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The road to Higgs and what comes next

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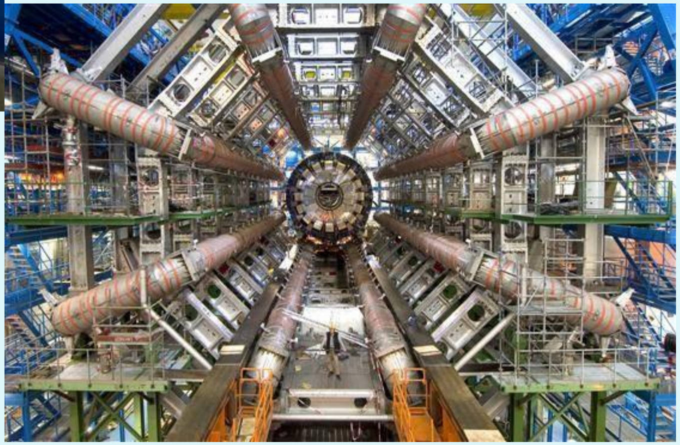
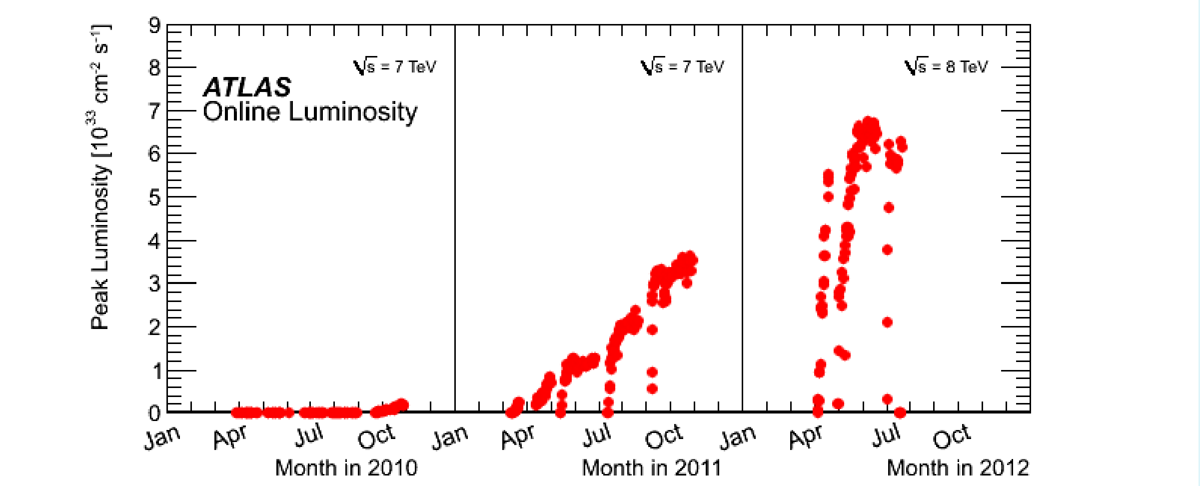
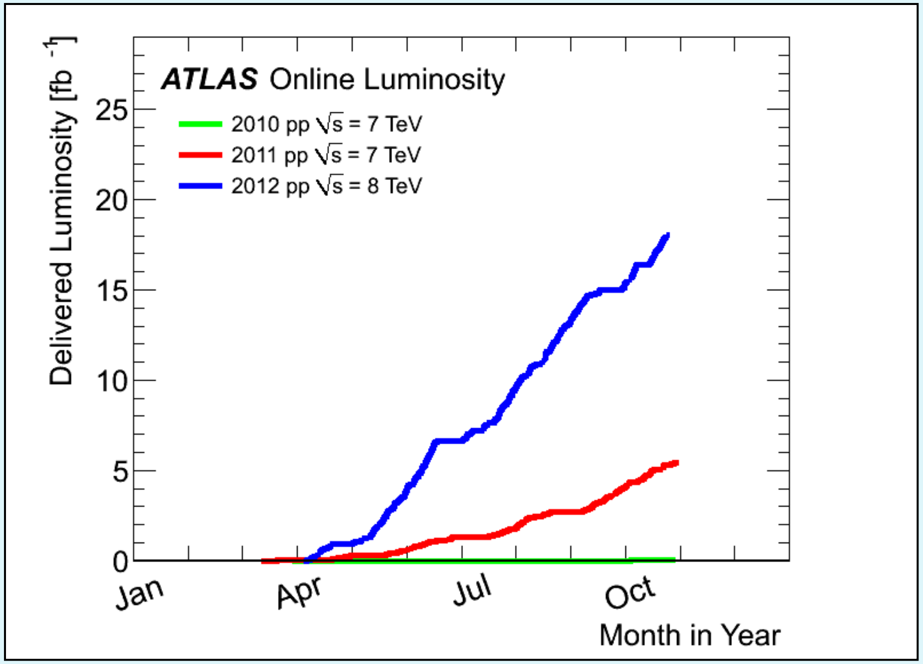
Large Hadron Collider LHC at CERN in Geneva



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



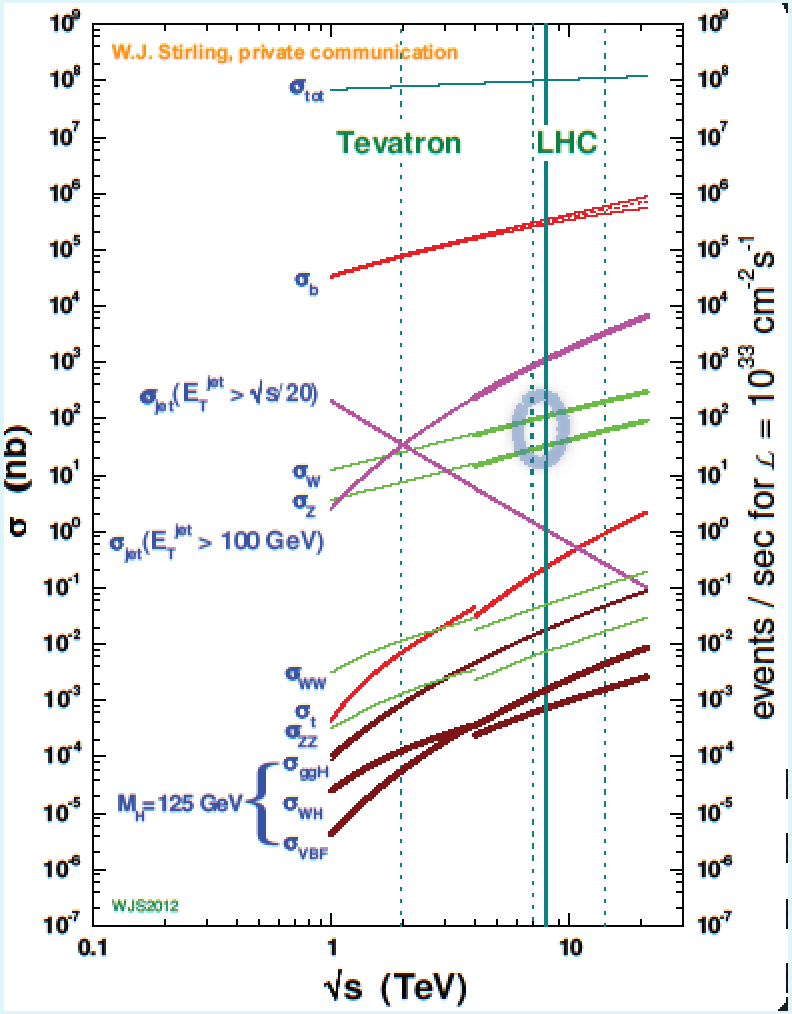
Time integrated luminosity in cm^{-2}

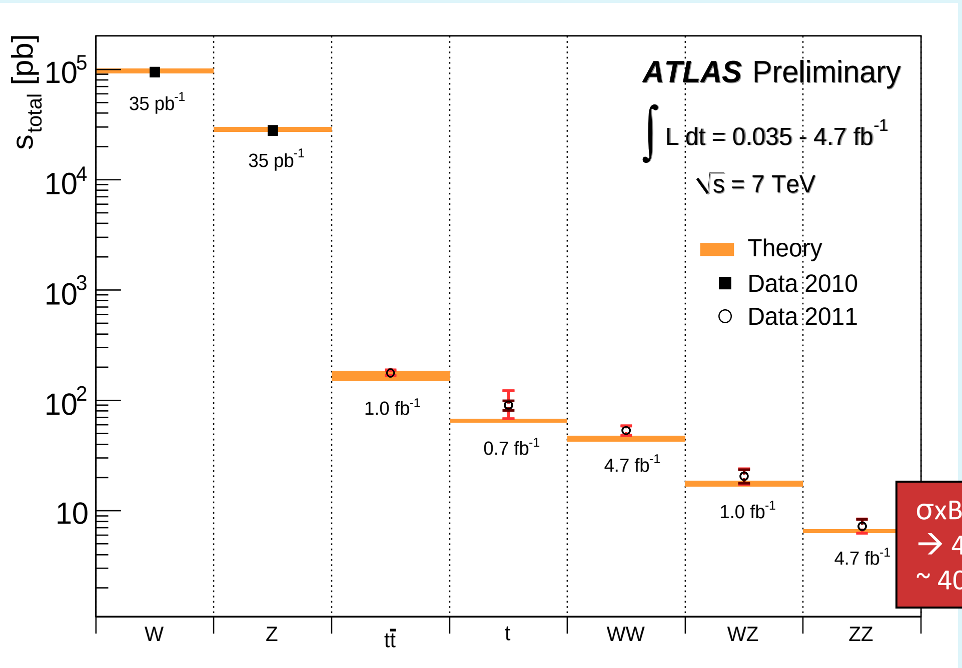


Production cross-sections

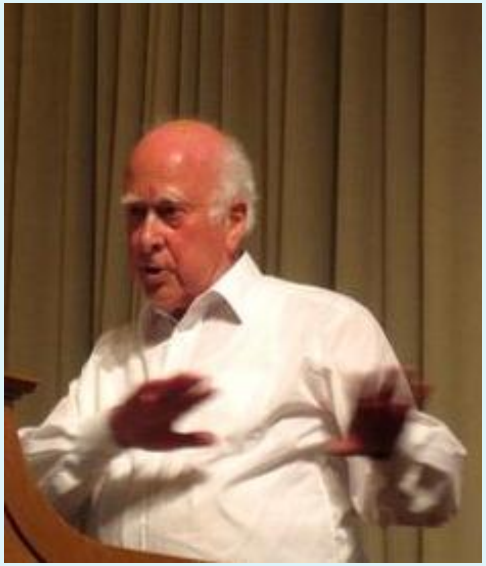
Standard Model cross-sections
As function of CM energy

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



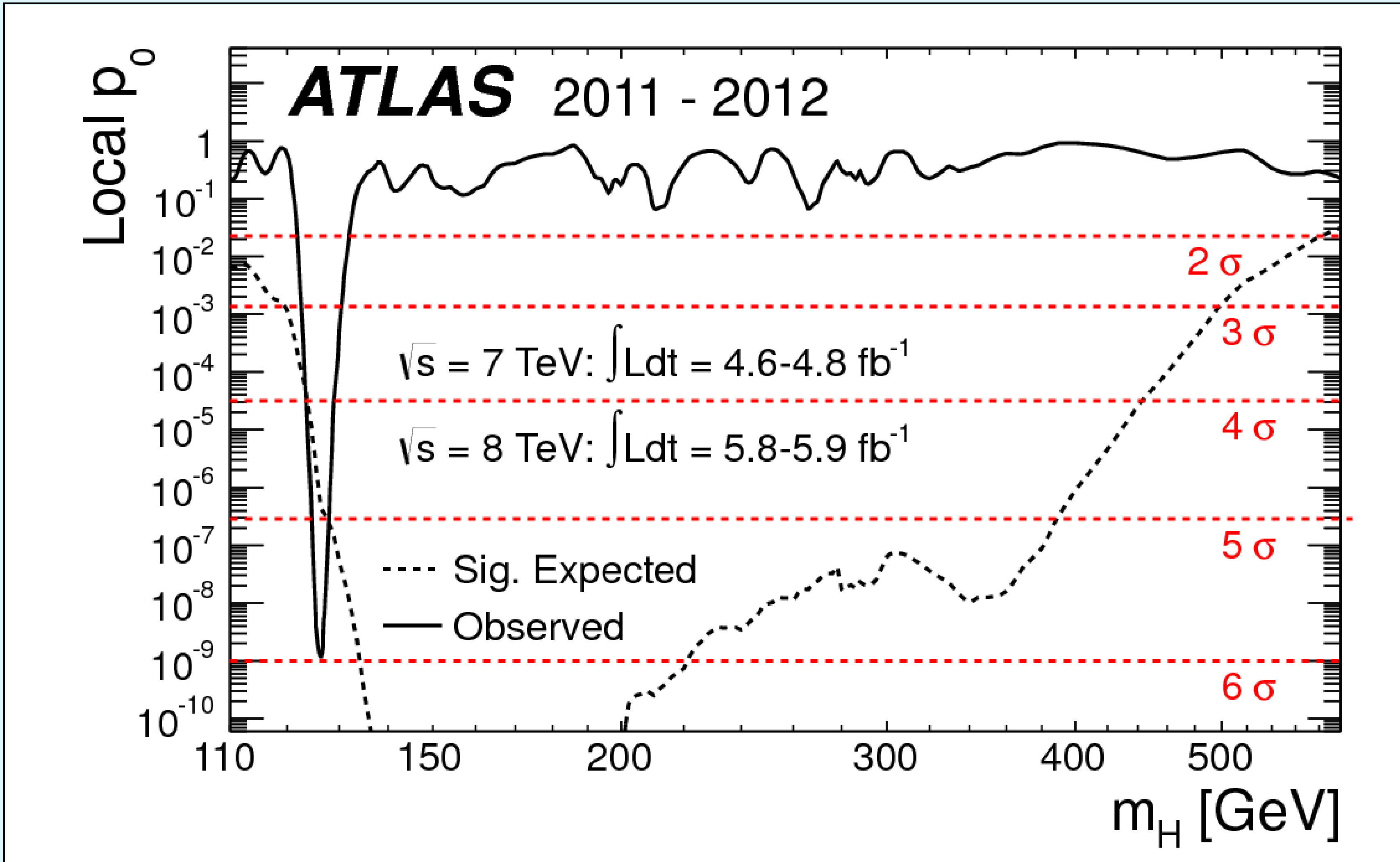


The Englert-Brout-Higgs field and boson

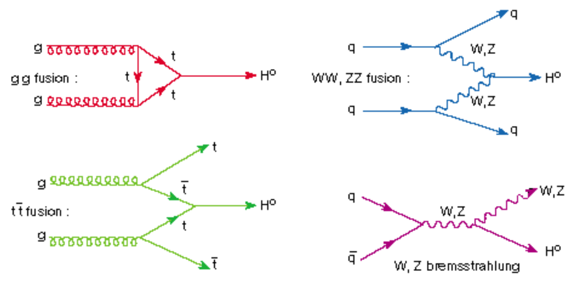


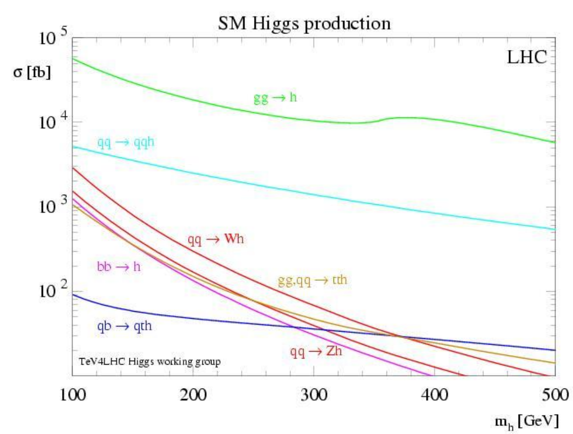
The six authors of publications 1964 PRL 1964, who received the J. J. Sakurai 2010 prize for their work. From left to right; Kibble, Guralnik, Hagen, Englert, Brout and Higgs.

