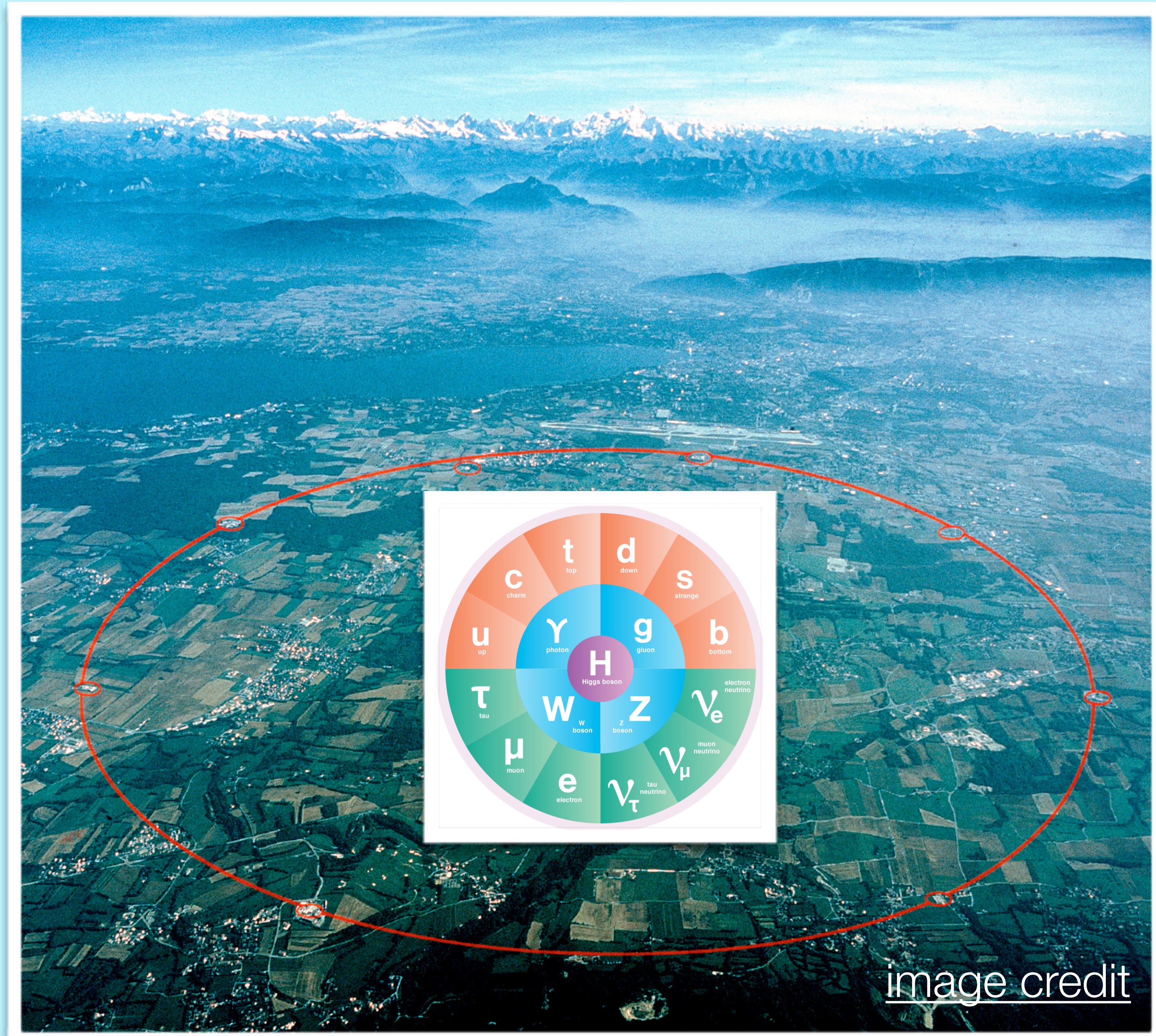
Standard Model and Higgs Physics Results from ATLAS and CMS



Presented at the SLAC Summer Institute 2017

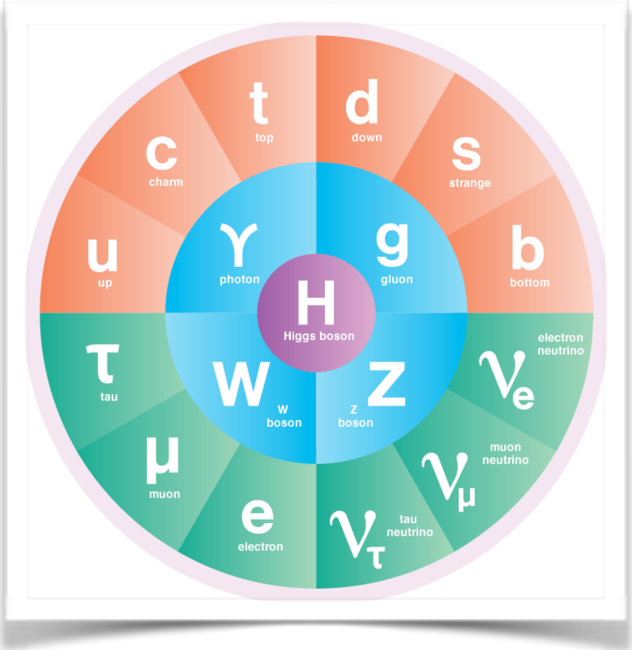
SSI

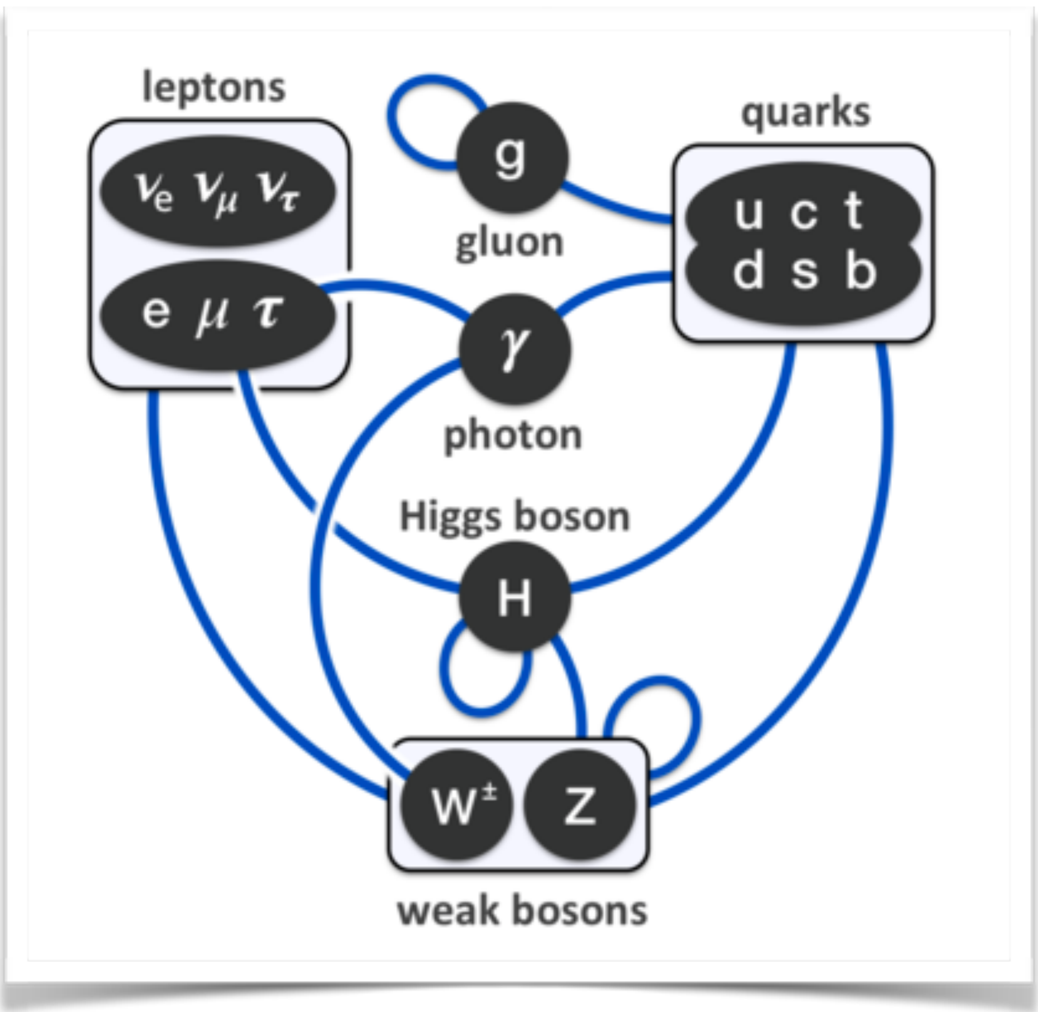
Heather M. Gray, LBNL, *on behalf of the ATLAS and CMS Collaborations*

The Standard Model

The Standard Model
24 elementary matter particles
3 forces
26 parameters

- Although the SM has many input parameters, it is very predictive
- Survived many experimental tests over a wide energy range
- With the discovery of the Higgs boson, it is fair to say that it is a good effective theory no matter what happens next

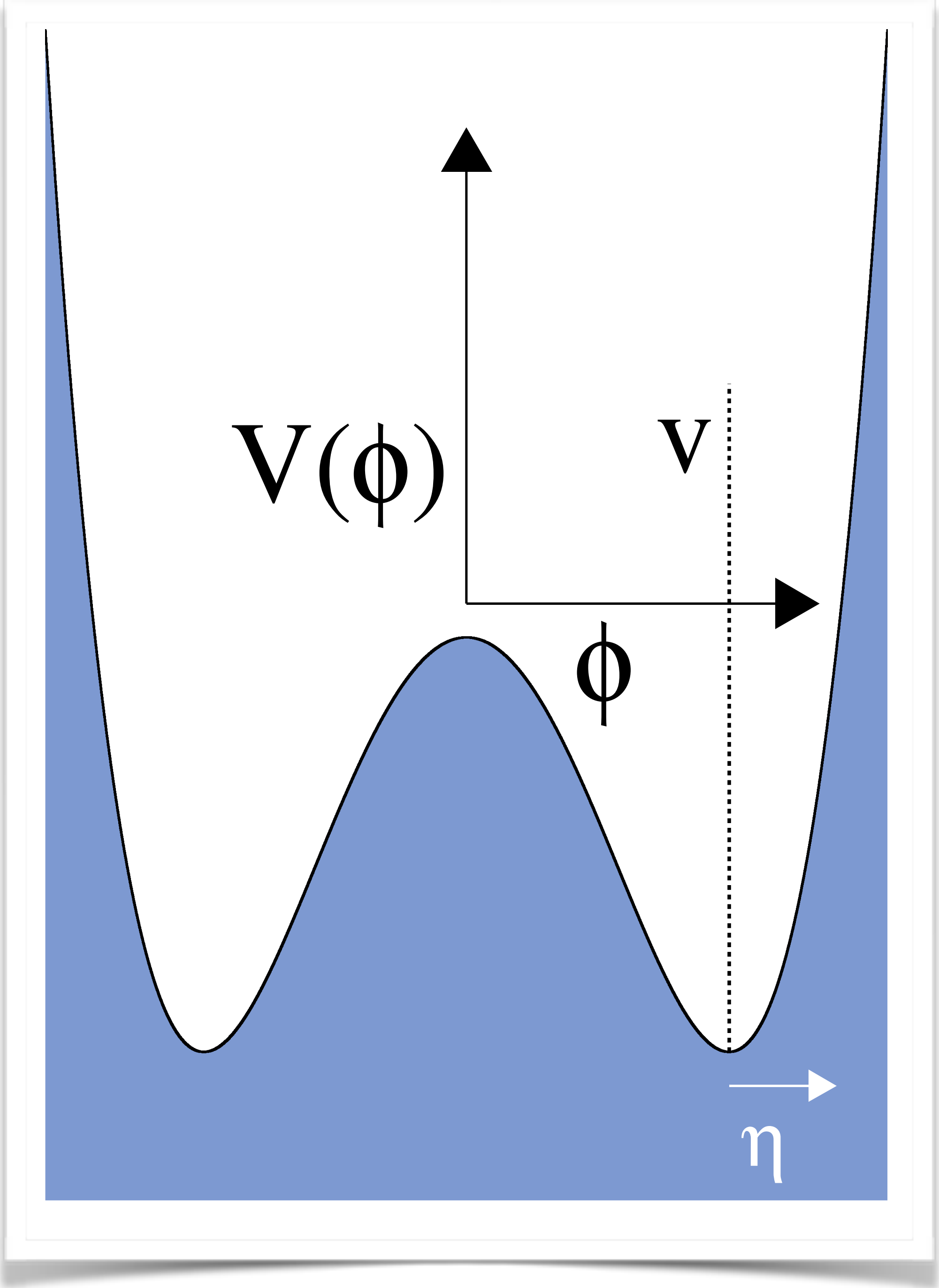




The Higgs boson in the Standard Model

F. Englert and R. Brout, PRL 13 (1964) 321, P.W. Higgs, PRL 13 (1964) 508, G. Guralnik, C. Hagen, and T.W.B. Kibble, PRL 13 (1964) 585.

- **Local gauge invariance** forbids explicit mass terms in the Lagrangian – but experimentally both gauge bosons and fermions have mass
- Introduce a new field with a very specific potential that keeps the full Lagrangian invariant but makes the vacuum not invariant
- **Higgs mechanism** predicts existence of a new, neutral boson: the **Higgs boson**
    - SM parameters: mass (**μ** or **m_H**) and vacuum expectation value, **v**



$\mu^2 < 0$

$$\mathcal{L} = |D^\mu \phi|^2 - y_i q_L^i q_R^i \phi - \mu^2 \phi^2 - \lambda \phi^4 + \ldots$$

Standard Model Lagrangian

$$
\begin{aligned}
&\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g^2_s f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \tfrac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)) - \\
&igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
&W^-_\nu\partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
&Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H\partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \\
&\beta_h\left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
&g\alpha_h M\,(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-) - \\
&\tfrac{1}{8}g^2\alpha_h\,(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2) - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c^2_w}Z^0_\mu Z^0_\mu H - \\
&\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
&\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
&M\,(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+) - ig\tfrac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
&W^-_\mu\phi^+) - ig\tfrac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
&\tfrac{1}{4}g^2W^+_\mu W^-_\mu\,(H^2+(\phi^0)^2+2\phi^+\phi^-) - \tfrac{1}{8}g^2\tfrac{1}{c^2_w}Z^0_\mu Z^0_\mu\,(H^2+(\phi^0)^2+2(2s^2_w-1)^2\phi^+\phi^-) - \\
&\tfrac{1}{2}g^2\tfrac{s^2_w}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
&W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c^2_w-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
&g^2 s^2_w A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\,\lambda^a_{ij}(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar e^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar\nu^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar u^\lambda_j(\gamma\partial + \\
&m^\lambda_u)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
&\tfrac{ig}{4c_w}Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\tfrac{4}{3}s^2_w - 1 - \gamma^5)d^\lambda_j) + \\
&(\bar u^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s^2_w + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt2}W^+_\mu\left((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
&\tfrac{ig}{2\sqrt2}W^-_\mu\left((\bar e^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
&\tfrac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_e(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \\
&\tfrac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_e(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar\nu^\lambda\nu^\lambda) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar e^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar e^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\,\bar\nu_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa - \\
&\tfrac{1}{4}\,\bar\nu_\lambda\,M^R_{\lambda\kappa}\,(1-\gamma_5)\hat\nu_\kappa + \tfrac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \\
&\tfrac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar d^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar G^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar G^a G^b g^c_\mu + \\
&\bar X^+(\partial^2 - M^2)X^+ + \bar X^-(\partial^2 - M^2)X^- + \bar X^0(\partial^2 - \tfrac{M^2}{c^2_w})X^0 + \bar Y\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar X^0 X^- - \\
&\partial_\mu\bar X^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar Y X^- - \partial_\mu\bar X^+ Y) + igc_w W^-_\mu(\partial_\mu\bar X^- X^0 - \\
&\partial_\mu\bar X^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar X^- Y - \partial_\mu\bar Y X^+) + igc_w Z^0_\mu(\partial_\mu\bar X^+ X^+ - \\
&\partial_\mu\bar X^- X^-) + igs_w A_\mu(\partial_\mu\bar X^+ X^+ - \\
&\partial_\mu\bar X^- X^-) - \tfrac{1}{2}gM\left(\bar X^+X^+H + \bar X^-X^-H + \tfrac{1}{c^2_w}\bar X^0X^0H\right) + \tfrac{1-2c^2_w}{2c_w}igM\left(\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-\right) + \\
&\tfrac{1}{2c_w}igM\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + igMs_w\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + \\
&\tfrac{1}{2}igM\left(\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0\right).
\end{aligned}
$$

T. Gutierrez

Standard Model Lagrangian

$$\begin{aligned}
\mathcal{L} = & -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{8}tr(\mathbf{W}_{\mu\nu}\mathbf{W}^{\mu\nu}) - \frac{1}{2}tr(\mathbf{G}_{\mu\nu}\mathbf{G}^{\mu\nu}) && \text{(U(1), SU(2) and SU(3) gauge terms)} \\
& +(\bar{\nu}_L, \bar{e}_L)\,\tilde{\sigma}^\mu i D_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} + \bar{e}_R \sigma^\mu i D_\mu e_R + \bar{\nu}_R \sigma^\mu i D_\mu \nu_R + \text{(h.c.)} && \text{(lepton dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{\nu}_L, \bar{e}_L)\,\phi M^e e_R + \bar{e}_R \bar{M}^e \bar{\phi} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}\right] && \text{(electron, muon, tauon mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{e}_L, \bar{\nu}_L)\,\phi^* M^\nu \nu_R + \bar{\nu}_R \bar{M}^\nu \phi^T \begin{pmatrix} -e_L \\ \nu_L \end{pmatrix}\right] && \text{(neutrino mass term)} \\
& +(\bar{u}_L, \bar{d}_L)\,\tilde{\sigma}^\mu i D_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} + \bar{u}_R \sigma^\mu i D_\mu u_R + \bar{d}_R \sigma^\mu i D_\mu d_R + \text{(h.c.)} && \text{(quark dynamical term)} \\
& -\frac{\sqrt{2}}{v}\left[(\bar{u}_L, \bar{d}_L)\,\phi M^d d_R + \bar{d}_R \bar{M}^d \bar{\phi} \begin{pmatrix} u_L \\ d_L \end{pmatrix}\right] && \text{(down, strange, bottom mass term)} \\
& -\frac{\sqrt{2}}{v}\left[(-\bar{d}_L, \bar{u}_L)\,\phi^* M^u u_R + \bar{u}_R \bar{M}^u \phi^T \begin{pmatrix} -d_L \\ u_L \end{pmatrix}\right] && \text{(up, charmed, top mass term)} \\
& +\overline{(D_\mu\phi)}D^\mu\phi - m_h^2[\bar{\phi}\phi - v^2/2]^2/2v^2. && \text{(Higgs dynamical and mass term)} \quad (1)
\end{aligned}$$

where (h.c.) means Hermitian conjugate of preceeding terms, $\bar{\psi} = \text{(h.c.)}\psi = \psi^\dagger = \psi^{*T}$, and the derivative operators are

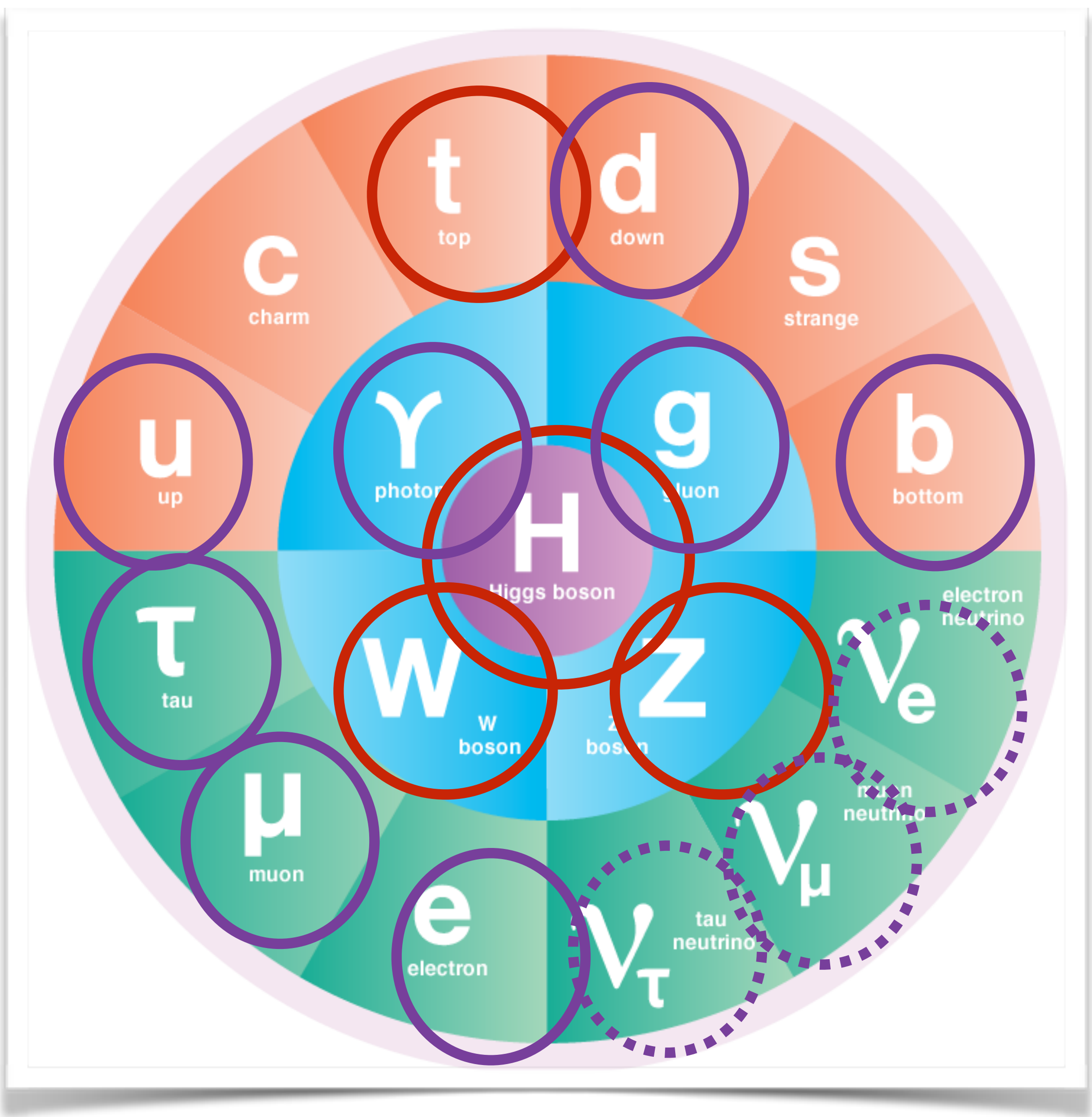
$$D_\mu \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = \left[\partial_\mu - \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad D_\mu \begin{pmatrix} u_L \\ d_L \end{pmatrix} = \left[\partial_\mu + \frac{ig_1}{6}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu + ig\mathbf{G}_\mu\right]\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad (2)$$

$$D_\mu \nu_R = \partial_\mu \nu_R, \quad D_\mu e_R = [\partial_\mu - ig_1 B_\mu]\, e_R, \quad D_\mu u_R = \left[\partial_\mu + \frac{i2g_1}{3}B_\mu + ig\mathbf{G}_\mu\right]u_R, \quad D_\mu d_R = \left[\partial_\mu - \frac{ig_1}{3}B_\mu + ig\mathbf{G}_\mu\right]d_R, \quad (3)$$

$$D_\mu \phi = \left[\partial_\mu + \frac{ig_1}{2}B_\mu + \frac{ig_2}{2}\mathbf{W}_\mu\right]\phi. \quad (4)$$

This talk

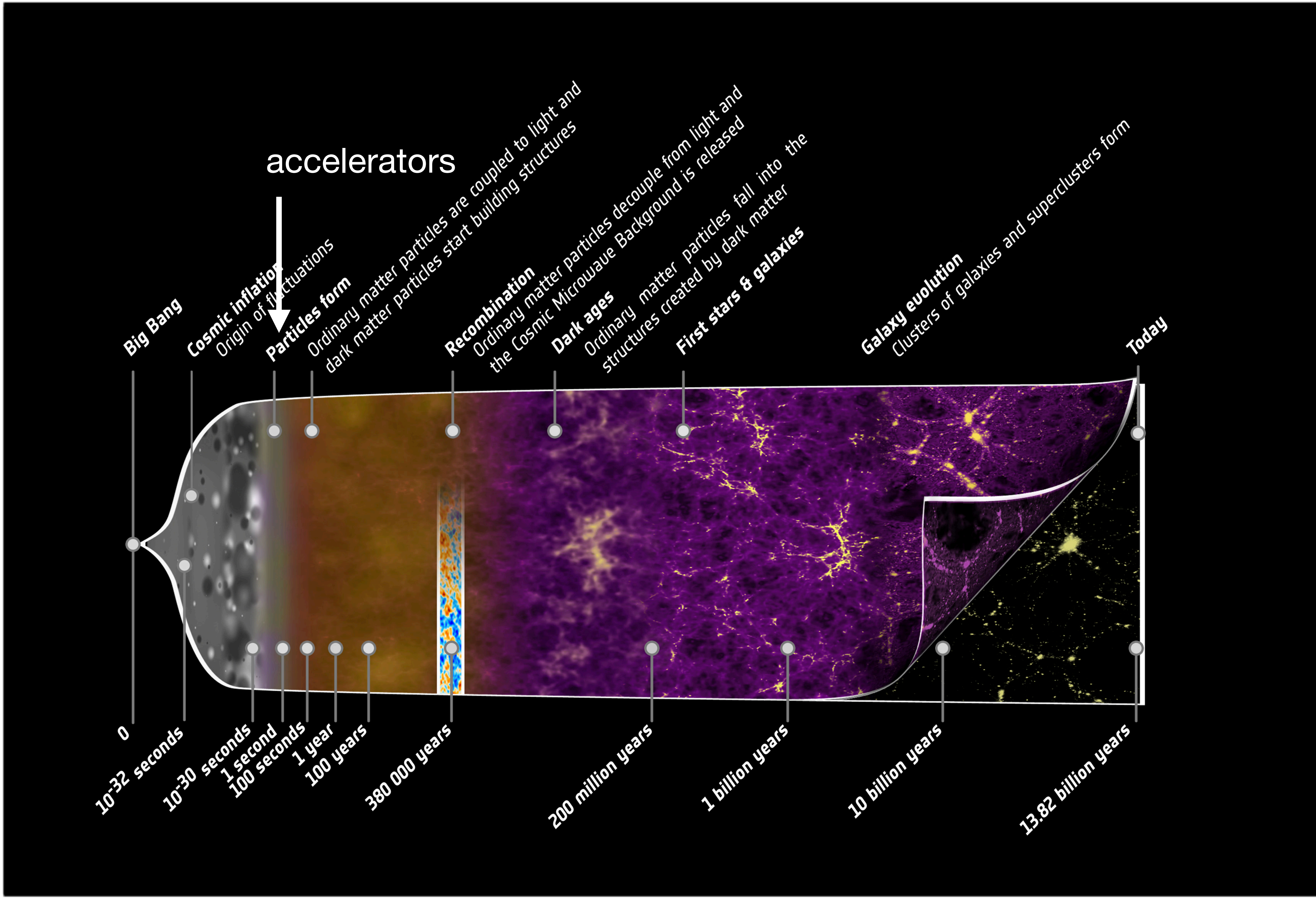
- Briefly introduce the LHC and the ATLAS and CMS detectors
- Select a few key Standard Model particles (W, Z, top and Higgs)
- Highlight key ATLAS and CMS results
  - See how this has improved our understand of the Standard Model



Selected particles

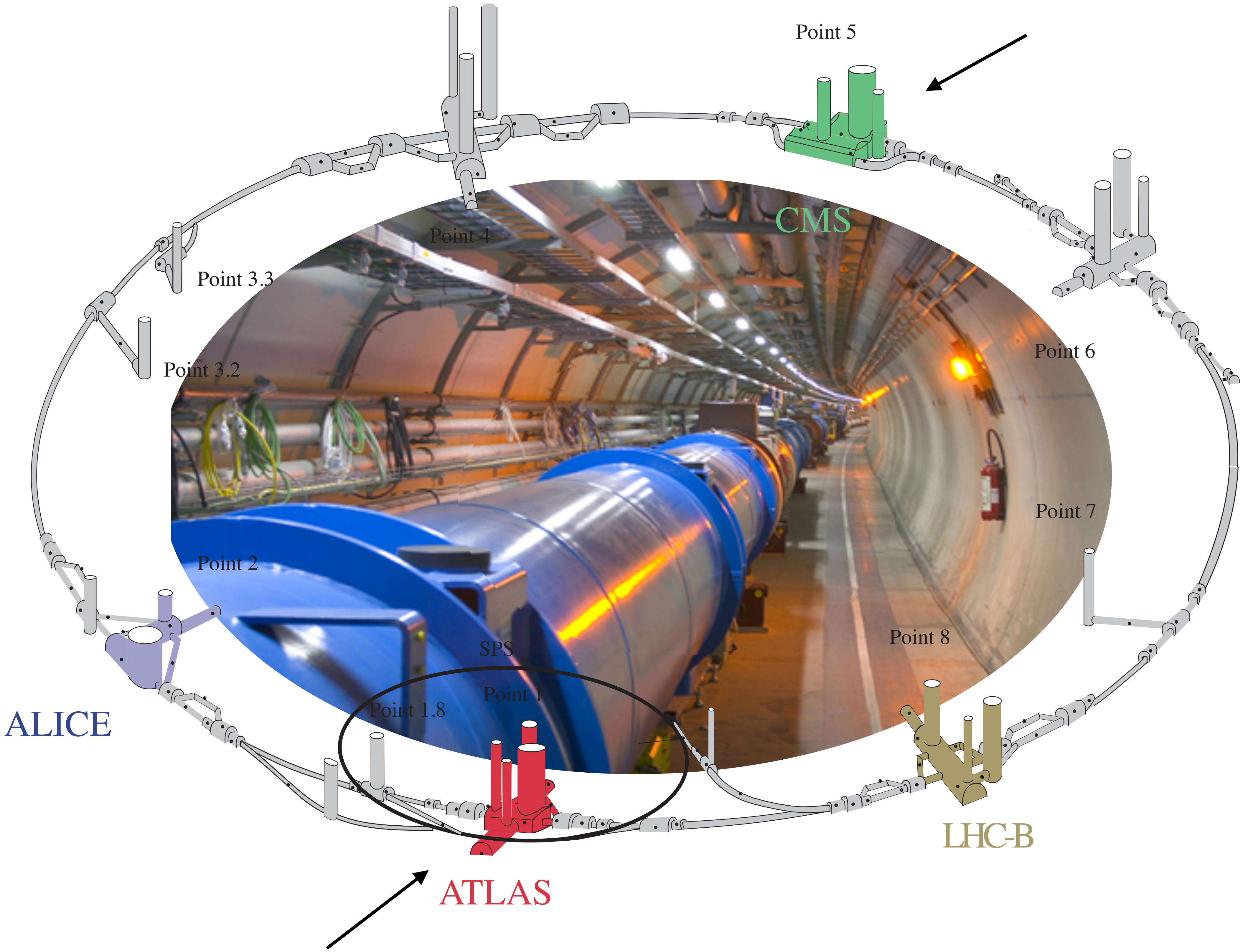
"Tools"

Disclaimer
Will typically present either CMS or ATLAS results in each case chosen at random


accelerators
Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and
dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and
the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the
structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

The Large Hadron Collider and the ATLAS and CMS Detectors

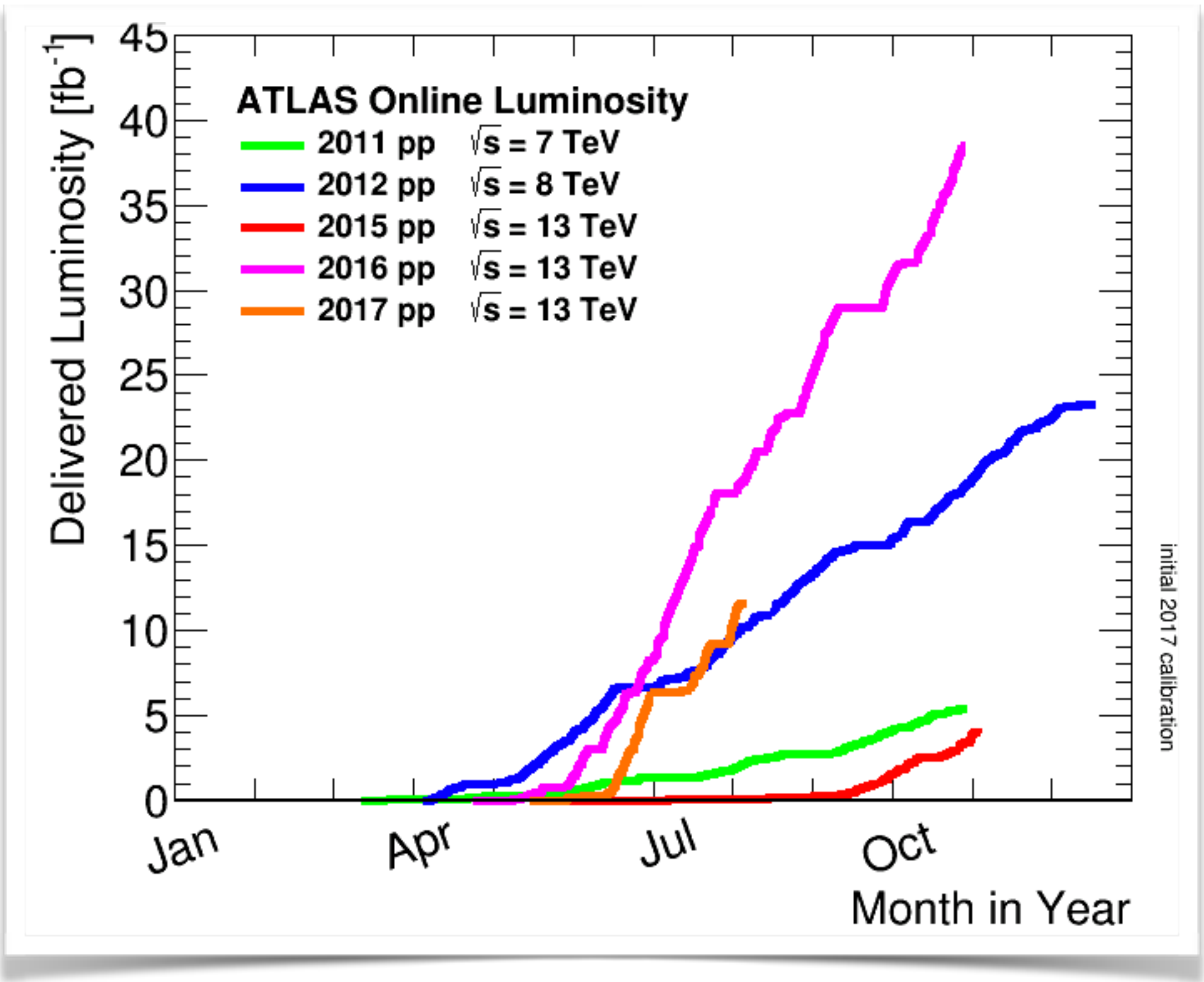
The Large Hadron Collider (LHC)



Side note: Cross-sections and luminosity

Number of events — Integrated Luminosity — Cross-section

$$N = \mathcal{L} \times \sigma$$

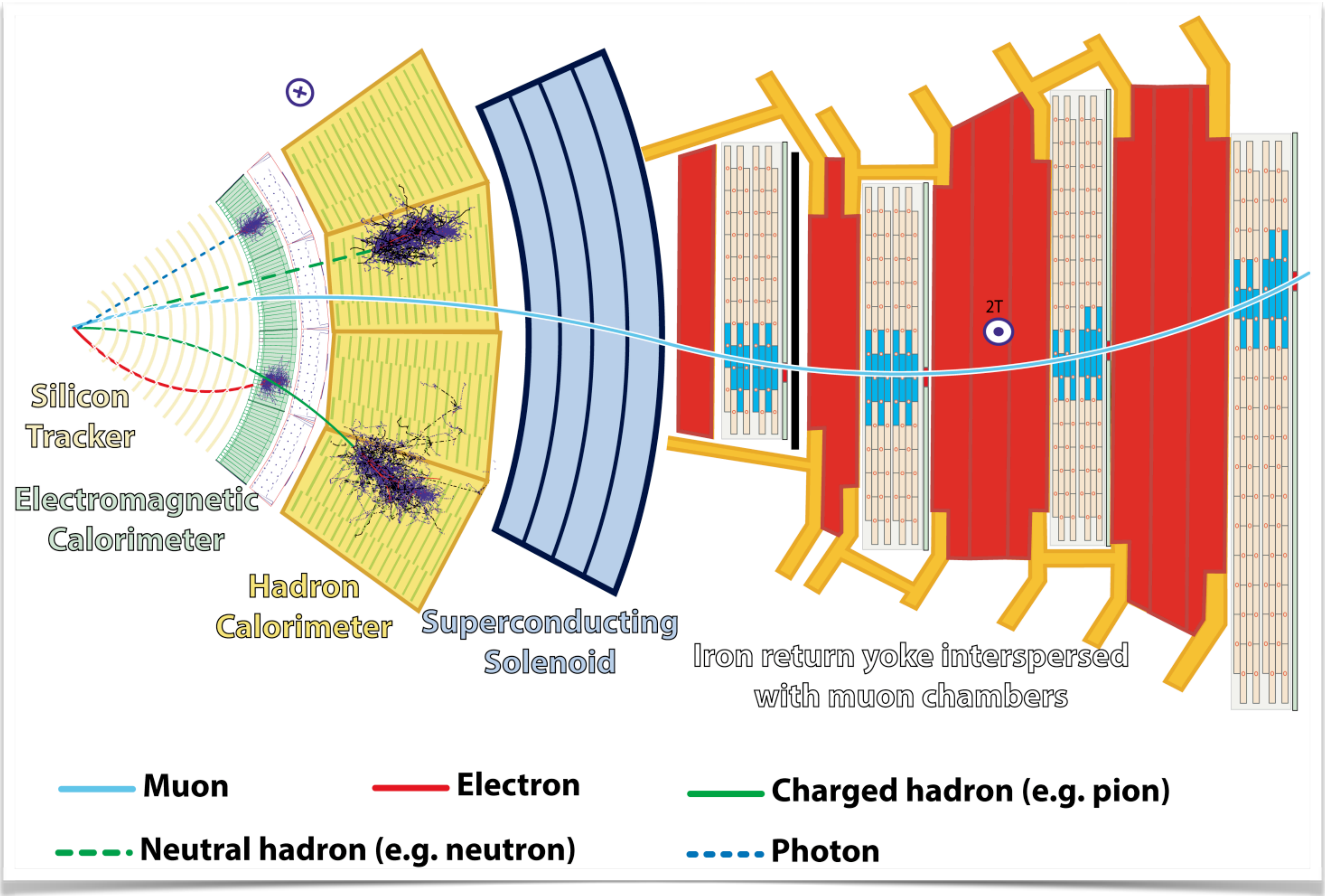


Already ~12 fb^{-1} of 2017 data!

