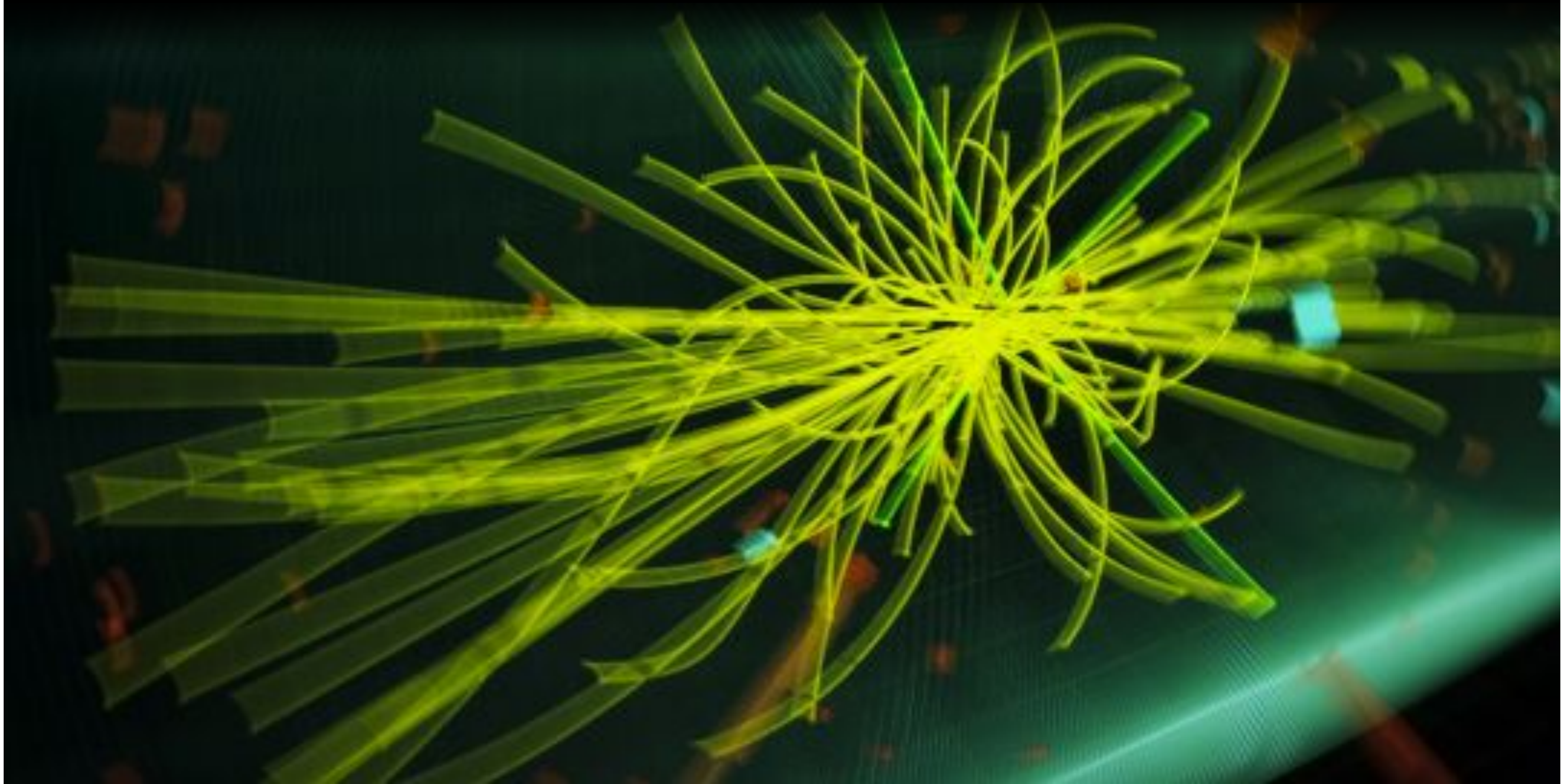
Higgs Searches at LHC

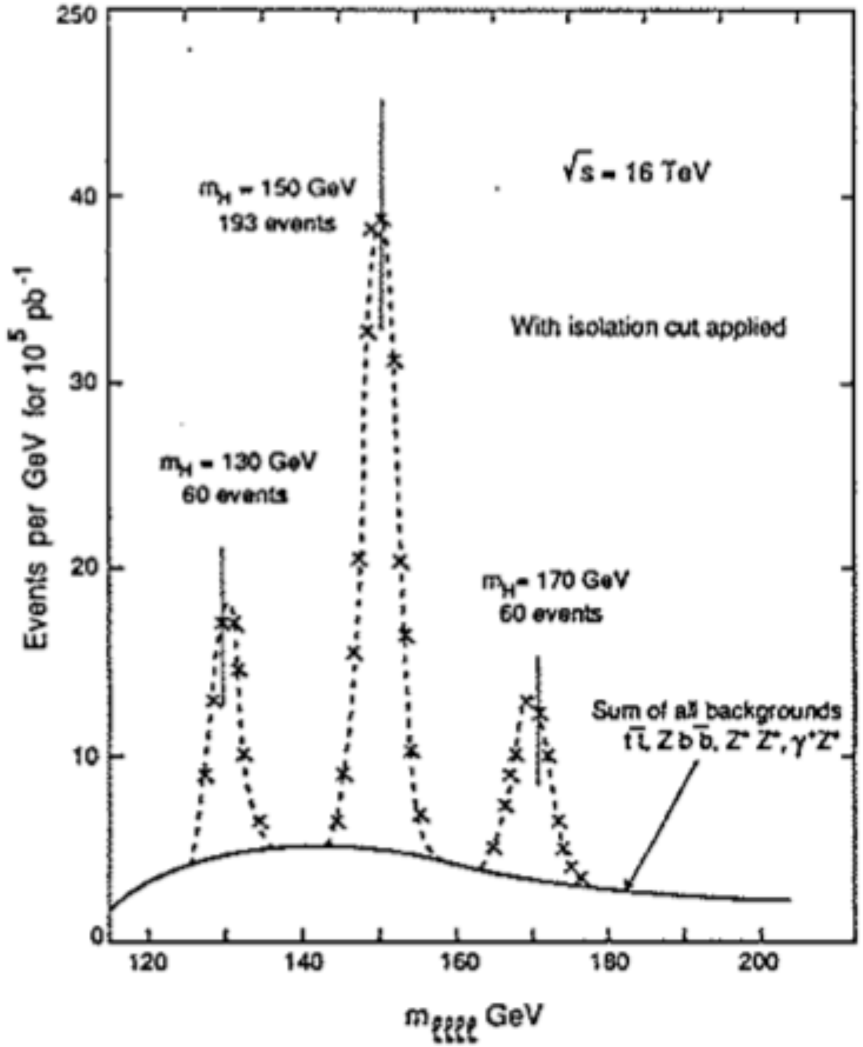


Marumi Kado

Laboratoire de l'Accélérateur Linéaire (LAL)
IN2P3, CNRS

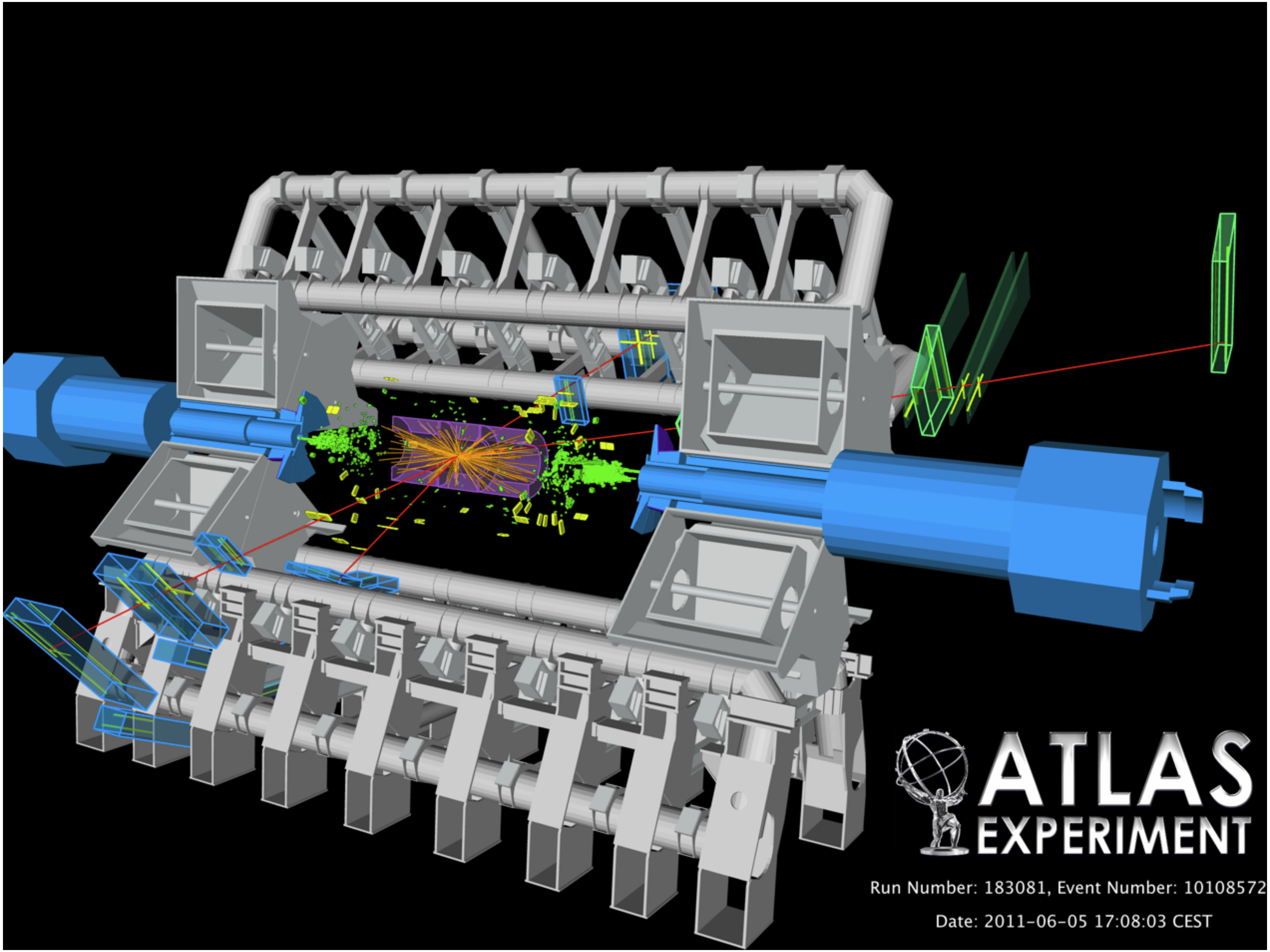
Half a Century of Higgs Hunt…

…almost half of which preparing the searches at LHC

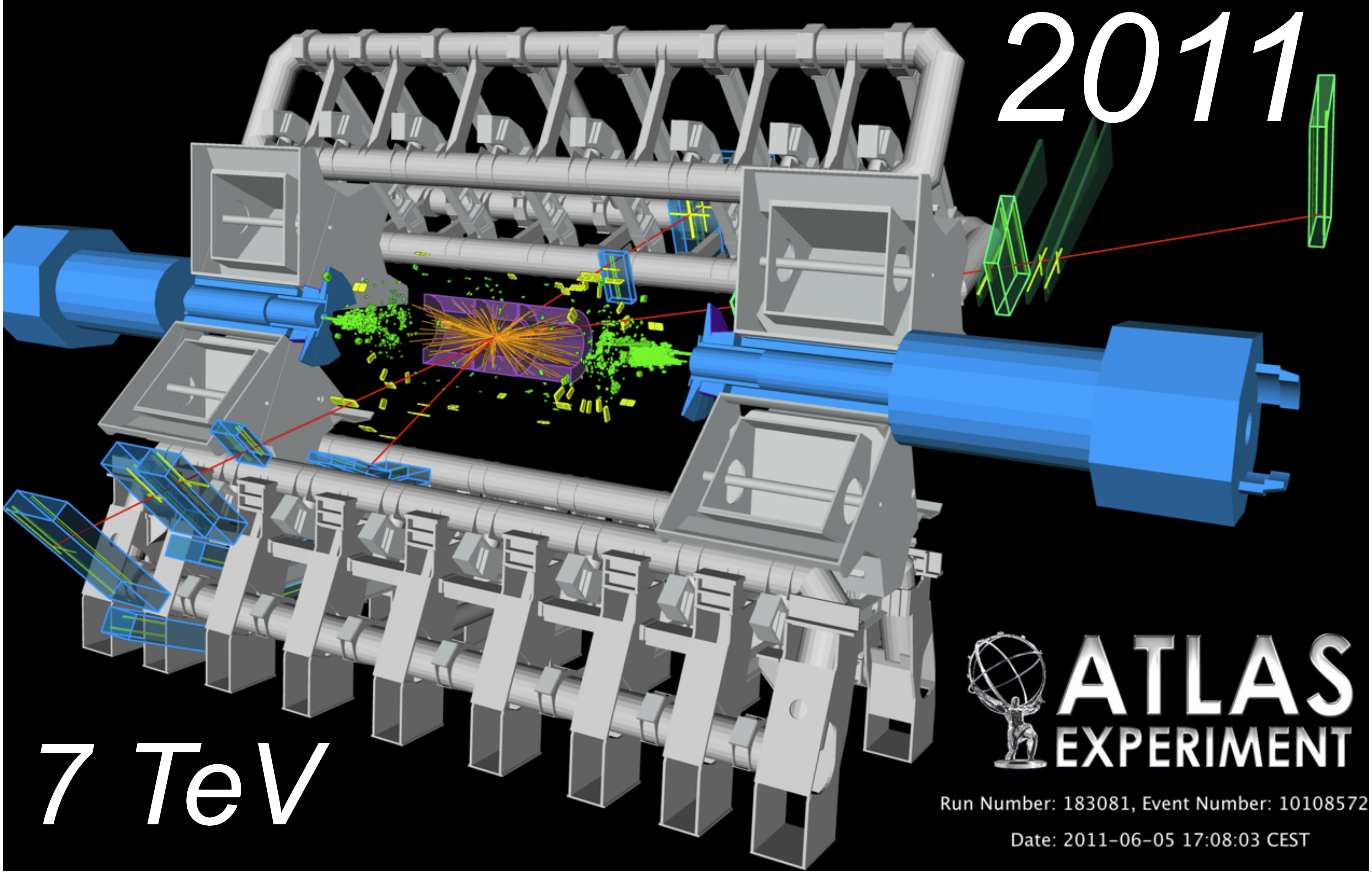


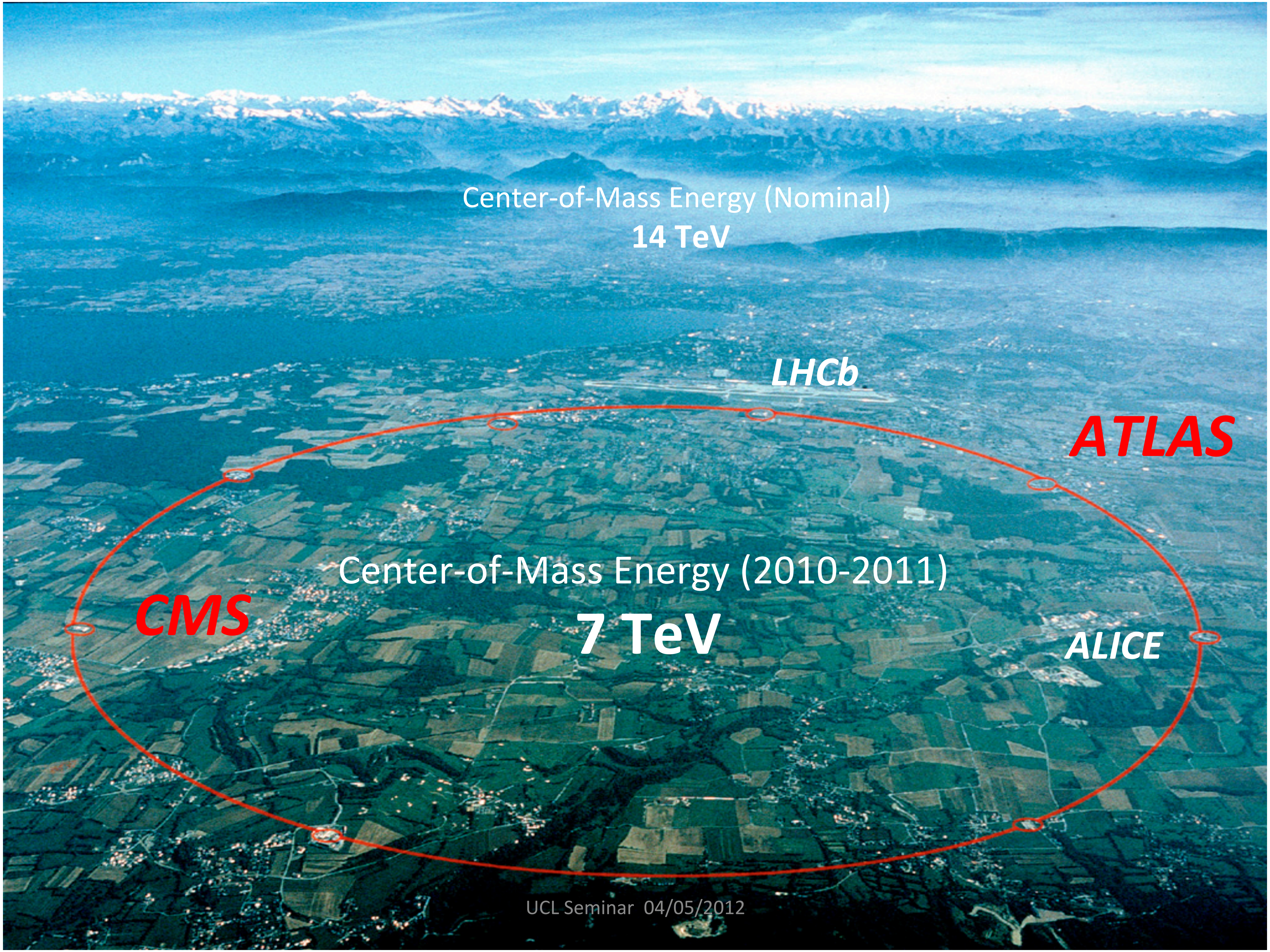
1990

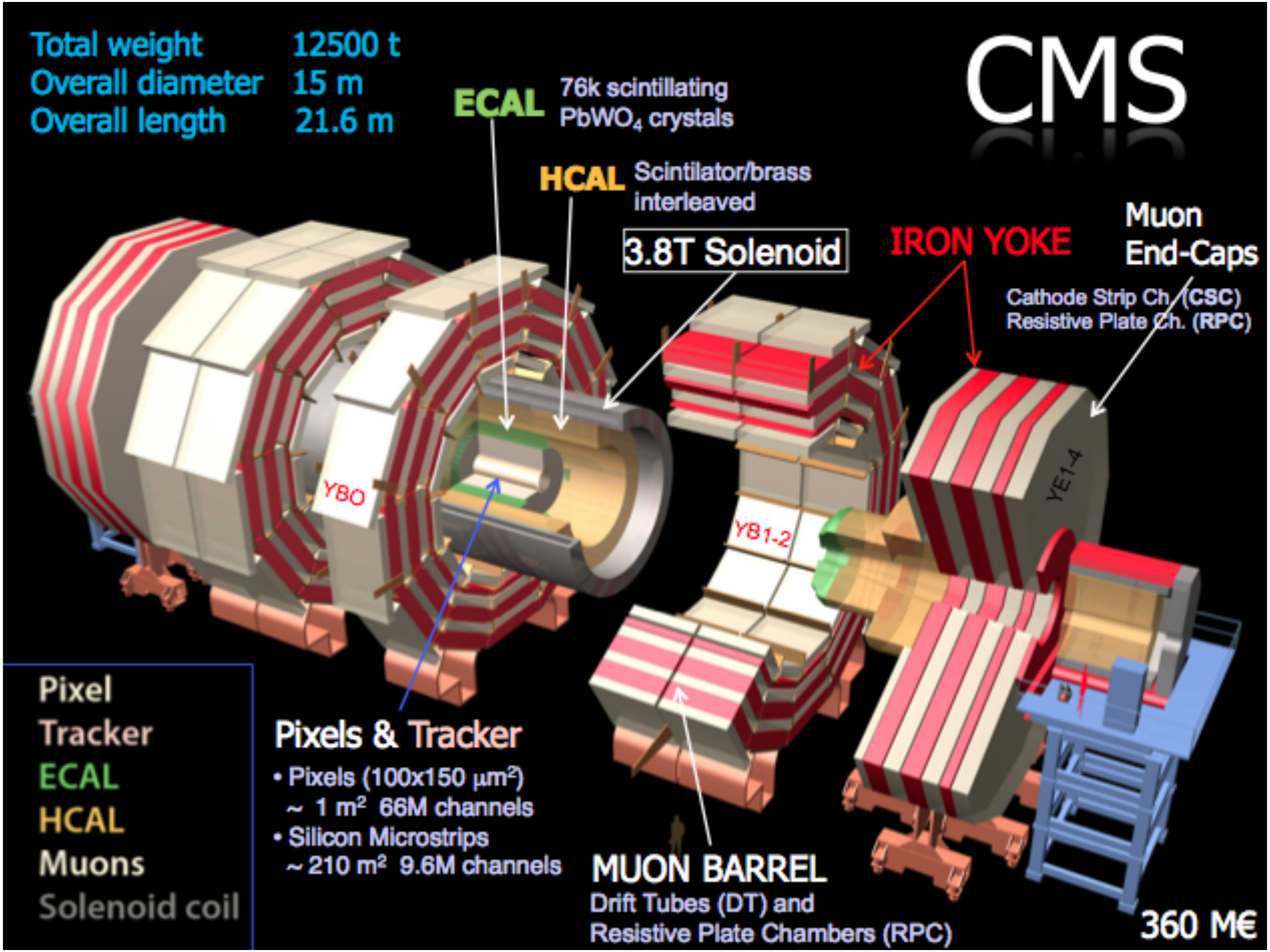
Proceedings of LHC Workshop (Aachen, 1990): $\sqrt{s}$ = 16 TeV, 100 fb^{-1}


ATLAS
EXPERIMENT
Run Number: 183081, Event Number: 10108572
Date: 2011-06-05 17:08:03 CEST

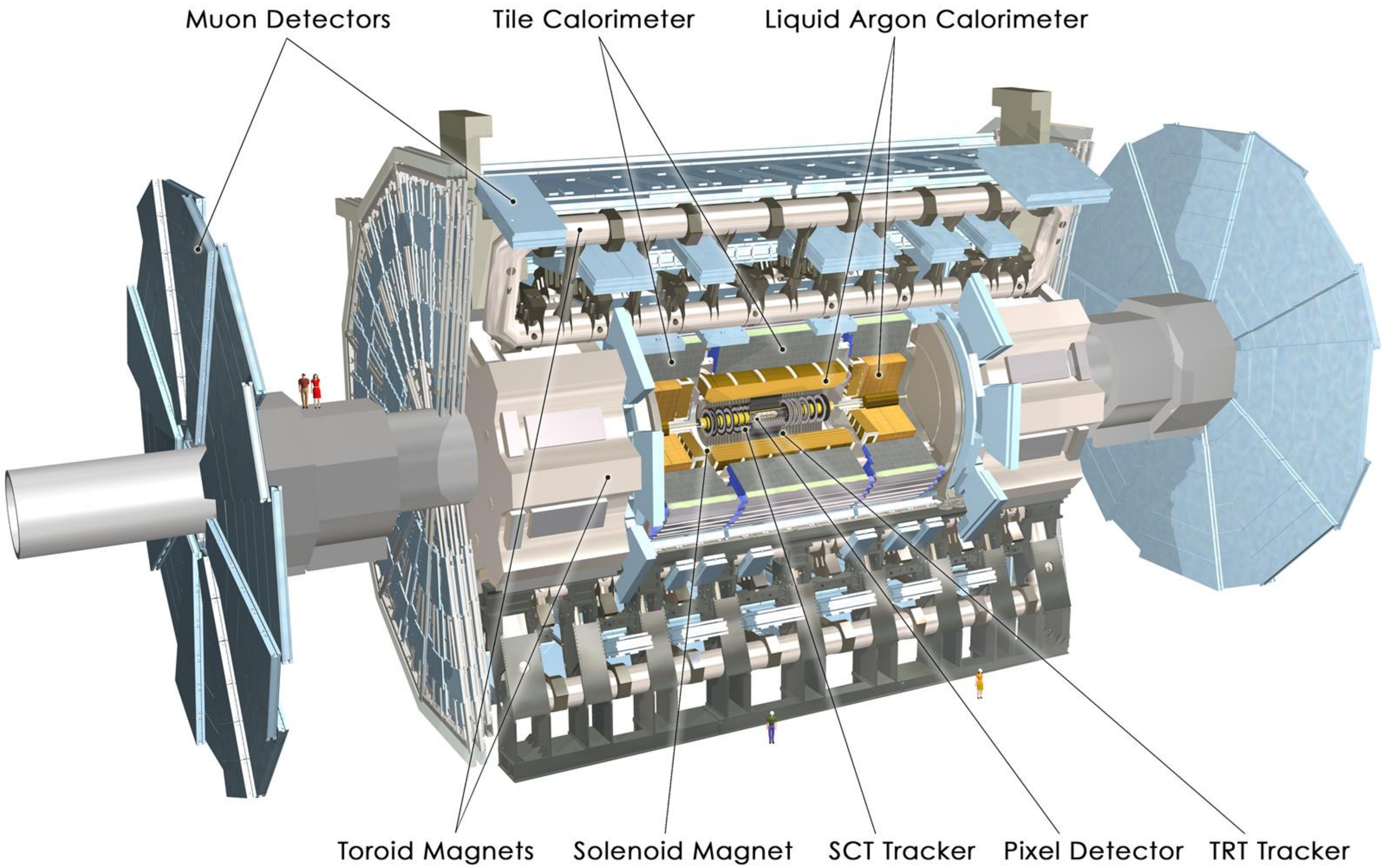
4 μ event … *Standard EW only or Higgs?*



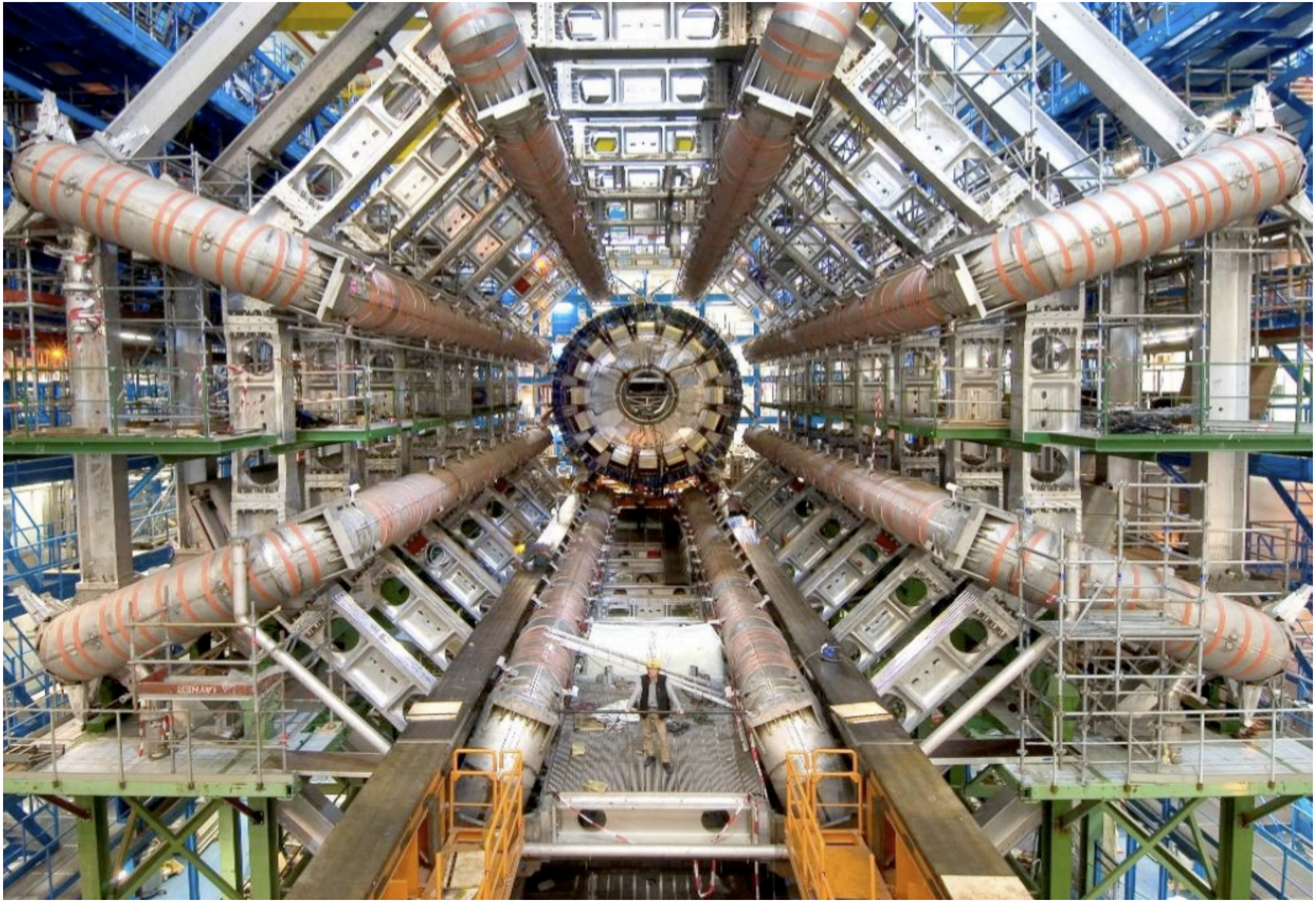

Center-of-Mass Energy (Nominal)
14 TeV
LHCb
ATLAS
Center-of-Mass Energy (2010-2011)
CMS
7 TeV
ALICE



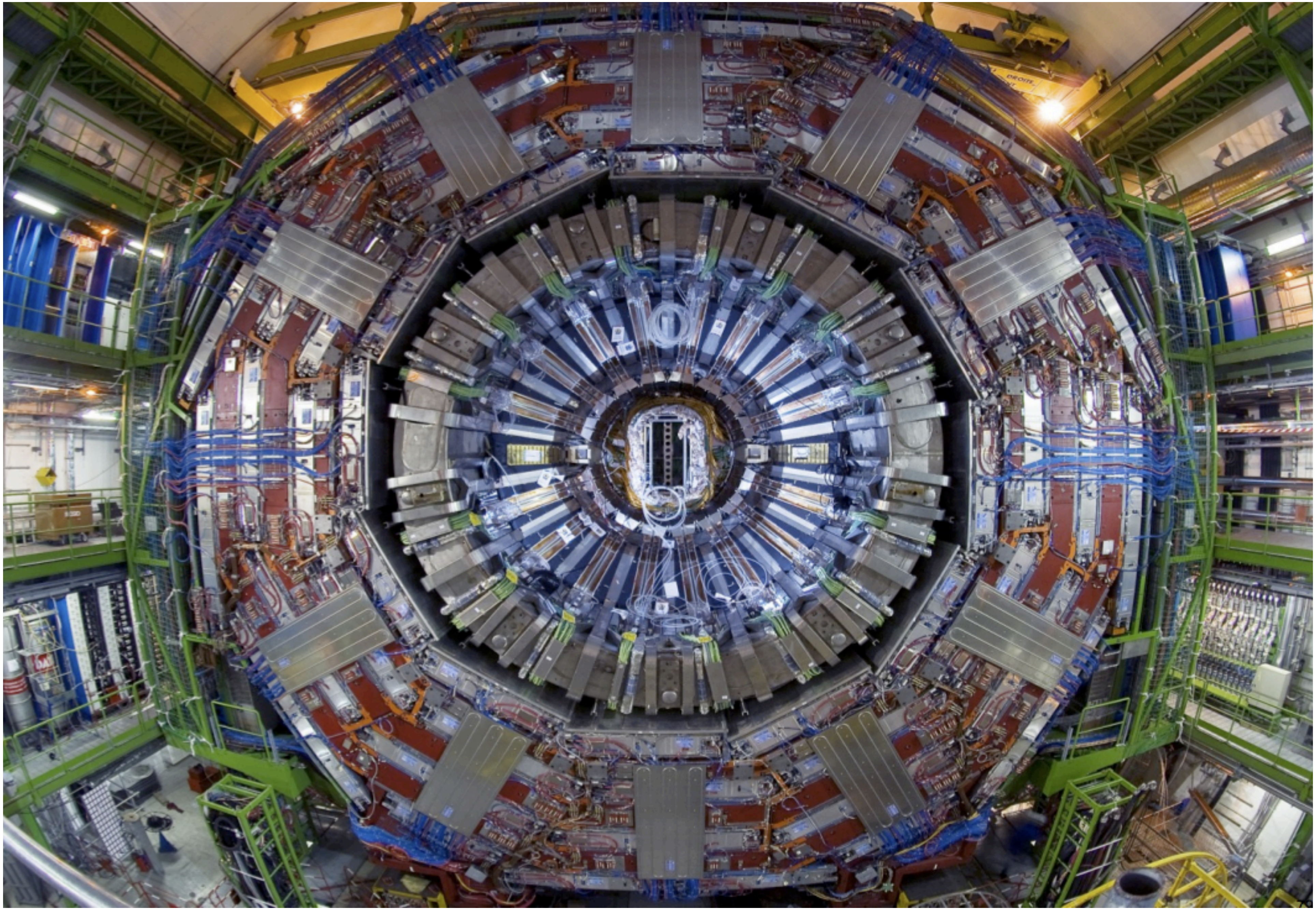
Total weight 12500 t
Overall diameter 15 m
Overall length 21.6 m
ECAL 76k scintillating PbWO4 crystals
HCAL Scintilator/brass interleaved
3.8T Solenoid
IRON YOKE
Muon End-Caps
Cathode Strip Ch. (CSC)
Resistive Plate Ch. (RPC)
CMS
YB0
YB1-2
YE1-4
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil
Pixels & Tracker
• Pixels (100x150 μm²) ~ 1 m² 66M channels
• Silicon Microstrips ~ 210 m² 9.6M channels
MUON BARREL
Drift Tubes (DT) and
Resistive Plate Chambers (RPC)
360 M€


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

ATLAS

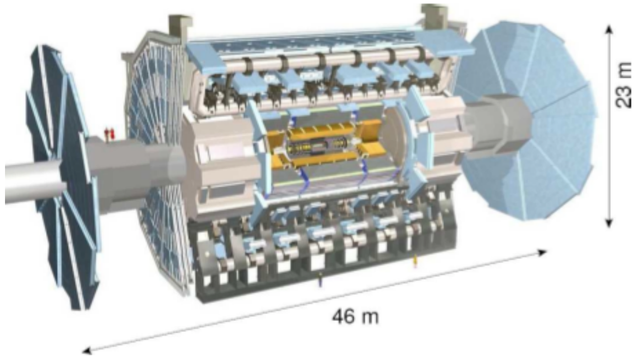
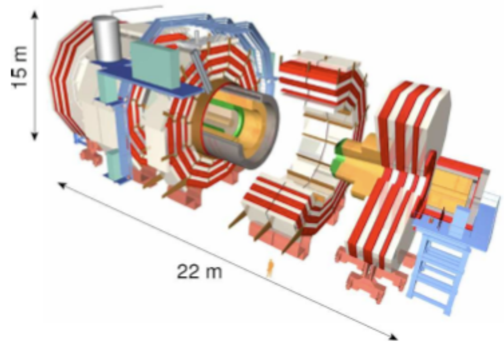


ATLAS



CMS

The ATLAS and CMS Detectors In a Nutshell

Sub System	ATLAS	CMS
Design		
Magnet(s)	Solenoid (within EM Calo) 2T 3 Air-core Toroids	Solenoid 3.8T Calorimeters Inside
Inner Tracking	Pixels, Si-strips, TRT PID w/ TRT and dE/dx $\sigma_{p_T}/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Pixels and Si-strips PID w/ dE/dx $\sigma_{p_T}/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM Calorimeter	Lead-Larg Sampling w/ longitudinal segmentation $\sigma_E/E \sim 10\%/\sqrt{E} \oplus 0.007$	Lead-Tungstate Crys. Homogeneous w/o longitudinal segmentation $\sigma_E/E \sim 3\%/\sqrt{E} \oplus 0.5\%$
Hadronic Calorimeter	Fe-Scint. & Cu-Larg (fwd) $\gtrsim 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. $\gtrsim 7\lambda_0$ Tail Catcher $\sigma_E/E \sim 100\%/\sqrt{E} \oplus 0.05$
Muon Spectrometer System Acc. ATLAS 2.7 & CMS 2.4	Instrumented Air Core (std. alone) $\sigma_{p_T}/p_T \sim 4\,\%$ (at 50 GeV) $\sim 11\,\%$ (at 1 TeV)	Instrumented Iron return yoke $\sigma_{p_T}/p_T \sim 1\%$ (at 50 GeV) $\sim 10\%$ (at 1 TeV)

Luminosity and Beam cross section

$$\mathcal{L} = \frac{N_p^2 k_b f_{rev} \gamma}{4\pi \beta^* \epsilon_n} F$$

Reduction factor W/ Beam crossing angle O(0.9)

Parameter	2010	2011	Nominal
N(10^{11} p/bunch)	1.2	1.35	1.15
k (N bunches)	368	1380	2808
Bunch spacing	150	50	25
ε (μm rad)	2.4-4	1.9-2.3	3.75
β^* (m)	3.5	1.5-1	0.55
L ($cm^{-2}s^{-1}$)	2×10^{32}	3.3×10^{33}	10^{34}

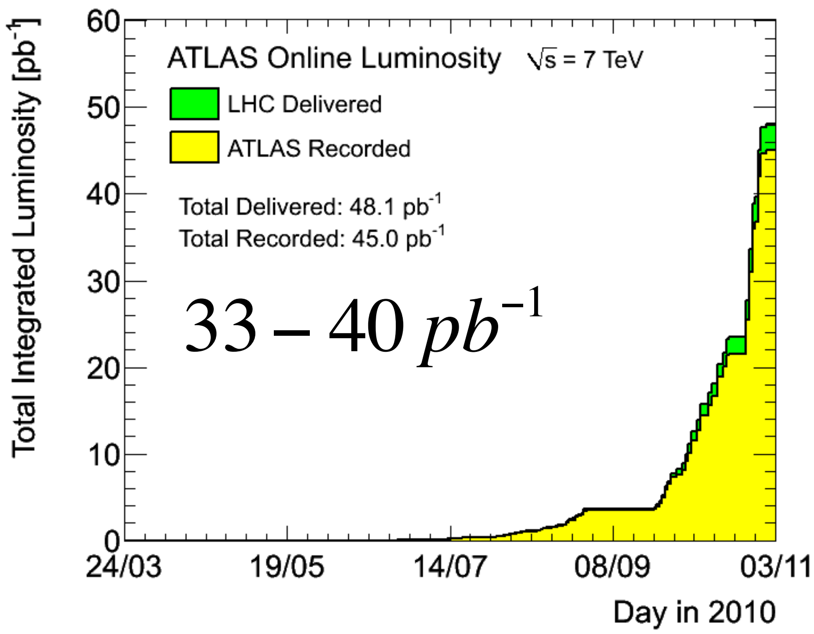
Beam parameters close to nominal in terms of luminosity

Two Years of Remarkable LHC operations

Glimpse at the Luminosity

2010

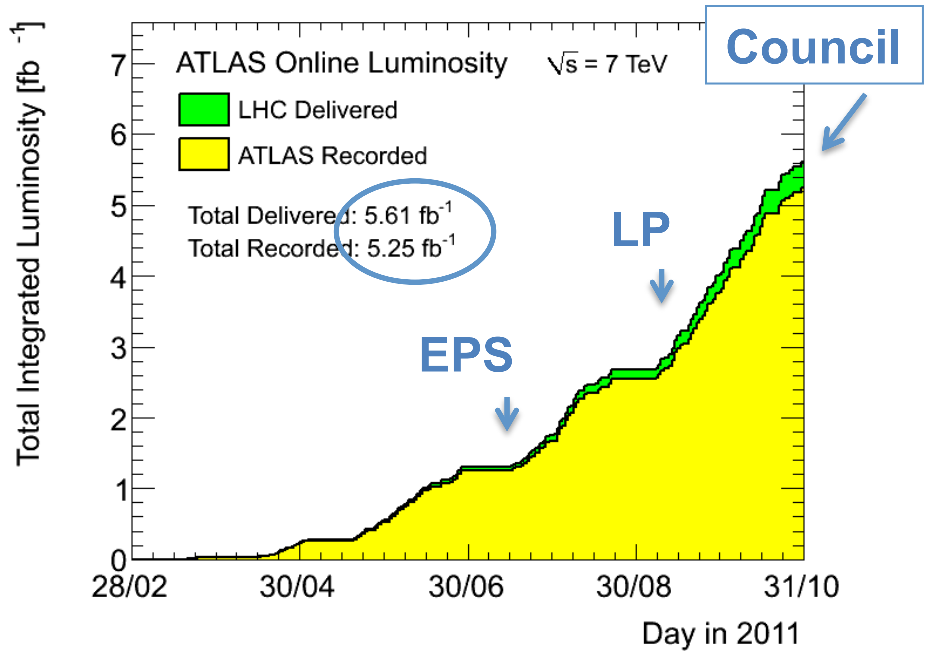
Re-discovery of the SM at LHC



Measurement of rather detailed properties of the W and Z boson production

2011

Closing in on the Higgs search



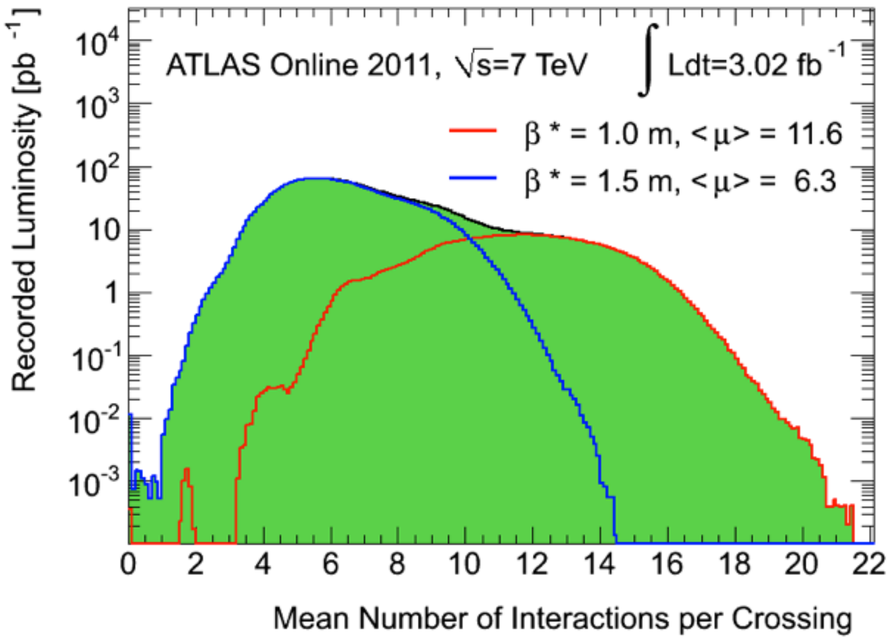
Measurement of di-boson production and Higgs searches

The 2011 Dataset

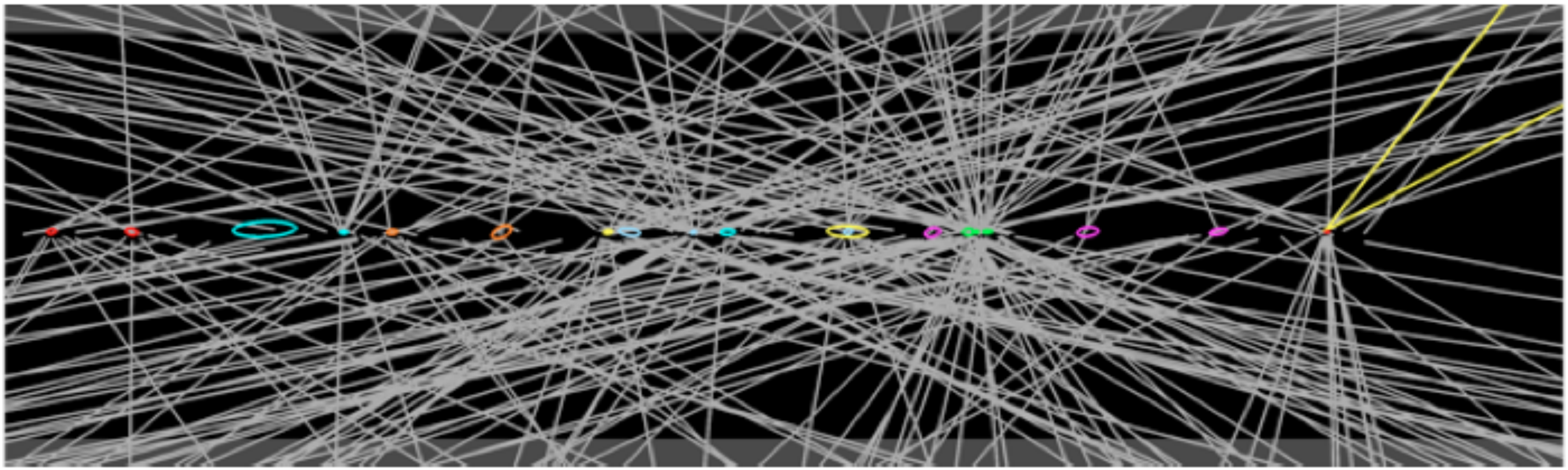
2011 (Fall)

$$\sim 5\,fb^{-1}$$

Quite high PU!



