LHC results on Higgs boson physics

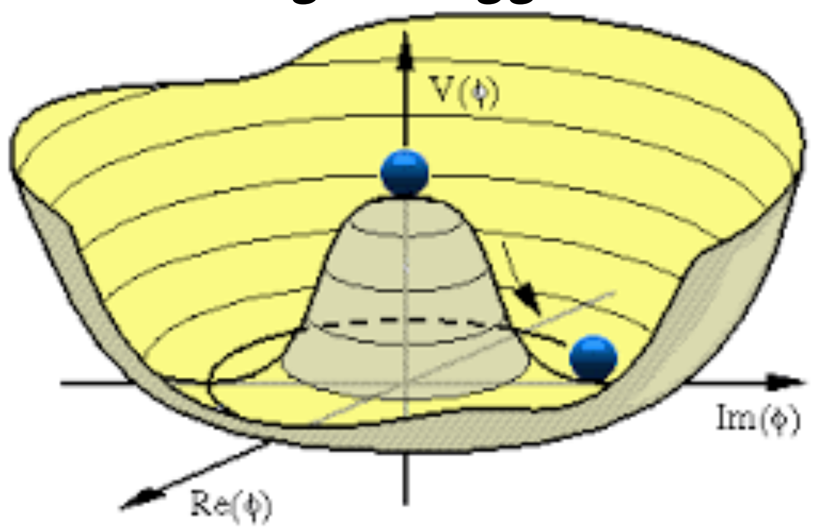
G.Unal (CERN)
Review of ATLAS and CMS results

TGSW, Tsukuba, September 30th 2015

The Higgs boson in the Standard Model

- The Standard Model of particle physics

  - Matter is made of fermions (quarks and leptons)
  - Electromagnetic, Weak and Strong interactions are described by gauge theories => Predicts massless intermediate vector bosons (like the photon)
  - W,Z bosons are very massive (~80-90 GeV). ***How to preserve the "good" features of gauge symmetry ?***
  - Spontaneous Symmetry Breaking => ***Brout-Englert-Higgs mechanism for gauge theories.***

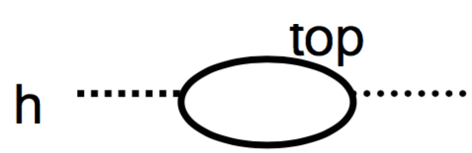


  - Applying this mechanism to the Standard Model predicts one massive scalar boson: **The Higgs boson**
  - Understanding electroweak symmetry breaking and studying the Higgs boson properties (if it exists) was a key goal of the CERN Large Hadron Collider (LHC)
  - In the Standard Model, fermion masses are also generated by this mechanism though Yukawa interactions between the Higgs fields and the fermions

Some properties of the Higgs boson

- Coupling proportional to particle mass
- Short lifetime (10^{-7} fs for a mass of ~125 GeV)
- Scalar particle
- Its mass is not protected by any fundamental symmetry
  - If new physics at scale Λ ~Planck mass, difficult to keep m(H) ~100 GeV

Radiative corrections to Higgs boson mass:



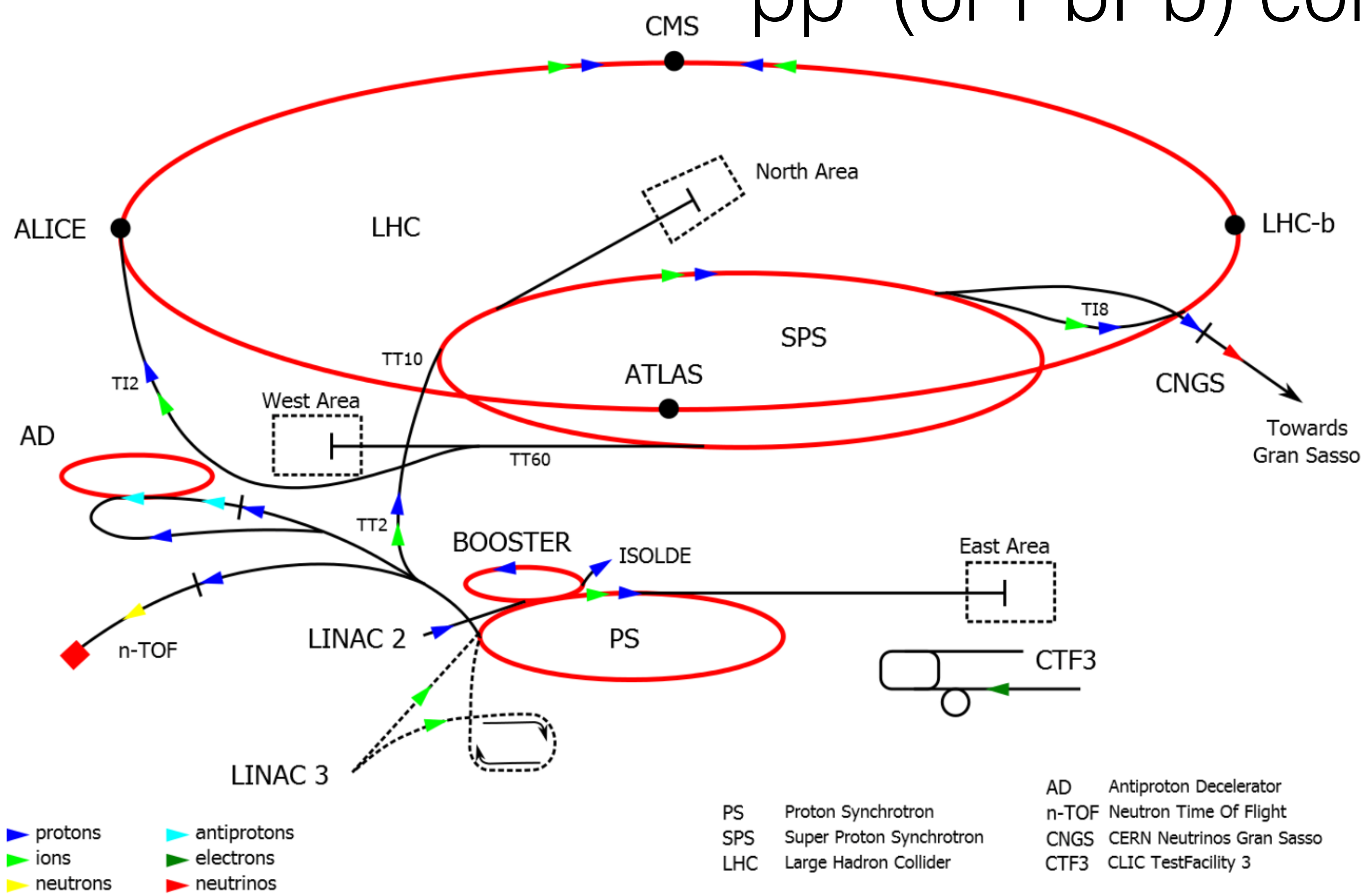
+loops with W,Z,h

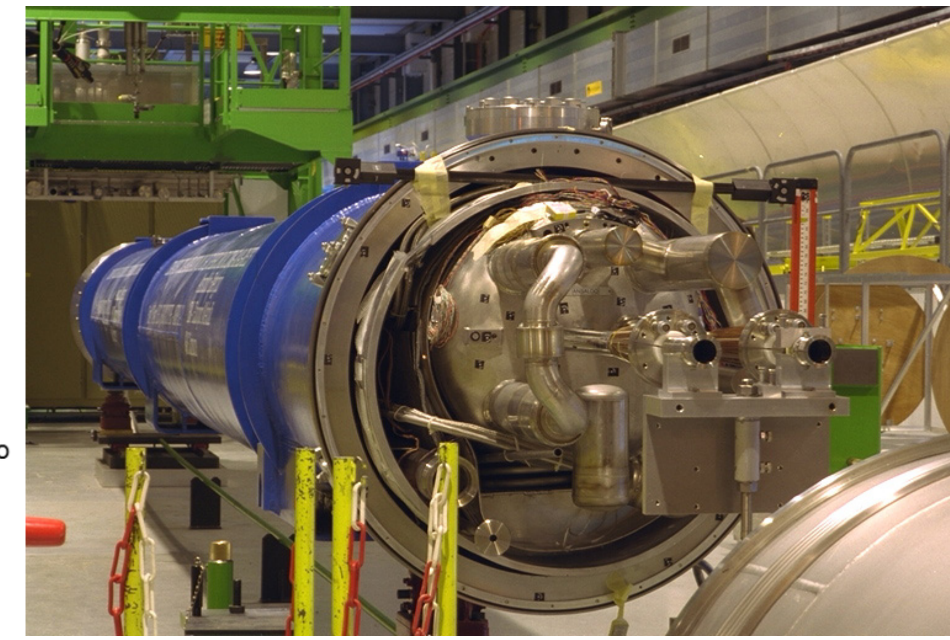
$\delta m_h^2 \sim - m_{top}^2/(4\pi^2 v^2)\ \Lambda^2$

  - Except if new physics at mass ~ 1 TeV
  - For instance supersymmetry
    - Contributions from new particles cancel Standard Model contributions

How to produce Higgs boson: The LHC accelerator at CERN

pp (or PbPb) collider





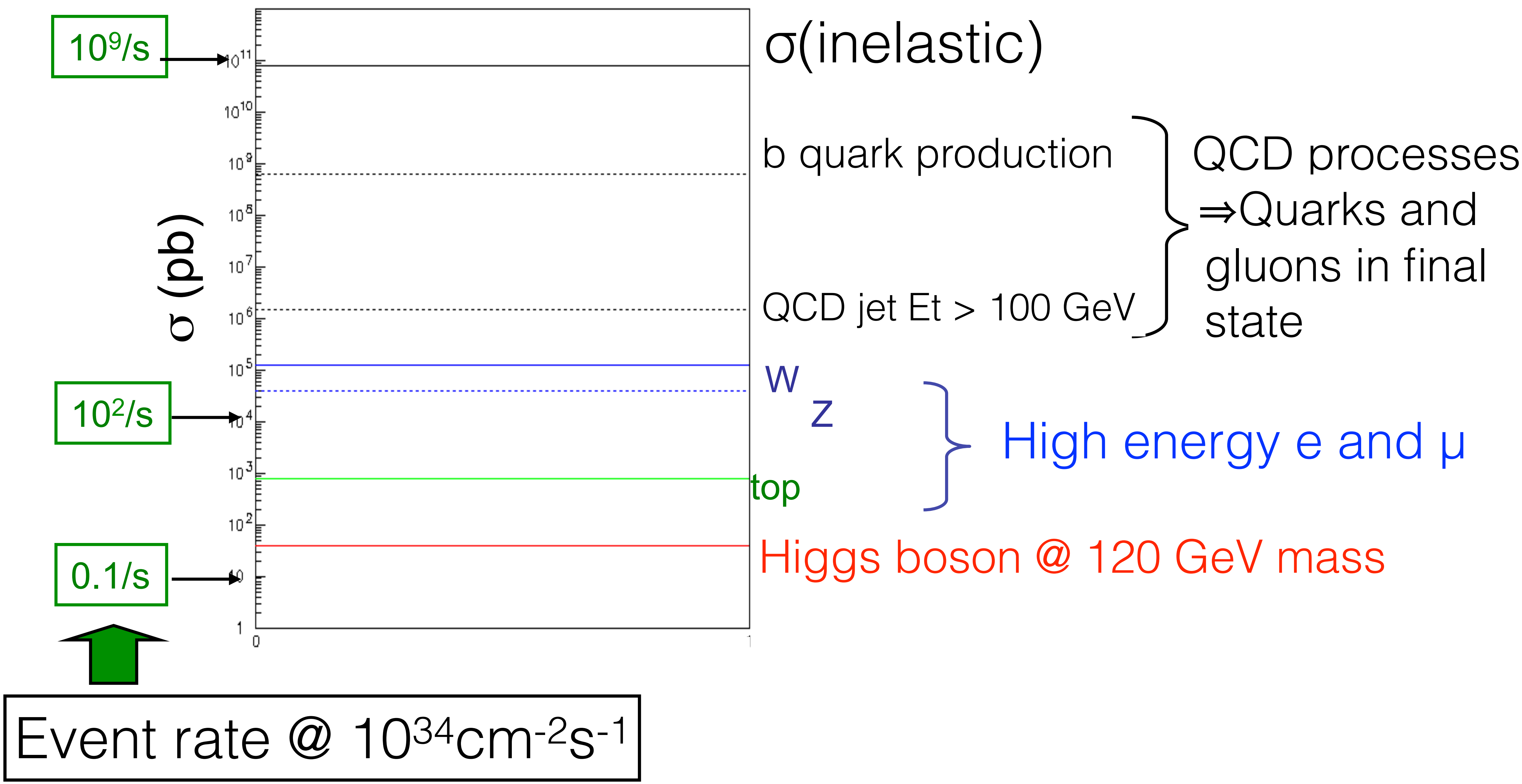
8.3 T dipoles to bend proton trajectories

NbTi @ T=1.9K

Integrated luminosity: 5 fb^{-1} at $\sqrt{s}$=7 TeV in 2011
20 fb^{-1} at 8 TeV in 2012

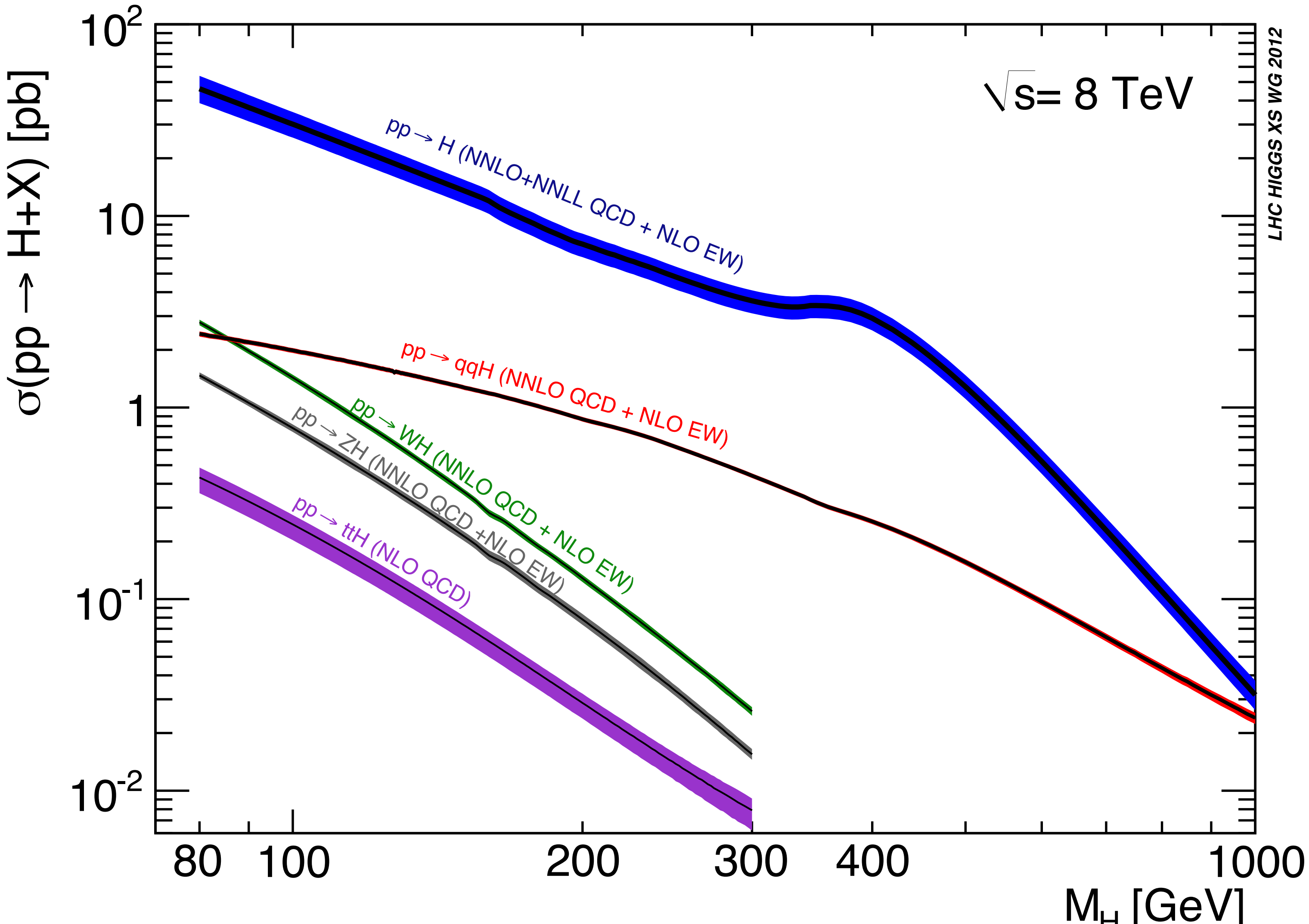
Higgs boson results are obtained thanks to the very good LHC performance

Main processes in high energy pp collisions

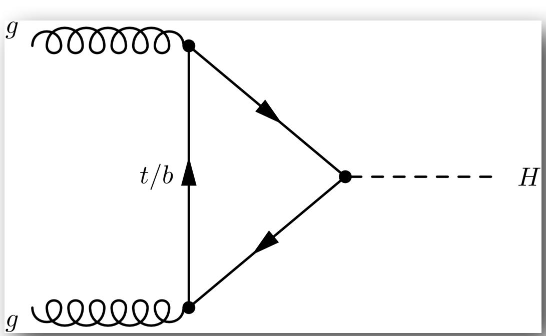


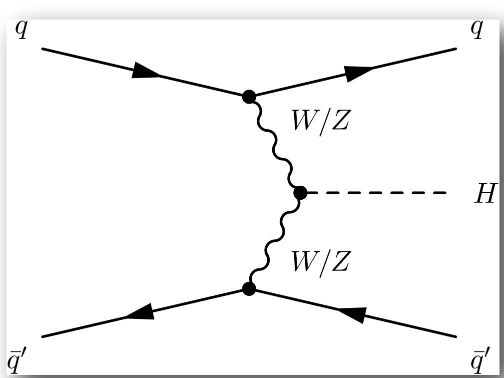
=> Online selection critical to record ~ 1 kHz event rate to disk for offline analysis