Cross-sections are measured in <u>barns</u>: 1 barn = 10^{-28} m^2 (100 fm^2)

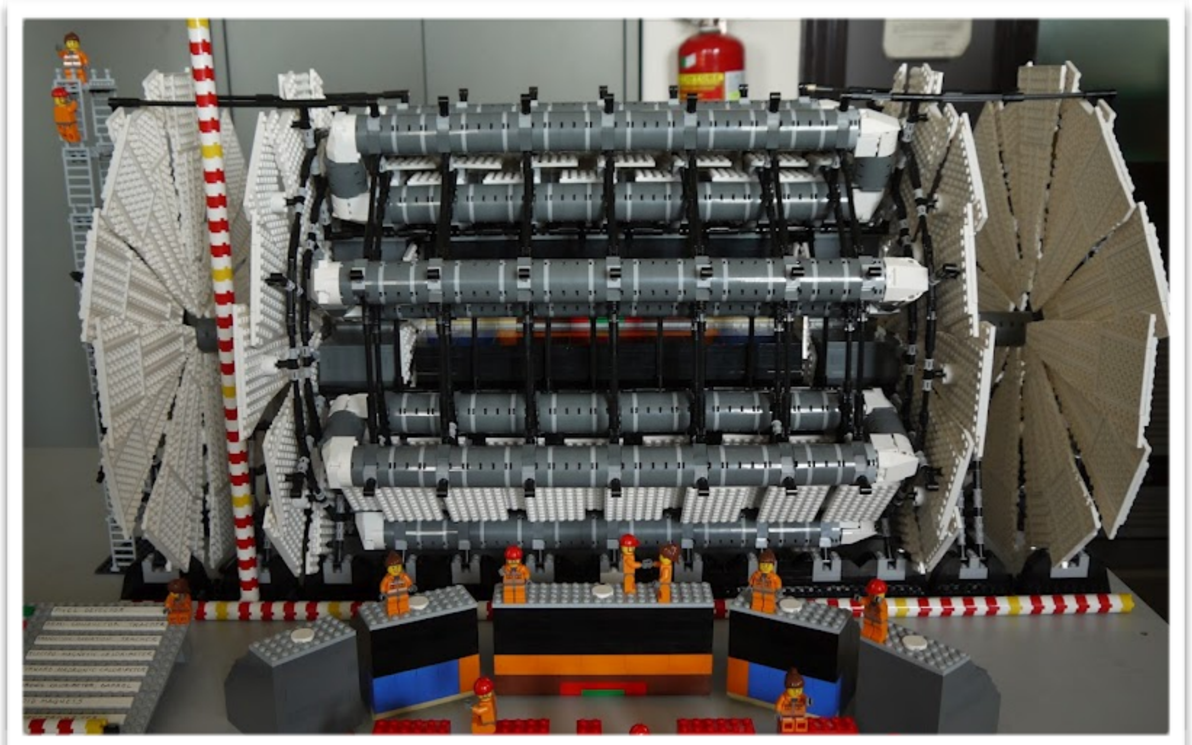
Range at the LHC: mb to fb

Measuring Particles

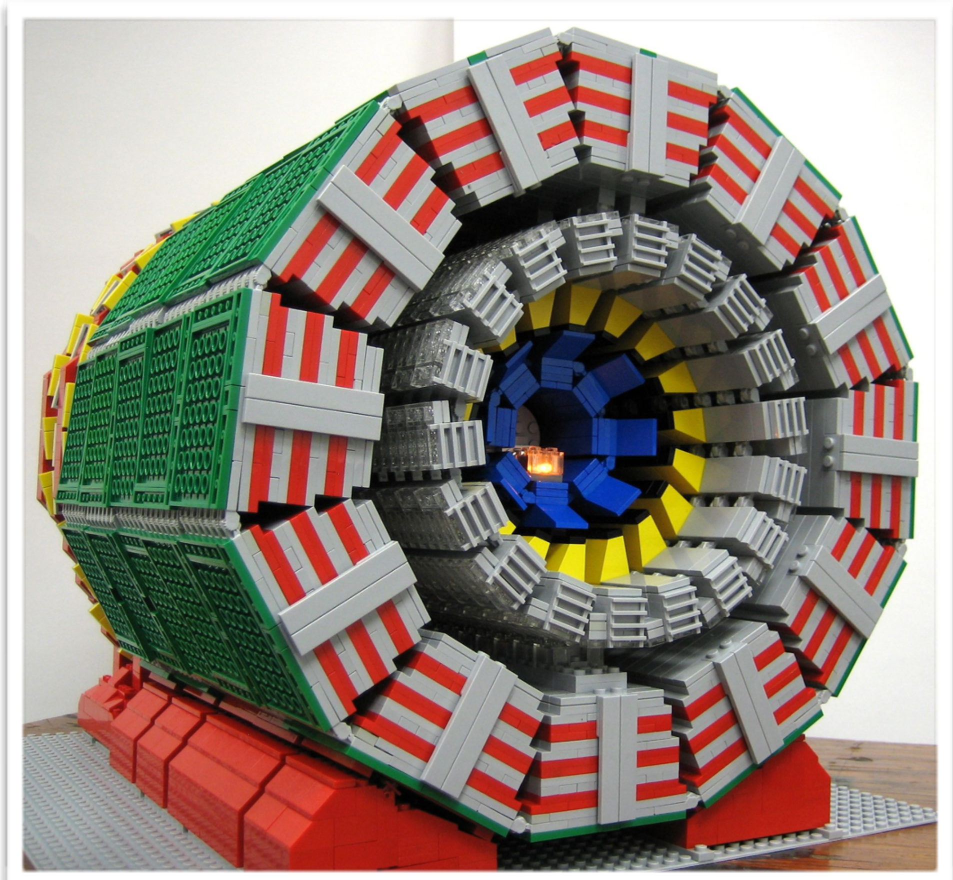


The General Purpose Detectors

ATLAS



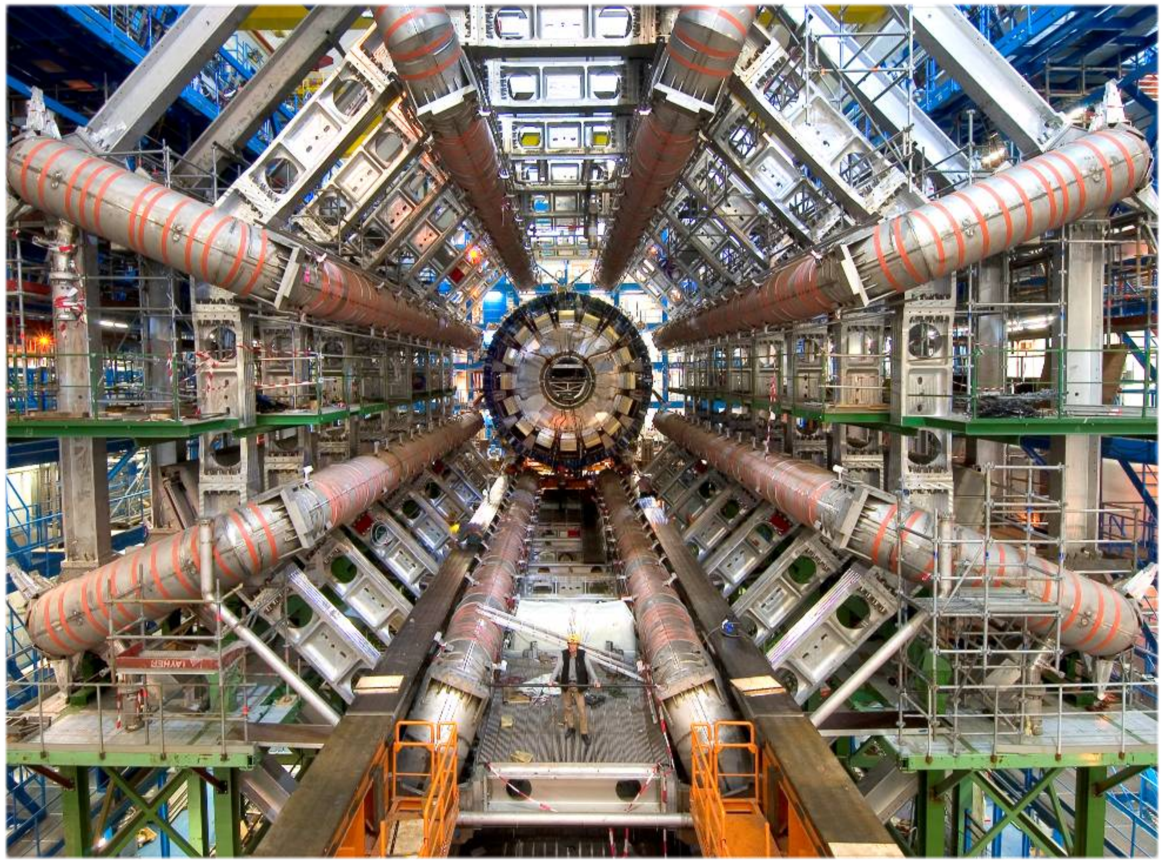
CMS



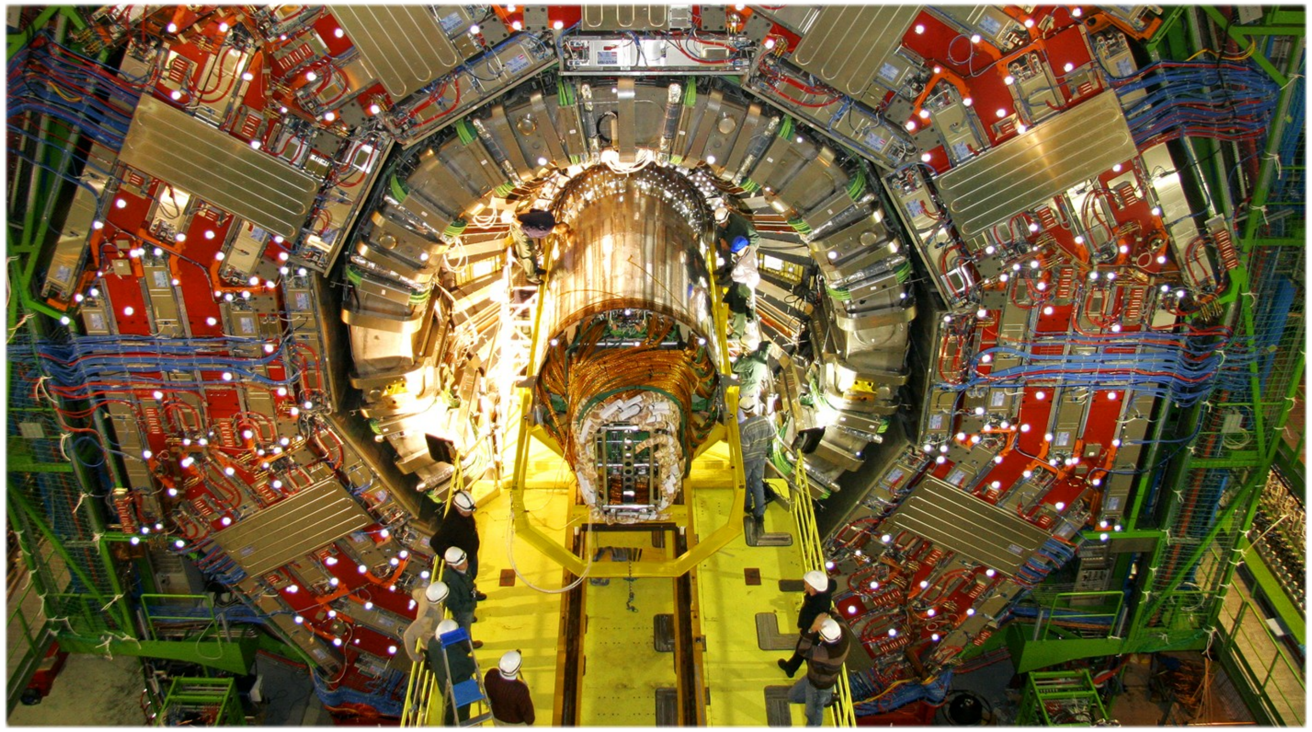
	Weight (tons)	Length (m)	Height (m)
ATLAS	7000	45	21
CMS	12500	25	15

The Detectors

ATLAS



CMS



	Weight (tons)	Length (m)	Height (m)
ATLAS	7000	45	21
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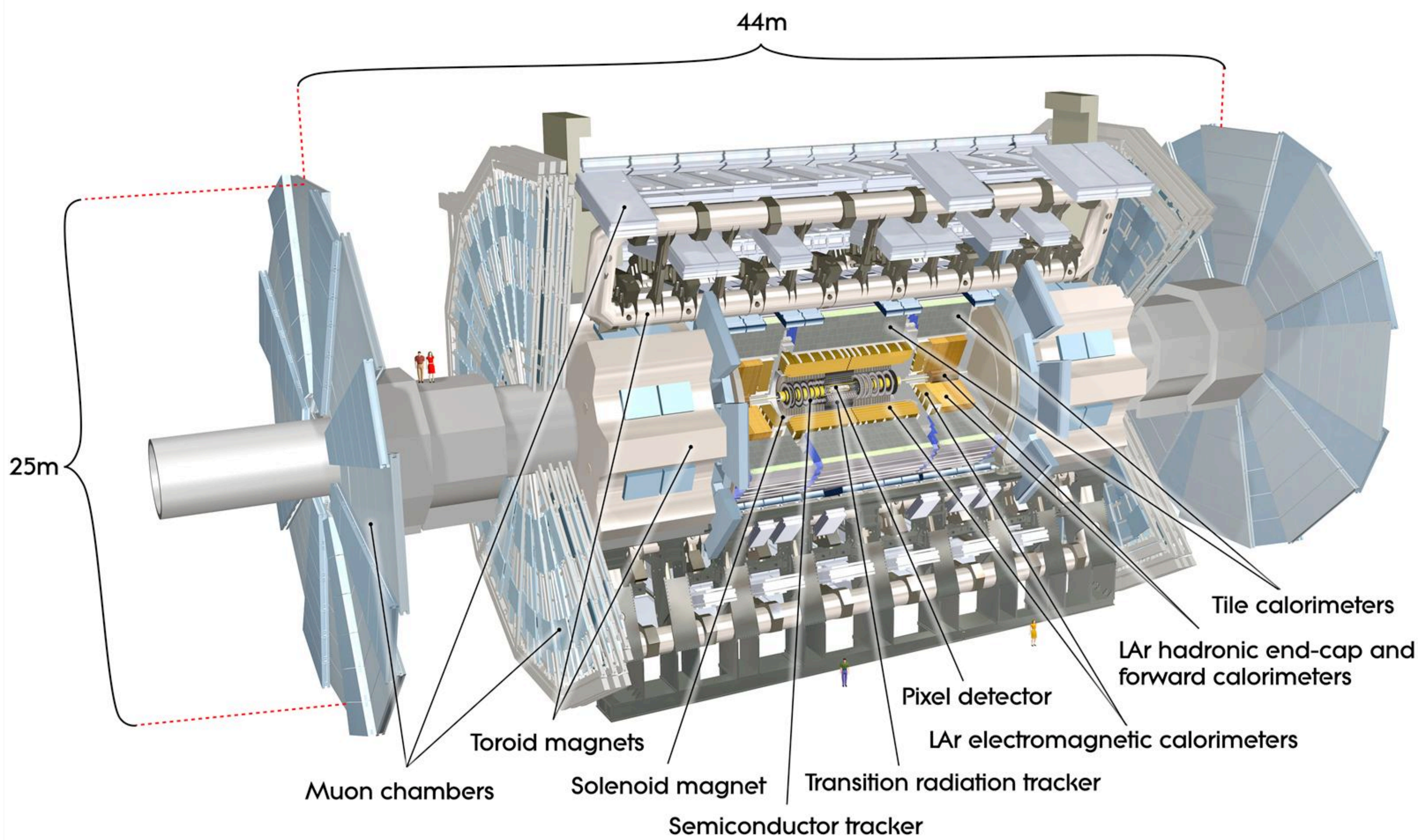
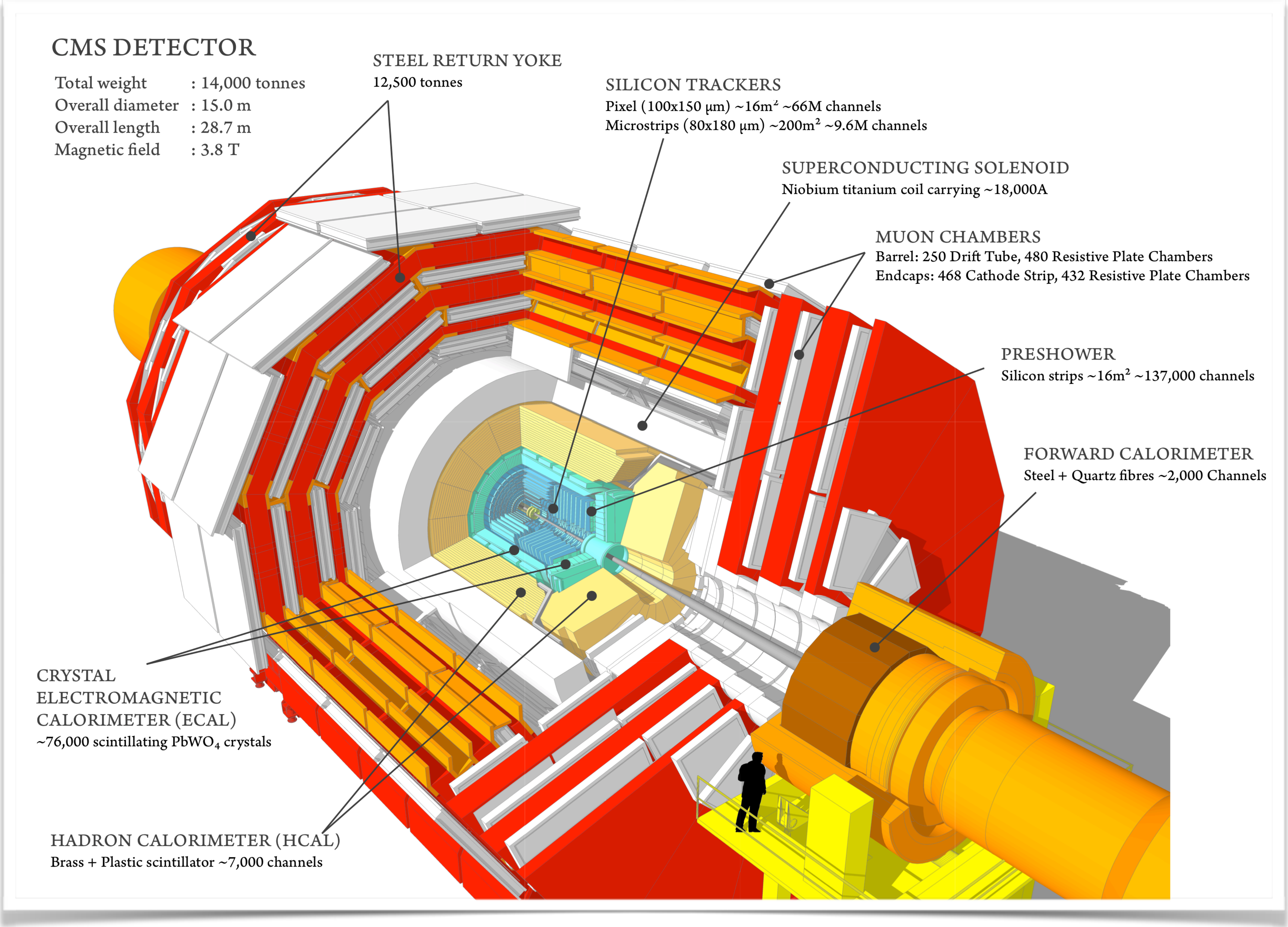
A Large Toroidal ApparatuS (ATLAS)

http://atlas.cern/



The Compact Muon Solenoid (CMS)

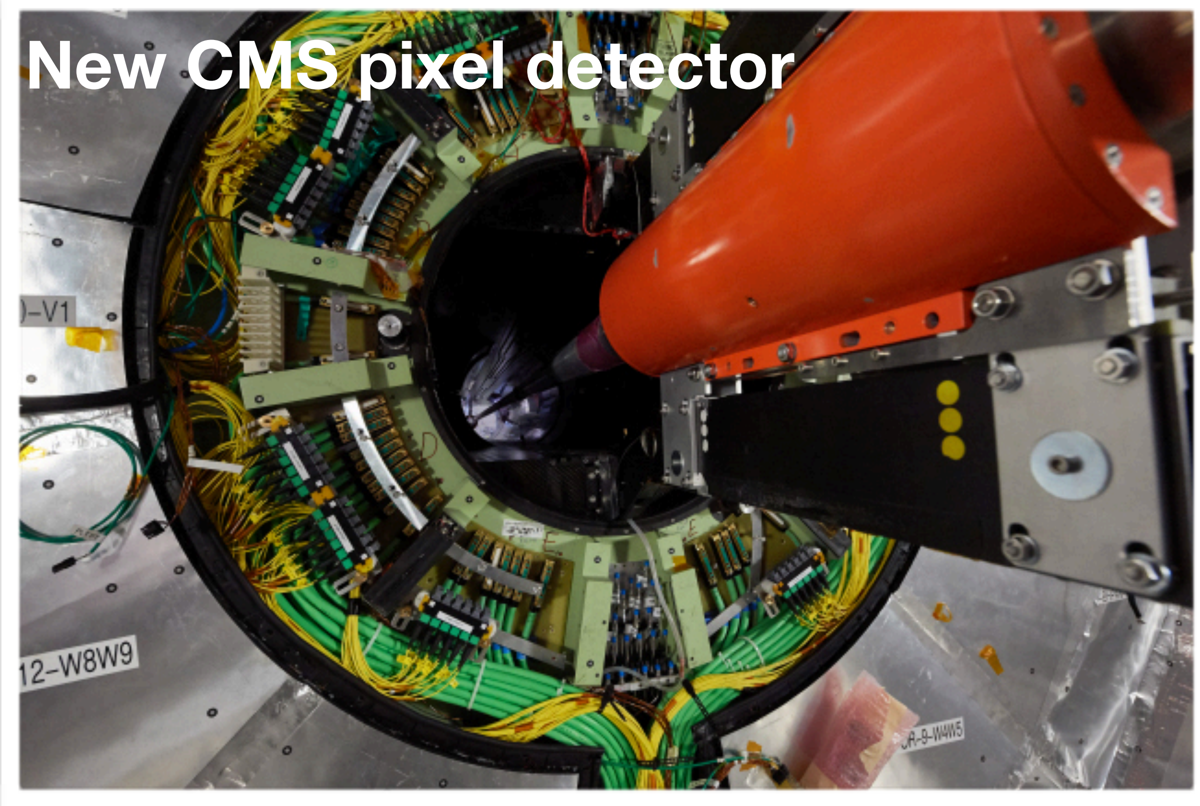
https://cms.cern/detector

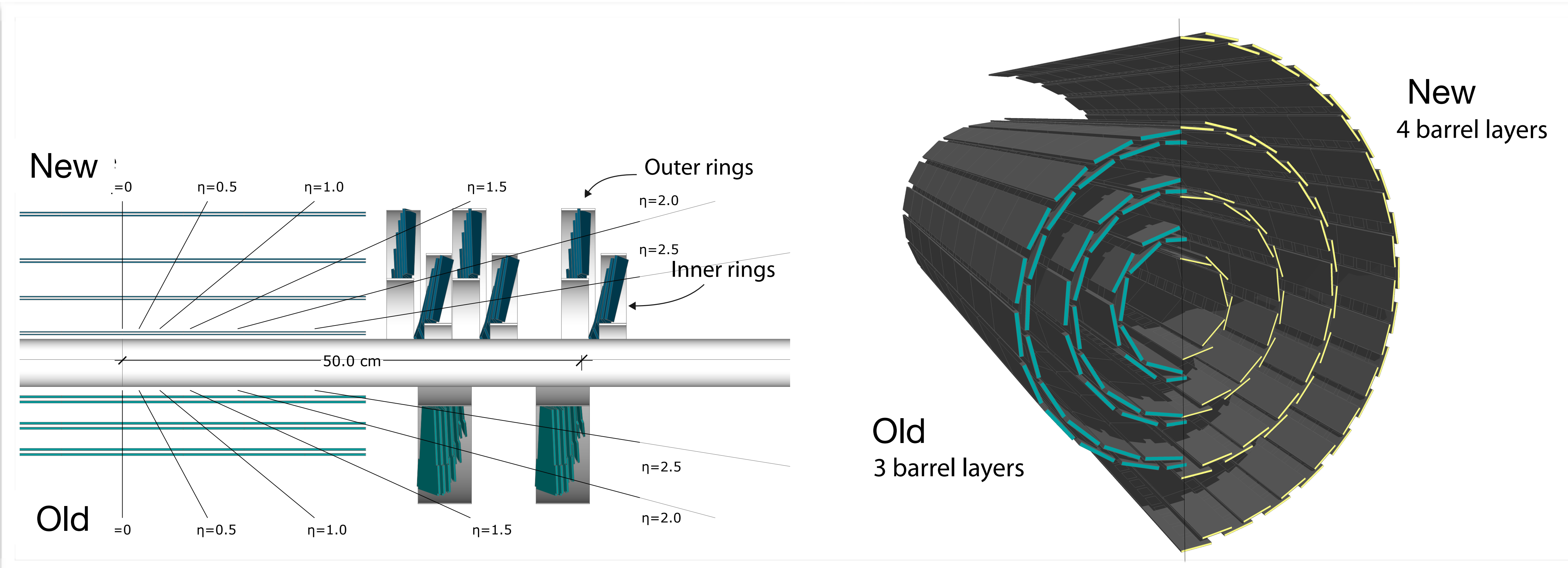


Something new: CMS Pixel Upgrade

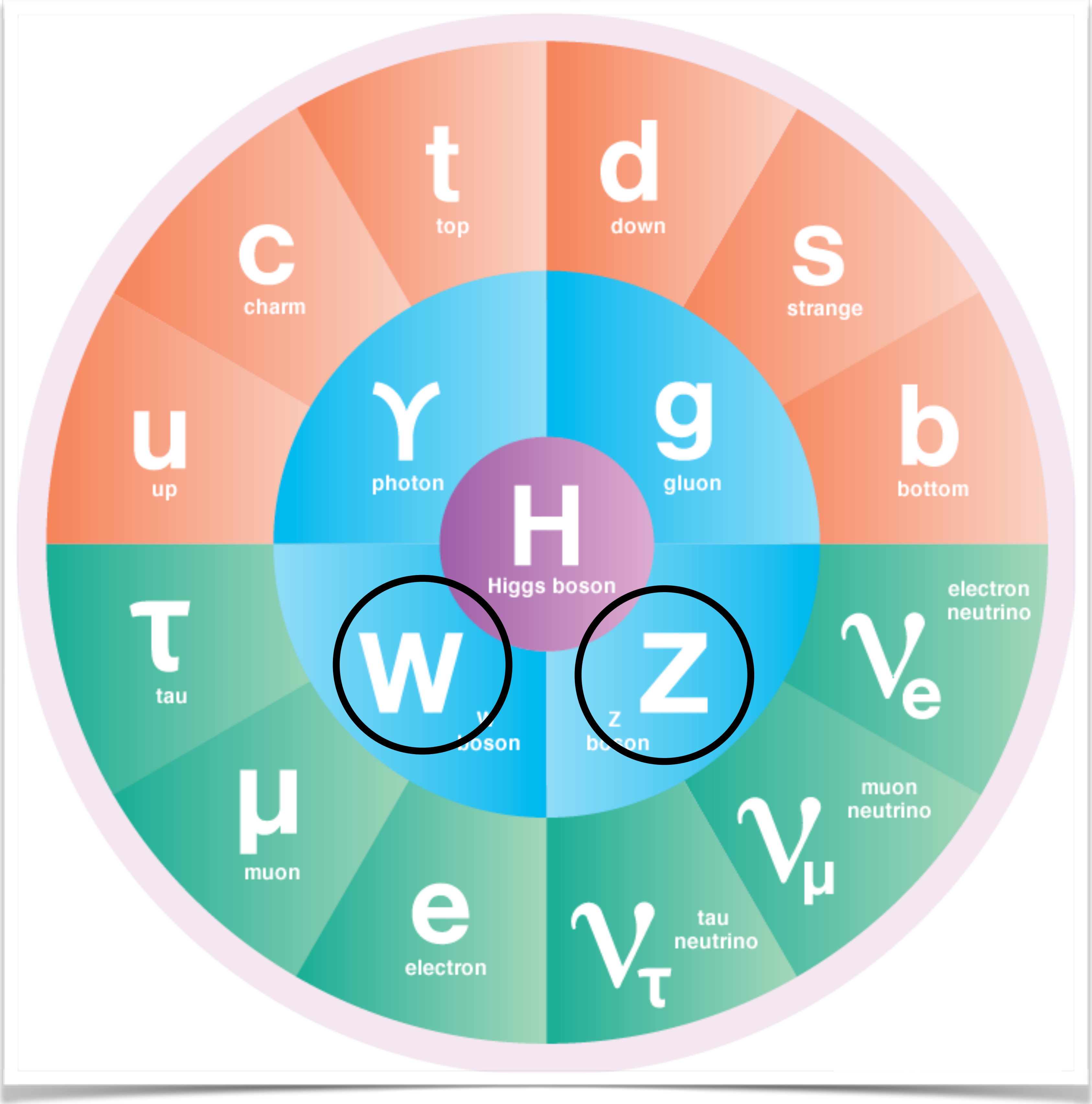
CMS Pixel TDR

- CMS pixel detector was completely replaced during the 2016-2017 shut-down
- Additional pixel layer
  - 3→4 barrel layers (smaller radius)
  - 2→3 end-cap disks
- e.g. 50% improvement in d_0 resolution





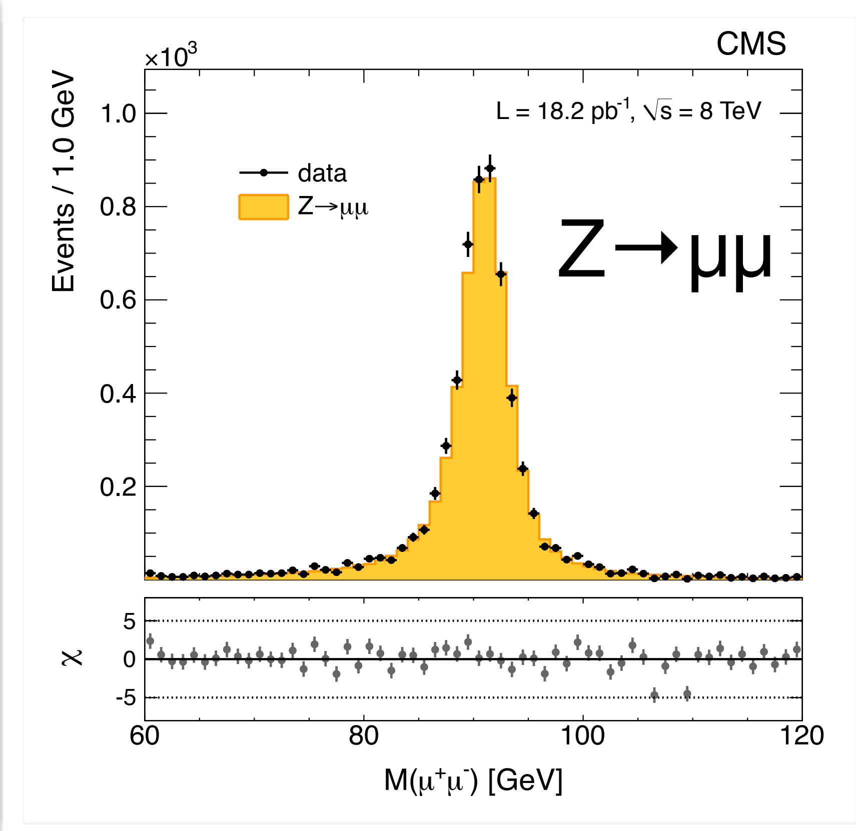
The Vector Bosons

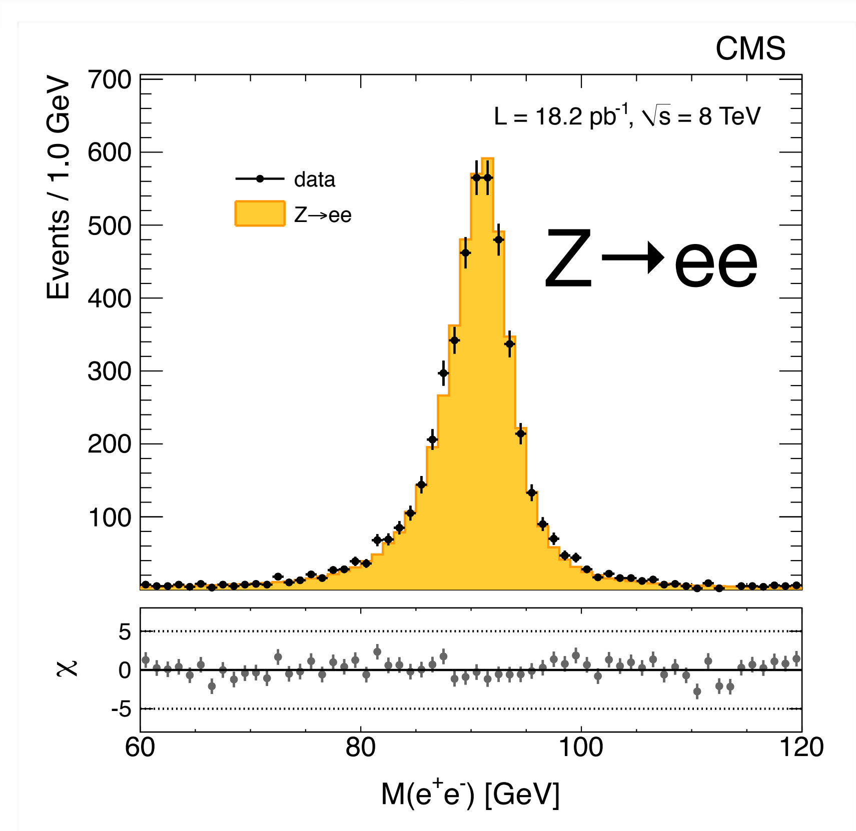


The Z boson

SMP-12-011

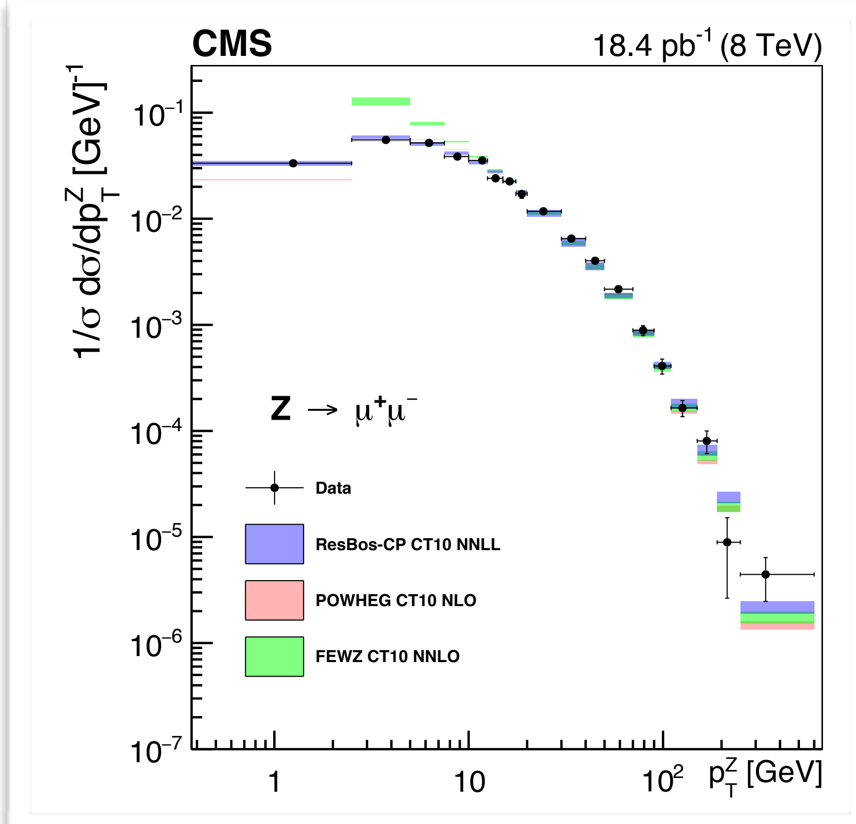
- Discovered in 1983 at the SPS at CERN
- Carrier of the weak force
- Reconstruct from a pair of leptons of the same flavour but with opposite charge typically with $p_T > 20$ GeV
- One of the easiest processes to identify
  - Almost background free
- Widely used for lepton calibration
- Highly accurate tests of the Standard Model

