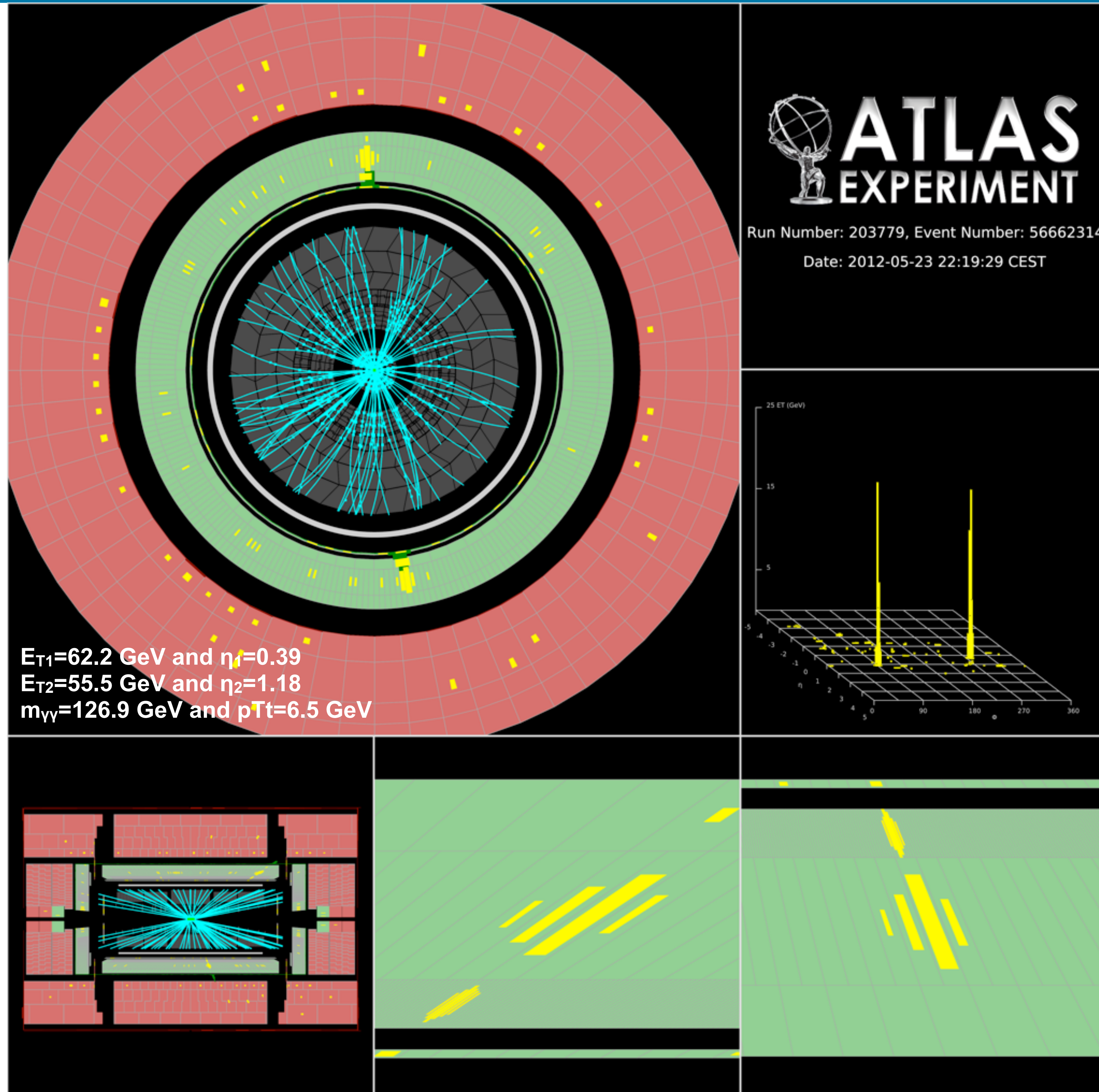
h→γγ

- Narrow peak in $m_{\gamma\gamma}$ (S/B ~3-4%)
- Main Backgrounds:
  - ~80% di-photon → $m_{\gamma\gamma}$ resolution
  - ~20% γj and jj → photon-ID
- Background from data side-bands
- Selection: Two isolated photons (|η| <2.47) with E_T>0.35(0.25)*$m_{\gamma\gamma}$

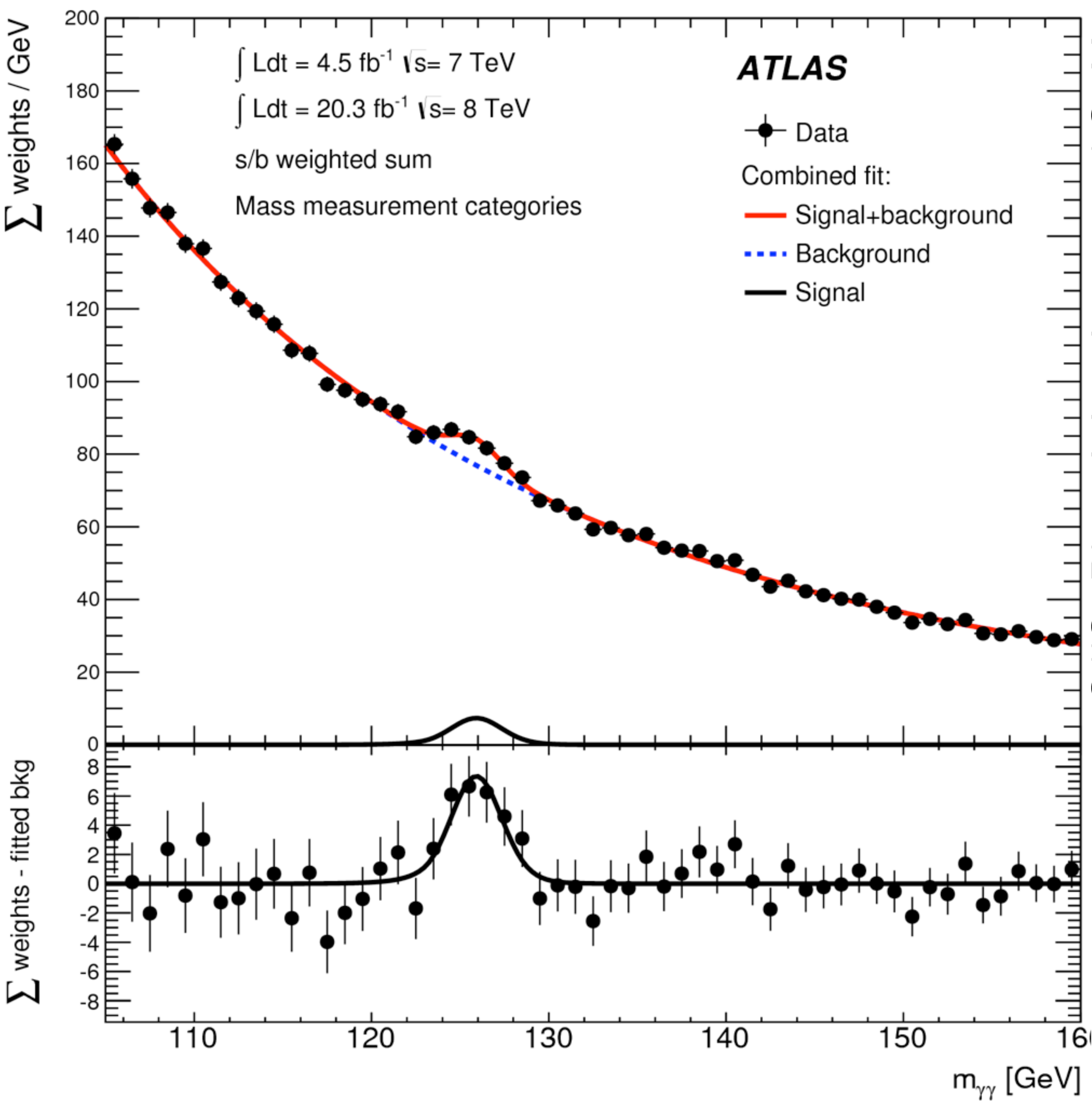


$$m^2_{\gamma\gamma}=2E_1E_2(1-\cos\alpha)$$

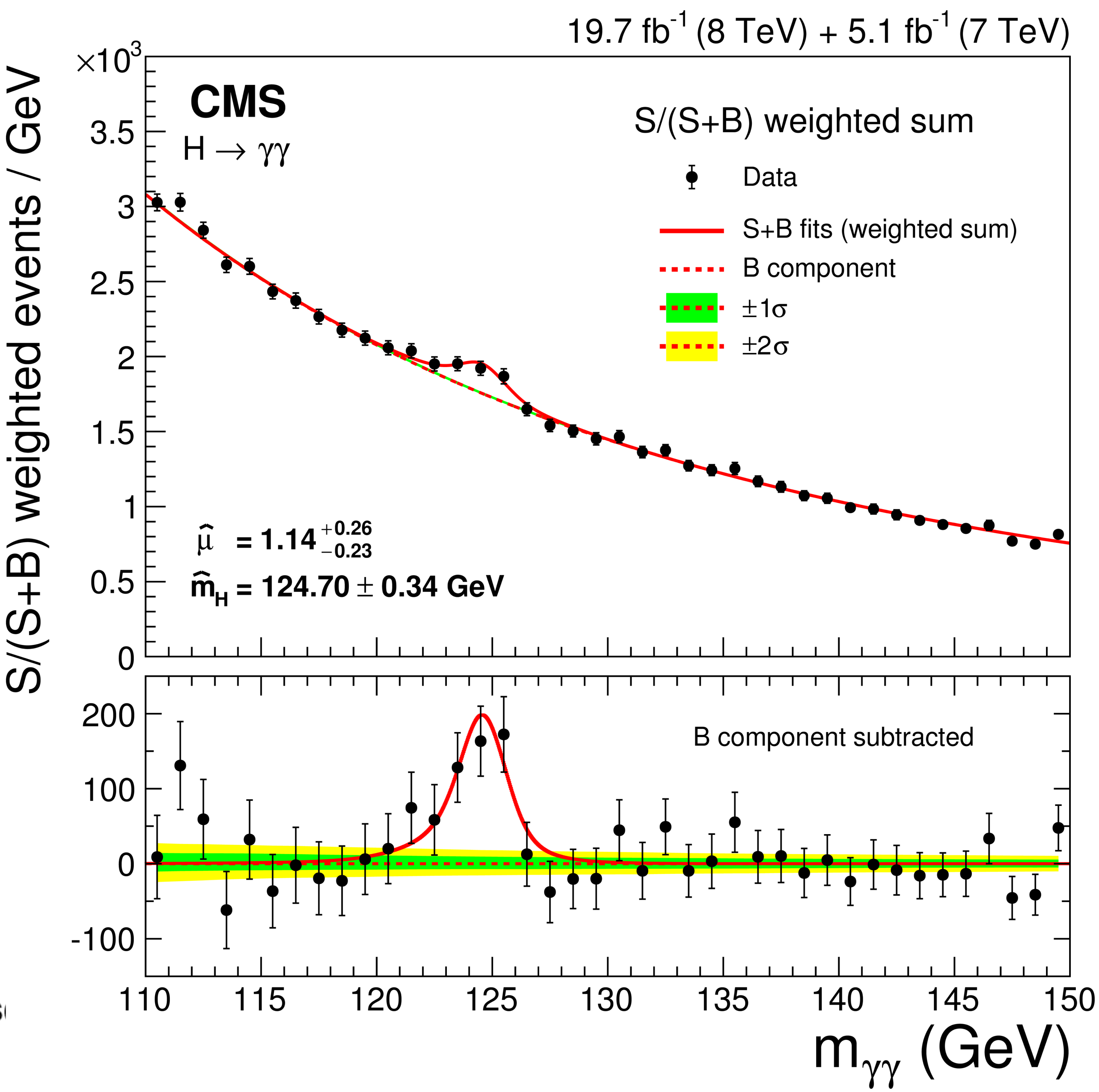




h→γγ



∫ Ldt = 4.5 fb⁻¹ √s= 7 TeV
∫ Ldt = 20.3 fb⁻¹ √s= 8 TeV
s/b weighted sum
Mass measurement categories
ATLAS
Data
Combined fit:
Signal+background
Background
Signal
∑ weights / GeV
∑ weights - fitted bkg
m_γγ [GeV]



19.7 fb⁻¹ (8 TeV) + 5.1 fb⁻¹ (7 TeV)
CMS
H → γγ
S/(S+B) weighted sum
Data
S+B fits (weighted sum)
B component
±1σ
±2σ
μ̂ = 1.14 +0.26 −0.23
m̂_H = 124.70 ± 0.34 GeV
B component subtracted
S/(S+B) weighted events / GeV
m_γγ (GeV)

Freakish Papers
(courtesy: times higher education)

https://www.timeshighereducation.com/blog/world-university-rankings-blog-dealing-freak-research-papers

nature International weekly journal of science

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NATURE | NEWS

Physics paper sets record with more than 5,000 authors

Detector teams at the Large Hadron Collider collaborated for a more precise estimate of the size of the Higgs boson.

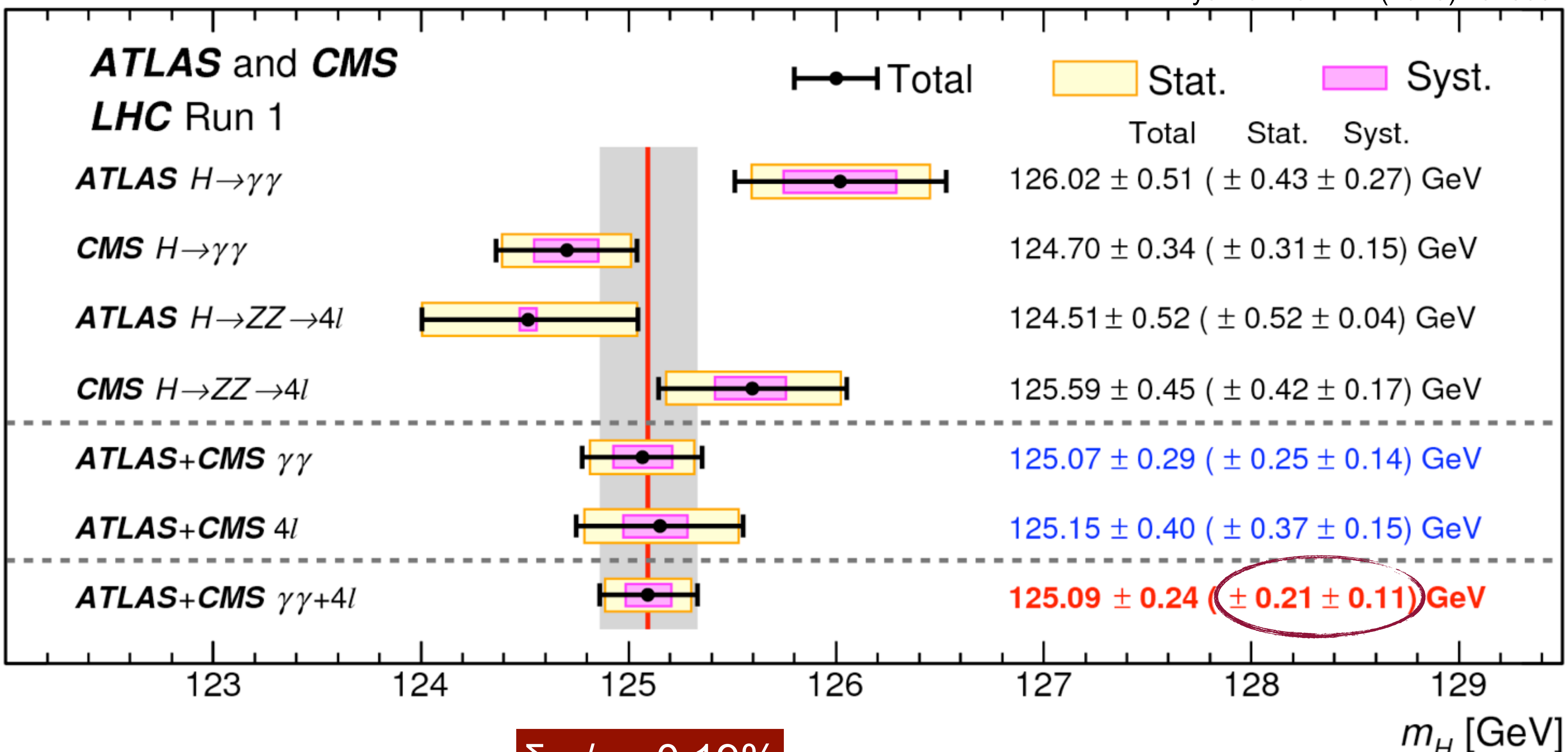
Davide Castelvecchi

15 May 2015

The Higgs boson mass

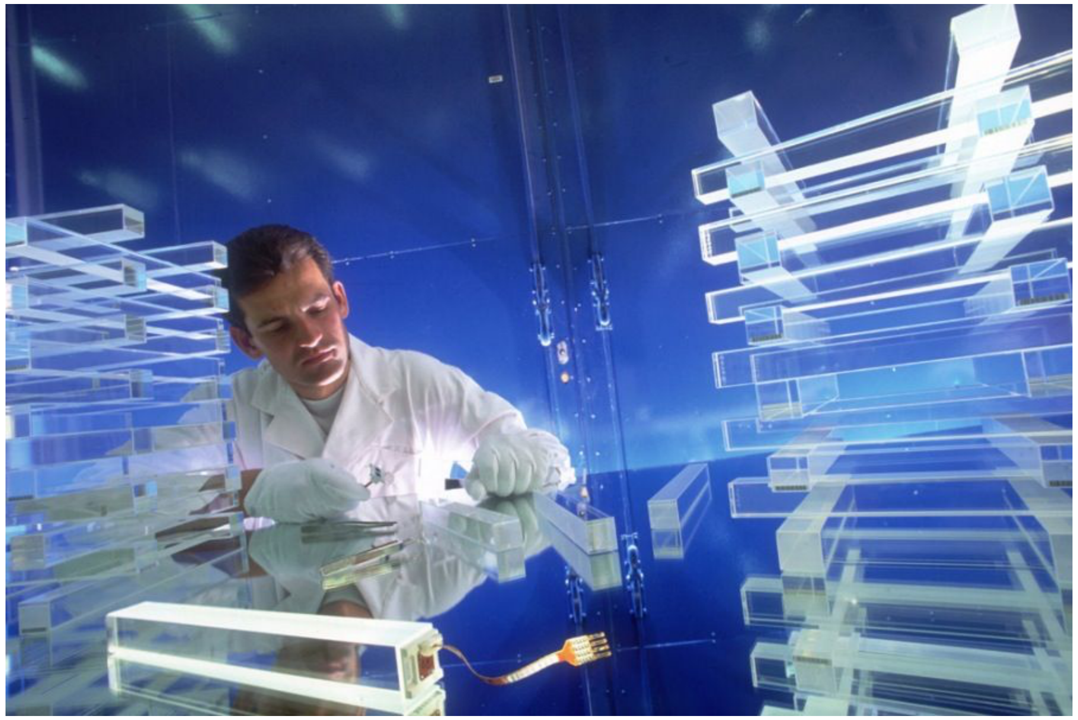
ATLAS measurement: 125.36 ± 0.37(stat) ± 0.18 (syst) GeV
CMS measurement: 125.02 $^{+0.26}_{-0.27}$ (stat) $^{+0.14}_{-0.15}$ (syst) GeV

