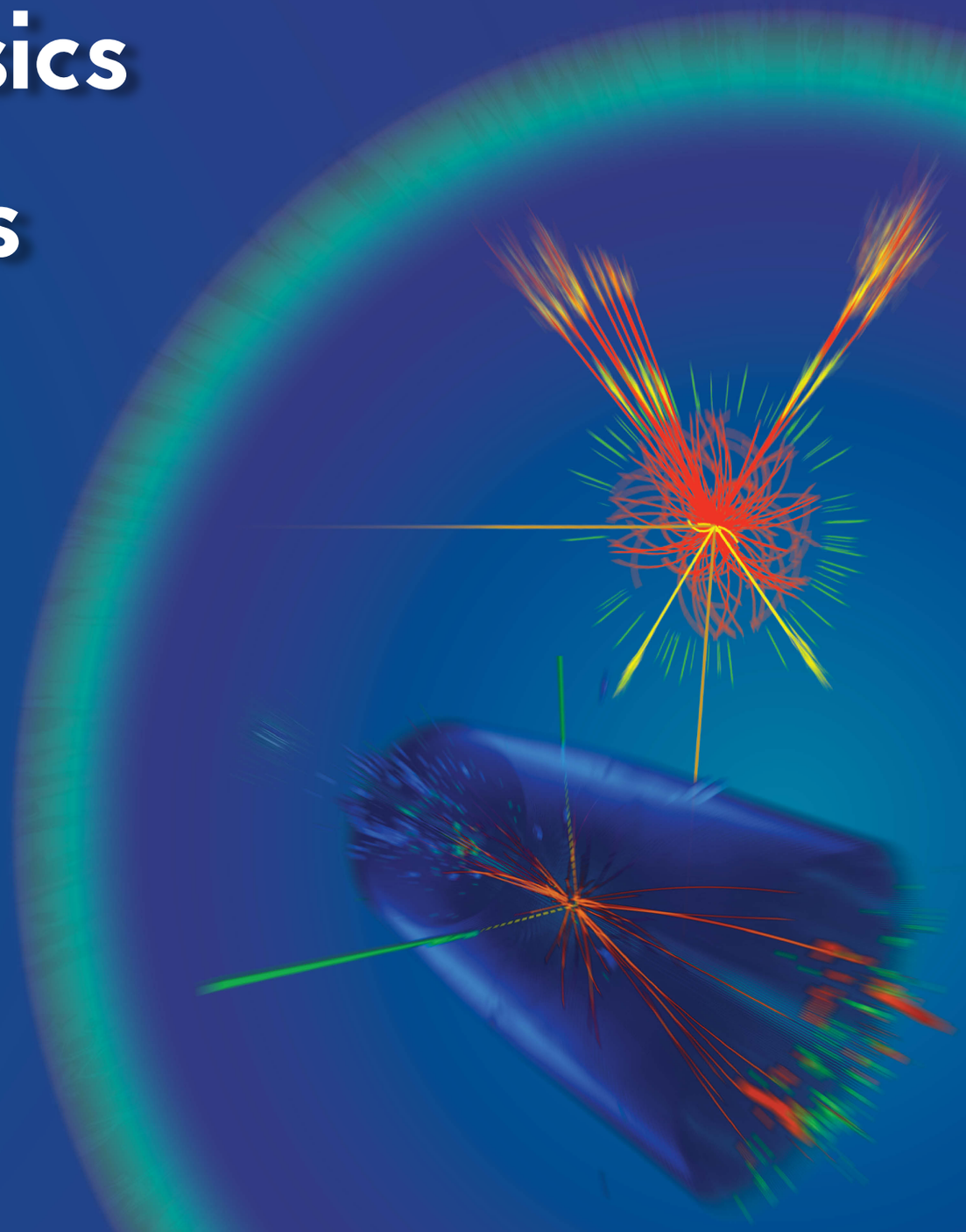
Standard Model Physics at Hadron Colliders

Third Lecture

Gautier Hamel de Monchenault

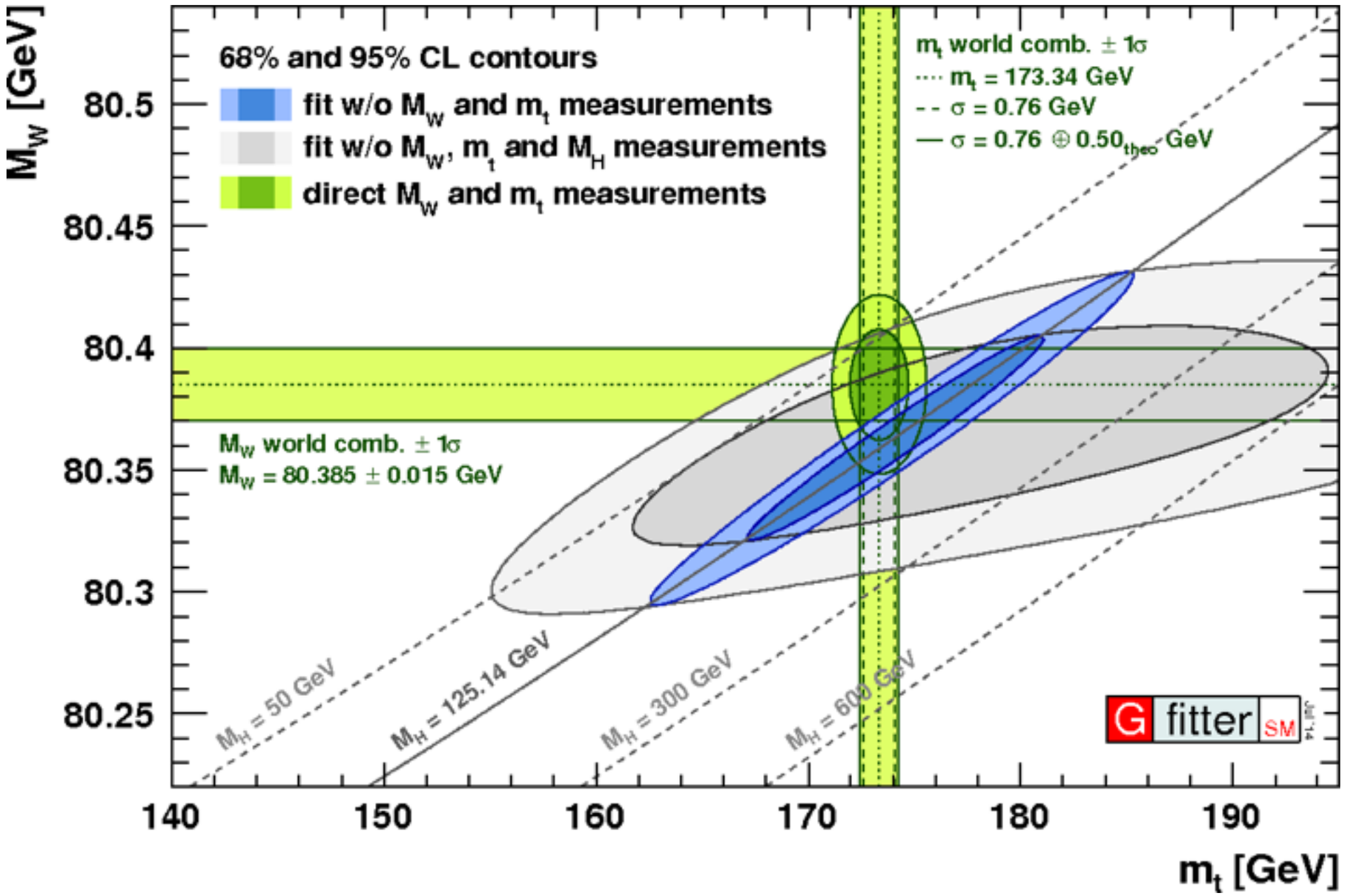
CEA-Saclay Irfu, France



July 2017

The Electroweak Fit

Internal consistency of the Standard Model through quantum corrections



Note the different scales!

The Top Quark

The top quark

- is the $SU(2)_L$ partner of the bottom quark
- is the heaviest known fundamental particle

$$m_t = y_t v/\sqrt{2} \simeq 173 \text{ GeV}$$

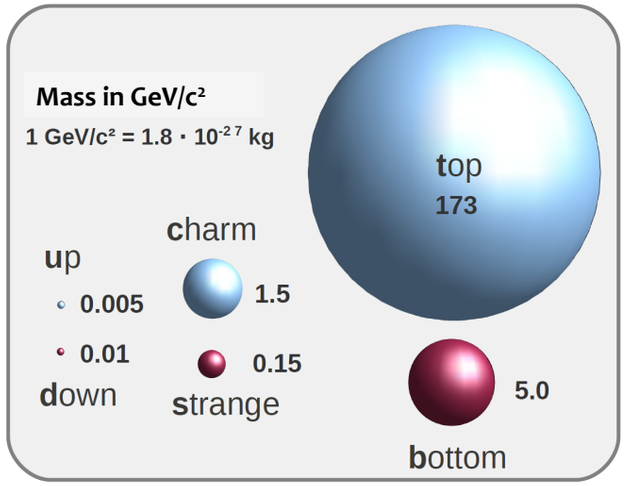
- is the only fermion with "natural" coupling to the Higgs field

$$\Rightarrow \quad y_t \simeq 1$$

- plays a special role in electroweak physics, flavour physics and Higgs physics
- decays almost exclusively to bW
- decays before it has time to hadronise

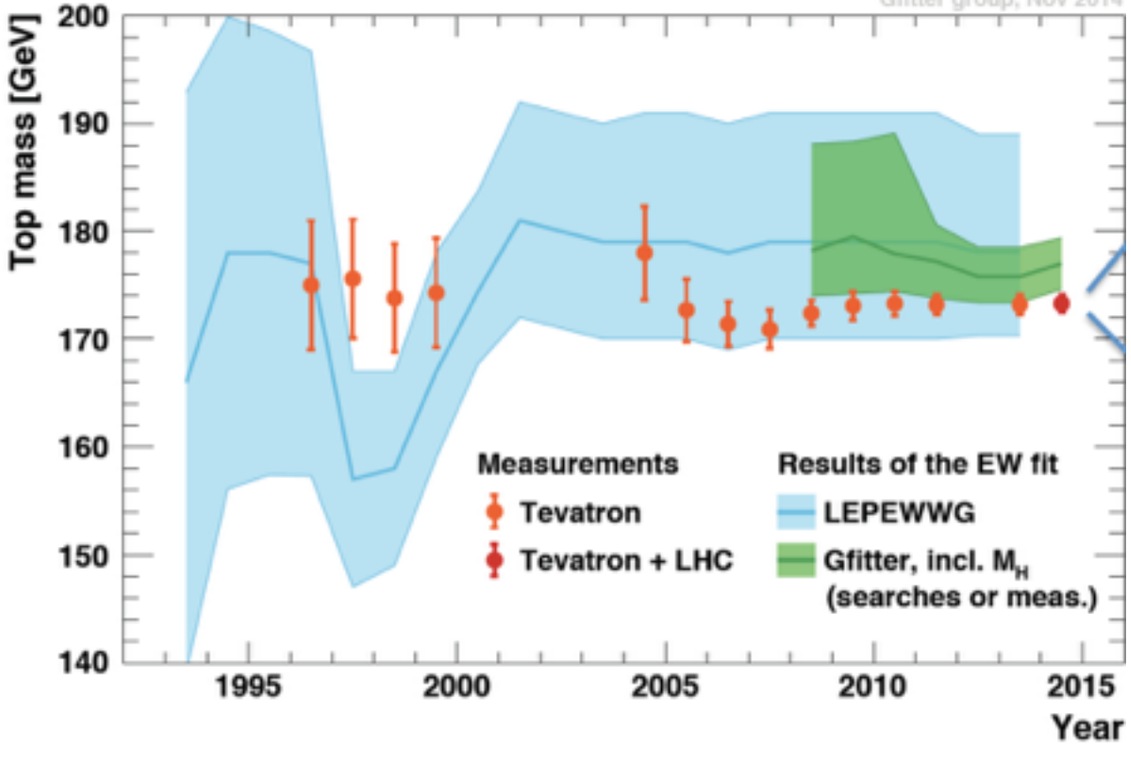
$$\Gamma(t \to bW^+) \approx \frac{\alpha}{16 s_W^2} |V_{tb}|^2 \frac{m_t^3}{m_W^2}$$

~1.5 GeV (> Λ_{QCD})



40 times heavier than the b quark

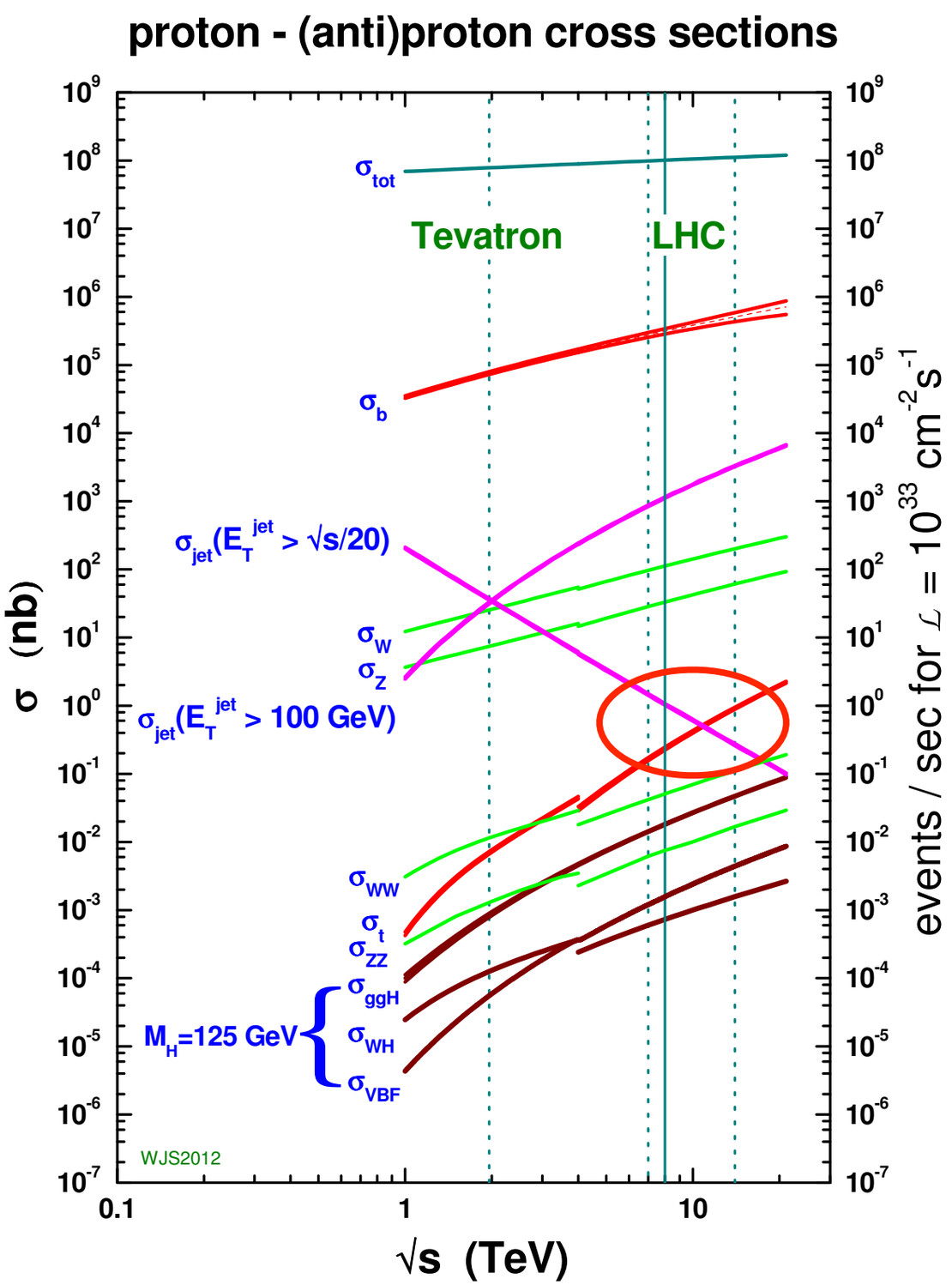
top quark first discovered "virtually"

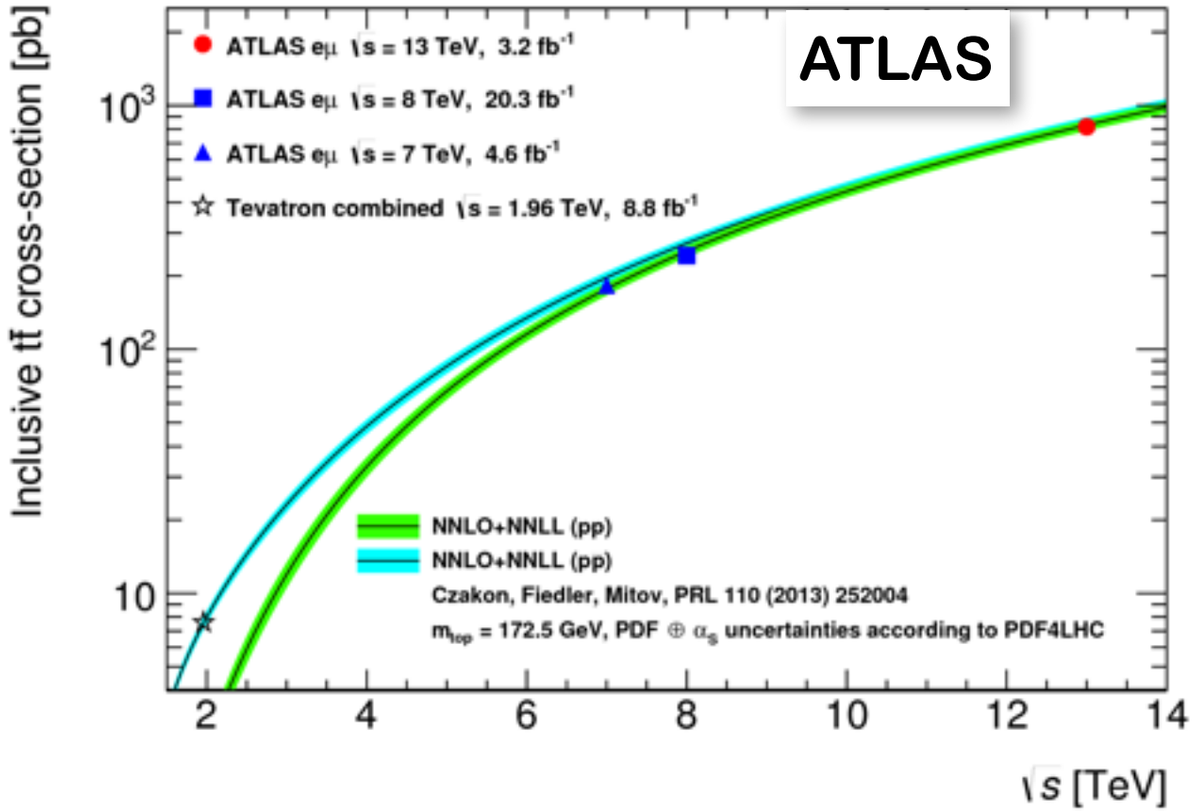


typical top decay time: 5 10^{-25} s

typical hadronisation time: 2 10^{-24} s

Top Quark Physics



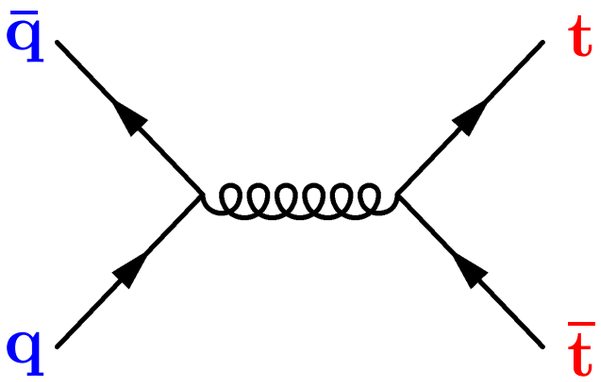


Top Quark QCD Production

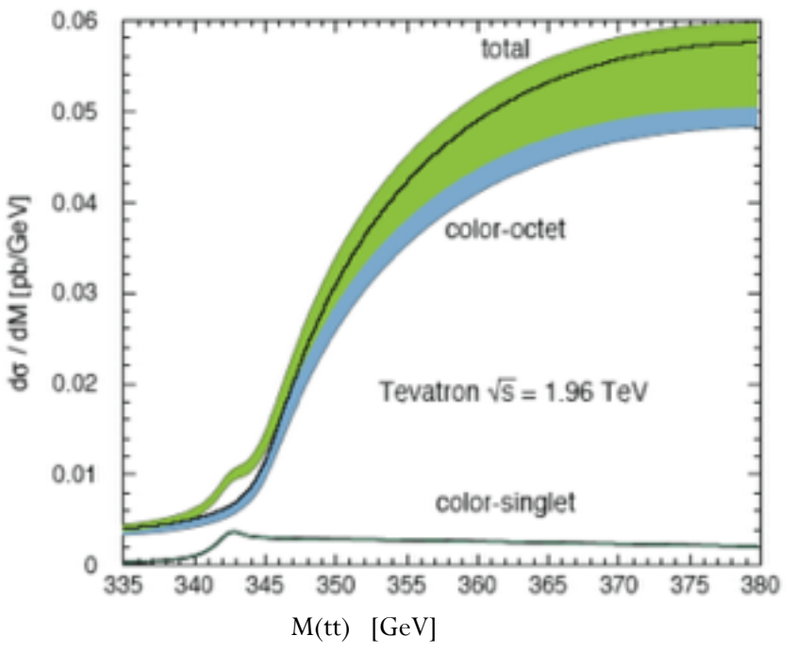
Tevatron (1.96 TeV)

σ_{TEV} = 7 pb

quark annihilation



85% of the cross section



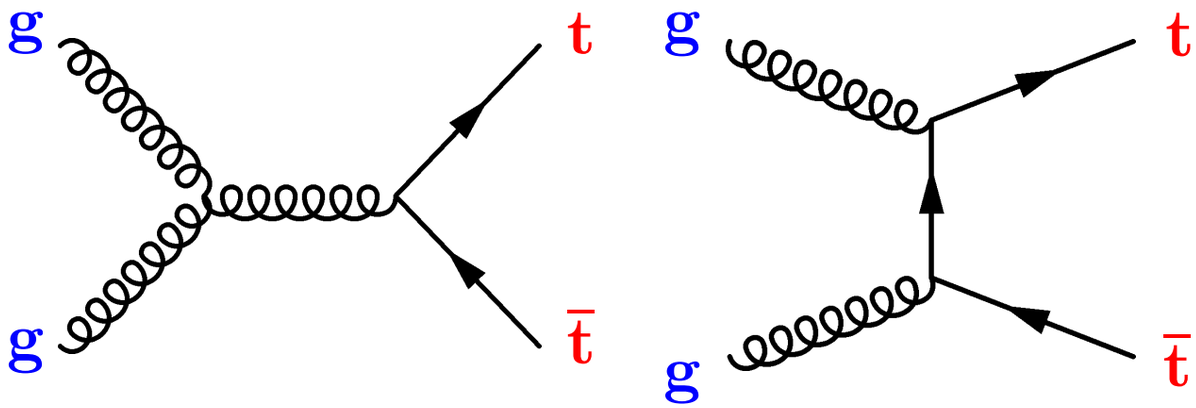
Tevatron
ten t-tbar pair
per day

near threshold in a $^3S_1$ state
parallel spins, 100% correlation

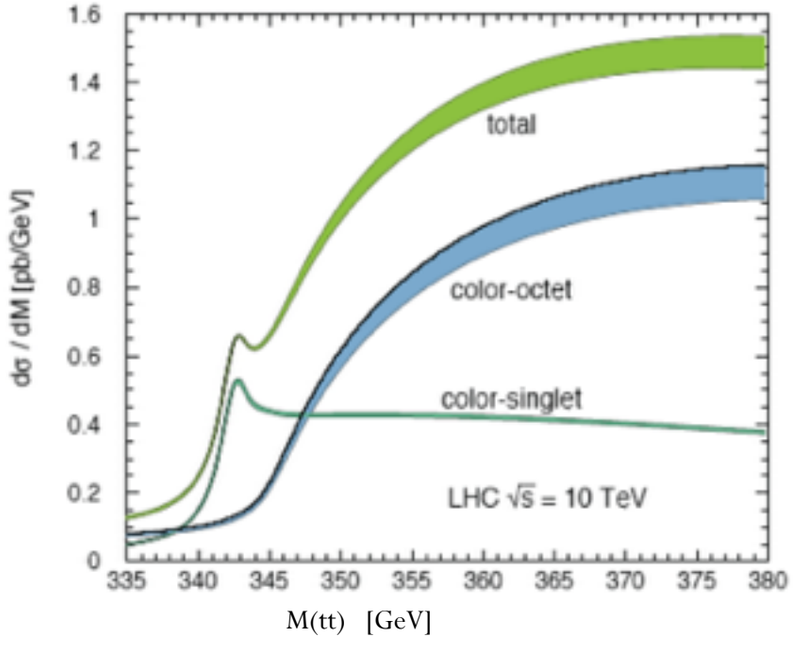
LHC (7/8 TeV)

σ_{LHC} = 220 pb

gluon fusion



80% of the cross section



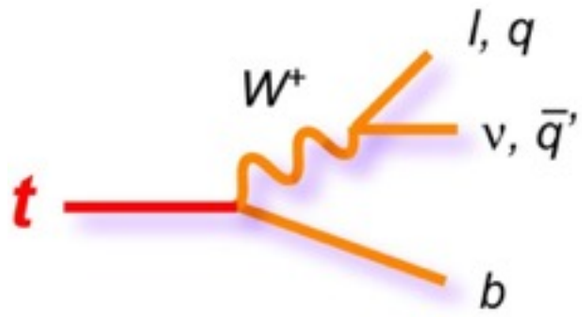
LHC:
one t-tbar pair
per second

in a $^1S_0$ state, not so close from threshold
anti-parallel spins, not 100% correlation

Top Pair Decay Channels

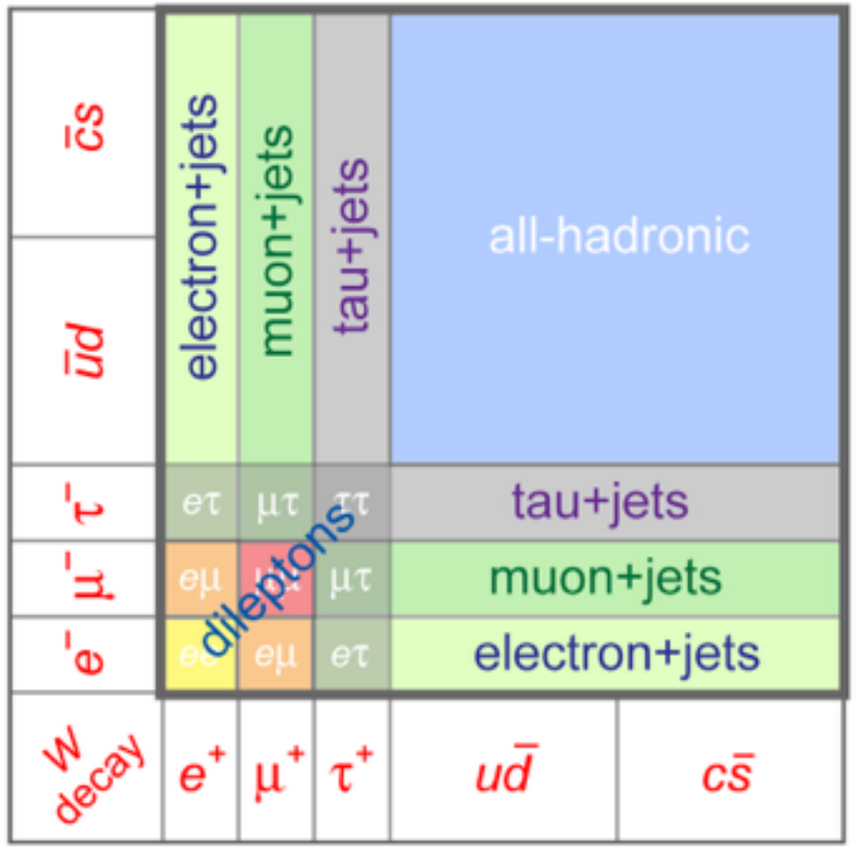
In the SM the top quark decays exclusively into a W boson and a b quark

$$\mathcal{B}(t \to Wb) \simeq 100\%$$

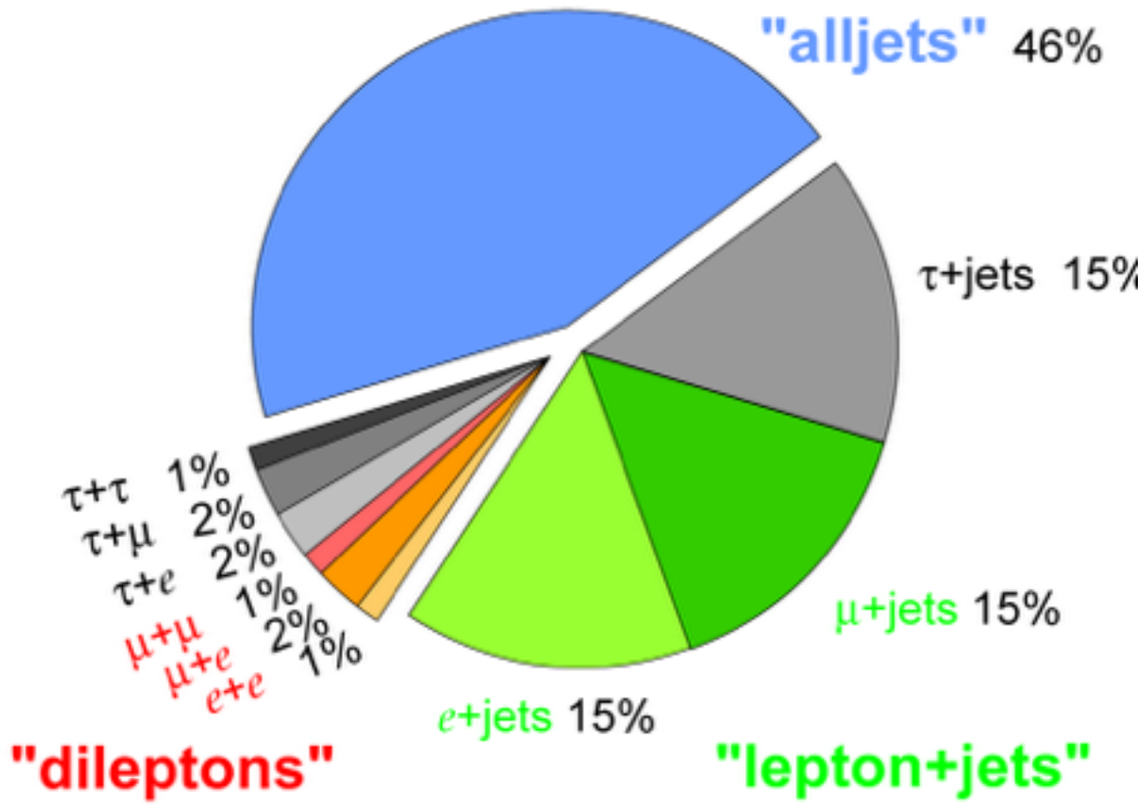


the branching fractions of the t-tbar final states depend on the W boson branching fractions

