INTRODUCTION TO EXPERIMENTAL PARTICLE PHYSICS: 3

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INTRODUCTION TO HIGGS PHYSICS

Celebrations on 4 July 2012

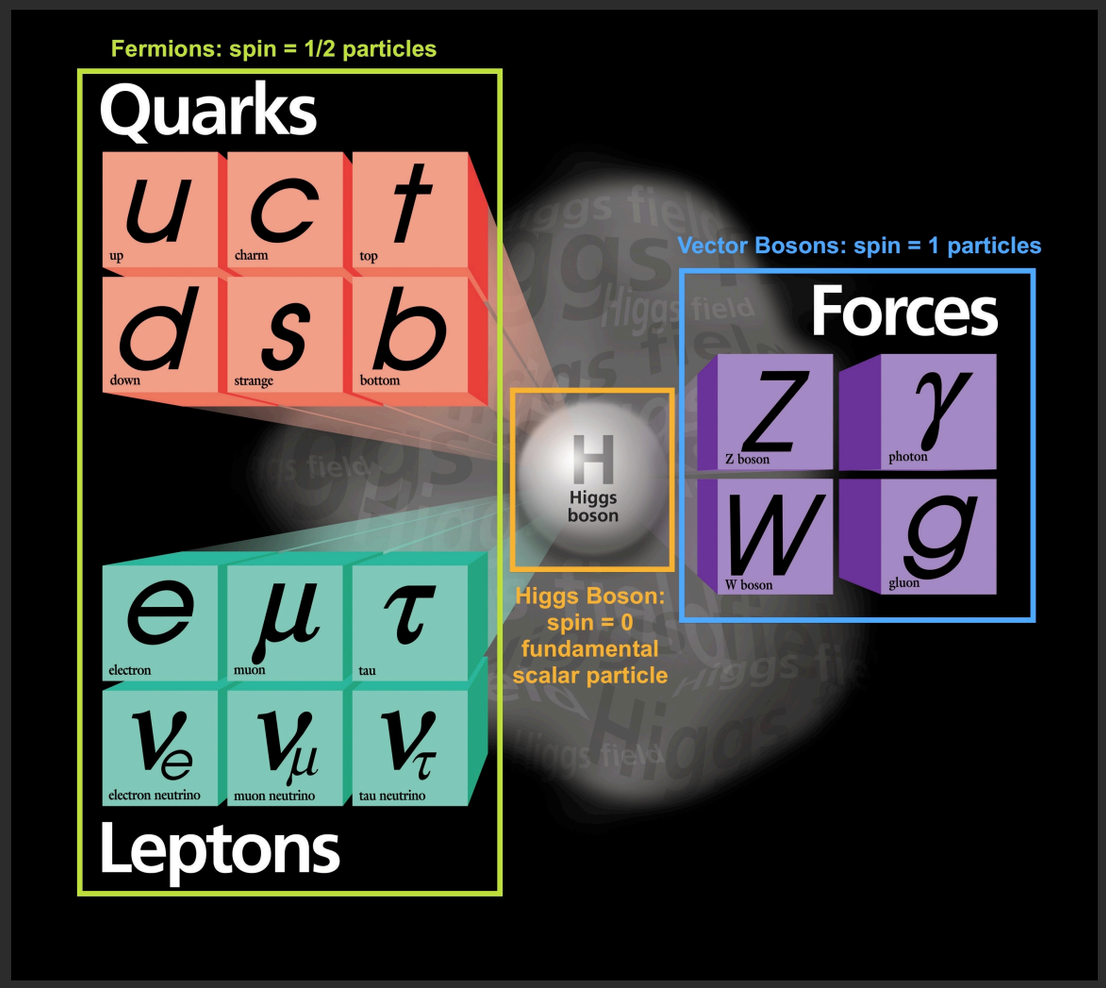
CERN , ICHEP Melbourne and all over the world!

Both CMS and ATLAS reporting 5 sigma evidence for a new particle with mass ~ 125 GeV

HIGGS MECHANISM

Symmetry in description of Electromagnetic and Weak forces allows unification: -> electroweak interaction

In the Standard Model with no Higgs mechanism, interactions are symmetric and particles do not have mass



Symmetry is *broken* however:

- Photon massless
- *W, Z* very massive -> **How?**

Higgs Mechanism:

- Higgs field breaks EWK symmetry
- Explains masses of *W, Z* and photon, and other particle's masses
- Additional consequence: new particle predicted to exist – Higgs boson!

HIGGS BOSON AND THE ORIGIN OF MASS

The Higgs boson is the ‘quantum excitation’ of the Higgs field

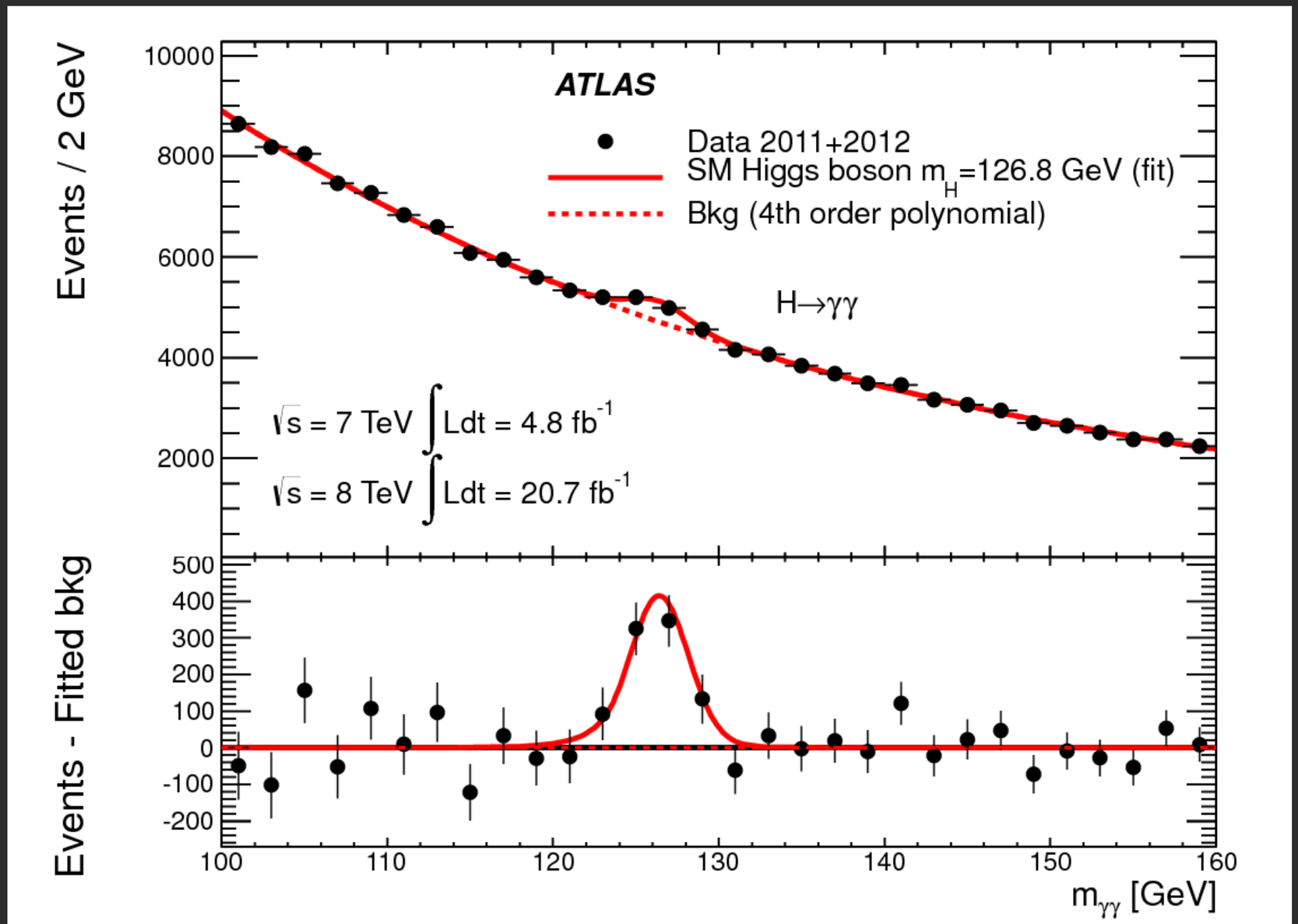
Just as the photon is the quantum excitation of the electromagnetic field

The theory predicts that the Higgs is a boson with zero spin, zero electric charge, zero colour charge

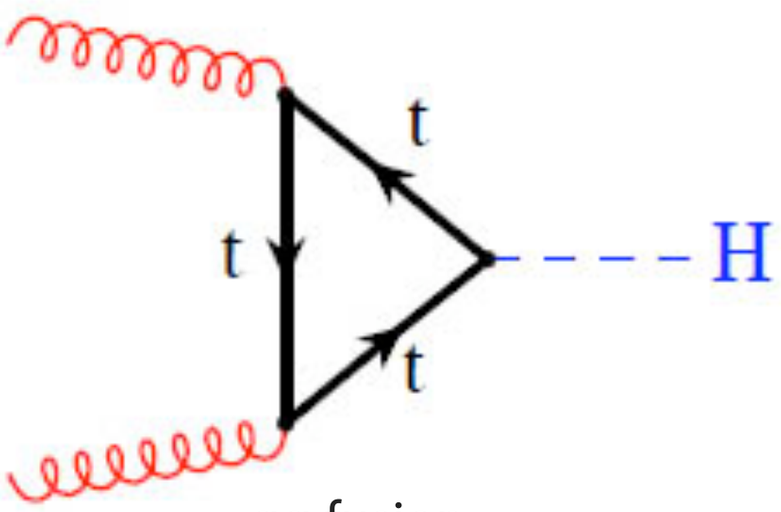
Zero spin -> a scalar particle. The first known scalar elementary particle in nature!

If we found the Higgs we would verify the Higgs field is how elementary particles acquire mass.

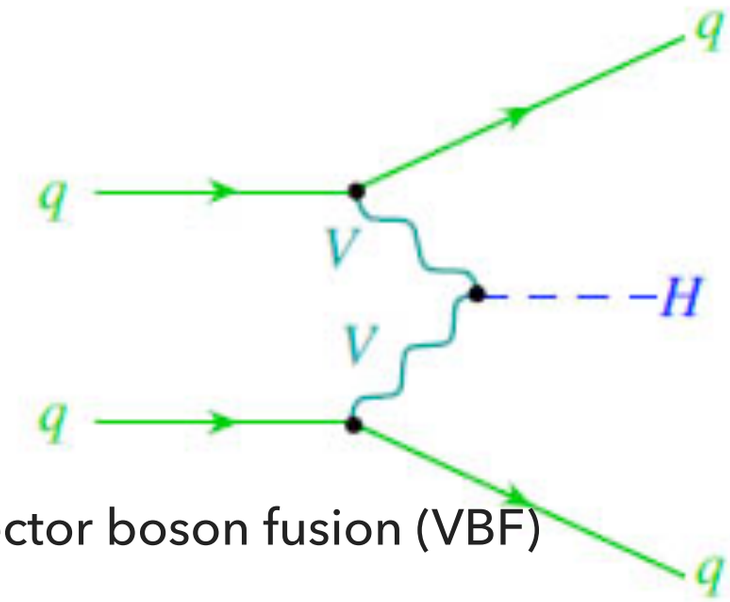
HIGGS BOSON AND THE ORIGIN OF MASS



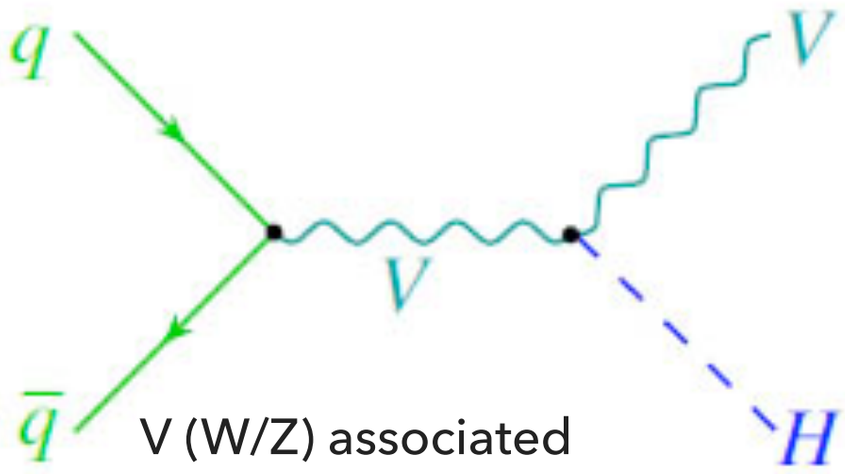
HIGGS PRODUCTION



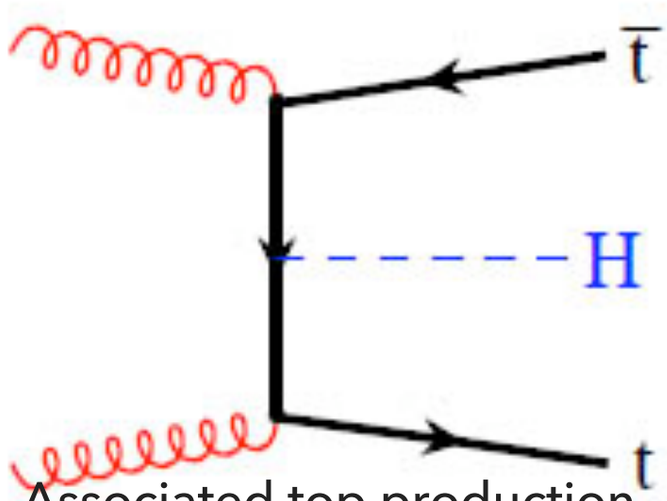
gg fusion



Vector boson fusion (VBF)



