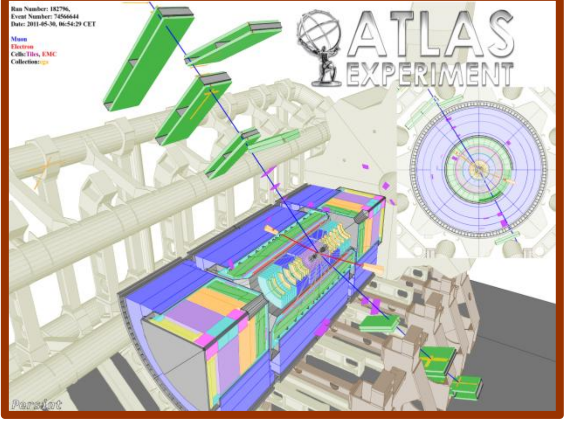
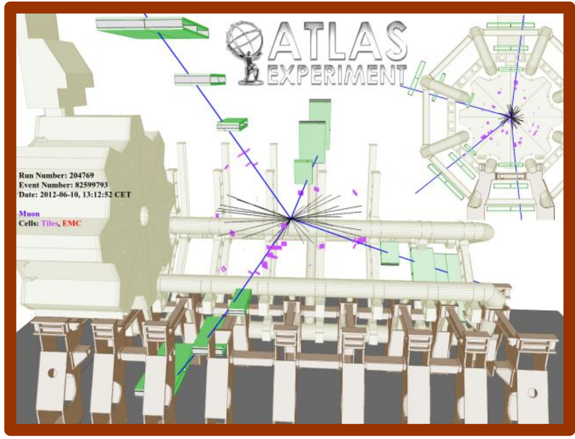
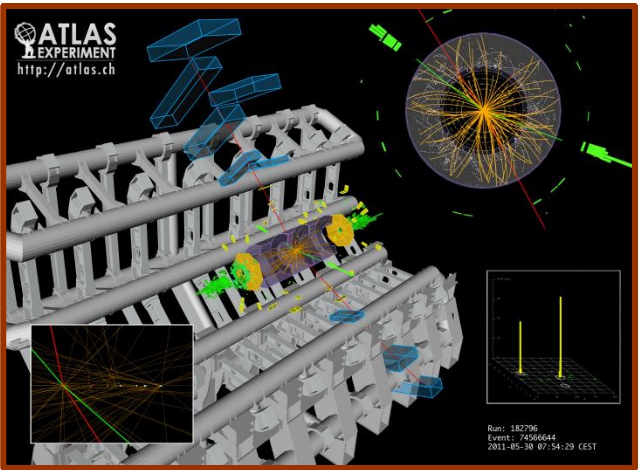


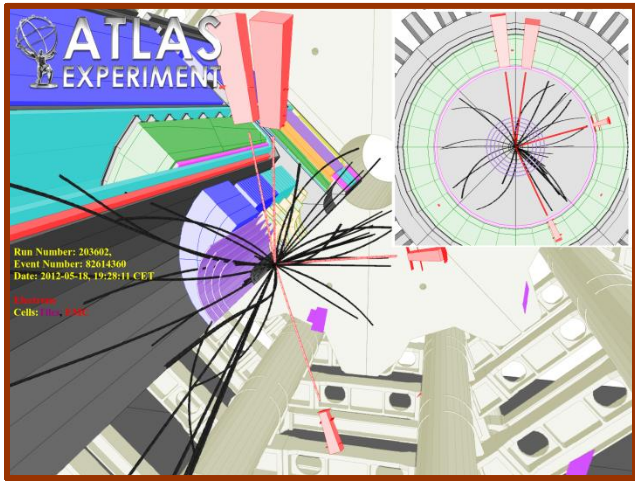


Review of ATLAS experimental results (II)

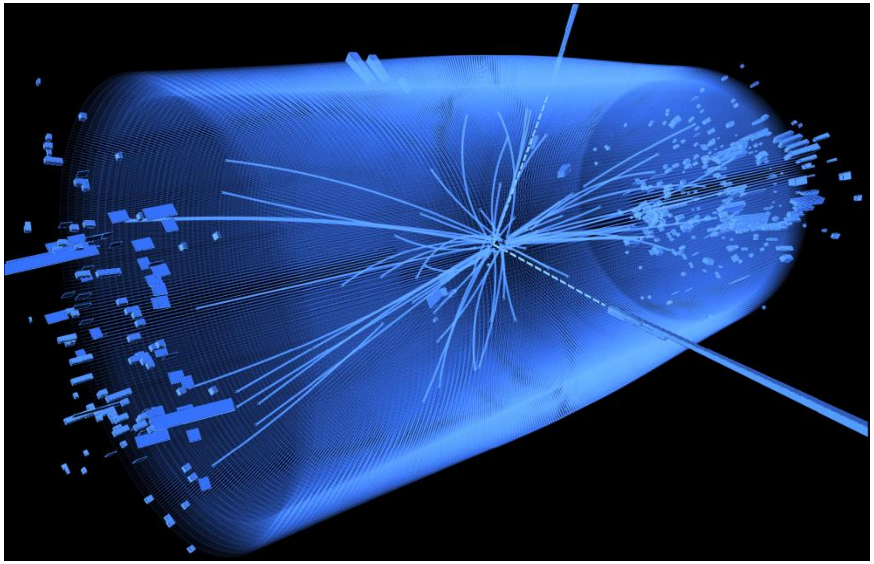
Rachid Mazini
Academia Sinica Taiwan



CTEQ 2012 summer school
Lima, Peru
30 July -8 August



Outline part II



- **Higgs searches**
  - **$H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, $H \rightarrow WW$**
- **BSM**
  - **SUSY,**
  - **Exotics: extra-dimensions, new resonances, everything else(?)**

Higgs day


July 3rd , 18:00h


July 3rd , 22:00h

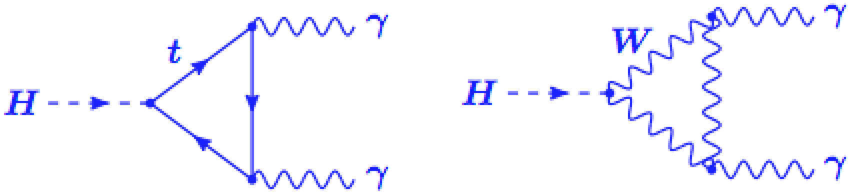

July 4rd , 7:00h


July 3rd , Interlude

H→γγ @ the LHC

- Small branching ratio (0.002)
- Higgs decays via top and W loops

σ x BR ~ 50 fb m_H ~ 126 GeV

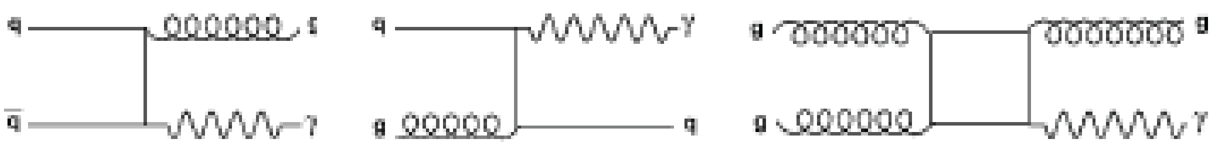


Advantage: **Nice 2 photon mass peak!**

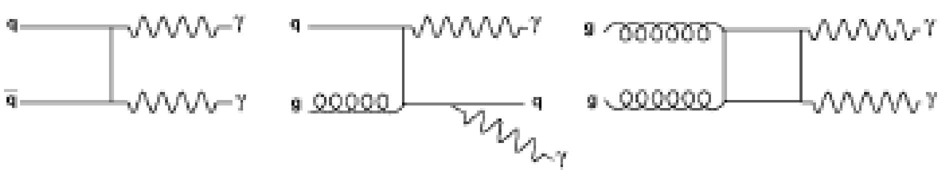
- Main background from pi0's
- Need large jet rejection factors to reduce background and to see possible signal

•Photon identification is crucial ! (shower shapes, no track) - Fit background with "assumed" function (**no peak in bkgr.)**

Reducible background: pp→γj , jj+ X



Irreducible background: pp→γγ + X

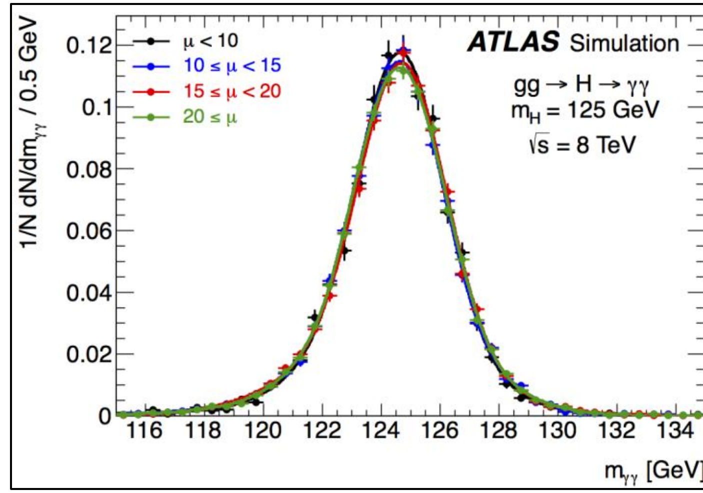


$H \to \gamma\gamma$: Mass resolution

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

- From Z, J/ψ → ee, W→ eν , data and MC:
  - E-scale at m_Z known to ~ 0.5%
  - Linearity better than 1% (few-100 GeV)
  - "Uniformity" (constant term of resolution): ~ 1% (2.5% for $1.37<|\eta|<1.8$)

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

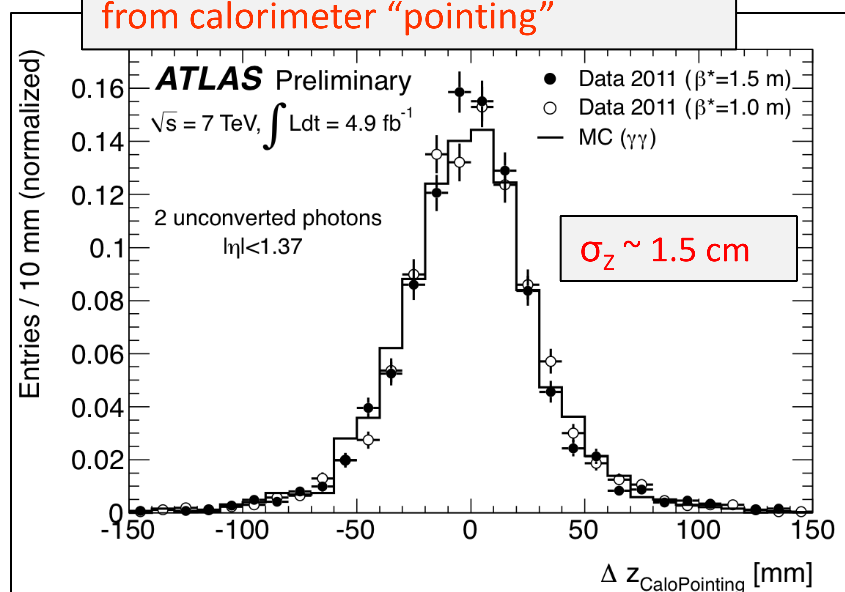


$m^2_{\gamma\gamma} = 2 E_1 E_2 (1-\cos\alpha)$

High pile-up: many vertices distributed over σ_Z (LHC beam spot) ~ 5-6 cm . Primary vertex from:

- EM calorimeter longitudinal (and lateral) segmentation
- tracks from converted photons
- hardness of associated tracks (Σp_T^2) → Efficiency to reconstruct correct vertex: ~ 80%
- vertex uncertainty reduced to ~ 1.5 cm

Z-vertex measured in γγ events from calorimeter "pointing"

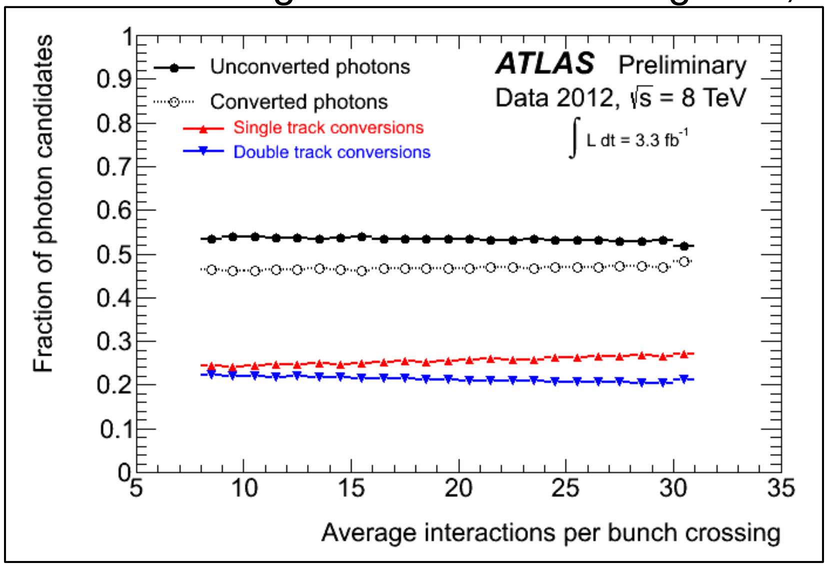


$Z(\gamma_1) - Z(\gamma_2)$

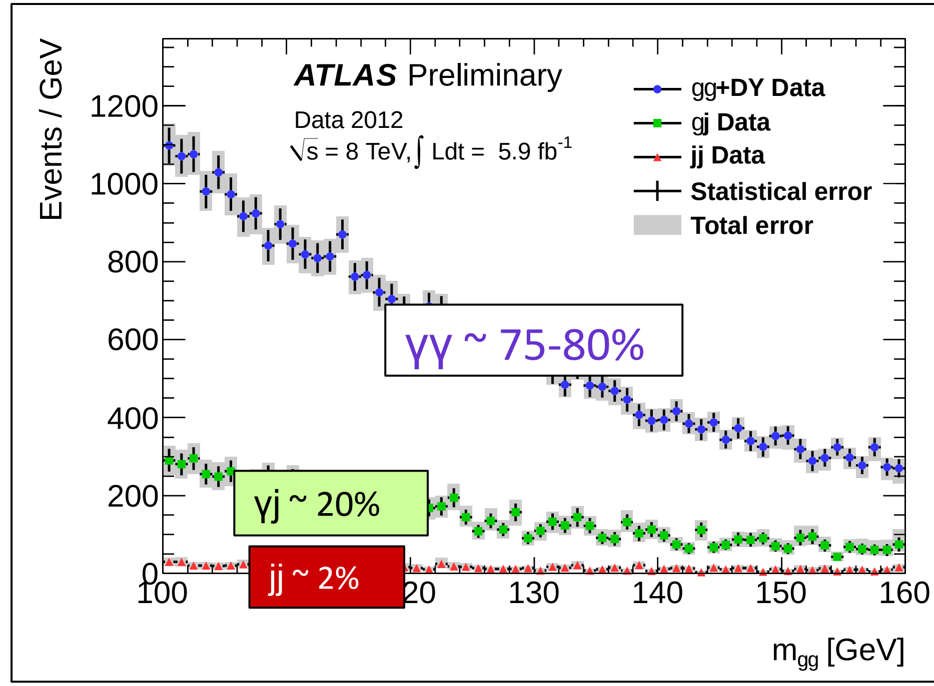
H→γγ: γ reconstruction and γ/jet separation

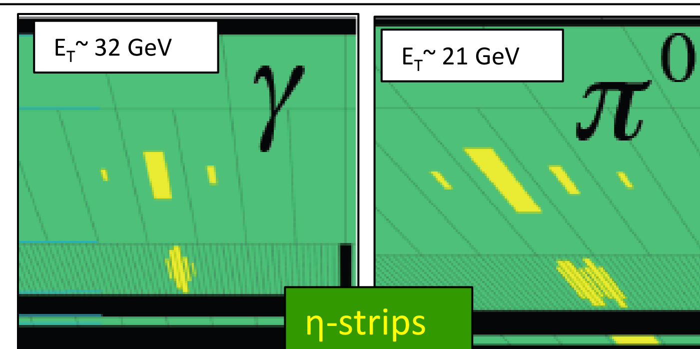
Fraction of converted and unconverted γ vs pile-up is stable (within 1%)

- small migration between categories,



Data-driven decomposition of selected γγ sample





In addition: Photon isolation requirement: $E_T < 4$ GeV inside cone $\Delta R < 0.4$ around γ direction.

Pile-up contribution subtracted using an "ambient energy density" event-by-event

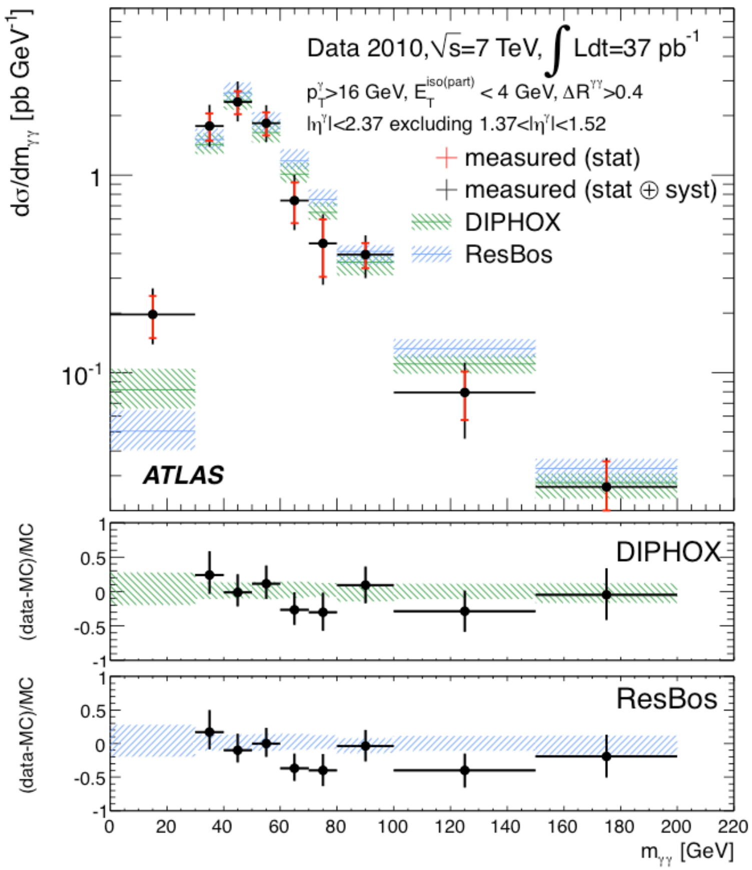
High γγ purity: $R_j \sim 10^4$

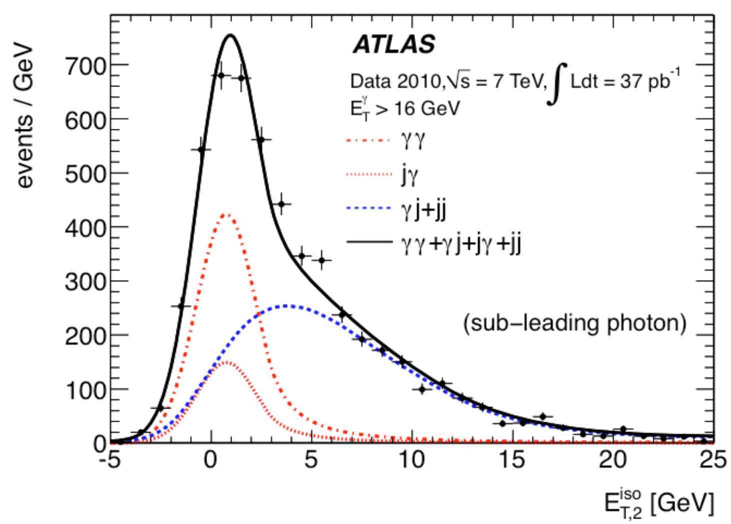
$\varepsilon(\gamma) \sim 85$-$90\%$

Background modelling

Estimate backgrounds from data

- Mass spectrum is smooth and non-resonant
- Simulation-based estimates subject to relatively large theory uncertainties, mis-modeling of large background rejection factors