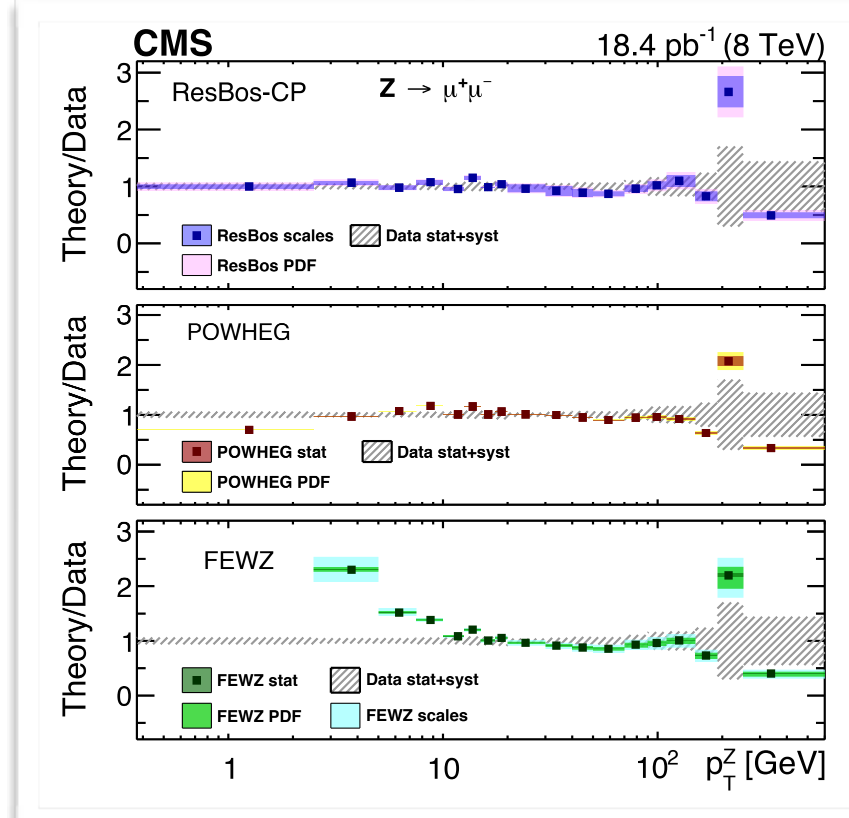




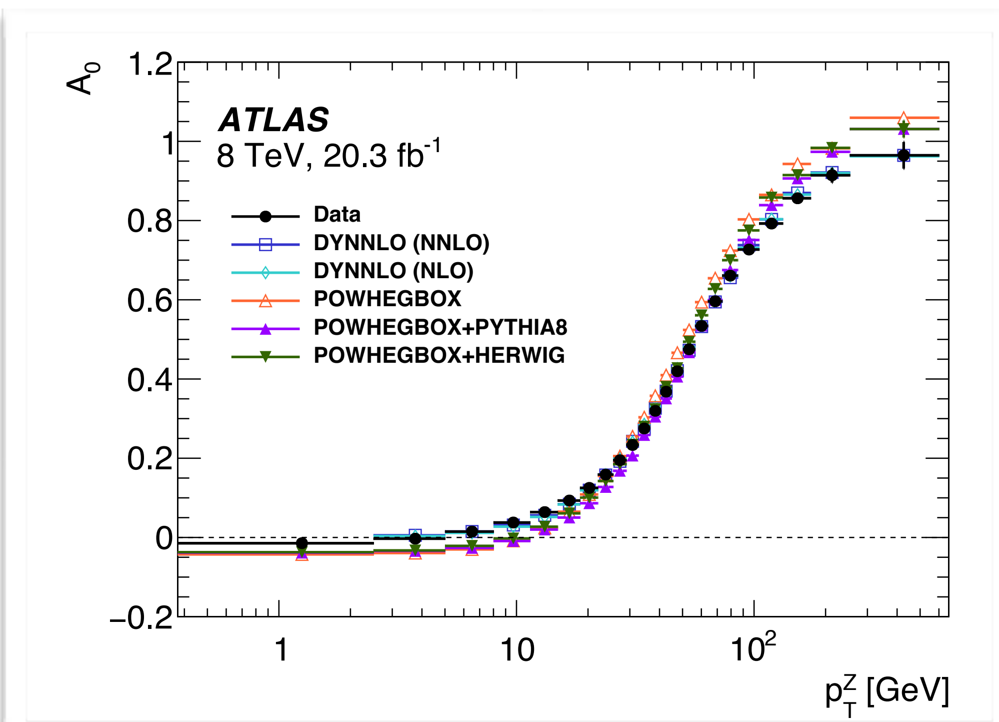
Z Boson Properties

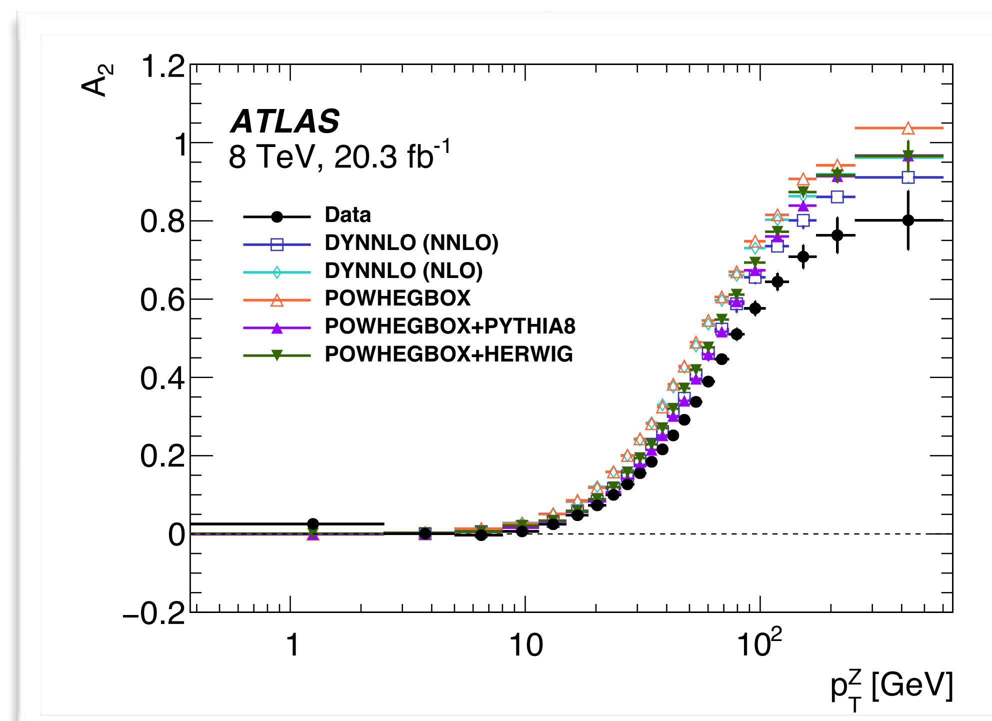
Precise measurement of the p_T distribution





Measure Z boson angular distributions to probe QCD dynamics

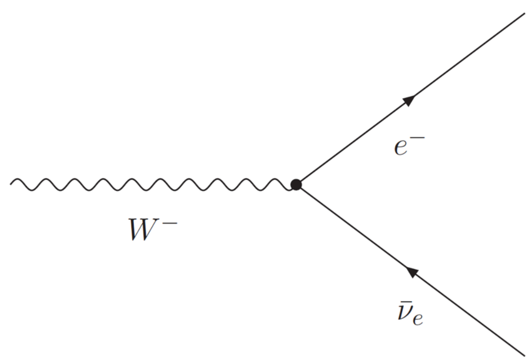




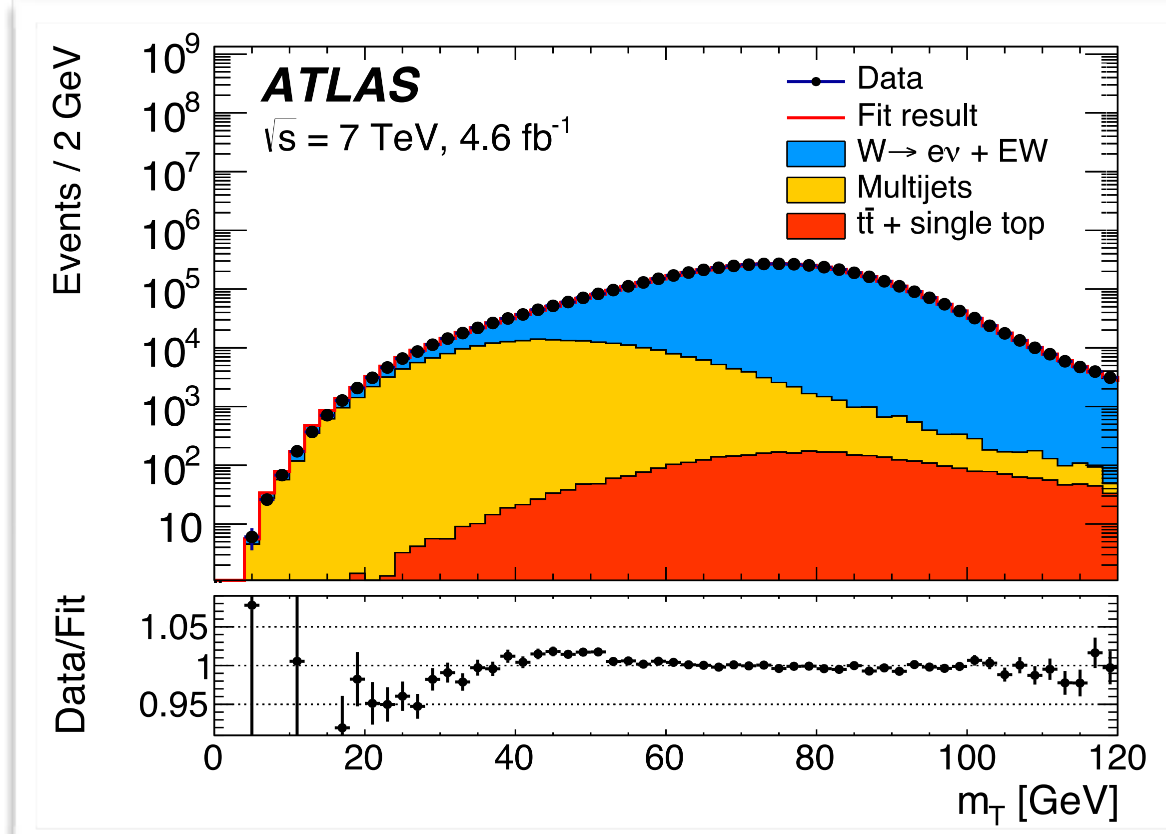
The W boson

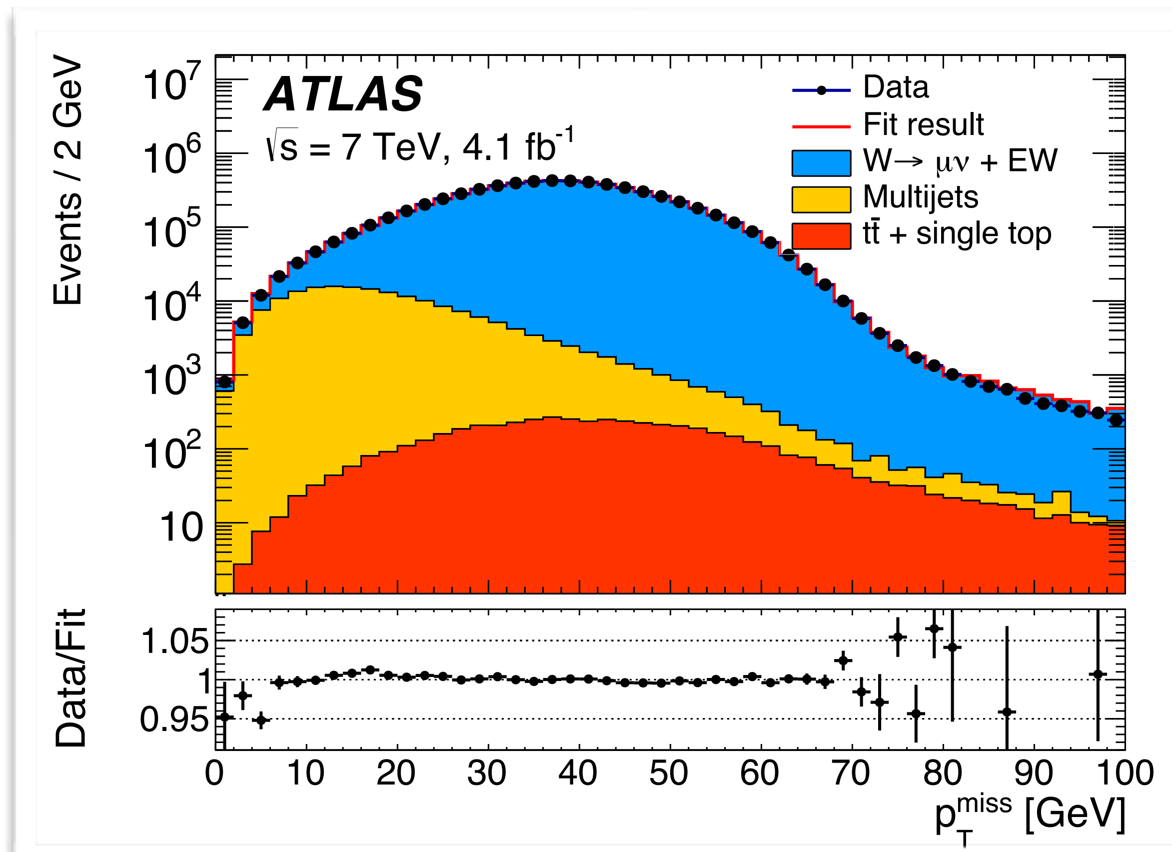
STDM-2014-18

- Also discovered in 1983 at the CERN SPS
- Other weak force mediator
- Most precise measurements reconstruct W boson from decay to a lepton and a neutrino



- Cannot reconstruct the full mass because the neutrino is only detected indirectly (missing energy)
- Backgrounds from multijet (fake lepton) and top quarks



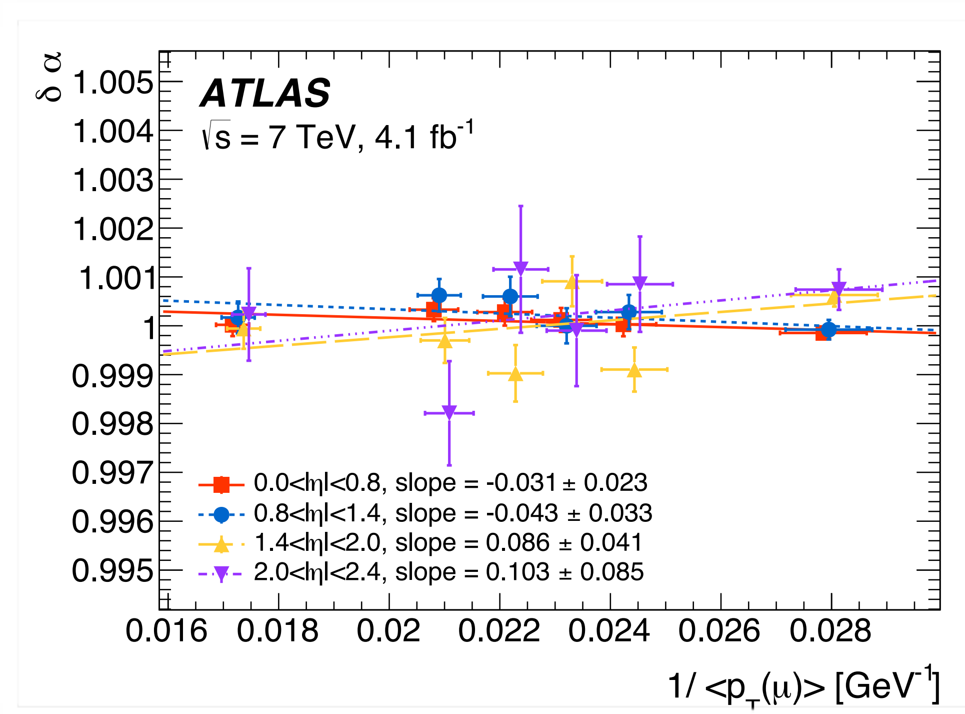


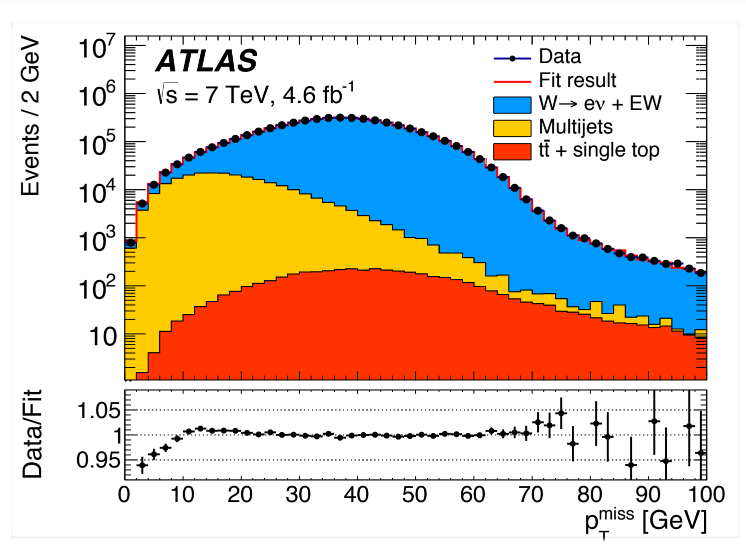
The W Mass

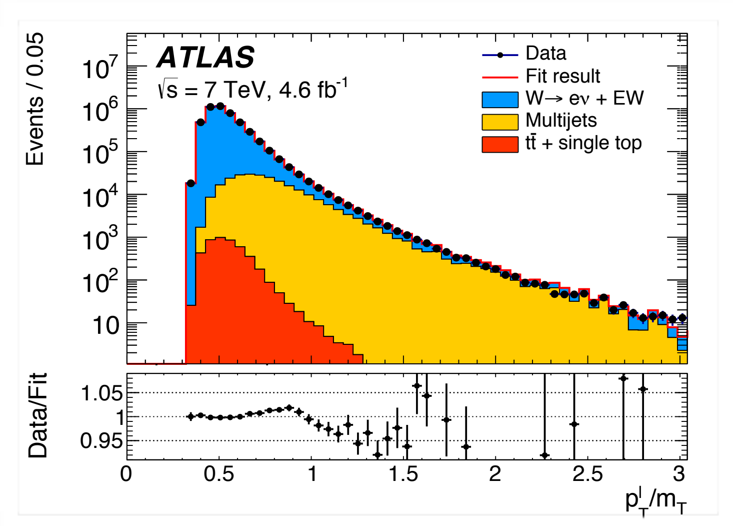
STDM-2014-18

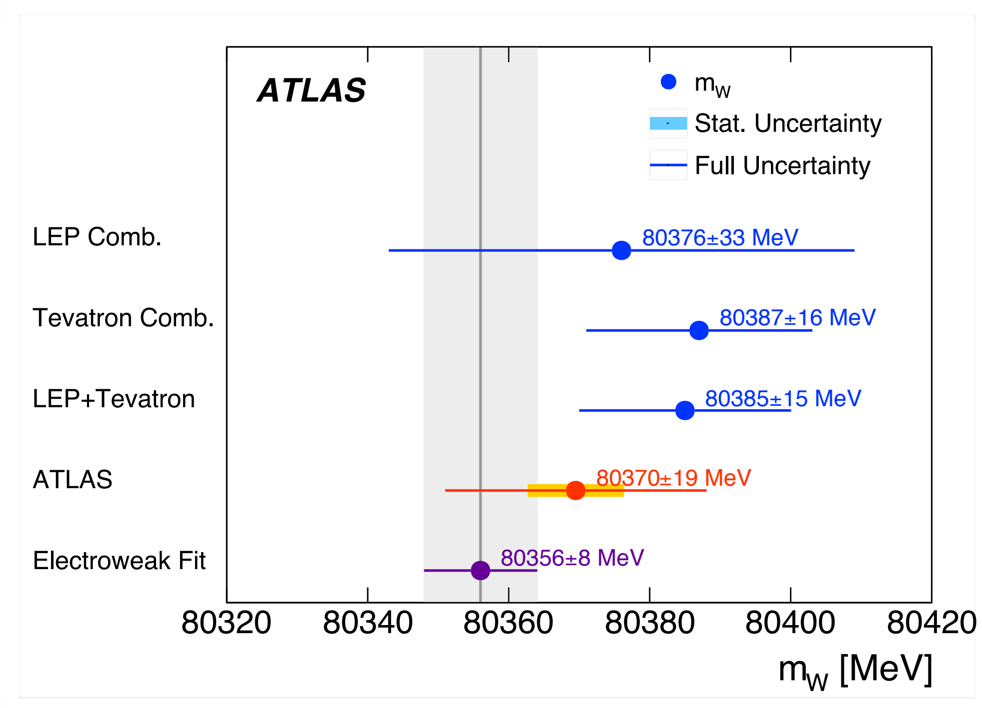
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu}$$

- Precision measurement of W mass tests consistency of Standard Model
- Extremely challenging measurement at a hadron collider
- Template fit to distributions sensitive to the W mass
- Requires careful calibration and detailed understanding of reconstructed objects
- m_W = 80370 ± 19 MeV





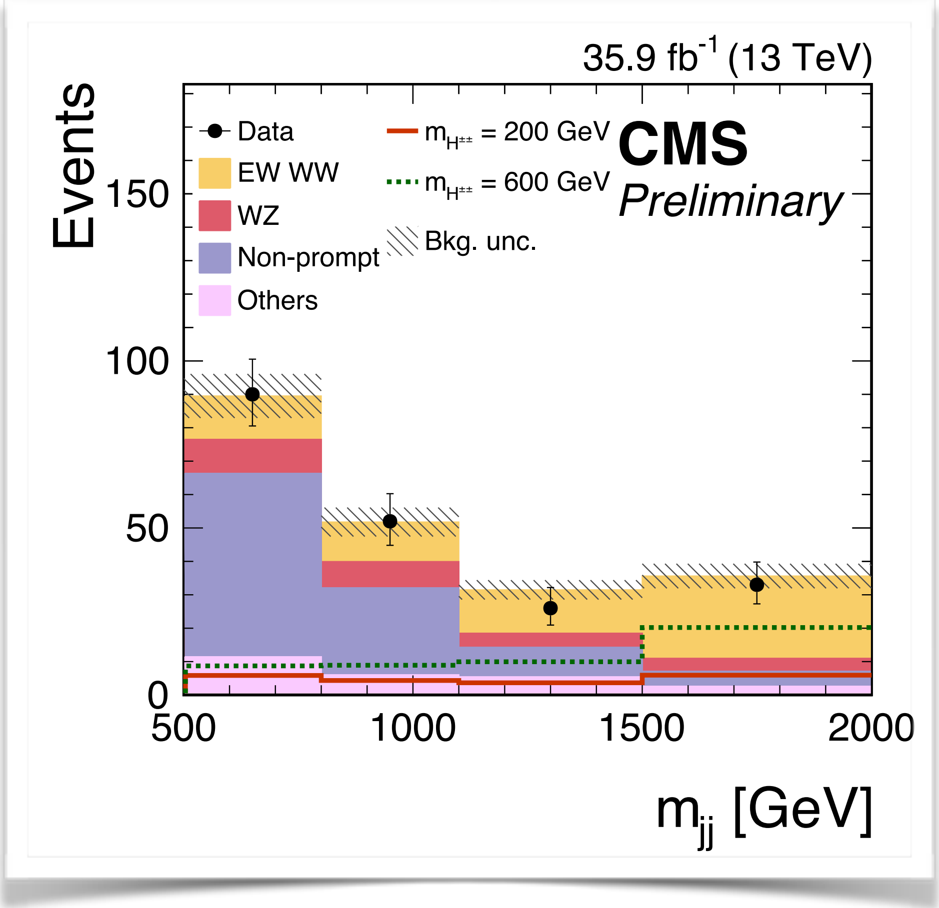


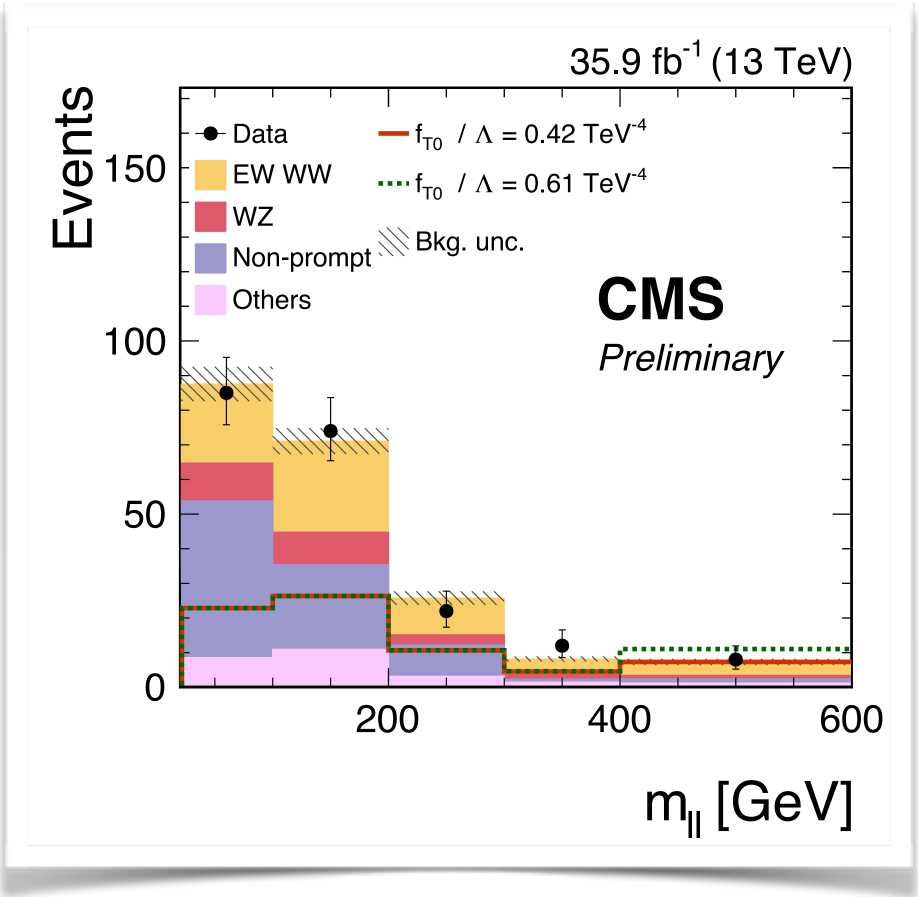


Observation of WW scattering

SMP-17-004

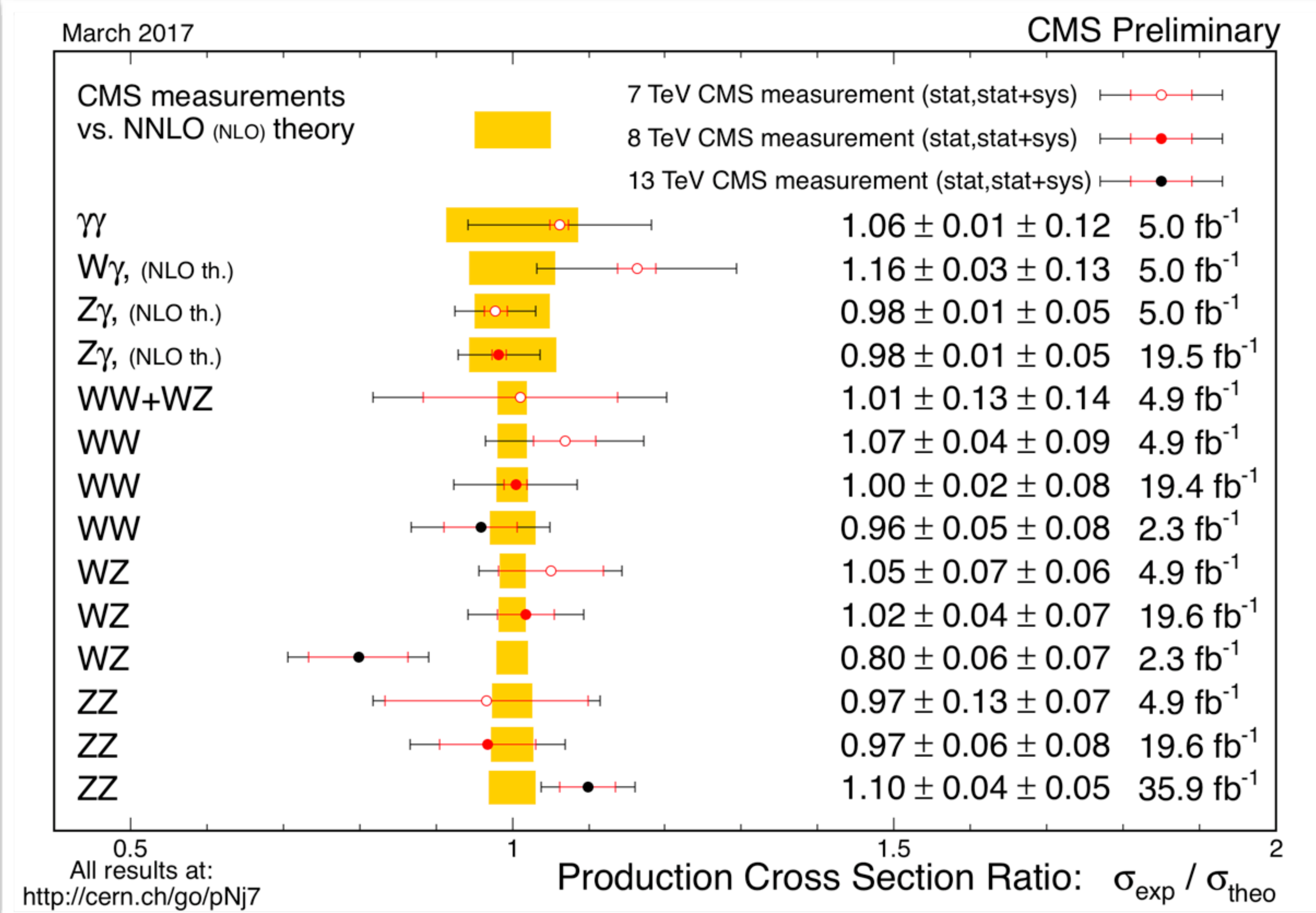
- In the SM without the Higgs, the cross-section for WW scattering was predicted to diverge at high energies
  - One component of the "no lose theorem" which argued that the LHC had to find something
- Exactly two leptons of the same charge and two jets with a rapidity gap
- Counting experiment in 6 categories by lepton flavour
- Observed (expected) significance is 5.5 (5.7)σ





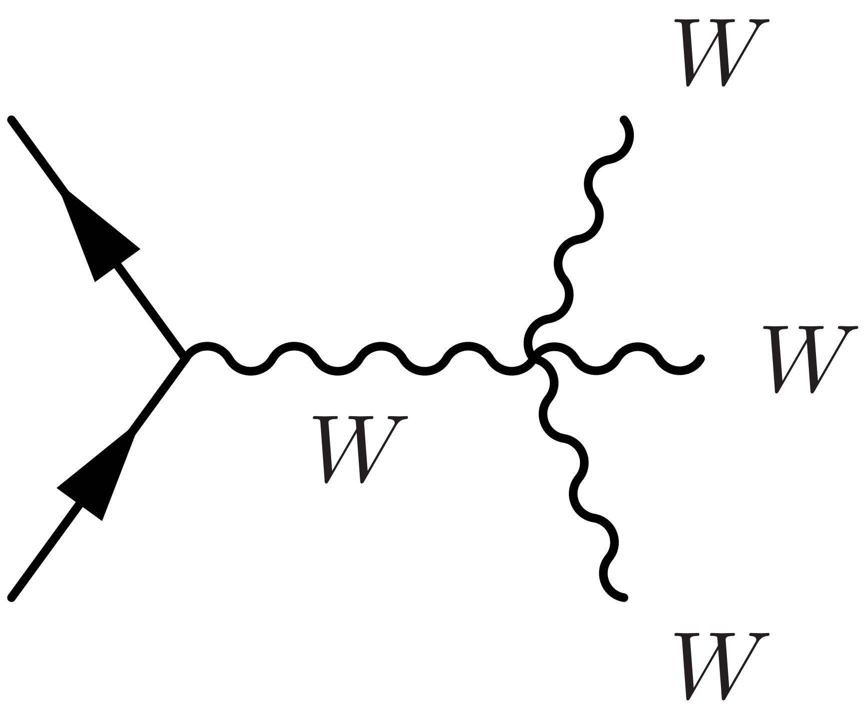
First observation of same-sign WW scattering!

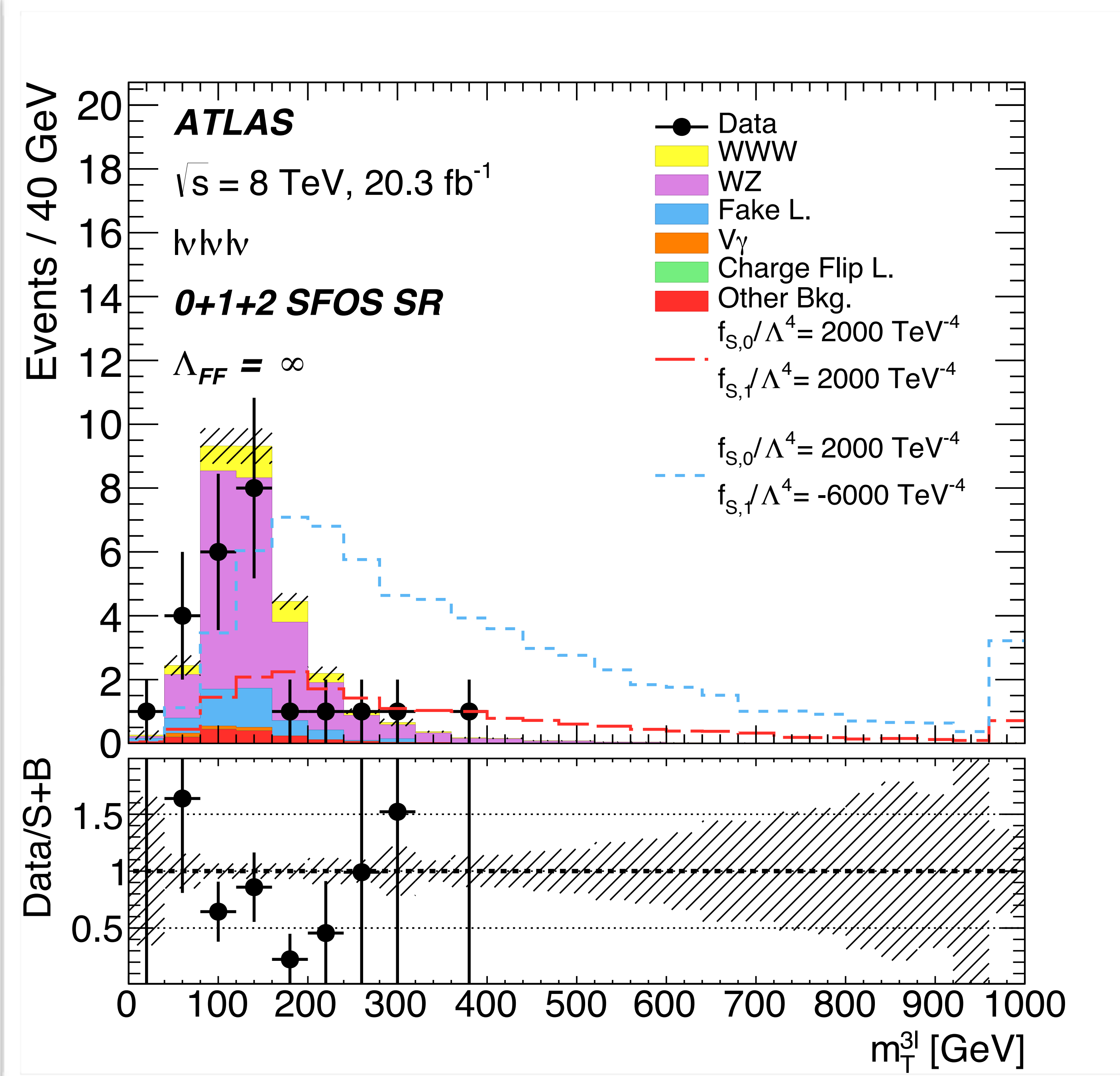
More than one: Diboson Results



Massive Triboson ?