Recent event with 15 Vertices



Preamble : Breakthroughs in Phenomenolgy

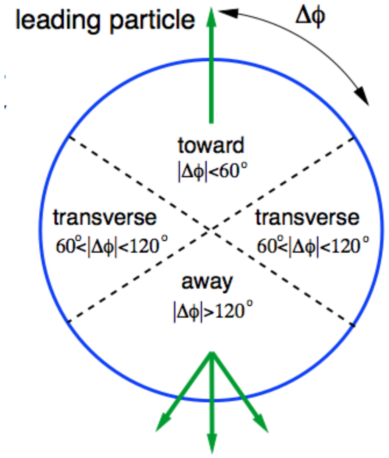
Several breakthroughs in the past decade have drastically changed the theory prospective to the hadron collider processes.

- The "Next-to…" revolution :
  - Breakthrough ideas in computation of loops (sewing together tree level amplitudes).
  - NLO generators, blackhat, NLOjet++, Phox, MCFM, etc…
  - NLO generators w/ PS, MC@NLO and POWHEG.
  - NLO+NLL or NNLL, CAESAR, ResBos, HqT
  - NNLO, FEHIP, FEWZ, HNNLO, DYNNLO
  - …
- NNLO PDFs sets
- Parton Shower (and Matrix Element matching) improvements :

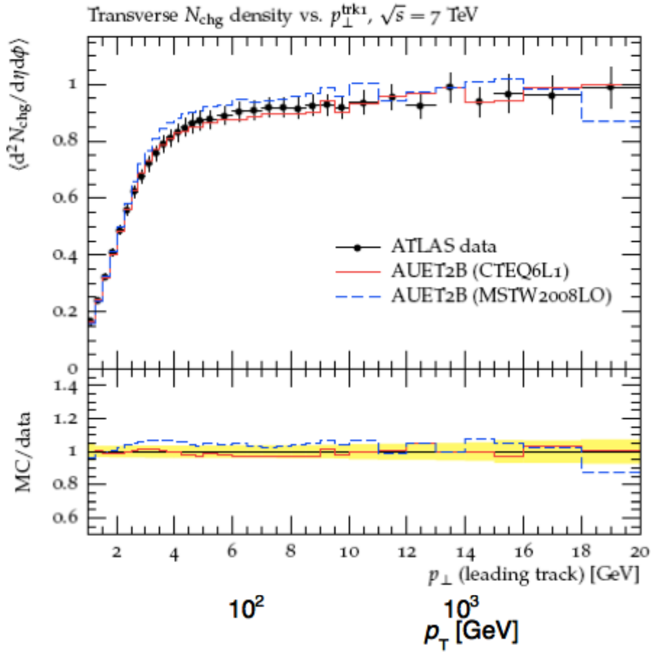
  Pythia (8.1), Herwig++, Sherpa and CKKW (1.3) and MadGraph (5.0) performing very well (Including description of the Pile Up and the underlying event).

- The Jet revolution (Fast Jet) : Allowing to compute in reasonable time infra-red safe k_T jets.

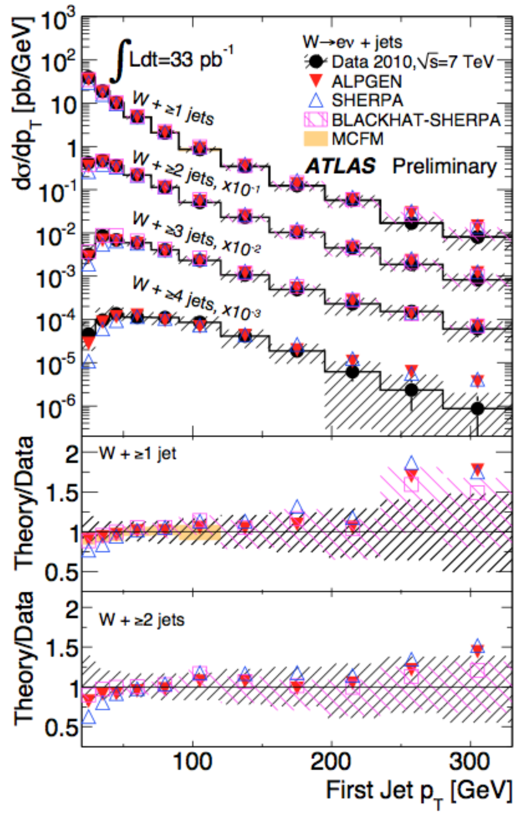
QCD



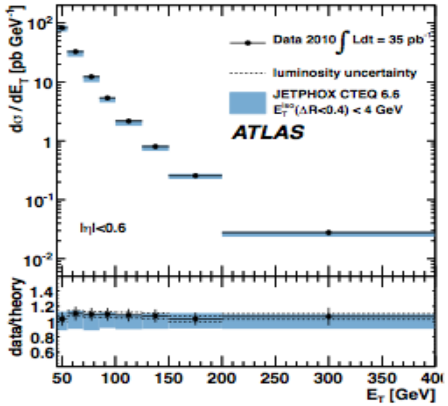
leading particle
Δφ
toward
|Δφ|<60°
transverse
60°<|Δφ|<120°
transverse
60°<|Δφ|<120°
away
|Δφ|>120°



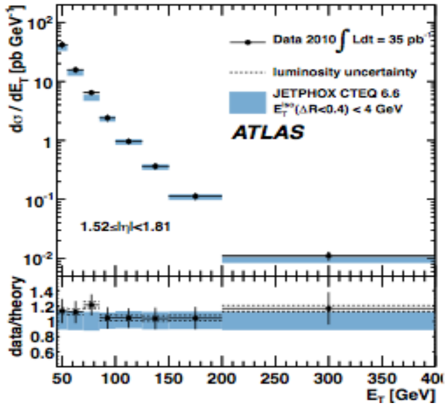
Transverse N_{chg} density vs. $p_\perp^{trk1}$, $\sqrt{s} = 7$ TeV
$\langle d^2 N_{chg} / d\eta\, d\phi \rangle$
ATLAS data
AUET2B (CTEQ6L1)
AUET2B (MSTW2008LO)
MC / data
$p_\perp$ (leading track) [GeV]
10^2
10^3
p_T [GeV]



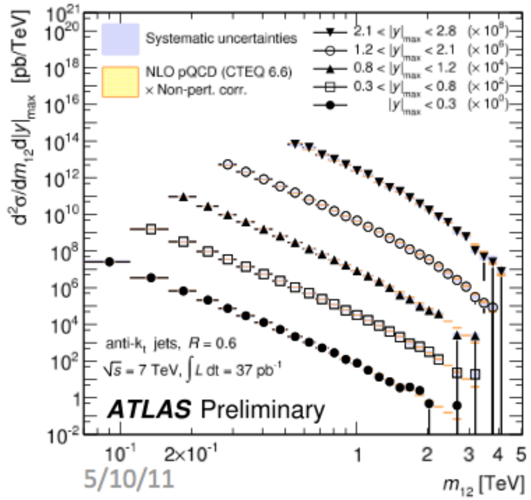
$d\sigma/dp_T$ [pb/GeV]
$\int Ldt = 33$ pb^{-1}
W→eν + jets
Data 2010, $\sqrt{s}$=7 TeV
ALPGEN
SHERPA
BLACKHAT-SHERPA
MCFM
ATLAS Preliminary
W + ≥1 jets
W + ≥2 jets, x10^{-1}
W + ≥3 jets, x10^{-2}
W + ≥4 jets, x10^{-3}
Theory/Data
W + ≥1 jet
W + ≥2 jets
First Jet p_T [GeV]



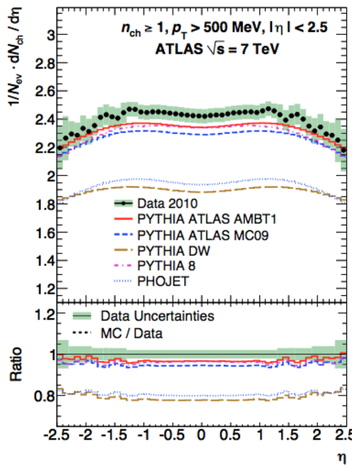
Data 2010 $\int$ Ldt = 35 pb^{-1}
luminosity uncertainty
JETPHOX CTEQ 6.6
$E_T^{iso}(\Delta R<0.4) < 4$ GeV
ATLAS
$d\sigma / dE_T$ [pb GeV^{-1}]
|η|<0.6
data/theory
E_T [GeV]



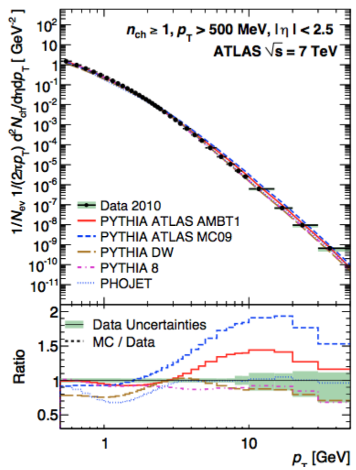
Data 2010 $\int$ Ldt = 35 pb^{-1}
luminosity uncertainty
JETPHOX CTEQ 6.6
$E_T^{iso}(\Delta R<0.4) < 4$ GeV
ATLAS
$d\sigma / dE_T$ [pb GeV^{-1}]
1.52≤|η|<1.81
data/theory
E_T [GeV]



Systematic uncertainties
NLO pQCD (CTEQ 6.6) × Non-pert. corr.
$2.1 < |y|_{max} < 2.8$ ($\times 10^8$)
$1.2 < |y|_{max} < 2.1$ ($\times 10^6$)
$0.8 < |y|_{max} < 1.2$ ($\times 10^4$)
$0.3 < |y|_{max} < 0.8$ ($\times 10^2$)
$|y|_{max} < 0.3$ ($\times 10^0$)
$d^2\sigma/dm_{12}d|y|_{max}$ [pb/TeV]
anti-k_t jets, $R = 0.6$
$\sqrt{s} = 7$ TeV, $\int L\, dt = 37$ pb^{-1}
ATLAS Preliminary
m_{12} [TeV]

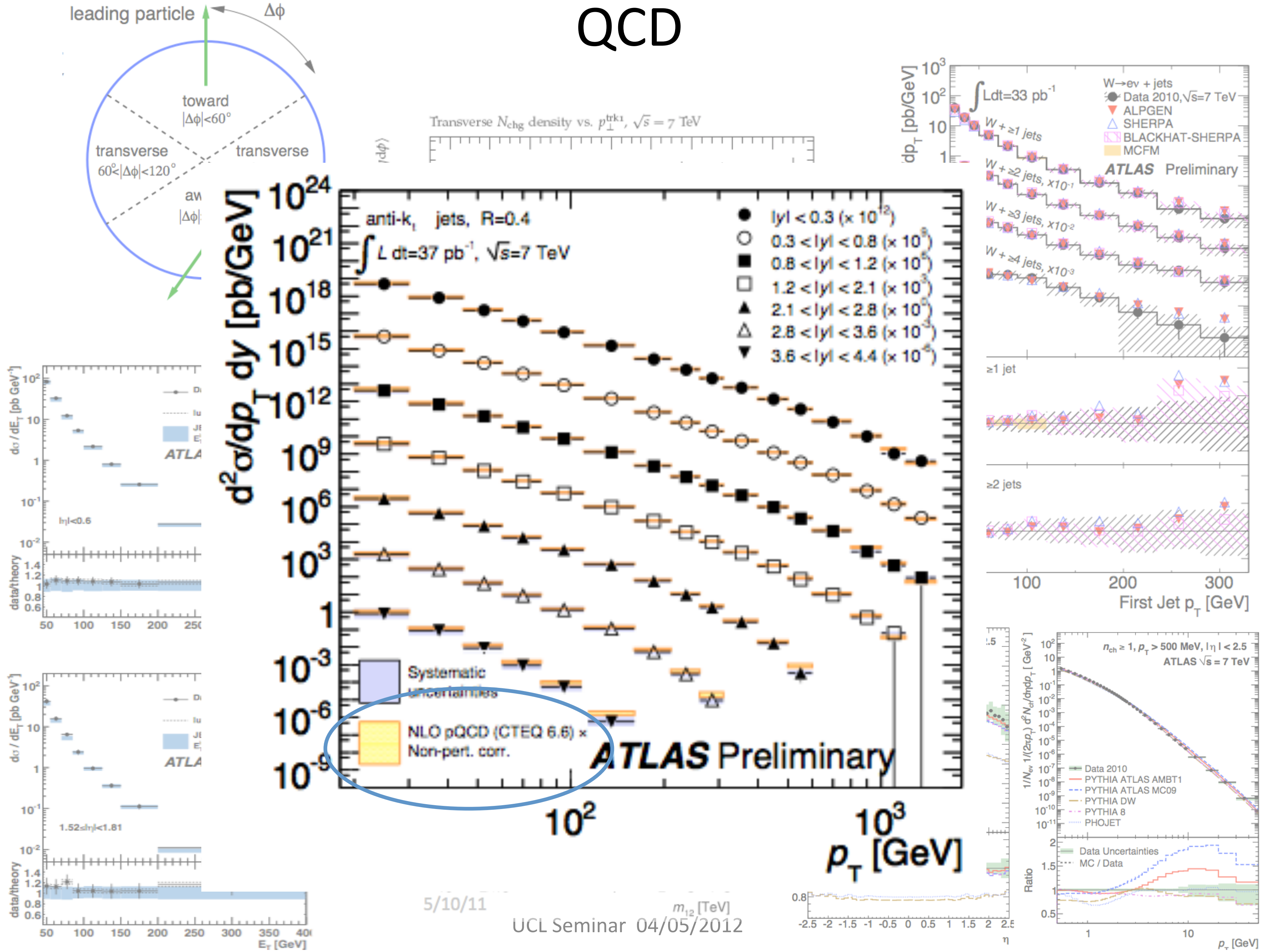


$n_{ch} \geq 1$, $p_T > 500$ MeV, $|\eta| < 2.5$
ATLAS $\sqrt{s}$ = 7 TeV
$1/N_{ev} \cdot dN_{ch}/d\eta$
Data 2010
PYTHIA ATLAS AMBT1
PYTHIA ATLAS MC09
PYTHIA DW
PYTHIA 8
PHOJET
Data Uncertainties
MC / Data
Ratio
η

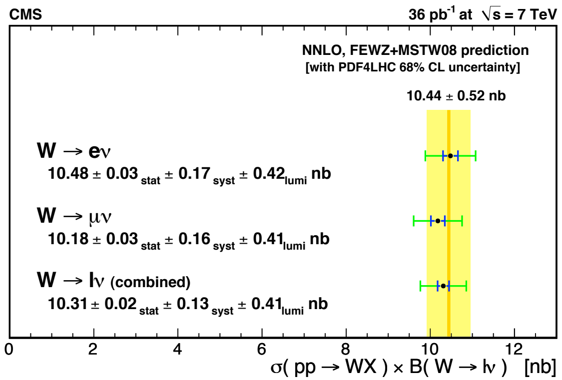


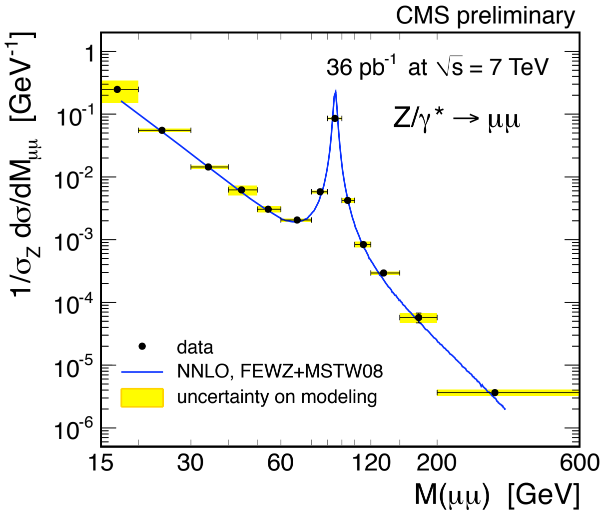
$n_{ch} \geq 1$, $p_T > 500$ MeV, $|\eta| < 2.5$
ATLAS $\sqrt{s}$ = 7 TeV
$1/N_{ev}\, 1/(2\pi p_T)\, d^2N_{ch}/d\eta dp_T$ [GeV^{-2}]
Data 2010
PYTHIA ATLAS AMBT1
PYTHIA ATLAS MC09
PYTHIA DW
PYTHIA 8
PHOJET
Data Uncertainties
MC / Data
Ratio
p_T [GeV]

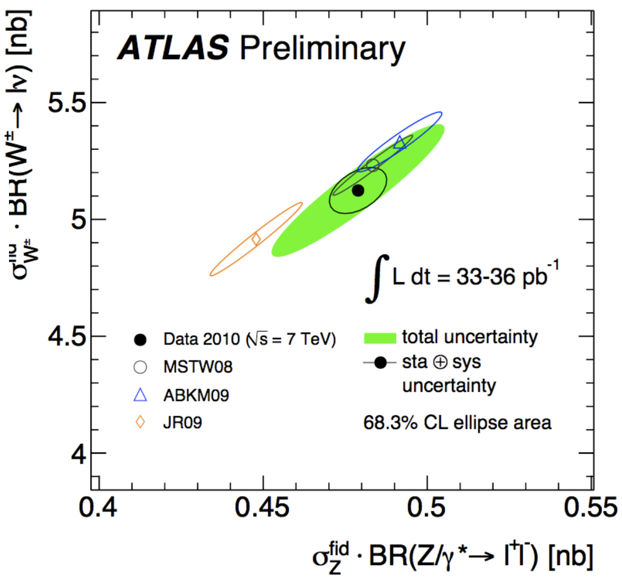
QCD

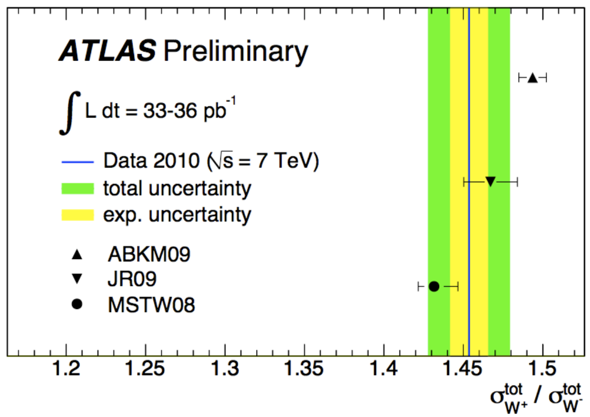

anti-k$_t$ jets, R=0.4
$\int L\,dt$=37 pb^{-1}, $\sqrt{s}$=7 TeV
|y| < 0.3 (× 10^{12})
0.3 < |y| < 0.8 (× 10^{9})
0.8 < |y| < 1.2 (× 10^{6})
1.2 < |y| < 2.1 (× 10^{3})
2.1 < |y| < 2.8 (× 10^{0})
2.8 < |y| < 3.6 (× 10^{-3})
3.6 < |y| < 4.4 (× 10^{-6})
Systematic uncertainties
NLO pQCD (CTEQ 6.6) × Non-pert. corr.
ATLAS Preliminary
$d^2\sigma/dp_T dy$ [pb/GeV]
p_T [GeV]
leading particle
Δφ
toward
|Δφ|<60°
transverse
60°<|Δφ|<120°
transverse
Transverse N_{chg} density vs. $p_\perp^{trk1}$, $\sqrt{s}$ = 7 TeV
W→eν + jets
Data 2010, $\sqrt{s}$=7 TeV
ALPGEN
SHERPA
BLACKHAT-SHERPA
MCFM
$\int$Ldt=33 pb^{-1}
ATLAS Preliminary
W + ≥1 jets
W + ≥2 jets, x10^{-1}
W + ≥3 jets, x10^{-2}
W + ≥4 jets, x10^{-3}
≥1 jet
≥2 jets
First Jet p$_T$ [GeV]
n_{ch} ≥ 1, p_T > 500 MeV, |η| < 2.5
ATLAS $\sqrt{s}$ = 7 TeV
Data 2010
PYTHIA ATLAS AMBT1
PYTHIA ATLAS MC09
PYTHIA DW
PYTHIA 8
PHOJET
Data Uncertainties
MC / Data
Ratio
p_T [GeV]
dσ / dE$_T$ [pb GeV^{-1}]
data/theory
|η|<0.6
1.52≤|η|<1.81
E$_T$ [GeV]
5/10/11
m_{12} [TeV]

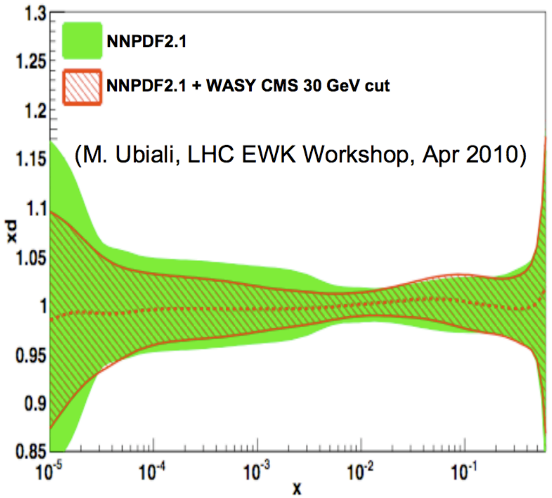
EW

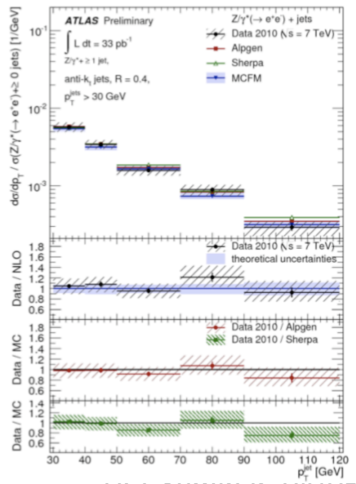

CMS
36 pb^{-1} at $\sqrt{s}$ = 7 TeV
NNLO, FEWZ+MSTW08 prediction
[with PDF4LHC 68% CL uncertainty]
10.44 ± 0.52 nb
W → eν
10.48 ± 0.03 stat ± 0.17 syst ± 0.42 lumi nb
W → μν
10.18 ± 0.03 stat ± 0.16 syst ± 0.41 lumi nb
W → lν (combined)
10.31 ± 0.02 stat ± 0.13 syst ± 0.41 lumi nb
σ(pp → WX) × B(W → lν) [nb]

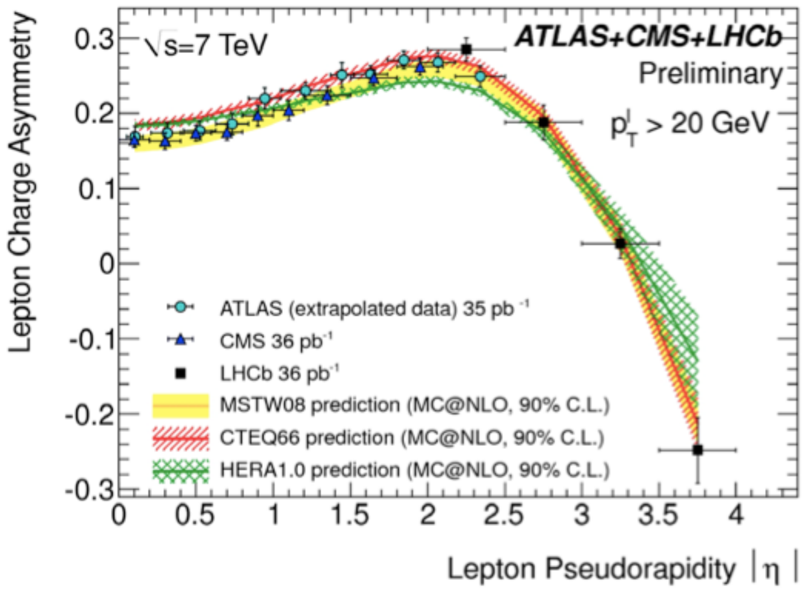

CMS preliminary
36 pb^{-1} at $\sqrt{s}$ = 7 TeV
Z/γ* → μμ
1/σ$_Z$ dσ/dM$_{μμ}$ [GeV^{-1}]
data
NNLO, FEWZ+MSTW08
uncertainty on modeling
M(μμ) [GeV]


ATLAS Preliminary
∫ L dt = 33-36 pb^{-1}
Data 2010 ($\sqrt{s}$ = 7 TeV)
MSTW08
ABKM09
JR09
total uncertainty
sta ⊕ sys uncertainty
68.3% CL ellipse area
σ$^{fid}_{W^\pm}$ · BR(W$^\pm$ → lν) [nb]
σ$^{fid}_Z$ · BR(Z/γ*→ l$^+$l$^-$) [nb]

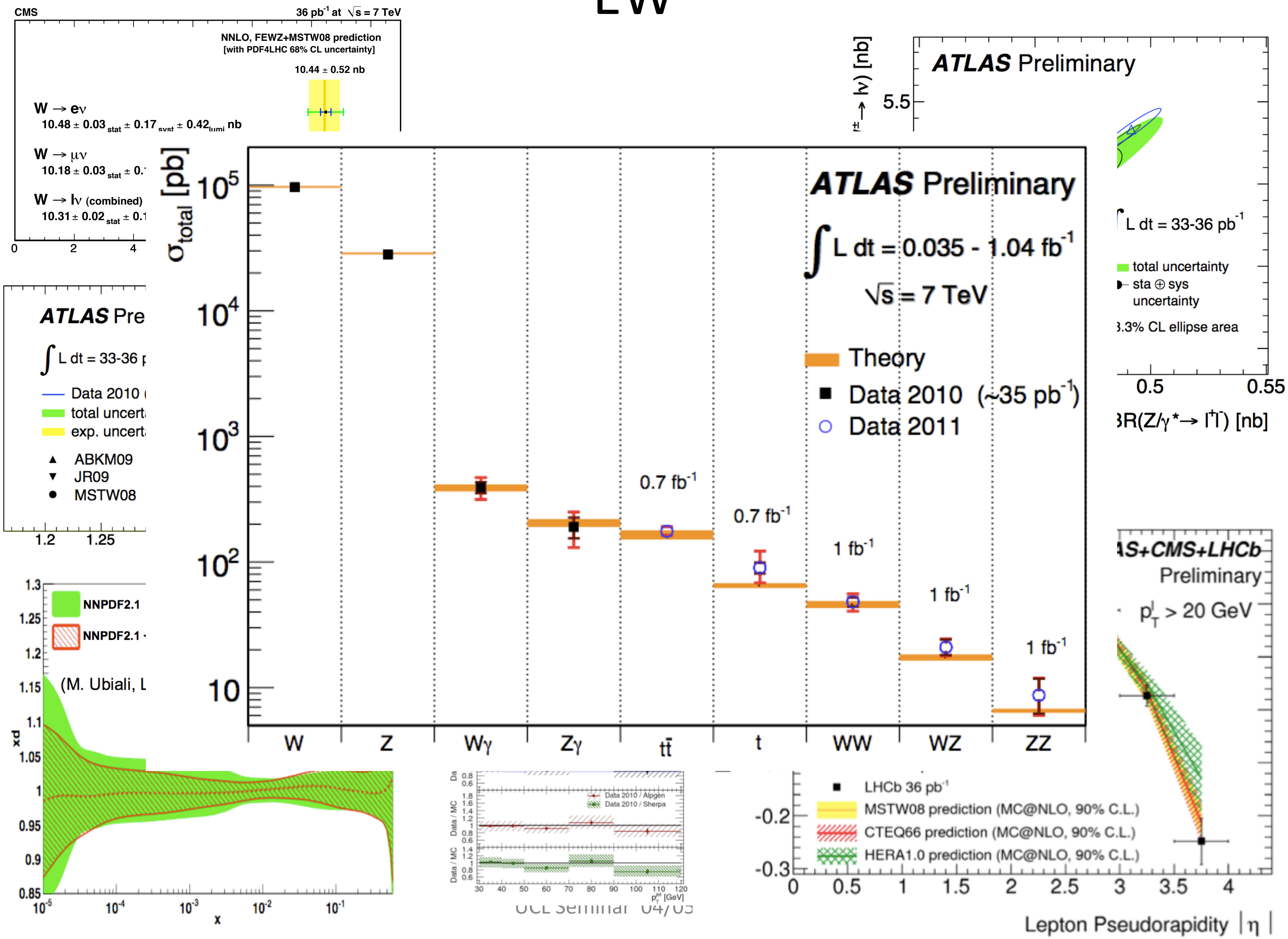

ATLAS Preliminary
∫ L dt = 33-36 pb^{-1}
Data 2010 ($\sqrt{s}$ = 7 TeV)
total uncertainty
exp. uncertainty
ABKM09
JR09
MSTW08
σ$^{tot}_{W^+}$ / σ$^{tot}_{W^-}$


NNPDF2.1
NNPDF2.1 + WASY CMS 30 GeV cut
(M. Ubiali, LHC EWK Workshop, Apr 2010)
xd
x

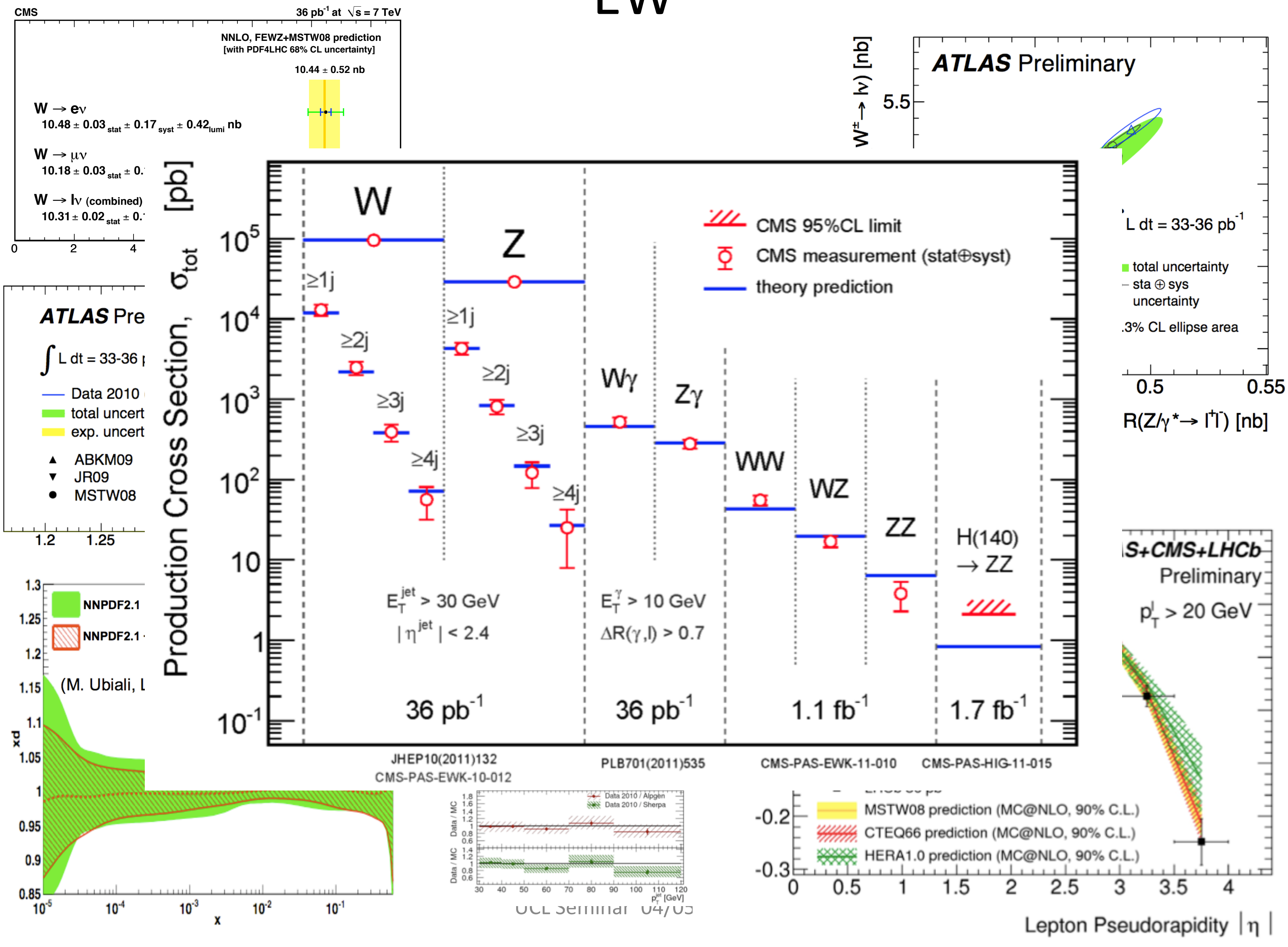

ATLAS Preliminary
Data 2010 ($\sqrt{s}$ = 7 TeV)
Alpgen
Sherpa
MCFM
theoretical uncertainties
Data / NLO
Data / MC


$\sqrt{s}$=7 TeV
ATLAS+CMS+LHCb
Preliminary
p^l_T > 20 GeV
ATLAS (extrapolated data) 35 pb^{-1}
CMS 36 pb^{-1}
LHCb 36 pb^{-1}
MSTW08 prediction (MC@NLO, 90% C.L.)
CTEQ66 prediction (MC@NLO, 90% C.L.)
HERA1.0 prediction (MC@NLO, 90% C.L.)
Lepton Charge Asymmetry
Lepton Pseudorapidity |η|

EW

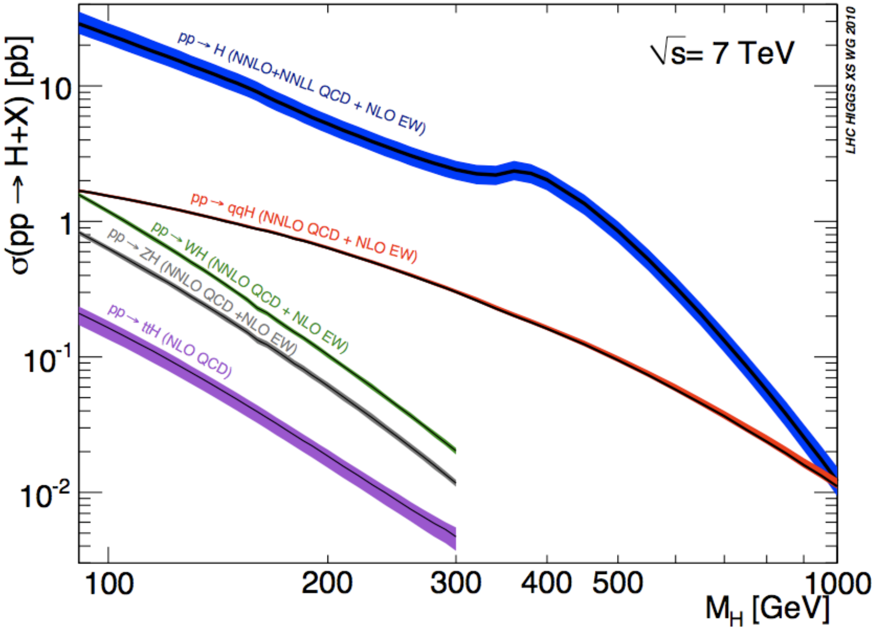

ATLAS Preliminary
∫L dt = 0.035 - 1.04 fb⁻¹
√s = 7 TeV
Theory
Data 2010 (~35 pb⁻¹)
Data 2011
σ_total [pb]
0.7 fb⁻¹
0.7 fb⁻¹
1 fb⁻¹
1 fb⁻¹
1 fb⁻¹
W
Z
Wγ
Zγ
tt̄
t
WW
WZ
ZZ
CMS
36 pb⁻¹ at √s = 7 TeV
NNLO, FEWZ+MSTW08 prediction
[with PDF4LHC 68% CL uncertainty]
10.44 ± 0.52 nb
W → eν
10.48 ± 0.03 stat ± 0.17 syst ± 0.42 lumi nb
W → μν
W → lν (combined)
ABKM09
JR09
MSTW08
NNPDF2.1
LHCb 36 pb⁻¹
MSTW08 prediction (MC@NLO, 90% C.L.)
CTEQ66 prediction (MC@NLO, 90% C.L.)
HERA1.0 prediction (MC@NLO, 90% C.L.)
Lepton Pseudorapidity |η|

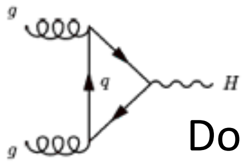
EW


CMS
36 pb^{-1} at $\sqrt{s}$ = 7 TeV
NNLO, FEWZ+MSTW08 prediction
[with PDF4LHC 68% CL uncertainty]
10.44 ± 0.52 nb
W → eν
10.48 ± 0.03 stat ± 0.17 syst ± 0.42 lumi nb
W → μν
W → lν (combined)
ATLAS Preliminary
Data 2010
total uncert
exp. uncert
ABKM09
JR09
MSTW08
NNPDF2.1
(M. Ubiali,
Production Cross Section, σ_{tot} [pb]
W
Z
≥1j
≥2j
≥3j
≥4j
Wγ
Zγ
WW
WZ
ZZ
H(140) → ZZ
CMS 95%CL limit
CMS measurement (stat⊕syst)
theory prediction
E_T^{jet} > 30 GeV
$|\eta^{jet}|$ < 2.4
E_T^{γ} > 10 GeV
ΔR(γ,l) > 0.7
36 pb^{-1}
36 pb^{-1}
1.1 fb^{-1}
1.7 fb^{-1}
JHEP10(2011)132
CMS-PAS-EWK-10-012
PLB701(2011)535
CMS-PAS-EWK-11-010
CMS-PAS-HIG-11-015
total uncertainty
uncertainty
R(Z/γ*→ l$^+$l$^-$) [nb]
Data 2010 / Alpgen
Data 2010 / Sherpa
Preliminary
p_T^l > 20 GeV
MSTW08 prediction (MC@NLO, 90% C.L.)
CTEQ66 prediction (MC@NLO, 90% C.L.)
HERA1.0 prediction (MC@NLO, 90% C.L.)
Lepton Pseudorapidity |η|

The Main Production Modes

Data driven background estimates legitimate use of NNLO cross sections!





