LHC Physics (Higgs I)

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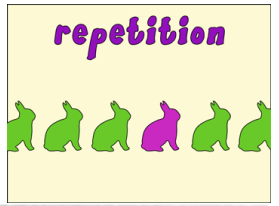
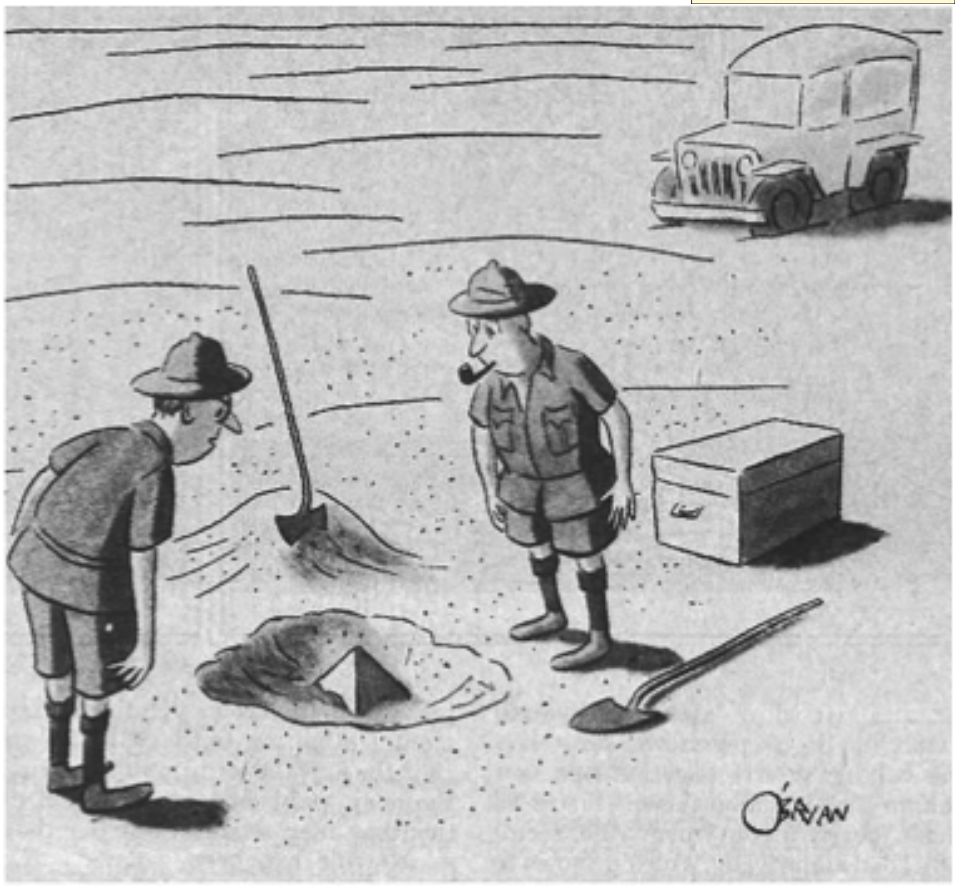
TAE, Benasque, September 2018

Outline for Part I



- Mass vs BEH Mechanism
- The BEH Mechanism
- Higgs boson production and decays
- Pre-LHC Higgs Searches at Colliders
- Building Blocks for a Discovery
- Higgs Discovery (Golden Channels)
- Higgs J^{PC}
- *Other (Silver) Channels*



"This could be the discovery of the century. Depending, of course, on how far down it goes."

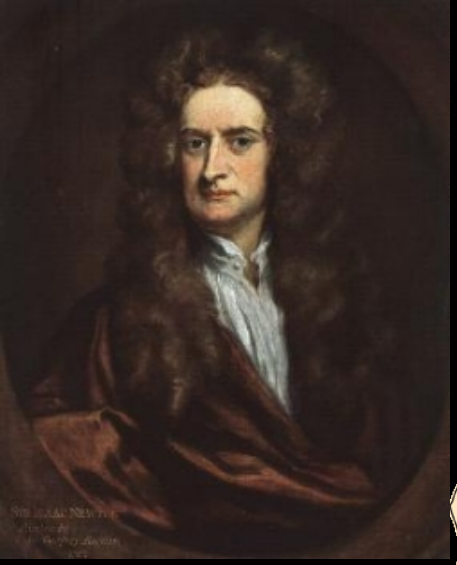
Disclaimer: completely unbalanced set of results from CMS and ATLAS
No attempt to have the latest results everywhere

Part II

J^{PC}

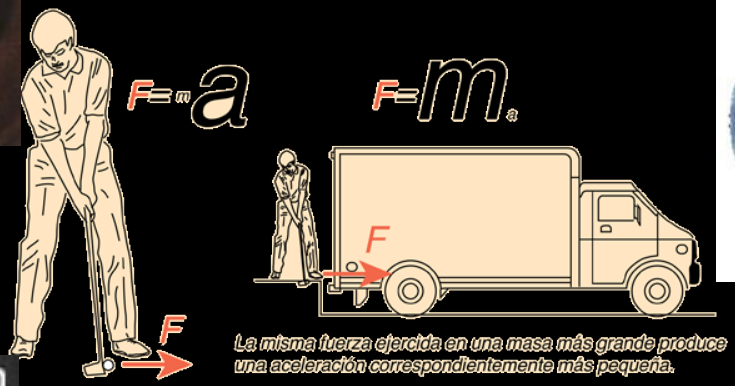
- *Other (Silver) Channels*
- **Detailed study on Couplings**
- **Higgs width**
- **Invisibly decaying Higgs**
- **Higgs and Vacuum Stability**
- **Hierarchy Problem & SUSY**
- **Search for other Higgs**
- **What to expect in the future ?**

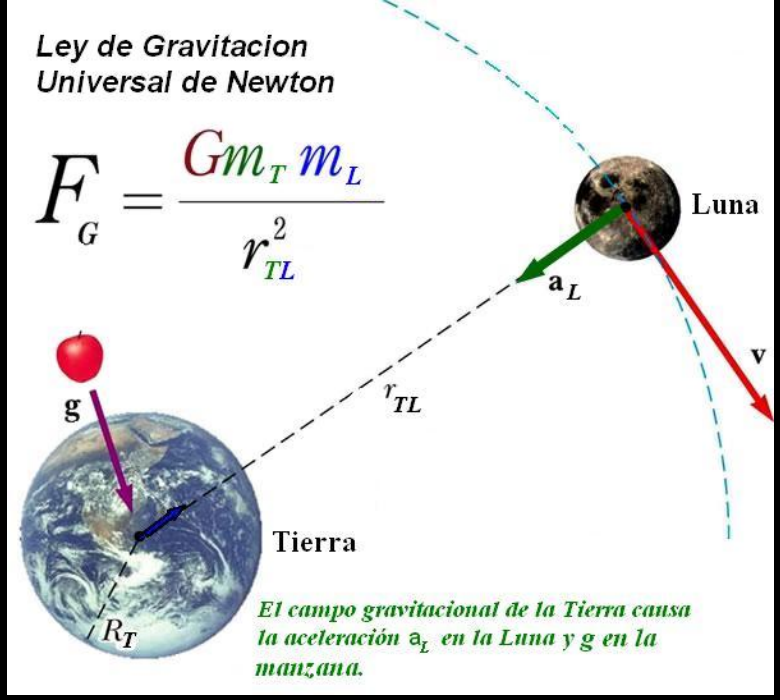
Mass

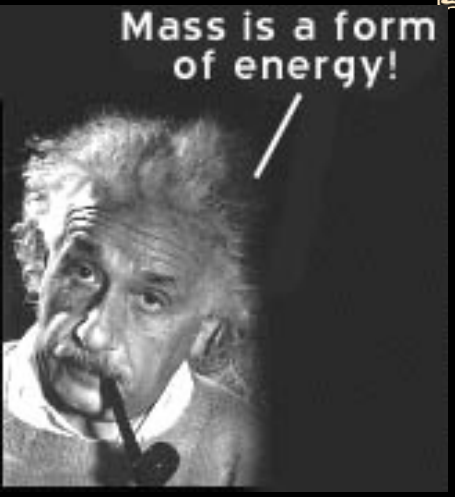


I. Newton

$F = M\,a$



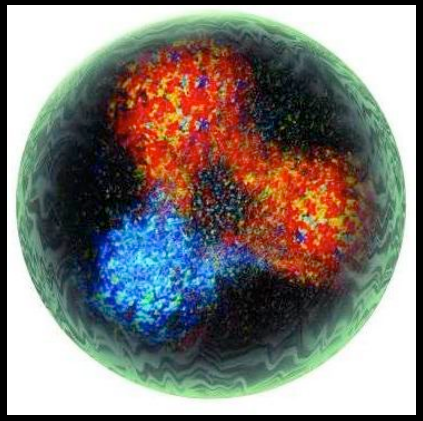




A. Einstein

$E = M\,c^2$

Mass as a form of energy



Protón (uud)

Only 2% of the proton mass is due to quarks…most of it is QCD confinement energy

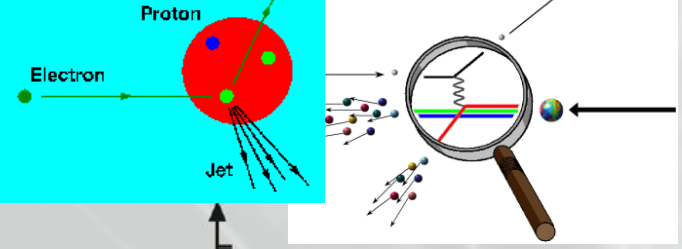
Lesson 0

Do not go around saying:

"The Higgs mechanism explains the origin of the mass in the Universe…"

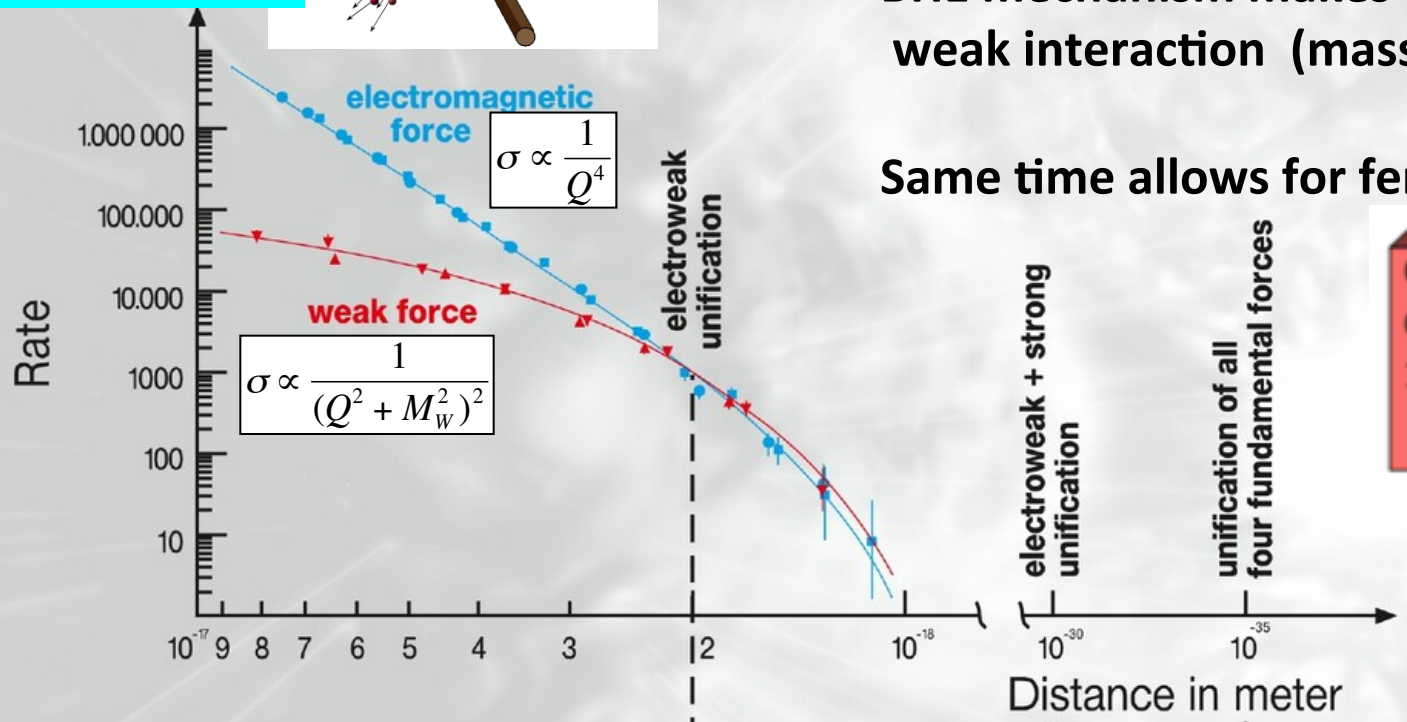
It is simply incorrect…

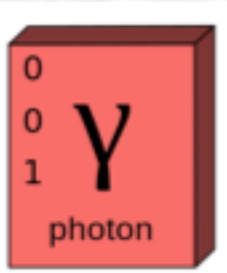
EWK Symmetry Breaking

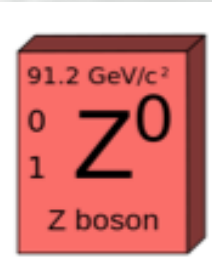


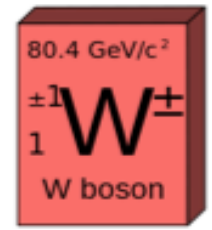
BHE mechanism makes the small range and weak interaction (massive Ws and Z)

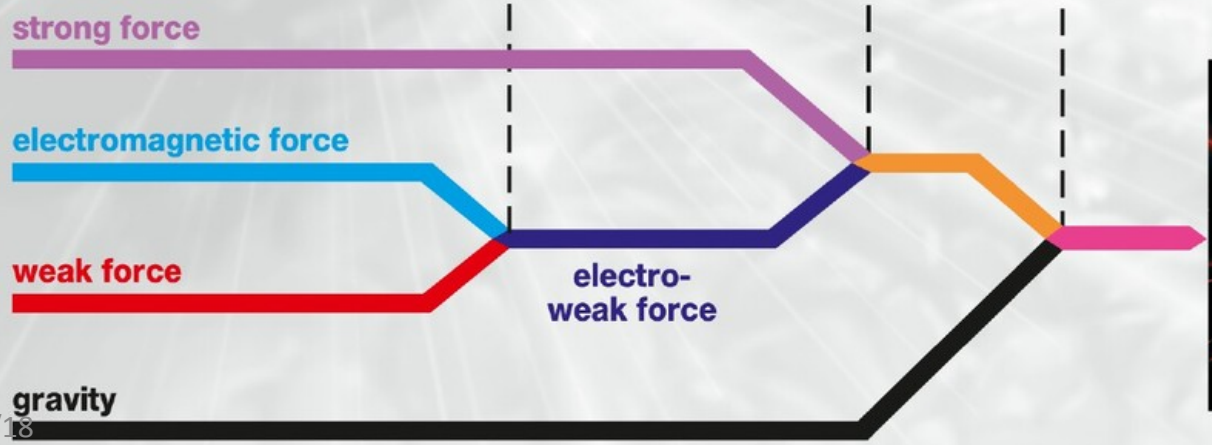
Same time allows for fermion masses







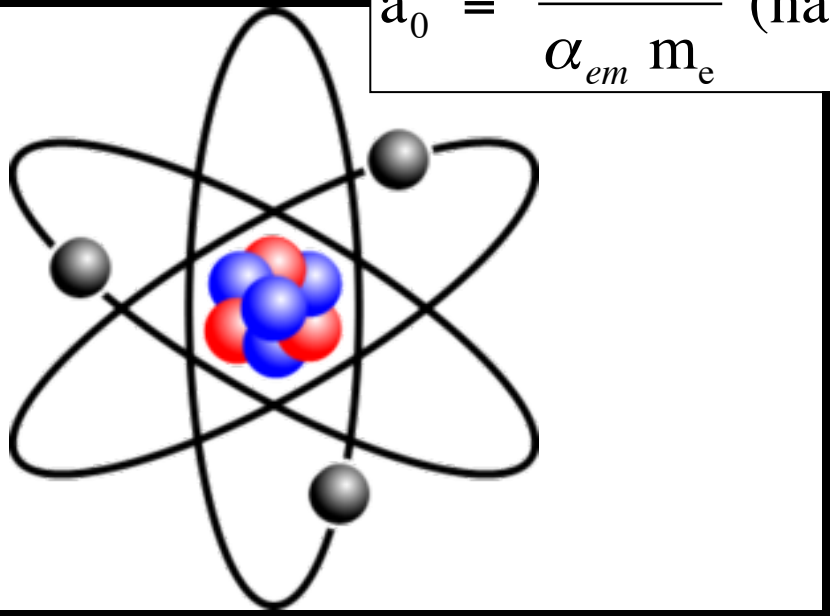




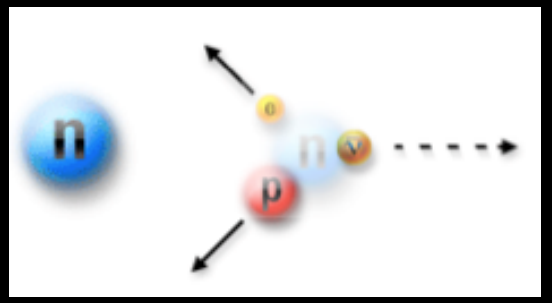
big bang

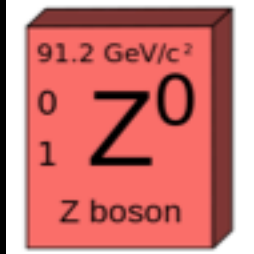
A world without mass ?

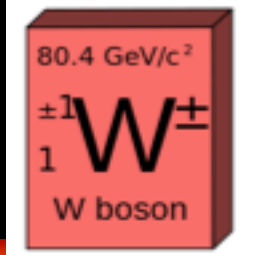
$$a_0 = \frac{1}{\alpha_{em}\, m_e} \quad \text{(natural units)}$$

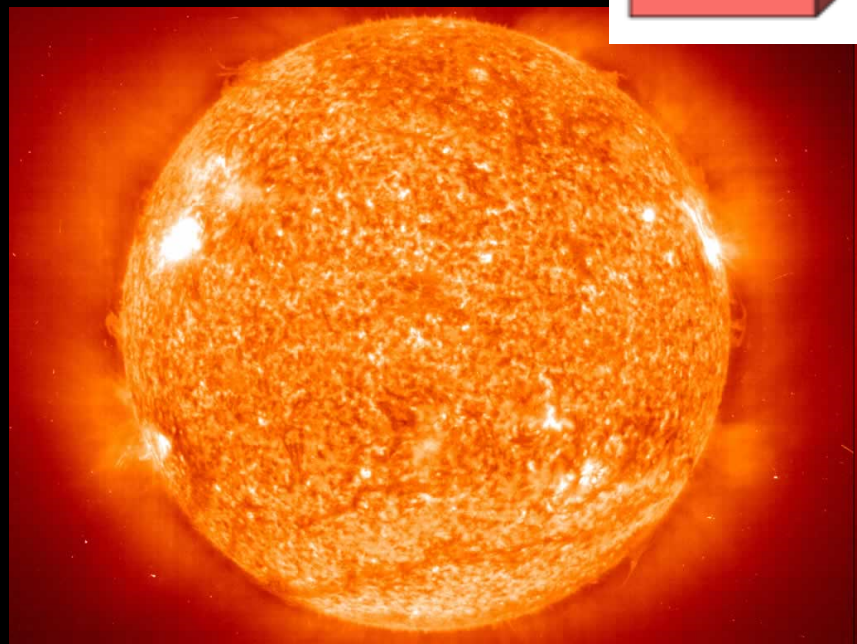


$$G_F \propto \frac{1}{M_W^2}$$









Without giving masses to fermions
it would be impossible to form stables atoms

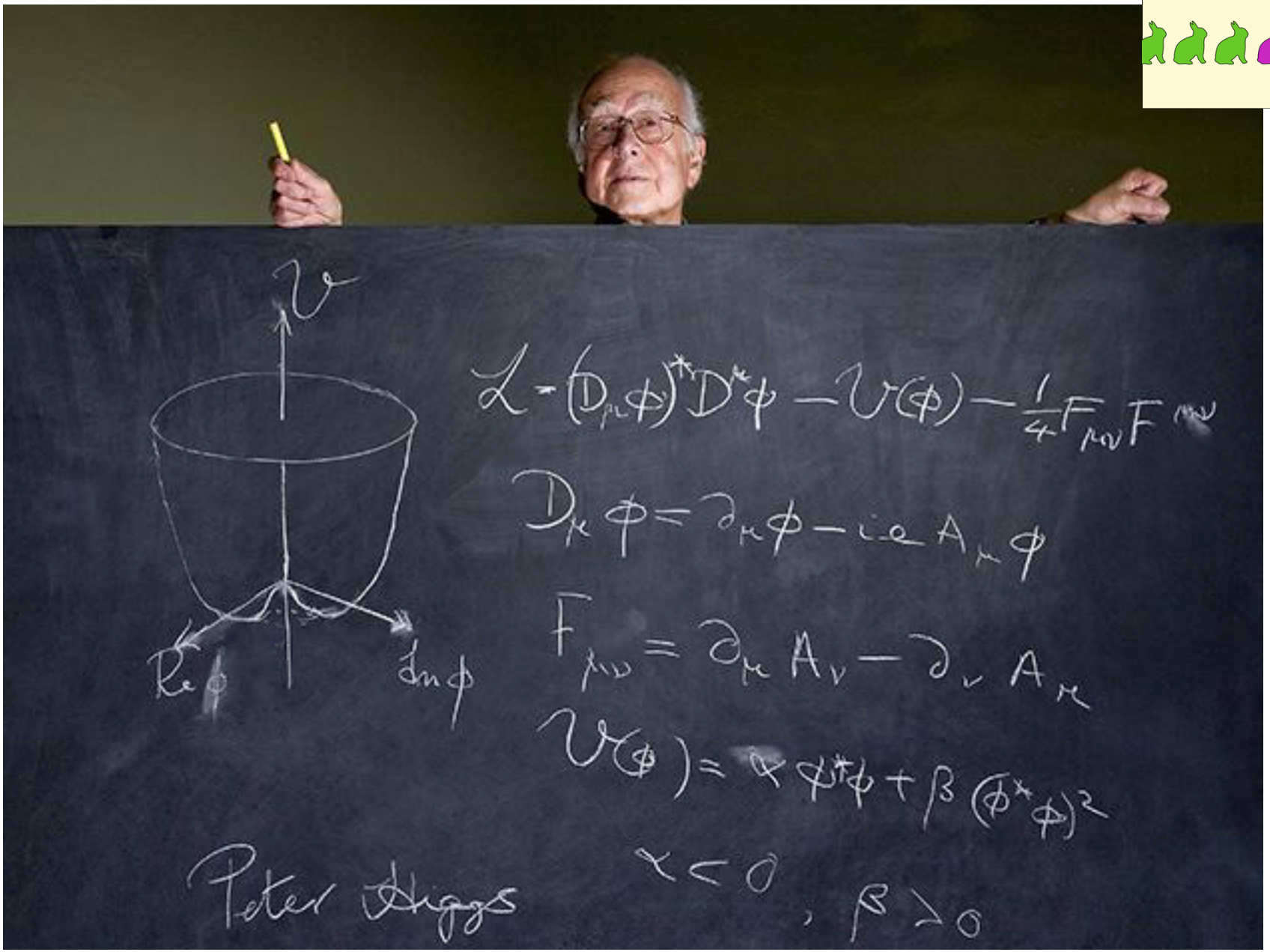
Light W ? → Faster reactions and a Cold Universe

How to include the mass ?

$$-m\psi\psi$$

These terms are not allowed by gauge invariance

repetition


v
Re φ
Im φ
$\mathcal{L} = (D_\mu \phi)^* D^\mu \phi - V(\phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$D_\mu \phi = \partial_\mu \phi - ie A_\mu \phi$
$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
$V(\phi) = \alpha \phi^* \phi + \beta (\phi^* \phi)^2$
Peter Higgs
$\alpha < 0, \beta > 0$

1964....

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

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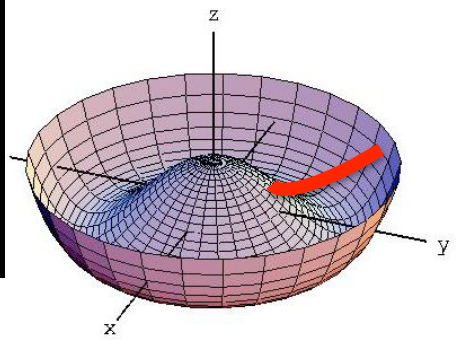
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

The BEH Mechanism

$SU(2)_L \times U(1)_Y \rightarrow U(1)_{EM}$



Introduce one complex scalar doublet of $SU(2)_L$ with $Y = 1/2$:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \longleftrightarrow \quad \mathcal{L} = (D^\mu \phi)^\dagger D_\mu \phi - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$

where $D_\mu \phi = (\partial_\mu - i g A^a_\mu \tau^a - i g' Y_\phi B_\mu)$, $(\tau^a = \sigma^a/2,\ a = 1, 2, 3)$.

The SM symmetry is spontaneously broken when $\langle \phi \rangle$ is chosen to be (e.g.):

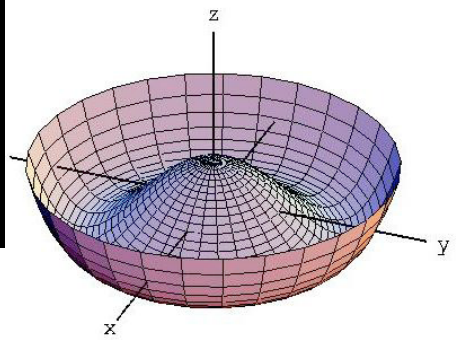
$$\langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{with} \quad v = \left(\frac{-\mu^2}{\lambda} \right)^{1/2} \qquad (\mu^2 < 0,\ \lambda > 0)$$

The gauge boson mass terms arise from:

$$(D^\mu \phi)^\dagger D_\mu \phi \quad \longrightarrow \quad \cdots + \frac{1}{8} (0 \ \ v) \left(g A^a_\mu \sigma^a + g' B_\mu \right) \left(g A^{b\mu} \sigma^b + g' B^\mu \right) \begin{pmatrix} 0 \\ v \end{pmatrix} + \cdots$$

$$\longrightarrow \quad \cdots + \frac{1}{2} \frac{v^2}{4} \left[g^2 (A^1_\mu)^2 + g^2 (A^2_\mu)^2 + (-g A^3_\mu + g' B_\mu)^2 \right] + \cdots$$

The BEH Mechanism



And correspond to the weak gauge bosons:

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(A_\mu^1 \pm A_\mu^2) \longrightarrow \boxed{M_W = g\frac{v}{2}}$$

$$Z_\mu^0 = \frac{1}{\sqrt{g^2+g'^2}}(gA_\mu^3 - g'B_\mu) \longrightarrow \boxed{M_Z = \sqrt{g^2+g'^2}\,\frac{v}{2}}$$

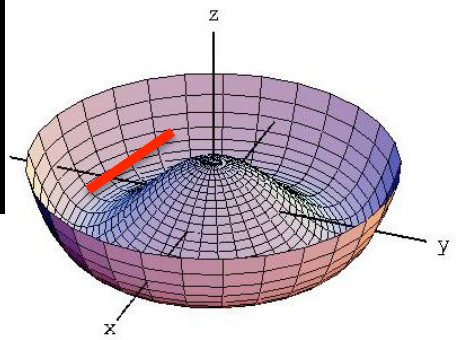
while the linear combination orthogonal to Z_μ^0 remains massless and corresponds to the photon field:

$$A_\mu = \frac{1}{\sqrt{g^2+g'^2}}(g'A_\mu^3 + gB_\mu) \longrightarrow \boxed{M_A = 0}$$

$$\cos\theta_w = \frac{g}{\sqrt{g^2+g'^2}} \quad , \quad \sin\theta_w = \frac{g'}{\sqrt{g^2+g'^2}}$$

the W and Z masses are related by: $\boxed{M_W = M_Z\cos\theta_w}$

The BEH Mechanism



The scalar sector becomes more transparent in the unitary gauge:

$$\phi(x) = \frac{e^{\frac{i}{v}\vec{\chi}(x)\cdot\vec{\tau}}}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \xrightarrow{SU(2)} \phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

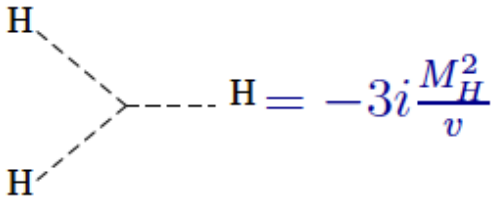
after which the Lagrangian becomes

$$\mathcal{L} = \mu^2 H^2 - \lambda v H^3 - \frac{1}{4} H^4 = -\frac{1}{2} M_H^2 H^2 - \sqrt{\frac{\lambda}{2}} M_H H^3 - \frac{1}{4} \lambda H^4$$

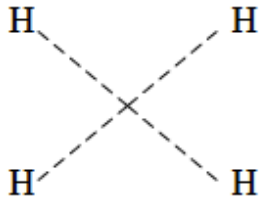
Three degrees of freedom, the $\chi^a(x)$ Goldstone bosons, have been reabsorbed into the longitudinal components of the $W_\mu^\pm$ and Z_μ^0 weak gauge bosons. One real scalar field remains:

the Higgs boson, H, with mass $\boxed{M_H^2 = -2\mu^2 = 2\lambda v^2}$

and self-couplings:

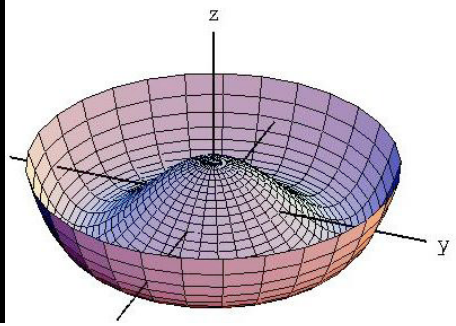


$$= -3i\frac{M_H^2}{v}$$

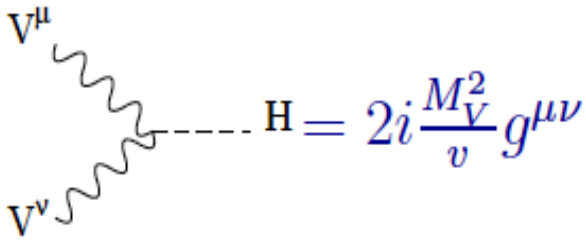


$$= -3i\frac{M_H^2}{v^2}$$

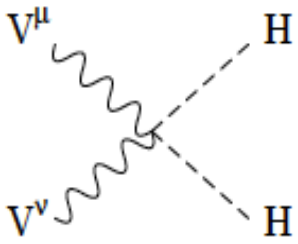
The BEH Mechanism



From $(D^\mu\phi)^\dagger D_\mu\phi \longrightarrow$ Higgs-Gauge boson couplings:



$$= 2i\frac{M_V^2}{v}g^{\mu\nu}$$



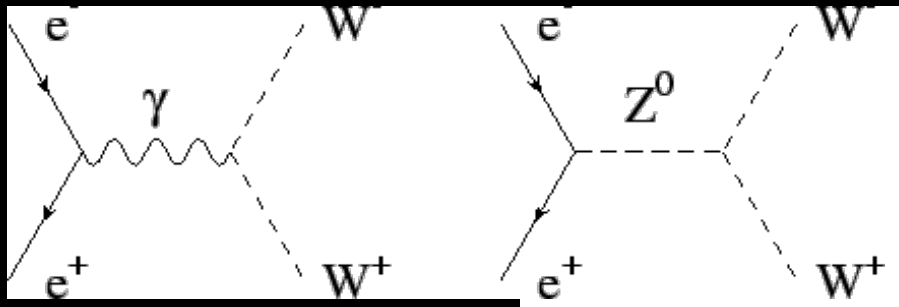
$$= 2i\frac{M_V^2}{v^2}g^{\mu\nu}$$

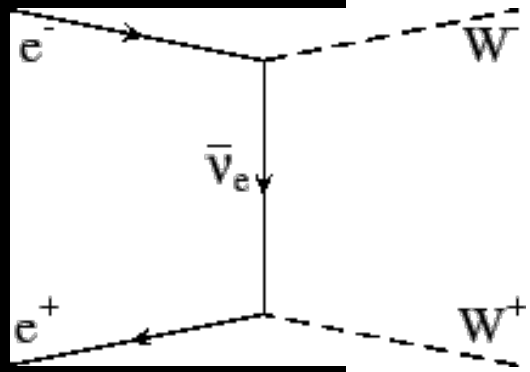
Notice: The entire Higgs sector depends on only two parameters, e.g.

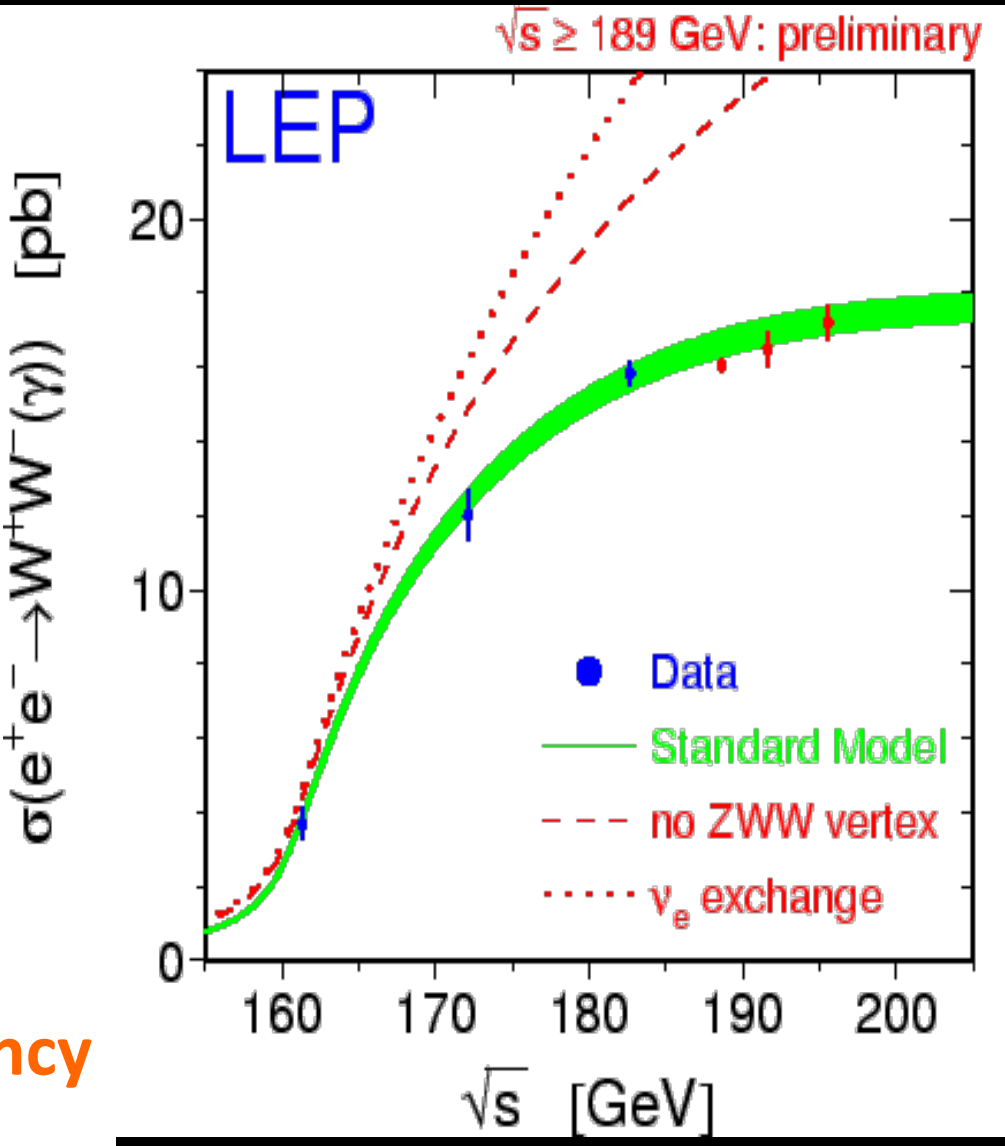
M_H and v

v measured in μ-decay:
$v = (\sqrt{2}G_F)^{-1/2} = 246$ GeV $\longrightarrow$ SM Higgs Physics depends on M_H

Consistency of Gauge Interactions

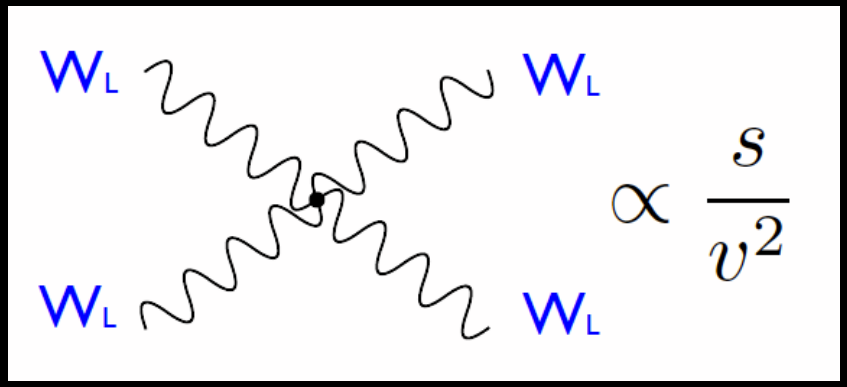


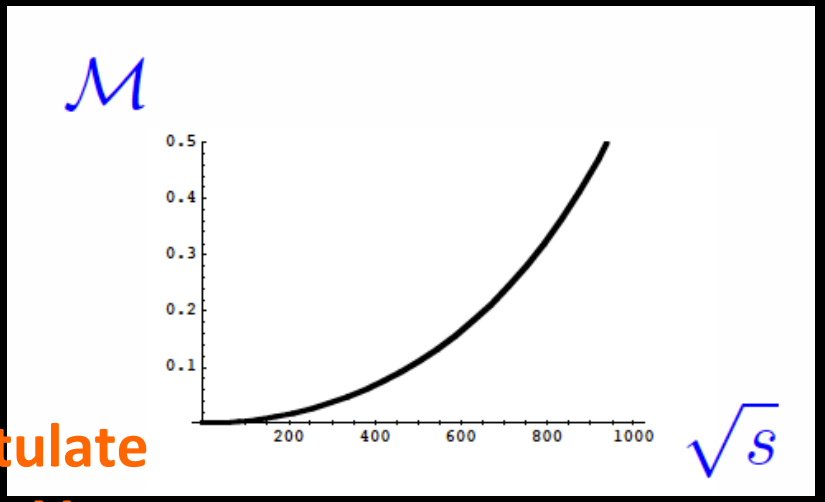




This illustrates the consistency of the Gauge Interactions

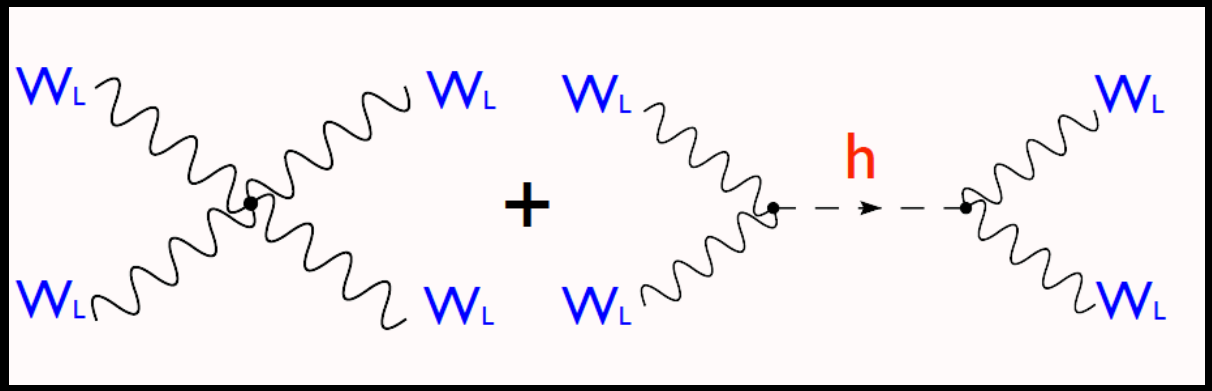
$W_L^+W_L^- \rightarrow W_L^+W_L^-$ scattering

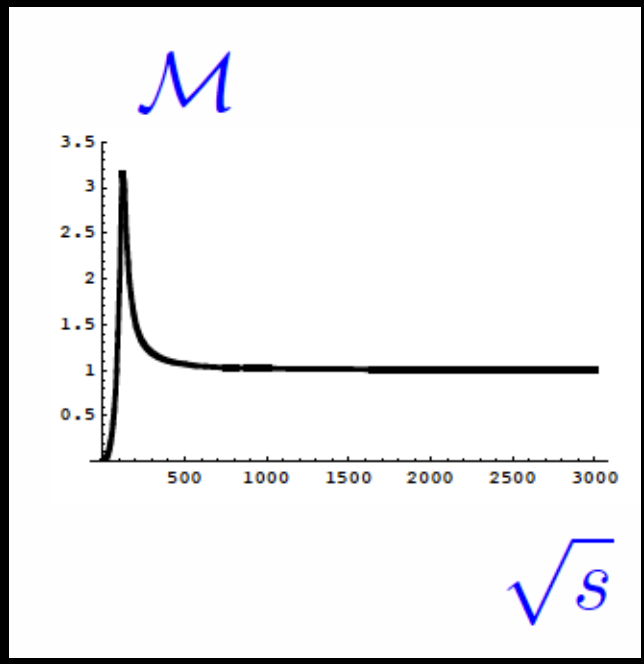




To restore unitarity one needs to postulate a Higgs boson with mass below 800 GeV

Otherwise new physics should come at the TeV scale to rescue us

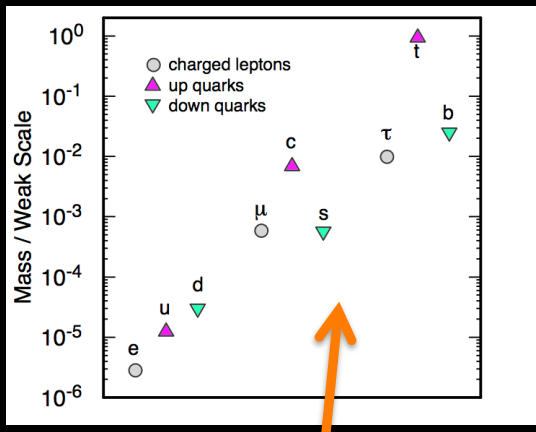




Fermion Masses

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad Y_\phi = +1$$

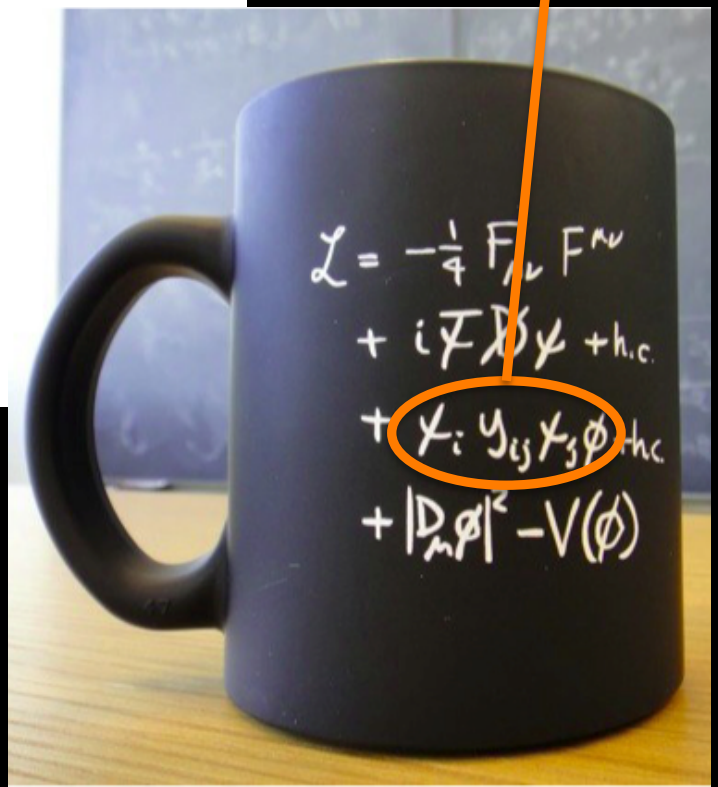
Most of the free parameters in the SM model come from here



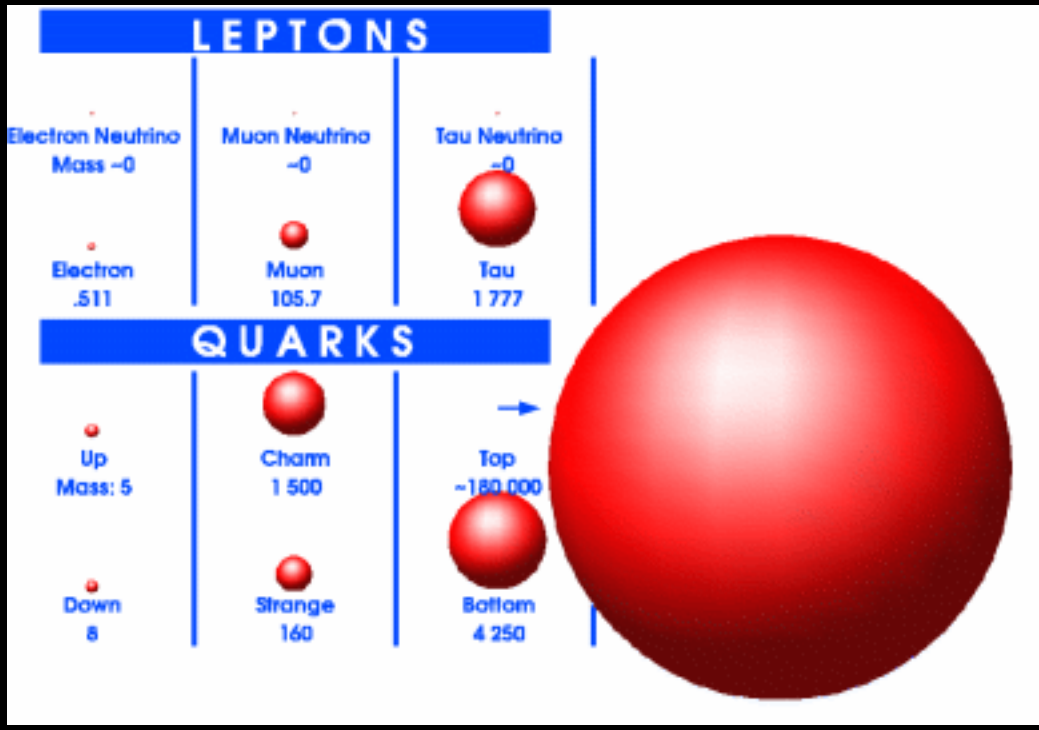
$$\mathcal{L}_F = -\lambda_e \bar{L}\,\Phi\, e_R - \lambda_d \bar{Q}\,\Phi\, d_R - \lambda_u \bar{Q}\,\tilde{\Phi}\, u_R \;+\; h.c.$$

$$\begin{aligned} \mathcal{L}_F &= -\frac{1}{\sqrt{2}}\lambda_e\,(\bar{\nu}_e, \bar{e}_L) \begin{pmatrix} 0 \\ v+H \end{pmatrix} e_R \;+\cdots \\ &= -\frac{1}{\sqrt{2}}\,\lambda_e\,(v+H)\,\bar{e}_L e_R \;+\cdots \end{aligned}$$

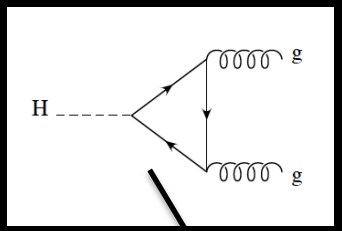
$$m_e = \frac{\lambda_e\, v}{\sqrt{2}}\;,\; m_u = \frac{\lambda_u\, v}{\sqrt{2}}\;,\; m_d = \frac{\lambda_d\, v}{\sqrt{2}}$$



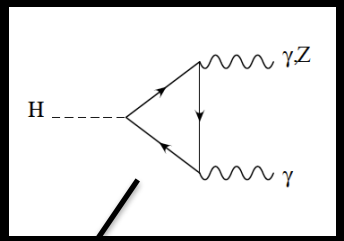
Why such a mass hierarchy ?