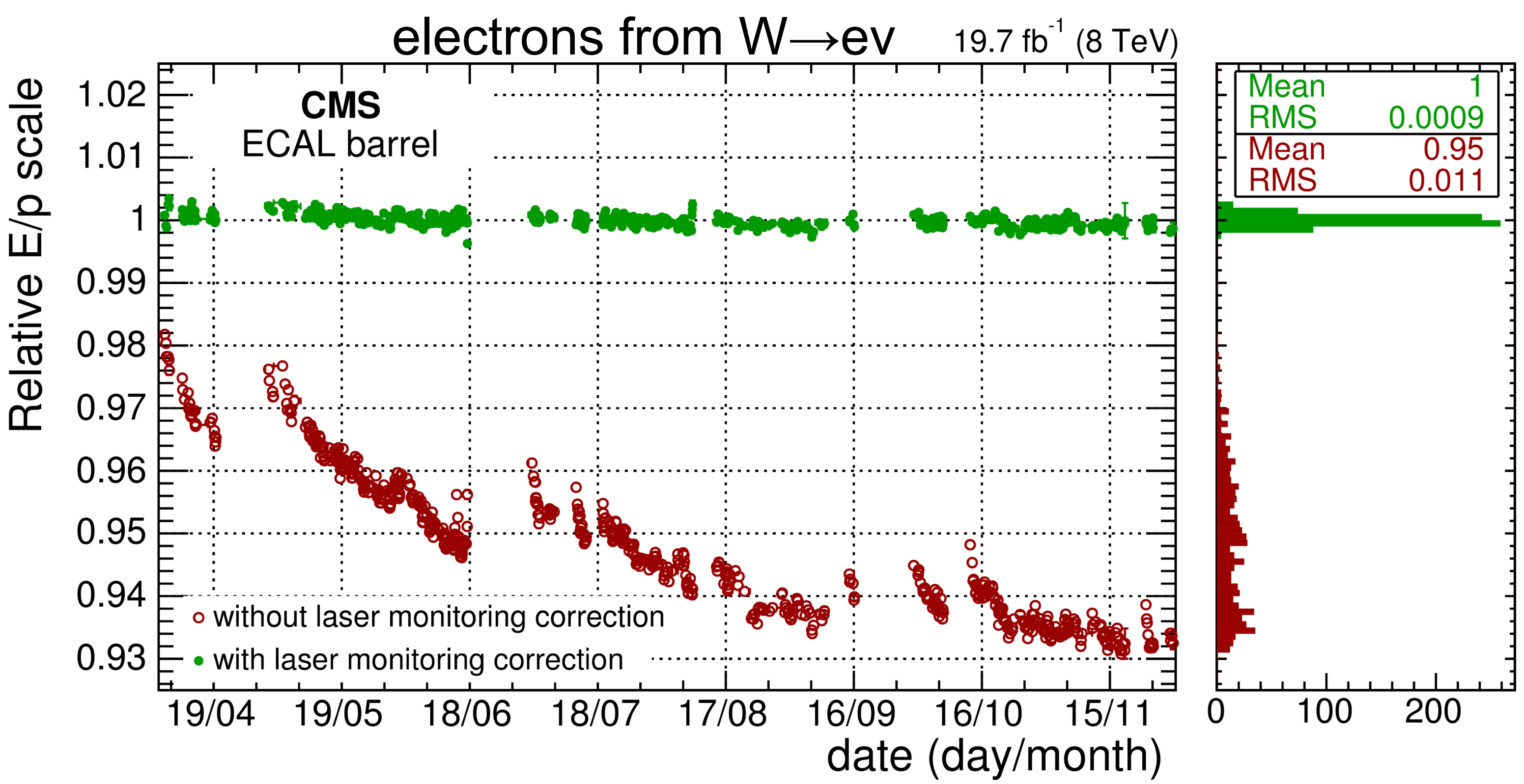
Phys.Rev.Lett 114 (2015) 191803

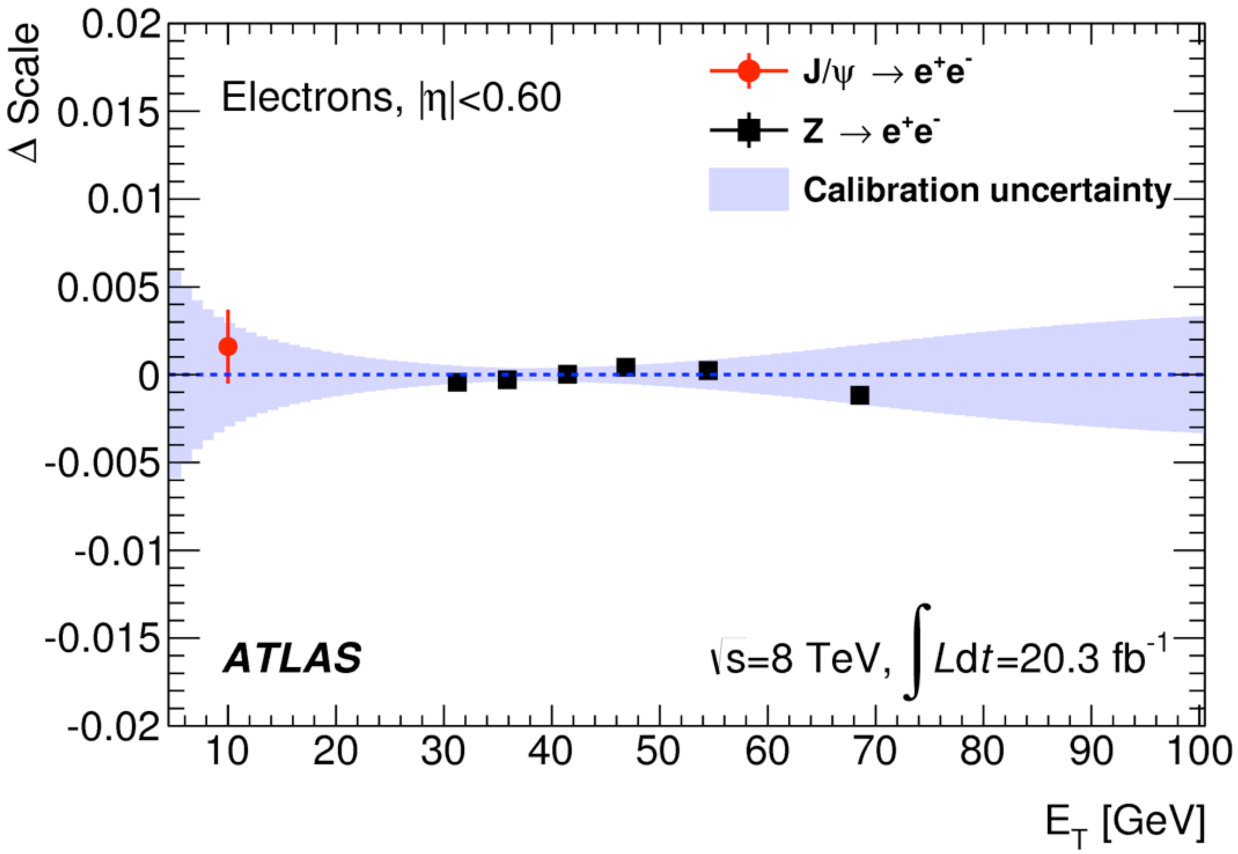


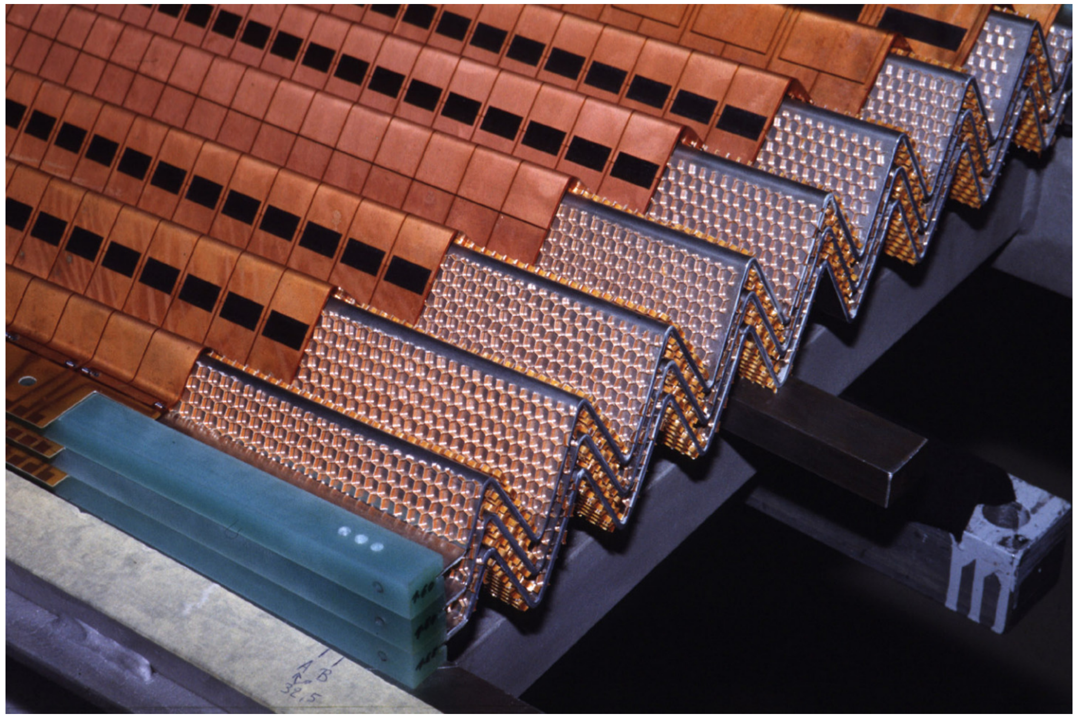
δm/m~0.19%

Calibration

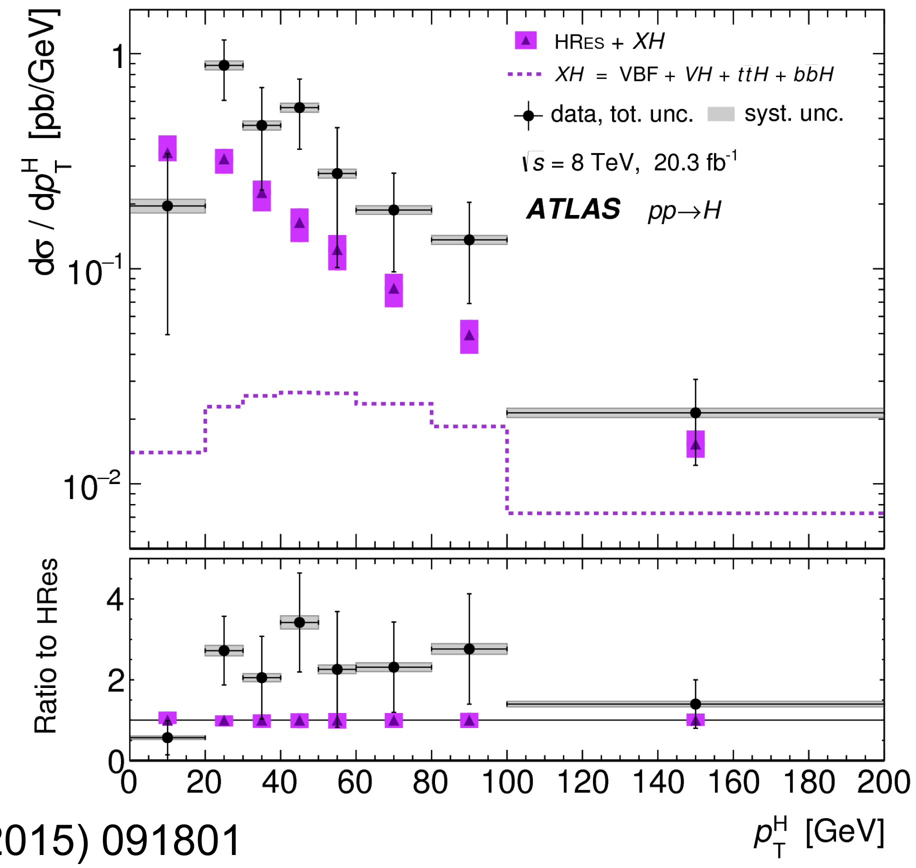




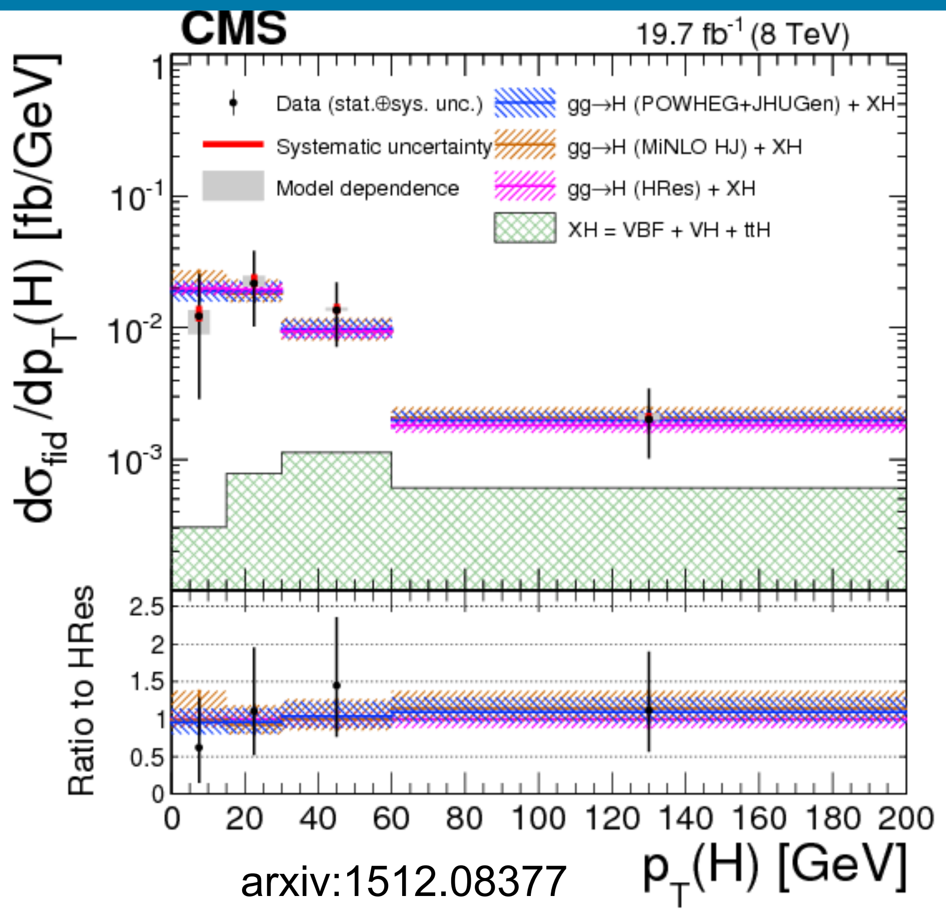




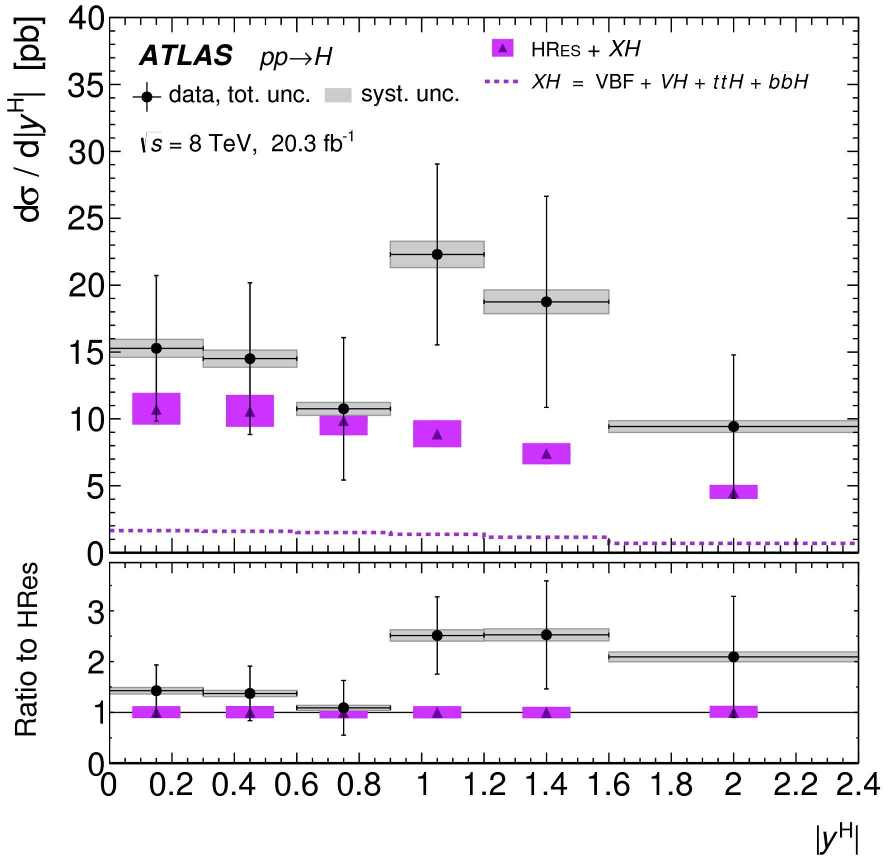
Differential cross sections

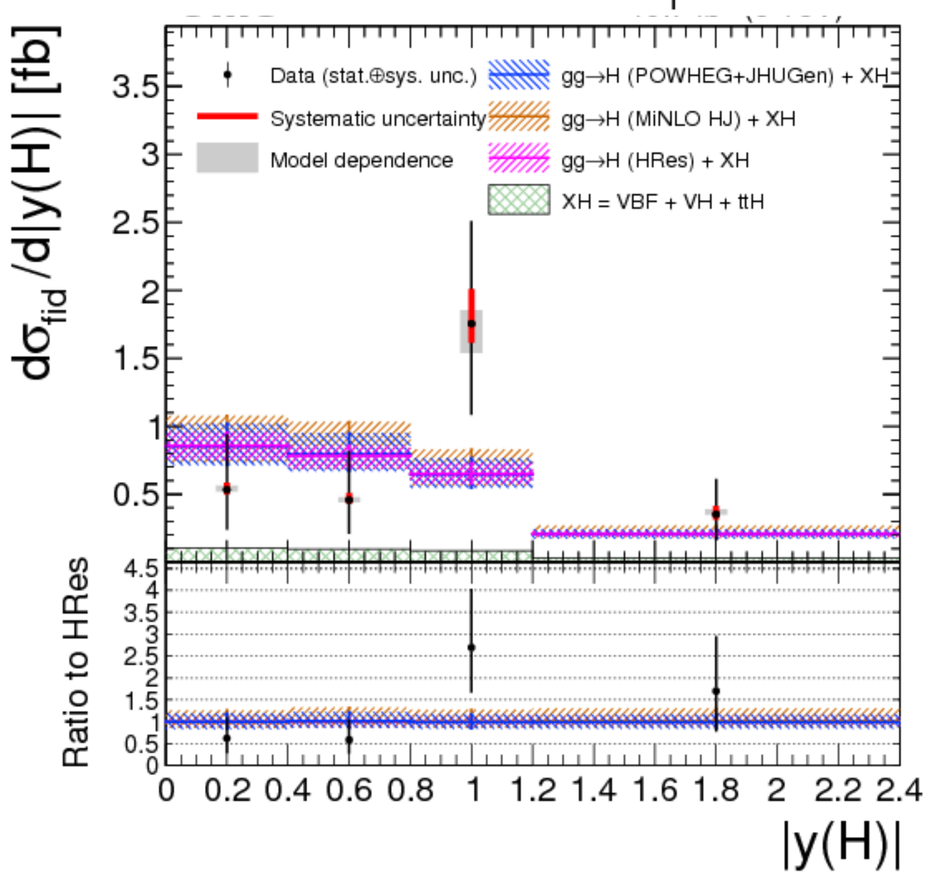


PRL115 (2015) 091801



arxiv:1512.08377



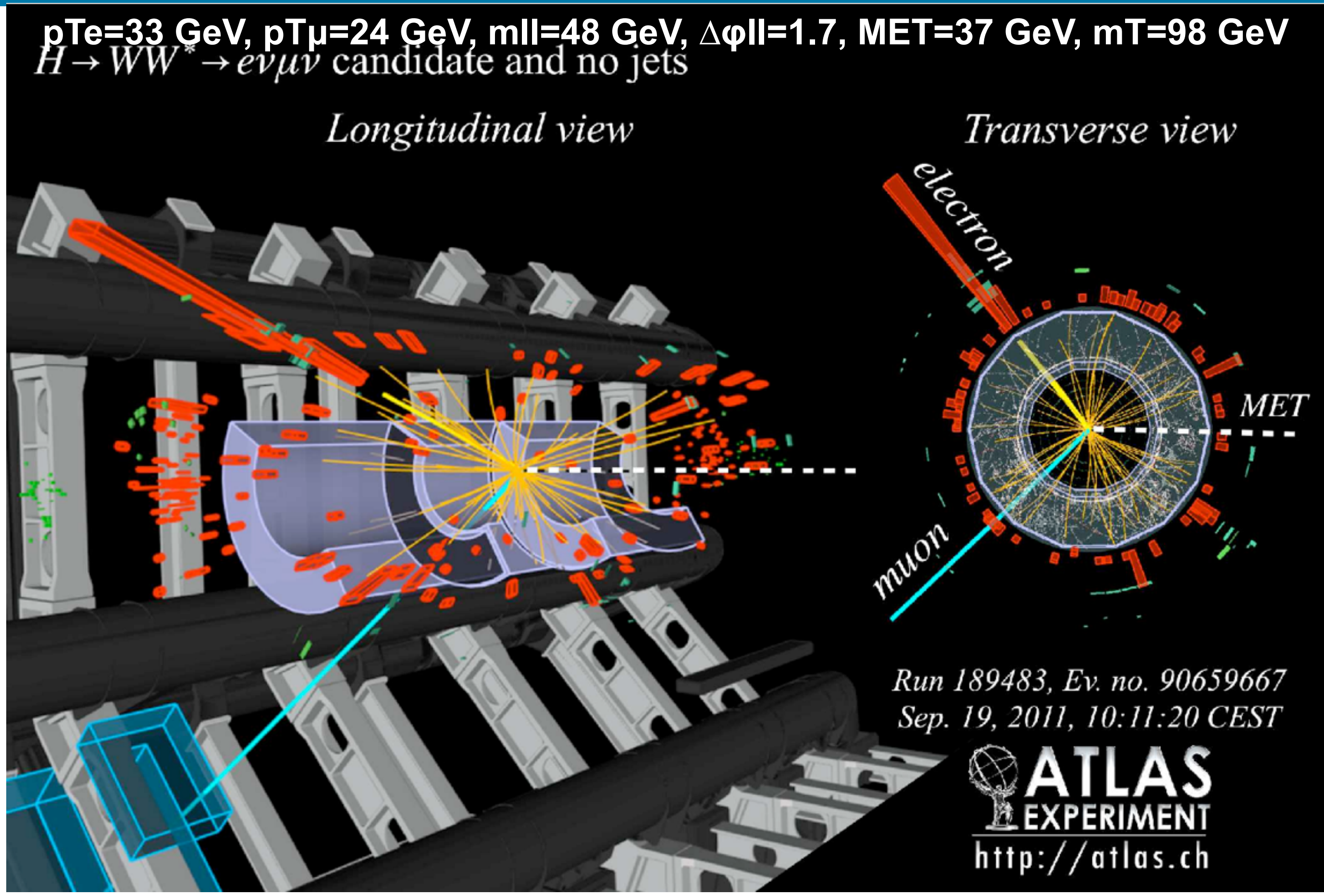


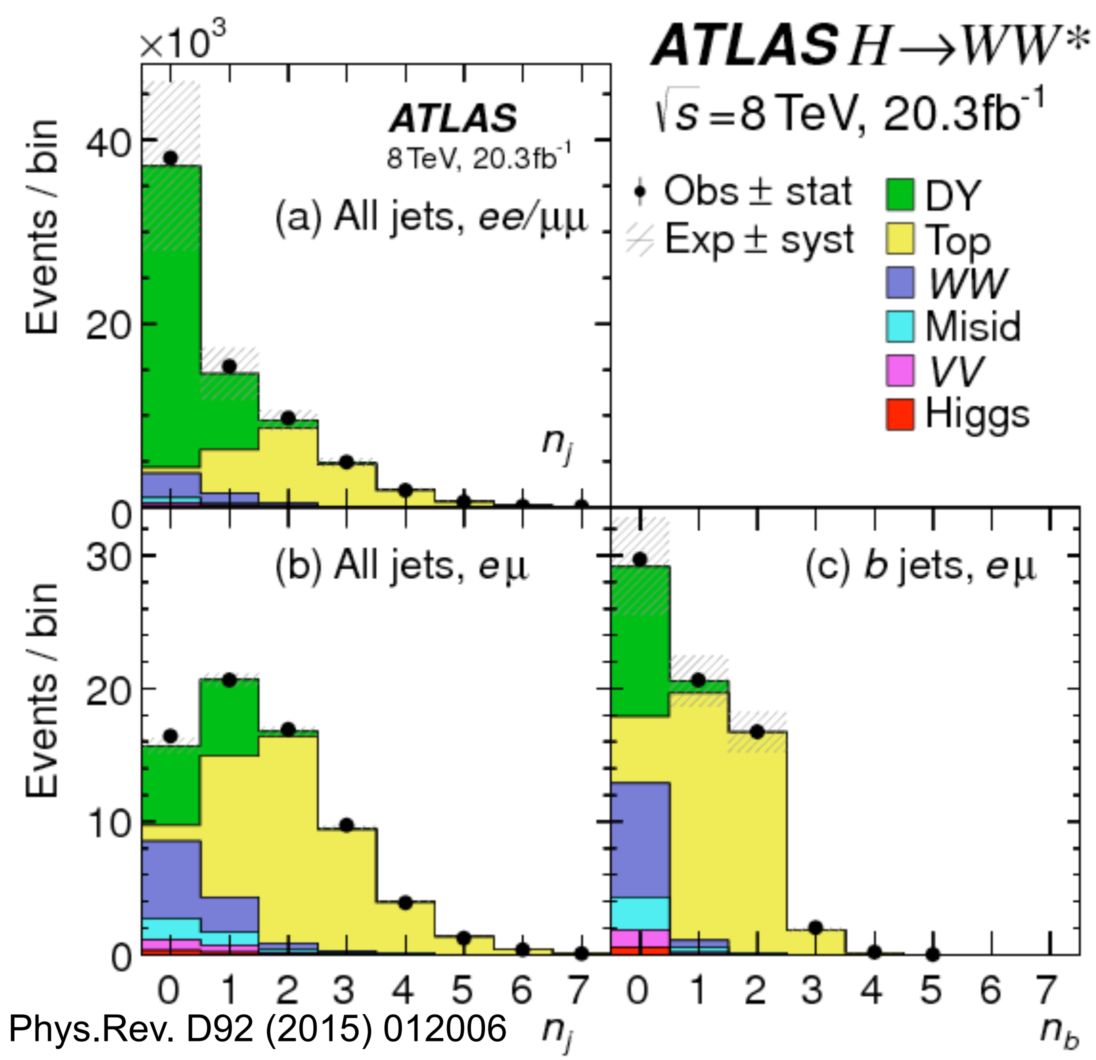
H→WW$^{(*)}$→lνlν

- Signature: l^+l^- + MET
- Main observable m_T

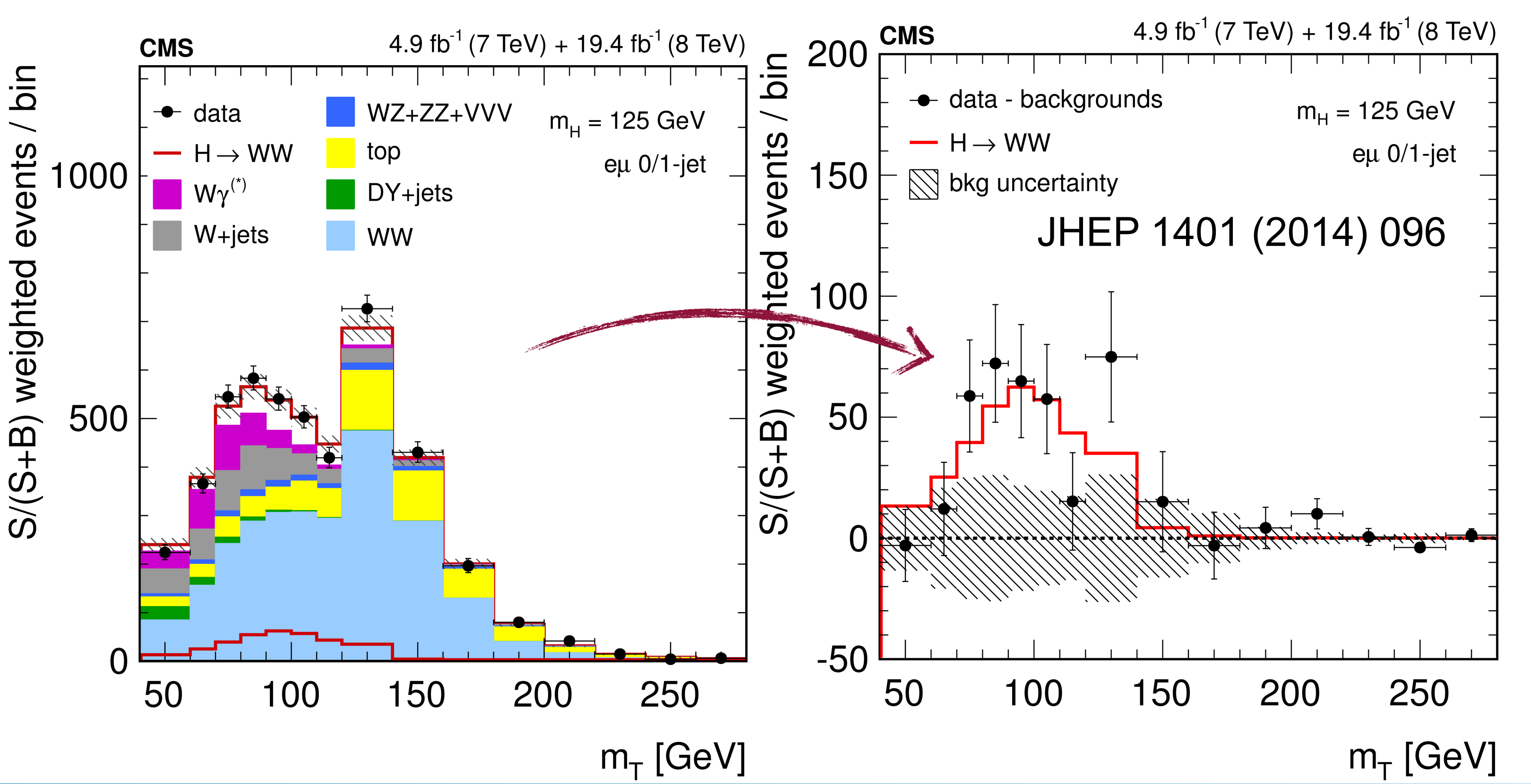
$$m_T = \sqrt{(E_T^{\ell\ell} + E_T^{miss})^2 - (\mathbf{P}_T^{\ell\ell} + \mathbf{P}_T^{miss})^2}$$

- Backgrounds: WW, tt/Wt, W/Z+jets, Wγ/Wγ*/WZ
- Separate final states:
  - lepton flavours: μe, eμ, μμ, ee
  - jet multiplicities: 0, 1, ≥2



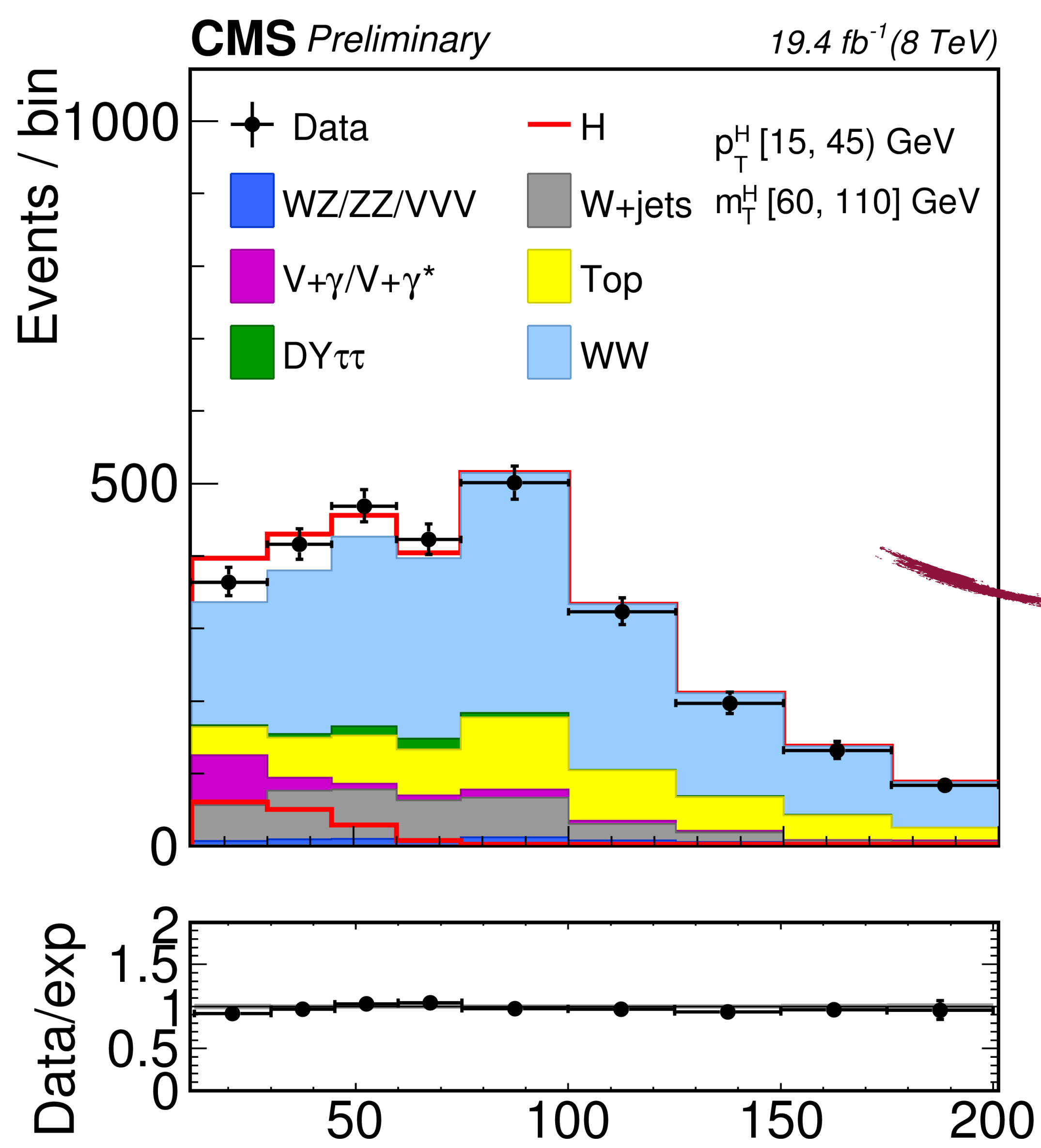


Phys.Rev. D92 (2015) 012006



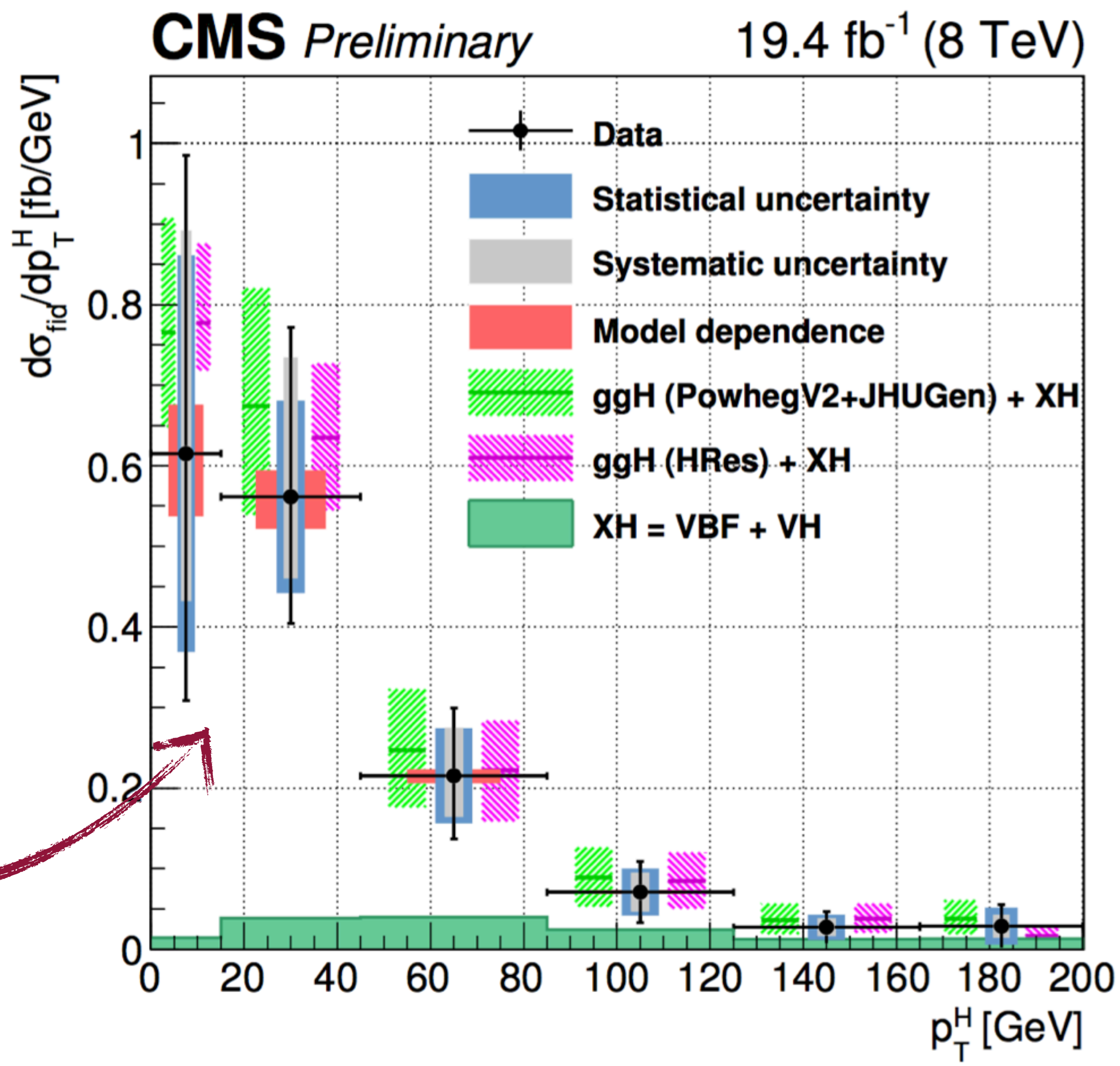
H→WW(*)→lνlν: Differential cross section

$$\vec{p}_T^{\,H} = \vec{p}_T^{\,\ell\ell} + \vec{E}_T^{\,\text{miss}}$$



CMS-PAS-HIG-15-010

CMS-PAS-HIG-15-010

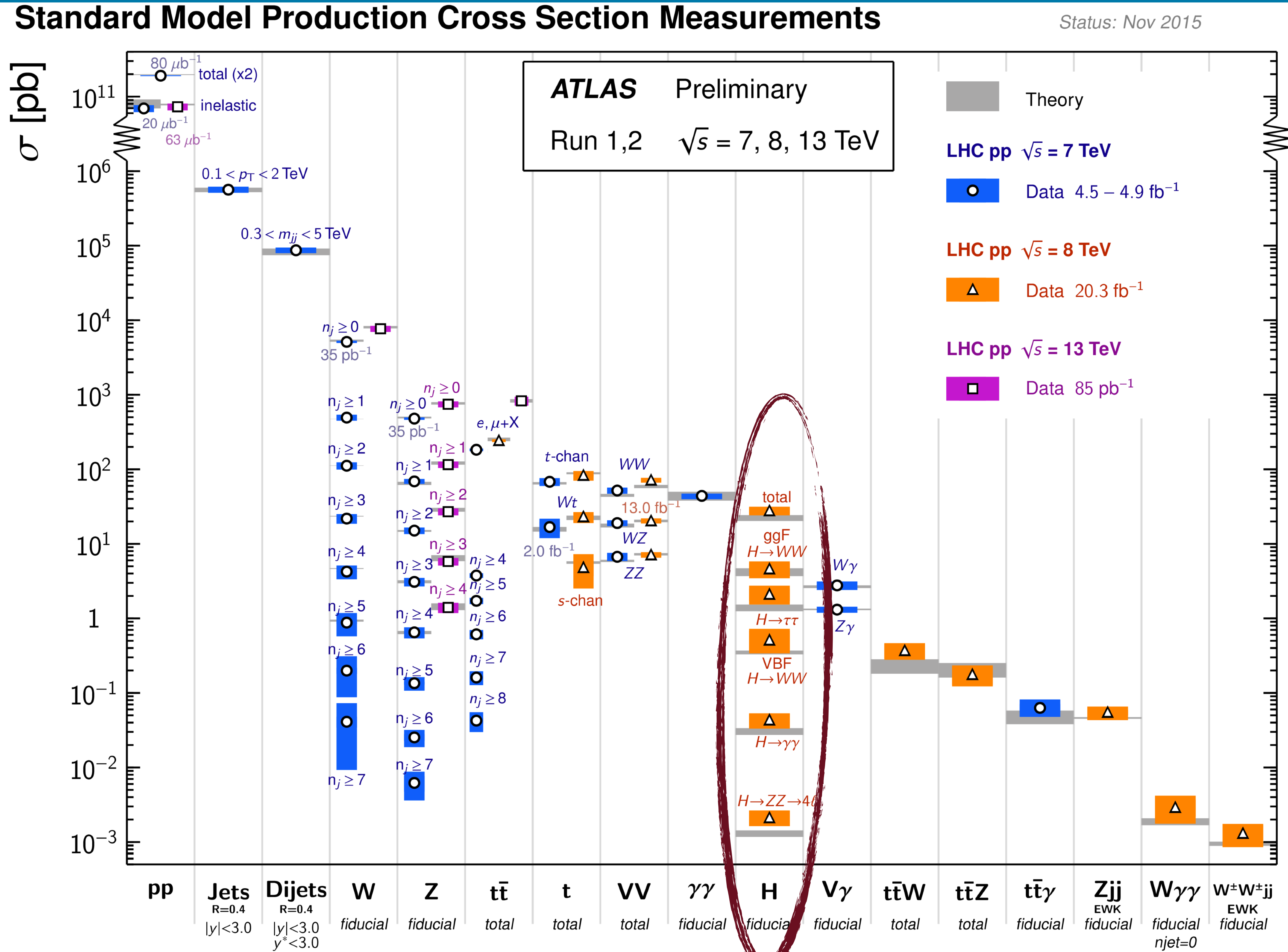


Use the eμ channel only

Analysis inclusive to the number of jets

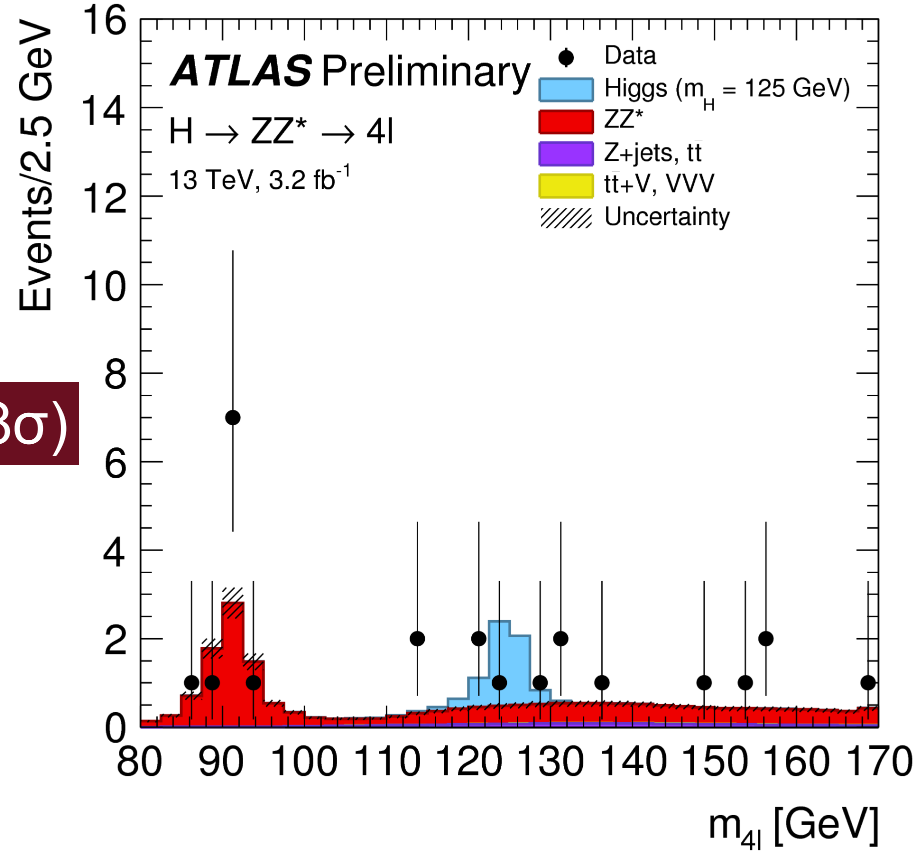
For each $p_{T,H}$ bin perform 2D fit in m_{ll} and m_T

Snapshot of cross section measurements



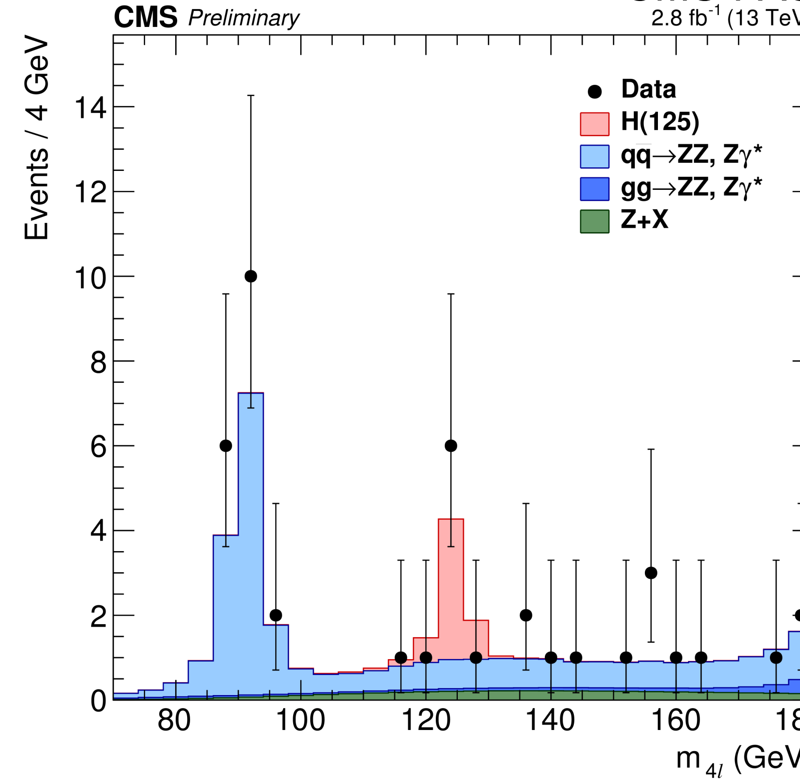
h→γγ and h→ZZ→4l: Run 2

ATLAS-CONF-2015-059



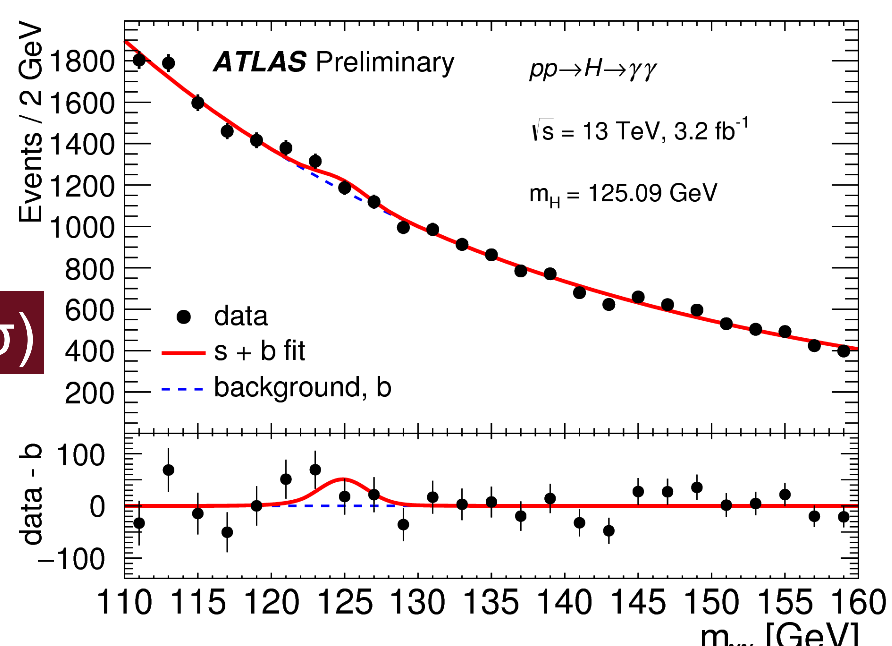
~0.6σ (2.8σ)

CMS-PAS-HIG-15-004

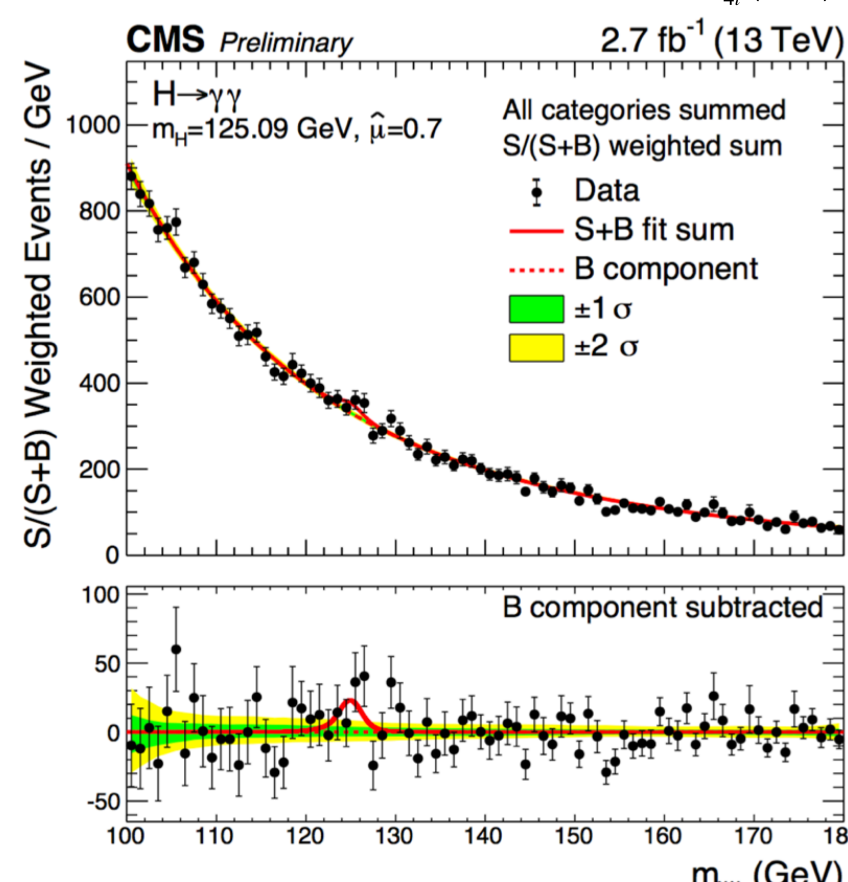


2.5σ (3.4σ)

1.5σ (1.9σ)



ATLAS-CONF-2015-060

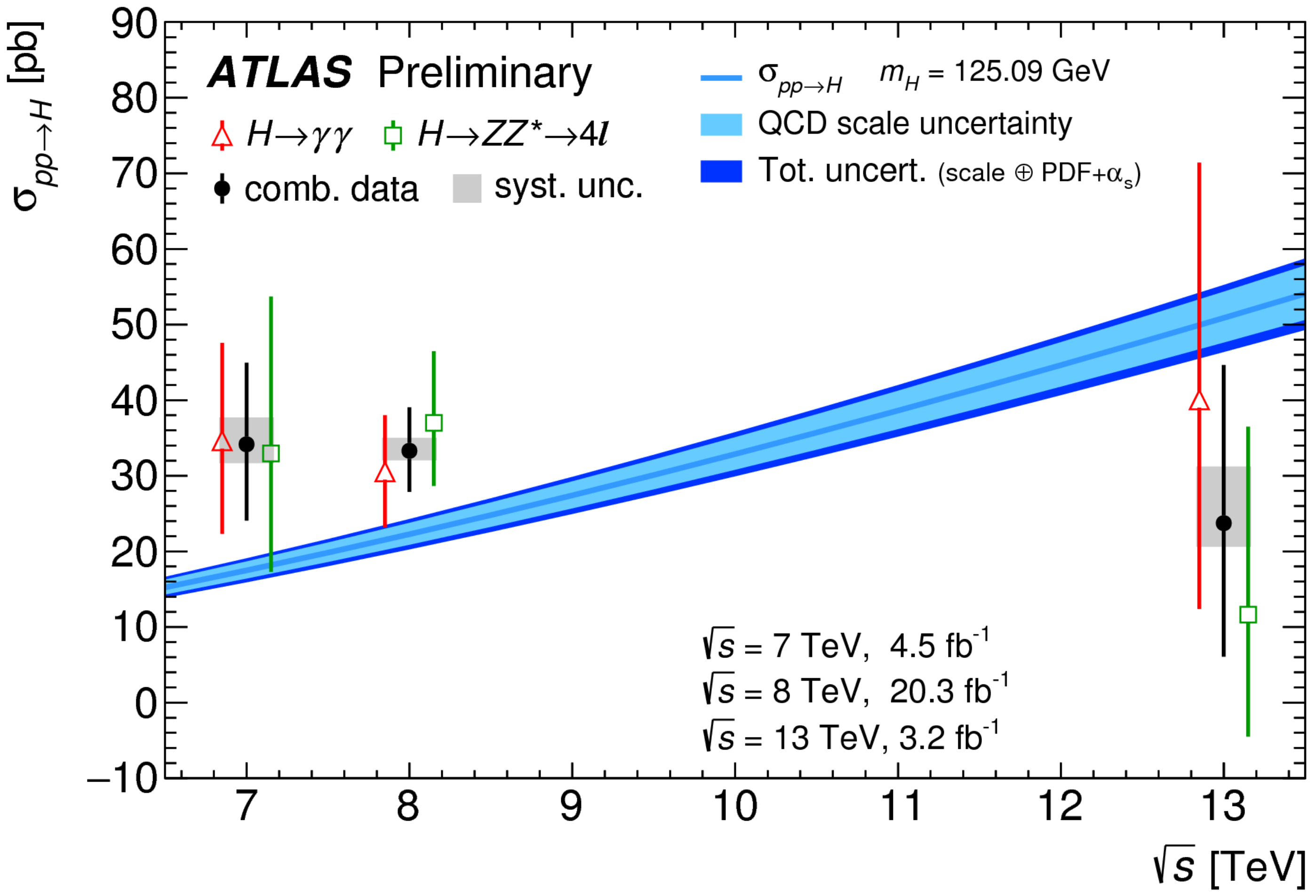


1.7σ (2.7σ)