- Gluon fusion process :

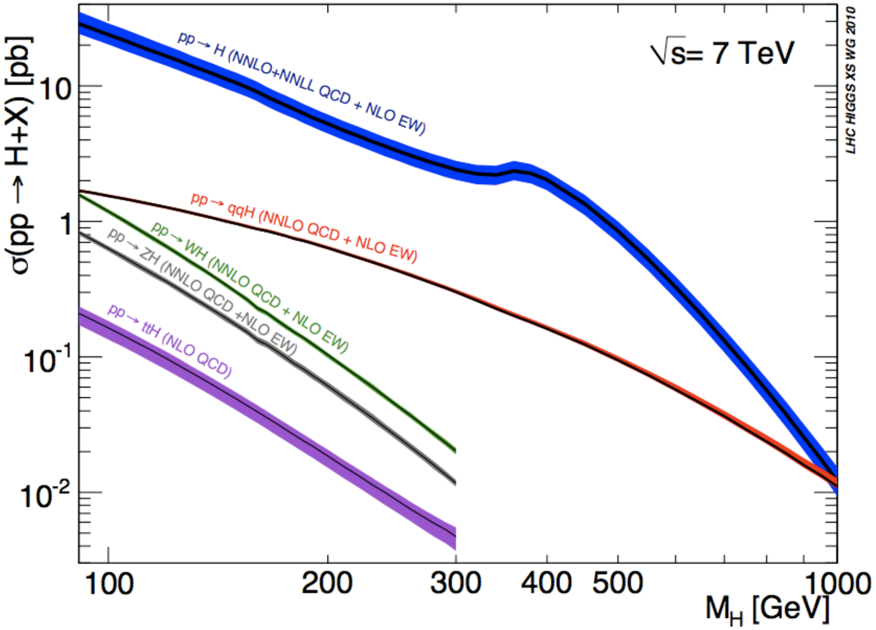
Dominant process known at NNnLO

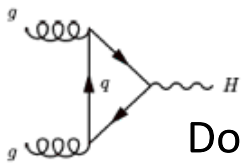
However rather large TH uncertainty* ~O(15%) due to the large corrections for gluon initiated process

* TH uncertainty mostly from scale variation and PDFs, $\delta\sigma_{PDF-\alpha s}$~8-10% and $\delta\sigma_{Scale}$~ 7-8%

The Main Production Modes

Data driven background estimates legitimate use of NNLO cross sections!





- Gluon fusion process :

Dominant process known at NNnLO

~100 kEvts produced at 120 GeV

* TH uncertainty mostly from scale variation and PDFs, $\delta\sigma_{PDF-\alpha s}$~8-10% and $\delta\sigma_{Scale\sim}$ 7-8%

The Main Production Modes

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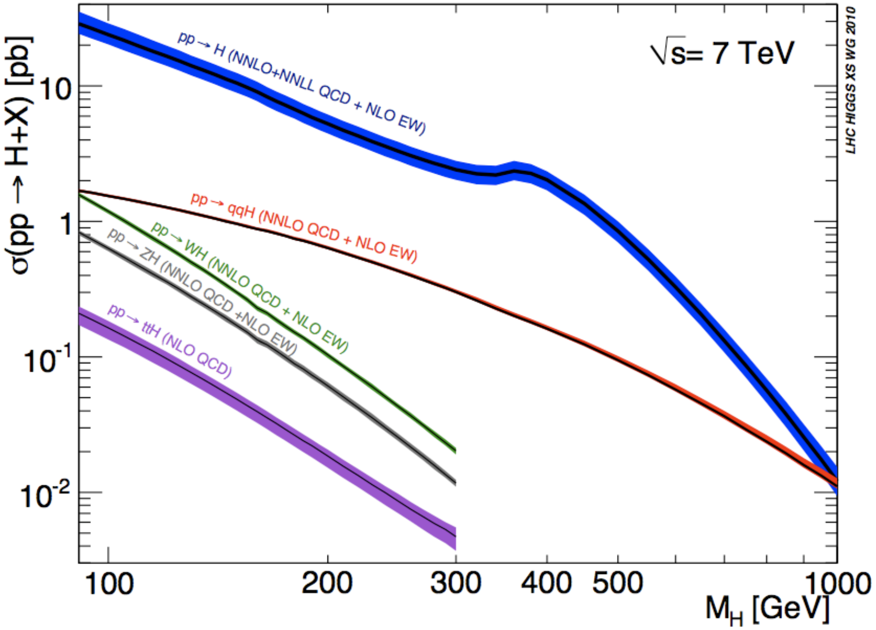

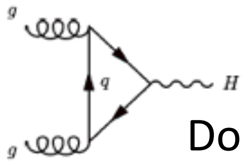

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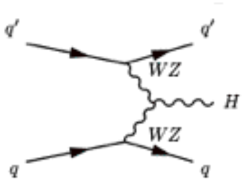

- Vector Boson Fusion :

known at NLO TH uncertainty ~O(5%)

Rather distinctive features w/ two conspicuous forward jets and a rapidity gap

* TH uncertainty mostly from scale variation and PDFs, $\delta\sigma_{PDF-\alpha s}$~8-10% and $\delta\sigma_{Scale}$~ 7-8%

The Main Production Modes

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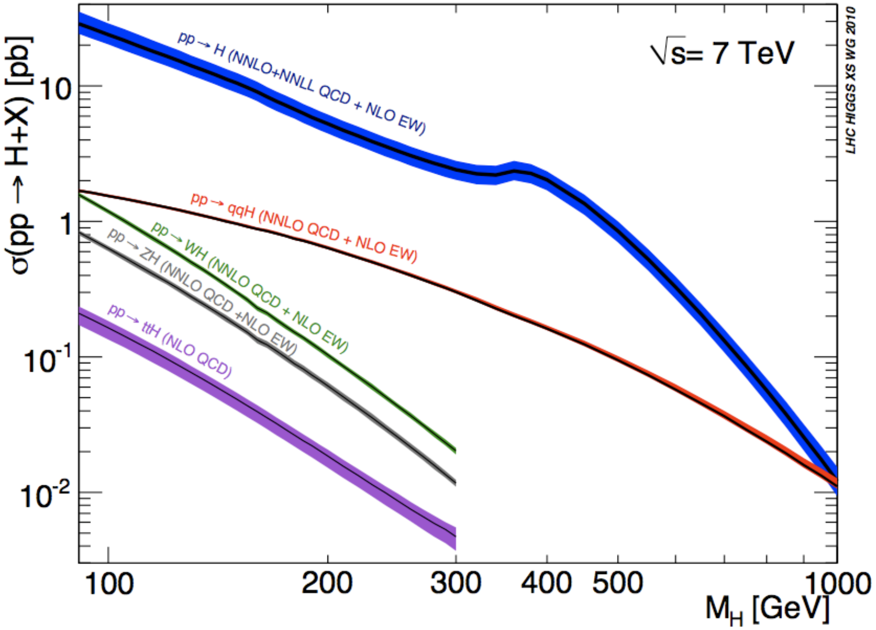

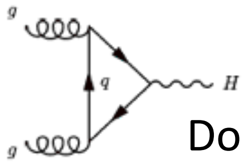

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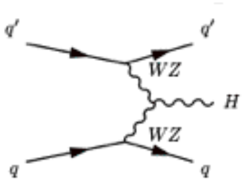

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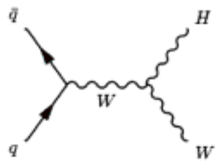
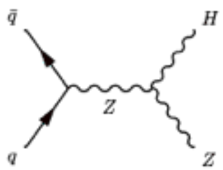
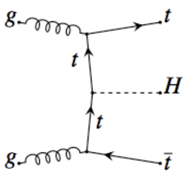




- Associated Production with W and Z :

known at NNLO TH uncertainty ~O(5%)

Very distinctive feature with a Z or W decaying leptonically



- Associated Production with top pair :

known at NLO TH uncertainty ~O(15%)

Quite distinctive but also quite crowded

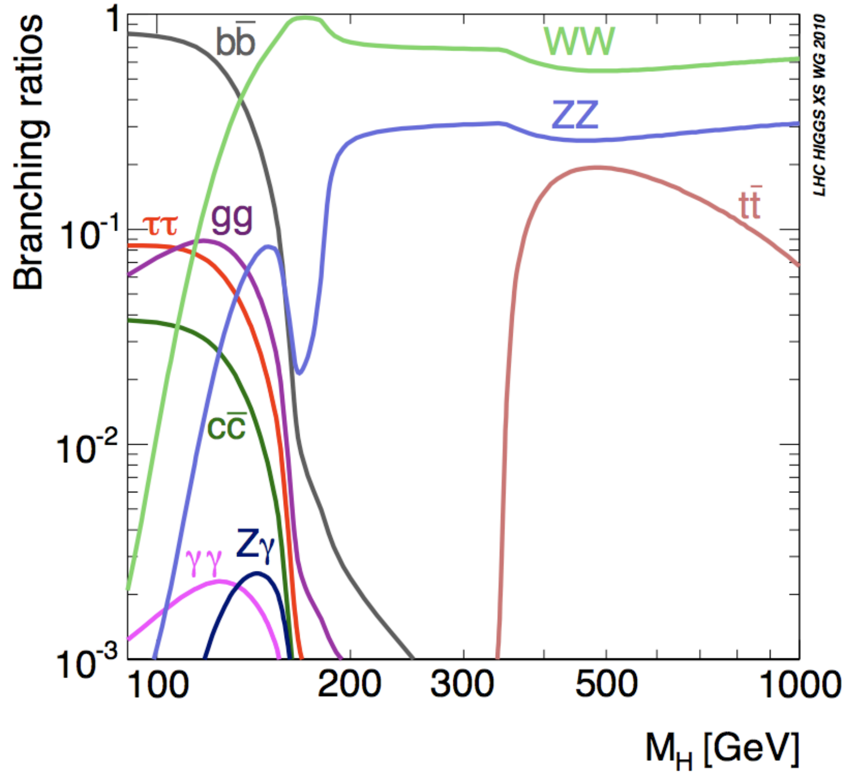
* TH uncertainty mostly from scale variation and PDFs, $\delta\sigma_{PDF-\alpha s}$ ~8-10% and $\delta\sigma_{Scale}$~ 7-8%

Decay Modes

Pure Branching Fractions

- The dominant b-decay channel

Huge backgrounds, needs distinctive features at production level and beyond… Associate production W,Z H and Boost!



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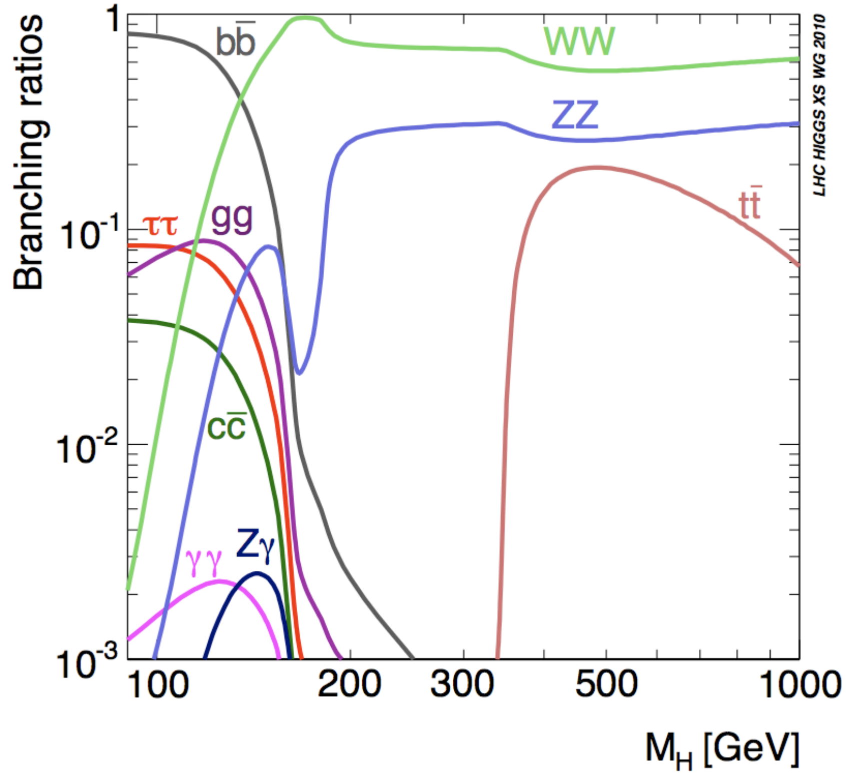
- The ττ channel

Also needs distinctive production features, typically VBF or VH. Hopes from NEW MASS RECOSTRUCTION techniques



Decay Modes

Exclusive Modes Cross Sections

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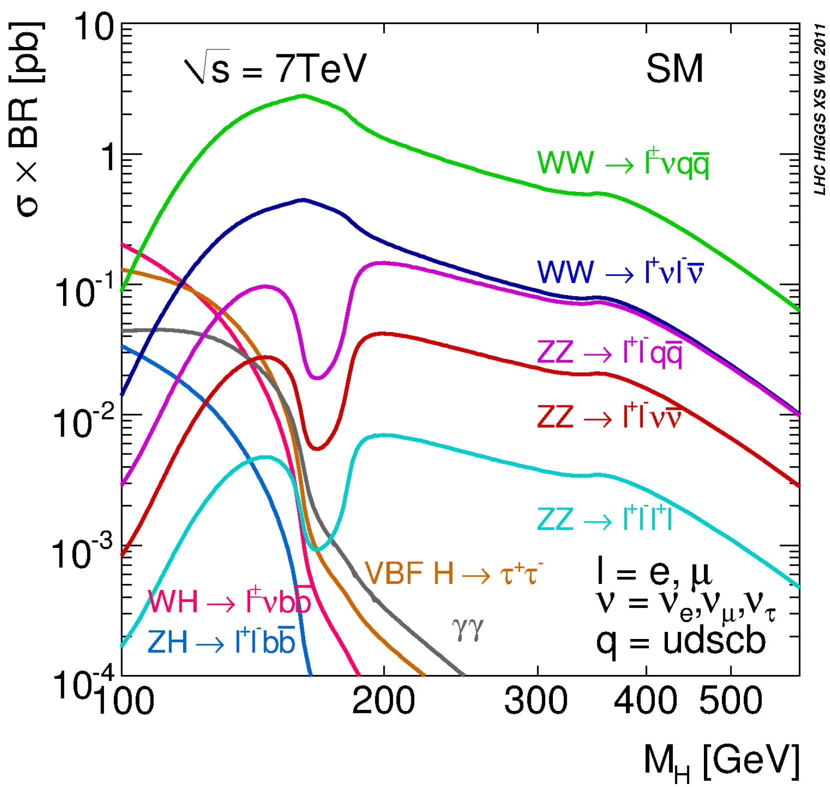
- The $\gamma\gamma$ channel

Dominant Channel in the very low mass range. Small branching but sizable yield. Very distinctive signature on its own.



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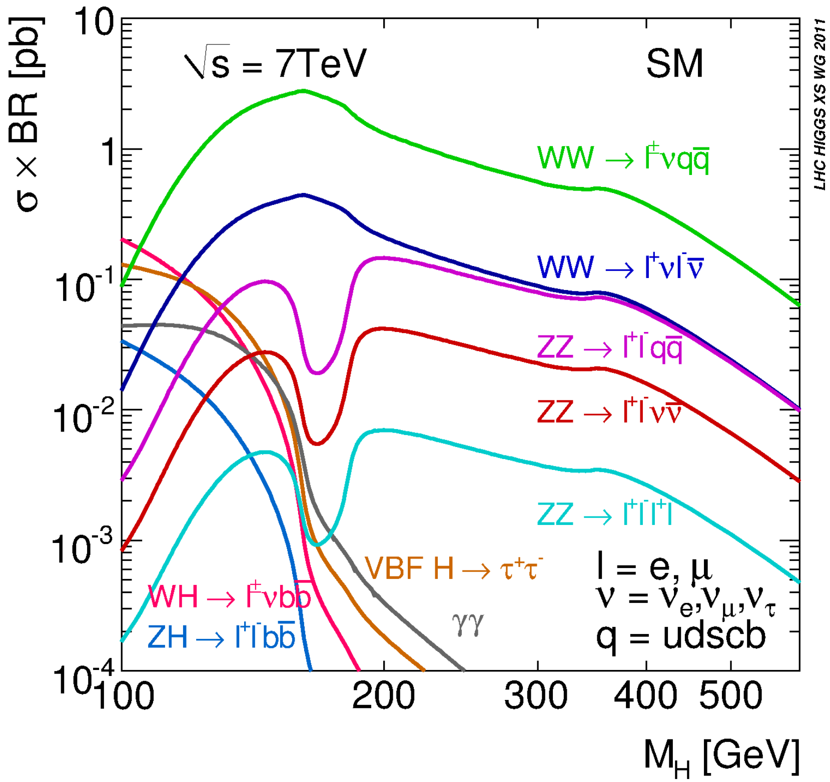

- The WW Channels

- Dilepton (lnln) channel is dominant in the low mass (very poor mass resolution, essentially counting experiment)
- Semi leptonic (lnqq) largest event yield effective at large mass where the background is smaller.

Decay Modes

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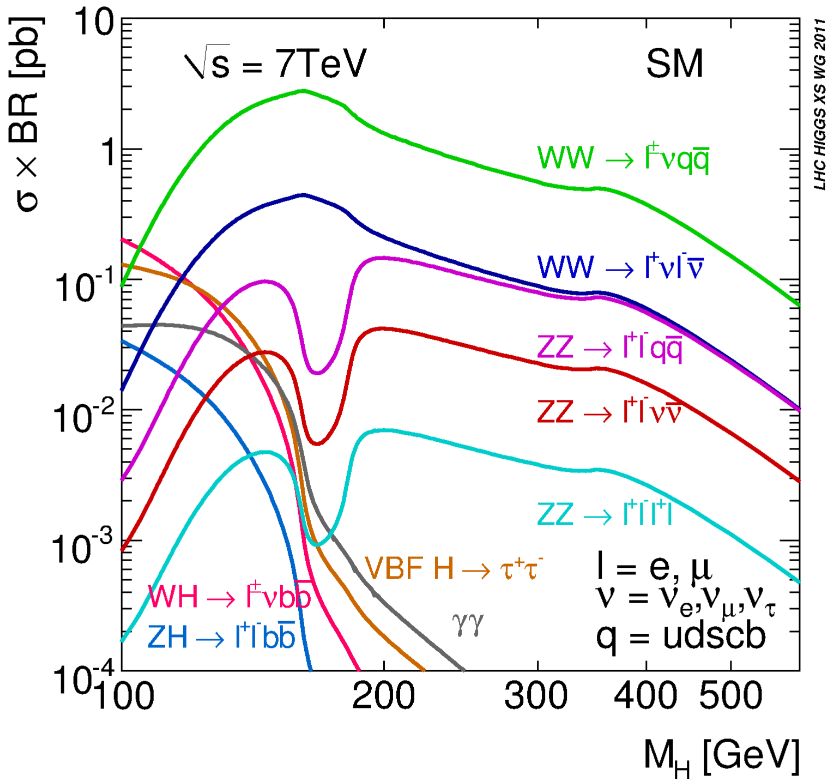


- The WW Channels

- Dilepton (lνlν) channel is dominant in the low mass (very poor mass resolution, essentially counting experiment)
- Semi leptonic (lnqq) largest event yield effective at large mass where the background is smaller.

- The ZZ Channels

- 4-leptons : "Golden mode" smallest event yield but large s/b ratio
- semi-leptonic (llqq) larger event yield but also much larger background (make use of the large branching Z in bb)
- 2-leptons 2-neutrinos (llνν) : Best compromise yield/purity. Dominant channel at high mass

Production Modes and Decay Channels

Channel		ggF	VBF	W,Z H	ttH	Range (GeV)
γγ		✓	✓	✓	✓	110-150
ττ		✓	✓			110-140
W,Z H (bb)				✓		110-130
ZZ (llll)		✓	✓			110-130
WW (lνlν)	0-jet	✓				110-600
	1-jet	✓	✓			110-600
	VBF	✓	✓			110-600
	WH*	✓		✓		110-200
WW** (lνqq)	0-jet	✓	✓			300-600
	1-jet	✓	✓			300-600
	VBF		✓			300-600
ZZ (llνν)		✓	✓			110-600
ZZ (llττ)*		✓	✓			200-600
ZZ (llqq)		✓	✓			130*-600

* CMS only / ** ATLAS only

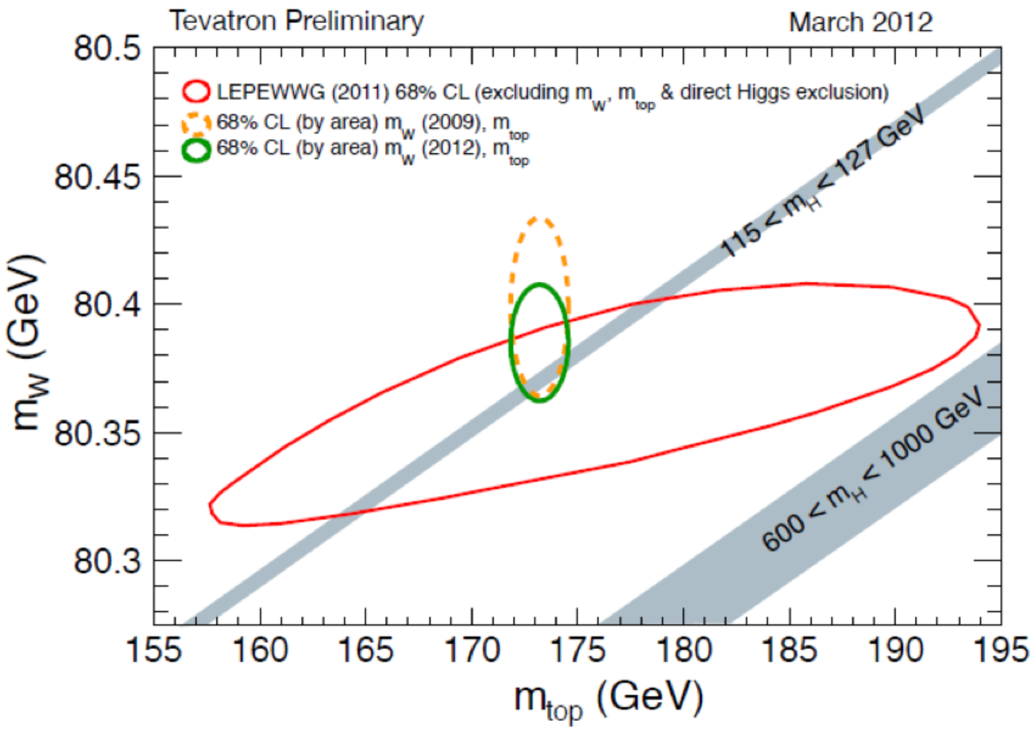
Low Mass : Challenging Range
110 -150 GeV/c^2

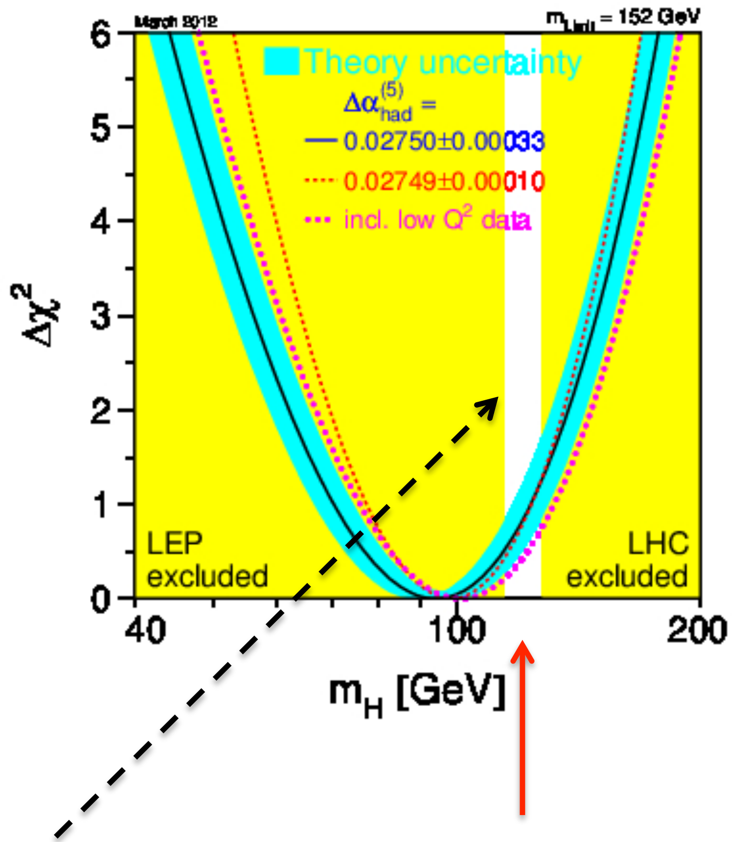
Intermediate : Wide Range
110 - 600 GeV/c^2

High Mass : Larger contribution from VBF
200 - 600 GeV/c^2

Not theory difficulties above 500 GeV/c^2

Indirect Constraints





With M_W = 80385±15 MeV

$M_H = 94^{+29}_{-24}$ GeV
$M_H < 152$ GeV @95% CL

LEP exclusion 114 GeV

Will concentrate on the low Higgs mass range [110-150] GeV

Selected Topics

Low mass channels only

Channel		ggF	VBF	W,Z H	ttH	Range (GeV)
$\gamma\gamma$		✓	✓	✓	✓	110-150
$\tau\tau$		✓	✓			110-140
W,Z H (bb)				✓		110-130
ZZ (llll)		✓	✓			110-130
WW ($l\nu l\nu$)	0-jet	✓				110-600
	1-jet	✓	✓			110-600
	VBF	✓	✓			110-600
	WH*	✓		✓		110-200
ZZ (llqq)		✓	✓			130*-600

* CMS only

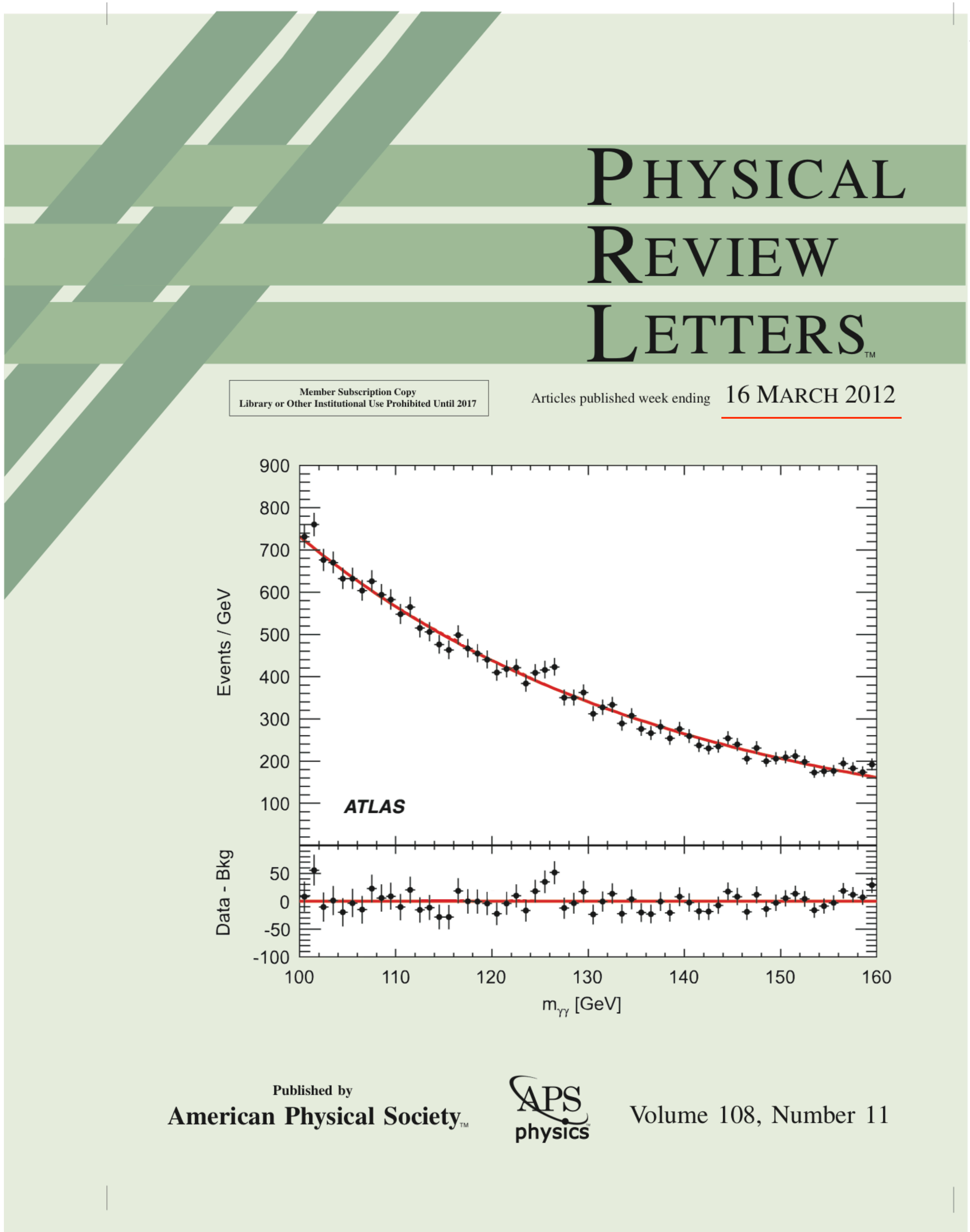
Will only cover SM Higgs searches and interpretation

← Lower Sensitivity at very low mass but very interesting (see backup)

← Very low sensitivty and does not cover vaery low masses (see backup)

Statistical Interpretation

How to read Higgs Search Plots



How to read Higgs Search Plots…

Starting from PRL Cover Plot

Statistical Interpretation

How to read Higgs Search Plots

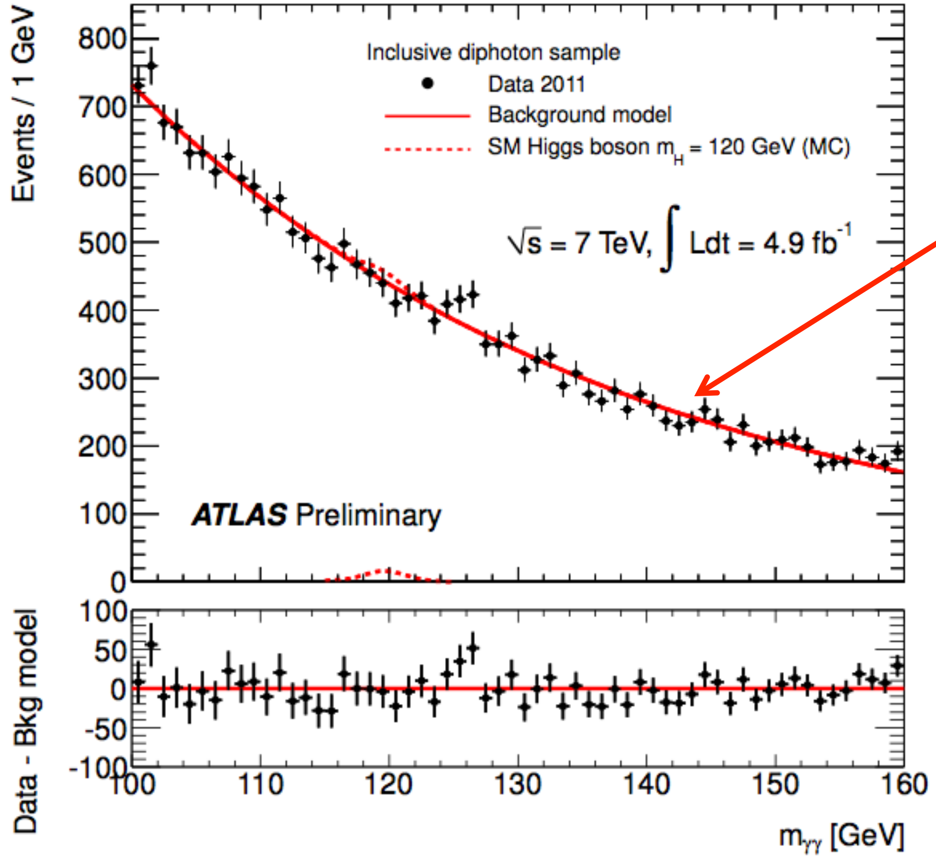
Hypothesis testing using the

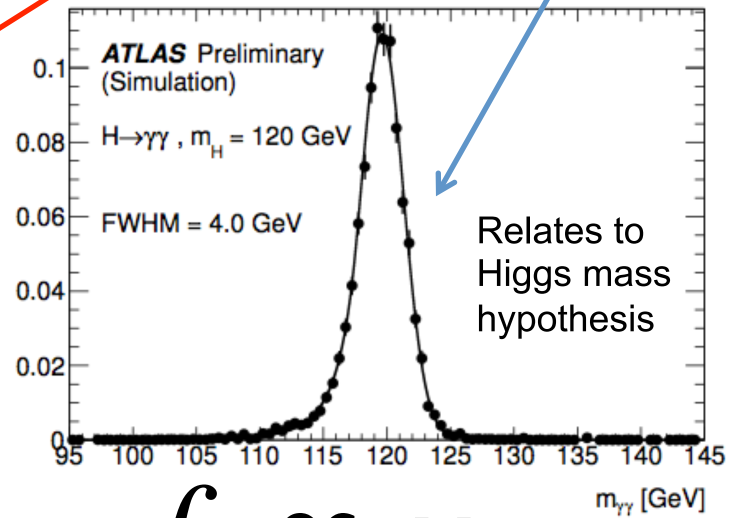
Profile likelihood ratio…

Likelihood Definition:

Simplified

$$L(\mu,\theta) = f_b\psi_b(M_{\gamma\gamma}) + f_s\psi_s(M_{\gamma\gamma})$$





Relates to Higgs mass hypothesis

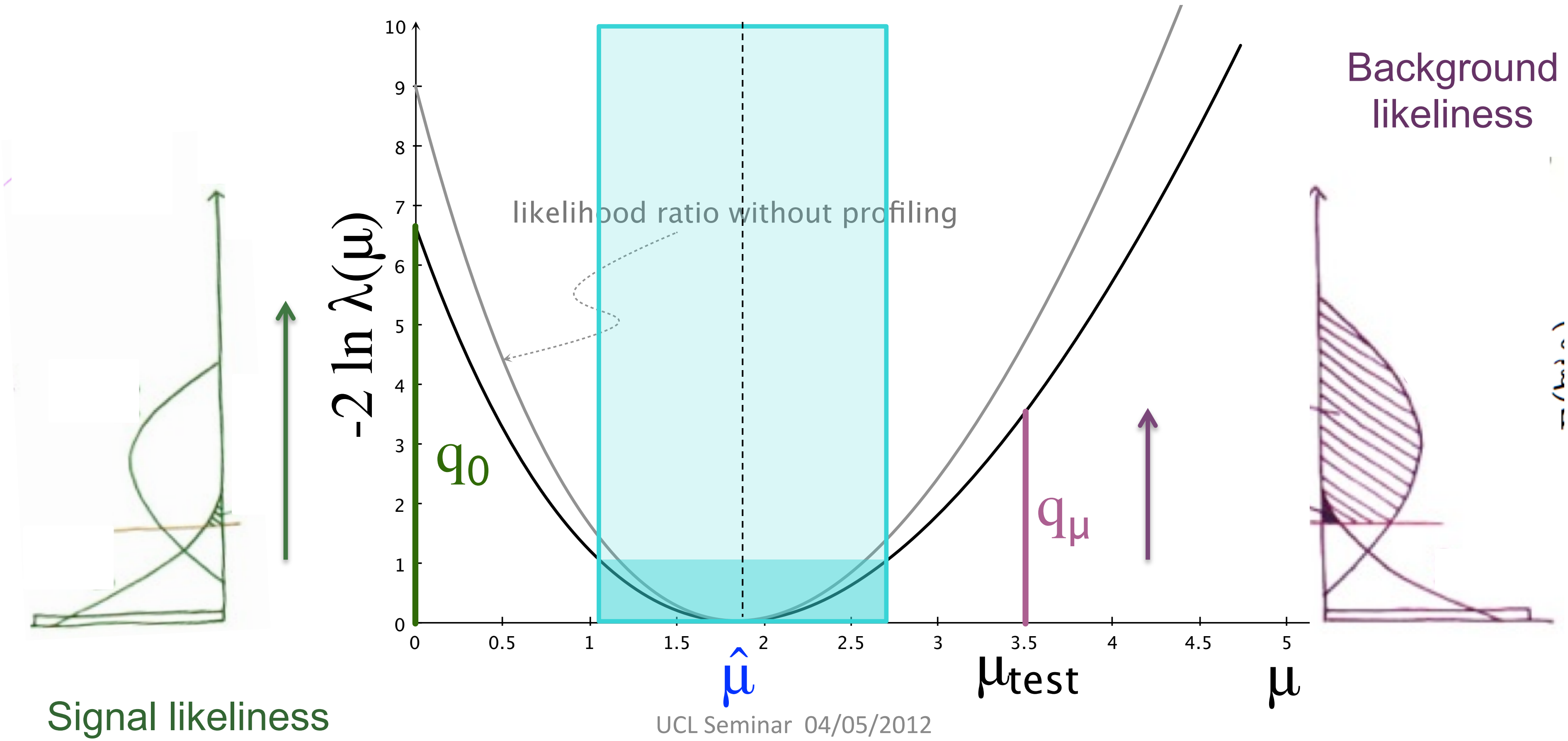
$$f_s \propto \mu$$

Global coherent factor

$$n_s = \mu\sigma BrL\varepsilon$$

How to Read Higgs Exclusion Limits Plots

$$\lambda_\mu = \lambda(\mu,\theta) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta})} \qquad q_\mu = -2\ln\lambda_\mu$$