Discovery 2012



H^{0} production at hadron colliders:

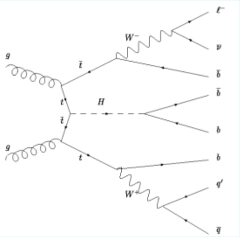


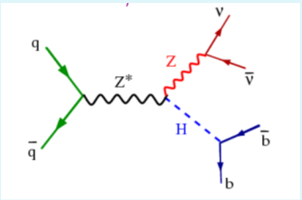


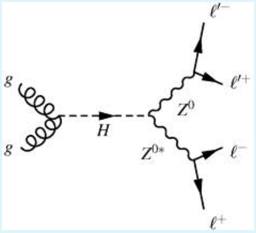
Dominant Higgs production mechanisms;

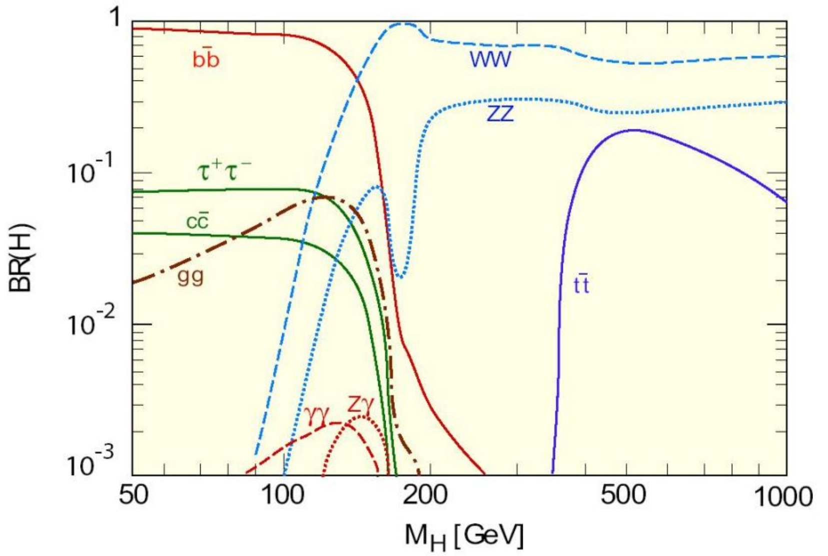
at LHC
gg->H
qq->H

H^{0} decay at hadron colliders:









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?

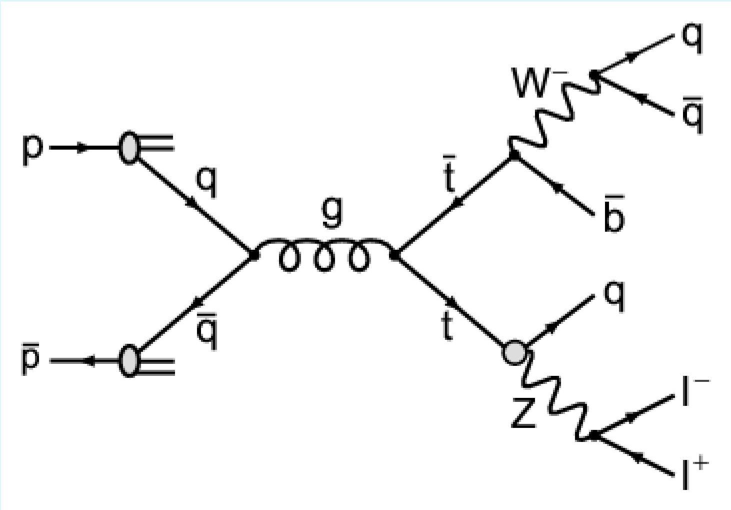
The luminosity collected by each experiment at the LHC in 2011 and 2012 is more than 20 fb^{-1} = 20'000 collisions per pb.

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

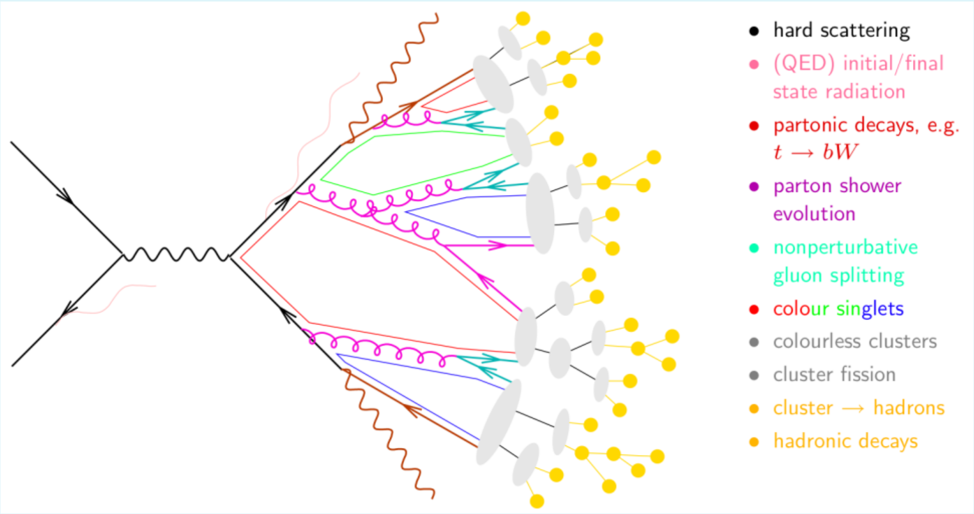
Well, the number is at least 20'000 pb^{-1} * 10 pb = 200'000 - in each of ATLAS and CMS!

If 200,000 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

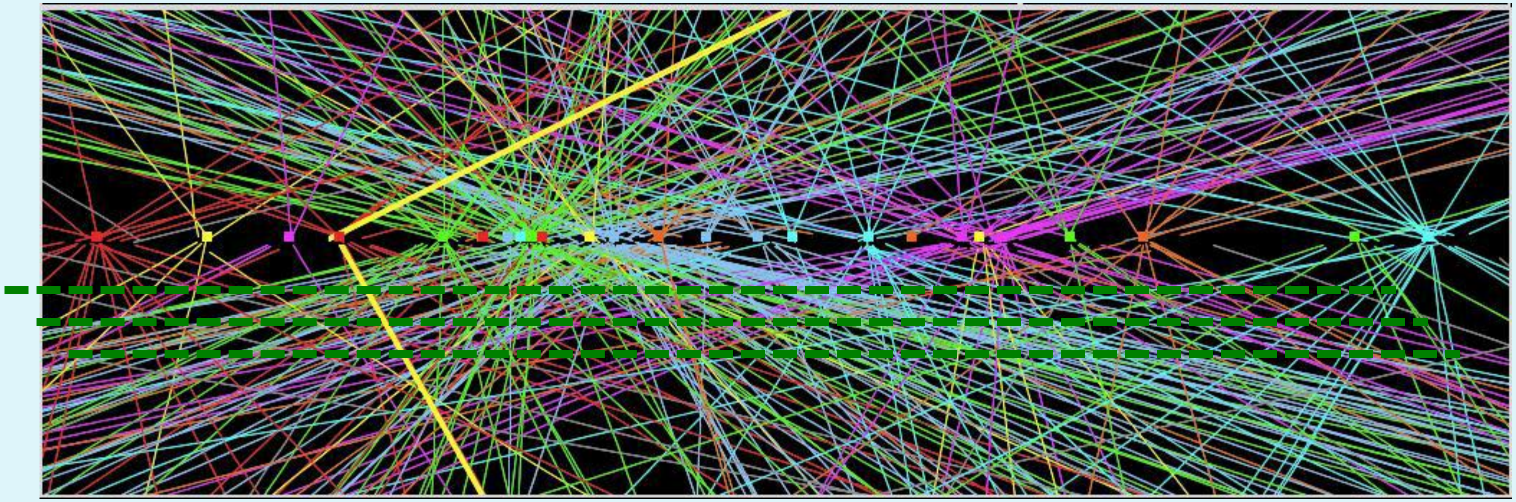


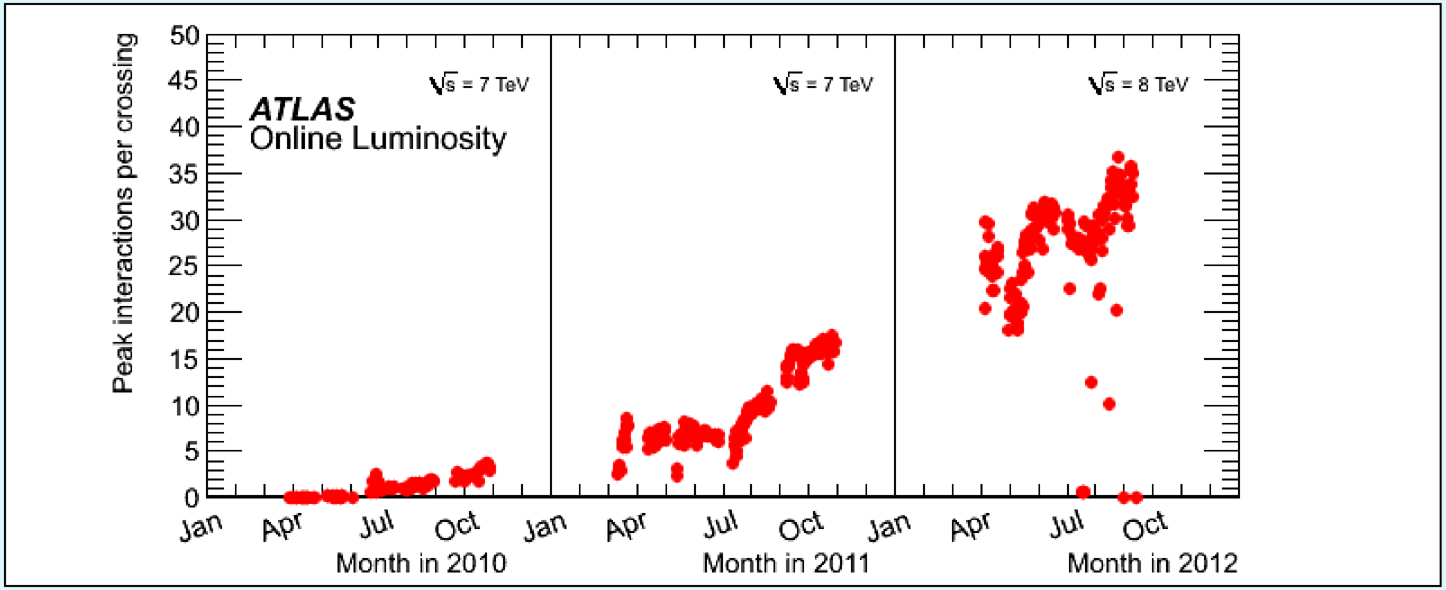
QCD background

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.

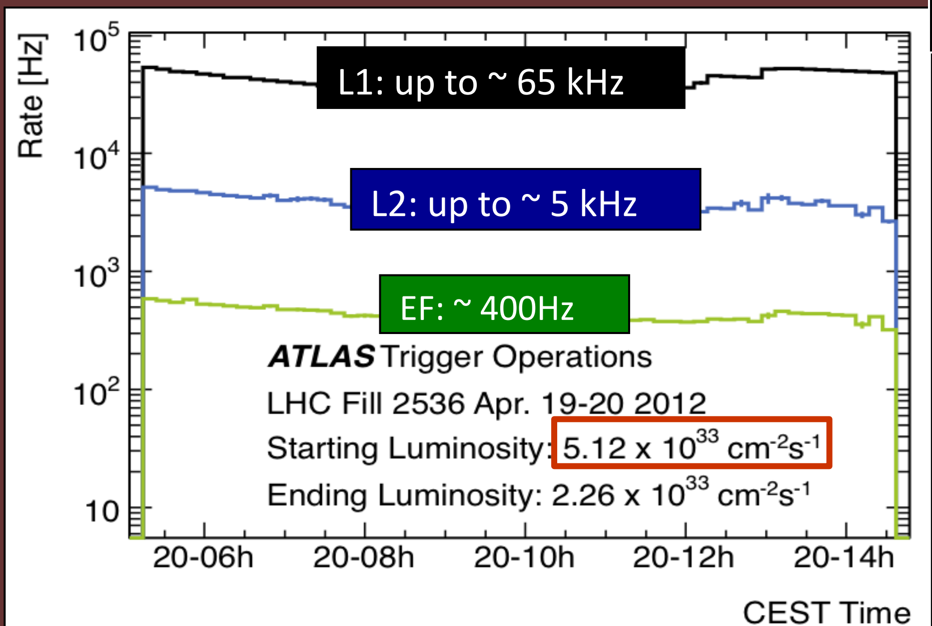
Furthermore, with $20*10^6$ bunch crossing per second (50 ns between bunch crossings) this makes of the order 30 collisions per bunch crossing – a formidabel pile-up of events.