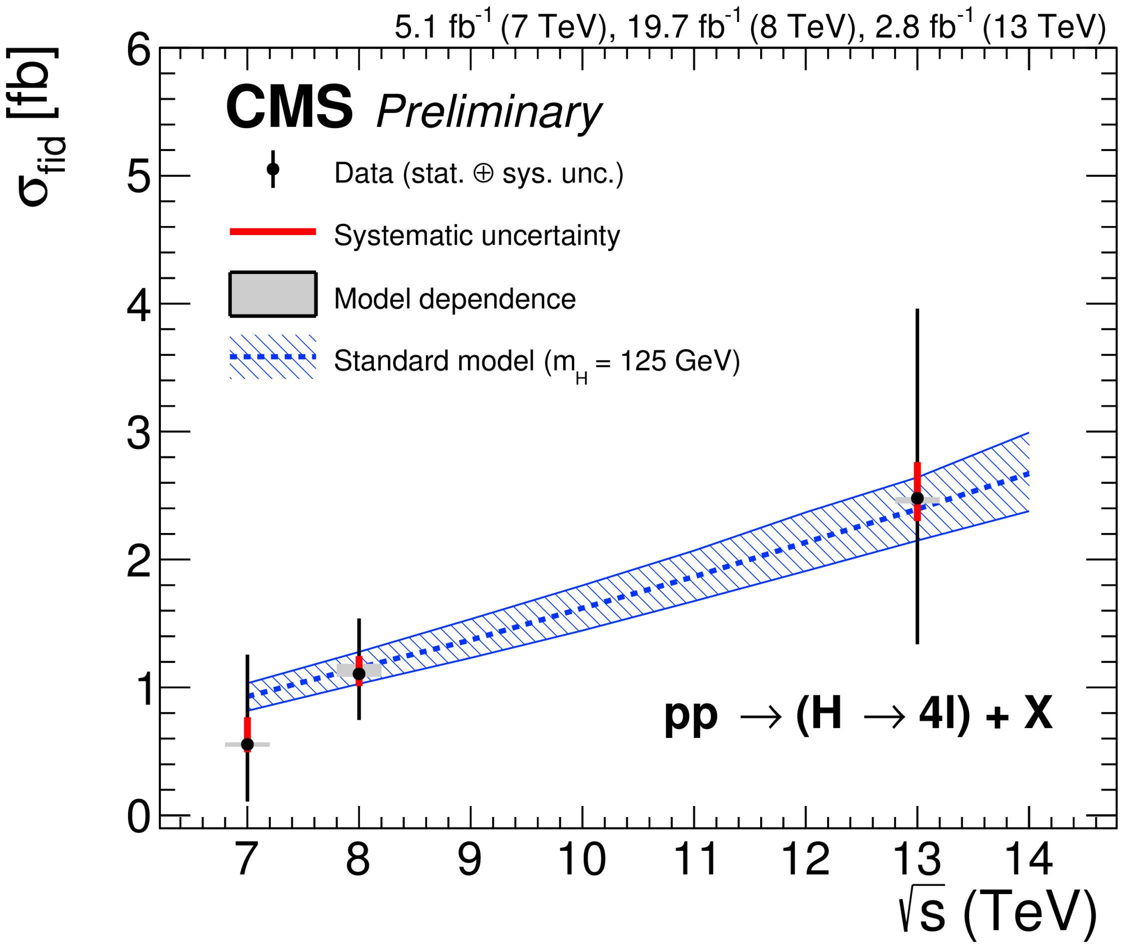
S. Zenz @ Moriond EW'16

Cross section versus energy

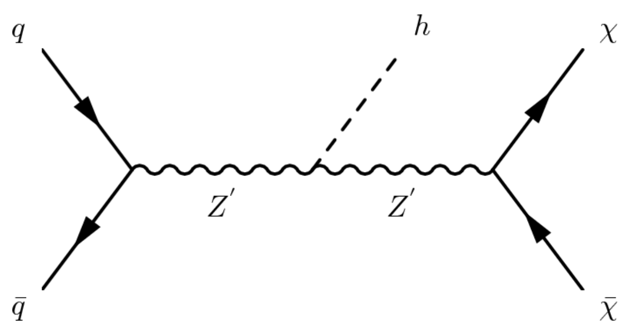
ATLAS-CONF-2015-069



CMS-PAS-HIG-15-004

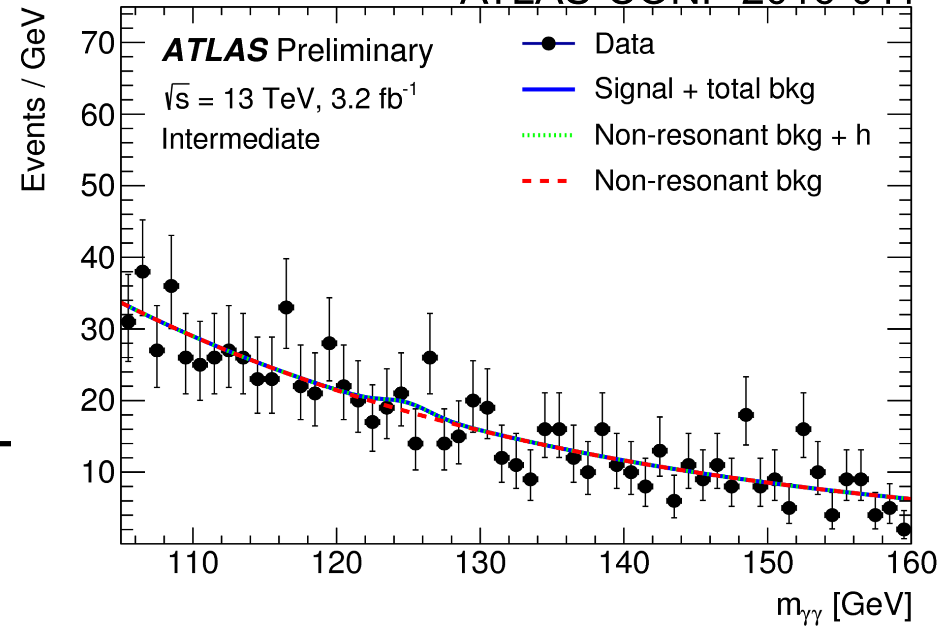


Search for New Physics

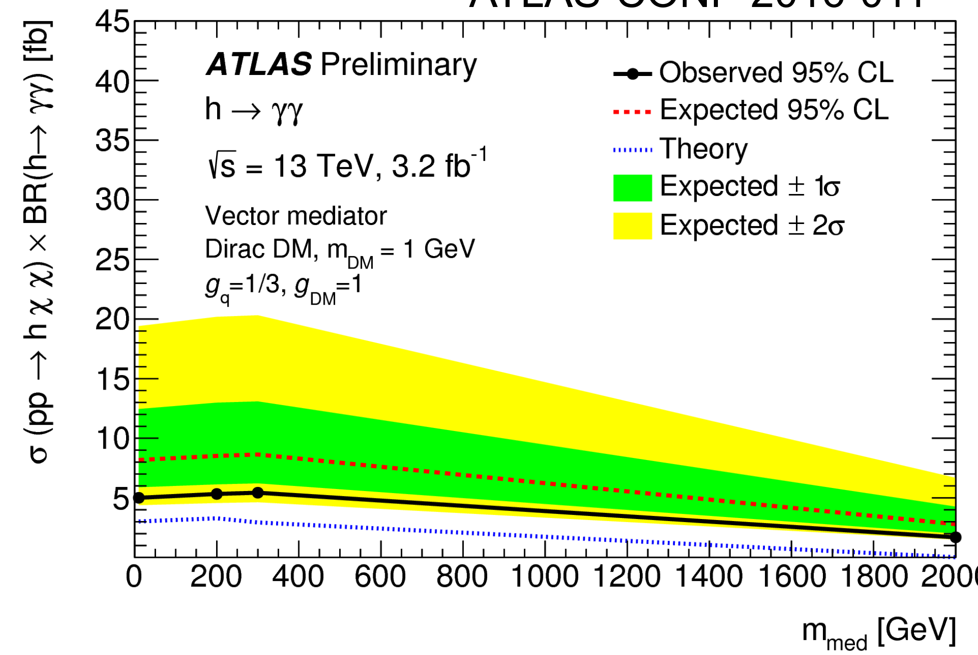


Search for Dark Matter candidates in h→γγ+MET

ATLAS-CONF-2016-011

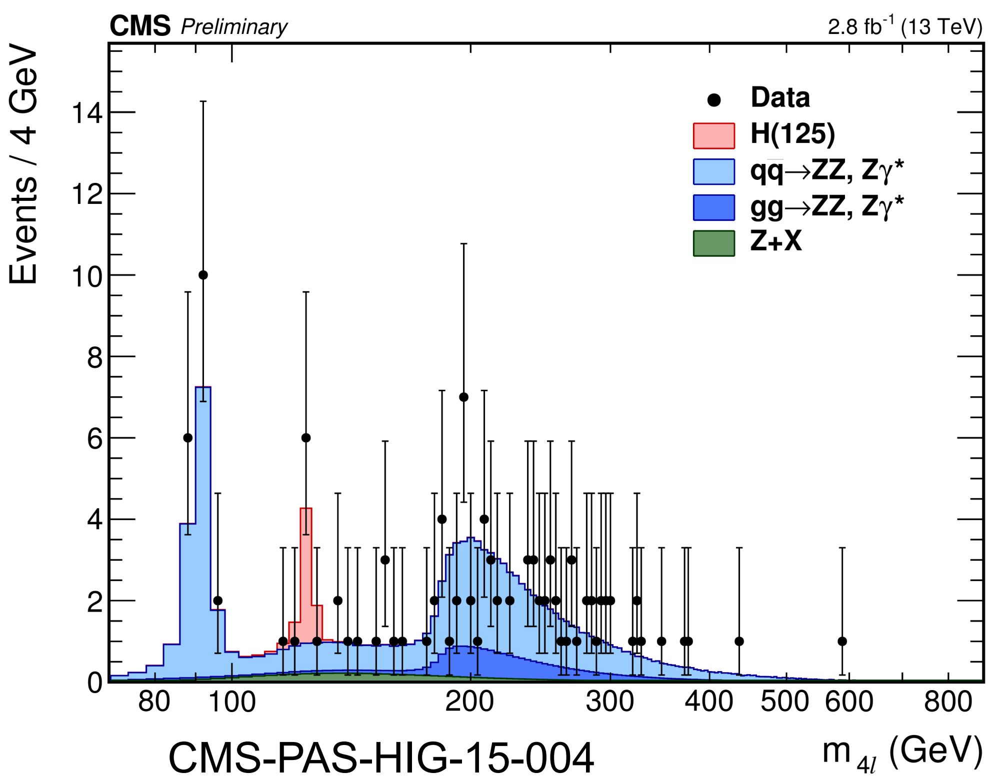


ATLAS-CONF-2016-011

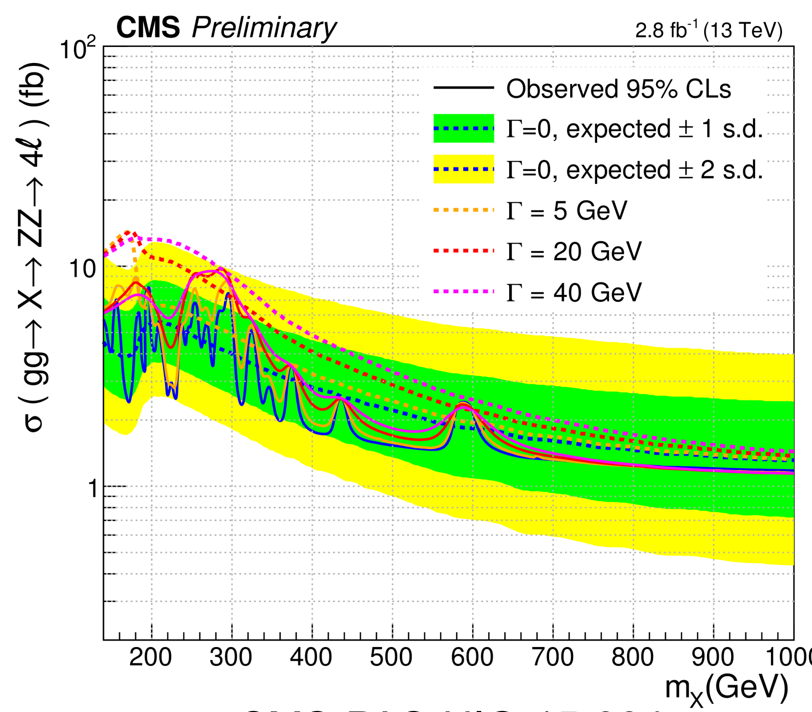


Searches for additional resonances in

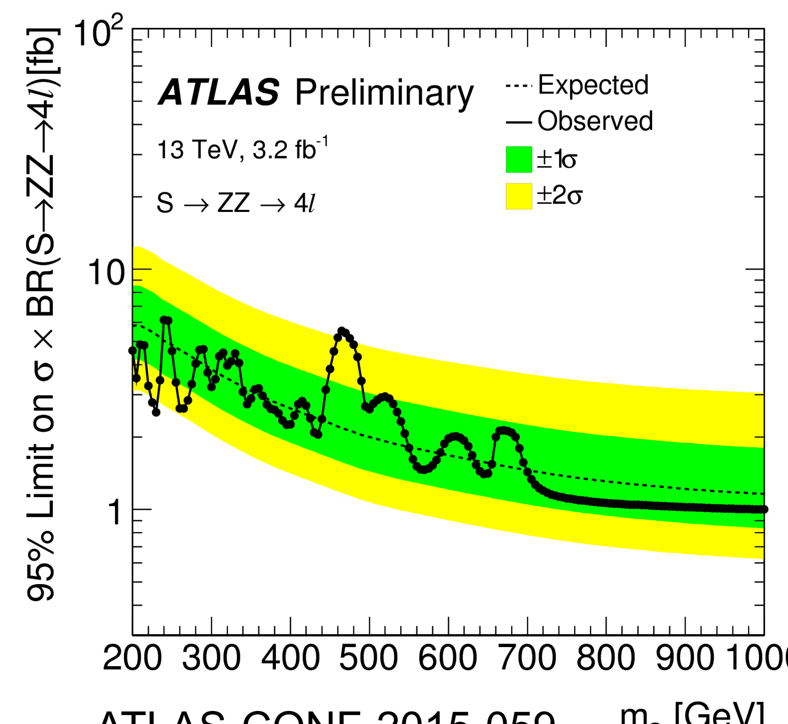
h→ZZ→4l



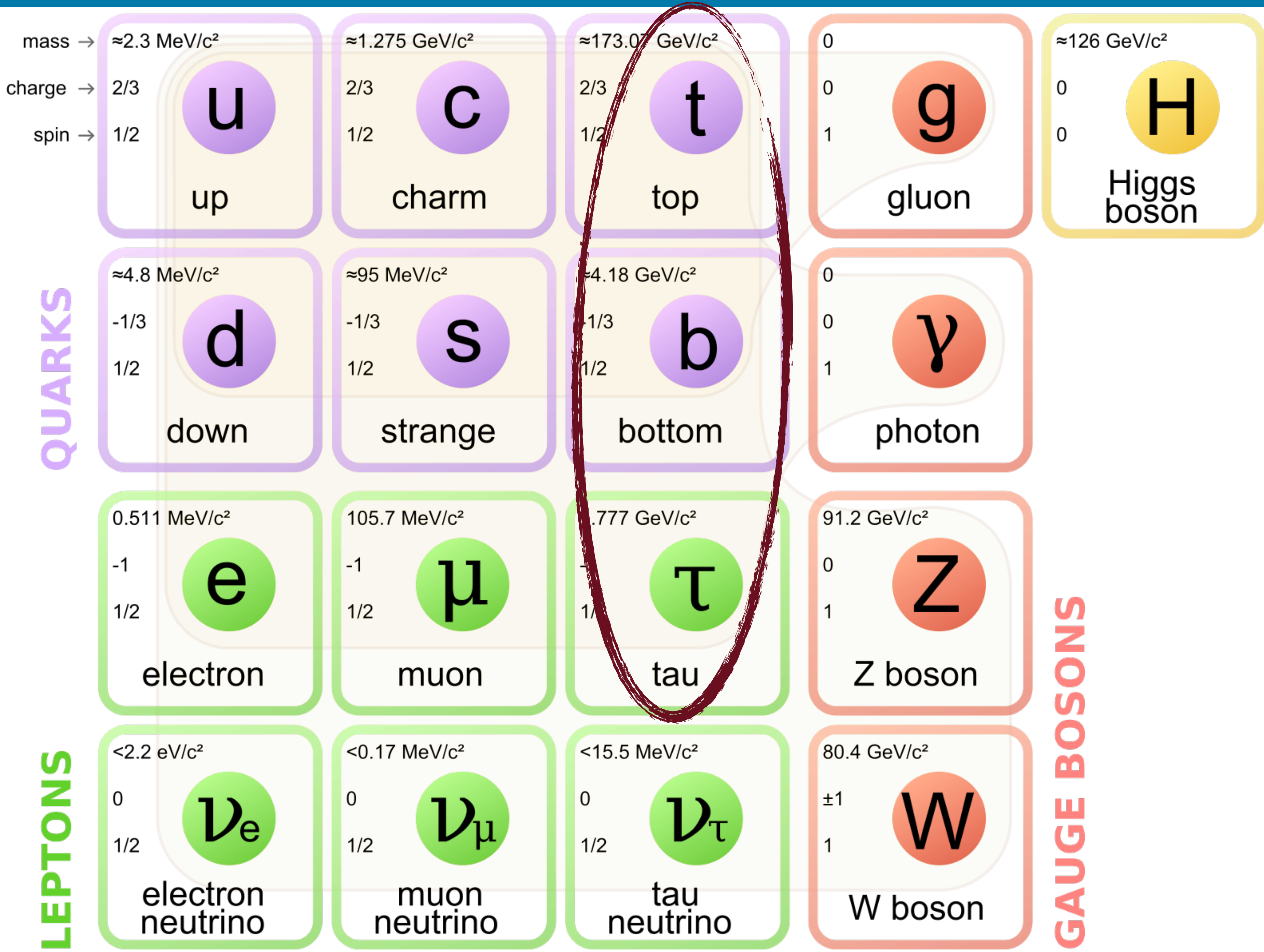
CMS-PAS-HIG-15-004



CMS-PAS-HIG-15-004

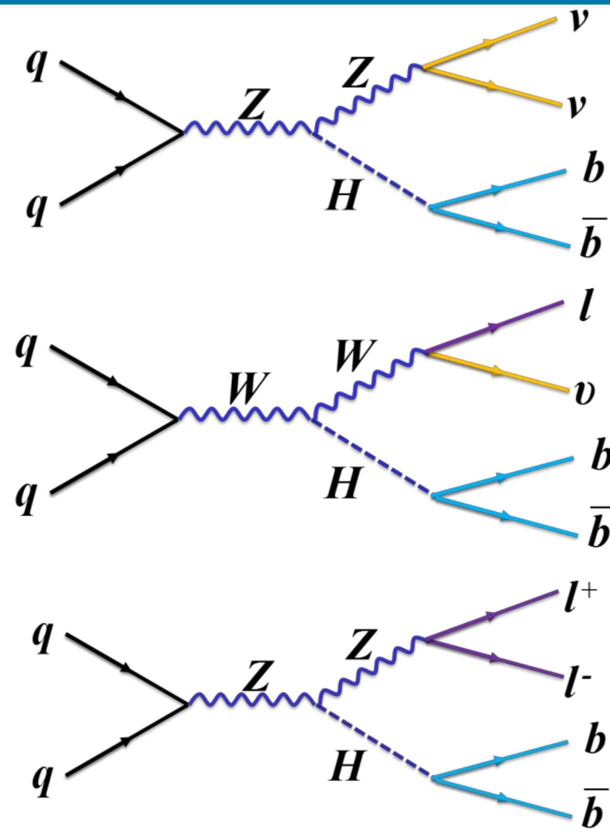


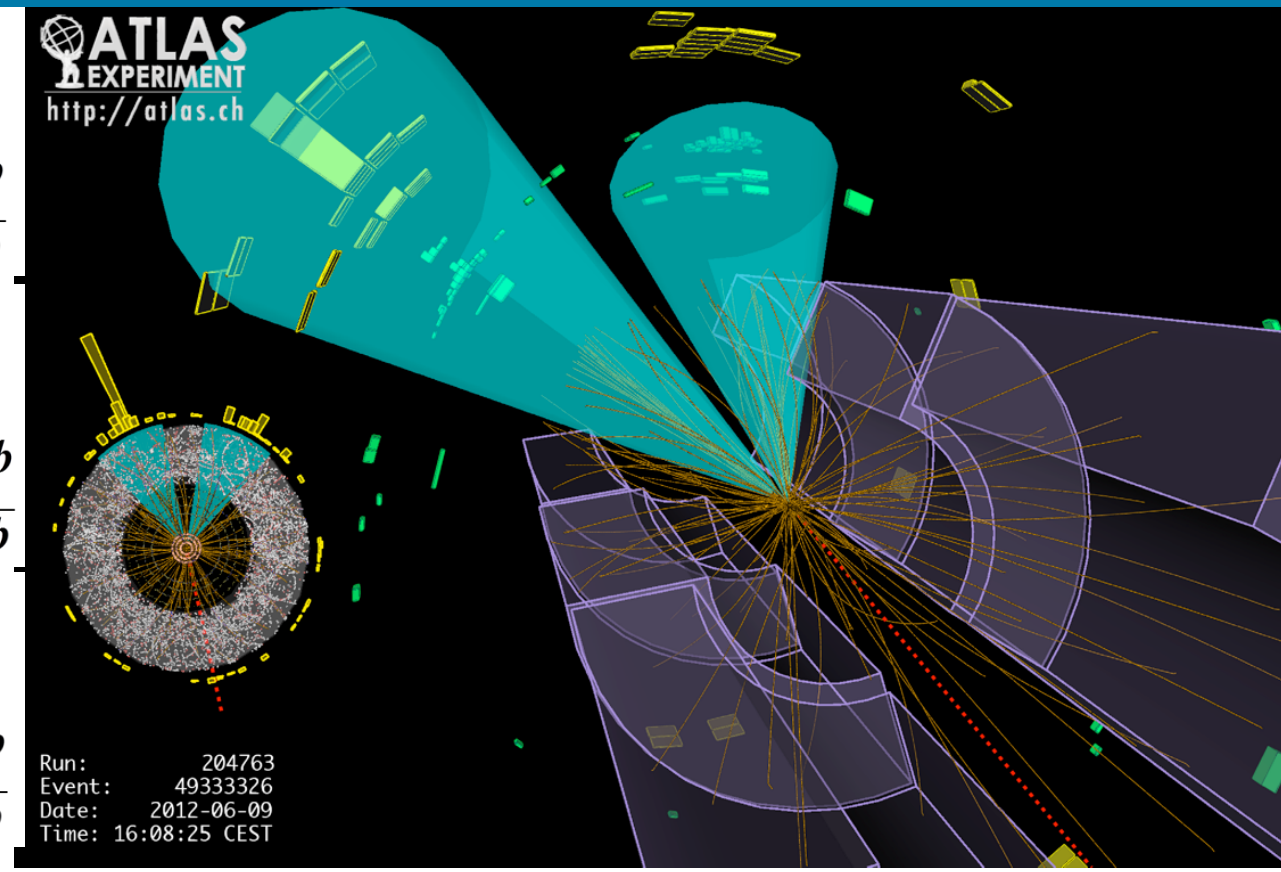
ATLAS-CONF-2015-059

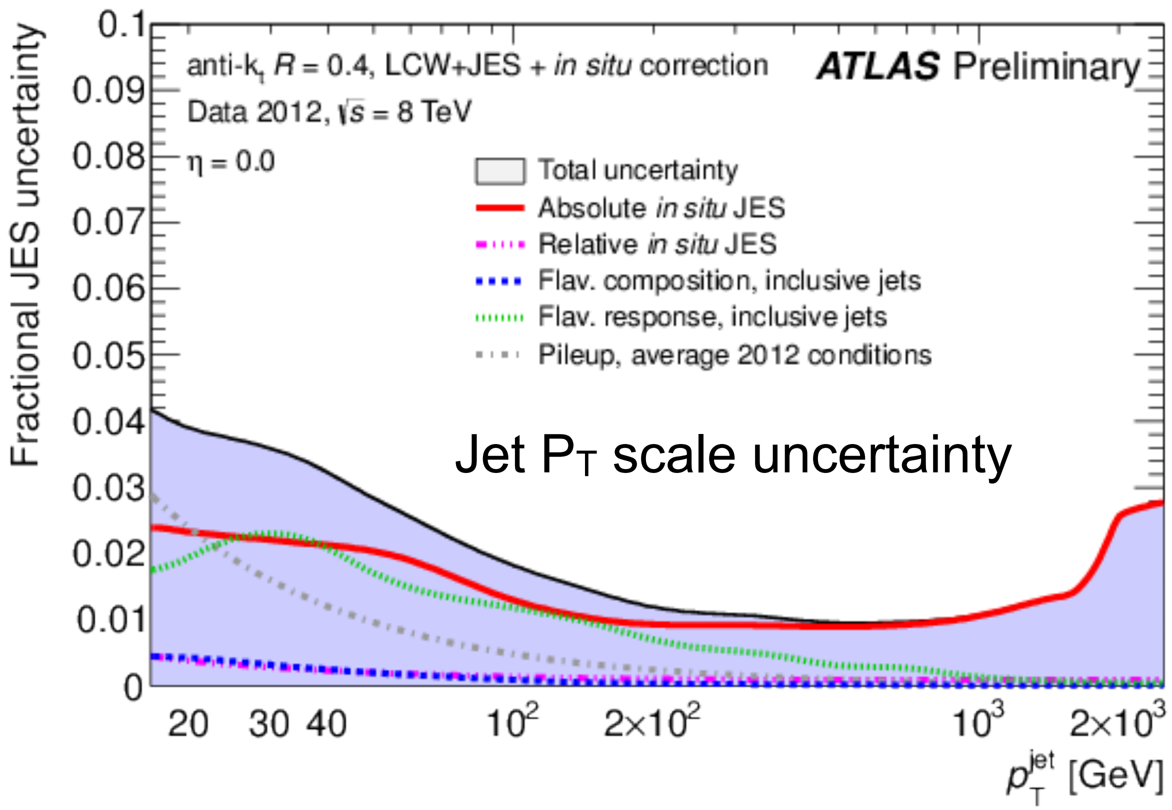

mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
.777 GeV/c²
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

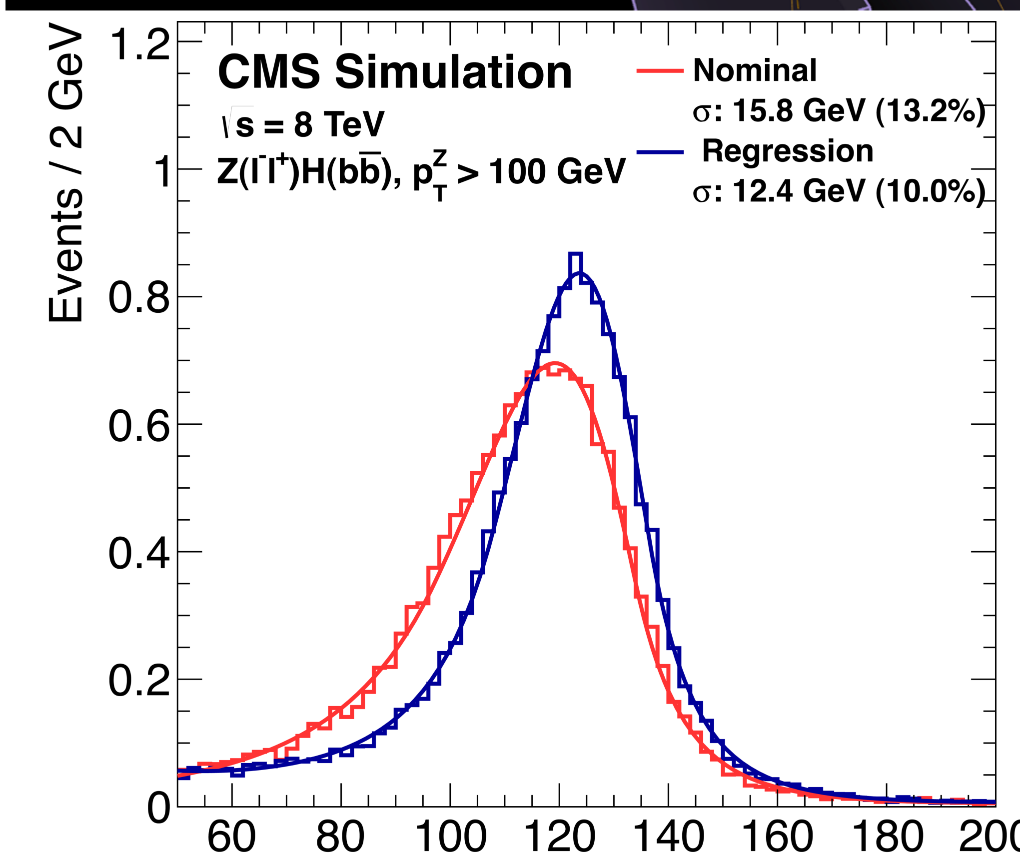
h→bb

- Largest BR (58%@m_H=125 GeV)
  - Large multi-jet background
- Associated production with W/Z
  - VBF also considered
- Backgrounds: W/Z+jets and top
- Final discriminant: BDT_{VH} including m_{bb}
- Separate final states:
  - number of leptons: 0, 1, 2
  - P_T(V) or MET
  - number of jets and b-tags



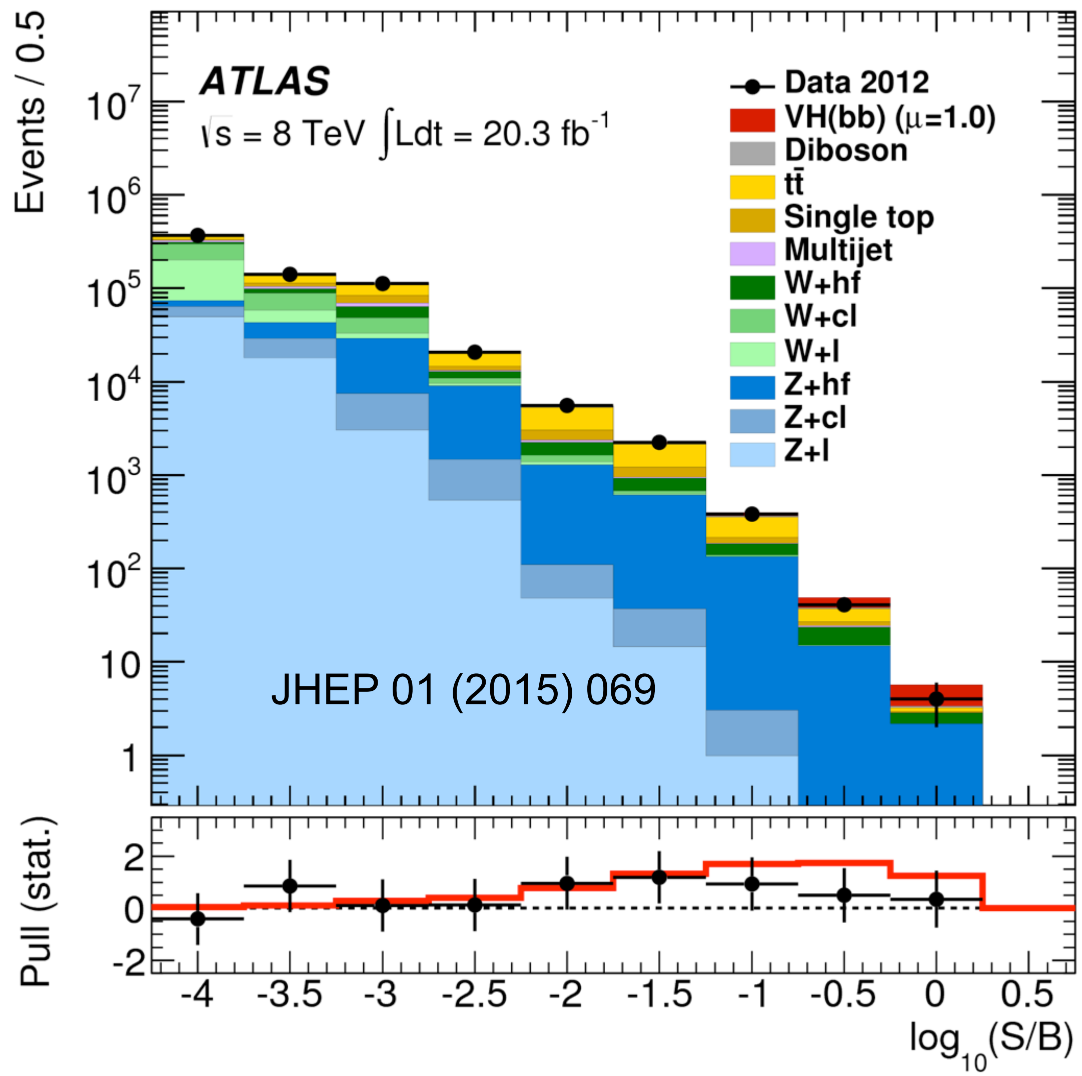


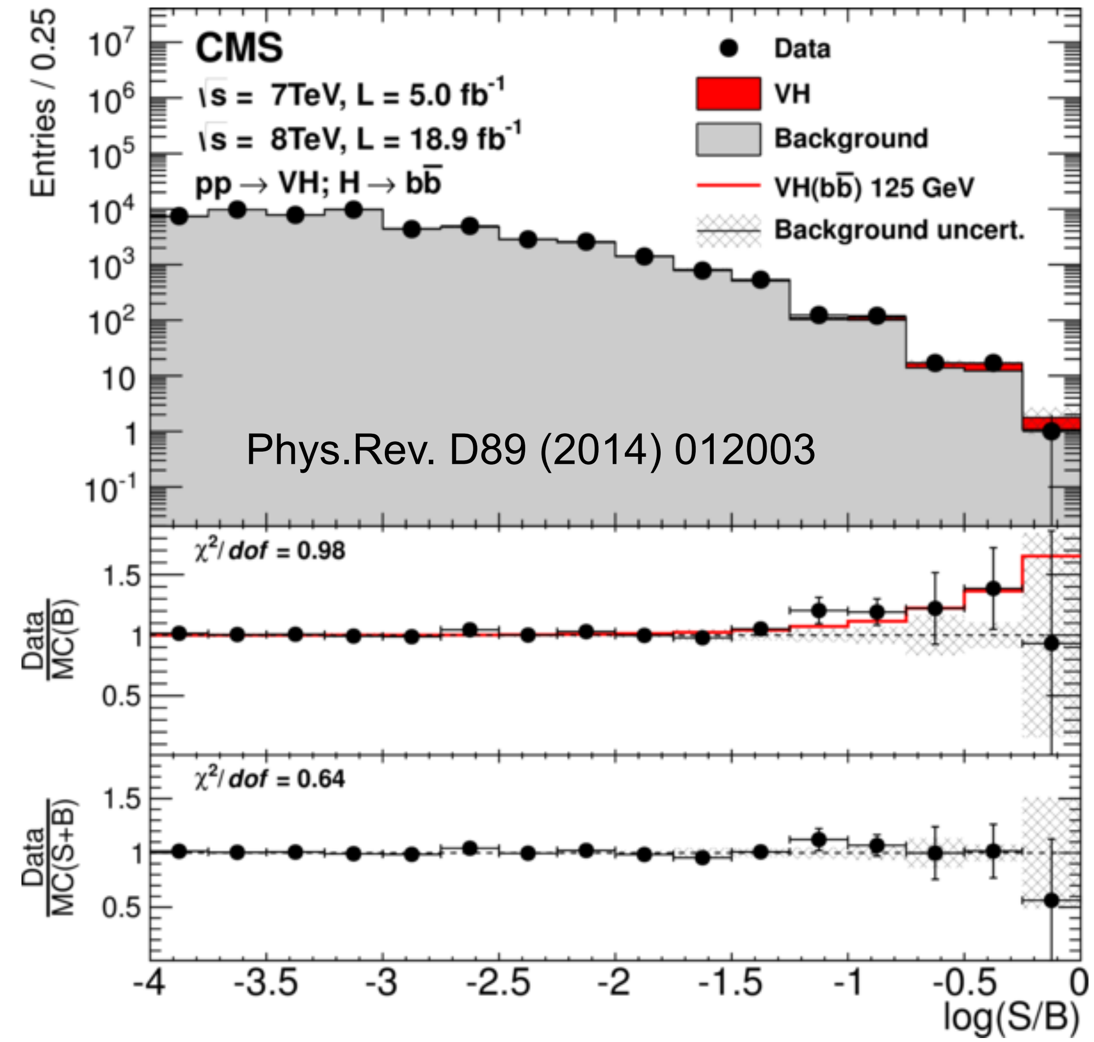




Phys.Rev. D89 (2014) 012003

h→bb





$m_H = 125$ GeV	σ/σ_{SM} (95% CL) median expected	σ/σ_{SM} (95% CL) observed	Significance expected	Significance observed
$W(\ell\nu,\tau\nu)H$	1.6	2.3	1.3	1.4
$Z(\ell\ell)H$	1.9	2.8	1.1	0.8
$Z(\nu\nu)H$	1.6	2.6	1.3	1.3
All channels	0.95	1.89	2.1	2.1

