The Search for the Higgs Boson: Results

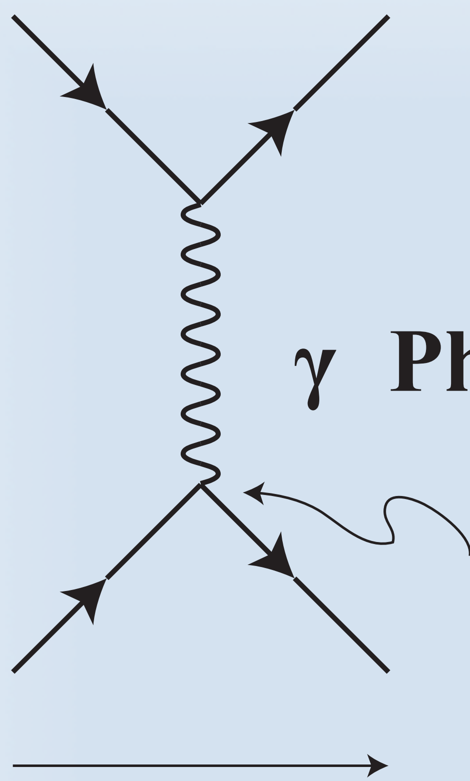
John Huth

Outline

- What is the Higgs boson?
- How do we make it?
- How do we see it?
- Data from ATLAS (and CMS)
- Significance
- The future

Foundational theory: Quantum Electrodynamics

electron
e



γ Photon

Vertex α

Time

e **– charge**

h **– Planck's const.**

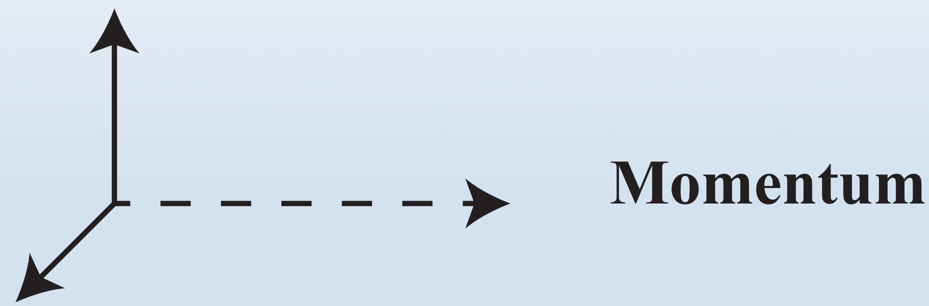
c **– speed of light**

Dimensionless coupling constant

$$\alpha = \frac{2\pi e^2}{hc} = \frac{1}{137}$$

The photon

Polarization states



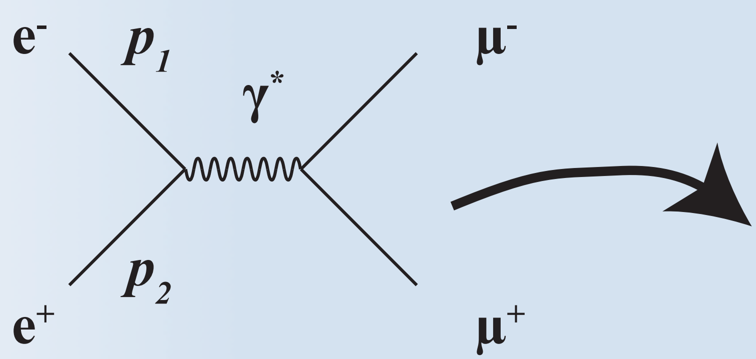
Massless

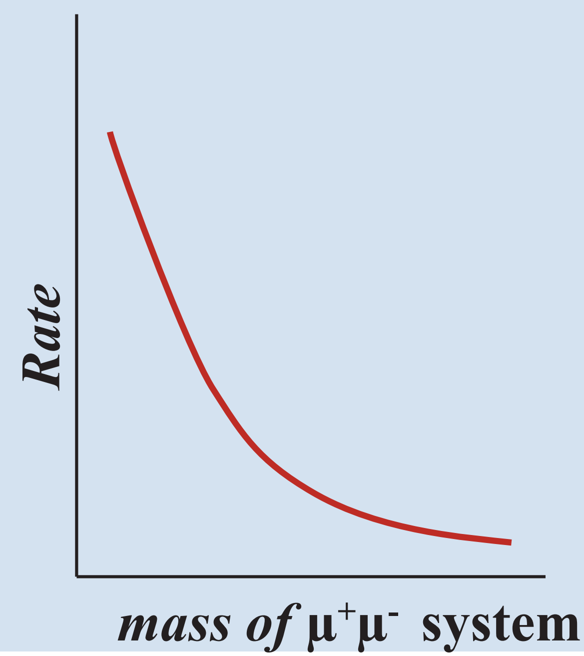
Spin 1

Couples to charge

A "gauge boson"

$q^2 = (p_1 - p_2)^2$



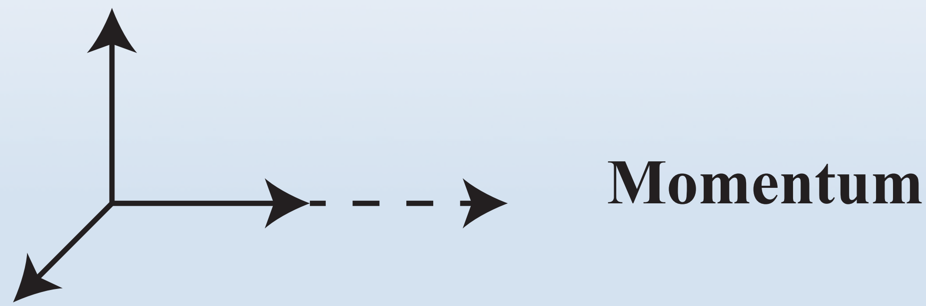


Propagator $\frac{1}{q^2}$

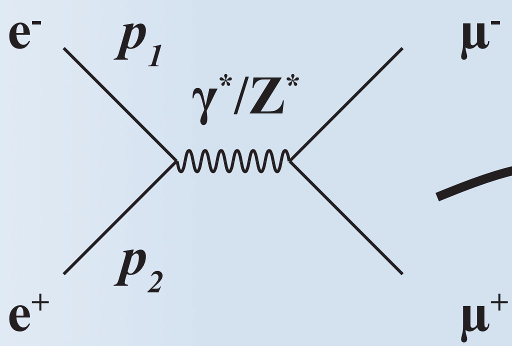
What if we gave the photon mass?

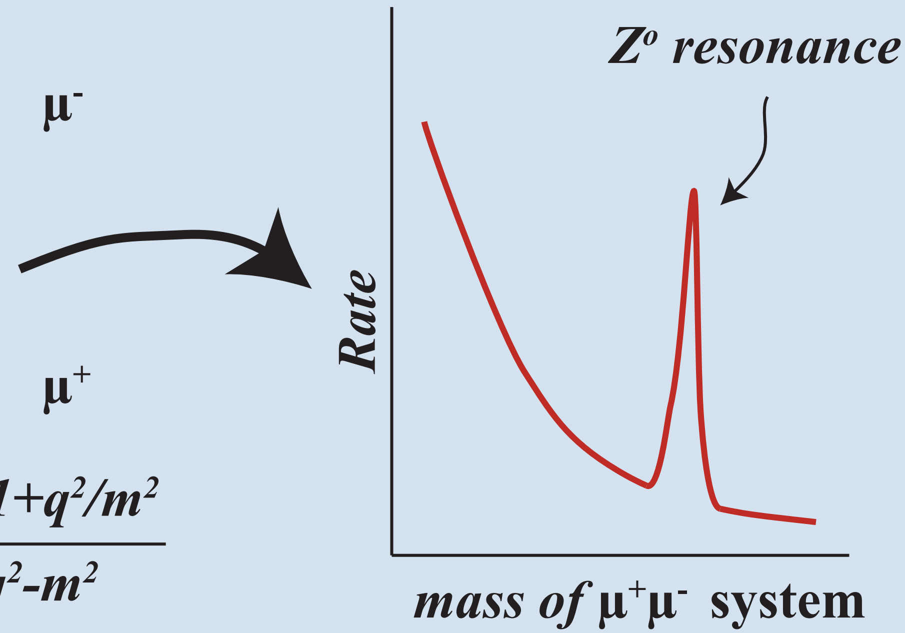
Gain a longitudinal polarization state ➔Grows with momentum

Polarization states



$$q^2 = (p_1 - p_2)^2$$





Z^o Propagator $$\frac{1+q^2/m^2}{q^2-m^2}$$

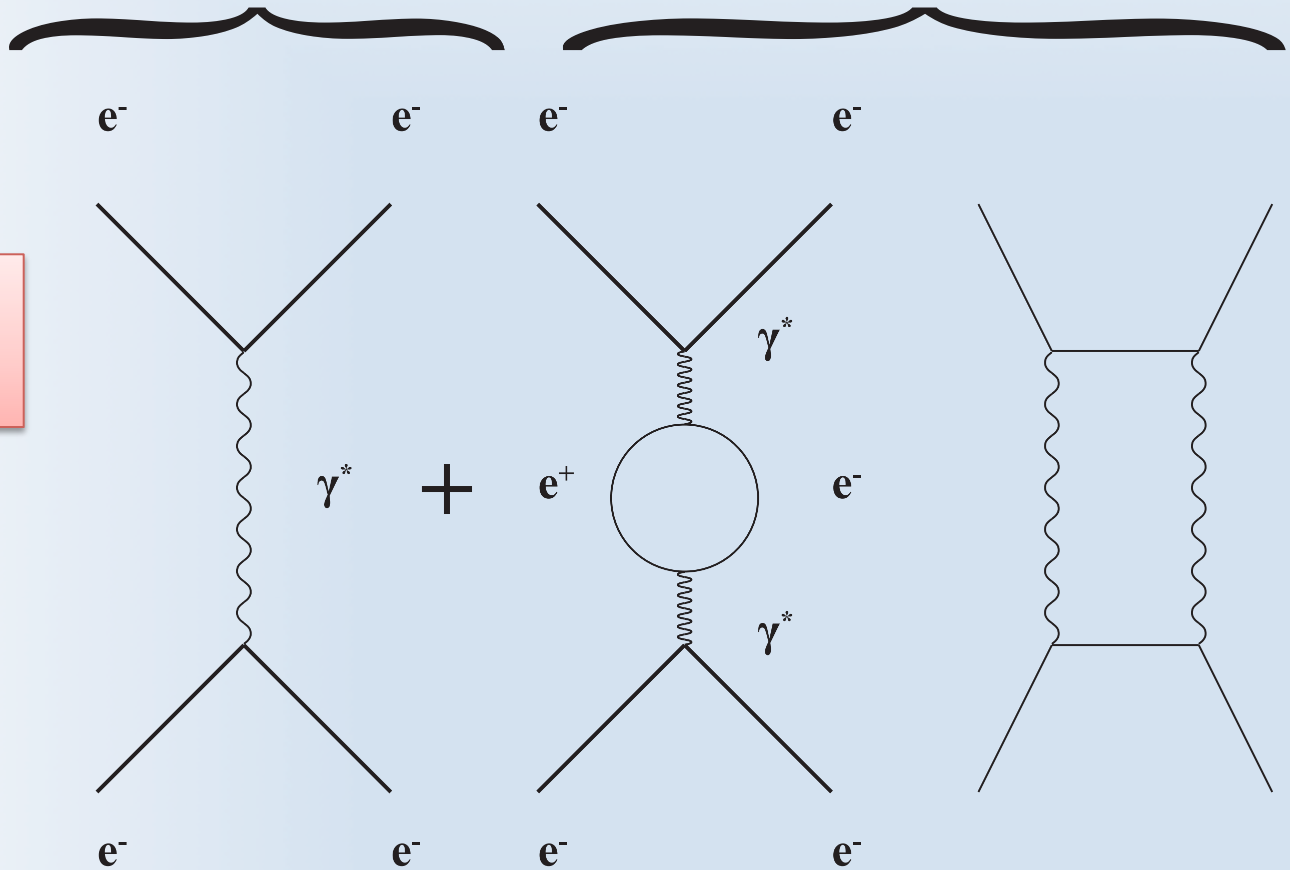
Quantum Electrodynamics (QED)

Sum terms

Integrate over internal states

Leading order
α^2

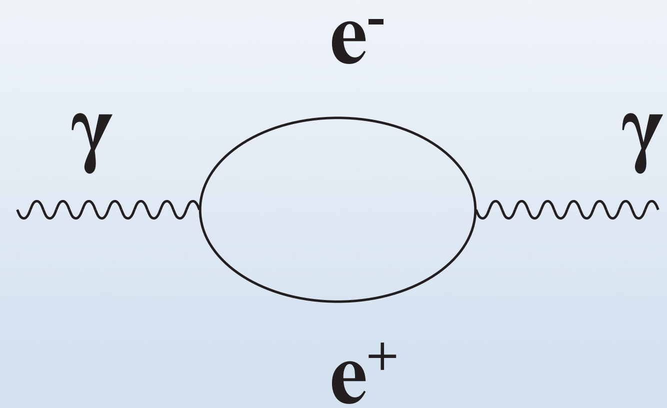
Higher order terms
α^4



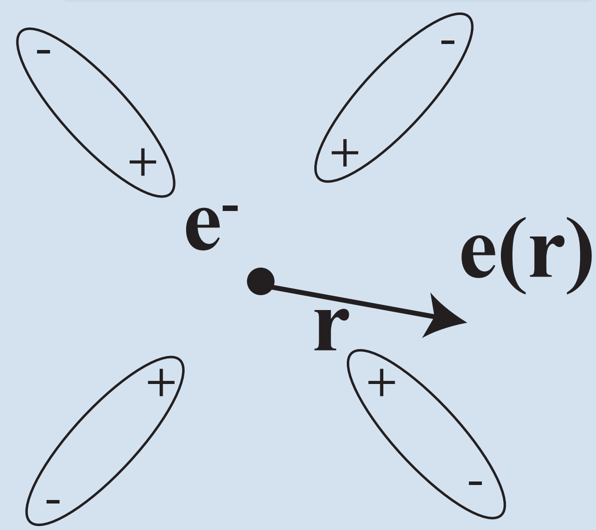
Taming infinities: renormalization

Classical E+M:
Energy in E-field diverges like 1/r

QED:
Energy in E-field diverges like log(r)



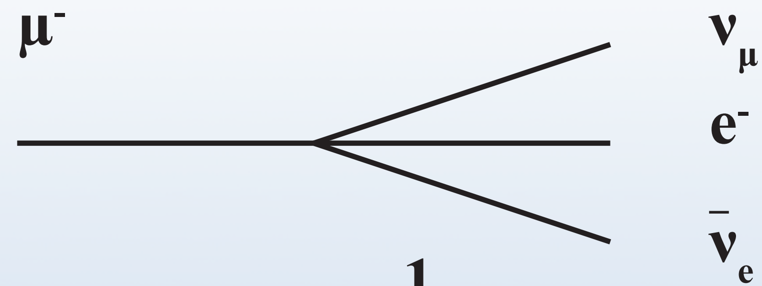
Charge screening



➔Infinities subtracted, finite results
Measurable quantities:
Lamb shift, charge screening…

The weak interaction: Muon decay

Early model – 4 fermi (Fermi beta decay theory)
➔ but, violates unitarity

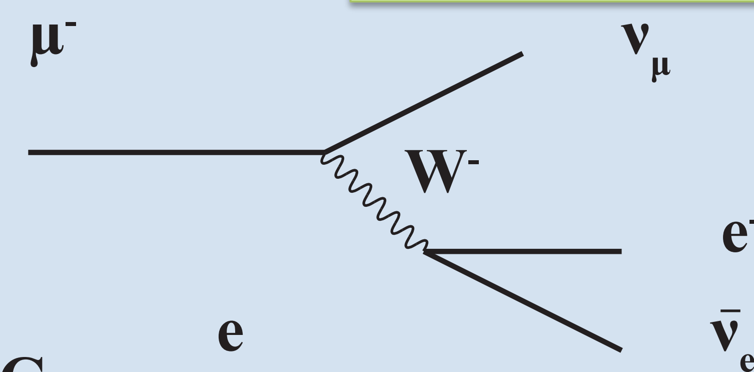


$$G_F \rightarrow \frac{1}{m^2}$$

$1.2\text{x}10^{-5}$ GeV^{-2}

More robust model:
QED is *part* of a larger theory with massive spin 1 force carriers

➔hidden (gauge) symmetry



$$G_F \rightarrow \frac{e}{m_W^2} \quad (m_W \sim 100 \text{ GeV})$$

W^+	γ	W^-
$\|1,1\rangle$	$\|1,0\rangle$	$\|1,-1\rangle$

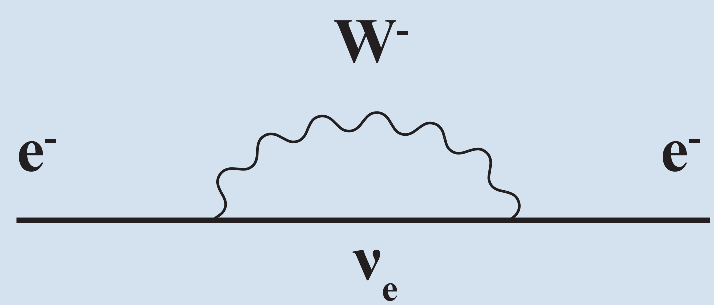
Problems with massive W's

Growth of longitudinal polarization state with momentum

➔Some processes still violate unitarity (WW scattering)

Some relief with a Z^o introduced

➔Theory is not renormalizable like this

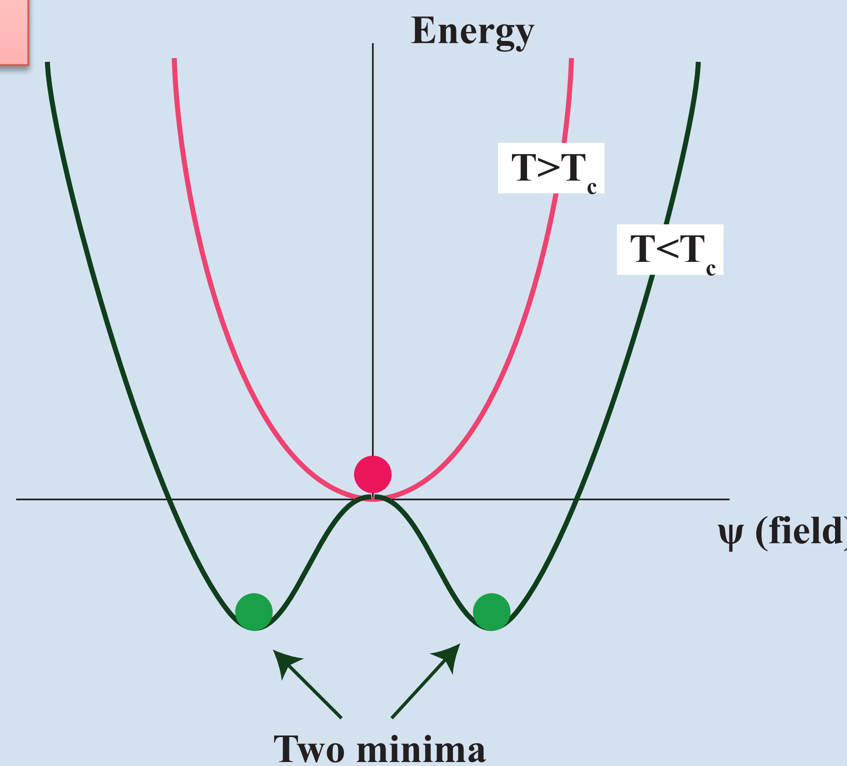


How does nature solve this problem?

