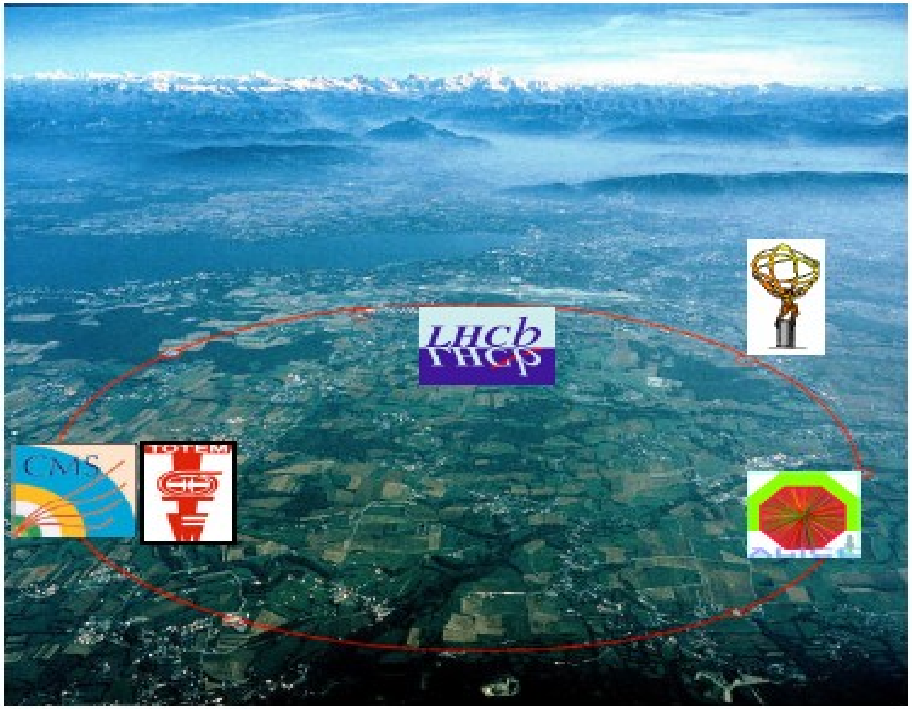
Physics with first fb^{-1}

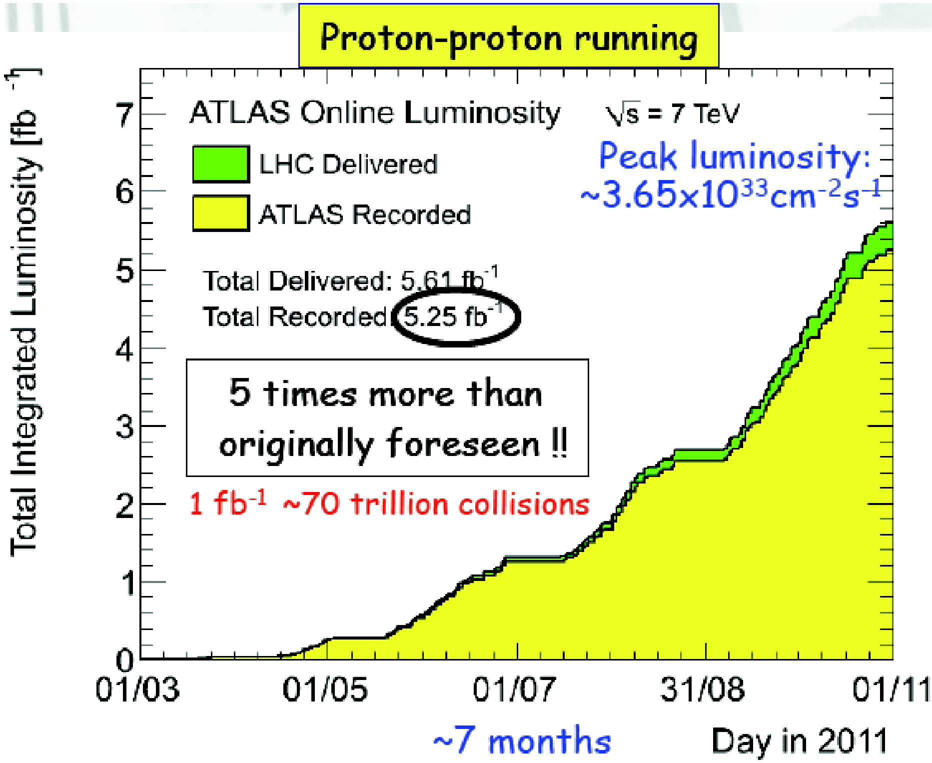
at Large Hadron Collider

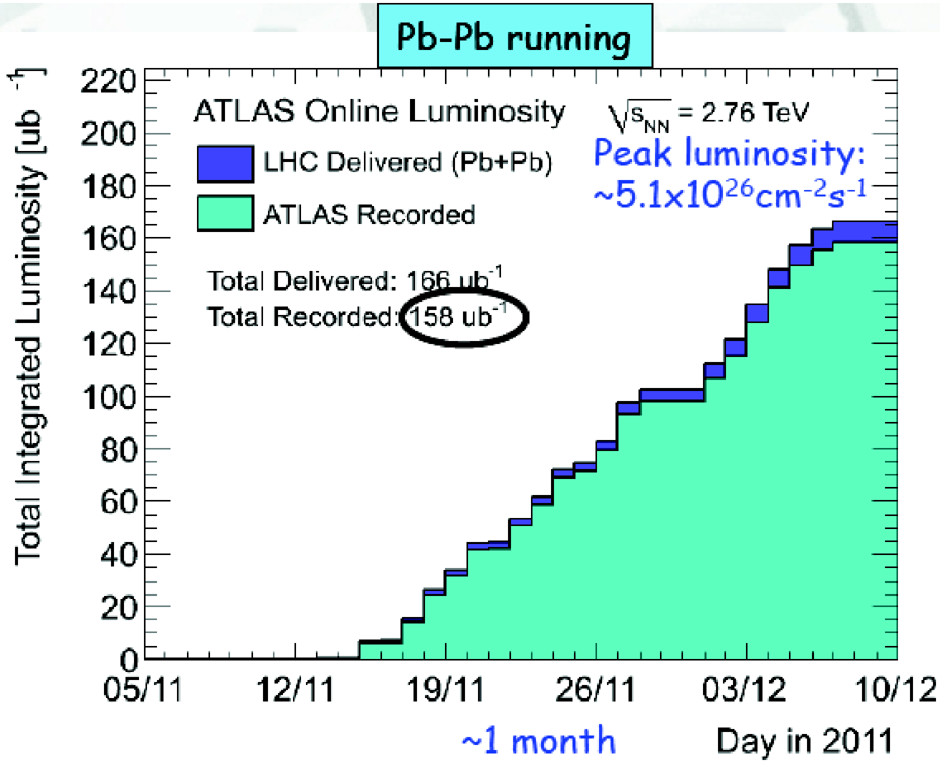
Today:

- **Searches for the Higgs boson(s)**



ATLAS data collected in 2011

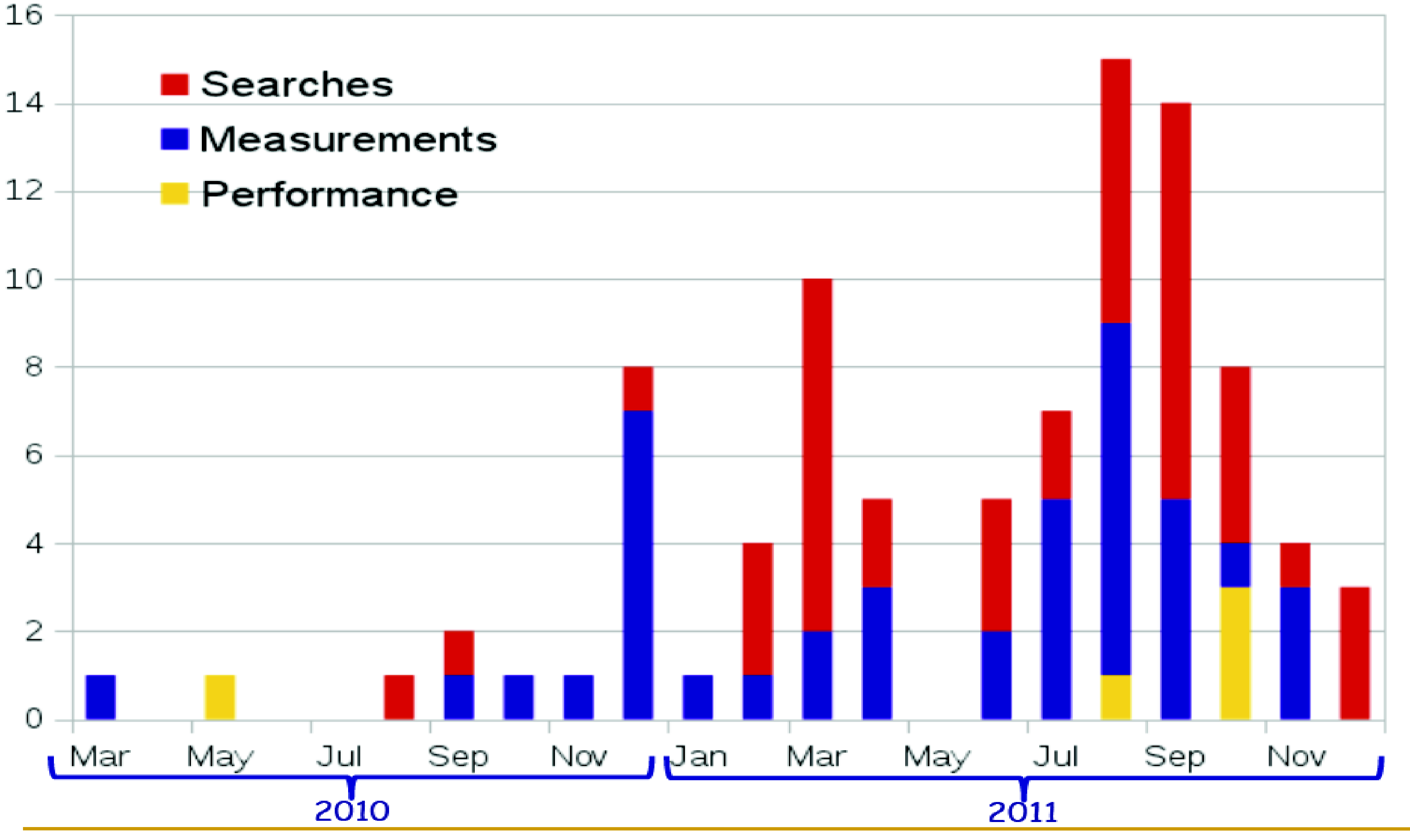




- $\geq$100 times more proton-proton collisions:
  - 45 pb^{-1} in 2010
  - 5250 pb^{-1} in 2011
- Excellent recording efficiency: ~94%

- 17 times more Pb-Pb collisions:
  - 9 μb^{-1} in 2010
  - 158 μb^{-1} in 2011
- Excellent recording efficiency: 95%

ATLAS publications

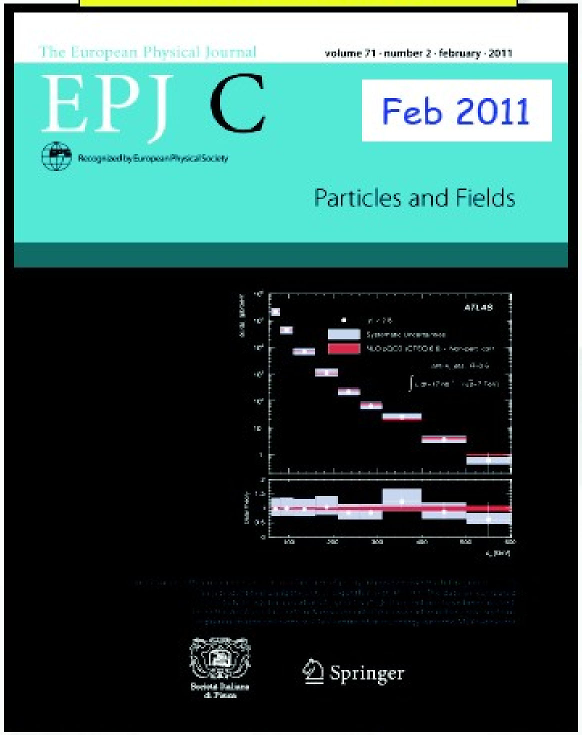


ATLAS publications

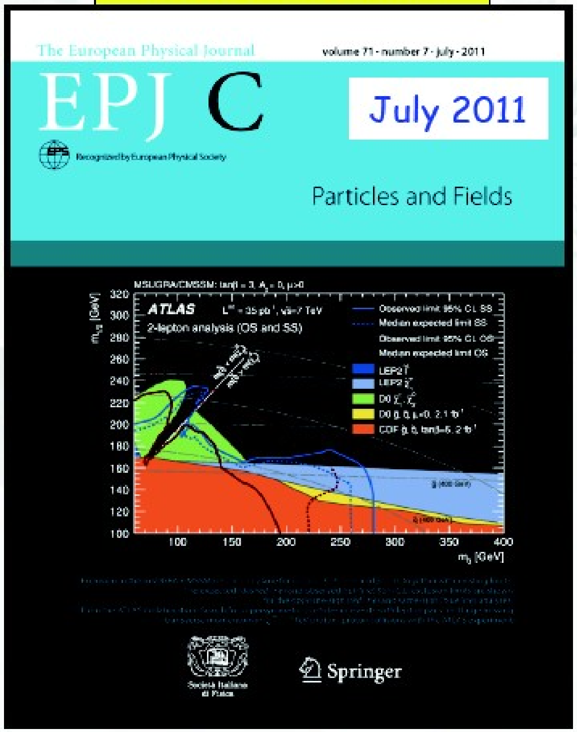
- ATLAS papers submitted for publication:
  - In 2010: 16 papers
  - In 2011: 75 papers

- Conference notes:
  - 265 since the start of data taking (~50 to summer conferences)

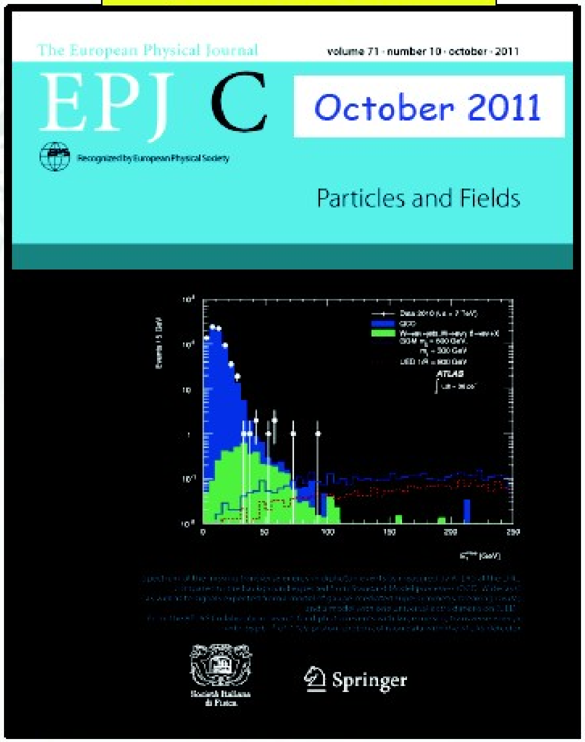
Jet cross-section measurement



SUSY searches in the 2l channel



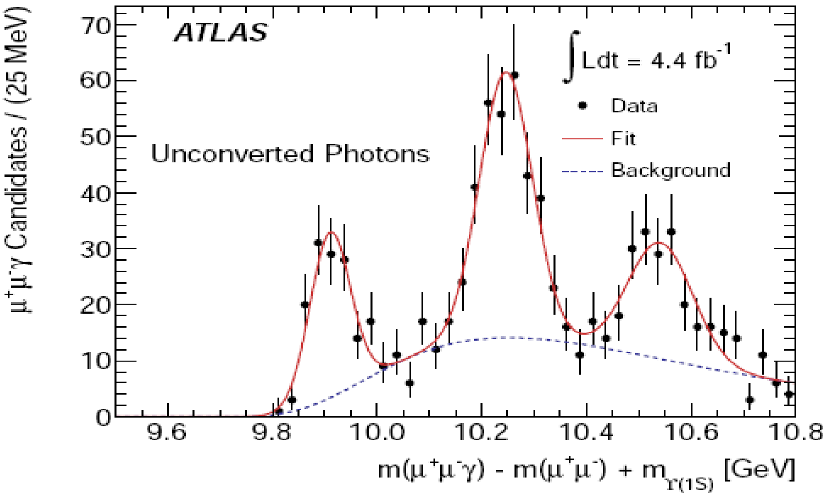
Search for di-photon events



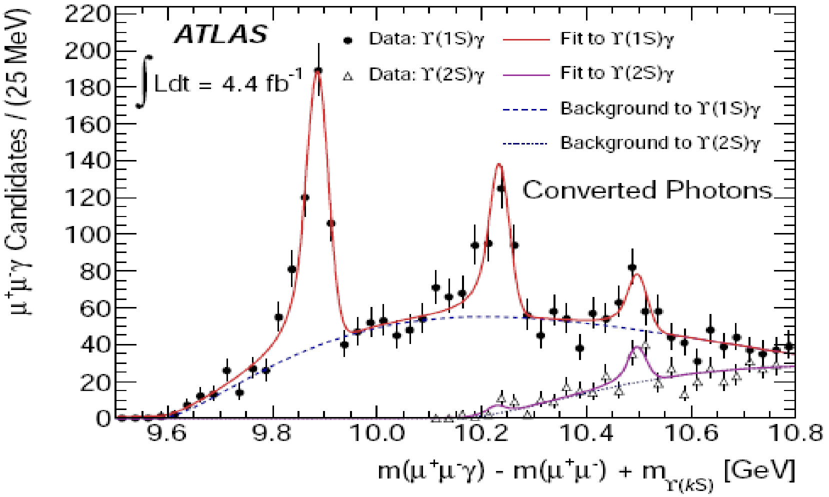
For Christmas: χ_b(3P) state observation

- The χ_b(nP) quarkonium states are produced in pp collisions
- Reconstructed through their radiative decays to Υ(1S,2S) with $\Upsilon \rightarrow \mu\mu$
- Observed known states:
  - χ_b(1P, 2P)$\rightarrow \Upsilon(1S)\gamma$
- Observed new structure in both $\Upsilon(1S)\gamma$ and $\Upsilon(2S)\gamma$ decay modes
  - Photons reconstructed using either conversion or from calorimetry
  - Centered at mass

  10.539±0.004(stat)±0.008(syst) GeV
  - Interpreted as χ_b(3P) system



(a)



