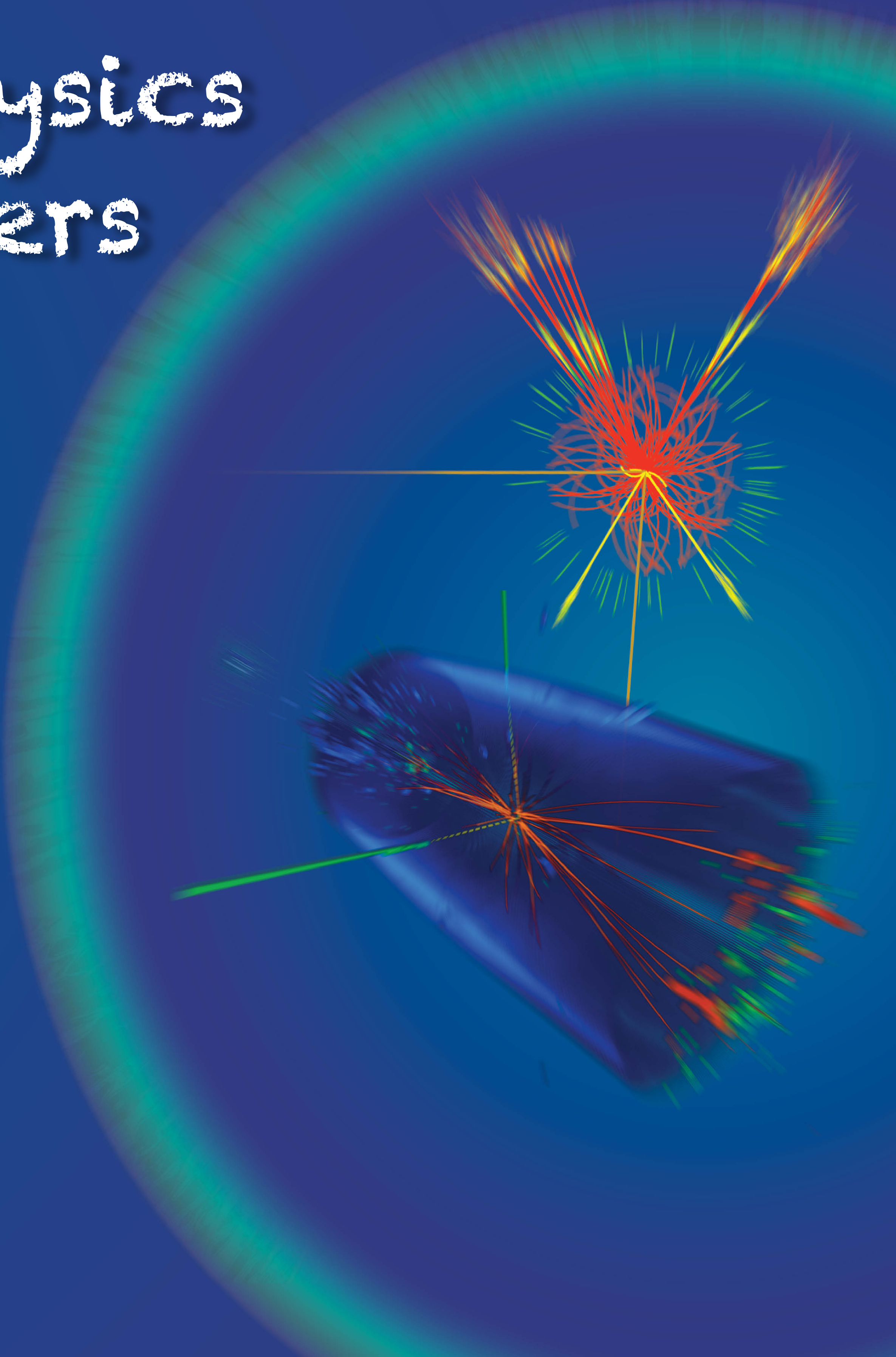
Standard Model Physics at Hadron Colliders

Third Lecture



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CEA-Saclay Irfu, France

July 2015

The Top Quark

The top quark

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

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

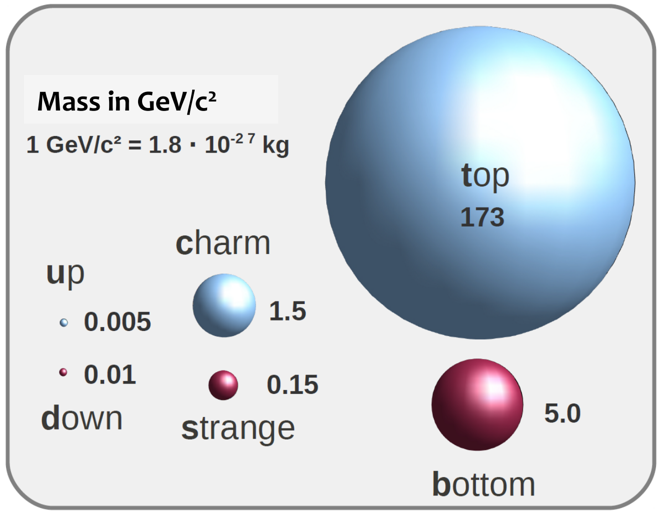
- is the only fermion with "natural" coupling to the Higgs field

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

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

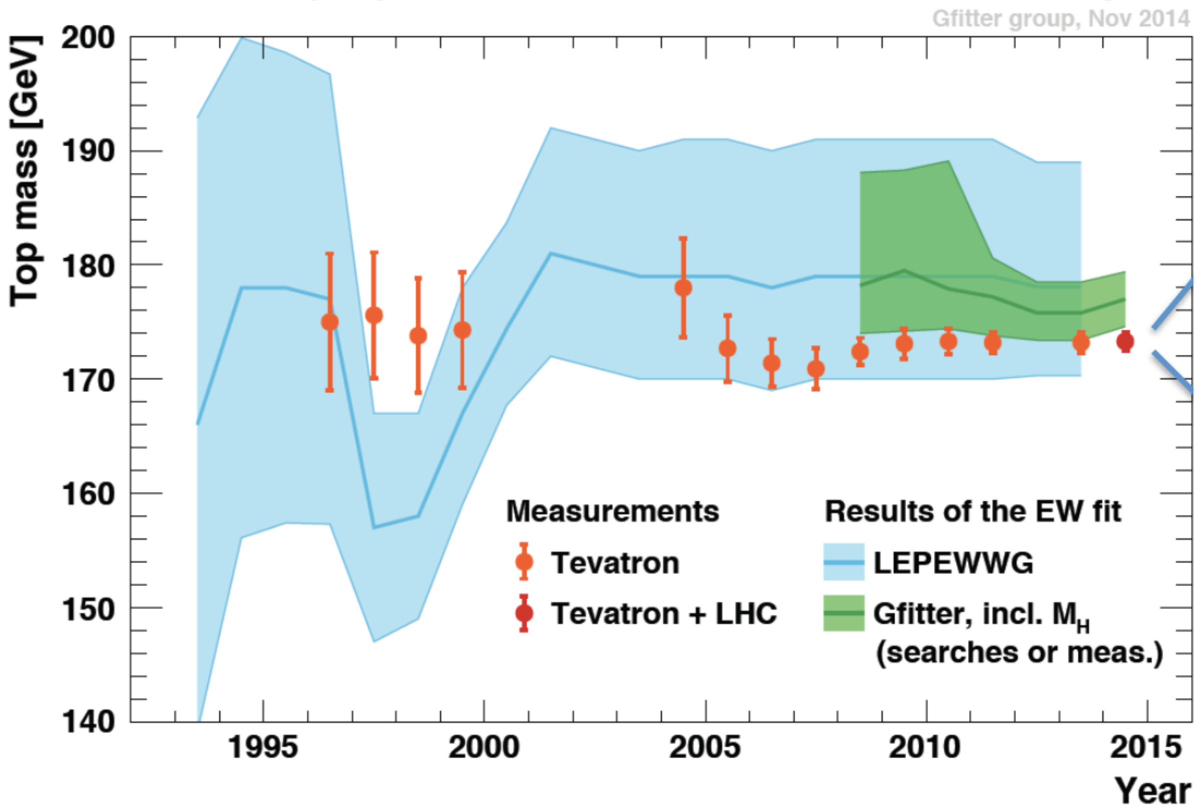
$$\Gamma(t \to bW^+) \approx \frac{\alpha}{16 s_W^2} |V_{tb}|^2 \frac{m_t^3}{m_W^2}$$

$\sim$1.5 GeV (> Λ_{QCD})



40 times heavier than the b quark

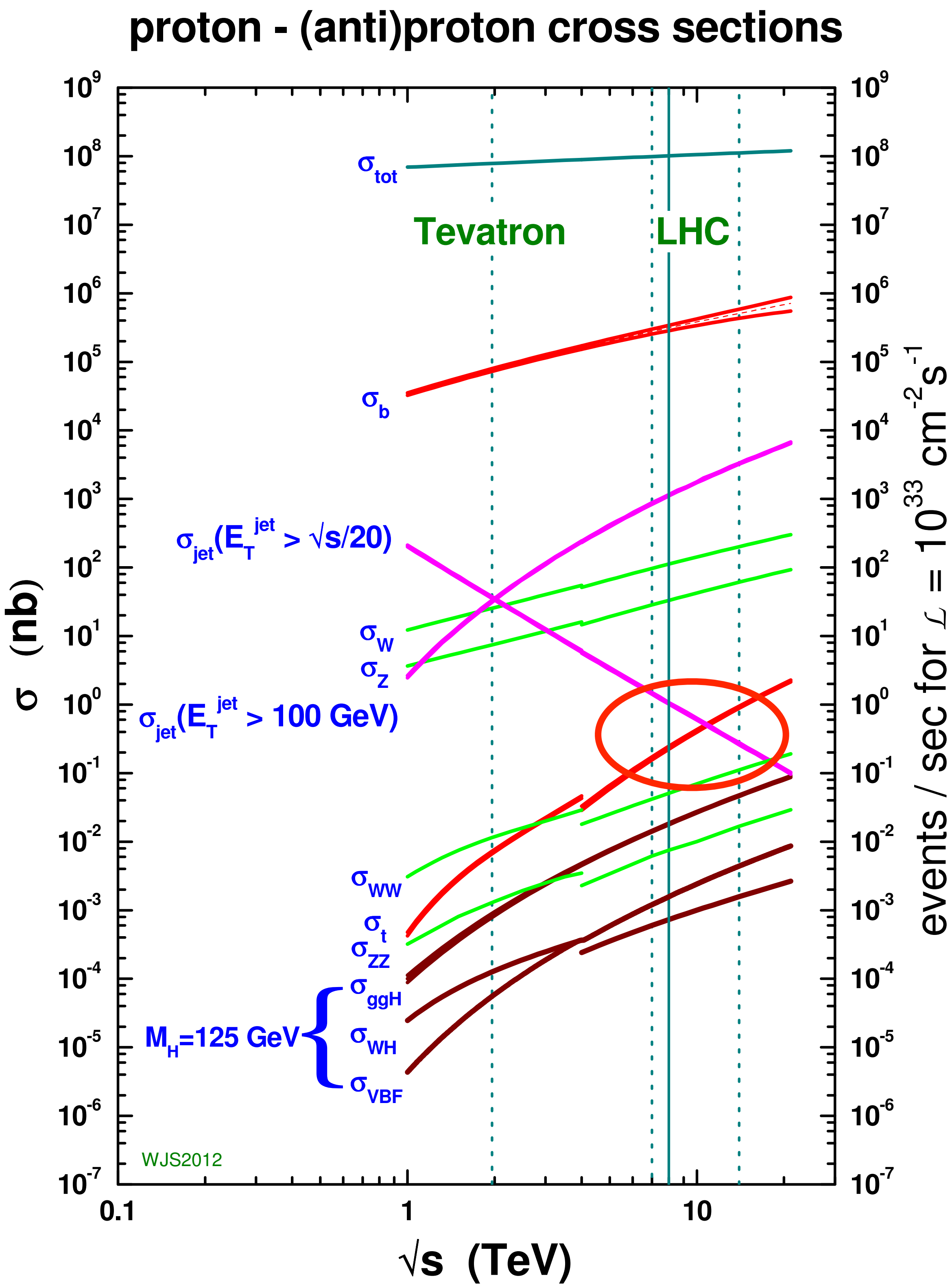
top quark first discovered "virtually"

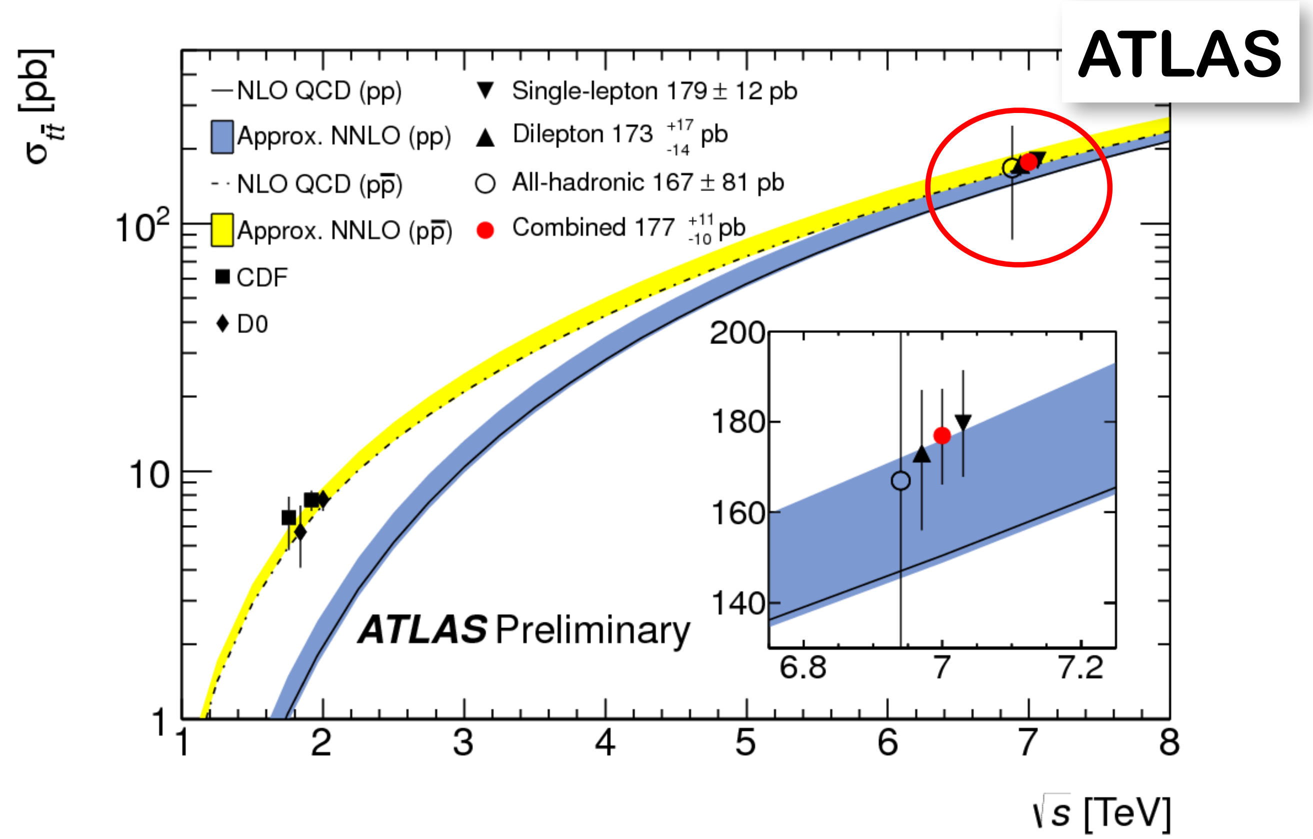


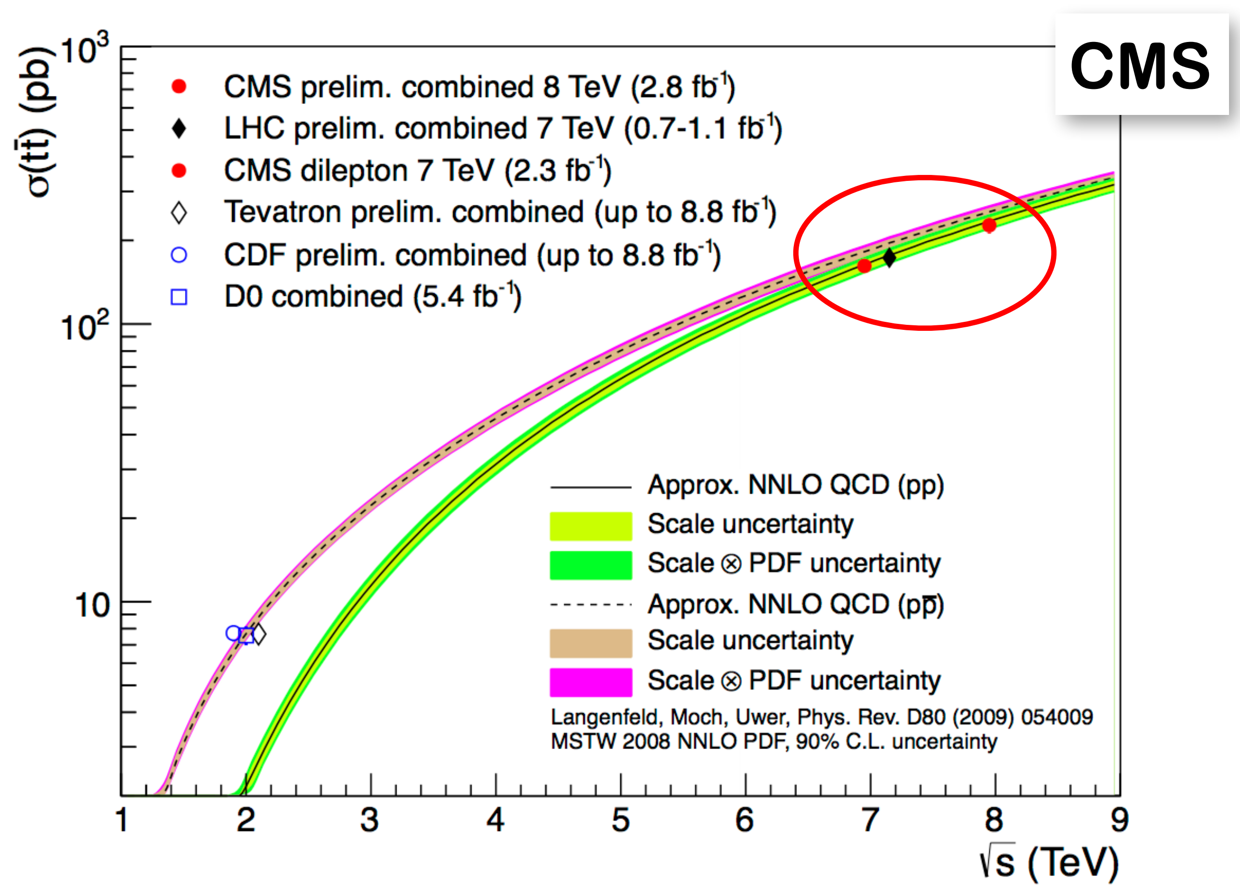
typical top decay time: 5 10^{-25} s

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

Top Quark Physics



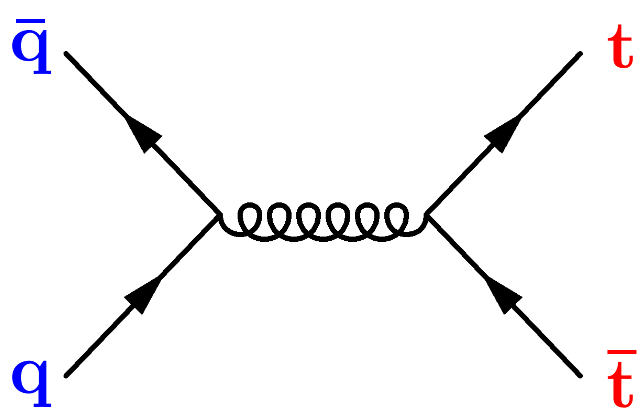




Top Quark QCD Production

Tevatron (1.96 TeV)
σ_{TEV} = 7 pb

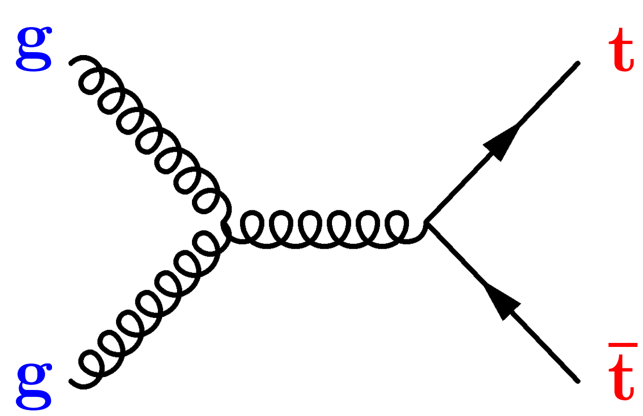
quark annihilation

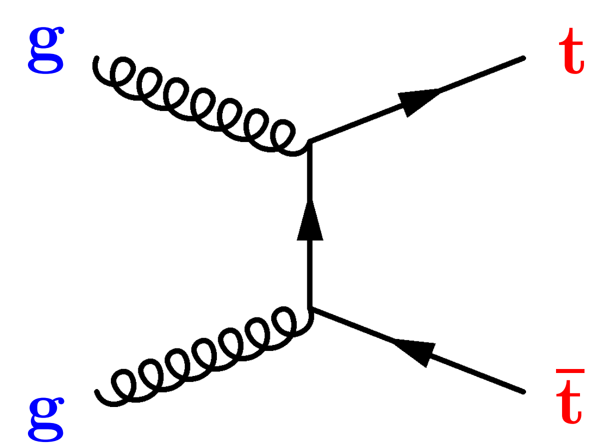


85% of the cross section

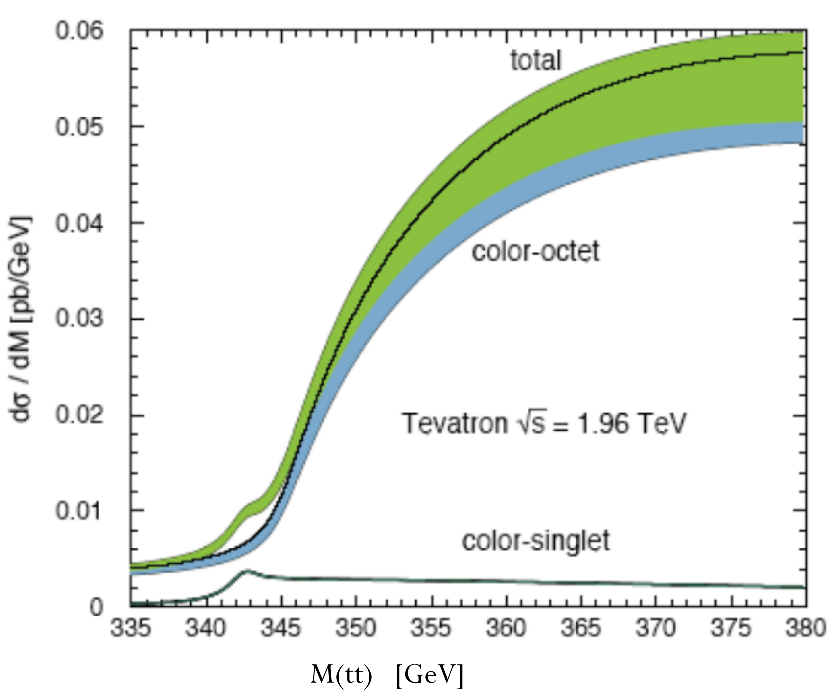
LHC (7/8 TeV)
σ_{LHC} = 220 pb

gluon fusion



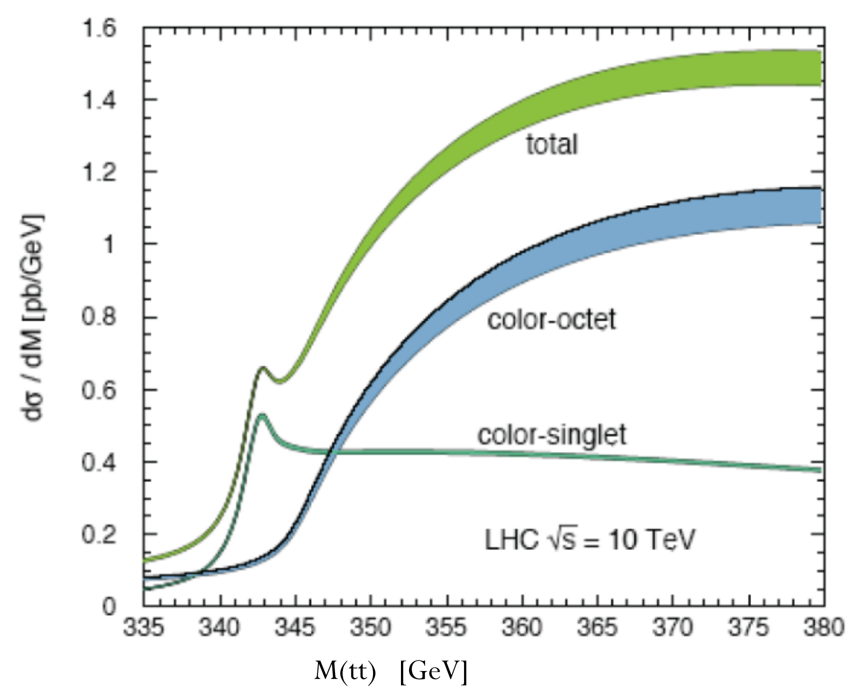


80% of the cross section



Tevatron
ten t-tbar pair
per day

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



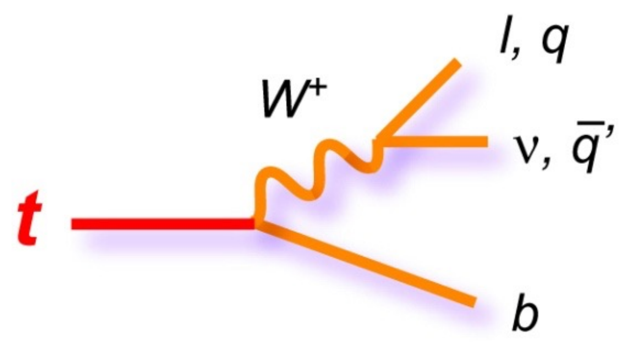
LHC:
one t-tbar pair
per second

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

Top Pair Decay Channels

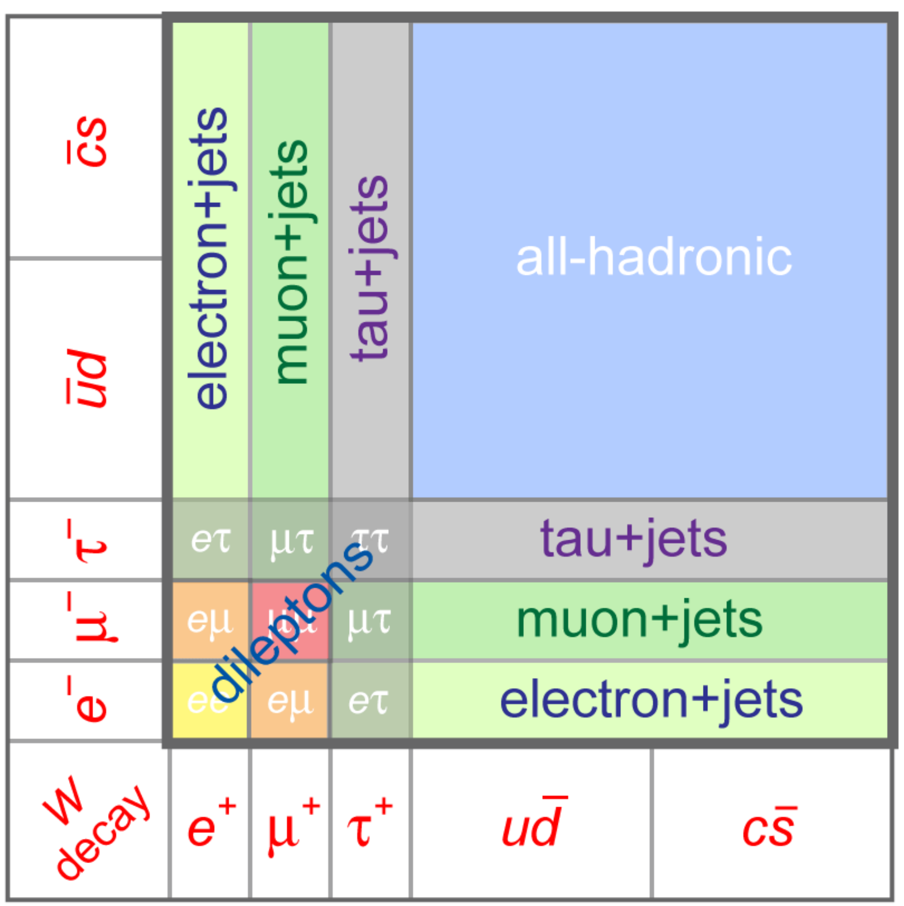
In the SM the top quark decays exclusively into a W boson and a b quark

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

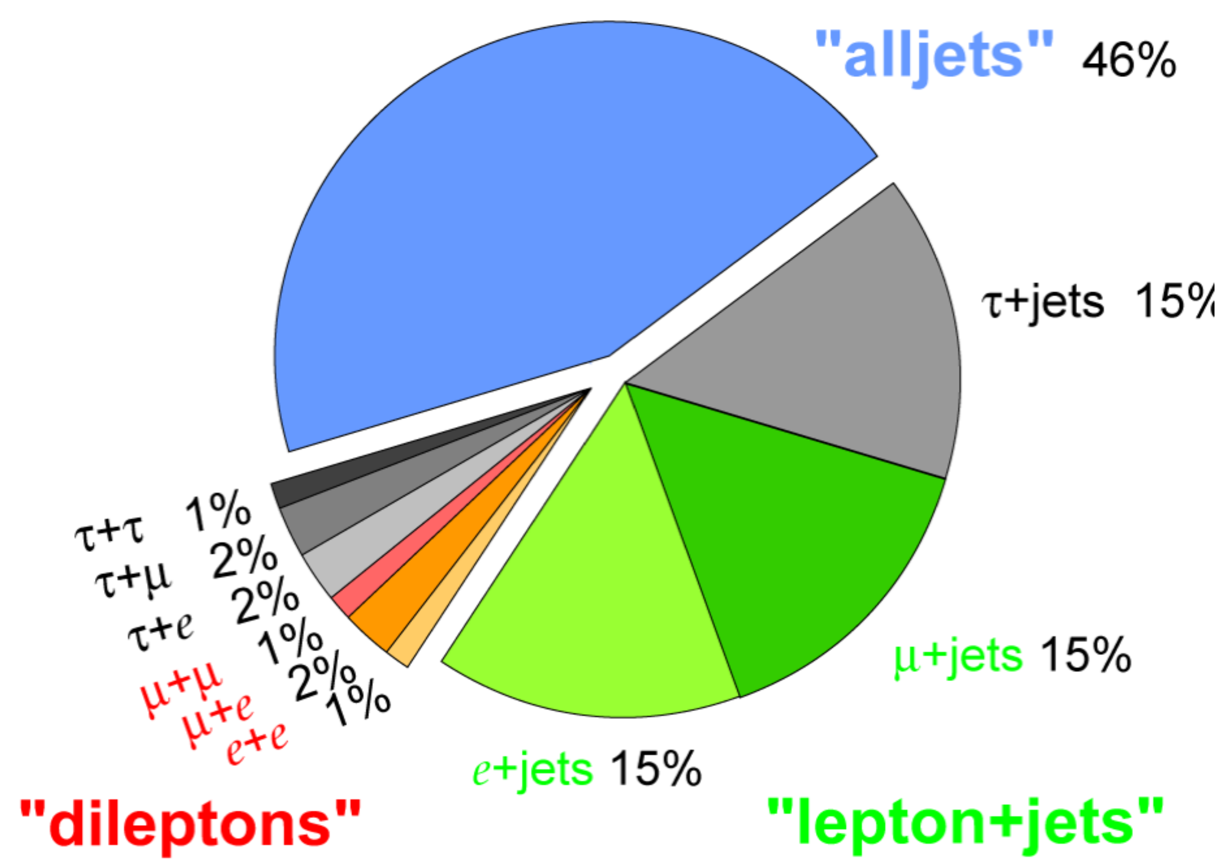


therefore the branching fractions of the t-tbar final states depend on the W boson branching fractions

Top Pair Decay Channels

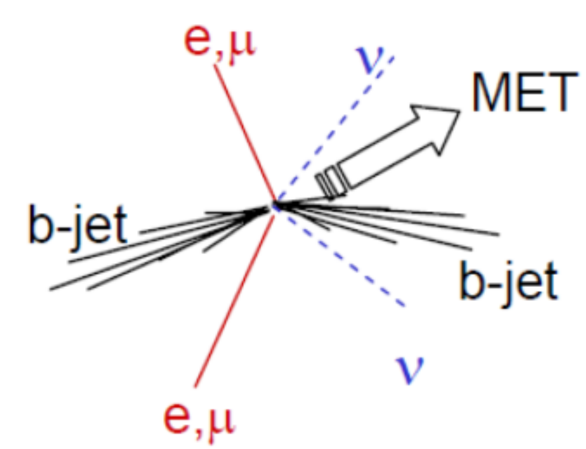


Top Pair Branching Fractions



Top Pair Event Classification

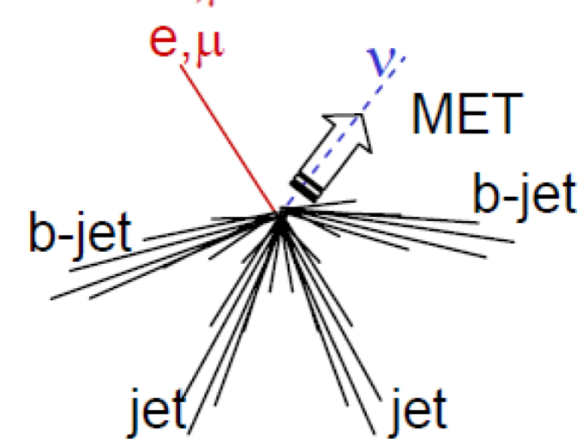
The classification of top pair events relies on the number of leptons in the final state



Dilepton

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

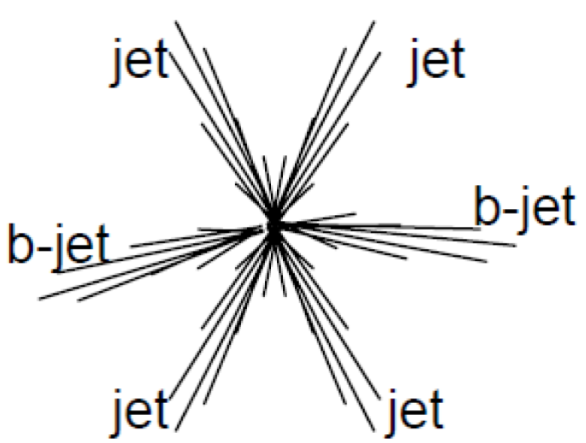
- 3 channels ee, μμ and eμ
- BR = 4.7% (1+1+2)
- very low backgrounds, mostly Drell-Yan



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}

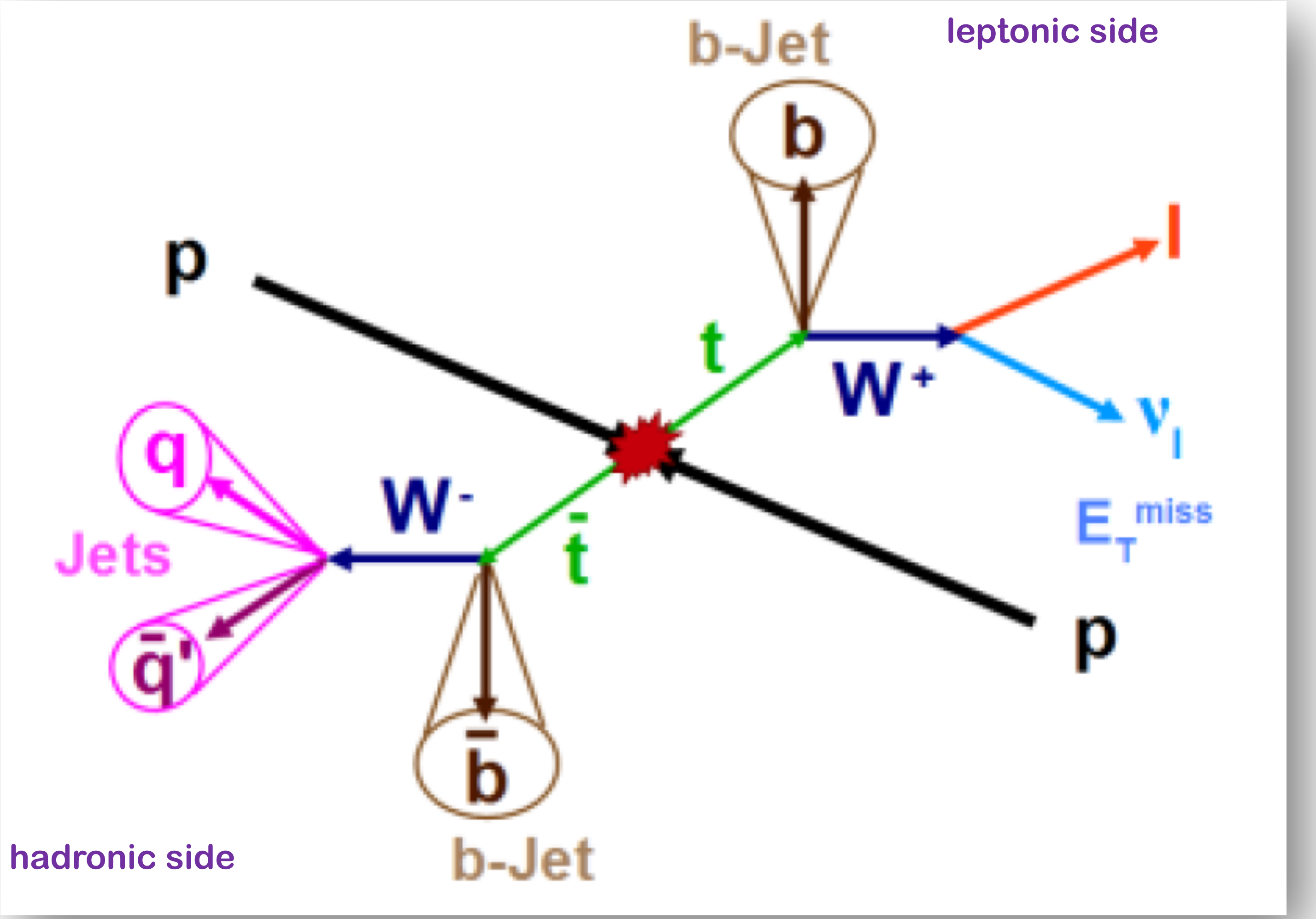
- BR = 45.7%
- large QCD-multijet background