Hints from superconductivity

Ginzburg-Landau theory (1950)
➔ Spin 0 'order parameter' field representing electrons in a superconductor

Spontaneous symmetry breaking



Anderson-Higgs mechanism:

Photons in a G-L superconductor acquire a mass

(but QED is still real and works!)

So, the Higgs boson

Complex scalar doublet
(4 degrees of freedom)

$$\phi = \begin{pmatrix} \phi^{+} \\ \phi^{o} \end{pmatrix}$$

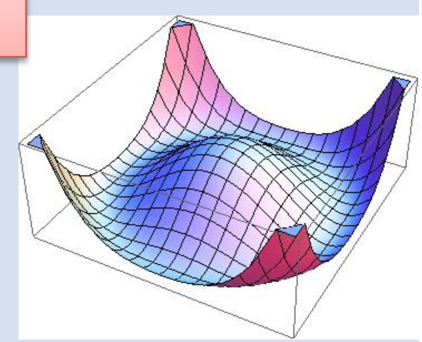
Non-zero 'vacuum expectation value', 'Mexican hat potential'

$$(\sqrt{2}G_F)^{-1/2} \approx 246 GeV$$

Couples to gauge bosons (W,Z), and fermions (e,muons, etc)

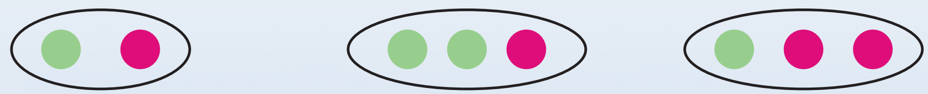
3 degrees of freedom become longitudinal polarization of W^{+},W^{-}, and Z^{o} (mass)

Remaining degree of freedom is the physical Higgs
Theory is renormalizable!!



Add quarks for the Standard Model

Pion	Proton	Neutron



u $\bar{d}$	u u d	u d d

$$q=0 \quad \begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$
$$-1$$

γ W^-

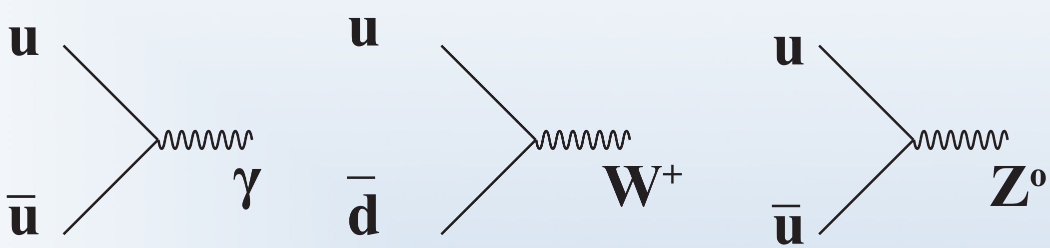
W^+ Z^o

$$2/3 \quad \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$
$$-1/3$$

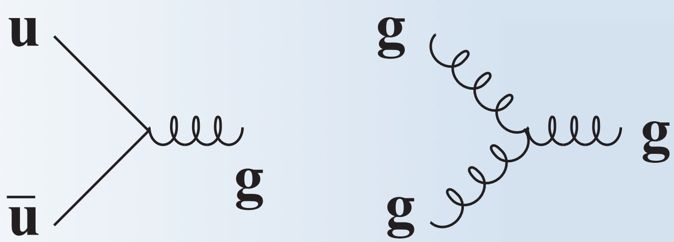
g (gluon)

H

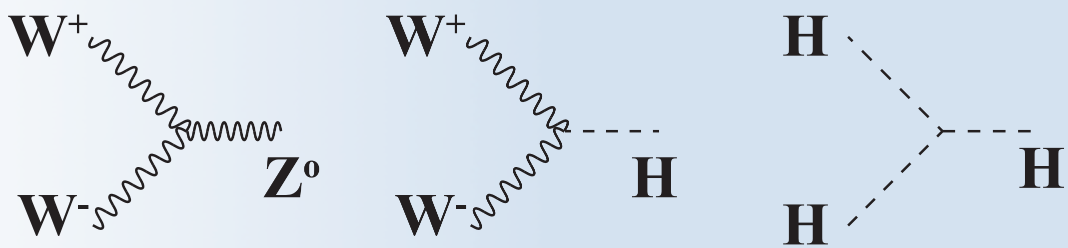
Couplings



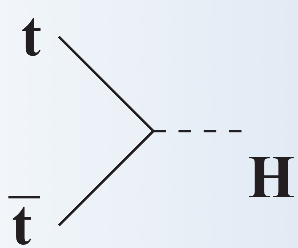
EWK-fermion



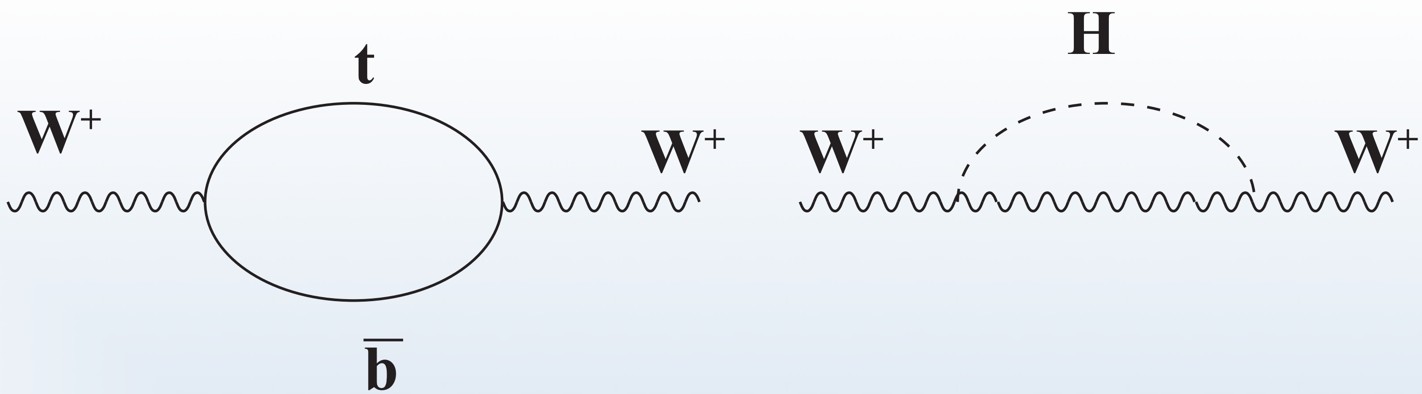
Strong (quarks and gluons)

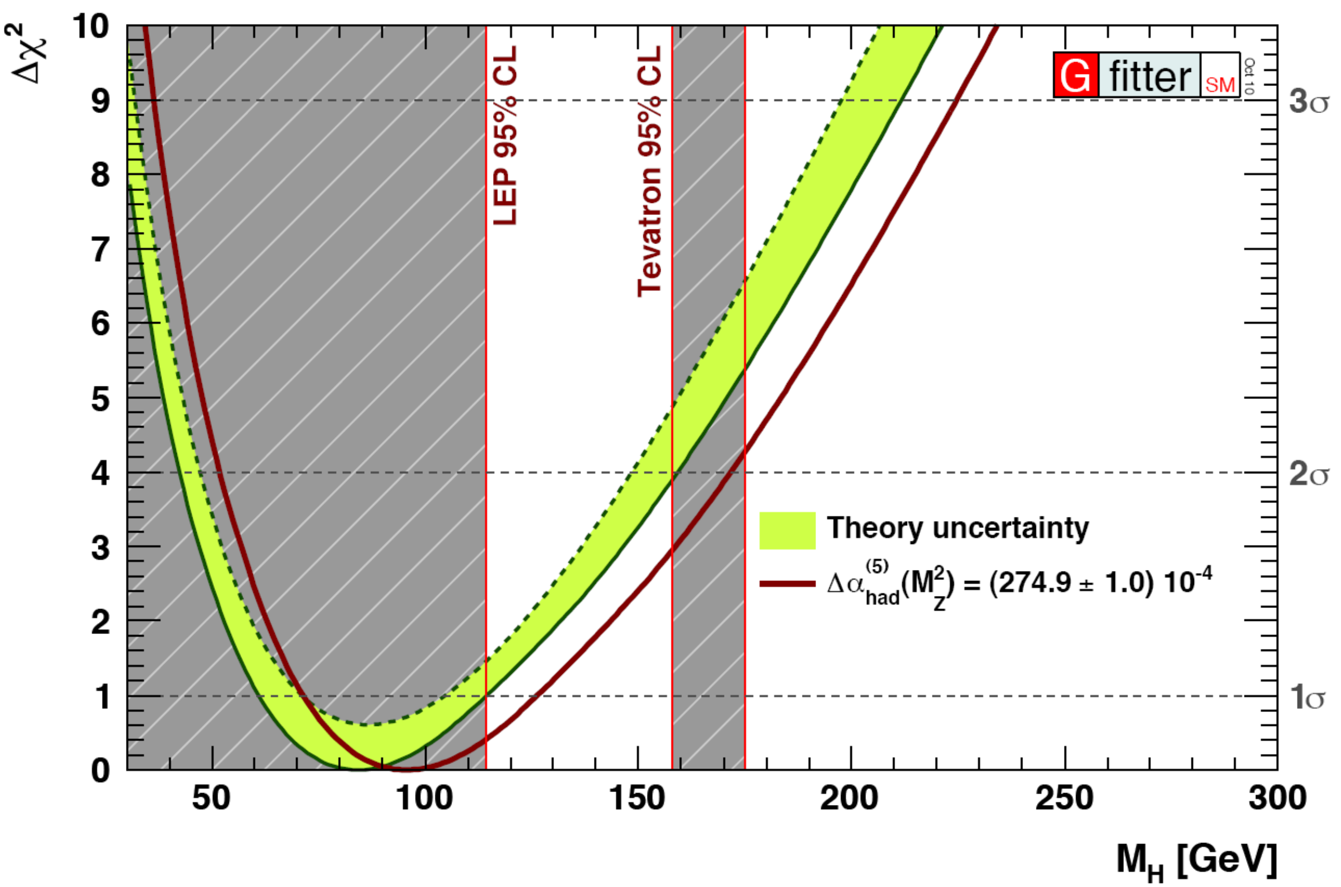


Boson couplings



Yukawa coupling

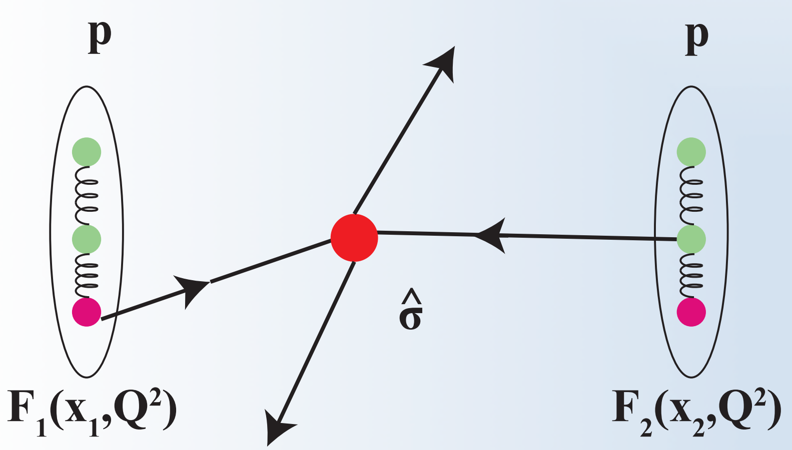




Indirect mass estimates Feb. 2011

M_H=96+/-30

Making the Higgs in pp collisions

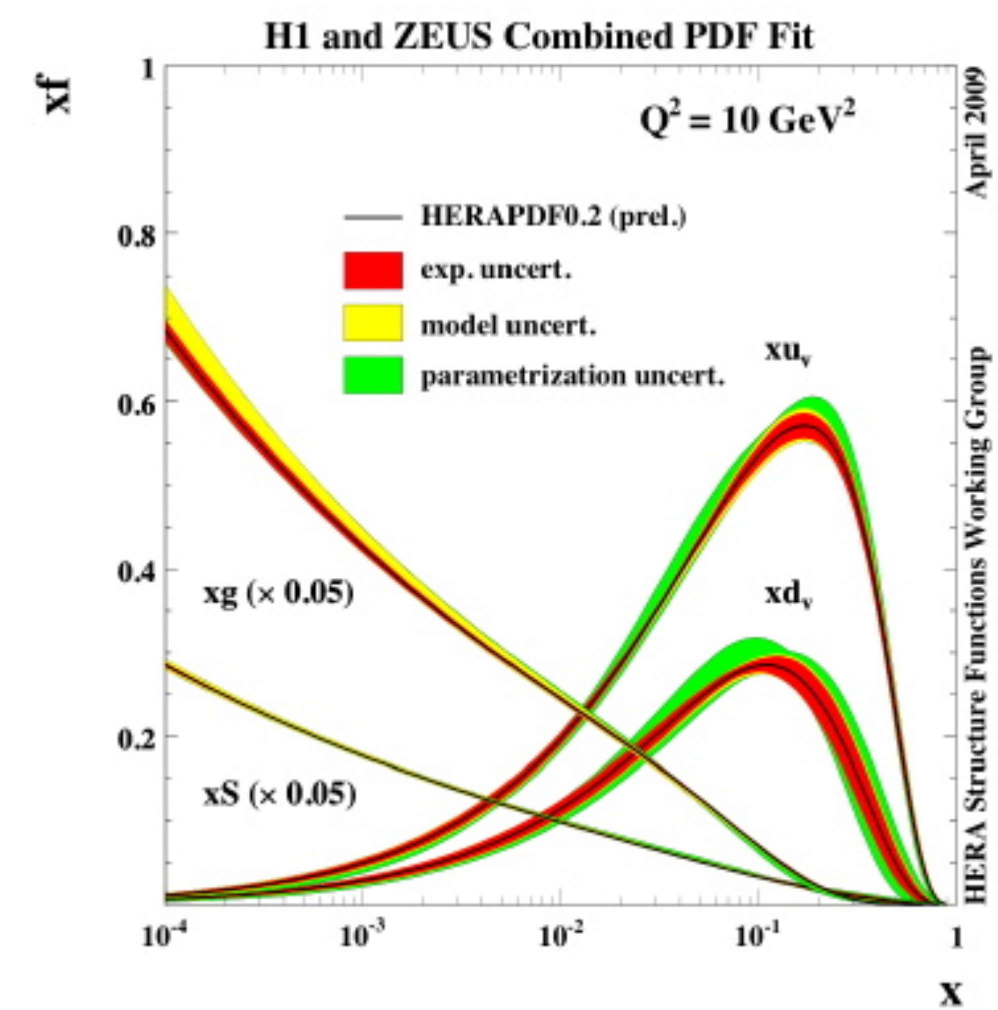


$\hat{\sigma}$ Point like process cross section
$F(x,Q^2)$ Parton Distribution Function
x fraction of proton momentum carried
Q^2 momentum transfer-squared