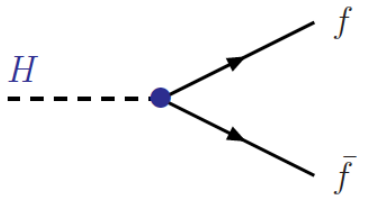
Higgs Couplings to SM



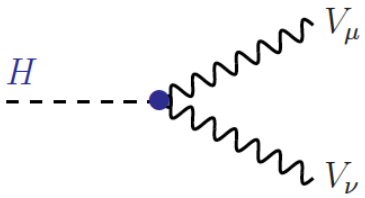
and via loops..



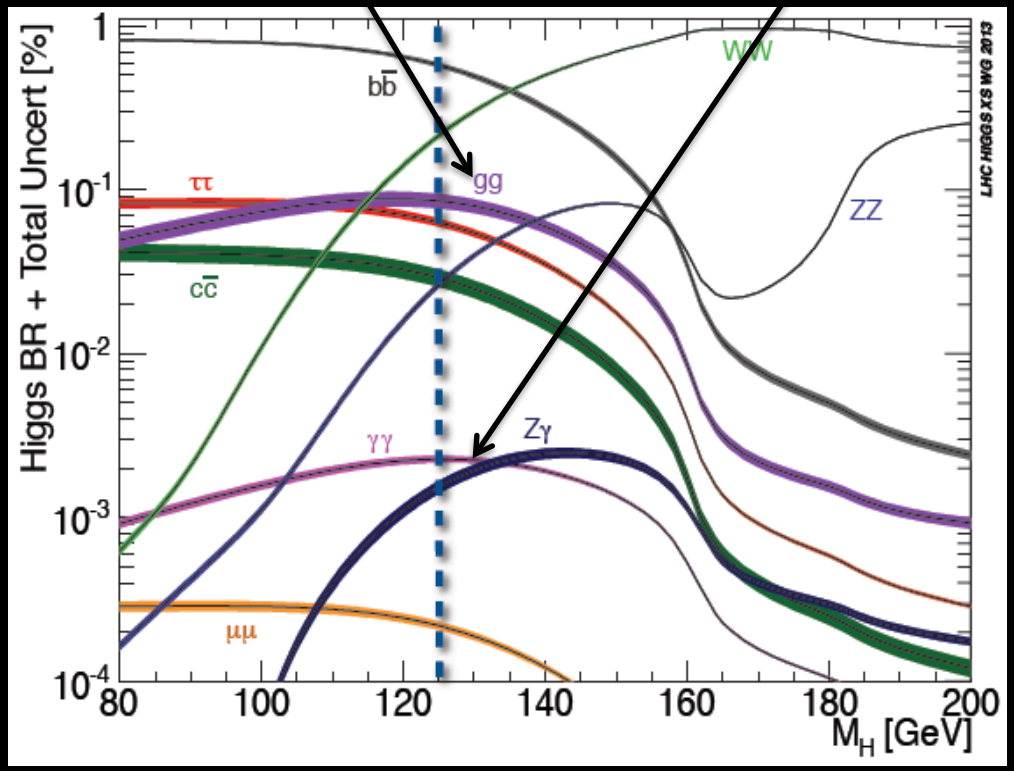
Couplings proportional to masses of particles
→ This determines the phenomenology

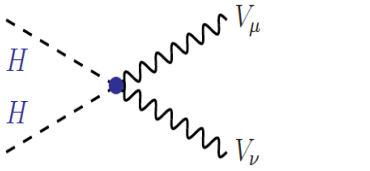


$$g_{Hff} = m_f/v$$

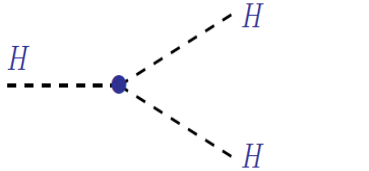


$$g_{HVV} = 2M_V^2/v$$

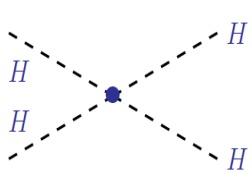




$$g_{HHVV} = 2M_V^2/v^2$$

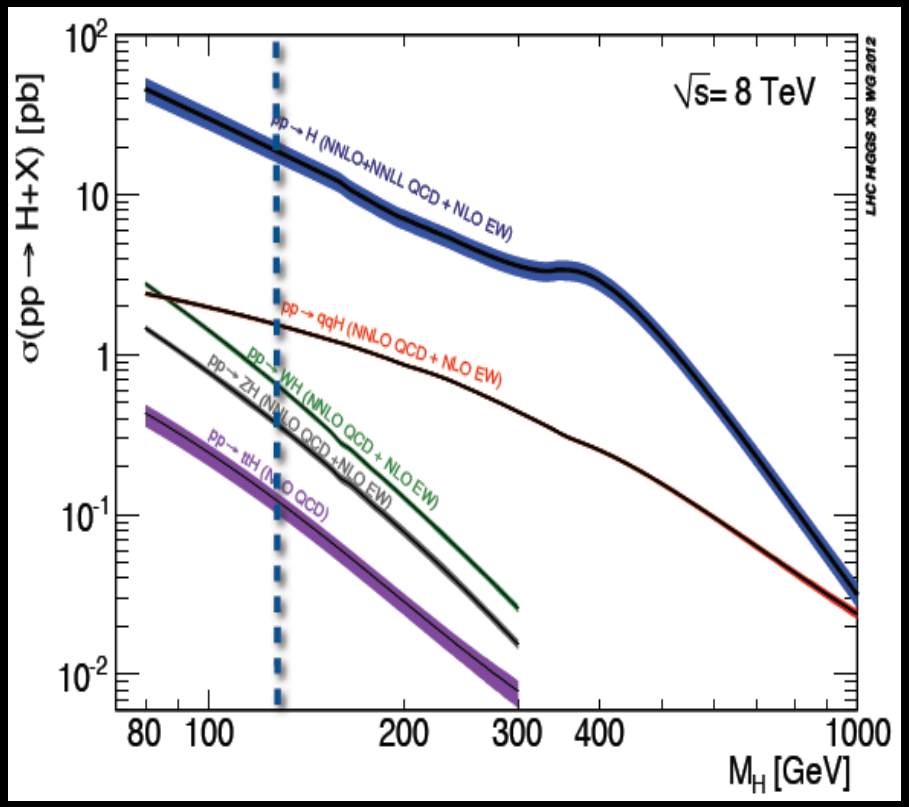


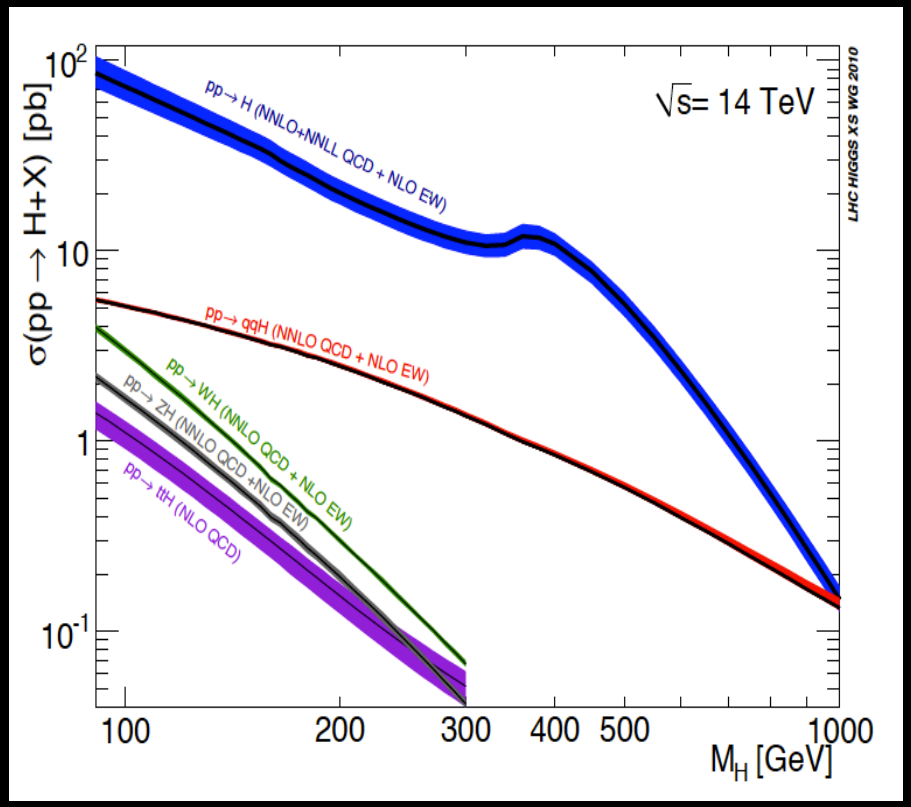
$$g_{HHH} = 3M_H^2/v$$



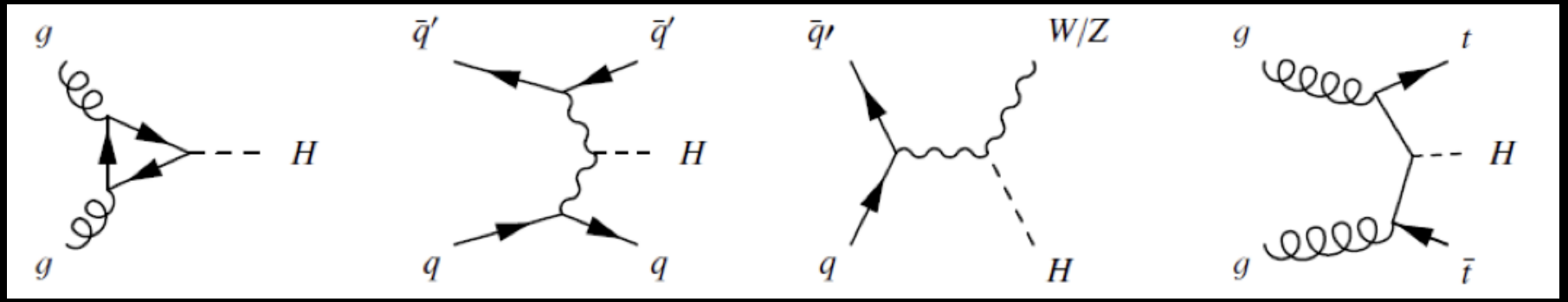
$$g_{HHHH} = 3M_H^2/v^2$$

Higgs Production (LHC)



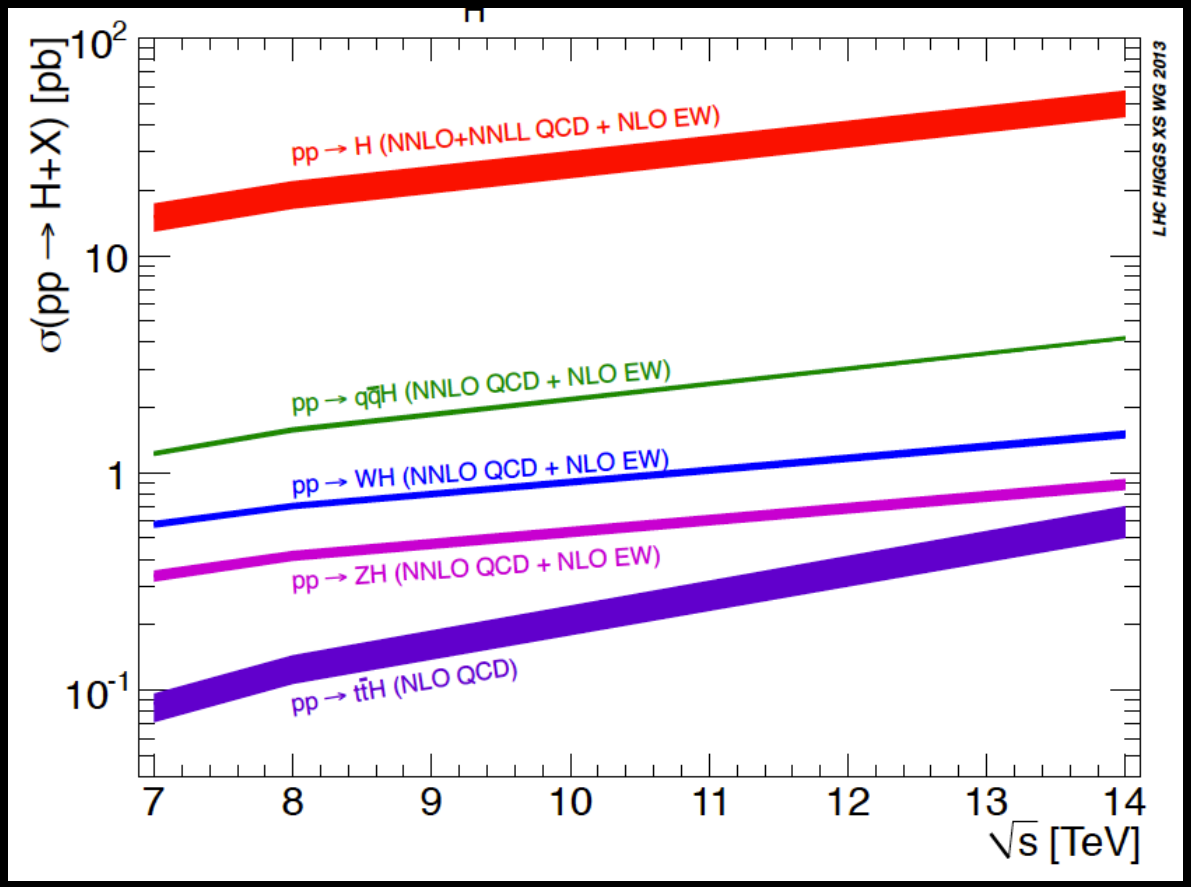


Decreasing cross section →

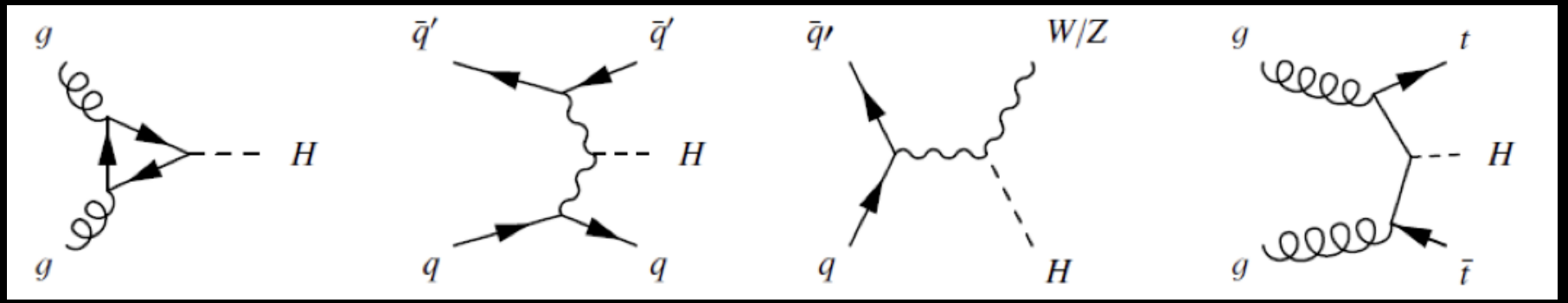


Higgs Production (LHC)

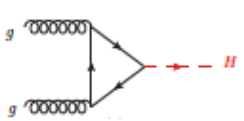
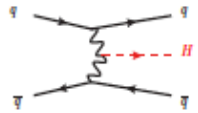
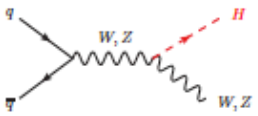
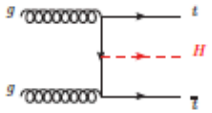
For a Higgs of 125 GeV



Decreasing cross section →



Higgs Program in a Glance

Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lnln)	✓	✓	✓	✓
ττ	X	✓	✓	✓
bb	X	✓	✓	✓
Zγ	✓	✓		
μμ	✓	✓		
Invisible	✓	✓	✓	

Beat the background

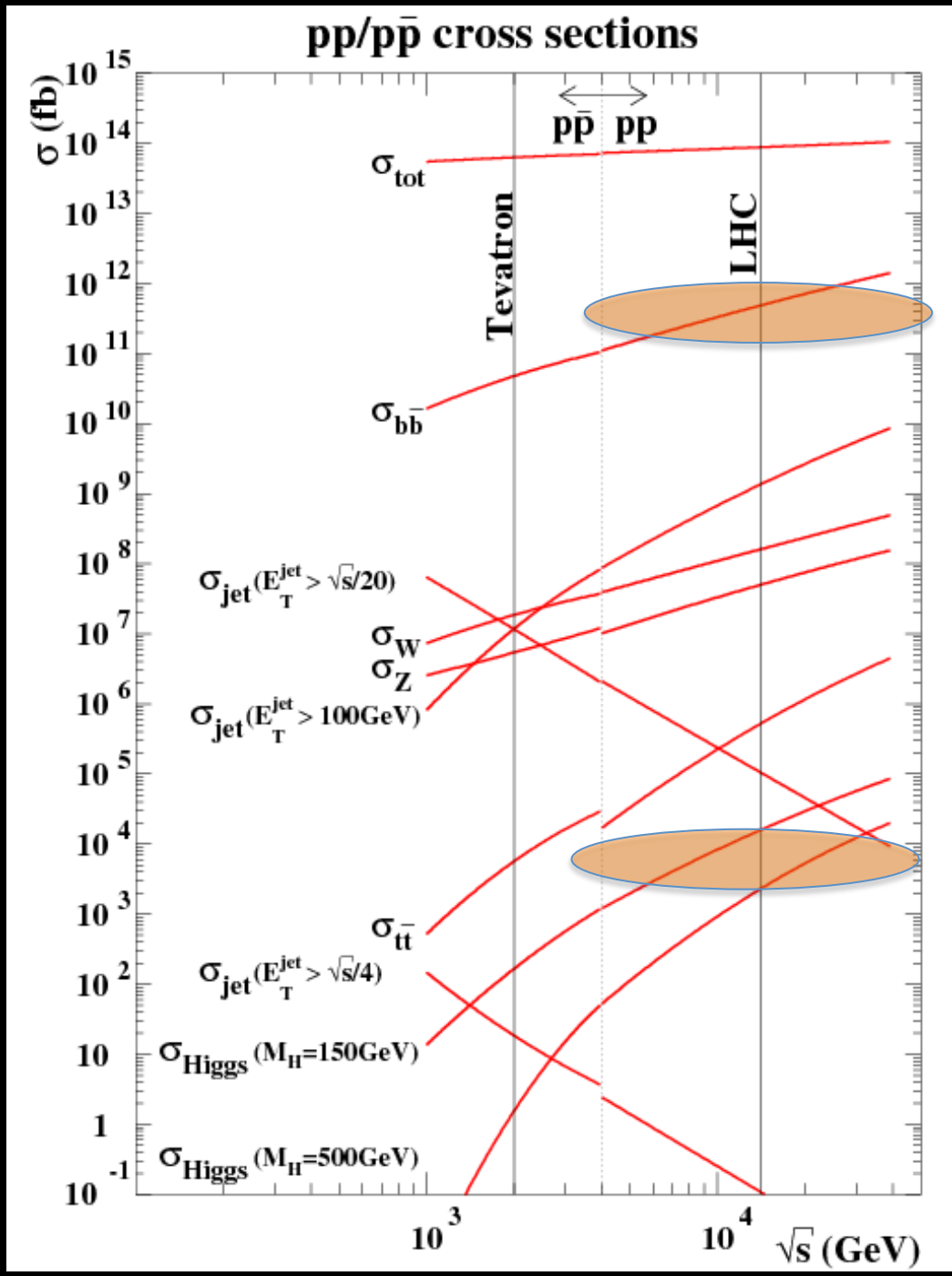
The discovery channels are subject of signal rate, mass resolution, and the capacity to beat the background

For example *the a priori* good channel for Higgs production

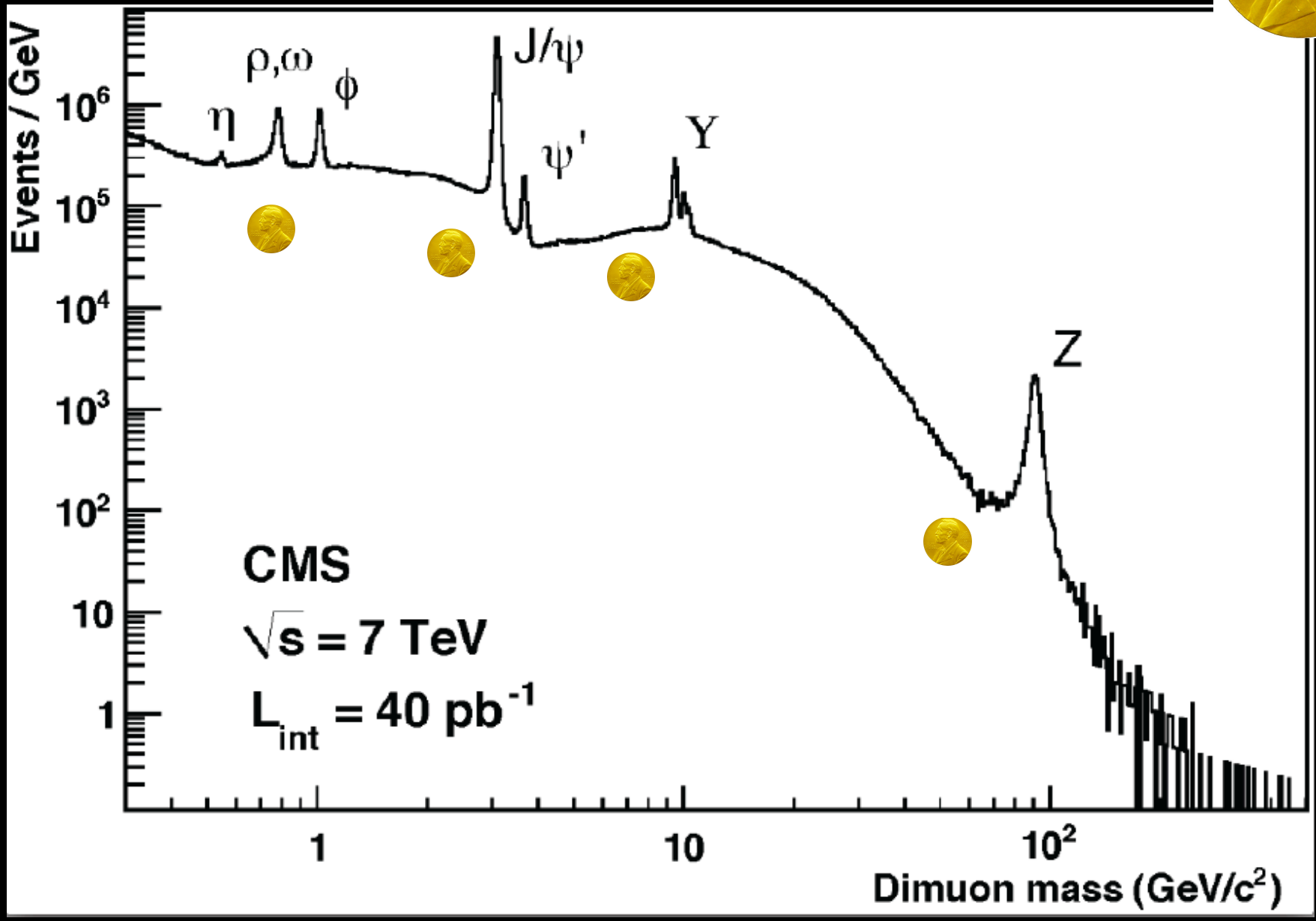
gg → H, H → b (anti)b

gets killed by the huge underneath (non-resonant) QCD-driven process

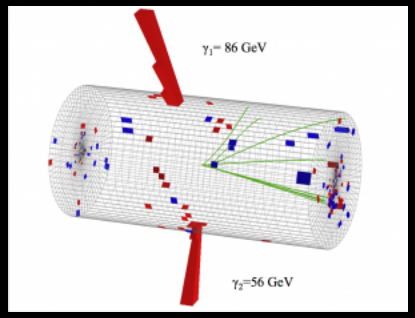
gg → b (anti)b

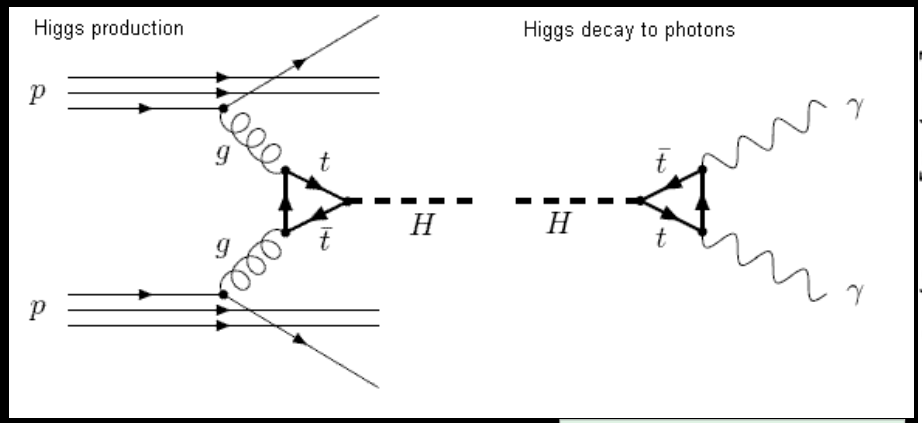


Want a Nobel?...find a resonance

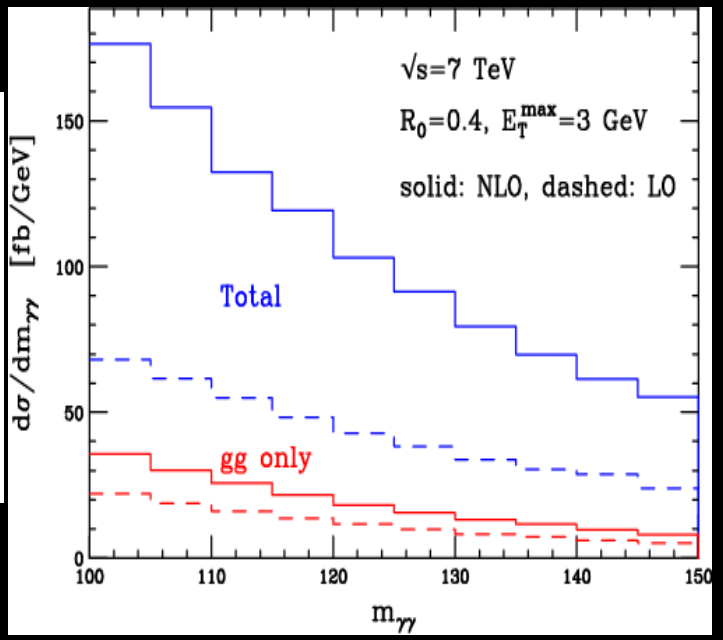


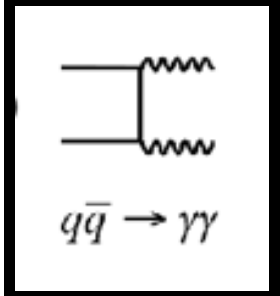
The Golden Channels

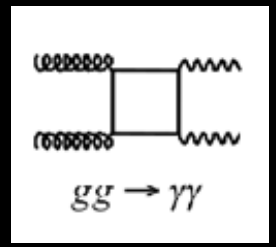


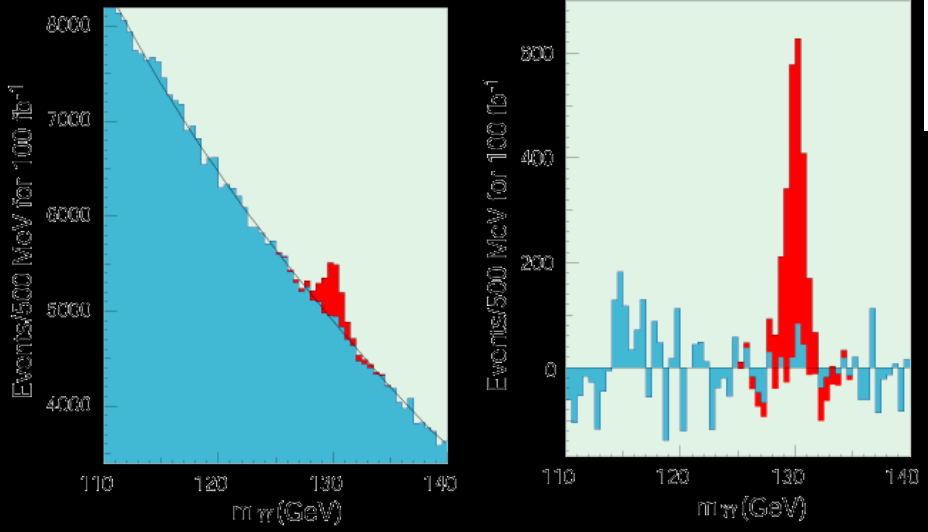


Irreducible background from di-photons

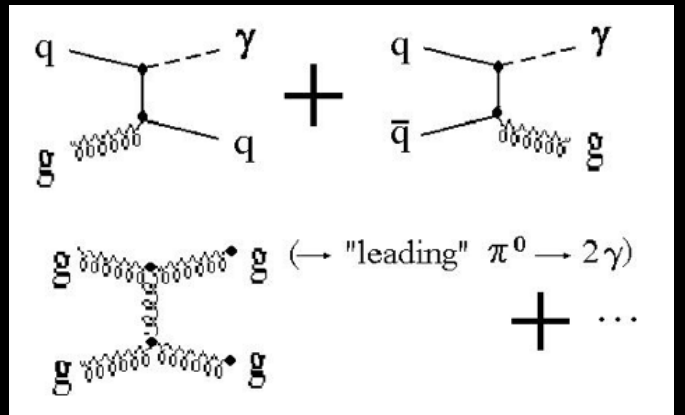






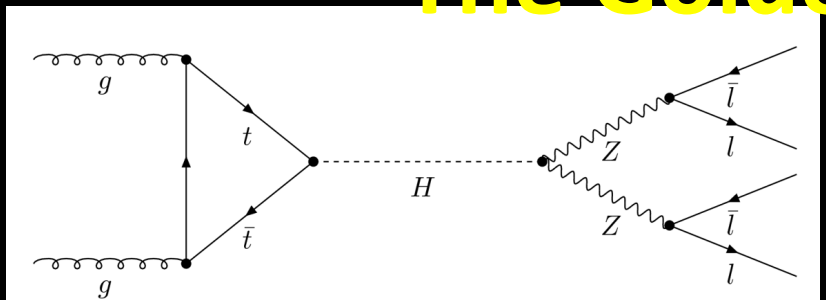


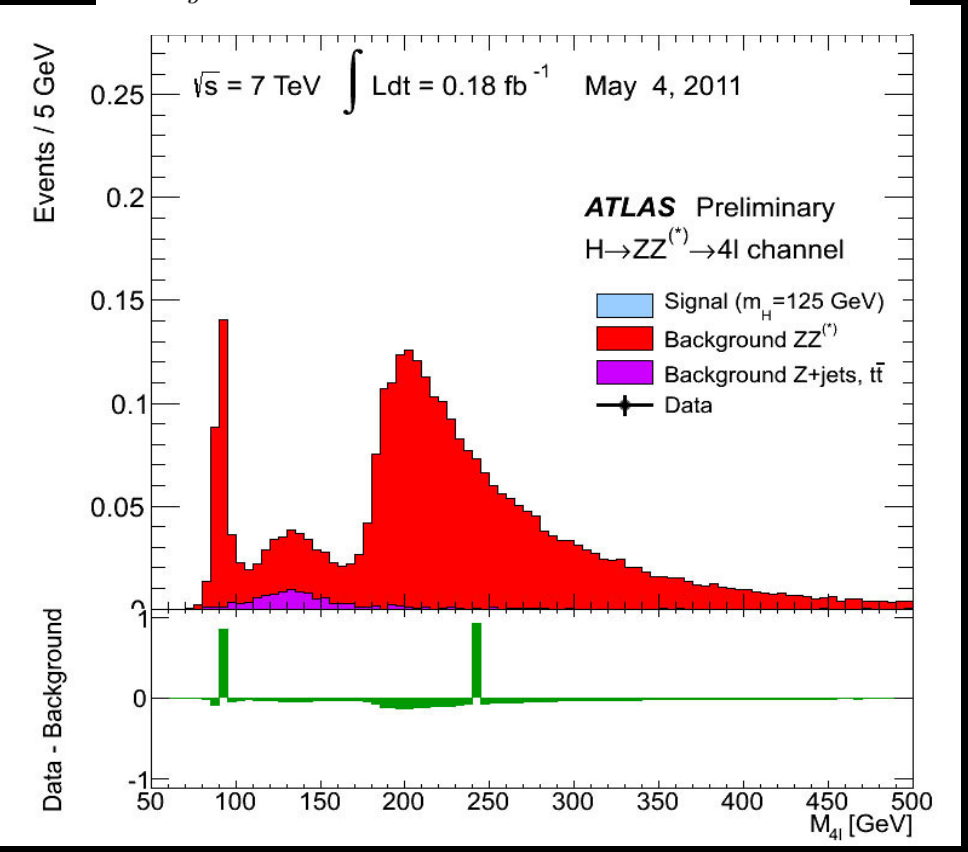
….and background from γ+jets and jet-jet with jets faking photon signals….



A resonance out of a huge non-resonant background
Key: good photon energy/momentum reconstruction

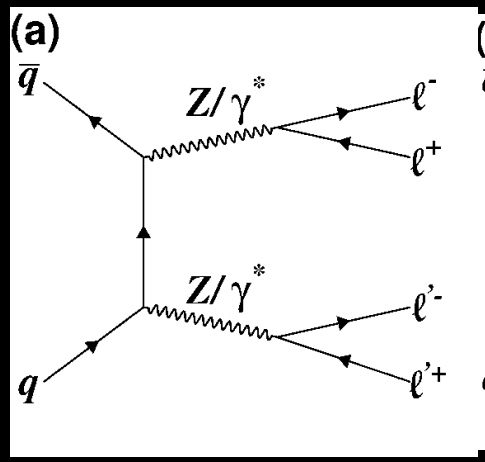
The Golden Channels

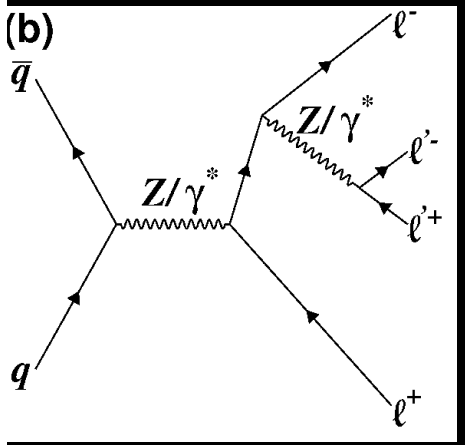


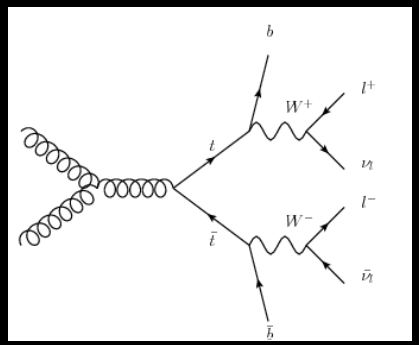


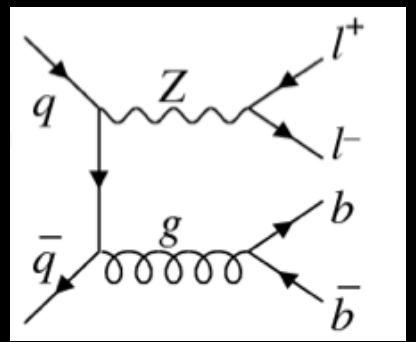
Background dominated by Diboson (ZZ*) w/wo resolved Zs

with contributions from other processes (Z+jets) and top production with jets faking leptons









Very clean and high-resolution channel (few events piling up in a given mass will be enough to claim discovery)

Pre-LHC Higgs Results

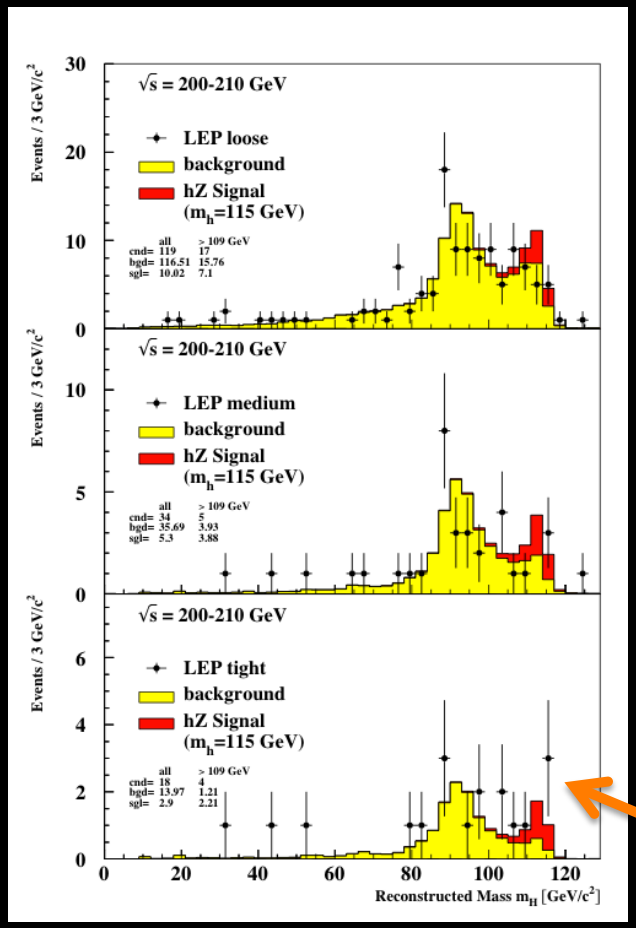
Electroweak Fits

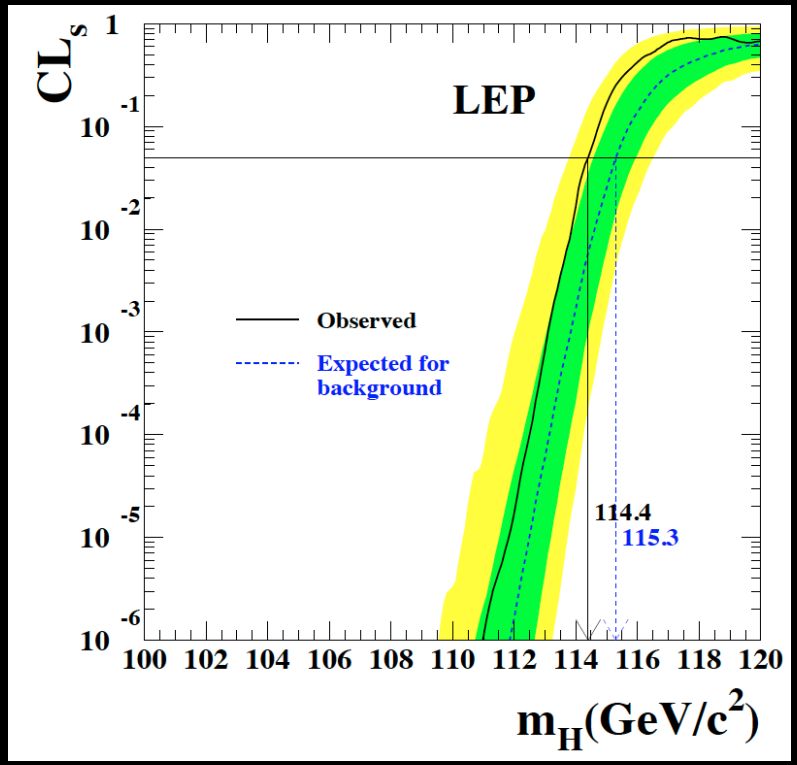
Tevatron Searches

Searches at LEP

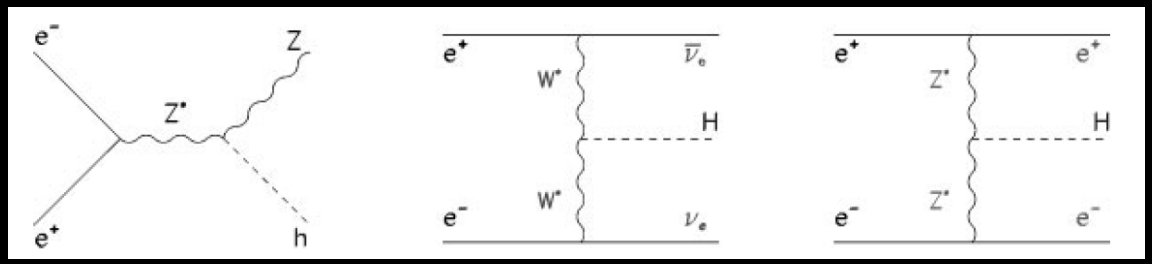
Absolute limits on Higgs from LEP

LEP : e+ e- collider @ CERN : up to 210 GeV





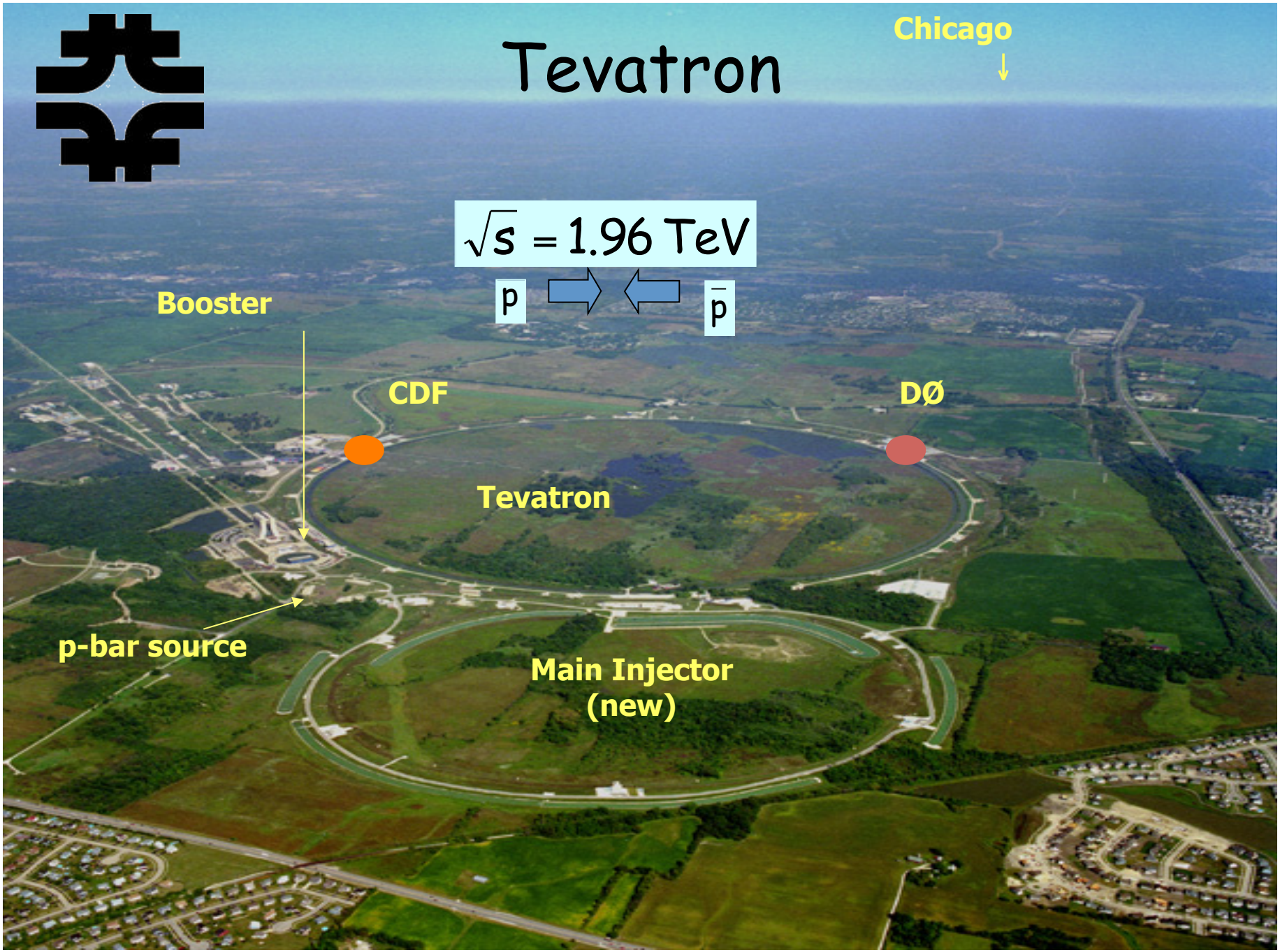
Hot days at CERN … by now we know it was nothing..



