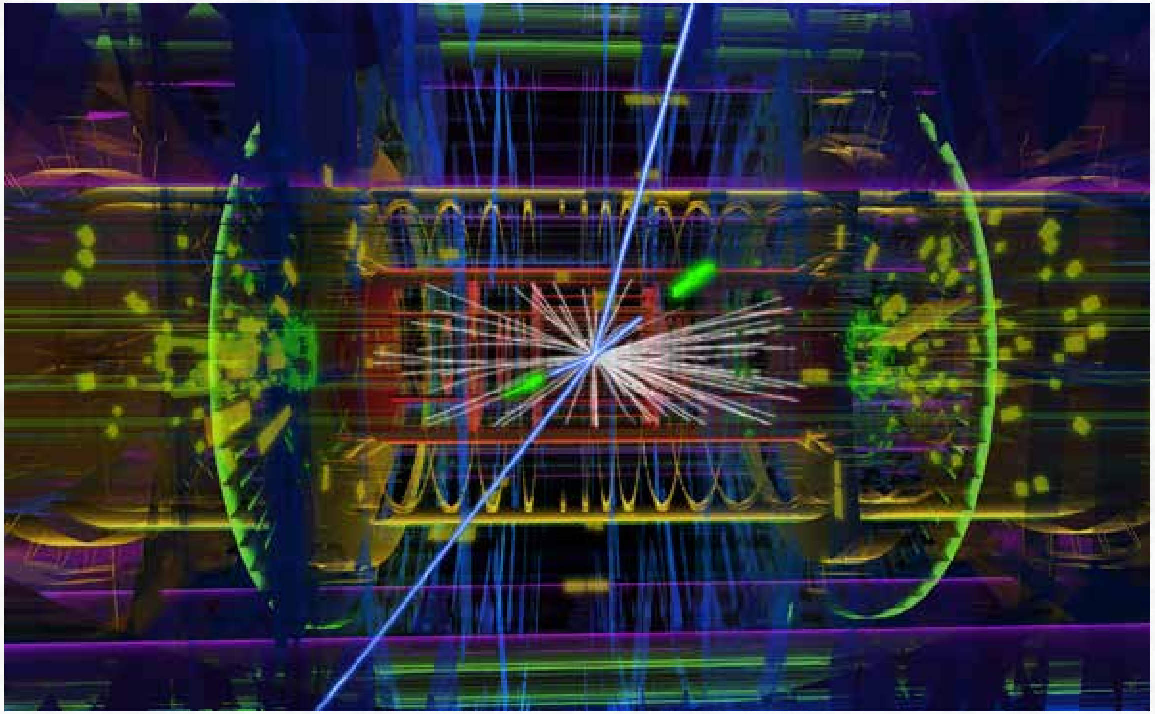
From the Discovery of the Higgs Boson to the Search for Dark Matter

-New results from the LHC-

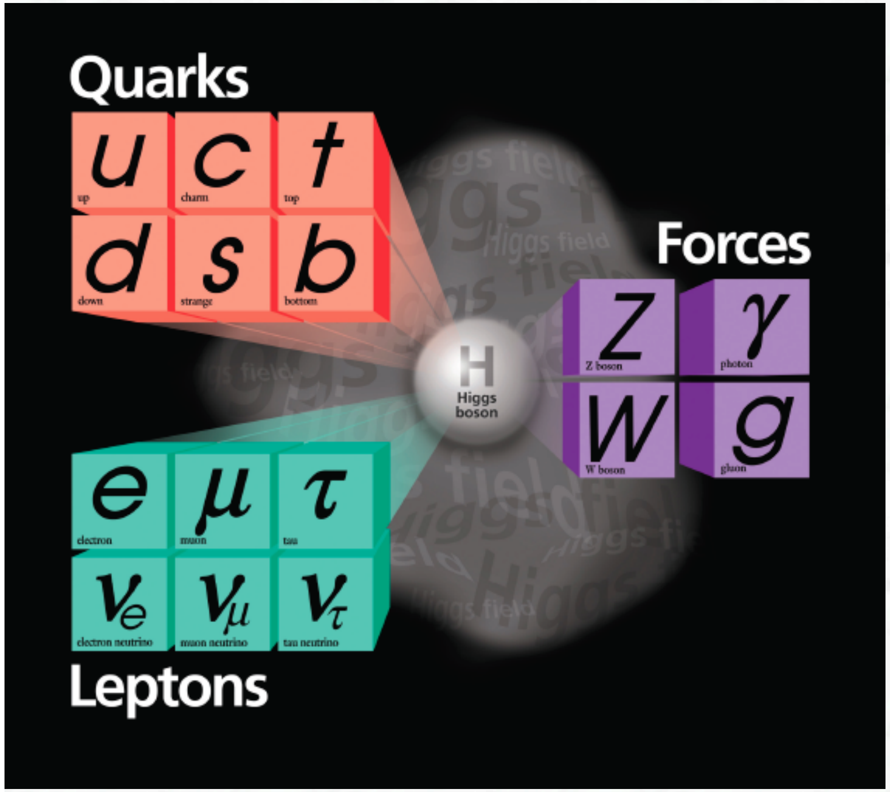


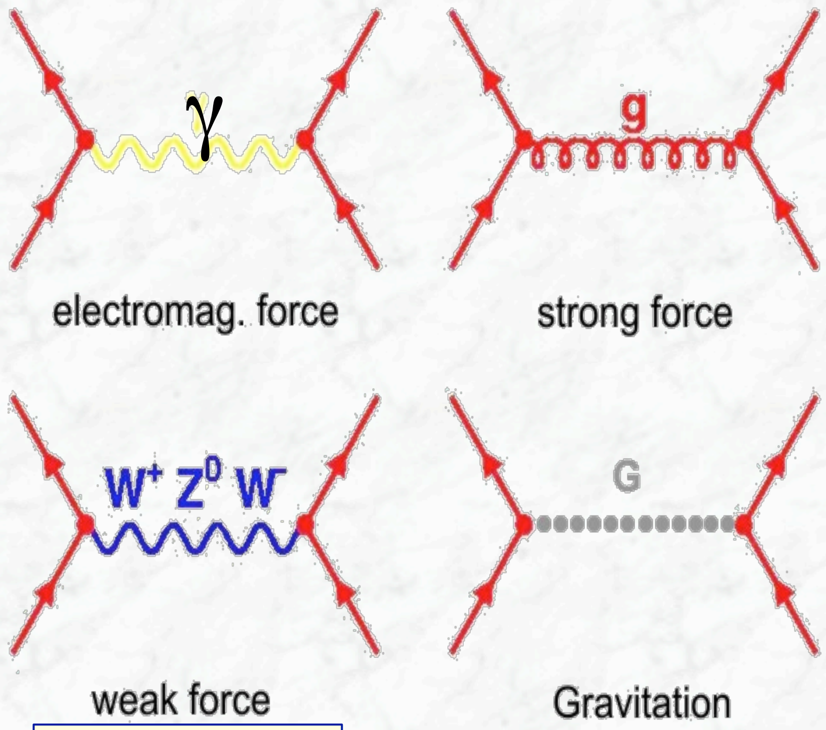
Karl Jakobs
Physikalisches Institut
Universität Freiburg / Germany

Announcement:
4th July 2012

- LHC and Data Taking,
  First look at the data at highest energies
- The profile of the Higgs Boson
  - What do we know today about the Higgs boson?
- Search for Physics Beyond the Standard Model
  (Focus on Dark Matter)
- Future: where do we go from here

The Standard Model of Particle Physics





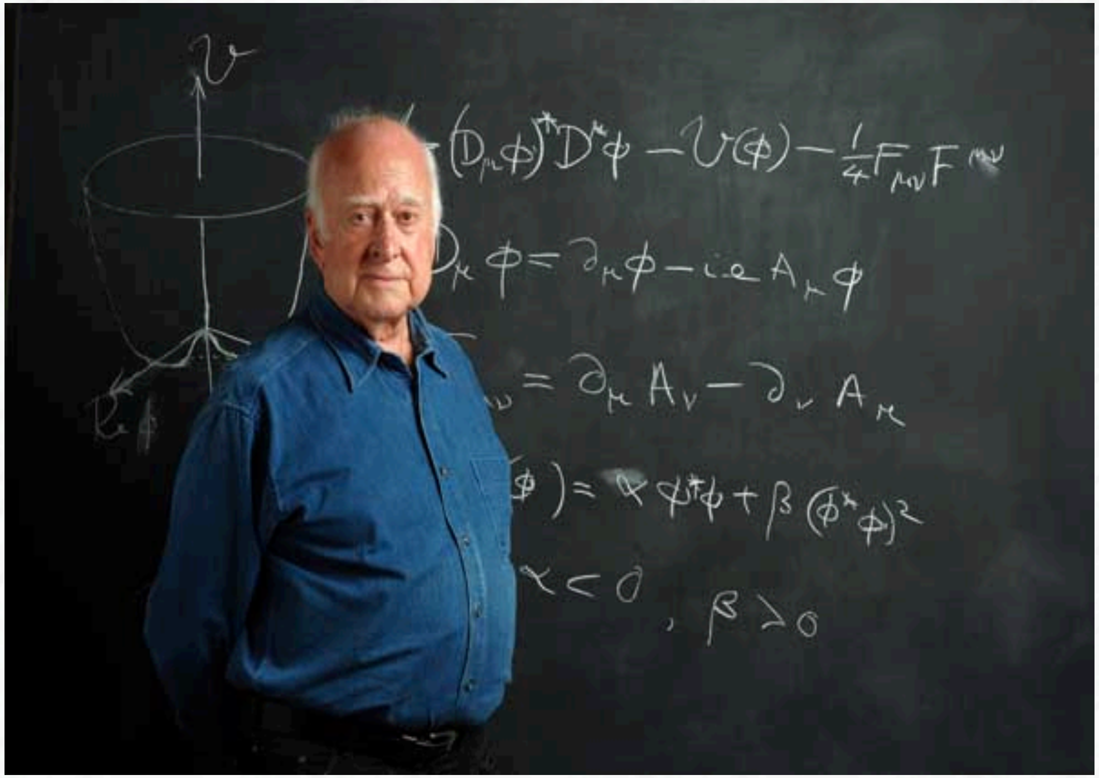
$m_W \approx 80.4$ GeV
$m_Z \approx 91.2$ GeV

(i) Constituents of matter: quarks and leptons (spin-½ fermions)

(ii) Four fundamental forces: described by quantum field theories (except gravitation)
→ massless spin-1 gauge bosons

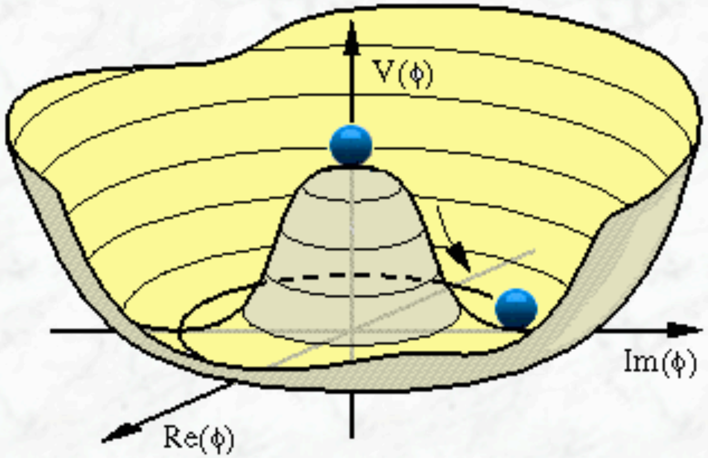
(iii) The Higgs field: → scalar field, spin-0 Higgs boson

The Brout-Englert-Higgs Mechanism



F. Englert and R. Brout. Phys. Rev. Lett. 13 (1964) 321;
P.W. Higgs, Phys. Lett. 12 (1964) 132, Phys. Rev. Lett. 13 (1964) 508;
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13 (1964) 585.

The Brout-Englert-Higgs Mechanism



Complex scalar (spin 0) field ϕ with potential:

$$V(\phi) = \mu^2(\phi^* \phi) + \lambda(\phi^* \phi)^2$$

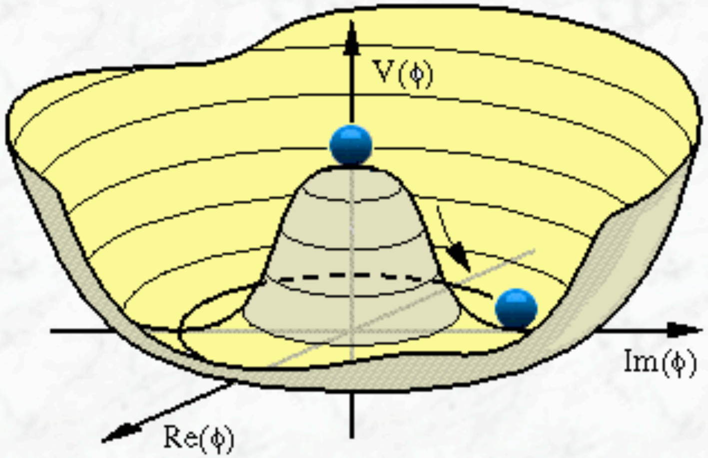
For $\lambda > 0$, $\mu^2 < 0$:
"Spontaneous Symmetry Breaking"

→ Omnipresent Higgs field: vacuum expectation value $v \approx 246$ GeV

→ Higgs Boson (mass not predicted, except $m_H <$ ~1000 GeV)

→ Particles acquire mass through couplings to the Higgs field

The Brout-Englert-Higgs Mechanism



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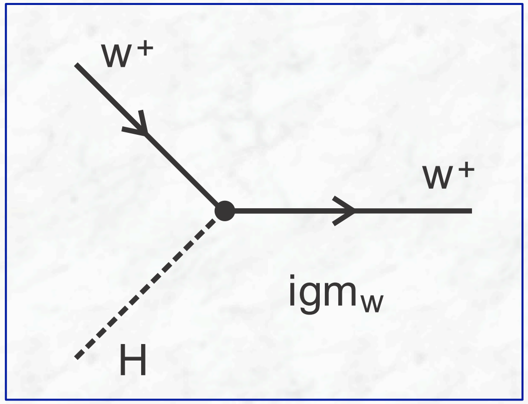
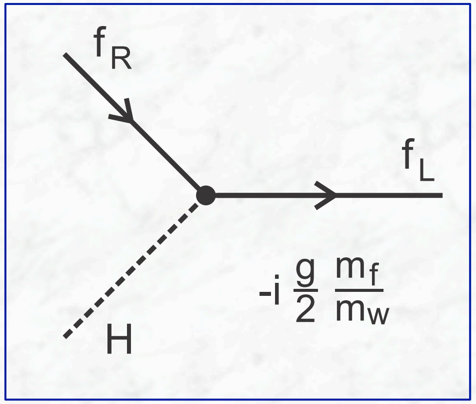
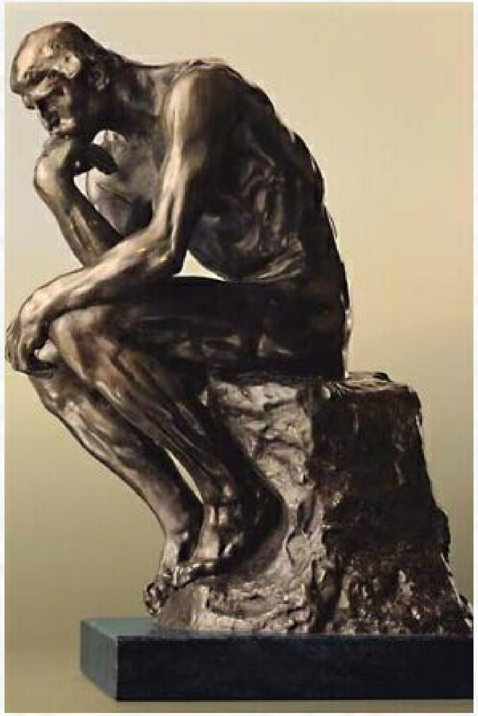


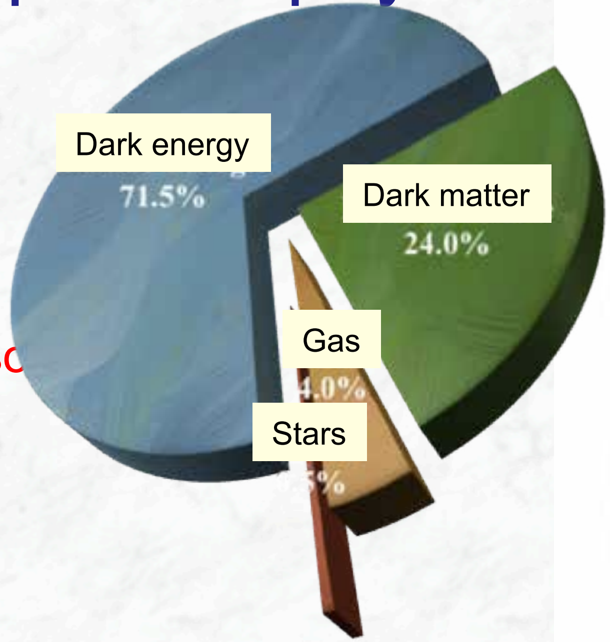


- Couplings proportional to mass
- Higgs boson decays preferentially into the heaviest accessible particles

The Open Questions



Key questions of particle physics



1. Mass

What is the origin of mass?

A Higgs particle seems to exist !

What is its profile?

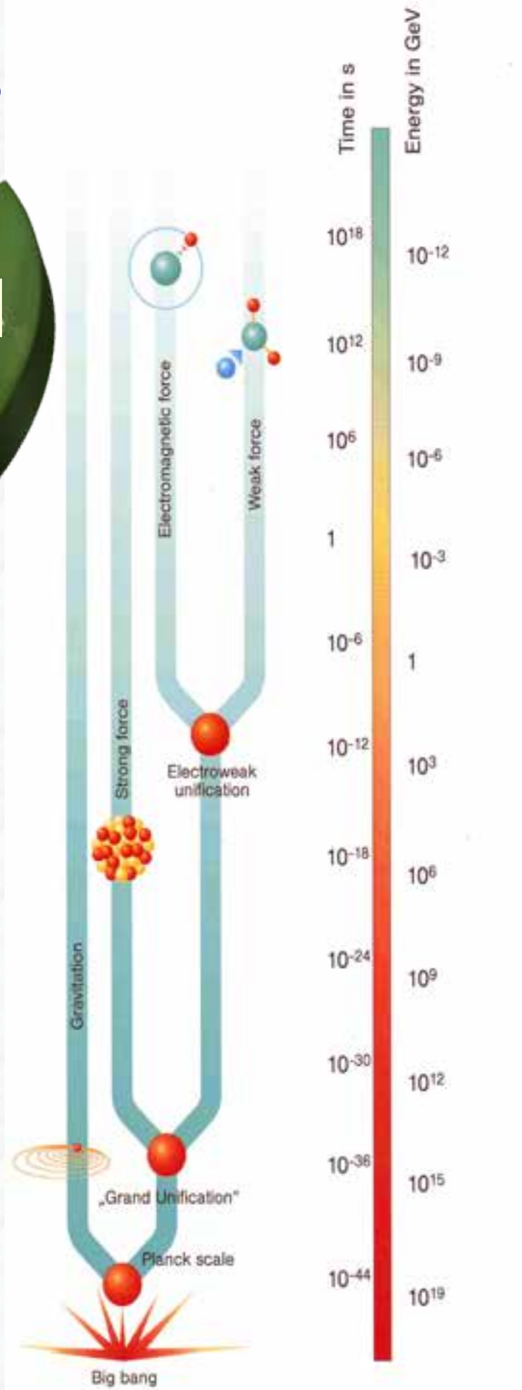
Is it the Standard Model Higgs boso

2. Unification

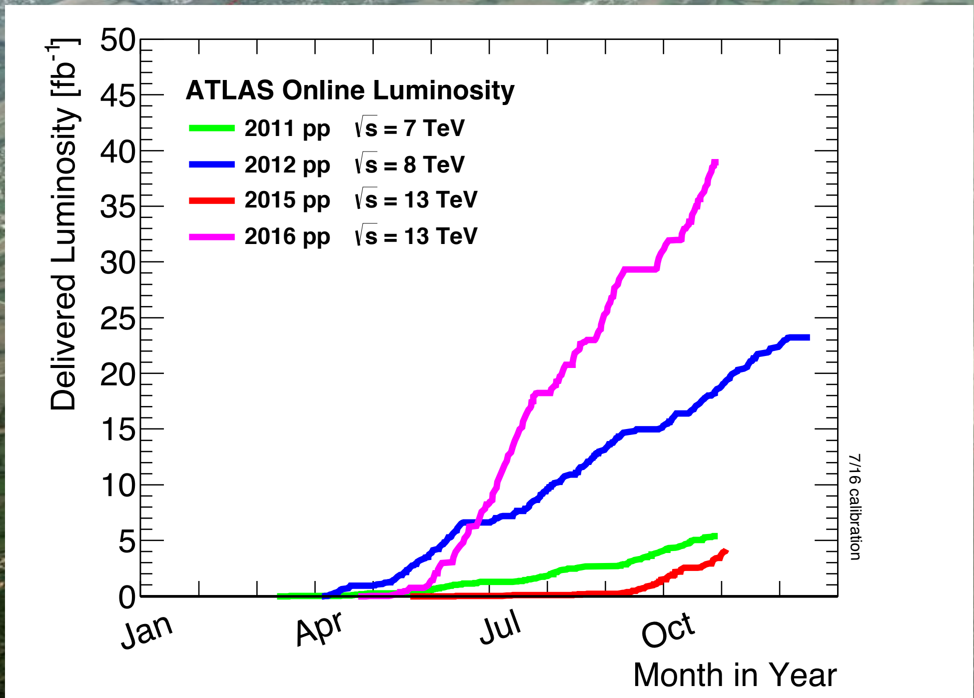
- Can the interactions be unified?
- Are there new types of matter, e.g. supersymmetric particles ? Are they responsible for the Dark Matter in the universe?