	Significance	$\mu^{95\%}_{upper}$
ATLAS	1.4σ (2.6σ)	1.2 (0.8)
CMS	2.1σ (2.1σ)	1.89 (0.95)
Combined	2.6σ (3.7σ)	-

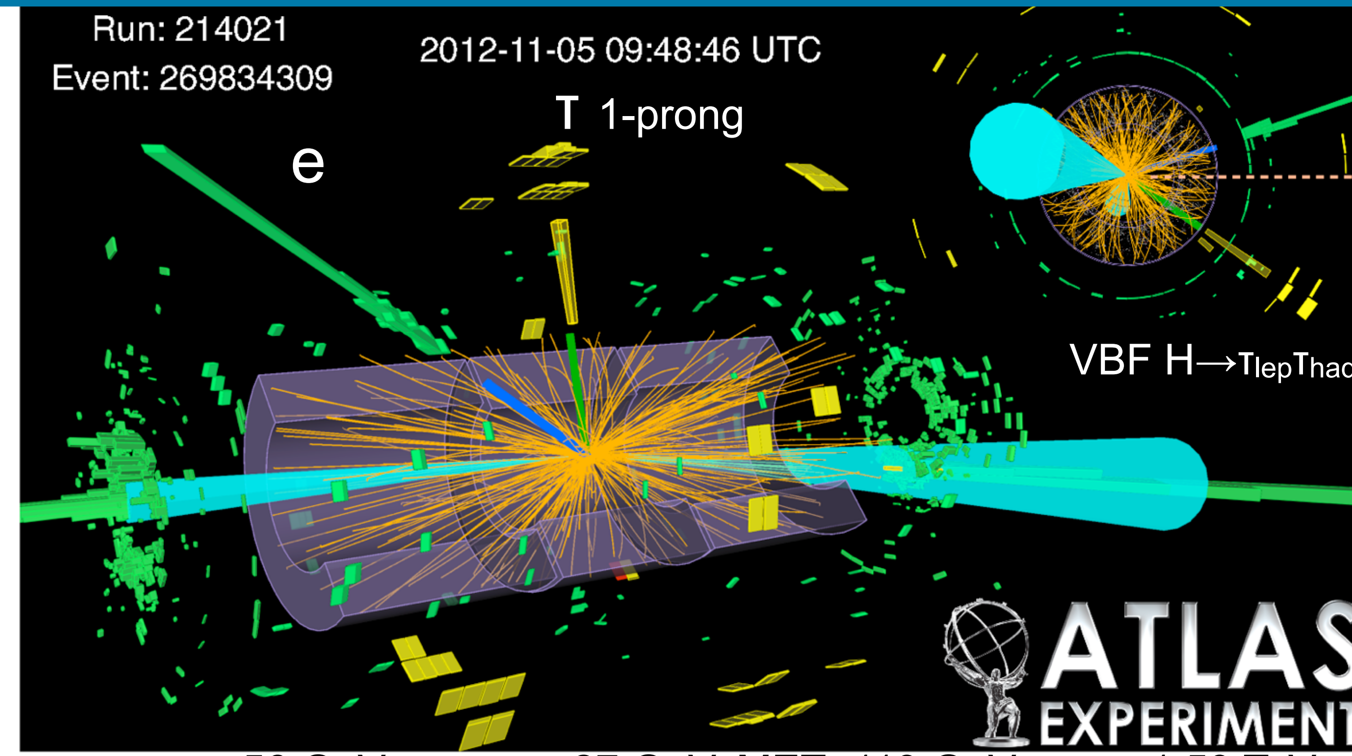
Run I dataset ~SM sensitivity
ATLAS/CMS observe excess over expected background

h→ττ

- Promising for down-type fermion/lepton couplings
- Backgrounds
  - Z → ττ dominant [embedding]
  - “Fakes”: Multijet, W+jets, top [data-driven]
  - “Other”: Dibosons/H->WW* [MC]
- Three sub-channels: $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$

[m_τ ~ 1.78 GeV and $c\tau$ ~ 87.1 μm, τ→leptons 35%, τ→hadrons 65%]

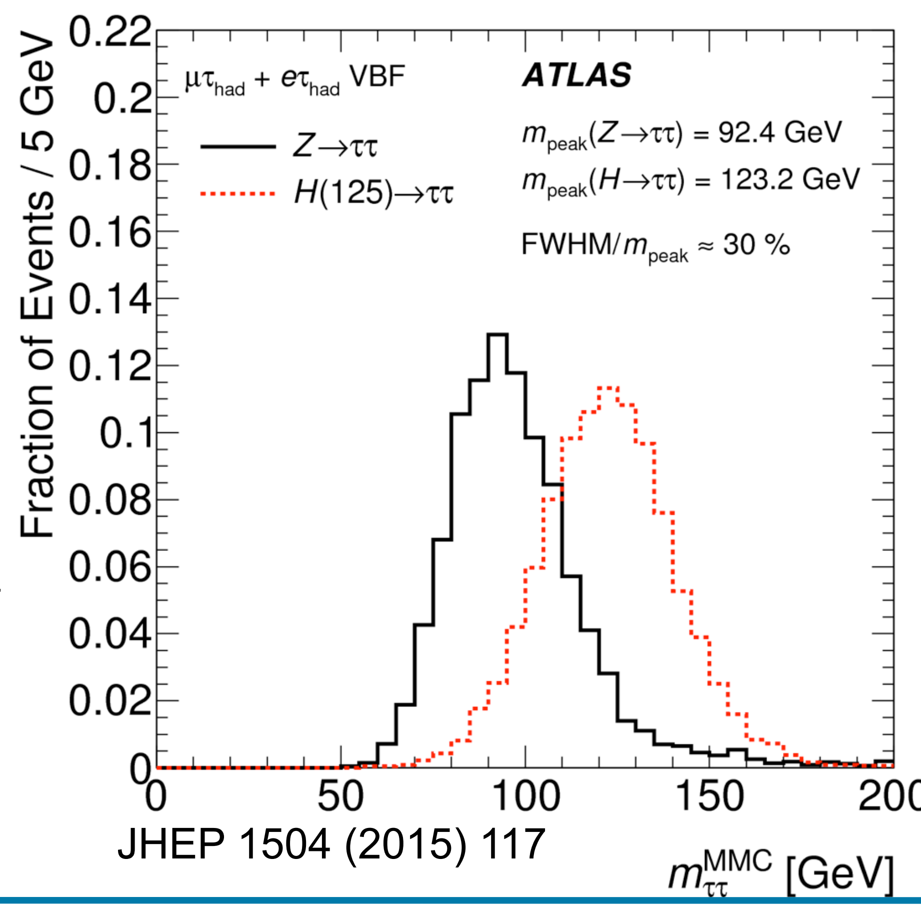
- Sensitivity from VBF and boosted topologies



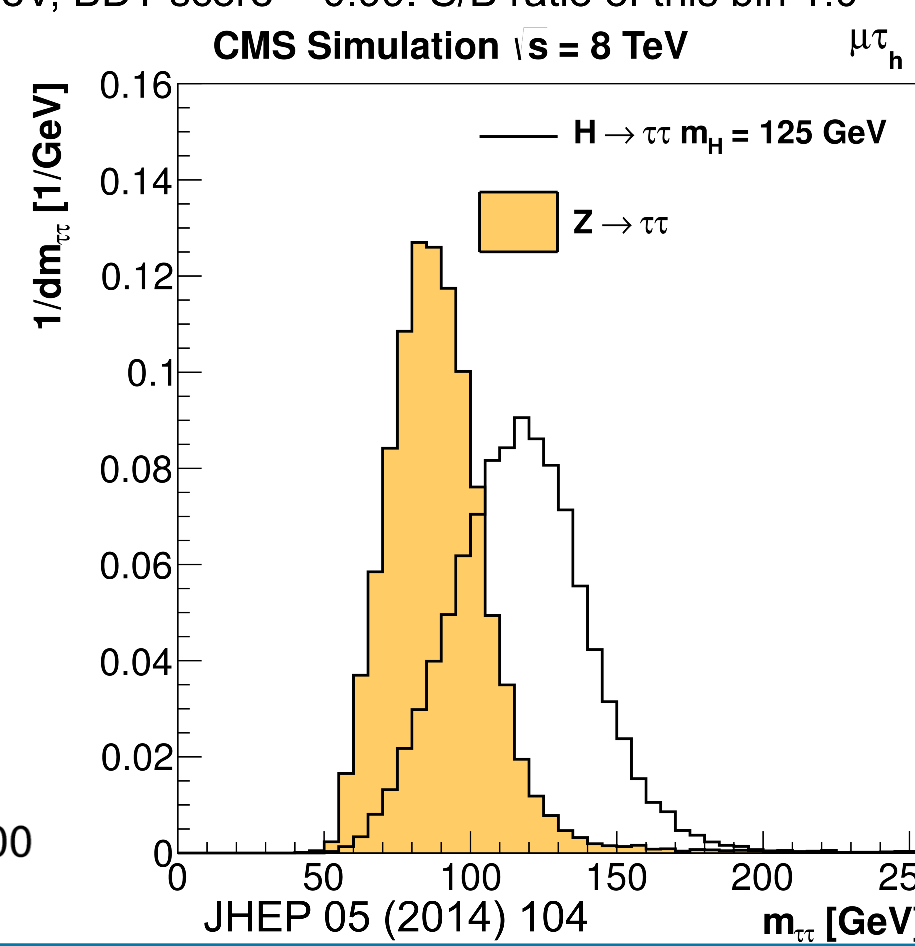
ep_T = 56 GeV, τ_{had} p_T = 27 GeV, MET=113 GeV, $m_{j1,j2}$=1.53 TeV, $m_{\tau\tau}^{MMC}$=129 GeV, BDT score = 0.99. S/B ratio of this bin 1.0

Final discriminant

- BDT for each category: *di-tau properties* ($m_{\tau\tau}$, $\Delta R_{\tau\tau}$, ...), *jet topology* (m_{jj}, $\Delta\eta_{jj}$, ...), *event activity/topology* (scalar/vector pT sum, object centralities, …)
- Detailed categorisation, fit of $m_{\tau\tau}$

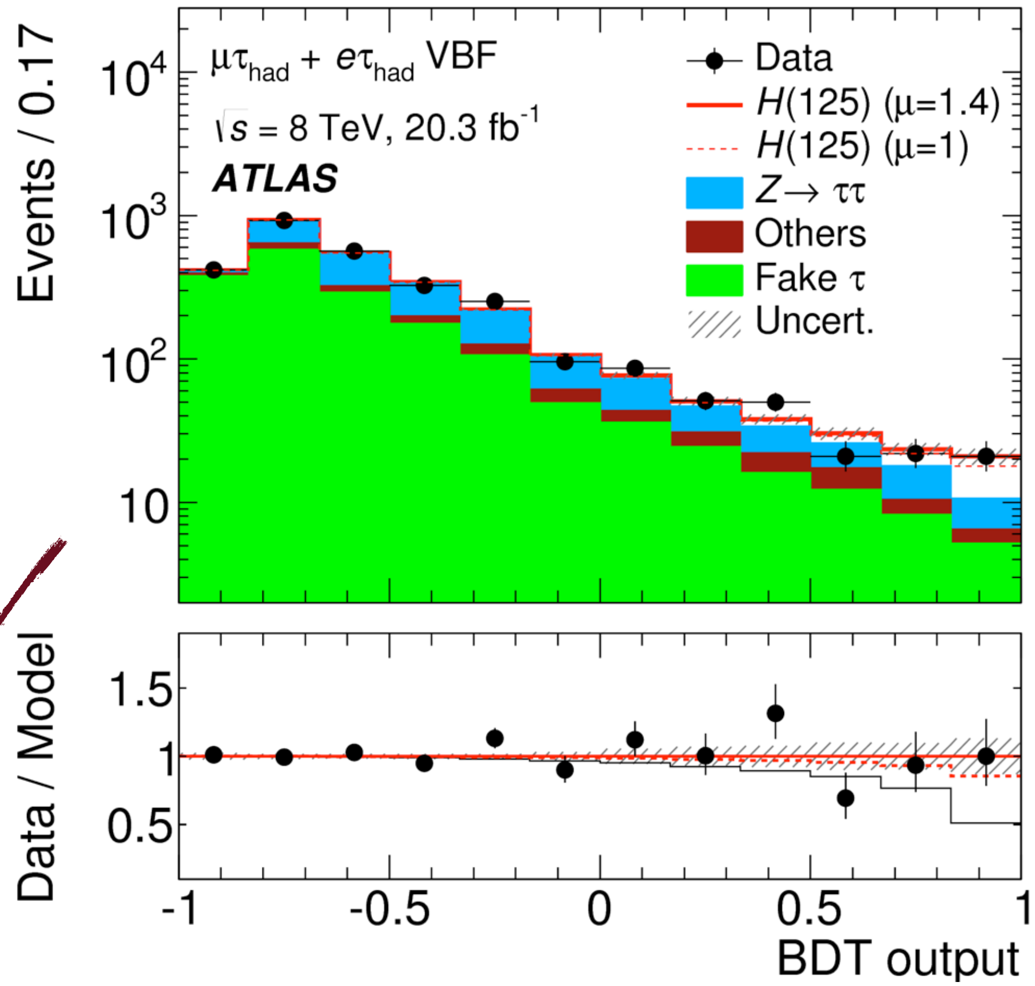


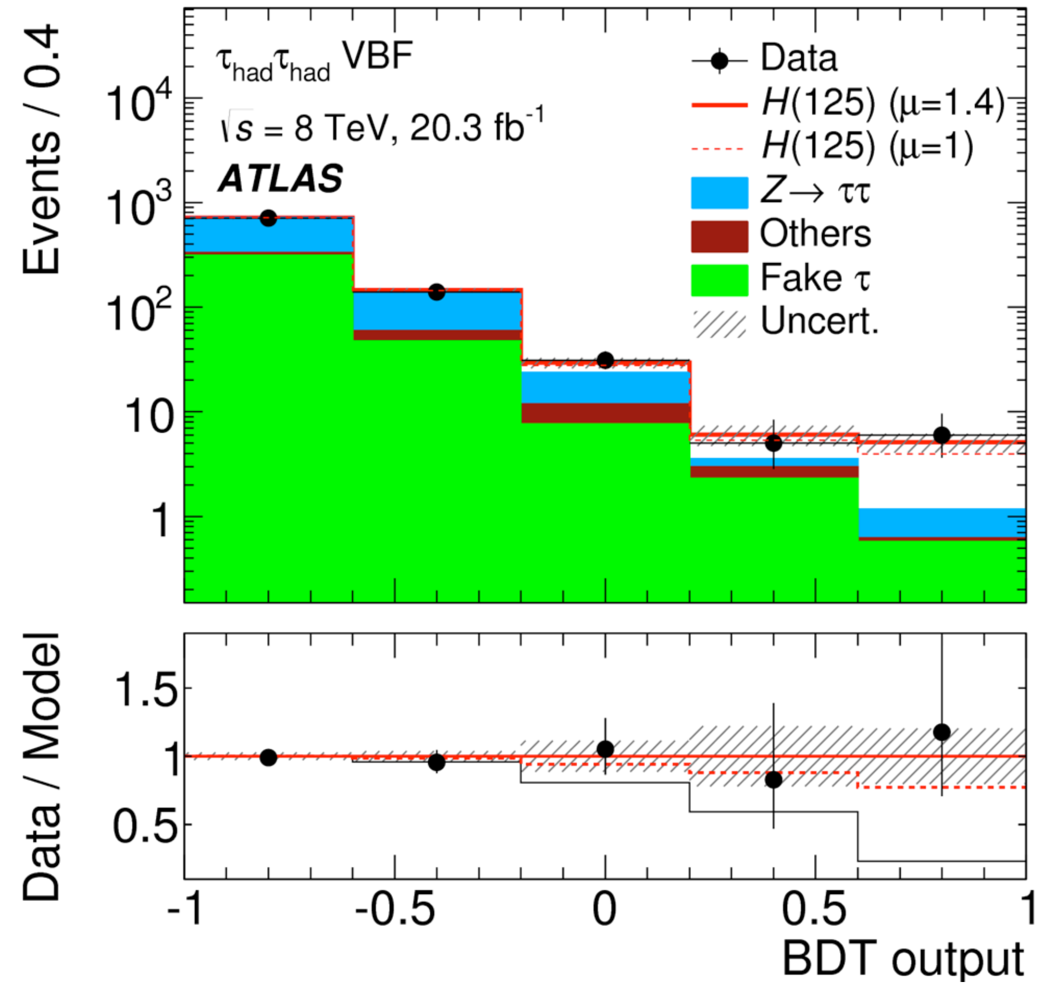
JHEP 1504 (2015) 117



JHEP 05 (2014) 104

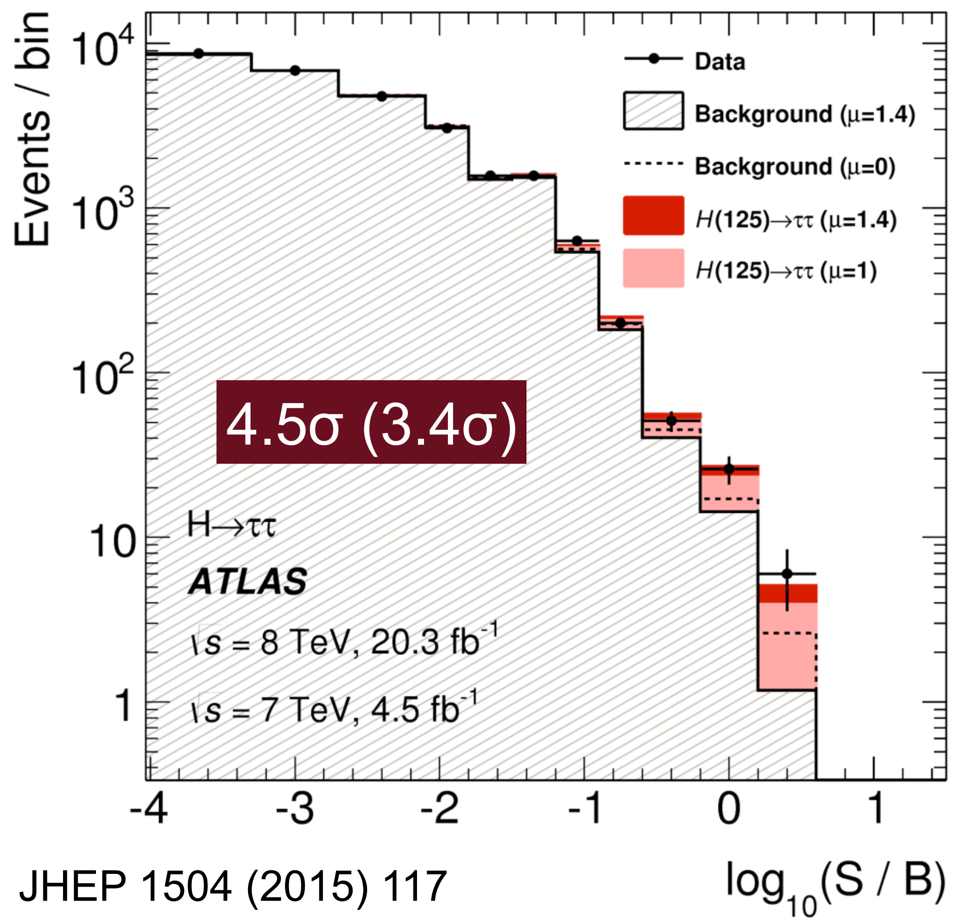
JHEP 1504 (2015) 117



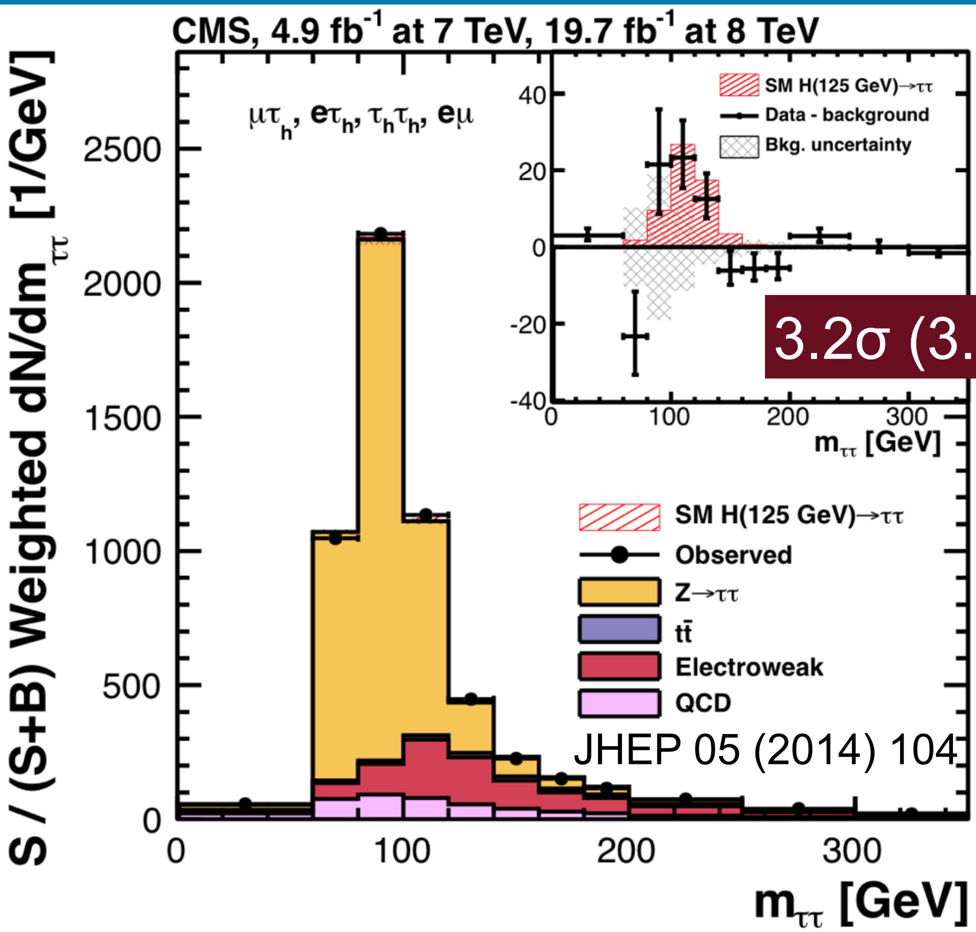


Channel and Category	Expected Significance (σ)	Observed Significance (σ)
$\tau_{lep}\tau_{lep}$ VBF	1.15	1.88
$\tau_{lep}\tau_{lep}$ Boosted	0.57	1.72
$\tau_{lep}\tau_{lep}$ Total	1.25	2.40
$\tau_{lep}\tau_{had}$ VBF	2.11	2.23
$\tau_{lep}\tau_{had}$ Boosted	1.11	1.01
$\tau_{lep}\tau_{had}$ Total	2.33	2.33
$\tau_{had}\tau_{had}$ VBF	1.70	2.23
$\tau_{had}\tau_{had}$ Boosted	0.82	2.56
$\tau_{had}\tau_{had}$ Total	1.99	3.25
Combined	3.43	4.54

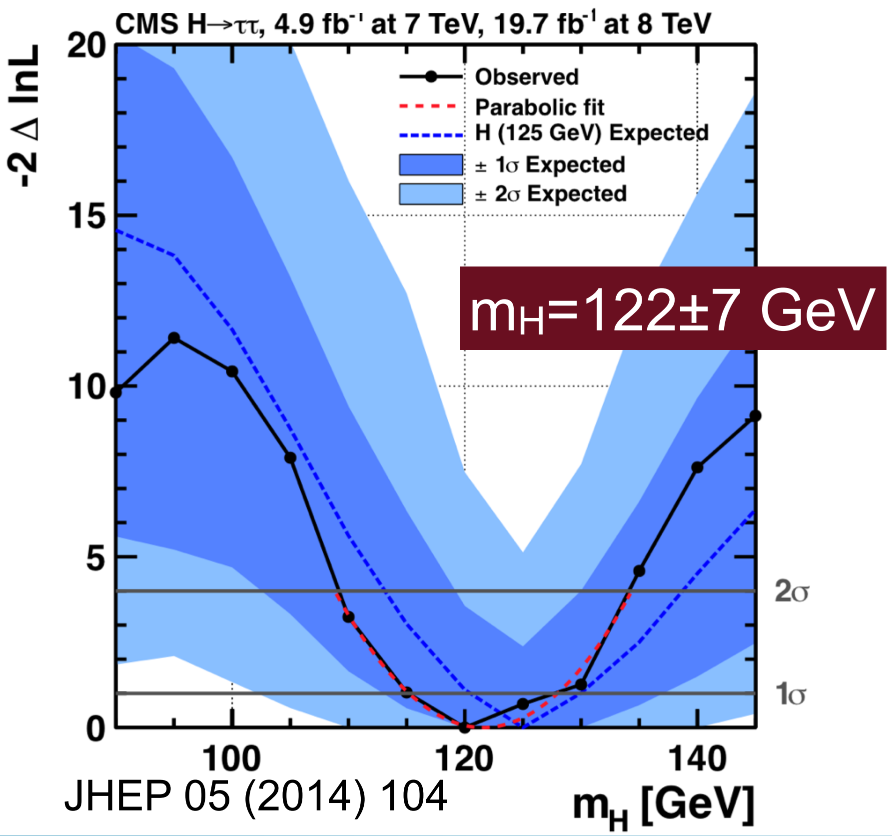
h→ττ: Results



JHEP 1504 (2015) 117



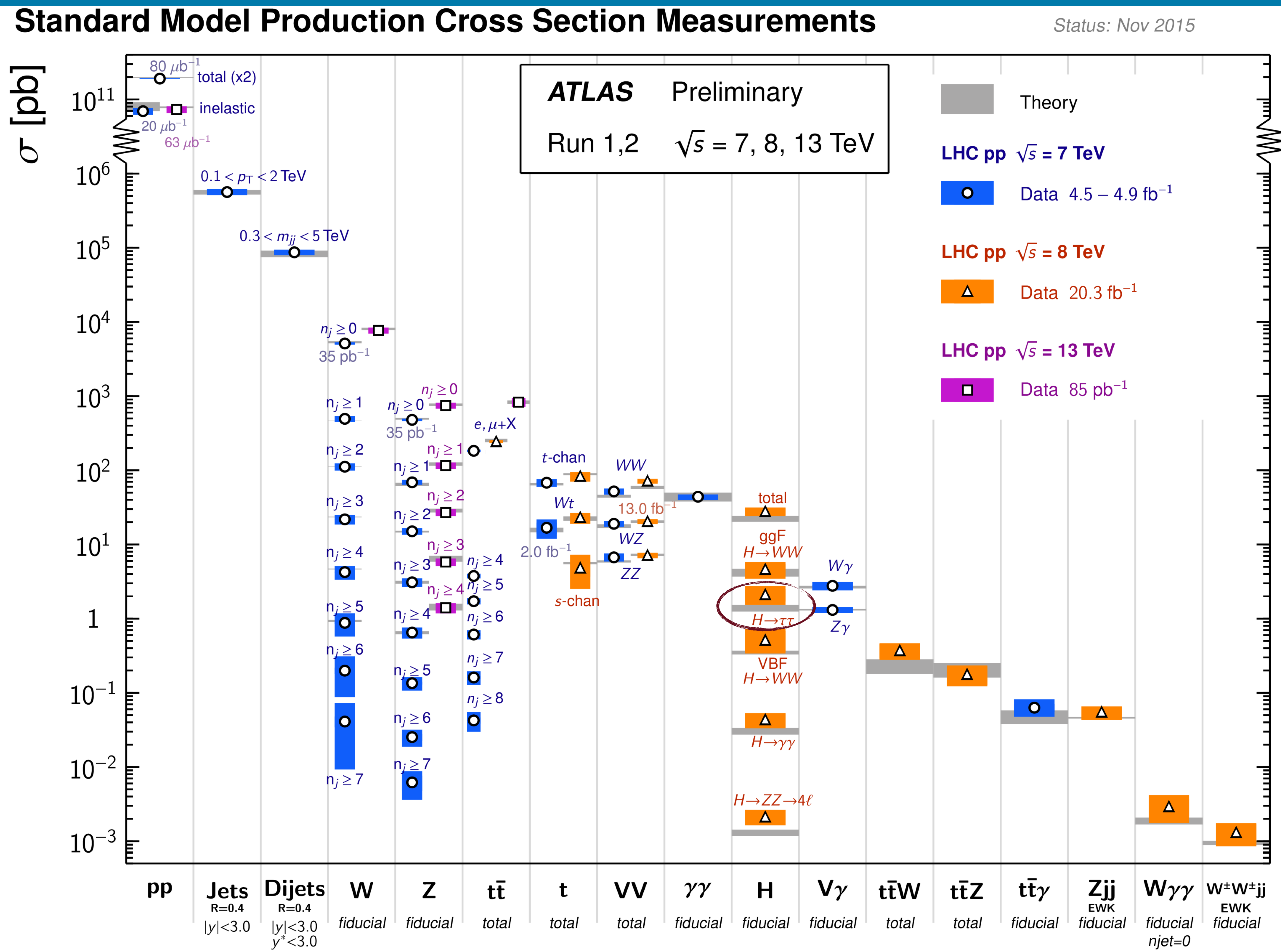
m_H=125.09 GeV	Significance	Signal Strength
ATLAS	4.5σ (3.4σ)	$1.41^{+0.40}_{-0.35}$
CMS	3.2σ (3.5σ)	$0.89^{+0.31}_{-0.28}$
Combined	**5.5σ (5.0σ)**	$\mathbf{1.12^{+0.25}_{-0.23}}$



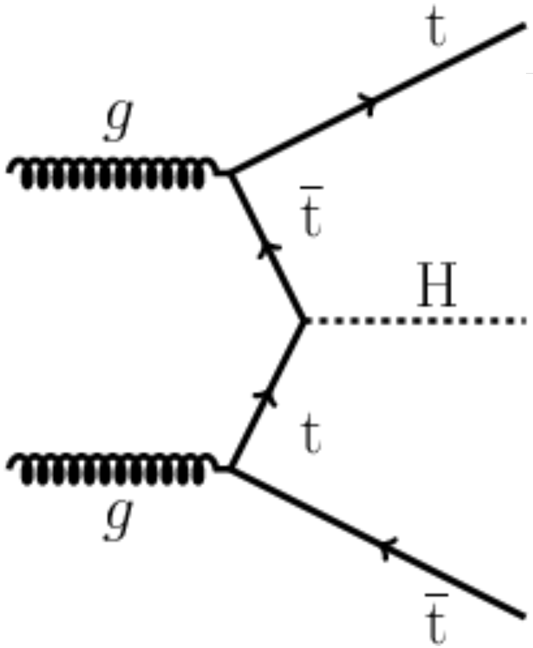
JHEP 05 (2014) 104

Evidence for Higgs boson decays to τ-leptons

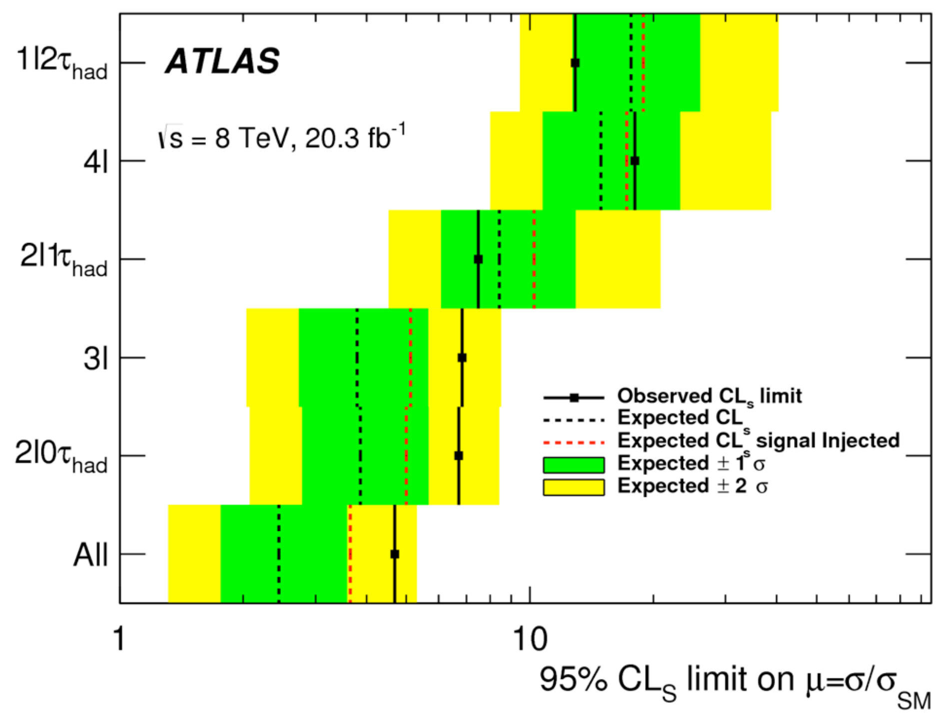
Snapshot of cross section measurements



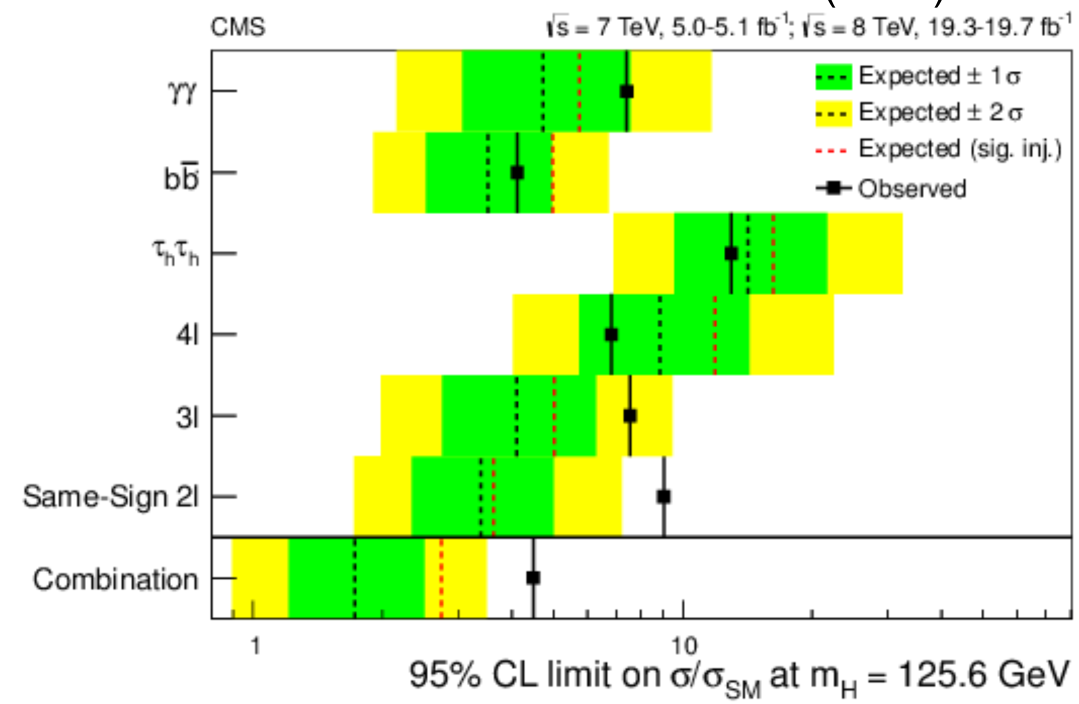
ttH



Phys.Lett.B749(2015)519



JHEP 1409 (2014) 087



h→ttbar kinematically forbidden; direct information on top-Yukawa through associated production