SM Higgs mass constraints

Experiment

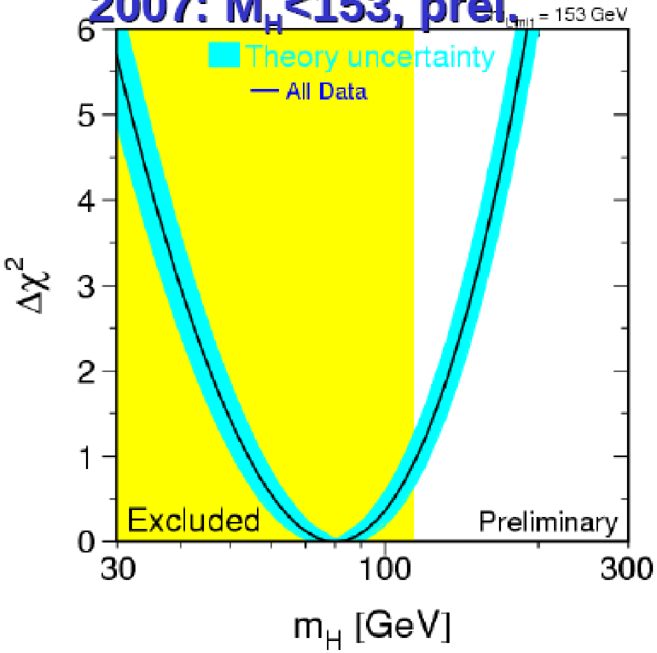
Indirect constraints from precision EW data :

M_H < 260 GeV at 95 %CL (2004)

M_H < 186 GeV with Run-I/II prelim. (2005)

M_H < 166 GeV (2006, ICHEP06)

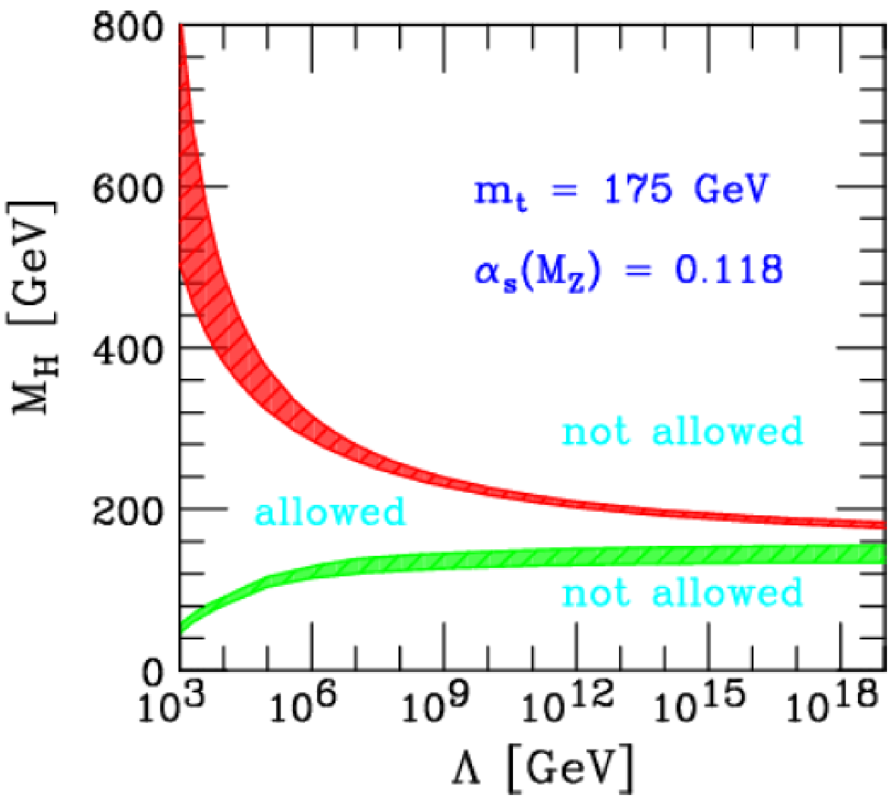
2007: M_H<153, prel.



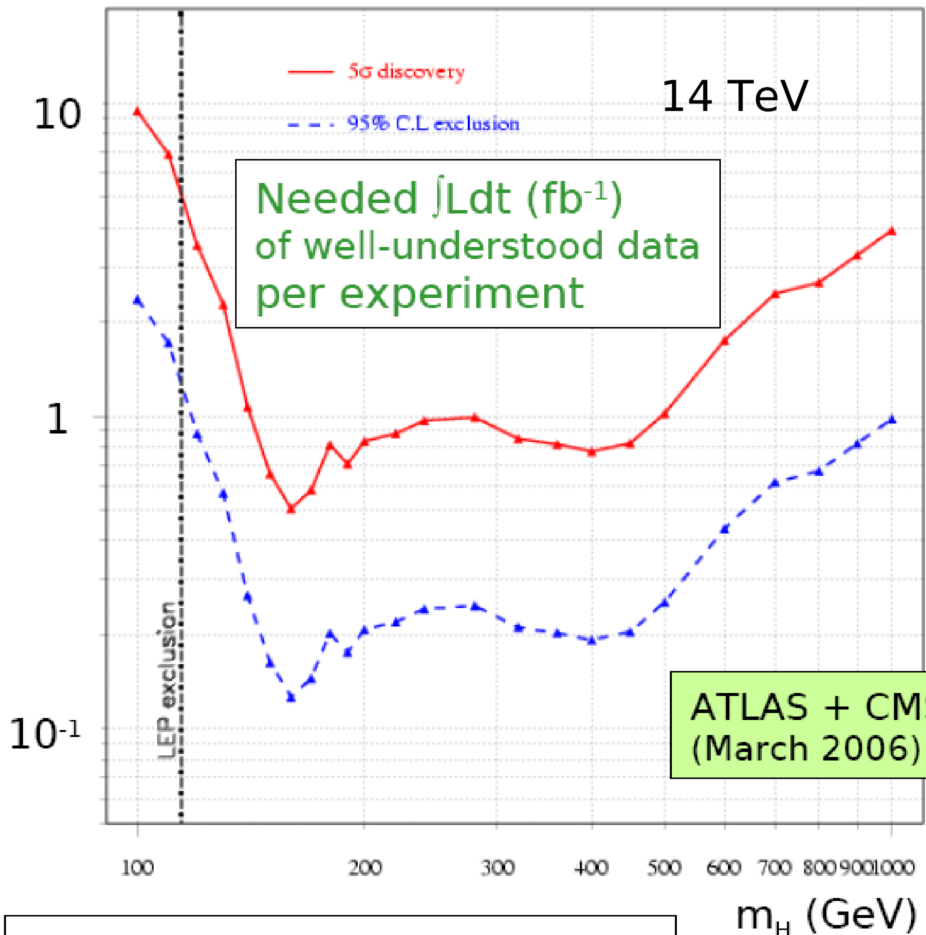
Direct limit from LEP: M_H > 114.4 GeV

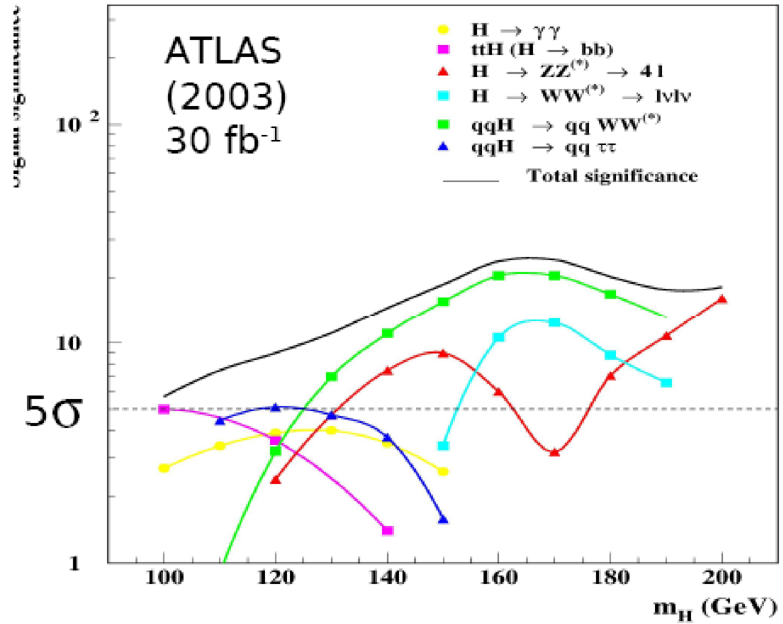
SM theory

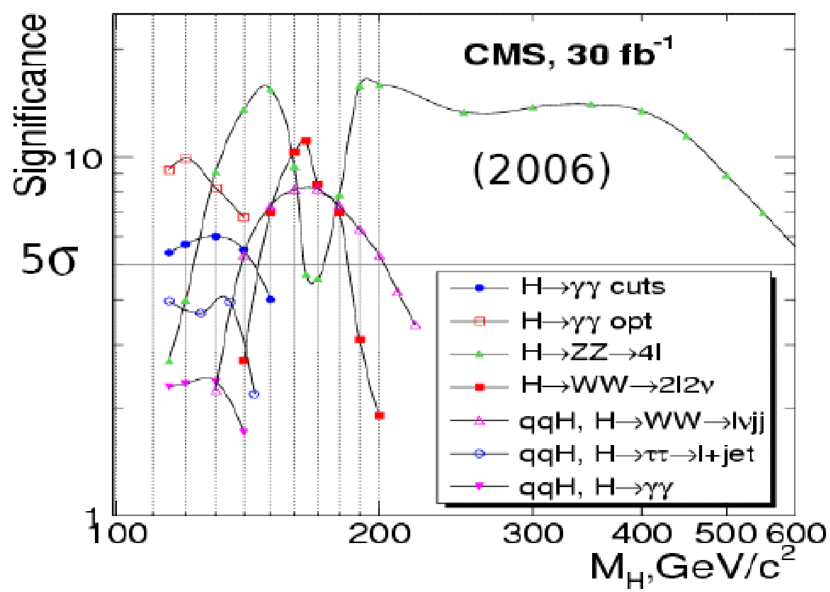
The triviality (upper) bound and vacuum stability (lower) bound as function of the cut-off scale Λ



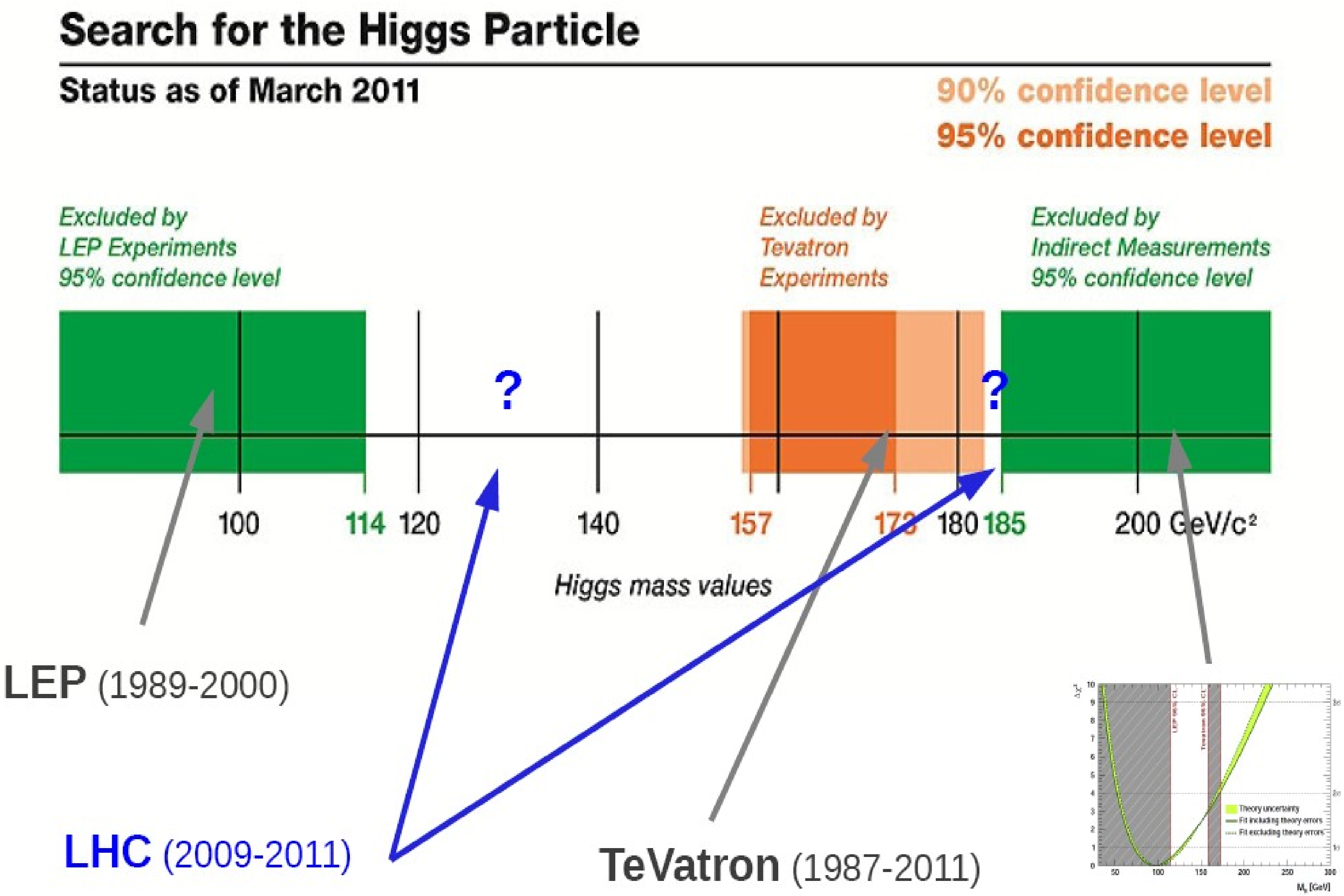
Discovery potential in a complete mass range



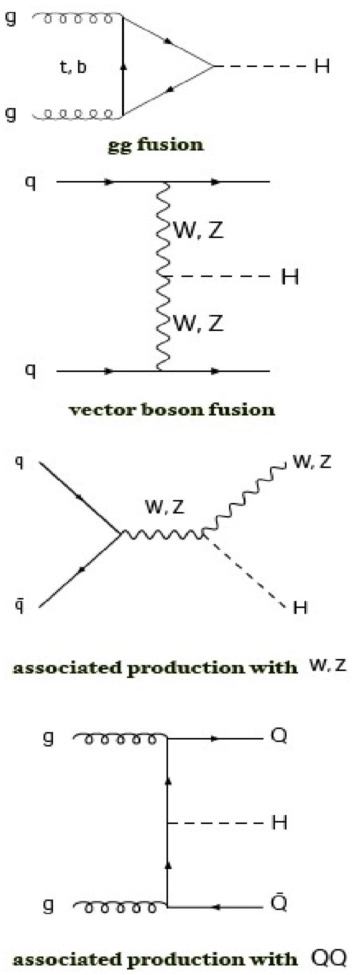


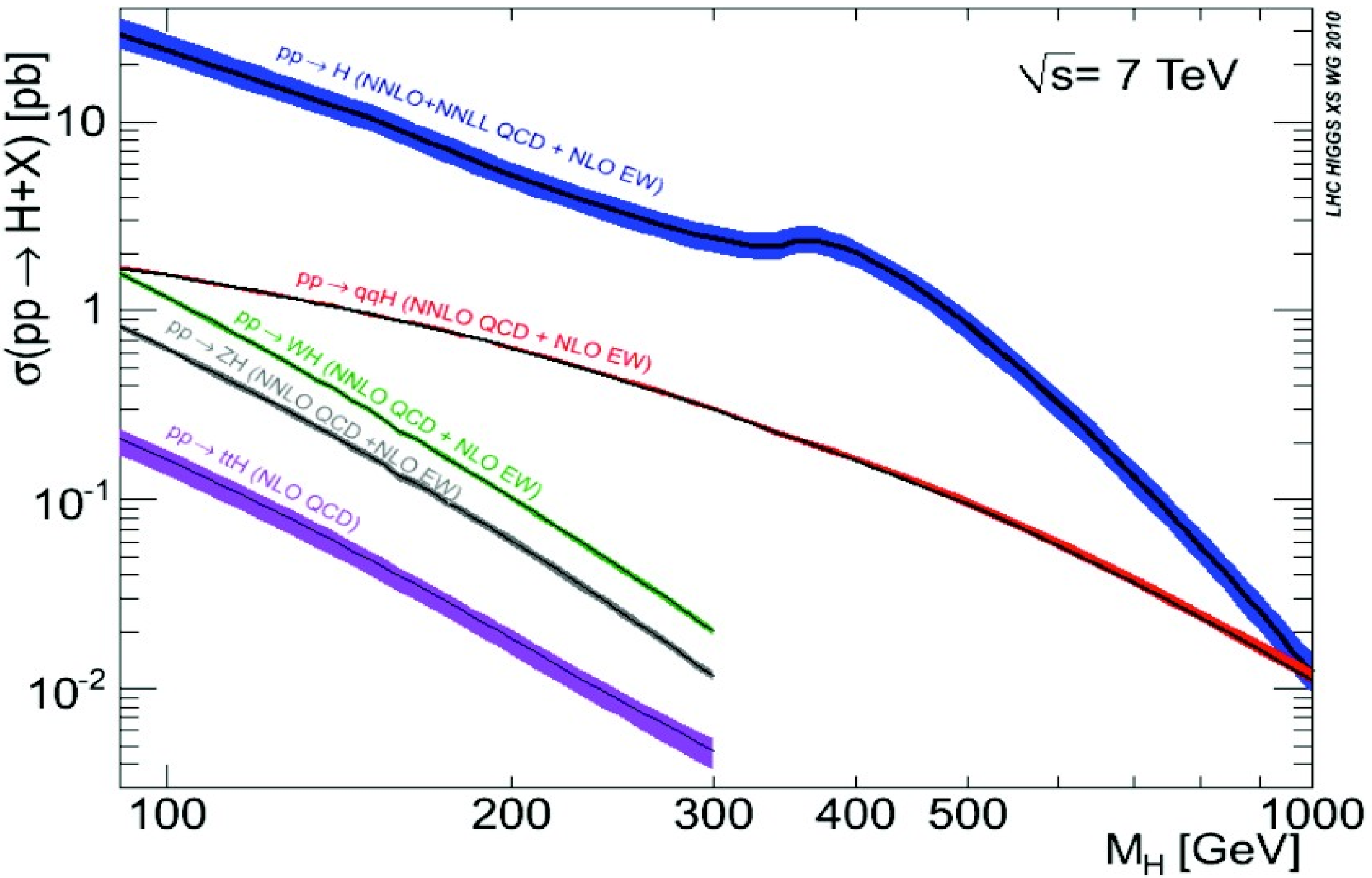


$\leq$ 1 fb^{-1} for 95% C.L. exclusion
$\leq$ 5 fb^{-1} for 5σ discovery
over full allowed mass range
Final word about Higgs
mechanism by 2010 ?