3. Flavour

- Why are there three generations of particles?
- What is the origin of the matter-antimatter asymmetry (Origin of CP violation)



The Large Hadron Collider



Data taking at the LHC (pp):

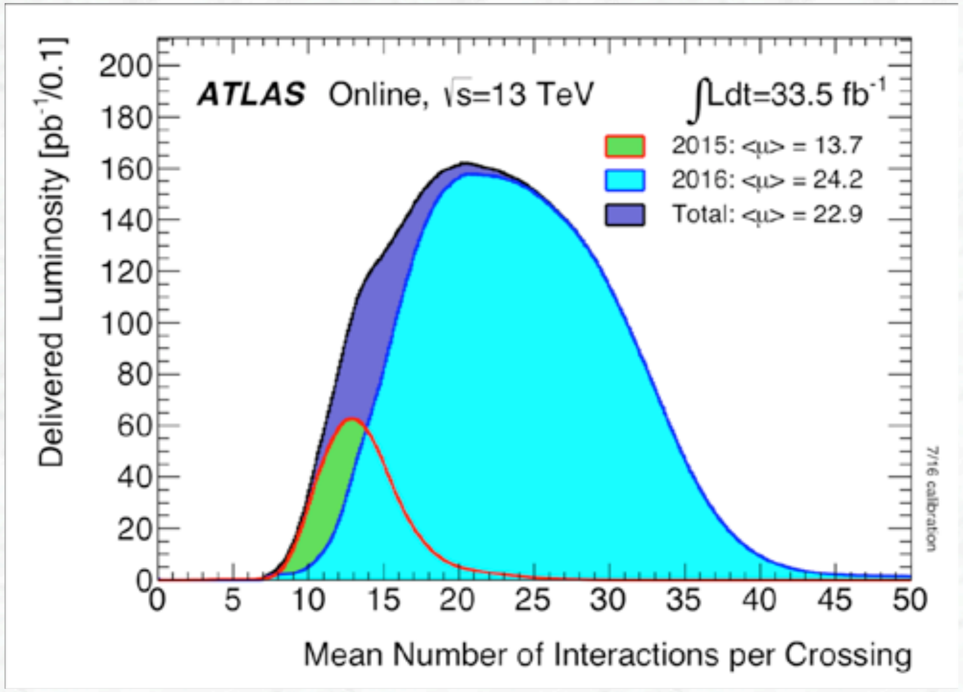
2011: $\sqrt{s}$ = 7 TeV L = 5 fb^{-1}

2012: $\sqrt{s}$ = 8 TeV L = 25 fb^{-1}

2015: $\sqrt{s}$ = 13 TeV L = 4 fb^{-1}

2016: L = 39 fb^{-1}

Data taking at the LHC



Until end of 2012:

> 10^{15} Proton-proton collisions
~ 10^{10} collisions recorded

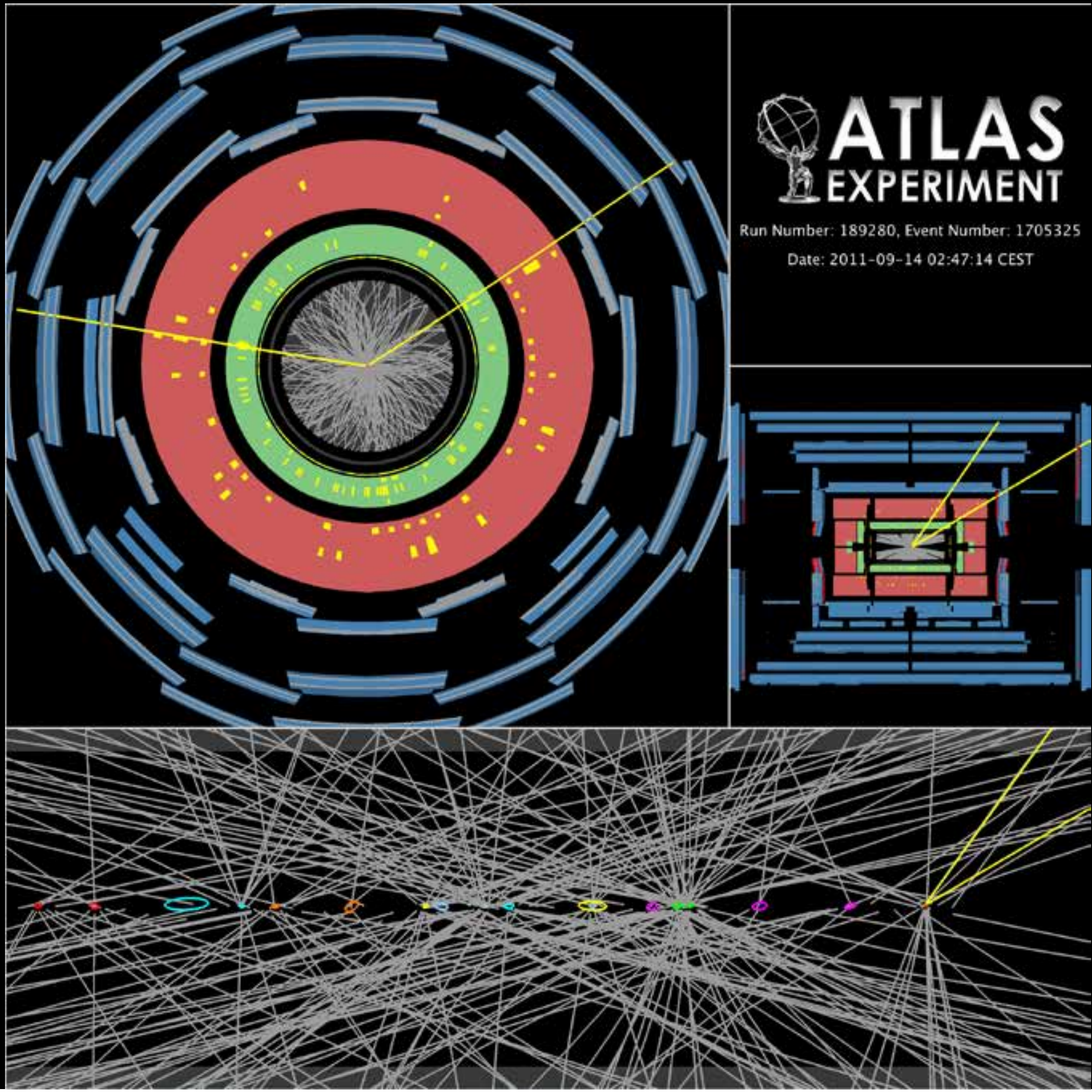
25 $\cdot 10^6$ Z → $\mu\mu$ decays registered

- Data taking extremely successful (beyond all expectations)

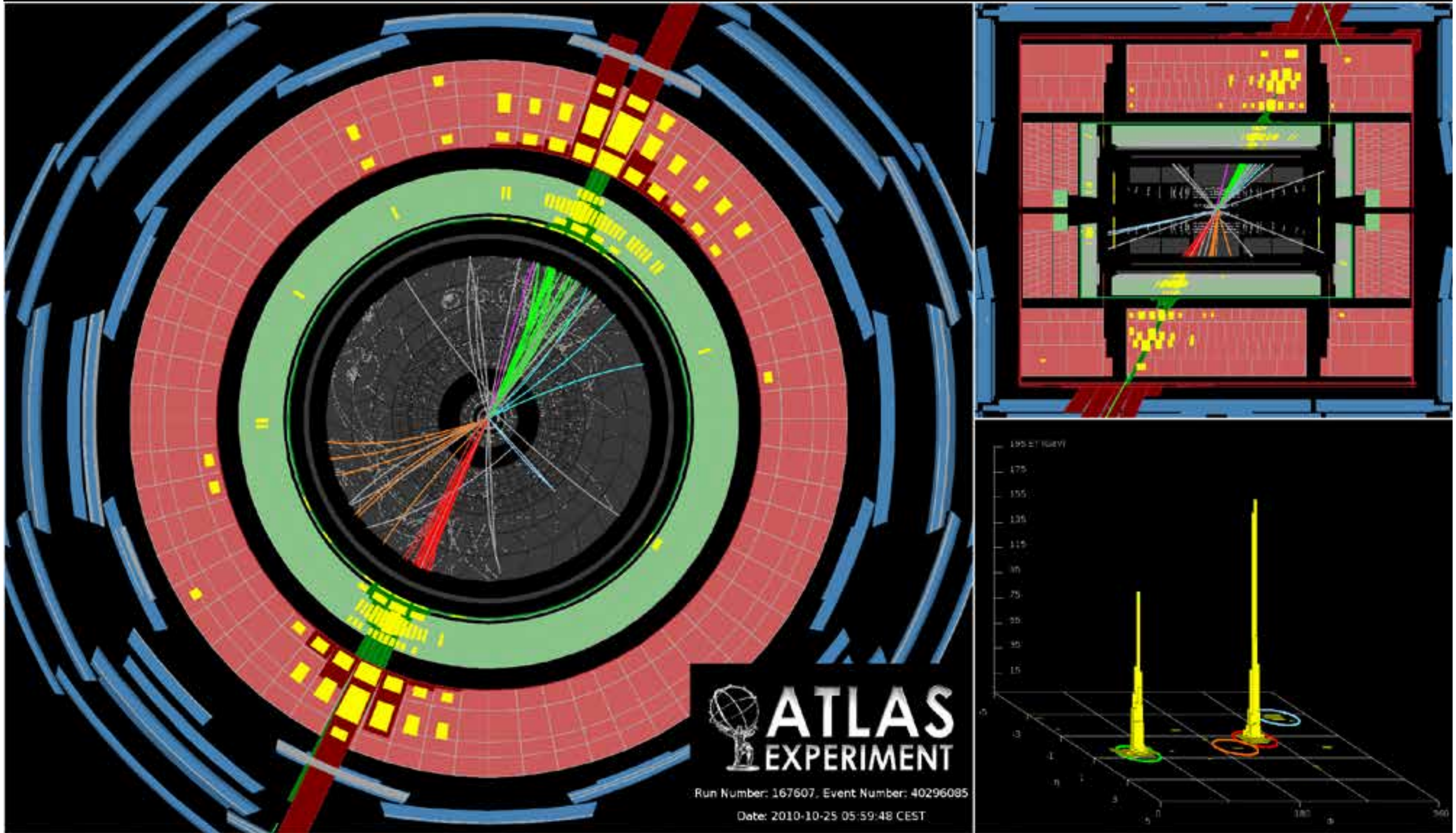
  Accelerator: beam intensity so high, that during one bunch crossing more than 20 proton-proton interactions take place

- Experiments: - High efficiency for recording the collision data: ~93.5%
  - Functioning detector channel >99%

$Z \rightarrow \mu^+ \mu^-$ with 20 reconstructed pp vertices

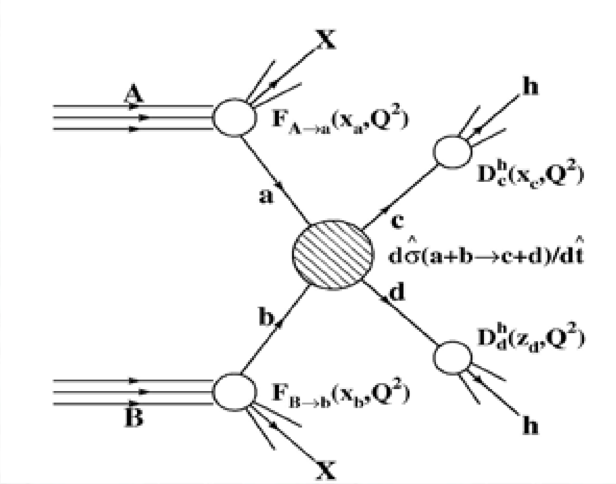


High p_T jet events at the LHC

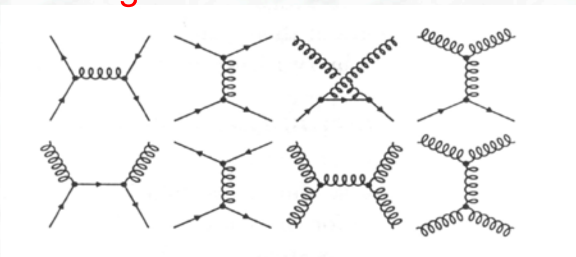


Event display that shows the highest-mass central dijet event collected during 2010, where the two leading jets have an invariant mass of 3.1 TeV. The two leading jets have (p_T, y) of (1.3 TeV, -0.68) and (1.2 TeV, 0.64), respectively. The missing E_T in the event is 46 GeV. From ATLAS-CONF-2011-047.

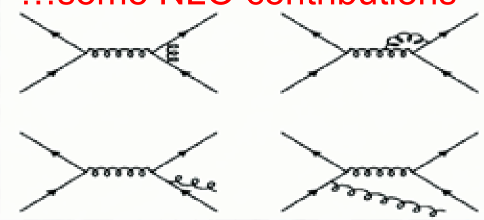
Double differential jet production cross sections, as a function of p_T and rapidity y (full 2015 data set, $\sqrt{s}$ = 13 TeV)

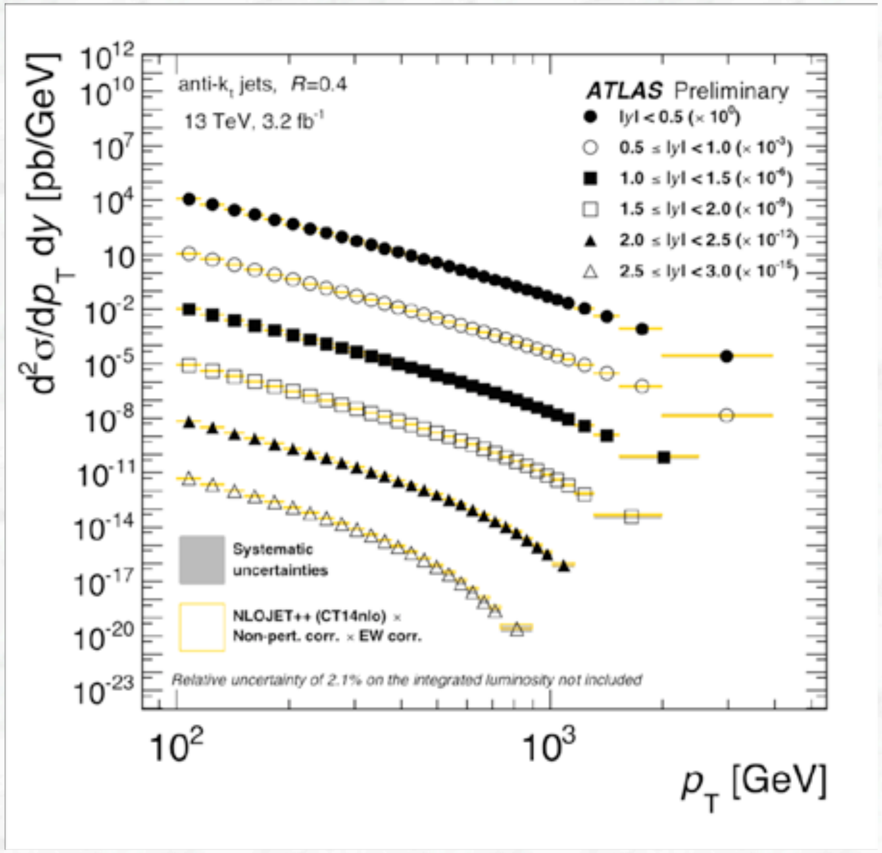


Leading order



…some NLO contributions





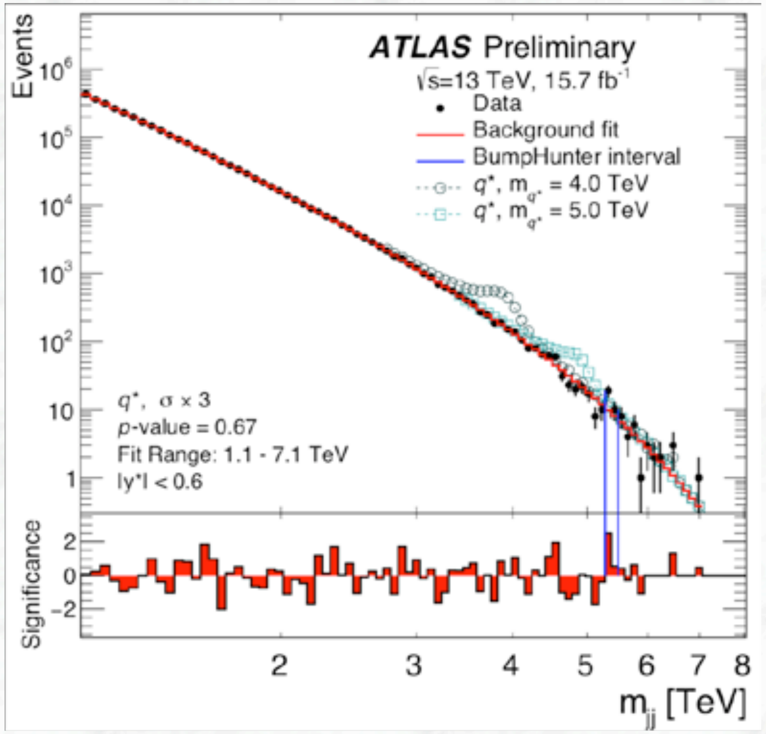
Also at the highest energies explored so far, the data are well described by NLO perturbative QCD calculations (NLOJet++)

In addition to QCD test: Sensitivity to New Physics

- Di-jet mass spectrum provides large sensitivity to new physics

  e.g. resonances decaying into qq, excited quarks q*, ….

- Search for resonant structures in the di-jet invariant mass spectrum

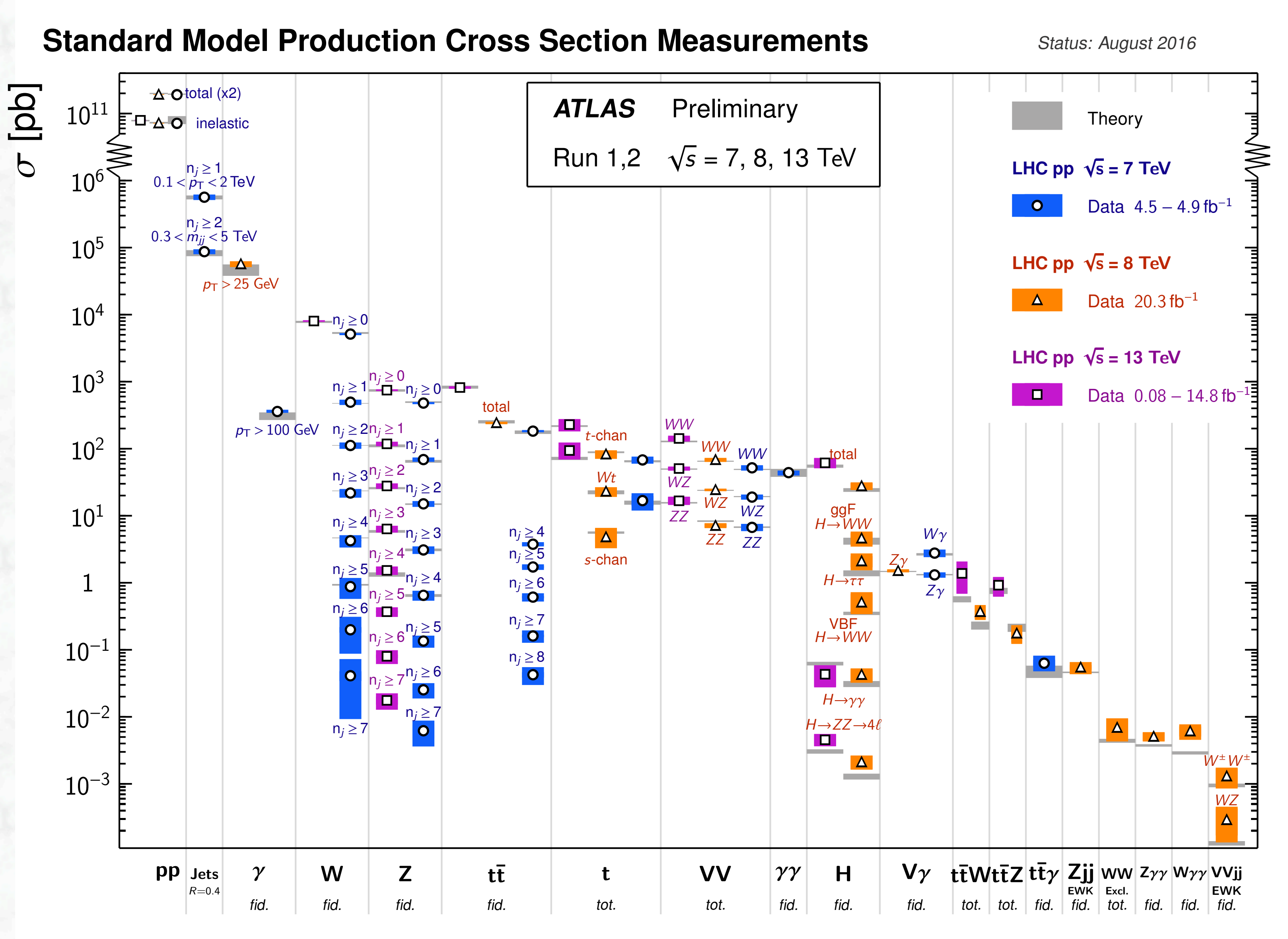


No evidence for resonant structures:

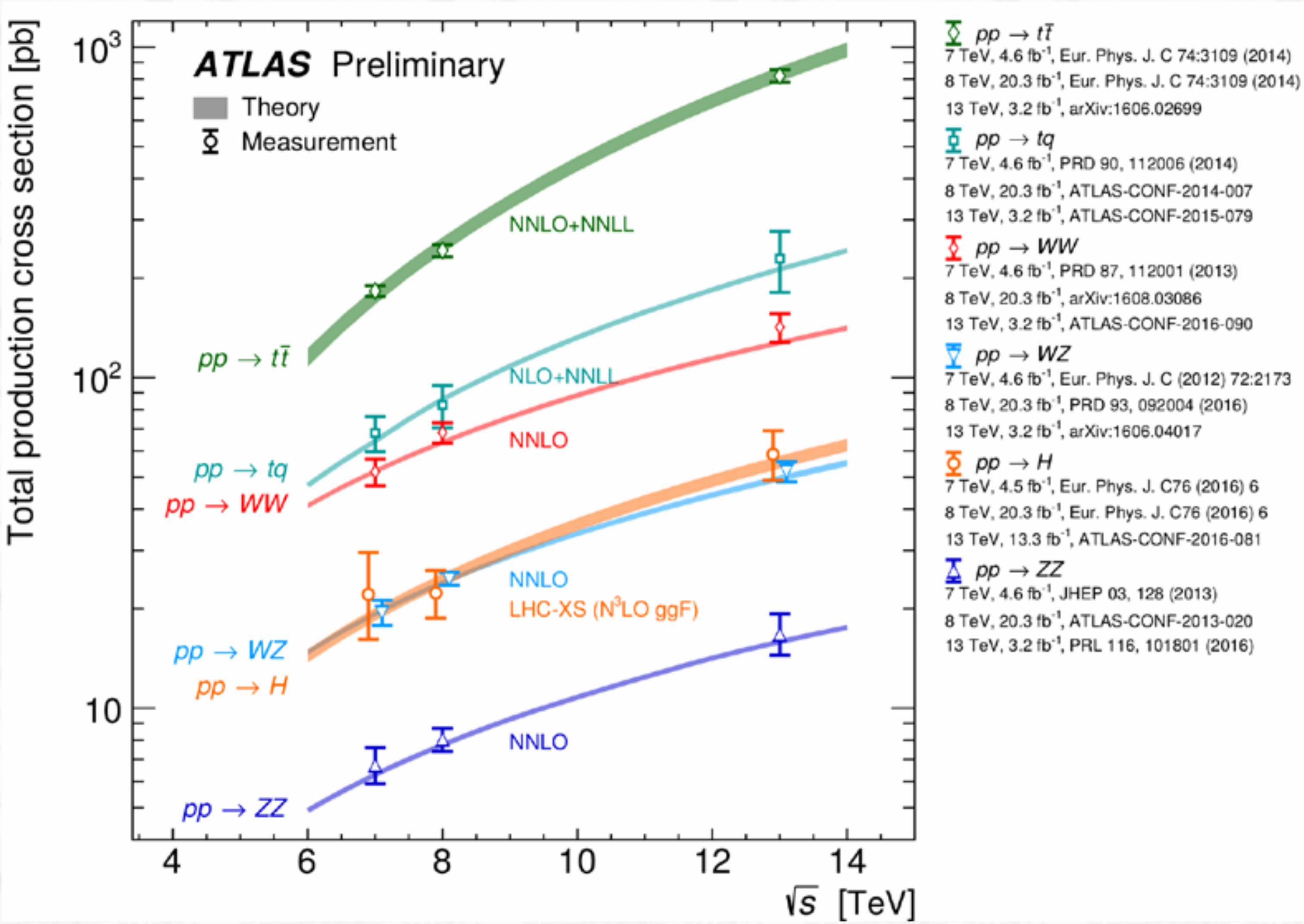
→ Excited quarks with masses $m_{q*} < 5.6$ TeV can be excluded (95% C.L.)