STDM-2015-07



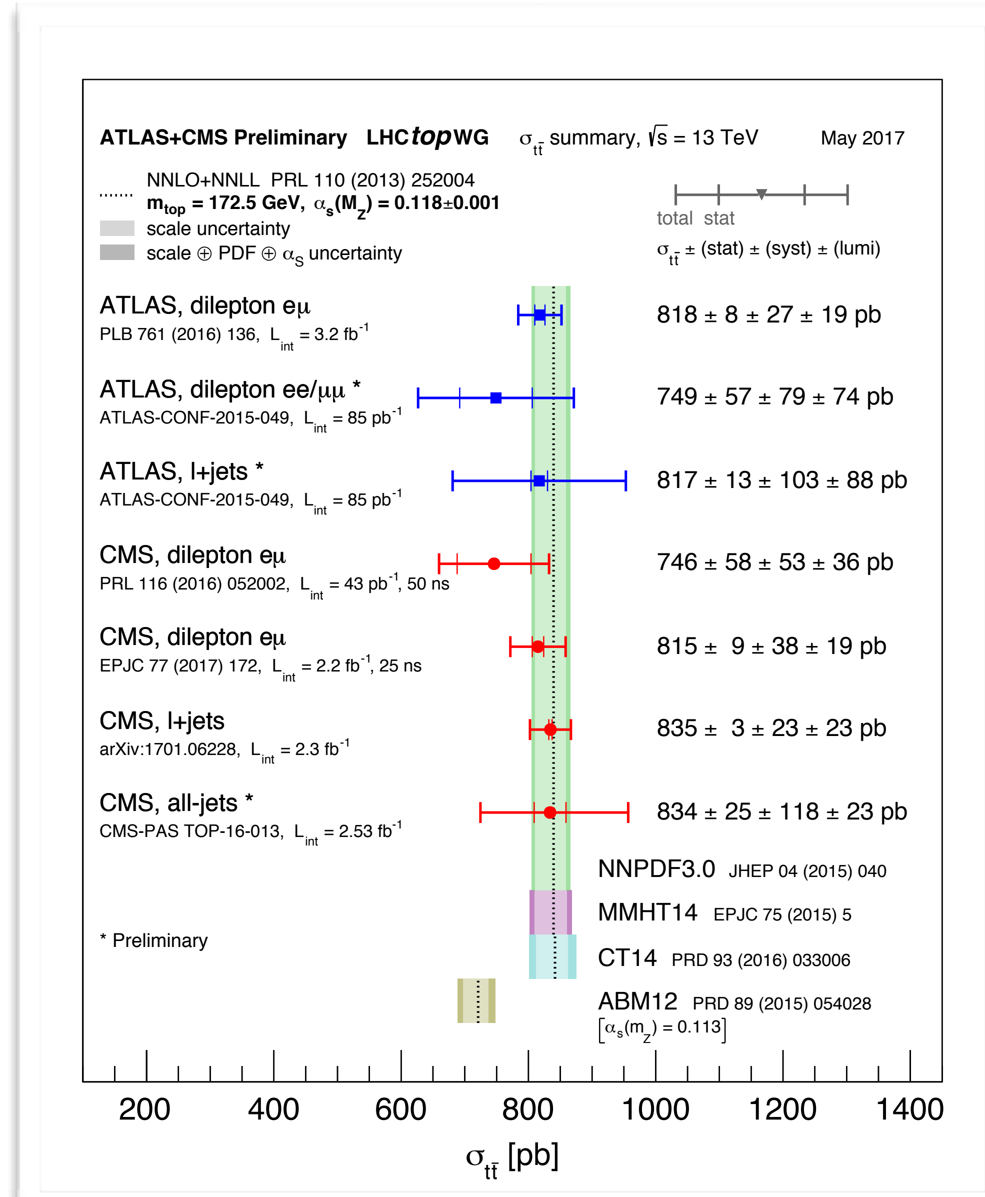


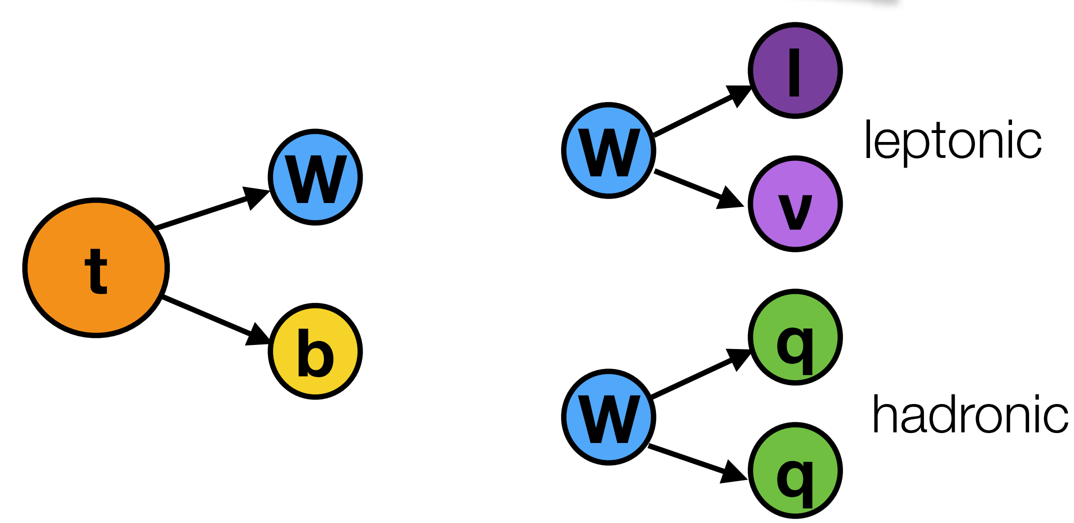
- Currently only a limit from ATLAS on WWWW coupling

The Top Quark

The Top Quark

- The heaviest particle in the Standard Model with a Yukawa (Higgs) coupling of ~1
- Discovered at the Tevatron, but large production rate at the LHC allows its properties to be studied in detail
- Typically study ttbar production
- Each top decays to a W-boson and a b-quark
  - Either leptonic or hadronic W decay
- Production cross-section measured to 4%
  - Consistent with theoretical predictions

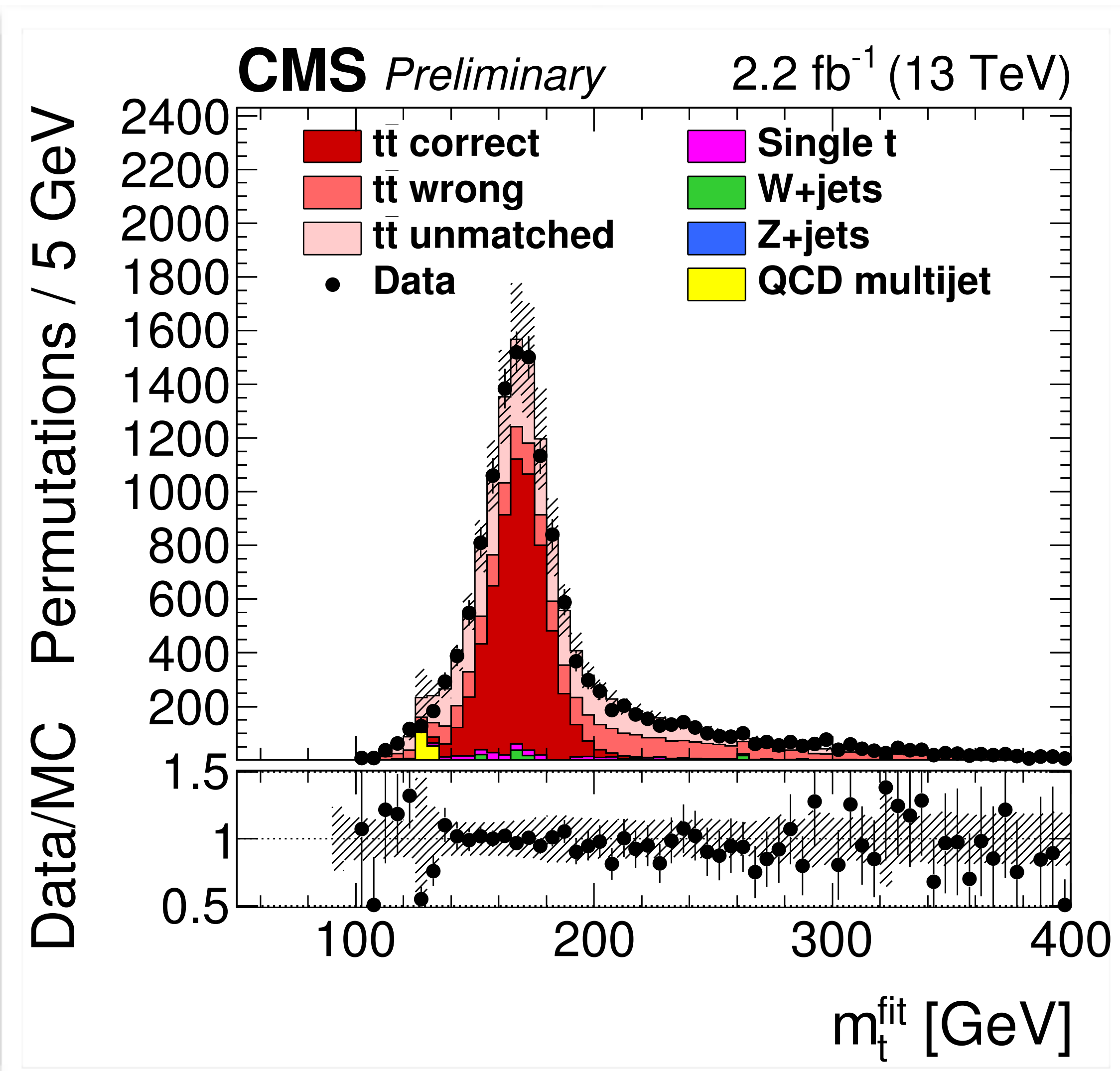


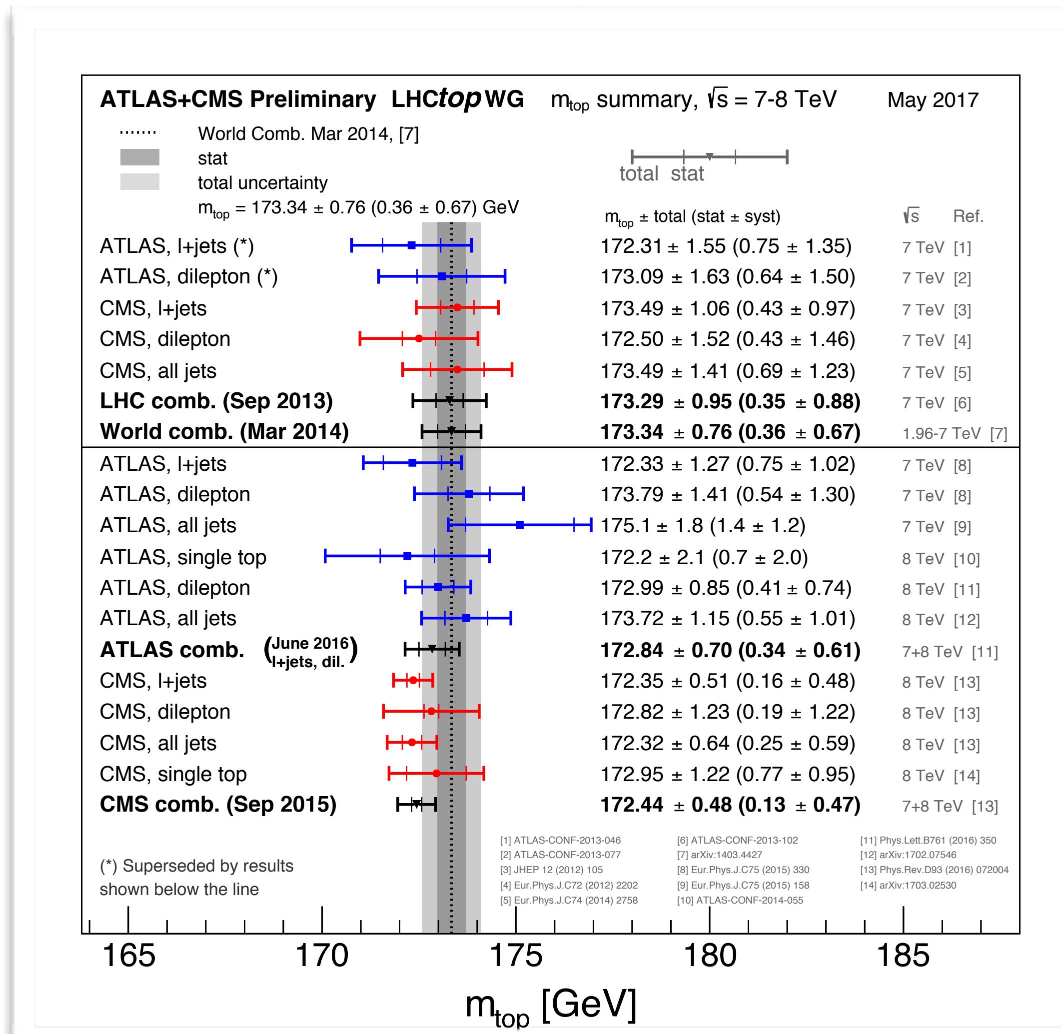


The Top Mass

TOP-16-022

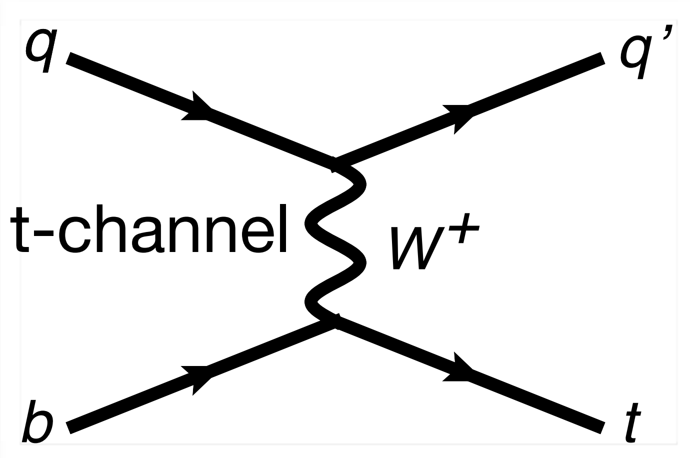
- Another key parameter of the Standard Model
- Measured using analogous techniques to the W mass measurement, but more challenging as it requires both leptons and jets
- Theory interpretation is challenging
  - Measured top mass ≠ theoretical pole mass

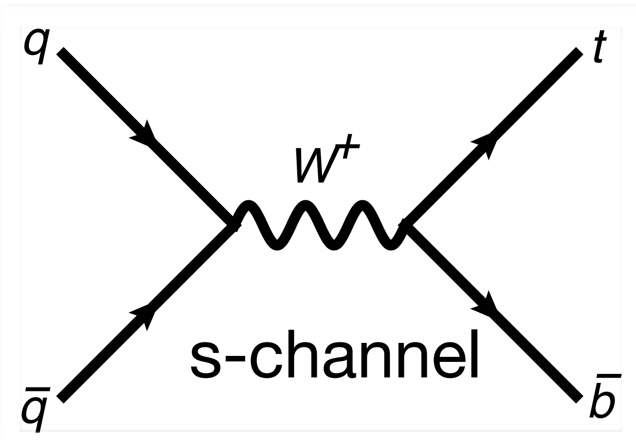


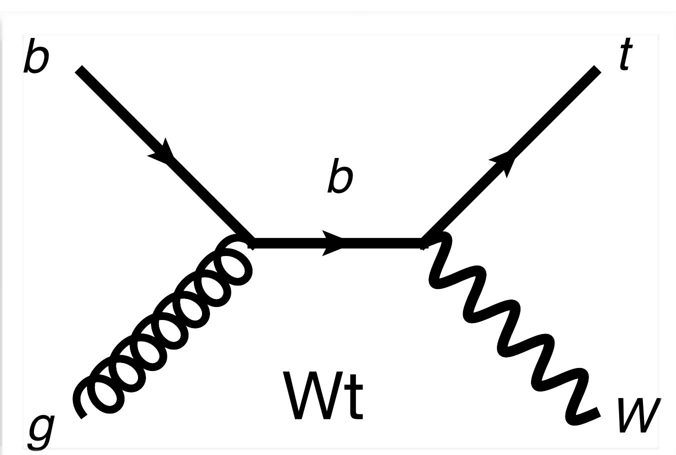


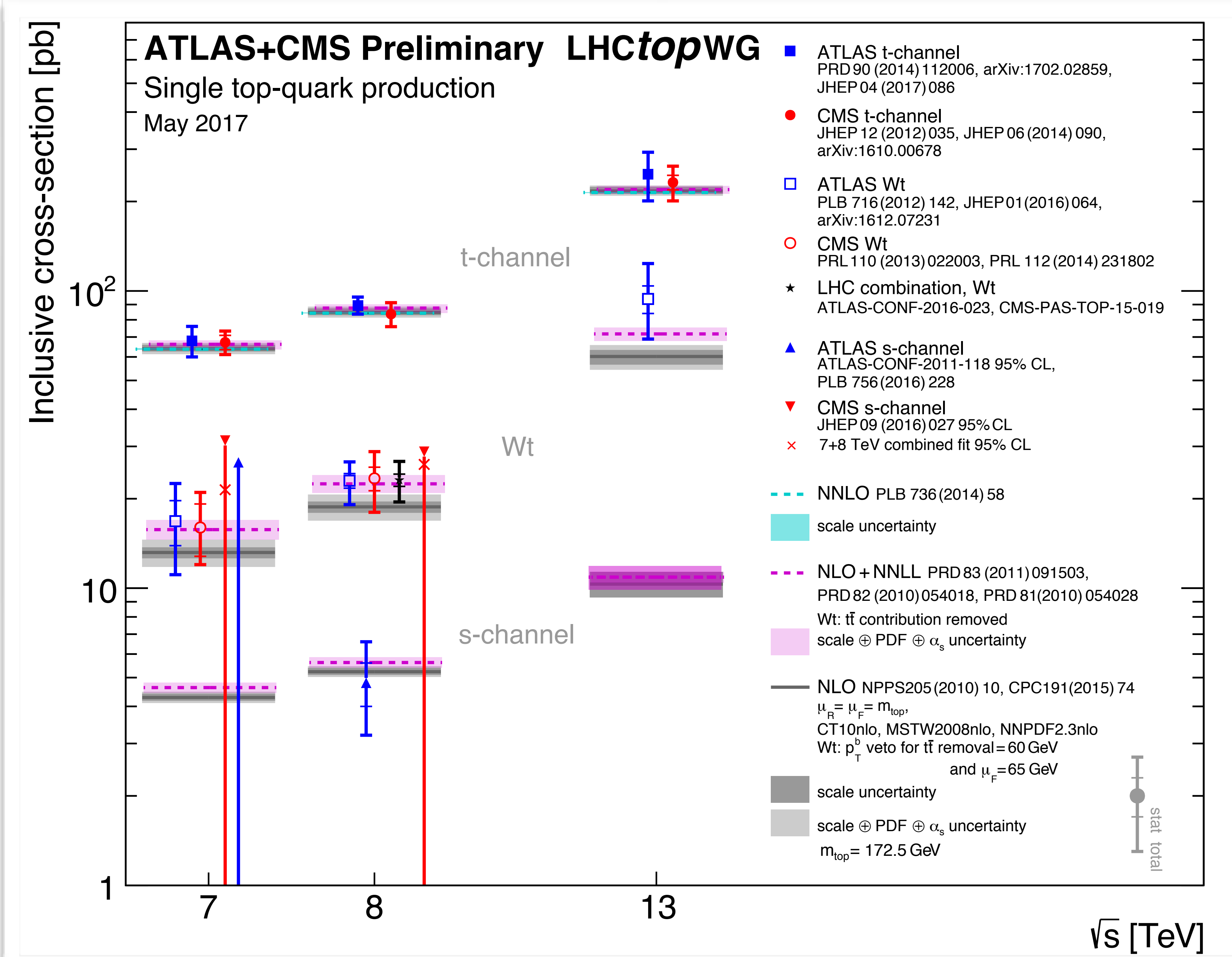
Single top production

Measurements of the top produced by itself









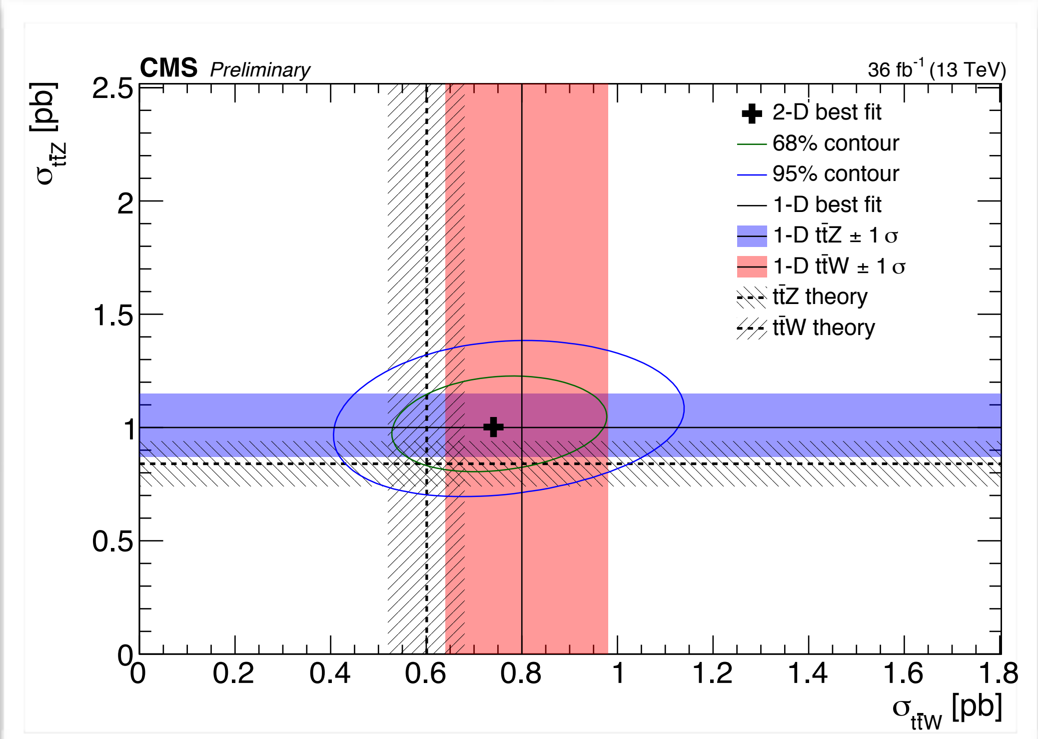
Top and other particles

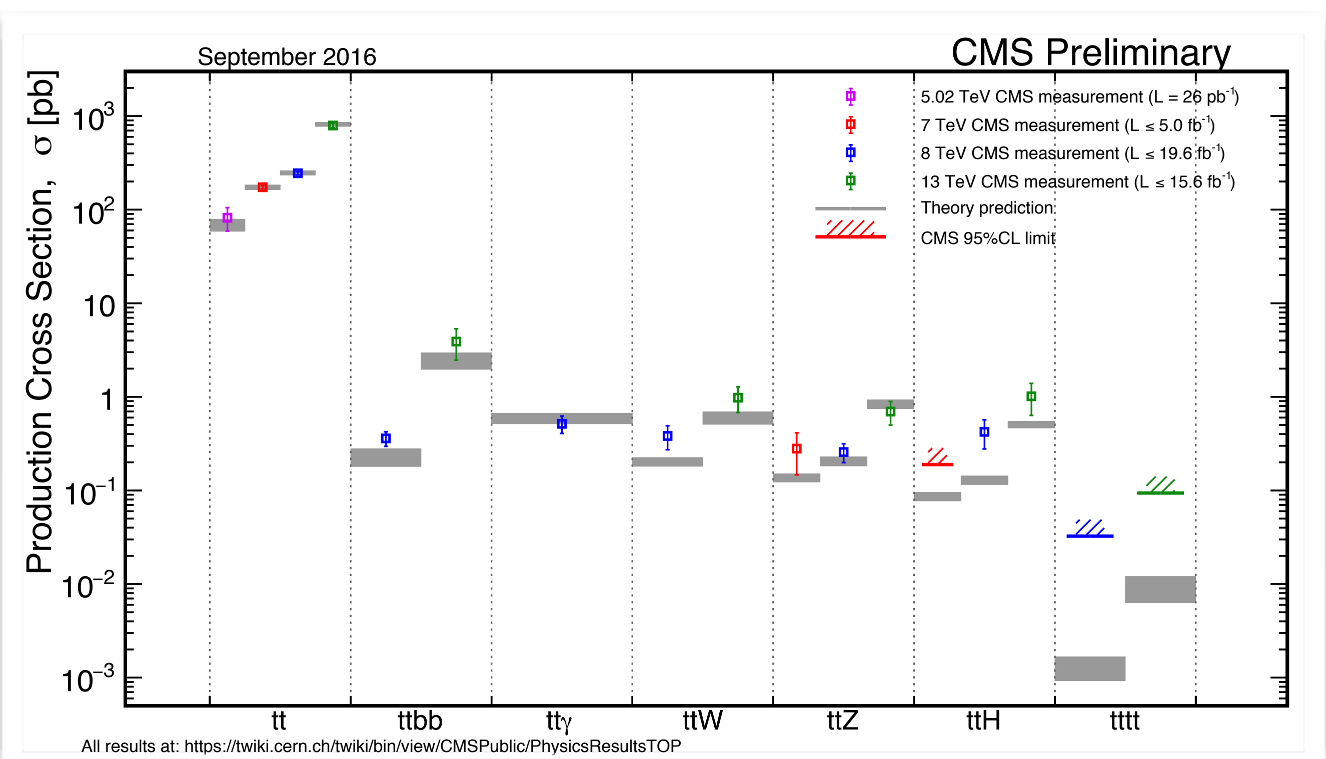
TOPQ-2015-21
TOP-17-005

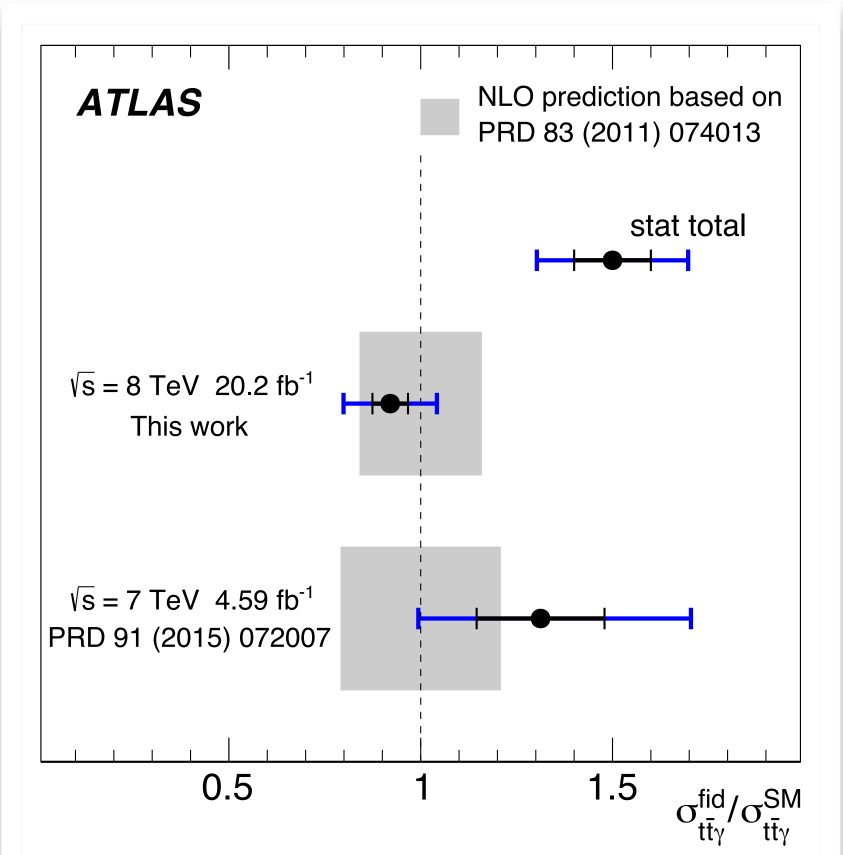
- Probe the production of the top together with other particles
- Measurement of ttW and ttZ cross-sections:

$$\sigma(t\bar{t}W) = 0.80^{+0.12}_{-0.11}\ (\text{stat.})\ ^{+0.13}_{-0.12}\ (\text{sys.})\ \text{pb} \qquad \sigma(t\bar{t}Z) = 1.00^{+0.09}_{-0.08}\ (\text{stat.})\ ^{+0.12}_{-0.10}\ (\text{sys.})\ \text{pb}$$

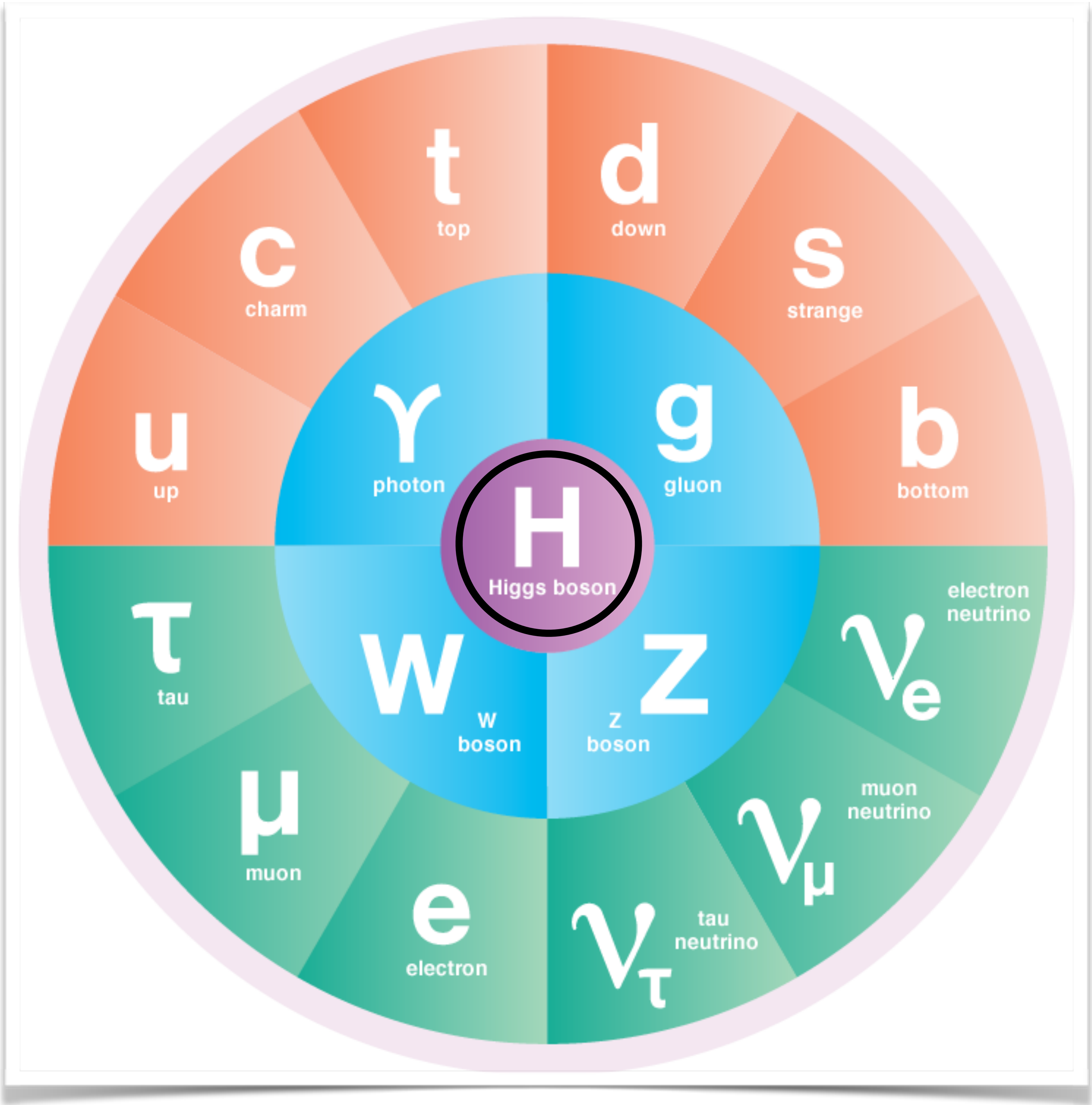
- Measurement of ttγ cross-section
  - 139±7(stat.)±17(syst.) fb







The Higgs Boson



The Higgs Boson

- Predictions date from the 1960s
- Discovered at CERN by ATLAS and CMS in 2012
- Only known elementary scalar
- Particle associated with the Higgs mechanism which provides elementary particles with their mass

H^0 $J = 0$

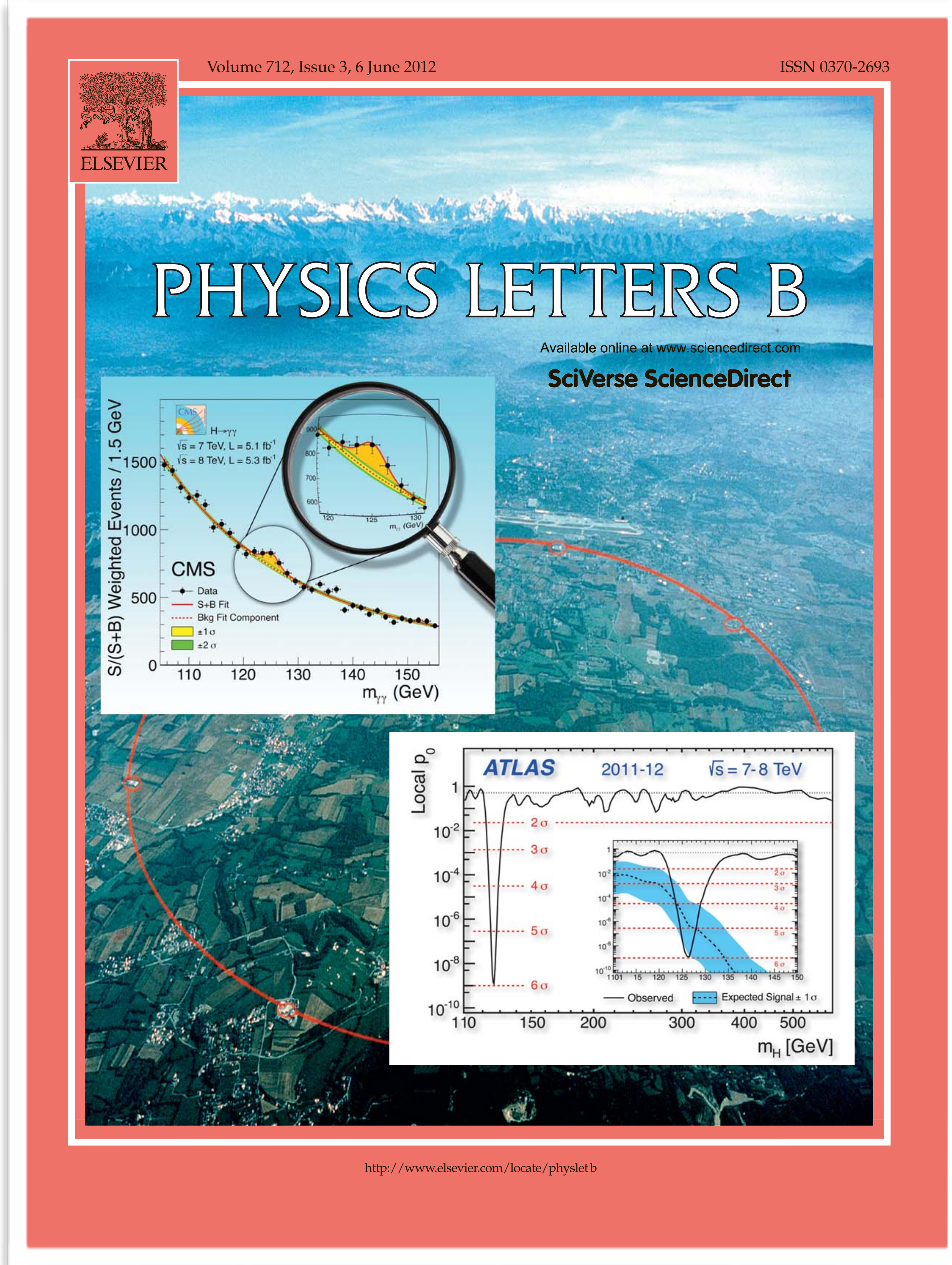
In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^{\pm}$ and $H^{\pm\pm}$)", respectively.