Search for the Higgs Particle
Status as of March 2011
90% confidence level
95% confidence level
Excluded by LEP Experiments 95% confidence level
Excluded by Tevatron Experiments
Excluded by Indirect Measurements 95% confidence level
?
?
100
114
120
140
157
173
180
185
200 GeV/c²
Higgs mass values
LEP (1989-2000)
LHC (2009-2011)
TeVatron (1987-2011)

Higgs cross-section

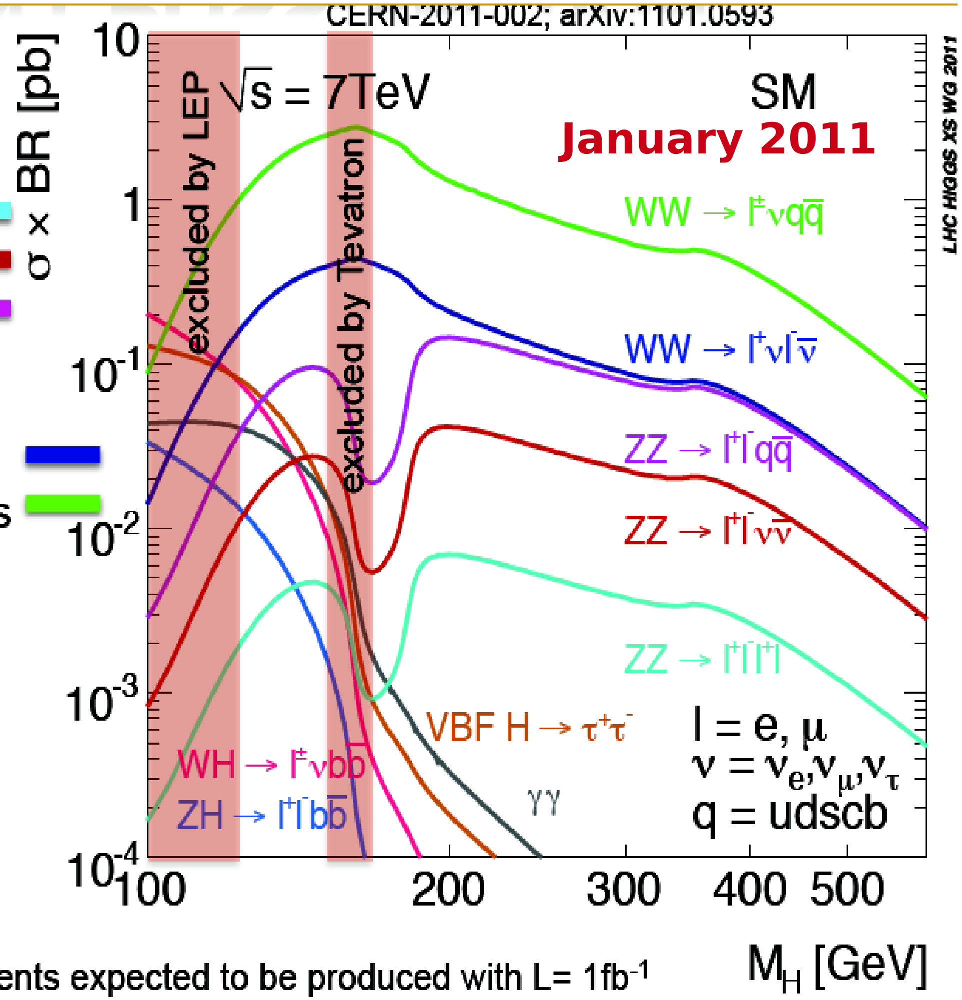




Large gluon luminosity → gg fusion is the dominant production channel over the whole range of m_H

Most important channels :

- $H \to ZZ^{(*)}$:
  - $ZZ \to llll$: "golden" mode
  - $ZZ \to ll\nu\nu$: good for high mass
  - $ZZ \to llqq$: good at high mass
- $H \to WW^{(*)}$:
  - $WW \to l\nu l\nu$: most sensitive
  - $WW \to l\nu qq$: important at high mass
- $H \to \gamma\gamma$:
  - rare channel
  - best for low mass
- $H \to \tau\tau$:
  - good s/b
  - low mass
  - rare
- $H \to bb$:
  - with associated production
  - useful but difficult

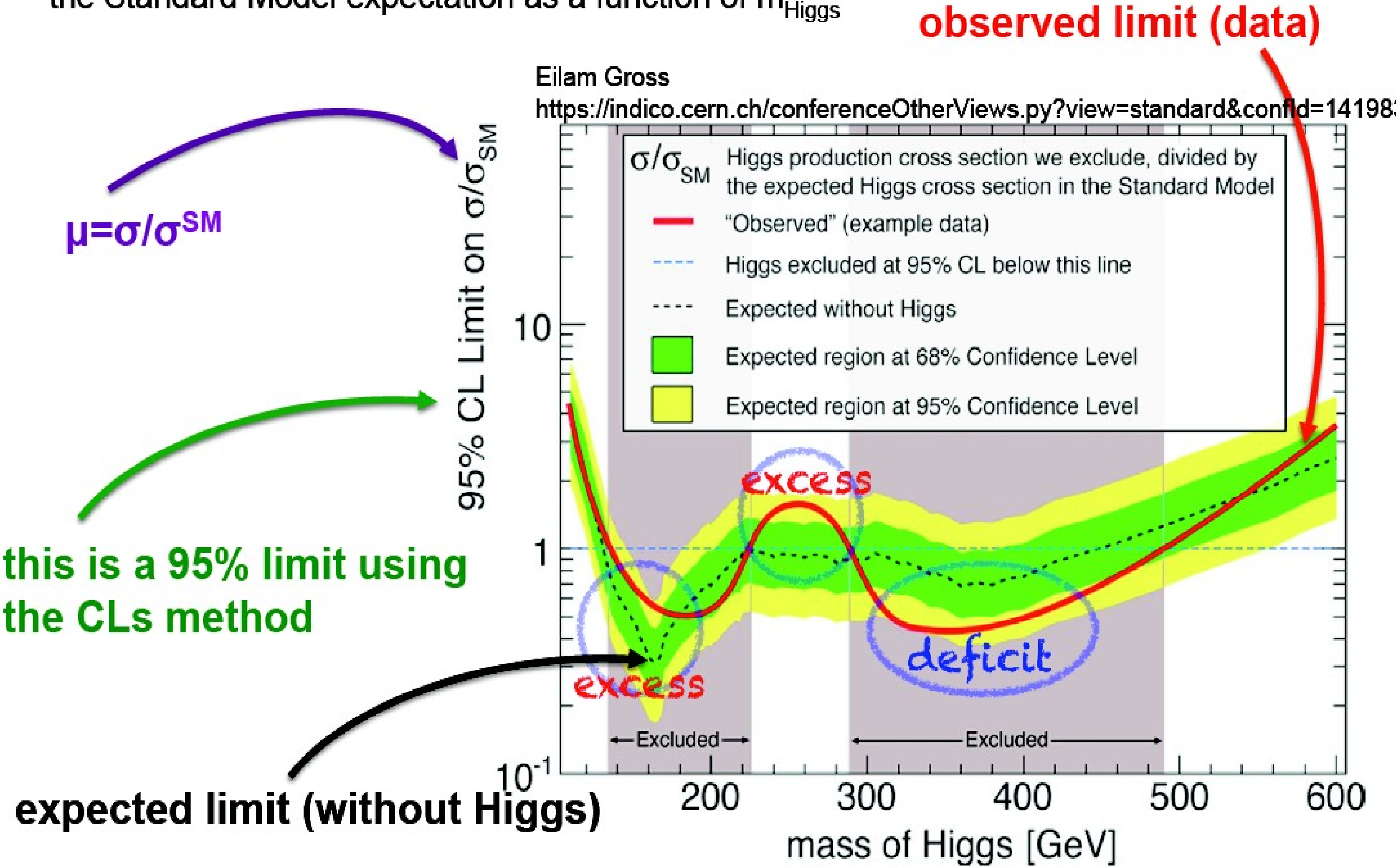


Events expected to be produced with L= 1fb^{-1}

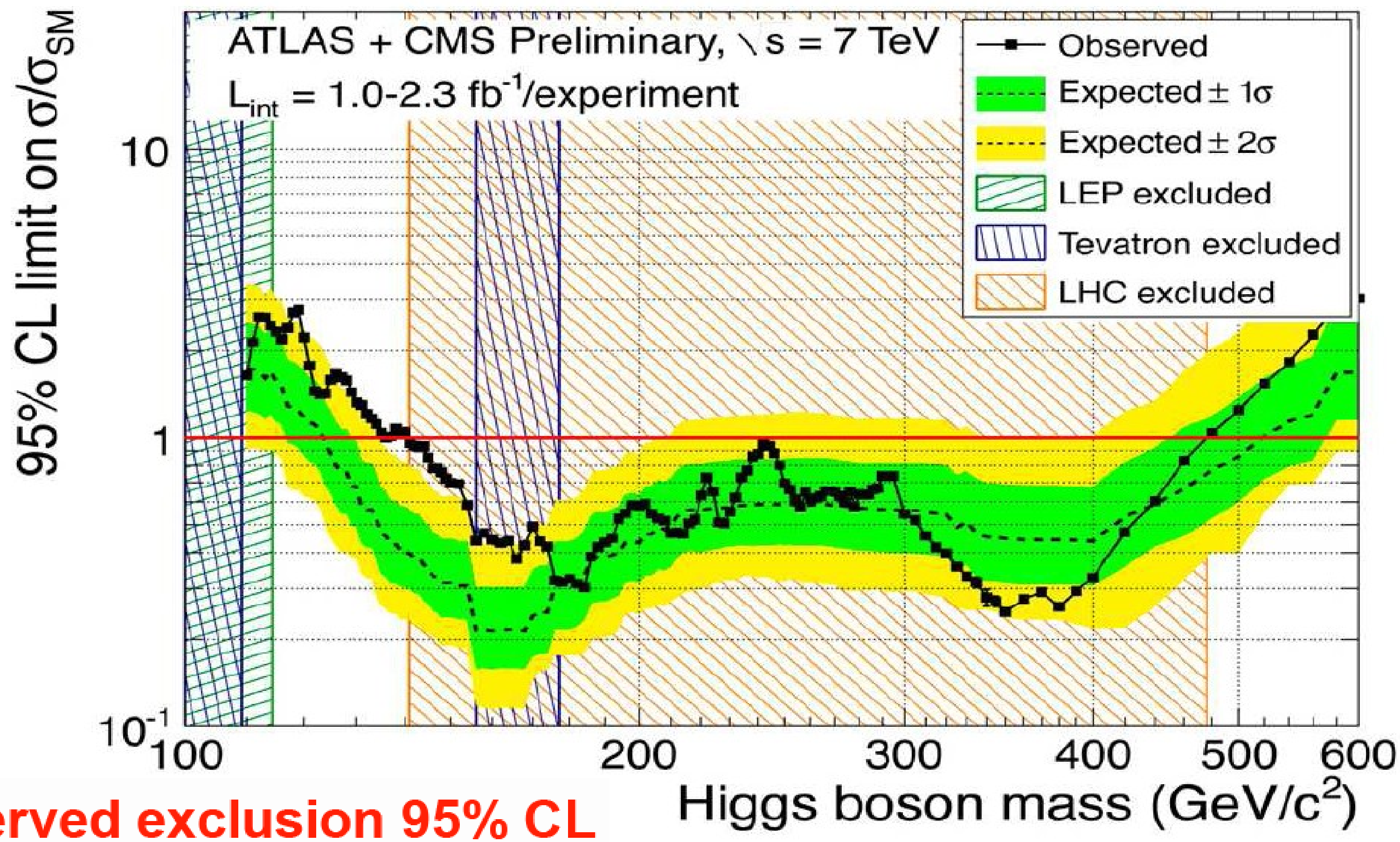
m_H, GeV	$WW \to l\nu l\nu$	$ZZ \to 4l$	$\gamma\gamma$
120	127	1.5	43
150	390	4.6	16
300	89	3.8	0.04

Understanding of the Yellow and Green bands :

- Upper limit on the Standard Model (SM) Higgs Boson production cross section divided by the Standard Model expectation as a function of m_{Higgs}



News from HCP (Paris, Nov. 2011)

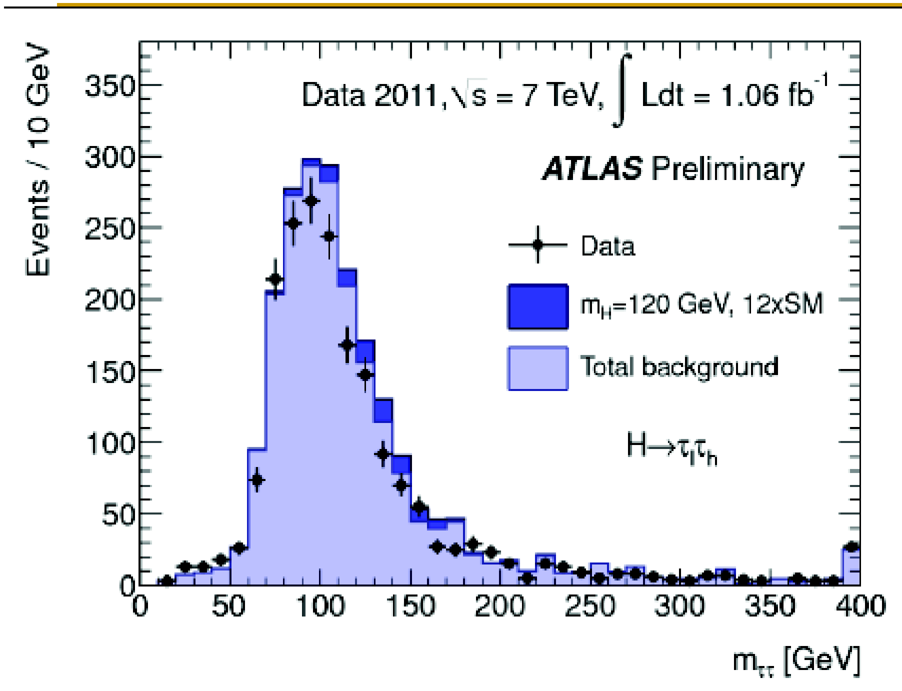


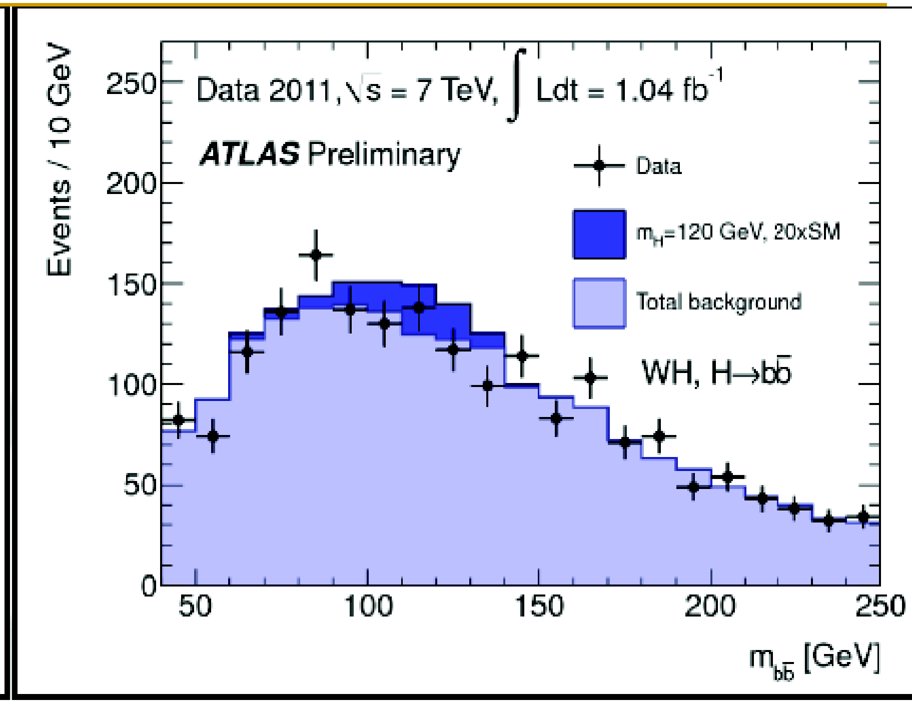
Observed exclusion 95% CL
141-476 GeV

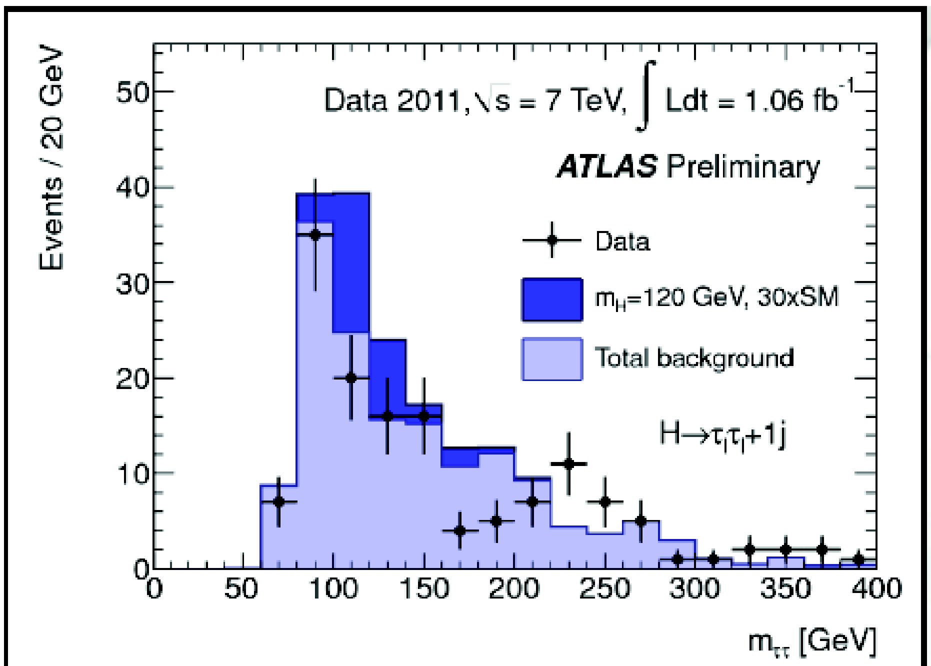
Expected exclusion 95% CL
124-520 GeV

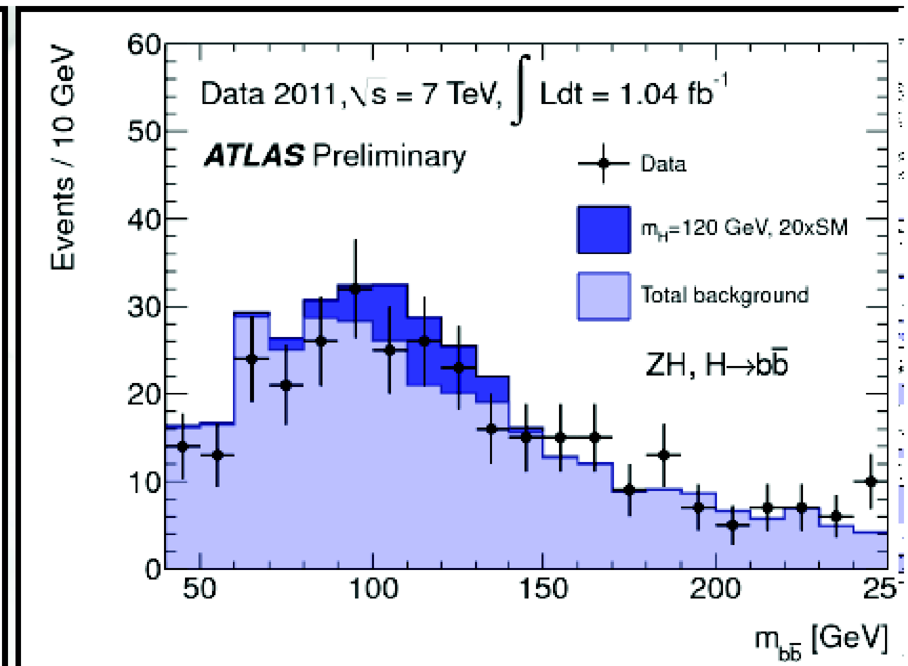
Summary of present SM Higgs boson searches (ATLAS)