(For comparison: pre-LHC m_{q*} limit was at 0.87 TeV, from the Tevatron)

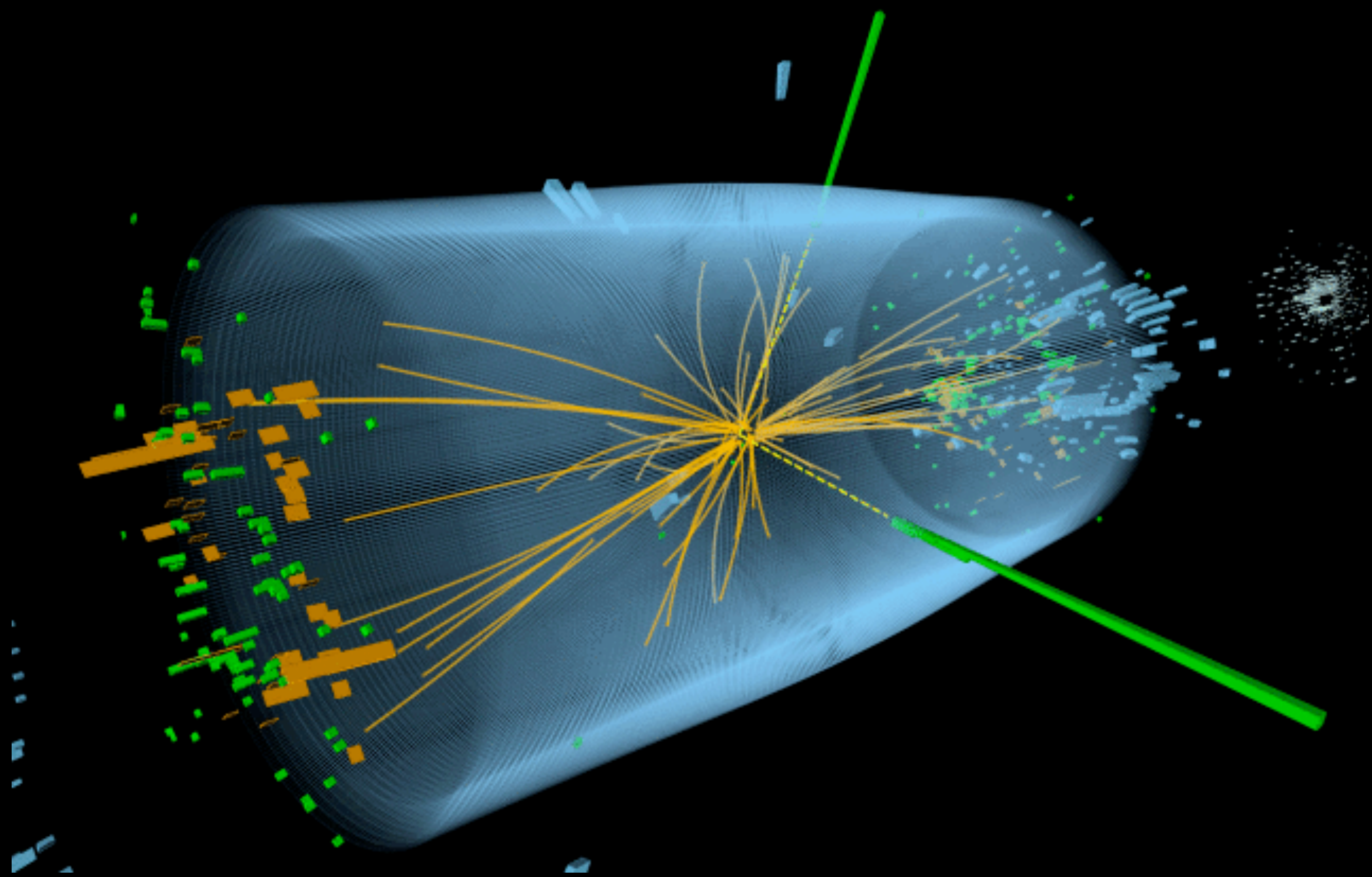
Standard Model processes at the LHC



Summary of important Standard Model cross sections



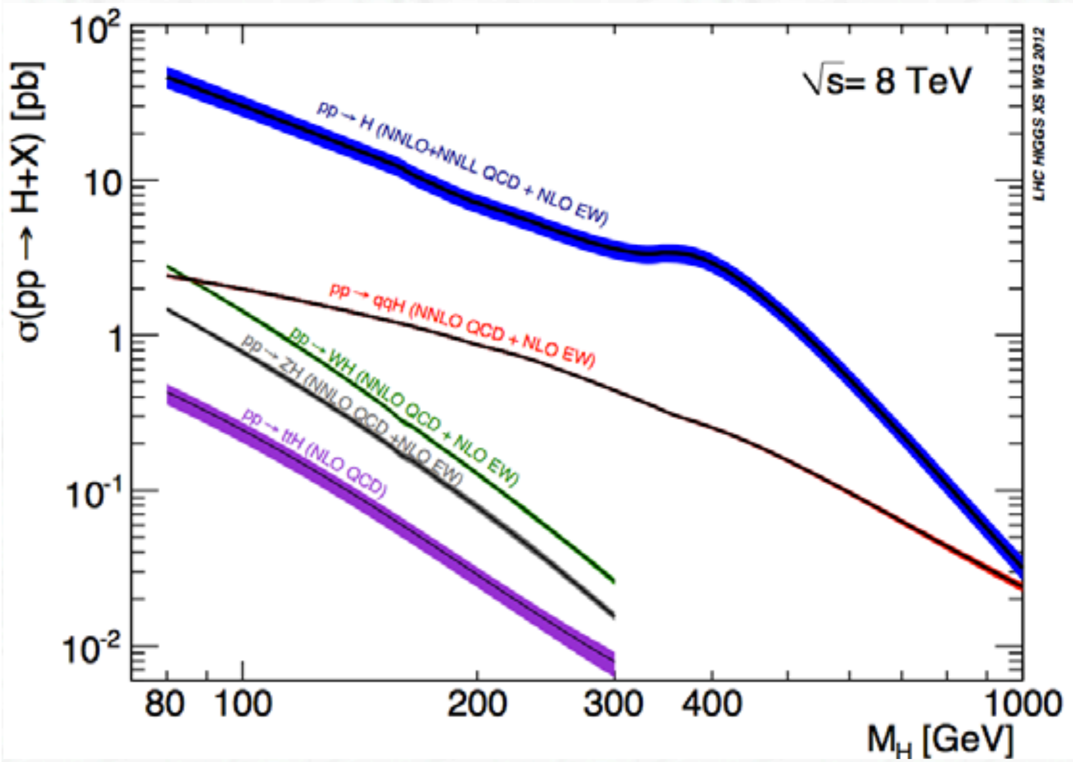
Status of Higgs Boson measurements

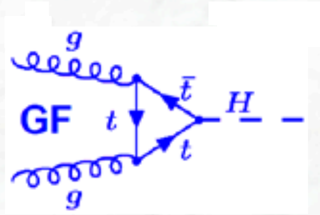


Expected number of decays in data:
m_H = 125 GeV

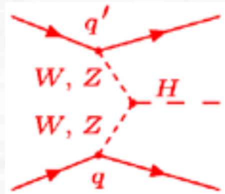
~ 950 H → $\gamma\gamma$
~ 60 H → ZZ → 4 ℓ
~ 9000 H → WW → $\ell\nu$ $\ell\nu$

Higgs Boson Production



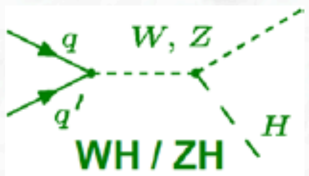


Gluon fusion

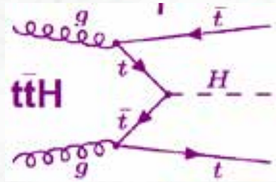


VBF

Vector boson fusion



WH/ZH associated production



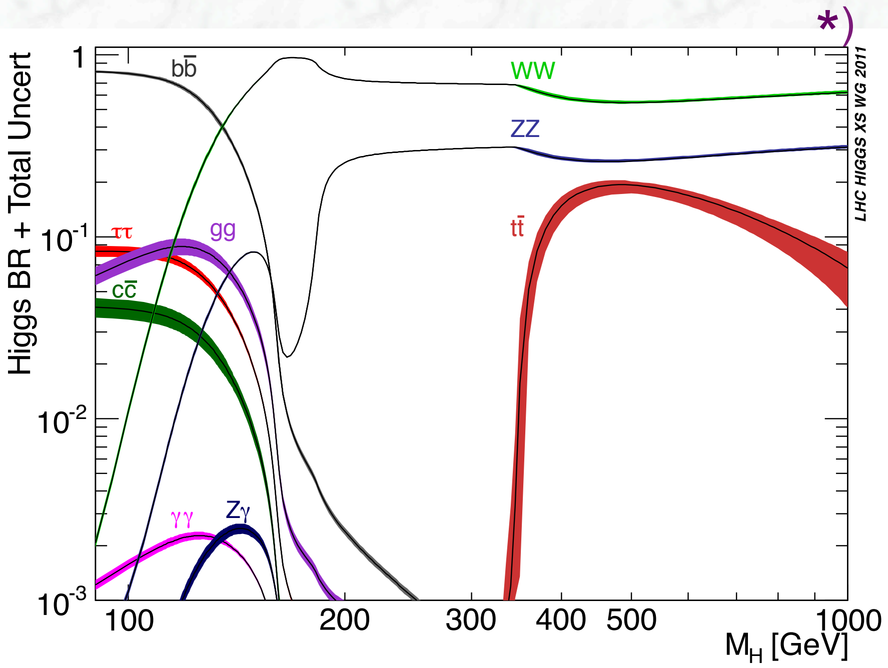
tt associated production

*) LHC Higgs cross-section working group
Large theory effort

Meanwhile the NNNLO = N^3LO calculation for the gluon-fusion process exists;
B. Anastasiou et al. (2015)

→ LHC = Long and Hard Calculations

Higgs Boson Decays



Useful decays at a hadron collider:

- Final states with leptons via WW and ZZ decays

- γγ final states (despite small branching ratio)

- ττ final states (more difficult)

- In addition: H → bb decays via associated lepton signatures
  (Higgs should be produced in association with a vector boson or top quarks)

SM predictions (m_H = 125.5 GeV):

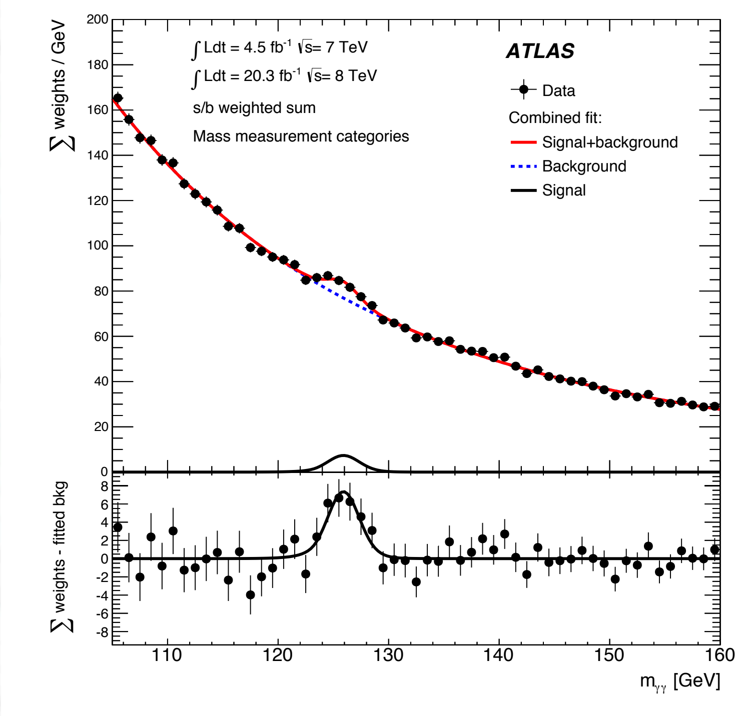
BR (H→ WW) = 22.3% BR (H → bb) = 56.9%
BR (H → ZZ) = 2.8% BR (H → ττ) = 6.2%
BR (H → γγ) = 0.24% BR (H →μμ) = 0.022%

→ at 125 GeV: only ~11% of decays not observable (gg, cc)

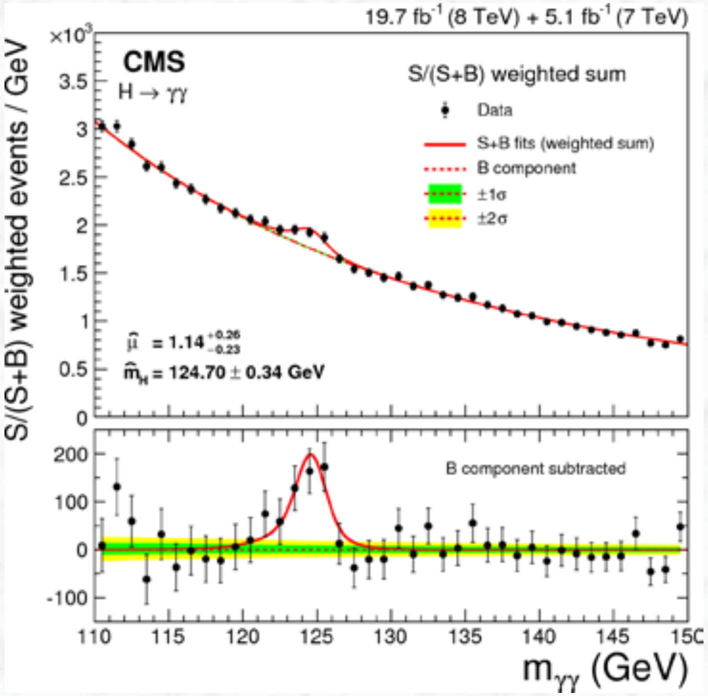
*) LHC Higgs cross-section working group

Result of the Searches for H → γγ

Phys. Rev. D90 (2014) 112015



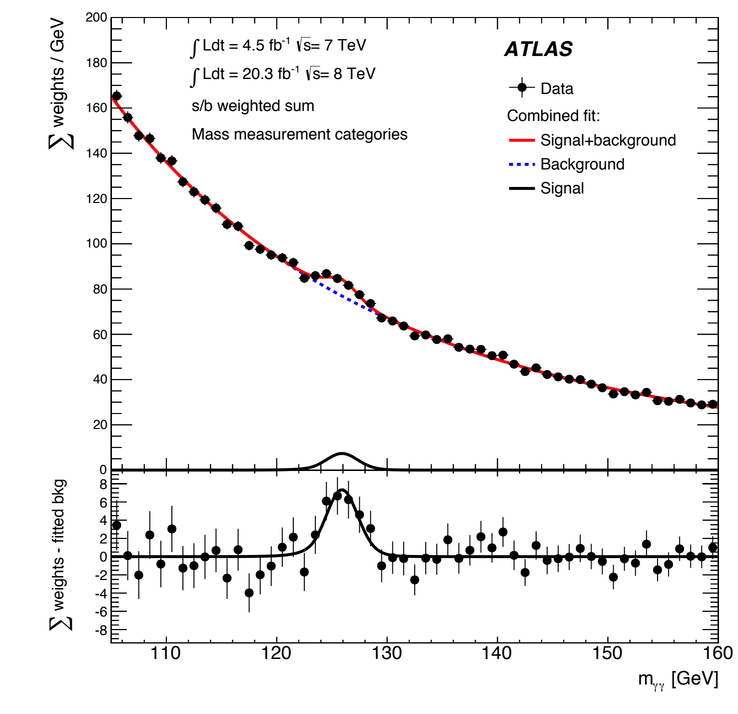
EPJ C74 (2014) 3076



- Background interpolation in the region of the excess (obtained from sidebands)
- High signal significance in both experiments: ATLAS: 5.2σ (4.6σ expected)
CMS: 5.7σ (5.2σ expected)
- Establishes the discovery in this channel alone

Result of the Searches for H → γγ

Phys. Rev. D90 (2014) 112015



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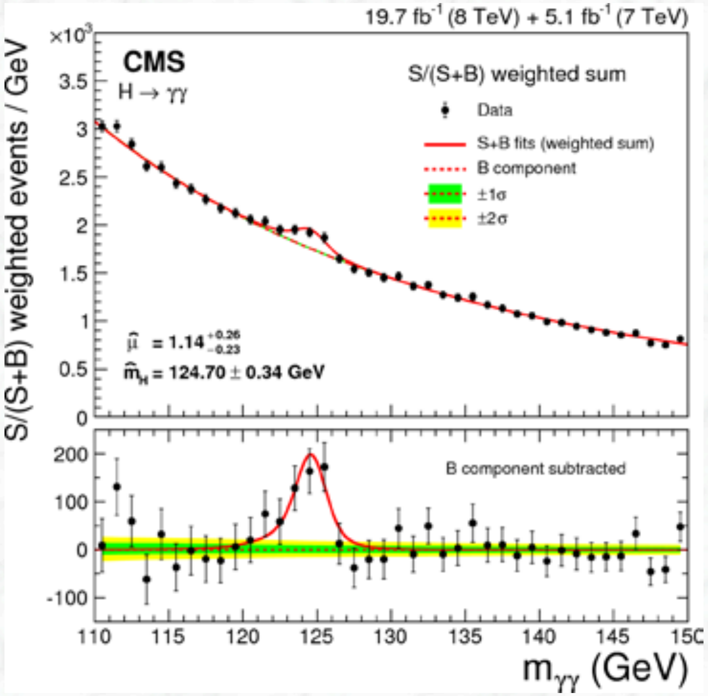


Measured signal strengths: $\mu = \sigma_{obs} / \sigma_{SM}$

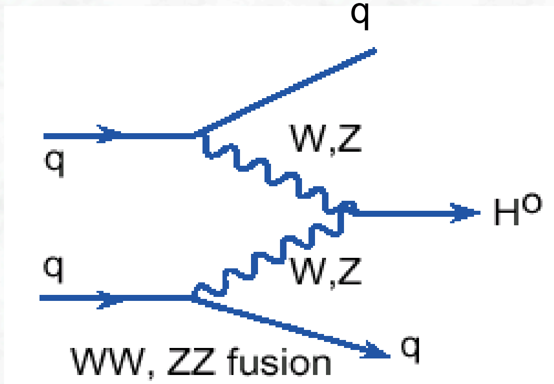
ATLAS: $\mu = 1.17 \pm 0.27$

CMS: $\mu = 1.14 \pm 0.26$

Vector Boson Fusion qqH

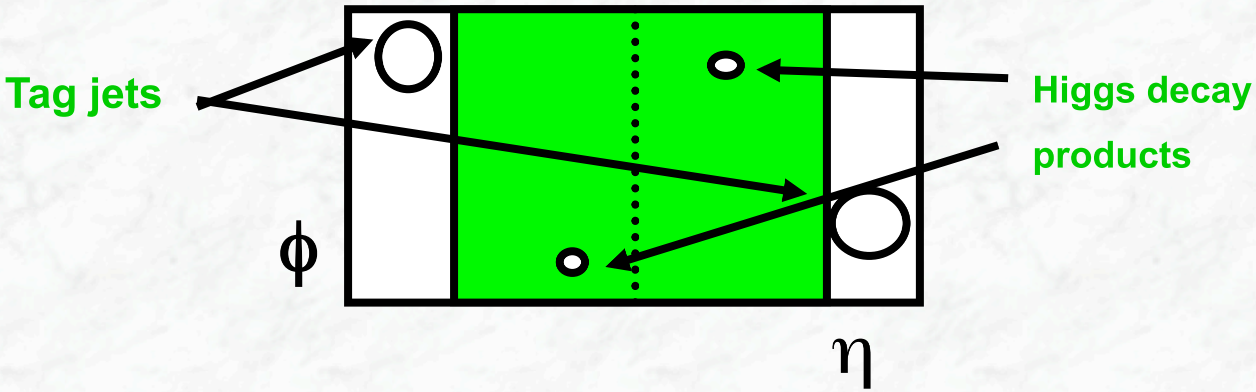
Motivation: Increase discovery potential at low mass
Improve and extend measurement of Higgs boson parameters
(couplings to W and Z bosons,
and fermions in the decays, e.g. τ leptons)

Distinctive Signature of:

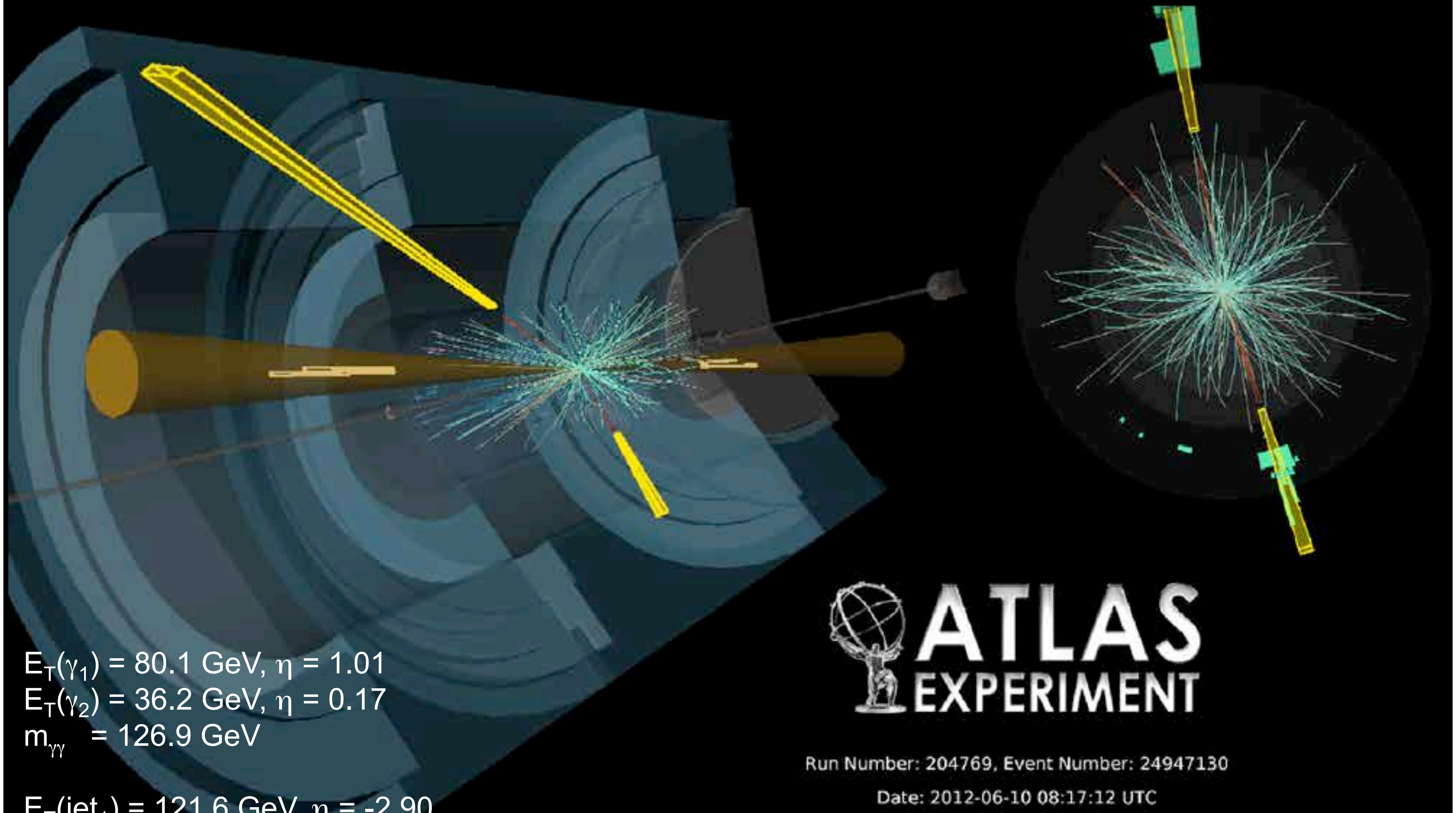


- Two high p_T forward jets (tag jets)
  Large invariant mass, large η separation

- Little jet activity in the central region
  (no colour flow)
  $\Rightarrow$ central jet Veto