$$\sigma = \iint \hat{\sigma}\, F_1(x_1,Q^2)\, F_2(x_2,Q^2)\; dx_1 \; dx_2$$

Overall cross section

Parton distribution functions



Cross sections

σ Cross sections expressed as area

1 barn = 10^{-24} cm^2

Accelerator delivers luminosity

$$L = \frac{N_{p1} N_{p2}}{cm^2 \ sec}$$

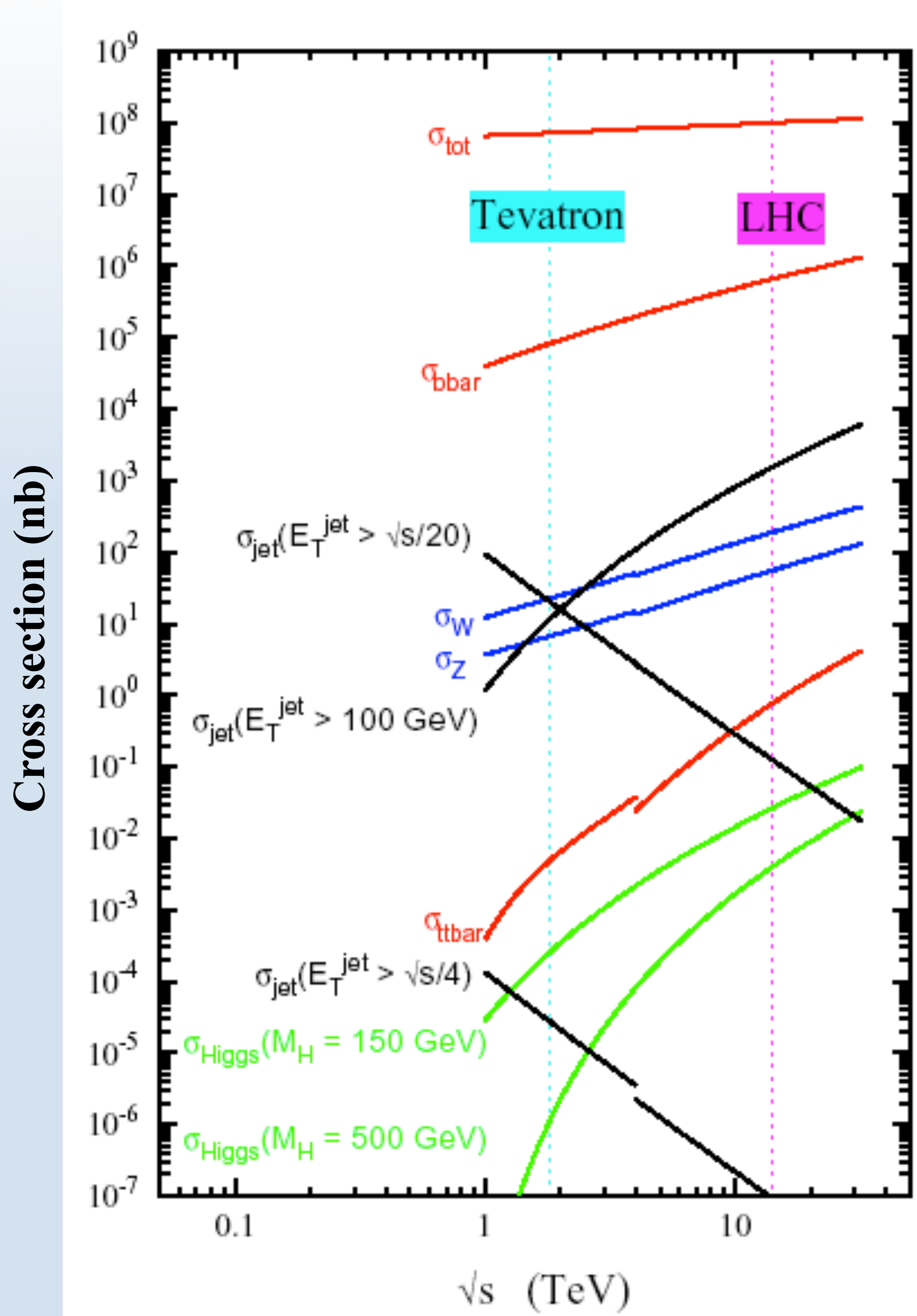
Integrated luminosity

$\int L \, dt$ Units nb^{-1} , pb^{-1}, fb^{-1} etc

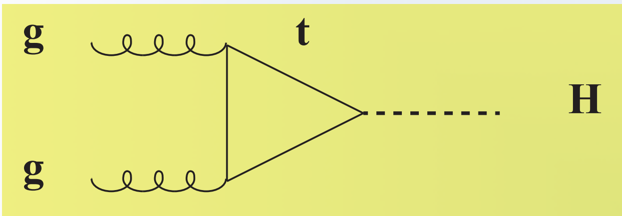
Event yield

$$N_{ev} = \sigma \int L \, dt$$

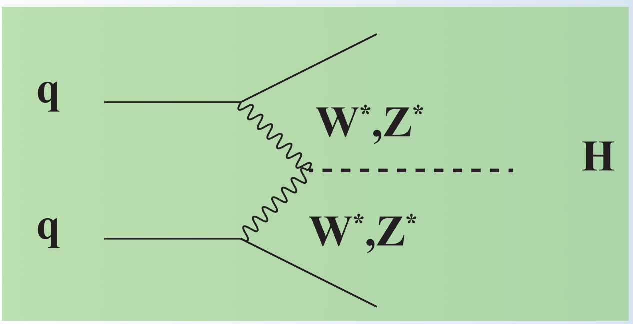
E.g. 1 pb*100 pb^{-1} = 100 events



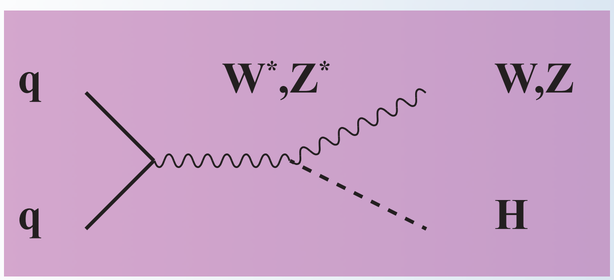
Production and decay



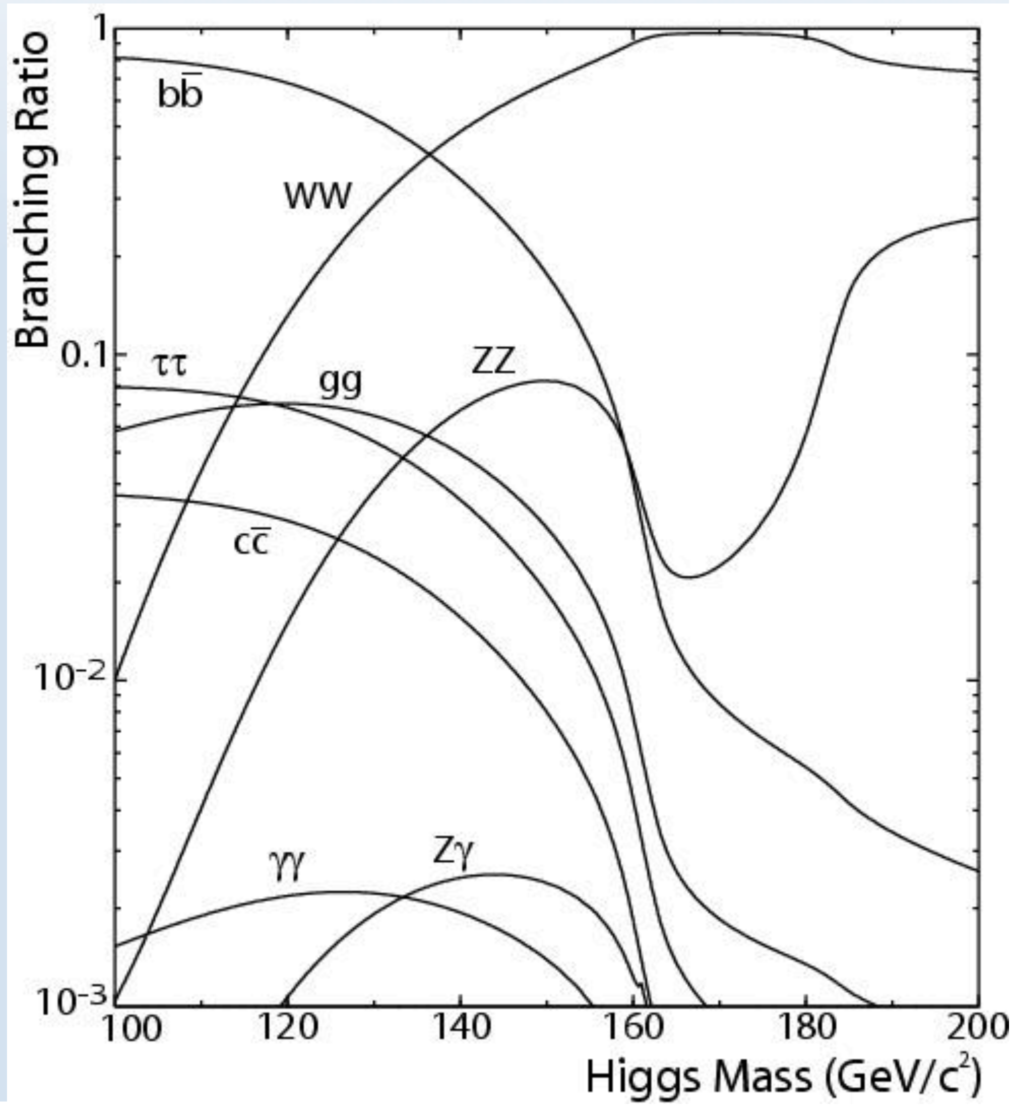
Gluon fusion



Vector boson fusion



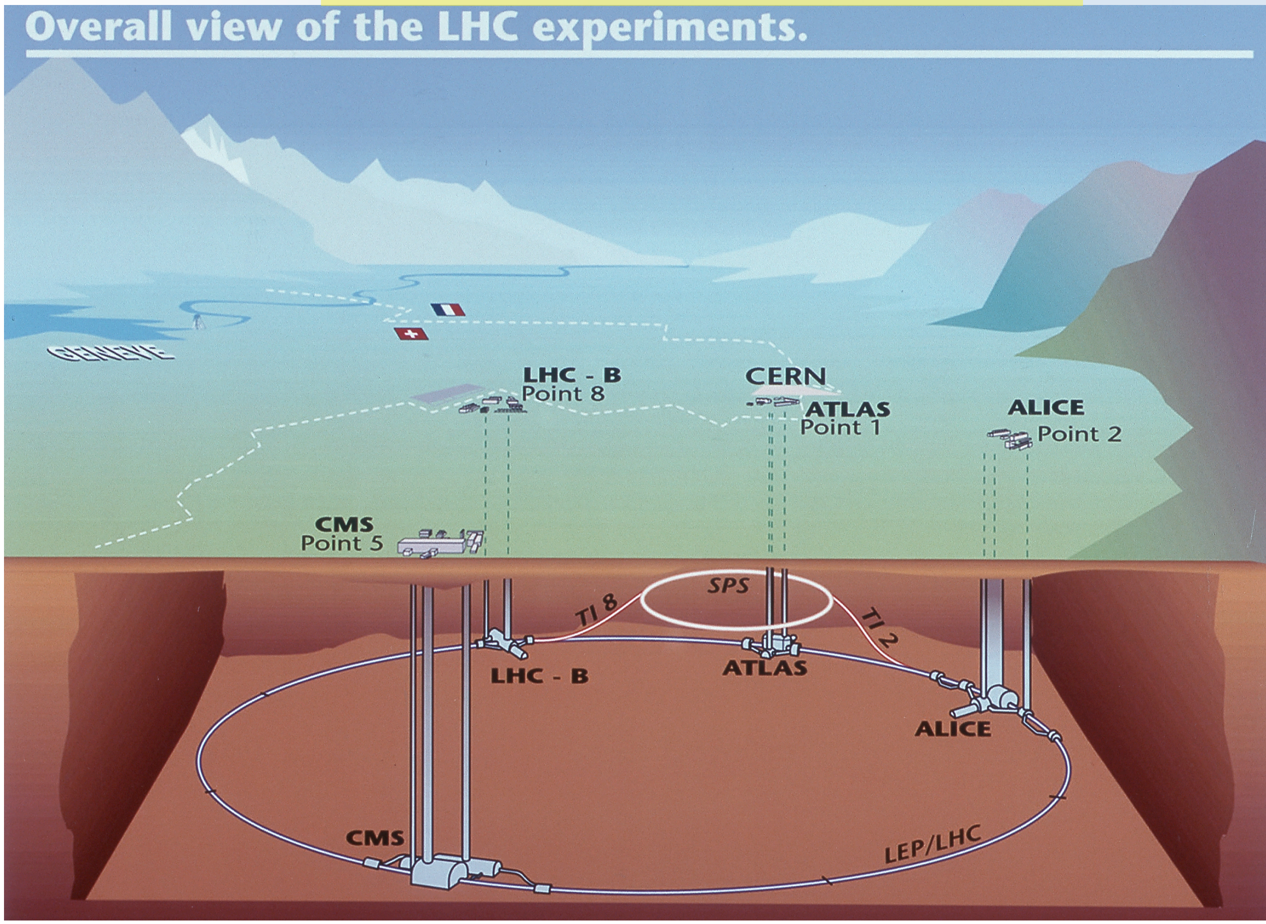
Associated production



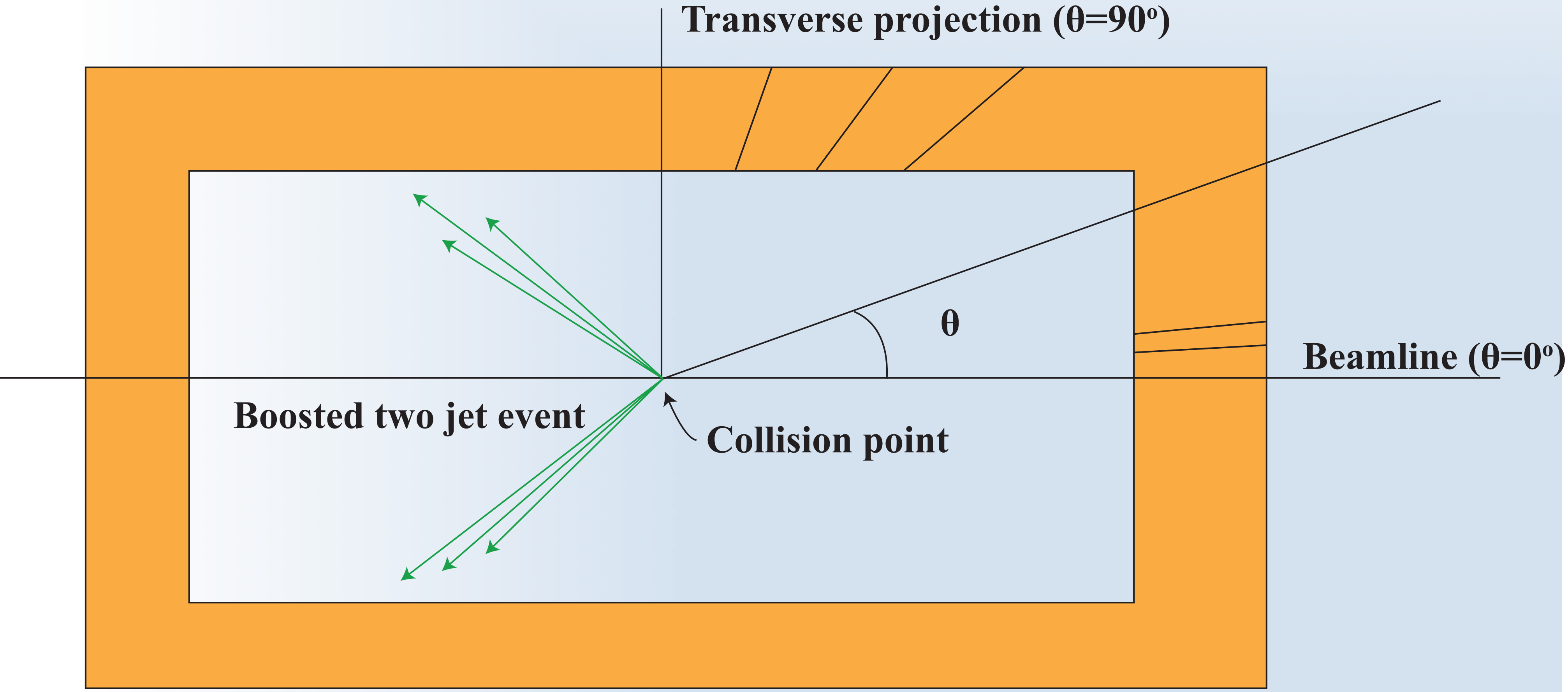
LHC

p-p CM energy = 7,8 TeV
Peak $L \approx 7\text{x}10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$
$\int L\ \text{dt} \approx 5\text{+}5\ \text{fb}^{-1}$