Hadronic Tau

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

- BR = 4.7% + 14.6%

Lepton+Jets

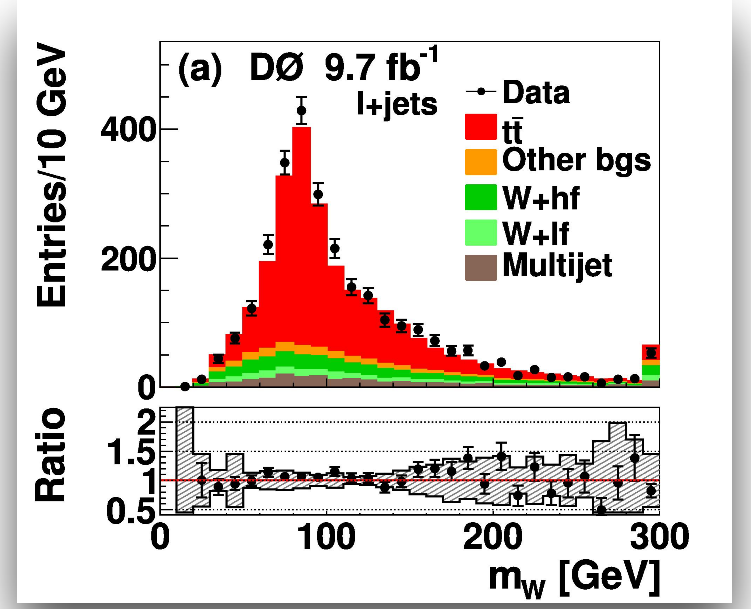


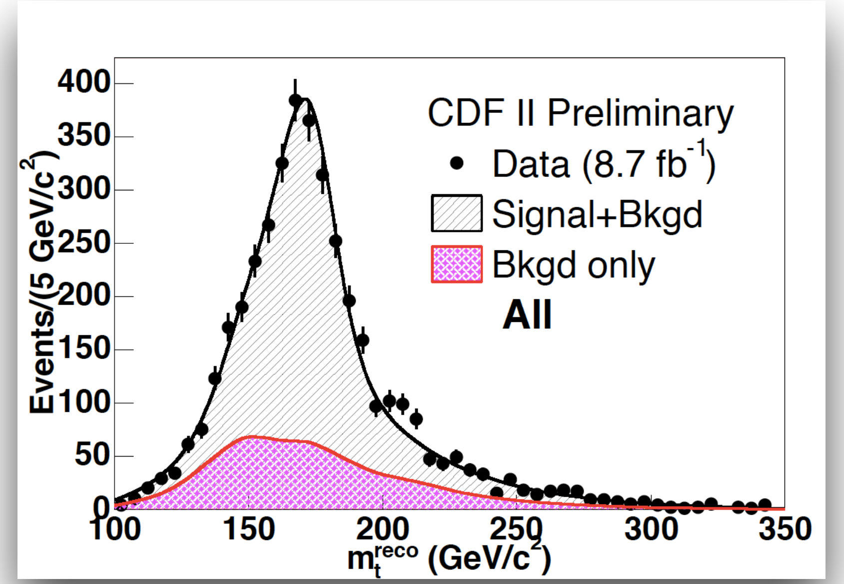
Golden mode at the LHC

- 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

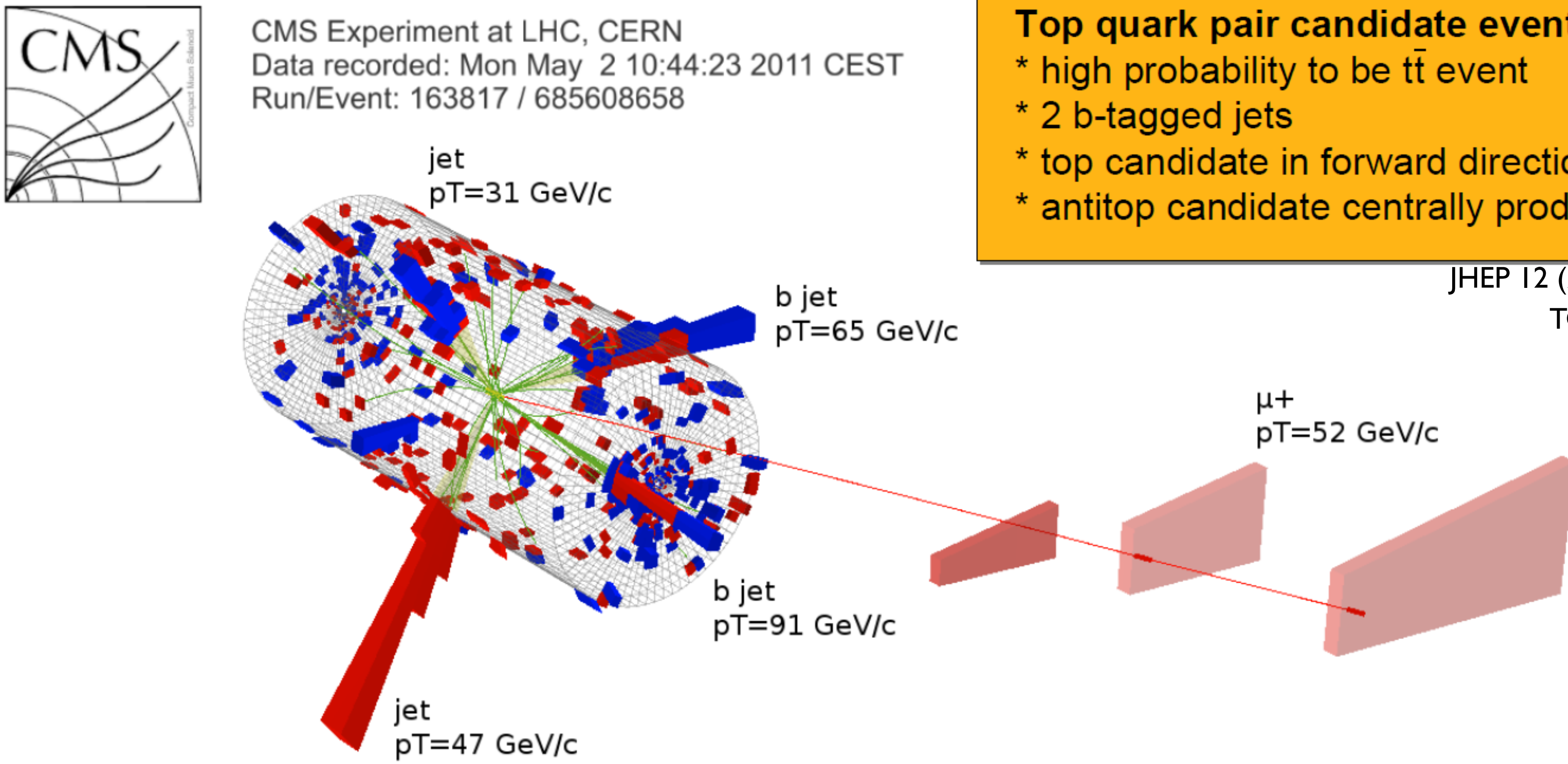




D0 and CDF signals with full statistics

~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

JHEP 12 (2012) 105
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, CMS

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

- t-tbar purity: 94%

Kinematical fit with constraints

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

Each permutation weighted by

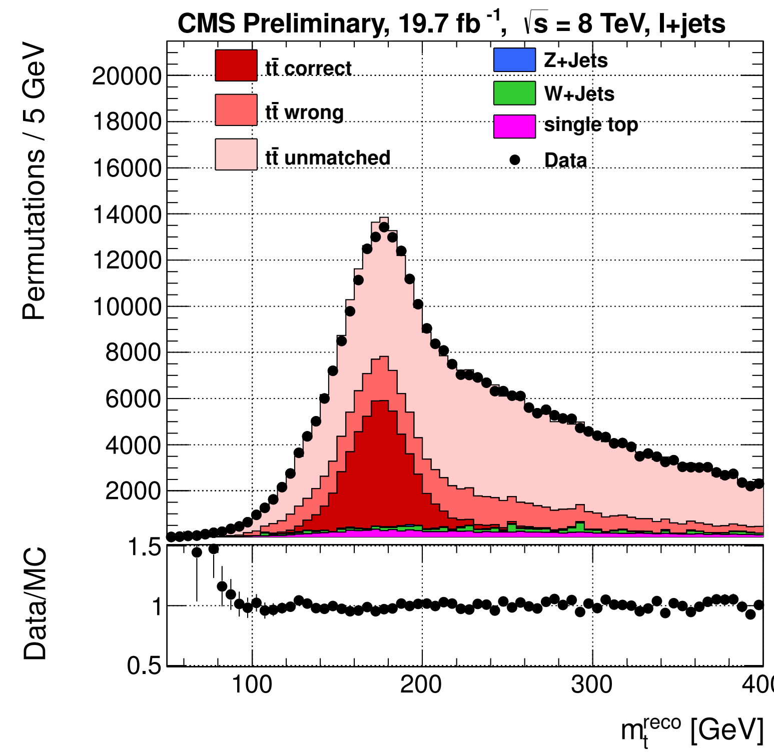
- $P_{gof} = \exp(-1/2\ \chi^2)$

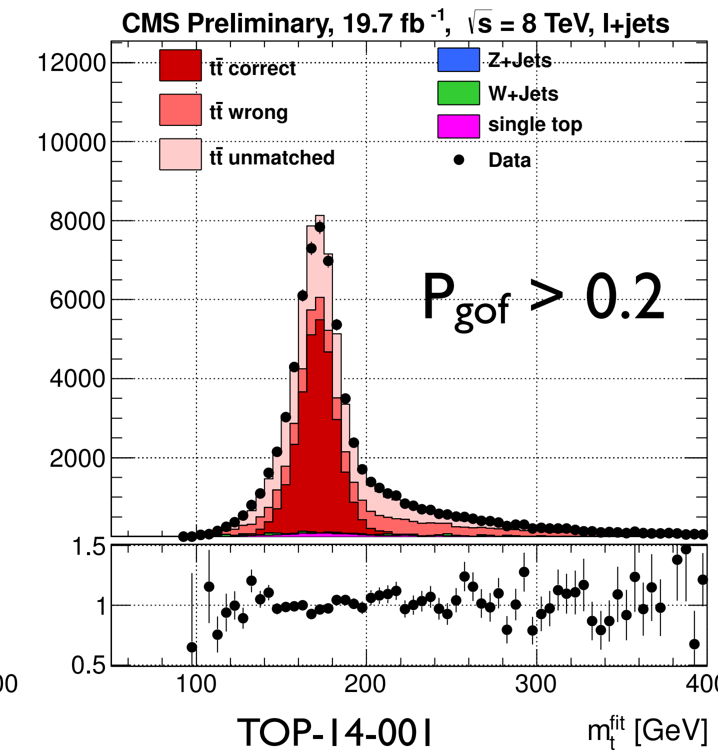
Jet Energy Scale Factor (JSF)

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

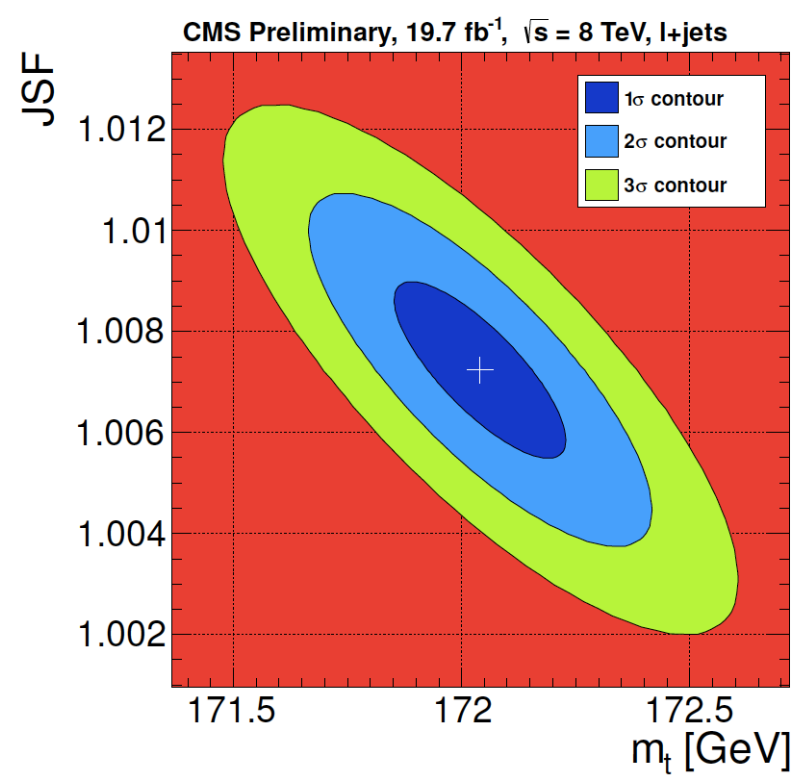
Ideogram method

- event likelihood as the convolution of the signal with a resolution function with wrong-pairing and backgrounds





TOP-14-001



m_t = 172.04 GeV

Uncertainties

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

JSF = 1.007 ± 0.012

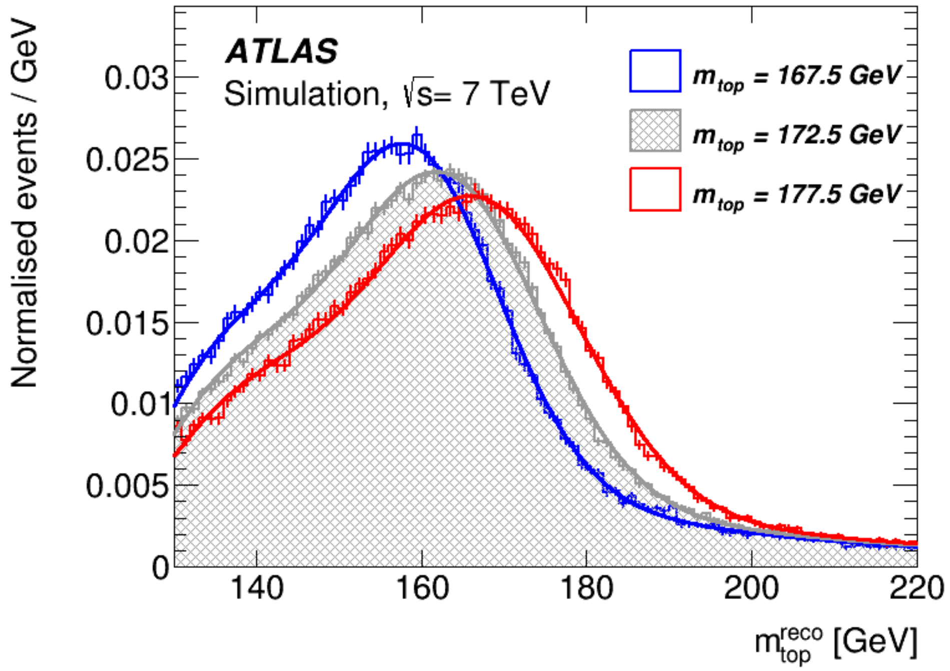
Lepton+Jets, ATLAS

22 000 events in 20 fb^{-1}@8 TeV

- t-tbar purity: 81%

3D-Template method

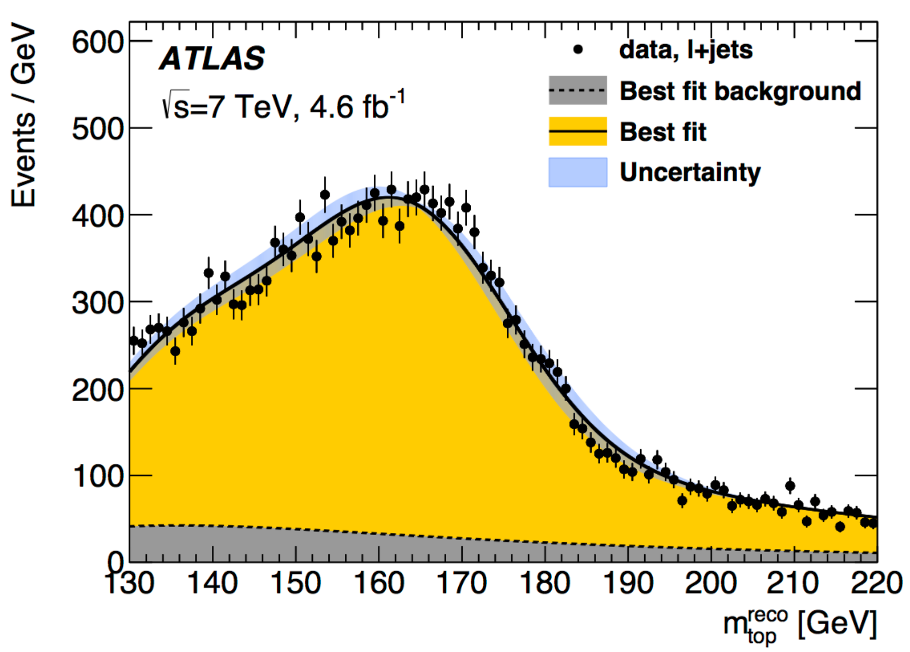
- mt, JSF, b-to-light JSF (bJSF)
- m_t, m_W , R_{bq}, m_{lb} distributions

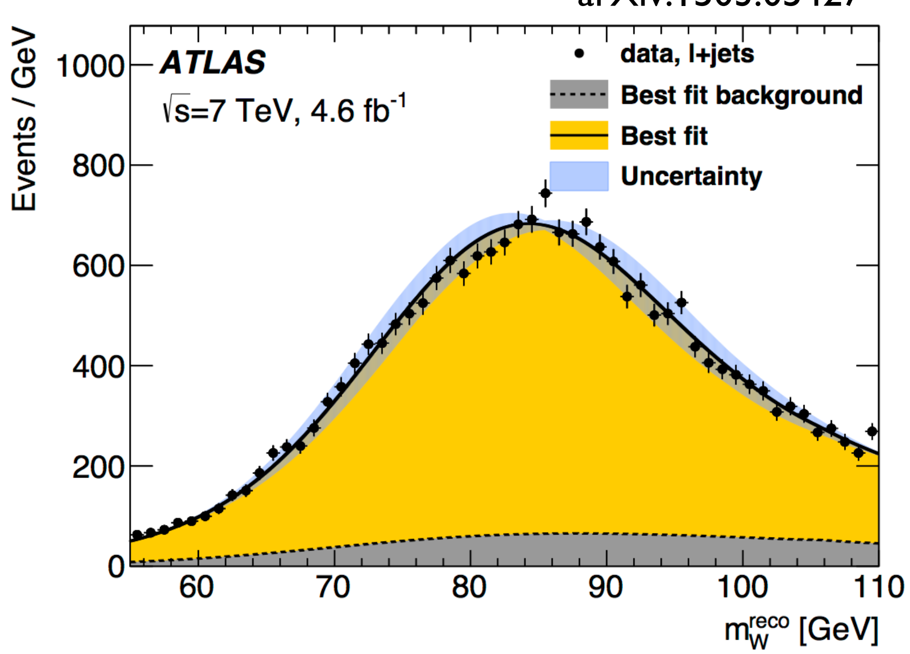


Template method

- fit observables with MC distributions generated assuming varying values of the top quark mass

arXiv:1503.05427





m_t = 172.33 GeV

Uncertainties

- stat+(b)JSF = 480 MeV
- syst = 1.02 GeV

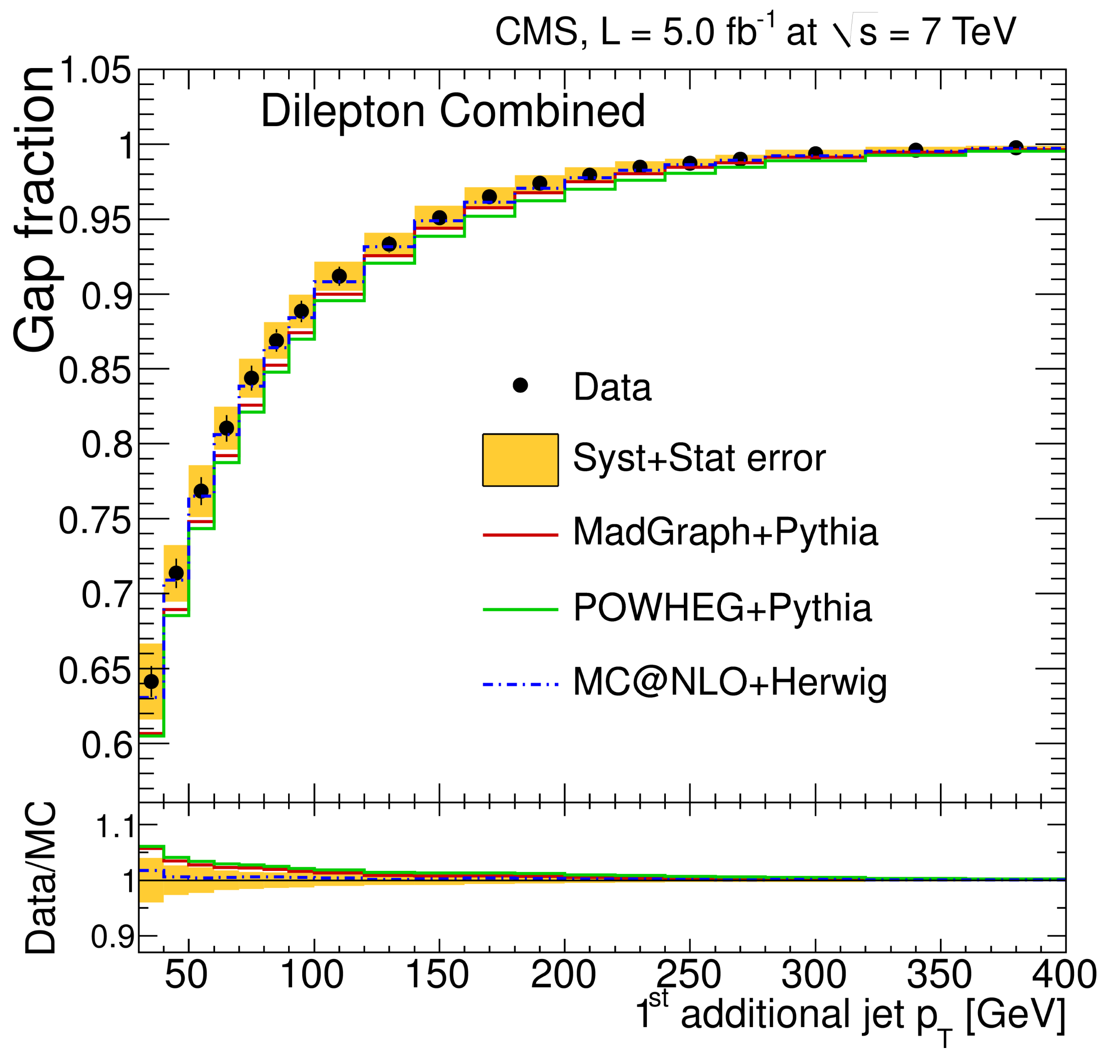
JSF = 1.019 ± 0.027

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

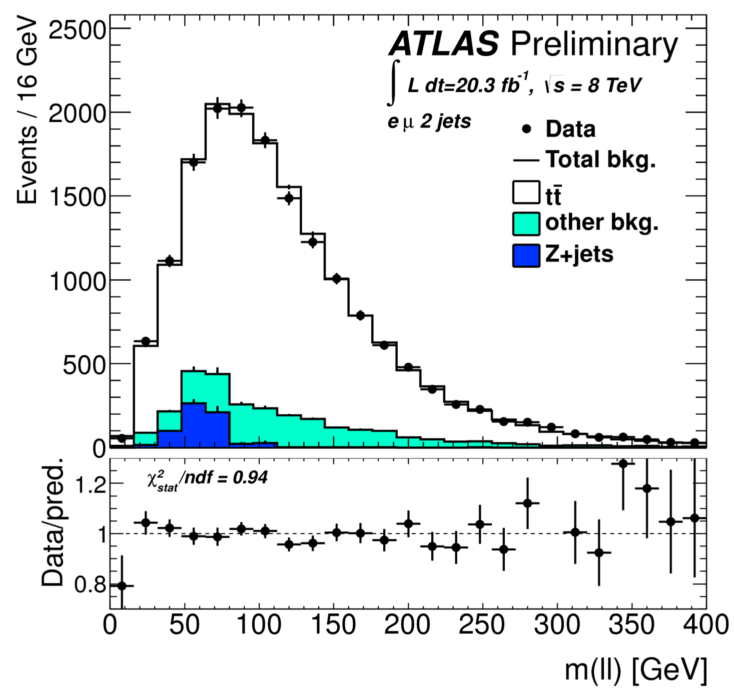
Other Channels

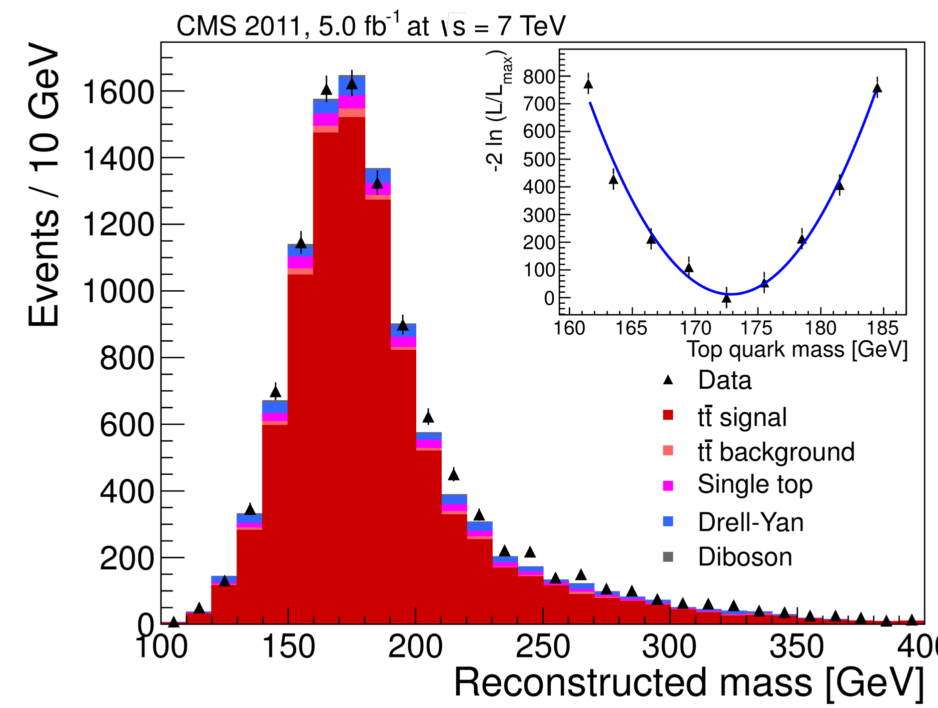
(illustration plots — not final — not comparable)

ATLAS

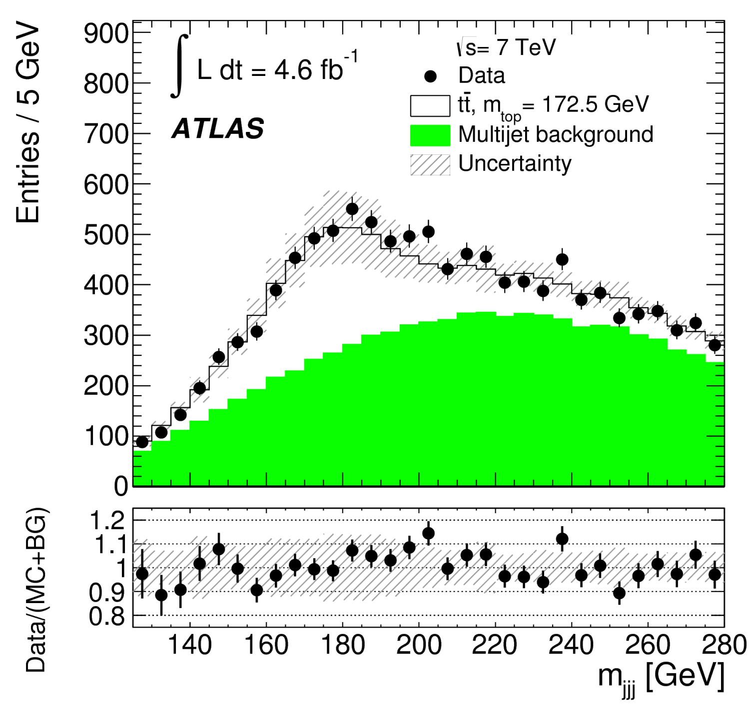
CMS

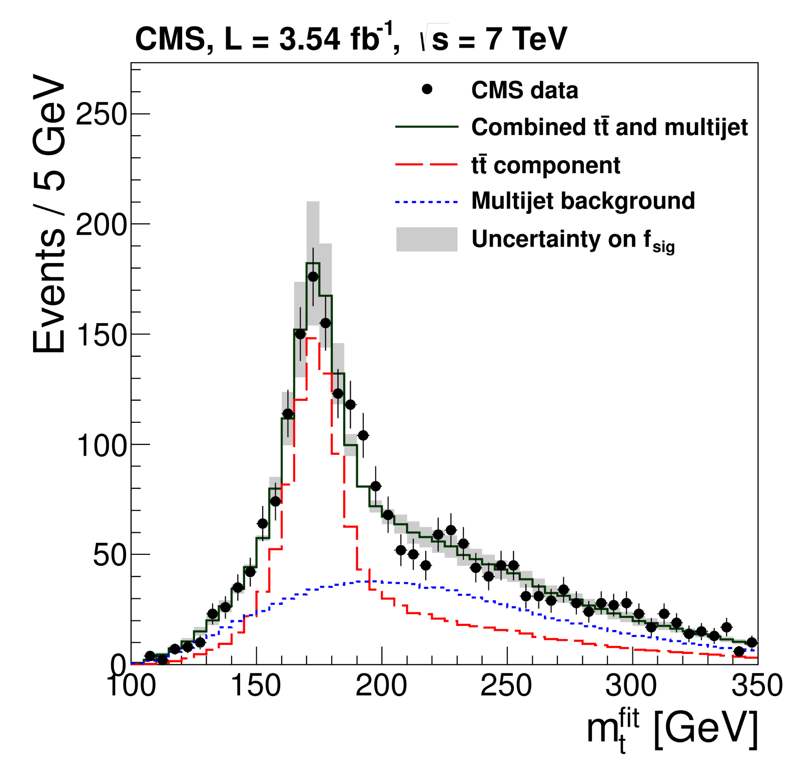
Dilepton



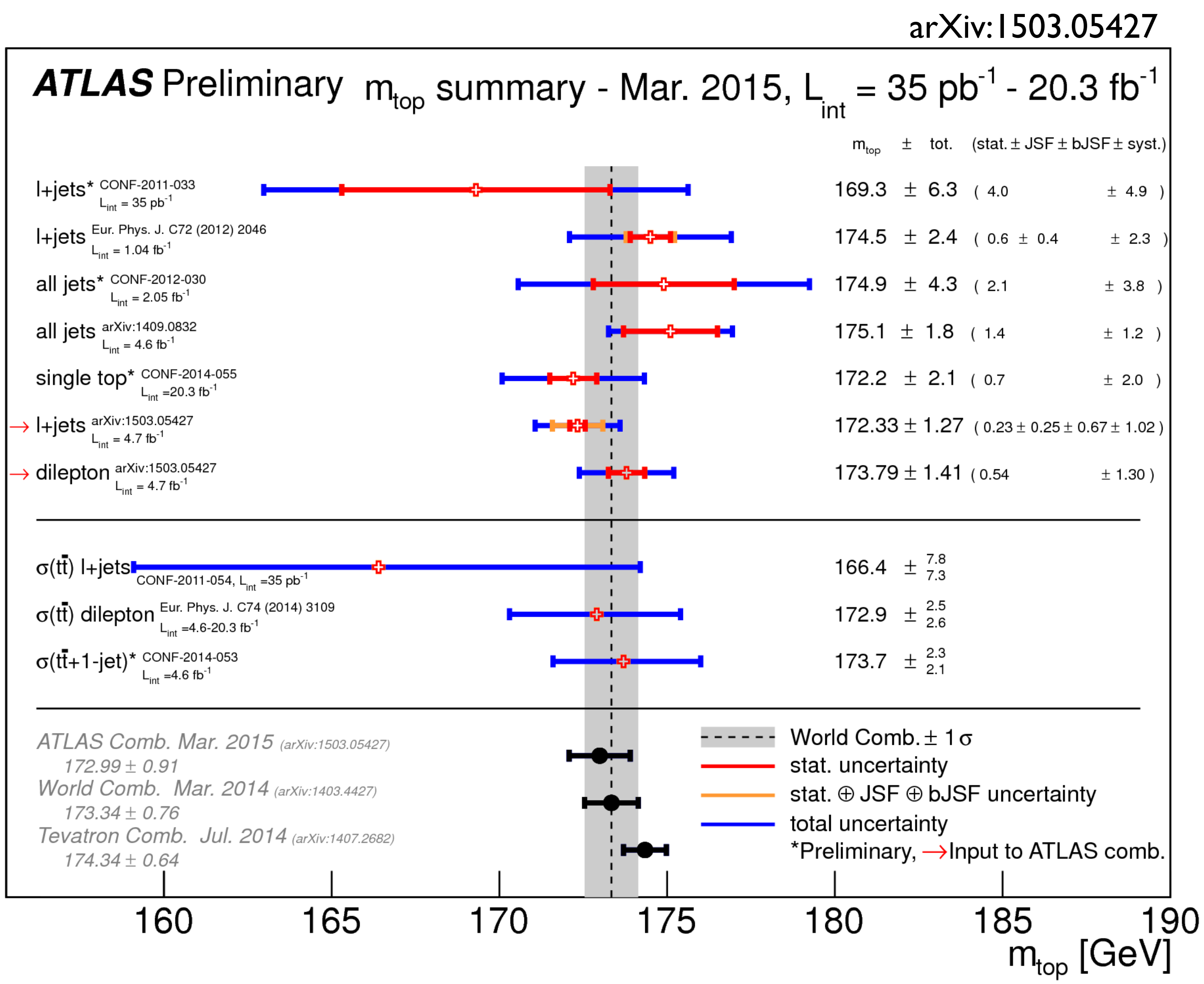


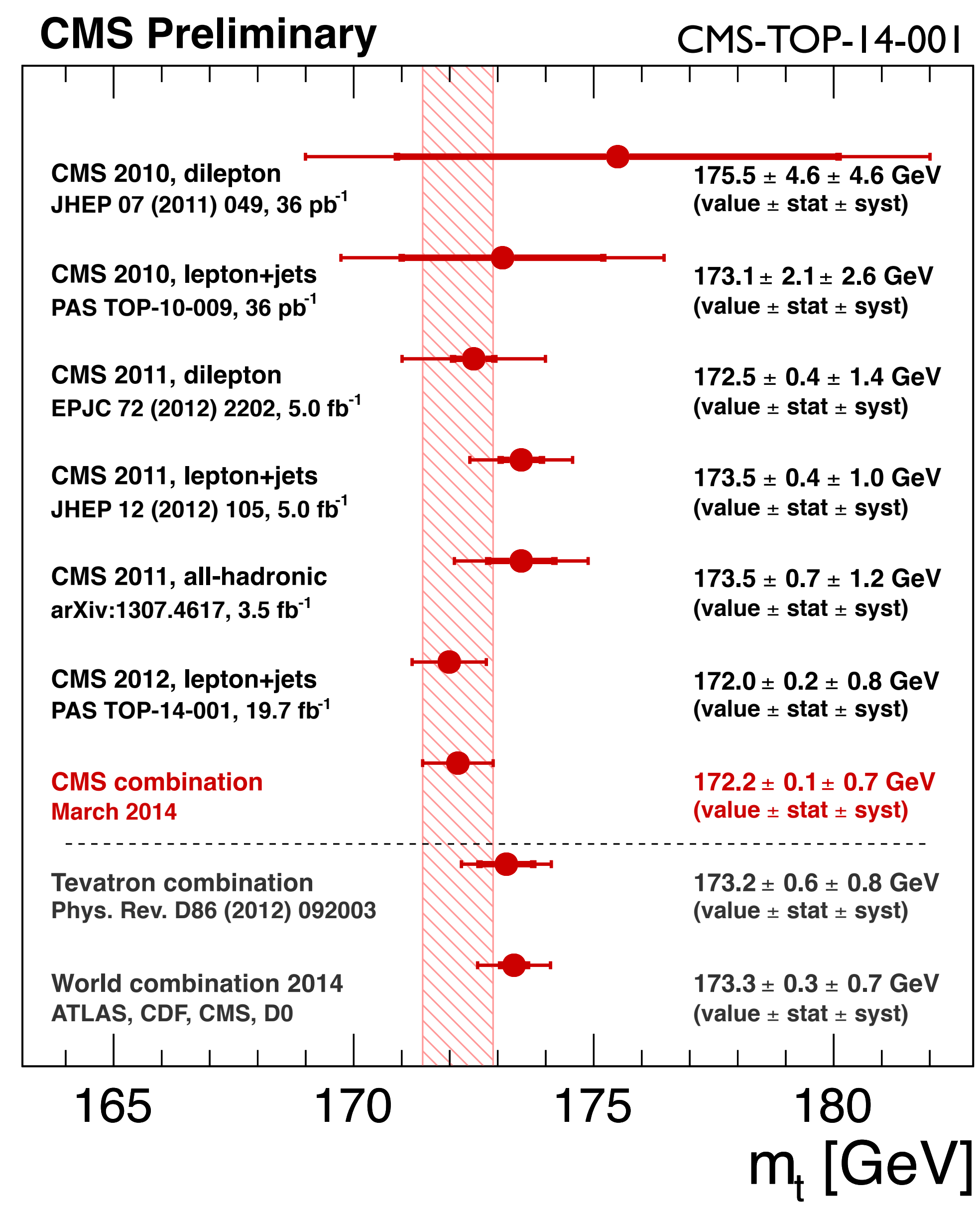
All hadronic





Summary of Mass Measurements





ATLAS: m_t = 173.0 ± 0.9 GeV

CMS: m_t = 172.2 ± 0.7 GeV

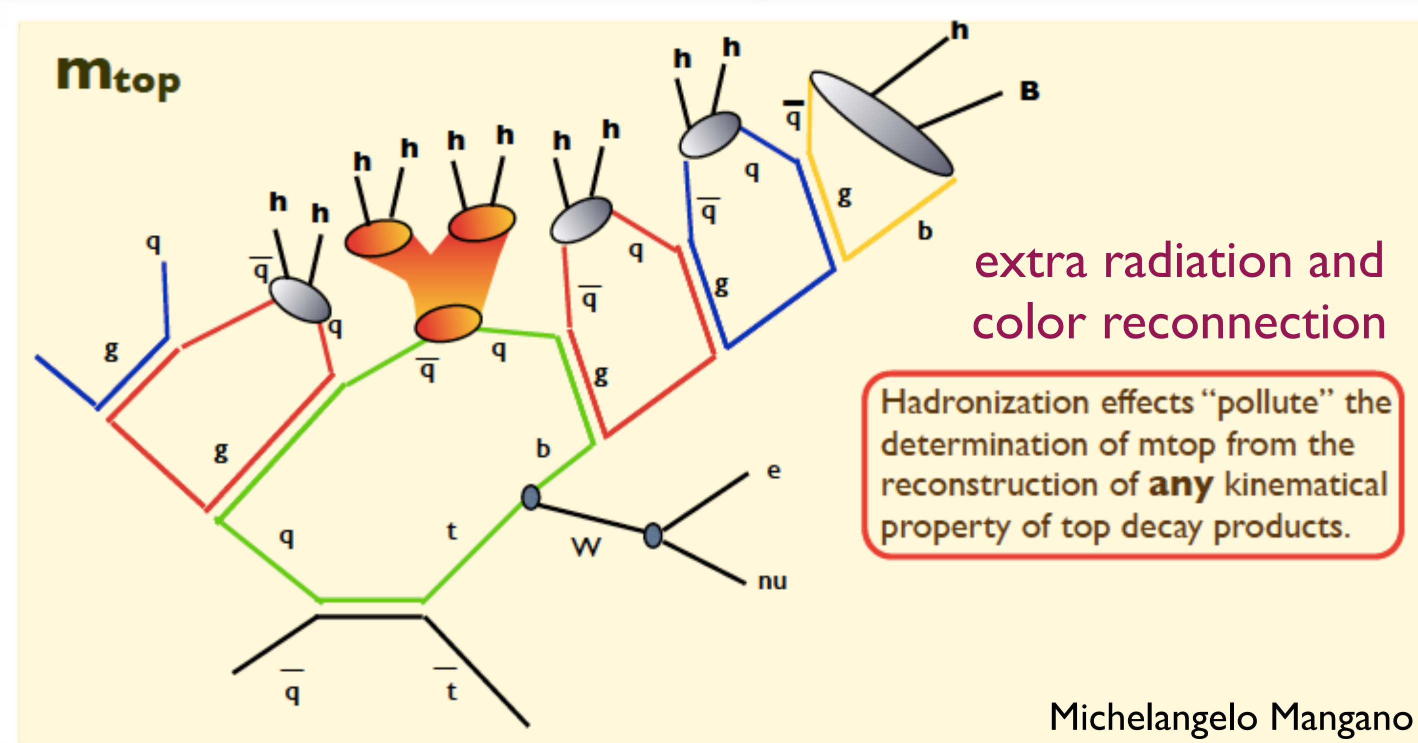
- excellent agreement between ATLAS and CMS

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?

