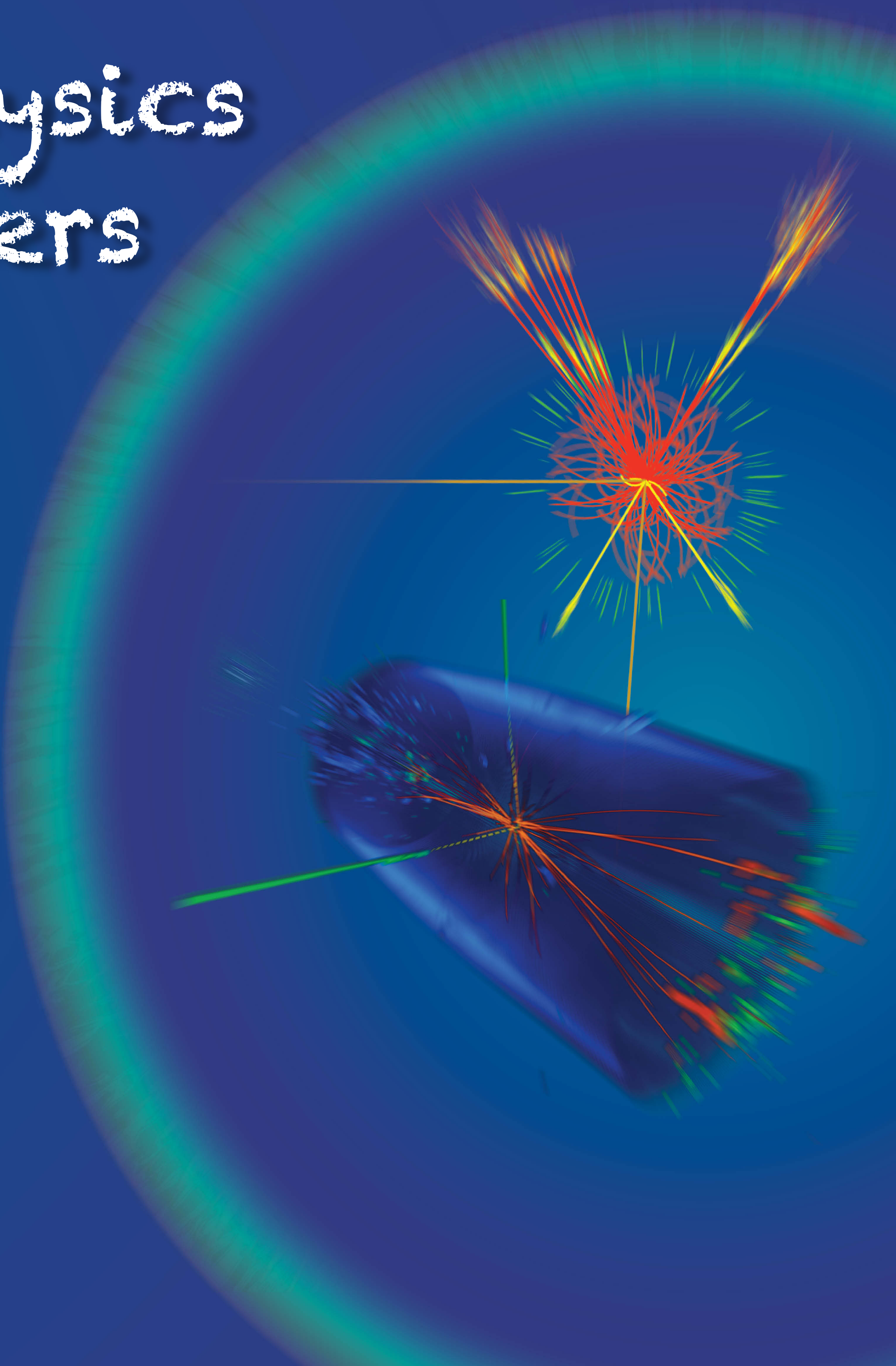
Standard Model Physics at Hadron Colliders

Third Lecture



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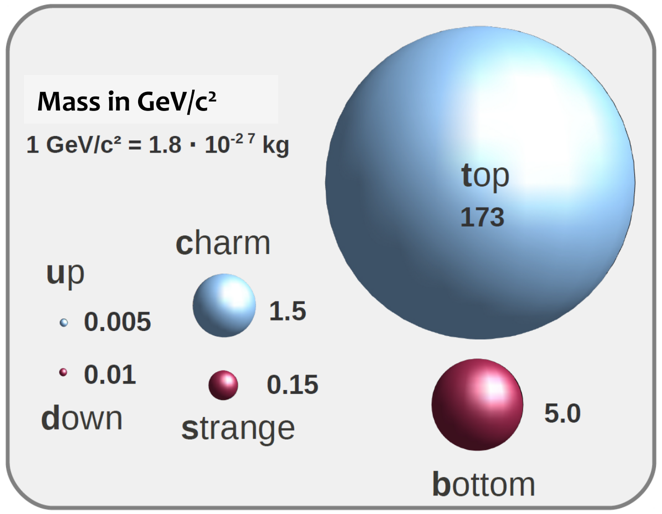
The Top Quark

The top quark

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

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

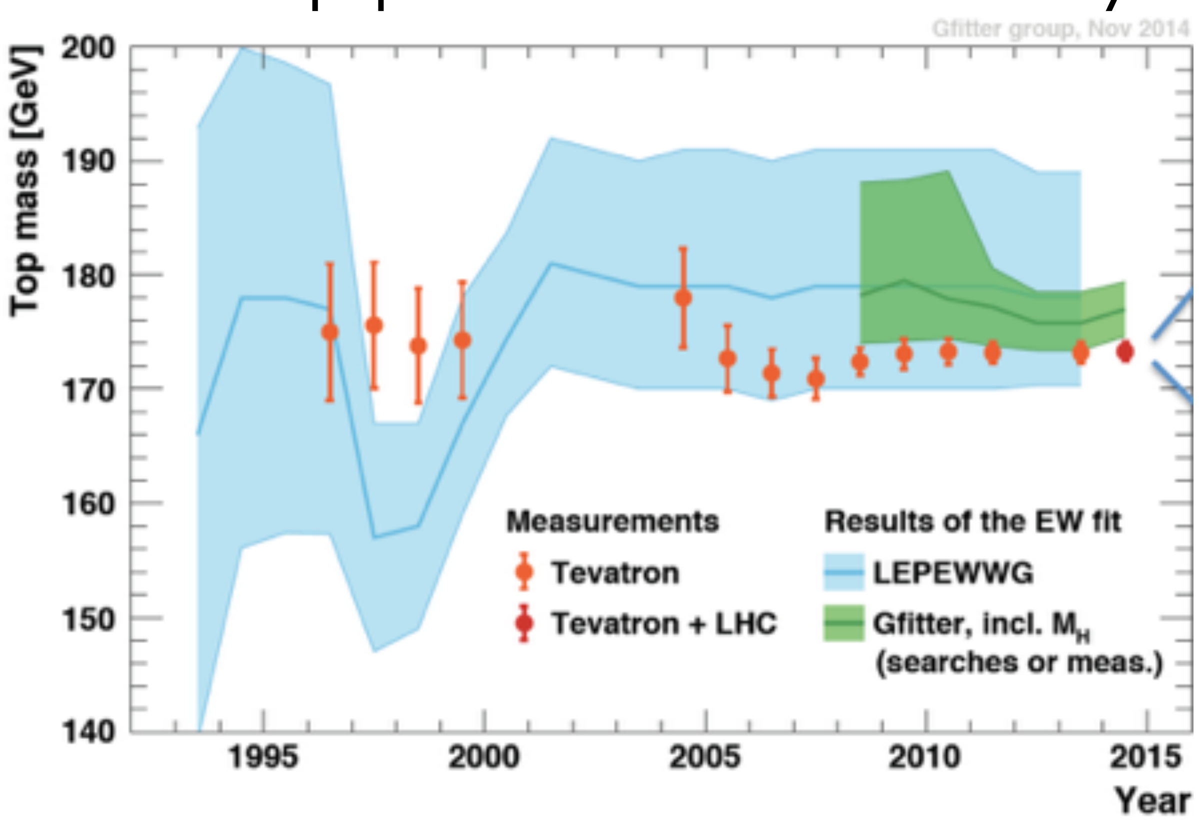


40 times heavier than the b quark

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

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

top quark first discovered "virtually"



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

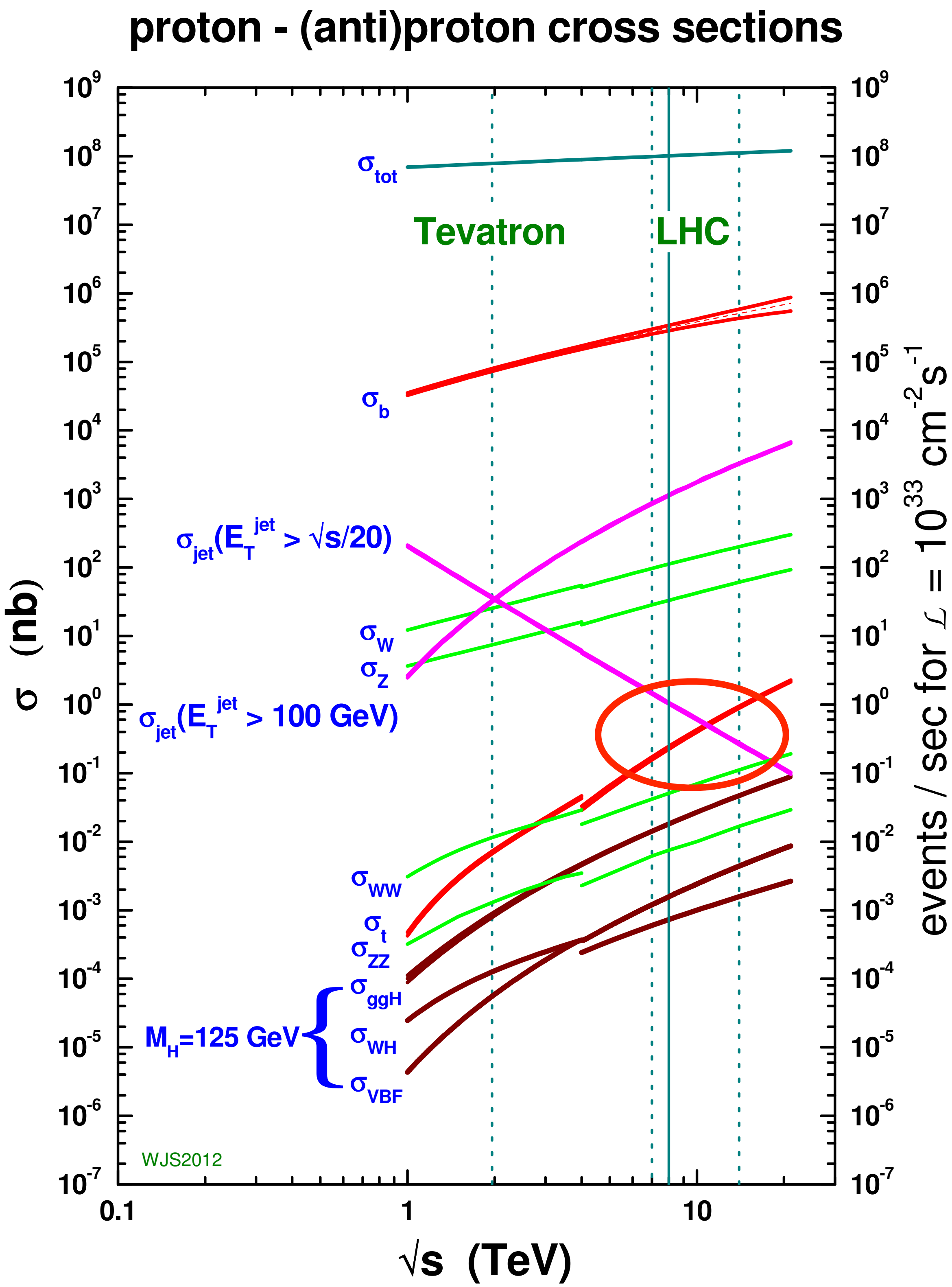
$$\Gamma(t \to bW^+) \approx \frac{\alpha}{16 s_W^2} |V_{tb}|^2 \frac{m_t^3}{m_W^2}$$

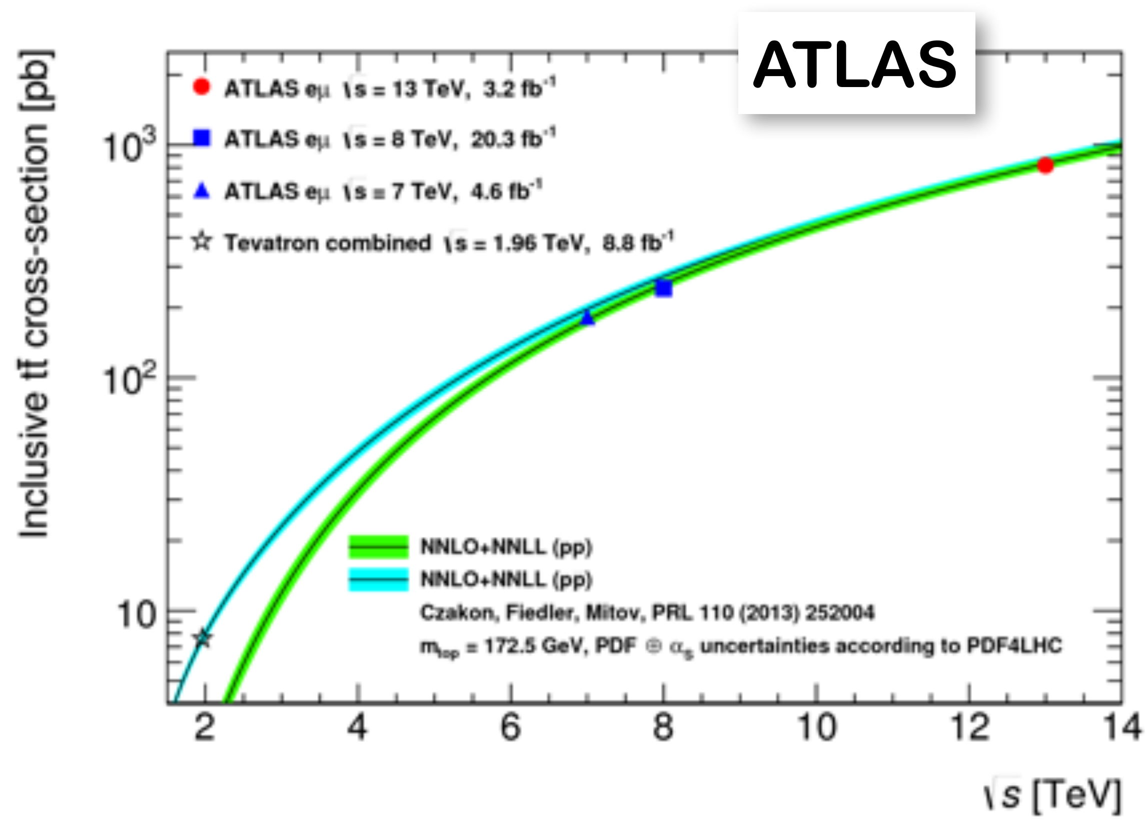
$\sim$1.5 GeV (> Λ_{QCD})

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

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

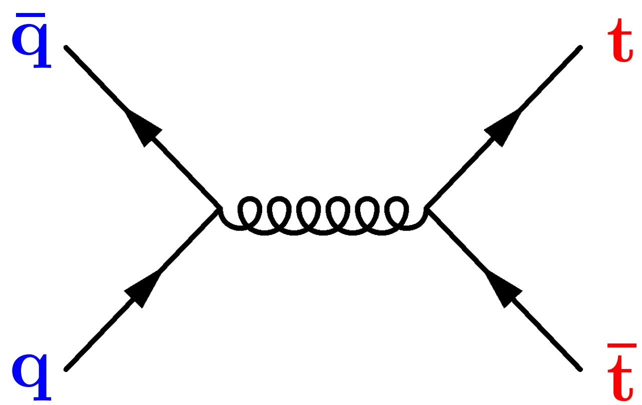
Top Quark Physics

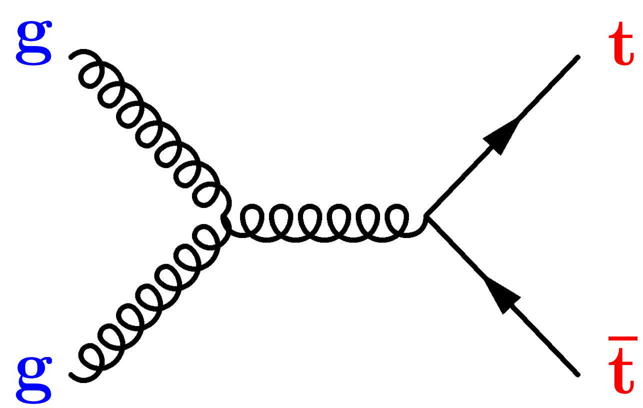


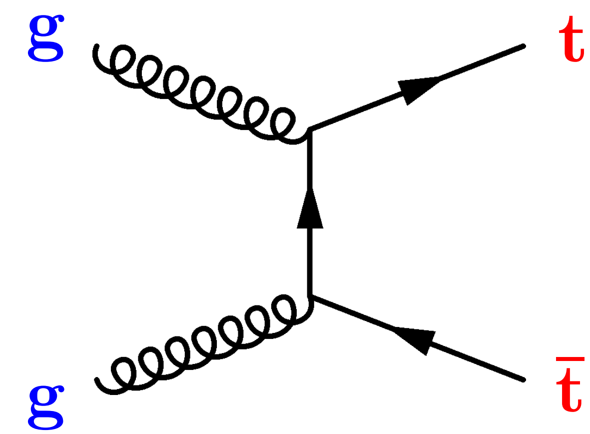


Top Quark QCD Production

Tevatron (1.96 TeV)	LHC (7/8 TeV)
σ_{TEV} = 7 pb	σ_{LHC} = 220 pb
quark annihilation	gluon fusion

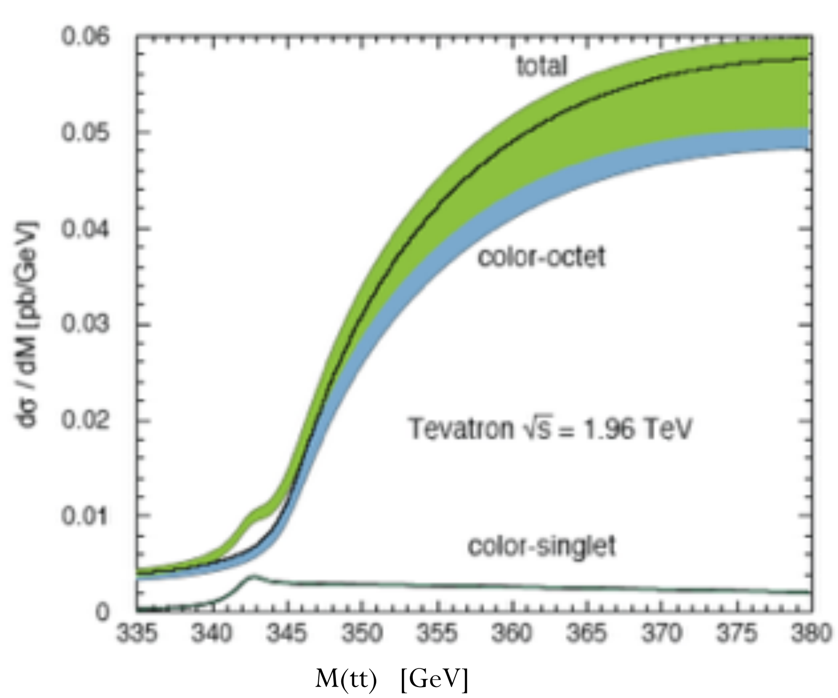






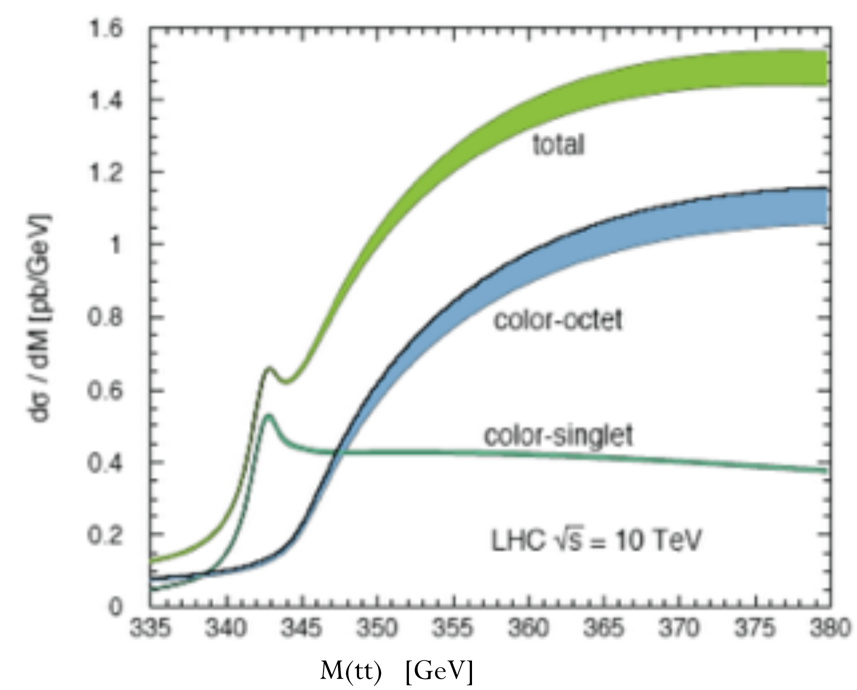
85% of the cross section

80% of the cross section



Tevatron
ten t-tbar pair
per day

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



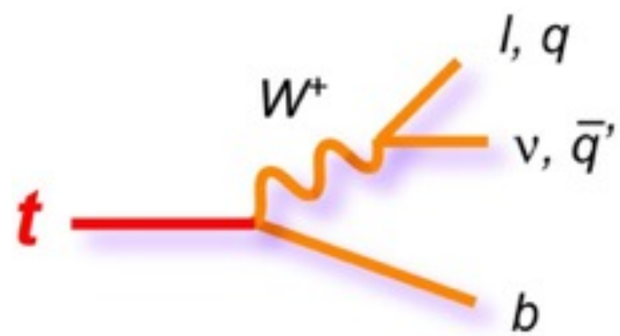
LHC:
one t-tbar pair
per second

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

Top Pair Decay Channels

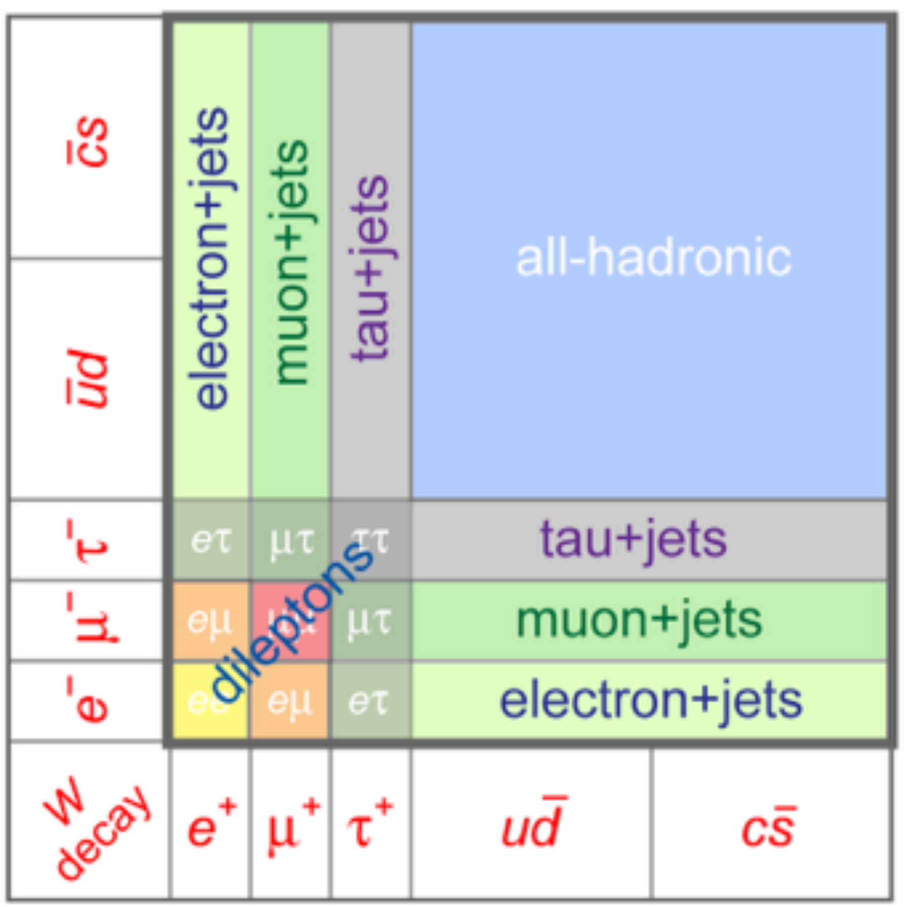
In the SM the top quark decays exclusively into a W boson and a b quark

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

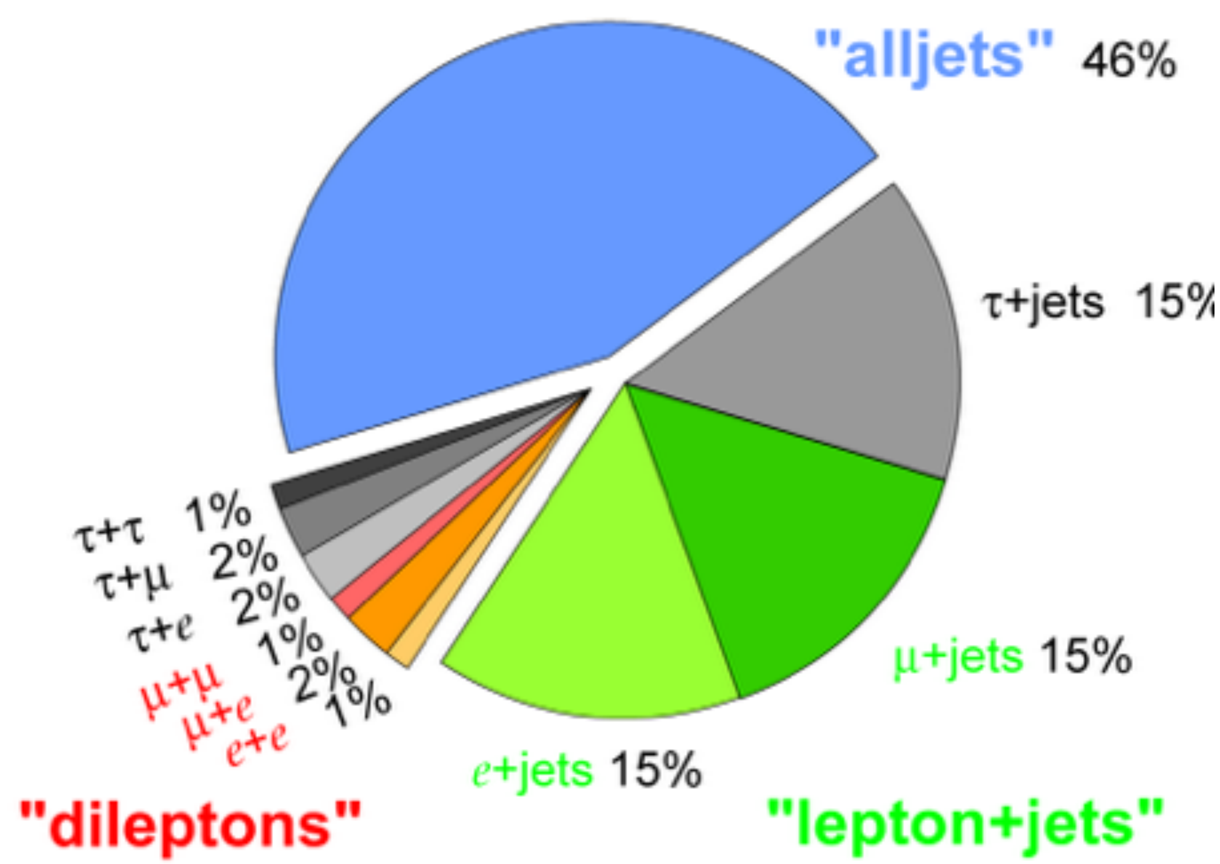


therefore the branching fractions of the t-tbar final states depend on the W boson branching fractions

Top Pair Decay Channels

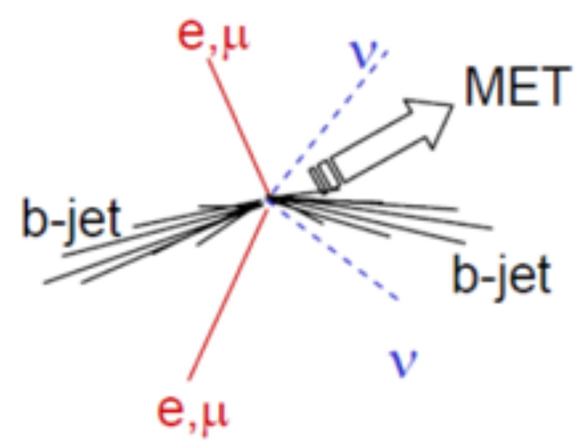


Top Pair Branching Fractions



Top Pair Event Classification

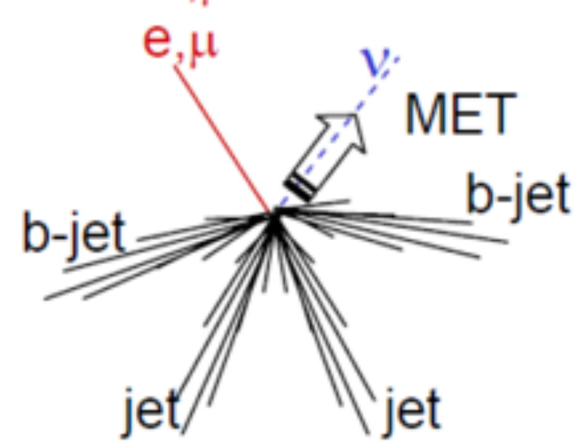
The classification of top pair events relies on the number of leptons in the final state



Dilepton

- 2 isolated OS leptons (e or μ)
- 2 b-jets
- large E_T^{miss}

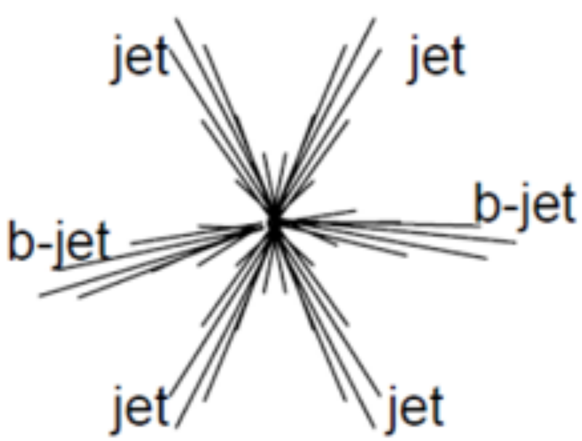
- 3 channels ee, μμ and eμ
- BR = 4.7% (1+1+2)
- very low backgrounds, mostly Drell-Yan



Lepton+Jets

- 1 isolated lepton (e or μ)
- 2 b-jets
- 2 light-quark jets
- moderate E_T^{miss}

- 2 channels e+jets and μ+jets
- BR = 29.2% (1+1)
- moderate background, mostly W+jets (charge asymmetric)



All Hadronic

- no lepton
- 2 b-jets
- 4 light-quark jets
- no E_T^{miss}

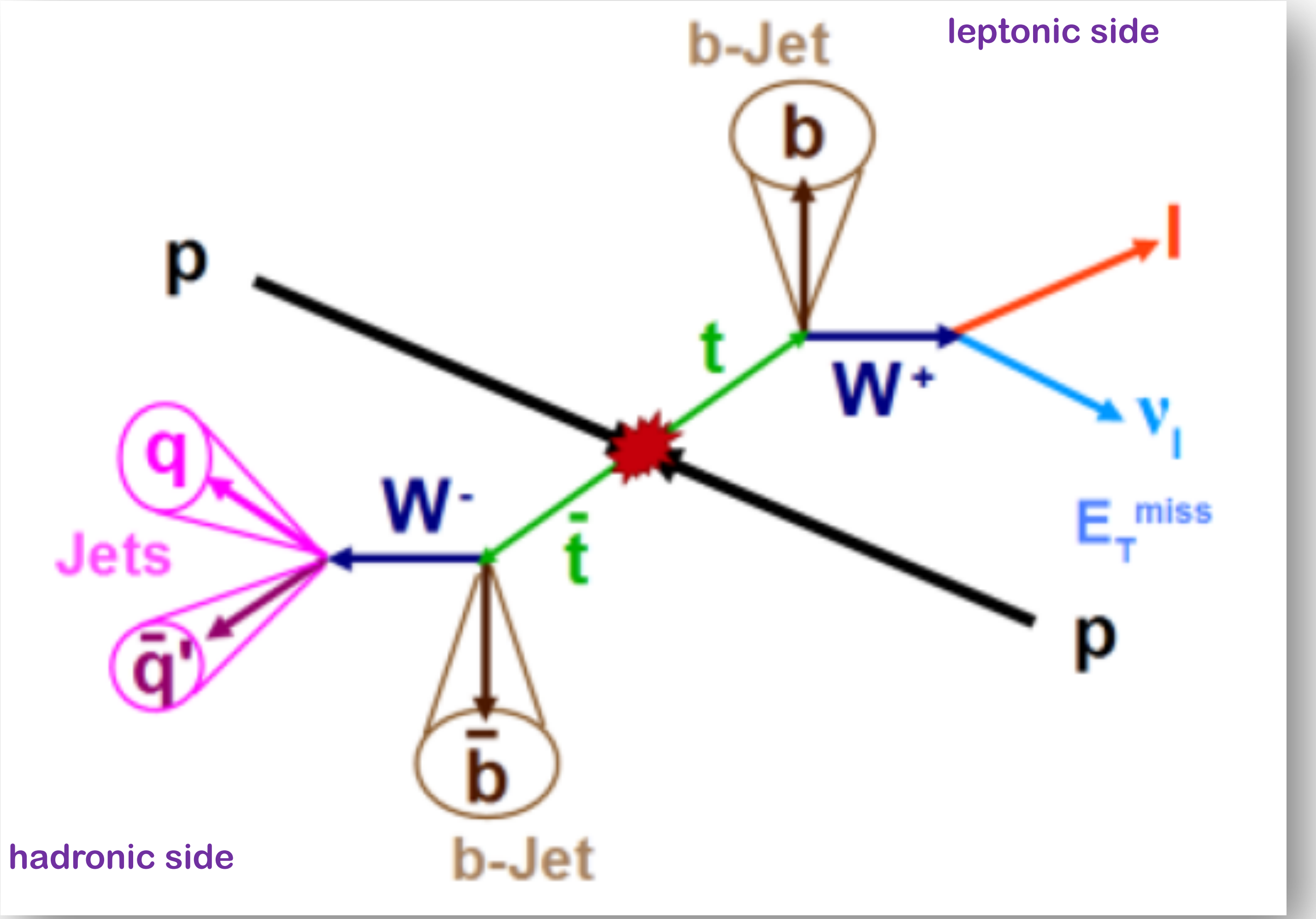
- BR = 45.7%
- large QCD-multijet background