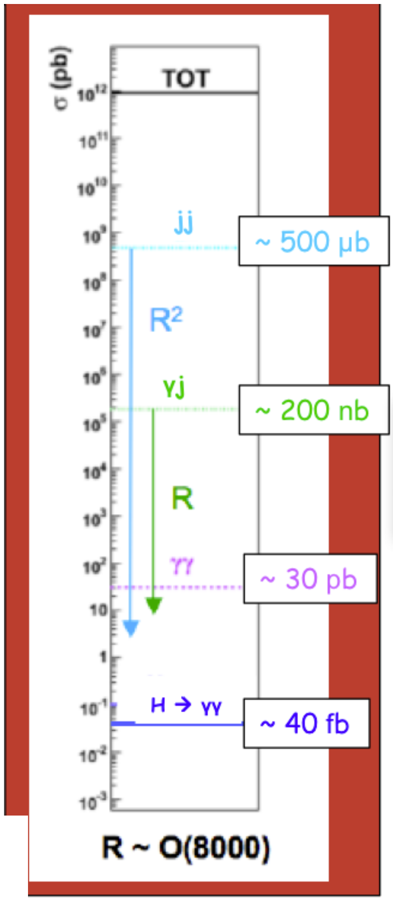


Multijets

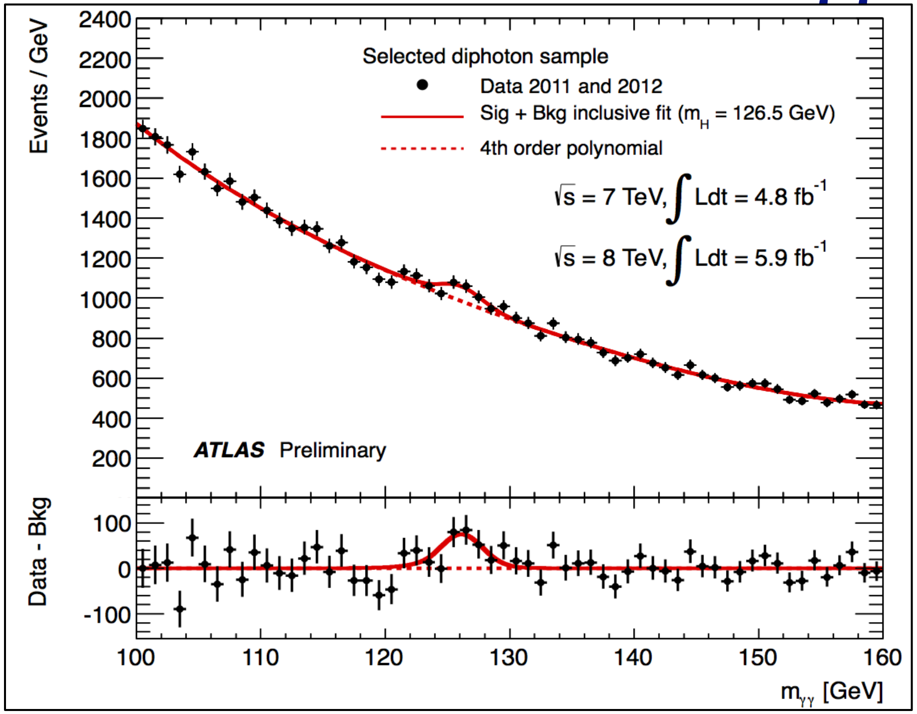
Photon+jet

Diphoton

Higgs



H→γγ: Results

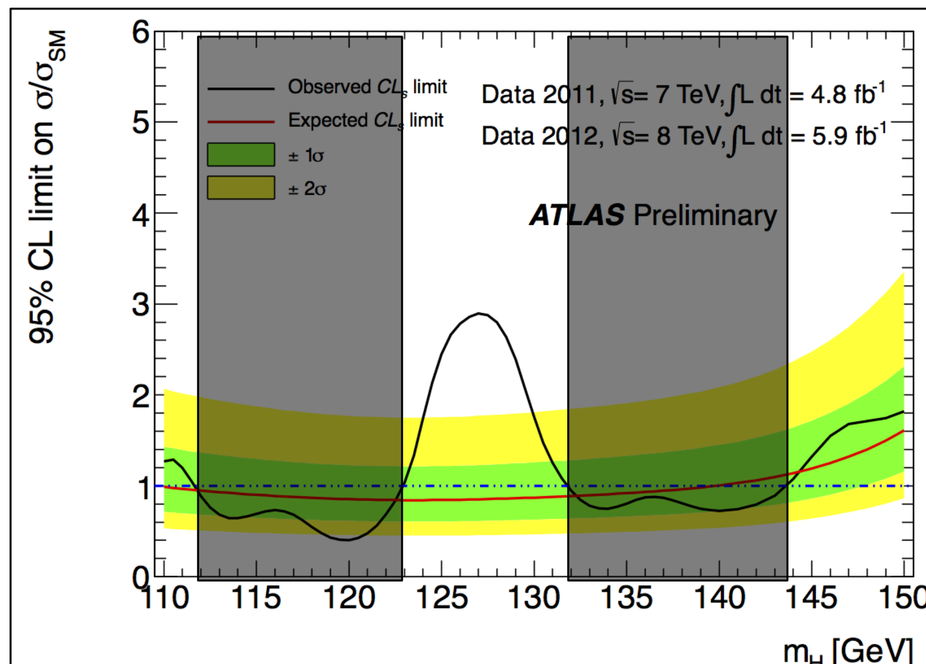


of events in $m_{\gamma\gamma}$=126.5 ± 3 GeV

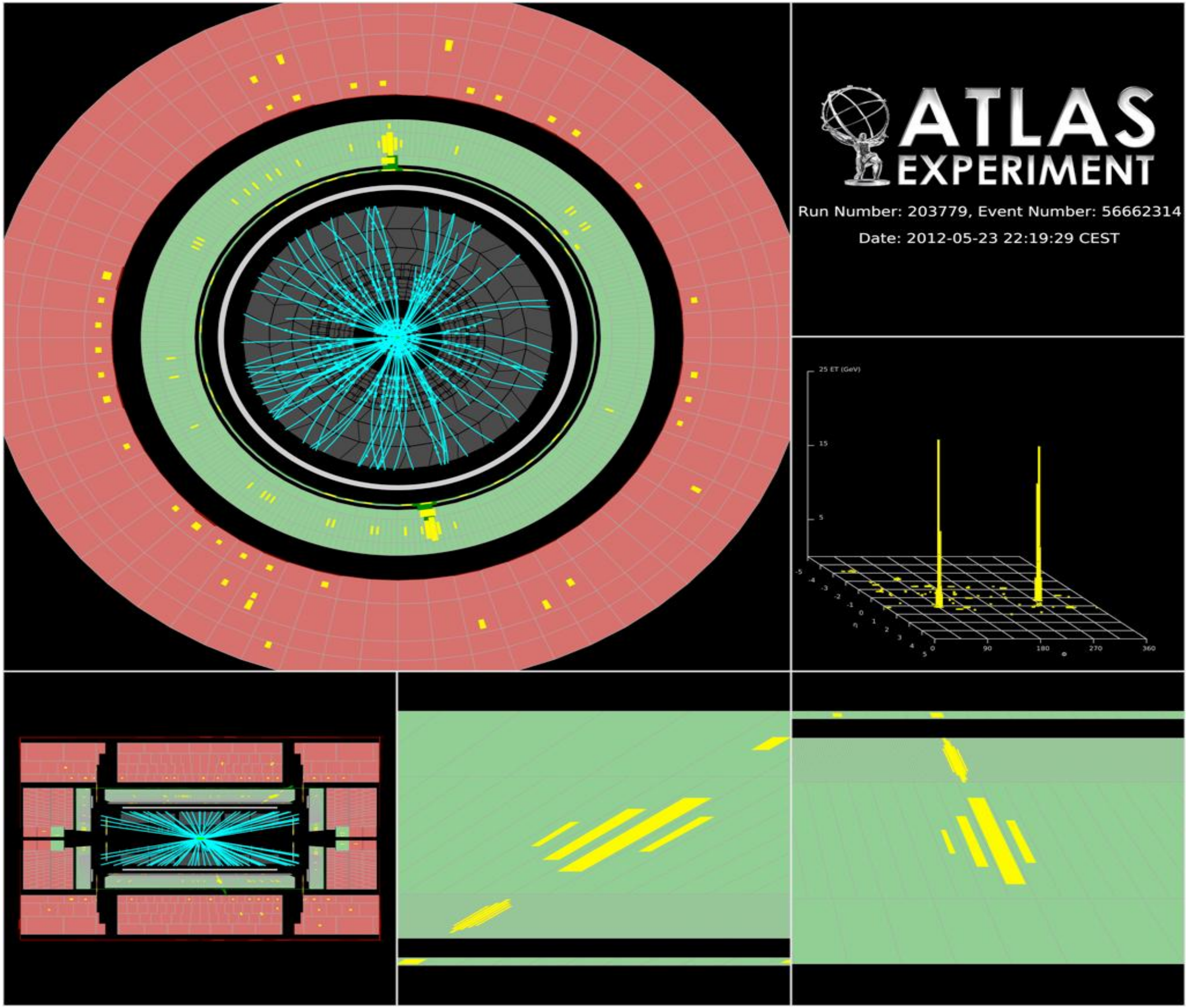
Observed	6494
Expected from background	6340
Expected from signal	170

Main systematic uncertainties

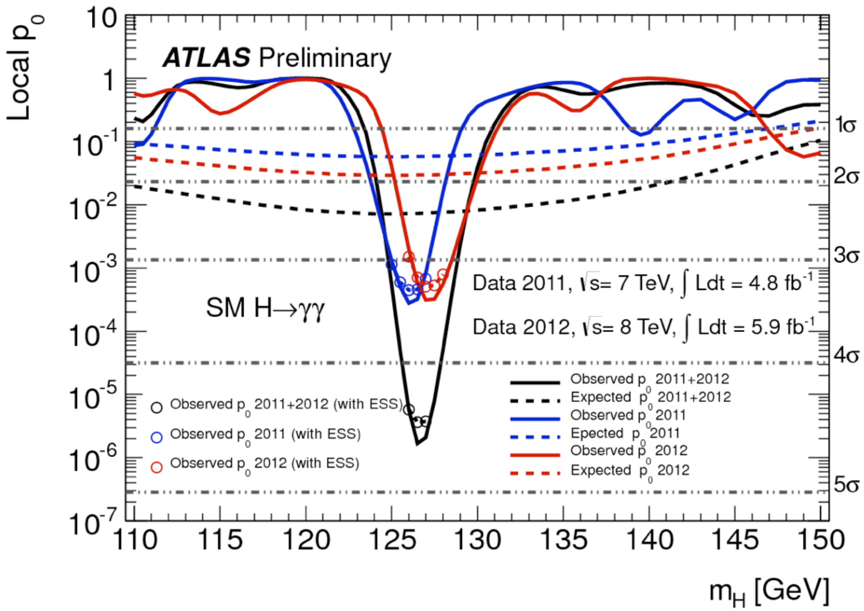
Signal yield (theory)	~ 25%
Photon efficiency	~ 5%
H→ γγ mass resolution	~ 14%
Background model	~ 10%
Migration between categories	
Higgs p_T modeling	up to ~ 10%
Conv/unconv γ	up to ~ 6%
Jet E-scale	up to 20% (2j/VBF)
Underlying event	up to 30% (2j/VBF)



$H \to \gamma\gamma$: Results



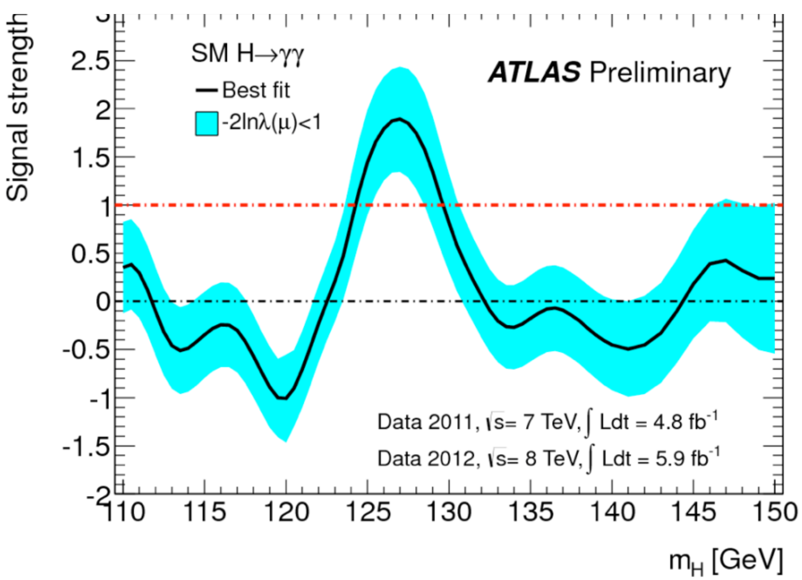
H→γγ: Consistency with background and strength

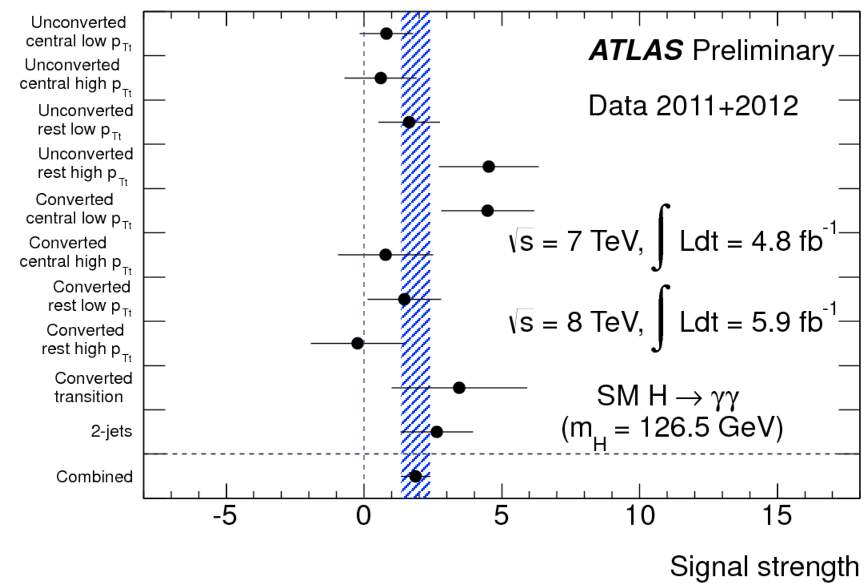


Maximum deviation from background expectation at m_H=126.5 GeV

- Local significance of 4.5σ (exp. 2.4σ)
  - 7 TeV: 3.3σ (exp 1.6σ) 126 GeV
  - 8 TeV: 3.3σ (exp 1.9σ) 127 GeV
- Global significance (110–50 GeV) is 3.6σ
- Analysis without categories: 3.5σ

(local, 4th order polynomial background, no photon energy syst. (reduce by 0.1–0.2σ))

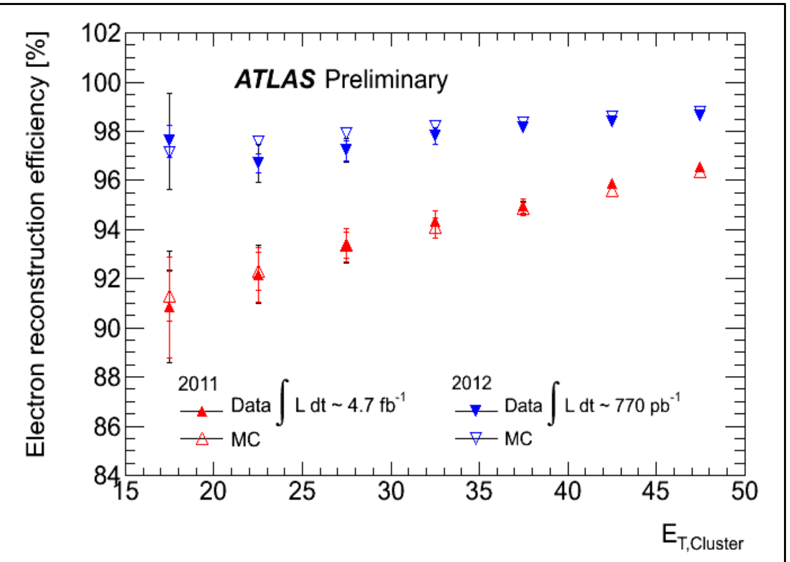




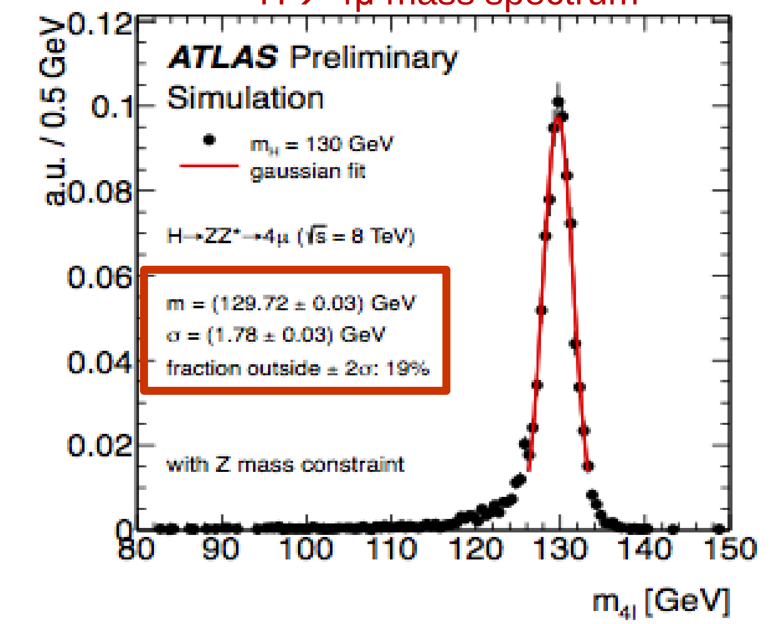
Best combined fit for mH = 126.5 GeV is 1.9±0.5 times the SM prediction

- Results compatible across the 10 categories

$H \rightarrow ZZ^* \rightarrow 4l$



H→ 4μ mass spectrum



Very clean final state: select four isolated leptons (e/μ) and look for a peak in m4l

- Four lepton requirement suppresses most backgrounds to a negligible level
- Remaining backgrounds are "irreducible" continuum ZZ (leading source of real four-lepton events in the SM) and Z+jets, top, Z+bb (leading sources of <4 real lepton + 1 or more fake leptons)

Many-lepton signal requires large acceptance, high reconstruction and identification efficiencies

- At least one of the four leptons is often forward or very low pT (m_H < 160 GeV ⇒ Z Z*)
- For 2012, improved electron reconstruction and ID (e.g. stable against pile-up)
- Additional muon acceptance (|η|<0.1, 2.5<|η|<2.7)
- Re-optimization for low mass (finalized before looking at 2012 data)
- Re-analysis of 2011 data

Efficiency (%)	4μ	2μ2e	4e
2011 data (old)	27	18	14
2011 data (new)	43	23	17
2012 data (new)	41	27	23