H^0 MASS

VALUE (GeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
125.09±0.21±0.11	[1,2] AAD 15B	LHC	pp, 7, 8 TeV

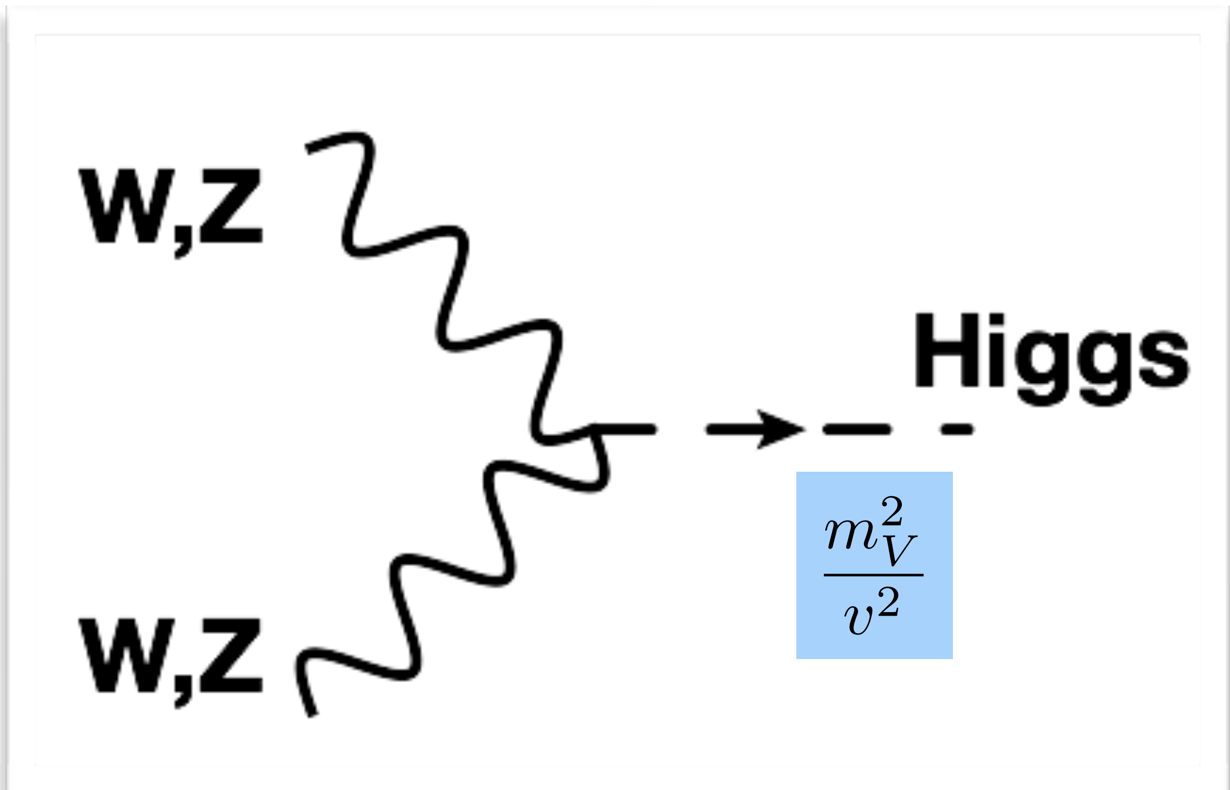
• • • We do not use the following data for averages, fits, limits, etc. • • •



Producing the Higgs

$$\mathcal{L} = |D^\mu \phi|^2 - y_i q_L^i q_R^i \phi - \mu^2 \phi^2 - \lambda \phi^4 + \ldots$$

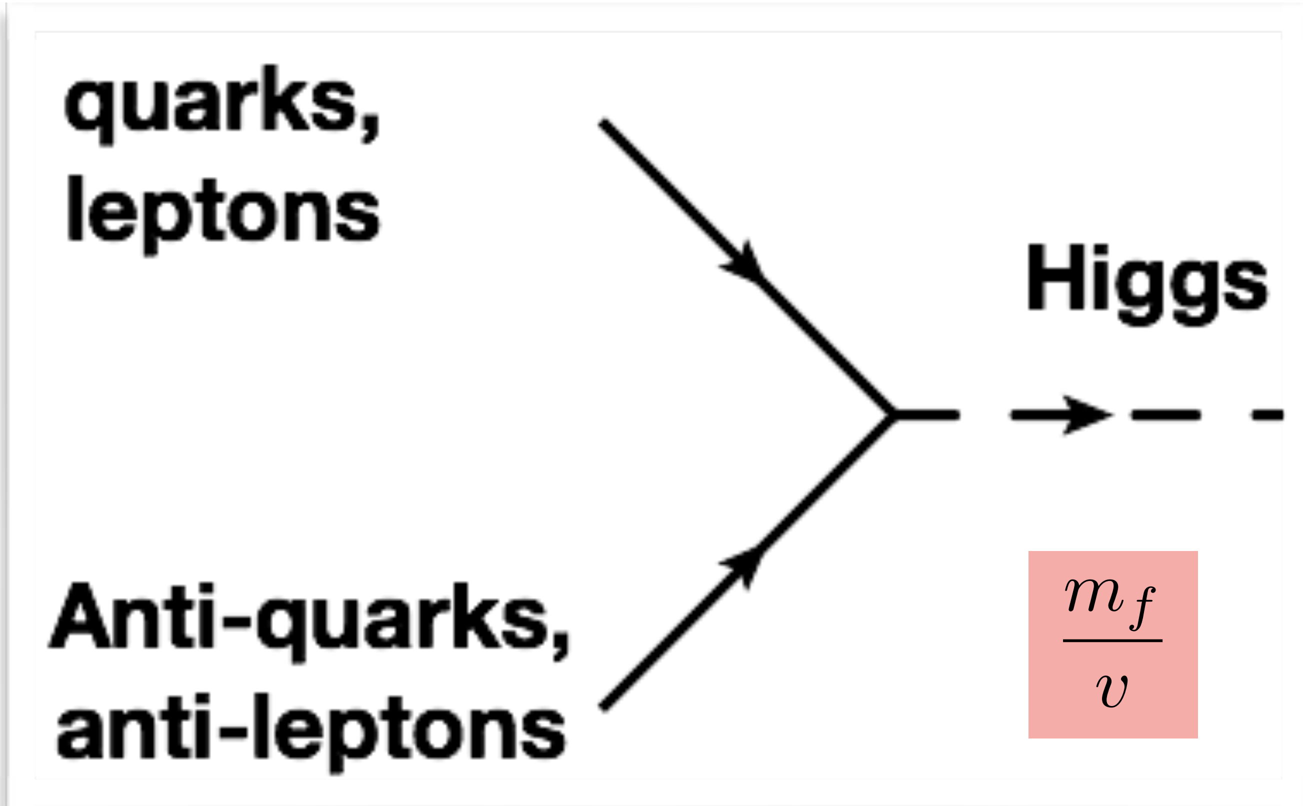
Coupling to bosons



Massive gauge boson?

…then it couples to the Higgs

Coupling to fermions



Massive fermion?

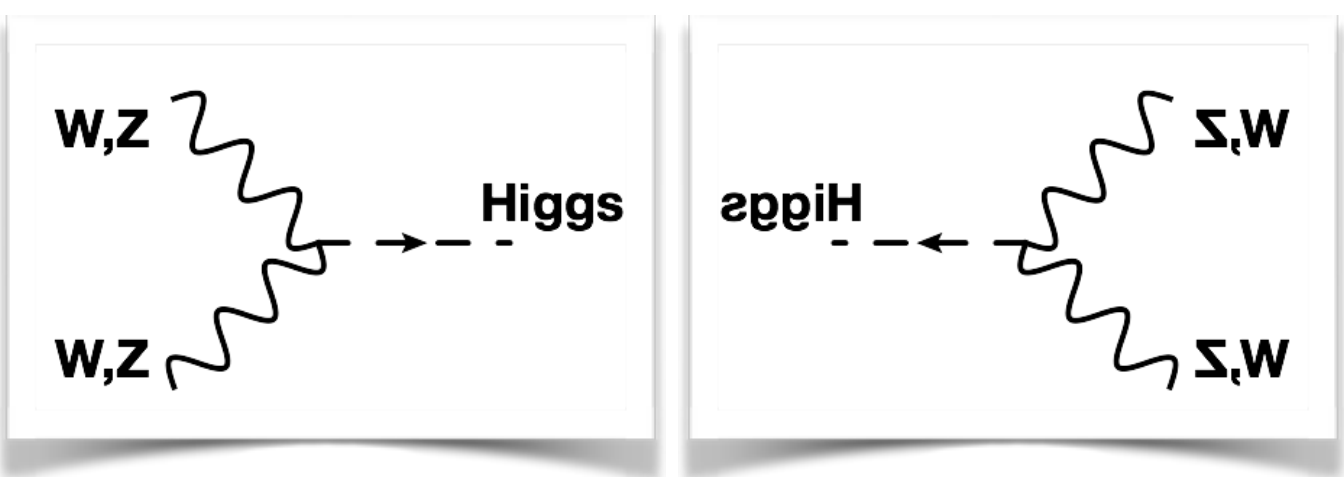
…then it couples to the Higgs

Studying the Higgs? Decays

Gauge bosons

Massive gauge boson?

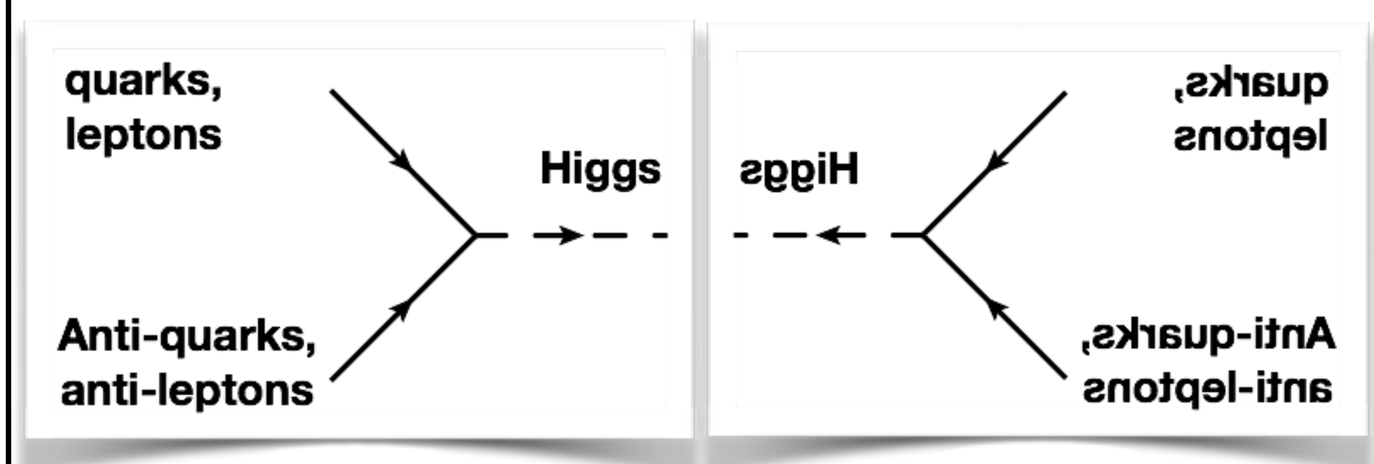
…then it couples to the Higgs



Fermions

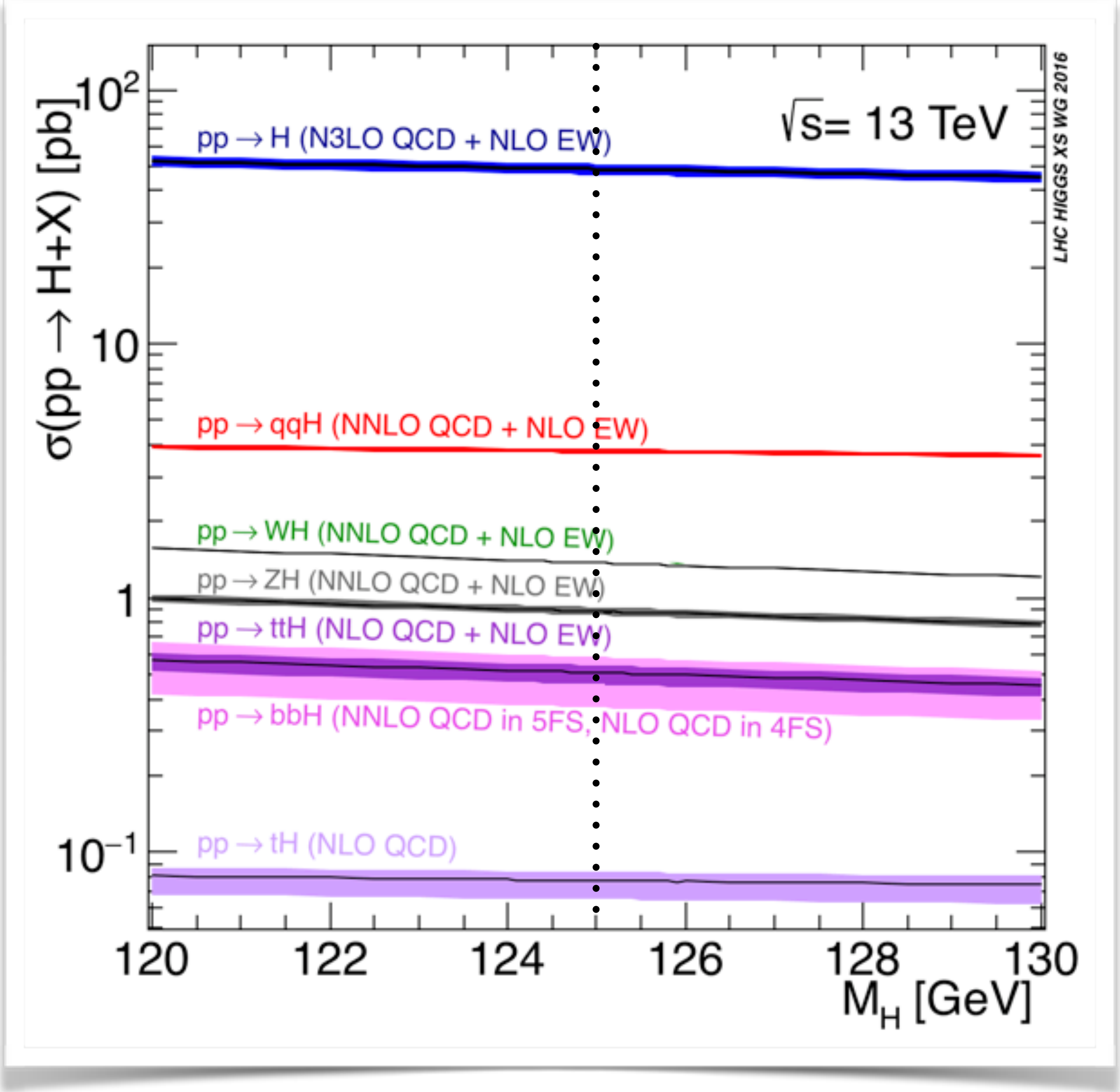
Massive fermion?

…then it couples to the Higgs

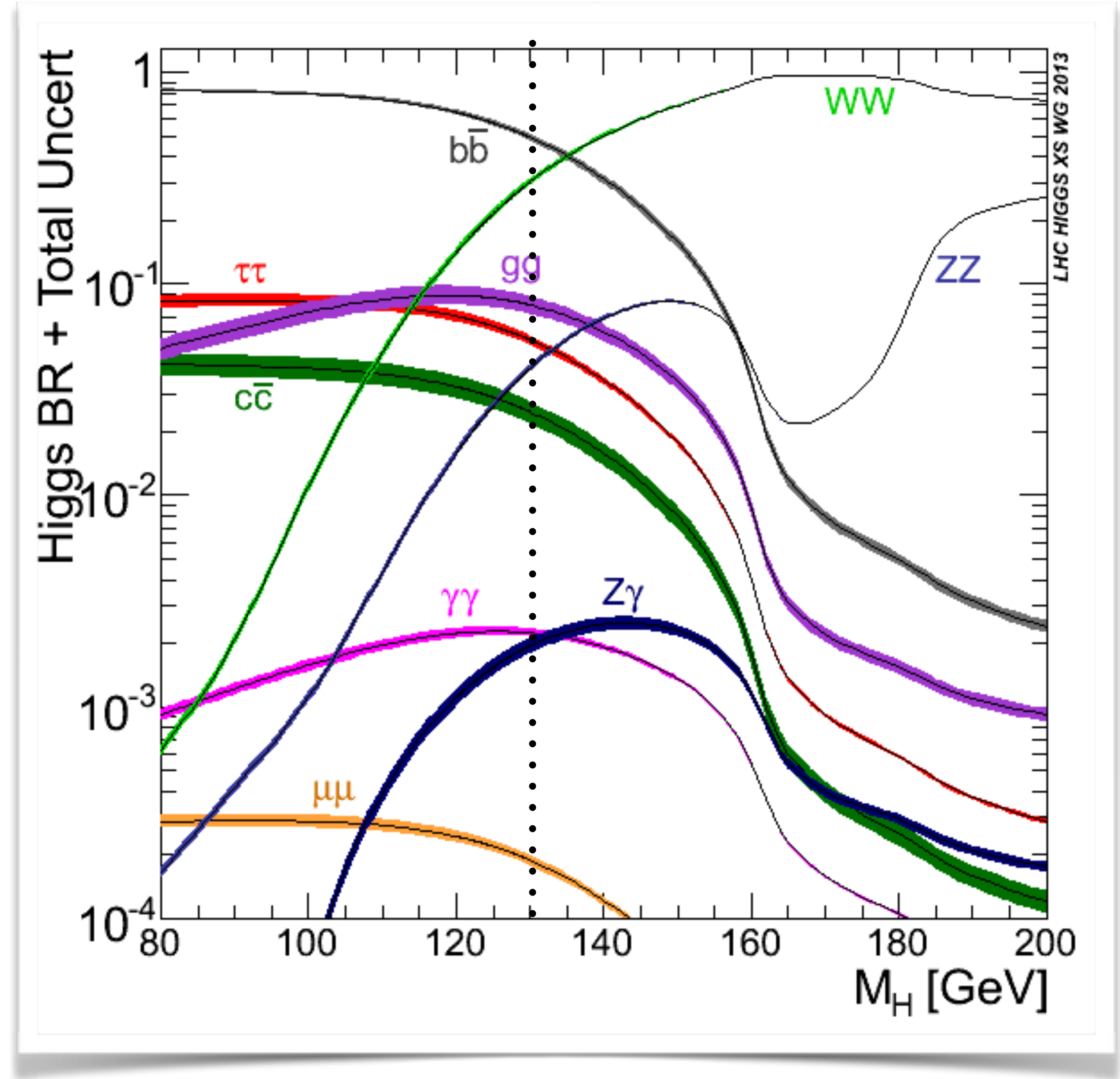


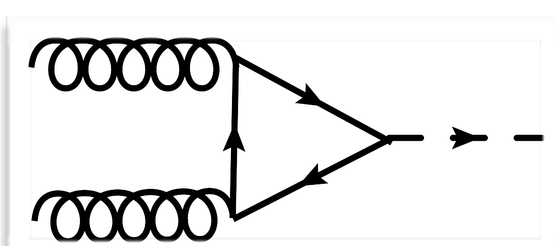
Higgs Production and Decays

Higgs Production

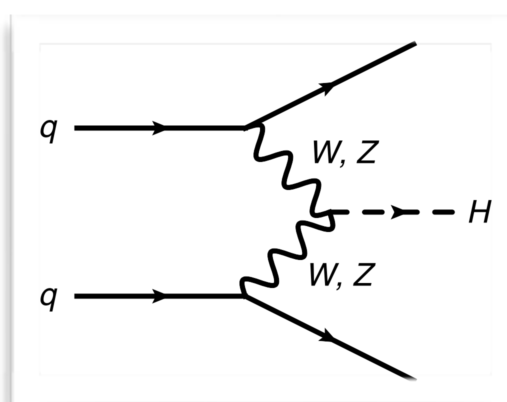


Higgs Decay

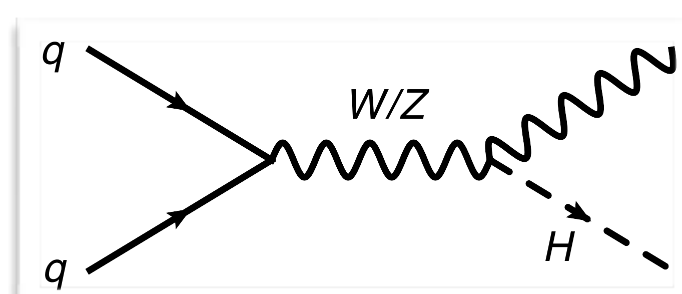




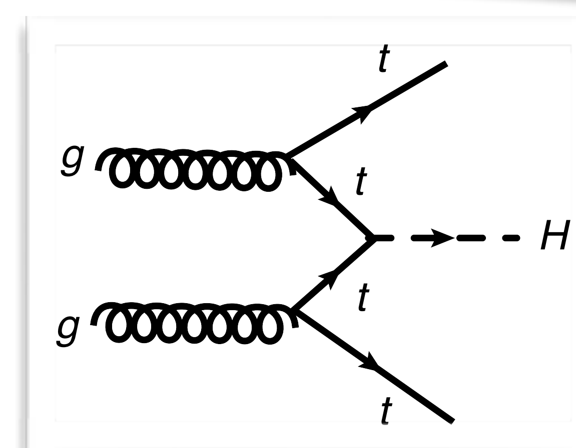
Gluon-gluon fusion



Vector boson fusion



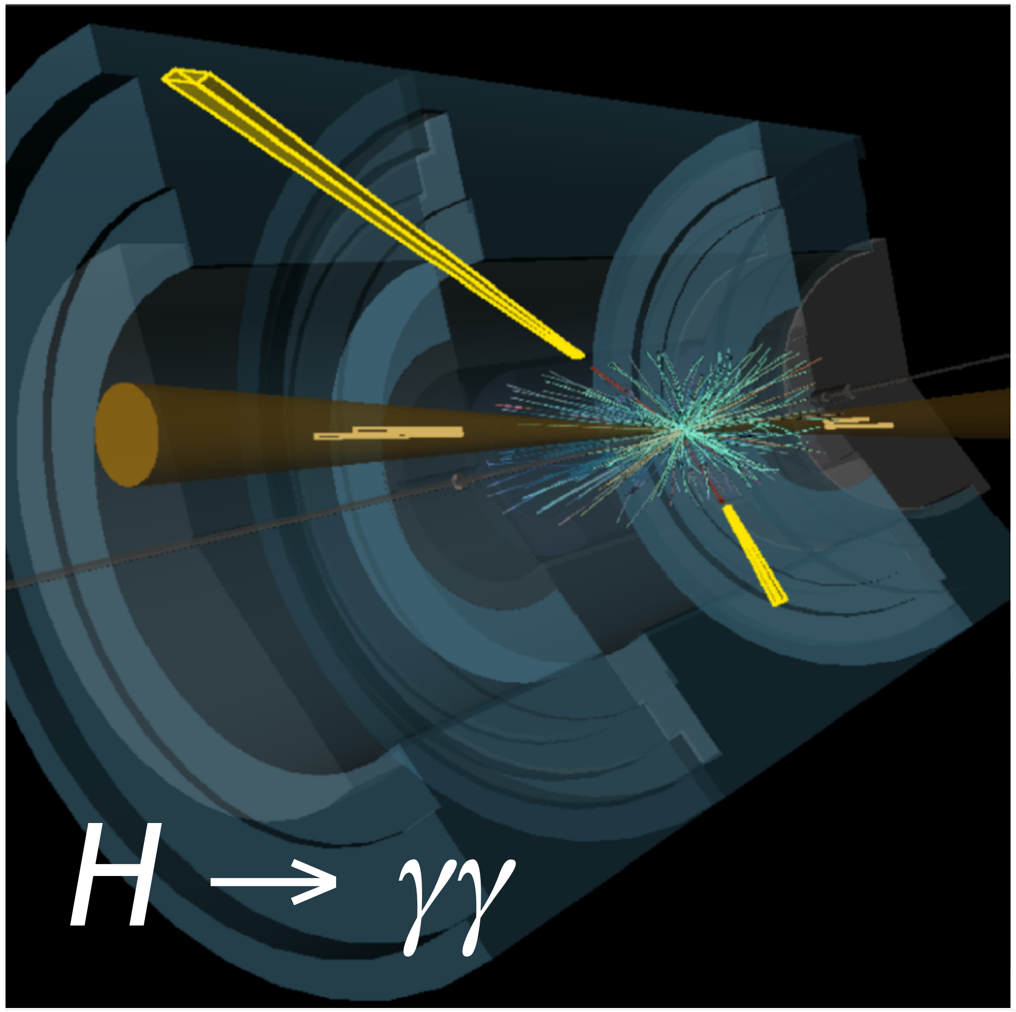
W/Z associated production



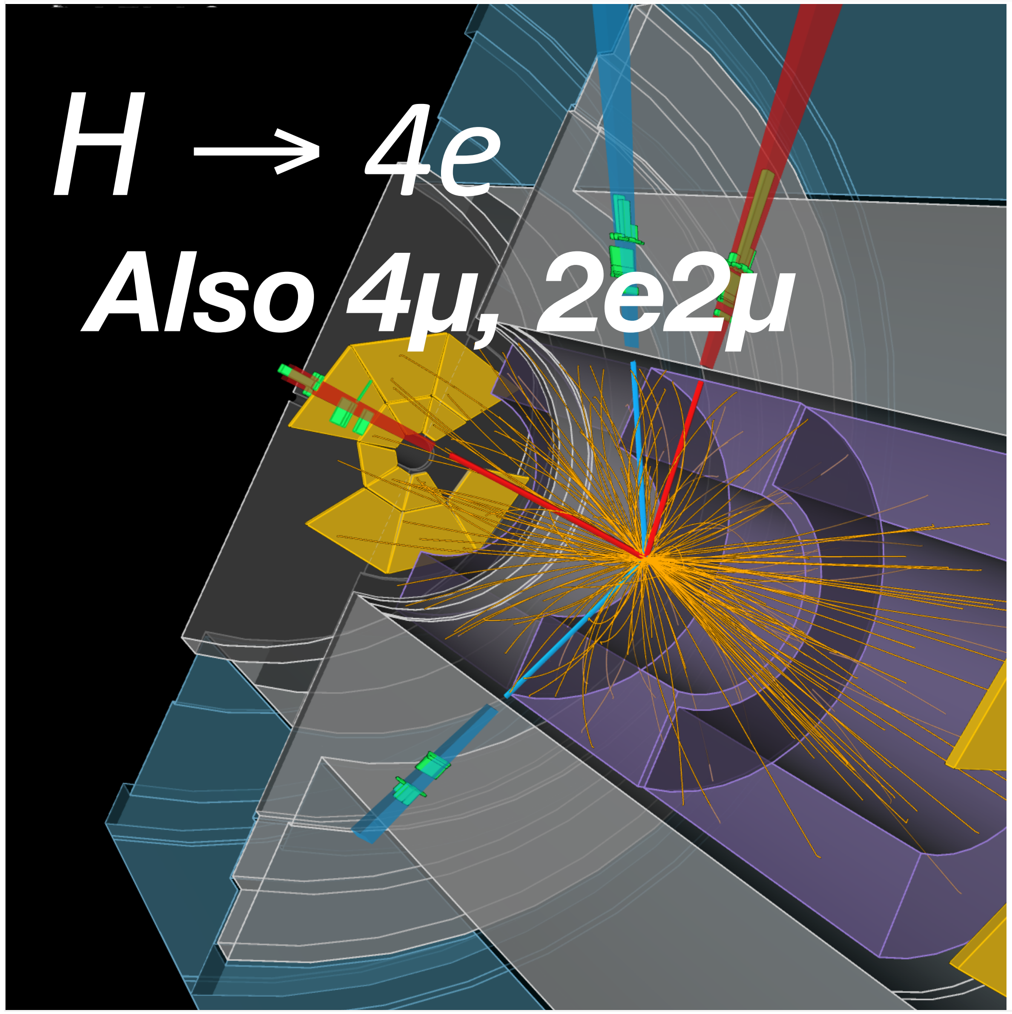
Top fusion

Discovery Channels

An excellent channel for m_H = 125 GeV



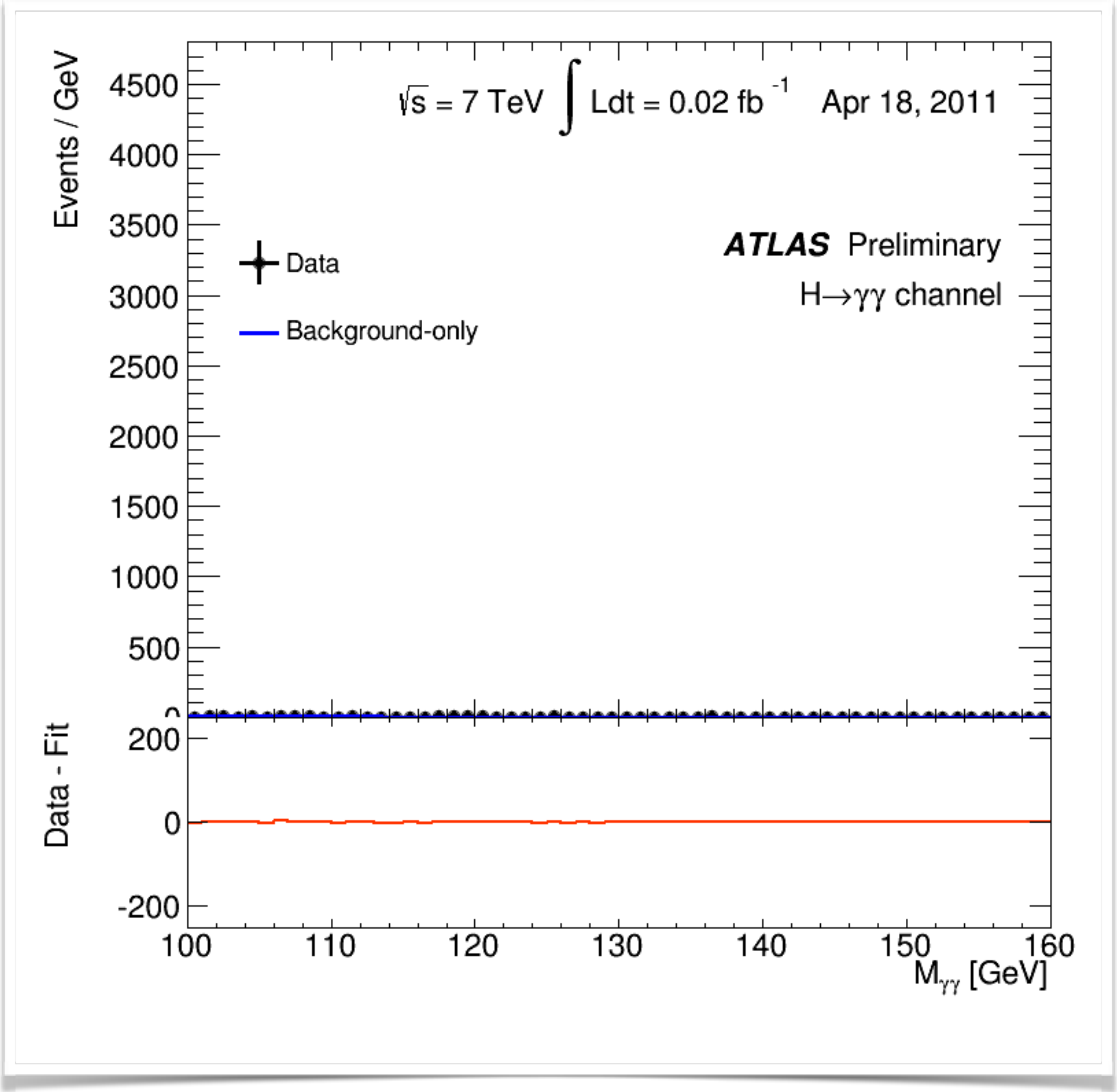
Golden channel over a wide mass range



Simple channels with excellent mass resolution

Higgs to two photons (H→γγ)

Movie link

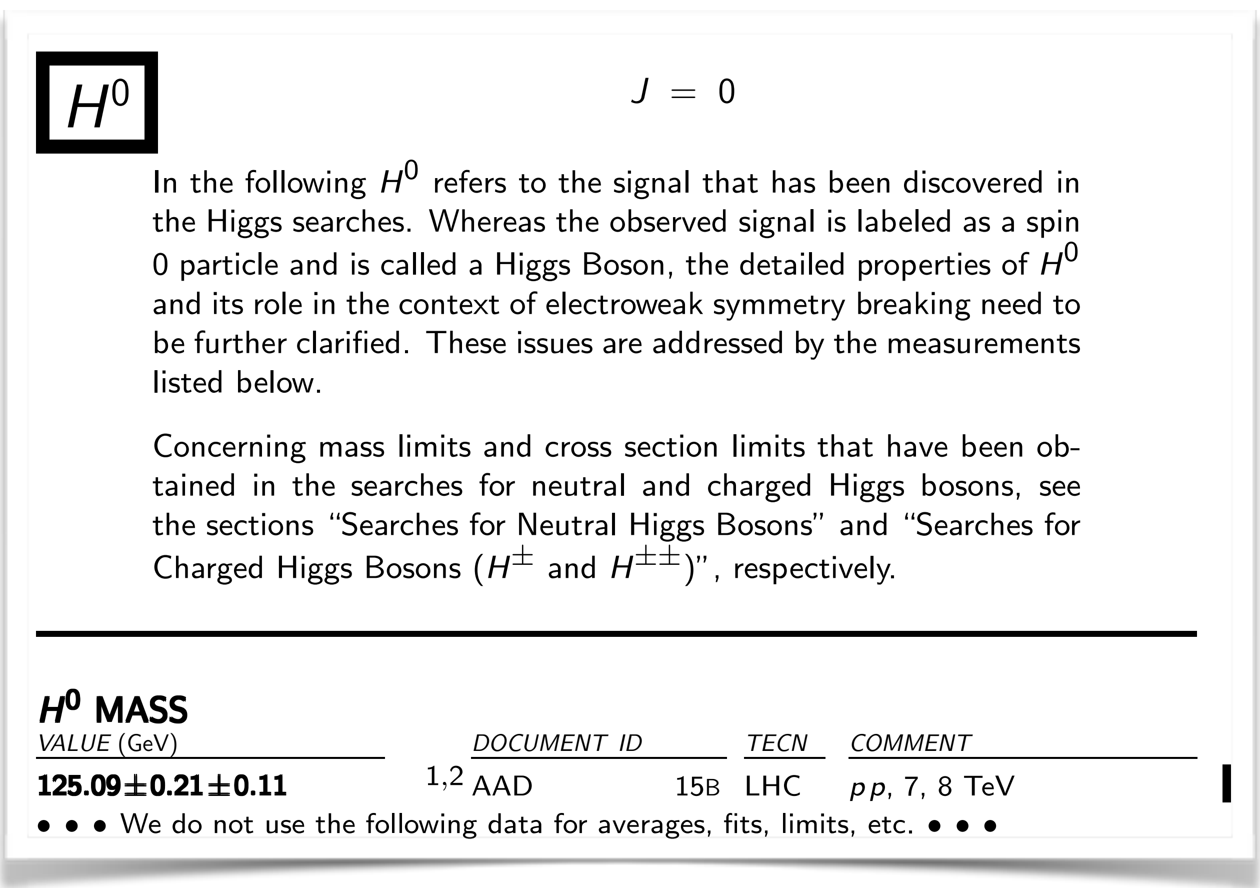


4 July 2012

What do we know about the Higgs?