Hadronic Tau

- 2 channels: τ_{had}+e/μ, τ_{had}+jets

- BR = 4.7% + 14.6%

Lepton+Jets

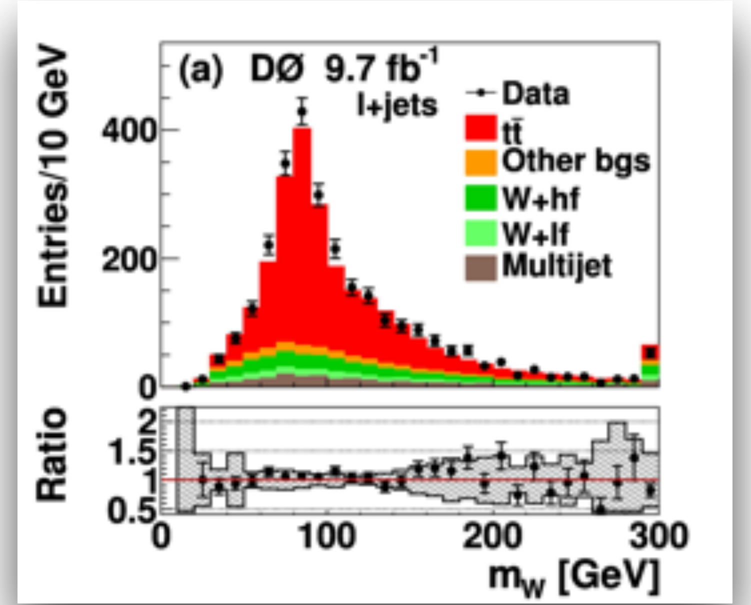


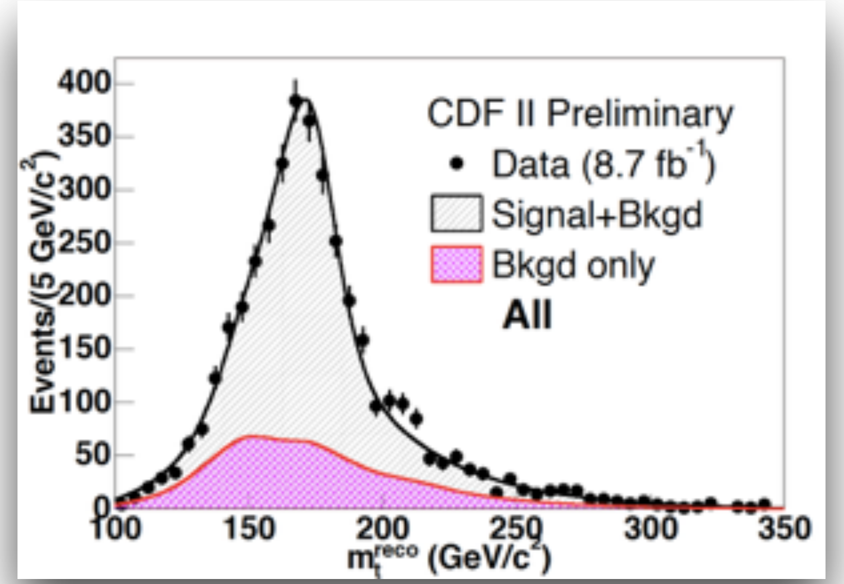
Golden mode at the LHC

- 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

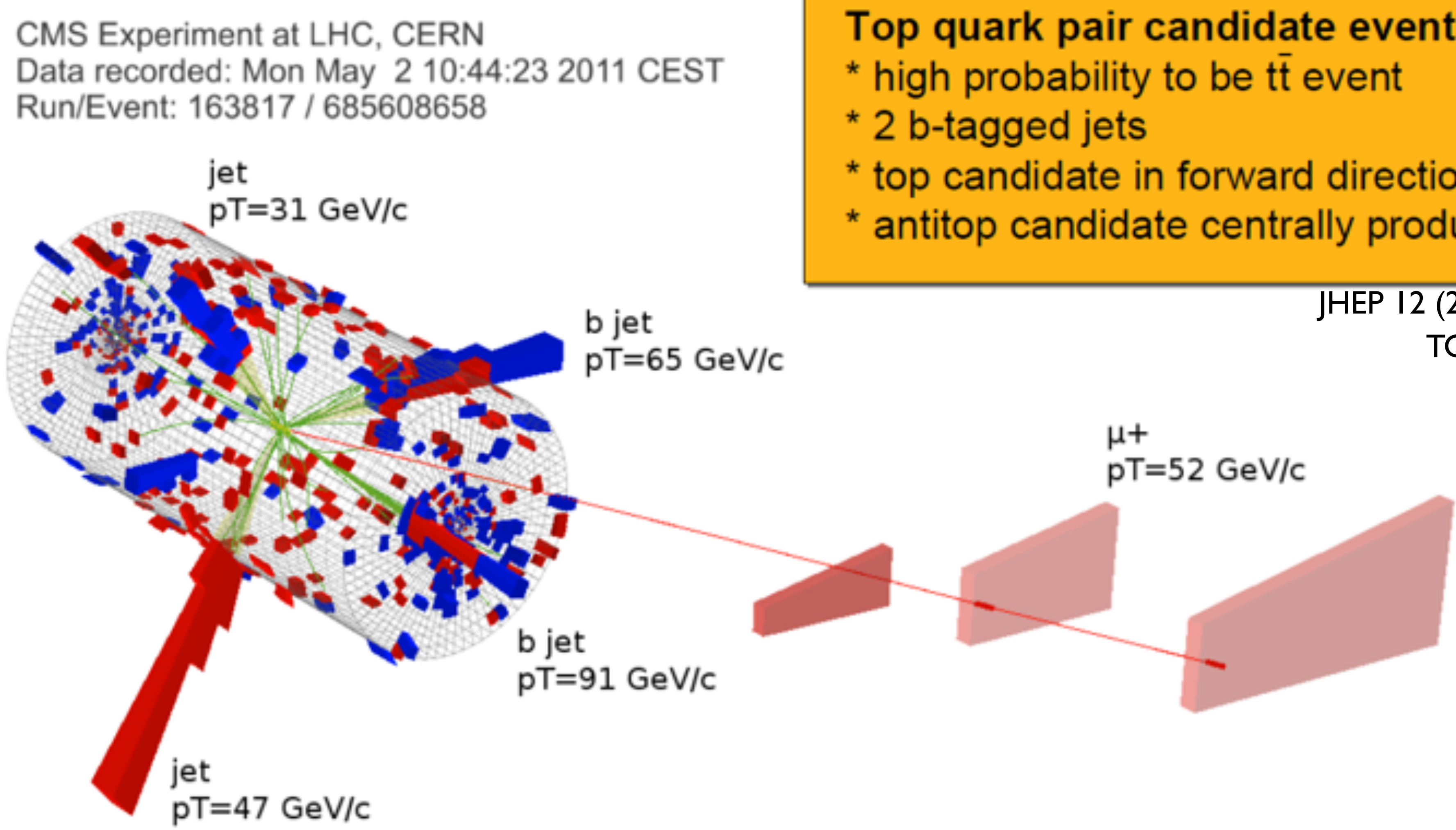




D0 and CDF signals with full statistics

~2,500 events

Lepton+Jets Event Selection



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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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

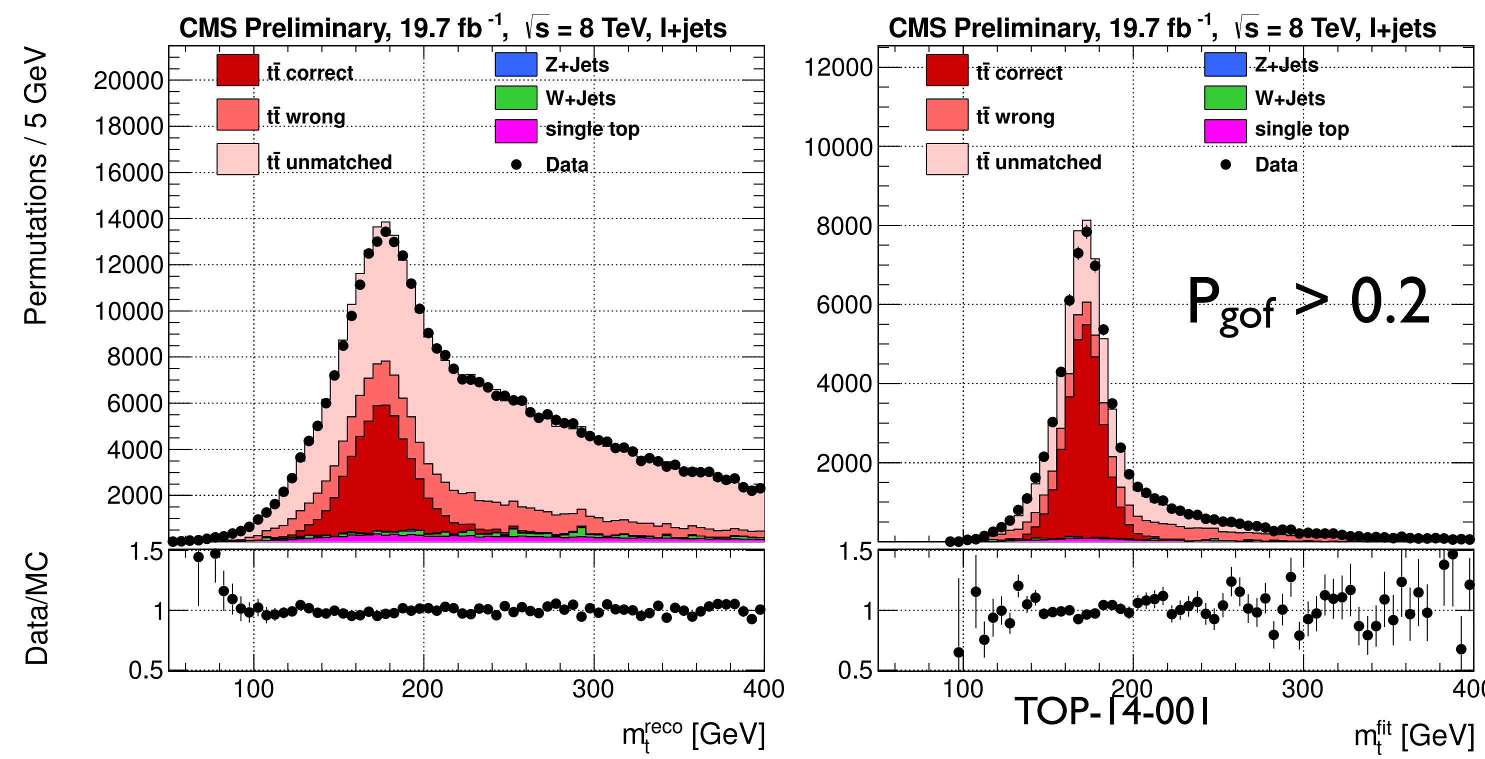
- t-tbar purity: 94%

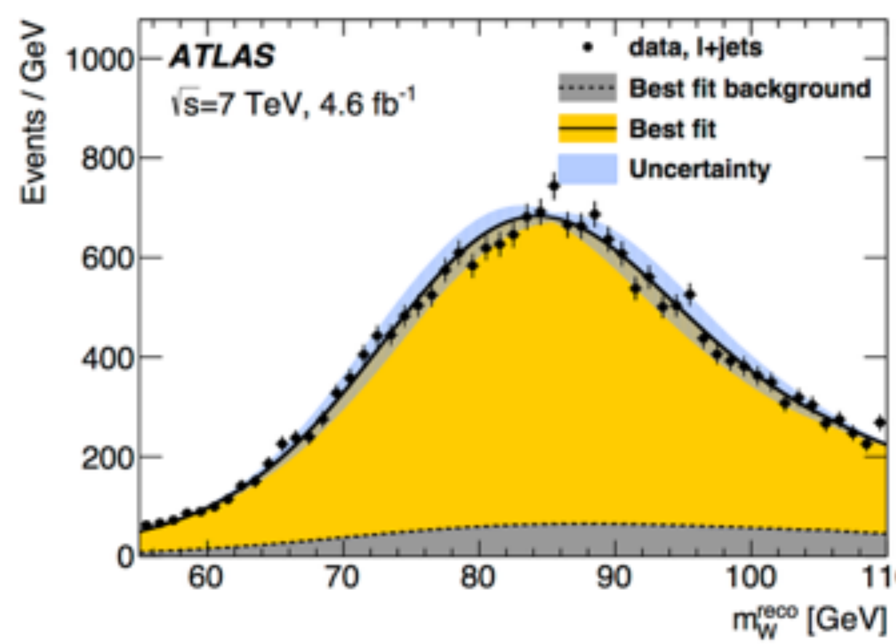
Kinematical fit with constraints

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

Jet Energy Scale Factor (JSF)

- in situ calibration using invariant mass of light-jet pair





CMS

m_t = 172.04 GeV

Uncertainties

- stat+JSF = 190 MeV
- syst = 750 MeV

JSF = 1.007 ± 0.012

ATLAS

m_t = 172.33 GeV

Uncertainties

- stat+(b)JSF = 480 MeV
- syst = 1.0 GeV

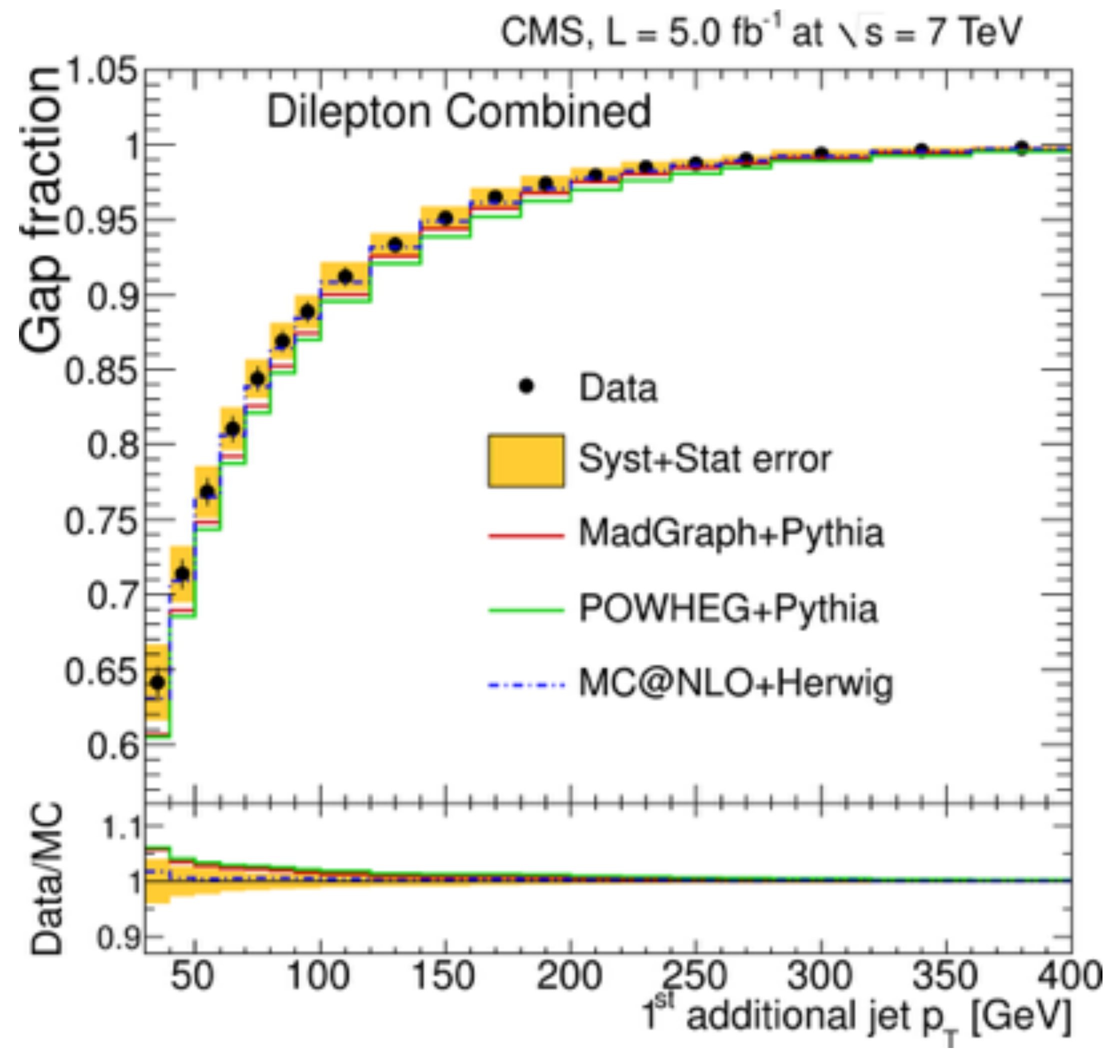
JSF = 1.019 ± 0.027

bJSF = 1.003 ± 0.027

Main Sources of Systematics

Systematic uncertainties for lepton+jet measurements

- jet energy scale
  - light jets, detector response [0.2-0.7 GeV]
  - b jets [0.1-0.6 GeV]
- modelling of gluon radiation [0.3-0.5 GeV]
- modelling of underlying event [0.1-0.2 GeV]
- modelling of color reconnection [0.2-0.5 GeV]
- modelling of pile-up [0.1-0.3 GeV]
- hadronisation, b-fragmentation [0.3-0.6 GeV]
- parton densities functions [0.1-0.2 GeV]
- b-tagging [0.1-0.8 GeV]



Data is used to constrain the various sources of uncertainties, e.g., gluon radiation

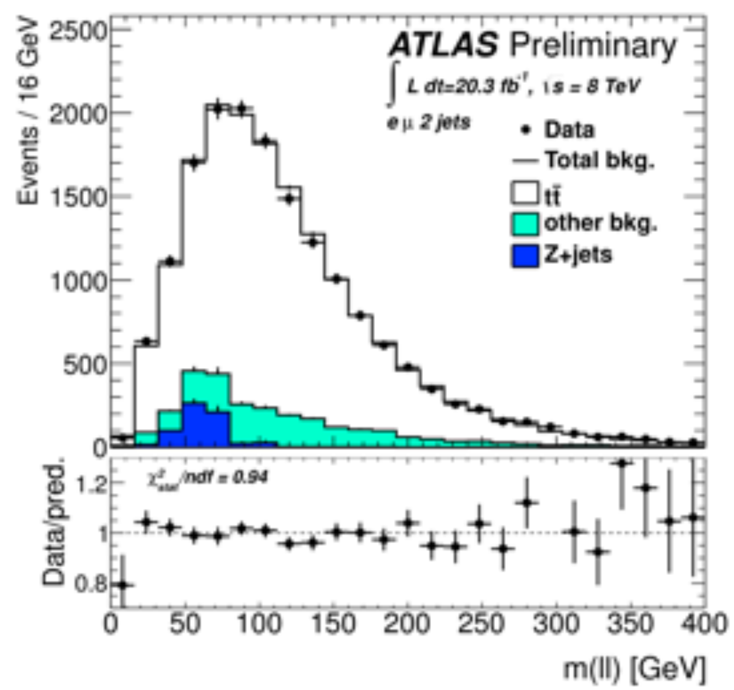
from Roberto Tenchini

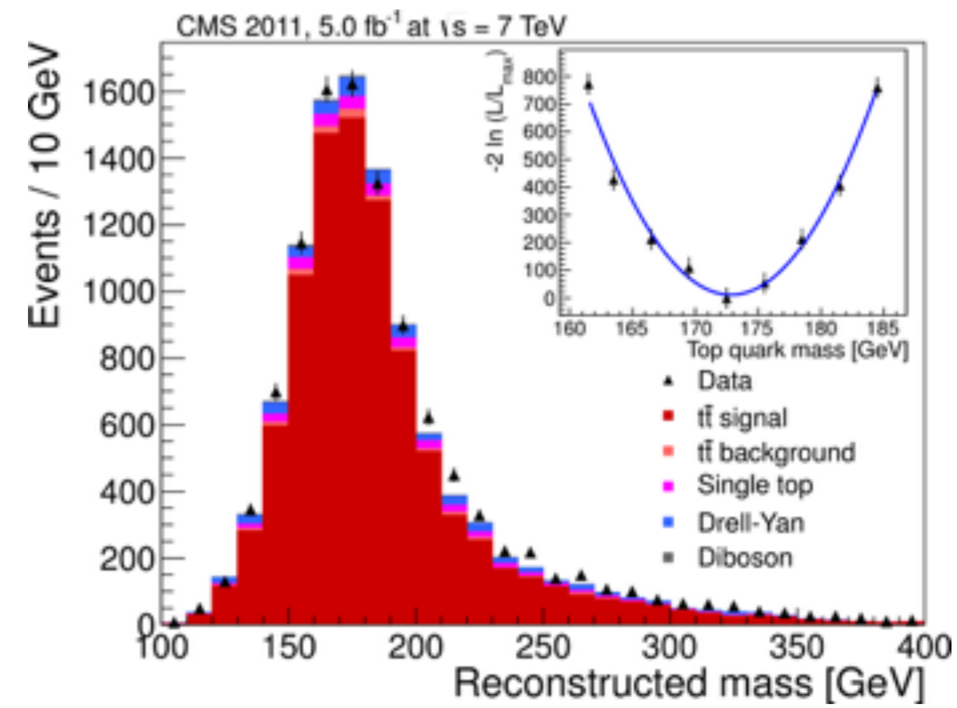
Other Channels

(illustration plots — not final — not comparable)

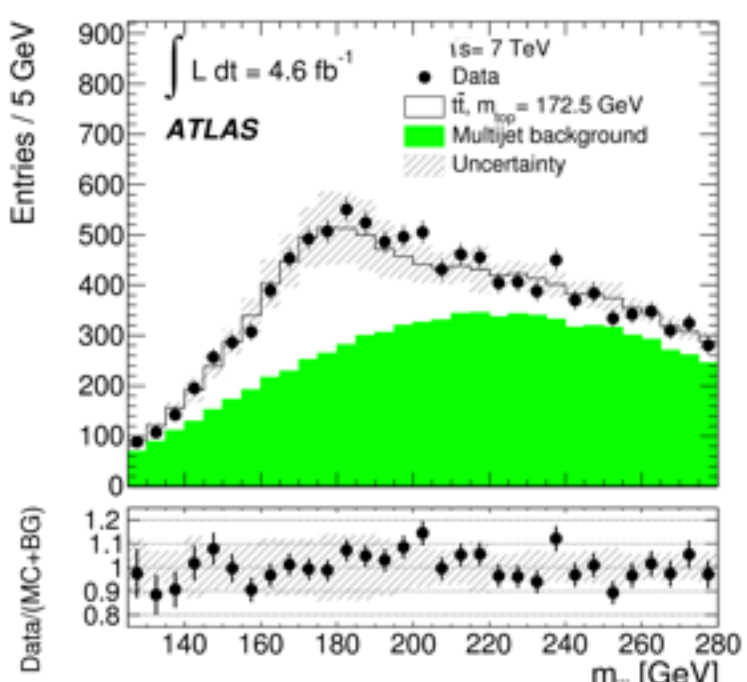
ATLAS | CMS

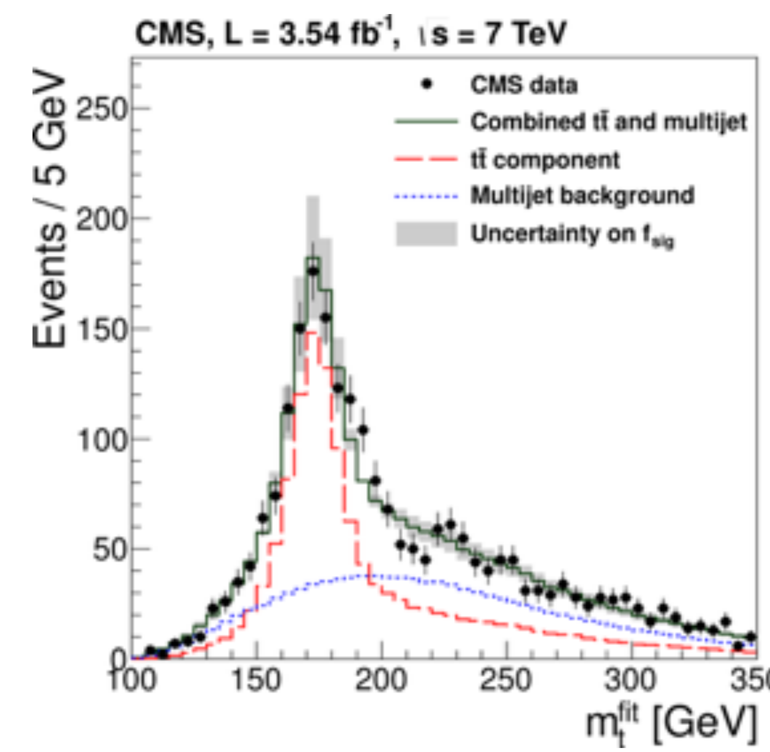
Dilepton



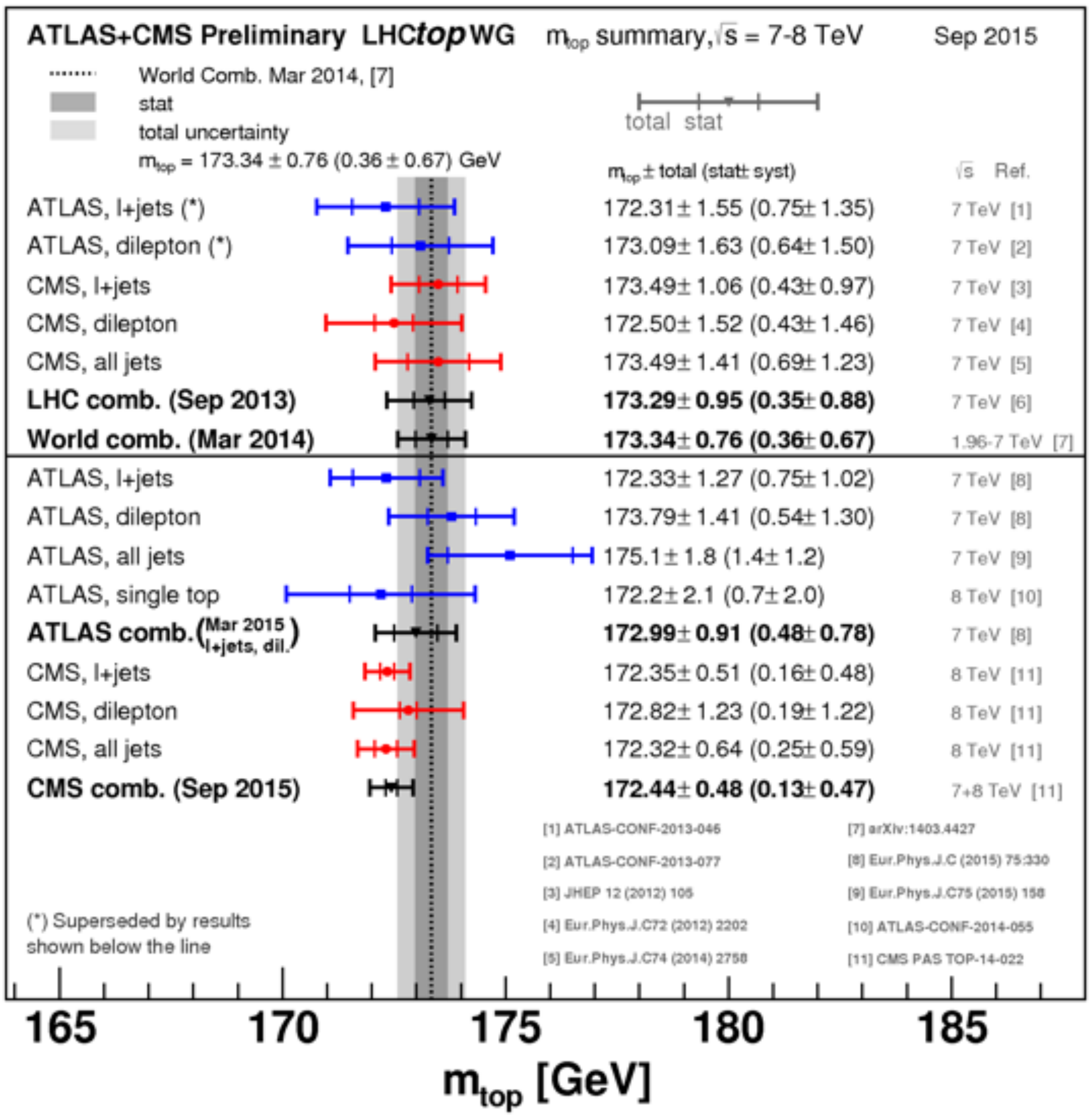


All hadronic





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

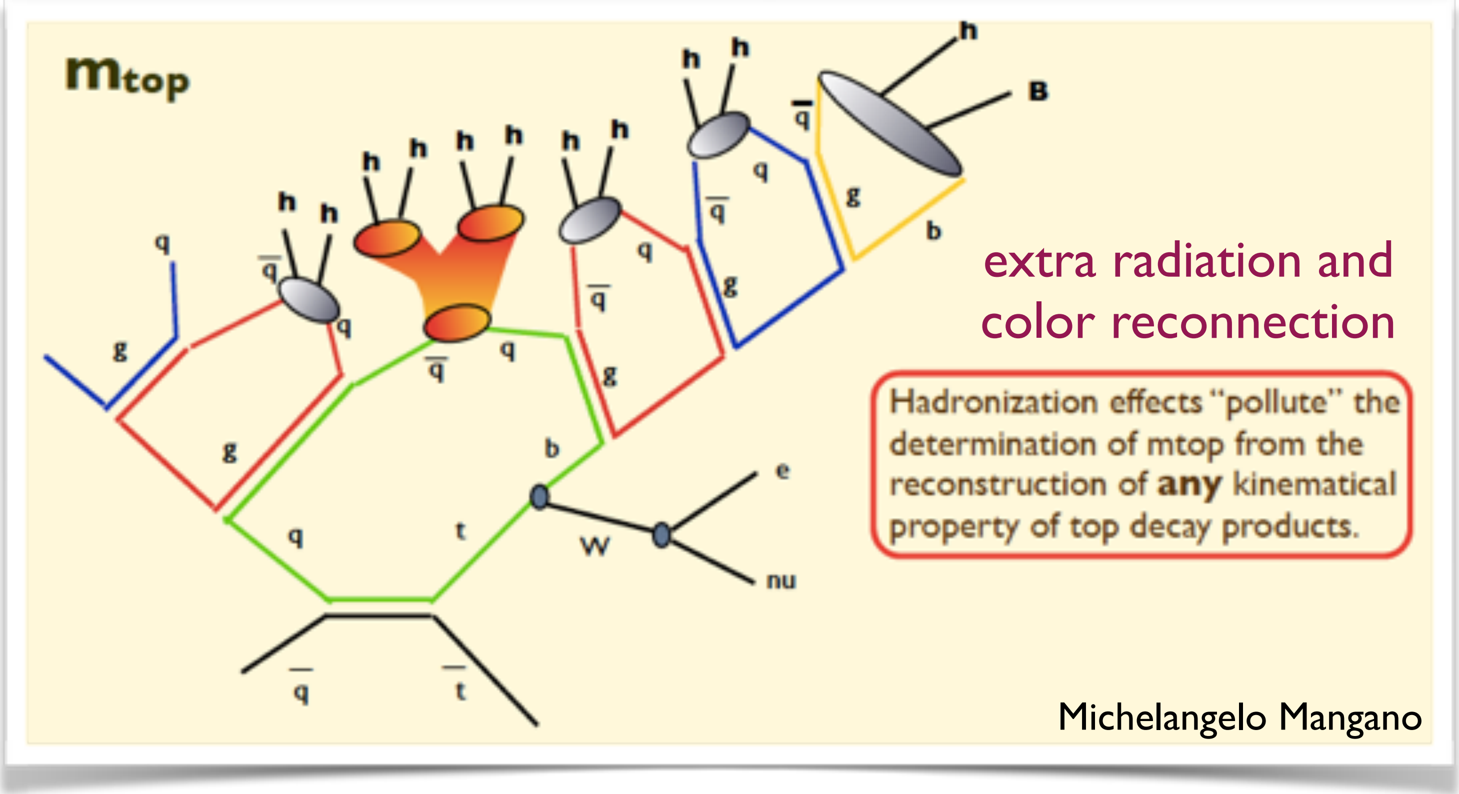
- excellent agreement between ATLAS and CMS

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} (≈ 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?

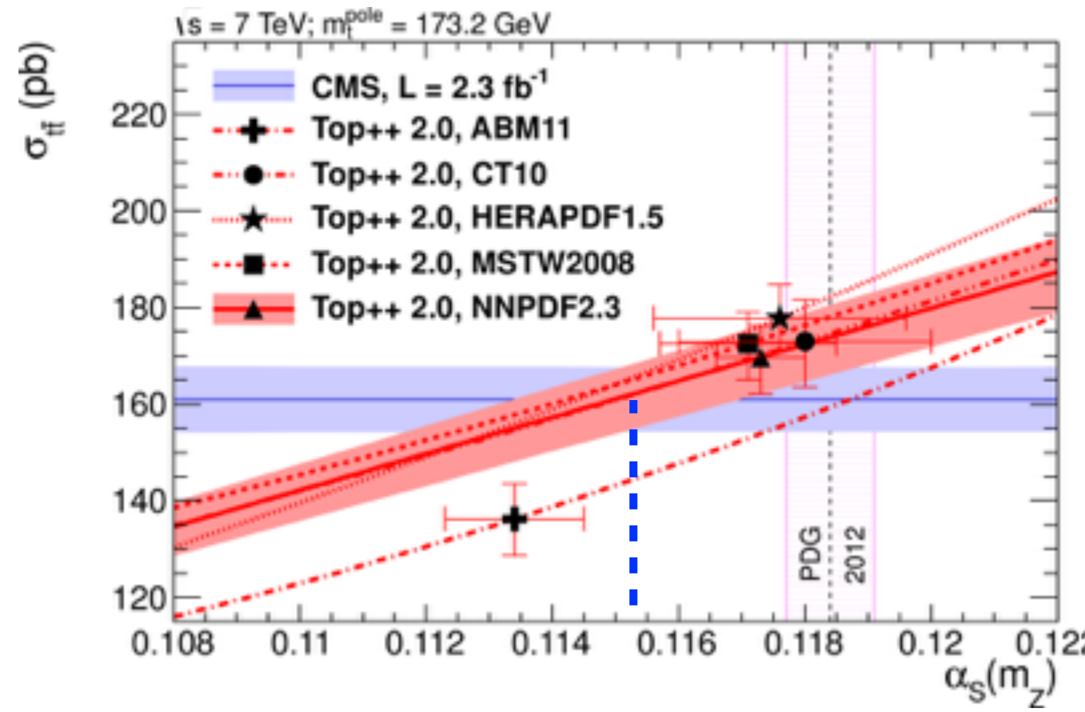


- Importance of measuring the mass using alternate techniques
  - mass and end point of $b\ell$ spectrum
  - decay length (boost) of B hadrons

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

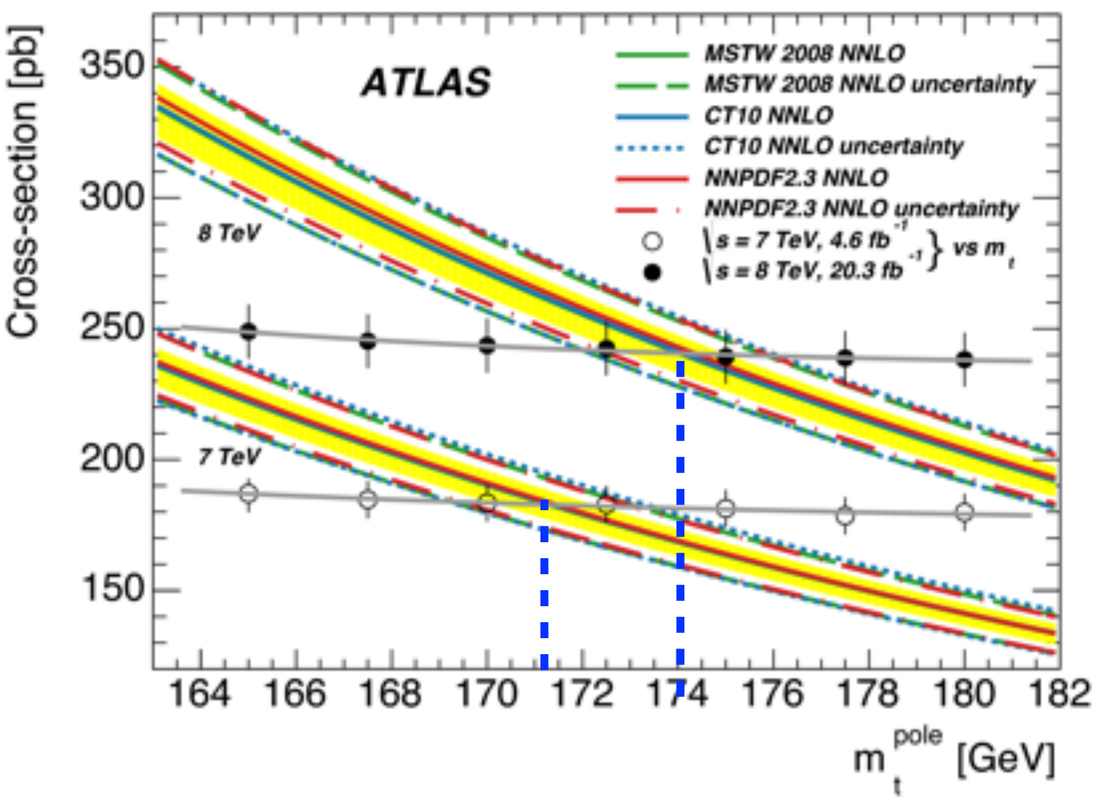
Mass from Cross Section

- 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



theo. 7 TeV

exp. 7TeV



exp. 8TeV

theo. 8 TeV

exp. 7TeV

theo. 7 TeV

From cross section:

