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Collider Physics

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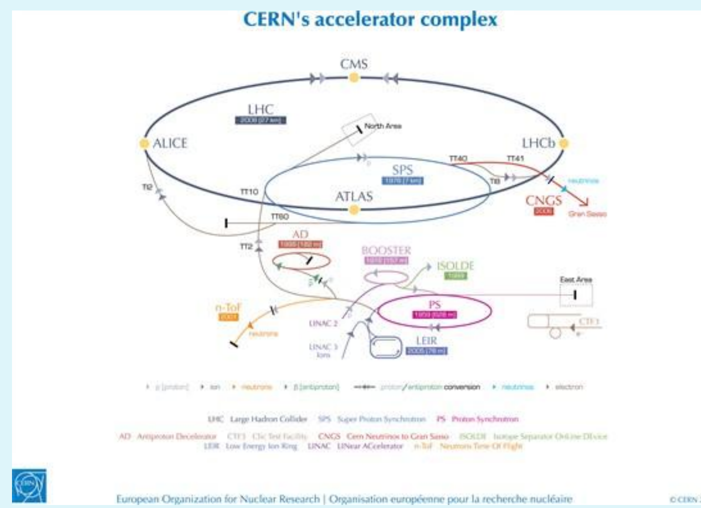
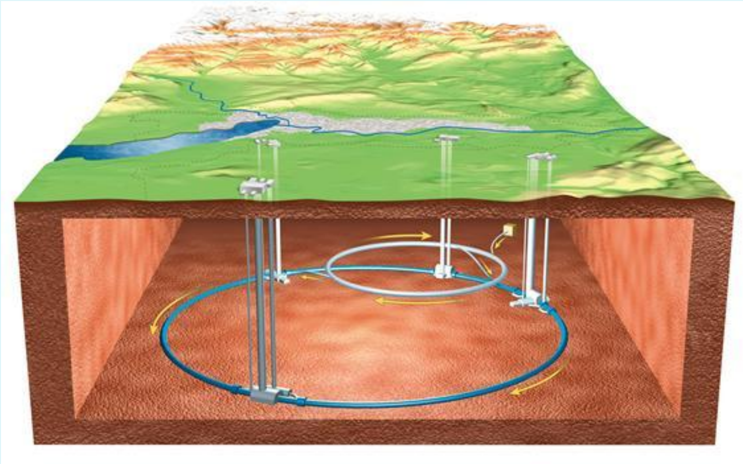
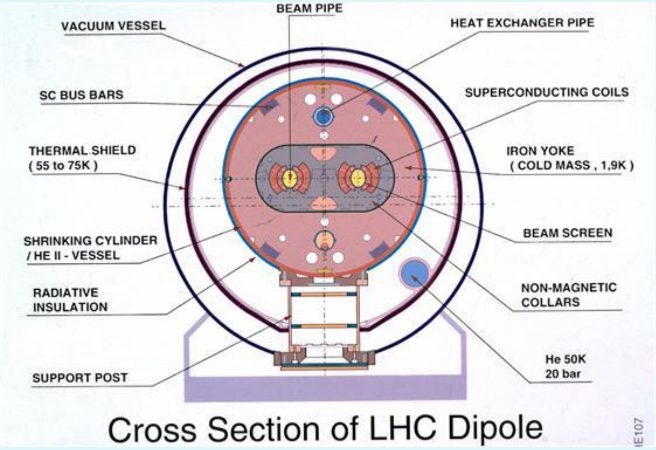
The CERN laboratory in Geneva



The 8 (14) TeV Large Hadron Collider LHC

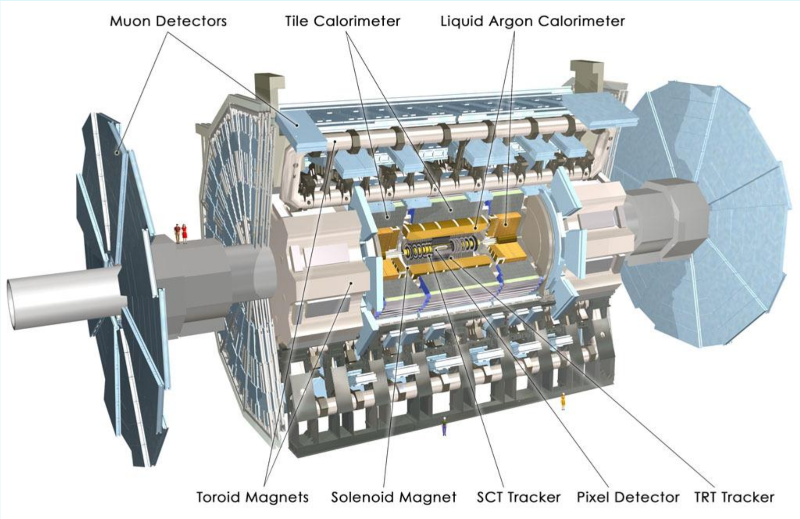


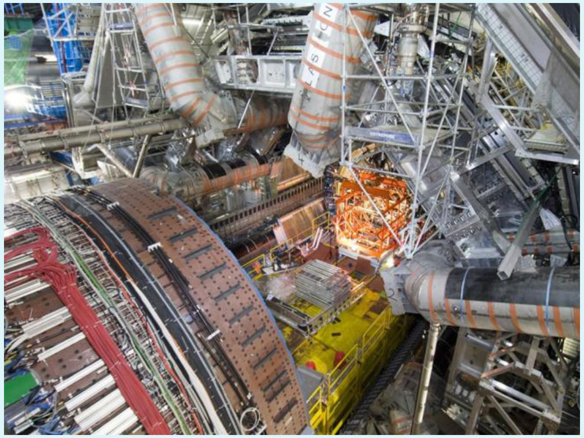


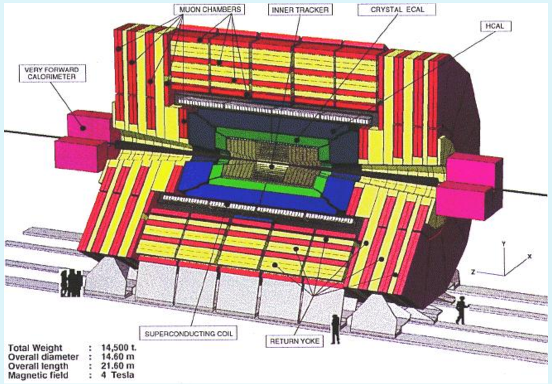
LHC parameters

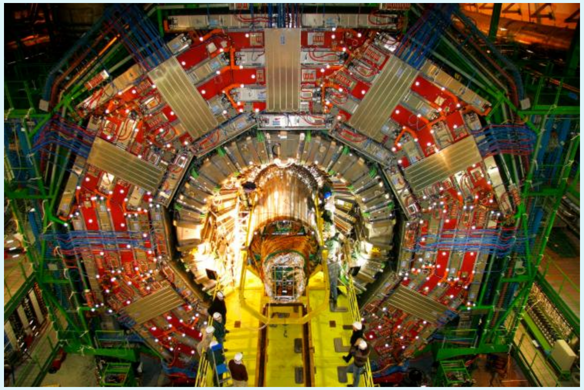
Circumference (km)	26.7	100-150m underground
Number of Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K)	1.9	Superconducting magnets needed for the high magnetic field Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field 1ppm resolution
Beam Intensity (A)	0.5	$2.2.10^{-6}$ loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current 1MJ melts 2kg Cu
Magnet Stored Energy (MJoules)/octant	1100	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

Experiments ATLAS and CMS

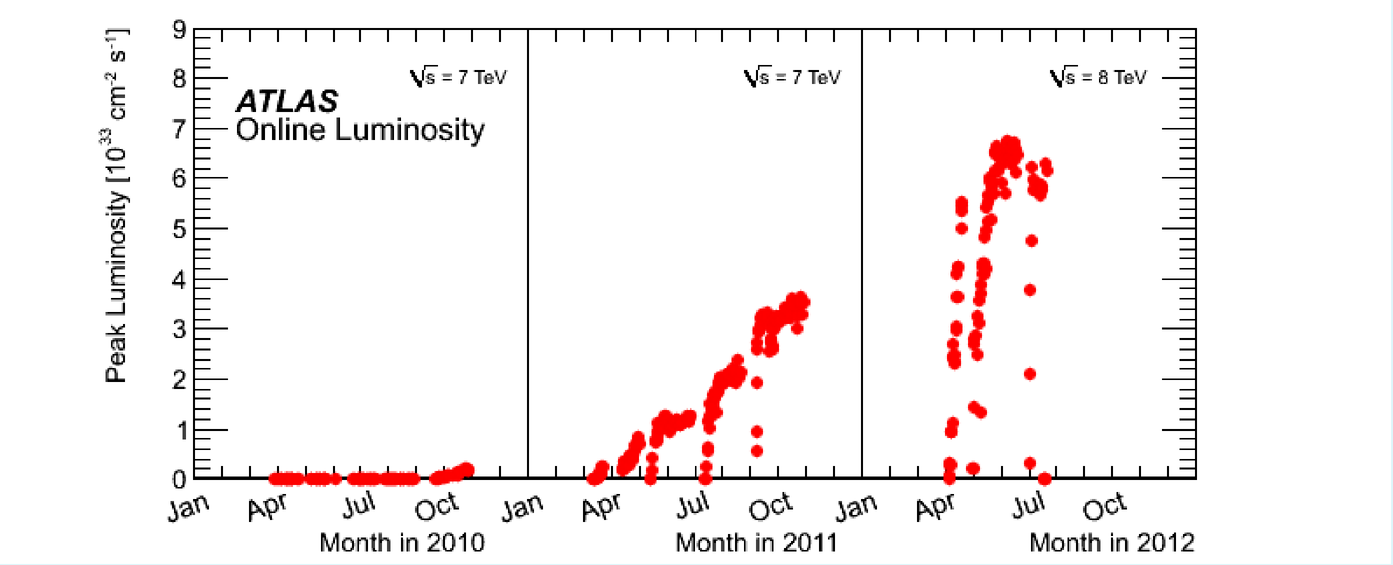




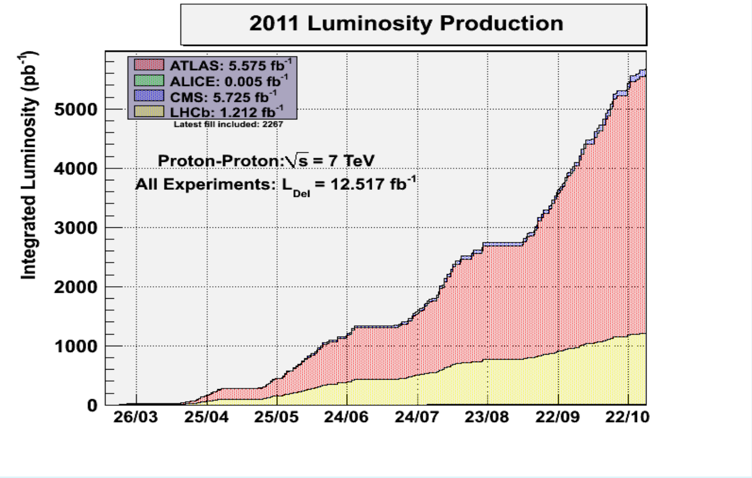




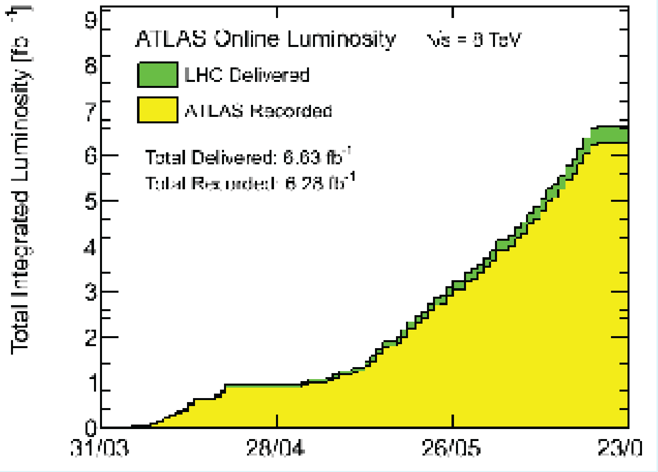
Peak instantaneous luminosity) i $cm^{-2}s^{-1}$ (ATLAS, CMS similar)



Time integrated luminosity in cm^{-2}

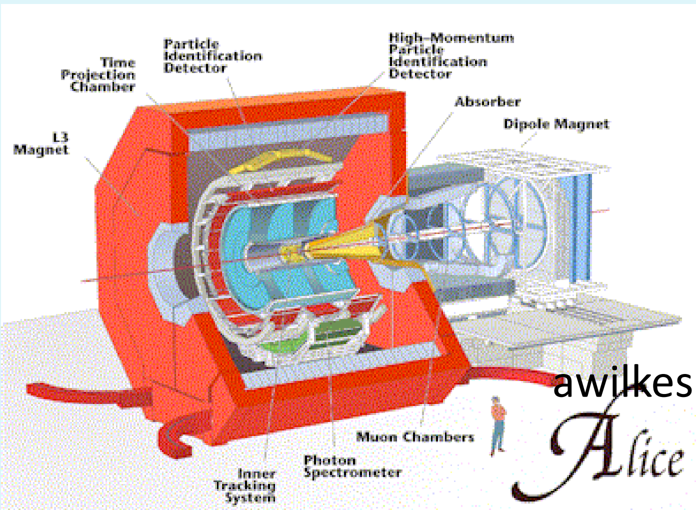


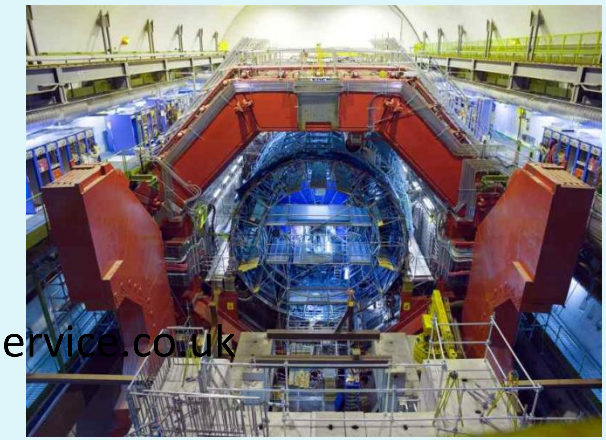
In 2011

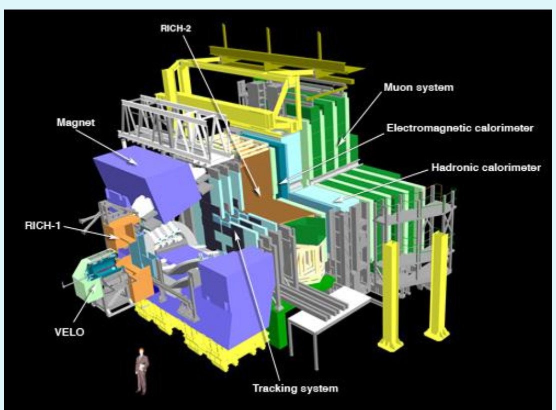


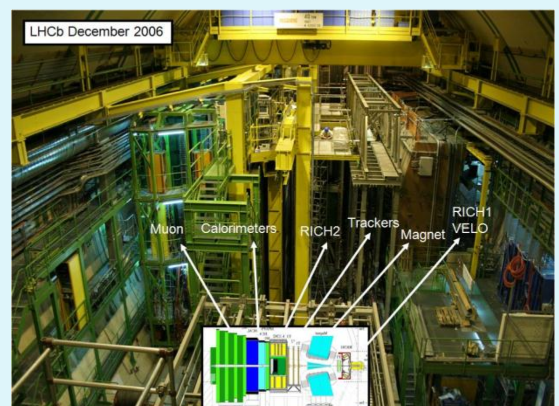
In 2012 – by ICHEP end June

Experiments ALICE and LHCb

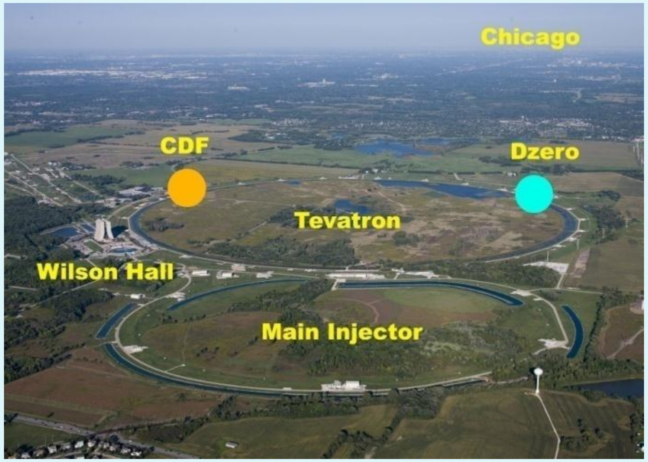








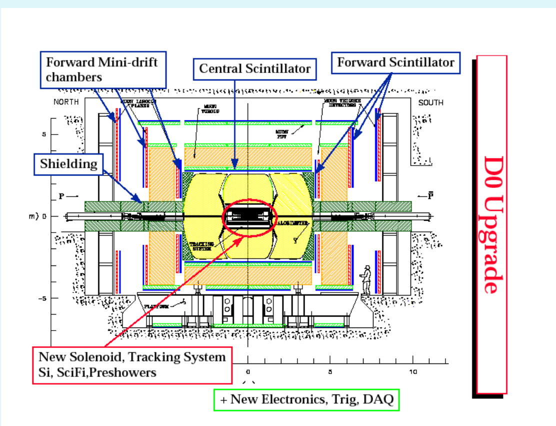
The 2 TeV Tevatron at the Fermilab laboratory in Chicago



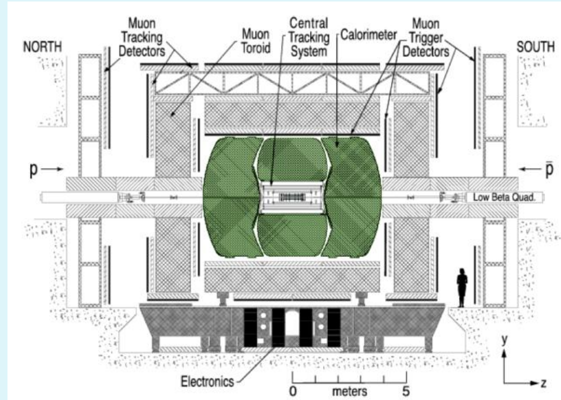
The Tevatron (6.3km around) and its’s injector