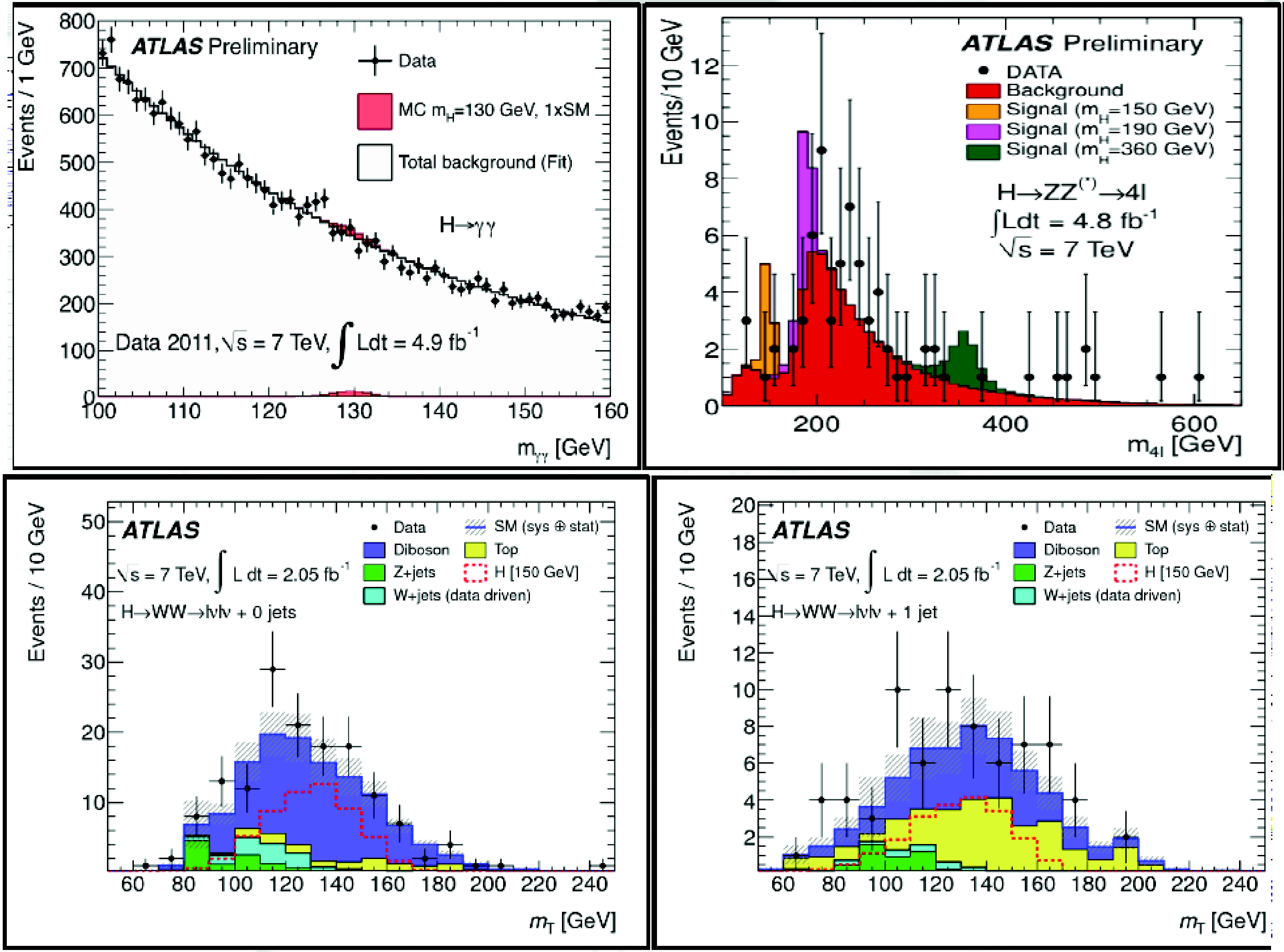
Channel	m_H range (GeV)	Int. lumi fb^{-1}	Main backgrounds	Number of signal events after cuts	S/B after cuts	Expected σ/σ_{SM} sensitivity
$H \to \gamma\gamma$	110-150	4.9	$\gamma\gamma$, γj, jj	~70	~0.02	1.6-2
$H \to \tau\tau \to ll+\nu$	110-140	1.1	$Z \to \tau\tau$, top	~0.8	~0.02	30-60
$H \to \tau\tau \to l\tau_{had}$	100-150	1.1	$Z \to \tau\tau$	~10	~5 10^{-3}	10-25
$W/ZH \to bbl(l)$	110-130	1.1	W/Z+jets, top	~6	~5 10^{-3}	15-25
$H \to WW^{(*)} \to l\nu l\nu$	110-300	2.1	WW, top, Z+jet	~20 (130 GeV)	~0.3	0.3-8
$H \to ZZ^{(*)} \to 4l$	110-600	4.8	ZZ*, top, Zbb	~2.5 (130 GeV)	~1.5	0.7-10
$H \to ZZ \to ll\,\nu\nu$	200-600	2.1	ZZ, top, Z+jets	~20 (400 GeV)	~0.3	0.8-4
$H \to ZZ \to ll\,qq$	200-600	2.1	Z+jets, top	2-20 (400 GeV)	0.05-0.5	2-6
$H \to WW \to l\nu qq$	240-600	1.1	W+jets,top,jets	~45 (400 GeV)	10^{-3}	5-10


Data 2011, √s = 7 TeV, ∫ Ldt = 1.06 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 12xSM
Total background
H→τ_l τ_h
Events / 10 GeV
m_ττ [GeV]

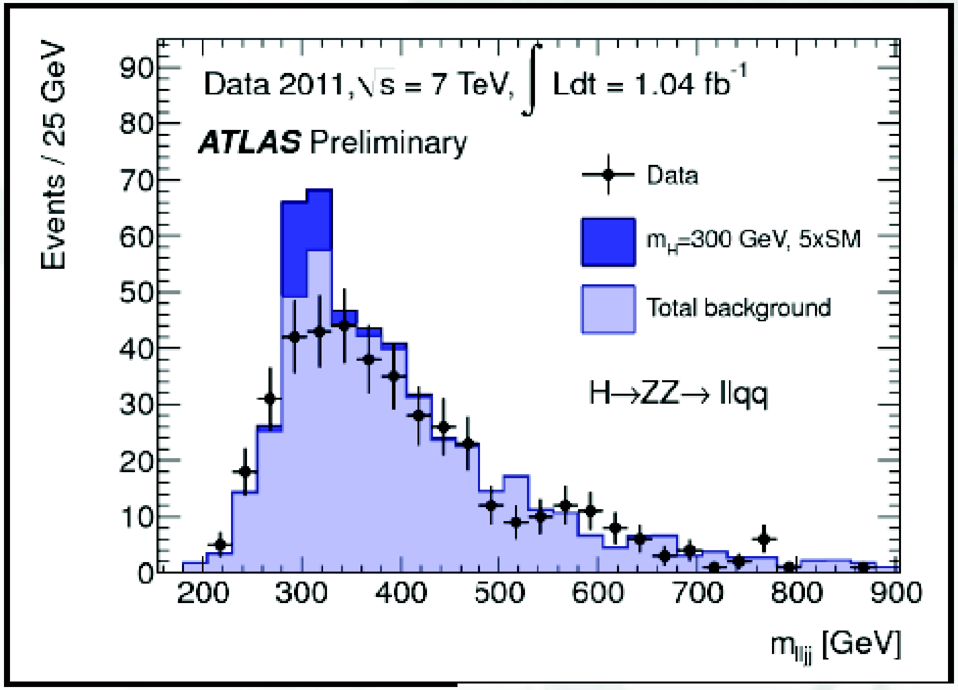

Data 2011, √s = 7 TeV, ∫ Ldt = 1.04 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 20xSM
Total background
WH, H→bb̄
Events / 10 GeV
m_bb̄ [GeV]

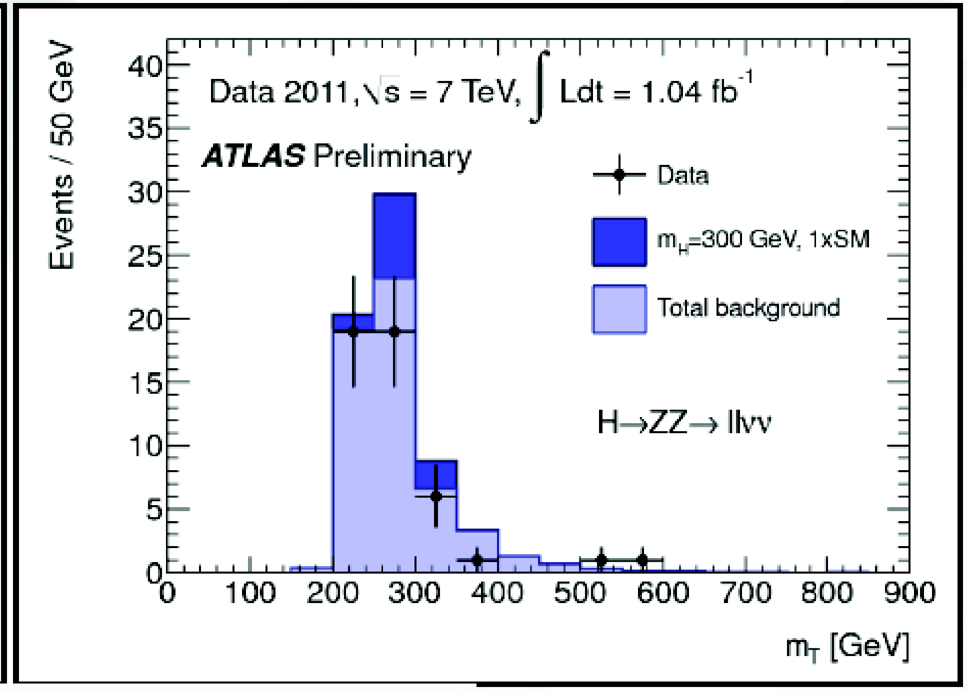

Data 2011, √s = 7 TeV, ∫ Ldt = 1.06 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 30xSM
Total background
H→τ_l τ_l+1j
Events / 20 GeV
m_ττ [GeV]

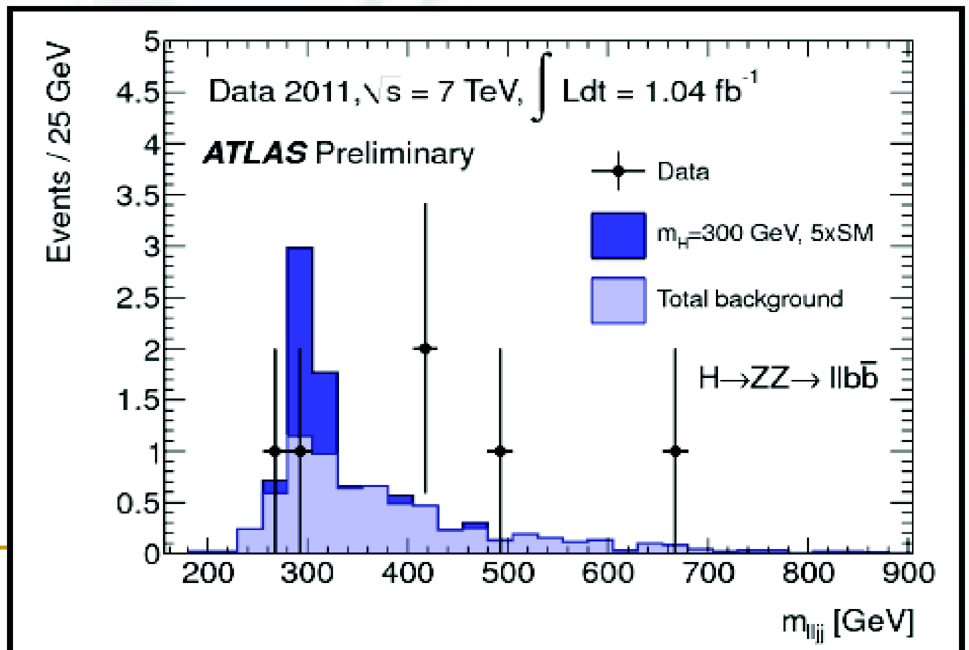

Data 2011, √s = 7 TeV, ∫ Ldt = 1.04 fb⁻¹
ATLAS Preliminary
Data
m_H=120 GeV, 20xSM
Total background
ZH, H→bb̄
Events / 10 GeV
m_bb̄ [GeV]



ATLAS Preliminary
Data
MC m_H=130 GeV, 1xSM
Total background (Fit)
H→γγ
Data 2011, √s = 7 TeV, ∫ Ldt = 4.9 fb⁻¹
Events / 1 GeV
m_γγ [GeV]
ATLAS Preliminary
DATA
Background
Signal (m_H=150 GeV)
Signal (m_H=190 GeV)
Signal (m_H=360 GeV)
H→ZZ(*)→4l
∫Ldt = 4.8 fb⁻¹
√s = 7 TeV
Events/10 GeV
m_4l [GeV]
ATLAS
√s = 7 TeV, ∫ L dt = 2.05 fb⁻¹
H→WW→lνlν + 0 jets
Data
SM (sys ⊕ stat)
Diboson
Top
Z+jets
H [150 GeV]
W+jets (data driven)
Events / 10 GeV
m_T [GeV]
ATLAS
√s = 7 TeV, ∫ L dt = 2.05 fb⁻¹
H→WW→lνlν + 1 jet
Data
SM (sys ⊕ stat)
Diboson
Top
Z+jets
H [150 GeV]
W+jets (data driven)
Events / 10 GeV
m_T [GeV]


Data 2011, √s = 7 TeV, ∫ Ldt = 1.04 fb-1
ATLAS Preliminary
Data
mH=300 GeV, 5xSM
Total background
H→ZZ→ llqq
Events / 25 GeV
mlljj [GeV]
0
10
20
30
40
50
60
70
80
90
200
300
400
500
600
700
800
900

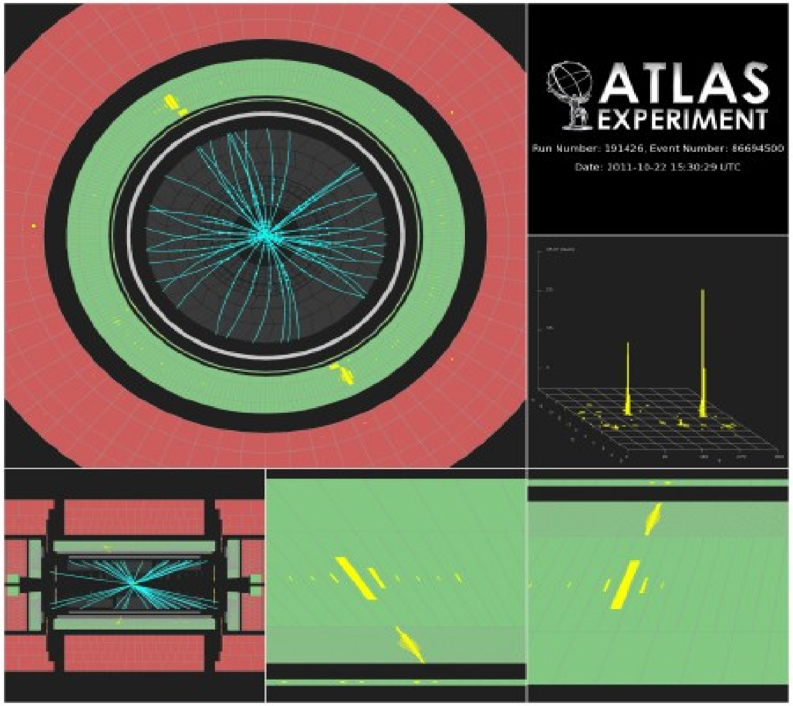

Data 2011, √s = 7 TeV, ∫ Ldt = 1.04 fb-1
ATLAS Preliminary
Data
mH=300 GeV, 1xSM
Total background
H→ZZ→ llνν
Events / 50 GeV
mT [GeV]
0
5
10
15
20
25
30
35
40
0
100
200
300
400
500
600
700
800
900


Data 2011, √s = 7 TeV, ∫ Ldt = 1.04 fb-1
ATLAS Preliminary
Data
mH=300 GeV, 5xSM
Total background
H→ZZ→ llbb̄
Events / 25 GeV
mlljj [GeV]
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
200
300
400
500
600
700
800
900

$H \rightarrow \gamma\gamma$

- At LHC, $H \rightarrow \gamma\gamma$ is the most sensitive channel in the low mass range (110 – 125 GeV)
  - Small branching ratio, but large event yield due to high selection efficiency
  - Signal peak is expected to be sharp in the $m_{\gamma\gamma}$ spectrum
  - Simple analysis: events with two high E_T photons.

Event selection



Event signature is very simple.

Event with two high-Et photons
($E_T(\gamma_1,\gamma_2)>40$, 25GeV)

- **2-photon trigger**
- **Primary vertex selection**
  (for selecting collision event)
- **Selection for di-photon event**

Photon is required to satisfy the following :

- $|\eta|<1.37$ or $1.52<|\eta|<2.37$
- $E_T(\gamma_1)>40$GeV, $E_T(\gamma_2)>25$GeV
- tight photon-ID (Selection based on the cluster shape in electromagnetic calorimeter.)
- isolation cut

Analysis

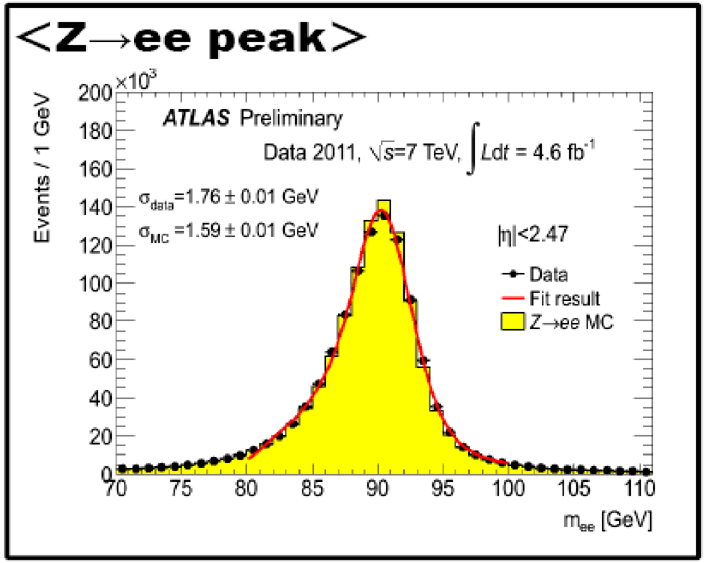
◆ **Backgrounds coming from SM events**

- **Irrreducible BG : γγ** ⬅ **Main contribution**
- **Reducible BG : γ+jets, di-jet**
- **Z→ee(DY) (・・・ very small contribution)**

◆ **M(γγ) reconstruction**

- $M(\gamma\gamma)^2 = 2E_1E_2 \cdot (1-\cos\alpha)$ (α : opening angle of the two photons)
- **For the precise reconstruction, careful understandings are needed for the followings :**
  - ✓ **Energy calibration & resolution** (related to E_1 and E_2)
  - ✓ **Primary vertex position** (related to α)

Energy calibration and resolution



Photon energy calibration

- **MC-based calibration**
  (Tuned by beam-test result)
- **After MC-based calibration, electron energy scale corrections are applied to photon energy of data.**
  (Scale factor is obtained from Z→ee.)

