Exploring the Standard Model with ATLAS and CMS

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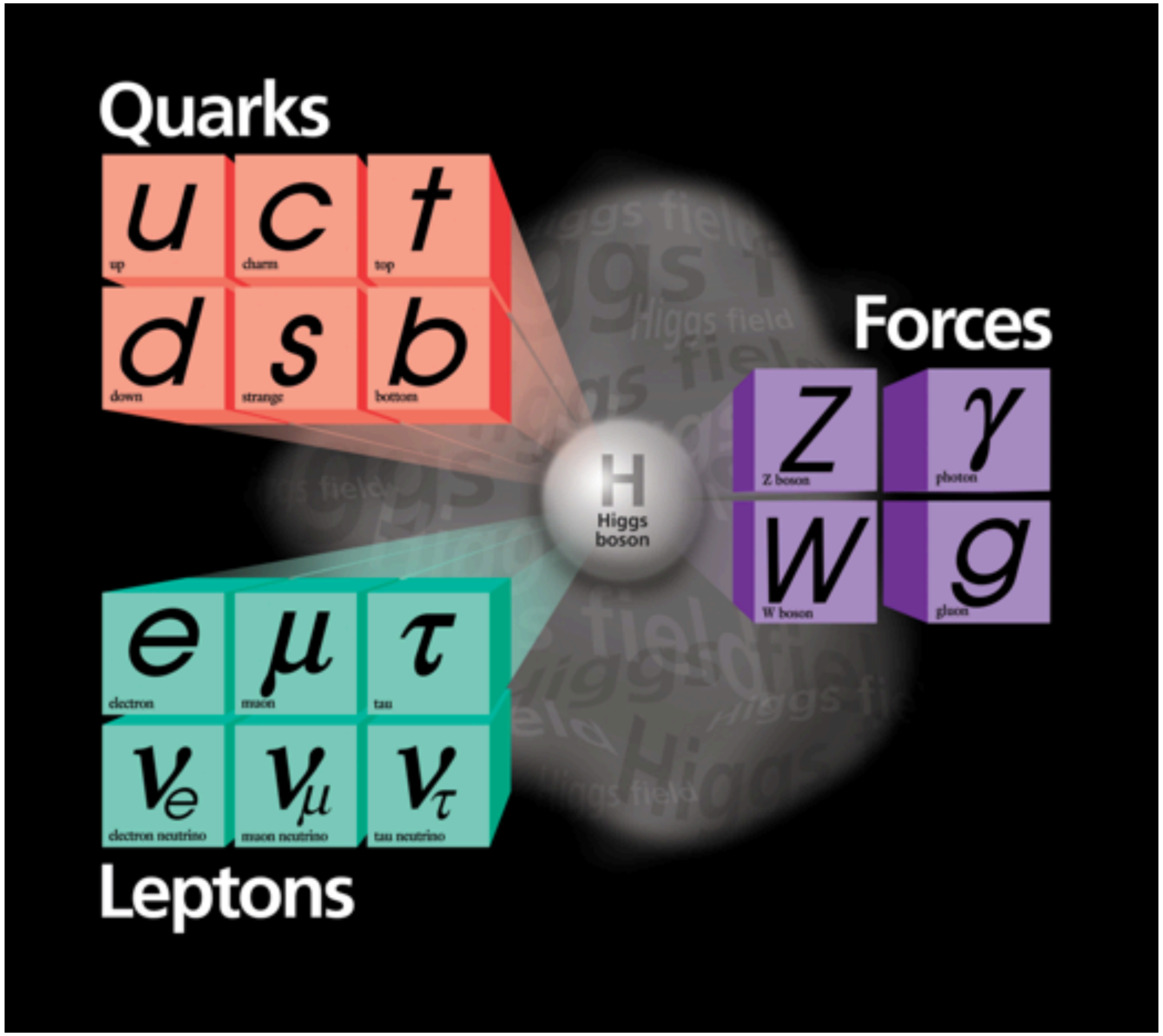
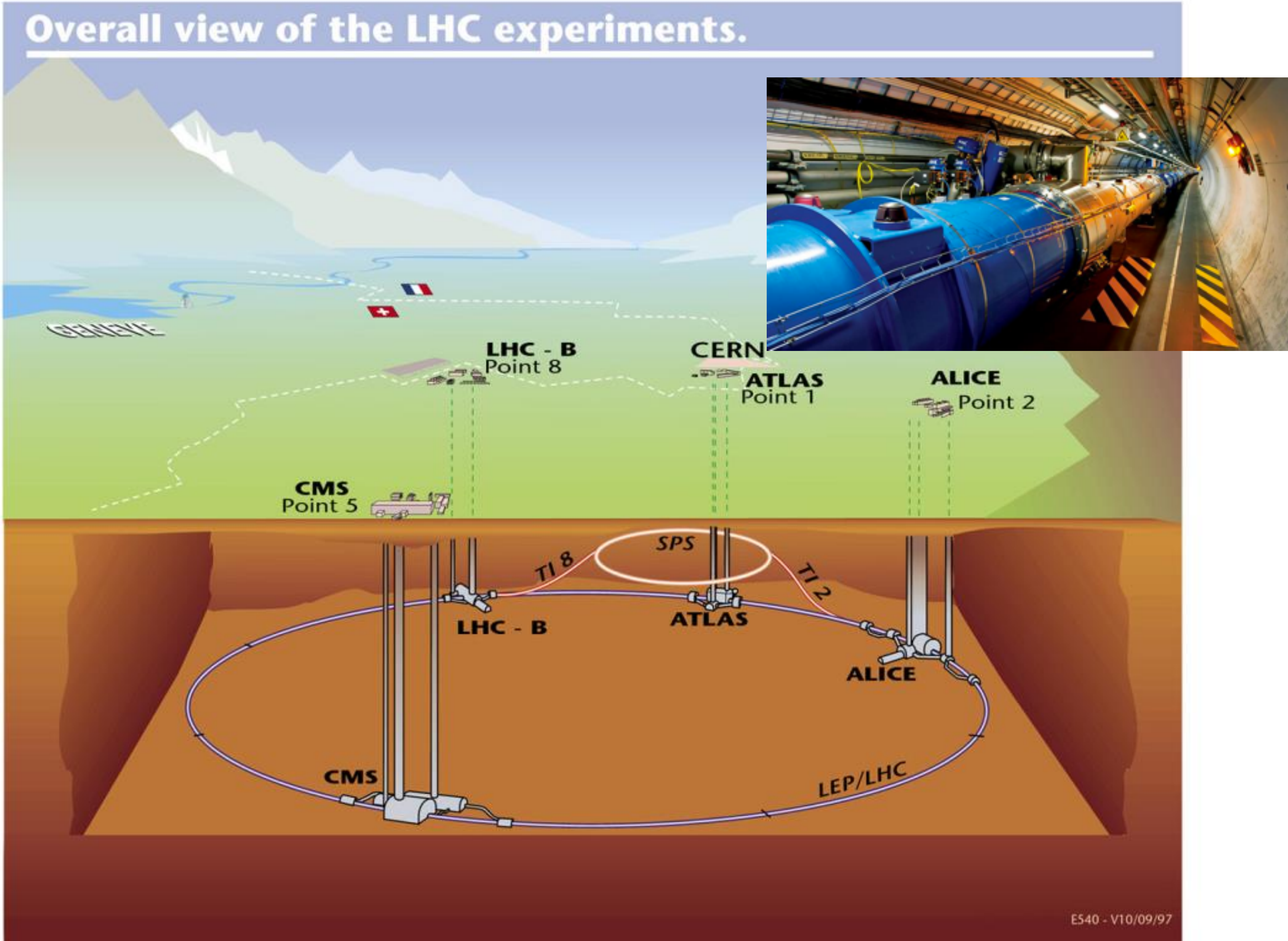
Thanks to Peter Mattig, Beate Heinemann and ATLAS and CMS!

The Standard Model



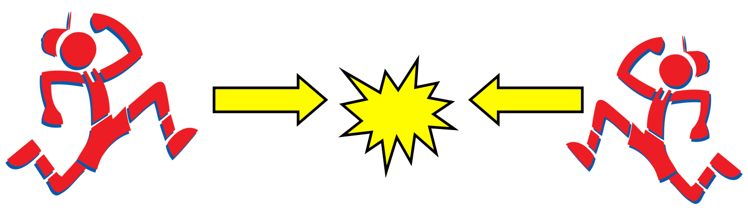
This lecture: how ATLAS and CMS (and D0) are used to explore the Standard Model

The LHC

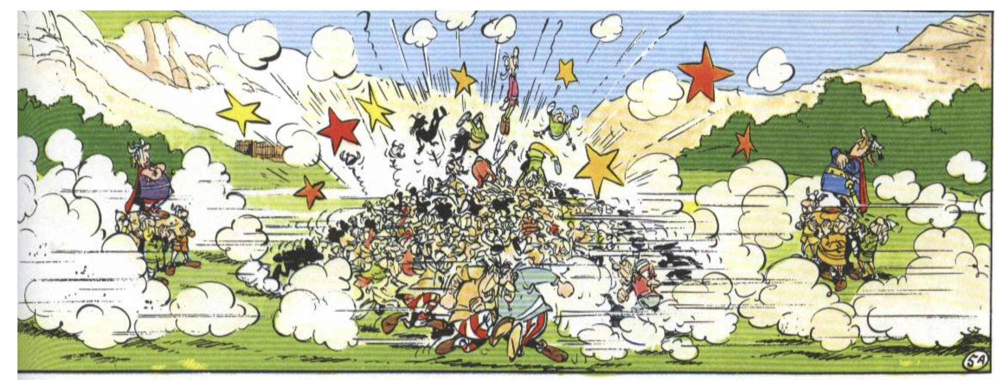

Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
E540 - V10/09/97

Why hadron colliders?

Lepton Collider (LEP)
Collision of two point-like particles

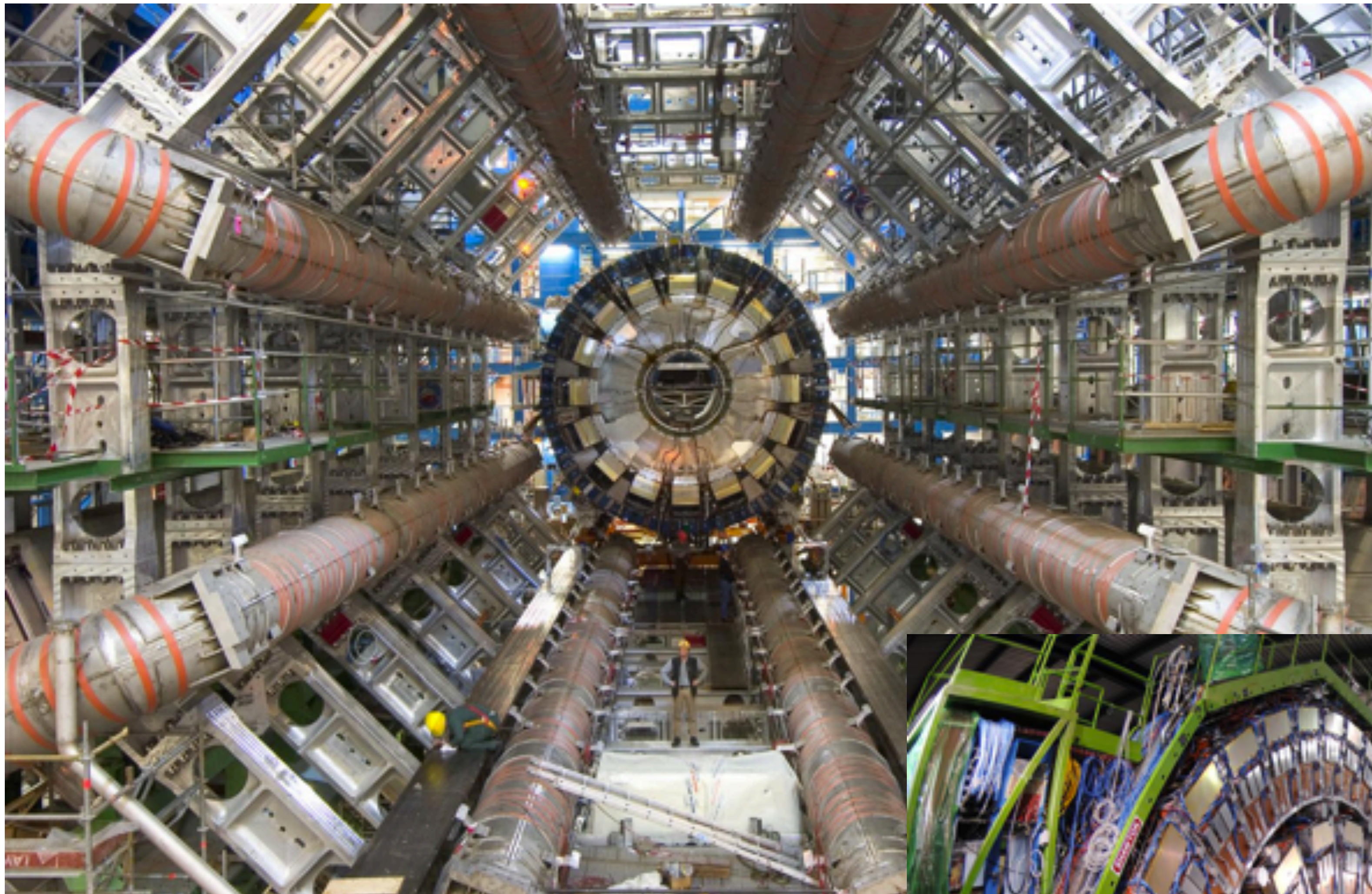


Hadron Collider (Tevatron, LHC)
Collision of ~50 point-like particles

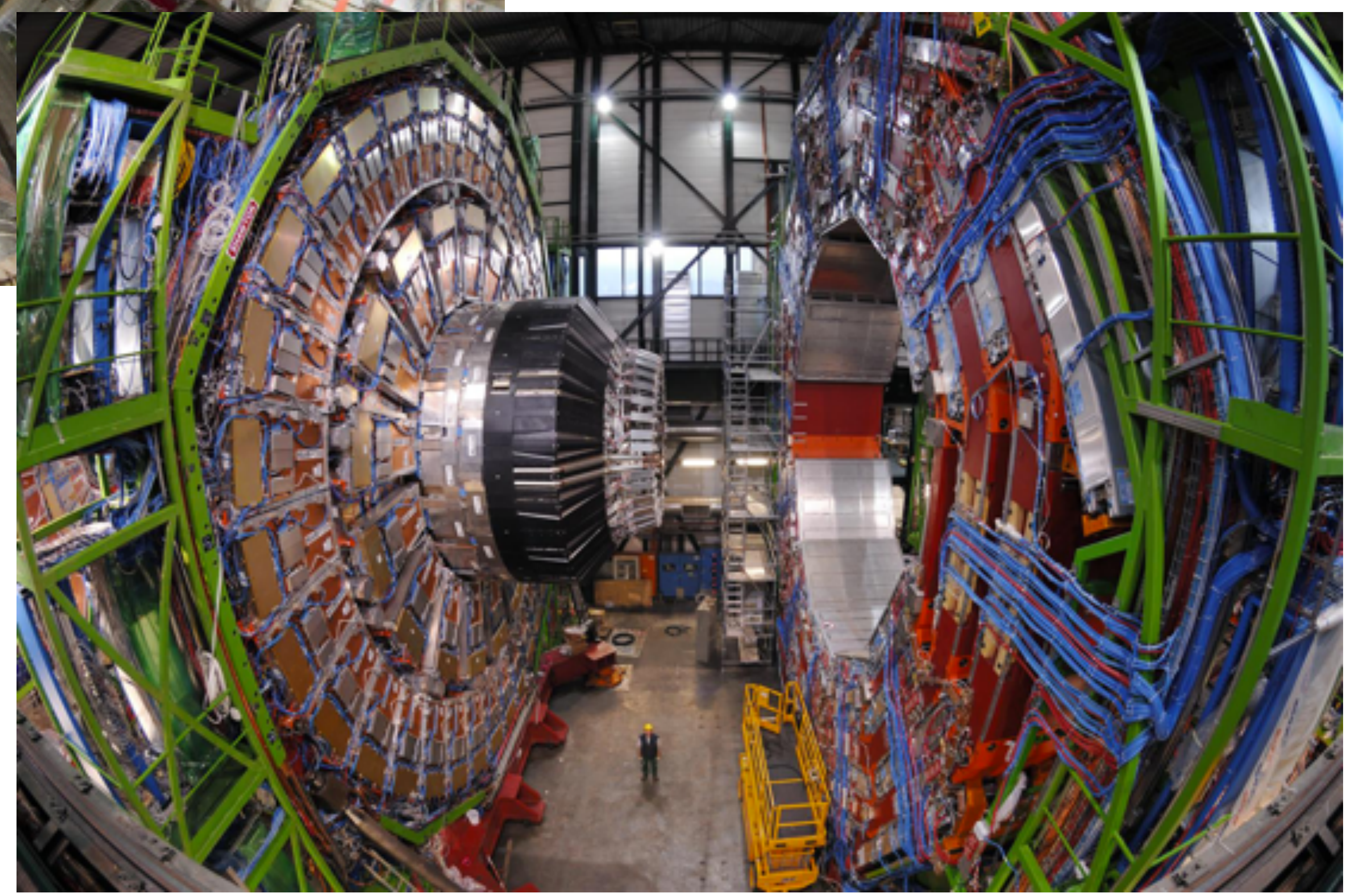


- Disadvantages
  - Hadrons are complex objects
  - High multiplicity of other stuff
  - Energy and type of colliding parton (quark, gluon) is unknown
- Advantage
  - Can access higher energies than e+e- colliders

ATLAS and CMS

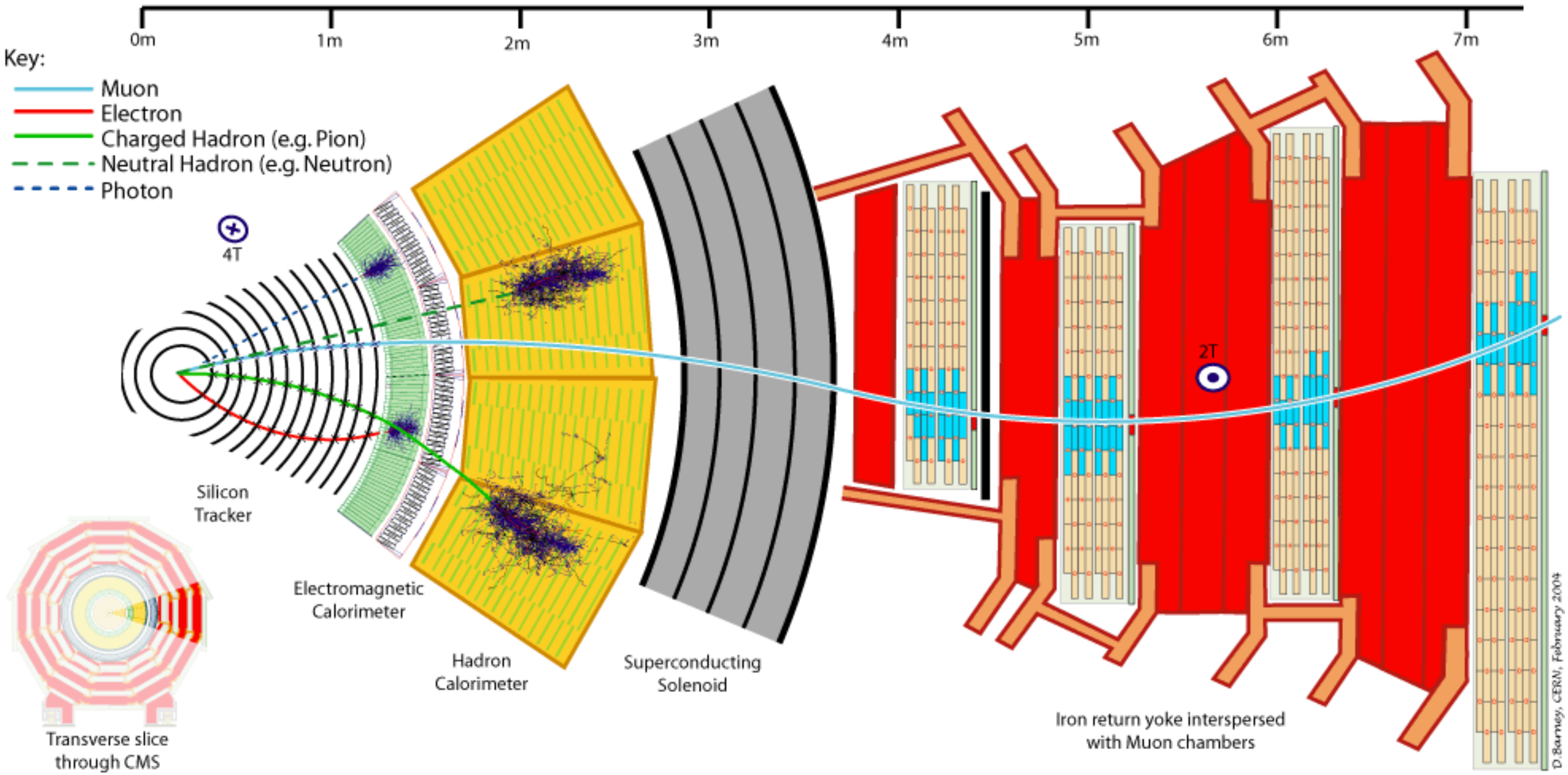


ATLAS



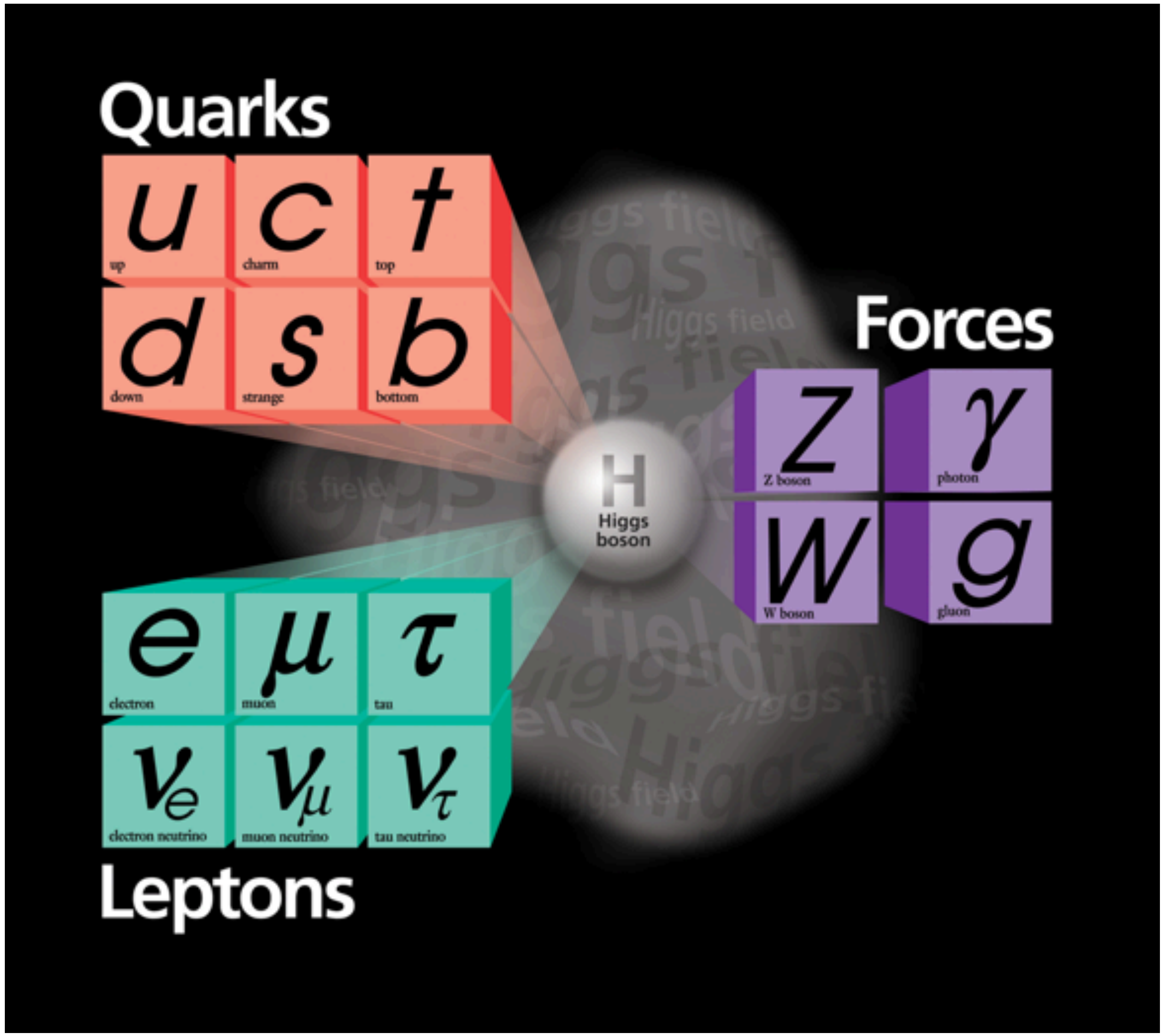
CMS

Reminder: Particles in a Detector



The Standard Model

A simplified picture



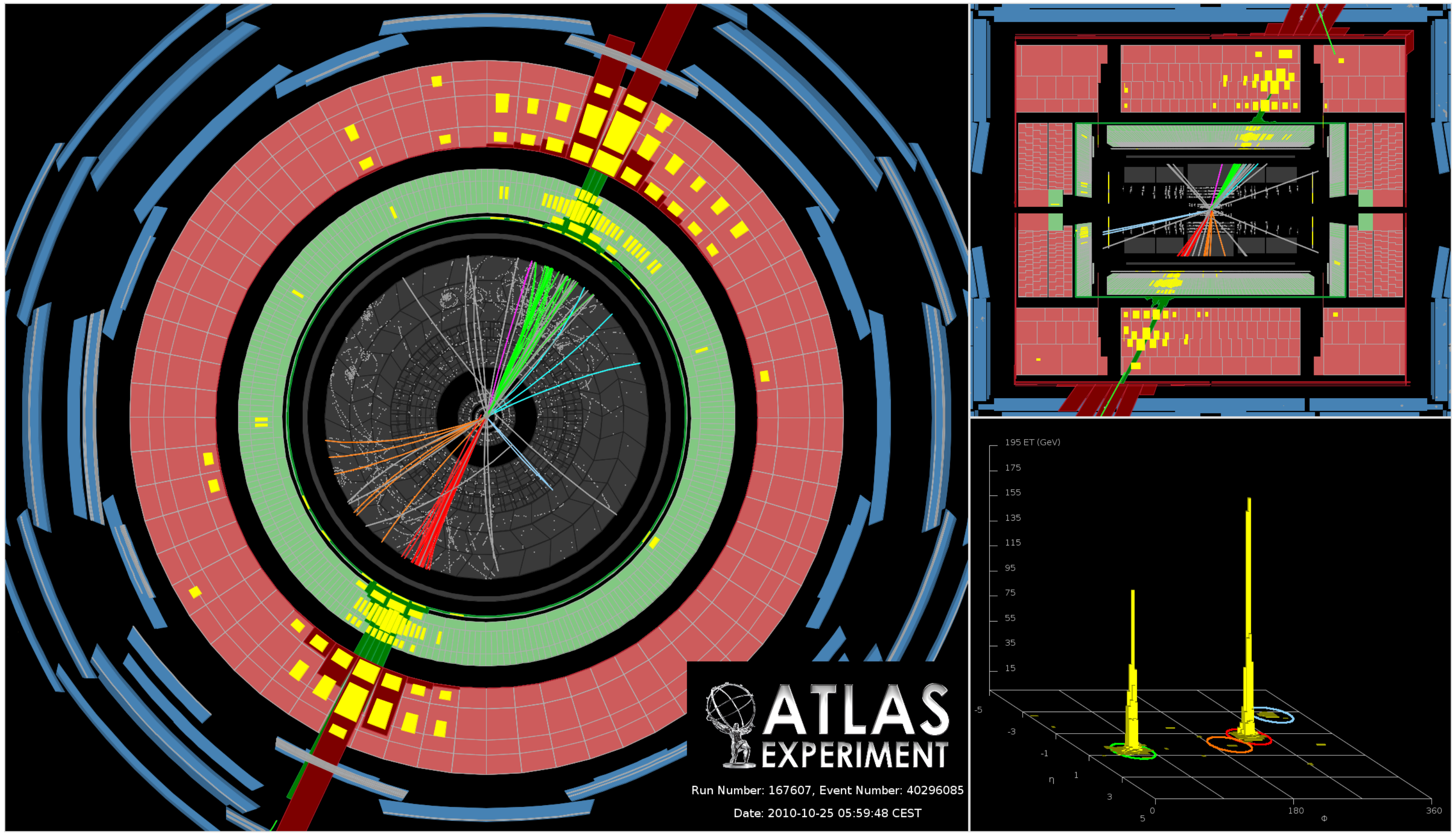
Force Carriers

Photons:
electromagnetic
force,
theory: Quantum
Electrodynamics
(QED)