$B \approx 8$ Tesla
$T\text{=}1.9^{o}$ K

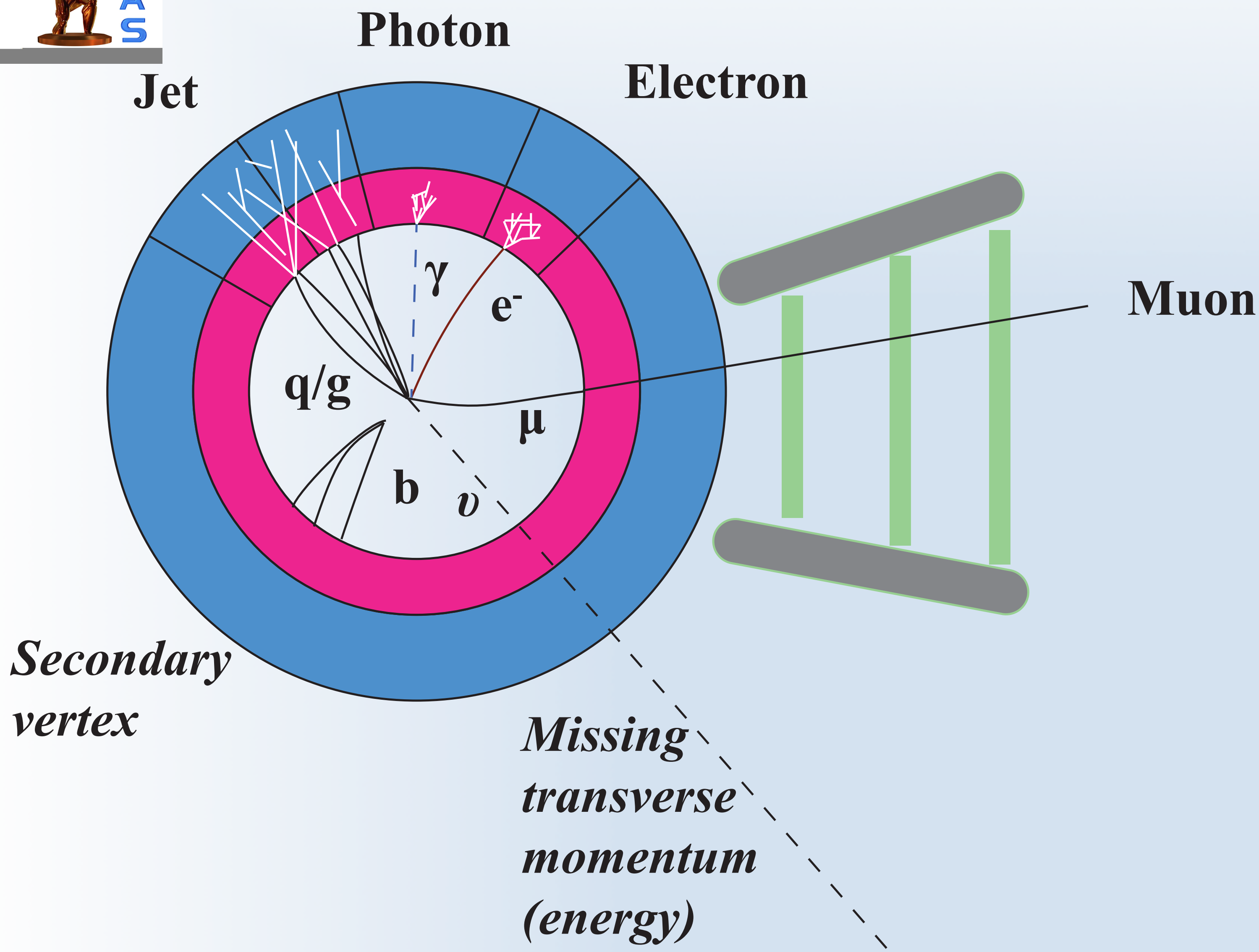


Detector construction

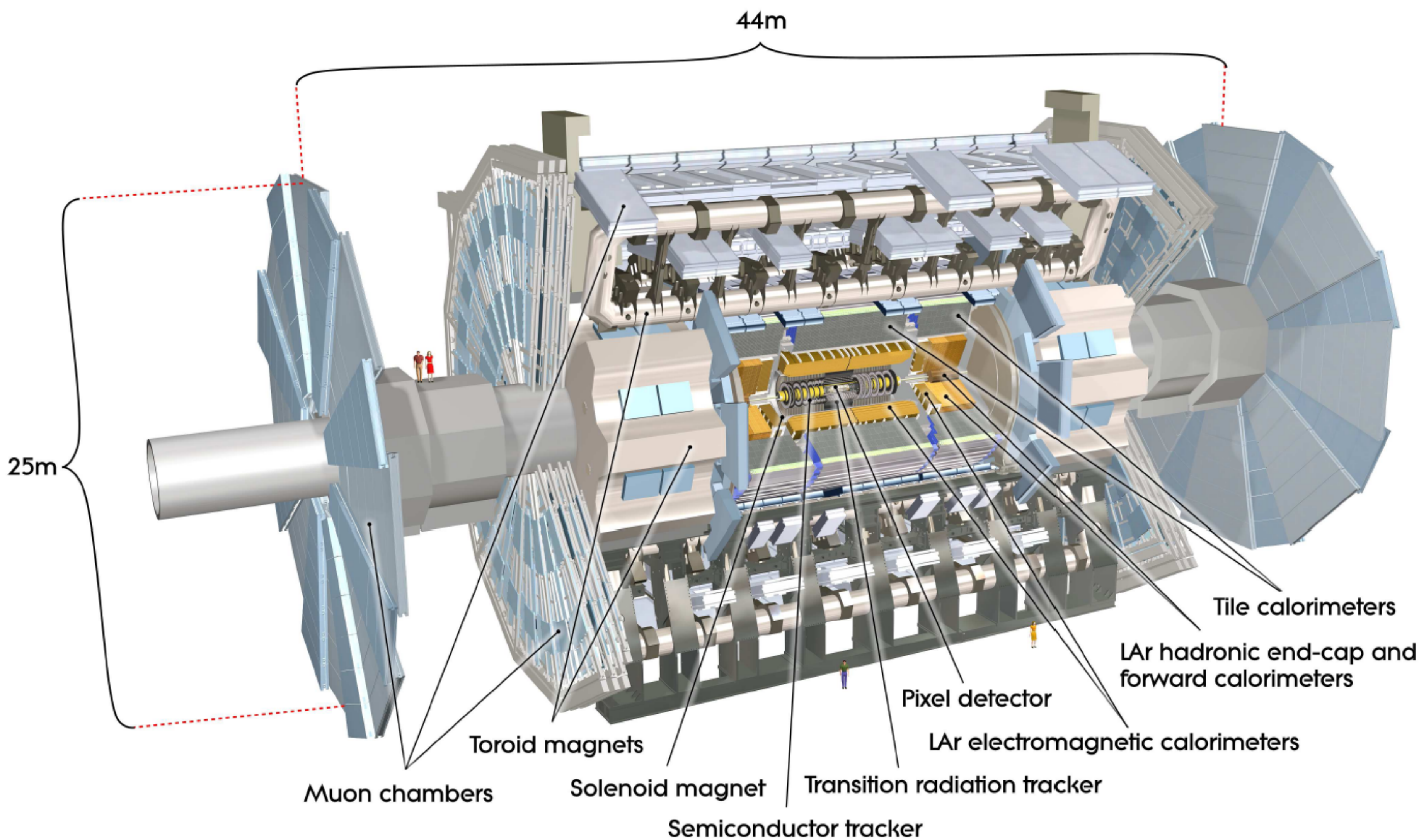


Pseudorapidity, $\eta = -\log(\tan(\theta/2))$

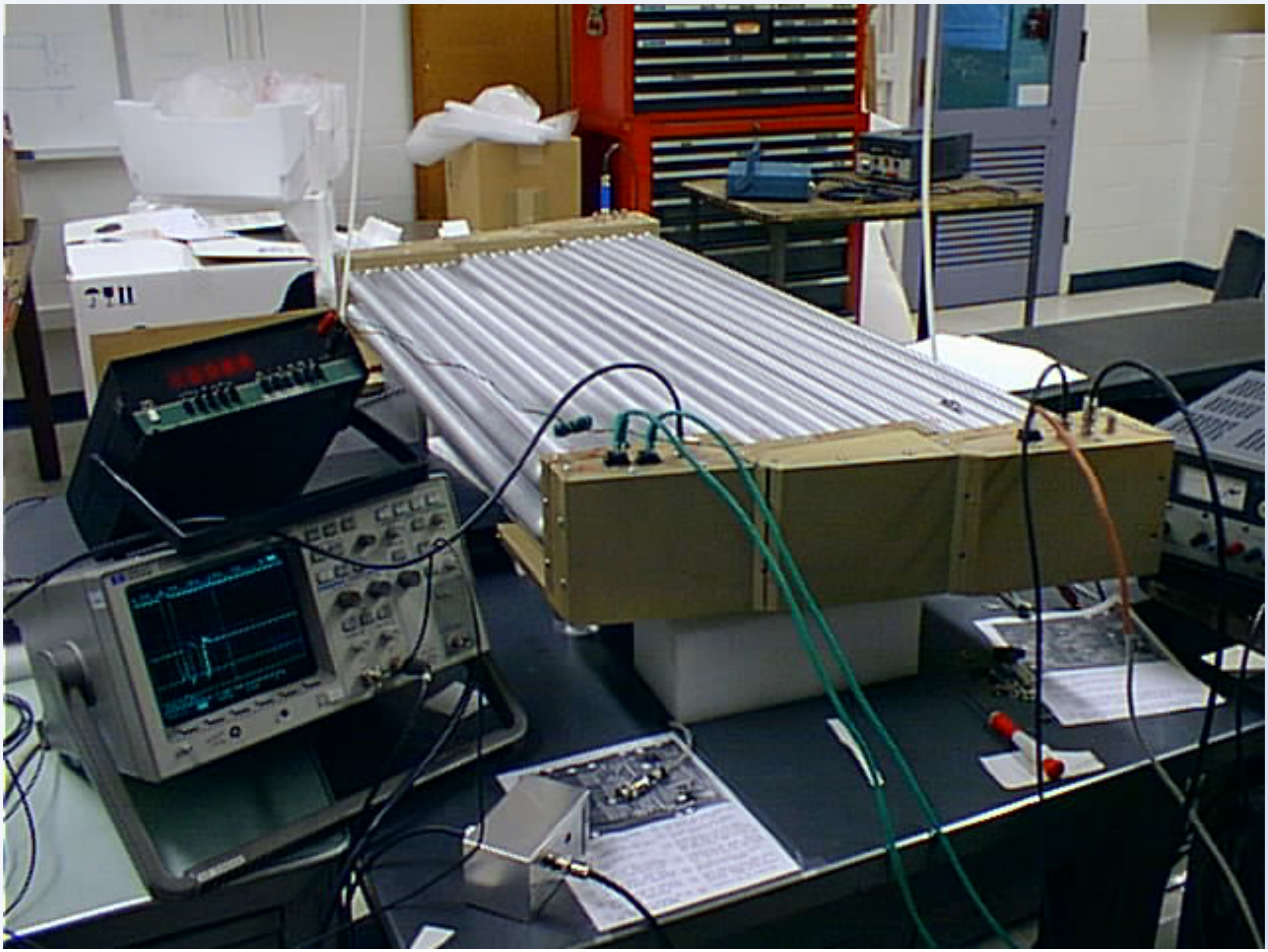
Detector observables



ATLAS
A Toroidal Lhc ApparatuS



Local Harvard Effort

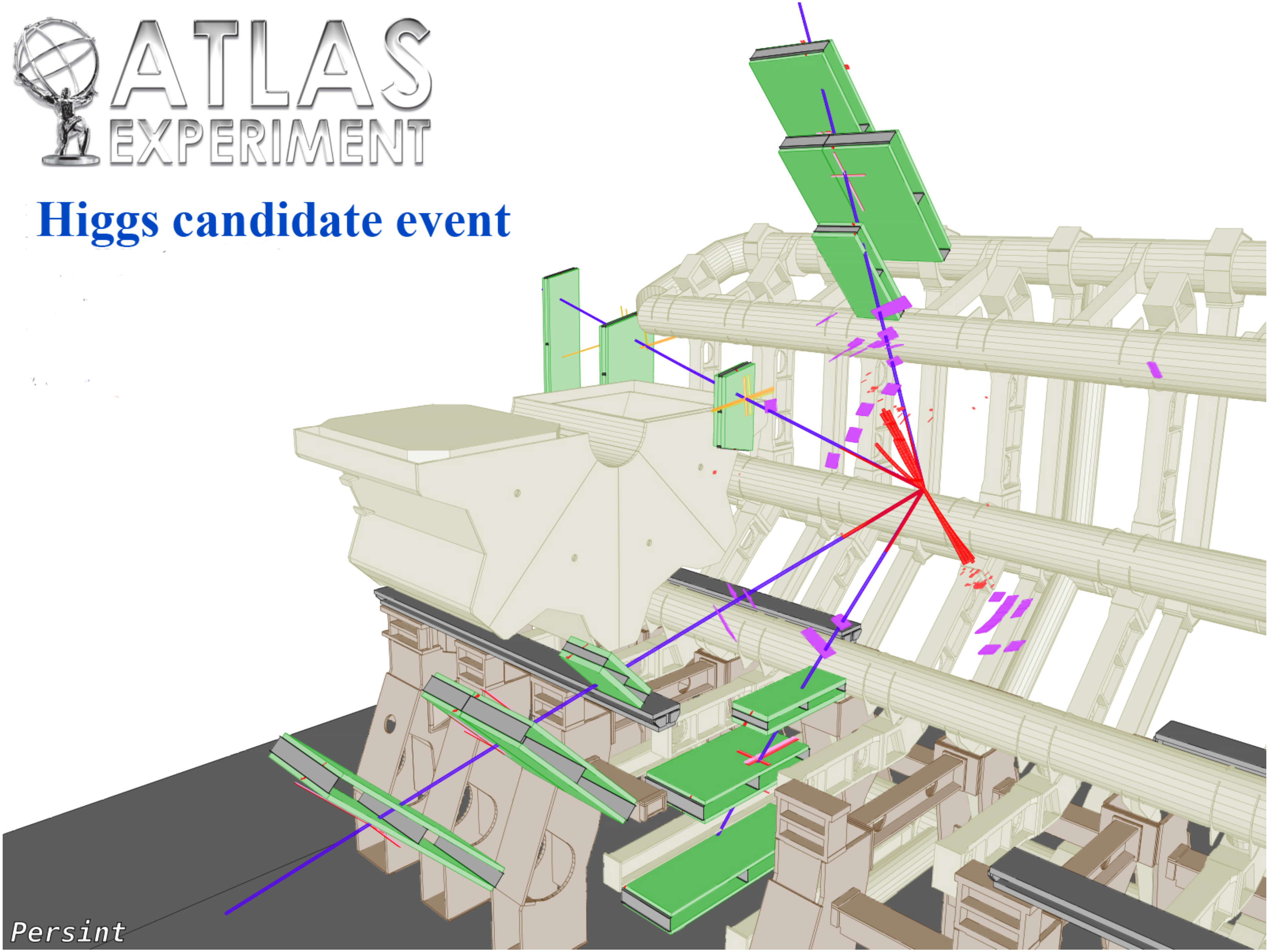


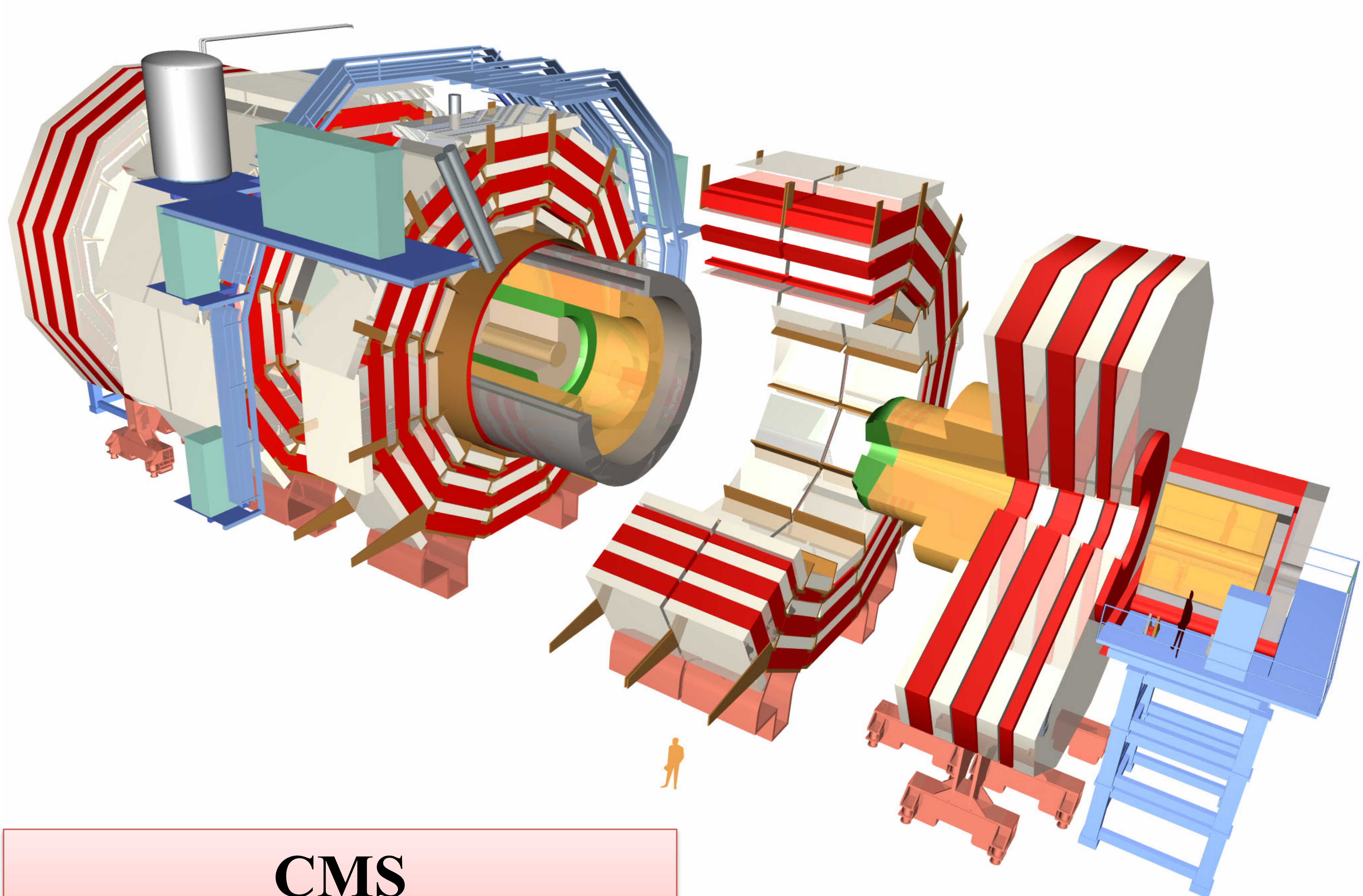
Muon System Installation Completed!
July 2008