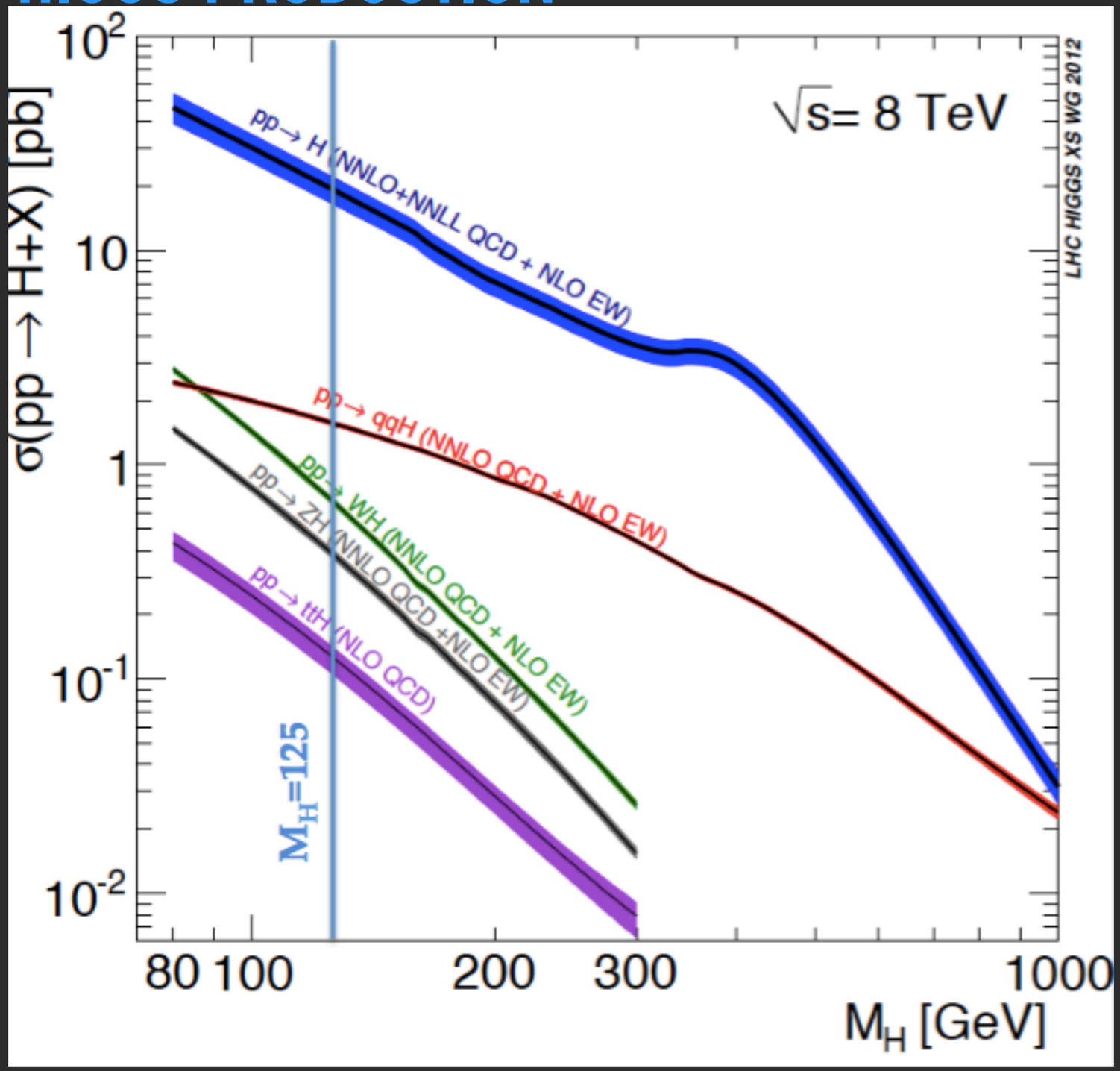
V (W/Z) associated production

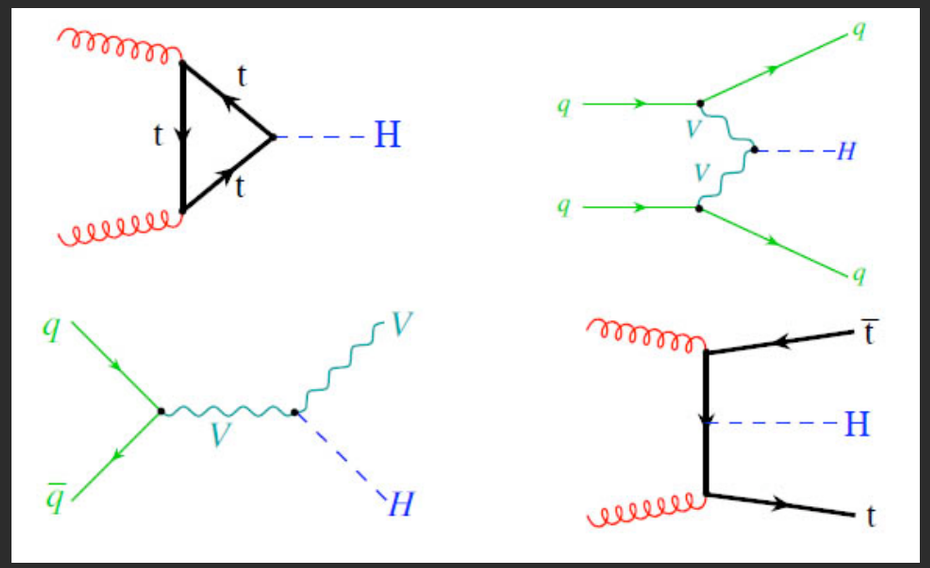


Associated top production

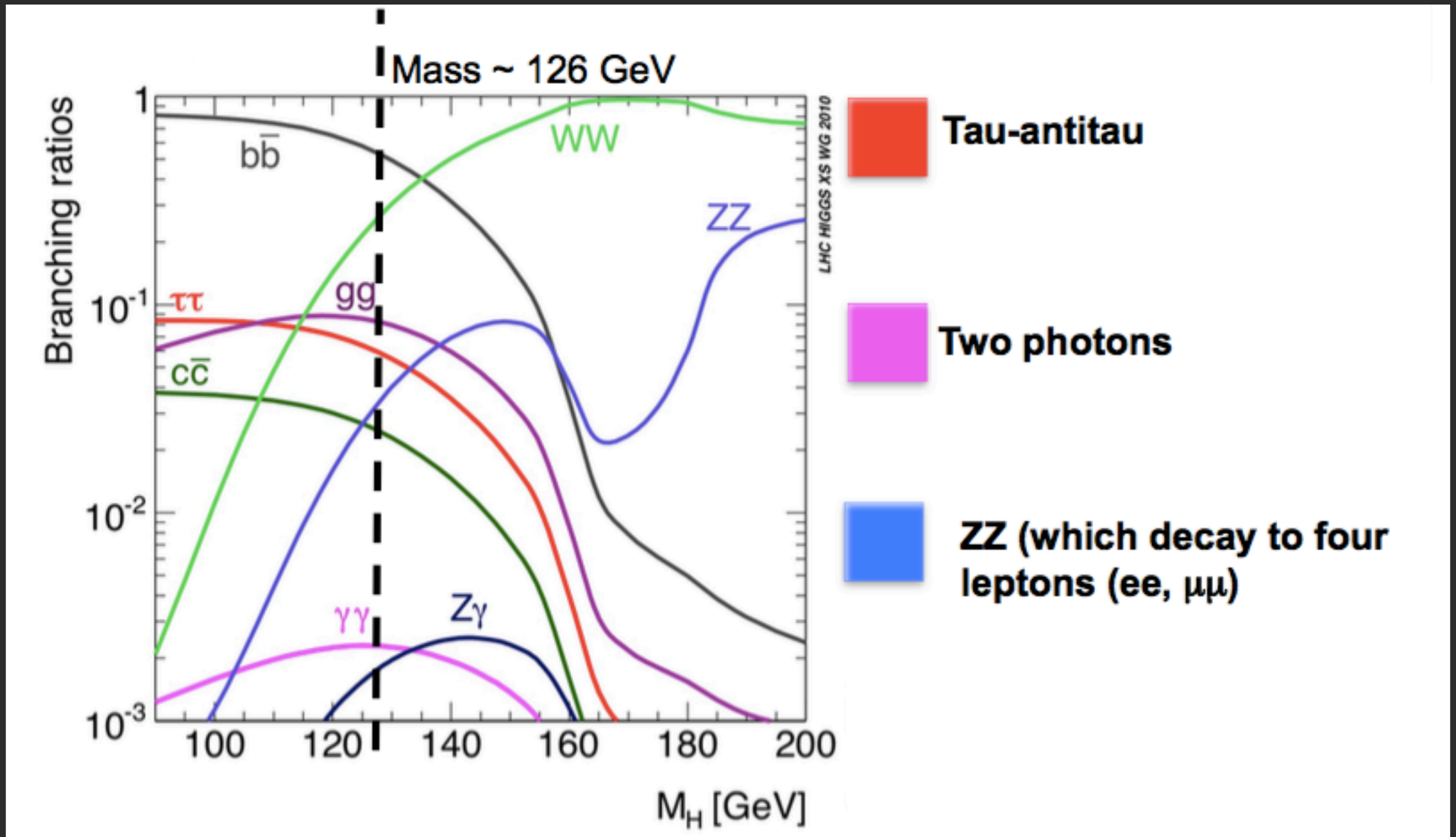
ttH is the most favorable production mode for a direct measurement of the top-quark's Yukawa coupling

HIGGS PRODUCTION



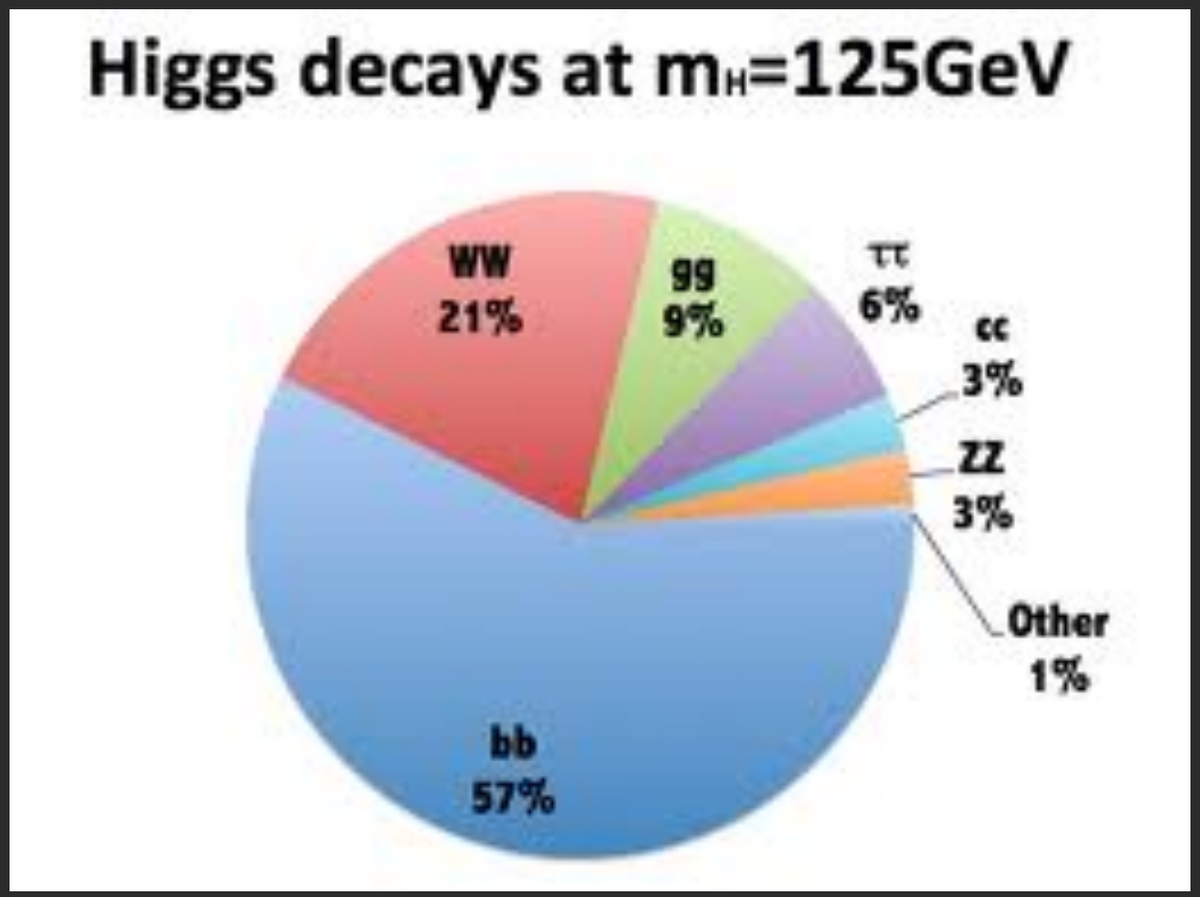


HIGGS DECAY



Rarer decay modes suffer from statistics but generally have lower levels of background processes obscuring the signal AND have a higher resolution on the mass of the Higgs before decay.