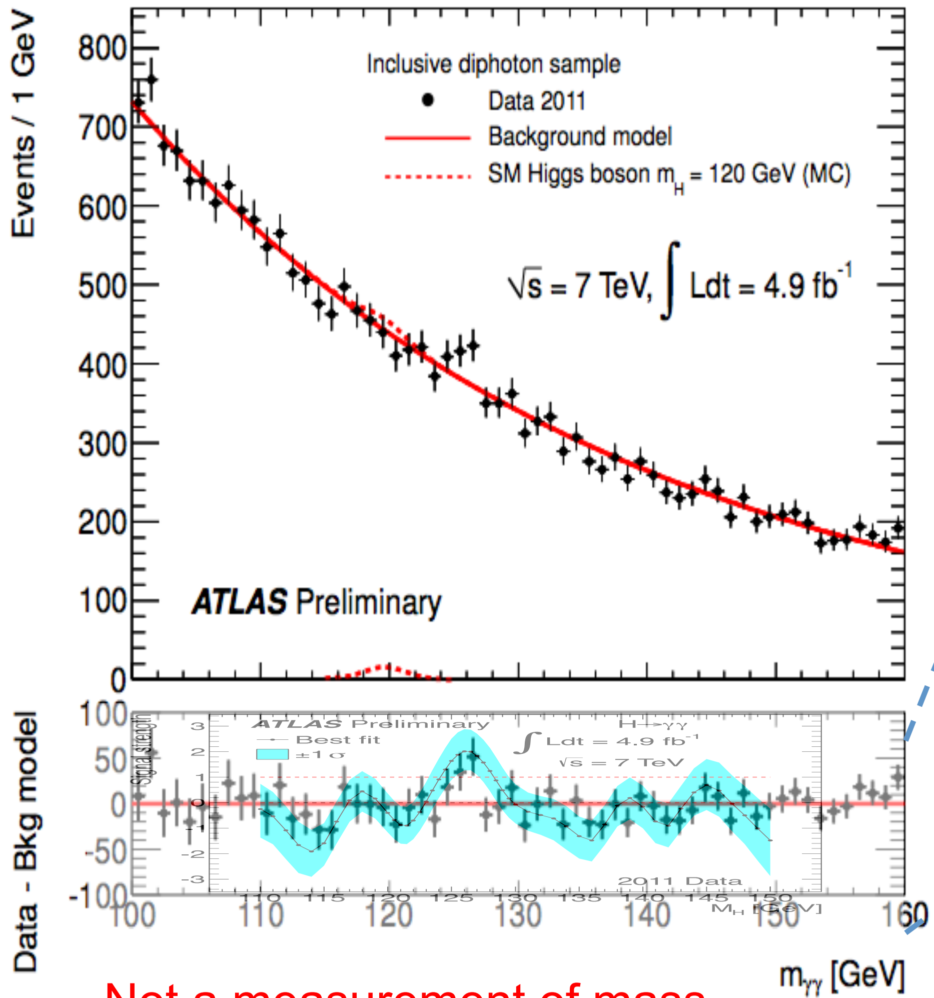


Statistical Interpretation

How to read Higgs Search Plots

Hypothesis testing using the Profile likelihood ratio…

$\hat{\mu}$

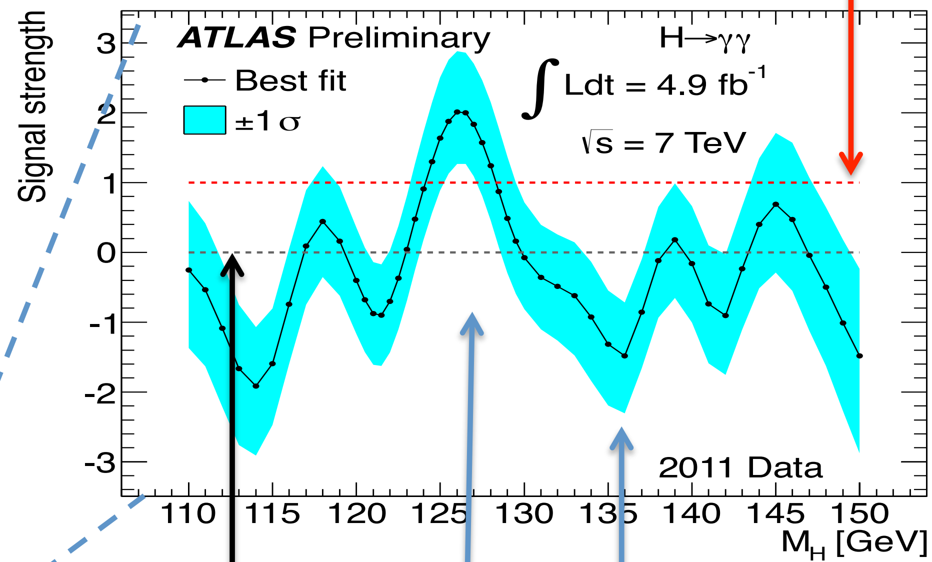


Not a measurement of mass

Not a measurement of cross section

Relate to Higgs mass hypothesis

Expected Signal

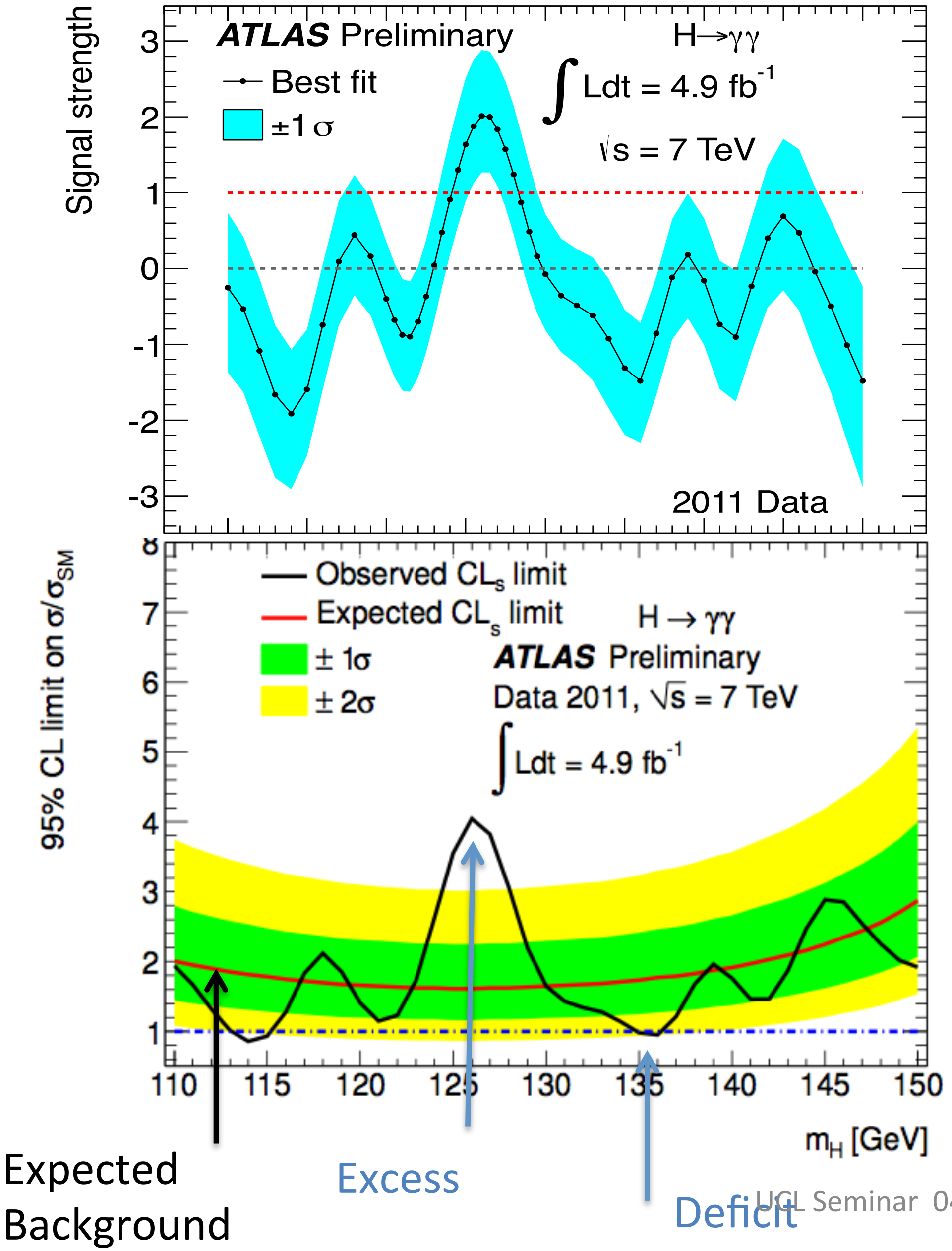


Expected Background

Excess

Deficit

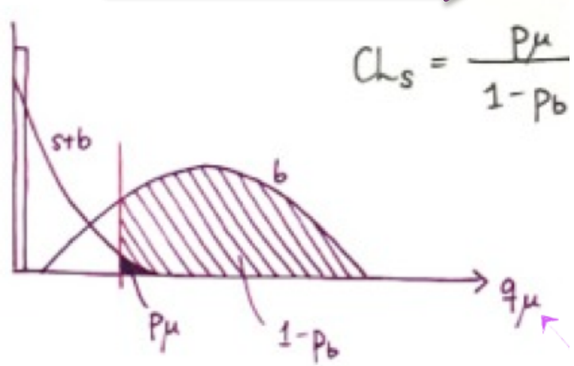
How to Read Higgs Exclusion Limits Plots



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

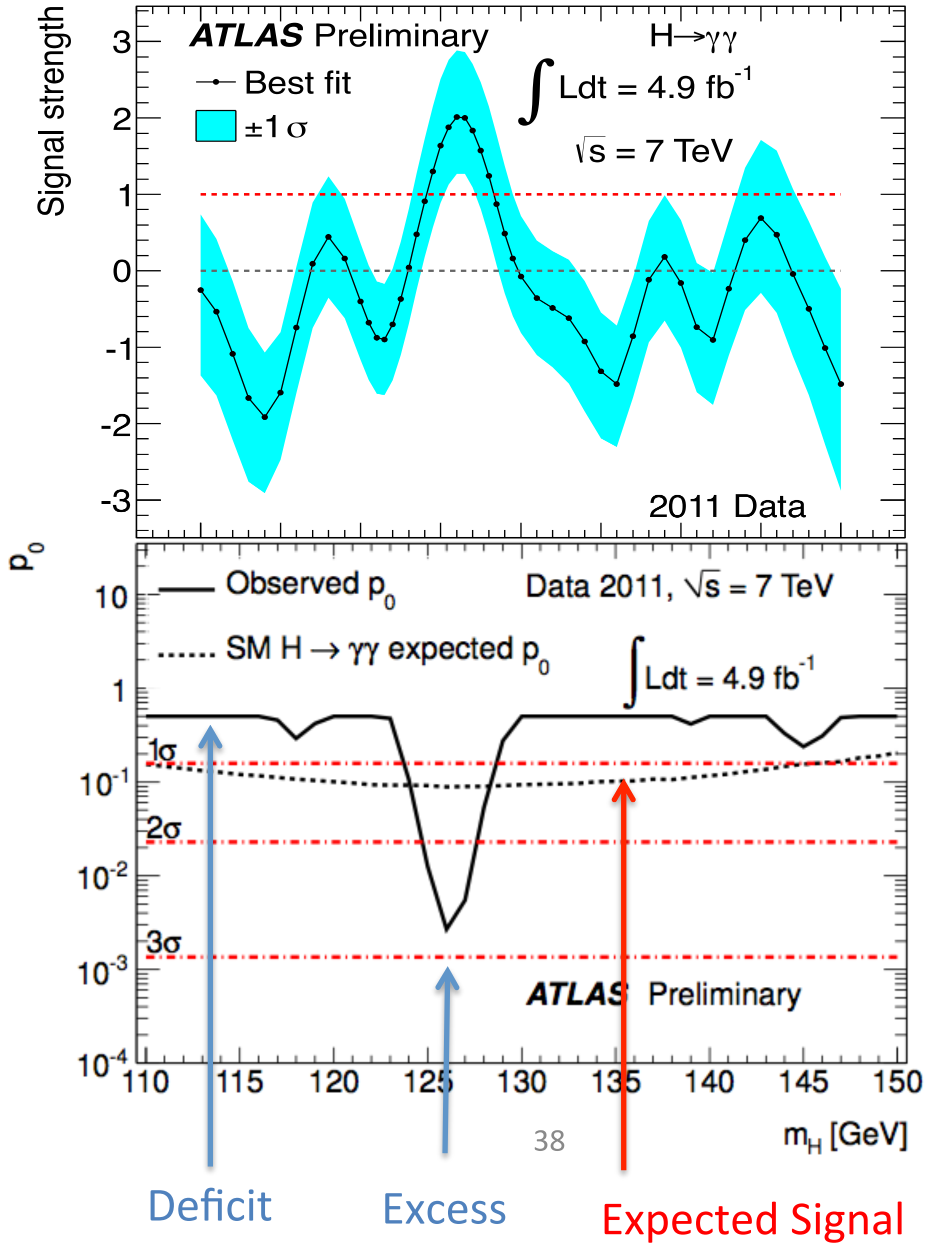
$$q_\mu = -2\ln\lambda_\mu$$

Background likeliness



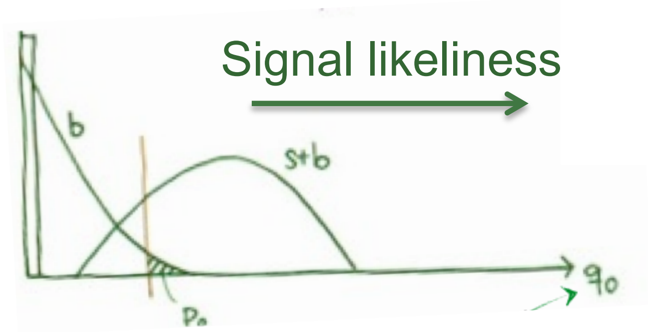
CL_{s+b} Probability that a signal-plus-background experiment be more background-like than observed

How to Read Higgs Observation Estimates



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

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

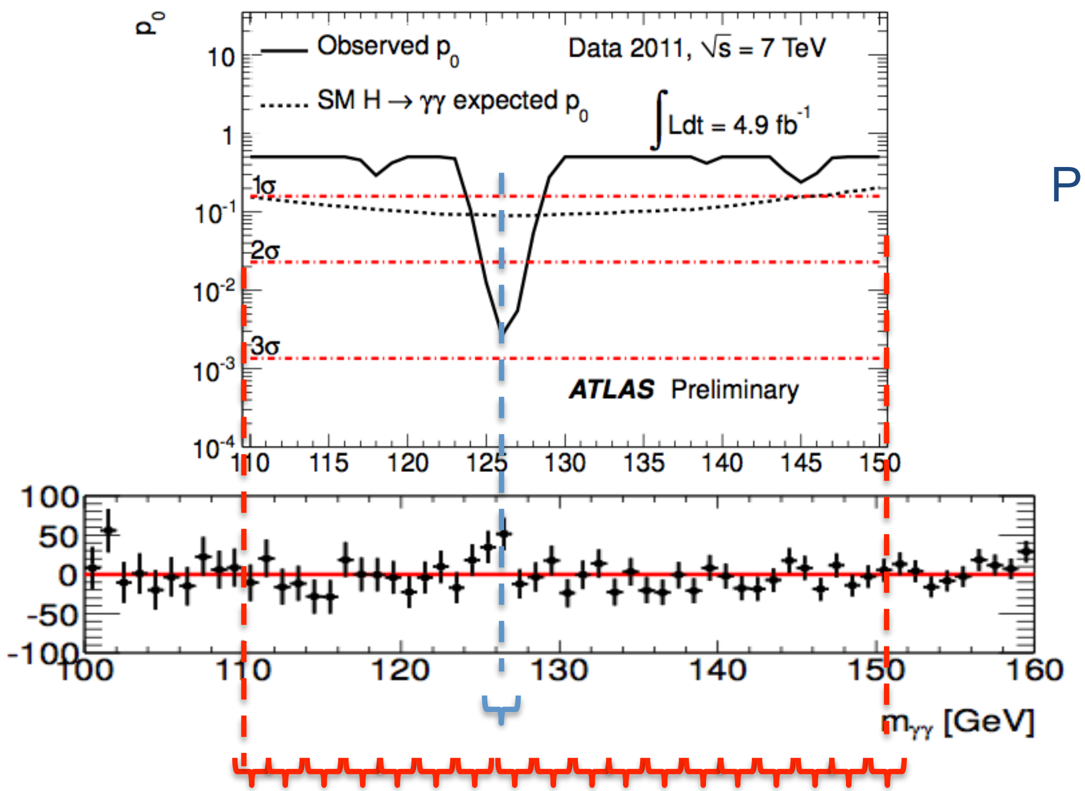


p_0 Probability that a background only experiment be more signal like than observed

Local vs. Global Probability

Look Elswhere Effect

(over)Simplified View



Probability of observing an excess at one specific mass (in absence of signal)…

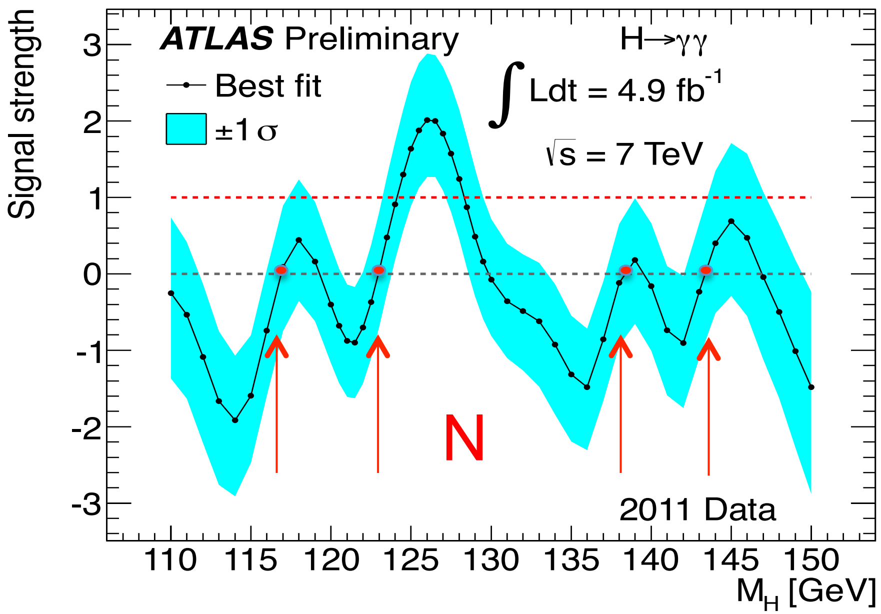
What is the probability of observing an excess at least as large as observed within a mass range ?

Trial factor ~ Number of possible independent outcomes within a mass range… (dependence on the significance)

Local vs. Global Probability

Look Elswhere Effect

Approximate Formula



Based on counting the numbers of up-crossings

Then applying the very simple following formula (Z is the local significance)

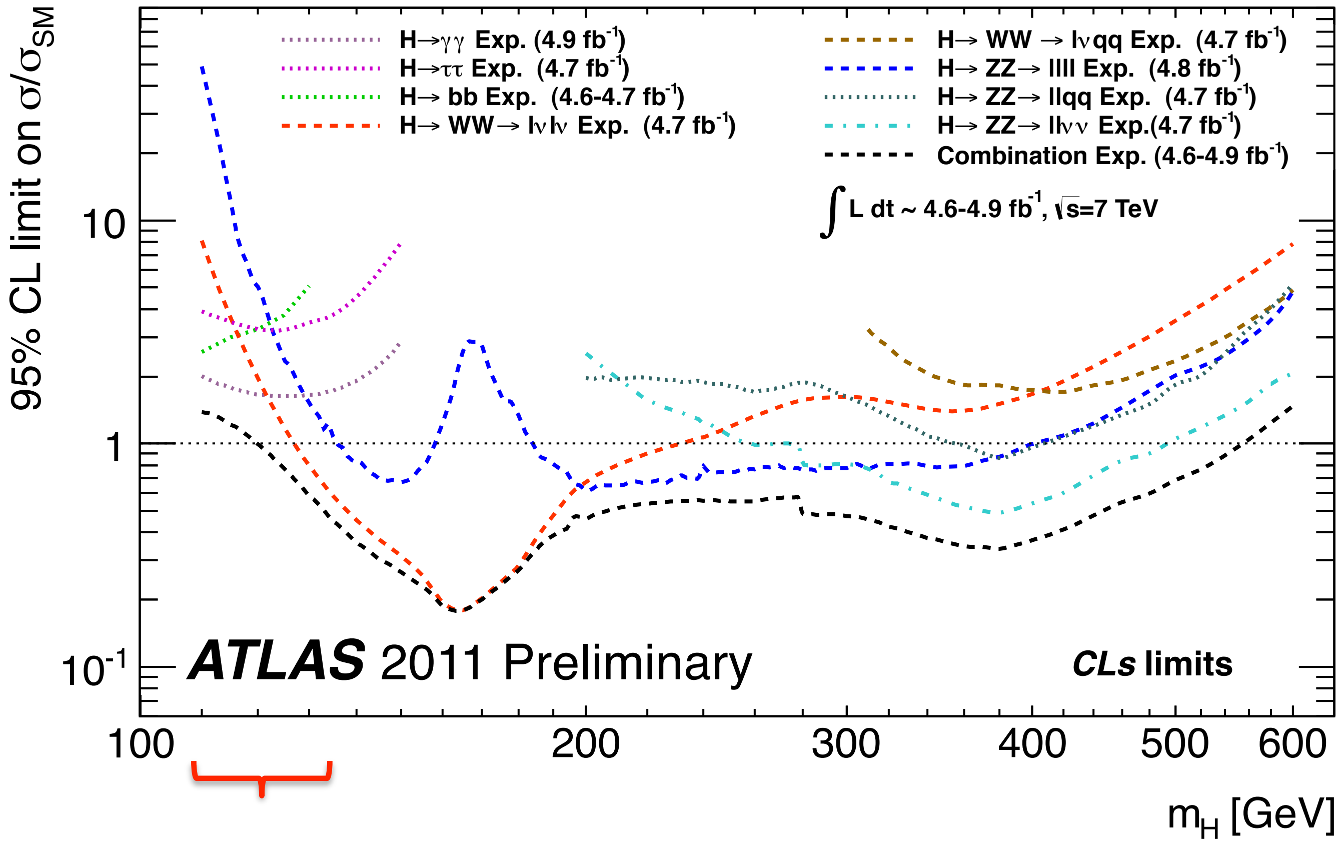
$$p_{global} = p_{local} + N \times e^{-\frac{Z^2}{2}}$$

Trial factor ~ Here the dependence is explicit…

E. Gross and O. Vitells, *Trial factors for the look elsewhere effect in high energy physics*, Eur. Phys. J. **C70** (2010) 525–530.

Channels Overview

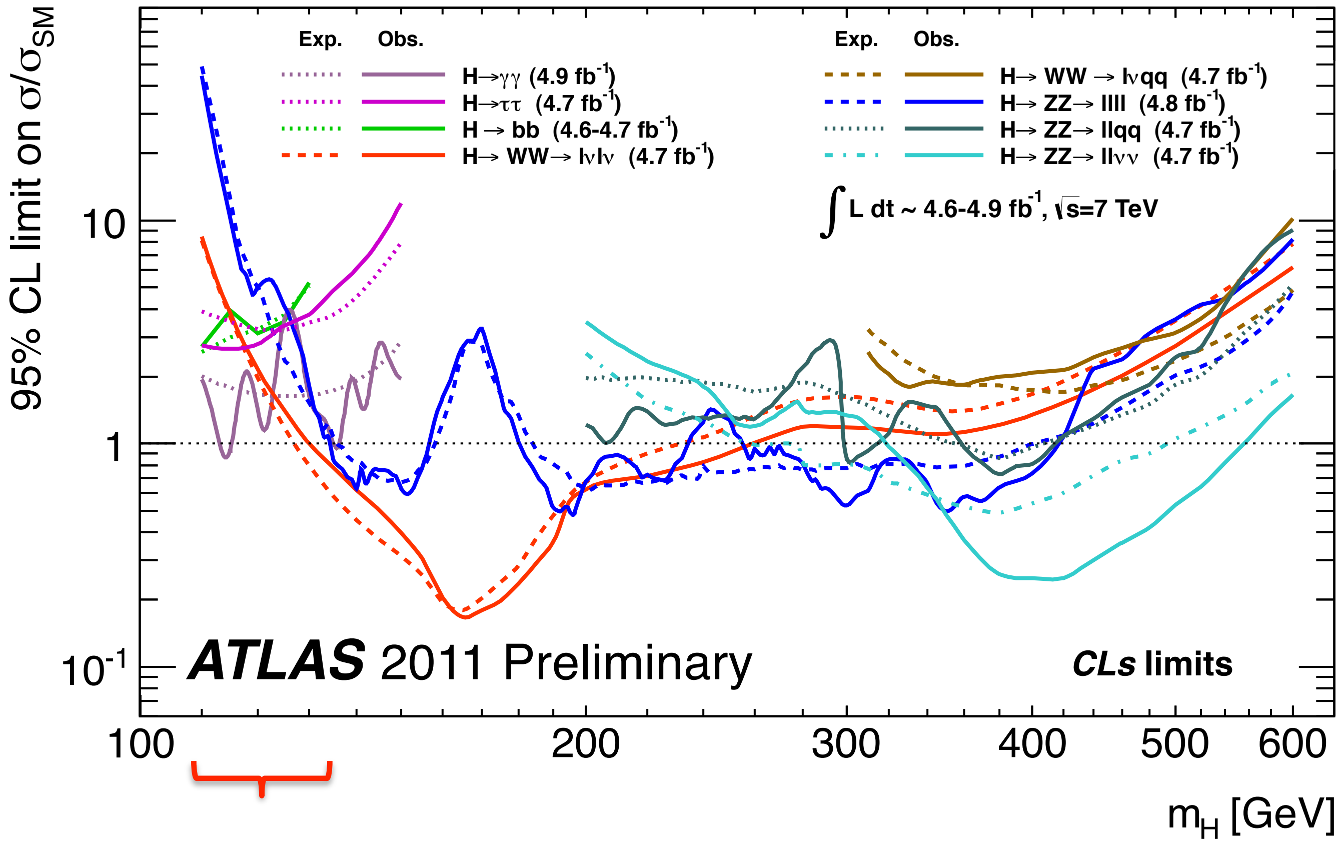
The Complete ATLAS Picture



Combination is Necessary to give a more quantitative result…
… but (caution) does not give the entire picture

Channels Overview

The Complete ATLAS Picture



Combination is Necessary to give a more quantitative result…

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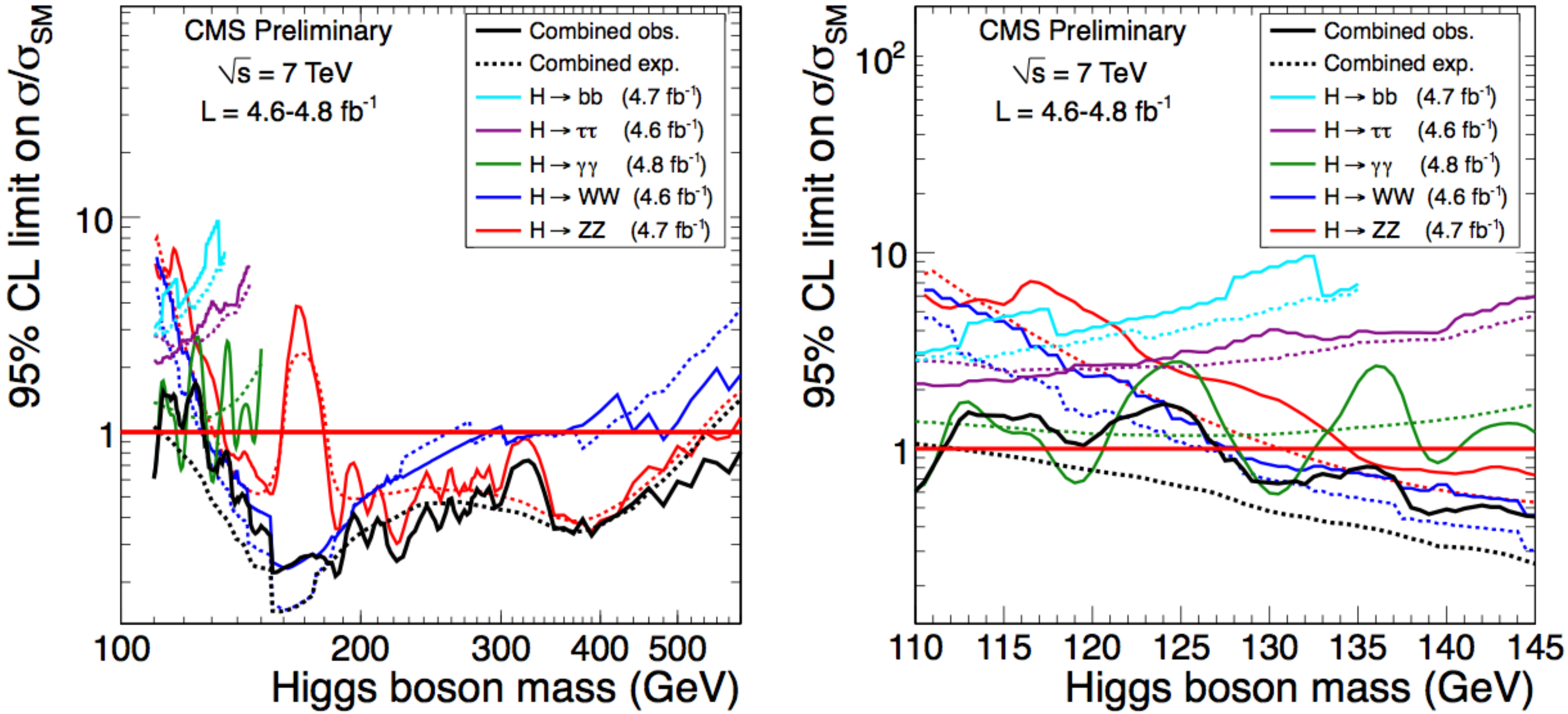
Channels Overview

The Complete CMS Picture



$$H \rightarrow \gamma\gamma$$

Most sensitive Channel in [115-125] GeV Mass range

ATLAS 4.9 fb^{-1}

CMS 4.8 fb^{-1}

Signal yield after cuts (low mass) ~O(80)

s/b ~ 1.5% to O(15)% depending on category

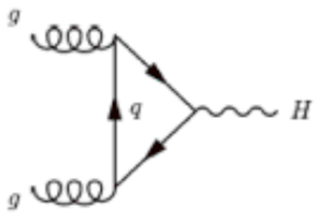
More Details in talks by Liwen Gao and Giovanni Marchiori

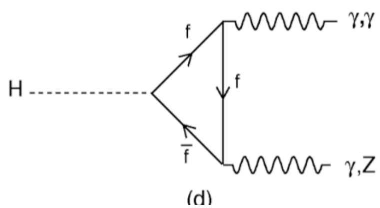
DiPhoton Channel

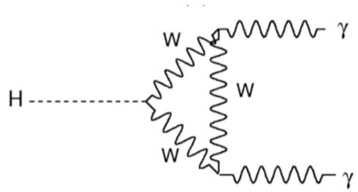
Common Misconceptions and Basic Facts

- Small branching… but amongst largest yields (Dominant Channel in the very low mass range 110-125 GeV)

- Main production and decay processes occur through loops :







A priori potentially large enhancement…

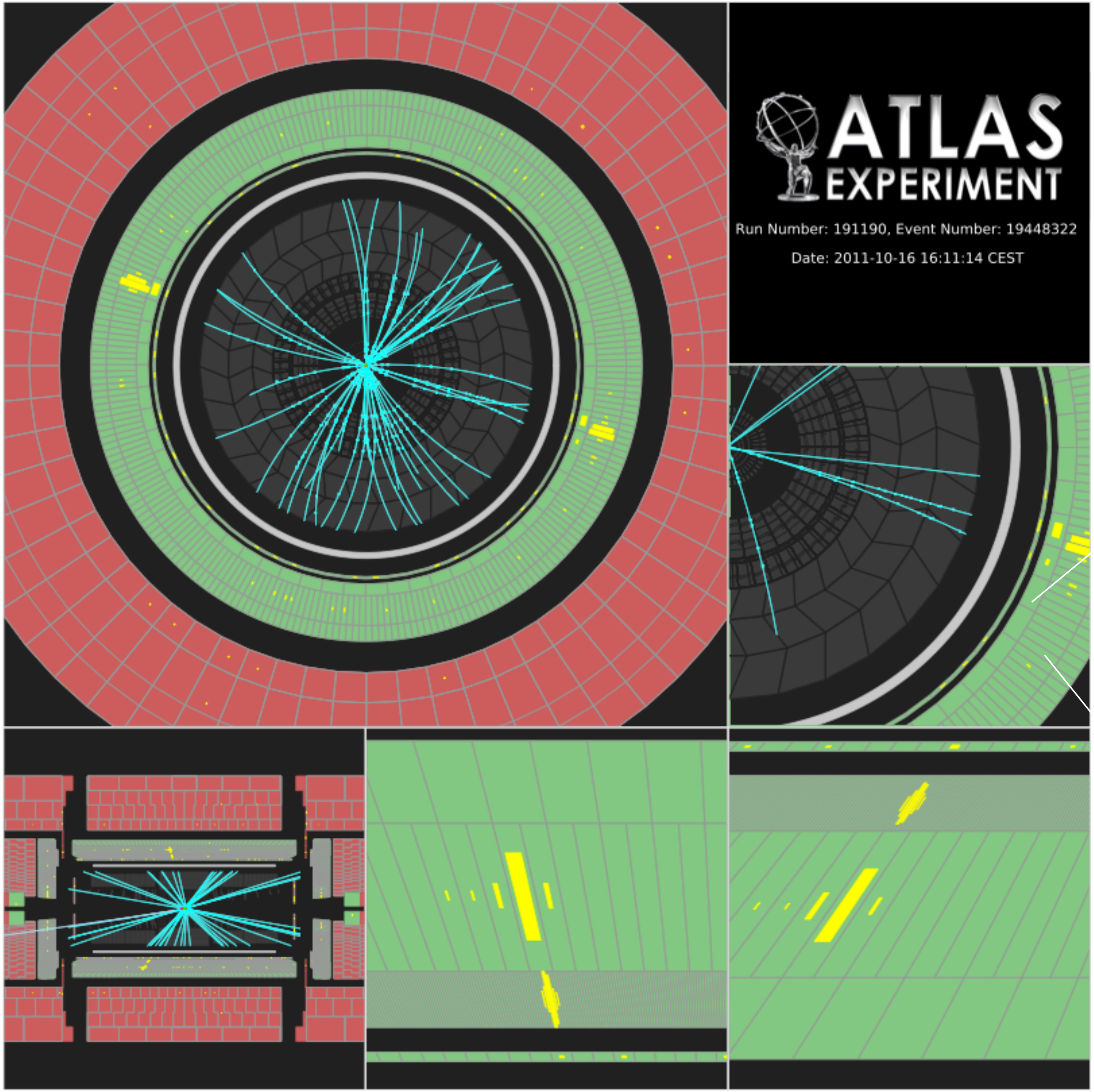
… Not so obviously enhanced (e.g. SUSY, SM4)

Still e.g. NMMSSM (U. Ellwanger Phys.Lett. ***B 698****, 293-296,2011) up to x6 at low masses, Fermiophobia…*

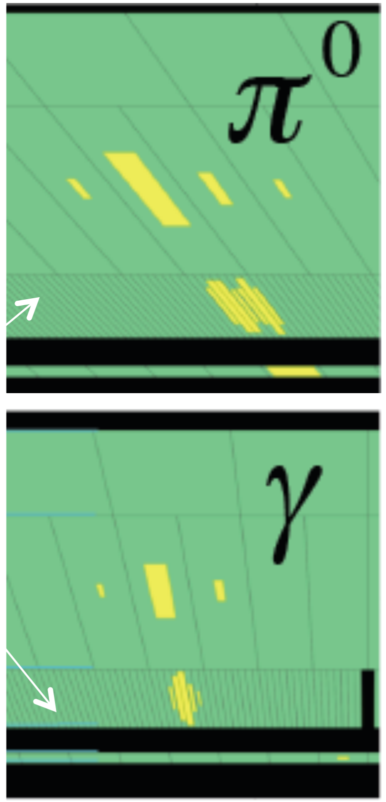
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem

L. Landau, Dokl. Akad. Nauk. , USSR **60**, 207 (1948) and C. N. Yang, Phys. Rev. **77**, 242 (1950).

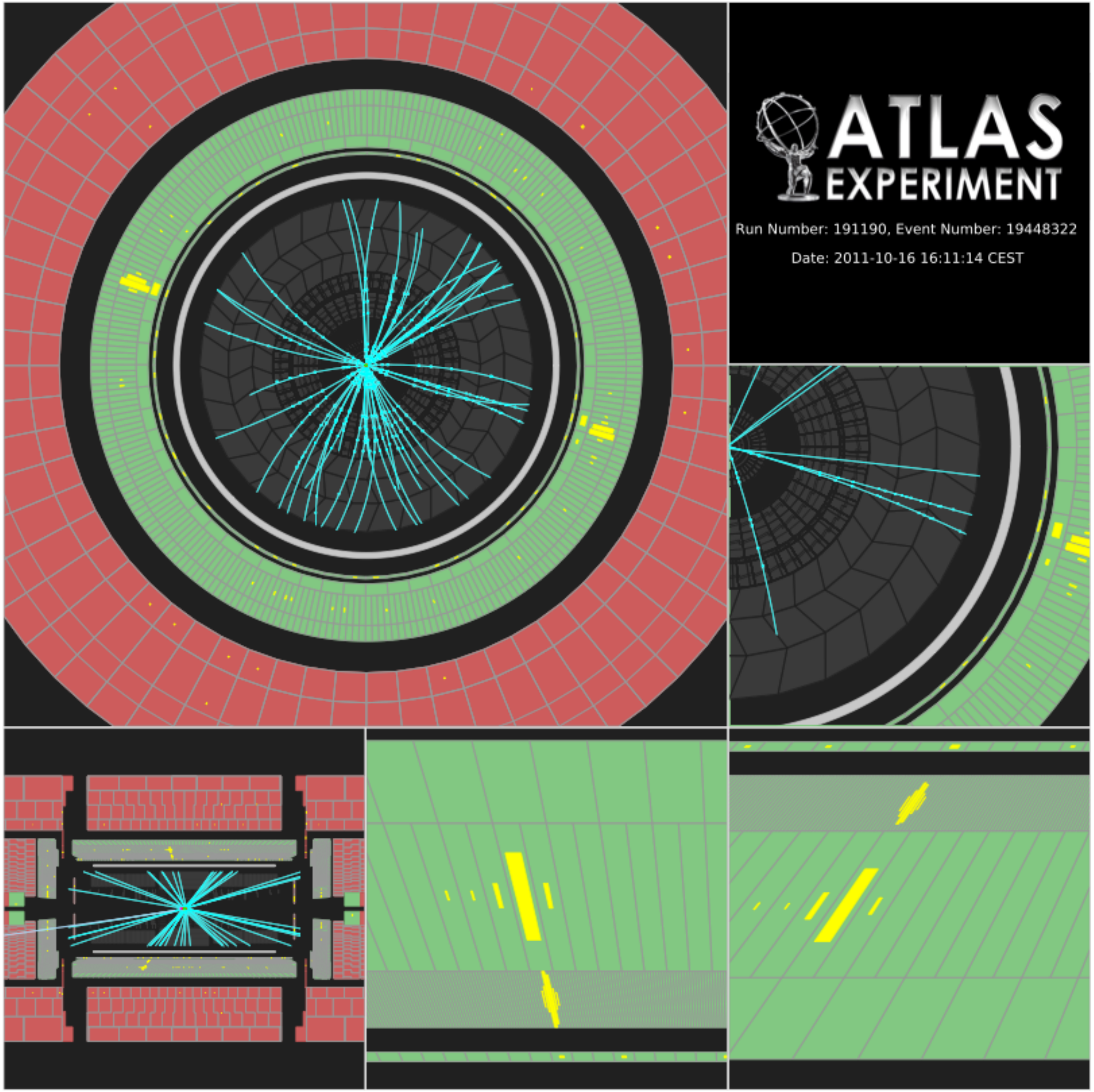
- Extremely simple event selection : two photons 25/40 GeV (ATLAS) and 30/40 GeV (CMS)

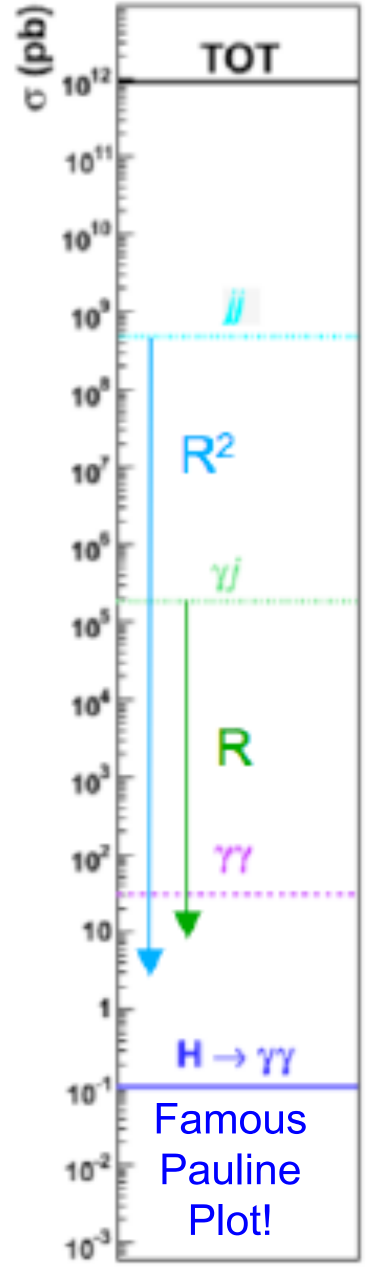


Background
From jets



Signal


ATLAS
EXPERIMENT
Run Number: 191190, Event Number: 19448322
Date: 2011-10-16 16:11:14 CEST


σ (pb)
TOT
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2
10^-3
jj
R²
γj
R
γγ
H → γγ
Famous
Pauline
Plot!