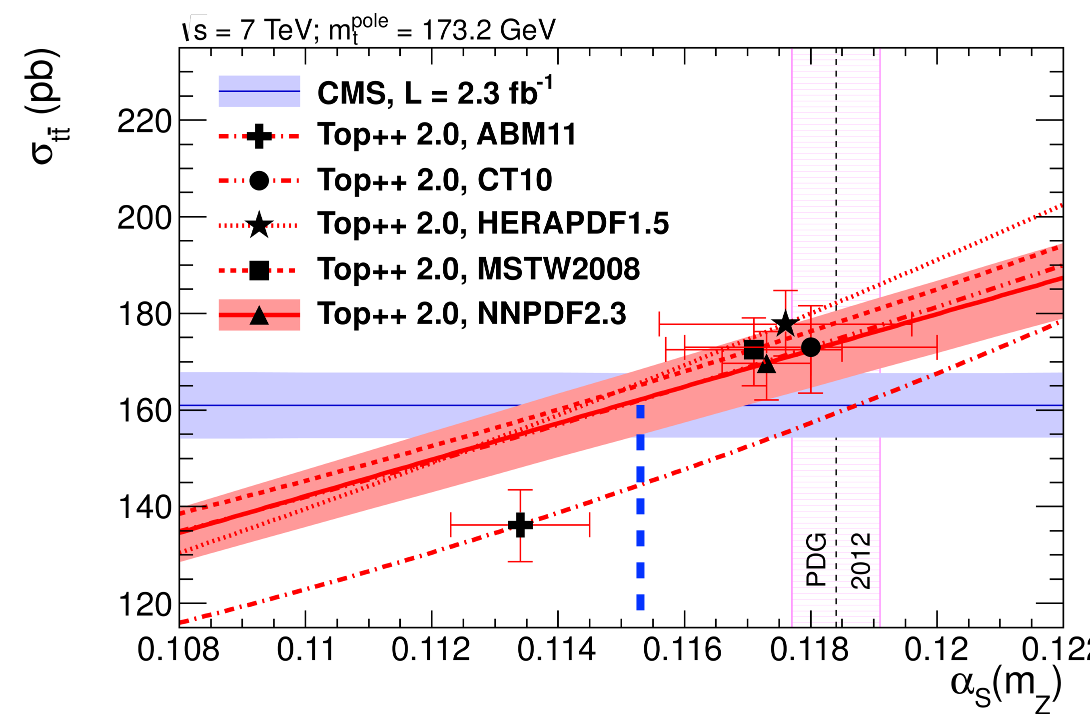


- Importance of measuring the mass using alternate techniques
  - mass and end point of $b\ell$ spectrum
  - decay length (boost) of B hadrons

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

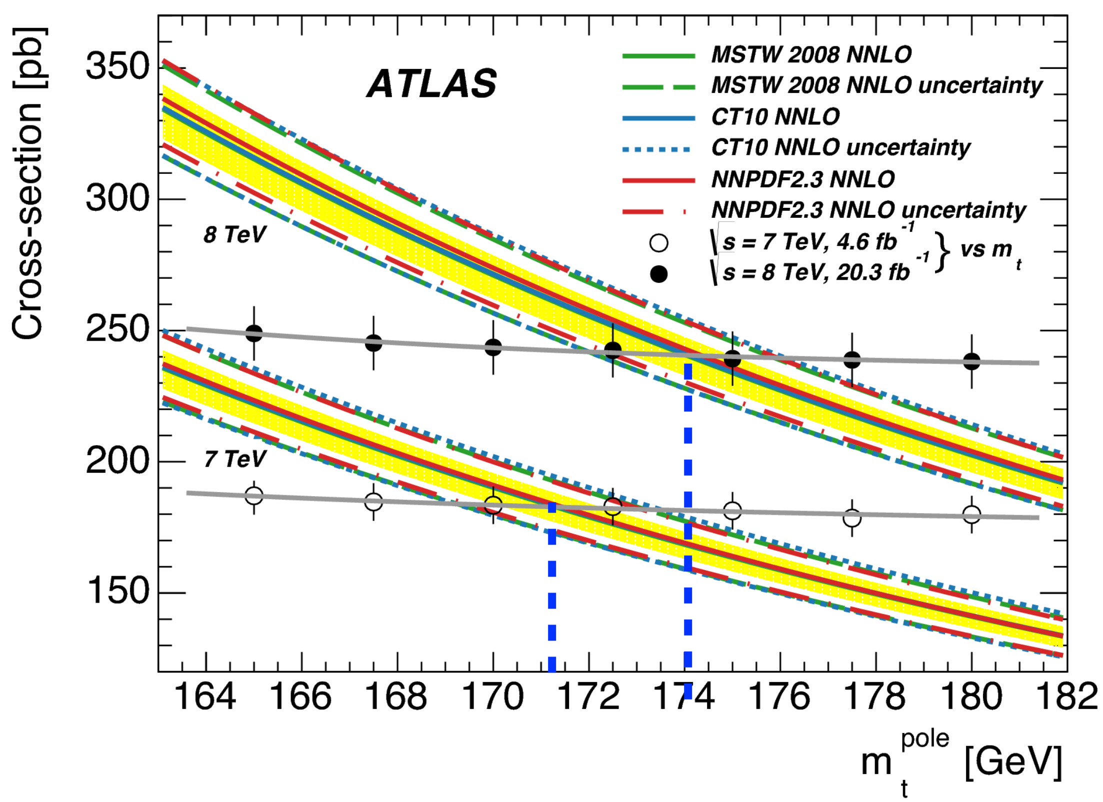
Mass from Cross Section

- 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

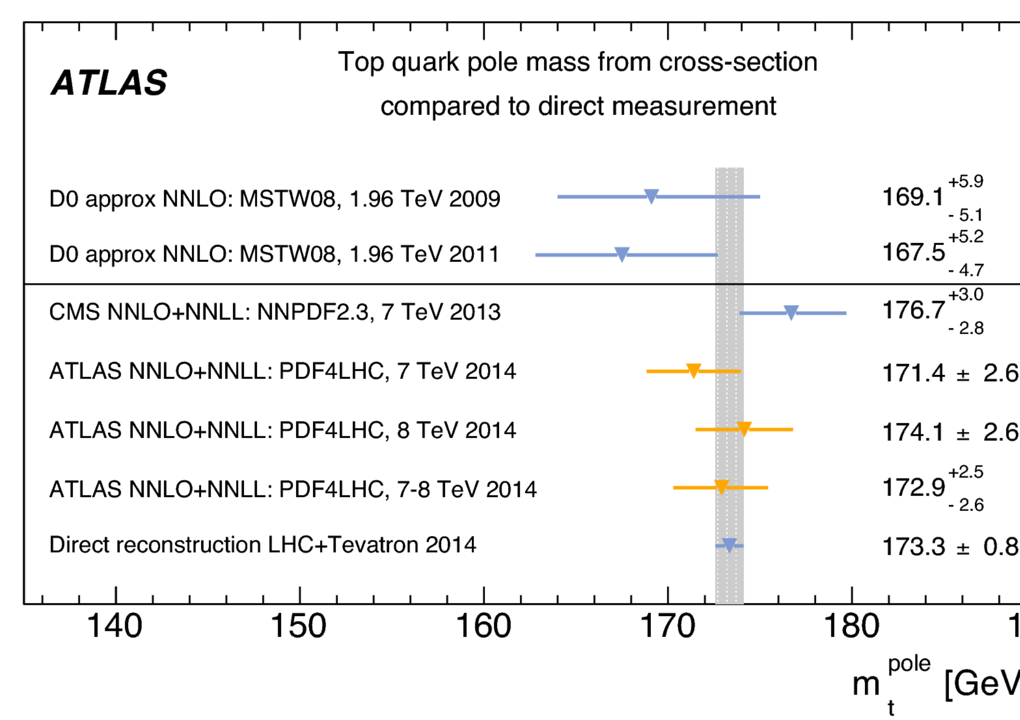


exp. 8TeV

theo. 8 TeV

exp. 7TeV

theo. 7 TeV

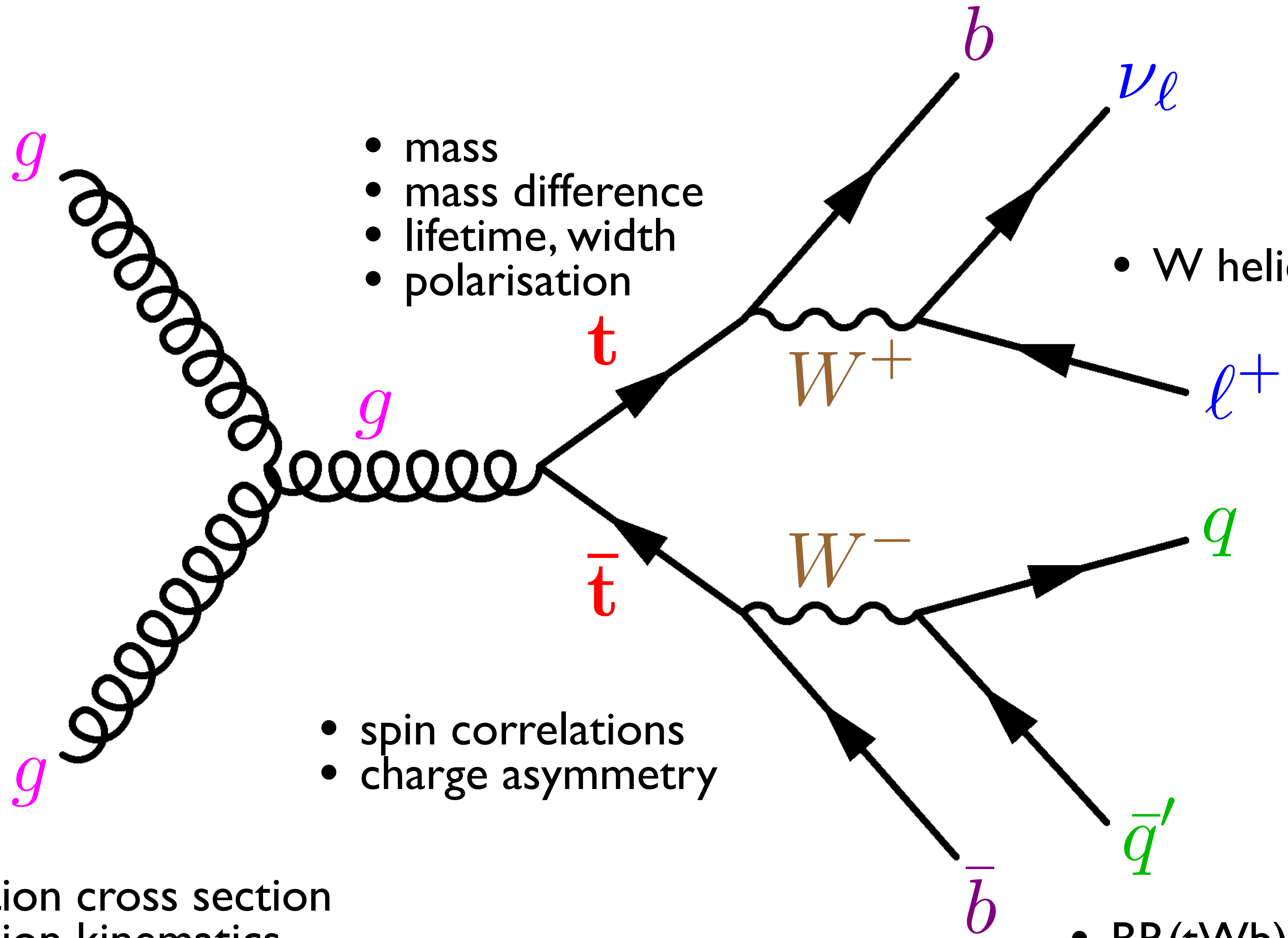


Limitation: PDFs and uncertainty on luminosity (2-5%)

Top Quark Properties

- mass
- mass difference
- lifetime, width
- polarisation

- W helicity



- spin correlations
- charge asymmetry

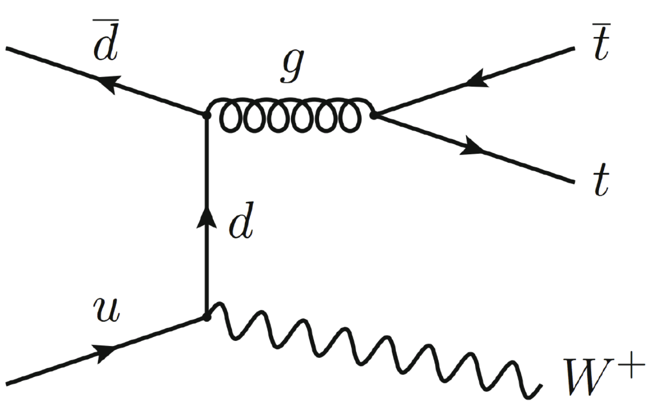
- production cross section
- production kinematics
- resonances, new particles

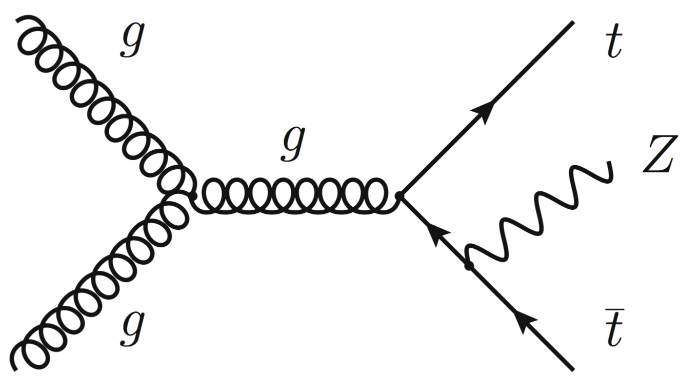
- BR(tWb)/BR(tWq)
- new decays

Associated Production ttV

Recent observation in multileptonic channels

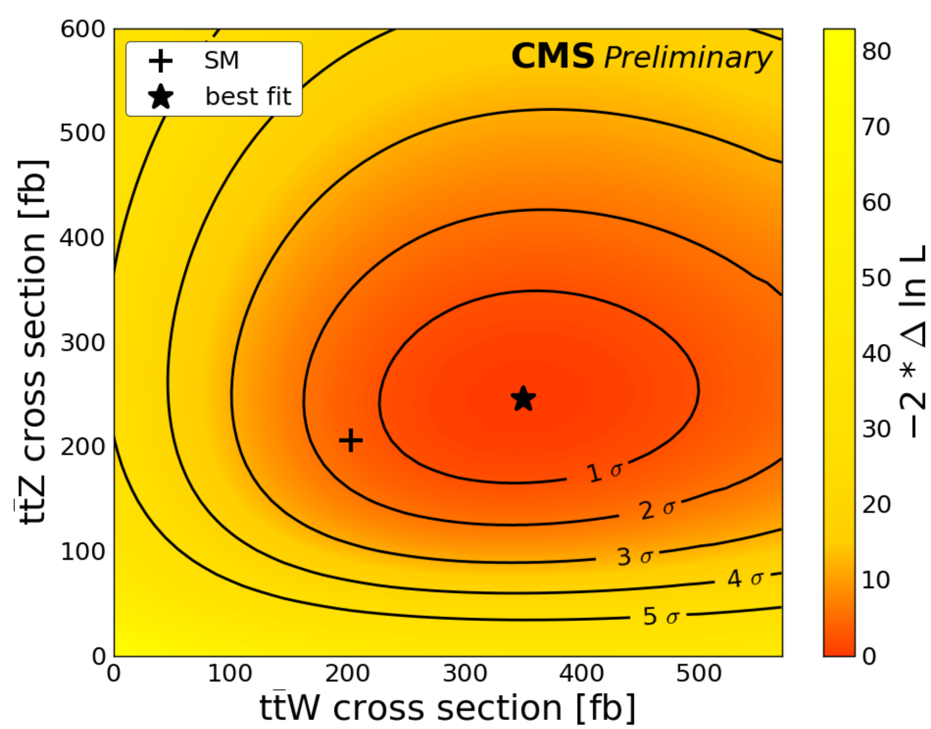
- expected cross sections: 0.2 pb !



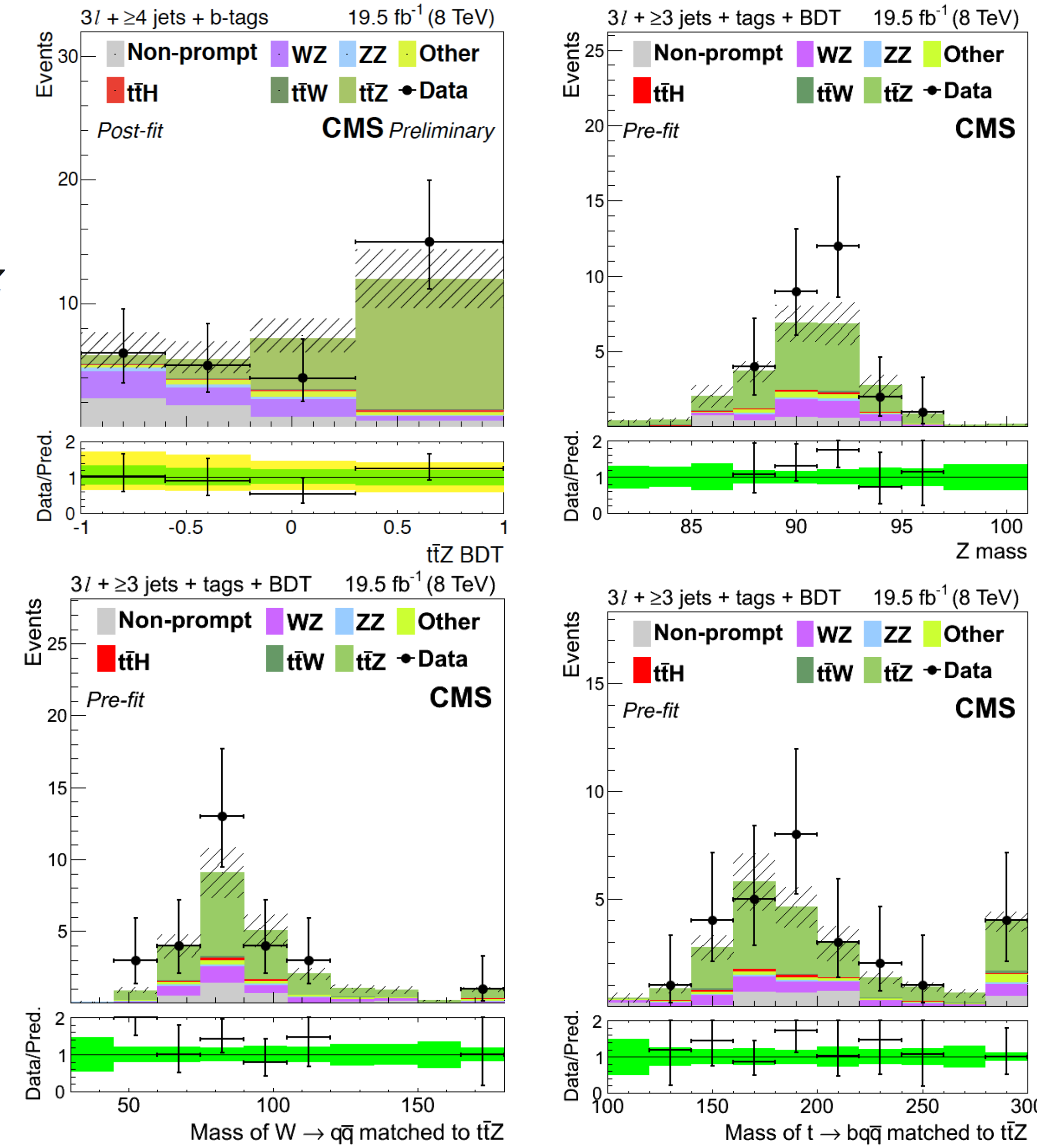


Direct access to top-Z couplings

- sensitive to New Physics



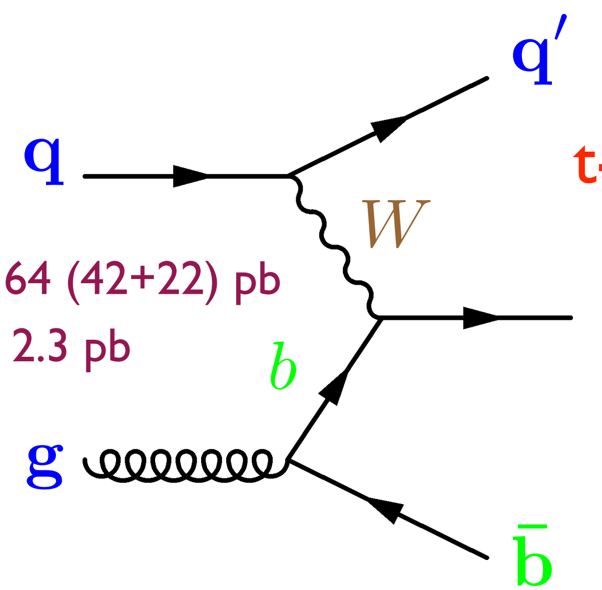
CMS-TOP-14-021



First observation of ttZ and strong evidence for ttW

Single Top

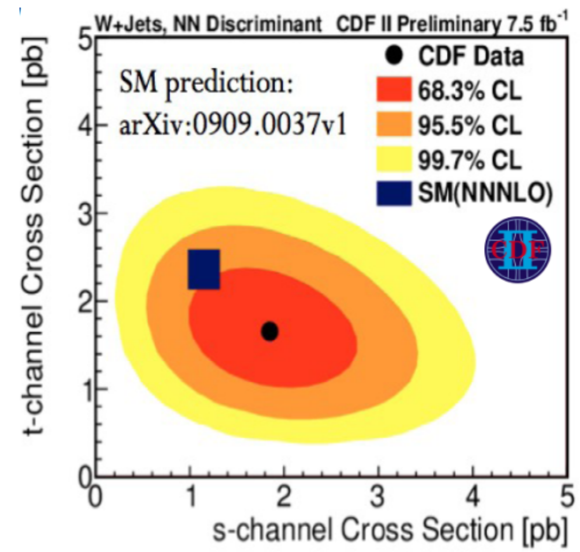
EW production of a top quark

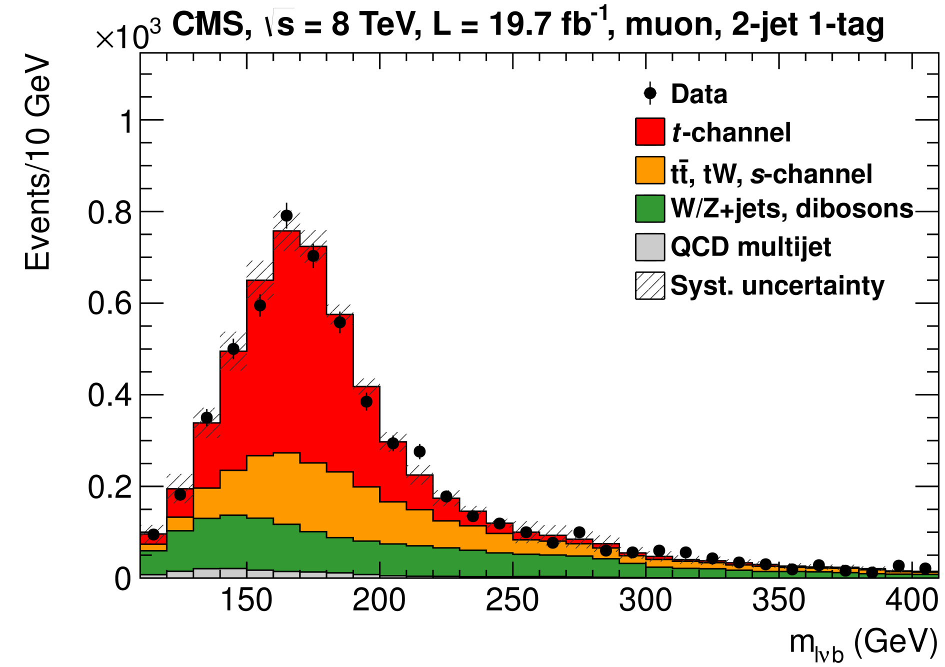


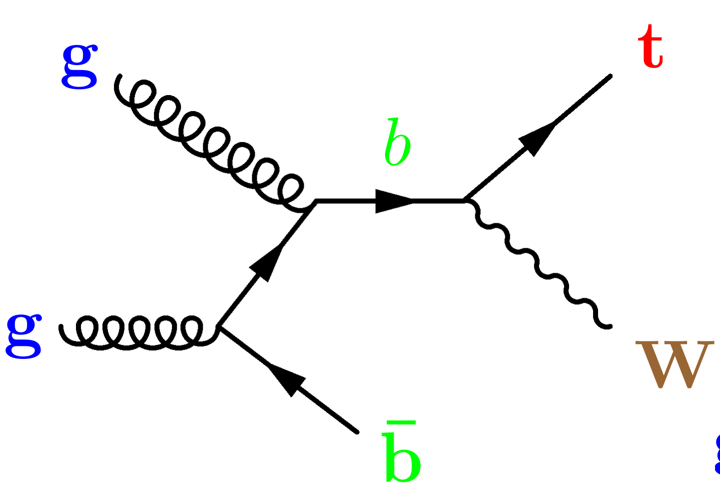
t-channel

LHC 64 (42+22) pb

TeV 2.3 pb



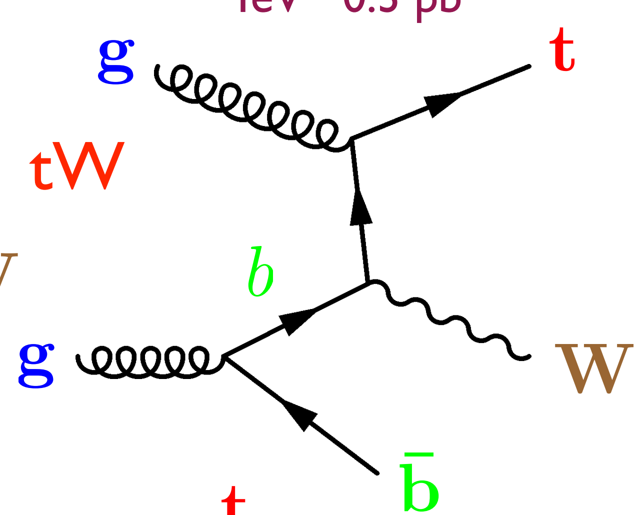


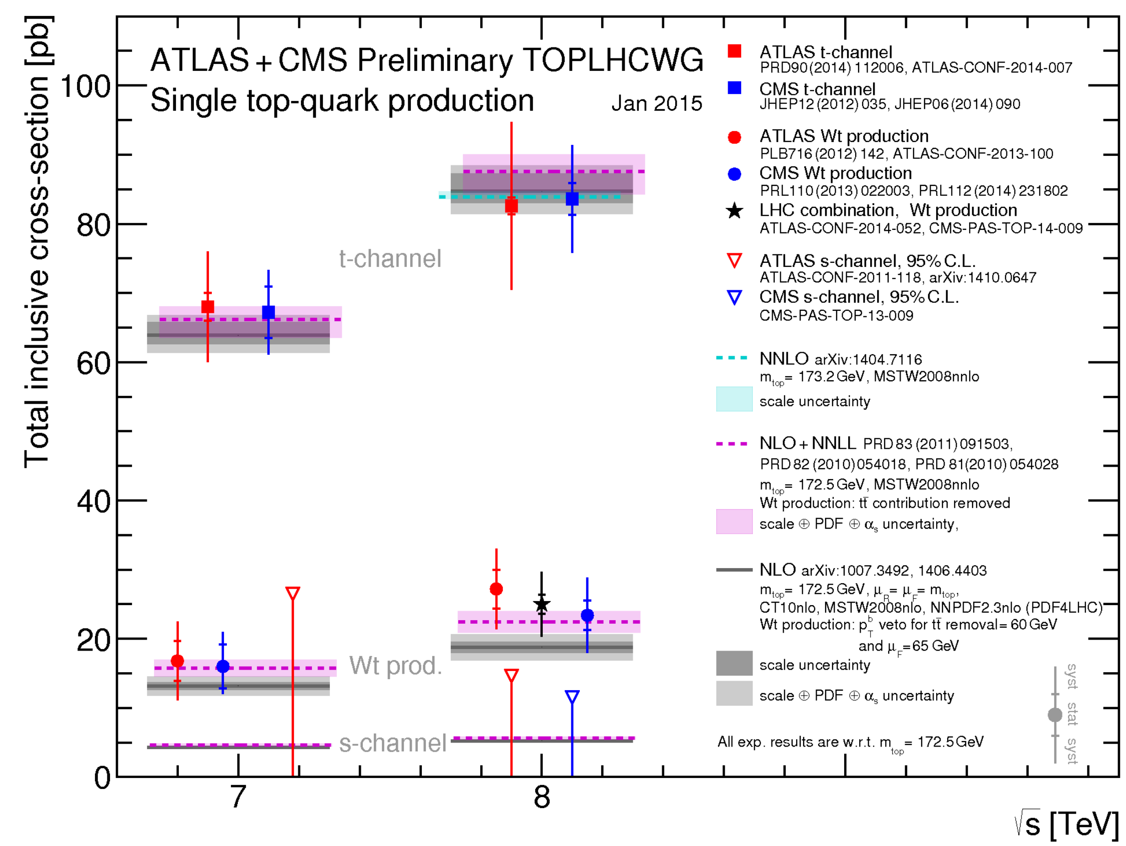


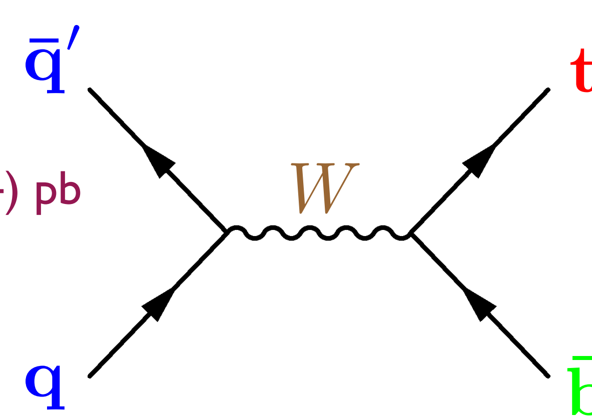
tW

LHC 16 pb

TeV 0.3 pb







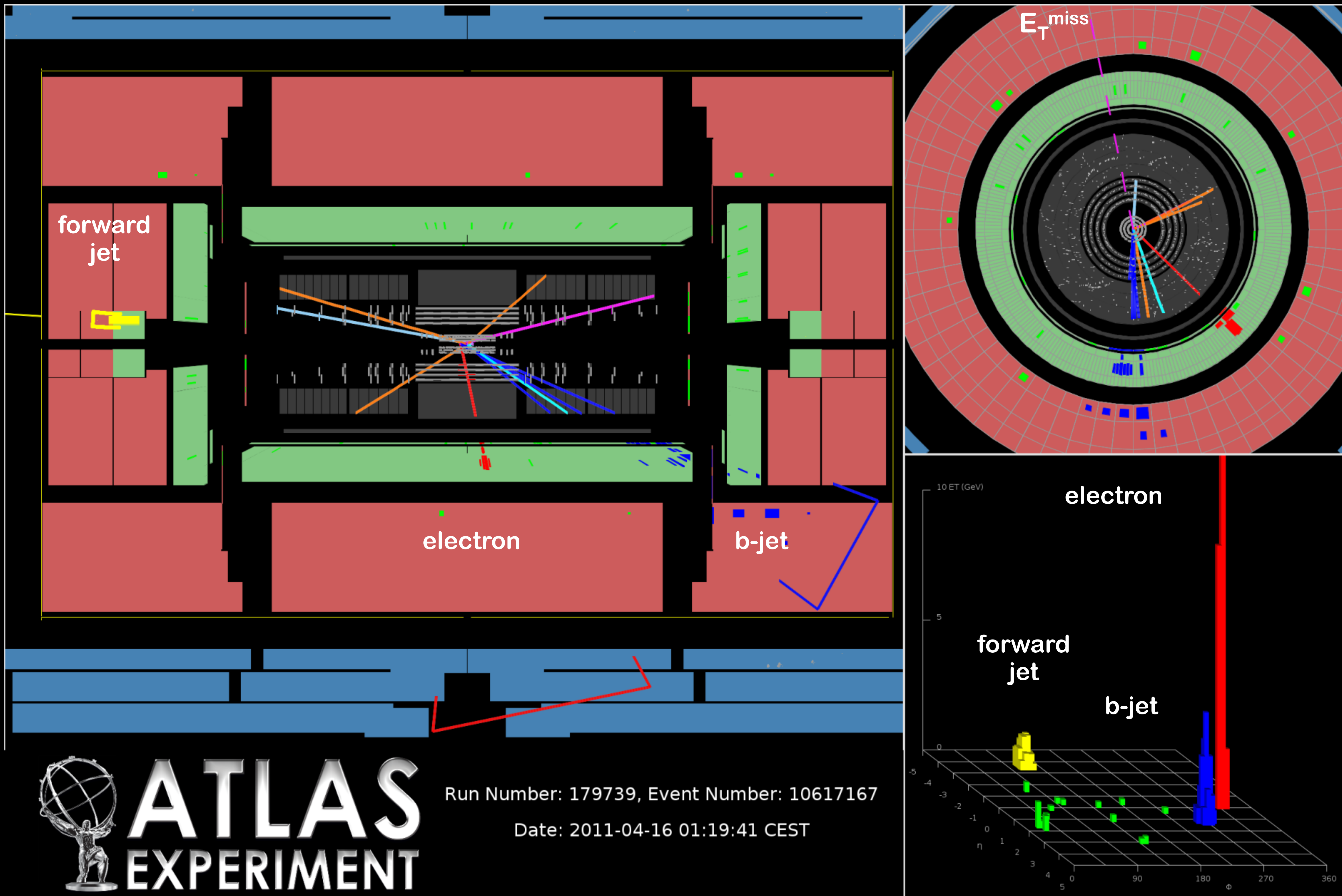
LHC 4.5 (3.2+1.4) pb

TeV 1.00 pb

s-channel

allows direct measurements of V_{tb}

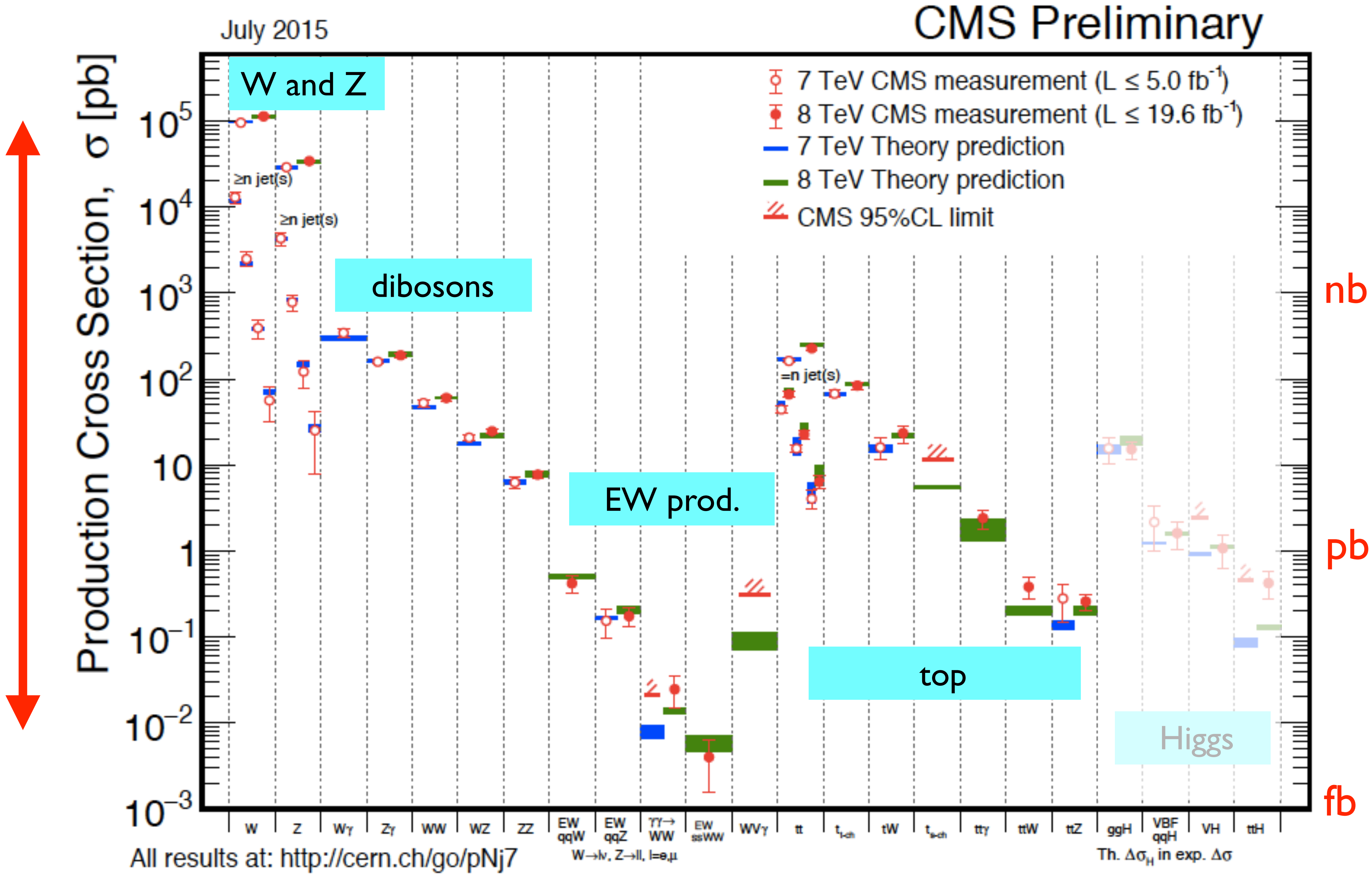
Single Top Candidate (t-channel)