JHEP 08 (2016) 045, PRL 114 (2015) 191803, EPJC 75 (2015) 212, Phys. Lett. B 726 (2013), pp. 120-144

- Measure basic properties
  - **Mass** and **width**
  - **Production** rate
  - **Spin** and **parity** (only elementary scalar): $J^{PC} = 0^{++}$
  - Measure **decays**



H^0

$J = 0$

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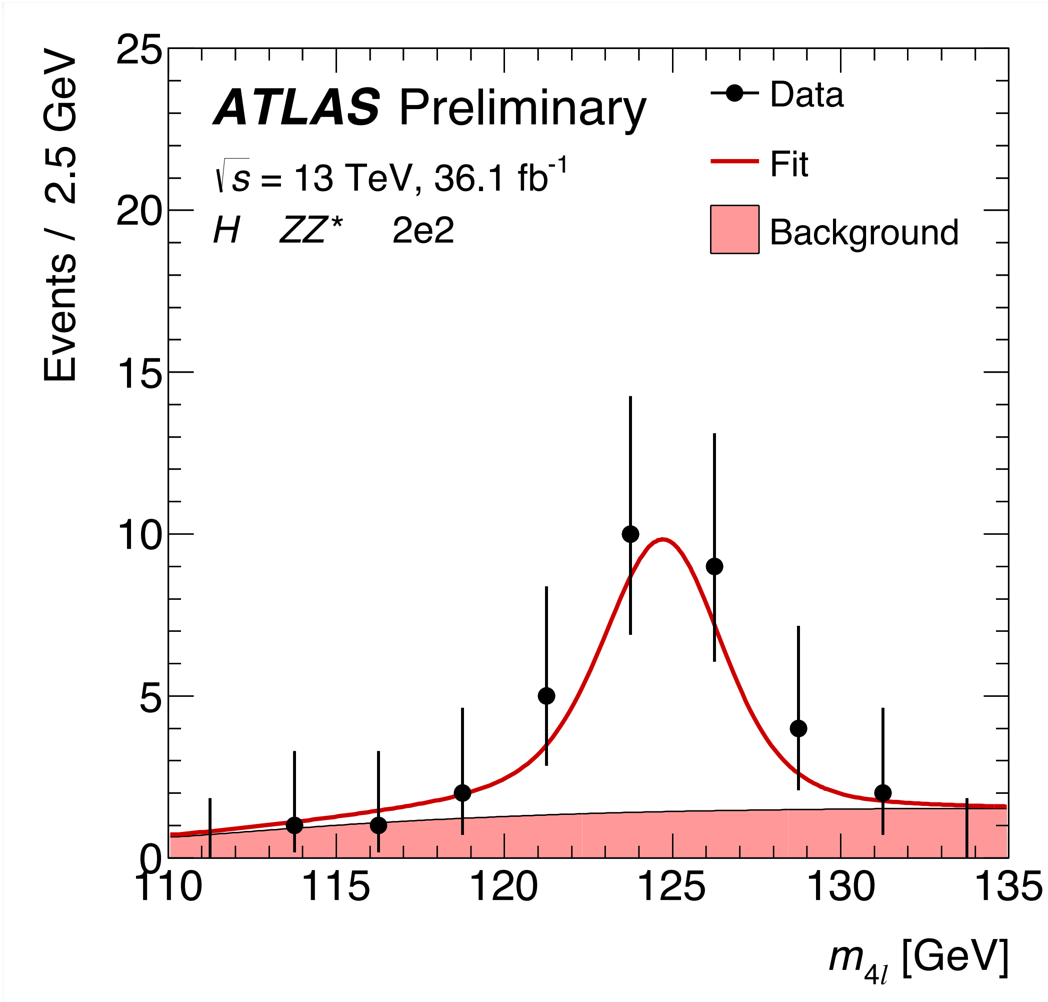
H^0 MASS

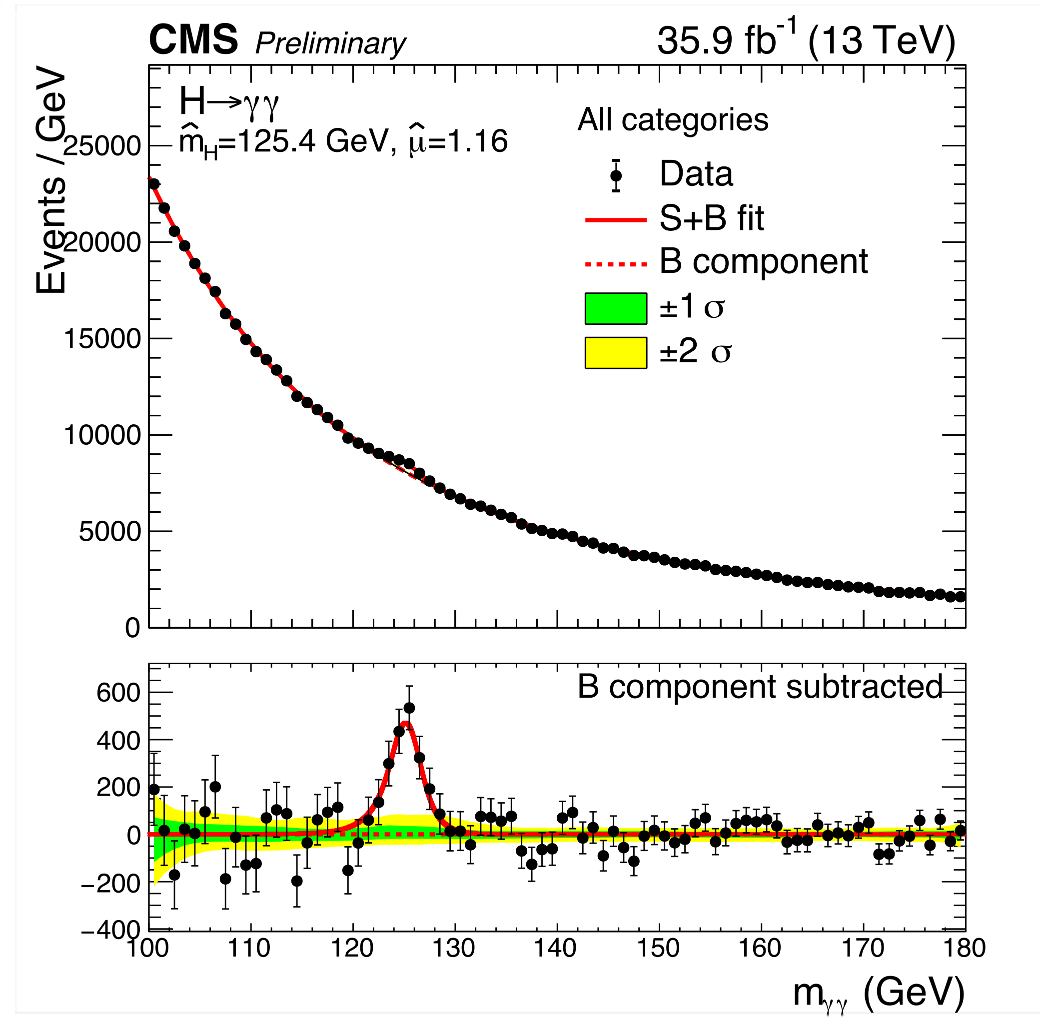
VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125.09±0.21±0.11	[1,2] AAD	15B	LHC	pp, 7, 8 TeV

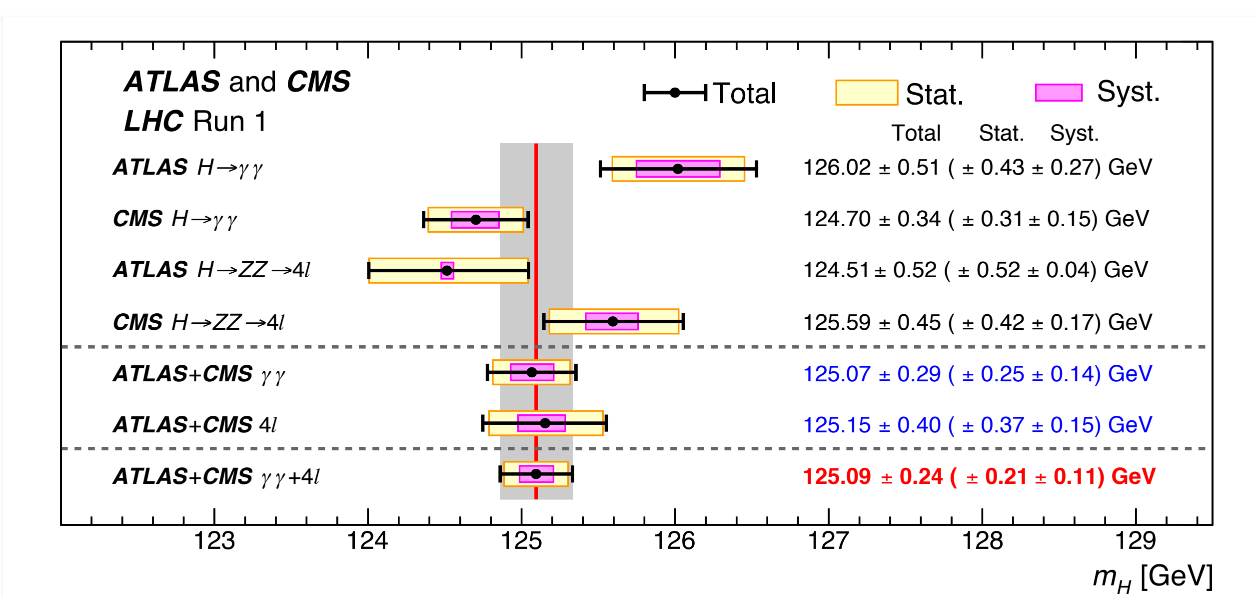
• • • We do not use the following data for averages, fits, limits, etc. • • •

Higgs Mass Measurement

HIGG-2014-14, ATLAS-CONF-2017-046, HIG-16-041





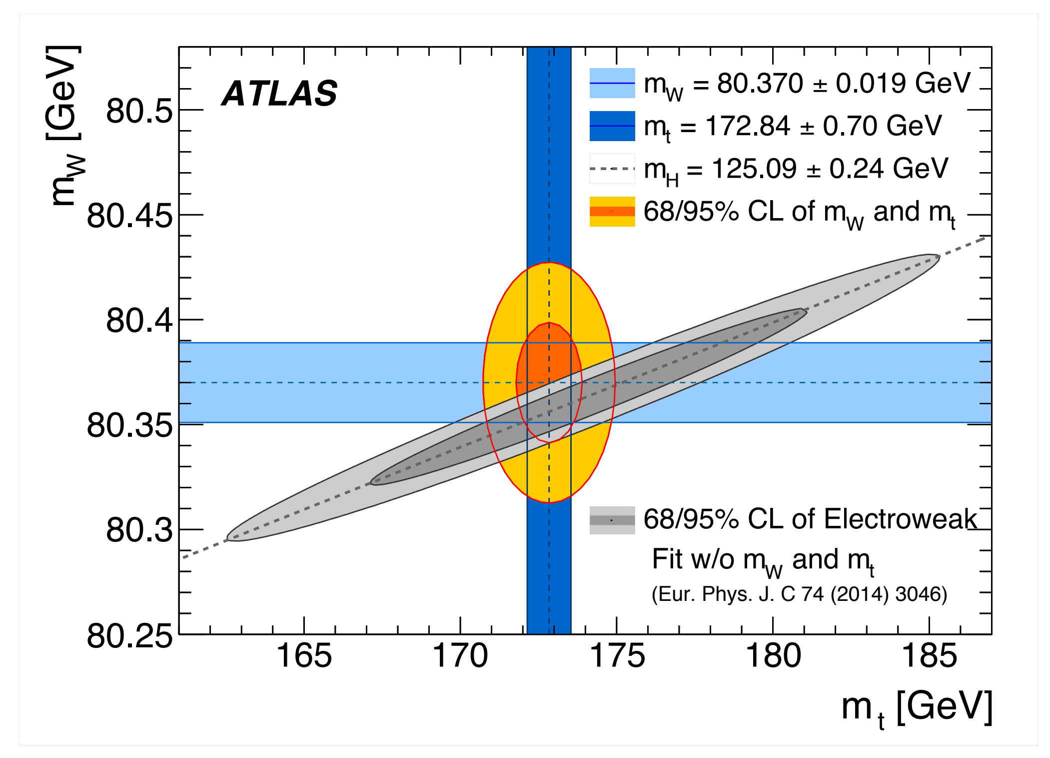


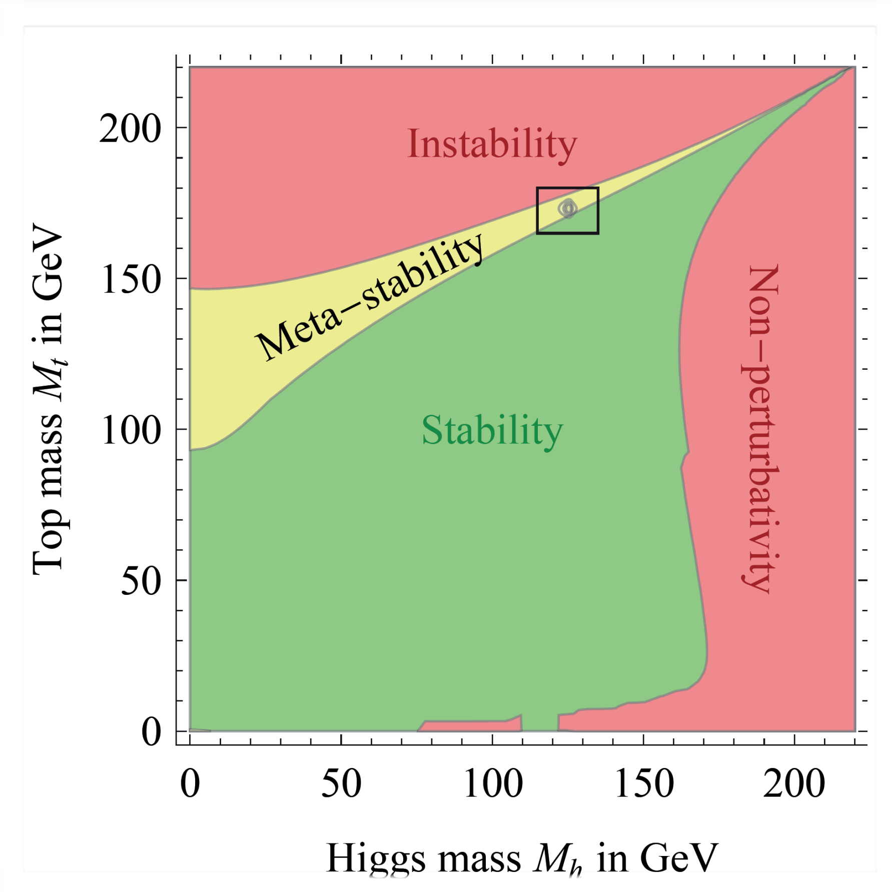
- Final Run-1: 125.09 ± 0.24 GeV
- CMS Run-2: 125.26 ± 0.21 GeV
- ATLAS Run-2: 124.98 ± 0.28 GeV

Higgs Mass Implications

axXiv:1205.6497

- Measured final SM parameter !
- Good consistency with m_W and m_{top}
- $m_H = 125$ GeV
    - A bit too heavy for supersymmetry, but not so heavy as to exclude supersymmetry
    - Perhaps a bit lighter than the mass needed for the Standard Model validity to Planck scale (modulo theory assumptions)
- $m_H = 125$ GeV → our universe may lie on the boundary between instability and stability
- No need to panic: metastability means that the universe is unlikely to end tomorrow
    - But intriguing, nonetheless

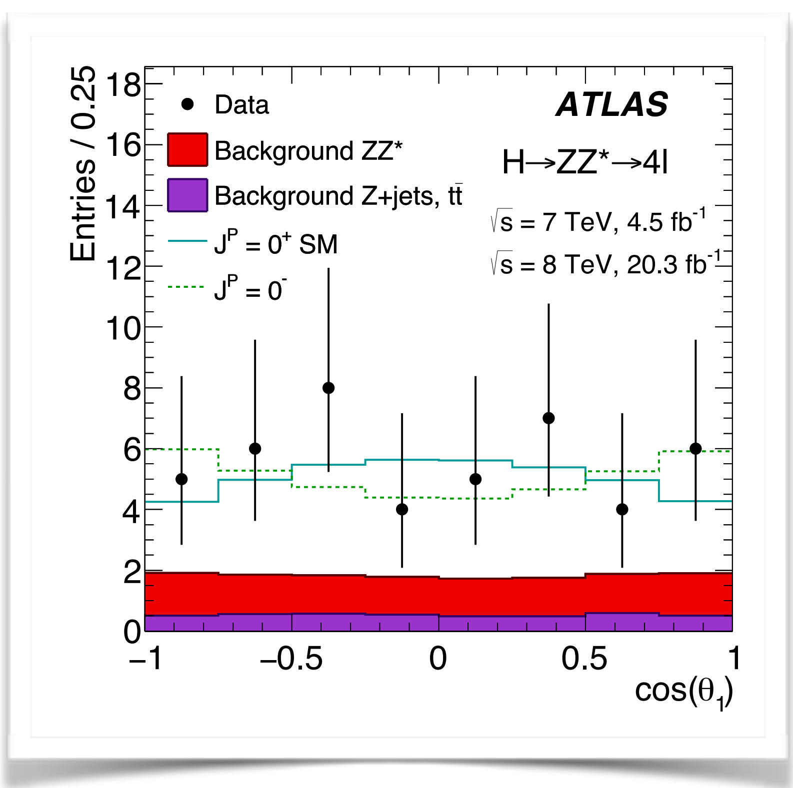


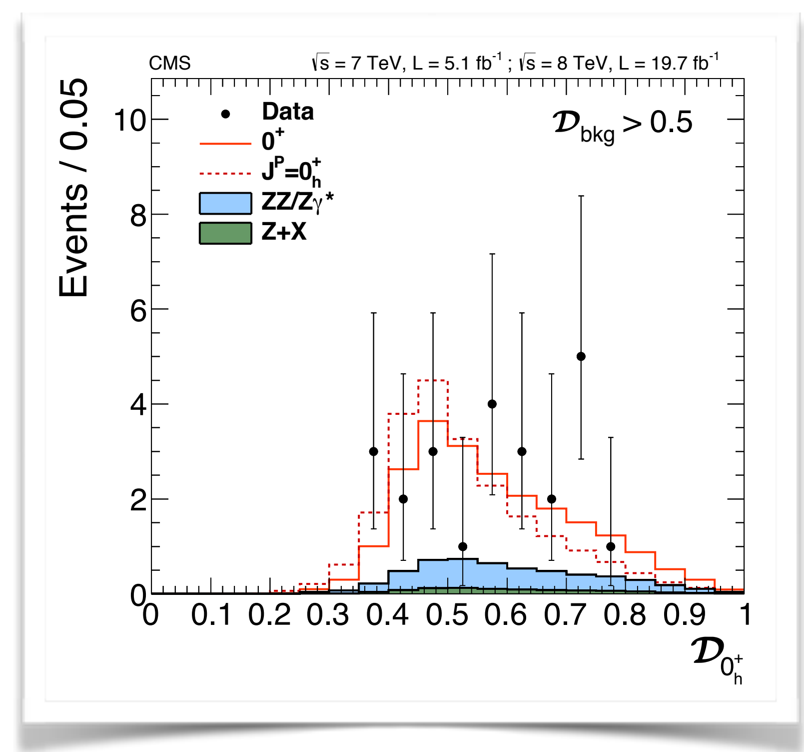


Spin/Parity

HIG-13-002
HIGG-2013-17

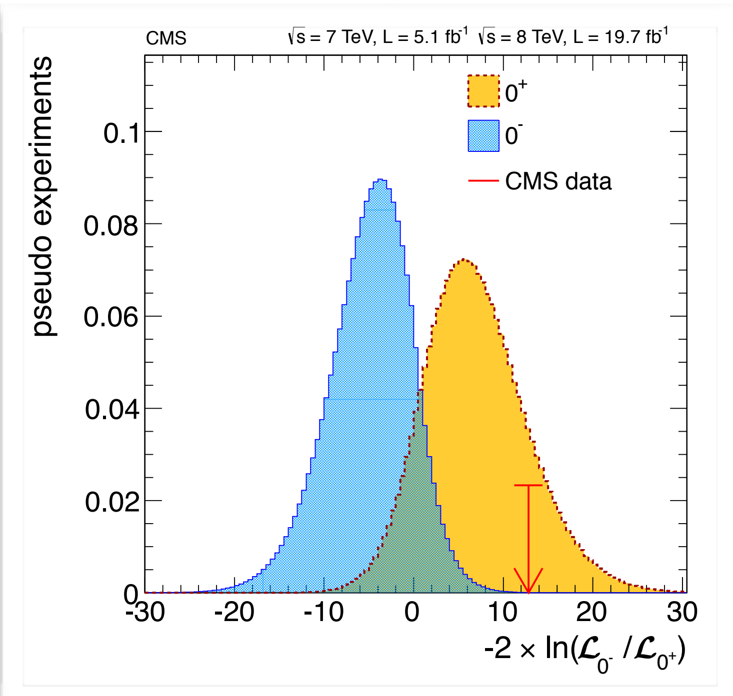
- Only elementary particle with **spin-0**
- Spin and parity determine angular distributions of decay products
  - Use γγ, ZZ and WW
- Don't forget, though, that the γγ observation implies
  - Does not originate from spin 1 : Landau-Yang theorem
  - Charge conjugation is +1 (assuming C and P separately conserved)
  - WW/ZZ channels disfavour CP odd hypothesis (can occur through loops)

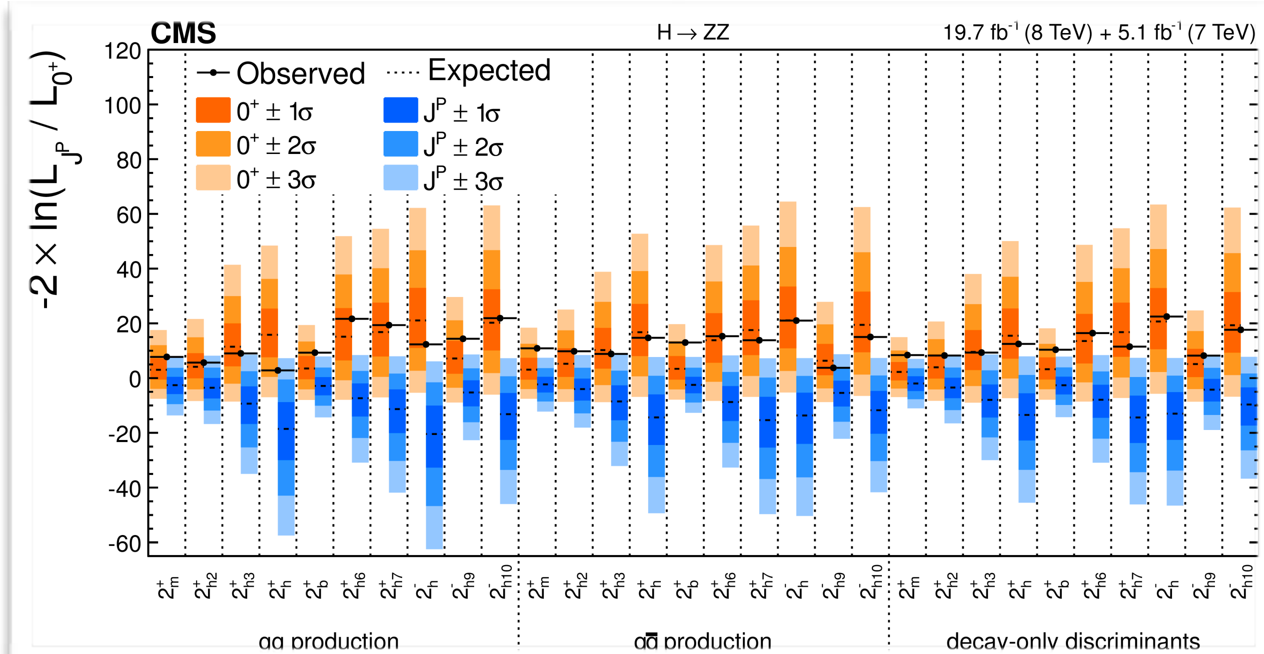




Spin/Parity Results

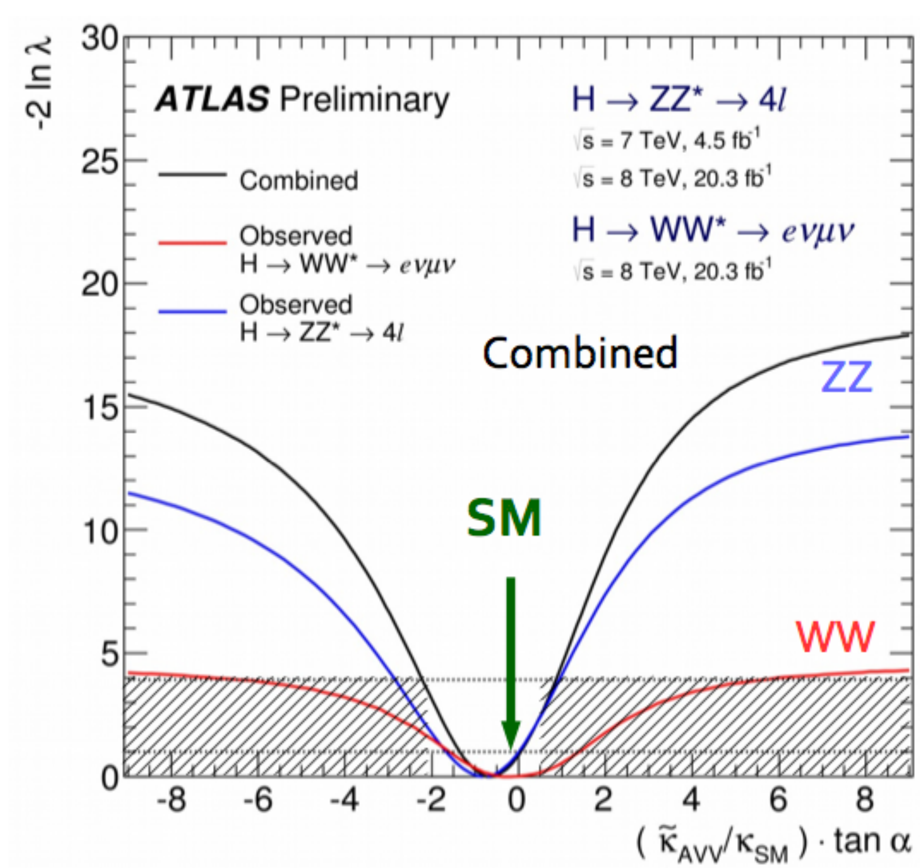
HIGG-2013-17, HIG-14-018

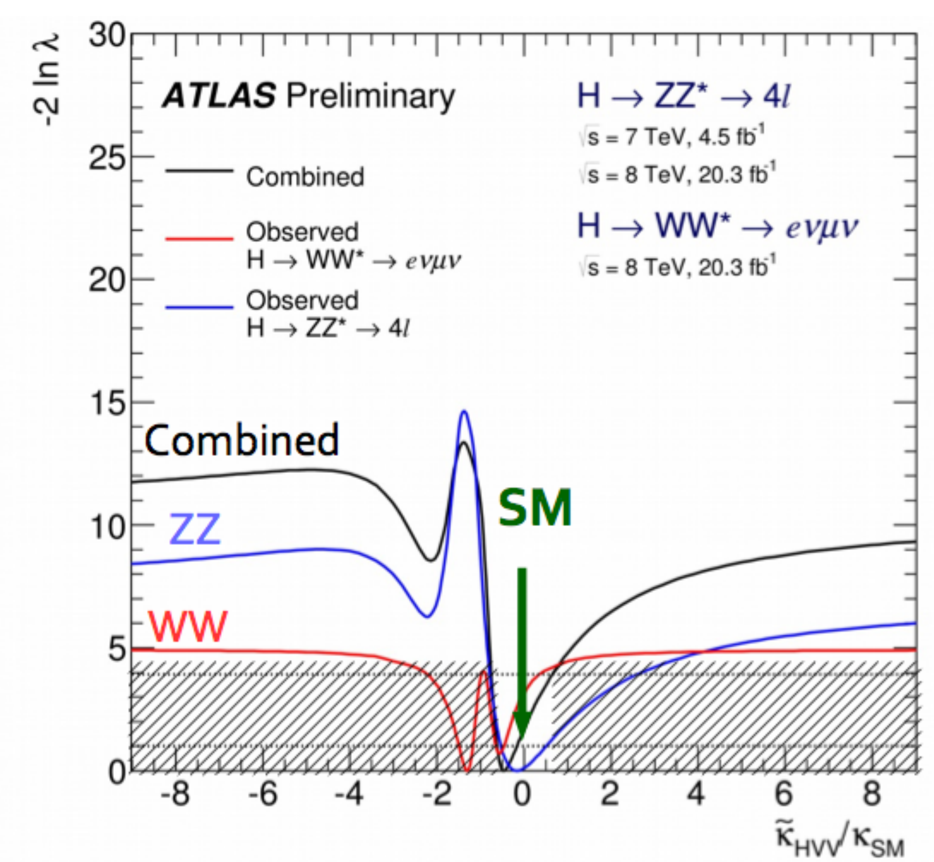




Strong evidence that the Higgs is 0+ as predicted by the Standard Model

Both ATLAS and CMS find that the observed Higgs boson is compatible with a standard CP-even

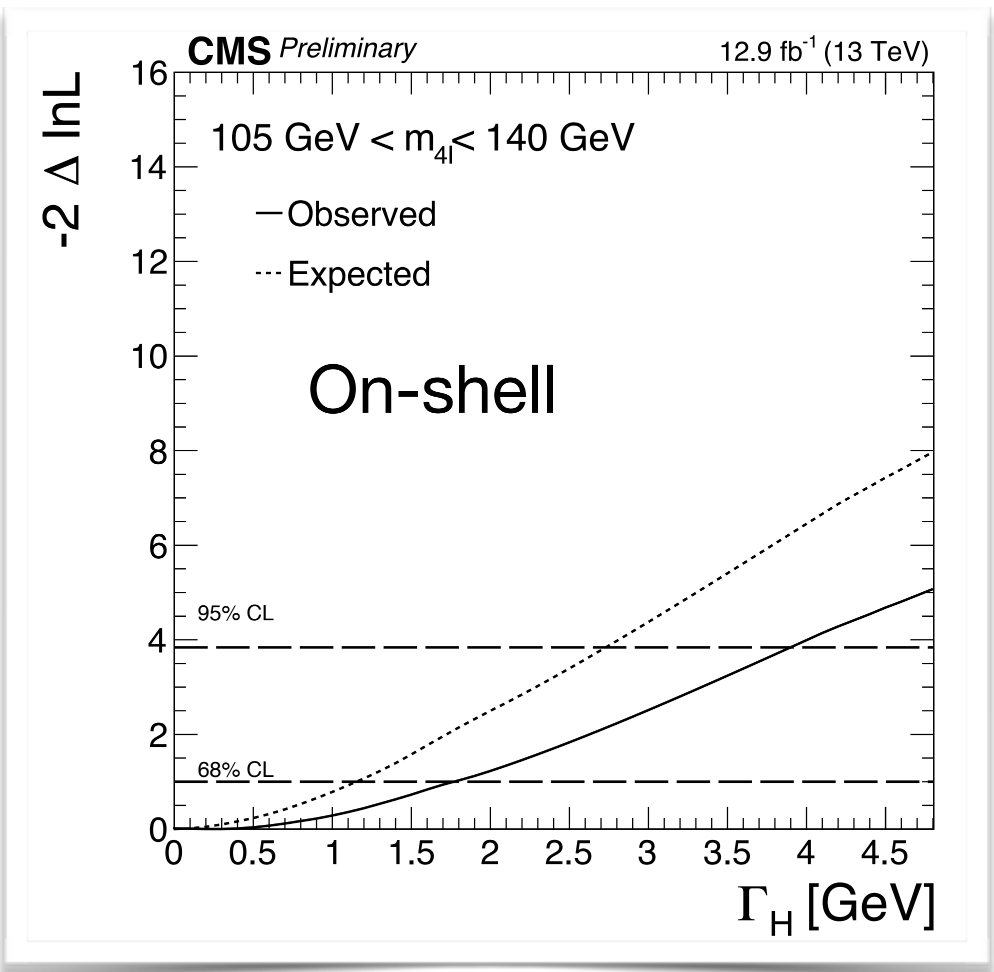


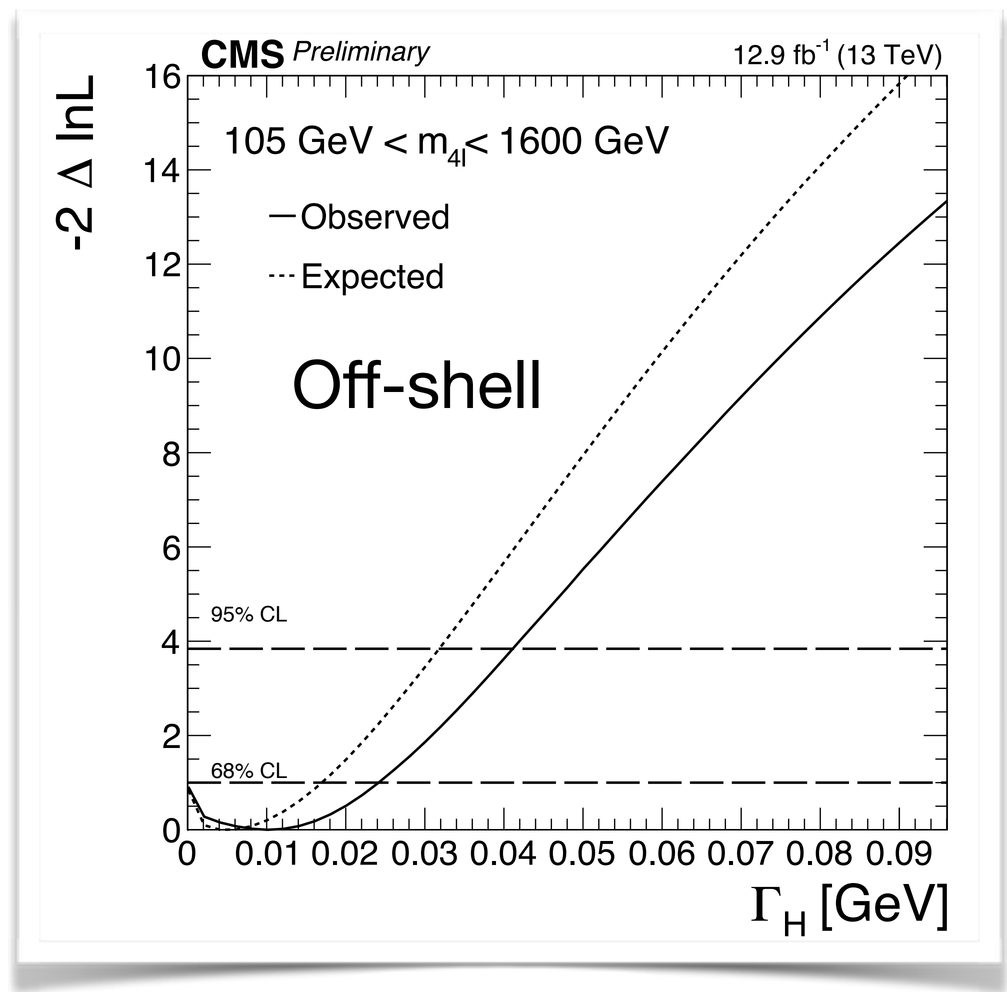


Higgs Width

Phys. Rev. D88 (2013) 054024
arXiv:1311.3589, HIG-16-033
https://arxiv.org/pdf/1206.4803.pdf

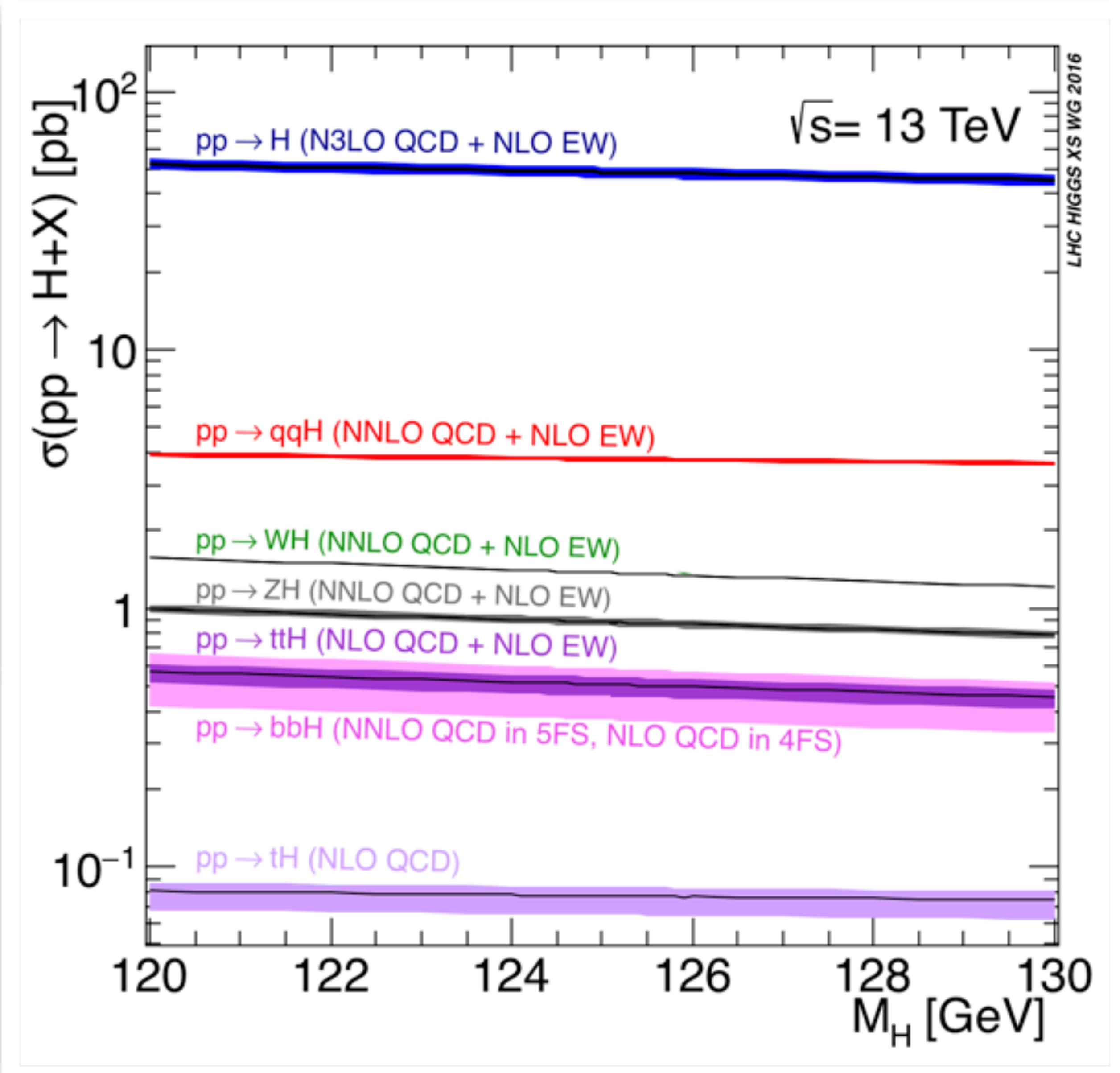
- Direct measurements of the Higgs width are limited by the detector resolution to a few GeV (SM: a few MeV)
- Can do much better with indirect measurements using the ratio of the off-shell to on-shell cross-section
  - Currently constraint width to a few tens of GeV
  - But: brings in model assumptions