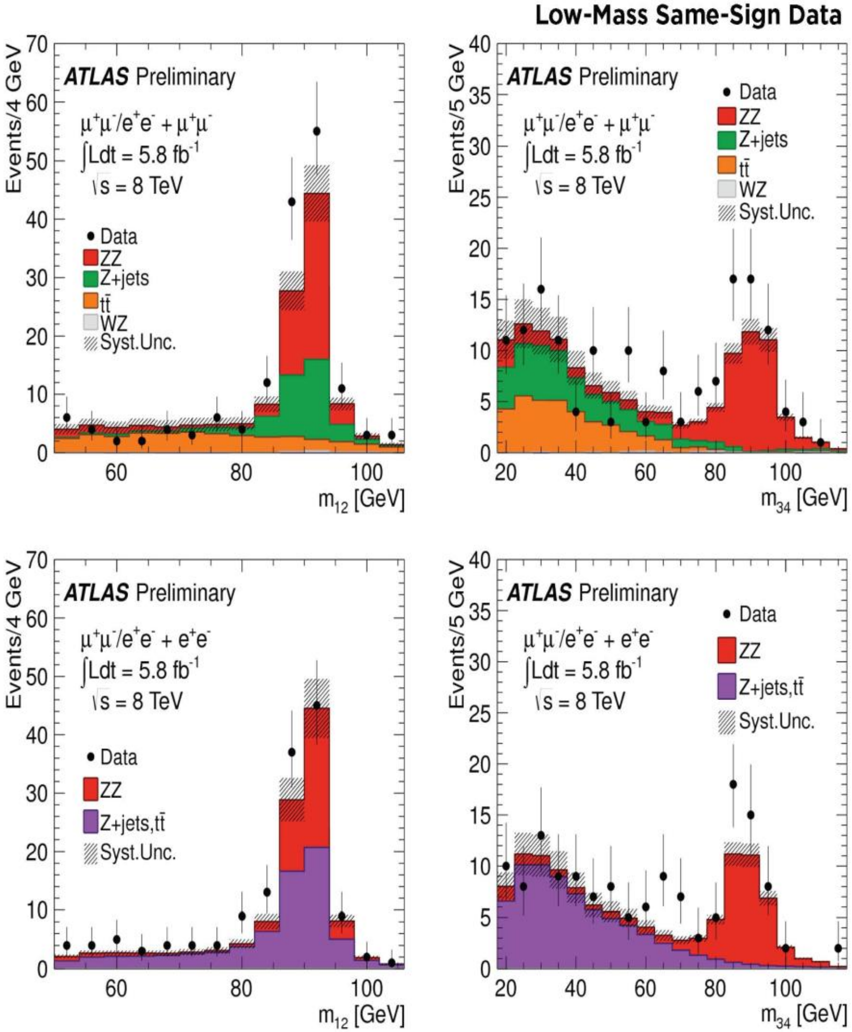
$H \rightarrow ZZ^* \rightarrow 4l$: Background estimation

Dominant background is below-threshold continuum ZZ* production

- Predicted by full simulation
- Normalization checked against data

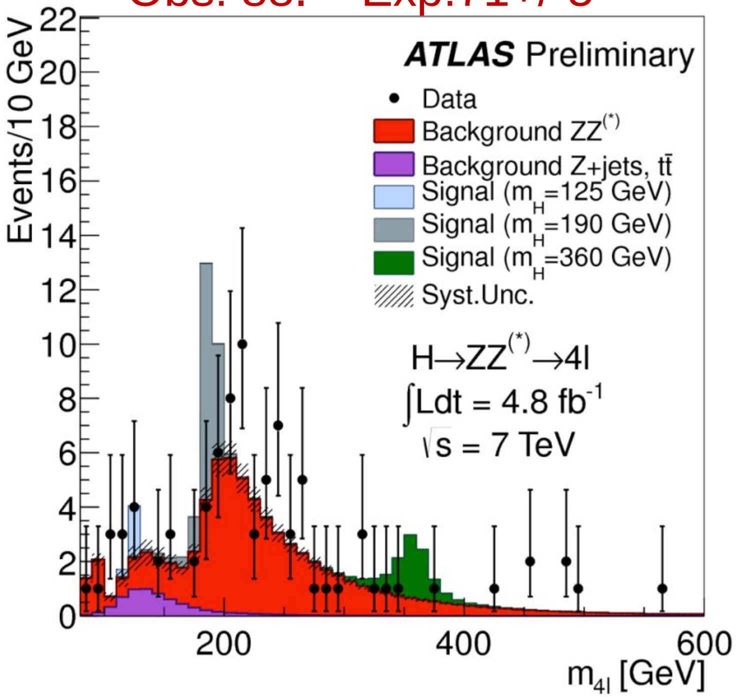
Backgrounds from Z+jets and tt also important at low p_T

- Reduced by the isolation and impact parameter cuts, largest for low mass electron pairs
- Predict Z+dimuon background from Zbb and tt using bb-enriched control data
- No isolation on low-mass muon pair, fail impact parameter cut
- Extract normalization from data CR,extrapolate Zbb and tt to signal region
- Predict Z+dielectron background from sidebands in electron ID variables
- Backgrounds from photon conversion, hadronic fakes, and semileptonic heavy-flavor decays
- Relax selection for templates, extract normalization in signal region with fit using innermost pixel hit, TRT high-threshold, and calorimeter shape variables
- Cross check with same-sign data

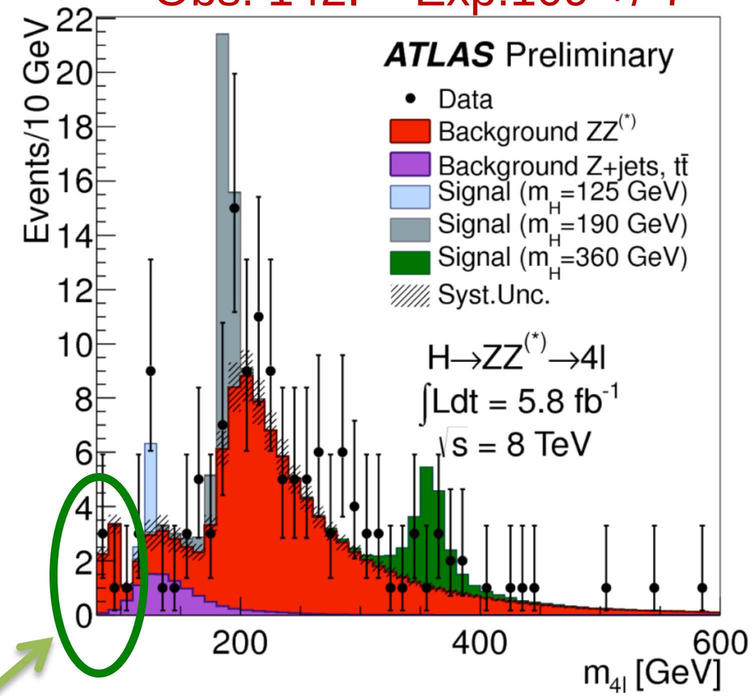


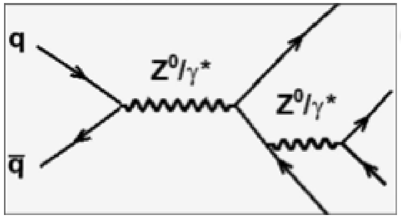
H → ZZ* → 4l : Results

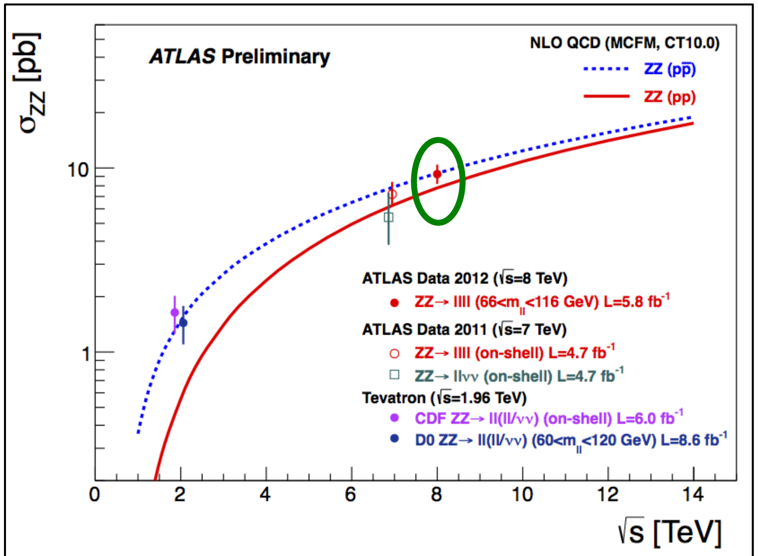
Obs: 88. Exp:71+/-5



Obs: 142. Exp:109 +/-7



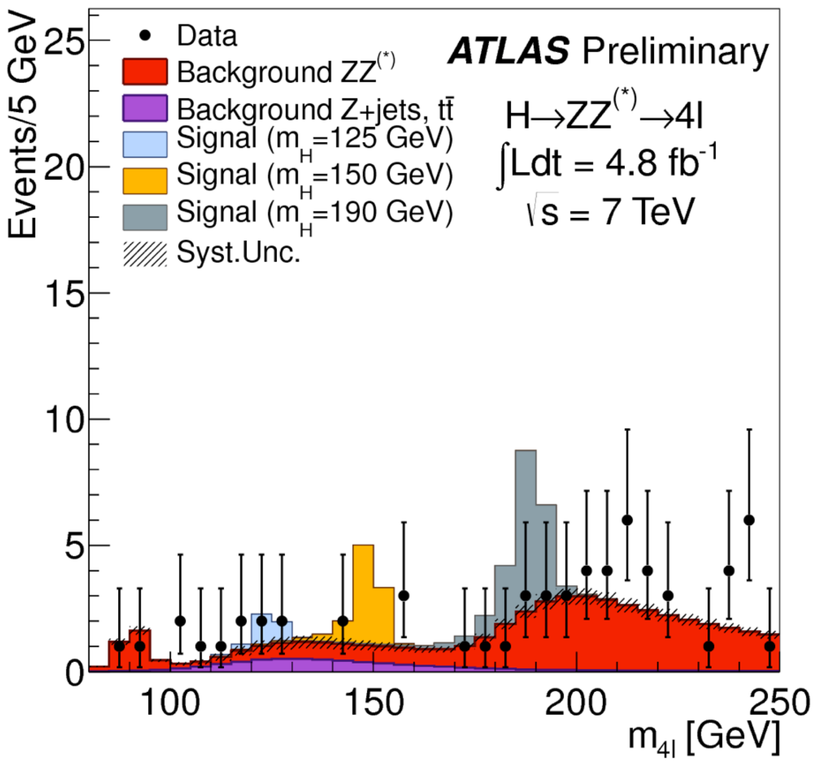


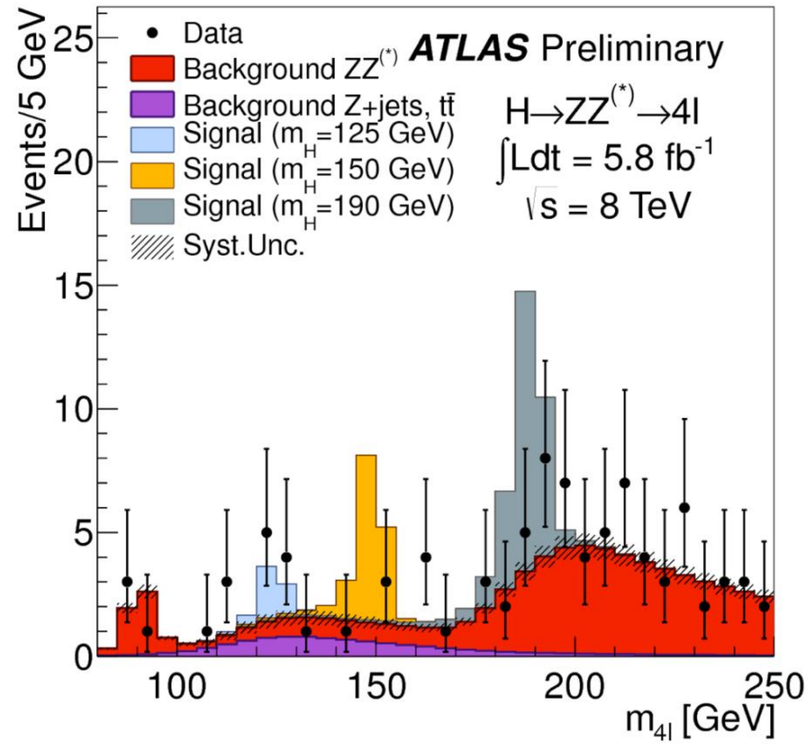


For m_{4l} > 160 GeV, observe 20–30% more events than predicted

- Event characteristics consistent with ZZ production
- Reported in the ATLAS ZZ cross section measurement

H → ZZ* → 4l: Results at low mass

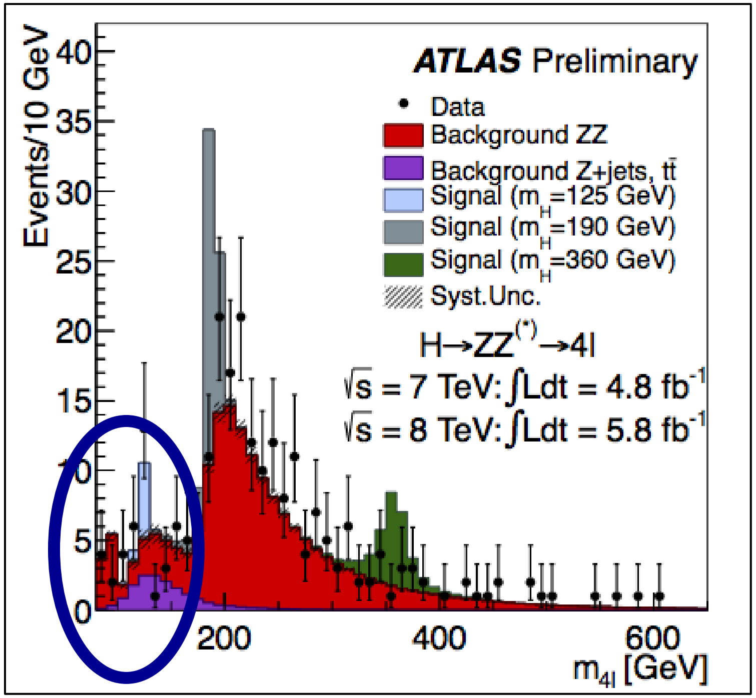


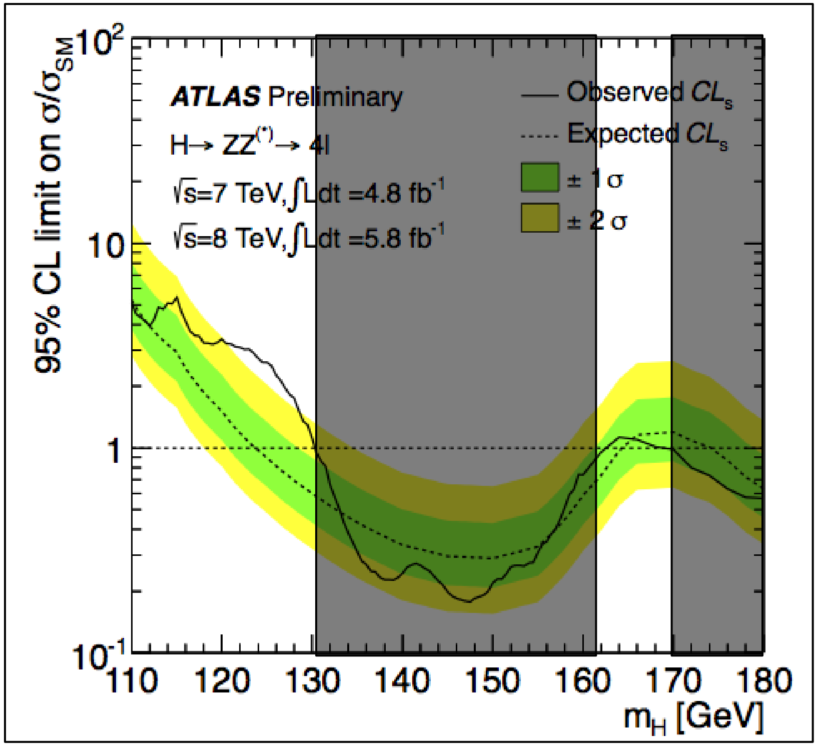


7+8 TeV	**4μ**	**2e2μ**	**4e**	**Sum**
Background	1.3±0.1	2.2±0.2	1.6±0.2	5.1±0.3
Data	6	5	2	13
m_H	2.1±0.3	2.3±0.3	0.9±0.1	5.3±0.4
S/B	1.6	1.0	0.6	1.0

Event counts for 120 < m4l < 130 GeV:
Distribution of excess across channels
is consistent with ZZ decay