Shut down
in September
2011

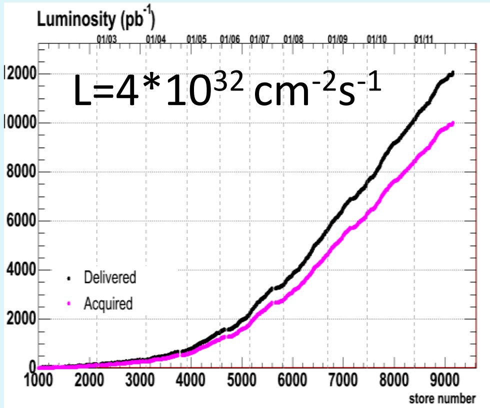
The Tevatron tunnel



The CDF detector

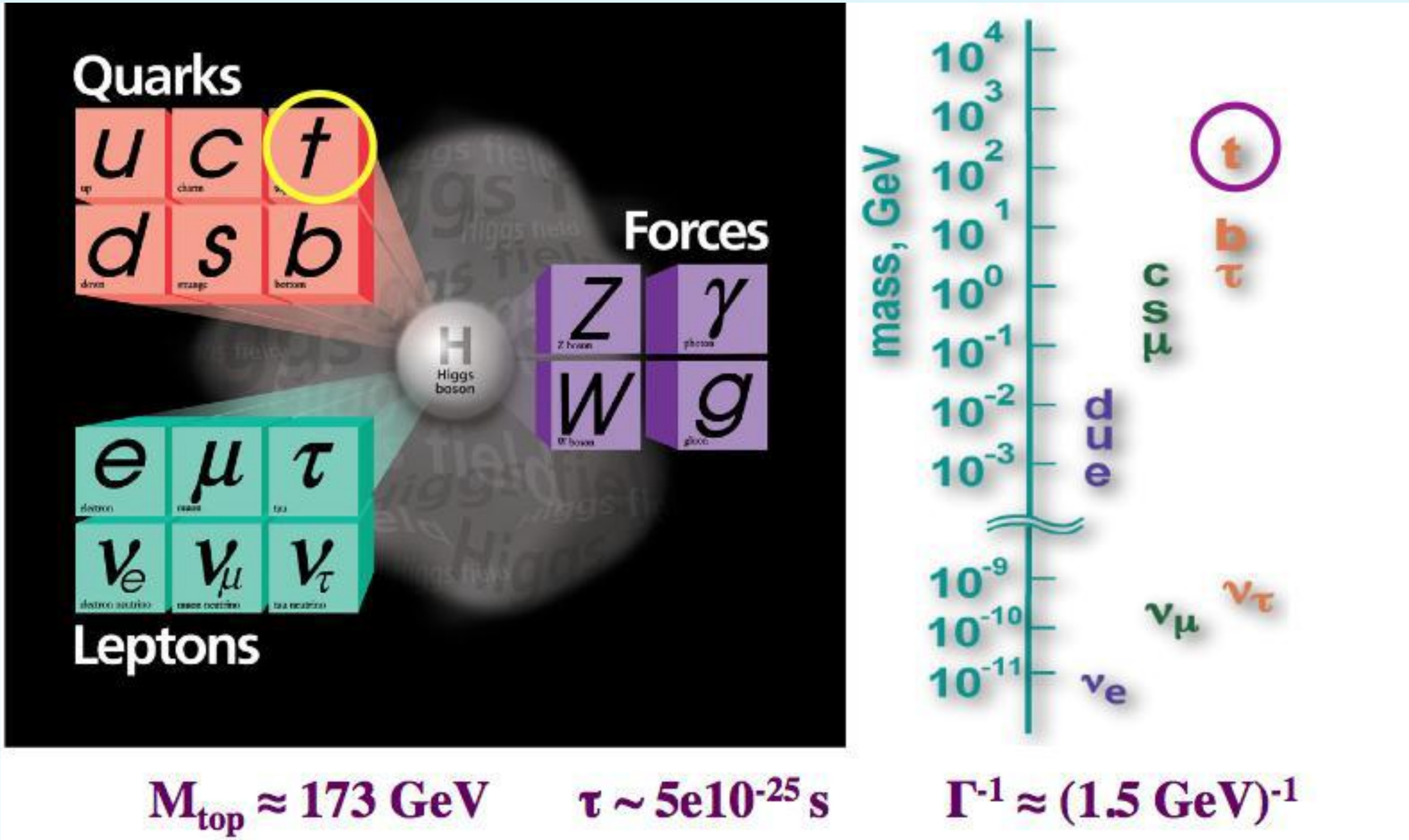


The D0 detector

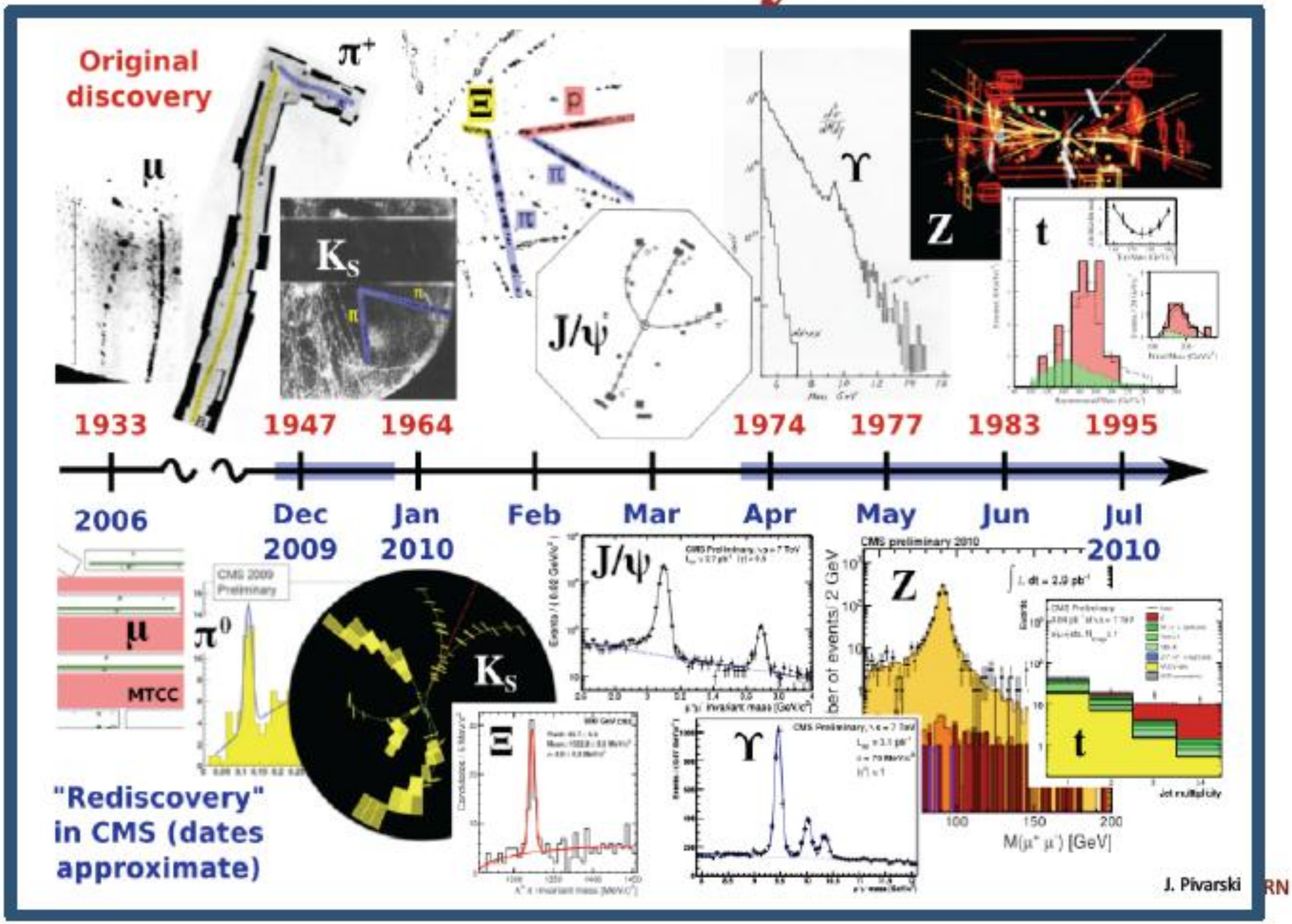


Luminosity

The Standard Model

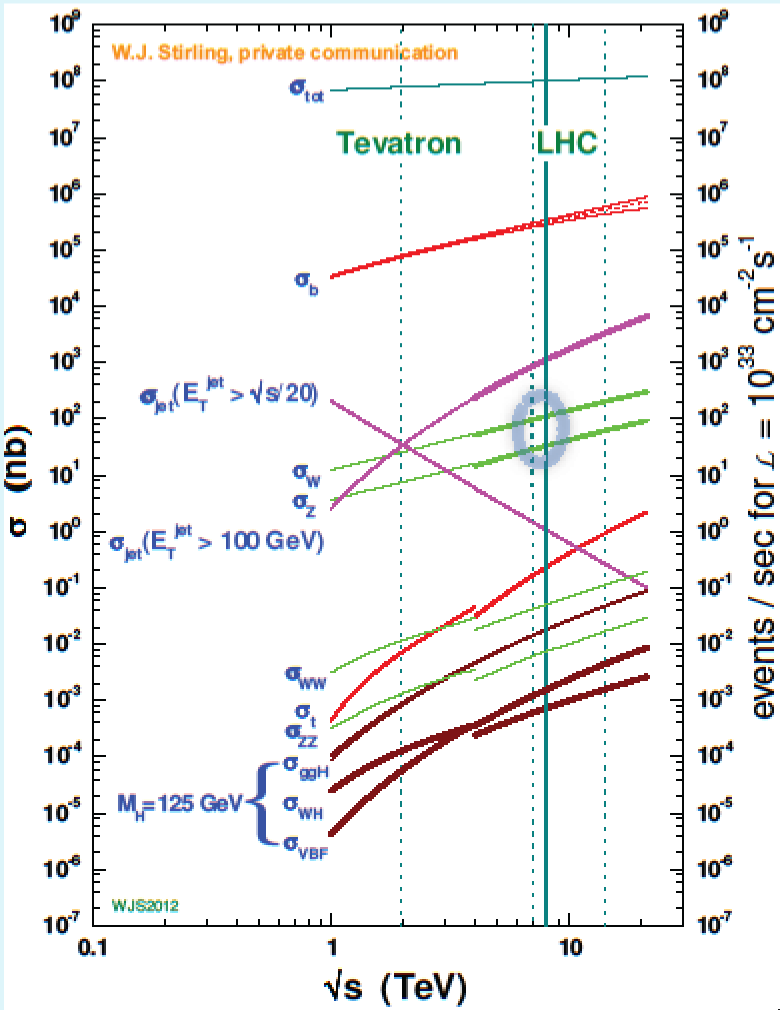


S.M. rediscovery in 2010

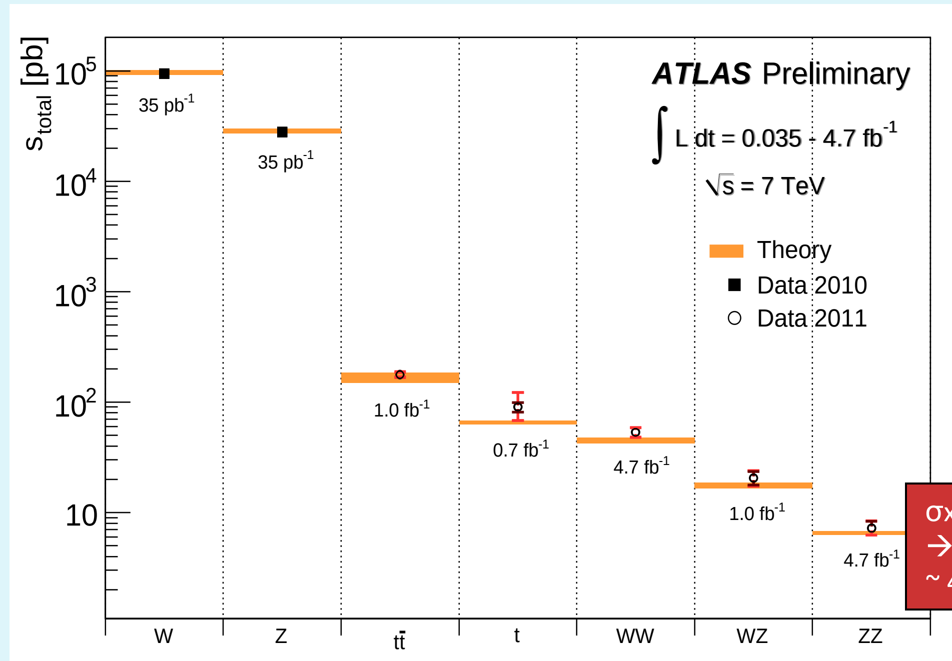


Production cross-sections

Standard Model cross-sections
As function of CM energy

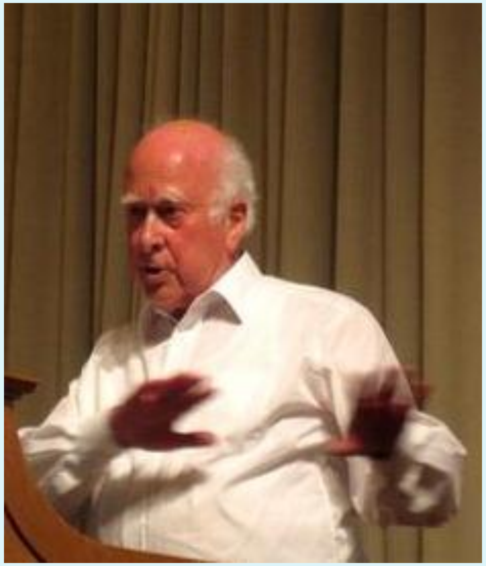


Production cross-sections measurements at
LHC of electroweak bosons and of the top quark.



σxBR(ZZ → 4l) ~ 40 fb

The Englert-Brout-Higgs field and boson



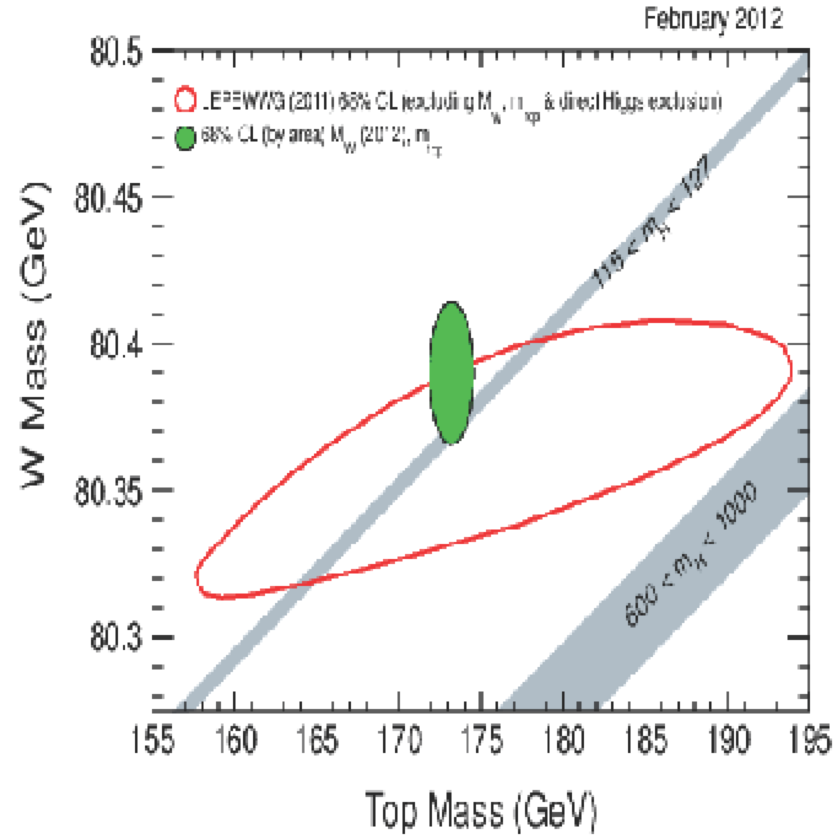
The six authors of publications 1964 PRL 1964, who received the J. J. Sakurai 2010 prize for their work. From left to right; Kibble, Guralnik, Hagen, Englert, Brout and Higgs.

Top quark mass

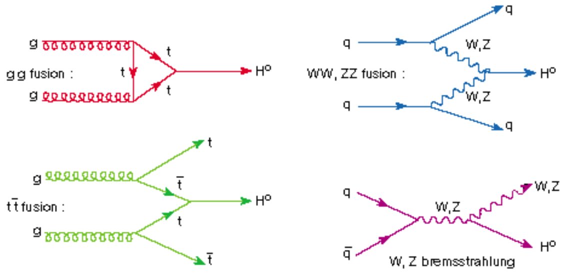
- Top quark mass is a fundamental parameter of the SM
  - Known with good accuracy from the Tevatron: 173.2±0.9 GeV (arXiv:1107.5255)
  - Indirect constraint on the Higgs boson mass via EW corrections
  - $\Rightarrow m_H=92^{+34}_{-26}$ GeV or <161 GeV

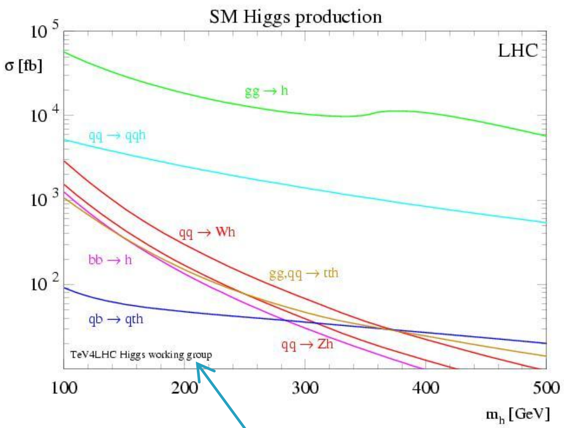
$\delta m_W \propto m_t^2$ $\delta m_W \propto \log m_h$

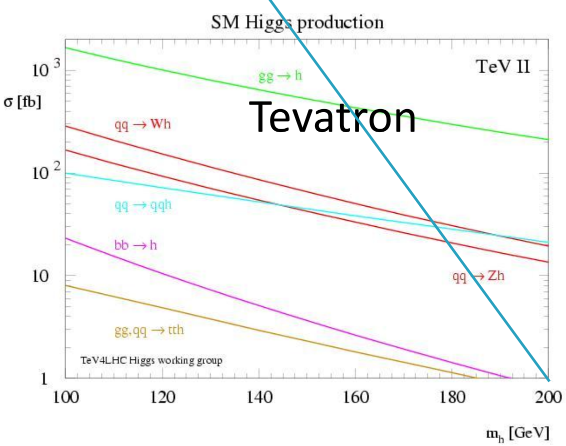
- Top is the only fermion with the mass of the order of EWSB scale
- Measuring precisely m_W and m_{top}
  - Test consistency of SM
  - Search for New Physics



H^0 production at hadron colliders:

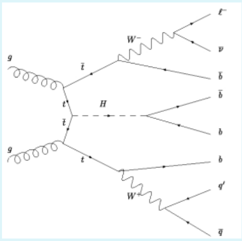


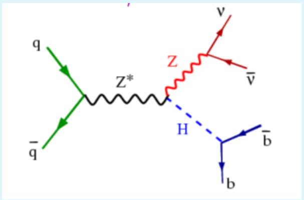


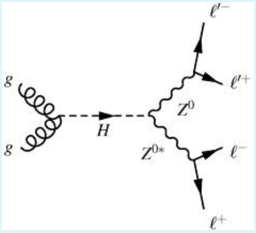


H^0 decay at hadron colliders:

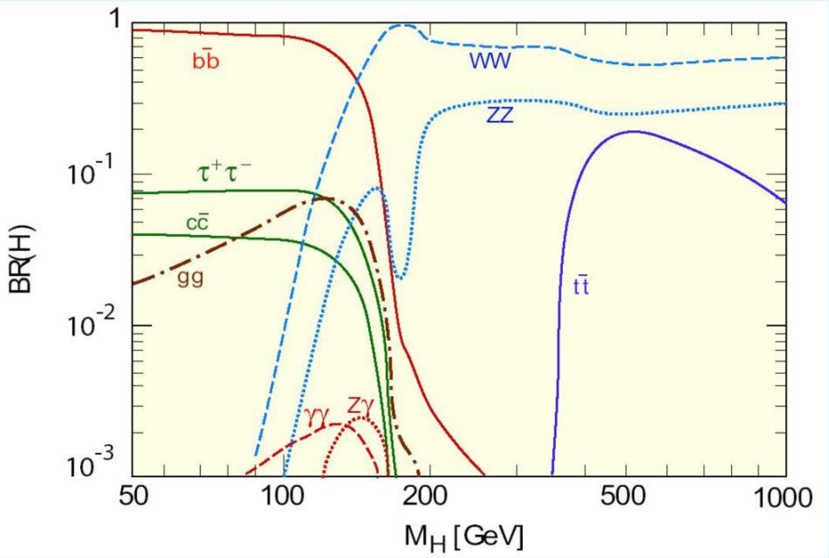
Dominant Higgs production mechanisms;







at LHC
gg->H
qq->H



at Tevatron
gg->H
qq->W/Z H

Higgs decay channels with good selectivity

H→ γγ, H→ ZZ* → 4l, H→ WW* → lνlν,
H → ττ, Z* → W/ZH → W/Zbb

According to the Standard Model the cross section for Higgs production at the LHC is around 10 pb (the exact value depending on the mass).

How many Higgs would in this case, according to the Standard Model, have been produced at the LHC by now?

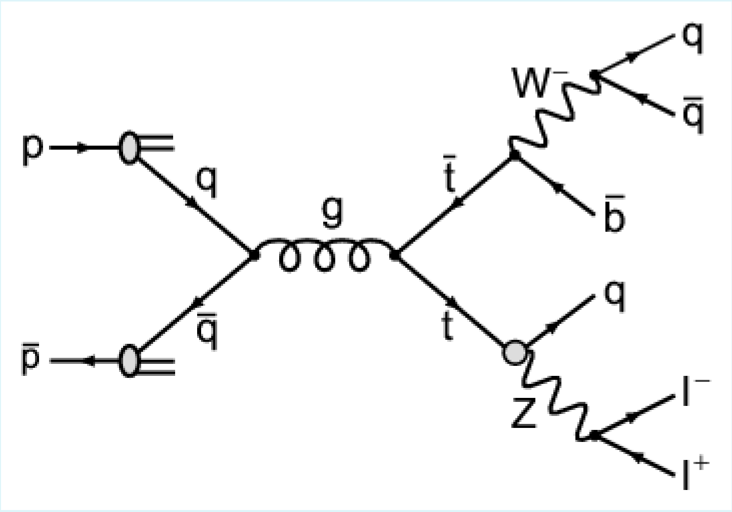
The luminosity collected by each experiment at the LHC in 2011 and 2012 is more than 10 fb^{-1} = 10'000 collisions per pb.

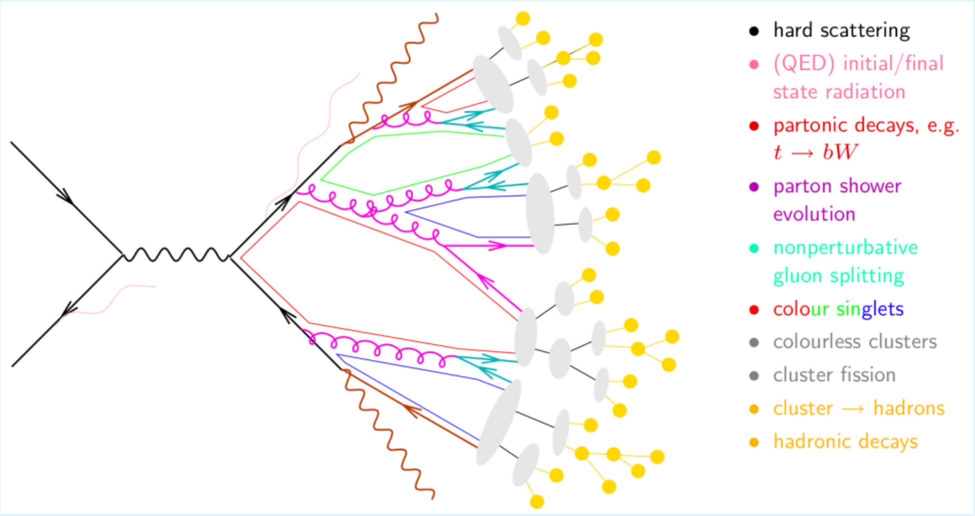
Which would the number of Higgs bosons produced at the LHC till now?