Vector bosons
(W, Z)
weak force,
theory: Quantum
Electrodynamics
(QED)

Gluons:
strong force,
theory: Quantum
Chromodynamics
(QCD)

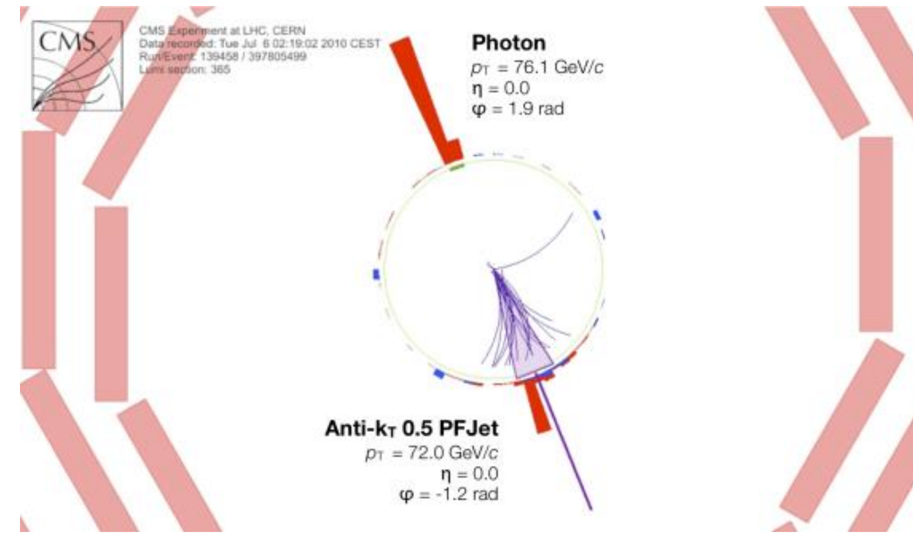
The Strong Interaction

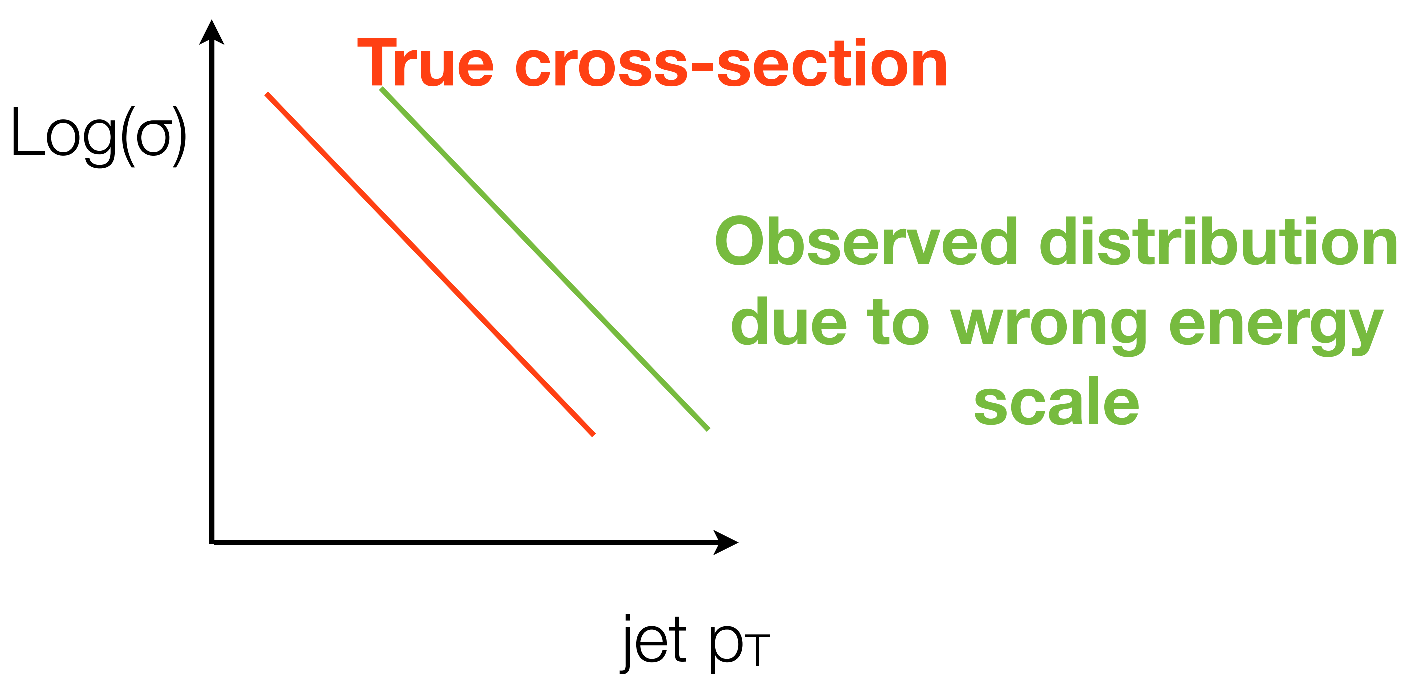


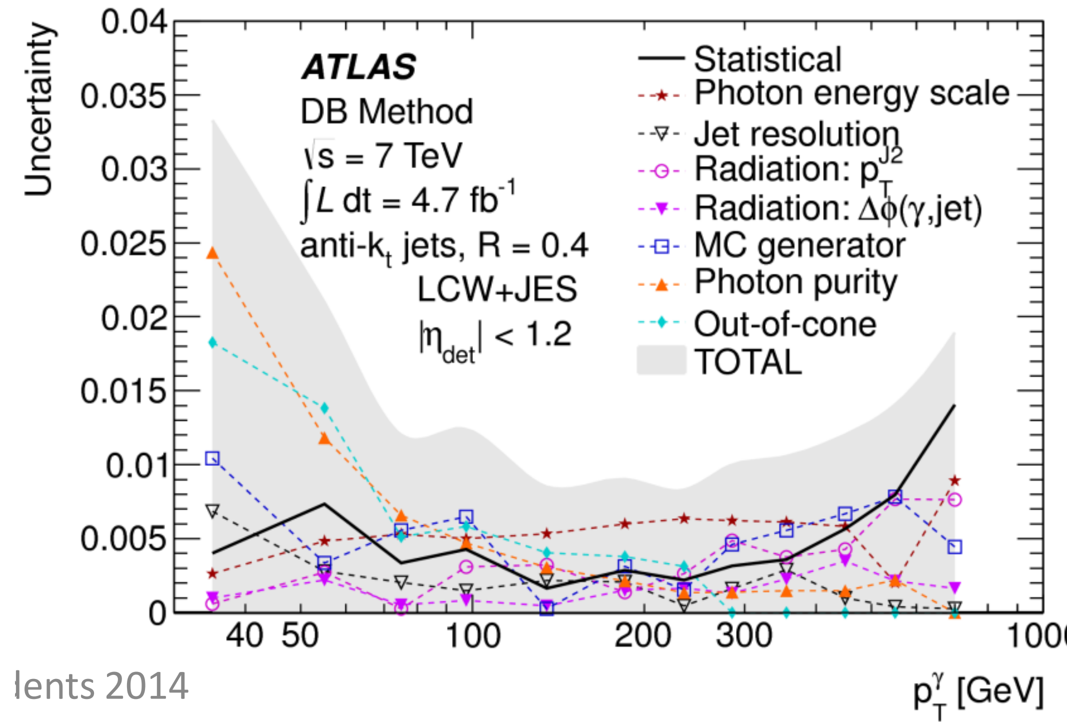
- **Jets**: energetic bundles of hadrons
    - How we observe quarks and gluons
    - Measure direction, energy and (sometimes) parton flavour
    - Allow direct tests of QCD: the **strong interaction**
    - Experimental challenge: extract jets from 1000 particles

Experimental Challenge: Jet Energy Scale

- Jet energy determined from calorimeter and tracking information
- How accurately is the scale known ?
  - Jet energy scale (JES) uncertainty
  - Large effects on cross-section measurements due to the steep slope
- Calibrate the jet energy scale using γ+jets data
  - Photon must balance the jet energy







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Test QCD at multi-TeV scales: jet cross-section

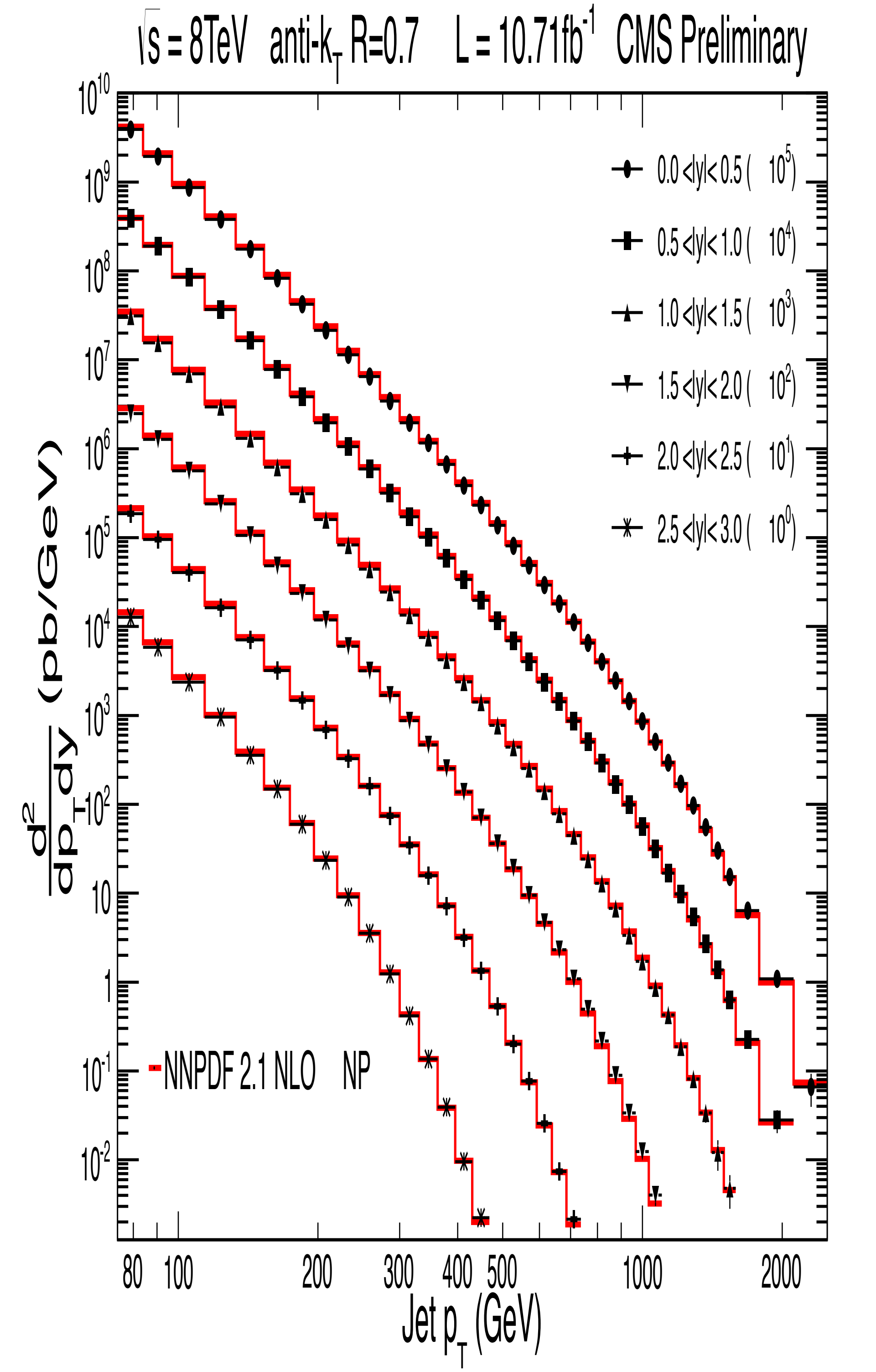
Number of observed events: counted

Background: measured from data/calculated from theory

$$\sigma = \frac{N_{\mathrm{meas}} - N_{\mathrm{bkg}}}{\epsilon \cdot \mathcal{L}}$$

Fraction of jet events retained after selection: optimised by experimentalist

Luminosity: How many proton collisions ?



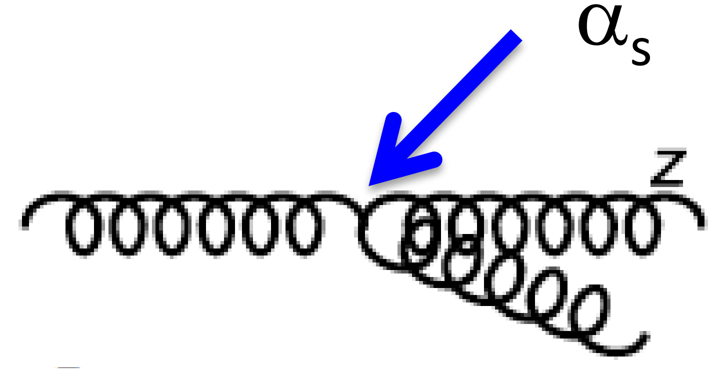
- Excellent agreement between theory and data over a huge range in phase space
  - 10 orders of magnitude
- Measure jets up to p_T of 2 TeV

Study the strong coupling

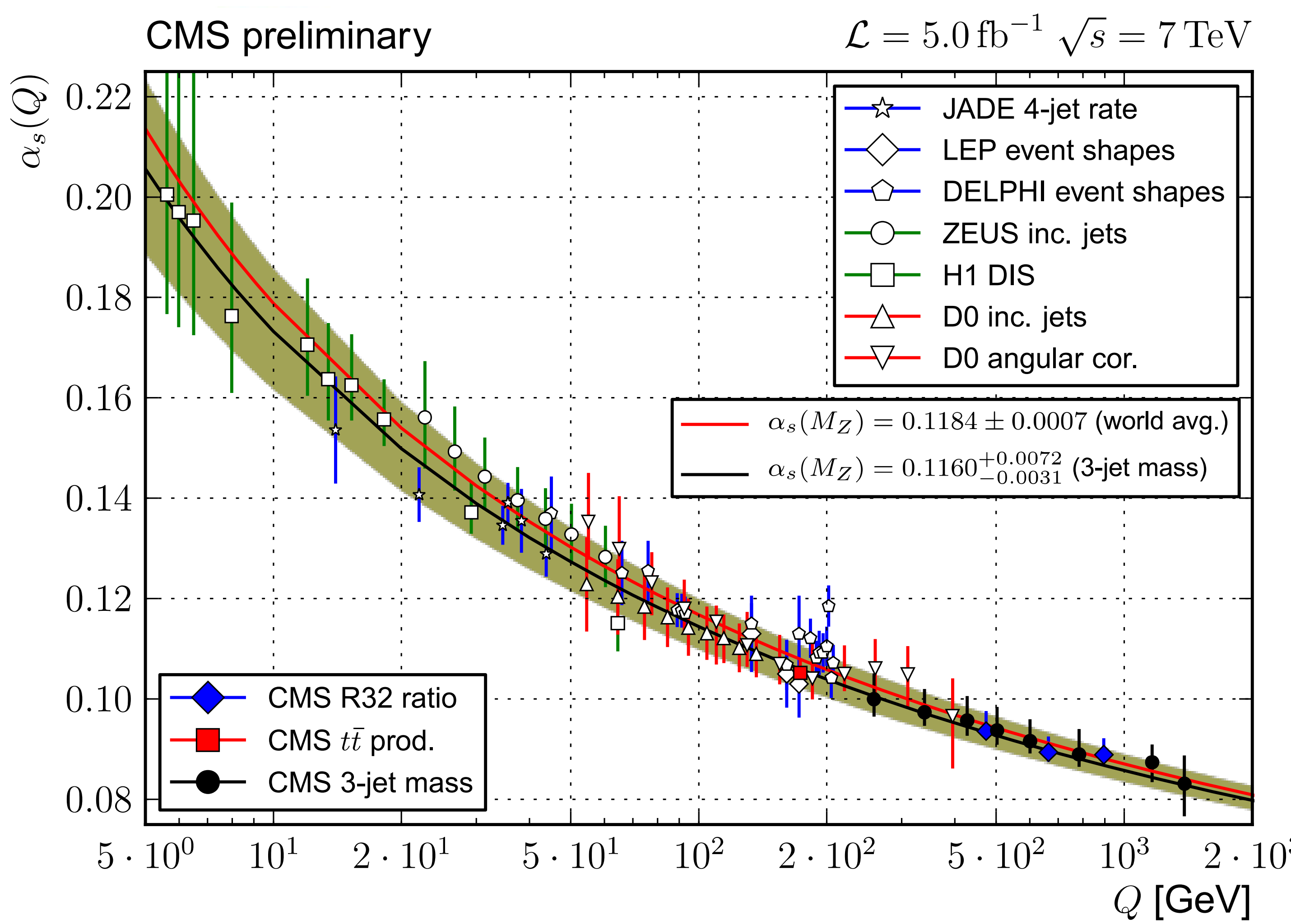
- Determine α_S from measurements using jets (3-jet fraction, jet mass)

$$\alpha_S^{\text{world}} = 0.1184 \pm 0.0007$$

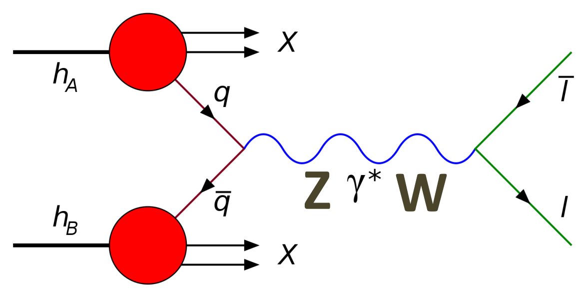
$$\alpha_S^{\text{LHC}} = 0.1160 \pm 0.0031$$



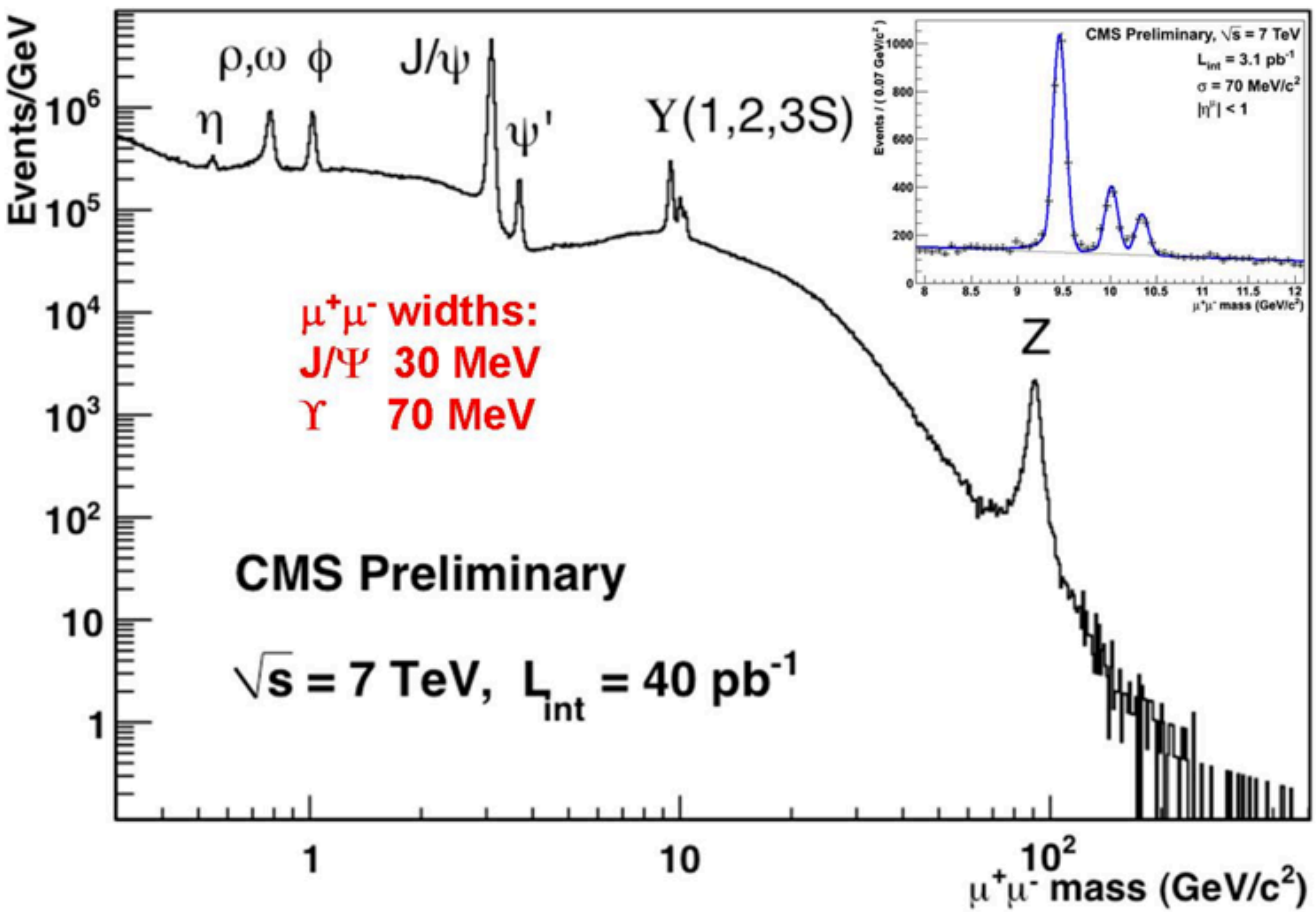
- Single value is less precise, but the LHC covers a huge energy range
- Energy dependence of α_S is clearly visible
    - running of the strong coupling