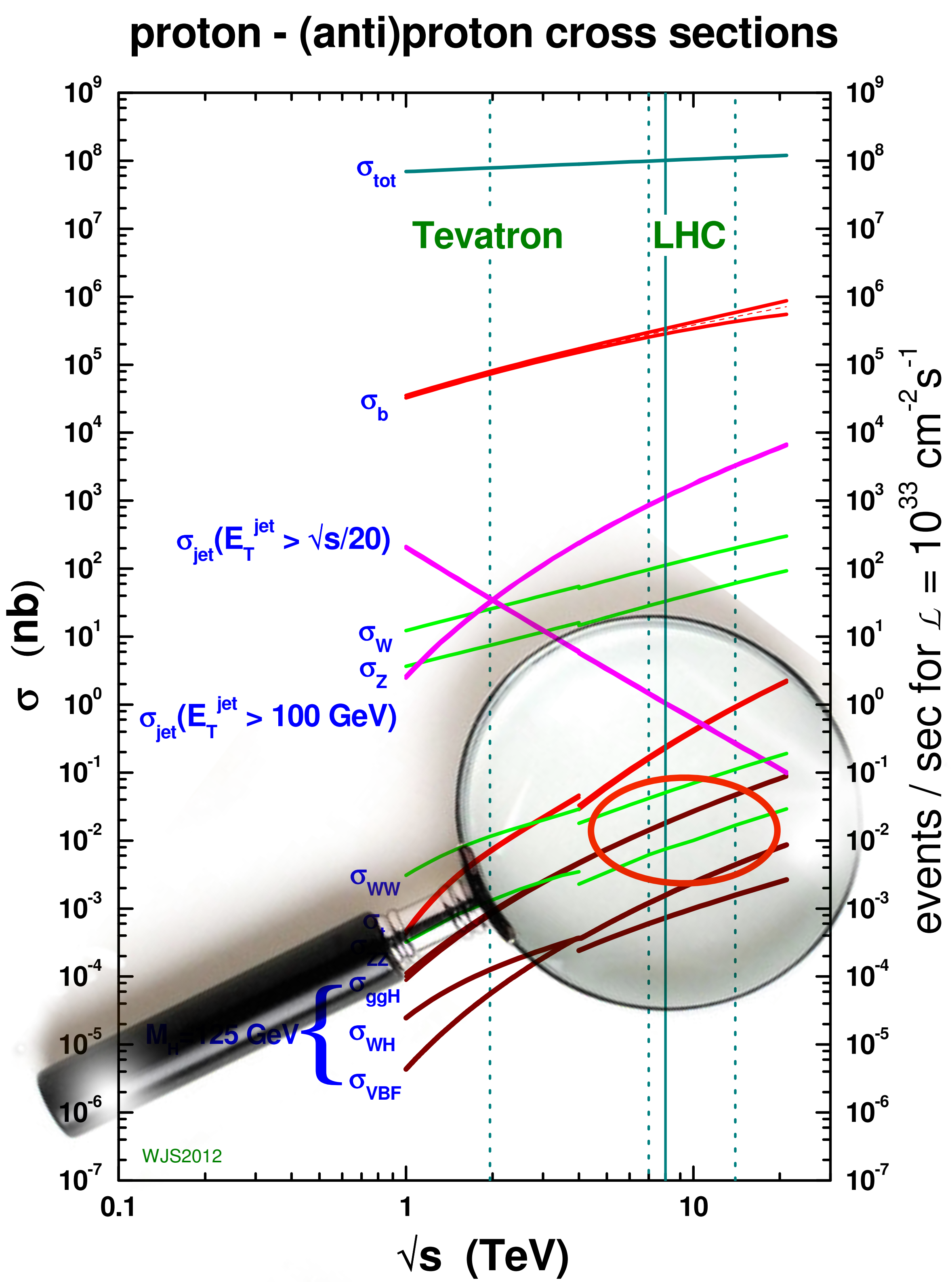
Summary of SM Measurements

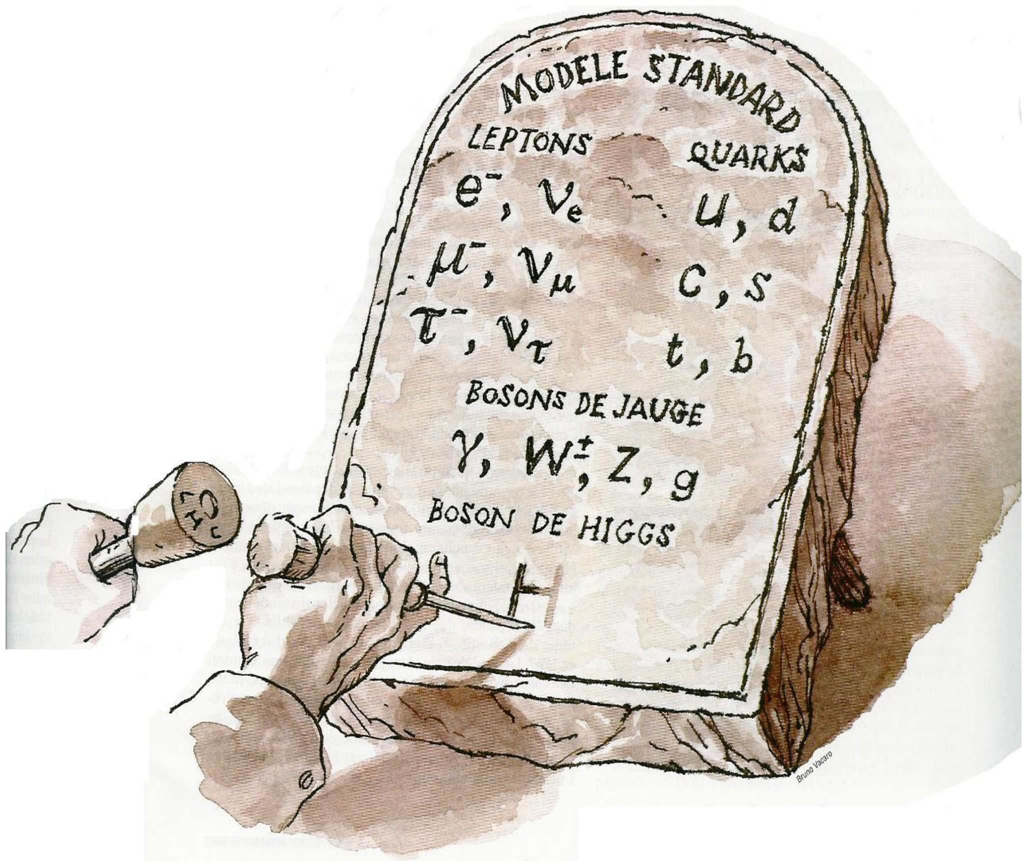
~ 70 billion inelastic collisions

Seven orders of magnitude



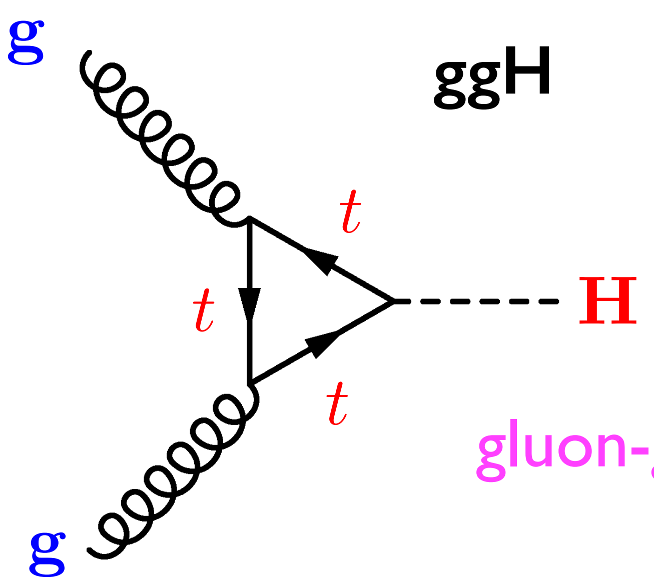
Higgs Physics





Production of the Higgs Boson

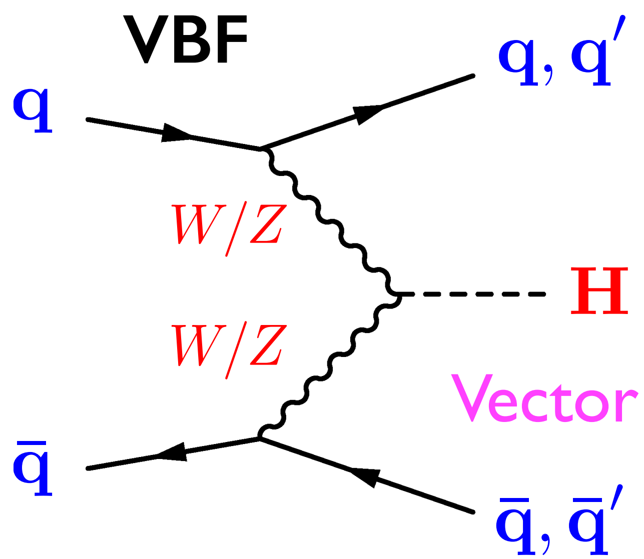
ggH



86%

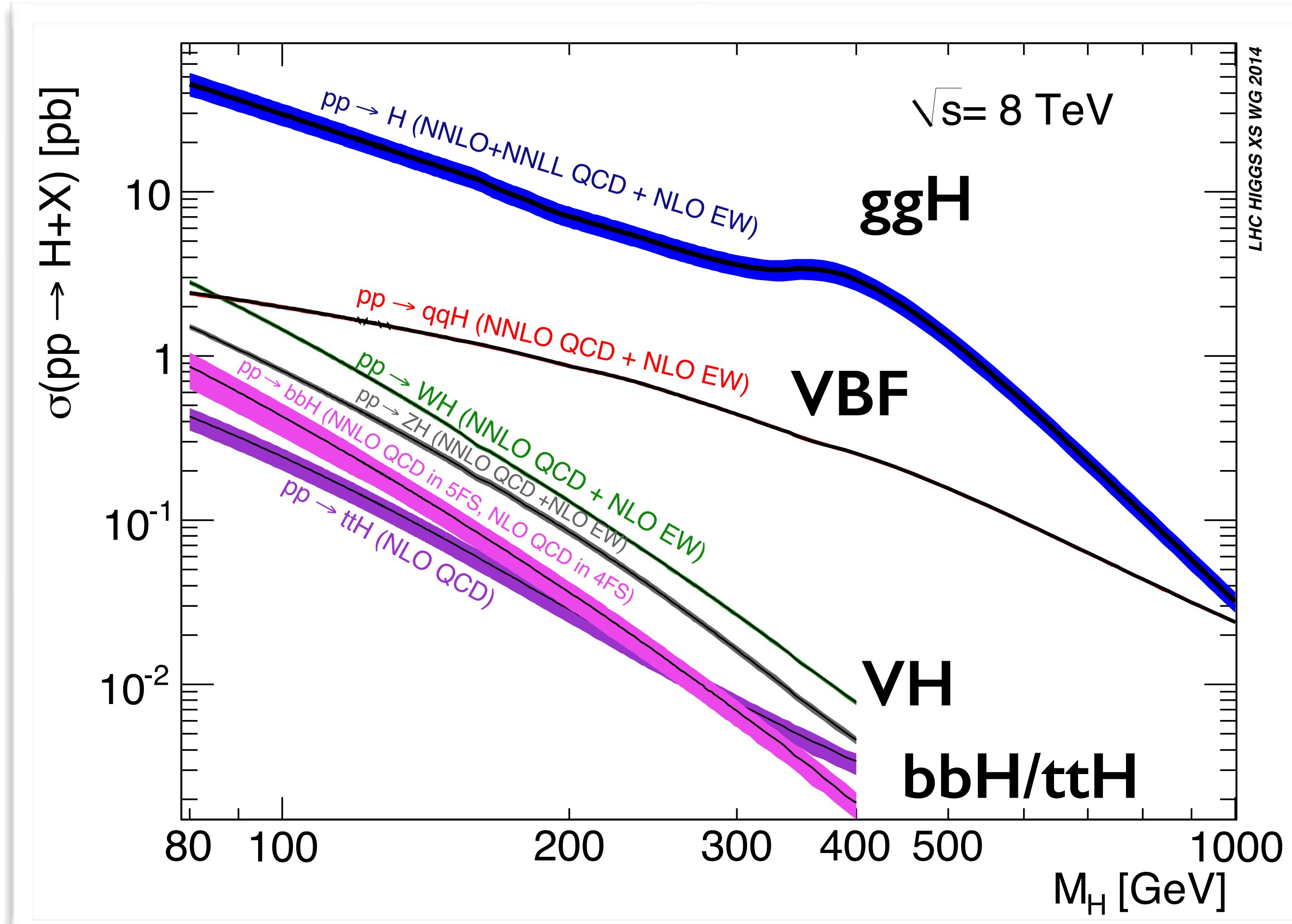
gluon-gluon Fusion

VBF

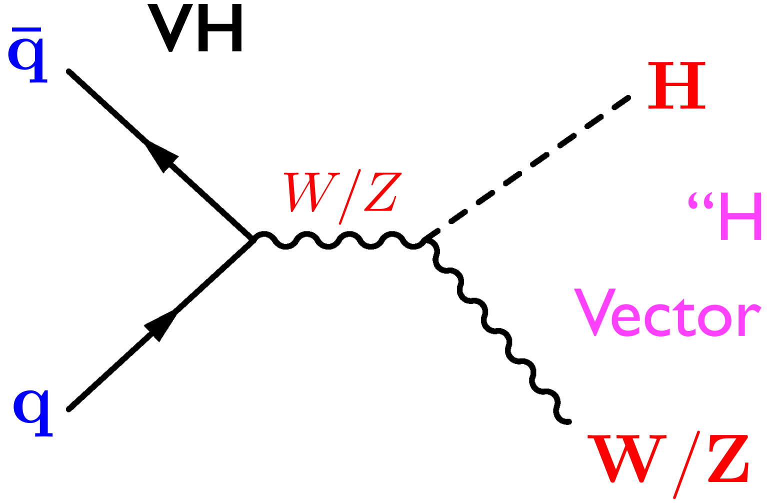


7%

Vector Boson Fusion



VH

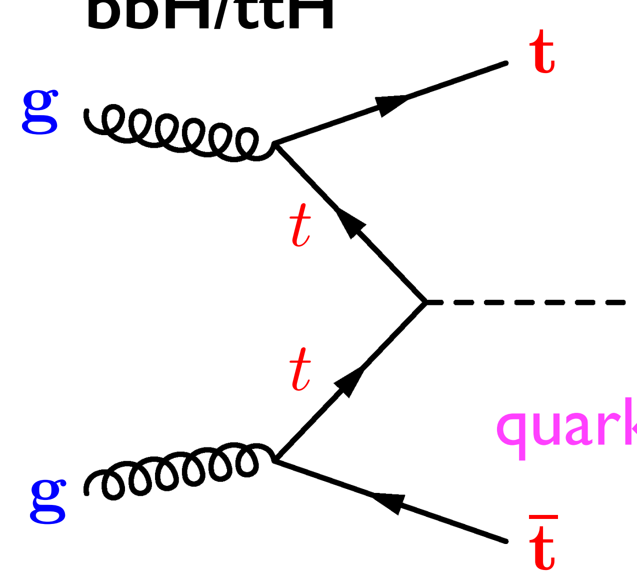


5%

“Higgsstrahlung”

Vector Boson associated

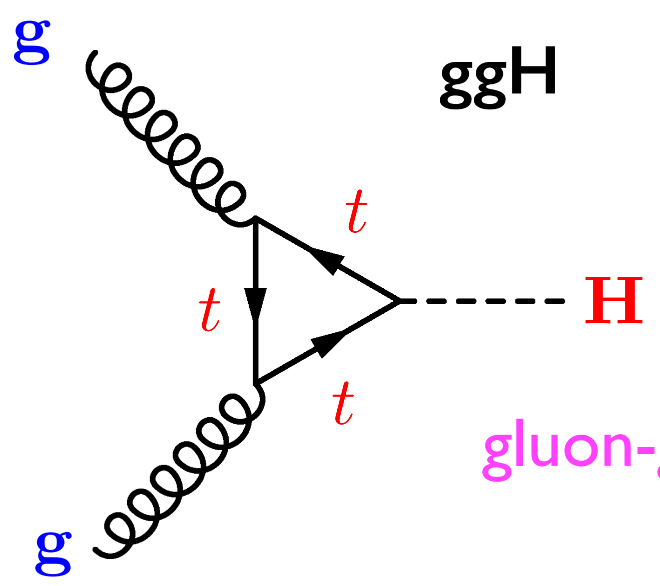
bbH/ttH



<2%

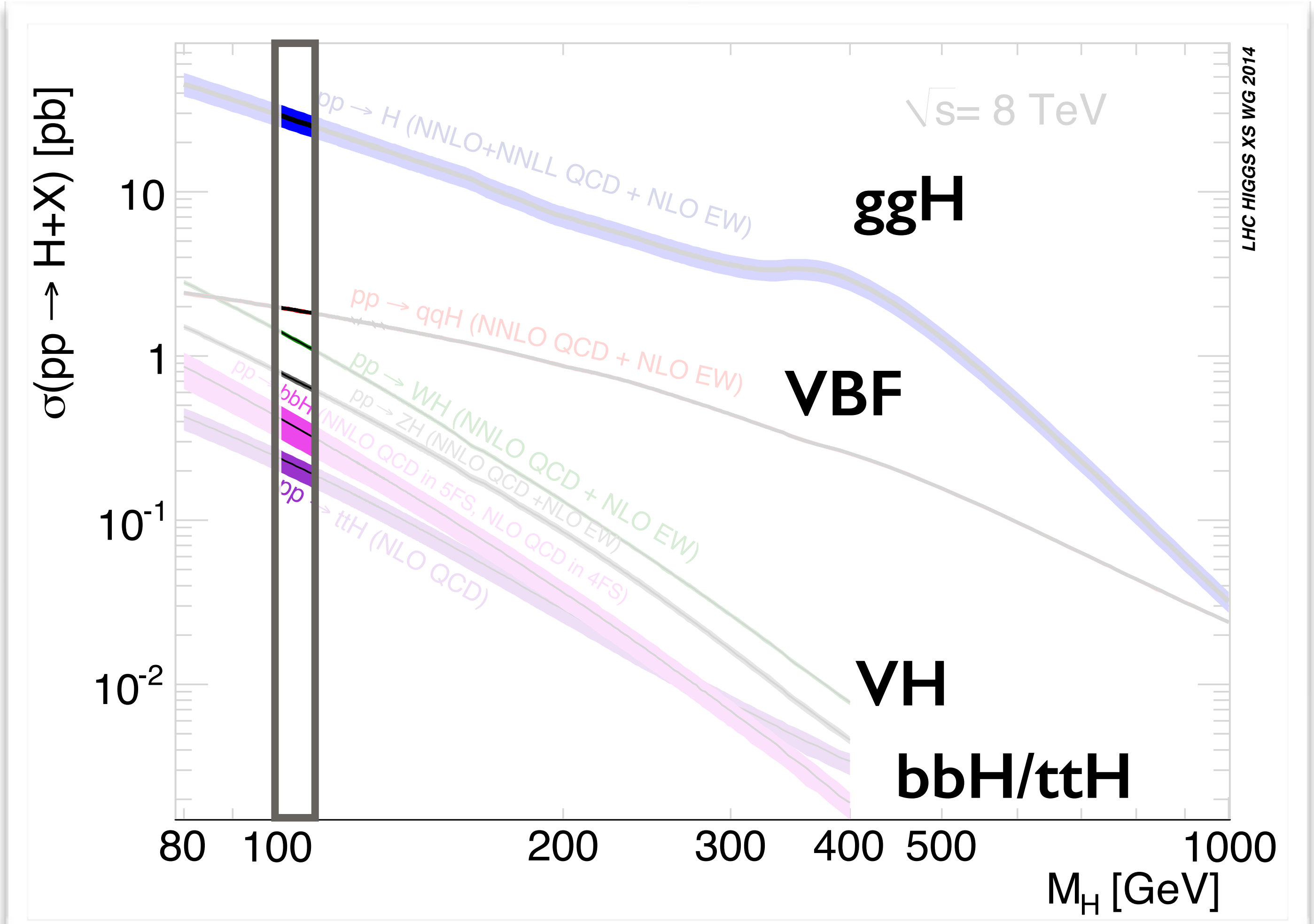
quark pair associated

Production of the Higgs Boson



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

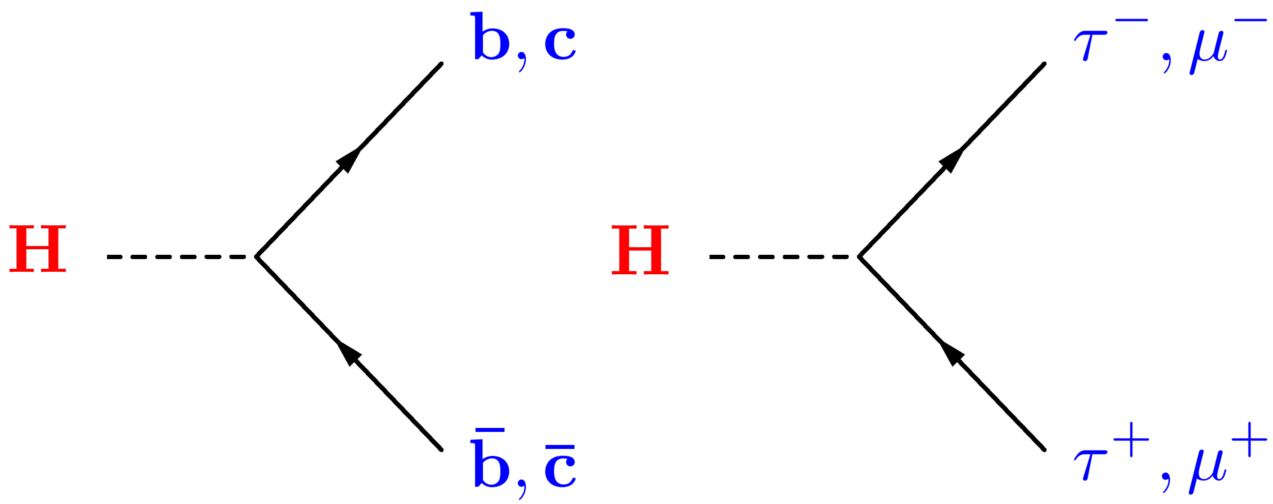
  ggH=86% VBF=7% VH=4% ttH=1%

Typical theory uncertainties

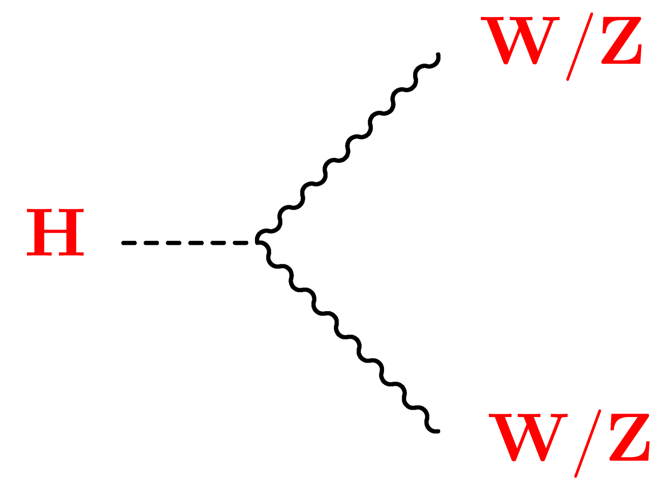
- ggH 15% NNnLO
- VBF 5% NLO
- VH 5% NNLO
- ttH 15% LO

Decays of the Higgs Boson

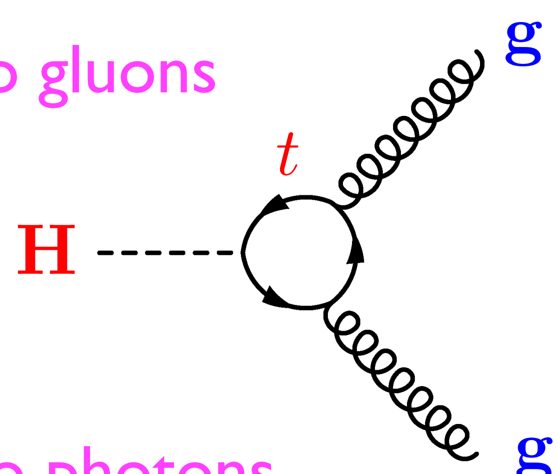
Decays to fermions (quarks and leptons)



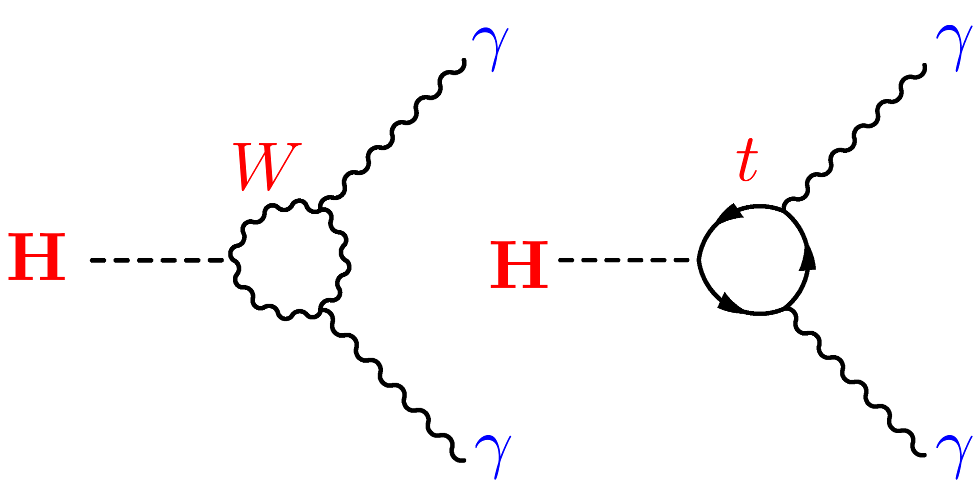
Decays to EW vector bosons

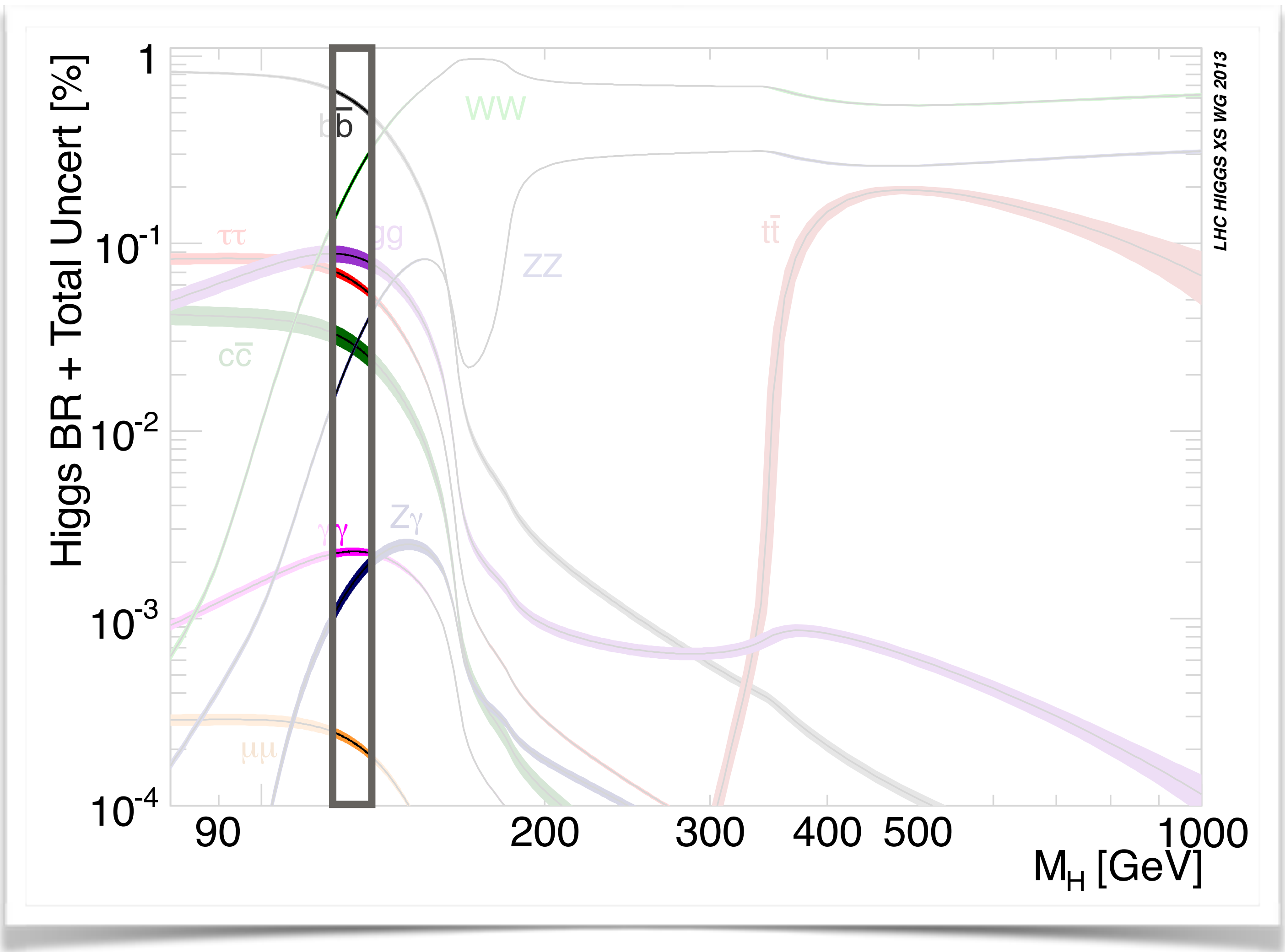


Decay to gluons

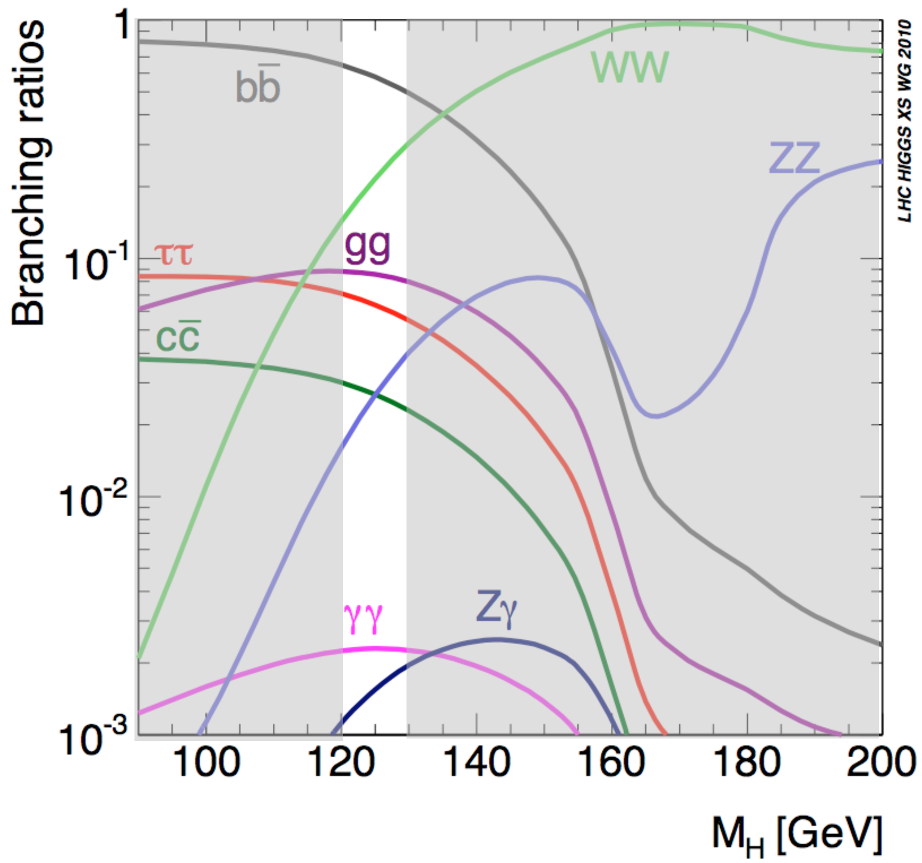


Decay to photons



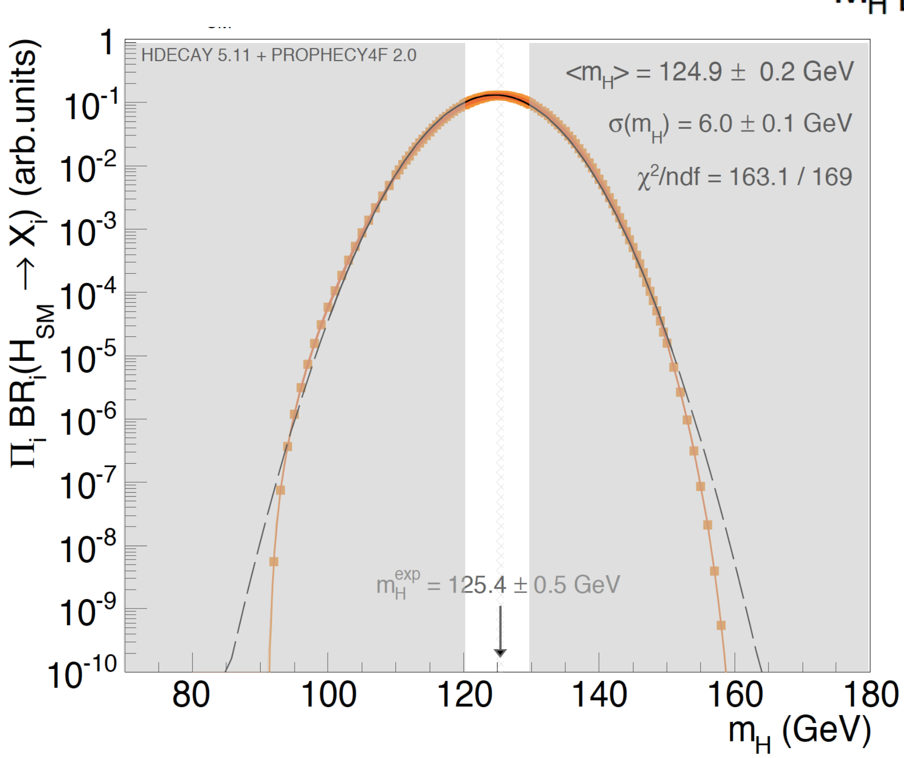


Decays at m_H = 125 GeV



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

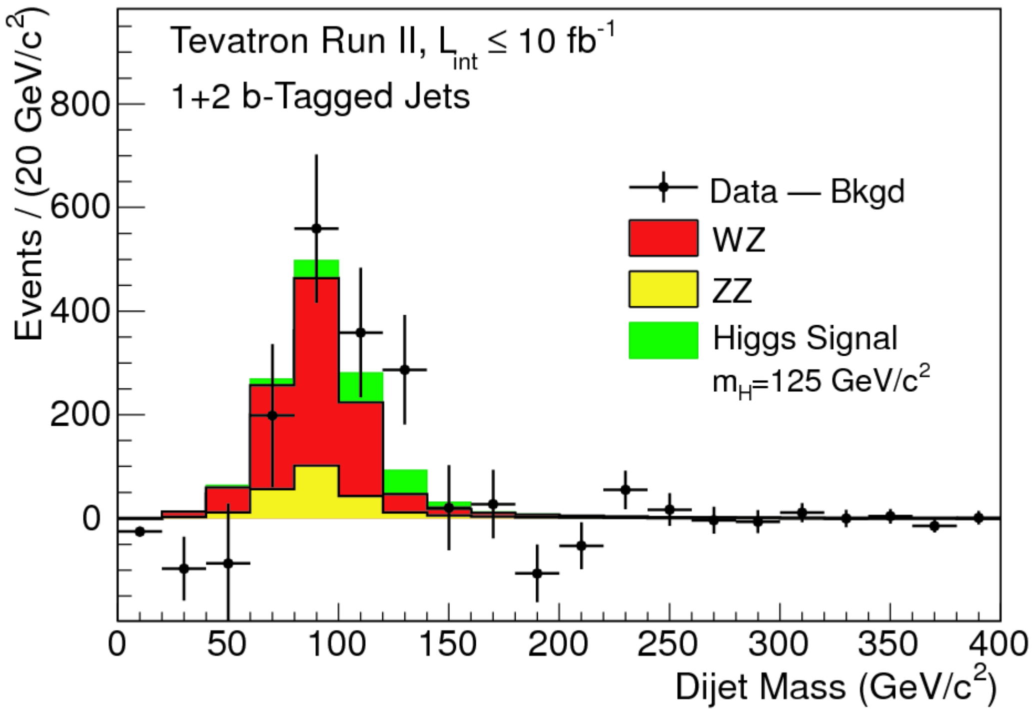
product of decay fractions

Nature has be kind to us

F. Gianotti

only about 11% of Higgs bosons decays are unobservable

Higgs Searches at the Tevatron



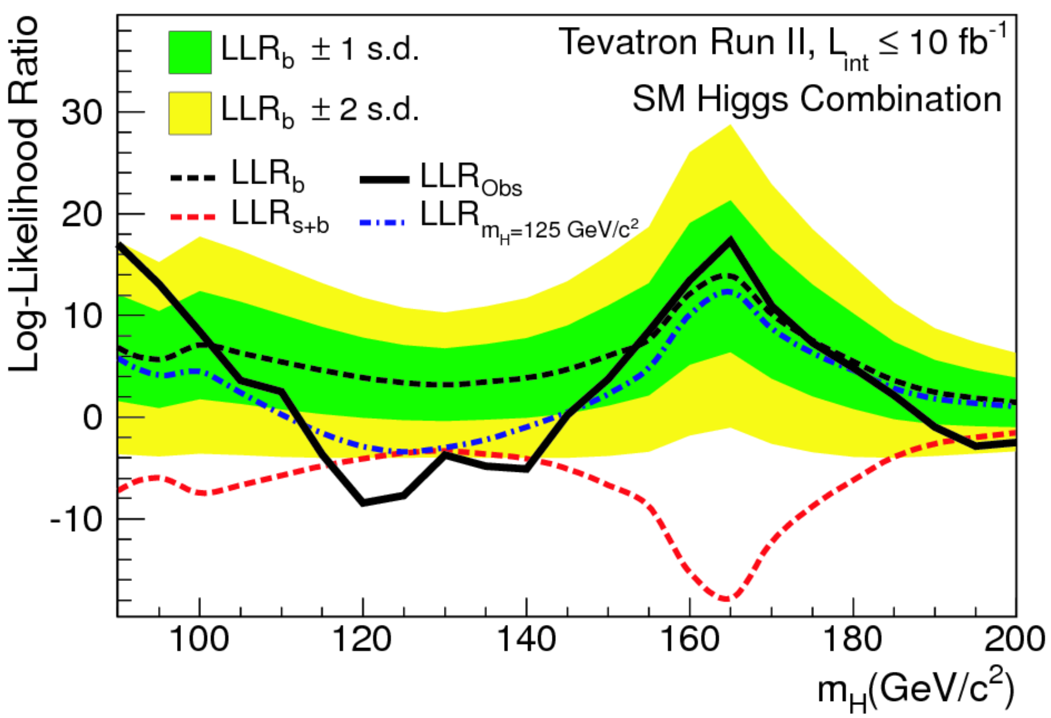
The Tevatron is sensitive to the signal in

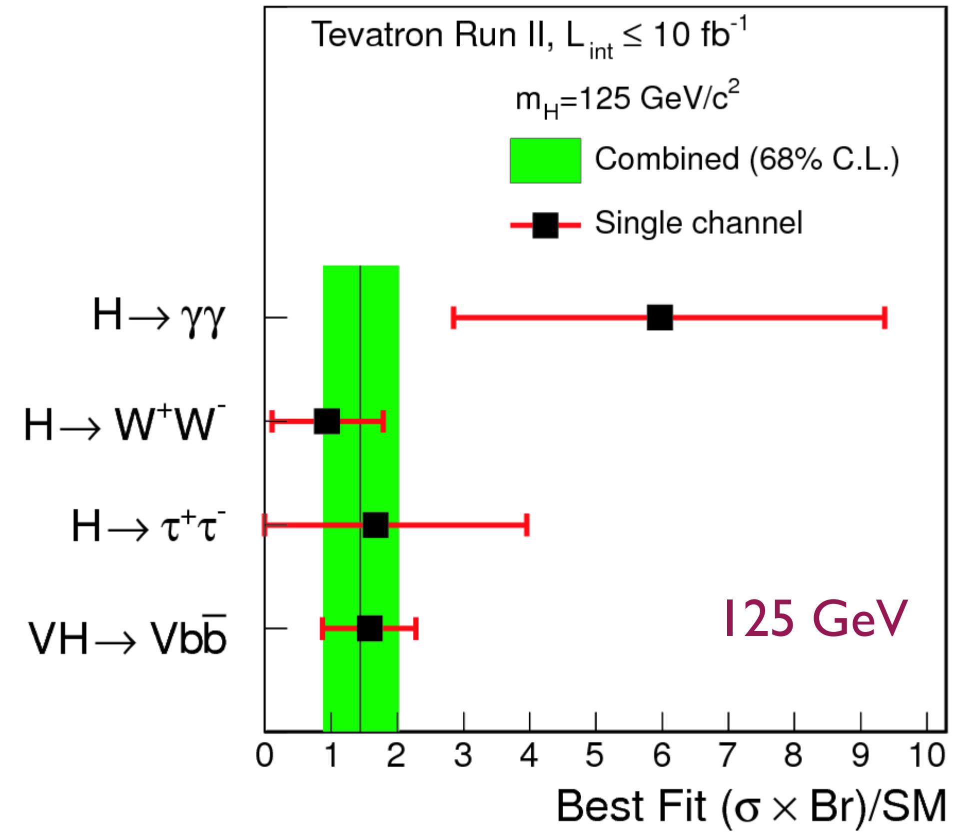
- the WW channel (for m_H around 160 GeV)
- the VH(→bb) channel

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

- consistent with the LHC discovery

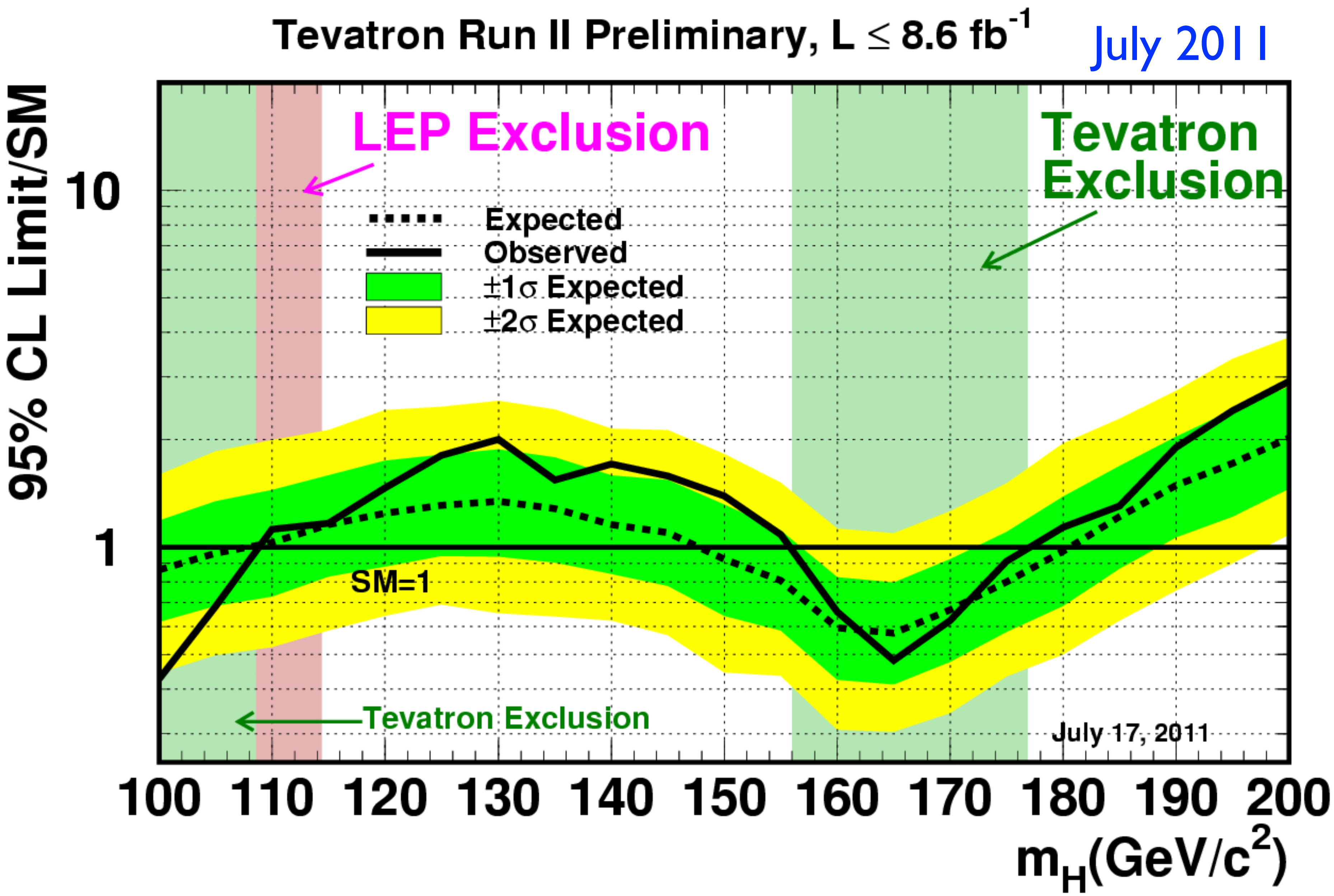
PRD 88 (2013) 052014





Direct Searches before LHC

July 2011



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

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

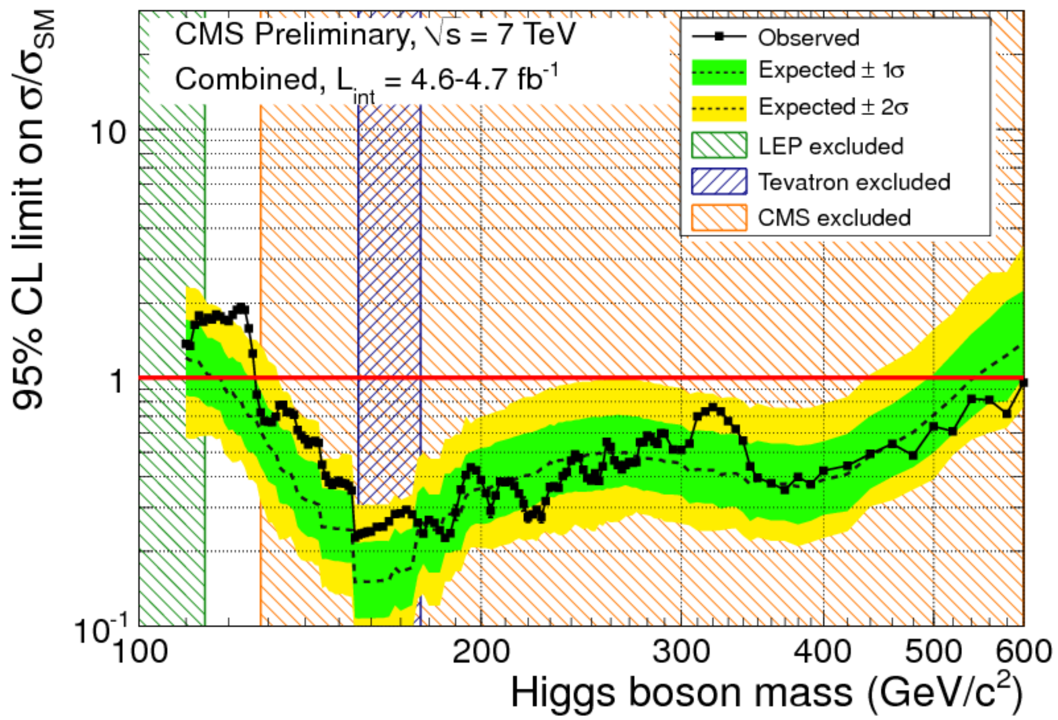
all channels multiplied by the same factor

(this introduces some level of model dependence)

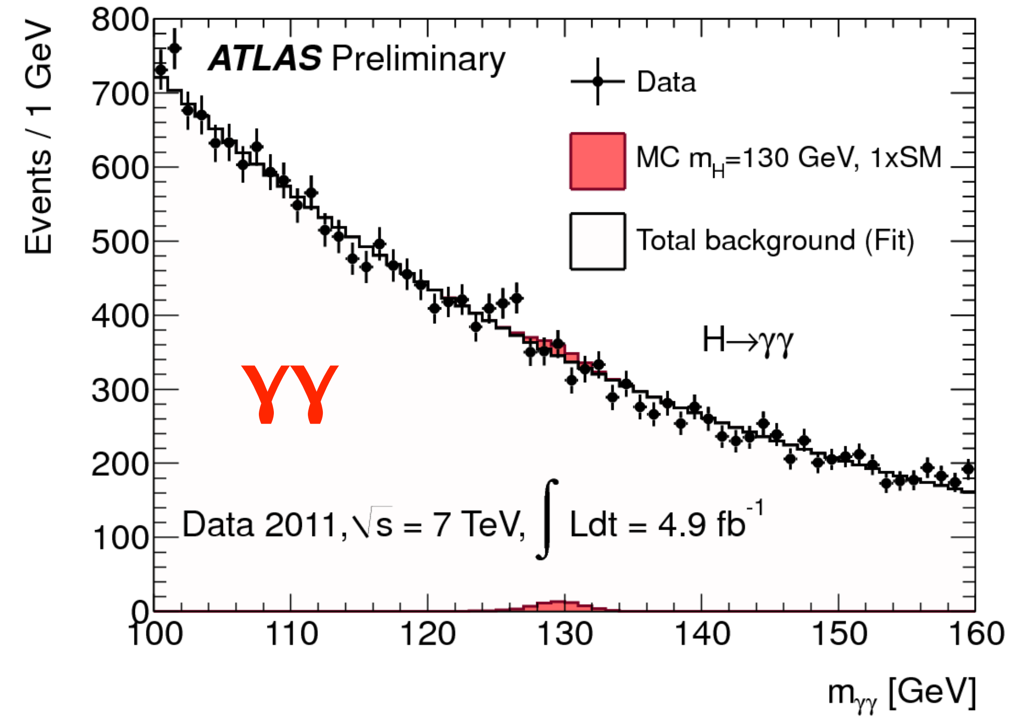
Higgs Searches at the LHC

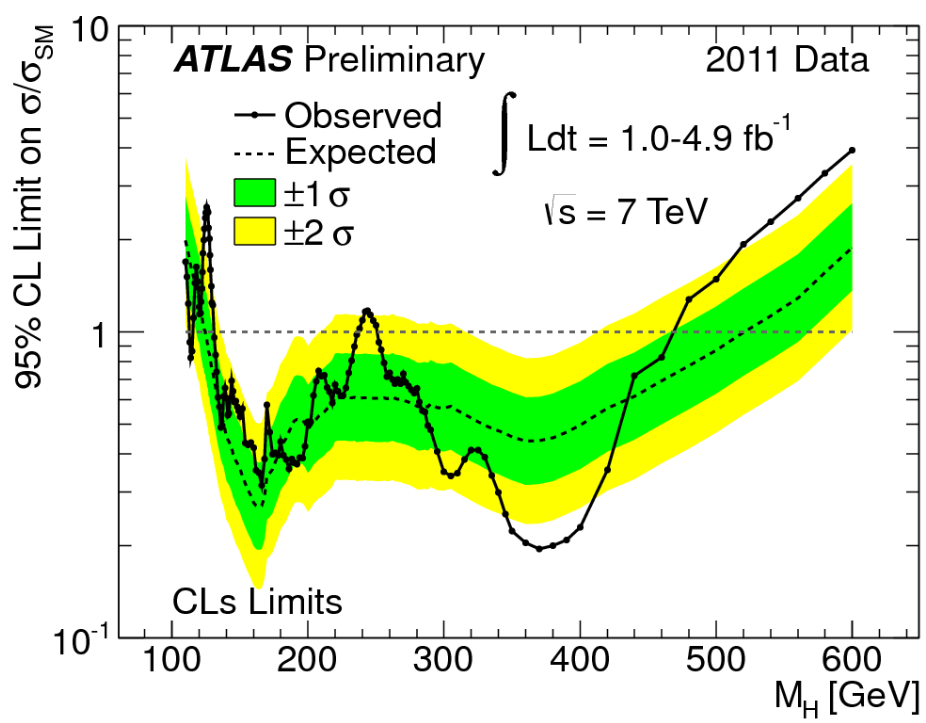
At the end of 2011 (CERN Jamboree) about 5 fb^{-1} / exp.