Well, the number is at least 10'000 pb^{-1} * 10 pb = 100'000 - in each of ATLAS and CMS!

If 100,000 Higgs bosons have been produced at the LHC by now, why have we not been able to discover the Higgs before?

The explanation is that there are many other processes that resemble the production and decay of Higgs – i.e. background processes





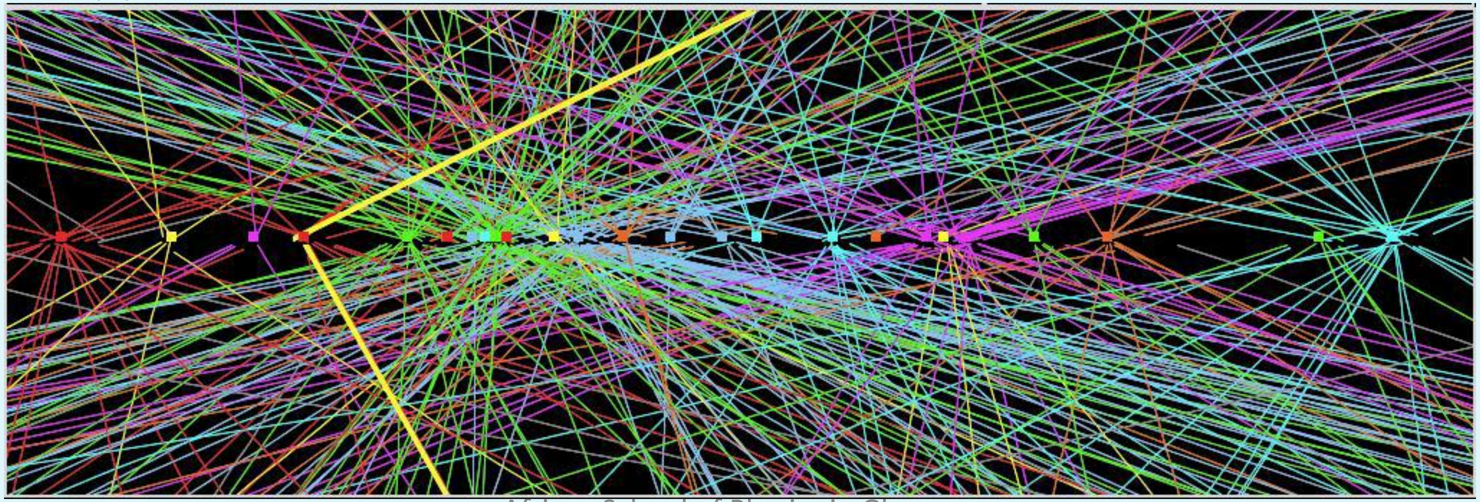
Electroweak backgrounds

QCD background

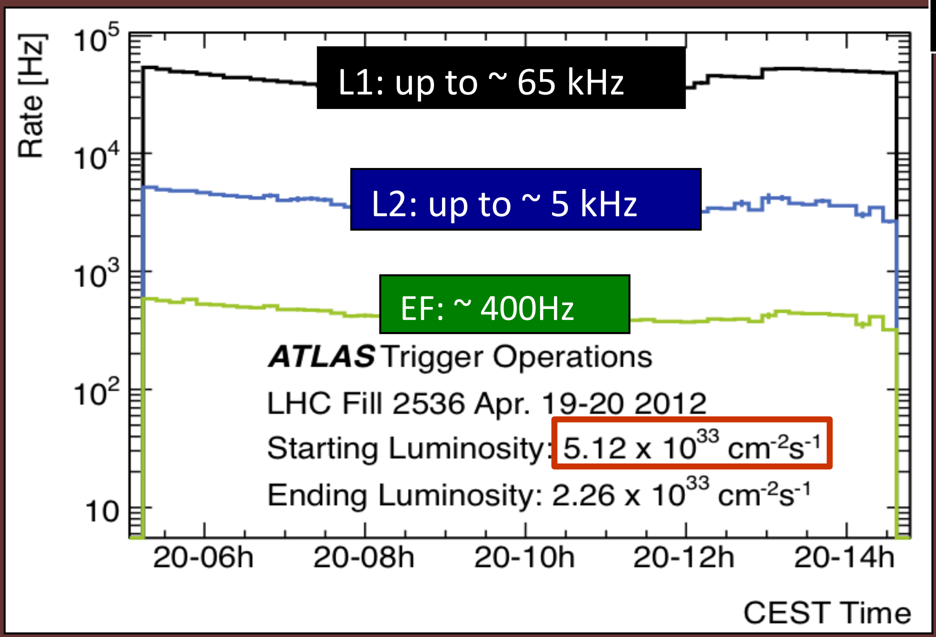
The total pp cross section at LHC is about 100 mb = 10^{-25} cm^2 and the instantaneous luminosity at present ca $6*10^{33}$ $cm^{-2}s^{-1}$, i.e. there are about $6*10^8$ collisions per second. There are (effectively) about 10^7 seconds in a year, implying just below 10^{16} events per year among which we should search for order 10^5 Higgs events, i.e. 1 event in 10^{11} in a situation where there are many other types of events mimicking the Higgs events – a formidable task.

Furthermore, with $20*10^6$ bunch crossing per second (50 ns between bunch crossings) this makes of the order 30 collisions per bunch crossing – a formidabel pile-up of events;

$Z^0 \to \mu\mu$ event from 2012 data with 25 reconstructed vertices



In the hunt for the Higgs the trigger plays a decisive role bringing down the collisions rate of nearly 1 GHz by a factor $2*10^6$ to a data acqusition rate of to ca $4*10^2$ Hz



Lowest unprescaled thresholds (examples)

Item	p_T threshold (GeV) ()=end 2011 if different	Rate (Hz) $4x10^{33}$
Incl. e	24 (22)	55
Incl. μ	24 (18)	37
ee	12	6
μμ	13 (10)	4
ττ	29,20	7
γγ	20	9
E_T^{miss}	80 (60)	8
5j	55 (30)	7

Typical recorded rates for main streams e/γ, Jets/τ/E_T^{miss} , Muons: ~ 100 Hz each
Note: almost 600 trigger items in total !

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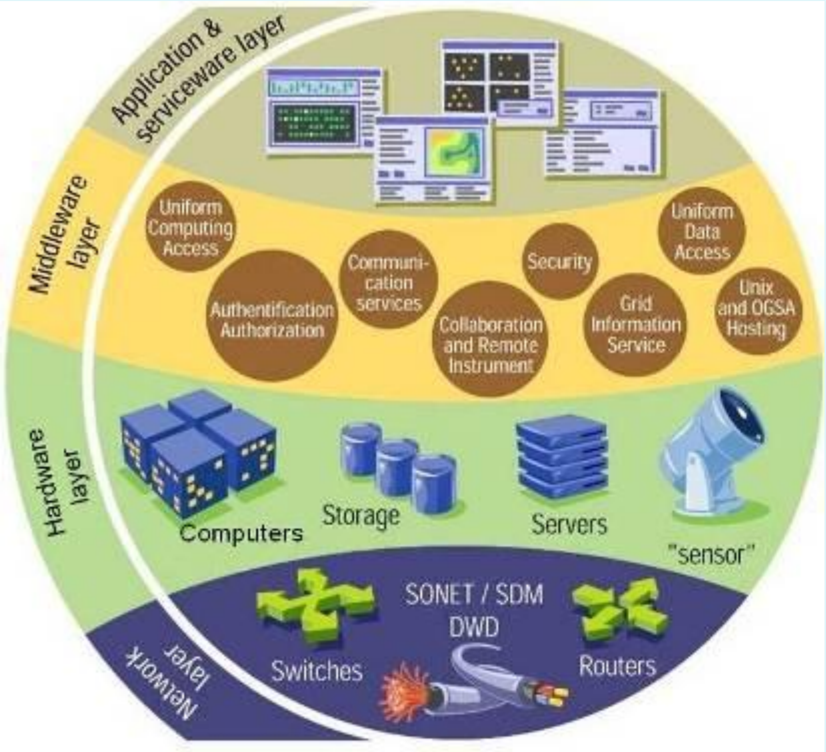
An equally decisive role in the Higgs hunt is played by the off-line software and the World Wide Computing Grid

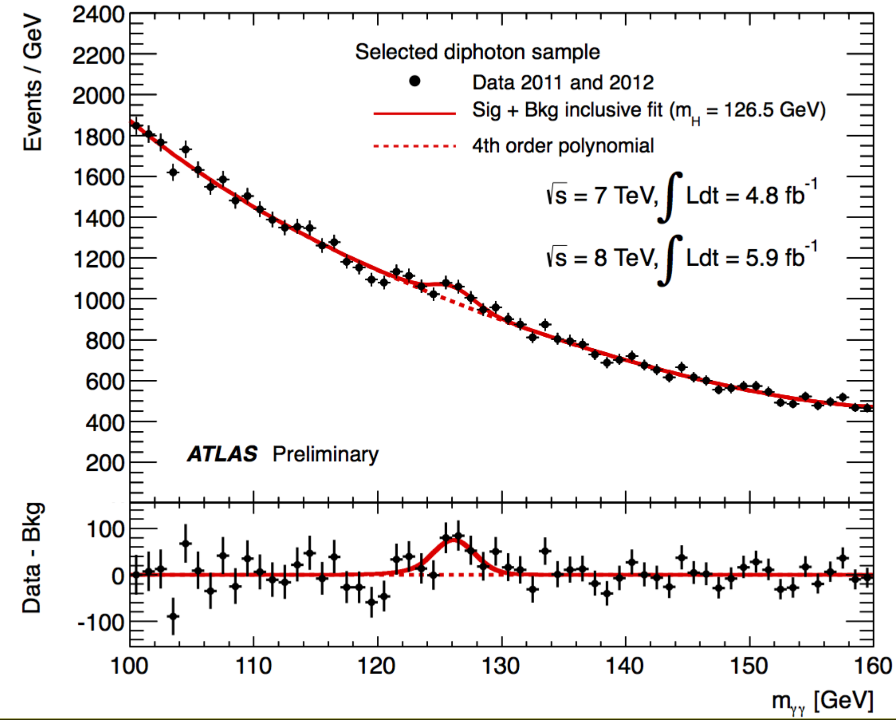
The data flow is 400 events per second i.e. of the order of 40 million events per year. Each event contains about 1.5 Mbytes of data, implying 10ths of Petabytes per year to be analysed and stored.

And from all this has by now been obtained few 10's or 100's of Higgs events (from order in total 10^5 produced Higgs events!)

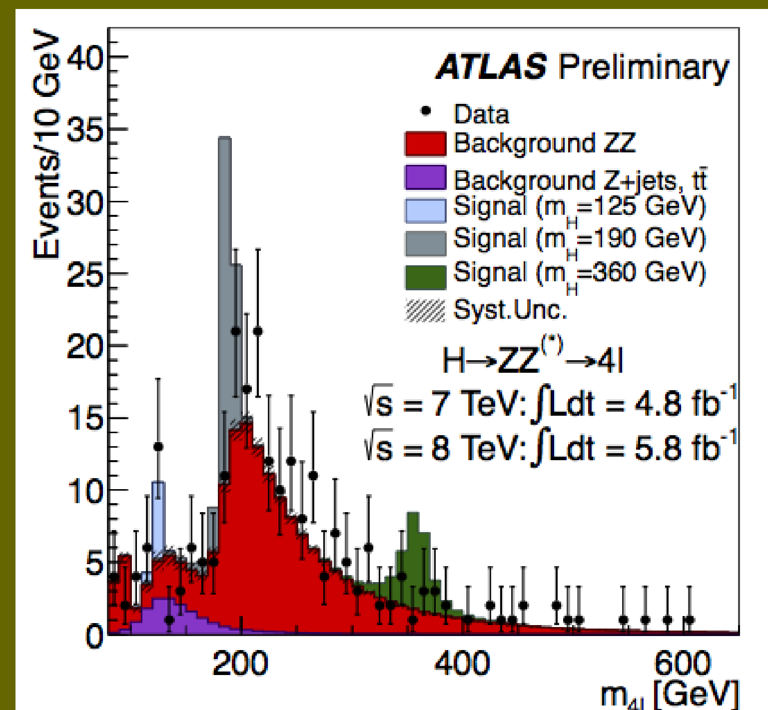


Current results of the ATLAS Higgs hunt

The high mass resolution channels for the Higgs decay are:
H → γγ et H → ZZ$^{(*)}$ → 4l (4e, 4μ, 2e2μ)   2011 + 2012 datat analysed by ATLAS



H→ γγ:
Not too low rate (σ x BR ~ 50 fb mH ~ 126 GeV)
•good mass resolution
•simple topology: two high-pT isolated photons
ET (γ1, γ2) > 40, 30 GeV
Main background: γγ continuum (irreducible, smooth)



H→ 4l:
Tiny rate (σ x BR ~ 2.5 fb at 126 GeV), BUT
•mass can be fully reconstructed -> events should cluster in a (narrow) peak and
•pure Signal/Background ~ 1
Signature 4 leptons: pT1,2,3,4 > 20,15,10,7-6 (e-μ) GeV
Main backgrounds: ZZ(*) (irreducible)

Other low-mass channels: H-> WW(*)-> lνlν, H->ττ, Z*->W/ZH->W/Z bb
Only 2011 data analysed by ATLAS so far

Mass resolution

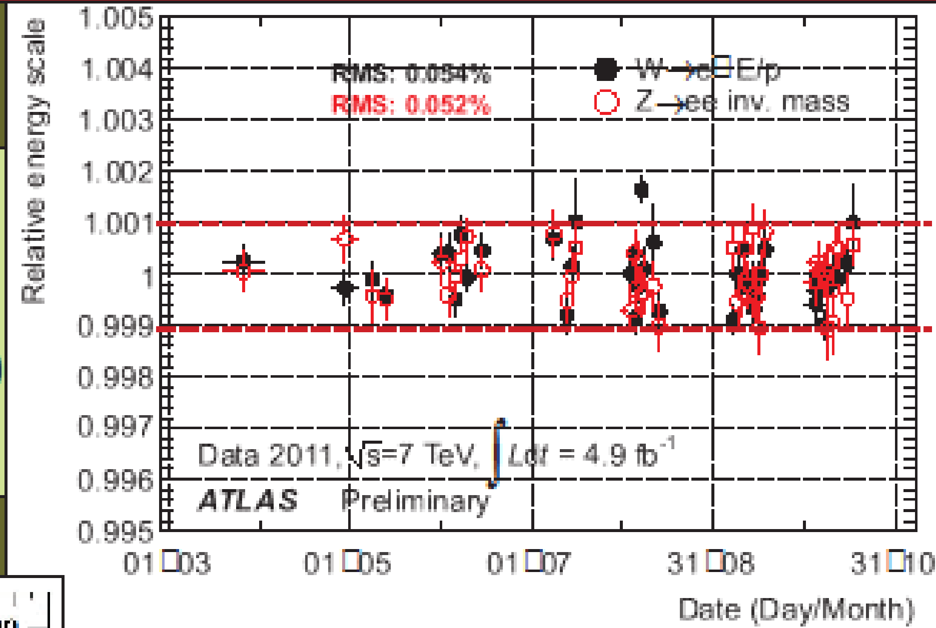
H -> γγ

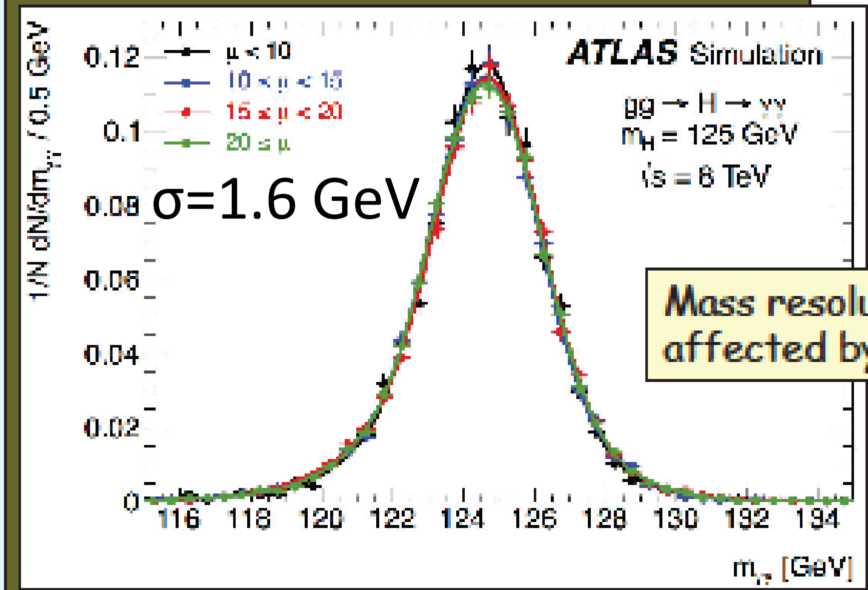
$m^2_{\gamma\gamma} = 2 E_1 E_2 (1-\cos\alpha)$

Present understanding of calorimeter E response (from Z, J/ψ → ee, W→ eν data and MC):

- E-scale at m_Z known to ~ 0.3%
- Linearity better than 1% (few-100 GeV)
- "Uniformity" (constant term of resolution): ~ 1% (2.5% for 1.37<|η|<1.8)

Stability of EM calorimeter response vs time (and pile-up) during full 2011 run better than 0.1%





Electron scale transported to photons using MC (small systematics from material effects)

Mass resolution not affected by pile-up

Mass resolution of inclusive sample: 1.6 GeV
Fraction of events in ±2σ: ~90%

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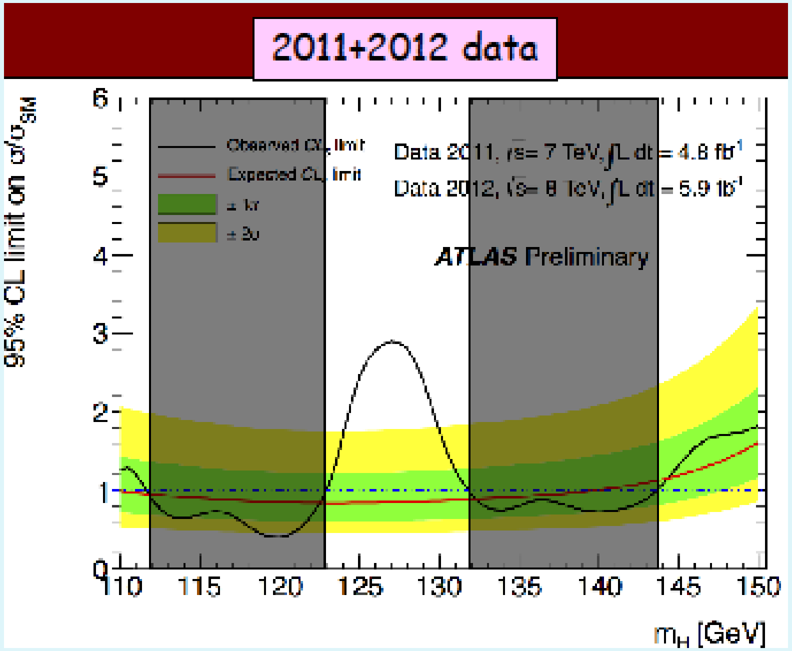
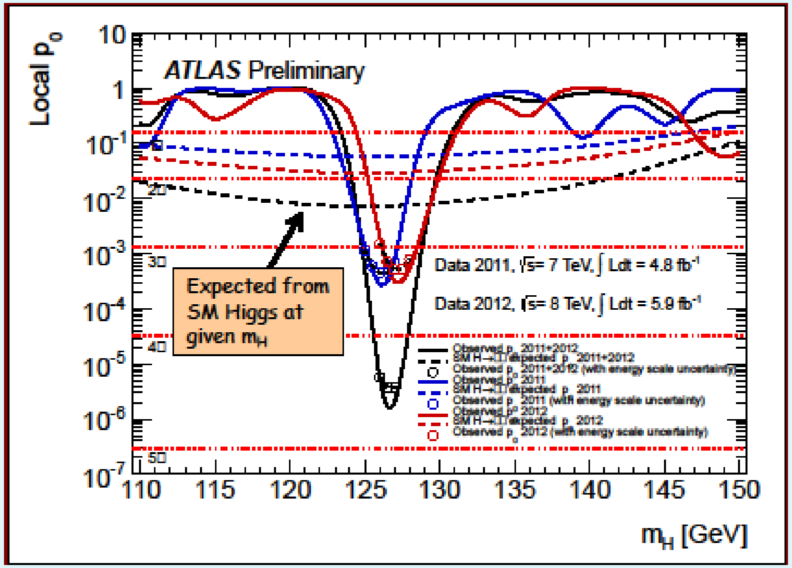
Results of H → γγ search in ATLAS



The vertical axis shows how much more data would be needed to exclude at 95% CL a Higgs signal with the Standard Model cross-section and of a mass as given on the horizontal axis. If the curve is below 1, the SM Higgs is excluded at 95% CL for that mass. The red curve shows the expectation and the black curve the data.