From the strong to the weak force

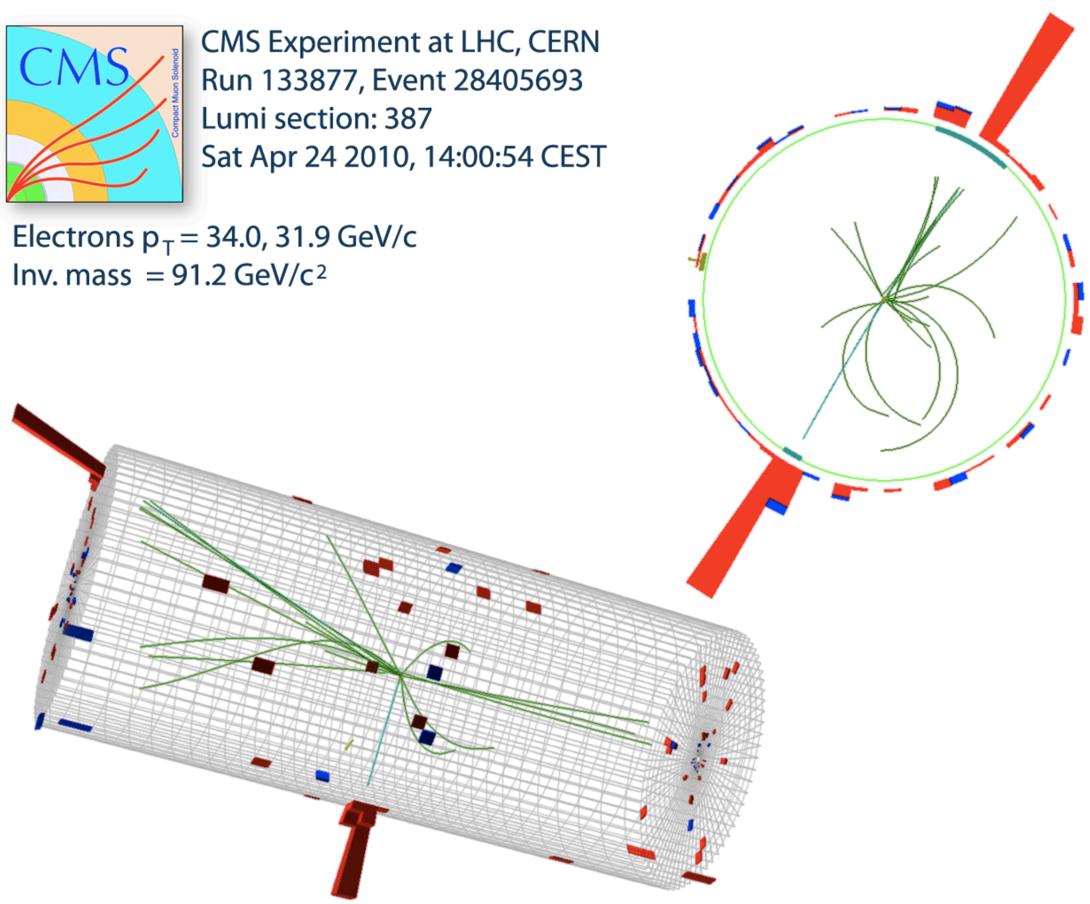


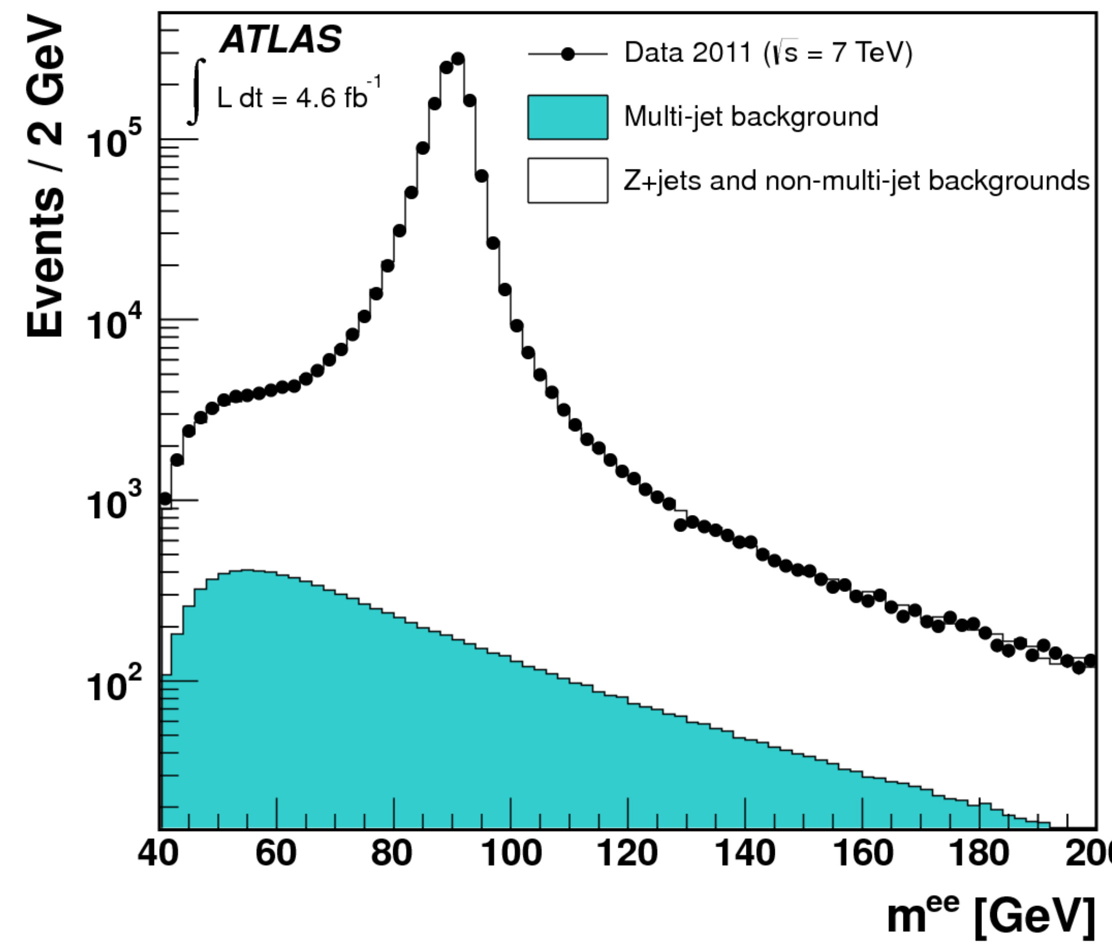
Use dilepton pairs to study resonances



Z reconstruction at the LHC

- When a Z decays to leptons, it is easy to reconstruct
  - e^+e, $^-\mu^+\mu^-$,$\tau^+\tau^-$
  - Only 3% of Z's decay into each lepton pair





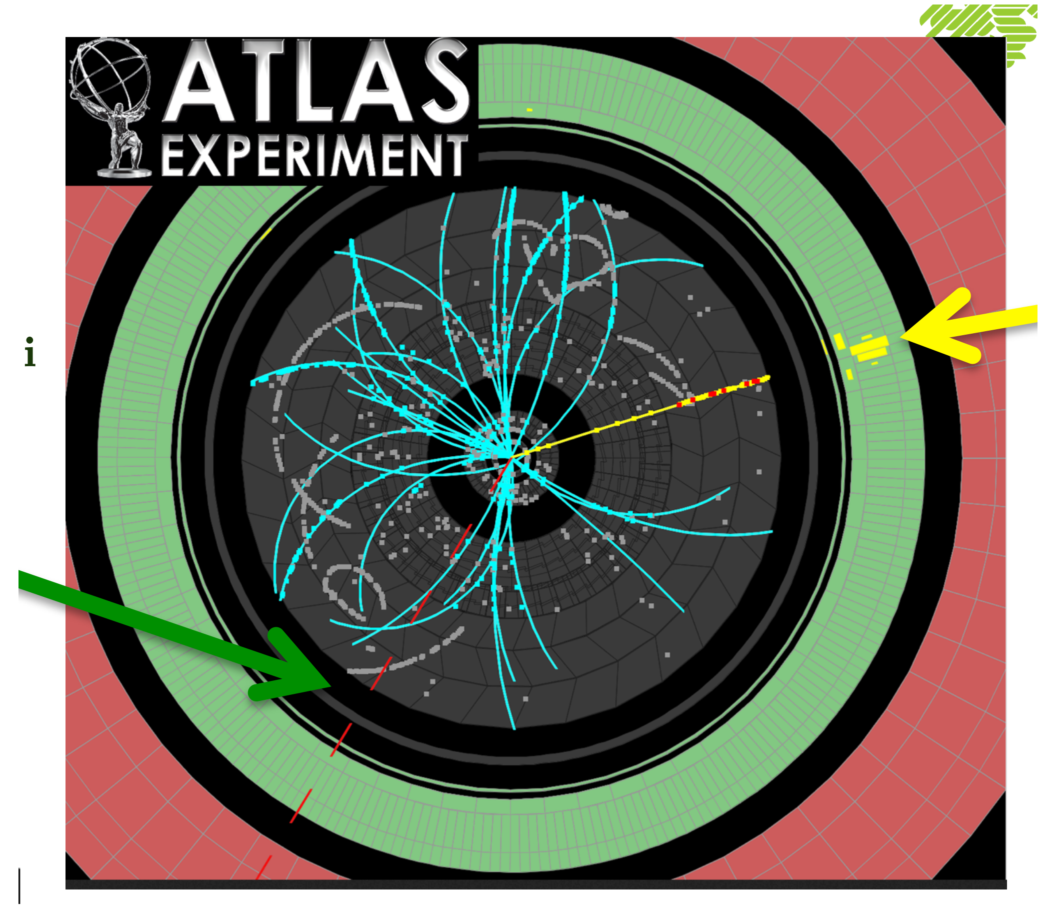
- Very clean signal and high statistics: 1 million Z^0/1 fb^{-1}
- A lot of physics! Important calibration tool

W reconstruction at the LHC

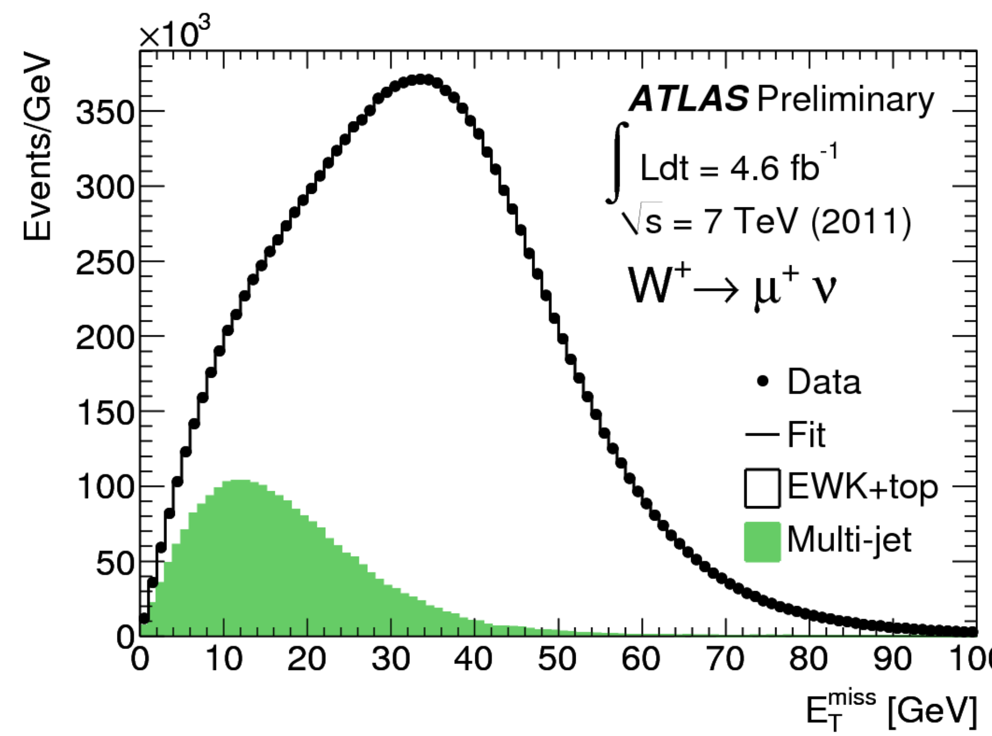
- Harder to reconstruct W's than Z's
  - Do not directly detect ν but rather look for unbalanced transverse momentum

$$\mathrm{MET}_{\mathrm{x}} = -\Sigma(p_{\mathrm{x}})_i$$

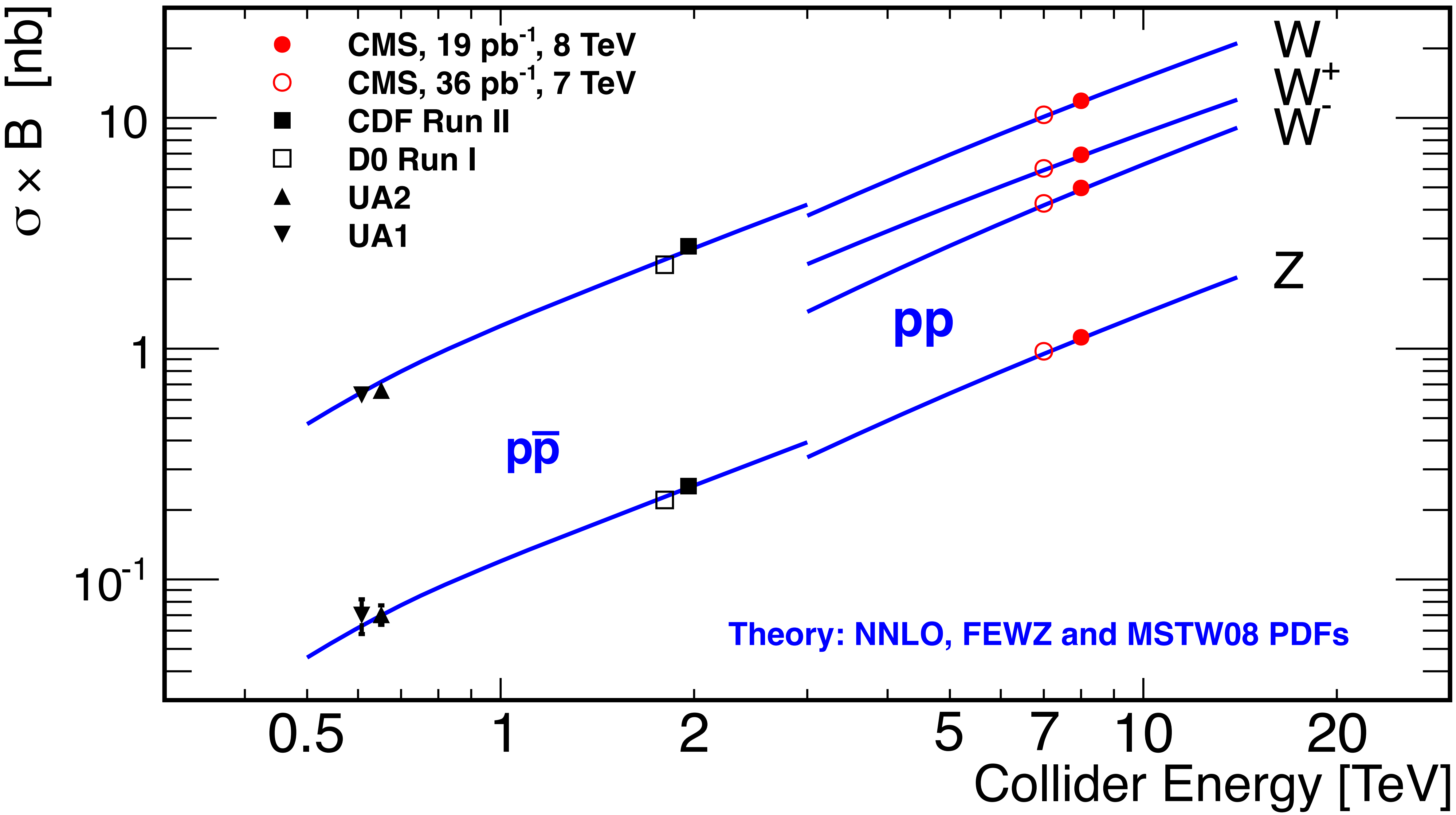
$$\mathrm{MET}_{\mathrm{y}} = -\Sigma(p_{\mathrm{y}})_i$$



- Fairly clean signal but no mass peak
- Cross-section is ~10x higher than for Z



W/Z Cross-section



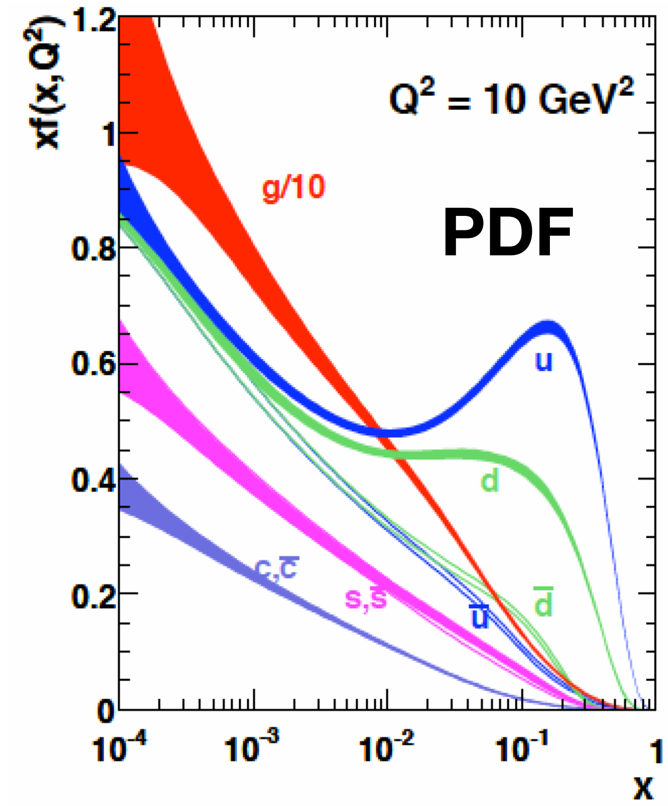
- Note different cross-sections for W^+ and W^- at the LHC

W± Bosons: A Closer Look

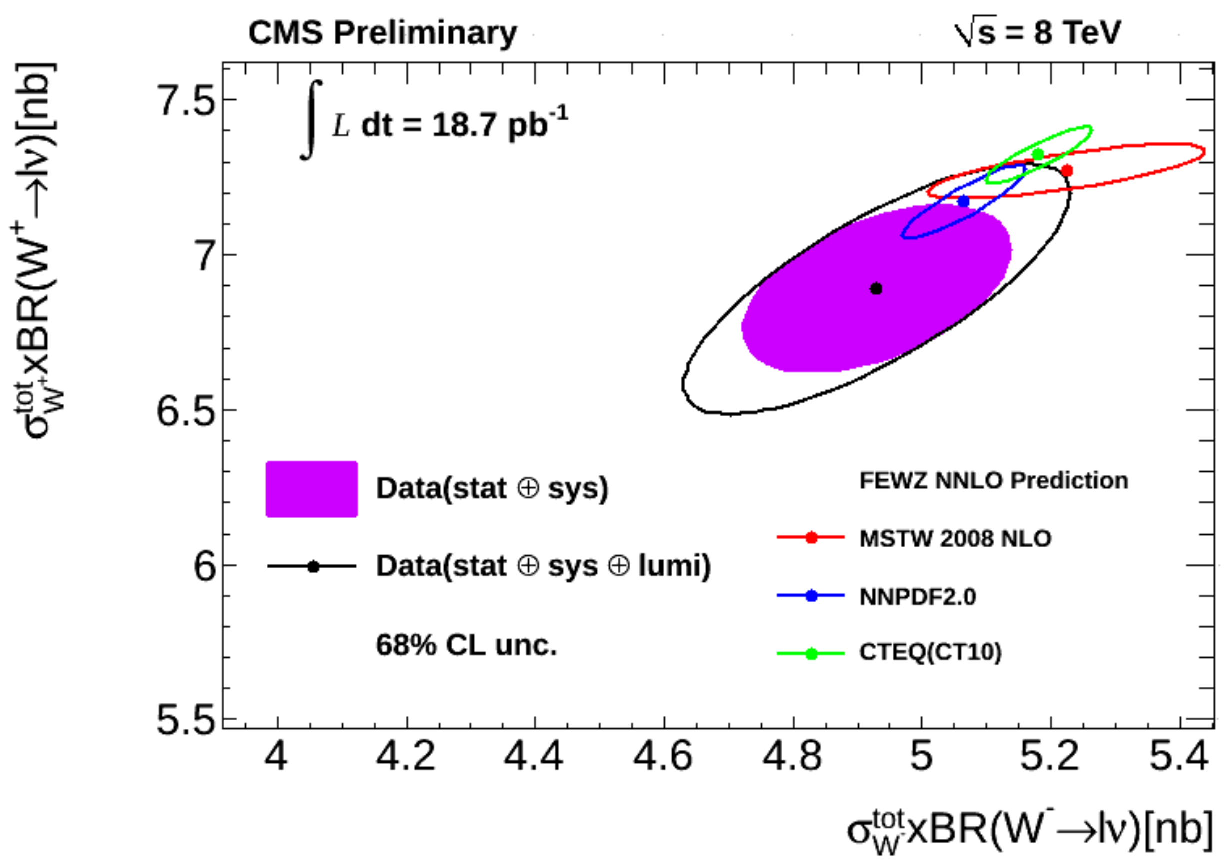
- W^+ and W^- production is slightly different

$$u\bar{d} \rightarrow W^+ \rightarrow \mu^+ \bar{\nu}_\mu$$

$$\bar{u}d \rightarrow W^- \rightarrow \mu^- \nu_\mu$$



- The valence quarks in the proton are uud
  - Easier to find u quarks than d quarks in the proton
- Sensitivity to different quark content constrains the parton density functions (PDFs)



The W mass

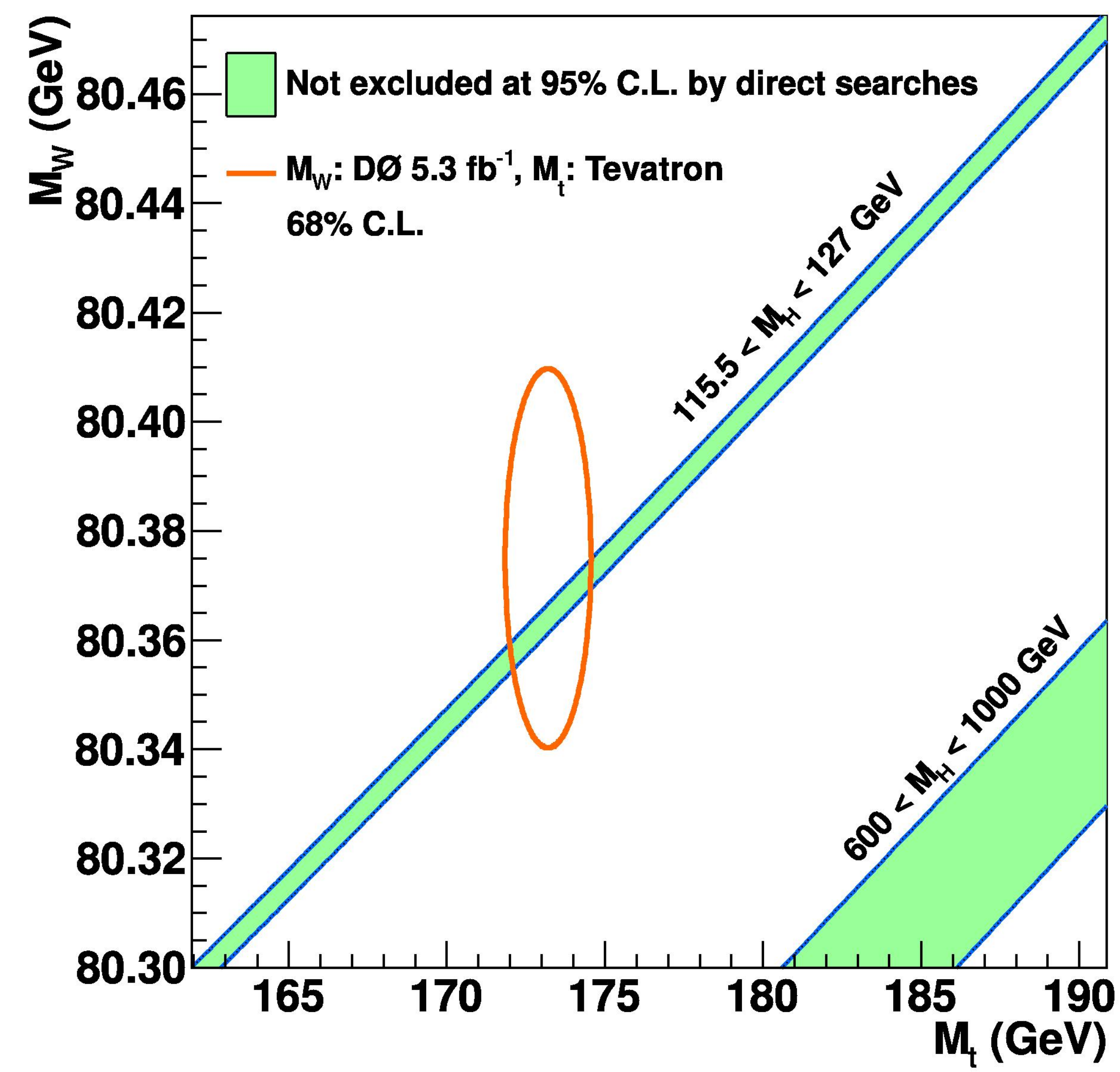
- Fundamental parameter of the Standard Model

$$G_\mu = \sqrt(2) \cdot \frac{g^2}{8 \cdot M_{\mathrm{W}}^2} = \frac{\pi\alpha}{\sqrt{2}} \frac{1}{M_{\mathrm{W}}^2 \cdot \sin^2\theta_W}$$