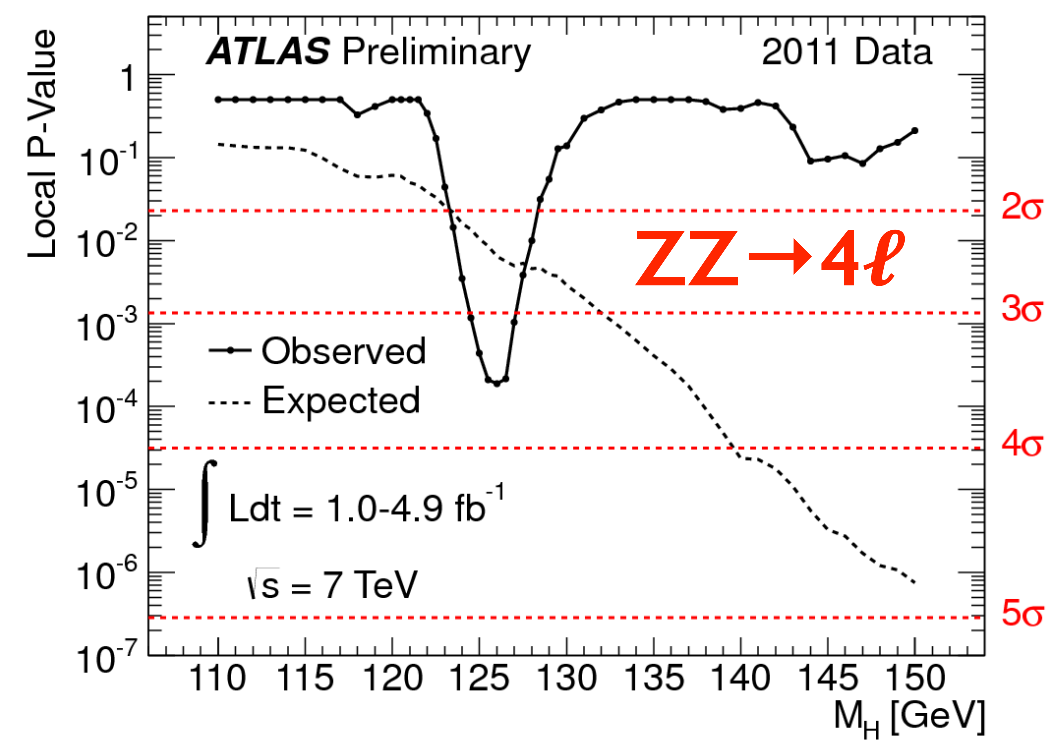
CMS: exclusion: m_H > 127 GeV



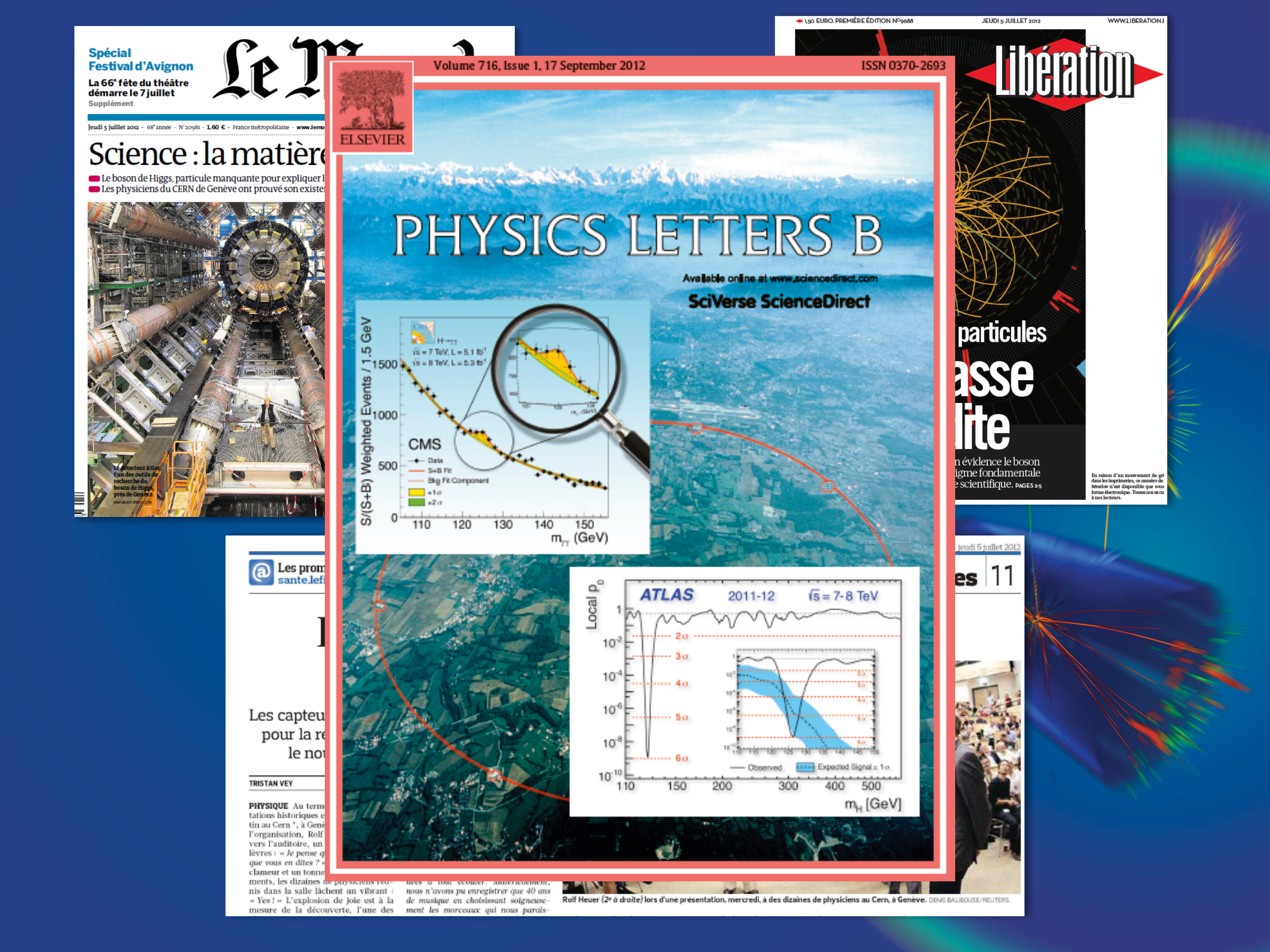
First hints of signal in ATLAS







CERN 4 July 2012



Spécial
Festival d'Avignon
La 66e fête du théâtre démarre le 7 juillet
Supplément
Jeudi 5 juillet 2012 - 68e année - N°20981 - 1,60 € - France métropolitaine
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
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)
Local p_0
ATLAS
2011-12
$\sqrt{s}$ = 7-8 TeV
Observed
Expected Signal ± 1σ
m_H [GeV]
1,50 EURO. PREMIÈRE ÉDITION N°9688
JEUDI 5 JUILLET 2012
WWW.LIBERATION.F
Libération
particules
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e scientifique. PAGES 2-5
jeudi 5 juillet 2012
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Les prom
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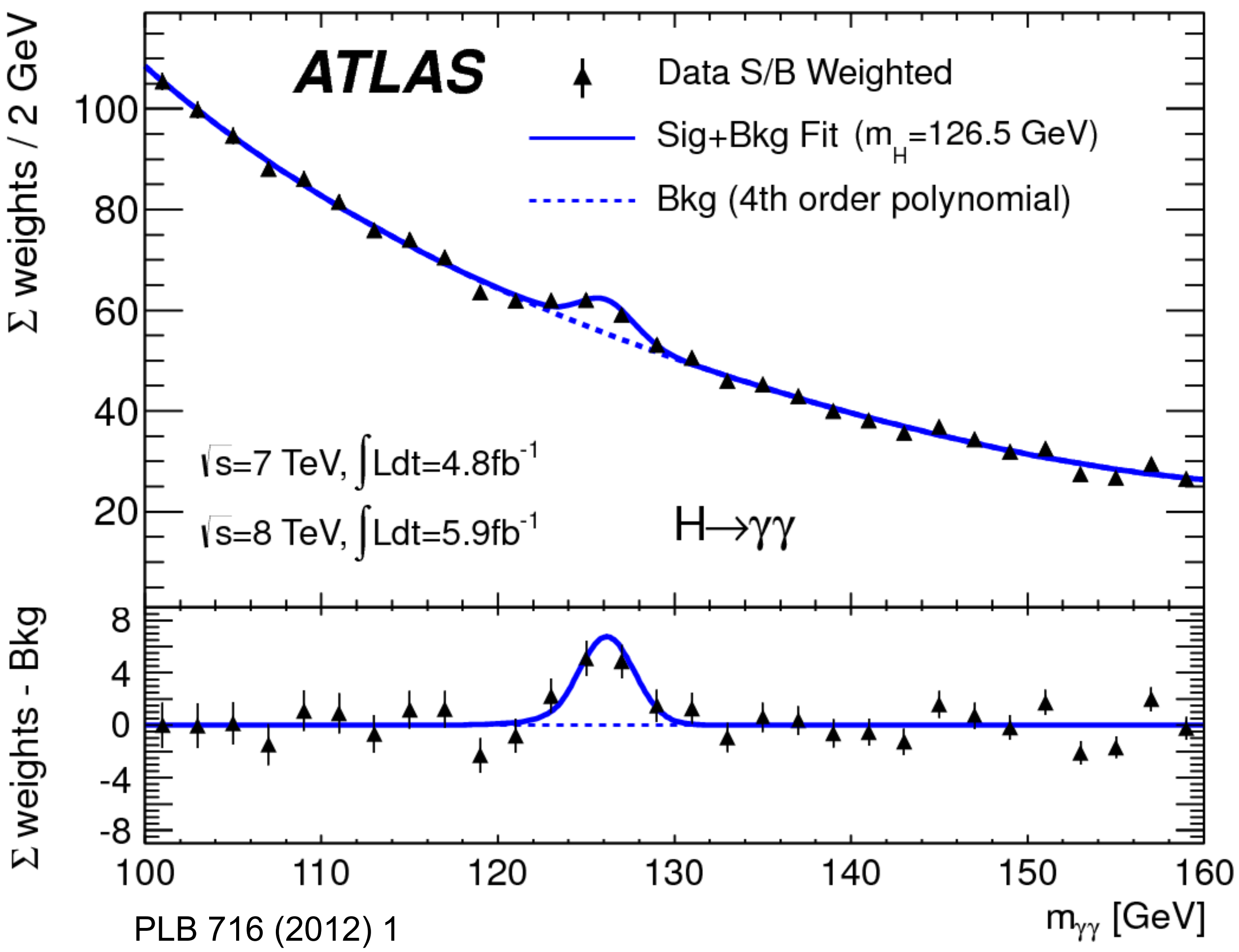
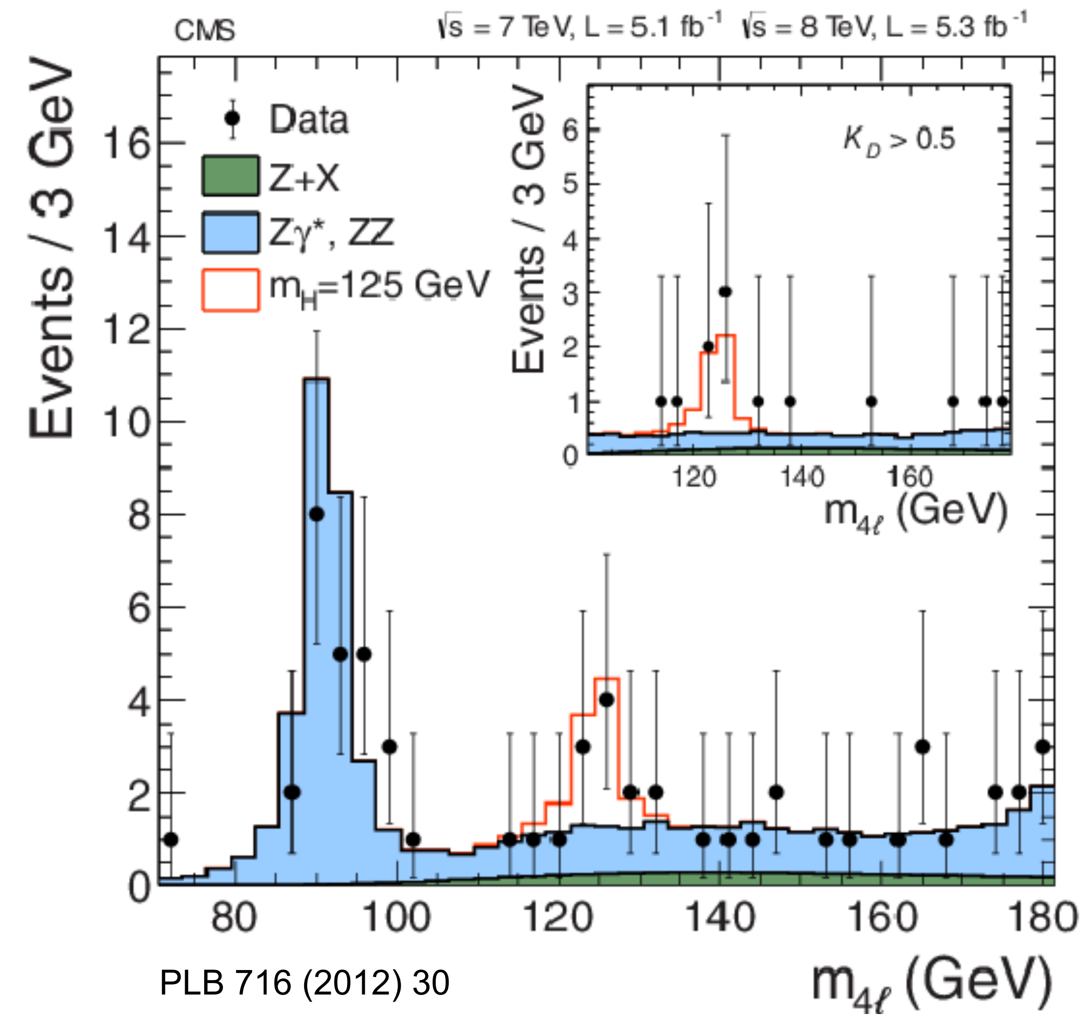
Les capteu
pour la re
le no
TRISTAN VEY
Rolf Heuer (2e à droite) lors d'une présentation, mercredi, à des dizaines de physiciens au Cern, à Genève. DENIS BALIBOUSE/REUTERS

The Discovery





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

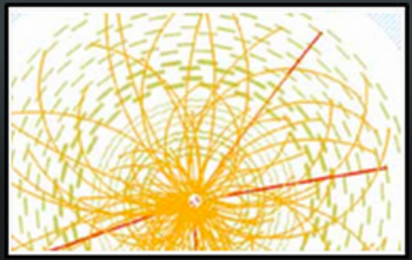
Three decay mode WW, ZZ and γγ

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

"Science" Breakthrough of the Year, 2012

Breakthrough of the Year, 2012

Every year, crowning one scientific achievement as Breakthrough of the Year is no easy task, and 2012 was no exception. The year saw leaps and bounds in physics, along with significant advances in genetics, engineering, and many other areas. In keeping with tradition, *Science*'s editors and staff have selected a winner and nine runners-up, as well as highlighting the year's top news stories and areas to watch in 2013.



FREE ACCESS

The Discovery of the Higgs Boson

A. Cho

Exotic particles made headlines again and again in 2012, making it no surprise that the breakthrough of the year is a big physics finding: confirmation of the existence of the Higgs boson. Hypothesized more than 40 years ago, the elusive particle completes the standard model of physics, and is arguably the key to the explanation of how other fundamental particles obtain mass. The only mystery that remains is whether its discovery marks a new dawn for particle physics or the final stretch of a field that has run its course.

Read more about the Higgs boson from the research teams at CERN.

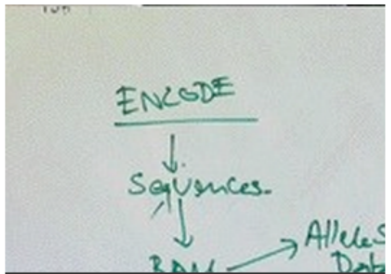
Runners-Up FREE WITH REGISTRATION

This year's runners-up for Breakthrough of the Year underscore feats in engineering, genetics, and other fields that promise to change the course of science.

Denisovan Genome

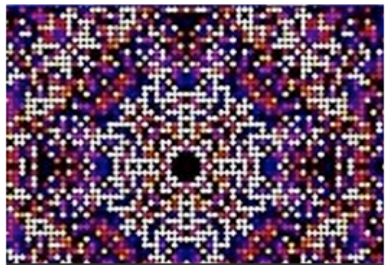
Genome Engineering

Neutrino Mixing Angle



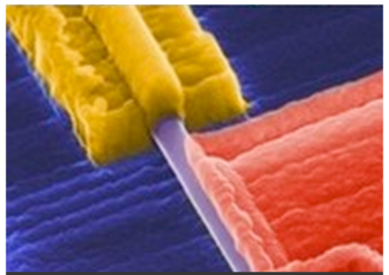
ENCODE

Curiosity Landing

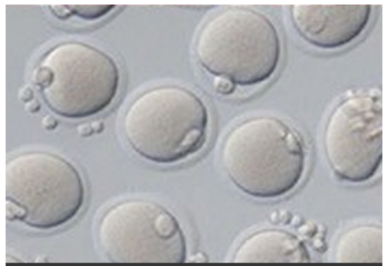


X-ray Laser Advances

Controlling Bionics



Majorana Fermions



Eggs from Stem Cells

LHC: Production and Decay

Not an exhaustive table!

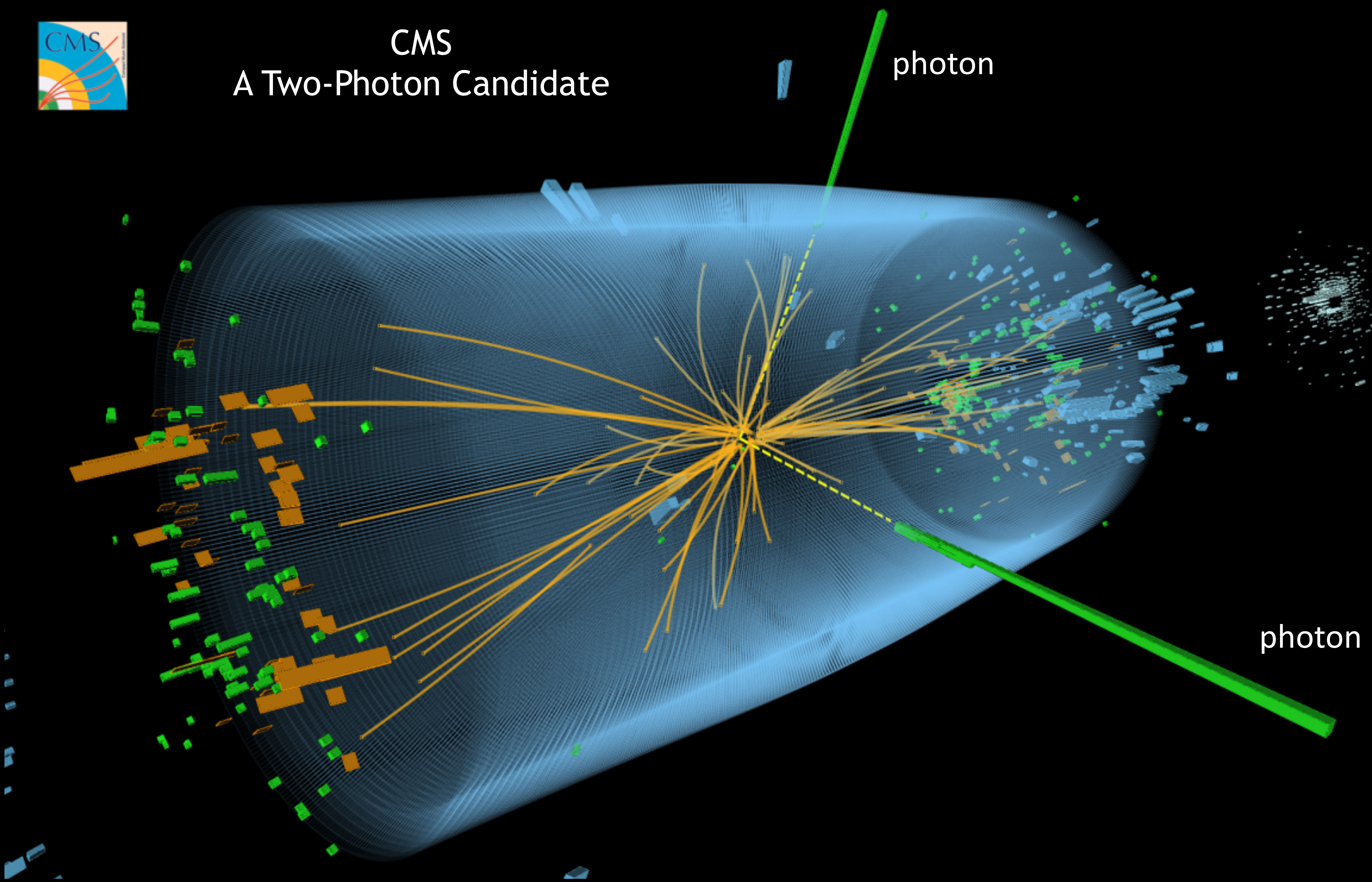
★ "seen" ☆ "tried"	H→bb	H→ττ	H→WW	H→ZZ	H→γγ	H→inv.	H→μμ
ggH		★	★	★	★		☆
VBF	☆	★	★	☆	★	☆	☆
VH	★	☆	☆	☆	☆	☆	
ttH	☆	☆	☆		☆		
	$\sigma(m_{bb})$ ~20%	$\sigma(m_{\tau\tau})$ 10-20%	$\sigma(m_{WW})$ ~16%	**$\sigma(m_{ZZ})$ 1-2%**	**$\sigma(m_{\gamma\gamma})$ 1-2%**		

courtesy André David

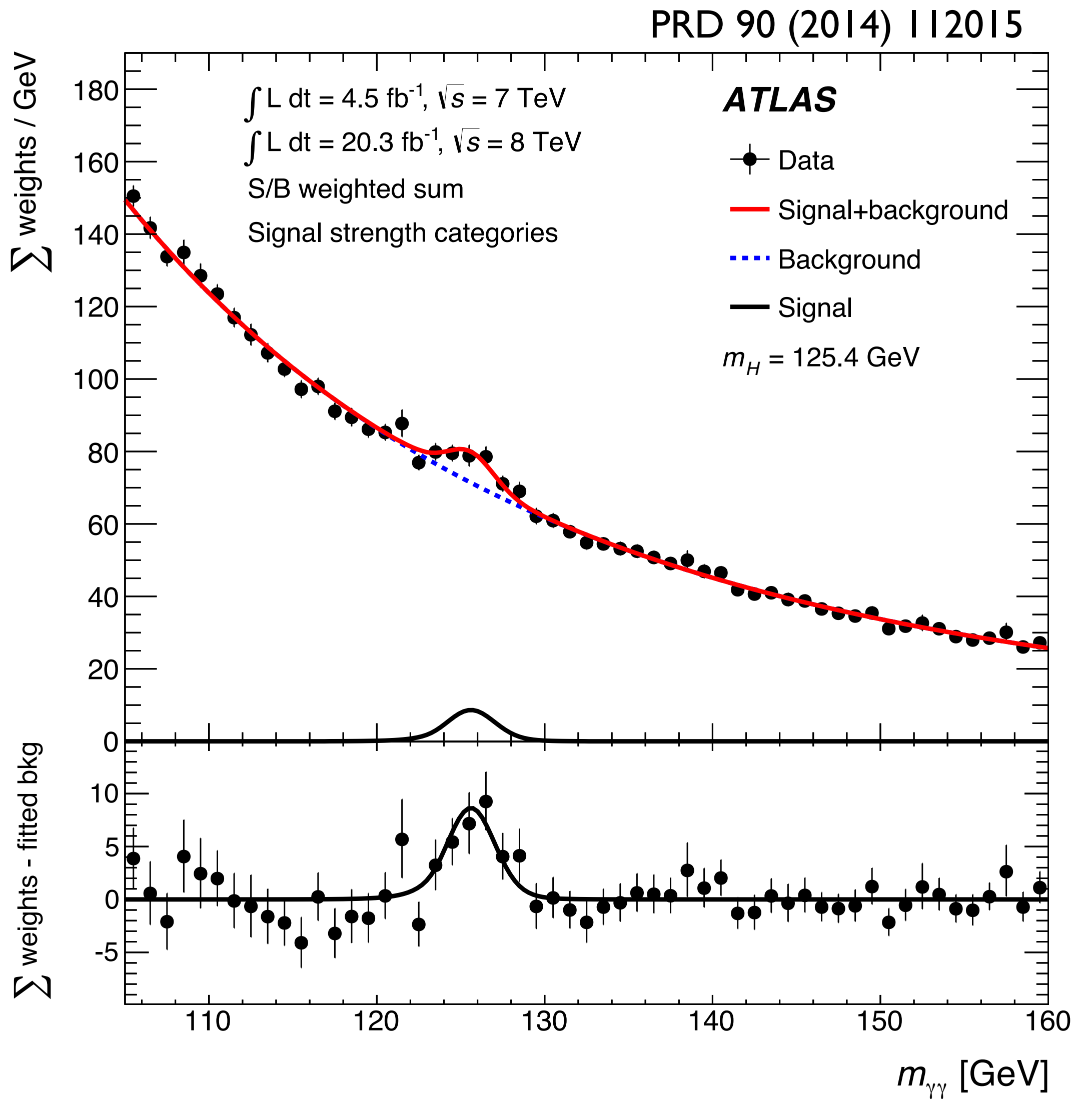
Expected number of decays for Run-1 before selection cuts (m_H = 125 GeV)

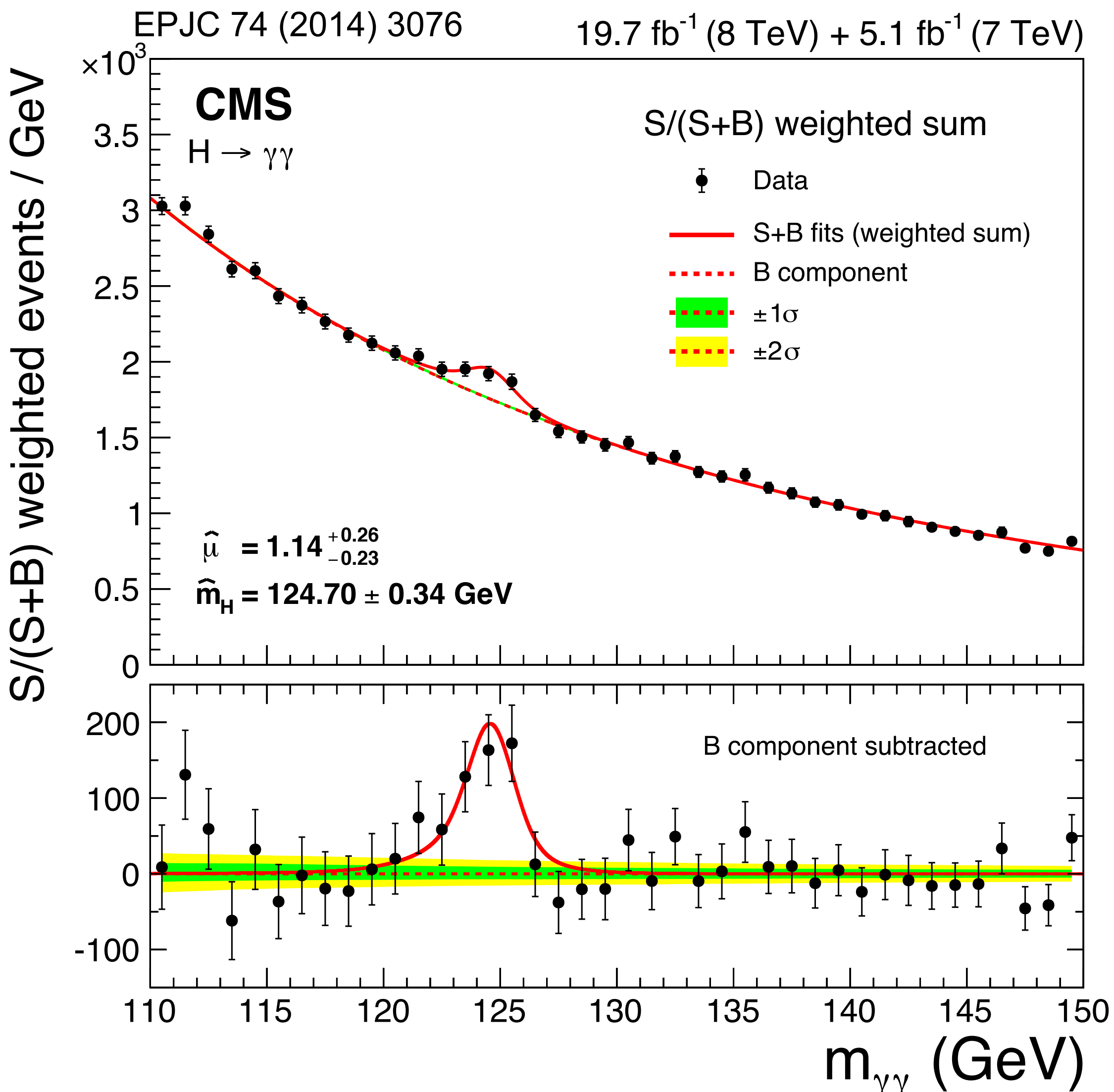
- 9,000 H → WW* → $\ell\nu\ell\nu$
- 900 H → γγ
- 60 H → ZZ* → 4ℓ

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

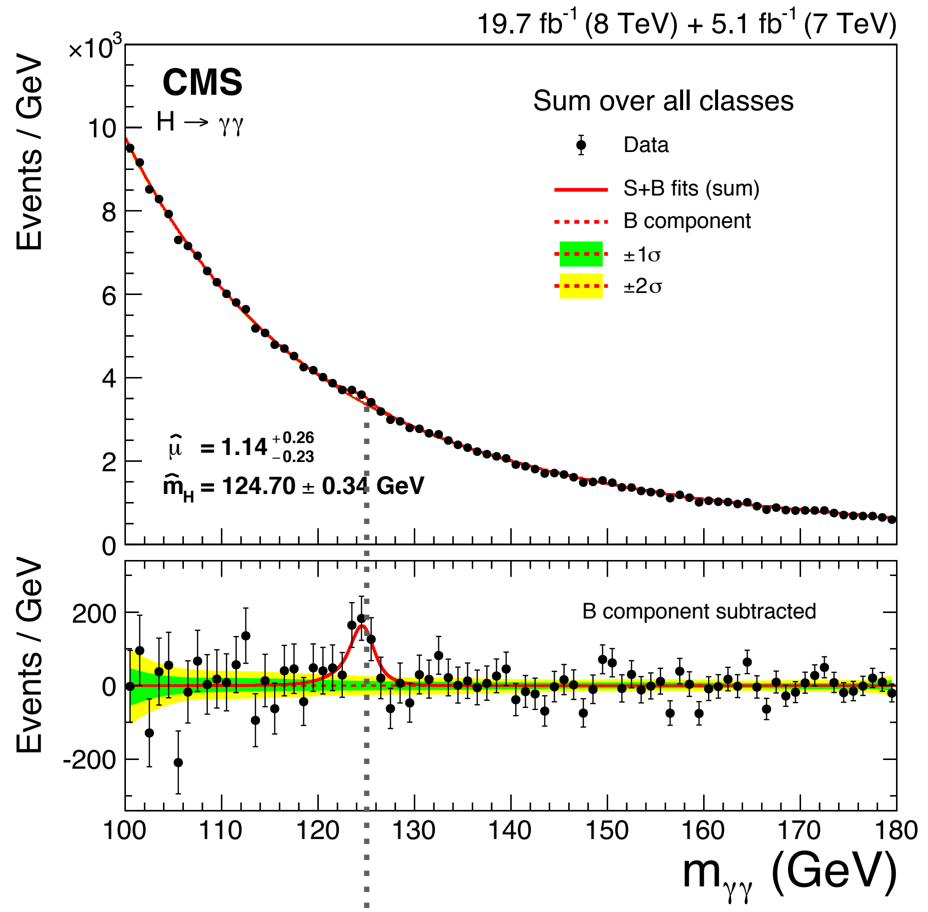
m_H = 124.70 ± 0.31 (stat) ± 0.15 (syst) GeV

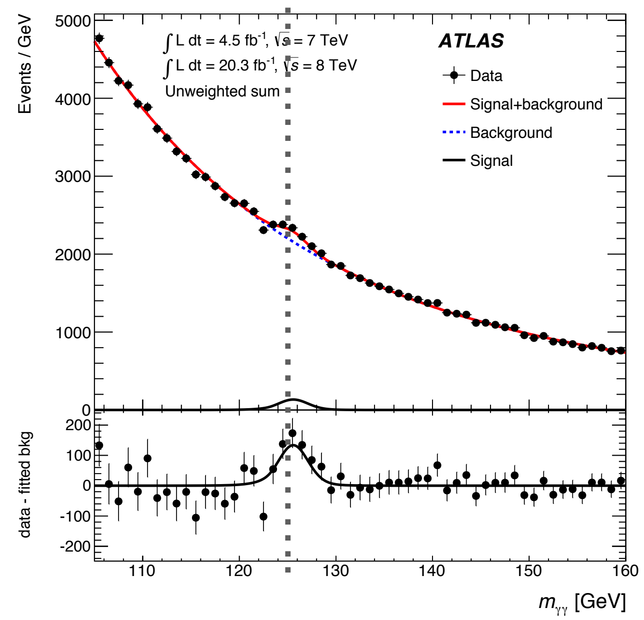
Background interpolation in the region of the signal