Z^0->μμ 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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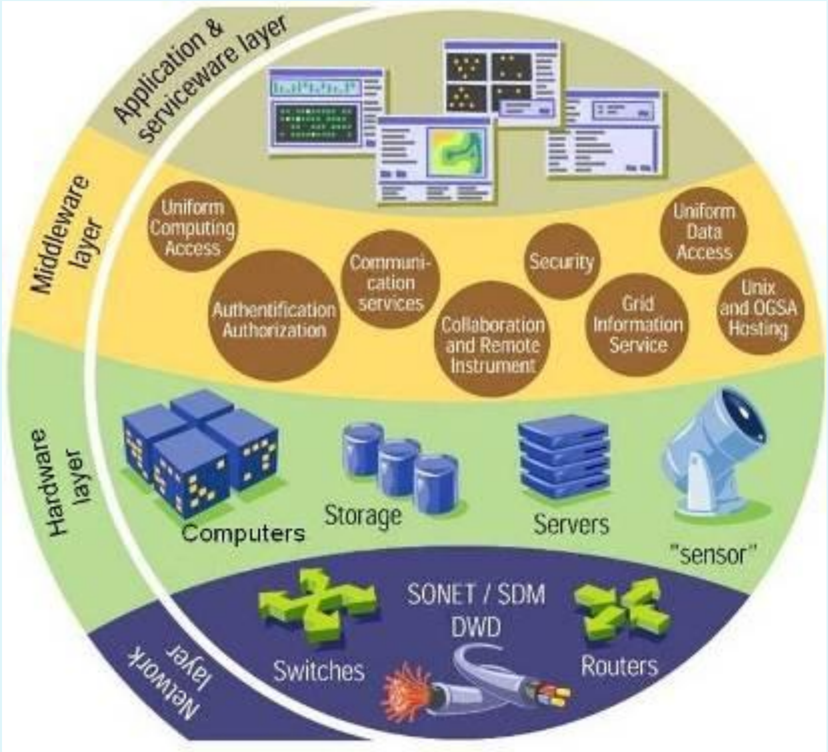
An equally decisive role in the Higgs hunt is played by the off-line software and the World Wide Computing Grid

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.

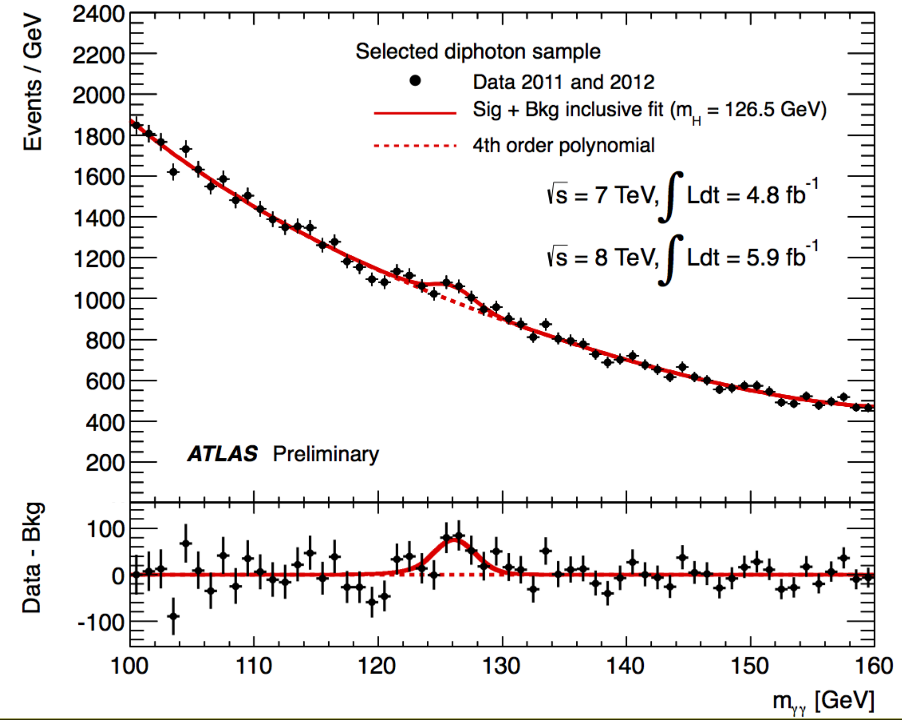


And from all this has by now been obtained few 10’s or 100’s of Higgs events (from order in total 10^5 produced Higgs events!)

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



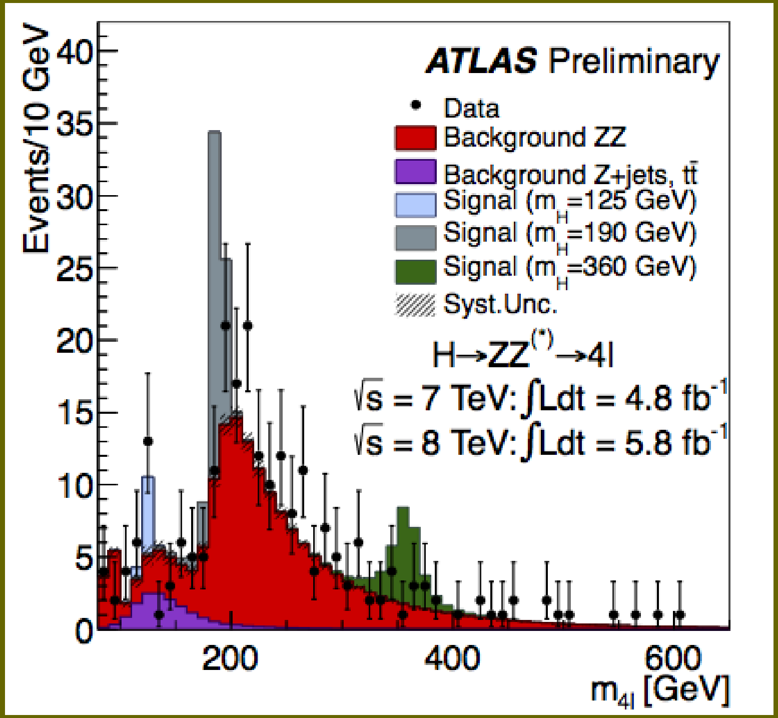
H→ γγ:

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

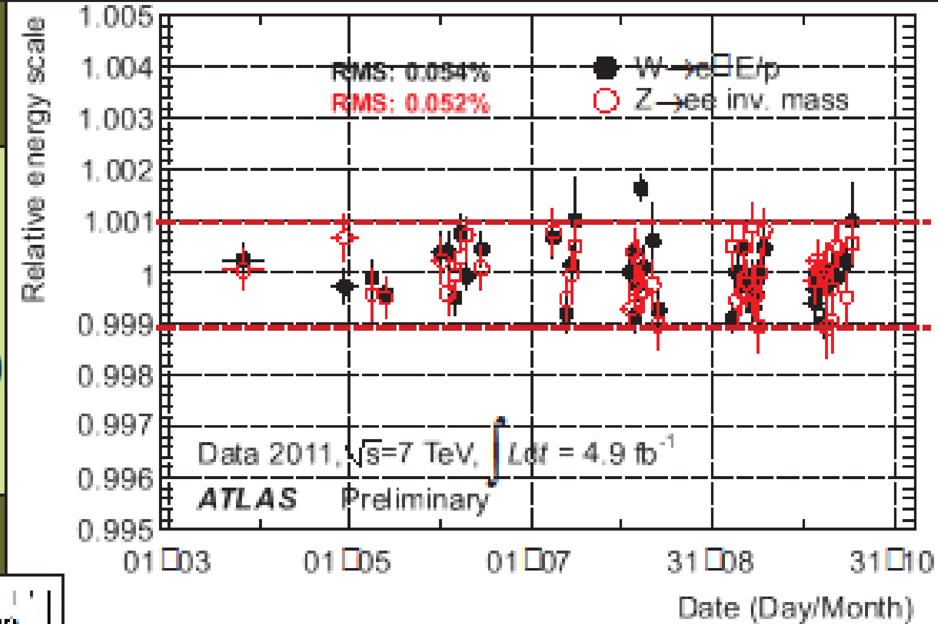
Mass resolution H -> γγ

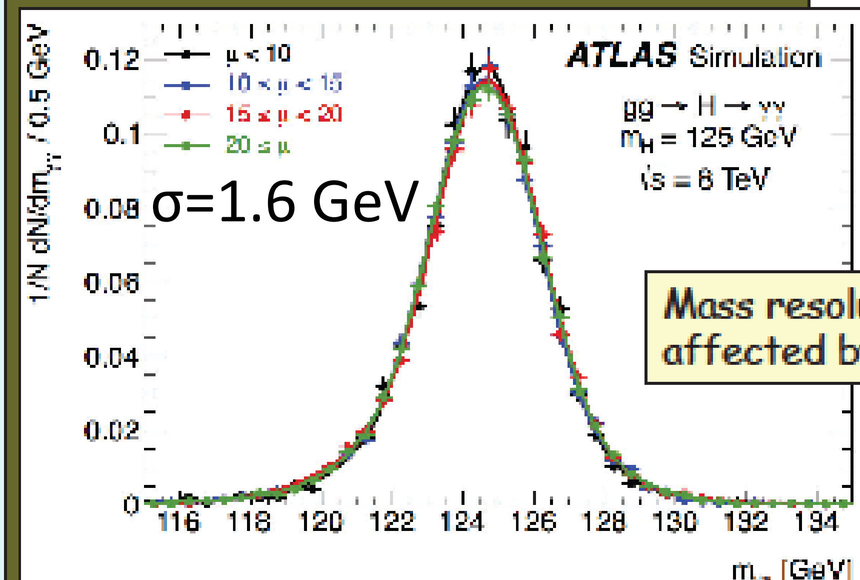
$m^2_{\gamma\gamma} = 2 E_1 E_2 (1-\cos\alpha)$

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%





Mass resolution not affected by pile-up

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

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

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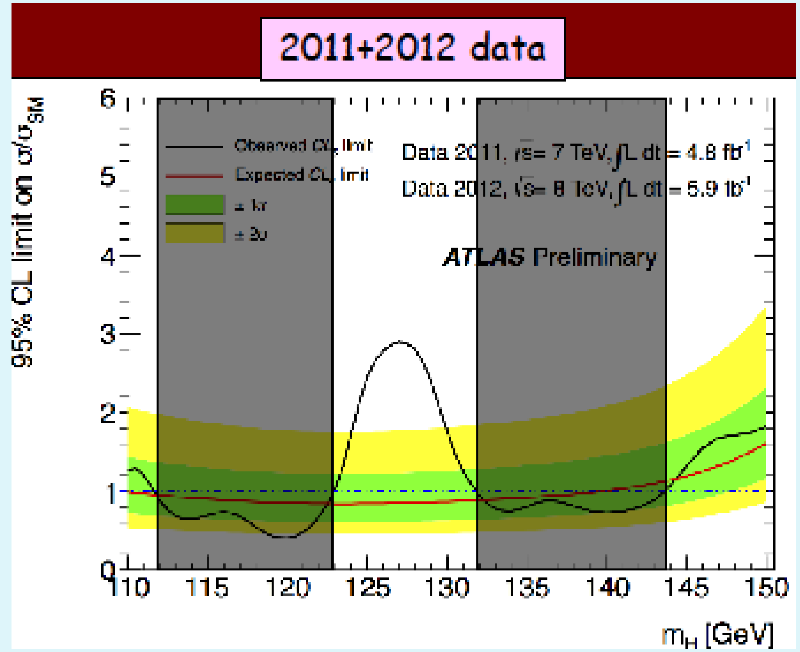
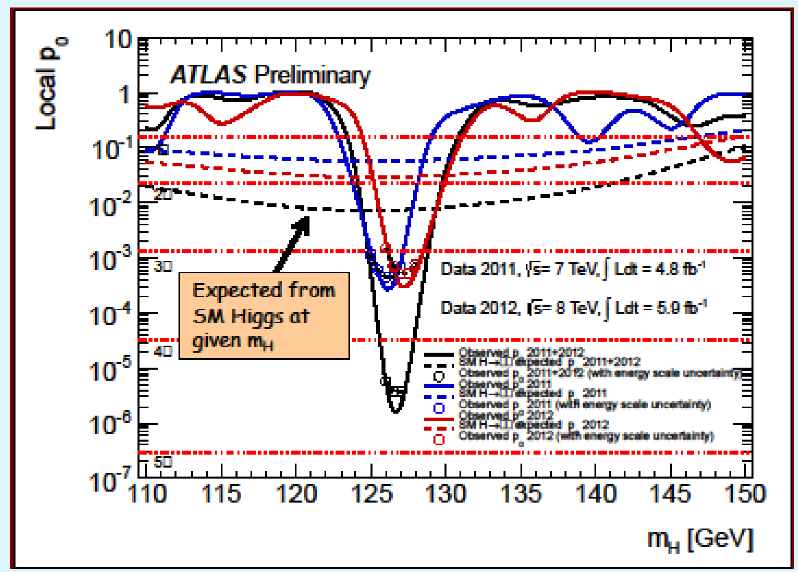
Results of H → γγ search in ATLAS

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.



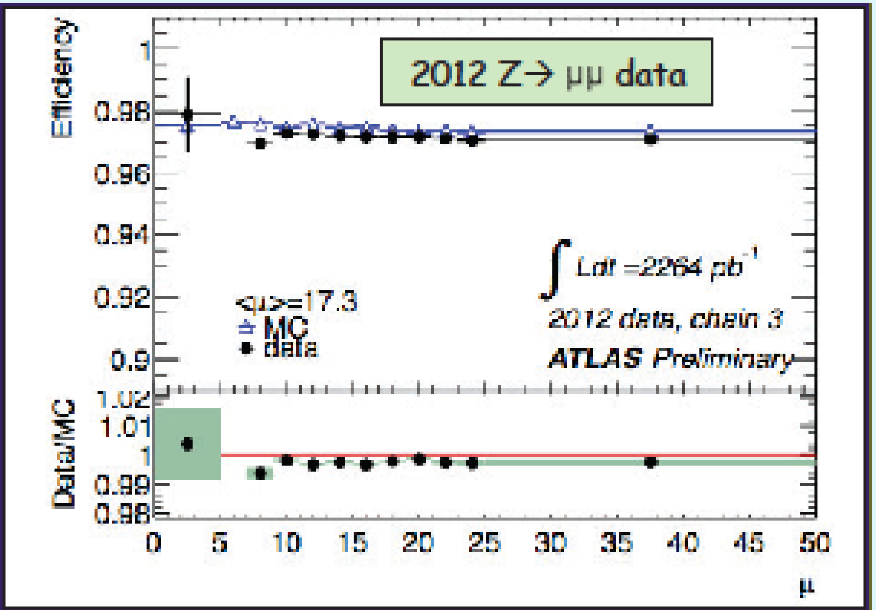
The vertical axis shows the probability for that the observed excess is a fluctuation in the data in the absence of a Higgs Signal. The hatched lines show the expectation of an excess in the presence of a Higgs signal and the full lines the data.