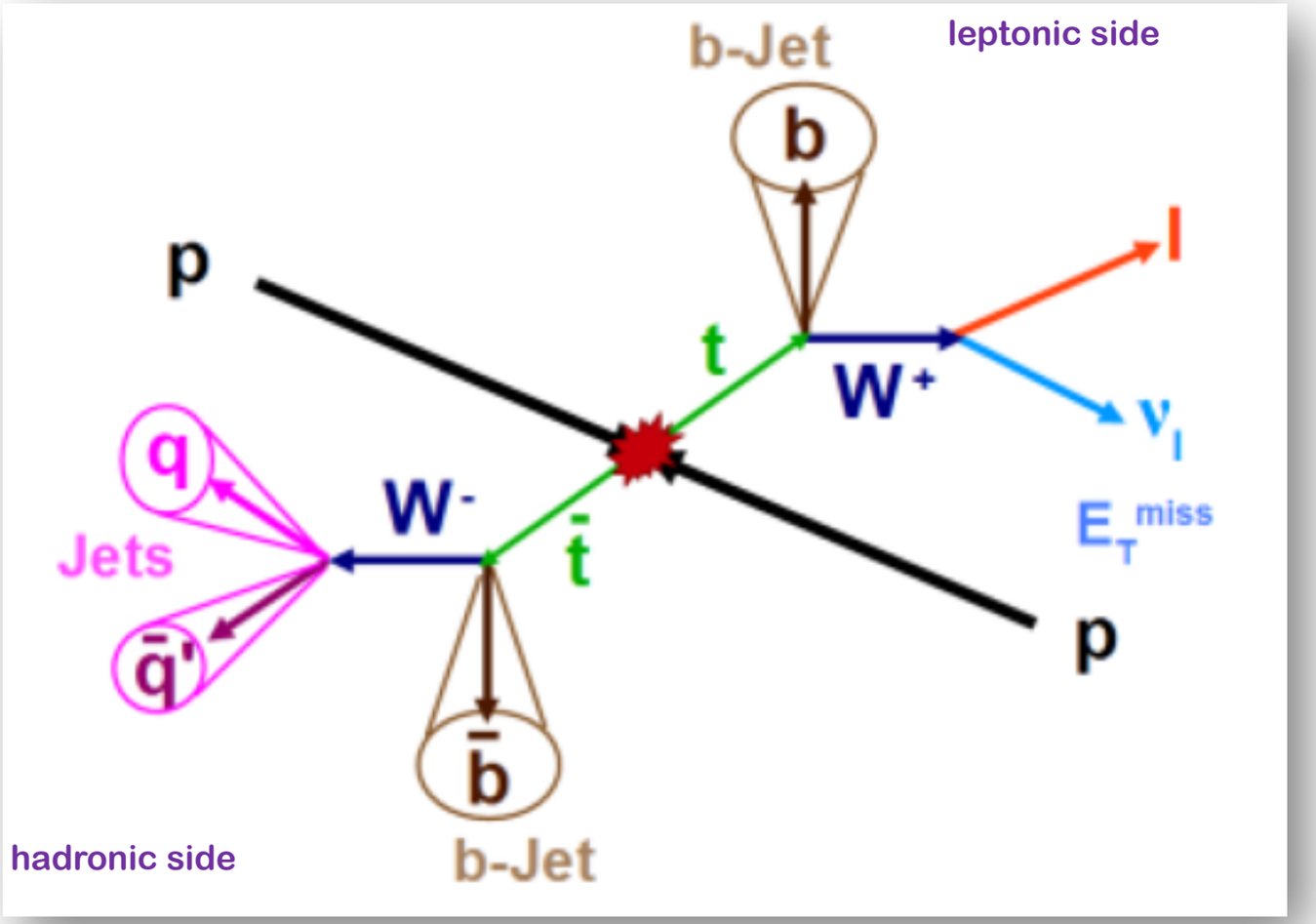
Top Pair Decay Channels



Top Pair Branching Fractions



Lepton+Jets

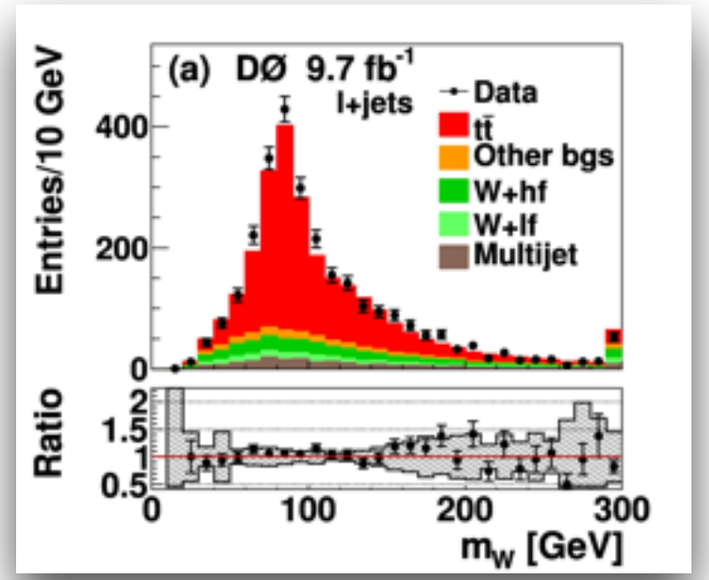


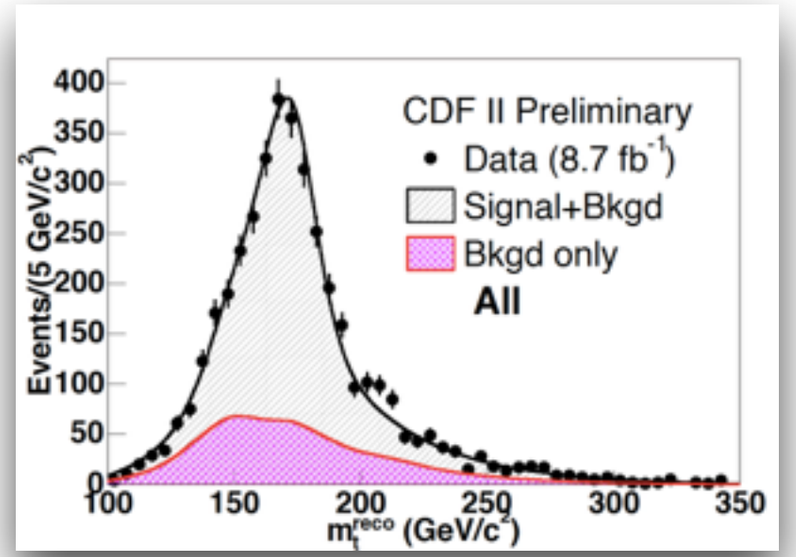
Golden mode at the LHC

- High rate: 30% of top pairs
- Low backgrounds: S/B>1
- W reconstructed in hadronic channel
  in situ constraint of jet energy scale
- full reconstruction of the top quark on the hadronic side
  direct mass measurement

But

- large combinatorics
  reduced by efficient b-tagging and good di-jet mass resolution



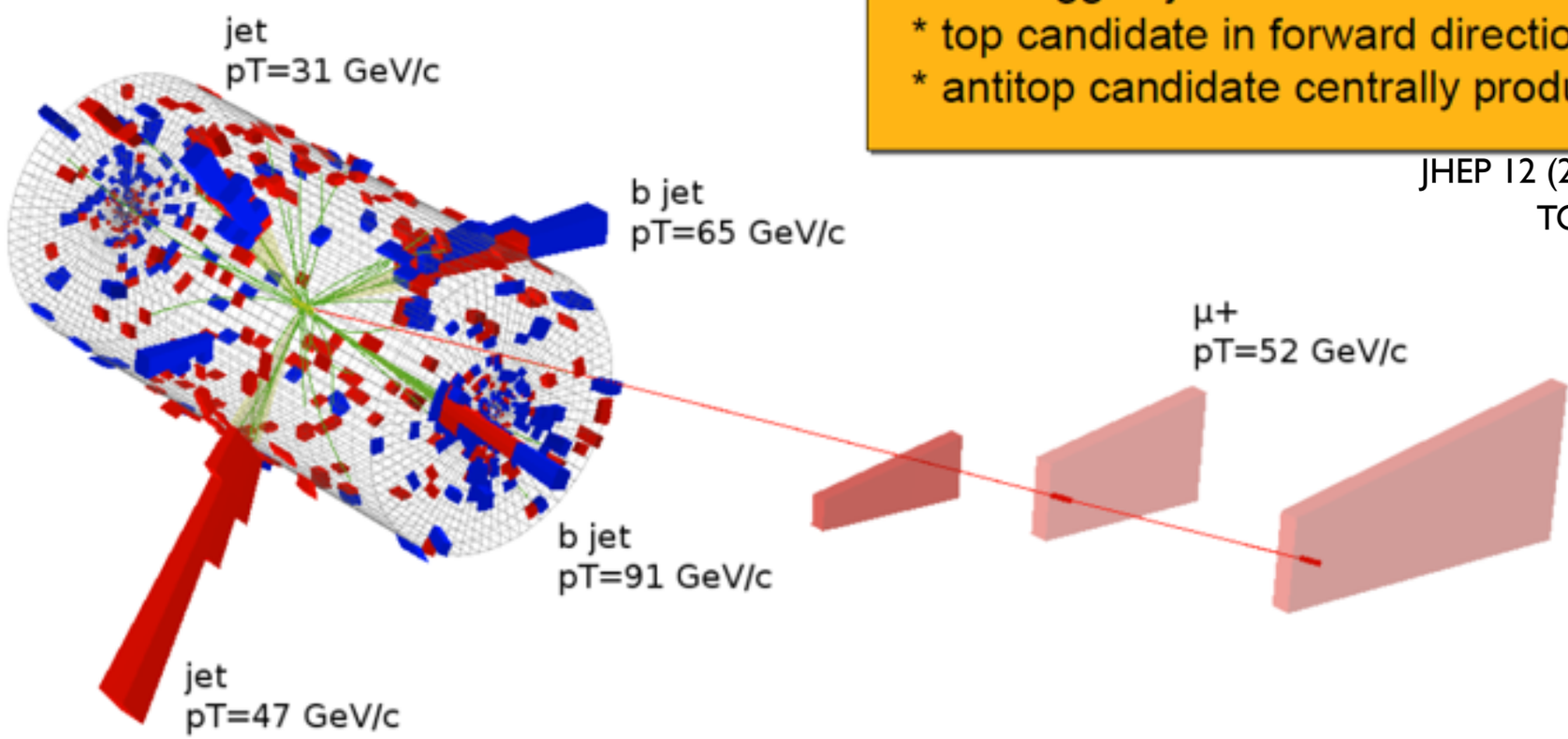


D0 and CDF signals with full statistics

~2,500 events

Lepton+Jets Event Selection

CMS Experiment at LHC, CERN
Data recorded: Mon May 2 10:44:23 2011 CEST
Run/Event: 163817 / 685608658



Top quark pair candidate event
* high probability to be $t\bar{t}$ event
* 2 b-tagged jets
* top candidate in forward direction
* antitop candidate centrally produced

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TOP-14-001

Typical event selection

- trigger lepton + jets
- exactly one lepton p_T > 30 GeV and and $|\eta|$ < 2.1
- ≥ 4 jets with p_T > 30 GeV and $|\eta|$ < 2.4
- 2 b-tagged jets among the 4 leading jets

Lepton+Jets

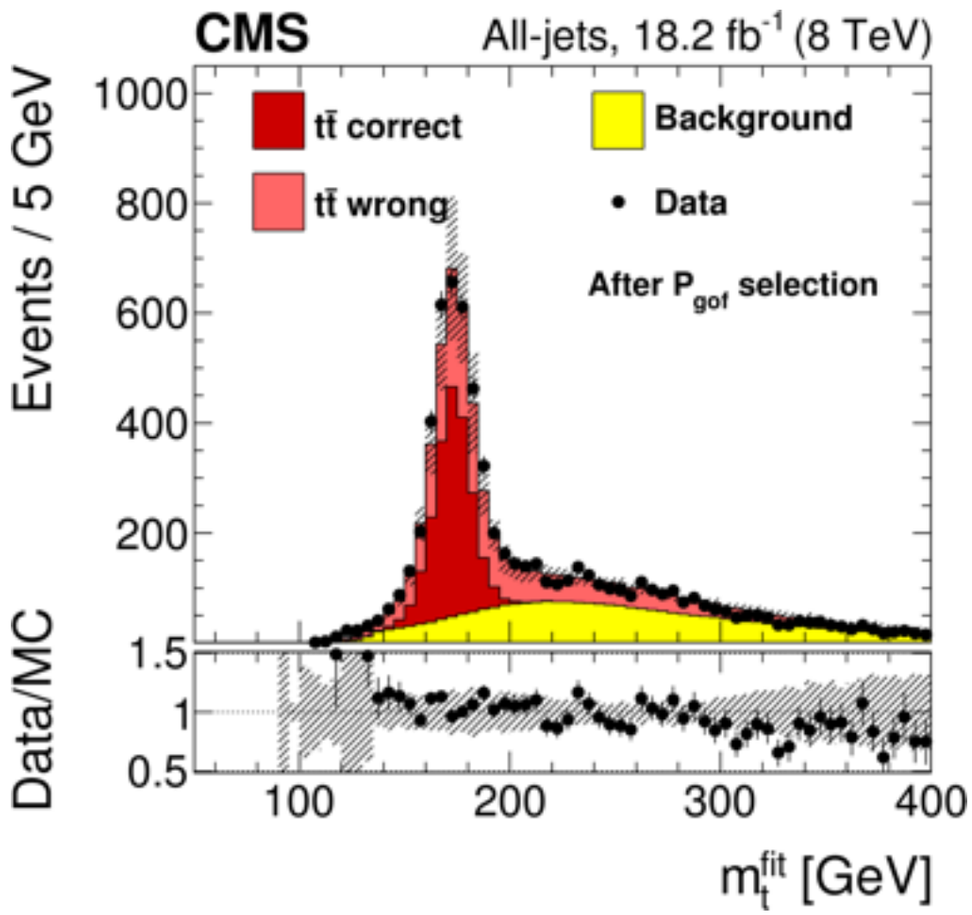
30 000 events in 20 fb^{-1}@8 TeV

- t-tbar purity: 94%

Kinematical fit with constraints

- m_W = 80.4 GeV
- $m_{tbar} = m_t$

- energy calibration using invariant mass of light-jet pair

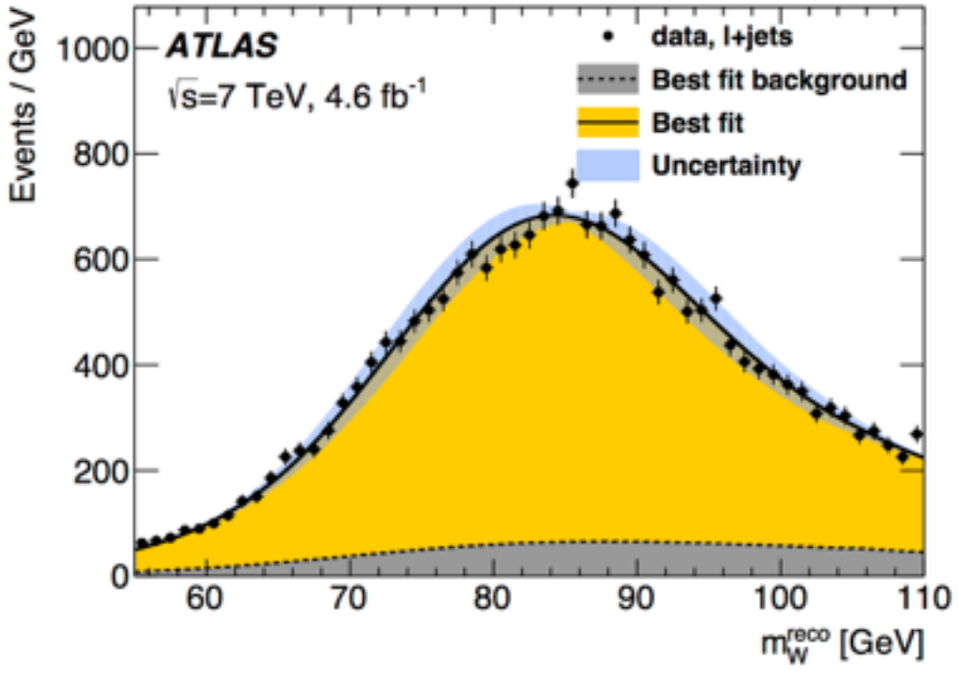


CMS

m_t = 172.04 GeV

Uncertainties

- stat = 190 MeV
- syst = 750 MeV



ATLAS

m_t = 172.33 GeV

Uncertainties

- stat = 480 MeV
- syst = 1.0 GeV

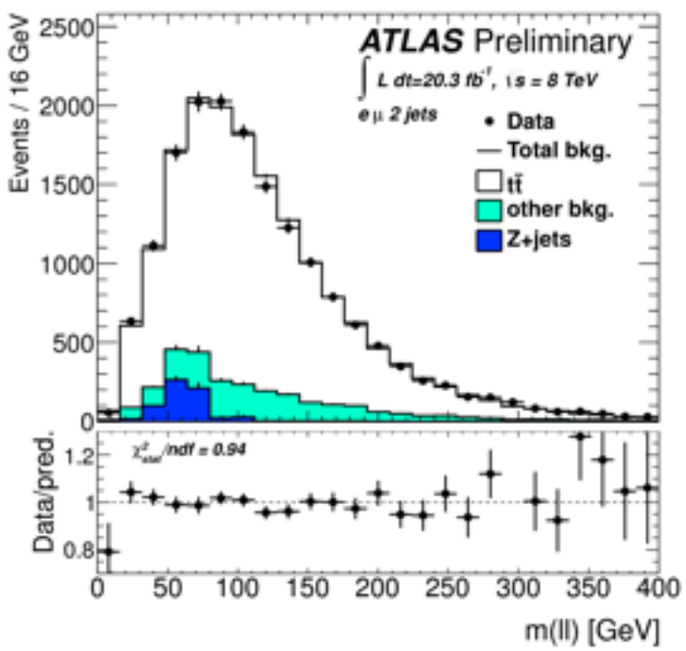
Other Channels

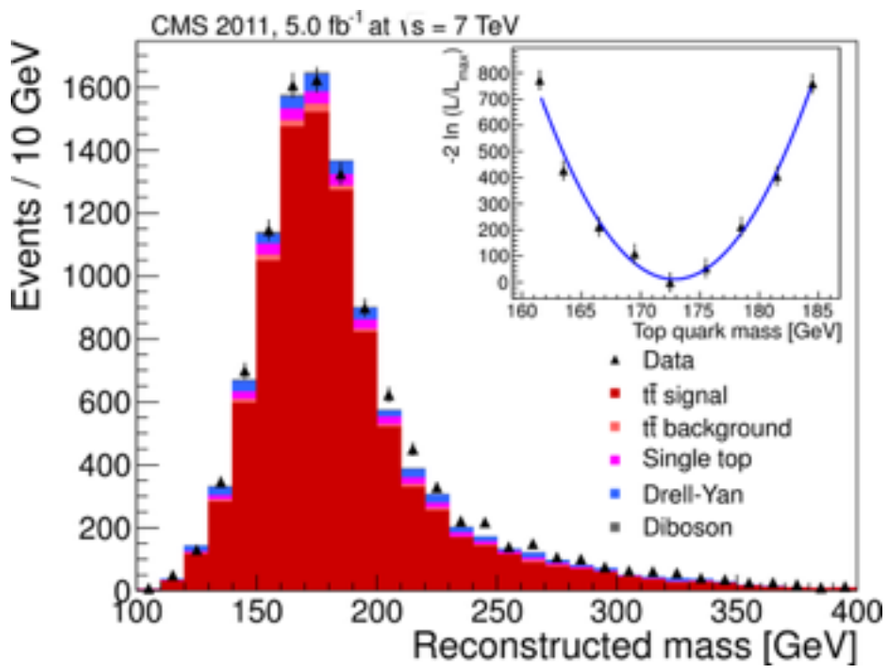
(illustration plots — not final — not comparable)

ATLAS

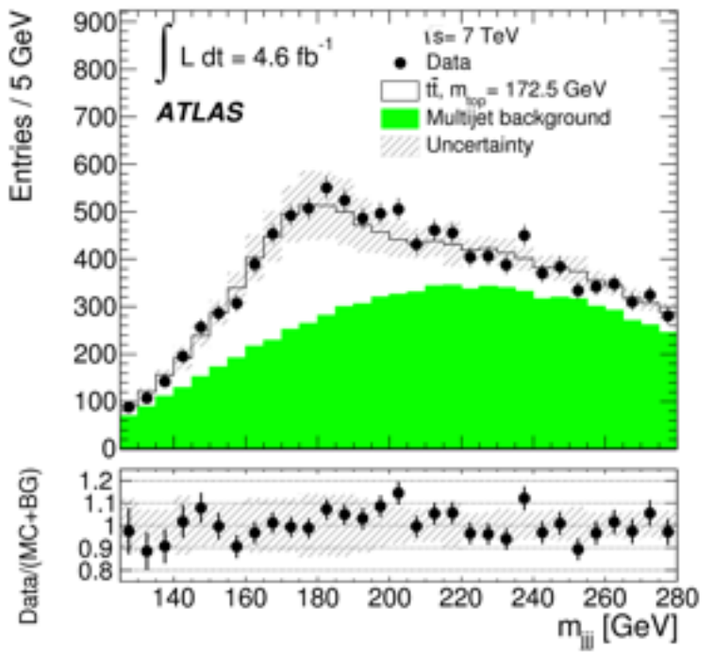
CMS

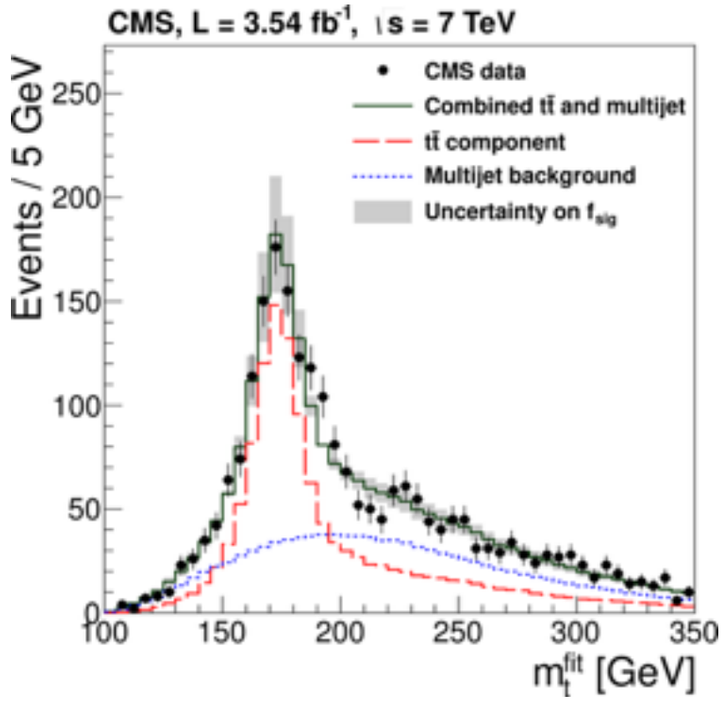
Dilepton



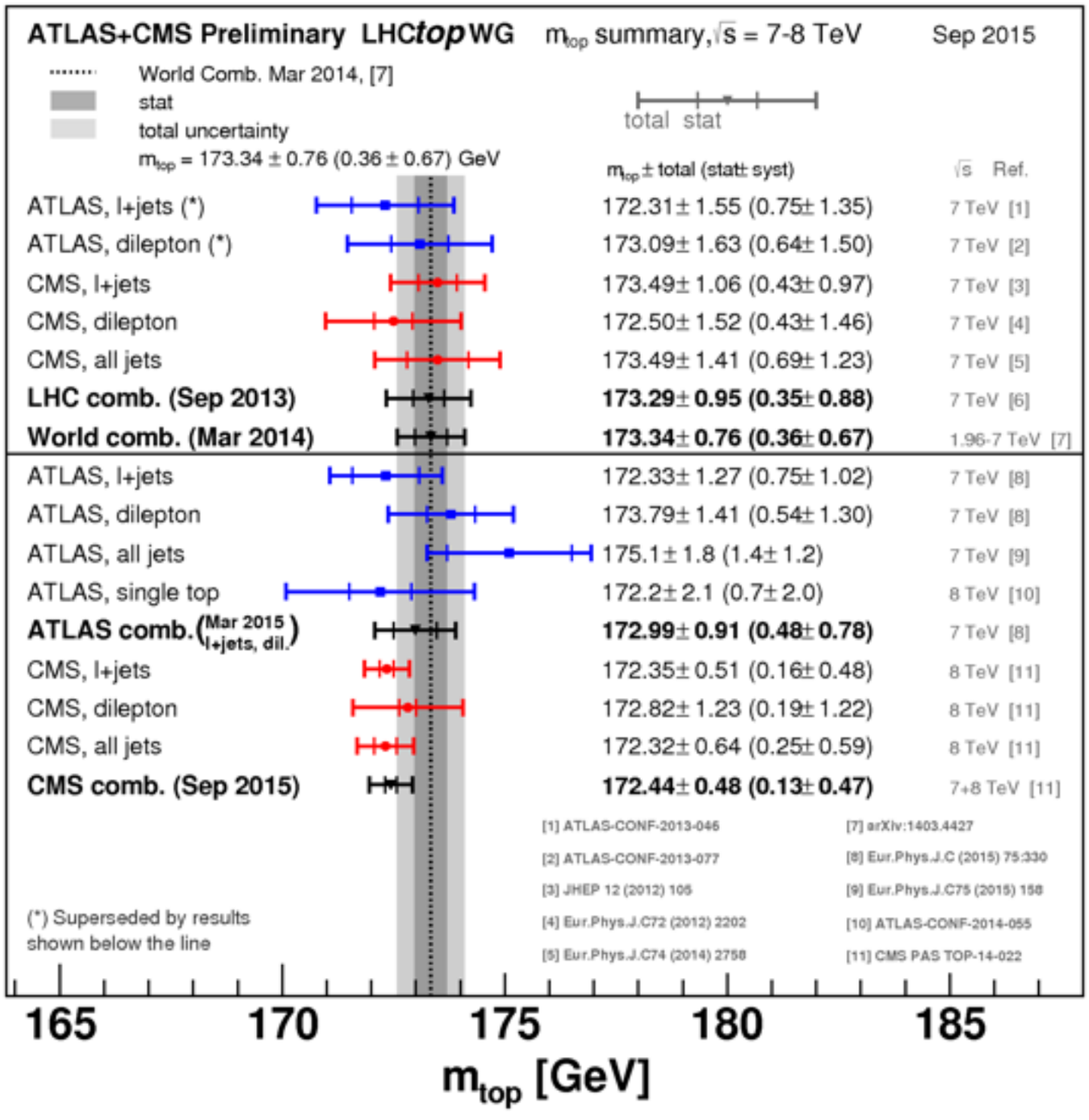


All hadronic





Summary of Mass Measurements



World-14: m_t = 173.3 ± 0.8 GeV

ATLAS: m_t = 173.0 ± 0.9 GeV

CMS: m_t = 172.4 ± 0.5 GeV

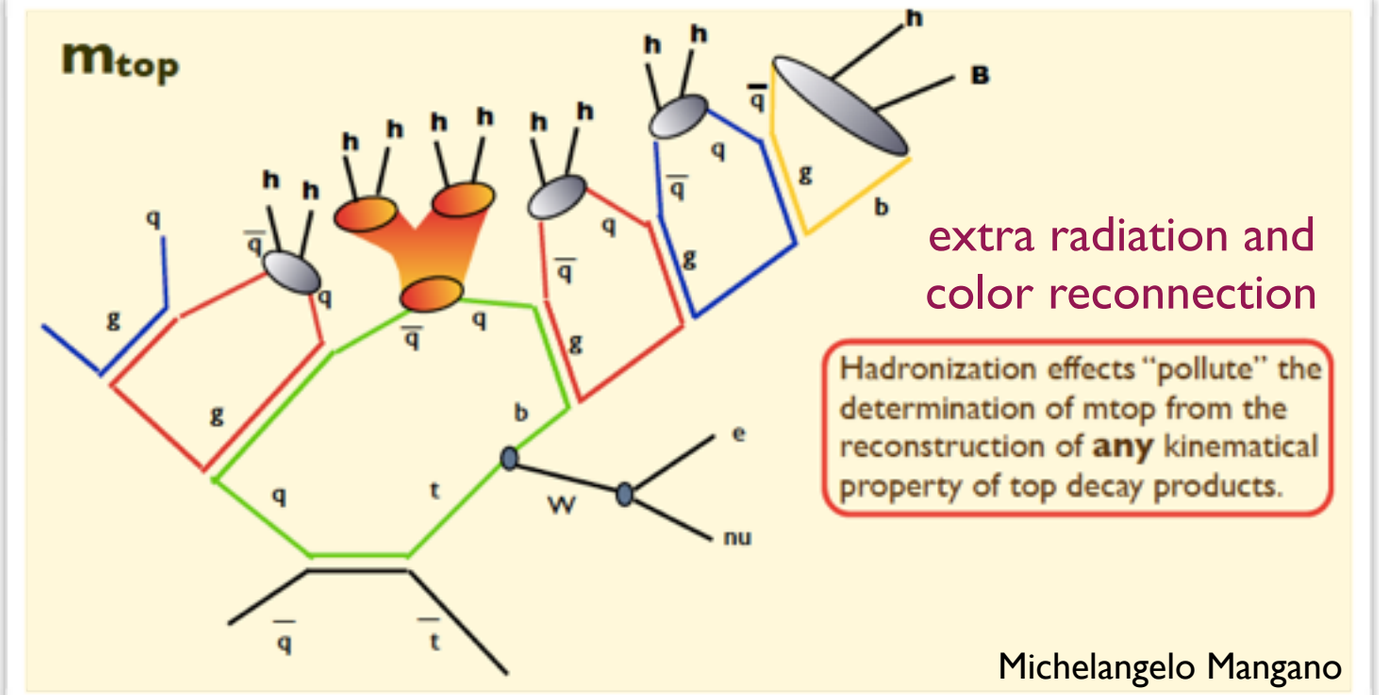
- excellent agreement between ATLAS and CMS

What Mass for the EW fit?