Energy resolution

Resolution correction is applied to MC.

(This correction factor is also determined by comparing the Zee peak between data and MC.)

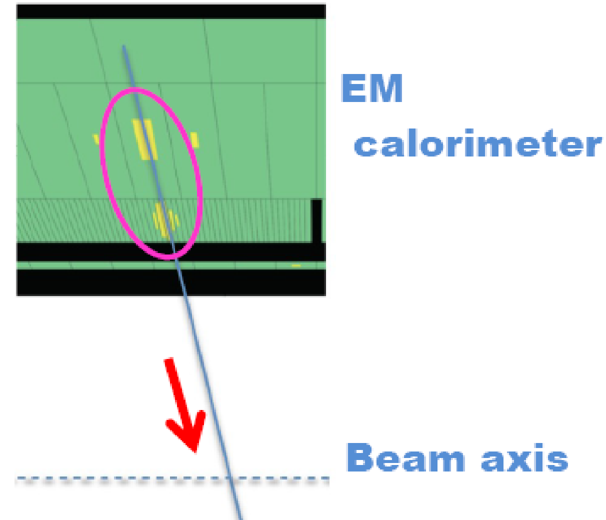
Vertex reconstruction

Vertex position is measured by "pointing method".

- **Unconverted photon :**
  "1^{st} + 2^{nd} layer of EM calorimeter"
- **Converted photon :**
  "1^{st} layer of EM calorimeter"
  + "conversion point ($\gamma \rightarrow ee$)"

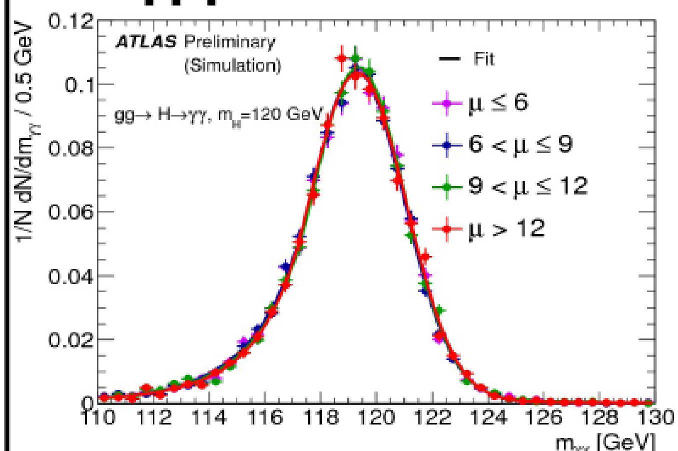
➡ **Robust measurement against pile-up.**

<Calorimeter pointing>



By measuring photon-direction, z of primary vertex is deduced.

<H→γγ peak with various conditions for pile-up>



By using "pointing method", M(γγ) resolution also becomes stable against pile-up effect.

Signal modeling

◆ **Signal MC** **(ggF, VBF, WH/ZH, ttH)**

Samples are available at 11 mass points.

(100-150GeV with 5GeV step)

◆ **Peak shape modeling**

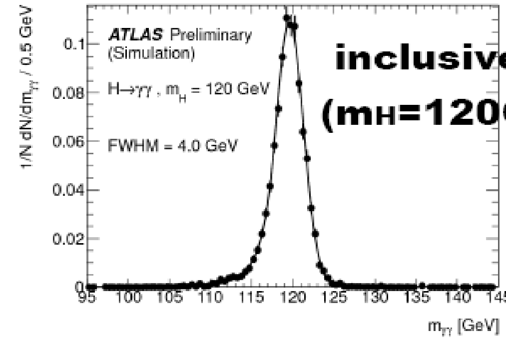
- **Function : "Crystal-ball + Gaussian"**
- **Global fit :**

  Simultaneous fit is performed for all mass points in each category.

↓

Some parameters for the peak shape are parameterized linearly as a function of m_H.

Signal shape



inclusive (m_H=120GeV)

Peak resolution

(m_H=120GeV)

	σ_{CB}(GeV)
inclusive	1.7
Best category (unconv central)	1.4
Worst category (conv transition)	2.3

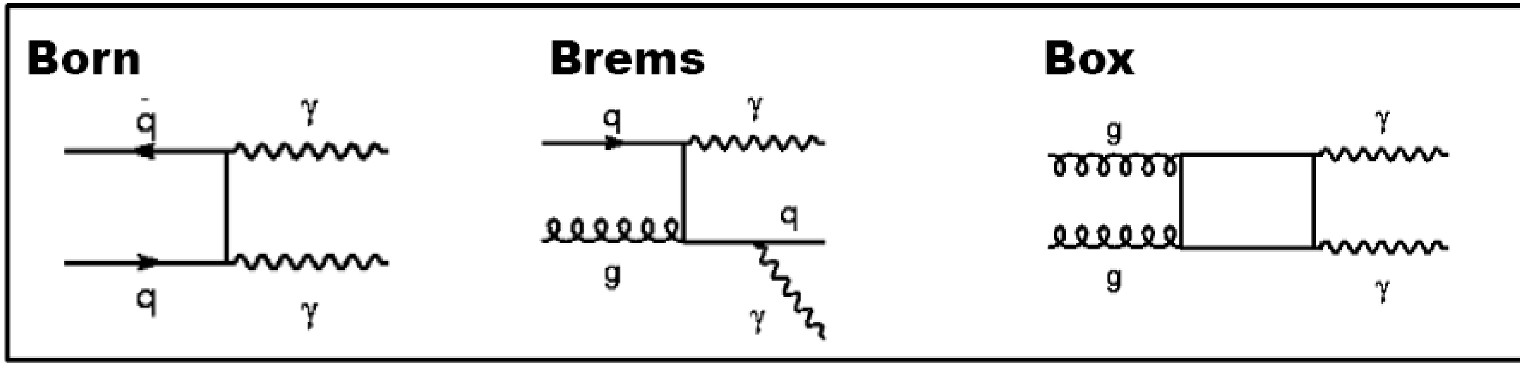
◆ **Expected # of signal events (4.9fb^{-1}, inclusive)**

m_H(GeV)	110	115	120	125	130	135	140	145	150
#evts	69.9	71.5	70.9	68.3	63.7	57.5	49.8	40.8	30.6

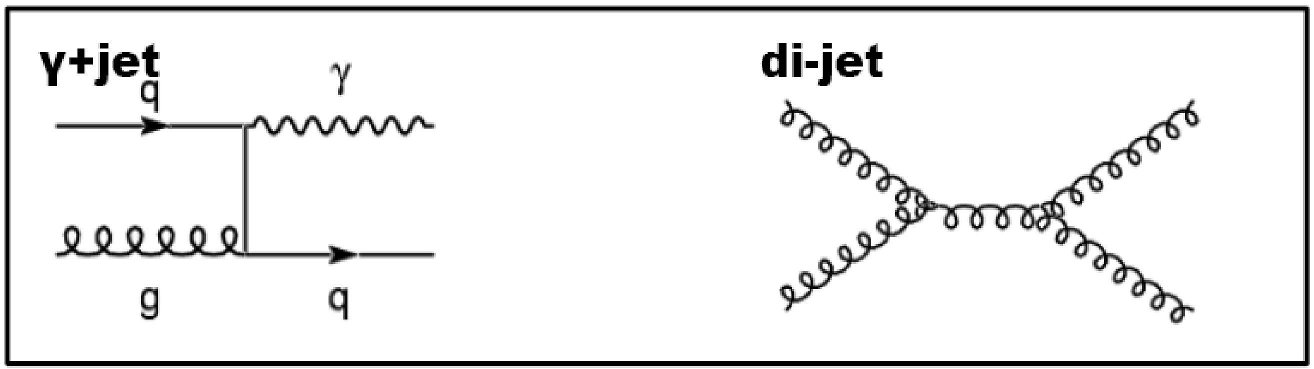
N_{sig} ~ 70evts (for m_H=110-125GeV)

Backgrounds

- **Irreducible background (γγ)**



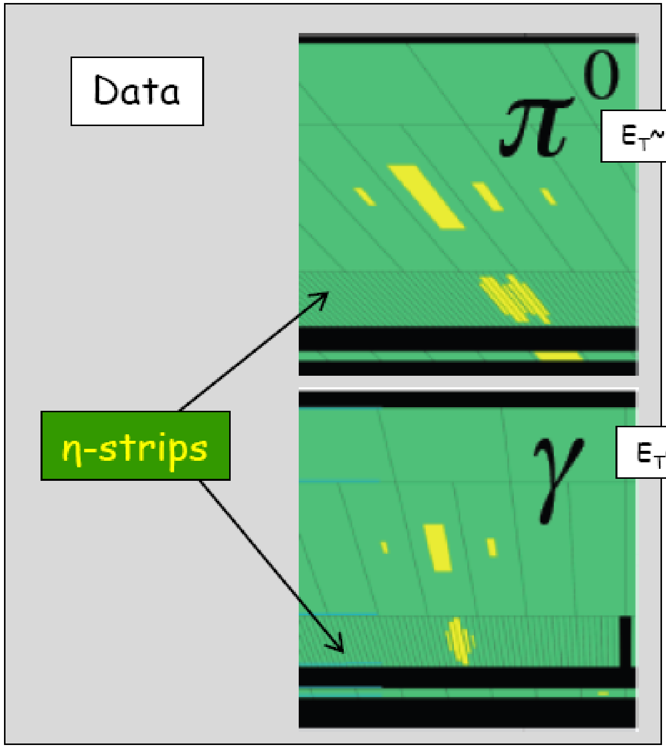
- **Reducible background (γ+jet, di-jet)**

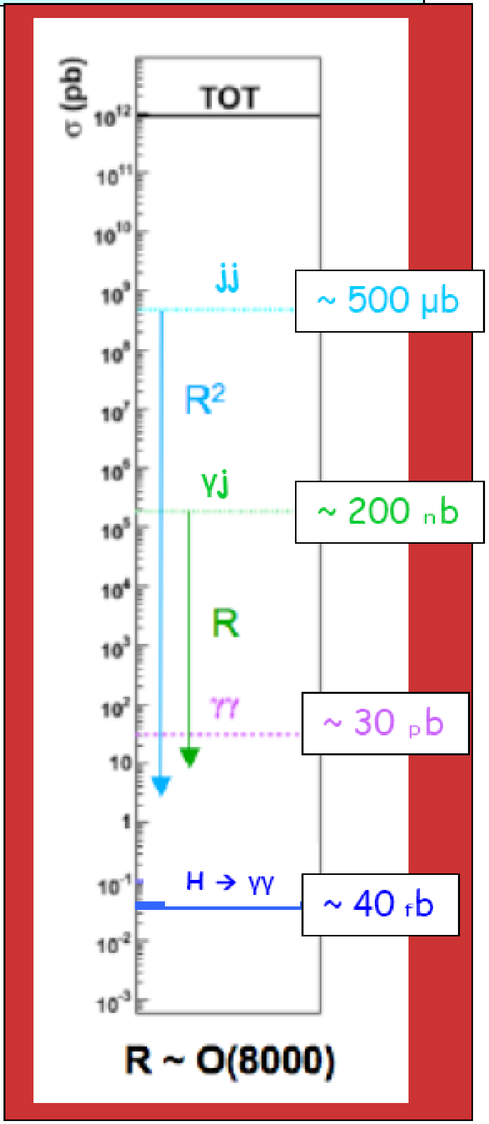


- **Drell-Yan (Z→ee)** ・・・ **Very small contribution**

Potentially huge background from γj and jj production with jets fragmenting into a single hard π^0 and the π^0 faking single photon

Determined choice of fine lateral segmentation (4mm η-strips) of the first compartment of ATLAS EM calorimeter





However: huge uncertainties on σ (γj, jj) !! → not obvious γj, jj could be suppressed well below irreducible γγ until we measured with data

Background decomposition

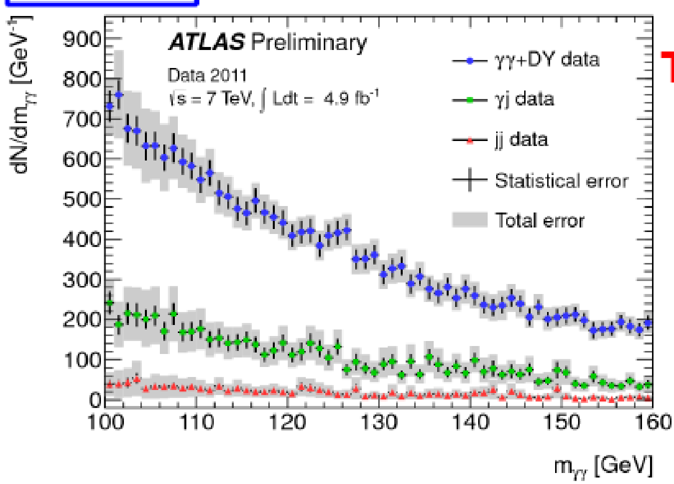
- **Decomposition for "γγ+DY", "γ+jets" and "di-jet" is performed in a data-driven manner.**

  Control sample is obtained from "anti-cut" region that is defined with photon-ID and isolation variables for the two photons.※

- **DY contribution is also estimated by using "eγ events" as a control sample.**

  (**Enriched with Z→ee where one electron is faking as photon.**)

Result



The contribution from irreducible BG (γγ) is dominant. (Fraction = 71%)

(**It could be also confirmed that the contribution from Zee is very small. (<1%)**)

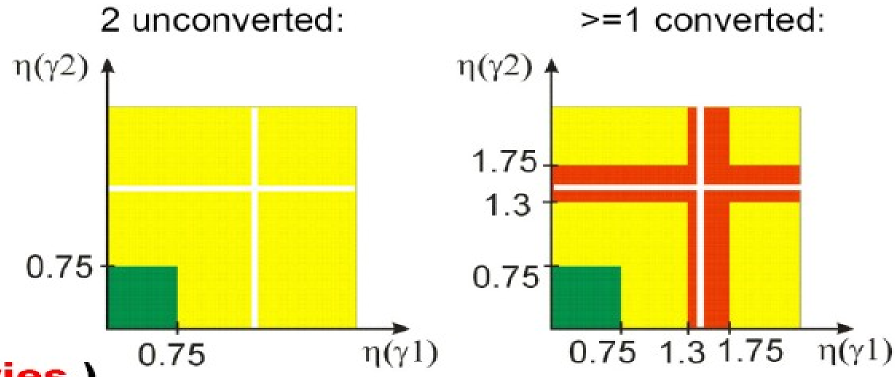
Event categorization

※To improve sensitivity, data sample is divided into 9 categories with different S/B and M(γγ) resolution.

9 categories based on conversion status, η and $p_{T,t}$

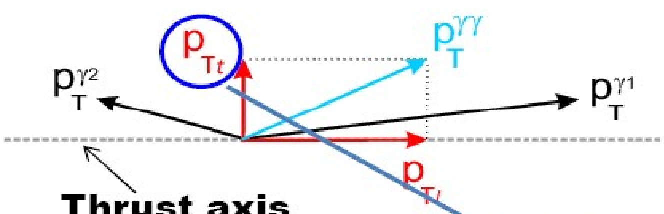
(a) Based on η and conversion (5 categories)

- **Both photons unconverted**
  - Central
  - Rest
- **At least one photon converted**
  - Central
  - Transition
  - Rest



(b) Based on $p_{T,t}$ (5 → 9 categories)

- **$p_{T,t}$: "p_T-thrust"**
- **"Central" and "Rest" categories are divided into "Low-$p_{T,t}$" and "High-$p_{T,t}$".**
  ("Transition" category is not divided.)



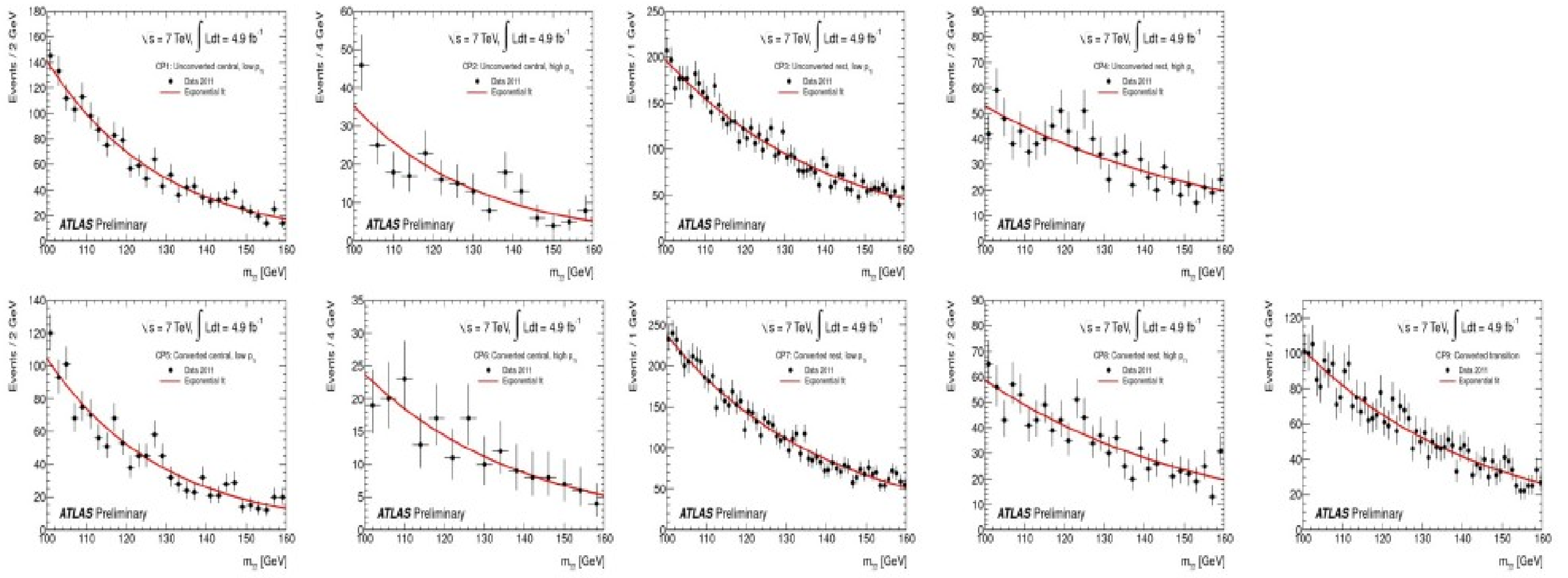
$\left(\vec{t} = \vec{p}_T(\gamma_1) - \vec{p}_T(\gamma_2) \right)$

- $p_{T,t}$ is the transverse component of $p_T(\gamma\gamma)$ with respect to the thrust axis.
- $p_{T,t}$ has more discriminative power than $p_T(\gamma\gamma)$.