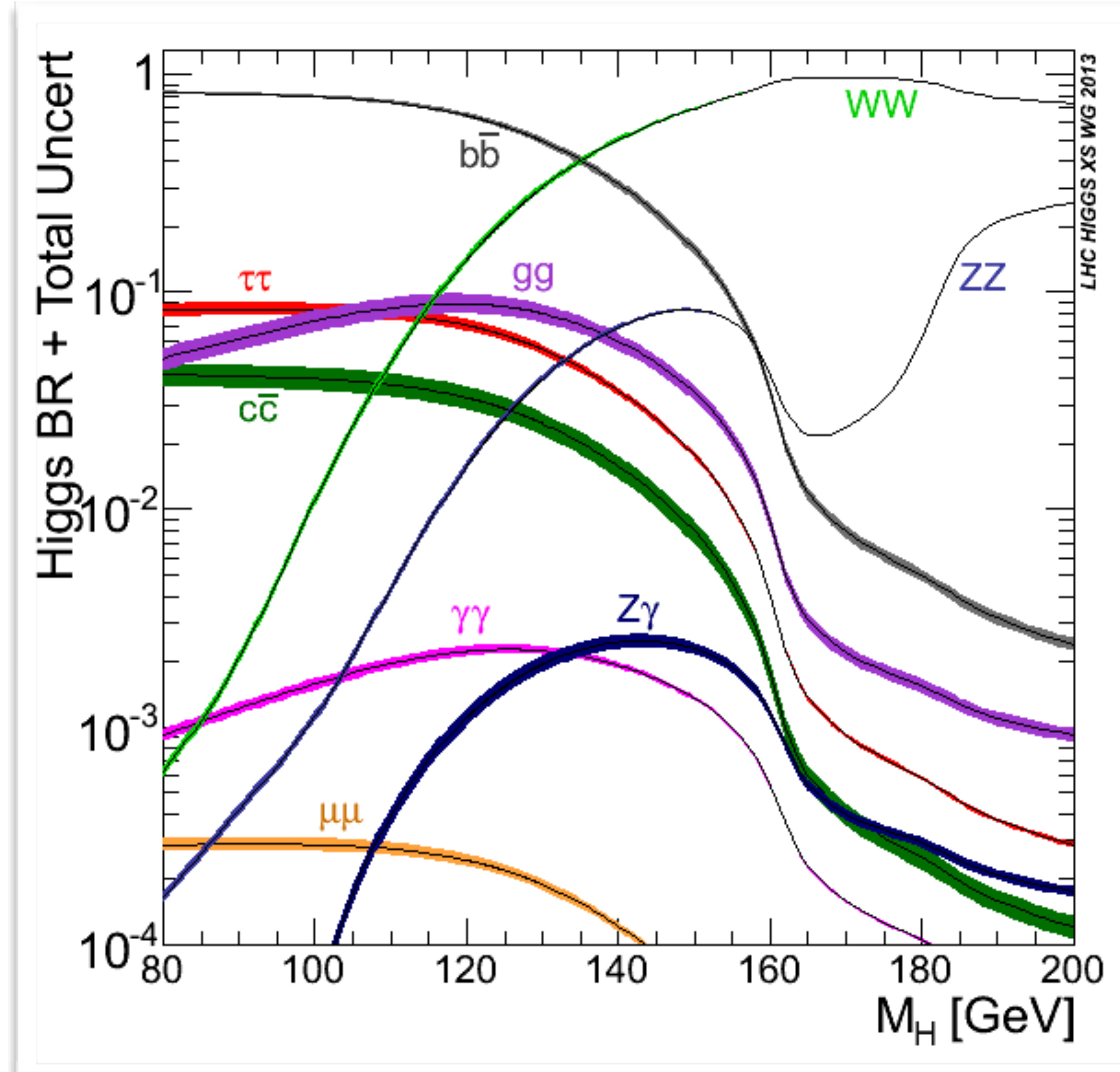


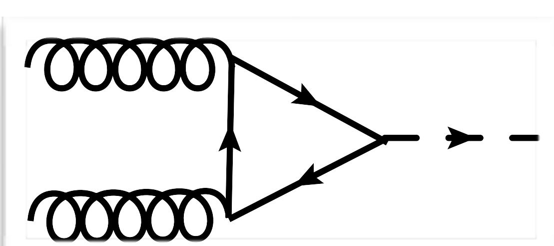
Higgs Production and Decays

Higgs Production

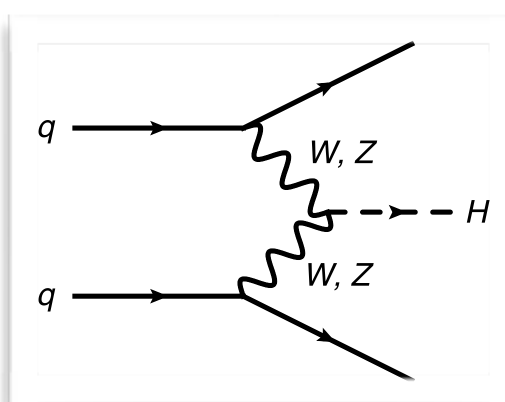


Higgs Decay

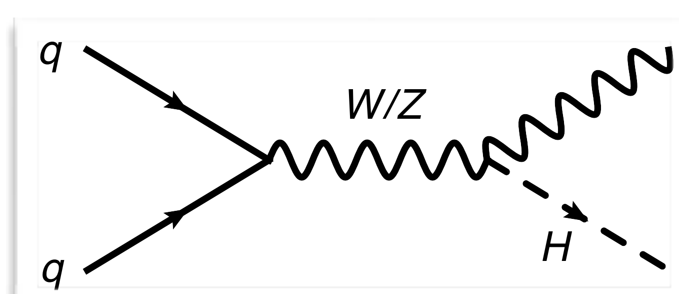




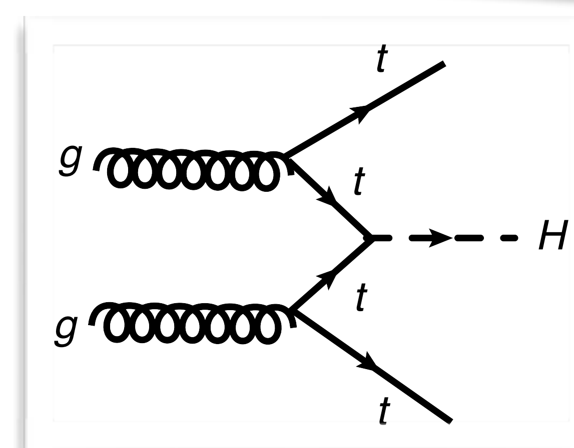
Gluon-gluon fusion



Vector boson fusion



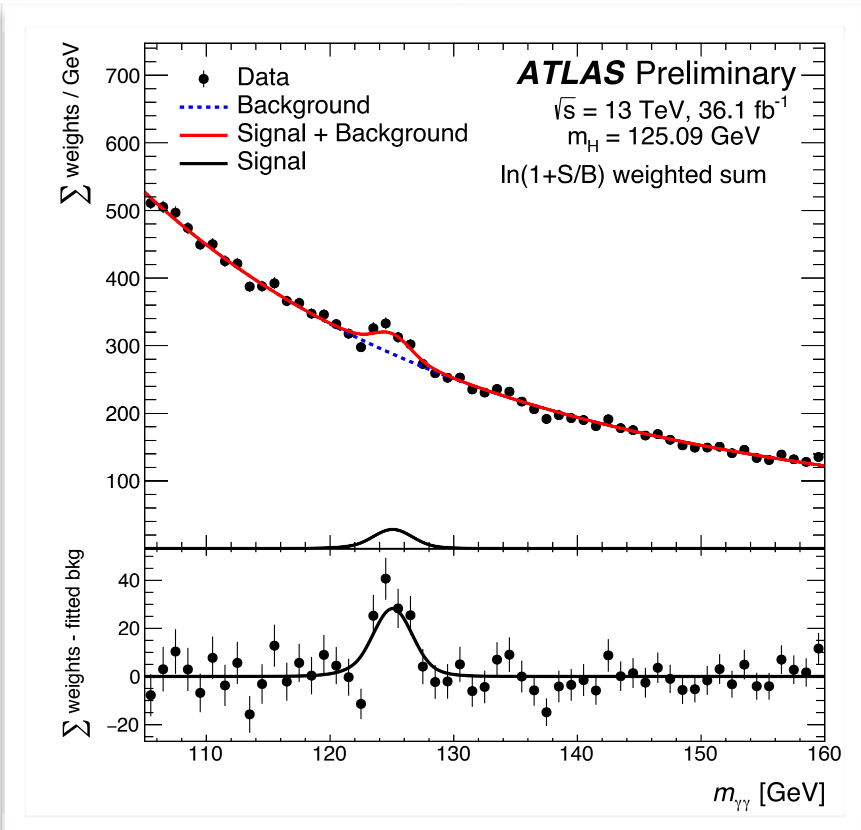
W/Z associated production

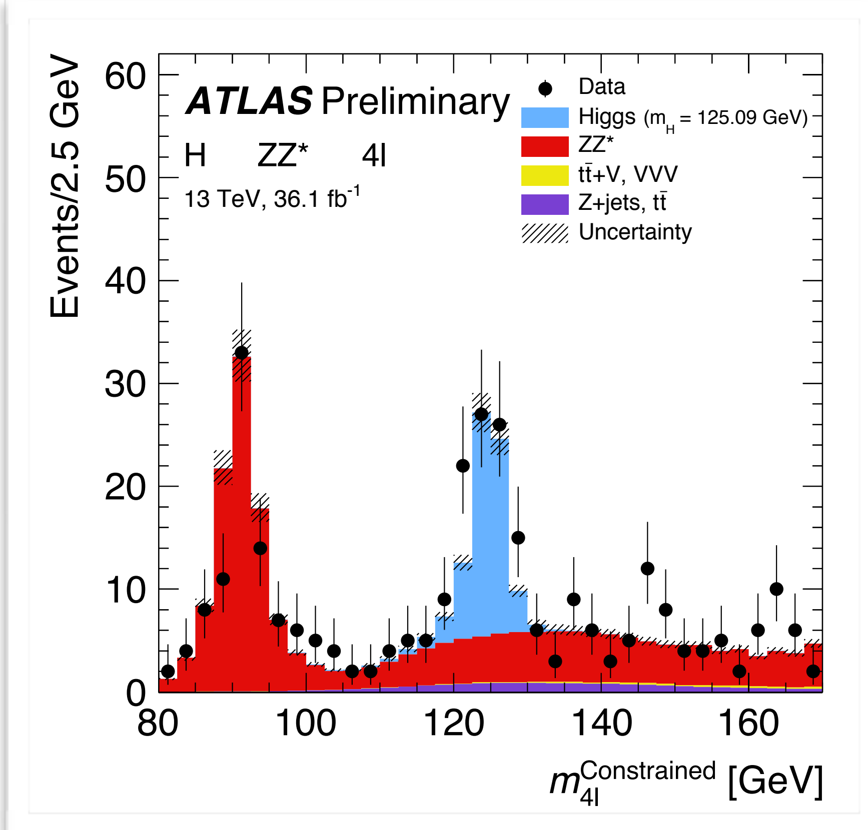


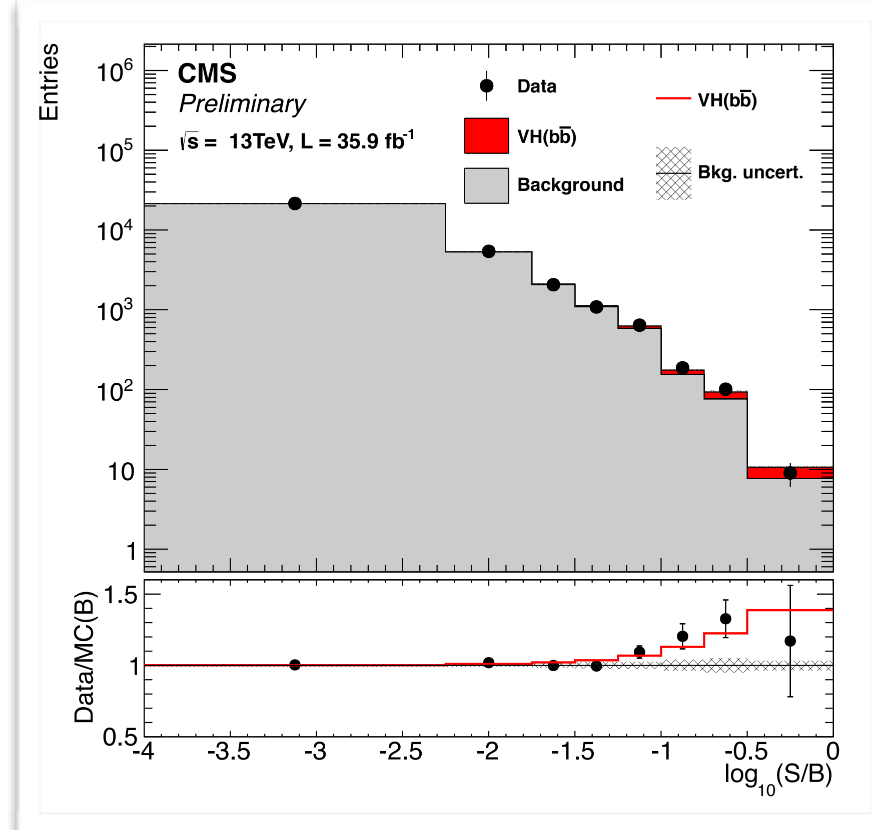
Top fusion

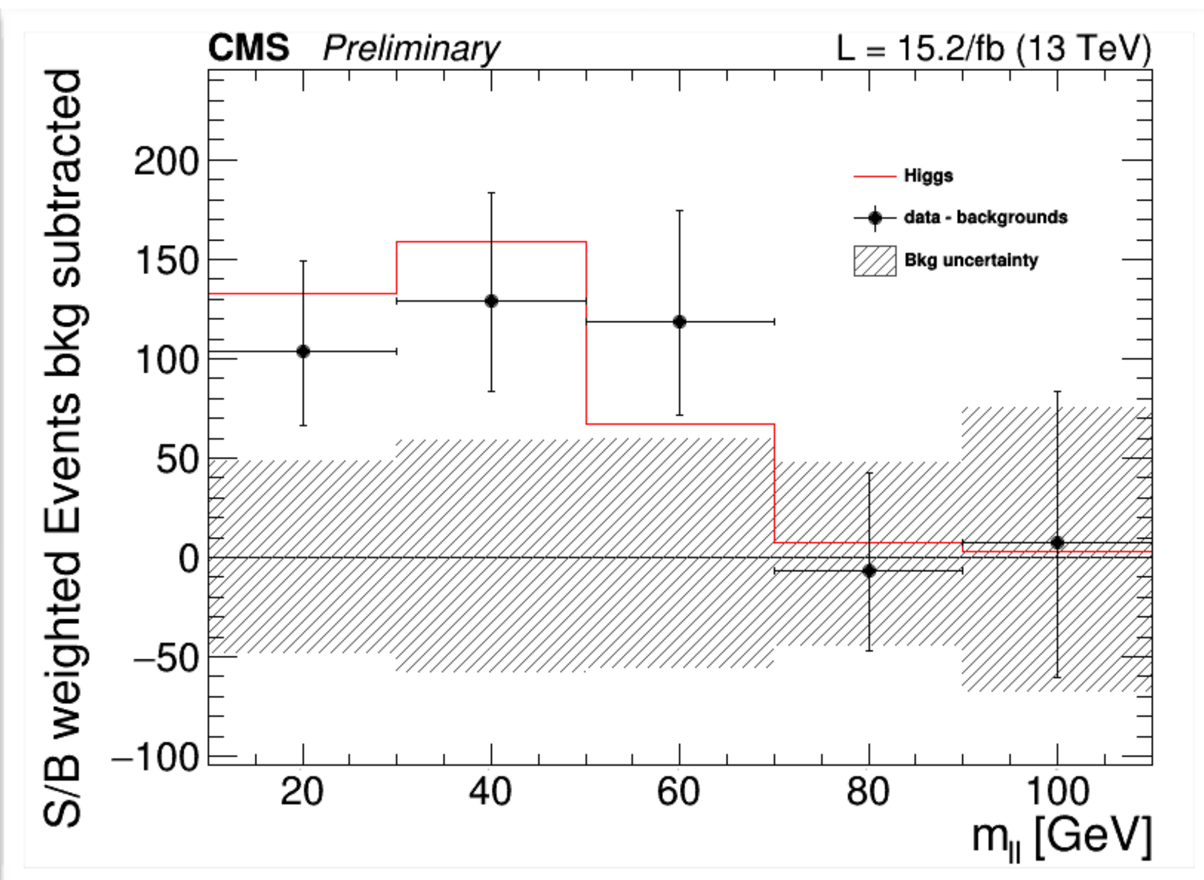
Higgs Results

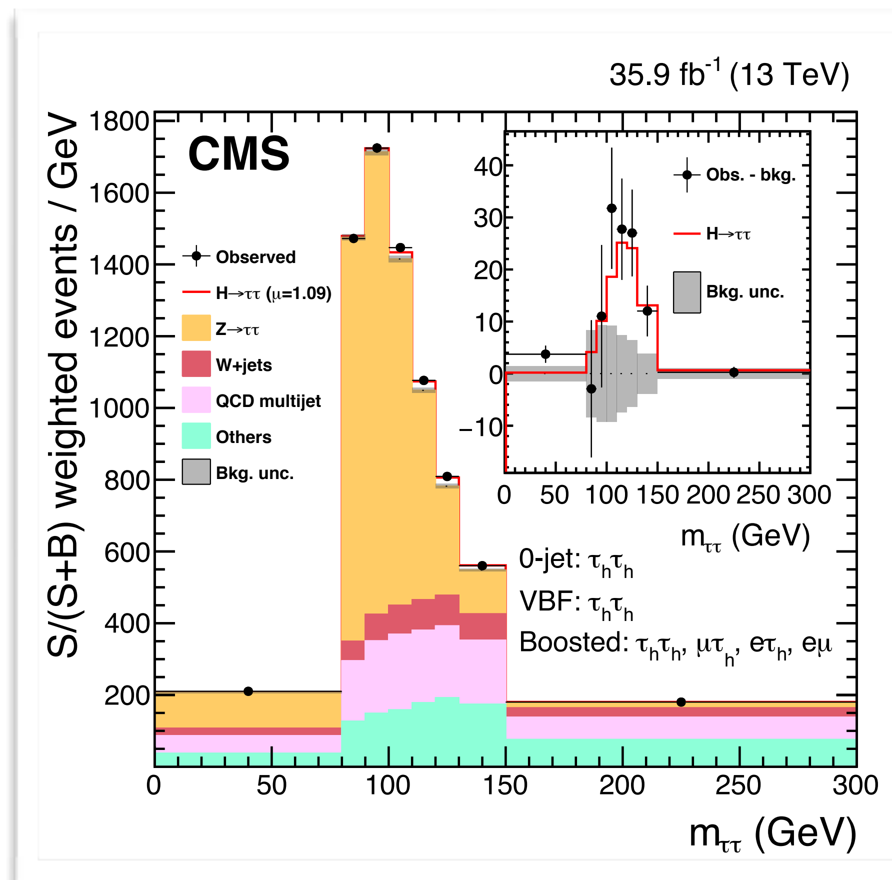
ATLAS-CONF-2017-045, ATLAS-CONF-2017-041, HIG-16-021, HIG-16-043, HIG-16-041, HIG-16-044, ATLAS-CONF-2017-043











Production and Decay Strengths

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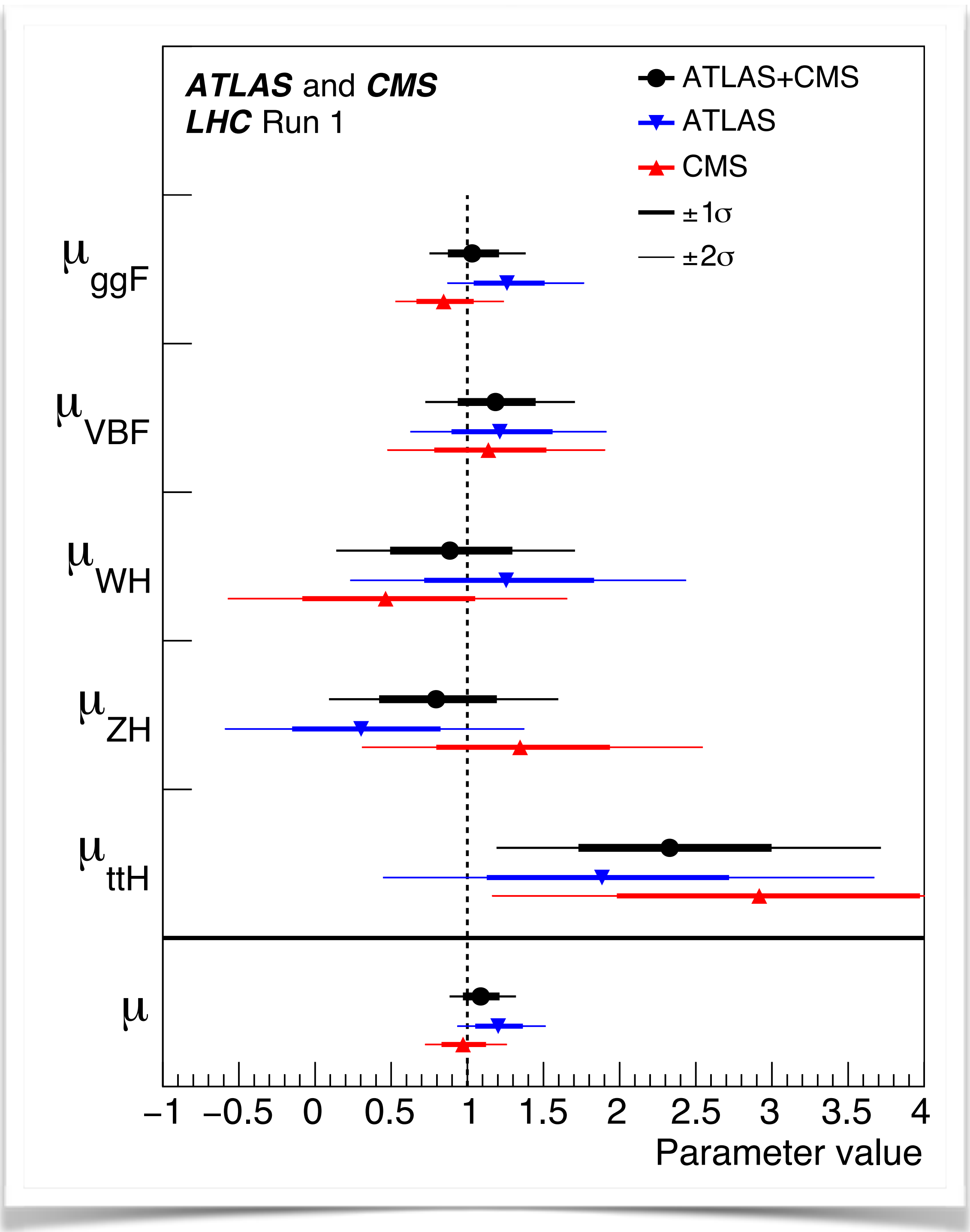
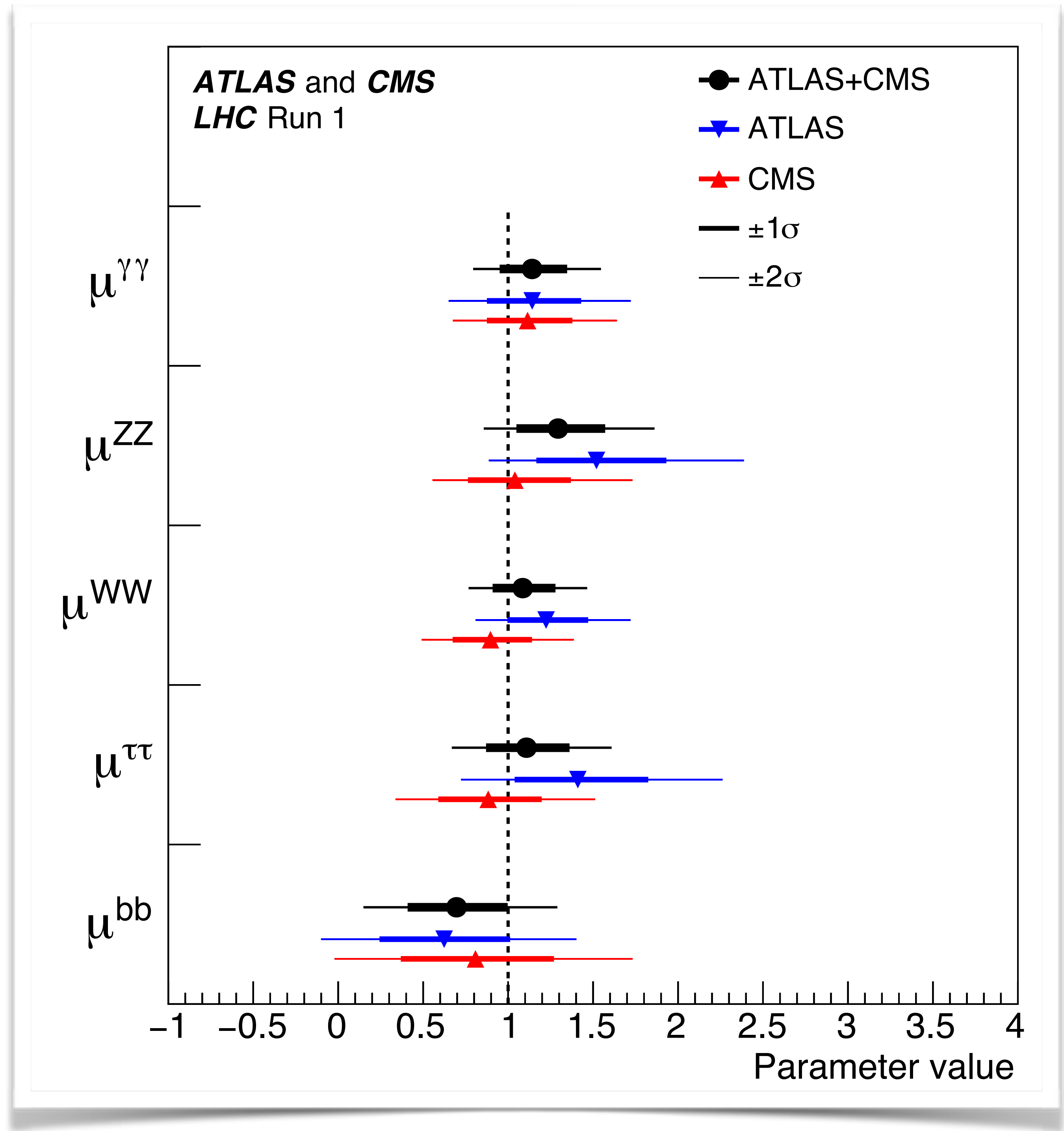
Production



Decay



Two independent fits: assume SM for the other

Interpretation as Couplings

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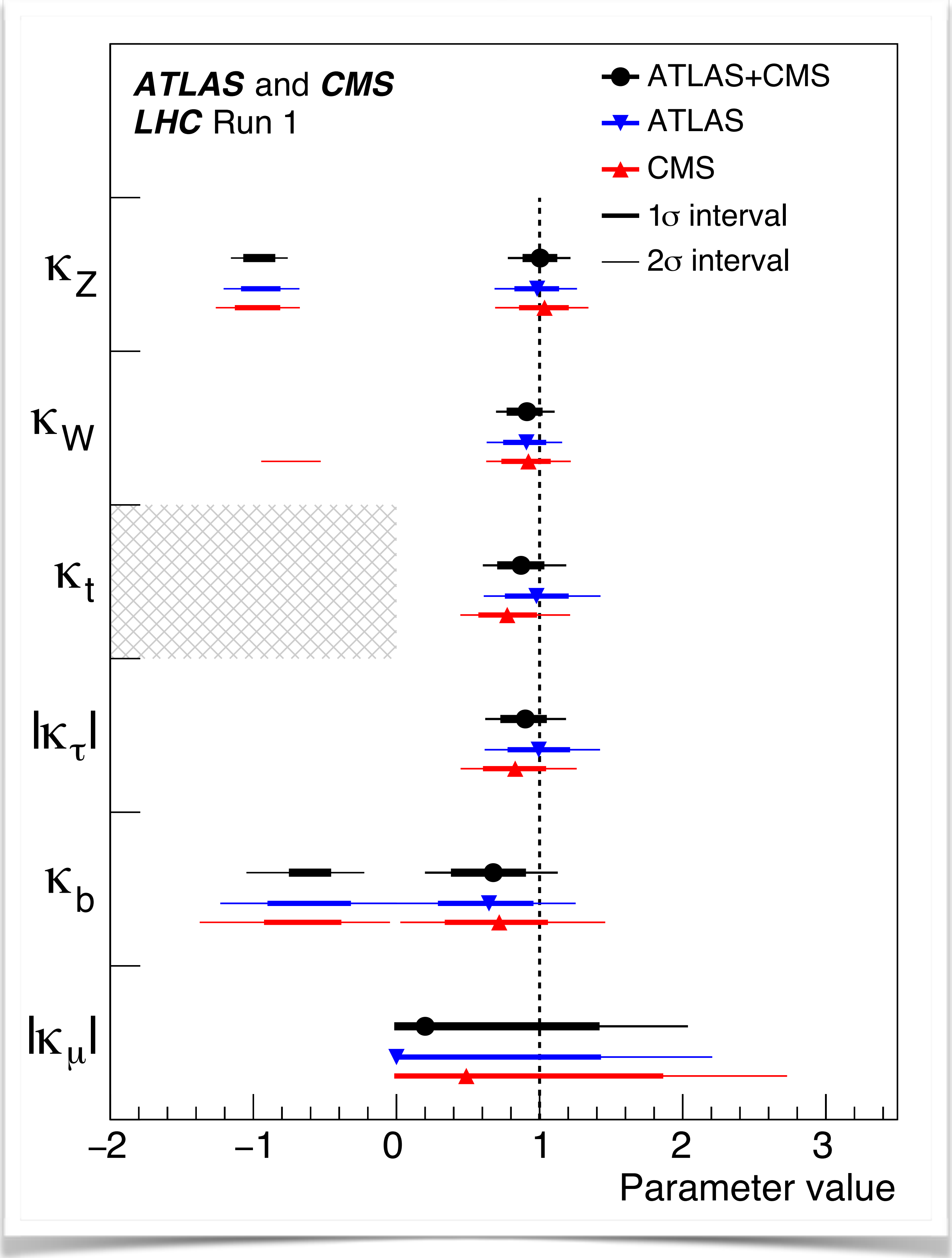
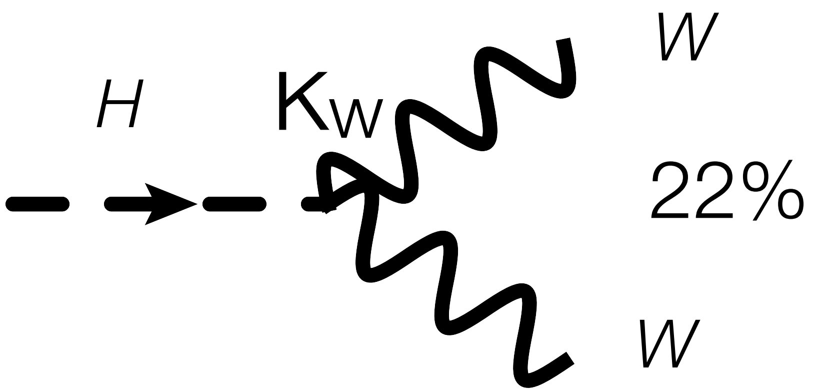




Assumptions:

No contributions to width from BSM particles (no decay to BSM particles)

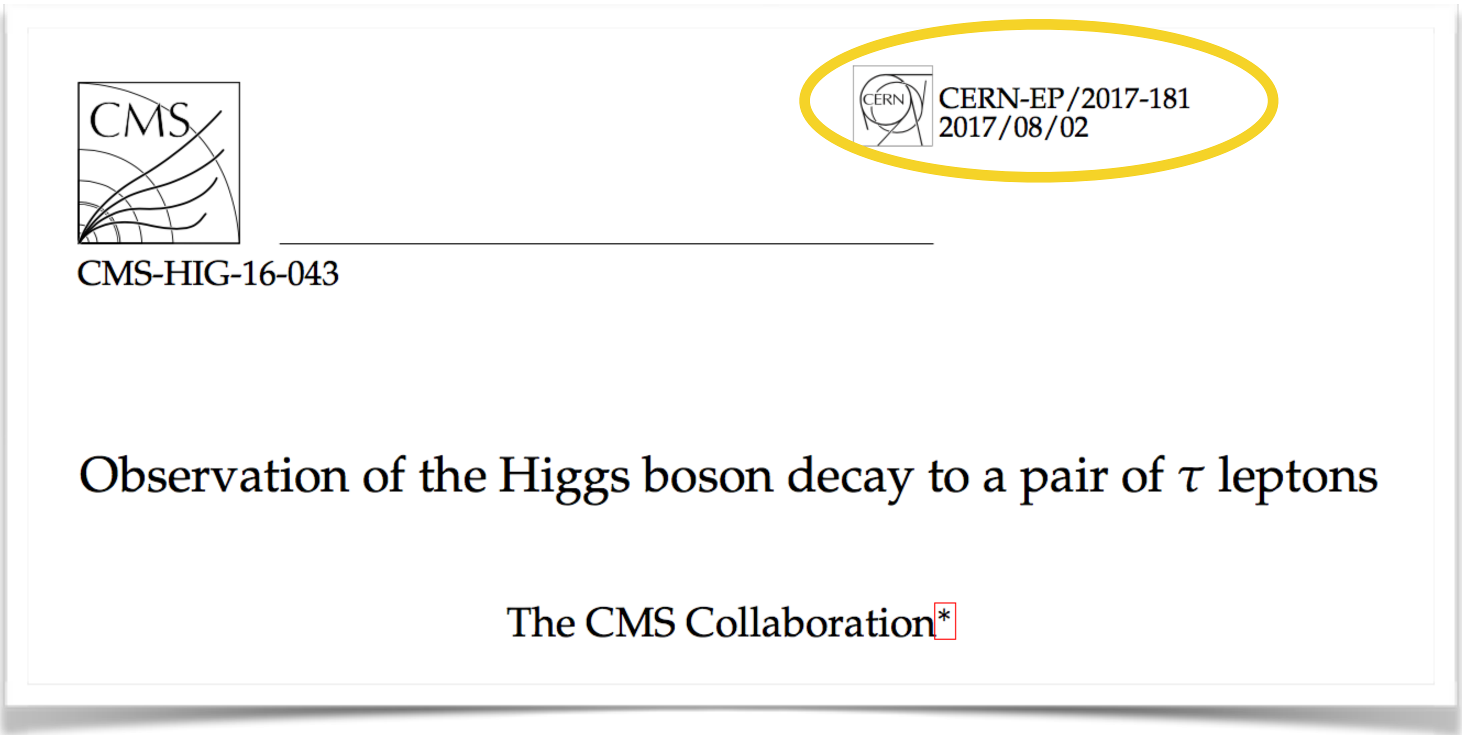
No contributions to loops from BSM particles