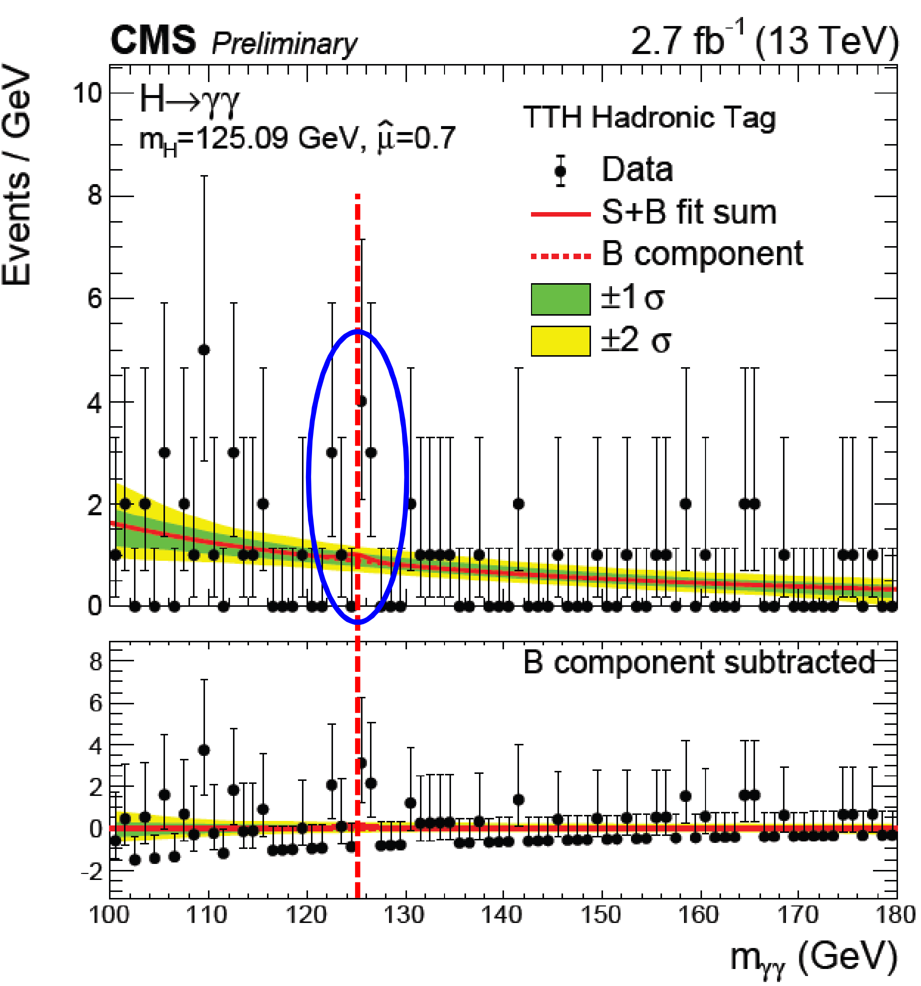
Complex final states:

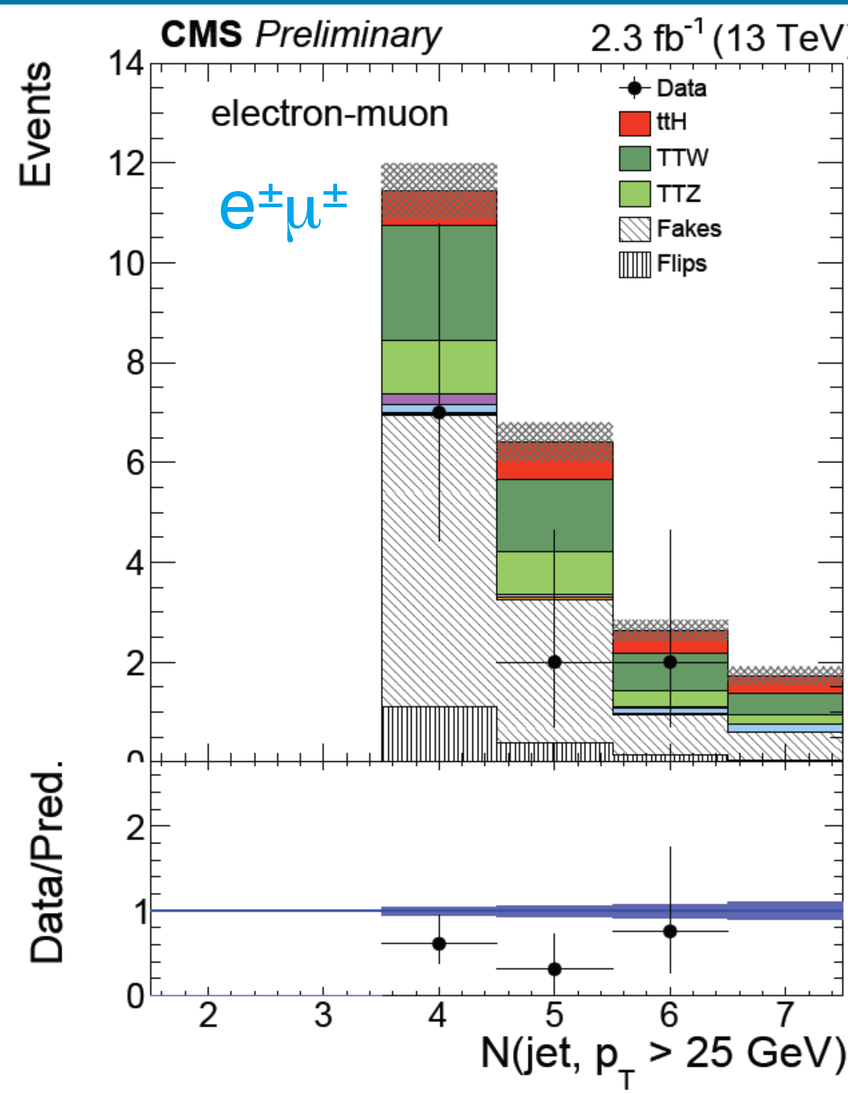
- tth→γγ
- tth→multi-leptons
  - (h→WW*,ZZ*, ττ)
- tth→bb

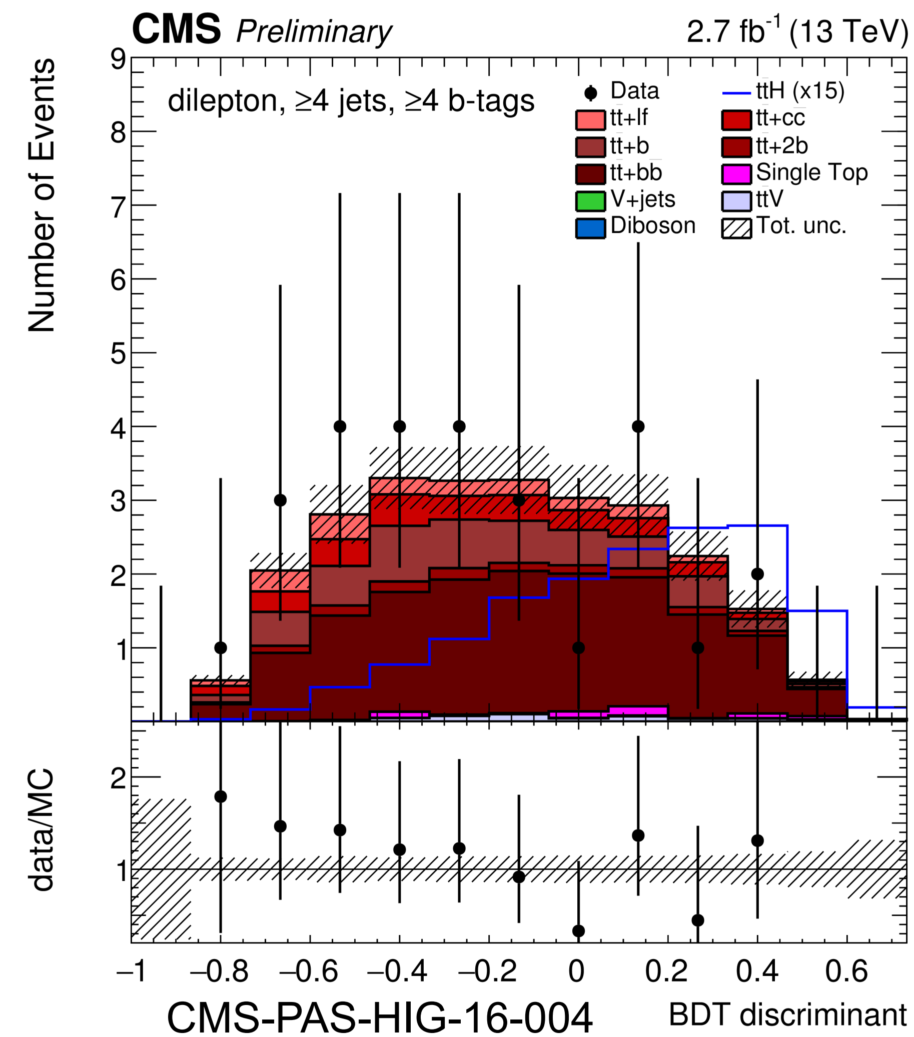
Categories based on the decays of the top quarks (di-leptons, l+jets,…)

m_h=125 GeV	$\mu^{95\%}_{upper}$	Significance	Reference
CMS (125.6 GeV)	4.5 (1.7)	3.4(1.2)	JHEP 1409(2014) 087
ATLAS bb	3.4 (2.2)	1.4(1.1)	Eur.Phys.J. C75 (2015) 349
ATLAS multi-leptons	4.7 (2.4)	1.8(0.9)	Phys.Lett.B749(2015)519
ATLAS γγ (125.4 GeV)	6.7 (4.9)	-	Phys.Lett. B740(2015) 222
ATLAS Couplings (125.36 GeV)	-	2.5(1.5)	Eur.Phys.J. C76 (2016) 6
Combined	-	4.4(2.0)	ATLAS-CONF-2015-044 CMS-PAS-HIG-15-002

ttH in Run 2







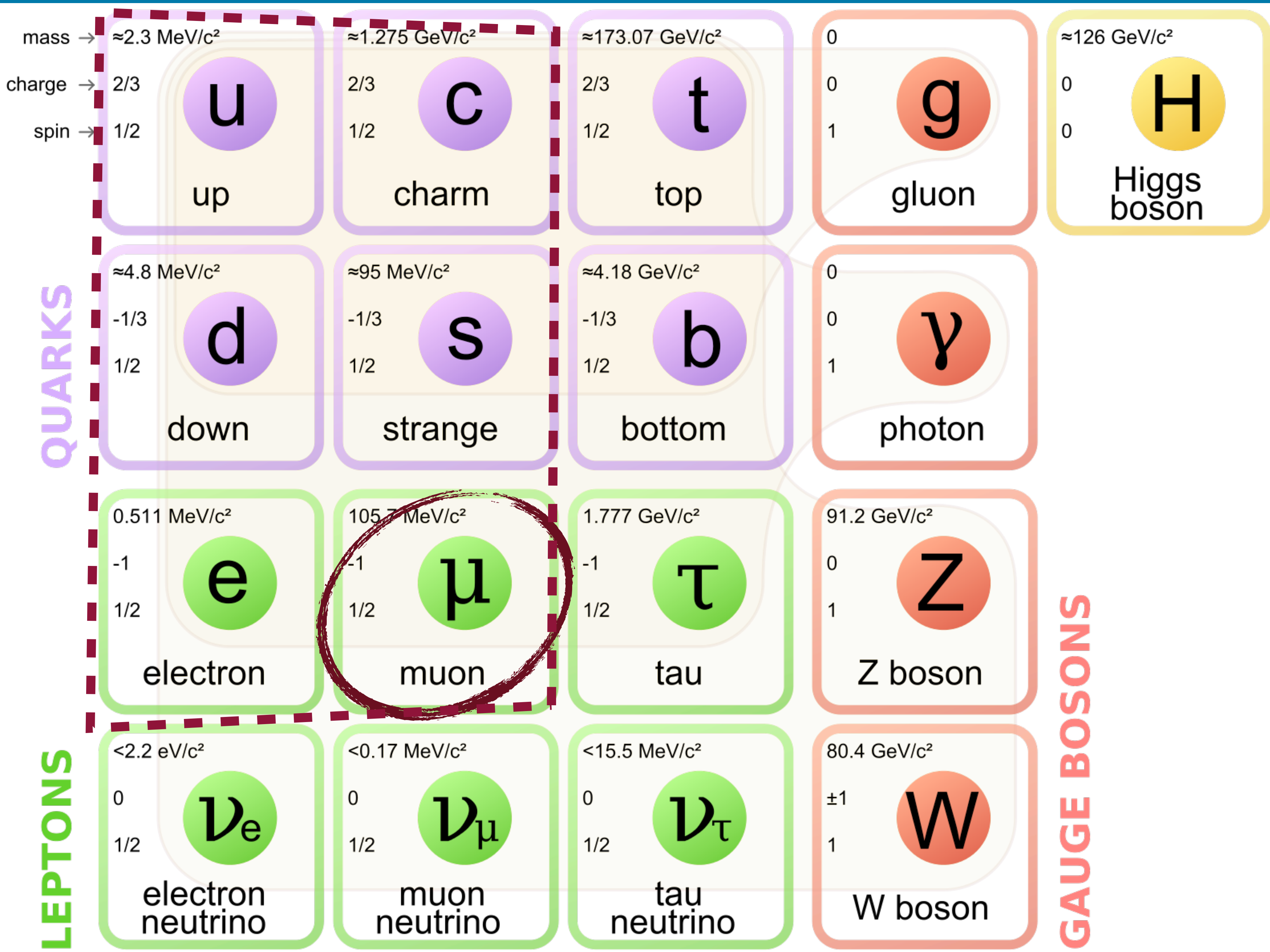
CMS updated all ttH analyses with Run 2 data
Amount effectively to ~50% of the Run 1 dataset
No conclusive, but ready for 2016 dataset!

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

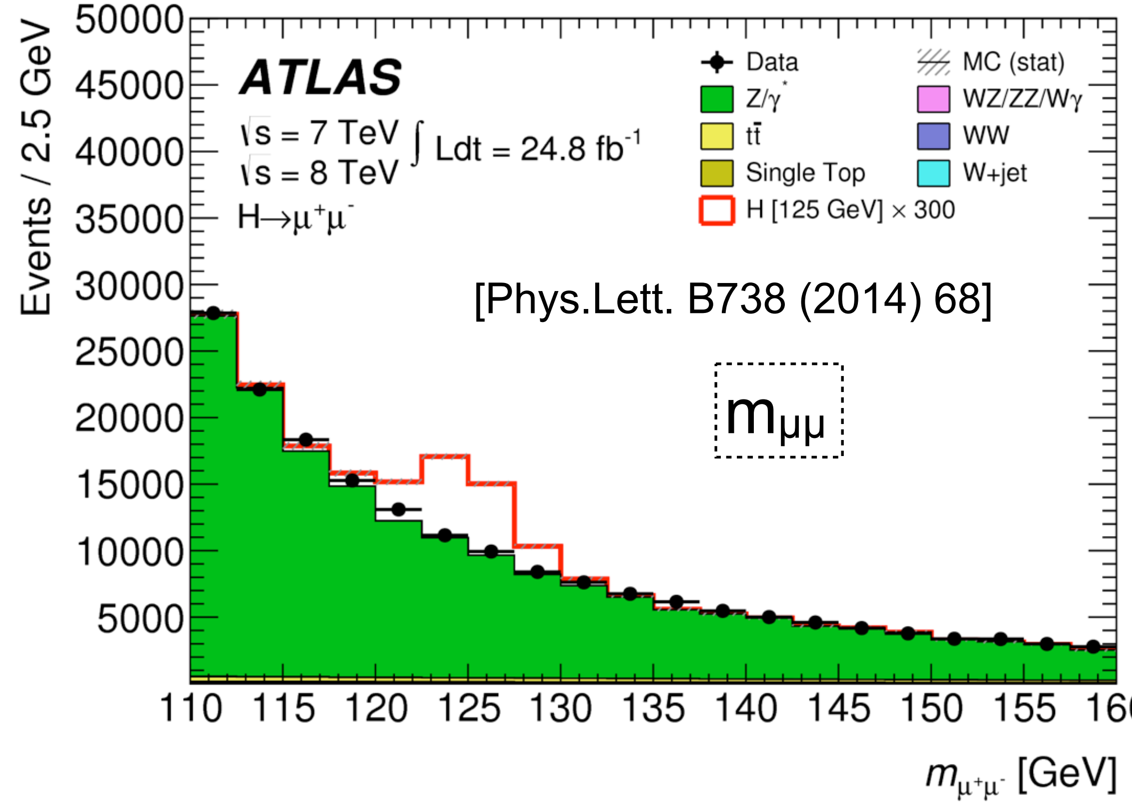
ttH(multilepton) $\hat{\mu}_{obs} = 0.6^{+1.4}_{-1.1}$

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

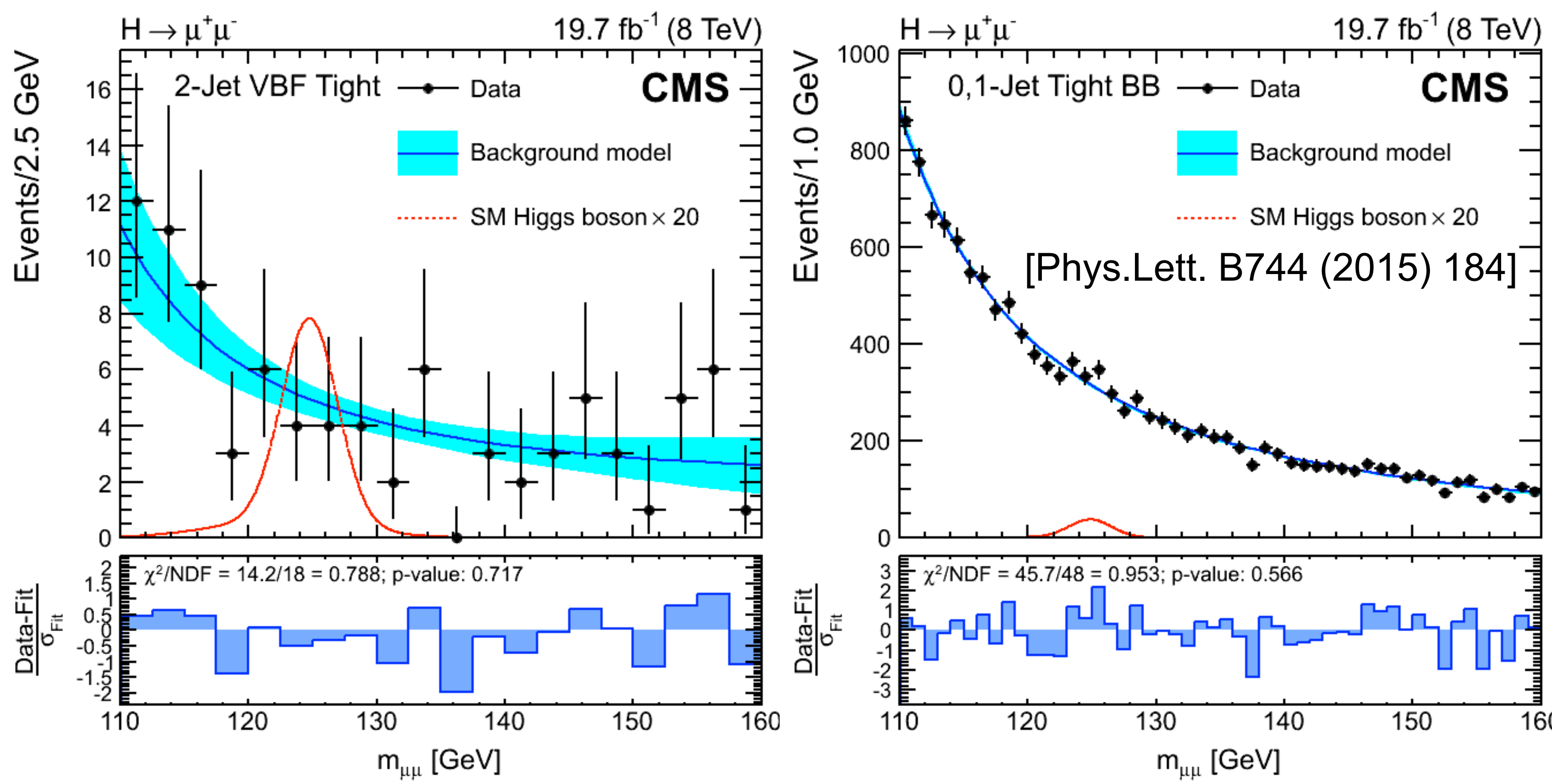
J. Hauk @ Moriond EW'16


mass
charge
spin
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
νe
electron neutrino
<0.17 MeV/c²
0
1/2
νμ
muon neutrino
<15.5 MeV/c²
0
1/2
ντ
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
QUARKS
LEPTONS
GAUGE BOSONS

- Probing 2nd generation Yukawa couplings
- $BR_{SM}\sim 2\cdot 10^{-4}$(125 GeV); S/B~0.2%
- Simple Final State
  - $\mu^+\mu^-$ (p_T>25,15 GeV, $p_{T\mu\mu}$>15 GeV)
- Backgrounds: Z/γ*→μμ, top, dibosons
  - Parametric Model: Breit-Wigner+Expo
- Categorisation: central/non-central muons and/or production mechanism
- 95% CL upper limit @m_H=125 GeV:
  ATLAS : 9.8 (8.2)xSM
  CMS : 7.4 (6.5)xSM

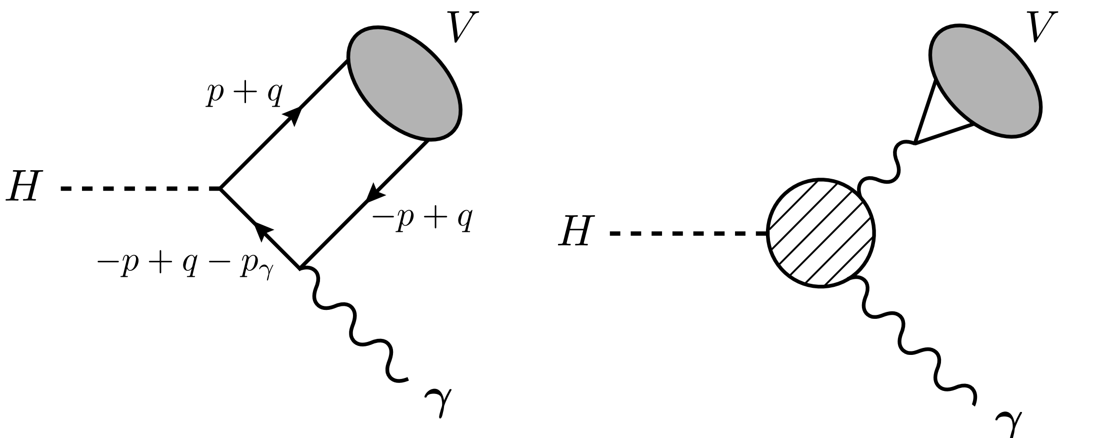


no universal Higgs boson coupling to fermions



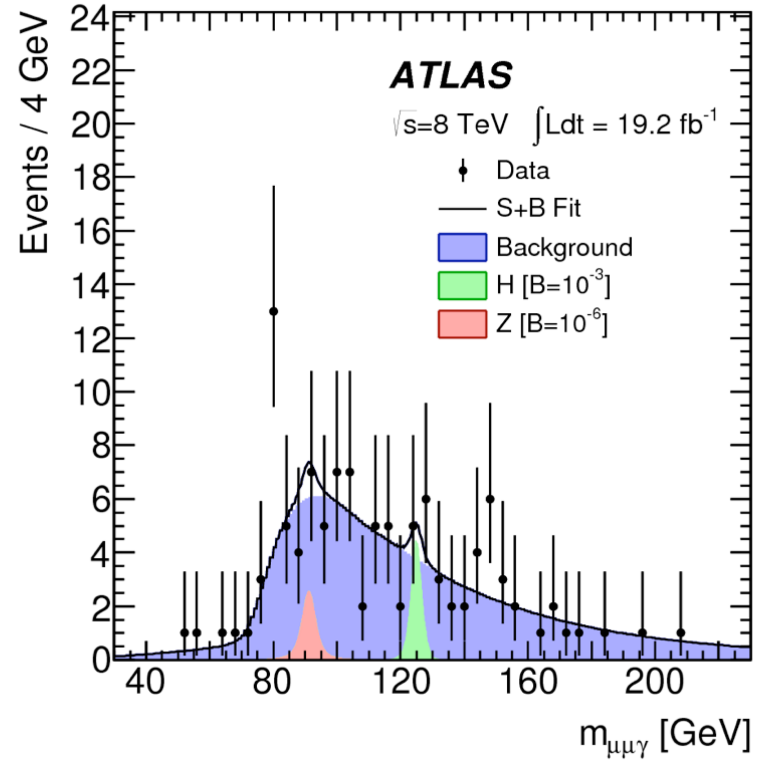
CMS search for $h\to e^+e^-$
$BR(h\to ee)<1.9\cdot 10^{-3}$
$BR_{SM}(h\to ee)\sim 5\cdot 10^{-9}$
[Phys.Lett. B744 (2015) 184]

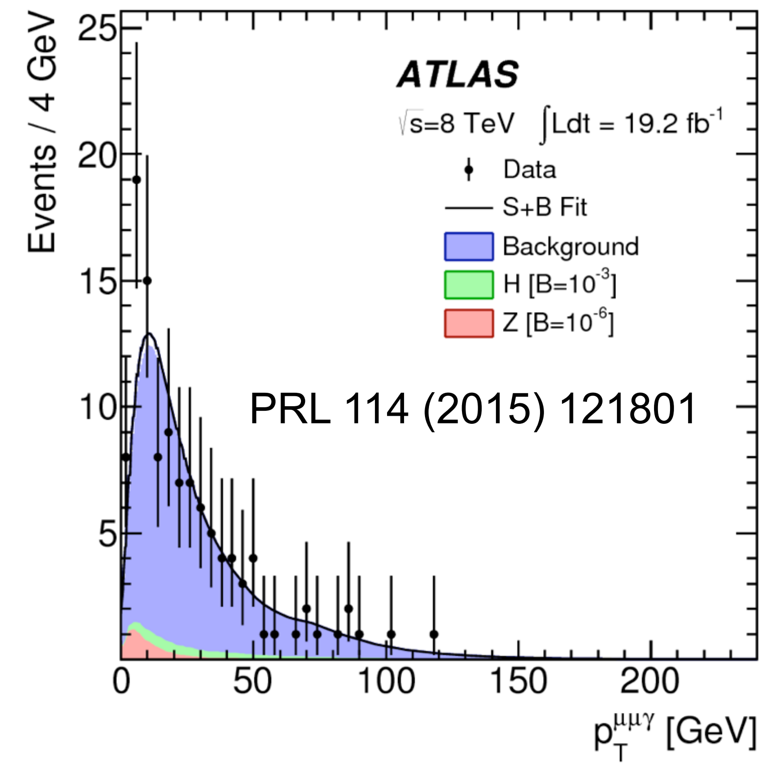
h→Qγ (Q=J/ψ,Υ)



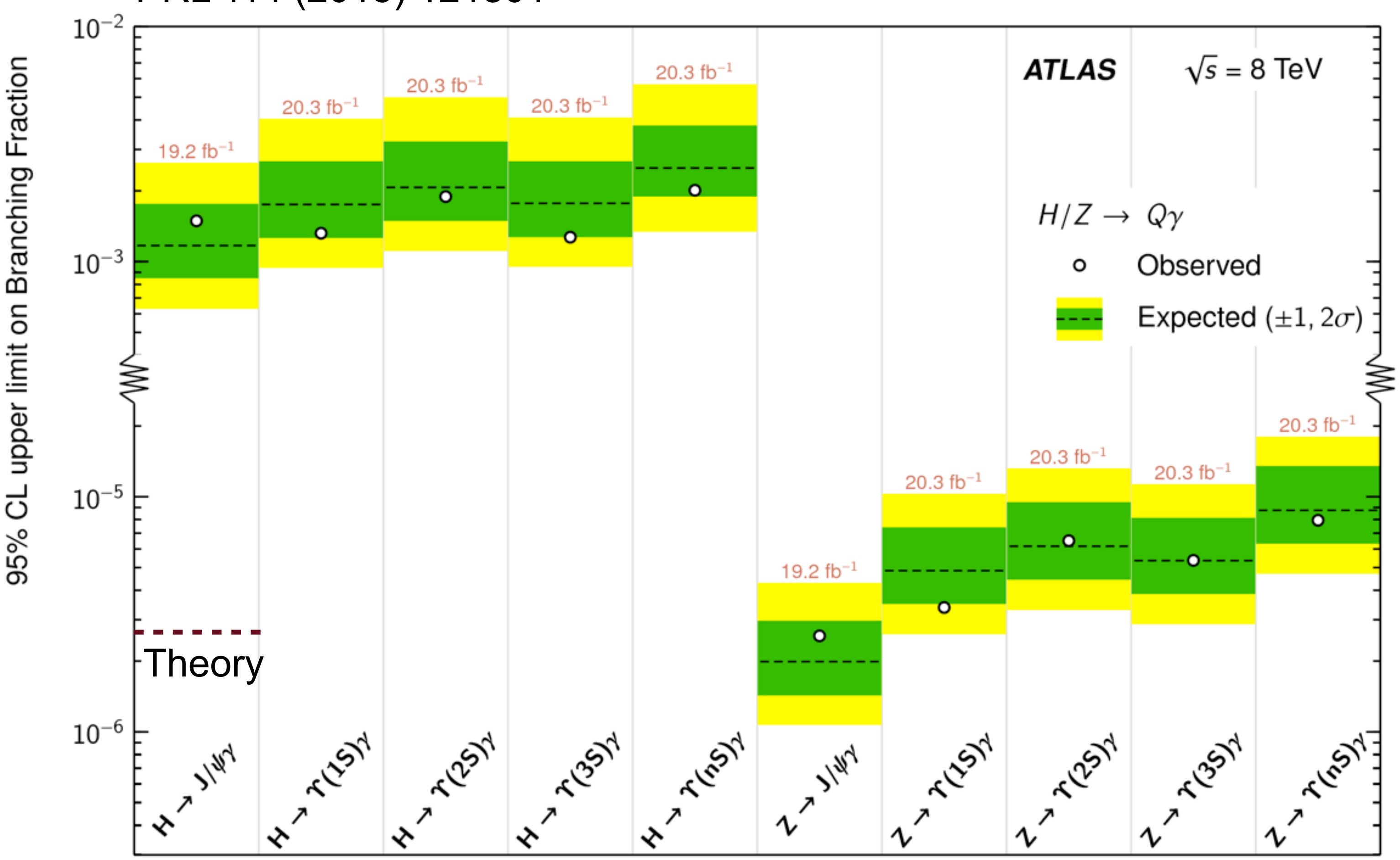
"Direct" "Indirect"

[Phys.Lett. B82 (1979) 411; Phys.Rev. D27 (1983) 2762; Yad.Fiz. 46, 864 (1987); Phys.Rev. D88 (2013) 053003; Phys.Rev. D90 (2014) 113010, JHEP 1508 (2015) 012]





PRL 114 (2015) 121801

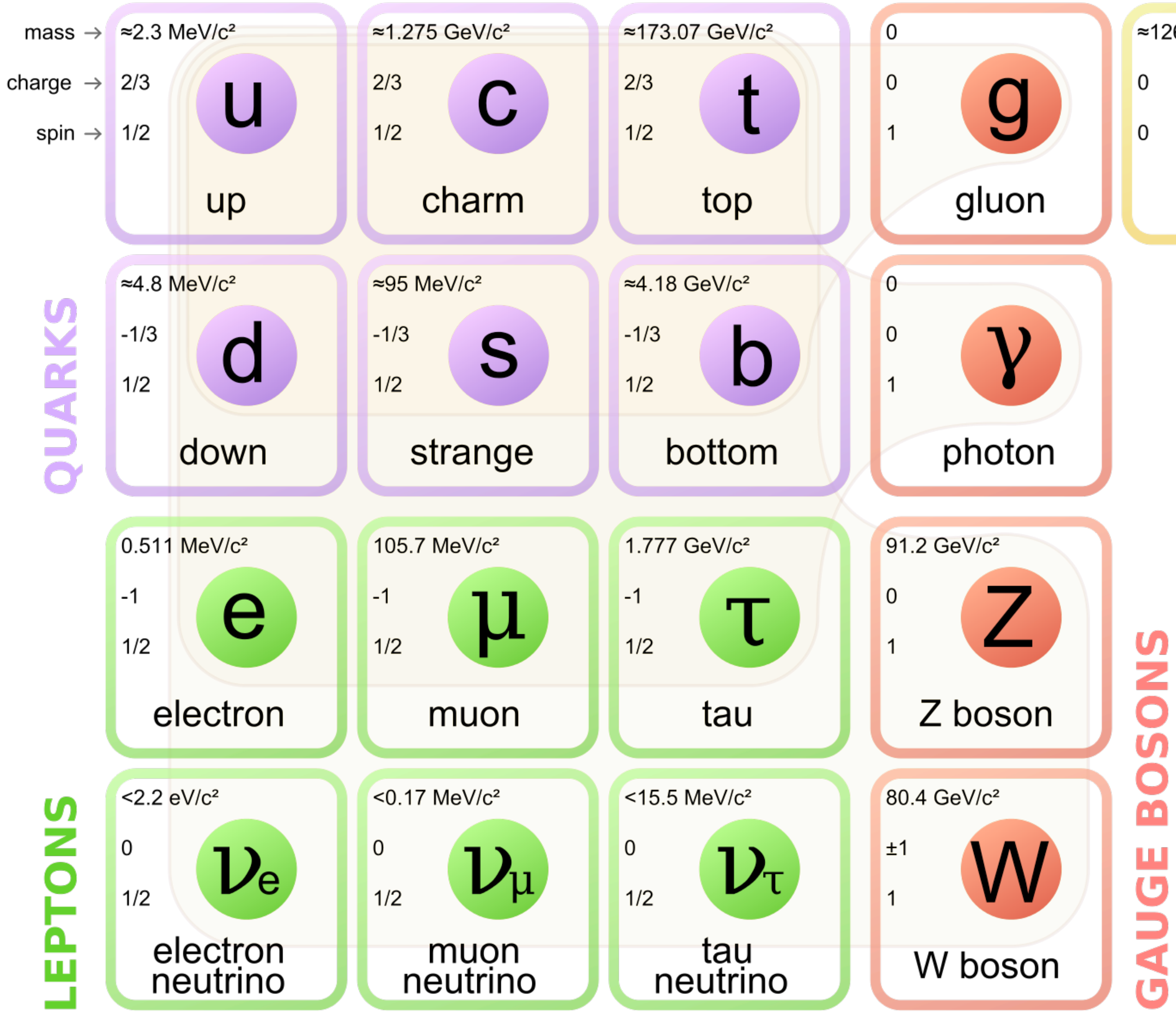


CMS 95% CL upper limit on BR[H→(J/ψ)γ] < 1.5×10^{-3}

[PLB 753 (2016) 341]

Indications for non-universal Higgs boson couplings to quarks.