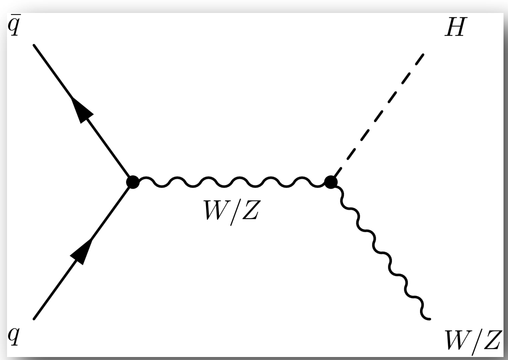
Higgs boson production at the LHC

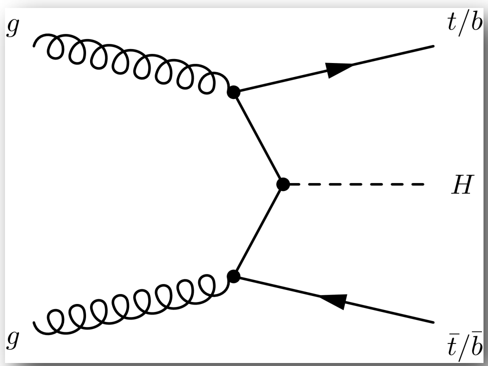


gluon fusion　vector boson fusion　WH, ZH　ttH

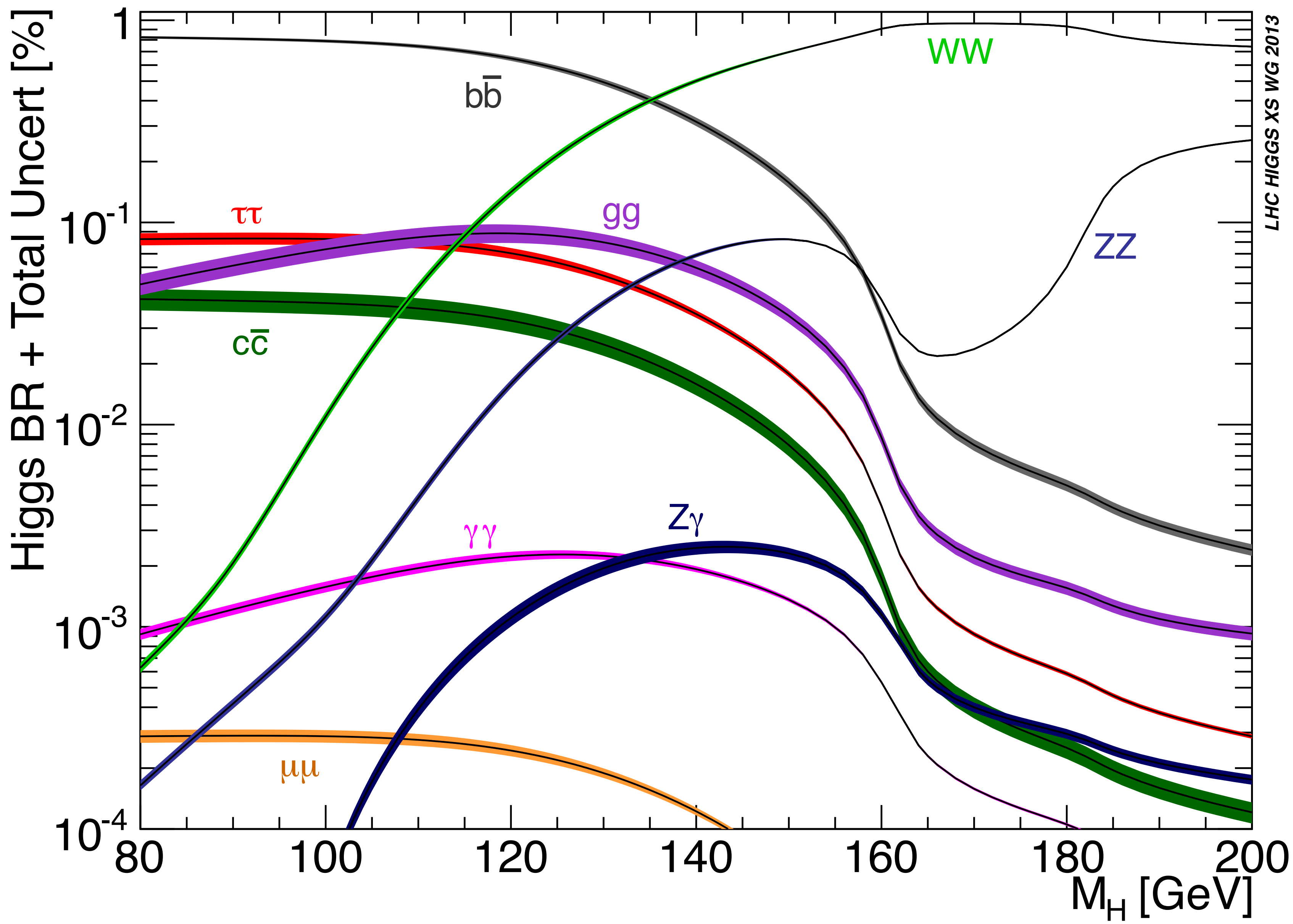






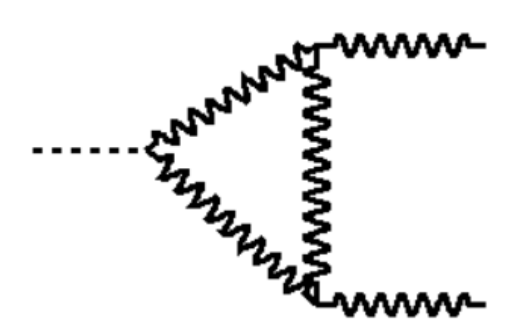


Higgs boson decay



Main decay modes: To heaviest particles kinematically allowed

Important exception: $H \rightarrow \gamma\gamma$ (via loop with W or top quarks)



Strategy to search for the Higgs boson and to study oit

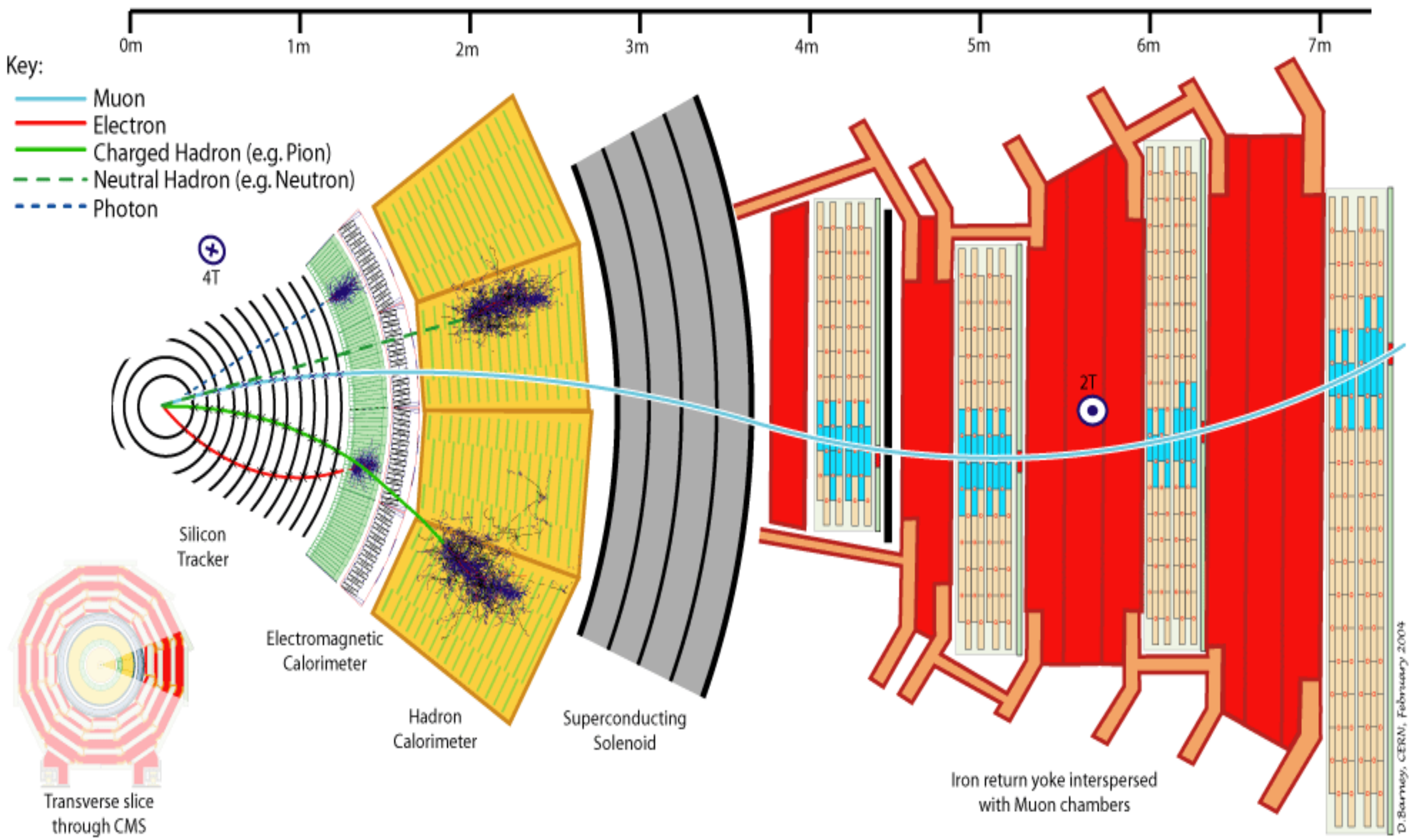
Combine production mode * decay mode to get a final state
which can be separated from background

	gg fusion	VBF	VH	ttH
H→γγ				
H→ZZ*→4l				
H→WW*→2l2ν				
H→ττ				
H→bb				
H→μμ				
H→Zγ				

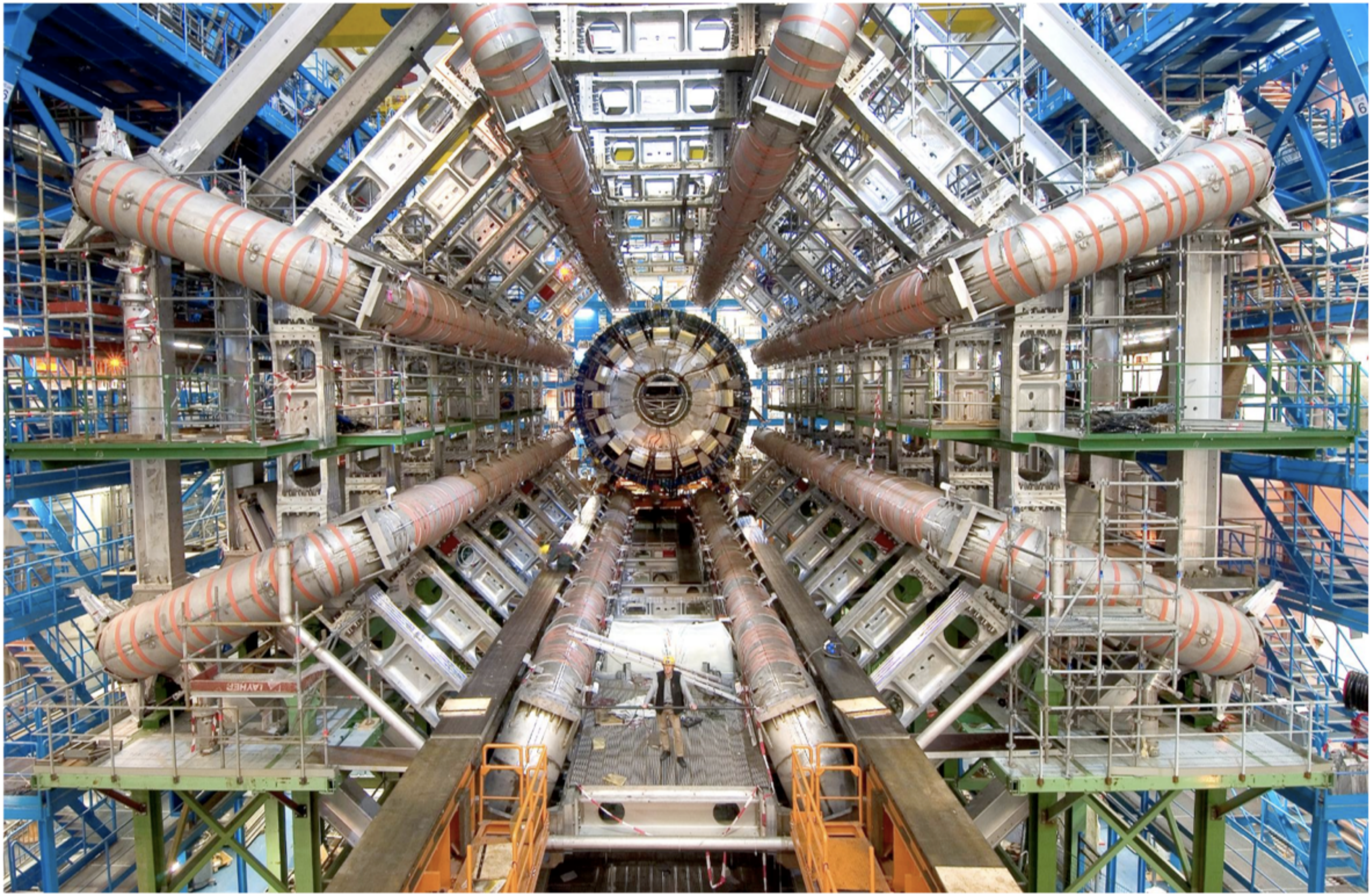
(l = e or μ)

Which detectors to observe the Higgs boson ?

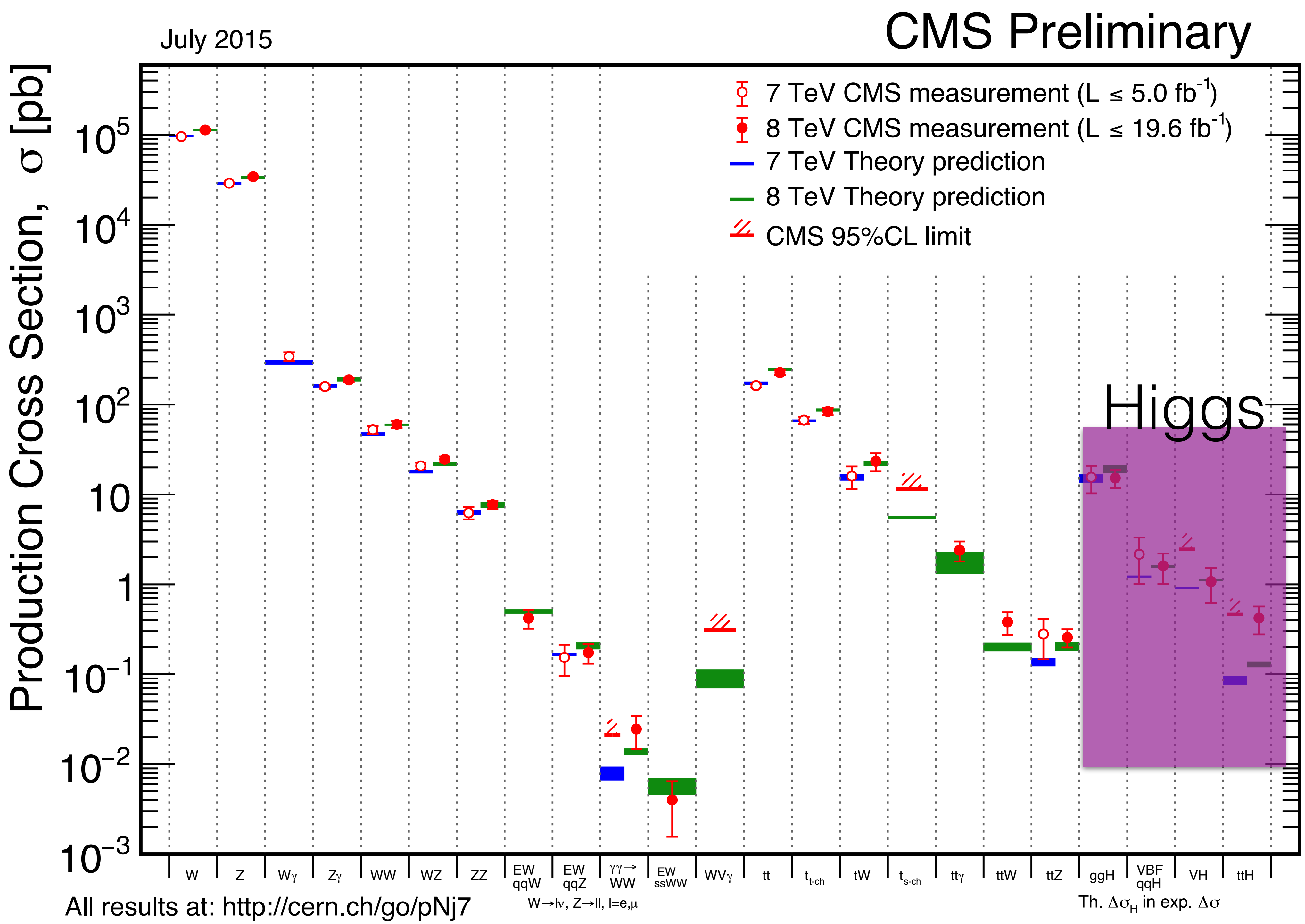
The CMS detector



The ATLAS detector during installation in 2005



Standard Model processes are measured and well understood



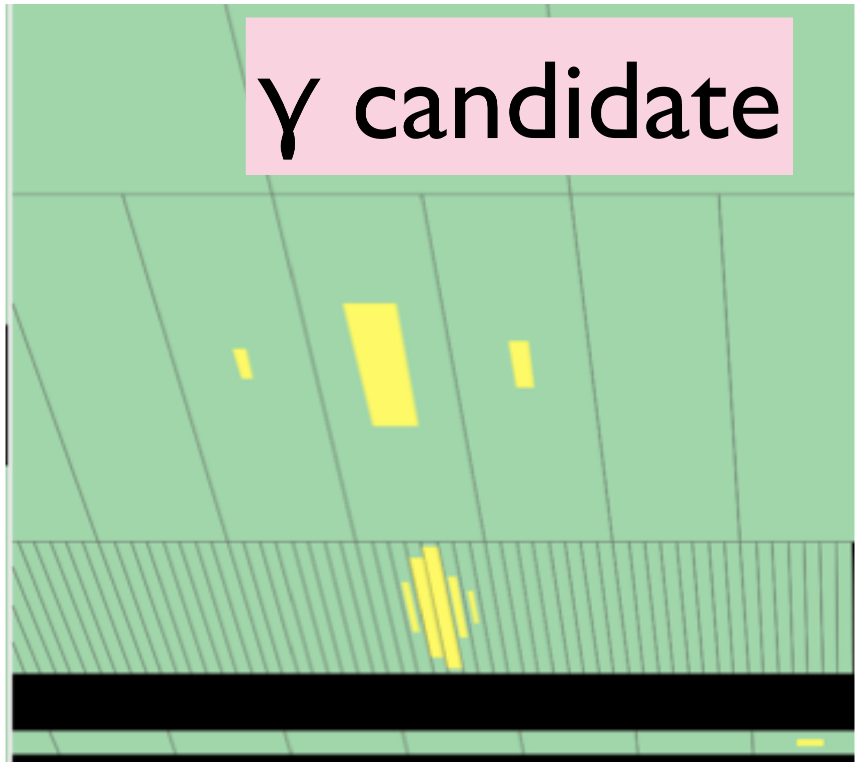
One example analysis: Higgs boson decay to two photons