July 24:
Last day of
unrestricted access
to the cavern

ATLAS EXPERIMENT

Higgs candidate event

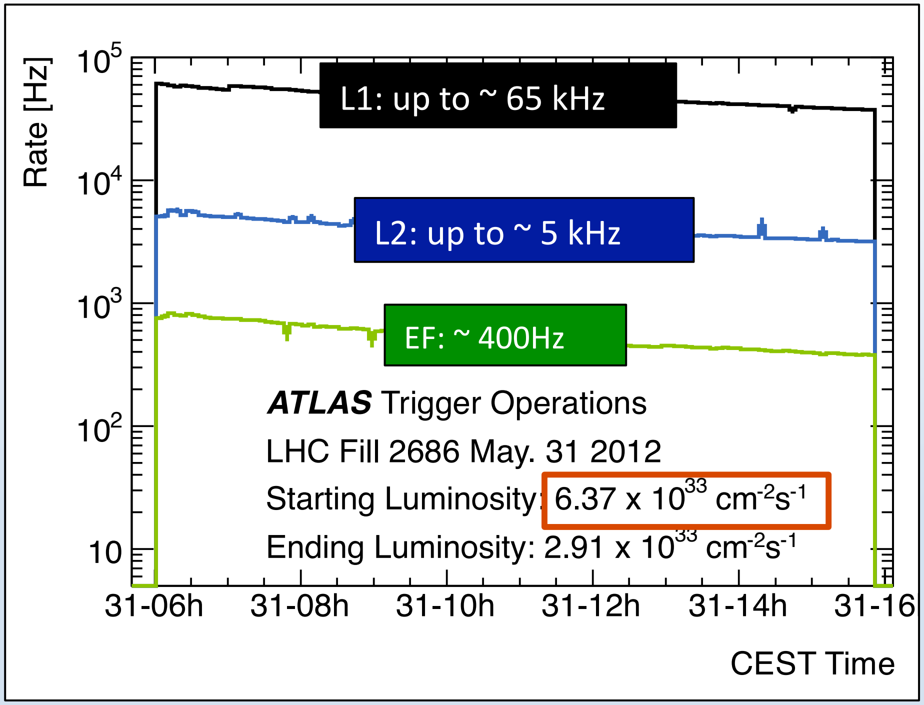




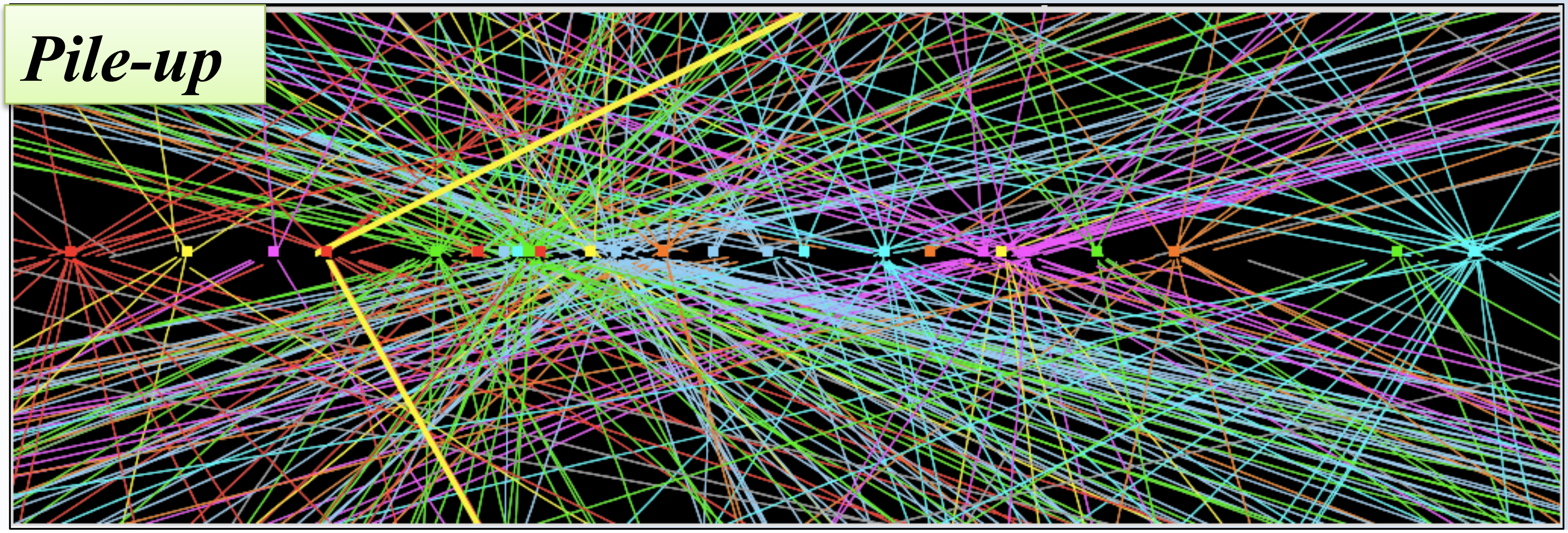
CMS
Compact Muon Solenoid

Challenges

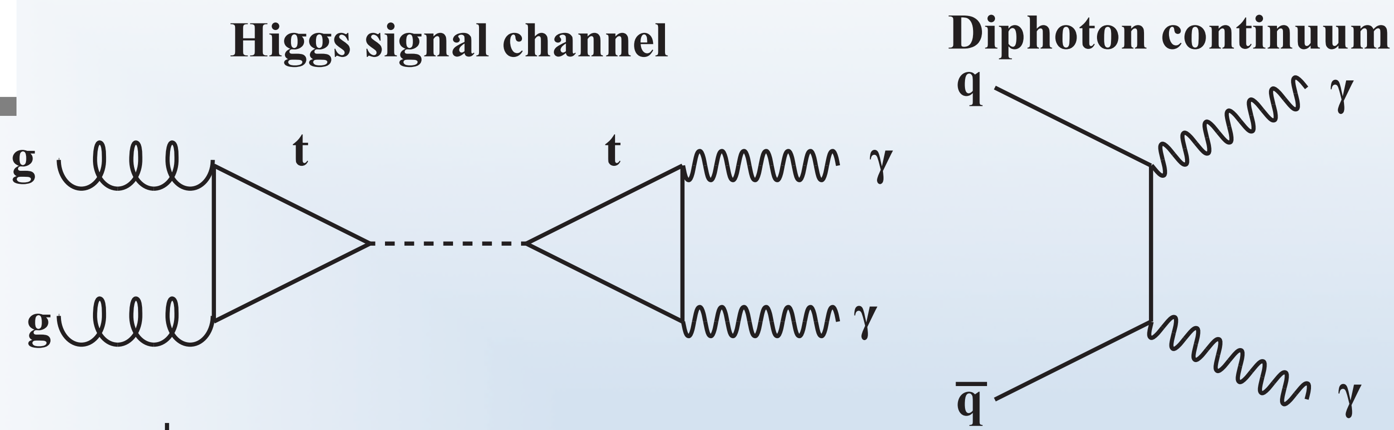
Trigger rate

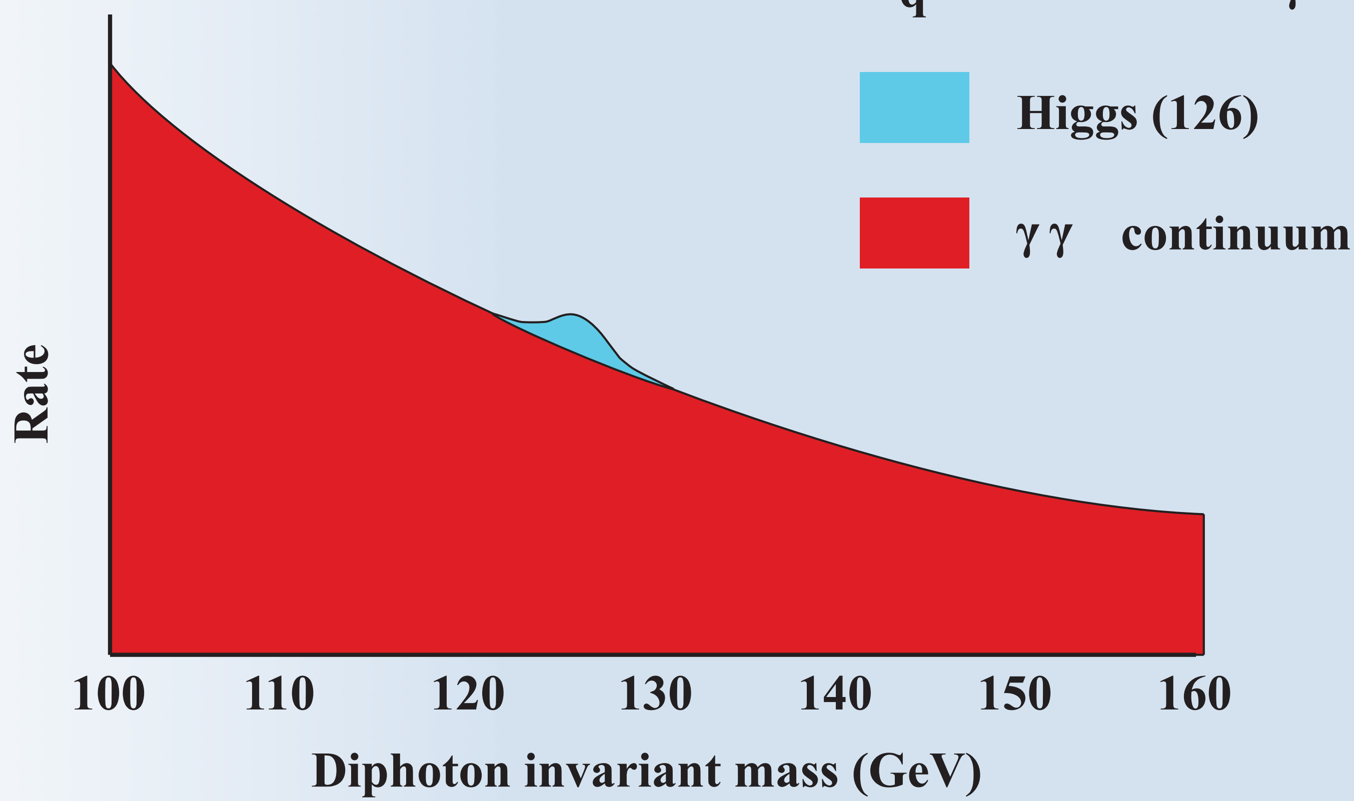


Pile-up



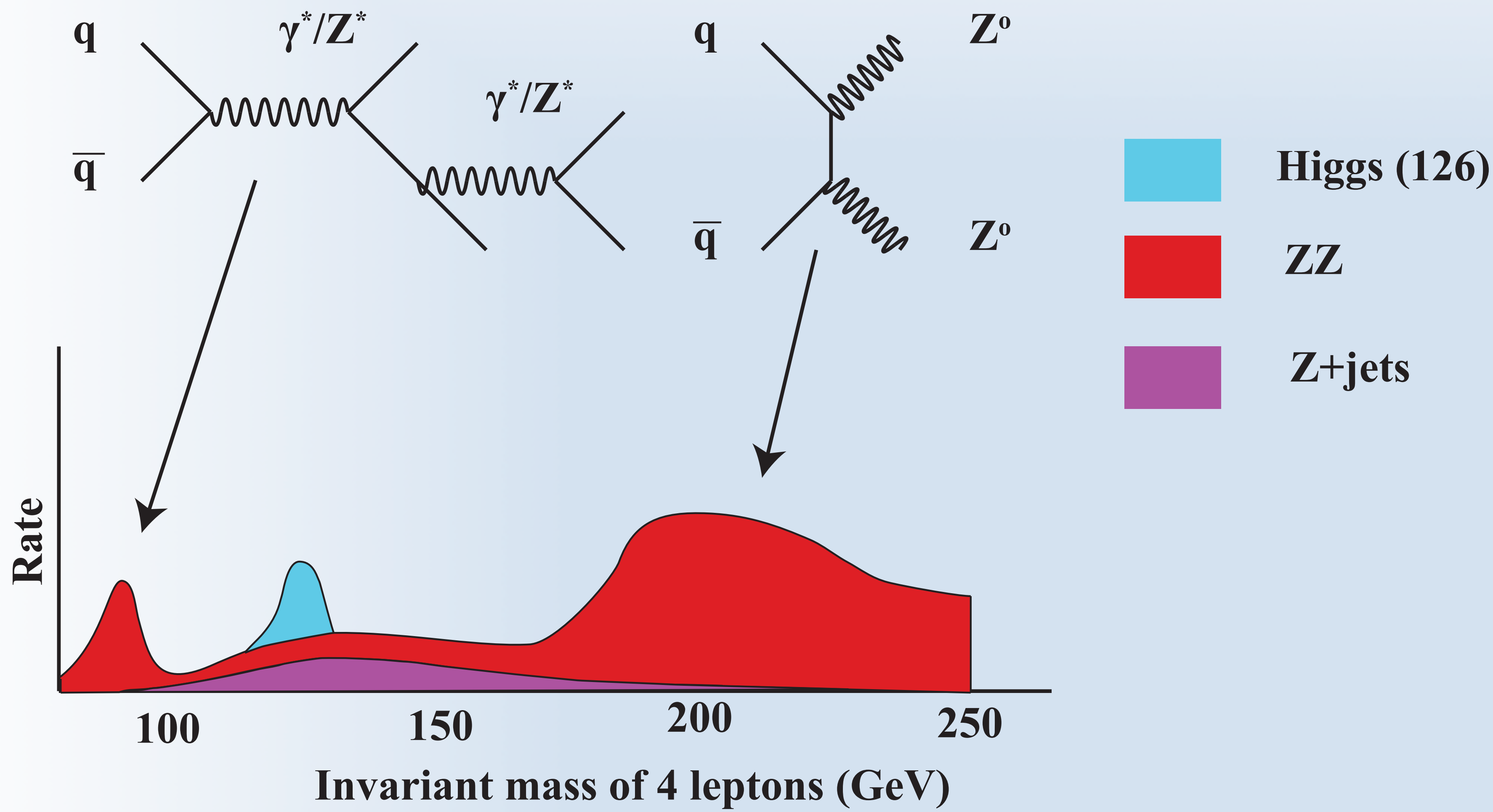
$H\to\gamma\gamma$





H→Z(*)Z→eeee, eeμμ,μμμμ

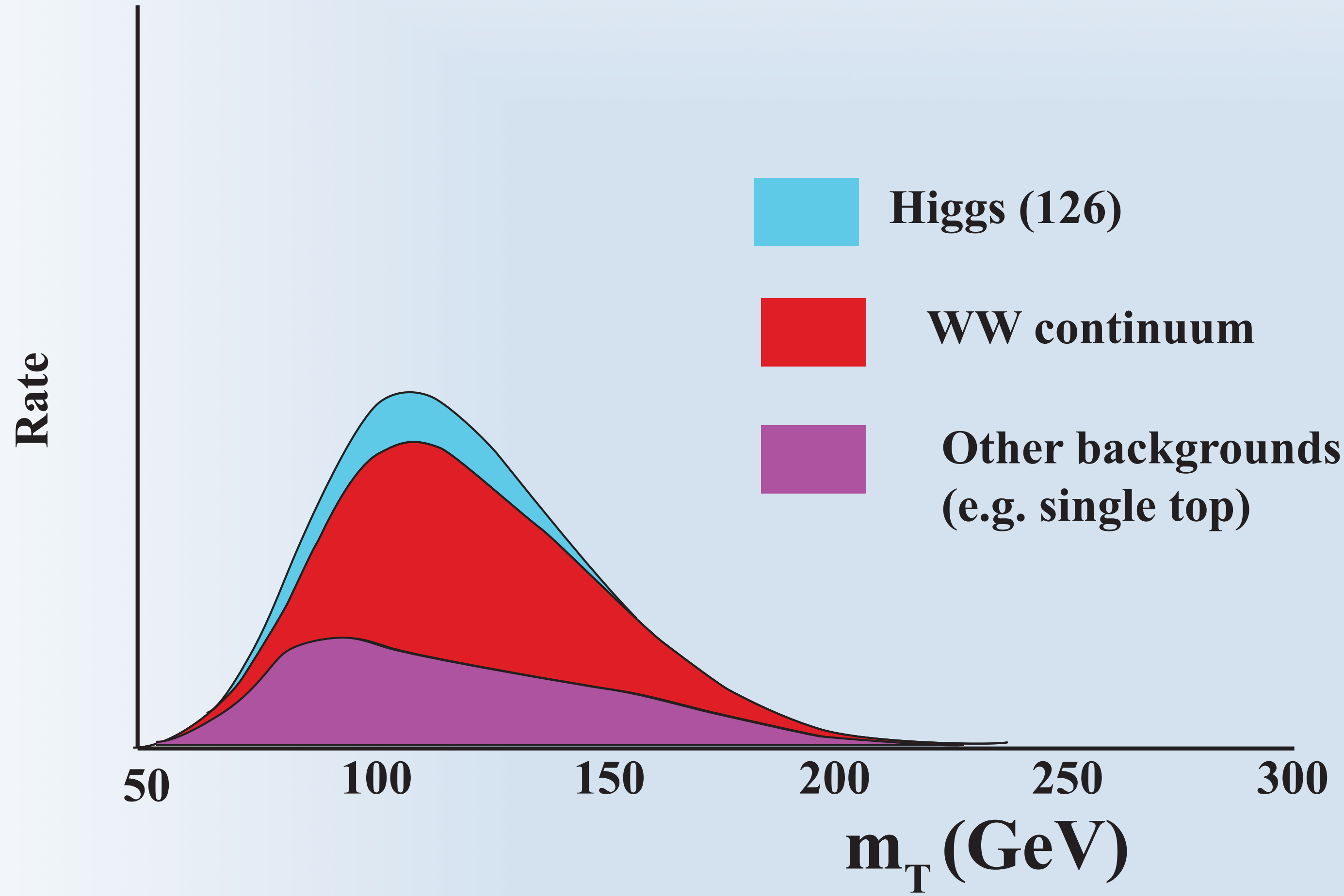
Main background: Standard Model ZZ production



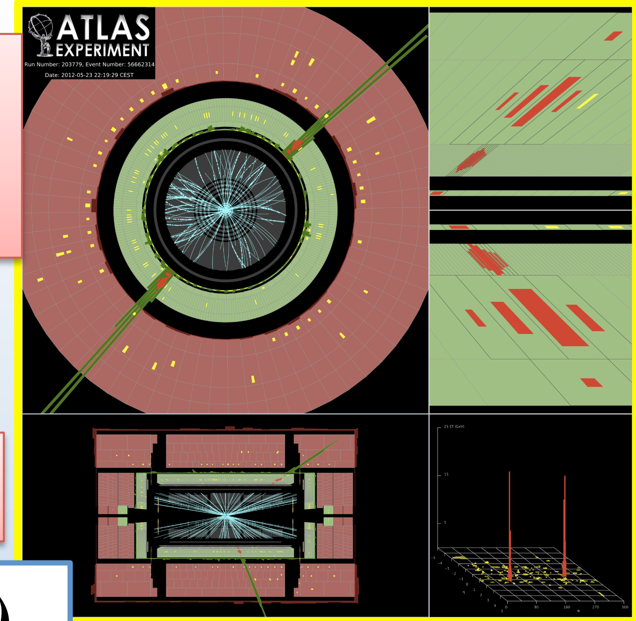
$H \rightarrow W^{(*)}W \rightarrow e\nu e\nu,\ e\nu\mu\nu, \mu\nu\mu\nu$

Transverse mass:

$$m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - |\vec{p}_T^{\,ll} + \vec{E}_T^{miss}|^2}$$

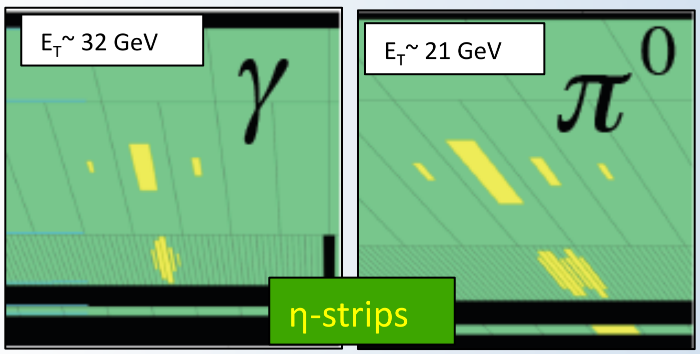


Higgs search in two photon channel

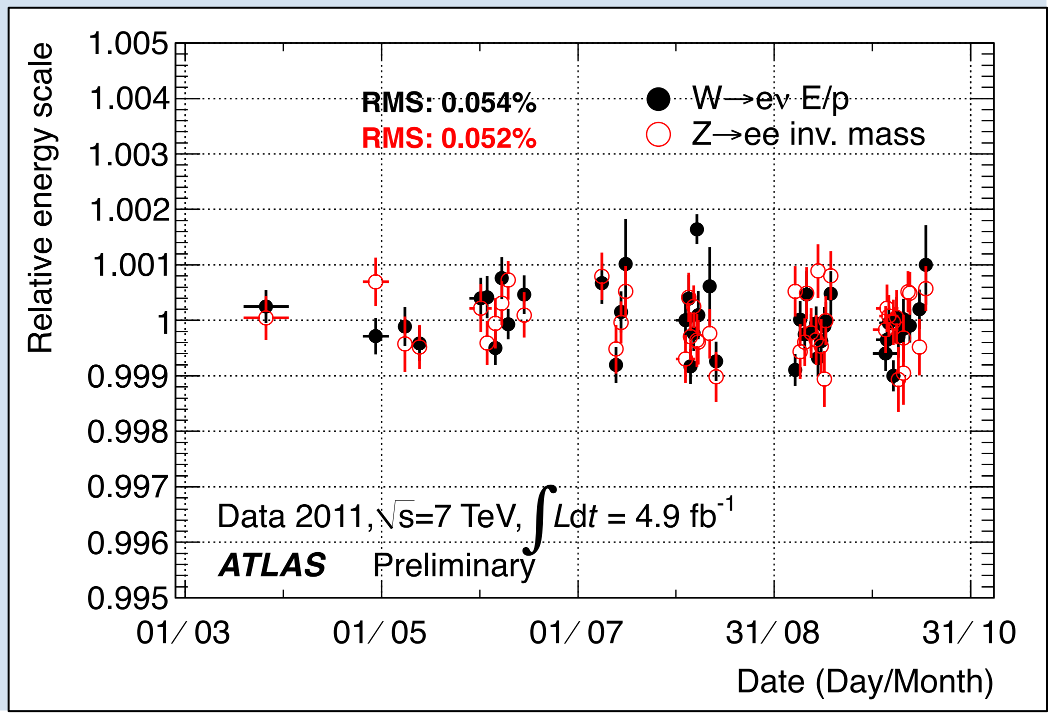


2 isolated photons, $E_t(1,2)>40, 30$ GeV

Excellent π^o rejection, γ efficiency (90%)



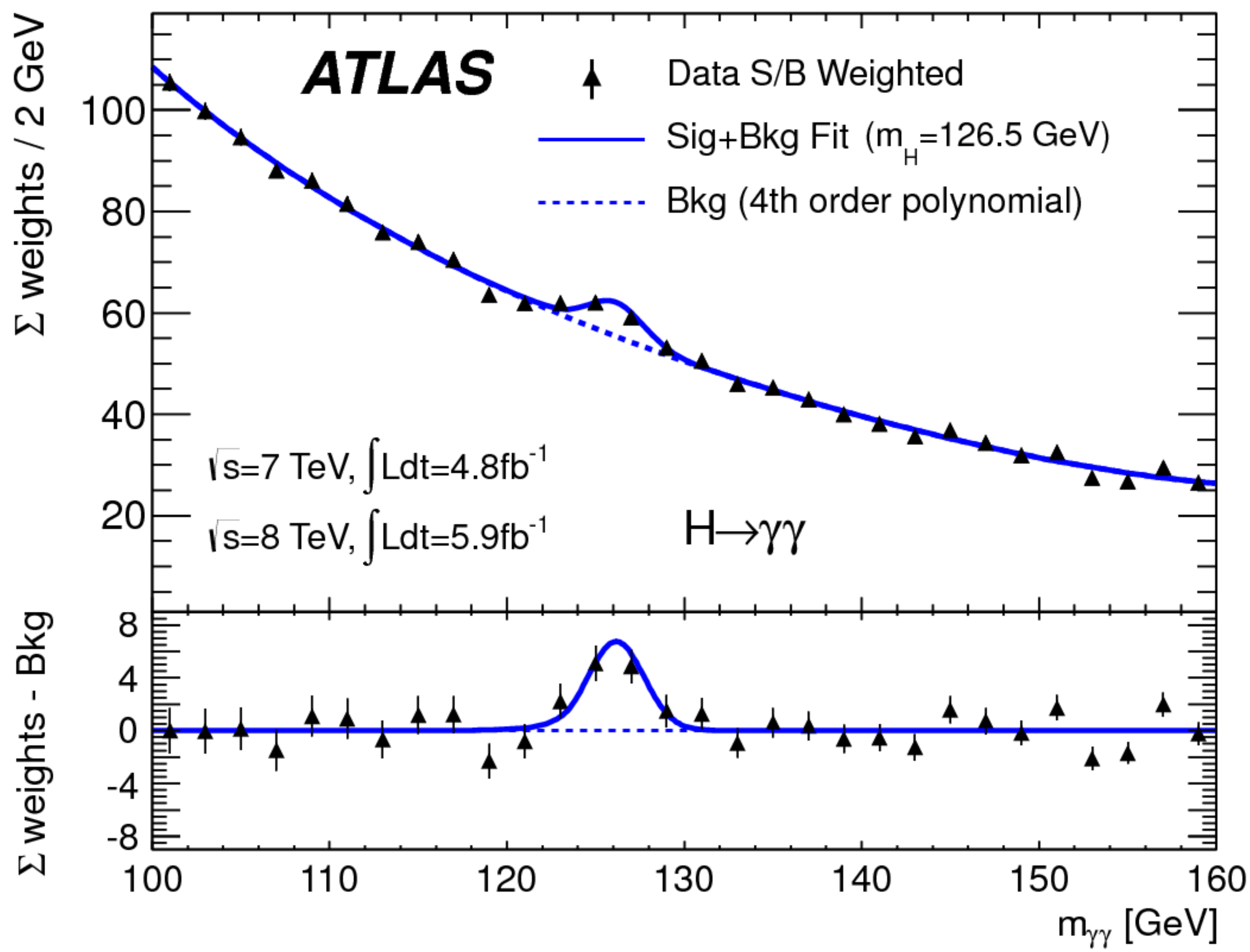
Mass resolution 1.6 GeV
E scale 0.3%
Uniformity, linearity 1%