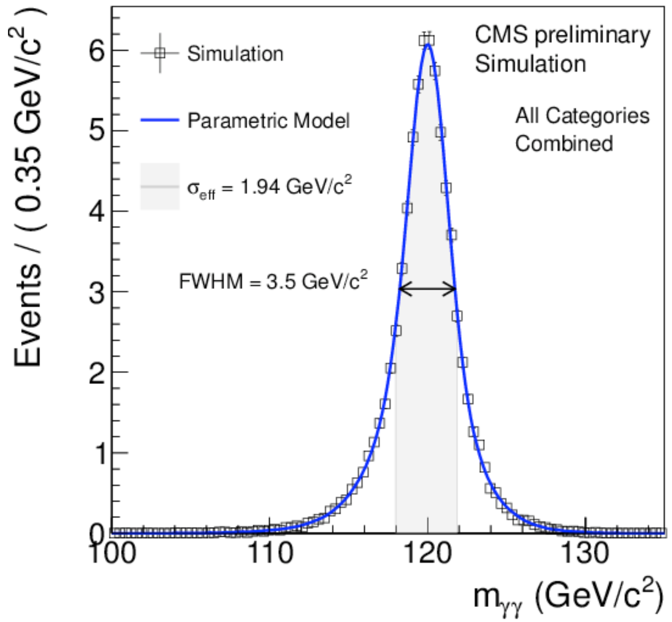
R ~ O(8000)

Key features :

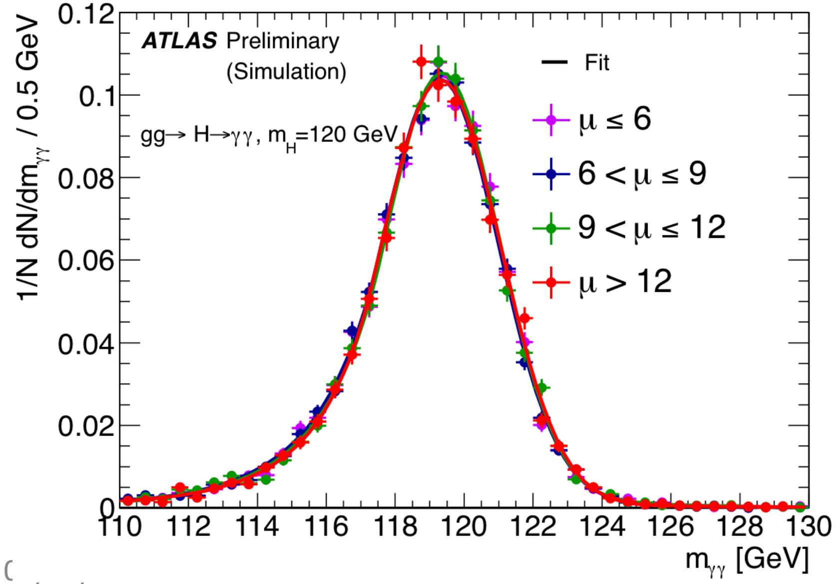
- Background rejection… but also…
- Invariant mass resolution
  - Energy response
  - Interaction vertex position

(IP spread of 5.6 cm, assuming (0,0,0) adds ~1.4 GeV in mass resolution)

$FWHM \sim 3.5$ GeV

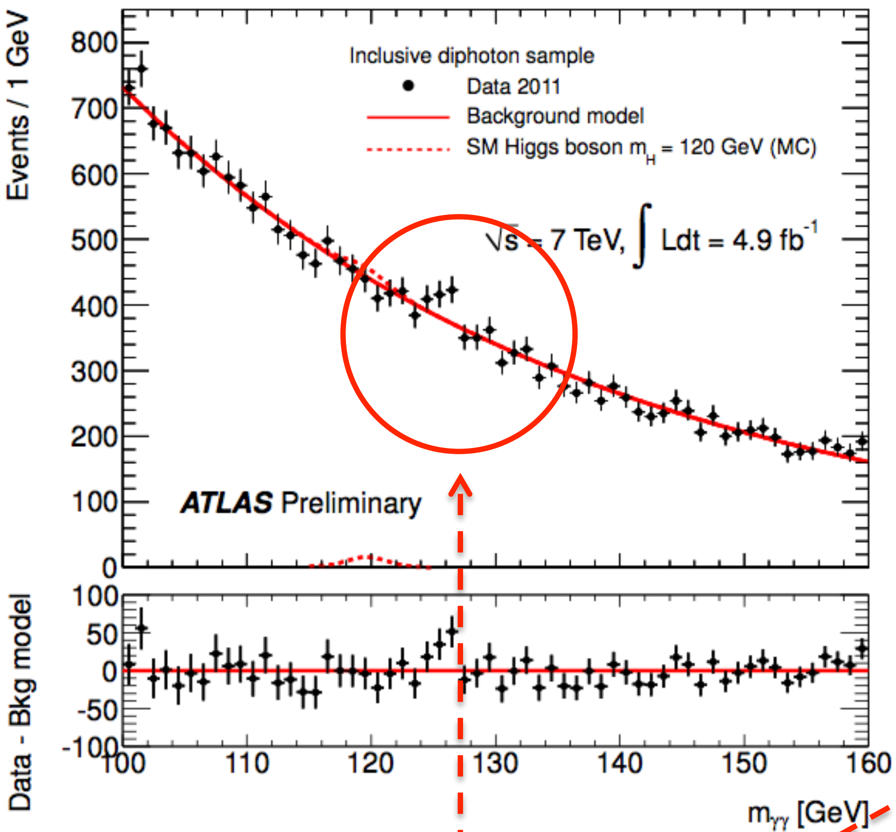


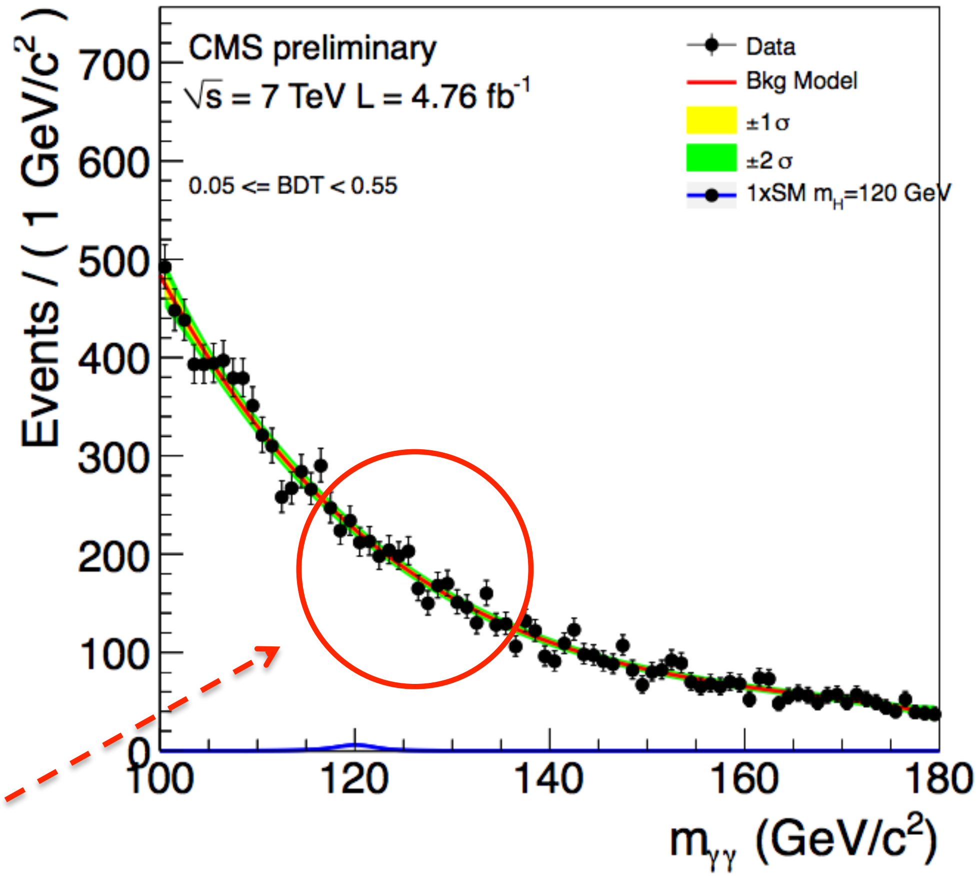
$FWHM \sim 4.0$ GeV



minar (

Inclusive Mass Spectra

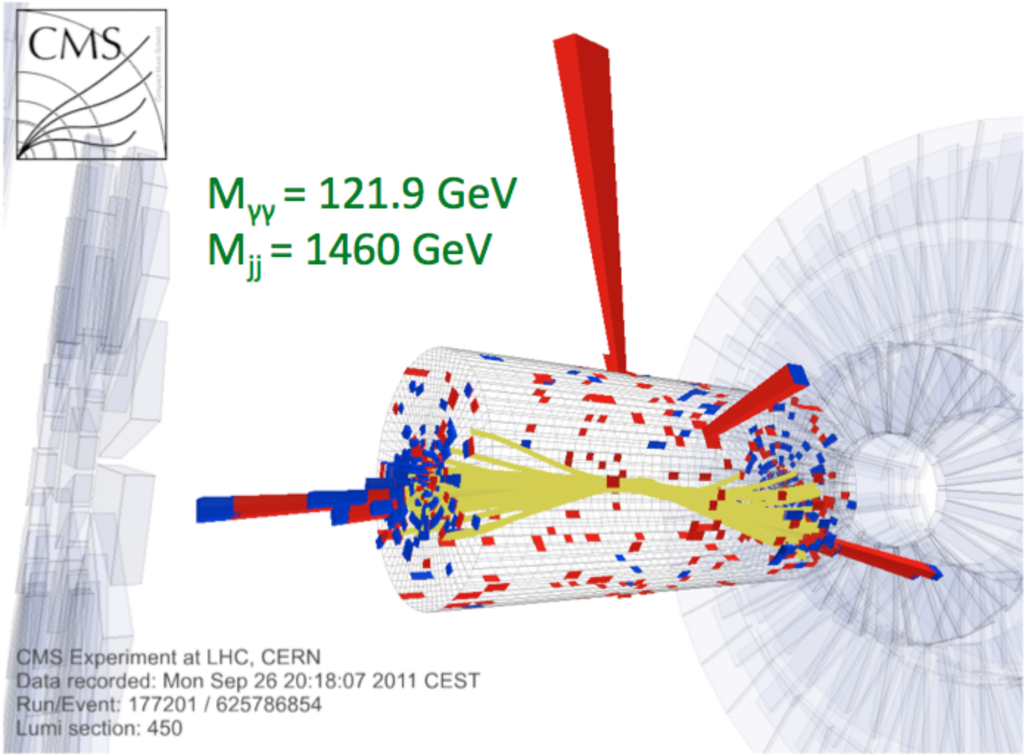




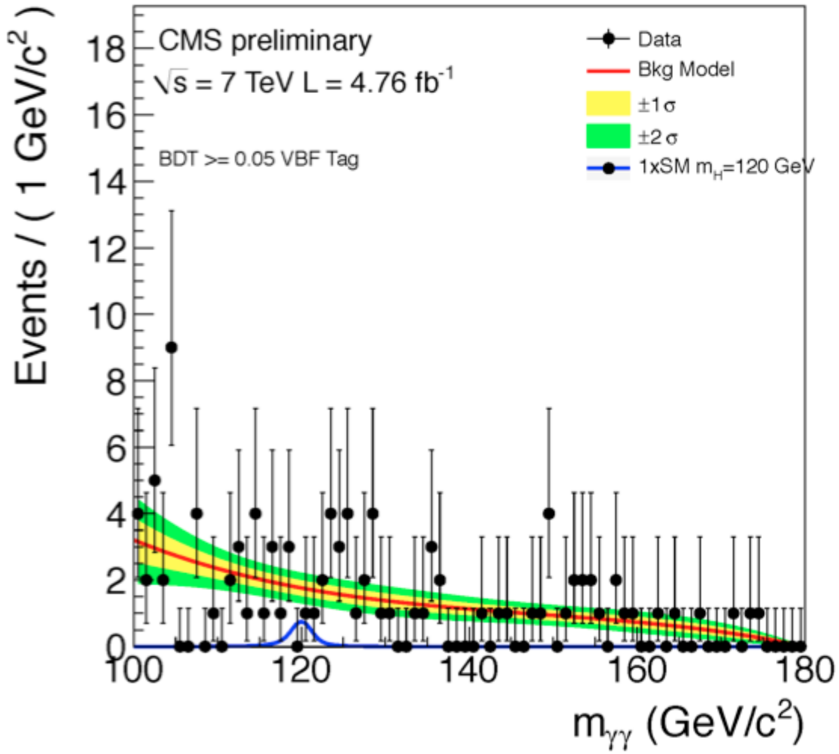
CMS has a slightly wider fit range

Excesses visible in the inclusive mass spectra

Event Categrization to fully profit from distinctive features



Dijet tag selection has high s/b, ~1/3

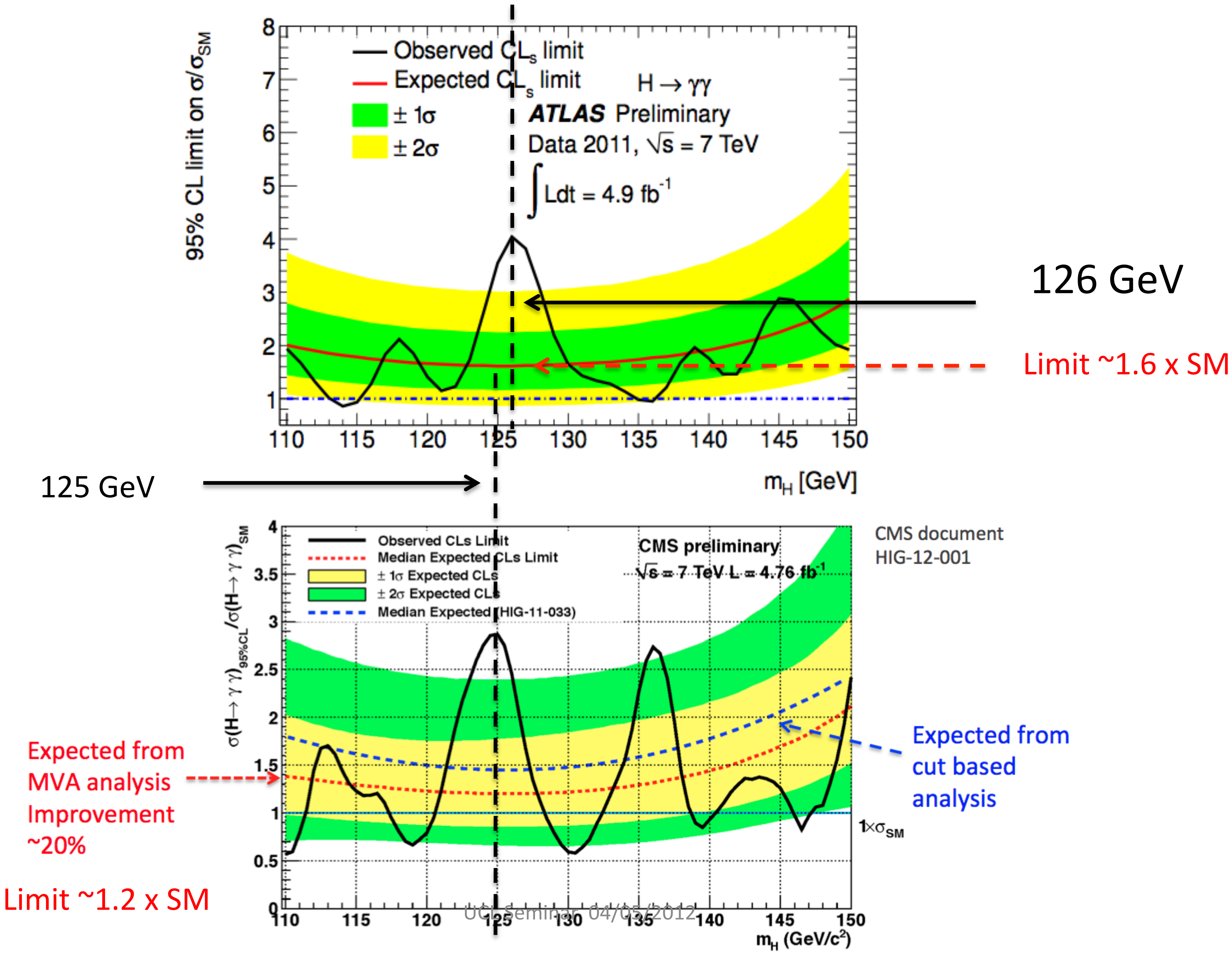


ATLAS (9 Categories) :

- Pseudo-rapidity
- Conversion status (tracks)
- Transverse momentum w.r.t. thrust axis

CMS (4 Categories) :

- MVA Analysis (4)
  - Kinematics
  - Conversion status
  - Resolution
- VBF (1)

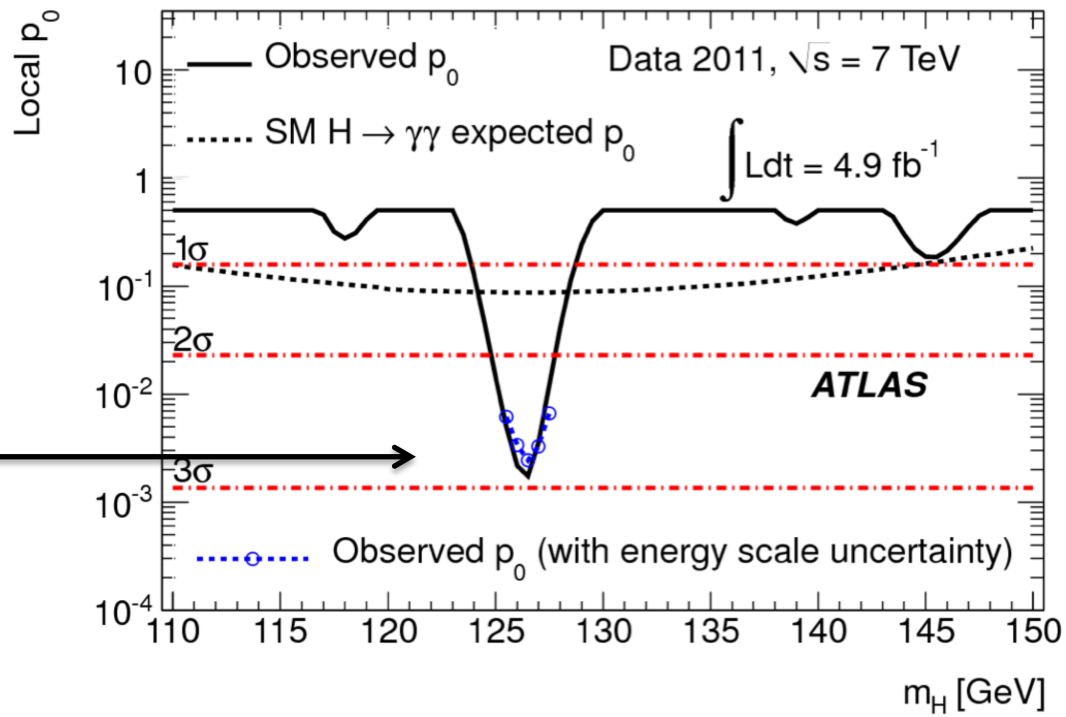


Observed CLs limit
Expected CLs limit
± 1σ
± 2σ
H → γγ
ATLAS Preliminary
Data 2011, √s = 7 TeV
∫Ldt = 4.9 fb-1
95% CL limit on σ/σSM
mH [GeV]
126 GeV
Limit ~1.6 x SM
125 GeV
Observed CLs Limit
Median Expected CLs Limit
± 1σ Expected CLs
± 2σ Expected CLs
Median Expected (HIG-11-033)
CMS preliminary
√s = 7 TeV L = 4.76 fb-1
CMS document
HIG-12-001
σ(H→γγ)95%CL/σ(H→γγ)SM
1×σSM
mH (GeV/c2)
Expected from
MVA analysis
Improvement
~20%
Limit ~1.2 x SM
Expected from
cut based
analysis

ATLAS

Excess of
2.8σ

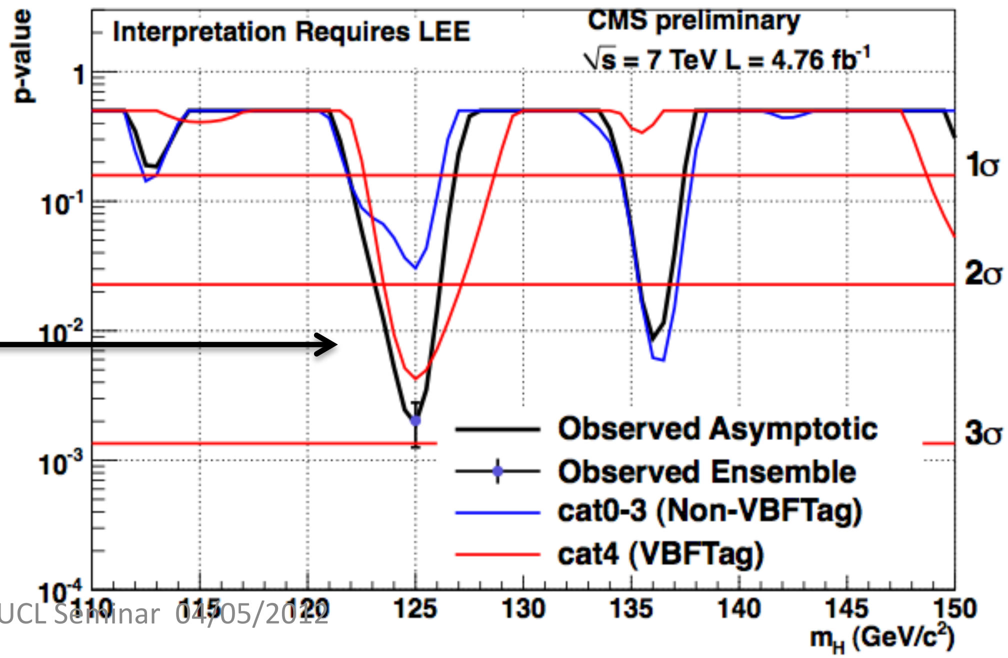
Global of 1.5σ



CMS

Excess of
2.9σ

Global of 1.6σ



$$H \to ZZ \to \ell\ell\ell\ell$$

The « Golden » Channel

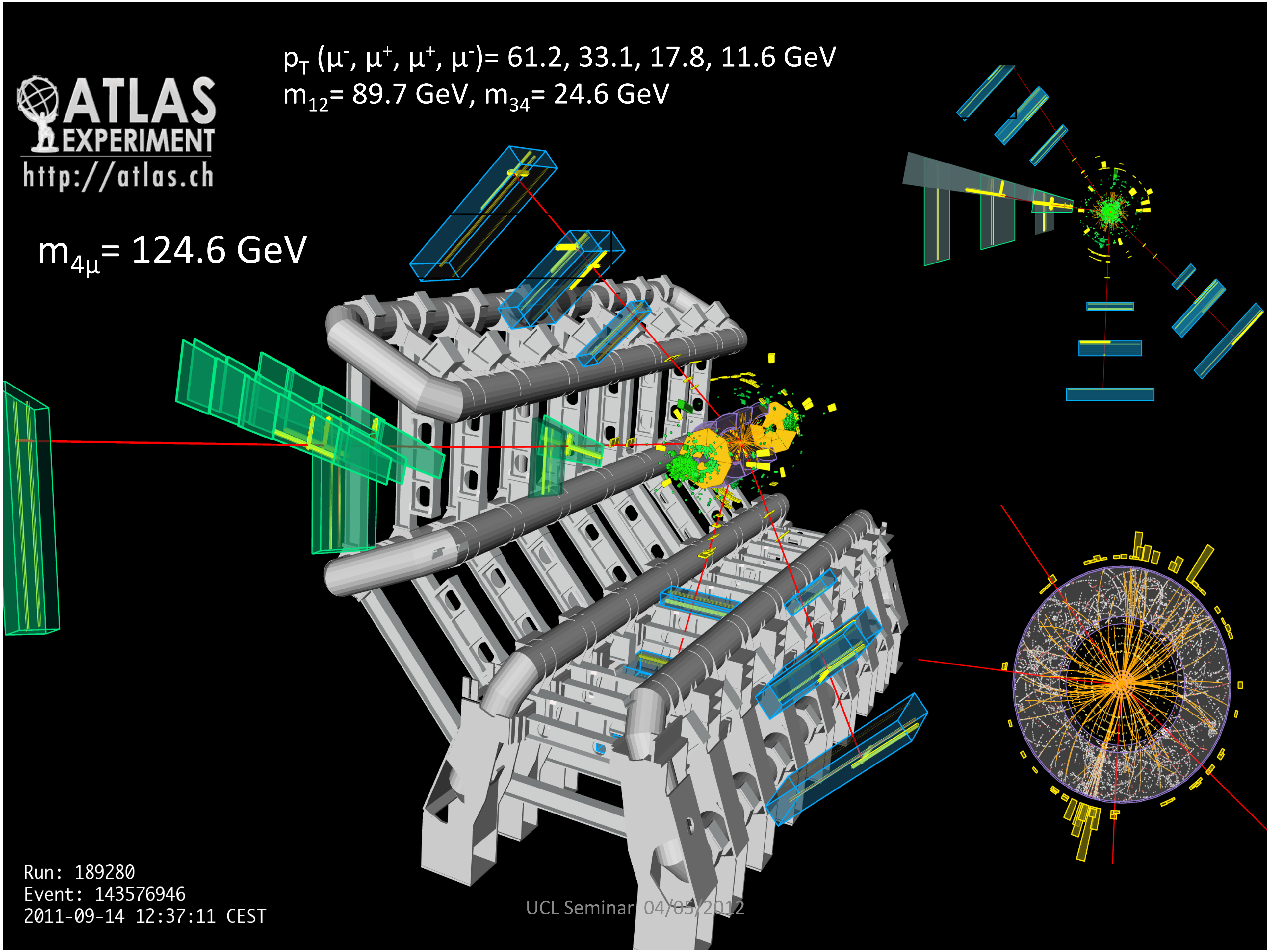
Most sensitive Channel in [180-250] GeV Mass range

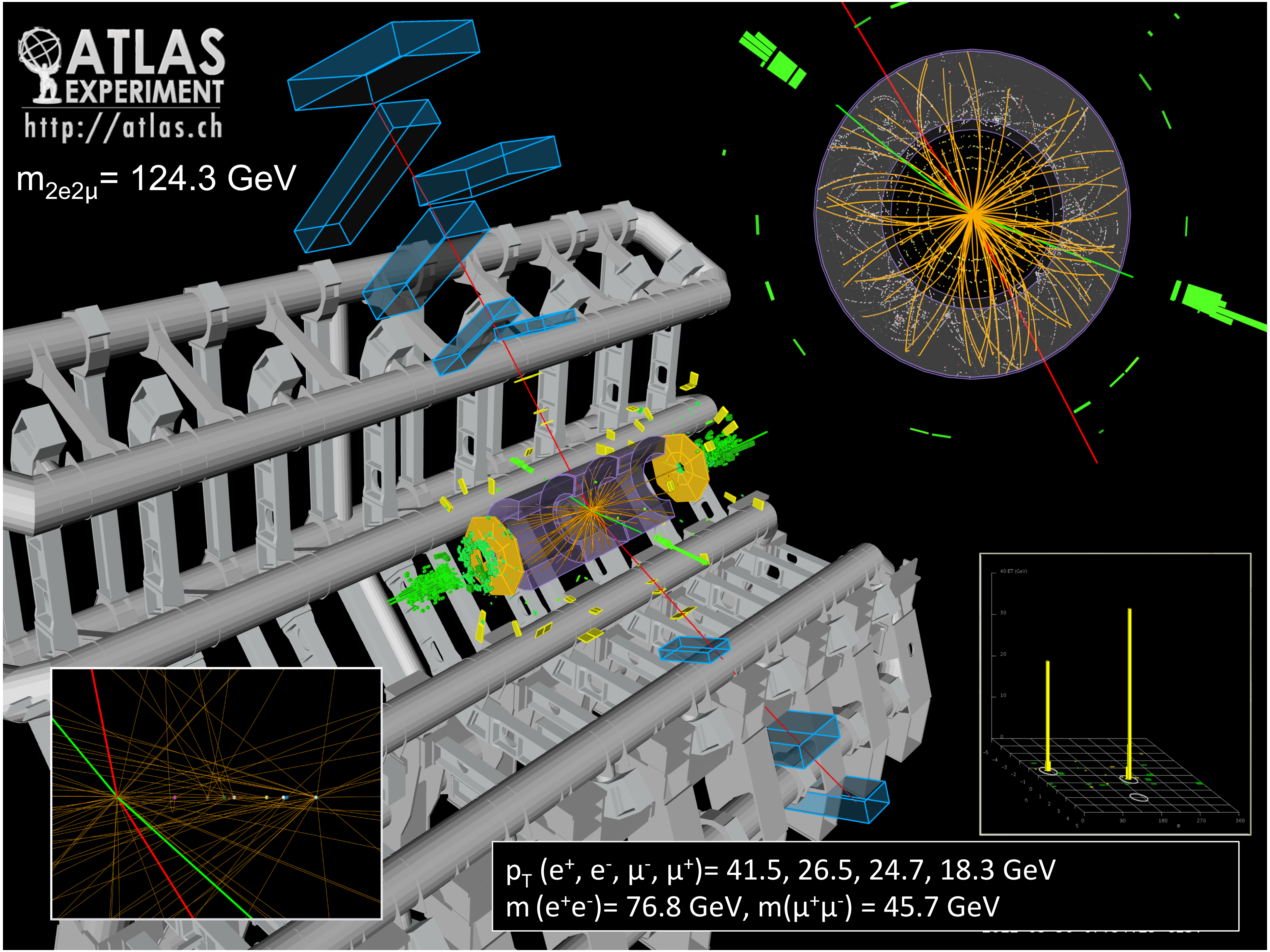
ATLAS 4.9 fb^{-1}

CMS 4.7 fb^{-1}

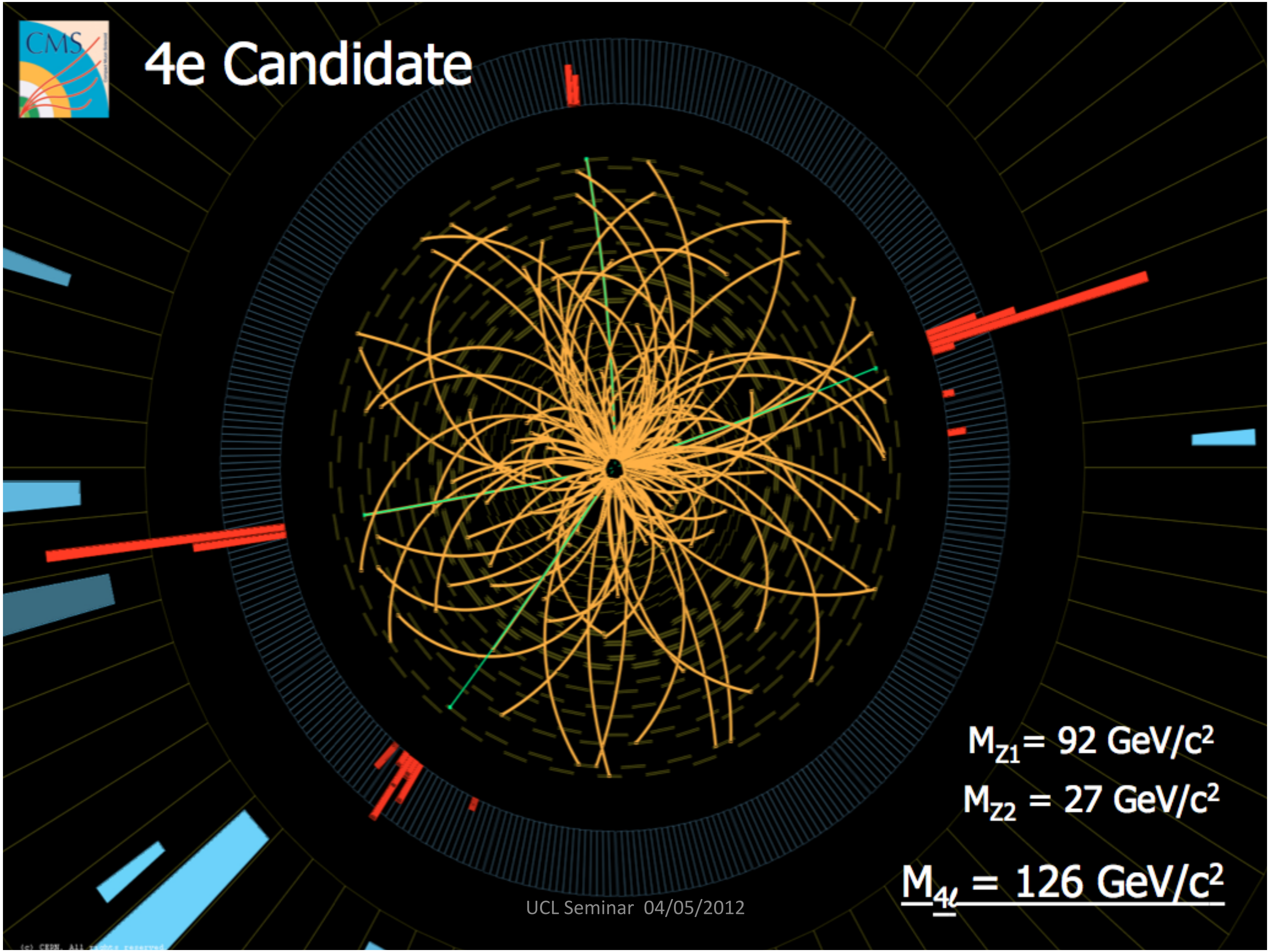
Signal yield after cuts (low mass) ~ O(5)

s/b ~ O(1) locally at 125 GeV

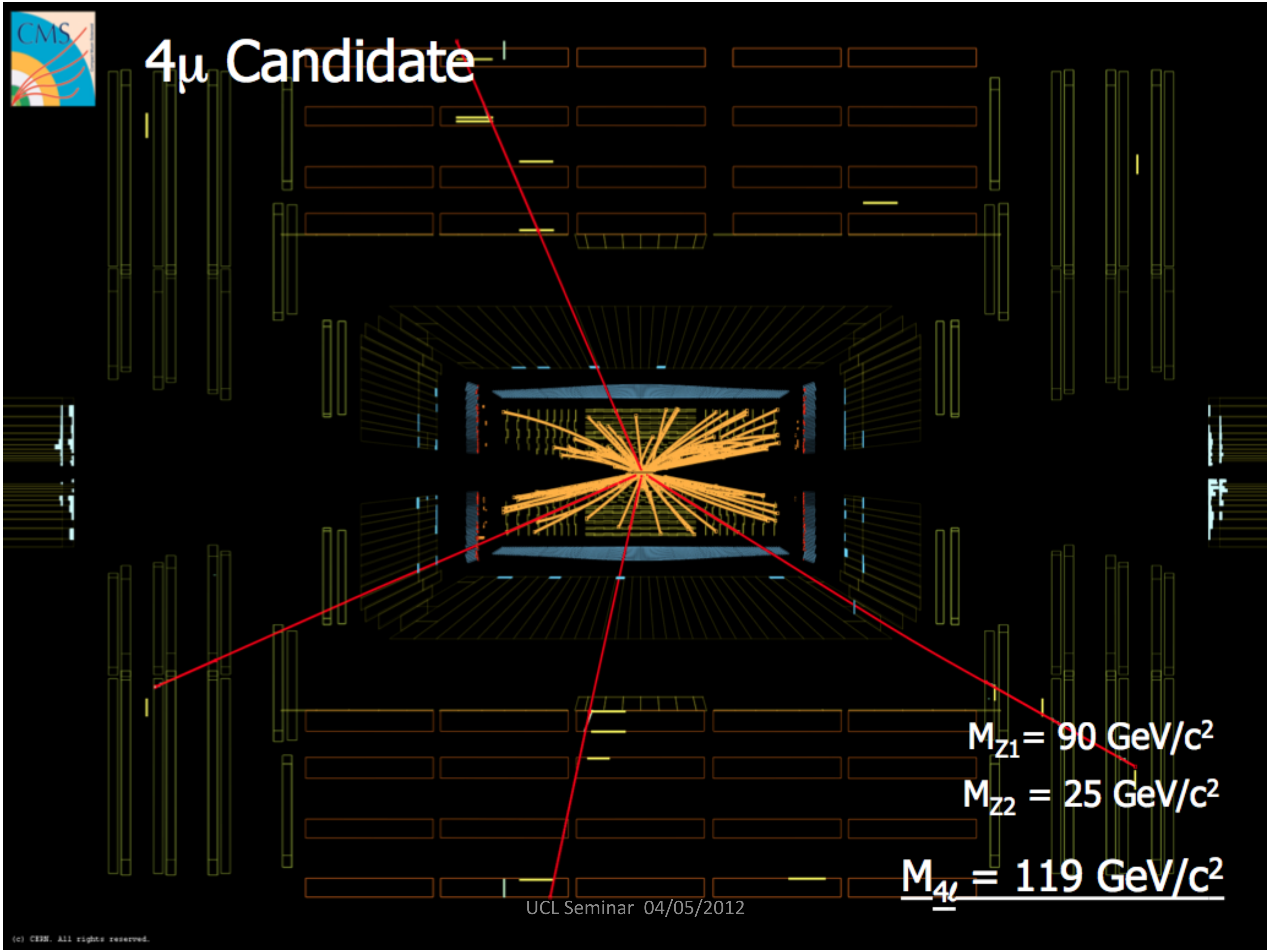

p_T (μ^-, μ^+, μ^+, μ^-)= 61.2, 33.1, 17.8, 11.6 GeV
m_{12}= 89.7 GeV, m_{34}= 24.6 GeV
ATLAS EXPERIMENT
http://atlas.ch
$m_{4\mu}$= 124.6 GeV
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST


ATLAS EXPERIMENT
http://atlas.ch
m2e2μ= 124.3 GeV
pT (e+, e-, μ-, μ+)= 41.5, 26.5, 24.7, 18.3 GeV
m (e+e-)= 76.8 GeV, m(μ+μ-) = 45.7 GeV