The definition of the mass of the top quark is ill-defined

- the mass measured from bW decay products is assumed to be close from pole m_{pole}
- problem: m_{pole} for a coloured particle cannot be determined with accuracy better than Λ_{QCD} ($\approx$ 0.2 GeV)
- the top quark decays before hadronising but still the b quark has to hadronise

Which final state particles to assign to the original top quark?

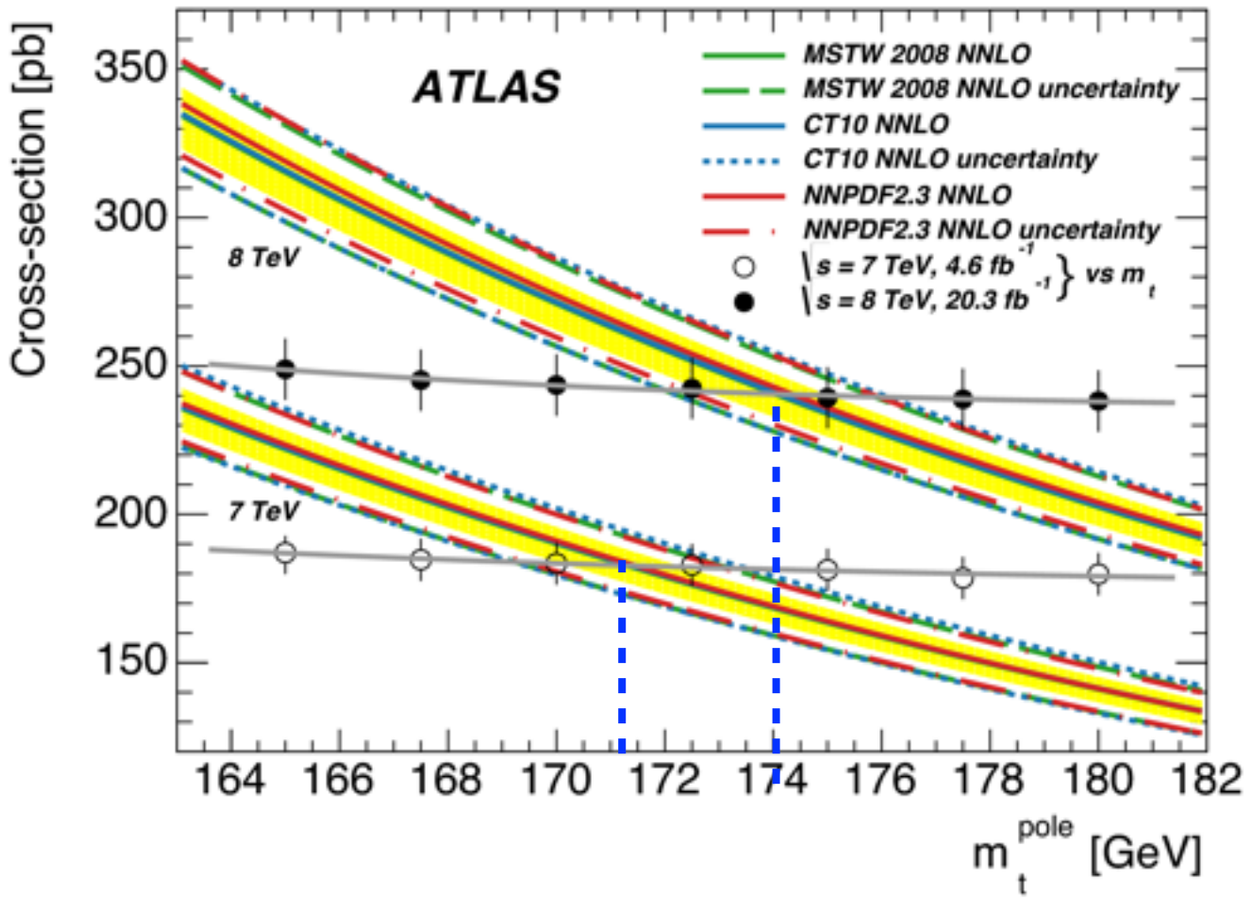


- Importance of measuring the mass using alternate techniques
  - mass and end point of bℓ spectrum
  - decay length (boost) of B hadrons

theoretically a good approach is to extract the mass from measurements of the cross section

Mass from Cross Section

- use the best x-section measurement (dilepton)
- use most recent NNLO calculations of top pair x-section to extract m_t
- also provide a measurement of the strong coupling constant at m_t



From cross section:

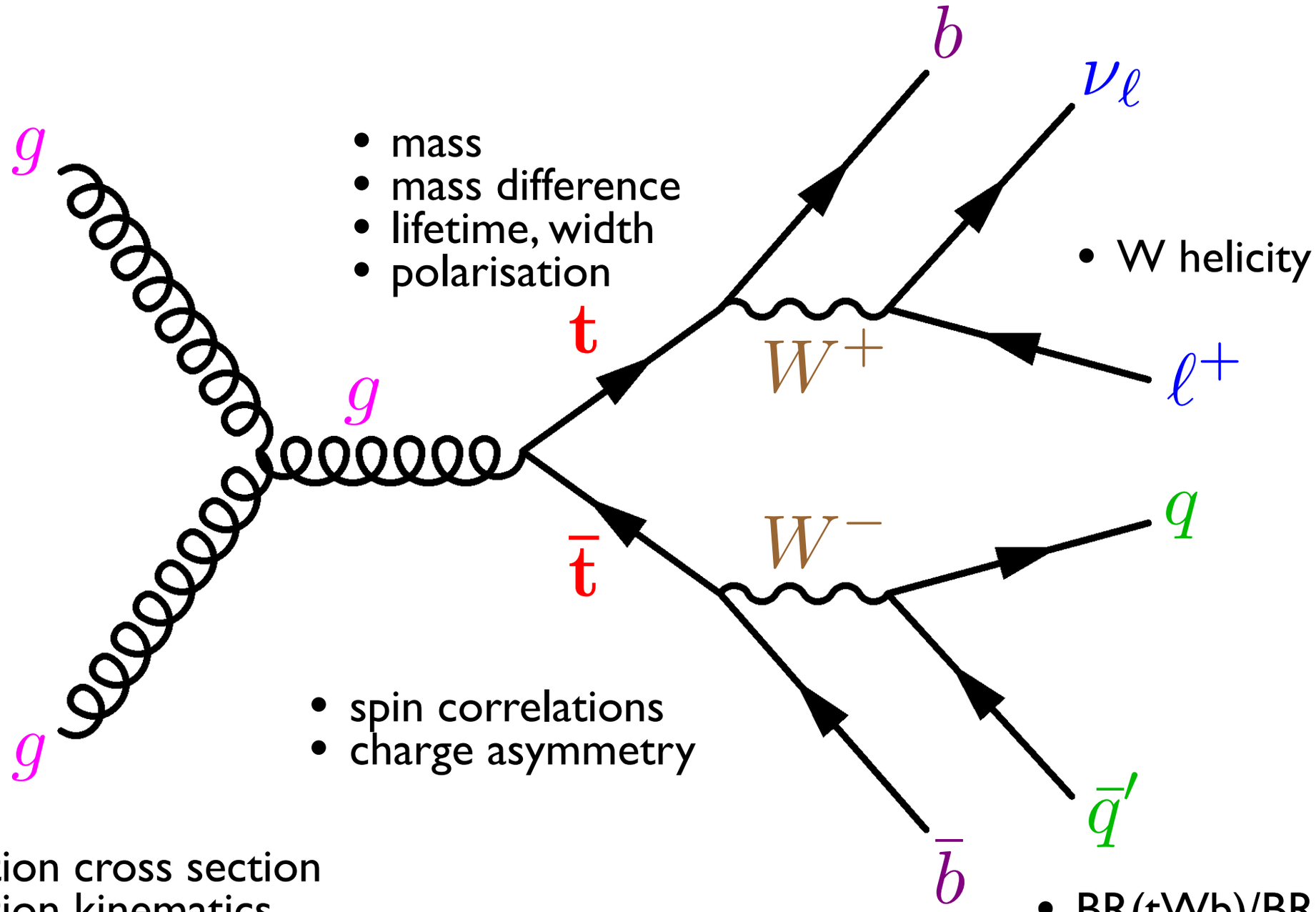
ATLAS (7+8 TeV): m_t = 172.9 ± 2.6 GeV

Limitation: PDFs and uncertainty on luminosity (2-5%)

Direct:

World-14: m_t = 173.3 ± 0.8 GeV

Top Quark Properties



- mass
- mass difference
- lifetime, width
- polarisation

- W helicity

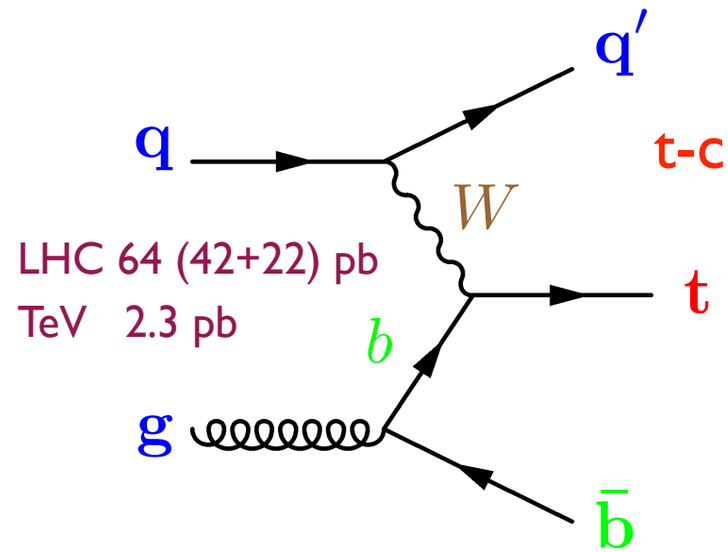
- spin correlations
- charge asymmetry

- production cross section
- production kinematics
- resonances, new particles

- BR(tWb)/BR(tWq)
- new decays

Electroweak Production: Single Top

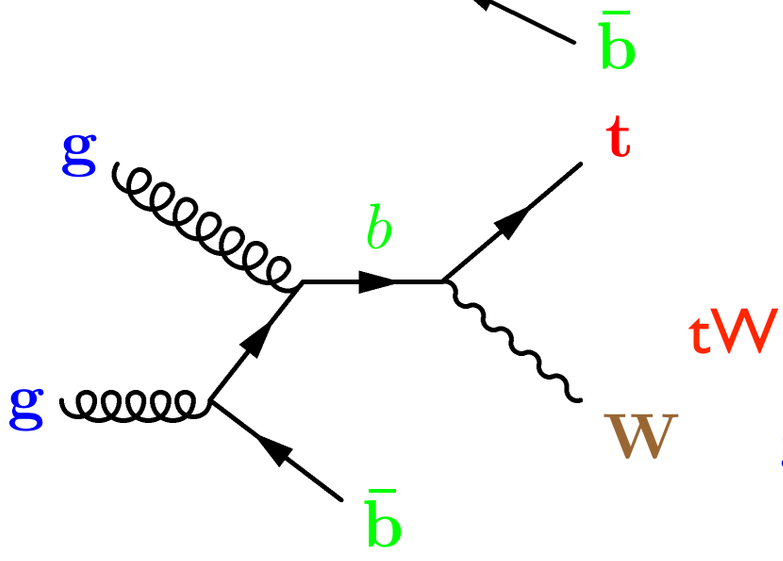
EW production of a top quark



t-channel

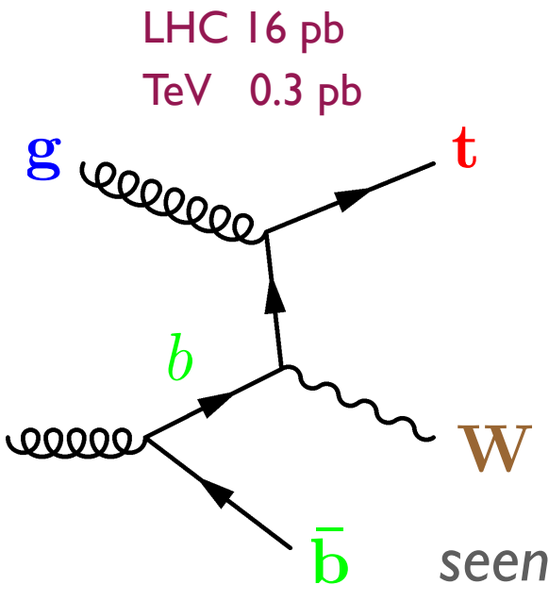
LHC 64 (42+22) pb
TeV 2.3 pb

measured

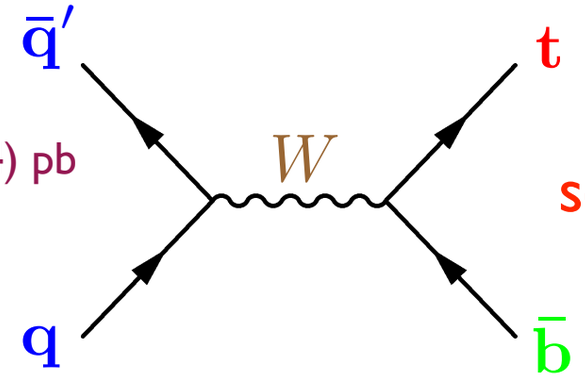


tW

LHC 16 pb
TeV 0.3 pb



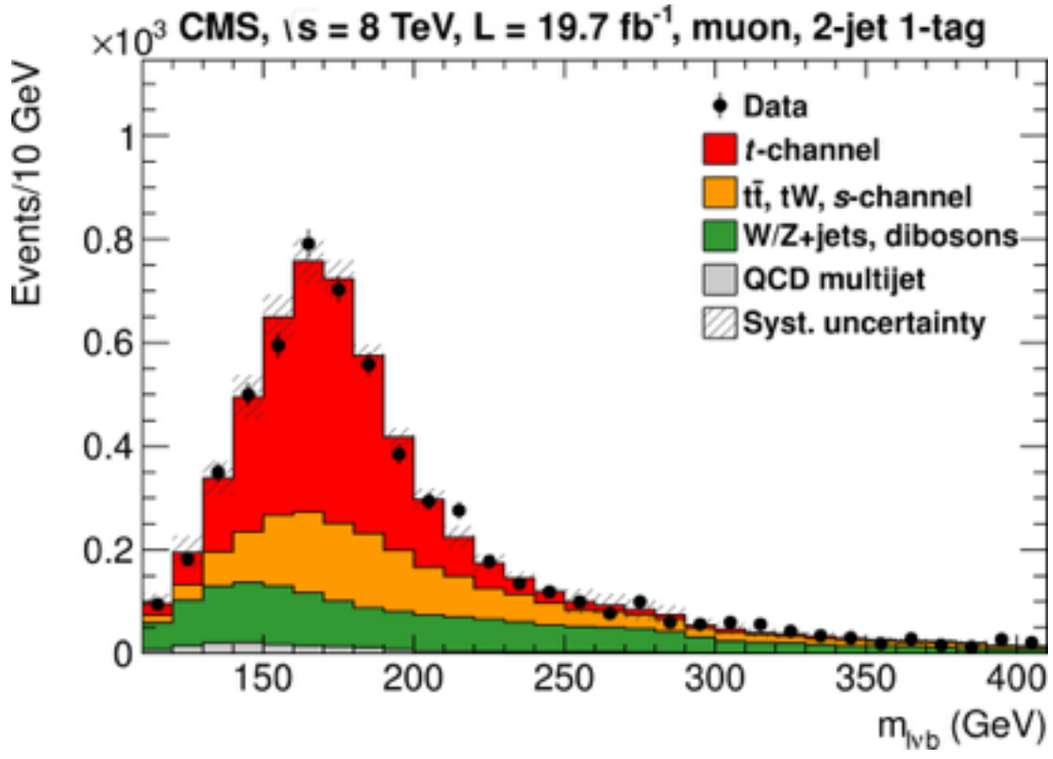
seen



s-channel

LHC 4.5 (3.2+1.4) pb
TeV 1.00 pb

not seen yet

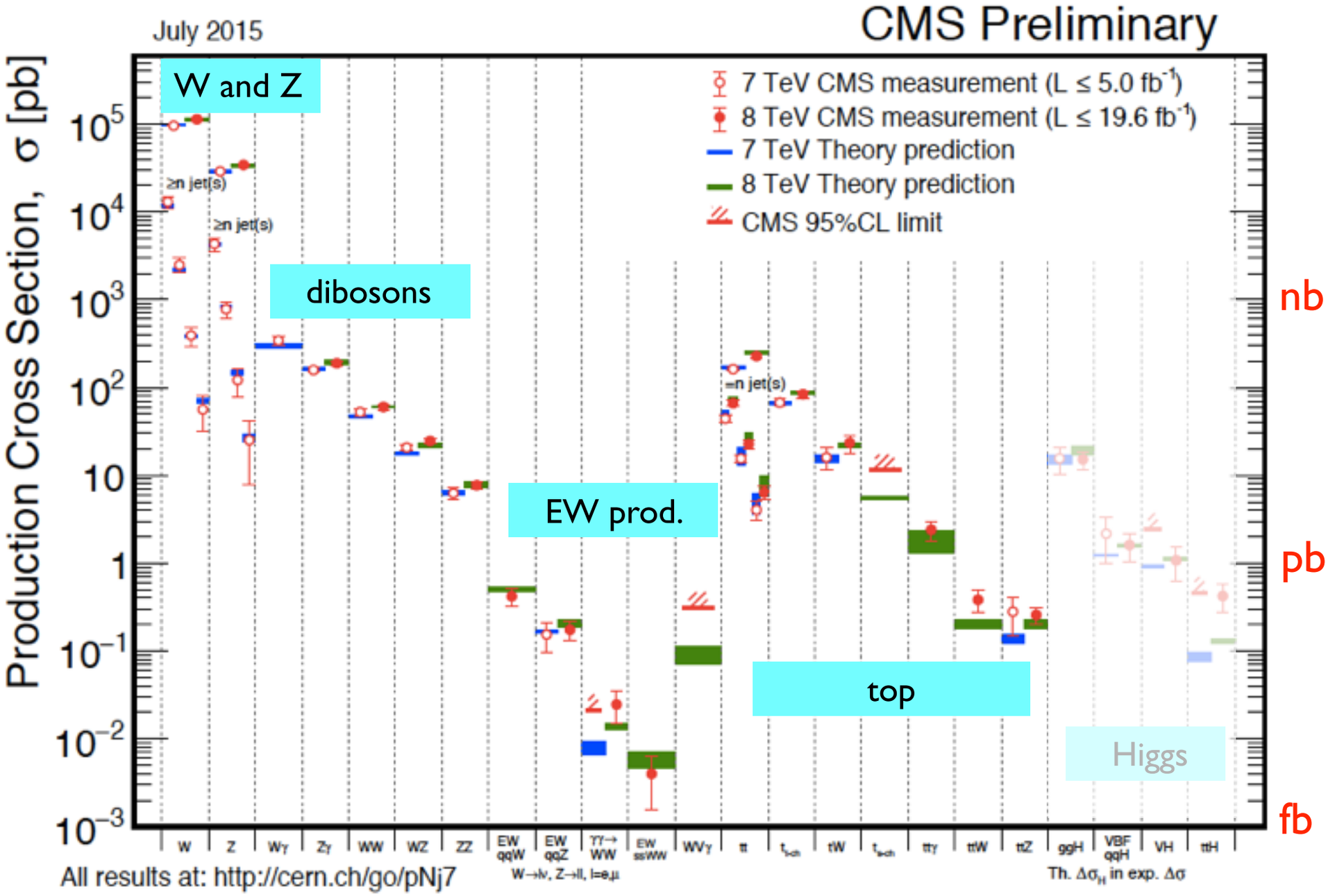


allows direct measurements of V_{tb}

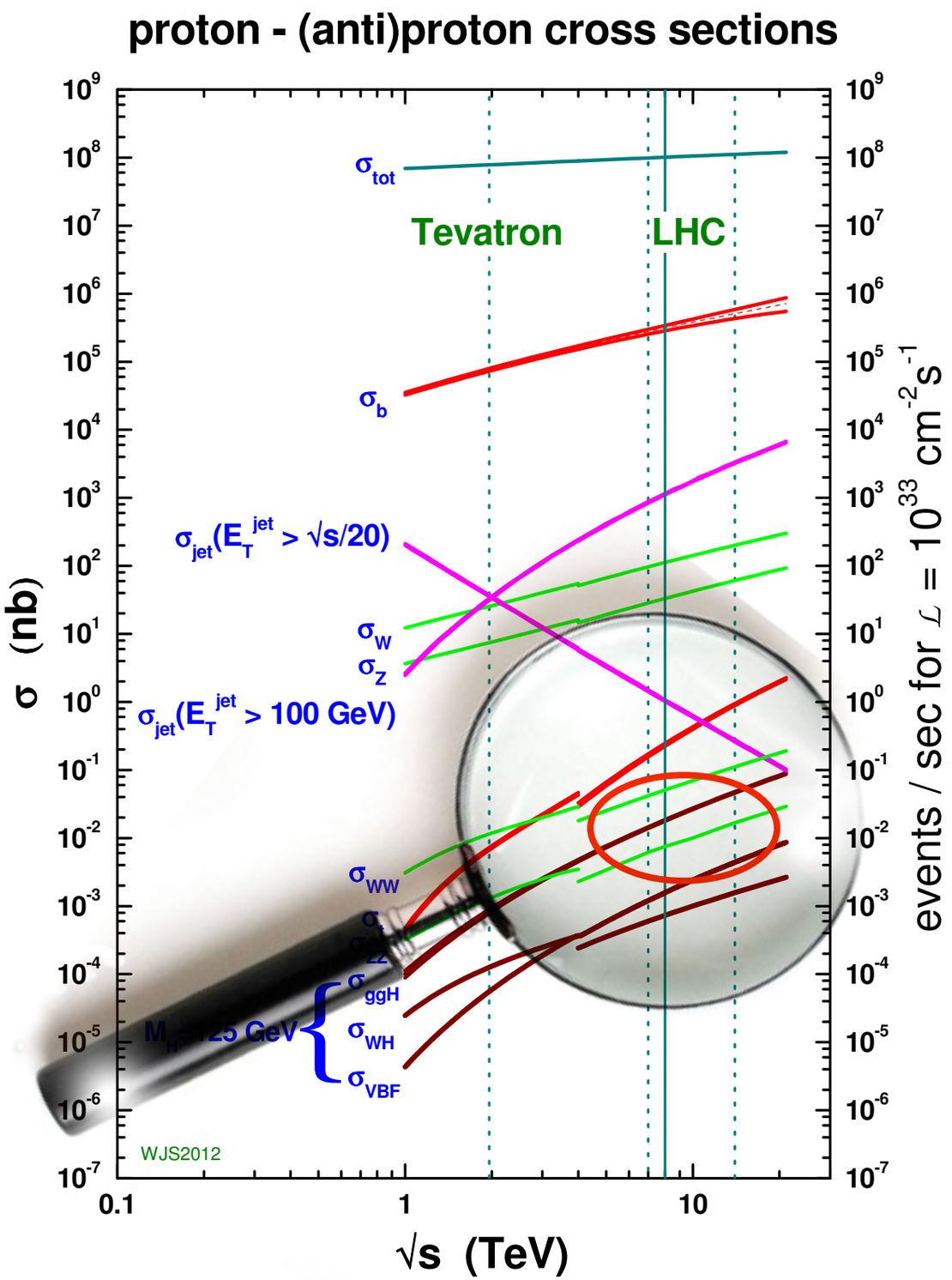
Summary of SM Measurements

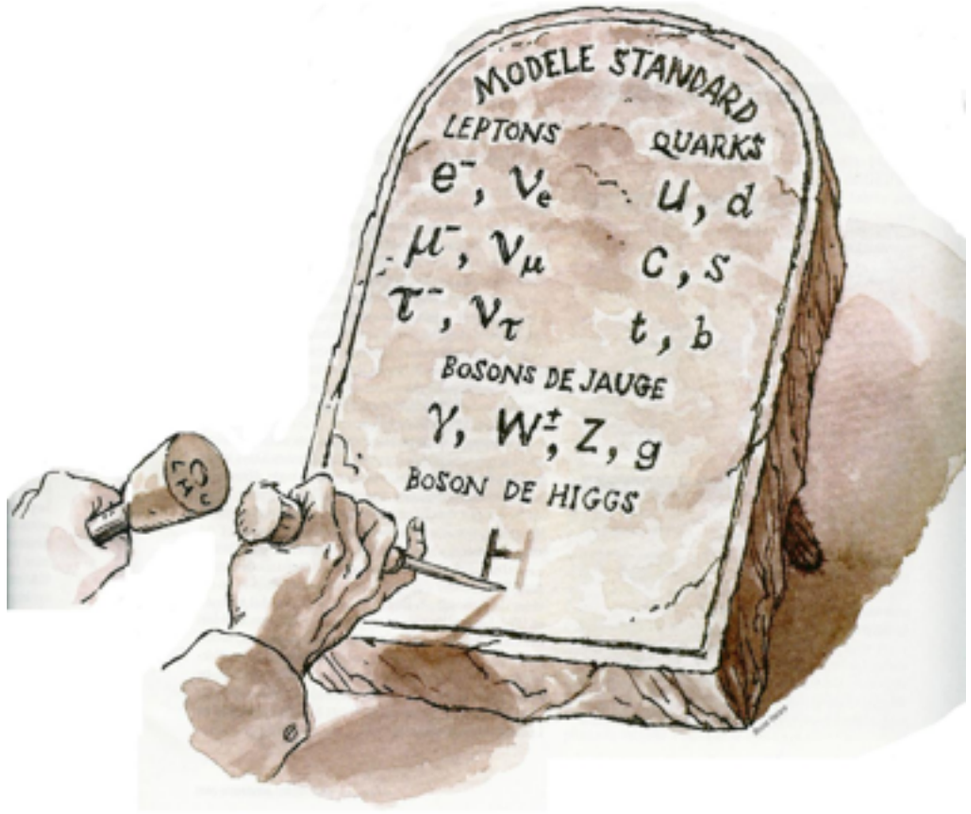
~ 70 billion inelastic collisions

Seven orders of magnitude

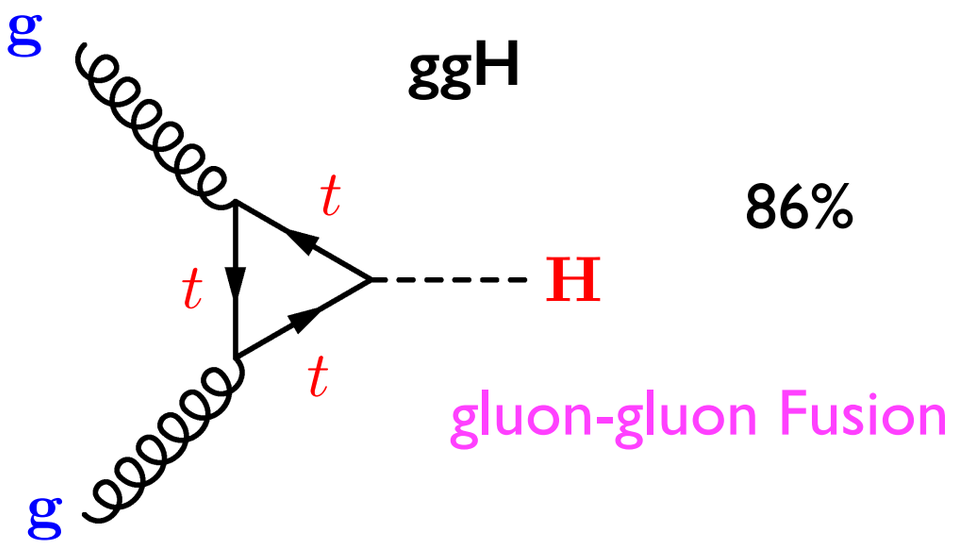


Higgs Physics



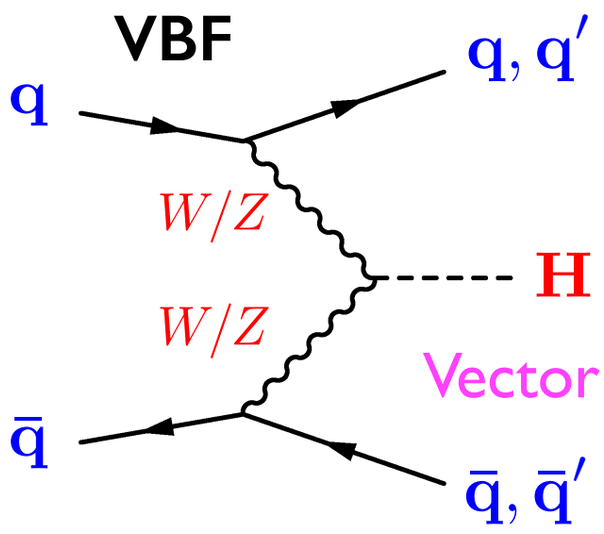


Production of the Higgs Boson



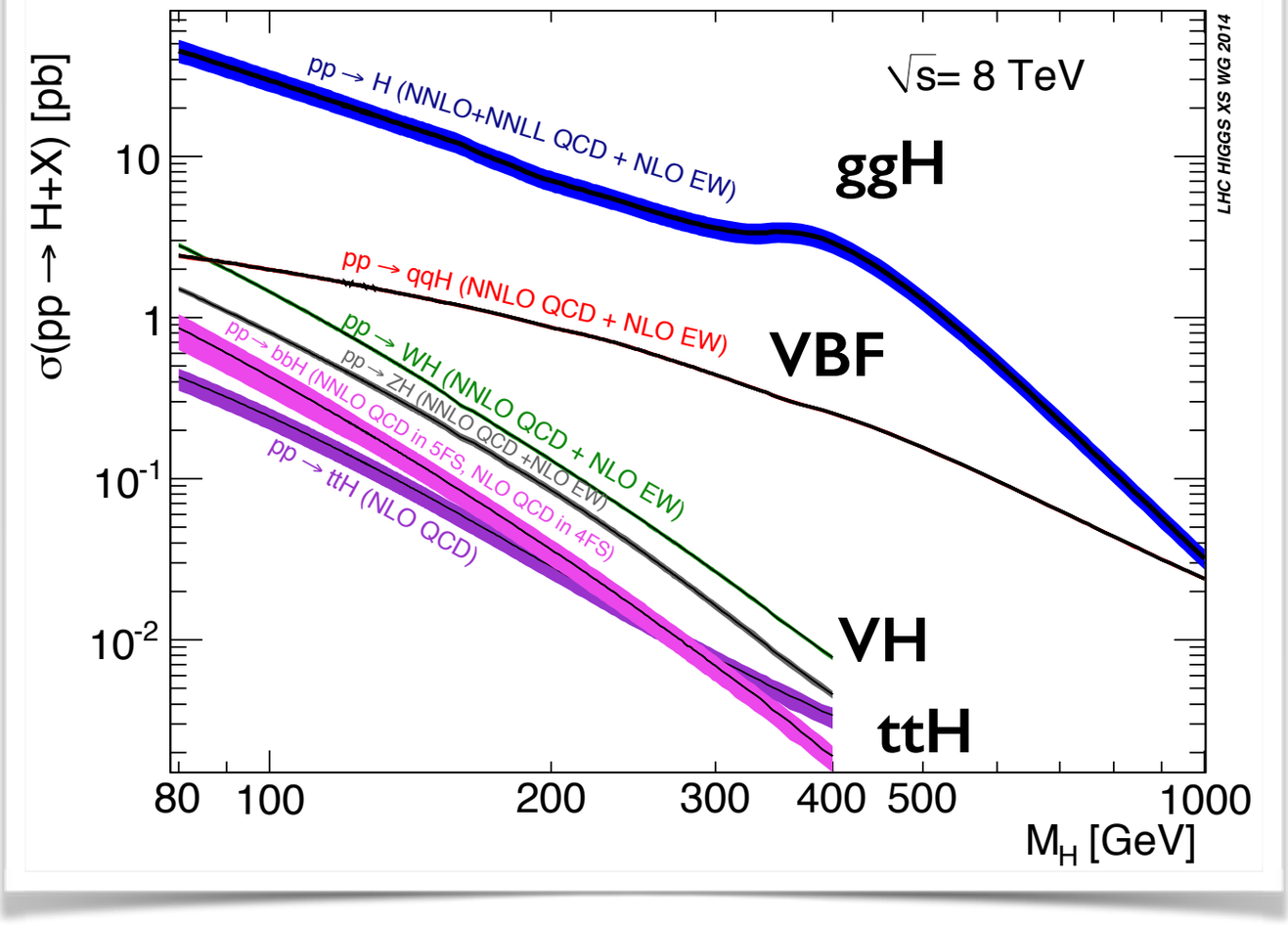
86%

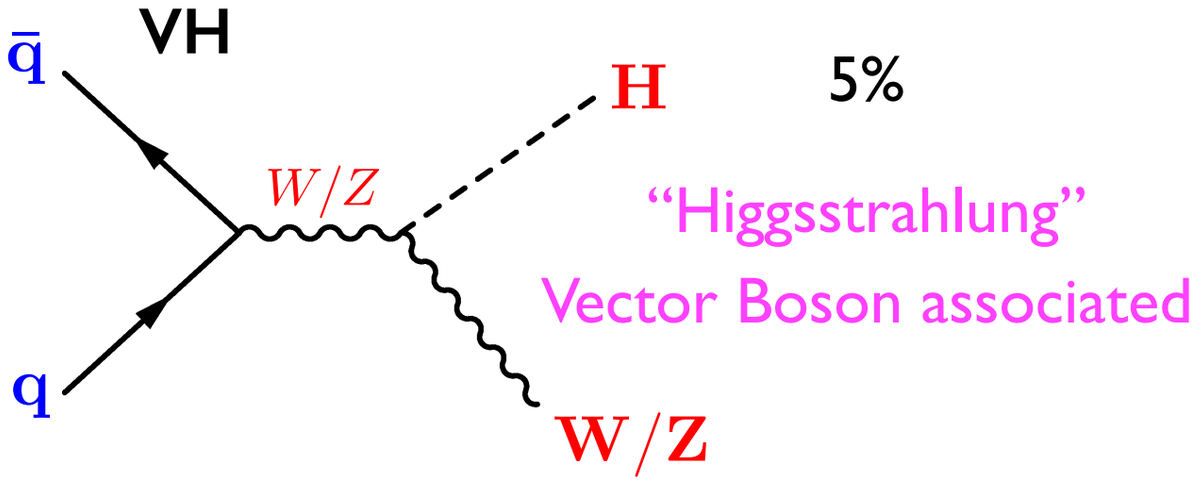
gluon-gluon Fusion



7%

Vector Boson Fusion

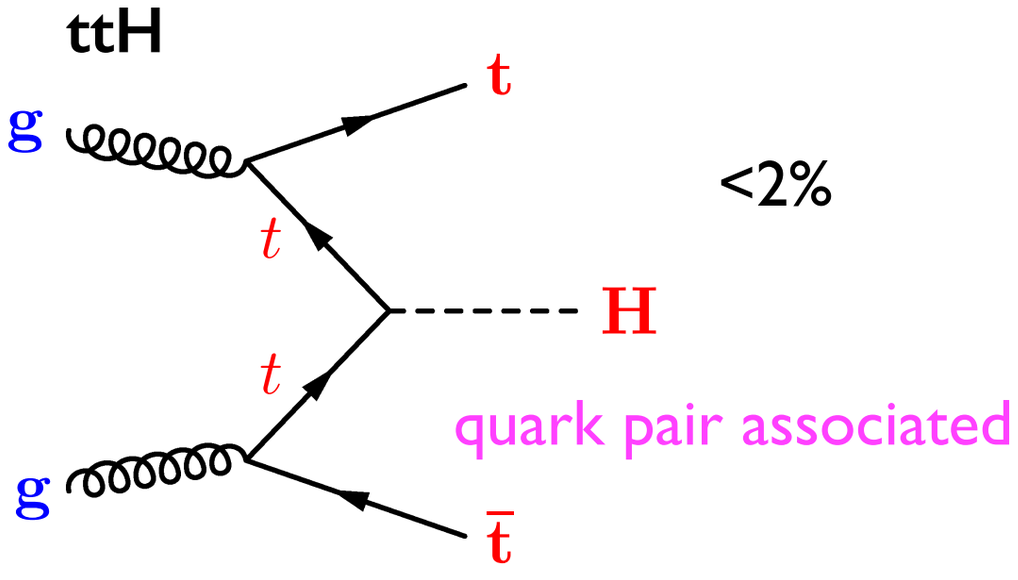




5%

"Higgsstrahlung"

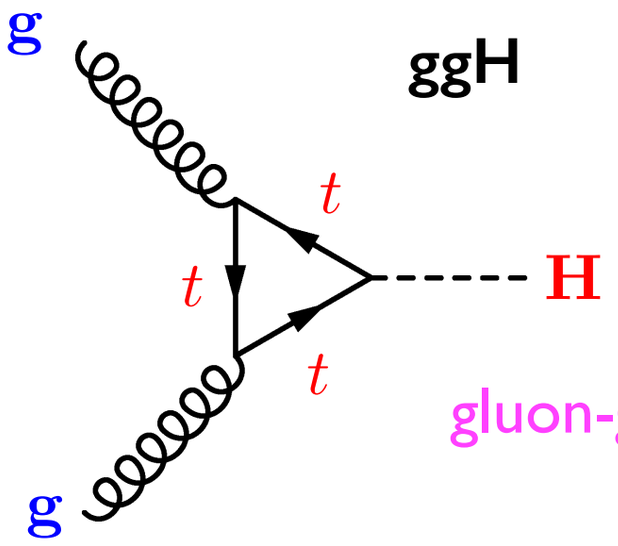
Vector Boson associated



<2%

quark pair associated

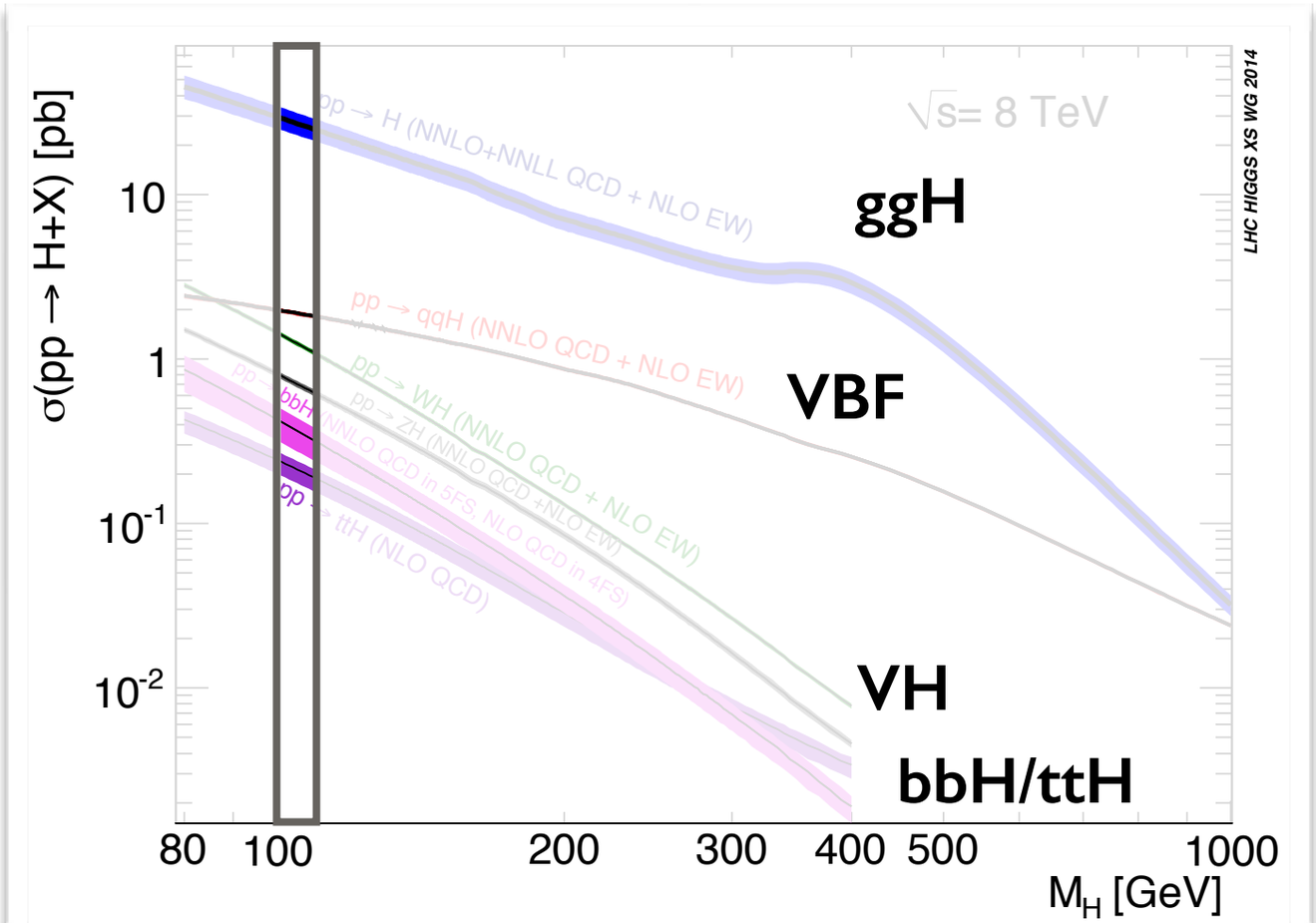
Production of the Higgs Boson



ggH

86%

gluon-gluon Fusion



Cross sections (m_H = 125 GeV)

- Tevatron 1.96 TeV

  1.2 pb

  ggH=78% VH=17% VBF=5%
- LHC 8 TeV

  23 pb

  ggH=86% VBF=7% VH=5% ttH<1%
- LHC 13 TeV

  51 pb

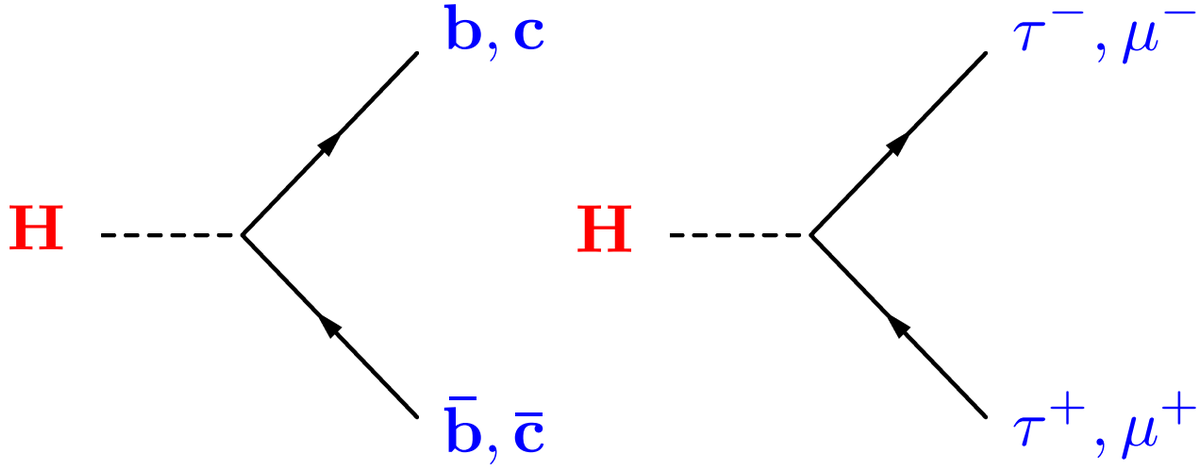
  ggH=86% VBF=7% VH=4% ttH=1%

Typical theory uncertainties

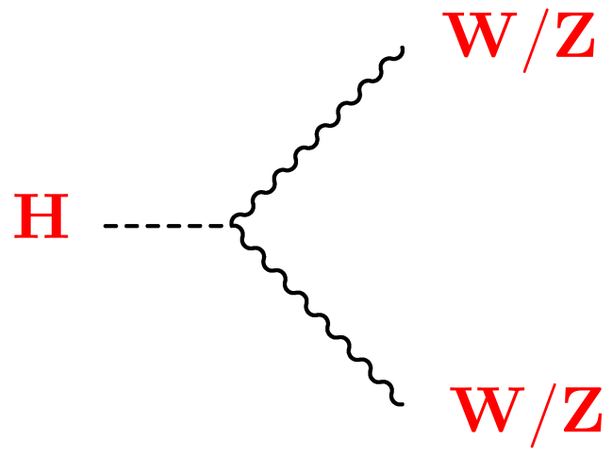
- ggH 15% NNnLO
- VBF 5% NLO
- VH 5% NNLO
- ttH 15% LO

Decays of the Higgs Boson

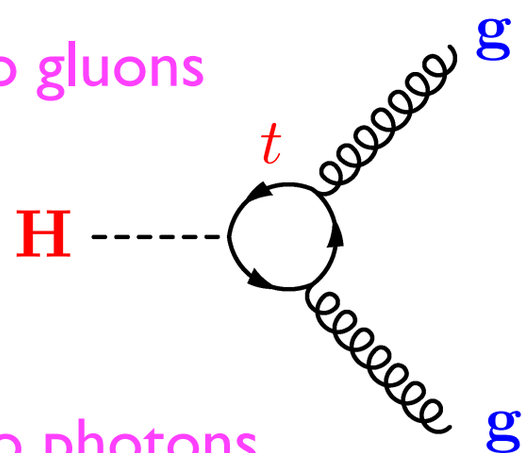
Decays to fermions (quarks and leptons)



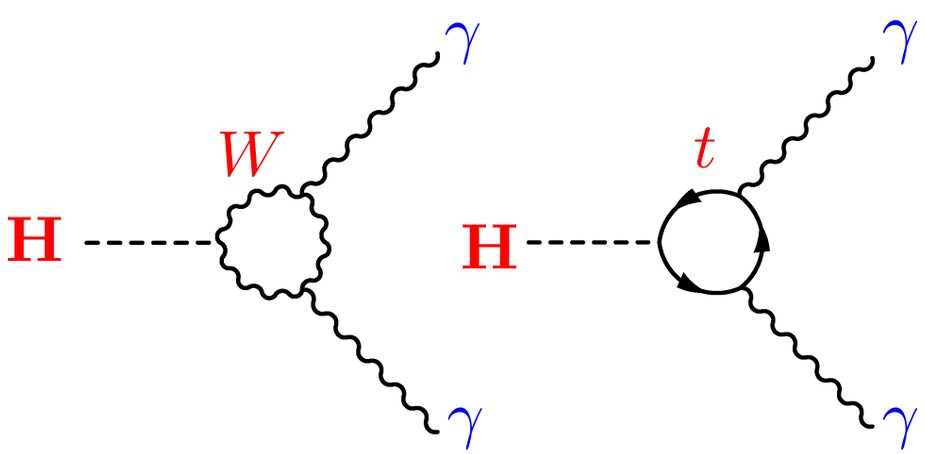
Decays to EW vector bosons

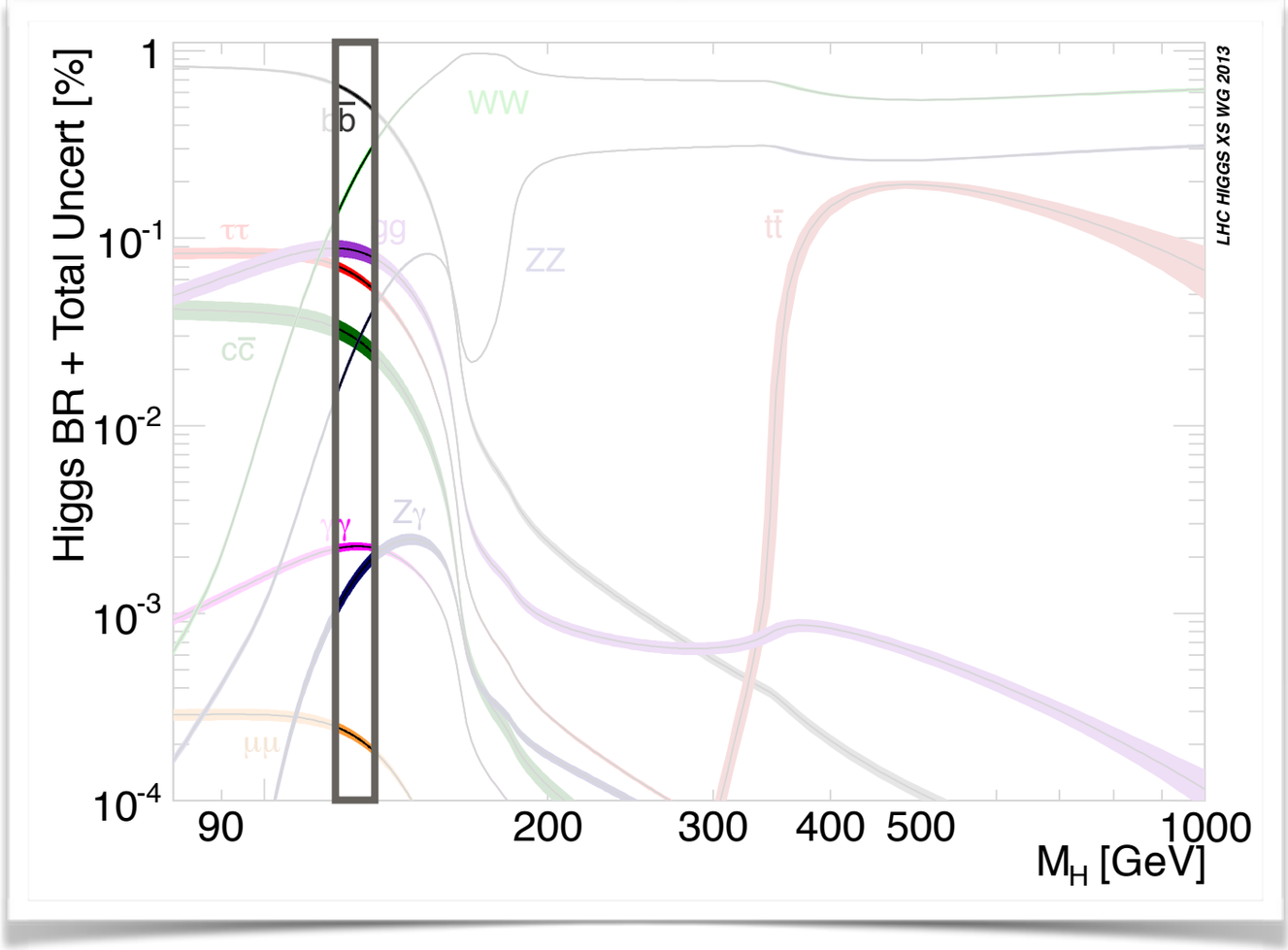


Decay to gluons

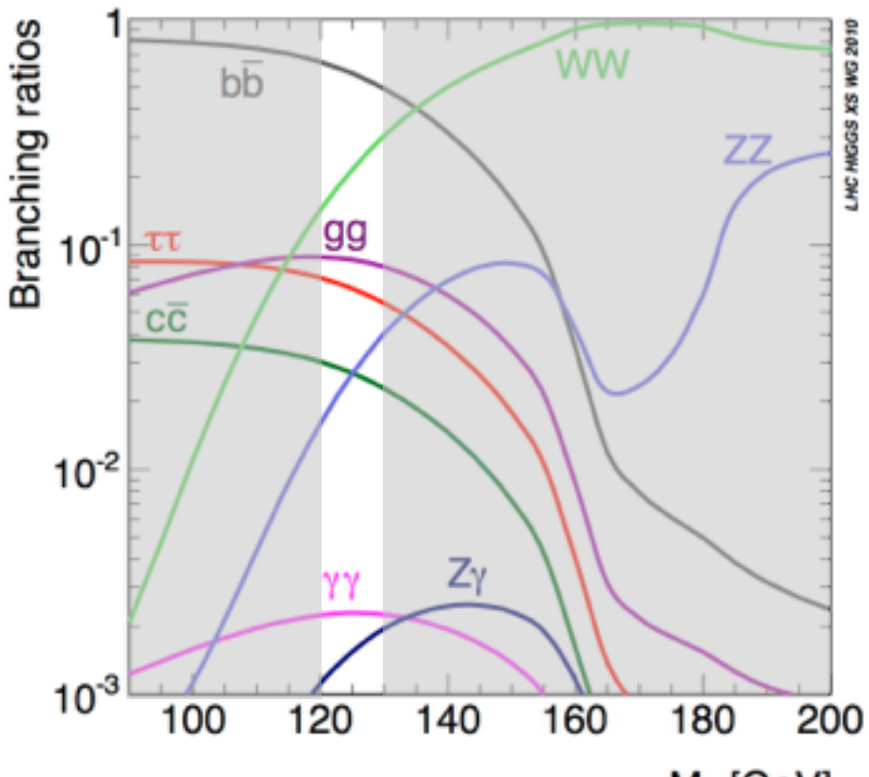


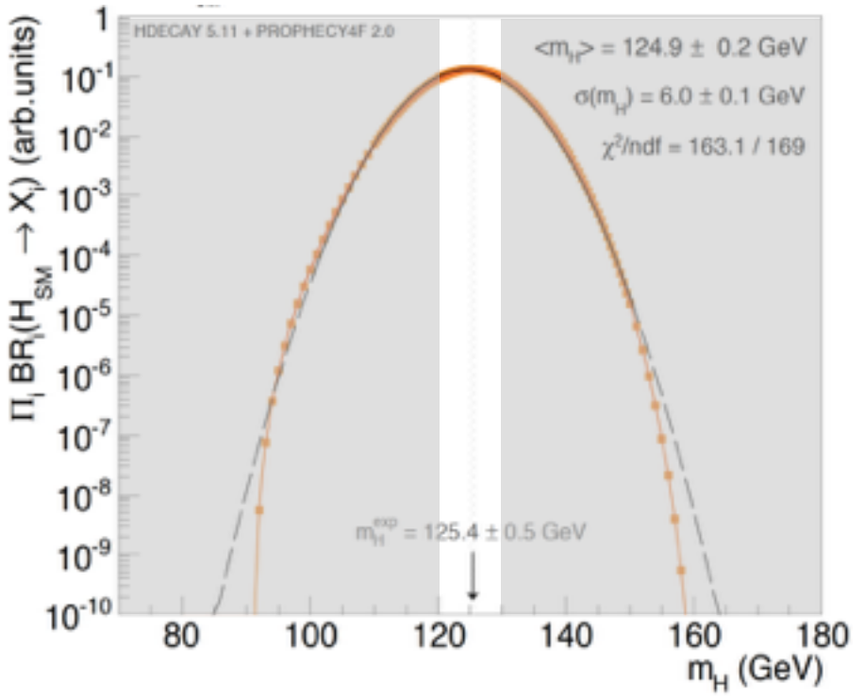
Decay to photons





Decays at m_H = 125 GeV



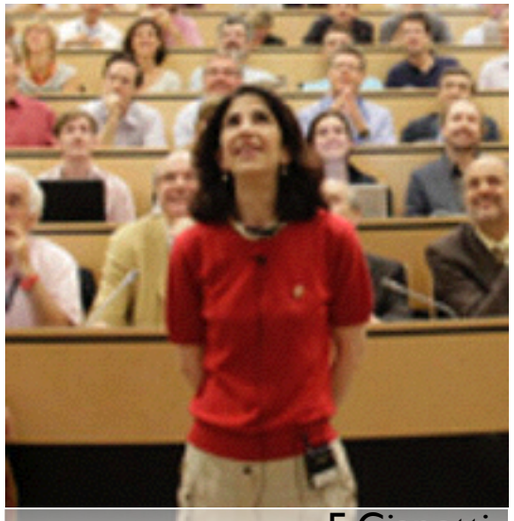


product of decay fractions

Decay Fractions as predicted for a 125 GeV Higgs boson mass

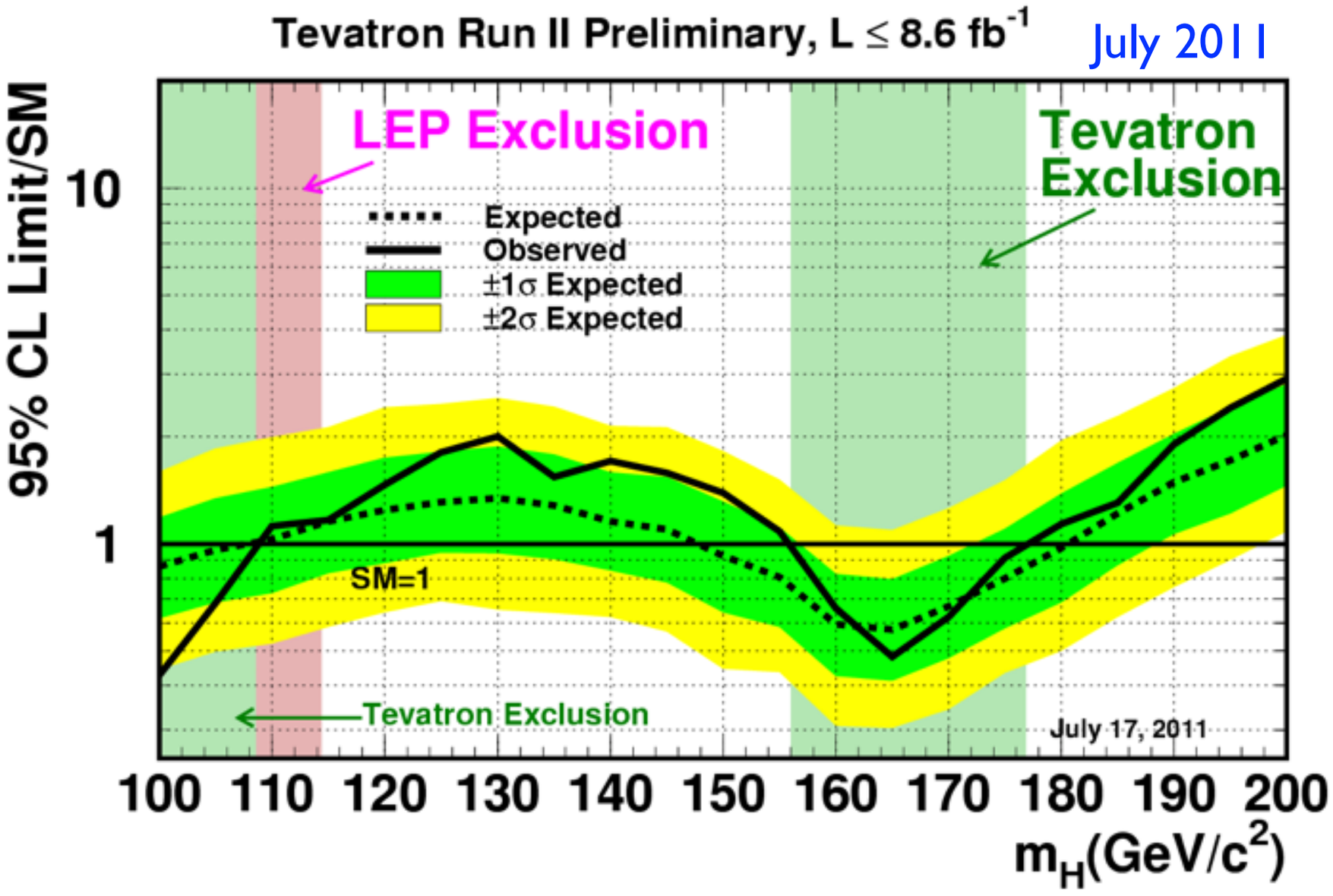
H → bb	58%
H → WW*	21%
H → τ+τ-	6.4%
H → ZZ*	2.7%
H → γγ	0.2%

Nature has be kind to us


F. Gianotti

only about 11% of Higgs bosons decays are unobservable

Direct Searches before LHC



95% CL exclusions

- LEP

$$m_H > 114 \text{ GeV}$$

- Tevatron

$$m_H \notin (156, 177) \text{ GeV}$$

To combine several channels, define the signal strength

$$\mu \equiv \sigma(\text{limit@95\%}CL)/\sigma_{\text{SM}}$$

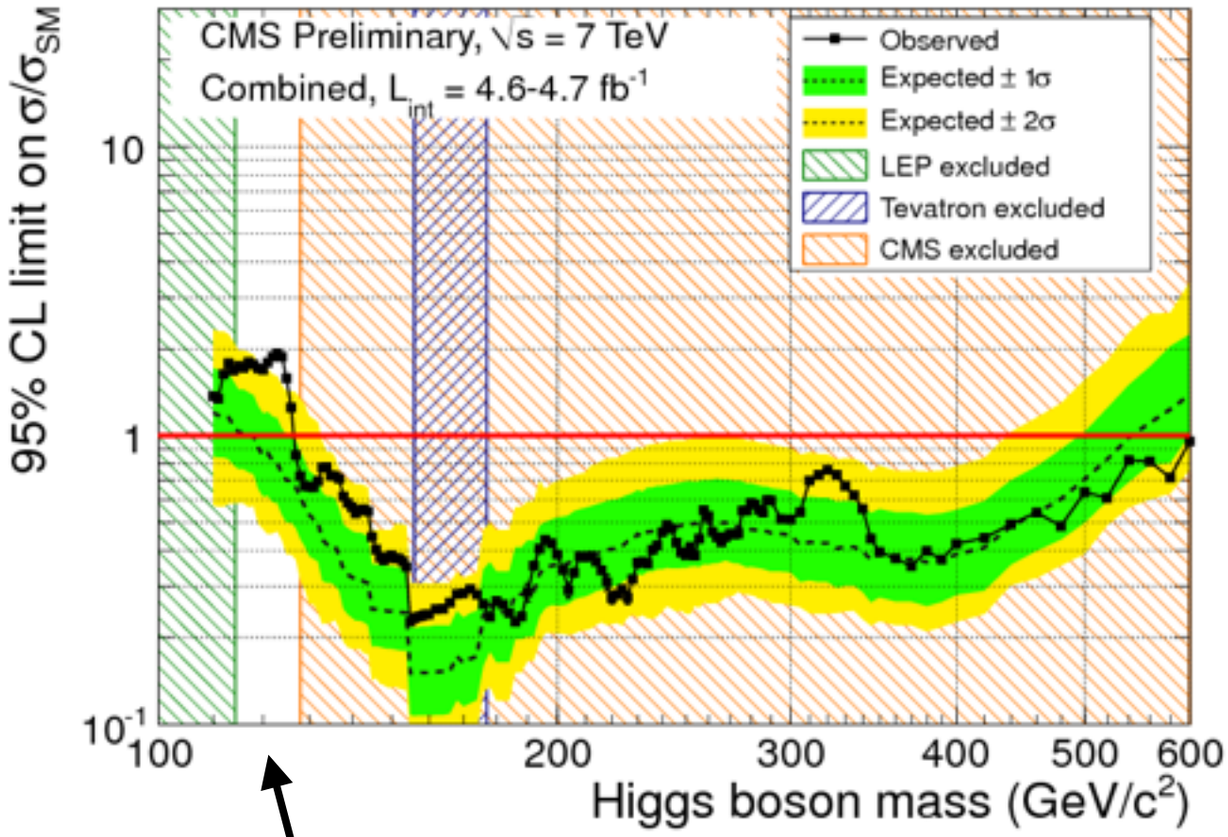
all channels multiplied by the same factor

(this introduces some level of model dependence)

Higgs Searches at the LHC

about 5 fb^{-1} / exp.