Excludes @ 95 % CL

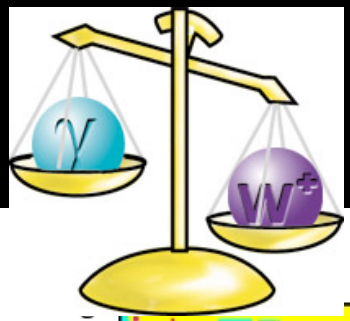
M_h < 114 GeV

A hard decision was taken to stop LEP and allow for the LHC program to start .. Quite the right decision.. we know now


Tevatron
Chicago
$\sqrt{s} = 1.96$ TeV
p
$\bar{p}$
Booster
CDF
DØ
Tevatron
p-bar source
Main Injector
(new)

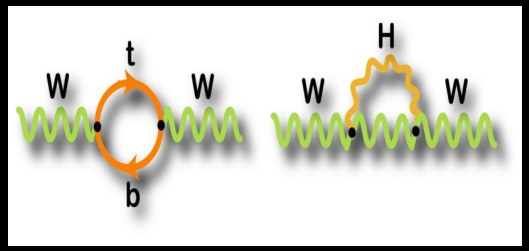
Electroweak Fits

(indirect Higgs Mass constrains)

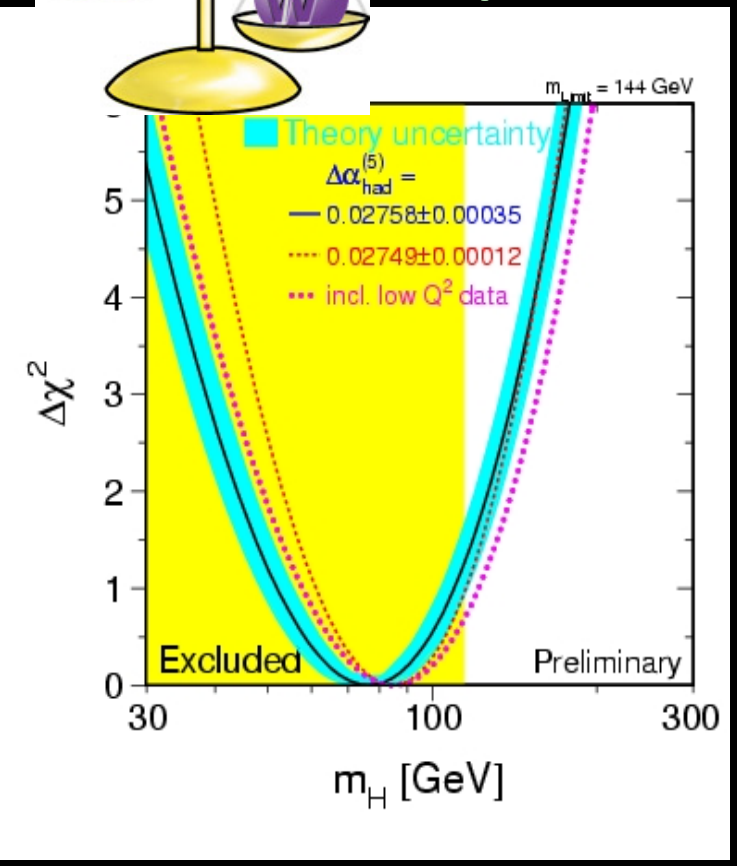


H

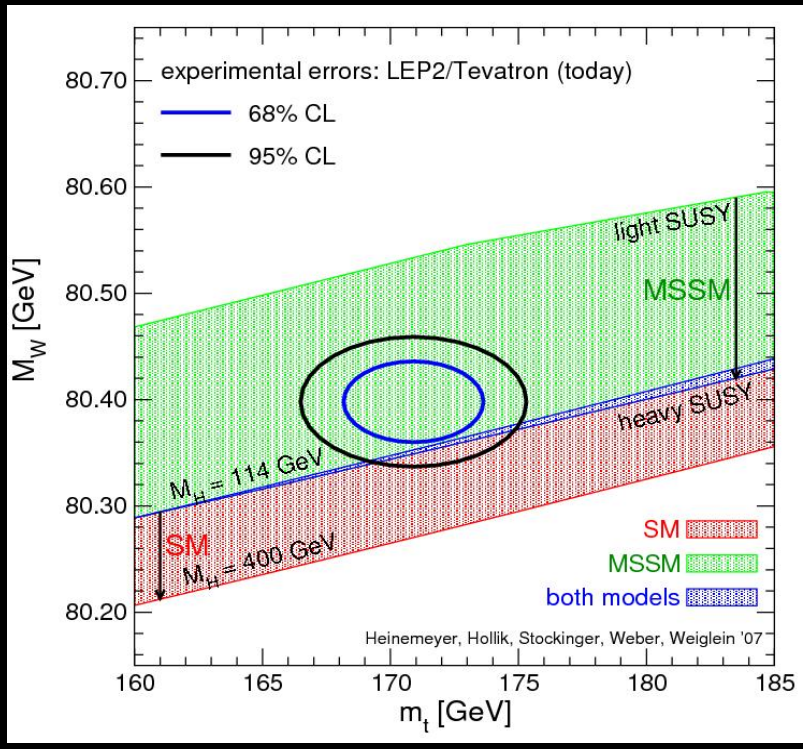
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



$\Delta r \sim \ln(m_H)$

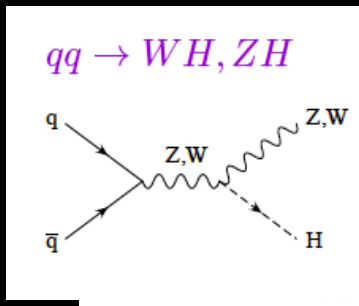


$\Delta r \sim m_{top}^2$



..as presented in Lepton Photon 2007

$$M_H < 160\ GeV/c^2$$



Tevatron in July 2010

Tevatron Run II Preliminary, <L> = 5.9 fb^{-1}

95% CL Limit/SM

LEP Exclusion

Tevatron Exclusion

Expected
Observed
±1σ Expected
±2σ Expected

H → bb ?? (limited resolution)

SM=1

Tevatron Exclusion

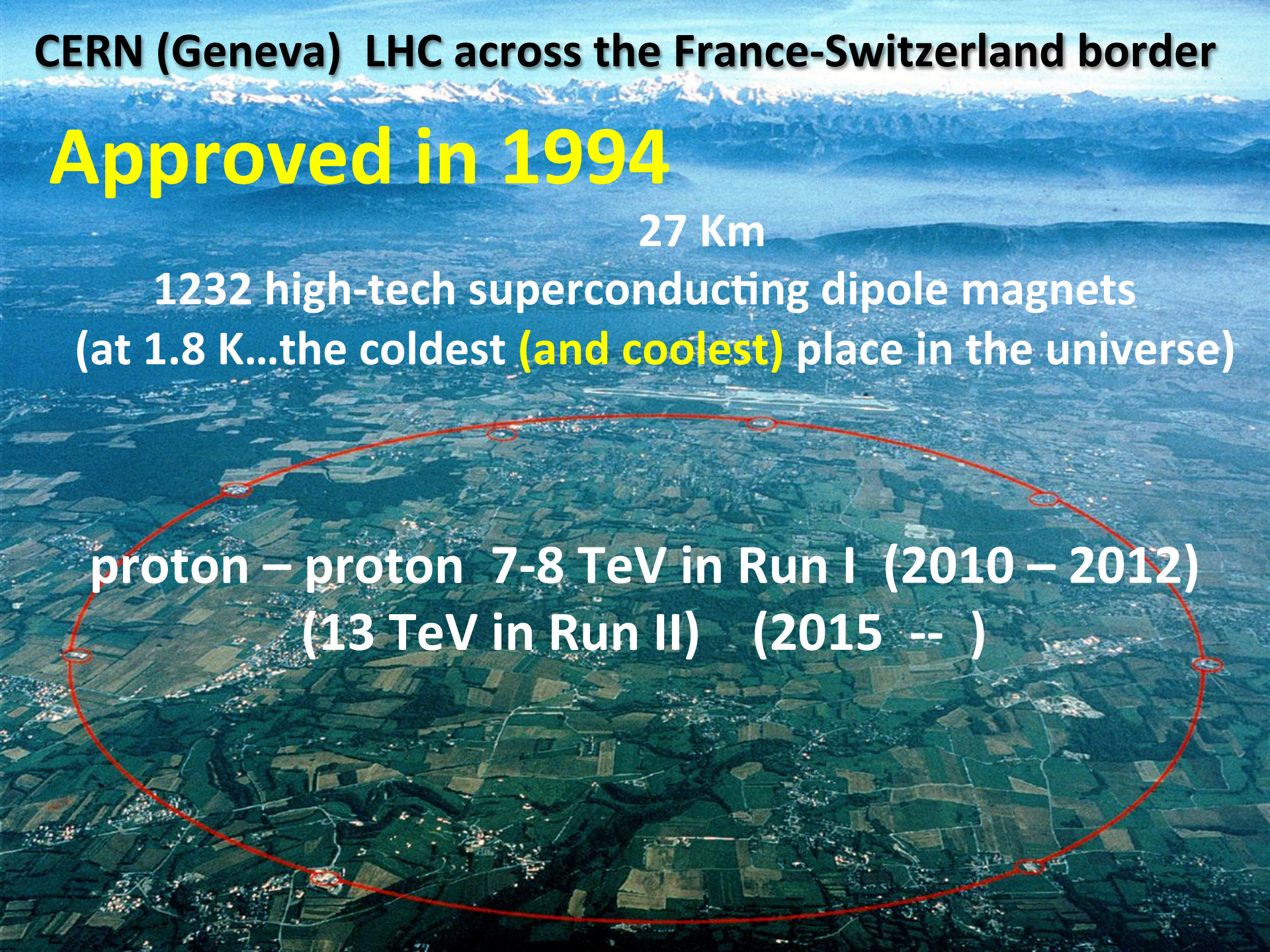
July 19, 2010

10
1

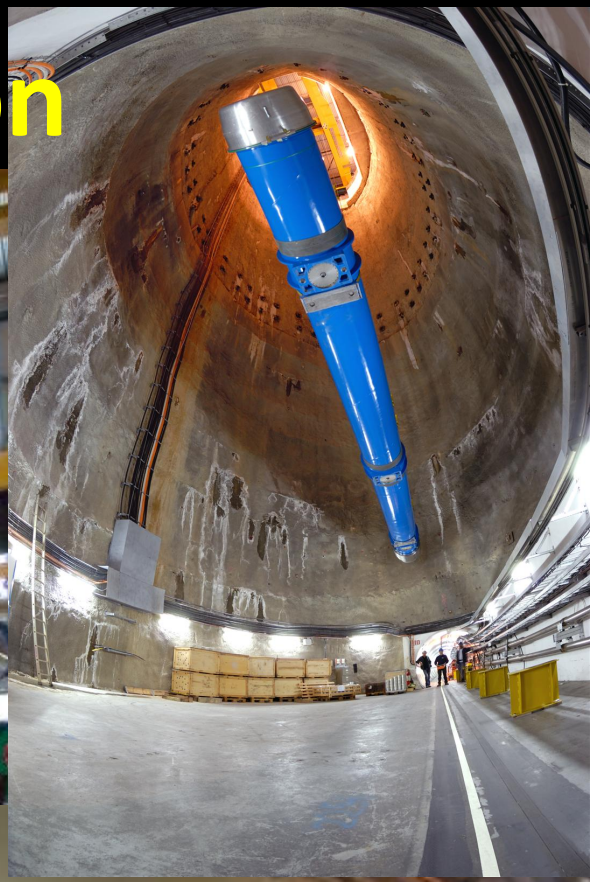
100 110 120 130 140 150 160 170 180 190 200

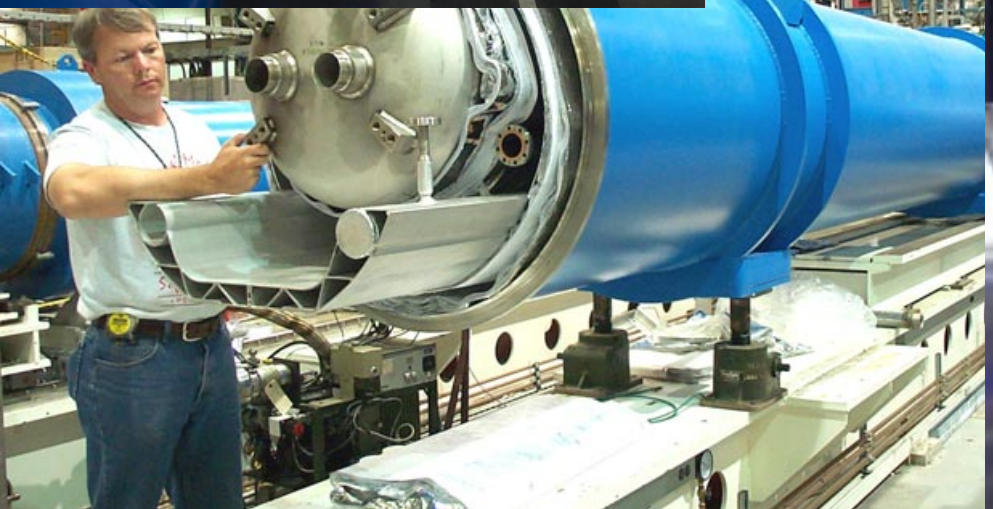
m_H(GeV/c^2)

If goes below 1 you exclude the SM Higgs for a given mass

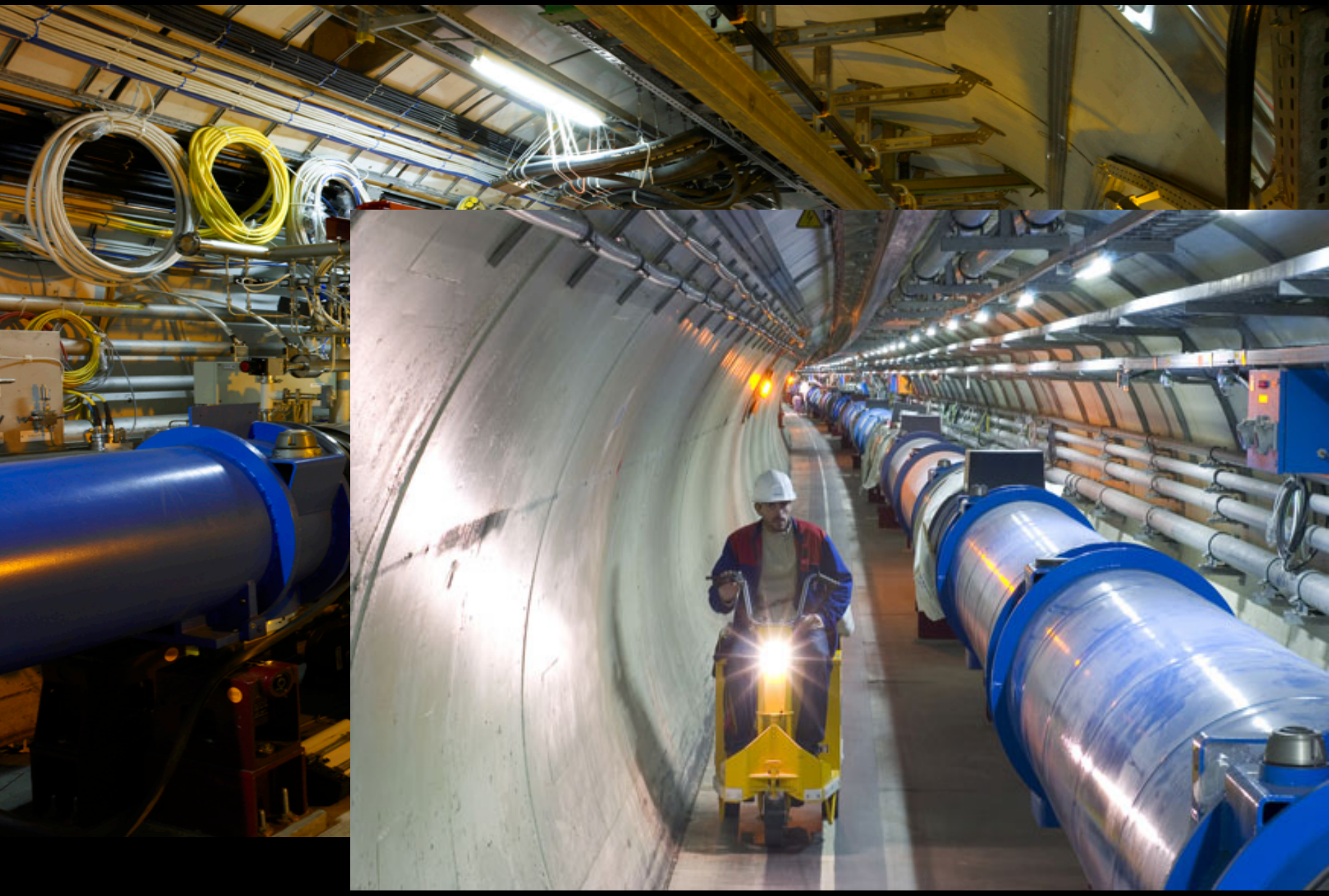

CERN (Geneva) LHC across the France-Switzerland border
Approved in 1994
27 Km
1232 high-tech superconducting dipole magnets
(at 1.8 K…the coldest (and coolest) place in the universe)
proton – proton 7-8 TeV in Run I (2010 – 2012)
(13 TeV in Run II) (2015 --)

LHC construction



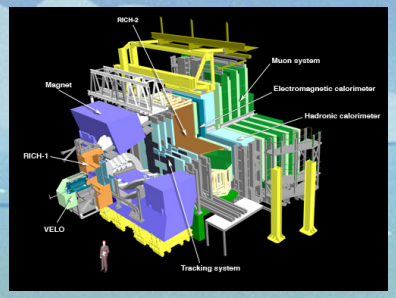


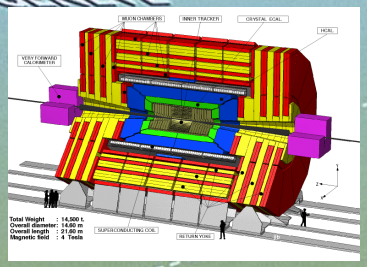
LHC Construction

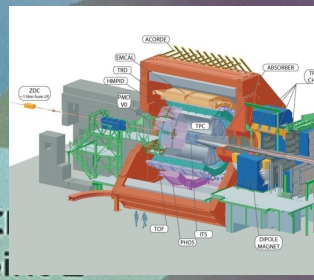


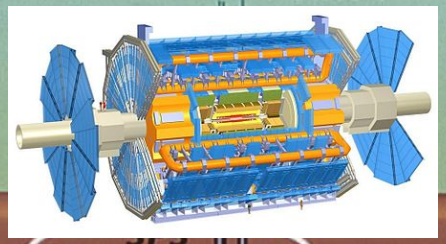
Overall view of the LHC experiments.

LHC will run for 15 years..
A total of 6 10^{15} collisions









LHC - B
Point 8

CERN

ATLAS
Point 1

ALIC
Poi

CMS
Point 5

TI 8

TI 2

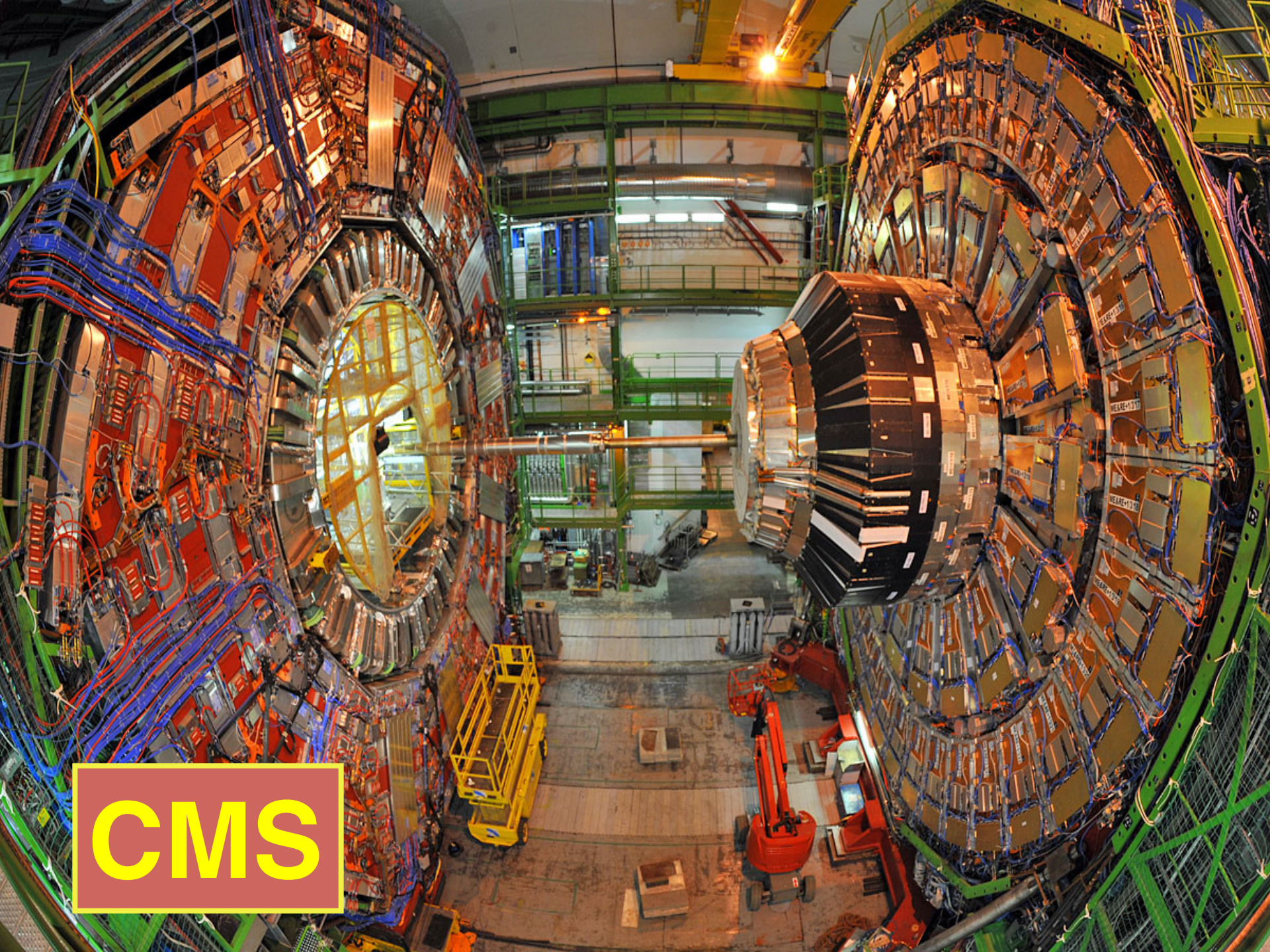
LHC - B

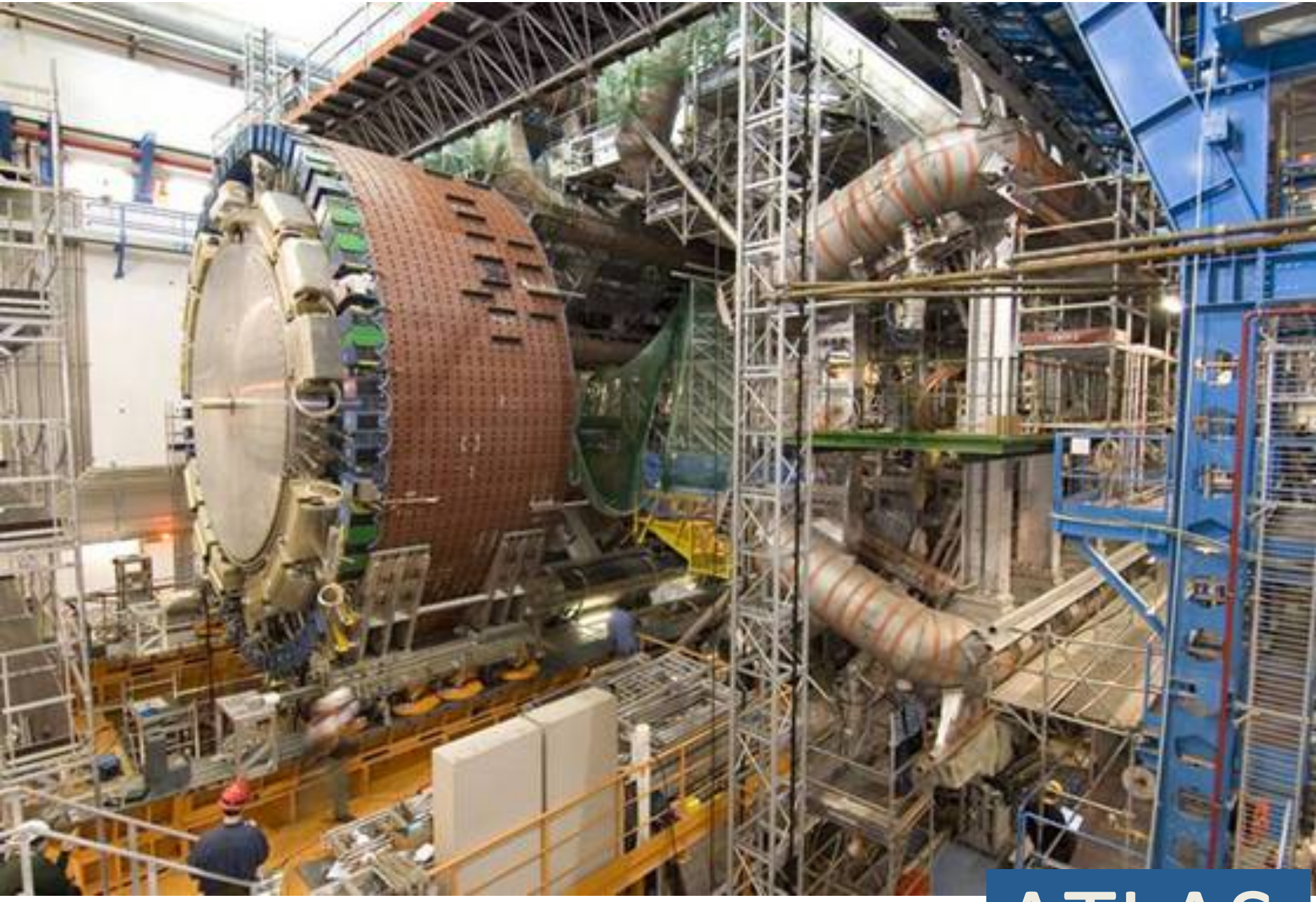
ATLAS

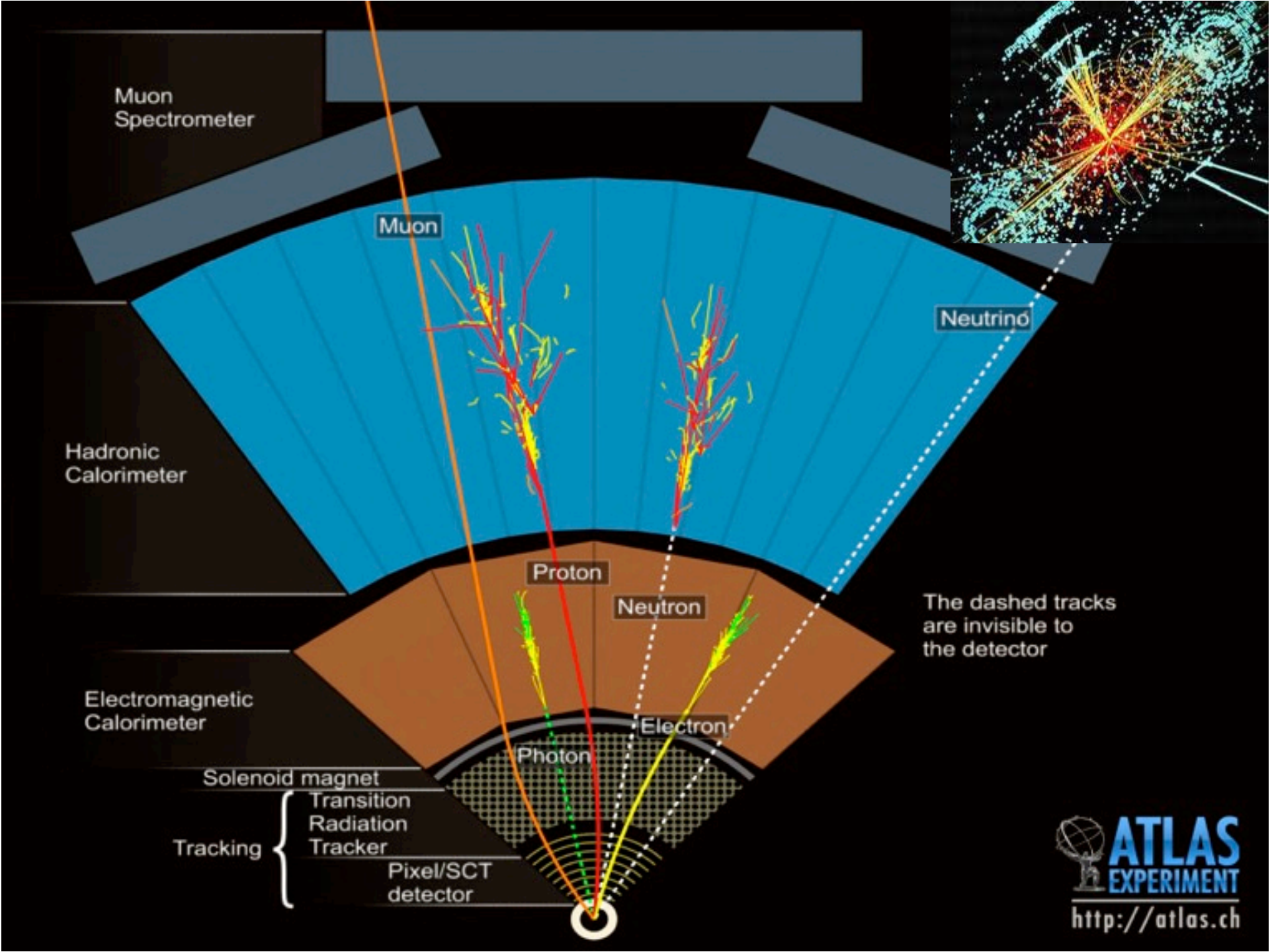
ALICE

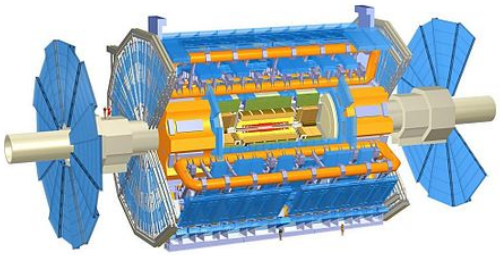
CMS

LEP/LHC


CMS

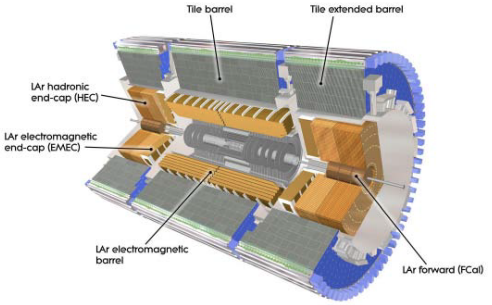

ATLAS

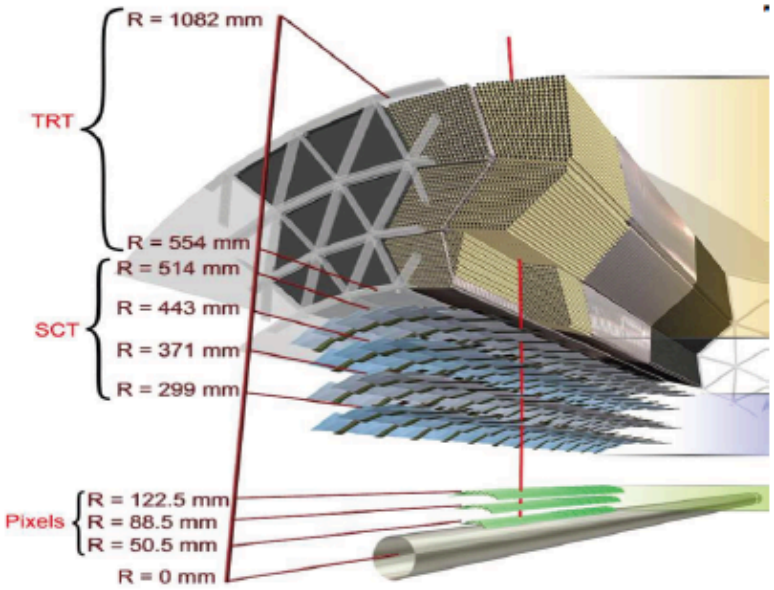

Muon Spectrometer
Muon
Neutrino
Hadronic Calorimeter
Proton
Neutron
The dashed tracks are invisible to the detector
Electromagnetic Calorimeter
Electron
Photon
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
ATLAS EXPERIMENT
http://atlas.ch



ATLAS

(relevant to photon ID)



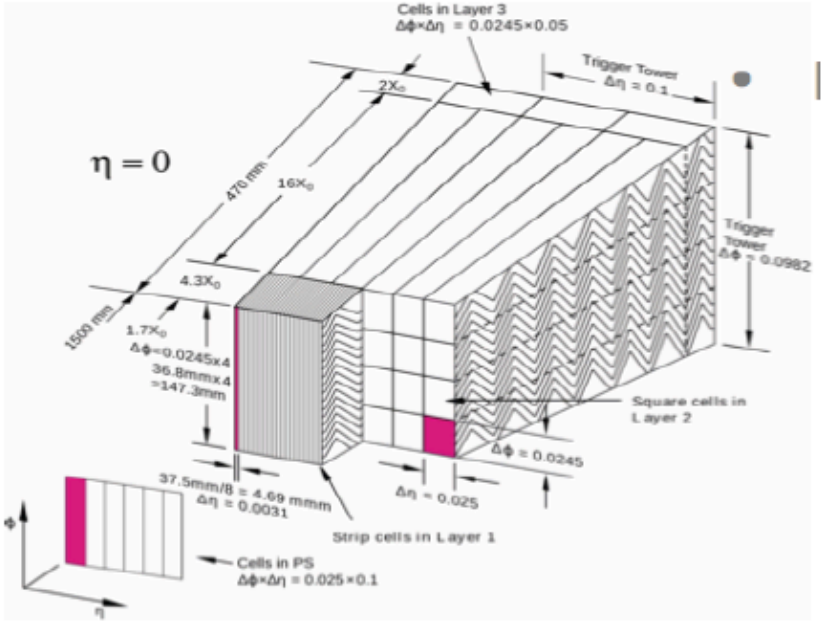


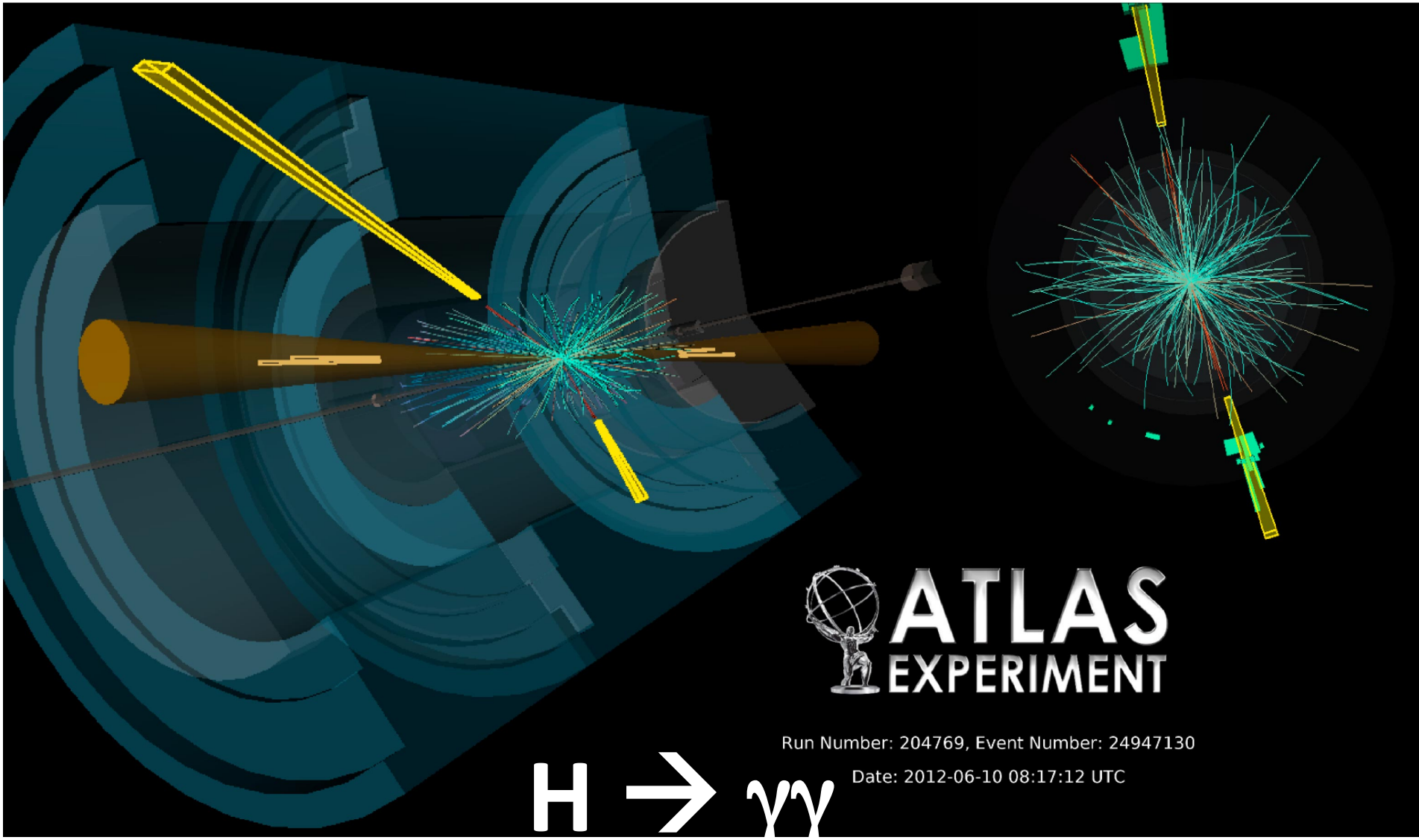
Inner Detector - Barrel (B)&End-cap (E) in 2T solenoidal magnetic field:

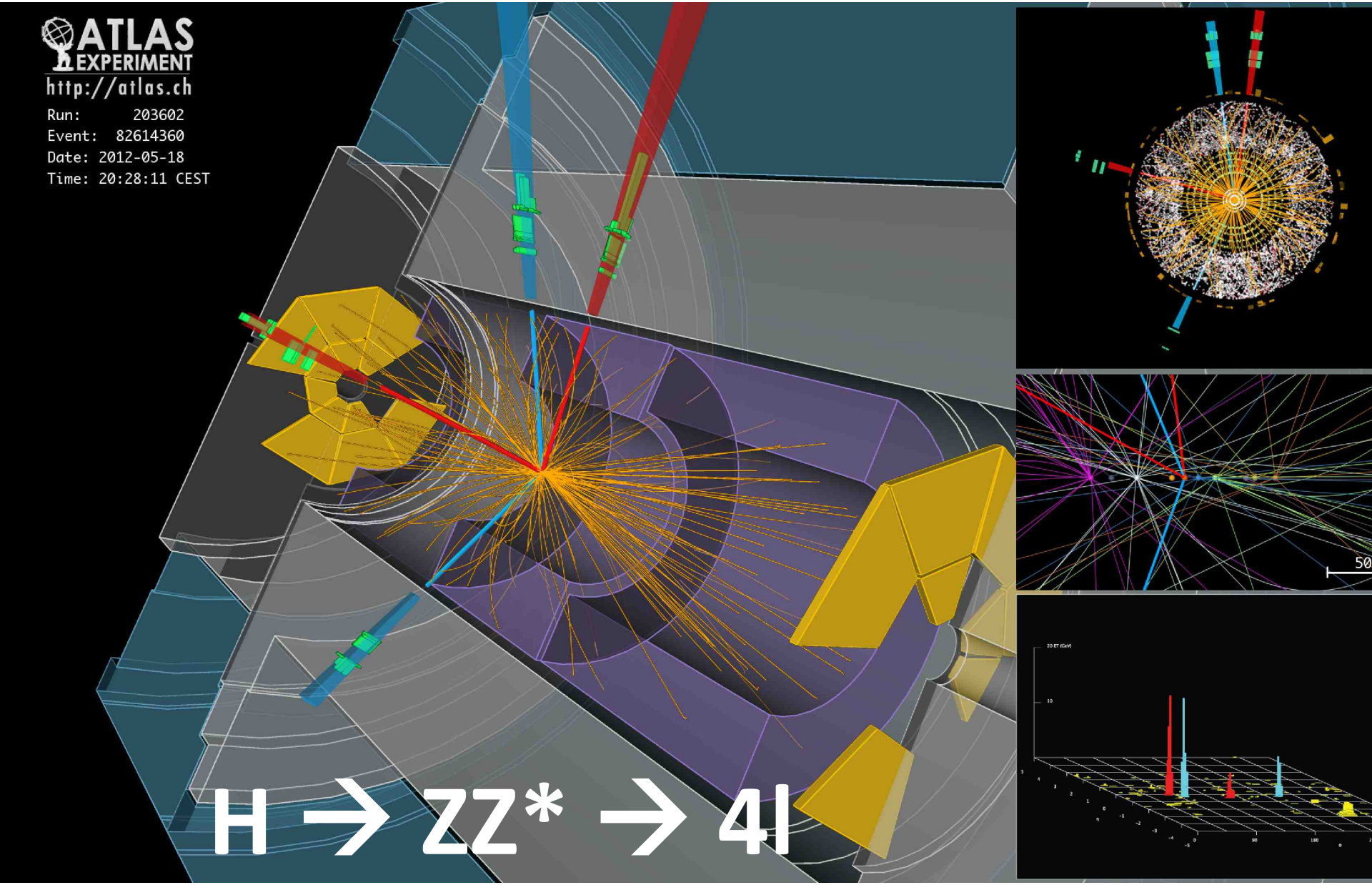
- Track reconstruction up to $|\eta|<2.47$;
- Conversion verticies reconstruction;
- e/γ and $e/\pi^{\pm}$ separation;
- Pixel: (B) 3 layers +(E) 2x3 disks $\sigma_{r\varphi}$~10 μm, σ_z~115 μm;
- Semi Conductor Tracker: (B) 4 layers +(E) 2x9 disks $\sigma_{r\varphi}$~17 μm, σ_z~580 μm;
- Transition Radiation Tracker: (B) 73 layers +(E) 2x160 layers σ_z~130 μm;

LAr lead sampling calorimeter with an 'accordion' geometry.