HIGGS DECAY



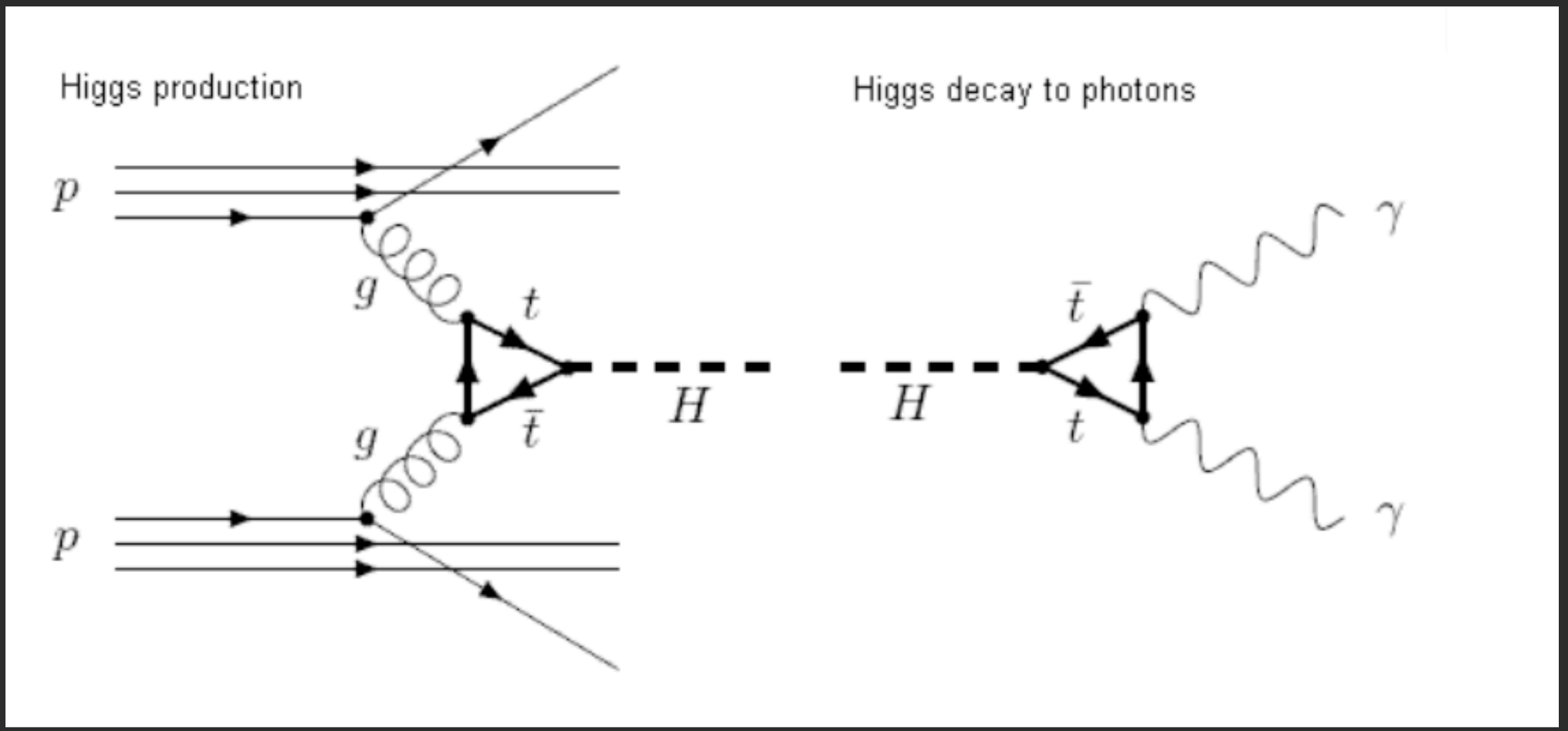
Dominant decay mode:

b-quark pair, large multijet background

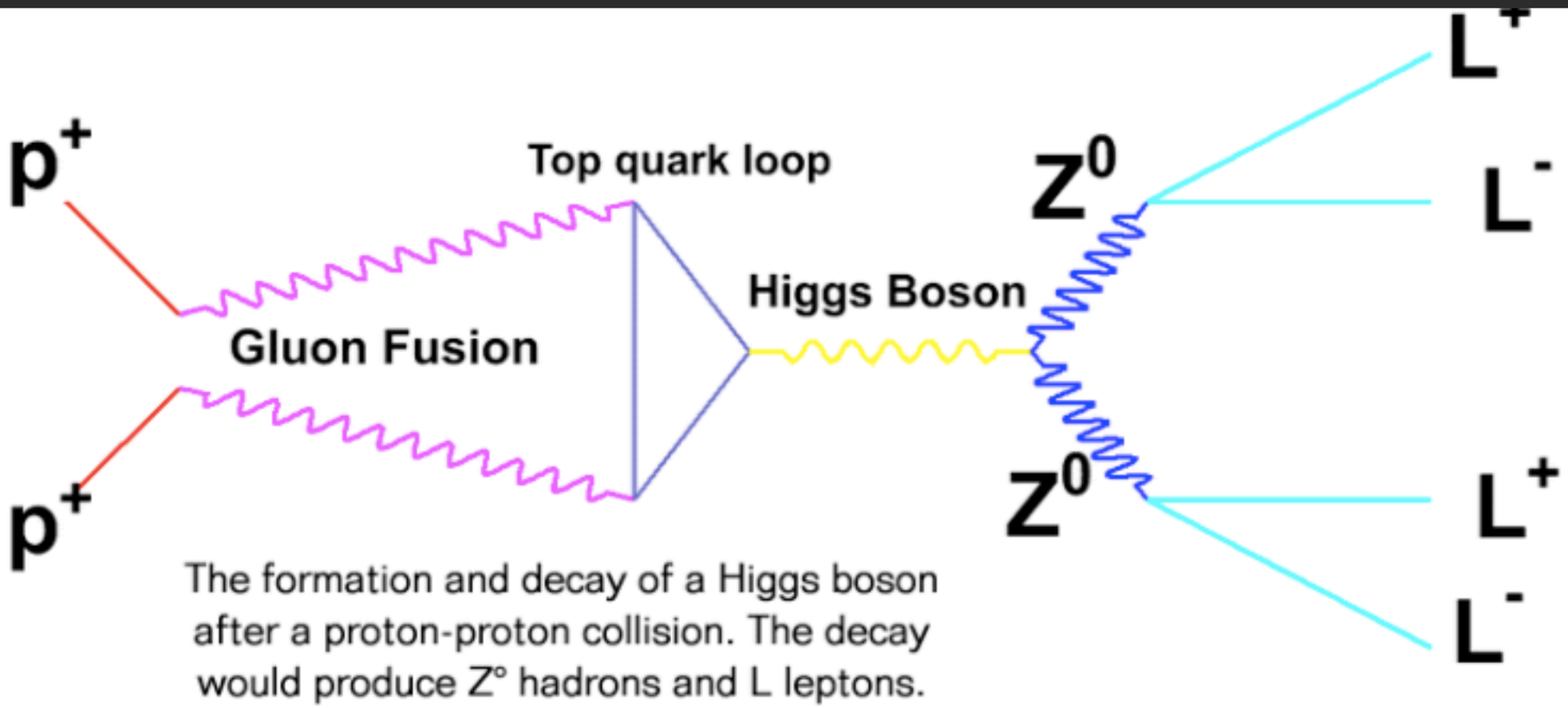
Golden channel:

ZZ -> 4 leptons (e, μ)

HIGGS PRODUCTION AND DECAY

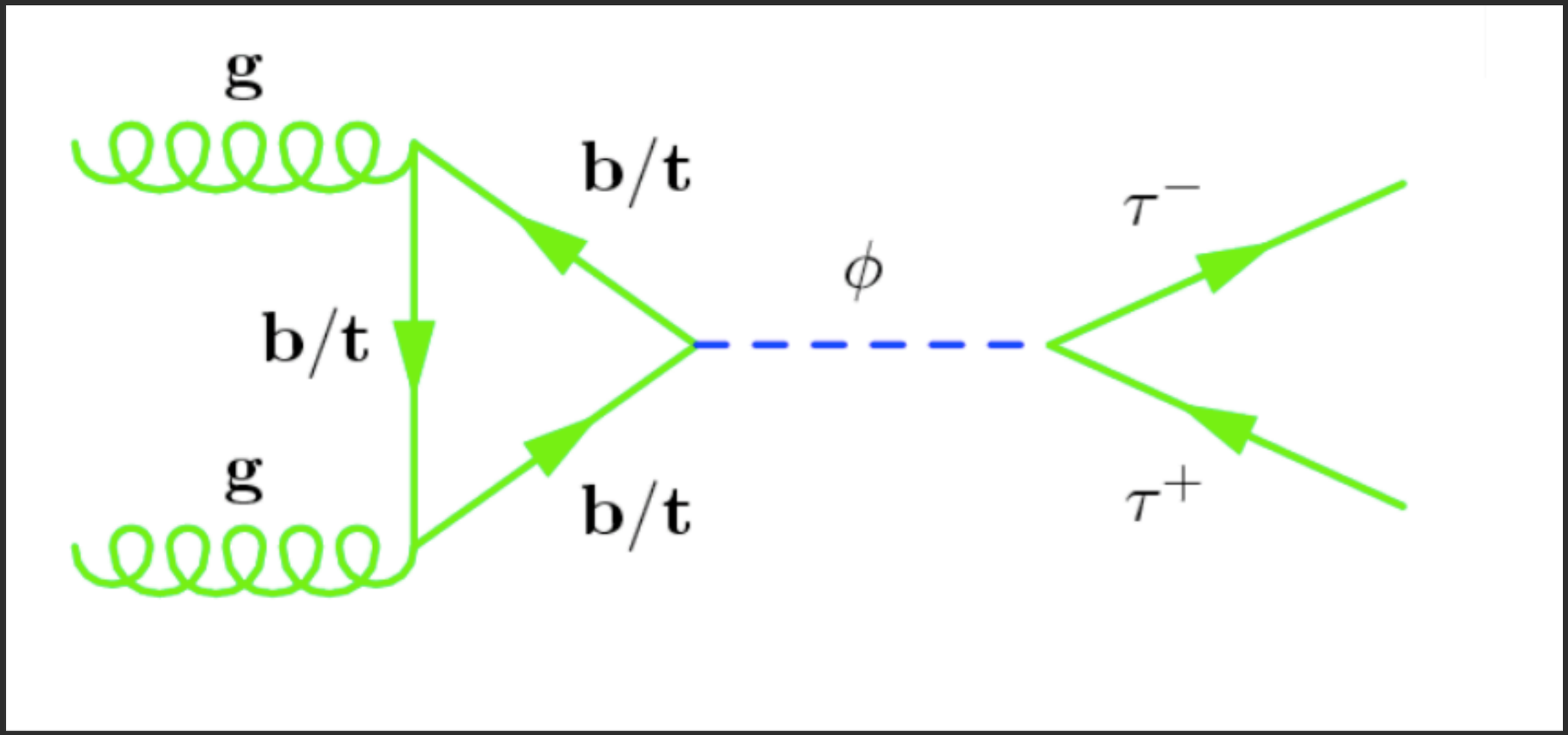


HIGGS PRODUCTION AND DECAY

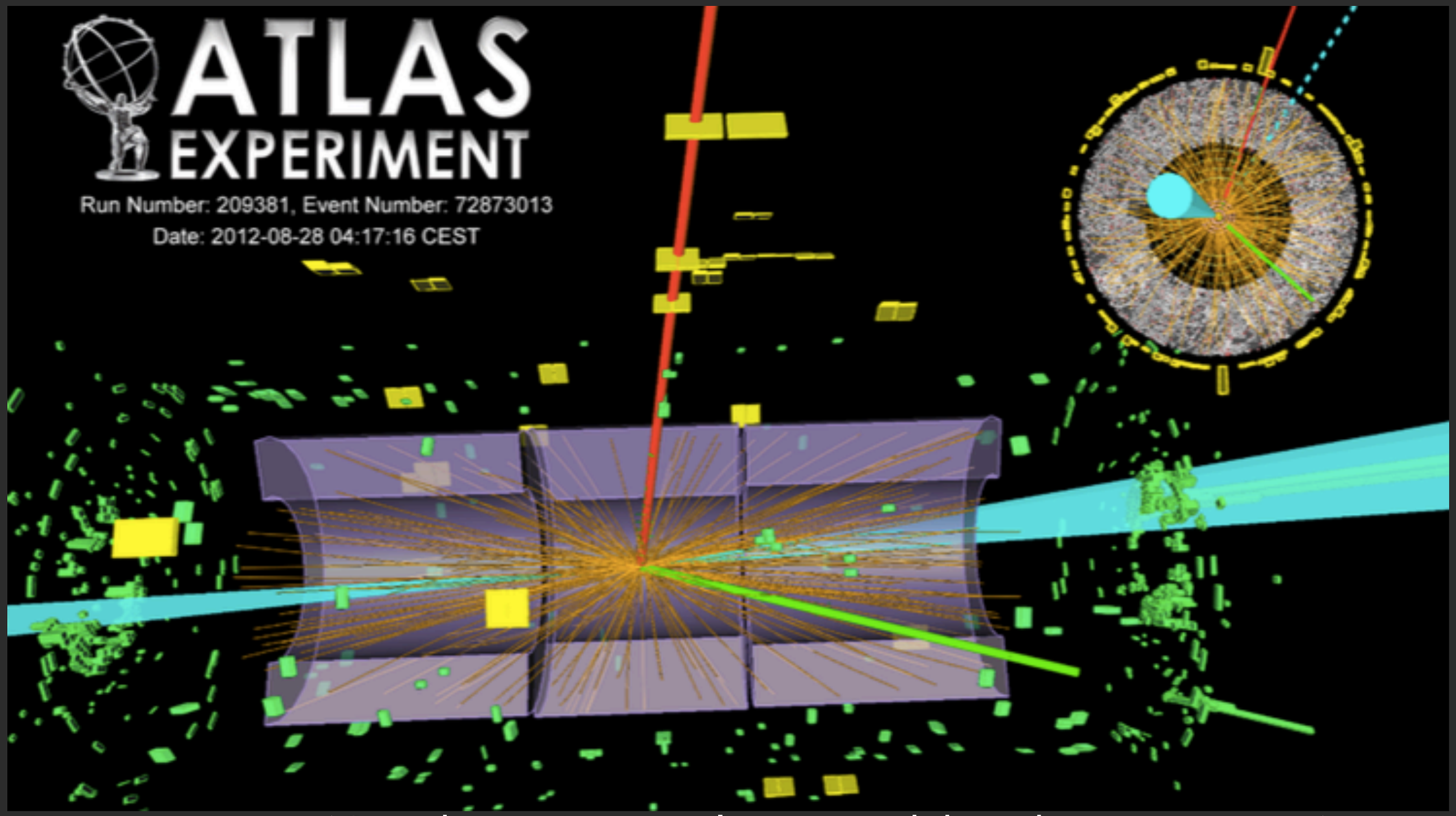


The formation and decay of a Higgs boson after a proton-proton collision. The decay would produce Z° hadrons and L leptons.