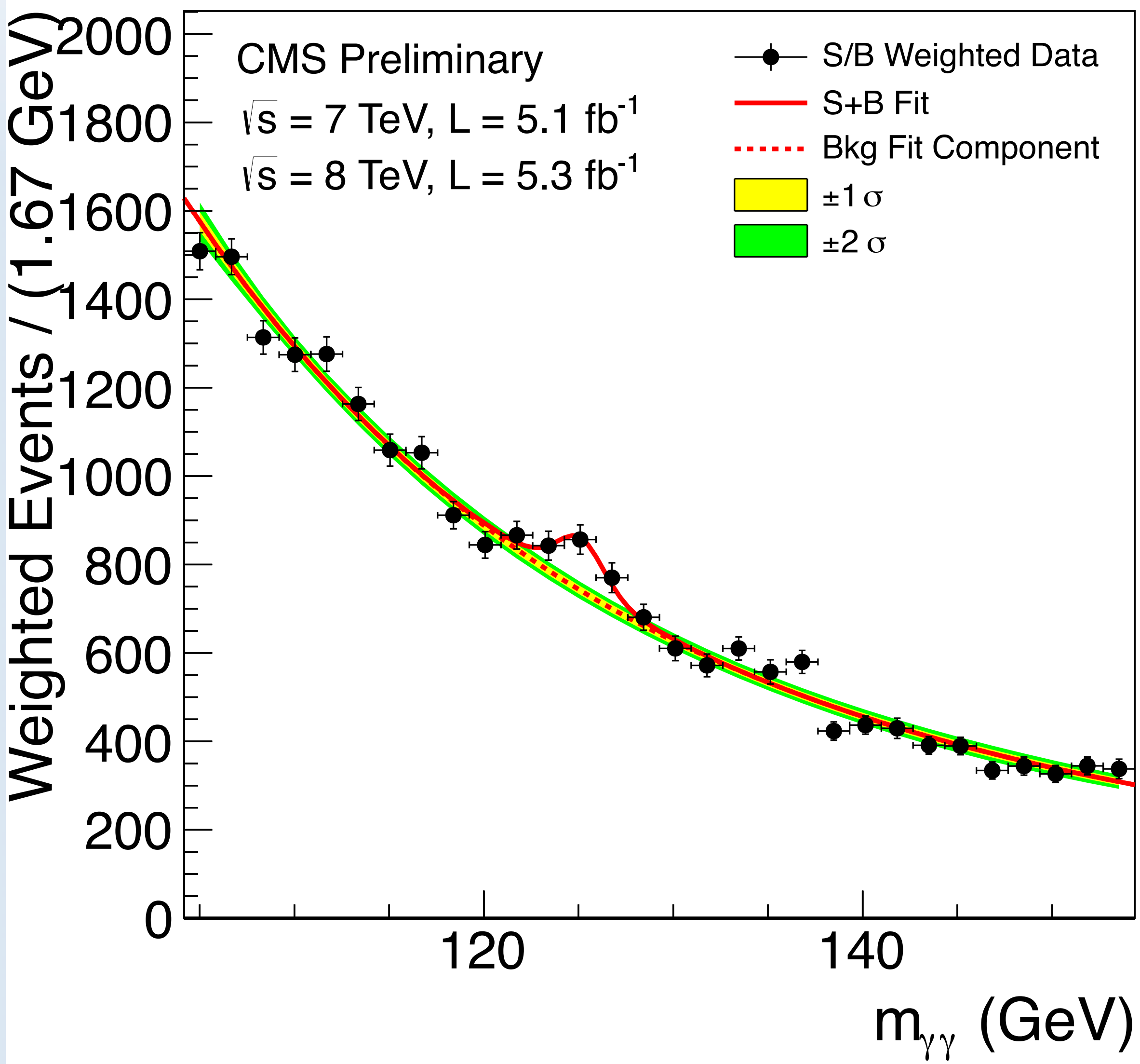
ATLAS Diphoton results

Bck. comp:
74% γγ
22% γj
3% jj
1% DY

Dom. unc:
Recon eff.
8, 11%



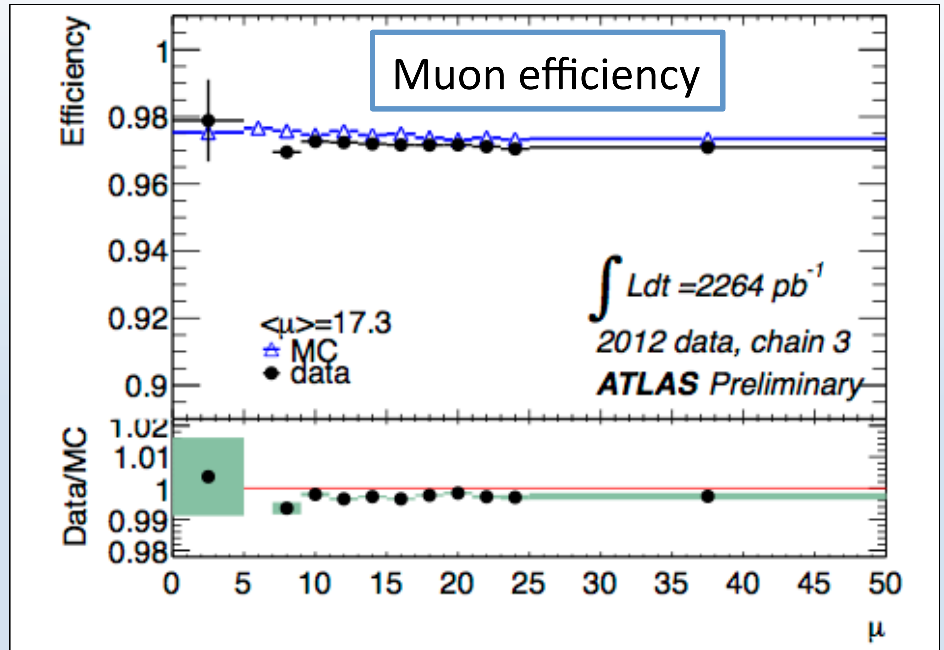
CMS Diphoton results

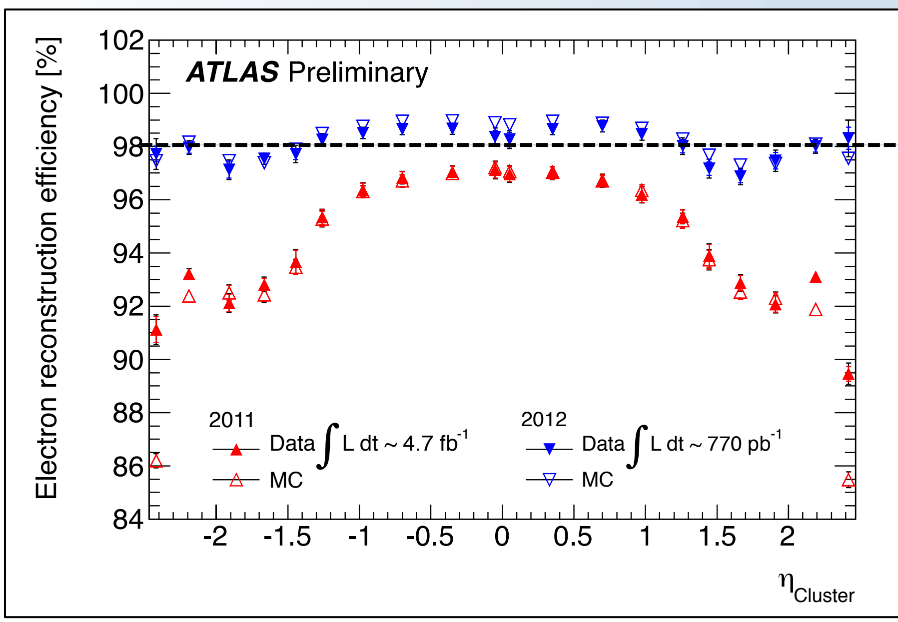


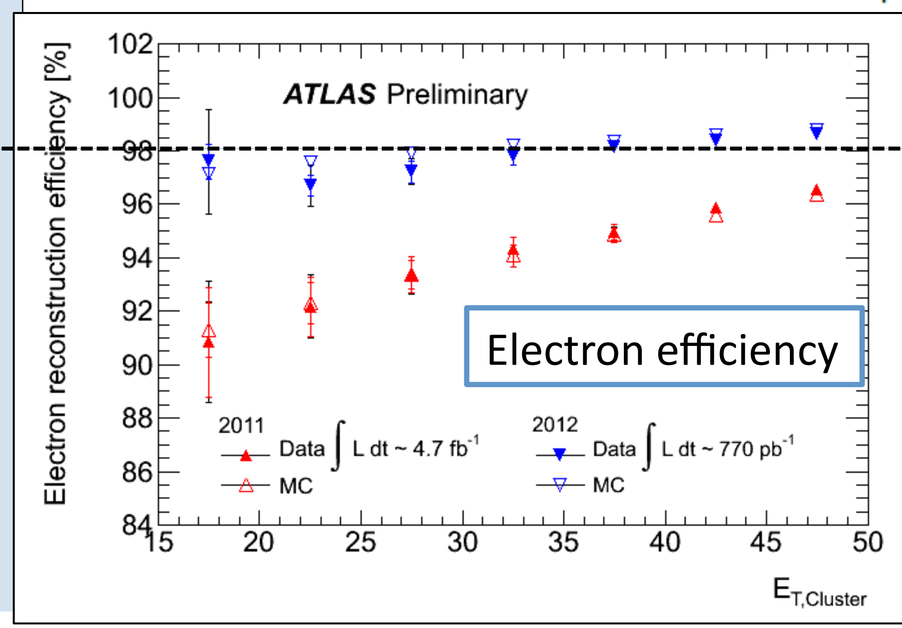
$Z^{(*)}Z$

2 opposite sign pairs of ee and/or μμ

p_t > 7 GeV electron
P_t > 6 GeV muon





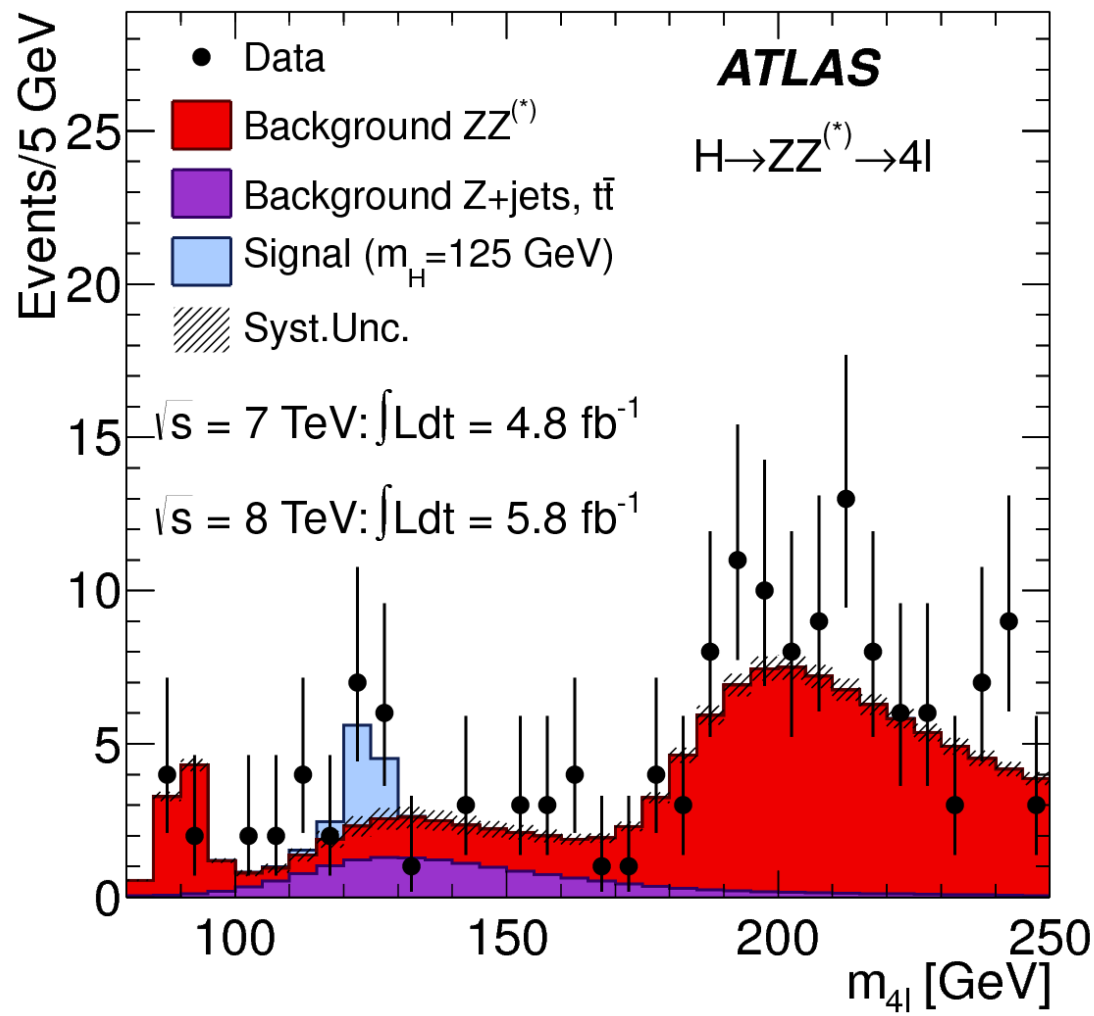


ATLAS ZZ results

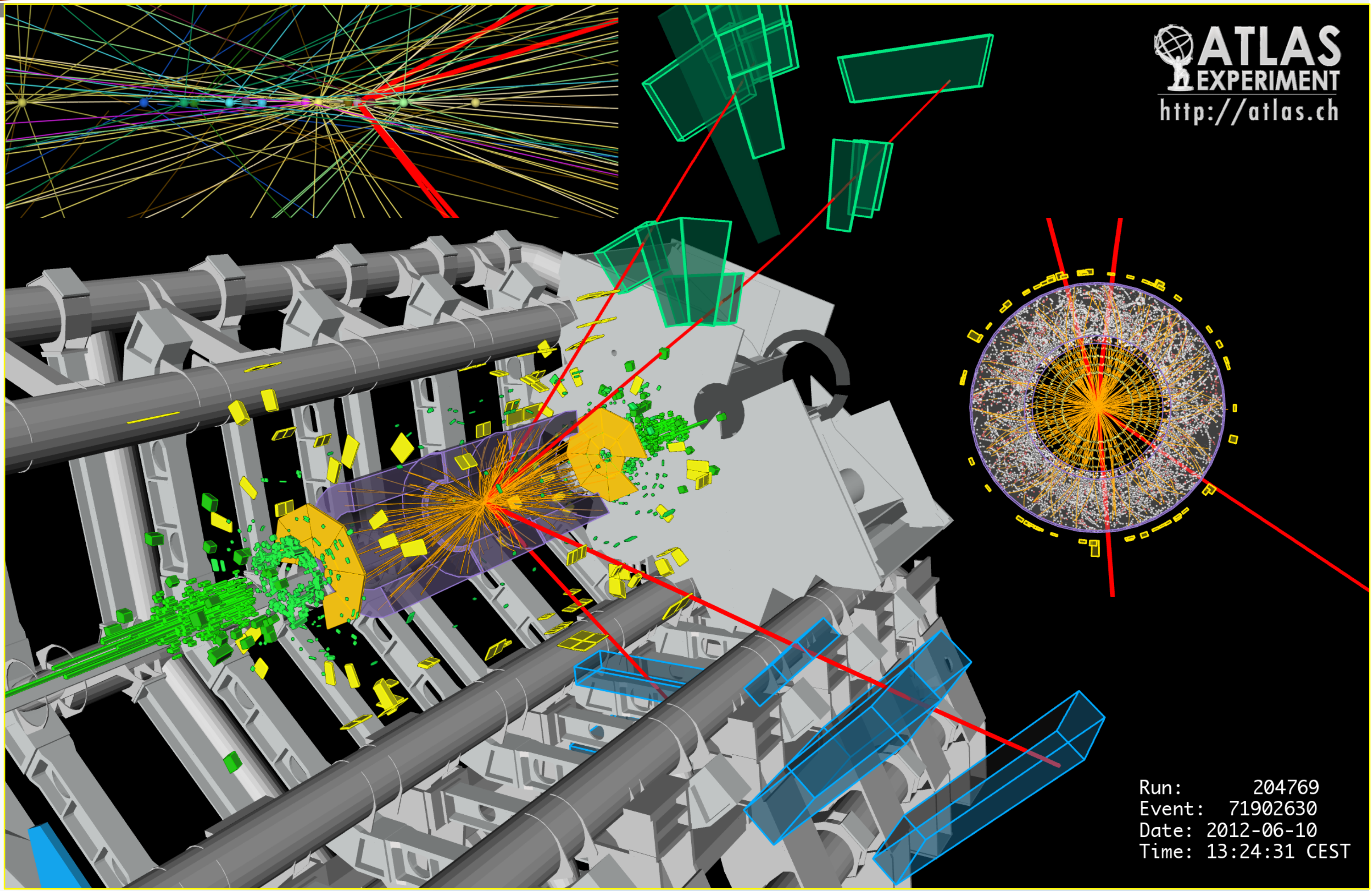
Efficiencies:

4μ – 36%
4e – 20%
2μ/2e – 22%

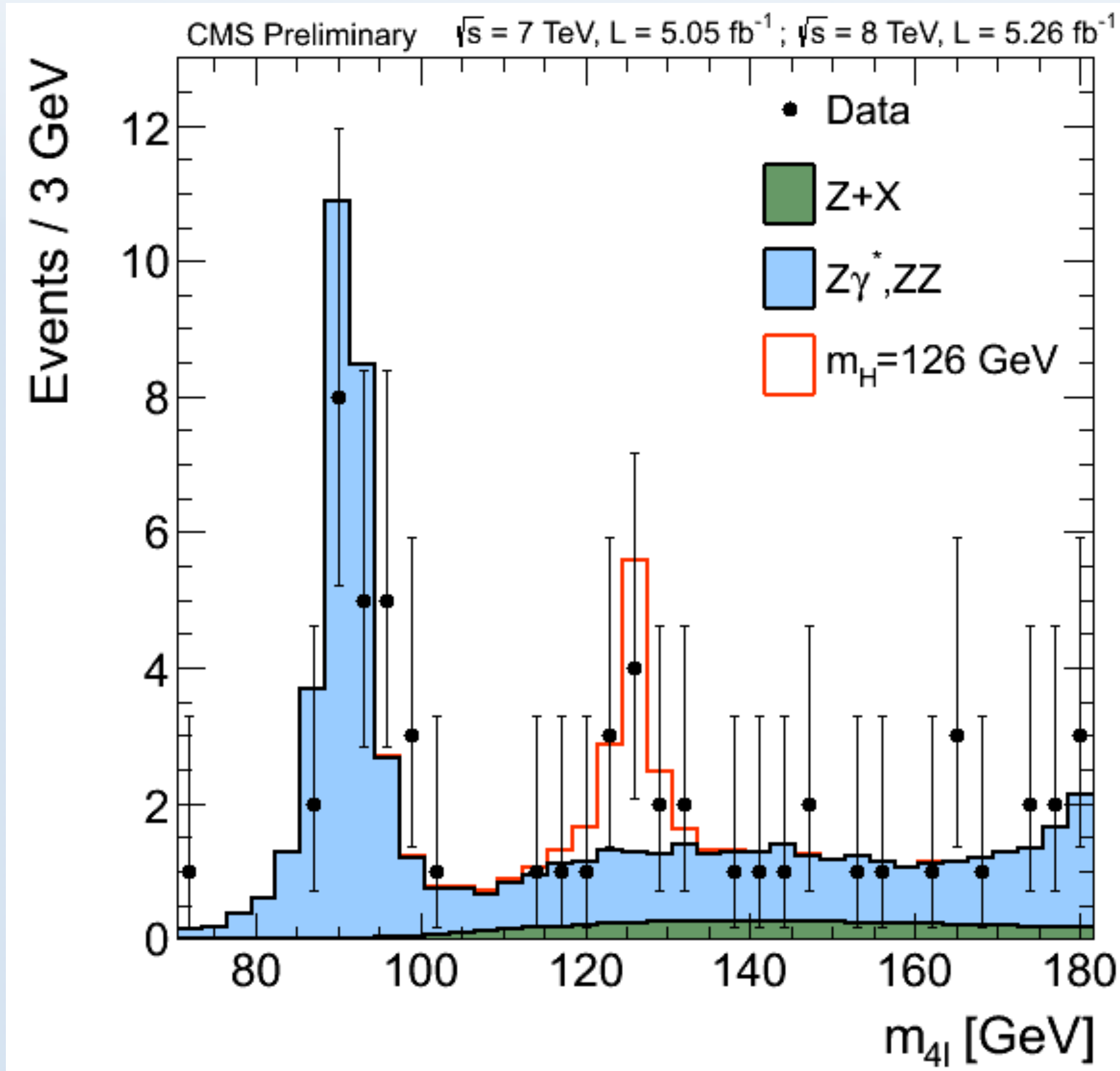
Z constrained fit for leading pair for m_{4l}<190 GeV



4μ candidate with $m_{4\mu}$= 125.1 GeV



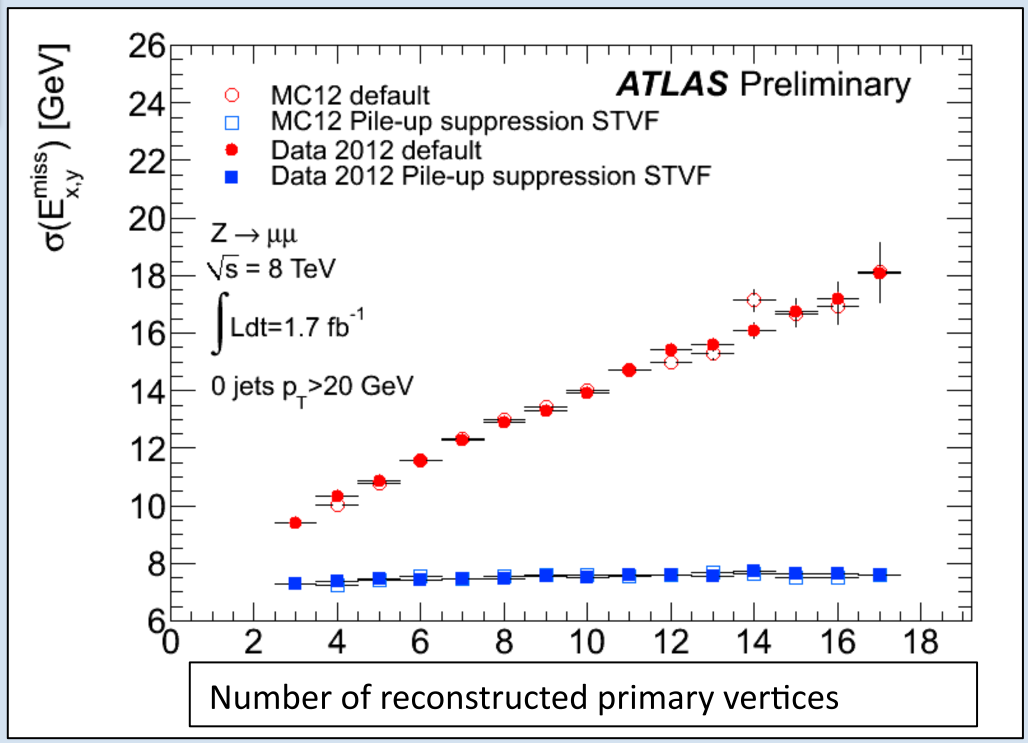
CMS ZZ results



ATLAS WW

e e, e μ, and μ μ and missing energy

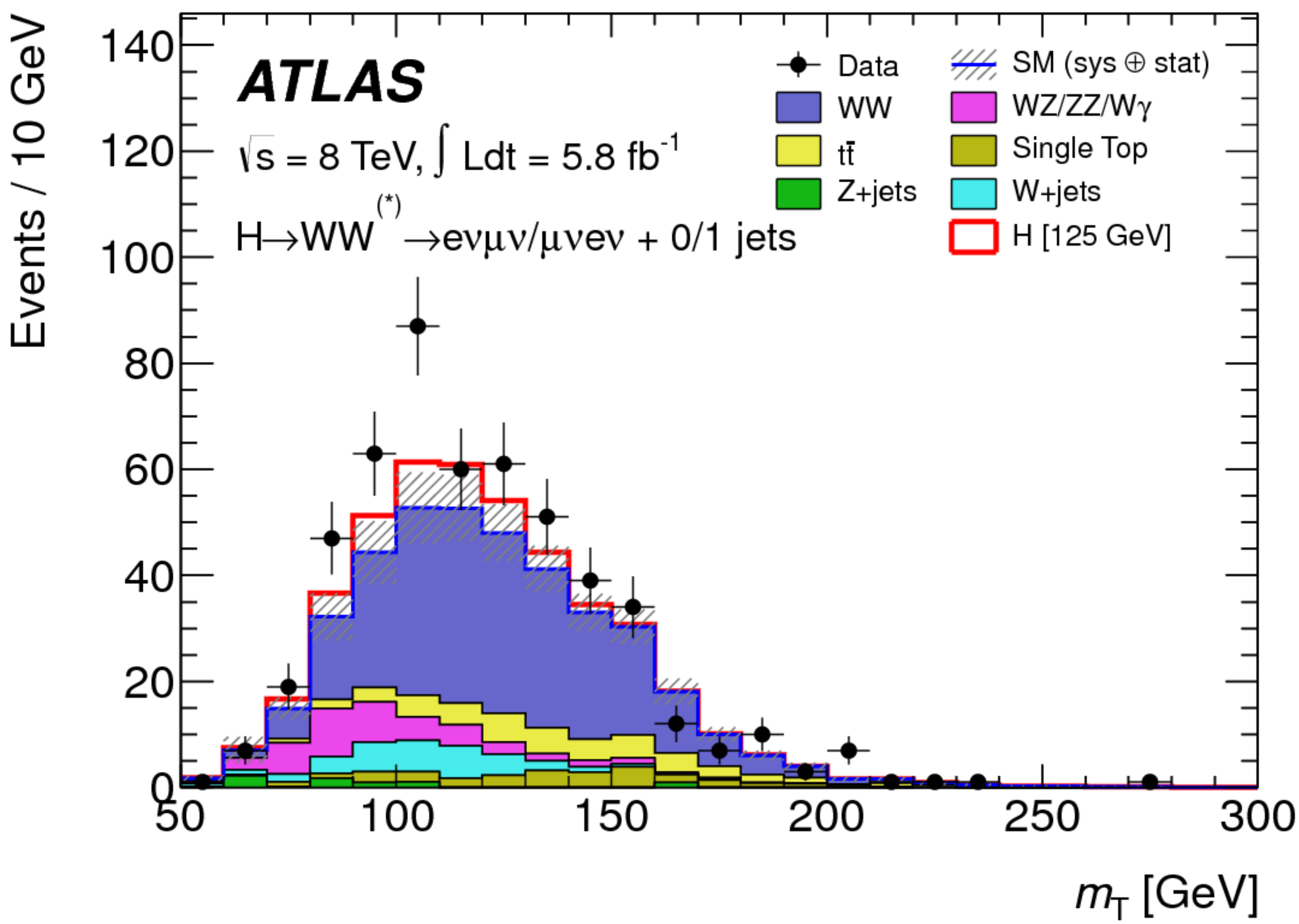
p_T leading > 25 GeV
p_T subleading > 15 Gev
E_T^{miss} >25 GeV



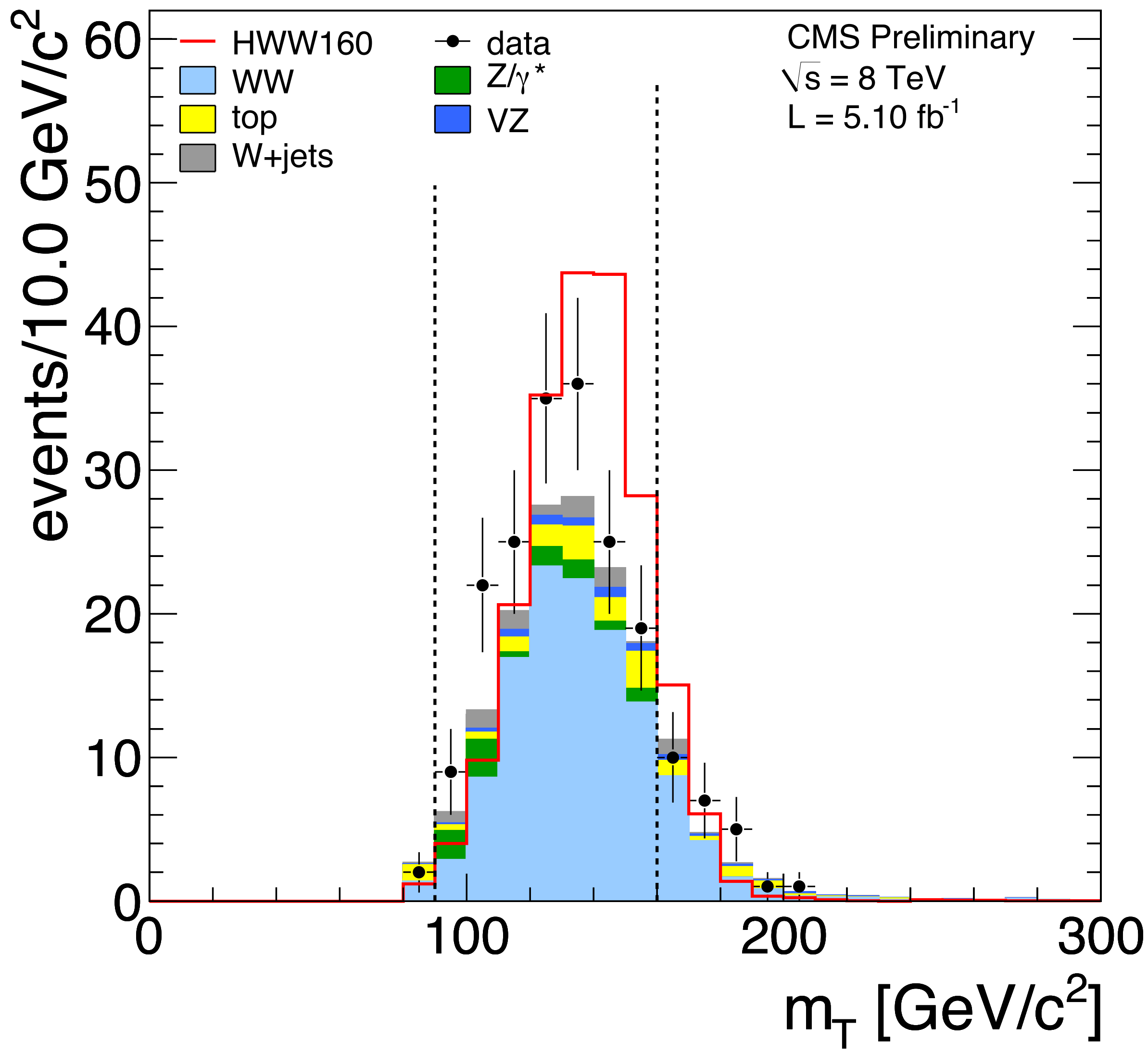
ATLAS WW

0,1 jet bins

Normalize w/ ≥ 2jet bins



CMS WW


HWW160
data
WW
Z/γ*
top
VZ
W+jets
CMS Preliminary
√s = 8 TeV
L = 5.10 fb-1
events/10.0 GeV/c2
mT [GeV/c2]
0
10
20
30
40
50
60
0
100
200
300

Significance testing

m_H Higgs mass
μ multiplier of SM cross section } Variables of interest

$\vec{\Theta}$ "nuisance parameters"

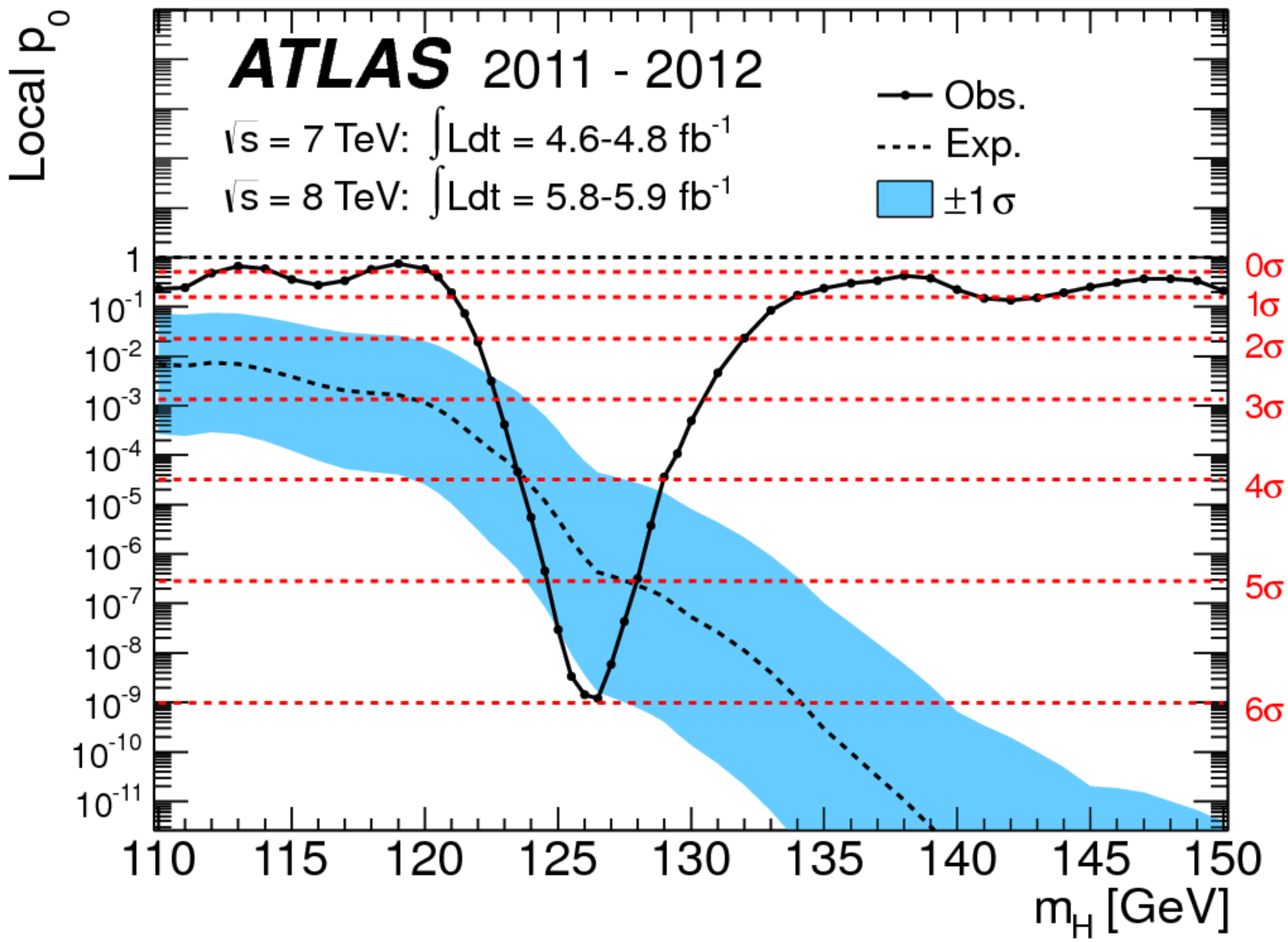
For a scan over m_H, form a liklihood: $L(\mu,\vec{\Theta})$

$$\lambda(\mu) = \frac{L(\mu,\hat{\hat{\vec{\Theta}}})}{L(\hat{\mu},\hat{\vec{\Theta}})}$$