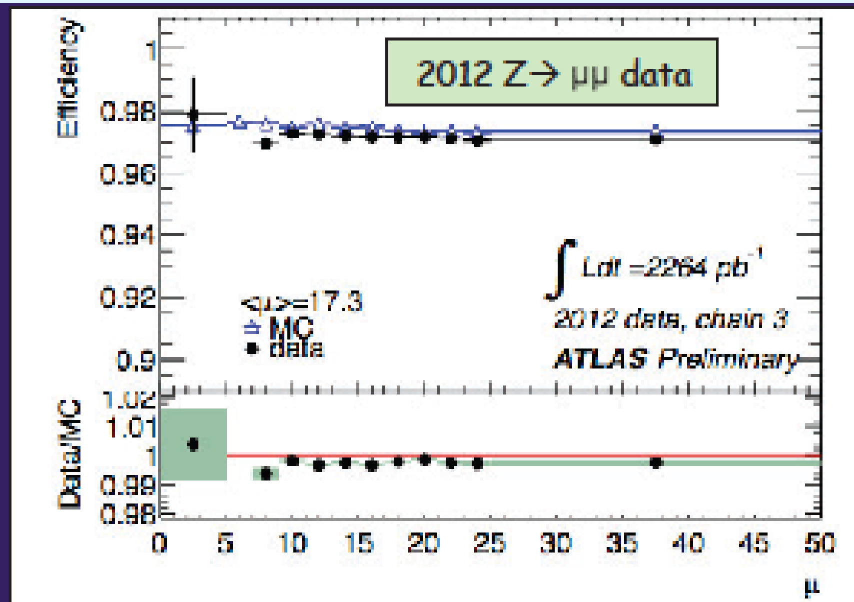
The vertical axis shows the probability for that the observed excess is a fluctuation in the data in the absence of a Higgs Signal. The hatched lines show the expectation of an excess in the presence of a Higgs signal and the full lines the data.

Muons reconstructed down to p_T = 6 GeV over |η|<2.7

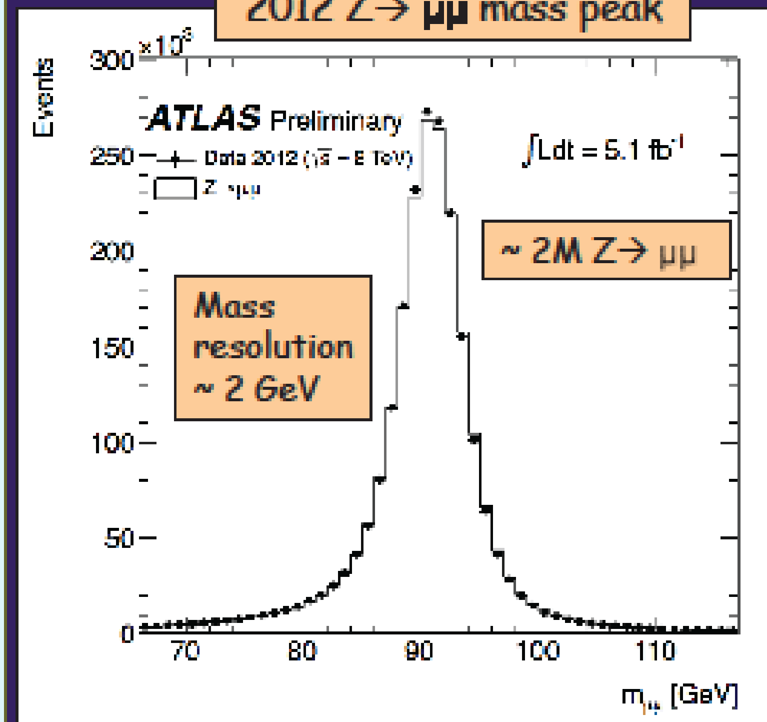
H->4μ

Reconstruction efficiency ~ 97%, ~ flat down to p_T ~ 6 GeV and over |η|~2.7

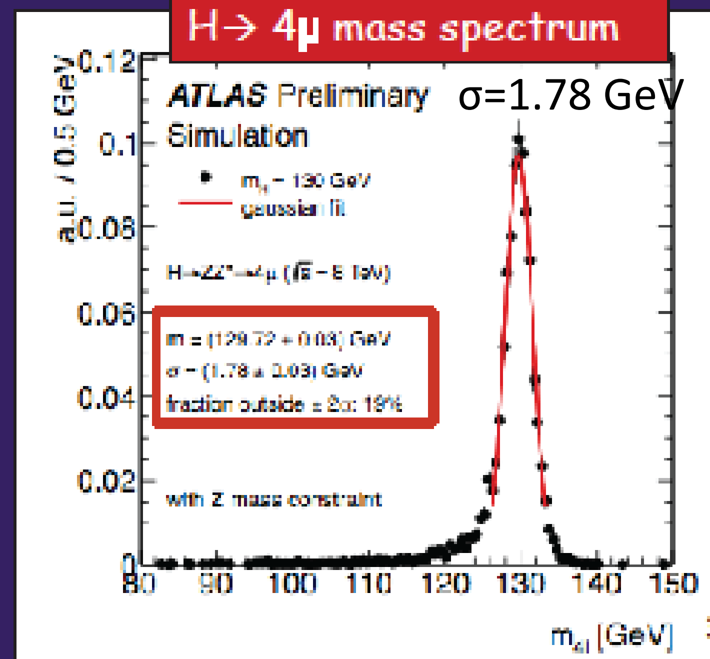
Total acceptance x efficiency for H→ 4μ: ~ 40% (+45% gain)



2012 Z→ μμ mass peak

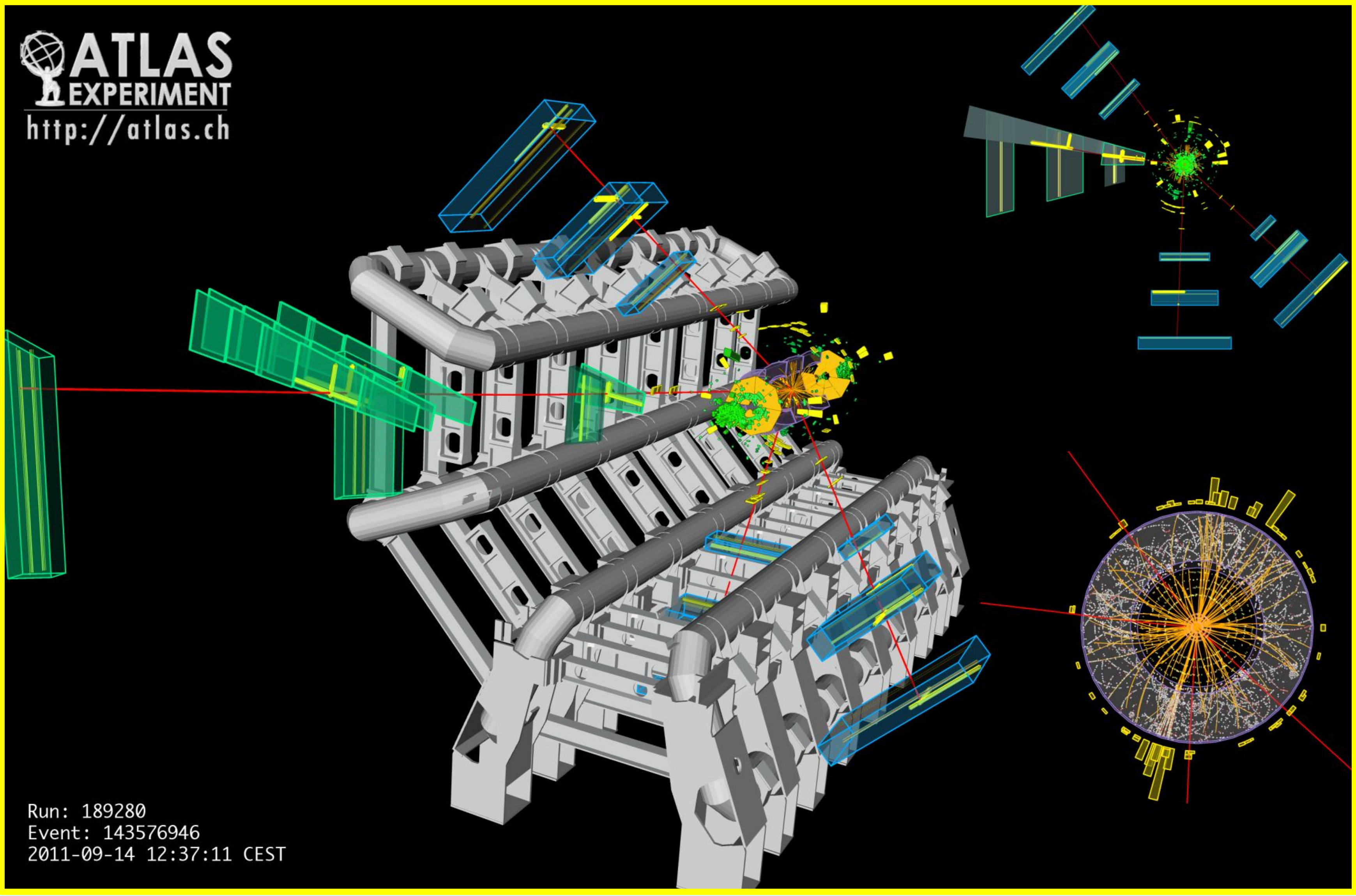


H→ 4μ mass spectrum



4μ candidate with $m_{4\mu}$= 124.6 GeV

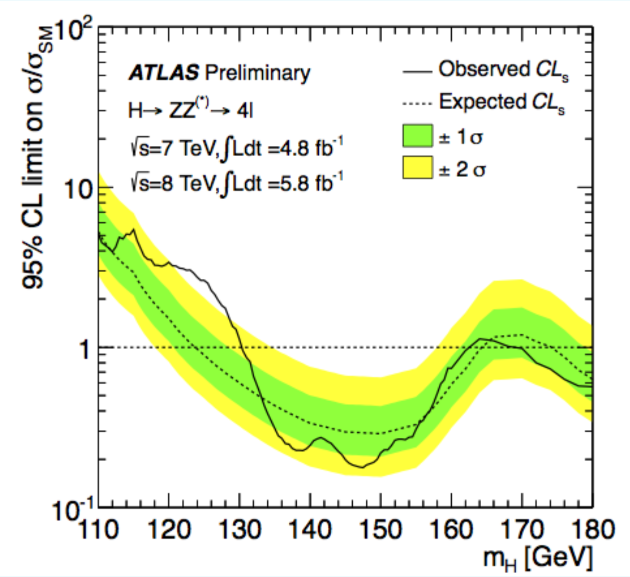
p_T (μ^-, μ^+, μ^+, μ^-)= 61.2, 33.1, 17.8, 11.6 GeV
m_{12}= 89.7 GeV, m_{34}= 24.6 GeV



Results of H →ZZ->4l search in ATLAS

2011-2012 data

The vertical axis shows how much more data would be needed to exclude at 95% CL a Higgs signal with the Standard Model cross-section and of a mass as given on the horizontal axis. If the curve is below 1, the SM Higgs is excluded at 95% CL for that mass. The red curve shows the expectation and the black curve the data.



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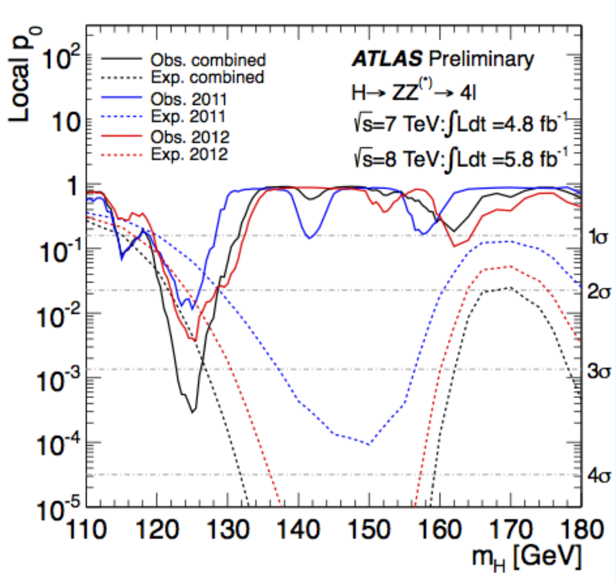
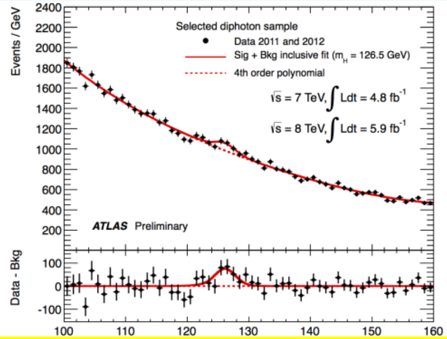
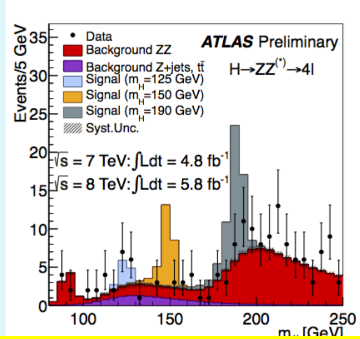
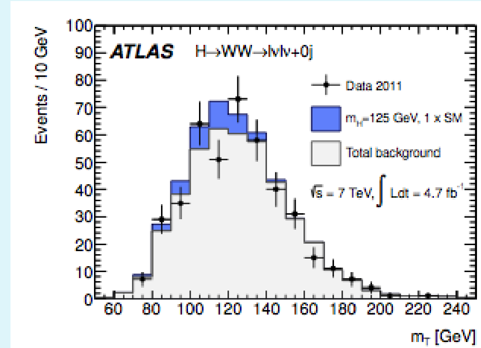
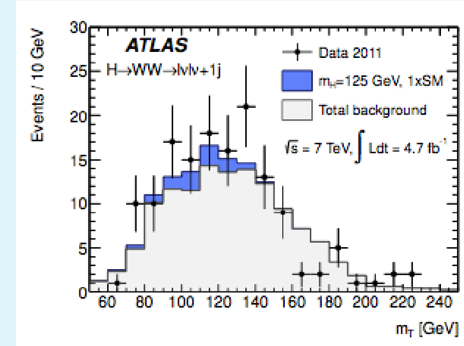






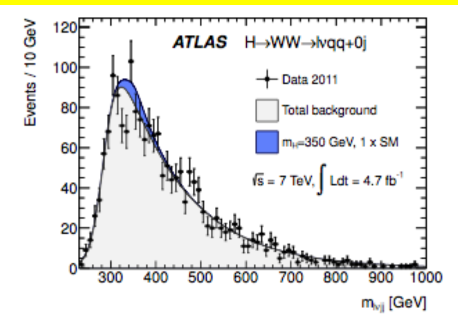


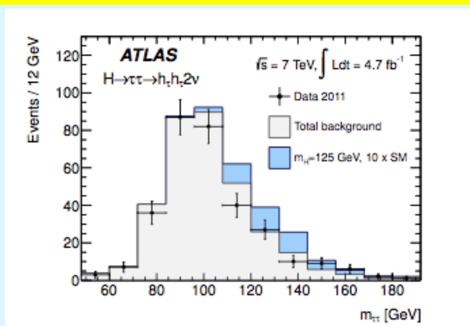


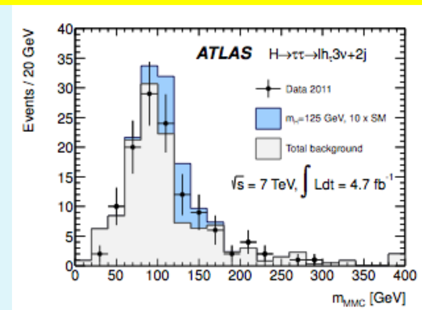
Combining all 12 channels together:

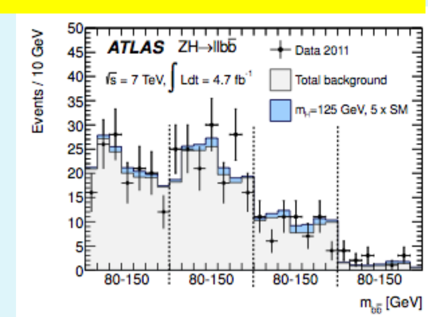
•H-> γγ, H-> 4l: full 2011 and 2012 datasets (~ 10.7 fb-1) and improved analyses

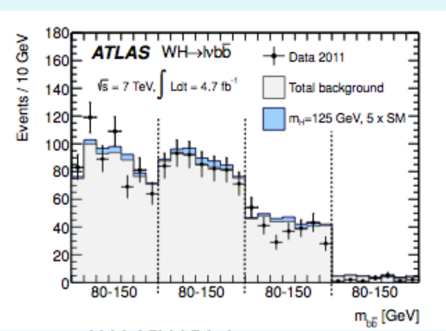
•All other channels H-> WW(*)-> lvlv, H-> WW->lvqq with 1 and 0 jet,
H-> ττ ->hh2v and hl3v +2j, ZH-> llbb, ZH-> vvbb ,WH-> lvbb,
H-> ZZ -> llqq , ZZ -> llvv, ZZ -> llbb, : full 2011 dataset (up to 4.9 fb-1)

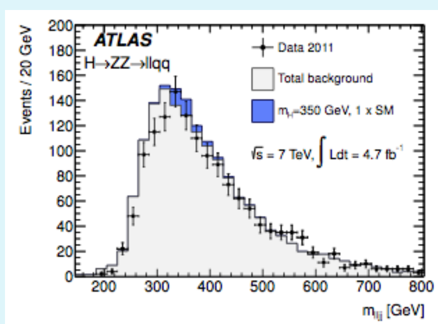


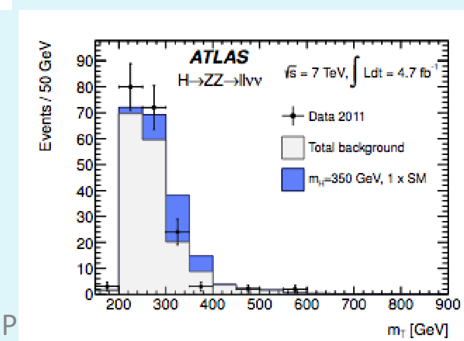


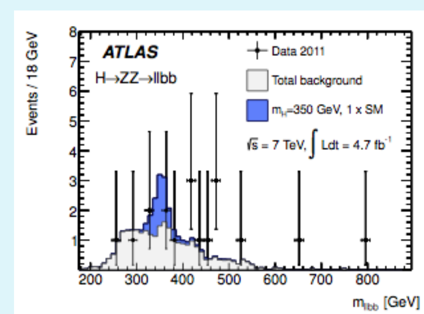








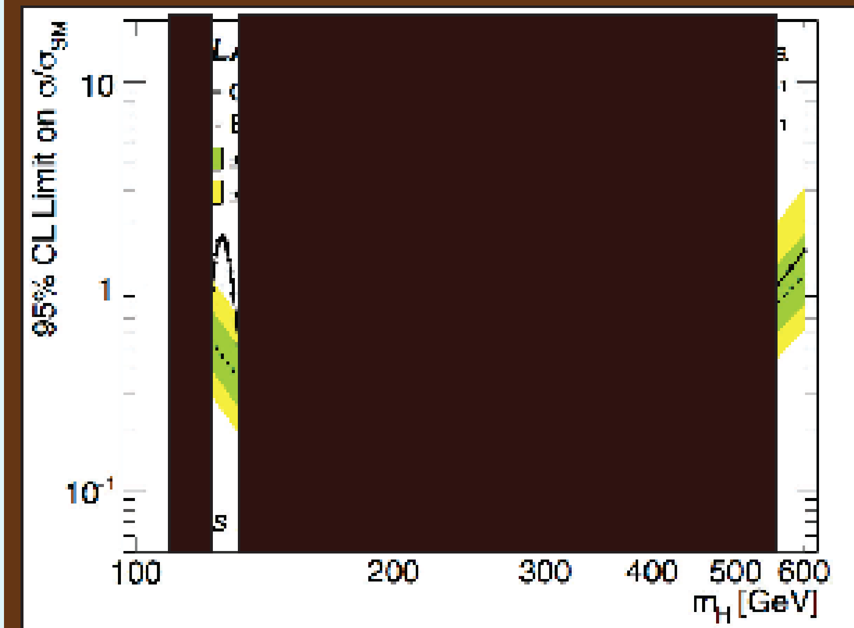


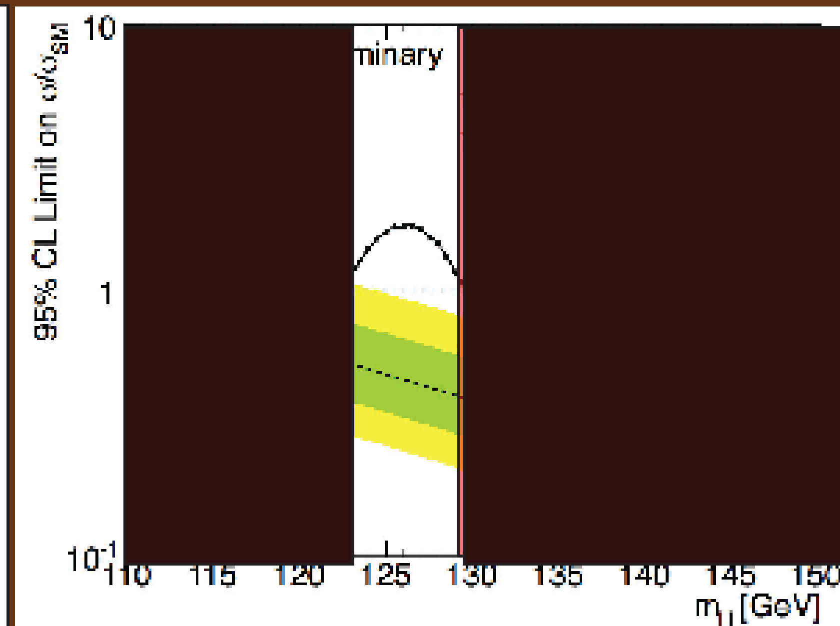


Combined results : exclusion limits

ATLAS today

Previous ATLAS results





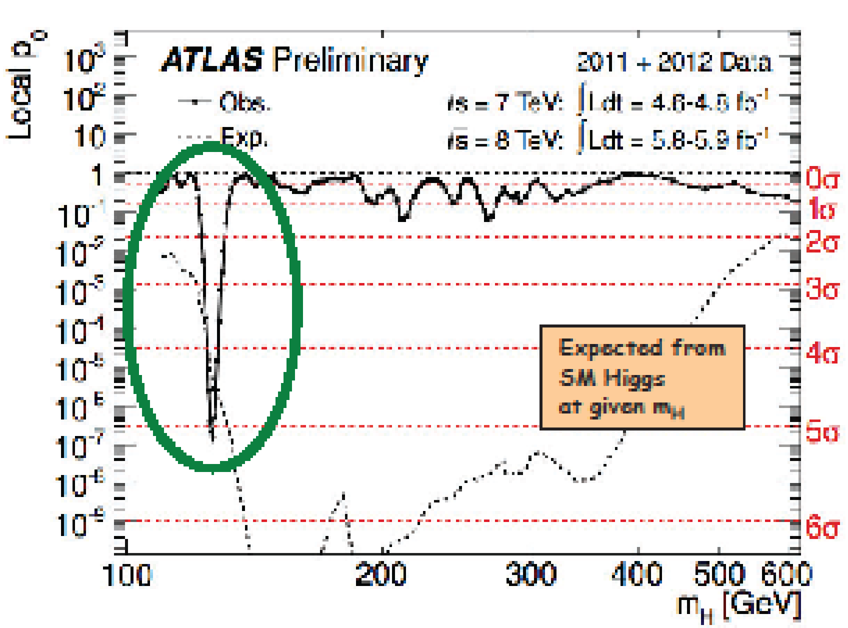
Excluded at 95% CL	110-122.6 129.7-558 GeV
Excluded at 99% CL	111.7-121.8 GeV 130.7-523 GeV