Background modeling

BG shape is defined by the fit with single-exponential in each of 9 categories. **(Fit region : 100<M(γγ)<160GeV)**

M(γγ) spectrum in each category **(100<M(γγ)<160GeV)**



Main systematics

(a) Signal yield : ~20%

(b) H→γγ
mass resolution : ~14%

(c) Migration of signal events
between categories
(Error on # of signals)

(ex.) Between low⇔high $P_{T,t}$:

$\triangle N_{sig}$ = ±8% (for high $P_{T,t}$-bin)

(d) BG modeling

$\triangle N_{sig}$ = 0.1-5.6 events (Depending on categories)

The intrinsic difference between
- Chosen background model (= exponential)
- True background shape

➡ It is included into sys uncertaintyon # of signals events.

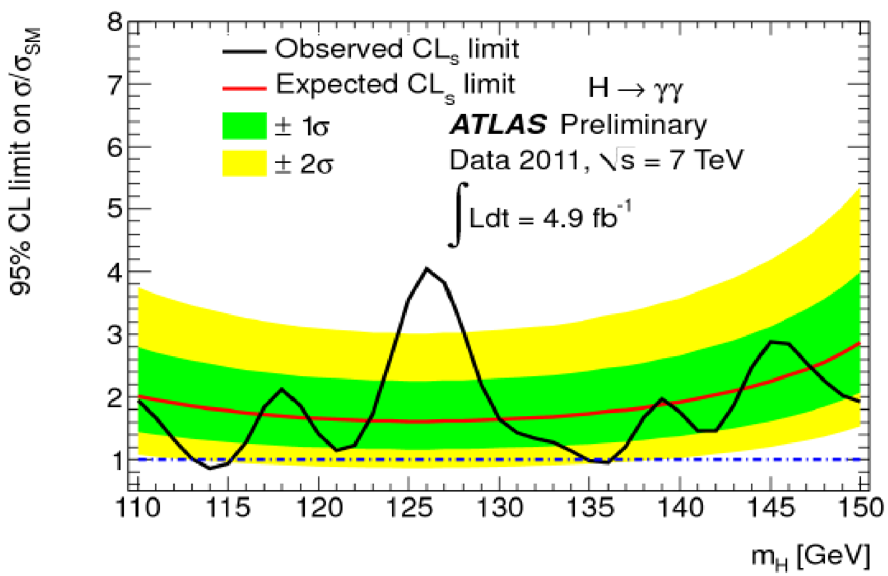
Summary of sys errors

Type and source	Uncertainty
(a) Event yield	
Photon reconstruction and identification	±11%
Effect of pileup on photon identification	±4%
Isolation cut efficiency	±5%
Trigger efficiency	±1%
Higgs boson cross section	+15%/ − 11%
Higgs boson p_T modeling	±1%
Luminosity	±3.9%
(b) Mass resolution	
Calorimeter energy resolution	±12%
Photon energy calibration	±6%
Effect of pileup on energy resolution	±3%
Photon angular resolution	±1%
(c) Migration	
Higgs boson p_T modeling	±8%
Conversion reconstruction	±4.5%

Results for H→γγ

Exclusion limit w.r.t SM prediction

(95%C.L.)



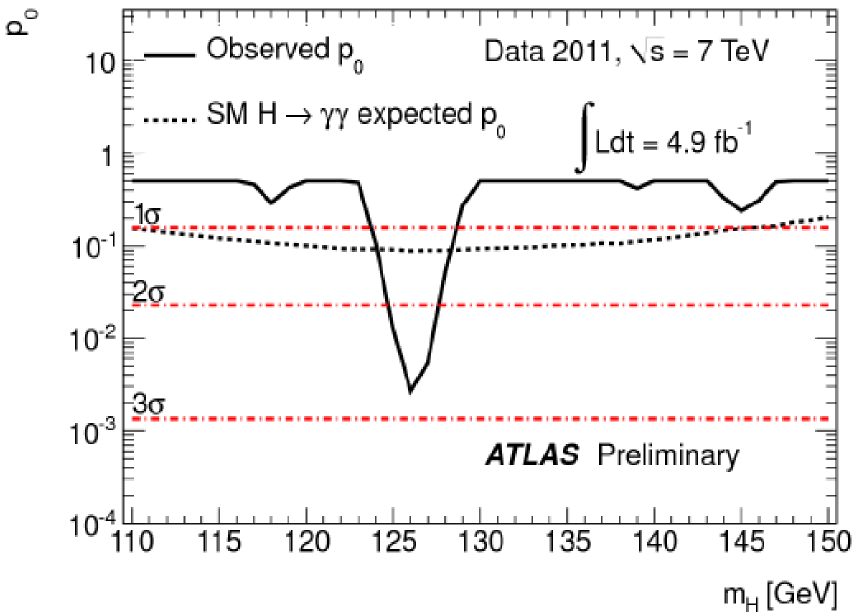
Limit setting

By using profile likelihood ratio method, exclusion limit is obtained with CLs.

- **Expected limit**
  - **(1.61-2.87)×SM @110-150GeV**
  - **(1.61-1.78)×SM @115-130GeV**
- **Observed exclusion**
  - **m_H =114-115GeV**
  - **m_H =135-136GeV**

Results for H→γγ

p_0-value (w/ including LEE (Look-Elsewhere-Effect))



※**p_0 value :**

Probability of seeing upward fluctuation in the background-only hypothesis as large as or larger than the obtained excess.

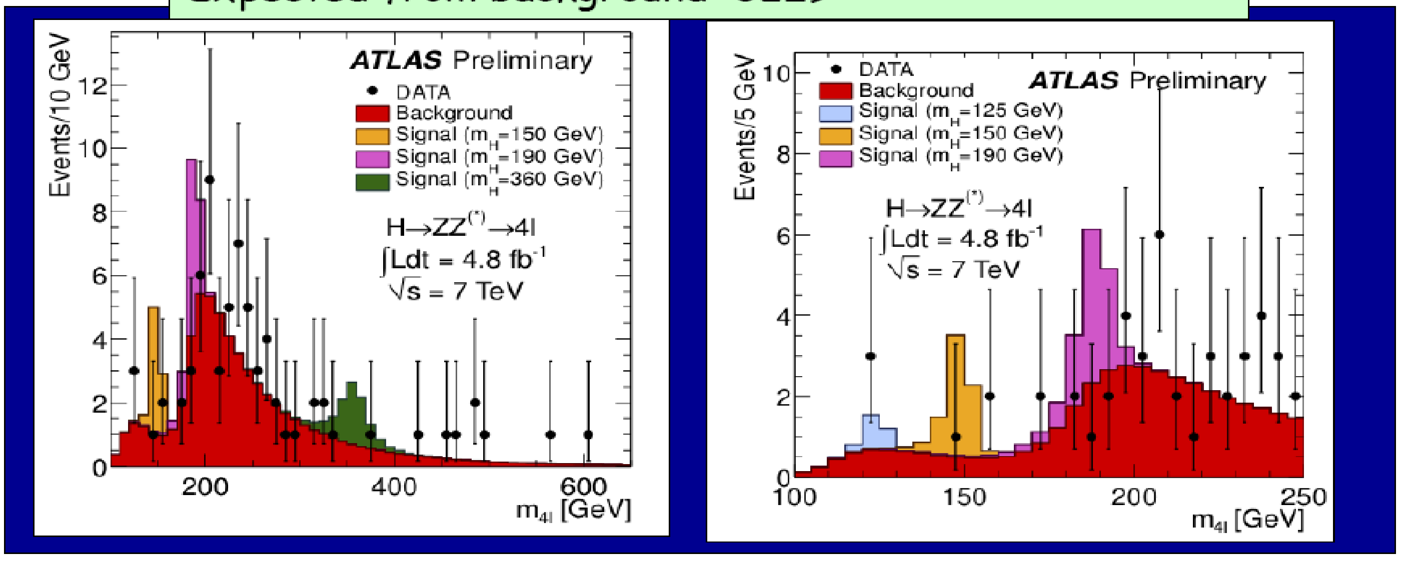
◆ **Observed excess at m_H=126GeV**

- **w/ including LEE : 2.8σ (p_0=0.27%)**
- **w/o including LEE : 1.5σ (p_0=6.5%)**

H→ ZZ$^{(*)}$→ 4l

After all selections: kinematic cuts, isolation, impact parameter

Observed in data: 71 events: 24 4μ + 30 2e2μ + 17 4e
Expected from background: 62±9



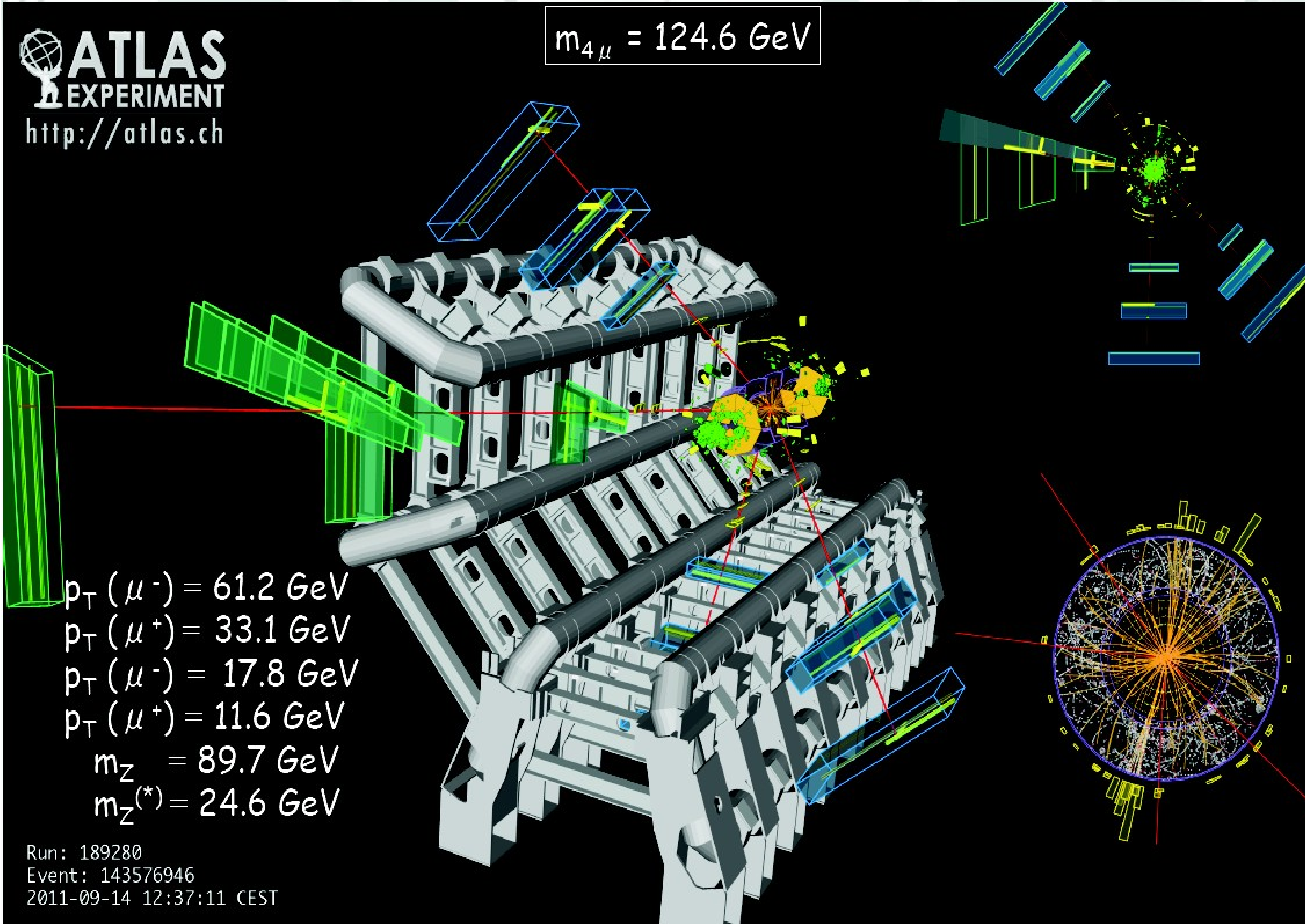
In the region m_H < 141 GeV (not already excluded at 95% C.L.) 3 events are observed: two 2e2μ events (m=123.6 GeV, m=124.3 GeV) and one 4μ event (m=124.6 GeV)

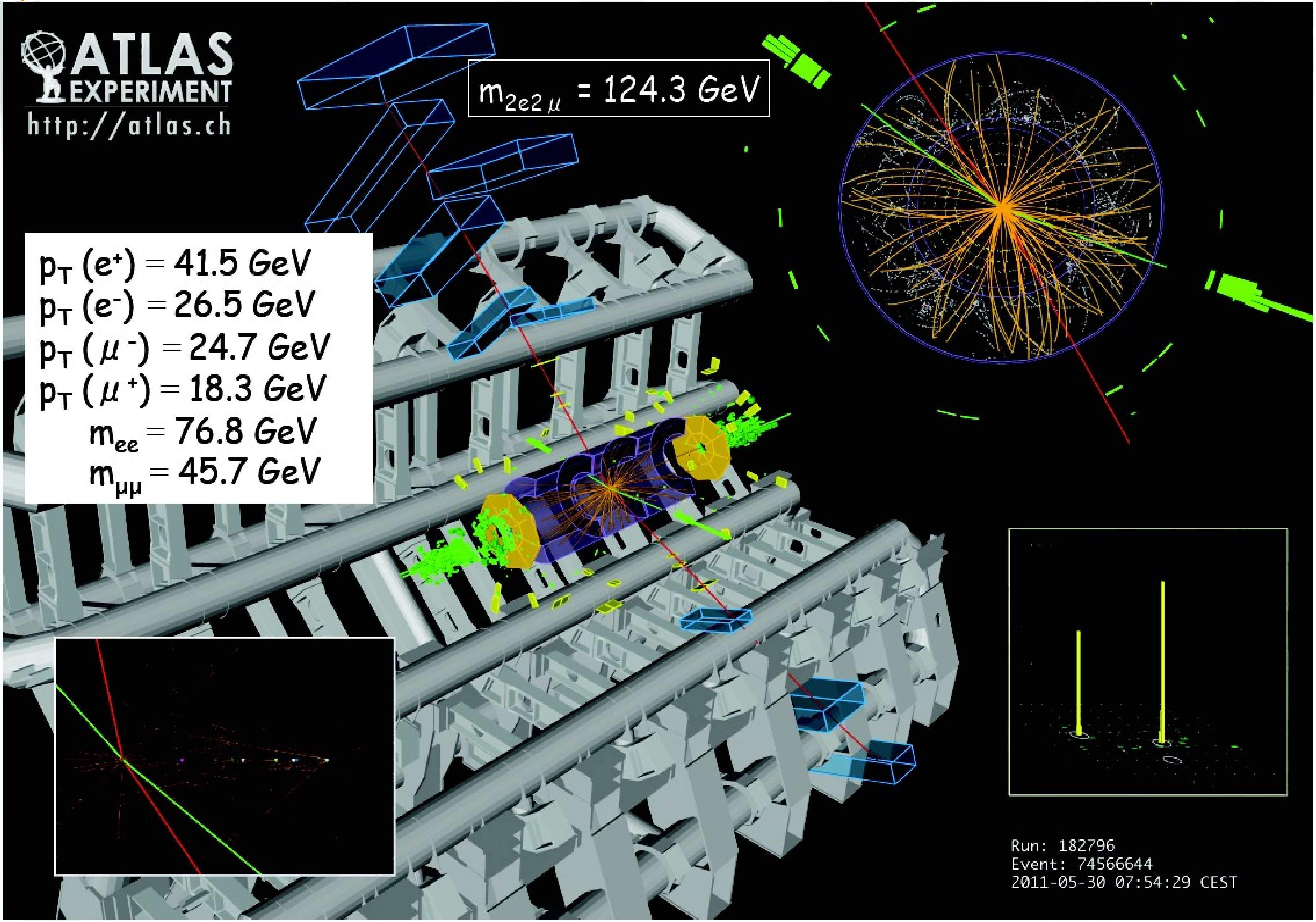
In the region 117< m_{4l} <128 GeV
(containing ~90% of a m_H=125 GeV signal):

- similar contributions expected from signal and background: ~ 1.5 events each
- S/B ~ 2 (4μ), 1 (2e2μ), ~0.3 (4e)
- Background dominated by ZZ* (4μ and 2e2μ), ZZ* and Z+jets (4e)

Main systematic uncertainties

Higgs cross-section	: ~ 15%
Electron efficiency	: ~ 2-8%
Zbb, +jets backgrounds	: ~ 40%
ZZ* background	: ~ 15%

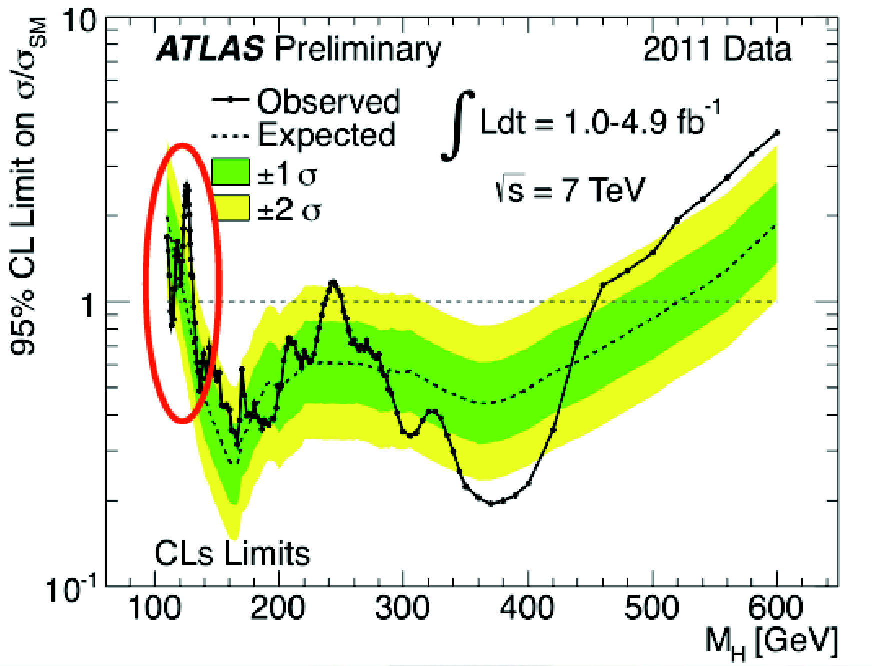

ATLAS EXPERIMENT
http://atlas.ch
$m_{4\mu}$ = 124.6 GeV
$p_T(\mu^-)$ = 61.2 GeV
$p_T(\mu^+)$ = 33.1 GeV
$p_T(\mu^-)$ = 17.8 GeV
$p_T(\mu^+)$ = 11.6 GeV
m_Z = 89.7 GeV
$m_{Z^{(*)}}$ = 24.6 GeV
Run: 189280
Event: 143576946
2011-09-14 12:37:11 CEST


ATLAS EXPERIMENT
http://atlas.ch
m2e2μ = 124.3 GeV
pT (e+) = 41.5 GeV
pT (e-) = 26.5 GeV
pT (μ-) = 24.7 GeV
pT (μ+) = 18.3 GeV
mee = 76.8 GeV
mμμ = 45.7 GeV
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