HIGGS PRODUCTION AND DECAY

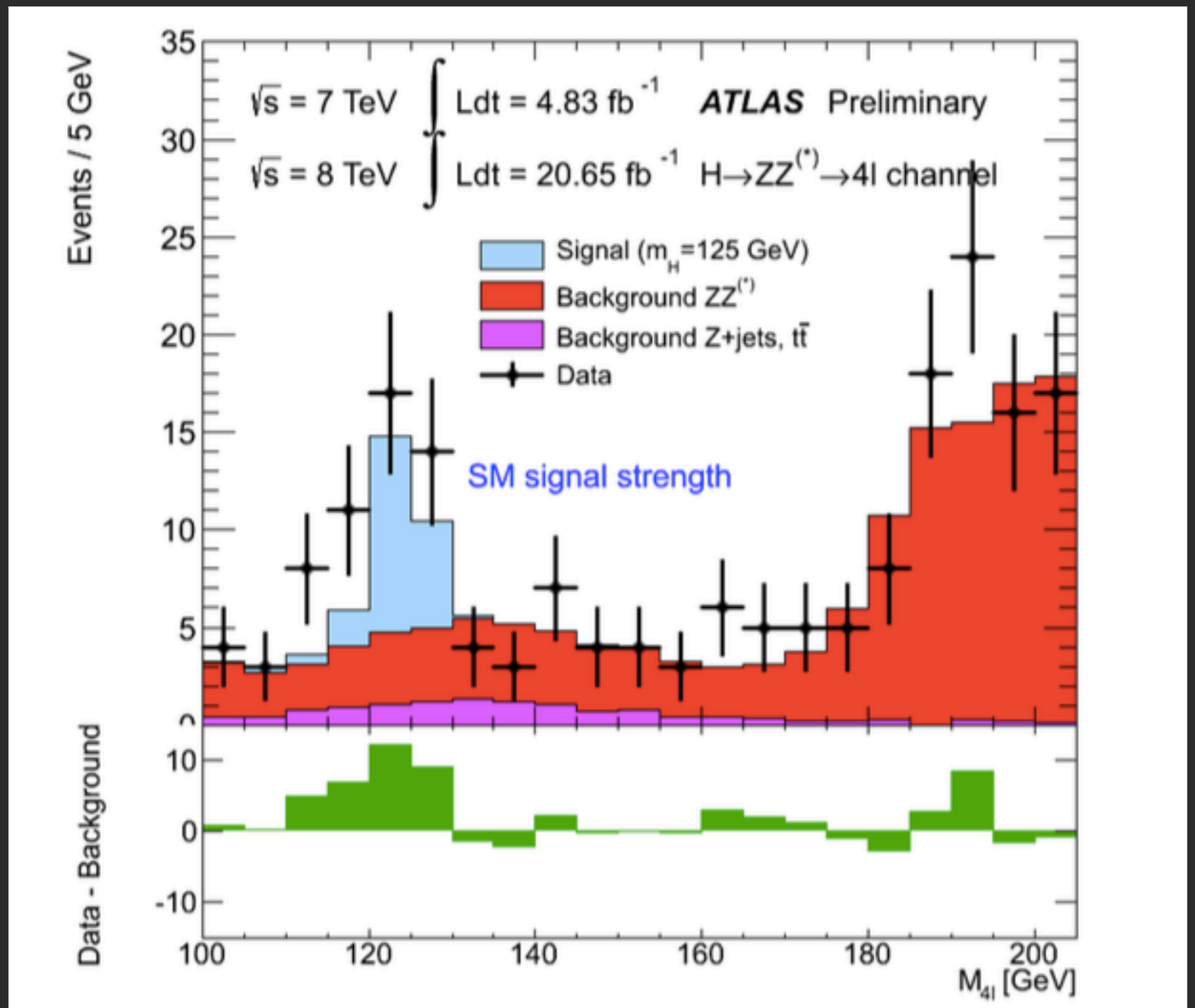


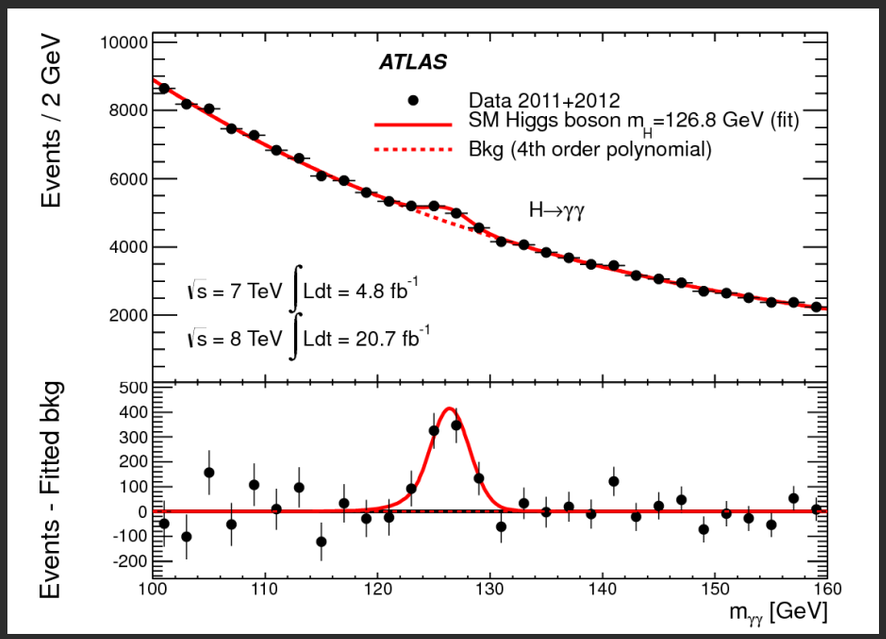
HIGGS PRODUCTION AND DECAY



Higgs -> tau tau (One decays into an electron and the other into a muon)

HIGGS DISCOVERY

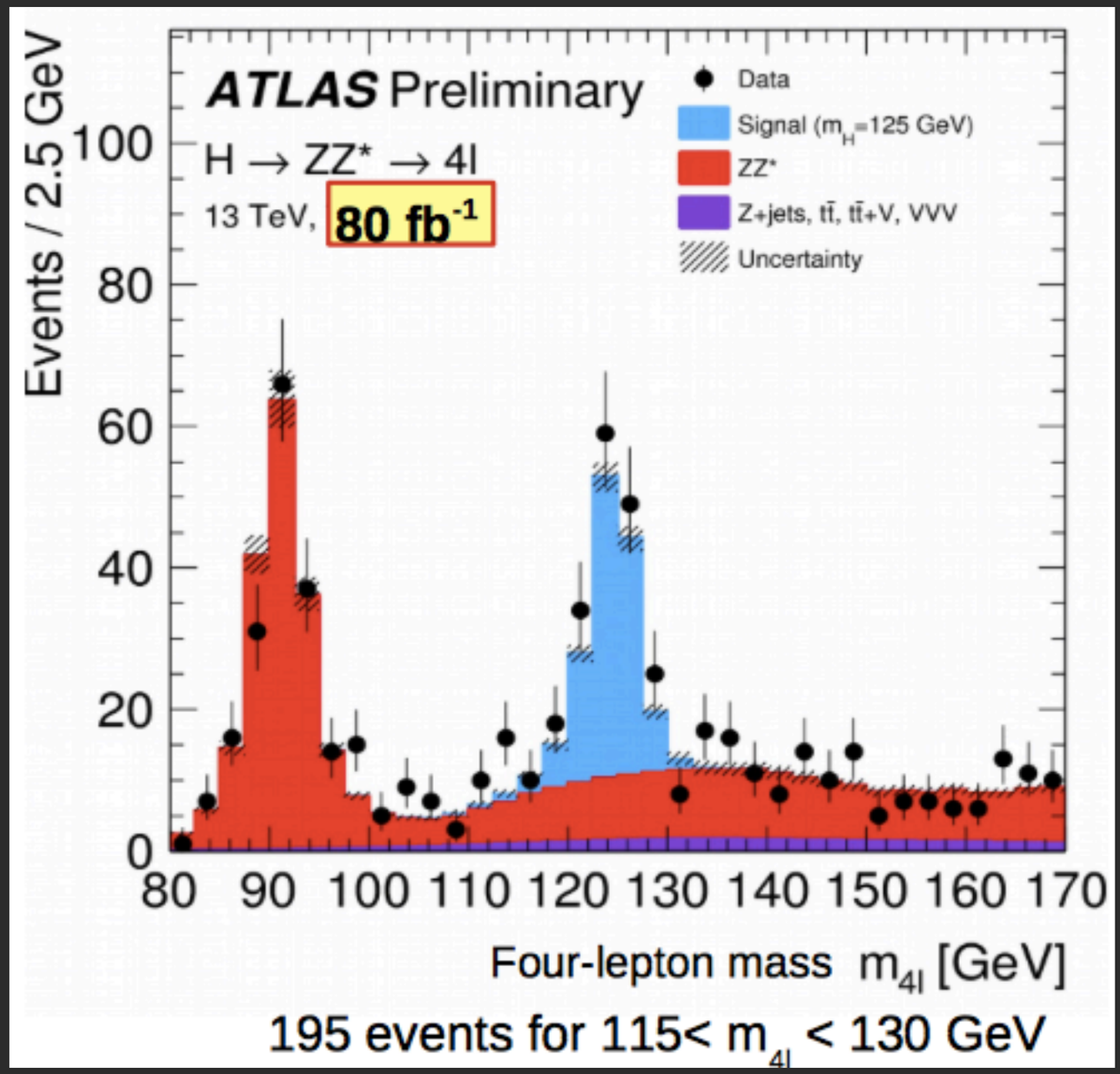




NEW HIGGS SLIDE

New Higgs boson discovered in 2012 – how did we discover it

Questions – is it the SM Higgs boson? Measure its properties – ned all production and decay modes



HIGGS DISCOVERY

"All the News That's Fit to Print"

The New York Times

Late Edition

Today, sunny to partly cloudy, rather hot, high 92. Tonight, mostly clear, low 72. Tomorrow, mostly sunny, hot and humid, high 90. Weather map appears on Page B16.

VOL. CLXI . . No. 55,823 © 2012 The New York Times NEW YORK, THURSDAY, JULY 5, 2012 $2.50

Oil Backed Up, Iranians Put It On Idled Ships

Subterfuge at Tankers as Embargo Tightens

By THOMAS ERDBRINK and CLIFFORD KRAUSS

BANDAR ABBAS, Iran — The hulking tanker Neptune was floating aimlessly this week in the warm waters of the Persian Gulf, a fresh coat of black paint barely concealing its true identity as an Iranian ship loaded with hundreds of thousands of barrels of oil that no one is willing to buy.

The ship's real name was Iran Astaneh, and it was part of a fleet of about 65 Iranian tankers serving as floating storage facilities for Iranian oil, each one given a nautical makeover to conceal its origin and make a buyer easier to find. The Neptune had been ing there for a month, a fishermen said there w even larger tankers nearby.

Iran, faced with in stringent economic sa posed by the internat munity to force it to sh ambitions to develo weapons, has been re reduce its oil productio that doing so could da wells. But Iran has insu space to store the crude it c sell. So while it furiously work build storage capacity on shore, has turned to mothballing at sea.

