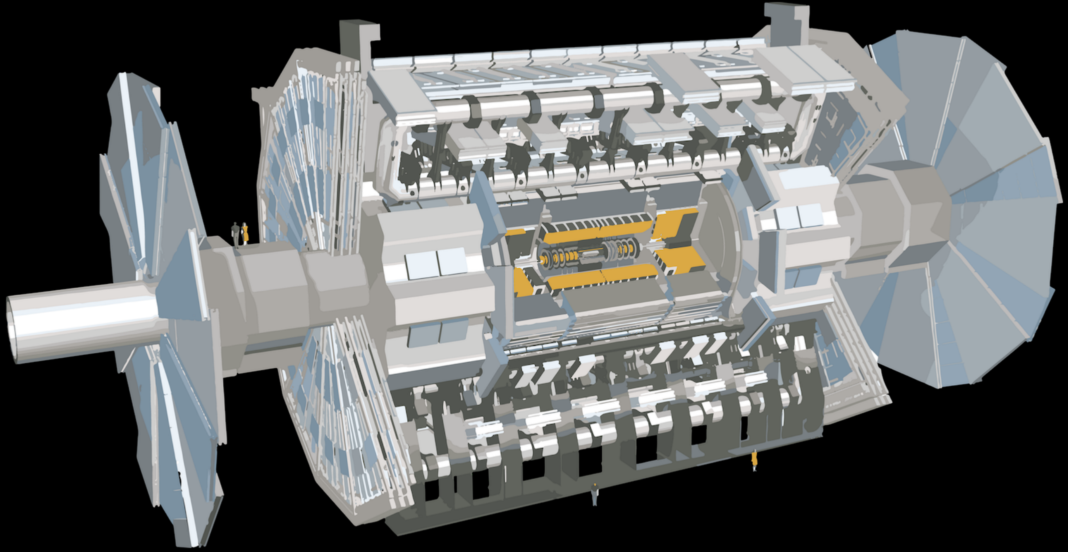
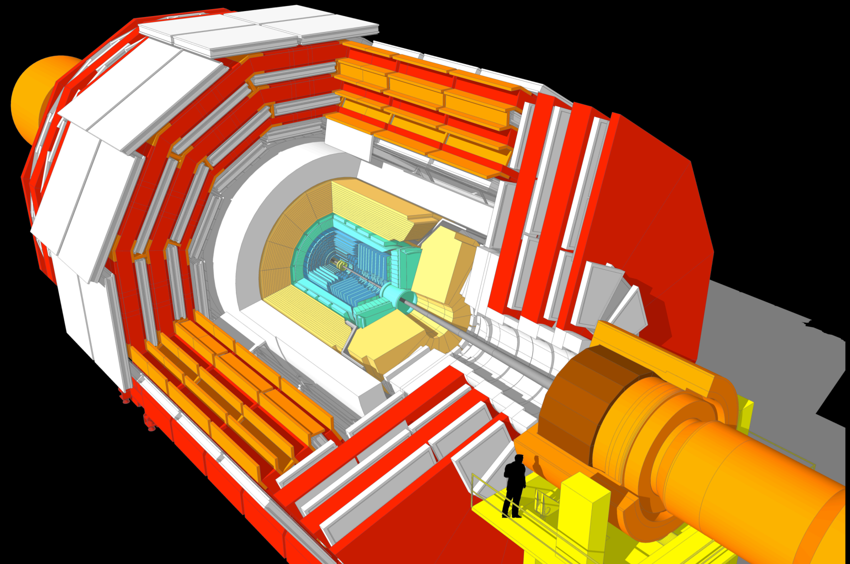




Les mesures de précision au LHC

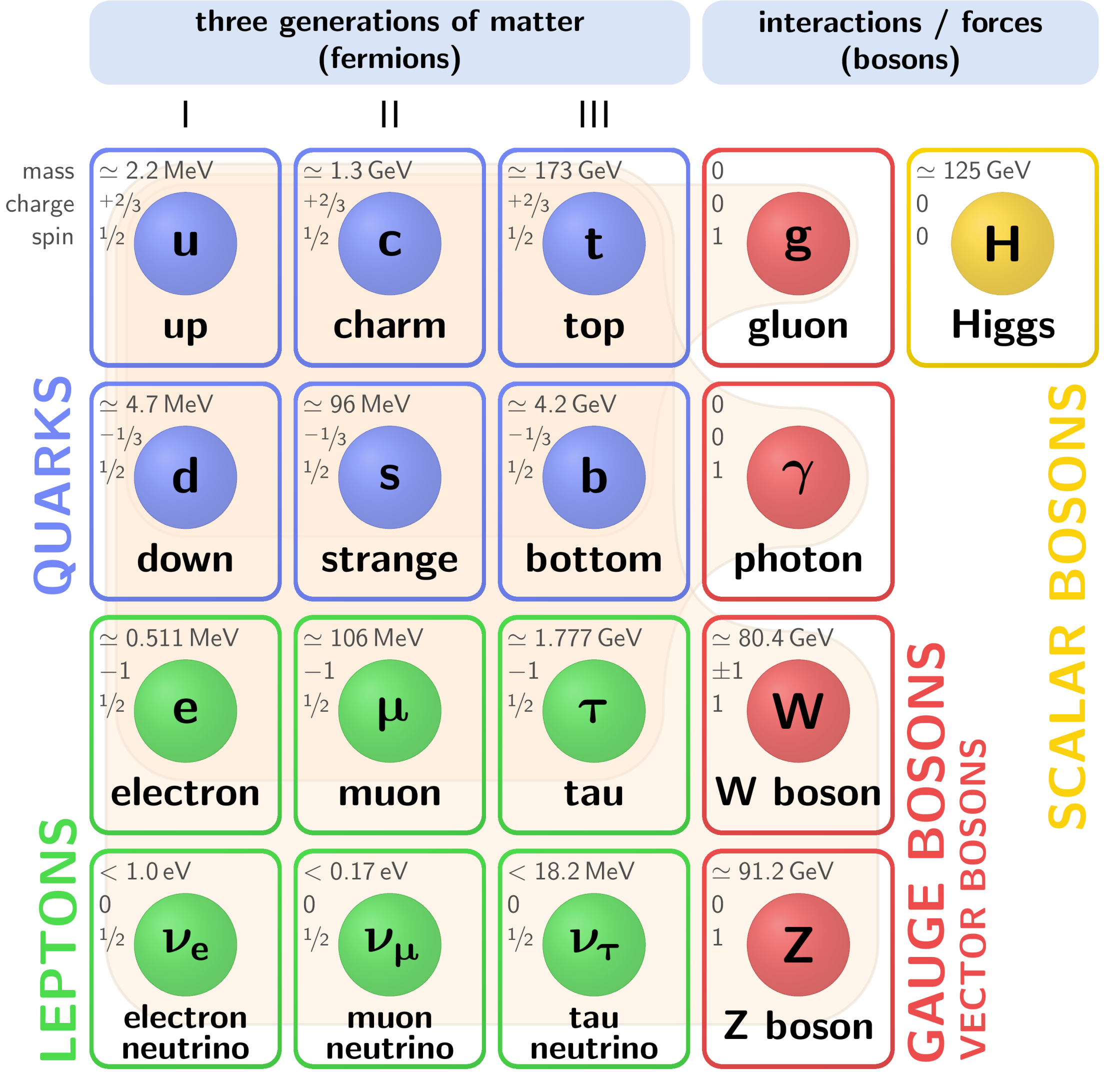
Fabrice Couderc, CEA-Irfu

Journée P2I,Orsay,

27 Novembre 2024

The Standard Model of particle physics

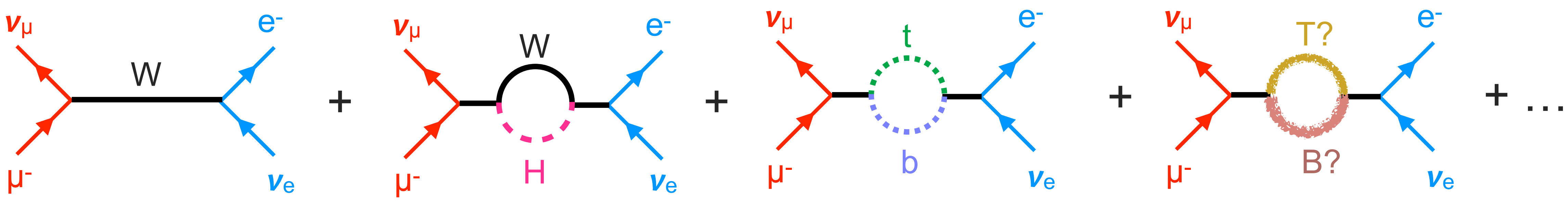
- Govern the world of sub-atomic particles
  - Glashow, Salam, Weinberg 1967
- Special relativity + Quantum Mechanics (field theory)
- 3 vectorial interactions
  - Electromagnetic (EM), Nuclear weak, Nuclear strong (QCD)
  - Carried spin1 particles: gauge bosons
- Mathematical consistency (gauge symmetry)
  - Massless gauge bosons
  - Massless fermions
- Higgs mechanism introduced in 1967 to describe massive weak bosons and massive fermions
- A "limited" number of parameters: 26
  - 12 fermions masses
  - 3 coupling constants
  - 2 CP weak phases + 1 CP strong phase
  - Higgs sector: Higgs boson mass + Higgs auto-coupling
  - 6 CKM/PMNS elements



QFT hide-hide !

In quantum field theory (QFT), predictions via Taylor expansion

- summing processes (Feynman diagrams) from the more important to the less important.

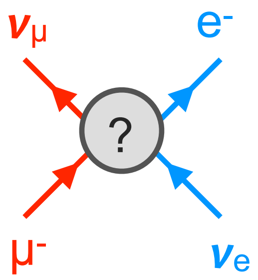


SM LO (main contribution)

SM NLO (corrections)

BSM NLO (corrections) ?

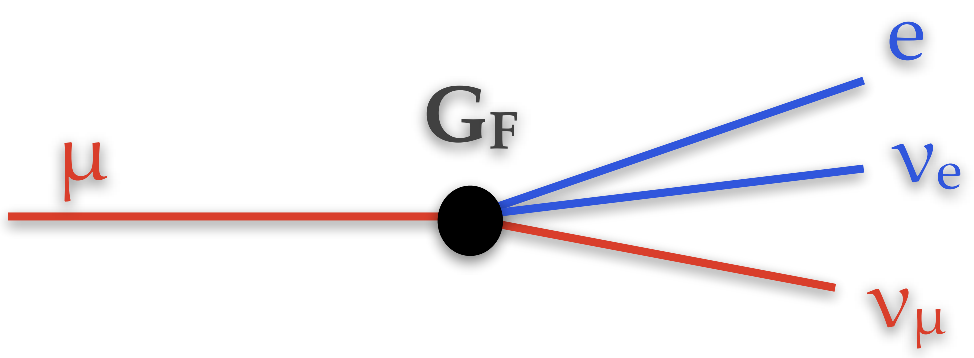
But we measure all at once !

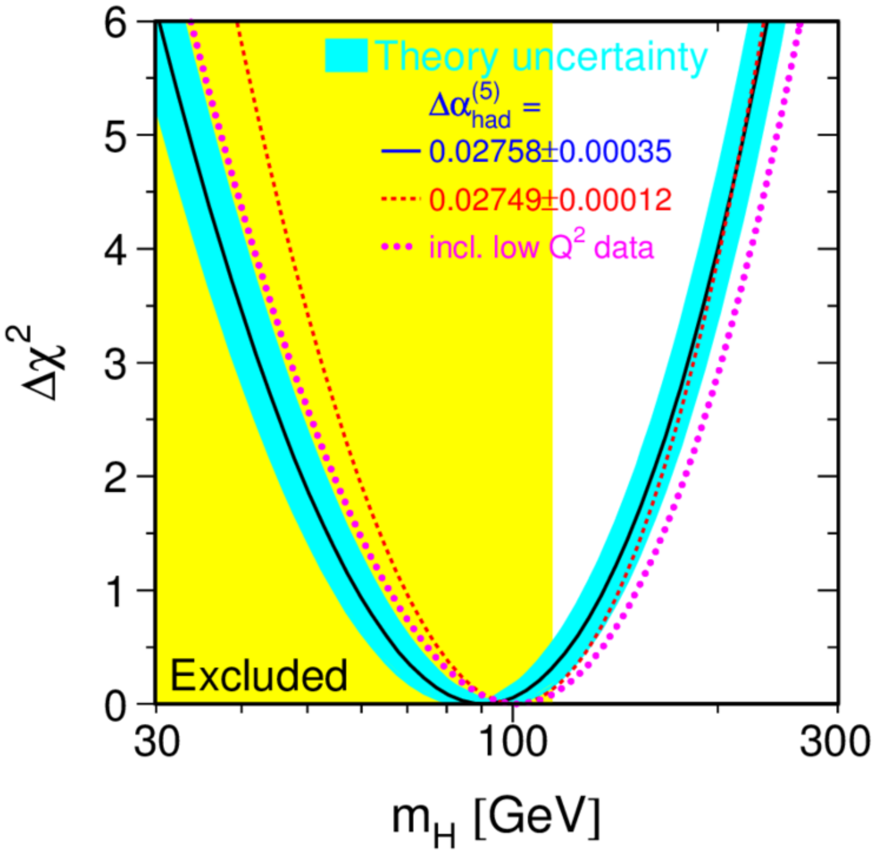


Measuring precisely this process: probe new physics at high energy scale (even if we can not directly produce T? and B?)

Why precision?
A three-particle waltz…

- SM parameters ⇒ physics from low to high energy
- The *masses' Waltz*
  - ✓ Fermi constant from the muon decay (related to W boson interaction) predicted from the SM
  - ✓ Quantum corrections to the Fermi constant link
    - **the W boson mass**
    - **the Higgs boson mass**
    - **the top quark mass**
  - ✓ Precise measurements of the top quark and the W-boson masses constrain the Higgs boson mass !
- The *LHC no-lose theorem* (2001)
  - ✓ SM is correct
    - the Higgs boson exists and $\mathbf{m_H \approx 100 \pm 30}$ **GeV**
  - ✓ SM is incorrect
    - Something else must exists !
  - ✓ LHC is the perfect collider to probe this energy range