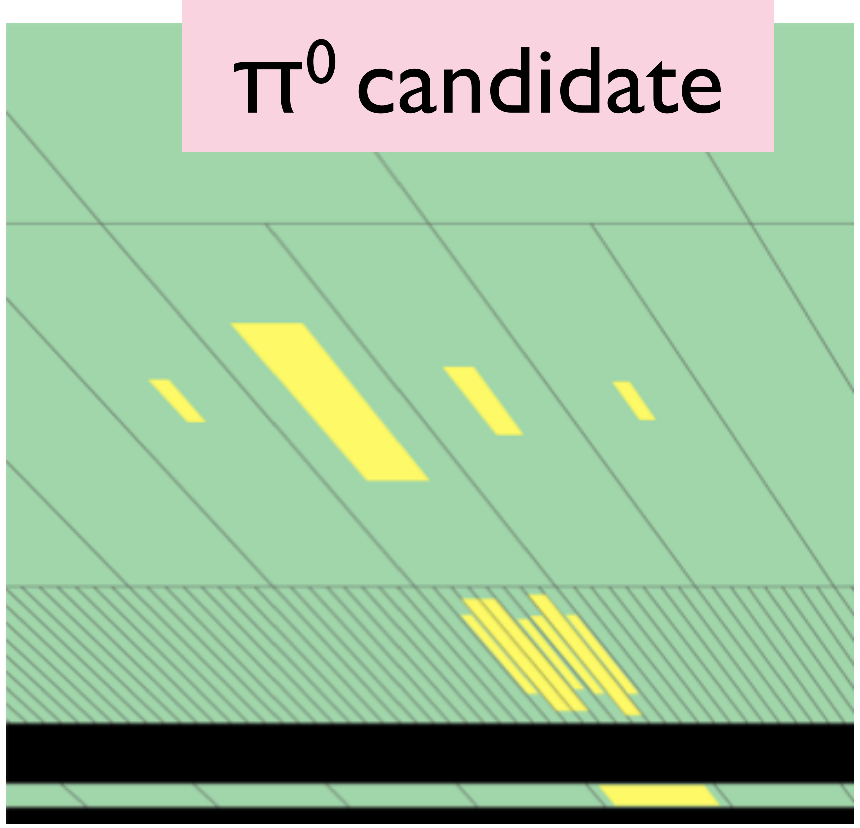
First step: Identify two high energy photons

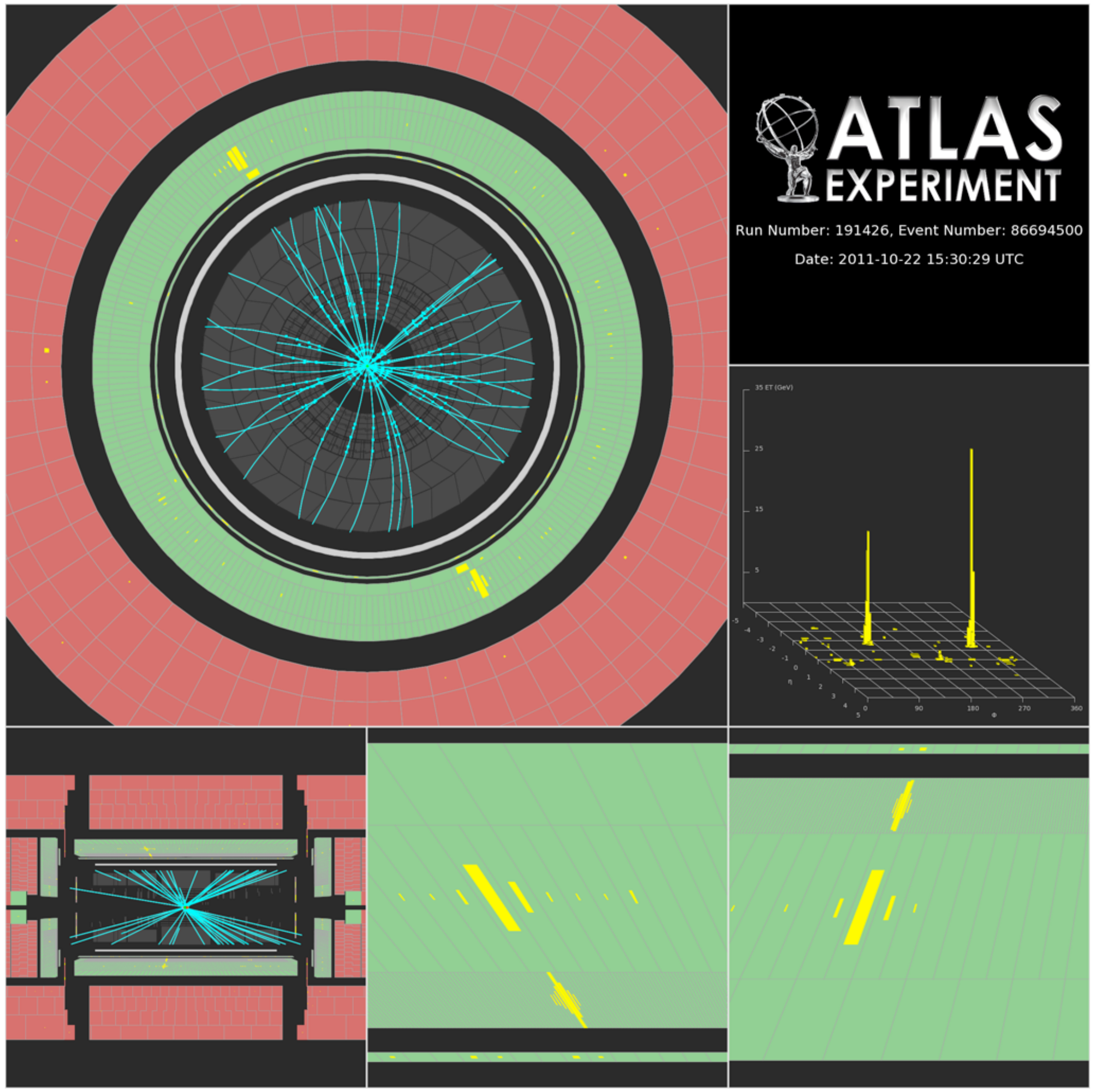
Need to reject photons coming from decay of hadrons (like π^0), otherwise overwhelmed by background processes

Exploits fine granularity of the electromagnetic calorimeter to achieve this goal

- Example in ATLAS: very fine segmentation of first calorimeter layer







Example pp collisions with two high energy photon candidates

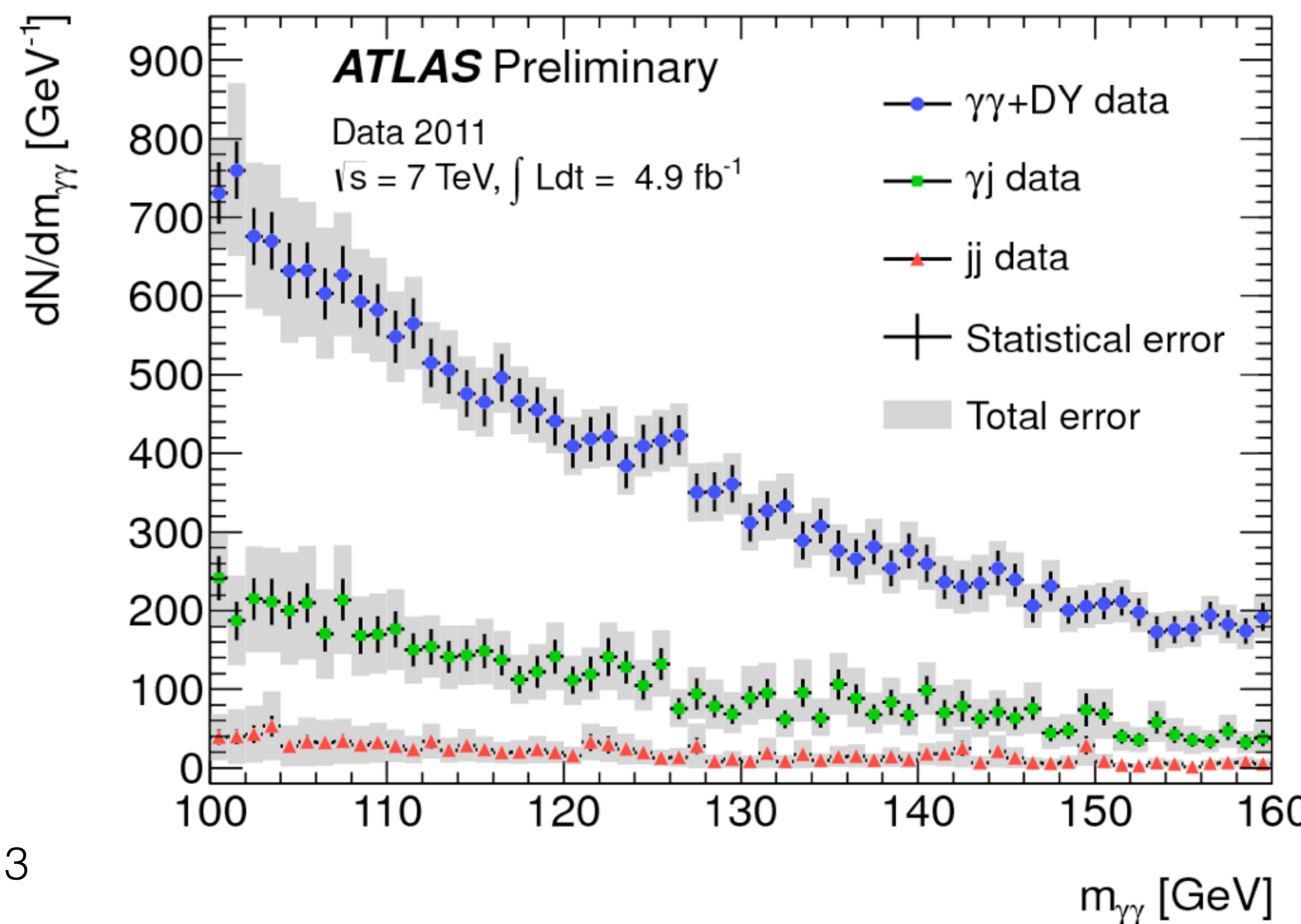
Second step: Measure invariant mass of the two photons

$$M^2 = 2\, E_1\, E_2\, (1-\cos\theta)$$

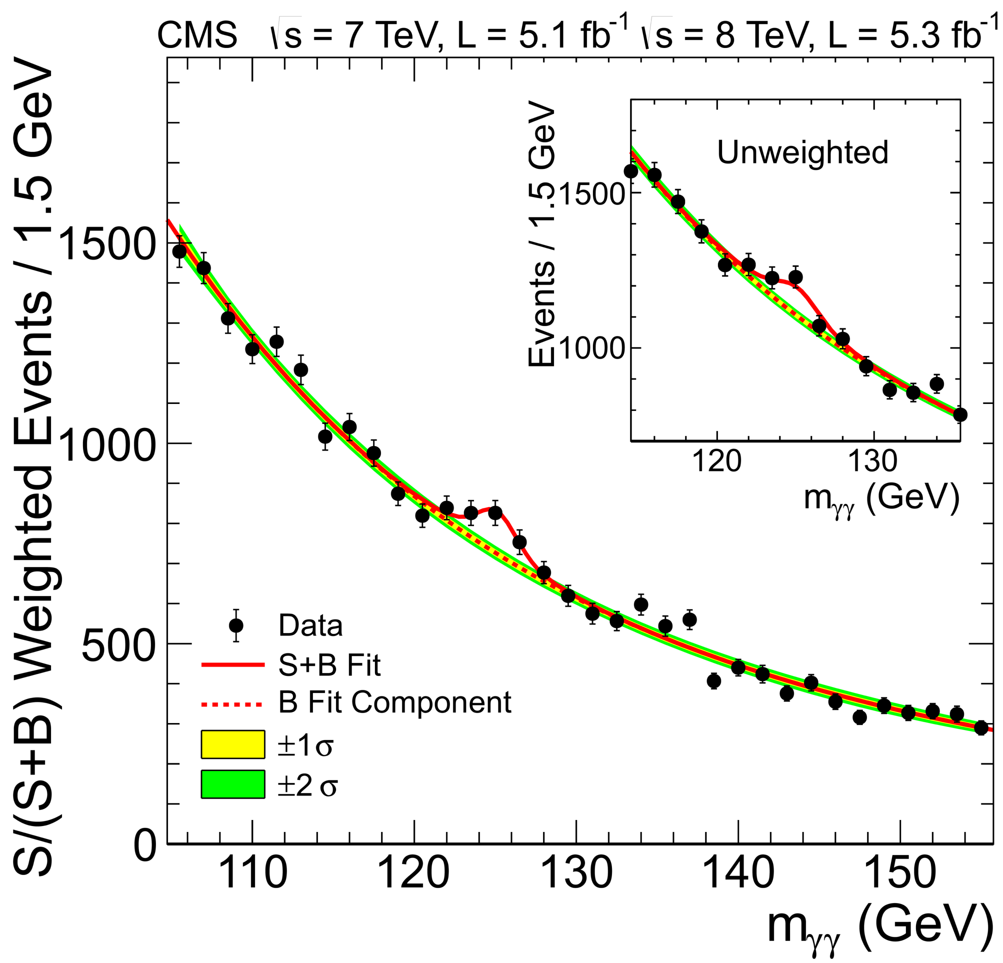
M(γγ) (2011 data)

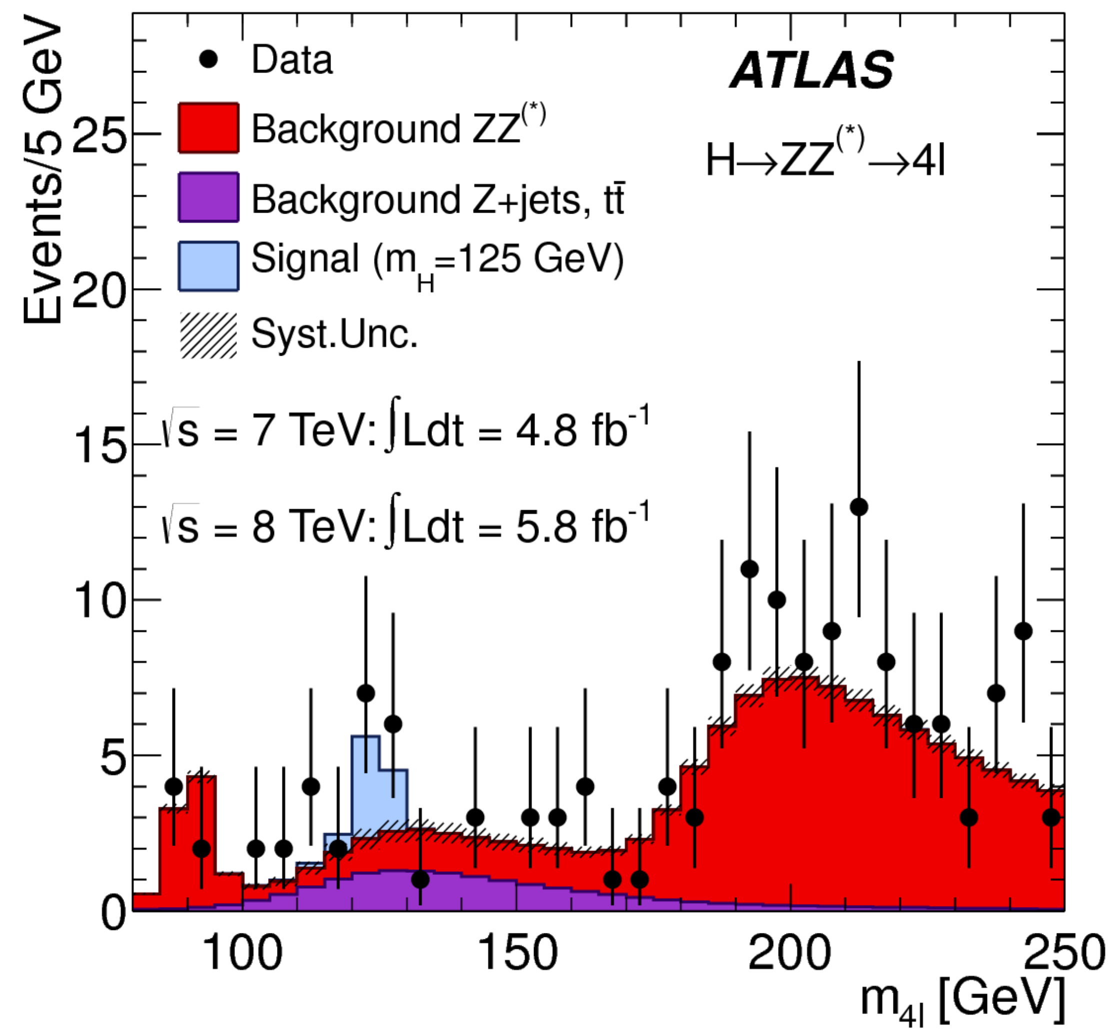
H→γγ gives a peak at M(H) => a very good resolution is needed to achieve a good sensitivity