4e Candidate



4μ Candidate



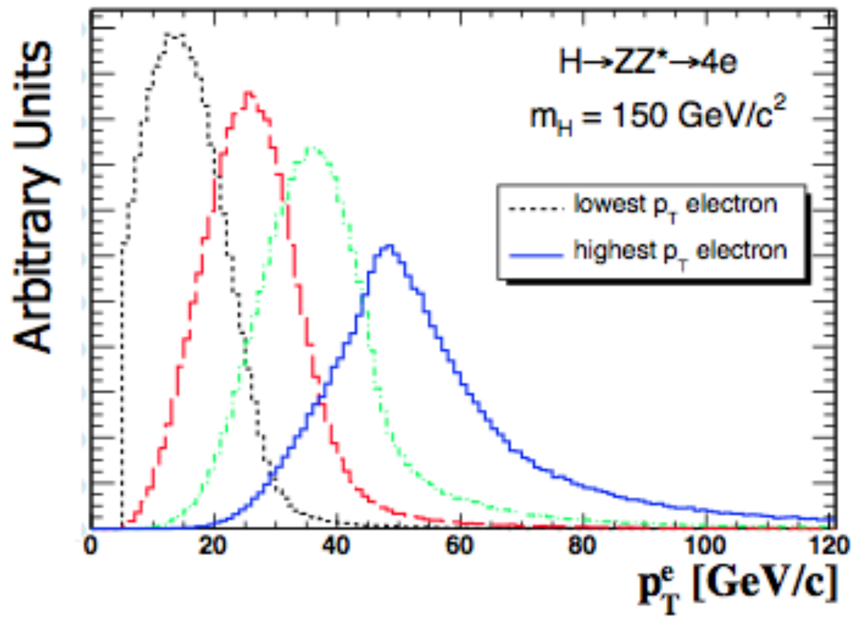
Higgs Boson Search in the $ZZ^{(*)} \rightarrow 4l$

Key features

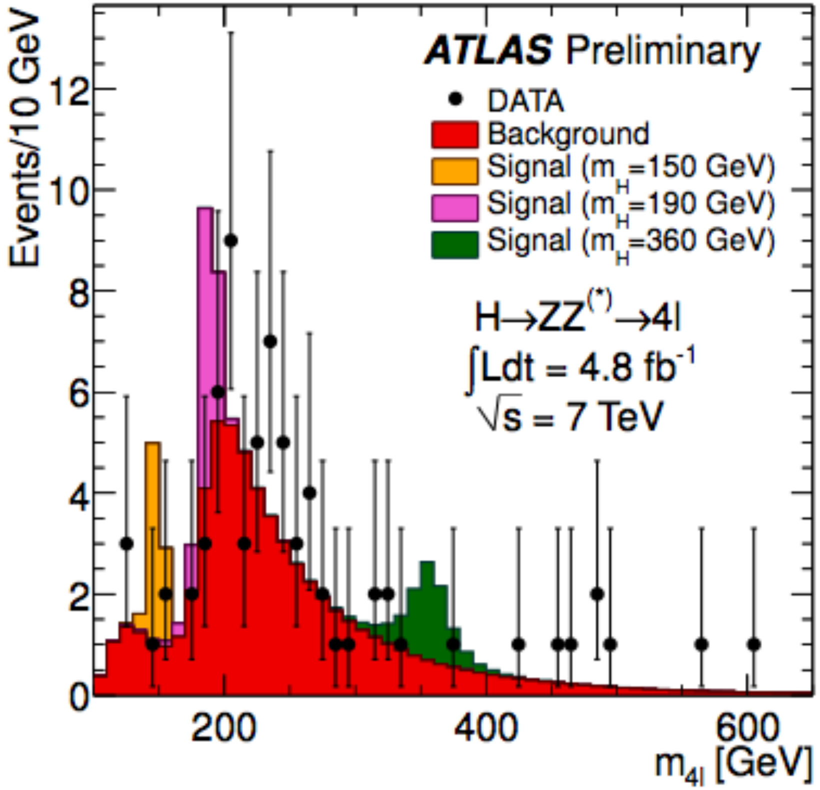
- One Z allowed to be off-mass shell (m_H < 180 GeV)
- low p_T lepton reconstruction very important
- Invariant mass selections also important to optimize low mass selection

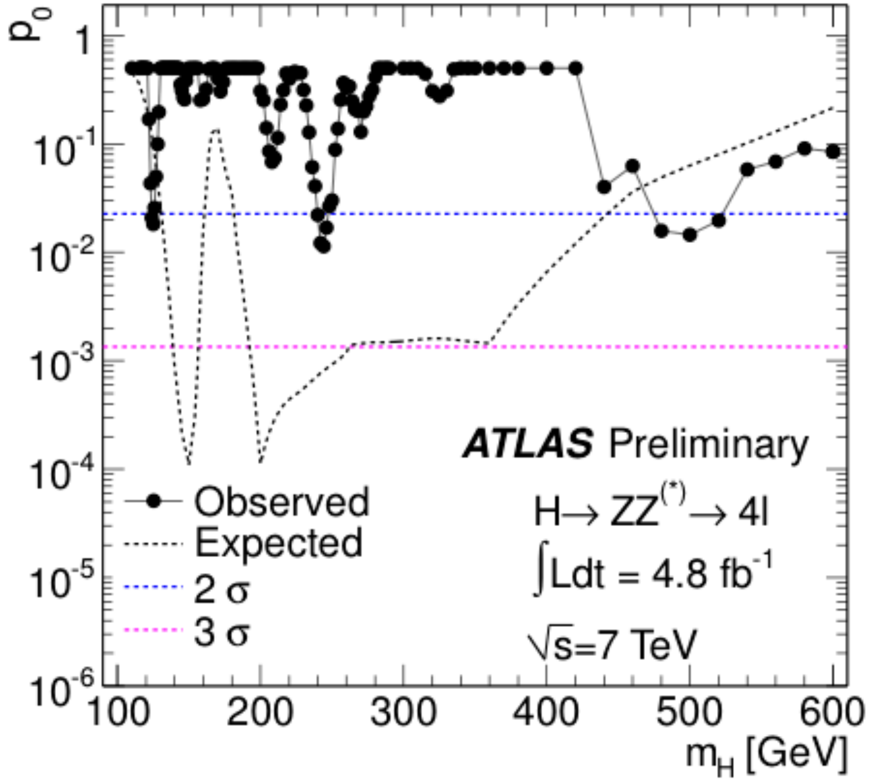
Low Background:

- Main Background ZZ from Monte Carlo (ATLAS) and derived from Z (CMS)
- Other backgrounds (Zbb and top) data driven (but small)



ATLAS $ZZ^{(*)} \rightarrow 4l$ (Low Mass)

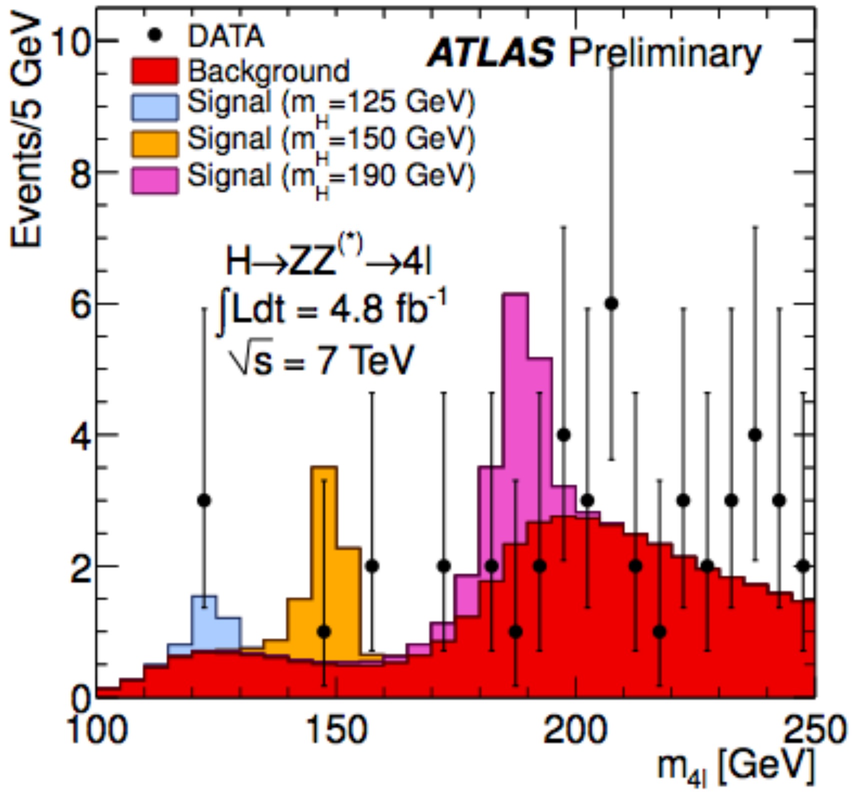


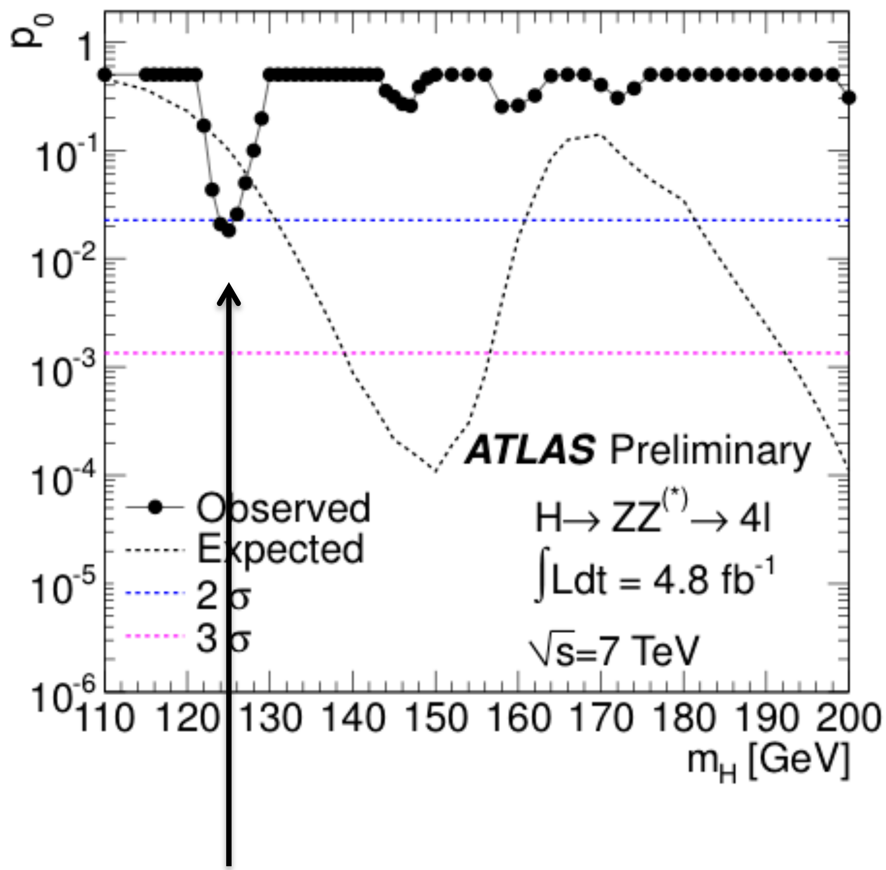


m_H (GeV)	Local (global) p_0	Local significance	Expected from SM Higgs
125	1.8% (~50%)	2.1 σ	1.4σ
244	1.1% (~50%)	2.3 σ	3.2σ
500	1.4% (~50%)	2.2 σ	1.5σ

Excluded at 95% C.L. → (244)

ATLAS $ZZ^{(*)} \rightarrow 4l$ (Low Mass)





Globally not significant

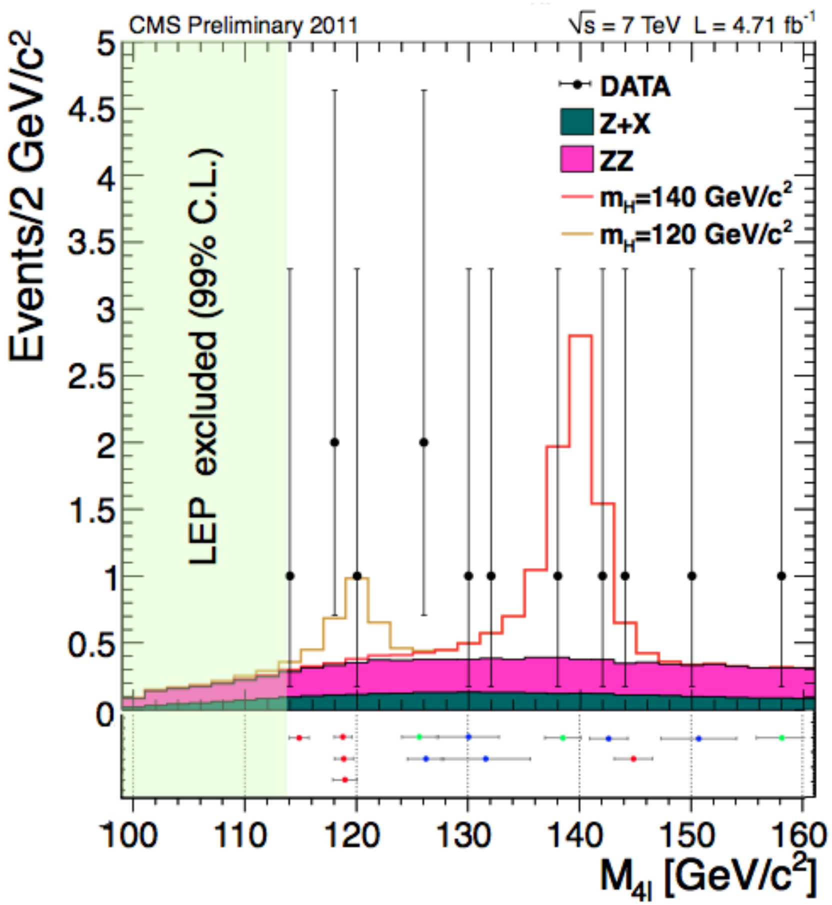
but at 125 GeV

ATLAS

Excess of

2.1σ

CMS $ZZ^{(*)} \to 4l$ (Low Mass)



Baseline Selection
$50 < M_{Z1} < 120$ GeV/c^2
$12 < M_{Z2} < 120$ GeV/c^2

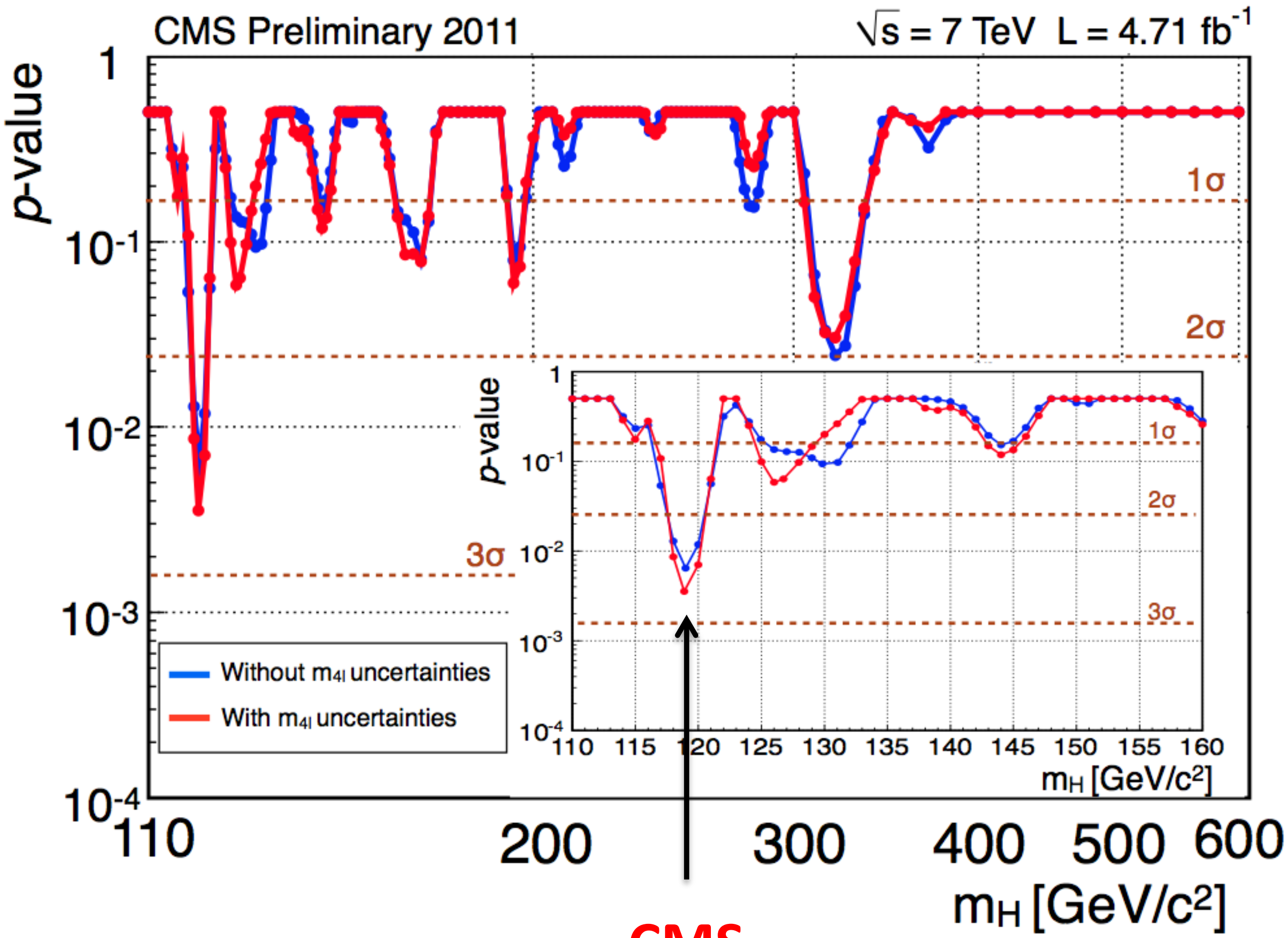
$\varepsilon(M_H \sim 120) \sim 20\%$ (4e), 40% (4μ), 25% ($2e2\mu$)
$\varepsilon(M_H \sim 160) \sim 42\%$ (4e), 75% (4μ), 55% ($2e2\mu$)

Event Yields:

Final state:	4e	4μ	$2e2\mu$
Obs. events:	3	5	5
Exp. events:	1.7	3.3	4.5

$100 < M_{4\ell} < 160$ GeV/c^2 Observed: 13 Expected: 9.5 ± 1.3 events

CMS $ZZ^{(*)} \rightarrow 4l$ (Low Mass)



CMS

Excess of

2.5σ

Globally not significant

and at 119 GeV

$$H \rightarrow W^{+}W^{-} \rightarrow \ell \upsilon \ell \upsilon$$

Most sensitive Channel in [125-180] GeV Mass range

ATLAS 4.7 fb^{-1}

CMS 4.6 fb^{-1}

Signal yield after cuts (low mass) ~O(30)

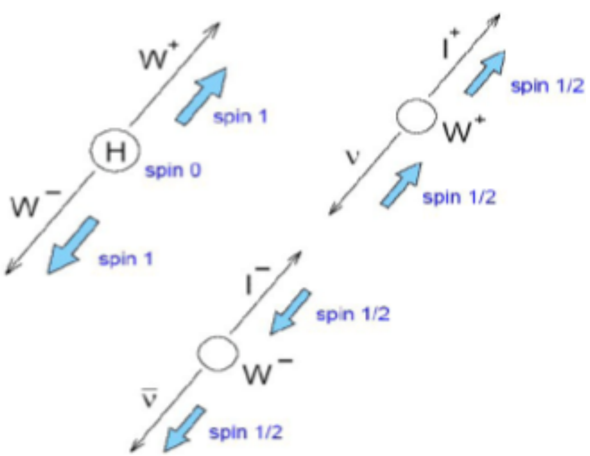
s/b ~ O(15)%

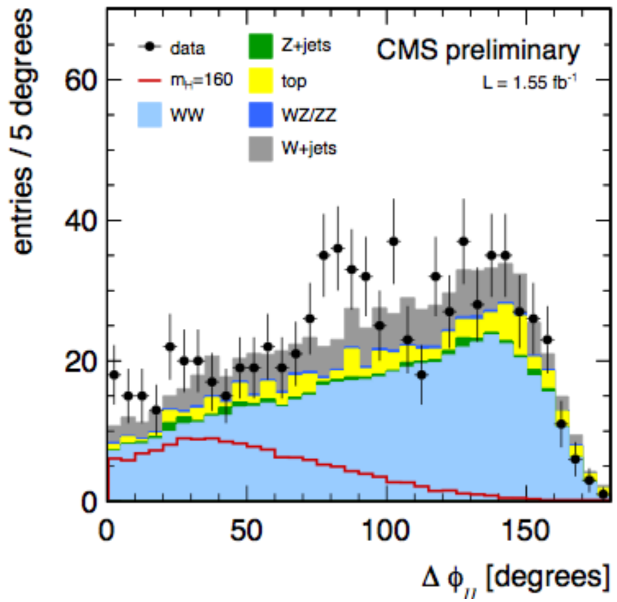
More Details in talk by Xifeng Ruan

Higgs Boson Search in the WW→lνlν

Key features :

- Poor resolution in mass (requires in particular a good control of MET)
- Search carried out in 0, 1-jet and VBF topologies
- ATLAS cut based only / CMS cut based and MVA
- Good control of the WW and top backgrounds is essential!
- Use of spin correlations is essential for the analysis and to define control regions… CMS also use a BDT (kinematic variables)

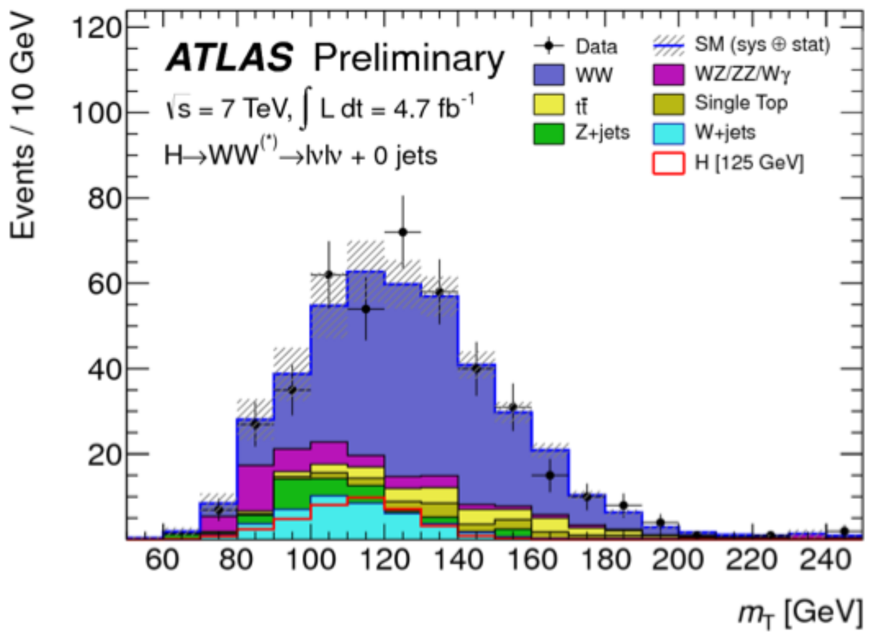


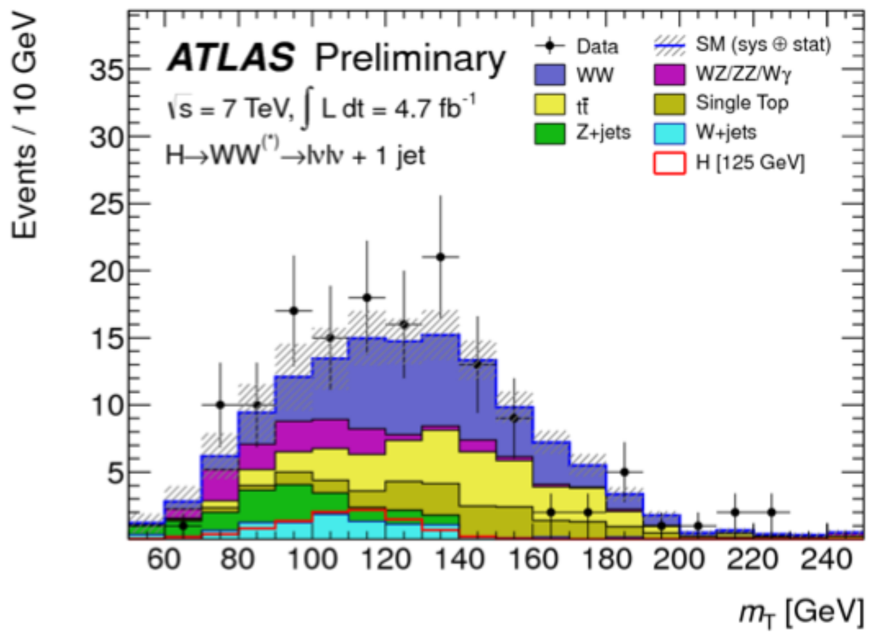


Higgs Boson Search in the WW→lνlν

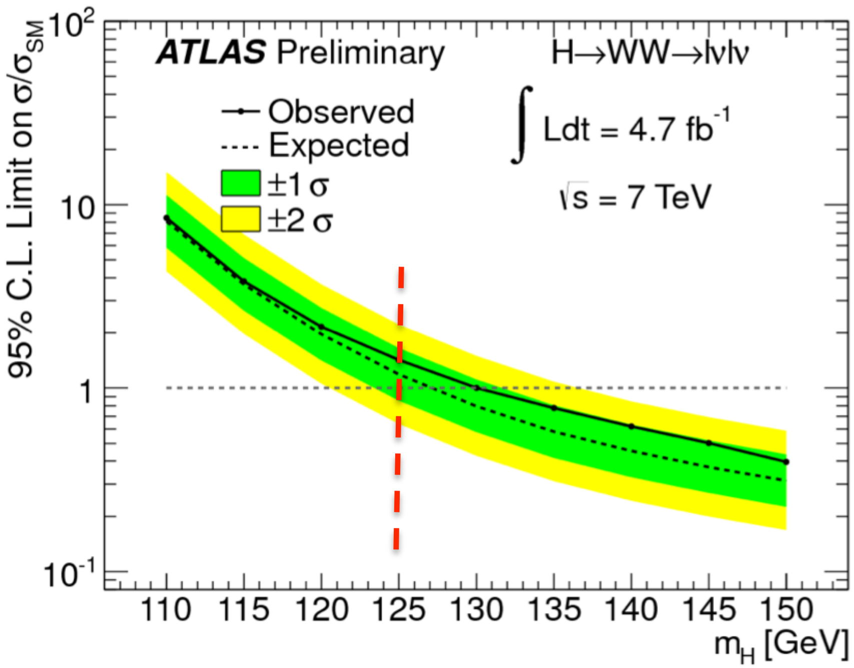
Key features :

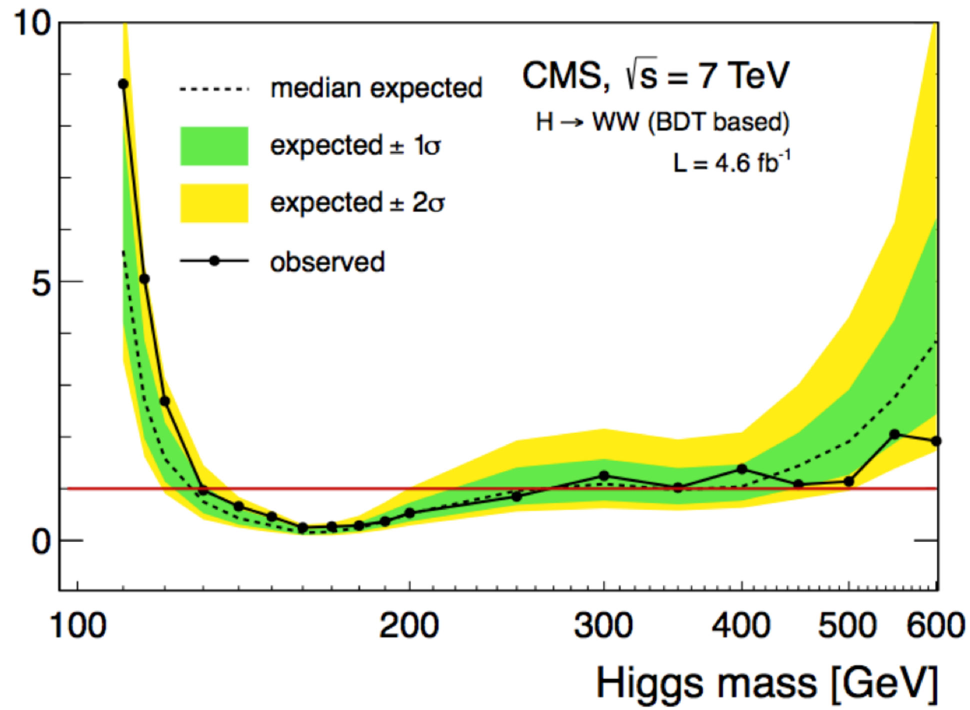
- Neutrinos : poor resolution in mass (requires in particular a good control of MET)
- Search carried out in 0, 1-jet and VBF topologies
- ATLAS cut based only / CMS cut based and MVA
- Good control of the WW and top backgrounds is essential!
- Use of spin correlations is essential for the analysis and to define control regions… CMS also use a BDT (kinematic variables)





Higgs Boson Search in the WW→lνlν





No excess in ATLAS…

(lvlv alone is sensitive to 125 GeV but does not exclude it)

Slight excess in CMS…

ATLAS and CMS (@125 GeV) Exp. Lim. ~1

No Significant Excesses Observed

Single most sensitive analysis for a 125 GeV Higgs

(and small trial factor)

$$W(Z)H \rightarrow \ell\upsilon(\ell\ell,\upsilon\upsilon)b\bar{b}$$

ATLAS 4.7 fb^{-1}

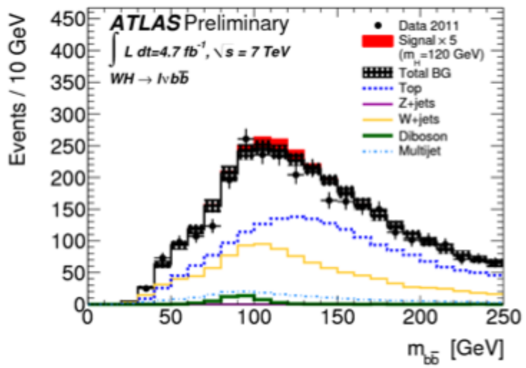
CMS 4.6 fb^{-1}

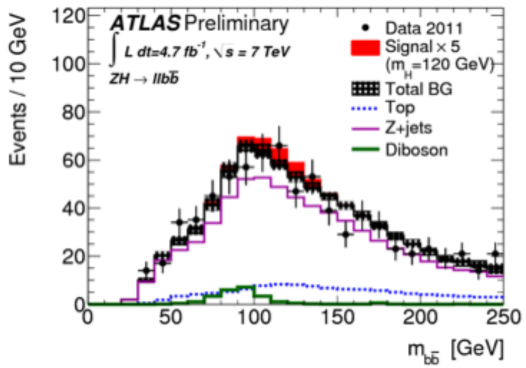
Signal yield after cuts (low mass, Highest boost) ~O(3-5)

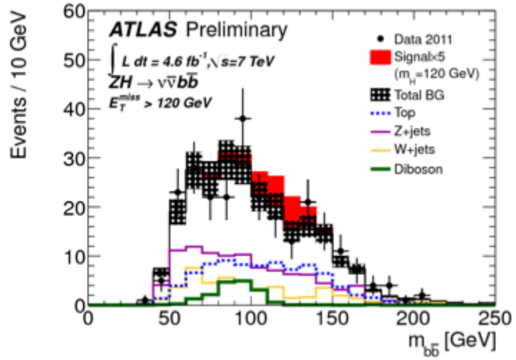
s/b ~ 10-15%

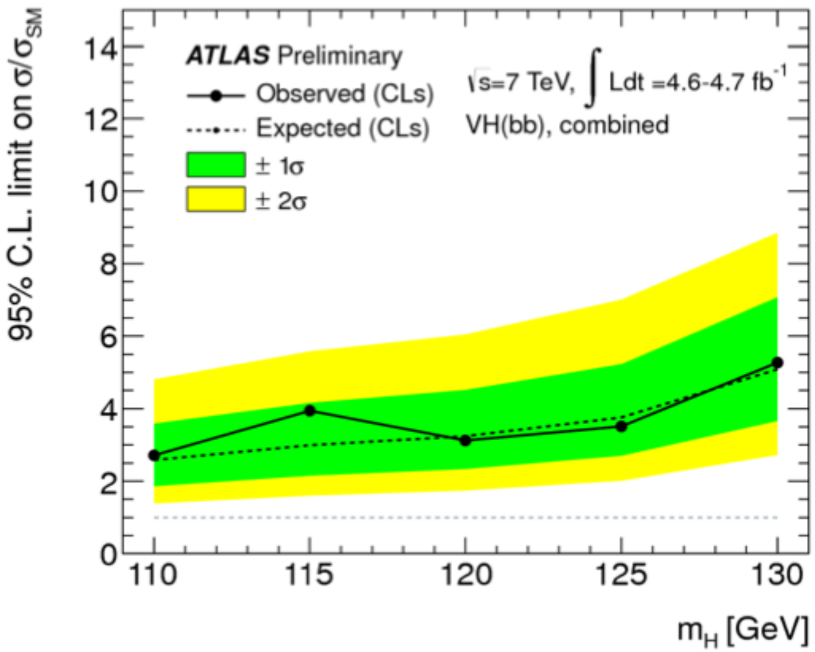
Key features :

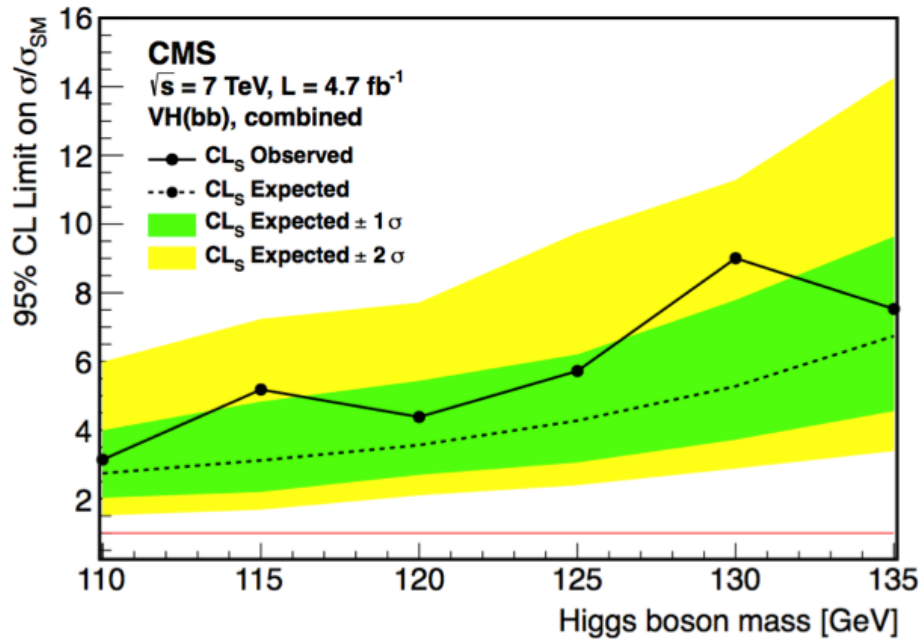
- Search carried out in three channels (ll,lv and vv) bb (Associated prod.)
- Higgs system boosted in the transverse plane (but no substructure)











ATLAS and CMS (@125 GeV) Exp. Lim. ~4

No Significant Excess Observed

$$(VBF)H \rightarrow \tau^{+}\tau^{-}$$

ATLAS 4.7 fb^{-1}

CMS 4.6 fb^{-1}

Signal yield after cuts (low mass and VBF) ATLAS ~O(3) / CMS~O(0.5)

ATLAS s/b ~ 2% / CMS s/b ~ 5%

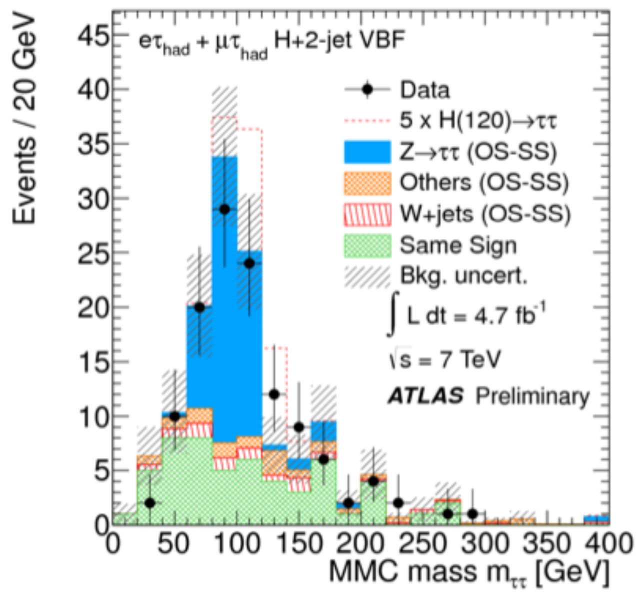
ATLAS and CMS different working points

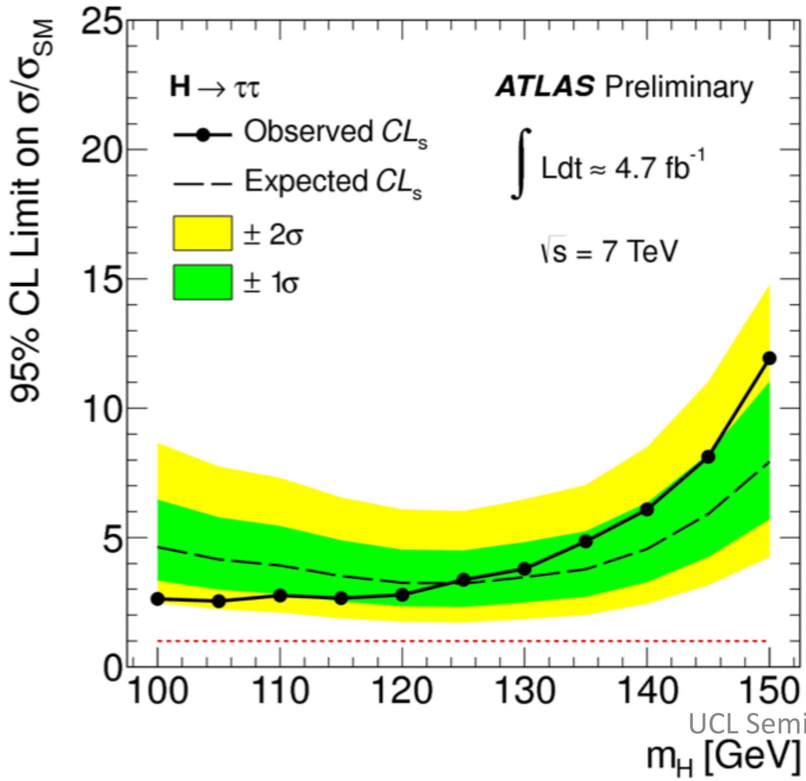
Key features :

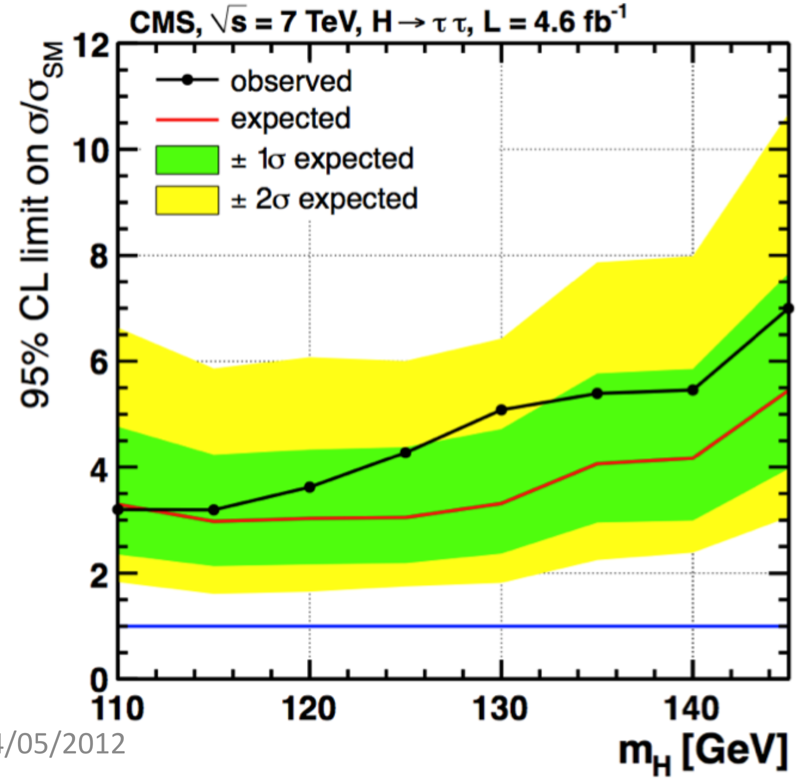
- Search carried out in ll, lh and hh channels
- Important use of VBF
- New Mass Reconstruction Techniques