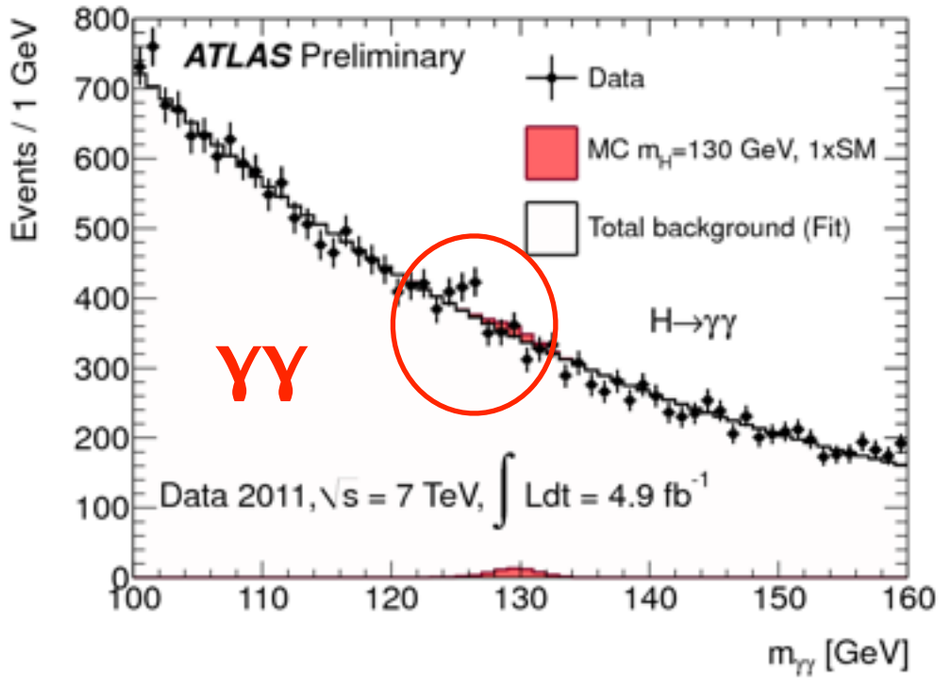
At the end of 2011 (CERN Jamboree)

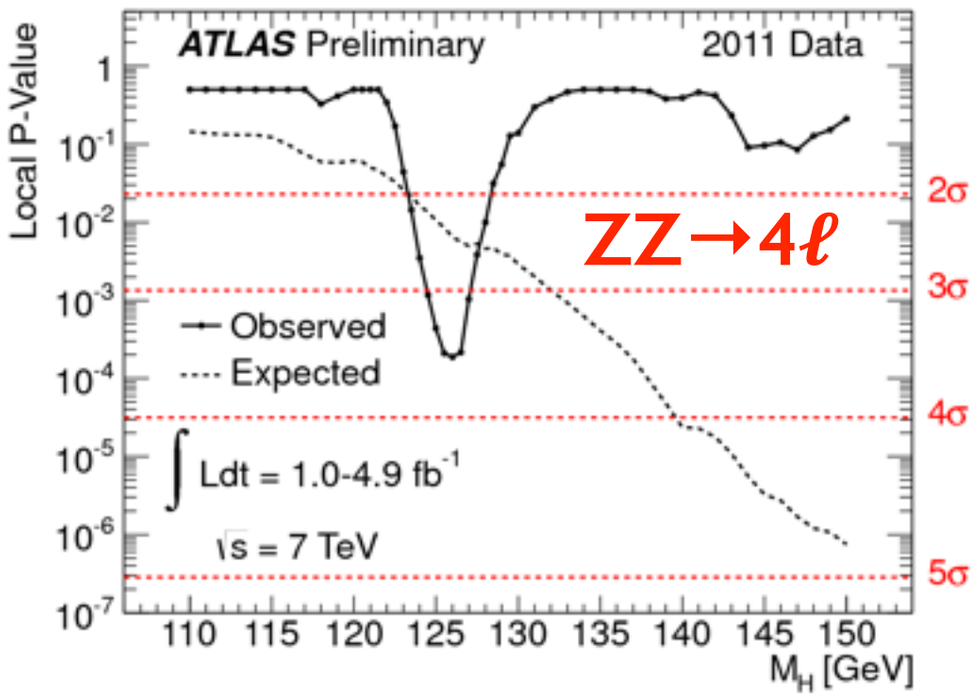


CMS: region non-excluded

$114 < m_H < 127$ GeV

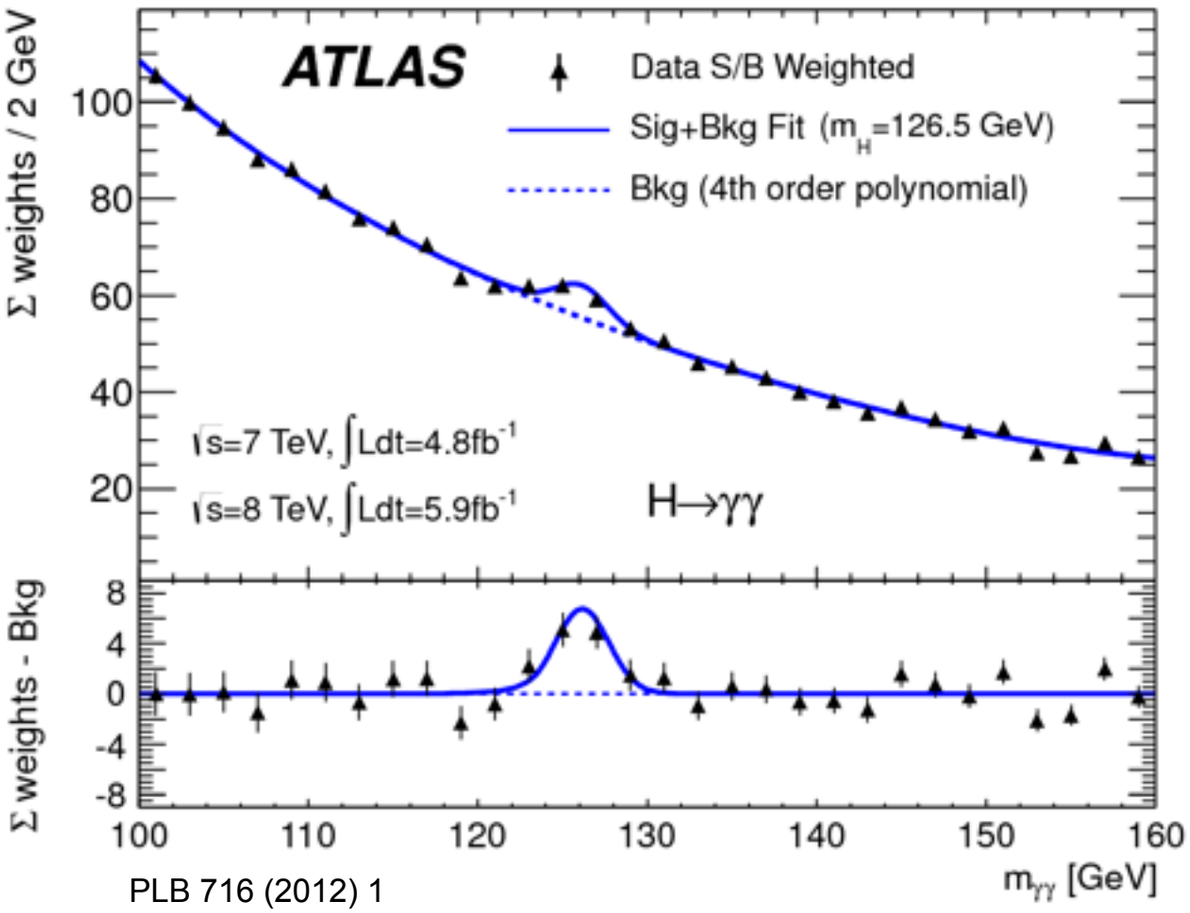
First hints of signal in ATLAS





CERN 4 July 2012

The Discovery

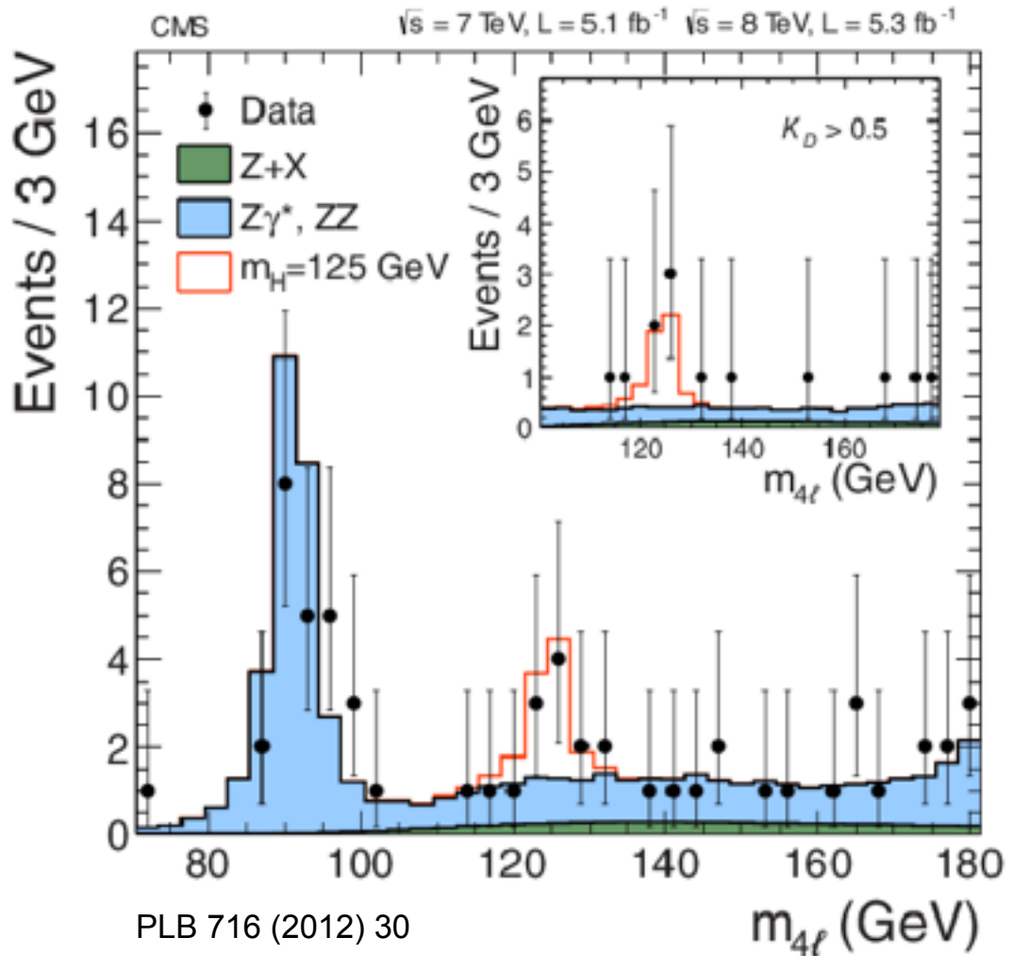


PLB 716 (2012) 1

m_H = 126.0 ± 0.4 (stat) ± 0.4 (syst) GeV

Combined significance: 5.9σ

Three decay mode WW, ZZ and γγ



PLB 716 (2012) 30

m_H = 125.3 ± 0.4 (stat) ± 0.5 (syst) GeV

Combined significance: 5.0σ

Five decay modes analysed but no significance signal in H → ττ and bb

Spécial
Festival d'Avignon

La 66e fête du théâtre démarre le 7 juillet

Supplément

Le M

Science : la matière

- Le boson de Higgs, particule manquante pour expliquer l
- Les physiciens du CERN de Genève ont prouvé son existe

Volume 716, Issue 1, 17 September 2012 ISSN 0370-2693

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PHYSICS LETTERS B

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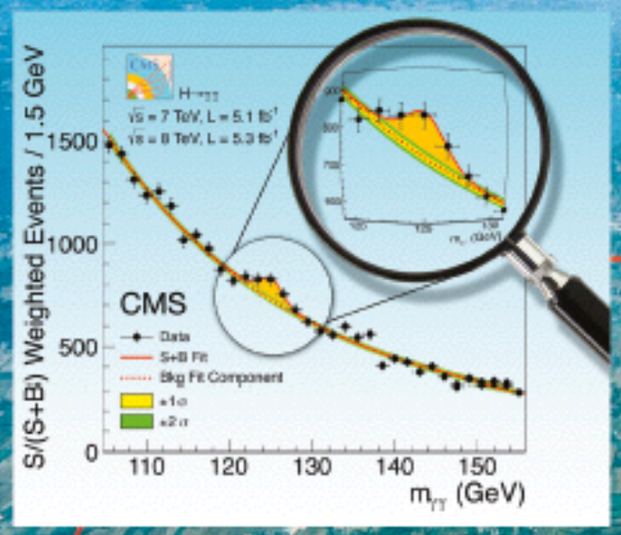
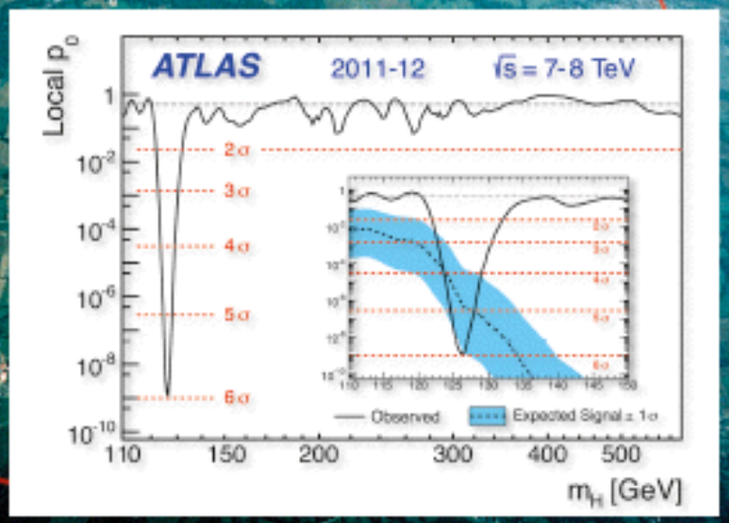




Les prom
sante.lef

Les capteu
pour la r
le nou

TRISTAN VEY

PHYSIQUE Au term
tations historiques
tin au Cern *, à Gen
l'organisation, Rolf
vers l'auditoire, un
lèvres : « *Je pense q*
que vous en dites ? »
clameur et un tonne
ments, les dizaines
nis dans la salle lâchent un vibrant :
« Yes ! » L'explosion de joie est à la
mesure de la découverte, l'une des
nes à tout écouter. Mais aussi, *nous n'avons pu enregistrer que 40 ans de musique en choisissant soigneusement les morceaux qui nous paraîs-*

jeudi 5 juillet 2012

es 11

Rolf Heuer (2e à droite) lors d'une présentation, mercredi, à des dizaines de physiciens au Cern, à Genève. DENIS BALIBOUSE/REUTERS

LHC: Production and Decay

Not an exhaustive table!

★ "seen" ☆ "tried"	H→bb	H→ττ	H→WW	H→ZZ	H→γγ	H→inv.	H→μμ
ggH		★	★	★	★		☆
VBF	☆	★	★	☆	★	☆	☆
VH	★	☆	☆	☆	☆	☆	
ttH	☆	☆	☆		☆		
	$\sigma(m_{bb})$ ~20%	$\sigma(m_{\tau\tau})$ 10-20%	$\sigma(m_{WW})$ ~16%	**$\sigma(m_{ZZ})$** **1-2%**	**$\sigma(m_{\gamma\gamma})$** **1-2%**		

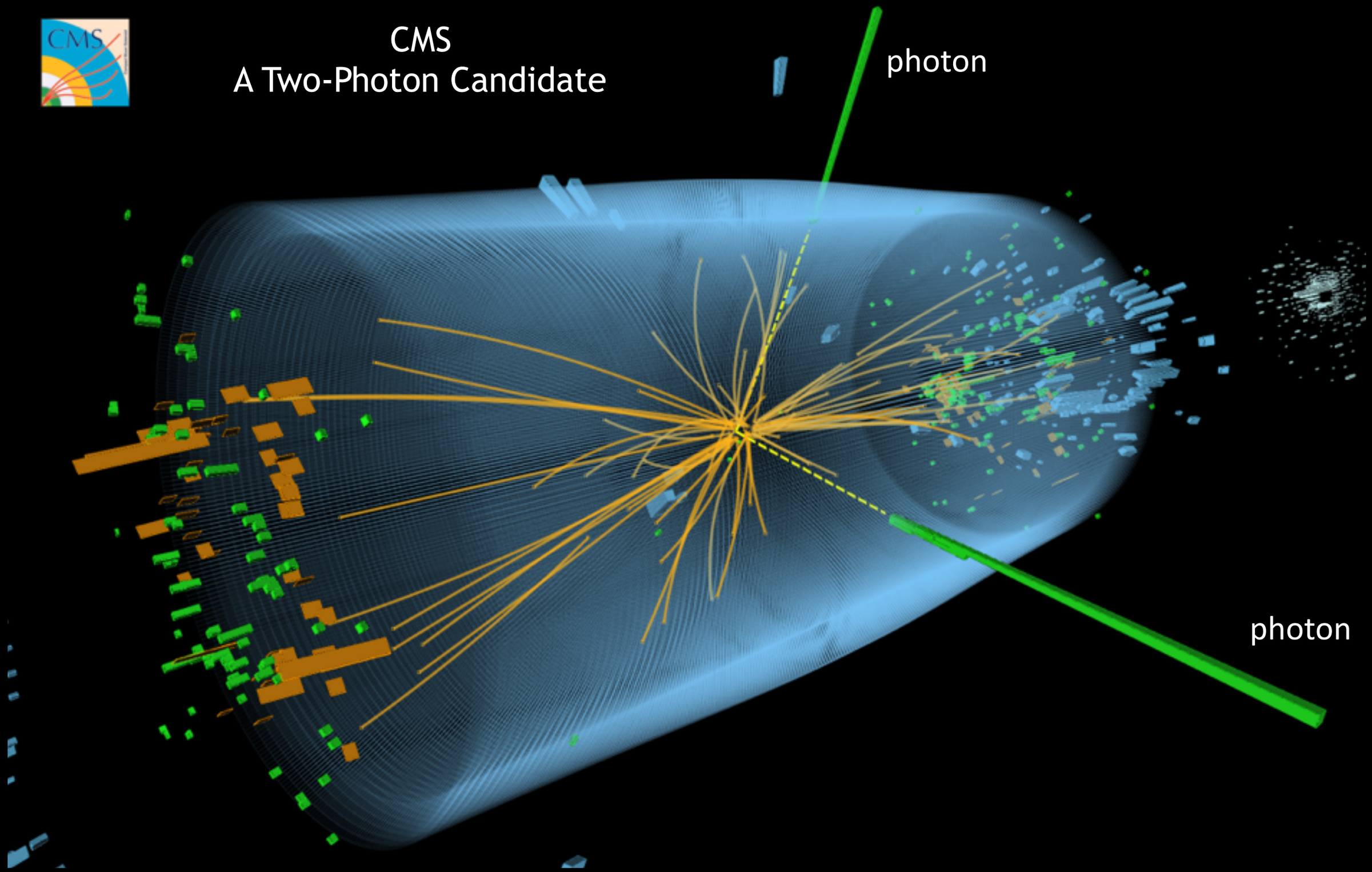
courtesy André David

Run-1 (25 fb^{-1} at 7 and 8 TeV):
Approximate number of Higgs boson decays before selection cuts (m_H = 125 GeV)