$H \rightarrow \gamma\gamma$ VBF candidate event

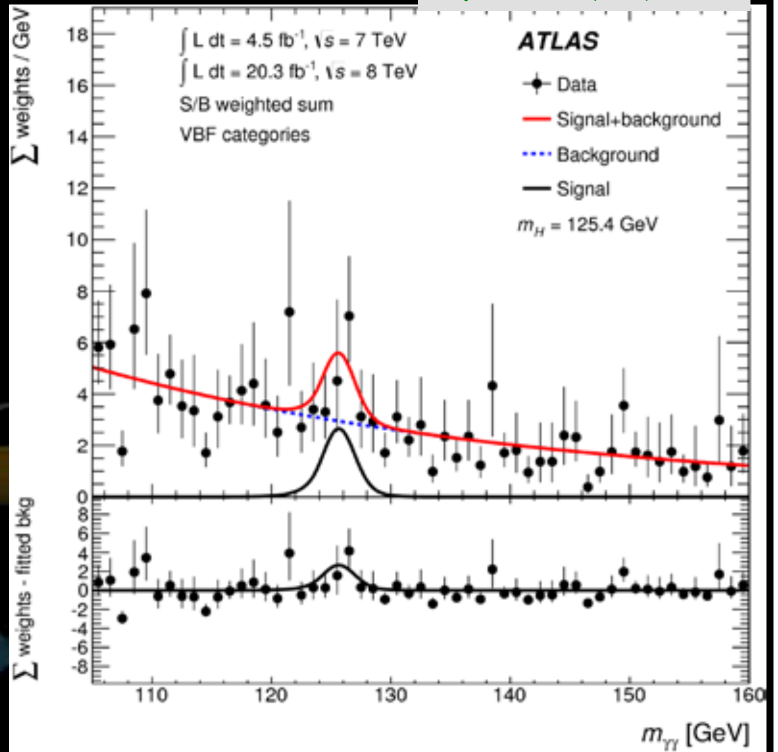


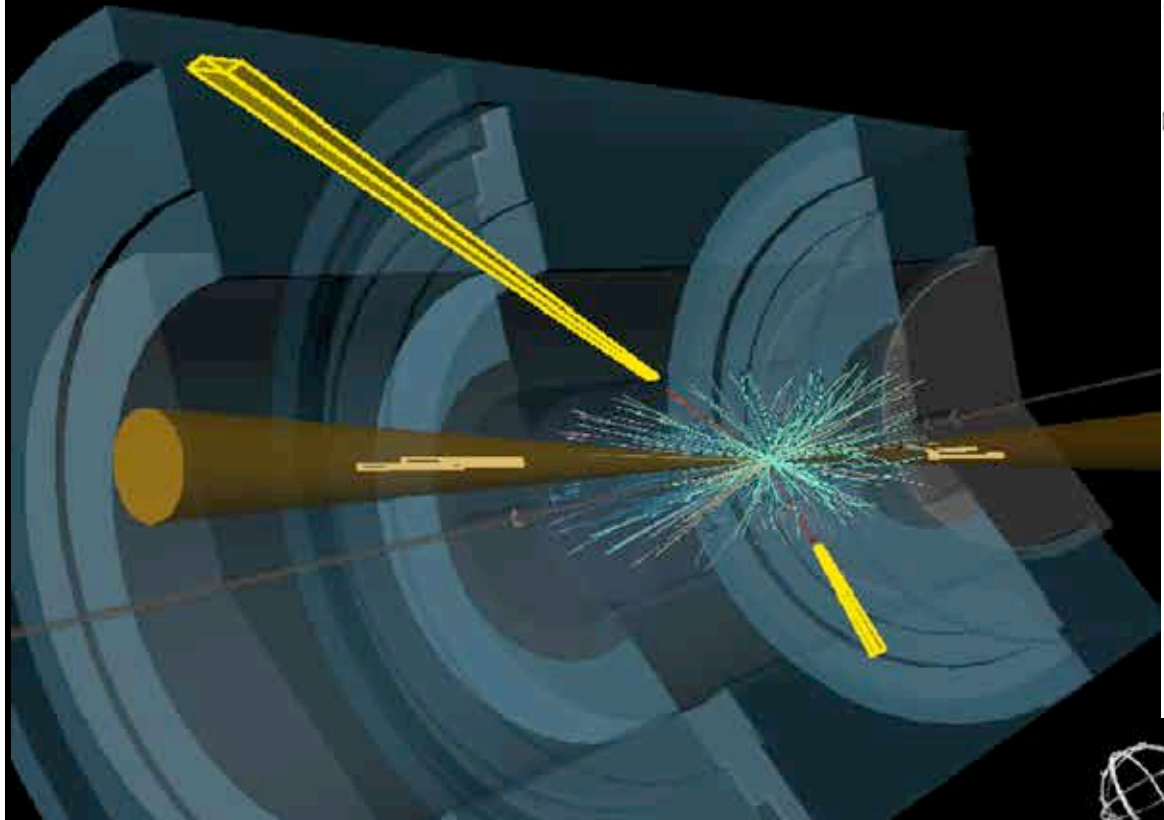
$E_T(\gamma_1)$ = 80.1 GeV, η = 1.01
$E_T(\gamma_2)$ = 36.2 GeV, η = 0.17
$m_{\gamma\gamma}$ = 126.9 GeV

$E_T(jet_1)$ = 121.6 GeV, η = -2.90
$E_T(jet_2)$ = 82.8 GeV, η = 2.72
m_{jj} = 1.67 TeV

$H \rightarrow \gamma\gamma$ VBF candidate event

Phys. Rev. D90 (2014) 112015





ATLAS EXPERIMENT

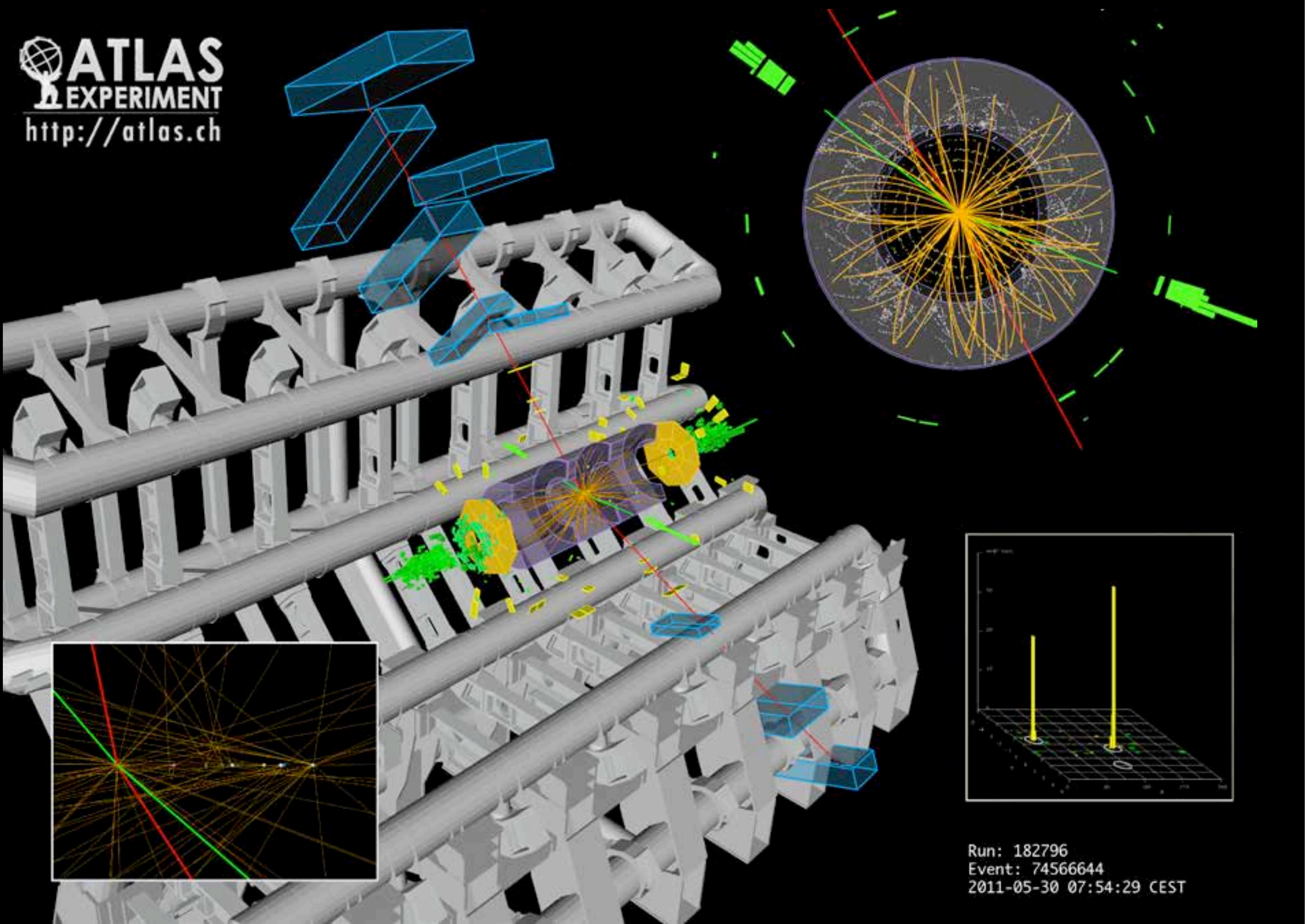
Run Number: 204769, Event Number: 24947130

Date: 2012-06-10 08:17:12 UTC

$E_T(\gamma_1)$ = 80.1 GeV, η = 1.01
$E_T(\gamma_2)$ = 36.2 GeV, η = 0.17
$m_{\gamma\gamma}$ = 126.9 GeV

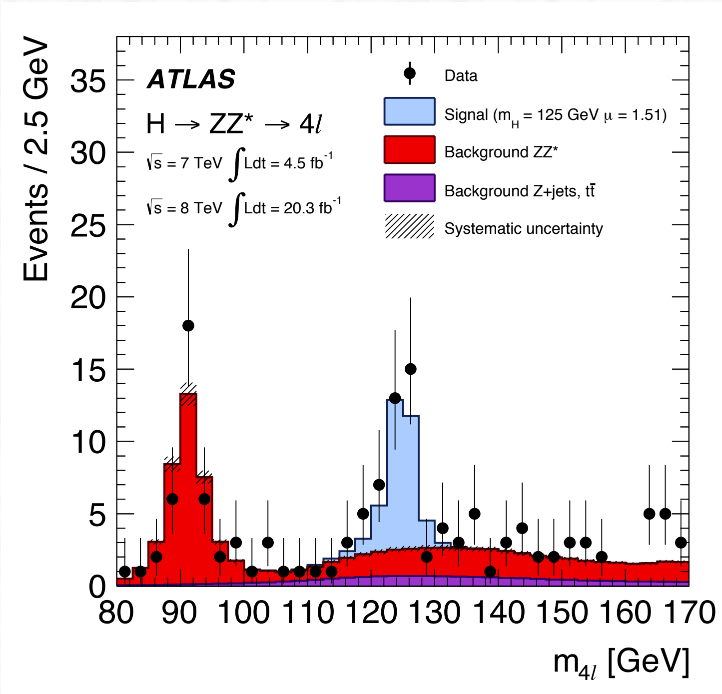
$E_T(jet_1)$ = 121.6 GeV, η = -2.90
$E_T(jet_2)$ = 82.8 GeV, η = 2.72
m_{jj} = 1.67 TeV

H → ZZ → $e^+e^- \mu^+ \mu^-$ candidate event

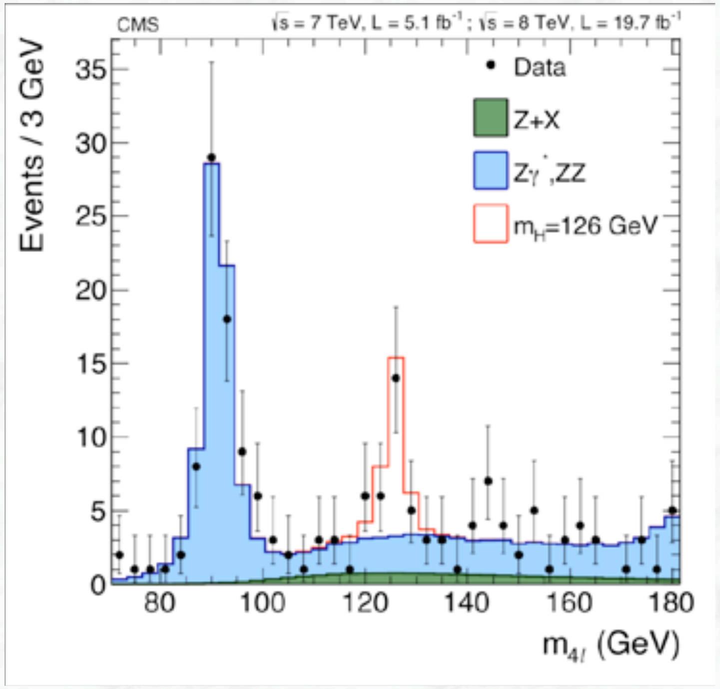


Reconstructed mass spectra from 4ℓ decays

Phys. Rev. D91 (2014) 012006



Phys. Rev. D89 (2014) 092007



Measured signal strengths:

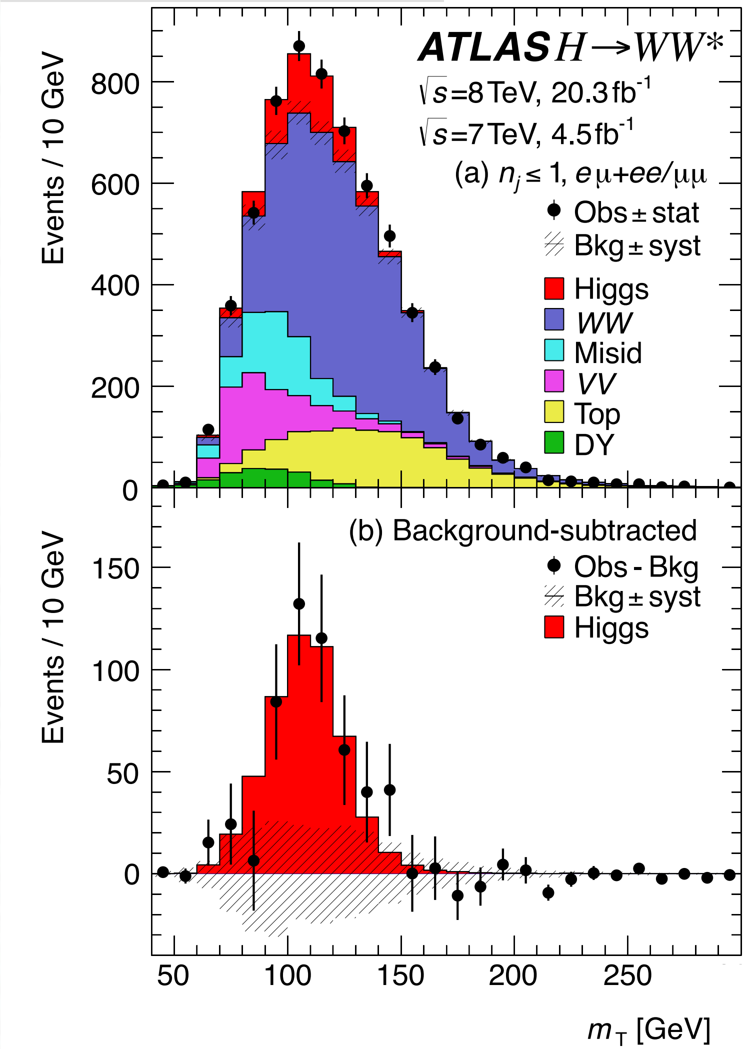
ATLAS: $\mu = 1.44^{+0.40}_{-0.33}$

CMS: $\mu = 0.93^{+0.29}_{-0.23}$

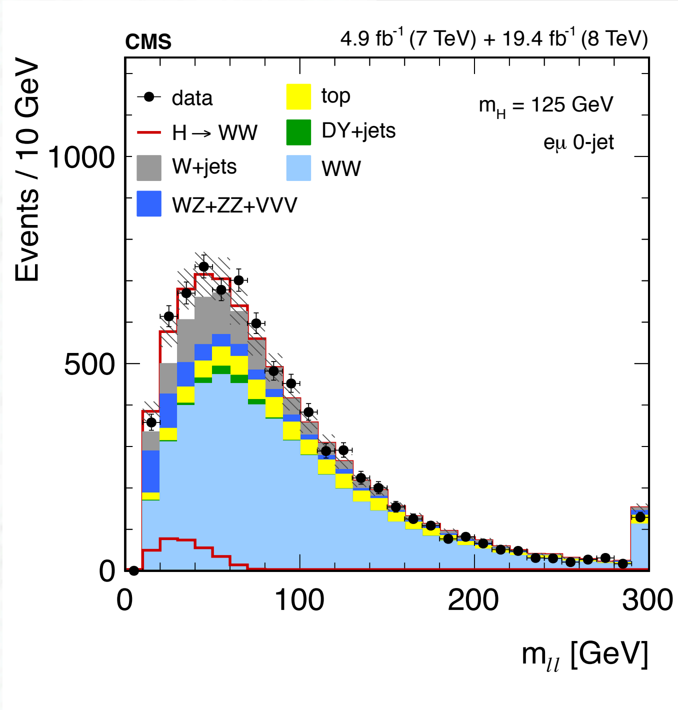
Significance in each experiment > 6σ

$H \to WW^* \to \ell\nu\,\ell\nu$ signal

Phys. Rev. D92 (2015) 012006



JHEP 01 (2014) 096



Measured signal strengths:

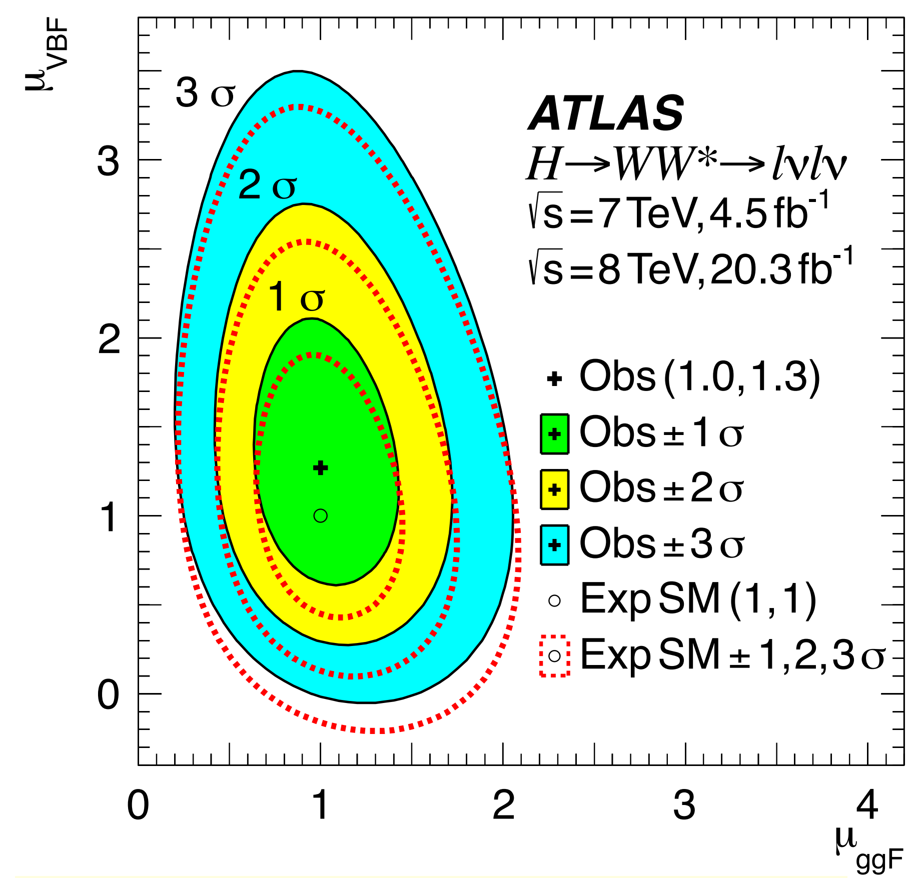
ATLAS: $\mu = 1.09\,^{+0.23}_{-0.21}$

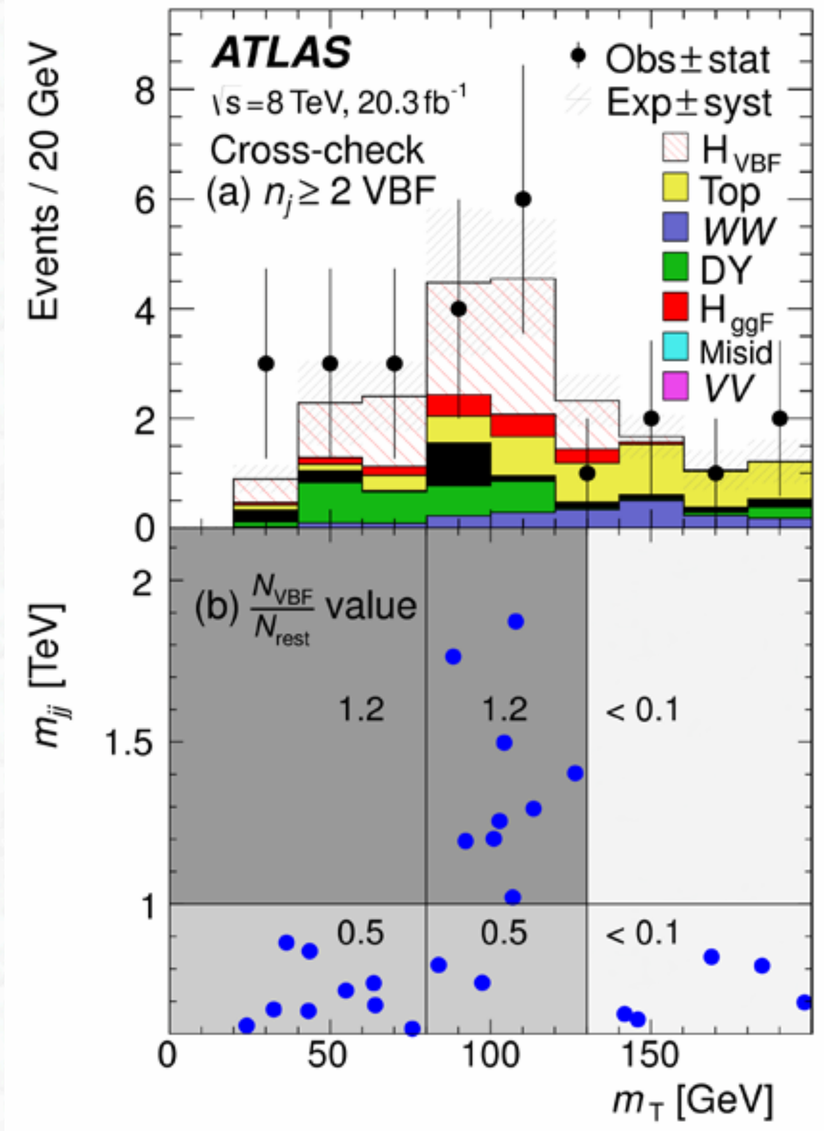
CMS: $\mu = 0.72\,^{+0.20}_{-0.18}$

- Very significant excesses visible in the “transverse mass” (ATLAS: 6.1σ) and $m_{\ell\ell}$ distributions (CMS: 4.5σ)

H → WW* → ℓν ℓν signal

Phys. Rev. D92 (2015) 012006



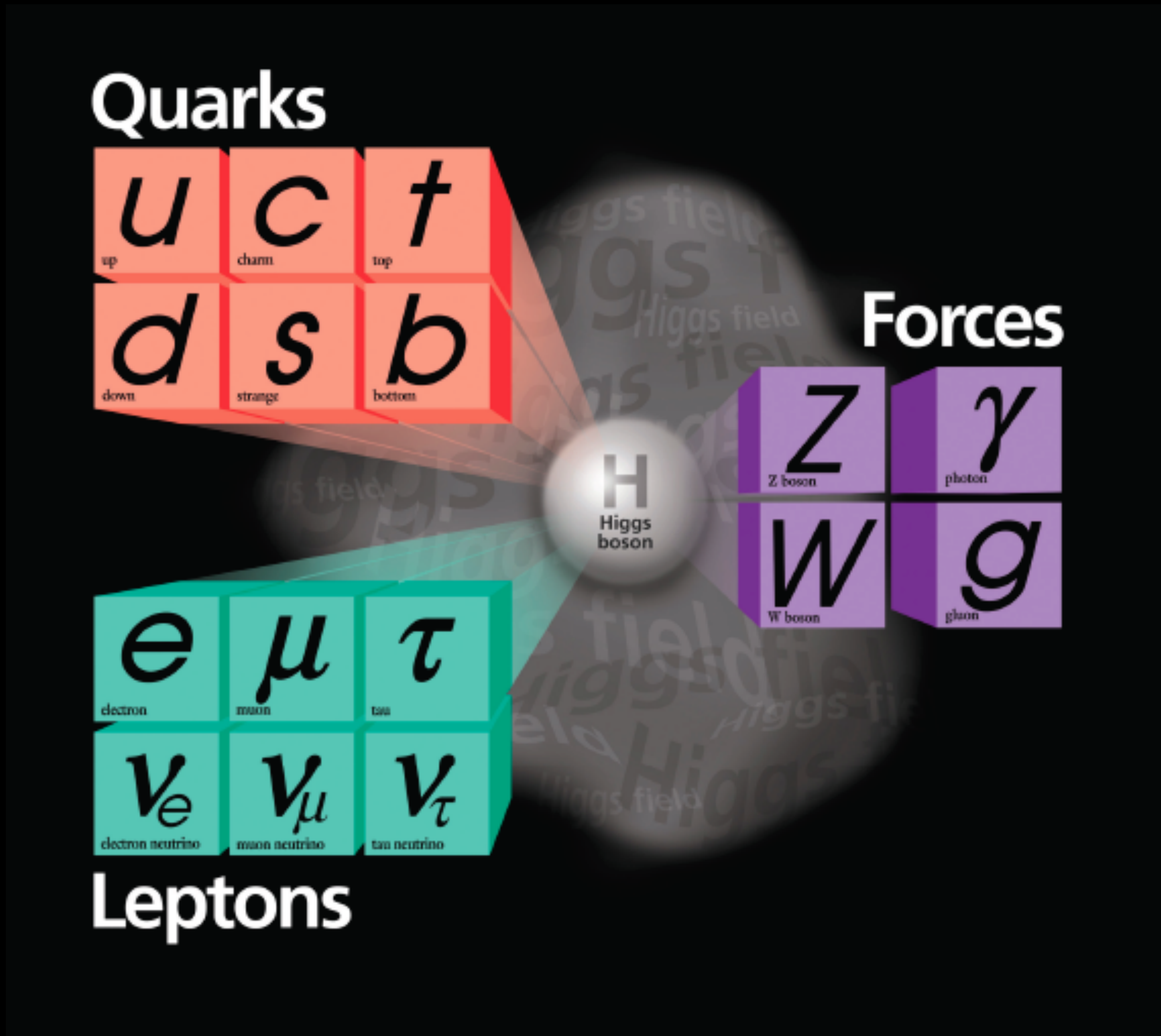


Measured signal strengths: ATLAS

Gluon fusion (ggF): $\mu = 1.02 \, ^{+0.29}_{-0.26}$

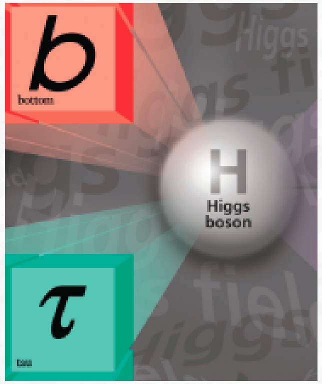
VBF: $\mu = 1.27 \, ^{+0.53}_{-0.45}$

Couplings to quarks and leptons ?