BR 95% CLs upper limits:
~10^{-3} level for Higgs boson decays (SM production) and
~10^{-6} for the Z boson decays



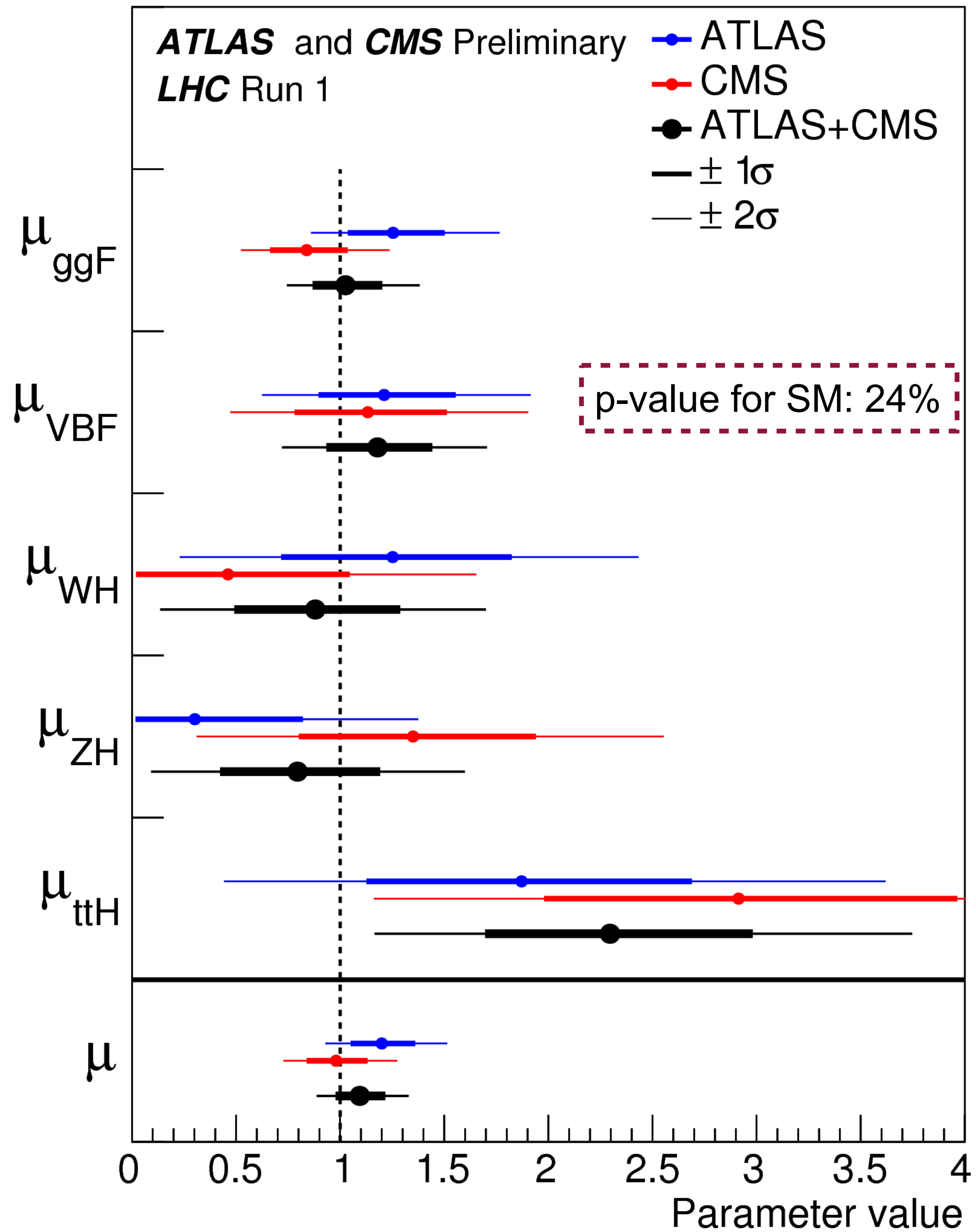
Coupling Combination

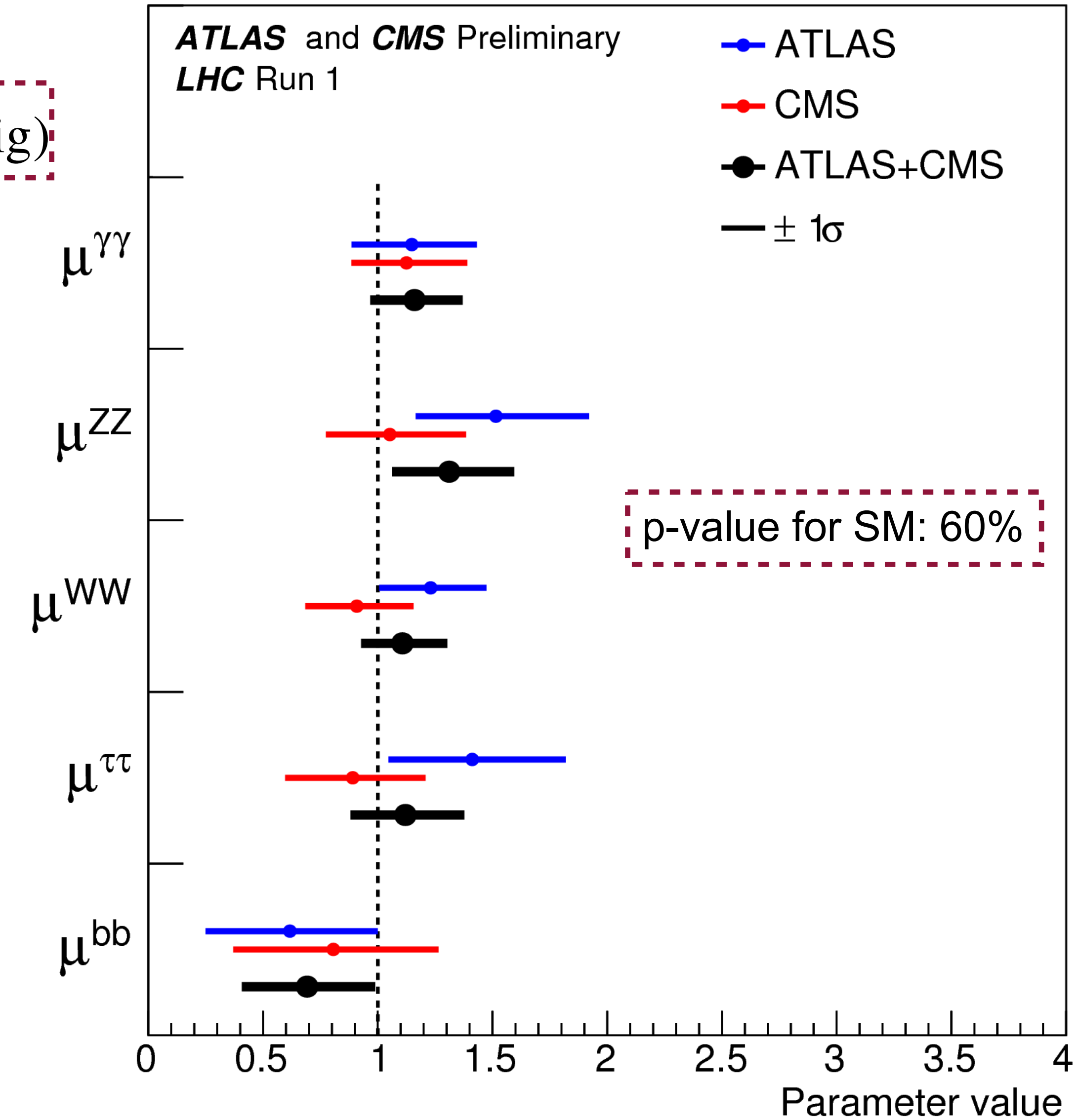
Higgs boson production and decay modes

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

ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

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





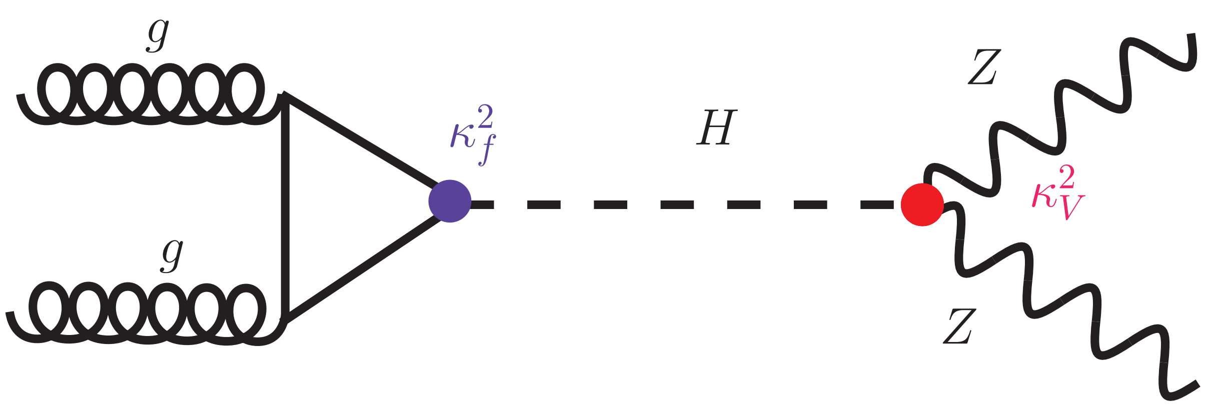
Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.7
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

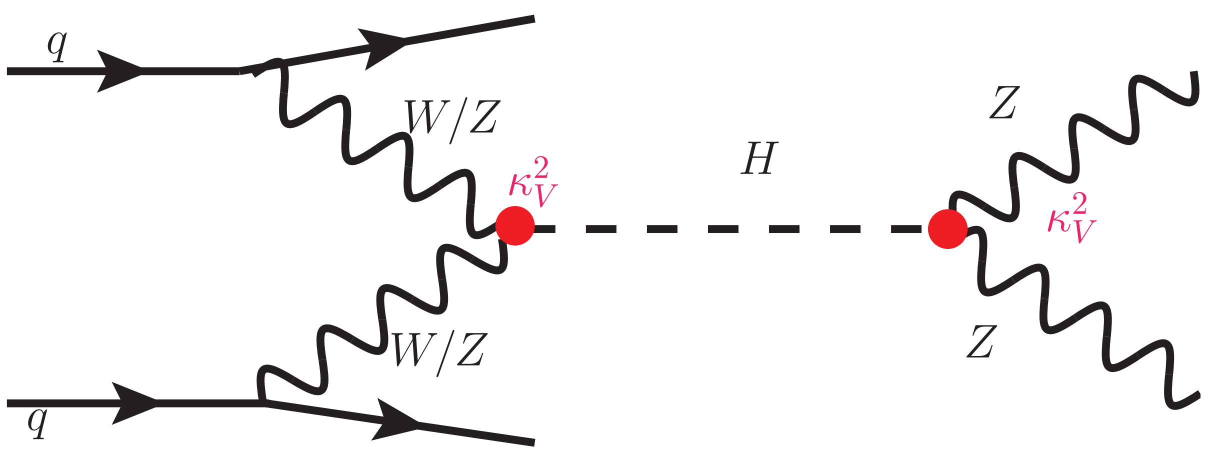
Probing the Higgs boson couplings

Framework for Couplings based on LHC Higgs Cross Section WG. Leading order framework:

- single resonance of 125.5 GeV
- narrow width approximation
- only modifications of the coupling strengths through multiplicative factors

<u>Reminder:</u> Production-based categorisation gives access to different Higgs boson couplings

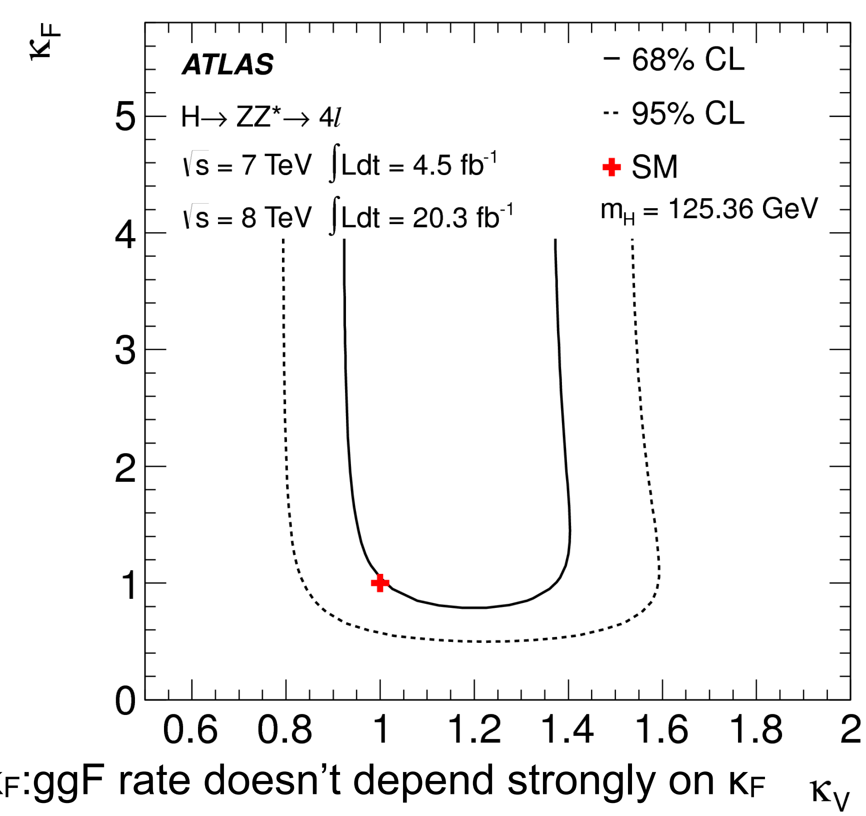




$$\kappa_H^2(\kappa_F^2, \kappa_V^2) = \alpha \cdot \kappa_F^2 + \beta \cdot \kappa_V^2$$

$$\mu_{ggF;H\to ZZ} = \frac{\sigma(ggF)\cdot BR(H\to ZZ)}{\sigma_{SM}(ggF)\cdot BR_{SM}(H\to ZZ)} = \frac{\kappa_F^2\cdot\kappa_V^2}{\alpha\cdot\kappa_F^2+\beta\cdot\kappa_V^2}$$

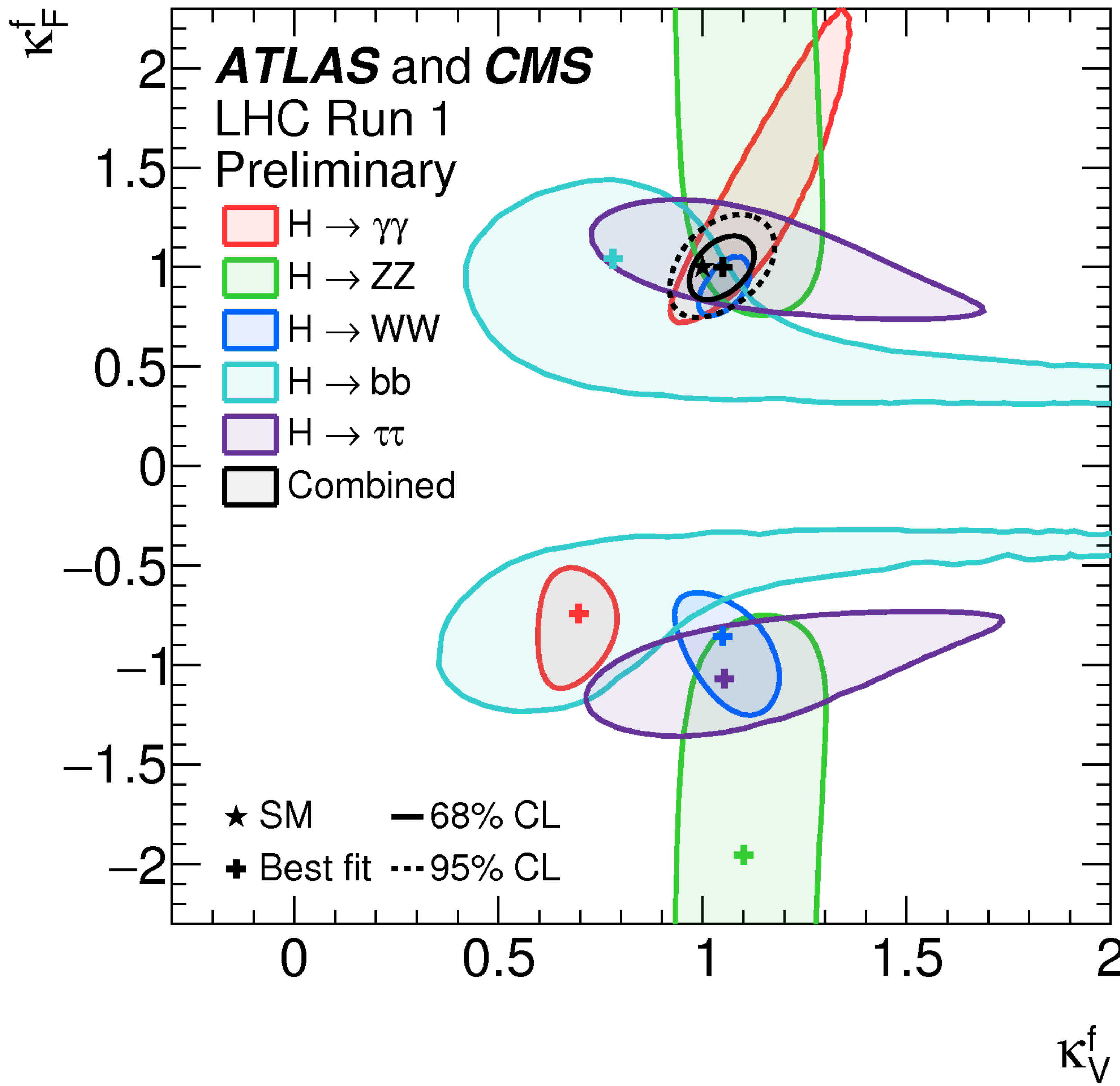
$$\mu_{VBF;H\to ZZ} = \frac{\kappa_V^2\cdot\kappa_V^2}{\alpha\cdot\kappa_F^2+\beta\cdot\kappa_V^2}$$



For large κ_F:ggF rate doesn't depend strongly on κ_F

Probing the Higgs boson couplings

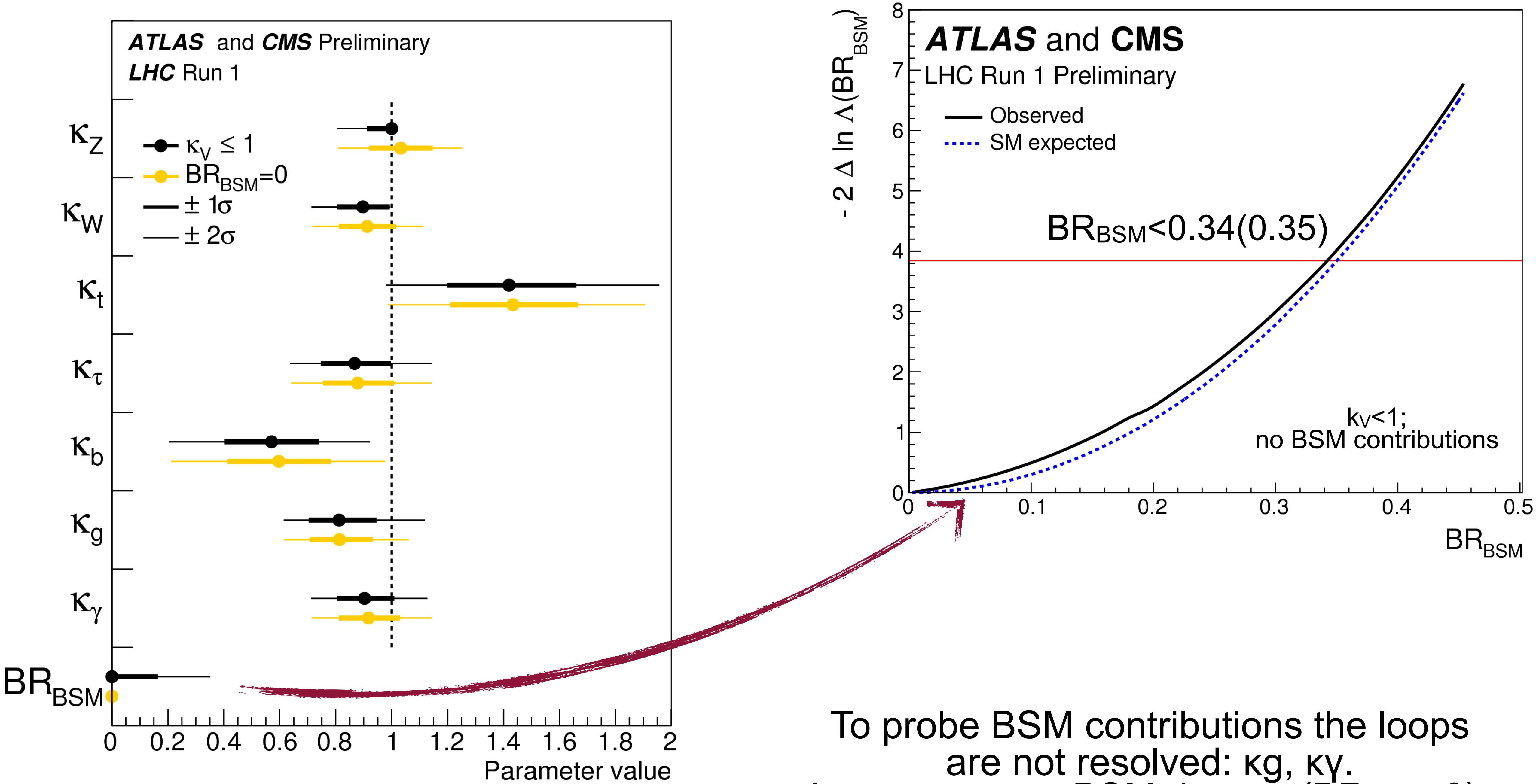
ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002



Common coupling scaling:
Fermions (κ_F) and
Bosons (k_V);
no BSM contributions

BSM contributions in decays/loops

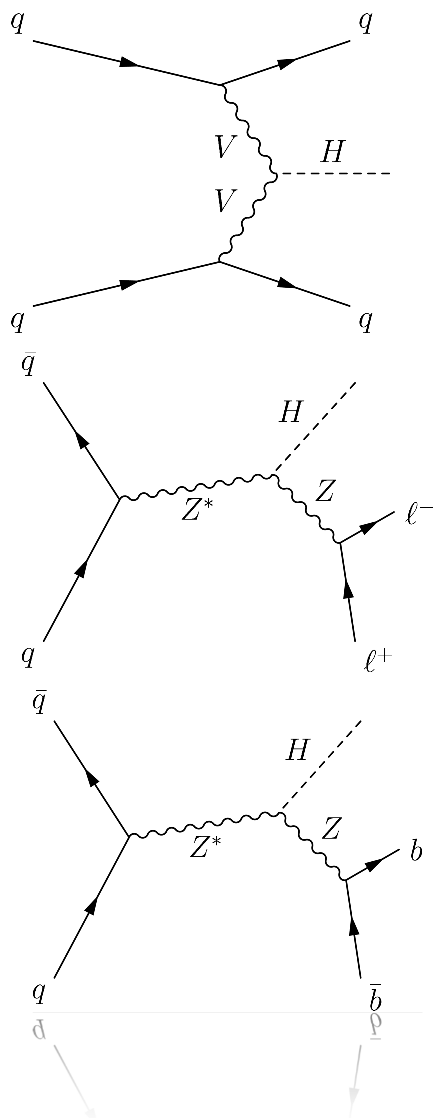
ATLAS-CONF-2015-044
CMS-PAS-HIG-15-002

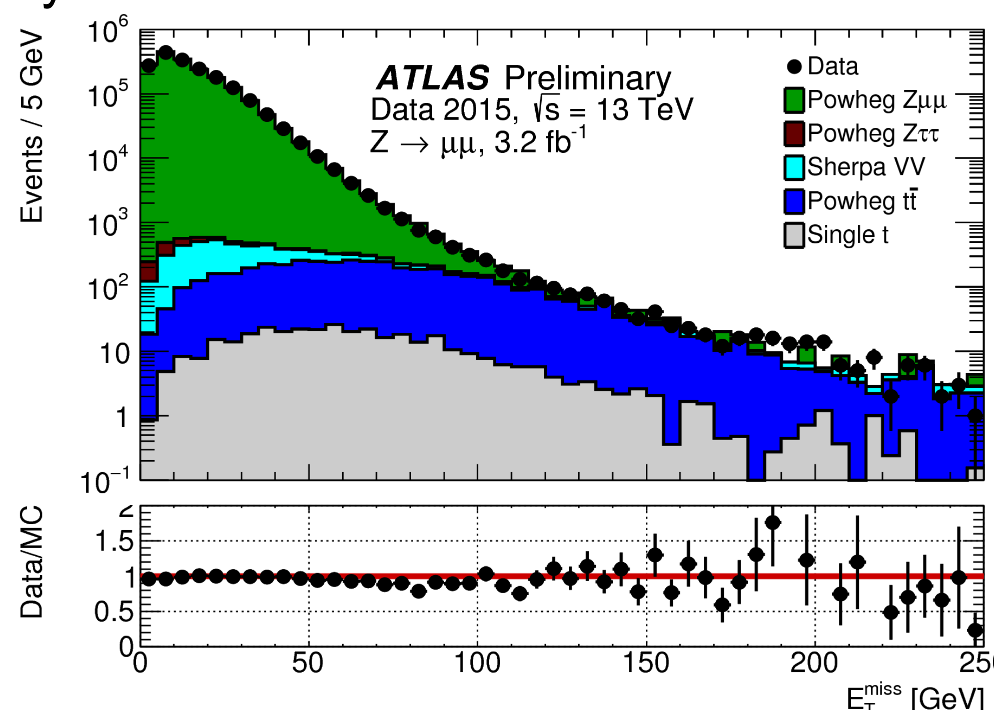


To probe BSM contributions the loops are not resolved: κg, κγ.
In one case no BSM decays ($BR_{BSM}=0$), in the other allowing BR_{BSM} to be free.

ZH(→inv)

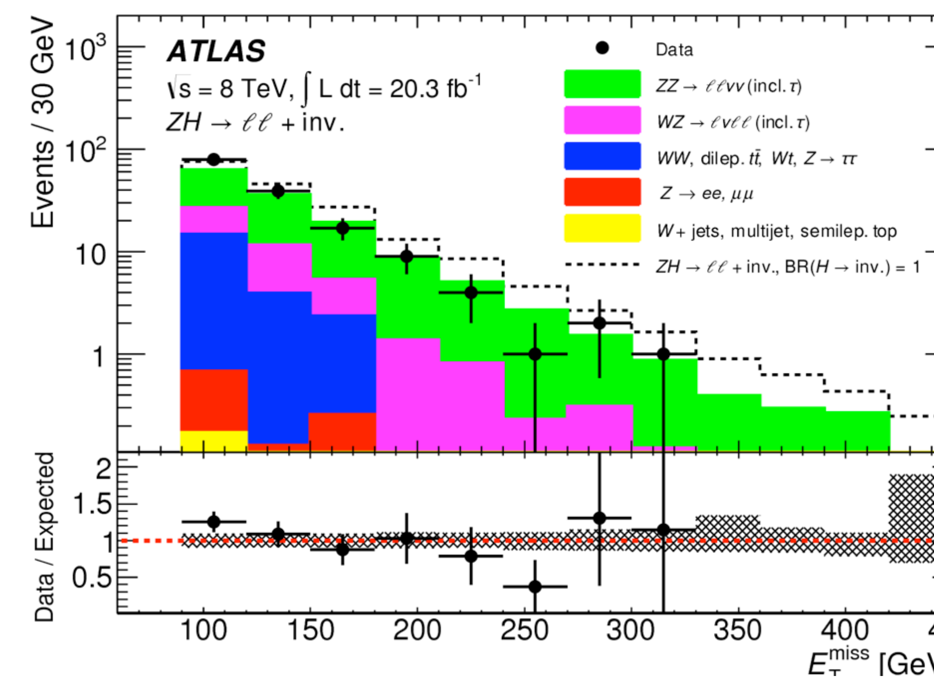
- SM “Invisible” decays suppressed; BR(H→ZZ*→4v)=$1.2\cdot10^{-3}$
  - Observation means New Physics!

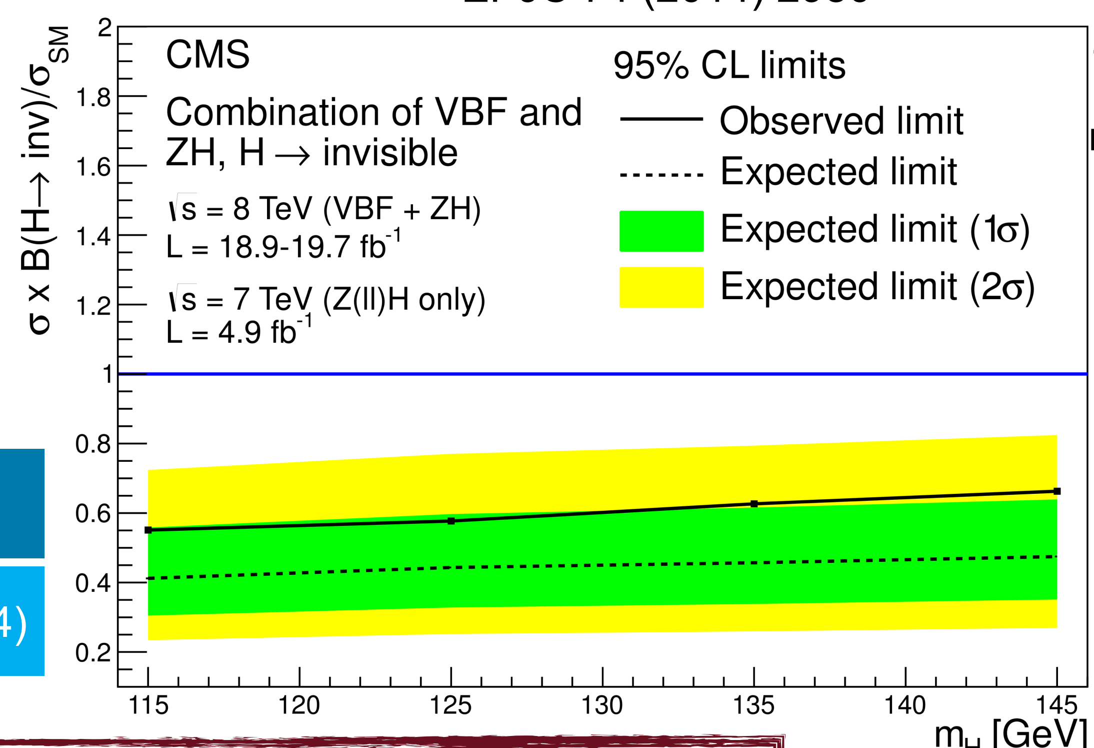


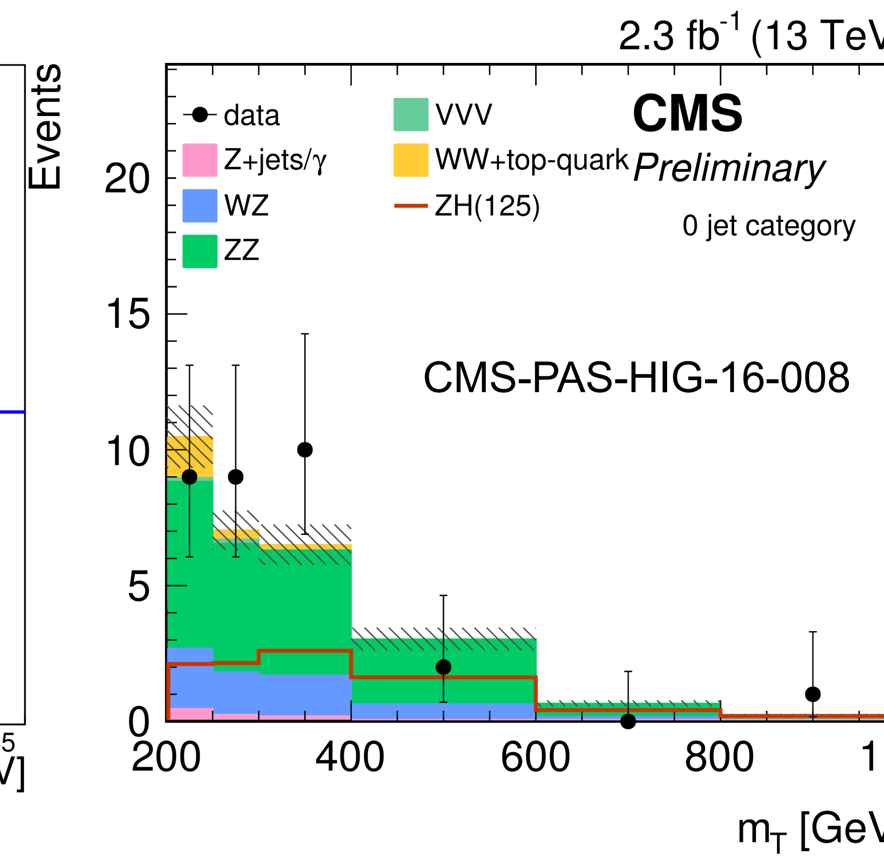


EPJC 74 (2014) 2980

Phys. Rev. Lett. 112, 201802 (2014)

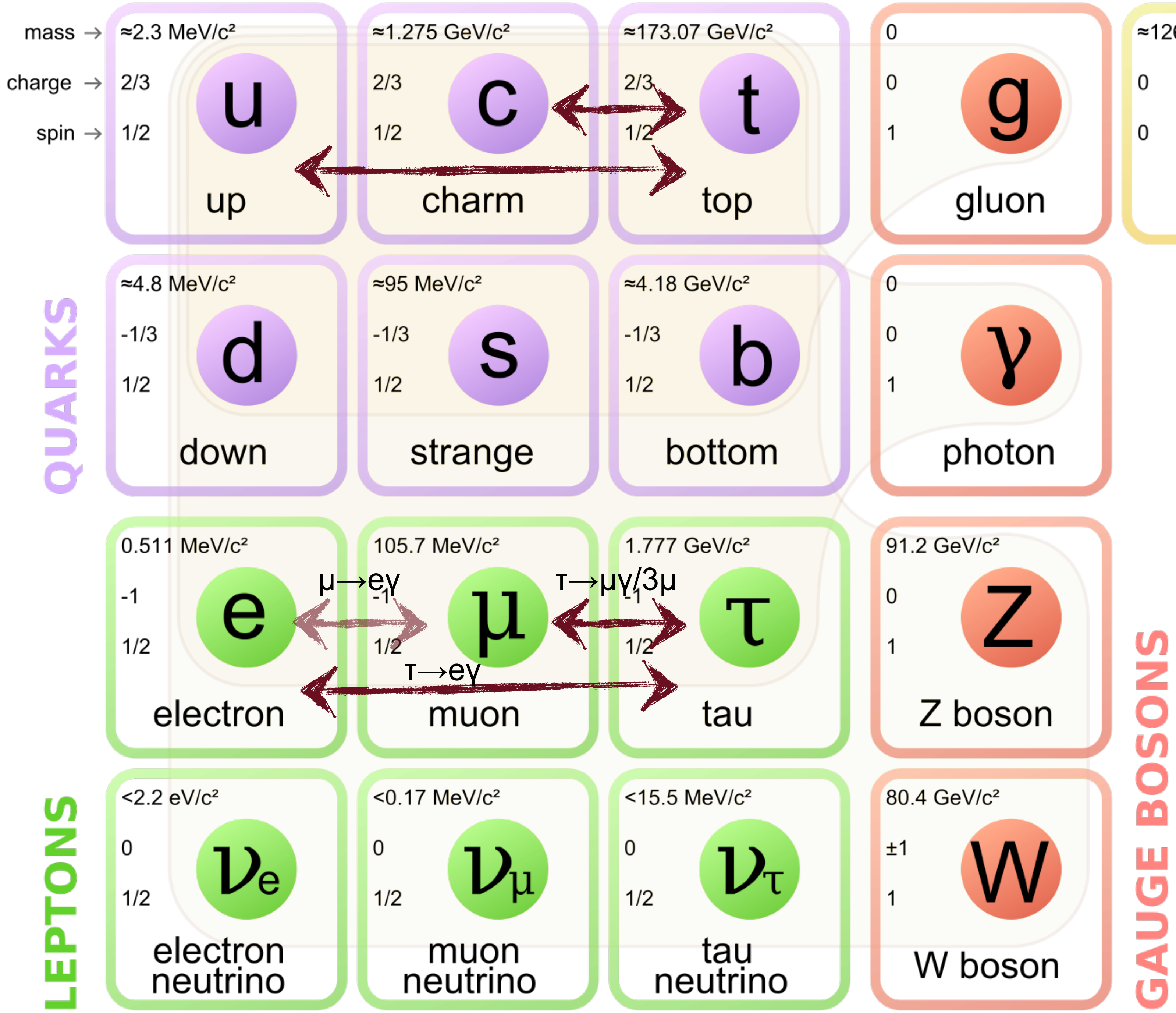






BR 95% CL Limit	ATLAS	CMS
h(125)→inv	<0.25(0.27)	<0.58(0.44)