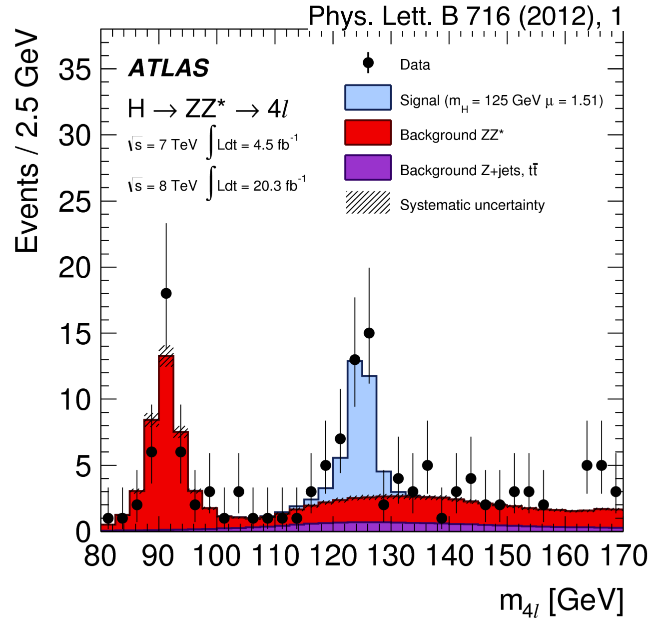


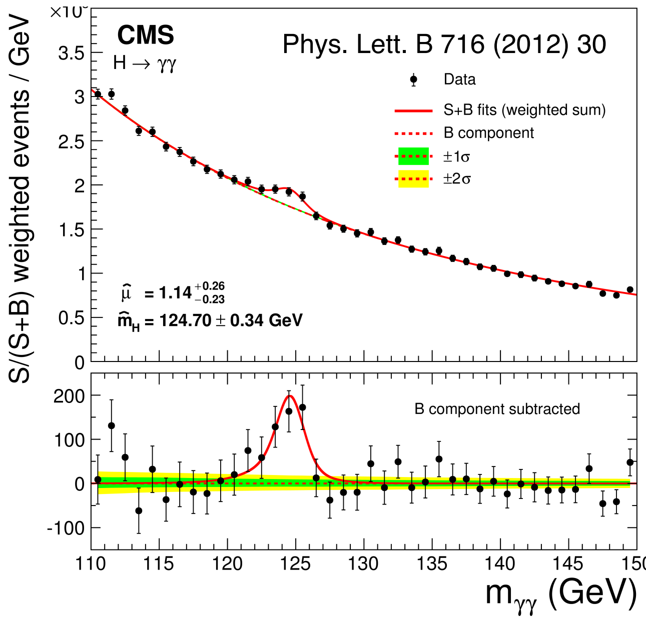


About 10 years later…
A 4th of July 2012

- SM parameters ⇒ physics from low to high energy
- Discovery of the Higgs boson

$$m_H = 125.1 \pm 0.1 \text{ GeV}$$



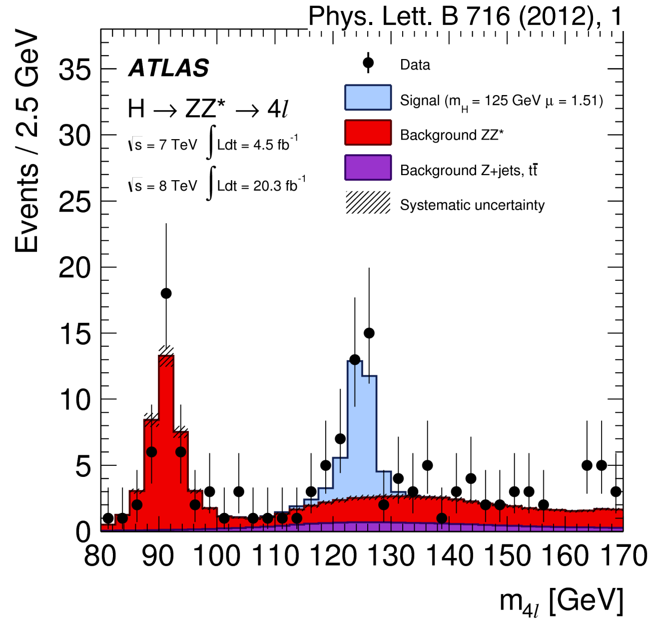


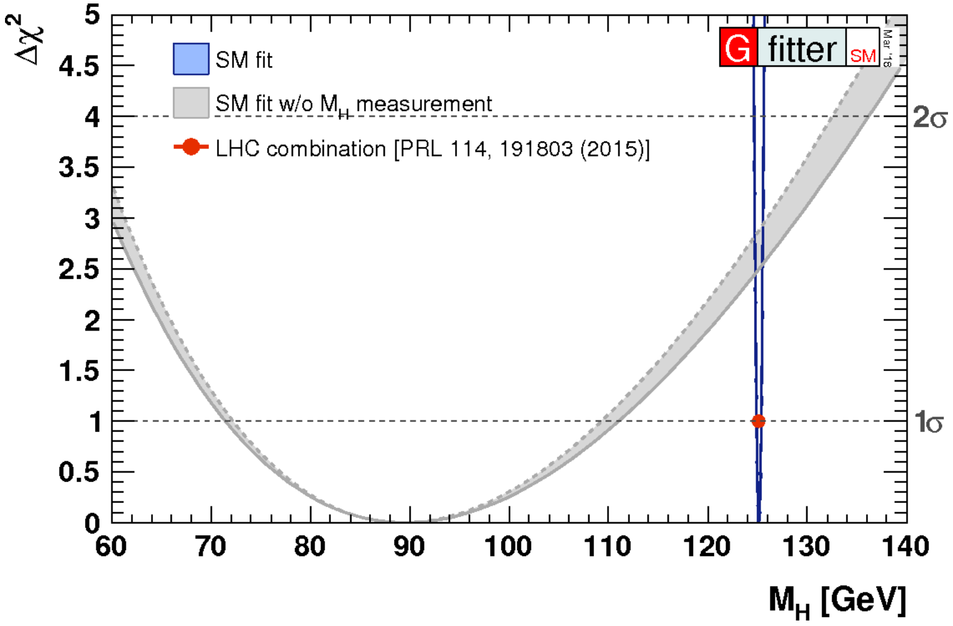
About 10 years later…
A 4th of July 2012

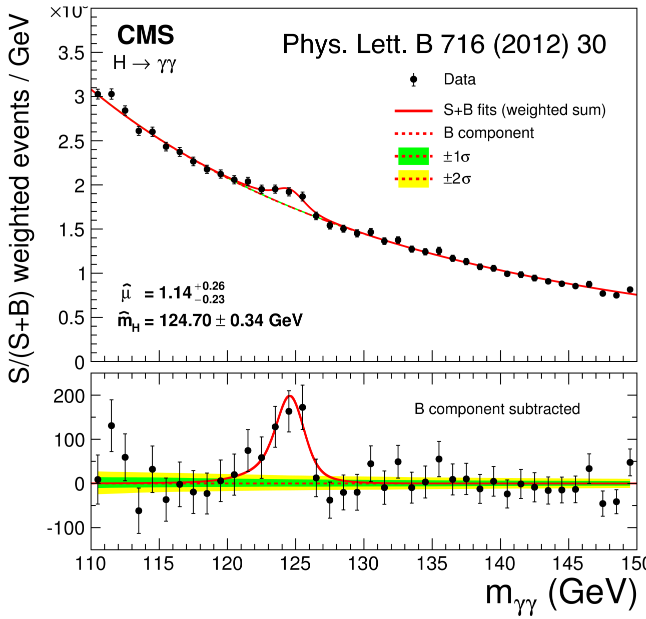
- SM parameters ⇒ physics from low to high energy
- Discovery of the Higgs boson

$$m_H = 125.1 \pm 0.1 \text{ GeV}$$

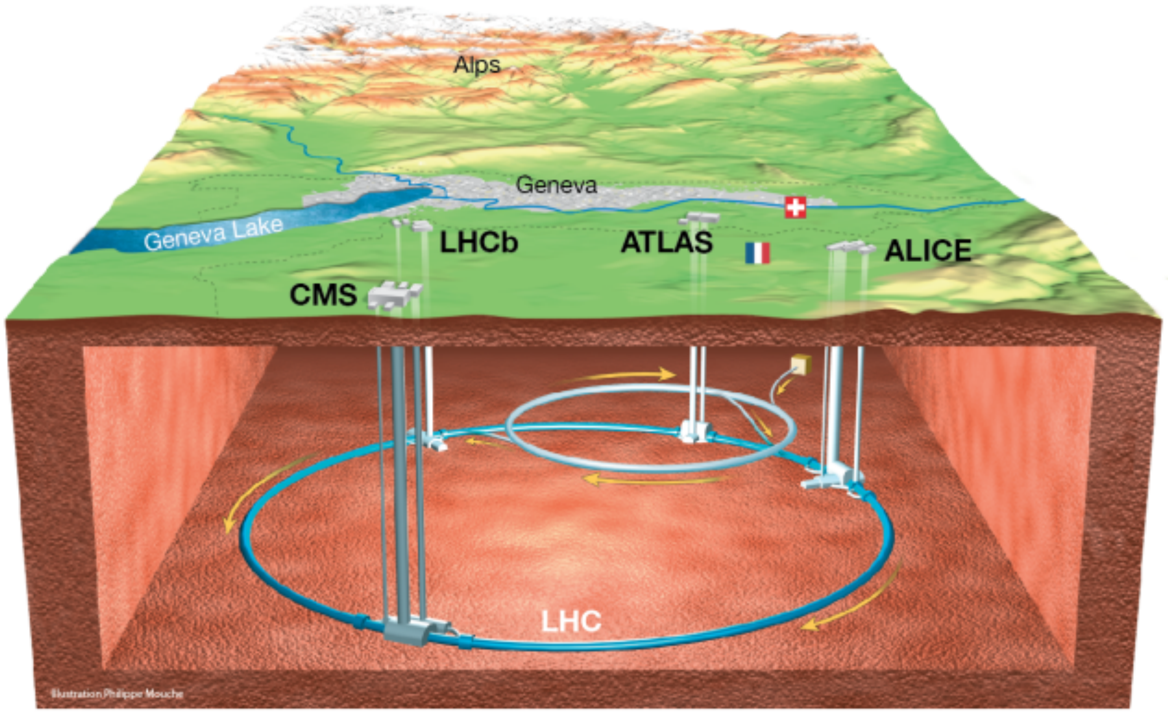
- The game is not over… Will the waltz turn out to be a menuet and a fourth particle included in danse ?







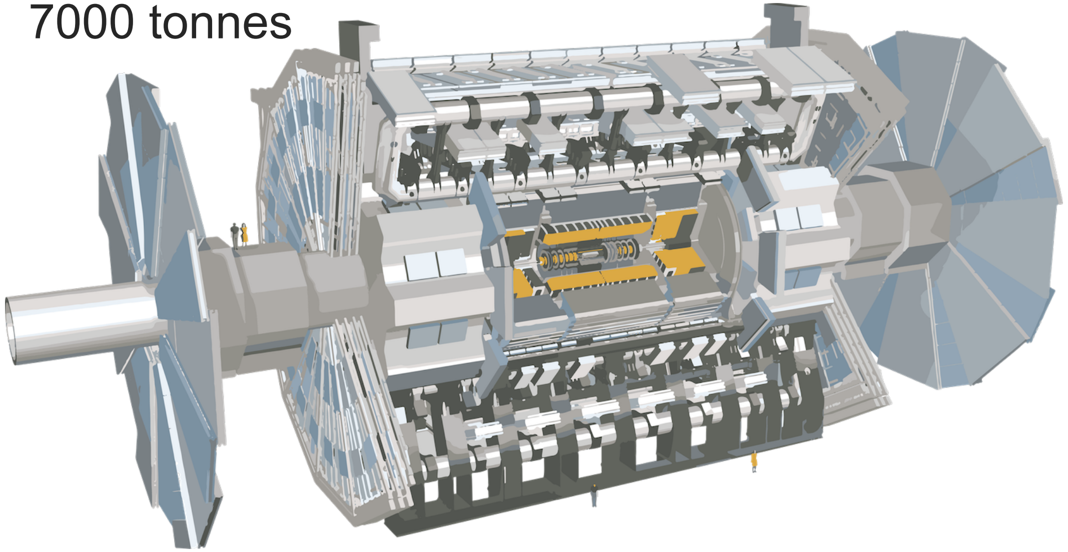
The LHC, Atlas, CMS...



27km long
Energy in the center of mass
- Run1: 7TeV (2011), 8TeV (2012)
- Run2: 13TeV (2015-2018)
- Run3: 13.6TeV (2022-2026)

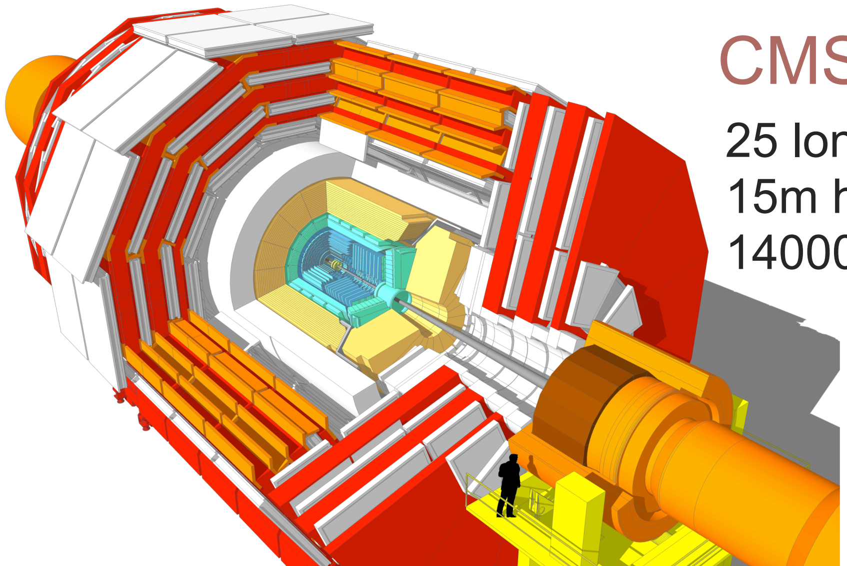
Atlas the gigantic

46m long
25m high and wide
7000 tonnes



CMS the heaviest

25 long
15m high and wide
14000 tonnes



Discovery vs precision machines…
Do we have to choose ?

2 types of colliders: p-p [LHC], e^+-e^- [LEP], (*)

p-p pros

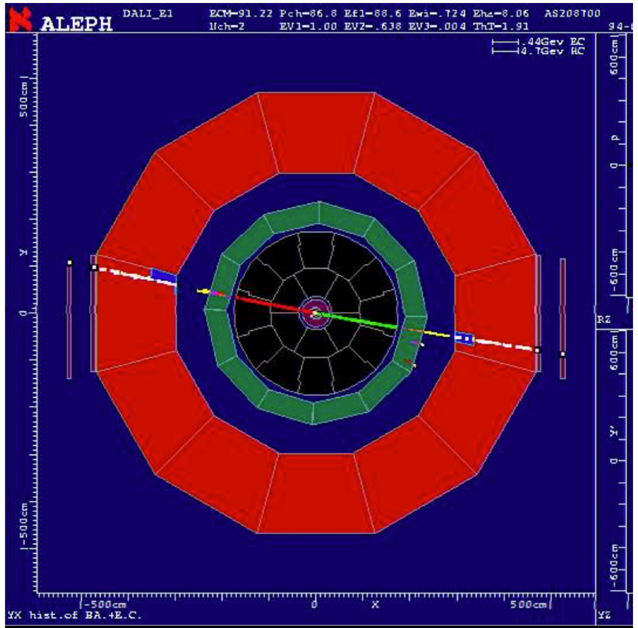
- $m_p >> m_e$: beam energy loss much smaller.
  Reach very high energy

p-p cons (proton are composite particles)

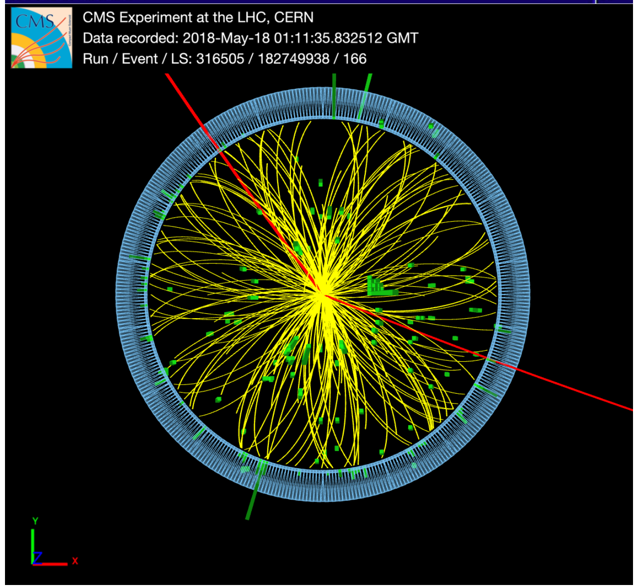
- Initial state kinematic is unknown
- A lot of side collisions (pile-up) blur the event
- Irradiation level affect detector performance
- Initial objects carry a strong interaction charge which limit theoretical predictions accuracy