- G_μ: muon lifetime
    - Prediction for M_W
- Radiative corrections
    - Sensitivity to the mass of the Higgs boson
- Precise measurement at LEP:

$$M_{\mathrm{W}} = 80.376 \pm 0.033\ \mathrm{GeV}$$

4%



Measuring the W mass I

- Use energy conservation and measurements of the electron/muon and the neutrino

$$m_W^2 = (E_\ell + E_\nu)^2 - (\vec{p_1} + \vec{p_2})^2$$

- Questions
  - How accurately do we know the energy of the e/μ ?
    - Use M_Z to calibrate the energy scale
  - What is the energy and direction of ν ?
    - Use only the transverse momentum of ν: identify with missing transverse energy

$$m_W^2 \geq (E_\ell + MET)^2 - (\vec{p_1} + M\vec{E}T)^2$$

Measuring the W mass II

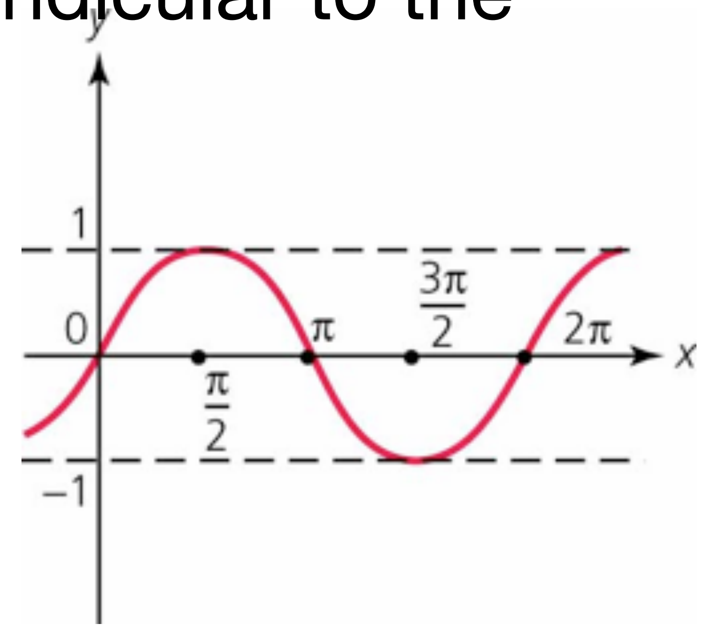
- Largest phase space if W boson decays perpendicular to the direction of flight

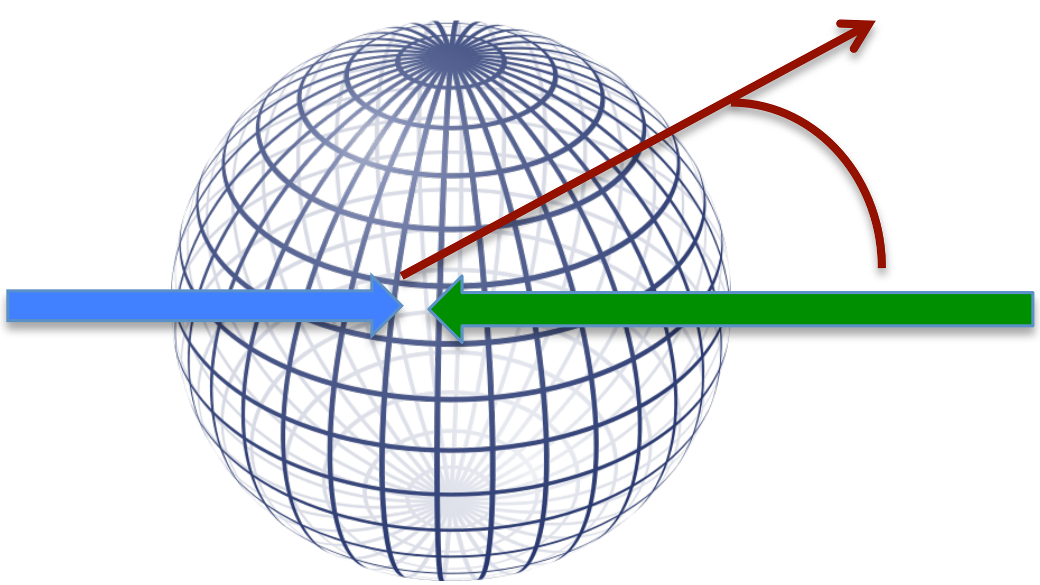
$$p_T(\ell) = \frac{m_{\mathrm{W}}}{2}\sin\theta^*$$

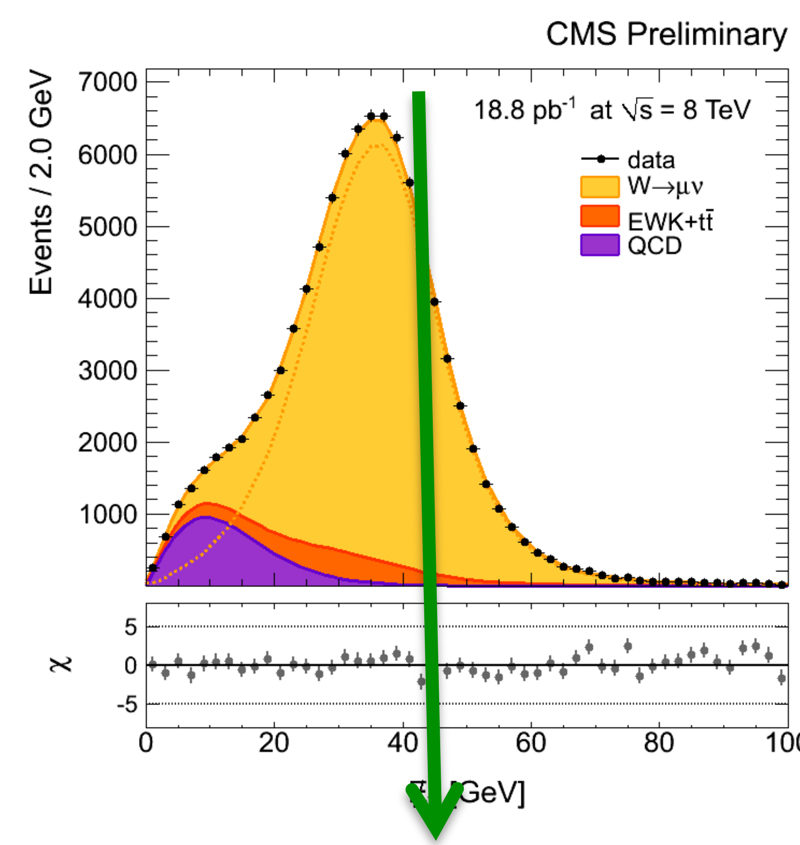
$$p_{\mathrm{T}}^{max} = m_{\mathrm{W}}/2 \qquad \theta^* = \pi/2$$

$$\cos\theta^* = \sqrt{1 - 4\cdot p_T^2/M_W^2}$$

$$\frac{d\sigma}{dp_T^2} = \frac{d\sigma}{d\cos\theta^*}\,\frac{2/m_W}{m_W^2 - 4\cdot p_T^2}$$

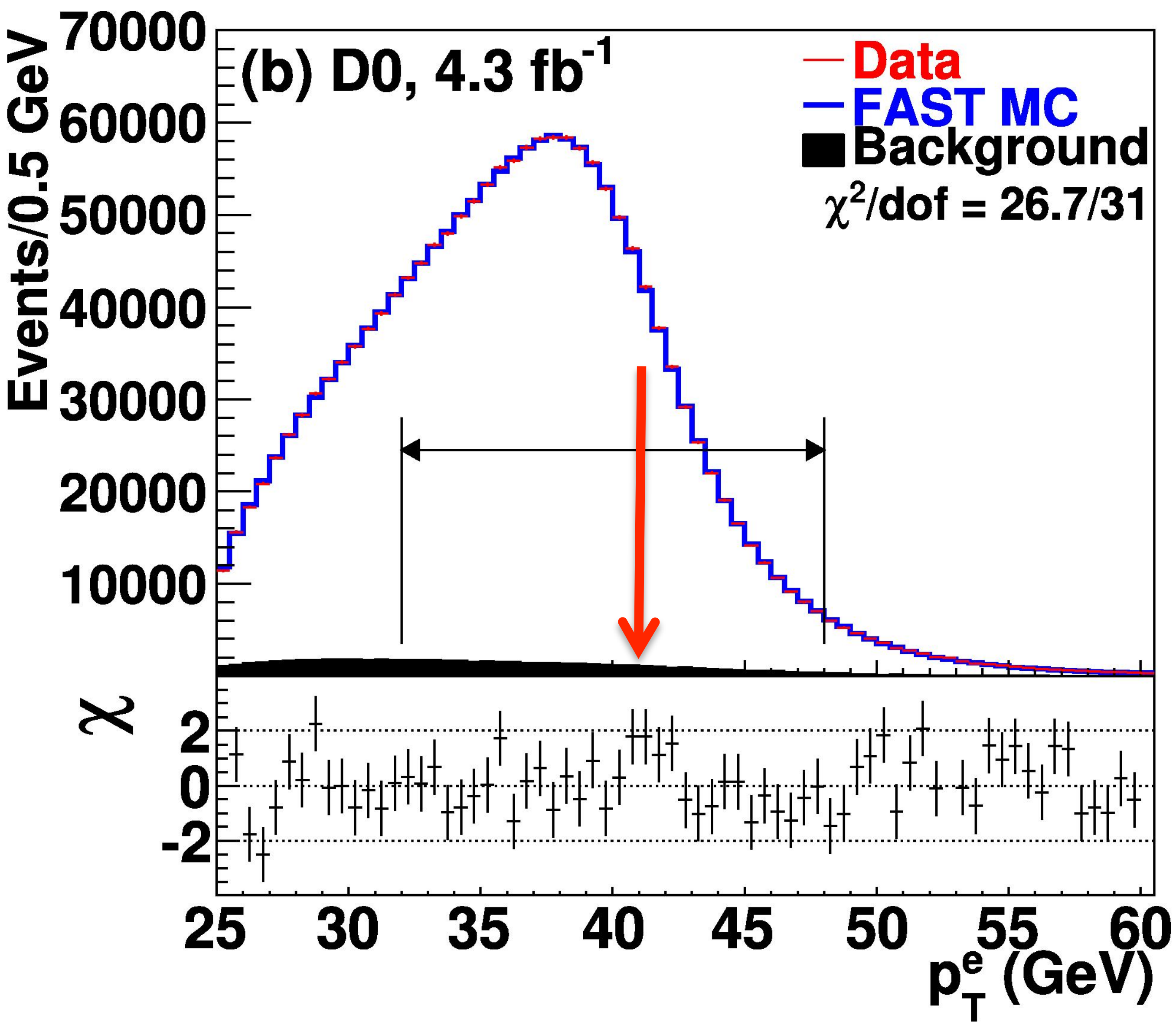






Sharp fall - off

Smearing

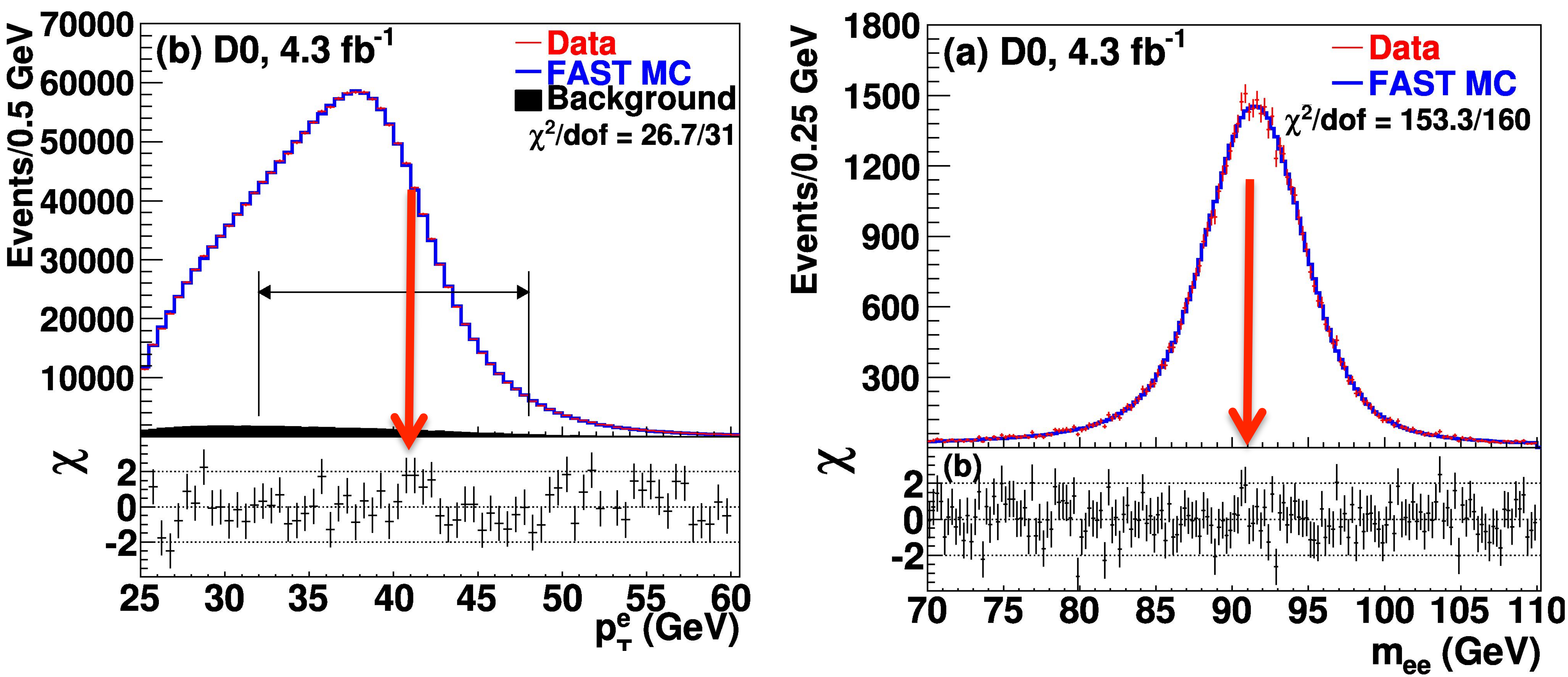


$$m_{\rm W} = 80.342 \pm 0.014 \text{ GeV}$$

- Fast drop around $m_W/2$ but smeared out
  - W boson width (~2 GeV)
  - QCD effects
  - detector distortion
- Experimental challenge
  - Accurate control of systematics
    - Use similarity between Z and W

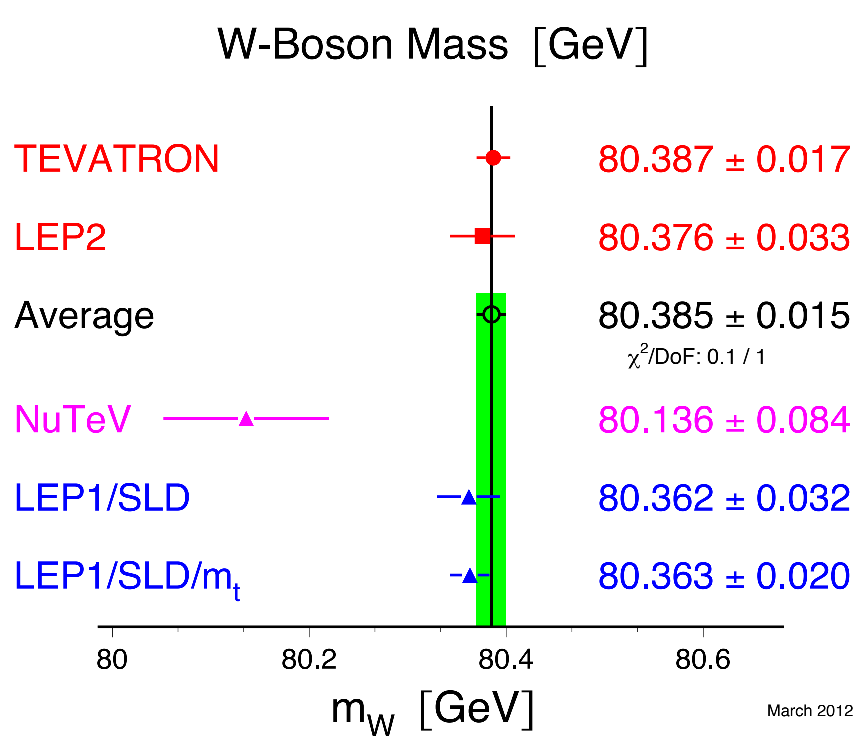
Measuring the energy

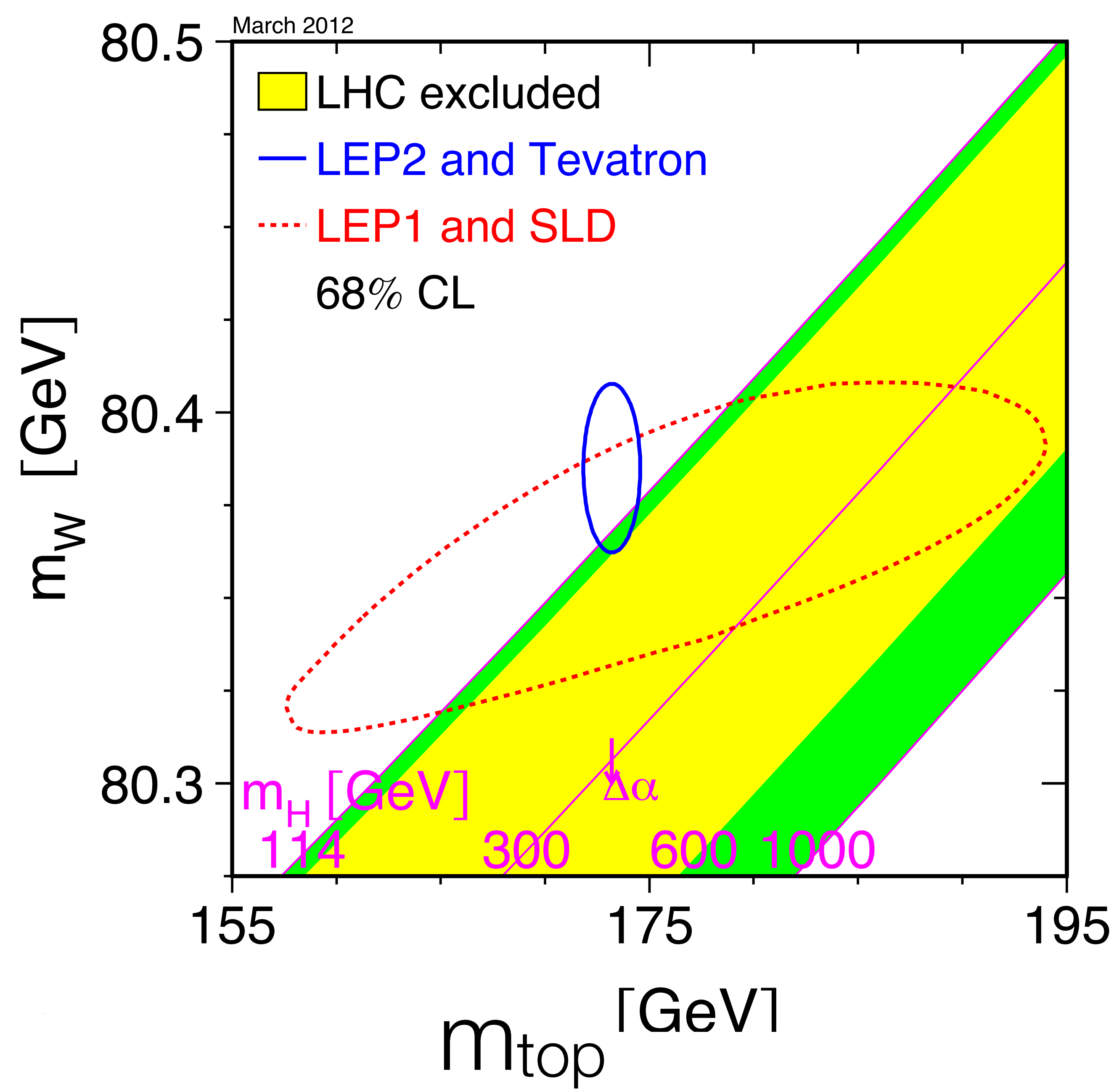
- How well do we know the true energy?
- Z measurement provides excellent control of the energy scale
- Measure Z: calibrate such that m_Z = 91.1882 GeV



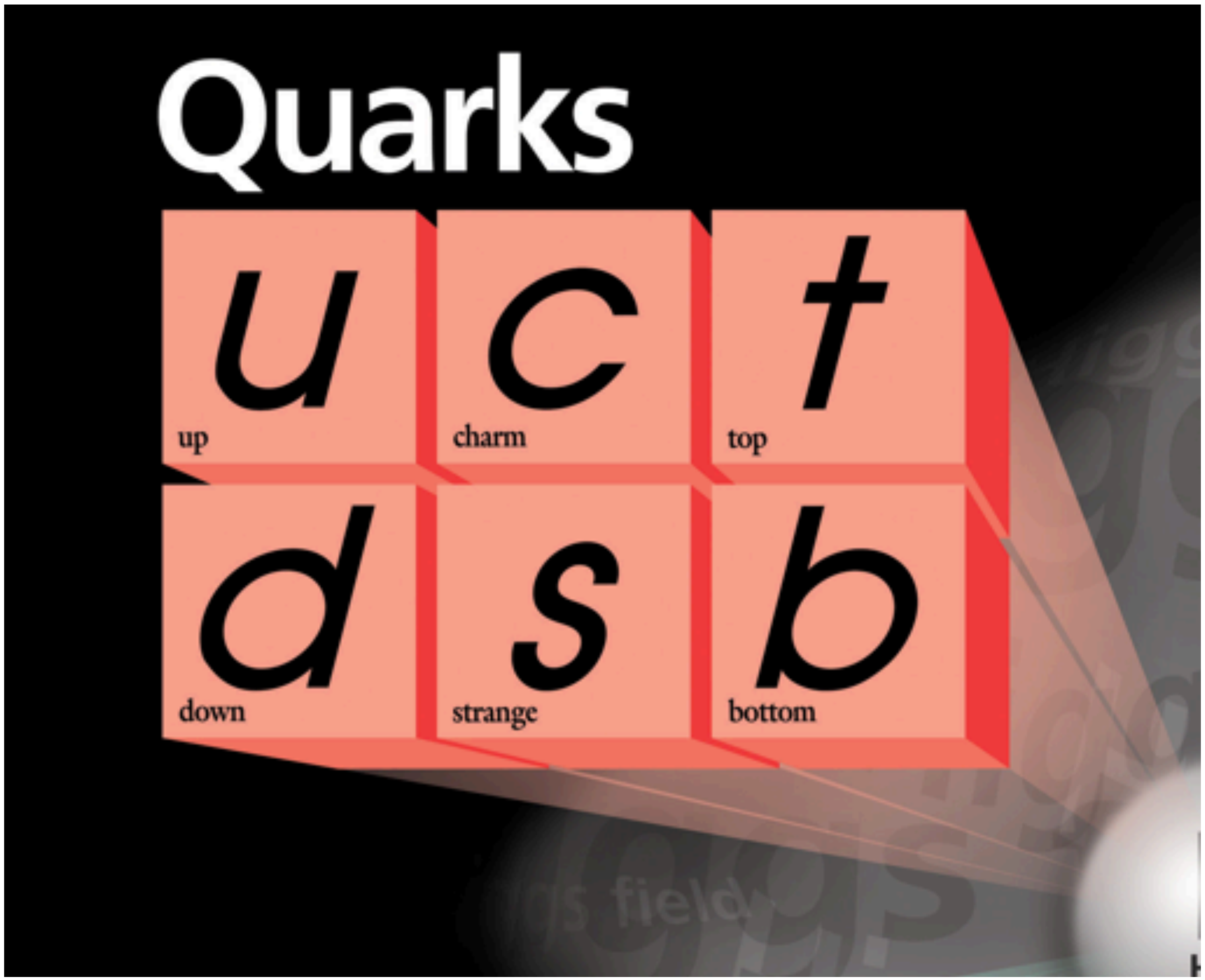
W mass result

- Obtain W mass from template fits to distributions: p_T, m_W, MET
- D0 measurement obtained same precision as the world average
  - Demonstrates the high precision is possible at hadron colliders
- Strong constraint on Standard Model Higgs





Quarks

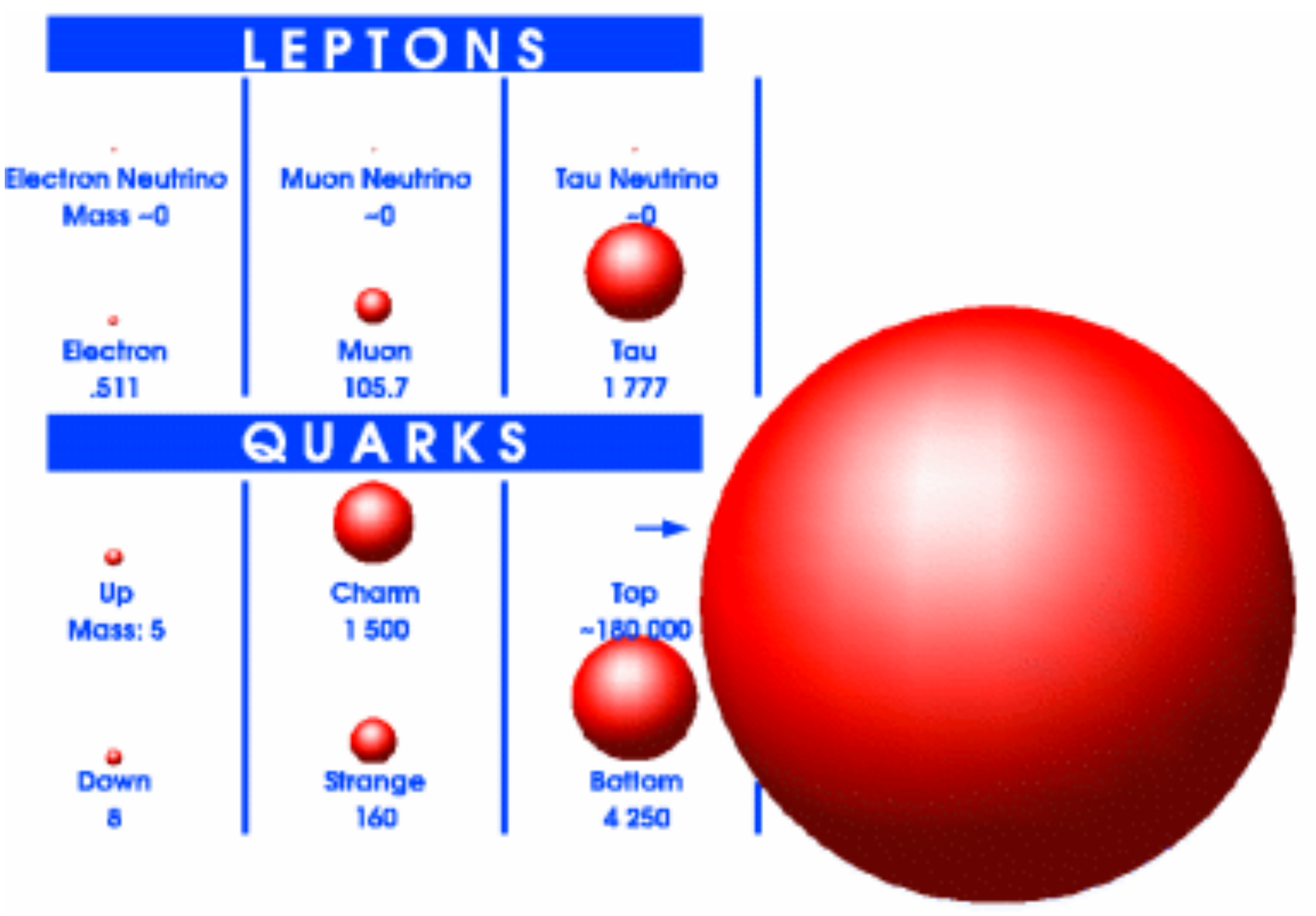


The mysterious top quark

- Top quark: no internal structure but as heavy as a gold atom

$$m_{\mathrm{t}} = 173.3 \pm 1.1 \text{ GeV}$$

- Coupling strength to Higgs boson scales with the mass



$$m_{\mathrm{t}} = \frac{\lambda_t \cdot v}{\sqrt{2}}$$

$$\lambda_{\mathrm{t}} = 0.996 \pm 0.006$$

Does the top quark have a special role ?