ATLAS and CMS (@125 GeV) Exp. Lim. ~3

No Significant Excess Observed





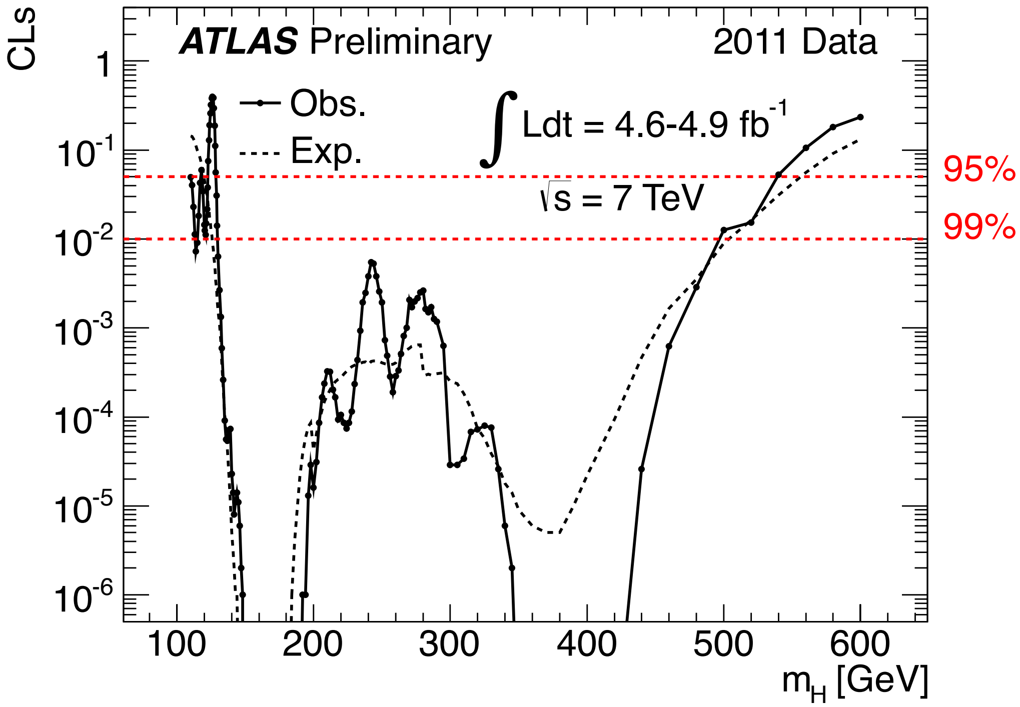


Combination(s)

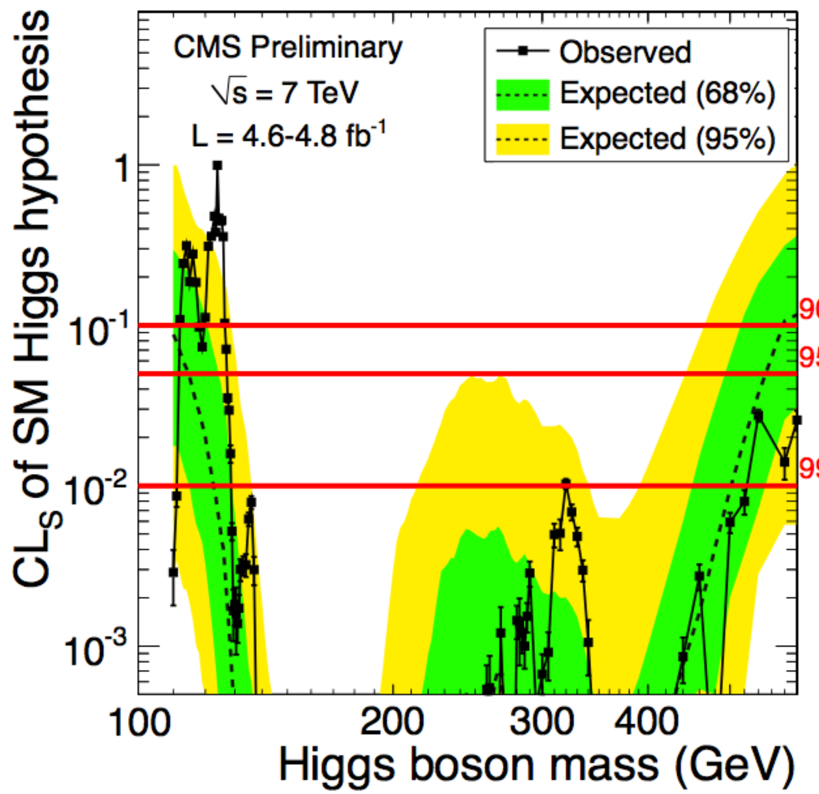
The Overall Picture

Combination of All Channels

The ATLAS and CMS Combinations



Expected (95% CL) : 120 – 555 GeV
Observed (95% CL) : 110-117, 117-122, 129-540 GeV
Expected (99% CL) : 126 – 500 GeV
Observed (99% CL) : 130-480 GeV

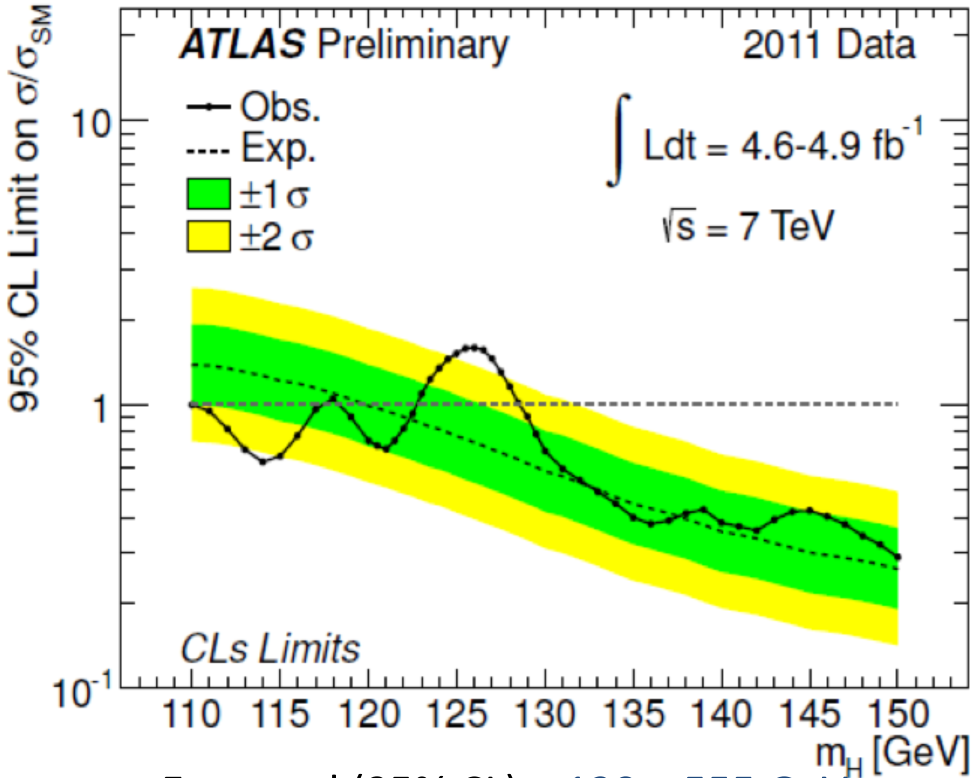


Expected (95% CL) : 114 – 540 GeV
Observed (95% CL) : 128 - 600 GeV

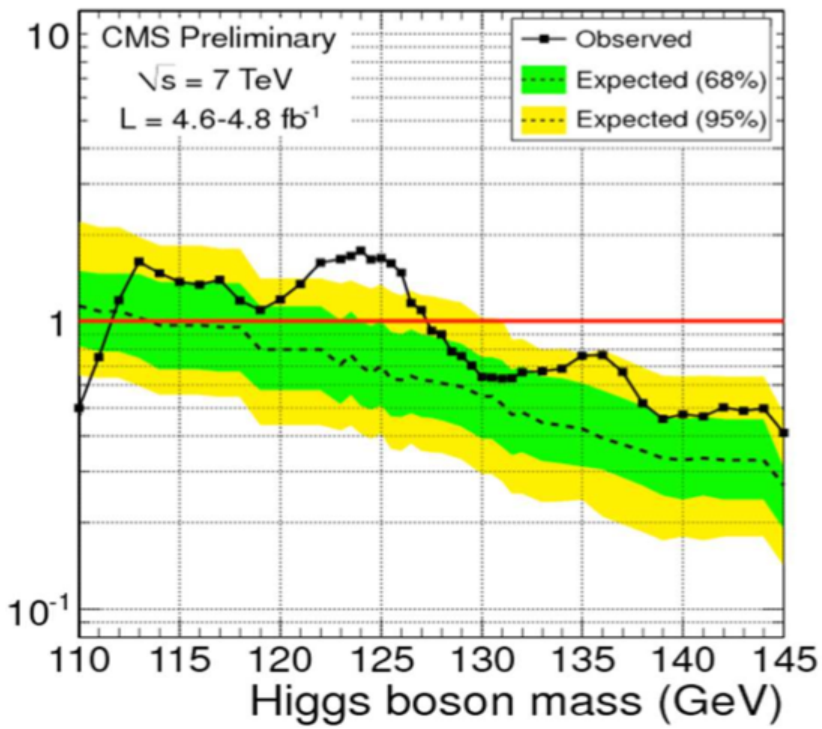
Observed (99% CL) : 129 – 520 GeV

Combination of All Channels

The ATLAS and CMS Combinations



Set to scale by J.-F. Grivaz (Moriond 2012)



Expected (95% CL) : 120 – 555 GeV
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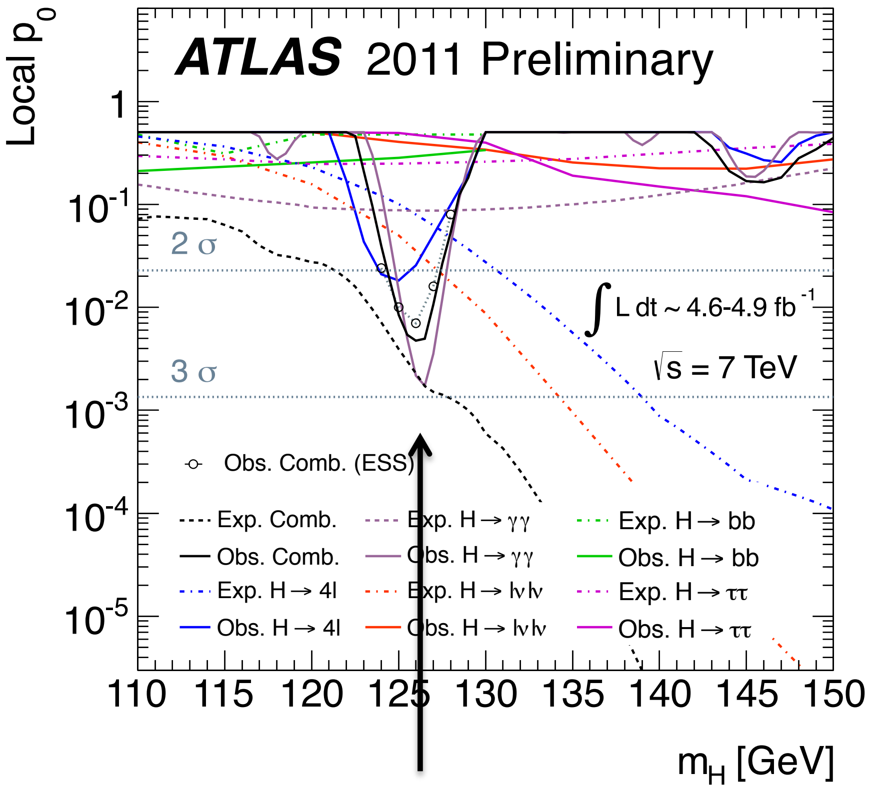
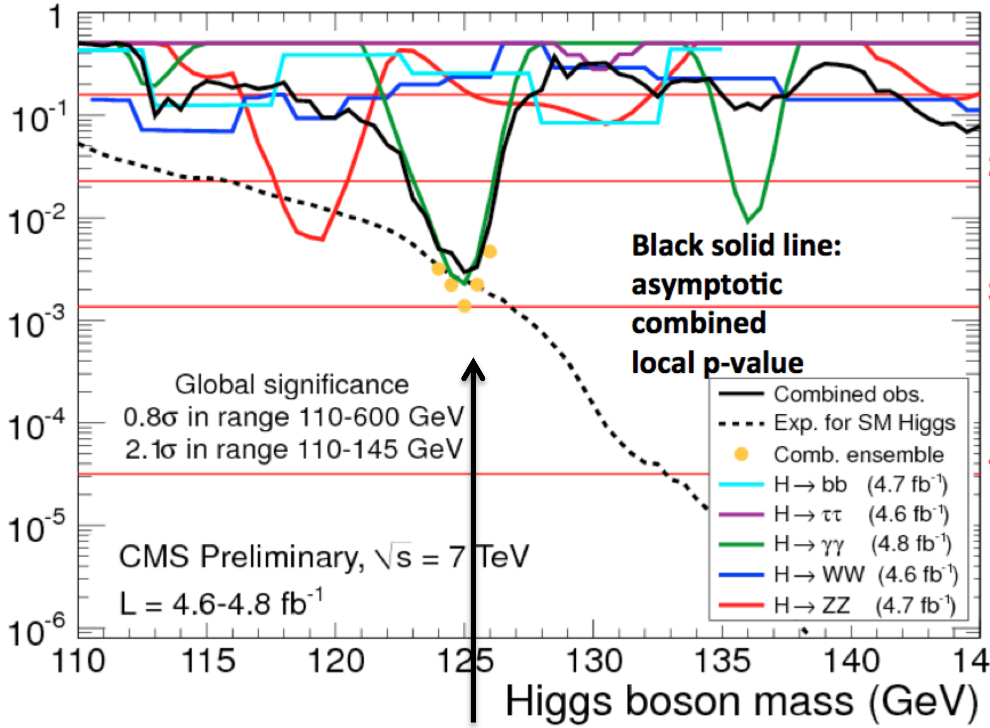
Expected (99% CL) : 126 – 500 GeV
Observed (99% CL) : 130-480 GeV

Expected (95% CL) : 114 – 540 GeV
Observed (95% CL) : 128 - 600 GeV

Observed (99% CL) : 129 – 520 GeV

Are there Hints of a Signal ?





ATLAS

Excess of

2.5σ

- Excess mostly in γγ
- Slight excess in 4l
- No excess in lνlν

Global of 1.5σ

Exp. local 2.9σ

CMS

Excess of

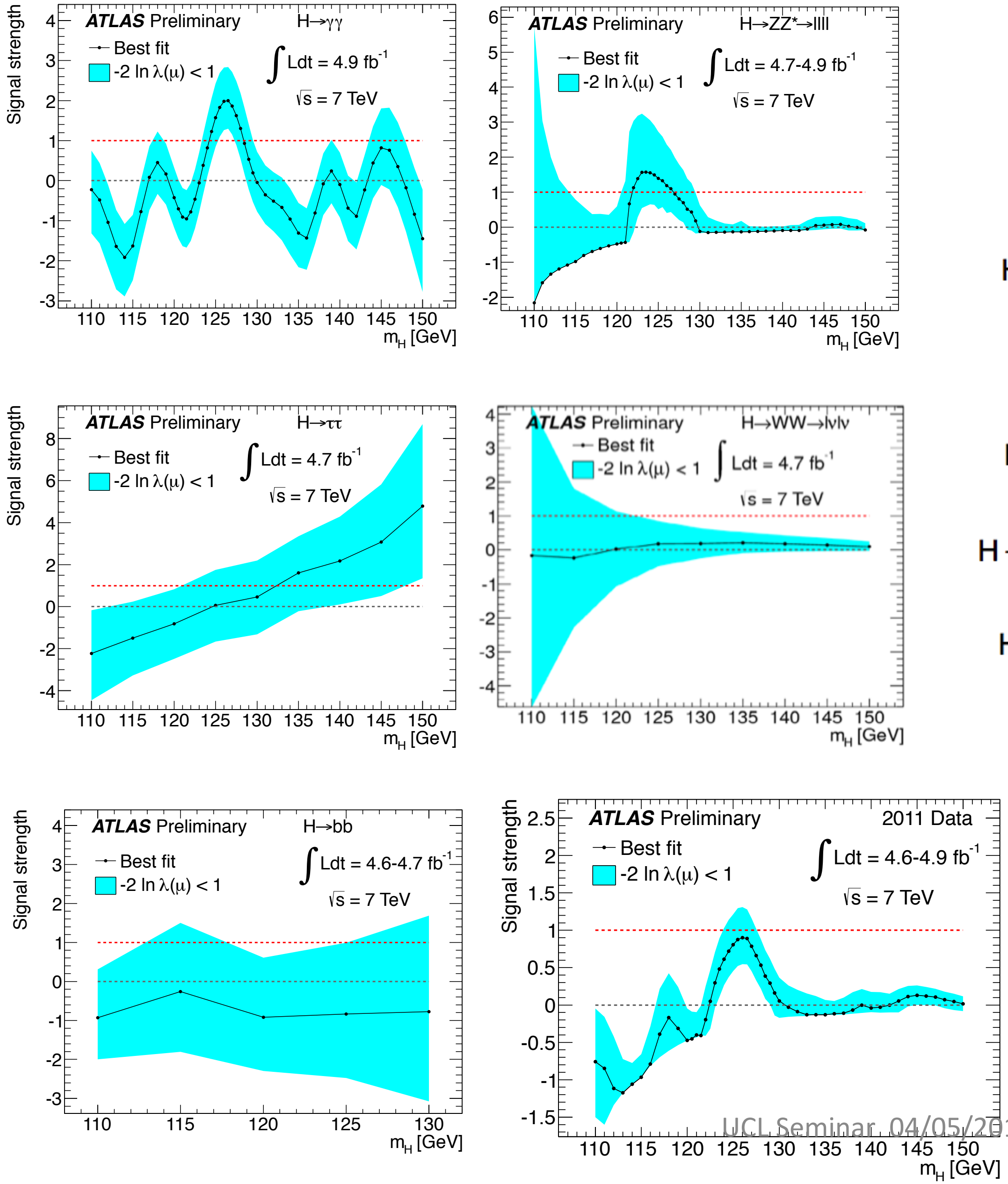
2.8σ

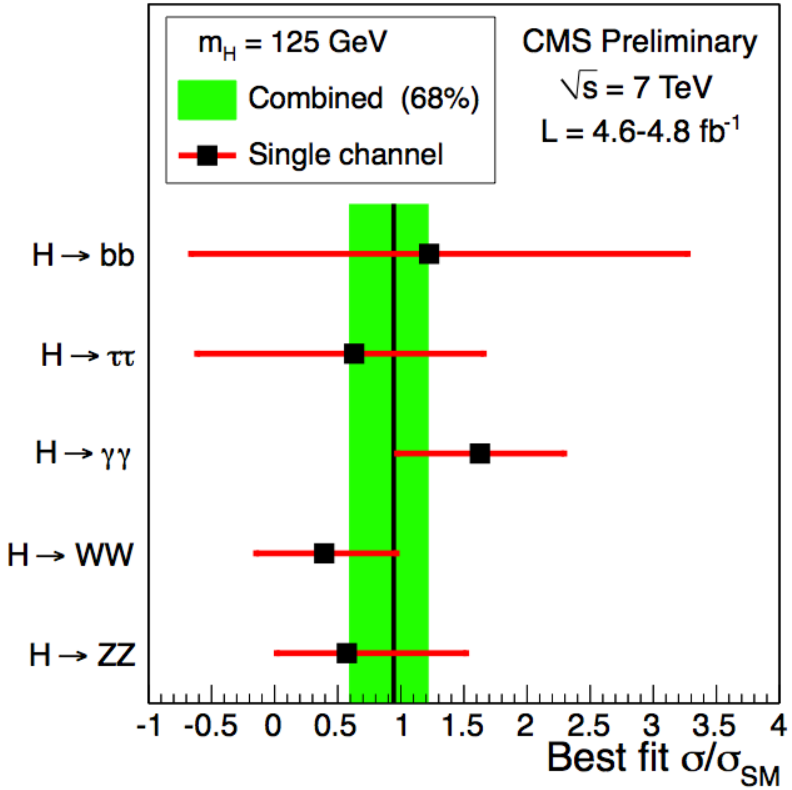
- Excess mostly in γγ
- Various small excesses

Global of 1.6σ

Exp. Local 2.8σ

Individual Channels Consistency





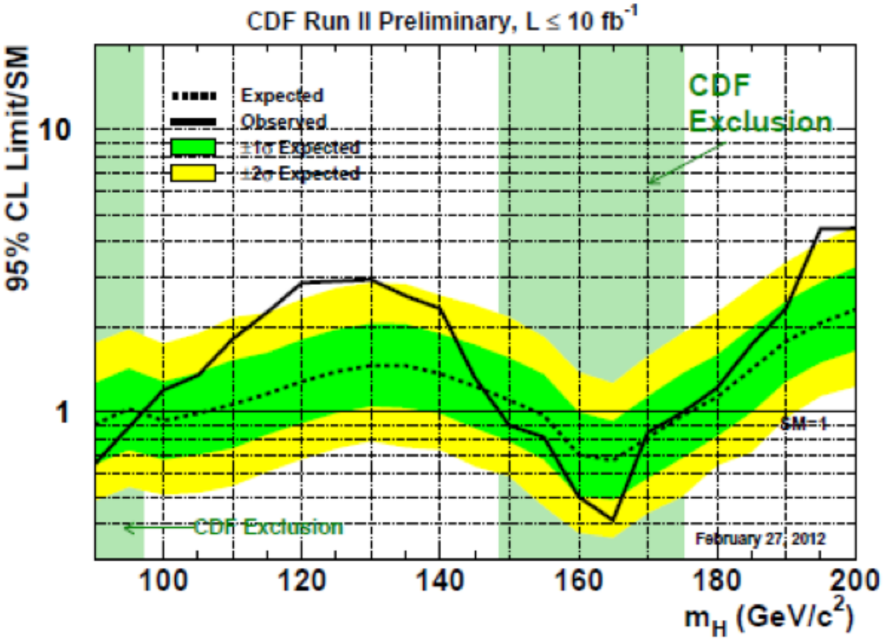
All channels compatible with SM signal hypothesis…

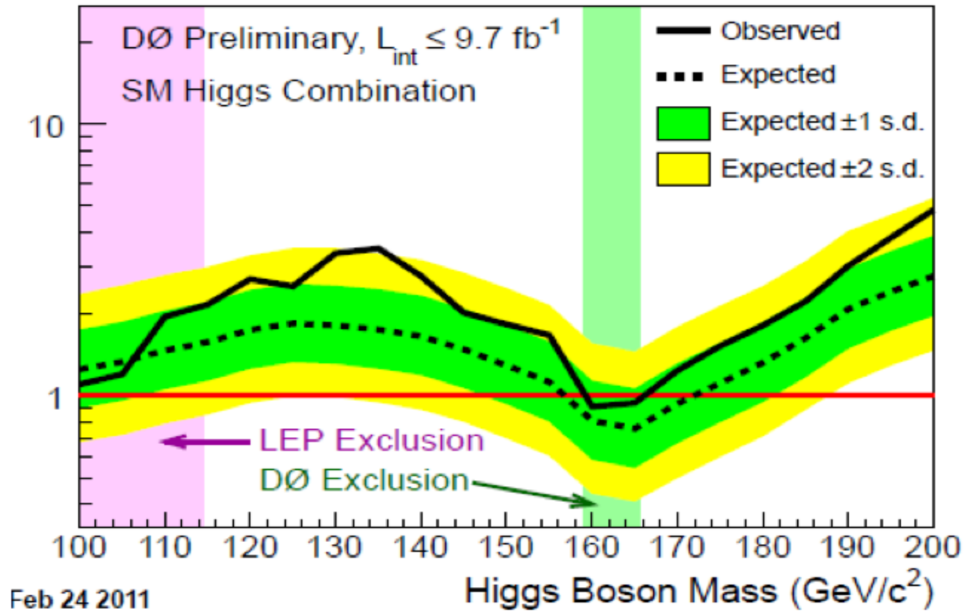
The specific case ATLAS lνlν…

Including the Latest (updated) TeVatron Results in the Overall Picture

The Tevatron ended its operations Fall 2011

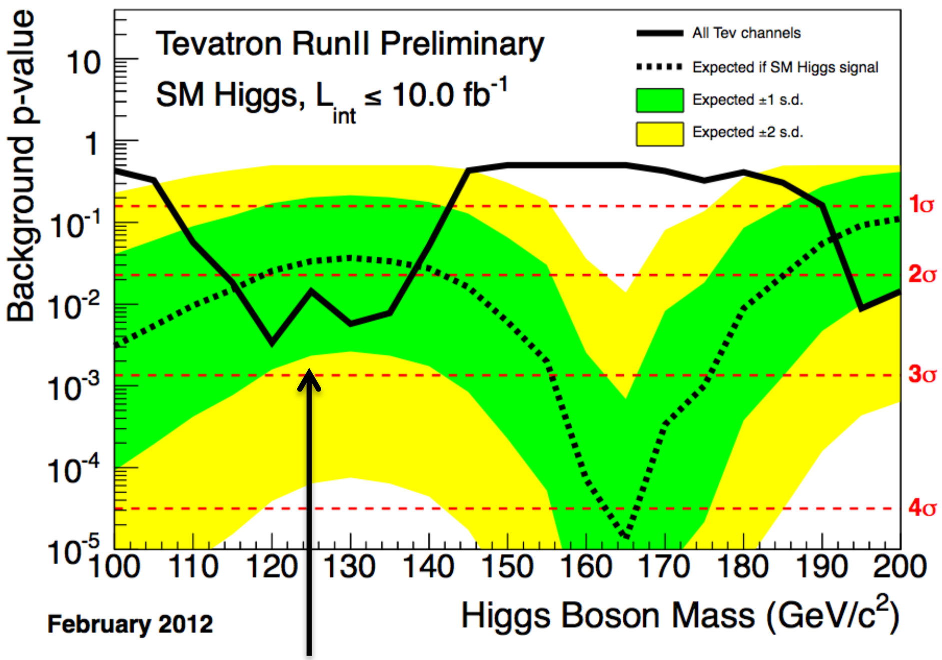
Including the Latest (updated) TeVatron Results in the Overall Picture

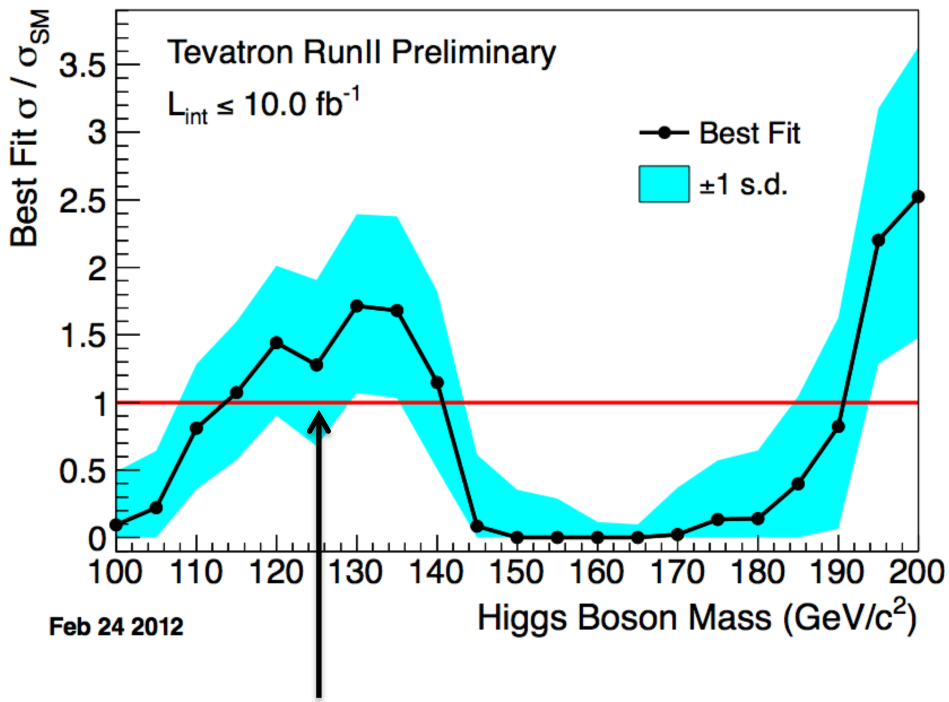




Consistent picture in both CDF and D0

Including the Latest (updated) TeVatron Results in the Overall Picture





Excess compatible with SM signal

TeVatron

Excess of

~2.7σ

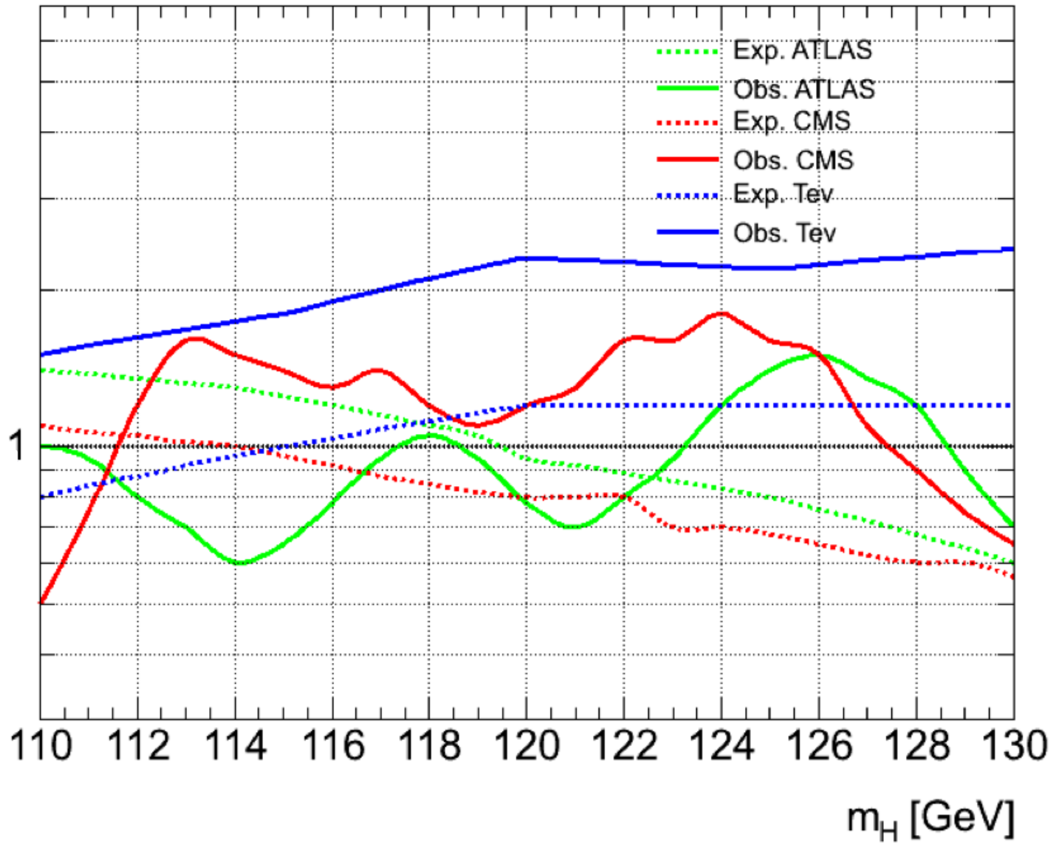
Global of 2.2σ

Exp. local ~1.8σ

- Excess largest in bb (Mostly CDF)
- Excess also in lvlv (Both CDF and D0)

The Full Picture

Courtesy of Bill Murray

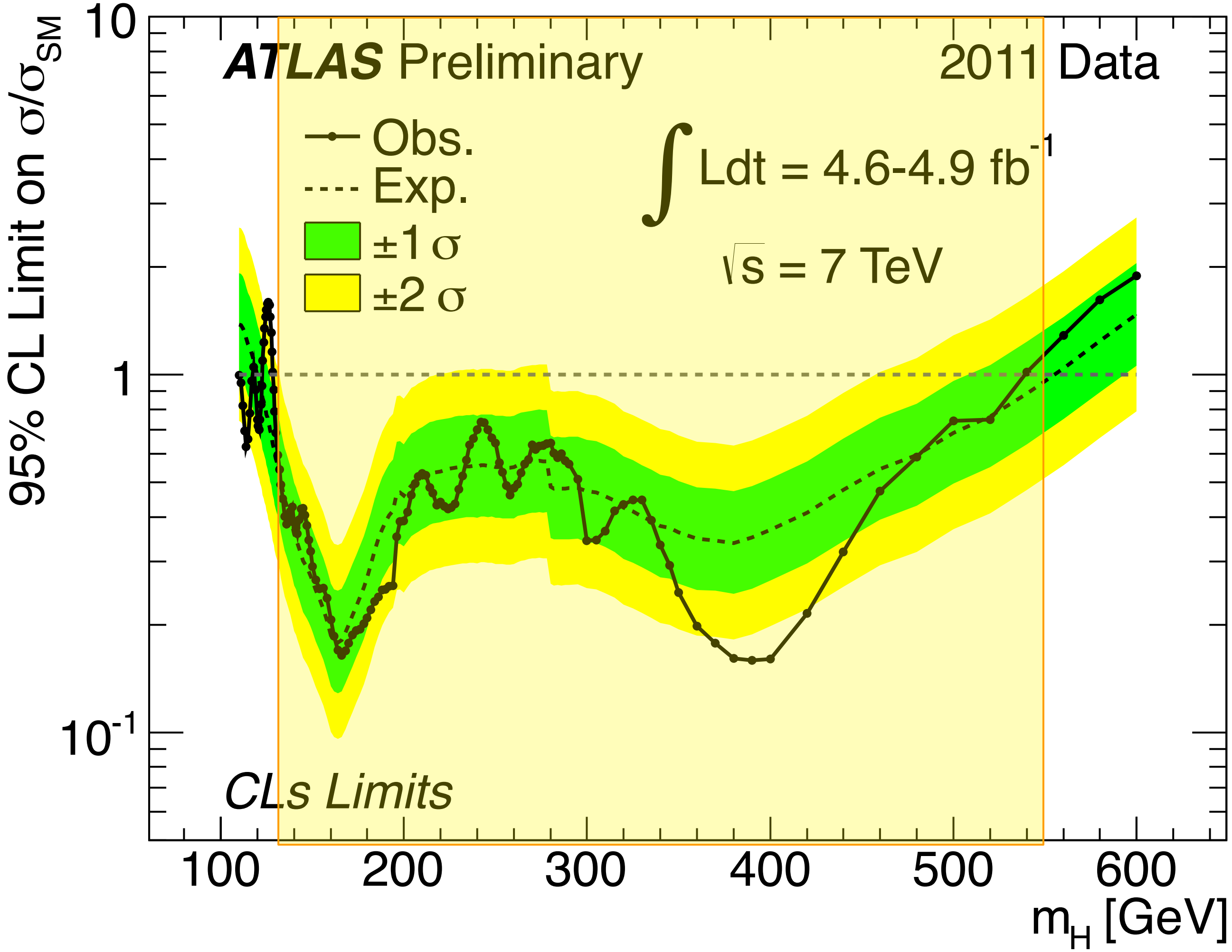


Impressively consistent picture :

- ATLAS, CMS and Tevatron consistently see excesses in a variety of channels
- ATLAS and CMS similar performance, TeVatron not so far lower

Conclusions and Outlook

New Landscape of Higgs Searches



The Standard Model Higgs search landscape has completely changed in one year.

Tantalizing Hints around 125 GeV…

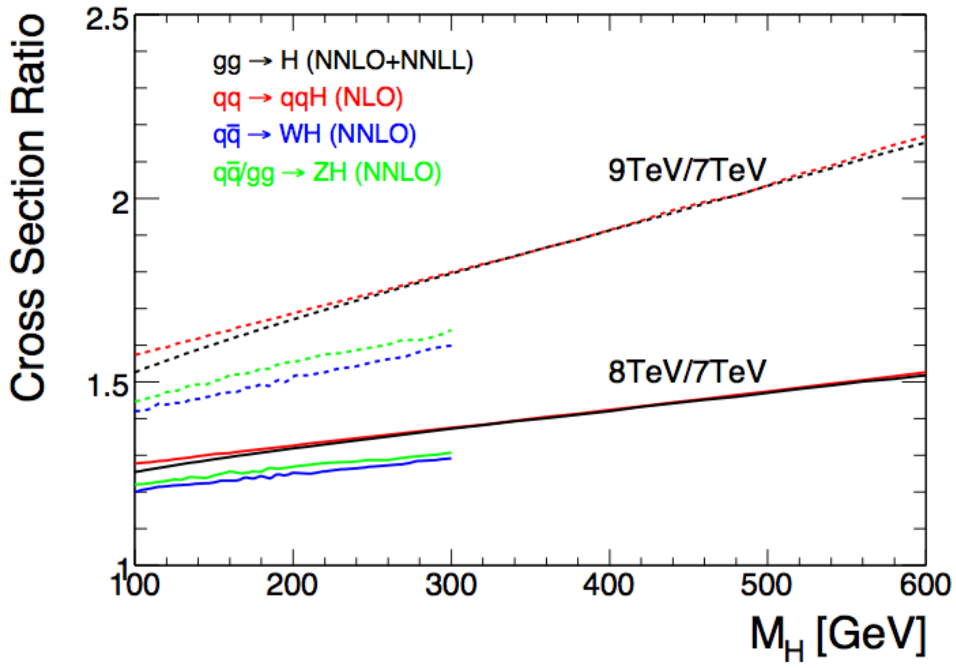
- ATLAS and CMS observe 2.5σ and 2.8σ (respectively)
- Agreement with the 2.9σ and 2.8σ expected
- Observation of the excess mostly in $\gamma\gamma$ for both channels but consistent with the observation of other channels

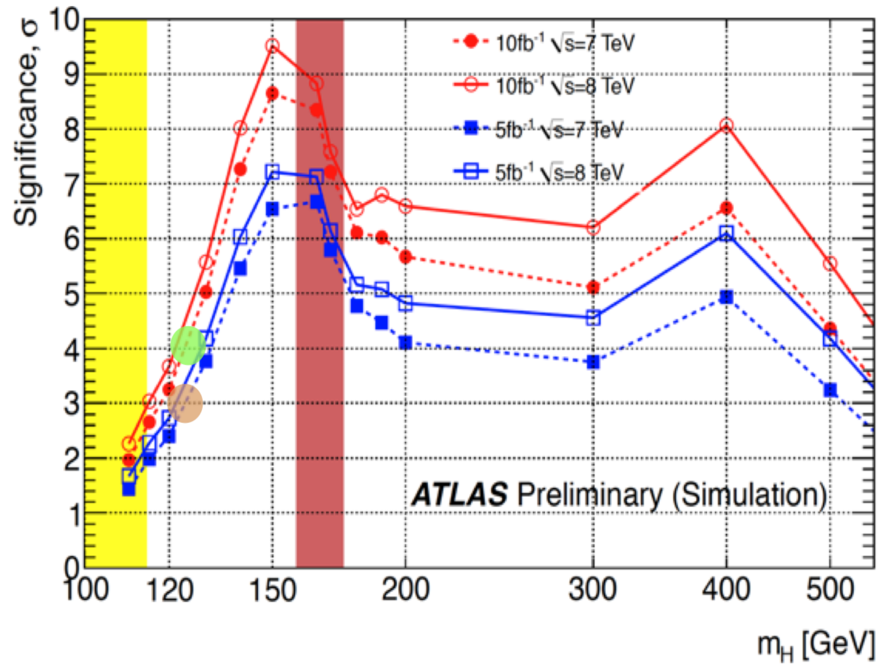
- TeVatron observes 2.7σ
- Agreement with expectation of 1.8σ
- Observation mostly in bb but also in lvlv

- Taken individually none of these observations are globally very significant
- Need more data for a definitive answer…

… However excellent mass domain experimentally

What Next? From 7 to 8 TeV





- Gain in signal cross section : ~20-30%
- Gain in sensitivity : ~10%
- Equivalent luminosity : ~20%

Taking into account the 5 fb^{-1} of data at 7 TeV need 7-8 fb^{-1} at 8 TeV to reach 5σ sensitivity at 125 GeV

Not negligible…

What Next? 8 TeV

~ 10% improvement in sensitivity

Parameter	2010	2011	2012	Nominal
k (N bunches)	368	1380	1380	2808
Bunch spacing	150	50	50	25
ε (μm rad)	2.4-4	1.9-2.3	2.5	3.75
β^* (m)	3.5	1.5-1	0.6	0.55
L ($cm^{-2}s^{-1}$)	$2x10^{32}$	$3.3x10^{33}$	$\sim 7x10^{33}$	10^{34}

More O(30) PU events!