VBF analysis dominates the limit.
CMS looked already at ZH→inv in 13TeV. More data needed



→ Indirect constraints from low-energy data; certain transitions still loosely constrained

[JHEP 03 (2013) 026; Phys.Lett. B712 (2012) 386]

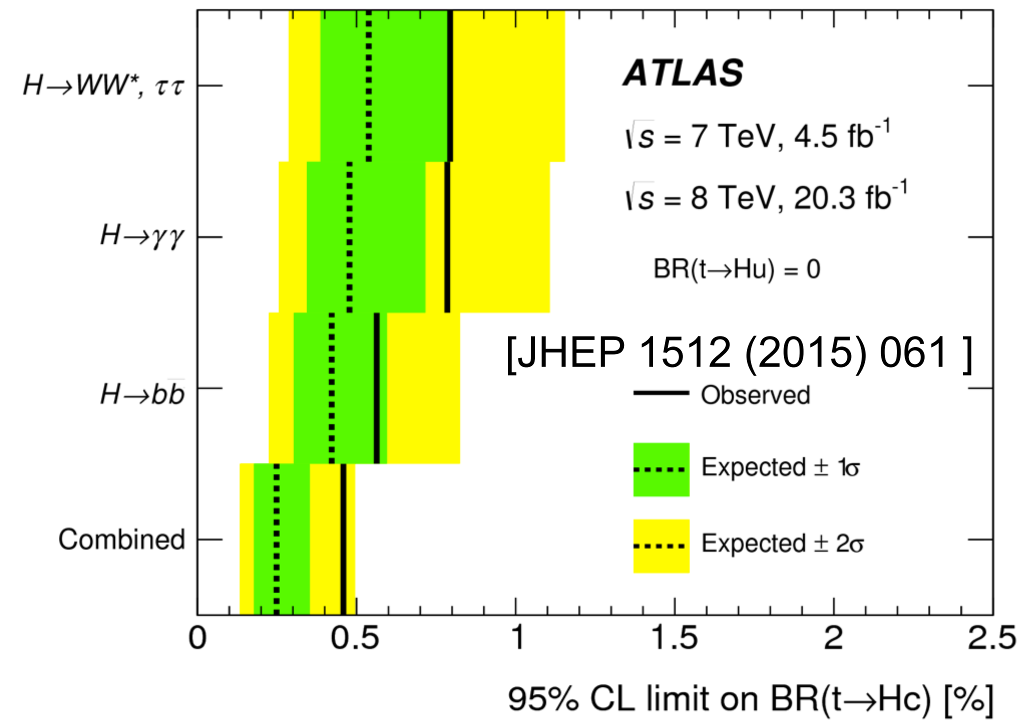
→ QFV: constraints from flavour physics

→ LFV: constraints from μ→eγ, τ→μ/eγ, μ/e g-2, EDM

BR(H→eμ)<10^{-8}; BR(H→eτ)≲10%; BR(H→μτ)≲10%

FCNC in t→qh

Process	SM	QS	2HDM-III	FC-2HDM	MSSM
$t \to u\gamma$	$3.7 \cdot 10^{-16}$	$7.5 \cdot 10^{-9}$	—	—	$2 \cdot 10^{-6}$
$t \to uZ$	$8 \cdot 10^{-17}$	$1.1 \cdot 10^{-4}$	—	—	$2 \cdot 10^{-6}$
$t \to uH$	$2 \cdot 10^{-17}$	$4.1 \cdot 10^{-5}$	$5.5 \cdot 10^{-6}$	—	10^{-5}
$t \to c\gamma$	$4.6 \cdot 10^{-14}$	$7.5 \cdot 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-9}$	$2 \cdot 10^{-6}$
$t \to cZ$	$1 \cdot 10^{-14}$	$1.1 \cdot 10^{-4}$	$\sim 10^{-7}$	$\sim 10^{-10}$	$2 \cdot 10^{-6}$
$t \to cH$	$3 \cdot 10^{-15}$	$4.1 \cdot 10^{-5}$	$1.5 \cdot 10^{-3}$	$\sim 10^{-5}$	10^{-5}



Light quarks challenging, focus on top-quark decays

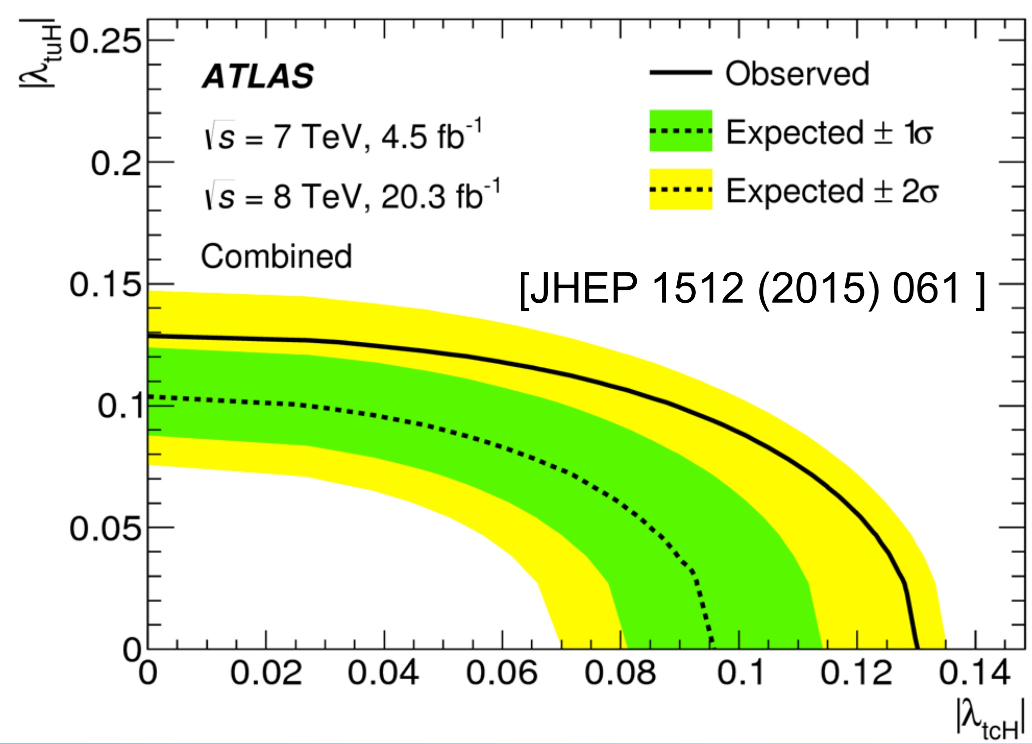
ATLAS search for t→qh(→γγ, bb, WW, ττ), where q=(c,u)

- 95% CL upper limit on BR(t→ch): 0.46% (0.25%)
- 95% CL upper limit on BR(t→uh): 0.45% (0.29%)

- CMS combined h→γγ and multi-lepton search.
  - 95% CL upper limit on BR(t→ch): 0.56% (0.65%)

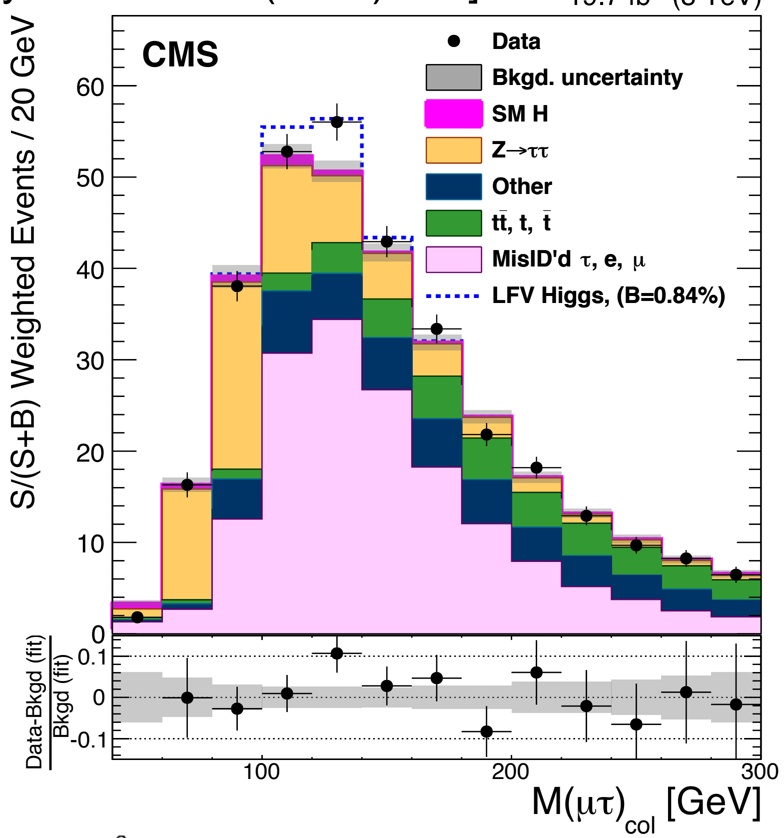
[Phys.Rev. D90 (2014) 112013]

$$\mathcal{L}_{\mathrm{FCNC}} = \lambda_{tcH}\bar{t}Hc + \lambda_{tuH}\bar{t}Hu + h.c.$$

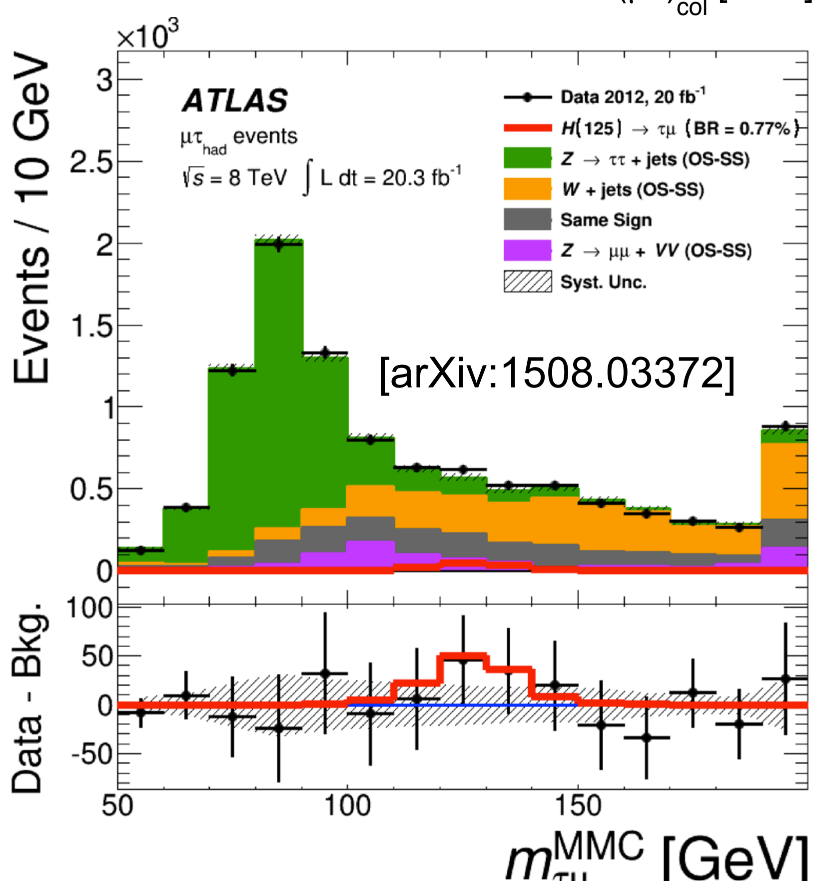


Lepton Flavour Violation: $h \to \tau\mu$, τe, μe

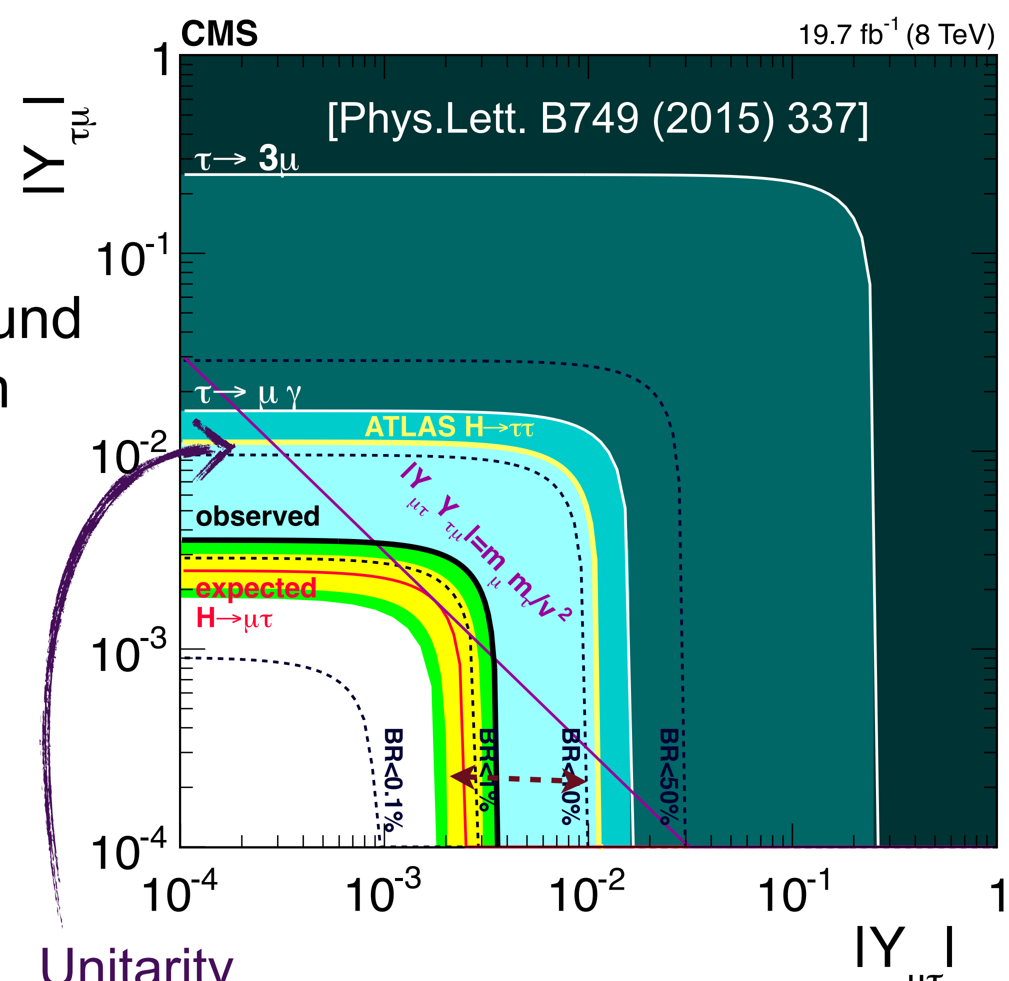
[Phys.Lett. B749 (2015) 337]



- Direct search for Lepton Flavour Violating $h \to \tau\mu$
  - $\tau_h\mu$
    - Background: fake τ from W+jets/QCD/ttbar, $Z \to \tau\tau$
  - $\tau_e\mu$
    - Background: $Z \to \tau\tau$
  - Small contribution from $h \to \tau\tau$
- Data driven background estimates
  - $Z \to \tau\tau$ embedding
  - fake τ from side-band method
- Discriminant: MMC (ATLAS), collinear mass of $\mu\tau$ system (CMS)



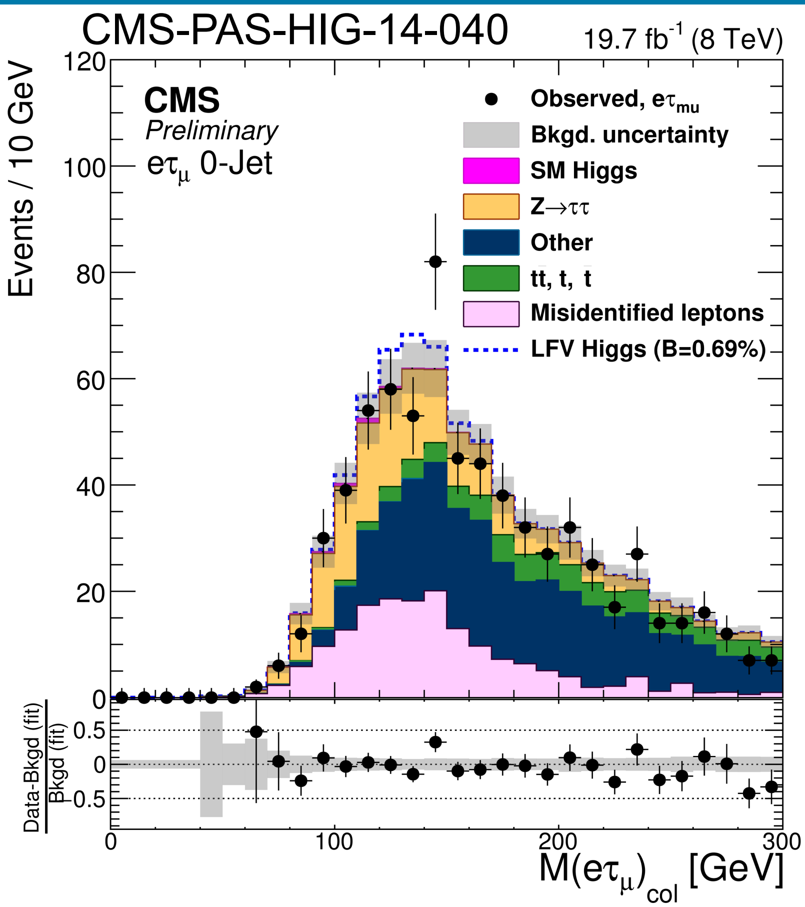
- CMS 95% CL upper limit on $BR(h \to \mu\tau) < 1.51\%$ (0.75%)
  - 2.4σ excess over background
- ATLAS 95% CL upper limit on $BR(h \to \mu\tau) < 1.85\%$ (1.24%)
- New for Moriond: ATLAS $BR(h \to \mu\tau) < 1.43\%$ (added $\tau_e\mu$)

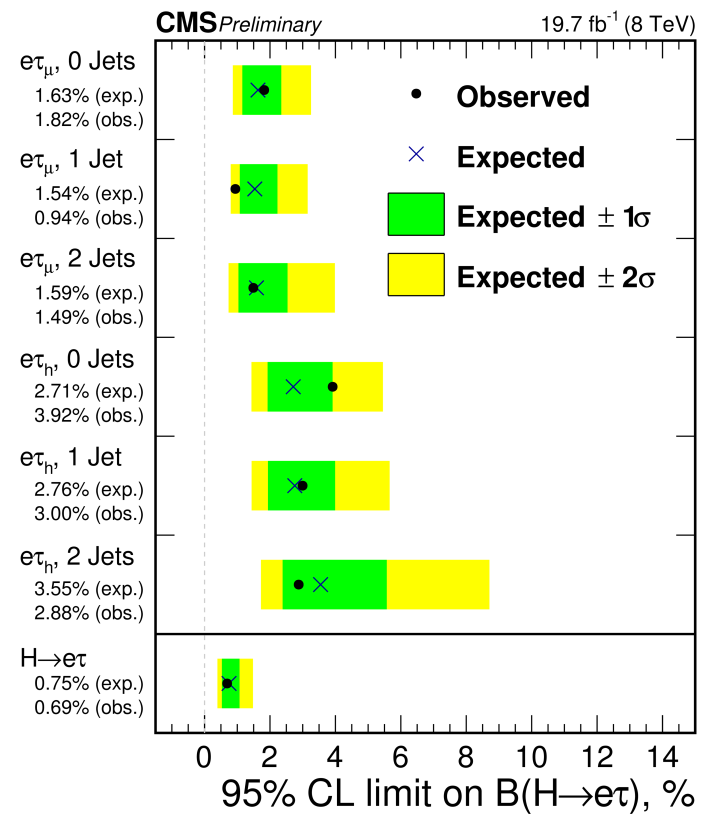


More stringent than indirect constraints

Lepton Flavour Violation: h→τμ, τe, μe

CMS-PAS-HIG-14-040

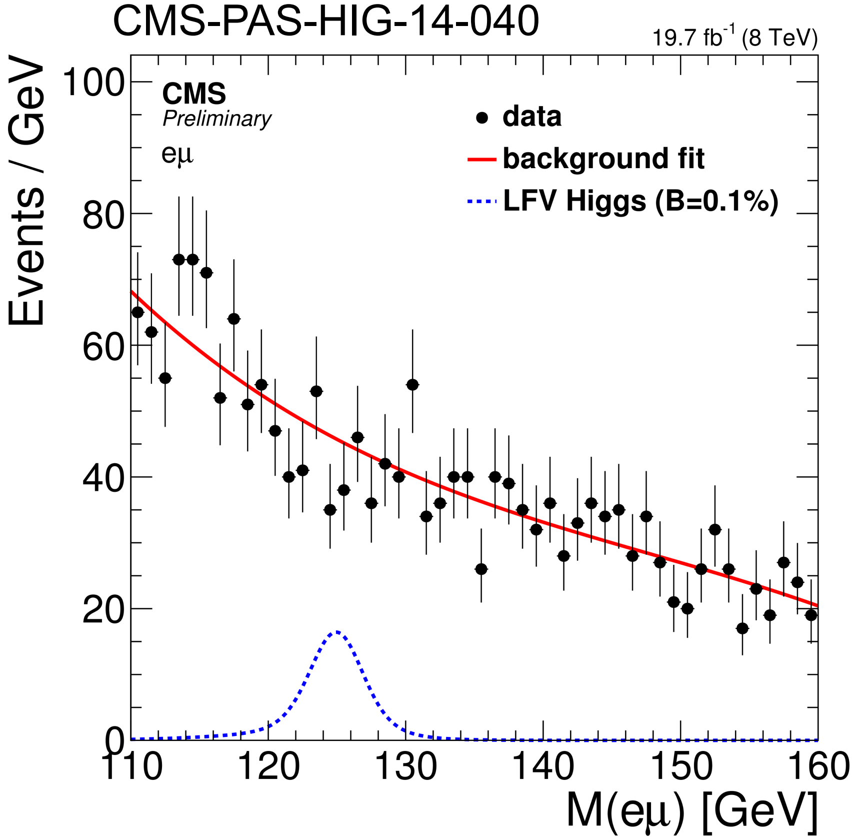


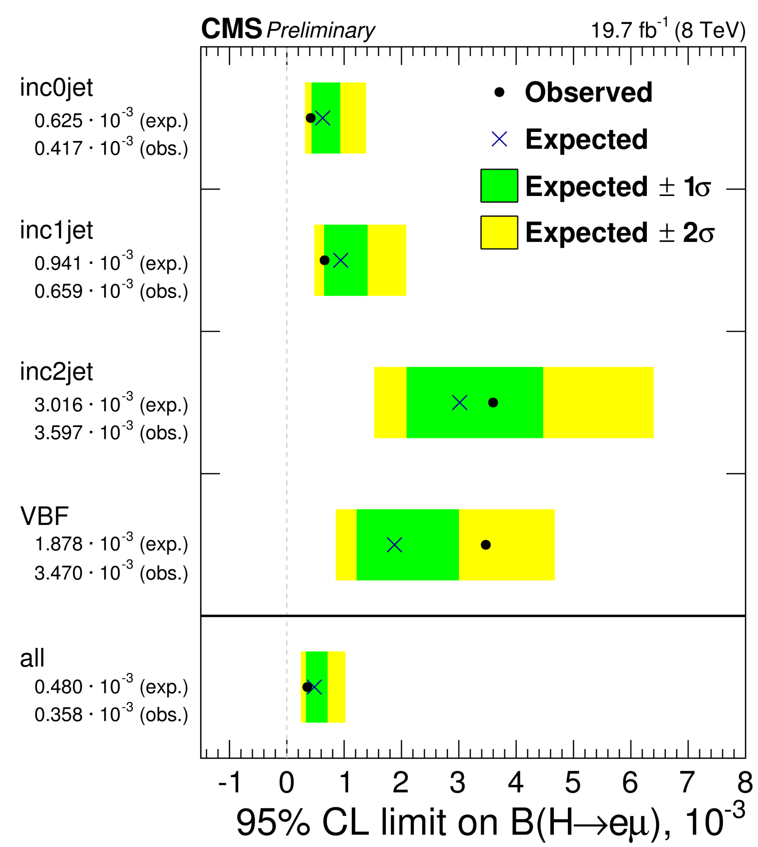


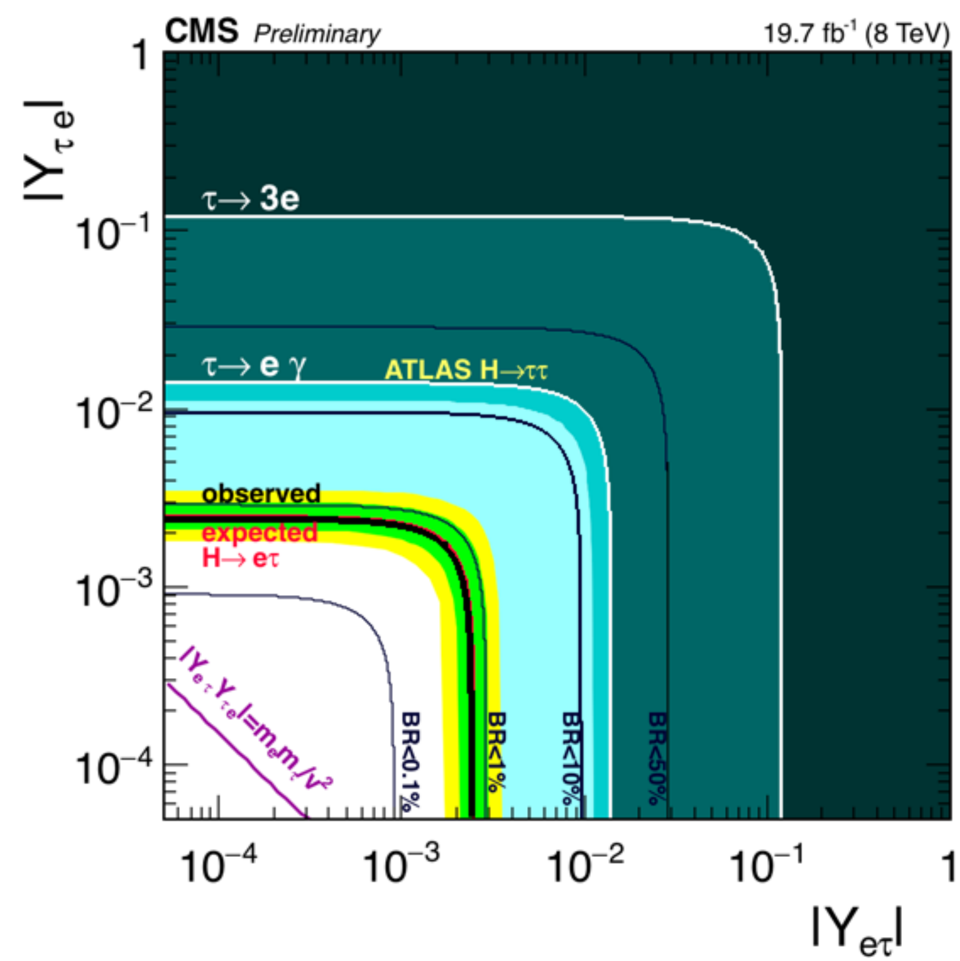
BR 95% CLLimit	ATLAS	CMS
τμ	<1.43%*	<1.51%
τe	<1.04%*	<0.69%
eμ	-	<0.036%

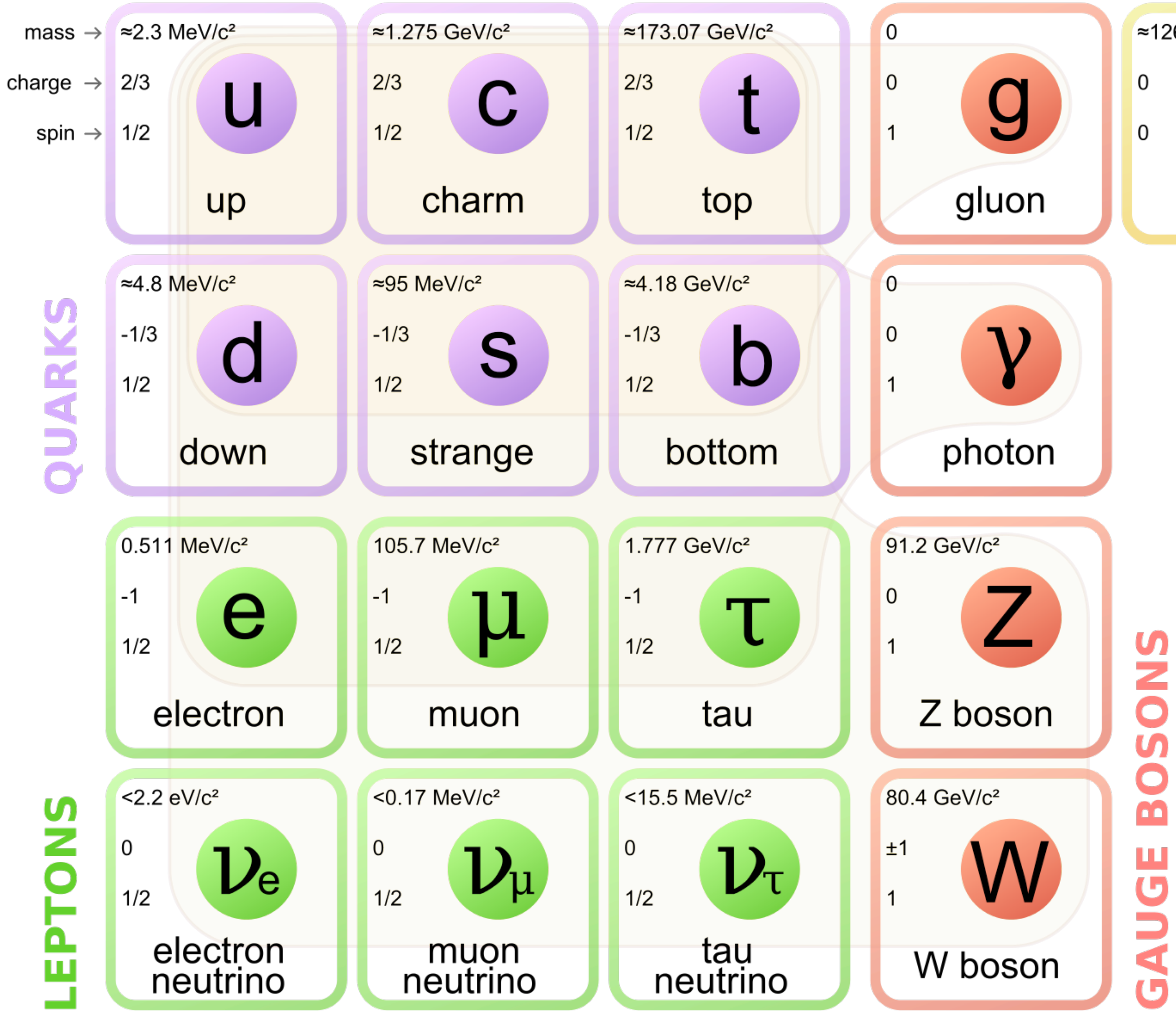
*New for Moriond

CMS-PAS-HIG-14-040







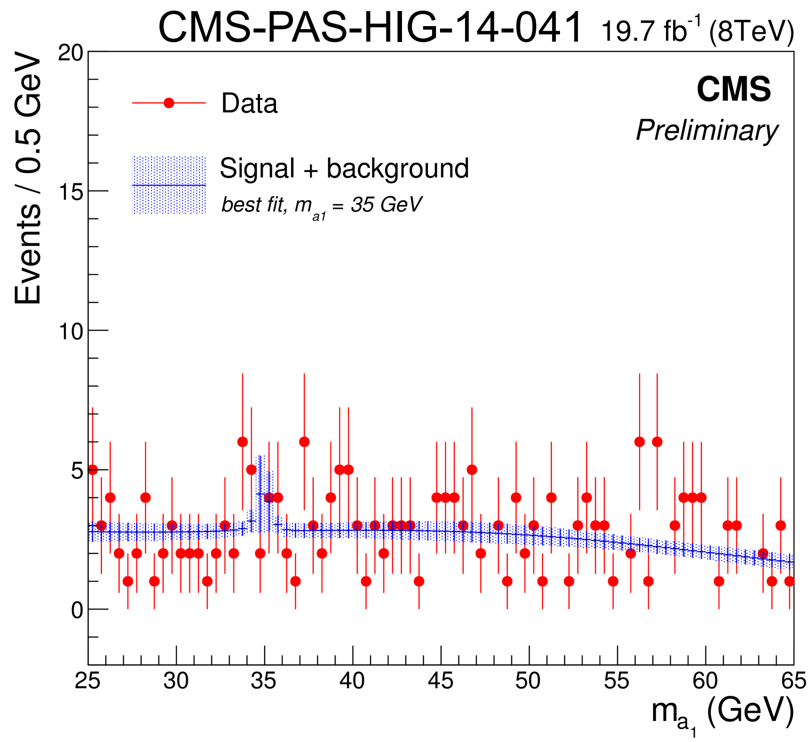


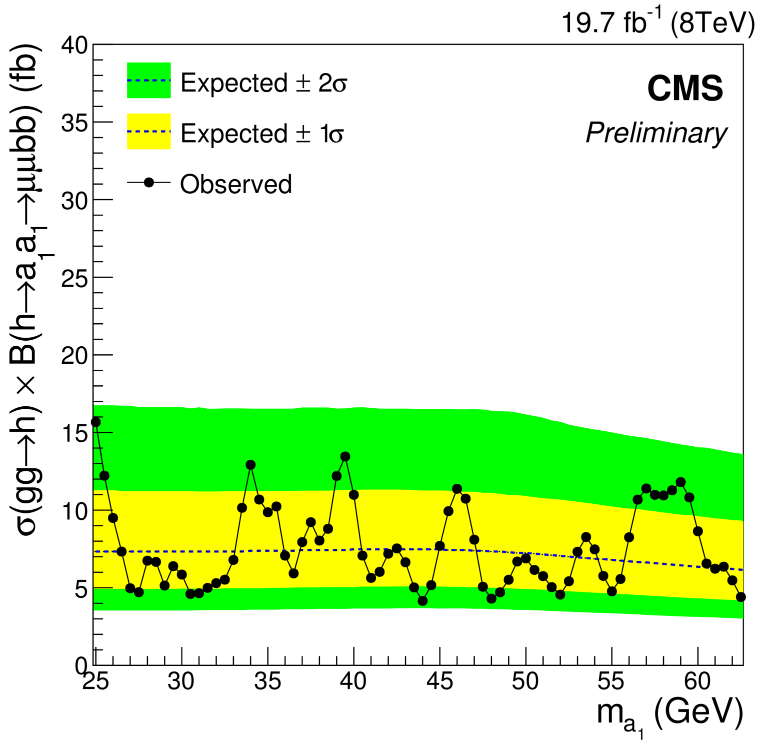
Extended Sectors

h→aa

h→aa→bbμμ

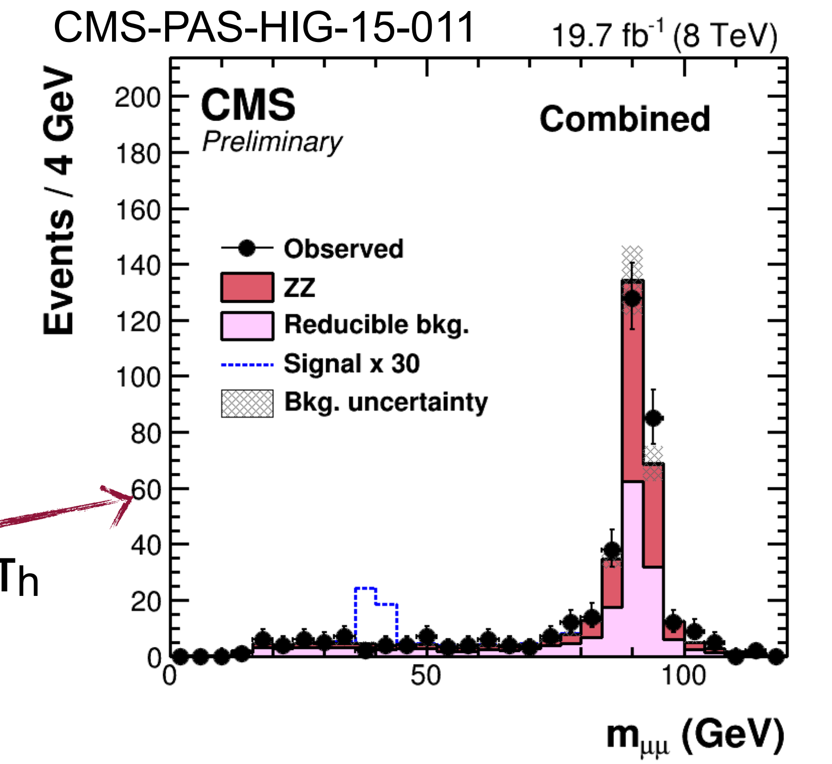
2 b-jets, 2μ, MET
significane<6
$|m_{bb\mu\mu}-m_h|<25GeV$