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

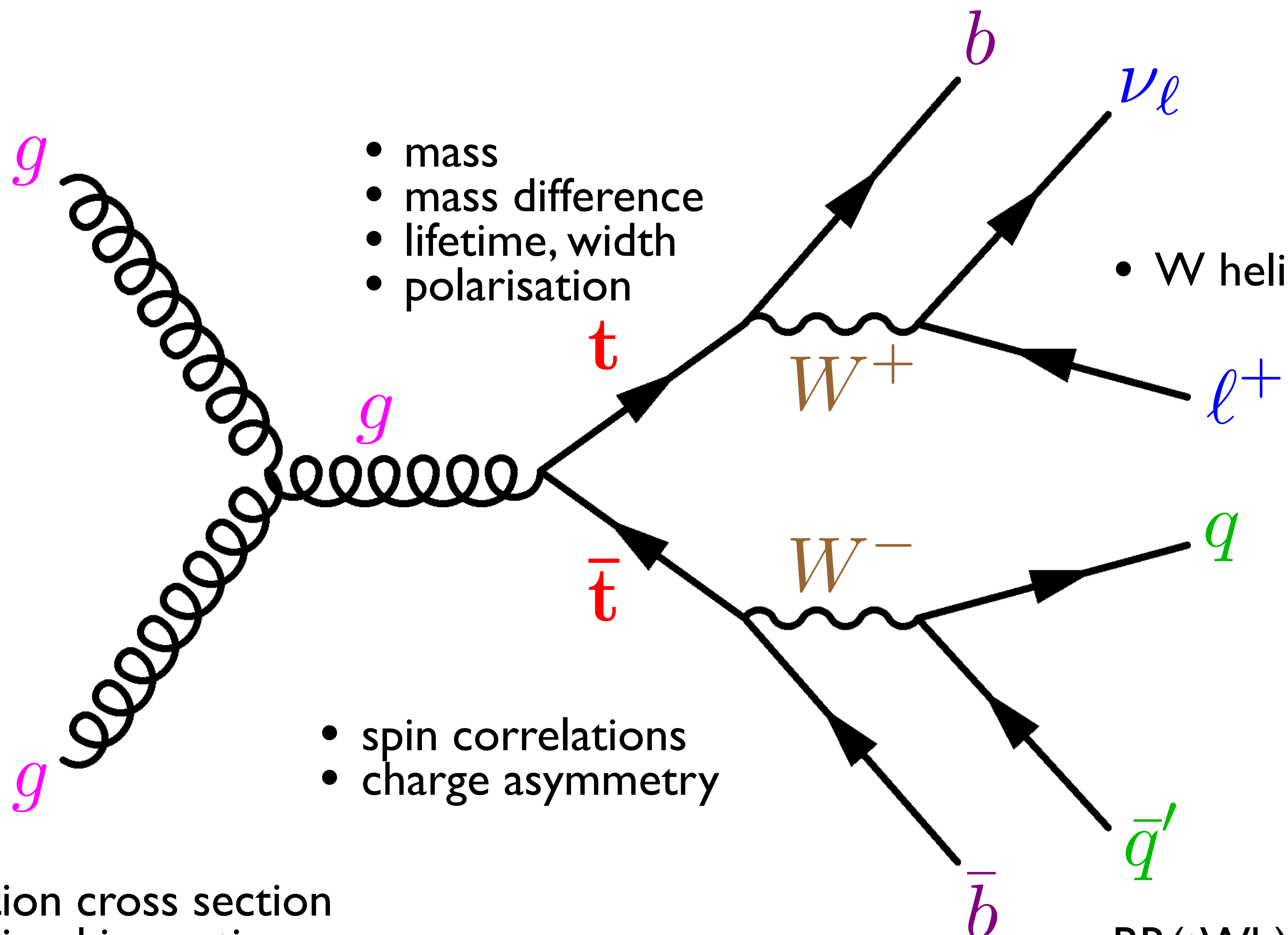
CMS (7 TeV): m_t = 176.7 ± 3.0 GeV

Direct:

World-14: m_t = 173.3 ± 0.8 GeV

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

Top Quark Properties



- mass
- mass difference
- lifetime, width
- polarisation

- W helicity

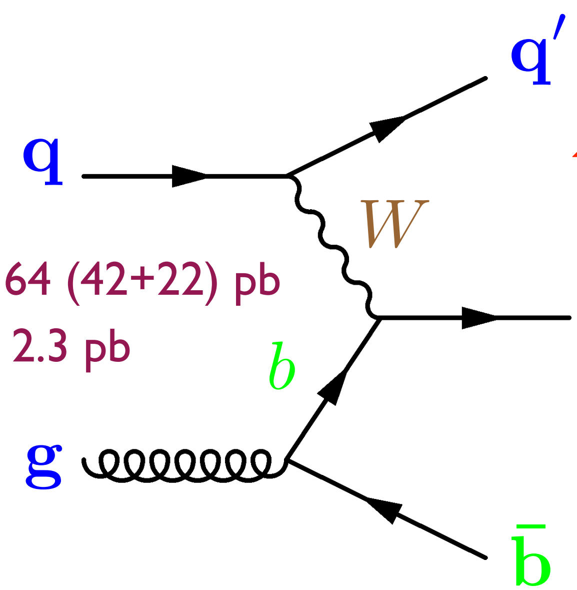
- spin correlations
- charge asymmetry

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

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

Single Top

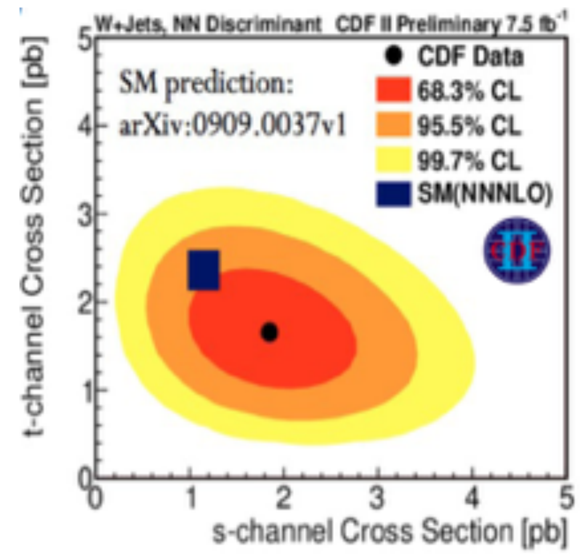
EW production of a top quark

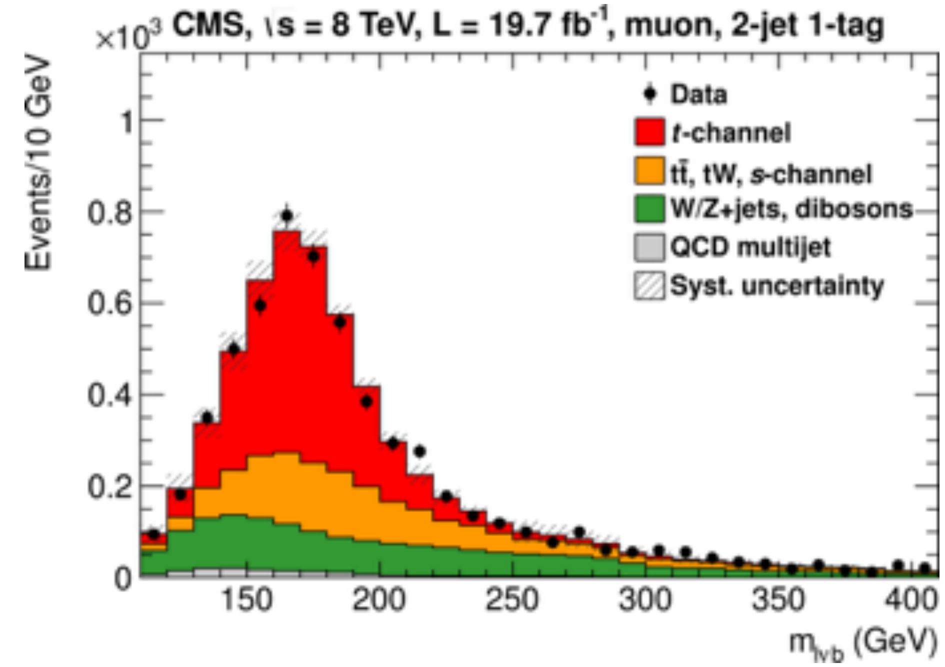


t-channel

LHC 64 (42+22) pb

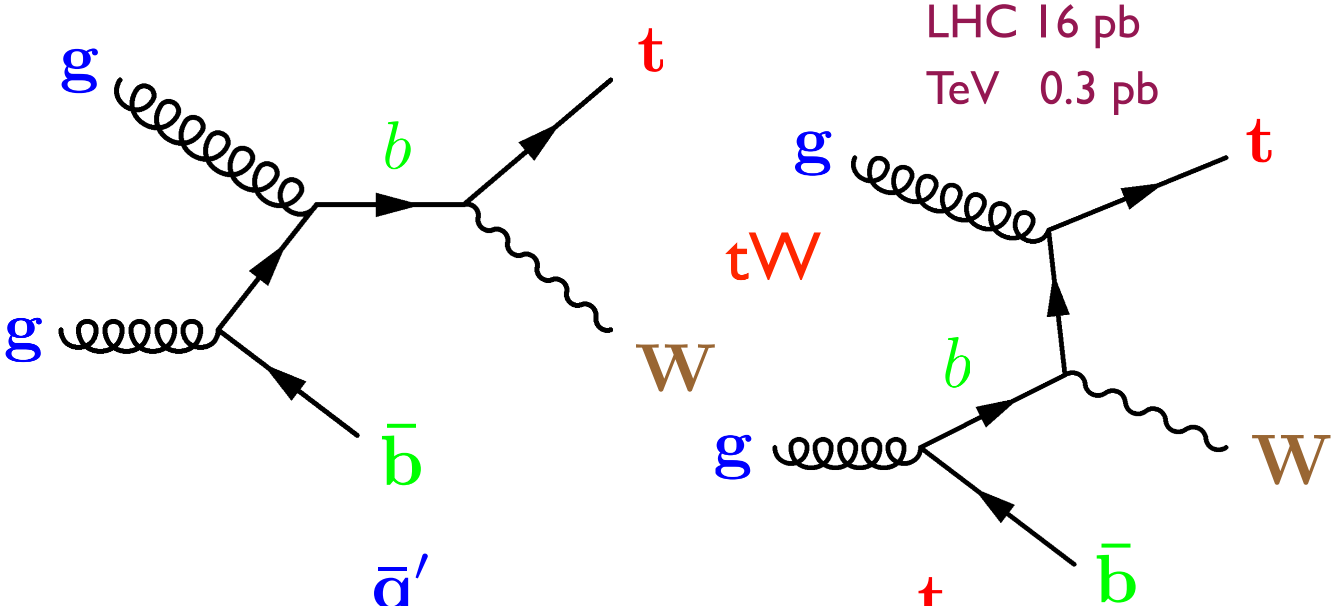
TeV 2.3 pb

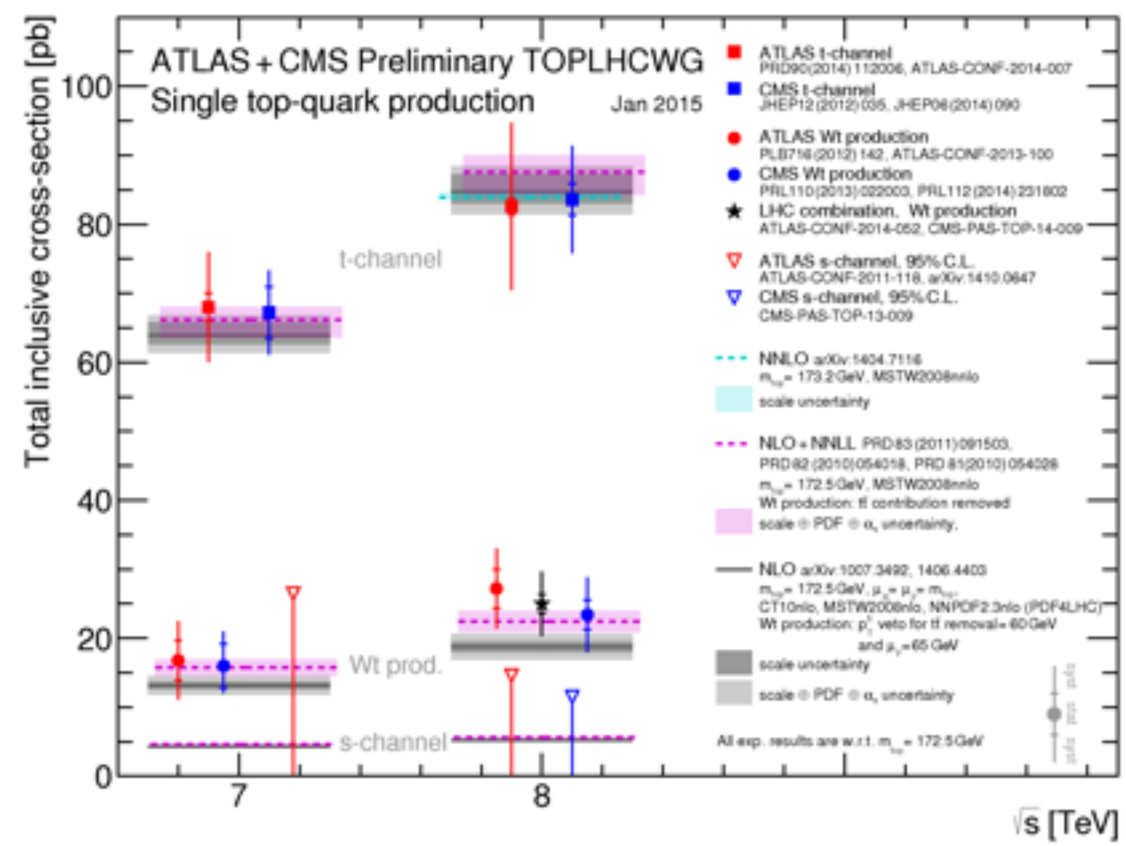


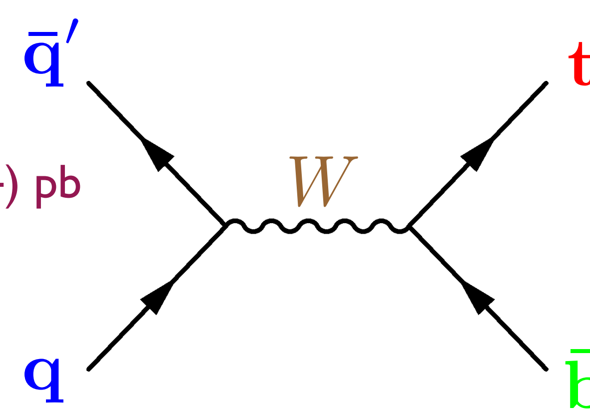


LHC 16 pb

TeV 0.3 pb







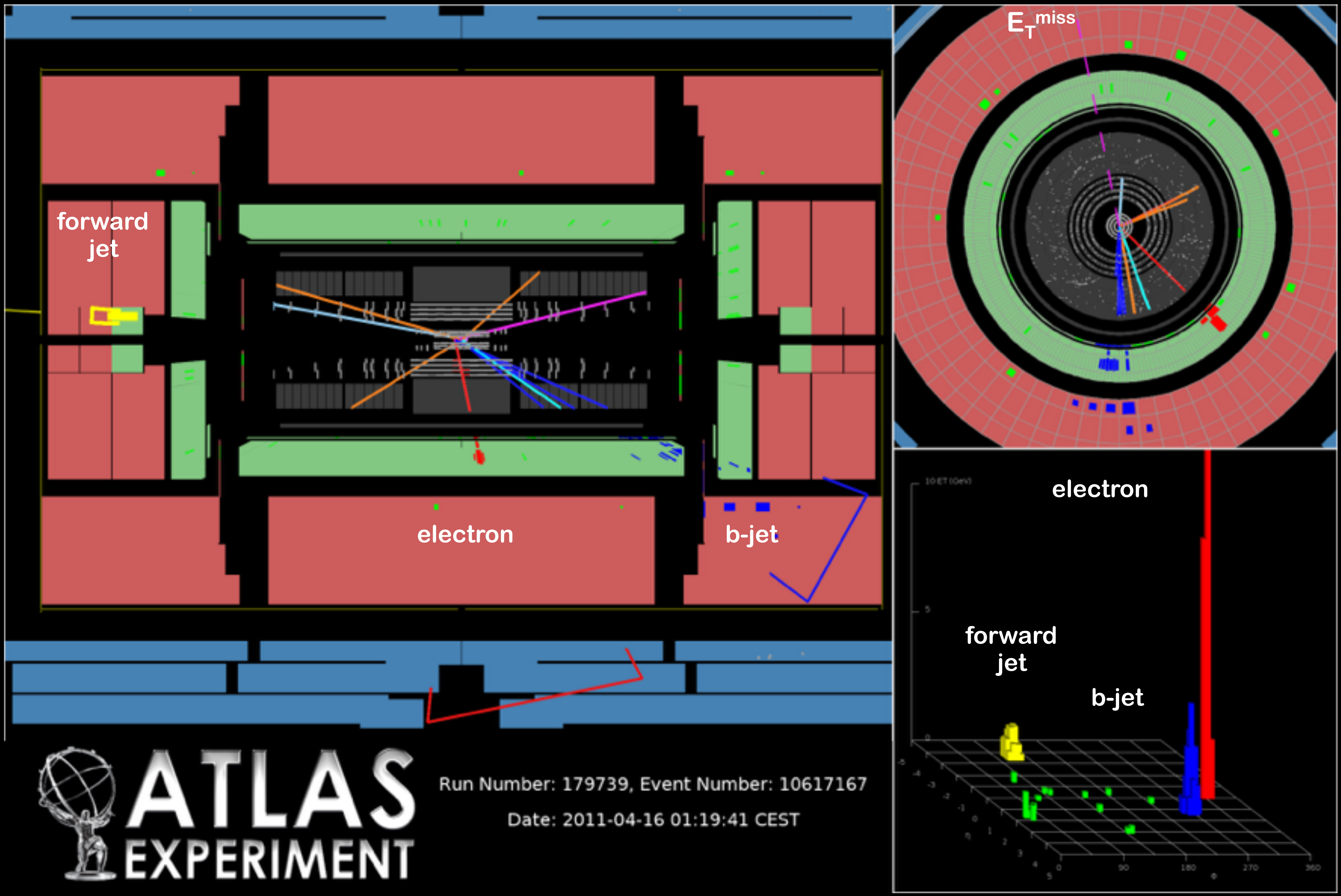
LHC 4.5 (3.2+1.4) pb

TeV 1.00 pb

s-channel

allows direct measurements of V_{tb}

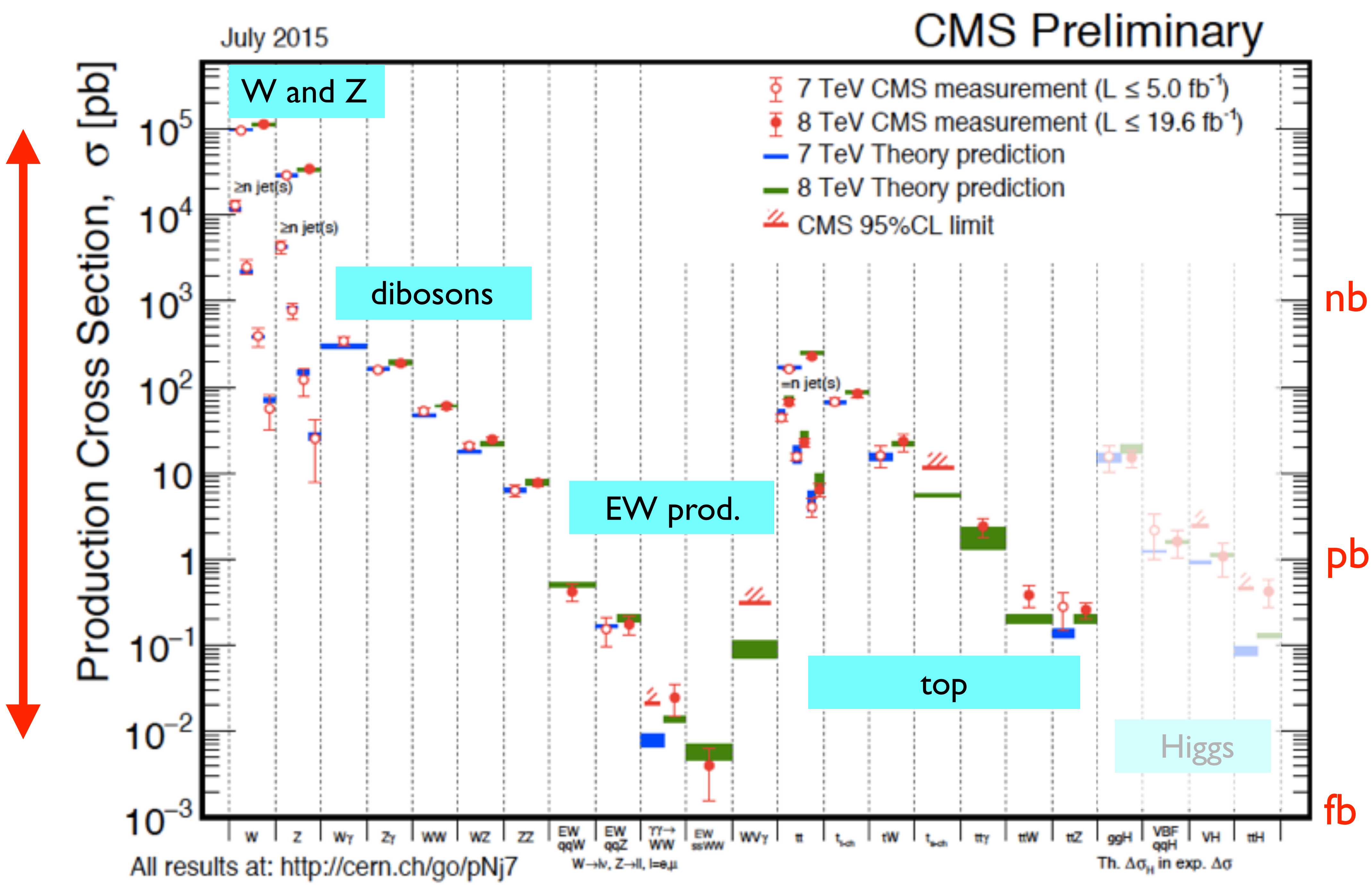
Single Top Candidate (t-channel)



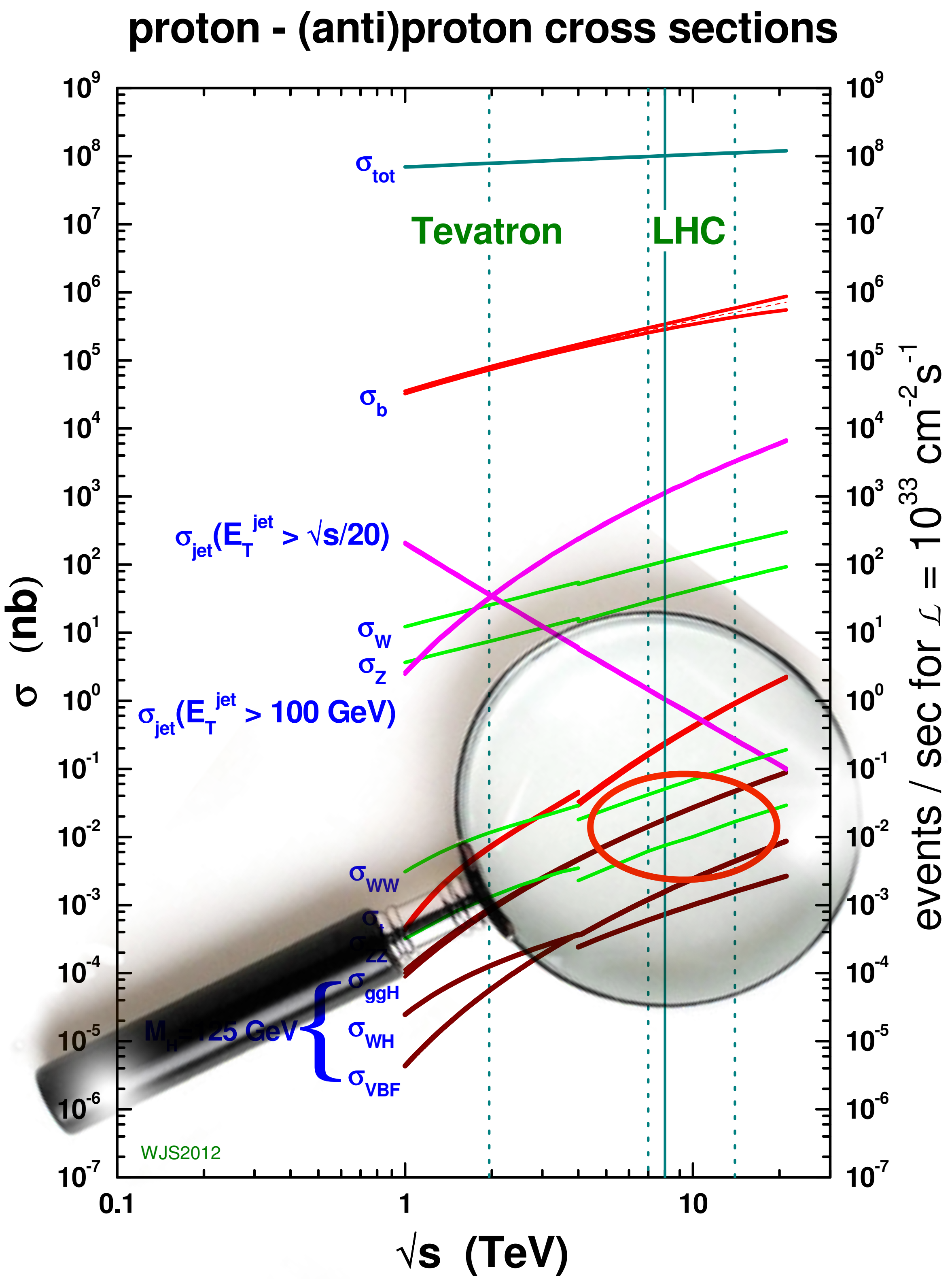
Summary of SM Measurements

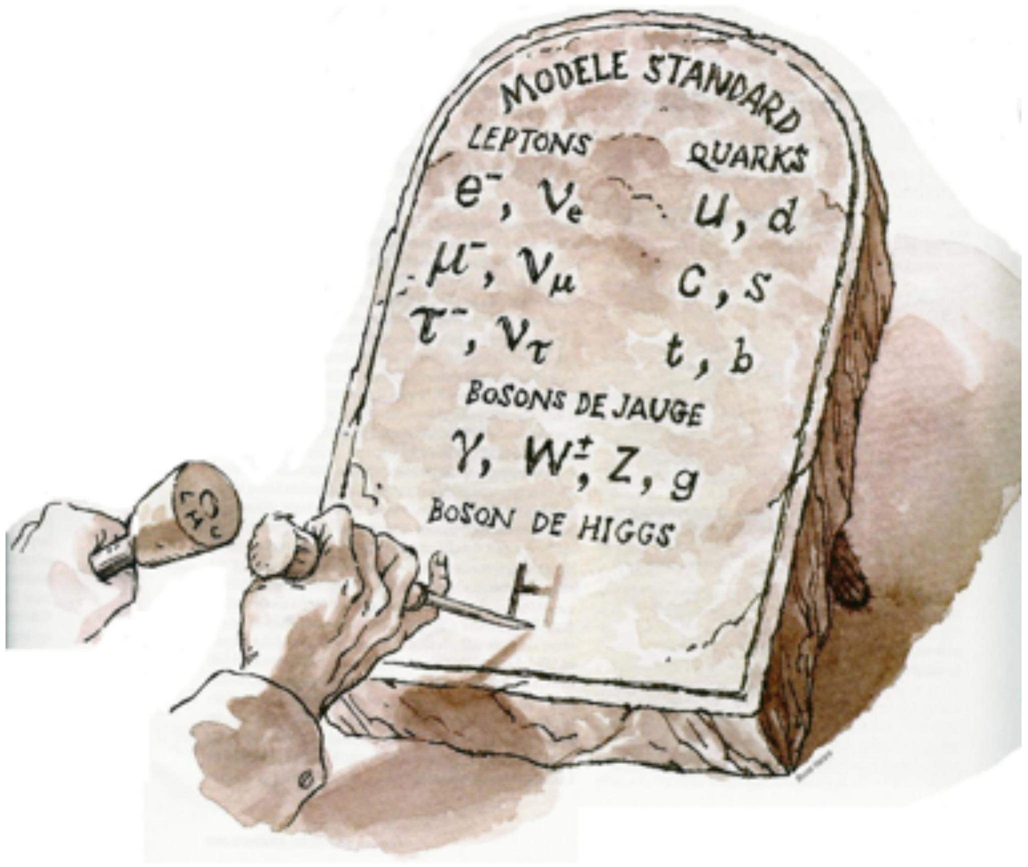
~ 70 billion inelastic collisions

Seven orders of magnitude



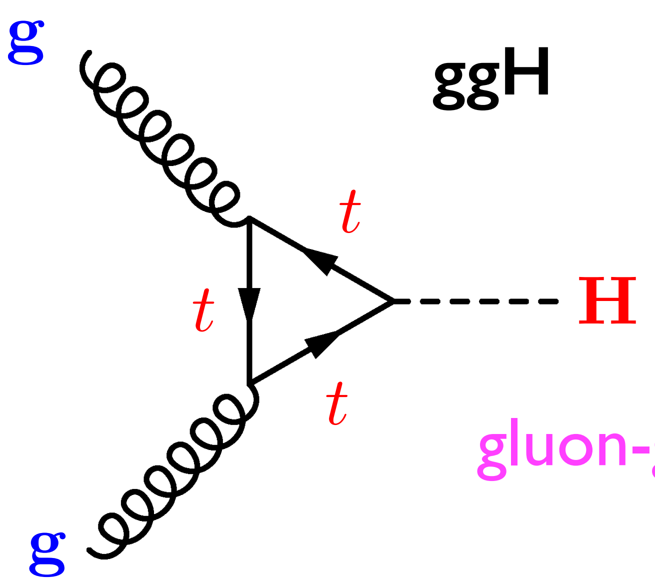
Higgs Physics





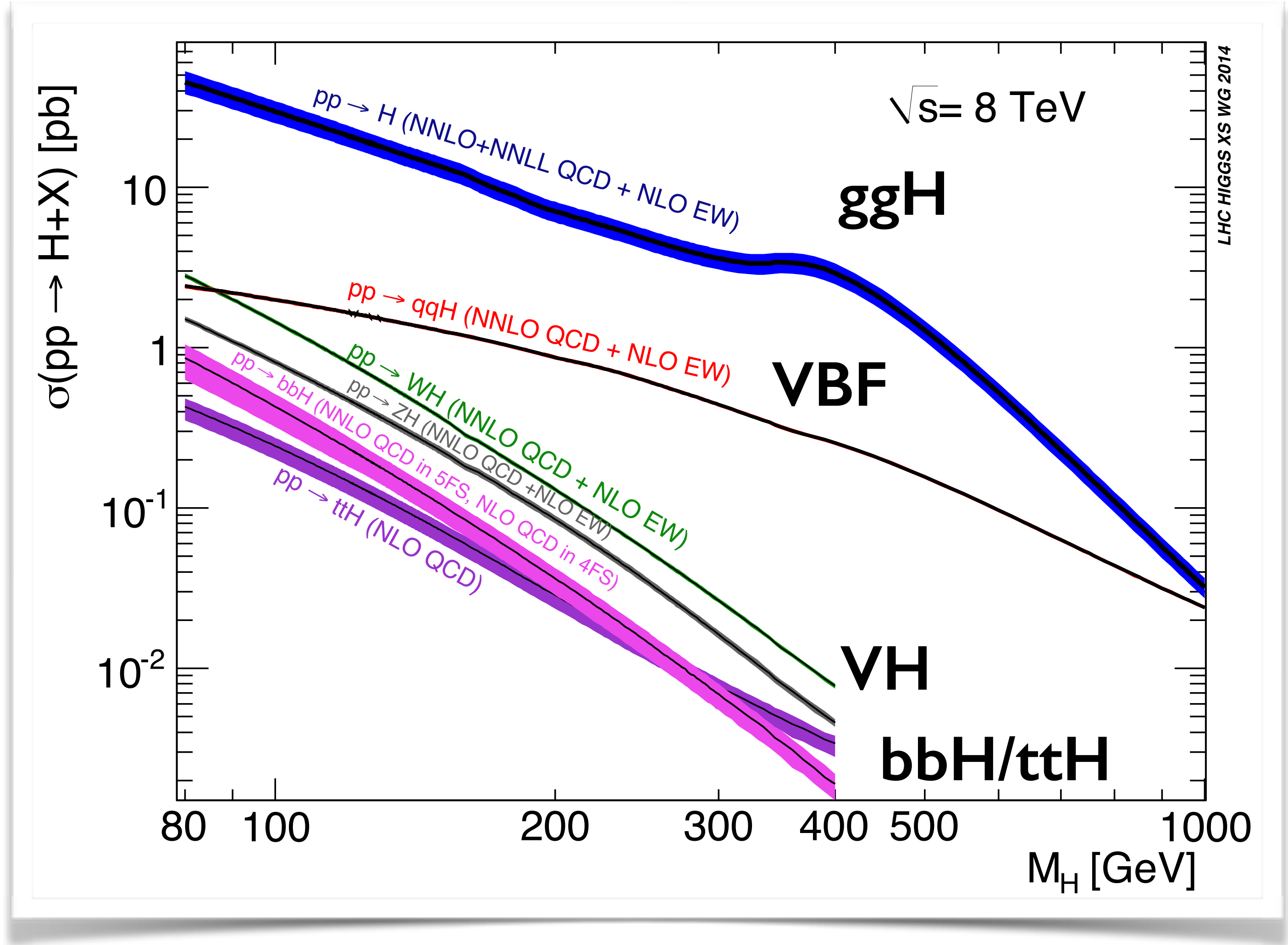
Production of the Higgs Boson

ggH

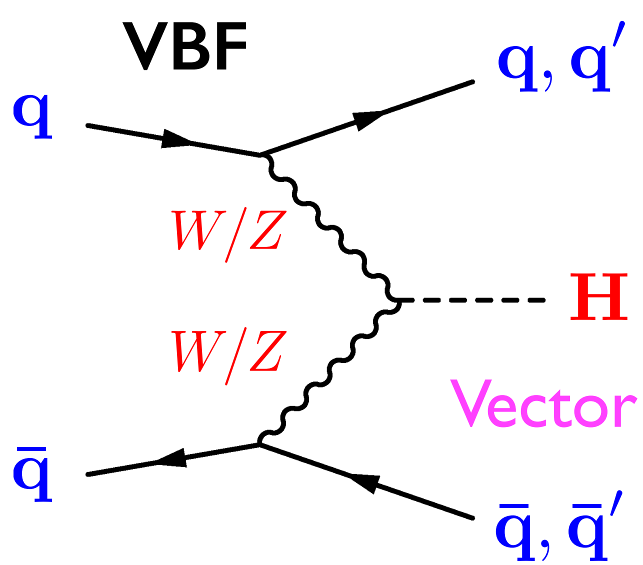


86%

gluon-gluon Fusion



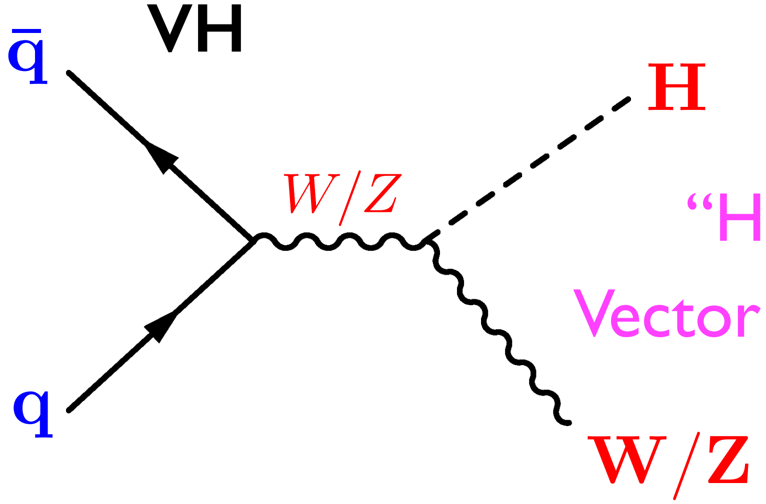
VBF



7%

Vector Boson Fusion

VH

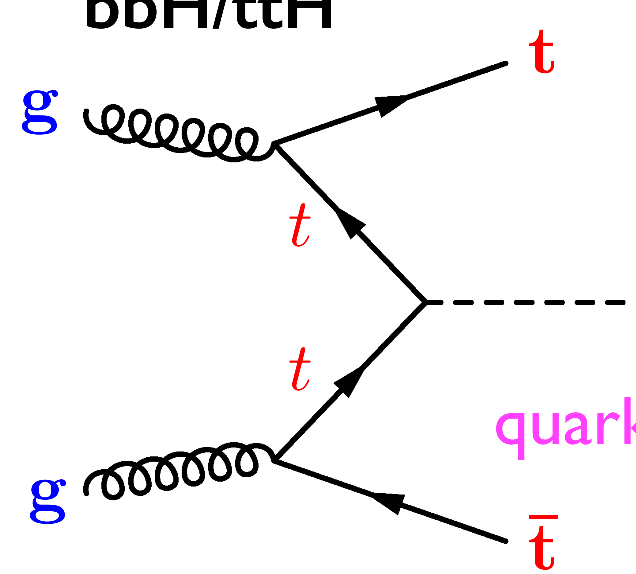


5%

"Higgsstrahlung"