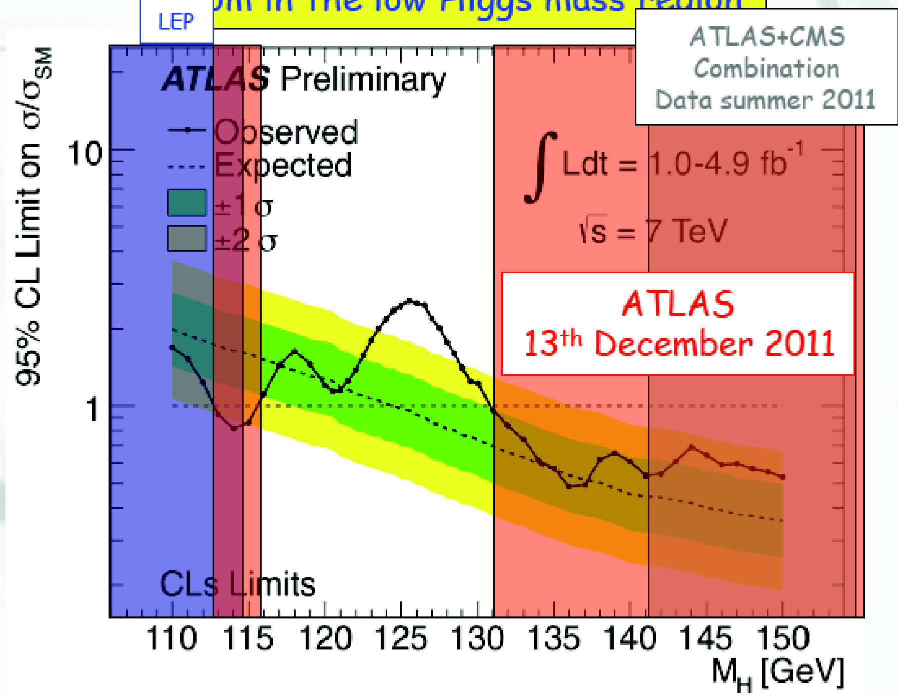
ATLAS exclusion of Higgs masses

$H\rightarrow\gamma\gamma$, $H\rightarrow\tau\tau$
$H\rightarrow WW^{(*)}\rightarrow l\nu l\nu$
$H\rightarrow ZZ^{(*)}\rightarrow 4l$, $H\rightarrow ZZ\rightarrow ll\nu\nu$
$H\rightarrow ZZ\rightarrow llqq$, $H\rightarrow WW\rightarrow l\nu qq$

Higgs masses with $\sigma/\sigma_{SM}<1$ excluded at 95%CL



Zoom in the low Higgs mass region



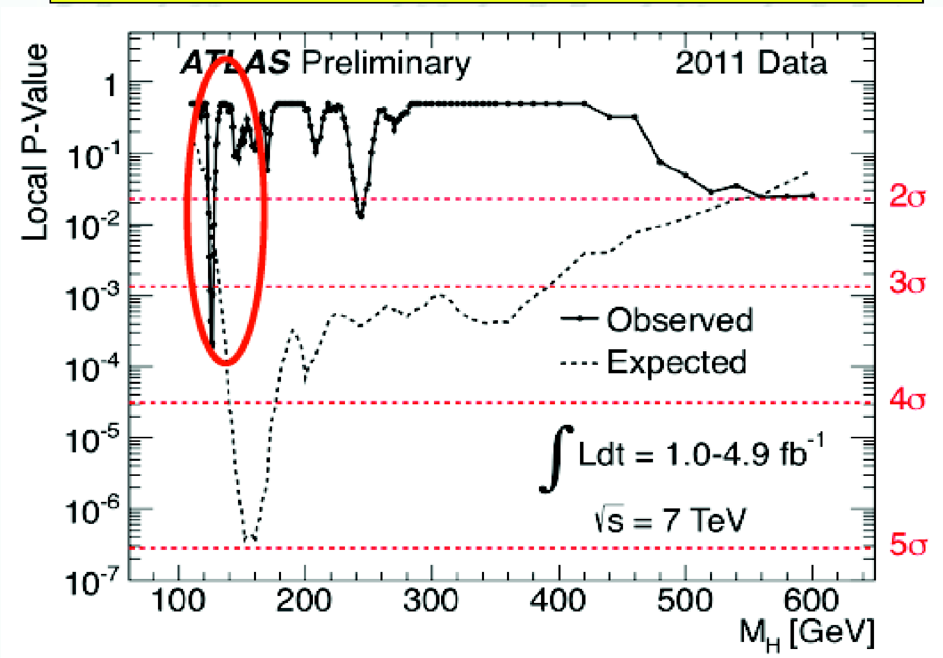
Excluded at 95% CL

$114.4 < m_H < 115.5$ GeV
$131 < m_H < 453$ GeV, except 237-251 GeV

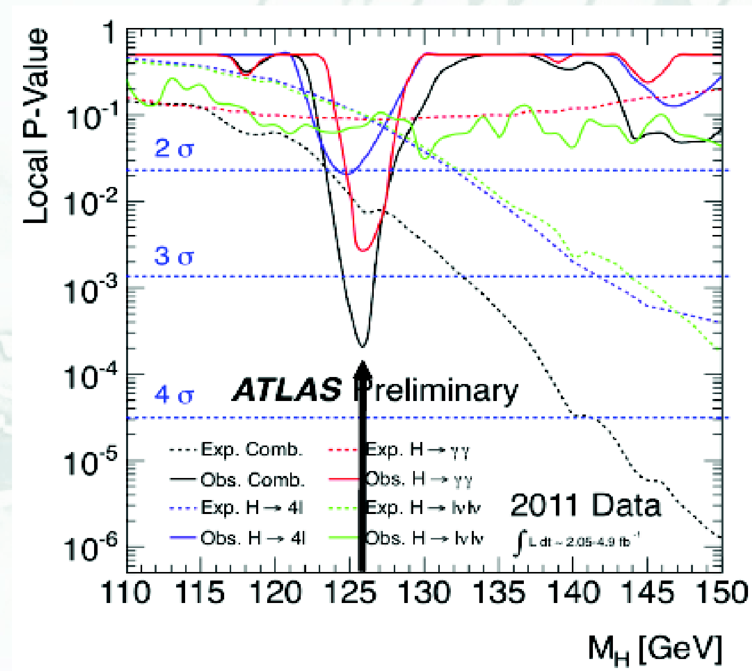
Most likely Higgs mass region at 95% CL: 115.5 – 131 GeV

Data and bgd only expectation consistency

Probability that the data is compatible with background only expectation



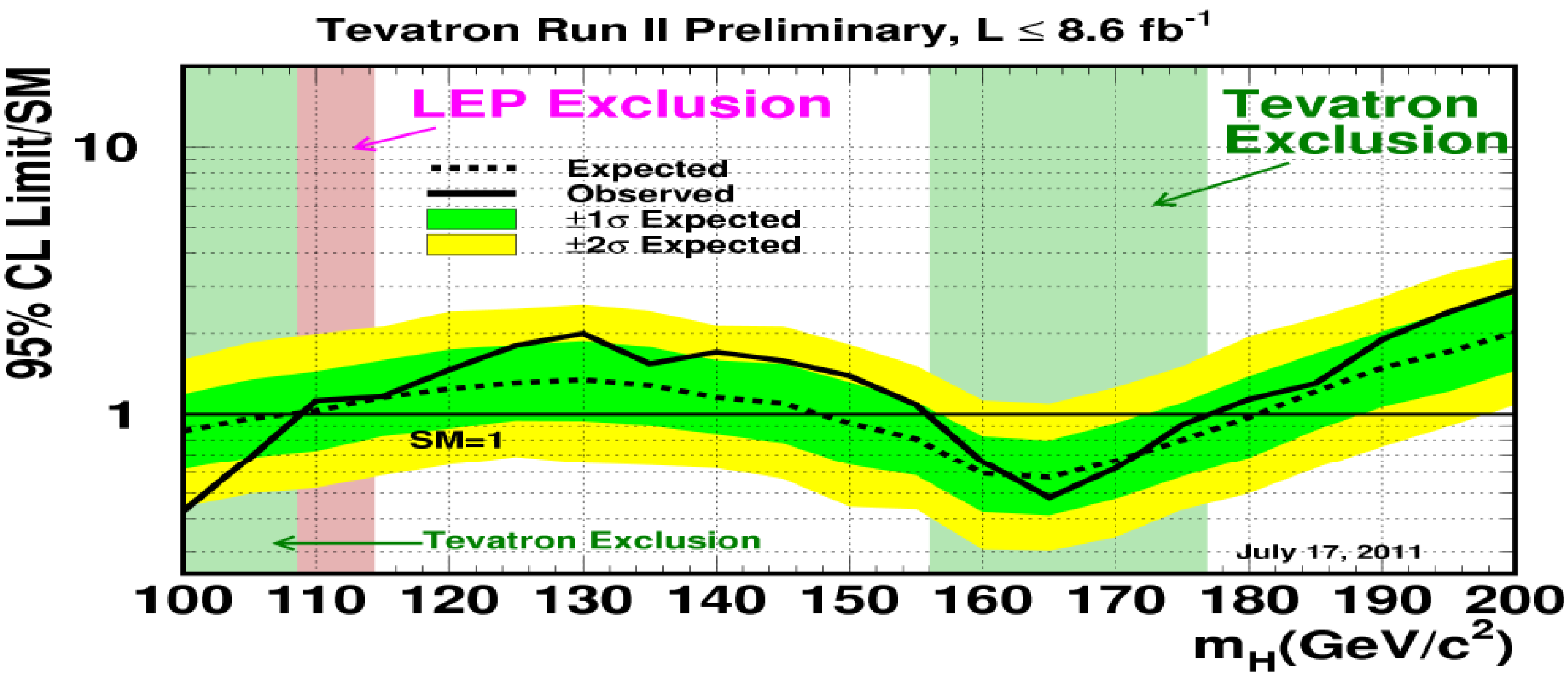
Zoom at the low Higgs mass region



- Maximum deviation from background only expectation observed at m_H ~126 GeV:
  - Local probability (p_0 value) = 0.019% Local excess significance = 3.6 σ
  - Global probability = ~1% Global excess significance = ~2.3 σ
    - Includes the probability for such an excess anywhere in a mass range (LEE)

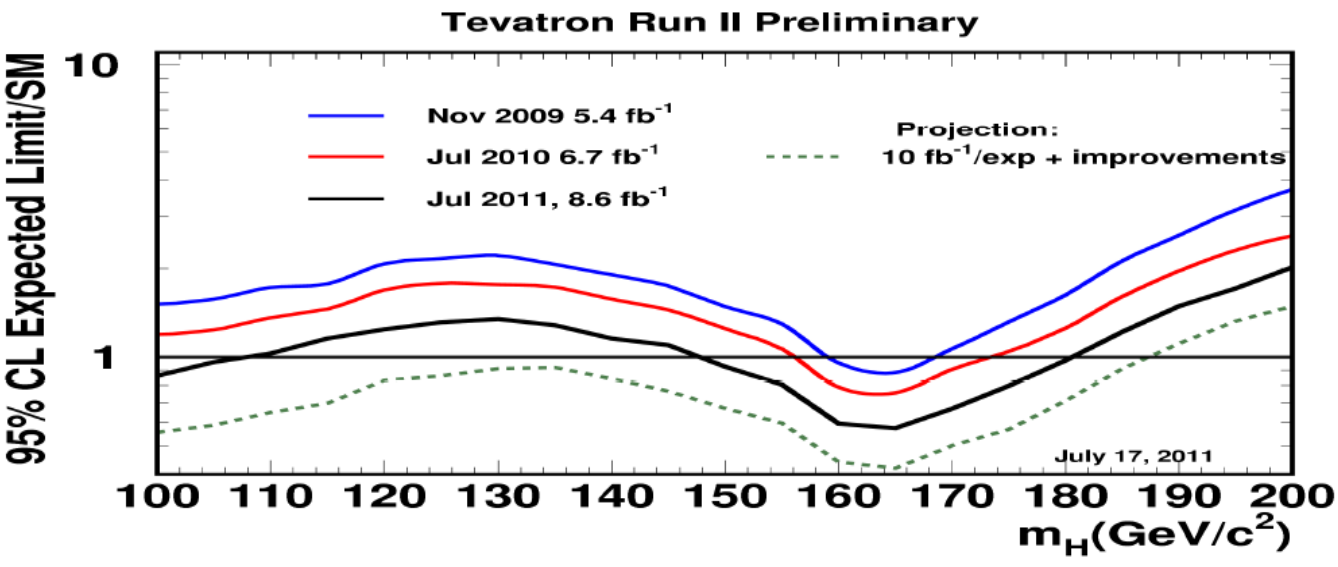
Tevatron combination

- **Observed Exclusion:** **$100<M_H<109$ & $156<M_H<177$ GeV/c^2 @95%CL.**
- **Expected Exclusion:** **$100<M_H<108$ & $148<M_H<181$ GeV/c^2@95%CL.**



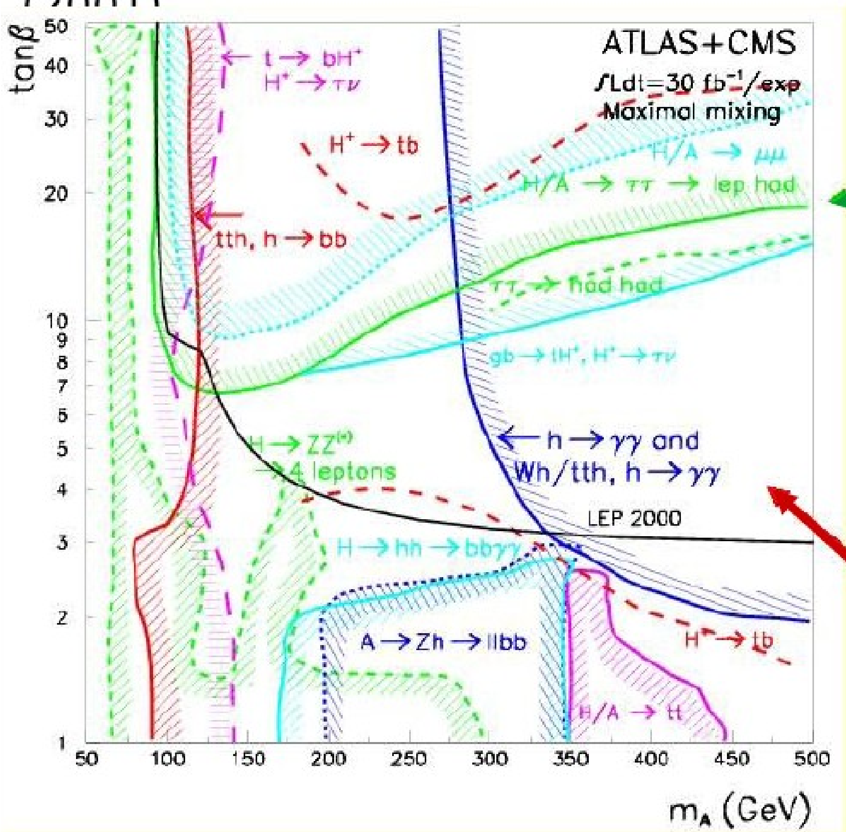
Tevatron projection

- Tevatron had a great run for last 28 years operation.
- With 10 fb^{-1} analyzable dataset and anticipated improvement, Tevatron will remain competitive to reach 95% CL exclusion sensitivity over the M_H range up to 185 GeV/c^2 next year.



MSSM Higgs sector : h, H, A, $H^{\pm}$

(2001)



$m_h < 135$ GeV , $m_A \approx m_H \approx m_{H\pm}$

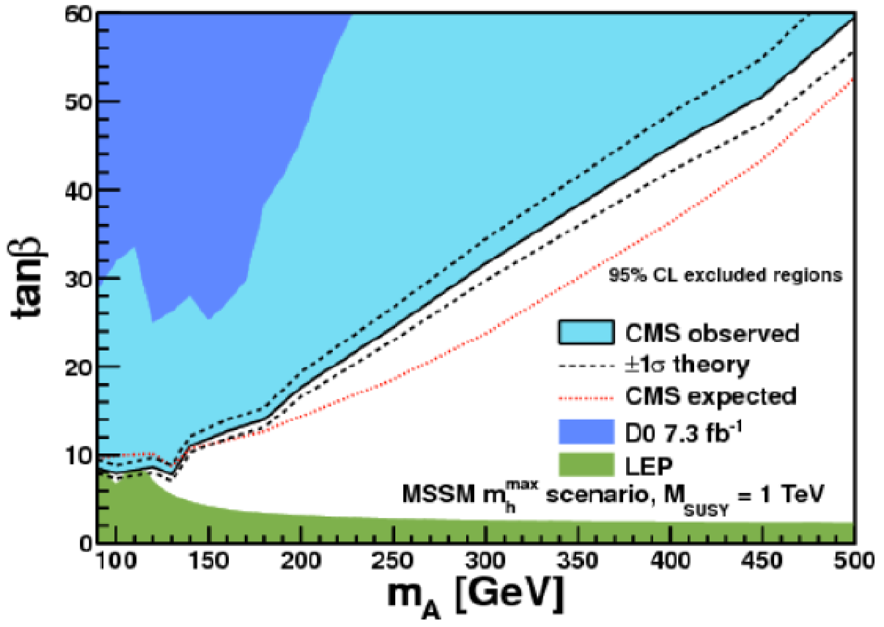
A, H, H^+ cross-sections $\sim \tan\beta^2$

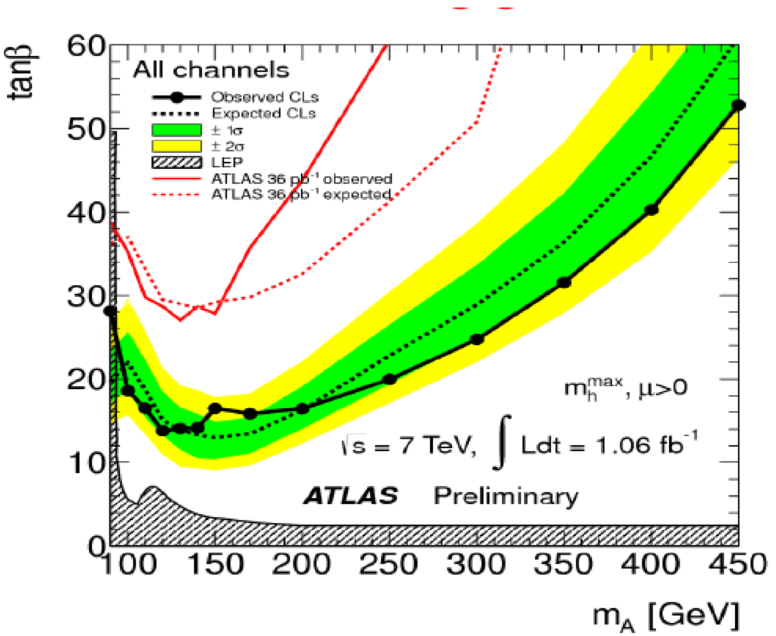
Best sentitivity from A/H->ττ, H^+->τν
not easy the first year