- 3 longitudinal layers with cell of $\Delta\eta\times\Delta\varphi$:
  - 1st layer (0.003÷0.006)x0.1;
  - 2nd layer 0.025x0.025;
  - 3rd layer 0.050x0.025.
- Presampler for $|\eta|<1.8$ $\Delta\eta\times\Delta\varphi$~0.025x0.1.
- Barrel-end-cap crack $|\eta|=1.37\div1.52$.
- $\sigma(E)/E=(10\text{-}17\%)(\eta)/\sqrt{E(GeV)} \oplus (1.2\div1.8\%)$.

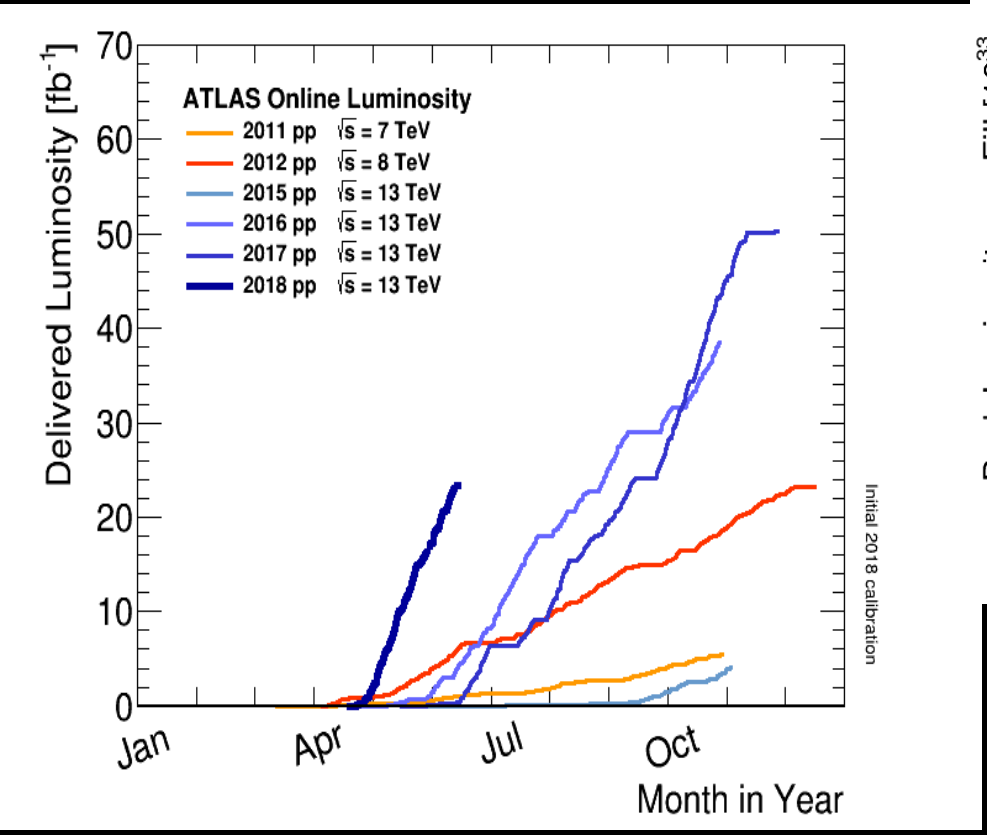


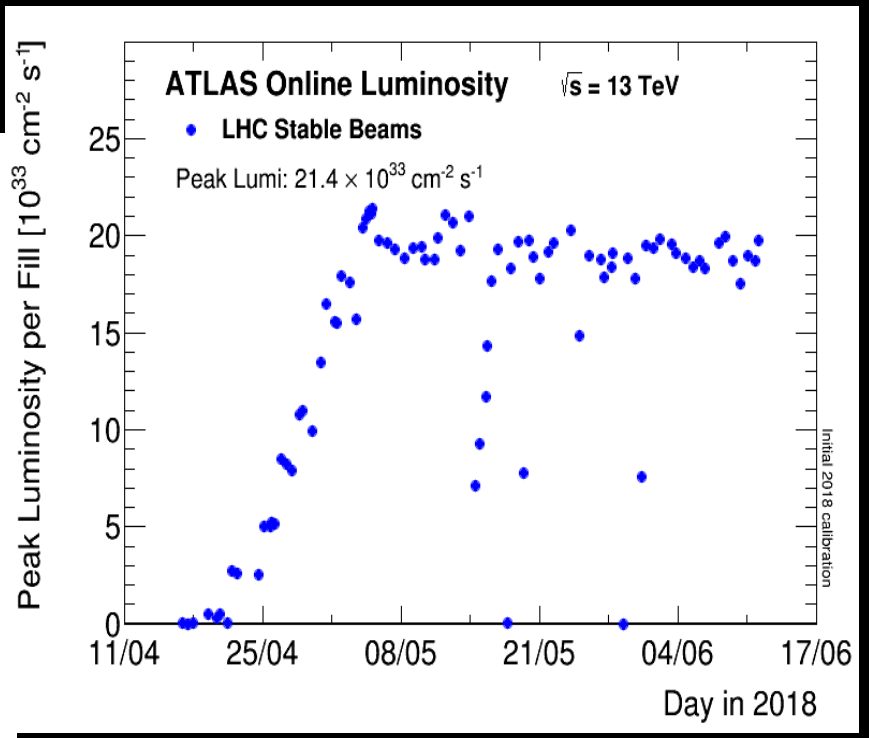

ATLAS
EXPERIMENT
Run Number: 204769, Event Number: 24947130
Date: 2012-06-10 08:17:12 UTC
H → γγ


ATLAS
EXPERIMENT
http://atlas.ch
Run: 203602
Event: 82614360
Date: 2012-05-18
Time: 20:28:11 CEST
H → ZZ* → 4l

LHC Performance (2010-2018)

Spectacular LHC performance (rapid increase of data samples)



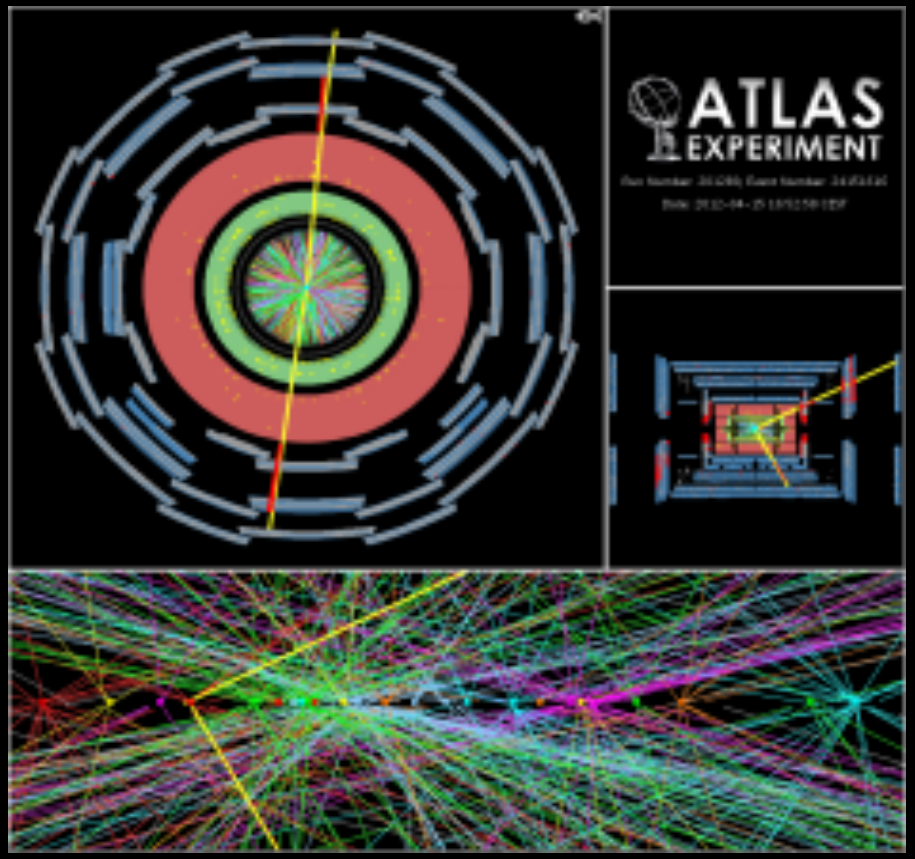


… rapid increase of pile-up conditions

LHC ended pp run at 7+8 TeV (28 fb^{-1})

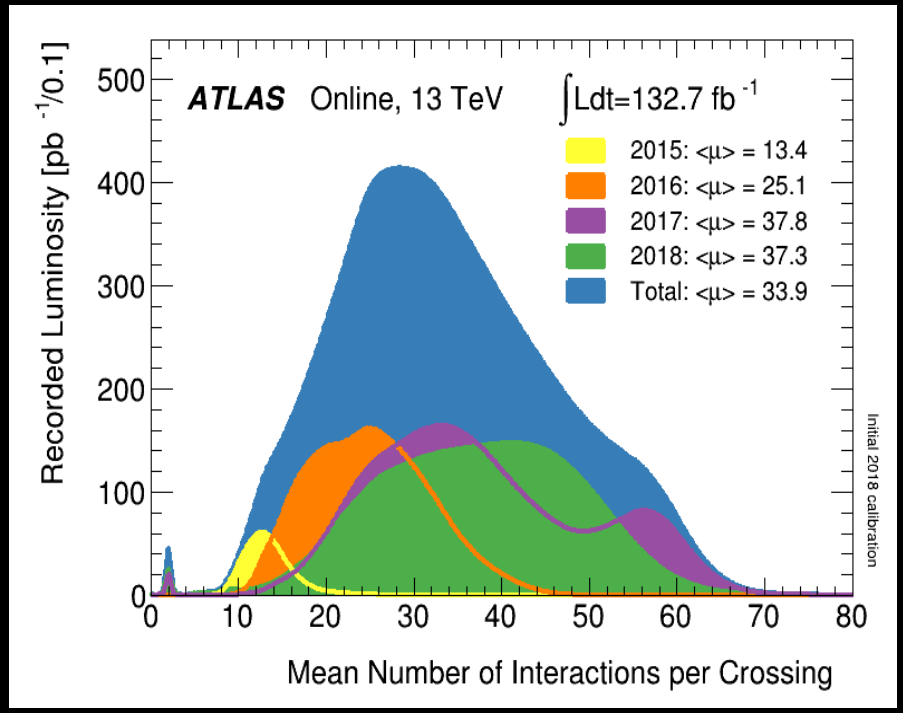
By now a total integrated luminosity for physics of 80 fb^{-1} at 13 TeV

Multiple Interactions



Up to 60 interactions / crossing

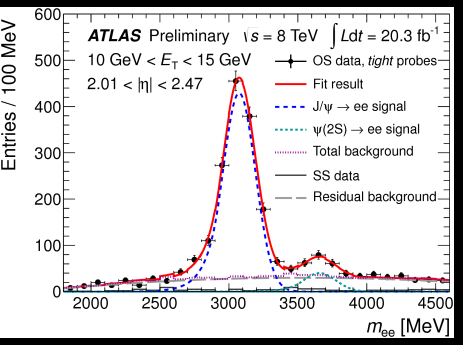
(requires enormous efforts to understand the reconstruction of the physics objects…)

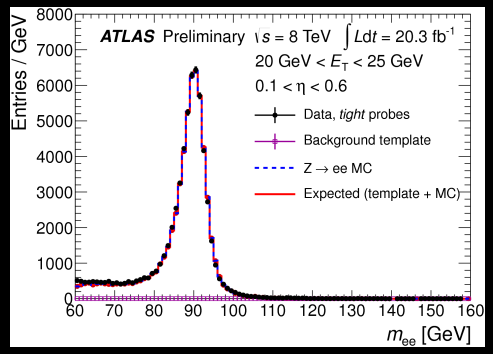


Z → μμ events with
20 interactions on top

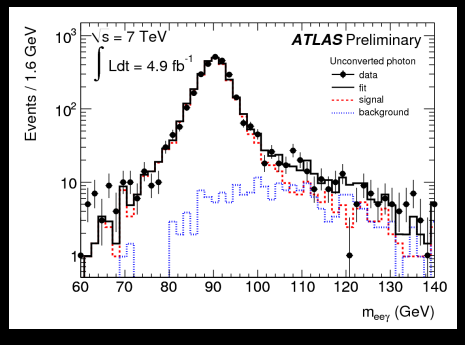
Building Blocks

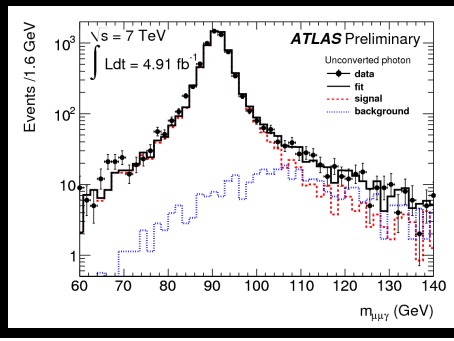
Z → ee , J/Psi → ee .....

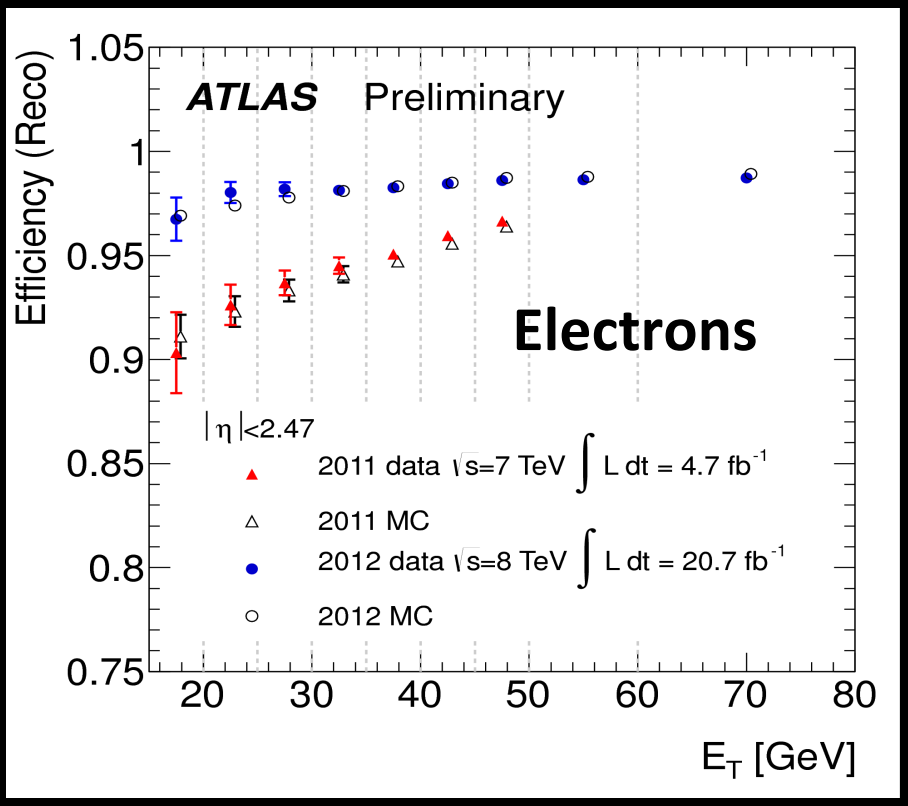


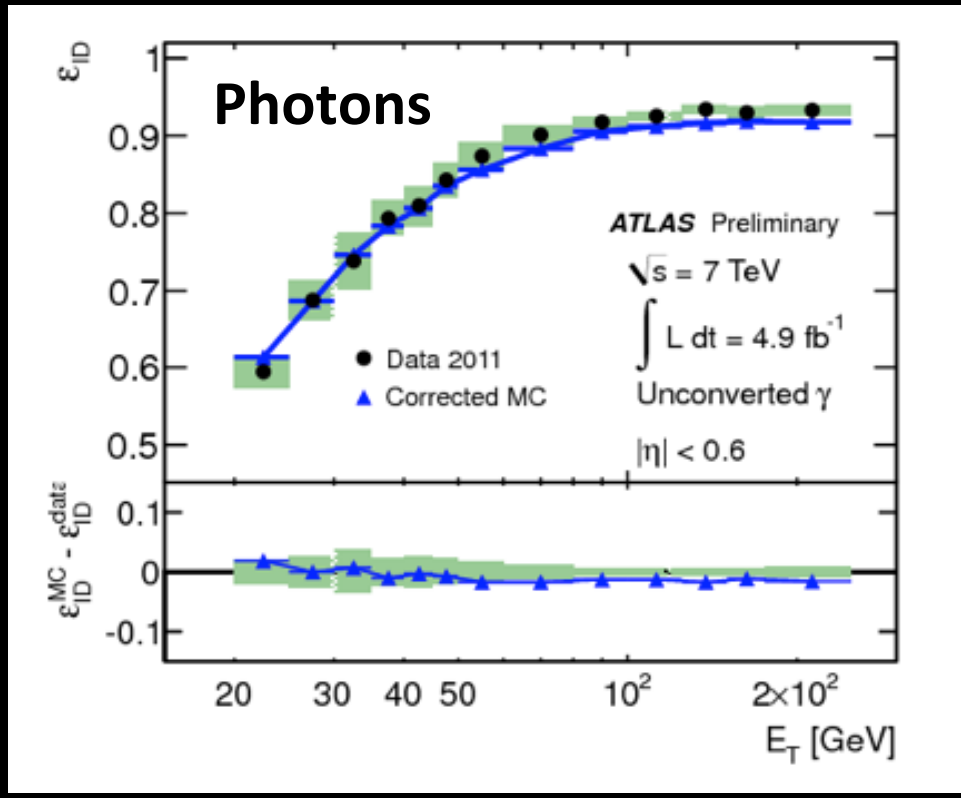


eeγ and μμγ



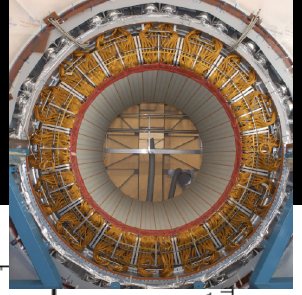


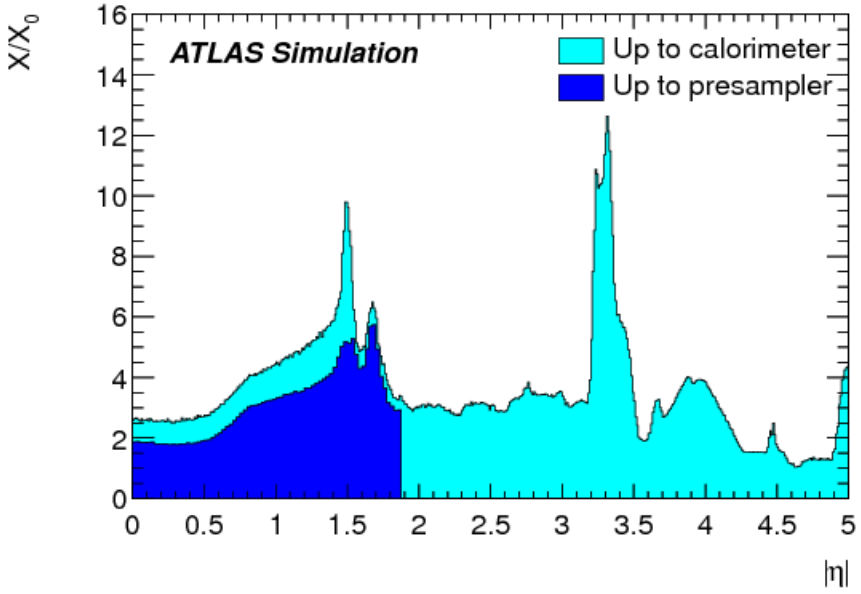




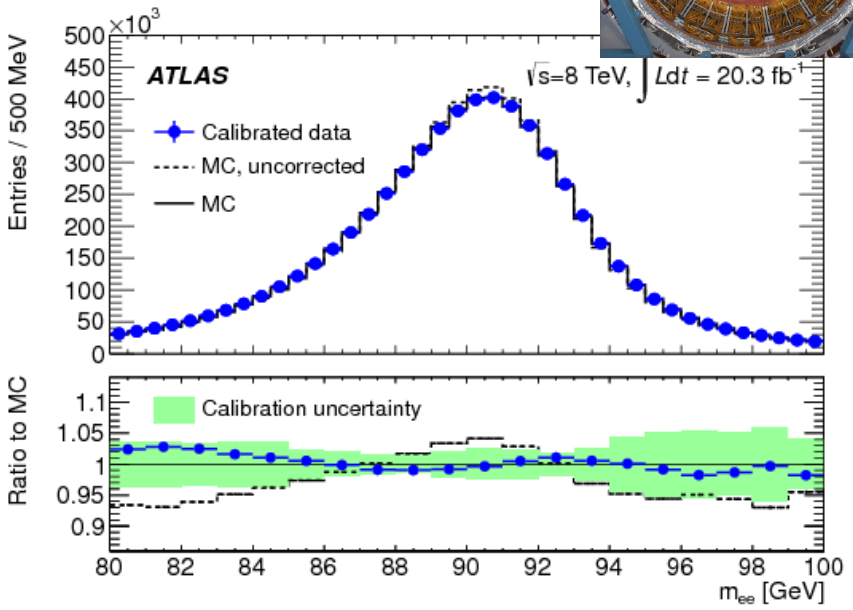
Building Blocks

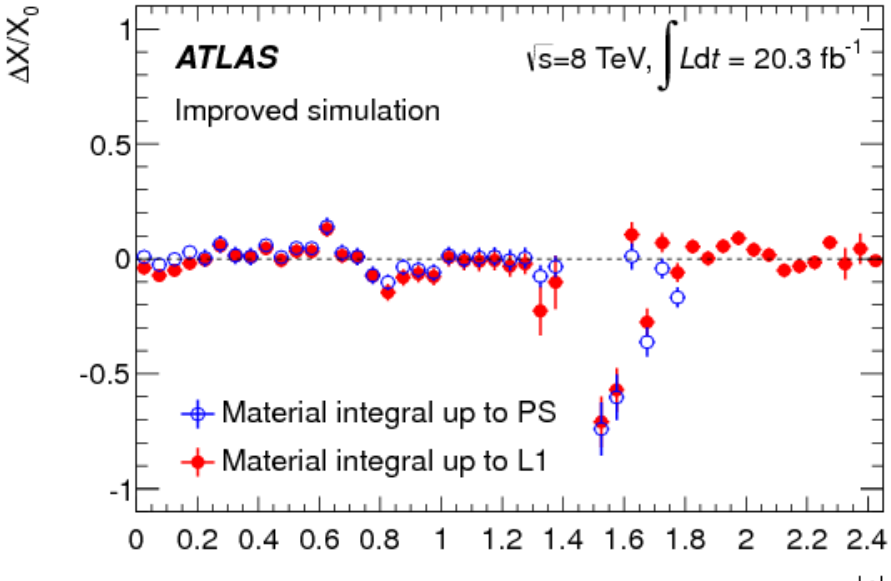
Detector Material

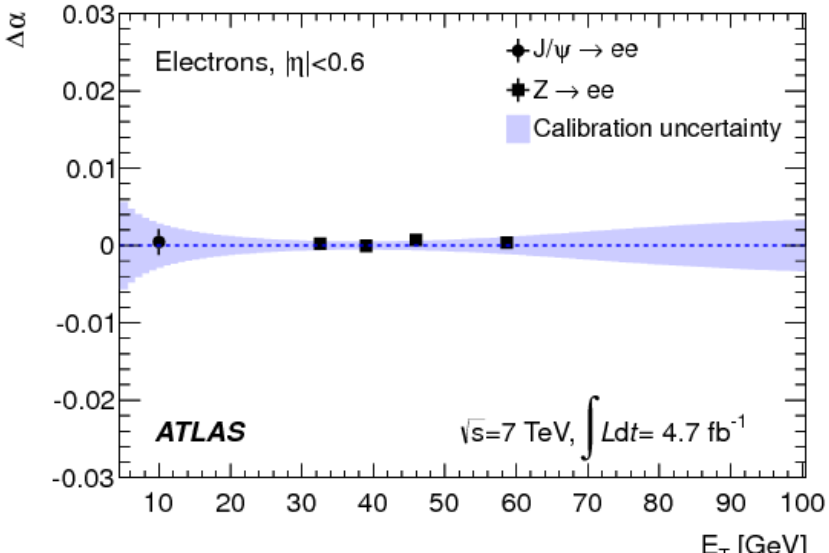




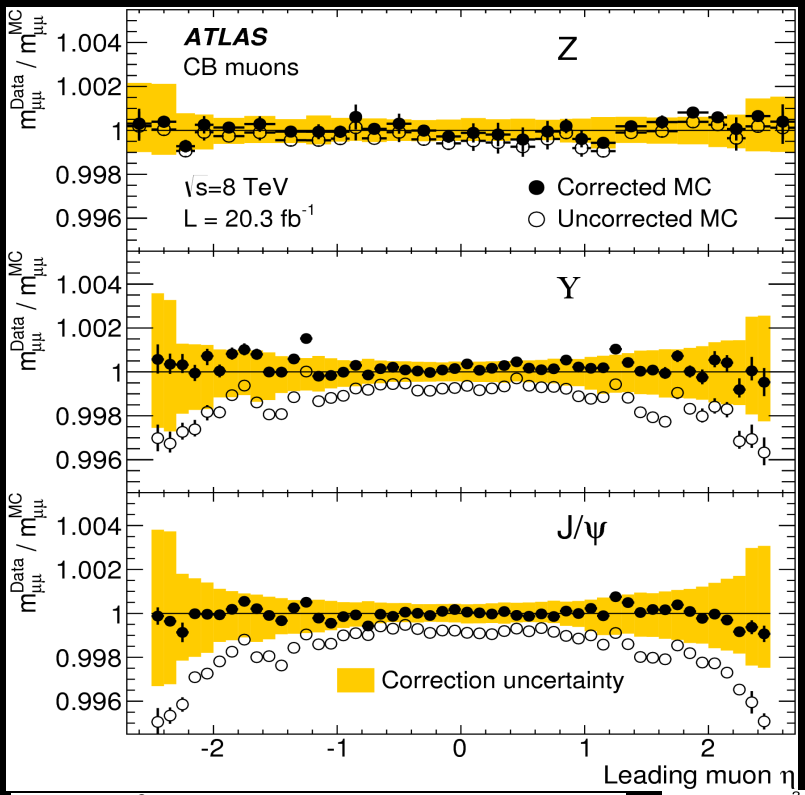
EM absolute scale



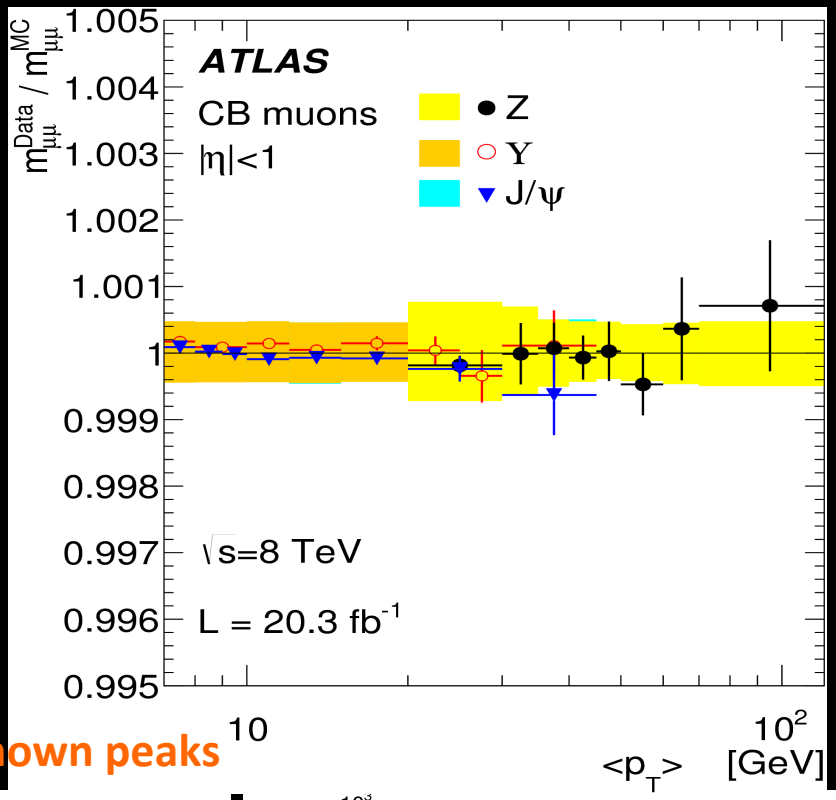




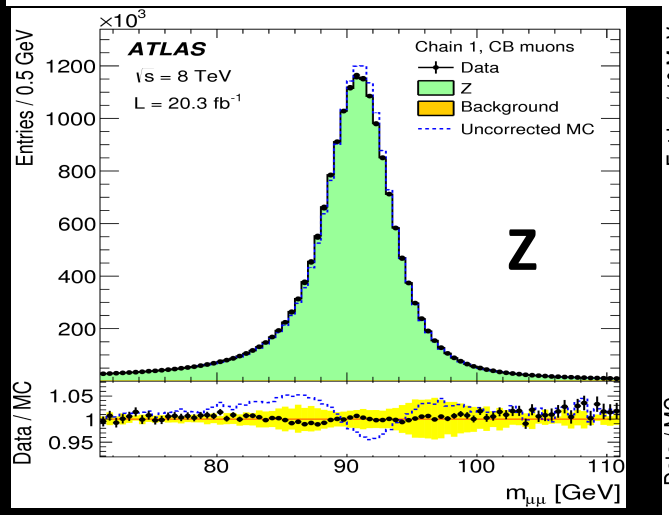
Building Blocks

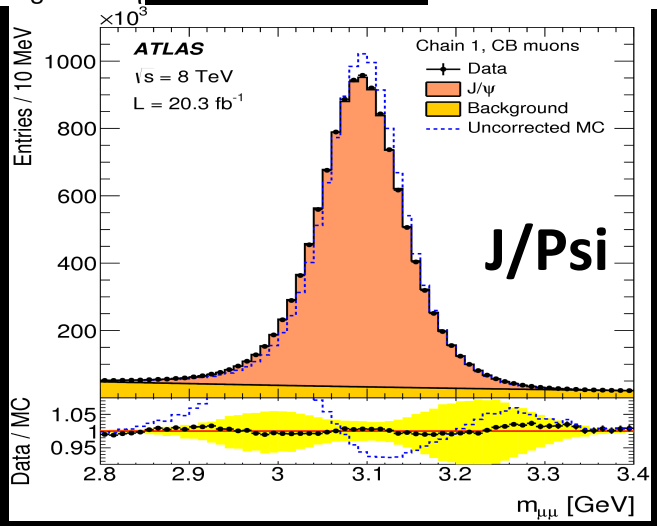


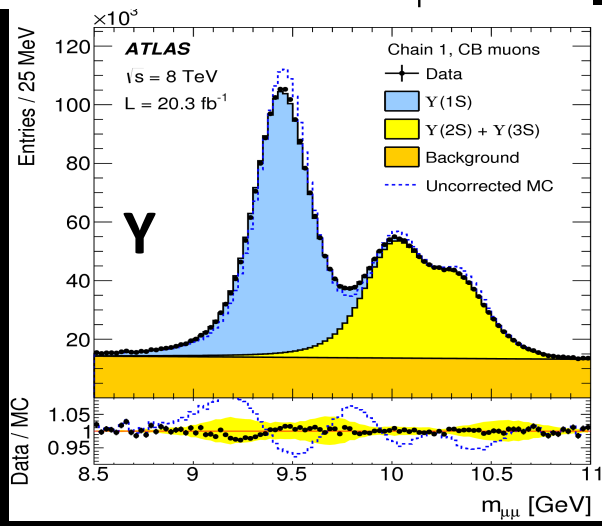
Alignment of trackers and muon chambers



Using well-known peaks

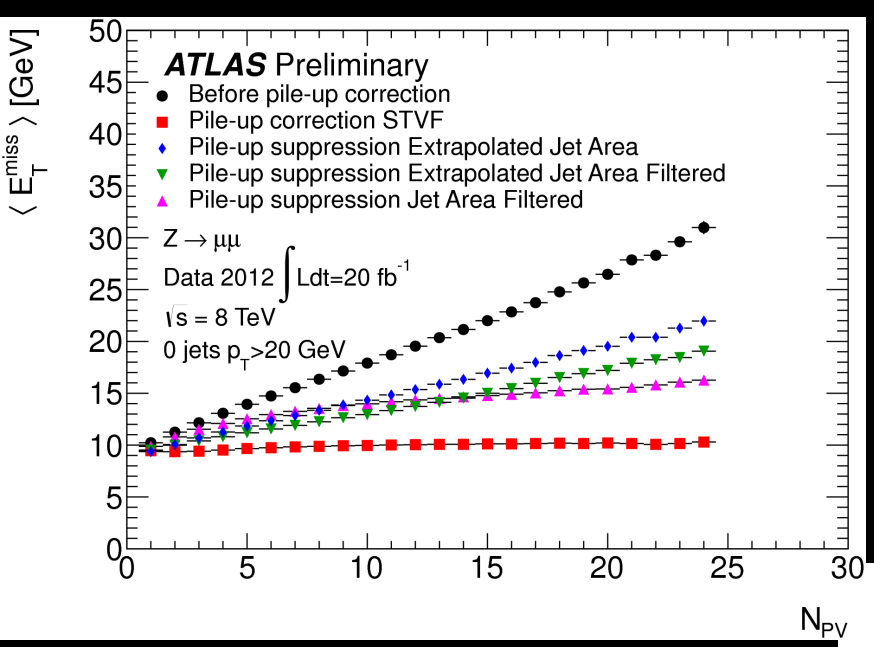




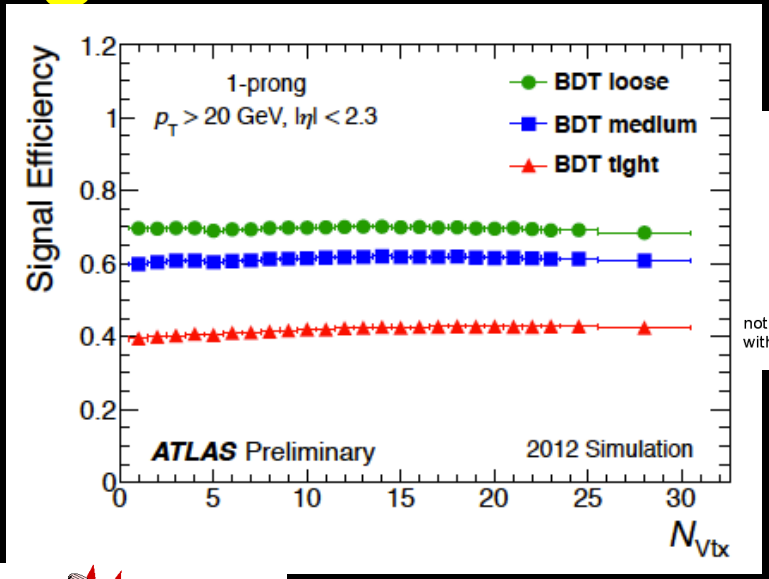


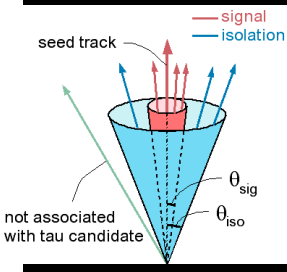
Building Blocks

Missing E_T vs PILEUP

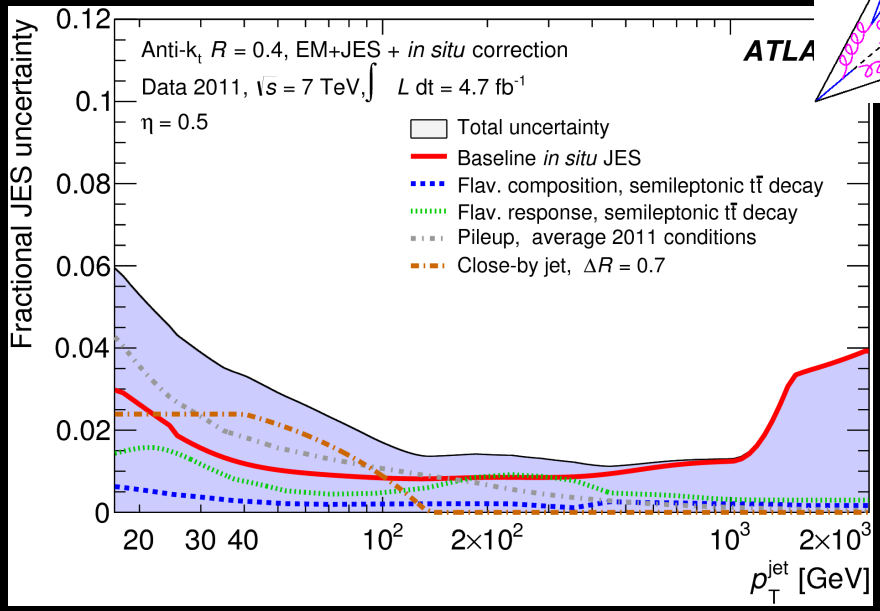


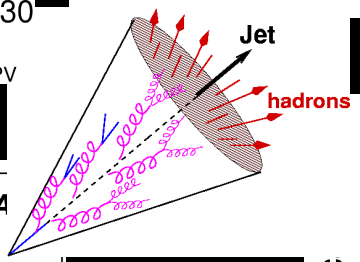
TAU ID vs PILEUP



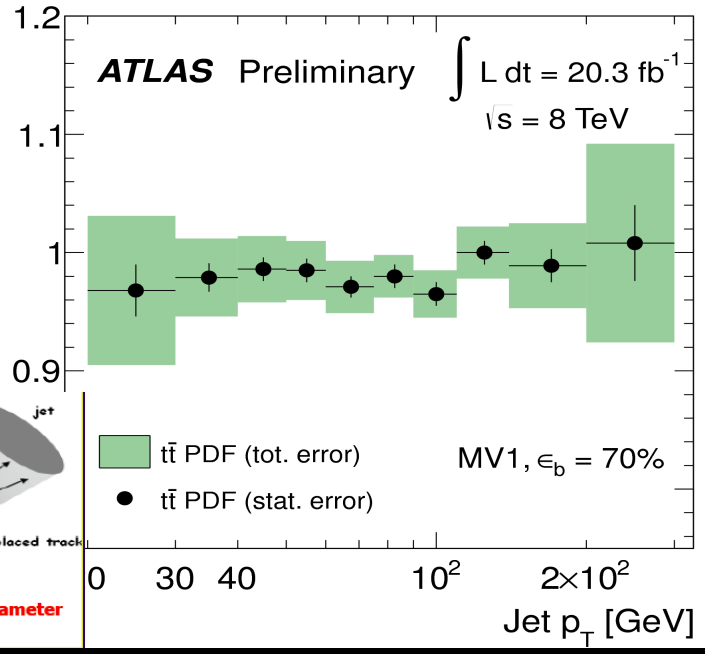


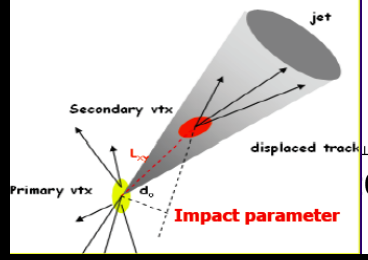
JET ENERGY SCALE UNCERTAINTY





B-JET TAGGING EFFICIENCY





SM Physics

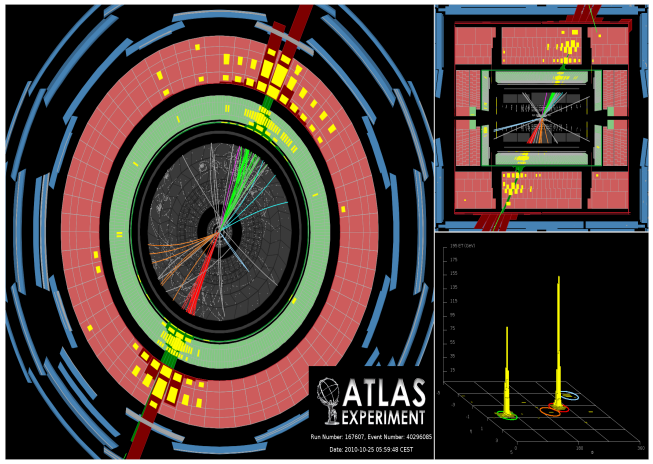
Selected results on

jets, photons, W/Z+jets,Top quark, Dibosons….