⇒ pp colliders considered as discovery machines

$Z \rightarrow \mu^+ \mu^-$



LEP (1994)
e^+e^- collider

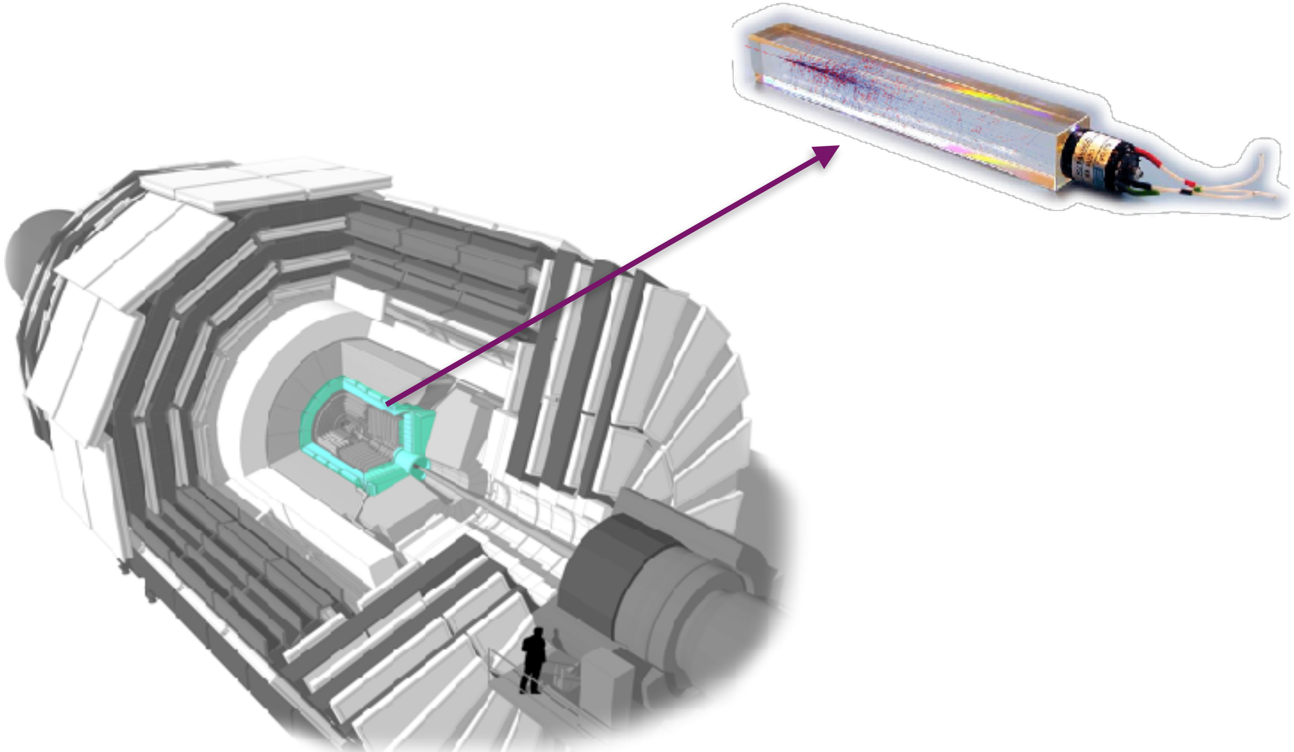


LHC (2018)
pp collider

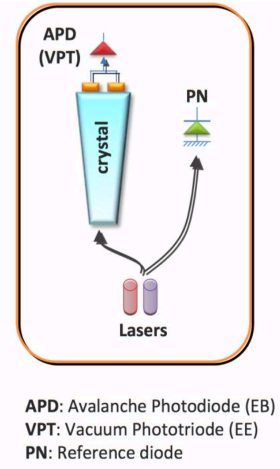
(*) A third type exists: e-p for specific purpose

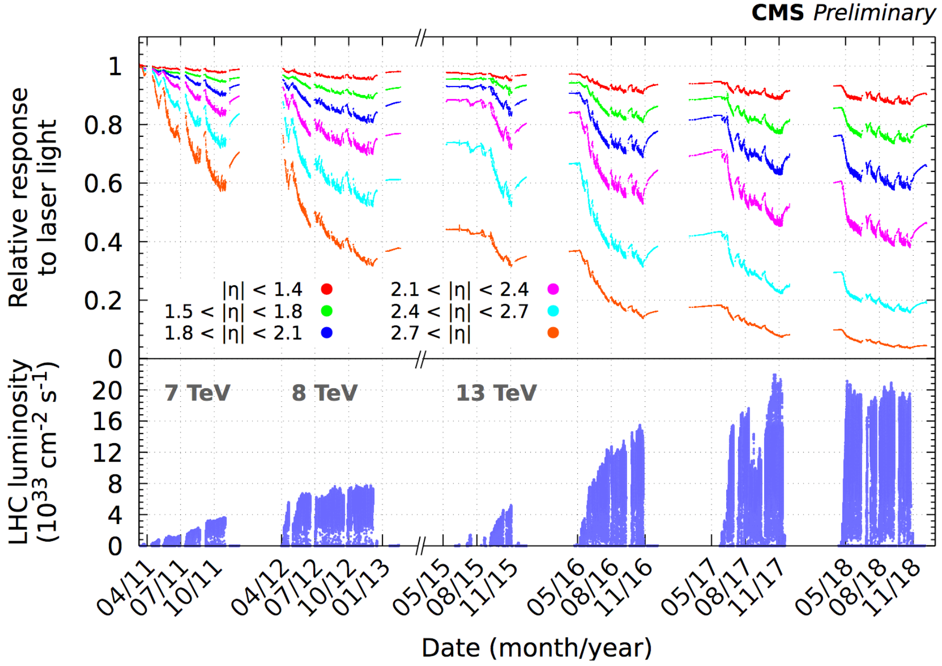
Precision physics at the LHC ?

- **Exquisite detectors** with sophisticated calibration methods allowing for very precise particle kinematic measurements



CMS electromagnetic calorimeter (ECAL)
Sending laser light in crystals every 40’ to monitor the transparency loss.
Energy precision: 0.2% !



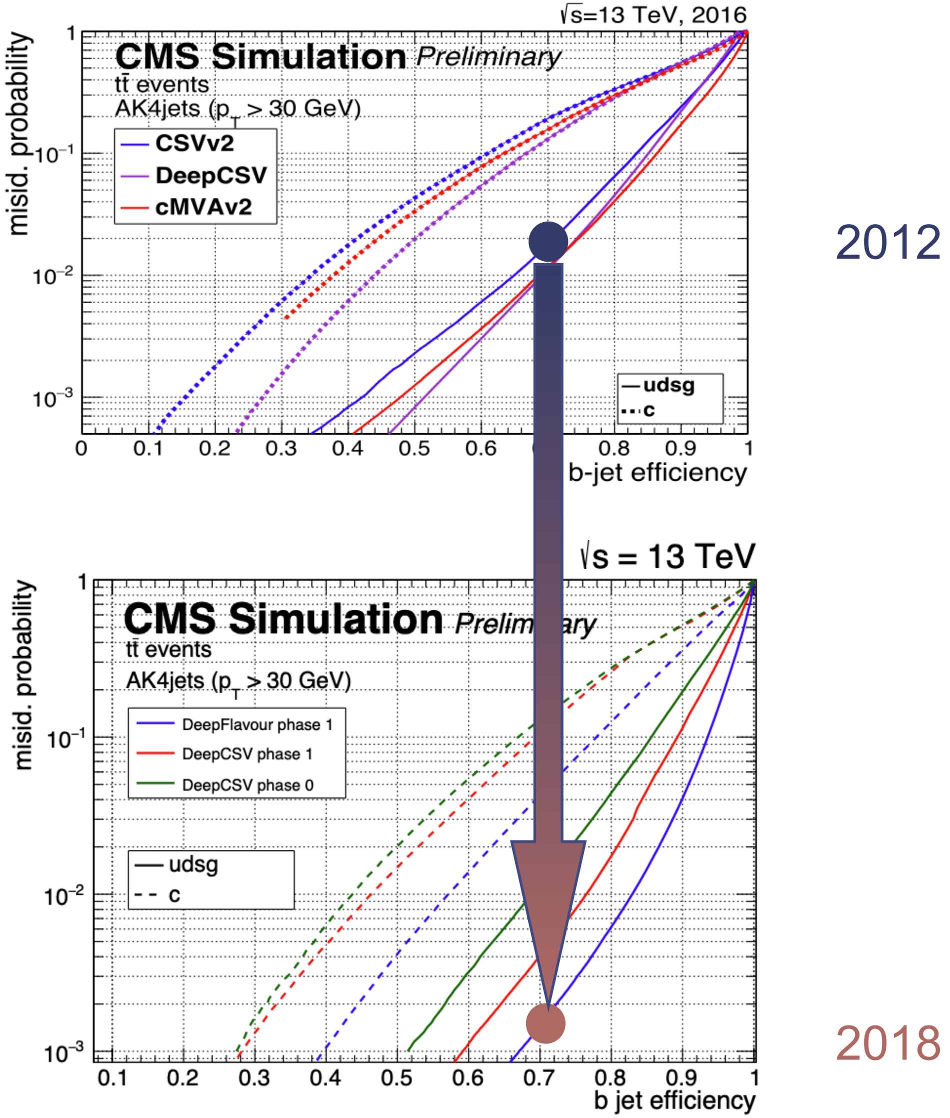


Precision physics at the LHC ?

- **Exquisite detectors** with sophisticated calibration methods allowing for very precise particle kinematic measurements
- Development of **innovative techniques** to cope with the harsh environment. More and more based on artificial intelligence (AI)…
  - ✓ The more complex the topology, the larger the improvement due to AI

The example of b-tagging

- Definition: capacity to identify jet of particles as coming from a b-quark
- From early days to 2018: AI allowed to gain a factor of 20… We are already doing better in 2024,

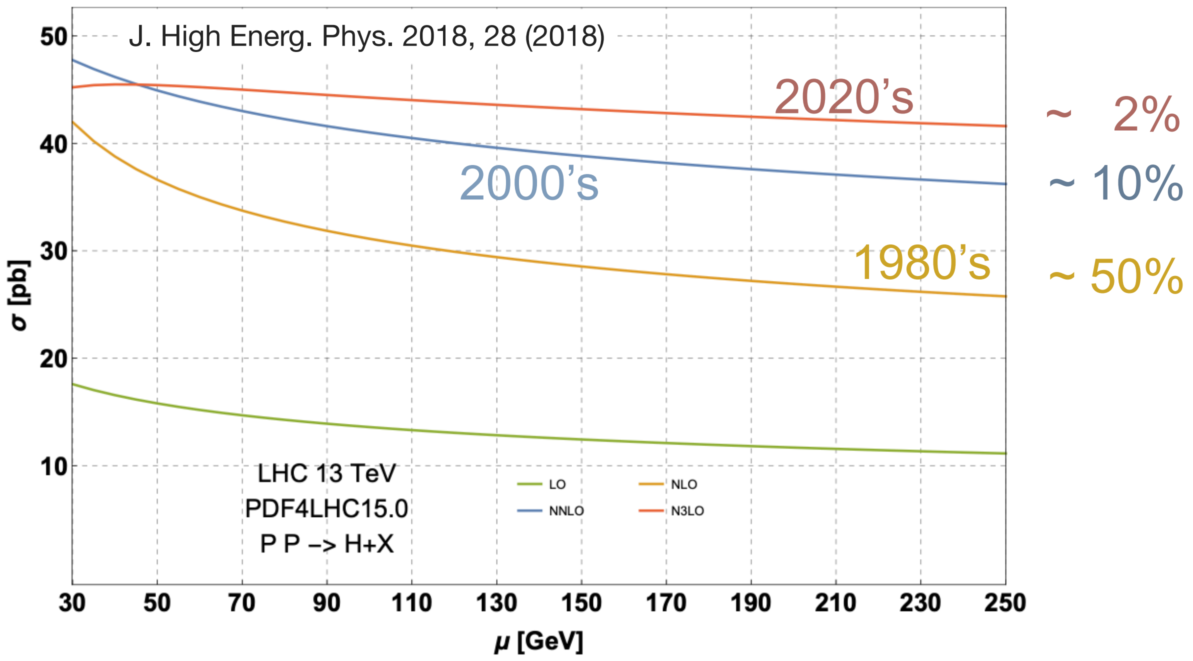


Precision physics at the LHC ?

- **Exquisite detectors** with sophisticated calibration methods allowing for very precise particle kinematic measurements
- Development of **innovative techniques** to cope with the harsh environment. More and more based on artificial intelligence (AI)…
  - ✓ The more complex the topology, the larger the improvement due to AI
- **Theoretical predictions** have also improved by several orders of magnitude. Thanks to new computation softwares, we can reach precision at the N3LO!

σ(pp→H+X) vs μ (perturbative scale)

Precision

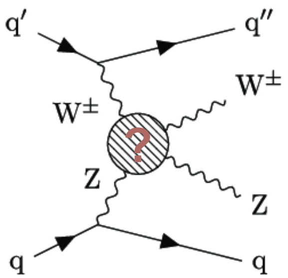


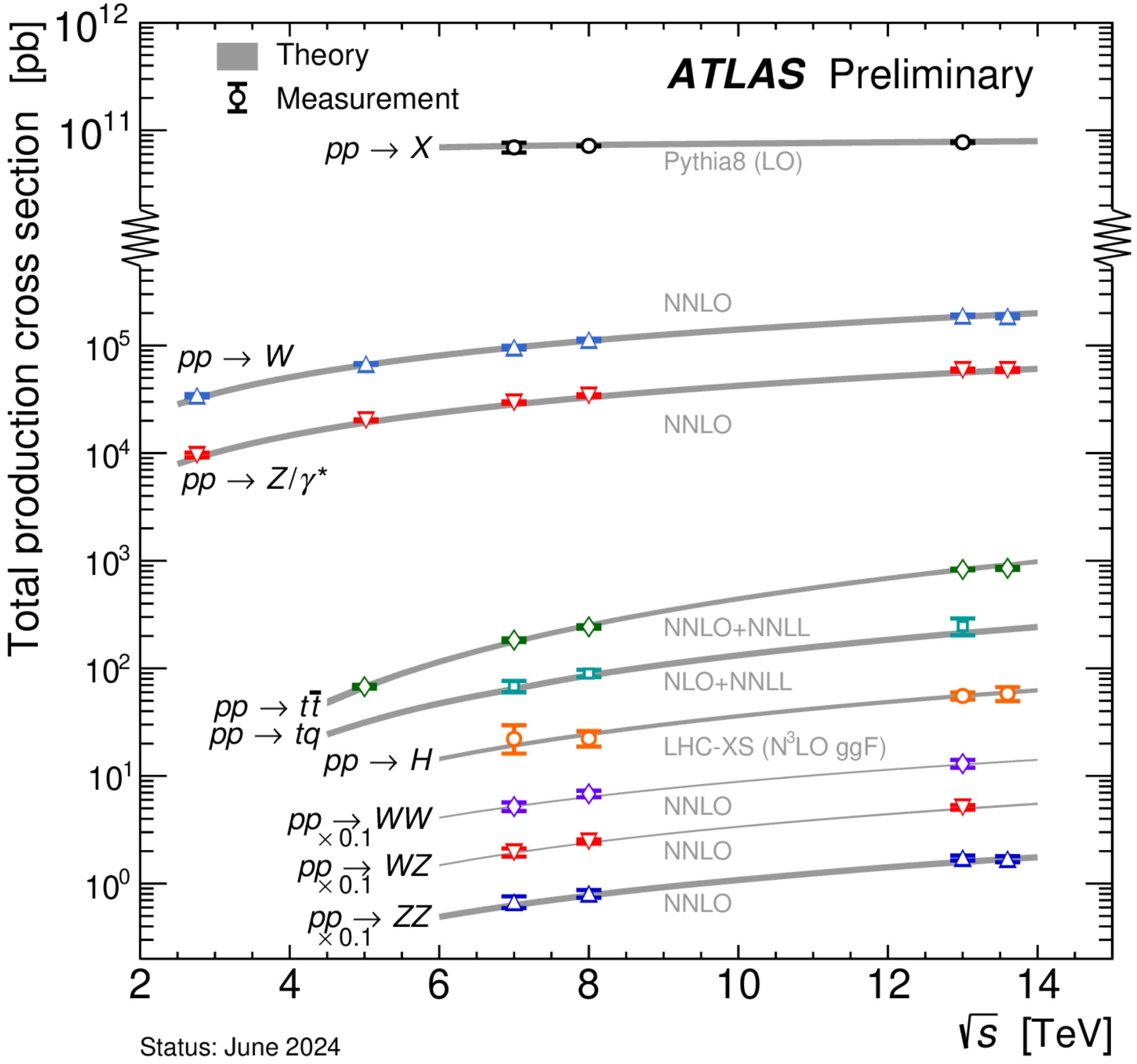
⇒ pp colliders are becoming precision machines