A constrained giant

- Top quark is similar to the up-quark, electron and neutrino
- All are matter particles

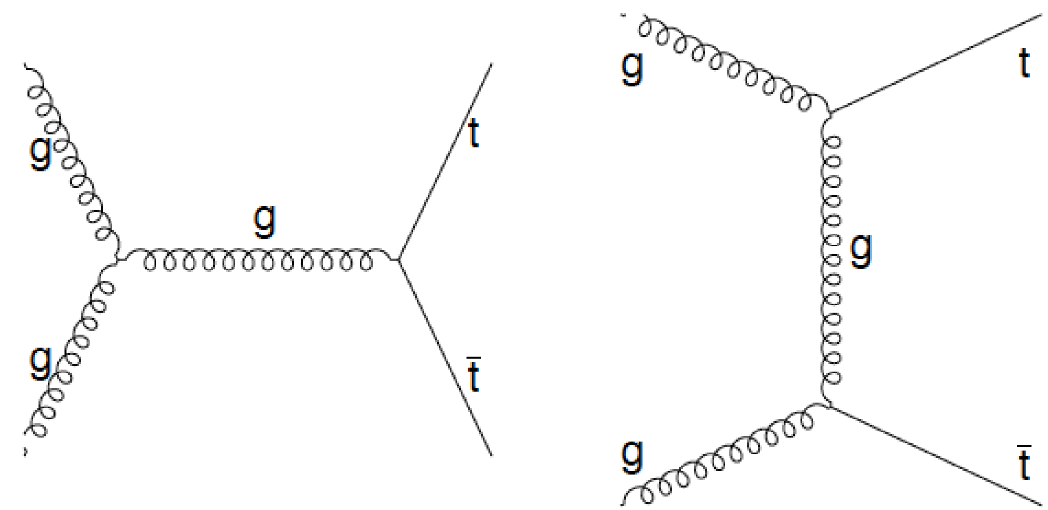
$$\frac{m_\nu}{m_{\rm top}} \sim 10^{-11} \qquad \frac{m_{\rm up}}{m_{\rm top}} \sim 10^{-5}$$

- Does the top quark have the same properties as light fermions ?
    - Coupling strength to photons, gluons, W bosons
    - Charge
    - Weak parity violation

A semileptonic top event

An example: Measuring the top cross-section

- Test QCD using massive quarks
- Measure the coupling strength of gluons to top quarks
- Event selection
  - 4 high p_T jets
  - isolated electron or muon
  - missing transverse energy



$$\sigma = \frac{N_{\mathrm{meas}} - N_{\mathrm{bkg}}}{\epsilon \cdot \mathcal{L}}$$

Luminosity

- Measure of the number of proton collisions
- Single most important quantity
- Drives our ability to detect new processes

revolving frequency: 11245.5 s^{-1}

number of bunches: 2808

protons per bunch: 1.15 x 10^{11}

$$L = \frac{f_{\rm rev} n_{\rm bunch} N_p^2}{4\pi\sigma_{\rm x}\sigma_{\rm y}}$$

Beam area: 40 μm

- Direct input to the rate of physics processes per unit time

Efficiency (ε): Optimised by experimentalist

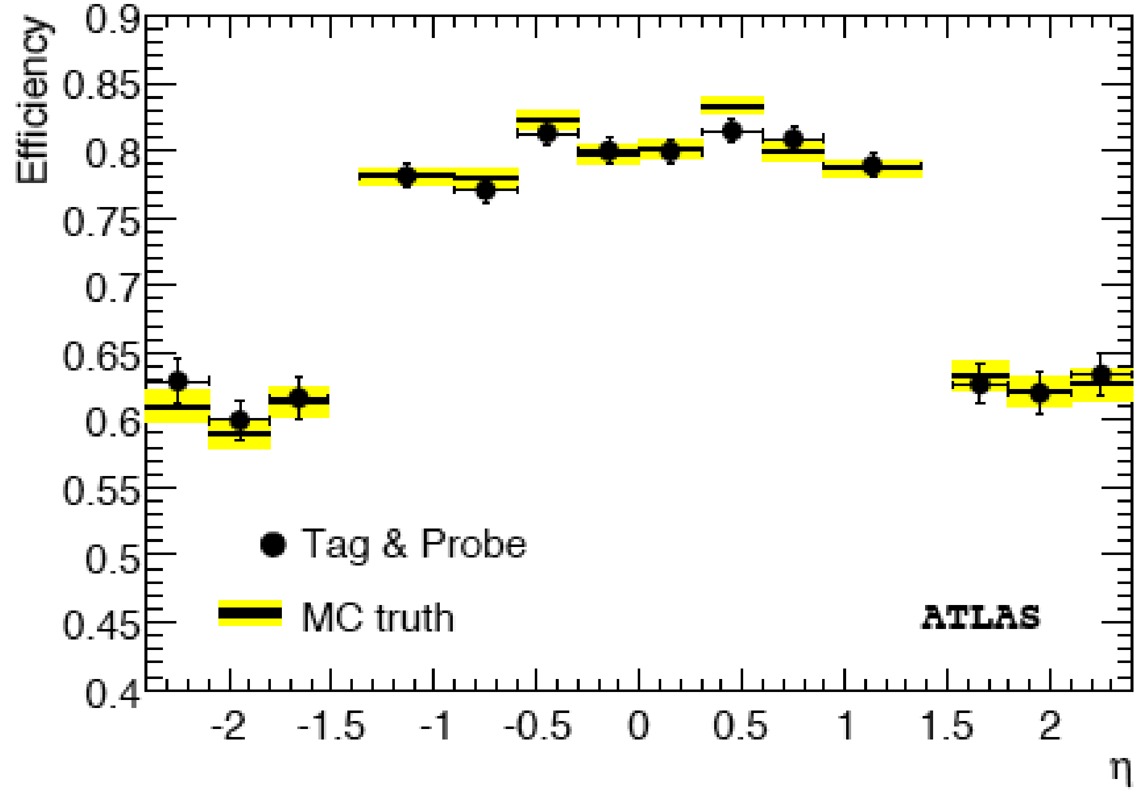
$$N_{\rm meas} = \int L dt \cdot \epsilon \cdot \sigma$$

Cross-section (σ): Given by nature and calculated by theorists

- Ability to observe or measure something depends on N_{meas}

Efficiency Example: Electrons

- Goal
  - **High efficiency** for (isolated) electrons
  - **Low misidentification** of jets
- Cuts: shower shape, low hadronic energy, track requirement, isolation
- Performance
  - Efficiency measured from Z's: tag and probe method
  - Measure "scale factor"
    - $$\mathrm{SF} = \frac{\epsilon_{\mathrm{data}}}{\epsilon_{\mathrm{MC}}}$$
    - 1 for perfect MC



Typical Efficiencies

Loose cuts: 88%

Tight cuts: 65%

$$\sigma = \frac{N_{\mathrm{meas}} - N_{\mathrm{bkg}}}{\epsilon \cdot \mathcal{L}}$$

Efficiency: Uncertainties

- How well do we know this efficiency ? **Uncertainty**
- For ATLAS, **material** in the inner detector is 20-90% X_0
- Material causes difficulties for electron/photon identification
  - Bremsstrahlung
  - Photon conversions
- Our uncertainty on the material directly translates into an uncertainty on the electron efficiency
- Constrain the material using data
  - Photon conversions
  - E/p distribution
  - Number of e^+e^- events

Cross-section determination

- How accurately we measure the cross-section depends on how accurately we measure each component
- **Largest uncertainties** are
  - Modelling of top
  - parton distribution function
  - number of background events
  - jet energy scale
  - selection efficiency e, μ
- **Total uncertainty** is 4.3%
  - Experimental: 2.3%
  - Luminosity: 3.1%
  - Beam energy: 1.7%

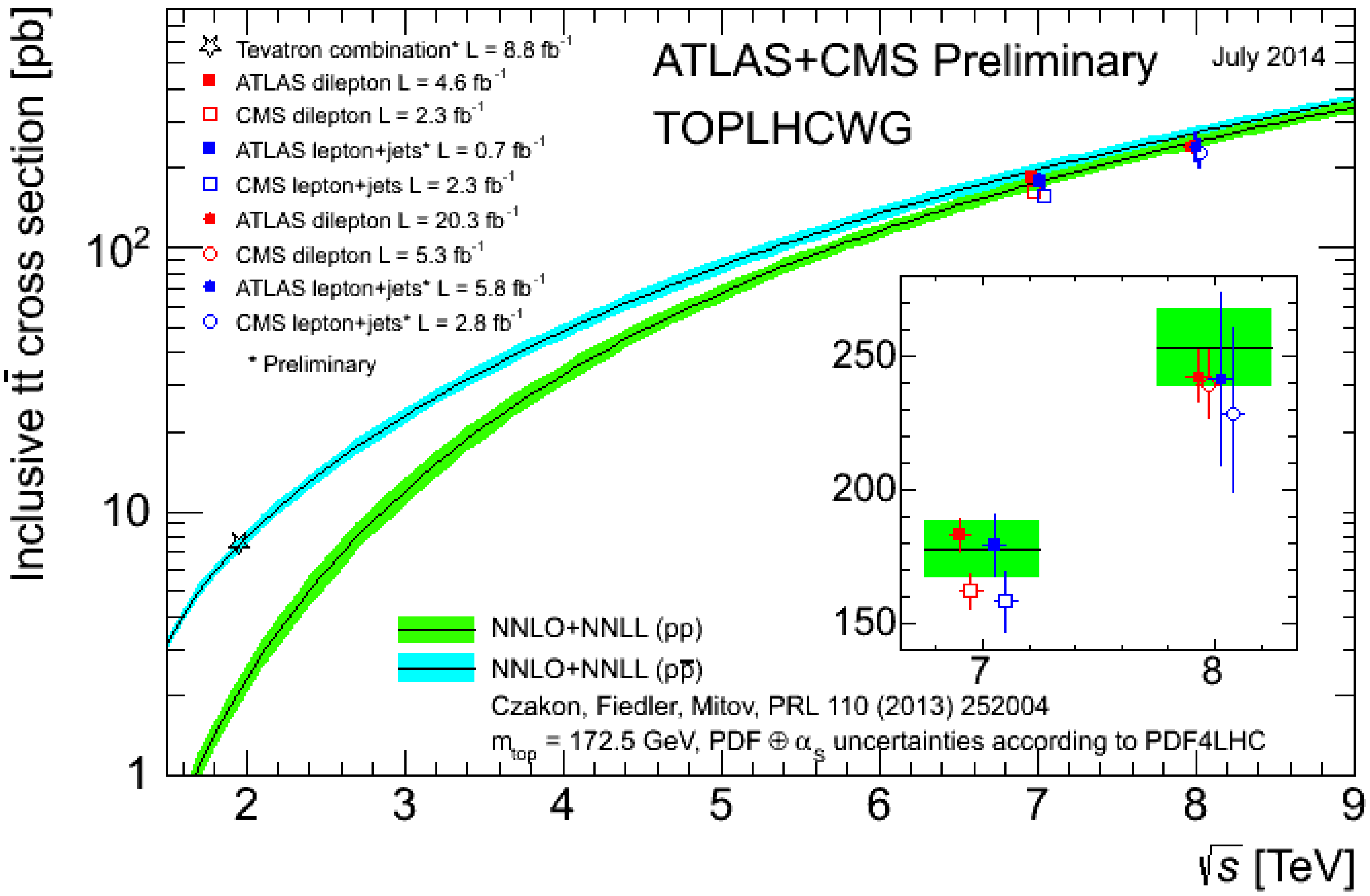
$$\sigma = \frac{N_{\text{meas}} - N_{\text{bkg}}}{\epsilon \cdot \mathcal{L}}$$

Systematic Uncertainties

- Typically **90% of the work** in an analysis
- **Systematic errors** cover our lack of knowledge
  - Need to be determined on every aspect of measurement by varying assumptions within sensible reasoning
  - Therefore: there is **no correct way**
    - But there are good ways and bad ways
    - You will need to develop a feeling and discuss with colleagues and theorists
- **What's better?** Overestimate or underestimate
  - Find new physics: be generous with systematics
  - Precision measurement: need to make best effort to neither overestimate or underestimate

Top Cross-section

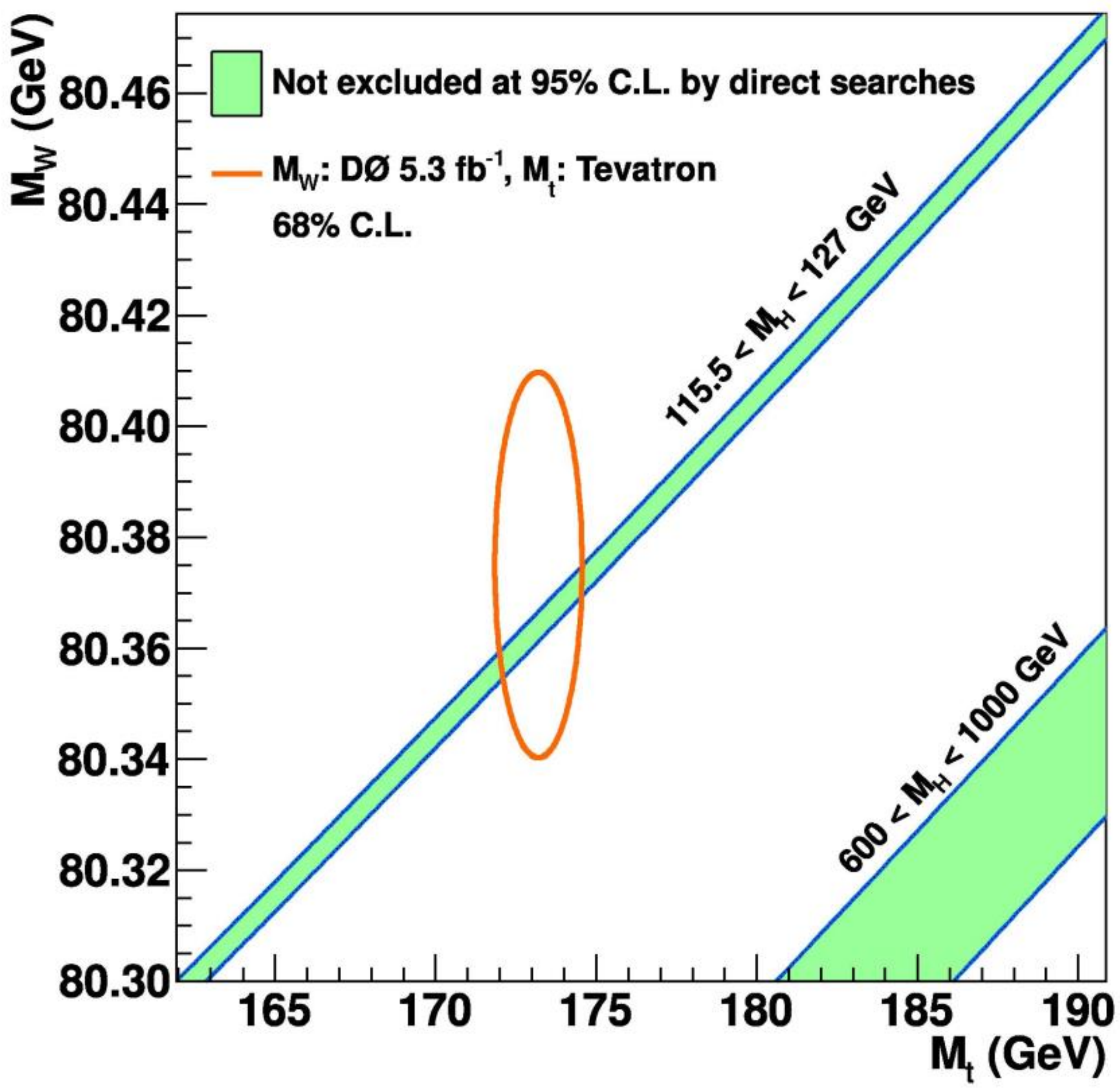
- Theoretical uncertainty <5%
- Theory and experimental uncertainties are approximately equal



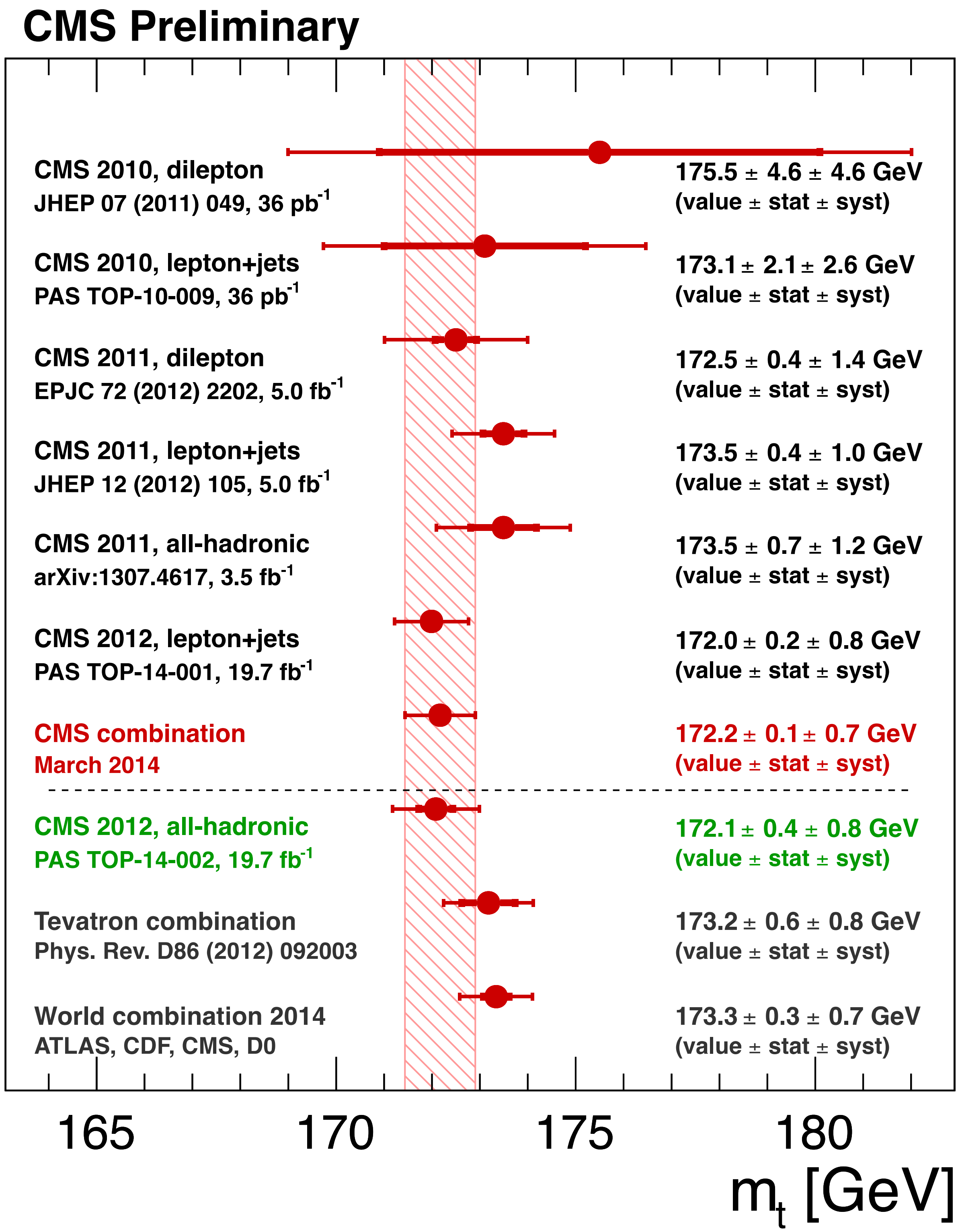
Very good agreement between data and expectation

Top Quark Mass

- Top quark mass is a fundamental parameter of the Standard Model
  - First time a quark mass can be measured directly
- A broad spectrum of decays and methods



Top Mass Measurement



- Combination of all measurements (March 2014)
- 173.3 ± 0.3 ± 0.7 GeV
  - 0.4% precision
- Caveat: Relation to ‘theoretical’ top mass somewhat uncertain due to QCD models

The Higgs Boson

Electroweak Symmetry Breaking

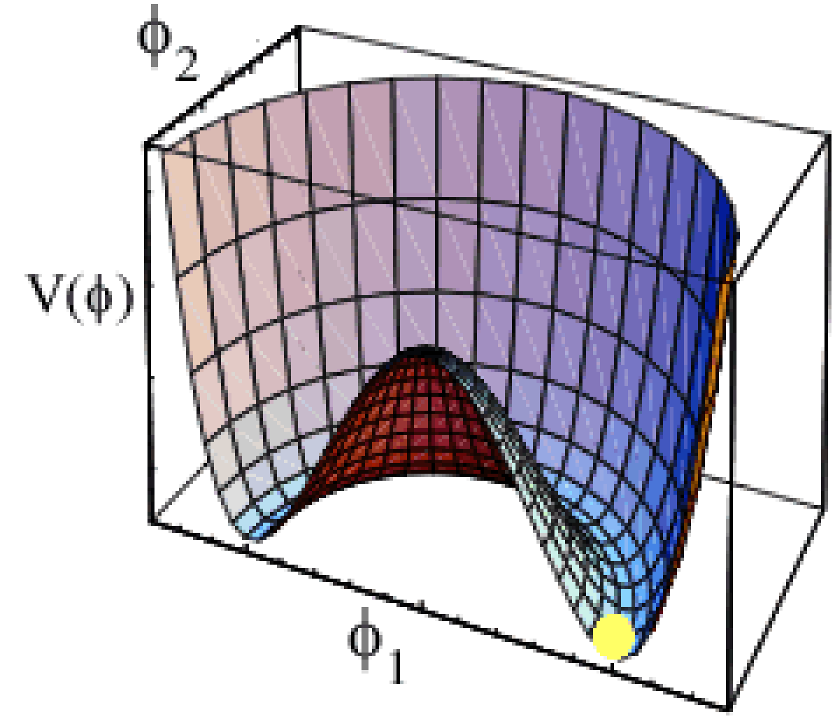
- Masses of boson and fermions are in conflict with local gauge invariance
- Boson masses lead to
  - Infinite cross-sections

$$m_{\mathrm{H}} \leq \sqrt{\frac{8\pi\sqrt(2)}{3G_{\mathrm{F}}}} \sim 1\ \mathrm{TeV}$$

  - Or strong coupling between W's -> many W's
- Way out: introduce a new scalar spin-0 particles

Solution: The Higgs Mechanism

- Standard Model solution: Higgs fields
  - gives mass to bosons
  - provides means for fermion masses
  - implies elementary physical particle
  - gives mass to Higgs boson
  - NOTE: no prediction of particle masses