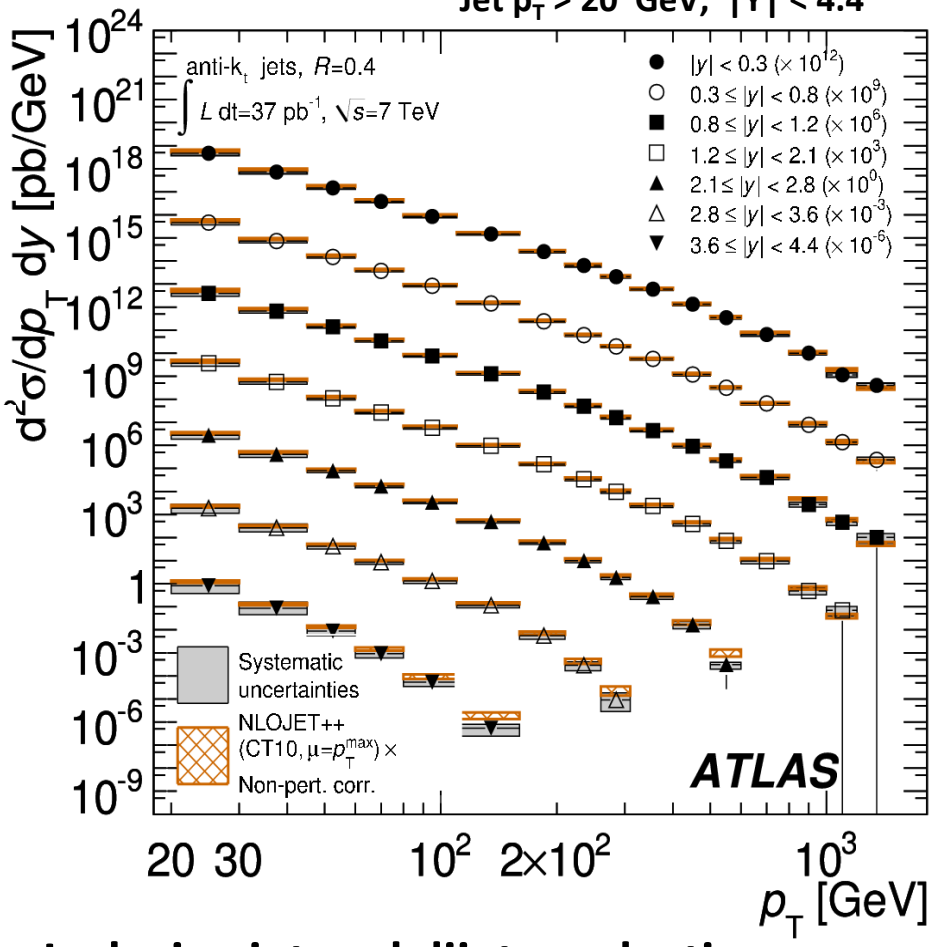
Just to illustrate the Glory of the SM
(processes relevant for searches later on…)

Jet Production

PRD86(2012)014022



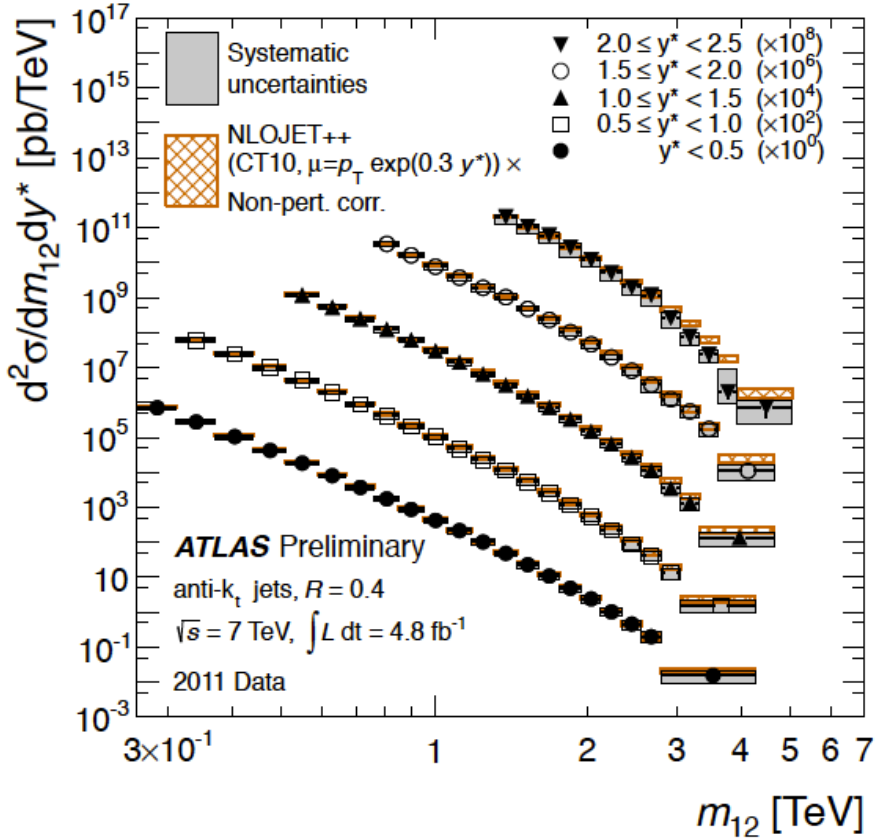
anti-K_T jets with R=0.4, 0.6
Jet p_T > 20 GeV, |Y| < 4.4



ATLAS-CONF-2012-021

$M_{jj} > 260 GeV$

$y^* = |y^1 - y^2|/2 < 2.5$



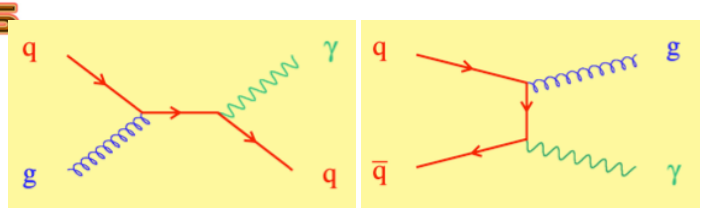
Inclusive jet and dijet production measured in a wide range of jet p_T , rapidity and dijet mass.

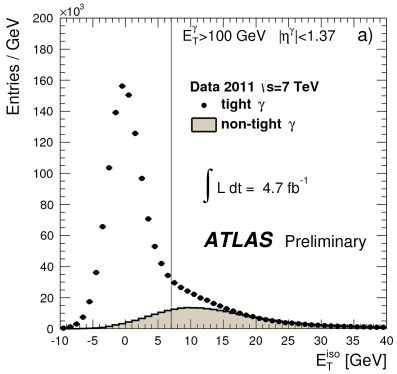
Well described by NLO pQCD predictions

Inclusive photons

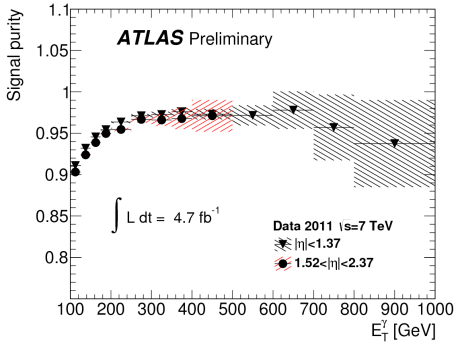
(cross section for isolated photons)

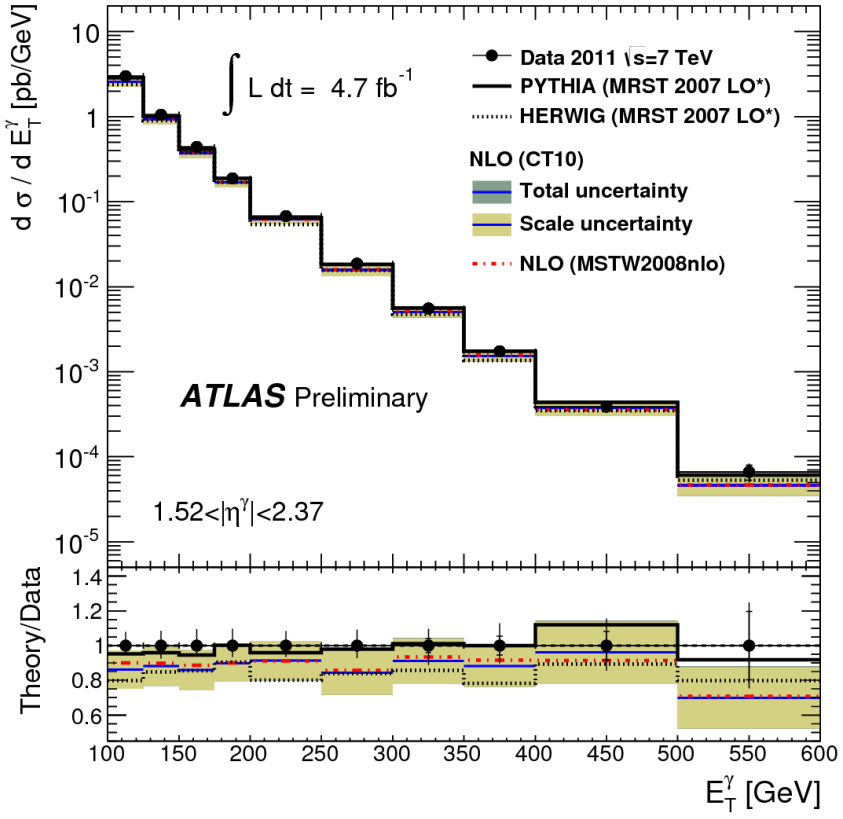
Phys. Lett. B706 (2011) 150-167
Phys. Rev. D83 (2011) 052005
ATLAS-CONF-2013-022

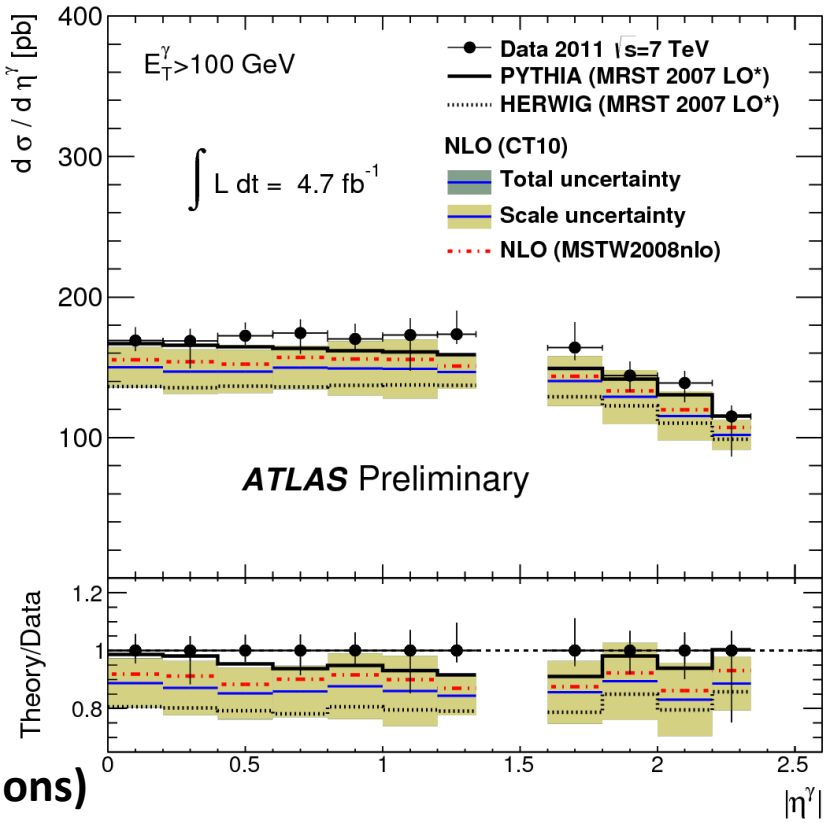




Isolation distribution used to extract the background contributions



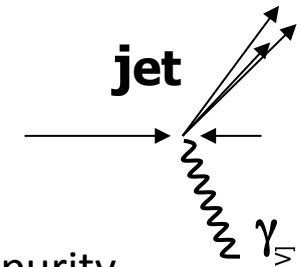




Good agreement with NLO pQCD predictions (at very low E_T^γ predictions are affected by the limited knowledge of the fragmentation contributions)

γ+jet

CERN-PH-EP-2012-009



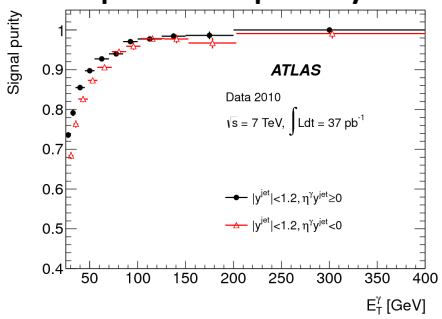
Jet $p_T > 20$ GeV
photon $E_T > 25$ GeV

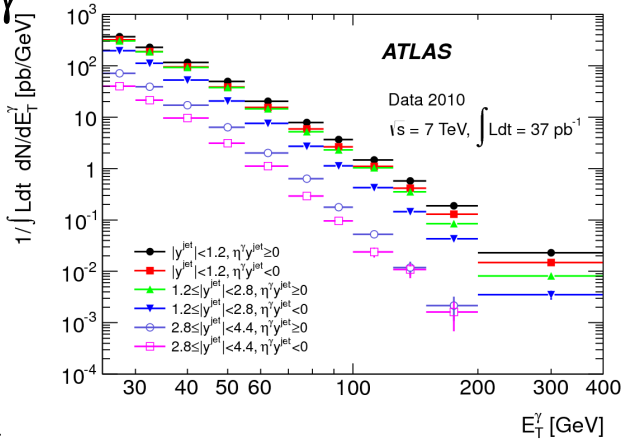
Measured cross sections with
$\eta^\gamma\, y^{jet} > 0$ & $\eta^\gamma\, y^{jet} < 0$

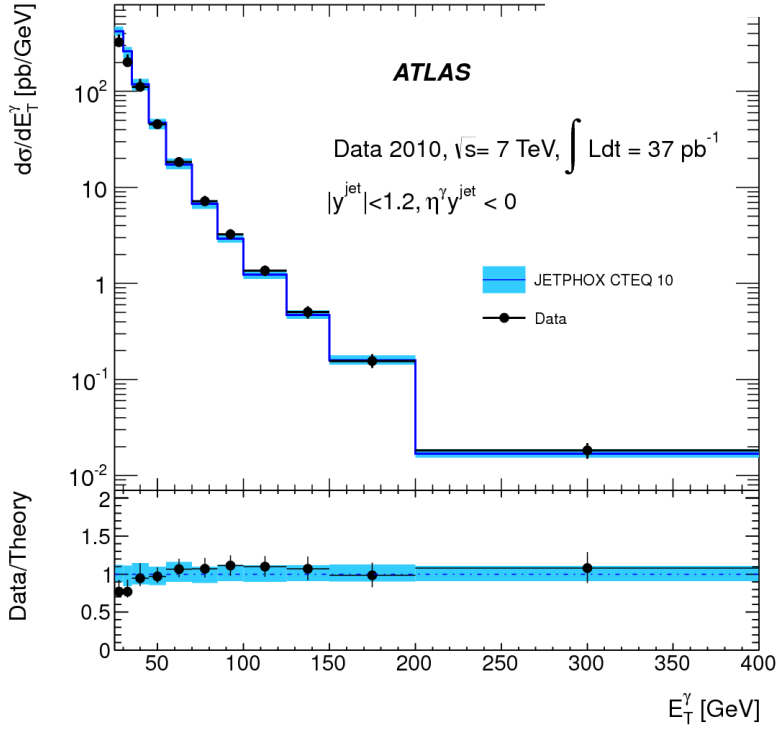
Fair agreement with NLO pQCD except at very low E_T^γ (< 45 GeV)

difficult region where photon purity decreases and non-pQCD corrections are sizable

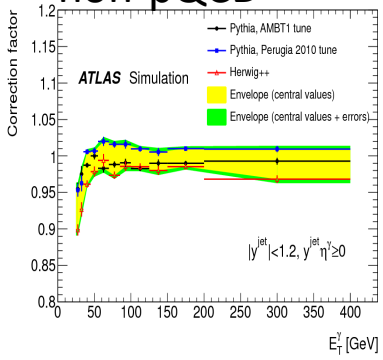
photon purity

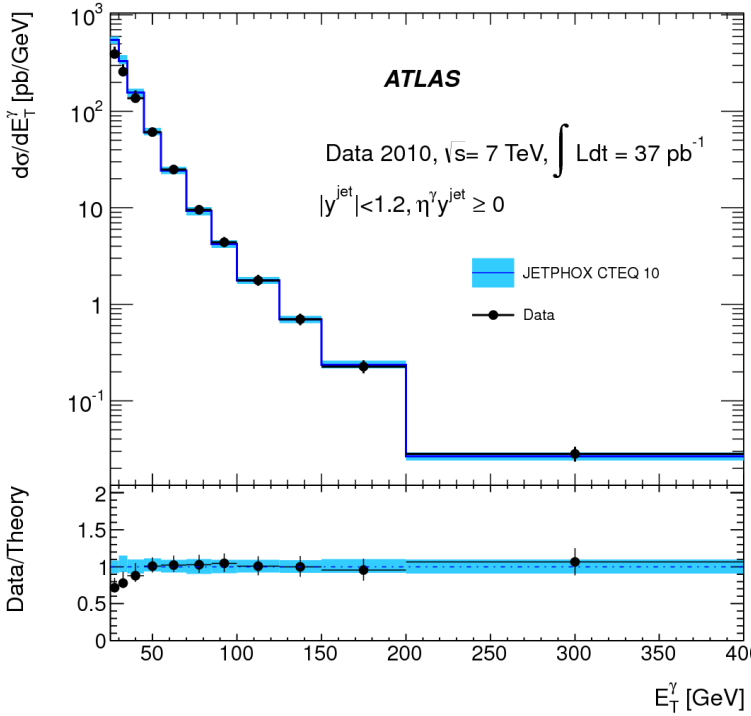






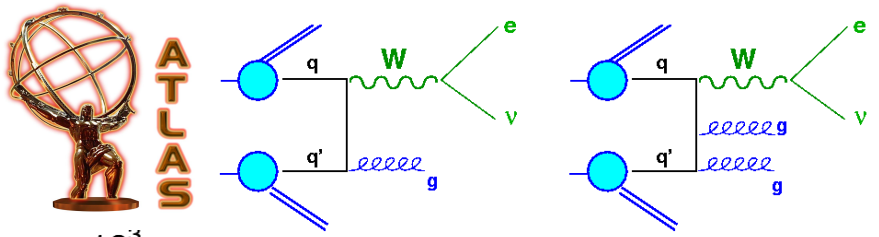
non-pQCD

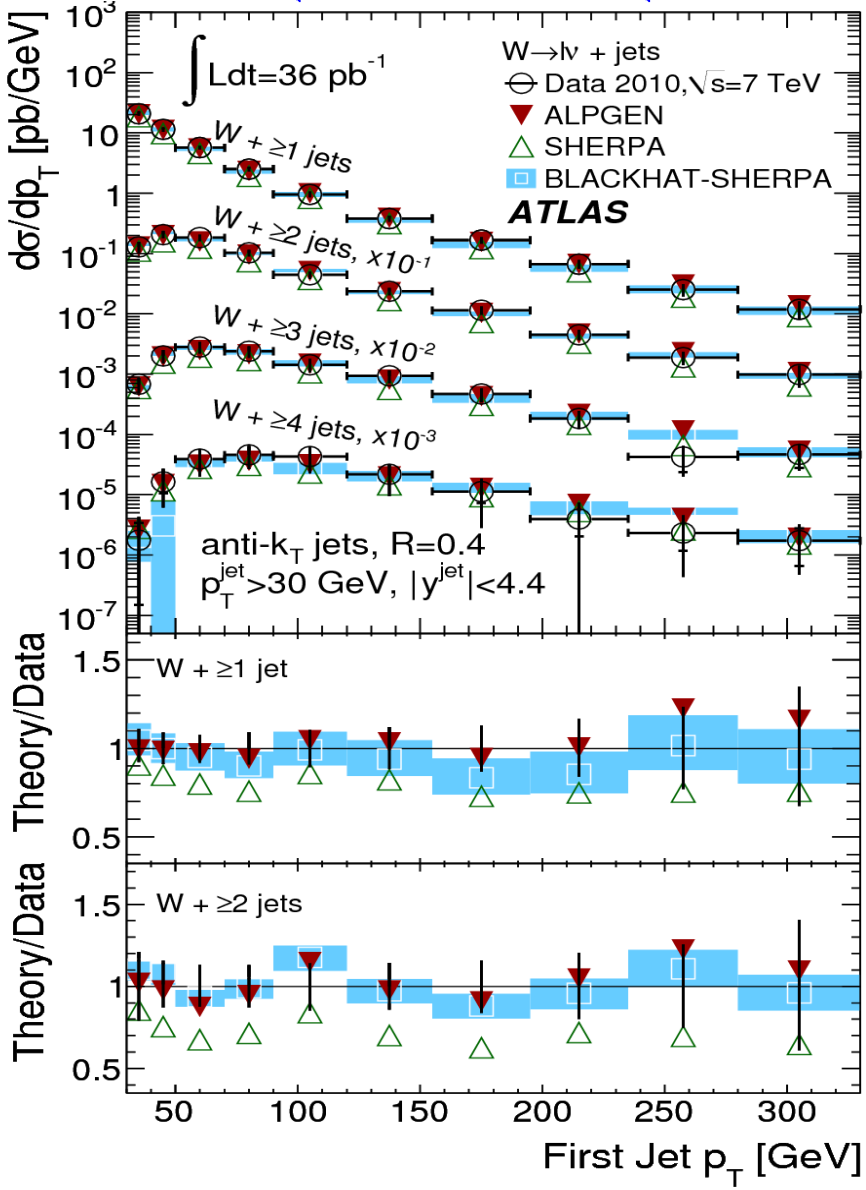


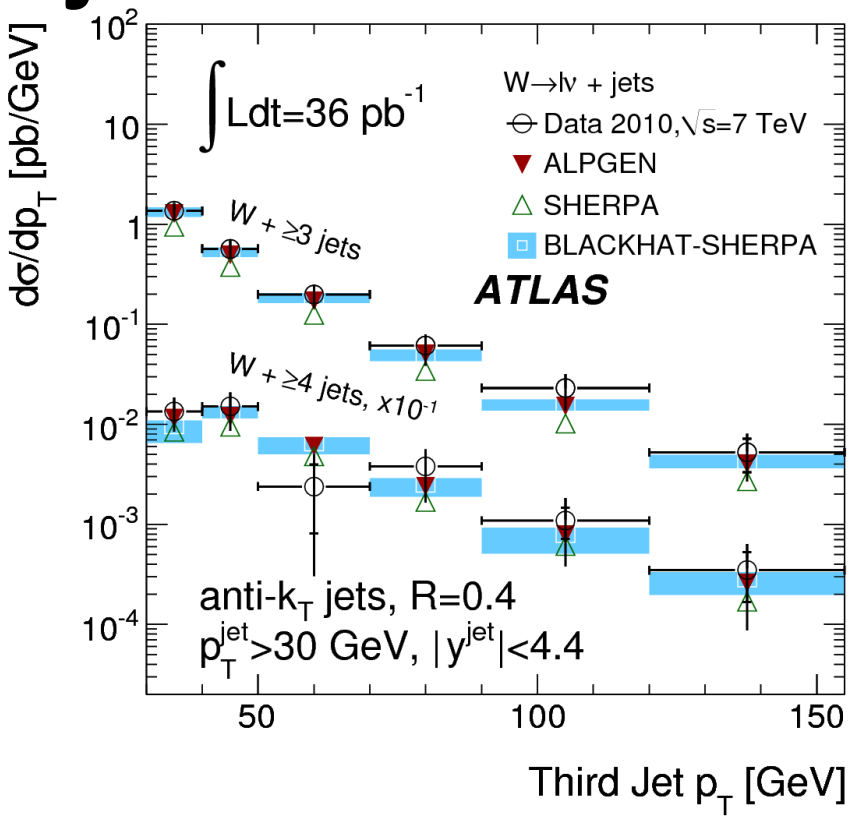


W+jets

Phys. Rev. D85 (2012) 092002







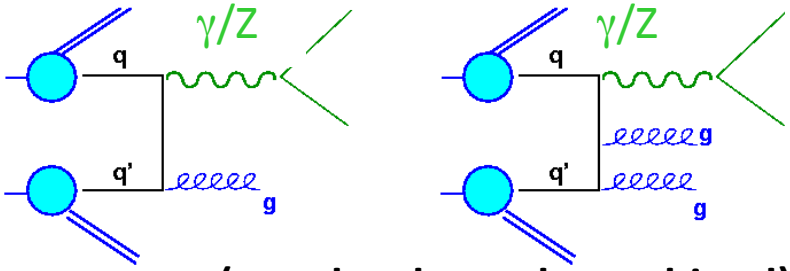
Very good description of the different Jet p_T distributions by NLO pQCD and LO ME + PS (ALPGEN)

Non trivial test of the ME - PS implementation & matching procedures built inside the MCs

→ Input to future MC tunes

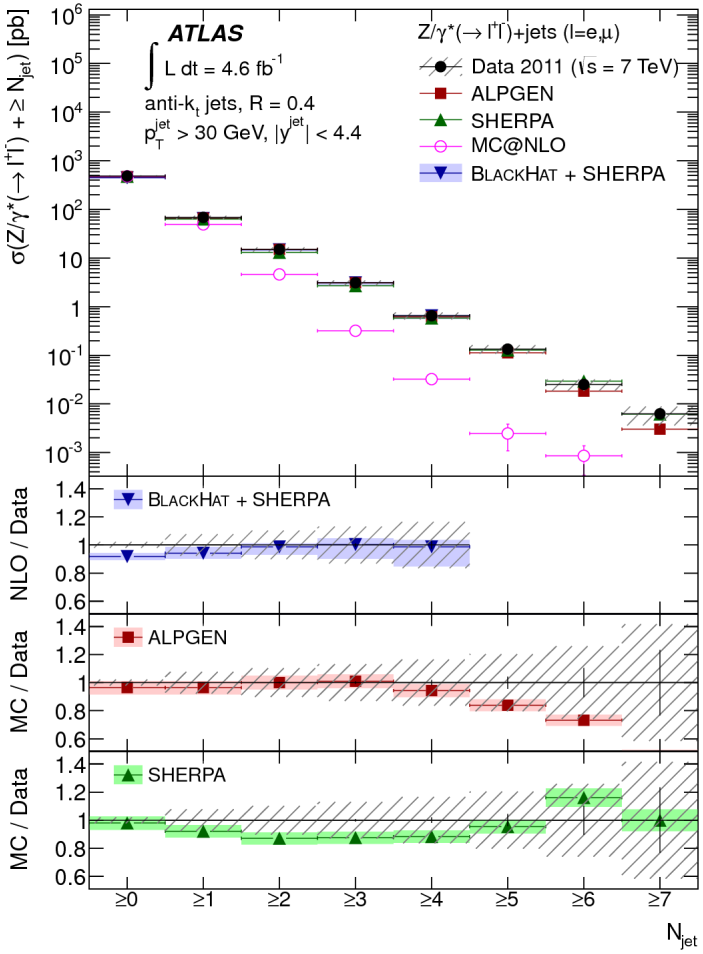
Z+jets

JHEP07(2013)032



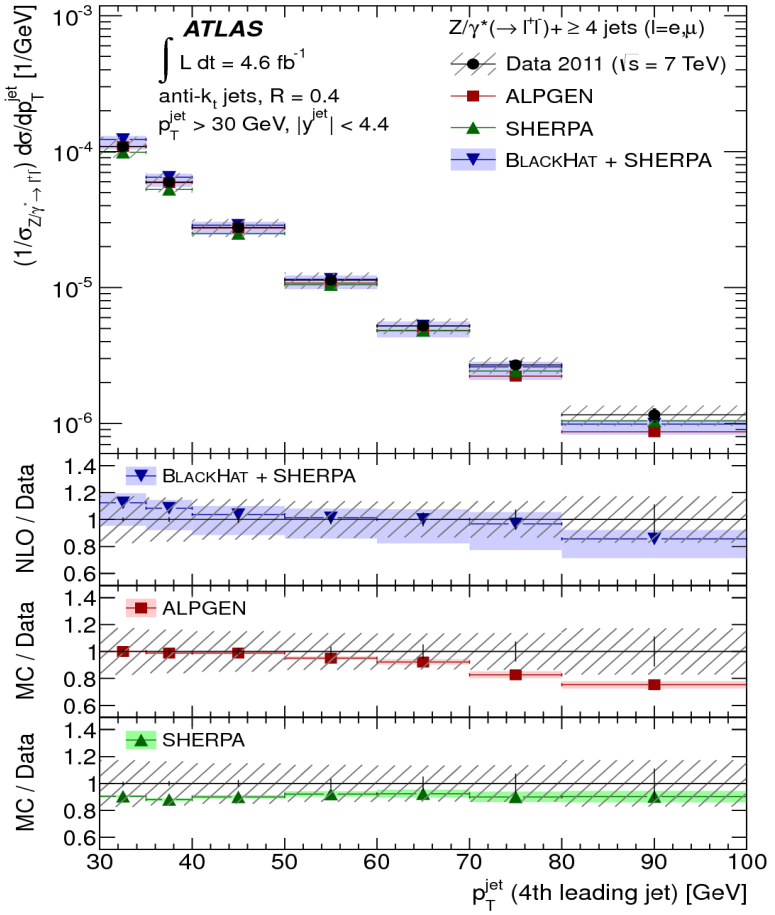
Z (→ νν)+jets irreducible background
In searches for SUSY, LED, etc….

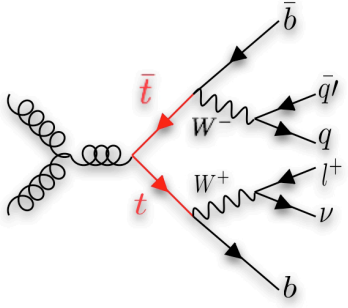
(e and μ channels combined)



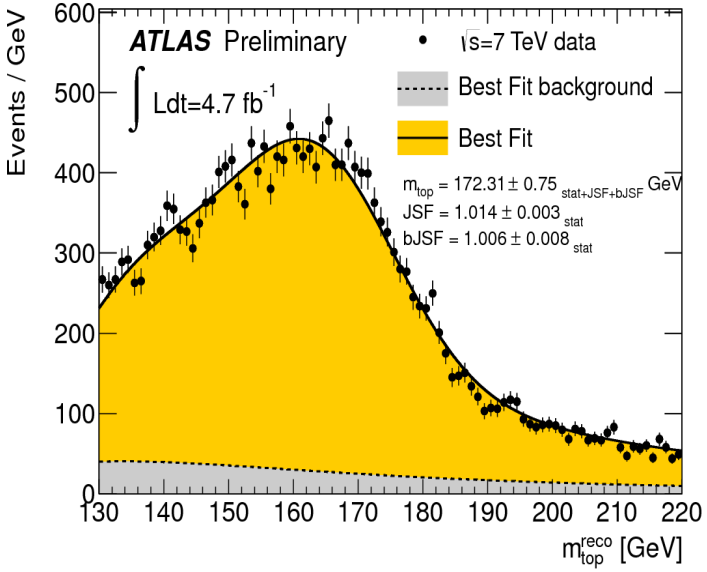
Data well described by NLO pQCD and ME + PS (ALPGEN/SHERPA) predictions

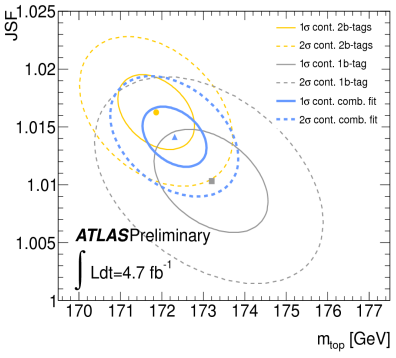
Z (→ ll)+jets fundamental SM measurement…
→ Very clean samples with no missing E_T

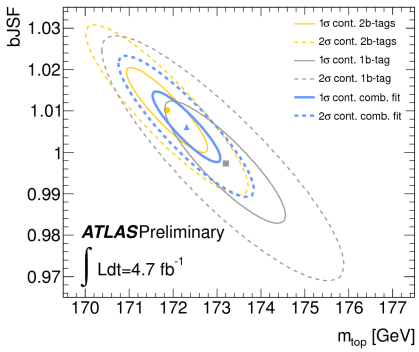




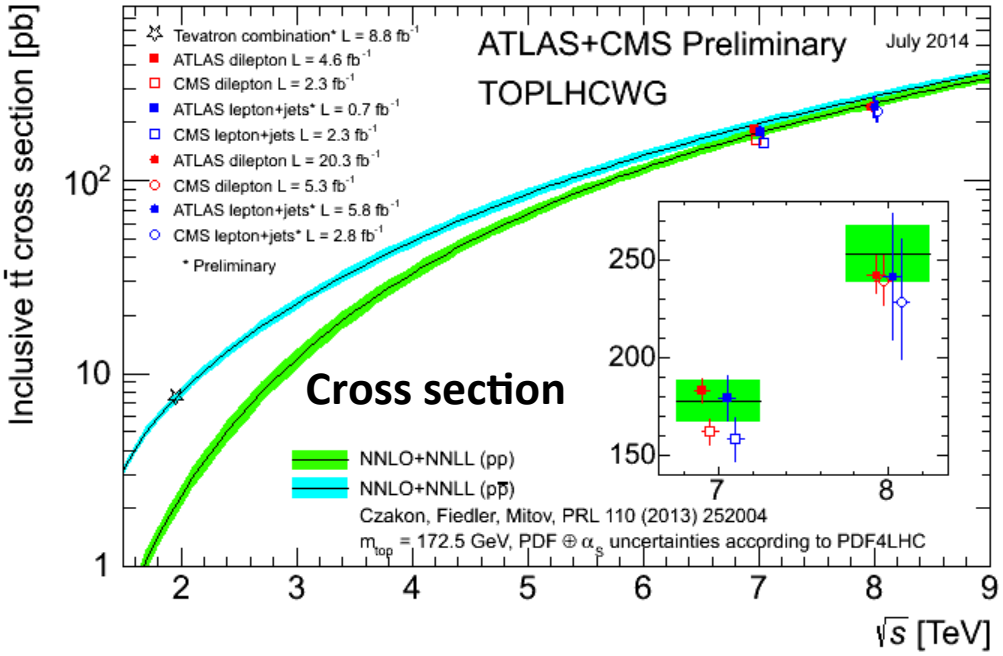
Top

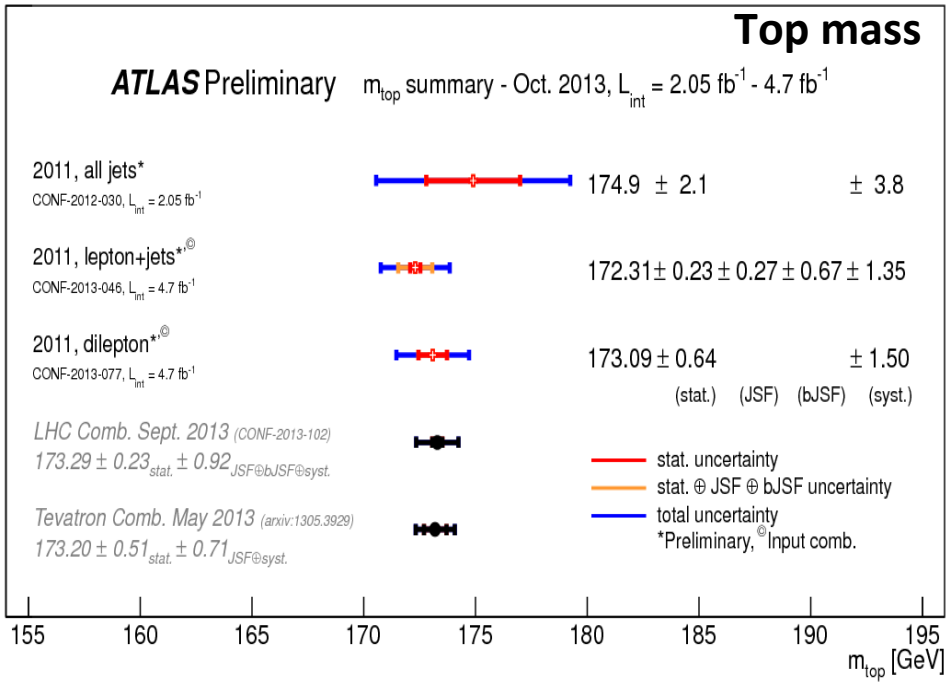






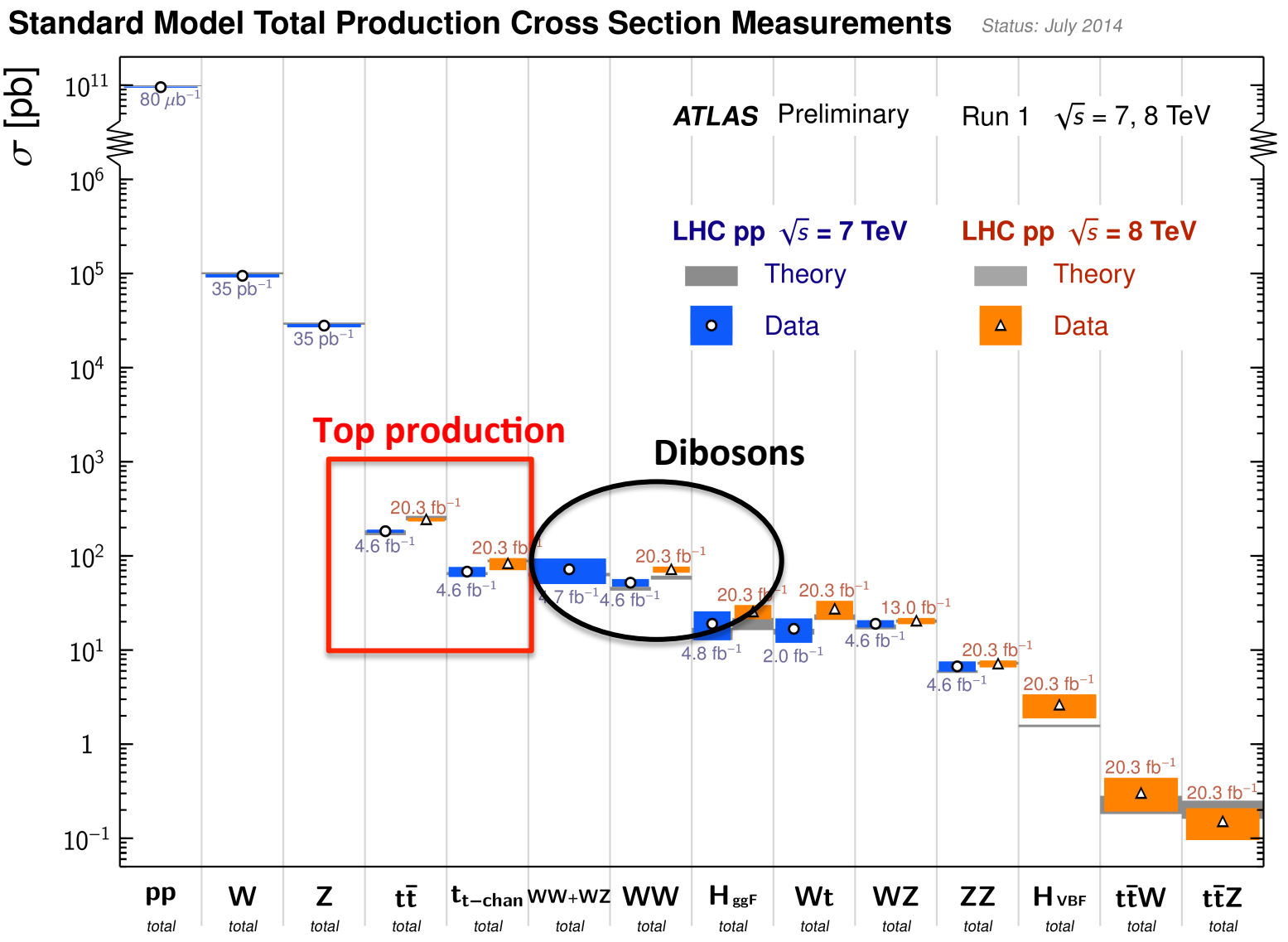
Simultaneous fit to top mass and JES





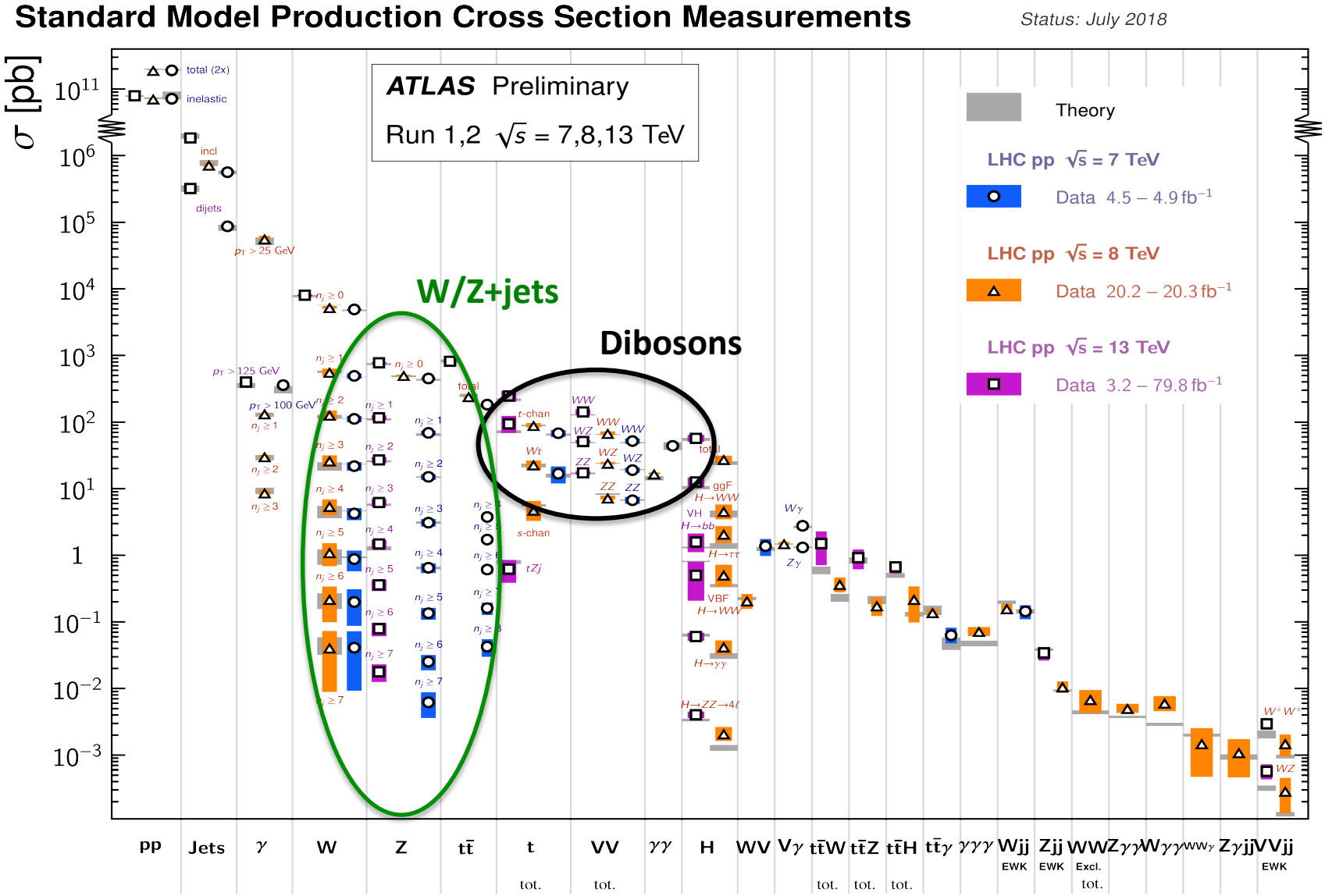
As by July 2014

SM Cross Section Summary



As by July 2018

SM Cross Section Summary

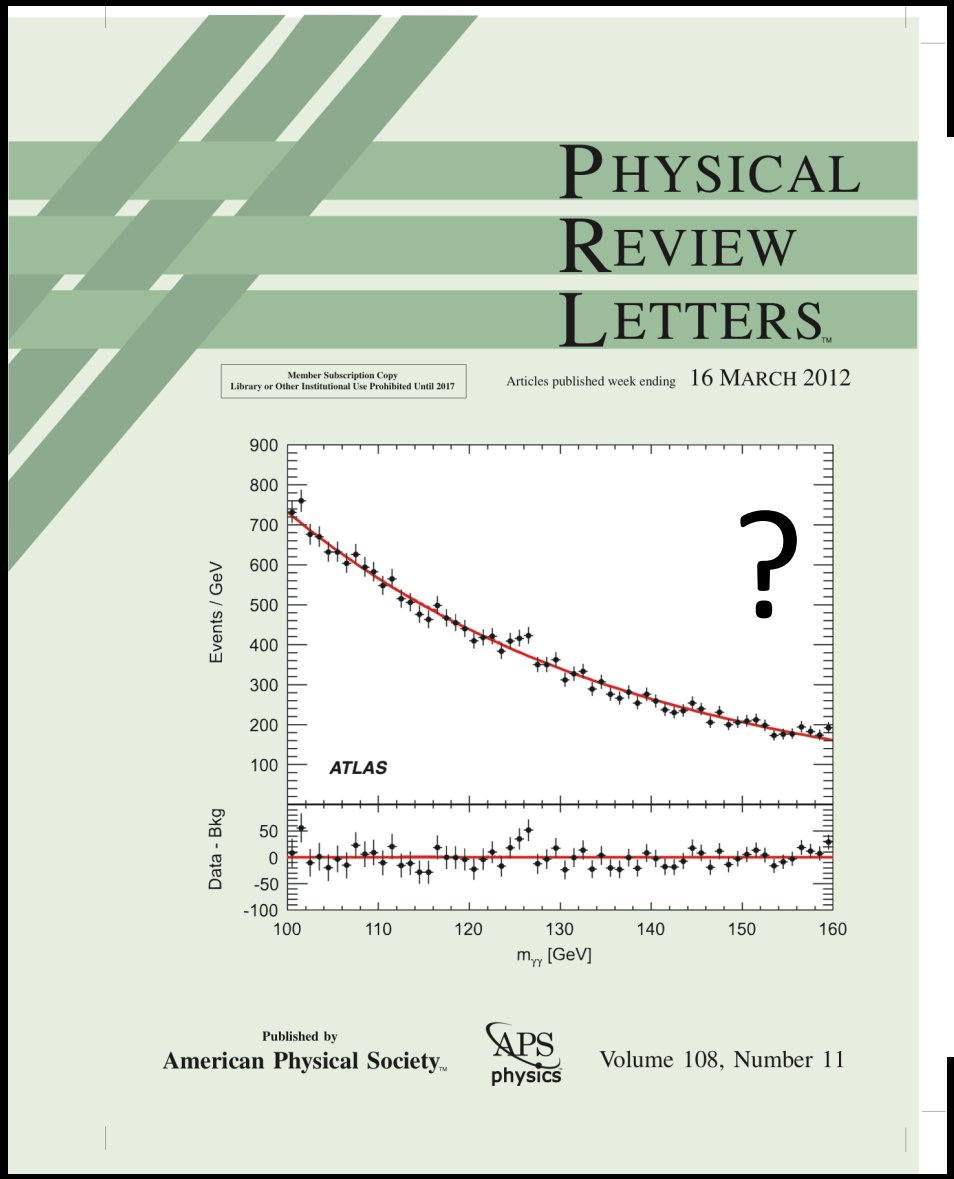


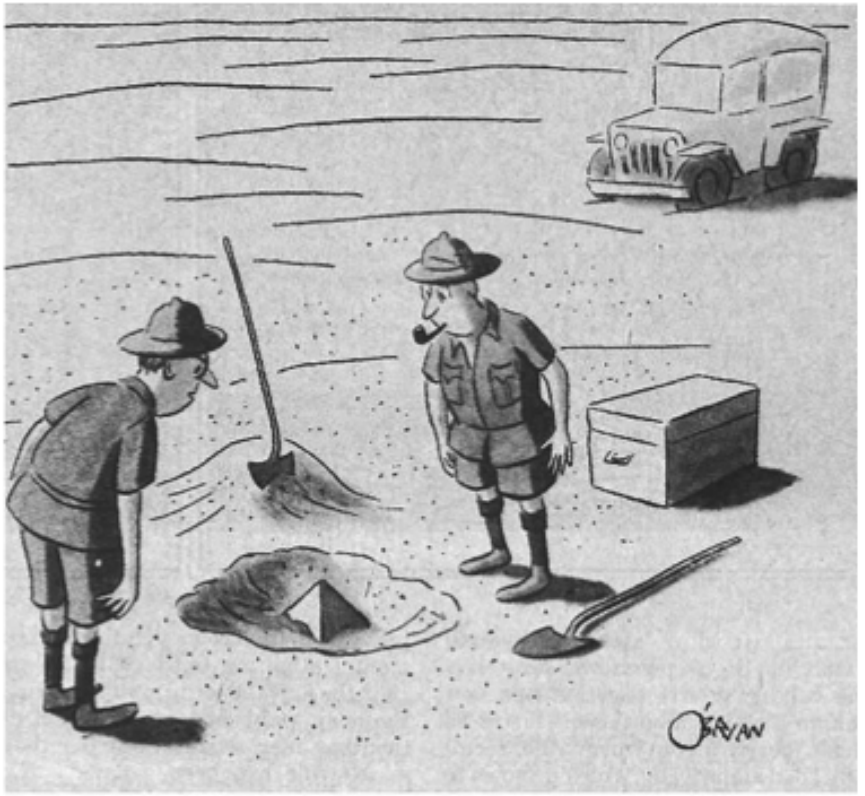
Towards the discovery

Notes on statistics

The discovery channels

Notes on Statistical Significance





"This could be the discovery of the century. Depending, of course, on how far down it goes."