Vector Boson associated

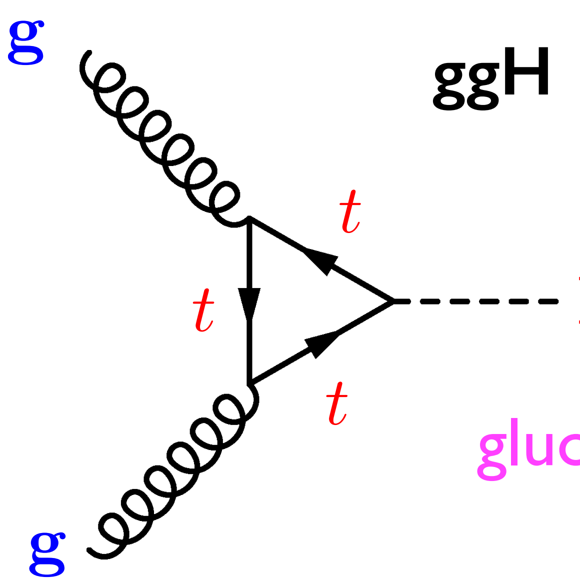
bbH/ttH



<2%

quark pair associated

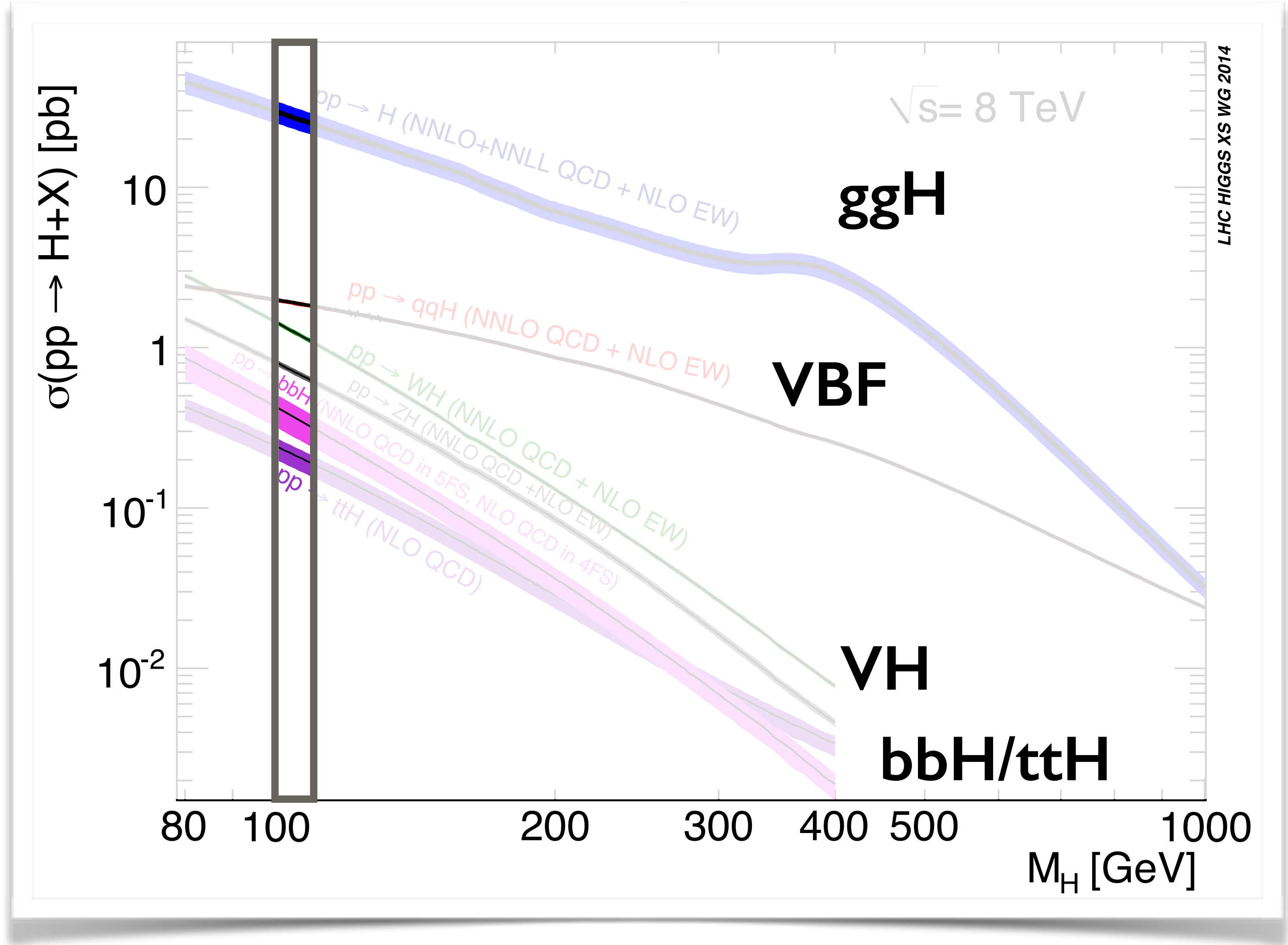
Production of the Higgs Boson



ggH

86%

gluon-gluon Fusion



Cross sections (m_H = 125 GeV)

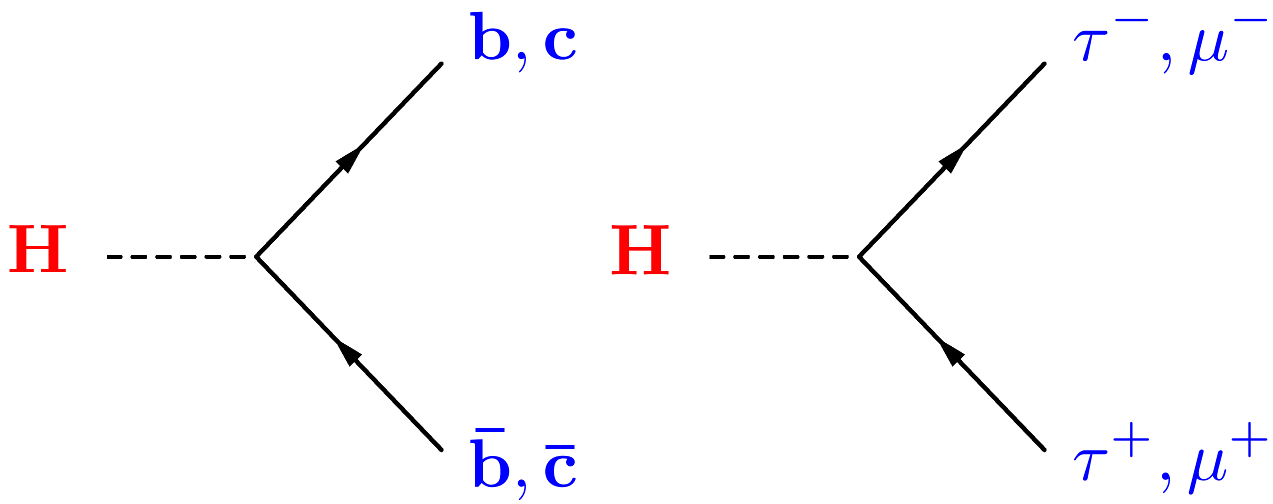
- Tevatron 1.96 TeV
  1.2 pb
  ggH=78% VH=17% VBF=5%
- LHC 8 TeV
  23 pb
  ggH=86% VBF=7% VH=5% ttH<1%
- LHC 13 TeV
  51 pb
  ggH=86% VBF=7% VH=4% ttH=1%

Typical theory uncertainties

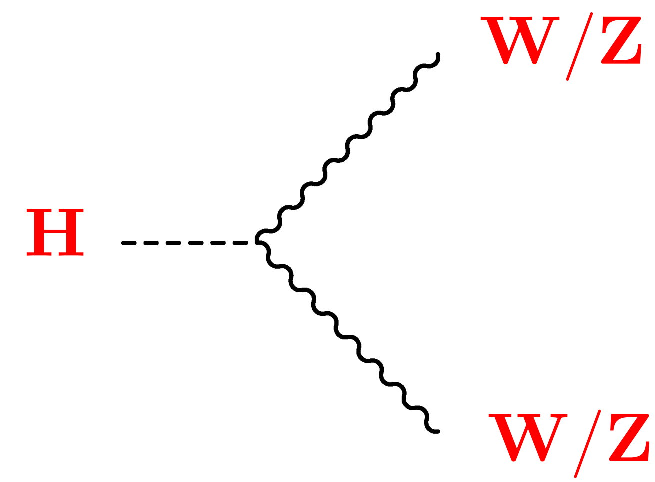
- ggH 15% NNnLO
- VBF 5% NLO
- VH 5% NNLO
- ttH 15% LO

Decays of the Higgs Boson

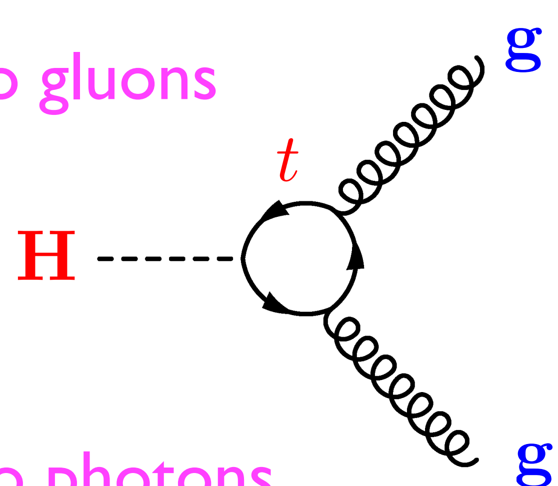
Decays to fermions (quarks and leptons)



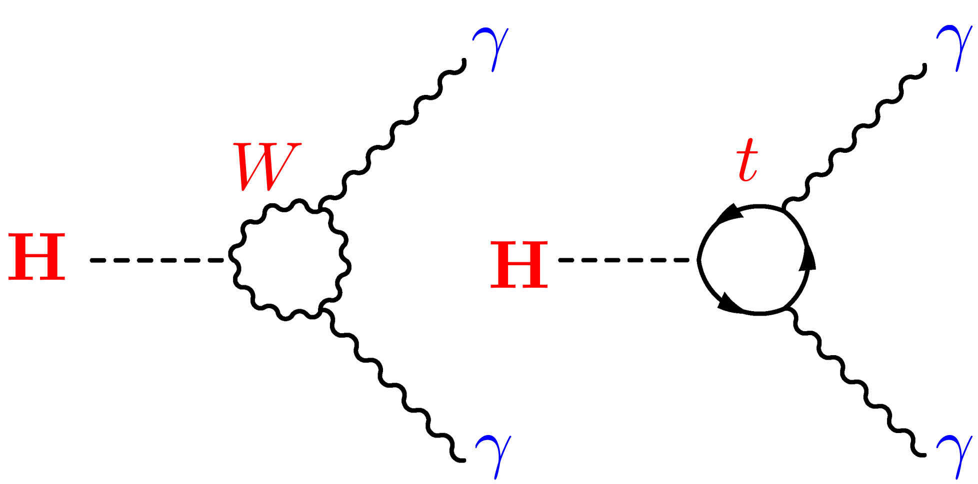
Decays to EW vector bosons

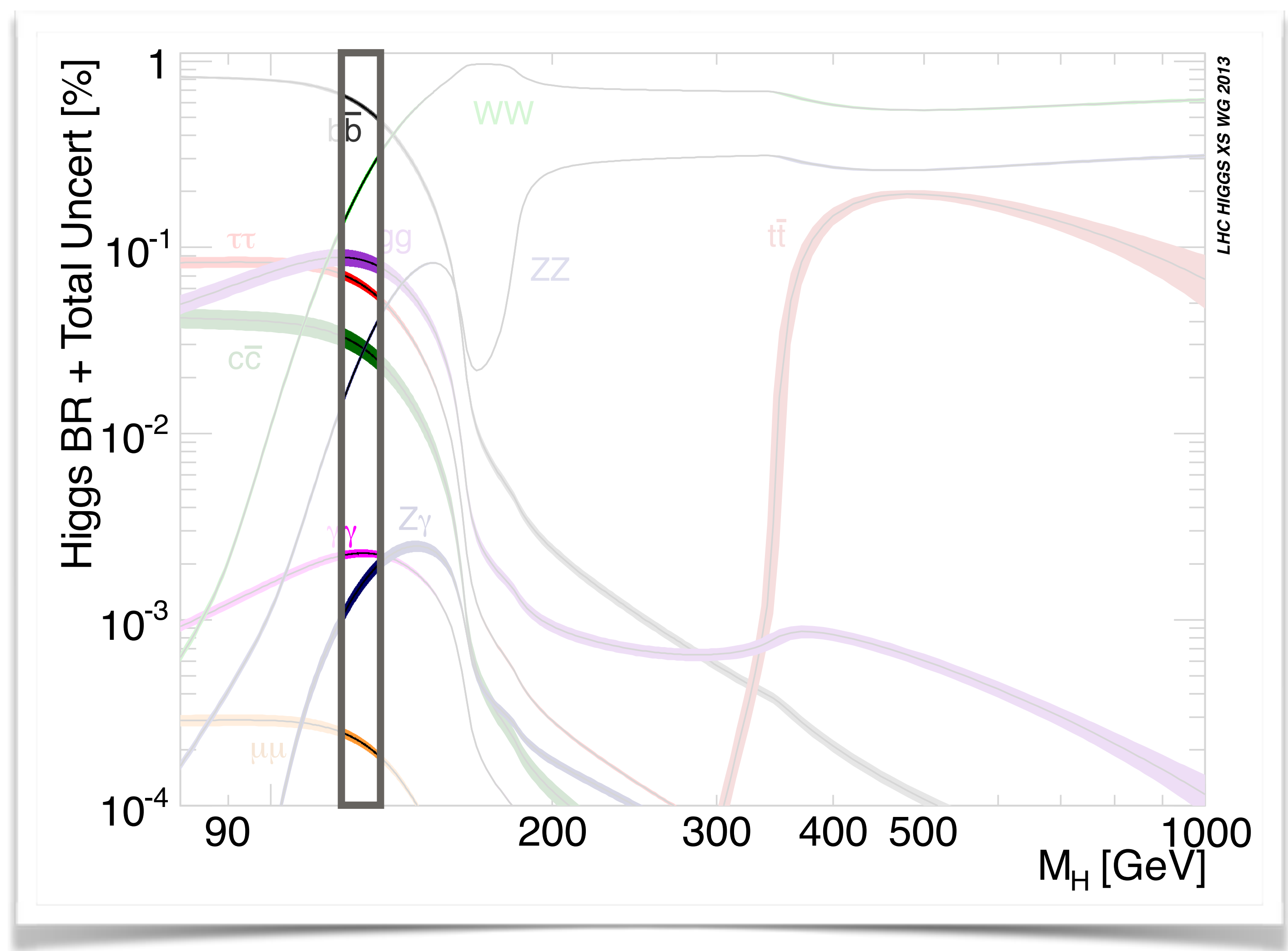


Decay to gluons

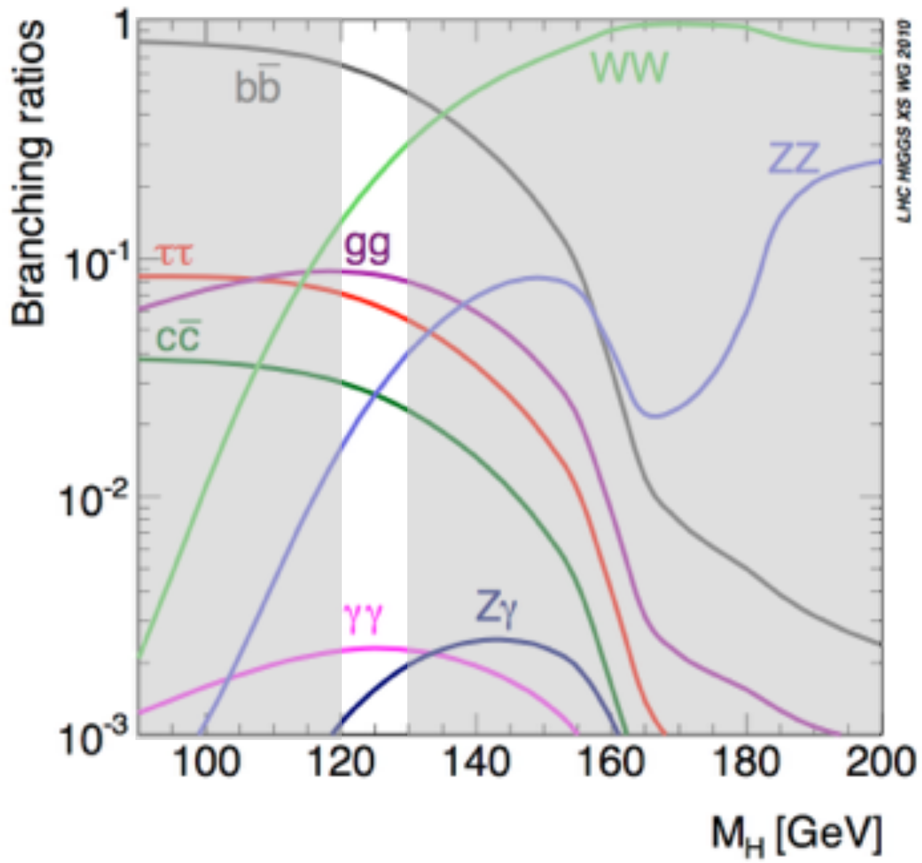


Decay to photons



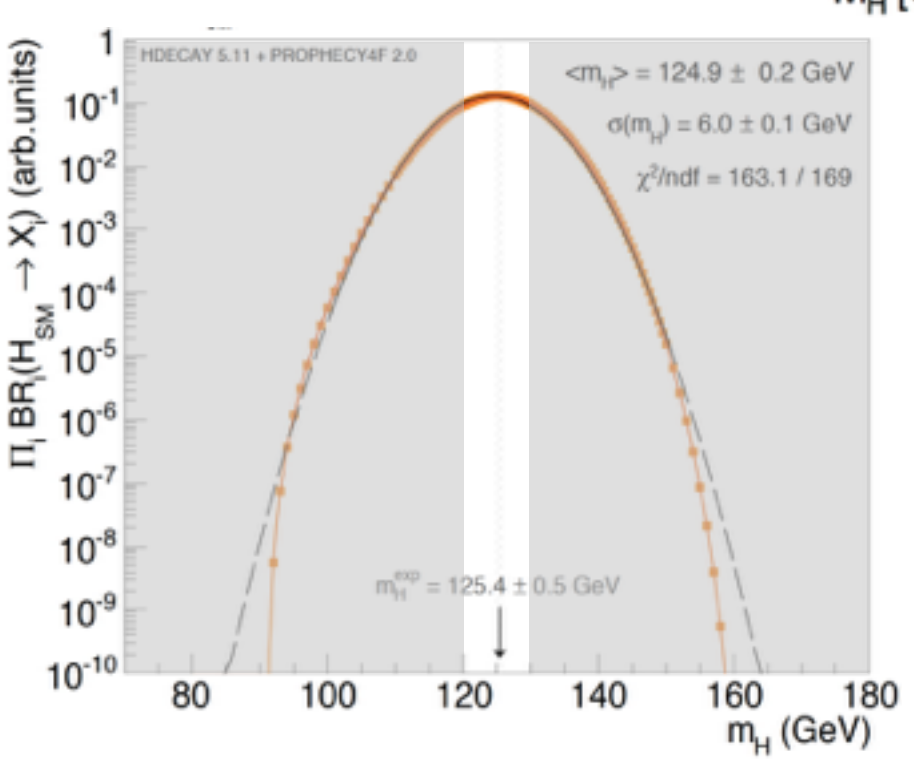


Decays at m_H = 125 GeV



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%



D. d'Enterria arXiv:1208.1993

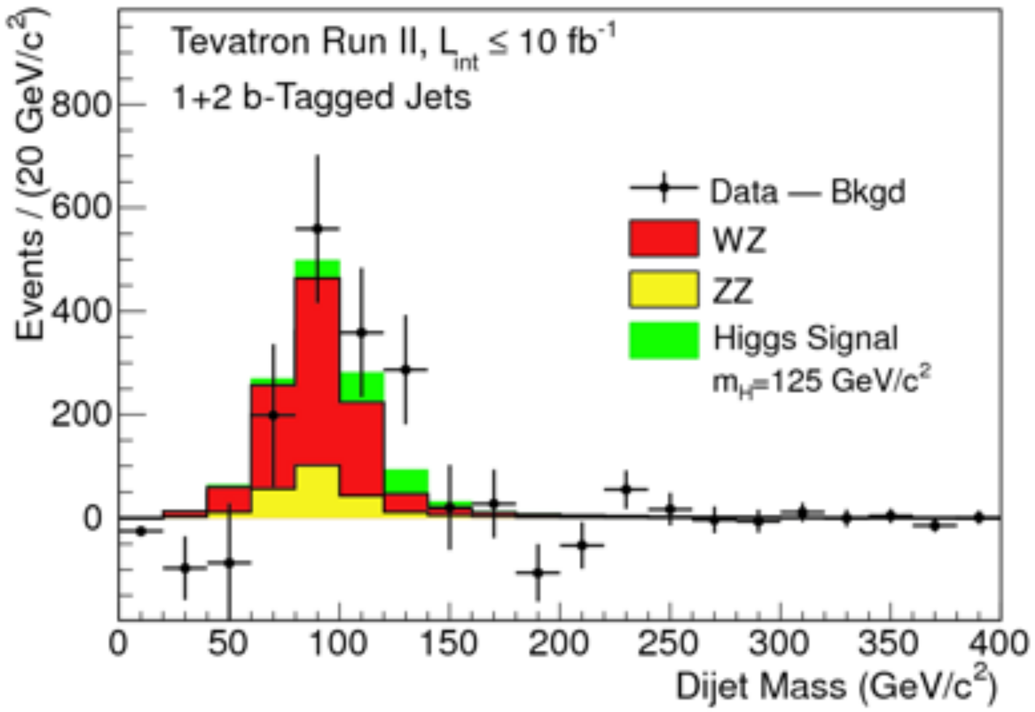
product of decay fractions

Nature has be kind to us

F. Gianotti

only about 11% of
Higgs bosons decays
are unobservable

Higgs Searches at the Tevatron



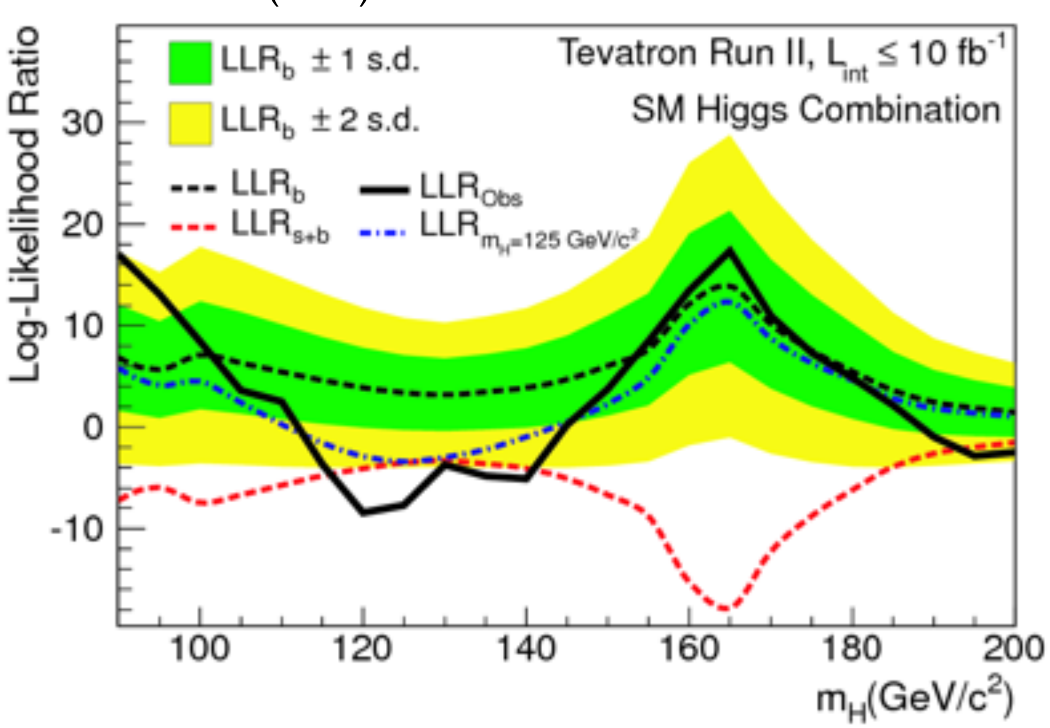
The Tevatron is sensitive to the signal in

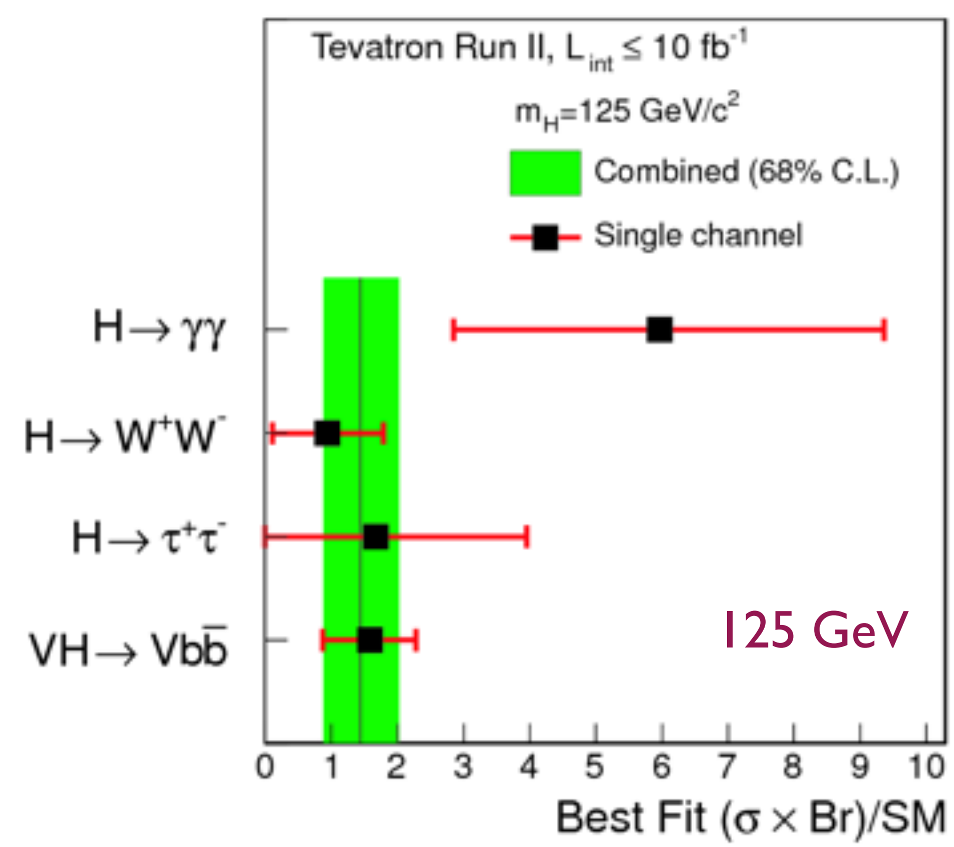
- the WW channel (for m_H around 160 GeV)
- the VH(→bb) channel

The combined CDF+D0 analysis shows an excess with local significance of 3σ at 125 GeV

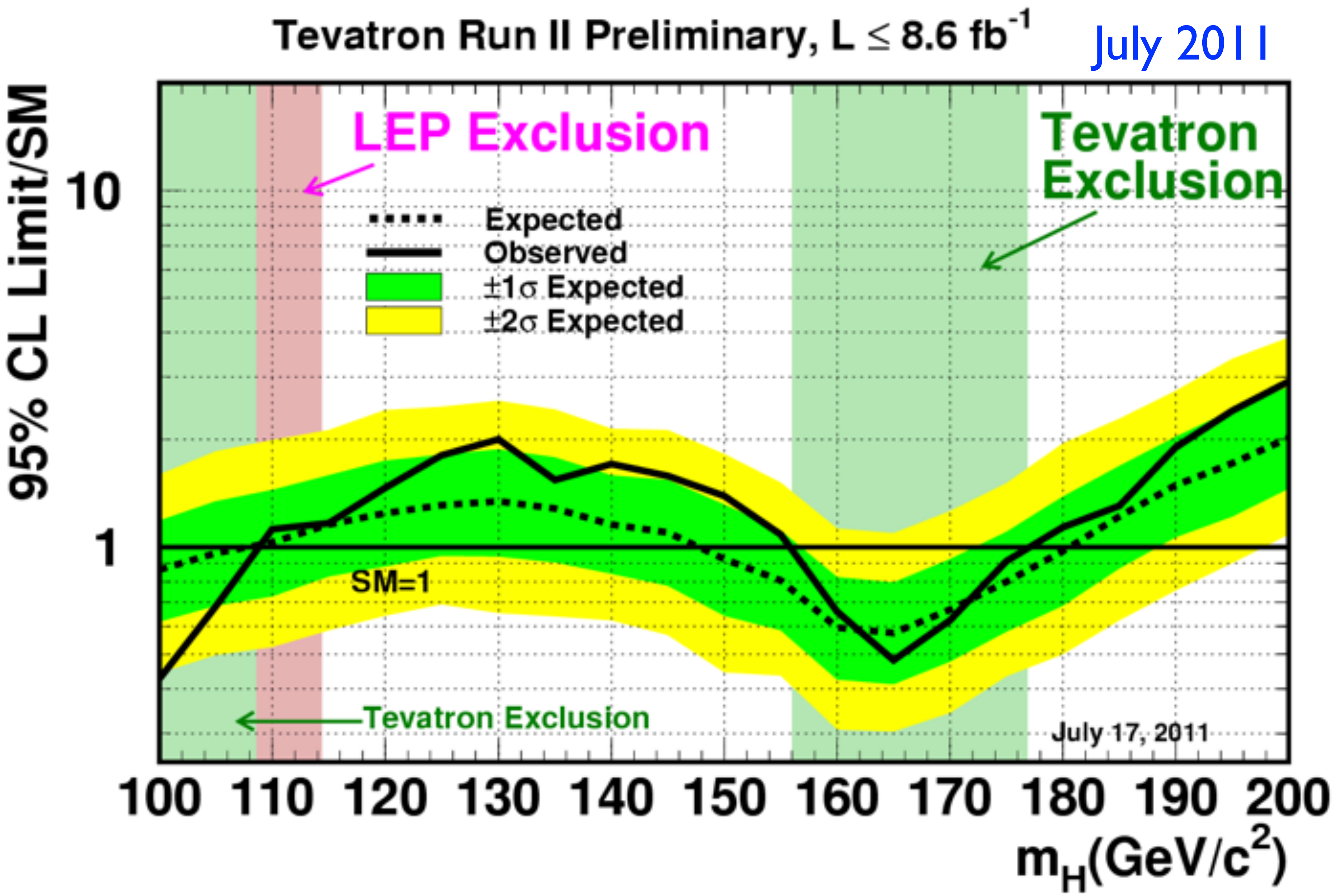
- consistent with the LHC discovery

PRD 88 (2013) 052014





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

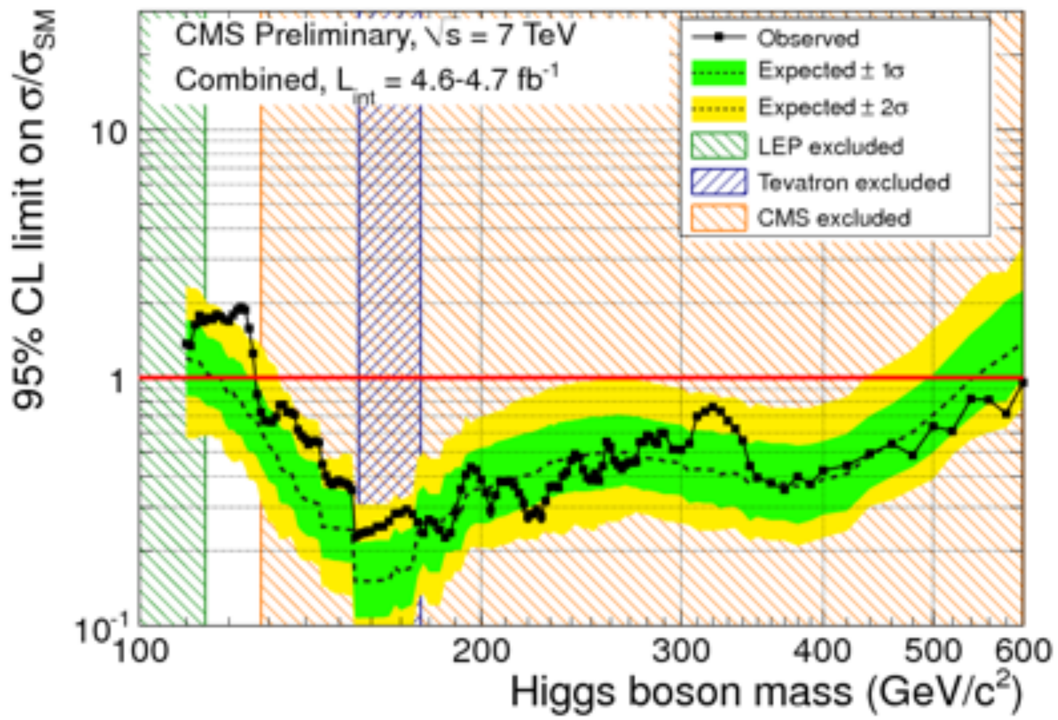
(this introduces some level of model dependence)

Higgs Searches at the LHC

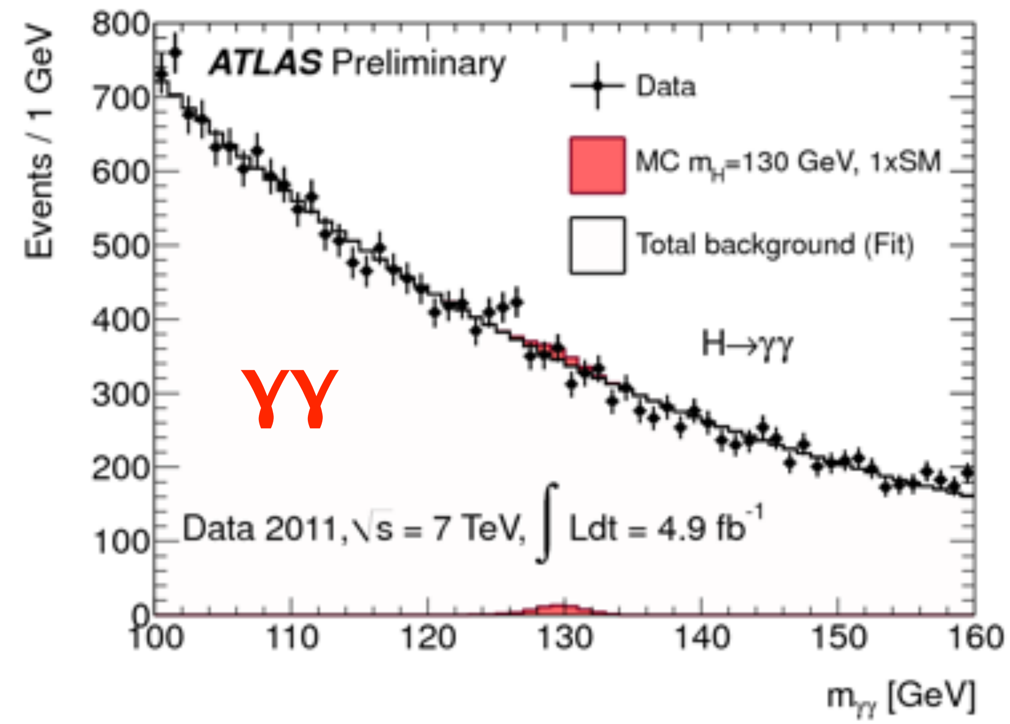
At the end of 2011 (CERN Jamboree)

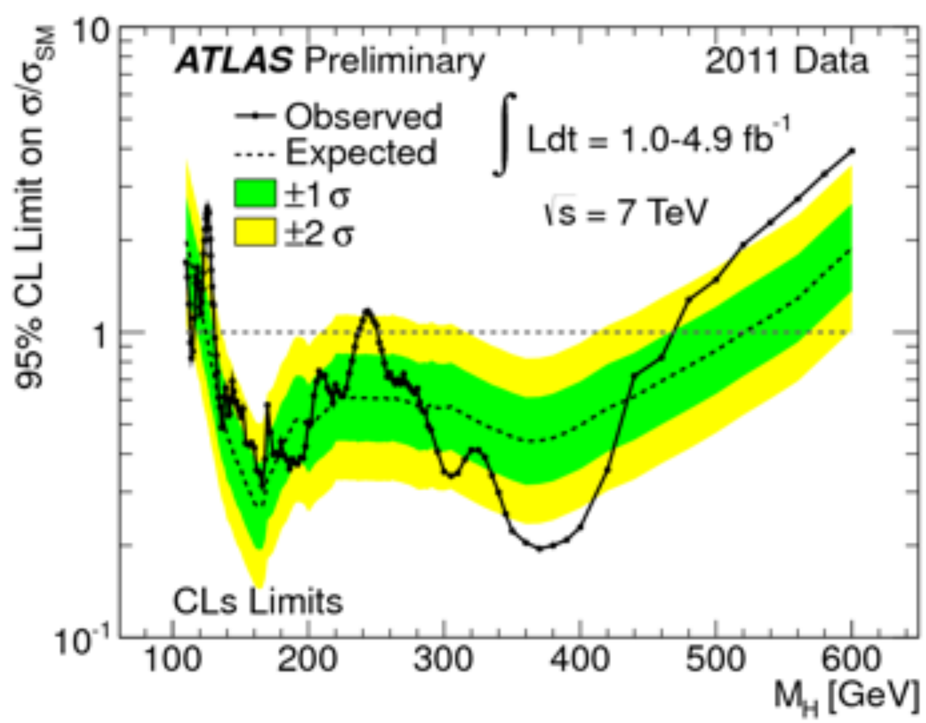
about 5 fb^{-1} / exp.