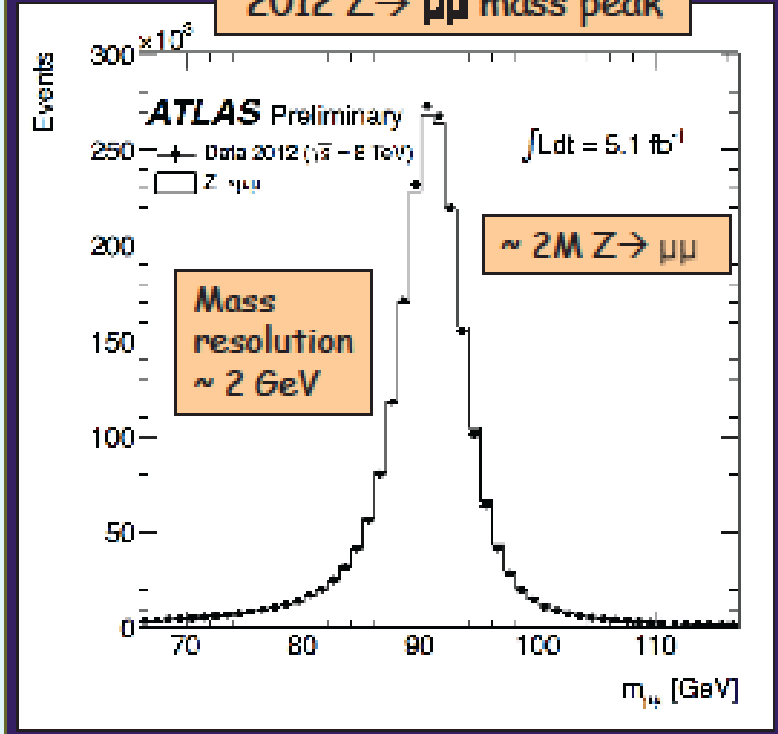
Muons reconstructed down to $p_T = 6$ GeV over $|\eta|<2.7$ H->4μ

Reconstruction efficiency ~ 97%,
~ flat down to $p_T \sim 6$ GeV and over $|\eta|\sim2.7$

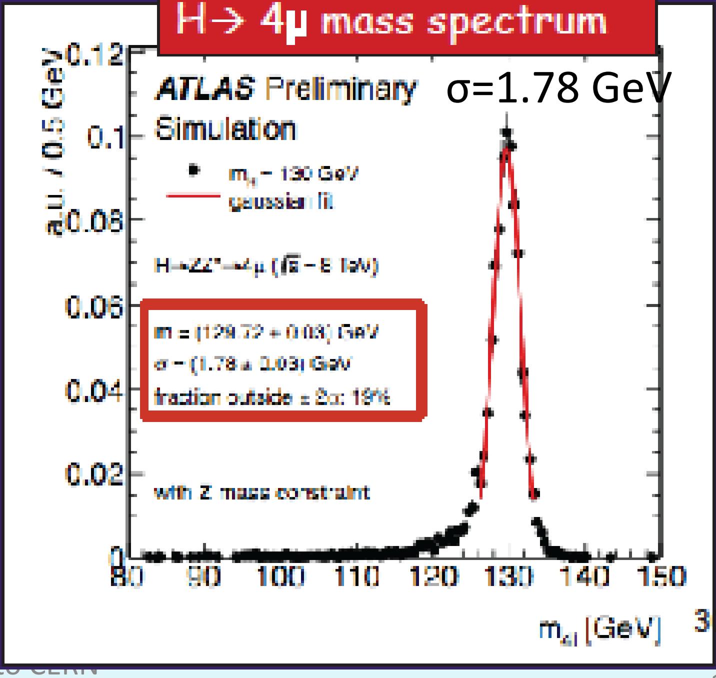
Total acceptance x efficiency for H→ 4μ: ~ 40% (+45% gain)



2012 Z→ μμ mass peak



H→ 4μ mass spectrum



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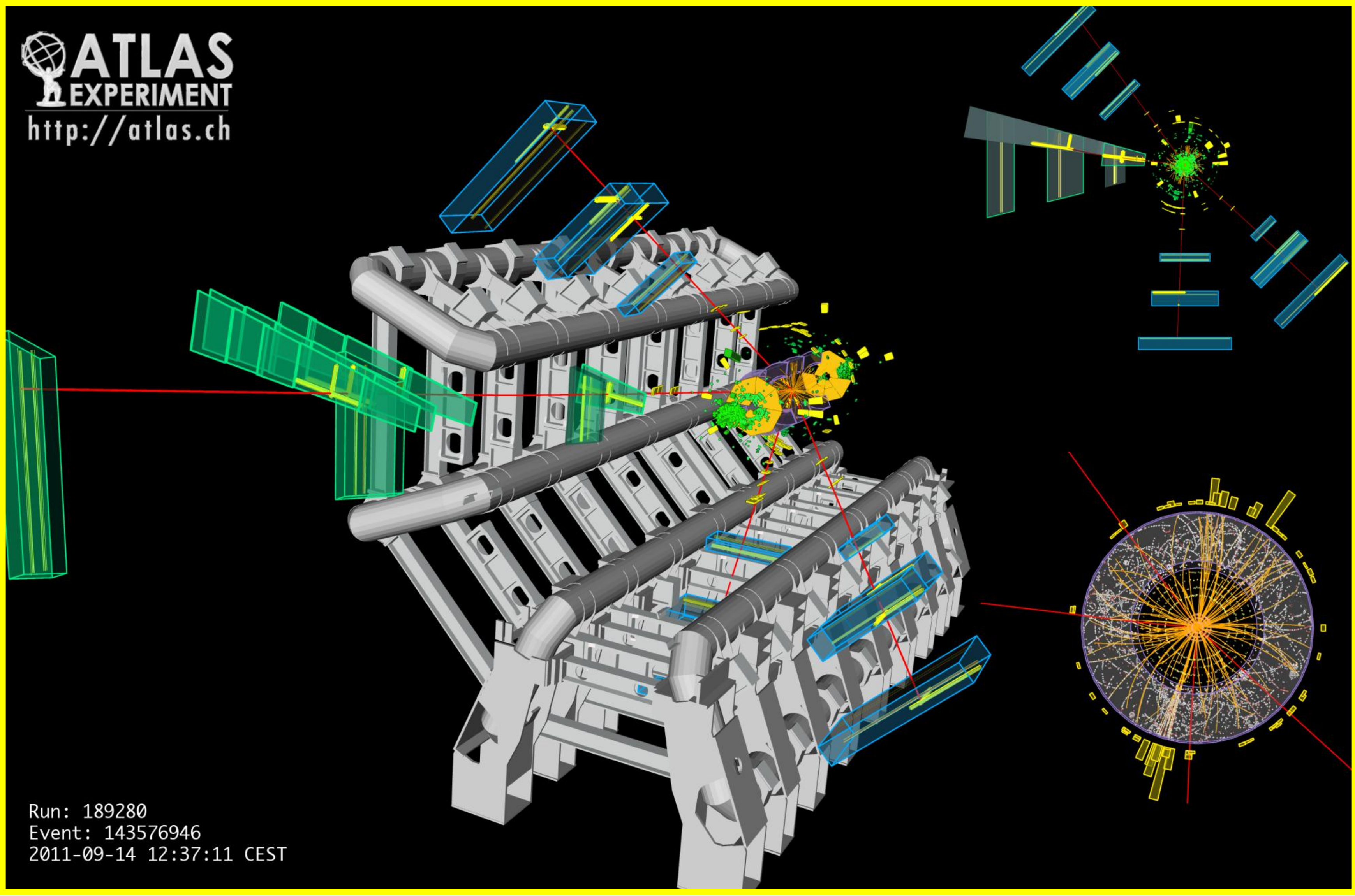
4μ candidate with $m_{4\mu}$= 124.6 GeV

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

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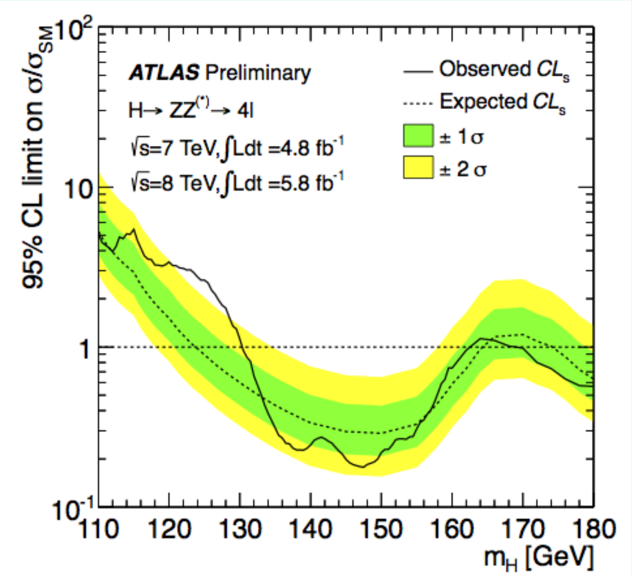

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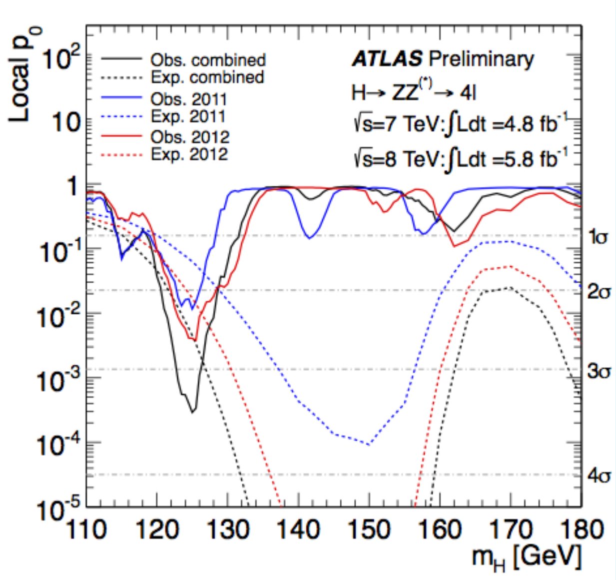
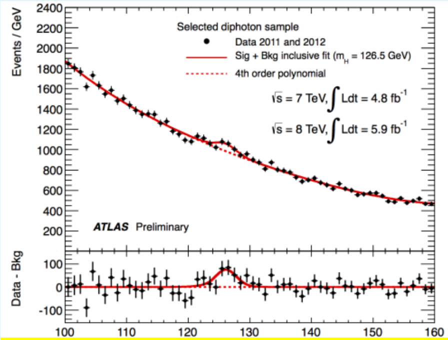
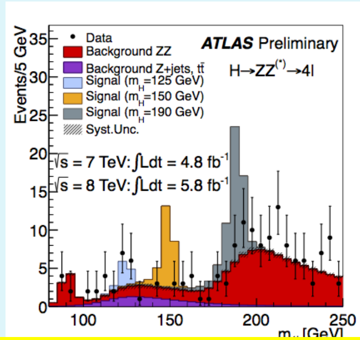
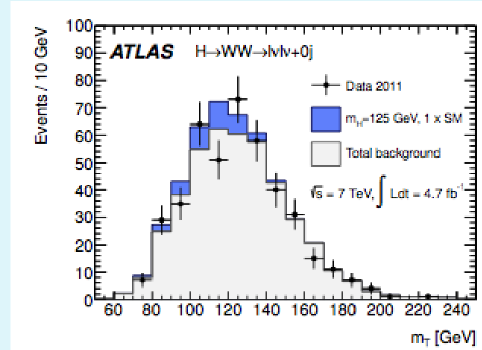
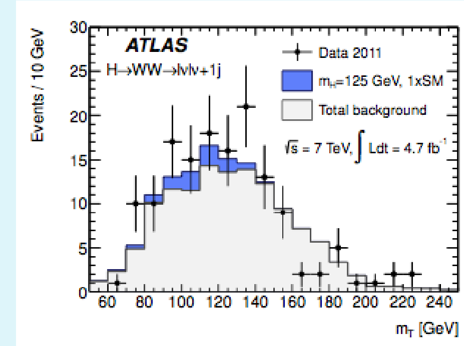






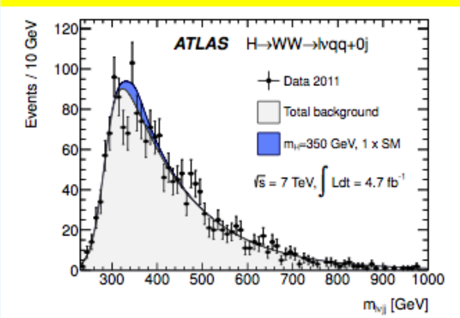


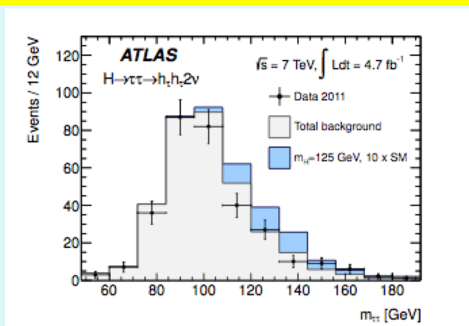


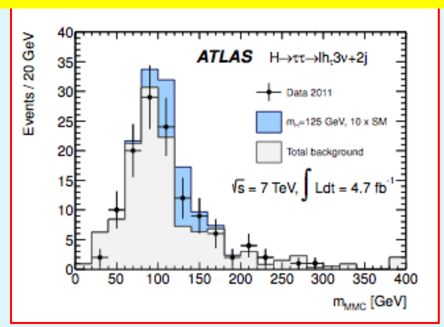
Combining all 12 channels together:

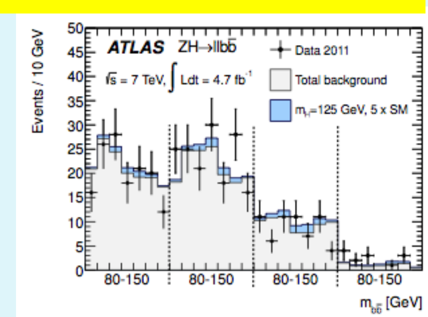
•H-> γγ, H-> 4l: full 2011 and 2012 datasets (~ 10.7 fb-1) and improved analyses

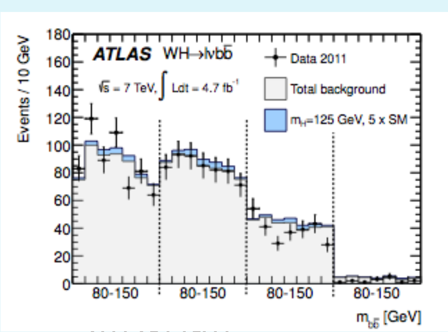
•All other channels H-> WW(*)-> lνlν, H-> WW->lνqq with 1 and 0 jet,
H-> ττ ->hh2ν and hl3ν +2j, ZH-> llbb, ZH-> ννbb ,WH-> lνbb,
H-> ZZ -> llqq , ZZ -> llνν, ZZ -> llbb, : full 2011 dataset (up to 4.9 fb-1)