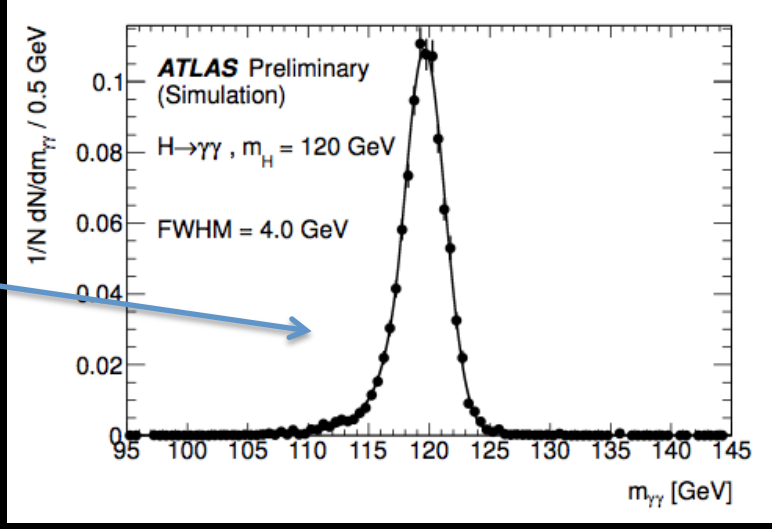
Likelihood ratio

$$L(\mu,\theta) = f_b \phi_b(m_{\gamma\gamma}) + f_s \phi_s(m_{\gamma\gamma})$$

$$f_s \propto \mu$$

$$n_s = \mu \sigma_s^{visible}$$

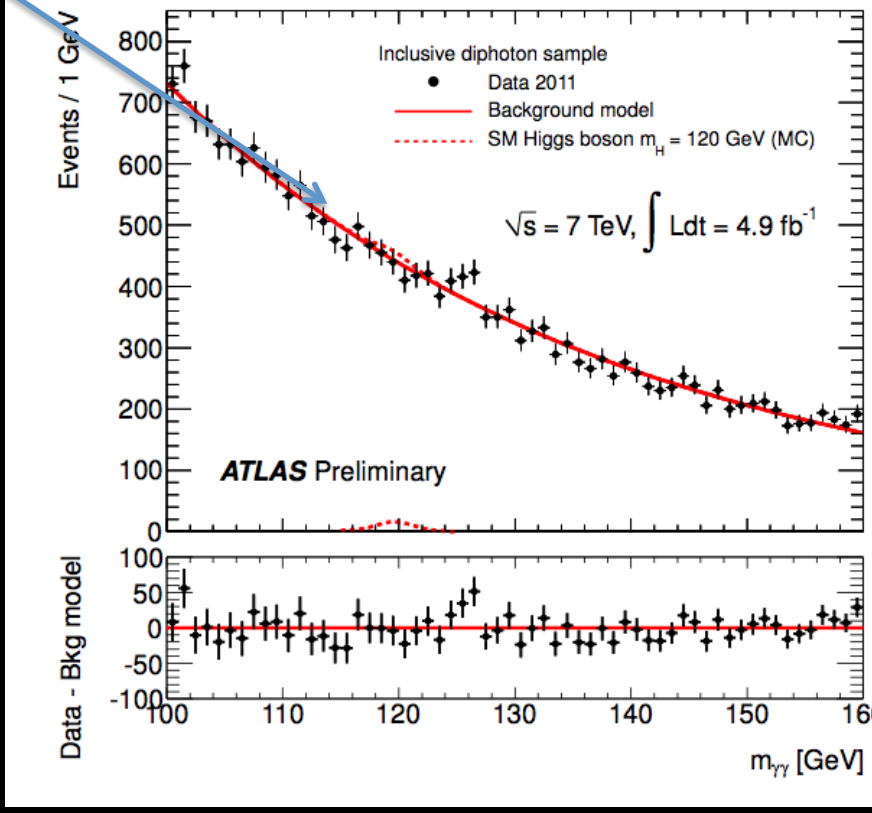
Nuisance parameters



$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})}$$

$$q_\mu = -2 \ln \lambda_\mu$$

$$p_\mu = \int_{q_{obs}}^{\infty} f(q_\mu \mid \mu) dq_\mu$$



Only background ?

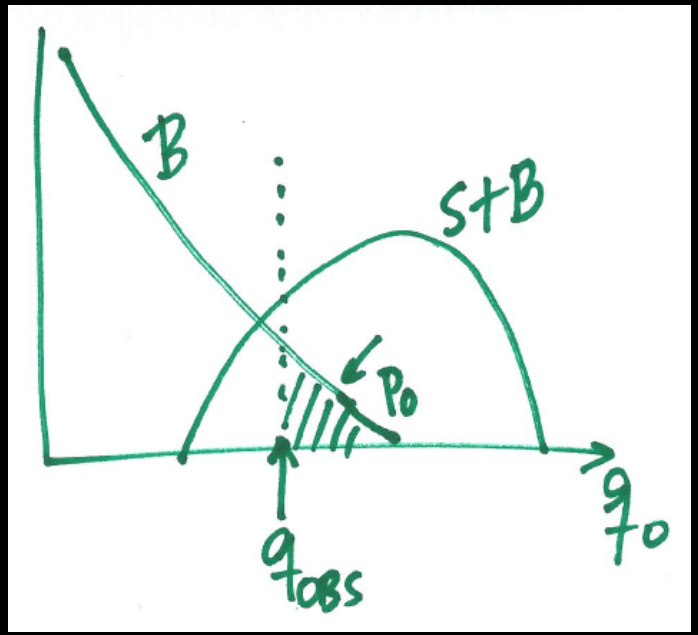
Test of “null” hypothesis of no signal

If a real signal appears … $p_0 \rightarrow 0$
(once $p_0 < 2.87 \times 10^{-7} \rightarrow$ Discovery)

$$\lambda_0 = \lambda(0,\theta) = \frac{L(0,\hat{\hat{\theta}}(0))}{L(\hat{\mu},\hat{\theta})}$$

$$q_0 = -2\ln\lambda_0$$

$$p_0 = \int_{q_{obs}}^{\infty} f(q_0 \mid 0)\, dq_0$$



CL_s

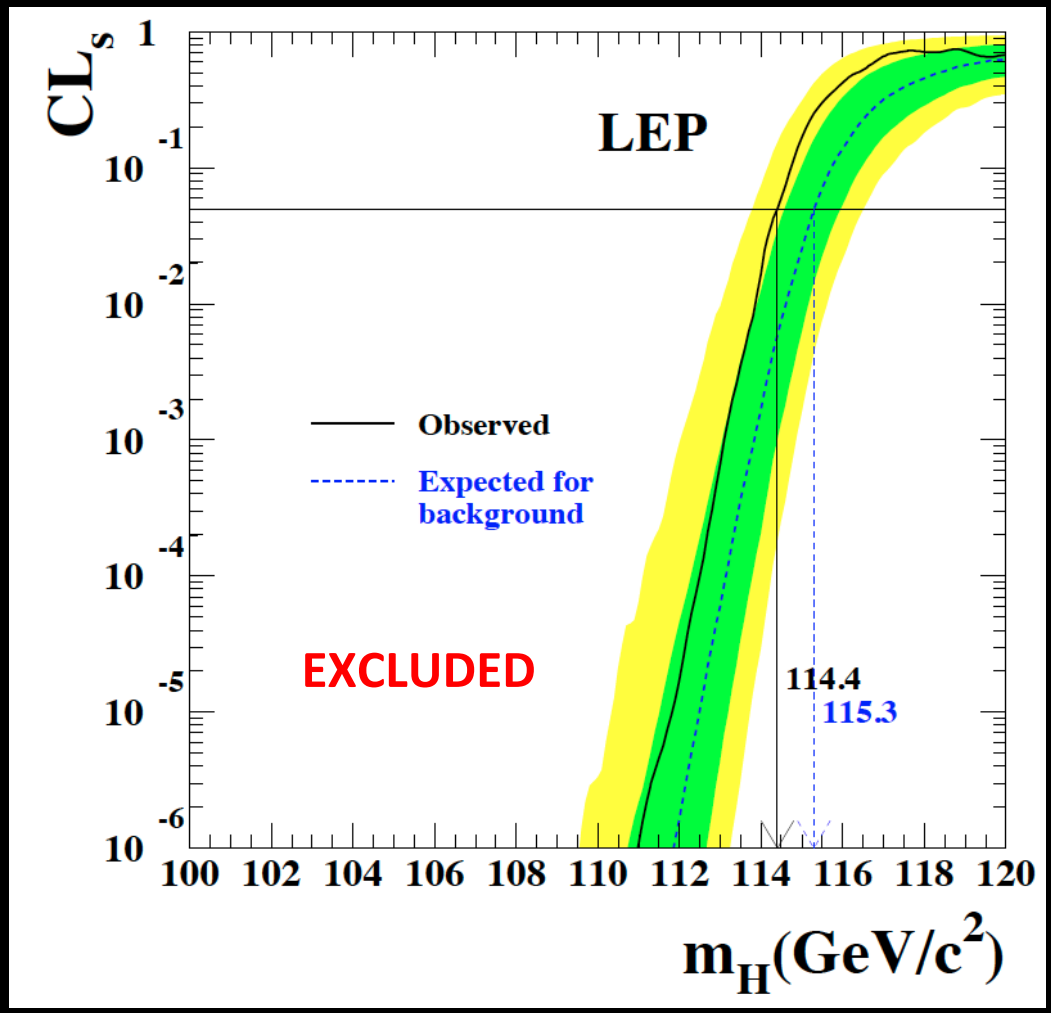
(do not exclude your signal…)

$$CL_S = \frac{p_s}{1 - p_b}$$

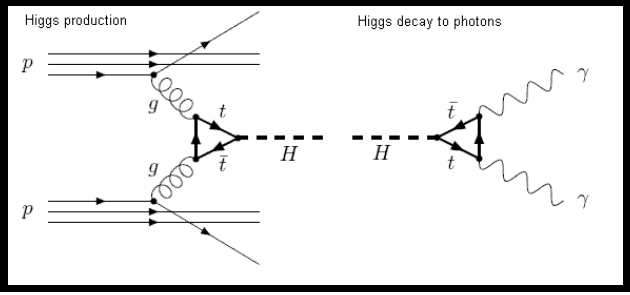
In the case of very small signals (limited sensitivity) the use of p_s to exclude signals can lead to false exclusions if the data fluctuates down….

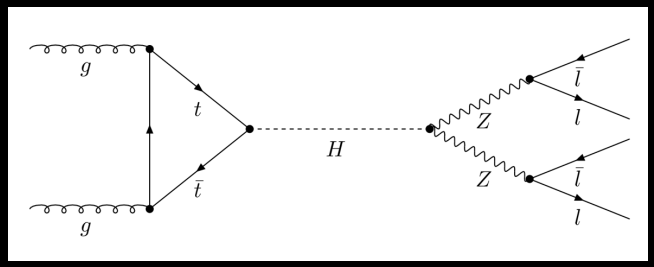
In these cases it is better to use CLs … which is conservative in the exclusion

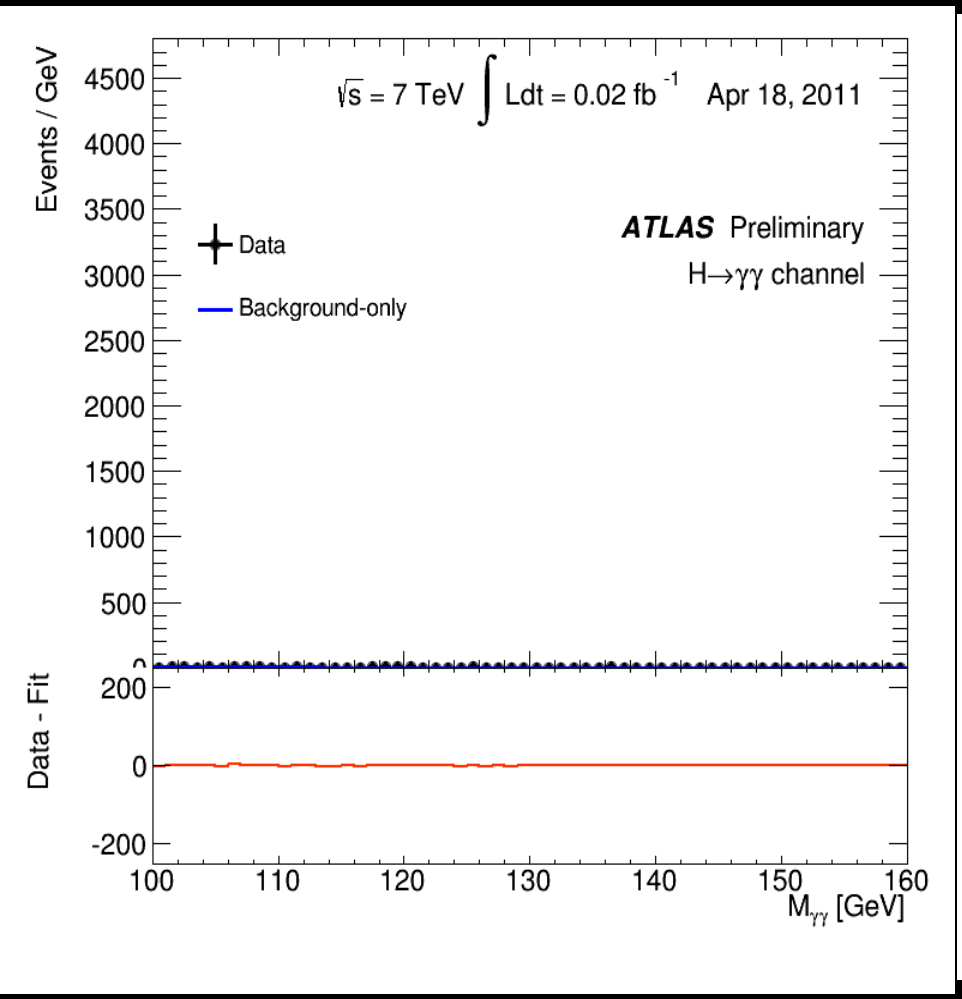
If CLs < 0.05 → excluded at 95% CL

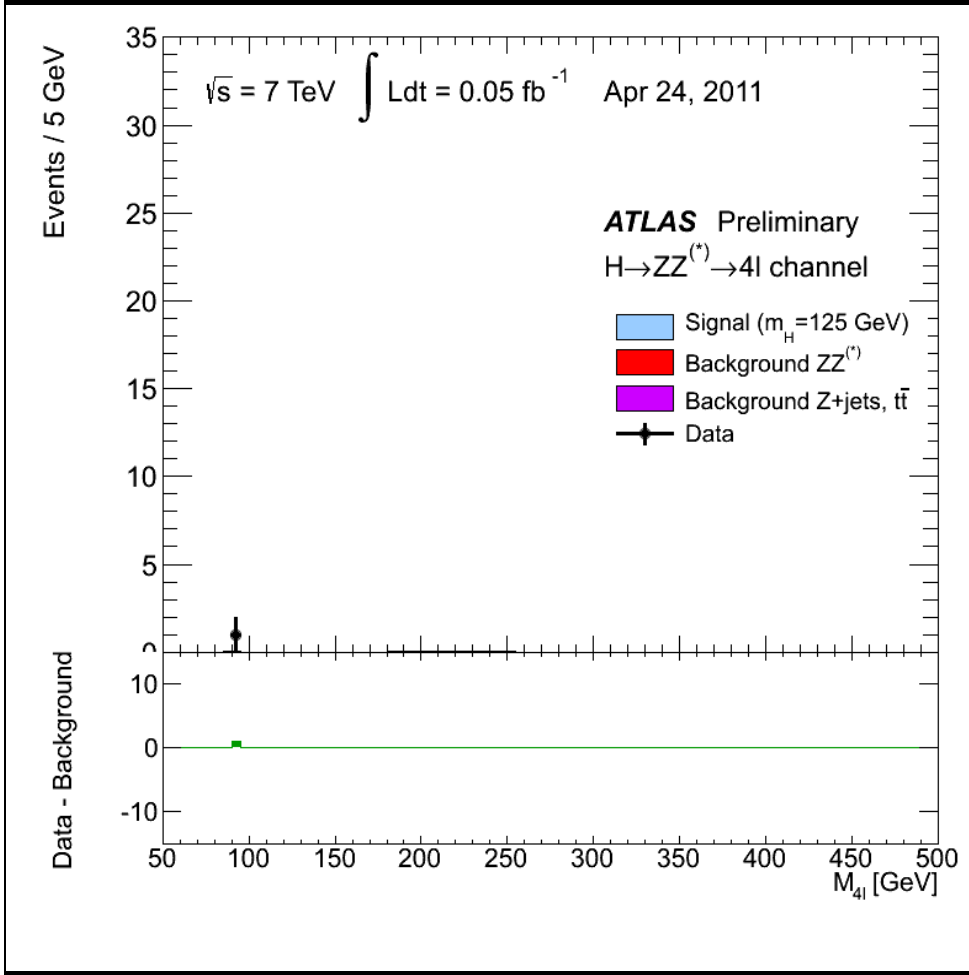


Building up the peaks..

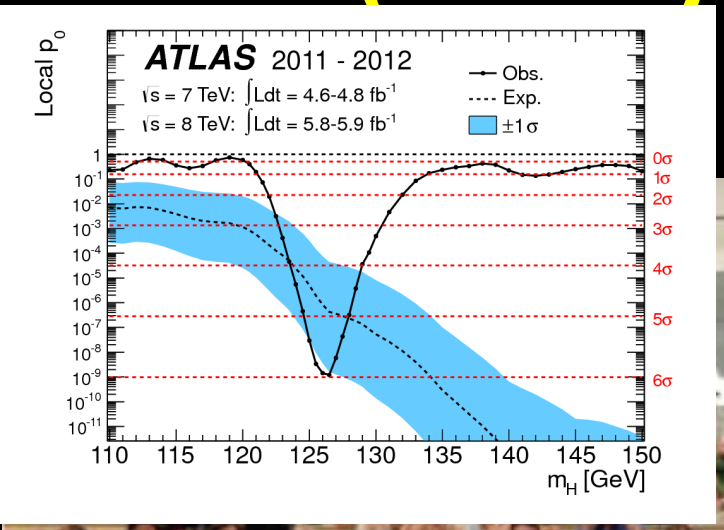








The Announcement (4th July 2012)

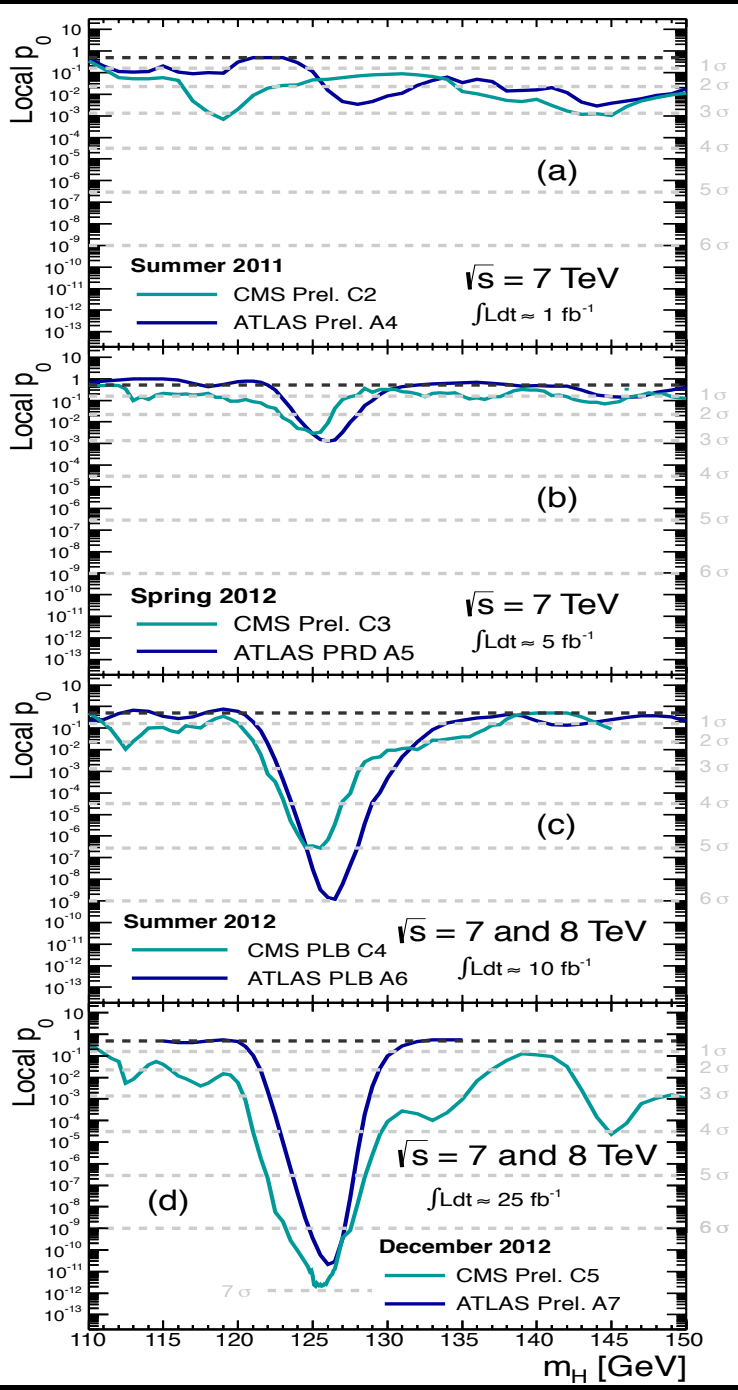


(picture: courtesy of A. Hoecker]

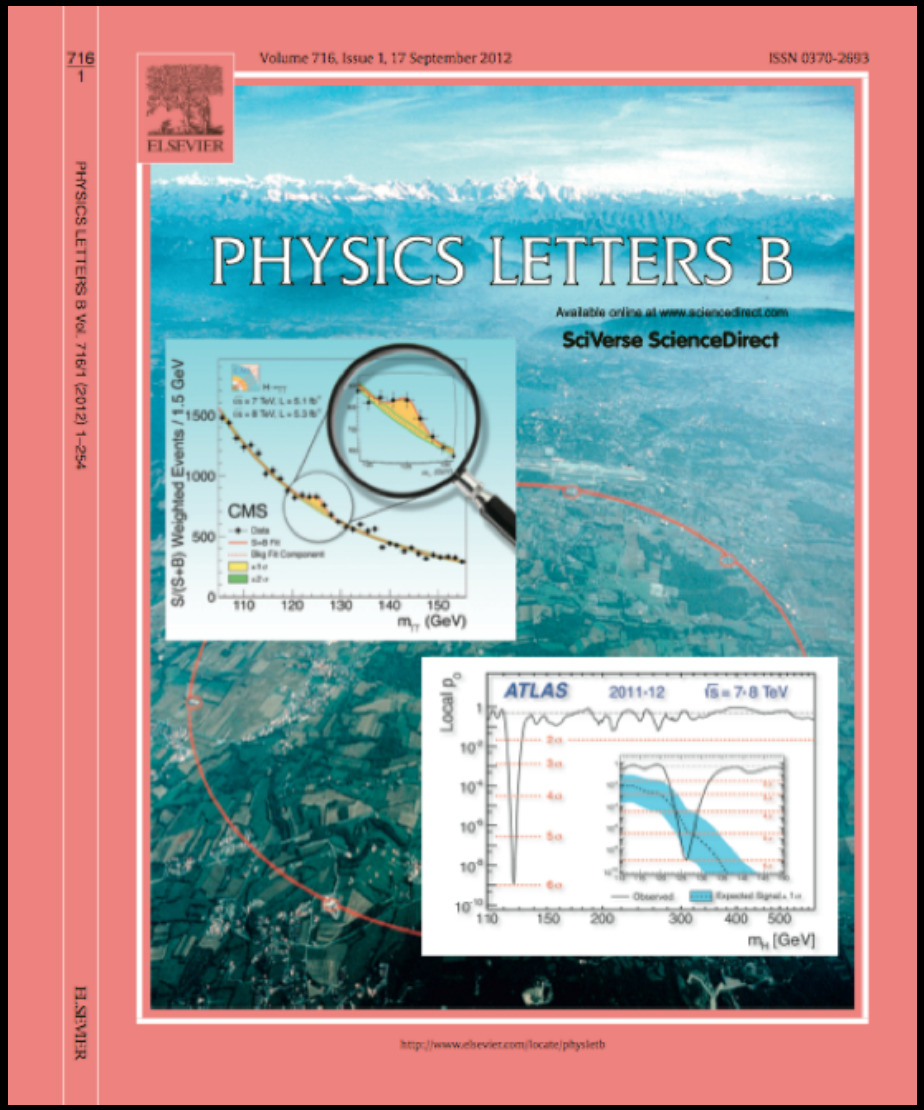
PRESS COVERAGE

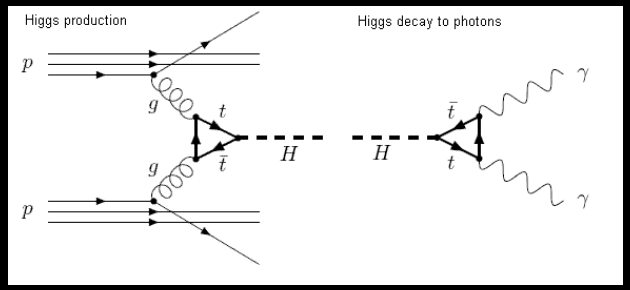
after July 4th seminars at CERN

CERN black board, Jul 2012



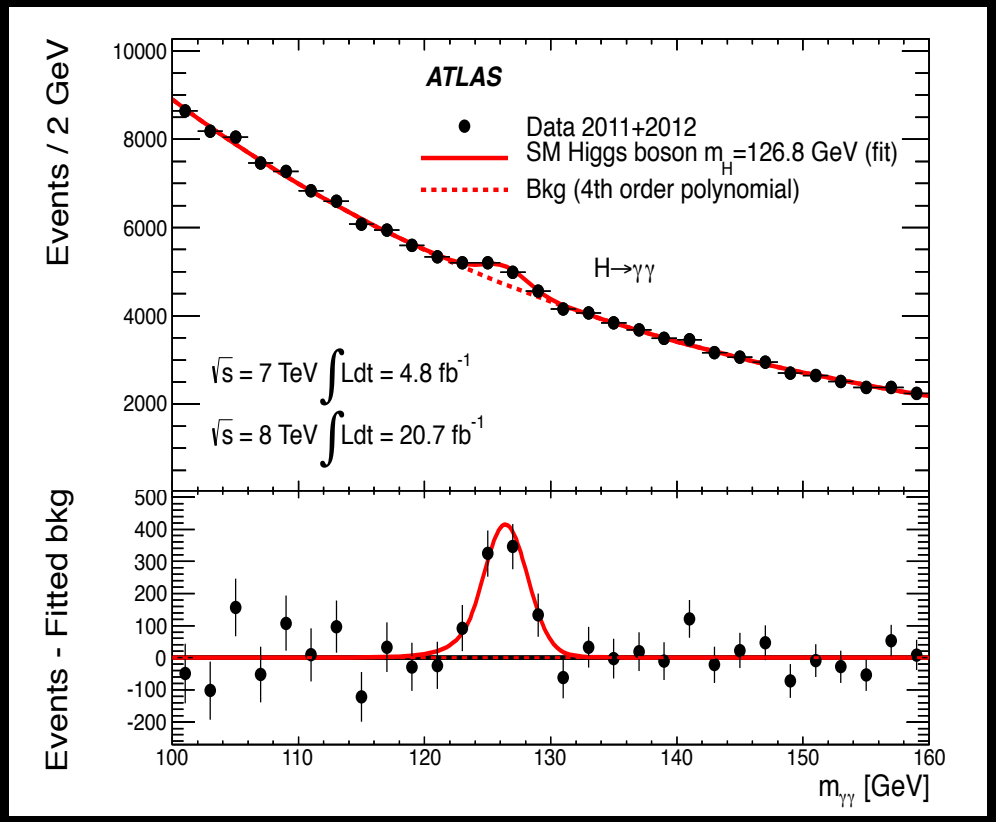
Exciting times....
2011-2012

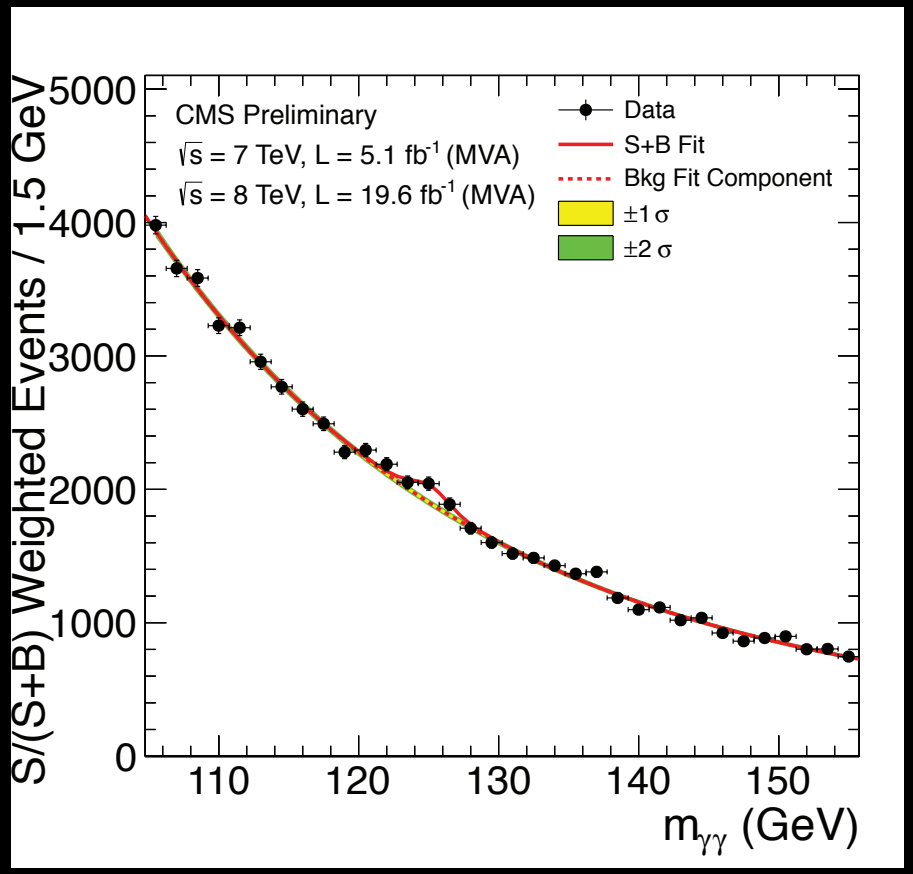




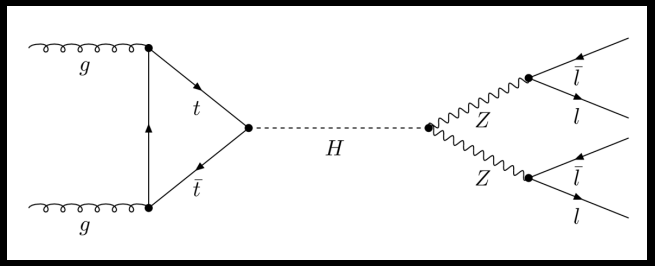
Higgs !!

As in Moriond 2013

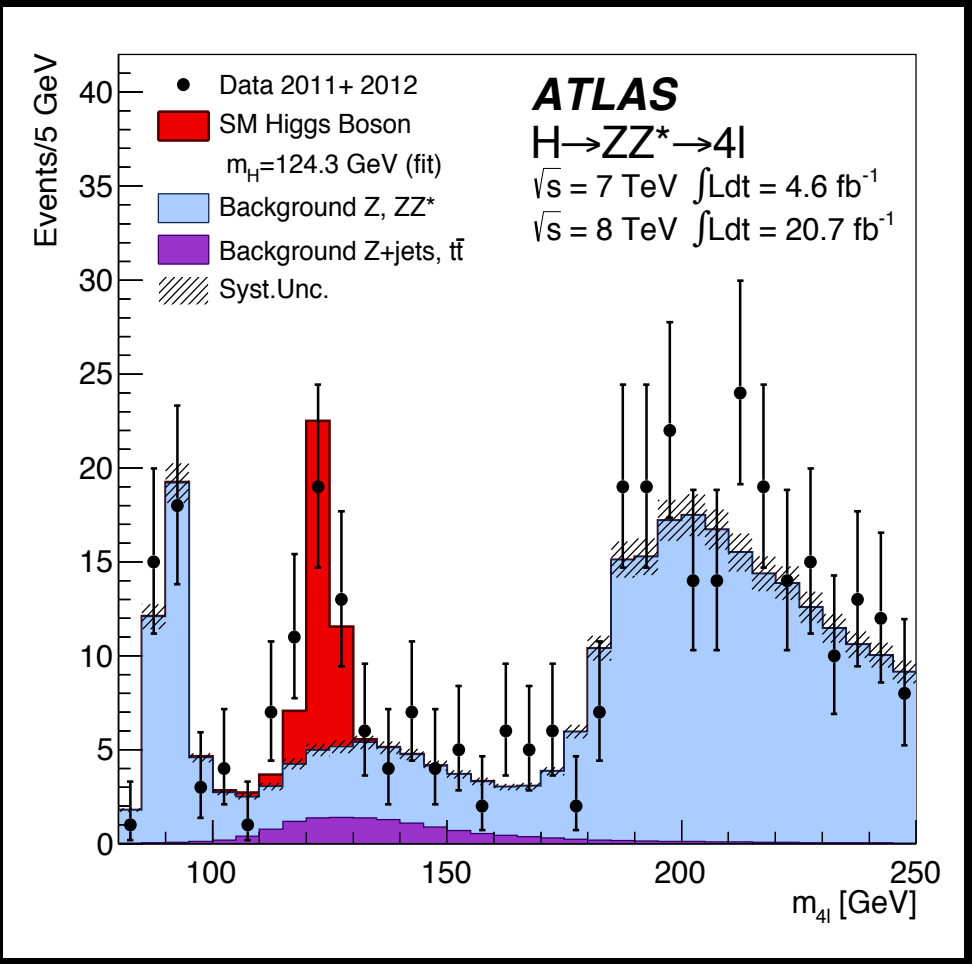


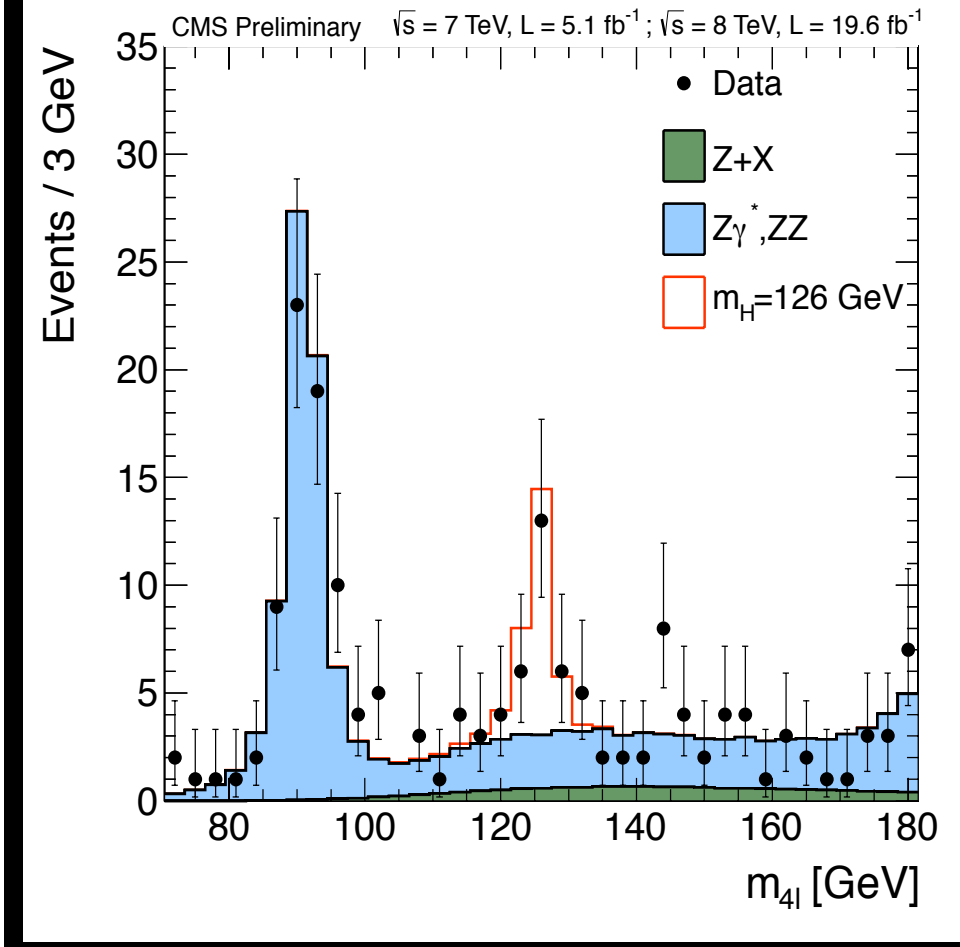


A mass peak in the vicinity of 125 GeV



Higgs !!





A mass peak in the vicinity of 125 GeV

EPS 2013 High Energy and Particle Physics Prize is awarded to…

"The ATLAS and CMS collaborations, for the discovery of a Higgs boson, as predicted by the Brout-Englert-Higgs mechanism

and to

Michel Della Negra, Peter Jenni, and Tejinder Virdee, for their pioneering and outstanding leadership rôles in the making of the ATLAS and CMS experiments"

…..it was announced during the LHCP Conference in Barcelona, May 17th 2013…

8th Oct. 2013

The Nobel Prize in Physics 2013
François Englert, Peter Higgs

The Nobel Prize in Physics 2013

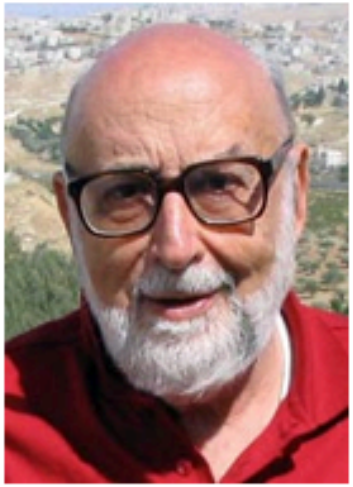


Photo: Pnicolet via Wikimedia Commons

François Englert

Photo: G-M Greuel via Wikimedia Commons

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs ***"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"***

Fundación Príncipe de Asturias

S.A.R. el Príncipe de Asturias
Presidente de Honor
de la Fundación

"…acuerda por unanimidad conceder el
Premio Príncipe de Asturias de Investigación Científica y Técnica 2013
de forma conjunta a los físicos Peter Higgs (Reino Unido) y François Englert (Bélgica) y a la institución internacional CERN, el Laboratorio Europeo de Física de Partículas, por la predicción teórica y detección experimental del Bosón de Higgs."

Oviedo, 29 de Mayo de 2013

Higgs at the PDG

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

H^0

$J = 0$

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^\pm$ and $H^{\pm\pm}$)", respectively.

H^0 MASS

A combination of the results from ATLAS and CMS, where a recent unpublished result from CMS is used, yields an average value of 125.6 ± 0.3 GeV, see the review on "Status of Higgs Boson Physics."