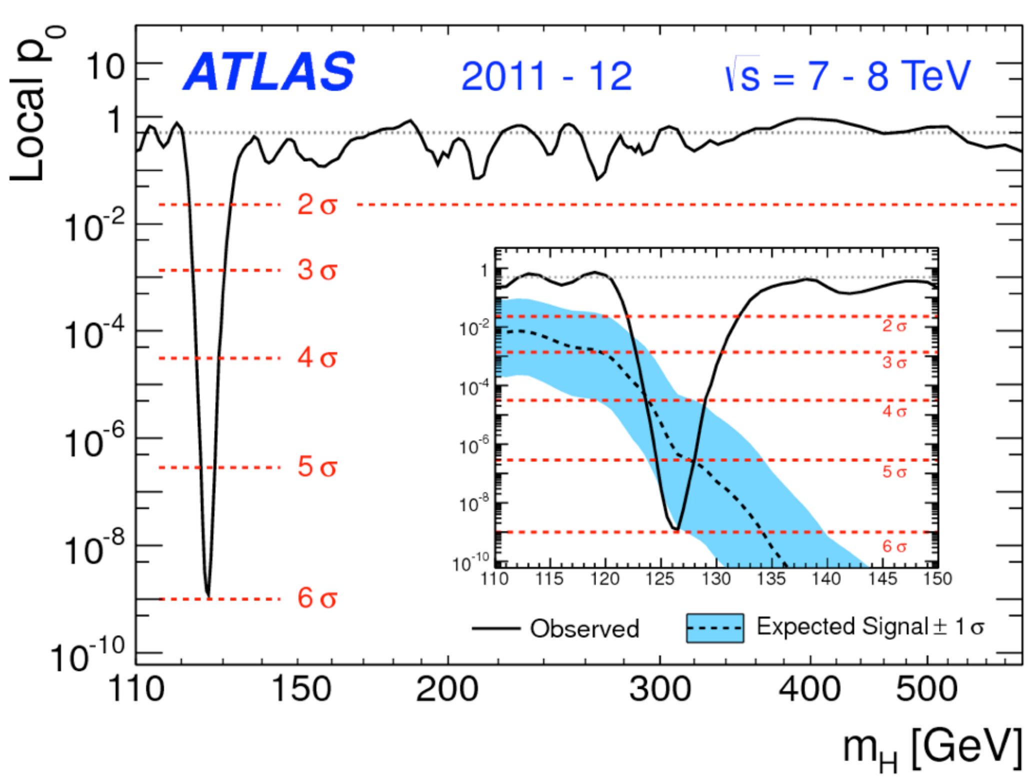
Résolution on M ~1%



Discovery of a new boson in July 2012







CERN seminar July 4th, 2012

2013 Nobel price for physics to Englert et Higgs

This is the beginning of the studies of this new boson

Characterizing the boson

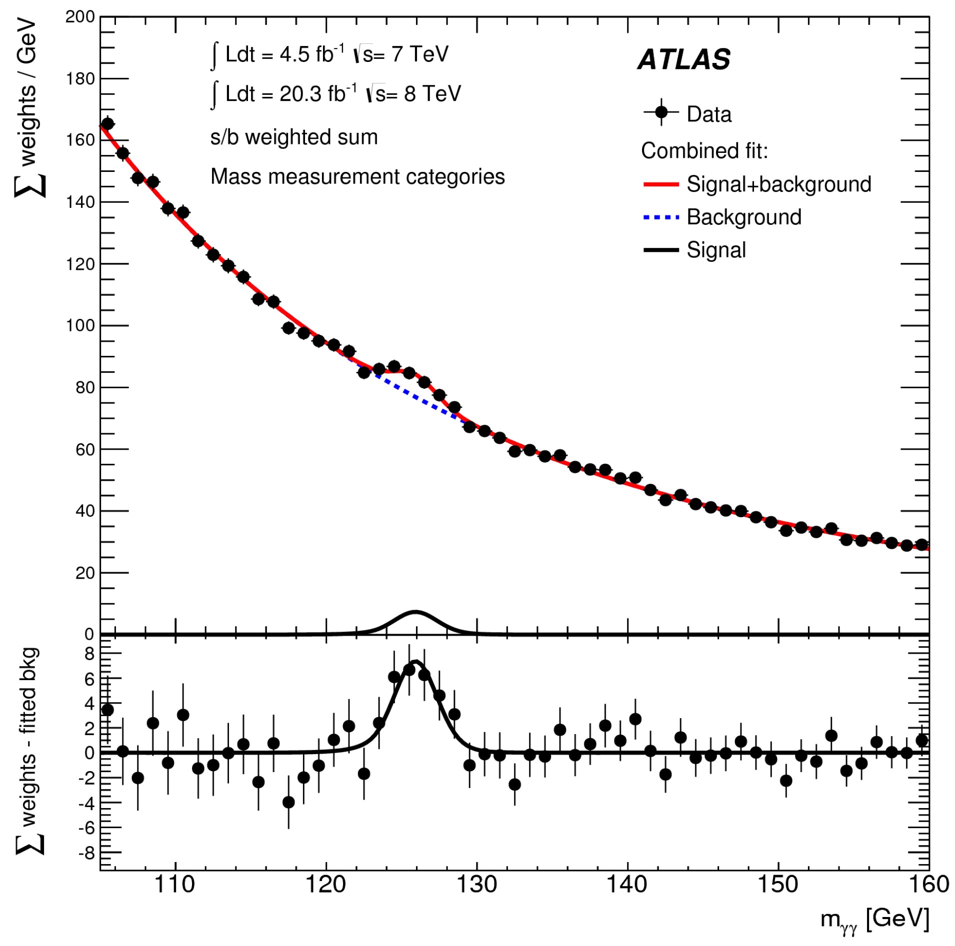
- **Mass measurement**
  - Not predicted in the Standard Model (but can be constrained through precision measurements)
  - Once the mass is determined, all properties of the Higgs boson are predicted in the Standard Model
- **Lifetime measurement (of decay width)**
  - Difficult to measure experimentally in the Standard Model (but new idea emerged recently)
- **Measurement of spin and parity**
  - Should be 0^+ for the boson linked to the BEH mechanism=> The alternative hypothesis have been strongly rejected by the analysis of the LHC data
- **Measurement of the coupling between the boson and other particles**
  - Sensitive to deviations from the Standard Model
  - Higgs decay width in the Standard Model is not that large => could be quite sensitive to new physics contributions

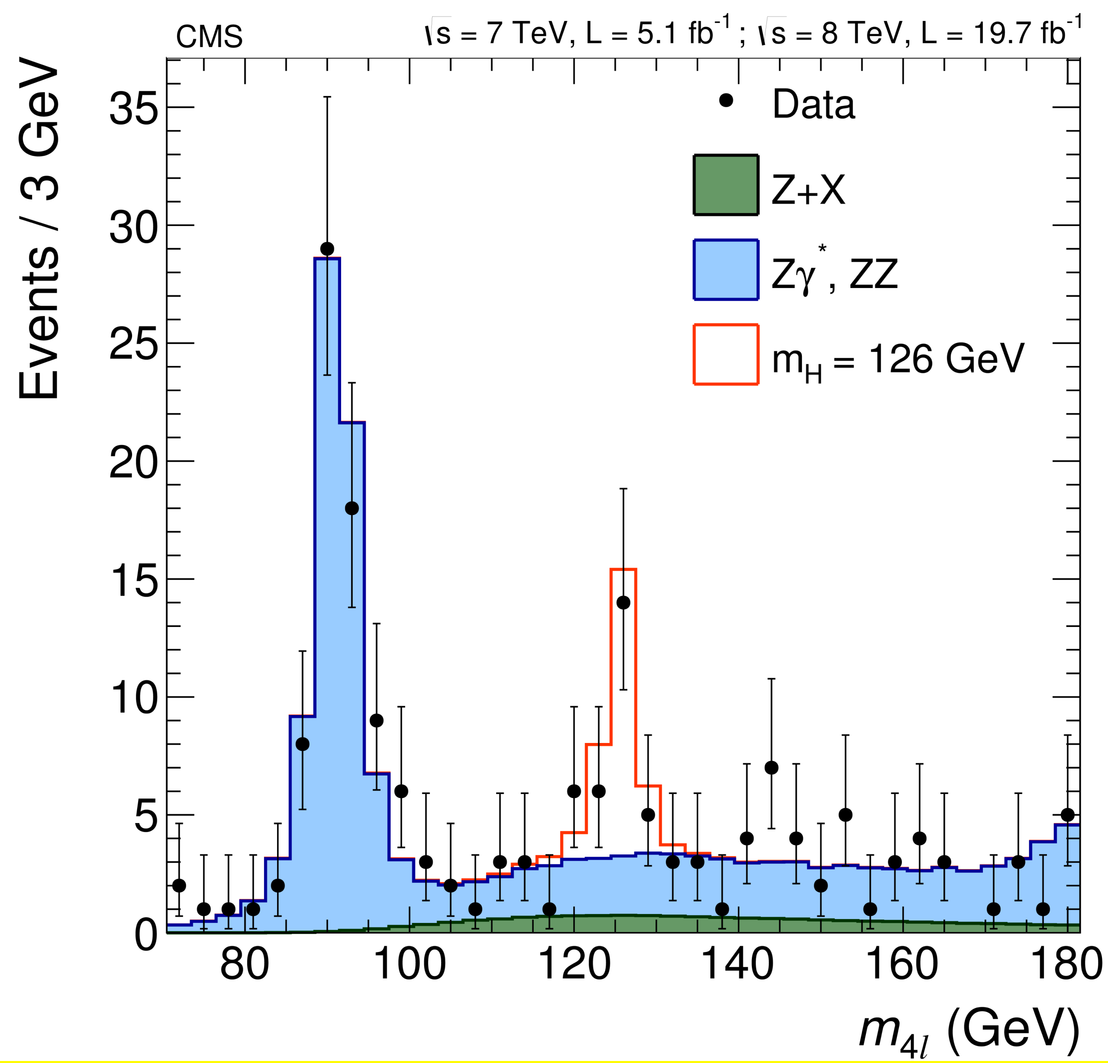
Mass measurement

Use the two channels with the best mass reconstruction resolution

$H \rightarrow \gamma\gamma$

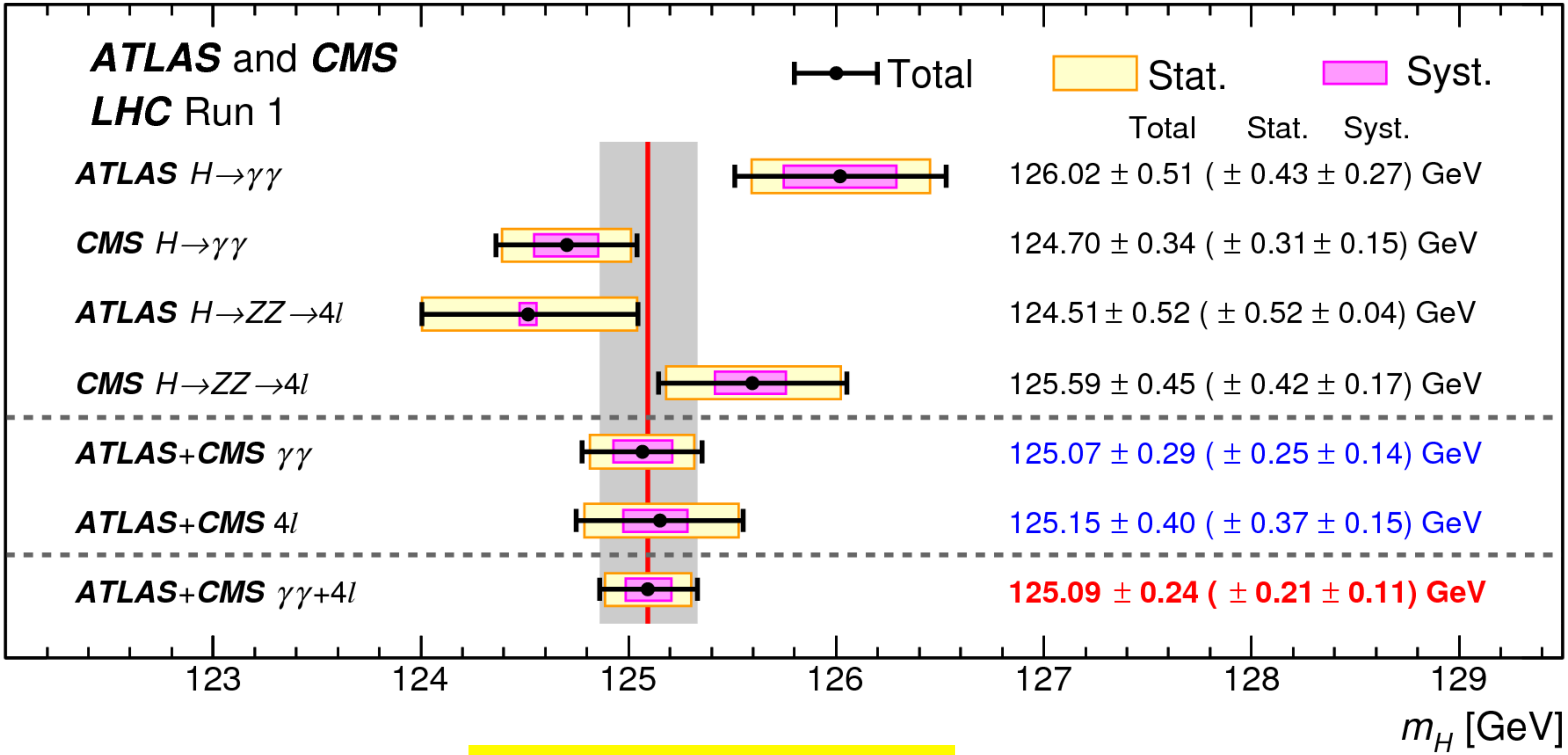
$H \rightarrow ZZ^* \rightarrow 4l$ (l=e or μ)





The analysis exploit the data as much as possible using categories with different S/B, different mass resolutions, etc..

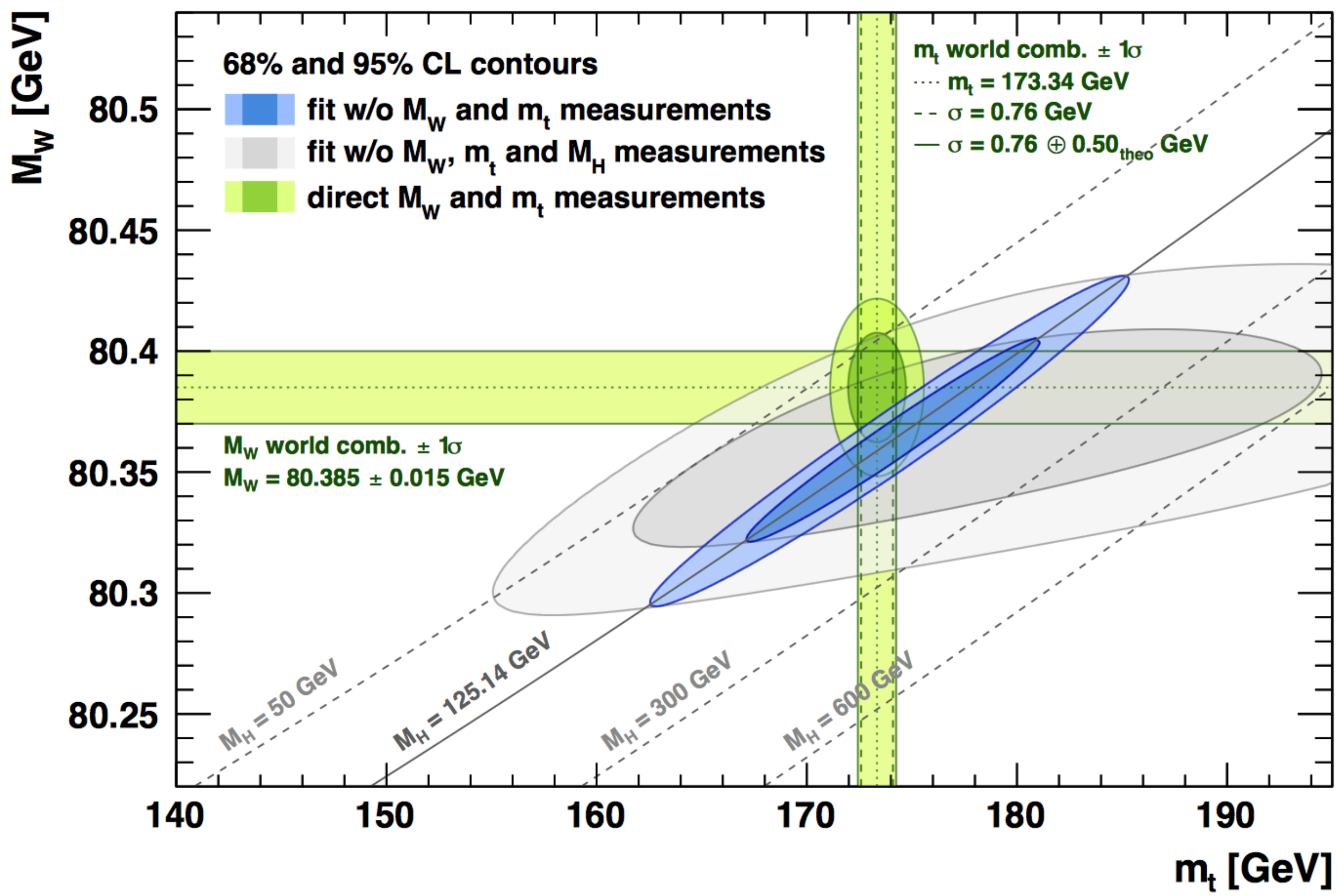
Results for the mass measurement



Accuracy < 0.2%

One implication of the mass measurement

In the Standard Model $M_W=f(M_Z,M_{top},M_H)$ via radiative corrections to the W and Z bosons propagators
=> M_W et M_{top} can be predicted from precision measurements done at LEP and elsewhere, especially if the Higgs mass is known