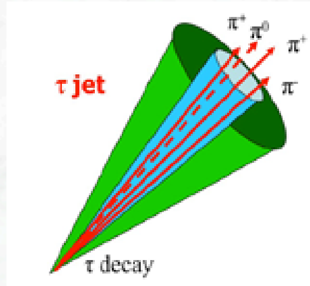
Search for H → ττ and H → bb decays

Couplings to quarks and leptons ?

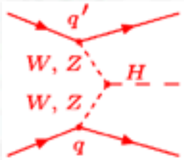


- Search for H → ττ and H → bb decays;

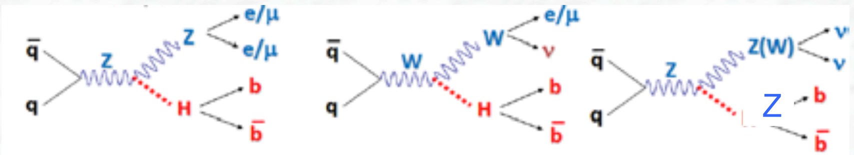
- Challenging signatures due to jets (bb decays) or significant fraction of hadronic tau decays



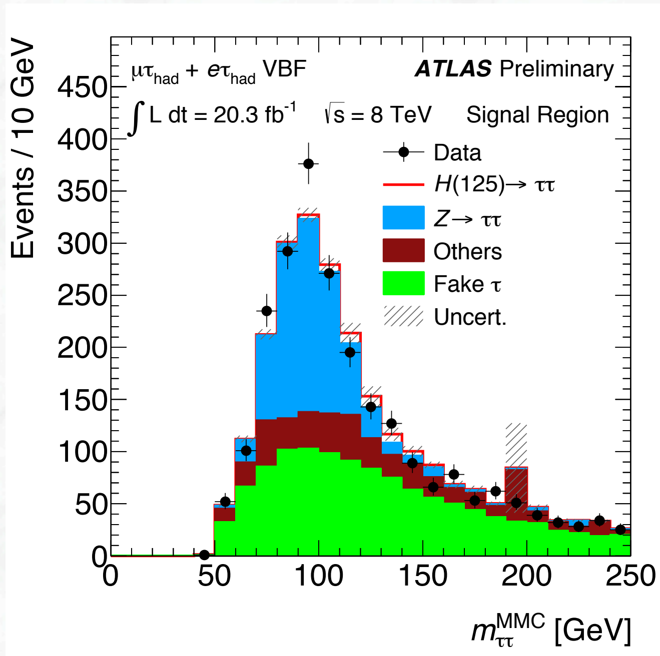
- Vector boson fusion mode essential for H → ττ decays



- Associated production WH, ZH modes have to be used for H → bb decays



- Exploitation of multivariate analyses



Evidence for H → ττ decays

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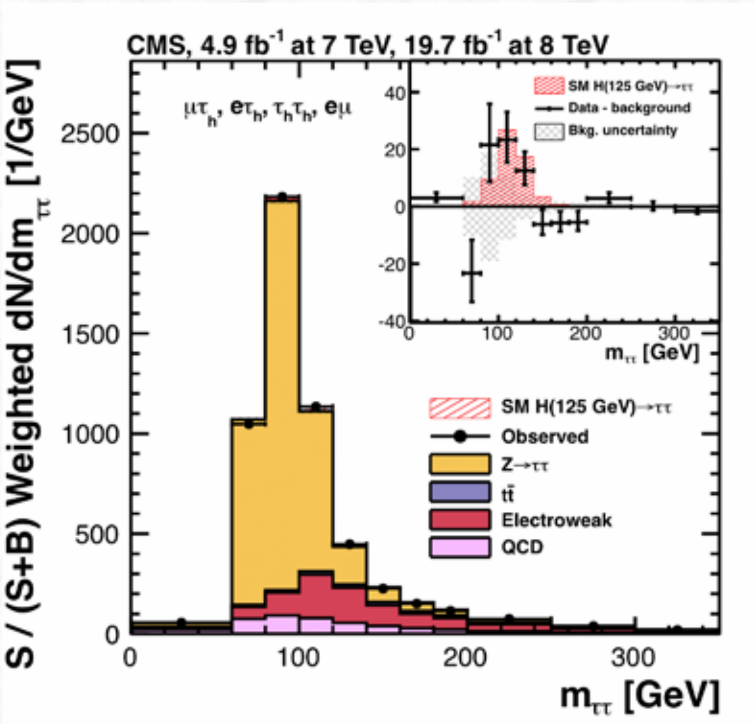
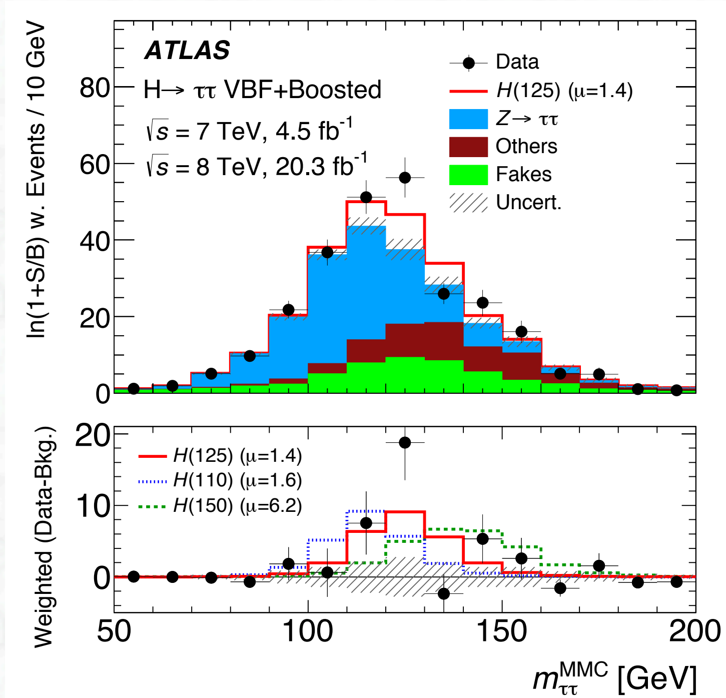


JHEP 04 (2015) 117



$m_{\tau\tau}$ distribution, events weighted by ln (1+S/B)

Measured signal strengths:

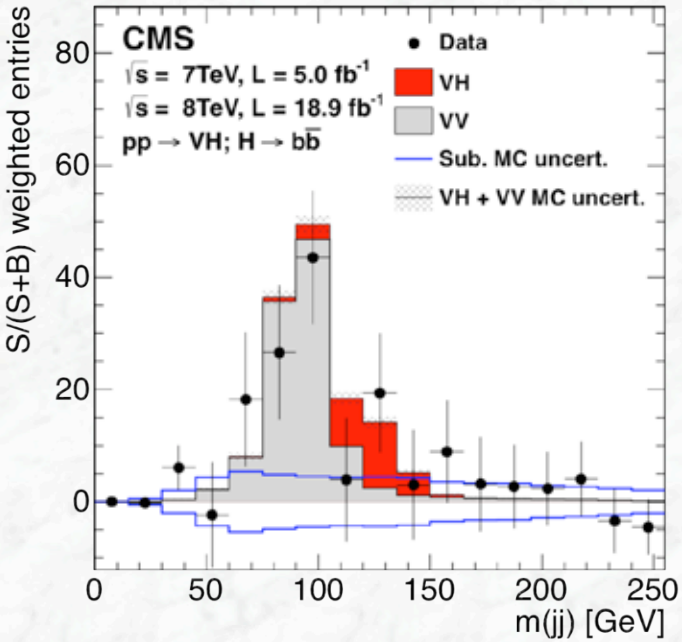
ATLAS: $\mu = 1.43 \, ^{+0.43}_{-0.37}$ (4.5σ)

CMS: $\mu = 0.78 \pm 0.27$ (3.2σ)

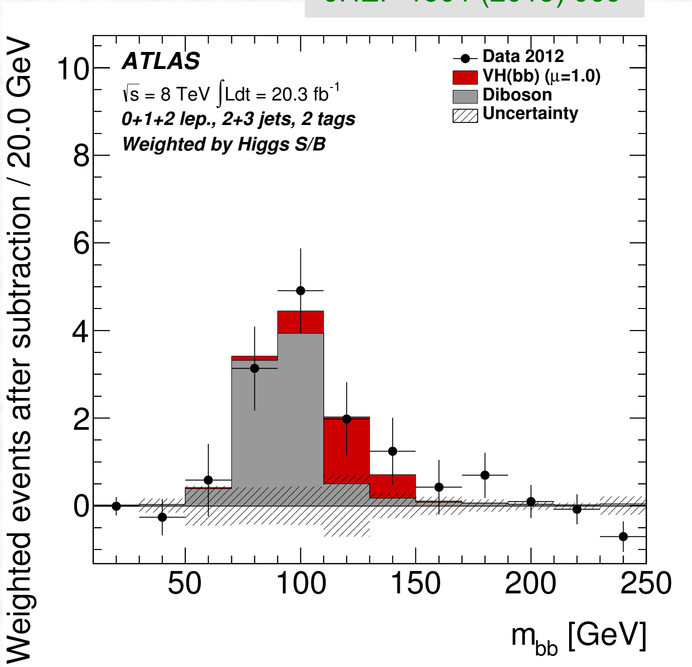
One of the most important LHC results in 2014 / 2015

Results on the search for H → bb decays

Phys. Rev. D89 (2014) 012003



JHEP 1501 (2015) 069



Reconstructed m_{bb} signals (after subtraction of major, non-resonant backgrounds)

- Reference signal from WZ, and ZZ with Z → bb seen
- Positive, but non-conclusive Higgs boson signal contribution observed

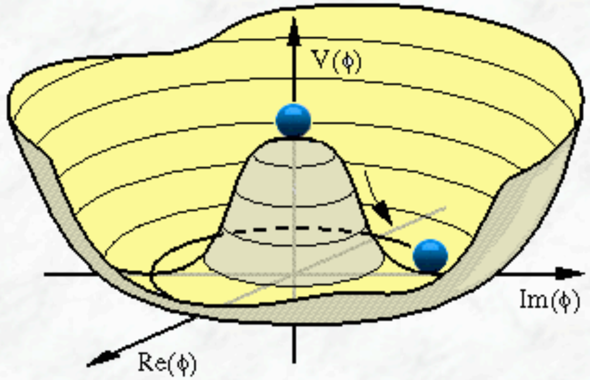
Signal strengths:

ATLAS: $\mu = 0.50 \pm 0.36$

CMS: $\mu = 1.0 \pm 0.5$

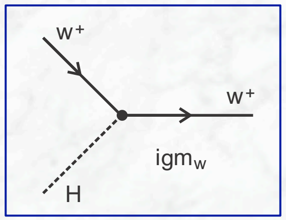
Profile of the New Particle

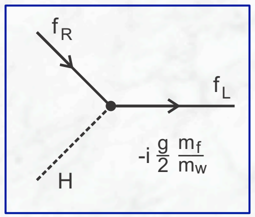
Is it the Standard Model Higgs Boson?



- Mass ("input parameter")
- Spin, J^{CP} quantum number
- Production rates

Couplings to bosons and fermions

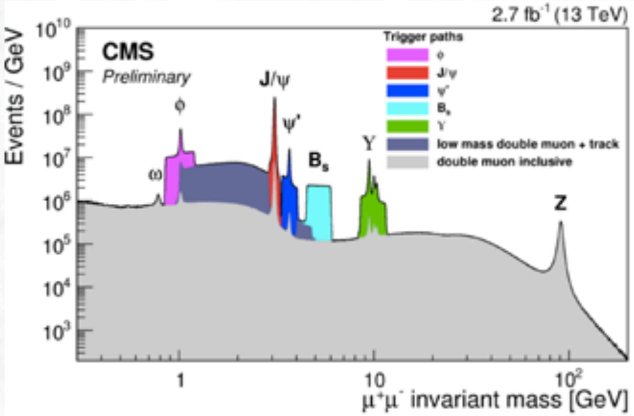




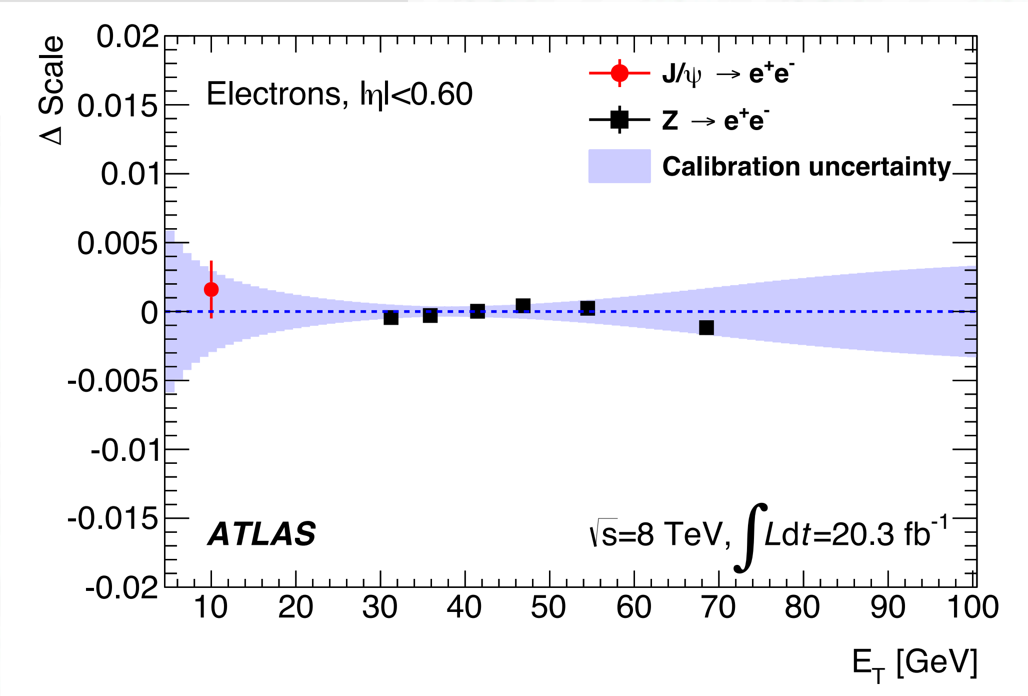
Higgs boson mass

- The two high resolution channels H → ZZ*→ 4ℓ and H → γγ are best suited (reconstructed mass peak, good mass resolution)

- Good control of the lepton and photon energy scales, calibration via Z → ℓℓ and J/ψ and ϒ signals, improved understanding of lepton and photon reconstruction



Phys. Rev. D90 (2014) 052004



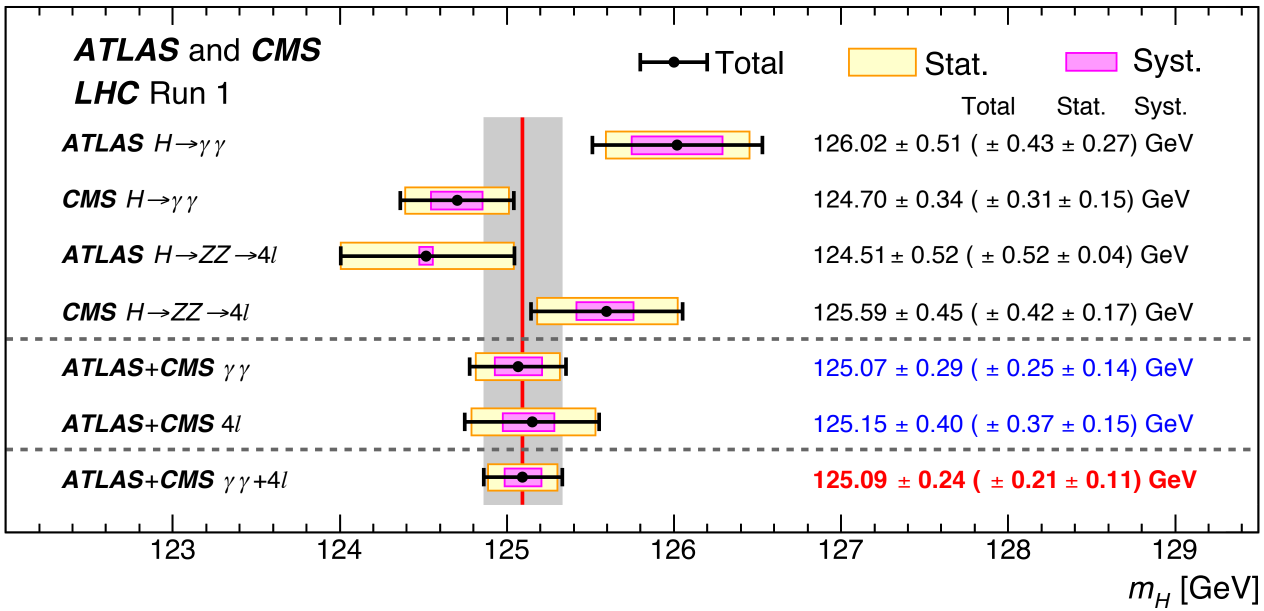
Impressive accuracy reached: 0.1 – 0.3%

Higgs boson mass (cont.)