- 9,000 H ⇢ WW* ⇢ $\ell\nu\ell\nu$
- 900 H ⇢ γγ
- 60 H ⇢ ZZ* ⇢ 4ℓ

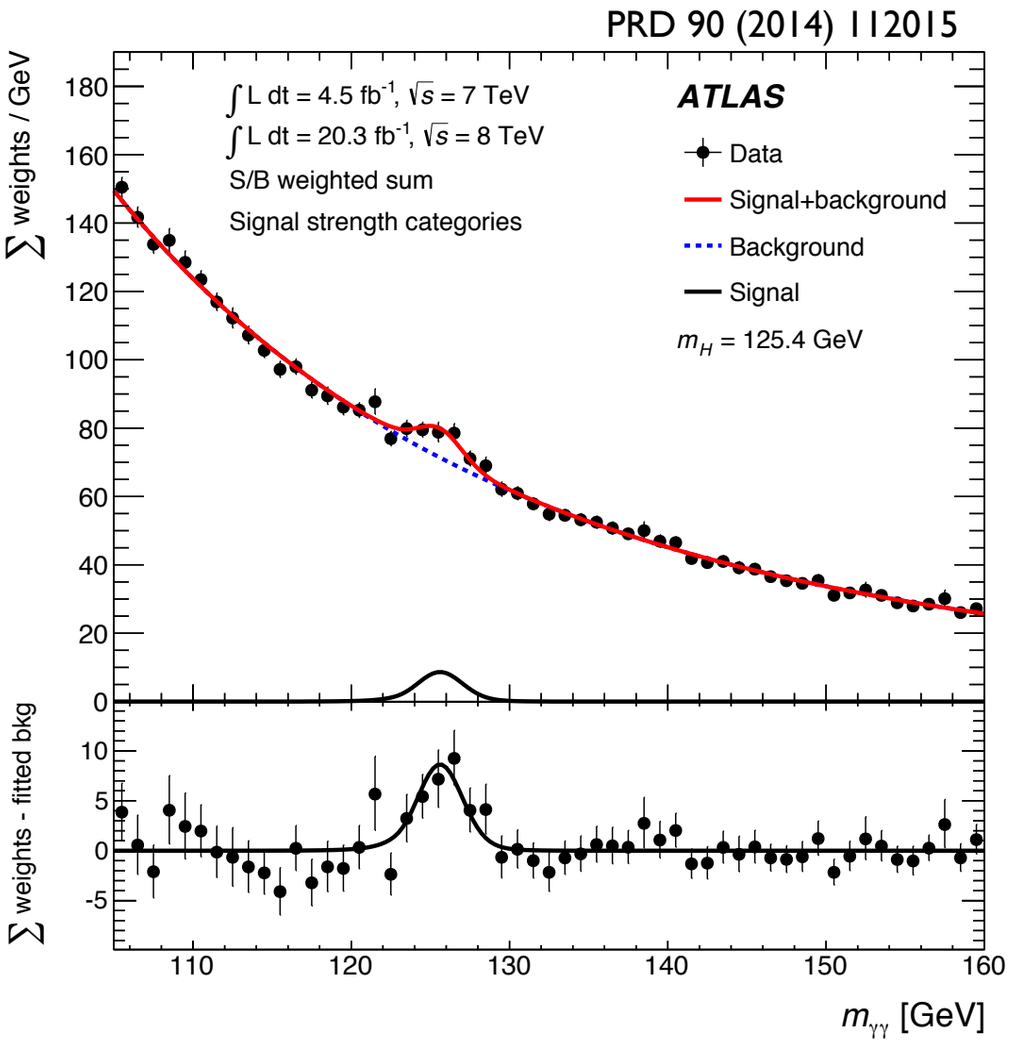
Two-Photon Final State

CMS
A Two-Photon Candidate



Two-Photon Decay

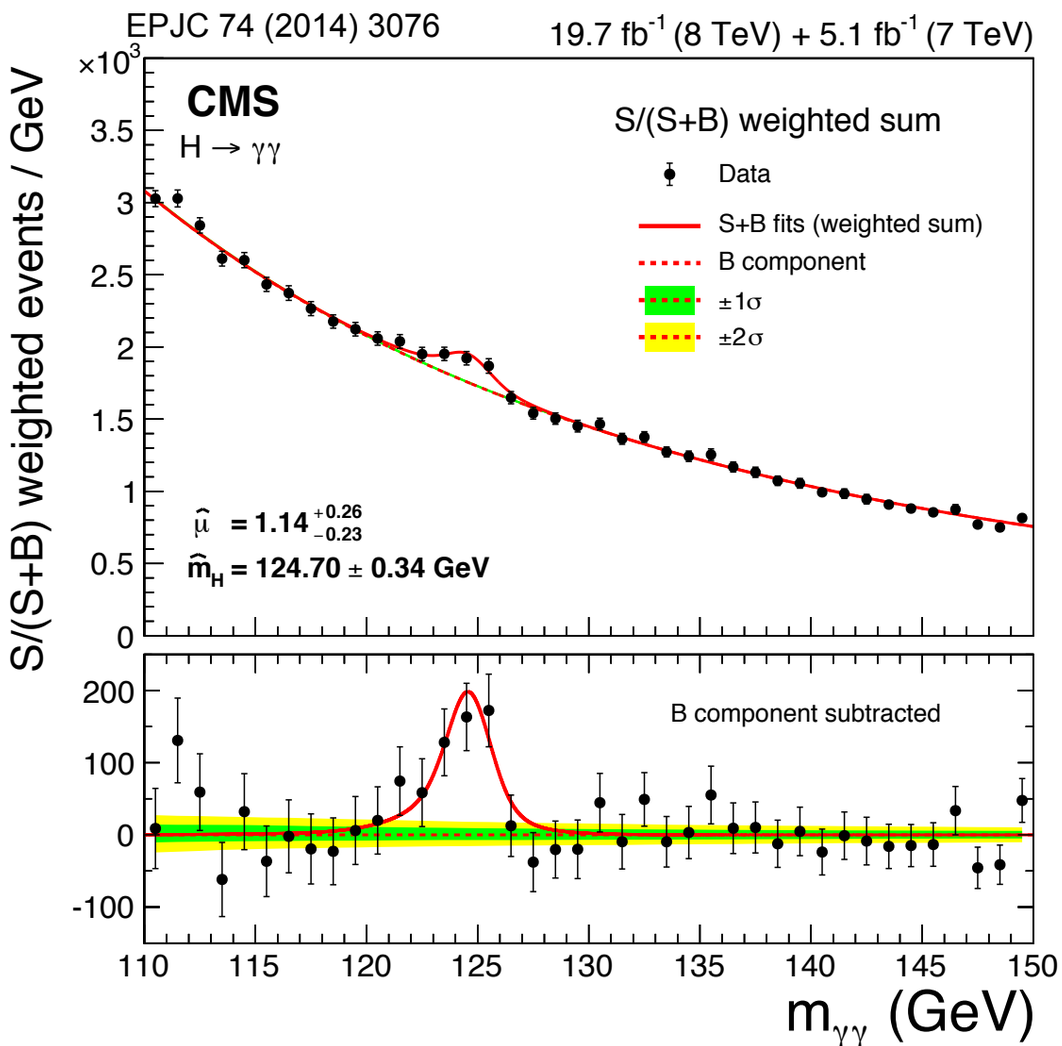
ATLAS



Significance
- observed : 5.2 **σ**
- expected: 4.6σ

m_H = 126.02 ± 0.43 (stat) ± 0.27 (syst) GeV

CMS

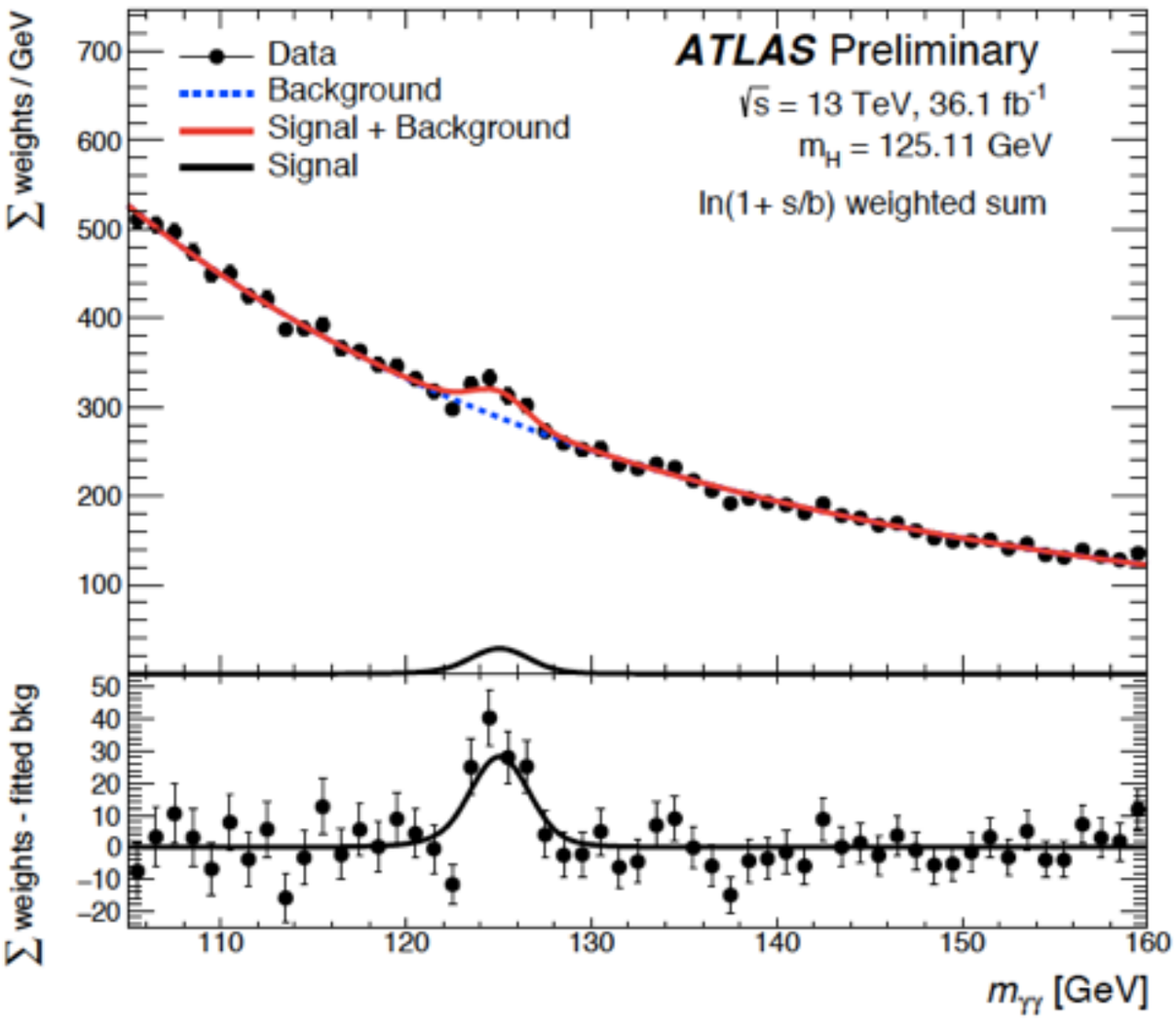


Significance
- observed : 5.7 **σ**
- expected: 5.2σ

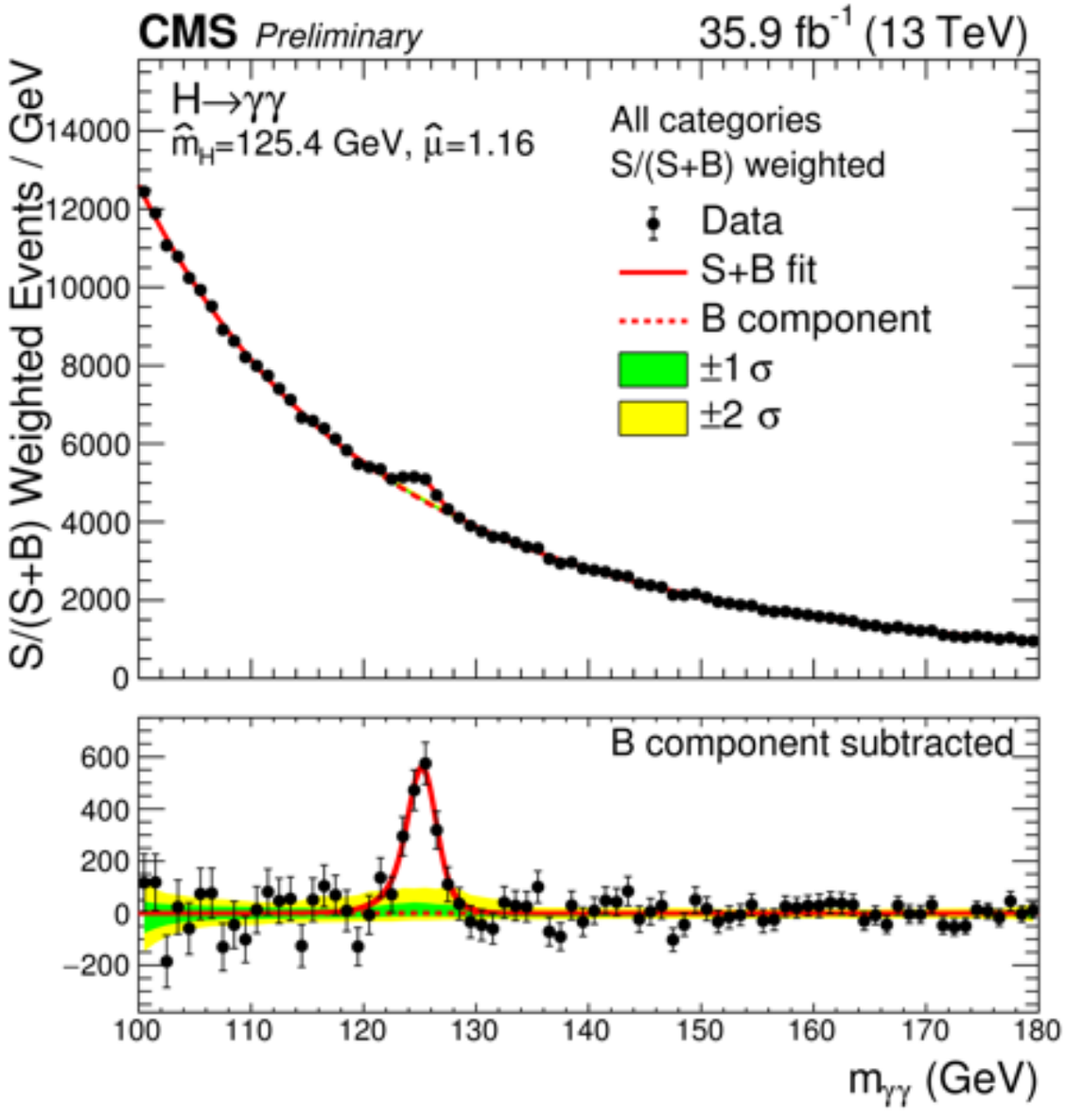
m_H = 124.70 ± 0.31 (stat) ± 0.15 (syst) GeV

Two-Photon Decay: Run-2

ATLAS



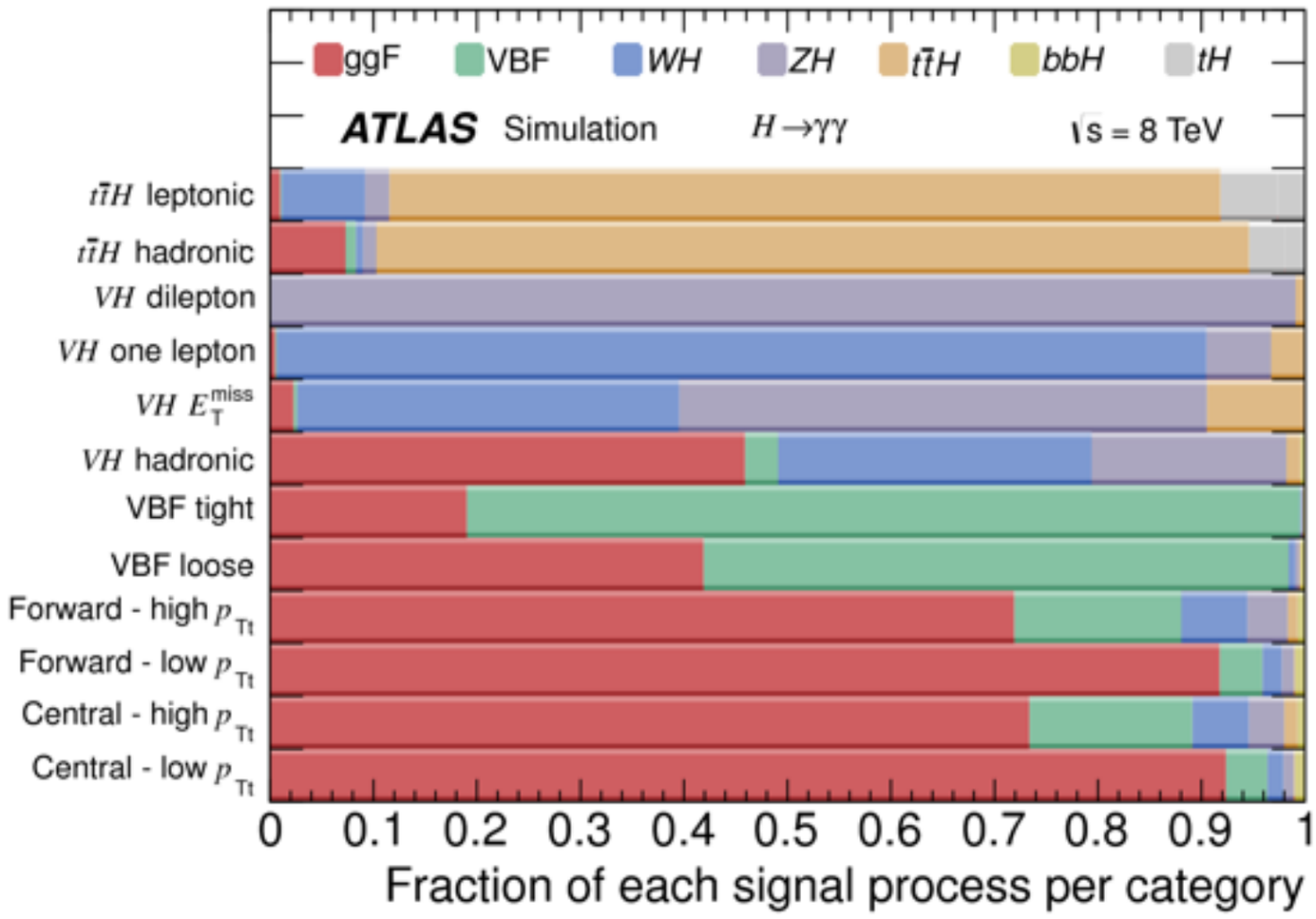
CMS

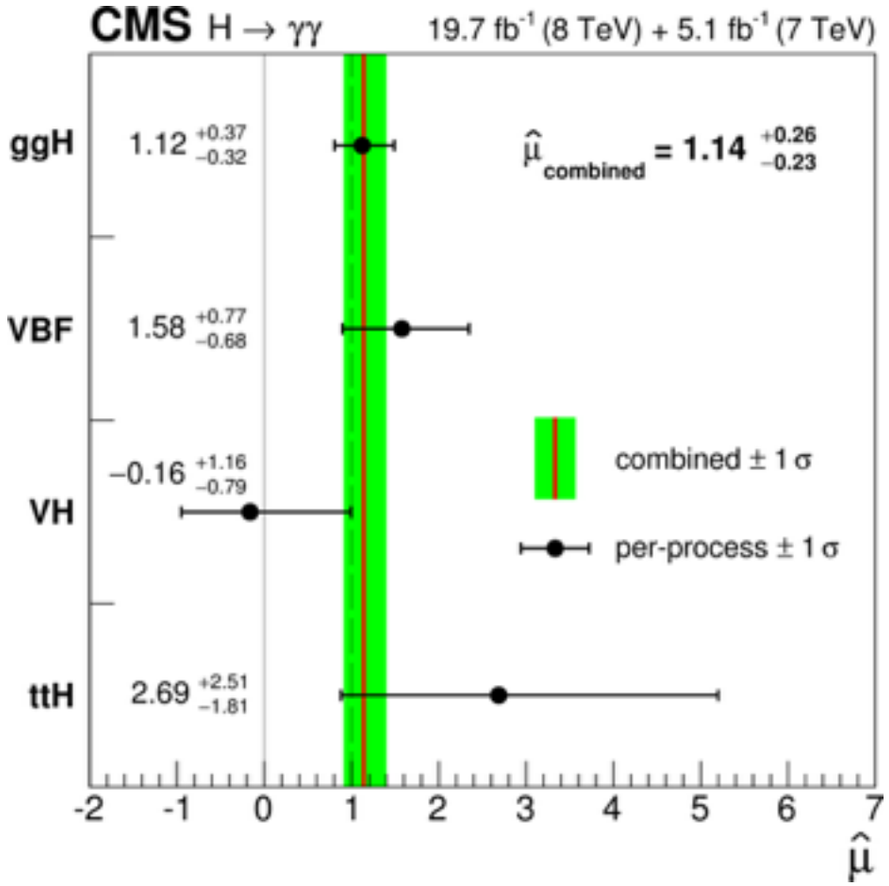


presented at the EPS 2017 Conference

Two-Photon: Categorisation

Categorisation to increase the overall sensitivity and the sensitivity to different production modes