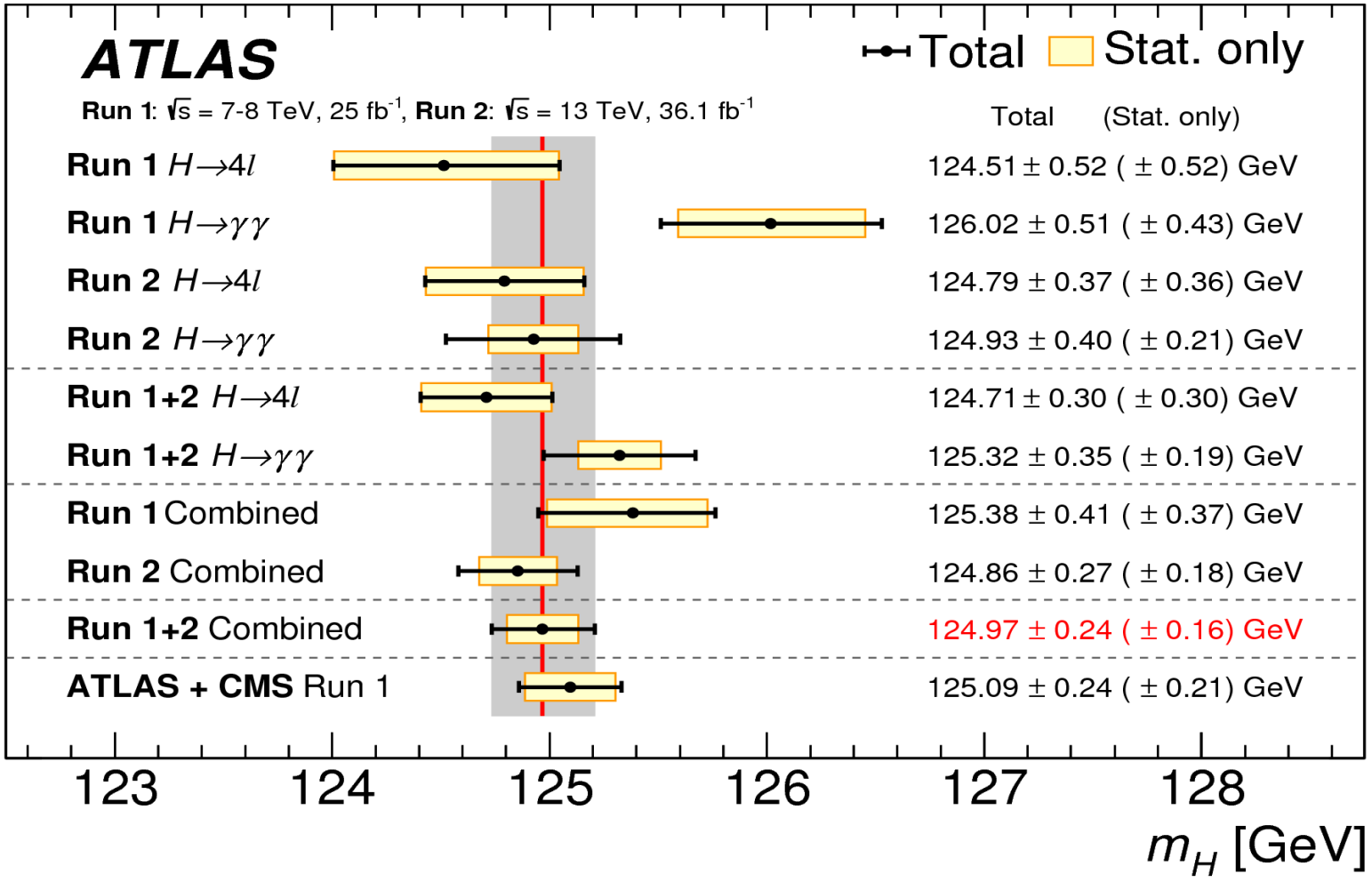
VALUE (GeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
125.7±0.4 OUR AVERAGE				
$125.5 \pm 0.2 \,^{+0.5}_{-0.6}$	[2]	AAD	13AK ATLS	pp, 7 and 8 TeV
$125.8 \pm 0.4 \pm 0.4$	[3]	CHATRCHYAN	13J CMS	pp, 7 and 8 TeV

Higgs at the PDG (as by 2016)

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

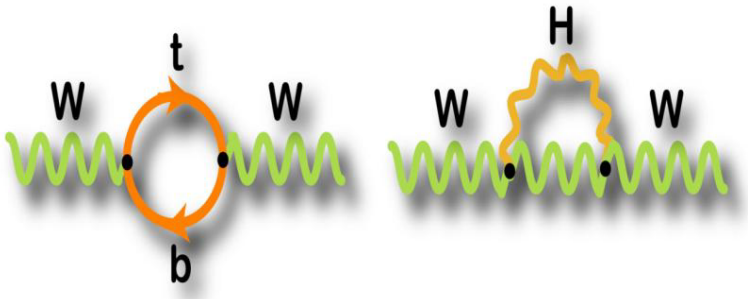
H^0

$J = 0$

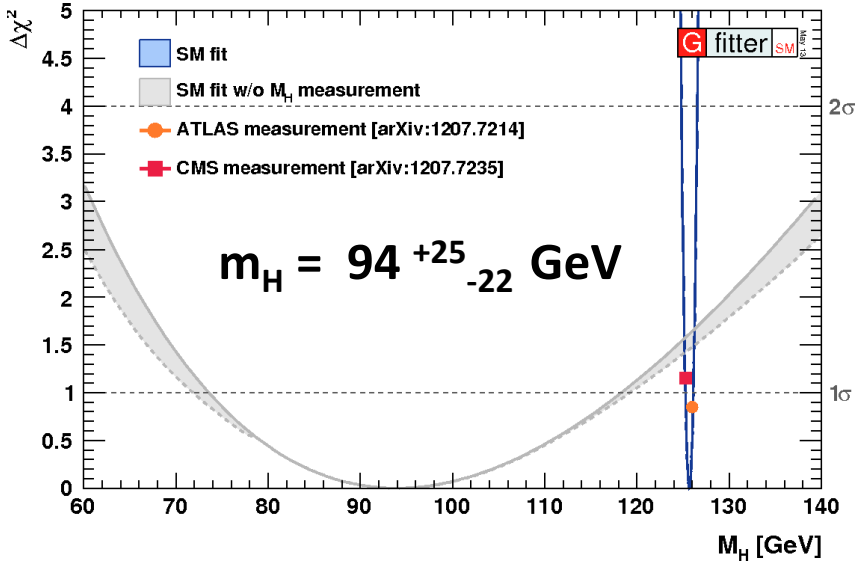


EWK fits vs Higgs

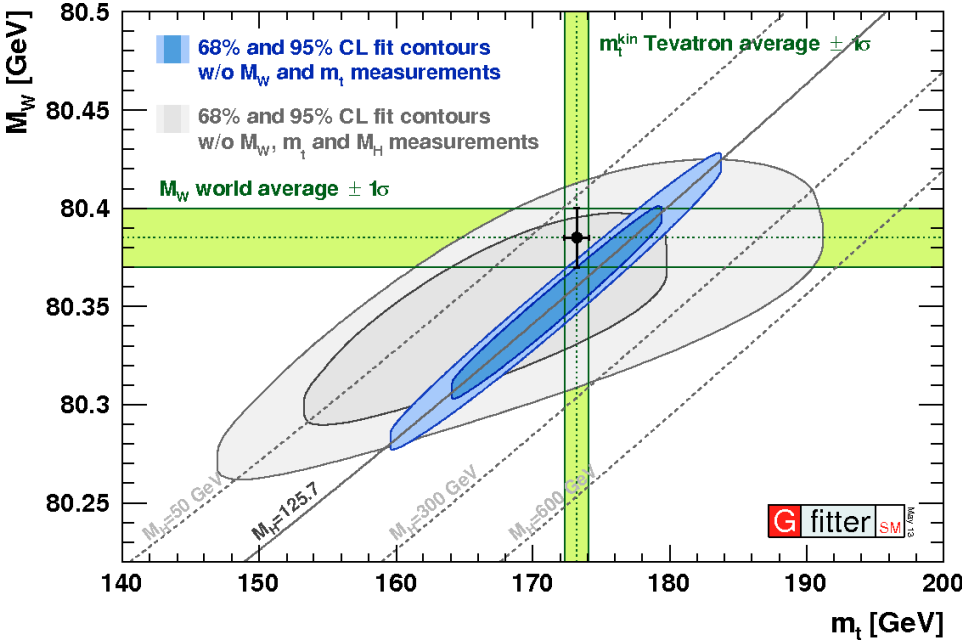
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$



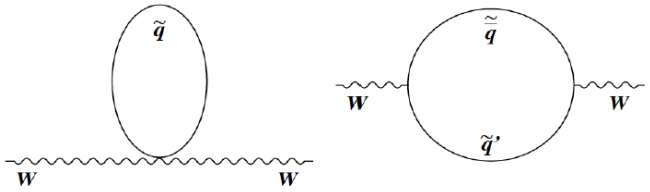
$\Delta r \sim m_{top}^2$ $\Delta r \sim \ln(m_H)$



Very remarkable agreement (within 1.3 σ) between direct m_H measurement and the indirect determination via EWK fits



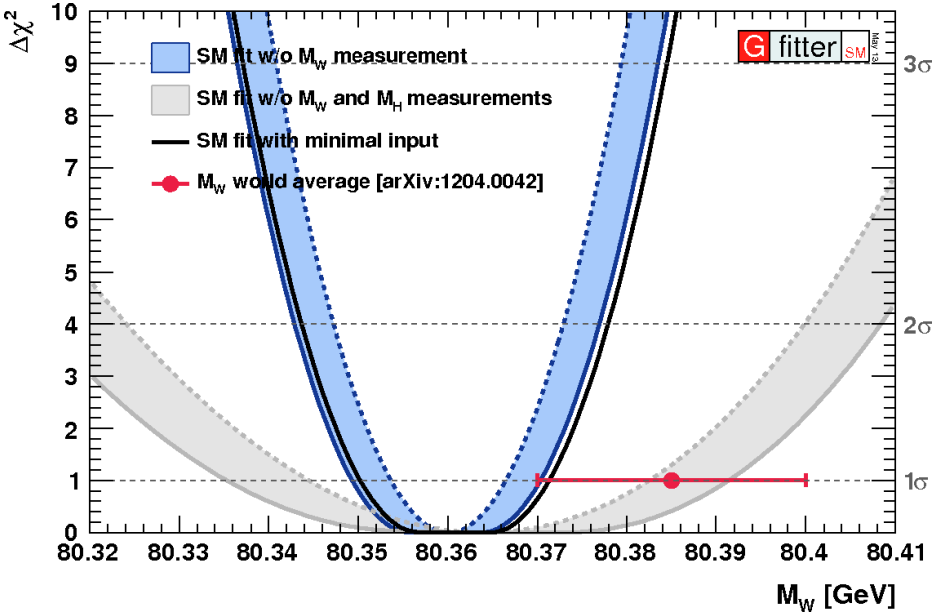
EWK fits vs Higgs

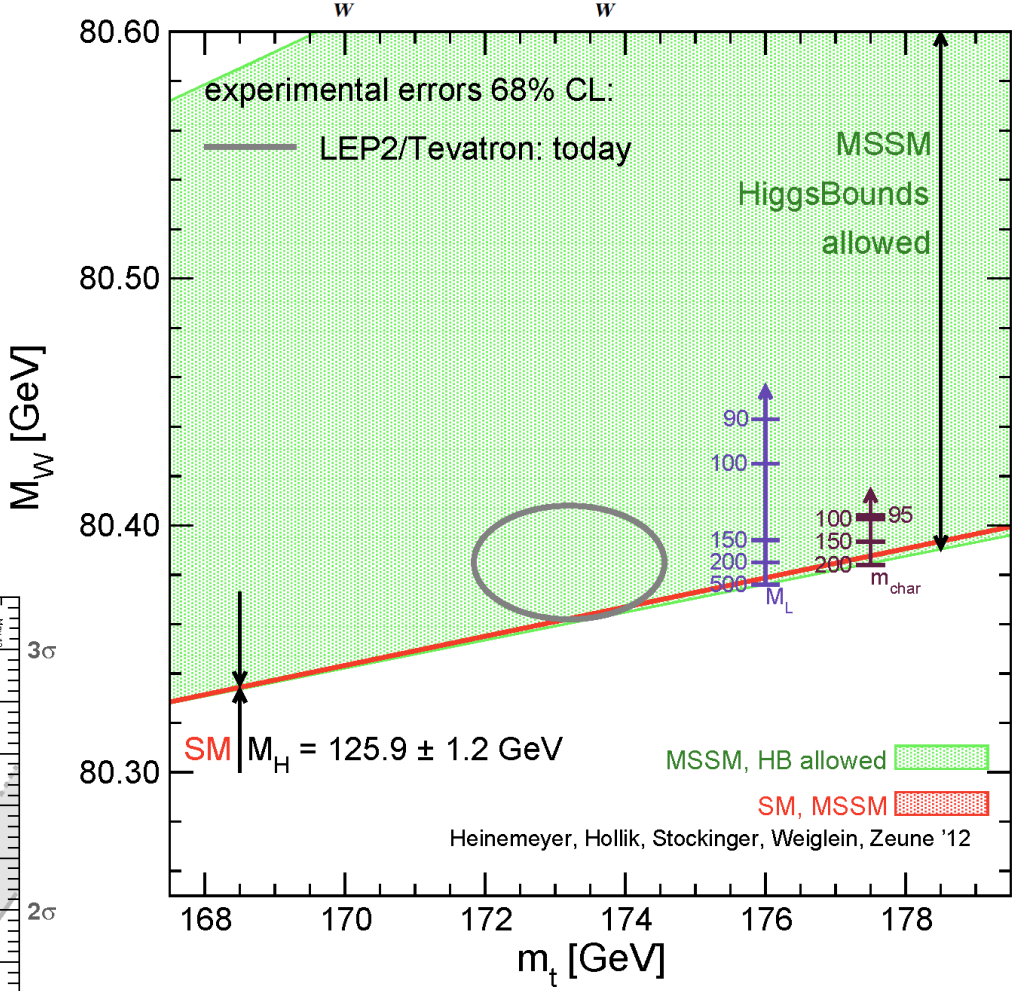


Indirect determination of M_W using measured Higgs mass as input leads to

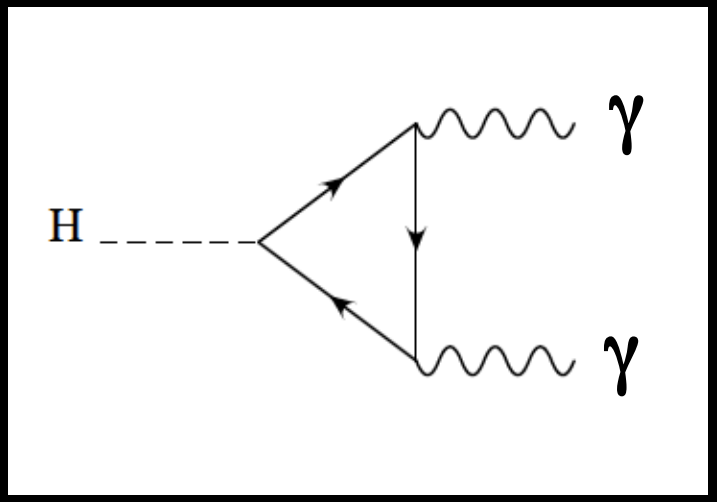
M_W (indirect) = 80.359 +- 0.011 GeV

→ Better than direct measurement (World Average : 15 MeV)





Room for improvement in M_W measurement (sensitive via loops to presence of new physics)

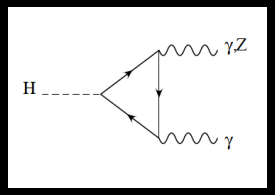


$$J \neq 1$$

$$C = +1$$

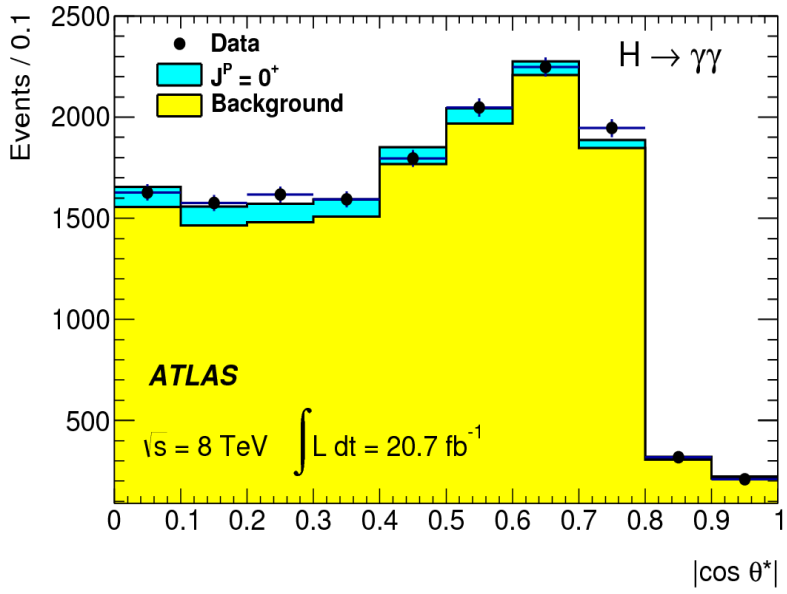
$$J^{PC}$$

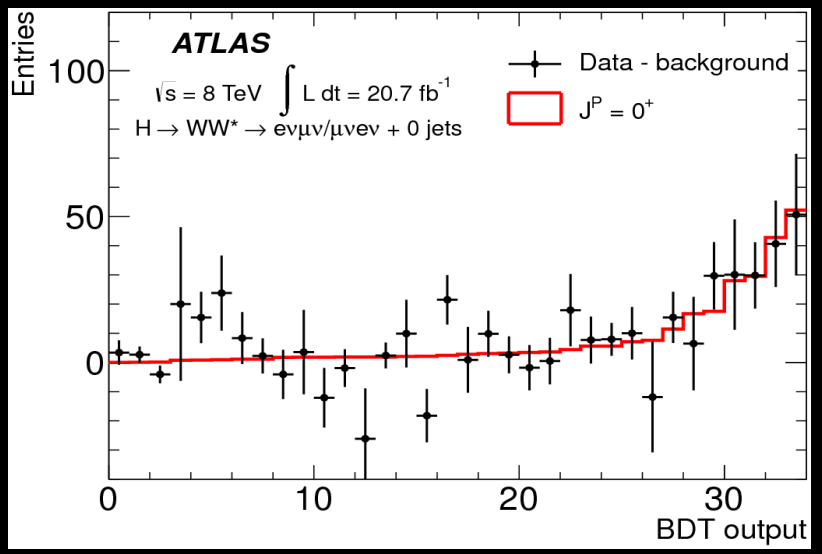
0^{++} , 0^{-+}, 2^{++} , 2^{-+} ….



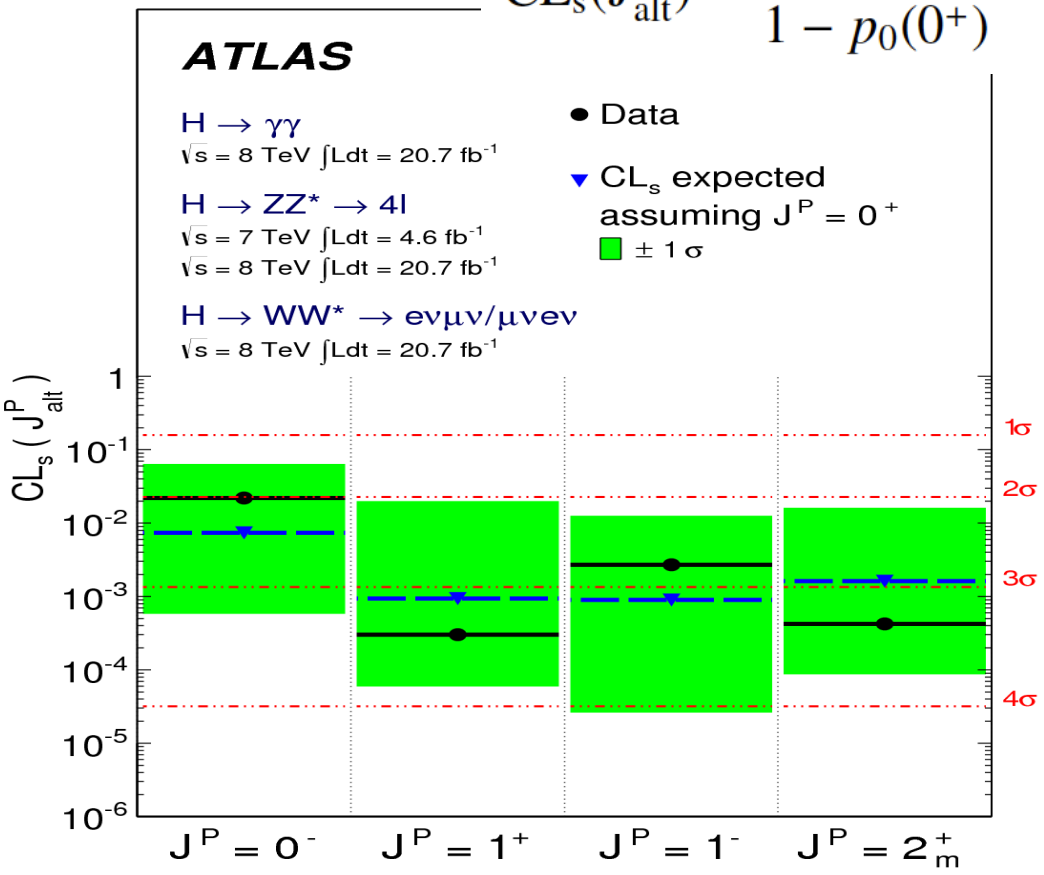
Higgs Spin/Parity

Phys. Lett. B 726 (2013), pp. 120





$$CL_s(J^P_{alt}) = \frac{p_0(J^P_{alt})}{1 - p_0(0^+)}$$

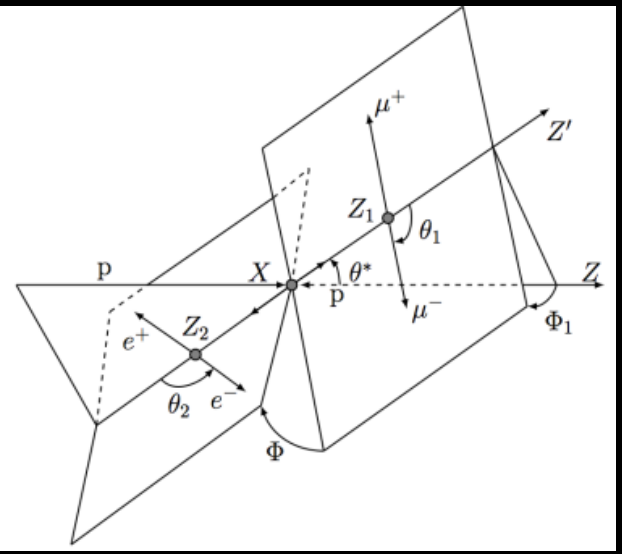


$J^P = 1^+$ and 1^- rejected at 99.7% CL

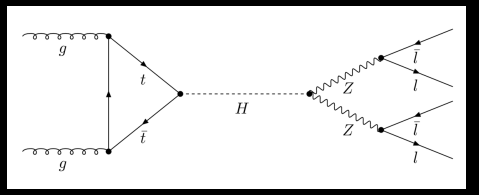
$J^P = 2^+$ rejected at 99.9% CL

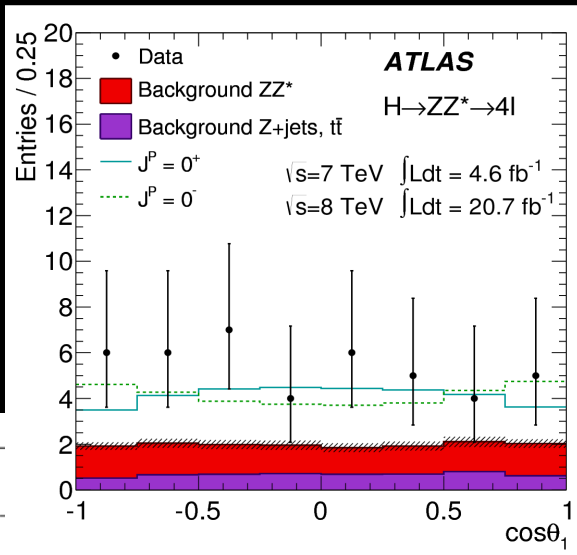
→ Evidence for $J^P = 0^+$

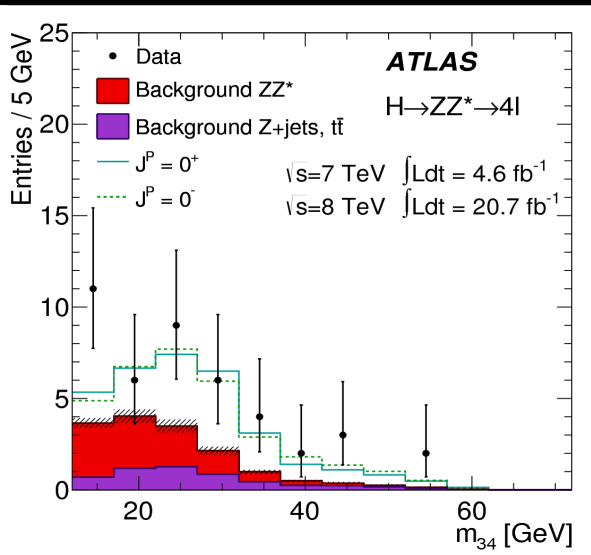
Higgs Spin/Parity ($J^P = 0^+$ vs 0^-)

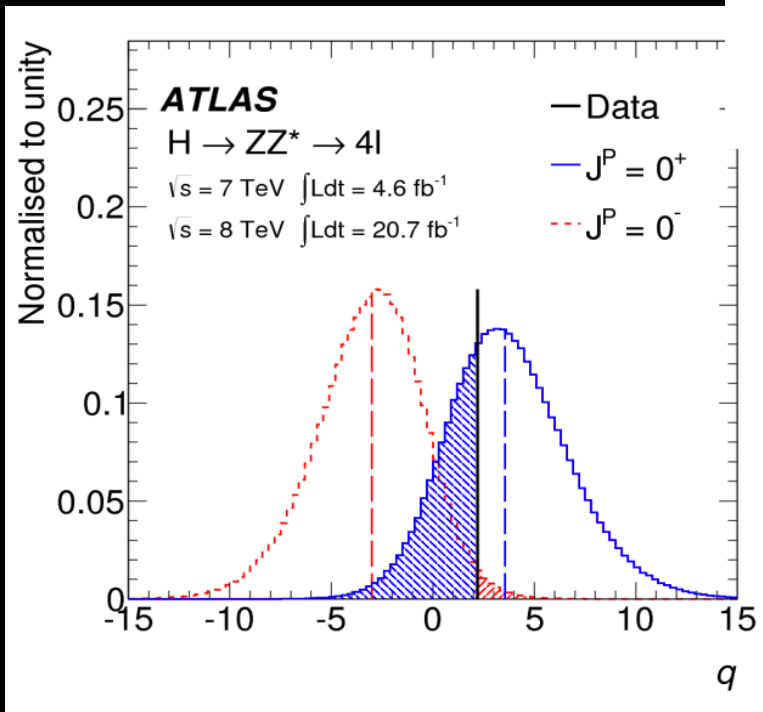


Phys. Lett. B 726 (2013), pp. 120









$$q = \log \frac{L(J^p = 0^+)}{L(J^p = 0^-)}$$

Data agree with 0^+ hypothesis

0^- solution excluded at 97.8 % CL

Other (Silver) Channels

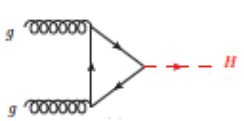
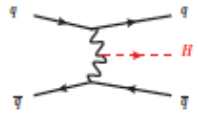
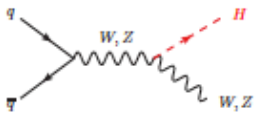
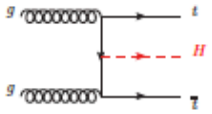
$H \rightarrow W^+W^-$

$H \rightarrow \tau\tau$

WH and ZH ($H \rightarrow bb$)

ttH

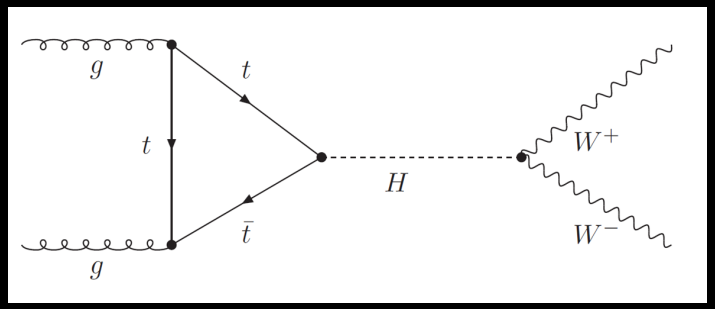
Higgs Program in a Glance

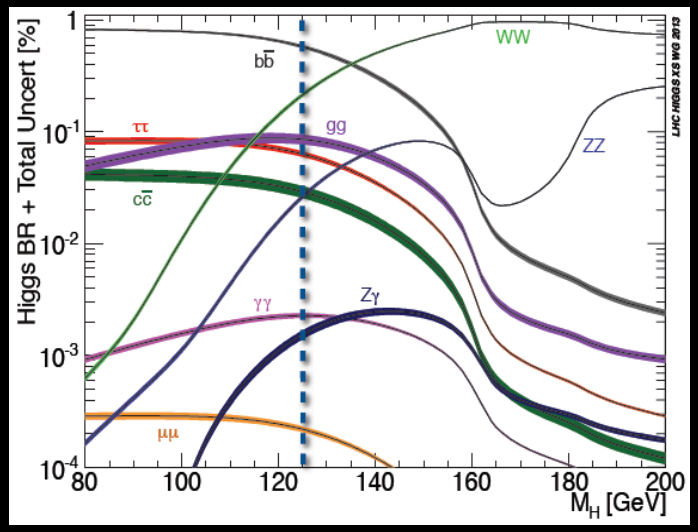
Channel categories	ggF 	VBF 	VH 	ttH 
γγ	✓	✓	✓	✓
ZZ (llll)	✓	✓	✓	✓
WW (lnln)	✓	✓	✓	✓
ττ	**difficult**	✓	✓	✓
bb	**very difficult**	✓	✓	✓
Zγ	✓	✓		
μμ	✓	✓		
Invisible	✓	✓	✓	

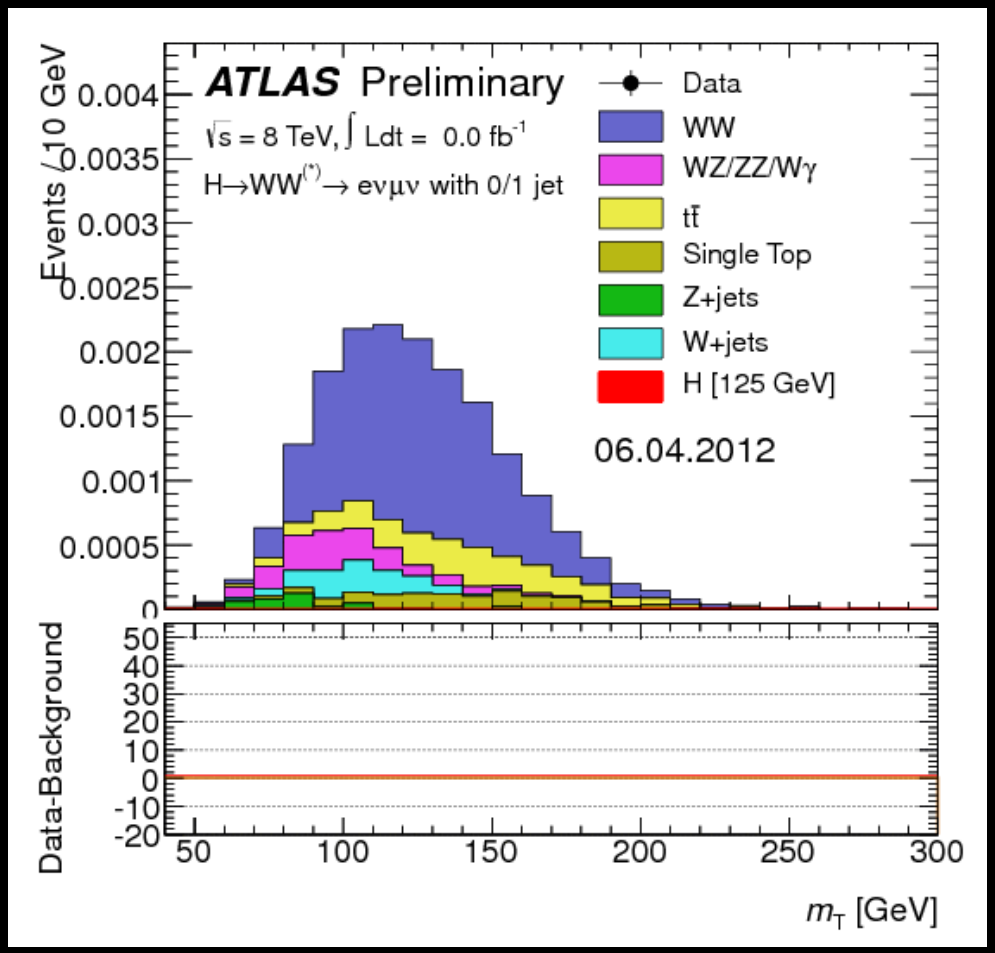
Lesson II

Rare Decays

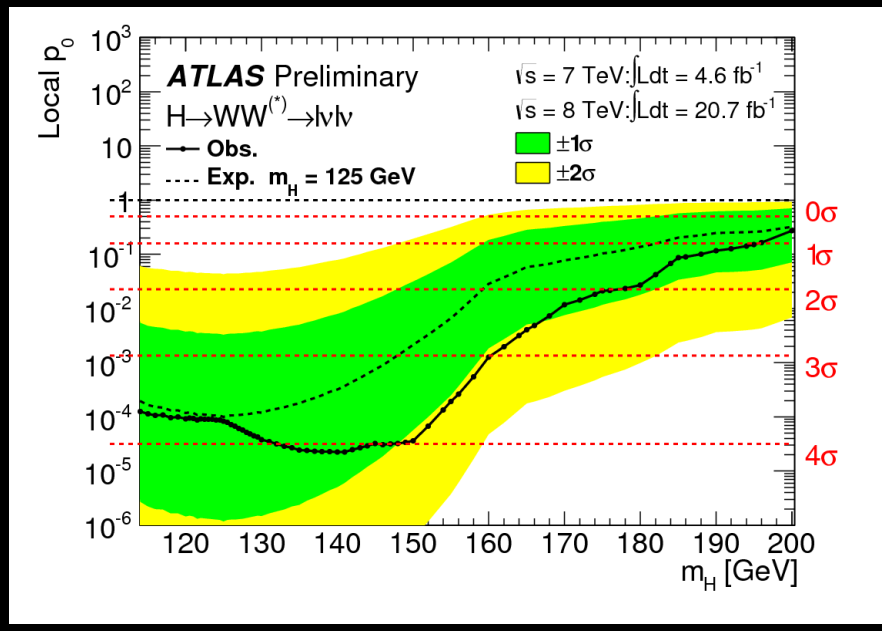
H → W^+W^- → lνlν







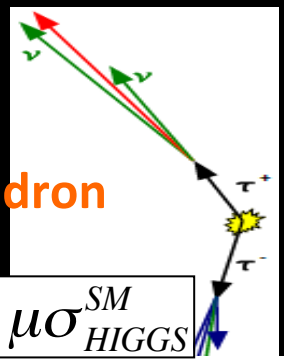
Limited mass resolution due to the presence of neutrinos



H → ττ

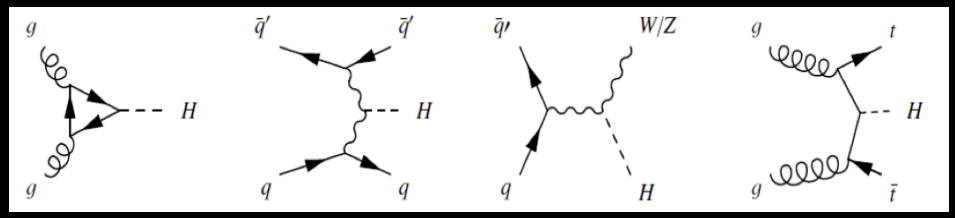
Analysis in mutiple channels with +0/1/2-jets in the final state

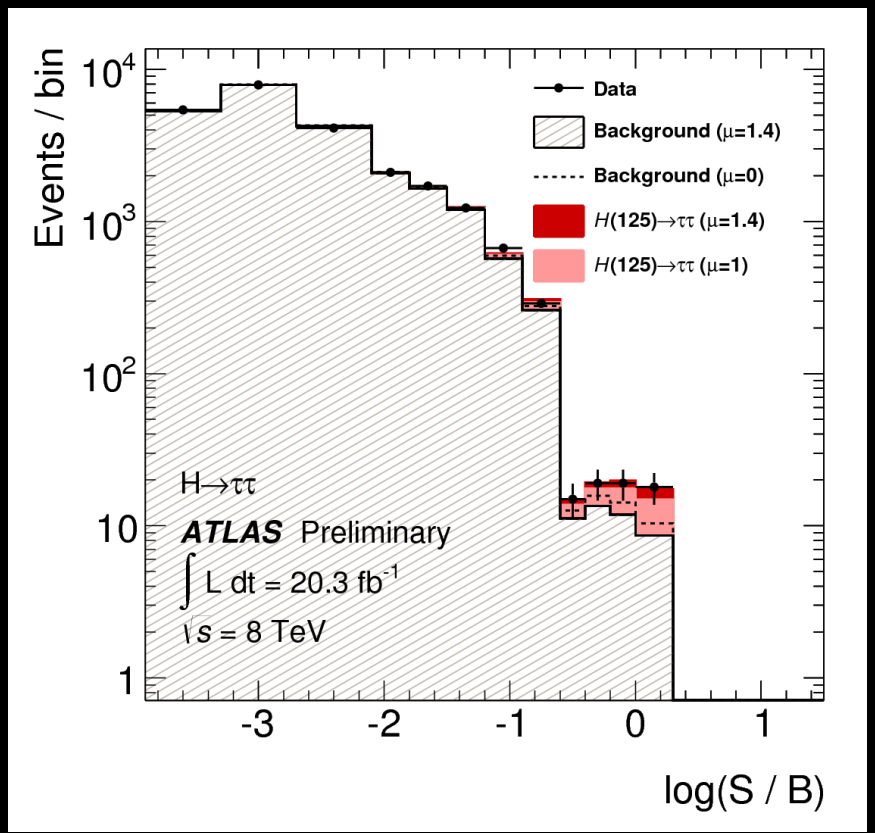
Considering lepton-lepton, lepton-hadron and hadron-hadron tau decay channels