- Introduce a potential by hand with two unknowns: λ, μ

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

$$\frac{\partial V}{\partial \phi} = 0 \implies \phi_0 = v^2 = \frac{\mu^2}{\lambda}$$

$$m_{\mathrm{W}} = \frac{1}{2} v \cdot g$$

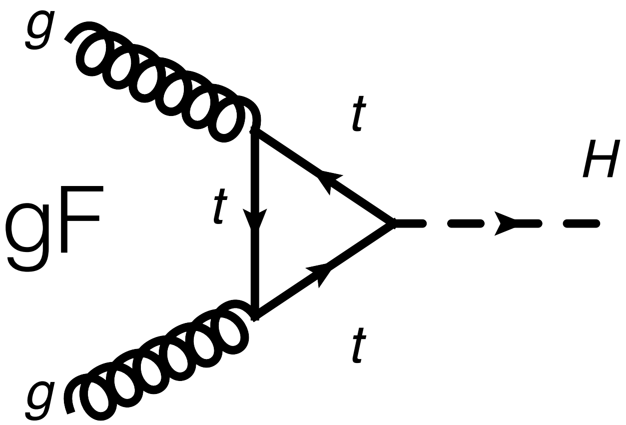
$$m_{\mathrm{h}} = \sqrt{2 \cdot \lambda} \cdot v$$

$$m_{\mathrm{f}} = \frac{1}{\sqrt{2}} G_f \cdot v$$

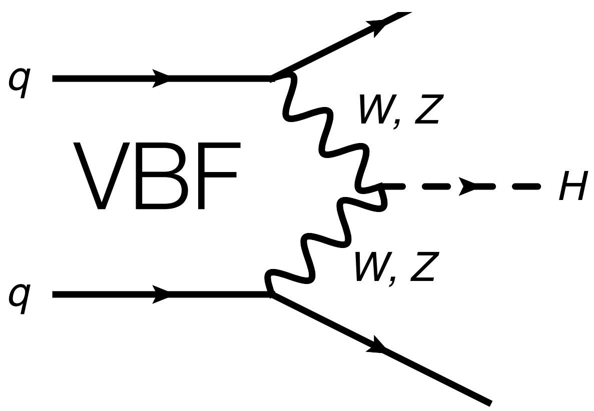
- V: vacuum expectation value
- m_W -> v = 246 GeV

Higgs Production

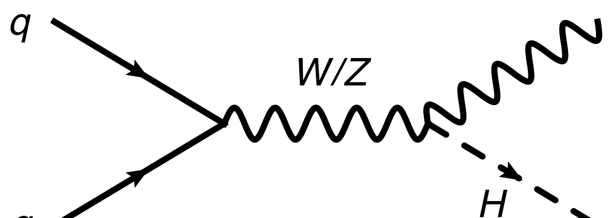
ggF



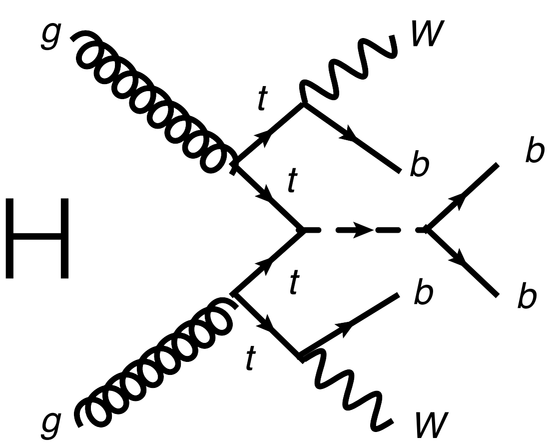
VBF

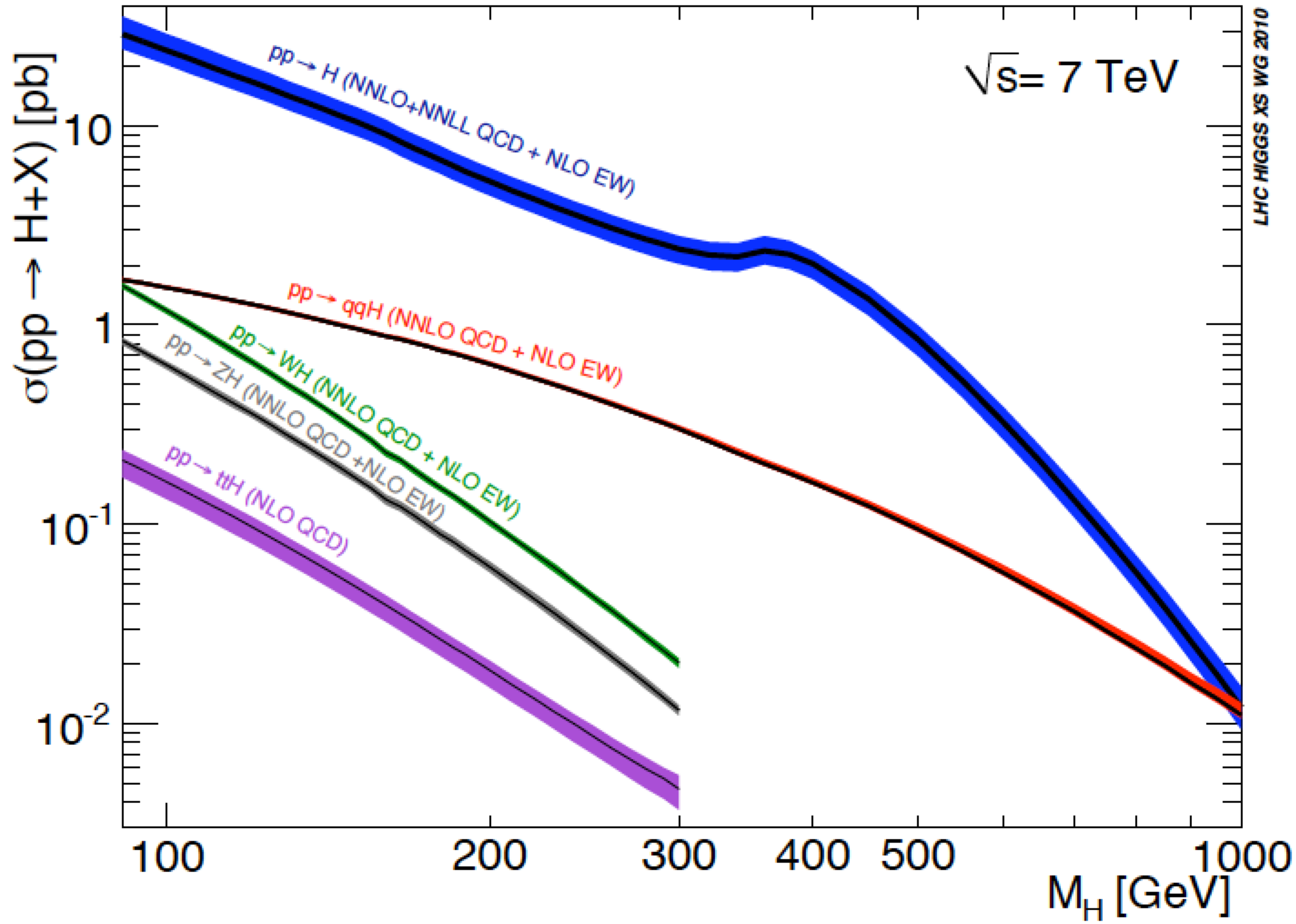


W,Z bremsstrahlung

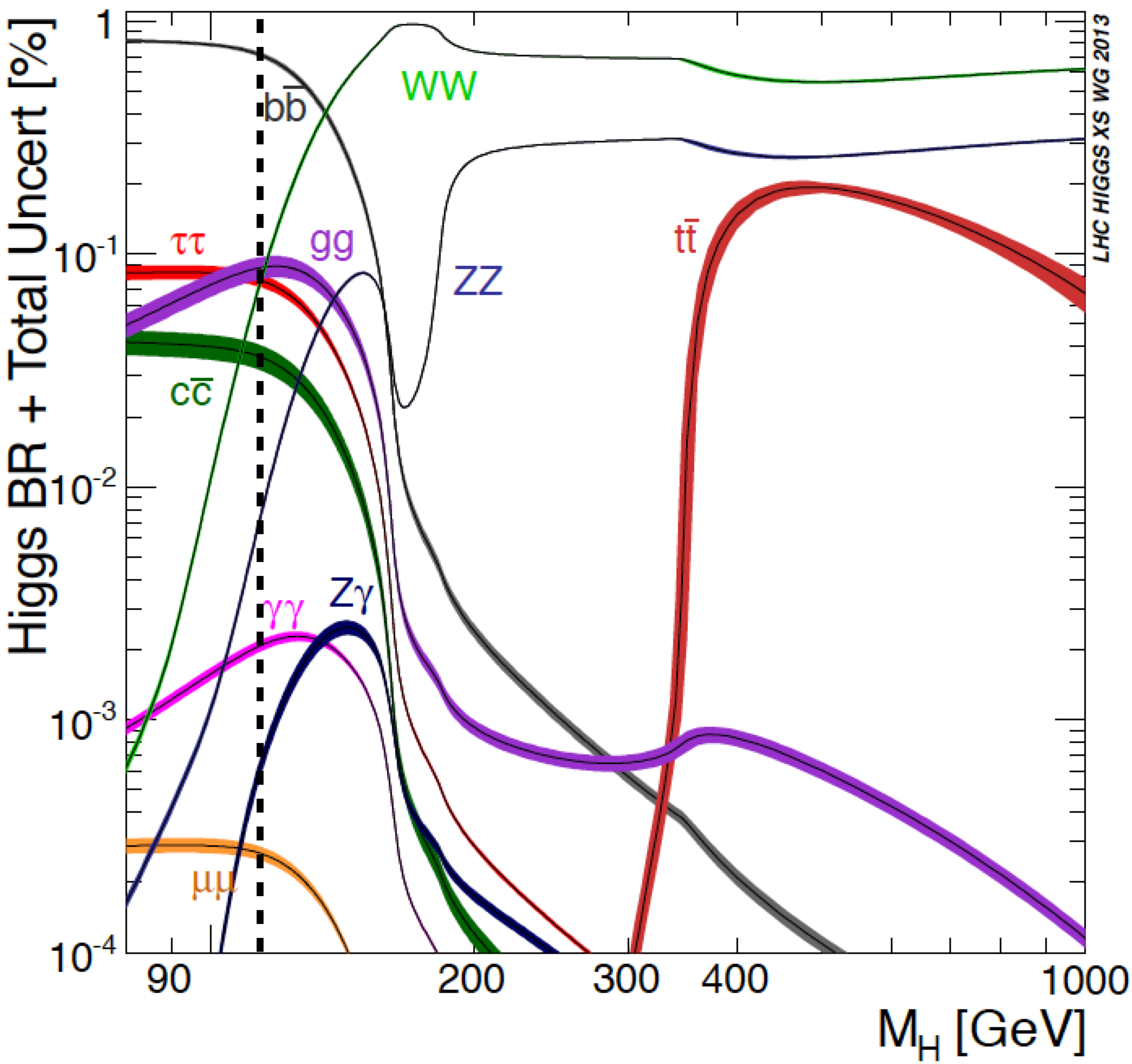


ttH



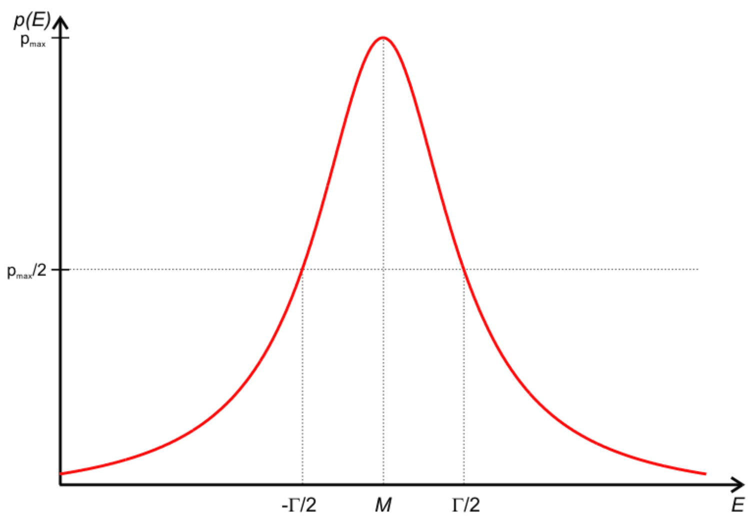


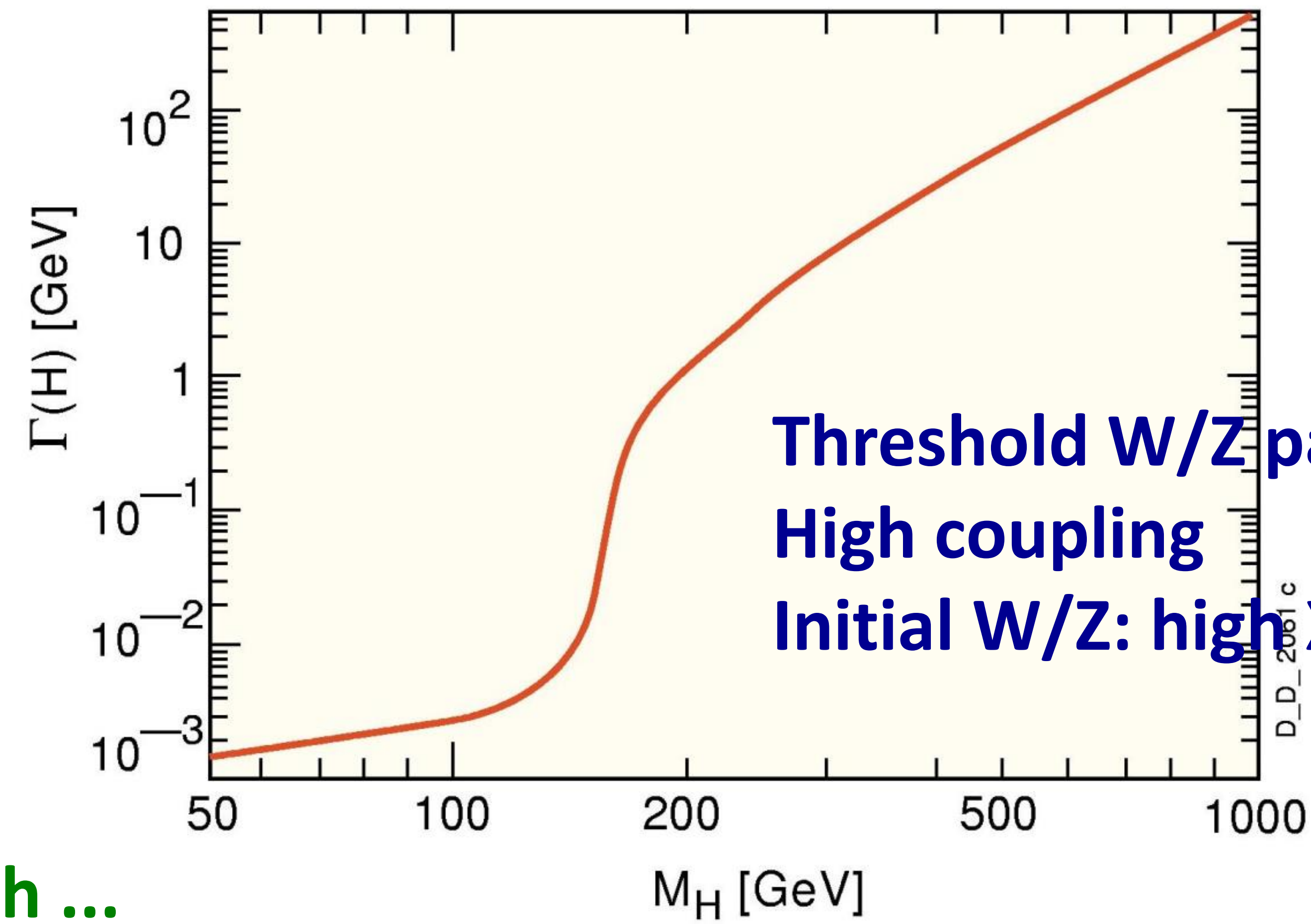
Higgs Decays



How strong is the coupling ?

- Width of the Higgs boson is proportional to the coupling



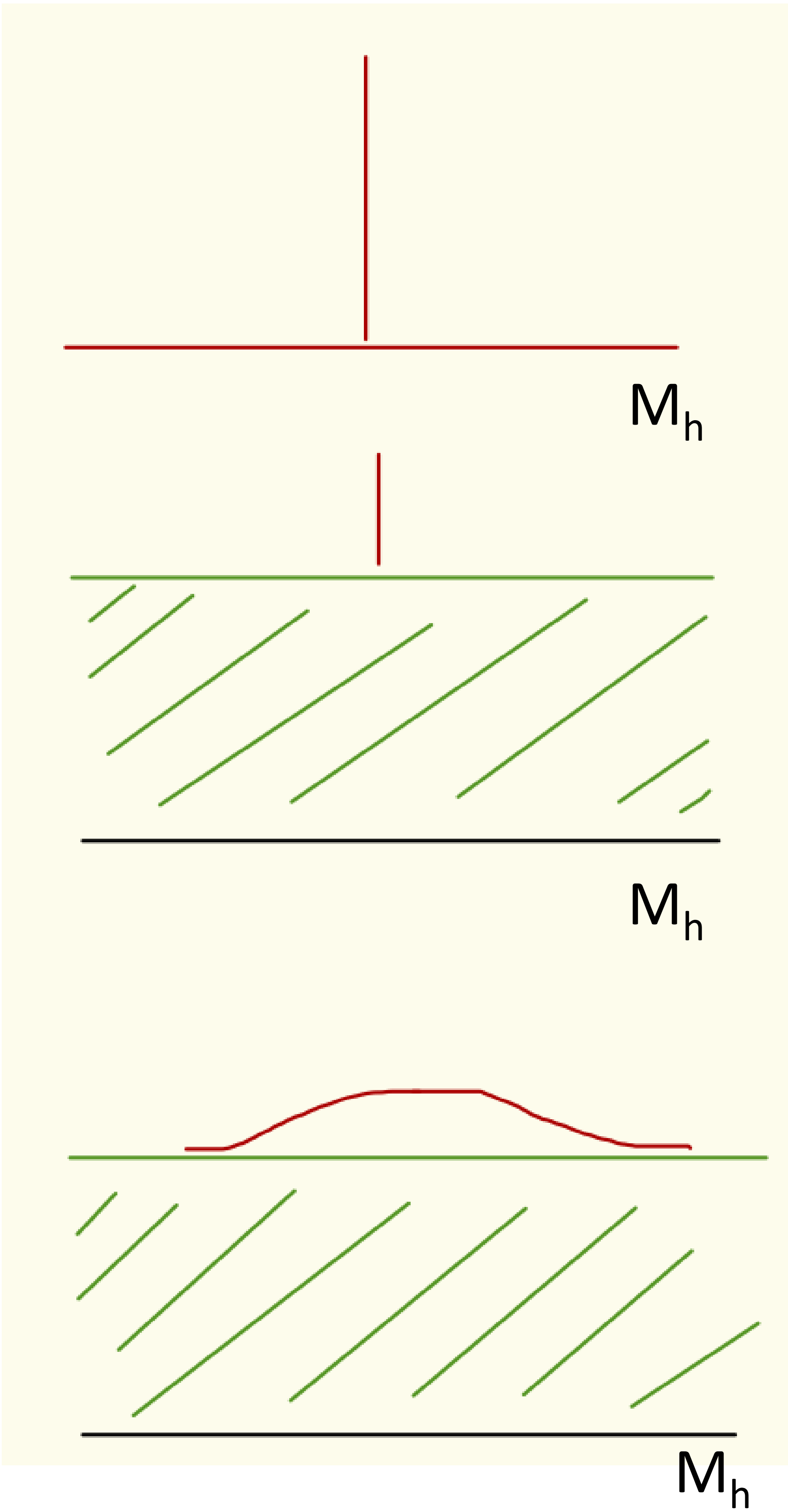


Threshold W/Z passed:
High coupling
Initial W/Z: high X-secti

h ...

Very small width ...
Very small coupling !

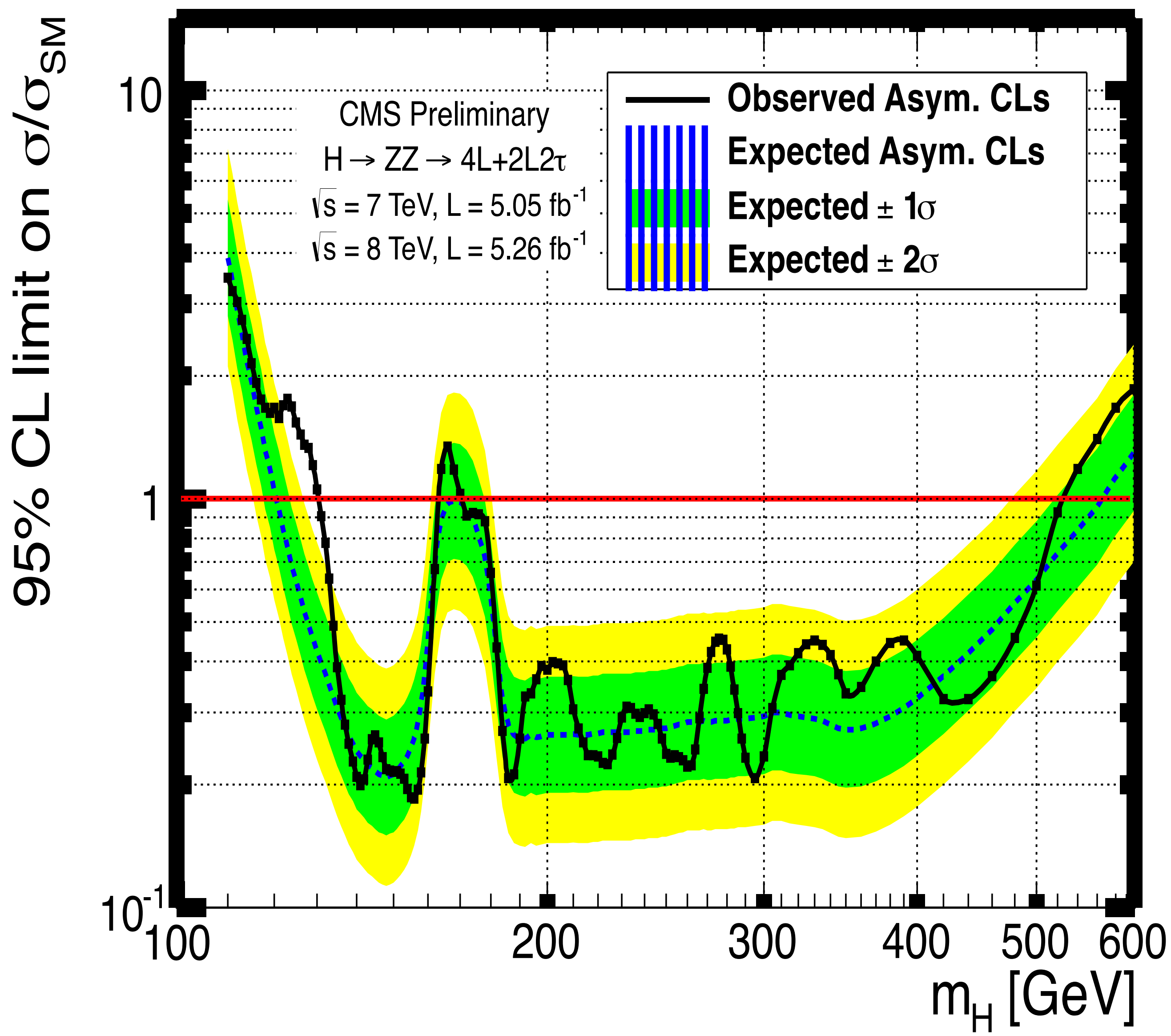
How the Higgs would show up



- **Ideal world**: a narrow excess at m_H ... nothing else
  - A handful (one!) of events is sufficient
- **Closer to reality**
  - Other processes have similar signature but smoothly distributed
- **Reality**
  - Other processes have similar signature but smoothly distributed
  - Experimental resolution broadens signal

1. Test if data exclude hypothesis

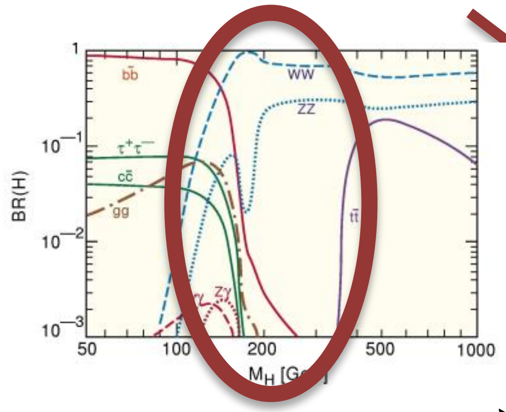
- Step 1: cross-section at mass m_H that can be excluded @ 95% CL
- Step 2: Plot ratio **σ(excl)/σ(SM expectation)**
- If expected is **above 1**: Higgs cannot be excluded because there is no sensitivity
- If **both below 1**: Higgs excluded in mass range
- If expected is **below 1** and observed **above** we say either hint or signal