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

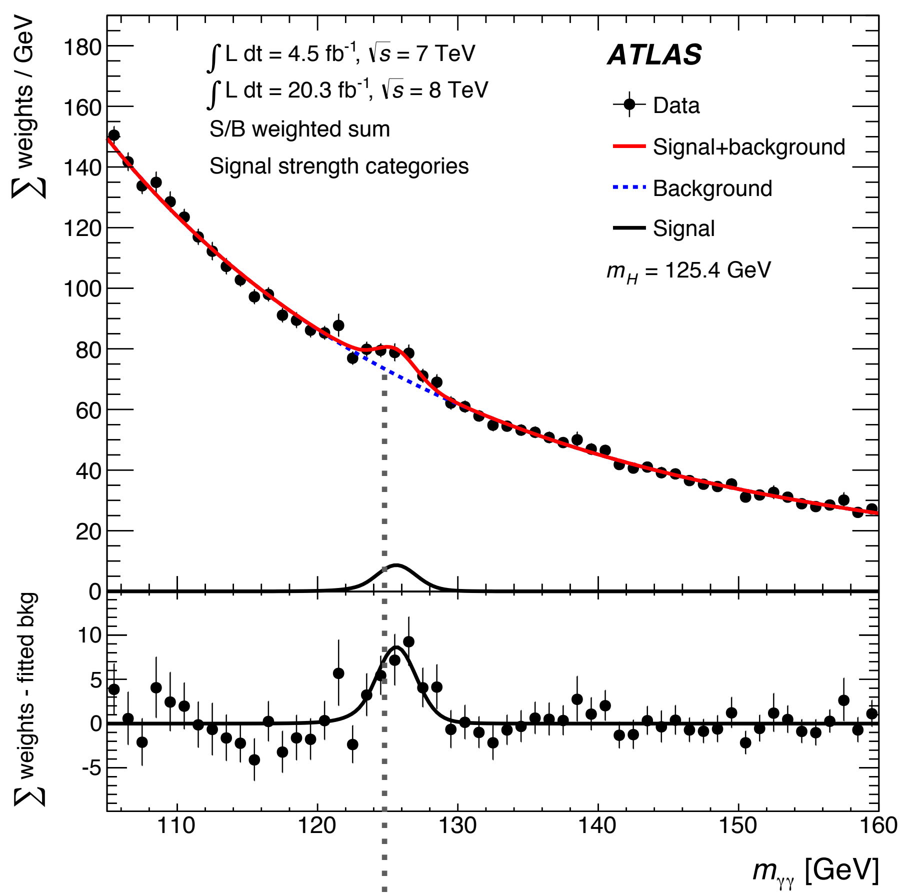
Two-Photon, Comparison

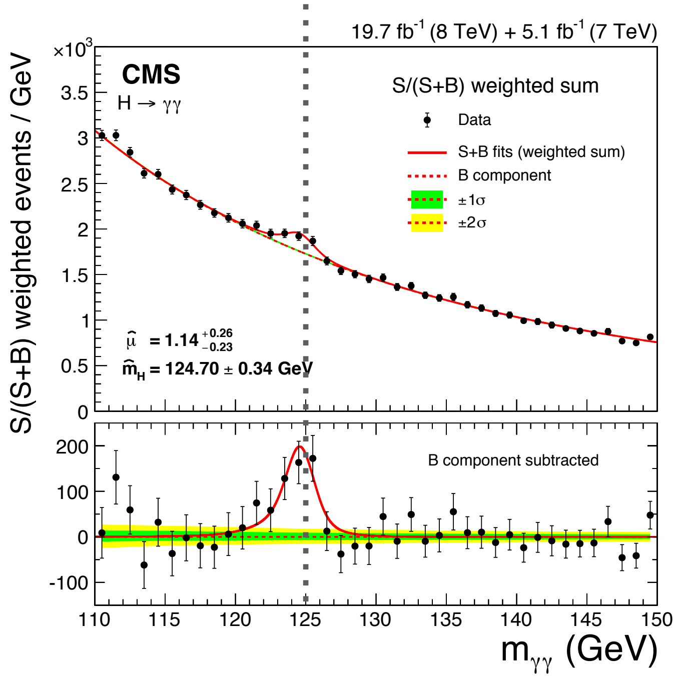
Unweighted Distributions





S/(S+B)-Weighted Distributions

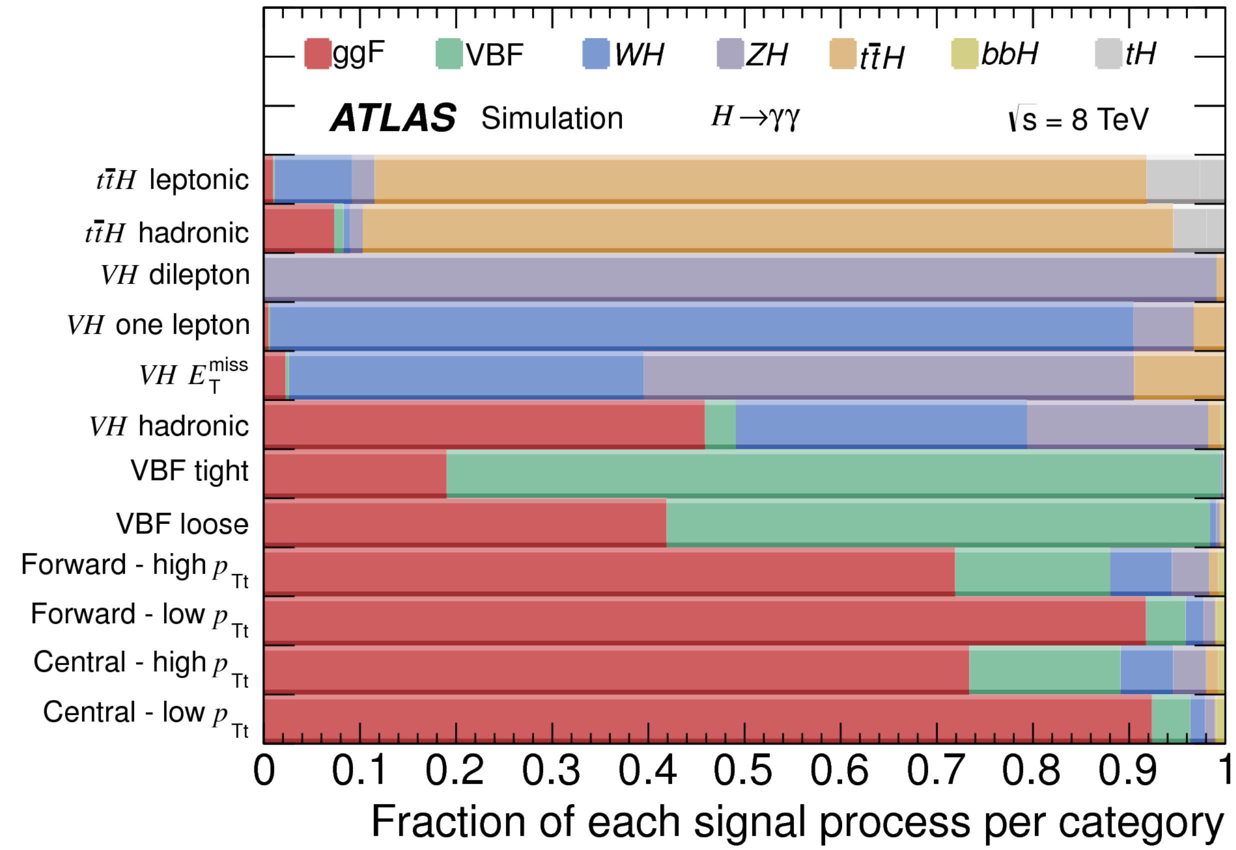




dotted lines at 125 GeV

Two-Photon: Categorisation

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

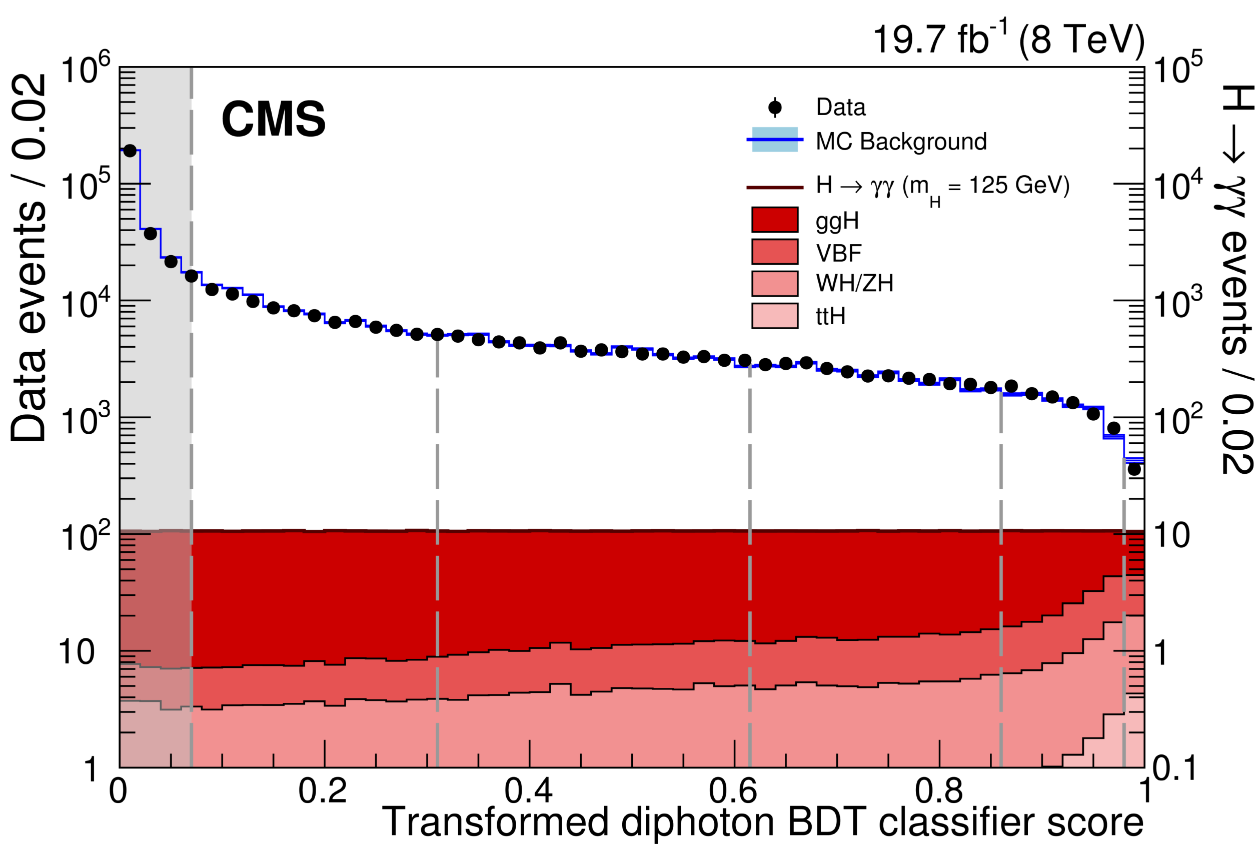


for example:

VBF = two jets with

large m_{jj} and rapidity separation (Δy)

loose and tight settings



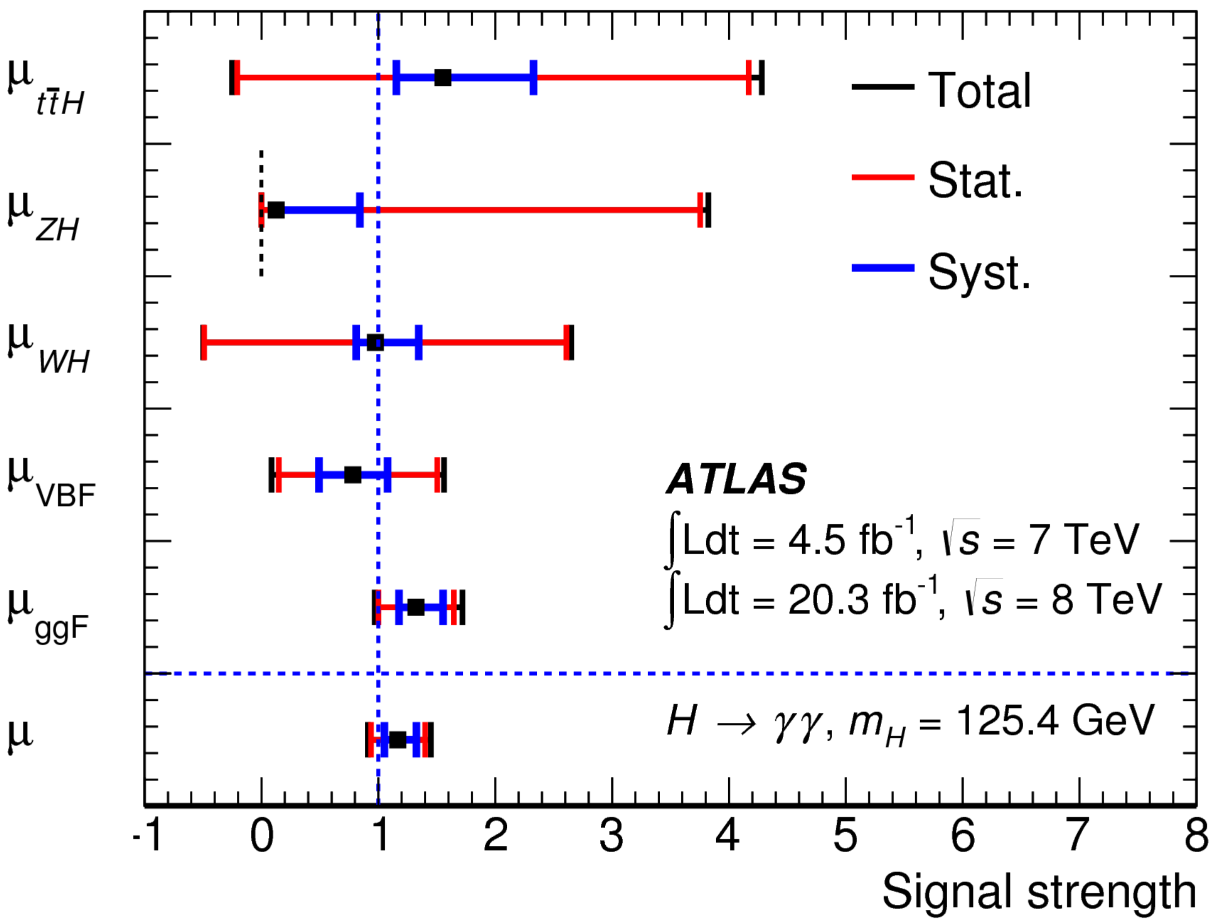
Event classifier (MVA) which compiles all the information into a discriminant

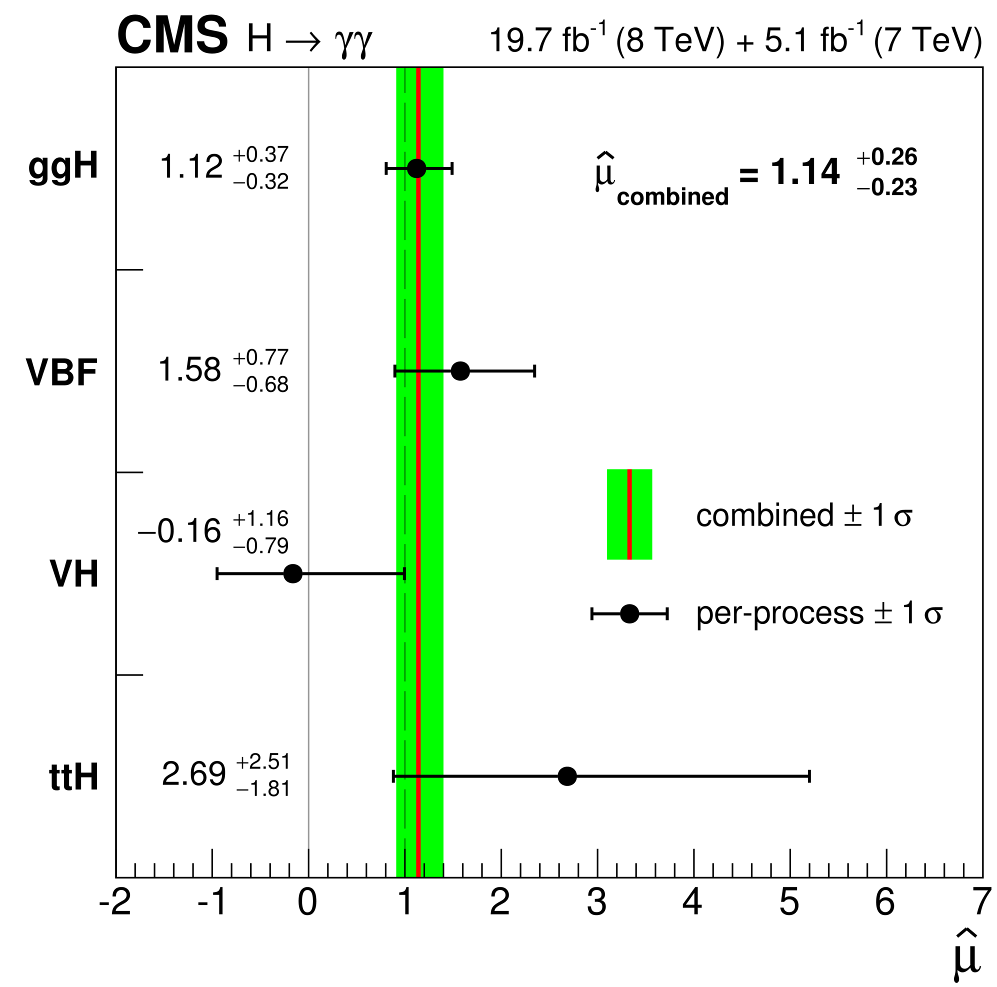
High score to events with

- signal-like kinematics (p_T and y of the $\gamma\gamma$ pair)
- good diphoton mass resolution
- high photon reconstruction quality

5 "untagged" categories + VBF + VH + ttH

Two-Photon: Production Modes





Individual production modes are consistent with SM expectations

- ggH is established
- there is strong evidence for VBF

Differential and Fiducial

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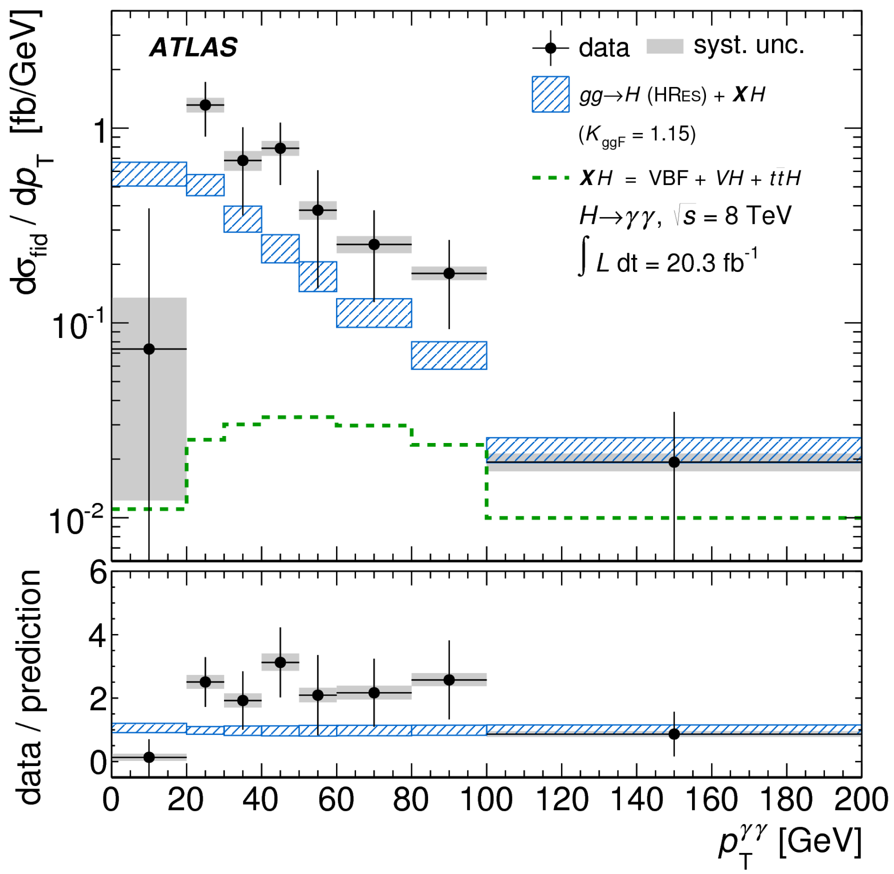
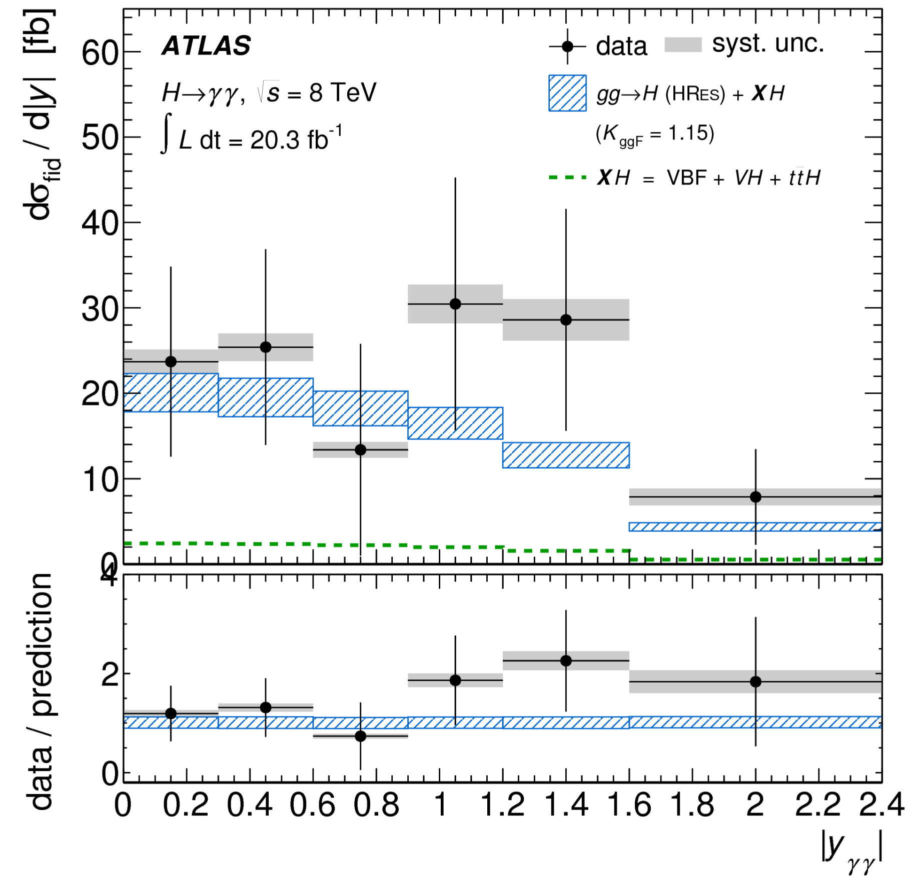
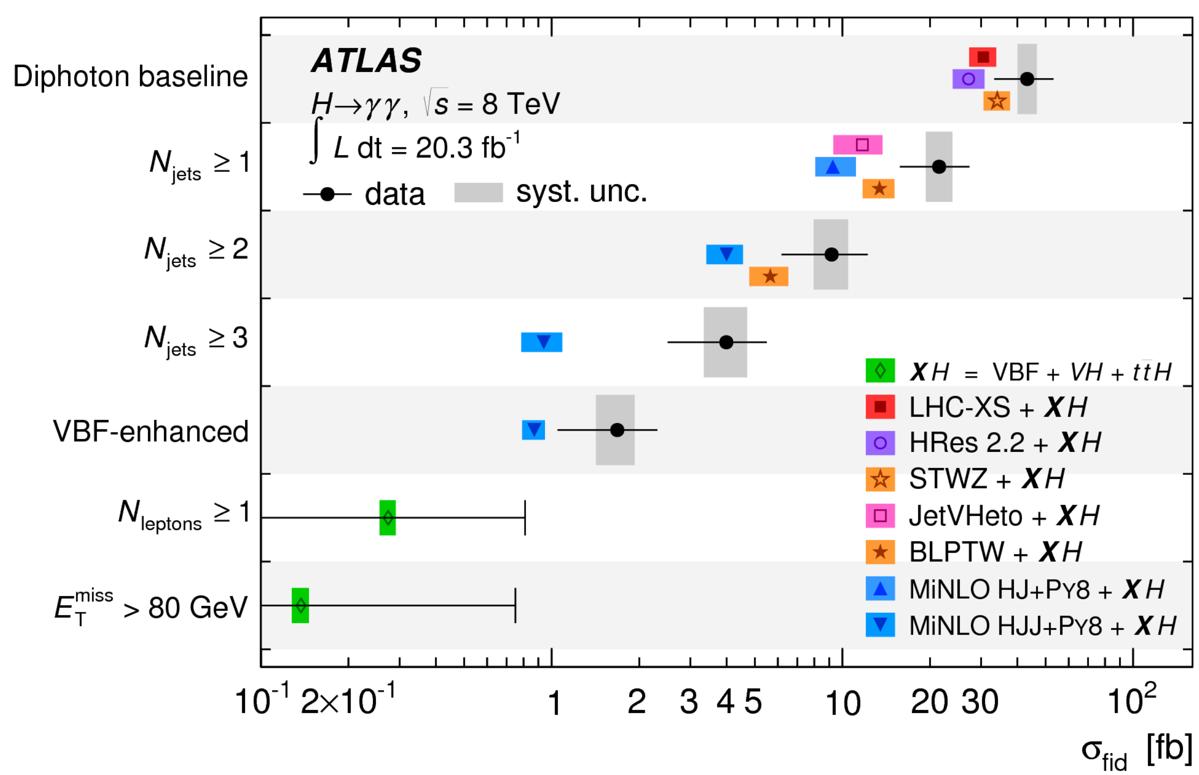
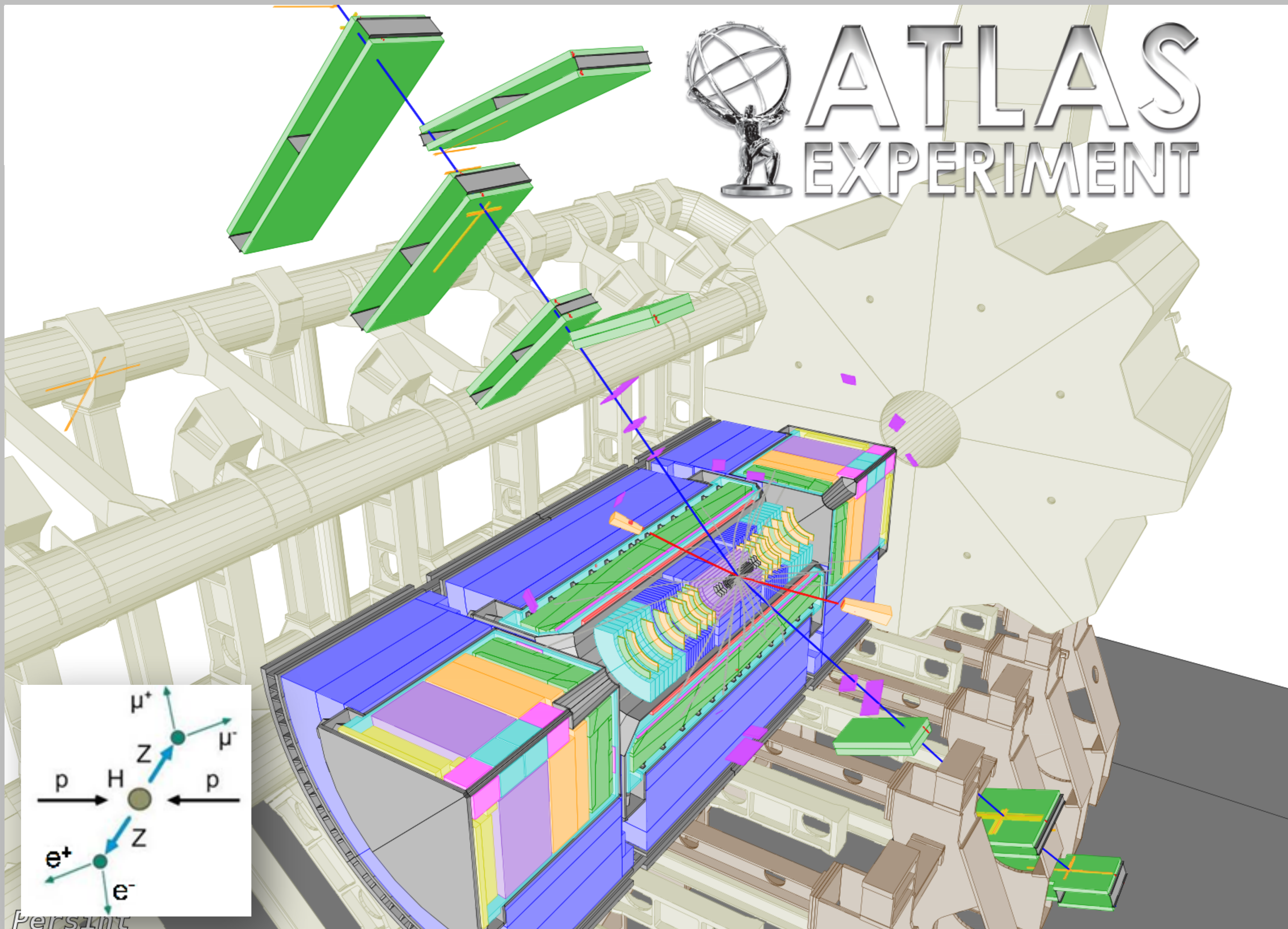


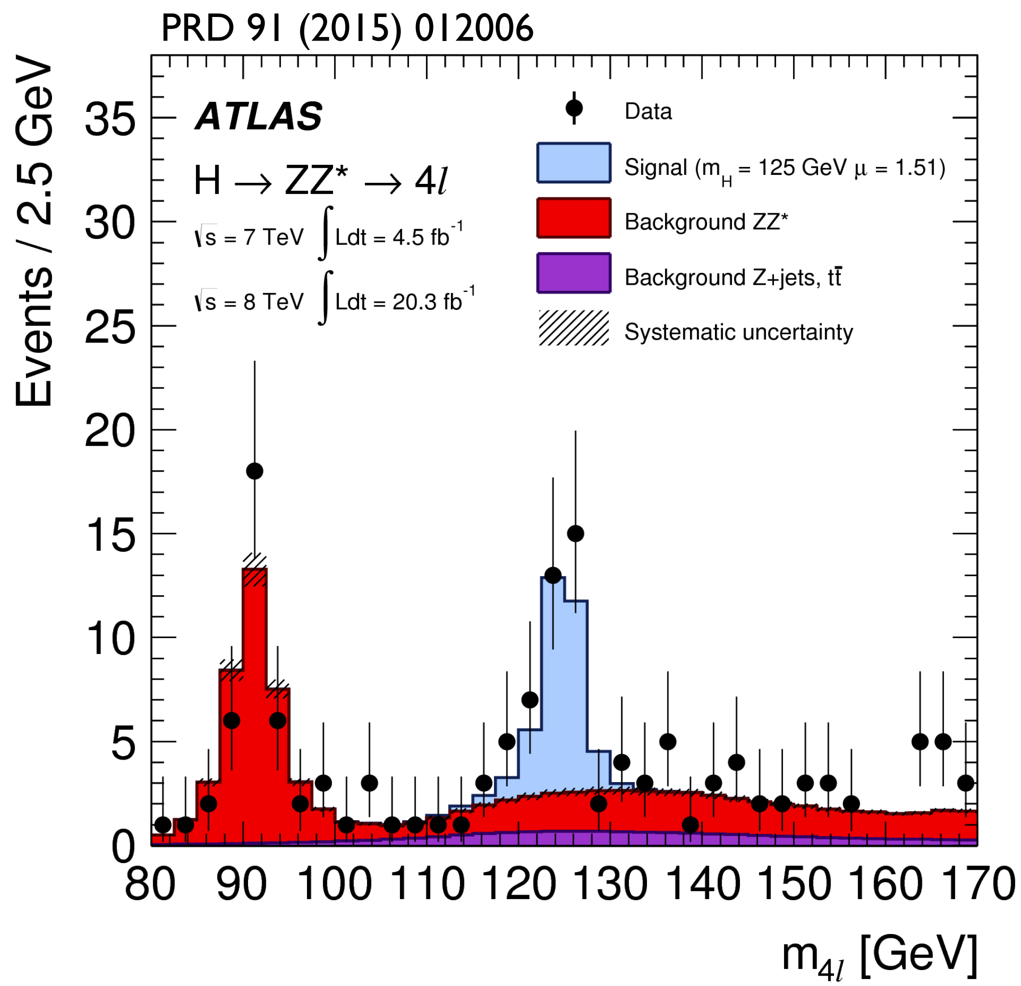


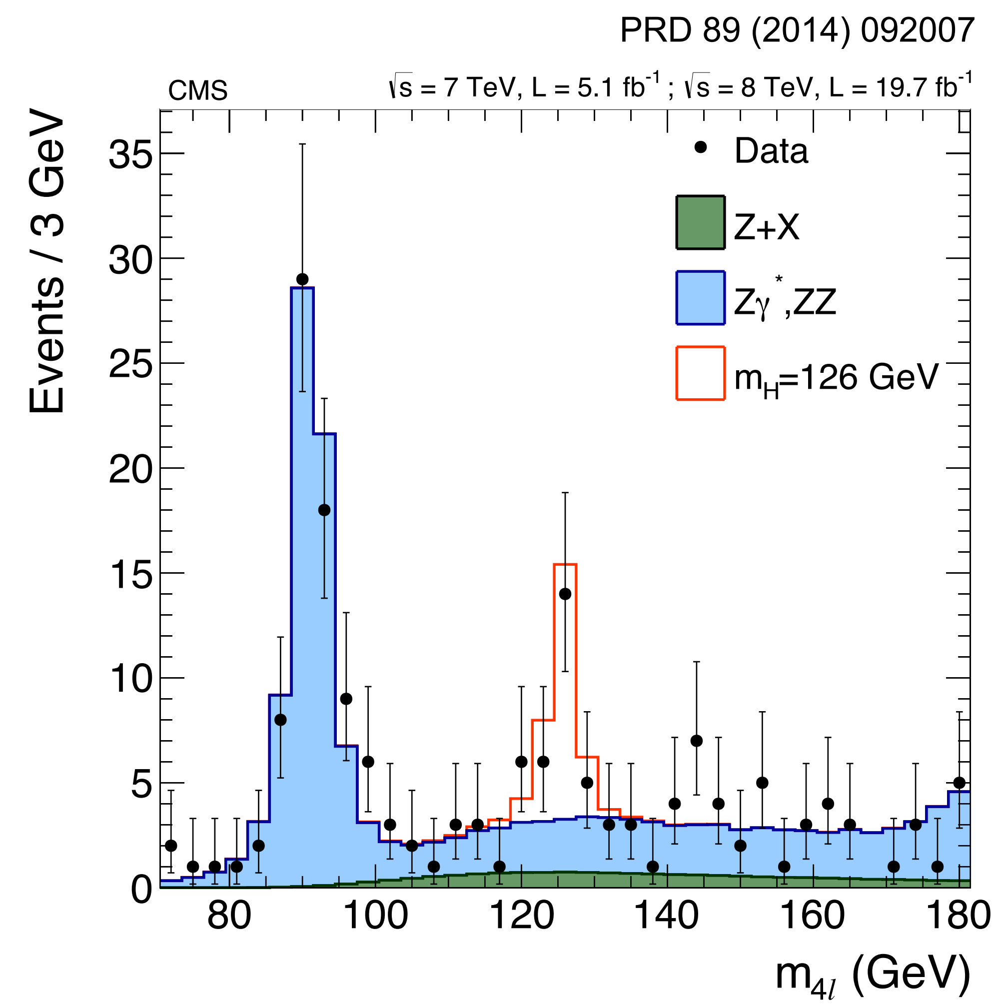


Four-Lepton Mode



Four-Lepton Decay



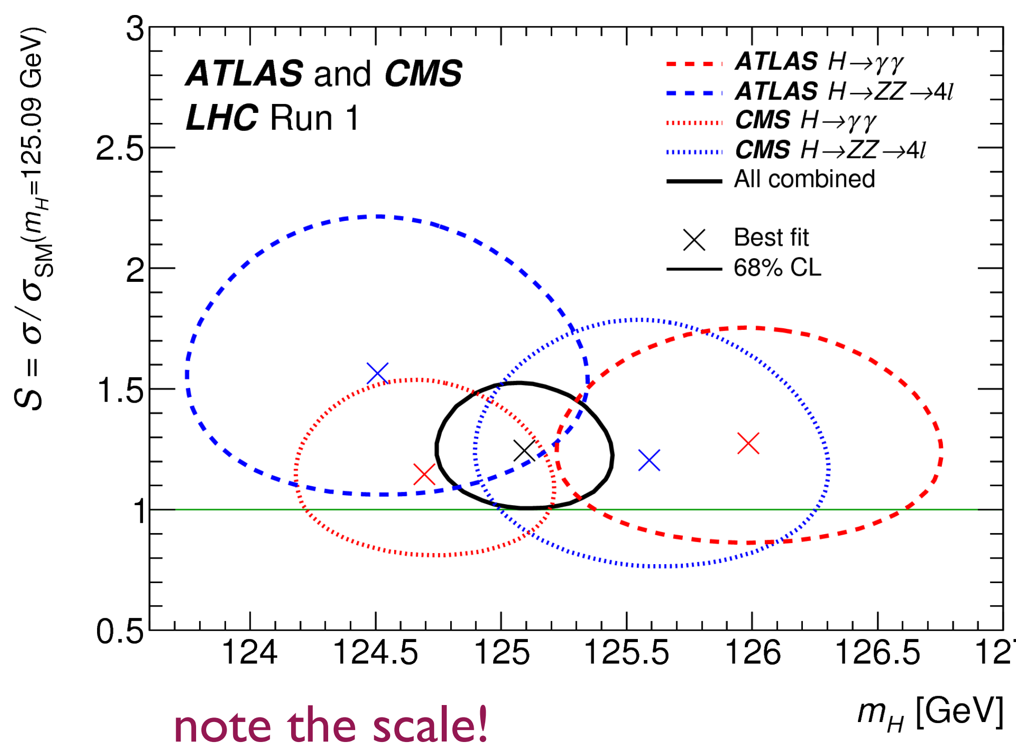


m_H = 124.51 ± 0.52 (stat) ± 0.04 (syst) GeV

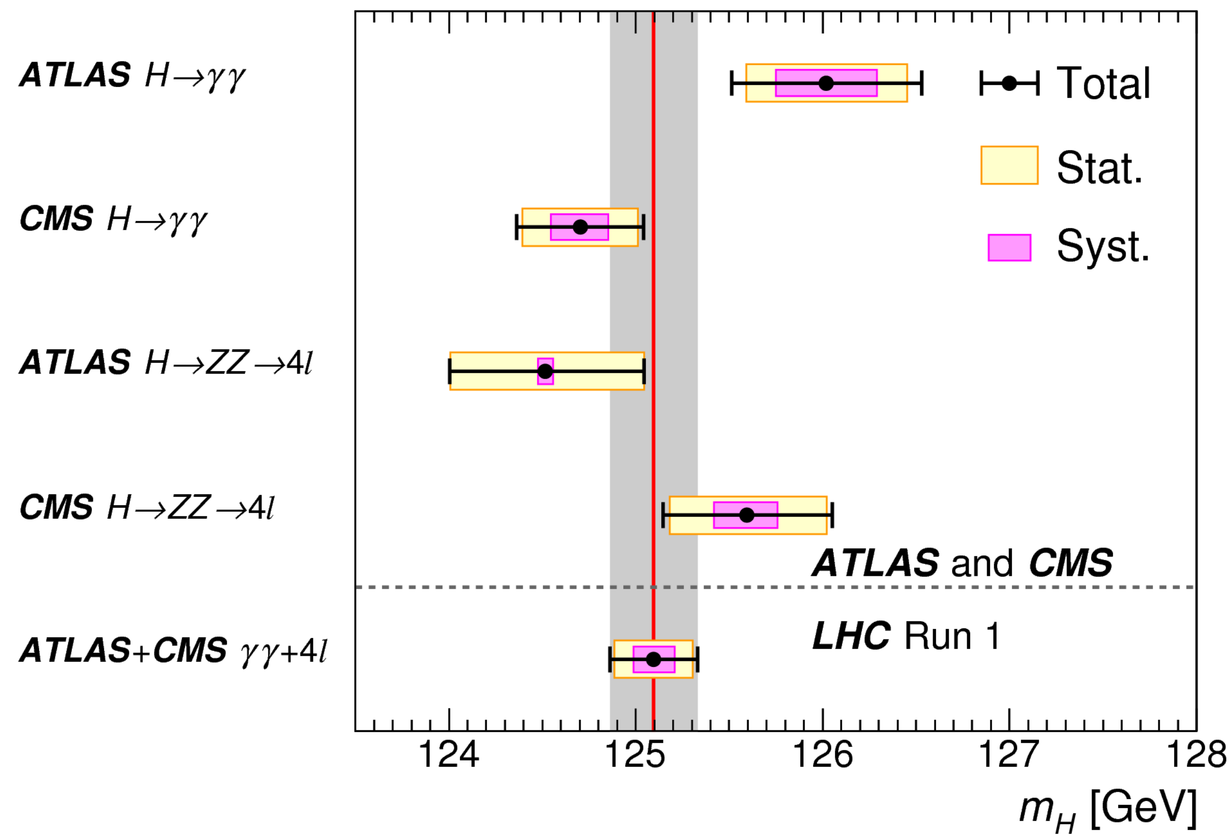
m_H = 125.59 ± 0.45 (stat) ± 0.17 (syst) GeV

Both experiments observe signals with > 6σ

Mass of the Higgs Boson



note the scale!



Combined fit to ATLAS and CMS data

in γγ and ZZ→4ℓ channels

- consistency between experiments
- consistency between channels

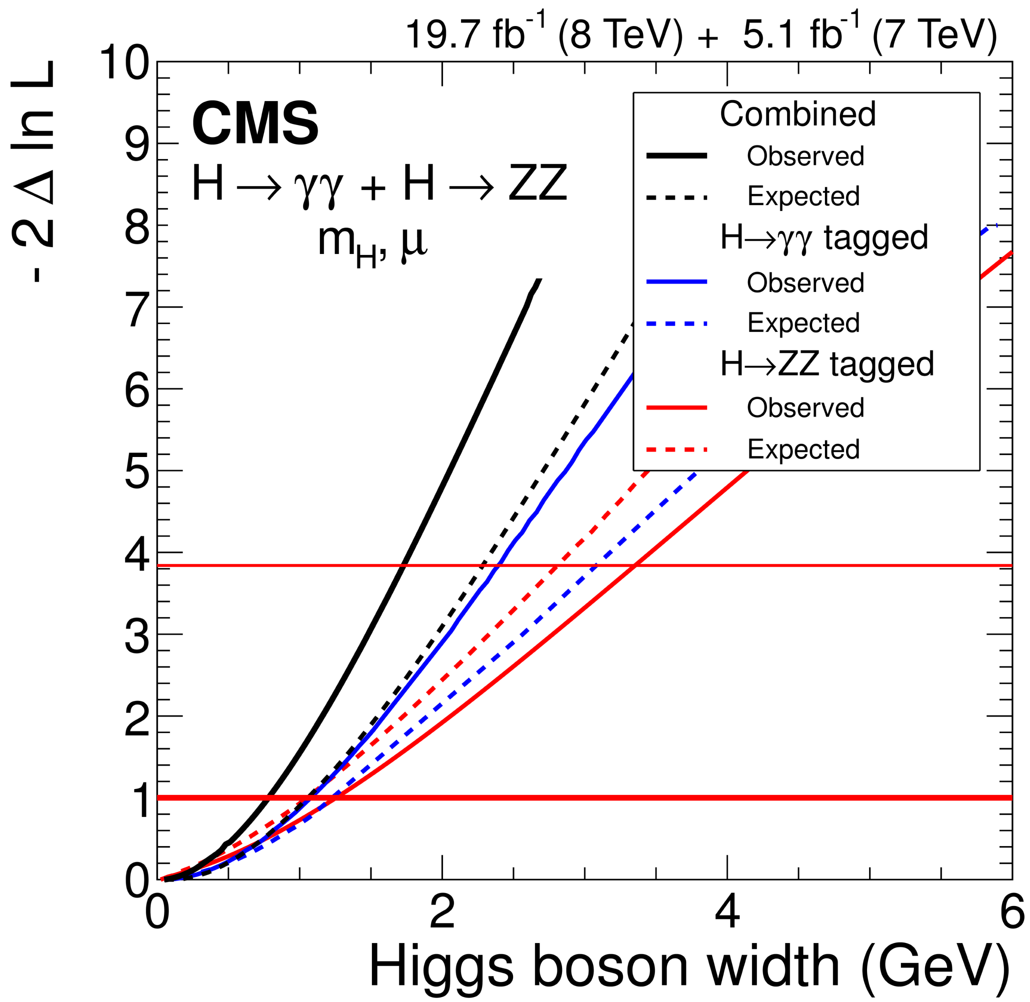
$$m_H = 125.09 \pm 0.24 \text{ GeV}$$
$$= 125.09 \pm 0.21 \text{ (stat)} \pm 0.11 \text{ (syst) GeV}$$

2‰ accuracy on the Higgs boson mass!