A/H->μμ experimentally easier specially for the beginning

Here only SM-like observable
If SUSY particles neglected

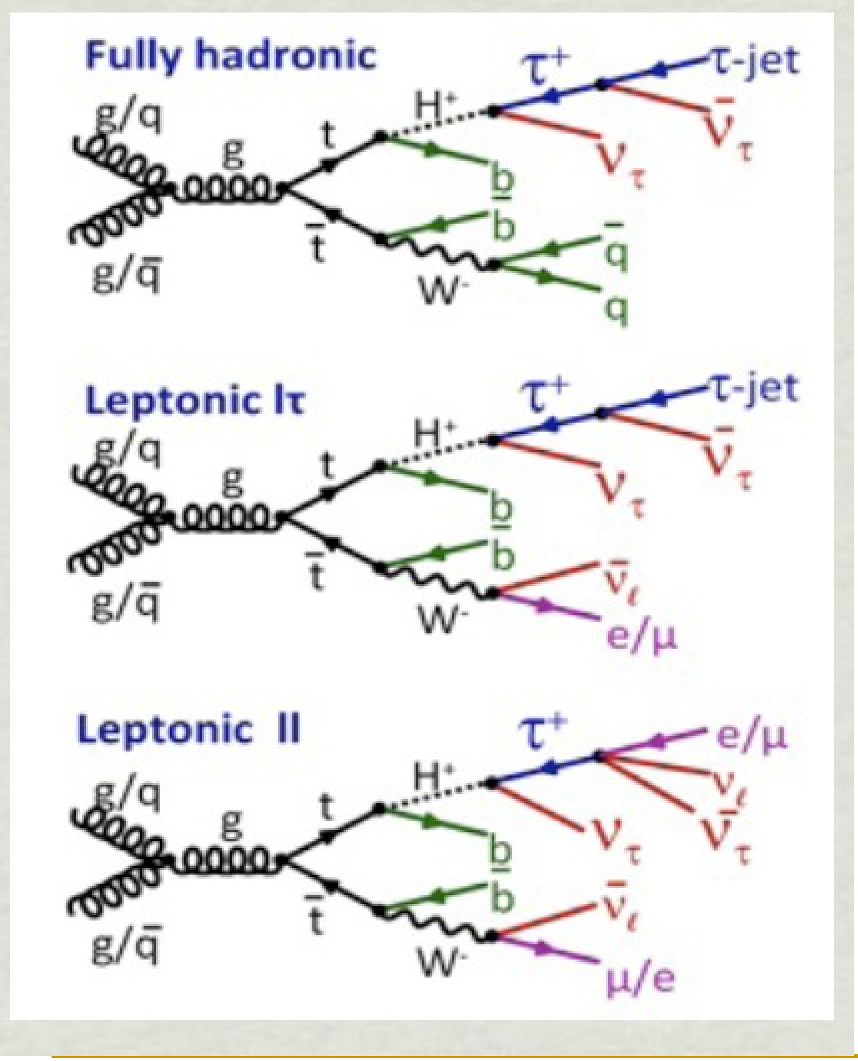
Neutral MSSM Higgs(es)





Direct searches sparticle searches have low sensitivity to tanβ and m(A) parameters of MSSM
Higgs searches provide highest sensitivity on these parameters
Already significant coverage from A→ττ
As we become sensitive to light higgs below 135-140 GeV more and more of the plane will be covered

Charged MSSM Higgs



The selections are similar in ATLAS and CMS.

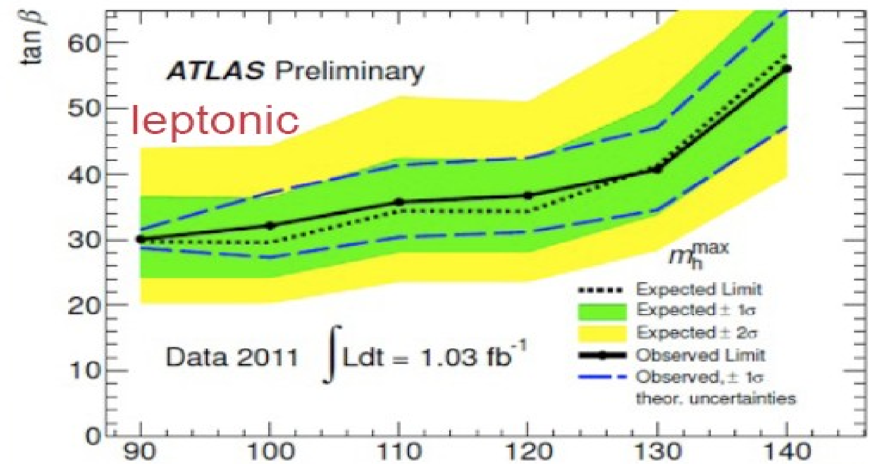
Selection in the Fully Hadronic channel is based on 1 tau jet,≥4 jets (≥1 b-tag), large MET.

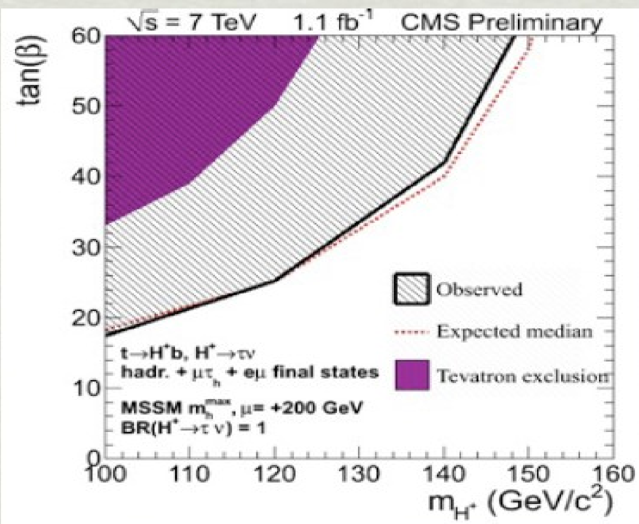
1/2 Lepton channel:
1/2 leptons, ≥3 jets (≥1 b-tag), MET

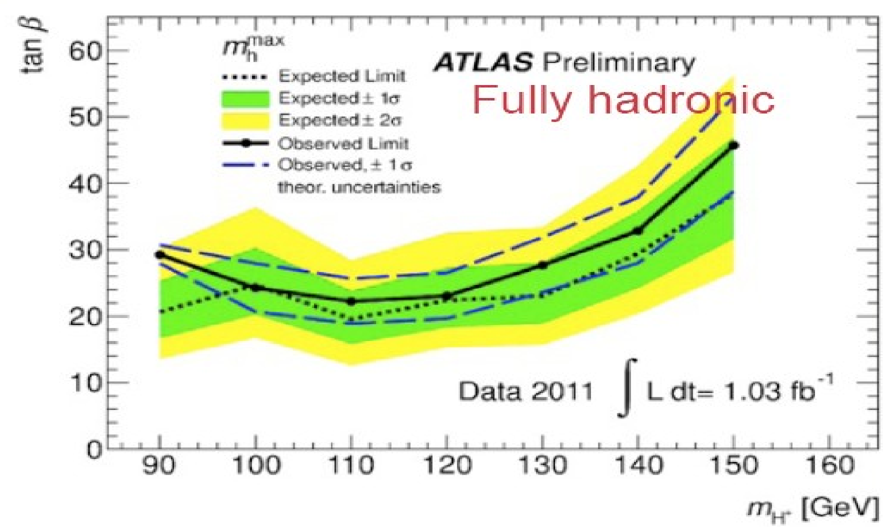
QCD multijet background Data Driven.

Charged MSSM Higgs

Limits in m_h-max scenario
superseed previous experiments







Plan

- Amazing how much could have been done with data accumulated in 2010-2011: numbers of results are still in the pile-line but already theory is being tested quantitatively.... and is holding its own (unfortunately)
- Some hints about SM Higgs boson with $5fb^{-1}$ .... so waiting now for more data in 2012
- Data of 2011 with $5fb^{-1}$ to be fully explored still

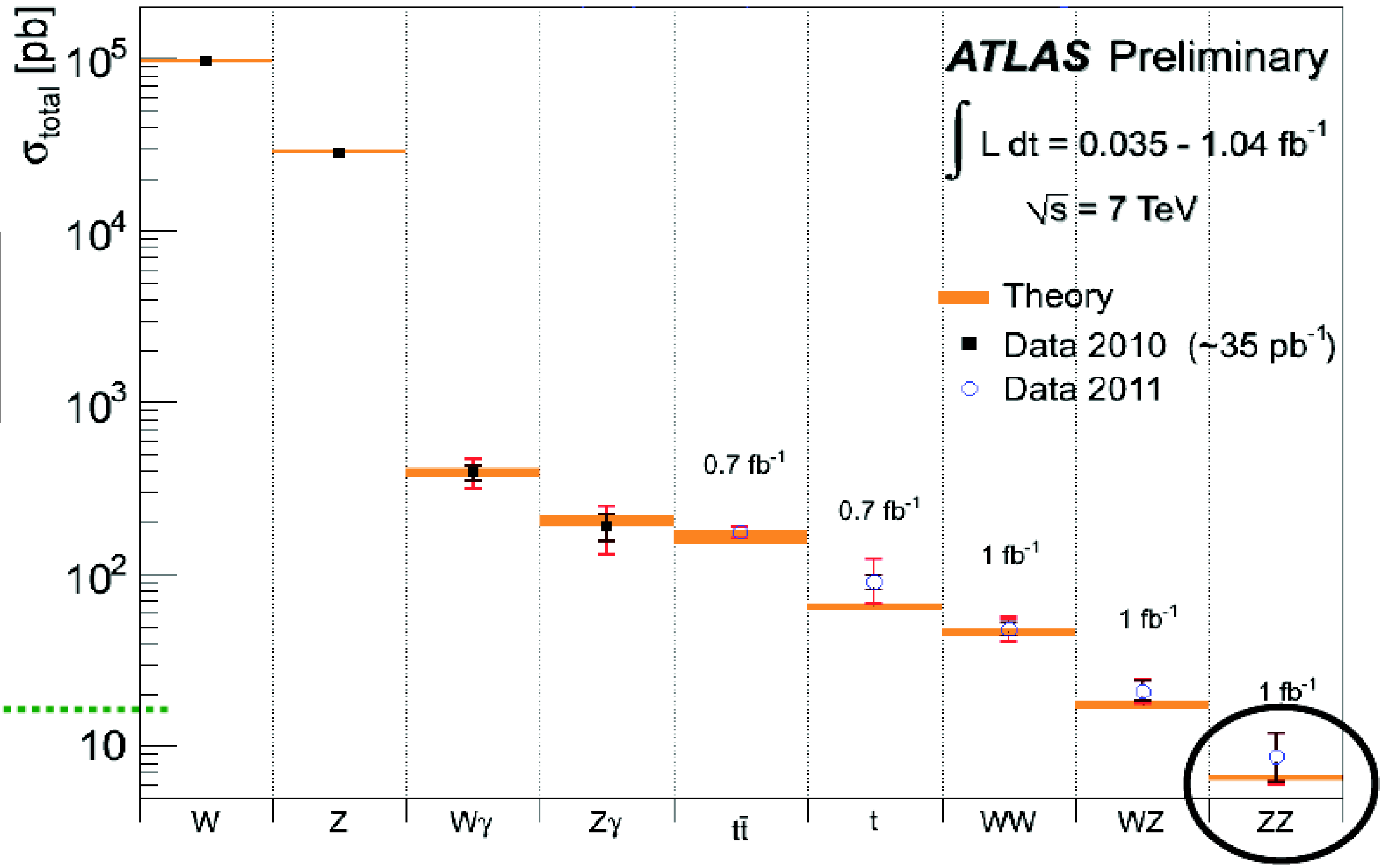
  18.01 What's new from New Physics searches?

The Standard Model cross-sections measurements in 2011

Events after selection cuts

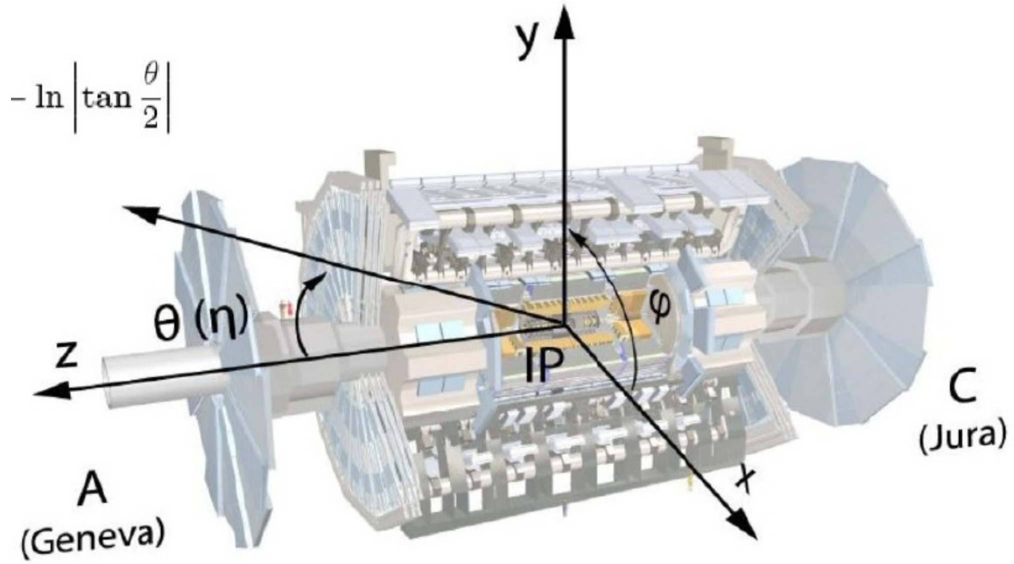
~30M W → μν, eν
~3M Z → μμ, ee
~60k top-pairs

σ (pp → H)
m_H=130 GeV



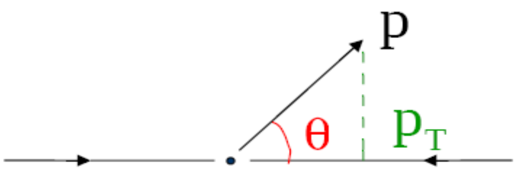
- The amount of data allowed measurements of "rare" physics processes:
  - In ~70 trillion pp collisions, ~40 ZZ → 4l events are produced
- Good agreement with the Standard Model expectations

ATLAS Detector



The ATLAS Detector is really big!

- Length : $\sim$ 46 m
- Radius : $\sim$ 12 m
- Weight : $\sim$ 7000 tons
- $\sim 10^8$ electronic channels
- 3000 km of cables



Transverse momentum

(in the plane perpendicular to the beam)

$$p_T = p \sin\theta$$

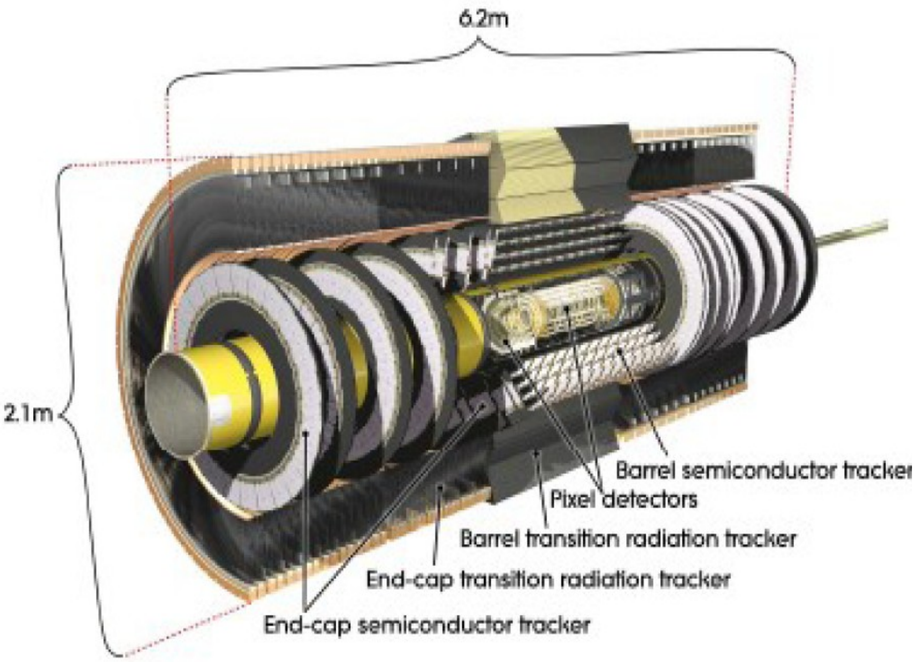
Rapidity: $\eta = -\log\left(\mathrm{tg}\,\frac{\theta}{2}\right)$

$\theta = 90^\circ \rightarrow \eta = 0$

$\theta = 10^\circ \rightarrow \eta \cong 2.4$

$\theta = 170^\circ \rightarrow \eta \cong -2.4$

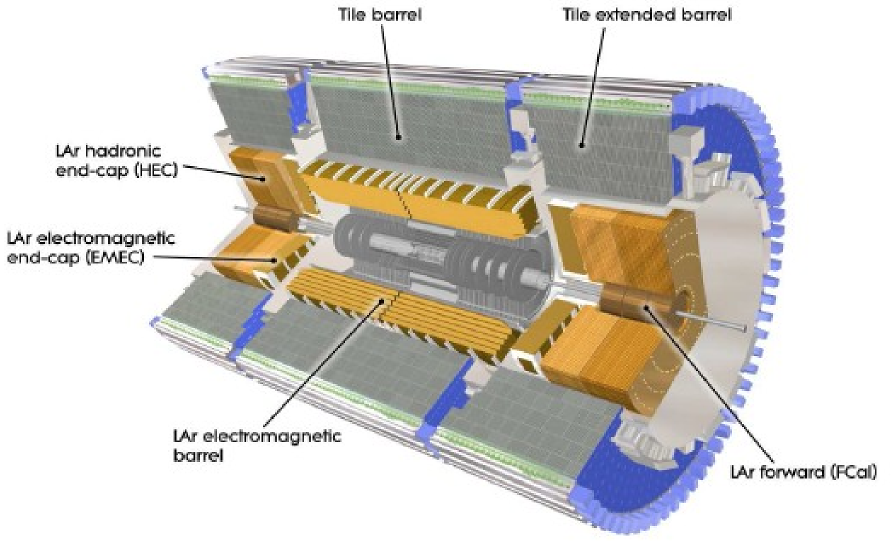
ATLAS Inner Detector



The inner detector $|\eta| < 2.5$ consists of

- Pixel detectors, semi-conductor tracker (SCT), transition radiation tracker
  - $\approx$ 87 million readout channels
  - Immersed in 2T solenoidal magnetic field
- Resolution of $\sigma/p_T = 5 \times 10^{-4} \oplus 0.015$

ATLAS Calorimeters



Electromagnetic and hadronic calorimeters

- Subsystem technology and granularity $\leftrightarrow$ shower characteristics
- Transverse and longitudinal sampling $\approx$ 200000 readout cells up to $|\eta| < 4.9$

Electromagnetic Calorimeters:

- Fine granularity $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ in central region
- Energy resolution $10\%/\sqrt{E}$

Hadronic Calorimeters:

- Granularity $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in central region, less segmented in forward region
- Energy resolution $50\%/\sqrt{E} \oplus 0.03$