1. Electroweak precision physics

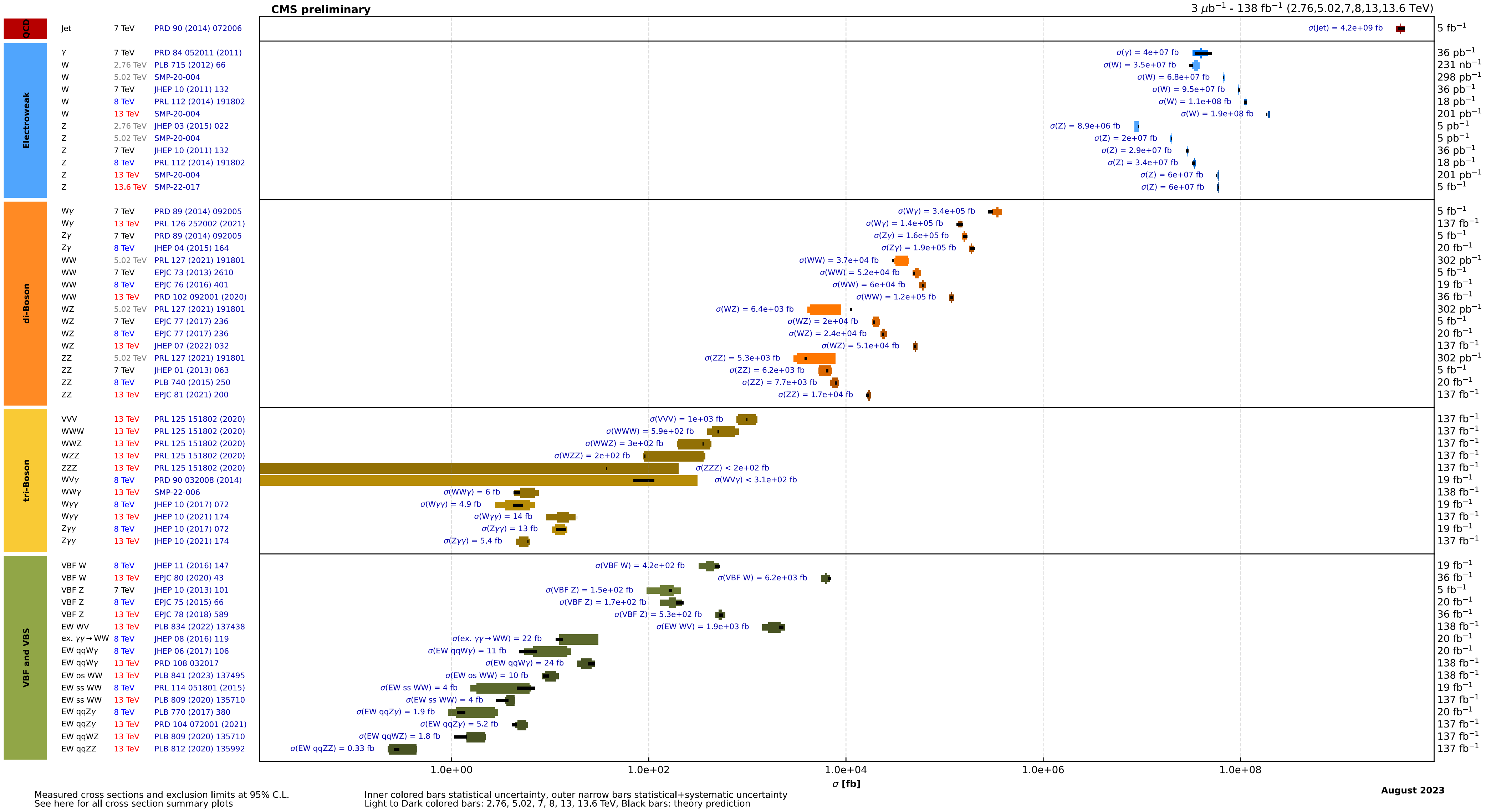
Producing Z and W bosons

1. Single boson production
   - Formidable tool to test and improve the underlying process (parton density function - pdf, tuning of parton showers…)
   - Reaching precision < 1%
2. Di-boson production
   - First observed by CDF/D0 experience
   - Precision of the order of 5%
   - Test the tri-boson coupling which may
3. Tri-boson production
   - Large amount of data collected allows now to probe the tri-boson production
   - First steps towards confirming the existence of the quartic coupling of W an Z boson !





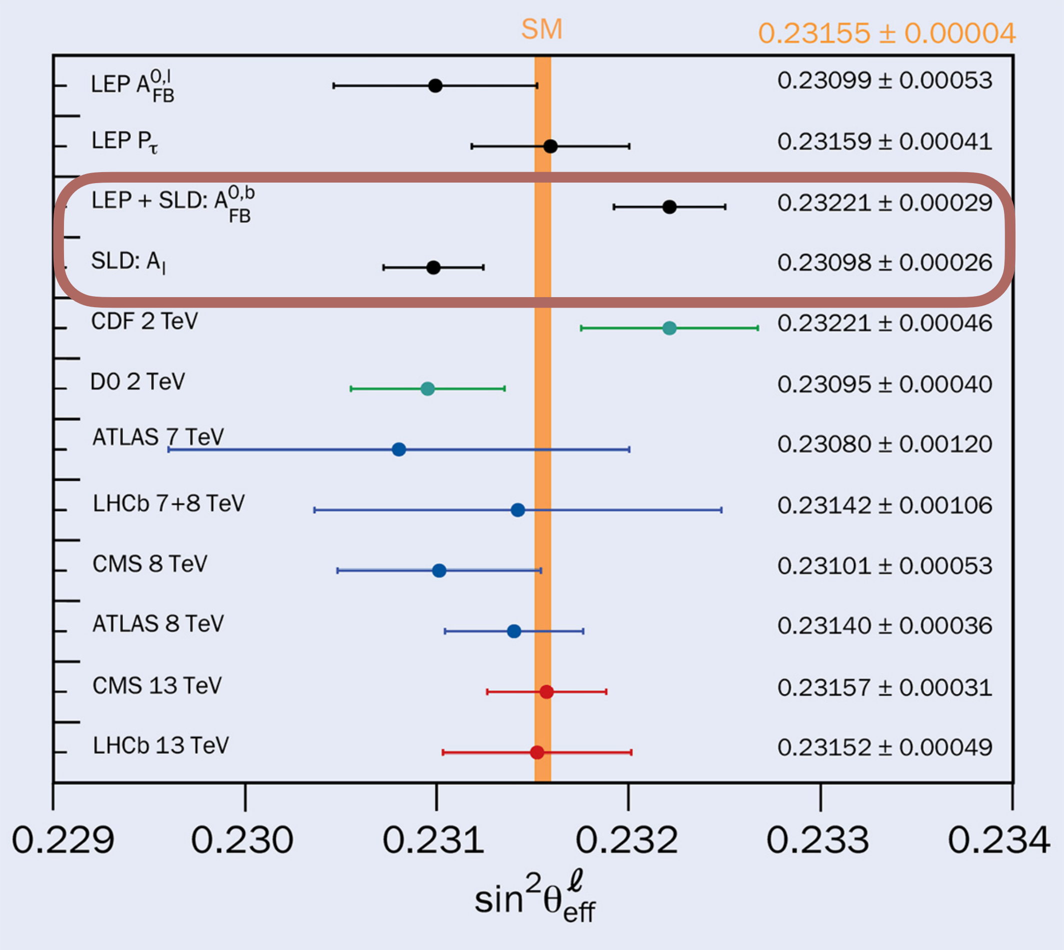
Producing Z and W bosons



The weak mixing angle $\sin^2\theta_W$

The weak mixing angle θ_W free parameter of the SM

- Early universe electroweak (EWK) gauge bosons are massless
- EWK symmetry breaking, mixing the gauge boson to form W, Z and γ bosons
  - ✓ θ_W is the mixing angle between Z and γ
  - ✓ Relates also m_Z to m_W
- Measured precisely at LEP (CERN) and SLC (SLAC)
  - ✓ Long standing tension in measurements



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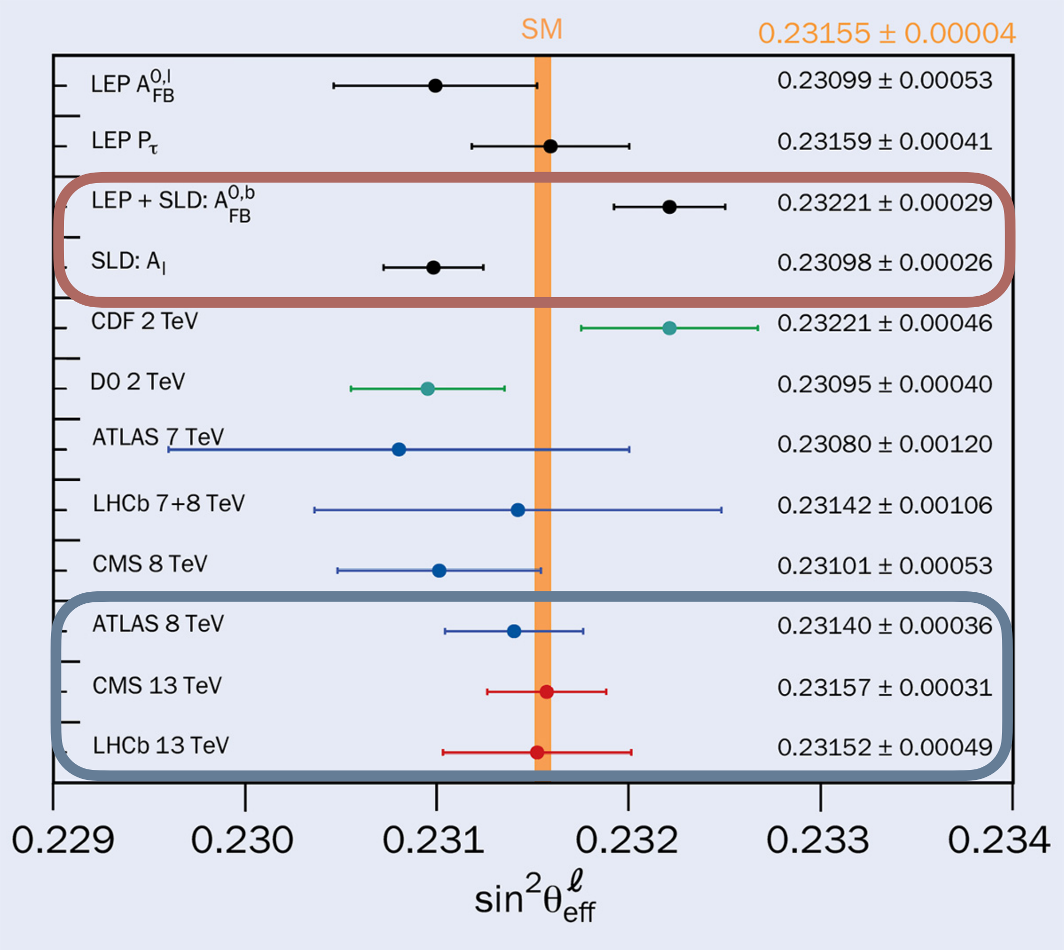
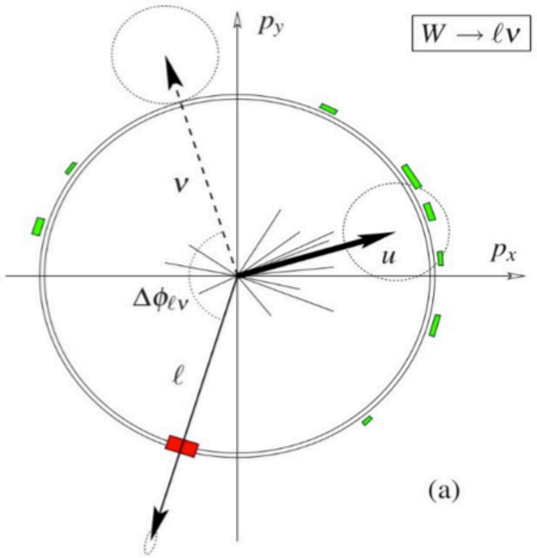
- Measured precisely at LEP (CERN) and SLC (SLAC)
  - ✓ Long standing tension in measurements
  - ✓ New measurements from LHC in between, reaching similar precisions as LEP/SLC

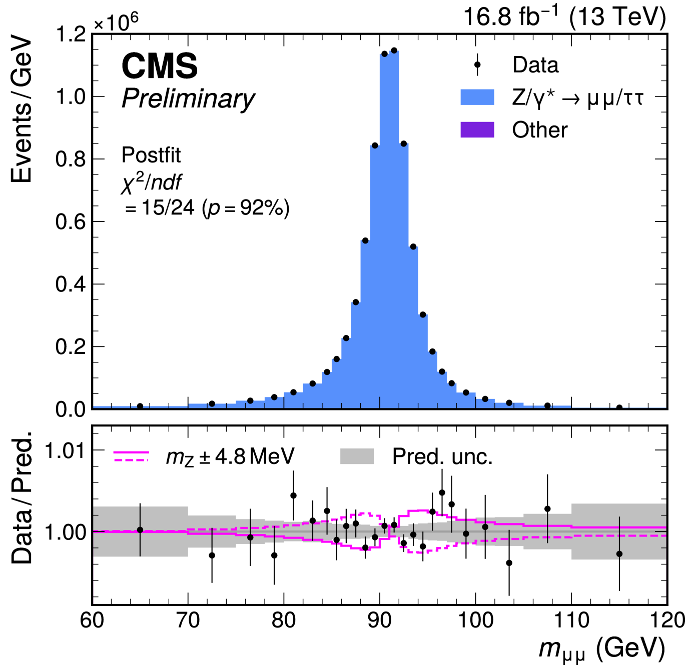


The W boson mass

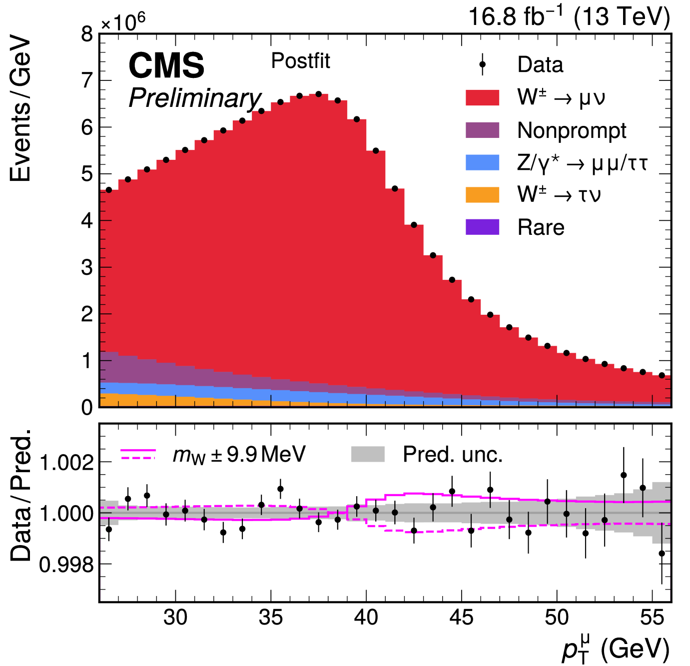
- Measuring the W boson mass is of paramount importance. Since it constrains the relationship between EWK parameters of the theory
- LEP legacy
  - ✓ Z boson mass @ 0.002%
  - ✓ W boson mass @ 0.04%
- LHC and Tevatron eras



Neutrinos escape detection !