H → ZZ* → 4l: 2011+2012 Results

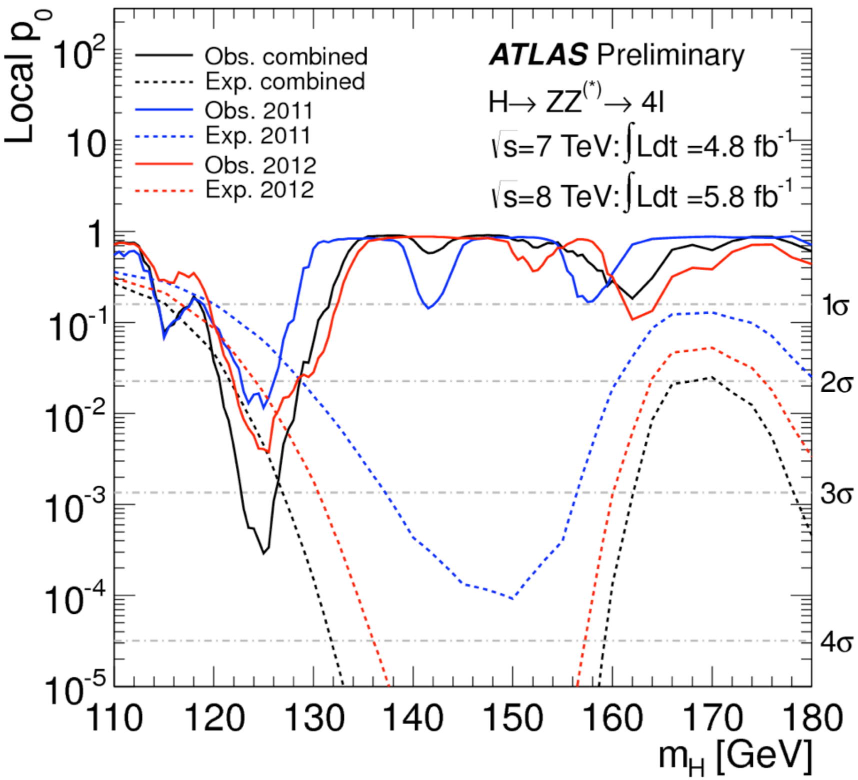


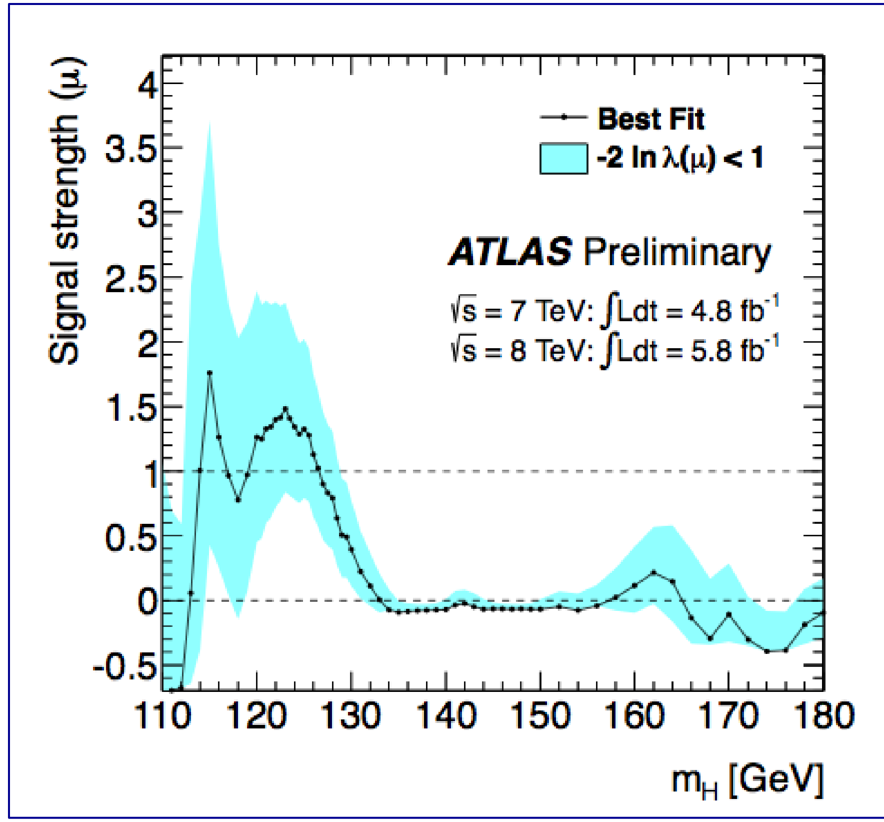


Excluded (95% CL):
131-162, 170-460 GeV

Expected:
124-164, 176-500 GeV

$H \rightarrow ZZ^* \rightarrow 4l$: Consistency with backgound

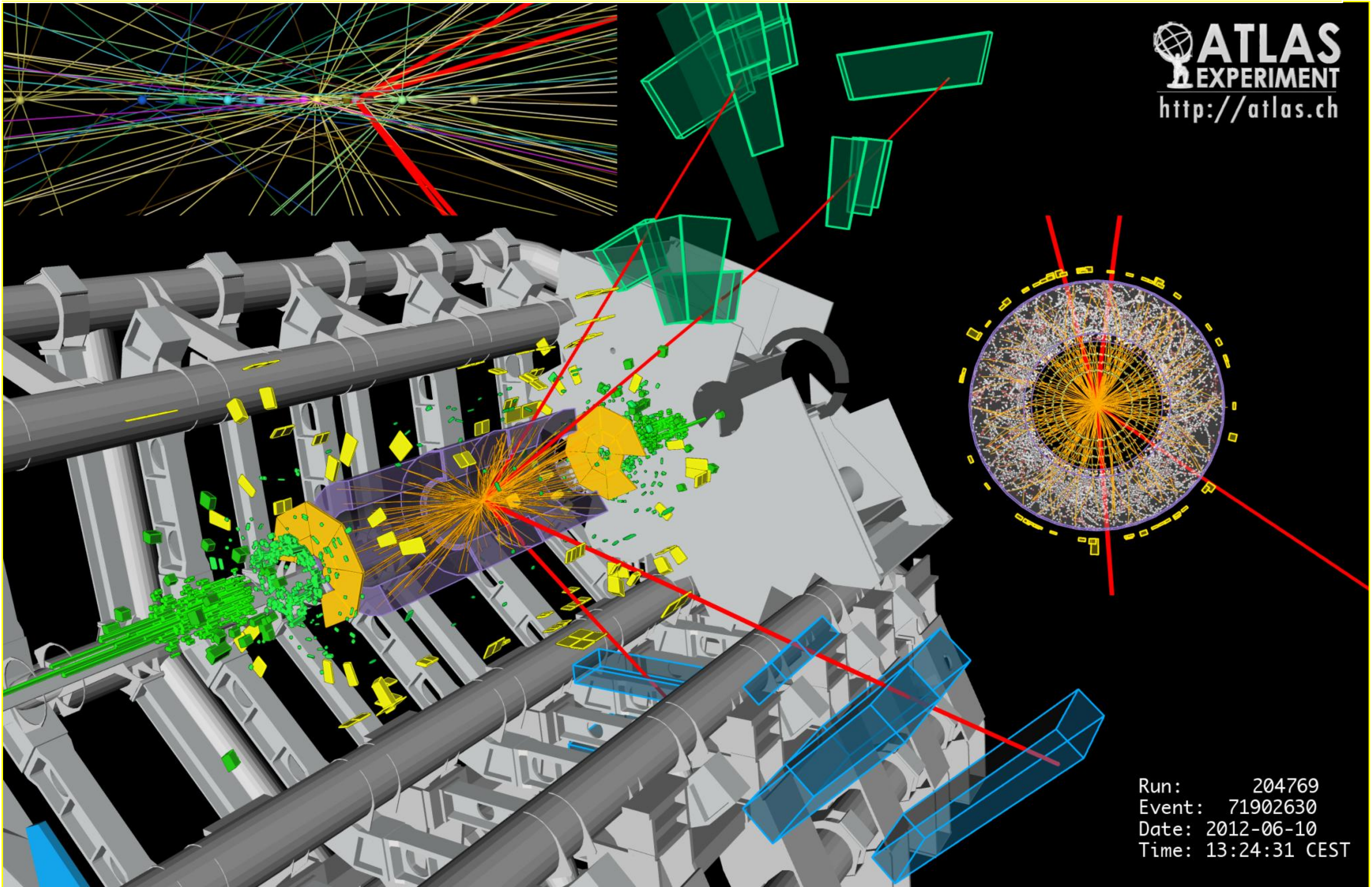




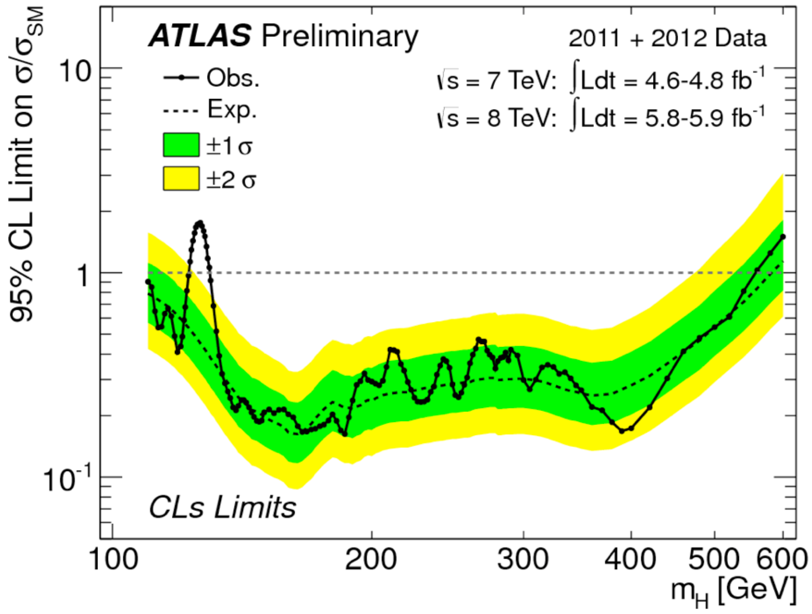
Data sample	m_H of max deviation	local p-value	local significance	expected from SM Higgs
2011	125 GeV	1.1%	2.3 σ	1.5 σ
2012	125.5 GeV	0.4%	2.7 σ	2.1 σ
2011+2012	125 GeV	0.03%	3.4 σ	2.6 σ

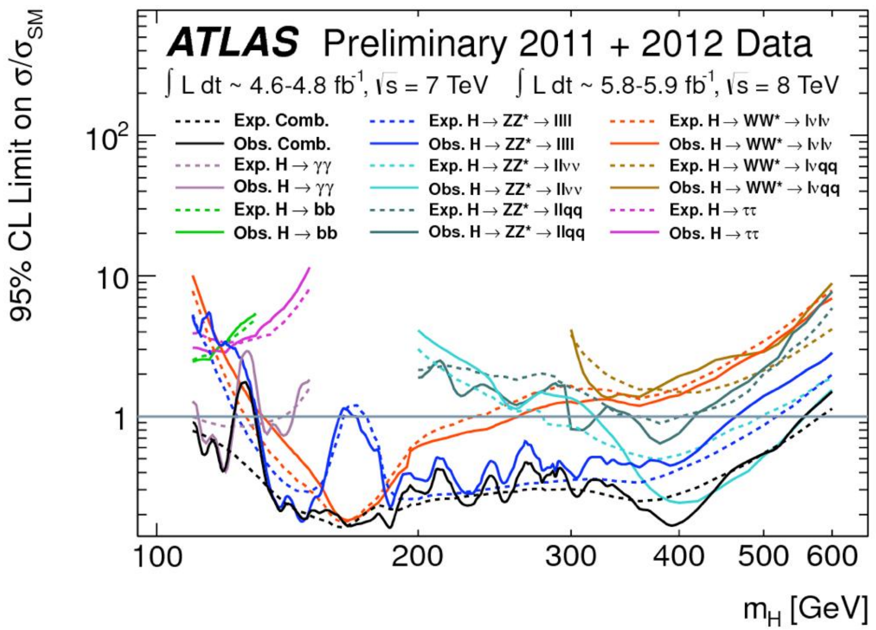
$H \rightarrow ZZ^* \rightarrow 4\mu$, $m_{4\mu}$= 125.1 GeV

p_T (muons)= 36.1, 47.5, 26.4, 71 .7GeV m_{12}= 86.3 GeV, m_{34}= 31.6 GeV
15 reconstructed vertices



Combination of H → ZZ* → 4l and H→γγ



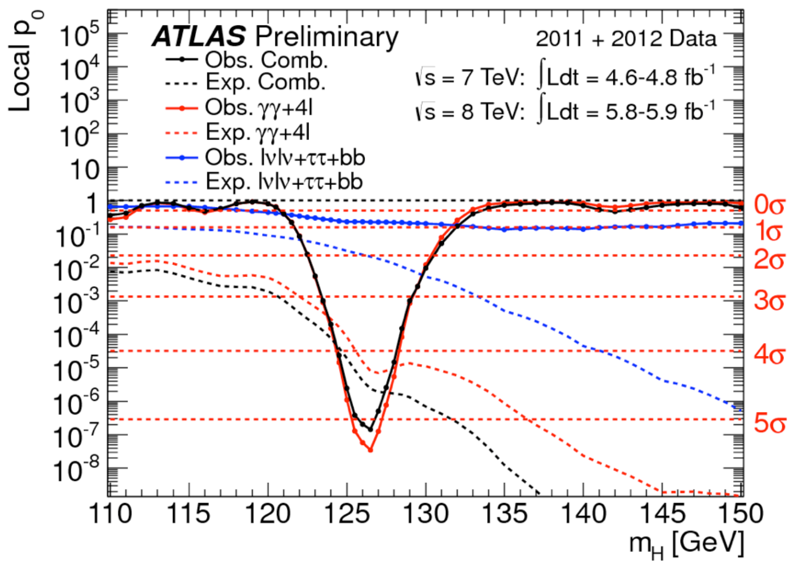


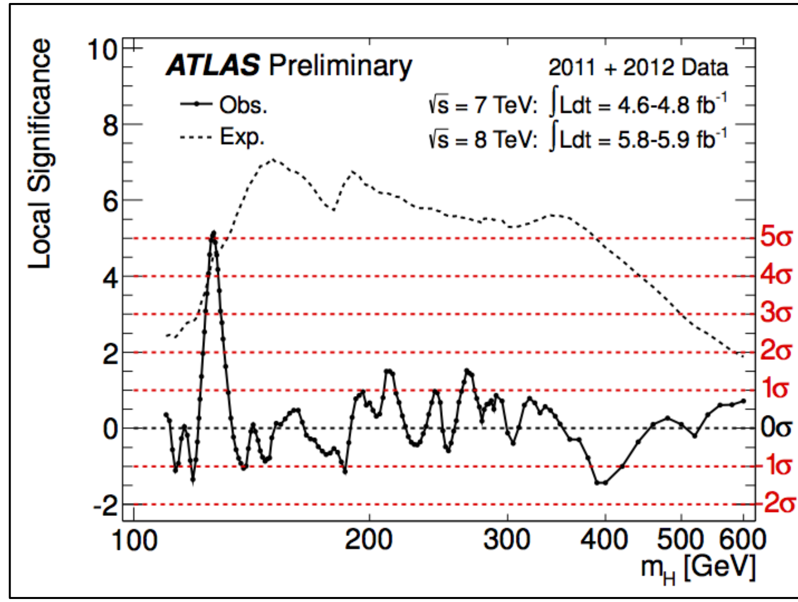
Excludes SM Higgs across almost entire mass range; pushes down to small fraction of SM expectation for large swath of possible masse

Excluded at 95% CL 110-122.6 129.7-557.6 GeV

Excluded at 99% CL 111.7-121.8 GeV 130.7-522.6 GeV

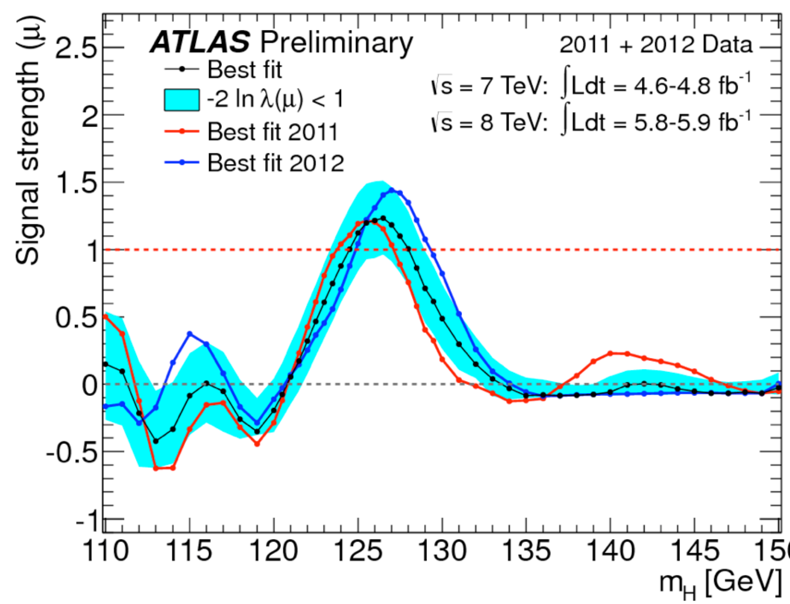
Combination of H → ZZ* → 4l and H→γγ



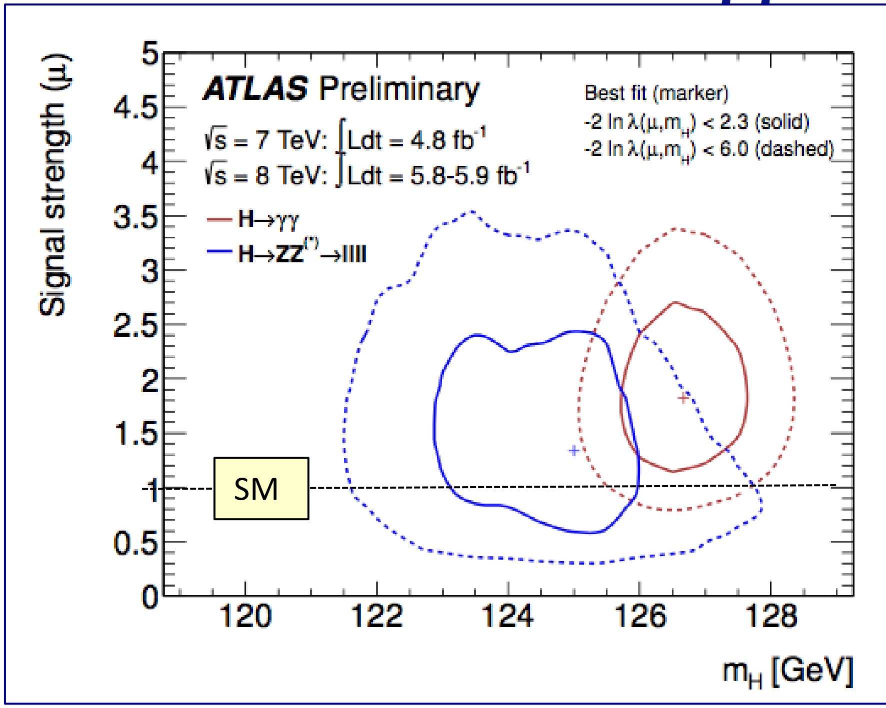


Maximum excess observed at m_H=126.5 GeV with local significance of 5.0**σ**

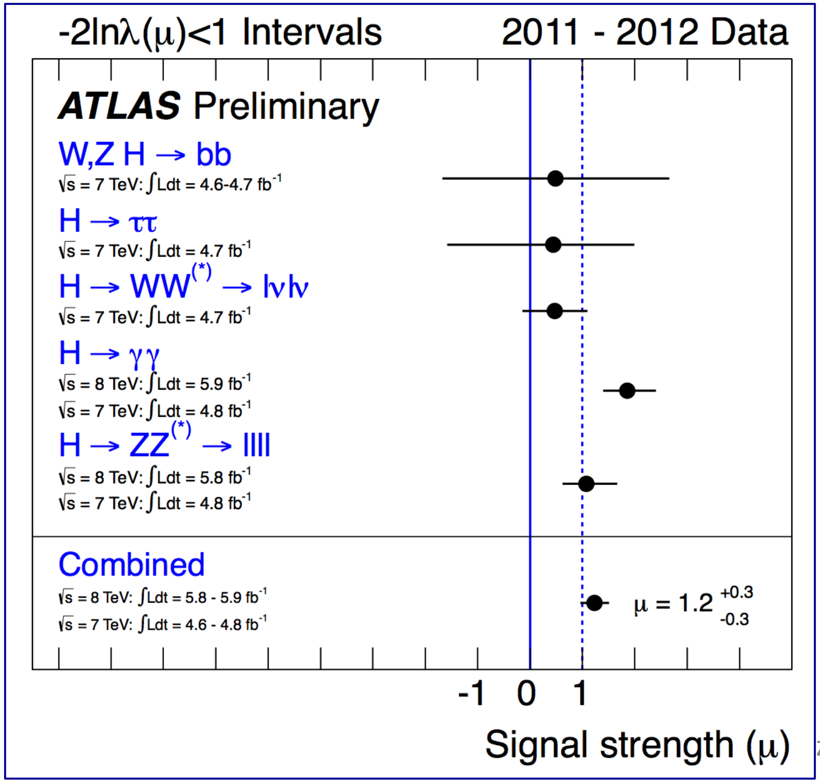
- Expectation for m_H = 126.5 GeV SM Higgs: 4.6σ
- Global significance: 4.1–4.3σ for over 110–600 GeV or 110–150 GeV
- Consistent across multiple channels, time



Combination of H → ZZ* → 4l and H→γγ



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, at m_H = 126.5 GeV, for all studied channels

$H \to WW^* \to ll\nu\nu$

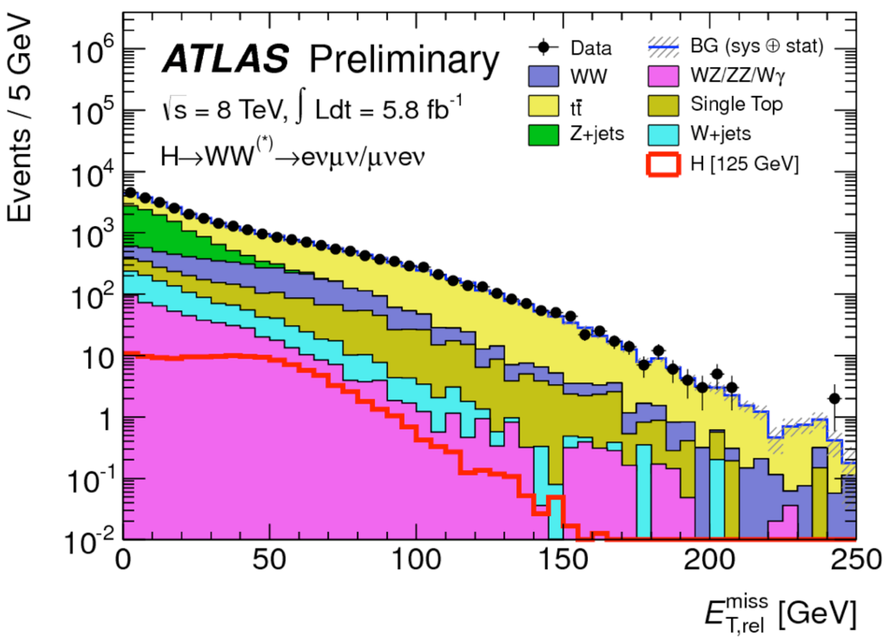
Most sensitive channel in a broad mass range, $m_H \sim$ 120-180 GeV.