-First ATLAS and CMS combination of Higgs boson results-

PRL 114 (2015) 191803

Individual and combined results:



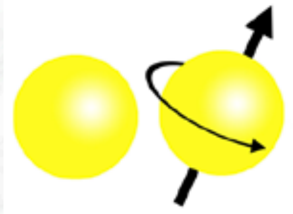
ATLAS + CMS:

m_H = 125.09 ± 0.21 (stat) ± 0.11 (syst) GeV

Precision of 0.2%

- Statistical uncertainty still dominant
- Major systematic uncertainties: Lepton and photon energy scales and resolutions
- Theoretical uncertainties small

Spin and CP

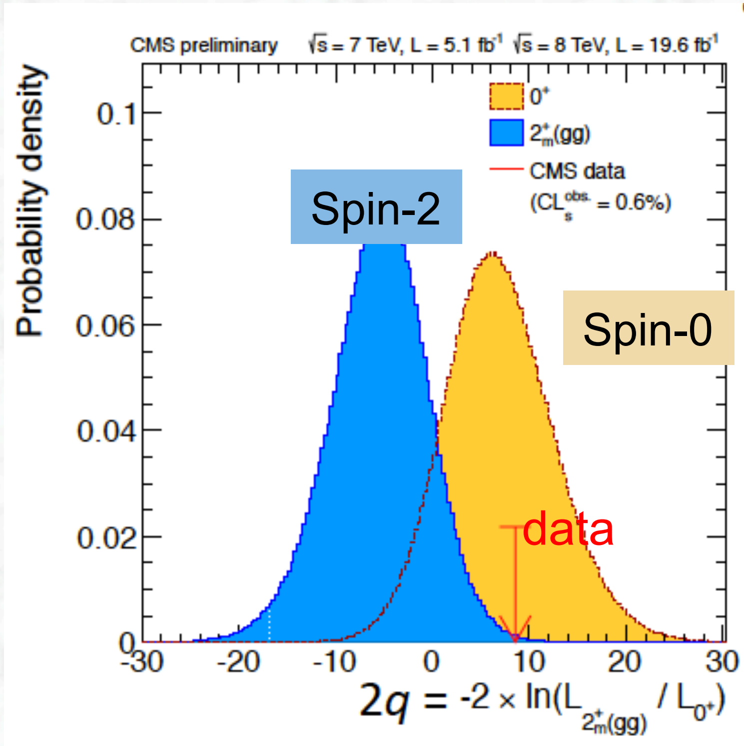


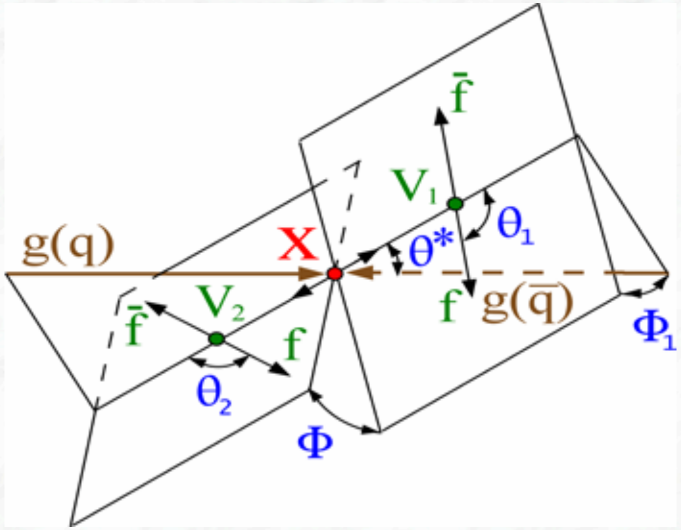
- Standard Model Higgs boson: $J^P = 0^+$

  → strategy is to falsify other hypotheses (0^-, 1^-, 1^+, 2^-, 2^+)

- Angular distributions of final state particles show sensitivity to spin

  In particular: H → ZZ* → 4ℓ decays
  (in addition: H → WW* → ℓν ℓν)

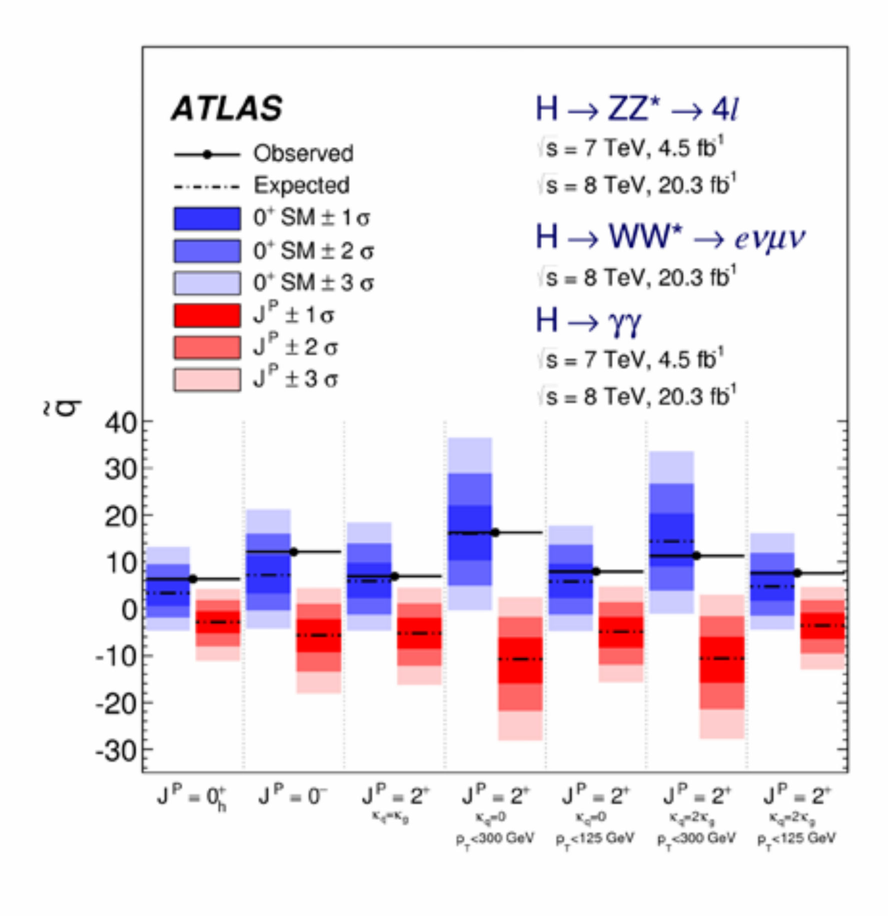




- Data strongly favour the spin-0 hypothesis of the Standard Model
- Many alternatives can be excluded with confidence levels > 99%)

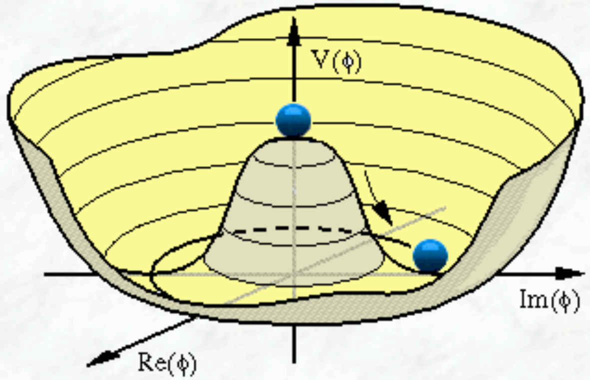
Result on different J^{CP} hypothesis tests

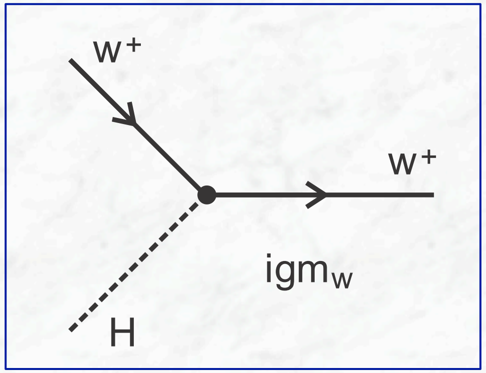
Eur. Phys. J C75 (2015) 476

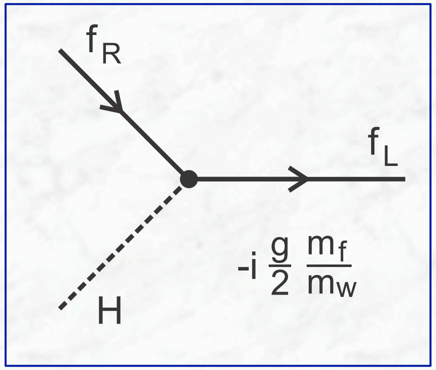


- In both experiments: data are consistent with $J^P = 0^+$ hypothesis, many alternative models are excluded with high significance

Couplings to bosons and fermions



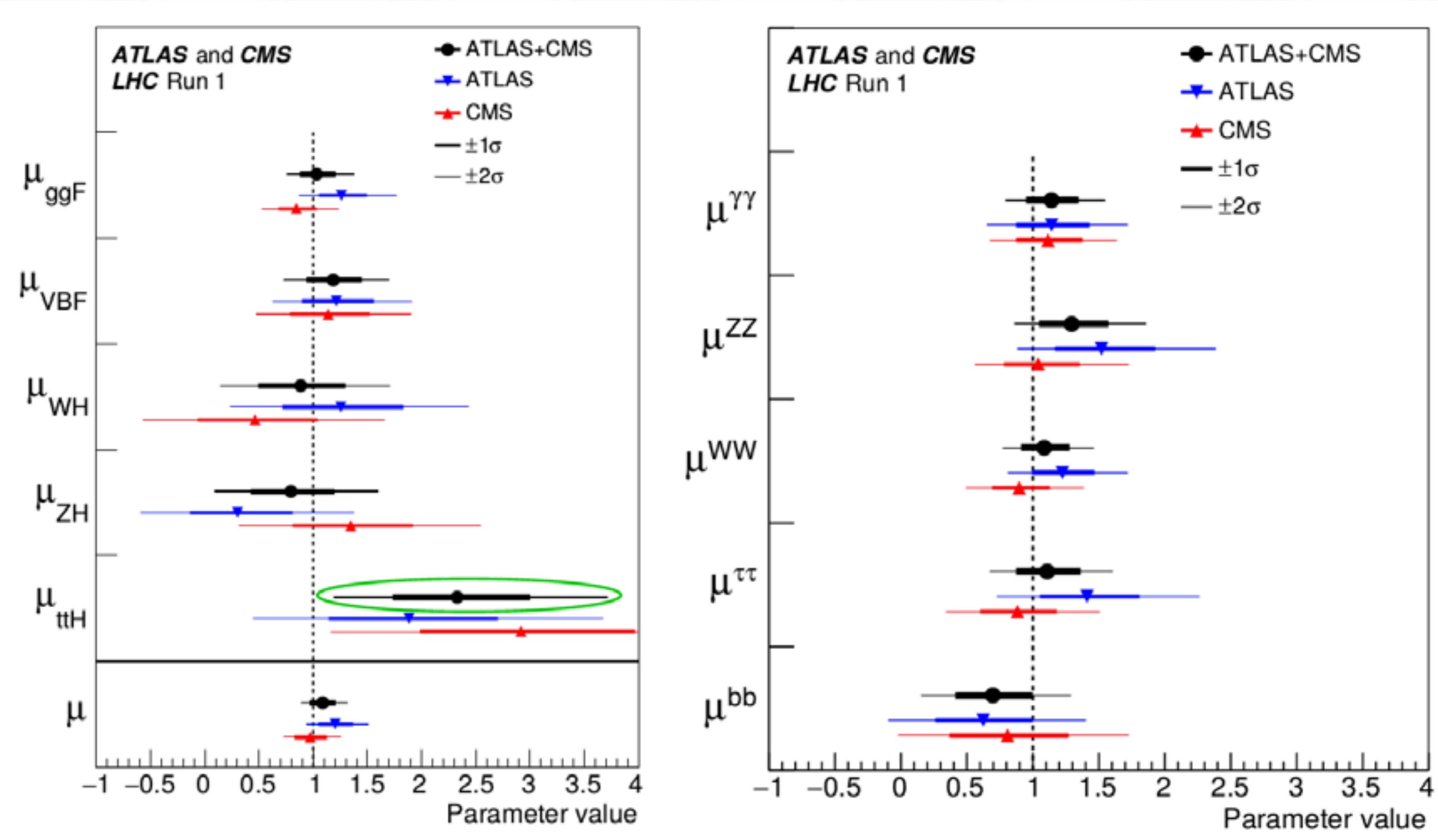




Signal strengths for various production and decay modes

Combined ATLAS + CMS results

arXiv:1606.02266



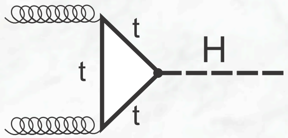
Rates for all production and decay modes consistent with the Standard Model expectations

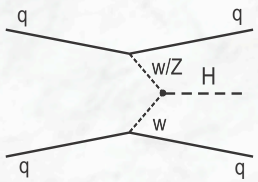
Higgs boson couplings

for experts

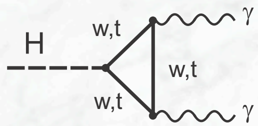
- Production and decay involve several couplings

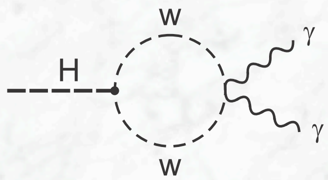
Production:





Decays: e.g H → γγ (best example)
(Decay widths depends on W and top coupling,
destructive interference)





- Benchmarks defined by LHC cross section working group (leading-order tree-levelframework):

- Narrow width approximation: → rates for given channels can be decomposed as:

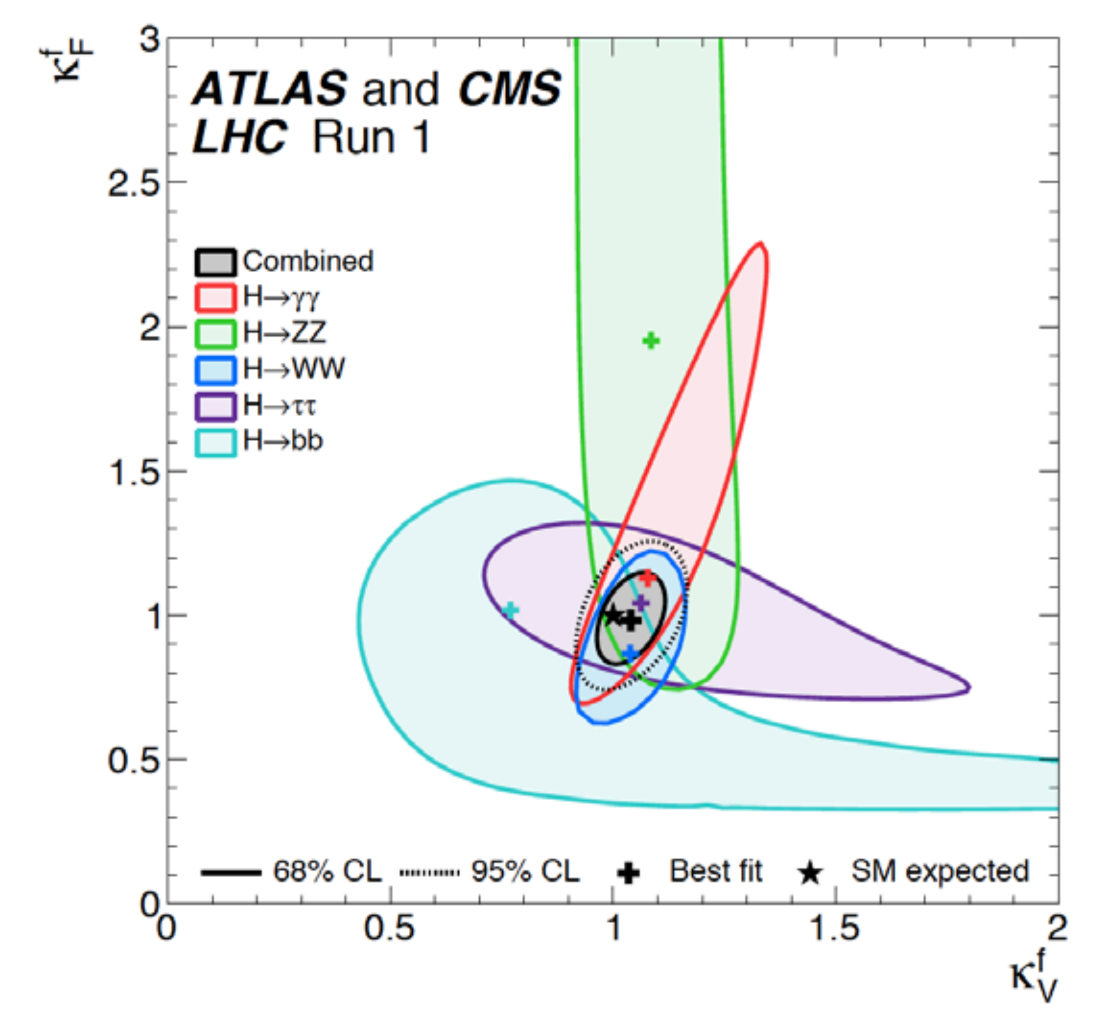
$$\sigma \cdot B\,(i \rightarrow H \rightarrow f) = \frac{\sigma_i \cdot \Gamma_f}{\Gamma_H}$$

i, f = initial, final state
Γ_f, Γ_H = partial, total width

- Modifications to coupling strength are considered (coupling scale factors κ), tensor structure of Lagrangian assumed as in Standard Model

Results on fit for boson and fermion coupling scale factor

JHEP 08 (2016) 045



Assume only one scale factor
for fermion and vector couplings:

$\kappa_V = \kappa_W = \kappa_Z$

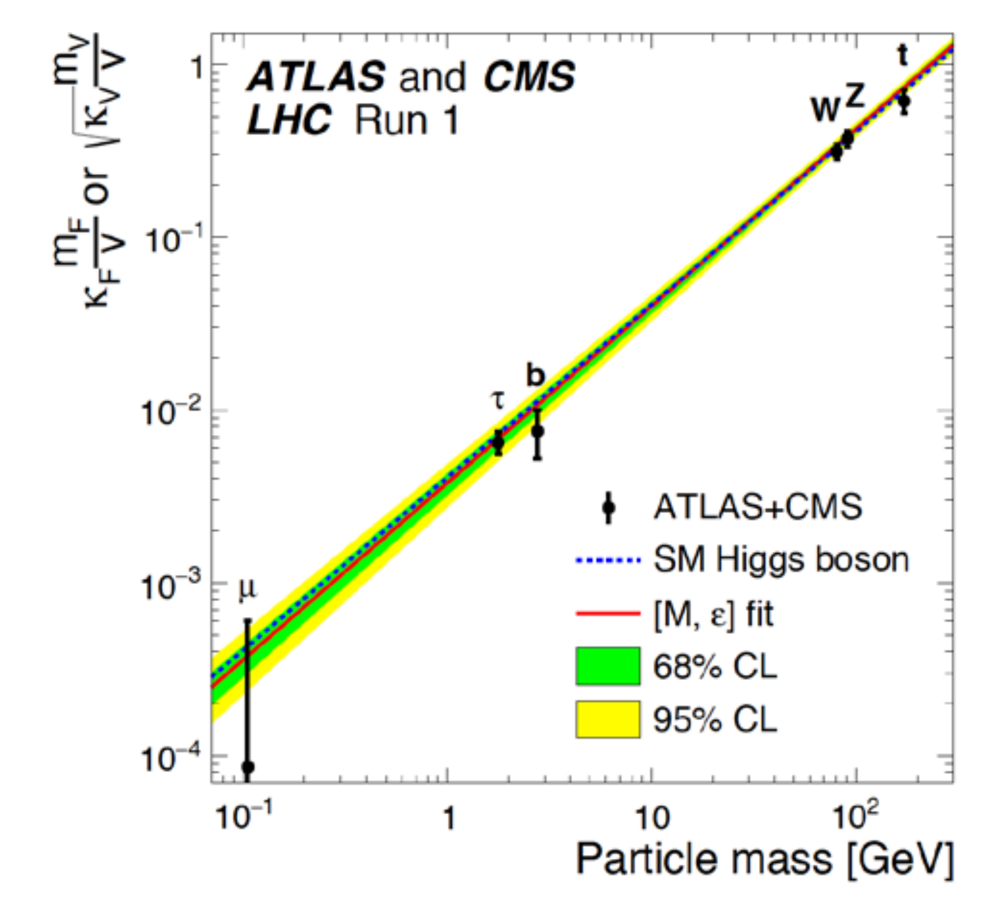
$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$

(top sensitivity via production
loop)