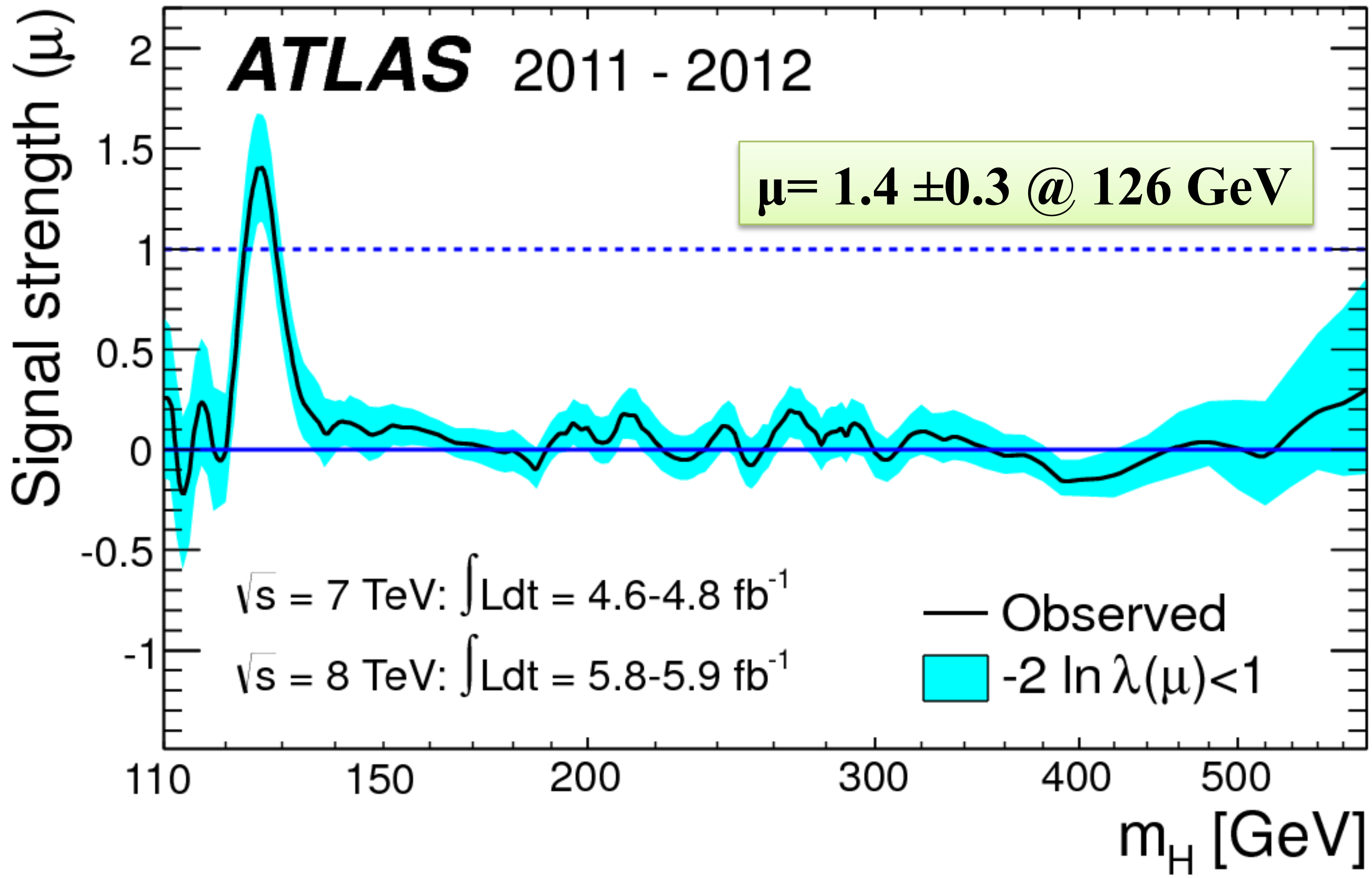
^ parameter maximizing L

$-2\ \ln\lambda(\mu) < 1$ gives bounds on μ (for any m_H)

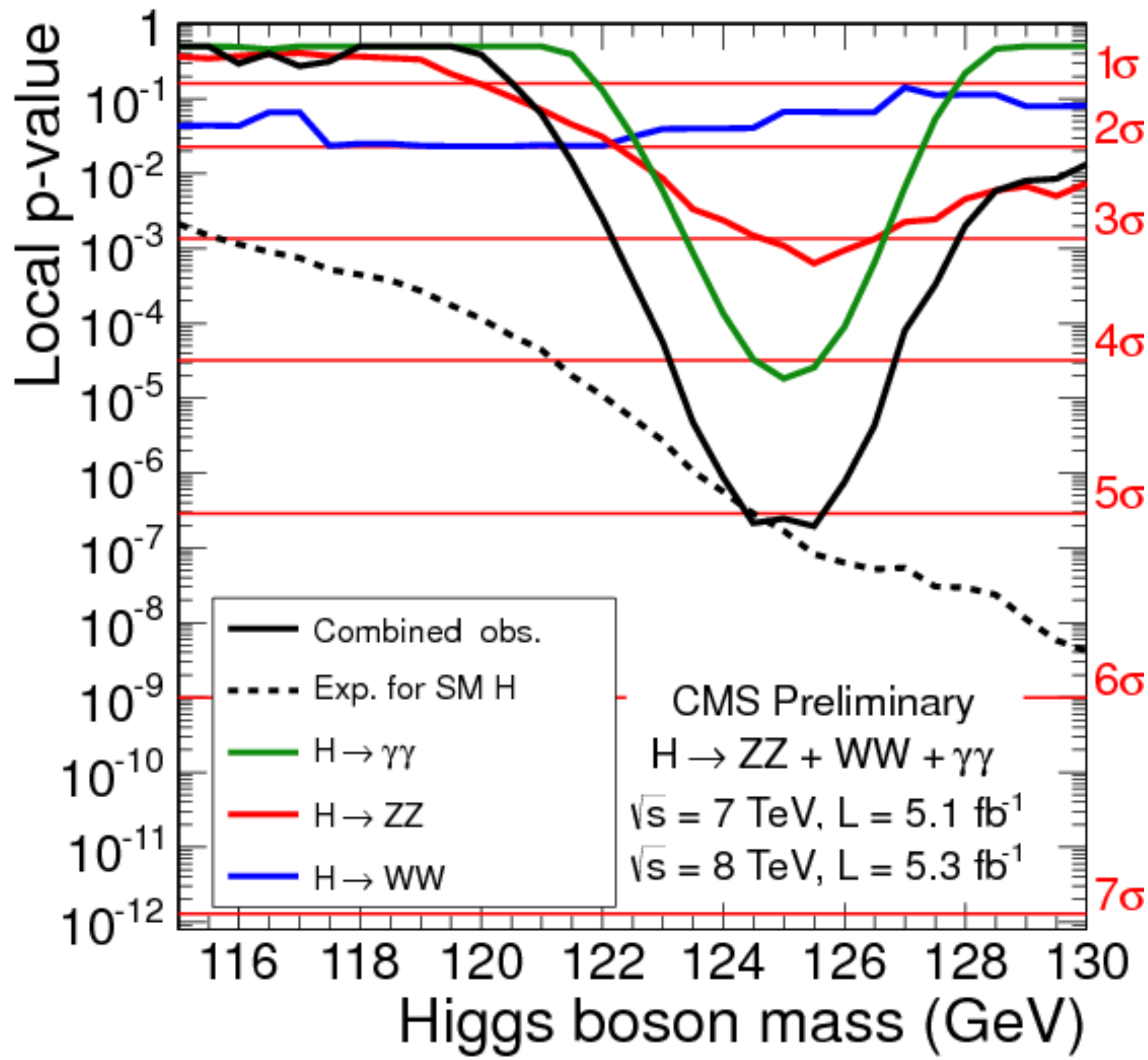
ATLAS combined results: Background only hypothesis: λ(o)



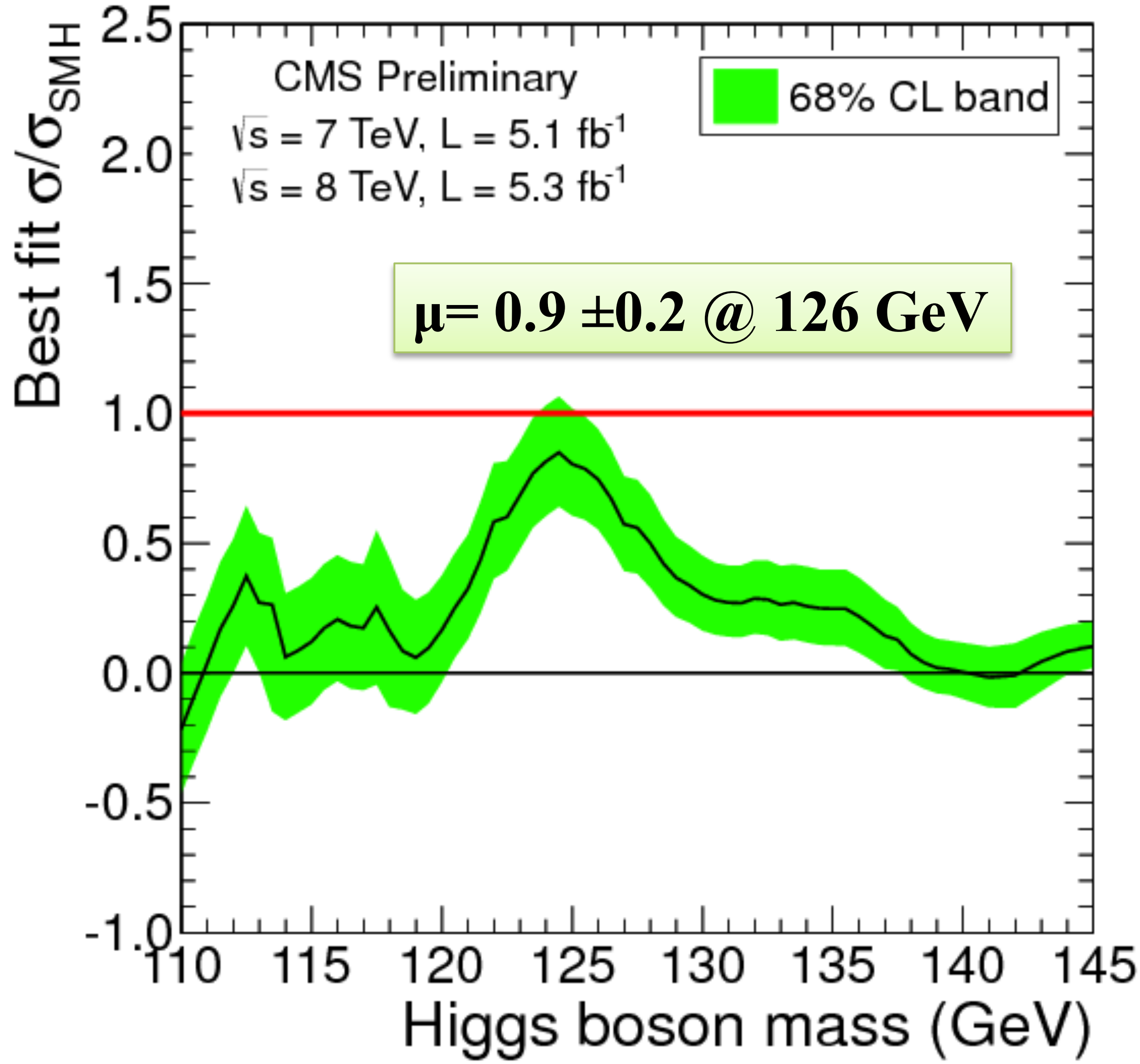
ATLAS combined results: Best fit for μ



CMS background only

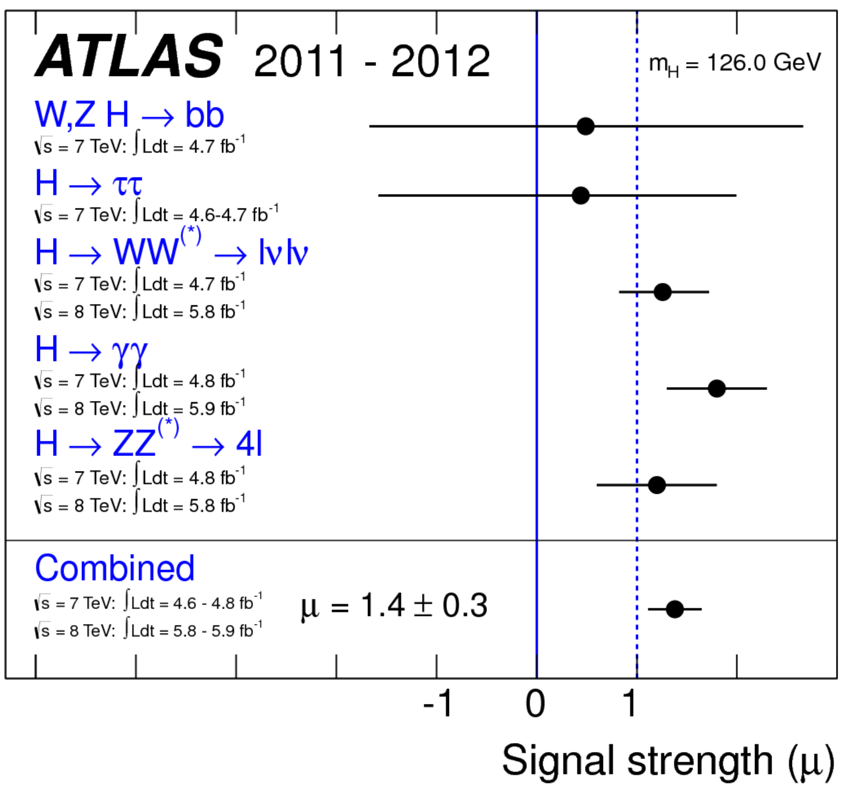


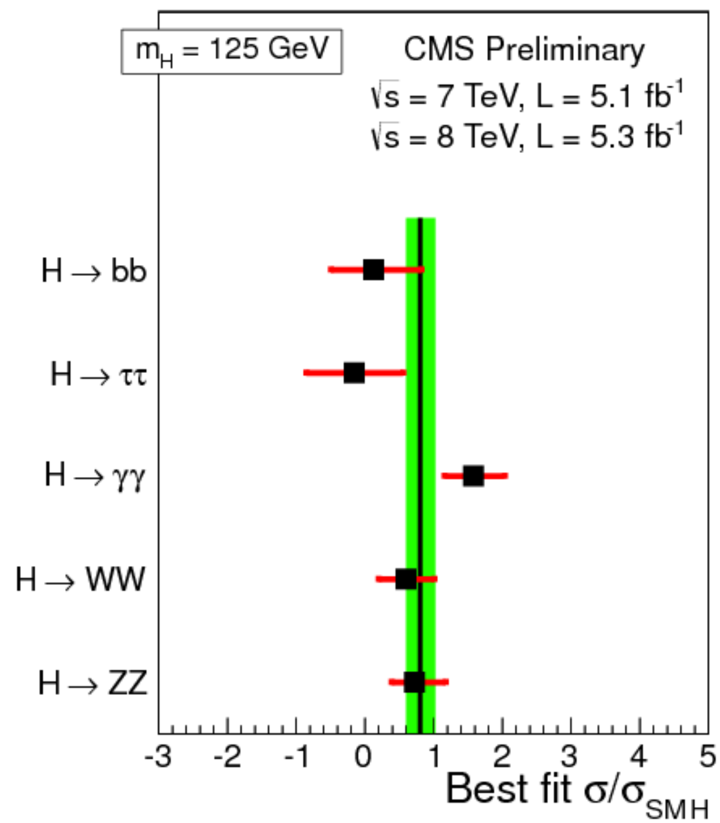
CMS combined results: Best fit for μ



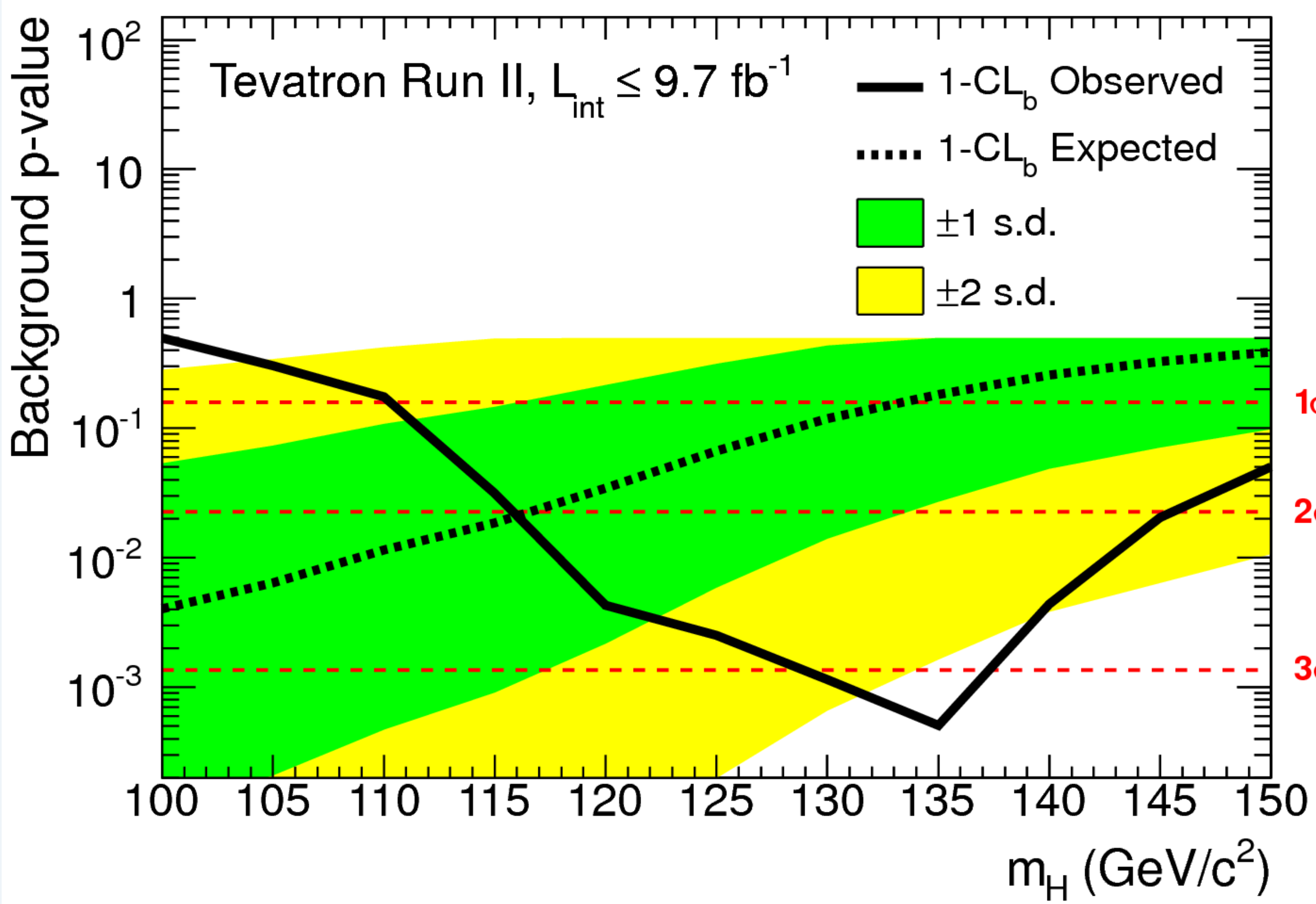
Mass and branching fractions

ATLAS m = 126.0 +/- 0.4 (stat) +/-0.4(sys)
CMS m = 125.3 +/-0.4 (stat) +0.5 (sys)





Tevatron results (mainly from bb production)



Next…

- 16 fb^{-1} now accumulated
- Measure spin and parity in ZZ
- Other properties – production characteristics
- Couplings to fermions (bb, tau tau)
- Longer term:
  - Rarer decays
  - Self coupling?

Summary

- **ATLAS and CMS have observed a new particle with a mass of approximately 125 GeV in a search for the Higgs boson. All evidence so far is consistent with the minimal Higgs in the Standard Model.**