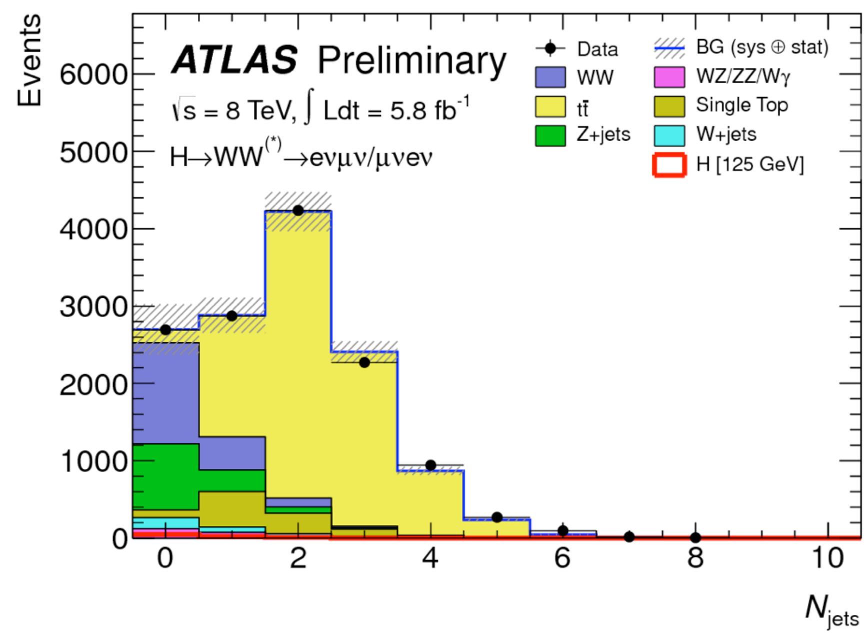
No mass reconstruction possible due to $2\nu \Rightarrow m_T = \sqrt{\left(E_T^{\ell\ell} + E_T^{miss}\right)^2 - \left|\vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,miss}\right|^2}$

Selection criteria	Background suppression
e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$ ($p_T > 20,10$ GeV)	$W+jets$, QCD
Large missing transverse energy (E_T^{miss}); Z veto	Drell-Yan, $Z+jets$
Jet multiplicity categories ($0/1/2_{VBF}$ jets), b-jet veto	$t\bar{t}$
Topological cuts using spin correlations ($m_{\ell\ell}, \Delta\phi_{\ell\ell}$)	WW

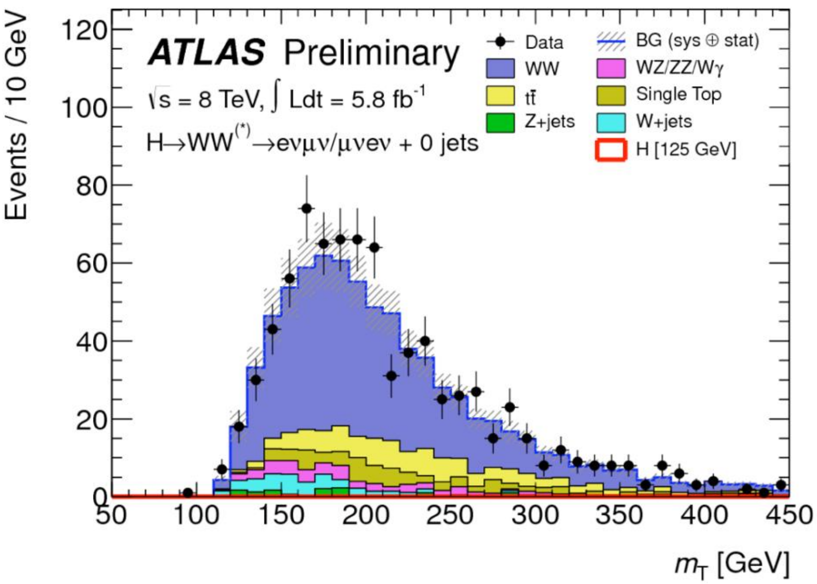
Remaining background contributions estimated from dedicated control data samples.

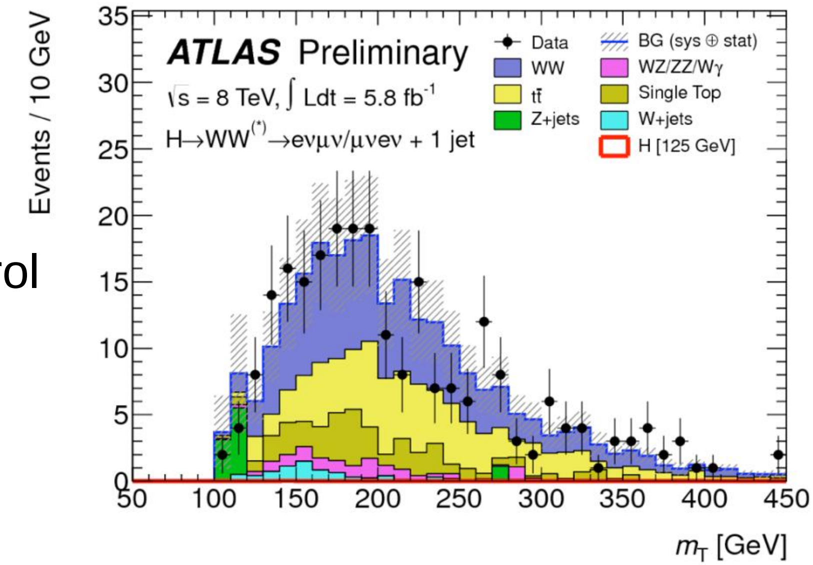
WW: reverted cut on $m_{\ell\ell}$. $t\bar{t}$: b-tagged jets. $W+jets$: inverted lepton ID and isolation.



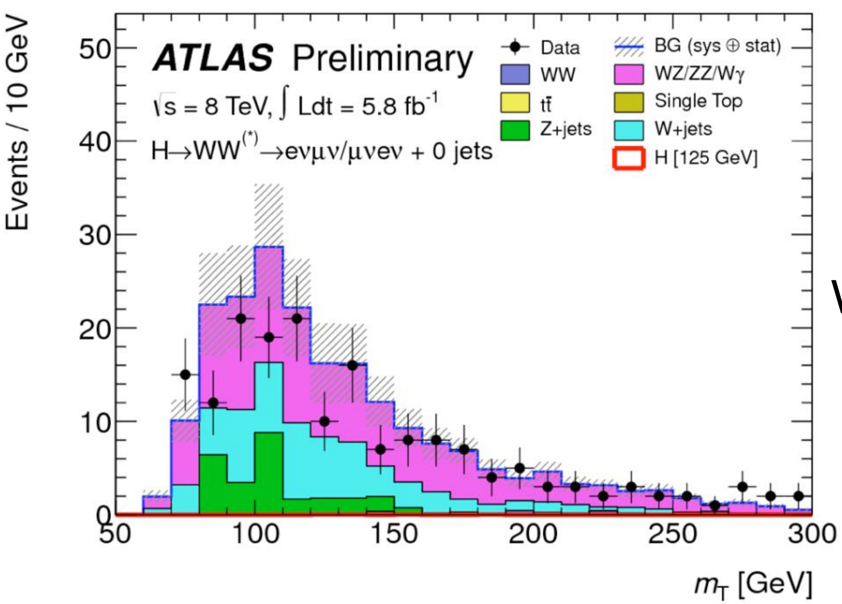


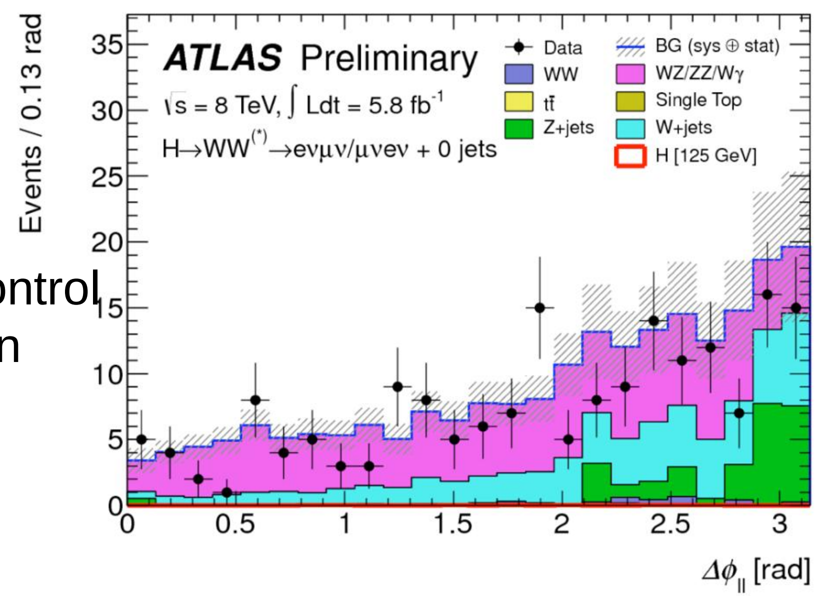
H → WW* → llνν: Background control regions





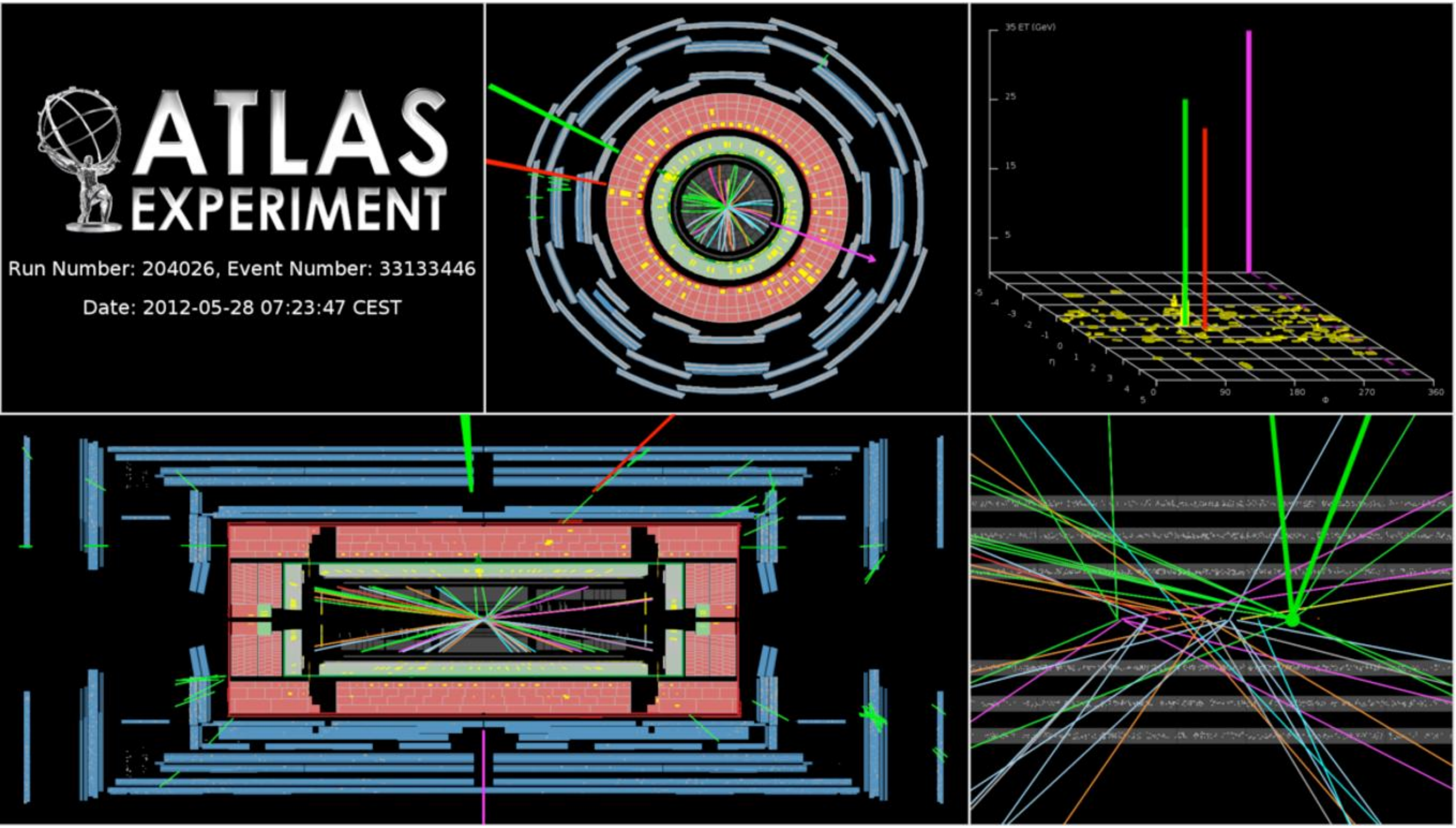
WW control region



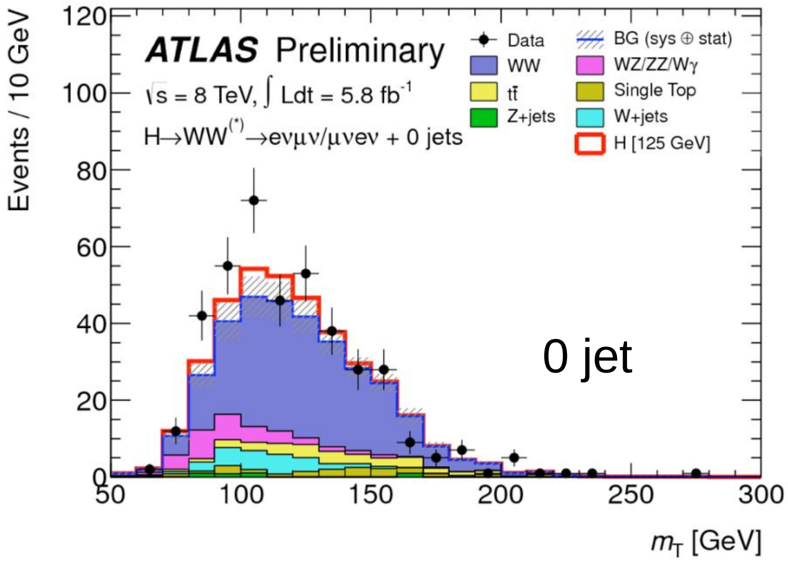


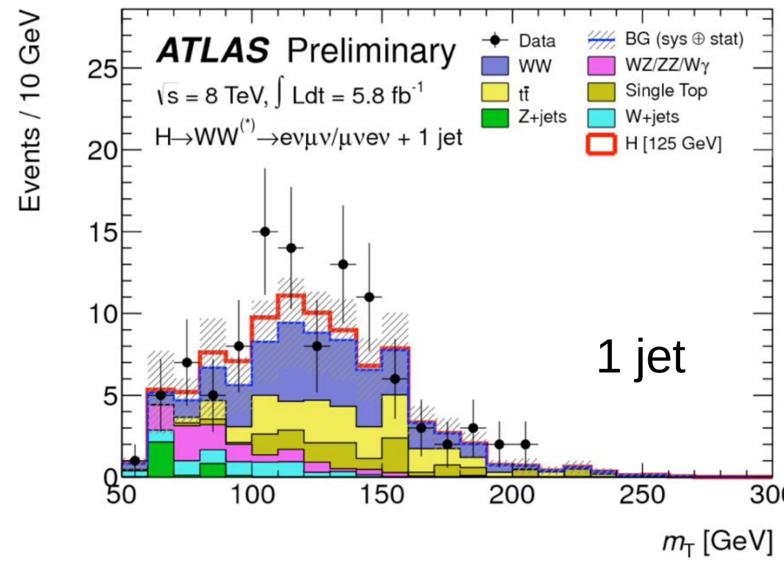
W+jets control region

$H \to WW^* \to ll\nu\nu$

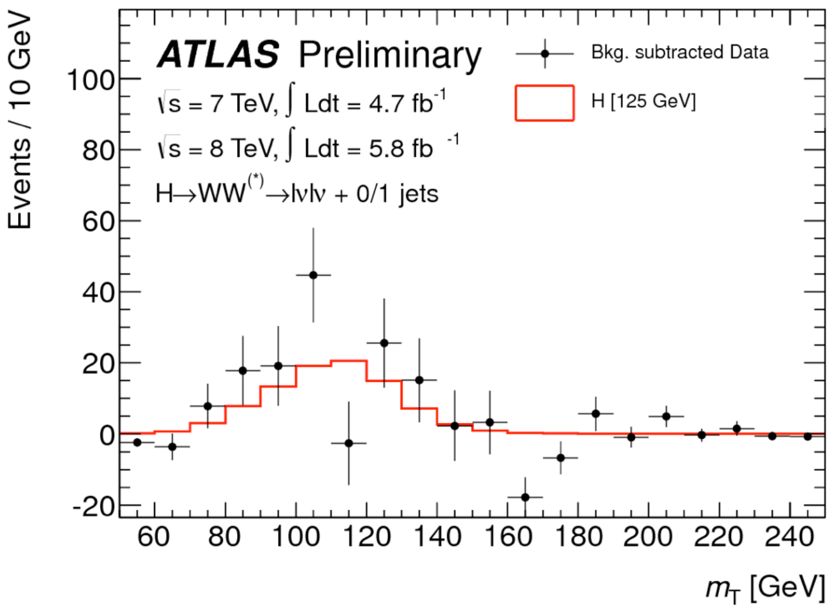


H → WW* → llνν: results





Background subtracted

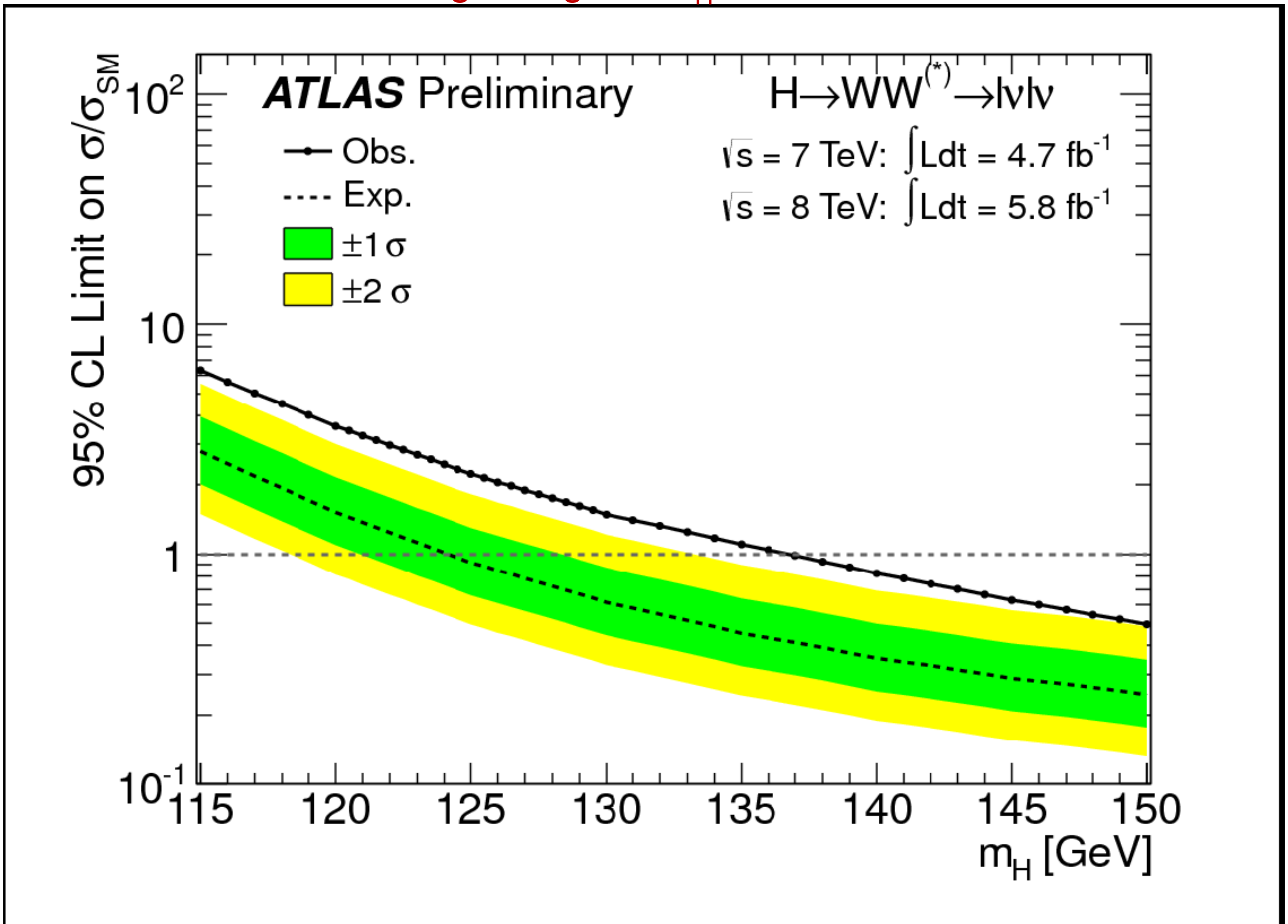


Signal region yield for $e\mu$ and μe channels separately

	0-jet $e\mu$	0-jet μe	1-jet $e\mu$	1-jet μe
Total bkg.	177 ± 4	162 ± 4	43 ± 2	40 ± 3
Signal	18.7 ± 0.3	14.9 ± 0.2	4.3 ± 0.1	4.2 ± 0.1
Observed	213	194	54	52