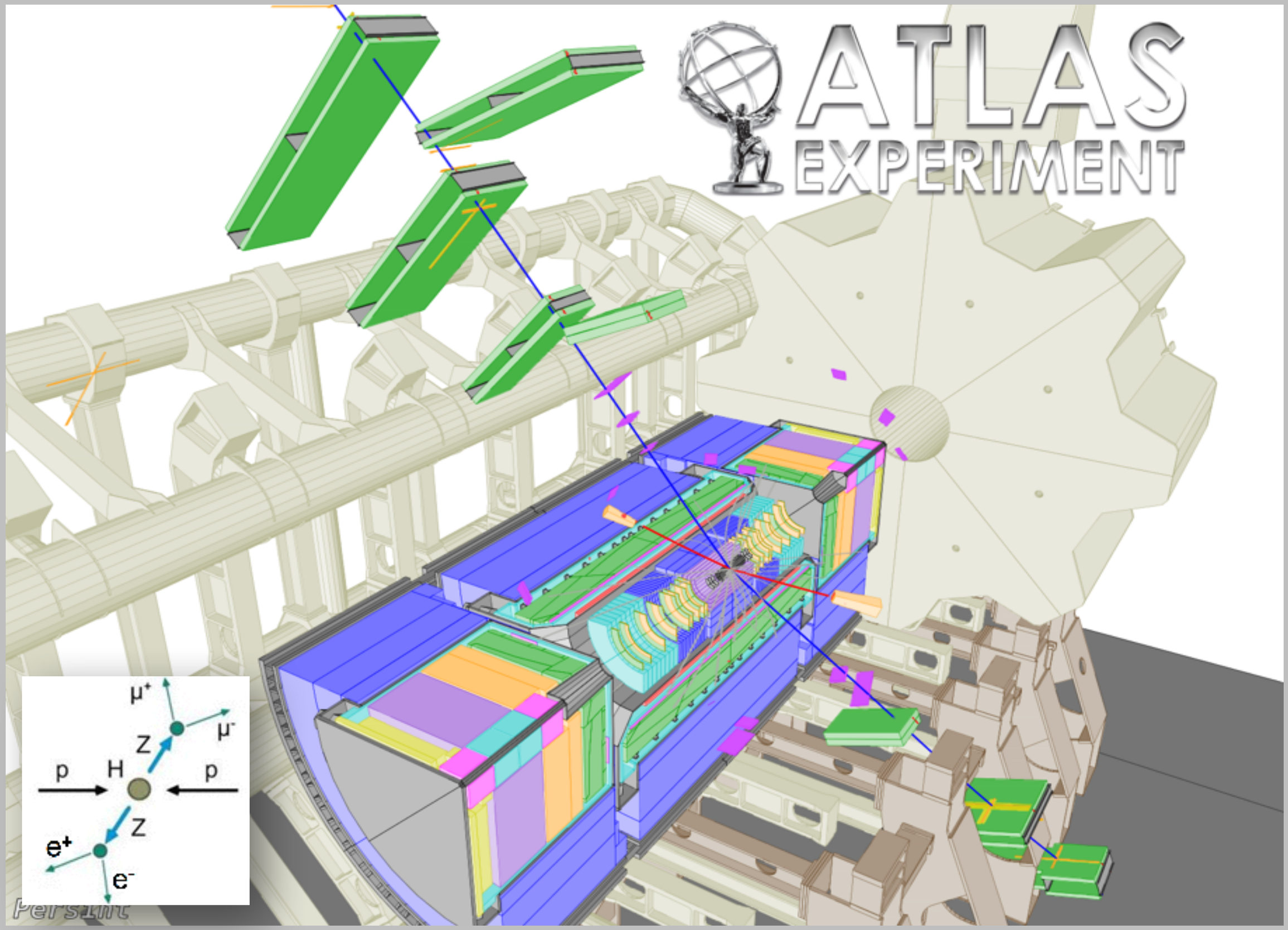




Individual production modes are consistent with SM expectations

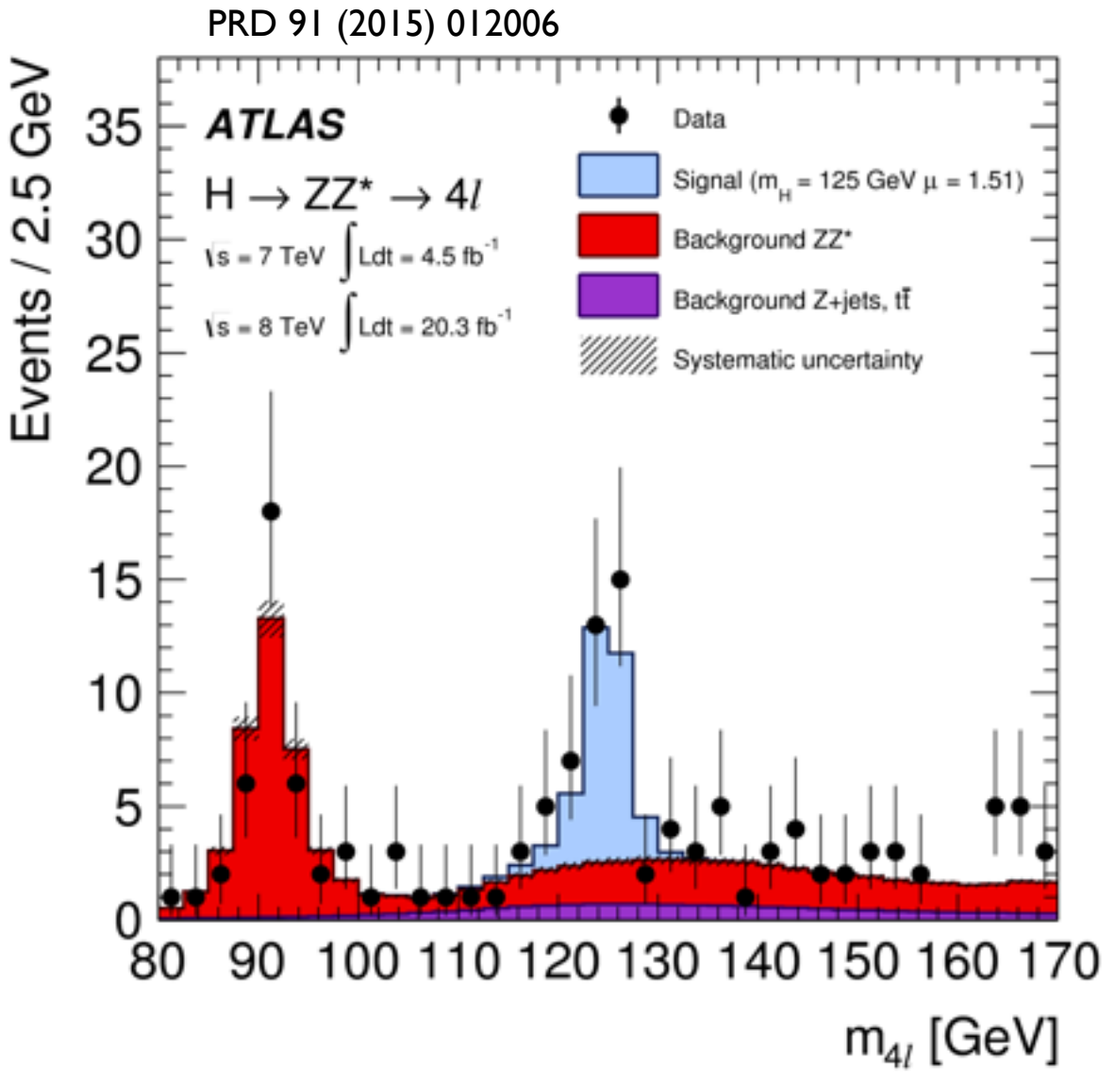
- ggH established
- evidence for VBF

Four-Lepton Mode



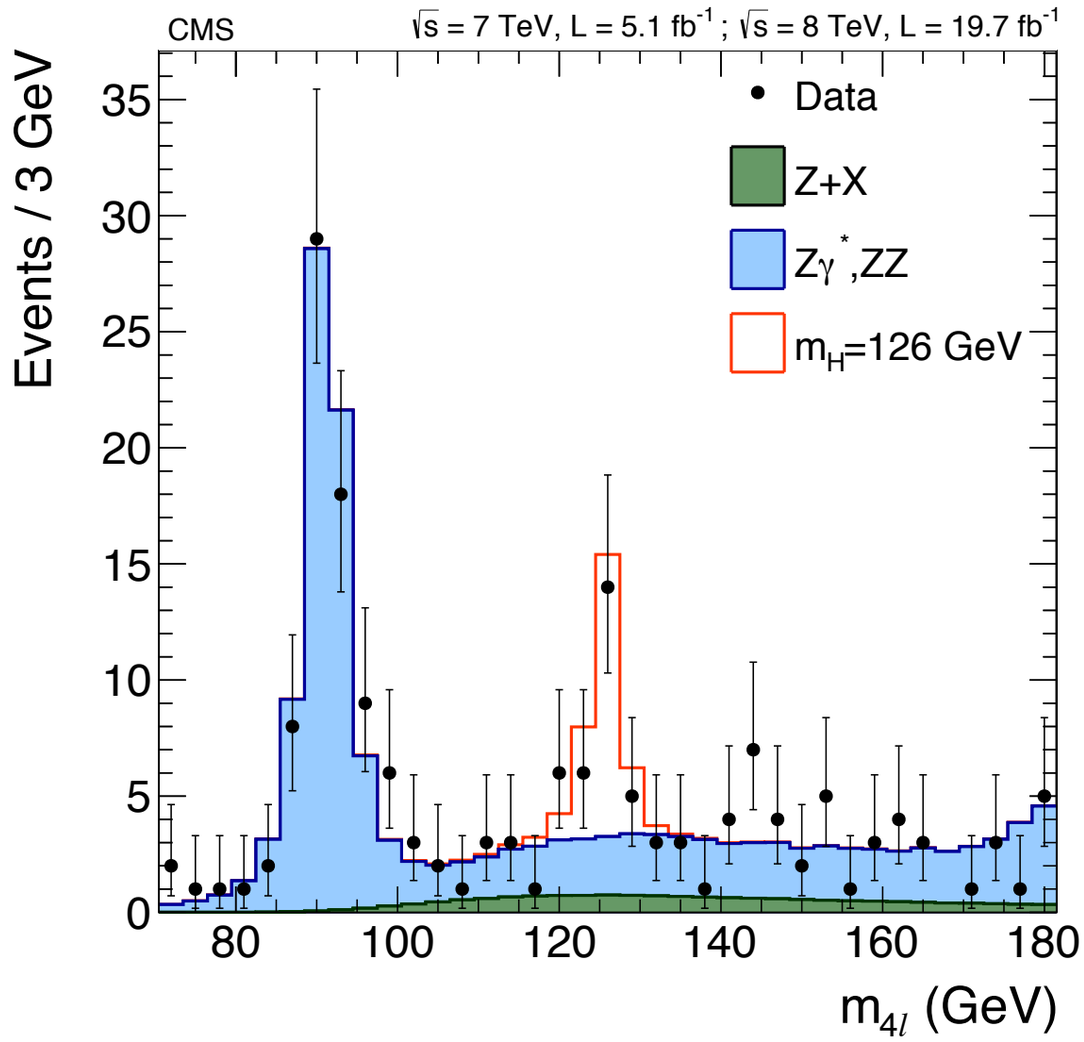
Four-Lepton Decay

ATLAS



m_H = 124.51 ± 0.52 (stat) ± 0.04 (syst) GeV

CMS

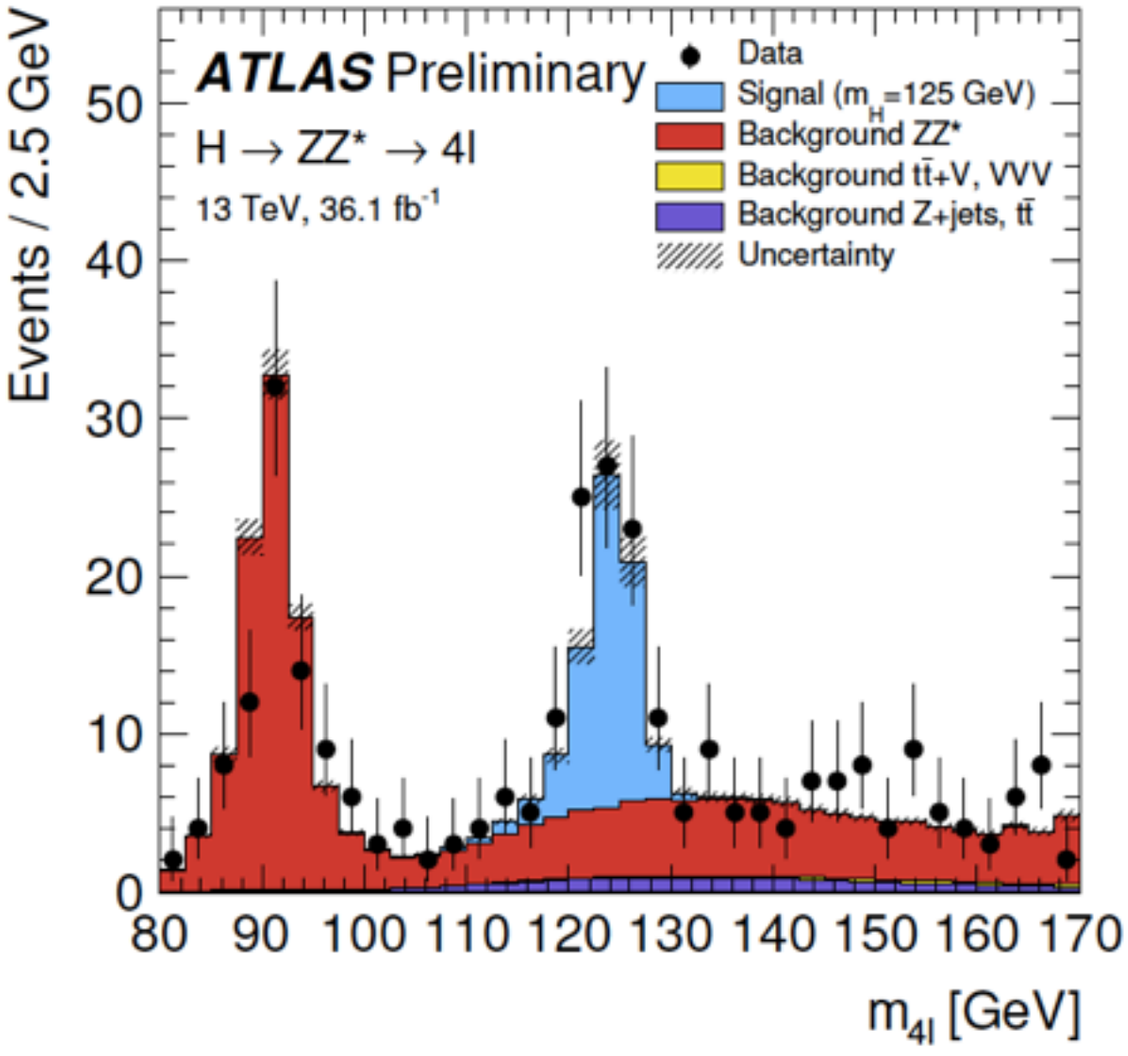


m_H = 125.59 ± 0.45 (stat) ± 0.17 (syst) GeV

Both experiments observe signals with > 6σ

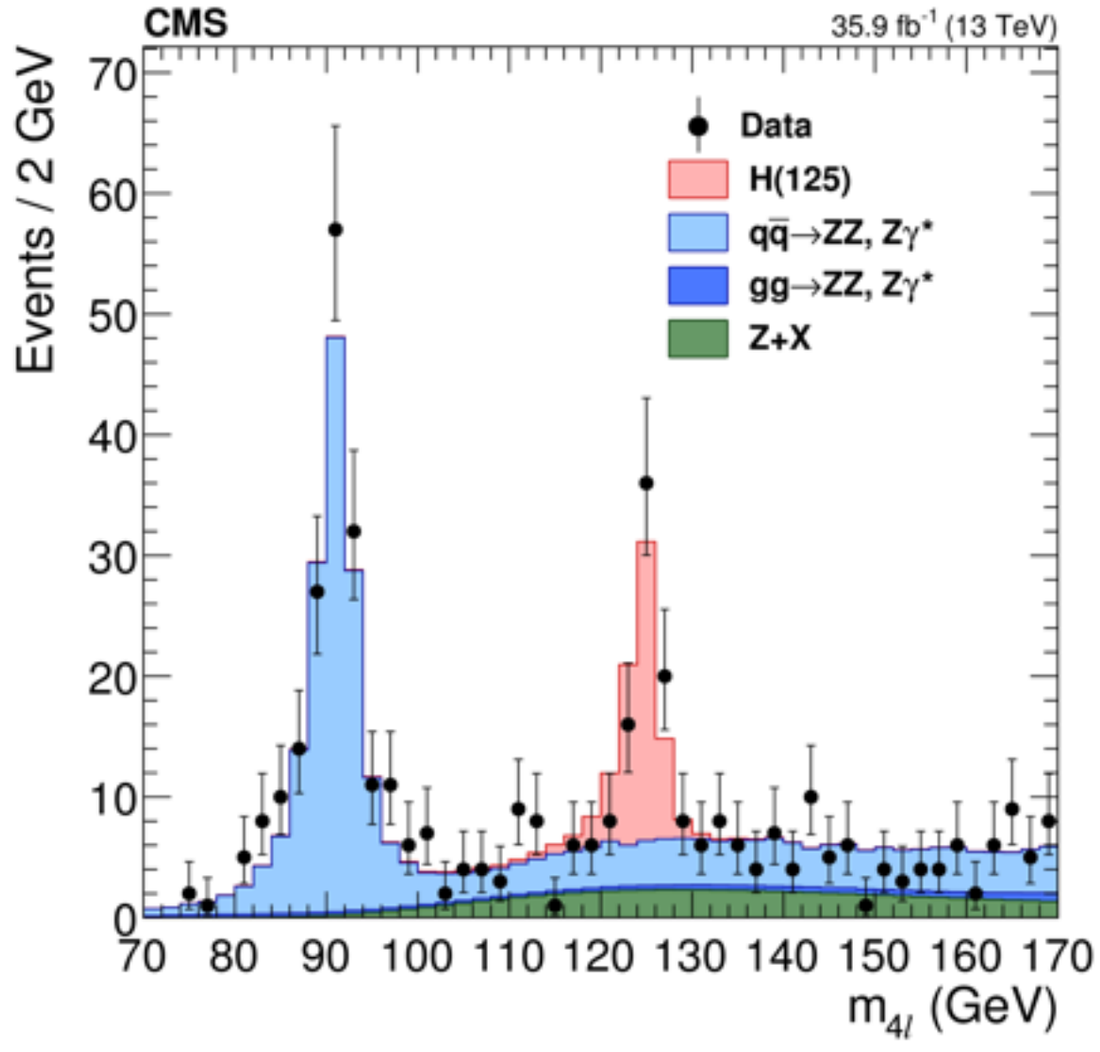
Four-Lepton Decay: Run-2

ATLAS



Full 2016 dataset at 13 TeV

CMS

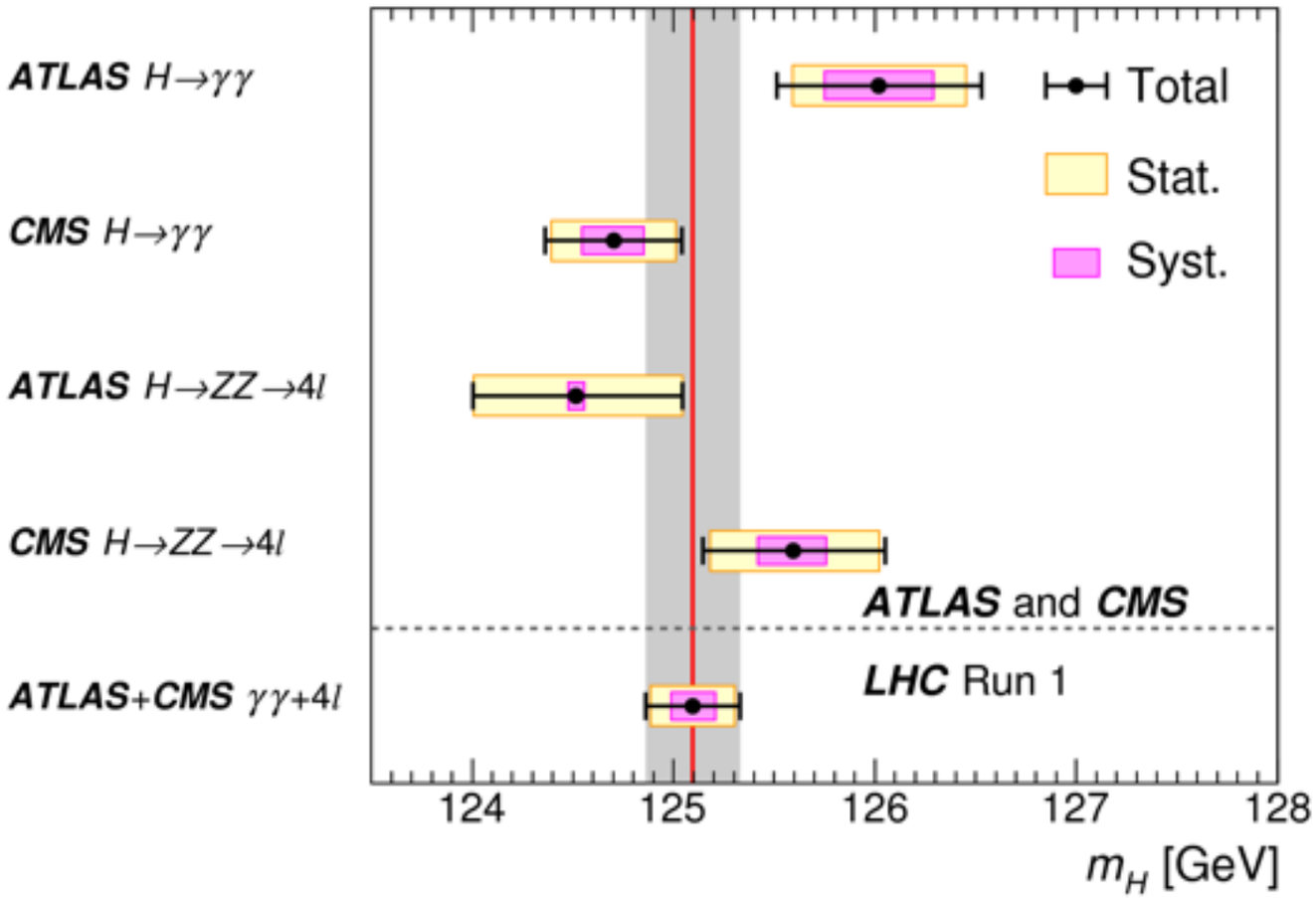


m_H = 125.26 ± 0.20 (stat) ± 0.08 (syst) GeV

HIG-16-041 Submitted to JHEP

presented at the EPS 2017 Conference

Mass of the Higgs Boson



Combined fit to ATLAS and CMS data

in γγ and ZZ→4ℓ channels

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$
$$= 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst)} \text{ GeV}$$

2‰ accuracy on the Higgs boson mass!

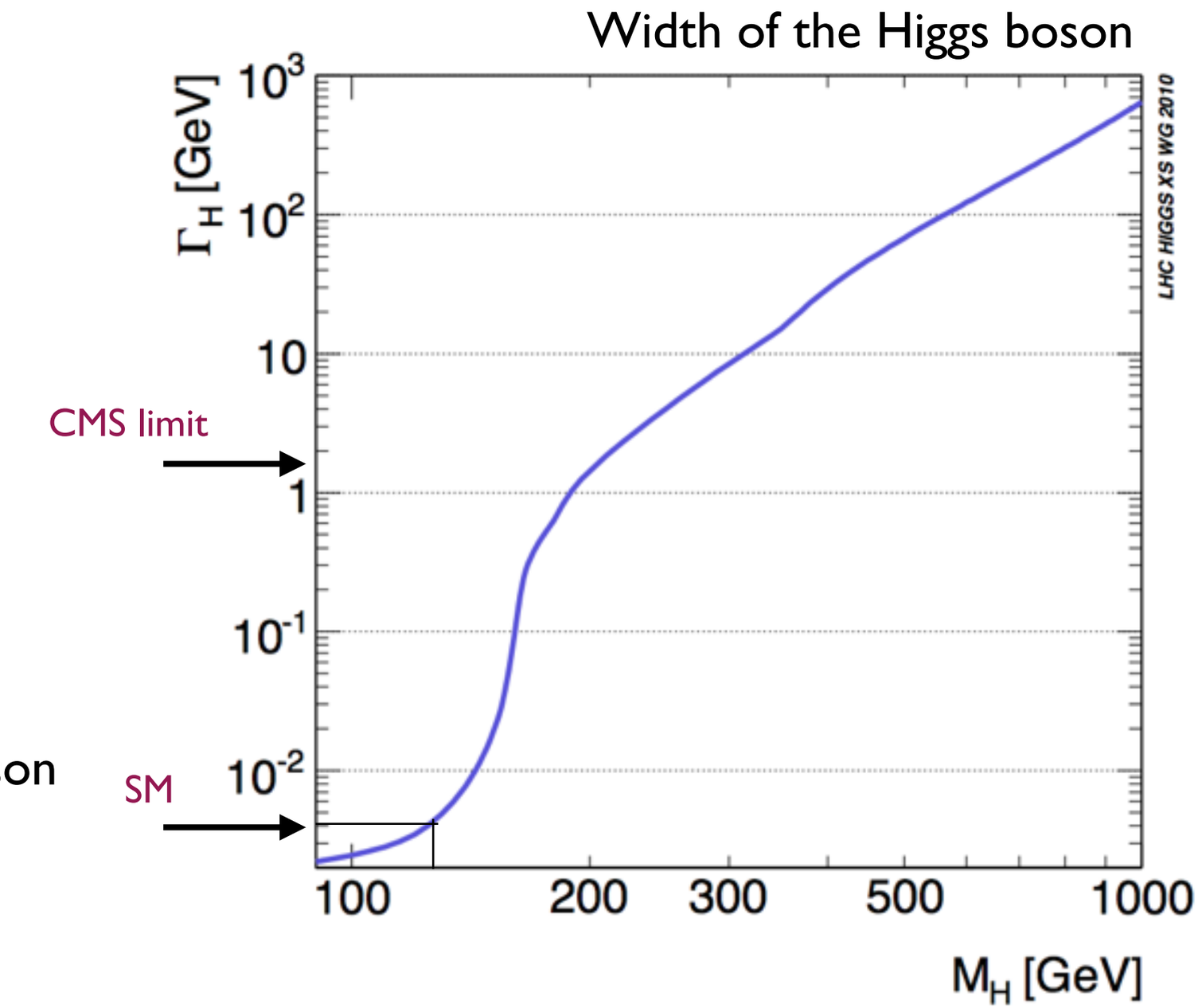
PRL 114 (2015) 191803

Width of the Higgs Boson

Upper limits on the width can be obtained from the mass peaks (at the level of the experimental resolution)

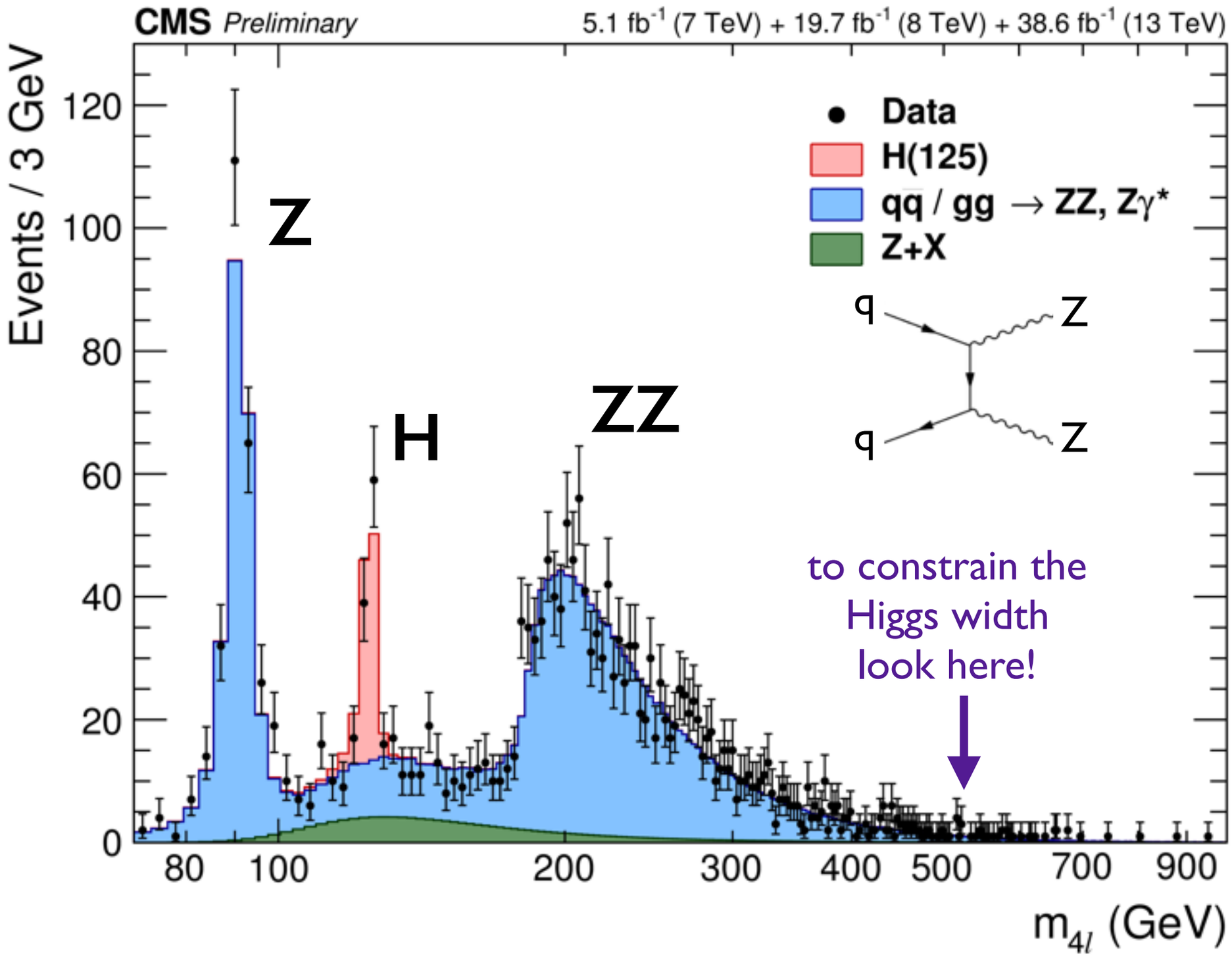
Γ_H < 1.7 GeV (95%CL)

The width of the SM Higgs boson is of the order of 4MeV



EPJC 75 (2015) 212

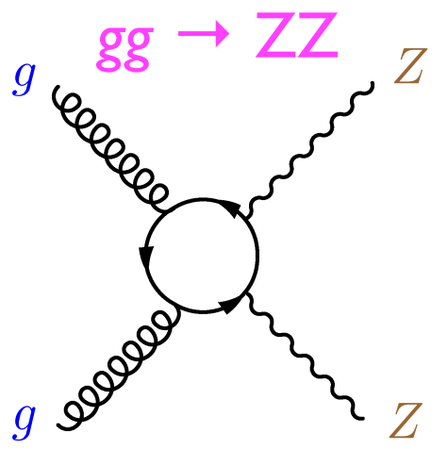
"Indirect" Measurement of the Width



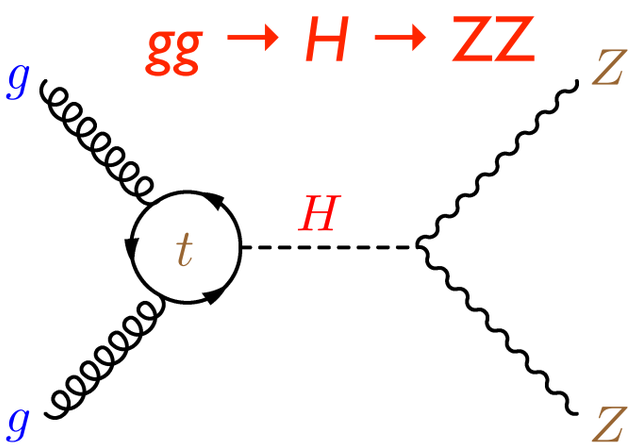
Off-Shell Higgs Boson

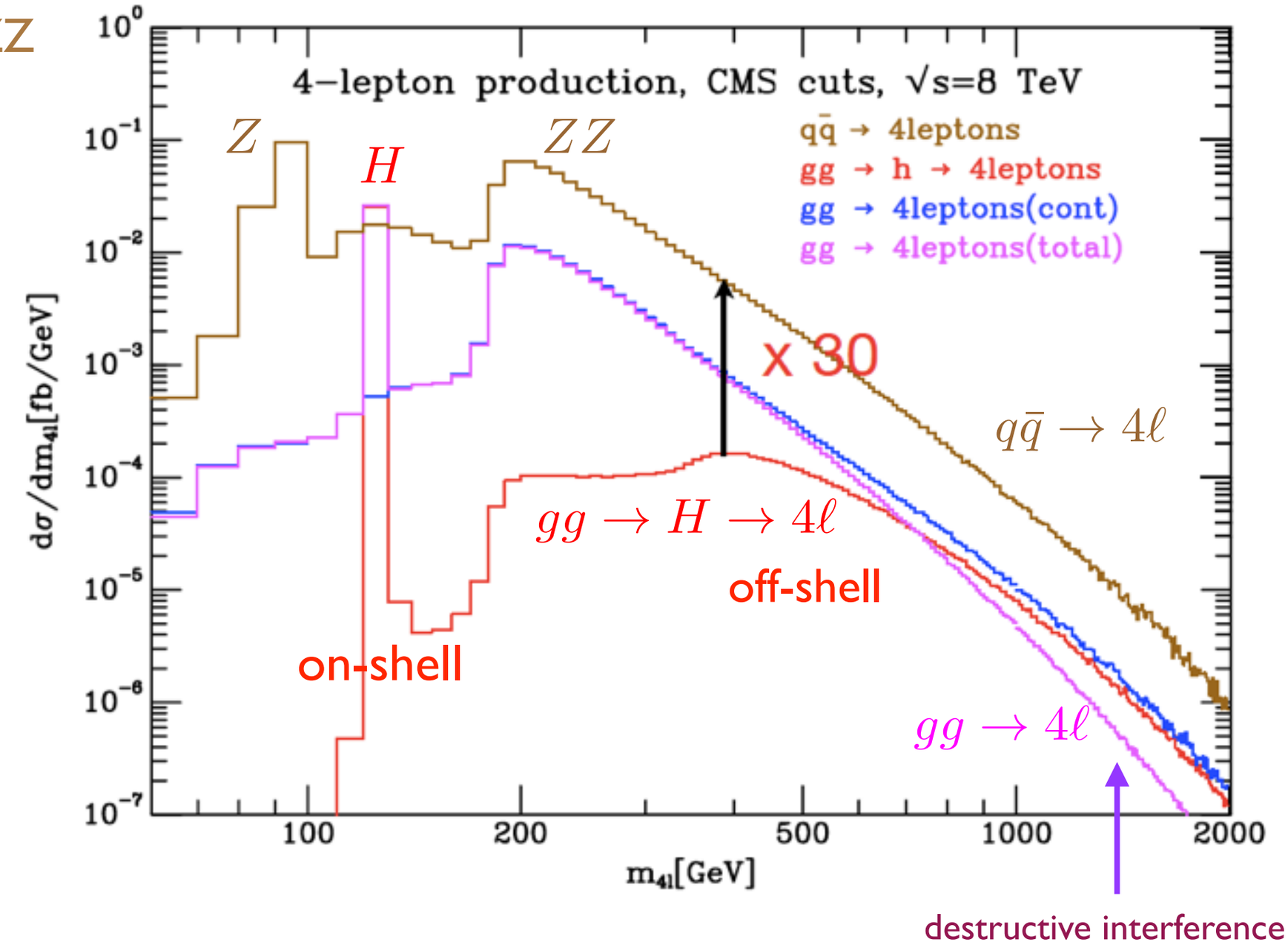
ZZ production = $qq \to ZZ$

but also



and



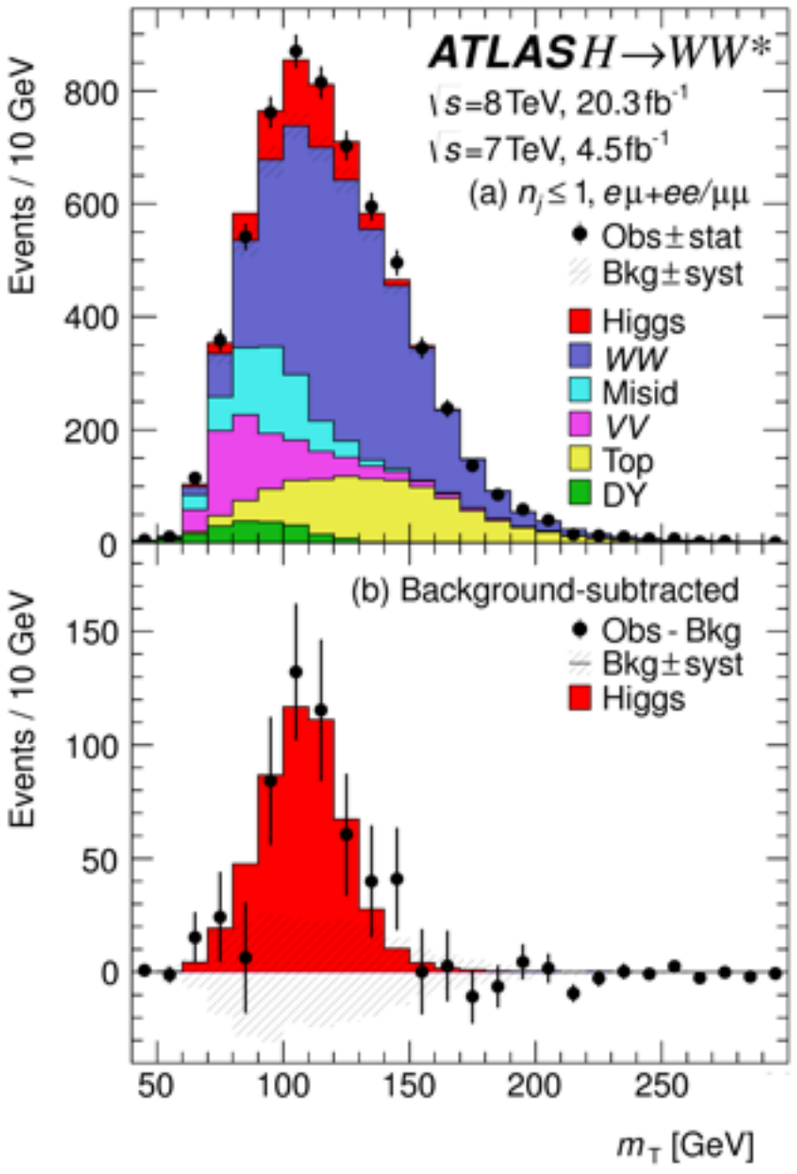


$$\frac{\sigma^{\text{off-shell}}_{gg\to H\to ZZ}}{\sigma^{\text{on-shell}}_{gg\to H\to ZZ}} \sim \Gamma_H$$

By studying the high mass ZZ region
CMS and ATLAS are able to set indirect limits on Γ_H
in the 20-30 MeV range!

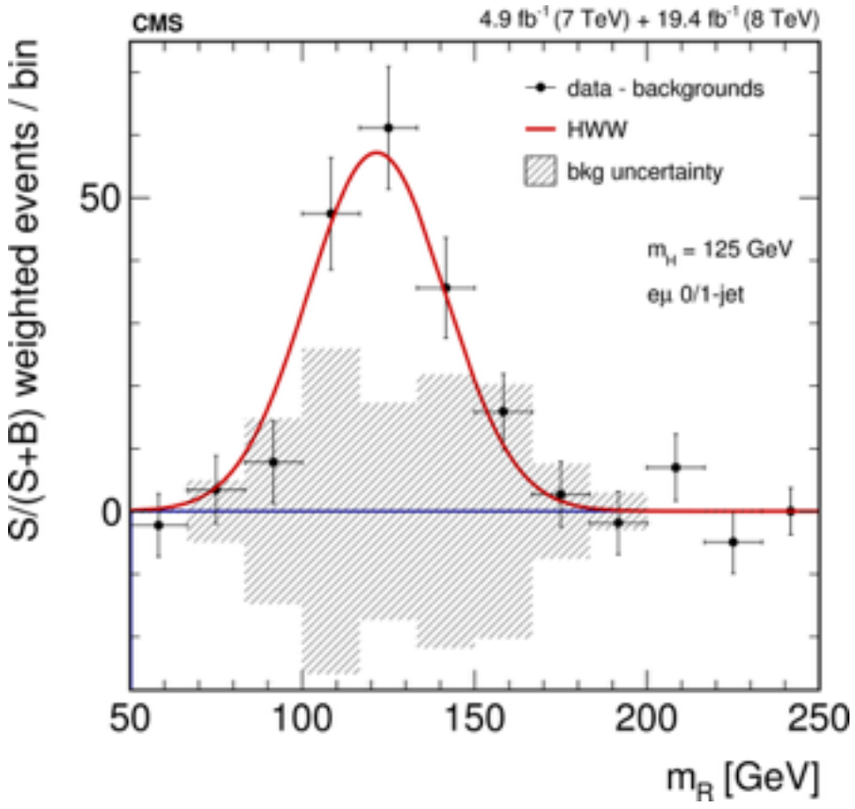
WW Decay

Phys. Rev. D 92, 012006 (2015)



Very significant H → WW signals for both ATLAS (6.1σ) and CMS (4.5σ)

Clear evidence of VBF production



Mass consistent with 125 GeV

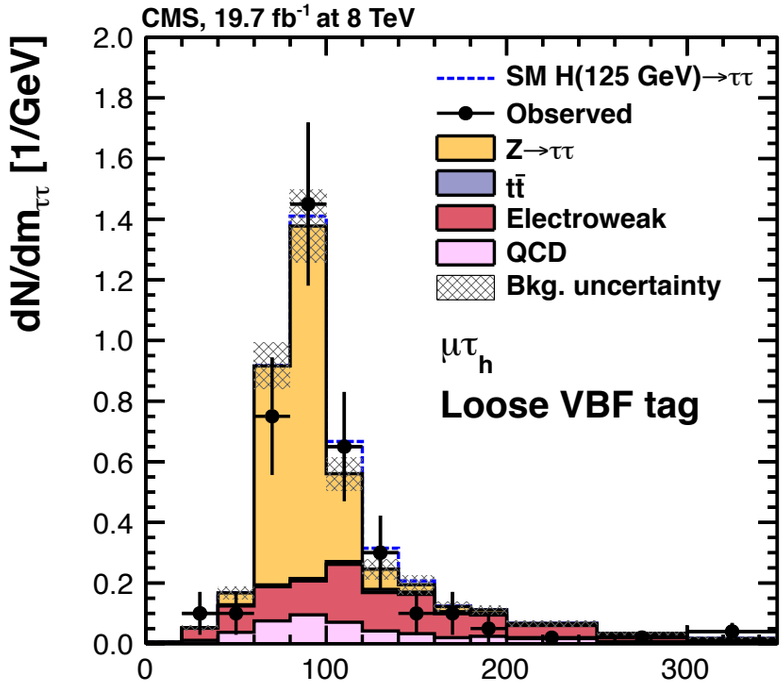
PRD 92 (2015) 012006

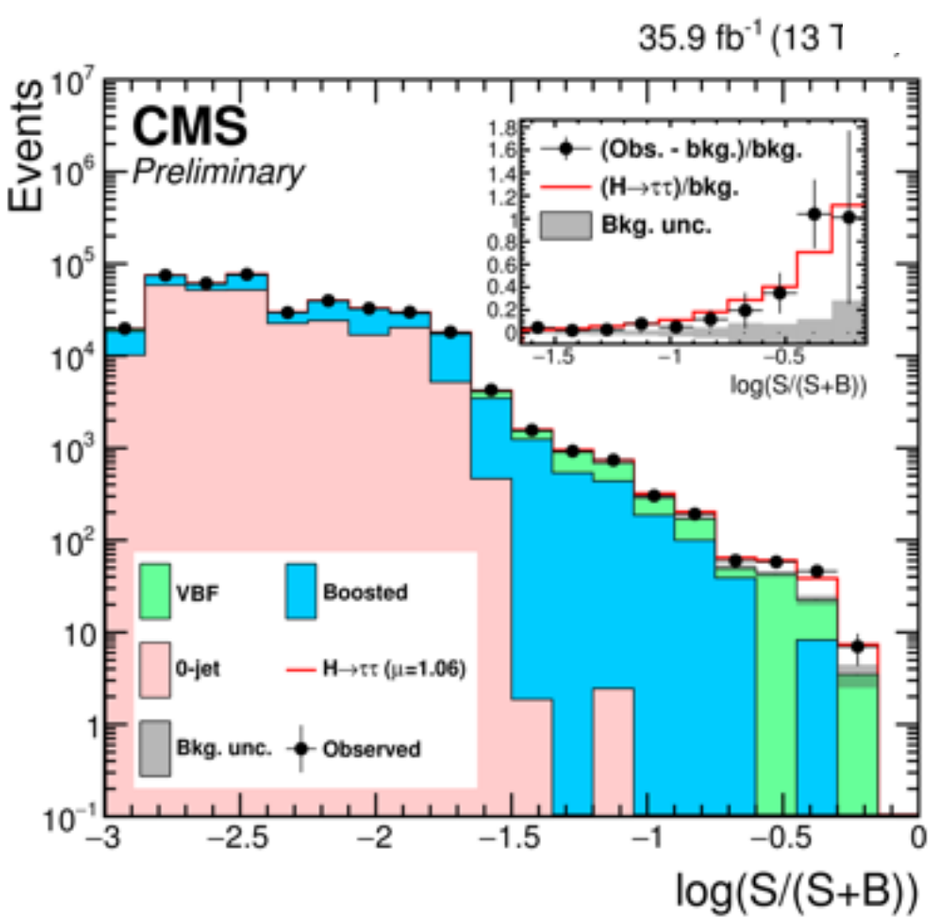
JHEP 01 (2014) 096

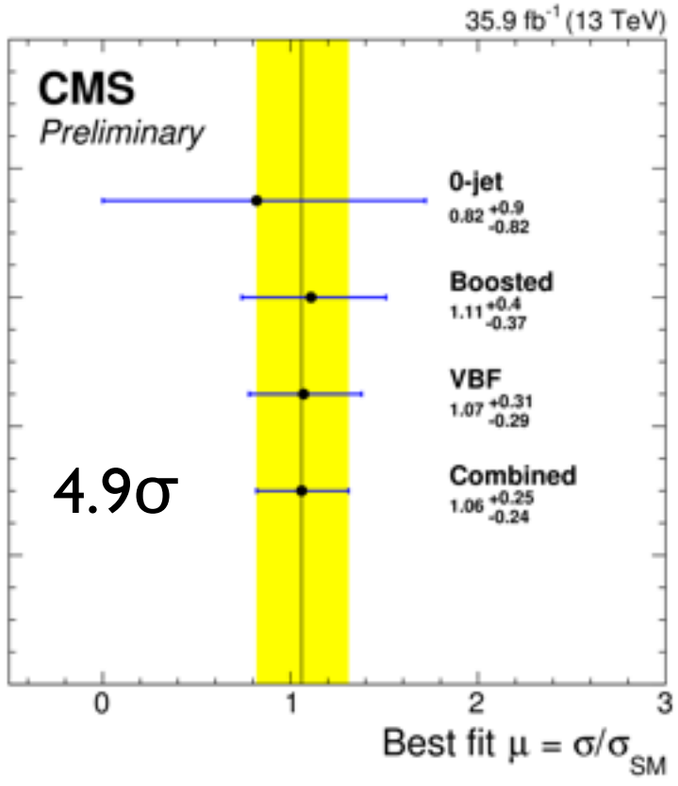
Decay to tau Leptons

- One of the most important results in 2014
- First evidence of Higgs coupling to fermions