Good consistency
=> a spectacular success for the Standard Model

Study of the Higgs boson couplings

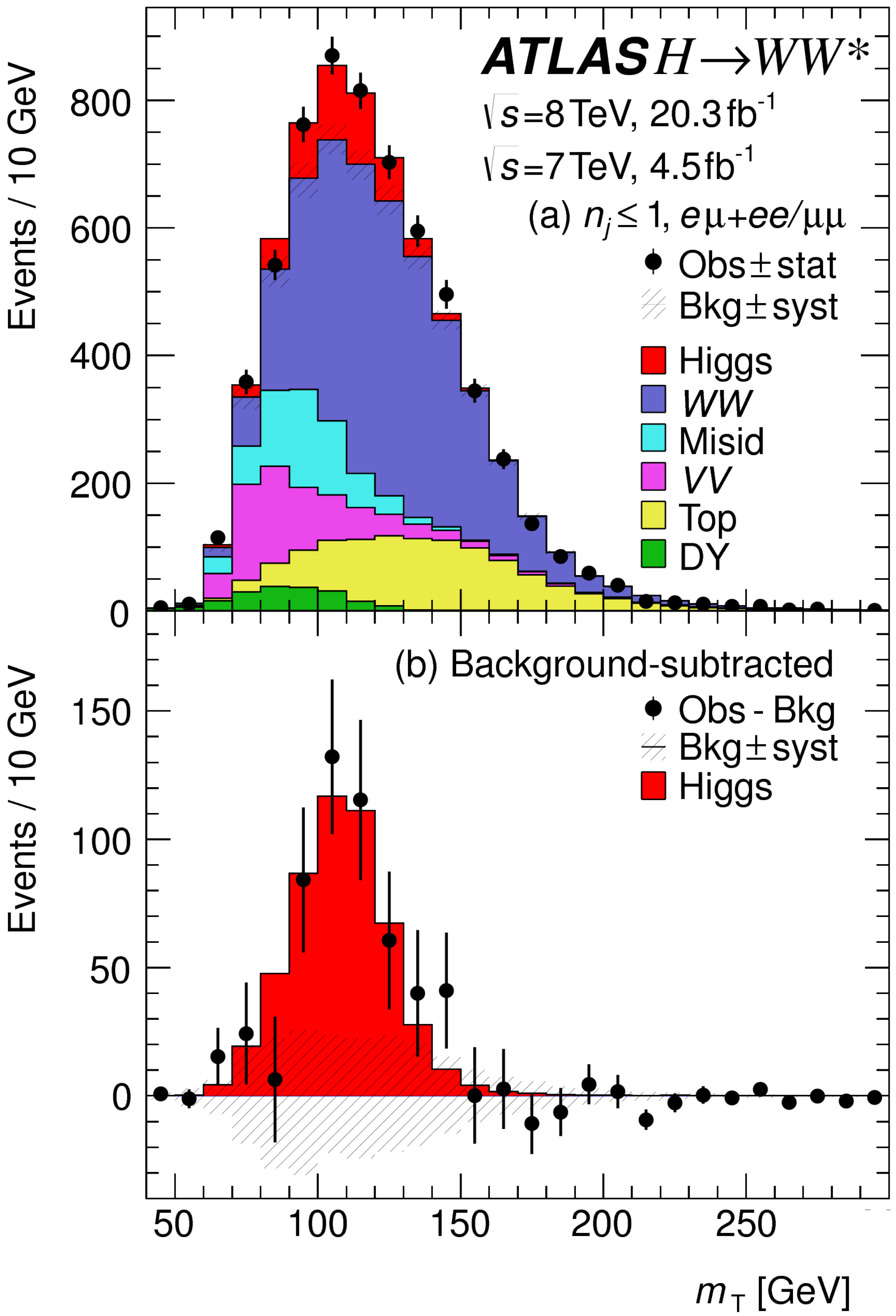
- Measure as much (production channel)*(decay mode) as possible
  - Some ratio measurements also allow one to reduce systematic uncertainties
- Assume only one boson with M ~125 GeV and spin 0
- Same Lagrangian structure as in the Standard Model
- Define multiplicative coupling modifiers κ
  - κ=1 for the Standard Model
  - Investigate different assumptions for the κ's: one per particle, or a smaller set of κ, and also different assumptions on particles running in loops
  - Not yet sensitive to Higgs coupling to itself (HH pair production)
- Can also allow "exotic" Higgs boson decays
  - Complementary of direct searches H→(invisible particles) (Dark Matter particles for instance), where no excess is observed (yet)

Look for signal in each five main decay channels for ~almost all production modes

Refined analysis (multivariate techniques) to maximize sensitivity

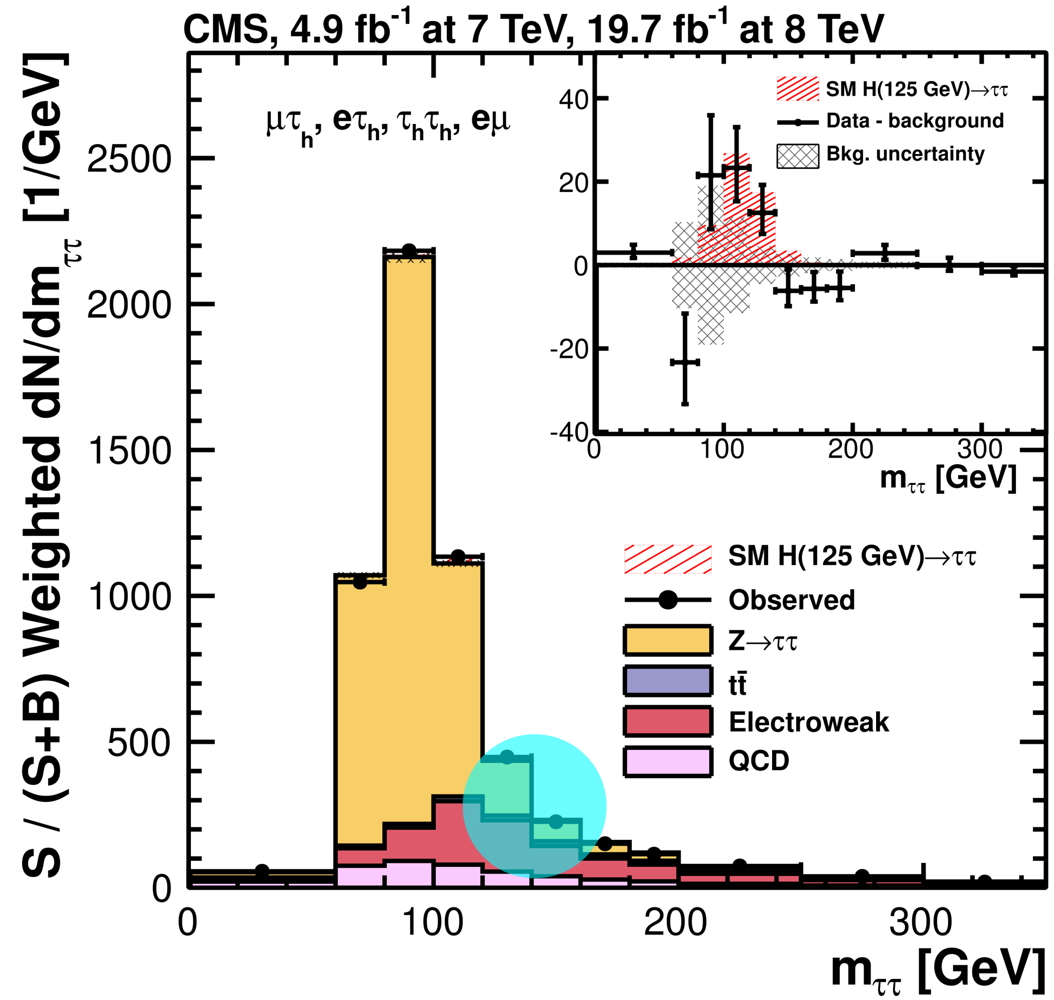
H→WW→llνν

Clearly observed



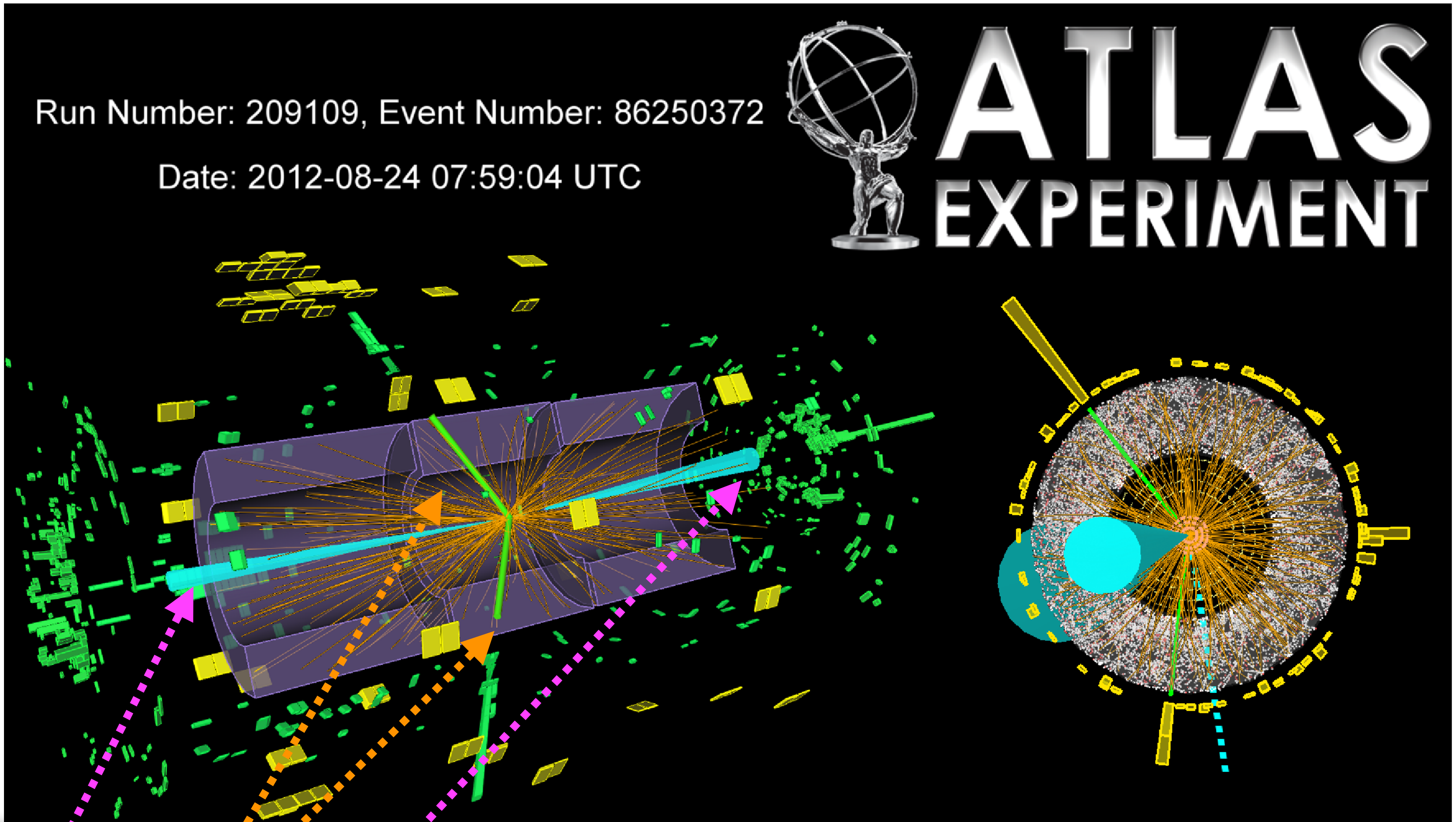
H→ττ

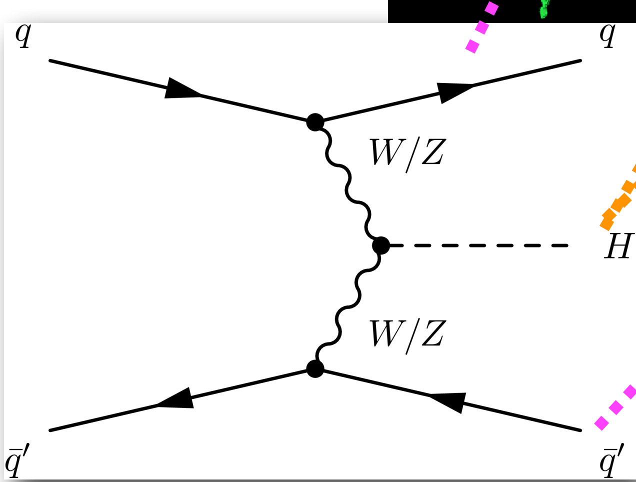
ATLAS+CMS Combination> 5 σ



Signal significance ~2-3 σ pour VH (H→bb)

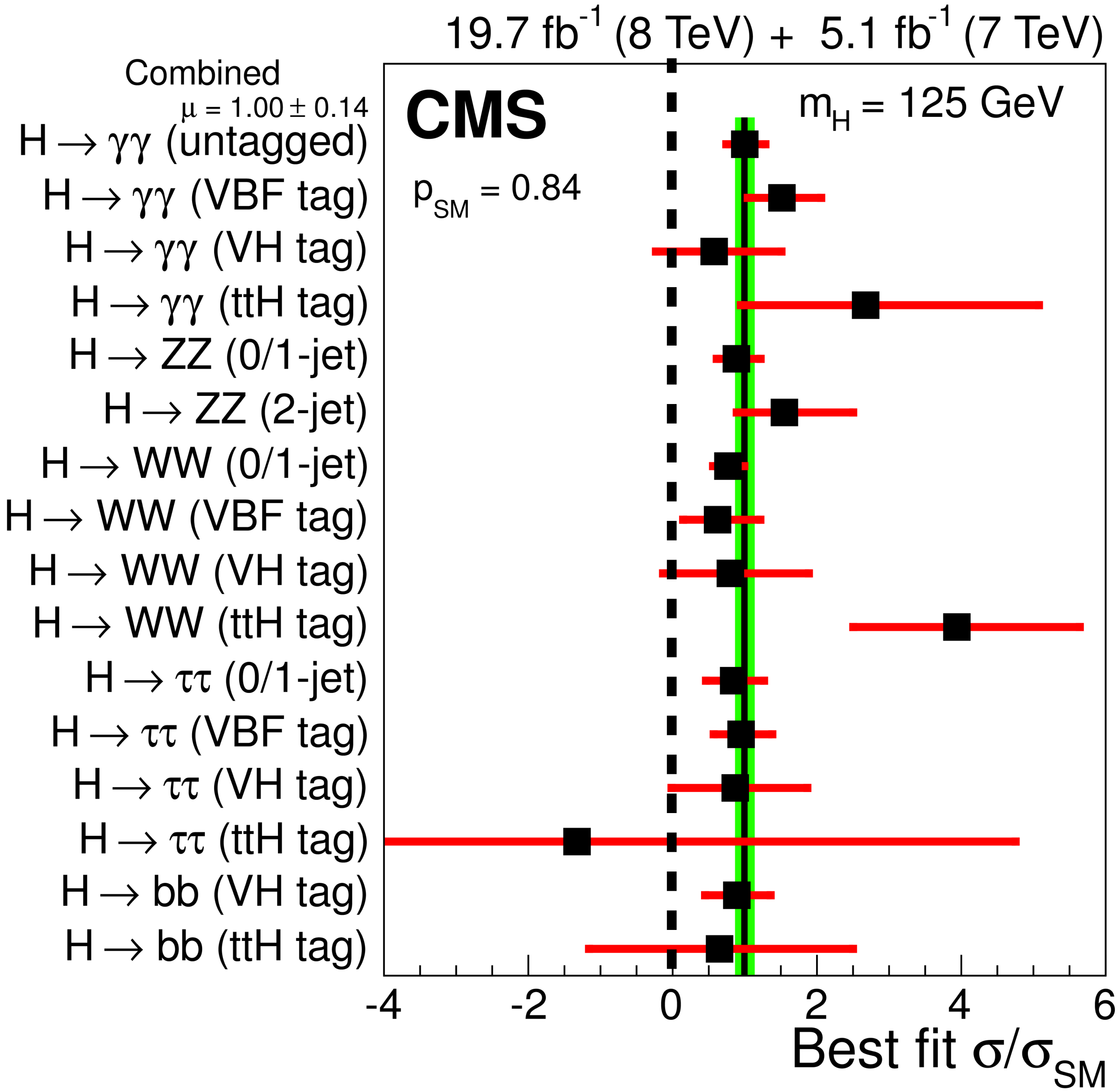
Separation by production mode:
Candidate H(→ττ) produced by vector boson fusion



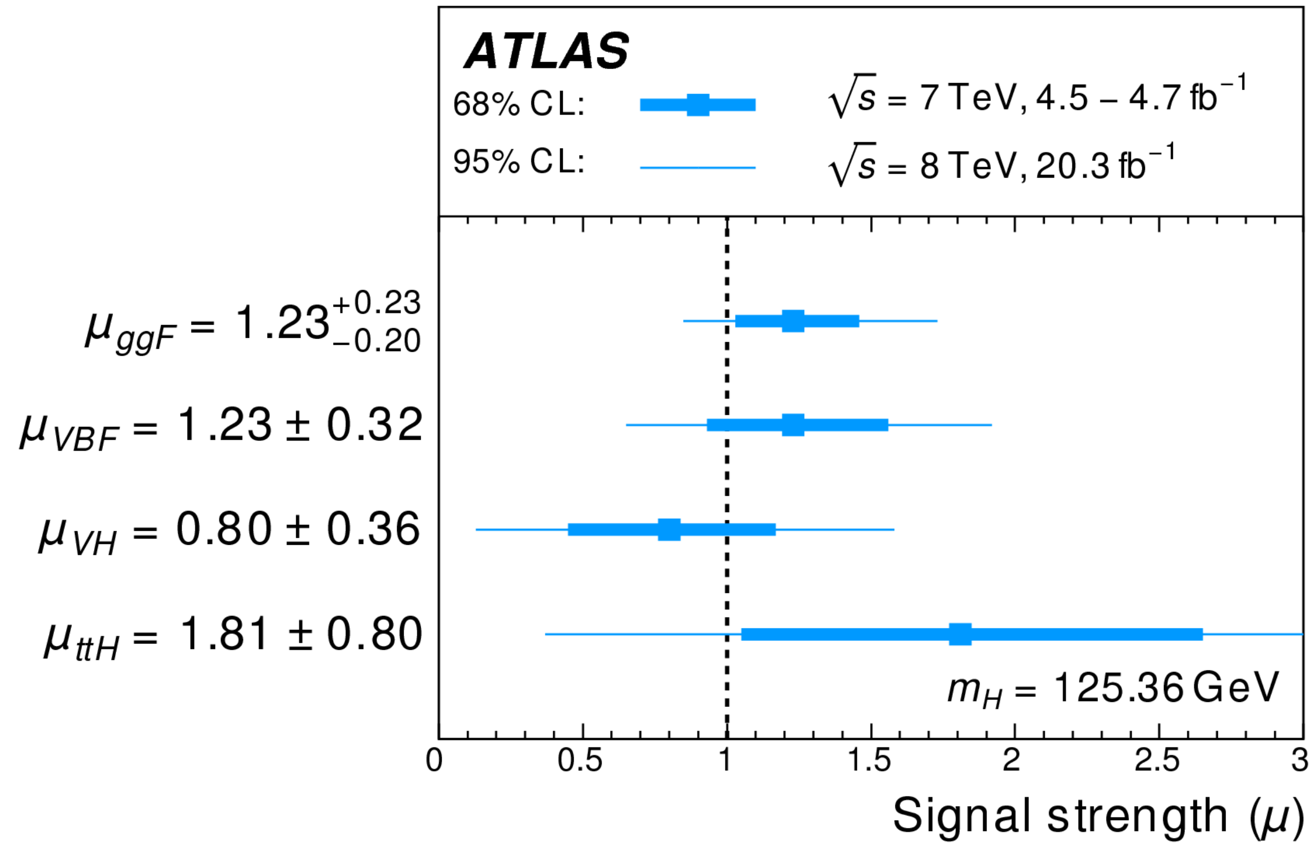


Difficulty: Correctly accounts the cross-contamination between different production modes