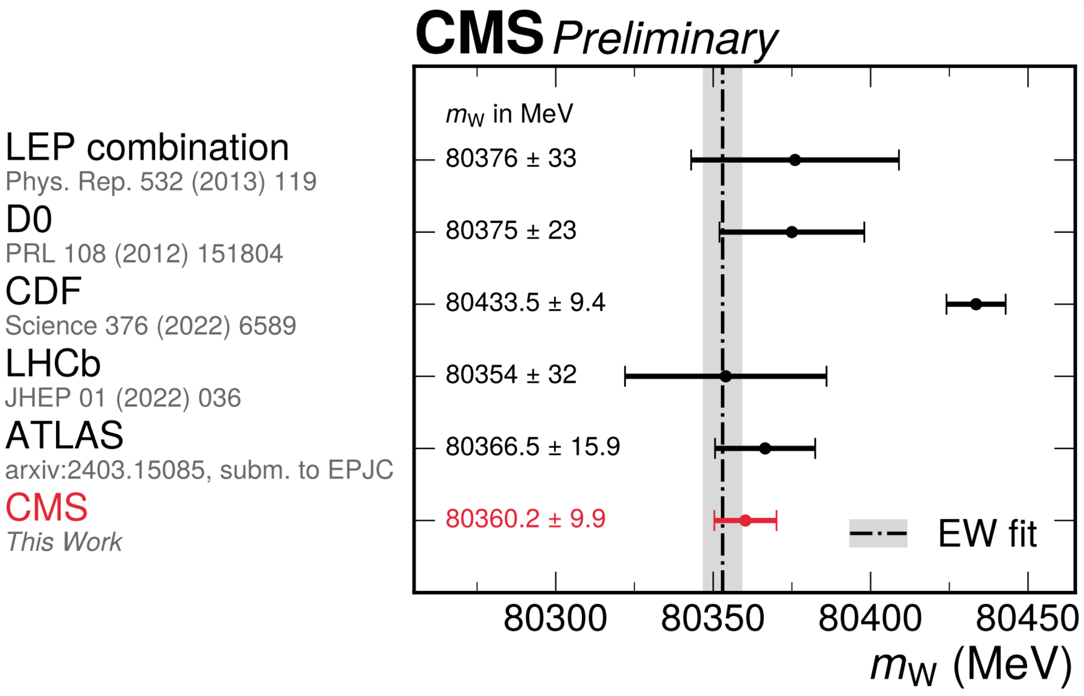
$Z \to \mu\mu$



$W \to \mu\nu$

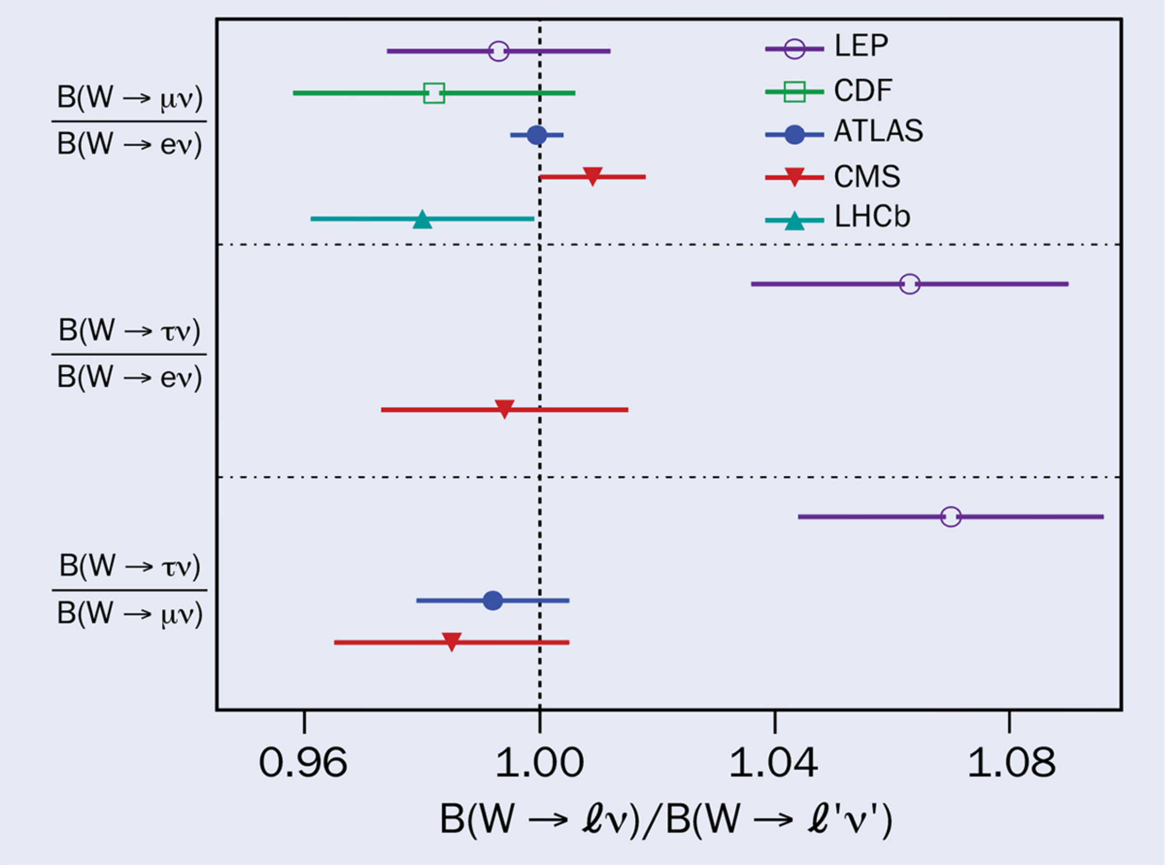
The W boson mass

- Measuring the W boson mass is of paramount importance. It constrains the relationship between EWK parameters of the theory
- LEP legacy
  - ✓ Z boson mass @ 0.002%
  - ✓ W boson mass @ 0.04%
- LHC and Tevatron eras
  - ✓ In 2022 CDF (based at Tevatron collider near Chicago) measurement hit the headlines in great tension with the SM
  - ✓ Atlas and recent CMS measurements in agreement with the SM 0.012% !
    - Such a precision can be achieved in a pp collider only with a perfect knowledge of the detector response and new technique to tackle theory uncertainties



Lepton Flavour Universality

- In the SM W/Z boson coupling to lepton are independent of the lepton type: e, μ, τ. This is very specific to weak interaction
- New physics could change the picture
- LEP legacy
  - ✓ Z boson LFU @ 0.3%
  - ✓ W boson LFU @ 2 %
- LHC data
  - ✓ LEP 2.6 σ deviation in W → $\tau\nu$
  - ✓ Not confirmed by Atlas/CMS. Atlas reaching the most precise measurements in this sector (1.3% for τ and 0.5% for e).



2. Higgs Boson precision

The Higgs Boson in the SM

- Responsible for particle masses
  - ✓ Z, W bosons masses (gauge mass)
  - ✓ Fermion masses (Yukawa coupling)
- Couplings to fermions (resp. gauge boson) is proportional to their mass (resp. mass²)
  - ✓ Comparing the coupling strength (measuring cross section) to the known particle masses
- Properties
  - ✓ Only scalar (spin 0) particle in the SM
  - ✓ Electric charge = 0
  - ✓ CP +

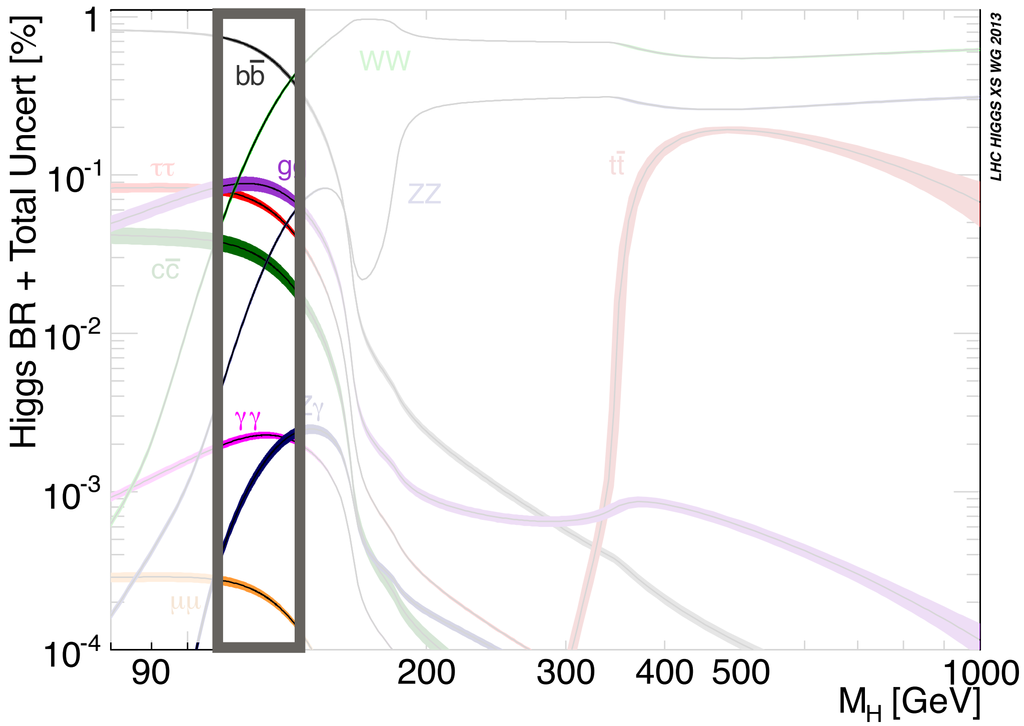
NB: the only interaction violating LFU in the SM !

Golden channels

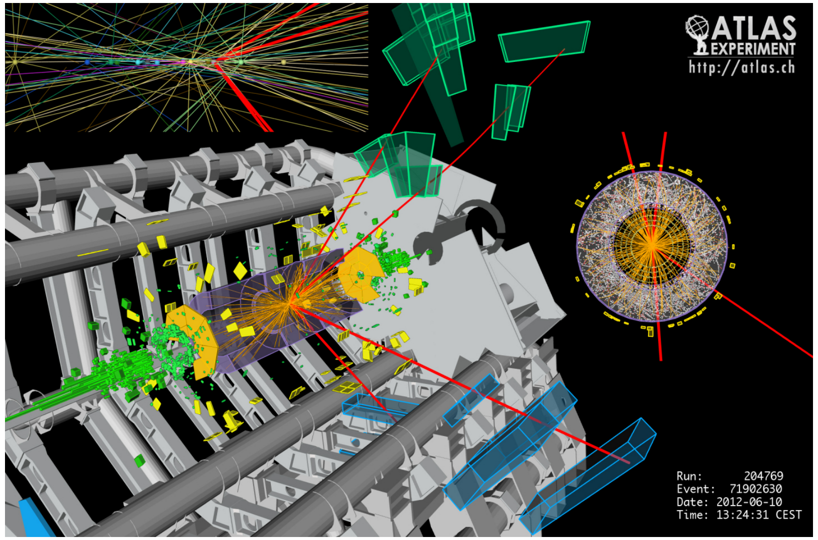
$H \rightarrow \gamma\gamma$: $B \approx 0.2\%$

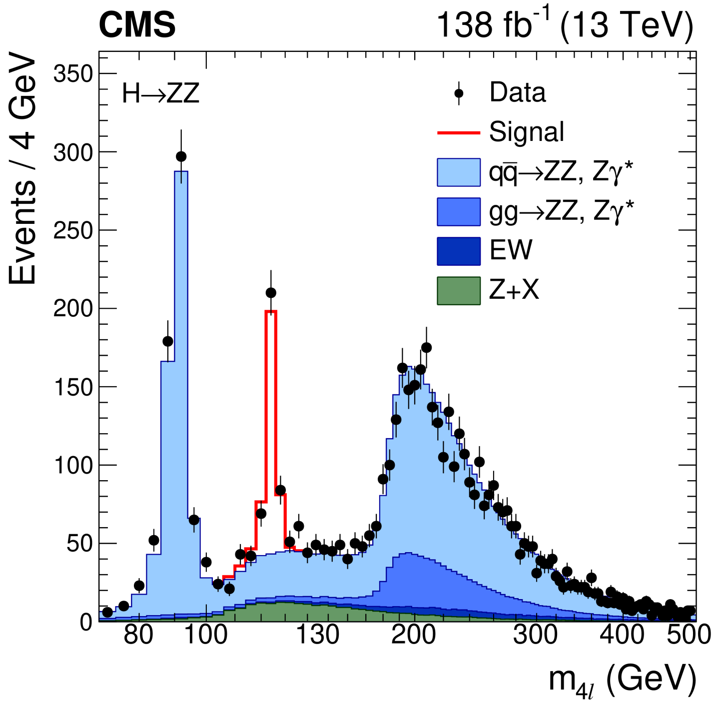
$H \rightarrow ZZ^* \rightarrow 4\ell$: $B \approx 0.03\%$

Small branching ratios but excellent invariant mass resolution: probe all production modes