$H \rightarrow WW^* \rightarrow ll\nu\nu$: results

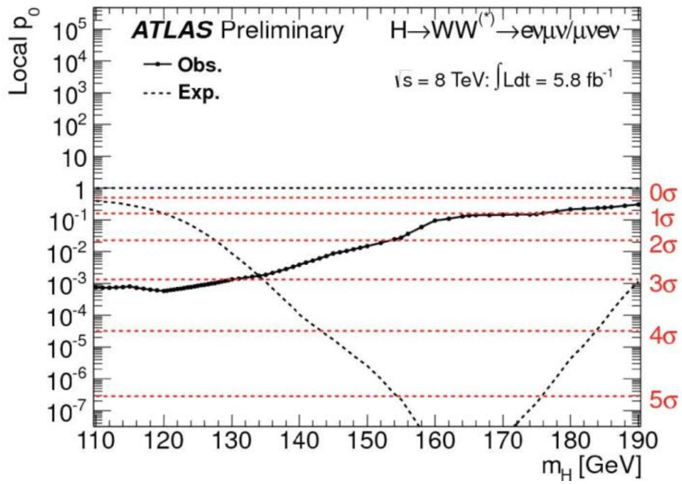
No Higgs mass reconstruction in $H \rightarrow WW^* \rightarrow ll\nu\nu$
Exess over a large range of m_H

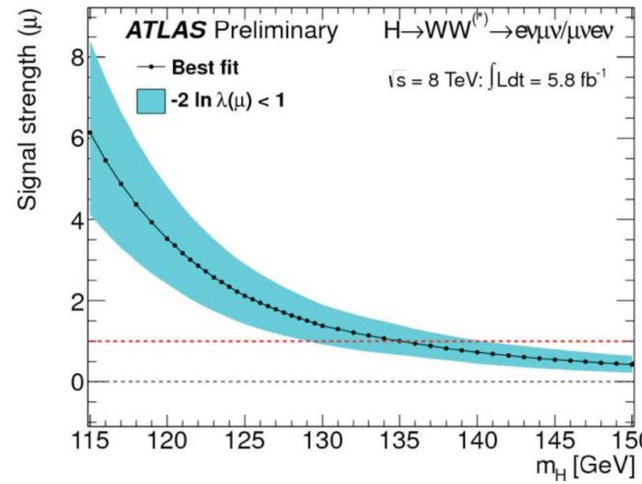


H → WW* → llνν: Consistency with background

Significant excess of events observed for m_H < 150 GeV in 8 TeV data

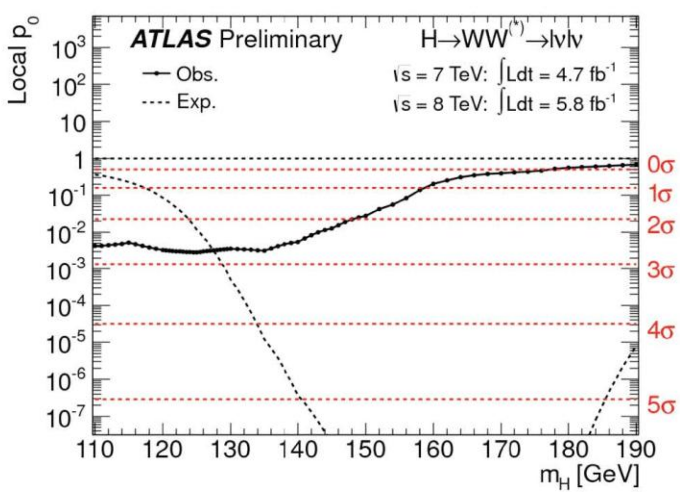
- Poor mass resolution ⇒ **broad excess**
- p-value at m_H = 120 GeV corresponds to 3.2σ

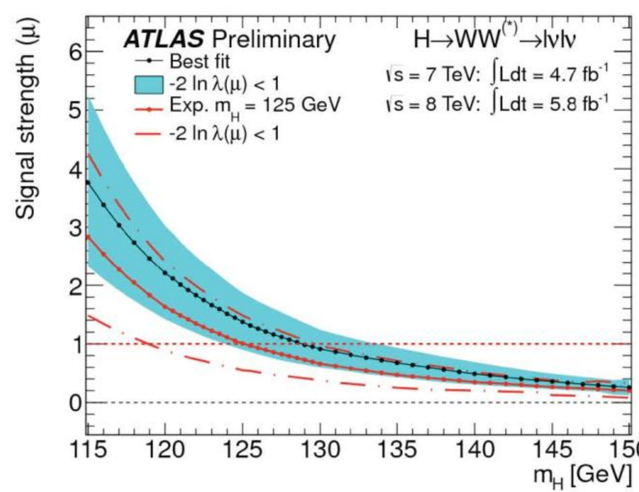




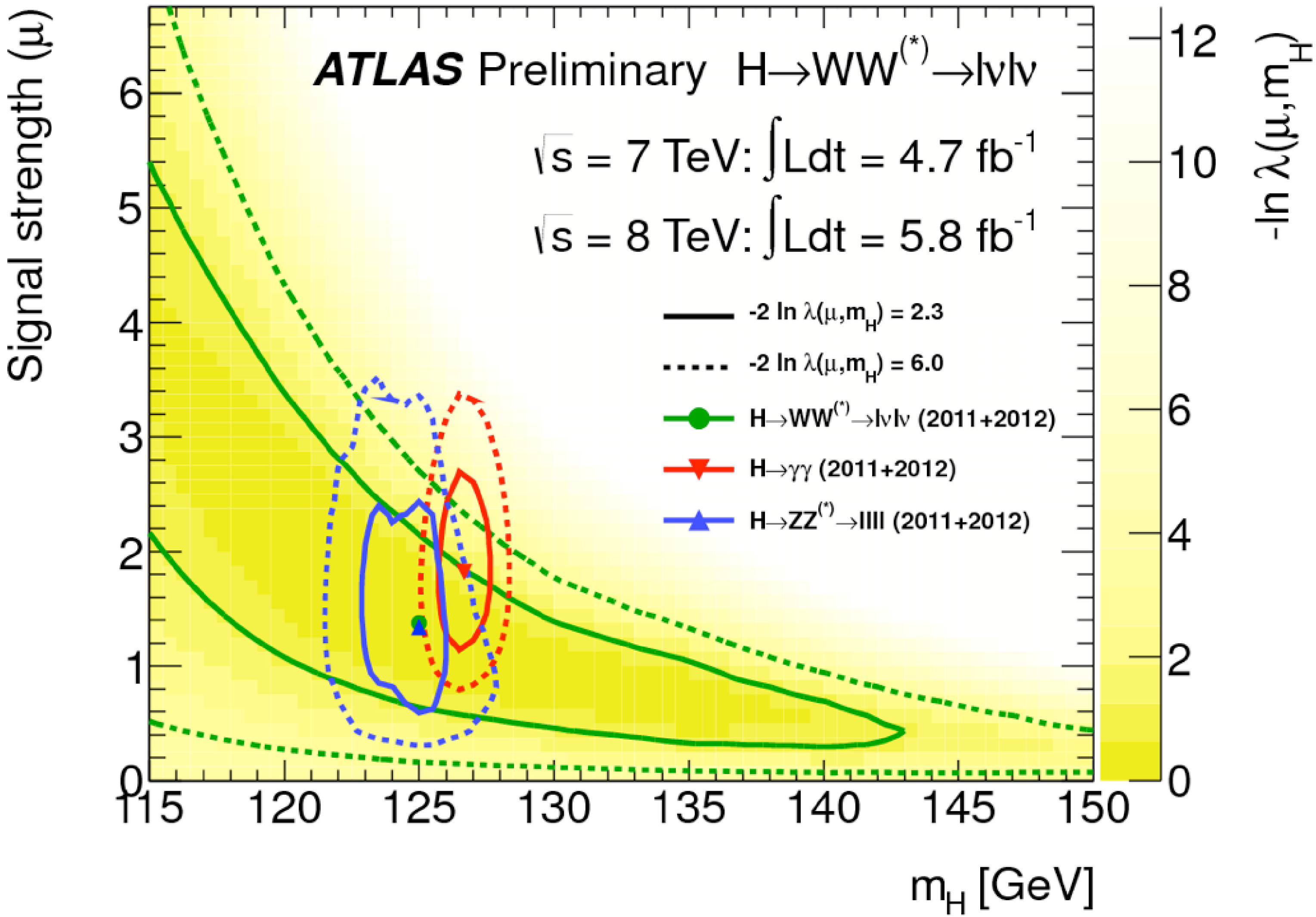
Statistical combination with prior 2011 result reduces significance

- p-value at m_H = 125 GeV corresponds to 2.8σ
- fitted signal strength is 1.4 ± 0.5 times the SM expectation at m_H = 125 GeV

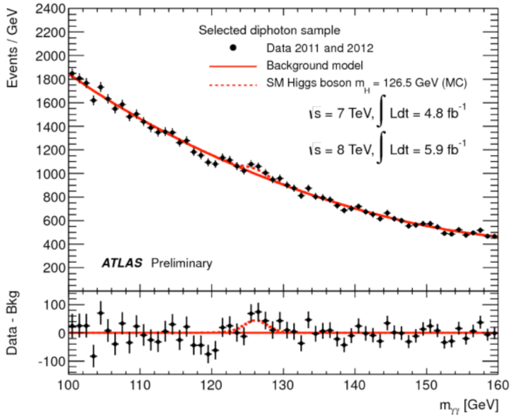


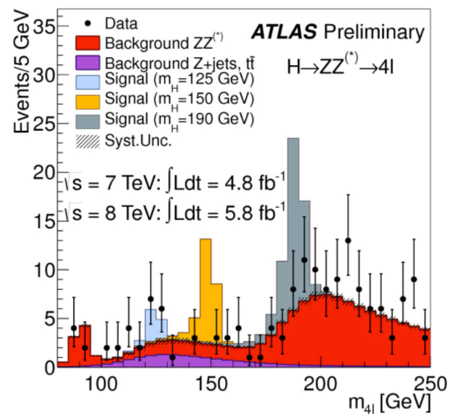


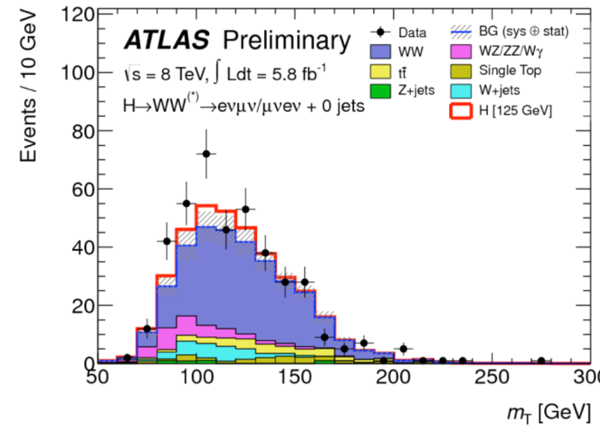
Consistency across channels



Summary







In both ATLAS we have discovered a new particle with a mass around 125 GeV, consistent with the Standard Model Higgs boson.

More analysis are exploring other channels in order to have a complete pictures of its decay properties

$H\rightarrow\tau\tau$, $H\rightarrow bb$, $H\rightarrow Z\gamma$, among many others

Expect new updates soon

More data are needed to determine the exact properties of this particle (mass, spin, CP).

Searches for physics Beyon the Standard Model

Many possible scenarios:

SUSY: most popular, provide DM candidates.
Extra dimensions
Technicolor models
New resonances….

Only a brief review presented here

SUSY as a BSM candidate

• "Easier QFT": Fermion and Boson loops protect the Higgs mass at large energies (reduces "fine tuning") if SUSY mass scale is not too large **(LHC)!**

• SUSY is a broken symmetry and thus offers (with R-parity conservation) weakly interacting massive particles for Dark Matter with a mass of O(100) GeV

• unification of 3 coupling constants at high energy in one point (GUT scale at 1016 GeV?). SUSY breaking connected to electroweak symmetry breaking ?

• Important draw back:
  - SUSY has not been found yet!
    - Some small fine tuning already exist in the model

• SUSY Higgs:
  - Mass of the lightest MSSM Higgs boson h0 must fulfill: $\mathbf{M(h_0) < \cos(2\beta)\, M_Z}$
  - M(h0)< 135 GeV if radiative corrections are included

Higgs of 126 GeV consistent with
a) Degenerate stops
b) Quite heavy stops

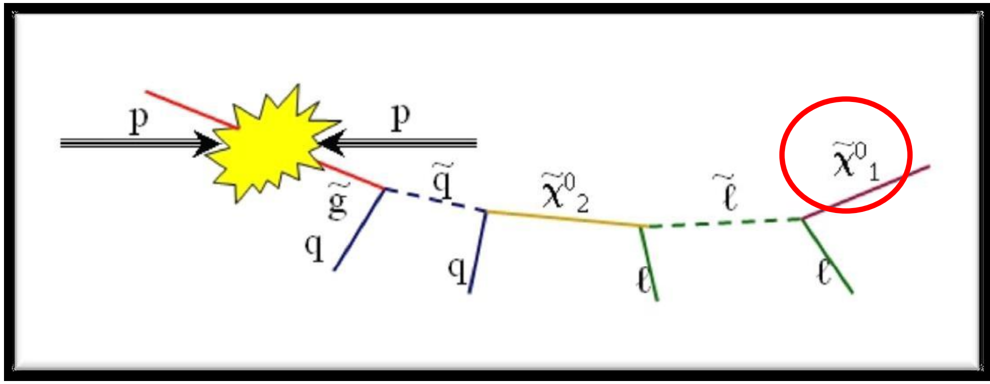
Scenario might be
- 1st and 2nd gen. heavy
- Light stop caused by naturalness
- Somehow light gluino

Most sensitive to stops and gluinos

SUSY at the LHC

If R-Parity is conserved then SUSY particles are pair produced

At the LHC, due to strong force, dominant production of **squarks and gluinos (if not too heavy)**



Mass pattern in general SUSY unknown ! Searches need to be quite general and model-parameter-independent

Cascade decay to lighter SUSY particles and finally the lightest SUSY particle (LSP)