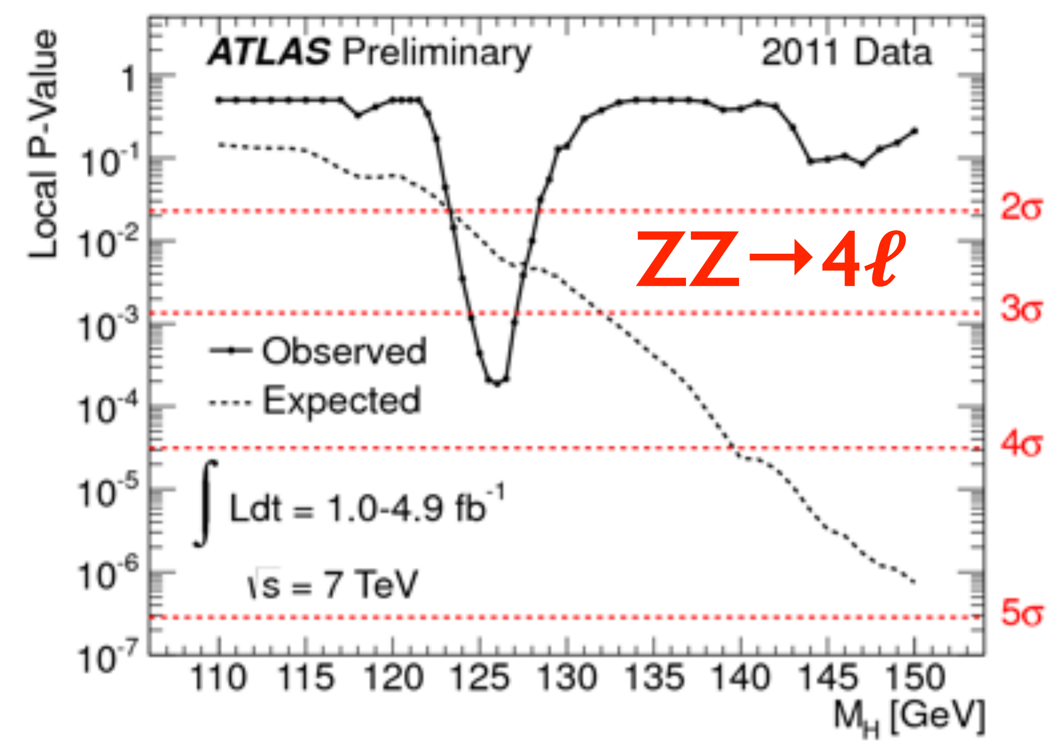
CMS: exclusion: m_H > 127 GeV



First hints of signal in ATLAS

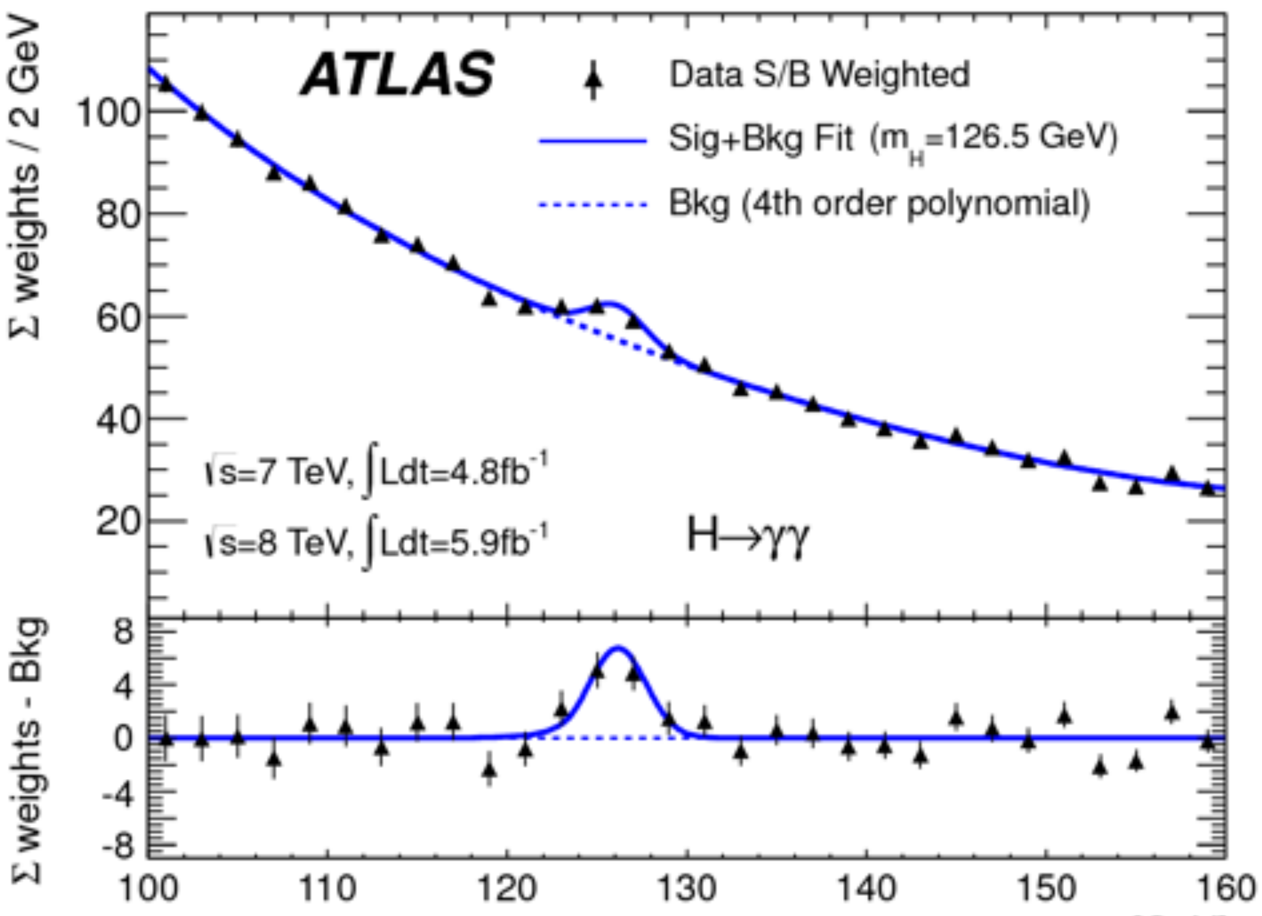




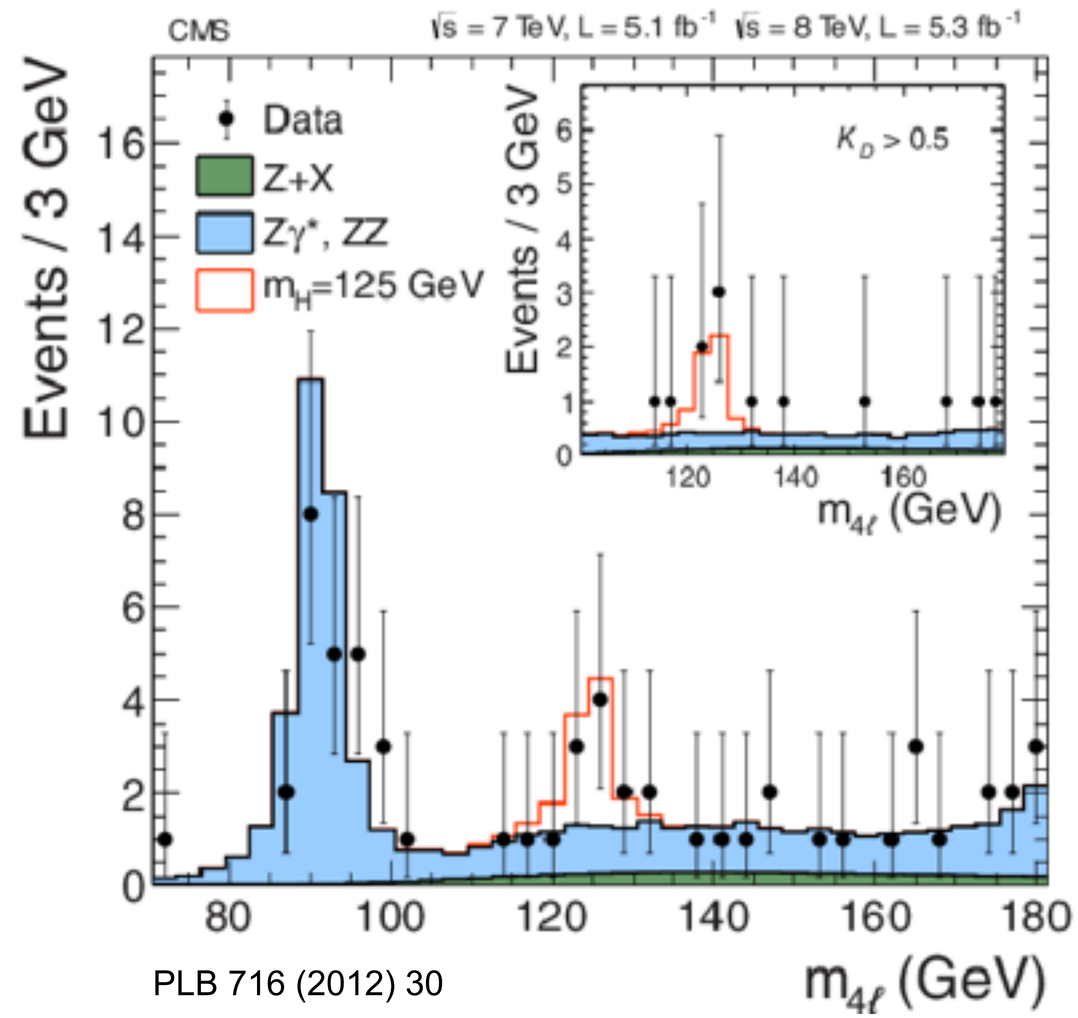


CERN 4 July 2012

The Discovery



PLB 716 (2012) 1



PLB 716 (2012) 30

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

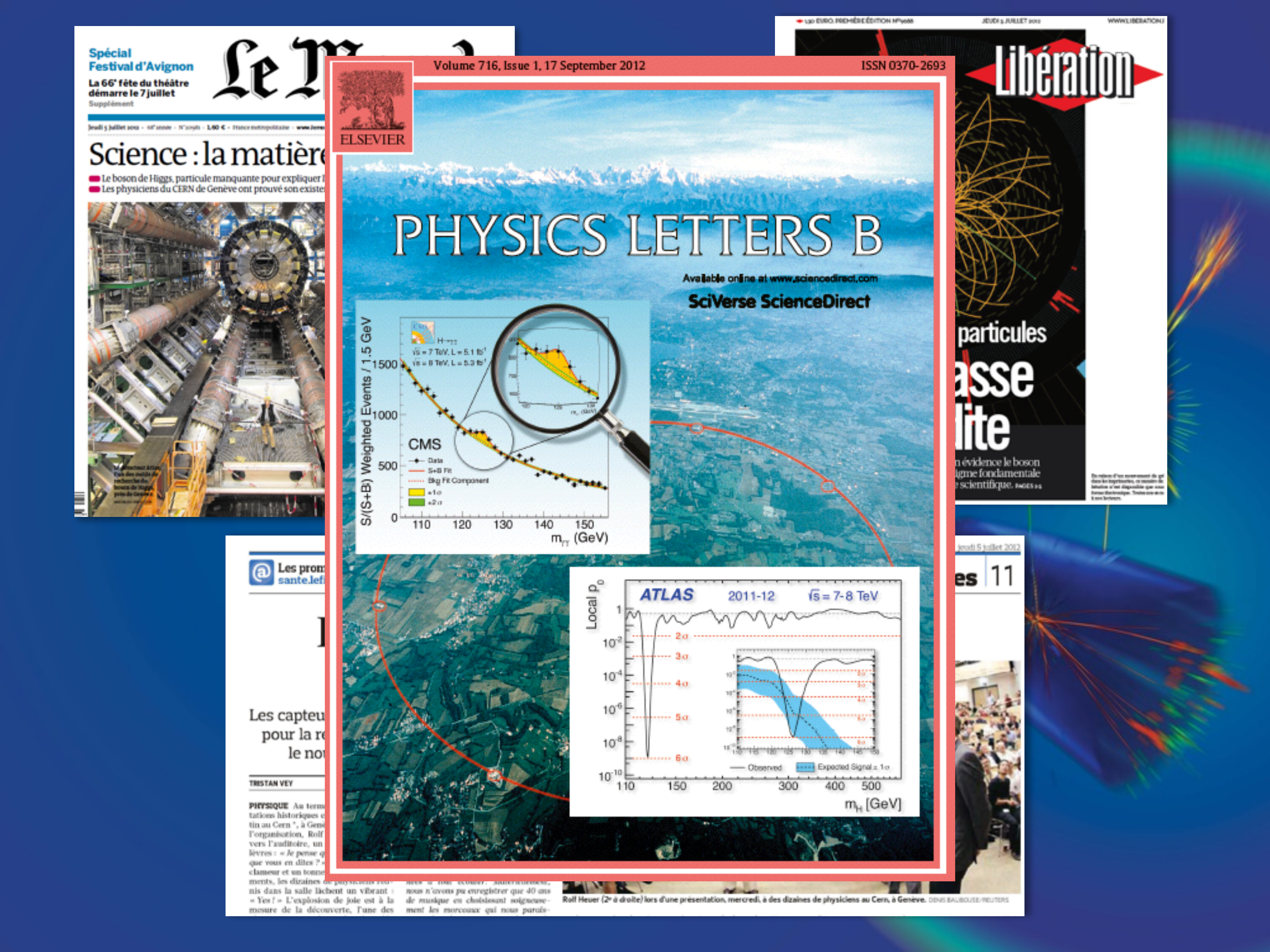
Combined significance: 5.9σ

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

Combined significance: 5.0σ

Three decay mode WW, ZZ and γγ

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
Science : la matièr
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
ELSEVIER
PHYSICS LETTERS B
Available online at www.sciencedirect.com
SciVerse ScienceDirect
S/(S+B) Weighted Events / 1.5 GeV
CMS
Data
S+B Fit
Bkg Fit Component
±1σ
±2σ
$m_{\gamma\gamma}$ (GeV)
ATLAS
2011-12
$\sqrt{s}$ = 7-8 TeV
Local p_0
Observed
Expected Signal ± 1σ
m_H [GeV]
Libération
particules
asse
lite
n évidence le boson
igme fondamentale
e scientifique.
Les capteu
pour la r
le no
TRISTAN VEY
11
Rolf Heuer (2e à droite) lors d'une présentation, mercredi, à des dizaines de physiciens au Cern, à Genève.

LHC: Production and Decay

Not an exhaustive table!

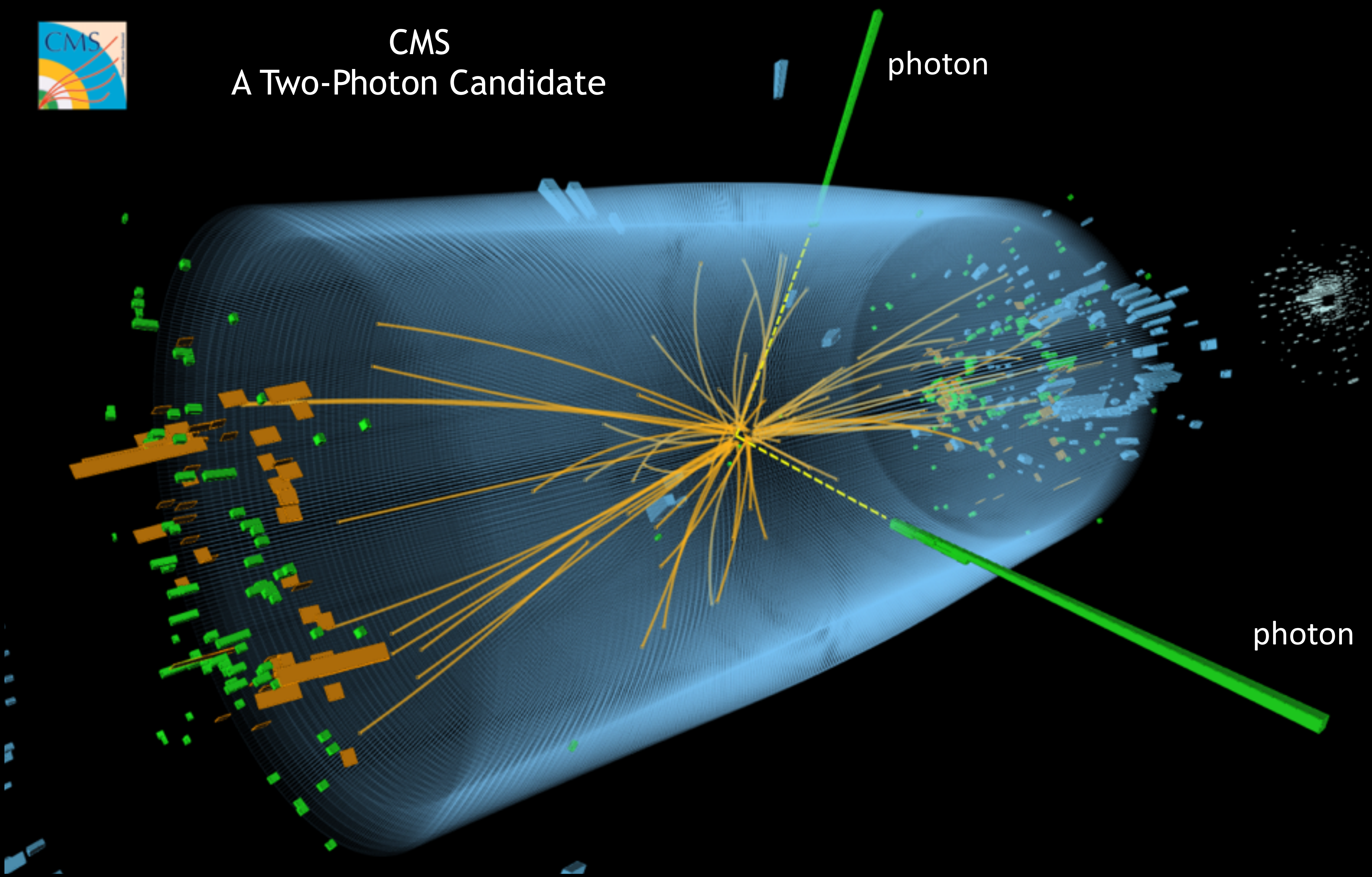
★ "seen" ☆ "tried"	H→bb	H→ττ	H→WW	H→ZZ	H→γγ	H→inv.	H→μμ
ggH		★	★	★	★		☆
VBF	☆	★	★	☆	★	☆	☆
VH	★	☆	☆	☆	☆	☆	
ttH	☆	☆	☆		☆		
	$\sigma(m_{bb})$ ~20%	$\sigma(m_{\tau\tau})$ 10-20%	$\sigma(m_{WW})$ ~16%	**$\sigma(m_{ZZ})$ 1-2%**	**$\sigma(m_{\gamma\gamma})$ 1-2%**		

courtesy André David

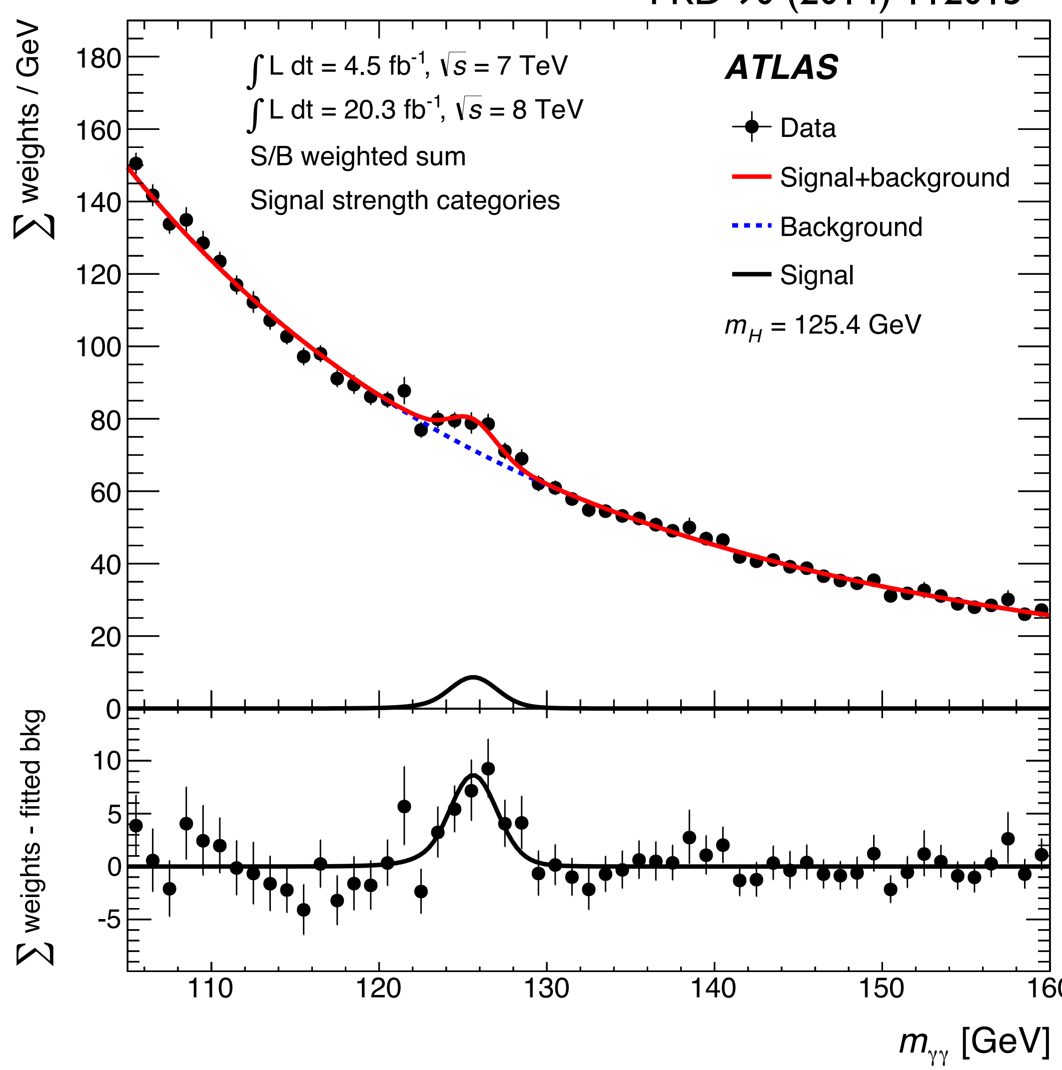
Expected number of decays for Run-I before selection cuts (m_H = 125 GeV)

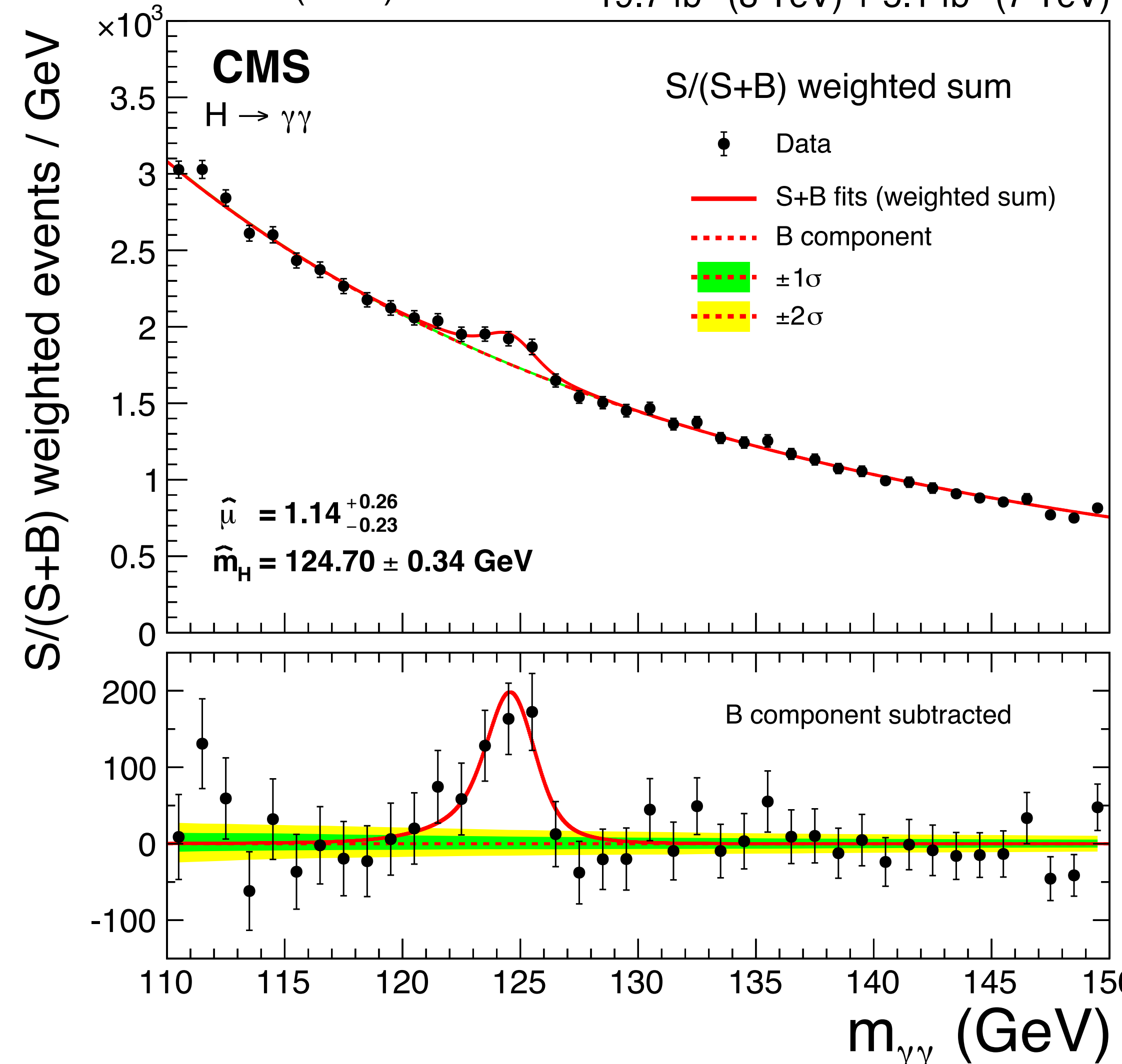
- 9,000 H ⟶ WW* ⟶ $\ell\nu\ell\nu$
- 900 H ⟶ γγ
- 60 H ⟶ ZZ* ⟶ 4ℓ

Two-Photon Final State



Two-Photon Decay





Significance
- observed : 5.2 σ
- expected: 4.6σ

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

Significance
- observed : 5.7 σ
- expected: 5.2σ

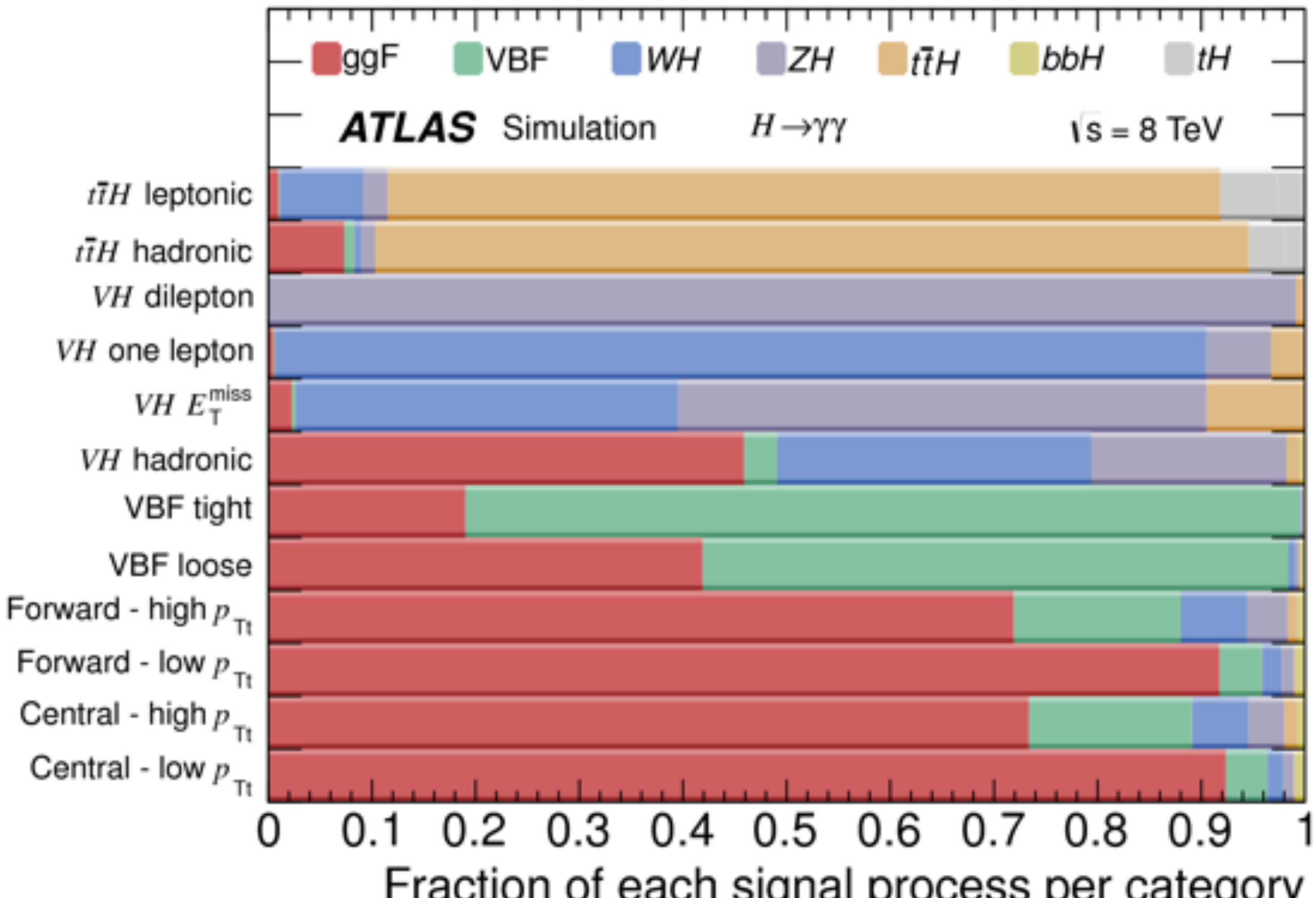
m_H = 124.70 ± 0.31 (stat) ± 0.15 (syst) GeV

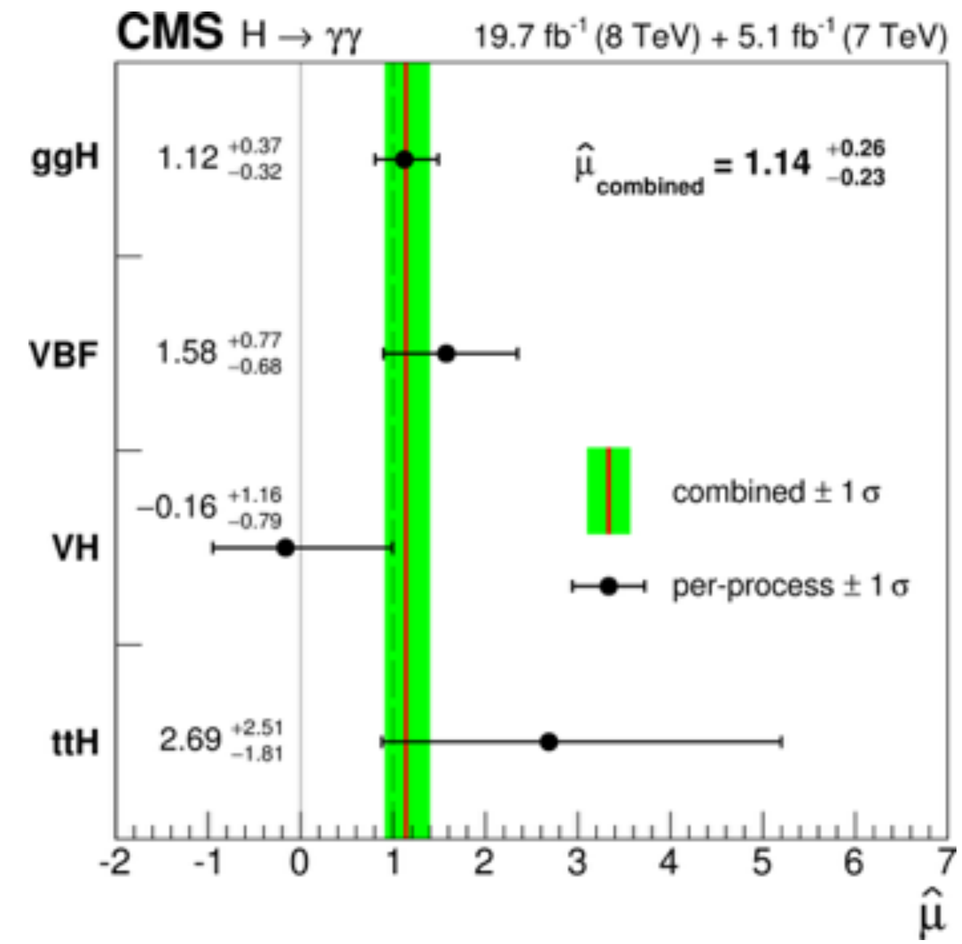
Background interpolation in the region of the signal

reducible γ+jet and jet+jet background at the level of 25%

Two-Photon: Categorisation

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





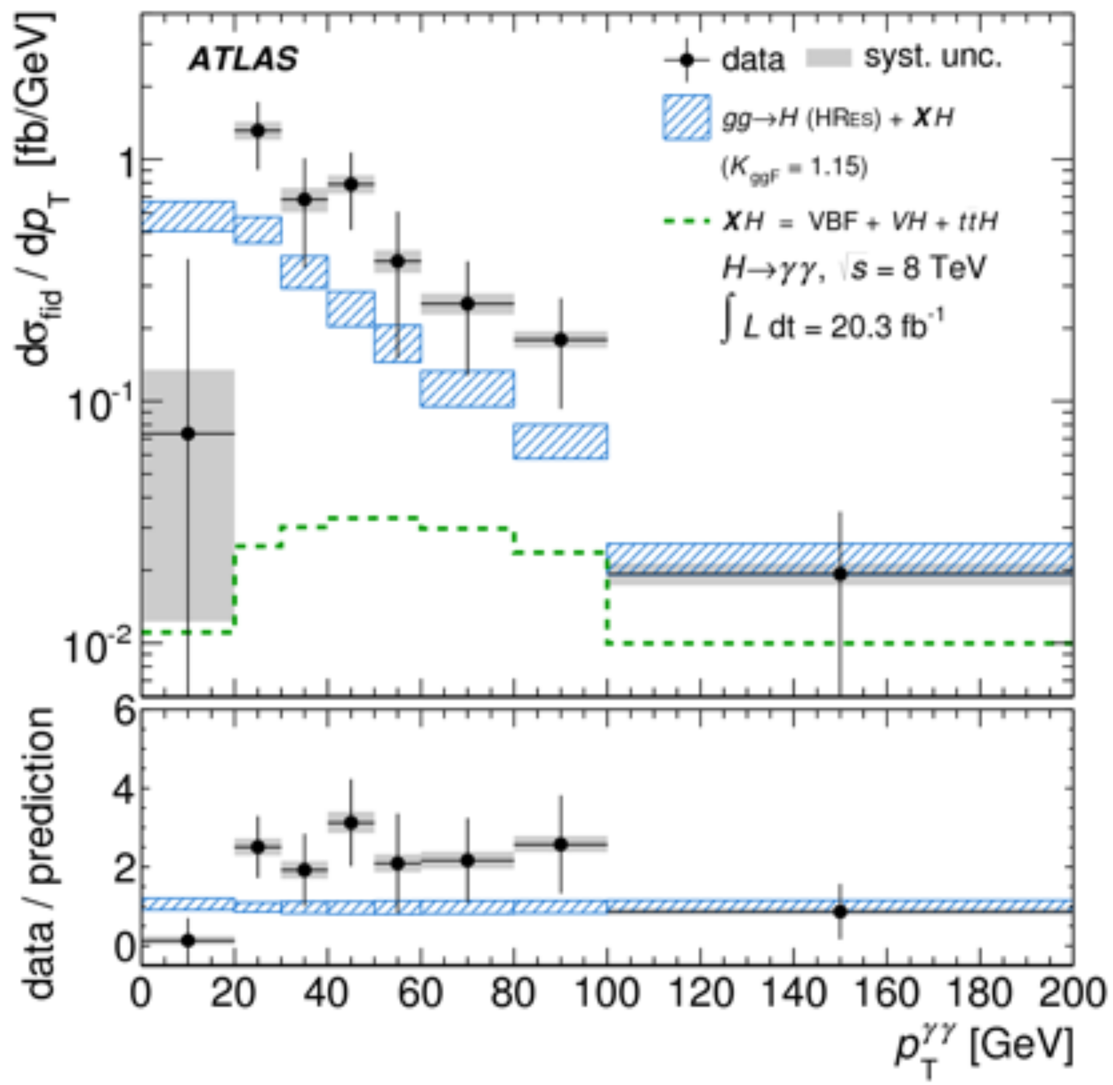
Individual production modes are consistent with SM expectations