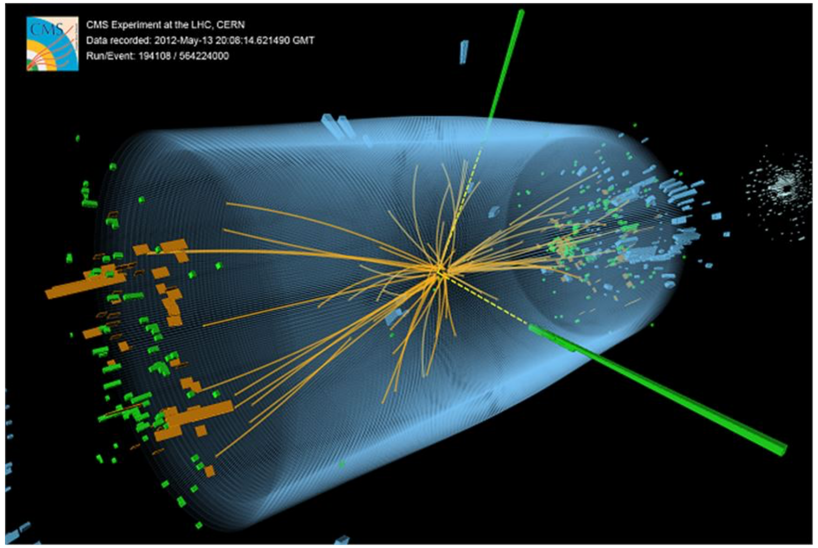


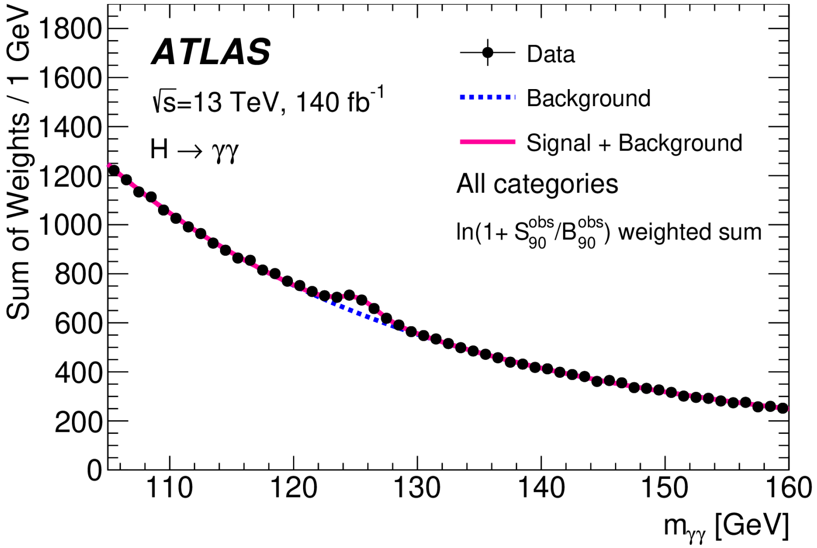
The golden channels





$H \rightarrow ZZ^* \rightarrow 4\ell$

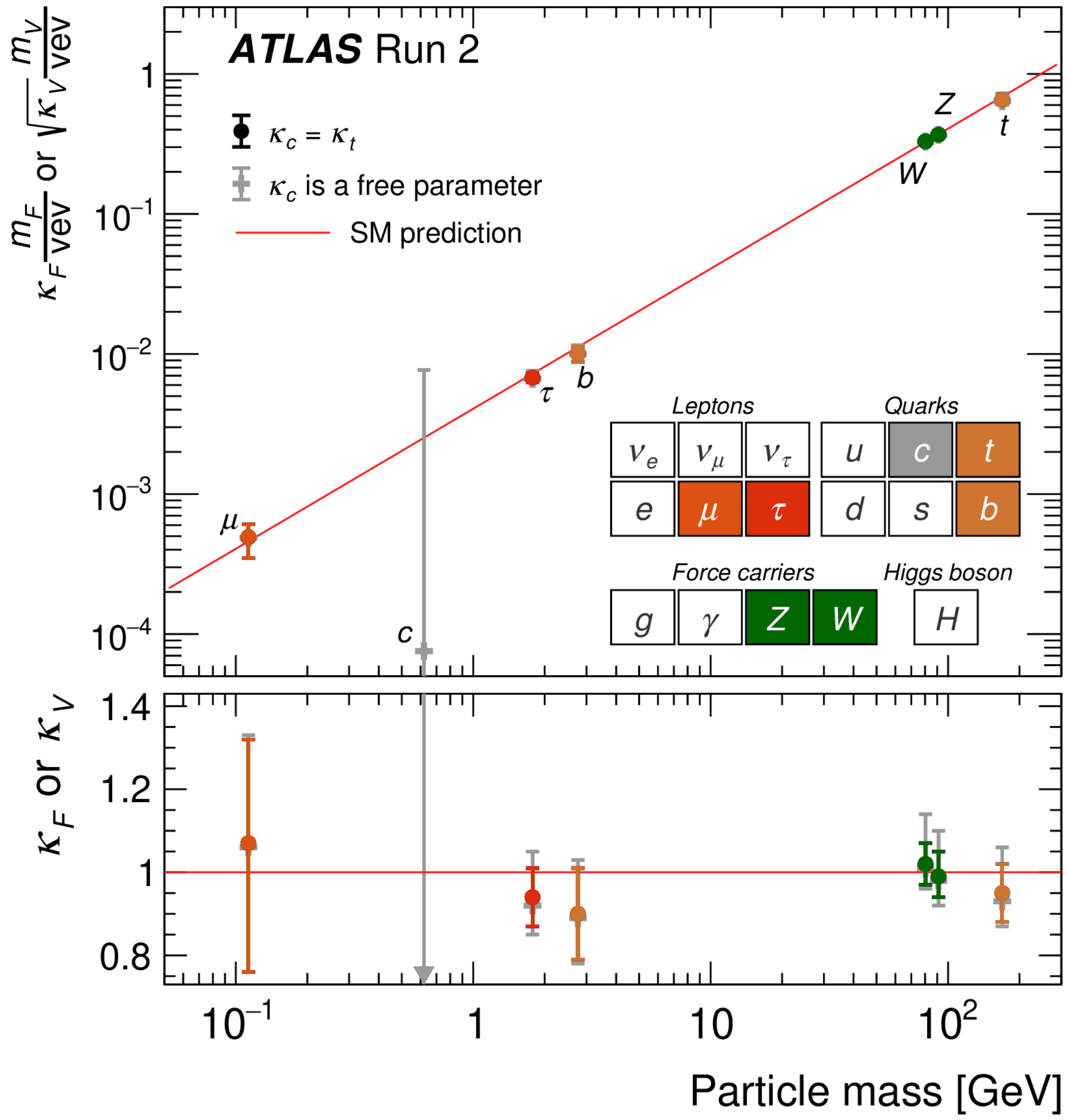




$H \rightarrow \gamma\gamma$

Higgs Boson couplings to SM particles

- ✓ Coupling to Z bosons: 7%
- ✓ Coupling to W bosons: 8%
- ✓ Coupling to top quarks: 11%
- ✓ Coupling to b quarks: 16%
- ✓ Coupling to τ lepton: 8%
- ✓ Coupling to μ lepton: 20-30%



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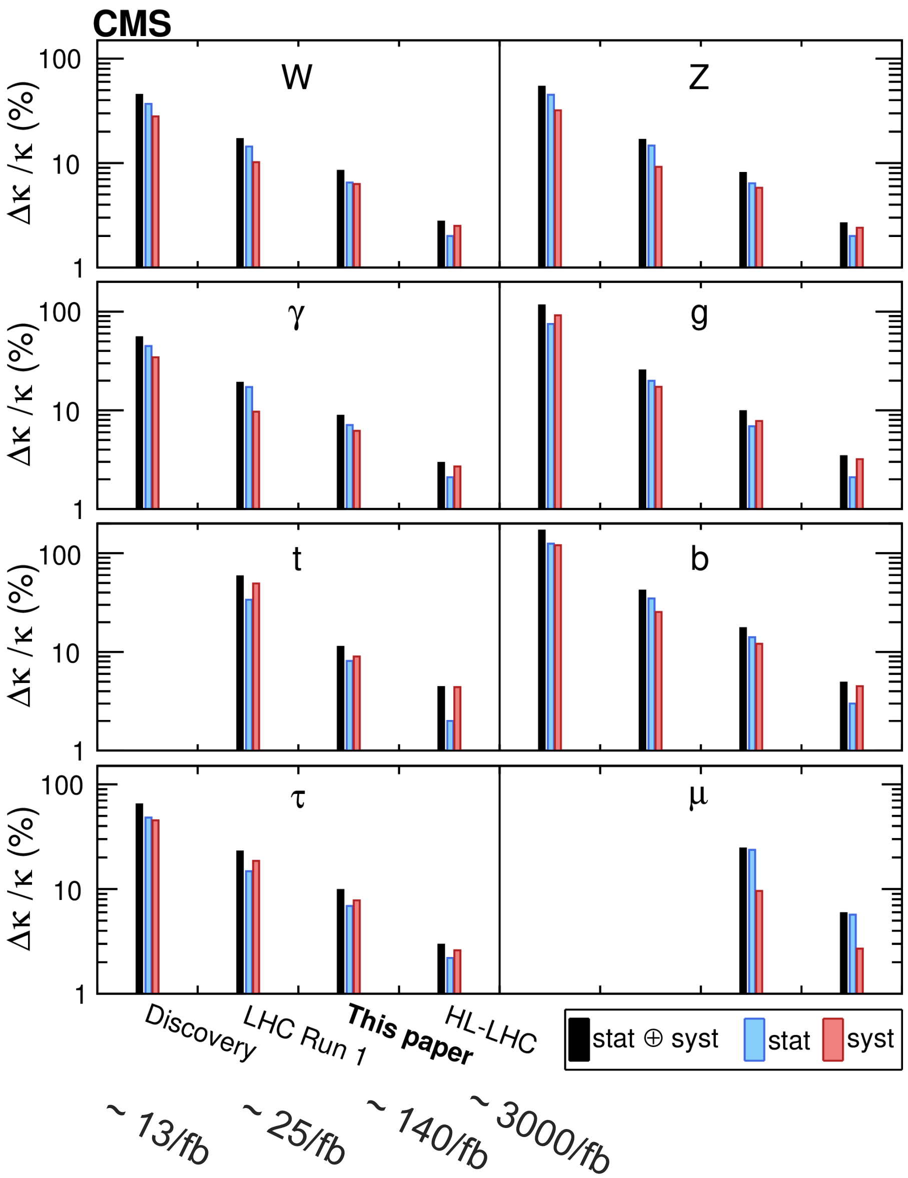
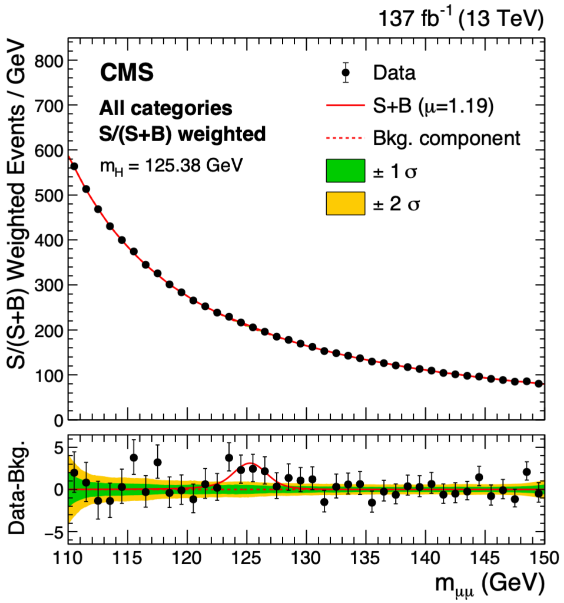


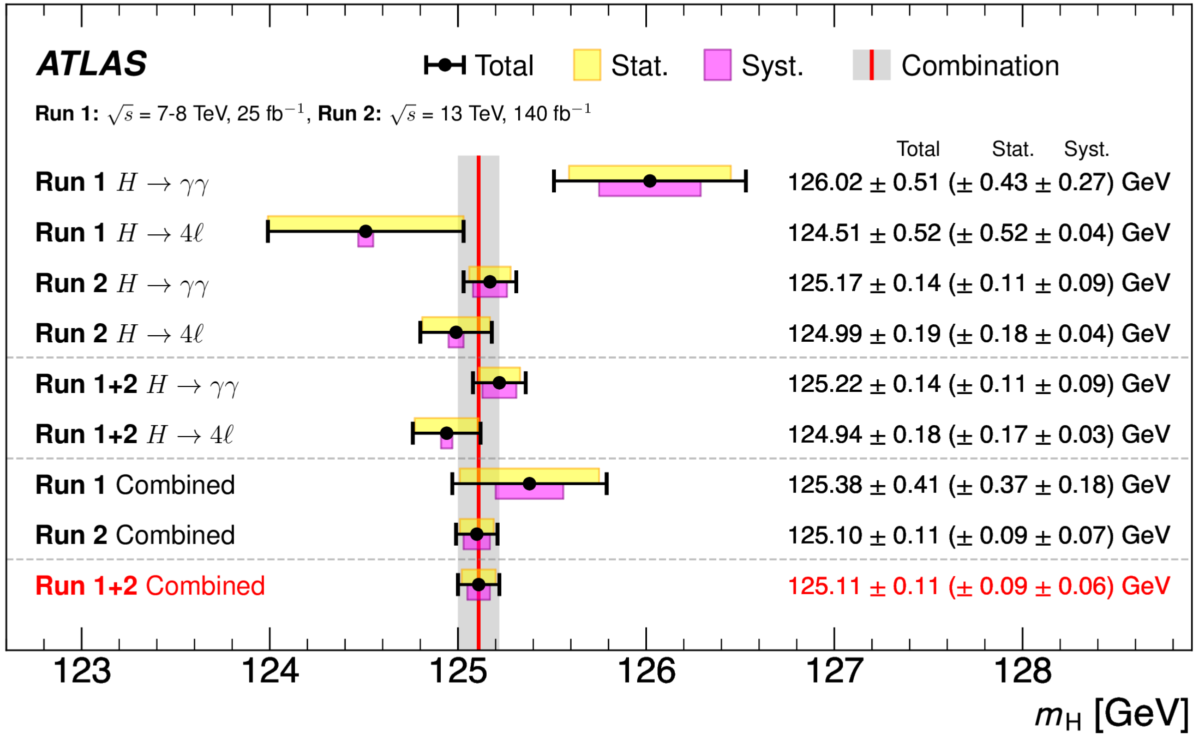


Evidence for H→μμ

$\mathcal{B}(H\to\mu\mu) \approx 2.10^{-4}$

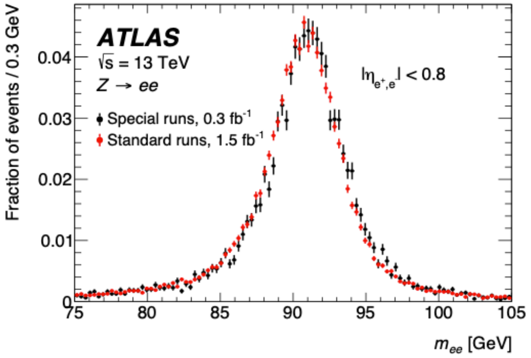
The Higgs boson mass

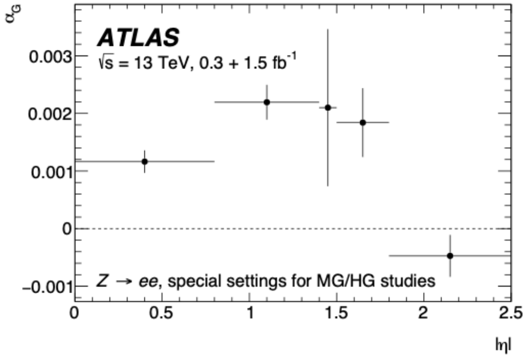
- Free parameter of the SM
- An experimental tour de force
  - ✓ Extremely precise calibration of the lepton/photon energy scale
  - ✓ δmH / mH ≈ 0.1%



Atlas refined photon calibration.

Dedicated runs with specific detector conditions !