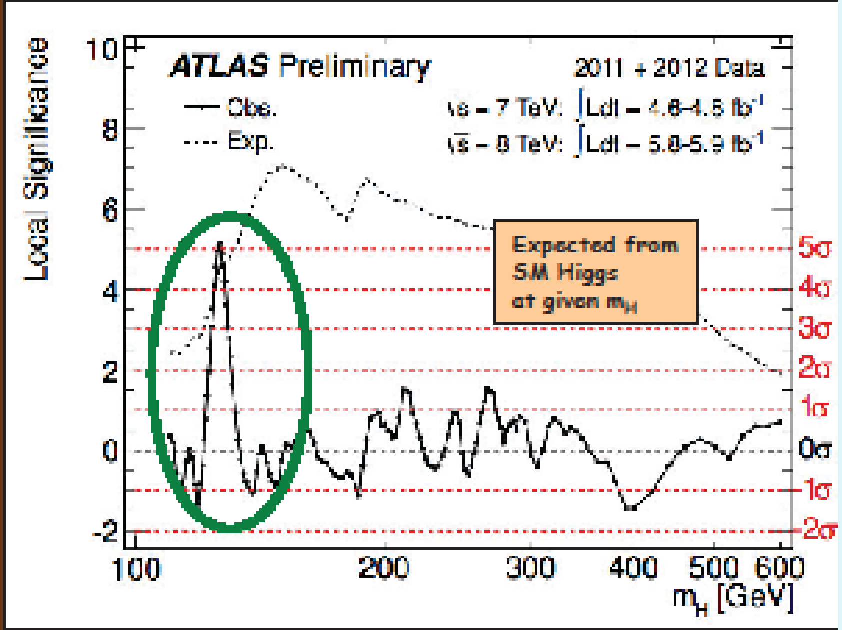
Expected at 95% CL if no signal

110-582 GeV

42

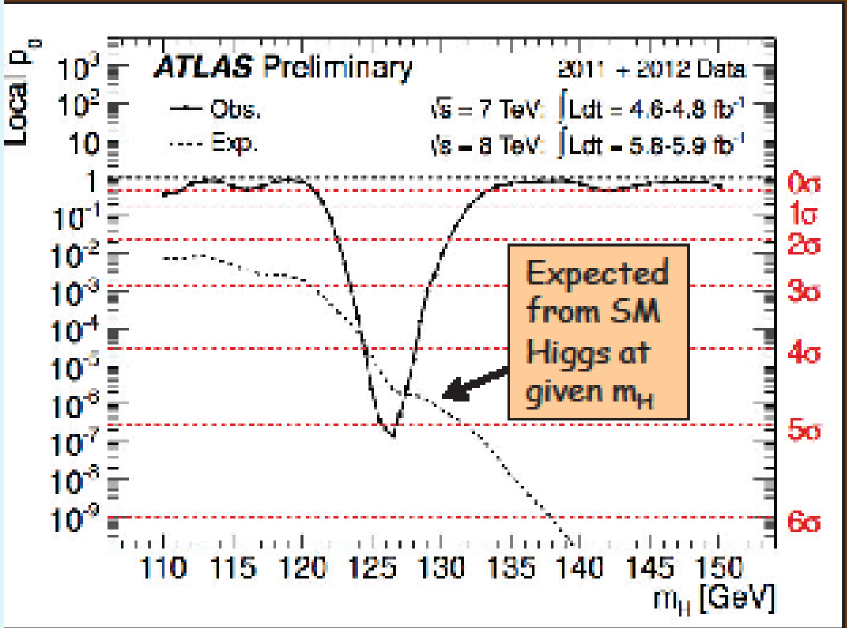
Combined results: consistency of the data with the background-only expectation and significance of the excess

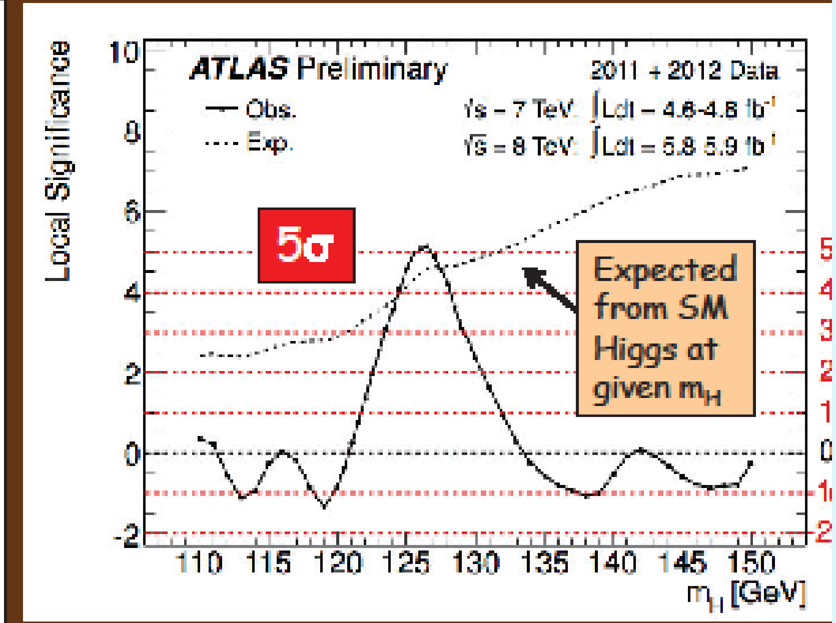




Excellent consistency (better than 2σ !) of the data with the background-only hypothesis over full mass spectrum except in one region

Combined results: the excess



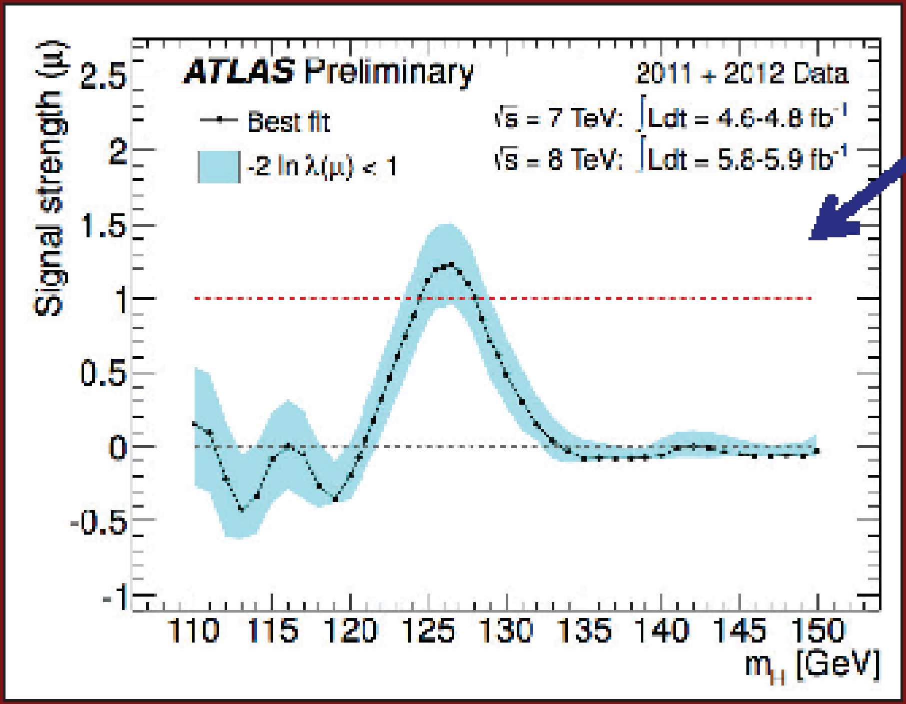


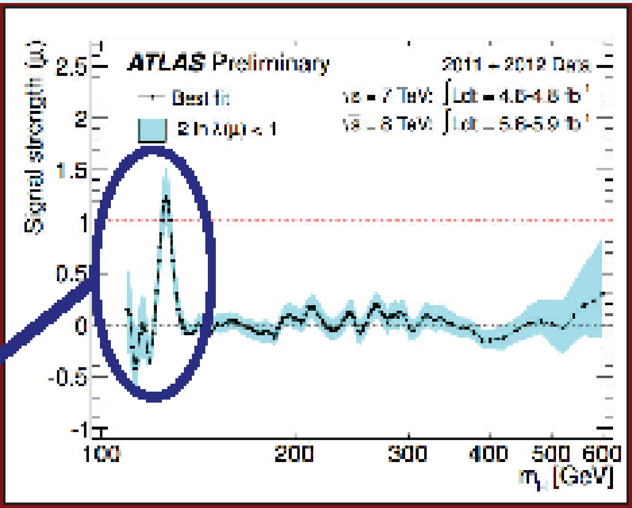
Maximum excess observed at	m_H = 126.5 GeV
Local significance (including energy-scale systematics)	5.0 σ
Probability of background up-fluctuation	3×10^{-7}
Expected from SM Higgs m_H=126.5	4.6 σ

Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)

Combined results: fitted signal strength

Normalized to SM Higgs expectation at given m_H (μ)





Best-fit value at 126.5 GeV:
$\mu = 1.2 \pm 0.3$

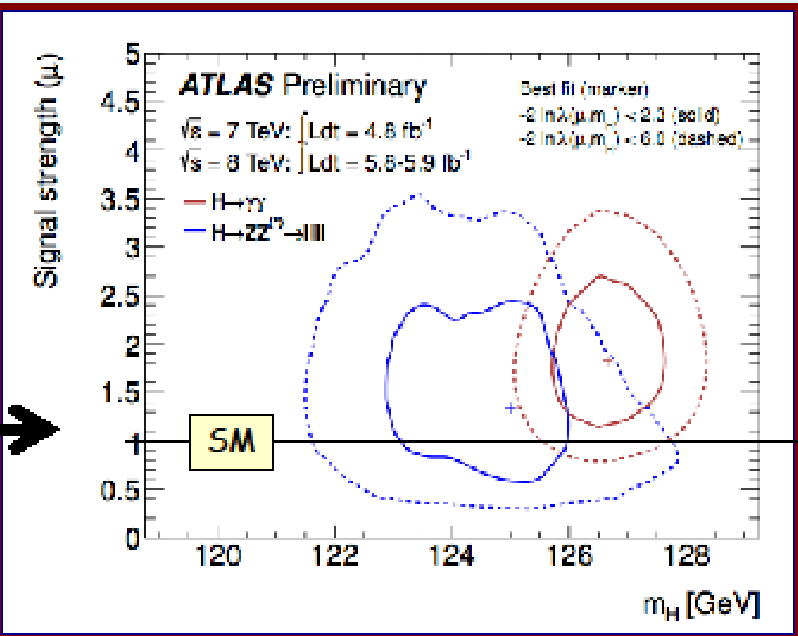
Good agreement with the expectation for a SM Higgs within the present statistical uncertainty

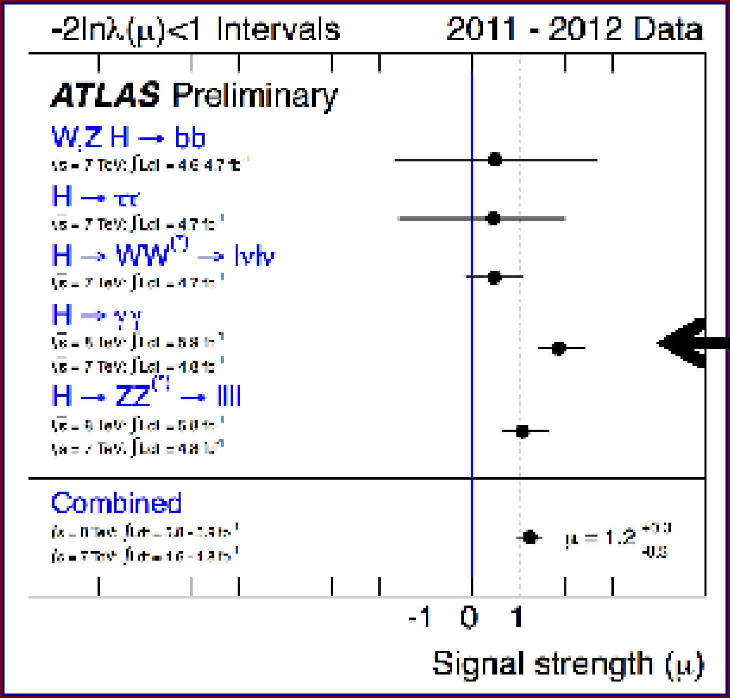
45

Combined results: consistency of the global picture

Are the 4l and γγ observations consistent ?

From 2-dim likelihood fit to signal mass and strength →curves show approximate 68% (full) and 95% (dashed) CL contours





Best-fit signal strengths, normalized to the SM expectations, for all studied channels, at m_H = 126.5 GeV,

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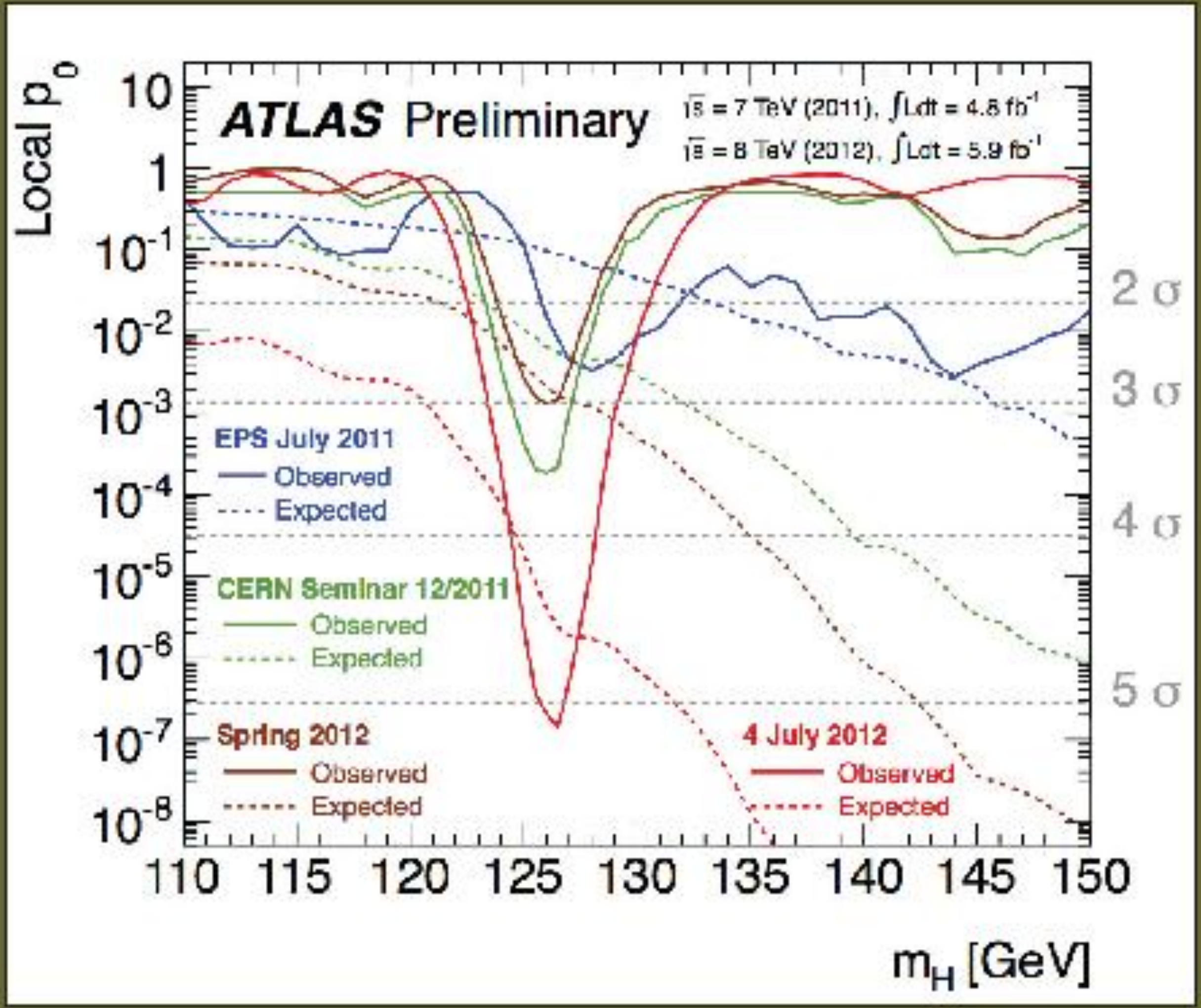
Evolution of the excess with time