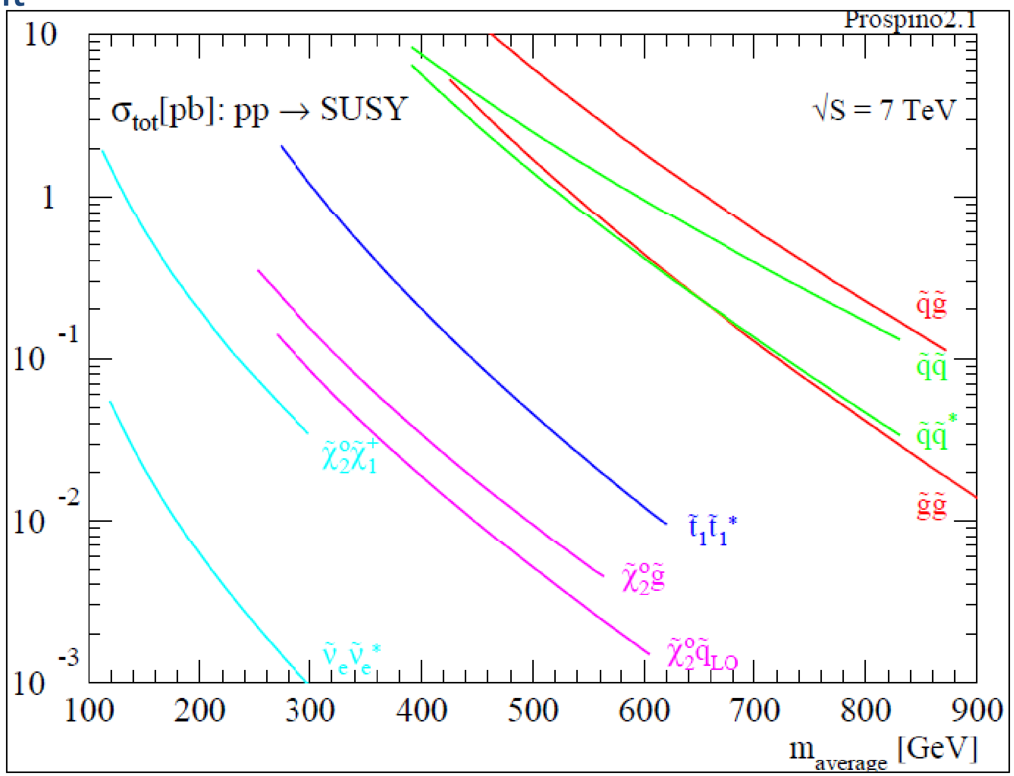
<u>Production rate</u>

5000

500

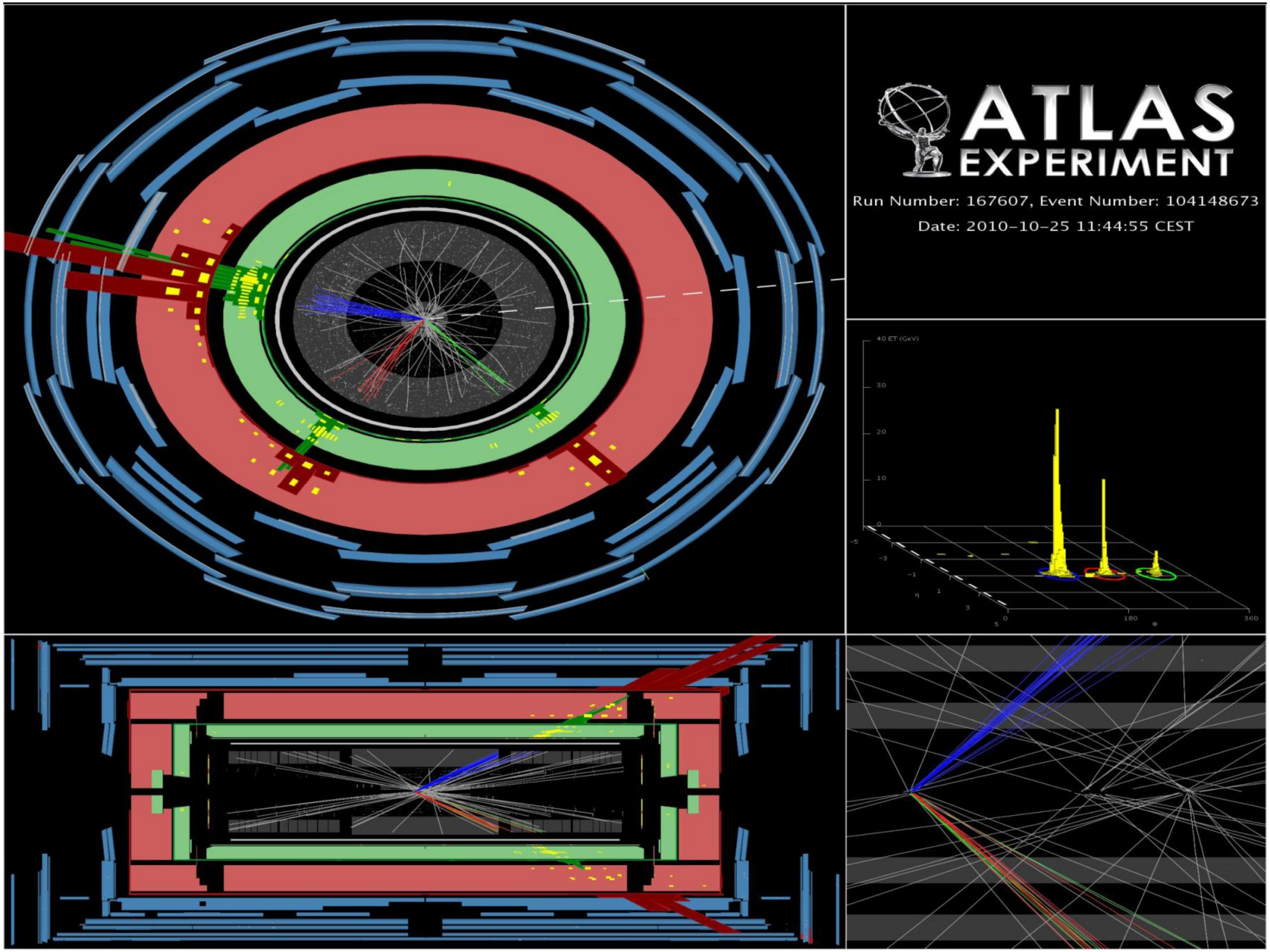
50

Events in 2011



Example of SUSY events in 2010

3 jets with pT of approximately 400 GeV, 120 GeV, 60 GeV and Etmiss=420 GeV



SUSY seraches overview

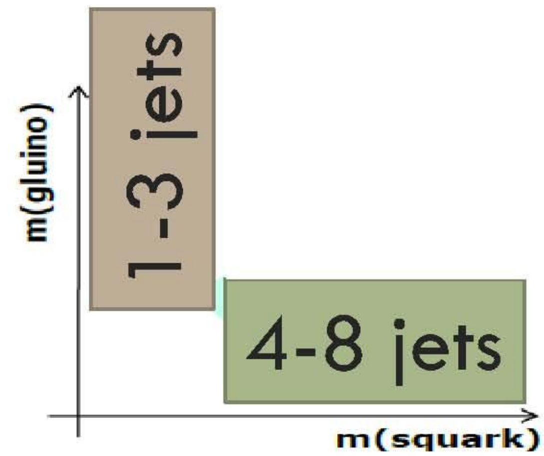
Short Title of the CONF note	Date	√s (TeV)	L (fb^{-1})	Document	Plots
Monophoton [ADD, WIMP] NEW	07/2012	7	4.7	ATLAS-CONF-2012-085	Link
Monojet [ADD, WIMP] NEW	07/2012	7	4.7	ATLAS-CONF-2012-084	Link
3 leptons + Etmiss [Direct Gauginos] NEW	07/2012	7	4.7	ATLAS-CONF-2012-077	Link
2 leptons + Etmiss [Direct Gauginos/sleptons] NEW	07/2012	7	4.7	ATLAS-CONF-2012-076	Link
Long-Lived Particles [R-hadron, slepton] NEW	07/2012	7	4.7	ATLAS-CONF-2012-075	Link
0 lepton + jets + Etmiss [Heavy Stop] NEW	07/2012	7	4.7	ATLAS-CONF-2012-074	Link
1 lepton + jets + Etmiss [Heavy Stop] NEW	07/2012	7	4.7	ATLAS-CONF-2012-073	Link
2 photons + Etmiss [GGM] NEW	07/2012	7	4.8	ATLAS-CONF-2012-072	Link
2 leptons + jets + Etmiss [Medium stop] NEW	07/2012	7	4.7	ATLAS-CONF-2012-071	Link
1-2 bjets + 1-2 leptons + jets + Etmiss [Light Stop] NEW					
2 leptons + jets + Etmiss [Very Light stop]					
3 bjets + 0lepton + jets + Etmiss [Gluino med. stop/sbo					
1 lepton + 3-4 jets + Etmiss					
Disappearing track + jets + Etmiss [AMSB]					
0 lepton + >=(2-6) jets + Etmiss					
Add. >=4 leptons + Etmiss Interpretation [RPV]					
Long lived Particle (Pixel-like)					
>=4 leptons + Etmiss	01/2012	7	2.05	ATLAS-CONF-2012-001	Link (inc. HEPData)
Z->ll + jets + Etmiss [GGM]	04/2012	7			
Add. 2 leptons + jets + Etmiss interpretation [GMSB]	11/2011	7			

ATLAS hunts now with a twofold strategy:

- Broad inclusive searches with many signal regions
- Highly optimized dedicated searches for exclusive SUSY signals

Also various searches on R-Parity violation

Example: Jets + E_T^{miss}

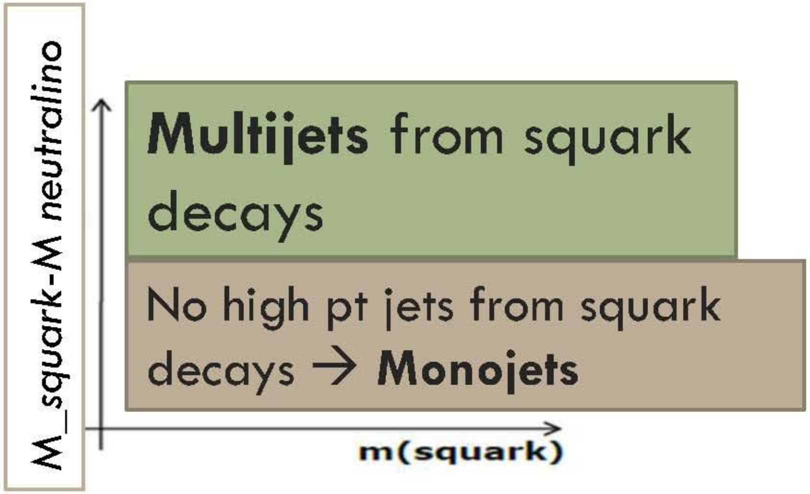


Studies are about 15 signal regions

From monojets to >8 jet events
(jets from squark/gluino decay
or if mass difference to LSP to low
No jets from squark/gluino decay)

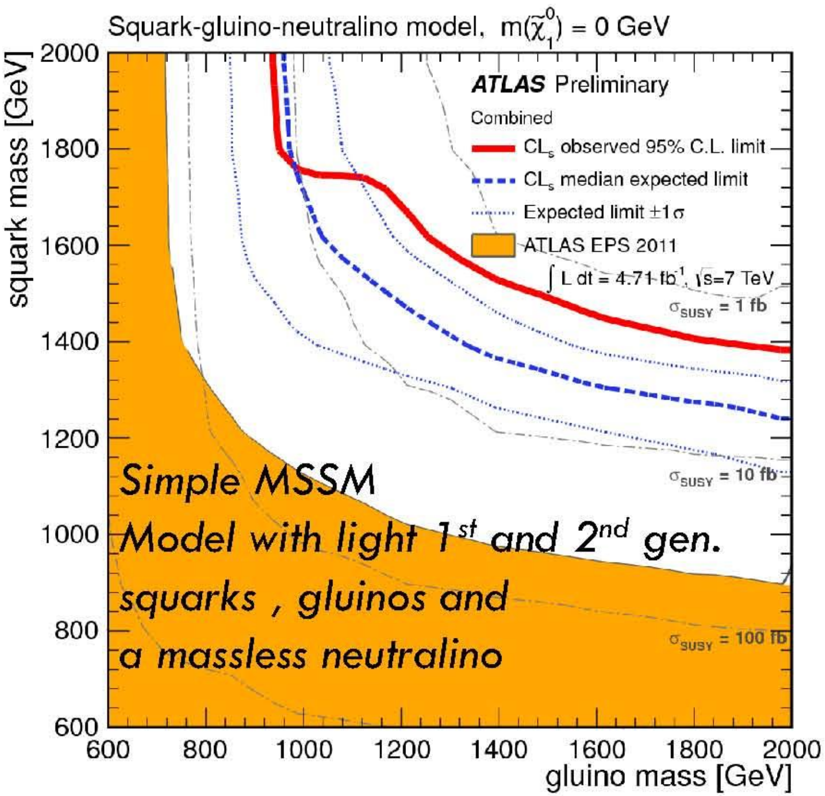
From low E_t^{miss} to high E_t^{miss}
(best cut depends on ratio of produced particle mass to neutralino mass)

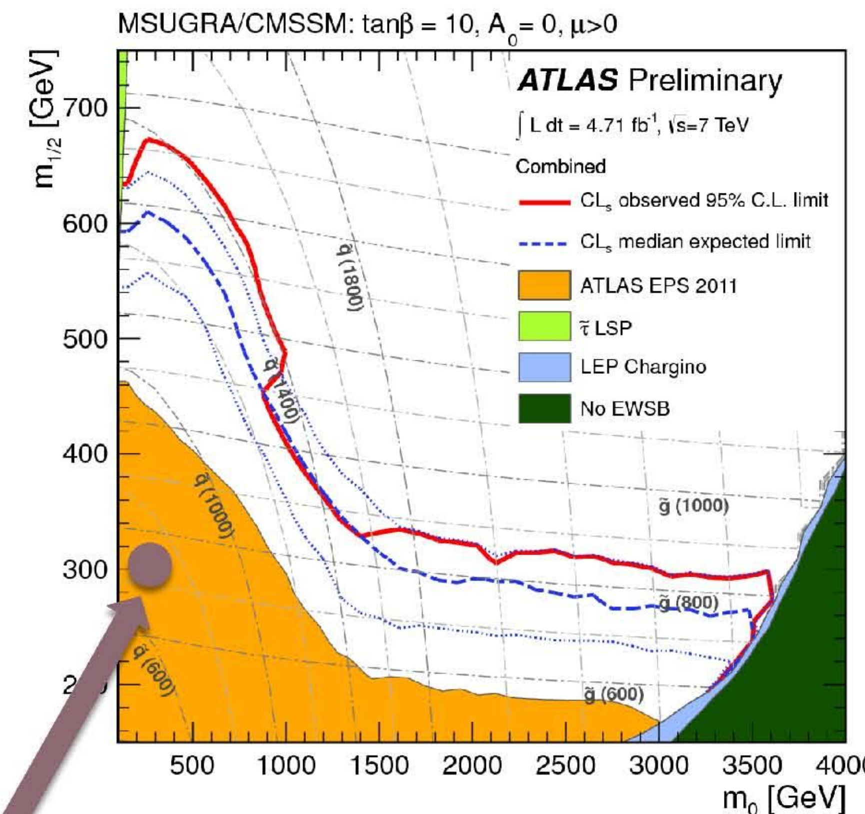
From high mass to low mass



Jets + E_T^{miss} : Results with 2011 data

Constrained MSSM Model with common Fermion and Boson Masses at the GUT scale

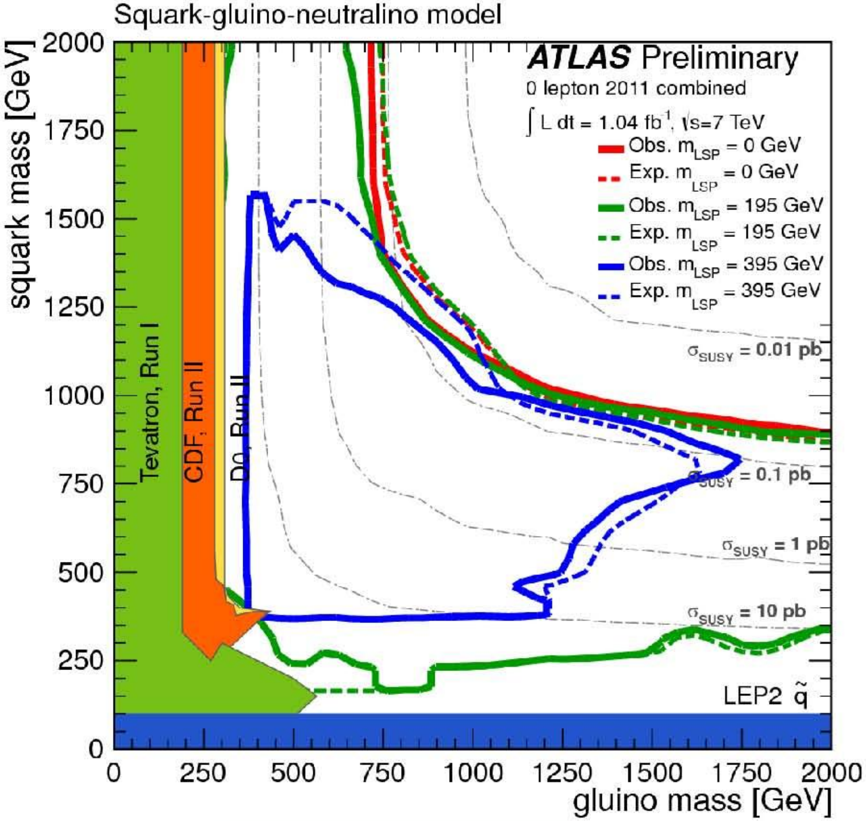




2009 "Best fit" cMSSM fit pre-LHC

Exclusion reach not strongly sensitive to sign(mu), tan beta and A_0

Jets + E_T^{miss} : LSP mass dependance



Not full dataset

SUSY parameter space very large !

Here e.g. dependence of limits on neutralino (LSP) mass (old data)

Investigated now with projections on "relevant" parameters (simplified models)

You can make your own limit for any model with a fast det. sim..
We are providing model independent limits on sigma * BR * efficiency
efficiencies etc. *at hepdata*

Stop search

Stop decays

Stop → top neutralino *(if kinematically allowed, and no chargino..)*

Stop → b chargino *(if chargino is light enough and likes to couple)*

Stop → charm neutralino *(if stop is heavier than chargino +LSP)*

(also other options)

Possible stop production

- **direct production**
  → Does not depend on other parameters
  (light gluino)
- **produce gluinos which decay to stops**
  → Potentially large cross section
  → Easier to detect

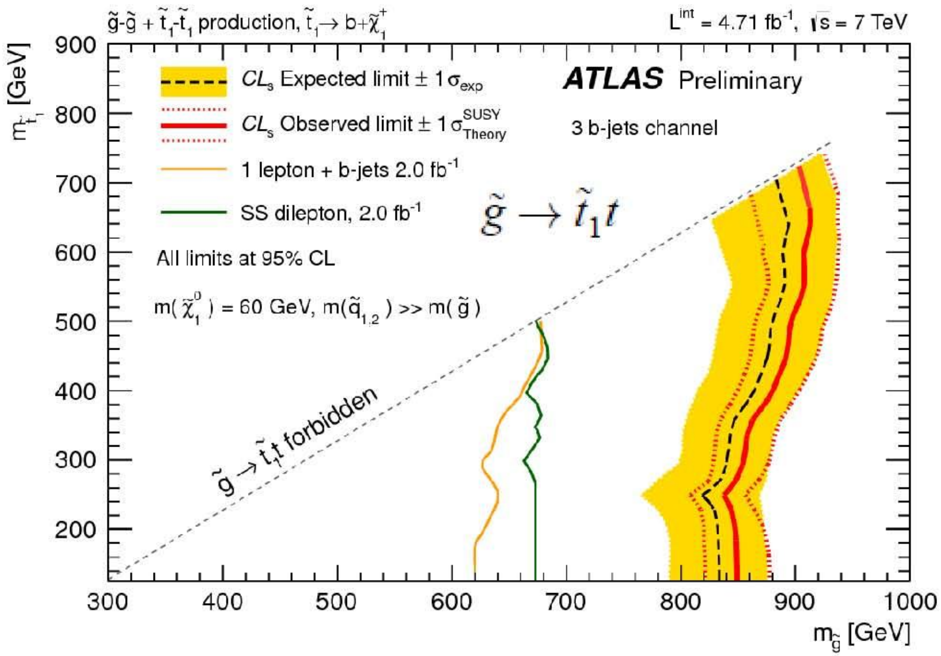
3rd generation example analysis

- Searching in events with 4-6 jets **where 3 jets are tagged as b-jets** and large missing transverse momentum

SR	$t\bar{t}$+jets (MC)	others	SM	data
SR4-L	33.3 ± 7.9 (32.6 ± 15.4)	11.1 ± 4.9	44.4 ± 10.0	45
SR4-M	16.4 ± 4.1 (16.1 ± 8.4)	6.6 ± 2.9	23.0 ± 5.4	14
SR4-T	9.7 ± 2.1 (11.4 ± 5.4)	3.8 ± 1.6	13.3 ± 2.6	10
SR6-L	10.3 ± 3.3 (10.0 ± 6.2)	2.4 ± 1.4	12.7 ± 3.6	12
SR6-T	8.3 ± 2.4 (7.9 ± 5.3)	1.6 ± 1.1	9.9 ± 2.6	8