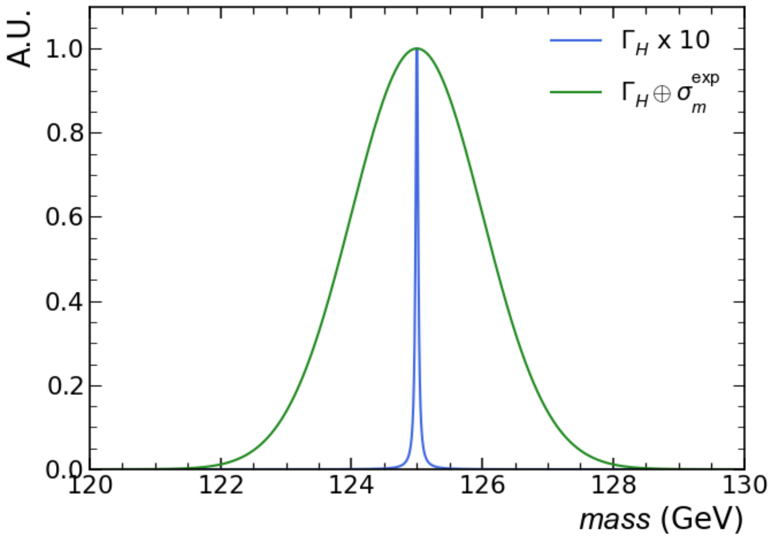




The Higgs boson natural width Γ_H

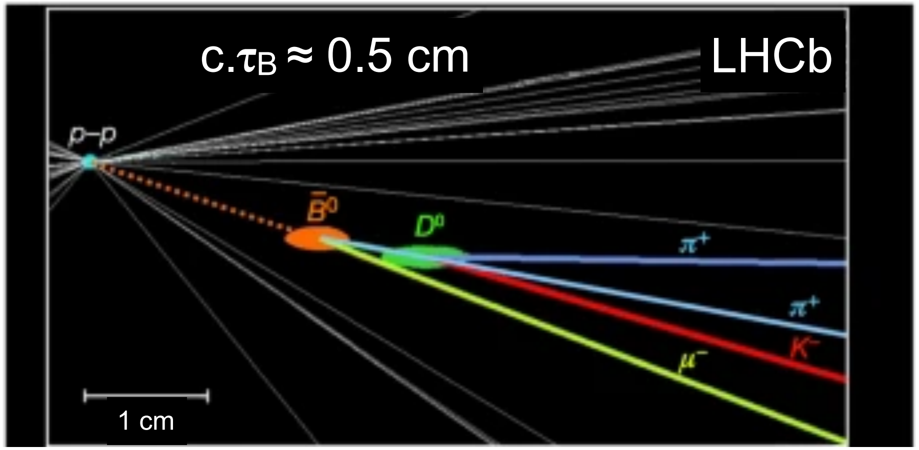
Particle width related to particle lifetime

- Heisenberg principle: $\Delta m \, \Delta t \approx \hbar$
- Related to m_H and to the allowed decays of the Higgs boson
  - ✓ Sensitive to decay to unknown particles (escaping detection)



A very challenging measurement

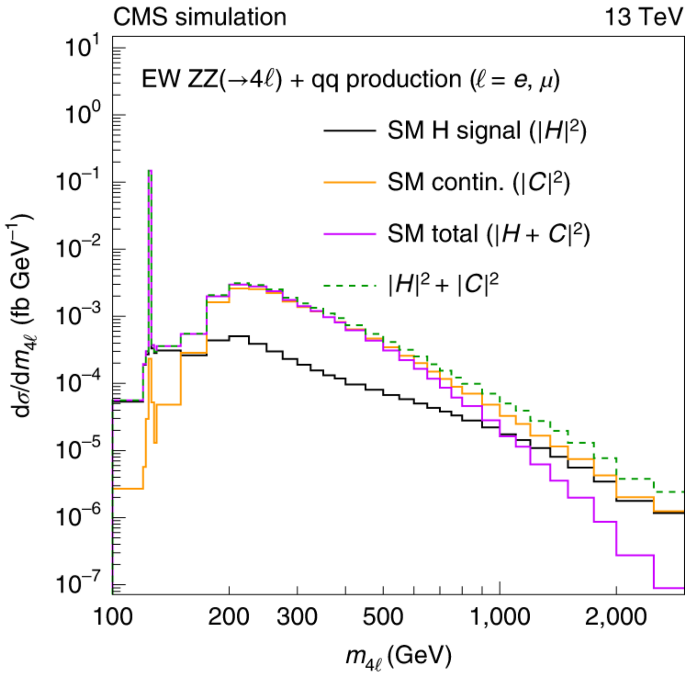
- Γ_H = 4.1 MeV << $\sigma_m^{exp} \approx 2\ 10^3$ MeV
- $c.\tau_H$ = 44 fm << $\sigma_{IP}^{exp} \approx 50\ 10^9$ fm

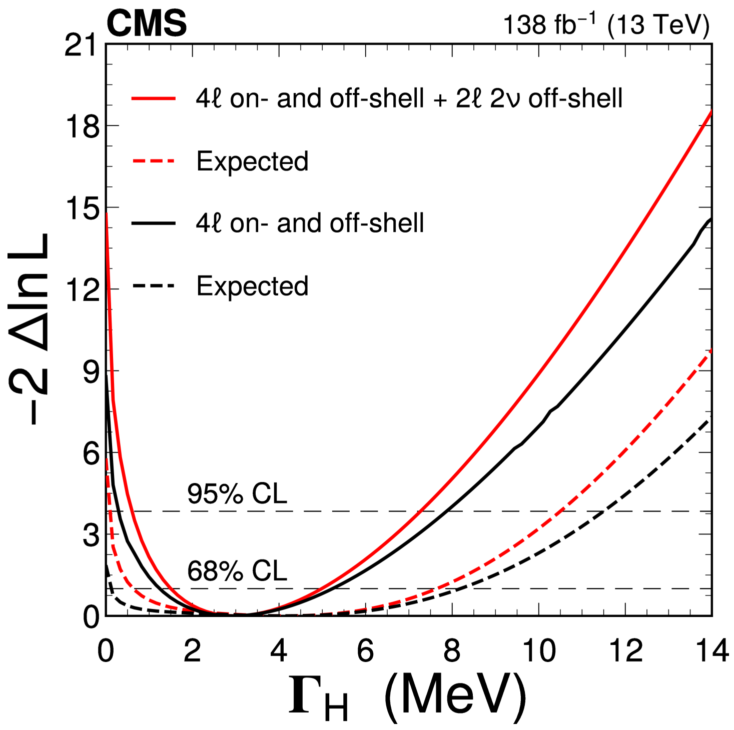


The Higgs boson natural width Γ_H

Innovative ideas !

- Measurement based on off-shell Higgs boson production and its interference with the SM background





Parameter	CMS	Atlas
m_H (GeV)	125.08 ± 0.12	
on-shell Γ_H (MeV)	<50 [<330]	
off-shell Γ_H (MeV)	$3.0^{+2.0}_{-1.5}$ [0.6, 7.3]	$4.5^{+3.0}_{-2.5}$ MeV.

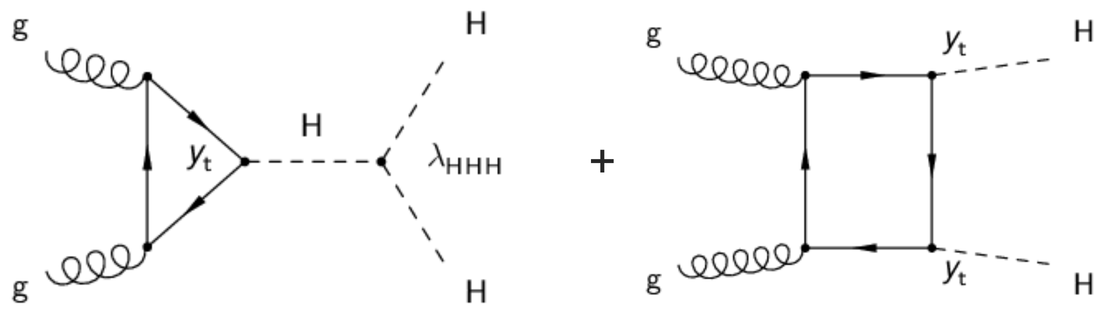
The next Graal: the Higgs boson auto-coupling

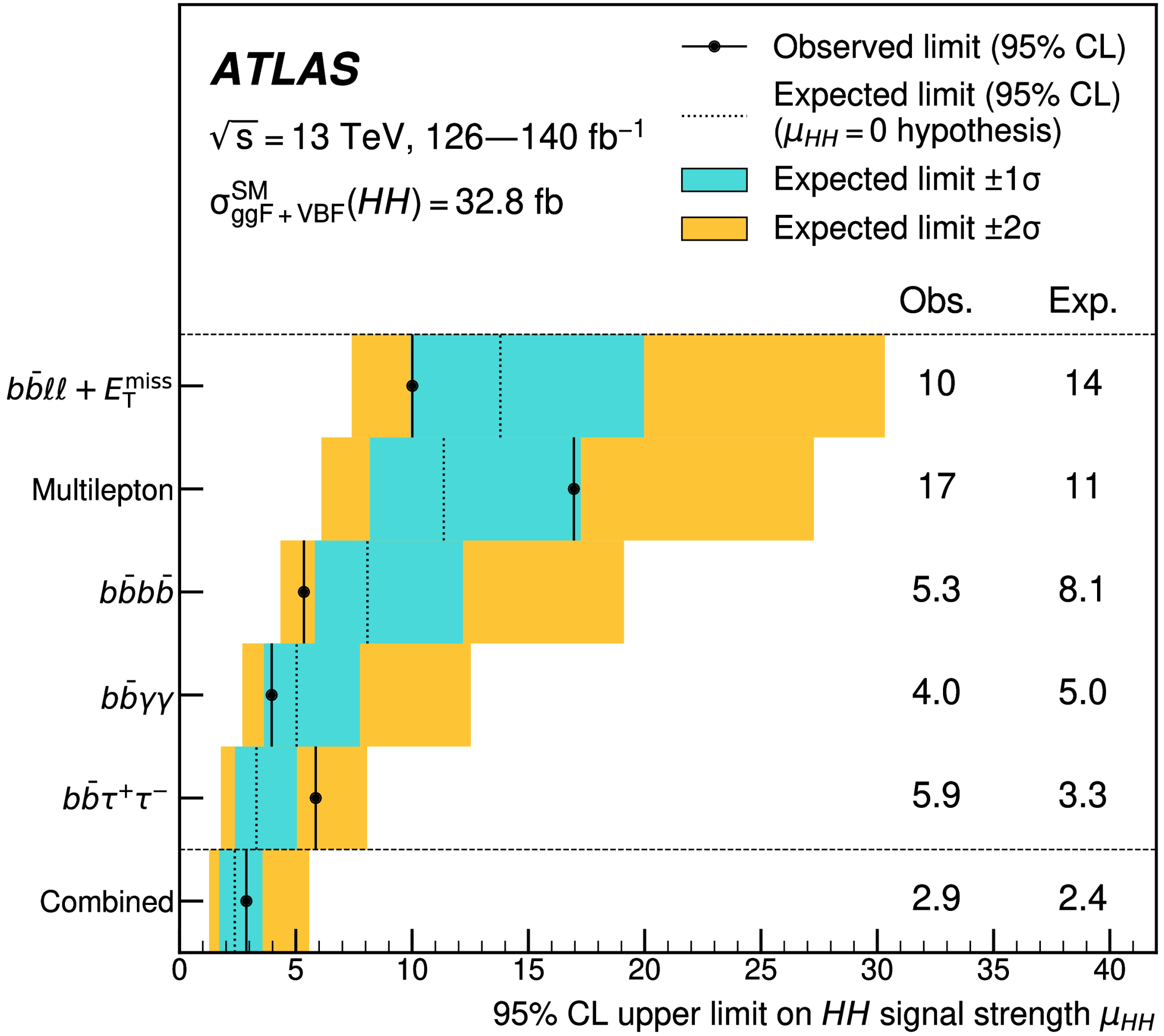
In the SM, Higgs boson couples to itself

- ✓ SM free parameter λ_{HHH}

Probe with HH production

- ✓ First need to observe HH
- ✓ Not the end of story: negative interference !

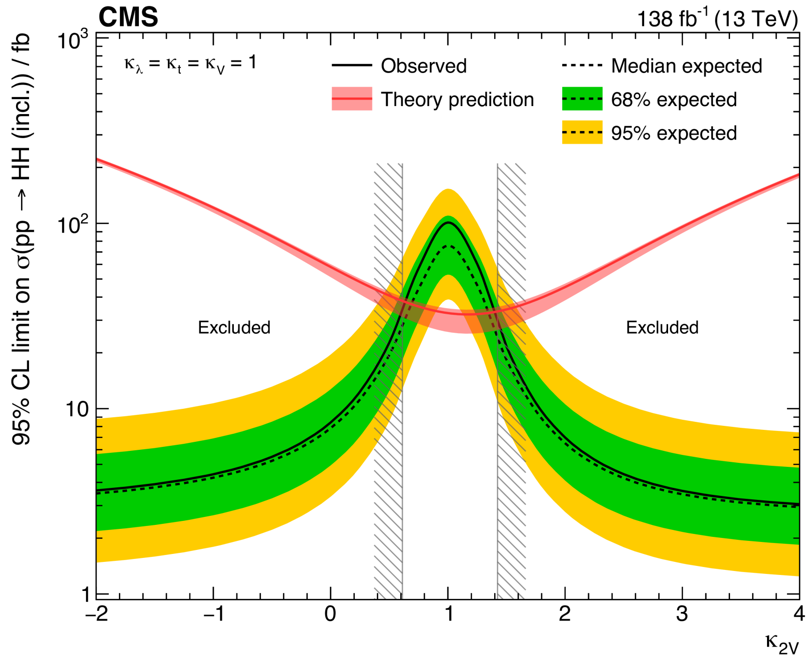




Double Higgs production fun fact !

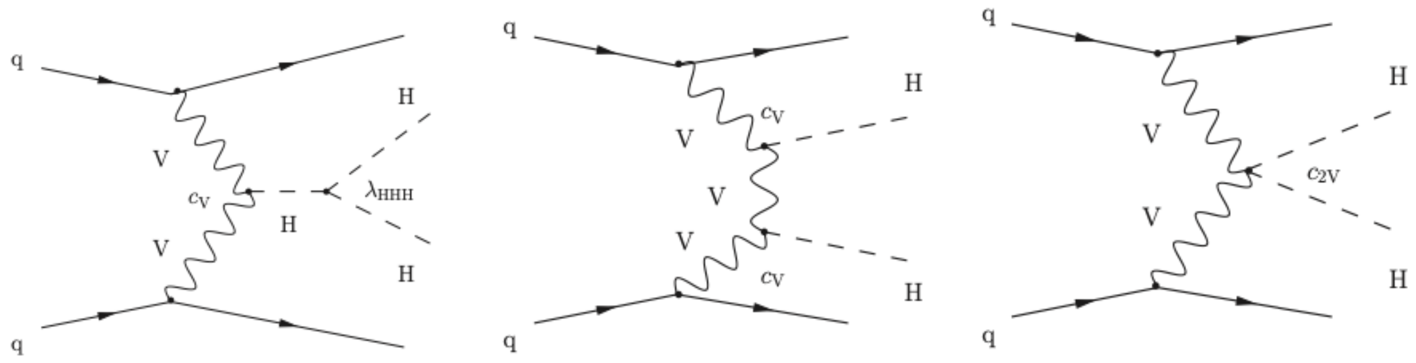
Vector boson fusion channel qqHH

- ✓ Final state with 2 Higgs and 2 jets
- ✓ Final state not observed
- ✓ Yet cery strong constraint on the c2V coupling !