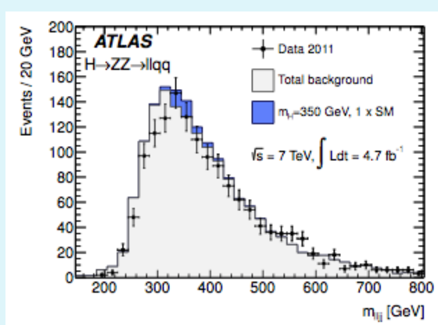


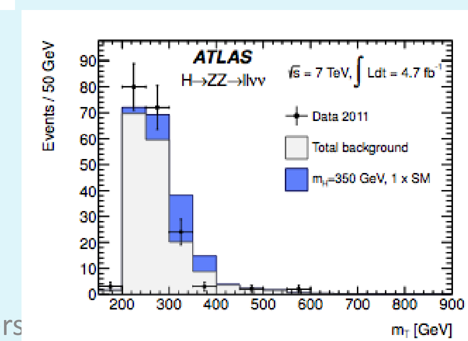


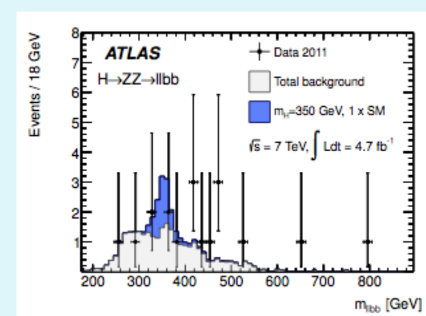


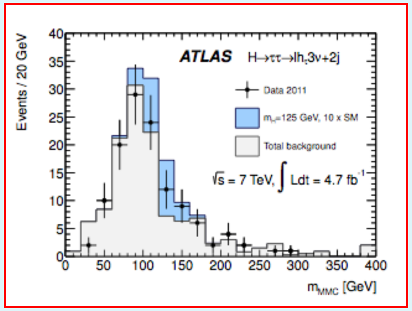




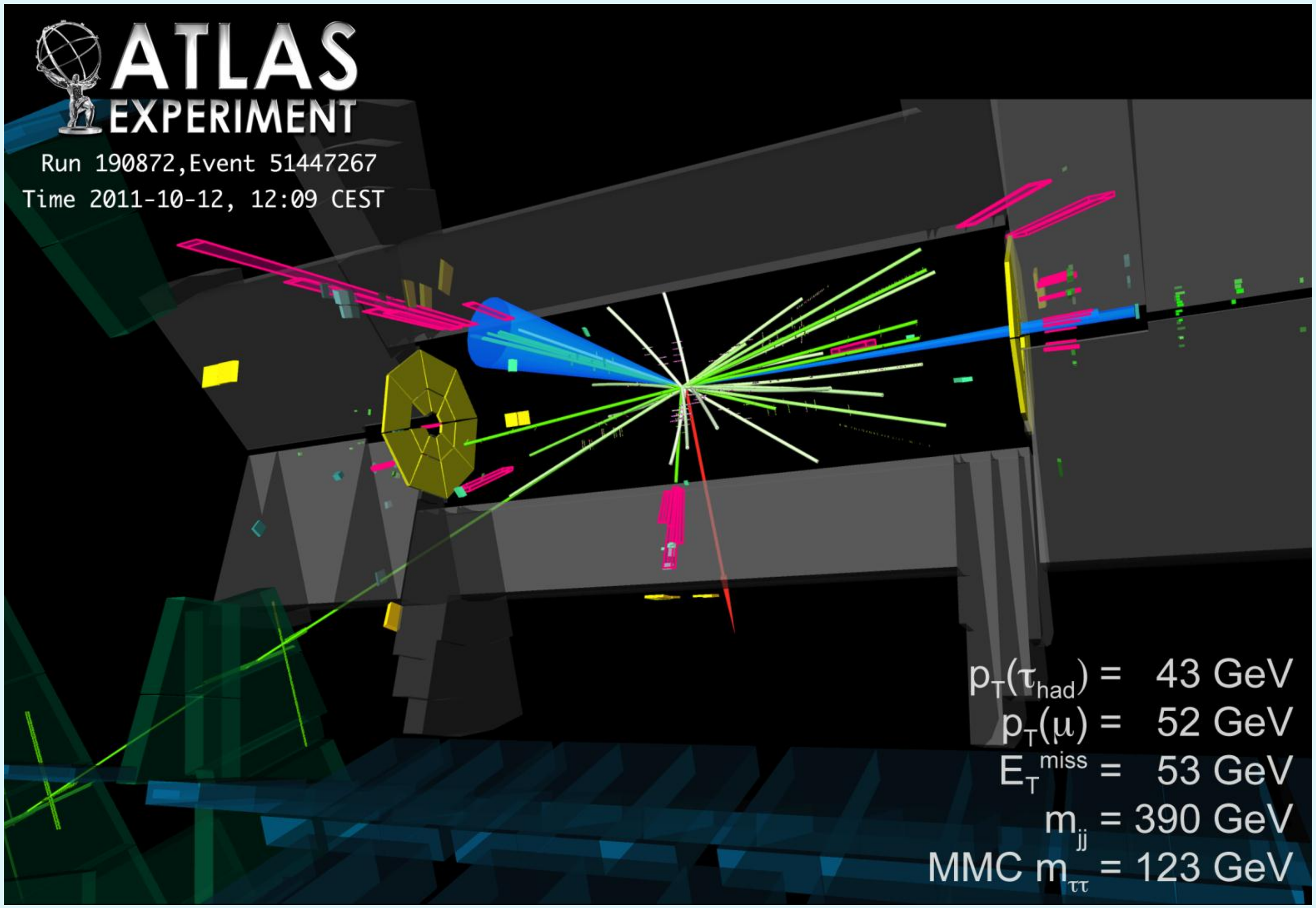


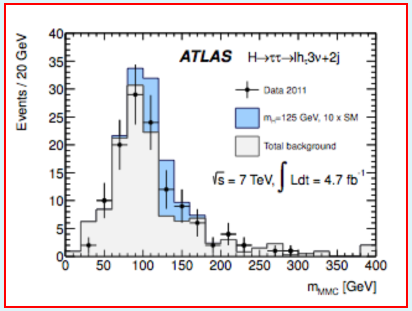




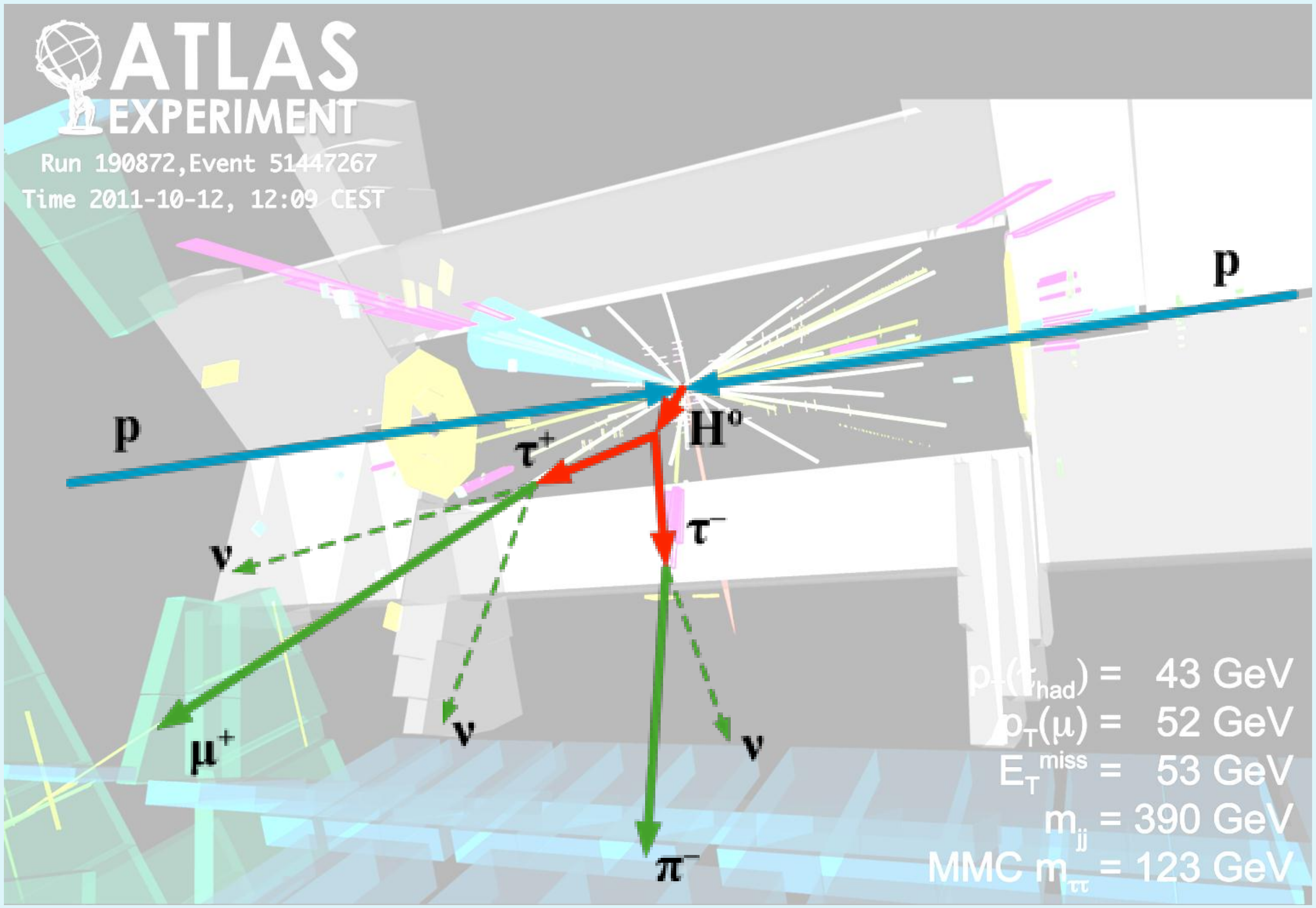


$H \to \tau^+ + \tau^- \to \mu^+ \nu\nu + \pi^- \nu$





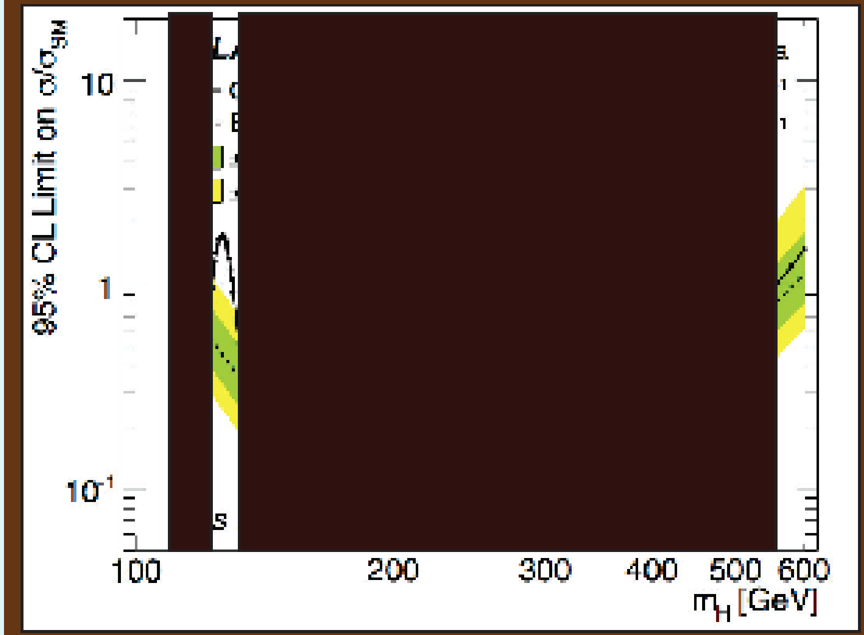
$H\text{->}\tau^{+}+\tau^{-}\text{->}\mu^{+}\nu\nu+\pi^{-}\nu$

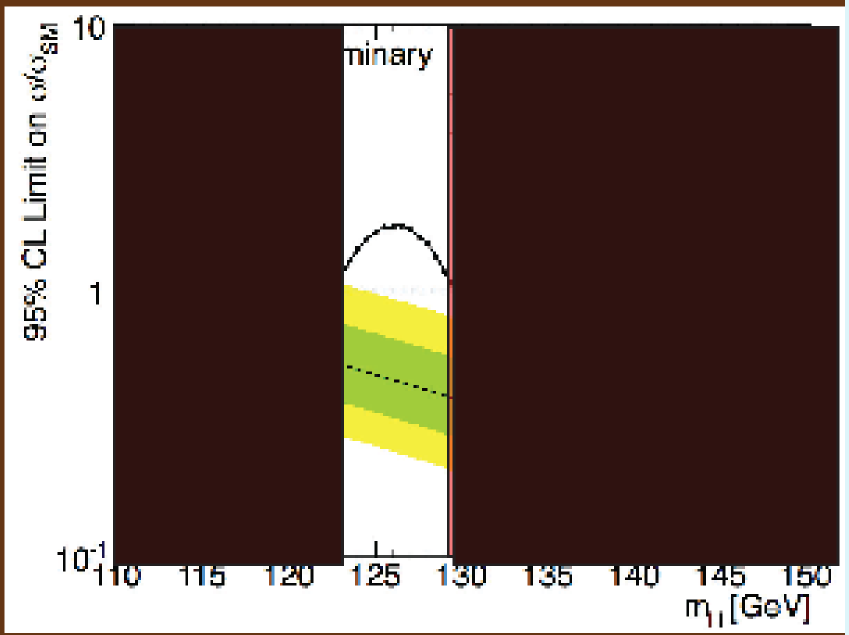


Combined results : exclusion limits

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

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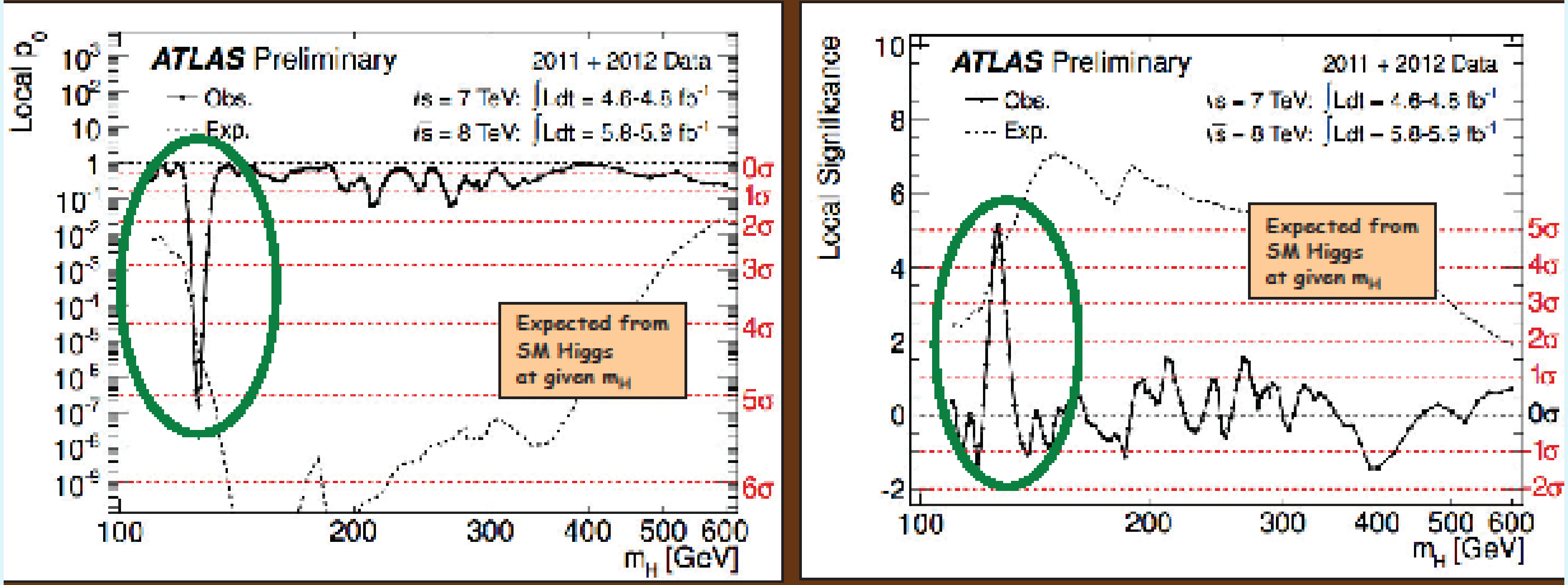
Combined results: consistency of the data with the background-only expectation and significance of the excess