Summary of the signal yield in each category compared to Standard Model predictions



Summary of cross-section measurement (assuming Standard Model decay yields)

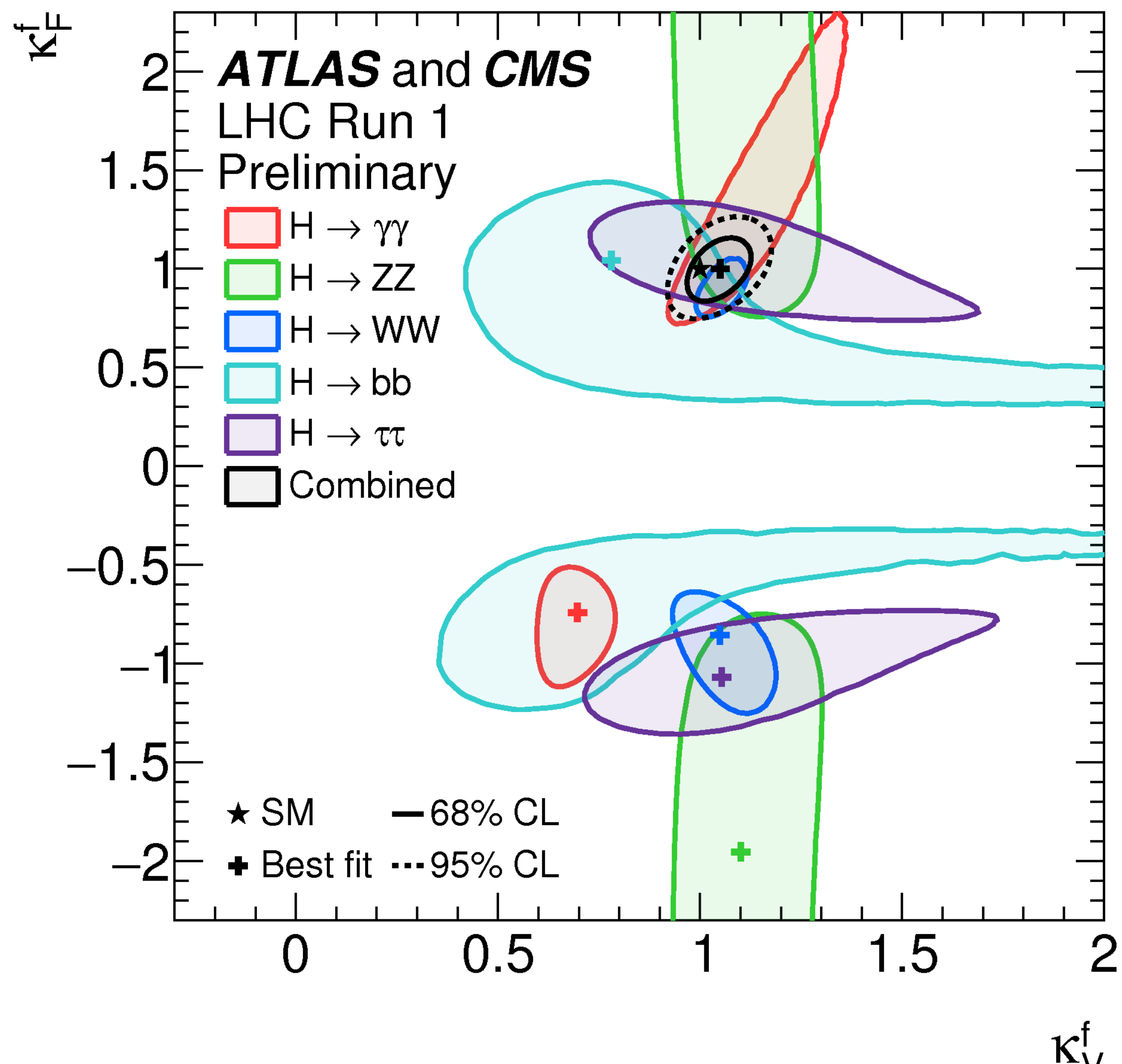


=σ(measured)/σ(predicted)

- Good consistency
- ttH production not yet established, but some hint of an excess
- To look closely with the run 2 data
- Uncertainty are mainly limited by data statistical uncertainties

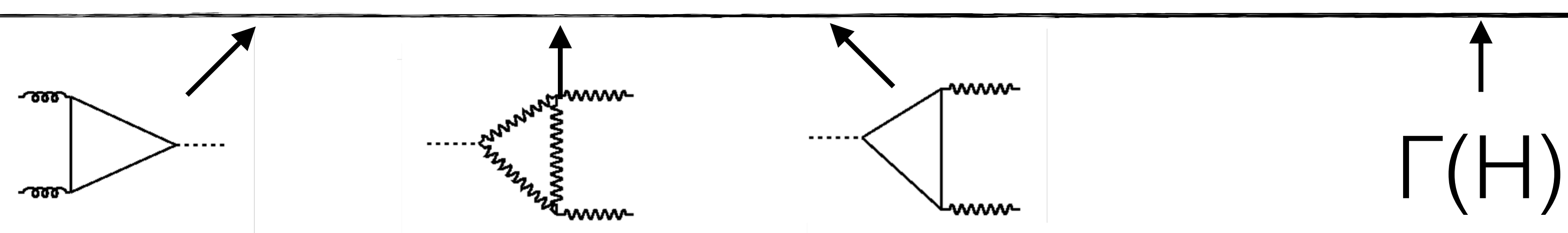
Fit with two coupling modifiers
κ_F for all fermions
κ_V for all bosons

(No new decay mode nor new particles in loop)



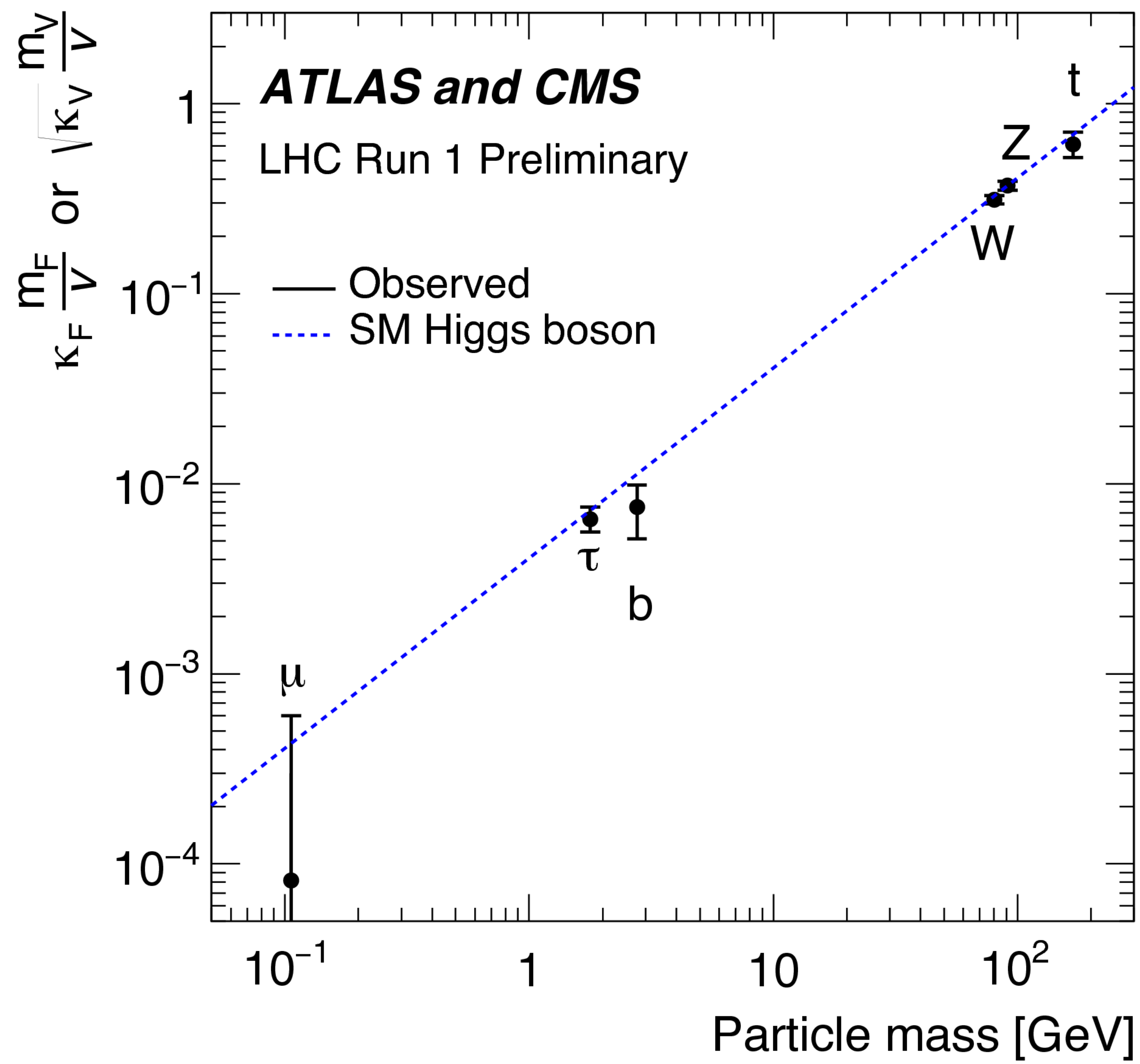
Example:

yield (gg→H→γγ) ~ κ_F^2 * $(1.6\ \kappa_V^2+0.07\ \kappa_F^2-0.66\ \kappa_F\ \kappa_V)\ /\ (0.75^*\ \kappa_F^2+0.25^*\ \kappa_V^2)$



Fit with one coupling modifier per Standard Model particle

(no new decay mode, no new particle in loops)



Typical accuracies on coupling modifiers are O(15-40)%
for more "flexible" models

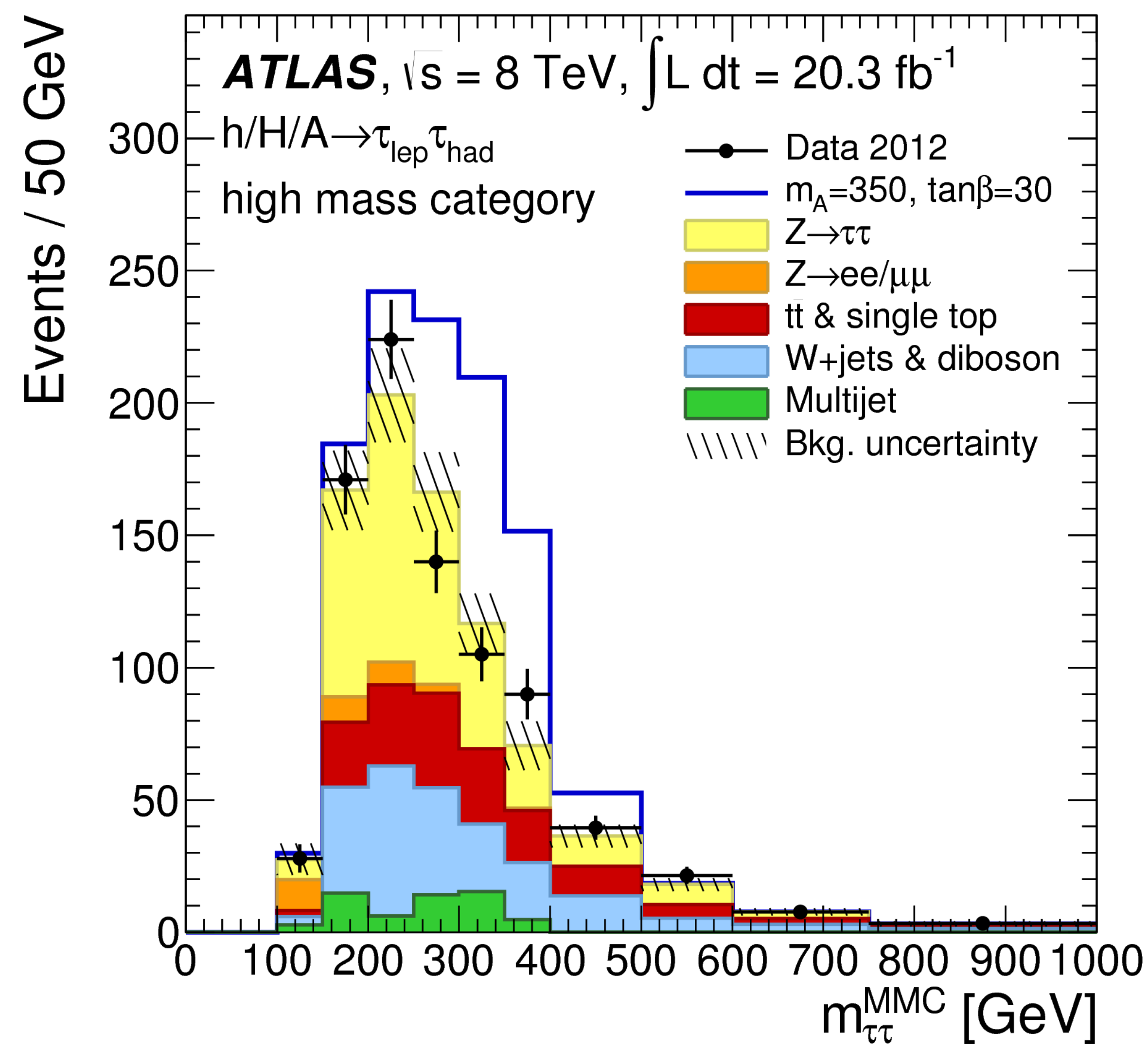
Other Higgs bosons ?

A richer scalar sector is possible

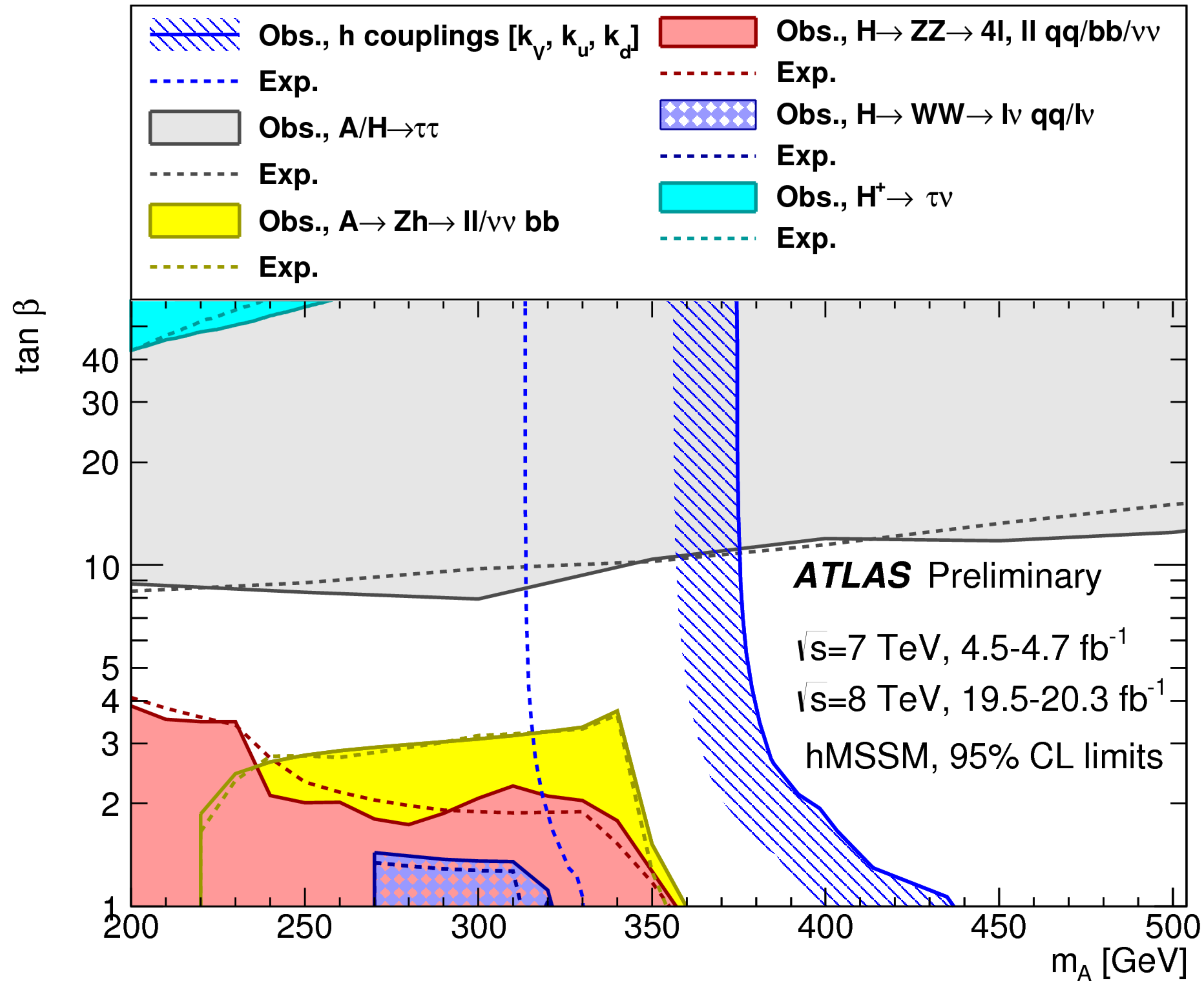
Main example: Supersymmetric theories predict 2 electroweak scalar doublets => 5 spin 0 particles after electroweak symmetry breaking:
h,H,A,H±

h = lightest scalar, could have properties very close to h(MS)