$c2v/c2v_{SM} \in [0.67, 1.38]$

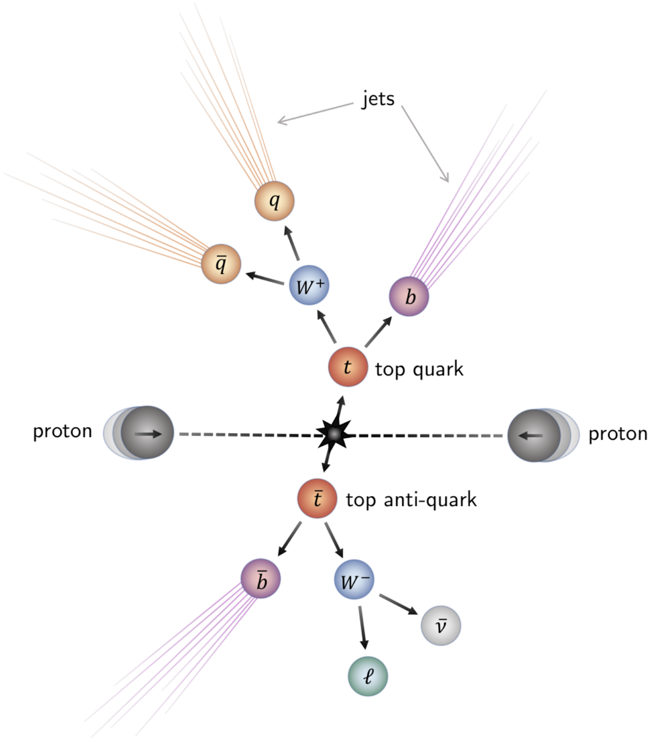
c2v = 0 excluded at 6σ level



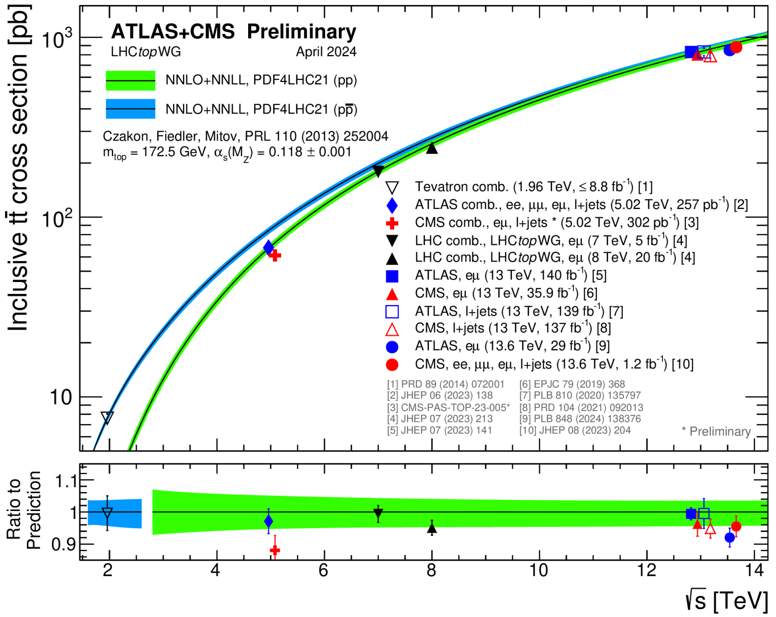
3. top quark

A peculiar fermion

- Last discovered quark in 1995
- The heaviest known particle $m_{top} \approx$ 170GeV
  $\Rightarrow y_{top} \approx 1$!
- Short lifetime $\Gamma_{top} \approx$1.4 GeV
  - ✓ The only quark to decay before it can hadronize
  - ✓ A unique laboratory to explore a bare quark (spin correlation at the production level, entanglement…)
- Sensitive to the strong interaction
  - ✓ Information on the proton constituents
  - ✓ Strong coupling constant in the top sector
- Reminder: W, top, Higgs masses

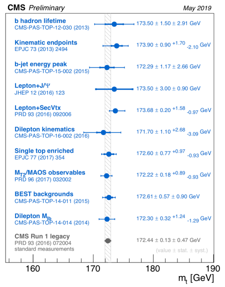


A very rich topology

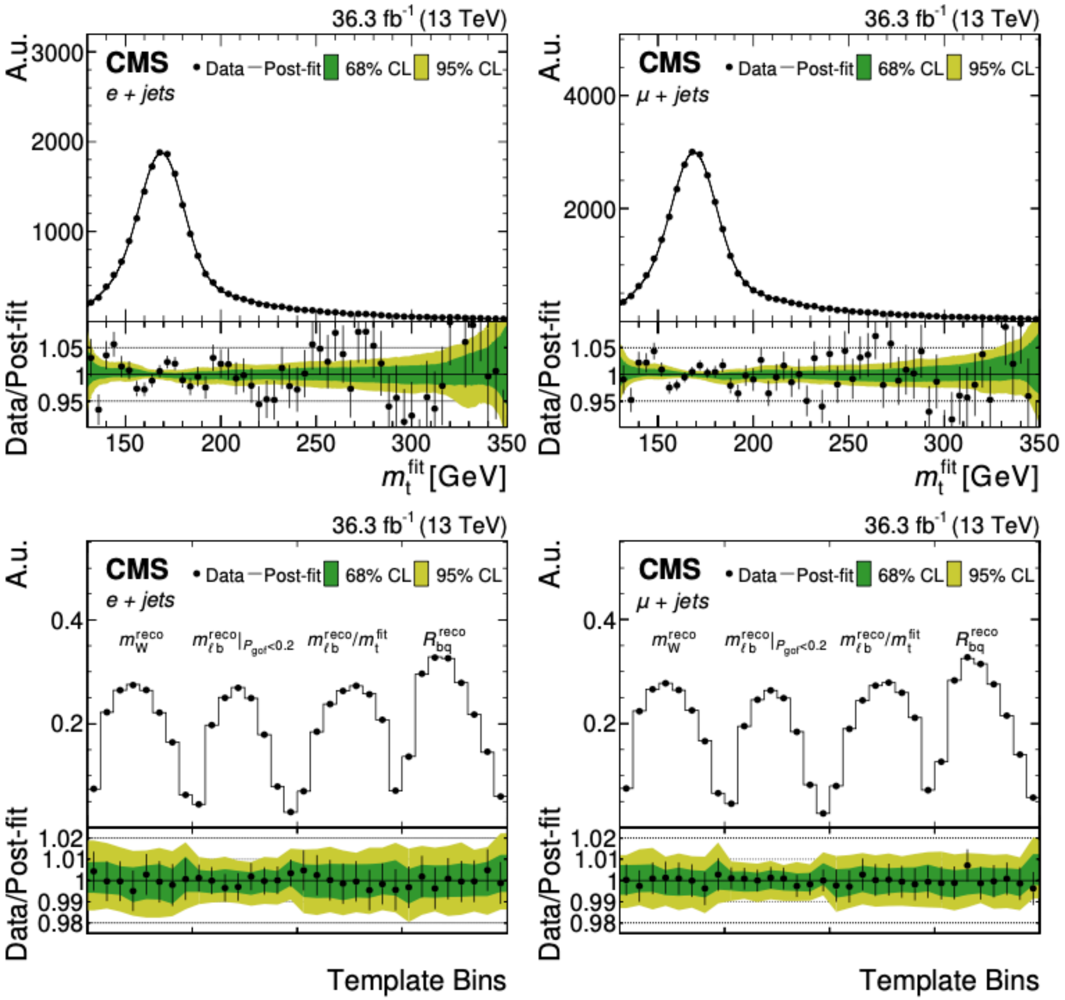


The top quark mass

- A challenging measurement
  - Energy scale for light and heavy quarks, leptons
  - Missing energy from neutrino
  - Ambiguity in the top reconstruction
- State of the art in Run1
  - Combine of up to 10 measurements
  - Atlas: m_{top} = 172.69 ± 0.48 GeV
  - CMS: m_{top} = 172.44 ± 0.48 GeV



- New ideas and innovative techniques
  - Improved b-tagging
  - Add side measurements to constraint dominant systematics (5D fit))
  - CMS: **m_{top} = 171.77 ± 0.37 GeV**



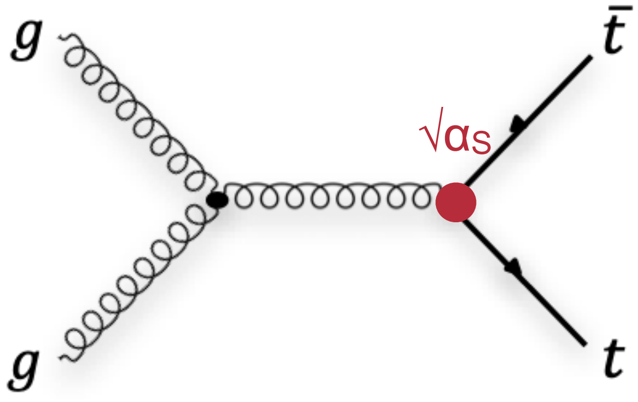
Top quark and QCD

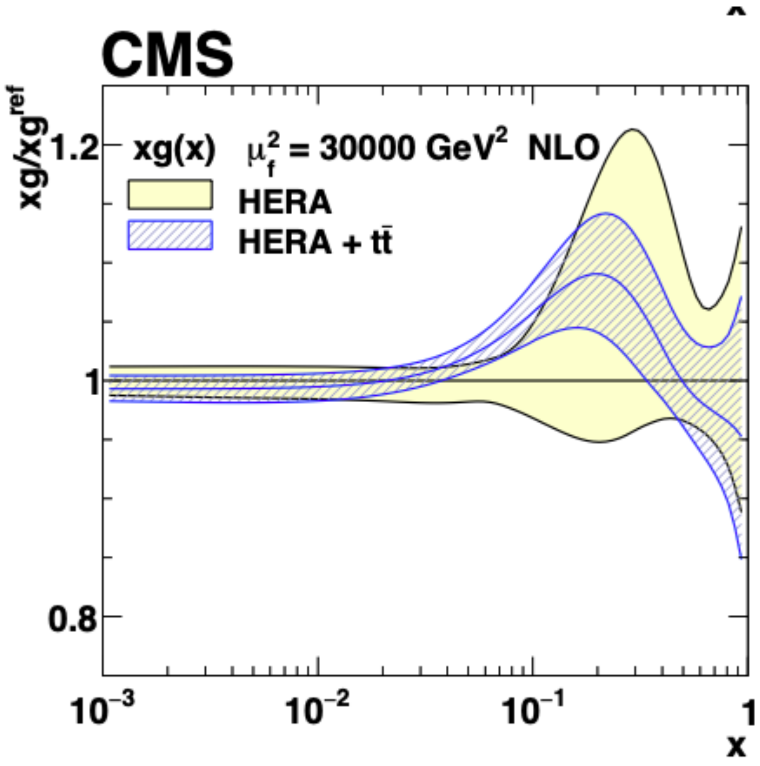
The proton structure (pdf) extensively studied with HERA data (ep collision)

Additional information from LHC data, for instance top quark production constrain gluon density

Simultaneously extracting the value of α_S

- α_S strength of the QCD coupling constant

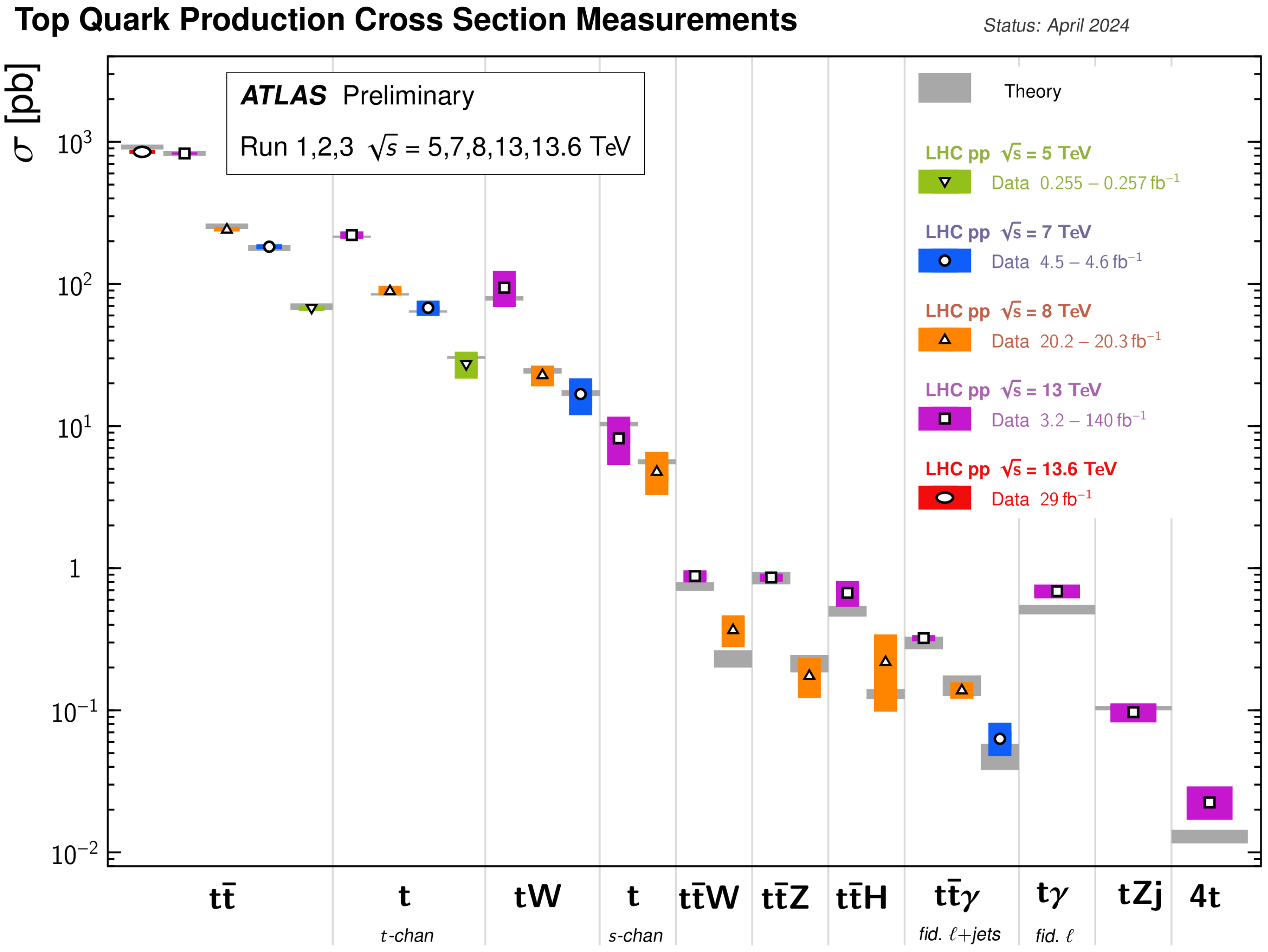


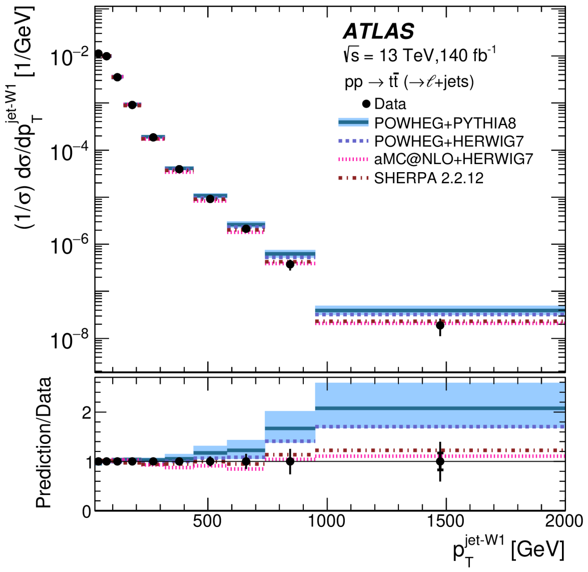


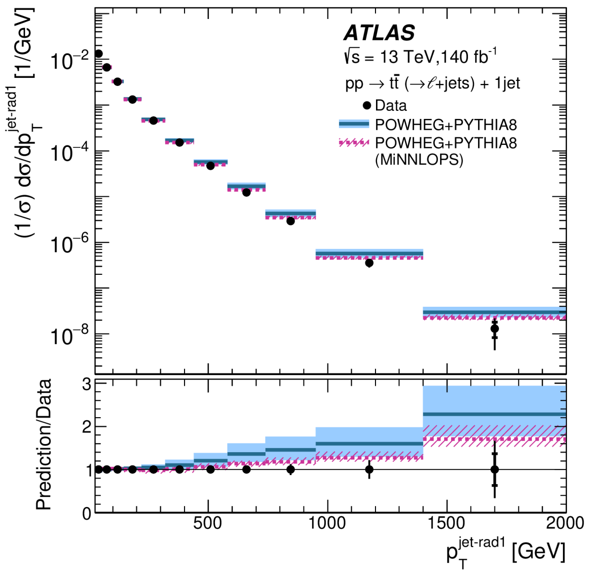
$\alpha_S(mZ) = 0.1135 \pm 0.0020$ (ttbar)

$\alpha_S(mZ) = 0.1181 \pm 0.0011$ (world average)

Top cross sections







4. Conclusion

Conclusion

- Only a very limited subset of results presented
- LHC data putting the SM under pressure with precision measurement
  - ✓ So far no sign for new physics…
- Yet, the SM is an effective low energy theory, new physics must exist at some scale
  - ✓ SM does not account for gravity
  - ✓ Quid of dark matter ? Dark energy ?
  - ✓ Neutrino masses ?
  - ✓ Matter/anti-matter asymmetry ?
- Starting from 2026, the LHC (and its detector) will undergo a major jouvence
  - ✓ # of PU ~ 150 (vs 60 now)
  - ✓ 3000/ab collected by 2041 (x10 vs now)
  - ✓ Improved precision by a factor 4-5