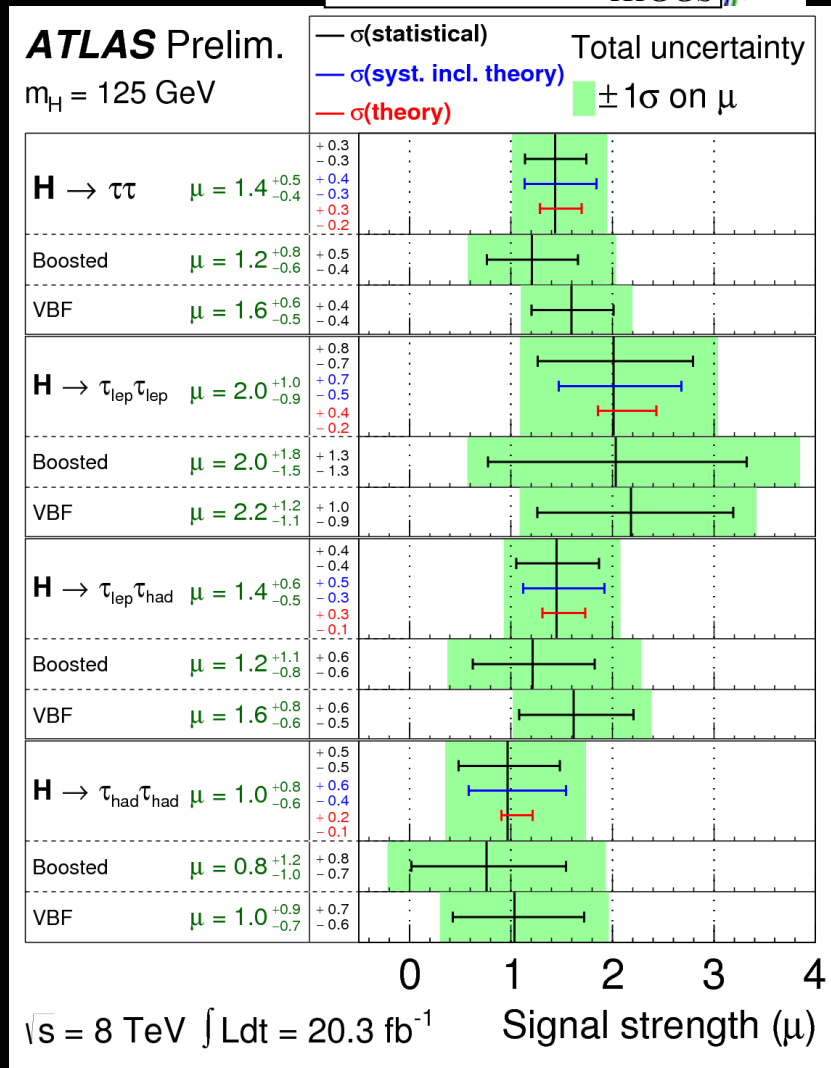


$$\sigma^{visible} = \mu\sigma^{SM}_{HIGGS}$$

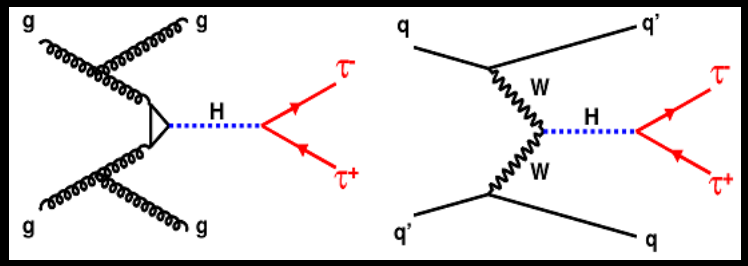
2-jet channels optimized for VBF and VH

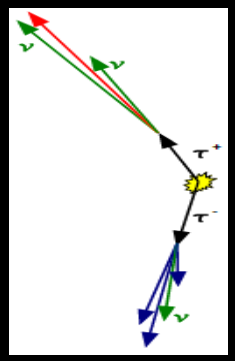


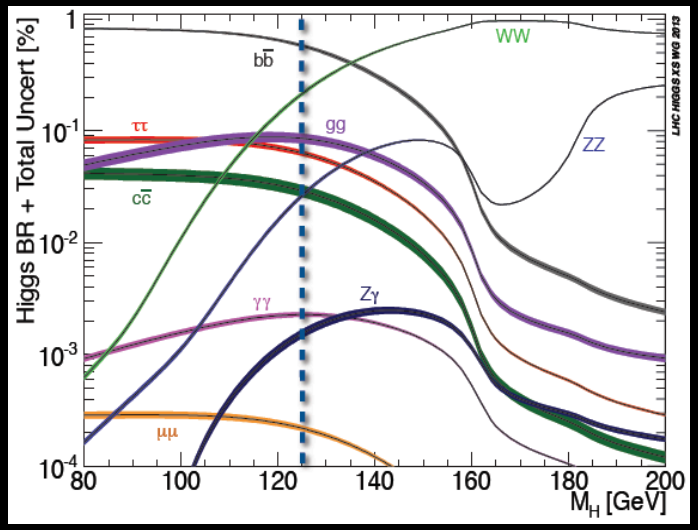


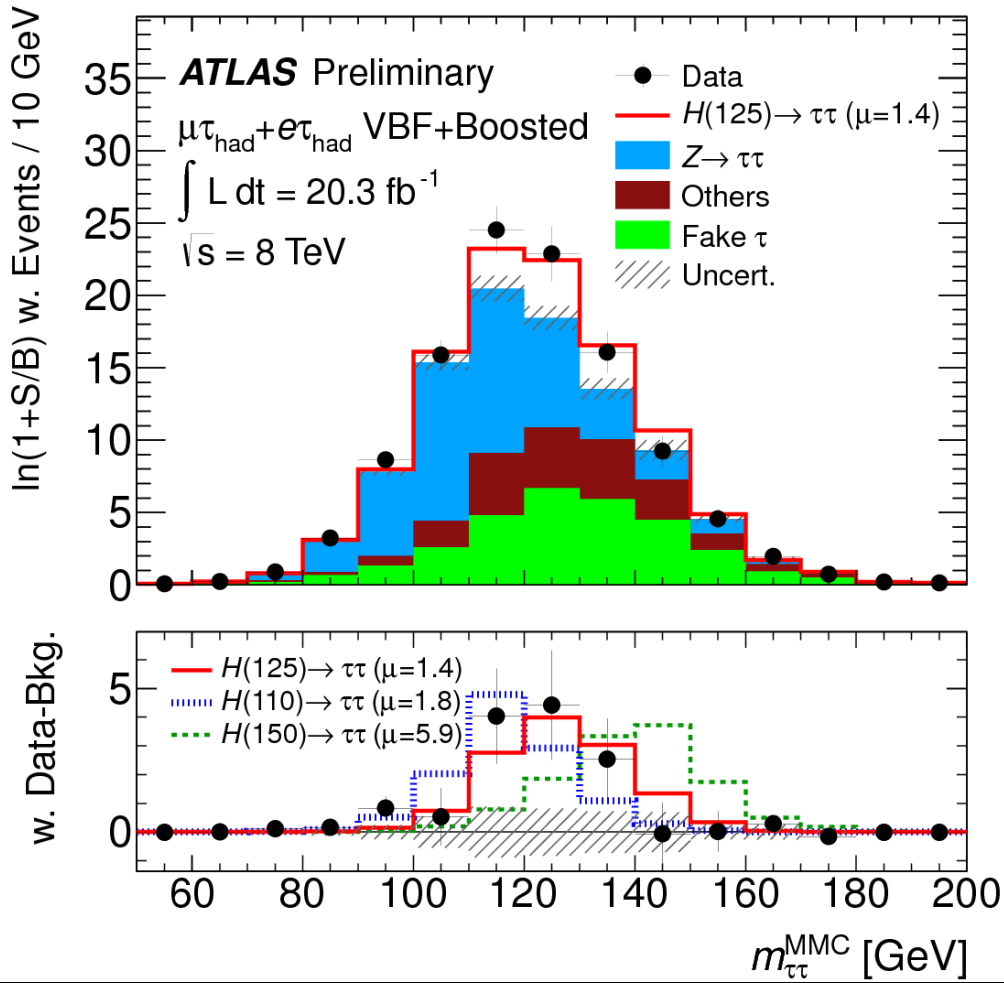


H → ττ

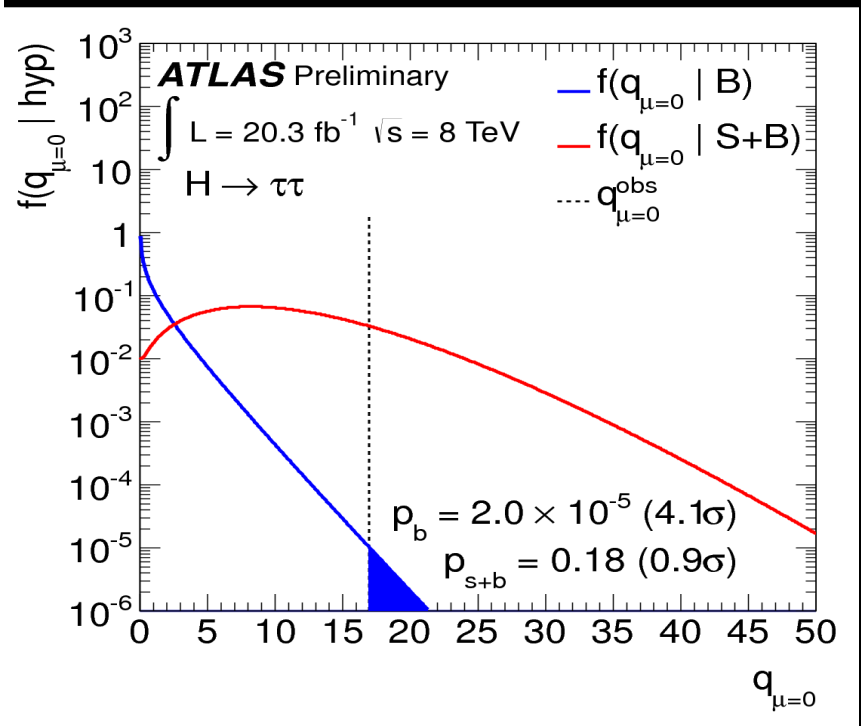




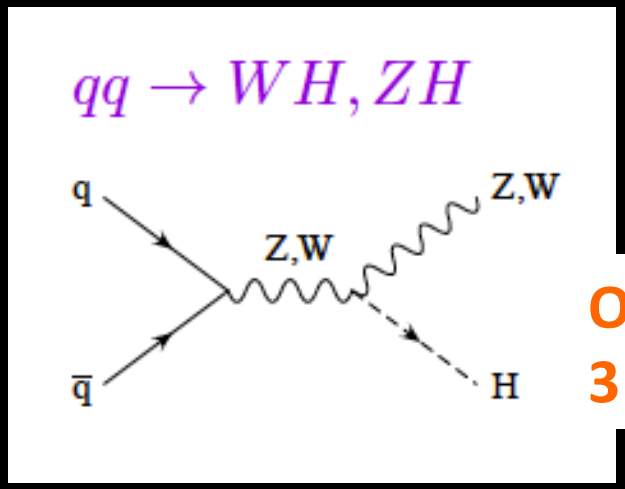




First indication of the Higgs couplings to fermions…

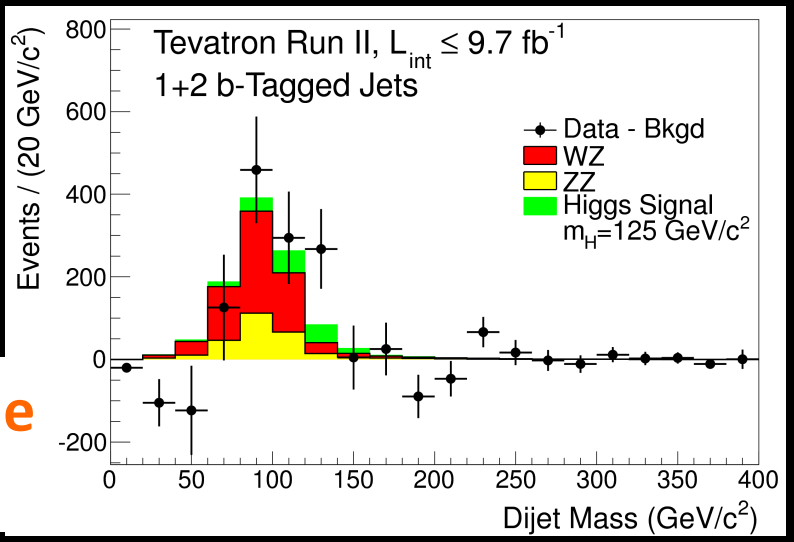


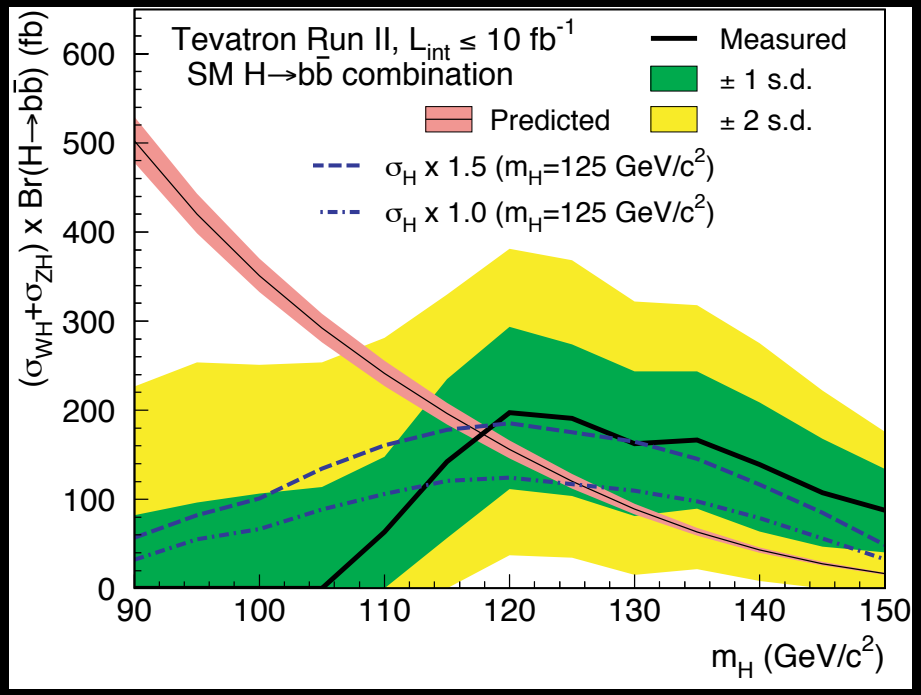
VH → bb

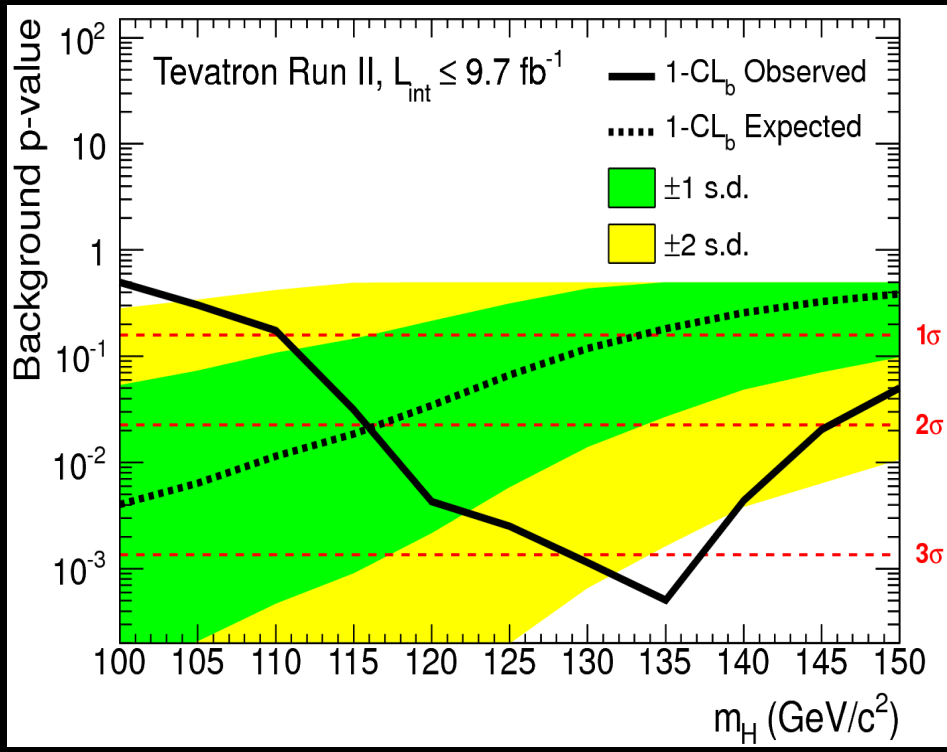


From Fermilab

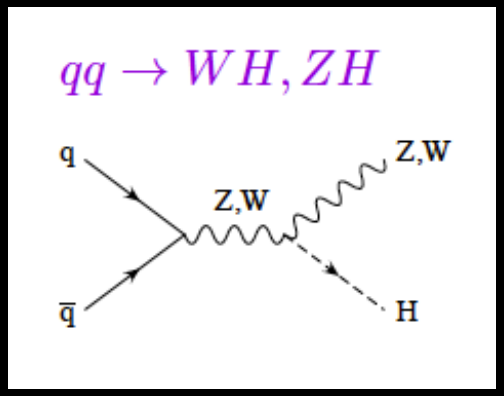
Observation at the 3 sigma level



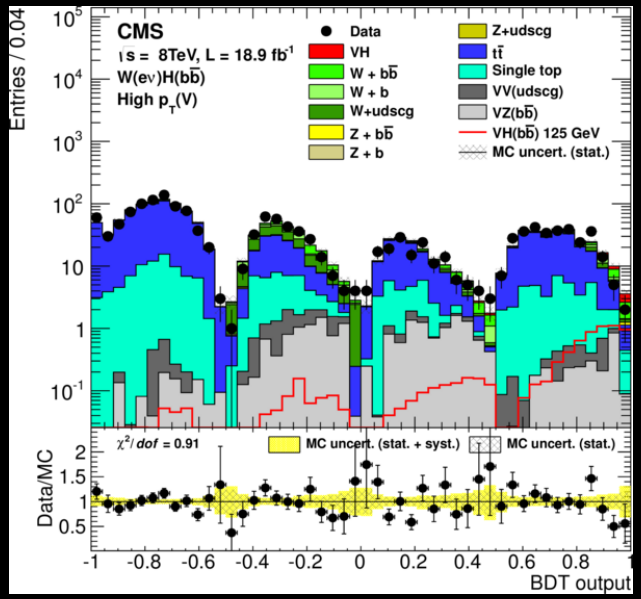


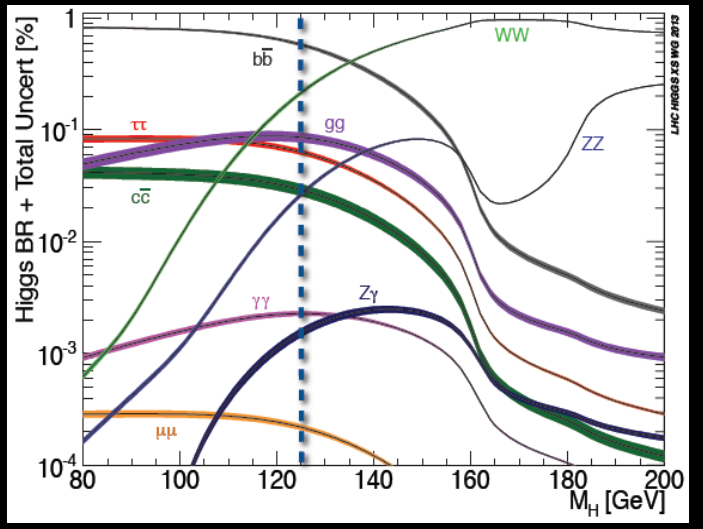


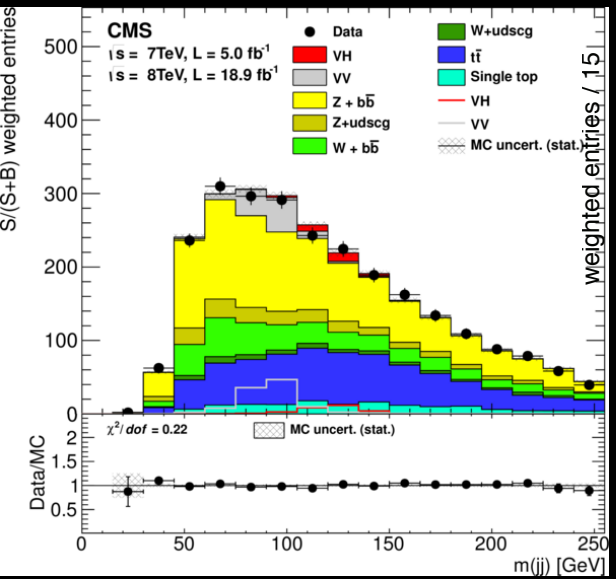
VH → bb

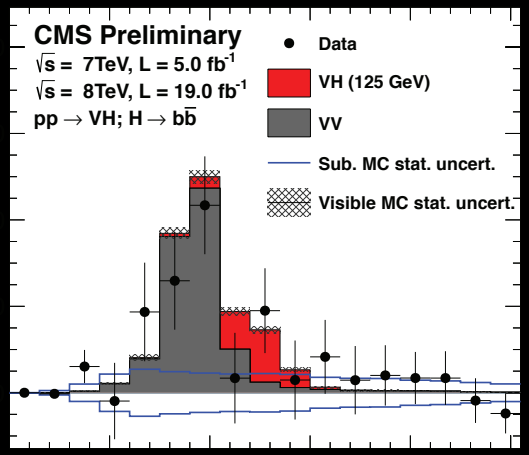


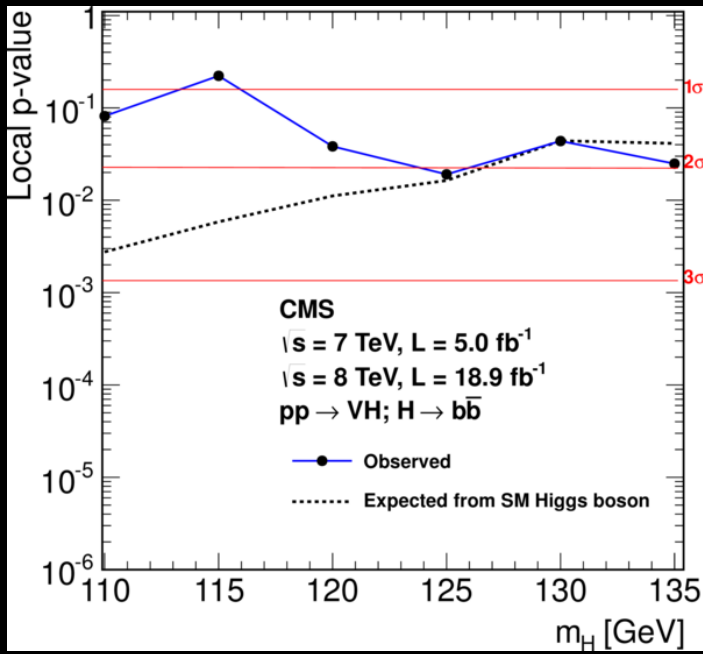
Intense use of Neural Nets to separate signal from background







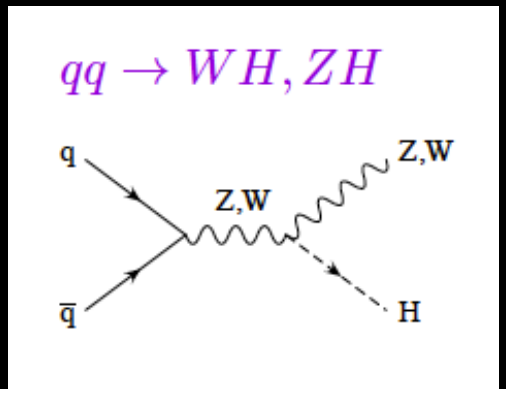




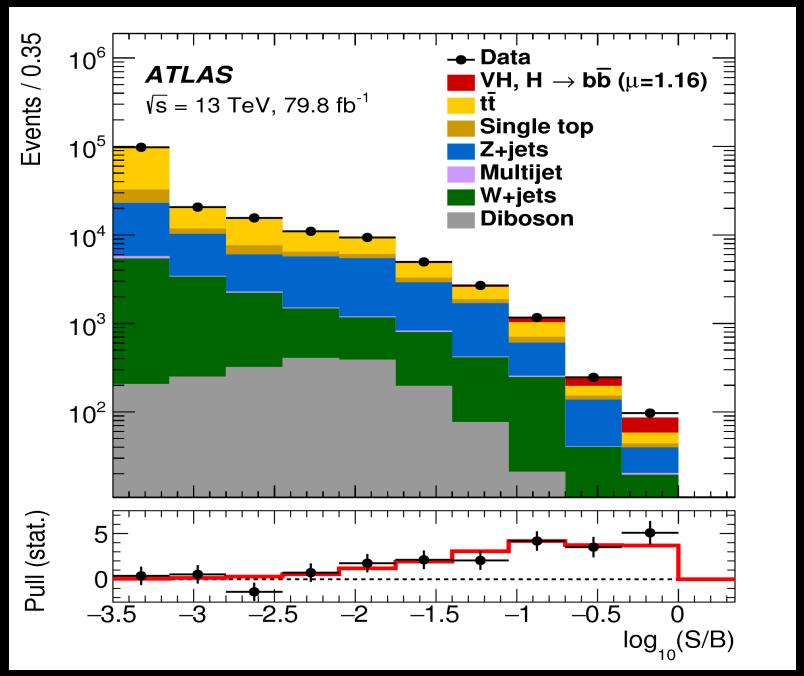
Run I results:

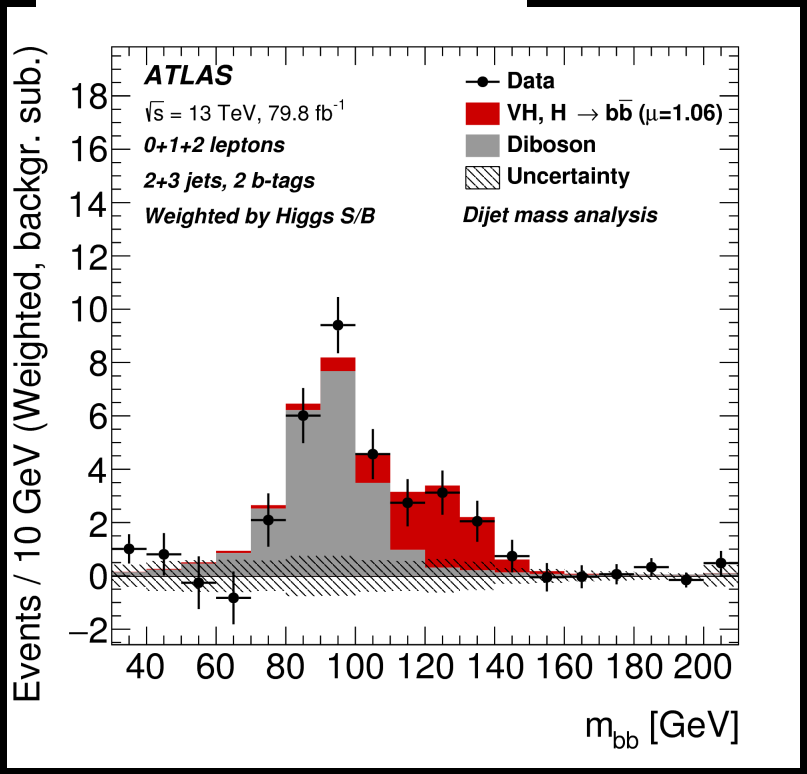
At the level of what is expected from the SM

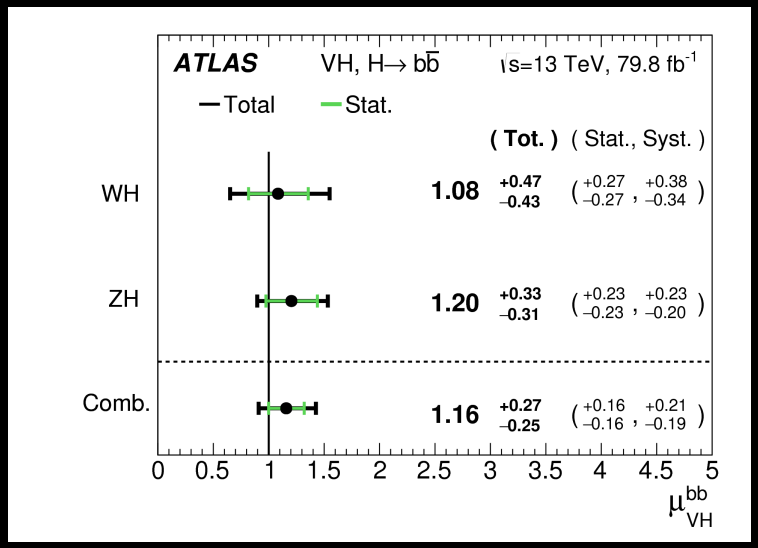
VH → bb



August 2018

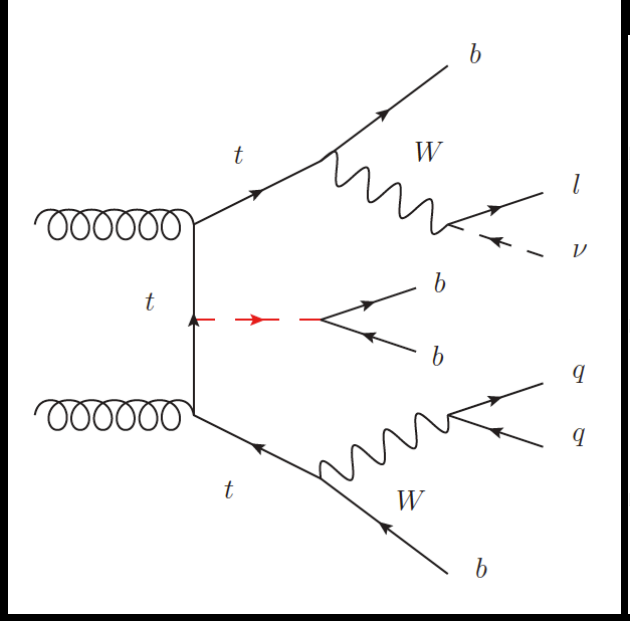


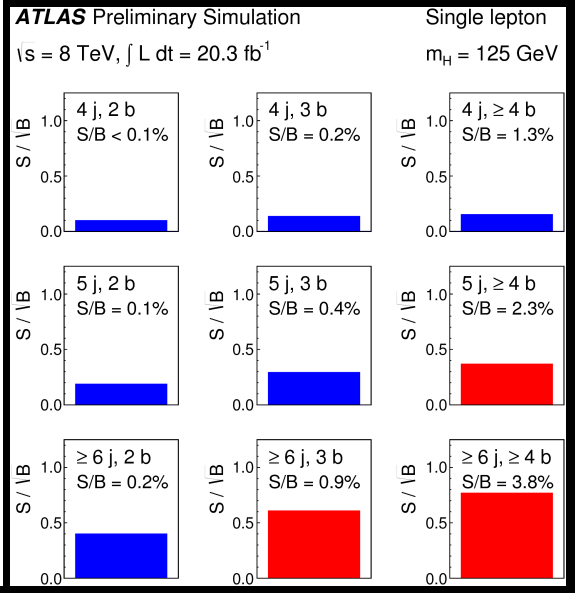


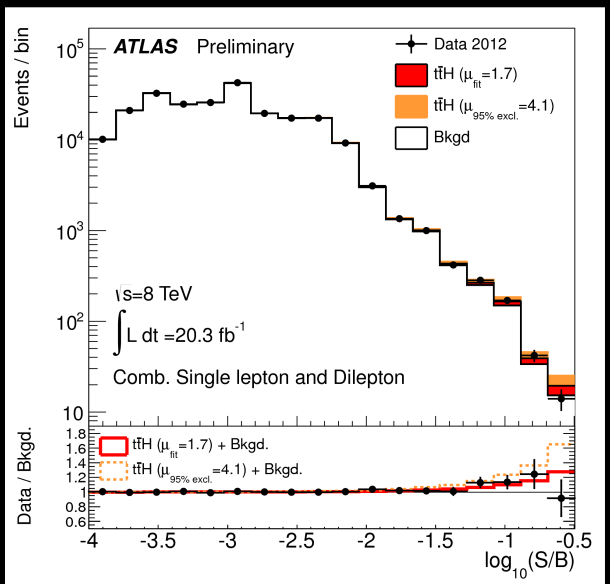


Run II @ 13 TeV (80 fb^{-1})
Observation of H→bb^{-} decays and VH production

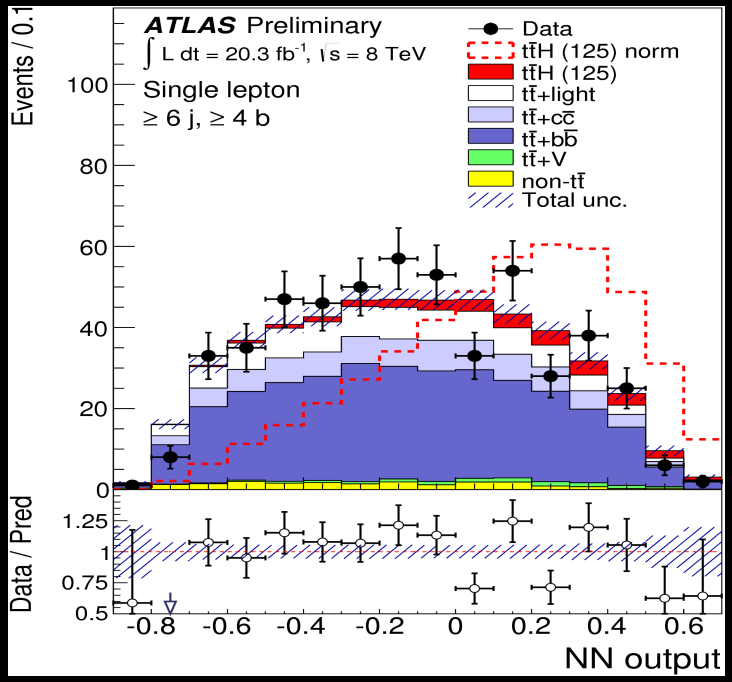
ttH

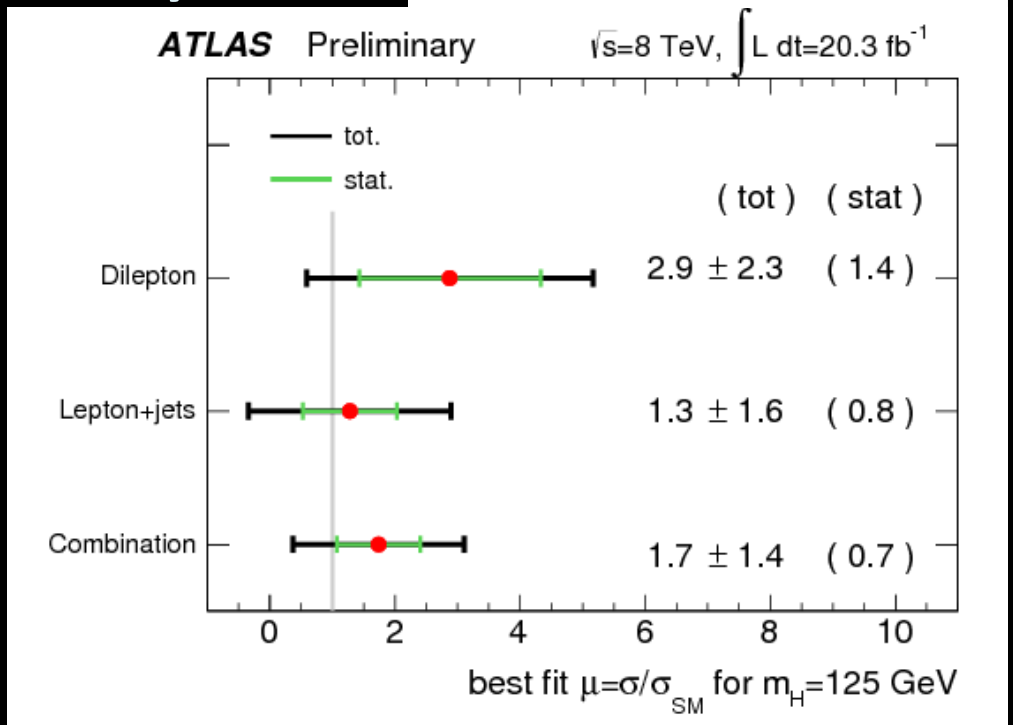




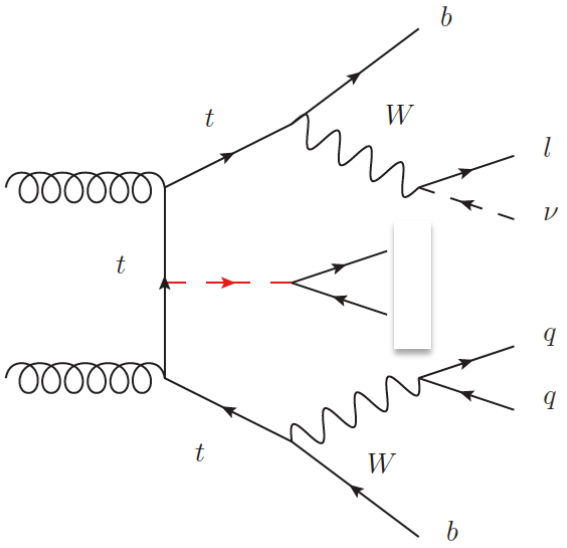


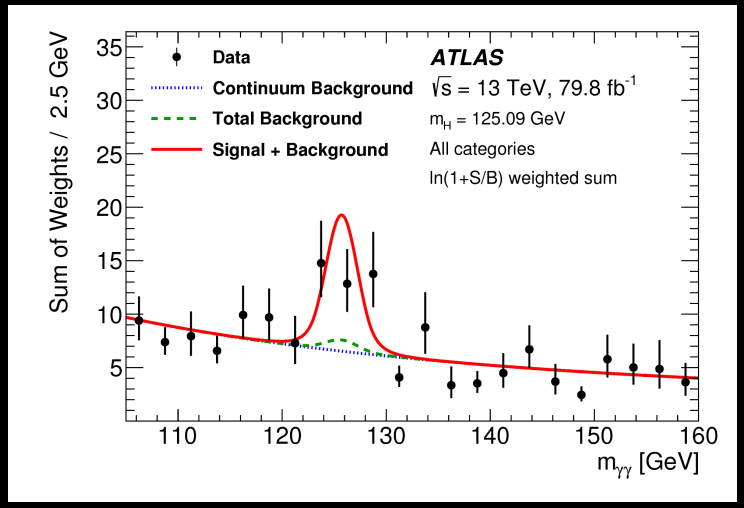
At the edge of the LHC Run I sensitivity…



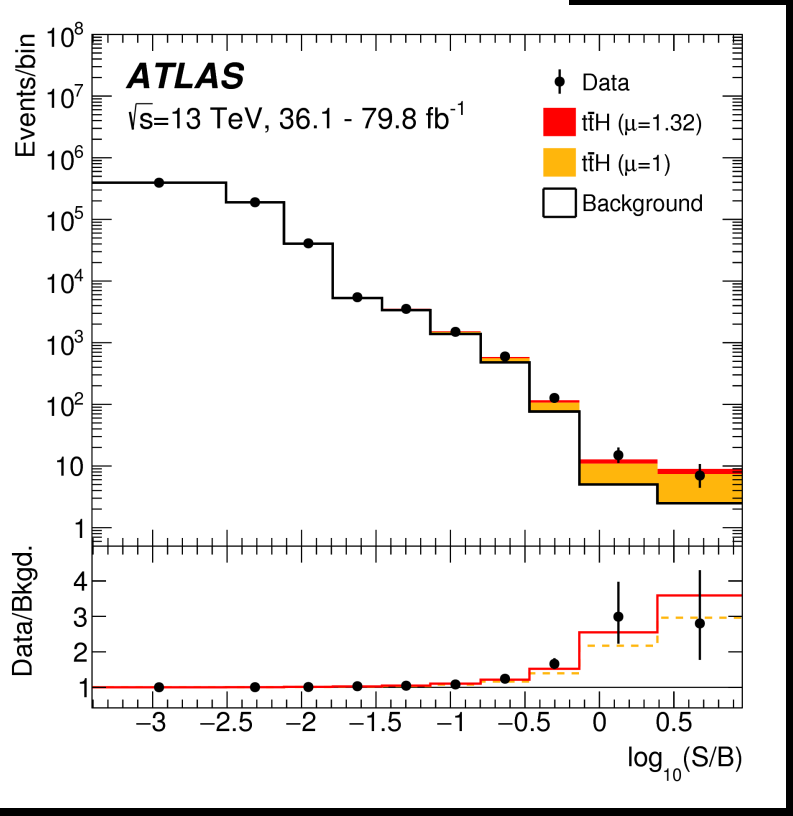


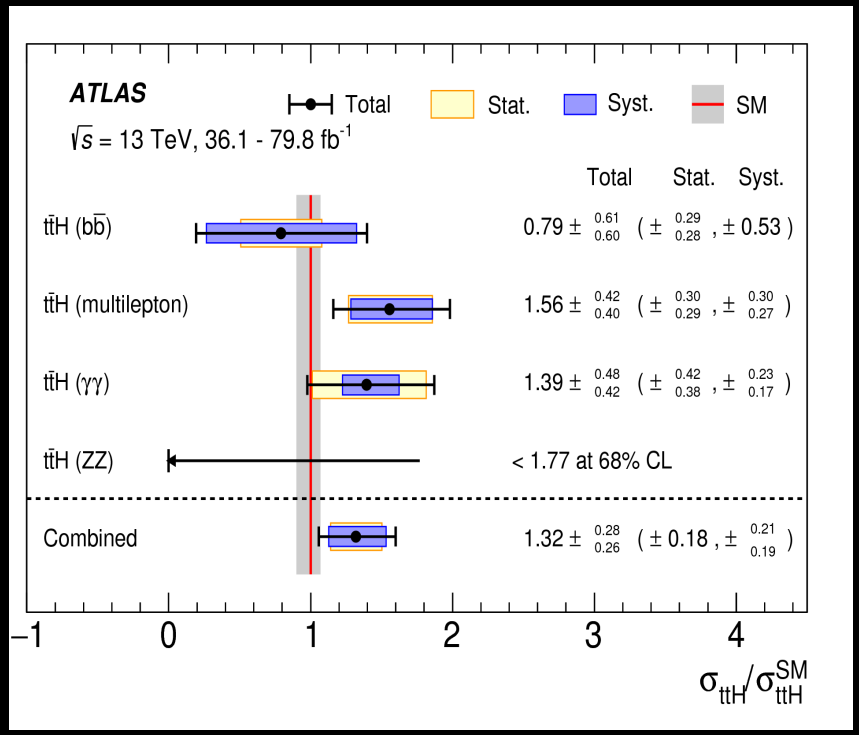
ttH





Run II@ 13TeV (80 fb^{-1})
Observation of ttH production (5.8 sigmas)





Part II

J^{PC}

- *Other (Silver) Channels*
- **Detailed study on Couplings**
- **Higgs width**
- **Invisibly decaying Higgs**
- **Higgs and Vacuum Stability**
- **Hierarchy Problem & SUSY**
- **Search for other Higgs**
- **What to expect in the future ?**

End Part I

Higgs Mechanism (Abelian Case)

To understand the mechanism

Spontaneous Breaking of a Gauge Symmetry

Abelian Higgs mechanism: one vector field $A^\mu(x)$ and one complex scalar field $\phi(x)$:

$$\boxed{\mathcal{L} = \mathcal{L}_A + \mathcal{L}_\phi}$$

where

$$\mathcal{L}_A = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} = -\frac{1}{4}(\partial^\mu A^\nu - \partial^\nu A^\mu)(\partial_\mu A_\nu - \partial_\nu A_\mu)$$

and $(D^\mu = \partial^\mu + igA^\mu)$

$$\mathcal{L}_\phi = (D^\mu \phi)^* D_\mu \phi - V(\phi) = (D^\mu \phi)^* D_\mu \phi - \mu^2 \phi^* \phi - \lambda(\phi^* \phi)^2$$

$\mathcal{L}$ invariant under local phase transformation, or local $U(1)$ symmetry:

$$\begin{aligned} \phi(x) &\rightarrow e^{i\alpha(x)} \phi(x) \\ A^\mu(x) &\rightarrow A^\mu(x) + \frac{1}{g} \partial^\mu \alpha(x) \end{aligned}$$

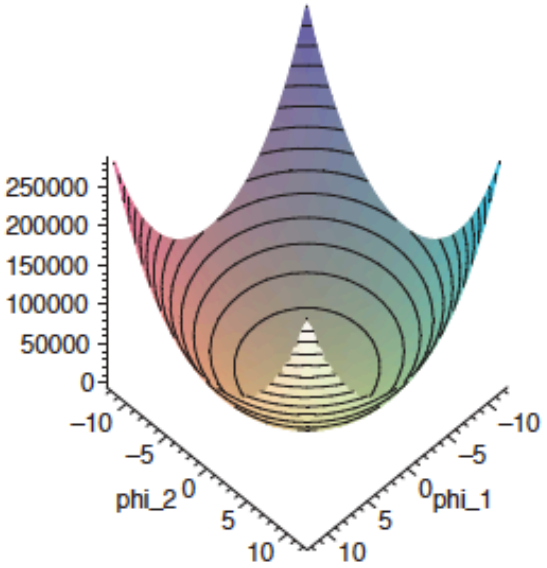
Mass term for A^μ breaks the $U(1)$ gauge invariance.

Can we build a gauge invariant massive theory? Yes.

Consider the potential of the scalar field:

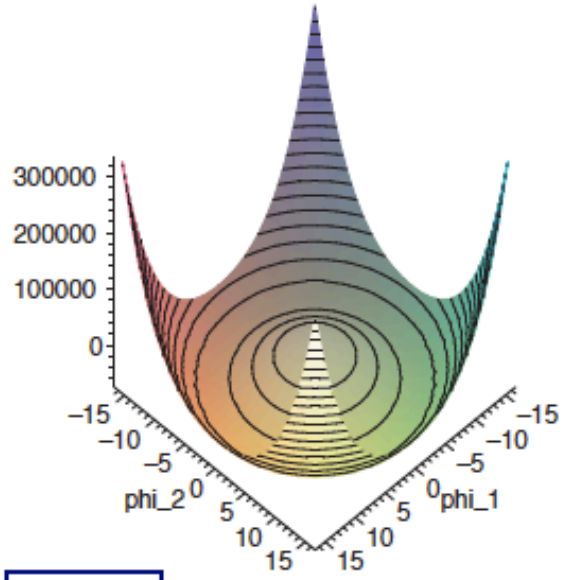
$$\boxed{V(\phi) = \mu^2 \phi^* \phi + \lambda (\phi^* \phi)^2}$$

where $\lambda > 0$ (to be bounded from below), and observe that:



$\boxed{\mu^2 > 0}$ → unique minimum:

$$\phi^* \phi = 0$$



$\boxed{\mu^2 < 0}$ → degeneracy of minima:

$$\phi^* \phi = \frac{-\mu^2}{2\lambda}$$

- $\mu^2 > 0 \longrightarrow$ electrodynamics of a massless photon and a massive scalar field of mass μ $(g = -e)$.
- $\mu^2 < 0 \longrightarrow$ when we choose a minimum, the original $U(1)$ symmetry is spontaneously broken or hidden.

$$\phi_0 = \left(-\frac{\mu^2}{2\lambda}\right)^{1/2} = \frac{v}{\sqrt{2}} \longrightarrow \phi(x) = \phi_0 + \frac{1}{\sqrt{2}}\left(\phi_1(x) + i\phi_2(x)\right)$$

$$\Downarrow$$

$$\mathcal{L} = \underbrace{-\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}g^2v^2A^\mu A_\mu}_{\text{massive vector field}} + \underbrace{\frac{1}{2}(\partial^\mu\phi_1)^2 + \mu^2\phi_1^2}_{\text{massive scalar field}} + \underbrace{\frac{1}{2}(\partial^\mu\phi_2)^2 + gvA_\mu\partial^\mu\phi_2}_{\text{Goldstone boson}} + \ldots$$

Side remark: The ϕ_2 field actually generates the correct transverse structure for the mass term of the (now massive) A^μ field propagator:

$$\langle A^\mu(k)A^\nu(-k)\rangle = \frac{-i}{k^2 - m_A^2}\left(g^{\mu\nu} - \frac{k^\mu k^\nu}{k^2}\right) + \cdots$$

More convenient parameterization (unitary gauge):

$$\phi(x) = \frac{e^{i\frac{\chi(x)}{v}}}{\sqrt{2}}(v + H(x)) \quad \xrightarrow{U(1)} \quad \frac{1}{\sqrt{2}}(v + H(x))$$

The $\chi(x)$ degree of freedom (Goldstone boson) is rotated away using gauge invariance, while the original Lagrangian becomes:

$$\mathcal{L} = \mathcal{L}_A + \frac{g^2 v^2}{2} A^\mu A_\mu + \frac{1}{2}\left(\partial^\mu H \partial_\mu H + 2\mu^2 H^2\right) + \dots$$

which describes now the dynamics of a system made of:

- a massive vector field A^μ with $m_A^2 = g^2 v^2$;
- a real scalar field H of mass $m_H^2 = -2\mu^2 = 2\lambda v^2$: the Higgs field.

$$\Downarrow$$

Total number of degrees of freedom is balanced