H,A,H± typically heavier
Look for instance for H,A→ττ



Complementarity between direct searches and precision measurements of h(125) properties in the context of some minimal supersymmetric model



Prospects

- Analysis of run 1 (2010-2012) LHC data is ~ final
  - A preliminary combination of ATLAS and CMS results was released few weeks ago
- Futur at the LHC
  - With runs 2 and 3 (until ~ 2022) => O(10) more data at higher collision energy
  - With the HL-LHC program => O(100) more data
    - Significant improvement in accuracy of signal yield measurements (between ~ 1% and 10%)
    - Precise measurement of ttH process
    - Also can observe rare decays (like $H\rightarrow\mu\mu$) and starts to explore HH production
  - Also search for heavier particles in scalar sector and other sectors (-> See H.Okawa's talk for di-boson resonance searches at high mass)
- The 125 GeV Higgs boson can be also accessed at future e^+e^- colliders
  - Would like O(1%) accuracy on coupling measurements to probe many realistic beyond the Standard Model theories

Conclusions

- The discovery of "a" Higgs boson has been the main result of the first LHC run
  - But should not shadow the many other interesting and important physics results
- This discovery confirms the Standard Model mechanism for generating masses to elementary particles
  - Several alternative theories are excluded
- But this scalar particle opens many unanswered questions
  - It is the first elementary particle with spin 0
  - Mass stability ?
  - Portal toward physics beyond the Standard Model ?
  - Links with other scalar fields and cosmology ?
  - Precision measurement of the properties open a new field of exploration complementary to direct searches at higher masses
  - With run 1 LHC data, Higgs boson coupling have been probed with ~ 15-40 % accuracy
  - A much better accuracy will be achieved in the future, this is only the beginning of Higgs boson measurements

Few references

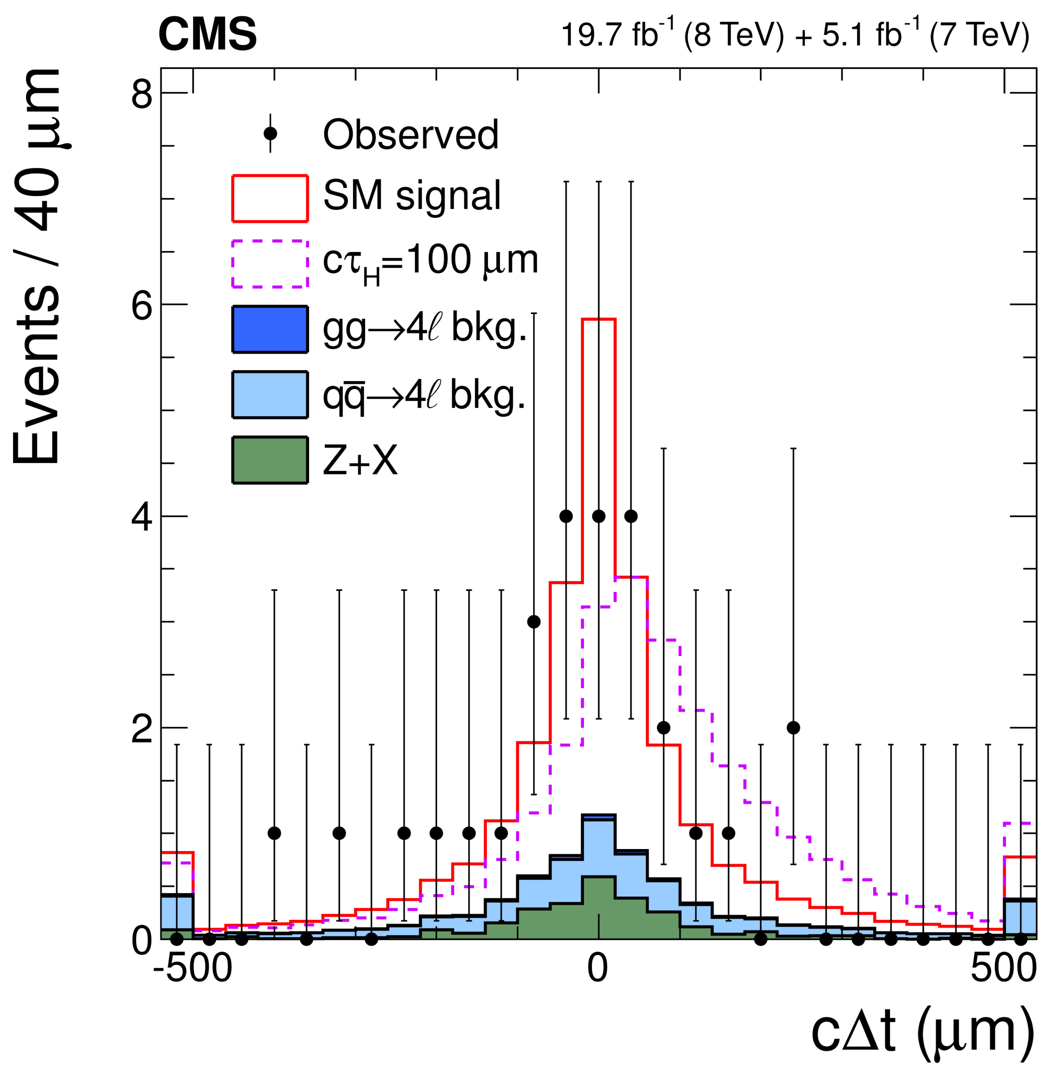
- Résultats ATLAS et CMS
  - http://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
  - http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG/index.html
- Mécanisme BEH
  - F. Englert and R. Brout, Broken symmetry and the mass of gauge vector mesons, Phys. Rev. Lett. 13 (1964) 321.
  - P. W. Higgs, Broken symmetries, massless particles and gauge fields, Phys. Lett. 12 (1964) 132.
  - P. W. Higgs, Broken symmetries and the masses of gauge bosons, Phys. Rev. Lett. 13 (1964) 508.
  - G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Global conservation laws and massless particles,Phys. Rev. Lett. 13 (1964) 585.
- Modèle Standard
  - S. L. Glashow, Partial-symmetries of weak interactions, Nucl. Phys. 22 no. 4, (1961) 579.
  - S. Weinberg, A Model of Leptons, Phys. Rev. Lett. 19 (1967) 1264.
  - A. Salam, “Weak and electromagnetic interactions”, in Elementary particle theory: relativistic groups and analyticity, N. Svartholm, ed., p. 367. Almqvist & Wiksell, 1968. Proceedings of the eighth Nobel symposium.
  - G. ’t Hooft and M. Veltman, Regularization and Renormalization of Gauge Fields, Nucl. Phys. B44 (1972) 189.
- Test de précision du Modèle Standard
  - M. Baak, J. Cuth, J. Haller, A. Hoecker, R. Kogler, K. Mönig, M. Schott, J. Stelzer Eur. Phys. J. C **74**, 3046 (2014)
- Metastabilité
  - Degrassi, Di Vita, Elias-Miro', Espinosa, Giudice, G.I., Strumia arXiv 1205.6497
  - V. Branchina, E. Messina, M. Sher, Phys.Rev.D91 (2015) 1, 013003
- Production off-shell
  - N. Kauer and G. Passarino, Inadequacy of zero-width approximation for a light Higgs boson signal, JHEP 08 (2012) 116, arXiv:1206.4803.
  - F. Caola and K. Melnikov, Constraining the Higgs boson width with ZZ production at the LHC, Phys. Rev. D 88 (2013) 054024, arXiv:1307.4935
  - J. M. Campbell, R. K. Ellis, and C. Williams, Bounding the Higgs width at the LHC using full analytic results for $gg \rightarrow e^-e^+\mu^-\mu^+$, JHEP 04 (2014) 060, arXiv: 1311.3589
  - J. M. Campbell, R. K. Ellis, and C. Williams, Bounding the Higgs width at the LHC: complementary results from $H \rightarrow WW$, Phys. Rev. D 89 (2014) 053011, arXiv:1312.1628.
- Calcul section efficaces et BR du Higgs
  - S. Dittmaier et al., Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables (2011), arXiv:1101.0593 [hep-ph].
  - S. Dittmaier et al., Handbook of LHC Higgs Cross Sections: 2. Differential Distributions (2012), arXiv:1201.3084 [hep-ph].
  - S. Heinemeyer et al., Handbook of LHC Higgs Cross Sections: 3. Higgs Properties (2013), arXiv:1307.1347 [hep-ph].
  - + references dans ces articles
  - C. Anastasiou, C. Duhr, F. Dulat, F. Herzog and B.Mistlberger, arXiv:1503.06056 (cacul N3LO)

Lifetime / Decay width

Γ(MS) ~4 MeV (lifetime ~ 1.6 10^{-7} fs, $c\tau$ ~50 fm)

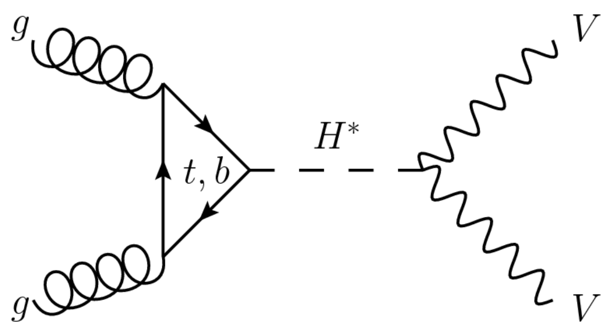
Direct measurement of width through width of M_H(measured)
=> Limit O(GeV) (experimental resolution on M)

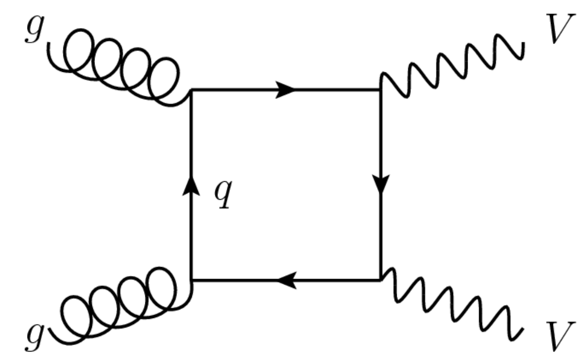
Can exclude very long lifetime by checking that Higgs boson decays at the position where it is produced
=> lifetime $c\tau < 57$ µm
i.e $\Gamma > 3.6\ 10^{-9}$ MeV



"Off-shell" events

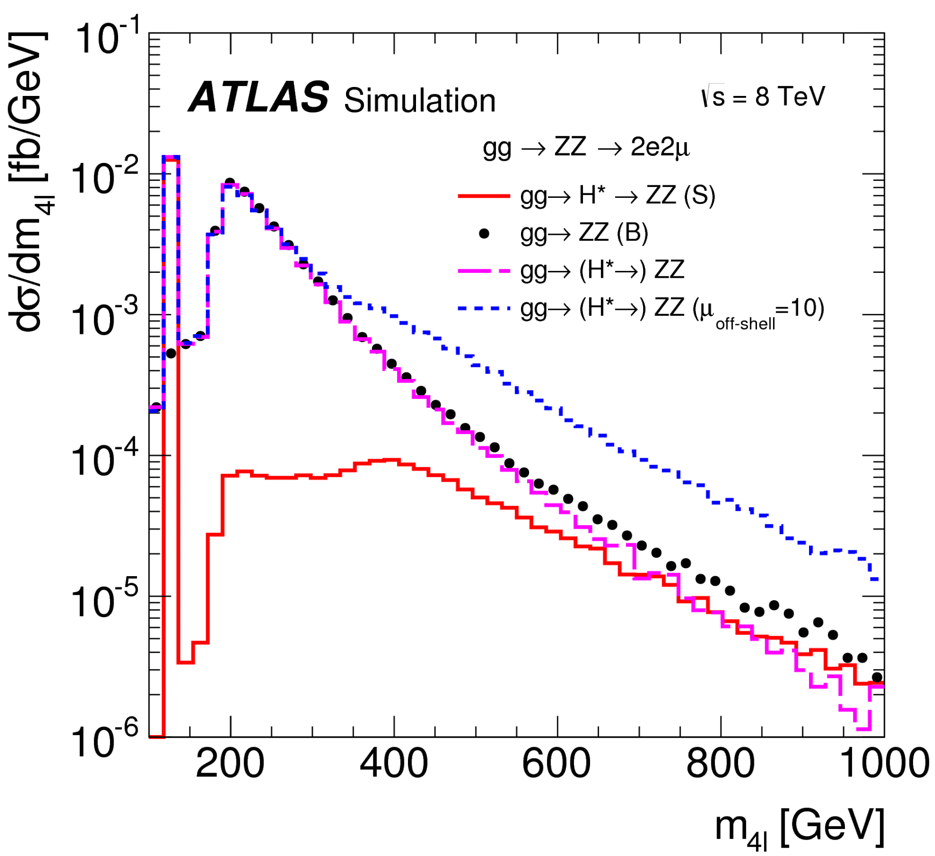
A new idea to constrain the width (with some caveat)

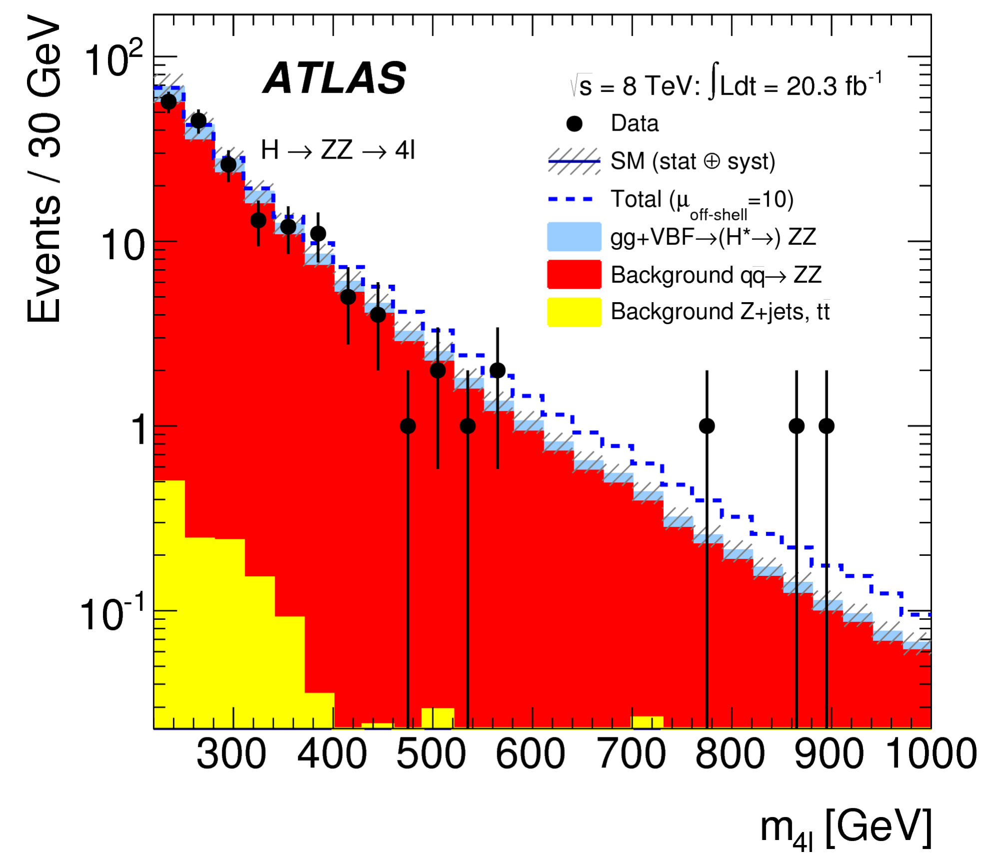




Interférence with "backgroun

$q \sim M_H$ $\sigma \sim 1/\Gamma_H$ *(couplings)
$q >> M_H$ $\sigma \sim$(couplings)