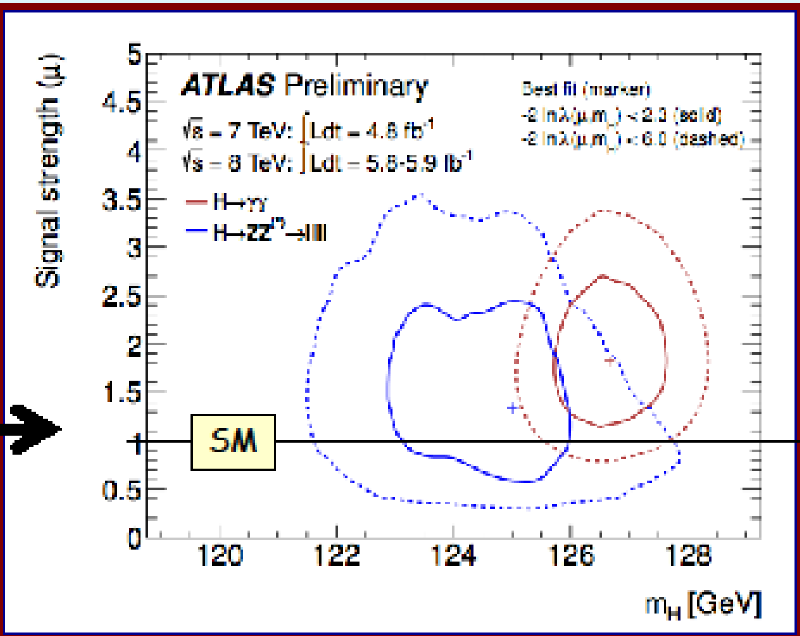


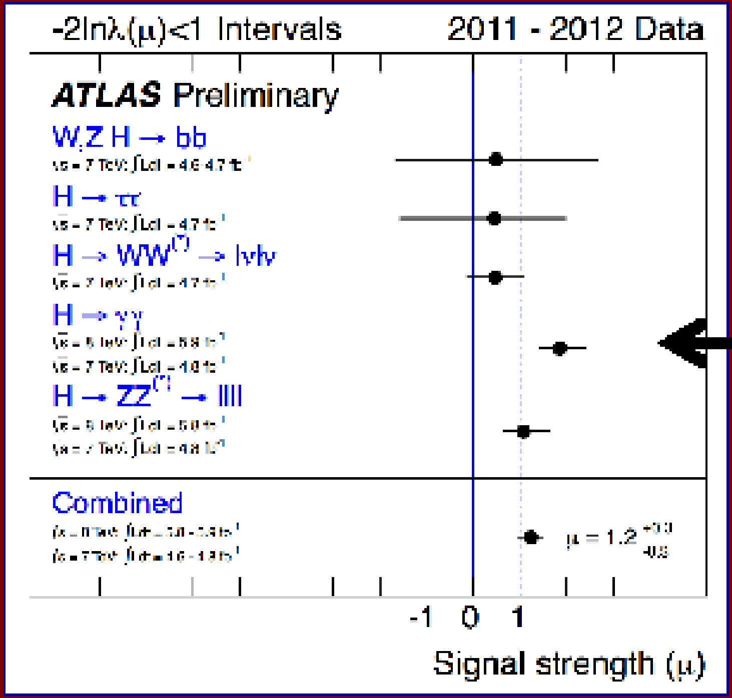
Excellent consistency (better than 2σ !) of the data with the background-only hypothesis over full mass spectrum **except in one region**

Combined results: 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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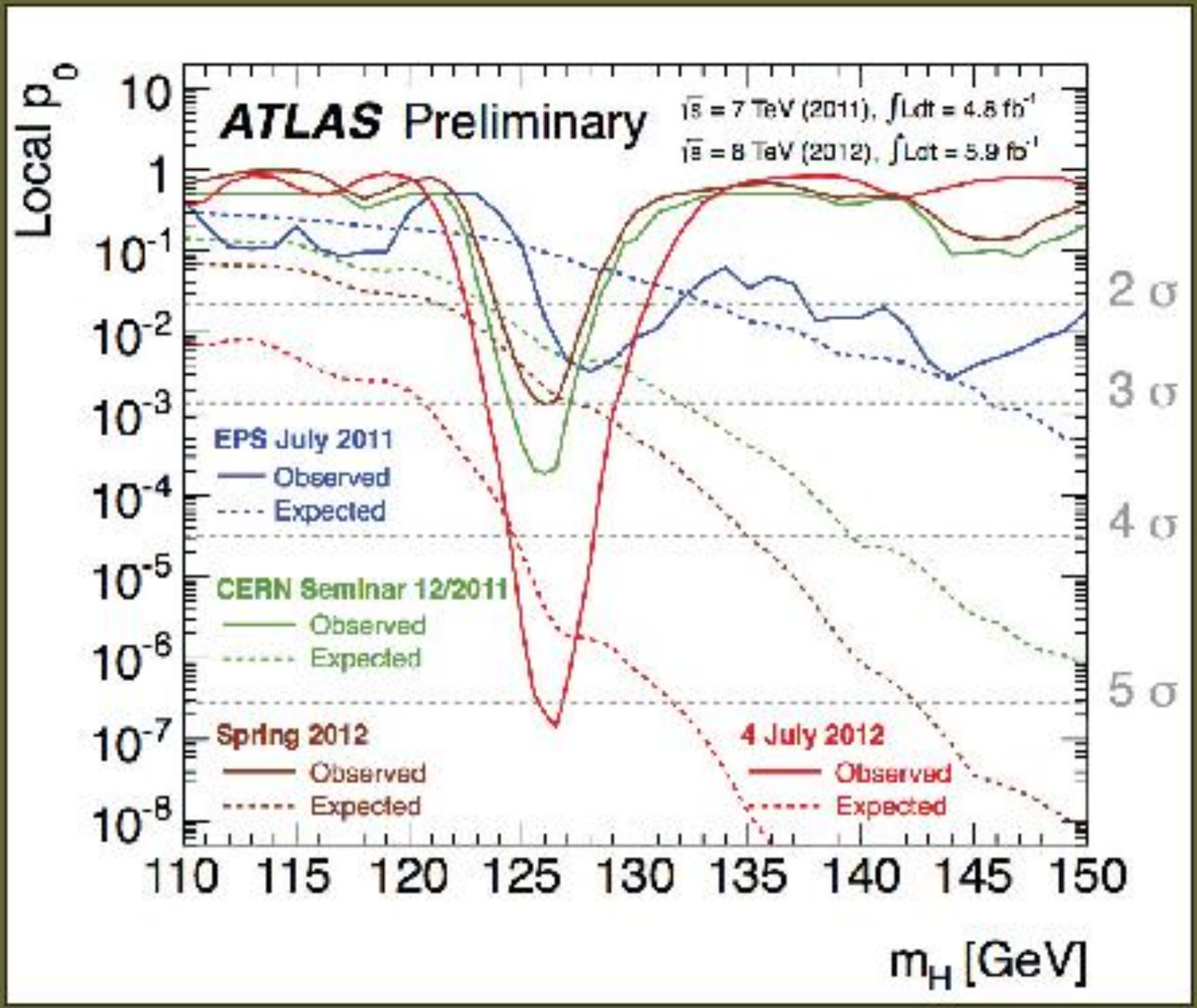
Evolution of the excess with time



Energy-scale systematics not included

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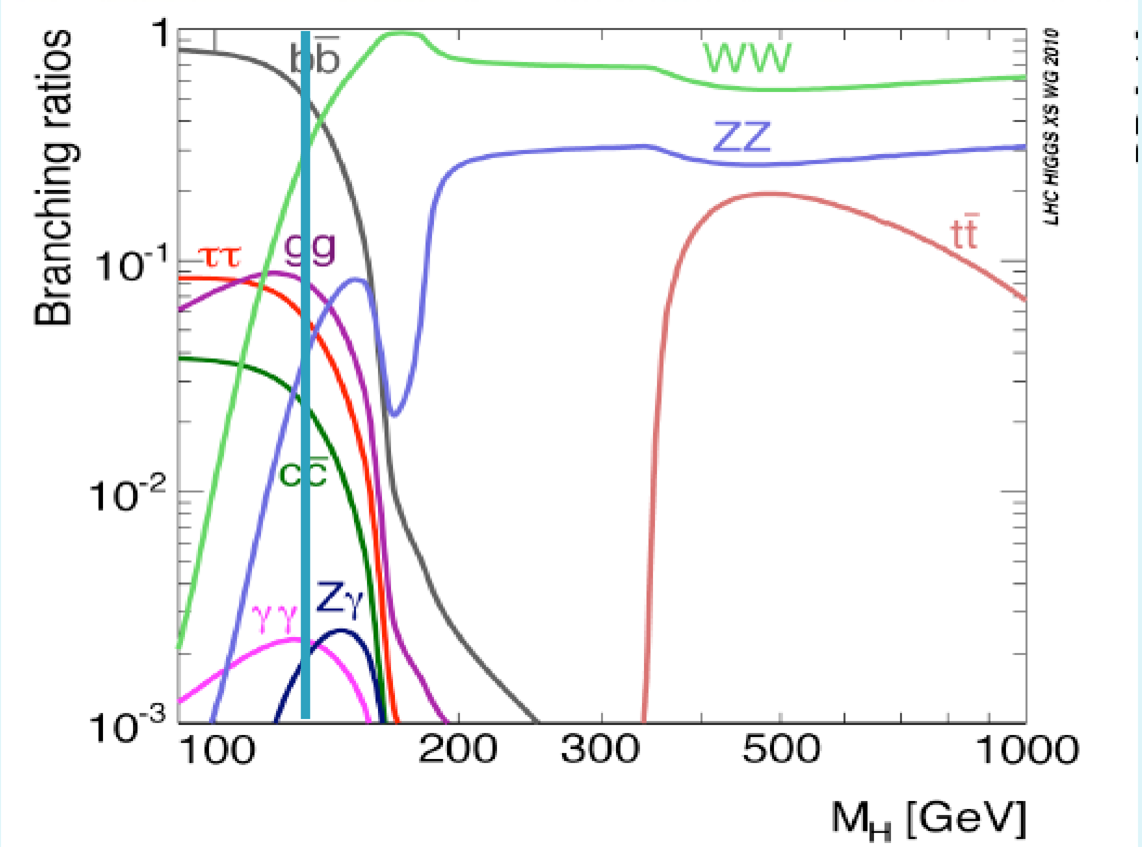
To now verify if it is really the Standard Model Higgs boson that has been found we need to compare the Higgs decay branching rations for different channels and compare with the predictions of the Standard Model which states that the Higgs coupling is proportional to mass.

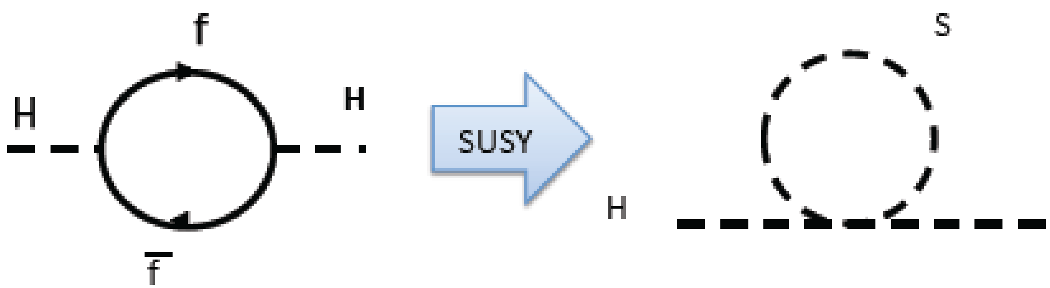
In this sence Nature has been very kind to us by letting the Higgs candidate have mass 126 GeV since all different decay channels bb , WW, gg, ττ, ZZ, $c\bar{c}$ all have a branching ratio which is above a few % (thus measurable) and the branching ratio to γγ is close to it's maximum (this channel could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



Beyond the Standard Model
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

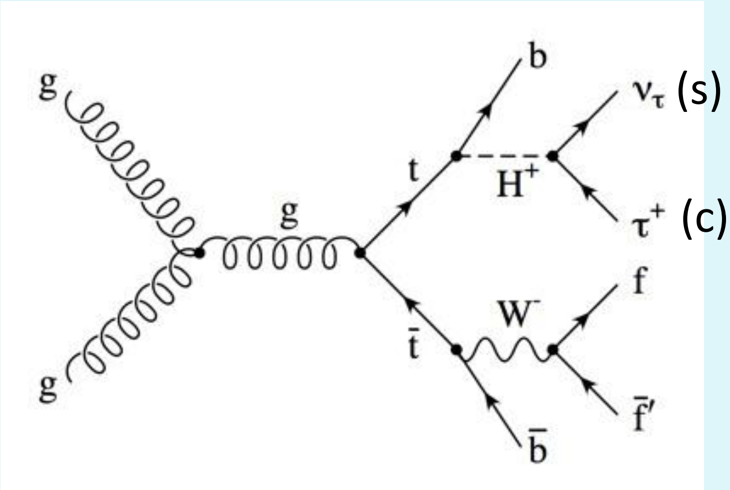
$$\Delta m_H^2 = \frac{\lambda_s}{16\pi^2}\left[\Lambda_{UV}^2 - 2m_s^2 \ln(\Lambda_{UV}/m_s) + \ldots\right]$$