Excellent agreement with the Standard Model predictions found

ATLAS and CMS summary on coupling results

JHEP 08 (2016) 045

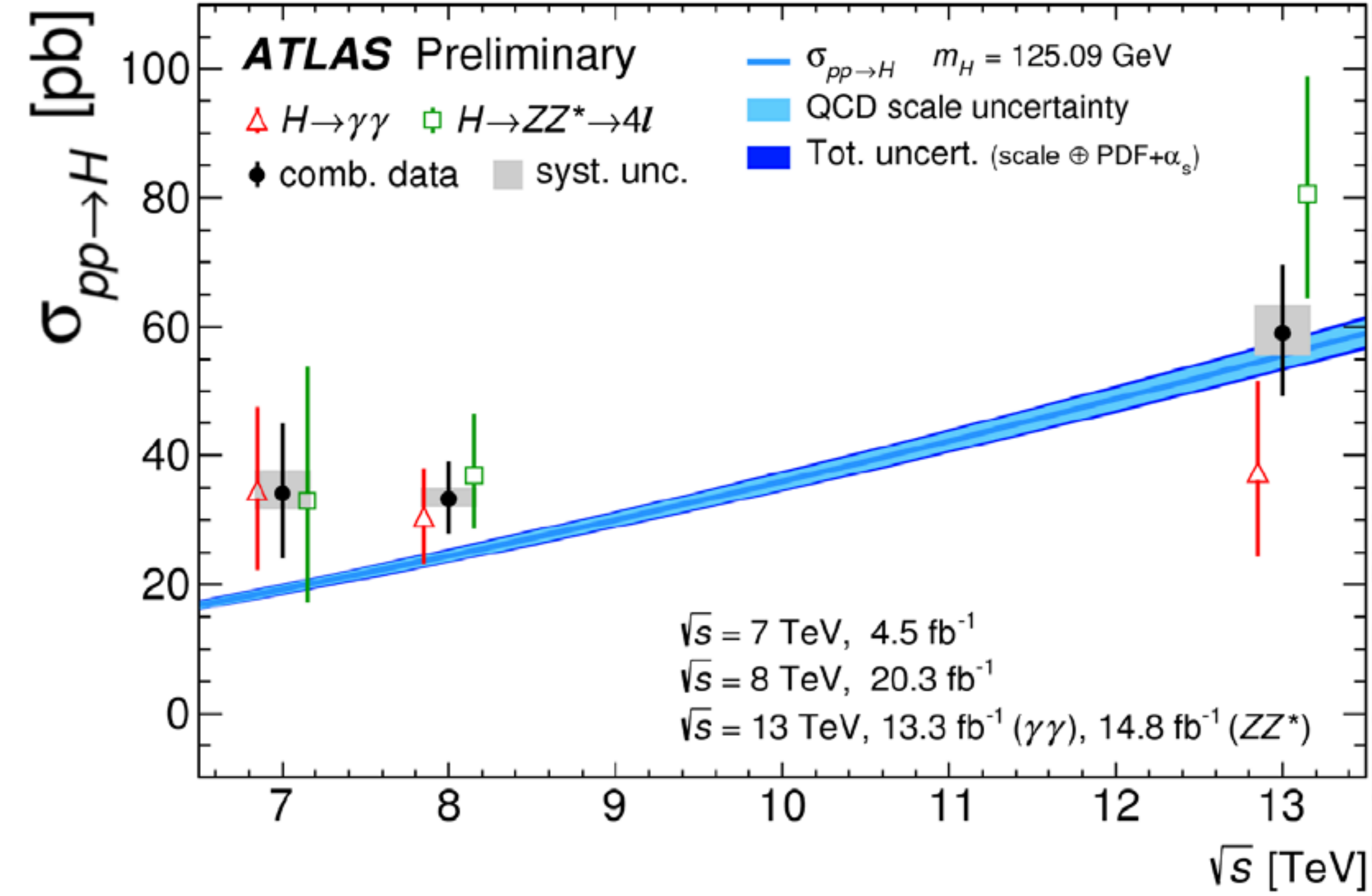


λ = Yukawa coupling for fermions

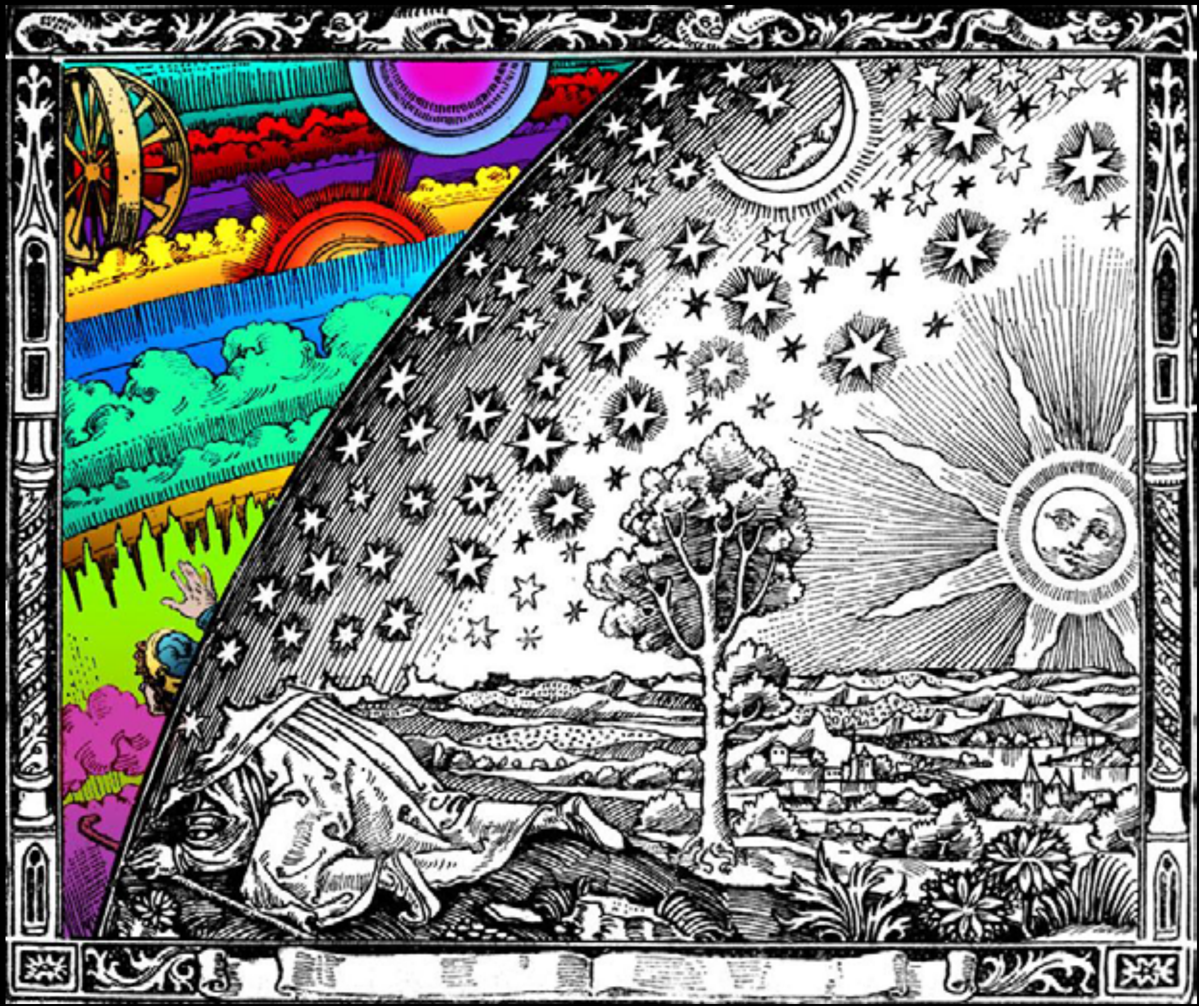
√g/2v = couplings for W/Z bosons

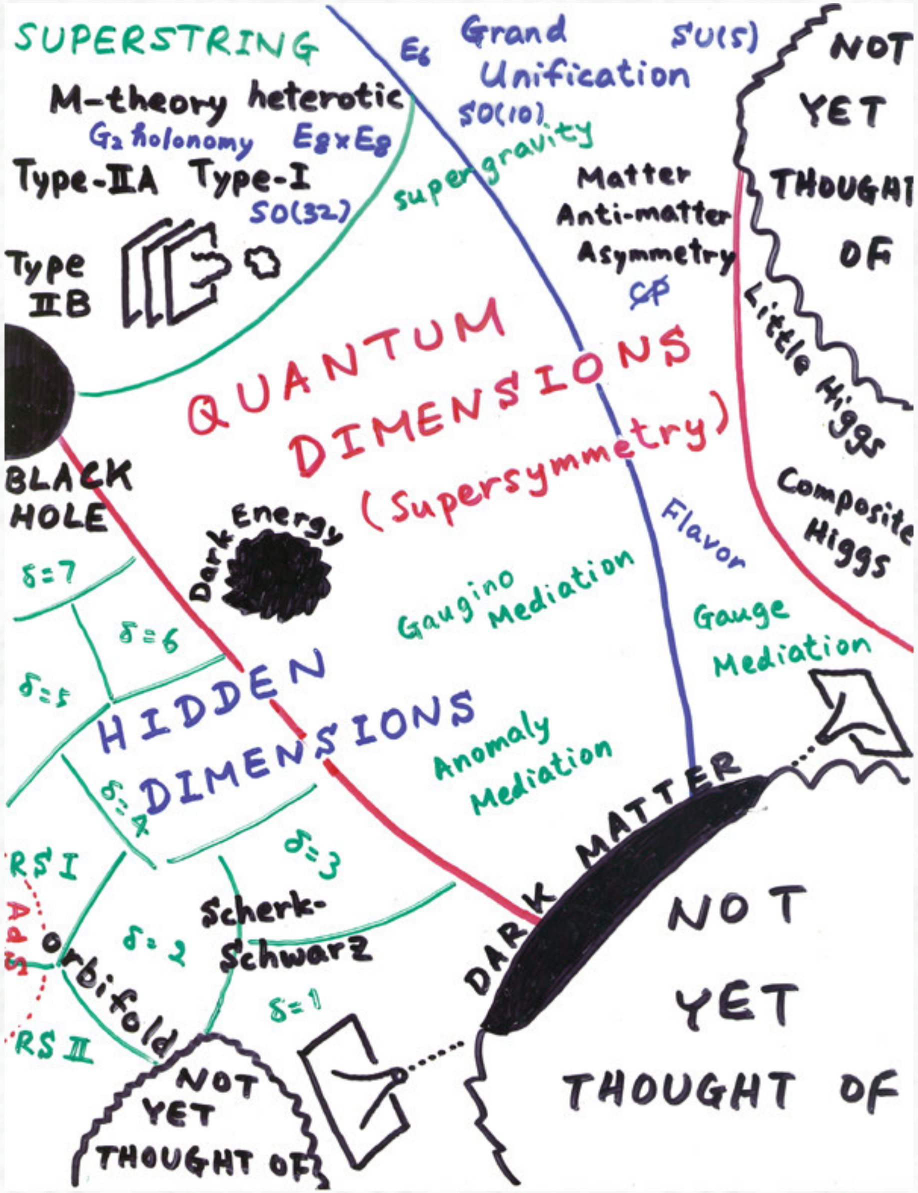
"The consistency of the couplings of the observed boson with those predicted for the Standard Model Higgs boson is tested in various ways, and no significant deviations are found."

First Higgs boson results from Run 2 at √s = 13 TeV



Physics Beyond the Standard Model

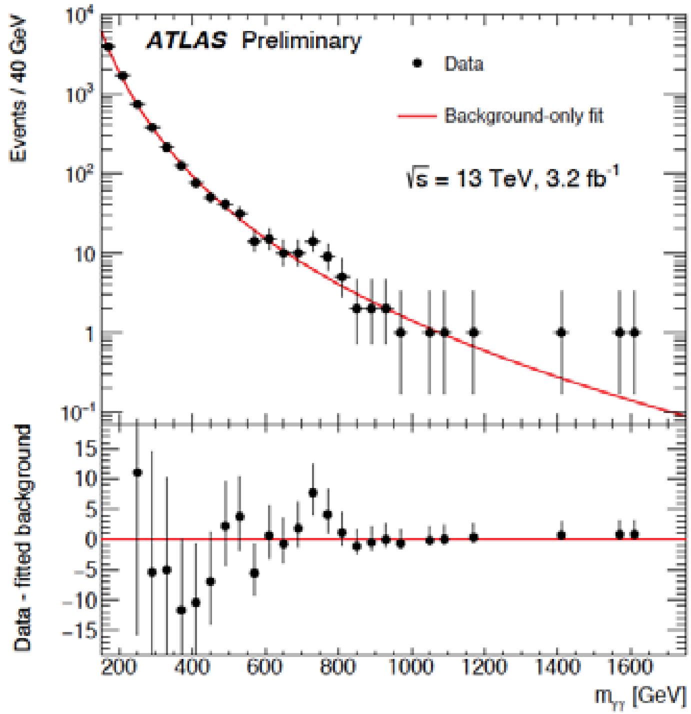


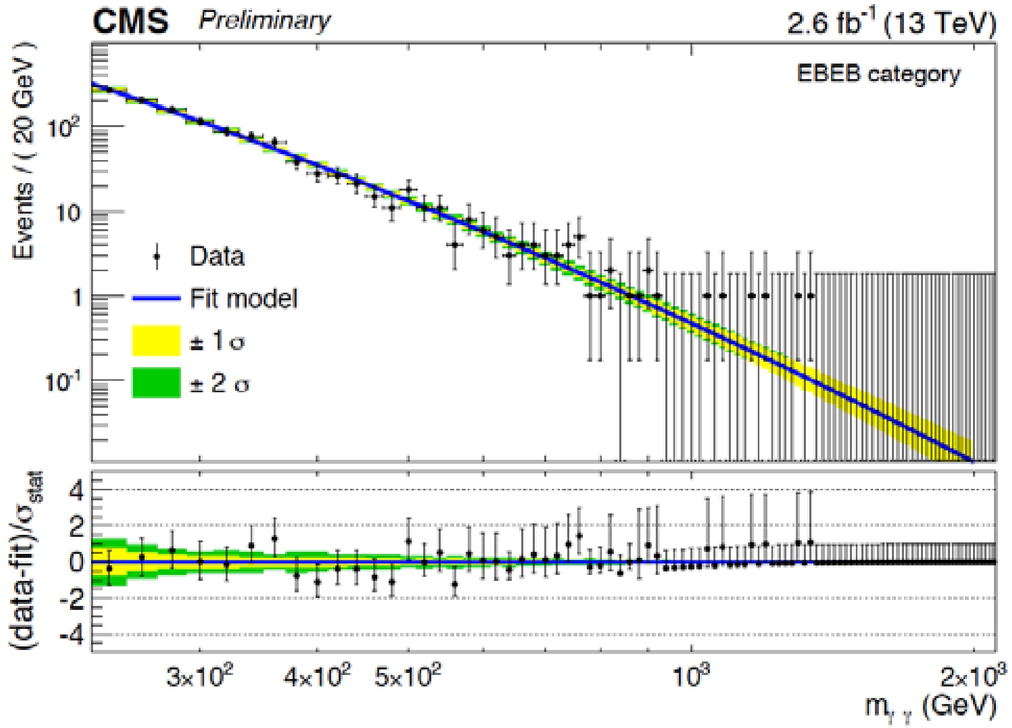


Hitoshi Murayama, IPMU Tokyo & Berkeley

Additional Higgs bosons / $\gamma\gamma$ resonances?

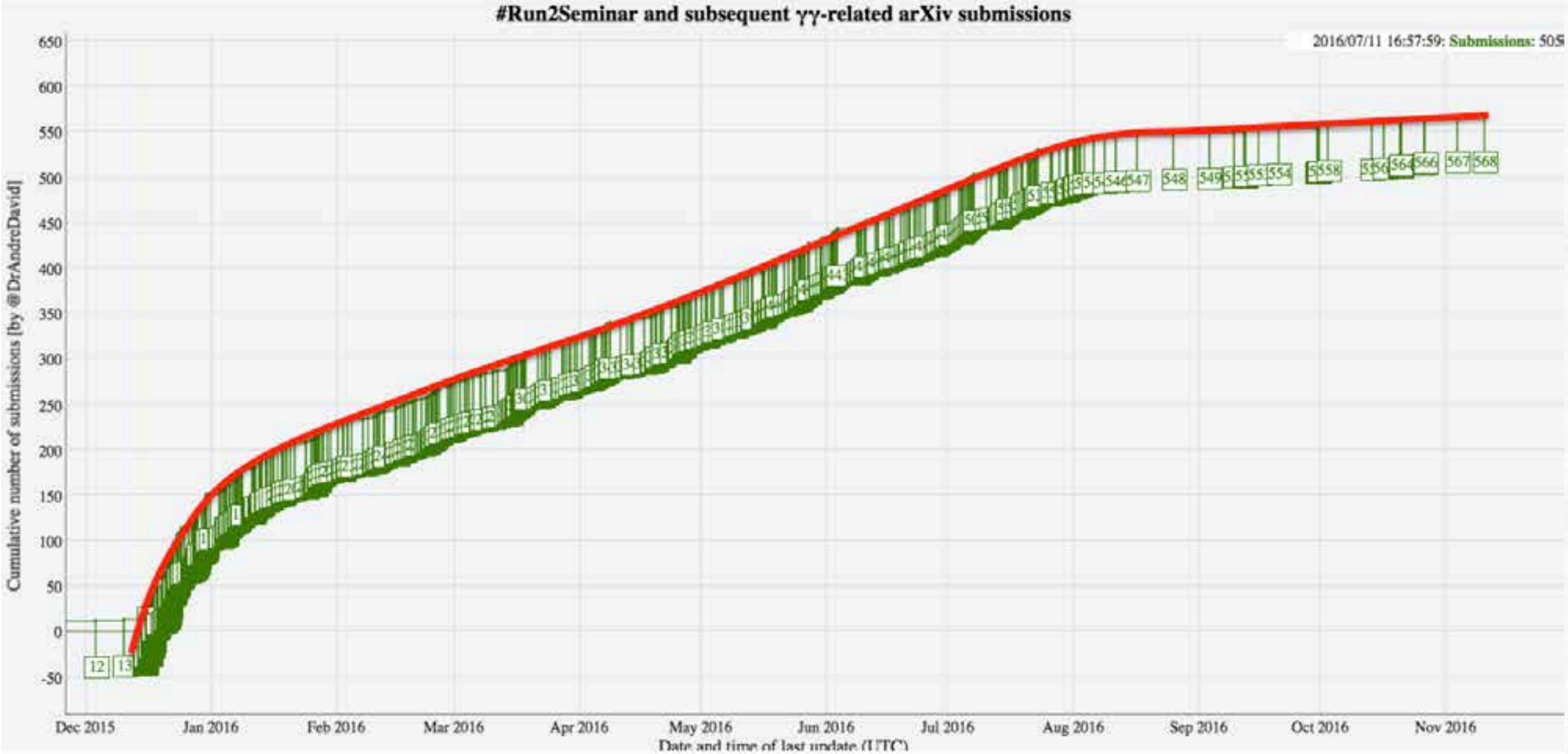
- Both ATLAS and CMS searched for resonances in di-photon events using 2015 data at $\sqrt{s}$ = 13 TeV
- Background determined by fitting the data with a smooth function, and independently from Monte Carlo simulation (normalized to data in the low mass region)





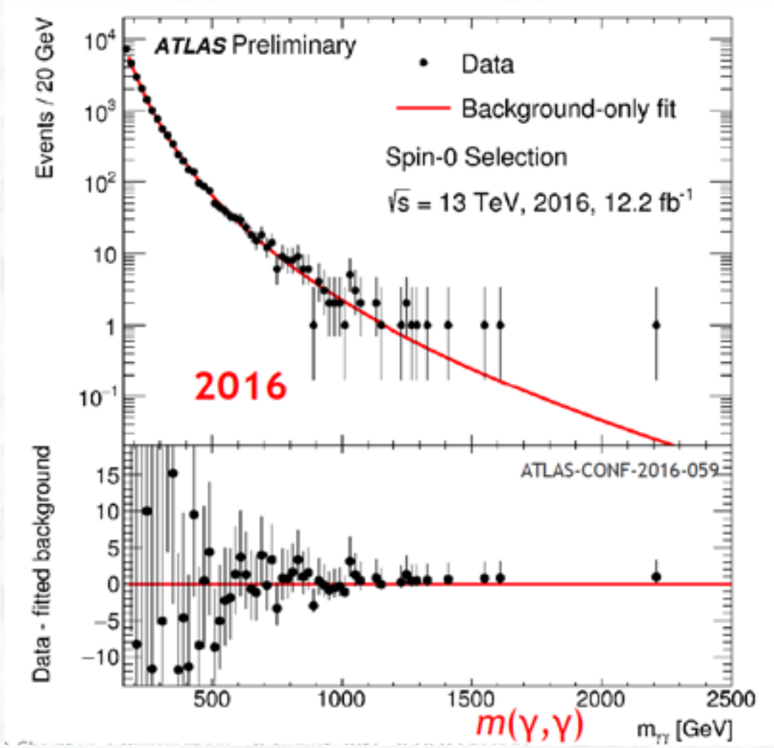
Excesses with local significances of 3.6σ (ATLAS) and 2.6σ (CMS)

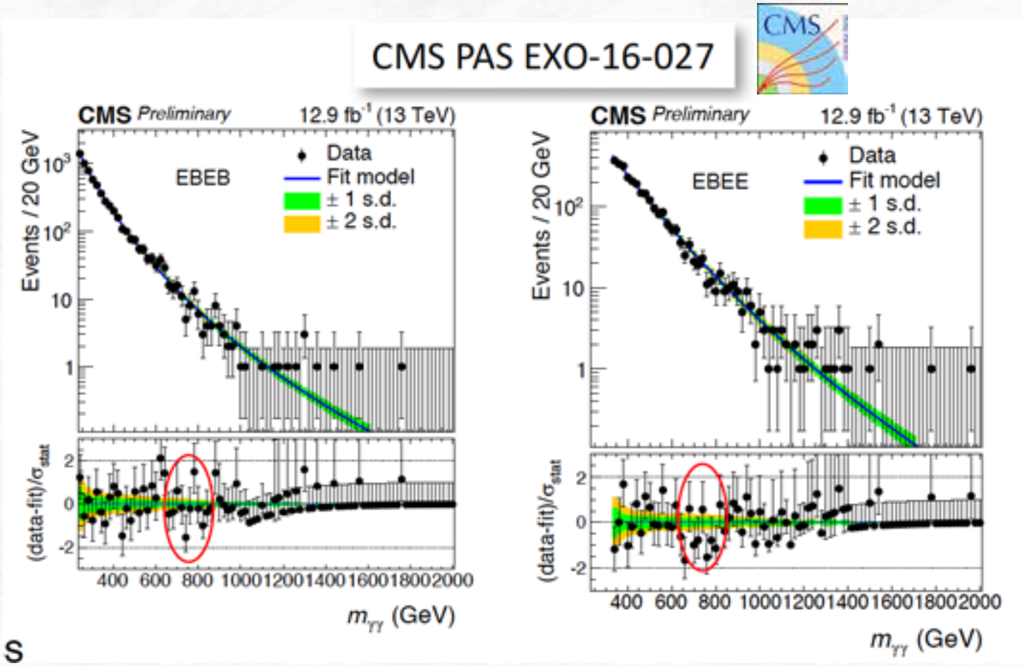
… led to lot of excitement in the theory community …



2016 data: excess at 750 GeV not confirmed

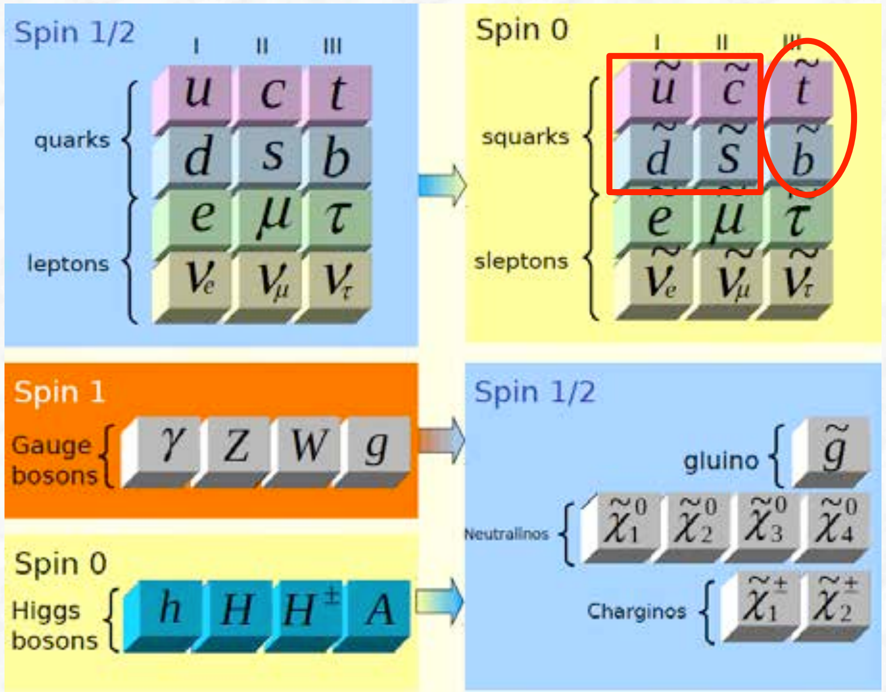
~~750~~

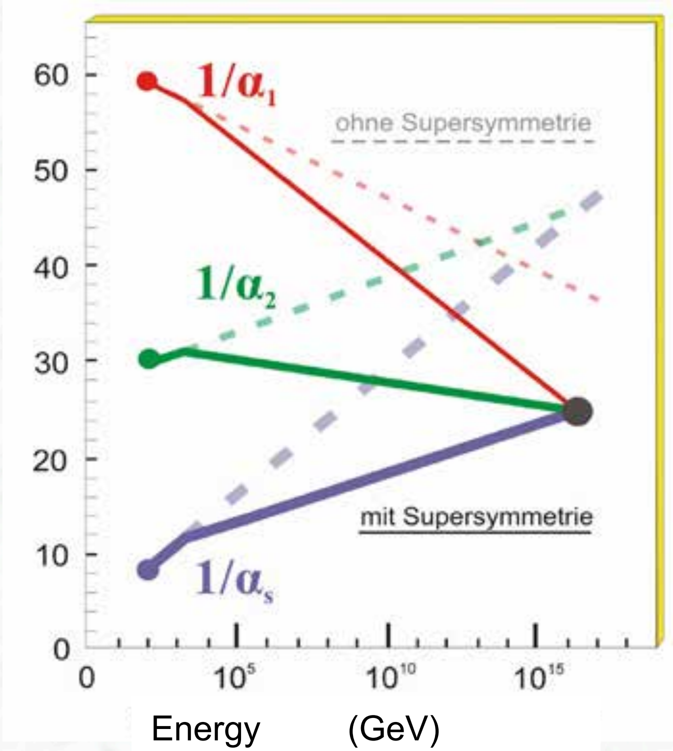




- 2016 data: - no clustering around 750 GeV, and 3.8 times more data
  - consistency with 2015 data at the 2.7σ level (ATLAS)
- It appears that the 2015 excess was a statistical fluctuation

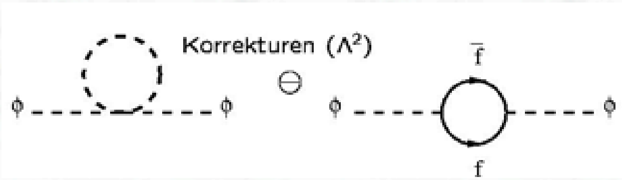
Supersymmetry

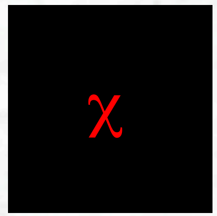




Important motivation:

- Supersymmetry provides a candidate for dark matter
- Unification of couplings of the three interactions seems possible
- Quadratically divergent quantum corrections are cancelled

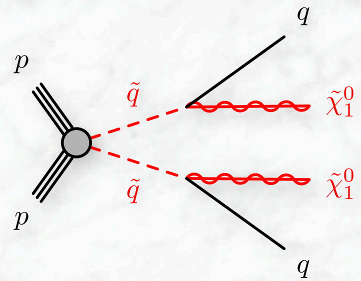




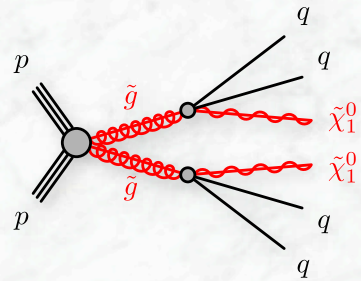
LSP: lightest super-symmetric particle

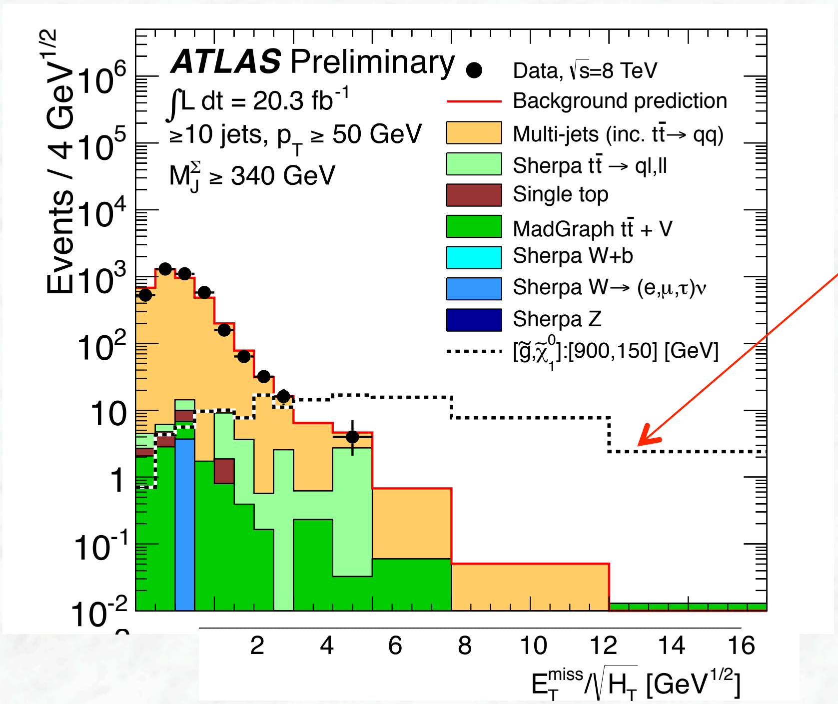
Results on the Search for Supersymmetry

- Example: search for squark and gluino production;
  decays to jets and LSP
  → jets + large missing transverse energy