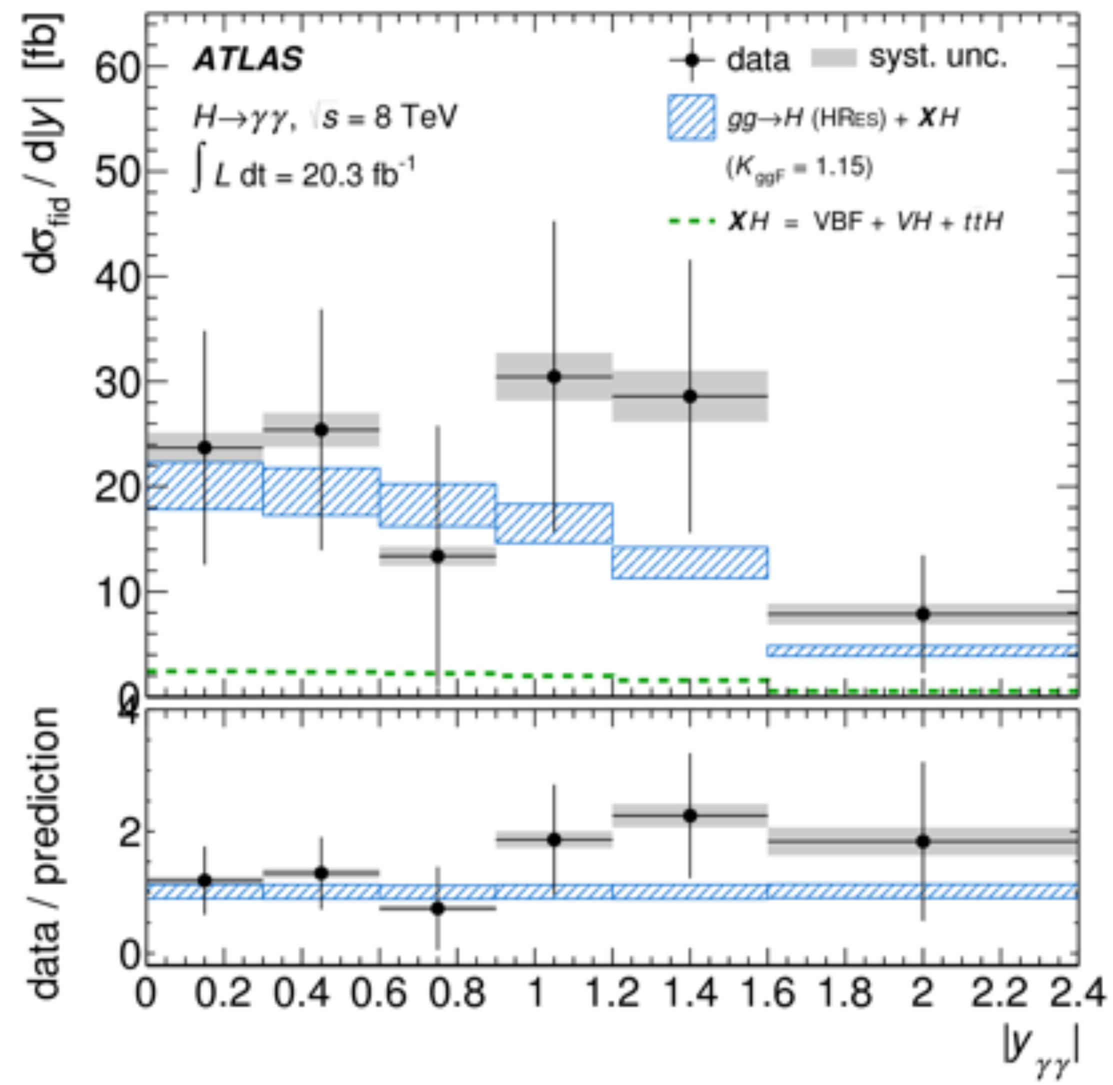
- ggH established
- strong evidence for VBF

Differential Cross Sections

JHEP 09 (2014) 112

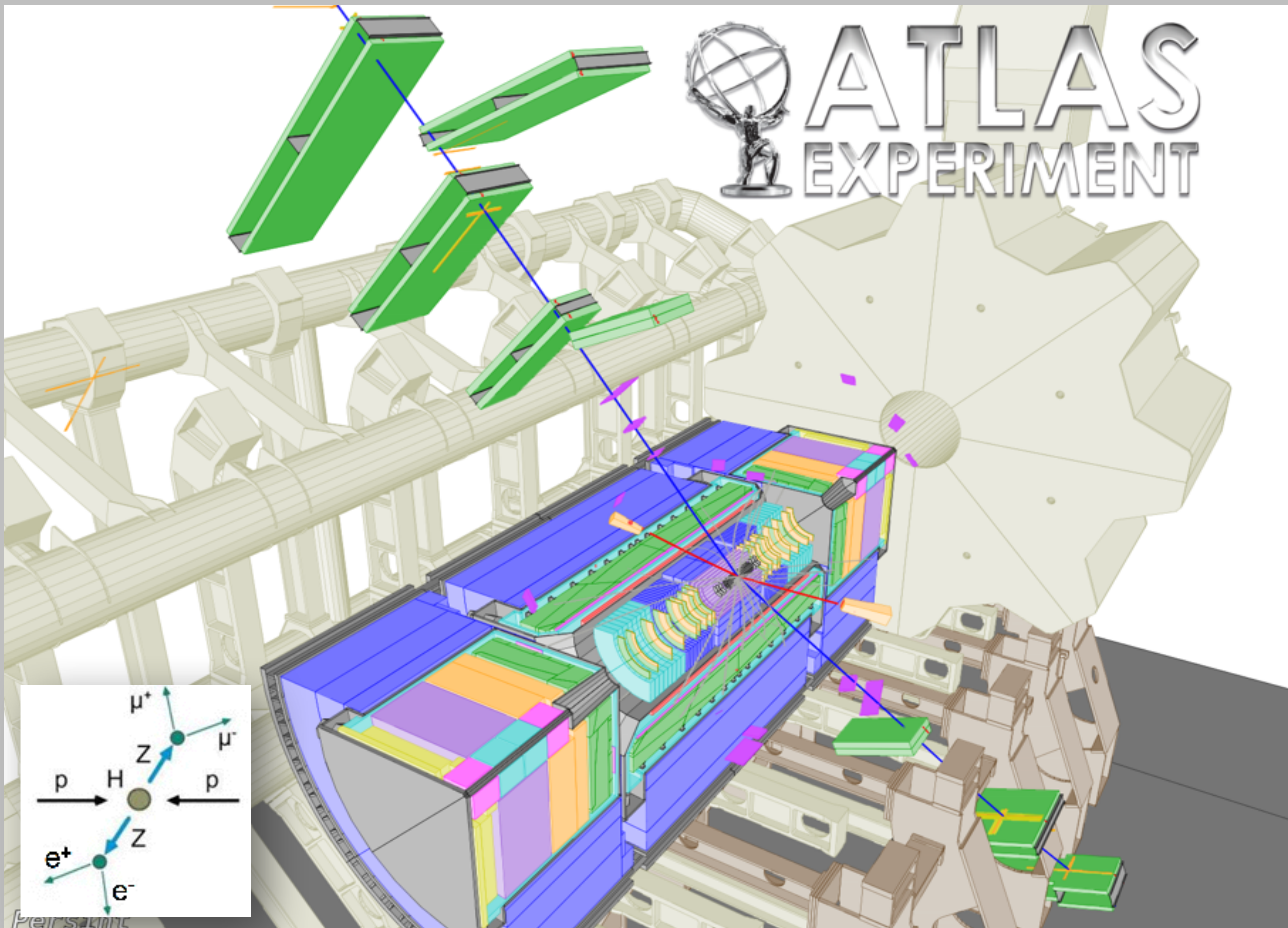
First tentatives to look at pT spectrum and rapidity distribution





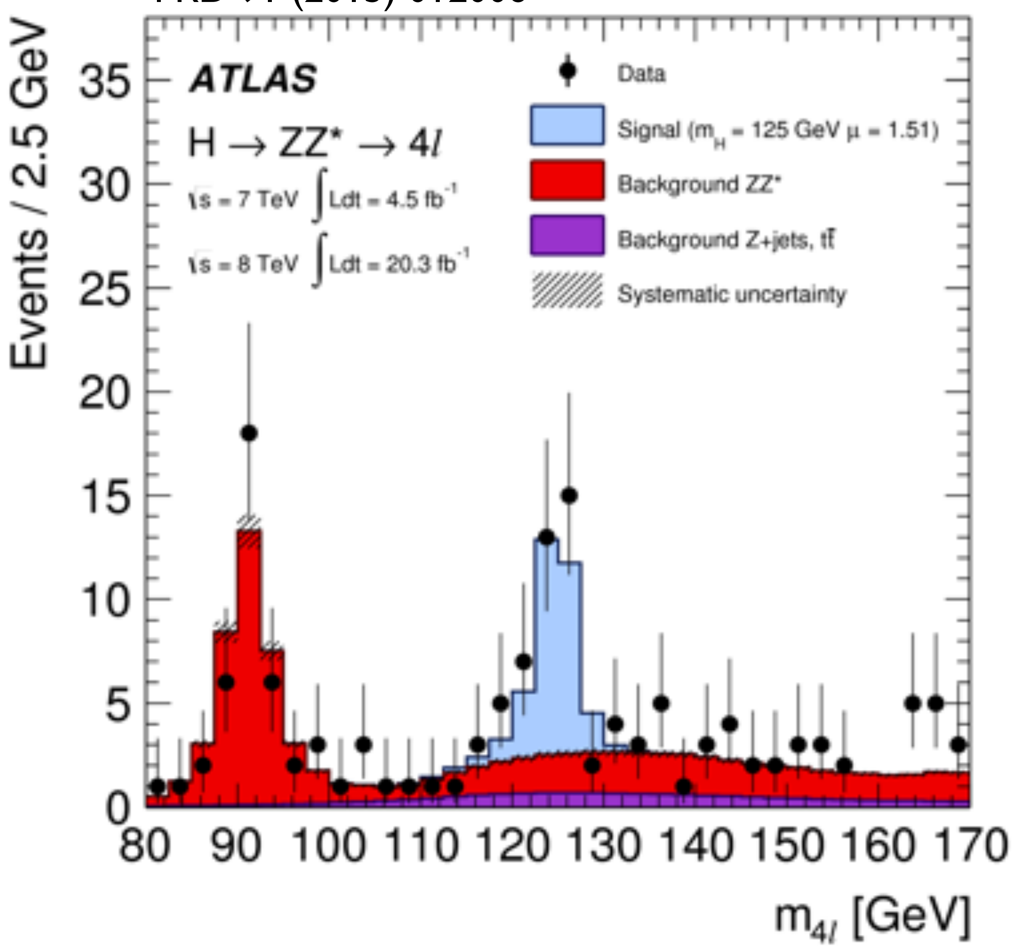
Obviously, not enough data yet … but very promising

Four-Lepton Mode

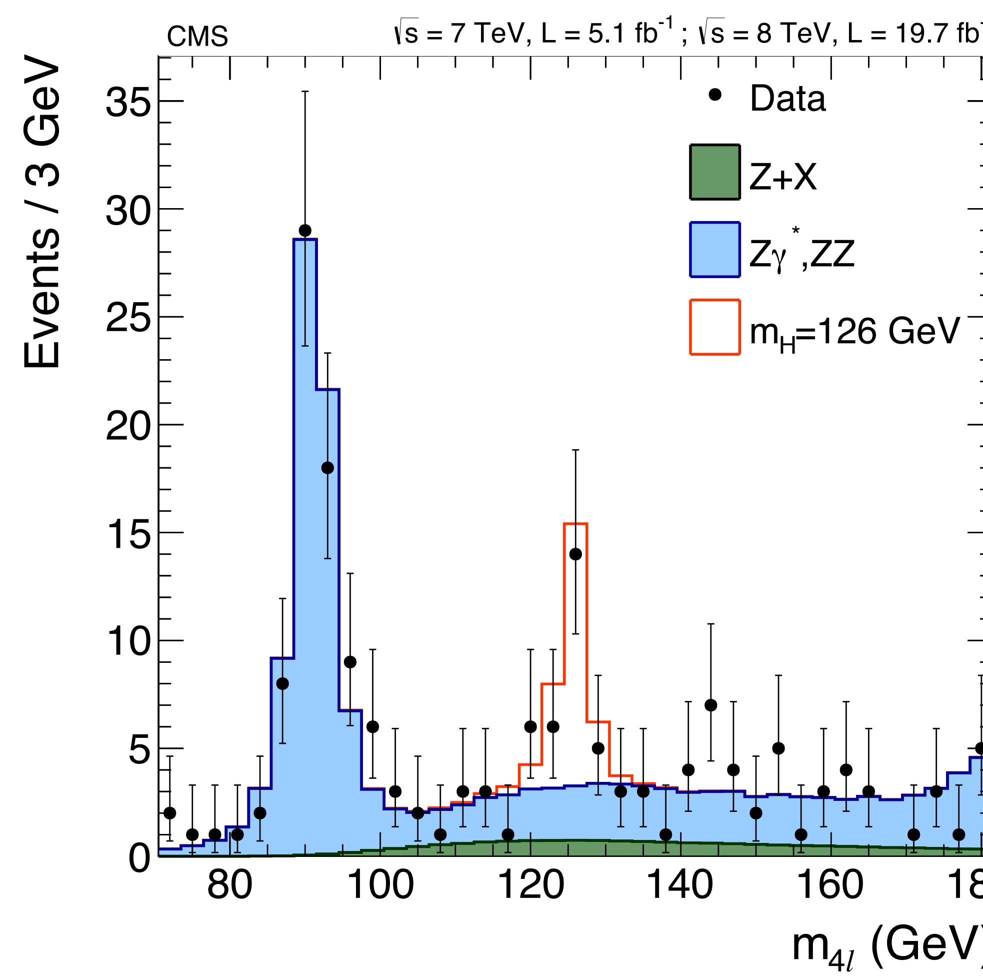


Four-Lepton Decay

PRD 91 (2015) 012006



PRD 89 (2014) 092007

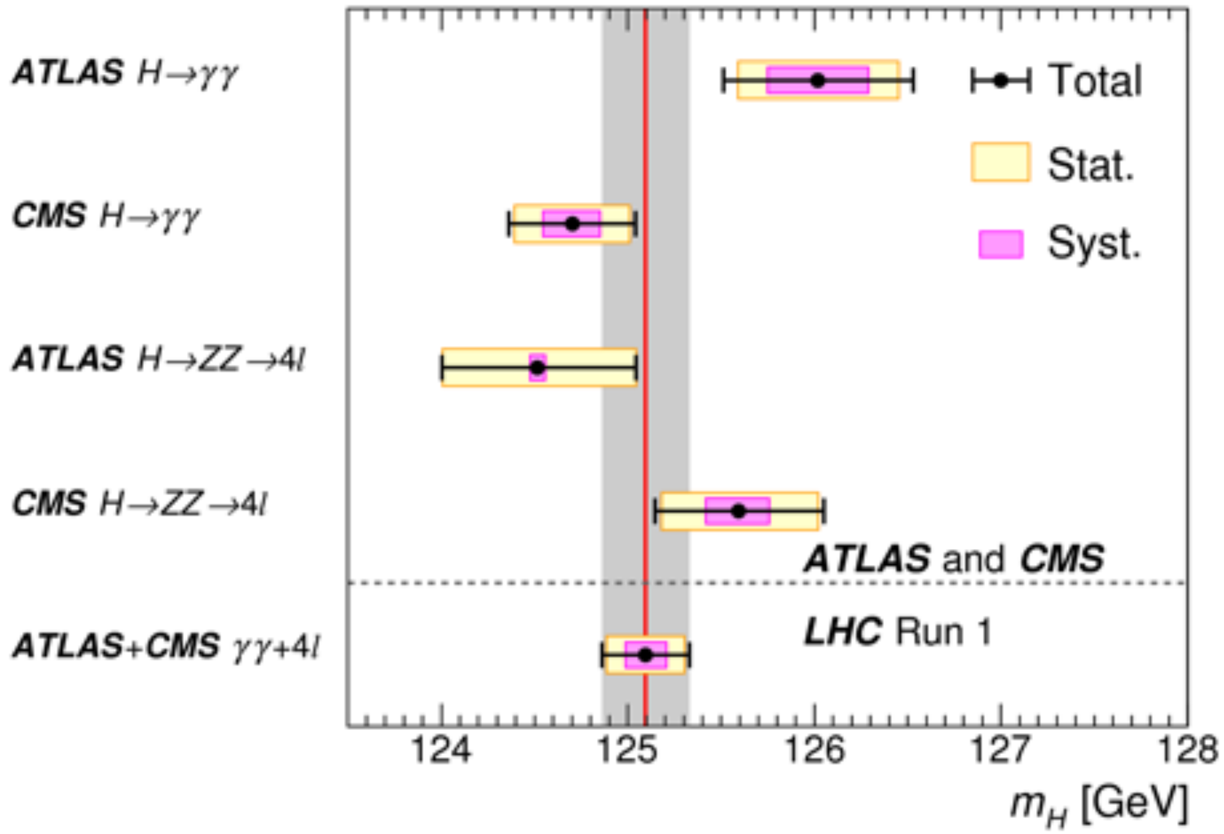


m_H = 124.51 ± 0.52 (stat) ± 0.04 (syst) GeV

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

Both experiments observe signals with > 6σ

Mass of the Higgs Boson



PRL 114 (2015) 191803

Combined fit to ATLAS and CMS data

in γγ and ZZ→4ℓ channels

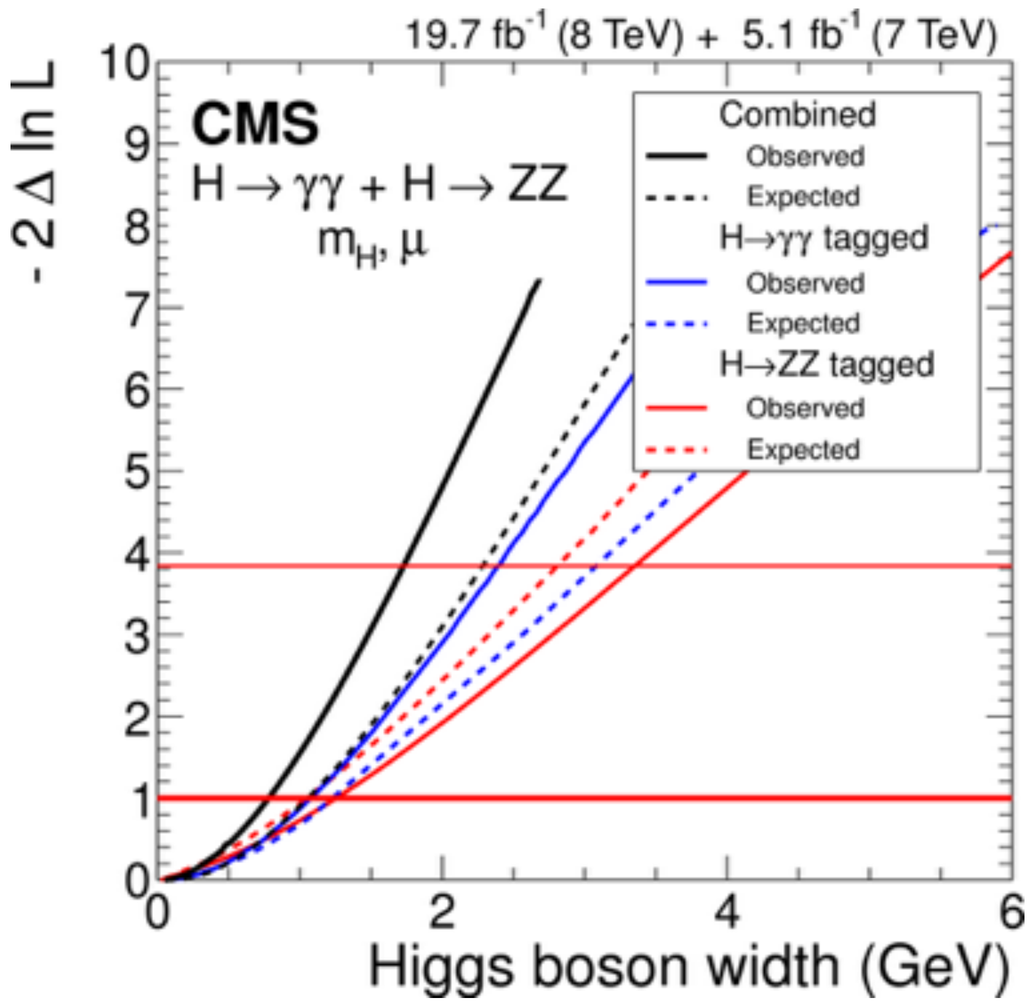
- consistency between experiments
- consistency between channels

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

2‰ accuracy on the Higgs boson mass!

Width of the Higgs Boson

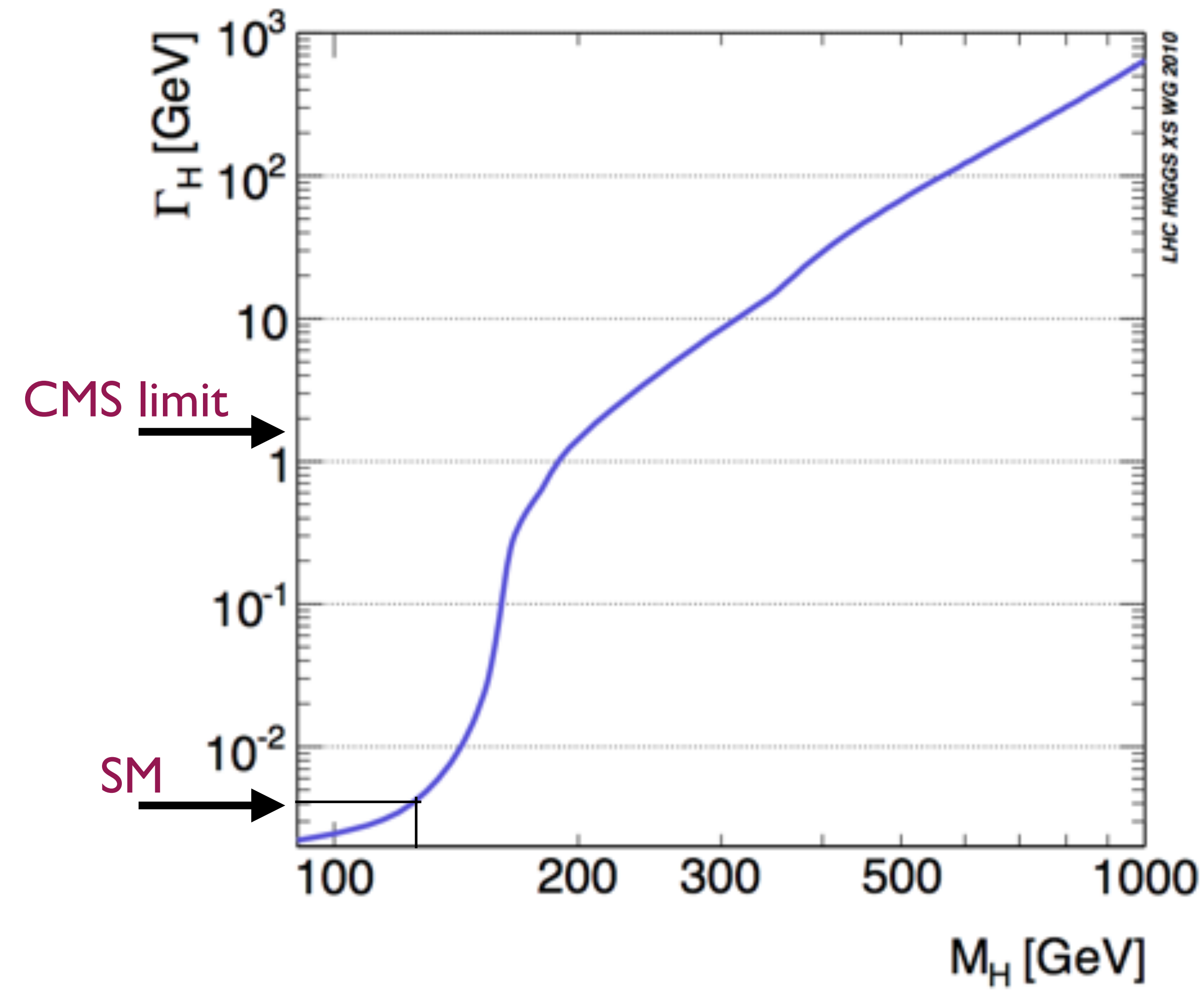
Upper limits on the width can be obtained from the mass peaks (at the level of the experimental resolution)



Γ_H < 1.7 GeV (95%CL)

EPJC 75 (2015) 212

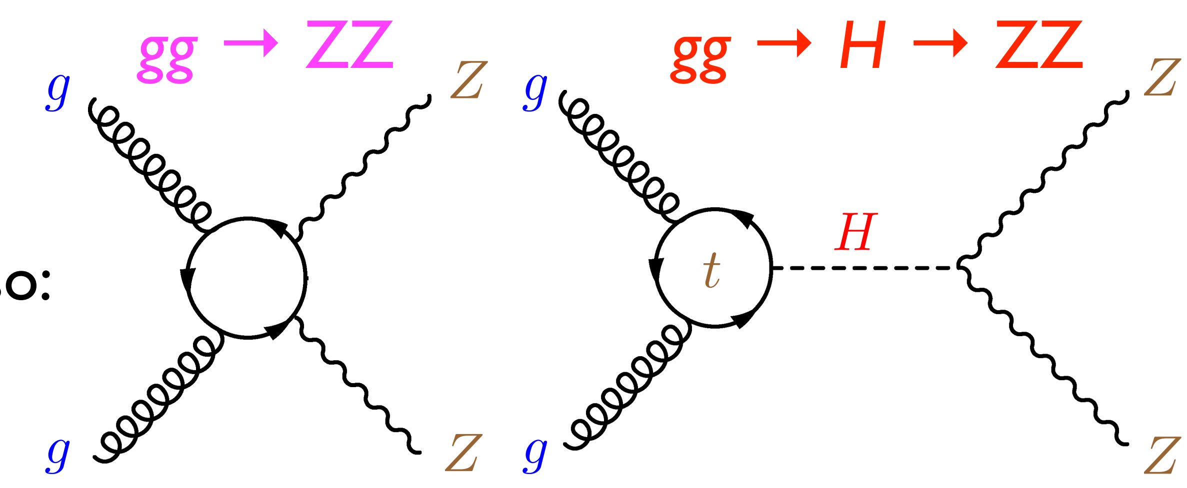
The width of the SM Higgs boson is expected of the order of 4MeV



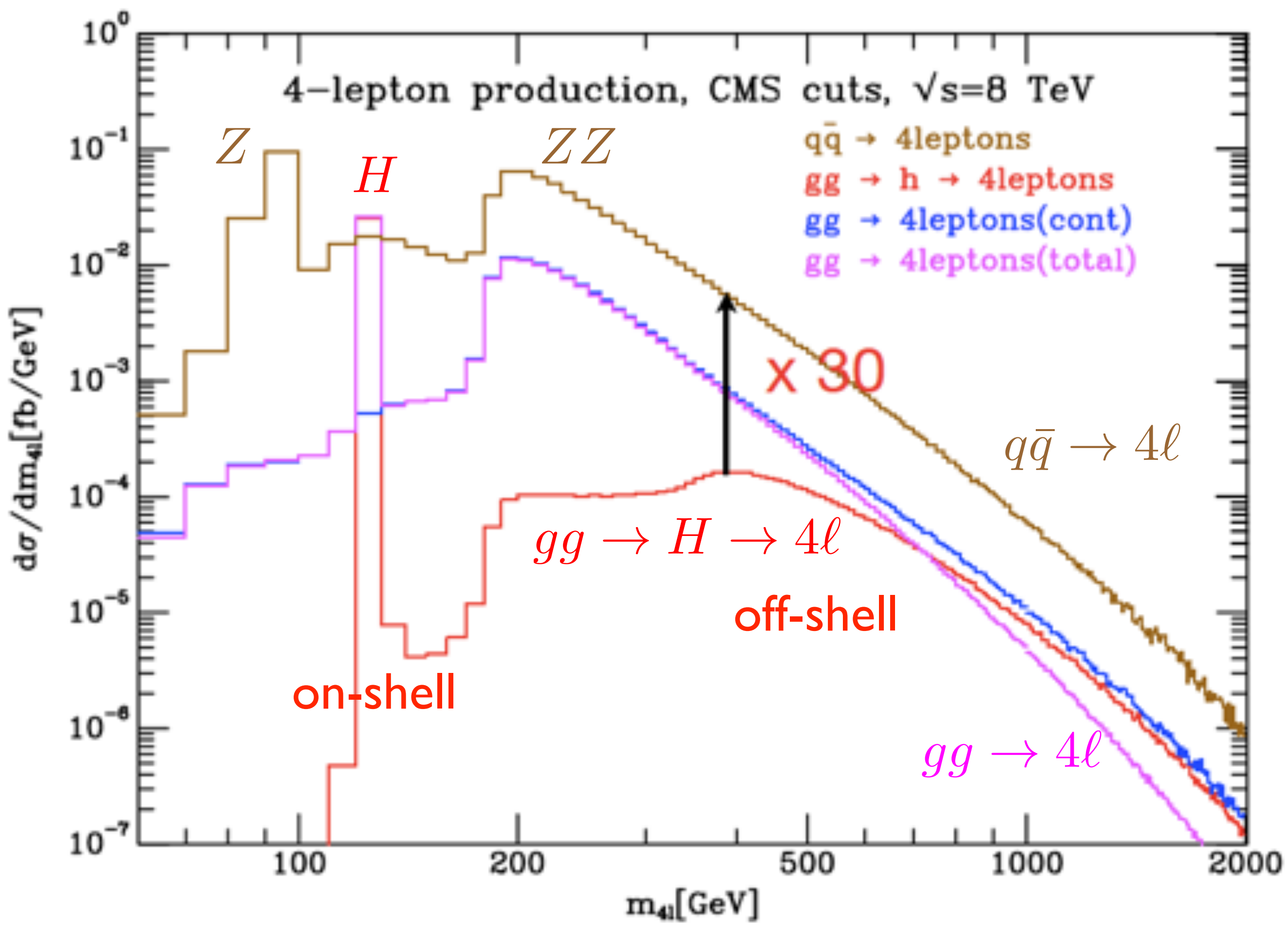
Off-Shell Higgs Boson

Main continuum 4ℓ production: $qq \to 4\ell$

also:



$$\frac{d\sigma_{gg\to H\to ZZ}}{dm^2_{ZZ}} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(m^2_{ZZ}-m^2_H)^2+m^2_H\Gamma^2_H}$$



on-shell ($m_{ZZ} \sim m_H$) $\quad \sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{m_H\Gamma_H}$

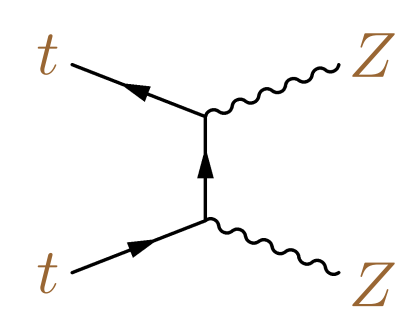
off-shell ($m_{ZZ} \gg m_H$) $\quad \sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \frac{g^2_{ggH}g^2_{HZZ}}{(2m_Z)^2}$

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

CMS/ATLAS set 95%CL upper limits on Γ_H around 22 MeV!
($\Gamma_{SM} \sim$ 4 MeV)

destructive interference at high mass

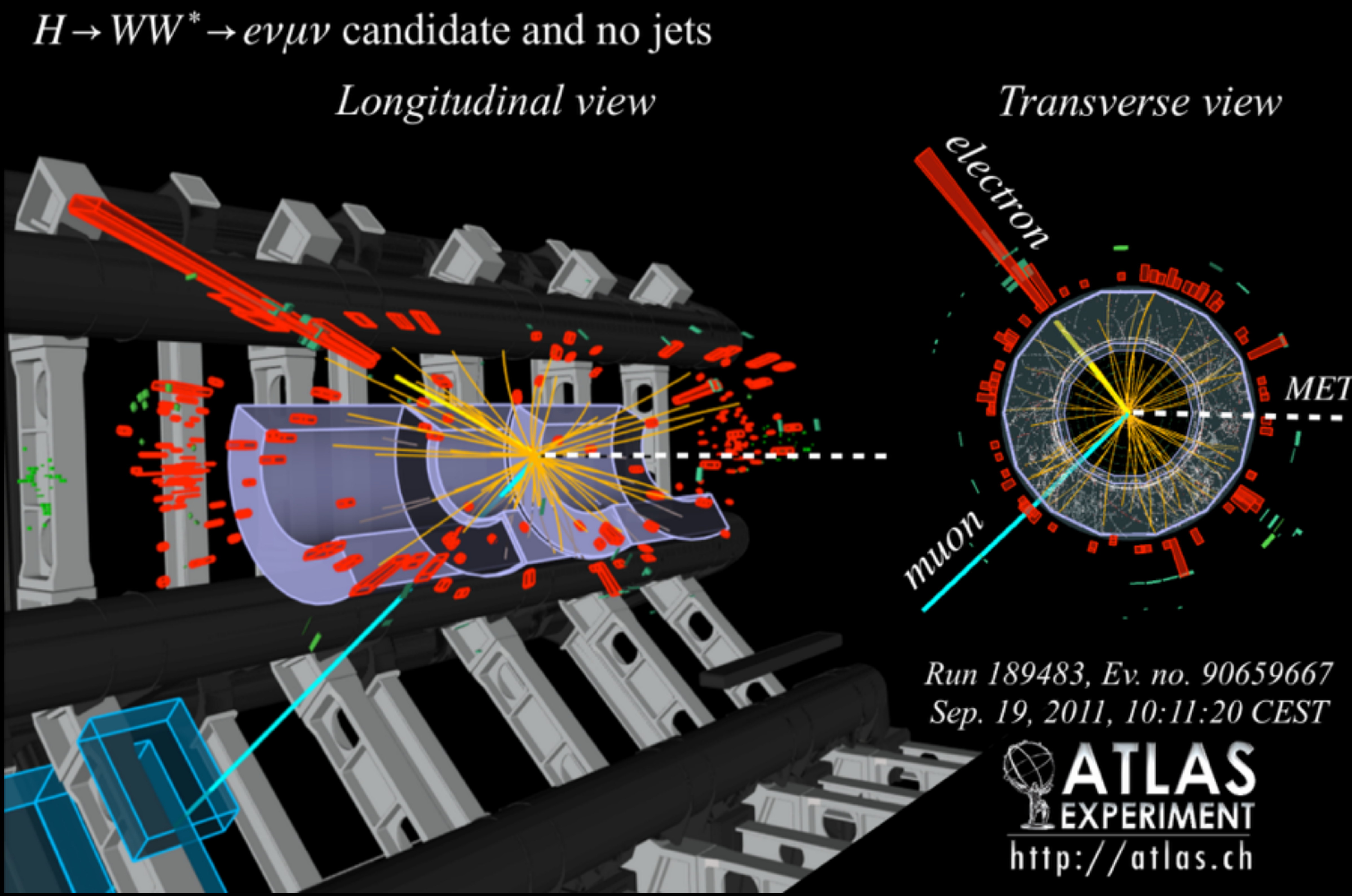
- as expected! Higgs tail has to be here to cancel the bad E^2 energy behaviour of tt→ZZ continuum diagrams



+… $\sim E^2$

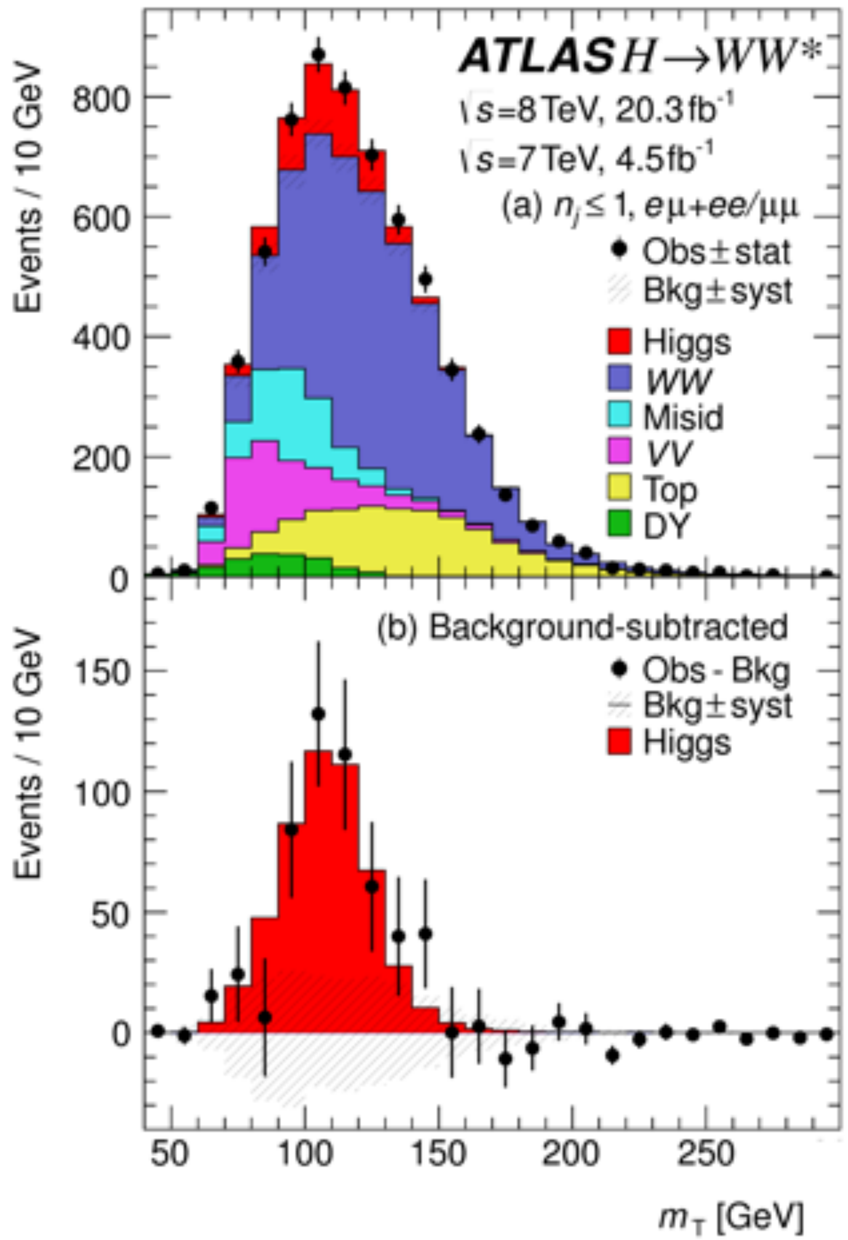
very fundamental! Higgs at work

WW Decays


$H \to WW^* \to e\nu\mu\nu$ candidate and no jets
Longitudinal view
Transverse view
electron
MET
muon
Run 189483, Ev. no. 90659667
Sep. 19, 2011, 10:11:20 CEST
ATLAS
EXPERIMENT
http://atlas.ch

WW Decay

[Phys. Rev. D 92, 012006 (2015)](#)