- In 2012 ~15 fb^{-1} : Foresee O(7) fb^{-1} for ICHEP
    - Confirm (5σ sensitivity)
    - Infirm (exclude at 95% CL with such a large excess)
- Next LS1 preparing for higher energies >12 TeV

2012 Should bring a definite answer to the search of the SM Higgs boson

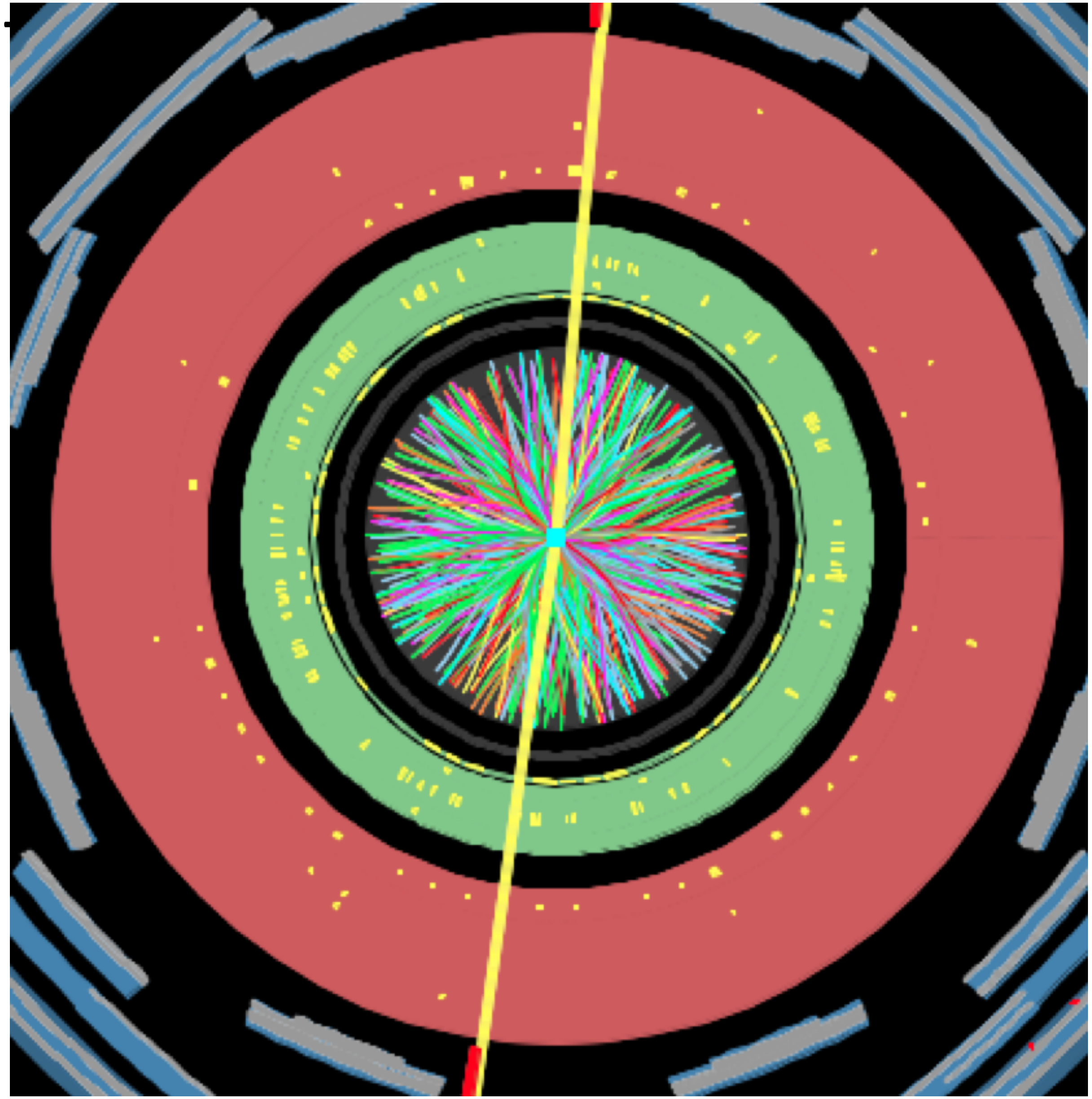
2012 Data

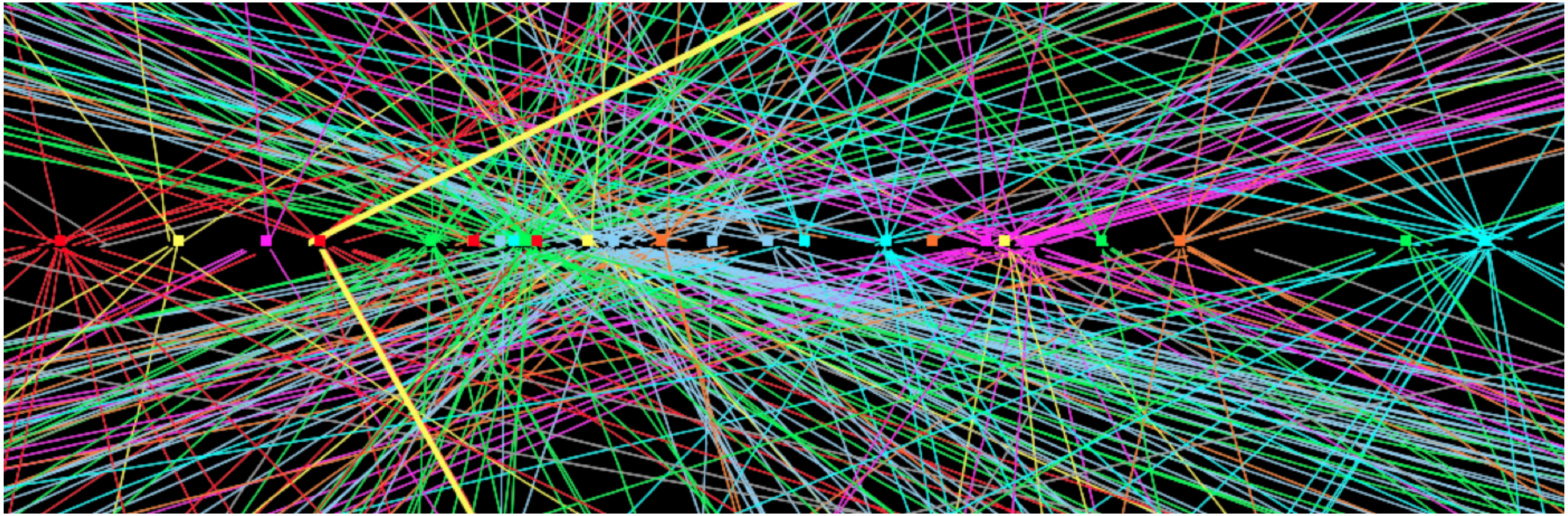
Up to yesterday

$$\sim 1 fb^{-1}$$

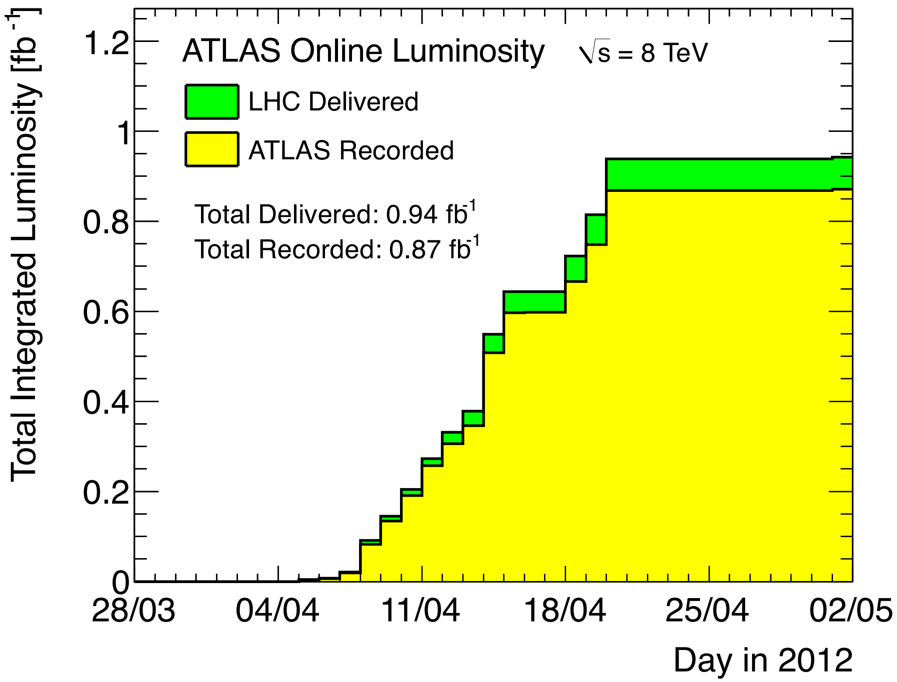
8 TeV

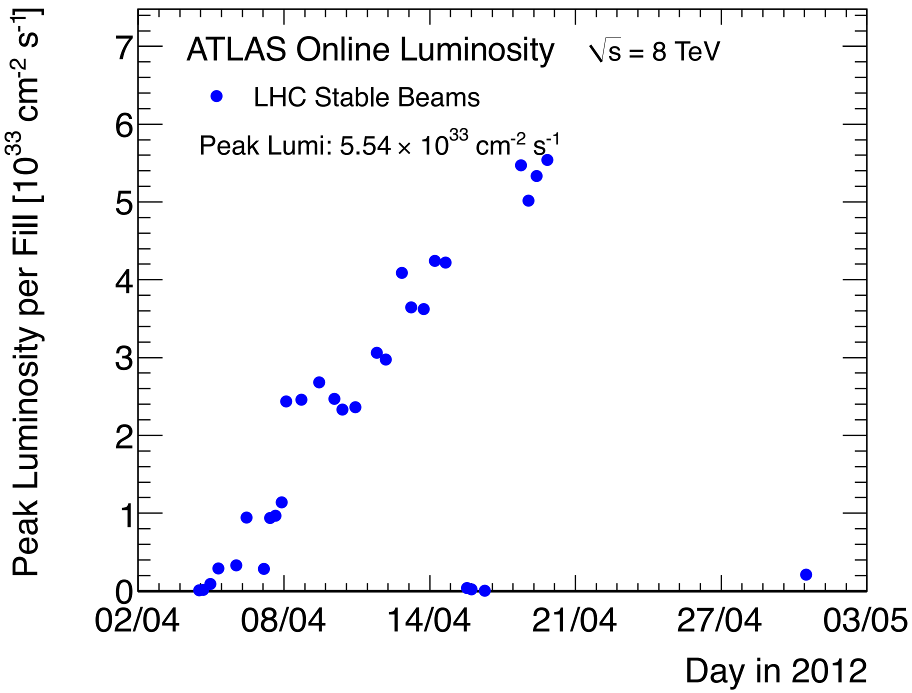
Much higher PU!





Recent event with ~25 vertices

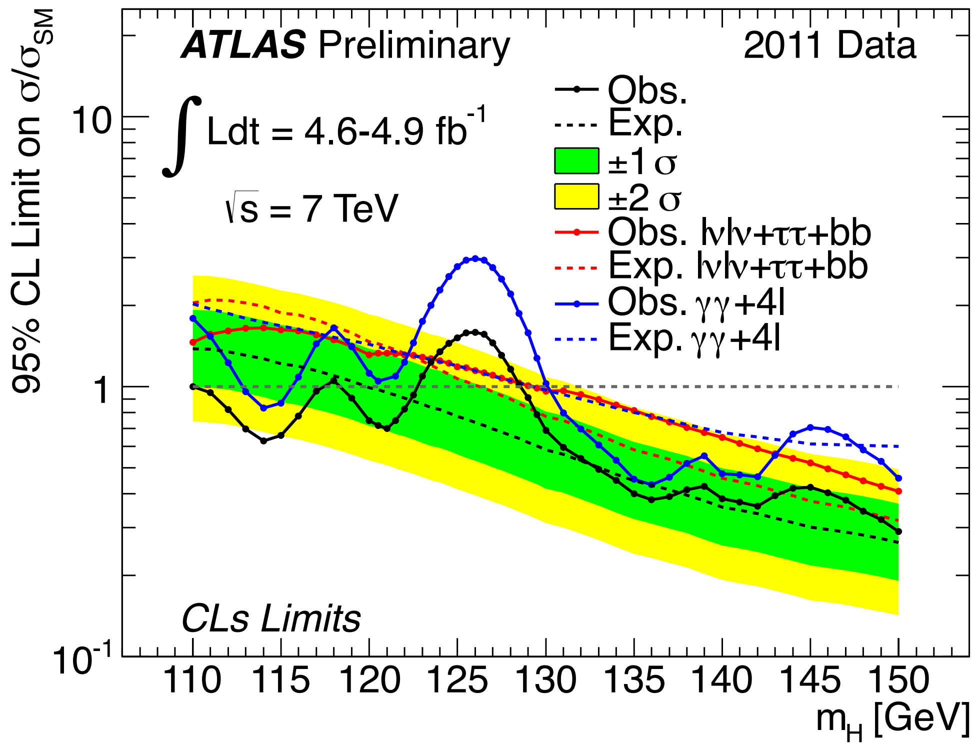


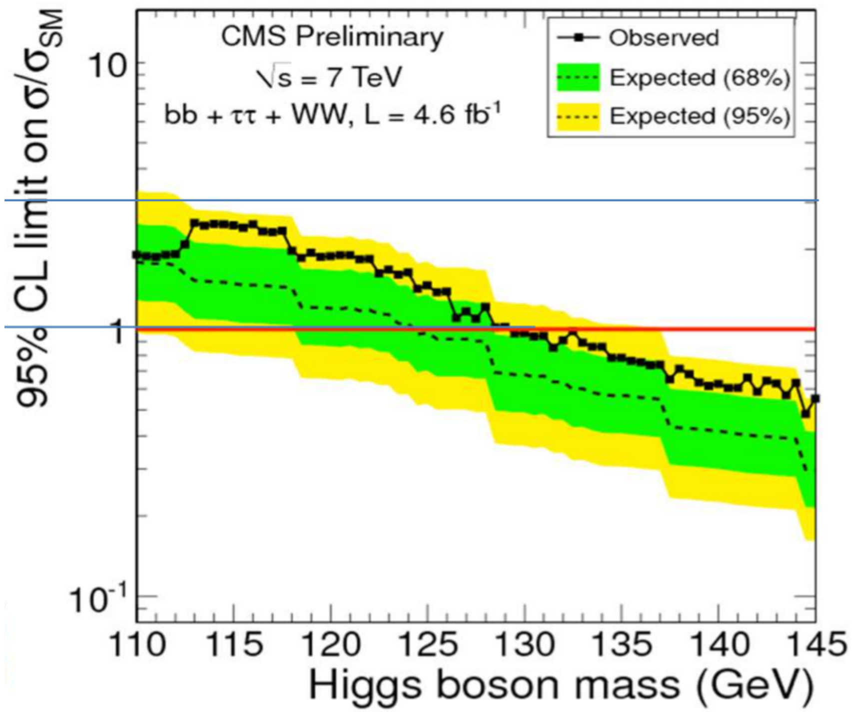


Backup

Sub-combinations Consistency

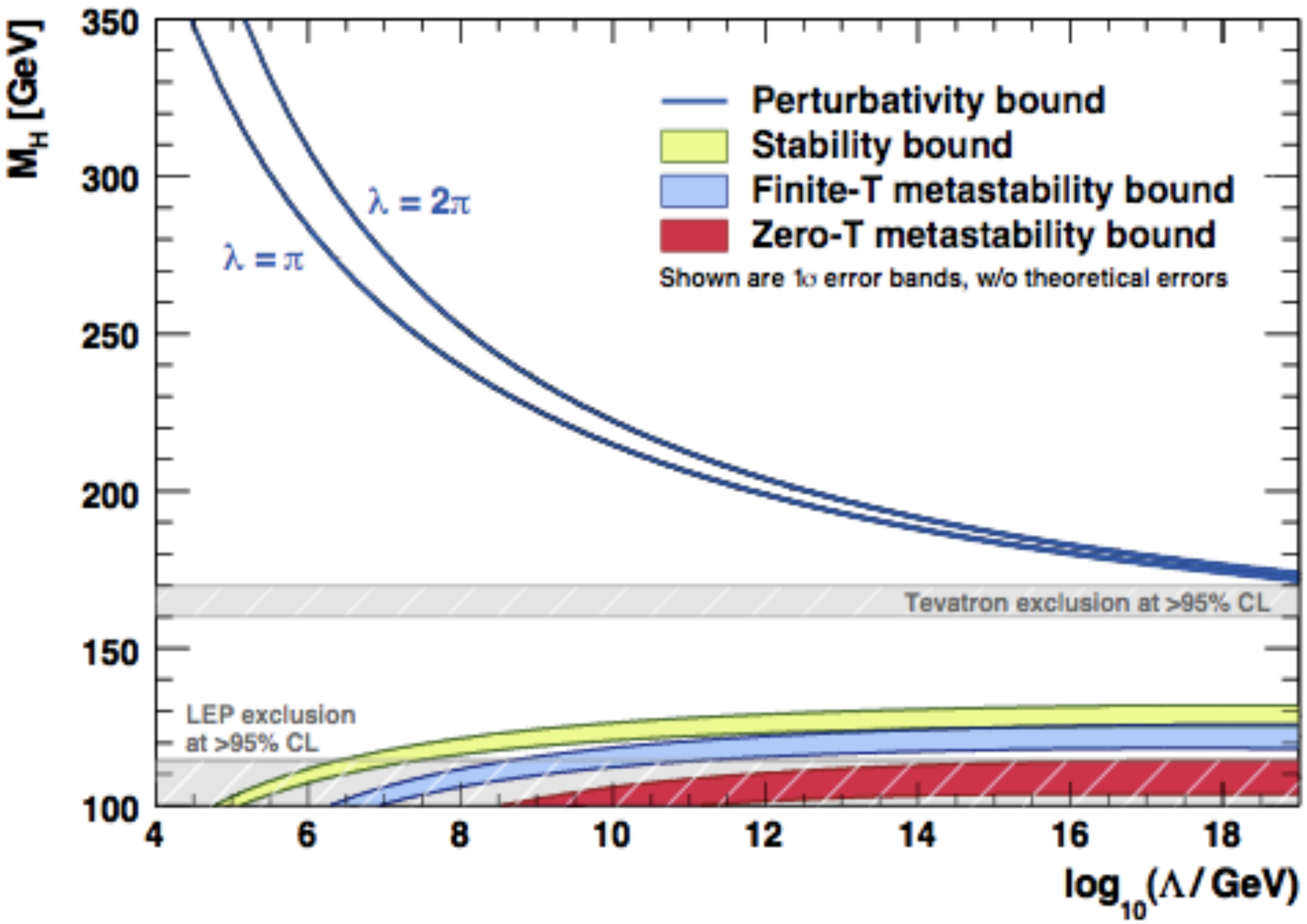
- Seen that High resolution channels are consistent
- Low resolution channels do not exclude the excess observed



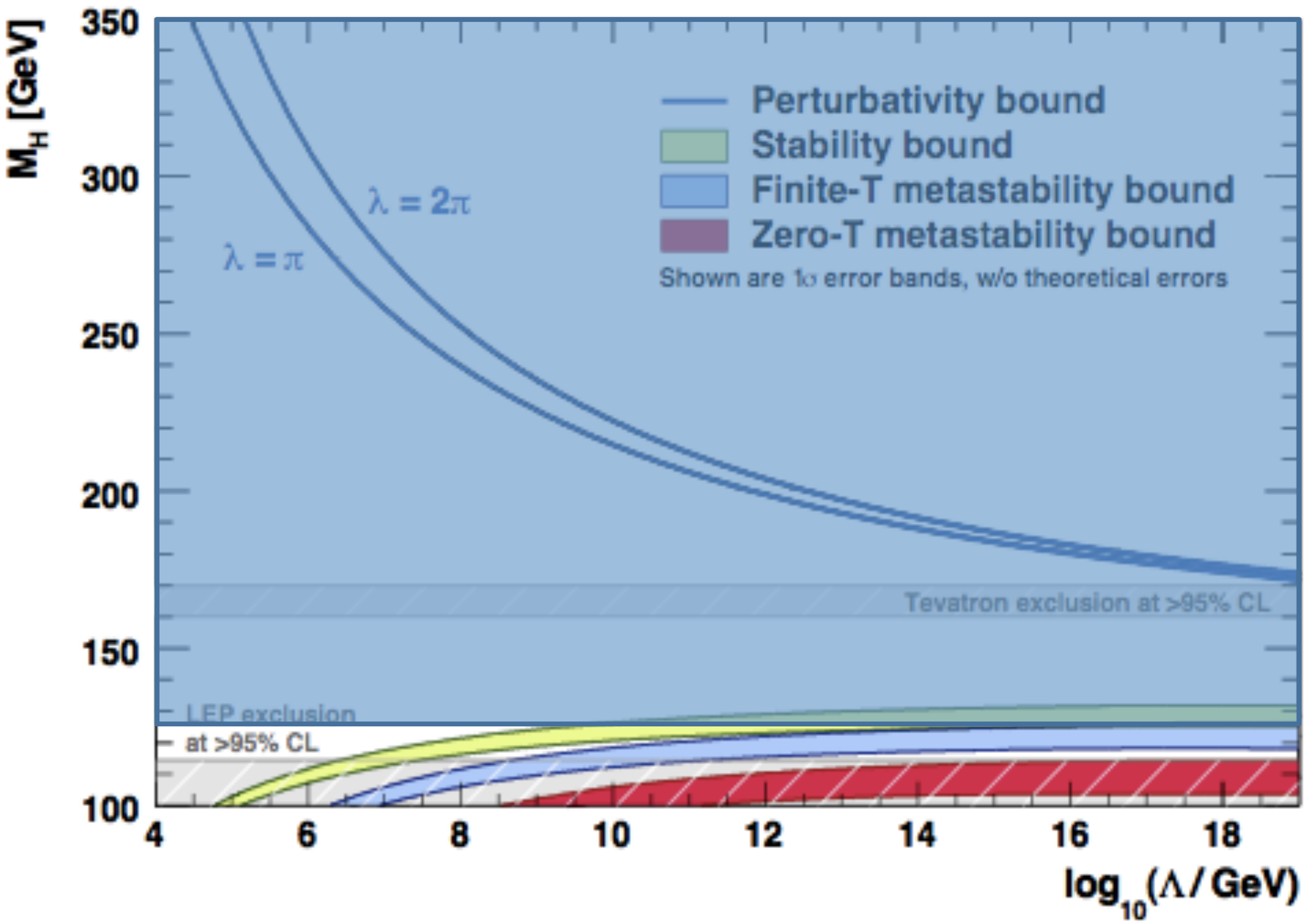


The sub-combinations do not contradicts (not exclude at 95% CL) the excess observed

What do we learn?



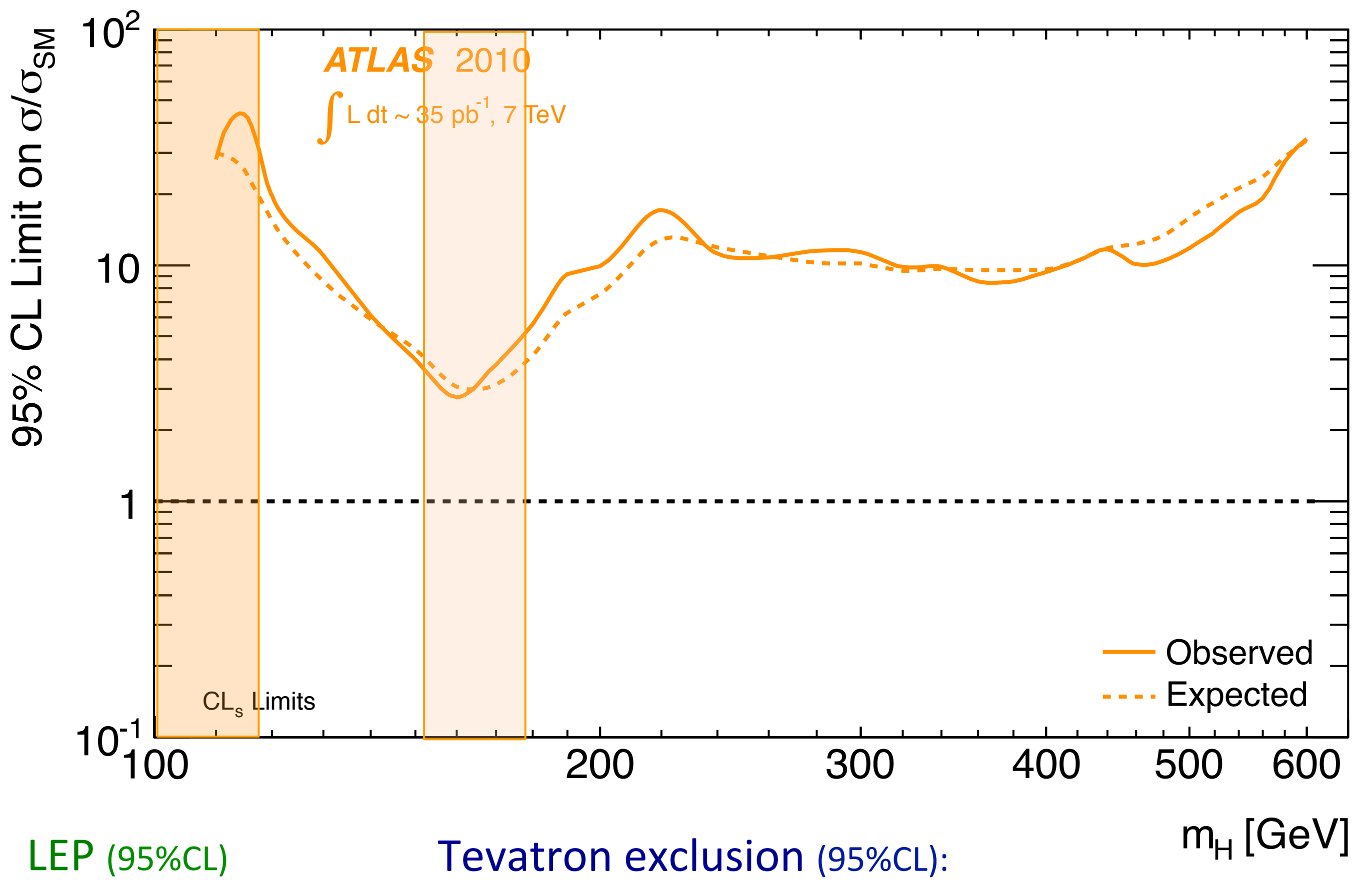
What do we learn?



Fast Forward Evolution Since Moriond 2011

…in ATLAS…

Moriond 2011 (2010 Data)



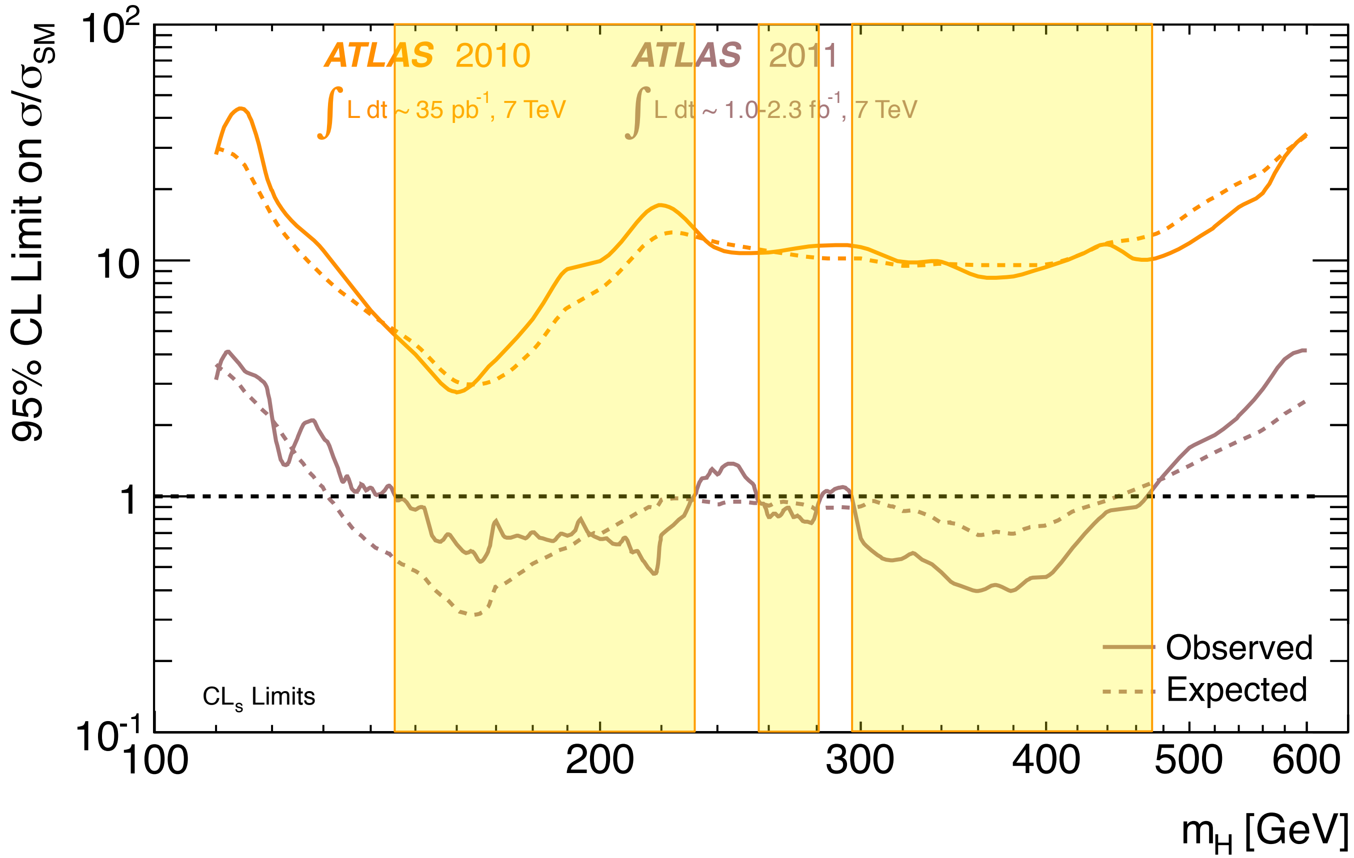
LEP (95%CL)
$m_H > 114$ GeV

Tevatron exclusion (95%CL):
$100 < m_H < 109$ GeV
$156 < m_H < 177$ GeV

Fast Forward Evolution Since Moriond 2011

…in ATLAS…

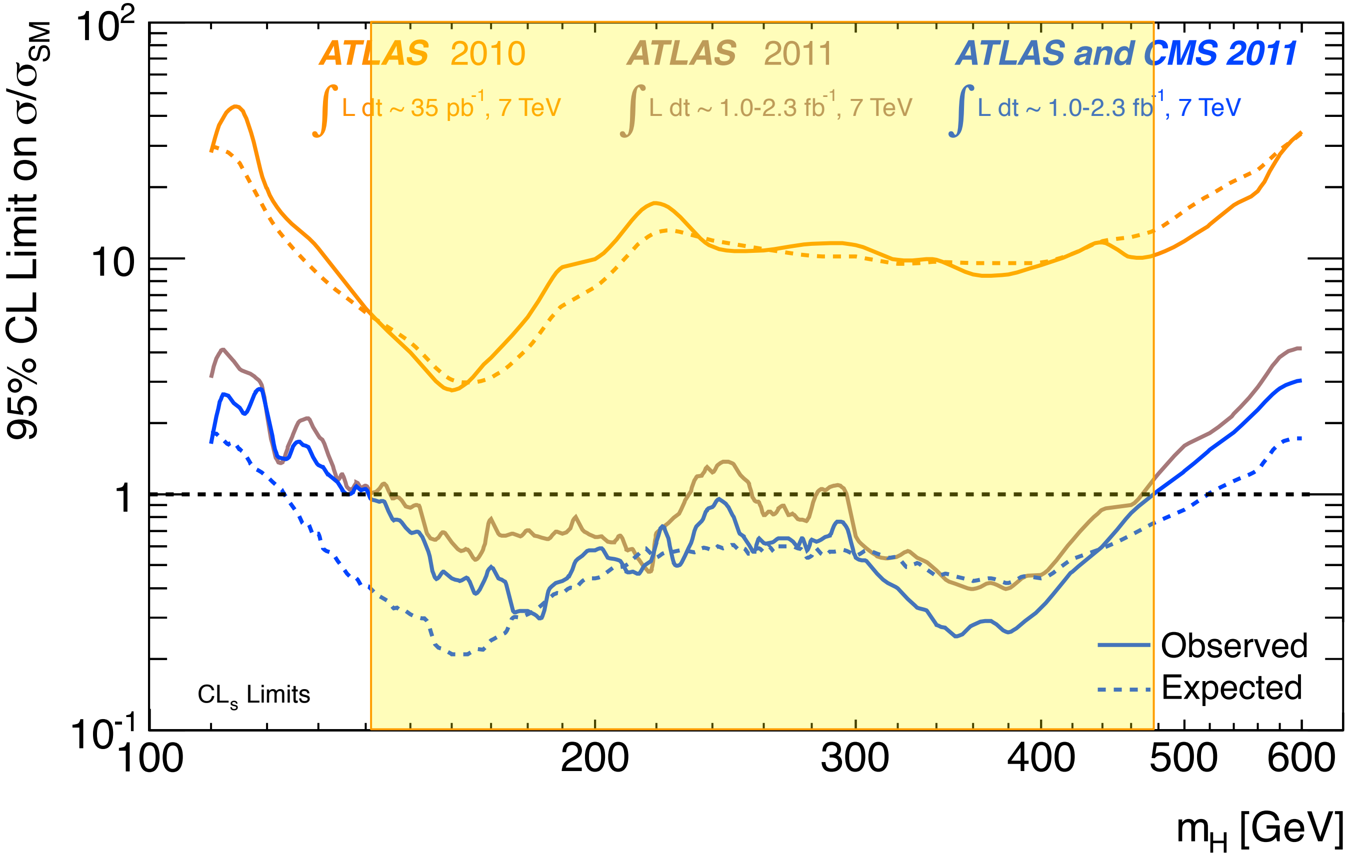
EPS 2011



Fast Forward Evolution Since Moriond 2011

…in ATLAS…

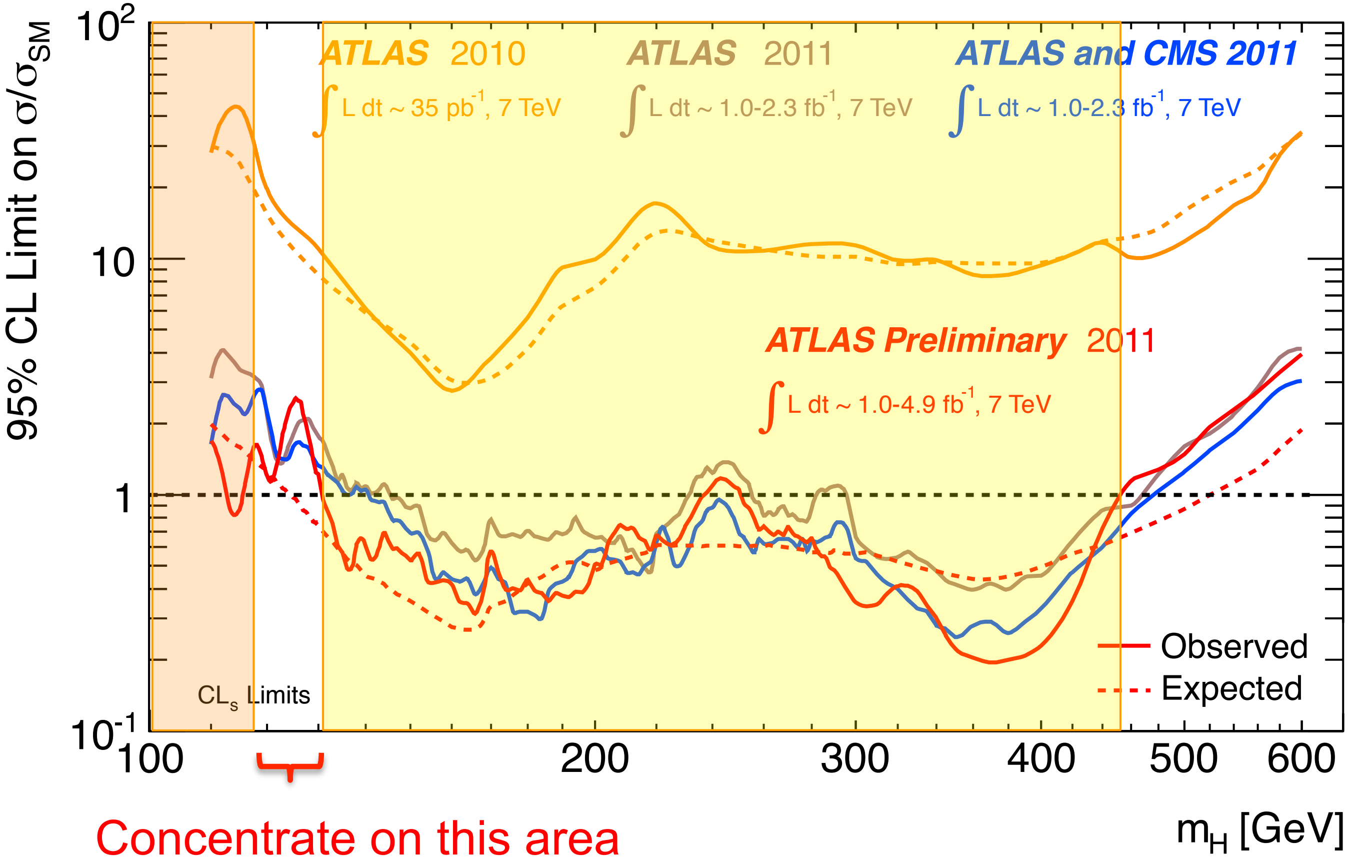
Combination HCP 2011



Fast Forward Evolution Since Moriond 2011

…in ATLAS…

Council 2011



Concentrate on this area

In the Italian News …

la Repubblica.it | Scienze

Half a Century of Higgs hunt…

the final dash?

FISICA

Bosone di Higgs, sprint finale verso il Nobel cambia nome

I prossimi mesi di esperimenti all'Lhc, l'acceleratore di particelle del Cern di Ginevra, saranno decisivi per la conferma dell'esistenza della 'particella di Dio', che potrebbe chiamarsi Beh (da Brout-Englert-Higgs). Si moltiplicano i libri di divulgazione e i convegni, in preparazione del premio più ambito

di ELENA DUSI

Lo leggo dopo

Il Large Hadron Collider

È PRONTO a ripartire. Lhc, l'acceleratore di particelle del Cern di Ginevra, dopo la pausa invernale tornerà mercoledì a far scontrare protoni a velocità che lambiscono quella della luce. Con una lunga cavalcata fino a dicembre 2012, il più grande apparecchio scientifico del mondo darà probabilmente la zampata finale a quel bosone di Higgs che i fisici cercano da quasi 50 anni.

L'unica particella mancante fra le 17 che compongono la materia a noi nota, soprannominata "particella di Dio", è ormai nel mirino degli scienziati dell'Organizzazione europea per la ricerca nucleare. Ma servono più dati per confermare che il frammento di materia generato nelle collisioni ad altissima energia di Lhc, e osservato negli ultimi mesi dell'anno scorso, sia davvero quello teorizzato dal fisico inglese Peter Higgs.

"La partita - ha più volte assicurato il direttore del Cern Rolf Heuer - sarà chiusa entro il 2012. Se il bosone di Higgs esiste, saremo in grado di trovarlo".

La statistica invita a una cautela più che altro formale. I dati ottenuti da Lhc l'anno scorso danno una probabilità del 99,5% che la particella osservata a Ginevra sia l'ultimo tassello mancante del modello standard: il quadro della realtà più preciso che la fisica è riuscita a disegnare finora.

Definitive answer to the quest for the Standard Model Higgs boson in 2012

In the News December 2011…

Le Cern aurait capté des "signaux" du boson de Higgs.

Le Monde

Science: les physiciens pensent avoir approché le mystérieux boson de Higgs.

Libération

Data Hints at Elusive Particle, but the Wait Continues

The New York Times

Higgs boson hunters scent their elusive quarry at the LHC.

theguardian

… in the CERN Press Release

Excerpts

Taken individually, none of these excesses is any more statistically significant than rolling a die and coming up with two sixes in a row (~3%).

What is interesting is that there are multiple independent measurements pointing to the region of 124 to 126 GeV.