- Data are in agreement with predictions from background from Standard Model processes



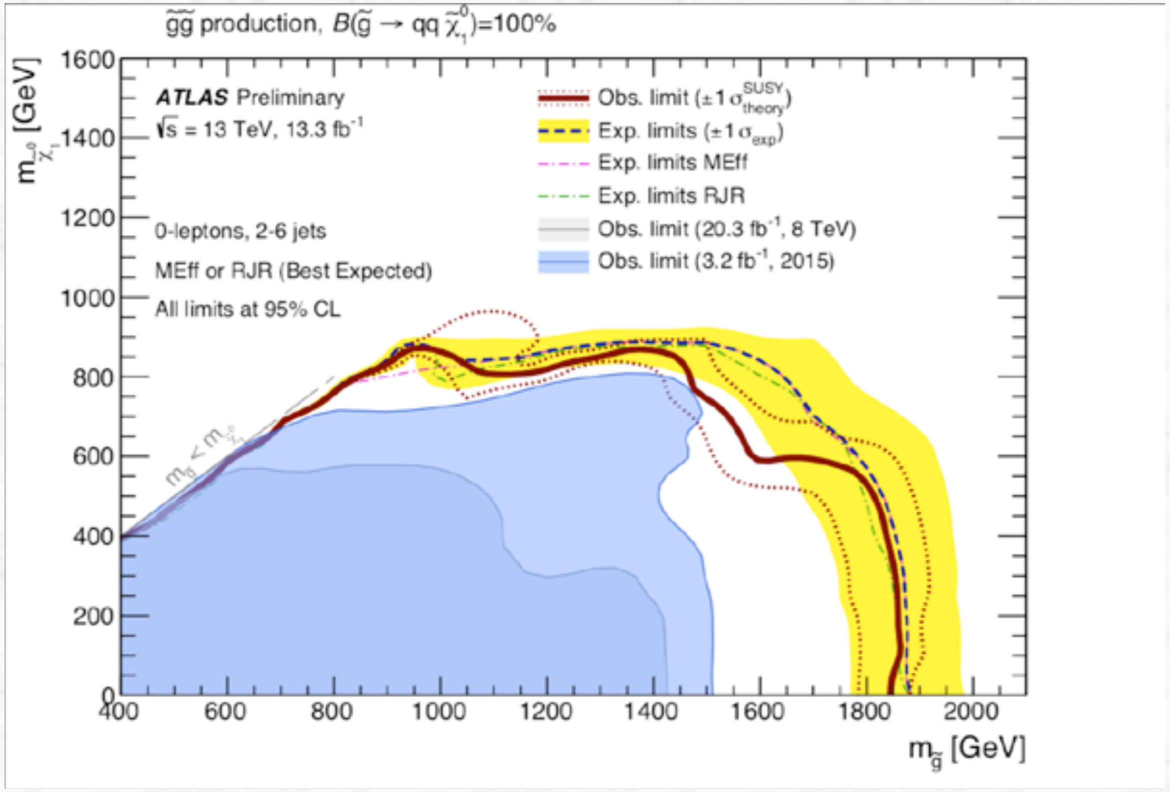


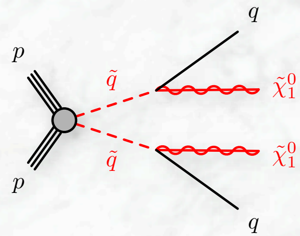
SUSY contribution would show up here

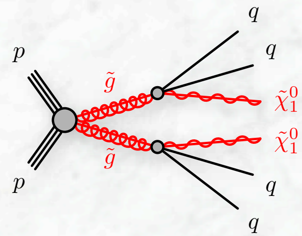
$E_T^{miss} / \sqrt{H_T}$ = missing transverse energy normalized to the square root of the total transverse energy (H_T) seen in the event

Results on the Search for Supersymmetry

→ Exclusion limits are set on masses of these particles





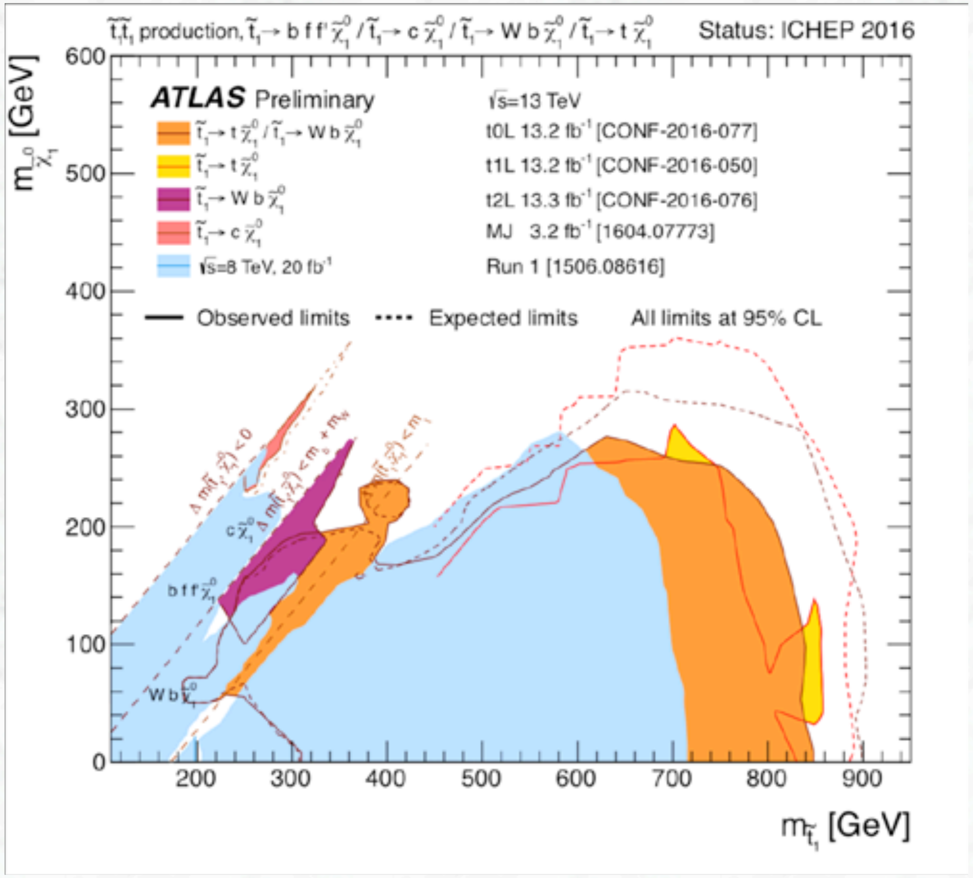


m(gluino) > 1.8 TeV (95% CL) for the partners of the first two generations and light LSPs;
(significant improvement from 1.4 TeV (Run 1))

however:

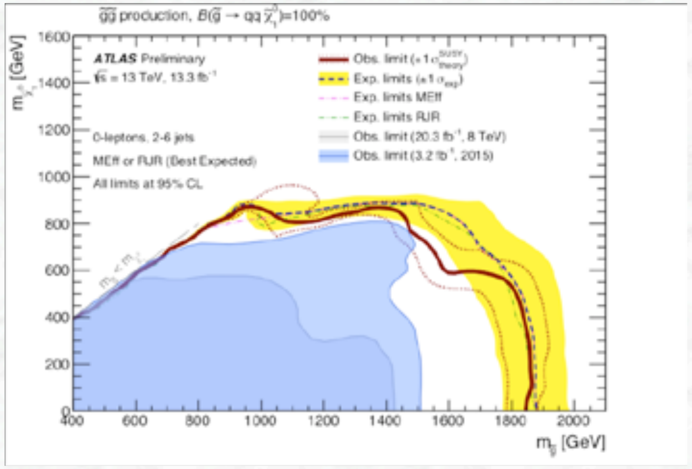
- Mass limits depend on assumptions on m_χ (LSP)
- So far, simple decay scenarios investigated (not most general search)
- Mass limits for third generation squarks are weaker

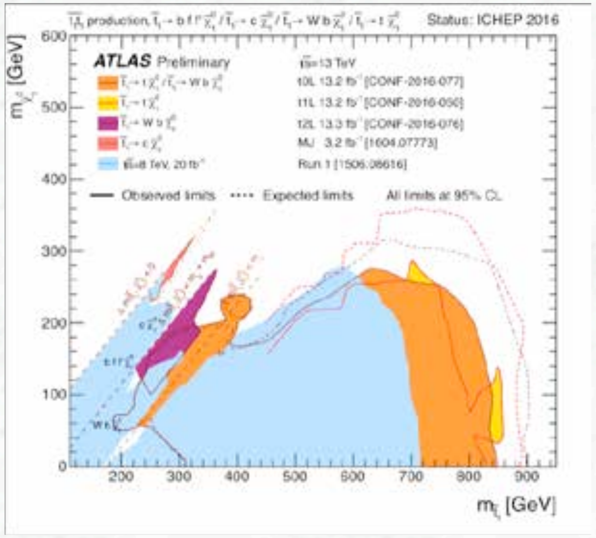
Results on dedicated searches for stop quarks



- Weaker mass limits for partners of the top quark (lower production rate, tt background)
- Dedicated searches, often with particular assumptions

→ significant improvements, however, parameter coverage not yet complete!

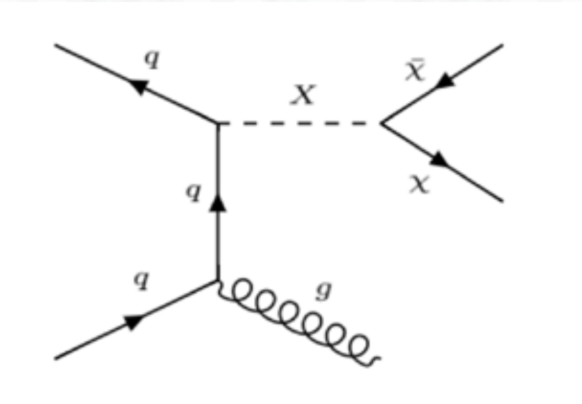




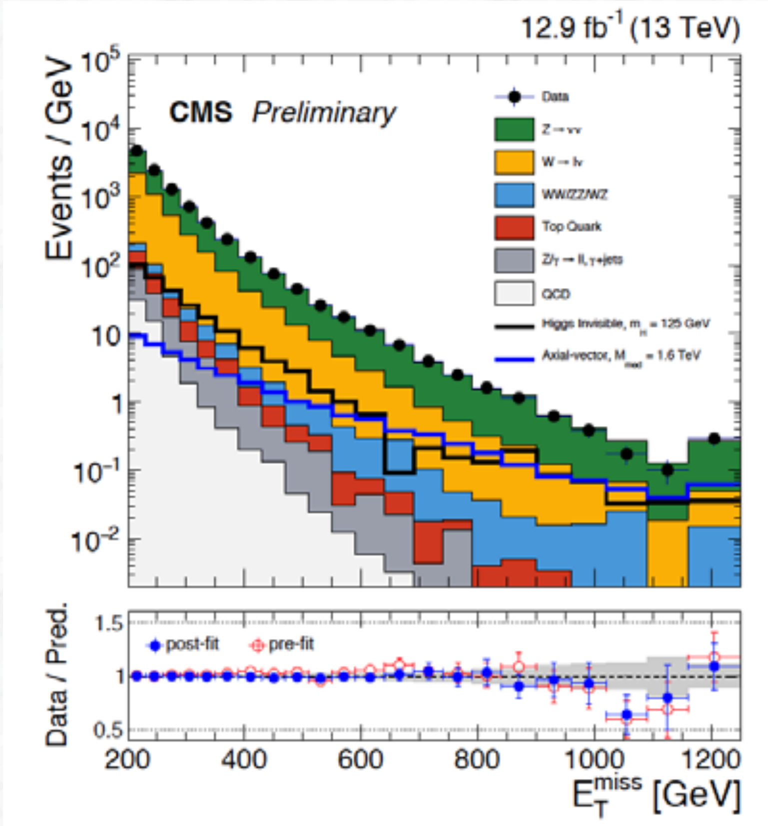
Is low-energy SUSY dead?

- *"Under attack from all sides, but not dead yet."*
- Some of the simplest models are ruled out, however, interpretations rely on many simplifying assumptions.
- Plausible "natural" scenarios still not ruled out; Light stop and/or RPV scenarios have fewer constraints.
- There is no reason to give up hope of finding SUSY at the LHC.

Further searches for Dark Matter particles
-using signatures with large missing energy-



Example: mono-jet search, E_T^{miss} spectrum



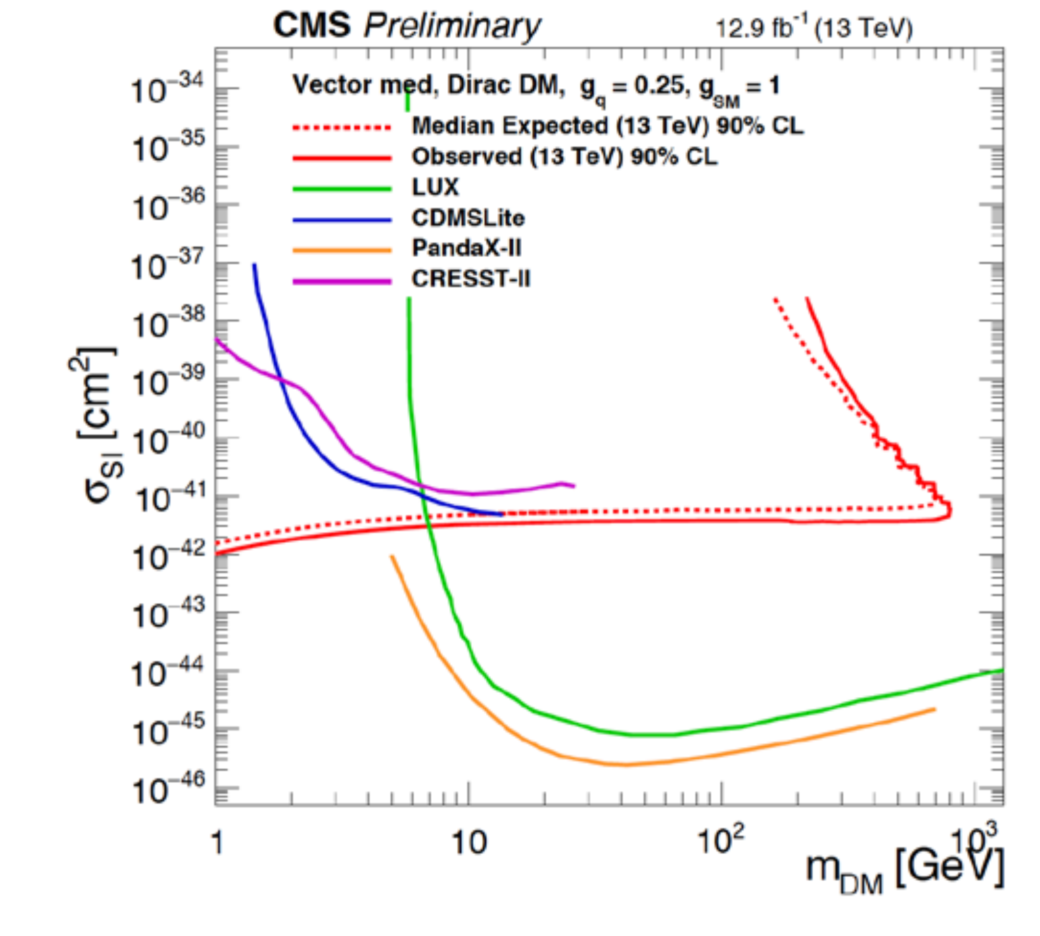
- Mono-jet
- Mono-photon
- Mono-W or mono-Z
- Mono Higgs (H → bb)
- Mono-top

Data are in good agreement with the expectations from Standard Model processes

(applies to all mono-X searches)

Interpretation in terms of spin-independent DM scattering cross sections
→ link to direct Dark Matter detection experiments

Model dependent (depends on mediator type (vector, axial-vector,..) and mass)
[active, emerging field of common and unified interpretations]

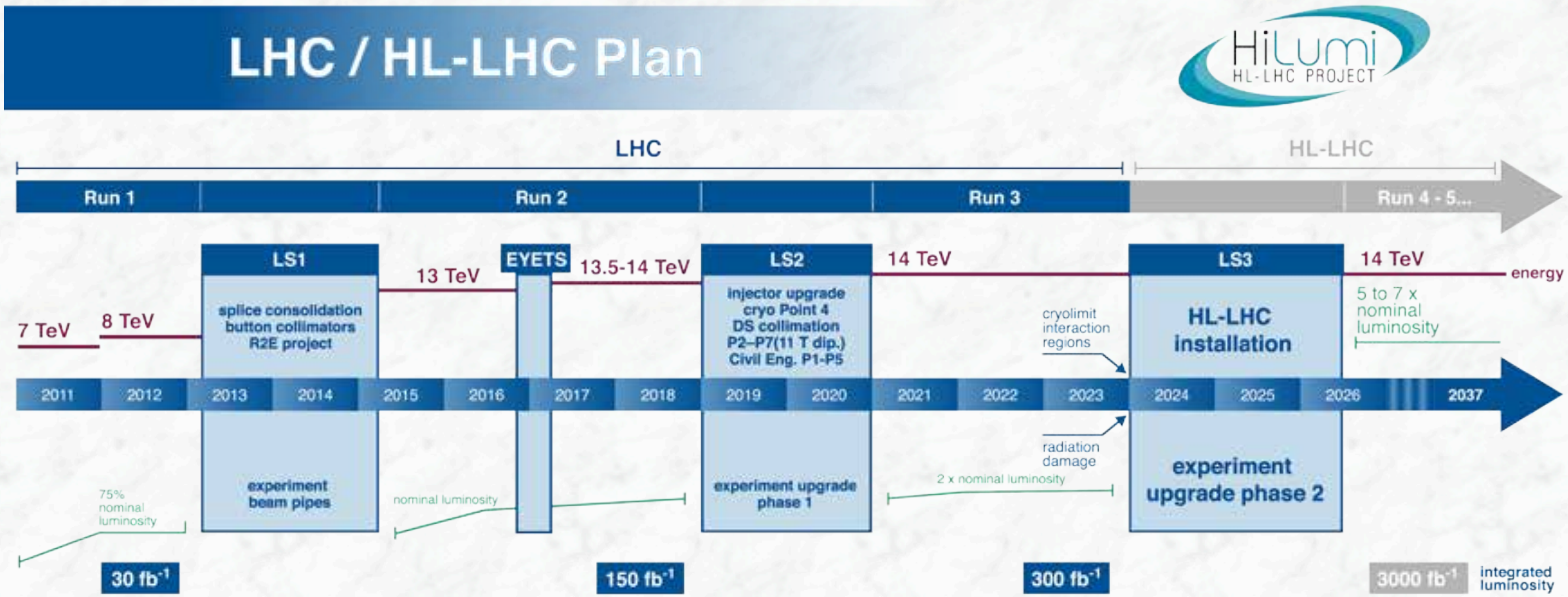


Example: vector-like mediators:

LHC shows sensitivity at low masses of DM particles

The Future

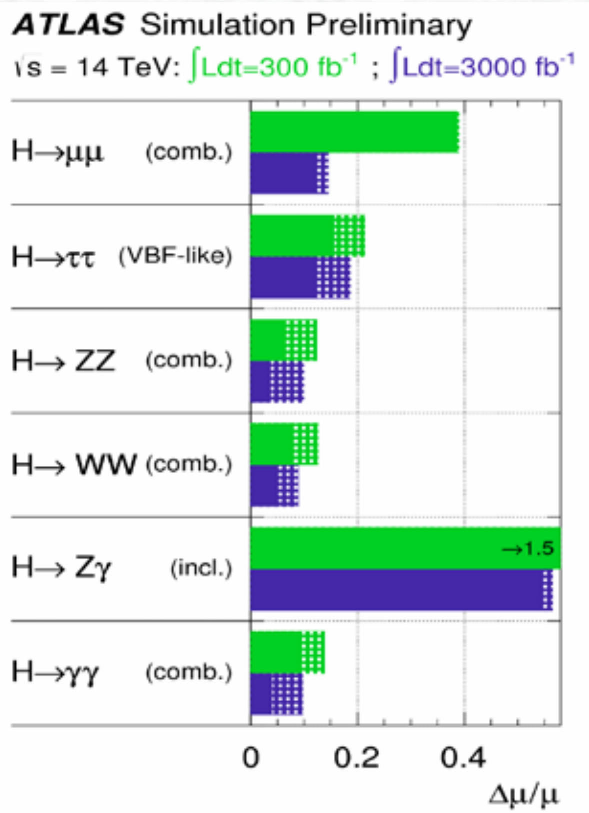
- Operation at the increased energy of √s = 13 TeV until end 2018 (Run 2)
- Upgraded detectors are needed to cope with the higher luminosity; Installation in Long Shutdowns (2019-2020) and (2024-2026)
- LHC long term running plans:



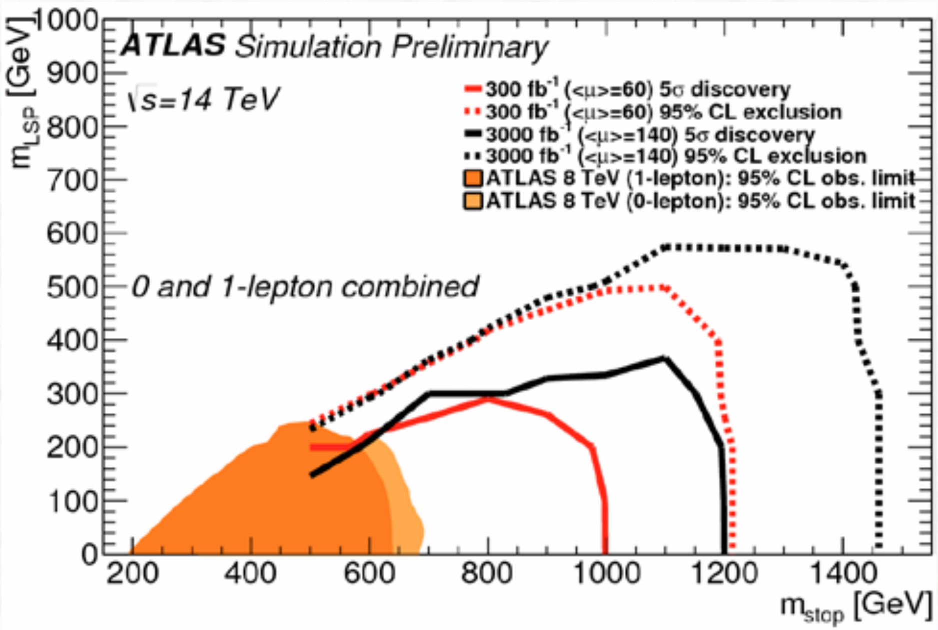
Major Physics Prospects

- Precise measurements of Higgs boson profile
  (rare, interesting decay modes, test of more exotic models, e.g. composite Higgs, Higgs self coupling, …)

- Extend the searches for New Physics in all possible directions, cover more complex scenarios, … + … look for the unexpected !



ATL-PUB-2013-014



ATL-PUB-2013-011

Conclusions

- With the operation of the LHC at high energies, particle physics has entered a new era

- Performance of the LHC and the experiments is superb

- A milestone discovery made in July 2012

  - Strong evidence that the new particle is the long-sought Higgs boson of the Standard Model;
  - We moved from the discovery to the measurement phase;
  - The Higgs boson might be portal to *New Physics* (precision required)

- So far no signals from New Physics, however, only a small fraction of the parameter space at reach at the LHC has been explored

- Exciting times ahead of us, with new, unexplored energy regime in reach