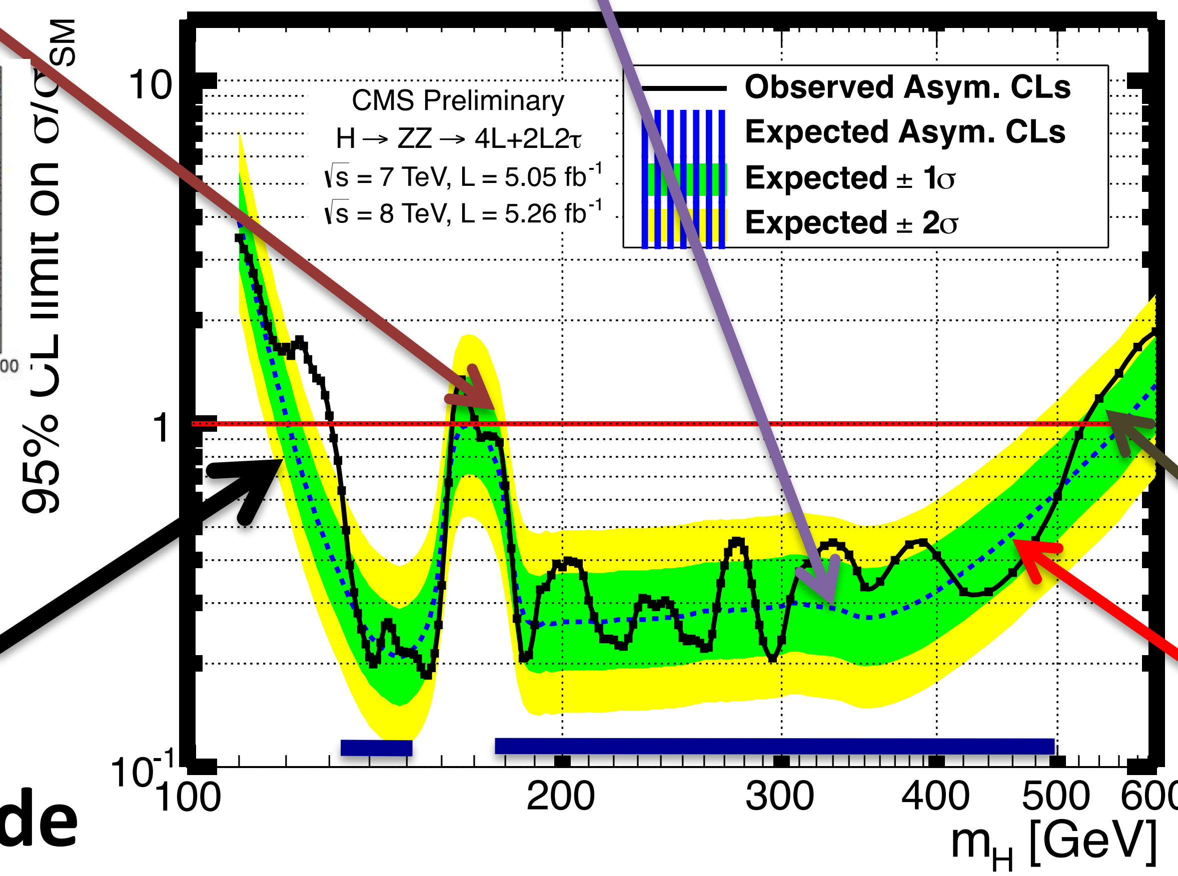


95% CL Limits ZZ → (l^+l^-) (l^+l^-)

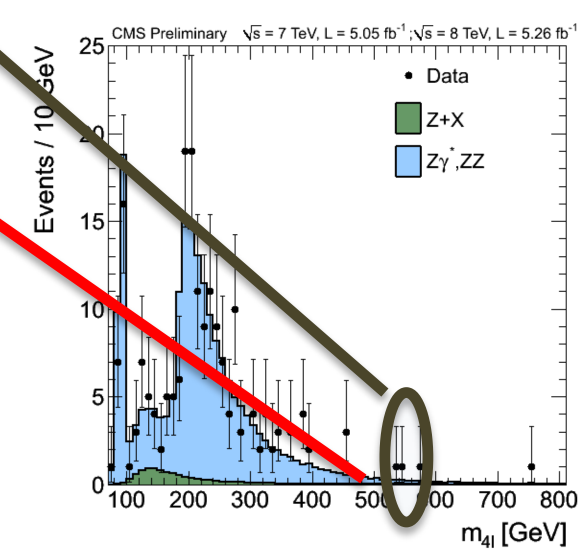
Simulation with NO signal, but luminosity, detector effects, ...
➔ EXPECTED limit

No sensitivity
Small σ*BR





Oscillations around expectation:
more or less events than background expectation

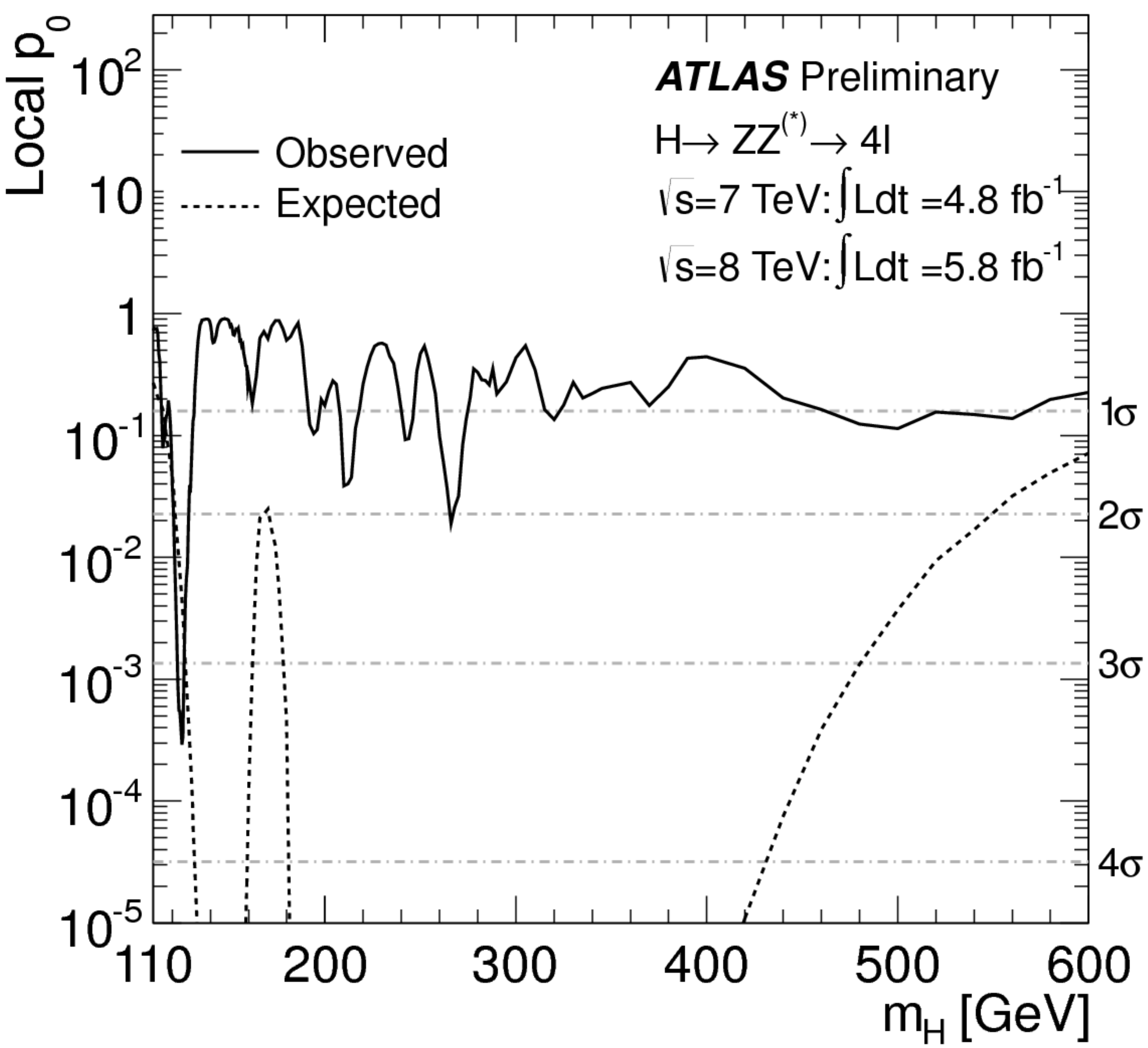


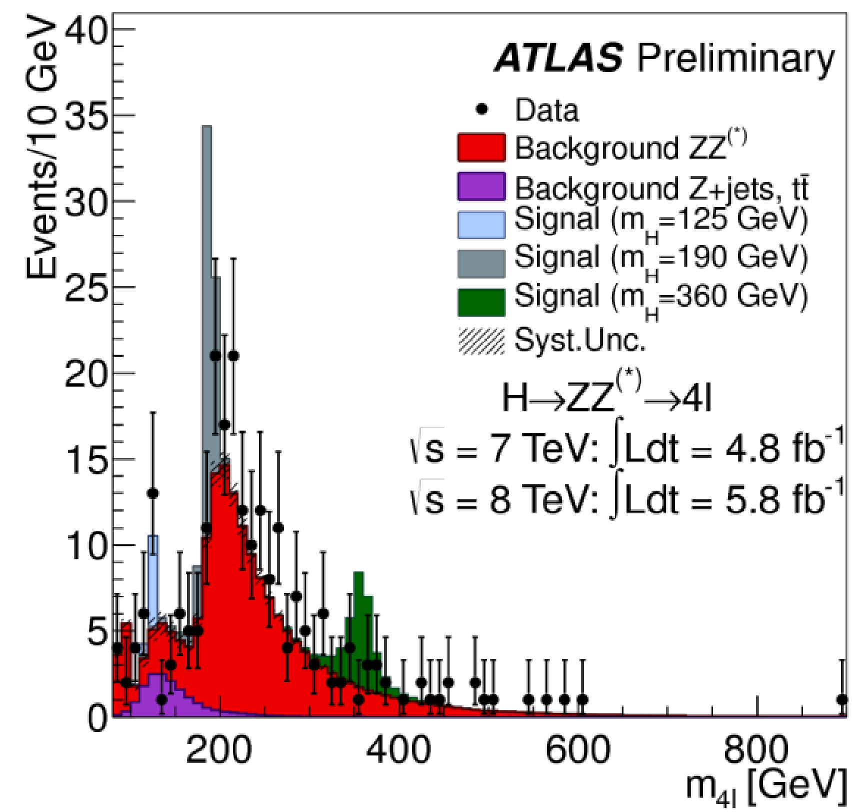
INTERESTING!
Data can exclude less than expected by large margin

Regions of ratio < 1
EXCLUSION!

p-value: probability of statistical fluctuation

- p-value: how likely is it that at a certain mass m_H
  - Expected background fluctuates upwards to produce at least the number of observed events





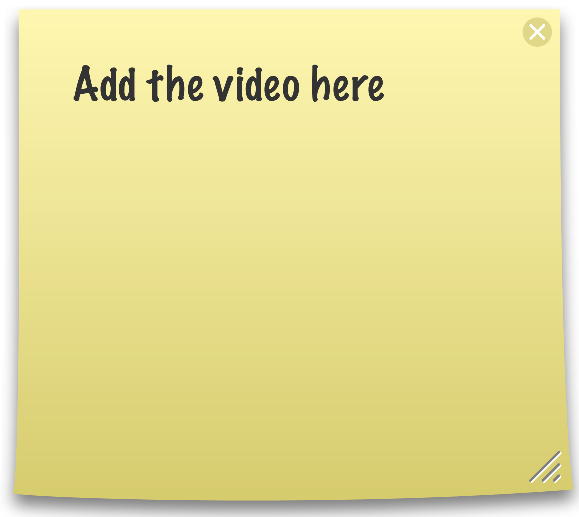
Observed dearth or excess reflected in wiggle

Convention:

evidence if p > 3σ

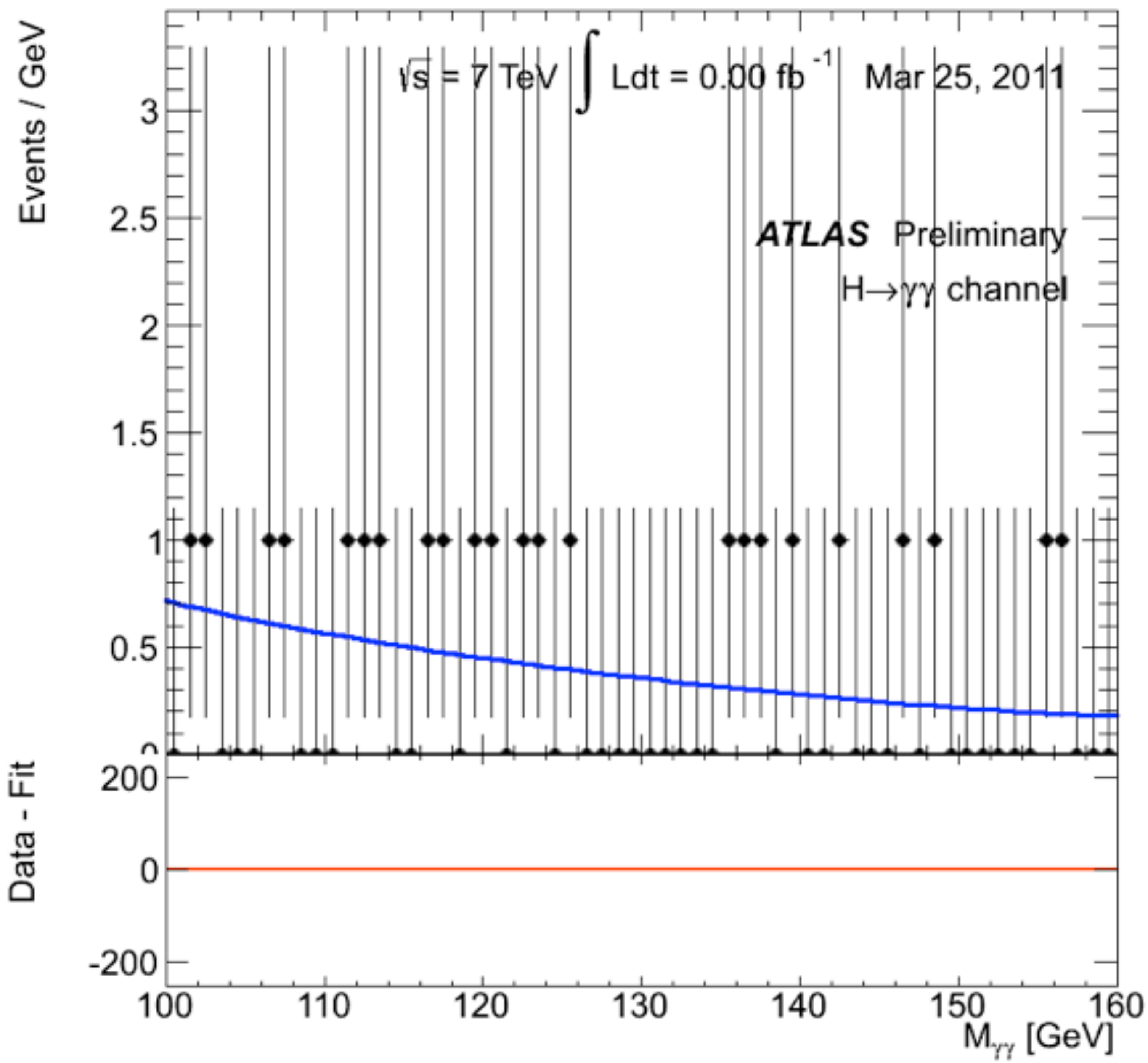
observation if p > 5σ

Higgs Discovery 1: Higgs -> γγ



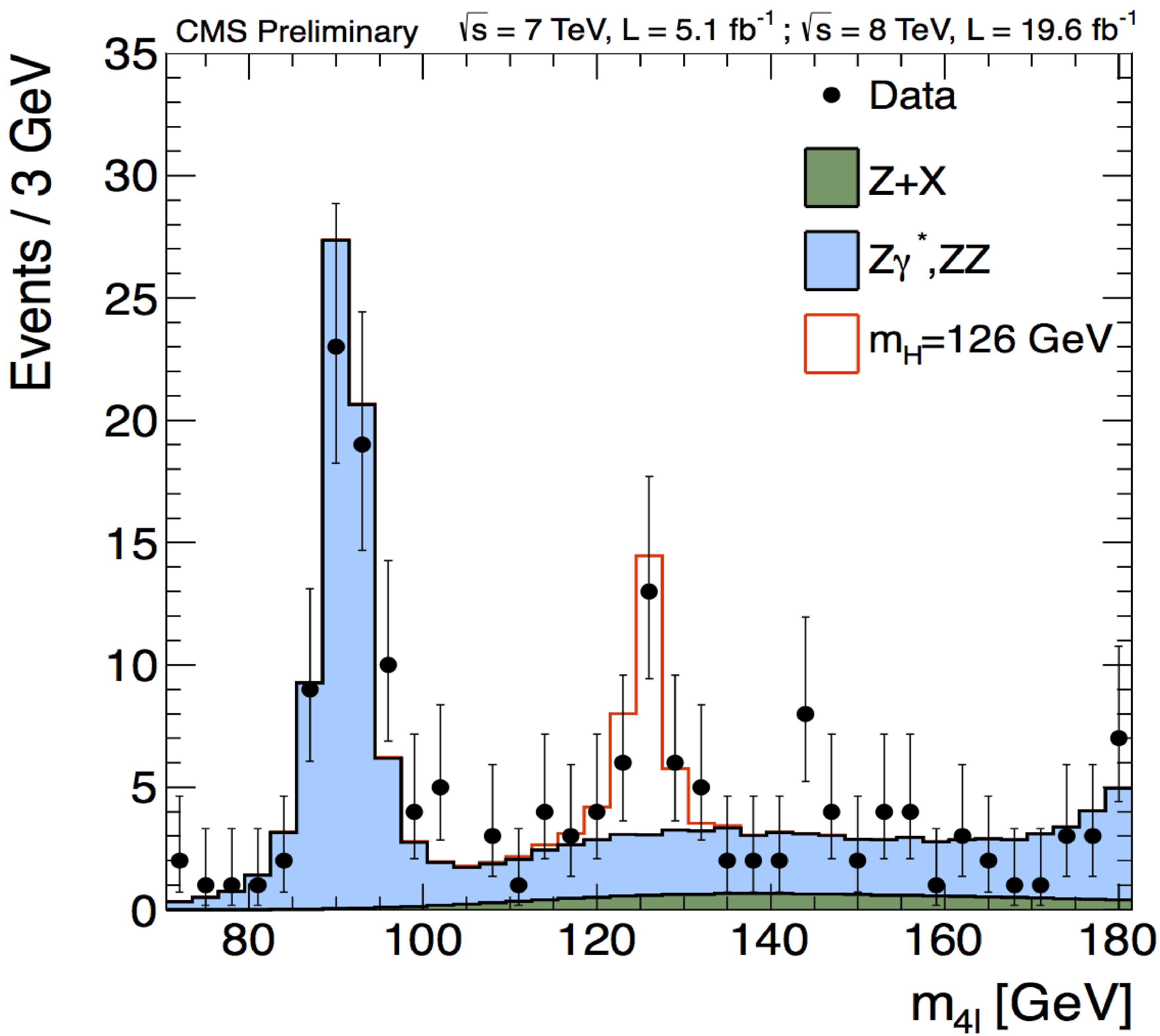
ATLAS: H->gg video

Higgs Discovery 1: Higgs -> γγ

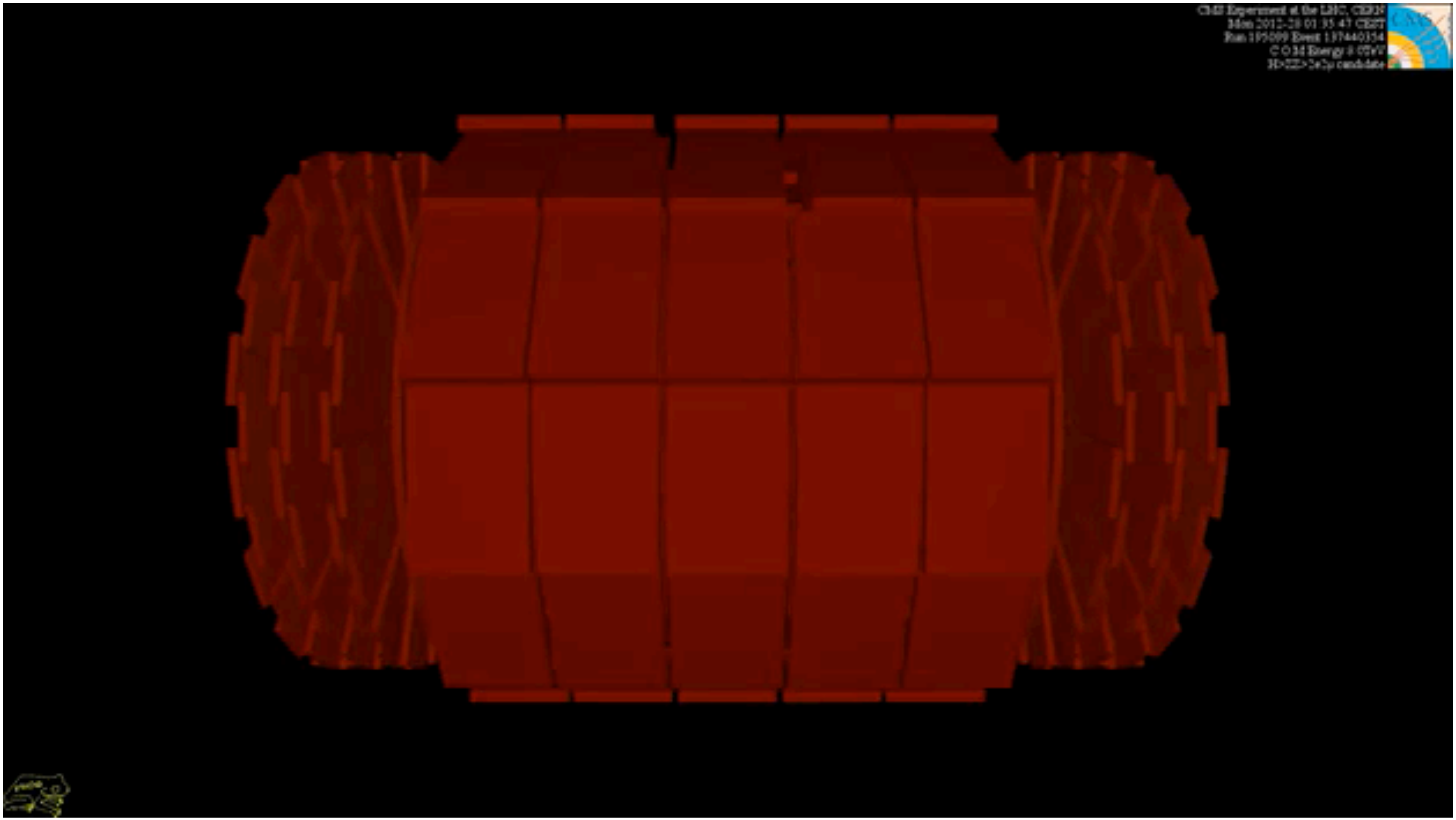


ATLAS: H->gg video

Higgs Discovery II: ZZ



Guess the Higgs event



CMS: Higgs event

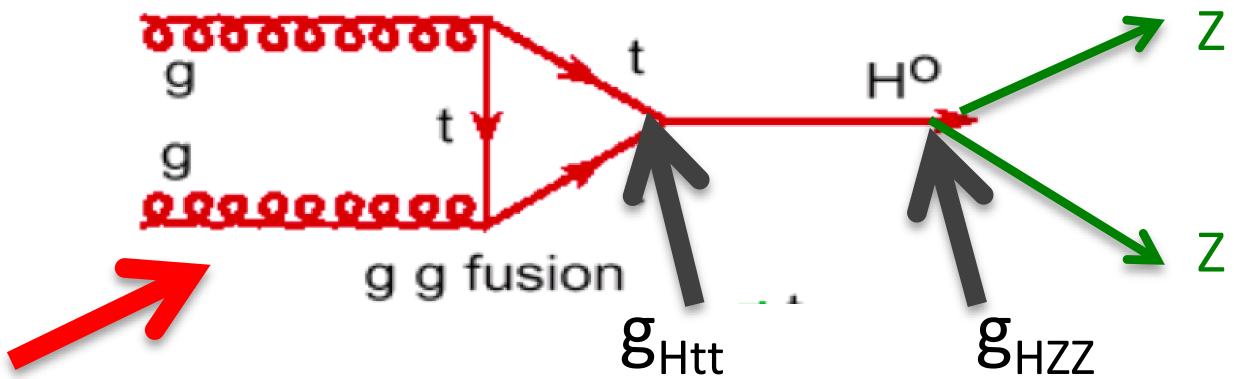
BERGISCHE UNIVERSITÄT WUPPERTAL

July 4, 2012: Announcement!

Now what?

- Qualitative: suggestive of a Higgs
  - **Mass** accords with expectation
  - It is a VBF: not spin 1, 2 !
  - Found in expected decay channels
- Move to quantify agreement: check if Higgs properties are exactly as predicted
  - All **production** modes
  - All **deca**y modes: measure branching ratios
  - **Width** of Higgs boson
  - **Spin** and **parity**
  - Higgs **self coupling** (potential)
- Already significant progress since discovery !

How to measure the couplings?