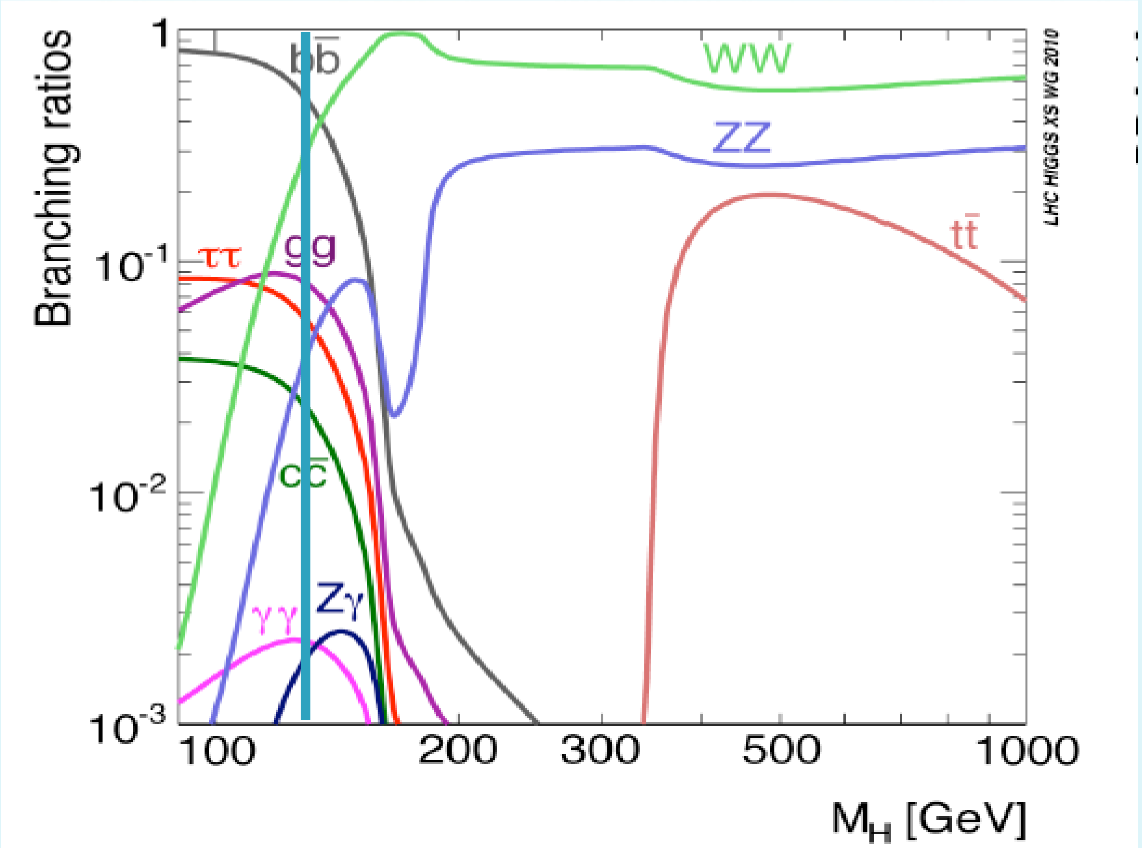


Energy-scale systematics not included

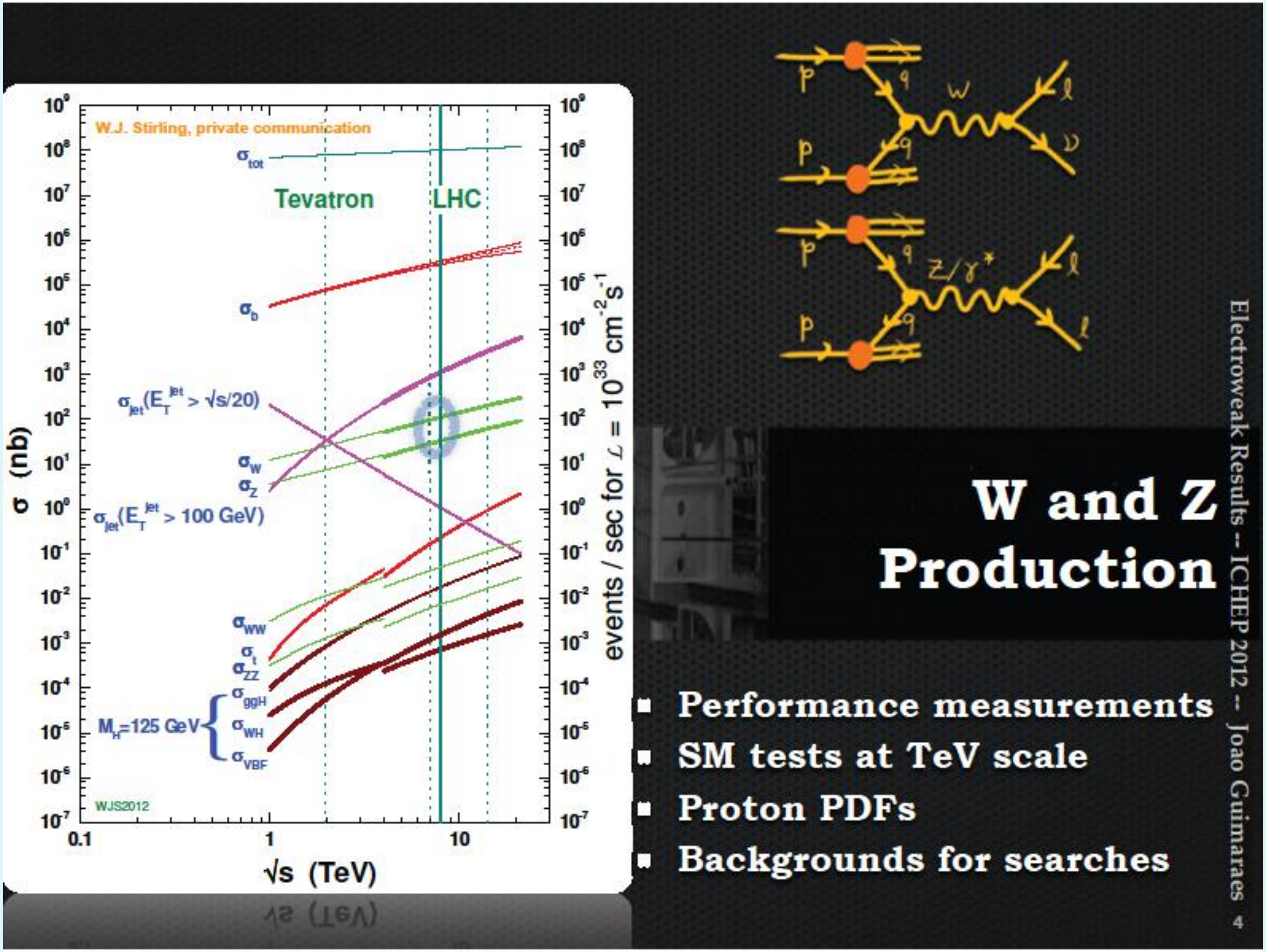
48

To now verify if it is really the Standard Model Higgs boson that has been found we need to compare the Higgs decay branching rations for different channels and compare with the predictions of the Standard Model which states that the Higgs coupling is proportional to mass.

In this sence Nature has been very kind to us by letting the Higgs candidate have mass 126 GeV since all different decay channels $b\bar{b}$, WW, gg, ττ, ZZ, $c\bar{c}$ all have a branching ratio which is above a few % (thus measurable) and the branching ratio to γγ is close to it's maximum (this channel could not have served for the discovery of a Higgs above 140 GeV)



Electroweak tests



W.J. Stirling, private communication
Tevatron
LHC
σ (nb)
events / sec for $\mathcal{L} = 10^{33}$ cm^{-2}s^{-1}
√s (TeV)
σ_{tot}
σ_b
$\sigma_{jet}(E_T^{jet} > \sqrt{s}/20)$
σ_W
σ_Z
$\sigma_{jet}(E_T^{jet} > 100$ GeV)
σ_{WW}
σ_t
σ_{ZZ}
M_H=125 GeV
σ_{ggH}
σ_{WH}
σ_{VBF}
WJS2012
W and Z Production
Performance measurements
SM tests at TeV scale
Proton PDFs
Backgrounds for searches
Electroweak Results -- ICHEP 2012 -- Joao Guimaraes
4

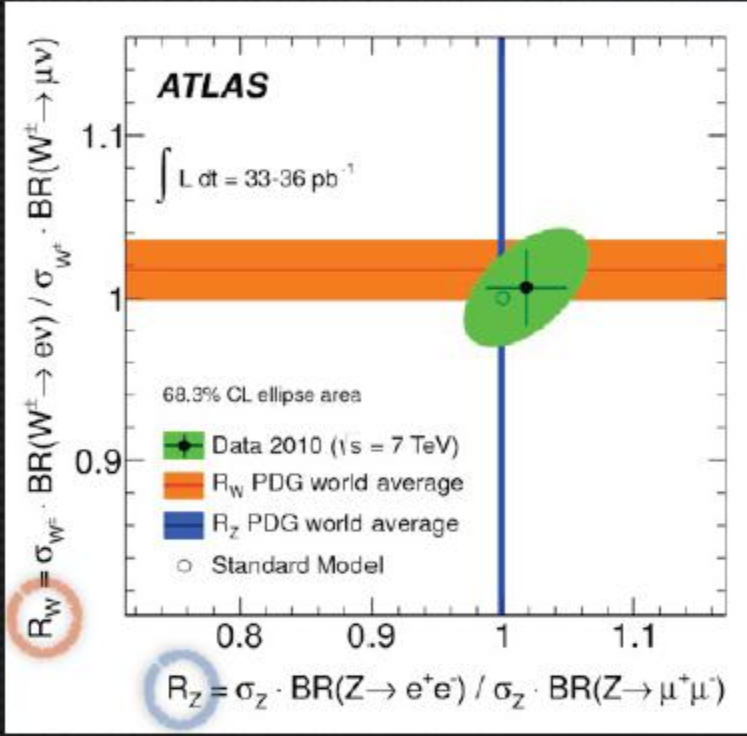
Lepton Universality

Phys. Rev. D85 (2012) 072004

$$R_W = \frac{\sigma^e_W}{\sigma^\mu_W} = \frac{Br(W \to e\nu)}{Br(W \to \mu\nu)} = 1.006 \pm 0.004\,(\text{sta}) \pm 0.006\,(\text{unc}) \pm 0.023\,(\text{cor}) = 1.006 \pm 0.024$$

$$R_Z = \frac{\sigma^e_Z}{\sigma^\mu_Z} = \frac{Br(Z \to ee)}{Br(Z \to \mu\mu)} = 1.018 \pm 0.014\,(\text{sta}) \pm 0.016\,(\text{unc}) \pm 0.028\,(\text{cor}) = 1.018 \pm 0.031$$

- **Result already close to best measurement (R_W)**
  - **PDG: 1.9%**
  - **This measurement: 2.4%**



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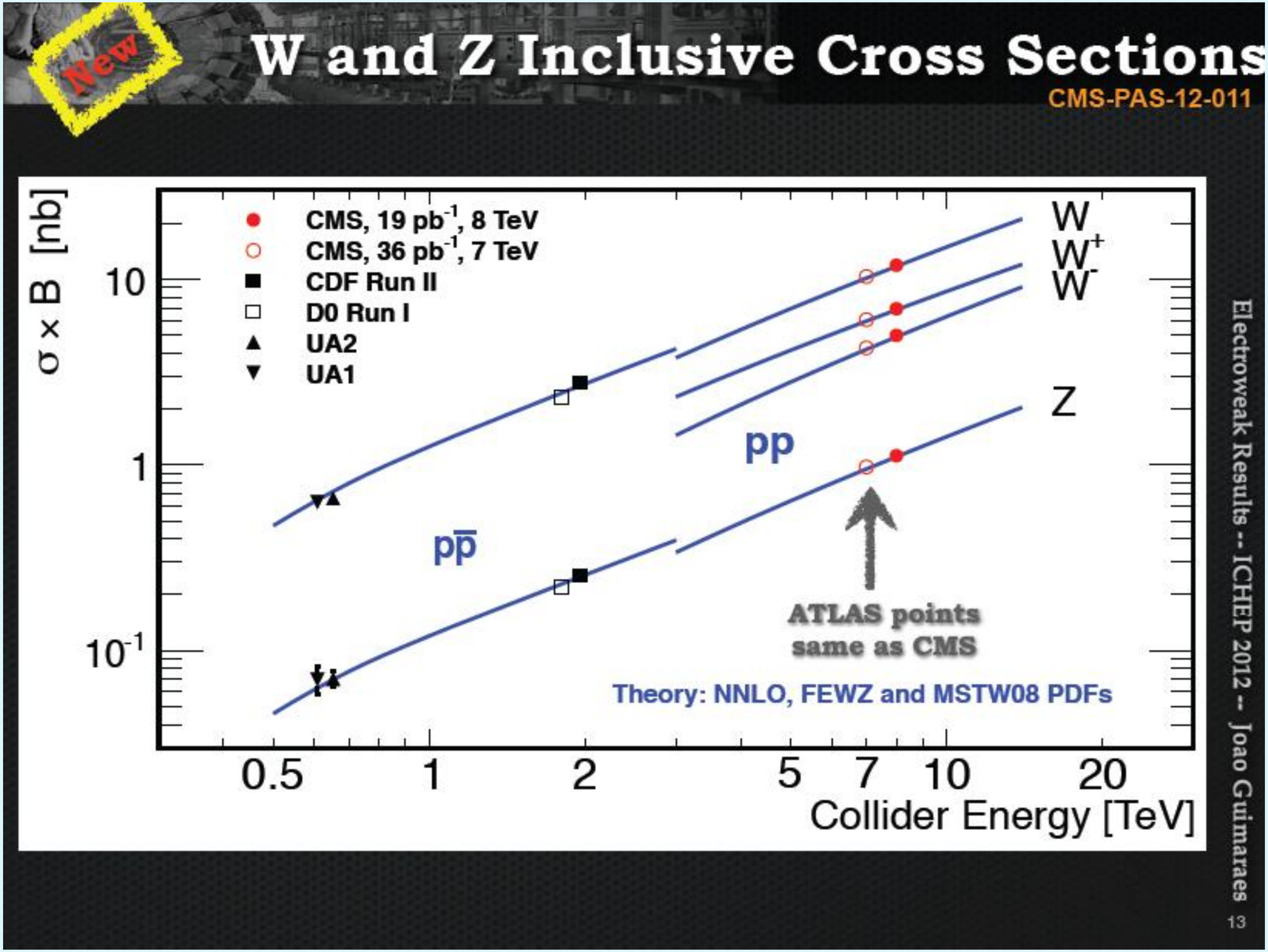
New
W and Z Inclusive Cross Sections
CMS-PAS-12-011
σ × B [nb]
10
1
10-1
CMS, 19 pb-1, 8 TeV
CMS, 36 pb-1, 7 TeV
CDF Run II
D0 Run I
UA2
UA1
W
W+
W-
Z
pp
pp̄
ATLAS points
same as CMS
Theory: NNLO, FEWZ and MSTW08 PDFs
0.5
1
2
5
7
10
20
Collider Energy [TeV]
Electroweak Results -- ICHEP 2012 -- Joao Guimaraes
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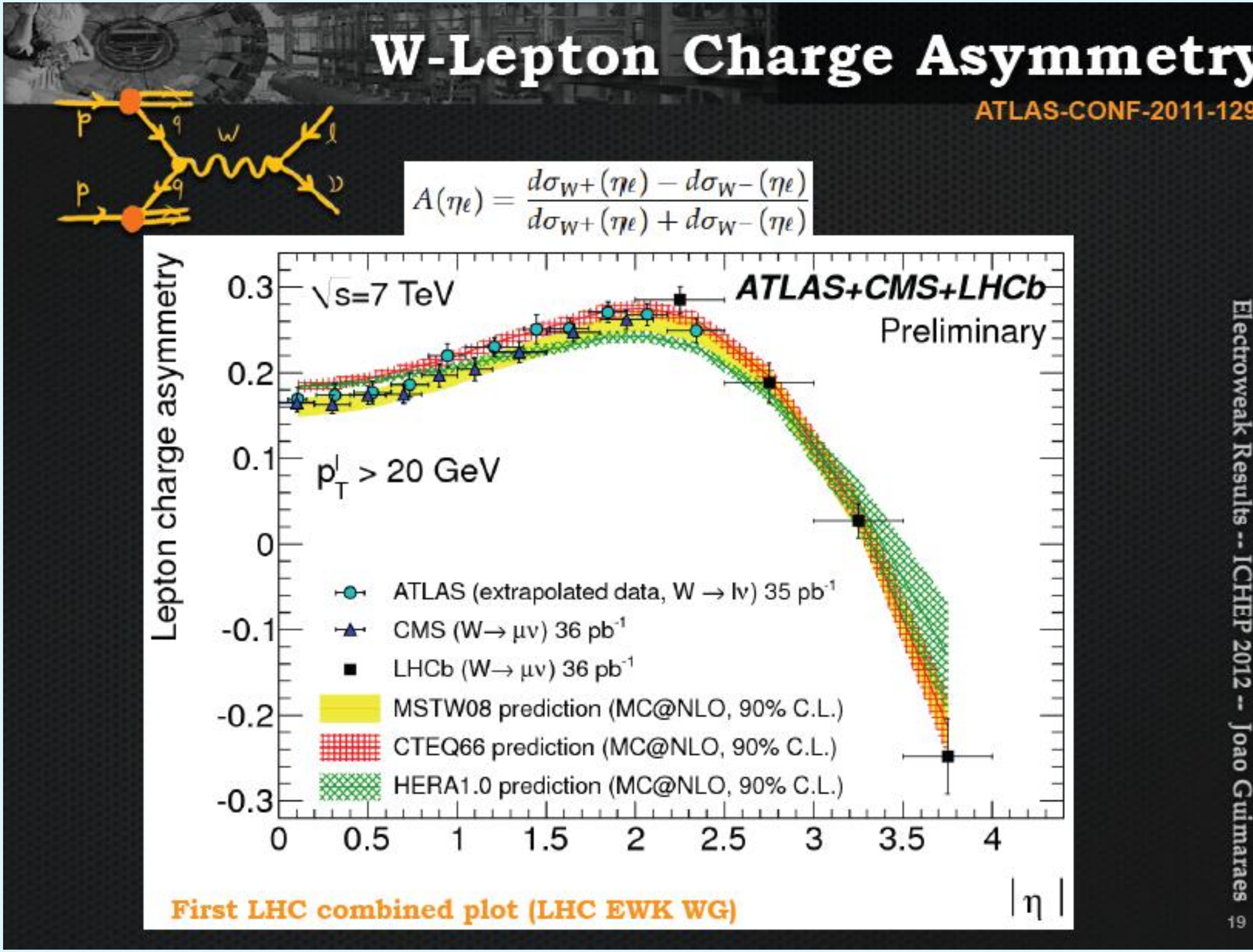
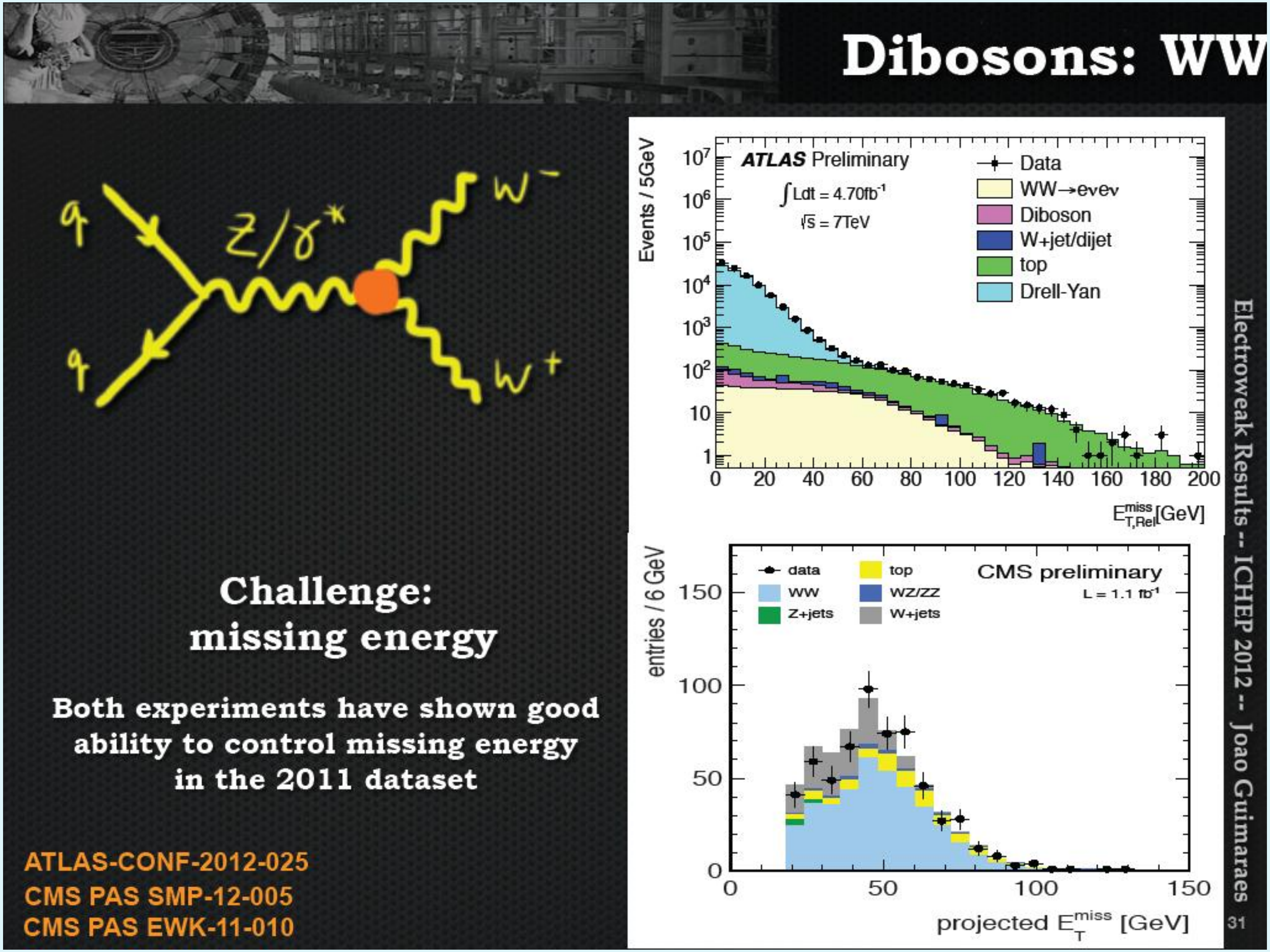

W-Lepton Charge Asymmetry
ATLAS-CONF-2011-129
p
p
q
q
W
l
ν
$A(\eta_\ell) = \frac{d\sigma_{W^+}(\eta_\ell) - d\sigma_{W^-}(\eta_\ell)}{d\sigma_{W^+}(\eta_\ell) + d\sigma_{W^-}(\eta_\ell)}$
Lepton charge asymmetry
$\sqrt{s}$=7 TeV
ATLAS+CMS+LHCb
Preliminary
$p_T^l > 20$ GeV
ATLAS (extrapolated data, $W \to l\nu$) 35 pb^{-1}
CMS ($W \to \mu\nu$) 36 pb^{-1}
LHCb ($W \to \mu\nu$) 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.)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
0.5
1
1.5
2
2.5
3
3.5
4
$|\eta|$
First LHC combined plot (LHC EWK WG)
Electroweak Results -- ICHEP 2012 -- Joao Guimaraes
19