"We have never seen so many just waiting around," said Ros-

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

SHIFT RENEWS CRITICISM

Move Aligns Him With Conservative Voices Within His Party

By JEREMY W. PETERS

WOLFEBORO, N.H. — Mitt Romney declared on Wednesday that President Obama's health care mandate was in fact a tax, shifting his campaign's characterization of [illegible] and aligning his [illegible]

Physicists Find Elusive Particle Seen as Key to Universe

ts in Geneva

Nigh

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Then one of the ma

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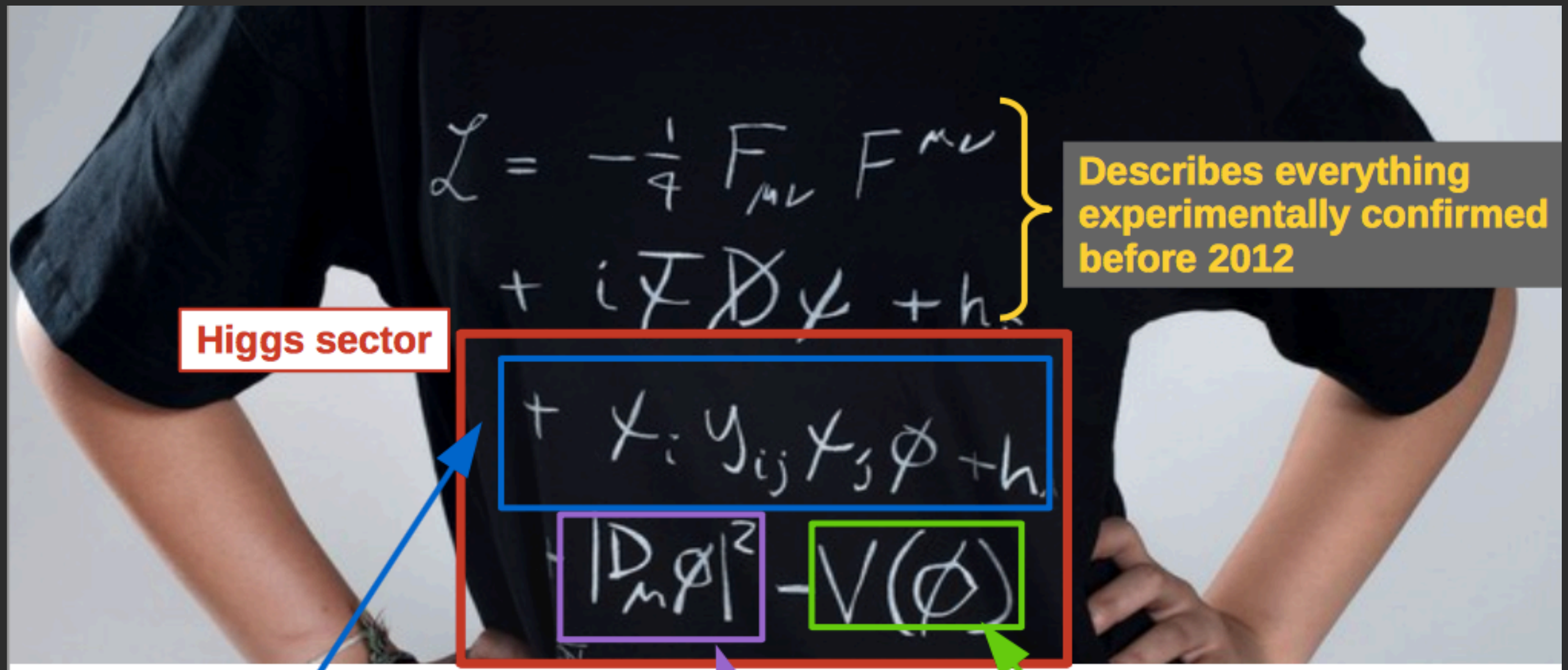
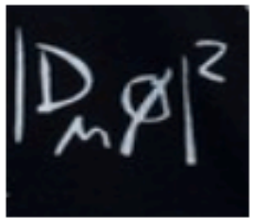
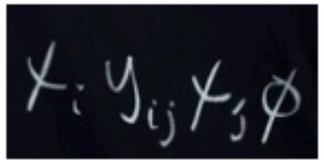
WHAT HAVE WE MEASURED



WHAT HAVE WE MEASURED



Interaction with gauge bosons:



Yukawa coupling to fermions:

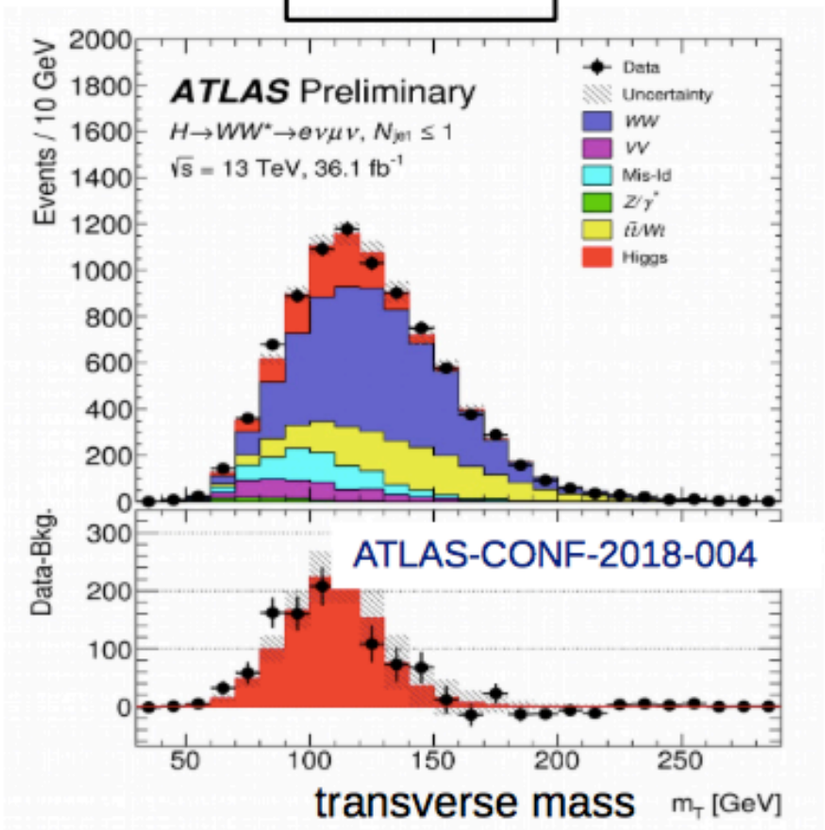
Earlier 7 and 8 TeV results:

At 7 and 8 TeV Higgs boson discovered.
Main channels: H → γγ, H → ZZ, H → WW

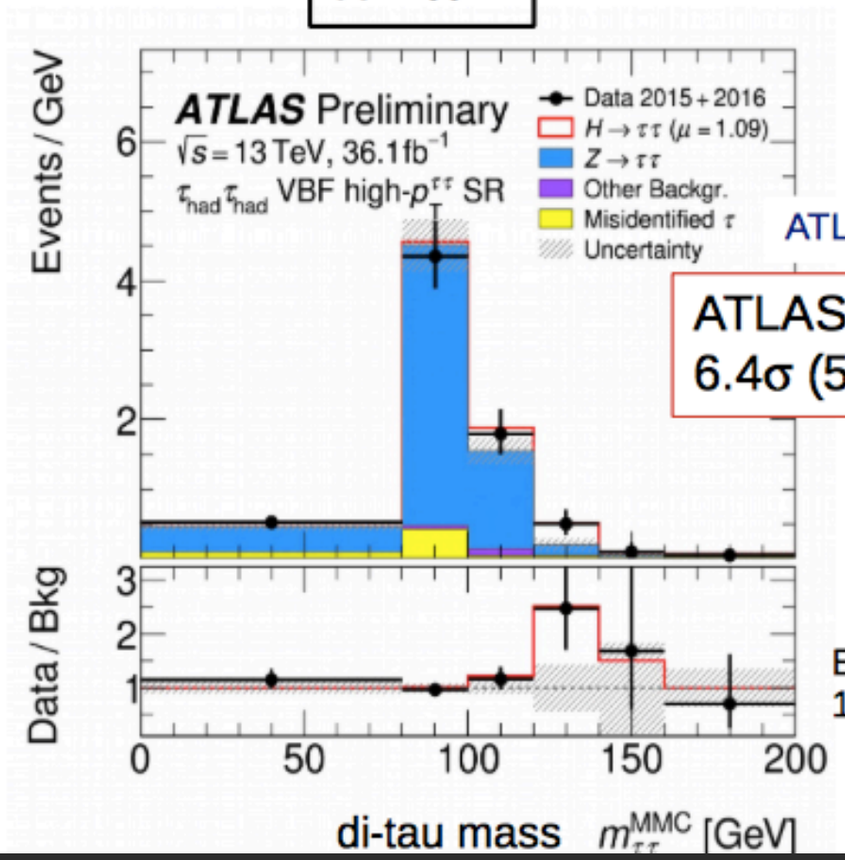
Only glimpse at 7 and 8 TeV (2012)
ATLAS/CMS combined H→ττ:
5.5σ (5.0σ) obs (exp) for 7/8 TeV
JHEP 08 (2016) 045

Recent 13 TeV results:

H→WW



H→ττ



ATLAS 7/8/13 TeV:
6.4σ (5.4σ) obs (exp)

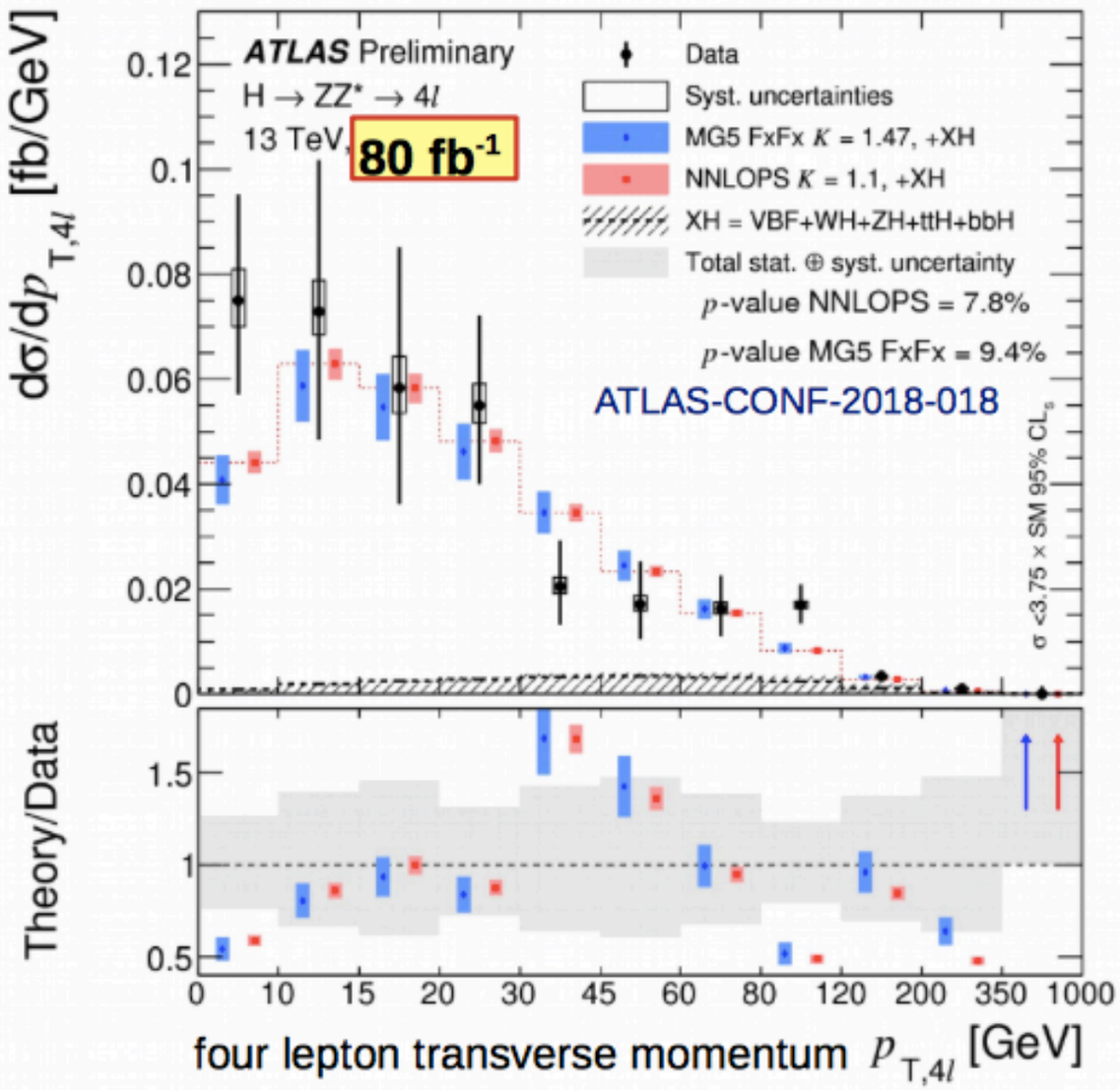
Example of mass in
1/13 signal categories