PRL 114 (2015) 191803

Width of the Higgs Boson

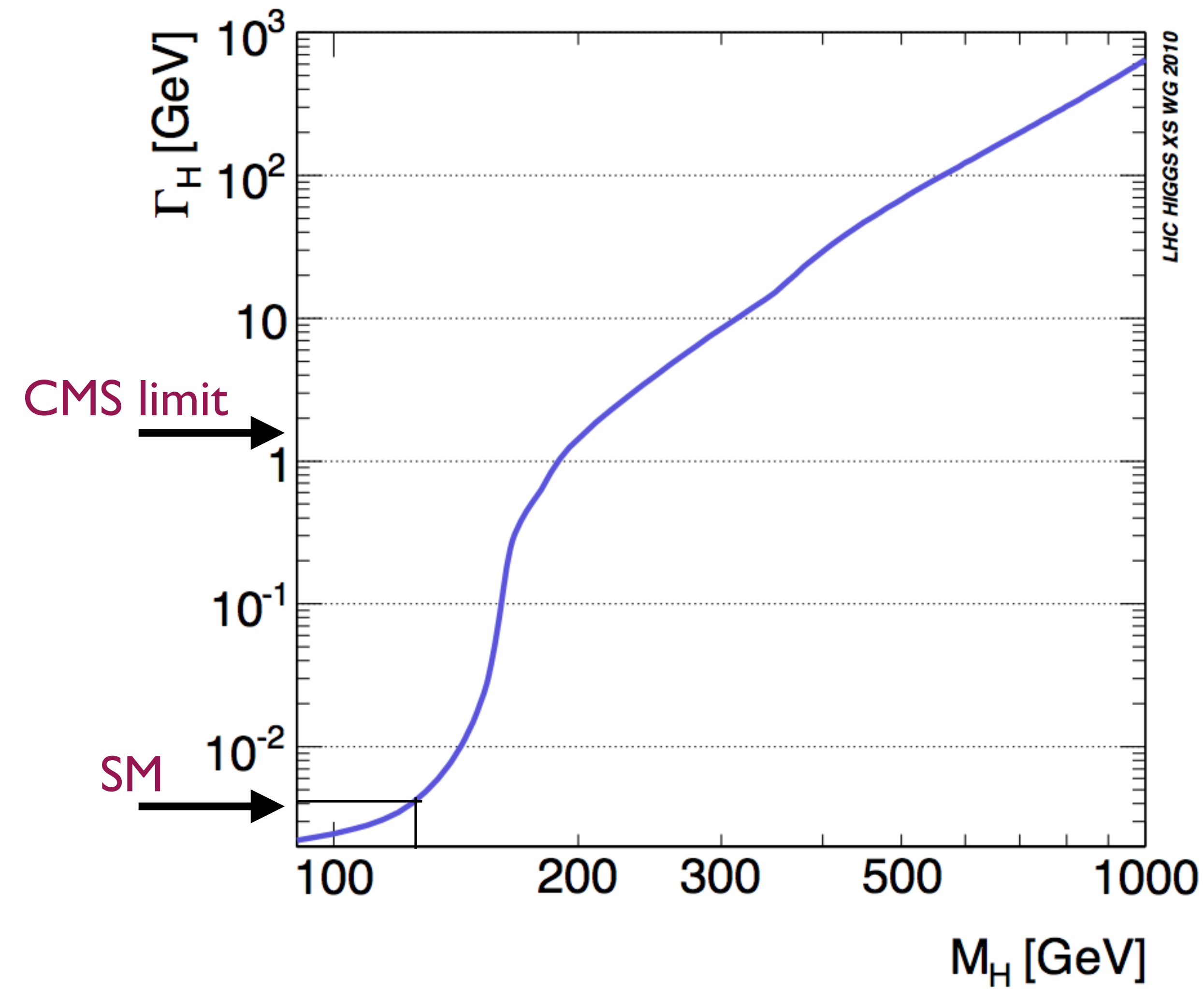
Upper limits on the width can be obtained from the mass peaks (at the level of the experimental resolution)



Γ_H < 1.7 GeV (95%CL)

EPJC 75 (2015) 212

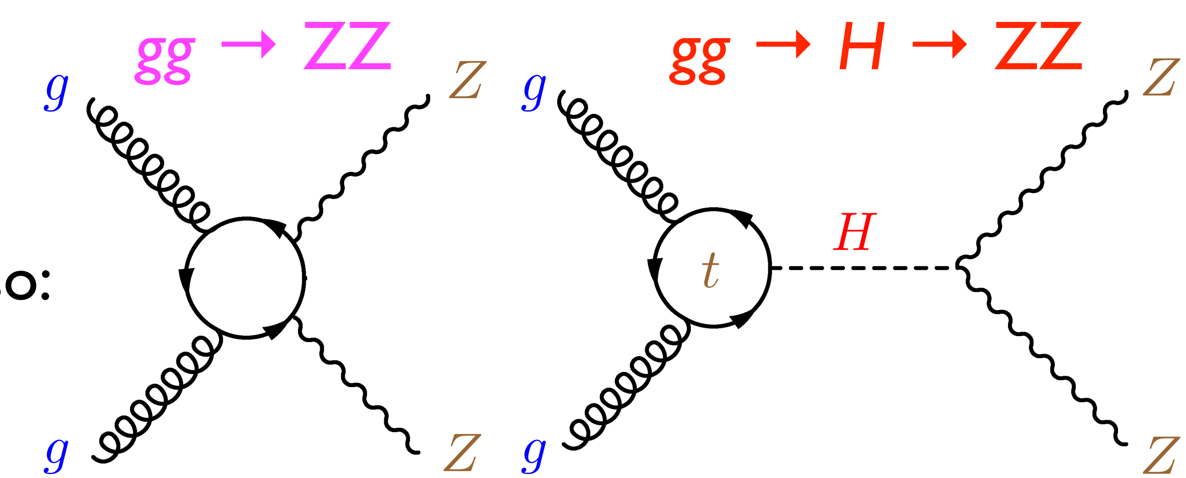
The width of the SM Higgs boson is expected of the order of 4MeV



Off-Shell Higgs Boson

Main continuum 4ℓ production: $q\bar{q} \to 4\ell$

also:



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

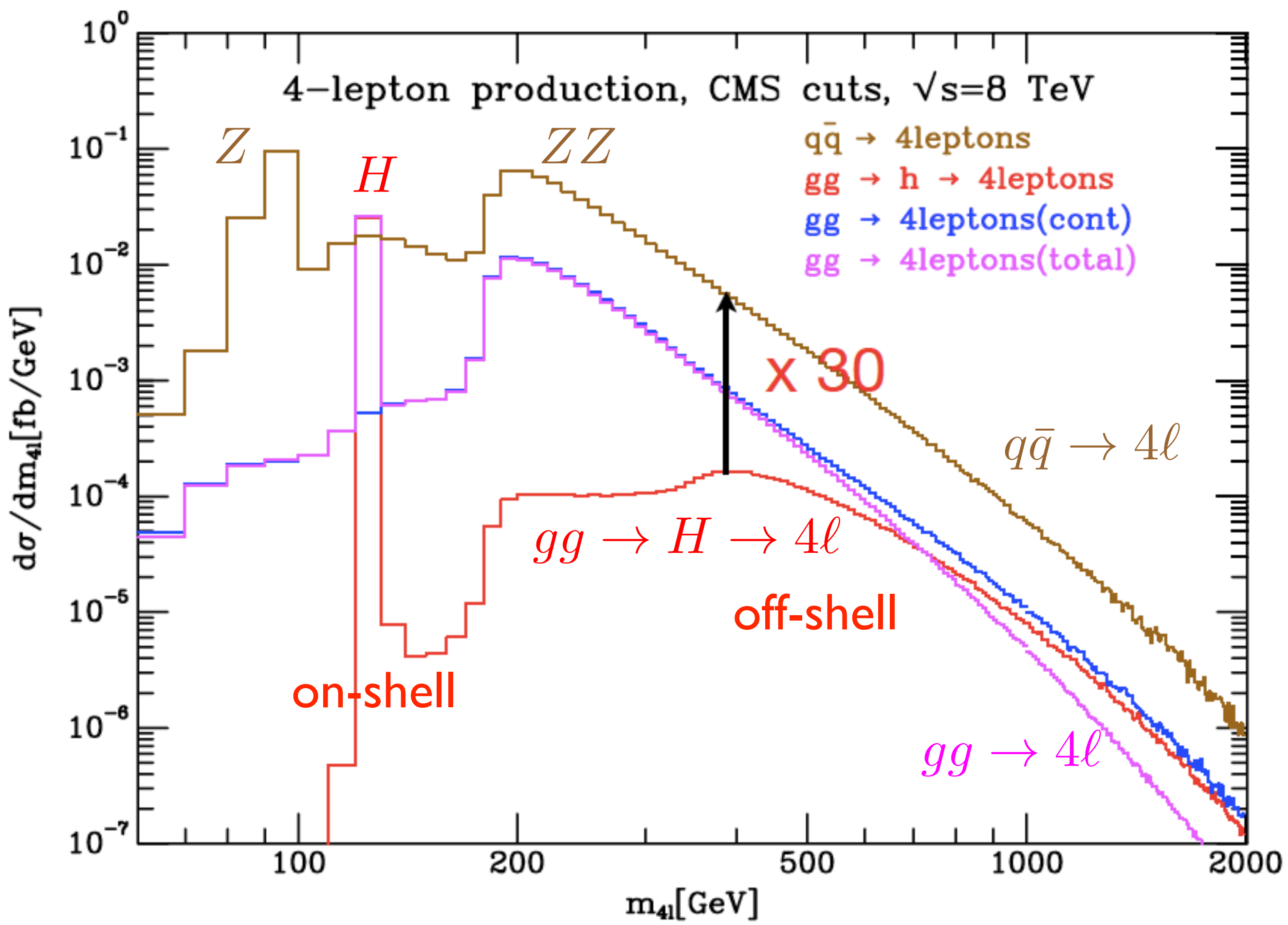
on-shell ($m_{ZZ} \sim m_H$) $\quad \sigma^{\text{on-shell}}_{gg\to H\to ZZ} \sim \dfrac{g^2_{ggH}\, g^2_{HZZ}}{m_H \Gamma_H}$

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

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

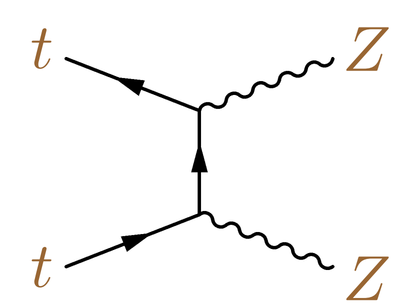
CMS/ATLAS set 95%CL upper limits on Γ_H around 22 MeV!

($\Gamma_{SM} \sim 4$ 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

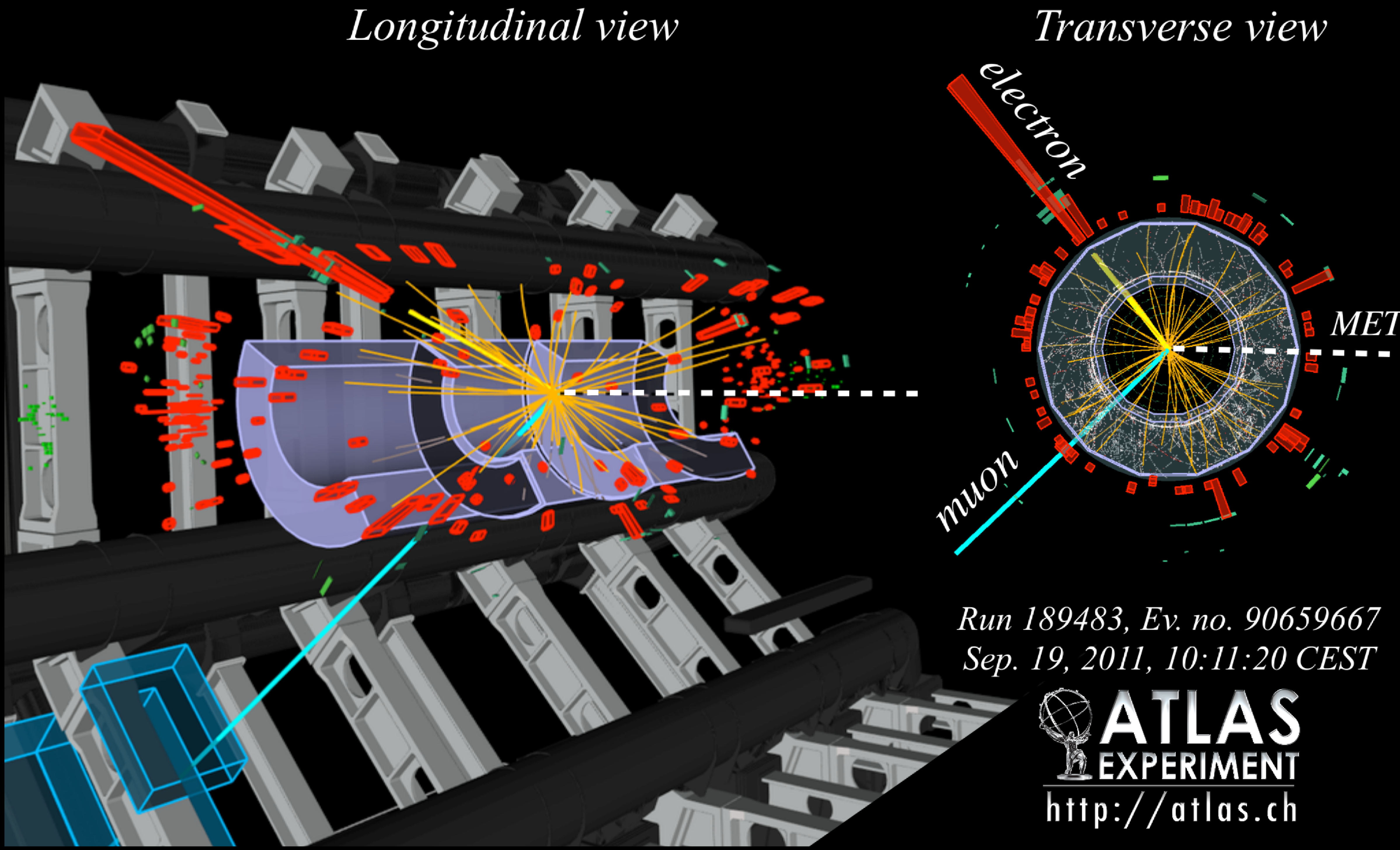


+… $\sim E^2$

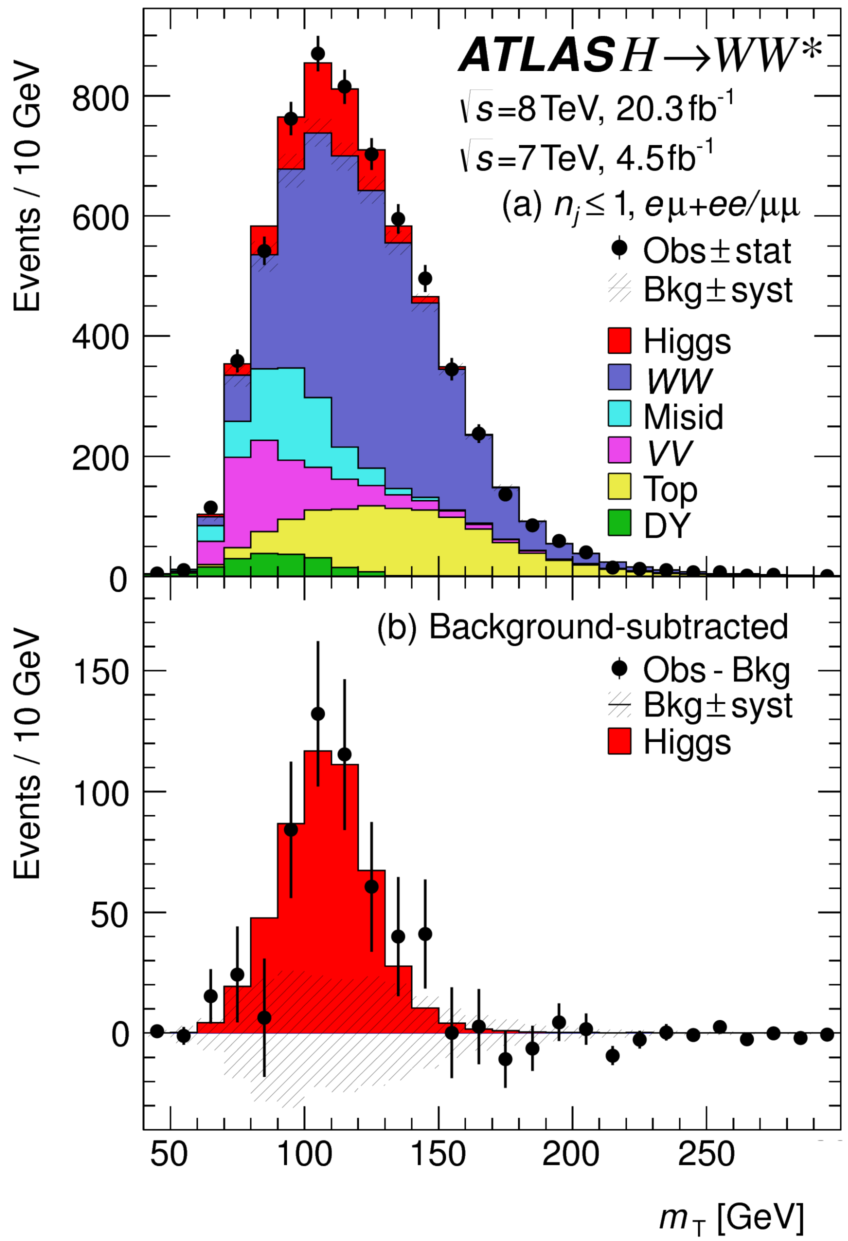
very fundamental! Higgs at work

WW Decays

$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and no jets



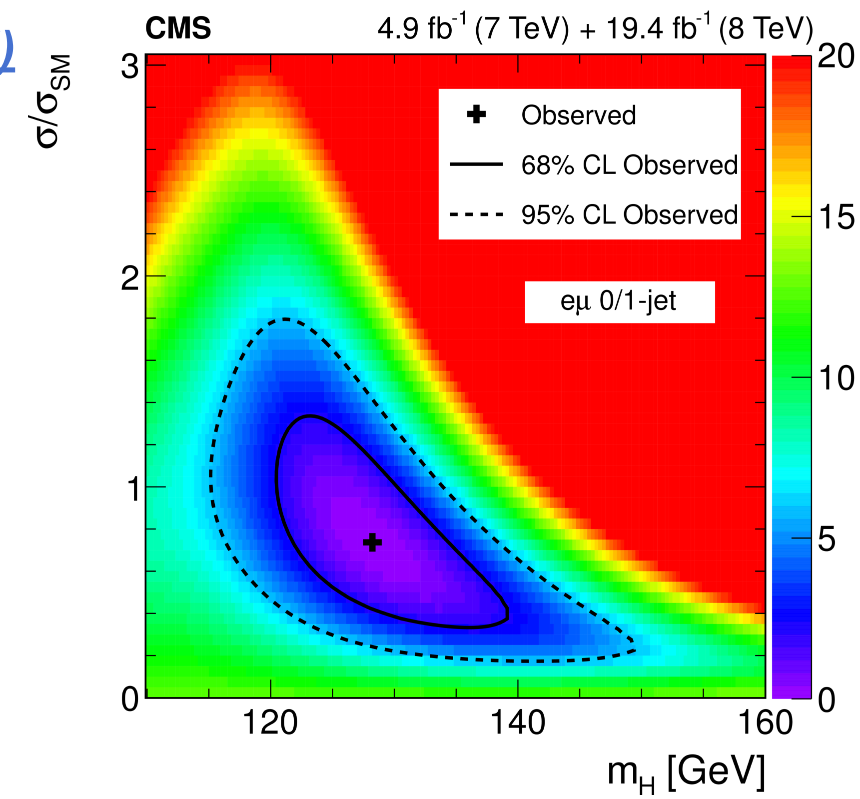
WW Decay

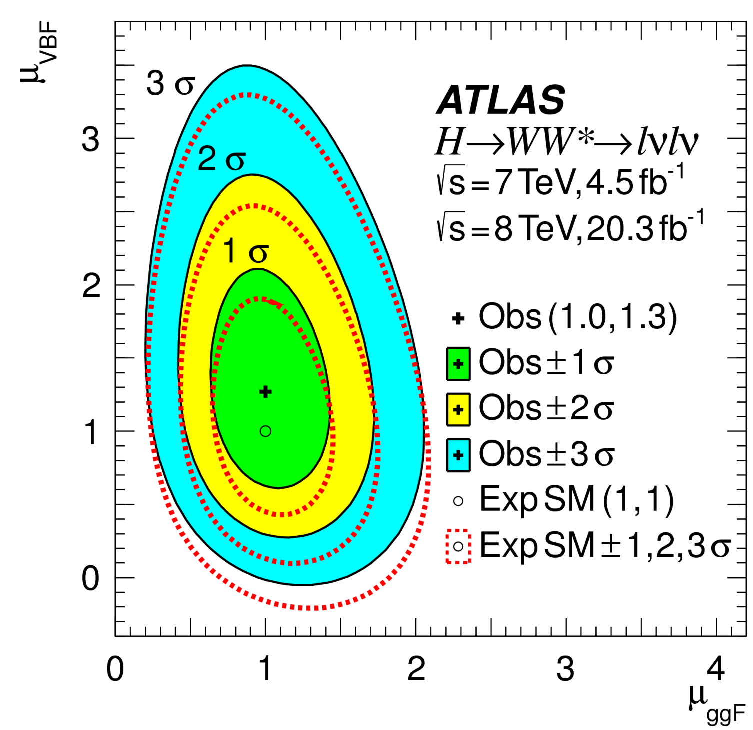


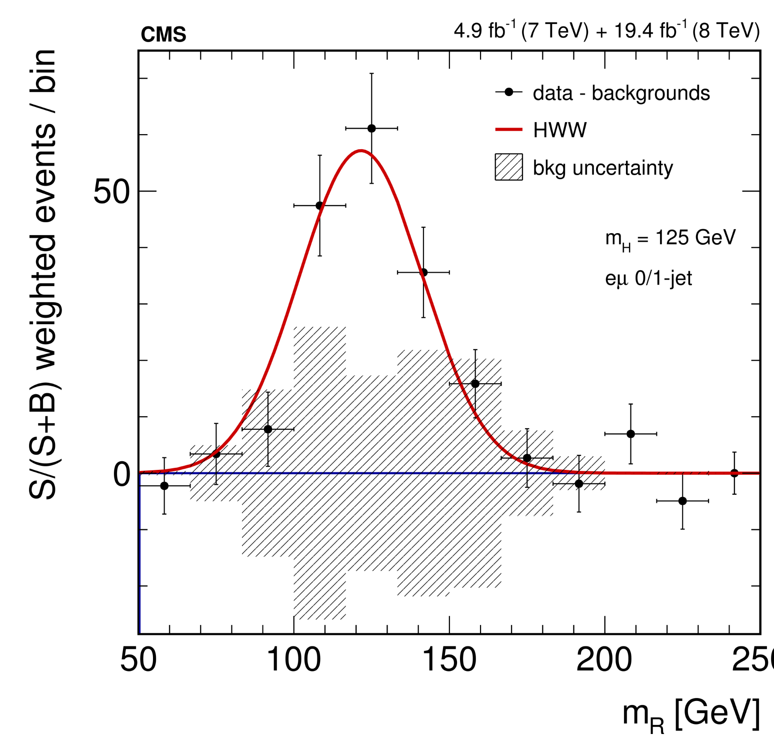
[Phys. Rev. D 92, 012006 (2015)]

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

Mass consistent with
125 GeV





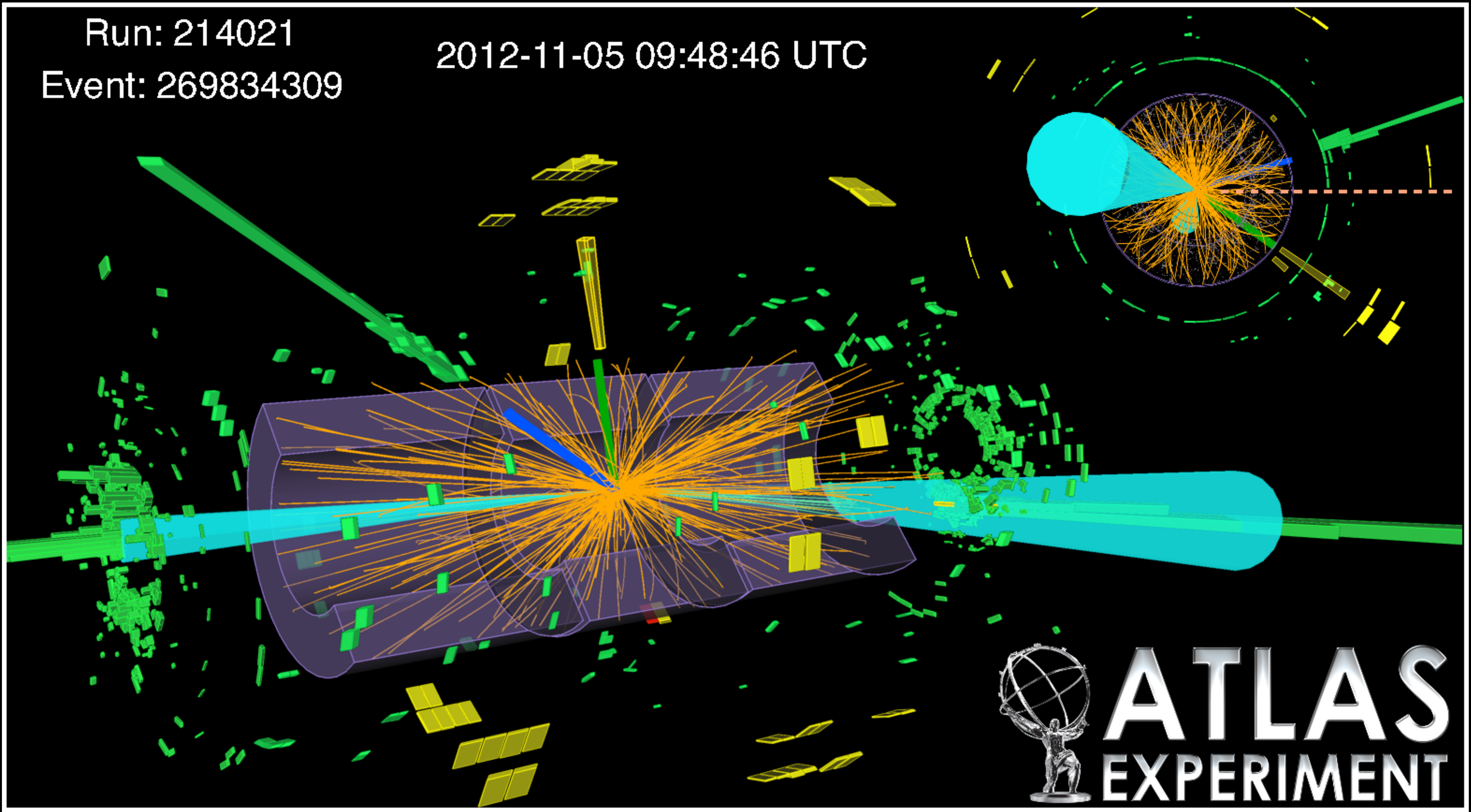


Clear evidence of
VBF production

PRD 92 (2015) 012006

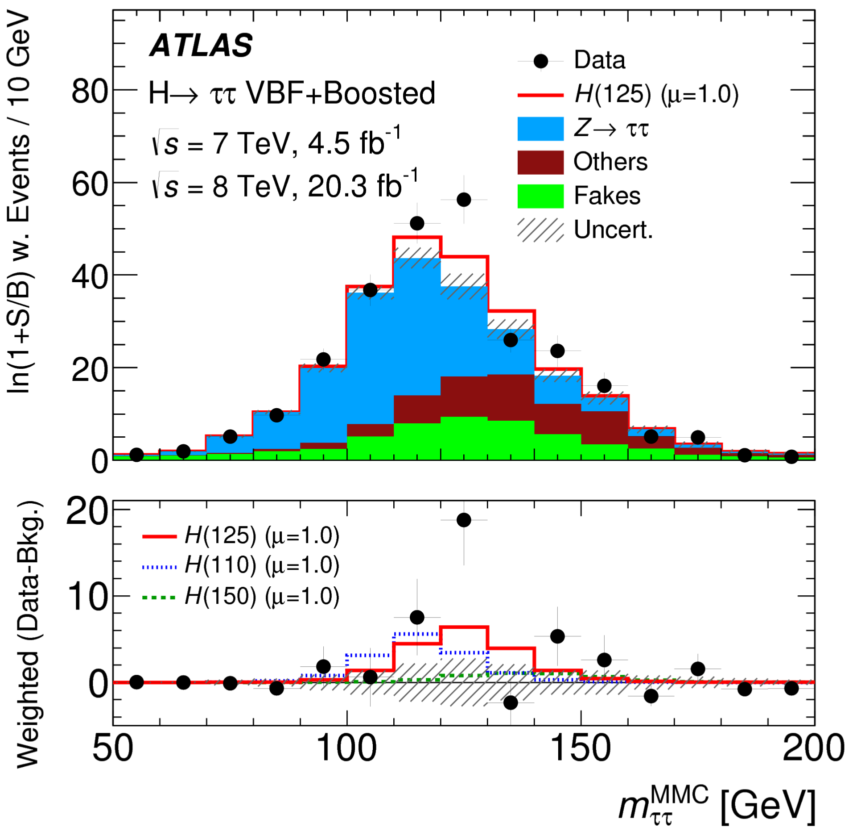
JHEP 01 (2014) 096

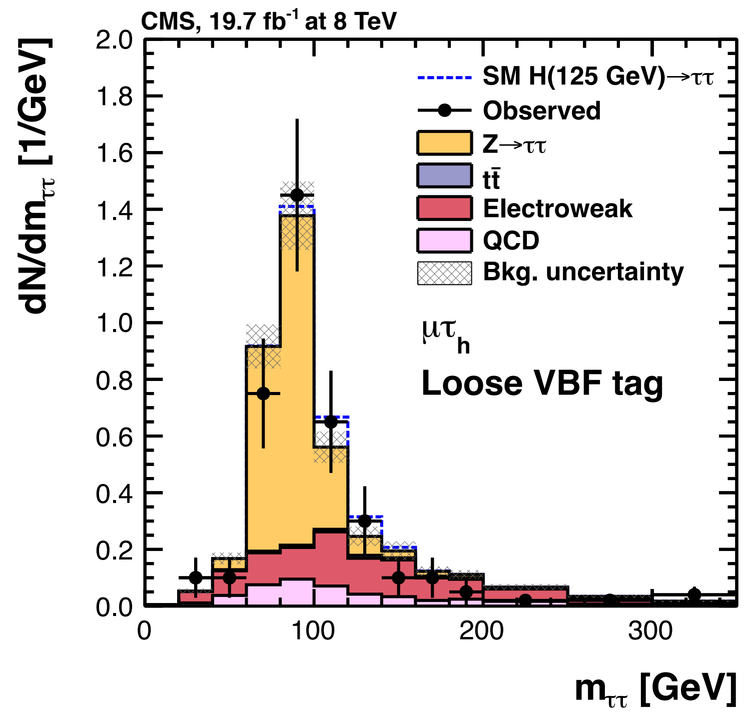
Decay to tau Leptons

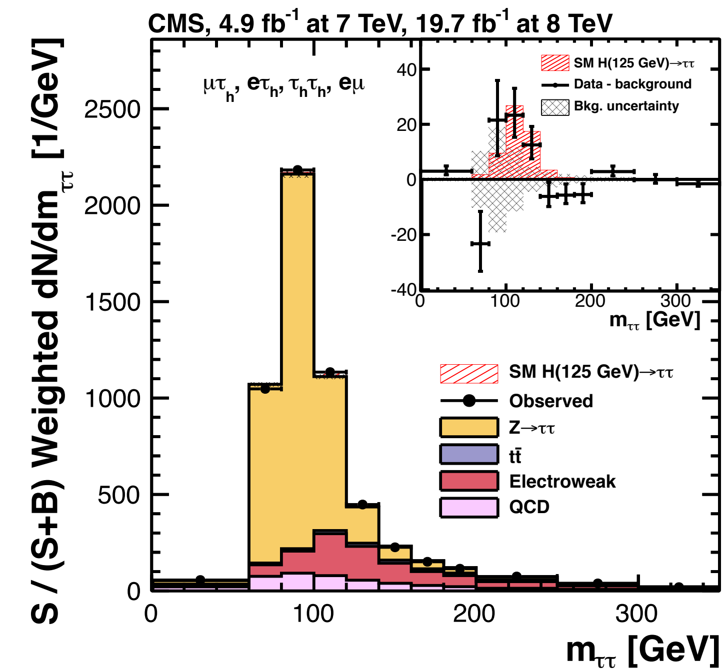


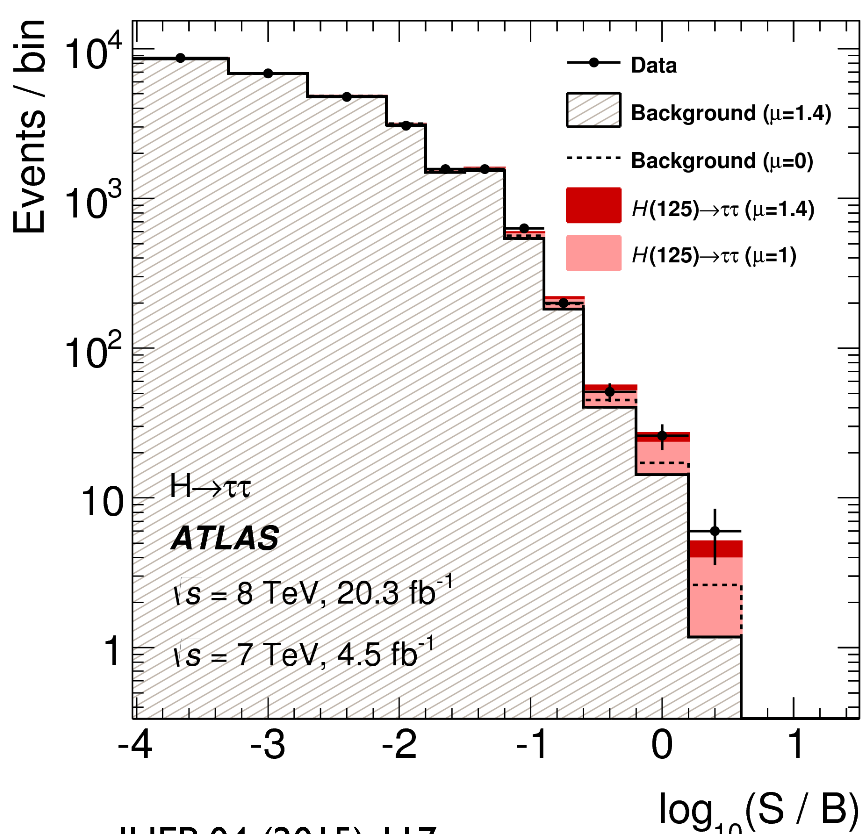
Event in the electron-jet VBF category with BDT=0.99 (S/B=1.0)

Decay to tau Leptons





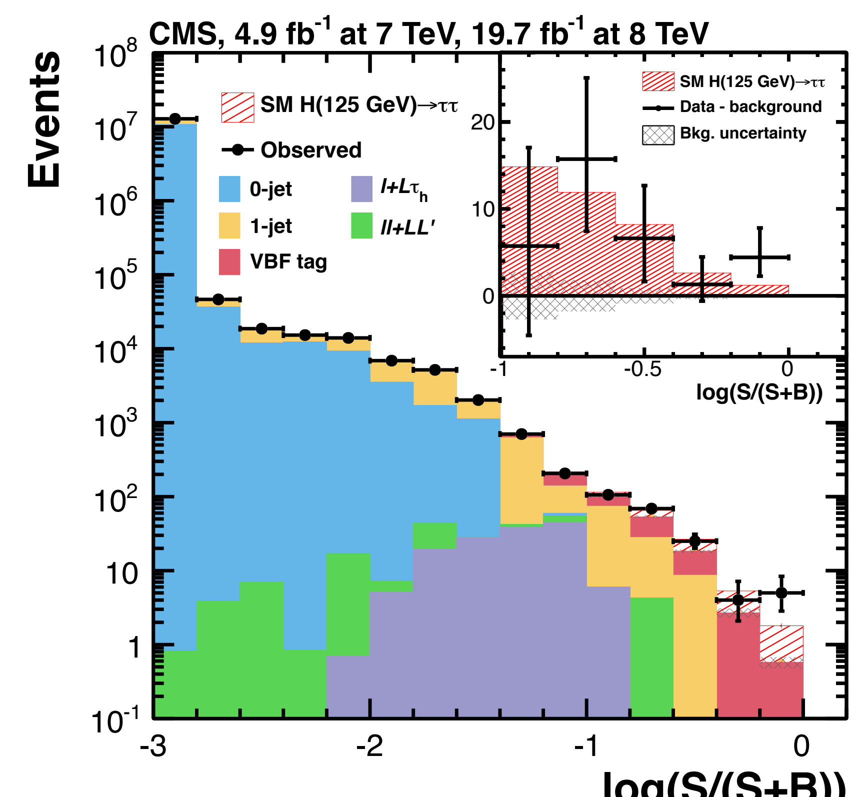




JHEP 04 (2015) 117

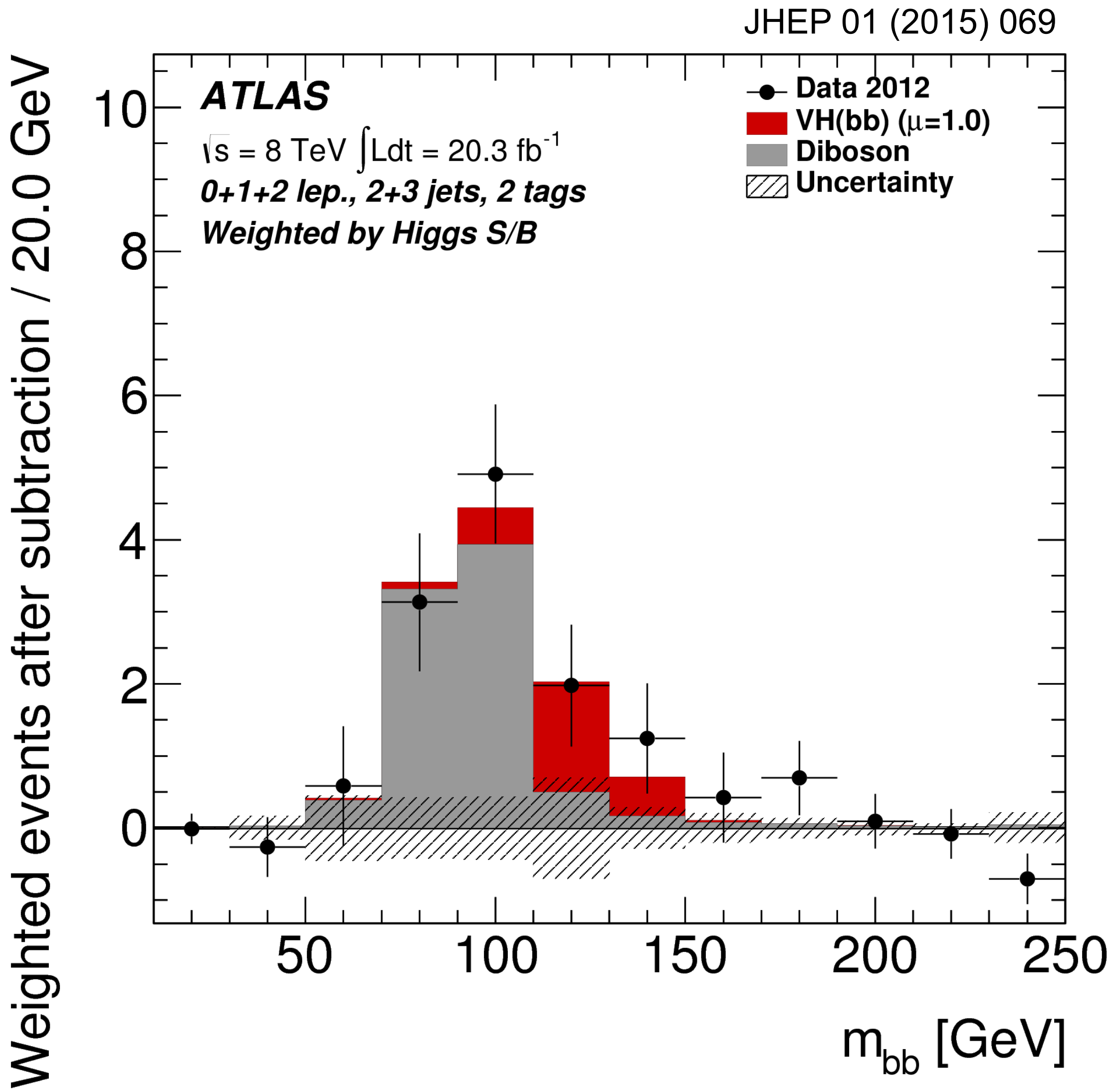
One of the most important results in 2014