Dibosons: WW
q
q
Z/γ*
W-
W+
ATLAS Preliminary
∫Ldt = 4.70fb-1
√s = 7TeV
Data
WW→eνeν
Diboson
W+jet/dijet
top
Drell-Yan
Events / 5GeV
E T,Rel miss [GeV]
CMS preliminary
L = 1.1 fb-1
data
WW
Z+jets
top
WZ/ZZ
W+jets
entries / 6 GeV
projected E T miss [GeV]
Challenge:
missing energy
Both experiments have shown good
ability to control missing energy
in the 2011 dataset
ATLAS-CONF-2012-025
CMS PAS SMP-12-005
CMS PAS EWK-11-010
Electroweak Results -- ICHEP 2012 -- Joao Guimaraes
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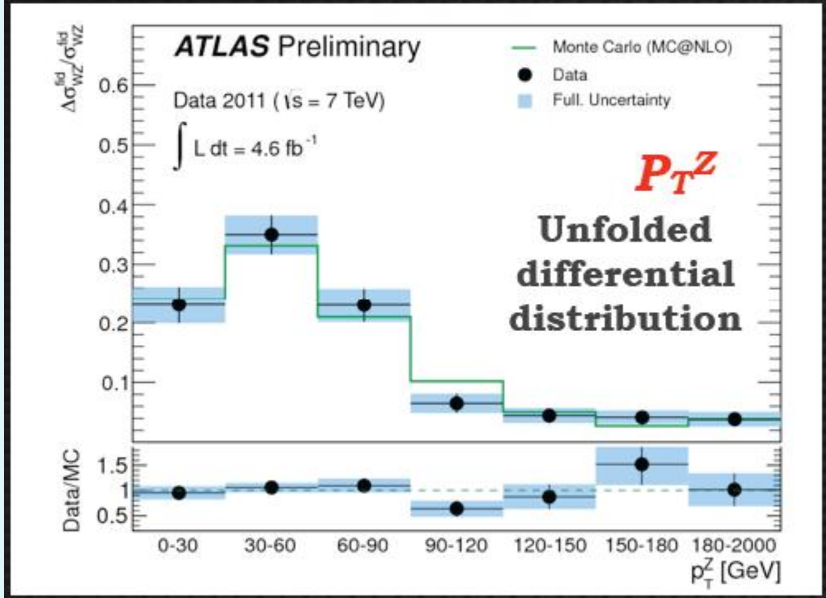
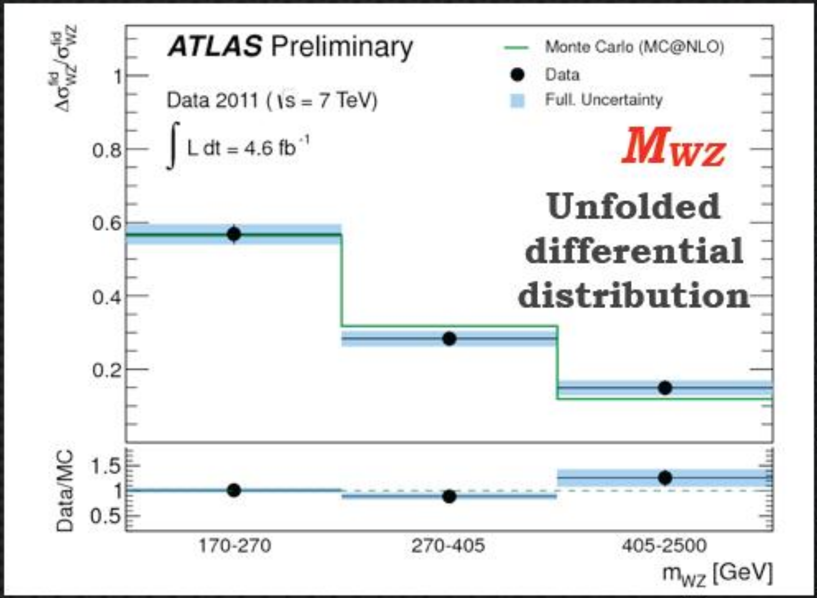
Dibosons: WZ @ 7 TeV

New





WZ	$N_{observed}$	N_{bkg}	$\sigma_{measured}$ (pb)	σ_{NLO} (pb)
ATLAS	317	68 ± 8	$19.0^{+1.4}_{-1.3} \pm 0.8 \pm 0.4$	$17.6^{+1.1}_{-1.0}$
CMS	75 (1.1 fb^{-1})	~9.1	17.0 ± 2.4 ± 1.1 ± 1.0	17.5 ± 0.6

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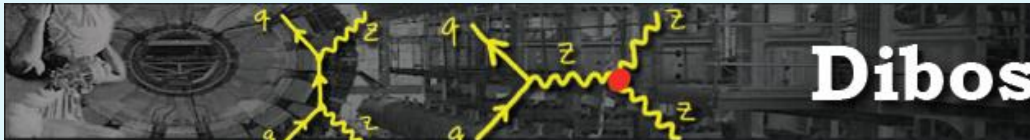
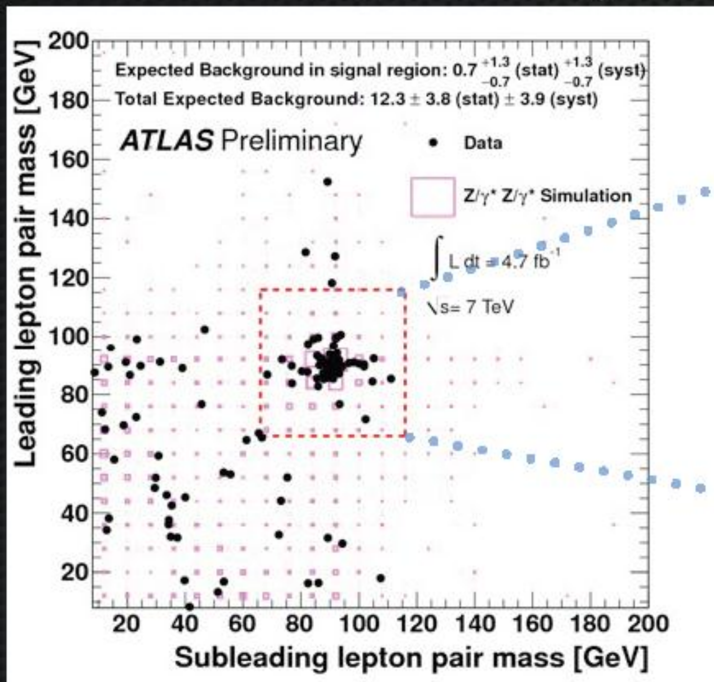


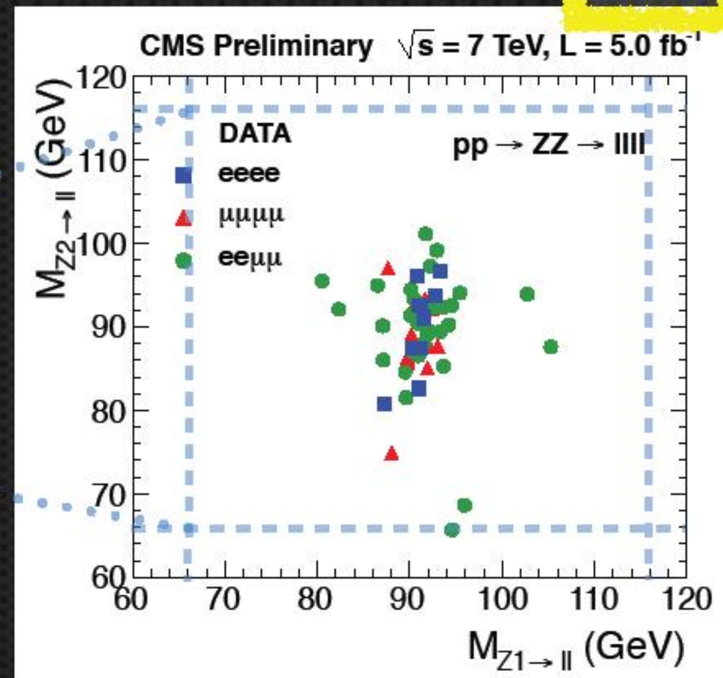
Dibosons: ZZ @ 7 TeV

ZZ → 4 leptons (eeee, μμμμ, eeμμ)

$\sqrt{s} = 7$ TeV

New





$66 < M_{Z1} < 116$ GeV
$66 < M_{Z2} < 116$ GeV

$60 < M_{Z1} < 120$ GeV
$60 < M_{Z2} < 120$ GeV

ATLAS-CONF-2012-027

CMS PAPER SMP-12-007

Electroweak Results -- ICHEP 2012 -- Joao Guimaraes

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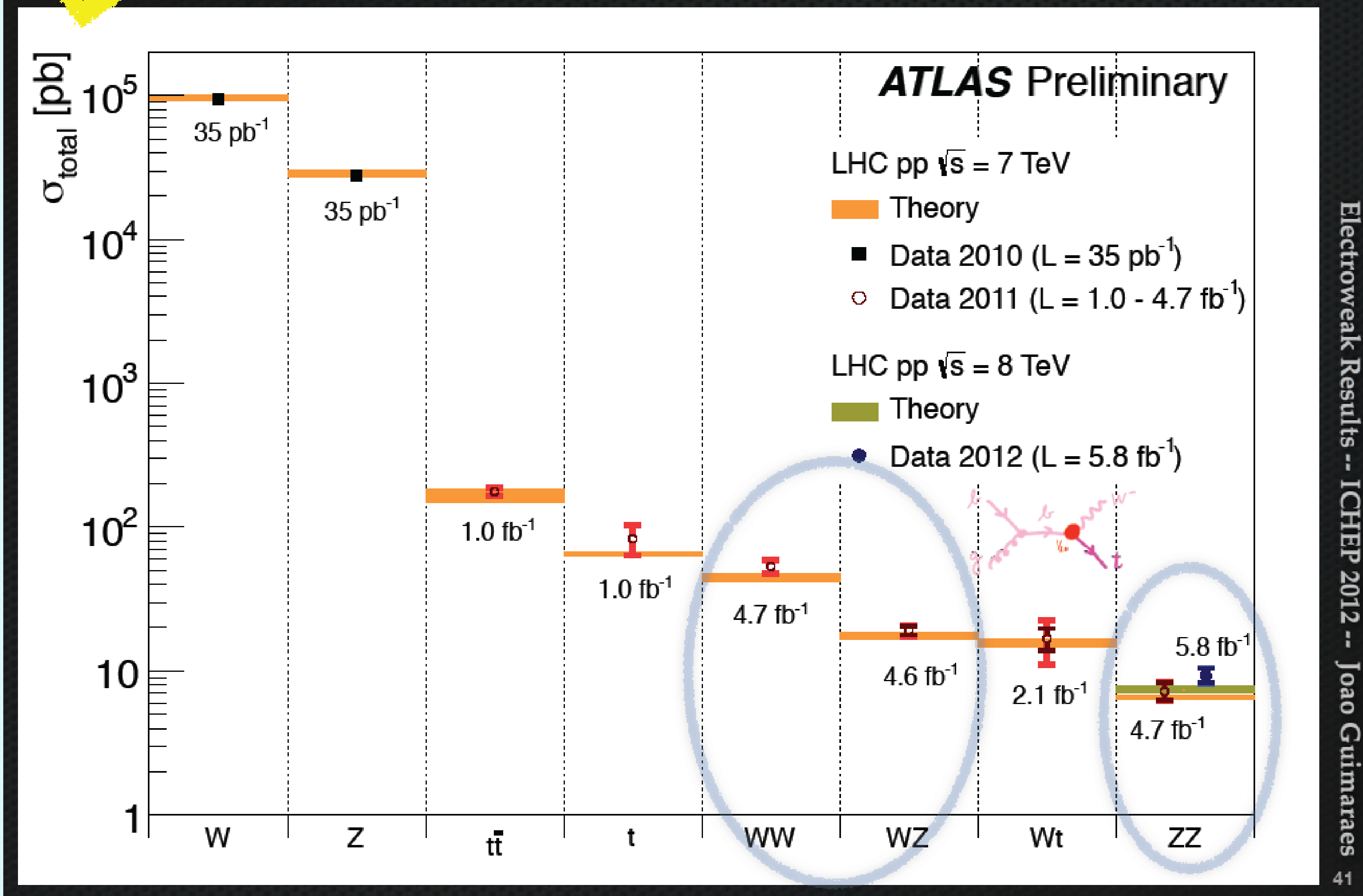
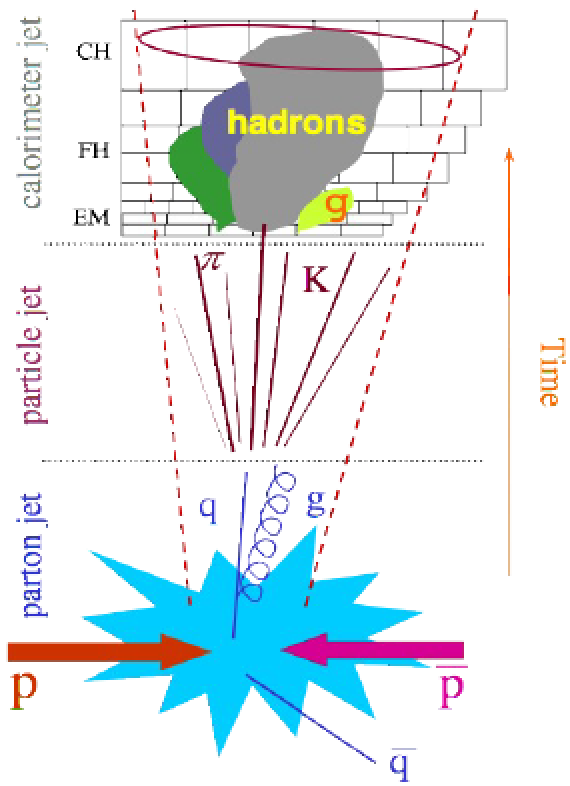
Production cross sections in ATLAS

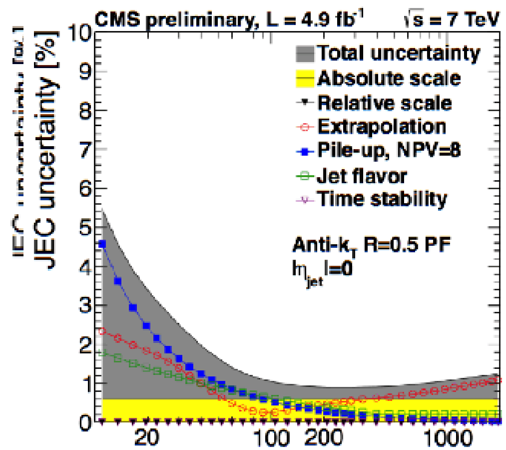


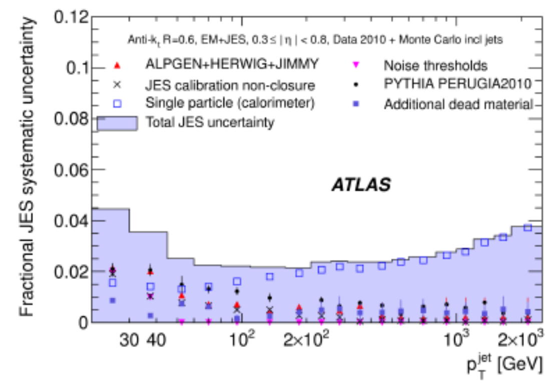
Jets

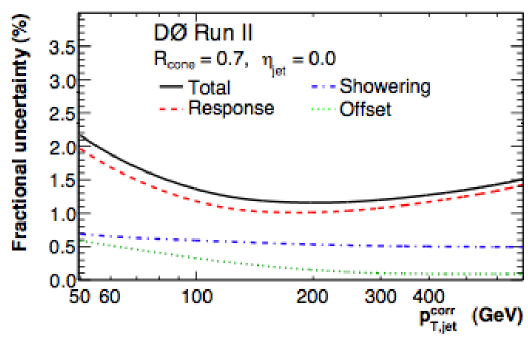
Quark and gluon energy scale = Jet energy scale

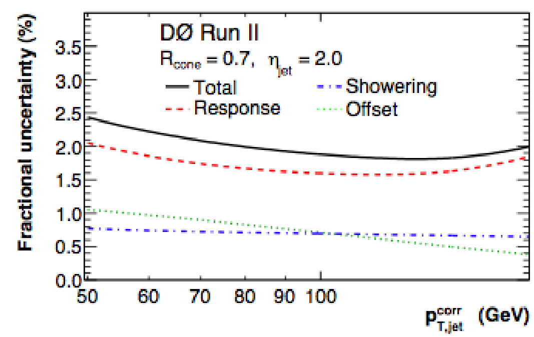
- Data and Theory are corrected to the particle level: very challenging experimental issue, especially JES
- Getting precise JES results takes time, but LHC making good progress by achieving Tevatron level of ~ 1-2%









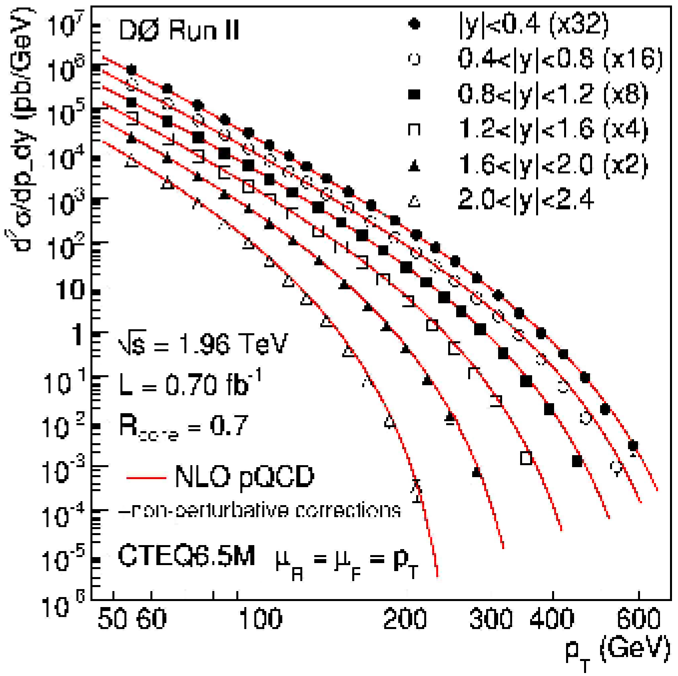


5

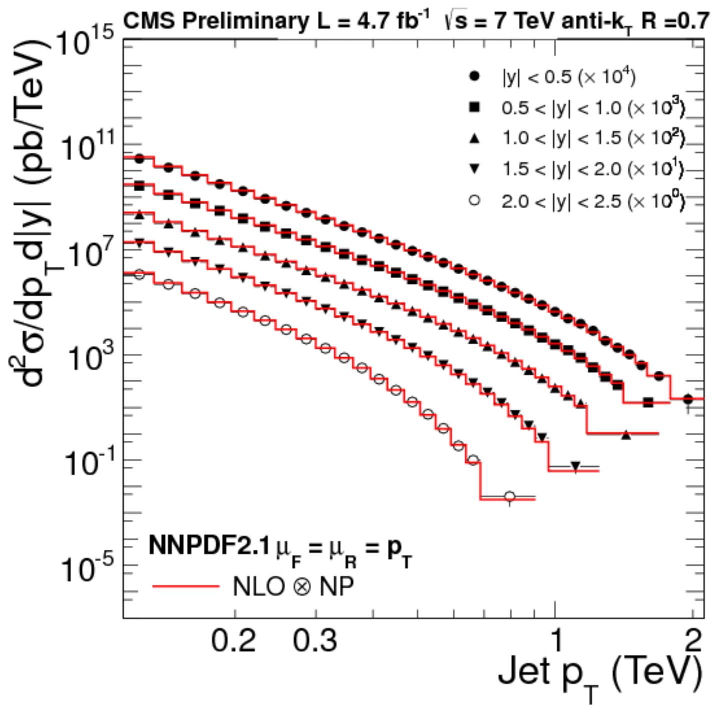
Inclusive jet production

- Inclusive is one of the most elementary measurements at hadron colliders.
- Inclusive jet cross sections at Tevatron/LHC test pQCD over 8-9 orders of magnitude up to 2 TeV
- Primary and powerful source of PDF constraint!
- LHC experiments are covering larger phase space in jet pT and |y| than Tevatron (probe down to $x \approx 0.5 \times 10^{-3}$, well studied earlier by DIS) but still have less sensitivity at high x.