WHAT HAVE WE MEASURED

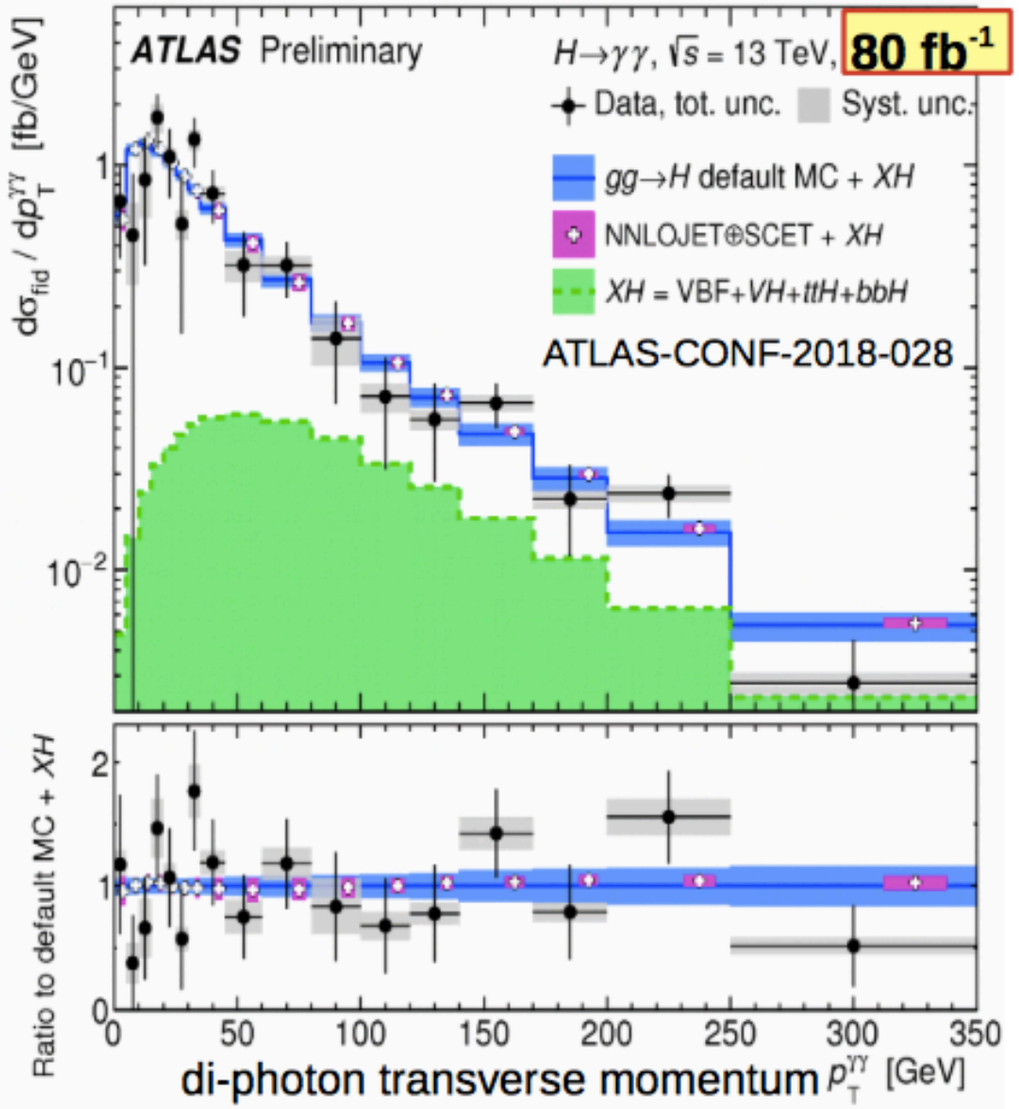
Higgs decays to gauge bosons used for differential cross-section measurements.

New

4 lepton channel



2 photon channel



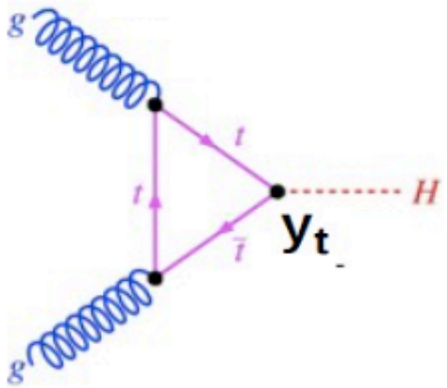
Differential cross-section becoming more and more precise with increasing statistics.
Data well described by recent SM predictions.

WHAT HAVE WE MEASURED

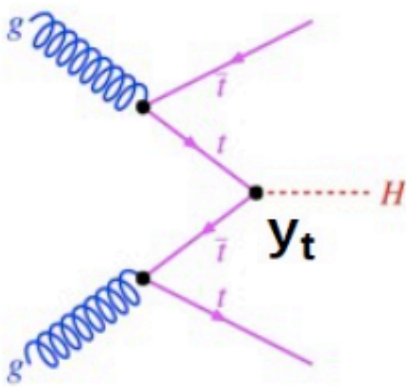
Associated Higgs top quark pair production

Higgs production:

Gluon-gluon fusion (ggF)



Associated ttH production (ttH)



Yukawa coupling:

$$y_t \approx v/(m_t\sqrt{2}) \approx 1$$

Large top mass → Higgs coupling is strong.
Top Yukawa y_t coupling is in loop for ggF
(might contain BSM contribution).
but ttH production gives direct constraint on $\mathbf{y_t}$

σ(ttH)~ 1% σ(H)

Branching fraction:

H → bb	58%
H → WW*	21%
H → ττ	6%
H → ZZ*	2.6%
H → γγ	0.2%

For H→WW and H→ZZ only leptonic decays

Evidence in December 2017 (36 fb^{-1}):

Channel	Significance	
	Observed	Expected
Multilepton	4.1σ	2.8σ
$H \to b\bar{b}$	1.4σ	1.6σ
$H \to \gamma\gamma$	0.9σ	1.7σ
$H \to 4\ell$	—	0.6σ
Combined	4.2σ	3.8σ

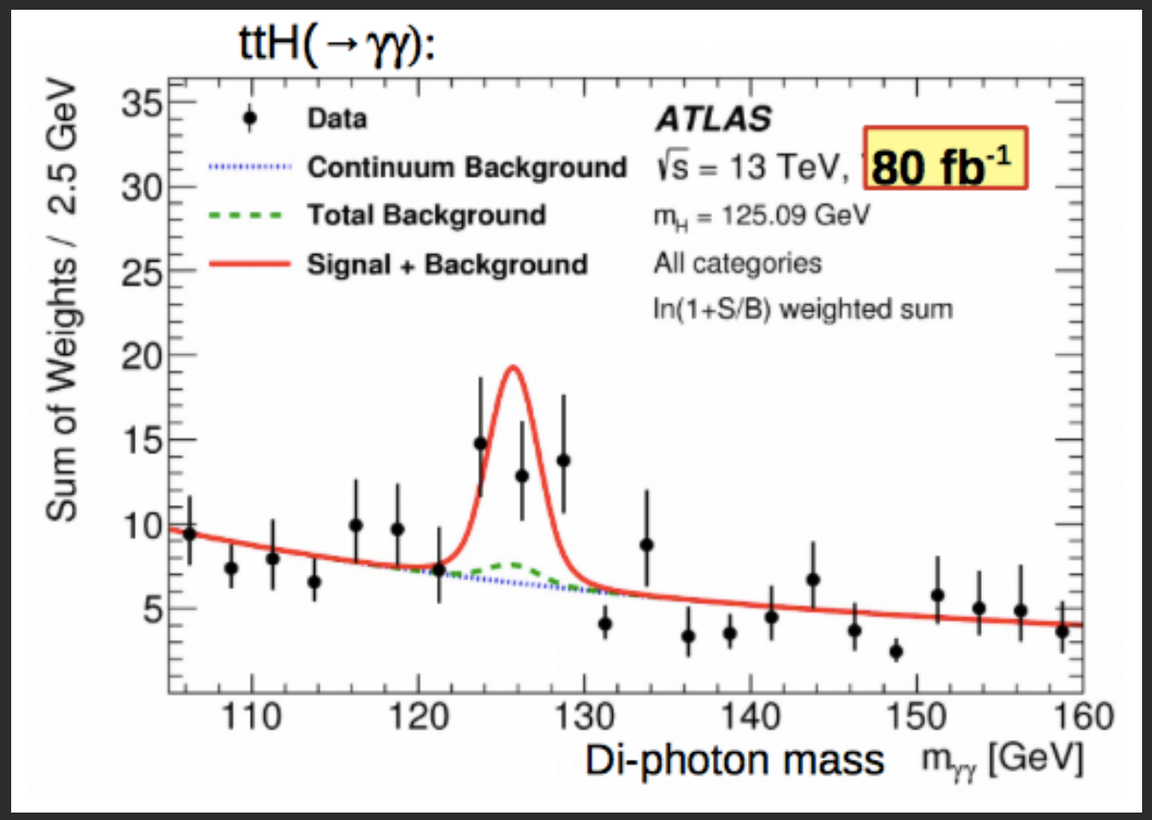
Phys.Rev. D 97 (2018) 072003
Phys. Rev. D 97 (2018) 072016
arXiv:1802.04146

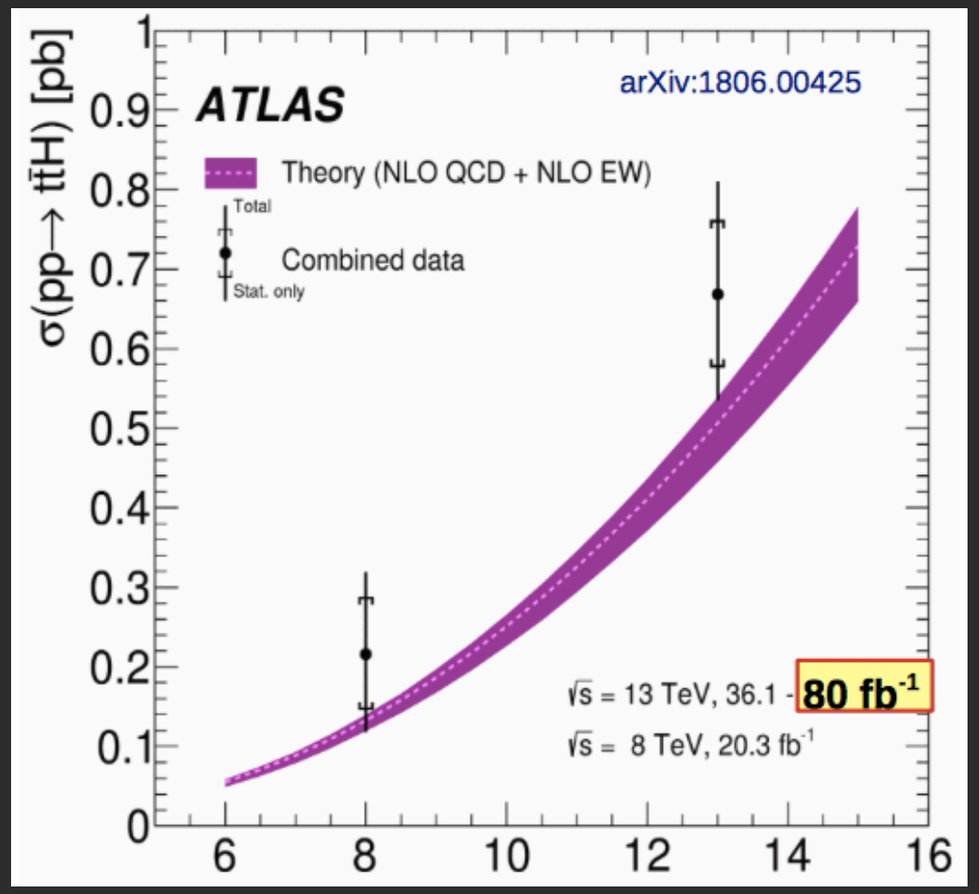
TTH

Direct observation of top Higgs coupling

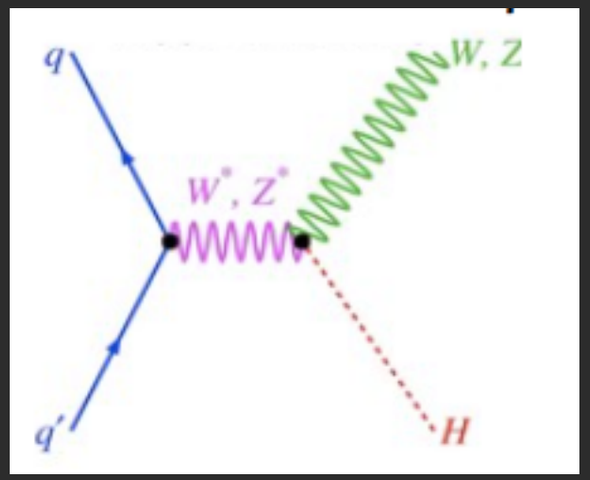
Confirmation of Yukawa coupling to fermions

Analysis	Integrated luminosity [fb^{-1}]	Expected significance	Observed significance
$H \to \gamma\gamma$	79.8	3.7 σ	4.1 σ
$H \to$ multilepton	36.1	2.8 σ	4.1 σ
$H \to b\bar{b}$	36.1	1.6 σ	1.4 σ
$H \to ZZ^* \to 4\ell$	79.8	1.2 σ	0 σ
Combined (13 TeV)	36.1–79.8	4.9 σ	5.8 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1–79.8	5.1 σ	6.3 σ