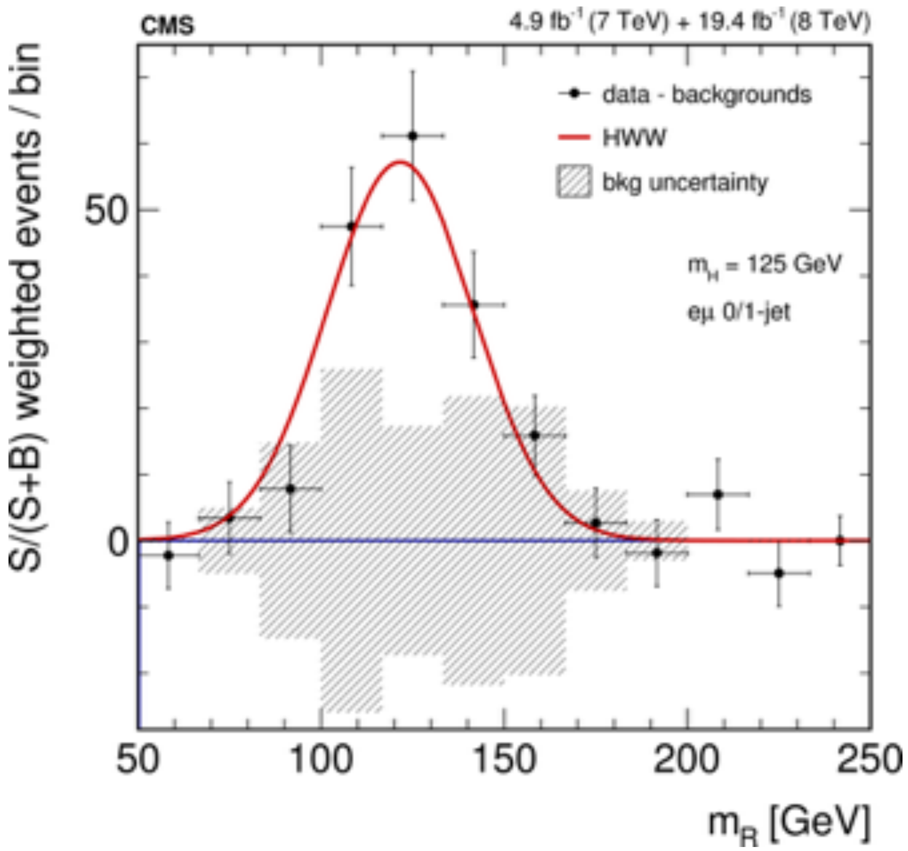


Very significant

H → WW signals for

both ATLAS (6.1σ)

and CMS (4.5σ)



Clear evidence of

VBF production

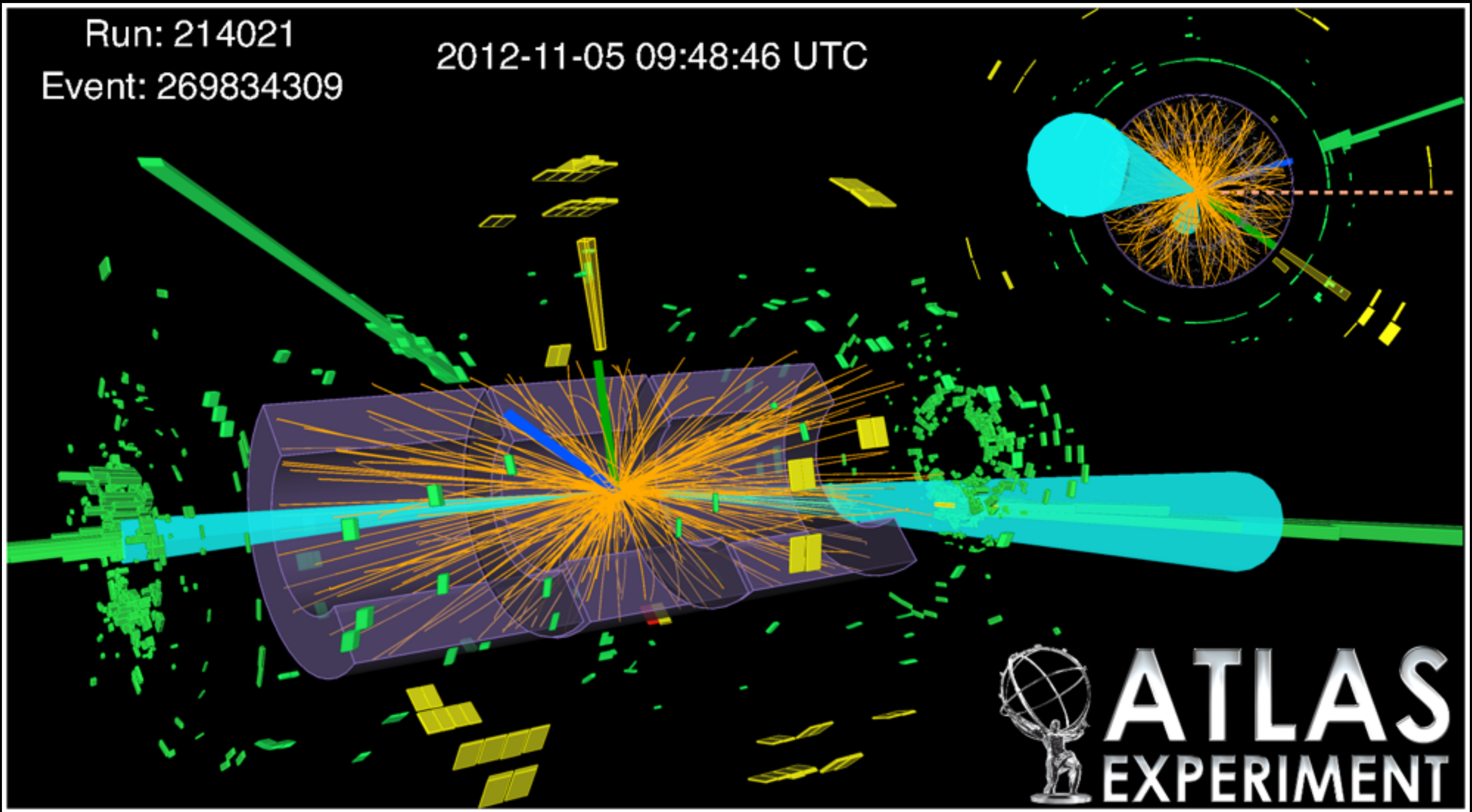
Mass consistent with

125 GeV

PRD 92 (2015) 012006

JHEP 01 (2014) 096

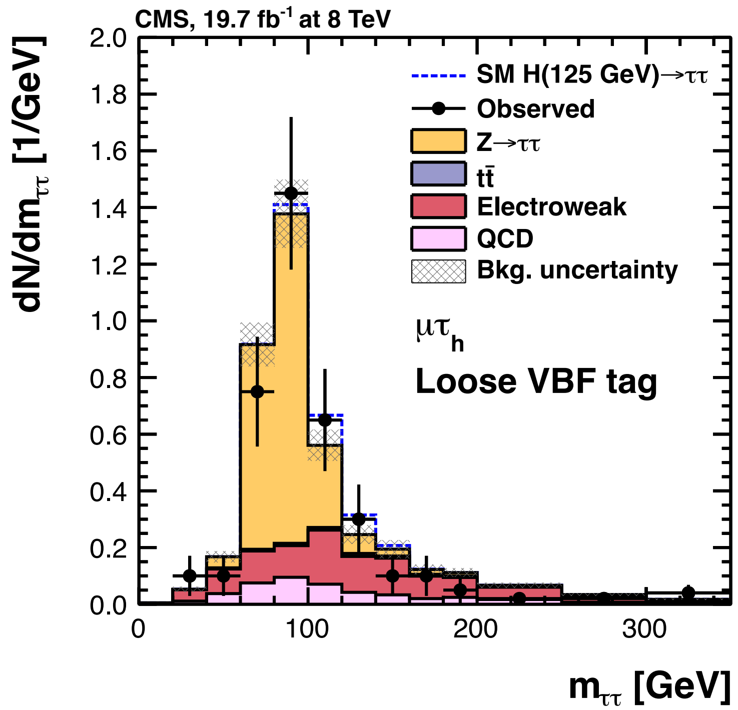
Decay to tau Leptons

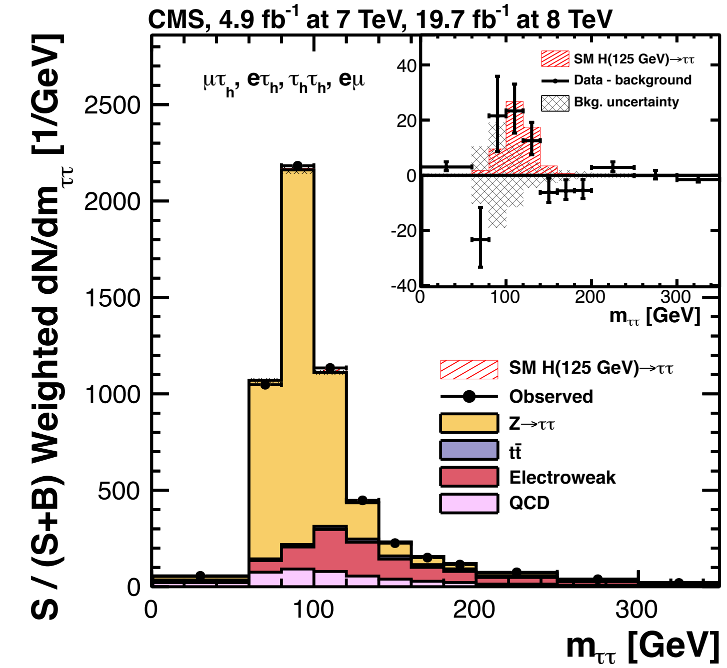


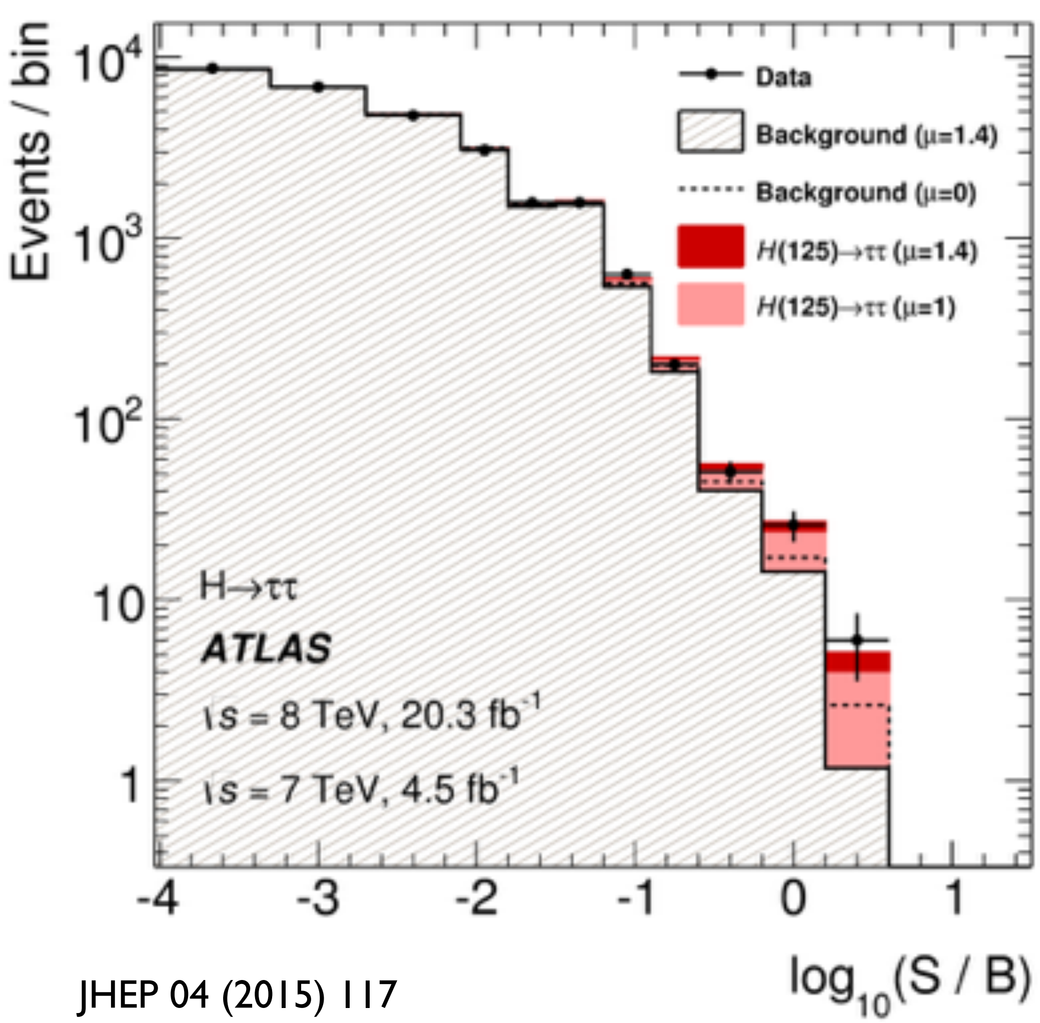
Event in the electron-jet VBF category with BDT=0.99 (S/B=1.0)

Decay to tau Leptons

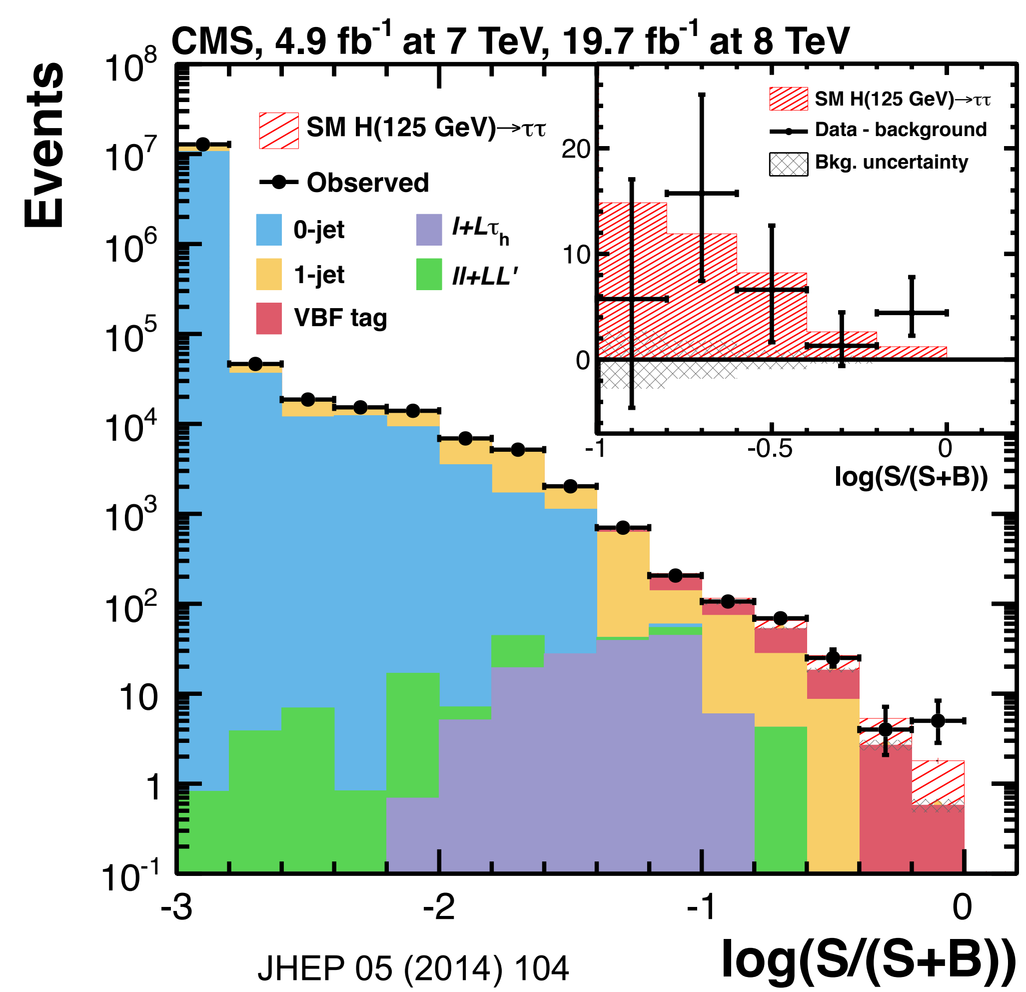
- One of the most important results in 2014
- First evidence of Higgs coupling to fermions







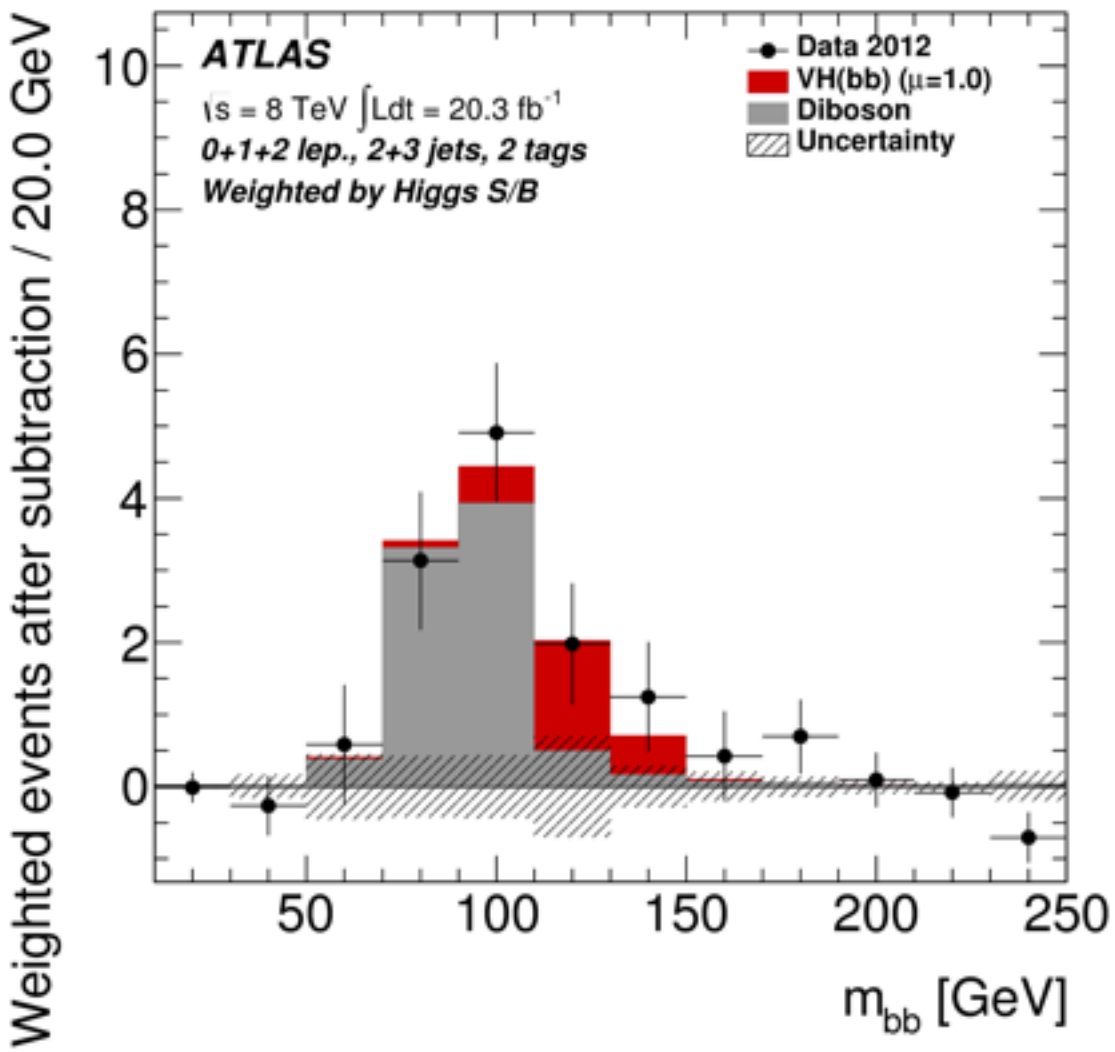
JHEP 04 (2015) 117



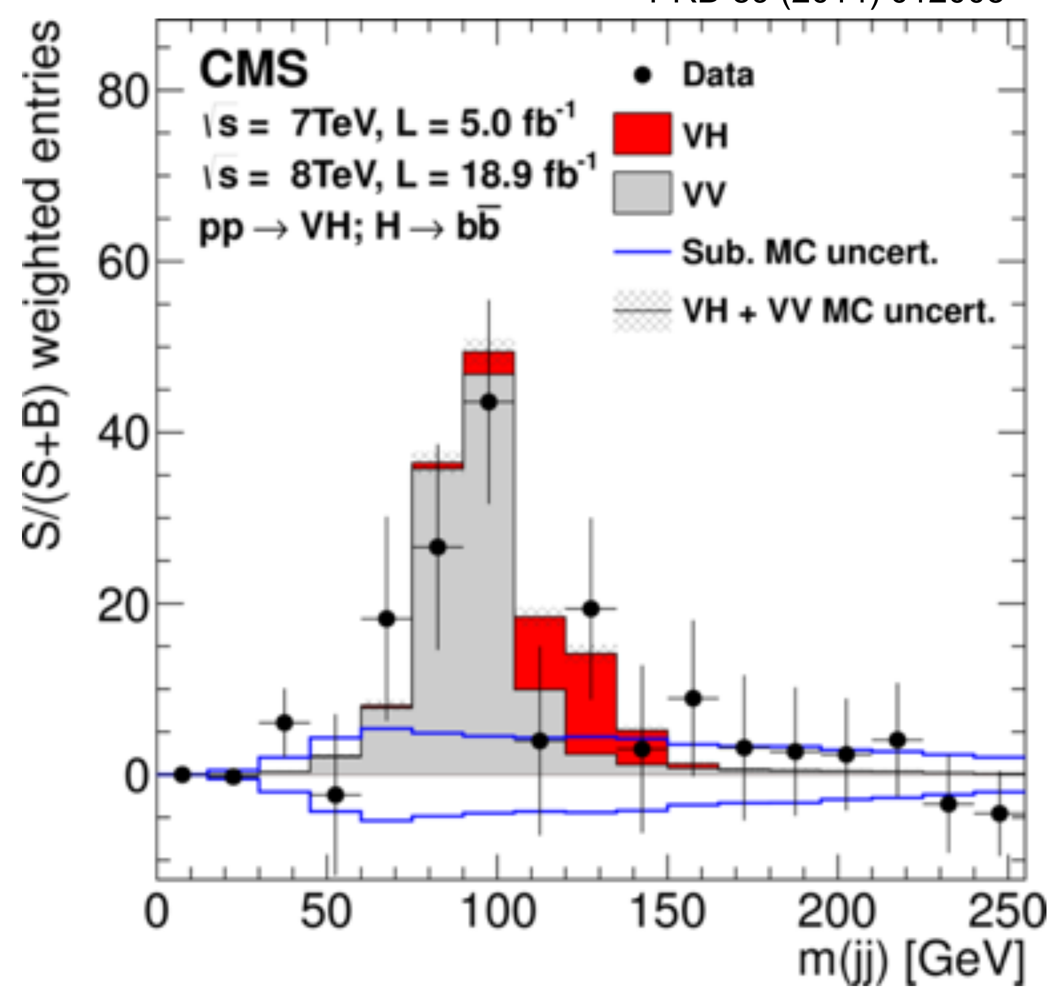
JHEP 05 (2014) 104
NP 10 (2014) 557-560

Decay to b Quarks

JHEP 01 (2015) 069



PRD 89 (2014) 012003



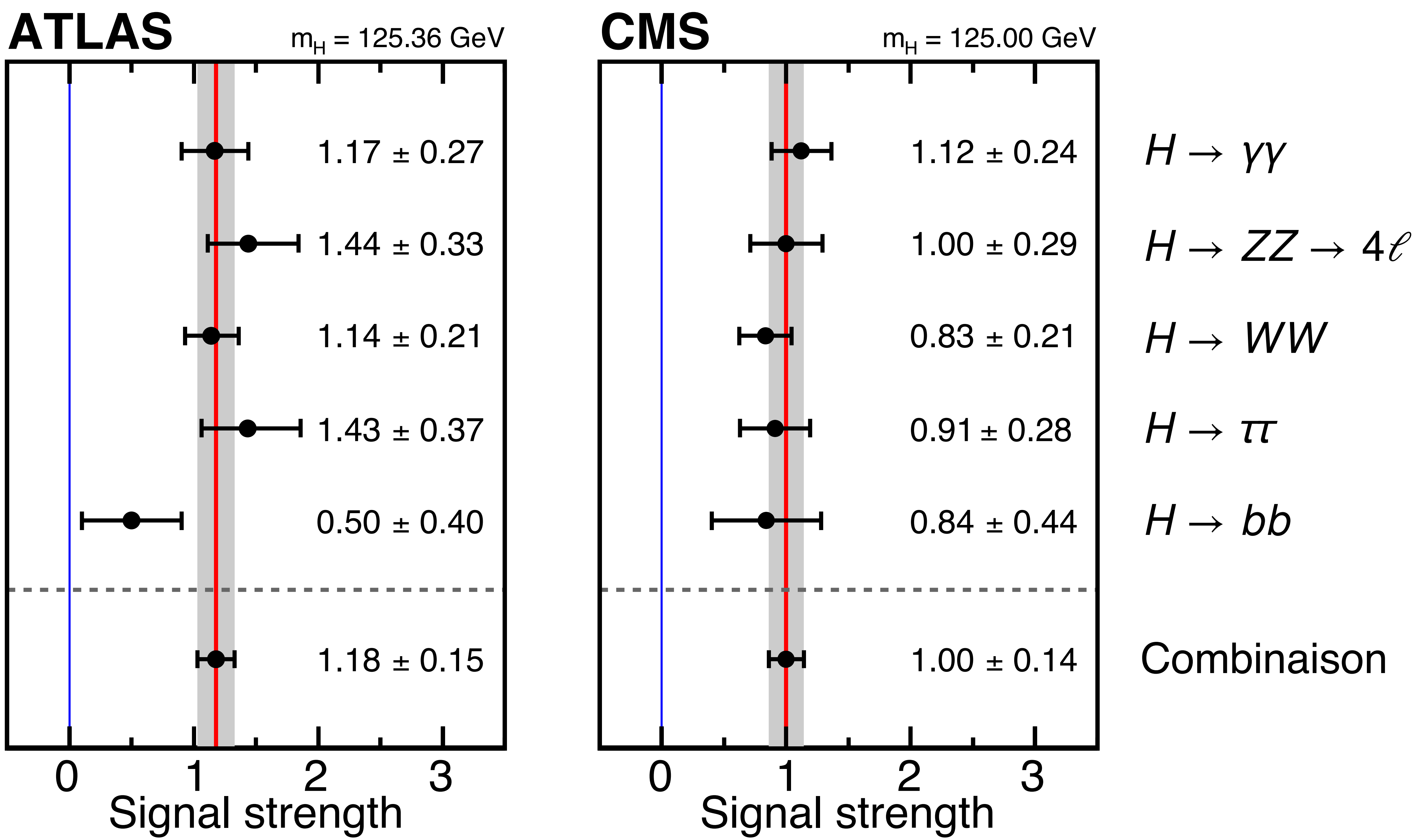
Reconstruction of bb signal after subtraction of major backgrounds

No contradiction with the SM but the signal is not yet significant in this mode

Signal Strengths

Legacy Run I

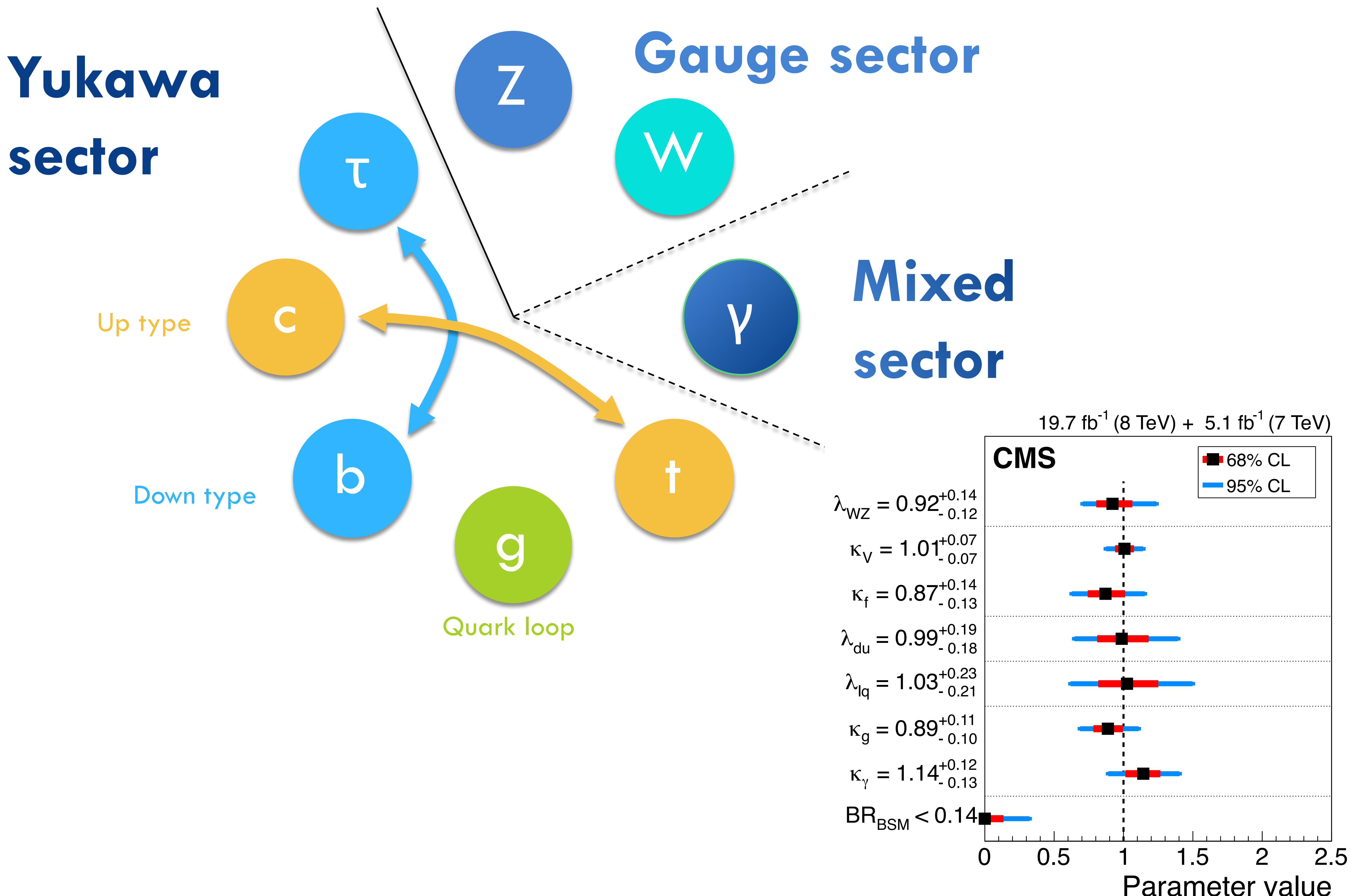
main five decay channels



> 5σ observation in di-boson channels

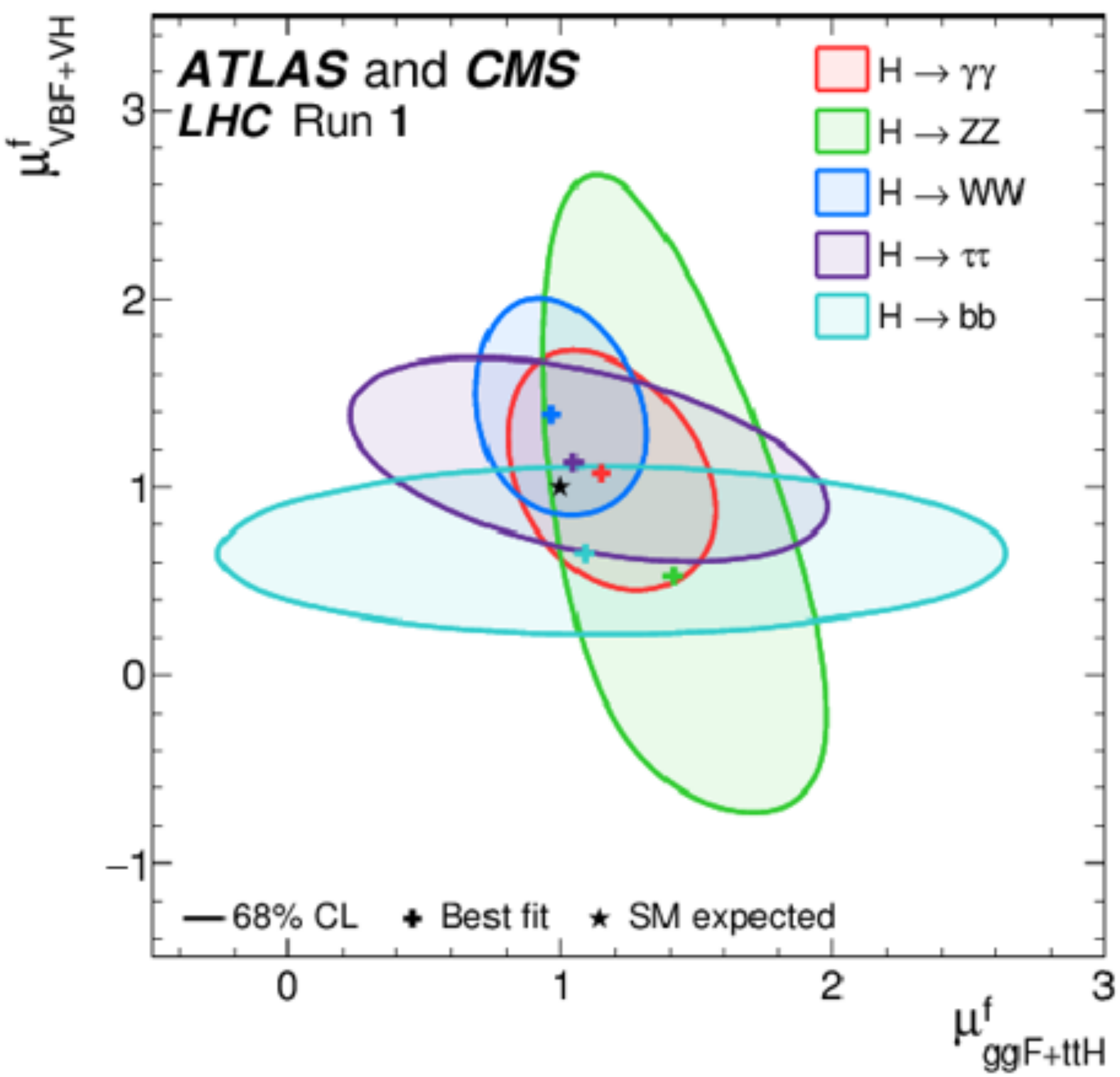
> 3σ evidence in di-tau channel

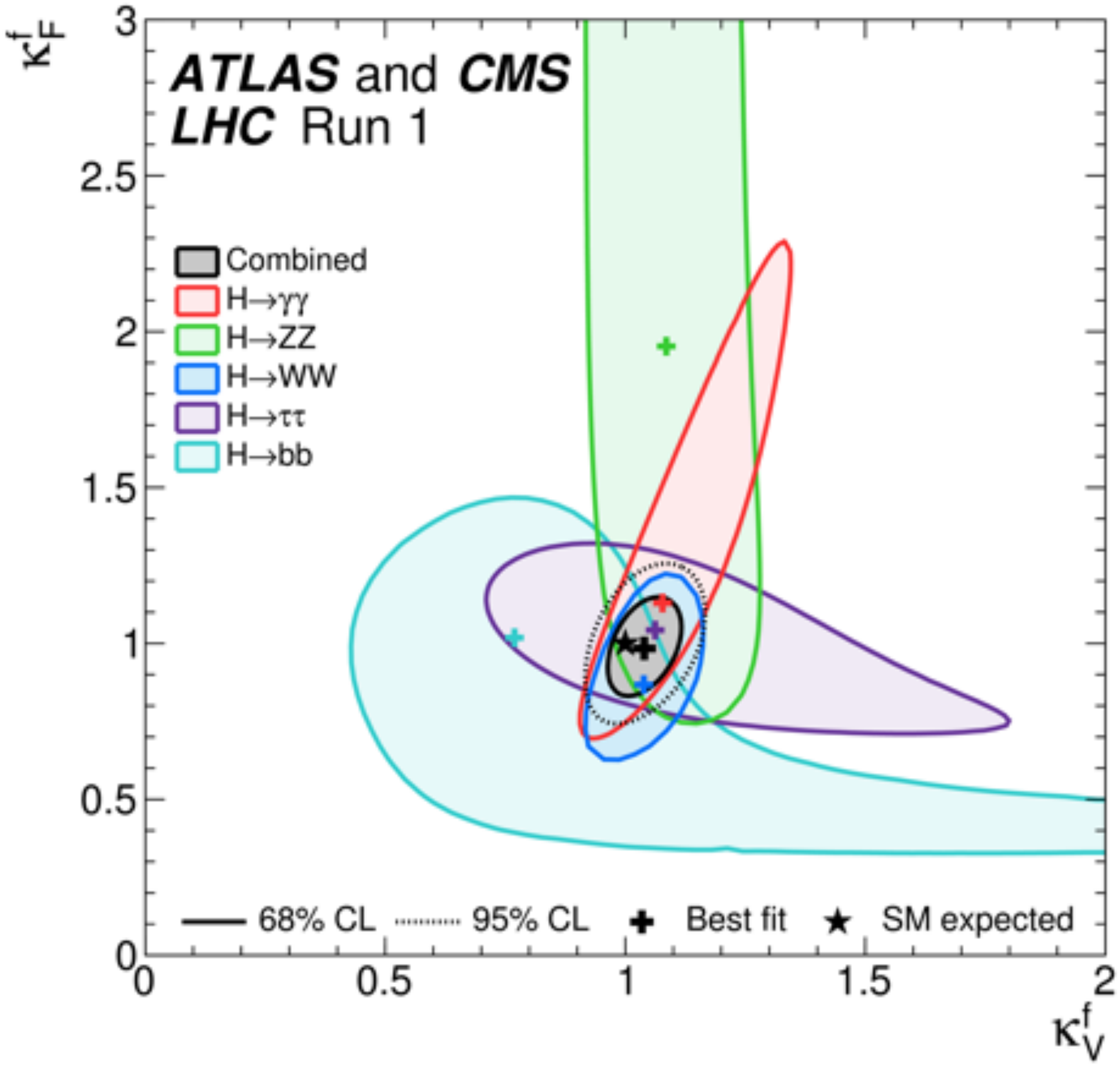
Couplings of the Higgs Boson



Courtesy André David

Production and Couplings



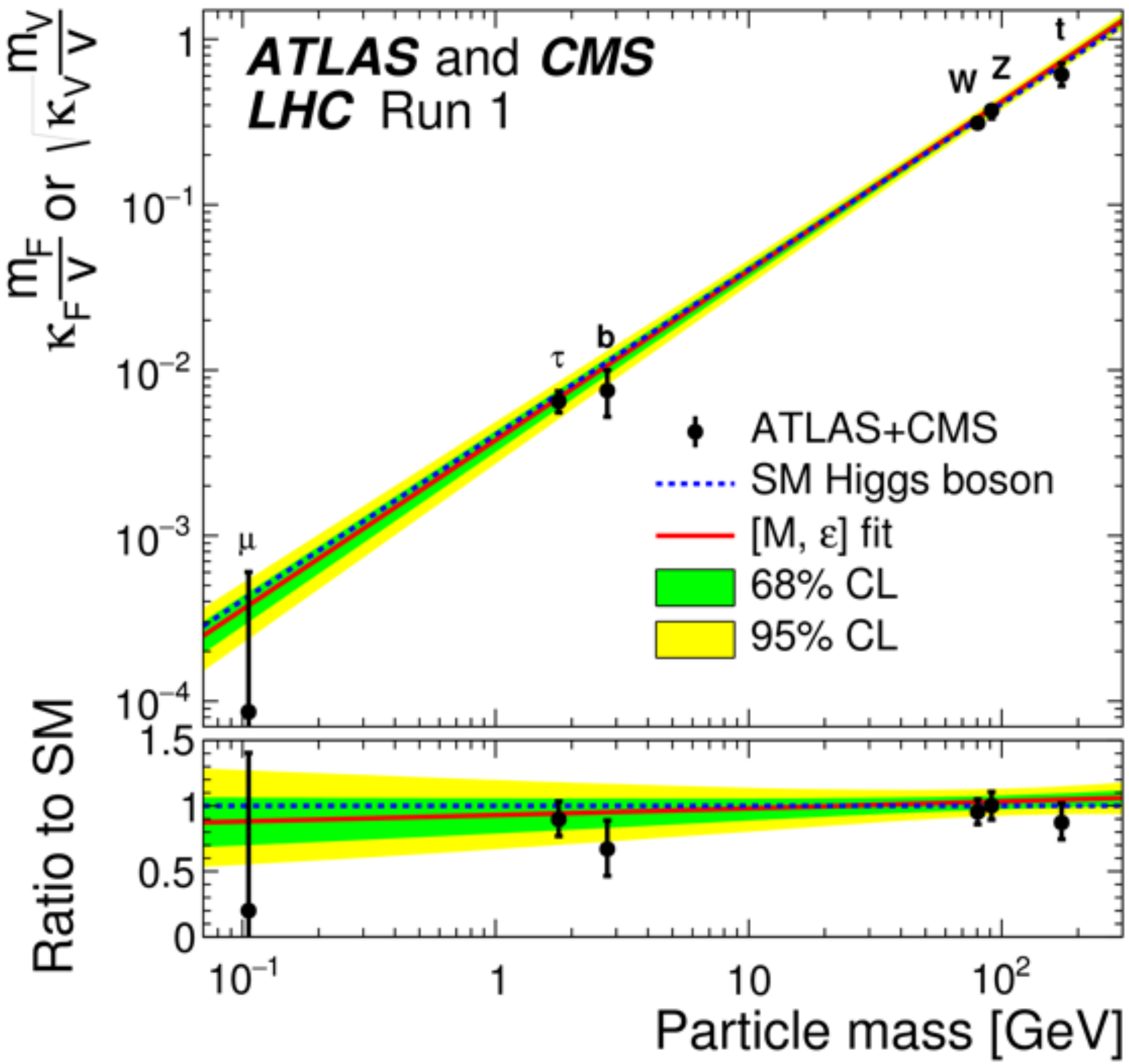


Individual production modes are consistent with SM expectations

- ggH established
- very strong 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