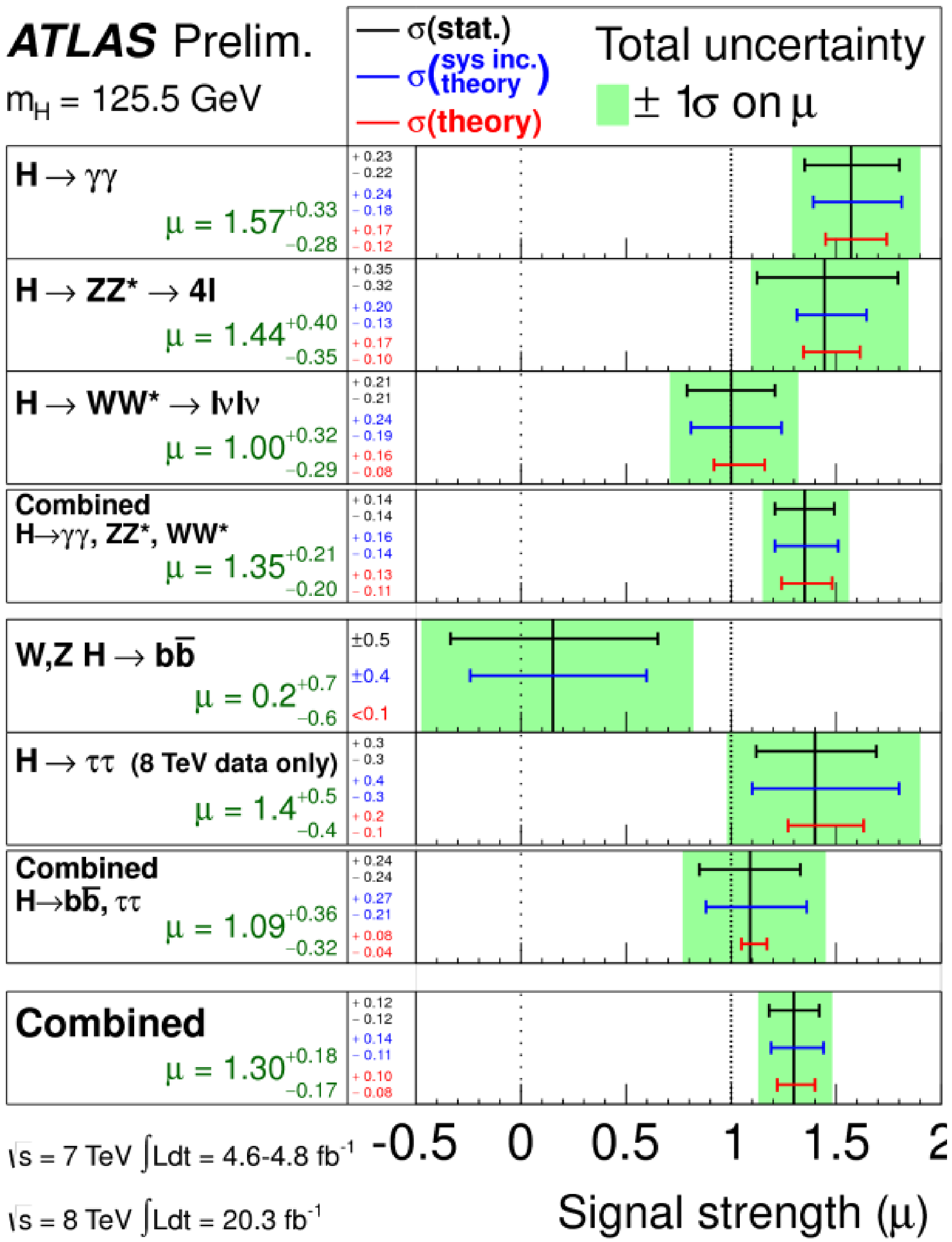
$$\sigma = |g_{H_{tt}} \cdot g_{H_{ZZ}}|^2$$

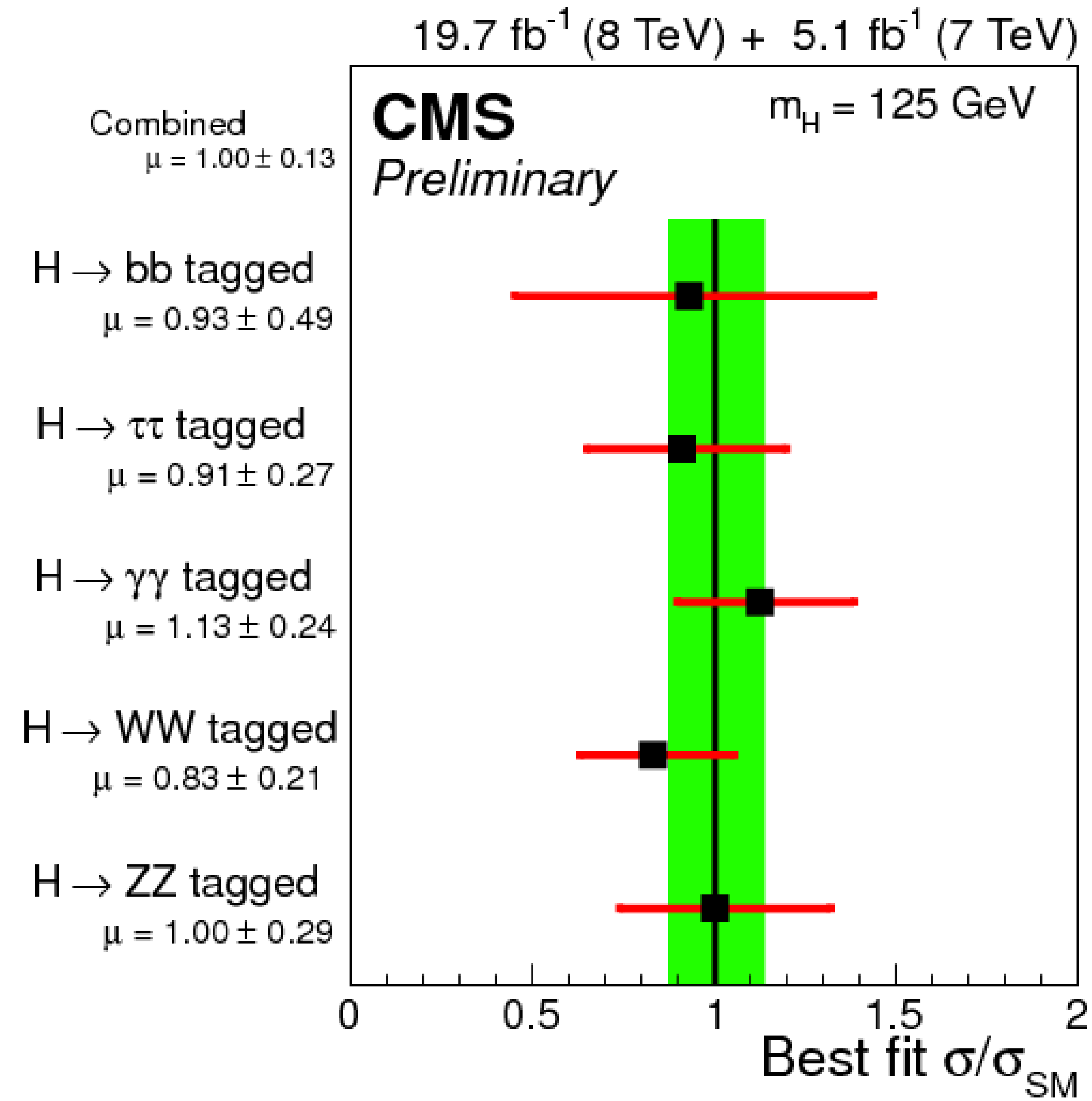
Gluon fusion cross section 'known'

- Compare **observed** cross-section to **predicted** one
  - Products of couplings for production and decay
- Theoretical predictions known to ~10%
- Make the same measurement with as many production and decay modes as possible

Comparing data and theory

Measure μ = σ(meas)/σ(pred) for different decays

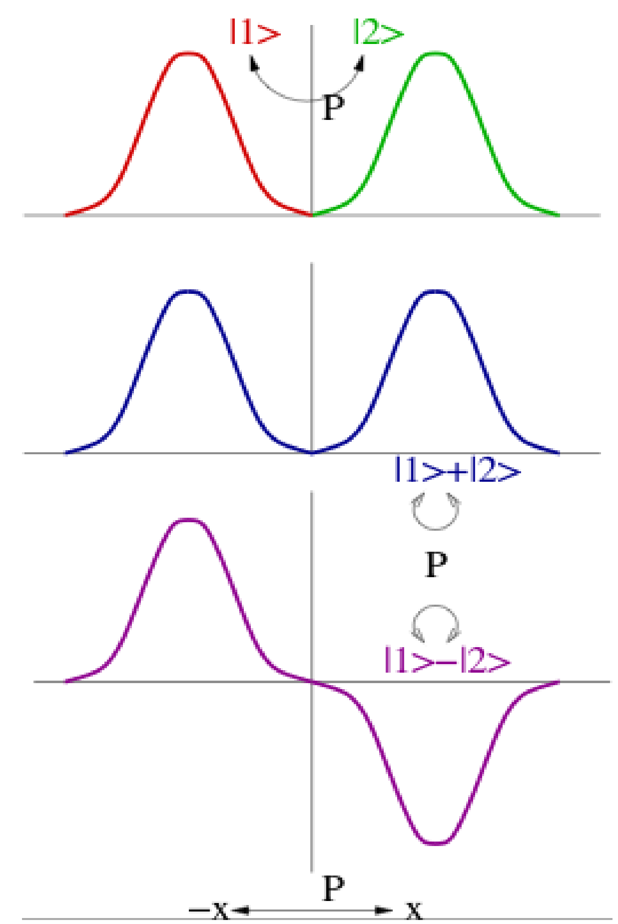




All results agree with expectation for SM Higgs!
Uncertainties on coupling to fermions substantial

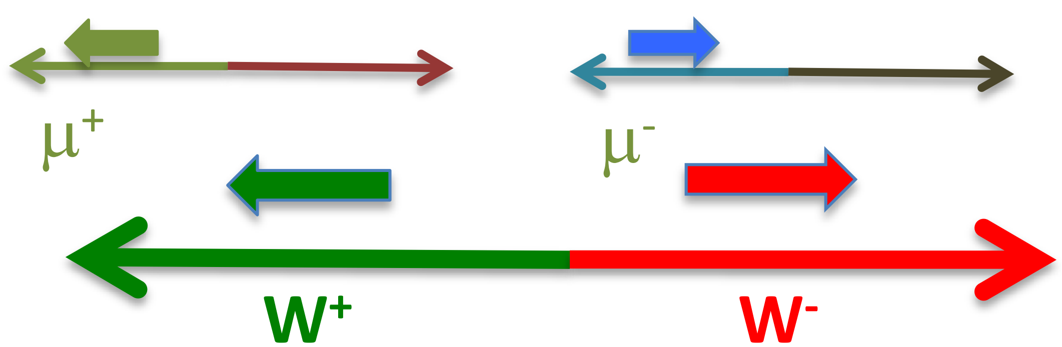
Spin and parity measurements

- A Standard Model Higgs has a spin and parity of 0+
- Spin: angular momentum of a point
  - Measured from the angular distribution of the Higgs decay products
- Parity: How does a particle look in a mirror ?
  - What is the symmetry of the wave function after parity transformation: (x, y, z, t) -> (-x, -y, -z, -t)
  - Measured in a similar way to spin

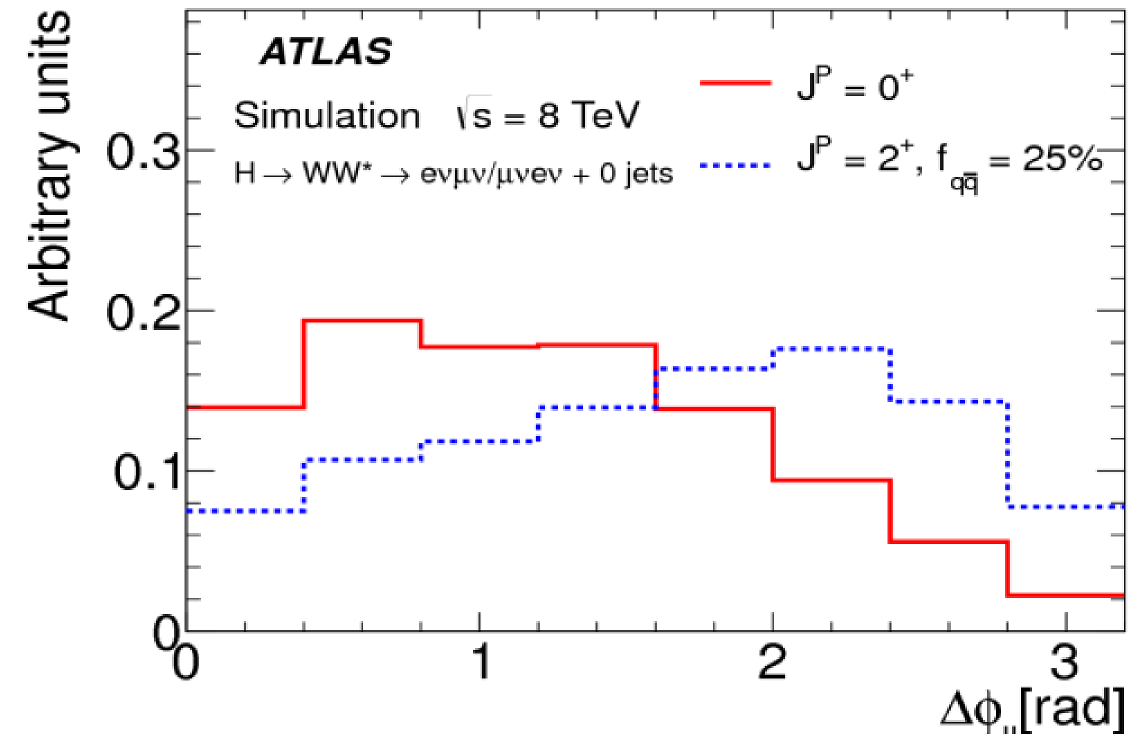


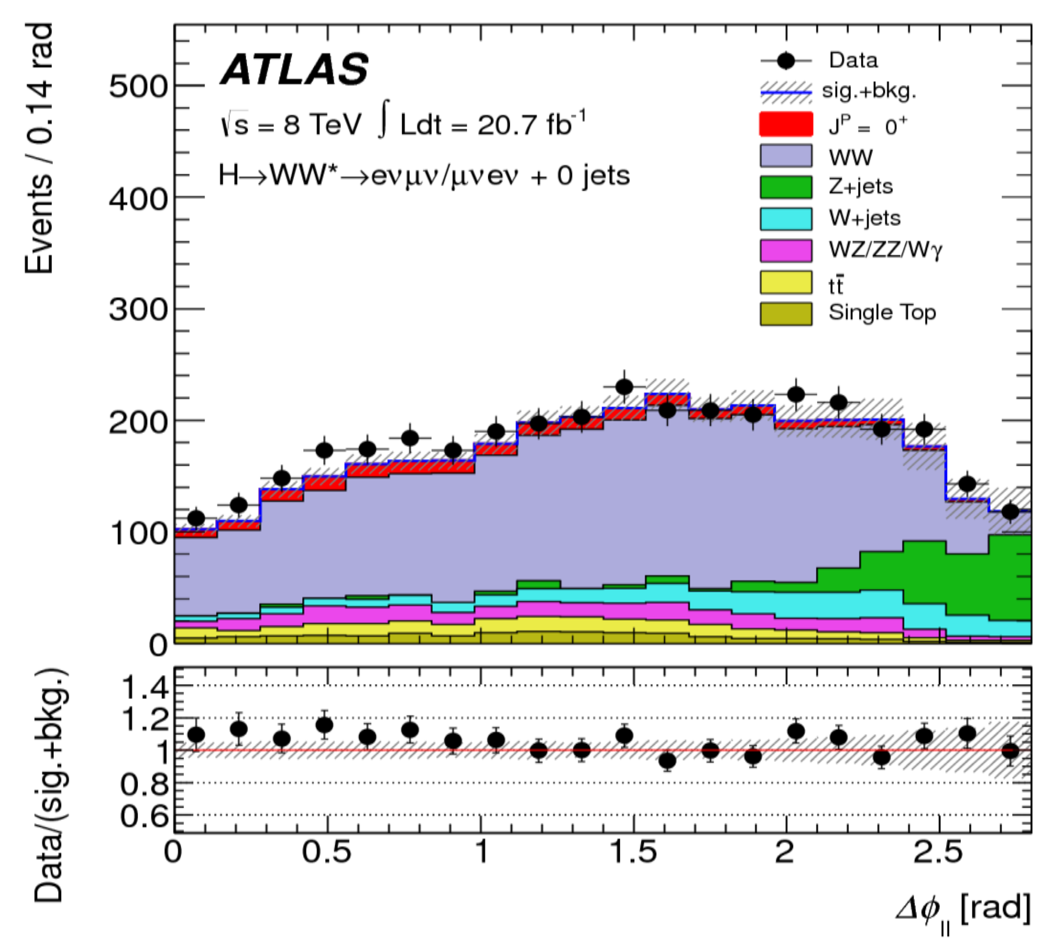
Spin of the Higgs

- Example: h->W+W-
- Spin 0
  - Spins of W's are opposites
  - μ's are aligned

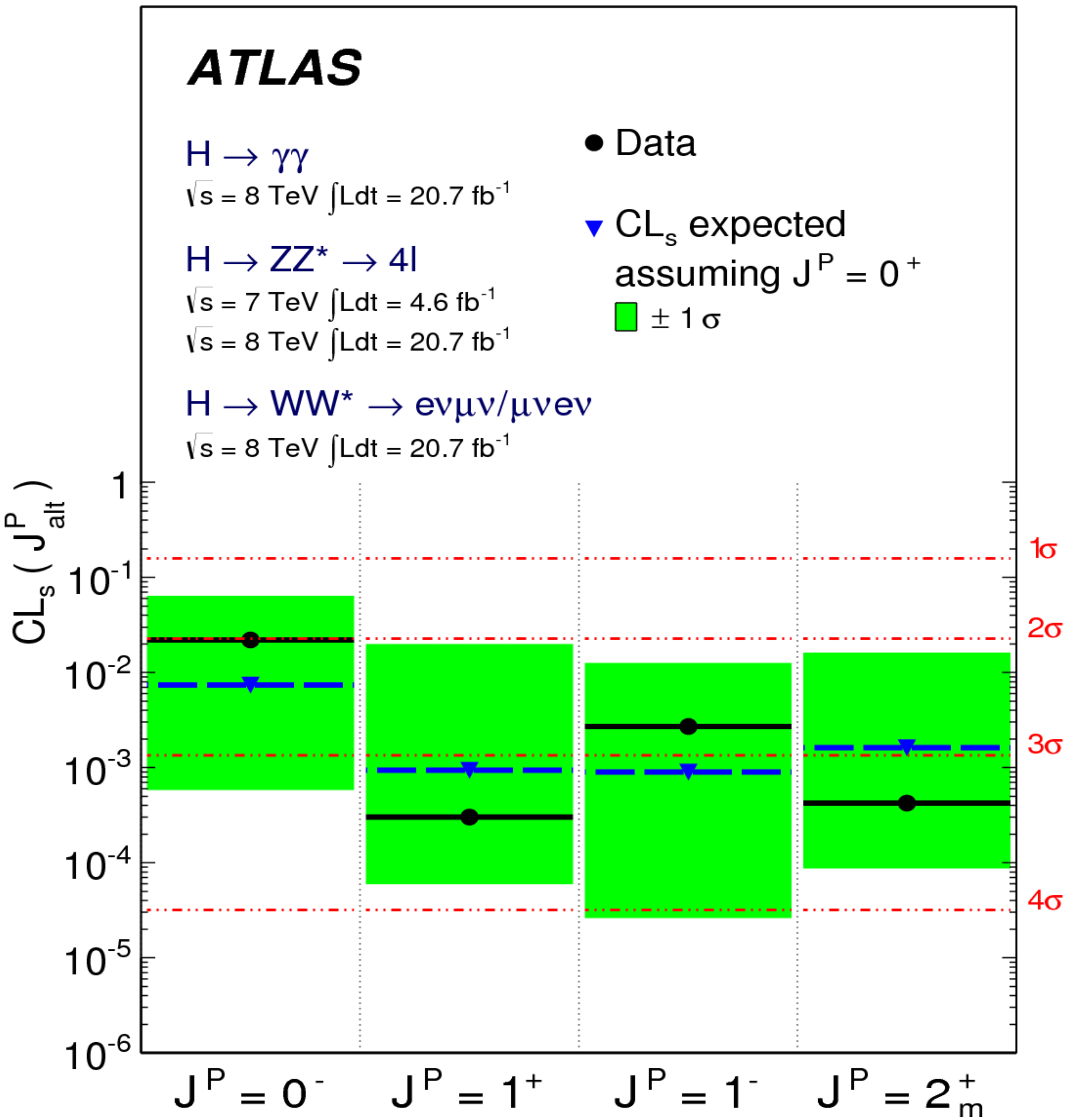


- Spin 2: no such correlation
- After subtracting the background, data agree better with spin 0





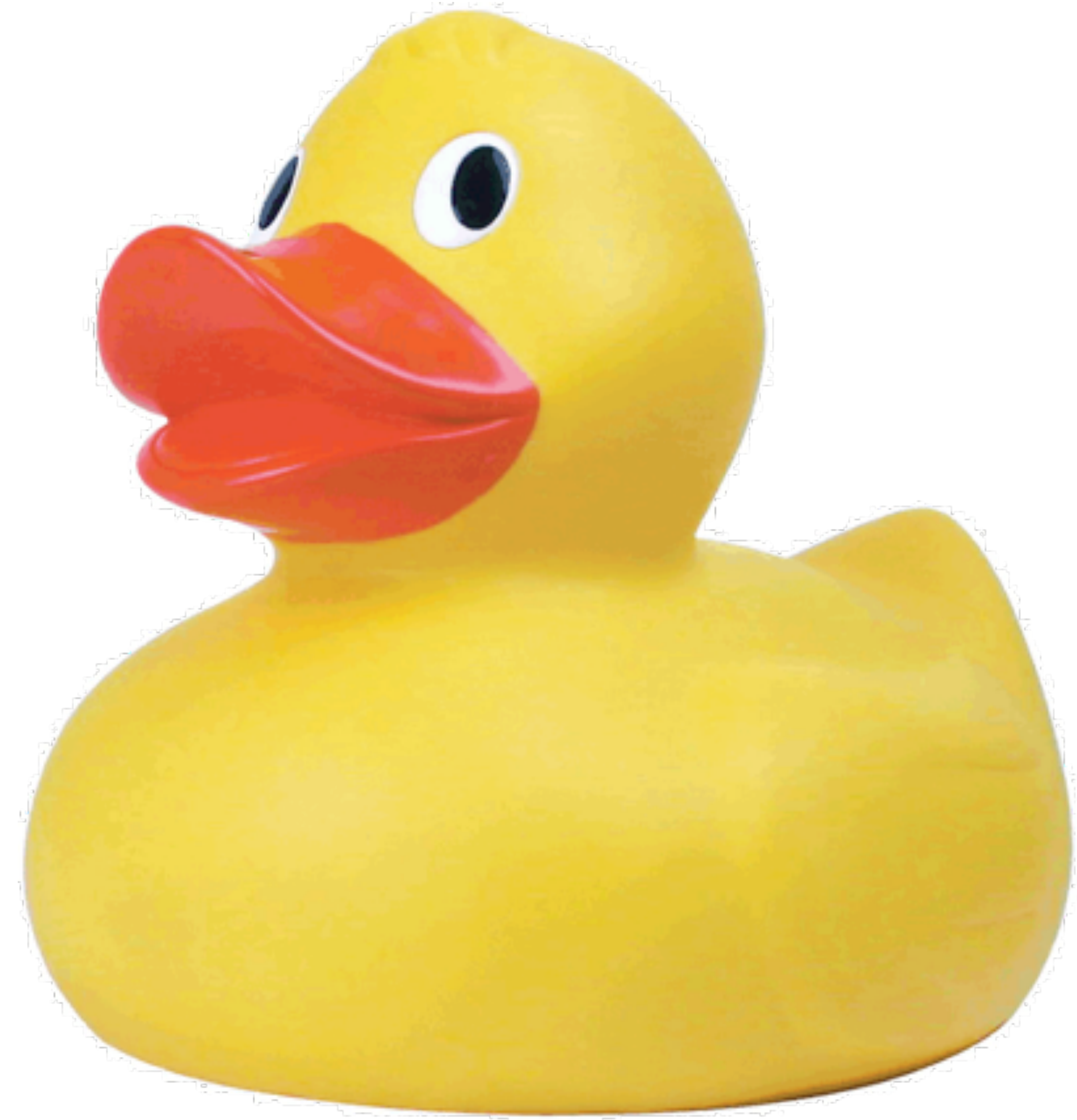
Spin-Parity Summary



- Compare Standard Model 0+ with other possibilities
- Other possibilities disfavoured with 10^{-2} - 10^{-4} probability
- Very consistent with the SM !

Is it the Higgs?

- **Mass** agrees with precision physics
- **Production** and **decay** rates as expected
- **Spin-parity** favours 0^+
- Precision still to be improved but, as yet, no disagreement
- It tastes like a Higgs, it smells like a Higgs, it feels like a Higgs
  - Indeed ‘we have found it” = “a **Higgs boson**”



Conclusion

- Lightening tour of **key measurements** of the Standard Model made at hadron colliders
- Selected examples to illustrate how different aspects are **measured**
  - **Jets** to study the strong coupling
  - **W and Z bosons** to study the weak coupling
  - Example: **top quark** cross-section measurement
  - The discovery of the **Higgs boson**
    - and ... what we've learnt since
- ATLAS and CMS have a wide ranging physics program and we use these detectors to measure as many aspects of the SM as possible
- Stay tuned for exciting physics ahead !