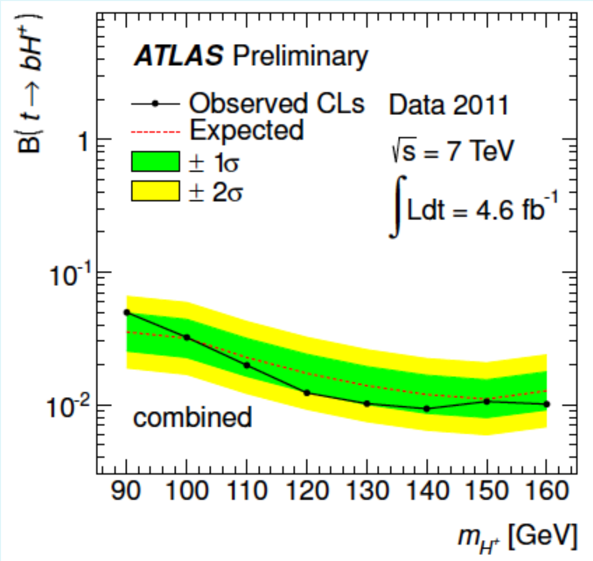
SUSY provides correct coupling and number of states for cancellations

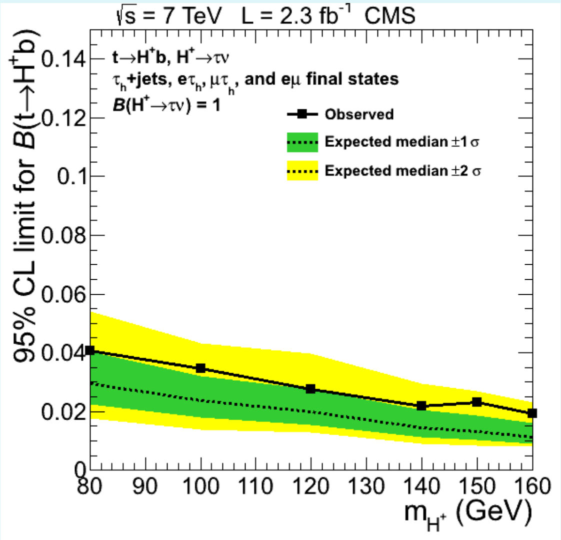
5

Searches for charged Higgs

t->bH+

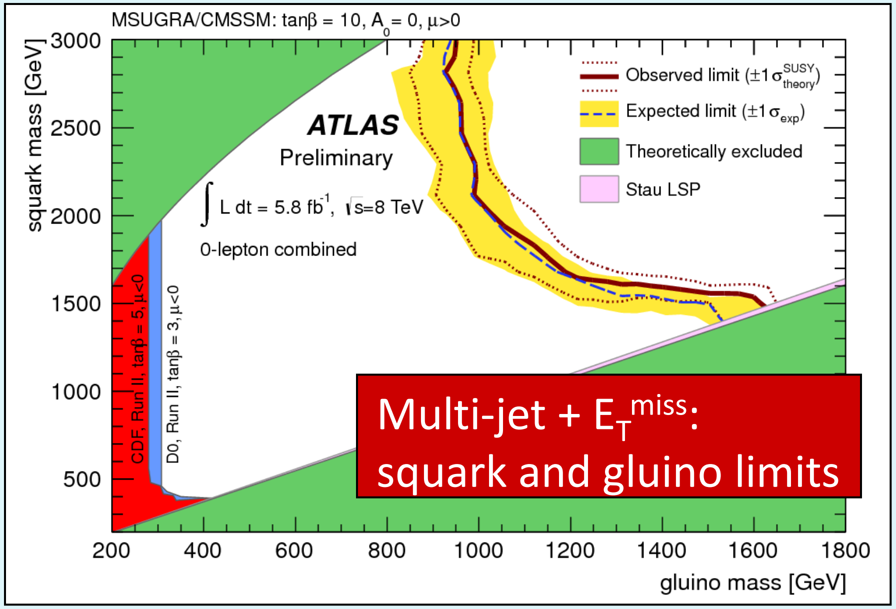




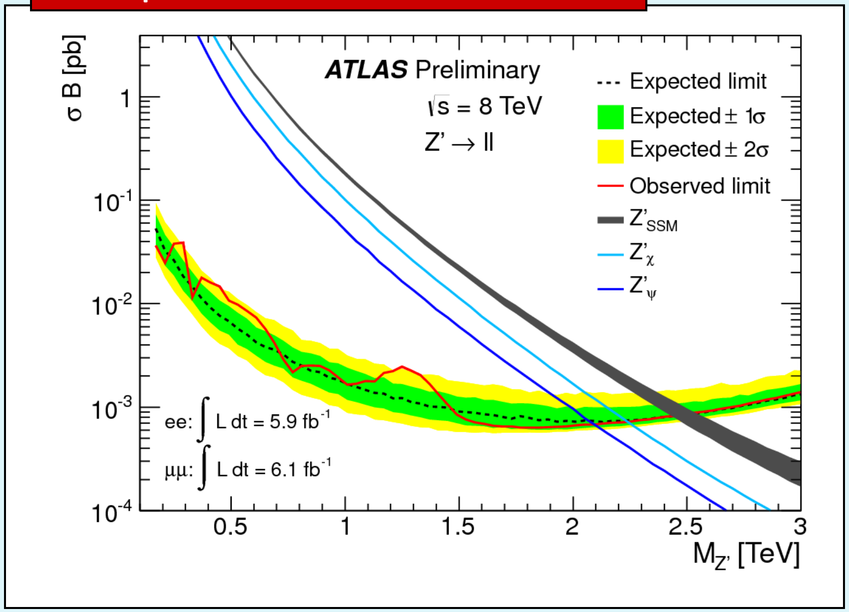


No other hints for New Physics, so far …

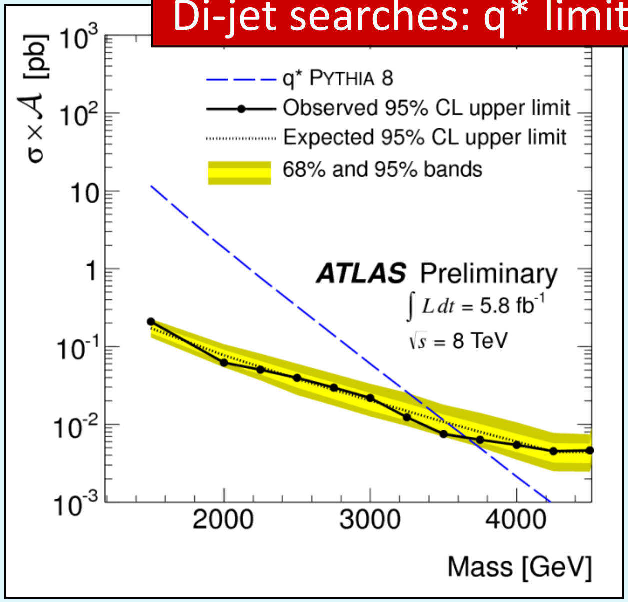
Multi-jet + E_T^{miss}: squark and gluino limits