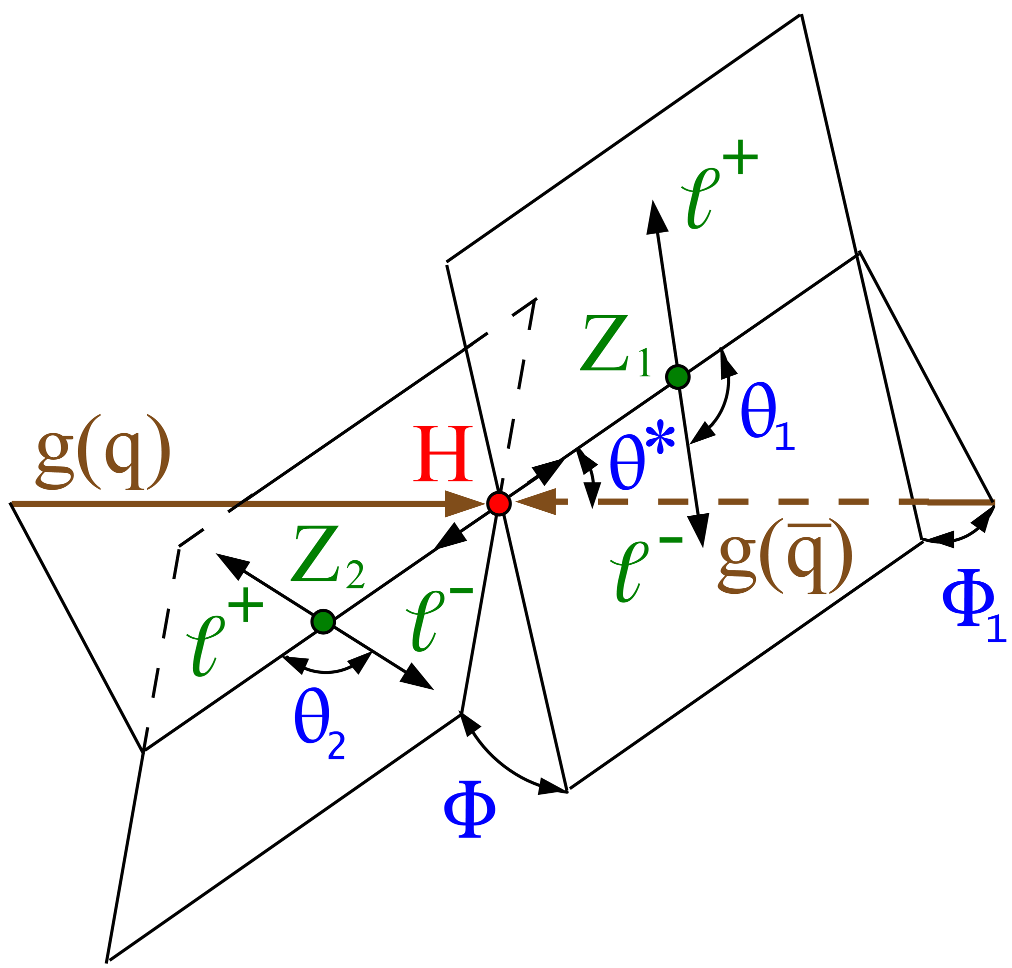


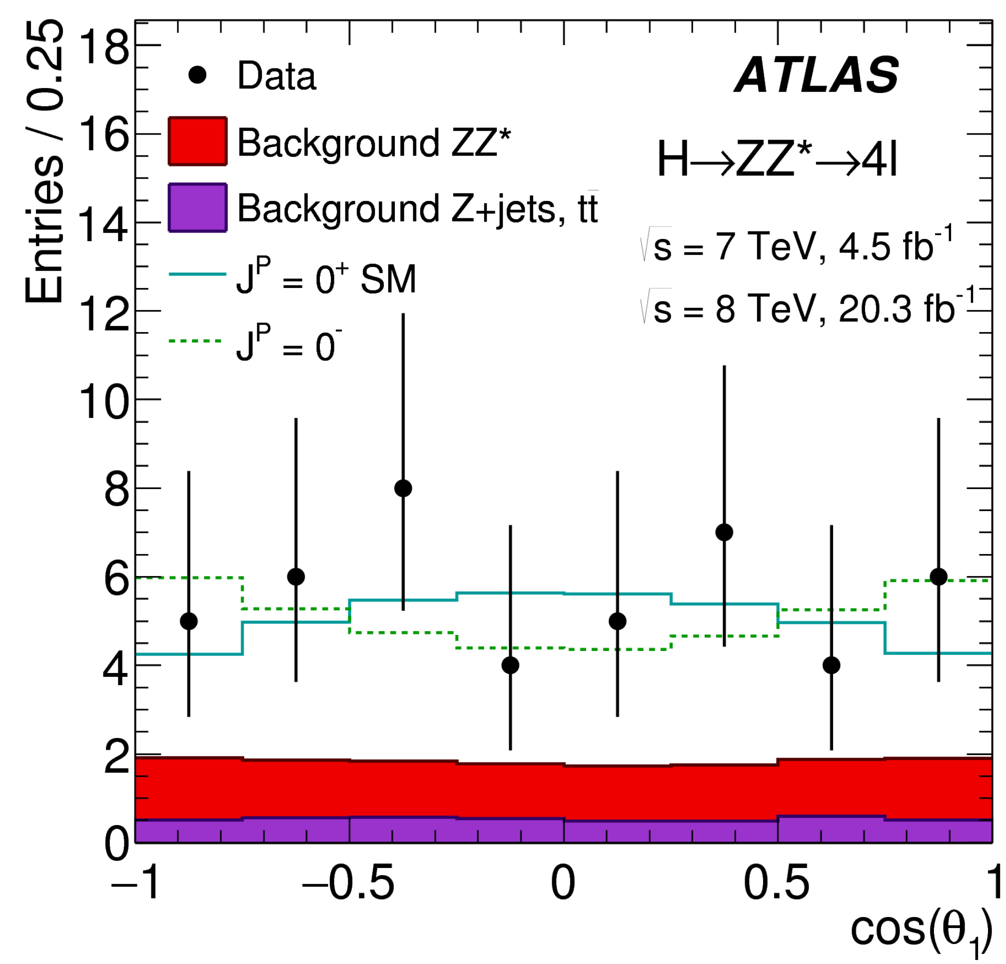


=> Γ/Γ(MS) < ~ (5-7)

Spin /CP

H→ZZ* is the ideal decay channel to measure these properties

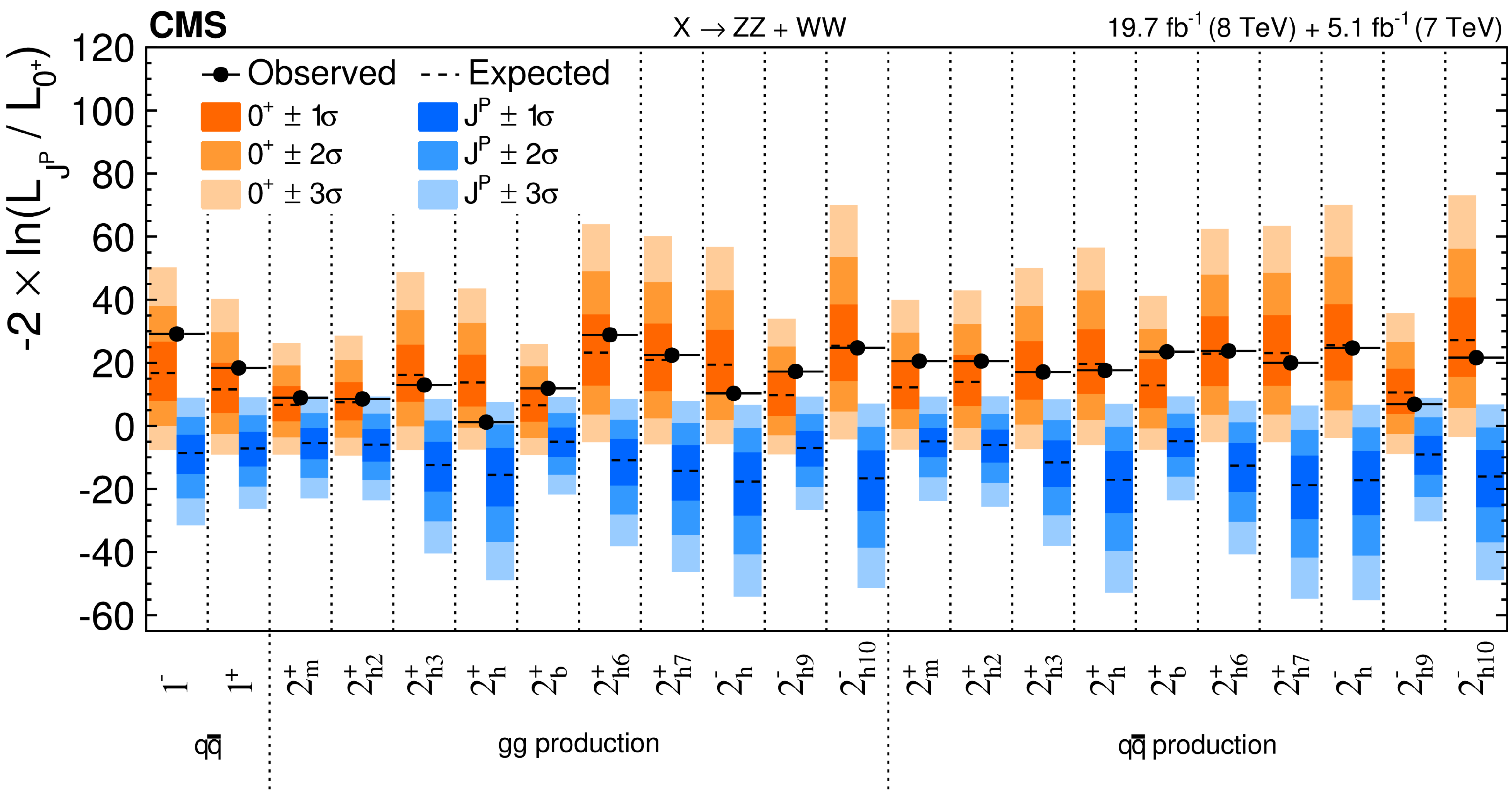




5 angular variables + 2 kinematic ones
=> combine all the informations for best sensitivity

Results for spin/CP

The O+ hypothesis is always favored compared to alternative hypothesis



Calibration of e and muon energy measurement:

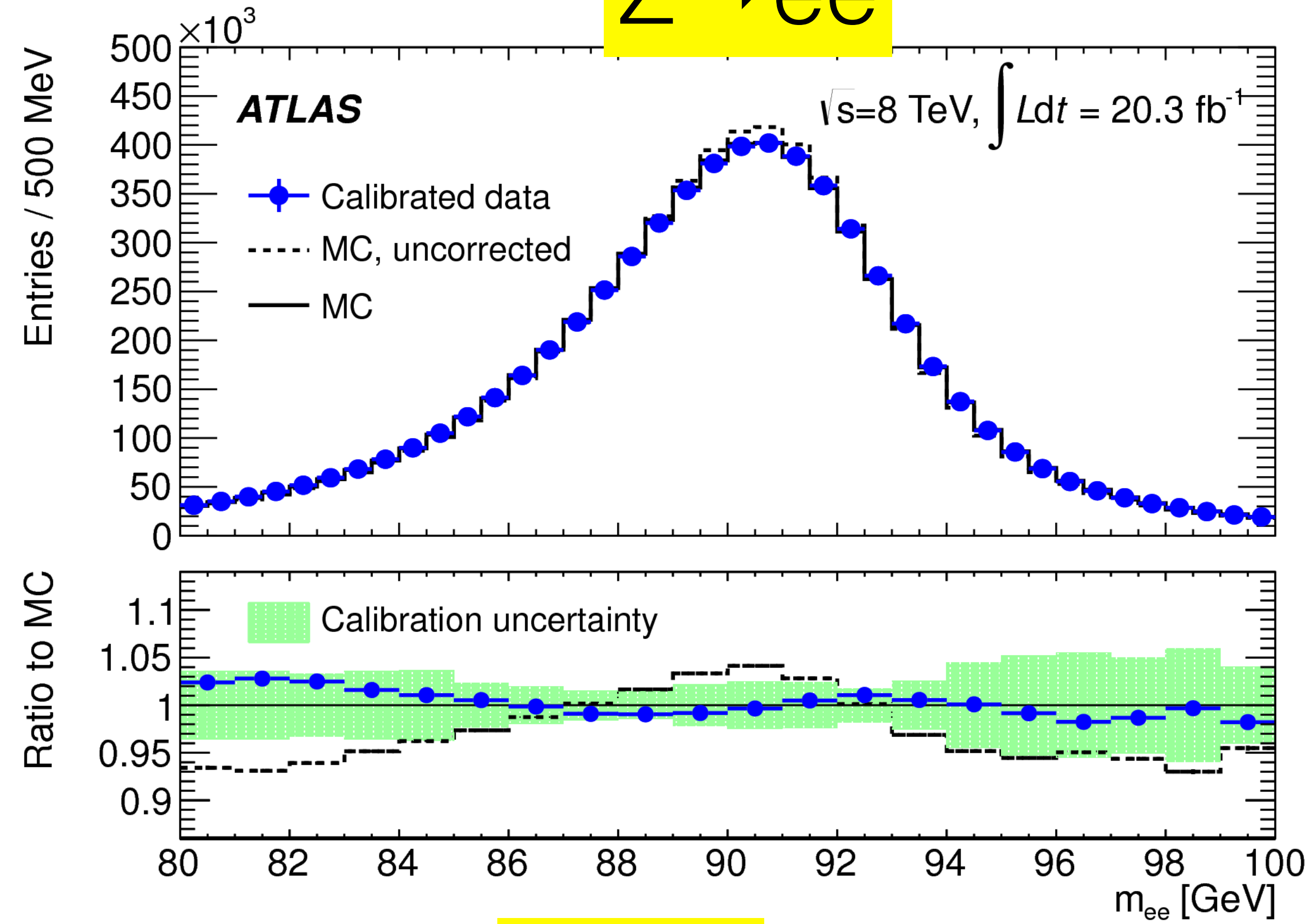
Use Z→ee ou μμ

M(Z) known to ~2.10^{-5} thanks to LEP (former e+e- collider at CERN)

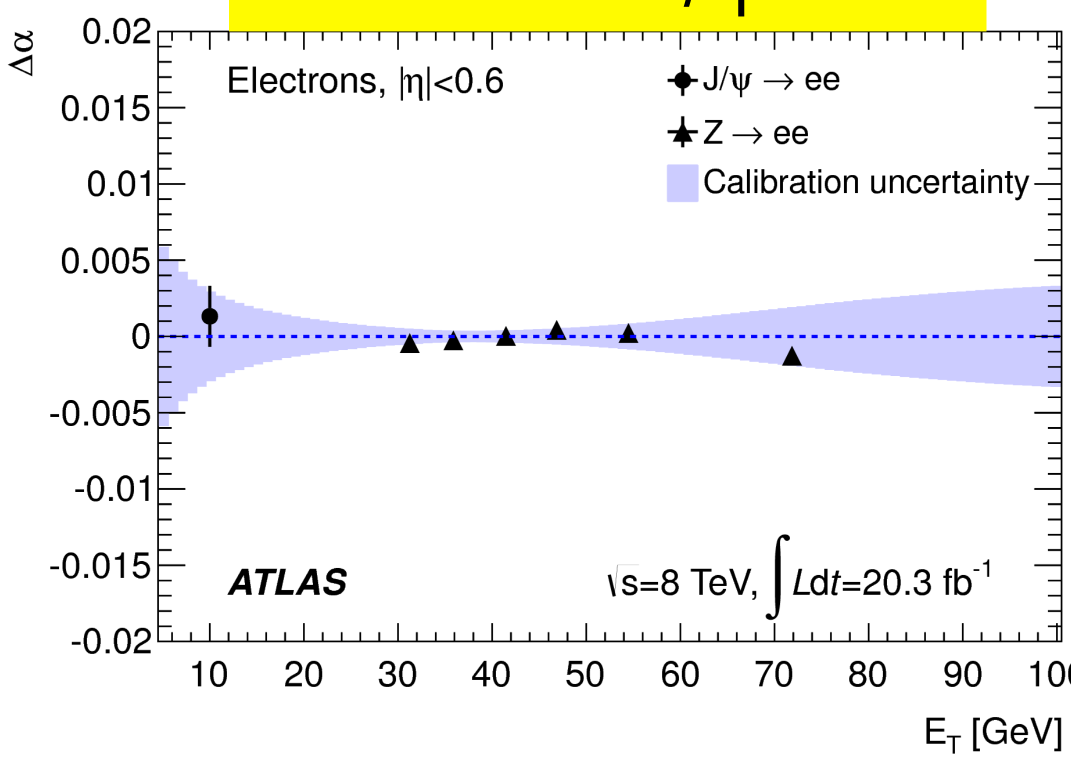
Candle to adjust energy scale

Then check stability and extrapolation e→γ

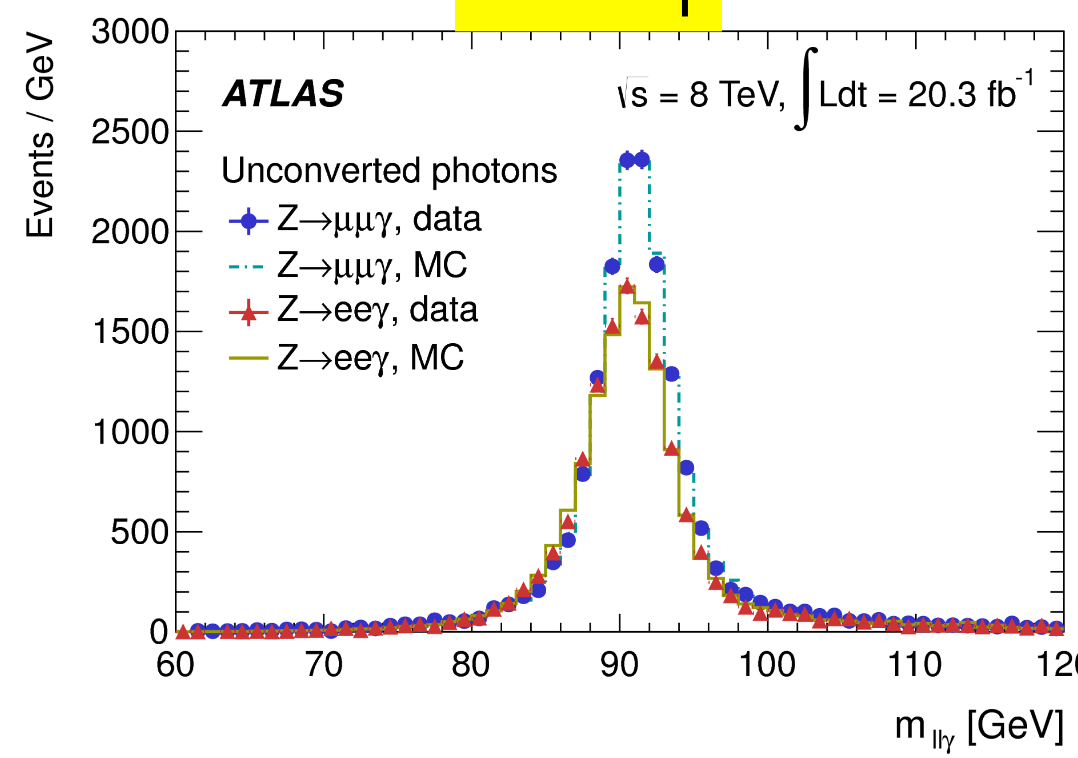
Z→ee



Z→ee et J/ψ→ee

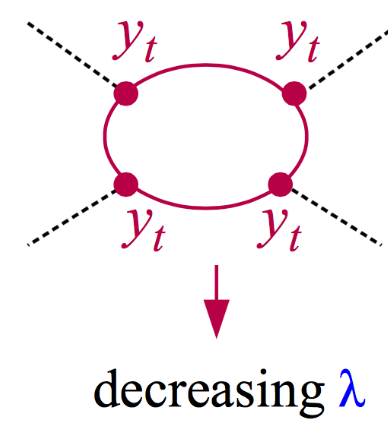


Z→llγ



Another implication of the mass measurement

$V(\phi) \sim \lambda(\phi)\, \phi^4$



In the SM, the Higgs potential has radiative corrections depending on M_{top}
=> The potential can be unstable at high values of the field
=> Vacuum instability or "metastability) (If the tunneling time is > the age of the universe))
The M_H value is close to this limit. Is it an accident ? $\lambda(M_{Planck}) \sim 0$?