HIGGS -> BB

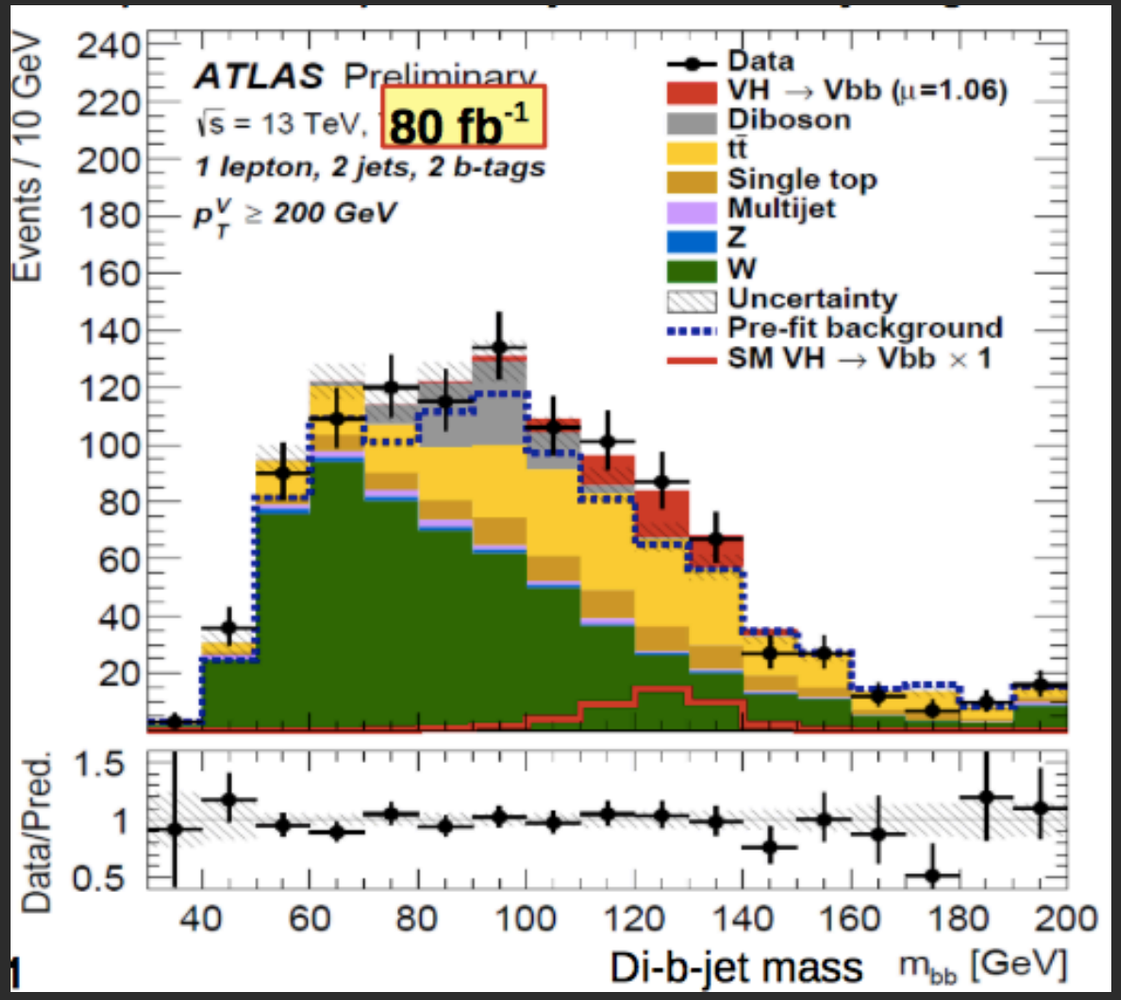


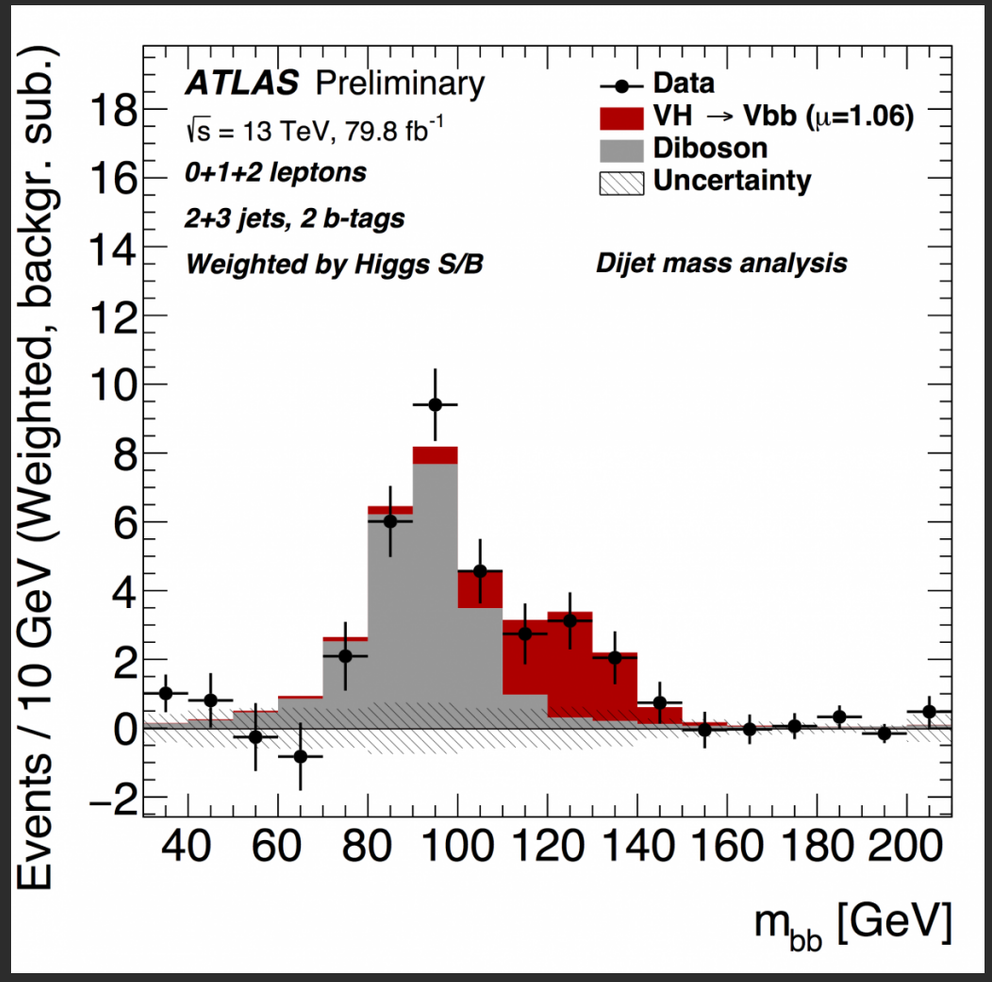
Associated VH production and H-> bb decay!

H-> bb highest branching ratio BR= 58 %

VH alone: 4.9σ (4.3σ) obs (exp) (13 TeV)

Combined (7,8,13 TeV) VBF, ttH, VH:
5.4σ (5.5σ) obs (exp)

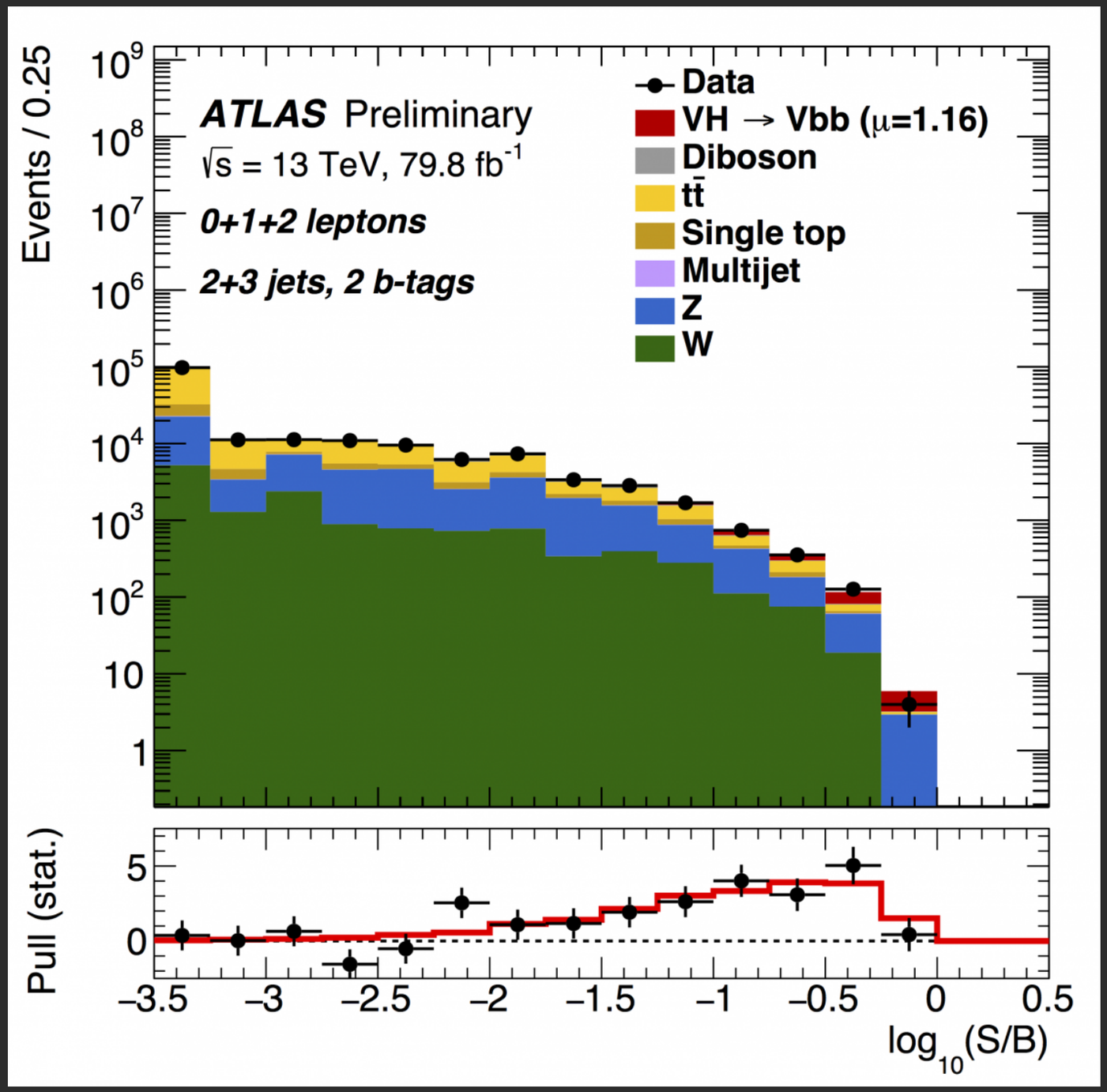




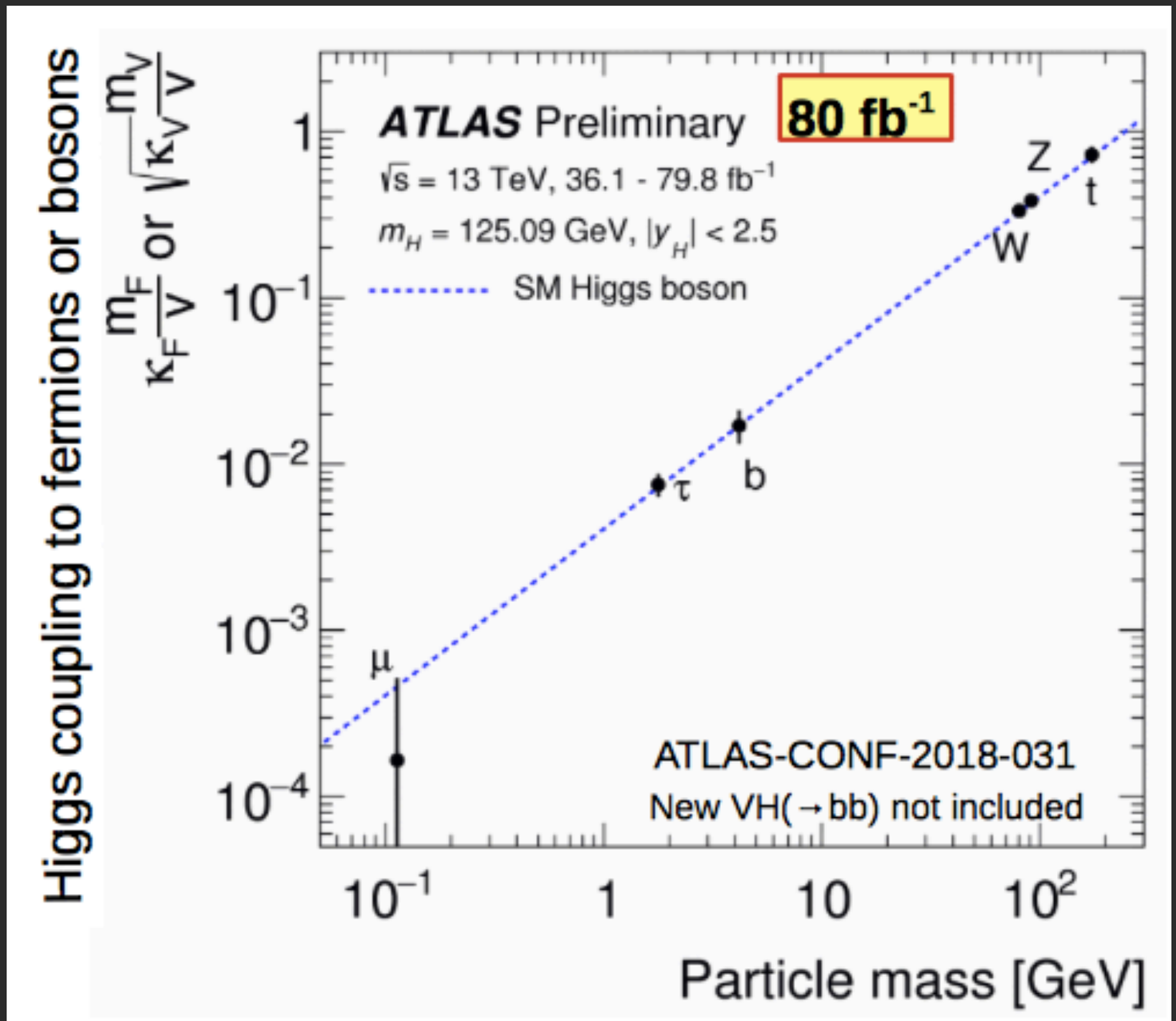
HIGGS -> BB

Mass of the b-jet pair is combined with other kinematic variables that show distinct differences between the signal and the various backgrounds,

This combination of multiple variables is performed using the technique of boosted decision trees (BDTs).