Generally good agreement with SM

Results for **fermions** are much weaker than for bosons

Observation of H→ττ

HIG-16-043



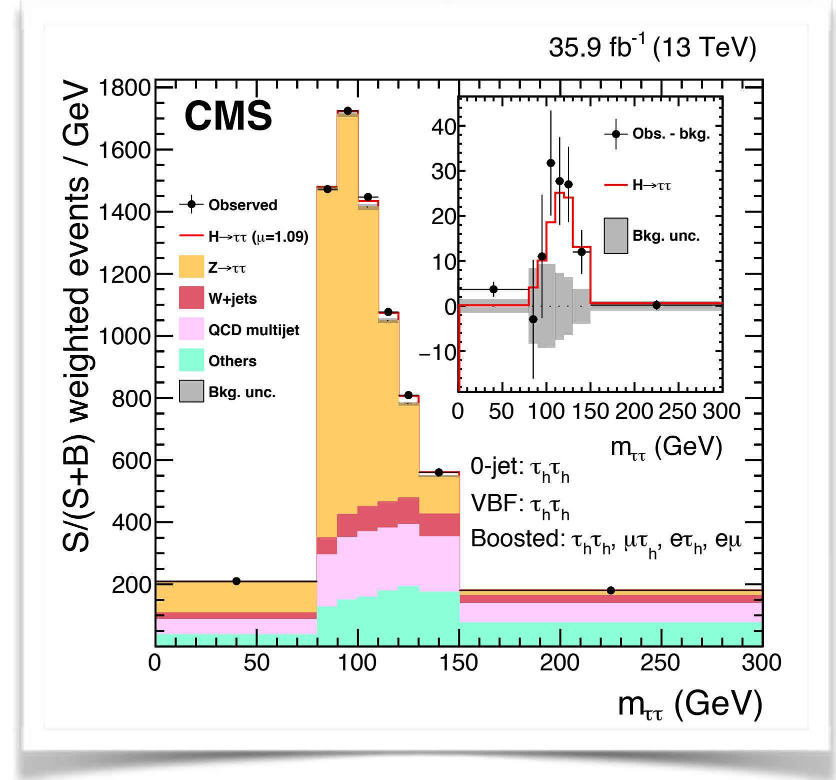
CMS

CMS-HIG-16-043

CERN-EP/2017-181
2017/08/02

Observation of the Higgs boson decay to a pair of τ leptons

The CMS Collaboration*

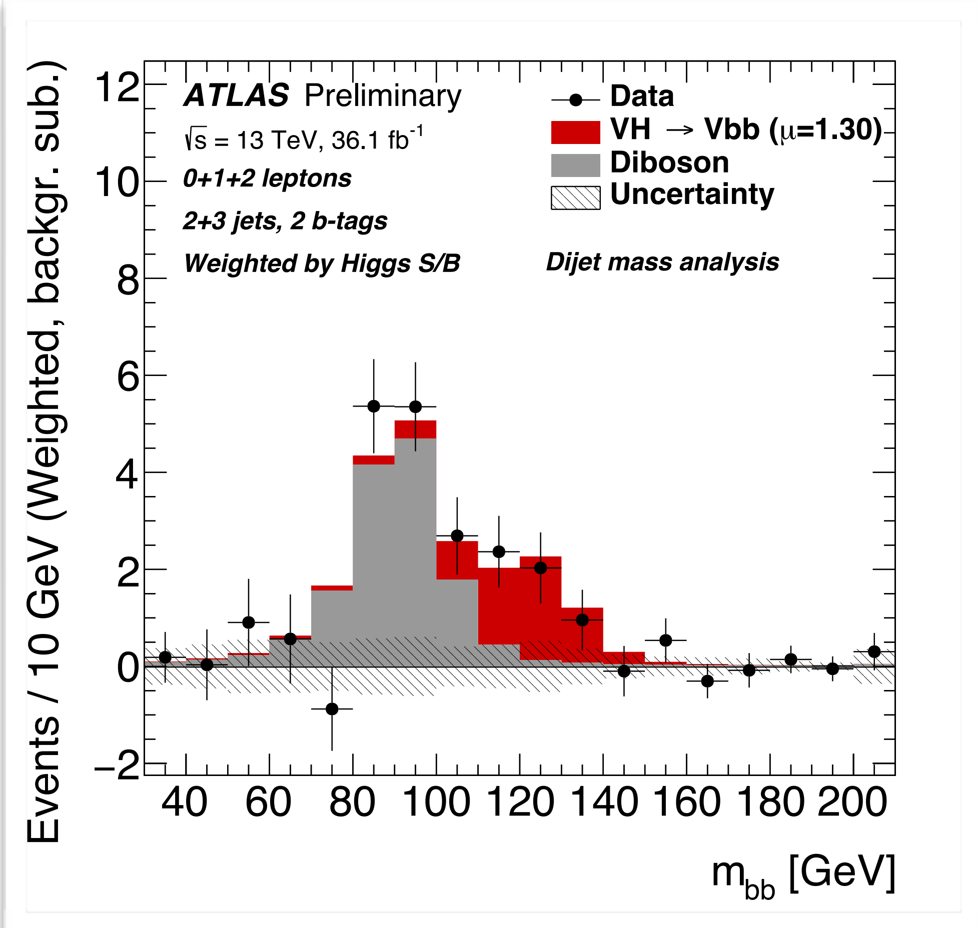


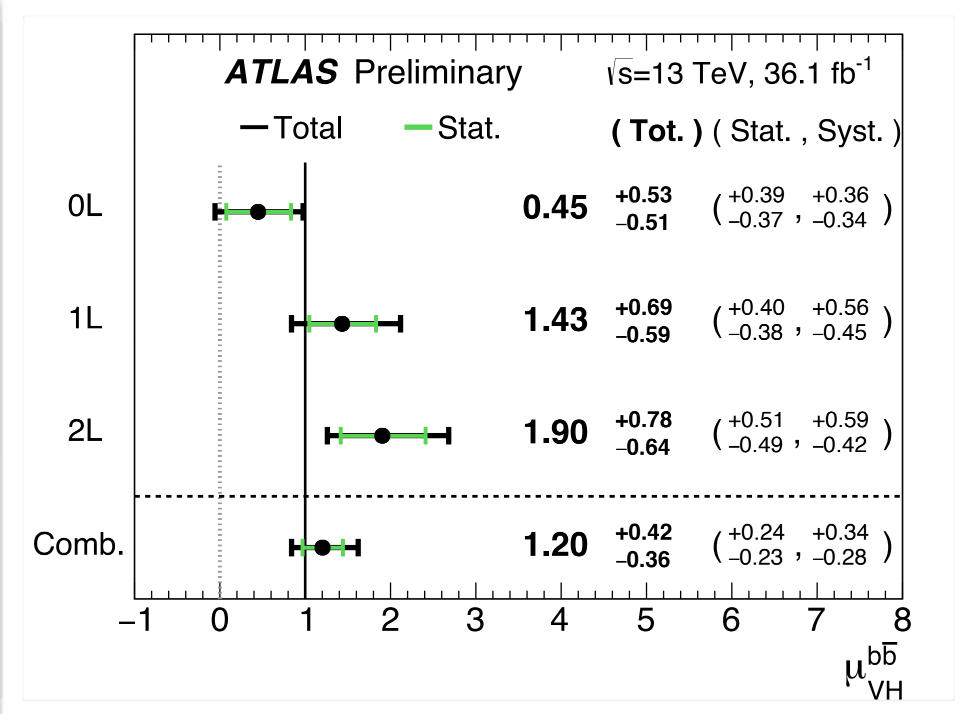
- CMS paper last week as first single experiment observation of the H→ττ (ATLAS+CMS observation in Run-1 combination)
- Only channel so far to directly observed the coupling to fermions
- Two channels (by τ decay): lepton-hadron, hadron-hadron
- Exploit both gluon-gluon fusion and VBF production
- Key elements: reconstructing the Higgs mass despite the presence of neutrinos and accurately estimating the Z→ττ background

Evidence for H→bb

HIG-16-044, ATLAS-CONF-2017-041

- H→bb is the most common decay (58%) but, due to the large backgrounds, it is very challenging
- Recent result from ATLAS provides the evidence for H→bb with an observed (expected) significance of 3.5σ (3.0σ)
- Use associated production with a W and Z boson
  - Leptonic decays provide trigger
  - Strongly reduce backgrounds
- Cross-check by measuring VZ production with Z→bb with an observed (expected) significance of 5.8σ (5.3σ)
- CMS combination of Run1+Run2 of 4.8σ

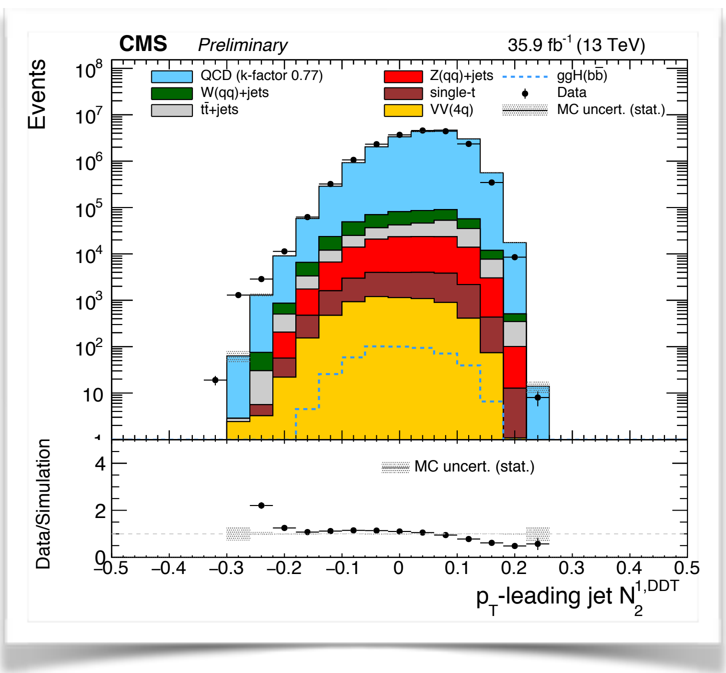


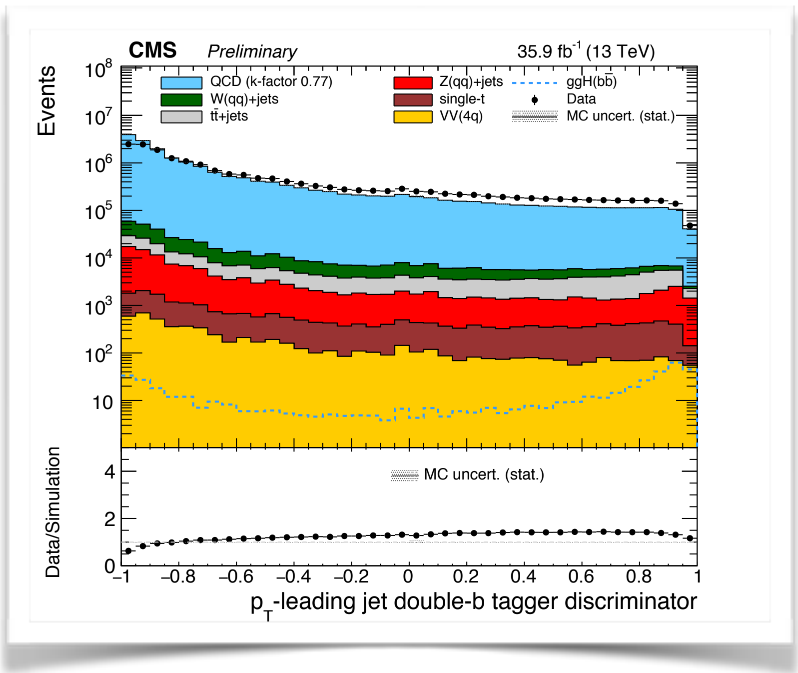


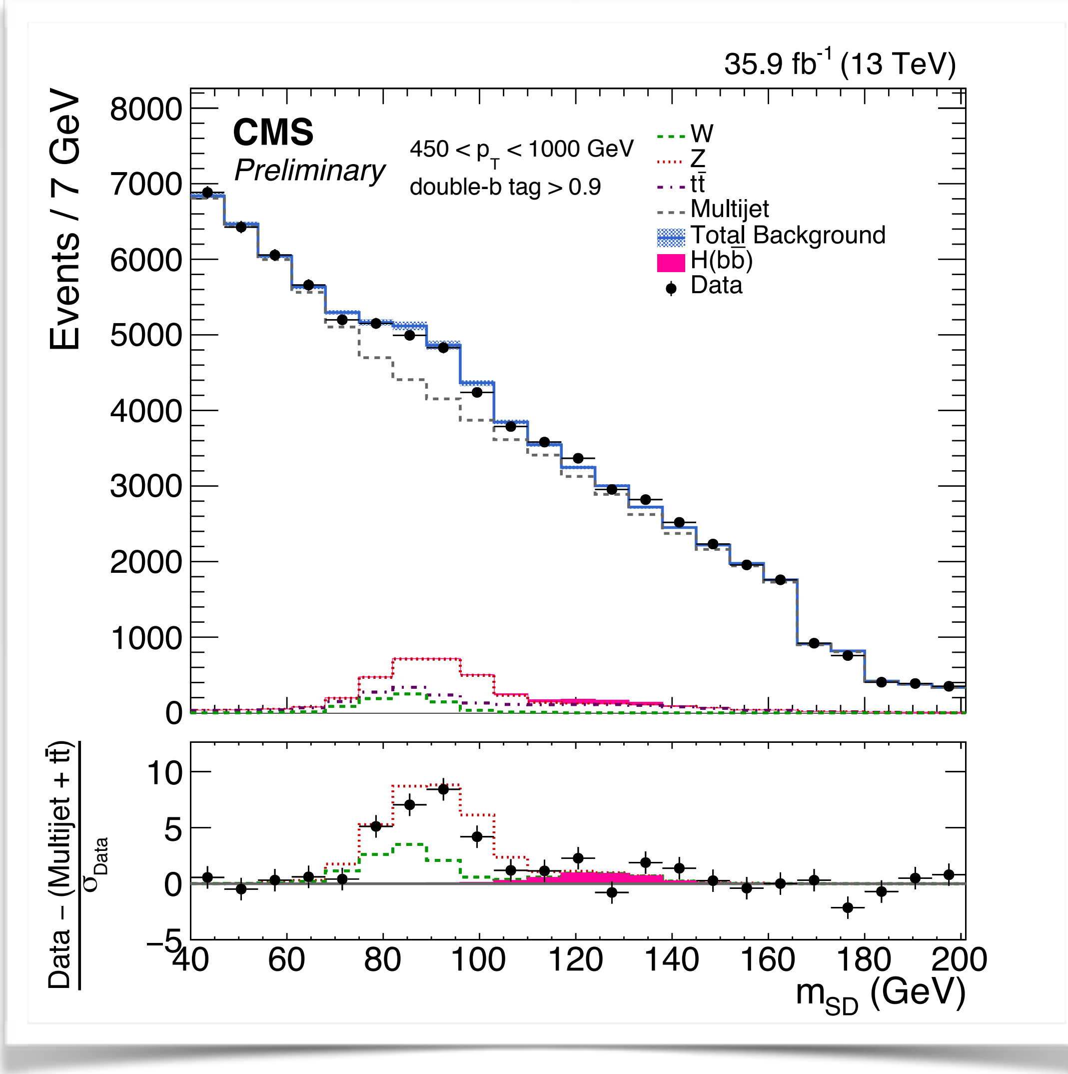
Novel High p_T H→bb Search

HIG-17-010

- Select events with a large radius jet with $p_T > 450$ GeV
  - Typically accompanied by a jet radiated off the Higgs
- Validate with Z→bb observation (5.1σ)
- Early days for the Higgs: observed (expected) significance of 1.5σ (0.7σ)



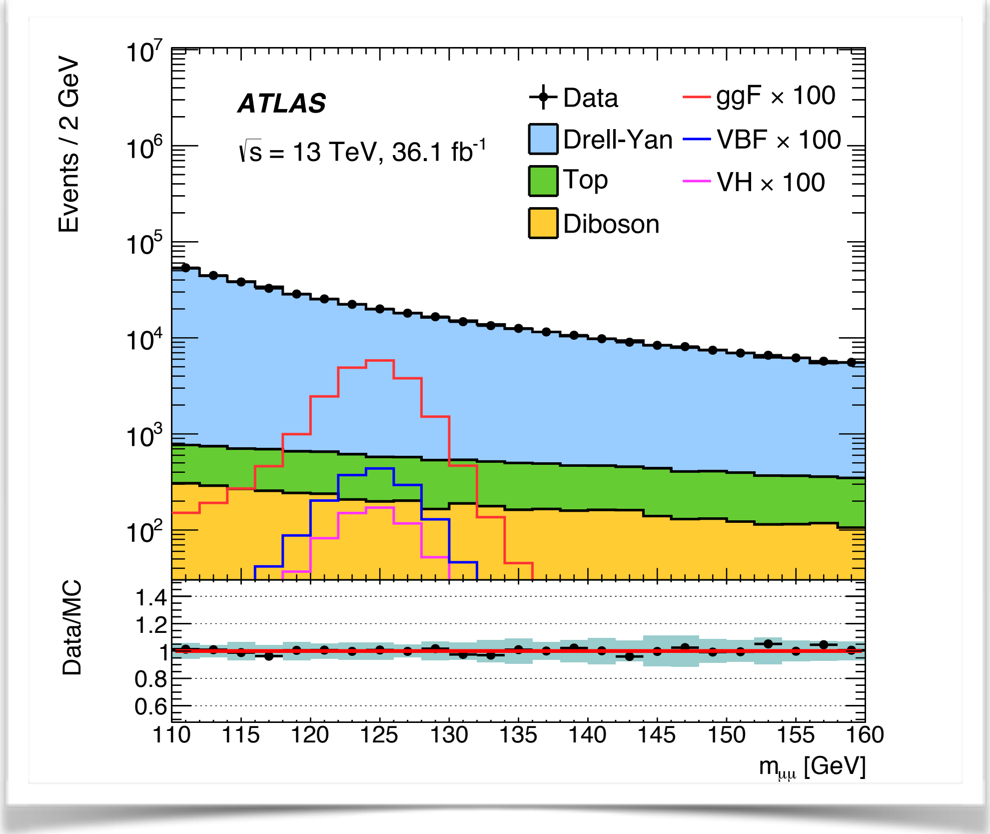


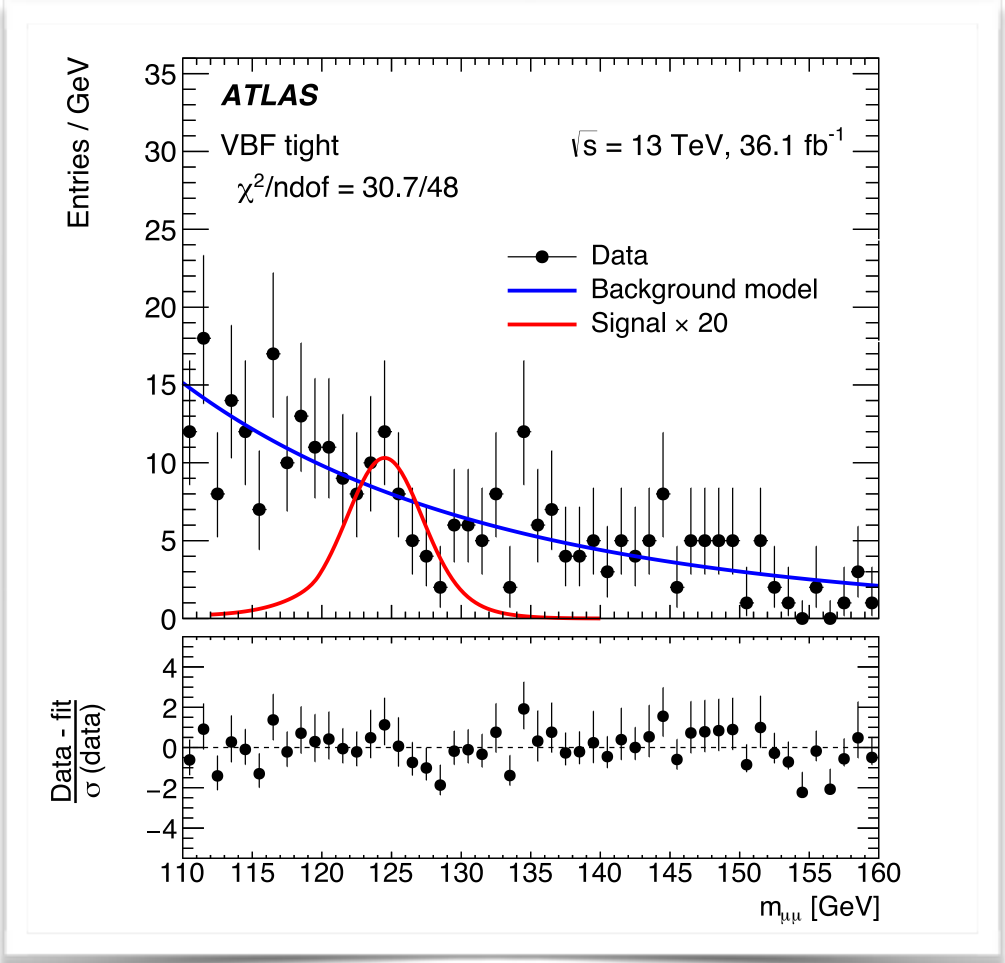


H→μμ

HIGG-2016-10

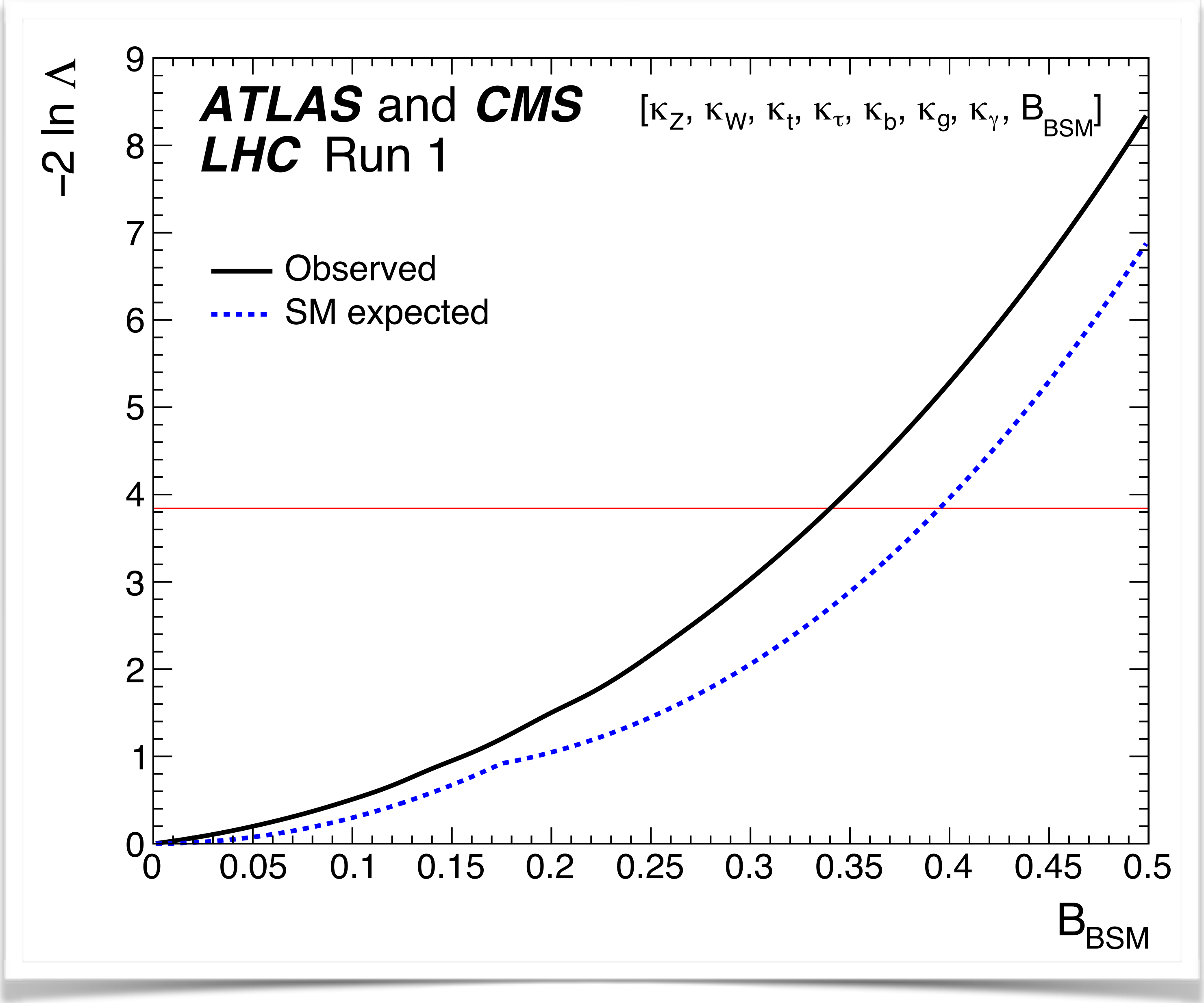
- So far, we've focussed on coupling of the Higgs to third generation fermions
- Structure of the fermionic sector is far from trivial !
- H→μμ will soon provide us with a means to probe the coupling of the Higgs to the second generation
- Higgs is easily identifiable via the two muons, but there is a background many orders of magnitude larger than the Higgs from Z→μμ decays
- Current limit is 2.8 (2.9) x the SM
    - Will become very interesting with more data!





Does the Higgs Decay to new particles?

Constraints on rate of decays to particles that we cannot see



$B_{inv} < 0.34$
(0.39) (95% CL)

Summary: Coupling vs Mass

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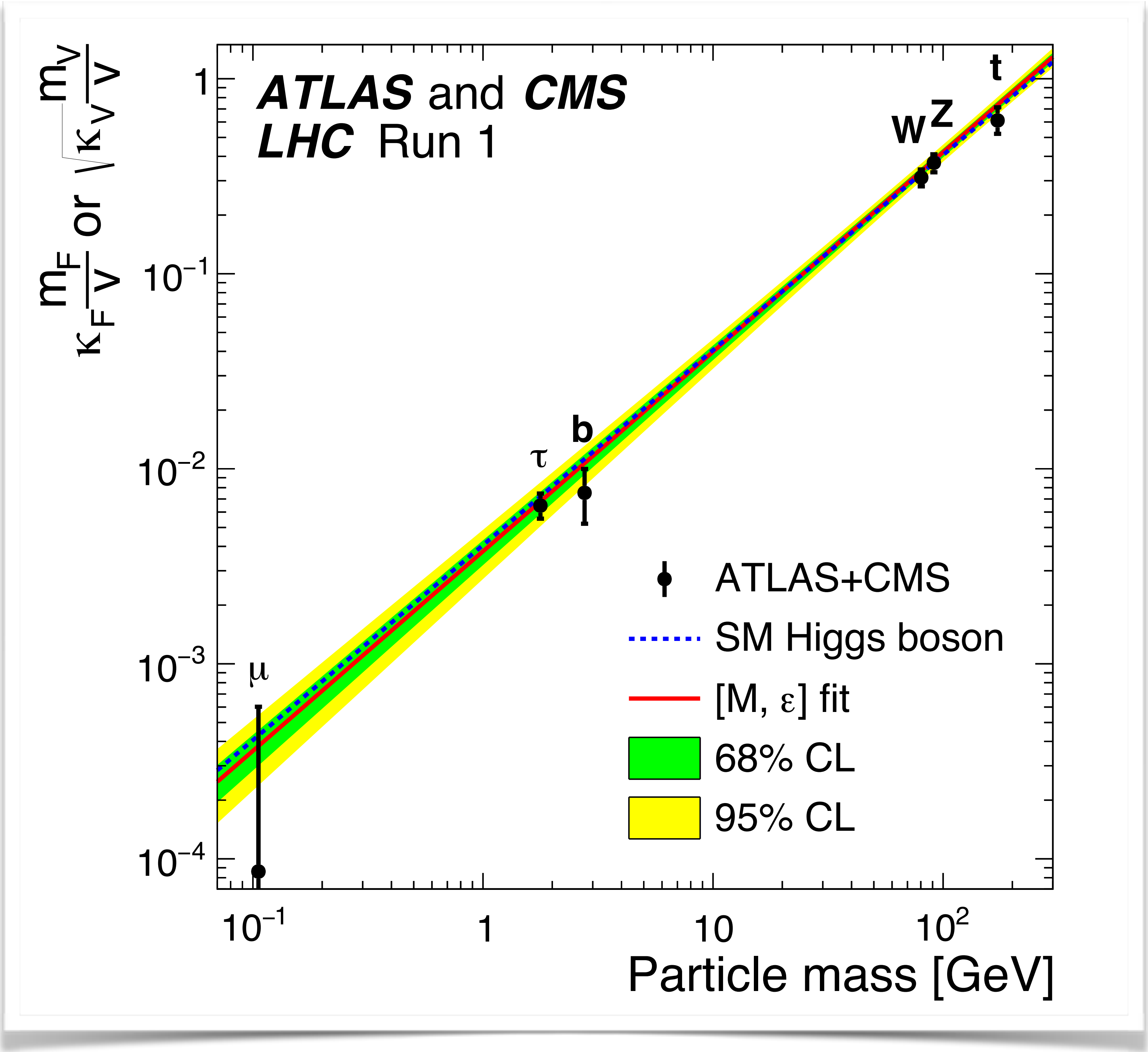


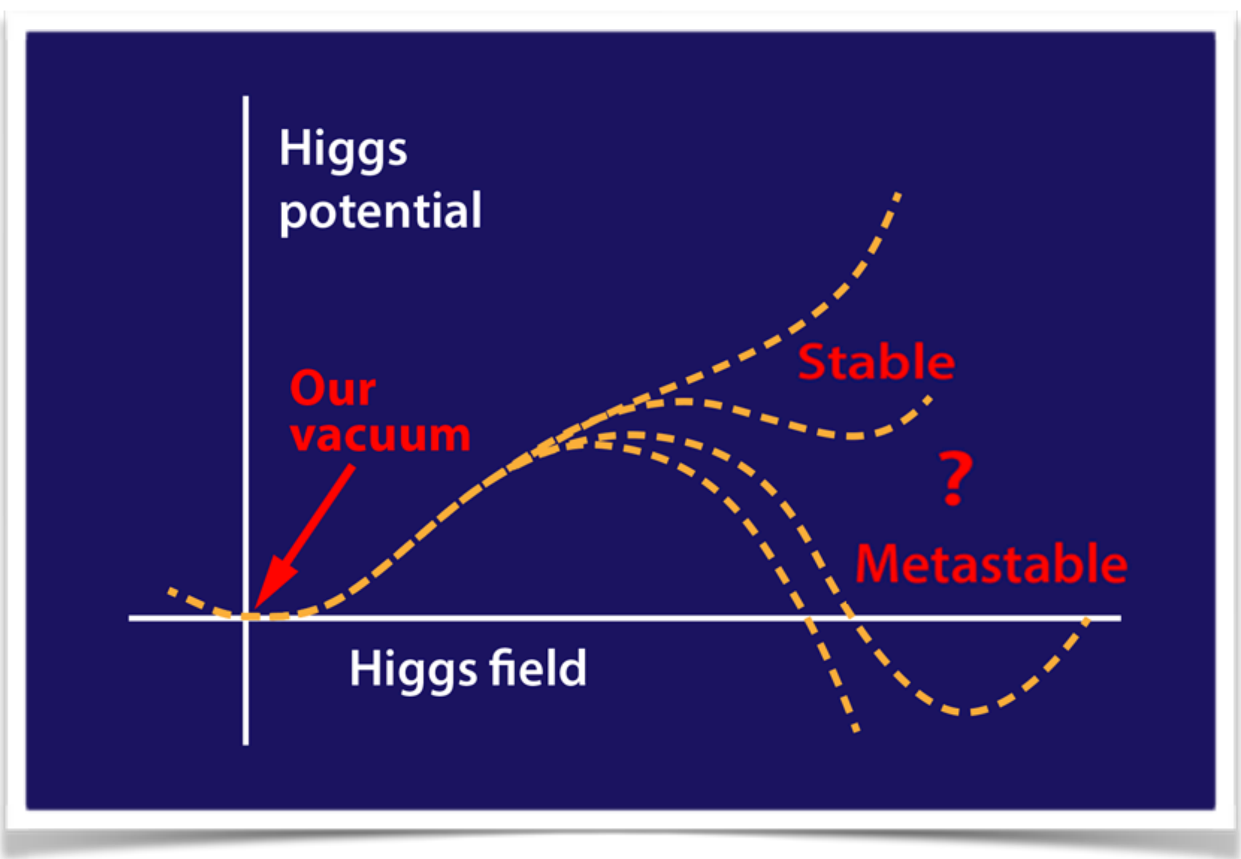
Good agreement but check the y-axis carefully

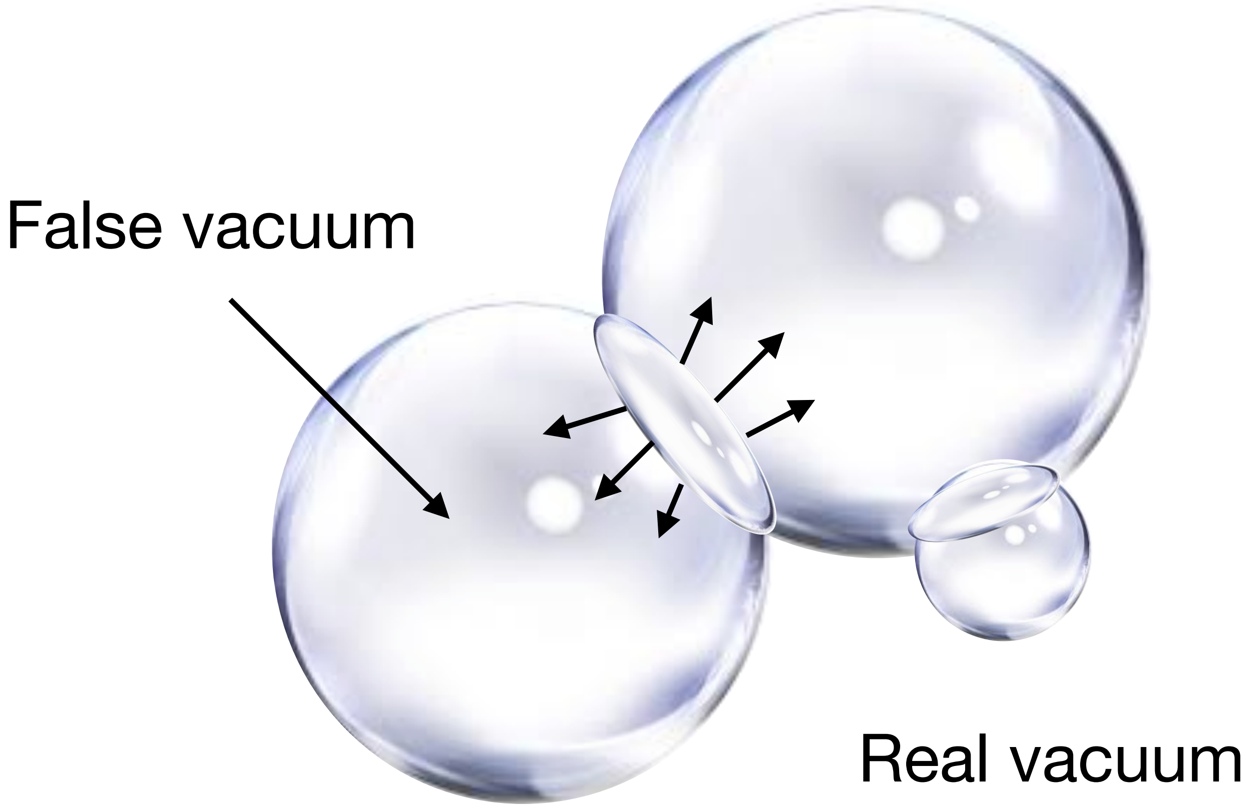
Overall conclusion: Generally very good agreement with the SM

Thins we don't know about the Higgs

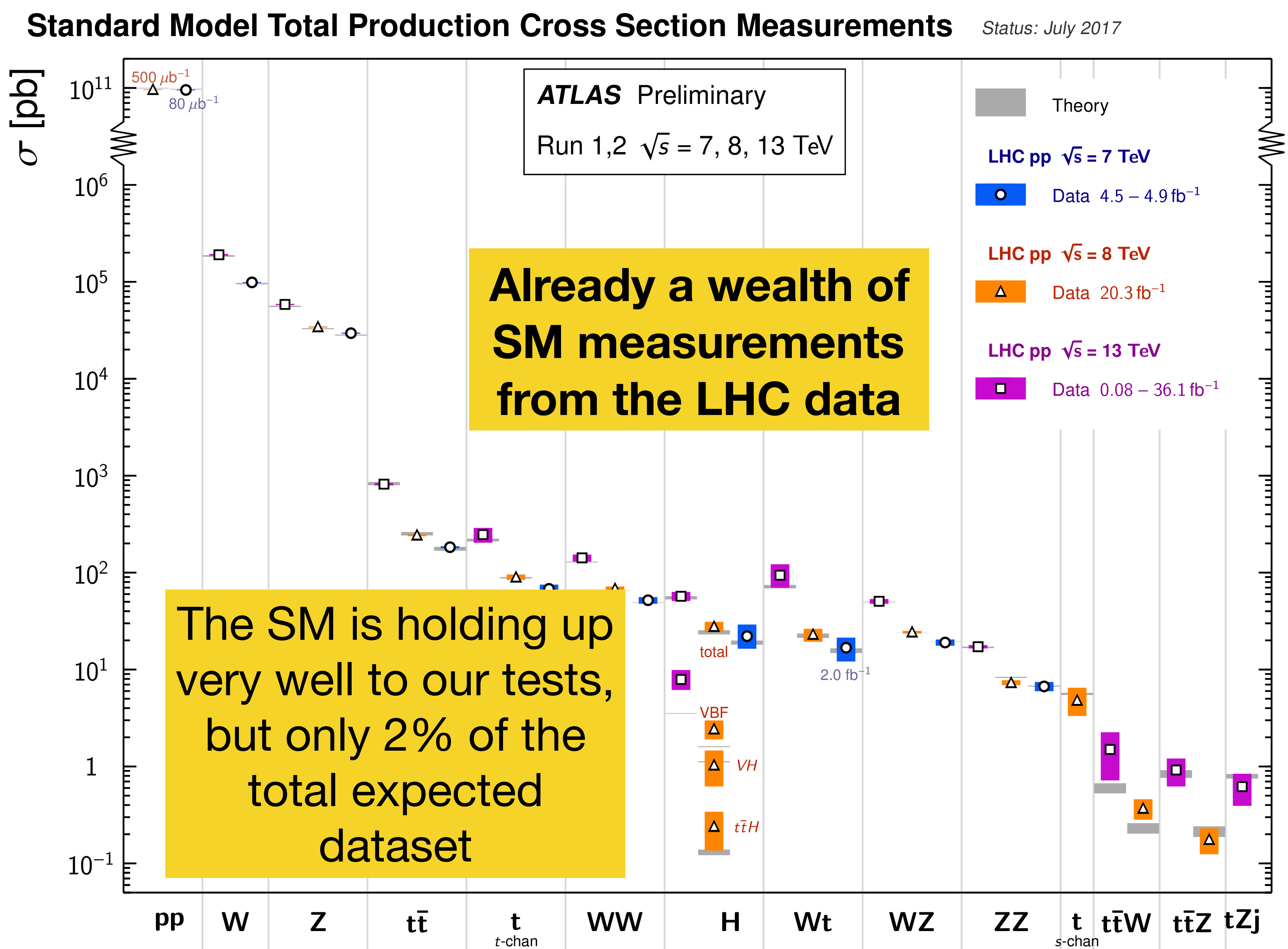
- Direct evidence for the Higgs-top Yukawa coupling
- Other rare Higgs decays, e.g. lepton flavour violation
- Confirm the Higgs self-interaction (HH production)
- Study the Higgs potential
  - Evolution from the early universe
  - Phase transition ? Connection to electroweak baryogengesis

Beginning of Higgs physics





Conclusion



Already a wealth of SM measurements from the LHC data

The SM is holding up very well to our tests, but only 2% of the total expected dataset