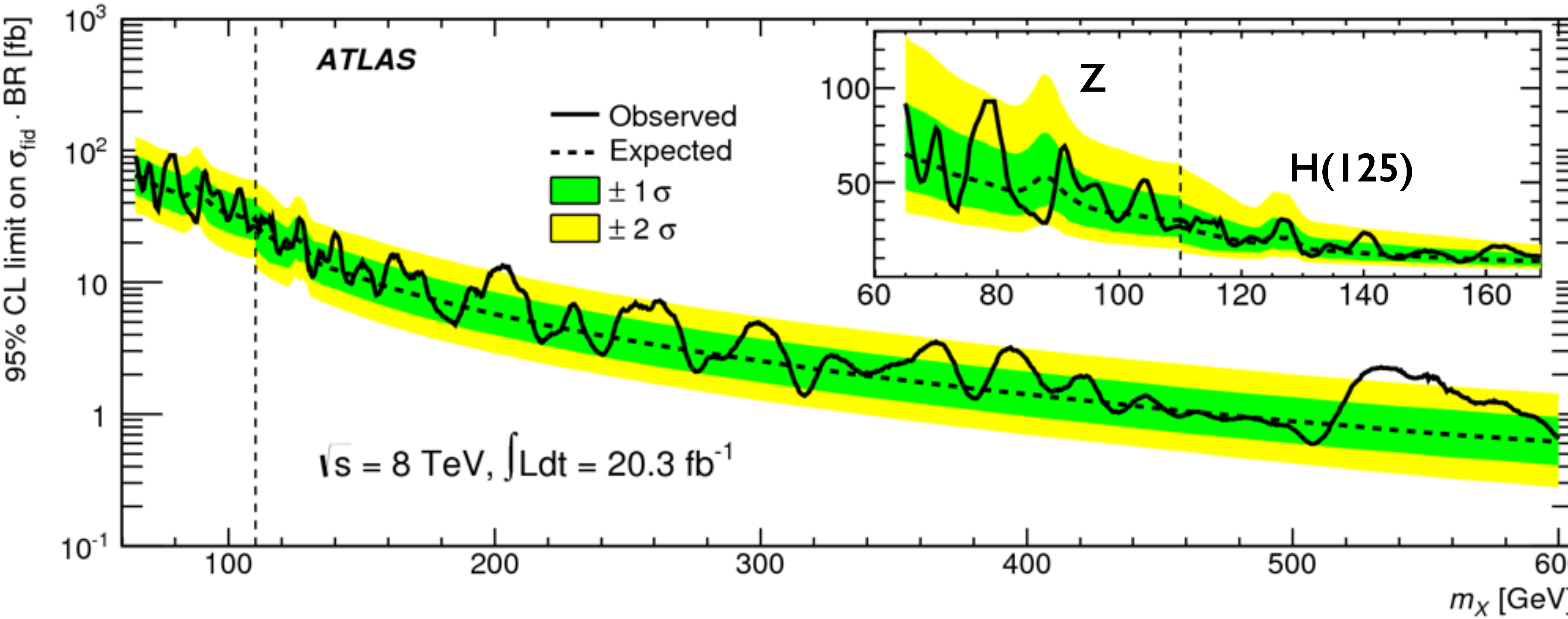
- the boson couples differently to particles
- the couplings depend on mass

Also: decay to electrons not seen

Searches for Other Higgs Bosons

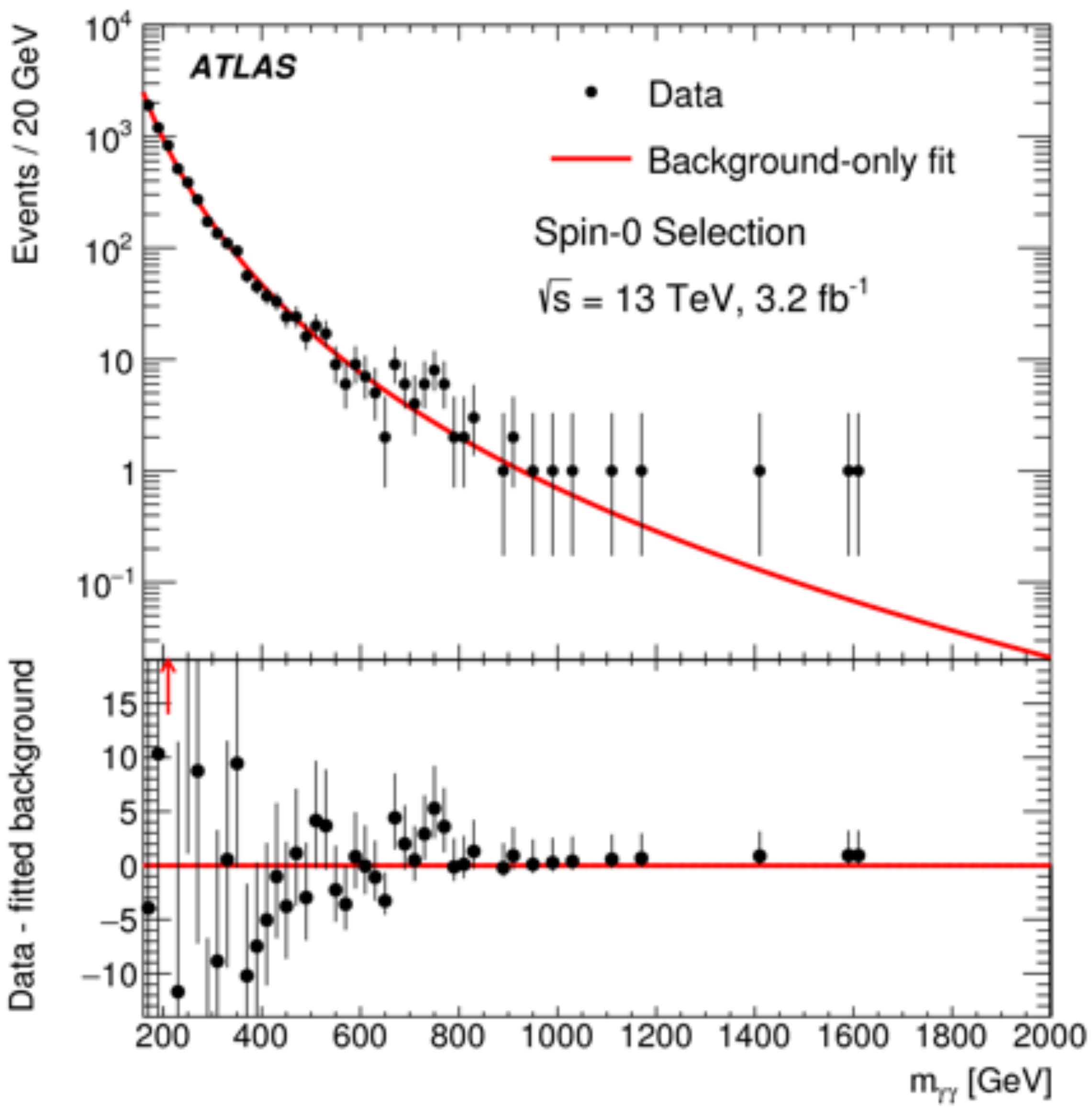
Example in the di-photon decay mode

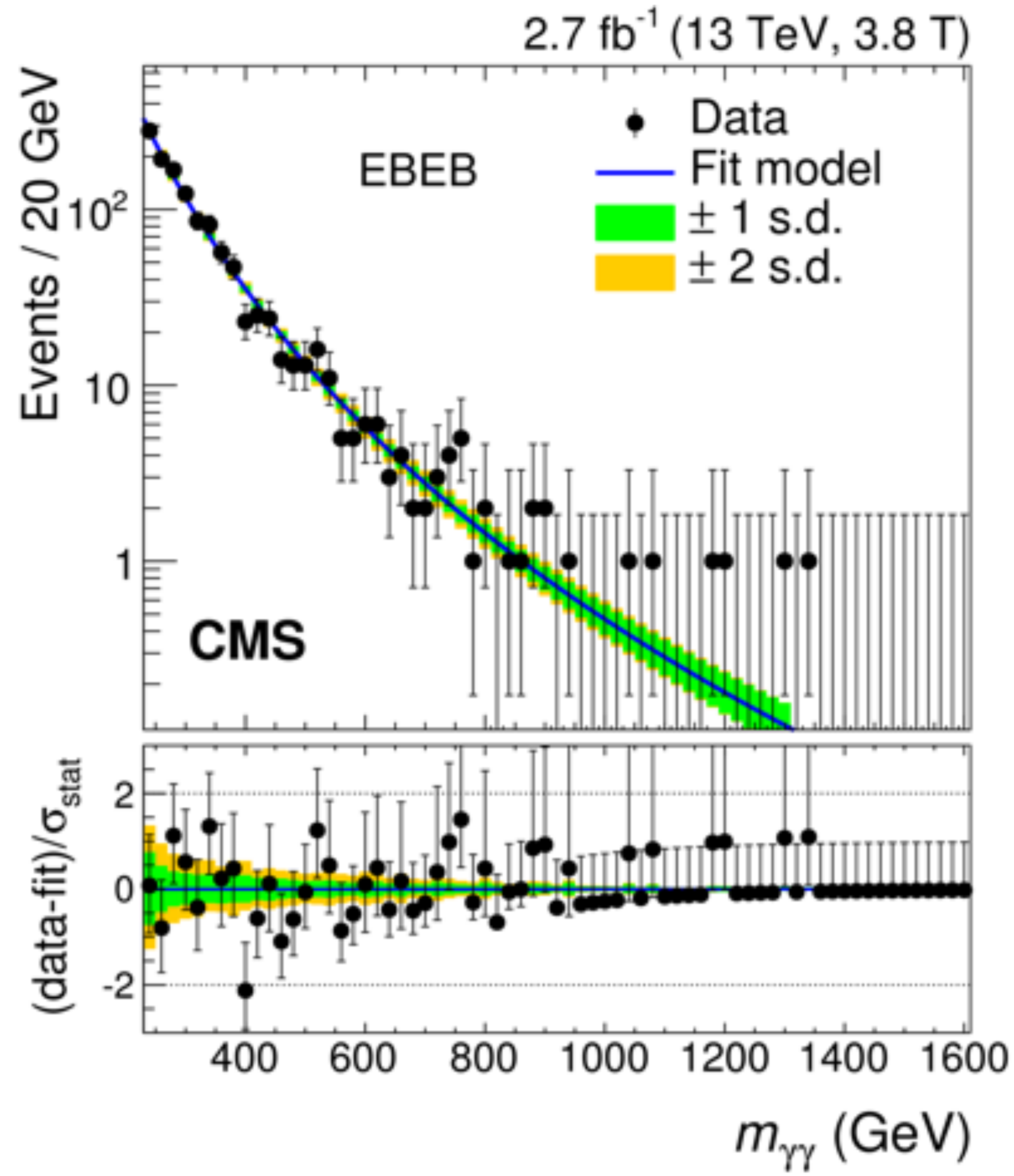
PRL 113 (2015) 171801



No sign of other Higgs bosons…

An Intriguing Bump at 750 GeV





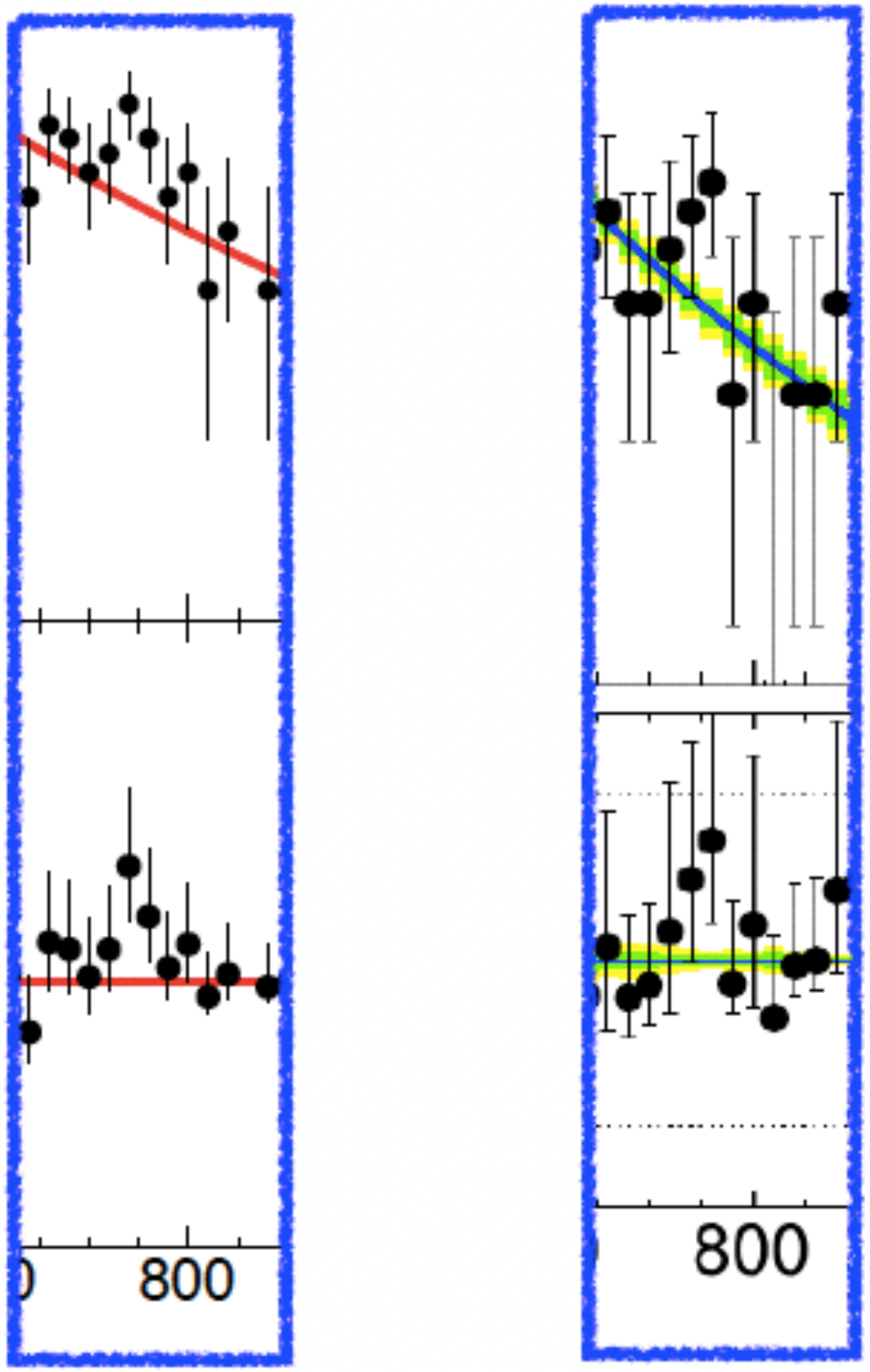
ATLAS, excess in the diphoton spectrum around 750 GeV: 3.9σ ($\Gamma/m \simeq 6\%$)

CMS, excess in the diphoton spectrum around 750 GeV : 3.0σ ($\Gamma/m \simeq 1.4\%$)

arXiv:1606.03833

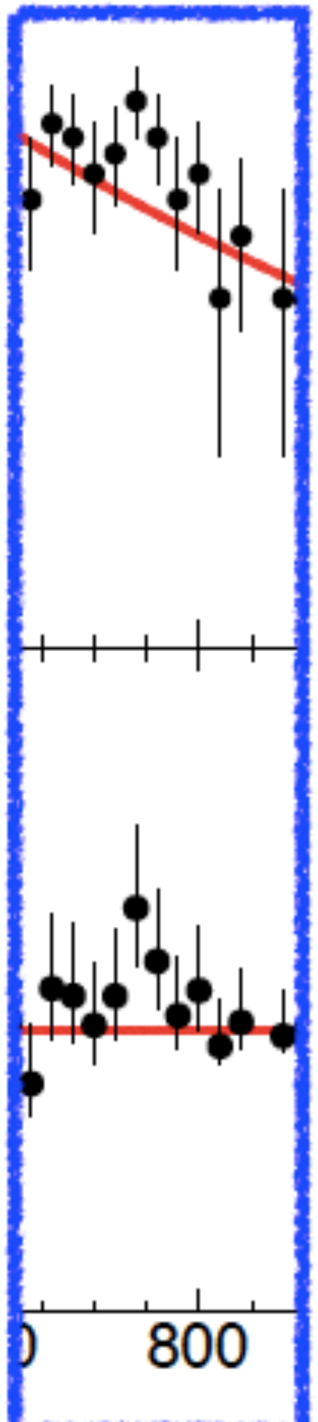
arXiv:1606.04093

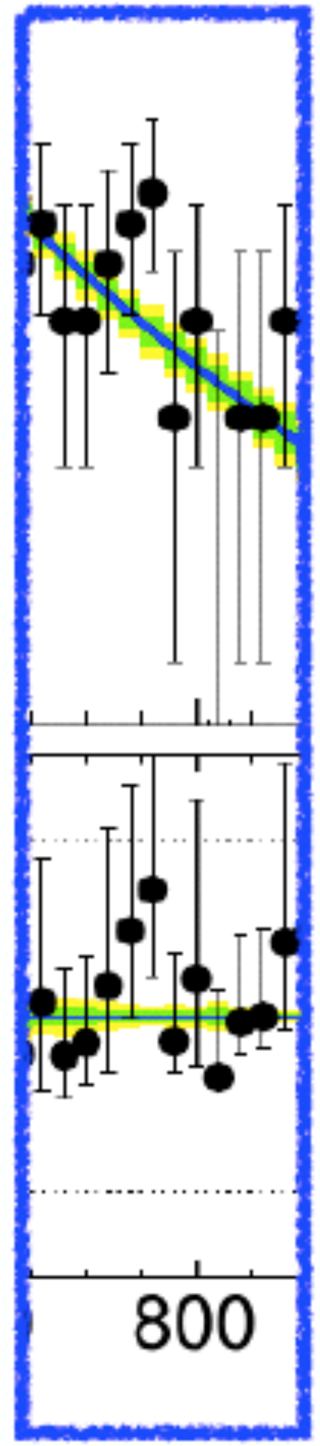
Revolution or Fluctuation?



Revolution or Fluctuation?

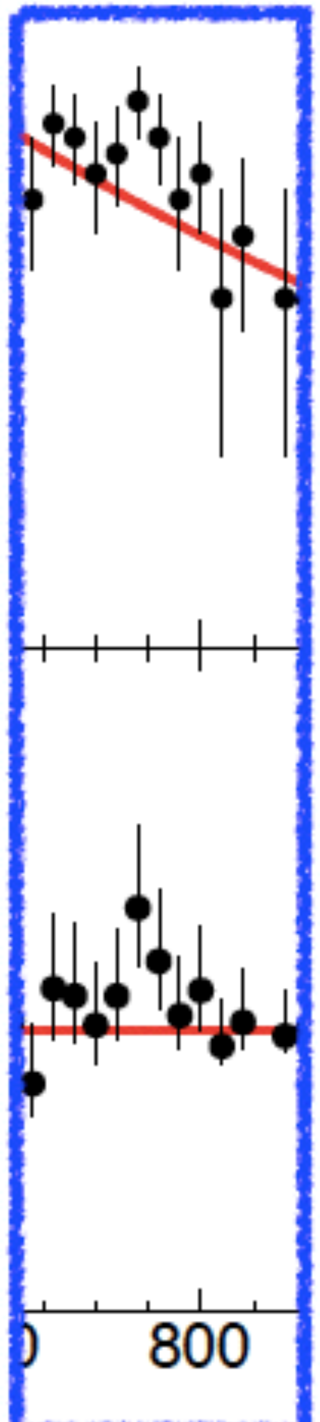
The experimentalist point of view:

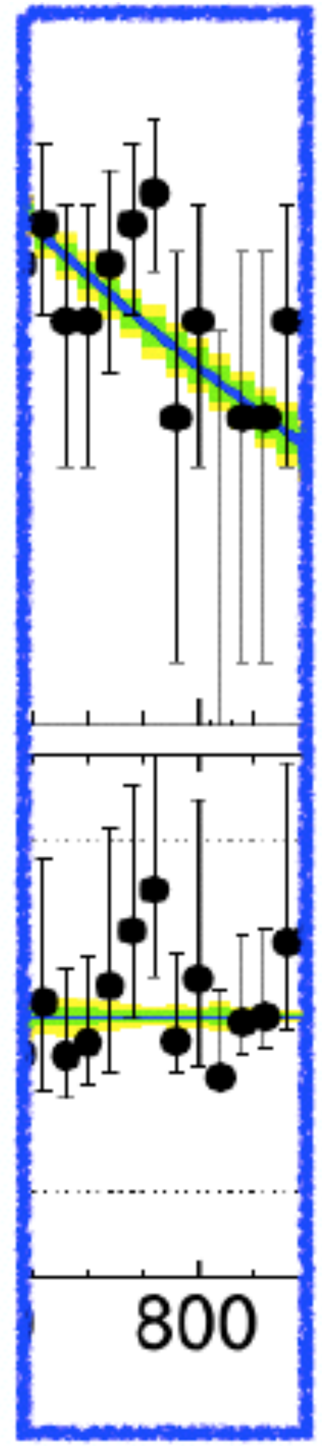




Revolution or Fluctuation?

The experimentalist
point of view:

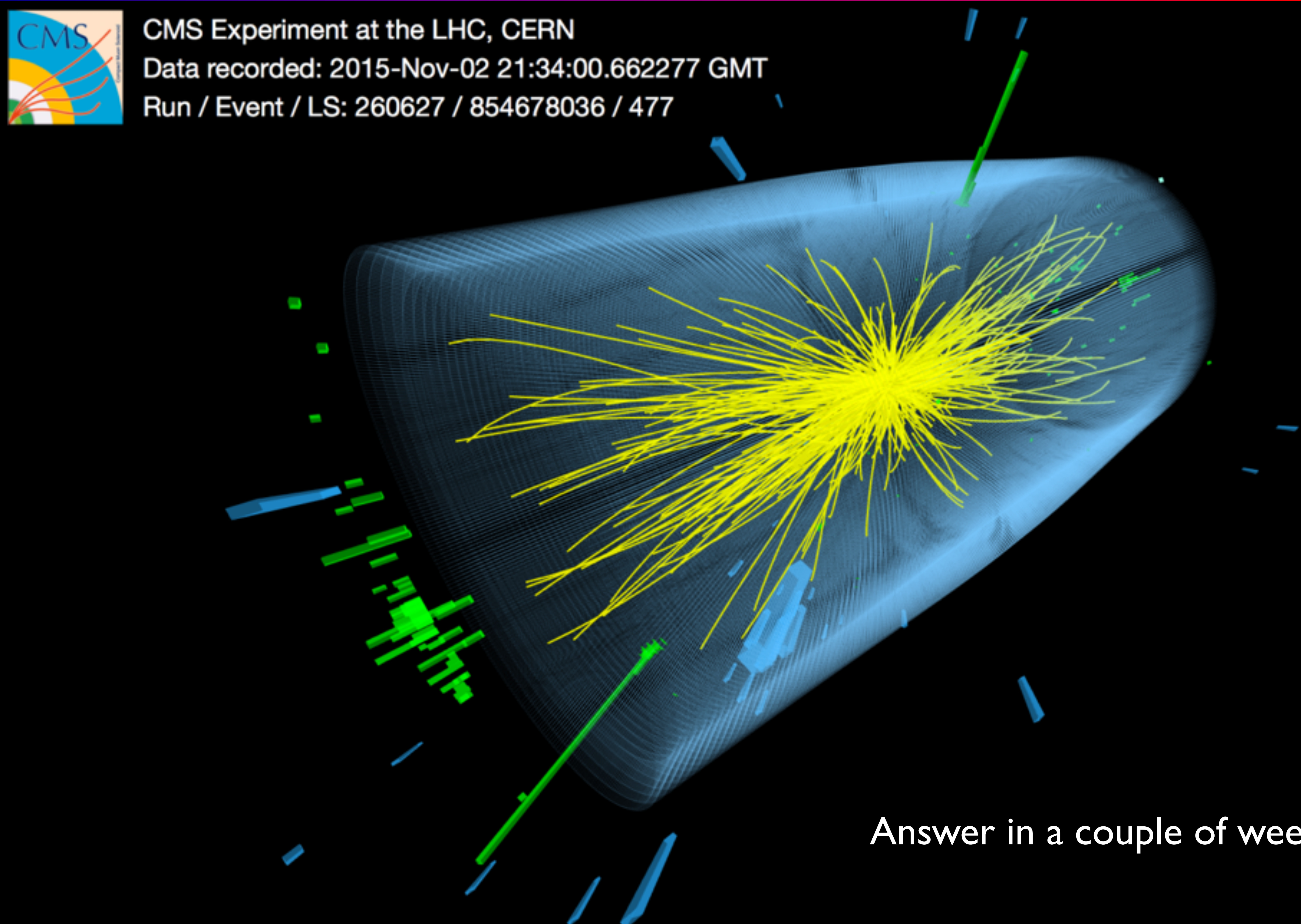




The theorist
point of view:

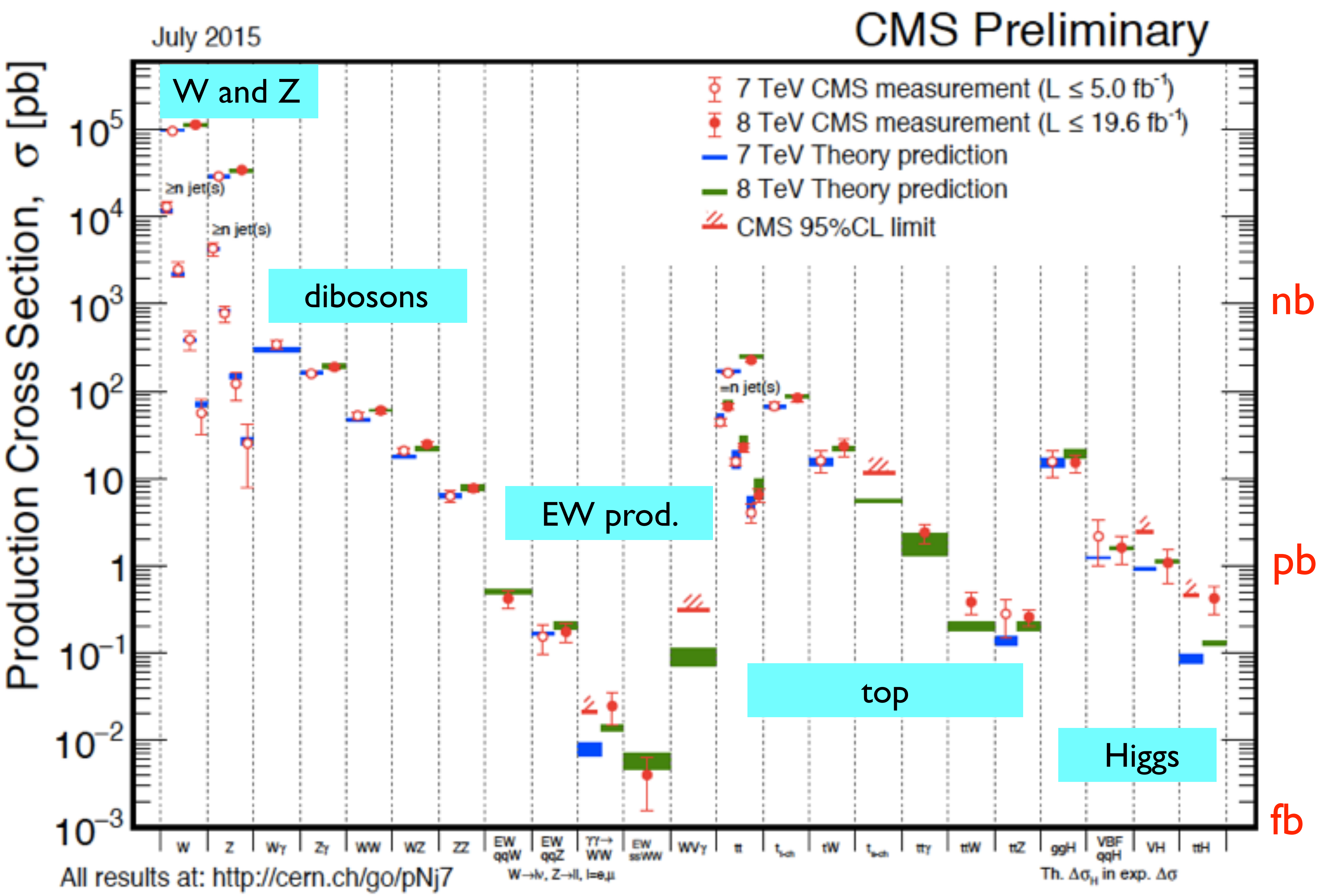
(from Alex Pomarol's Moriond EW 2016 summary talk)

Revolution or Fluctuation?



Answer in a couple of weeks

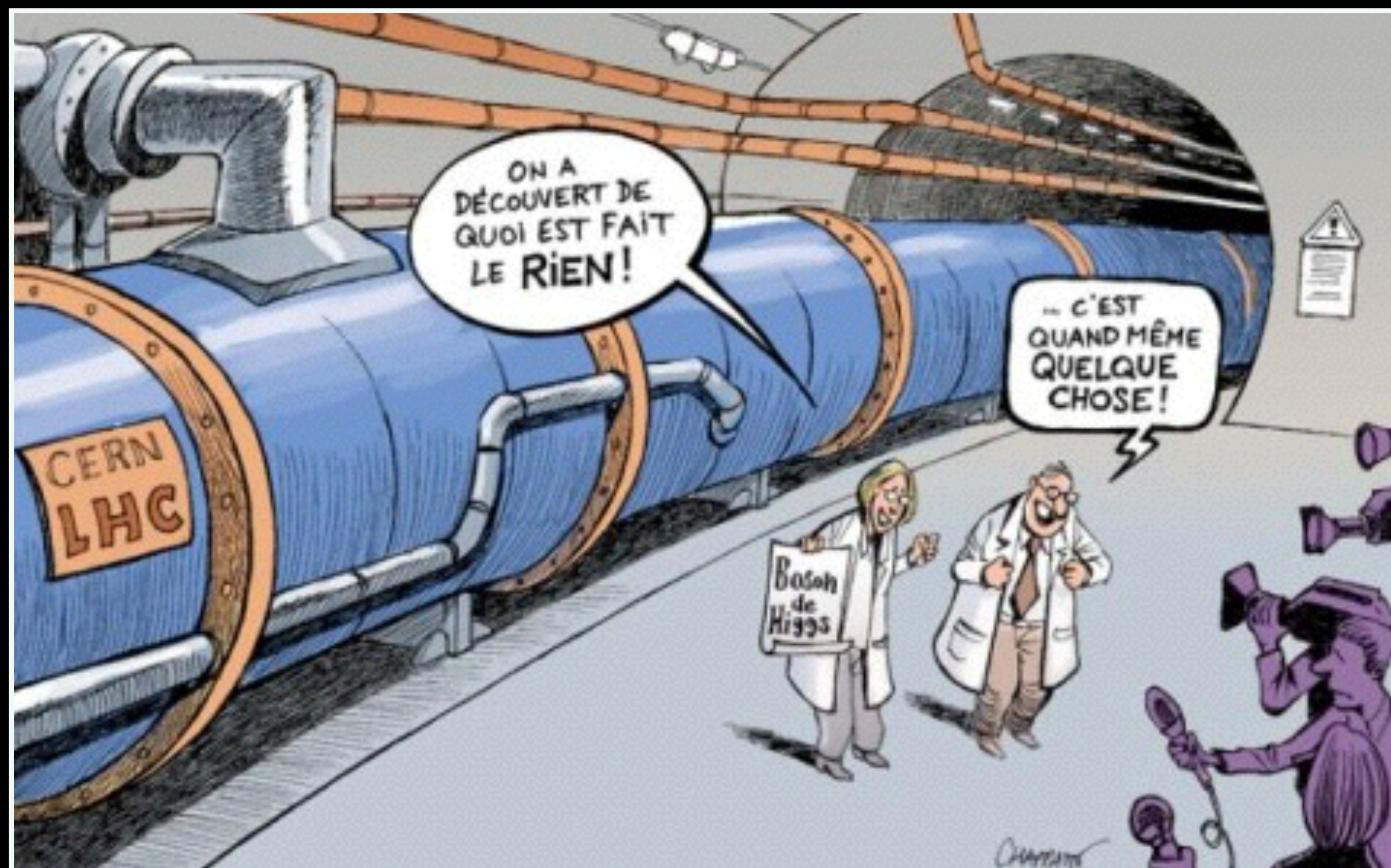
This Resumes our Journey in SM



Next stop

New Physics!

Thanks for your attention



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