HIGGS COUPLING



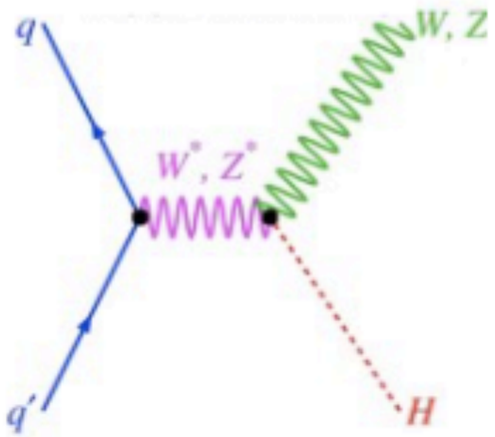
Higgs coupling depends on the particle mass

HIGGS PRODUCTION

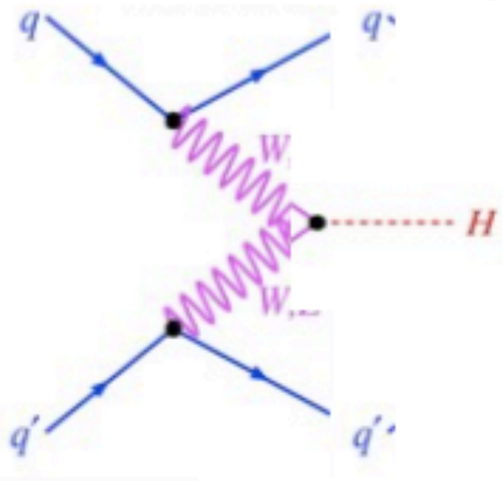
New

Higgs production modes

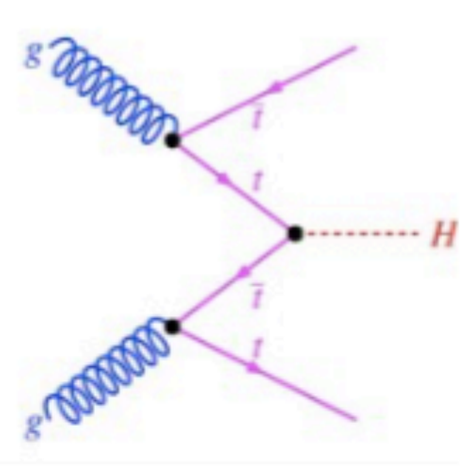
Associated WH or ZH production (VH)

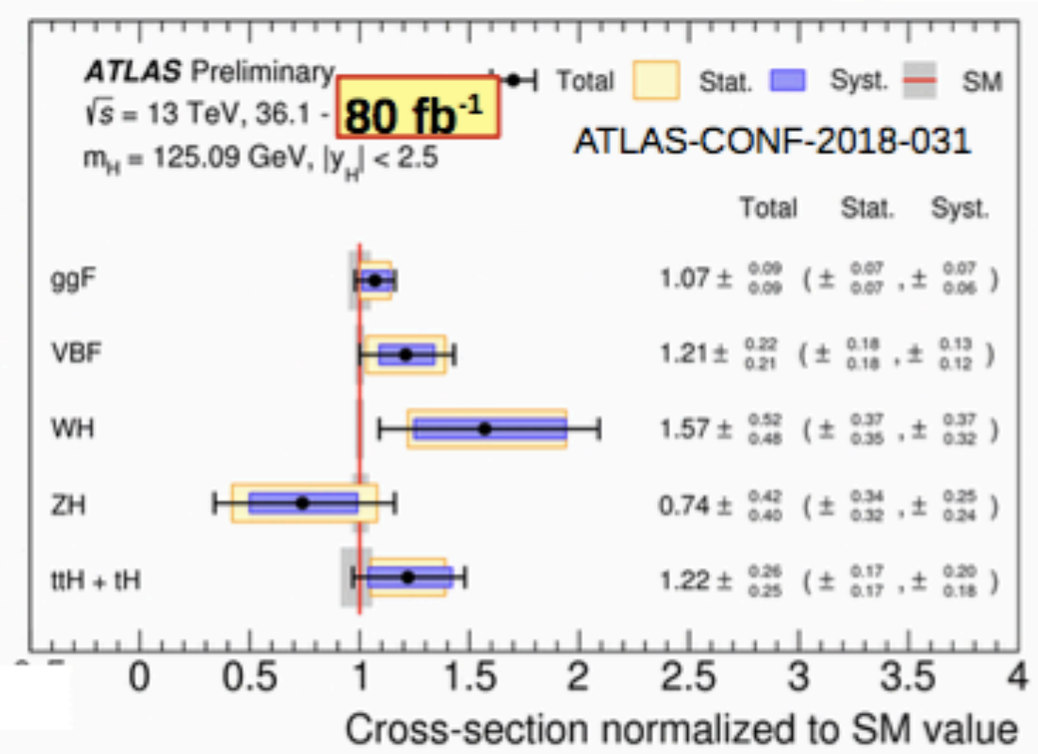


Vector-boson fusion (VBF)



Associated ttH production (ttH)



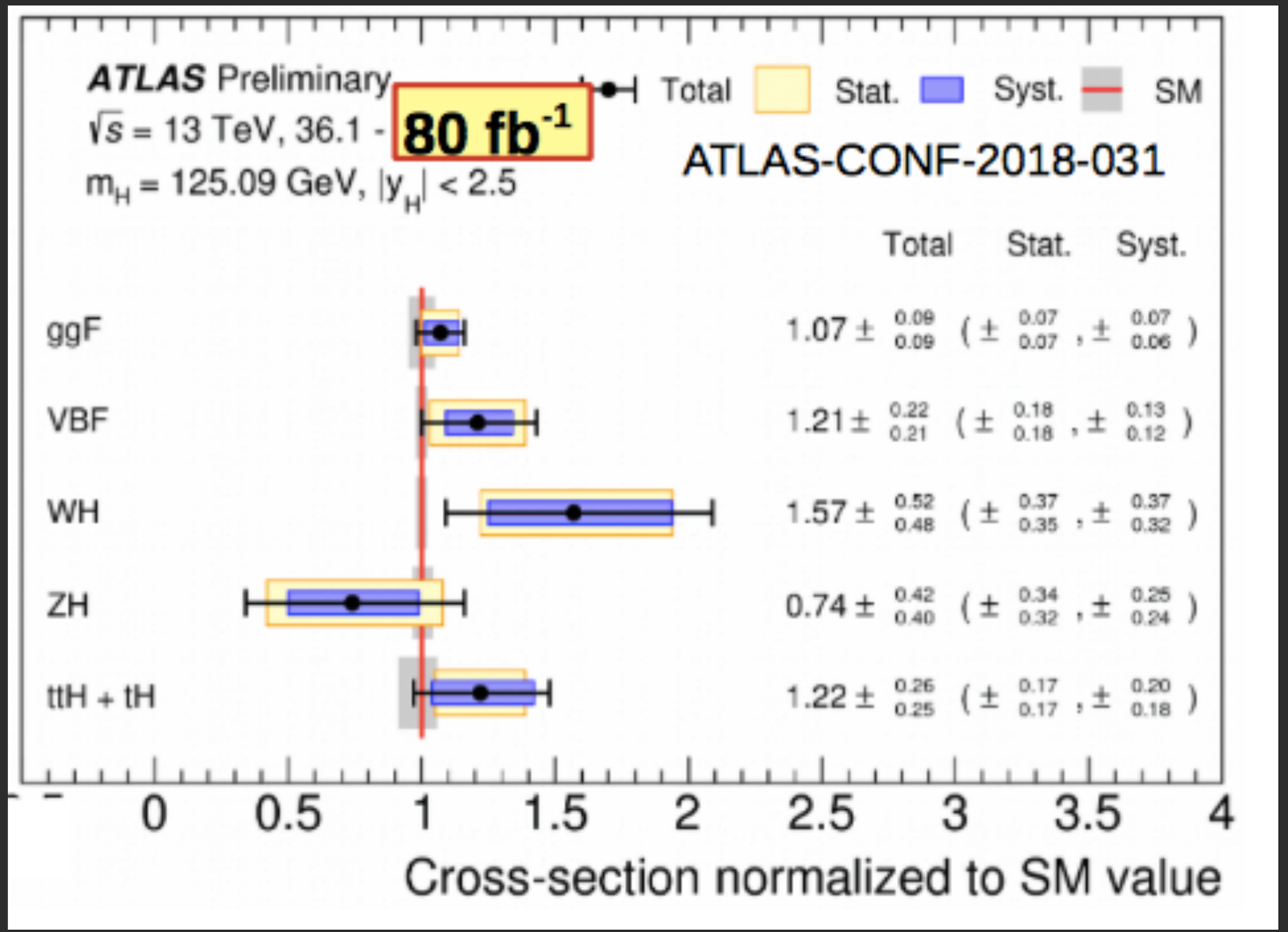


Gluon-gluon fusion (ggF) observed since 2012 and used for precision measurements (~10%).

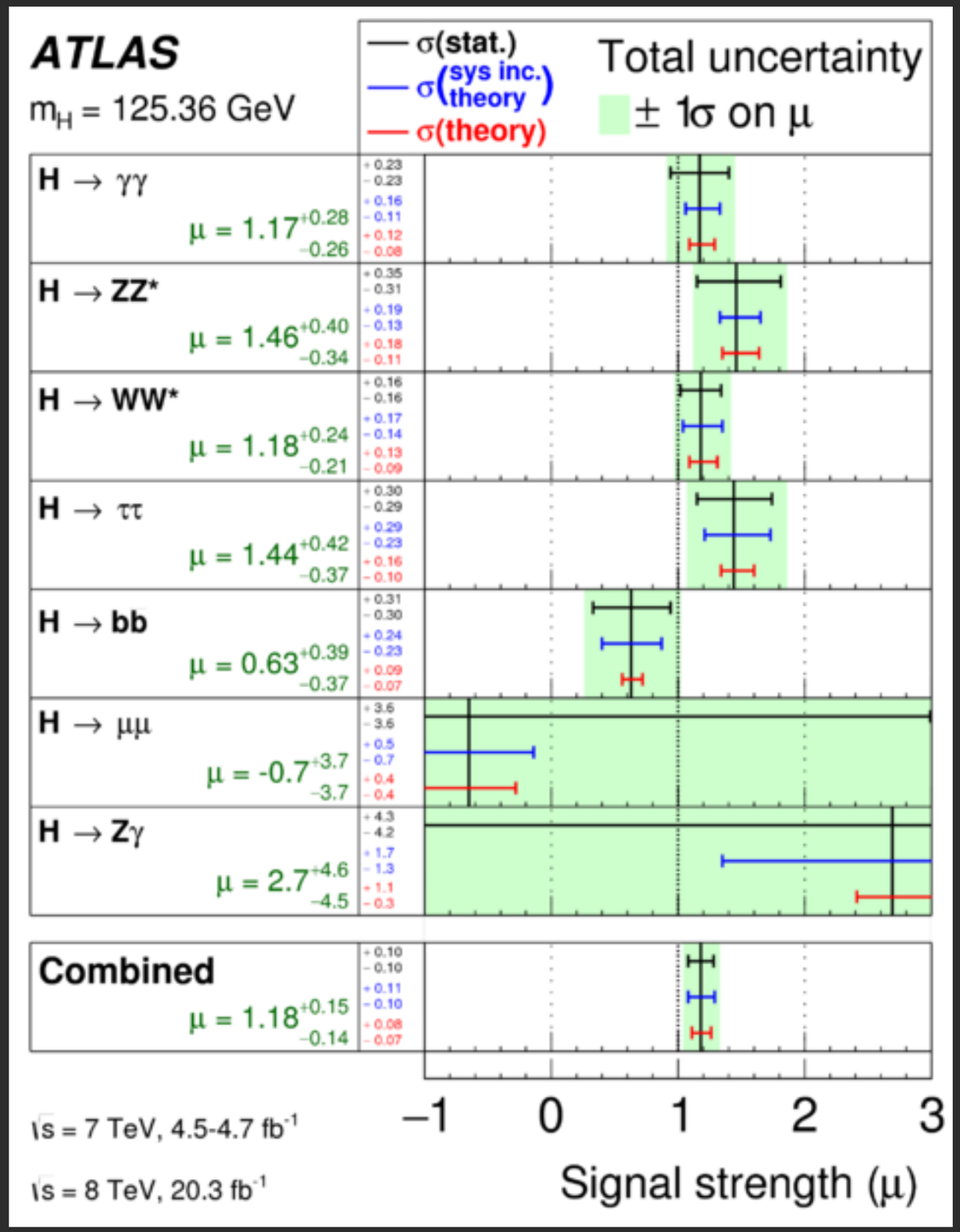
VH	5.3σ (4.8σ) obs (exp)	ATLAS-CONF-2018-036
VBF	6.5σ (5.3σ) obs (exp)	ATLAS-CONF-2018-031
ttH	6.3σ (5.1σ) obs (exp)	arXiv:1806.00425

Observed all major Higgs production modes !
Consistent with SM.

HIGGS PRODUCTION



HIGGS DECAY


ATLAS
m_H = 125.36 GeV
σ(stat.)
σ(sys inc. theory)
σ(theory)
Total uncertainty
± 1σ on μ
H → γγ
μ = 1.17 +0.28 −0.26
H → ZZ*
μ = 1.46 +0.40 −0.34
H → WW*
μ = 1.18 +0.24 −0.21
H → ττ
μ = 1.44 +0.42 −0.37
H → bb
μ = 0.63 +0.39 −0.37
H → μμ
μ = -0.7 +3.7 −3.7
H → Zγ
μ = 2.7 +4.6 −4.5
Combined
μ = 1.18 +0.15 −0.14
√s = 7 TeV, 4.5-4.7 fb-1
√s = 8 TeV, 20.3 fb-1
−1
0
1
2
3
Signal strength (μ)

Eur. Phys. J. C (2016) 76.6

HIGGS MASS COMBINATION