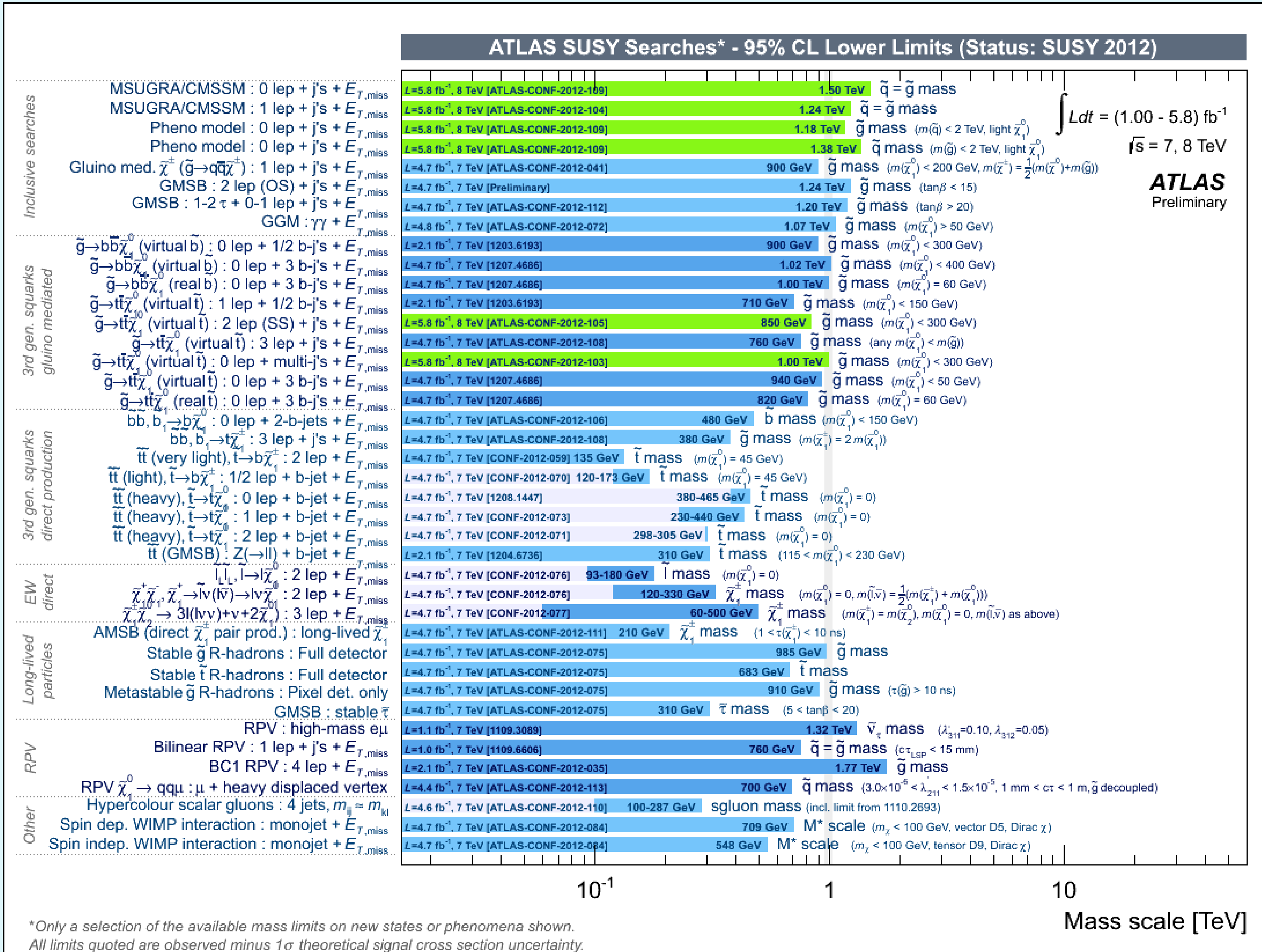


Di-lepton searches: Z' limits

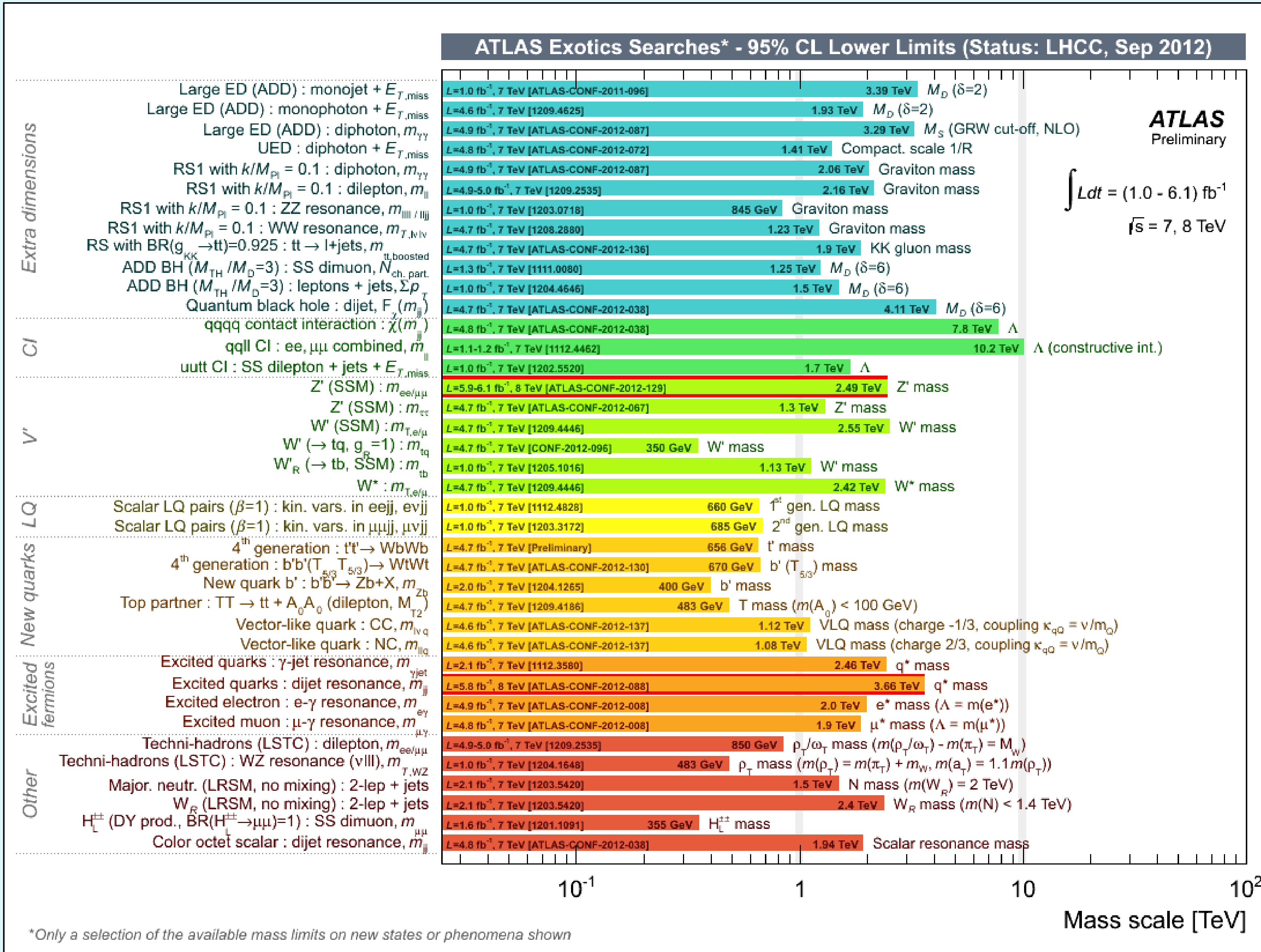


Di-jet searches: q* limits

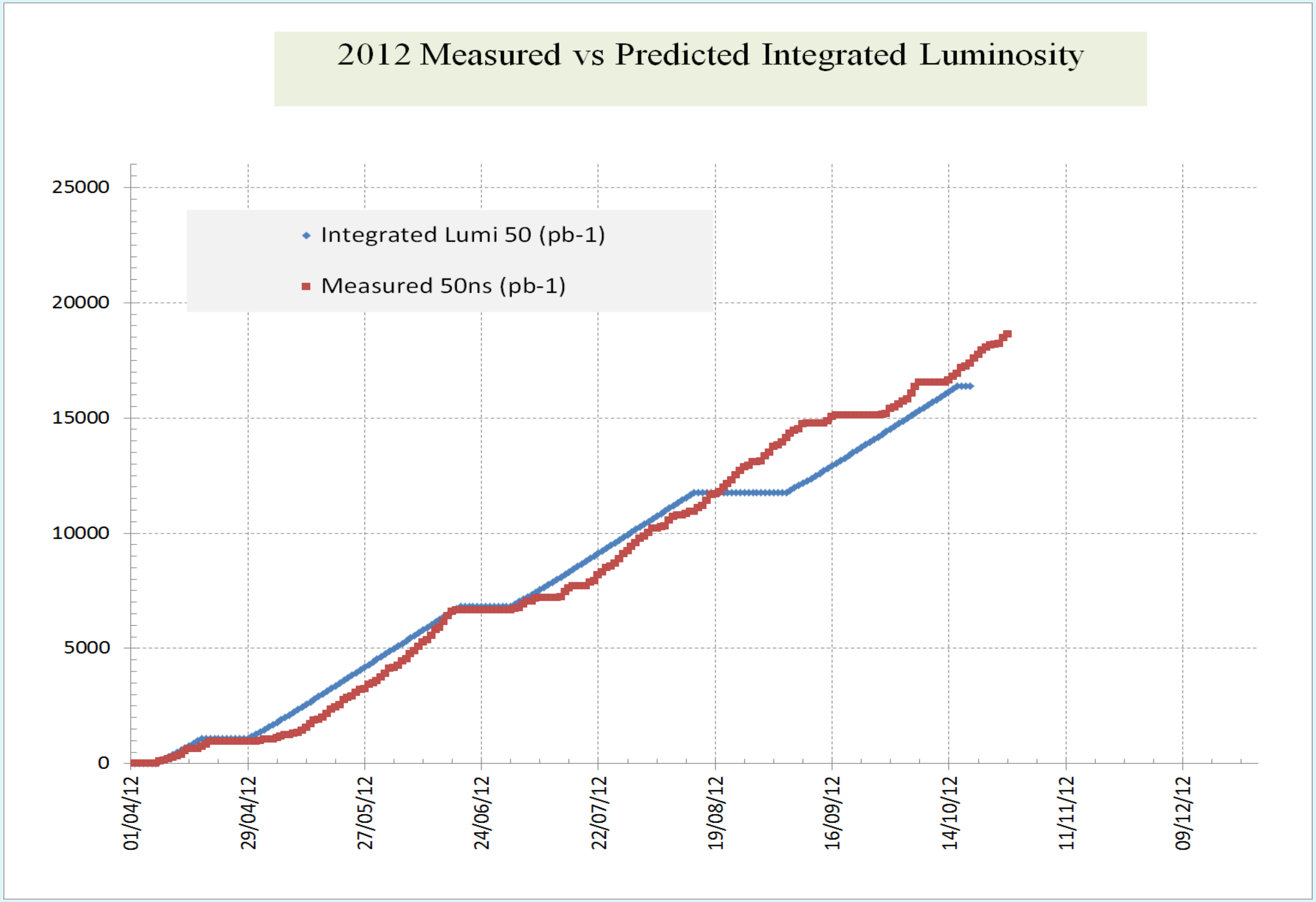




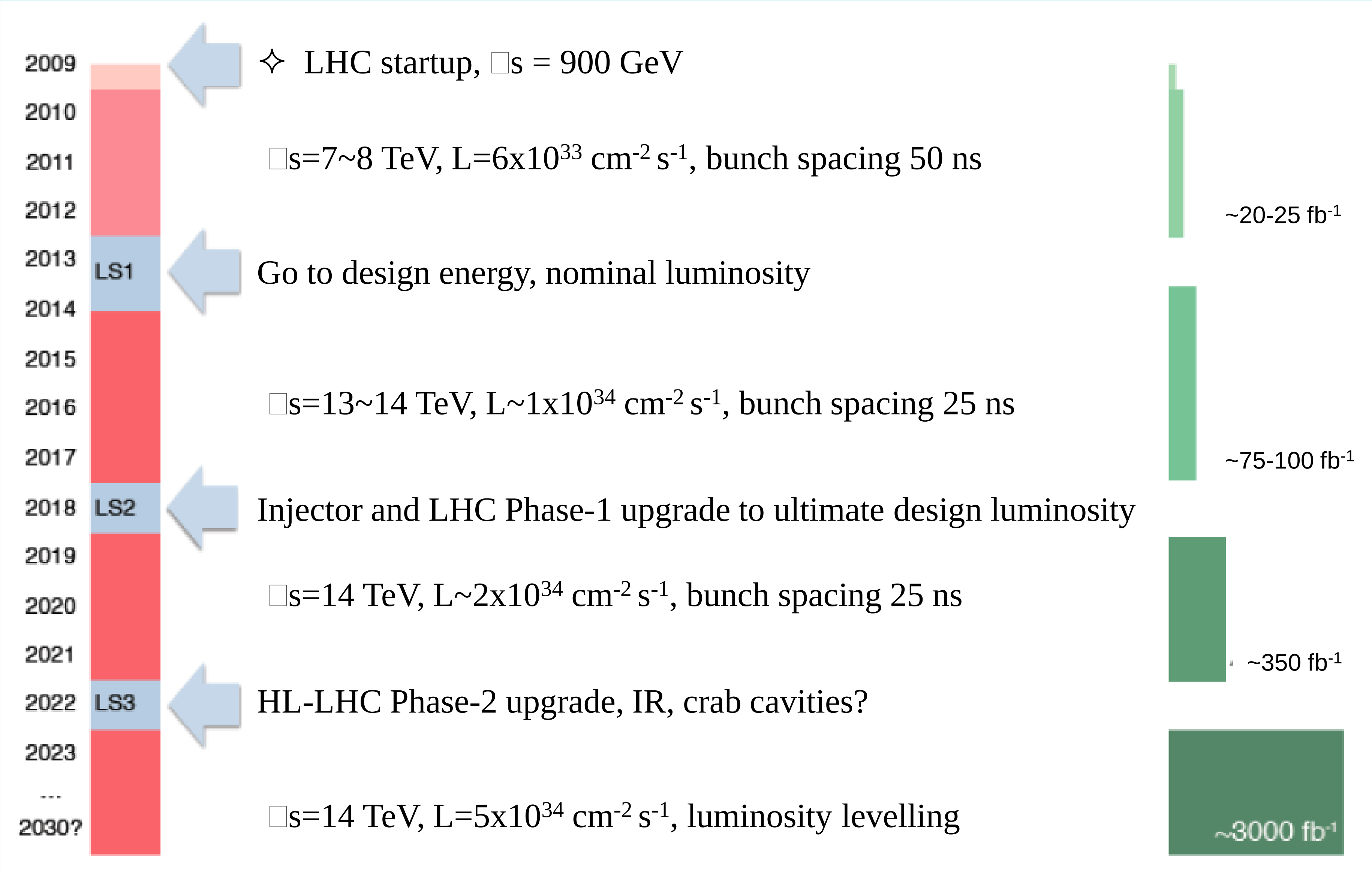
ATLAS SUSY Searches* - 95% CL Lower Limits (Status: SUSY 2012)
Inclusive searches
3rd gen. squarks gluino mediated
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Other
ATLAS
Preliminary
√s = 7, 8 TeV
10^-1
1
10
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown.
All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.


ATLAS Exotics Searches* - 95% CL Lower Limits (Status: LHCC, Sep 2012)
ATLAS
Preliminary
∫Ldt = (1.0 - 6.1) fb^-1
√s = 7, 8 TeV
Extra dimensions
CI
V'
LQ
New quarks
Excited fermions
Other
Large ED (ADD) : monojet + E_T,miss
L=1.0 fb^-1, 7 TeV [ATLAS-CONF-2011-096]
3.39 TeV
M_D (δ=2)
Large ED (ADD) : monophoton + E_T,miss
L=4.6 fb^-1, 7 TeV [1209.4625]
1.93 TeV
M_D (δ=2)
Large ED (ADD) : diphoton, m_γγ
L=4.9 fb^-1, 7 TeV [ATLAS-CONF-2012-087]
3.29 TeV
M_S (GRW cut-off, NLO)
UED : diphoton + E_T,miss
L=4.8 fb^-1, 7 TeV [ATLAS-CONF-2012-072]
1.41 TeV
Compact. scale 1/R
RS1 with k/M_Pl = 0.1 : diphoton, m_γγ
L=4.9 fb^-1, 7 TeV [ATLAS-CONF-2012-087]
2.06 TeV
Graviton mass
RS1 with k/M_Pl = 0.1 : dilepton, m_ll
L=4.9-5.0 fb^-1, 7 TeV [1209.2535]
2.16 TeV
Graviton mass
RS1 with k/M_Pl = 0.1 : ZZ resonance, m_llll / lljj
L=1.0 fb^-1, 7 TeV [1203.0718]
845 GeV
Graviton mass
RS1 with k/M_Pl = 0.1 : WW resonance, m_T,lνlν
L=4.7 fb^-1, 7 TeV [1208.2880]
1.23 TeV
Graviton mass
RS with BR(g_KK→tt)=0.925 : tt → l+jets, m_tt,boosted
L=4.7 fb^-1, 7 TeV [ATLAS-CONF-2012-136]
1.9 TeV
KK gluon mass
ADD BH (M_TH /M_D=3) : SS dimuon, N_ch. part.
L=1.3 fb^-1, 7 TeV [1111.0080]
1.25 TeV
M_D (δ=6)
ADD BH (M_TH /M_D=3) : leptons + jets, Σp_T
L=1.0 fb^-1, 7 TeV [1204.4646]
1.5 TeV
M_D (δ=6)
Quantum black hole : dijet, F_χ(m_jj)
L=4.7 fb^-1, 7 TeV [ATLAS-CONF-2012-038]
4.11 TeV
M_D (δ=6)
qqqq contact interaction : χ(m_jj)
L=4.8 fb^-1, 7 TeV [ATLAS-CONF-2012-038]
7.8 TeV
Λ
qqll CI : ee, μμ combined, m_ll
L=1.1-1.2 fb^-1, 7 TeV [1112.4462]
10.2 TeV
Λ (constructive int.)
uutt CI : SS dilepton + jets + E_T,miss
L=1.0 fb^-1, 7 TeV [1202.5520]
1.7 TeV
Λ
Z' (SSM) : m_ee/μμ
L=5.9-6.1 fb^-1, 8 TeV [ATLAS-CONF-2012-129]
2.49 TeV
Z' mass
Z' (SSM) : m_ττ
L=4.7 fb^-1, 7 TeV [ATLAS-CONF-2012-067]
1.3 TeV
Z' mass
W' (SSM) : m_T,e/μ
L=4.7 fb^-1, 7 TeV [1209.4446]
2.55 TeV
W' mass
W' (→ tq, g_R=1) : m_tq
L=4.7 fb^-1, 7 TeV [CONF-2012-096]
350 GeV
W' mass
W'_R (→ tb, SSM) : m_tb
L=1.0 fb^-1, 7 TeV [1205.1016]
1.13 TeV
W' mass
W* : m_T,e/μ
L=4.7 fb^-1, 7 TeV [1209.4446]
2.42 TeV
W* mass
Scalar LQ pairs (β=1) : kin. vars. in eejj, eνjj
L=1.0 fb^-1, 7 TeV [1112.4828]
660 GeV
1st gen. LQ mass
Scalar LQ pairs (β=1) : kin. vars. in μμjj, μνjj
L=1.0 fb^-1, 7 TeV [1203.3172]
685 GeV
2nd gen. LQ mass
4th generation : t't'→ WbWb
L=4.7 fb^-1, 7 TeV [Preliminary]
656 GeV
t' mass
4th generation : b'b'(T_5/3 T_5/3)→ WtWt
L=4.7 fb^-1, 7 TeV [ATLAS-CONF-2012-130]
670 GeV
b' (T_5/3) mass
New quark b' : b'b'→ Zb+X, m_Zb
L=2.0 fb^-1, 7 TeV [1204.1265]
400 GeV
b' mass
Top partner : TT → tt + A_0A_0 (dilepton, M_T2)
L=4.7 fb^-1, 7 TeV [1209.4186]
483 GeV
T mass (m(A_0) < 100 GeV)
Vector-like quark : CC, m_lνq
L=4.6 fb^-1, 7 TeV [ATLAS-CONF-2012-137]
1.12 TeV
VLQ mass (charge -1/3, coupling κ_qQ = ν/m_Q)
Vector-like quark : NC, m_llq
L=4.6 fb^-1, 7 TeV [ATLAS-CONF-2012-137]
1.08 TeV
VLQ mass (charge 2/3, coupling κ_qQ = ν/m_Q)
Excited quarks : γ-jet resonance, m_γjet
L=2.1 fb^-1, 7 TeV [1112.3580]
2.46 TeV
q* mass
Excited quarks : dijet resonance, m_jj
L=5.8 fb^-1, 8 TeV [ATLAS-CONF-2012-088]
3.66 TeV
q* mass
Excited electron : e-γ resonance, m_eγ
L=4.9 fb^-1, 7 TeV [ATLAS-CONF-2012-008]
2.0 TeV
e* mass (Λ = m(e*))
Excited muon : μ-γ resonance, m_μγ
L=4.8 fb^-1, 7 TeV [ATLAS-CONF-2012-008]
1.9 TeV
μ* mass (Λ = m(μ*))
Techni-hadrons (LSTC) : dilepton, m_ee/μμ
L=4.9-5.0 fb^-1, 7 TeV [1209.2535]
850 GeV
ρ_T/ω_T mass (m(ρ_T/ω_T) - m(π_T) = M_W)
Techni-hadrons (LSTC) : WZ resonance (νlll), m_T,WZ
L=1.0 fb^-1, 7 TeV [1204.1648]
483 GeV
ρ_T mass (m(ρ_T) = m(π_T) + m_W, m(a_T) = 1.1 m(ρ_T))
Major. neutr. (LRSM, no mixing) : 2-lep + jets
L=2.1 fb^-1, 7 TeV [1203.5420]
1.5 TeV
N mass (m(W_R) = 2 TeV)
W_R (LRSM, no mixing) : 2-lep + jets
L=2.1 fb^-1, 7 TeV [1203.5420]
2.4 TeV
W_R mass (m(N) < 1.4 TeV)
H_L^±± (DY prod., BR(H_L^±±→μμ)=1) : SS dimuon, m_μμ
L=1.6 fb^-1, 7 TeV [1201.1091]
355 GeV
H_L^±± mass
Color octet scalar : dijet resonance, m_jj
L=4.8 fb^-1, 7 TeV [ATLAS-CONF-2012-038]
1.94 TeV
Scalar resonance mass
10^-1
1
10
10^2
Mass scale [TeV]
*Only a selection of the available mass limits on new states or phenomena shown

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



Conclusion

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.