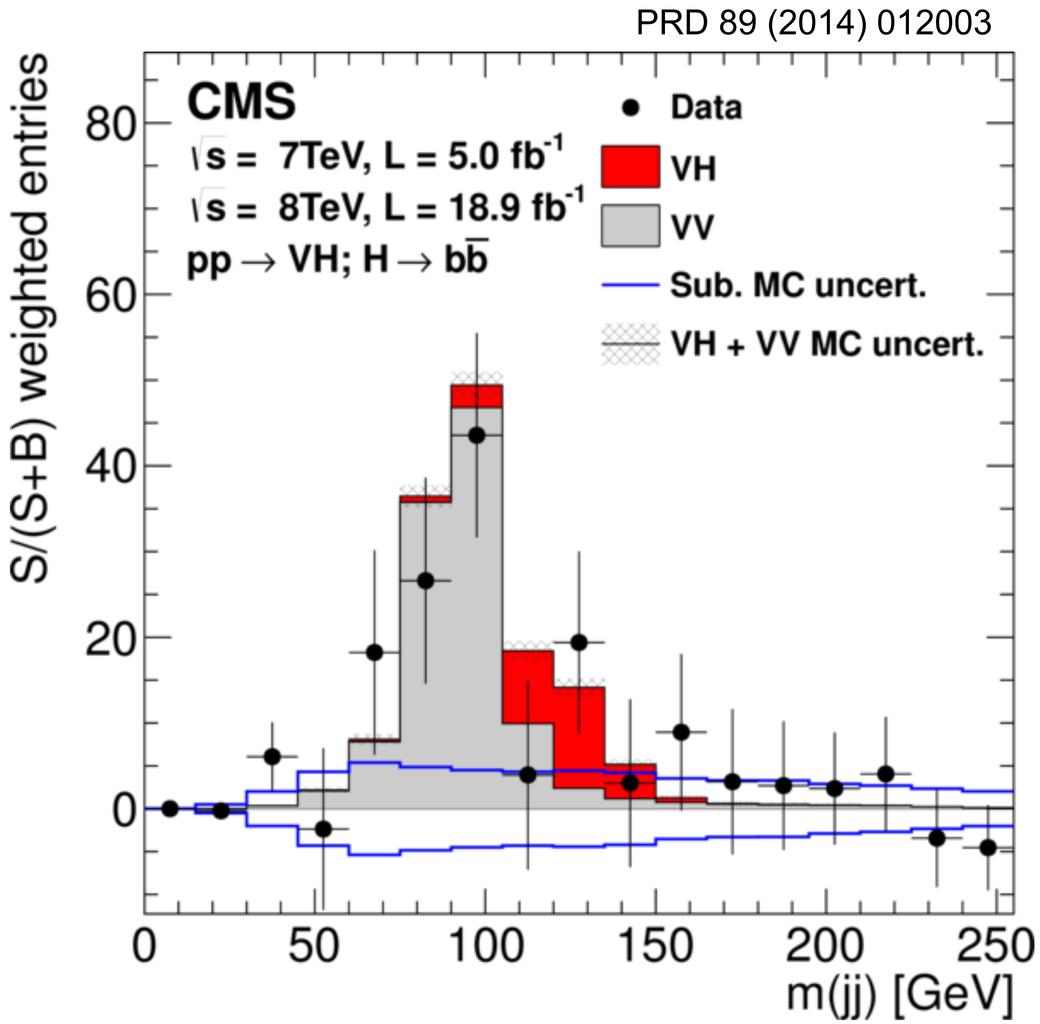
First evidence of Higgs coupling to fermions



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

Decay to b Quarks





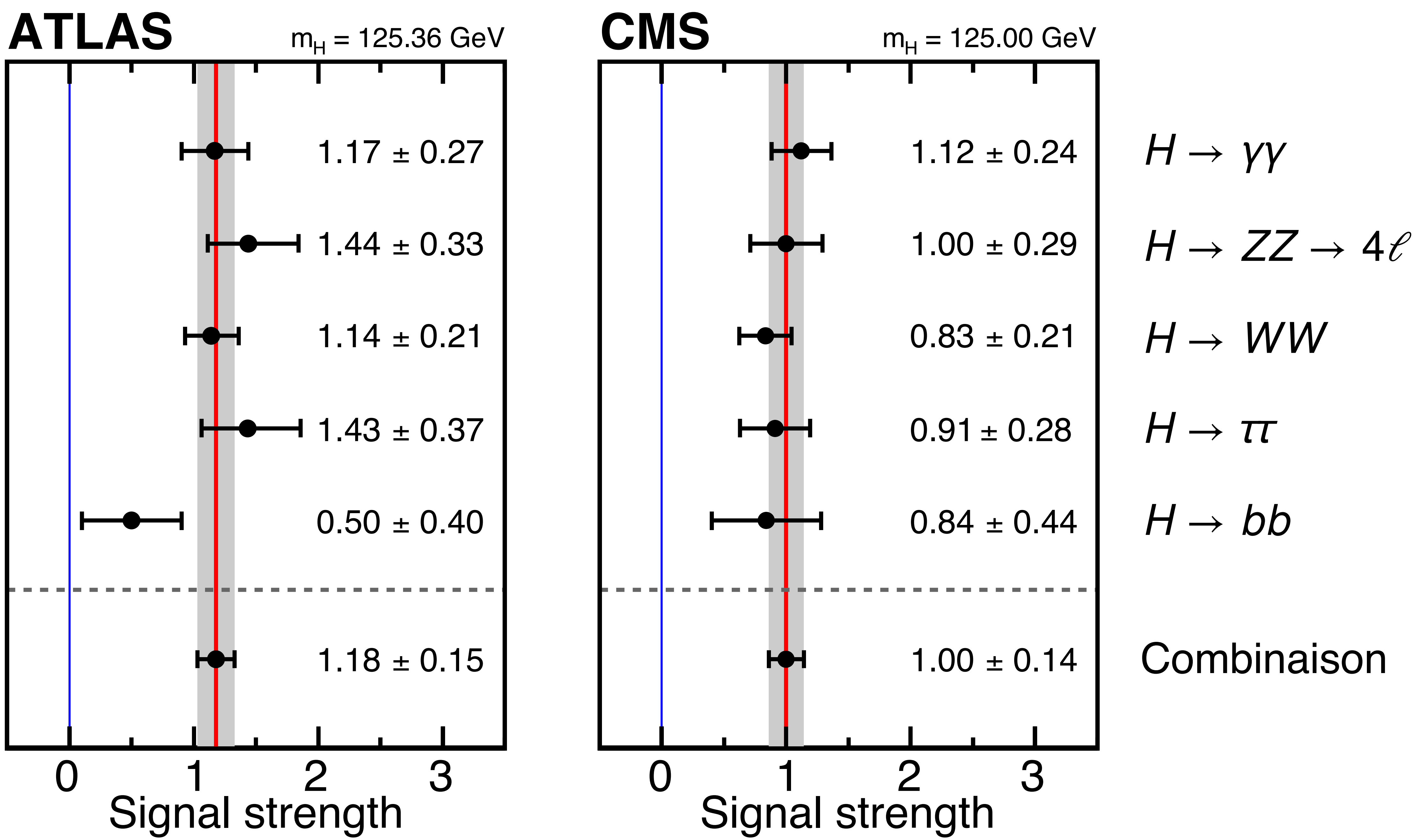
Reconstruction of bb signal after subtraction of major backgrounds

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

Signal Strengths

Legacy Run I

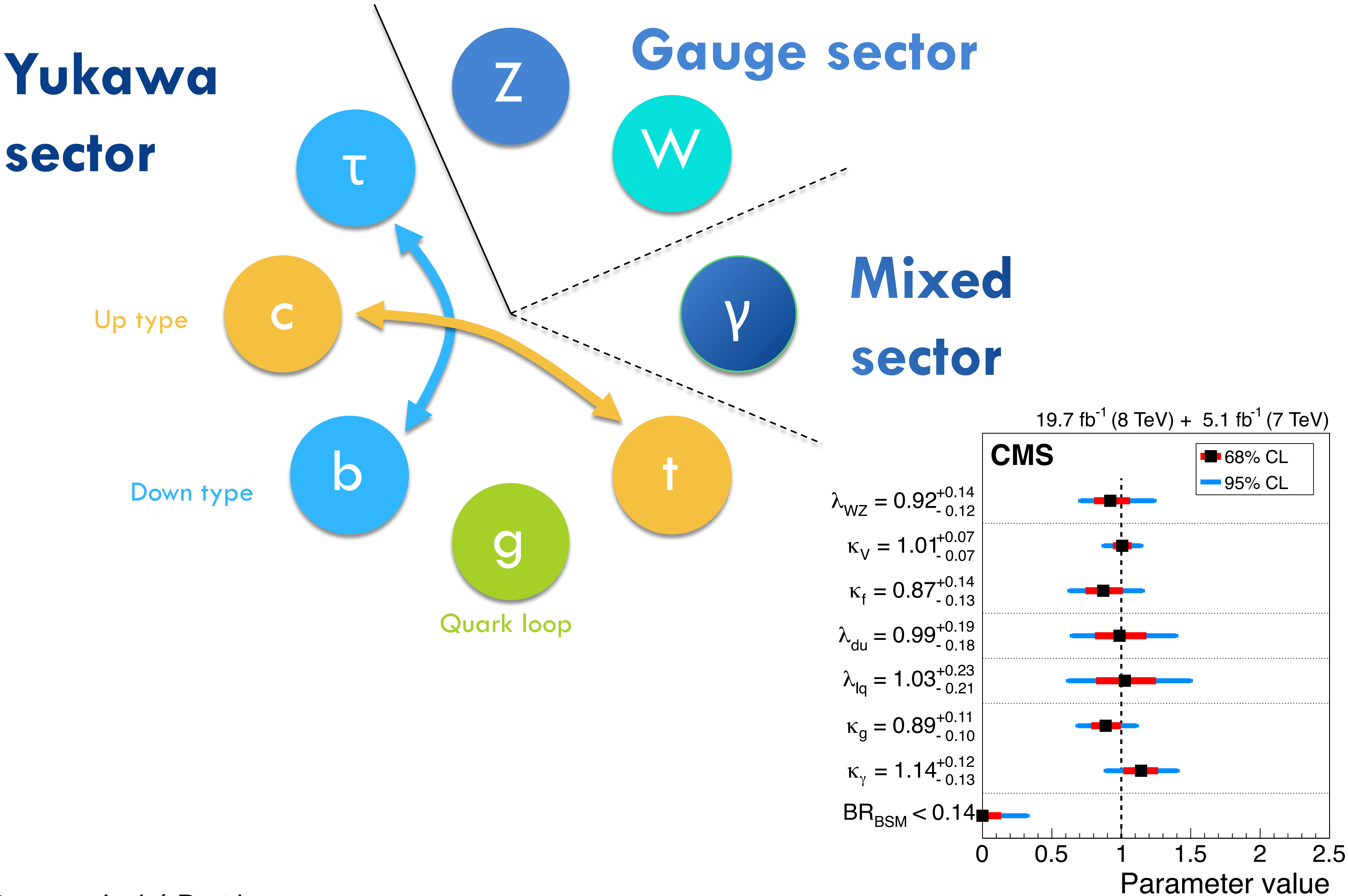
main five decay channels



> 5σ observation in di-boson channels

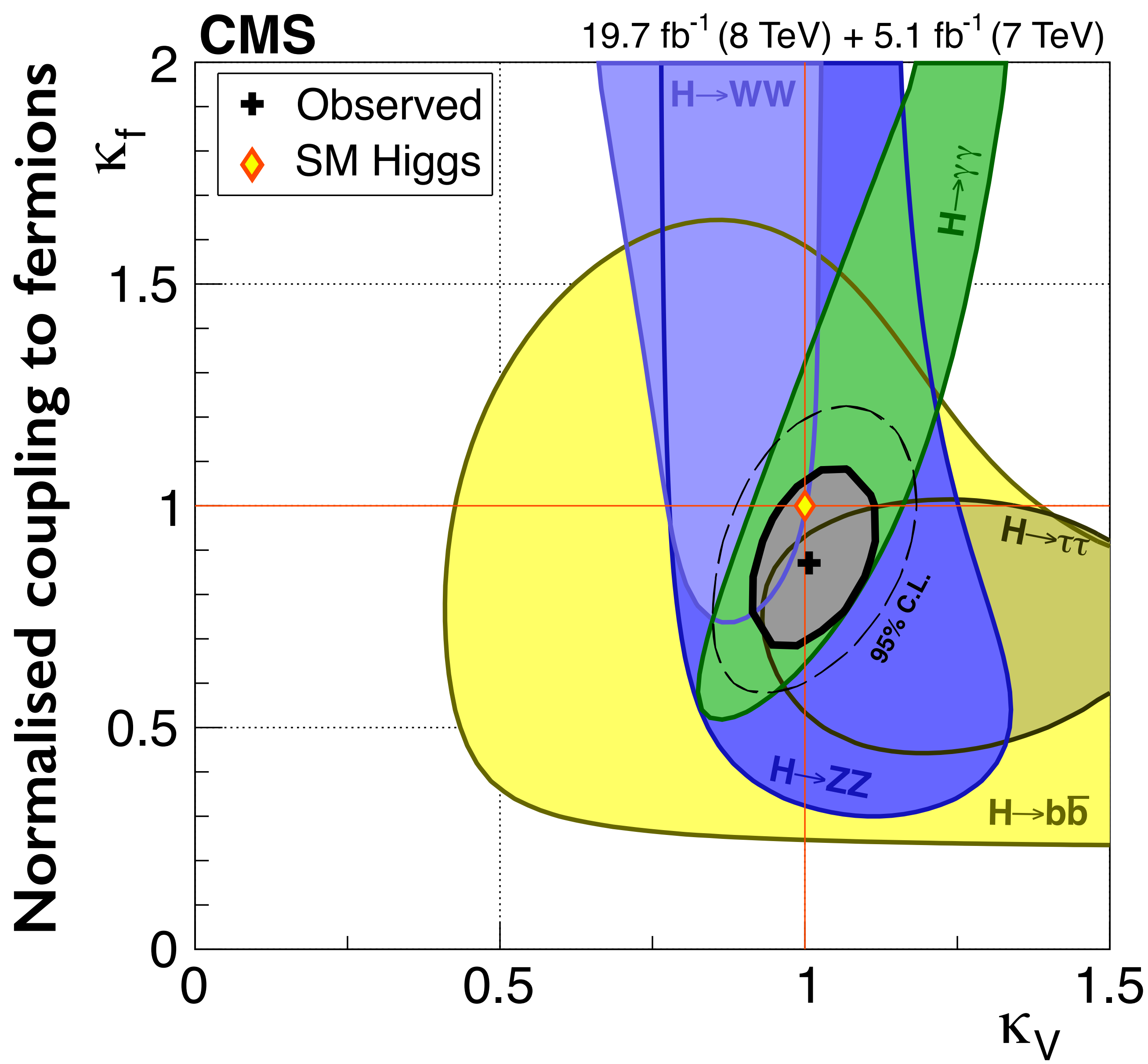
> 3σ evidence in di-tau channel

Couplings of the Higgs Boson



Courtesy André David

Couplings, Spin and Parity

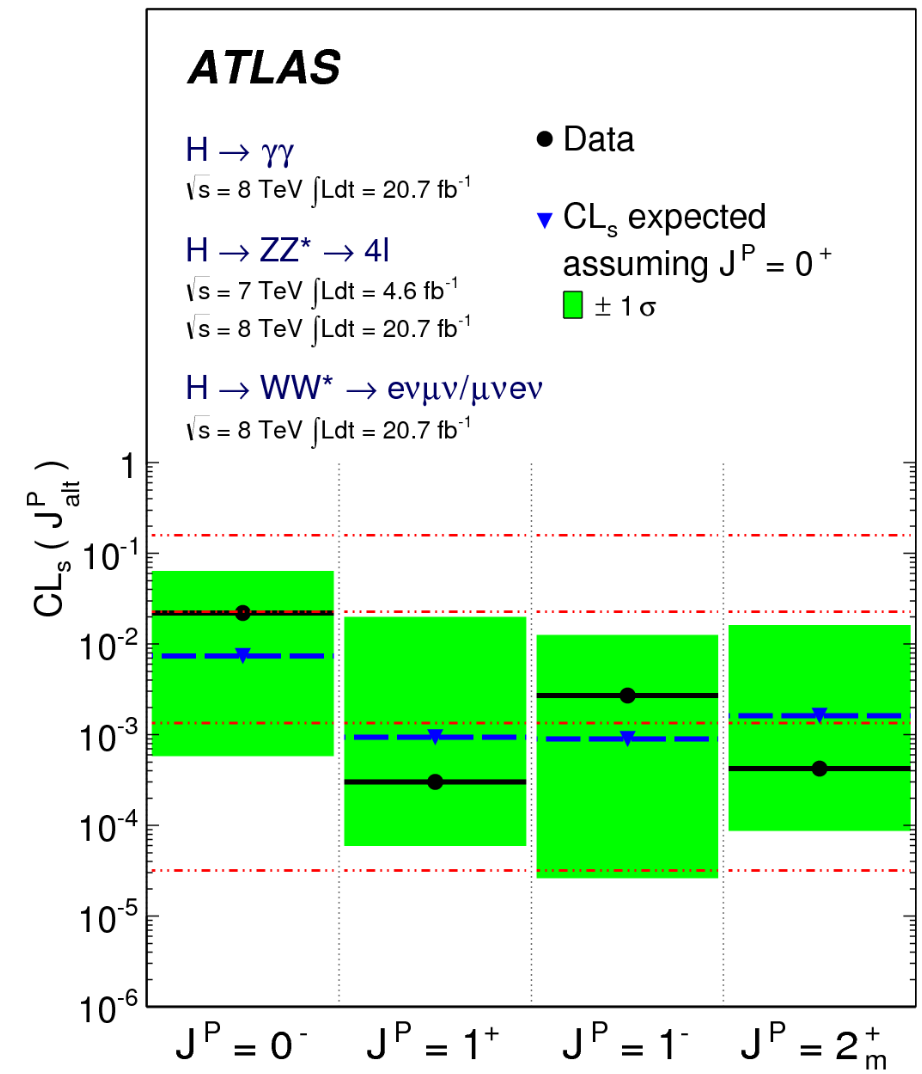


Normalised coupling to vector bosons

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

EPJC 75 (2015) 212

SM prediction 0+ tested against alternate spin hypotheses



0^- 1^+ 1^- 2^+

PLB 726 (2013) 120

Landau-Yang Theorem (1948)
A particle of spin 1 cannot decay into two photons

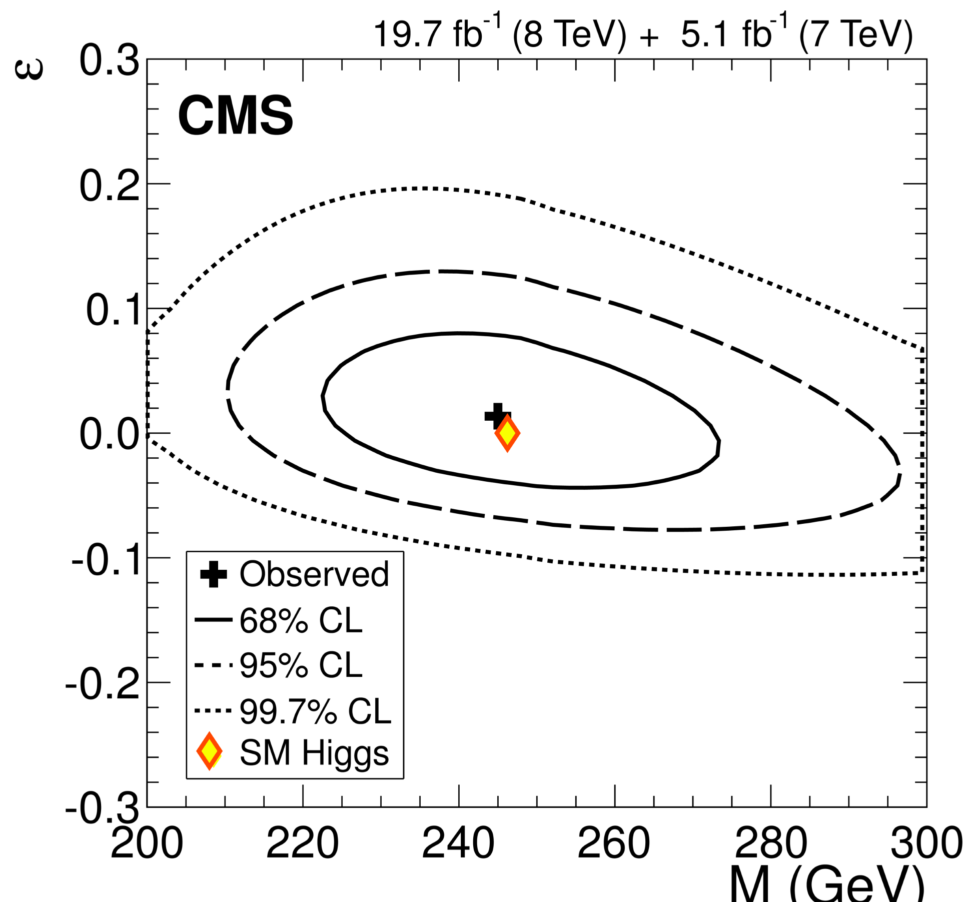
Couplings Versus Mass

Fit modifiers as a function of M and ε

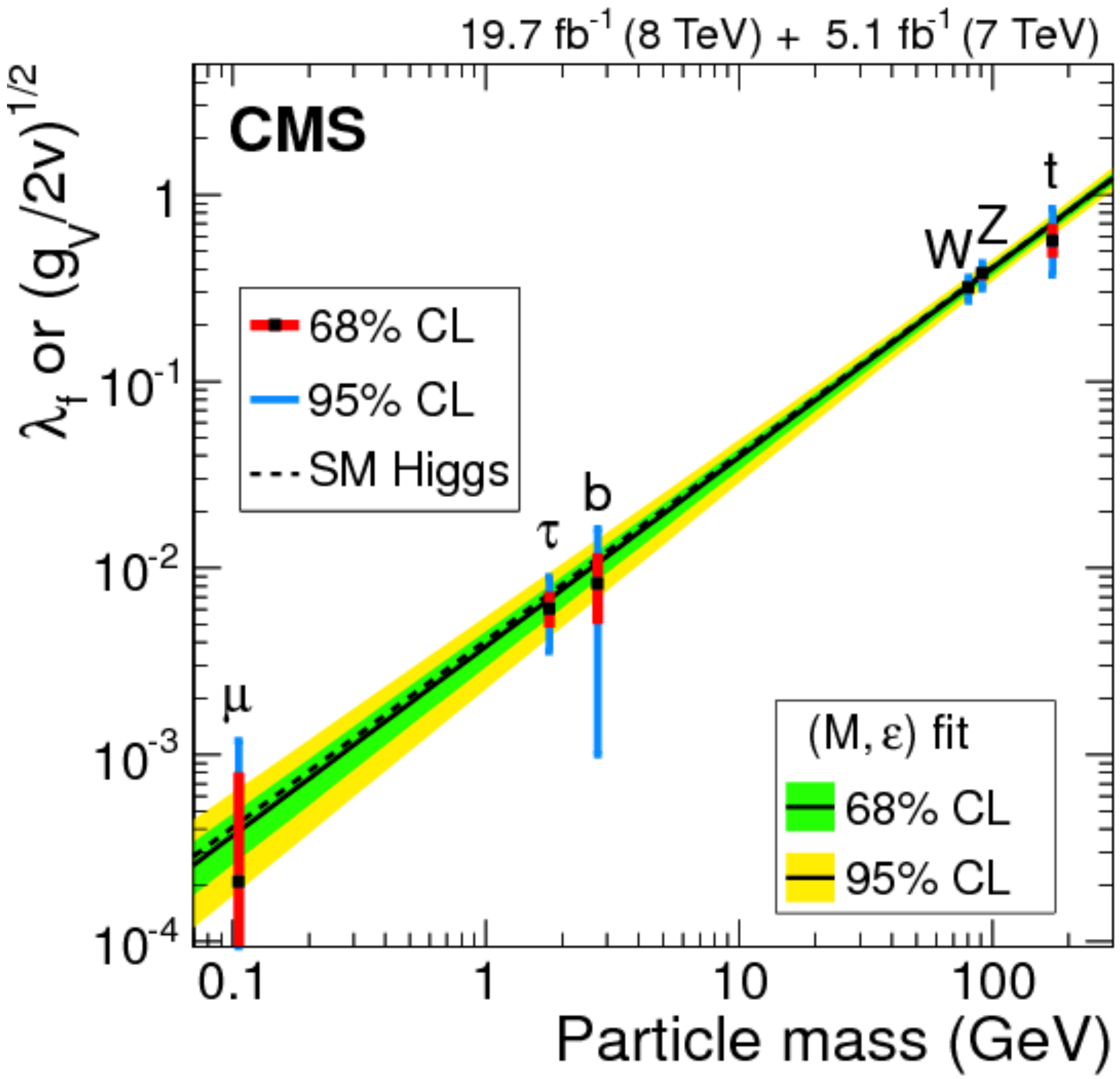
- fermions $\kappa_{\mathrm{f}} = v\, m_{\mathrm{f}}^{\epsilon} / M^{1+\epsilon}$
- bosons $\kappa_{\mathrm{V}} = v\, m_{\mathrm{V}}^{2\epsilon} / M^{1+2\epsilon}$

Standard Model: $(M, \epsilon) = (v, 0)$

no dependance with mass: $\epsilon = -1$



EPJC 75 (2015) 212



Over three order of magnitude in mass

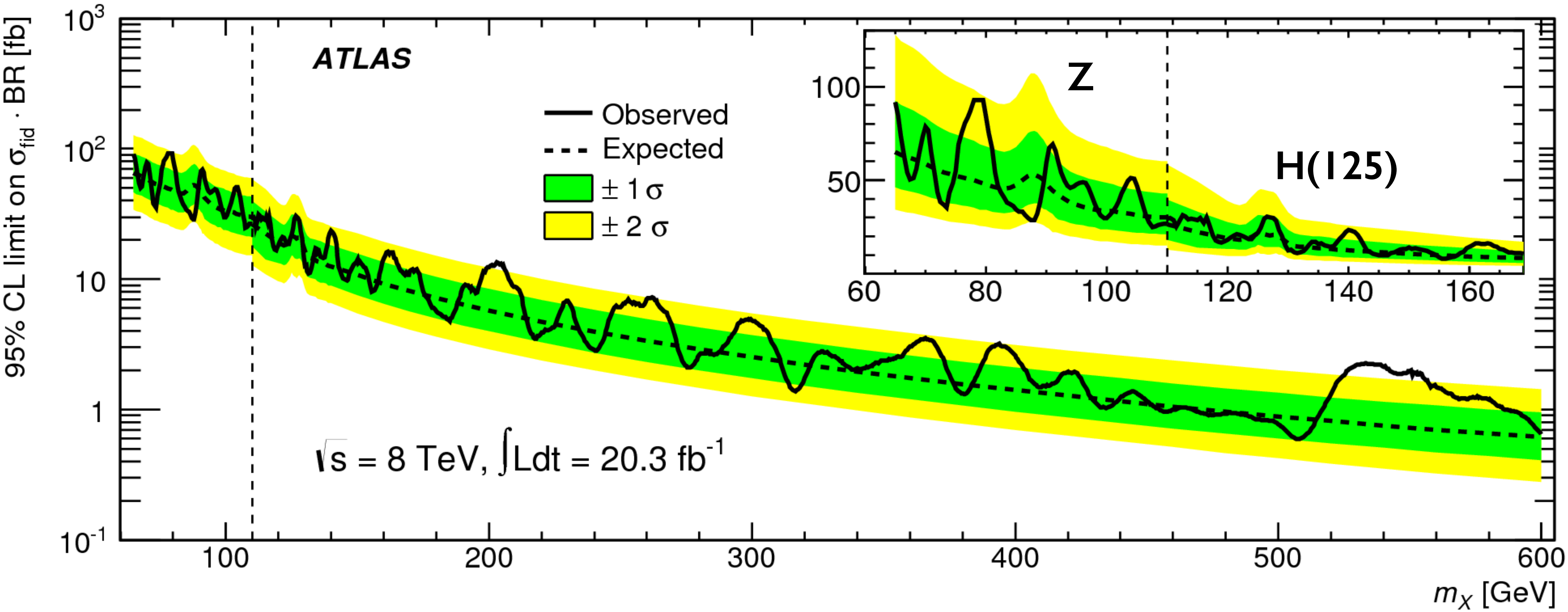
- the boson couples differently to particles
- the couplings depend on mass

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…

Search for FCNC

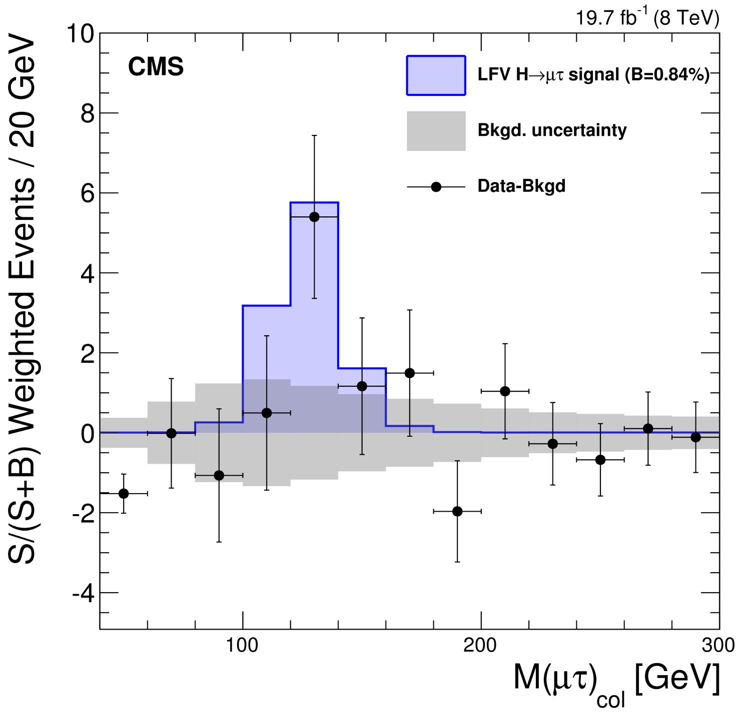
arXiv:1502.07400

direct search for lepton-flavour-violating decays

$H \to \tau\mu$

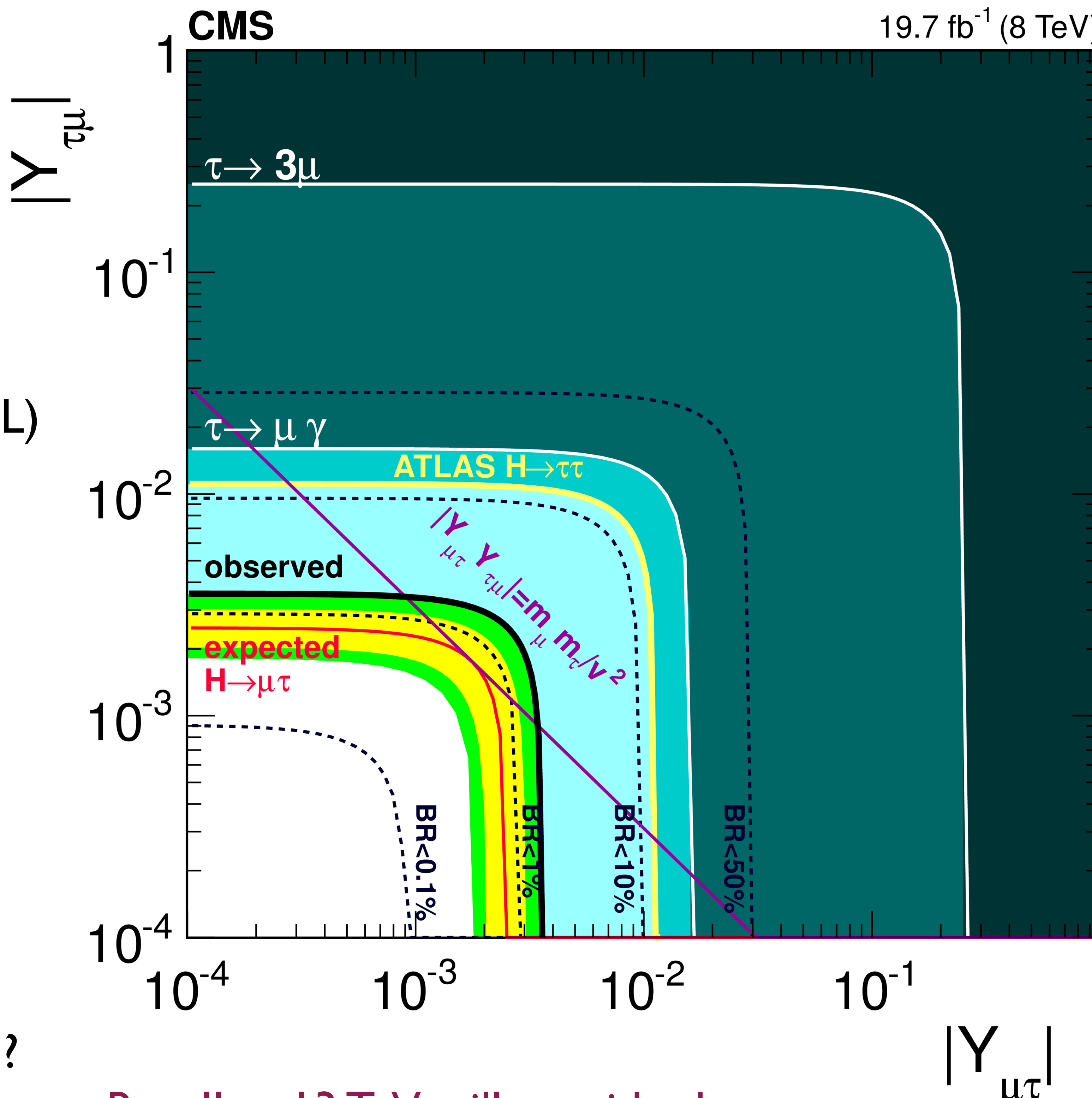
obtain best limit

BR($H \to \tau\mu$) < 1.5% (95%CL)



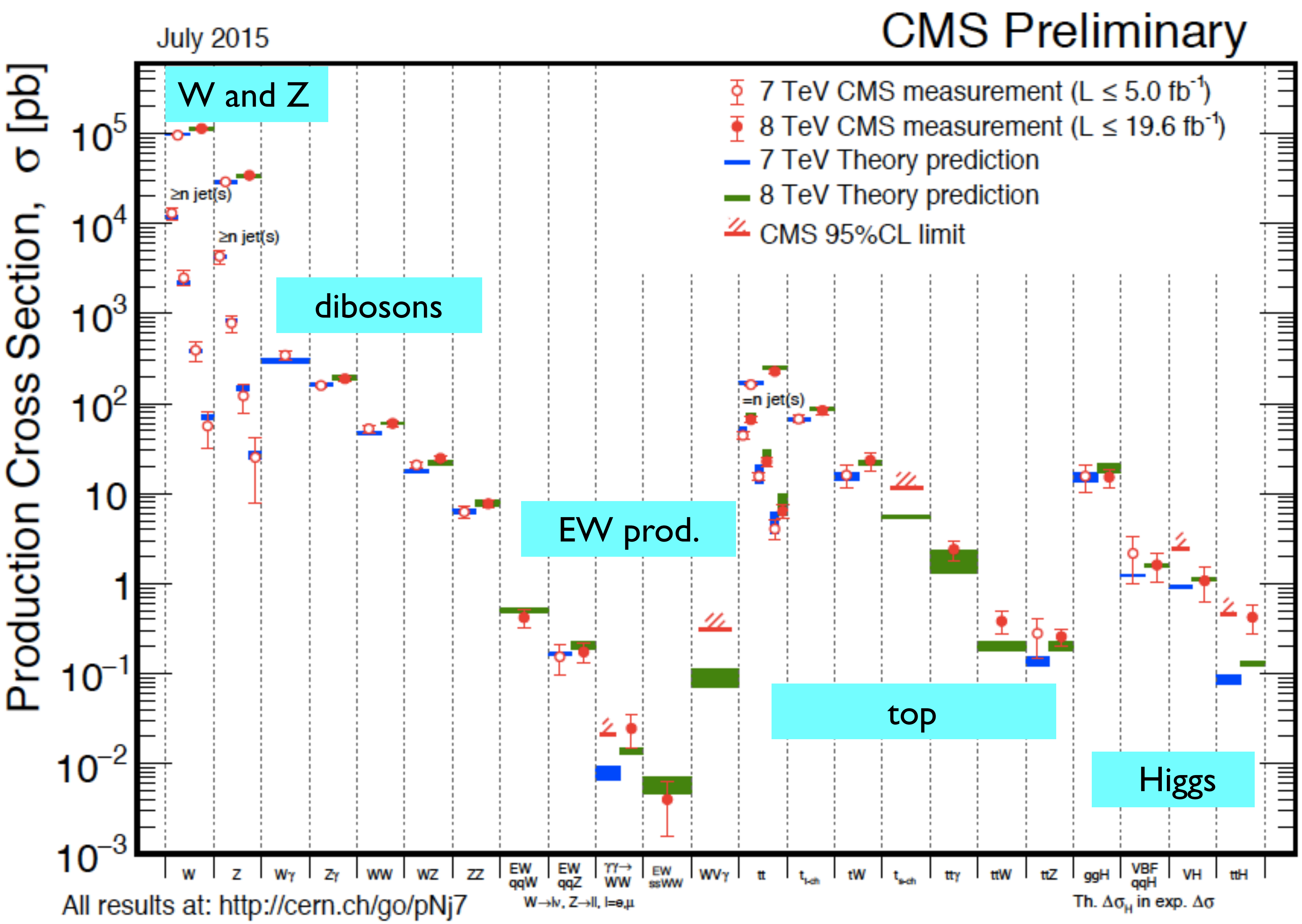
Small excess (2.4σ) = signal?

Too soon to tell!



Run-II at 13 TeV will provide the answer

This Resumes our Journey



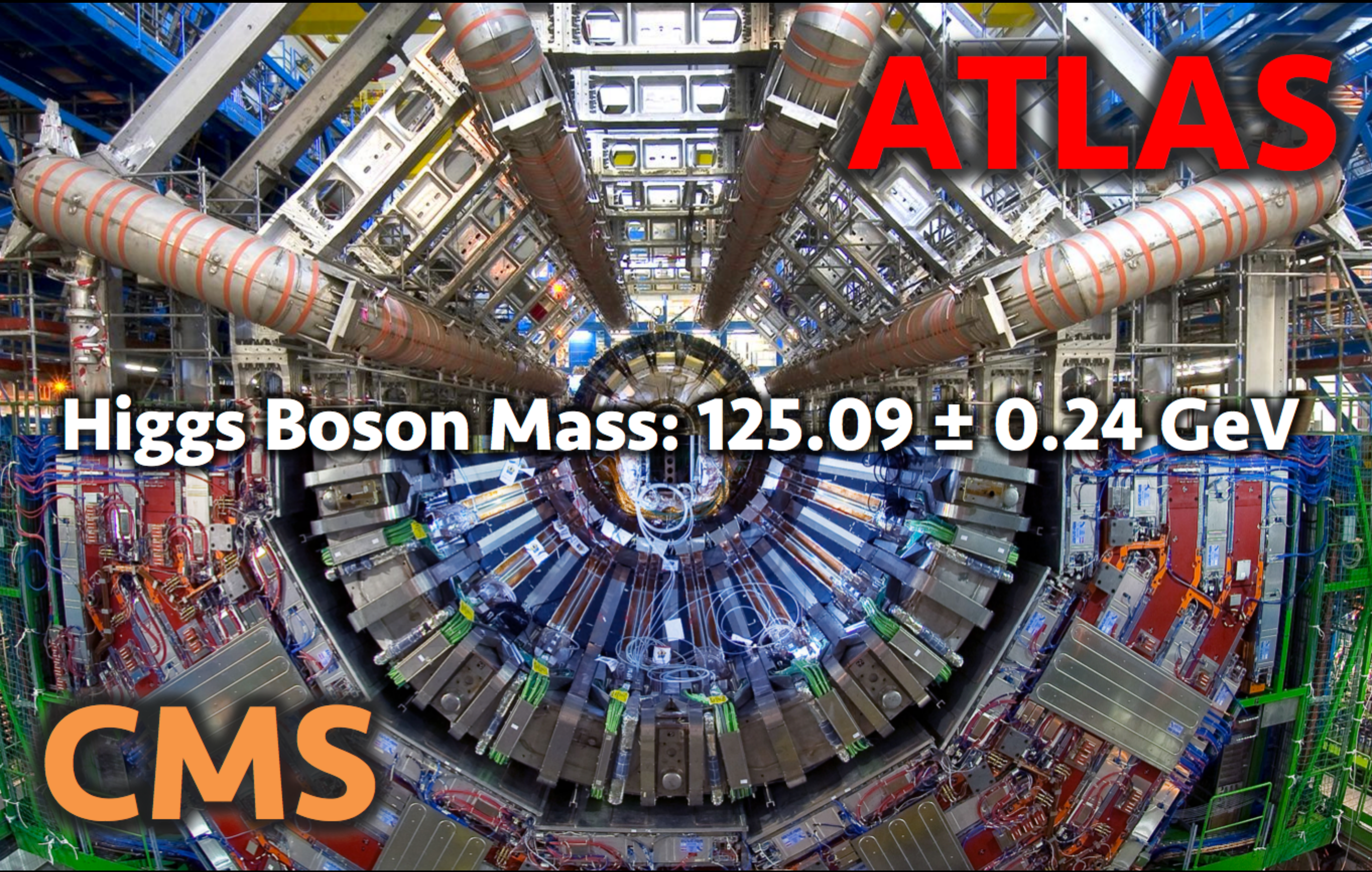
nb

pb

fb

Next stop

New Physics!


ATLAS
Higgs Boson Mass: 125.09 ± 0.24 GeV
CMS

Le Temps des Cathédrales