Tevatron



LHC @ 7 TeV (2011 data)



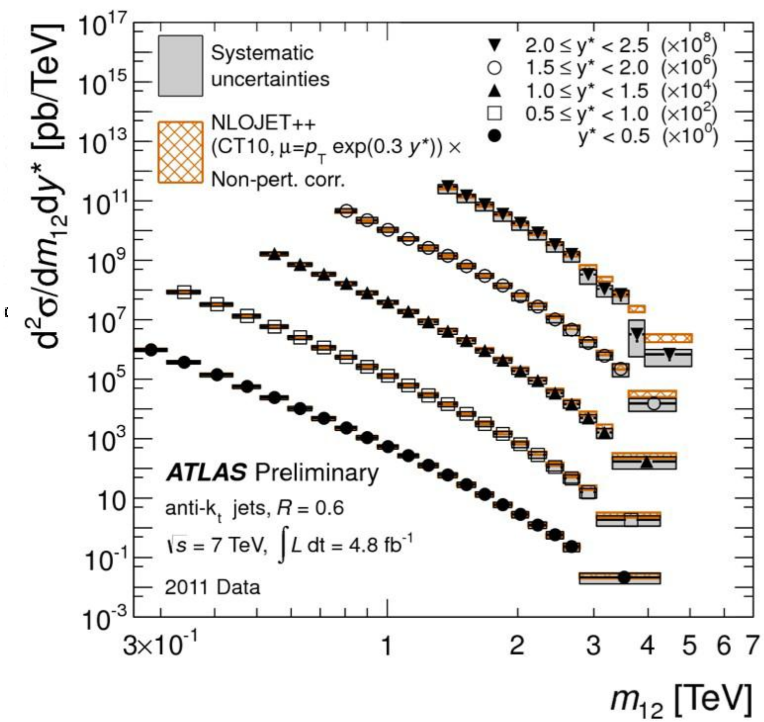
6

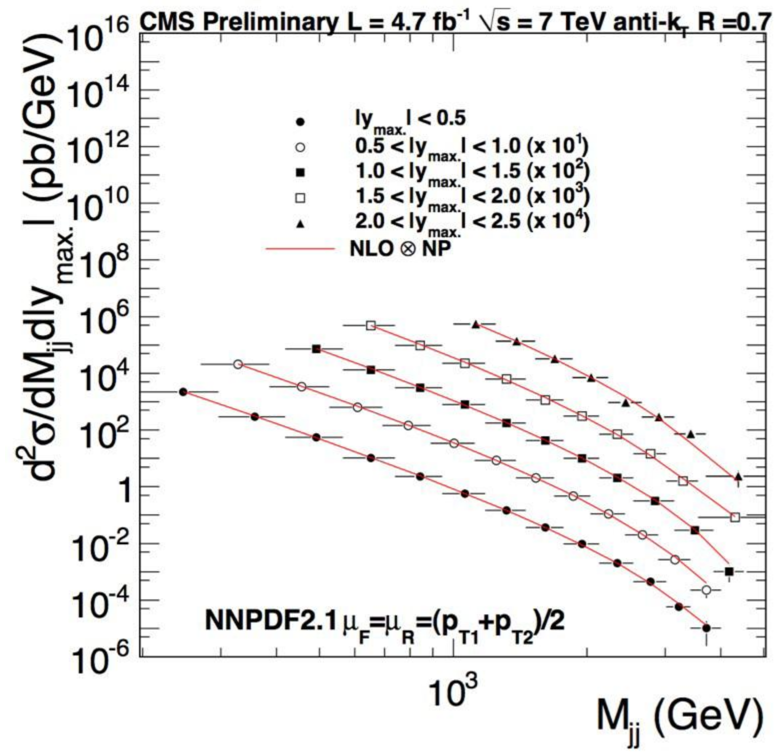
Dijet mass

With ~5/fb per experiment of 2011 data, jet physics extended to the TeV range
Dijet mass leads the way in highest energy reach, with highest masses ≥4 TeV
Excellent confirmation of perturbative QCD up to the very highest scales!

LHC @ 7 TeV

CMS: CMS PAS QCD-11-004
Atlas: arXiv:1112.6297



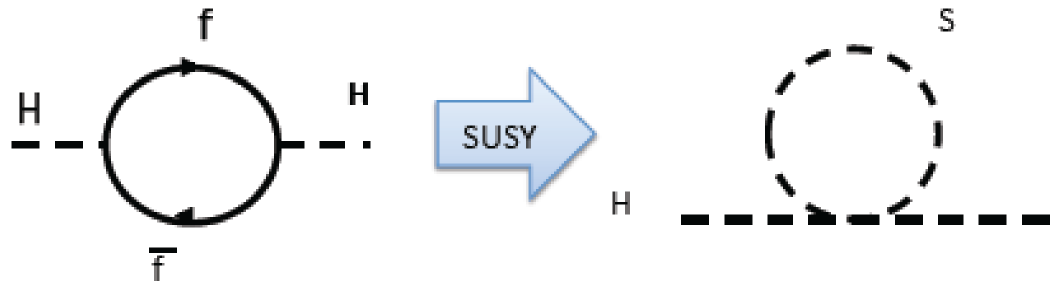


7

Supersymmetry

Why believe in SUSY?

- Two big reasons:
- Dark matter – strong evidence from astrophysics – WIMP miracle fits with SUSY
- Light Higgs – need new physics to stabilise mass



$$\Delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}\left[-2\Lambda_{UV}^2 + 6m_f^2 \ln(\Lambda_{UV}/m_f) + \ldots\right]$$

Need UV cut-off to get finite mass

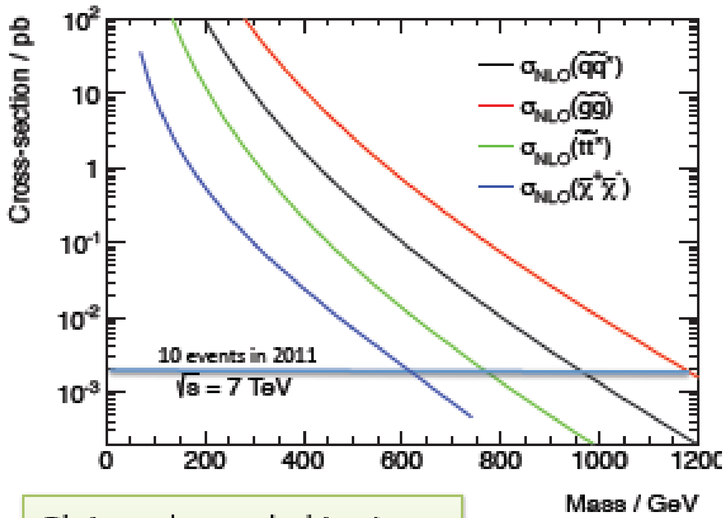
$$\Delta m_H^2 = \frac{\lambda_s}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_s^2 \ln(\Lambda_{UV}/m_s) + \ldots\right]$$

SUSY provides correct coupling and number of states for cancellations

5

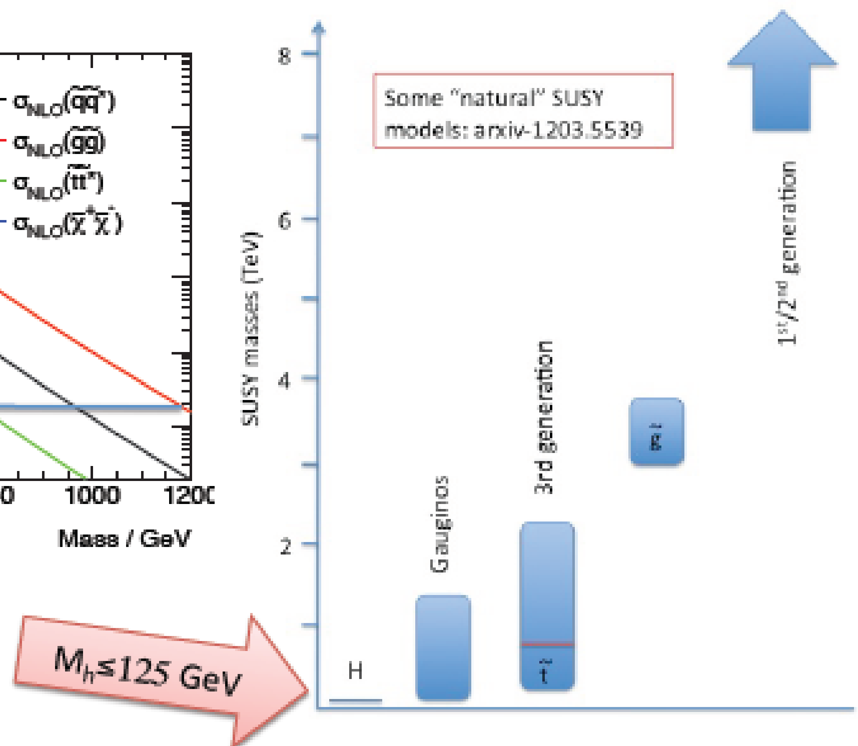
SUSY Mass spectrum and cross section

Sensitivity depends on which process is accessible.



Gluinos decoupled in stop cross-section estimate. (Thanks to TJ Khoo for plot)

Spectrum is model dependent



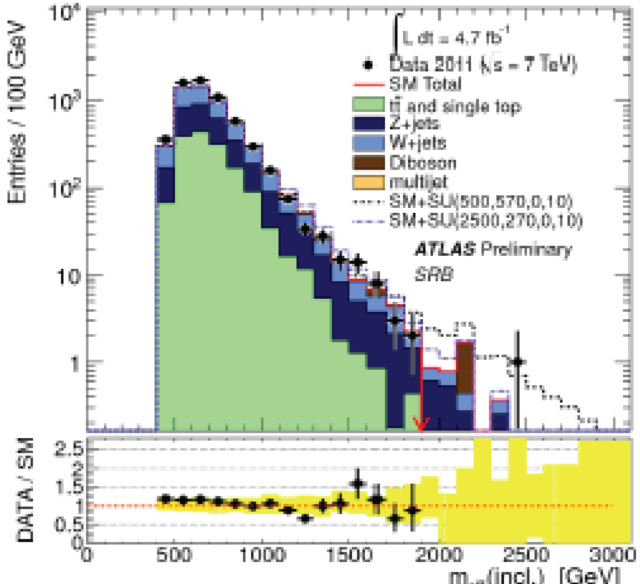
Limits are model dependent – assumptions affect production and decay. Use simplified scenarios for interpretation.

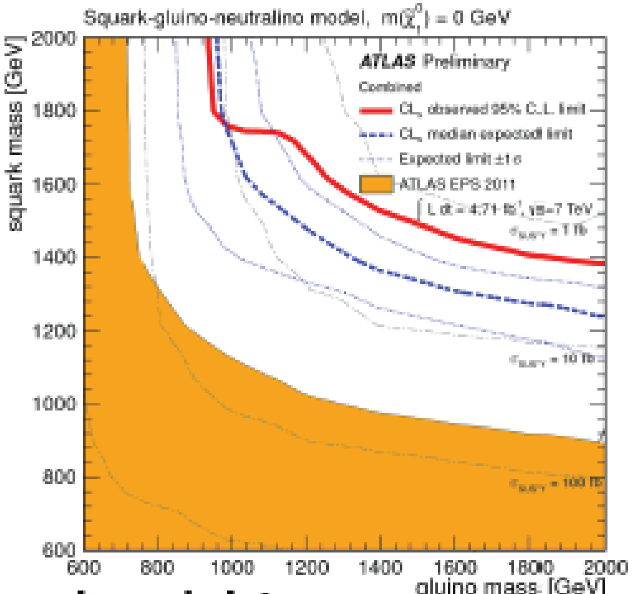
ATLAS 0-lepton search

2-6 jets + E_T^{miss}

M_{eff} defines signal regions

Look for squarks and gluinos with direct decays to SM+LSP





Search for strong production of squarks and gluinos.

Very strong limits from counting experiment.

Dominant background from Z–> νν.

Limits do not apply to stop/sbottom production.

ATLAS-CONF-2012-033

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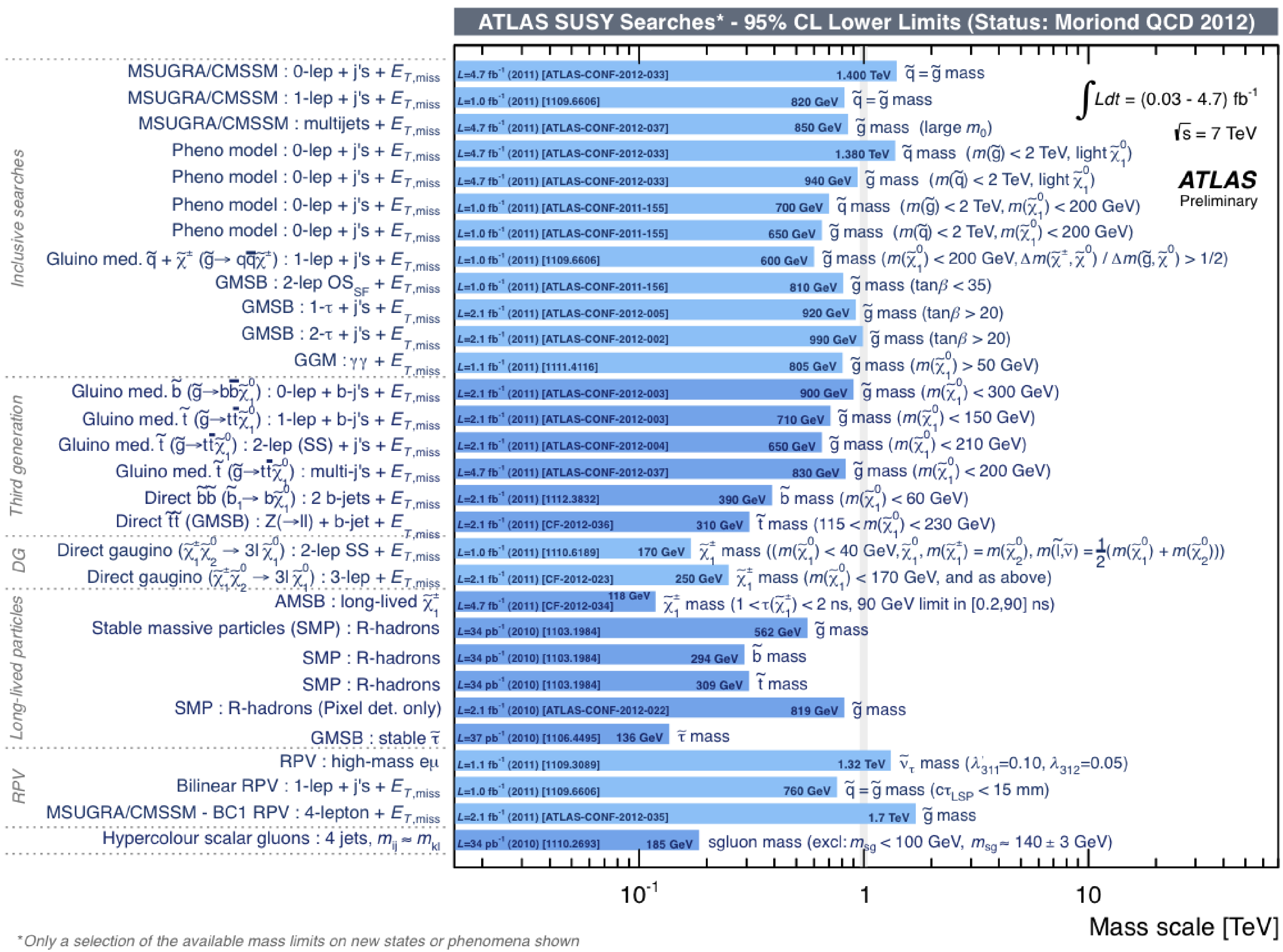
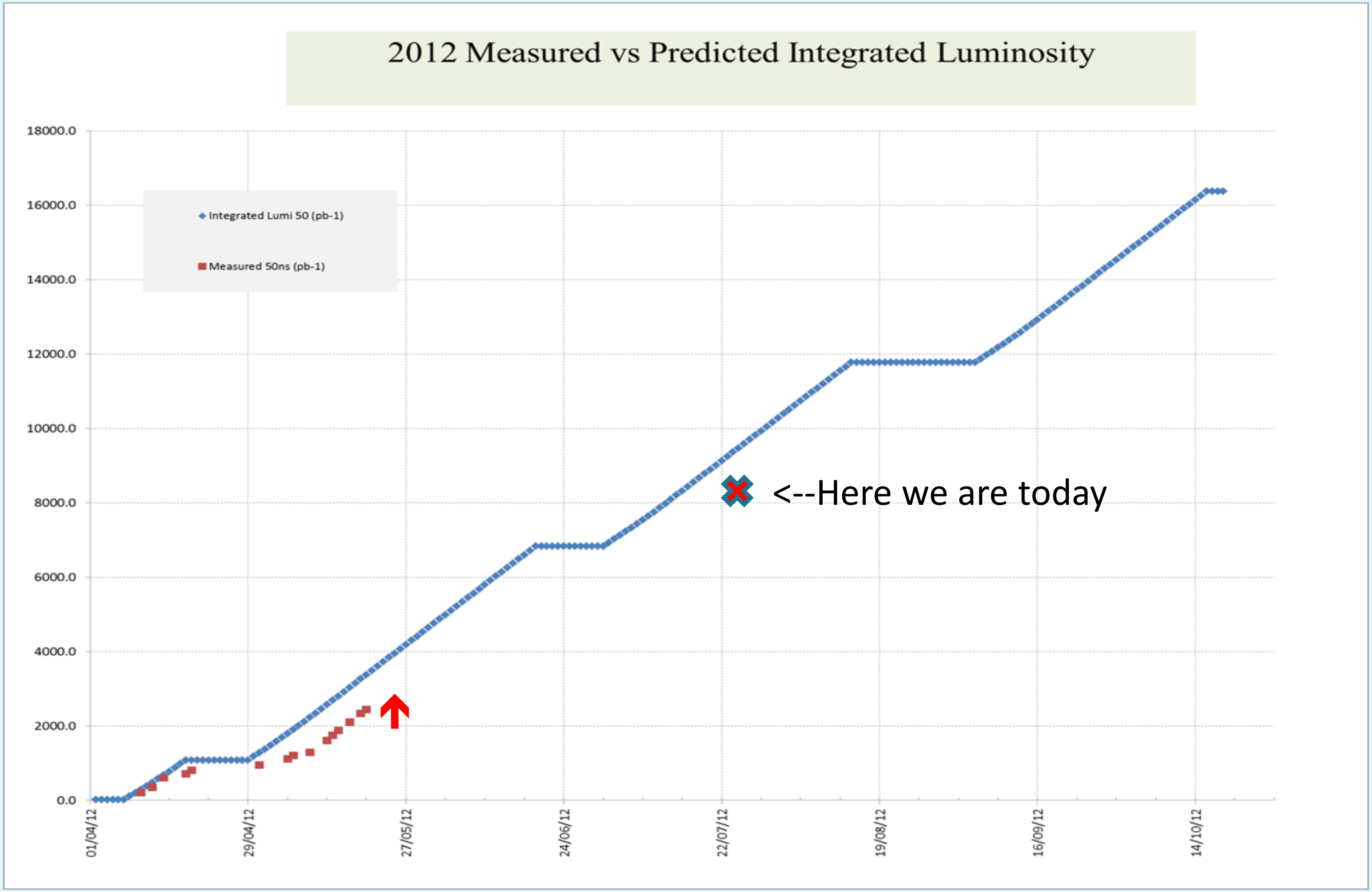
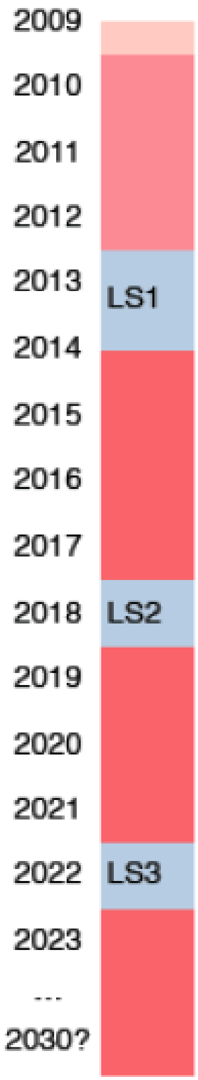
Result of ATLAS search for supersymmetric particle in 2011



Plan for the evolution of the accumulated luminosity during 2012 made at the beginning of the run



L'évolution de la luminosité du LHC au delà de 2012



✧ LHC startup, $\sqrt{s}$ = 900 GeV

$\sqrt{s}$=7~8 TeV, L=6x10^{33} cm^{-2} s^{-1}, bunch spacing 50 ns

Go to design energy, nominal luminosity

$\sqrt{s}$=13~14 TeV, L~1x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

Injector and LHC Phase-1 upgrade to ultimate design luminosity

$\sqrt{s}$=14 TeV, L~2x10^{34} cm^{-2} s^{-1}, bunch spacing 25 ns

HL-LHC Phase-2 upgrade, IR, crab cavities?

$\sqrt{s}$=14 TeV, L=5x10^{34} cm^{-2} s^{-1}, luminosity levelling

Conclusion

The LHC started in 2010 and during that first year it was possible to « rediscover » all already known particles.

In 2011 precision measurements of the top, W and Z particles were obtained, as well as a possible indication of a Higg boson of mass around 125 GeV.

By summer 2012 the discovery of a Higgs-like particle was announced. In view of this discovery it was decided change the earlier planning to stop pp-operation by the autumn 2012 and instead continue till the end of 2012.

During a shut-down 2013-2014 the beam energy of the LHC will be upgraded from the current value of 4 GeV to 6.5 GeV and the luminosity will be about doubled. This will allow, during the years after 2014, to make precision measurements of the Higgs boson and also to continue the hunt for SUSY particles and other hypothetical particles.

During shut downs in 2018 and 2022 the luminosity will be further increased with the goal to have accumulated by the end of the 2020's an integrated luminosity of about 3000 events per femtobarn, which is about 300 times what we have today.

What these 3000 events per femtobarn will reveal to us we do not know, maybe strings or branes…the adventure continues into the unknown territories of the structure and forces of Matter.