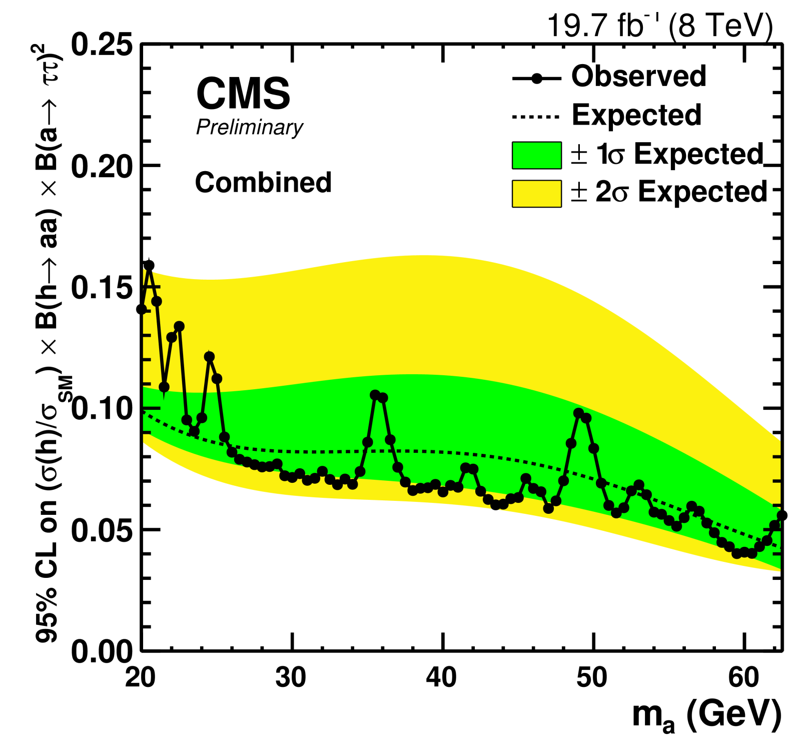


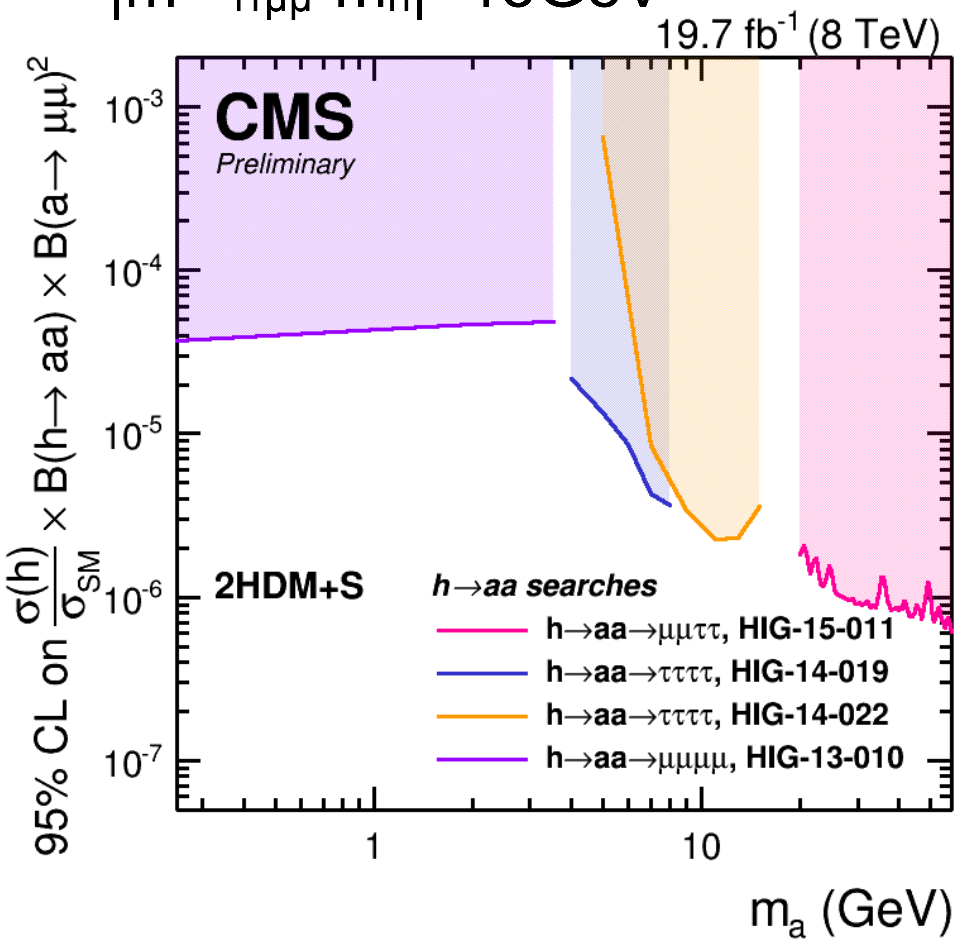


h→aa→ττμμ

5 final states:
$\mu\mu\tau_e\tau_e, \mu\mu\tau_e\tau_\mu, \mu\mu\tau_h\tau_e, \mu\mu\tau_e\tau_\mu, \mu\mu\tau_h\tau_h$
$|m_{\tau\tau\mu\mu}-m_h|<25GeV$
$|m_{\mu\mu}-m_{\tau\tau}|/m_{\mu\mu}<0.8$
$|m^{vis}_{\tau\tau\mu\mu}-m_h|>15GeV$





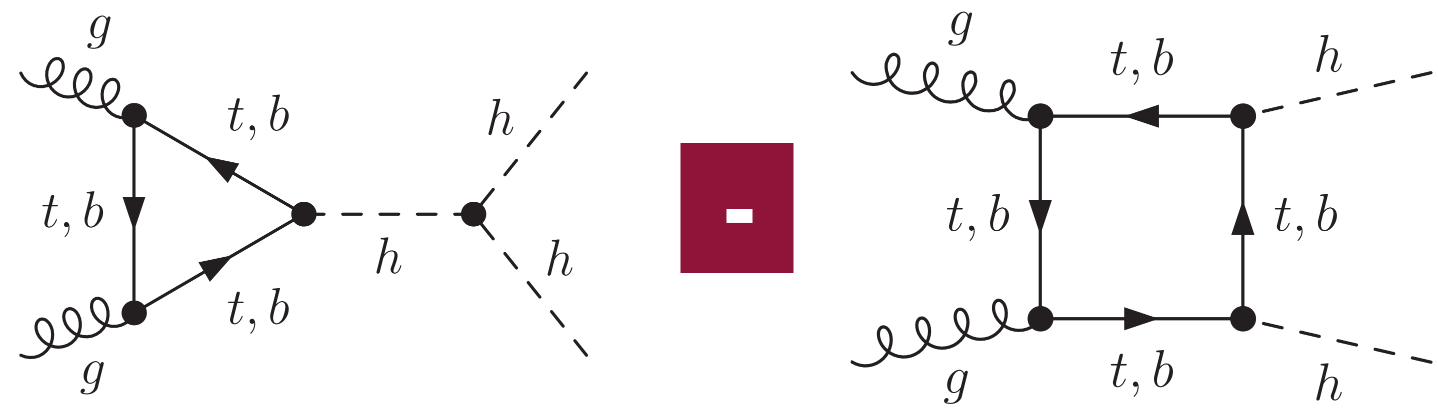


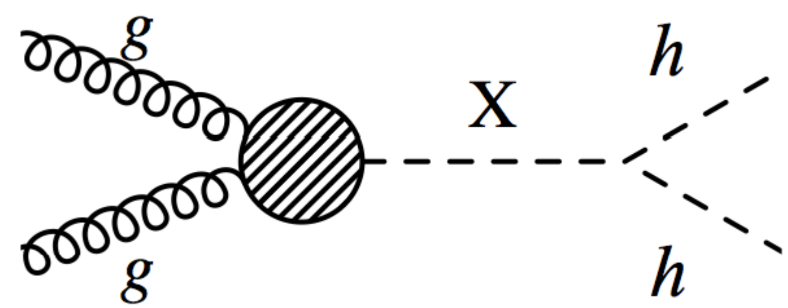
$$\frac{\Gamma(a\to\mu\mu)}{\Gamma(a\to\tau\tau)} = \frac{m_\mu^2\sqrt{1-(2m_\mu/m_a)^2}}{m_\tau^2\sqrt{1-(2m_\tau/m_a)^2}}.$$

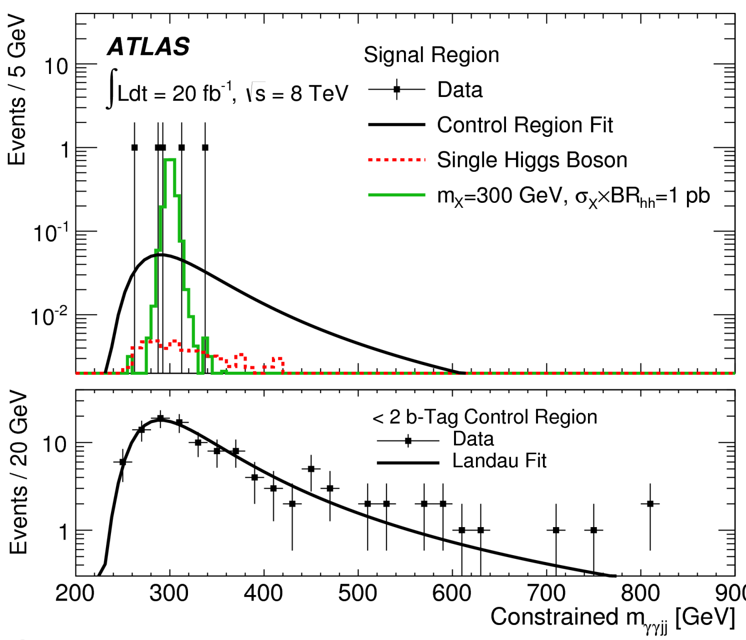
Higgs boson pair production

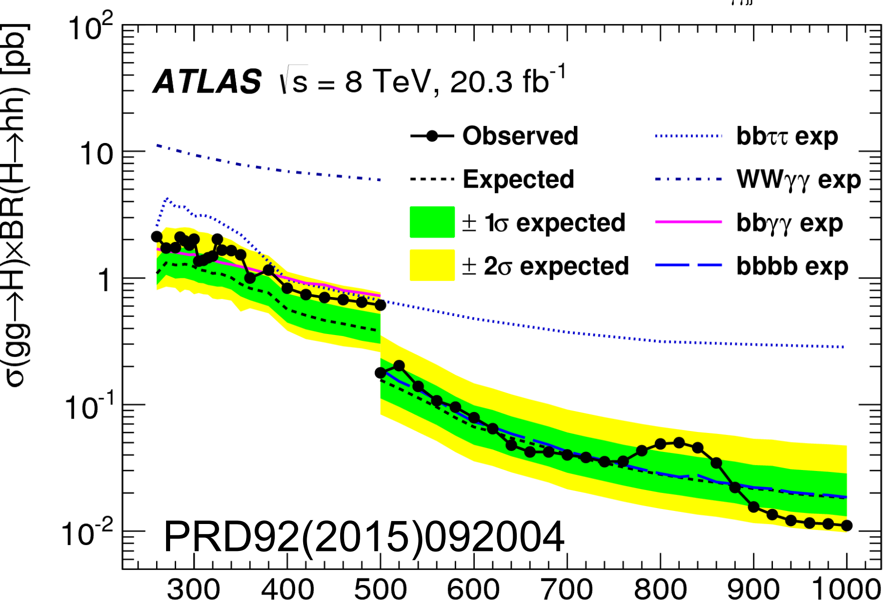
Sensitive to:
- trilinear Higgs boson self-coupling
- resonances decaying to hh

During Run 1 a number of final states have been considered: bbγγ, bbττ, bbbb, WWγγ

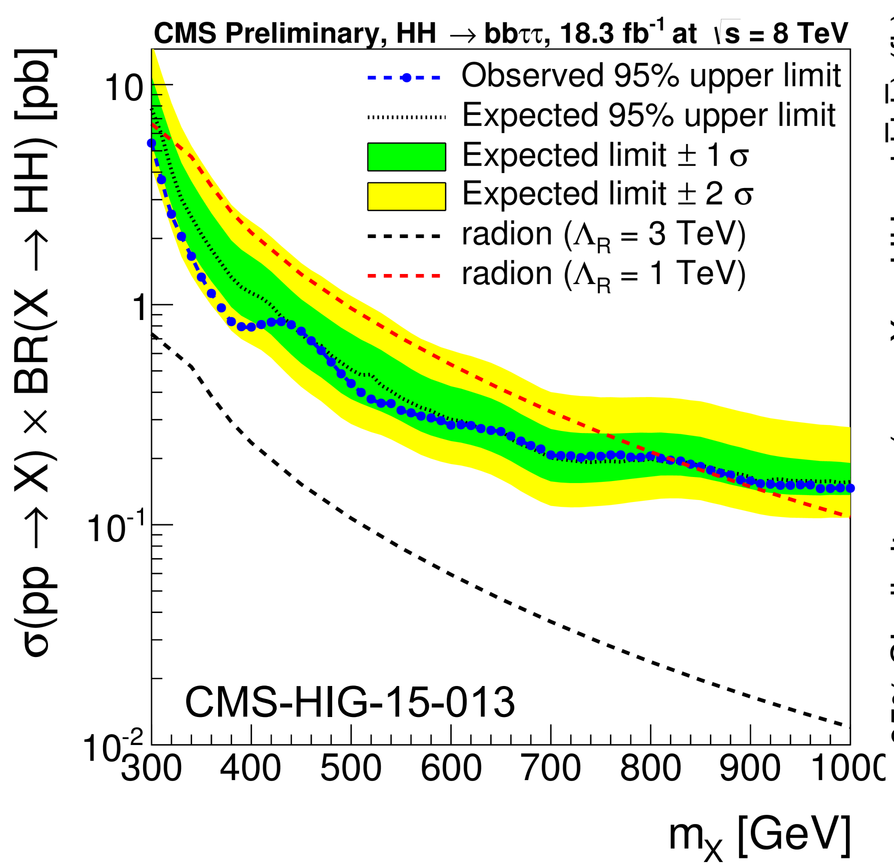


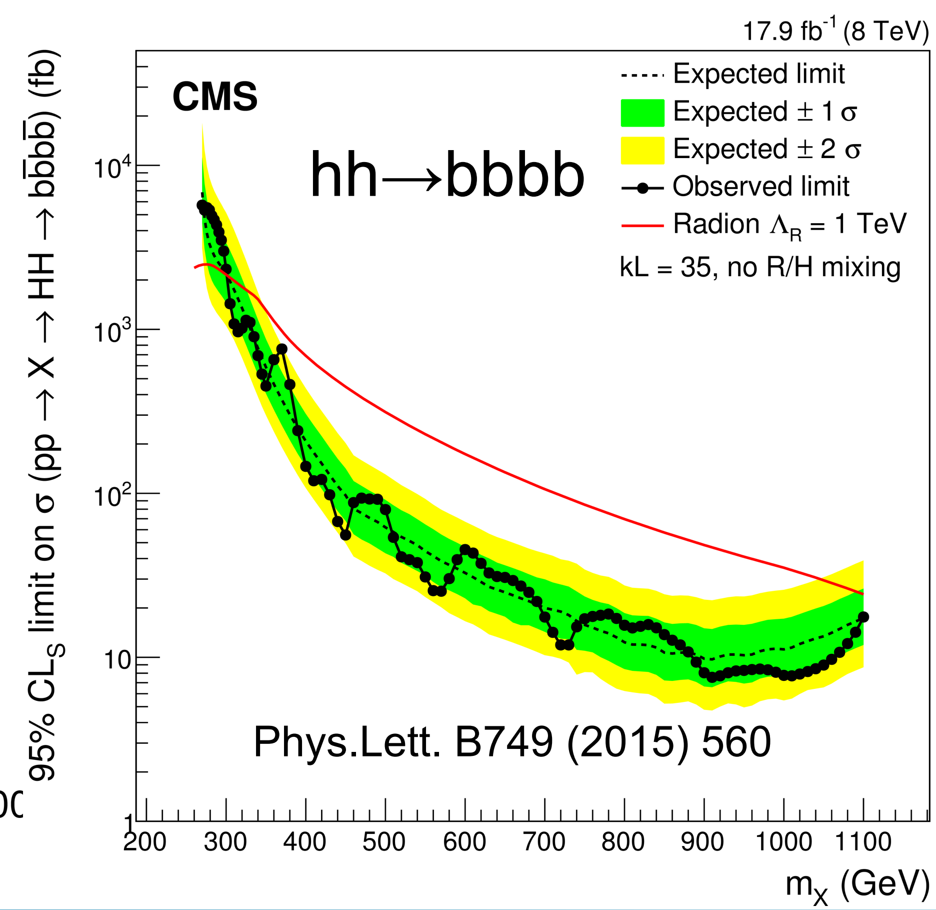




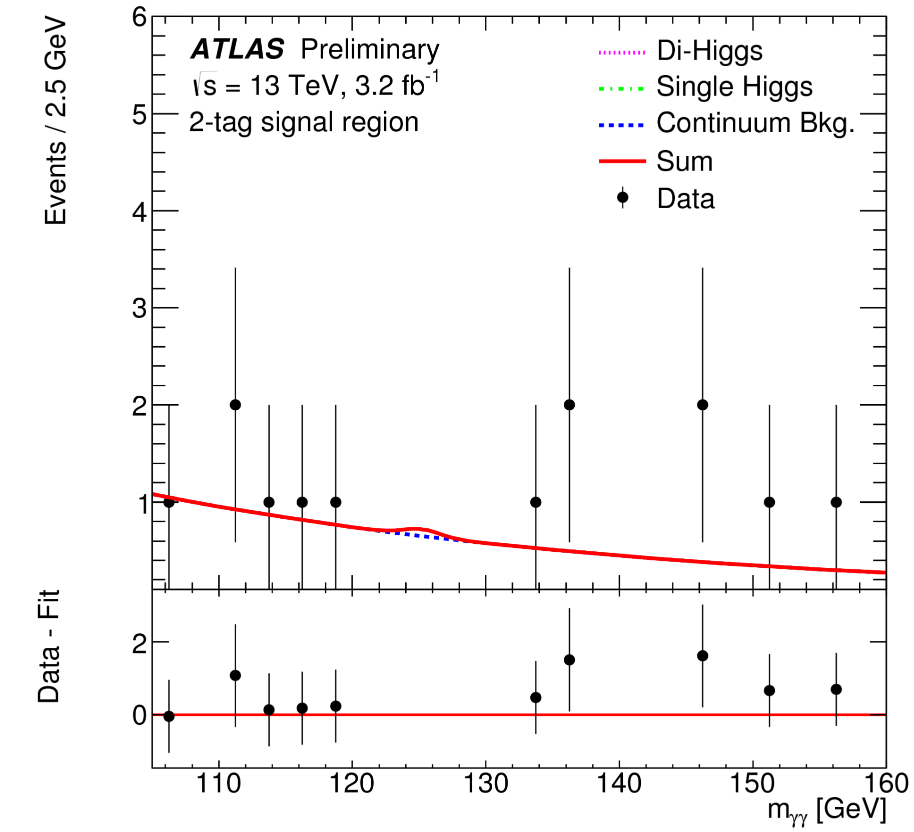


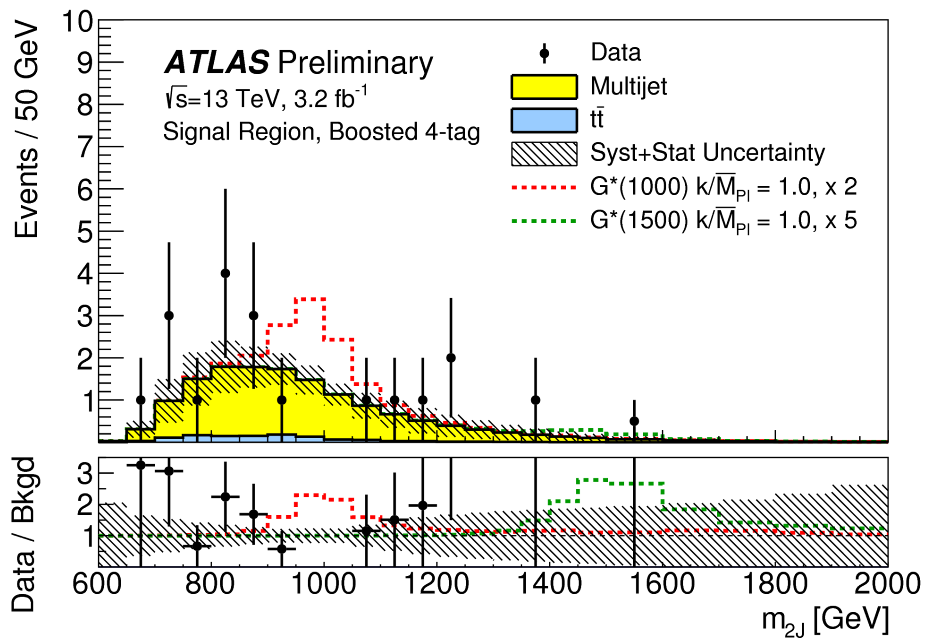
Non-resonant limit 70(48)xSM

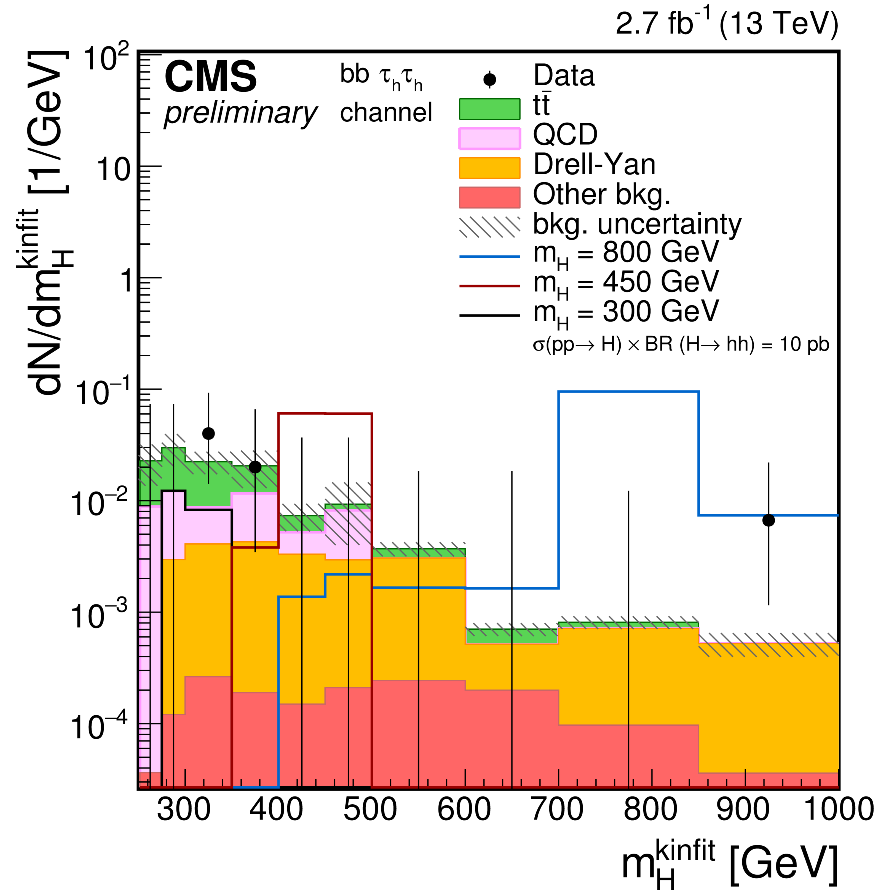


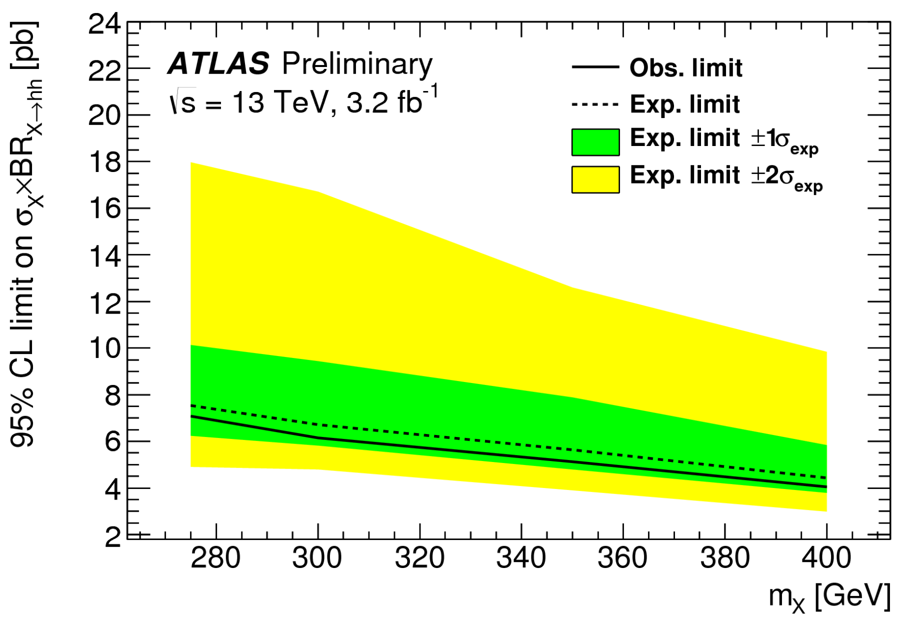


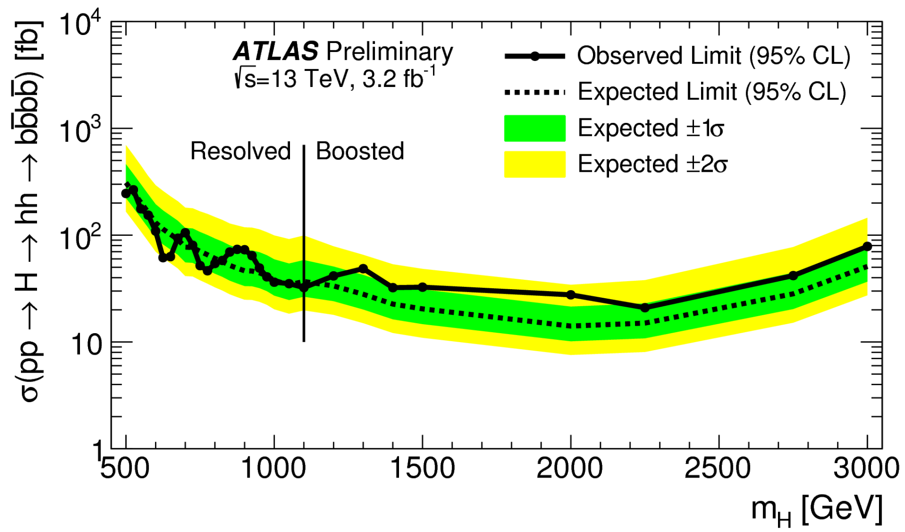
Higgs boson pair production at 13 TeV

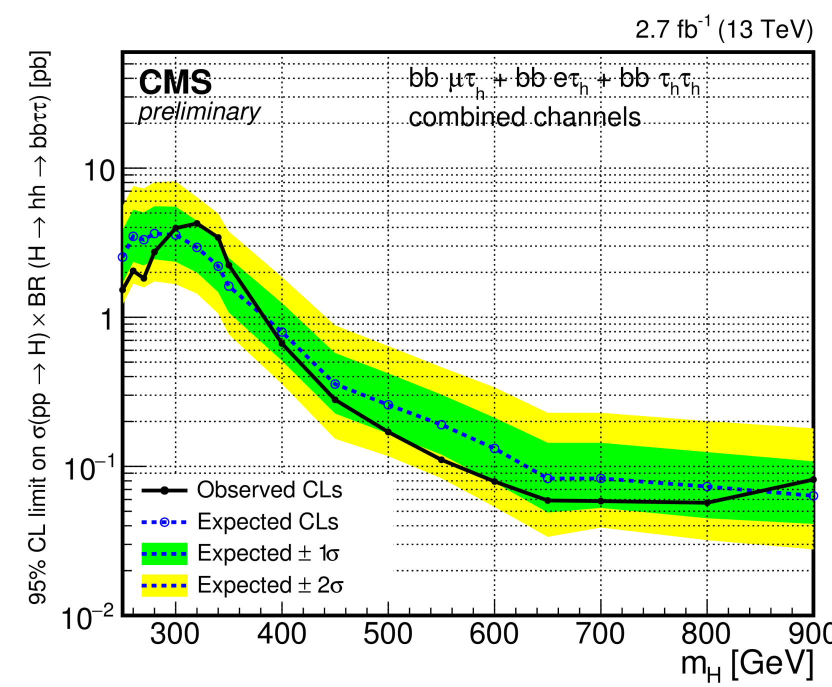




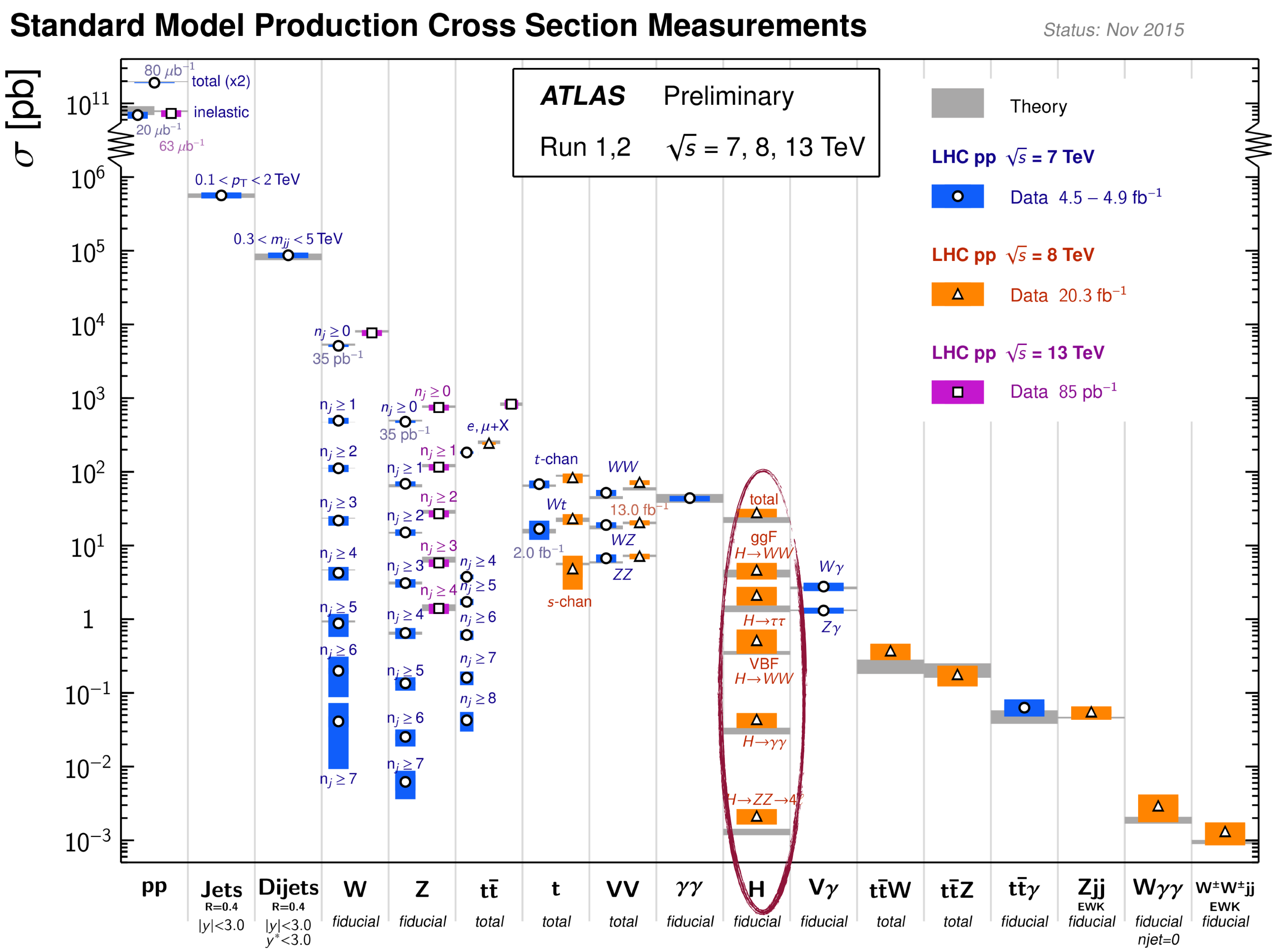








Summary



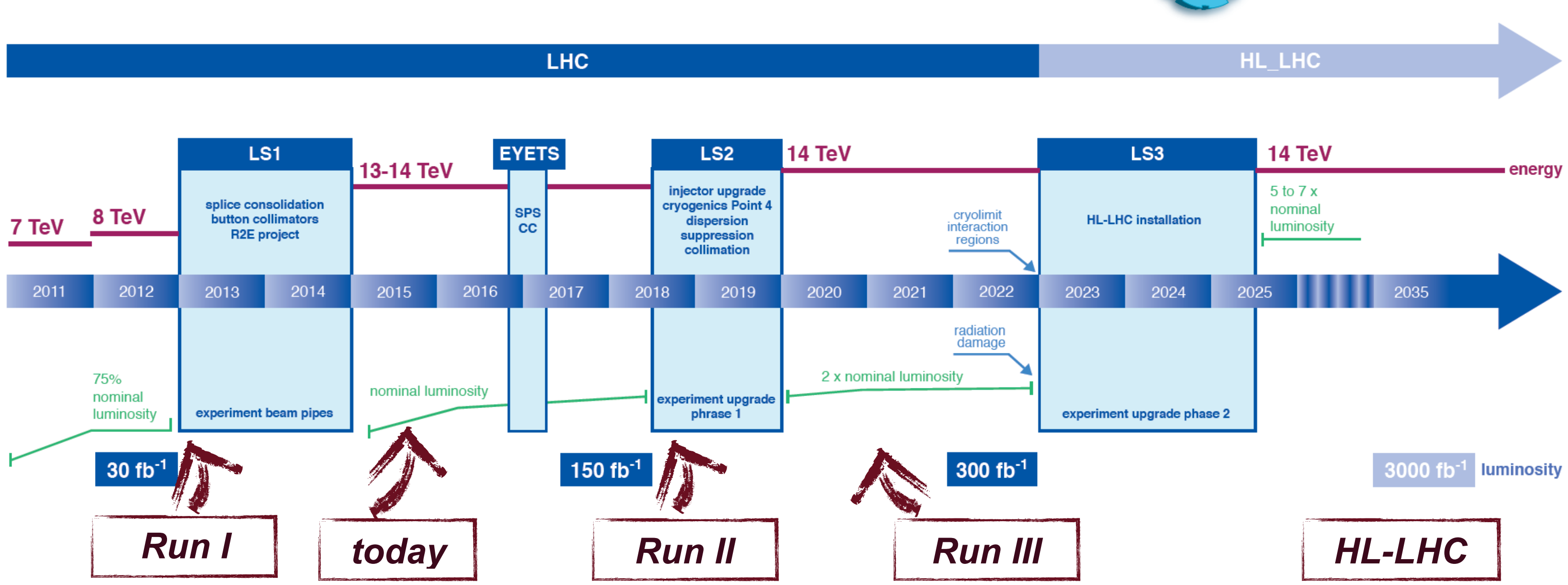
Higgs sector landscape transformed since July 4th, 2012!

Observed Higgs boson now a tool for probing New Physics:

- Precision property measurements (fiducial/differential cross-sections, couplings, etc.)
- Anomalous/rare production/decays (FCNC, LFV, h→Qγ, …)
- Extended sectors (H→hh, A→Zh, h→aa,…)

On-going Run 2 will provide substantially enhanced sensitivity in all of these directions!

LHC / HL-LHC Plan



Follow the updates at:
Latest ATLAS Higgs results
Lates CMS Higgs results