CMS: a new result at 13 TeV

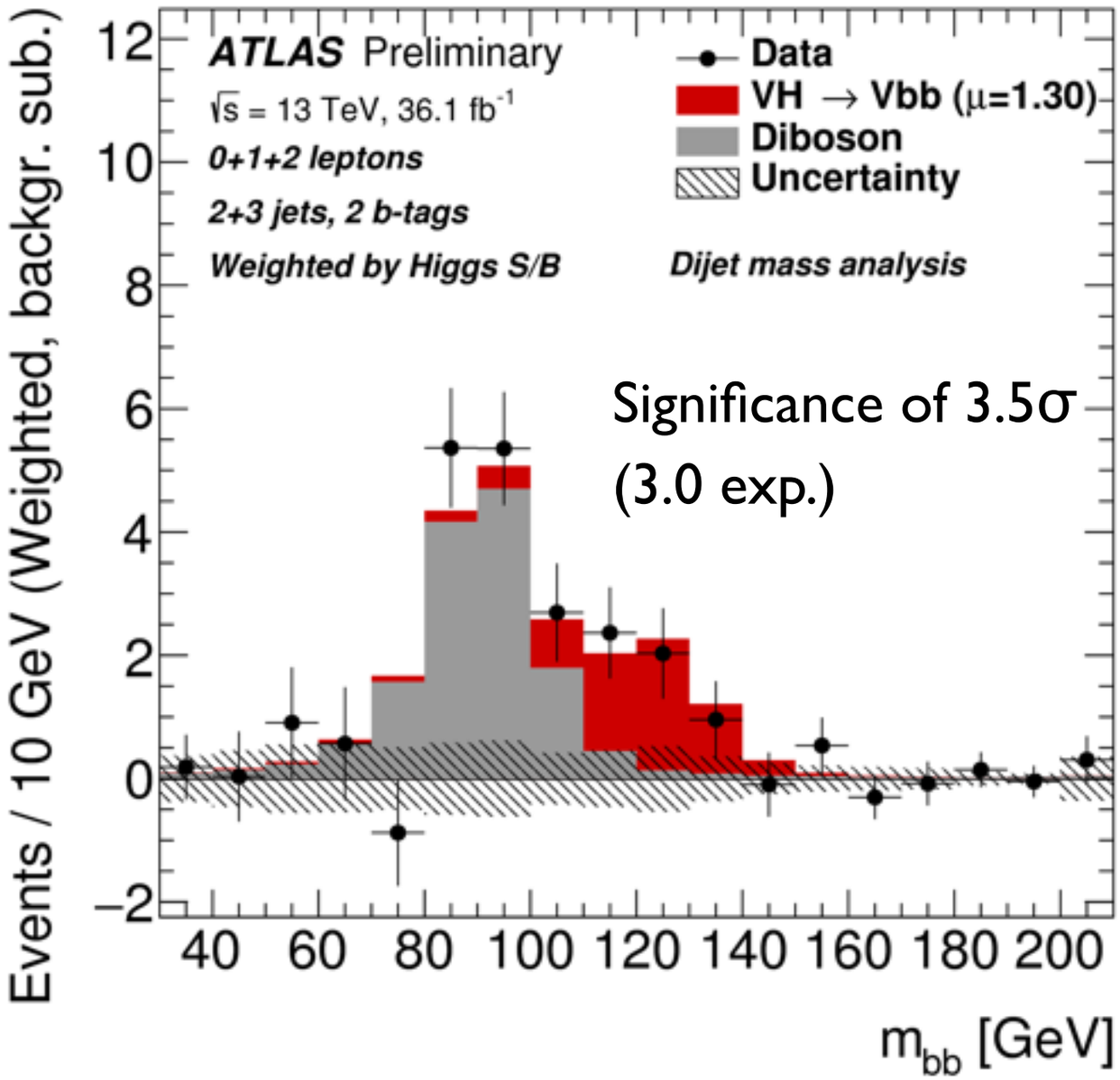






Recent Evidence for VH(bb) in ATLAS

Full ATLAS 2016 dataset at 13 TeV



Reconstruction of bb signal after subtraction of major backgrounds

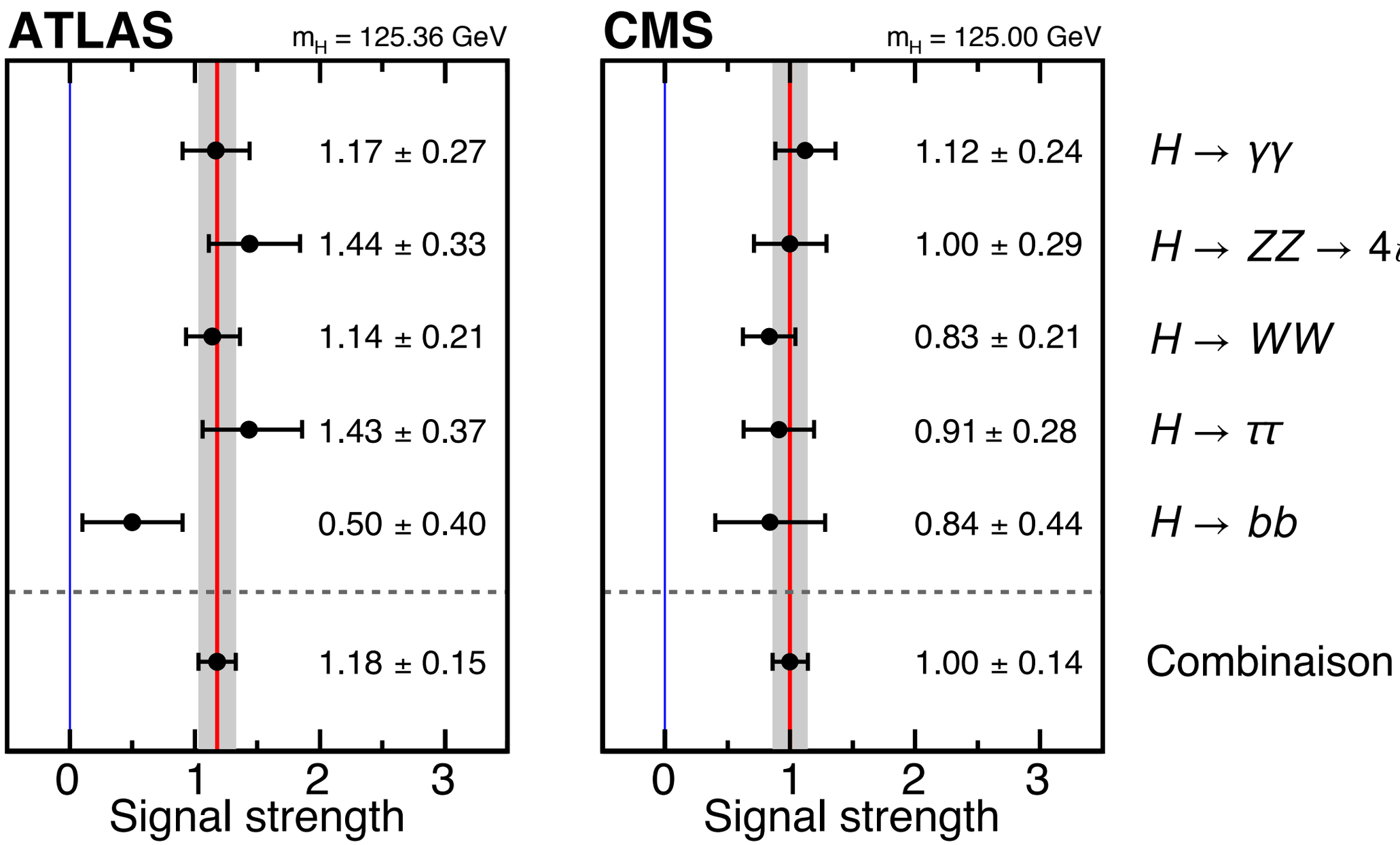
presented at the EPS 2017 Conference

ATLAS-CONF-2017-041

Signal Strengths

Legacy Run I

main five decay channels



> 5σ observation in di-boson channels

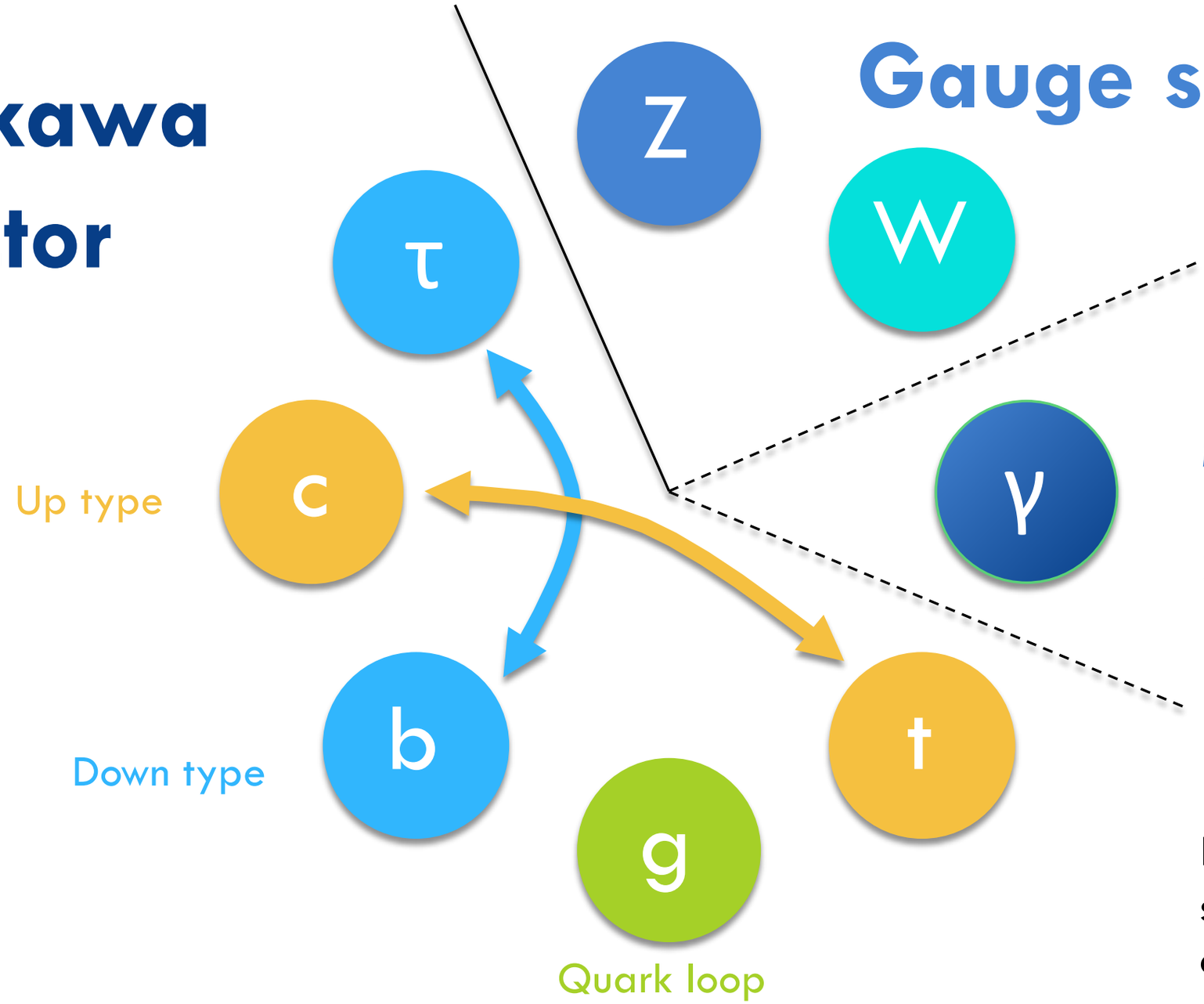
> 3σ evidence in di-tau channel

Couplings of the Higgs Boson

Yukawa sector

Gauge sector

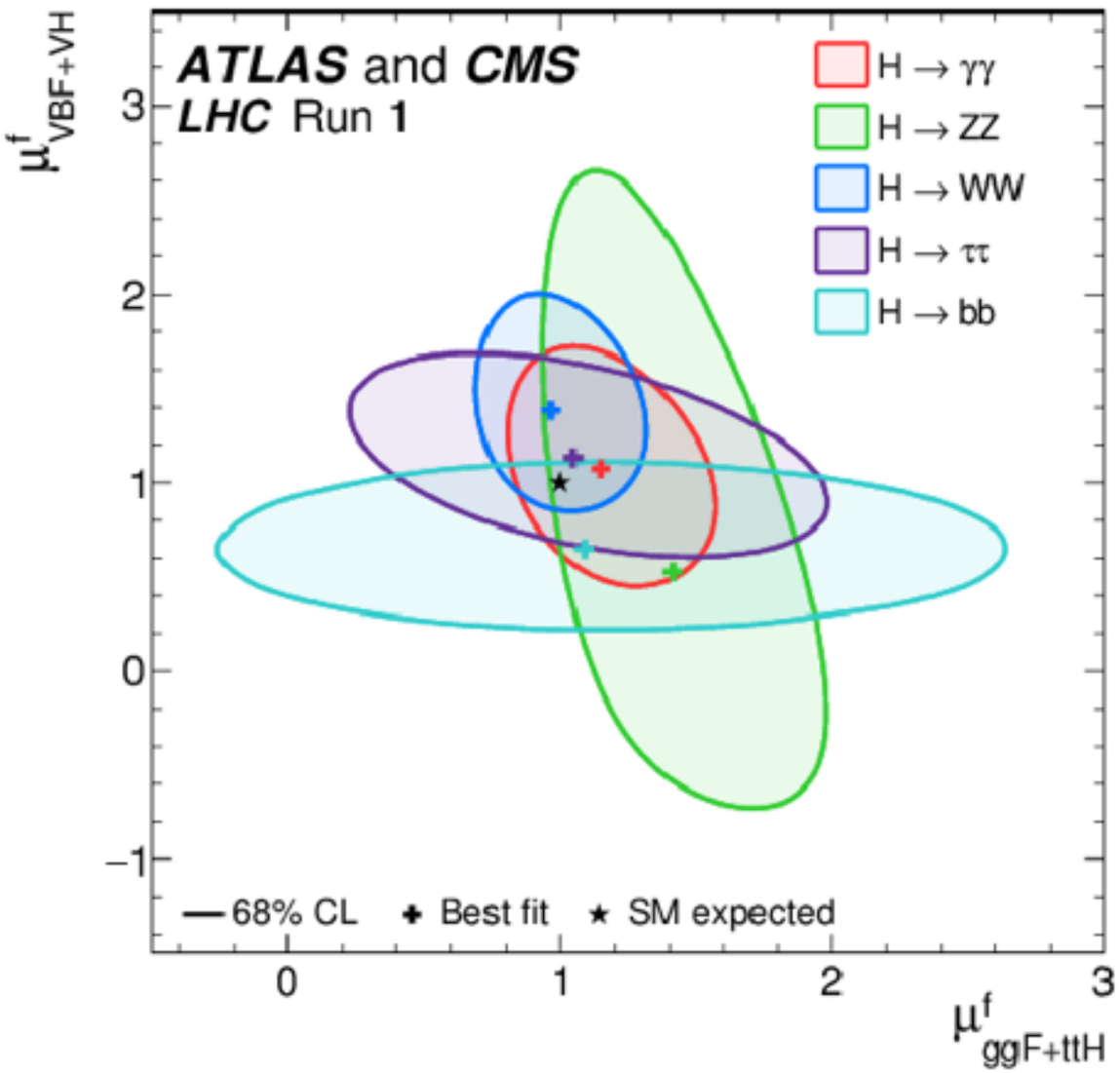
Mixed sector

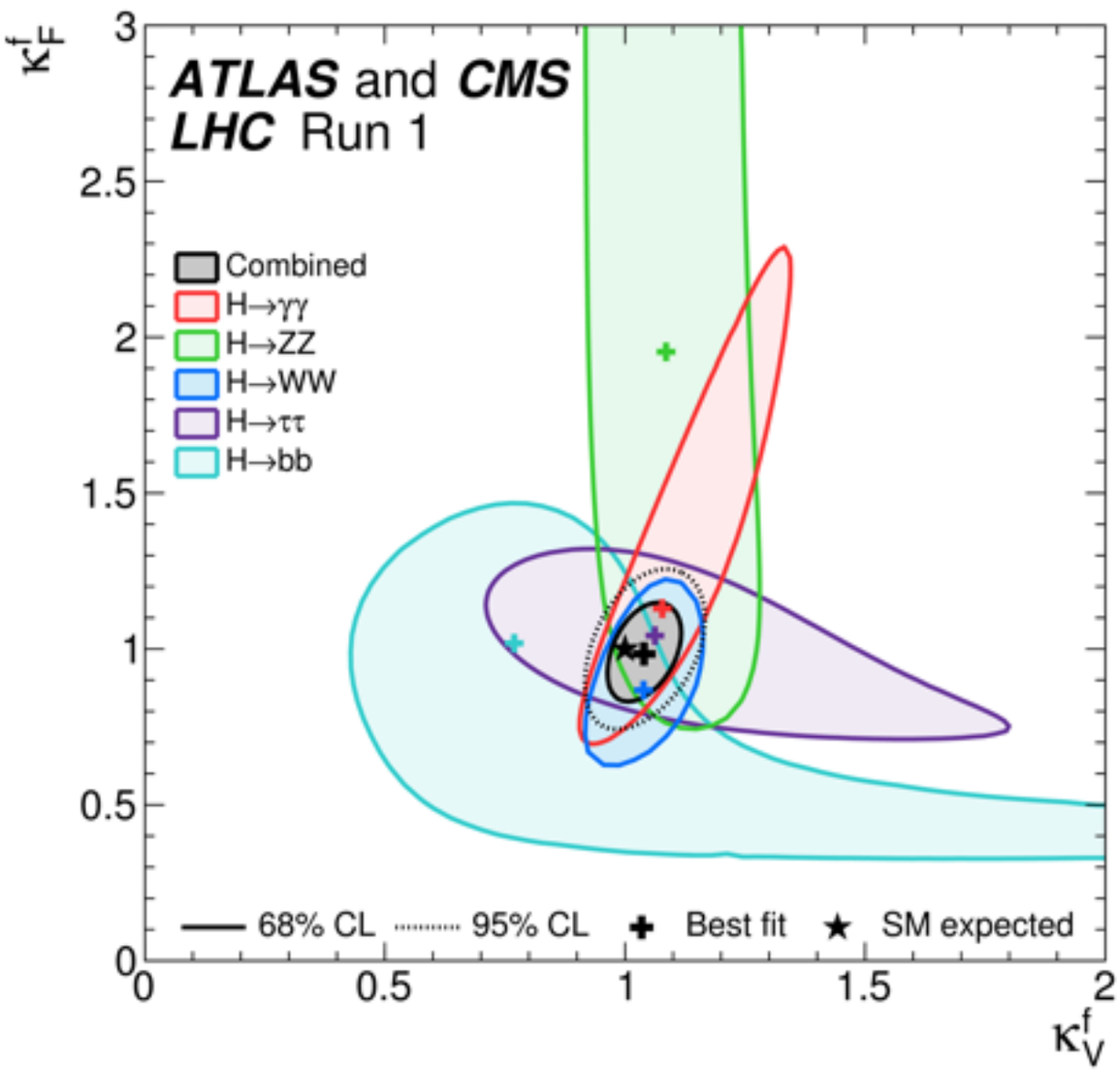


Loops (γ, g) are sensitive to BSM contributions.

Courtesy André David

Production and Couplings



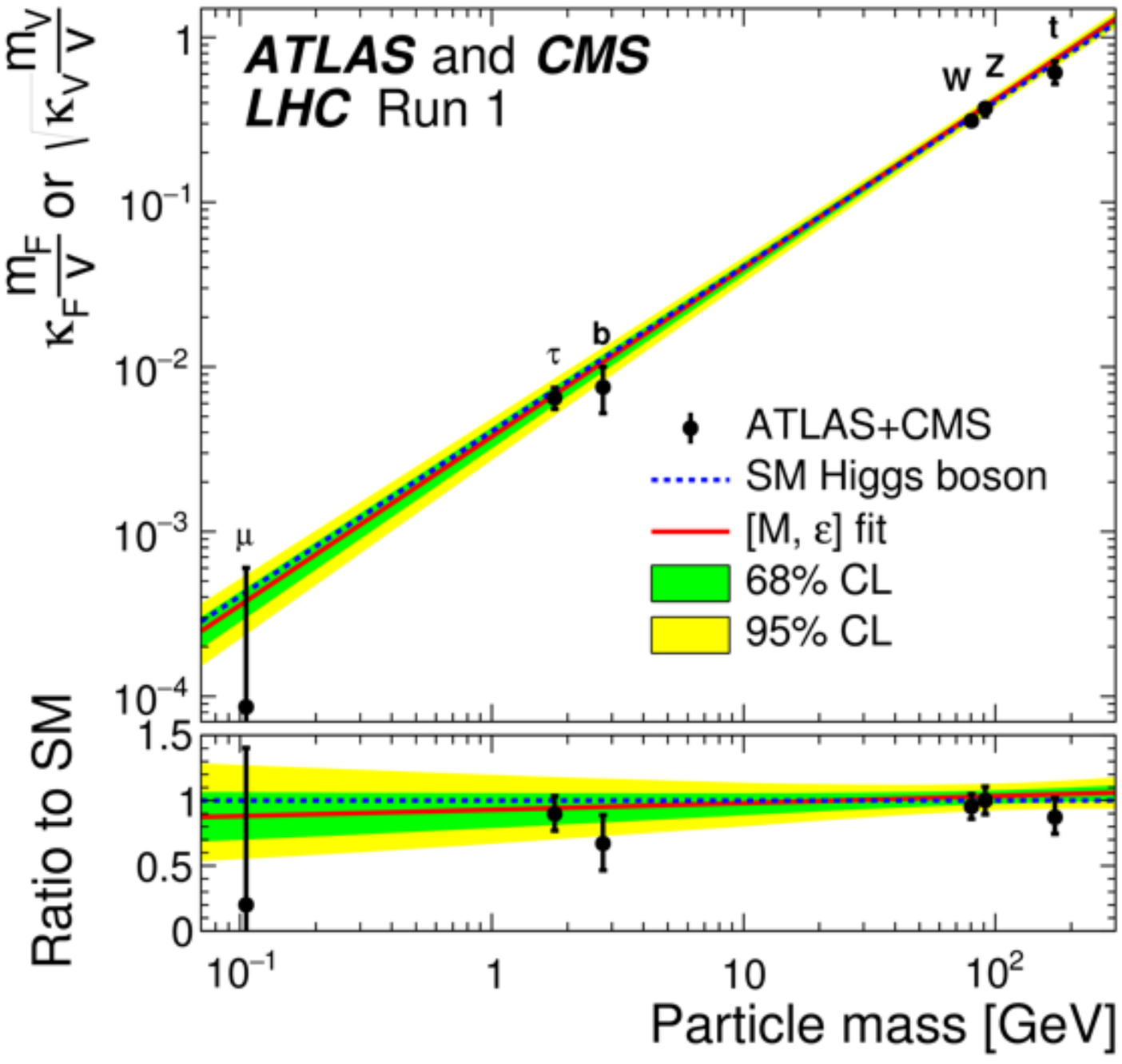


Individual production modes are consistent with SM expectations

- ggH established
- evidence for VBF

Couplings to bosons and to fermions are consistent with SM predictions and the new particle behaves as $J=0^+$ as predicted

Couplings Versus Mass

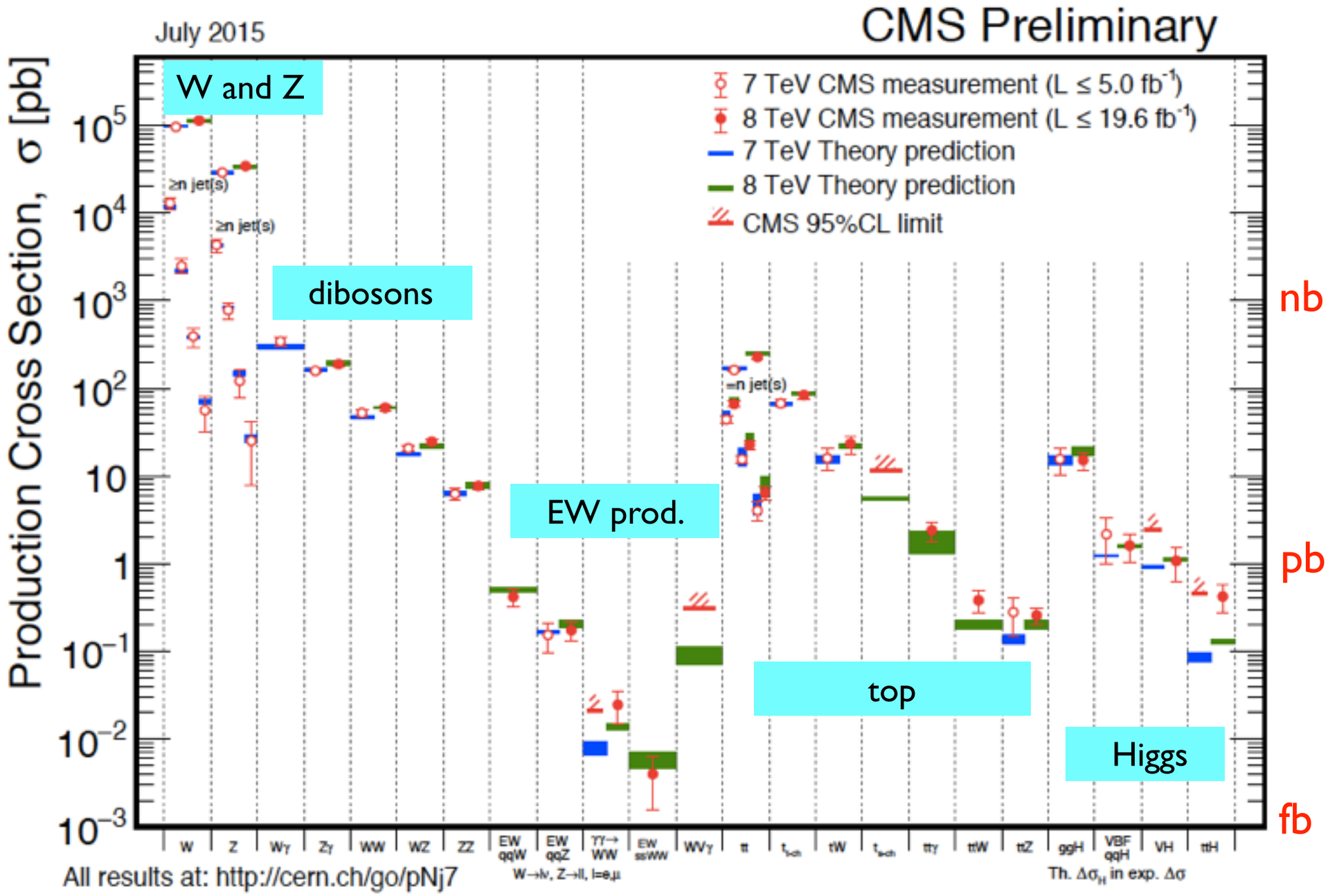


Over three order of magnitude in mass

- the boson couples differently to particles
- the couplings depend on mass

Also: decay to electrons not seen

This Resumes our Journey in SM Land



Next stop

New Physics!

Thanks for your attention

Gautier Hamel de Monchenault