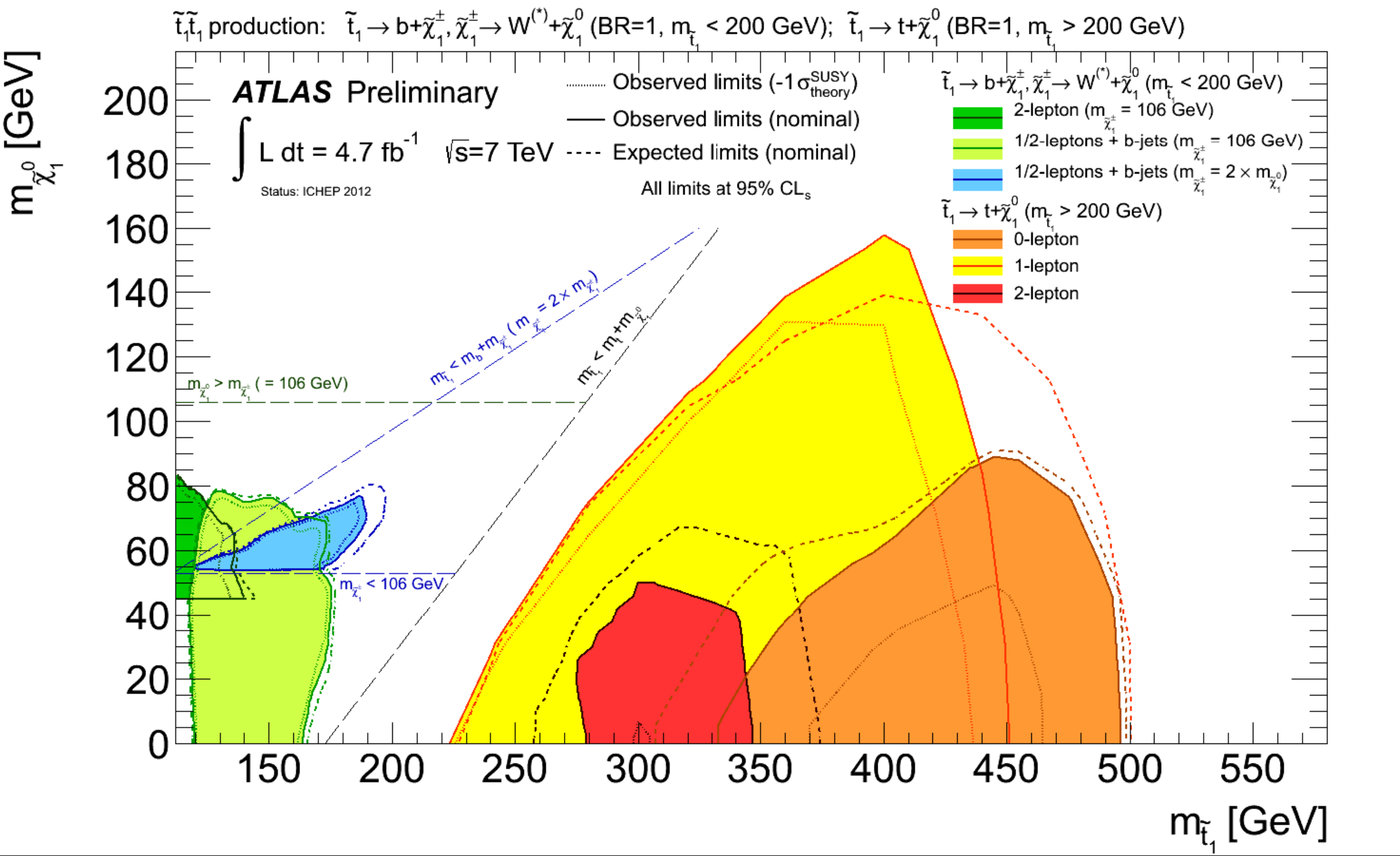
Consider, among others, models where gluino decays 100% to stop and top and stop decays to

$$\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$$



Gluino masses up to 1 TeV are excluded

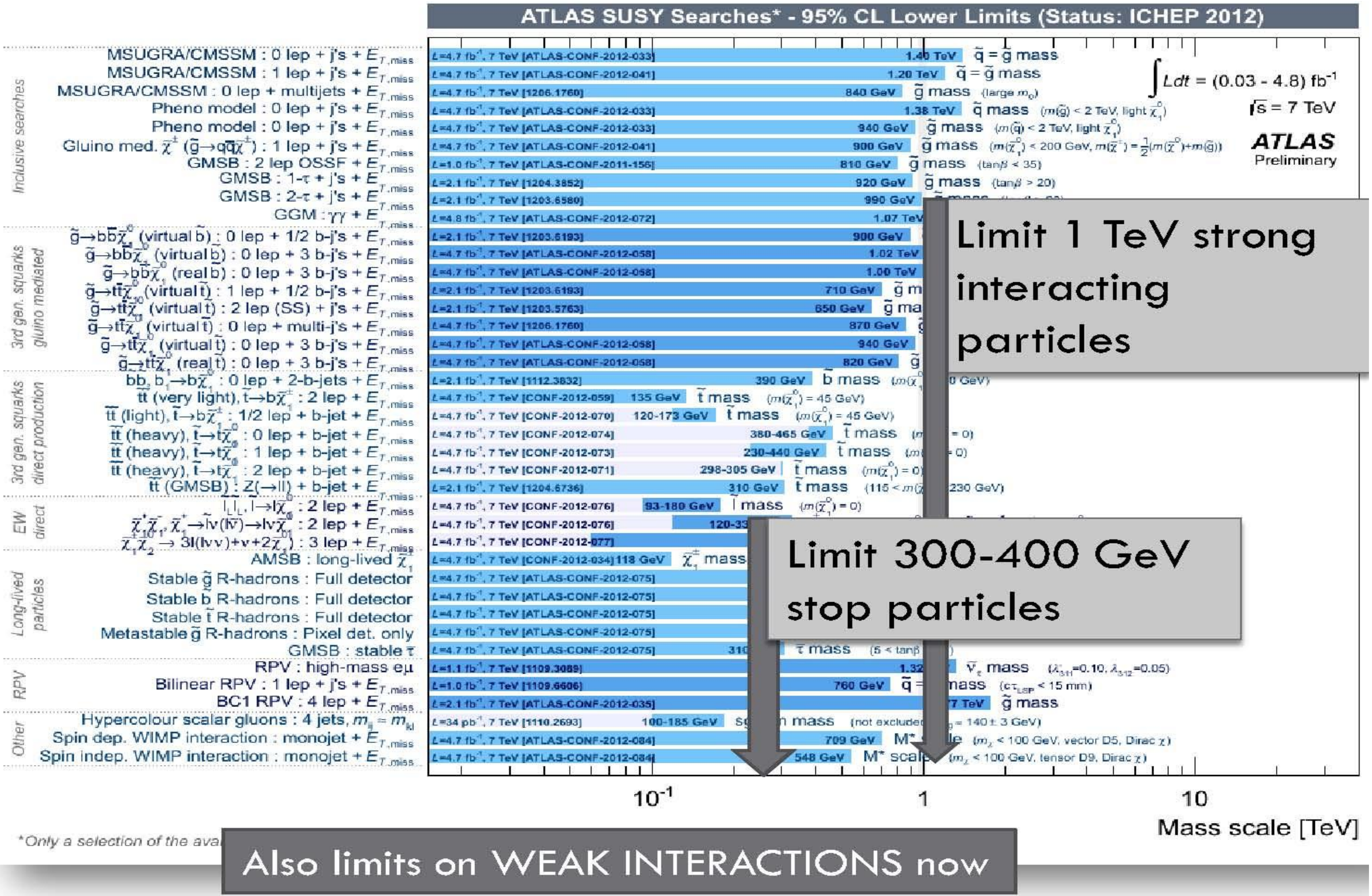
Summary direct stop production



DM production in SUSY decays

Summary of current limits, mostly on the production of Squarks and Gluinos

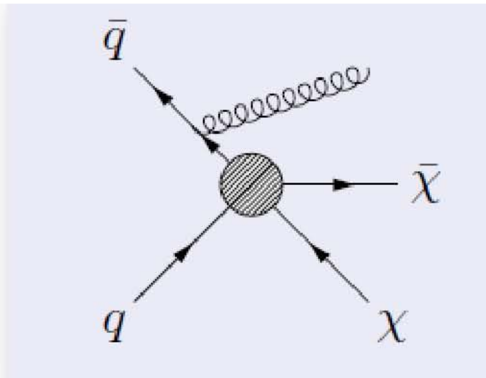
→ Strong constrains on SUSY models

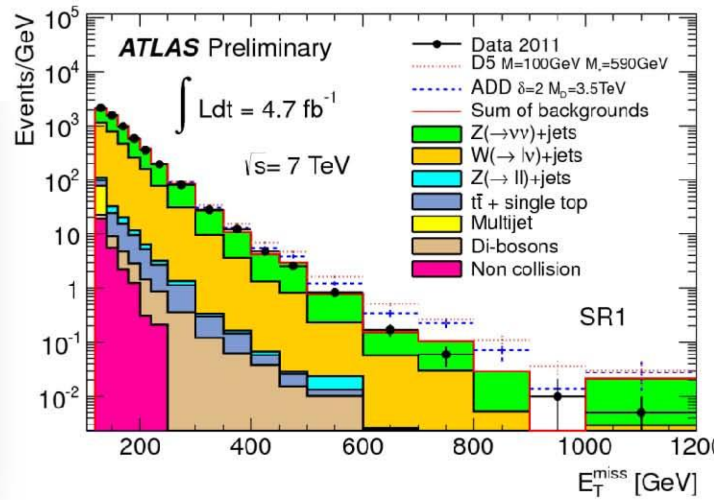


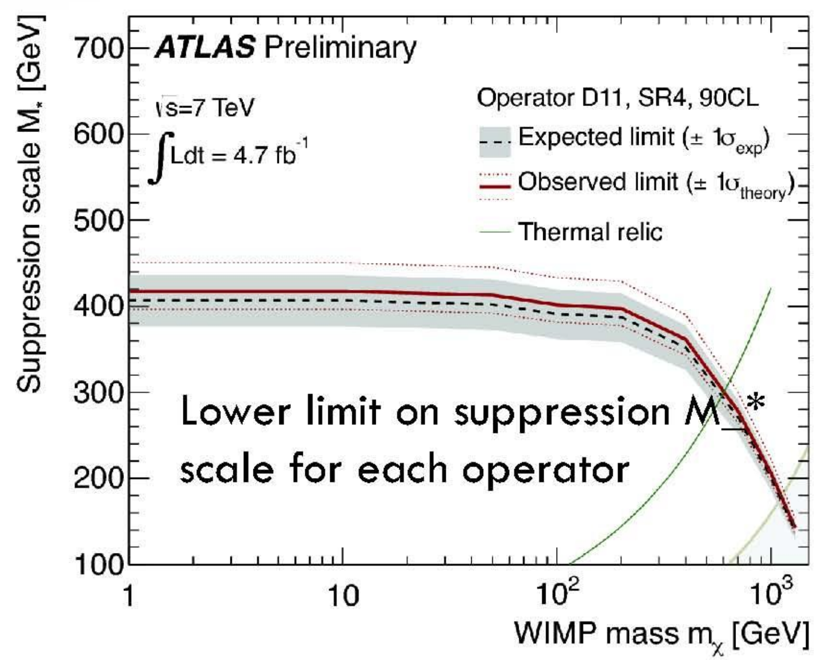
Monojets/Monophotons

Looking for a jet from initial state Radiation to search for WIMP WIMP Events

- Signal is a Monojet/monophoton event !
- Missing momentum distribution





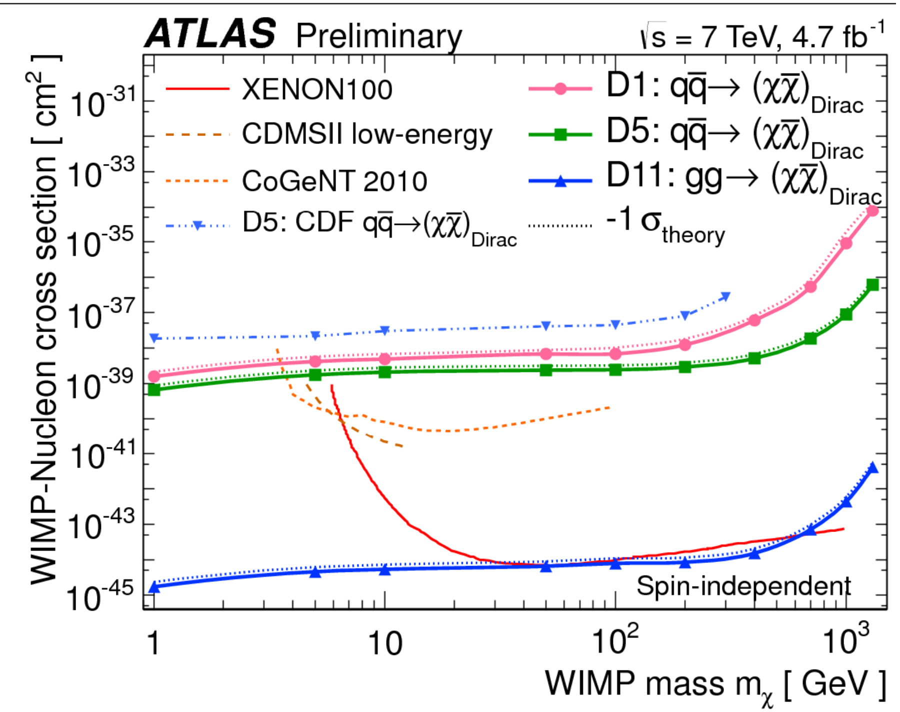


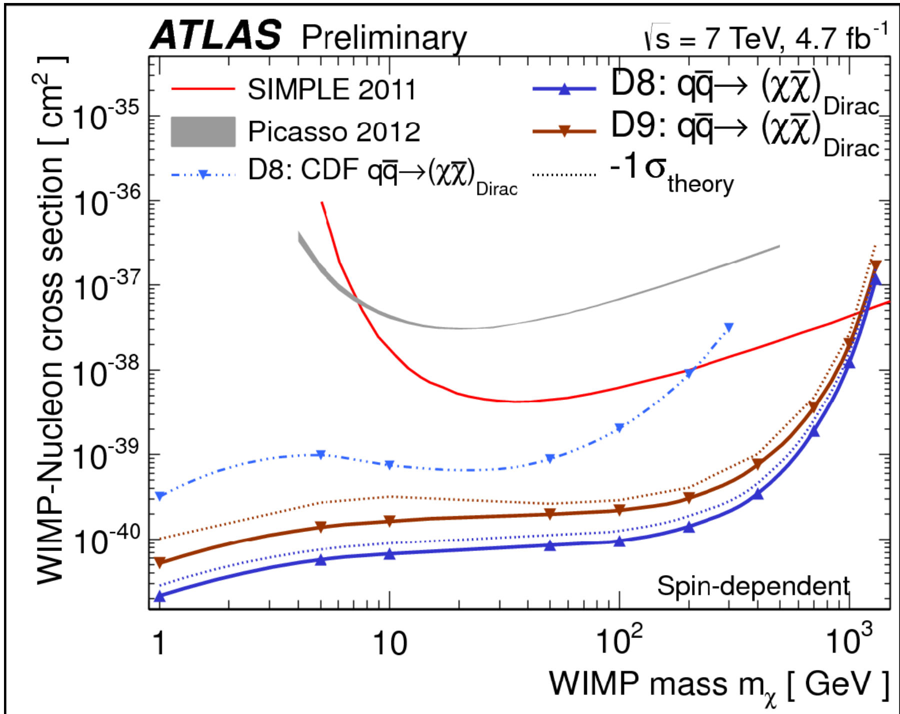
Lower limit on suppression M_* scale for each operator

Assuming coupling ATLAS monojet searches can give bounds on WIMP-nucleon spin dependent cross section **(assuming heavy mediator with free coupling)** *Collider limit competitive if WIMP couple only via D11 (gg) coupling and for very low WIMP masses*

Monojets/Monphotons

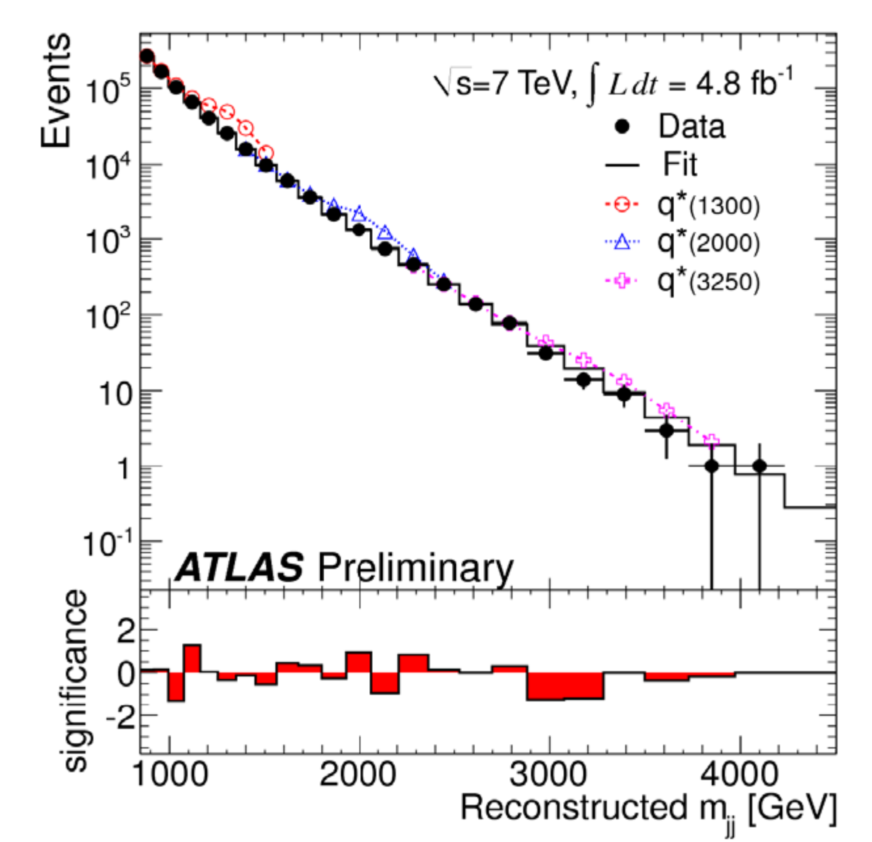
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$



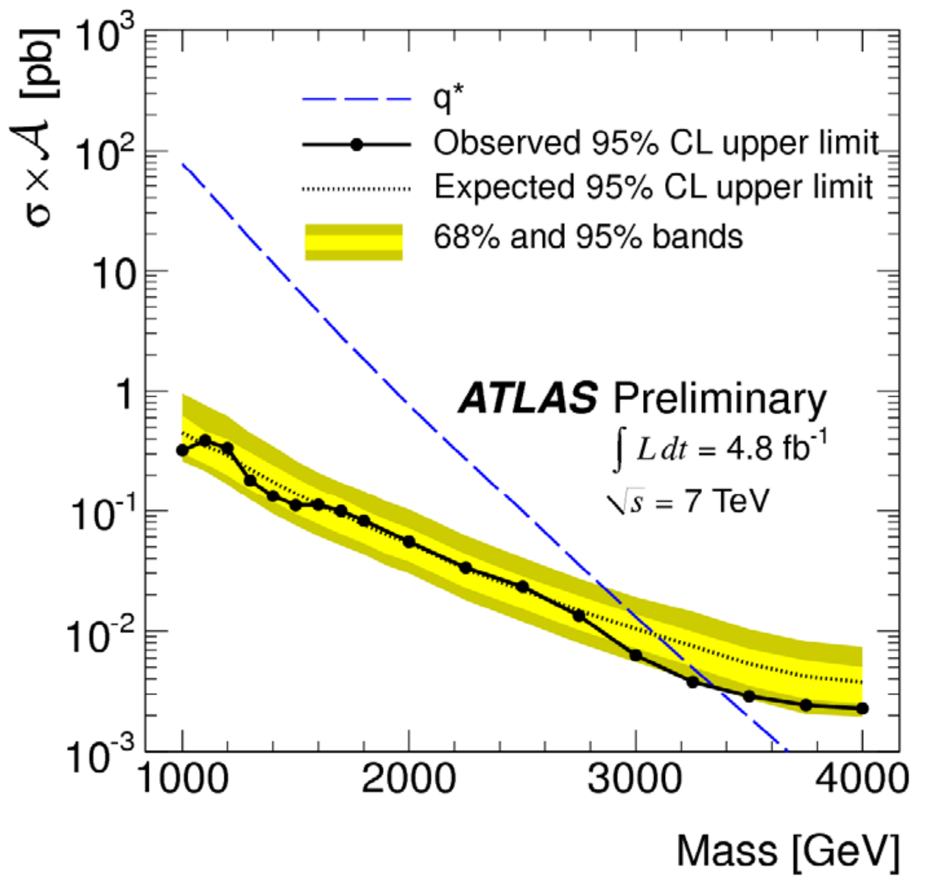


Excited quarks

Excited quark model: q*→qg



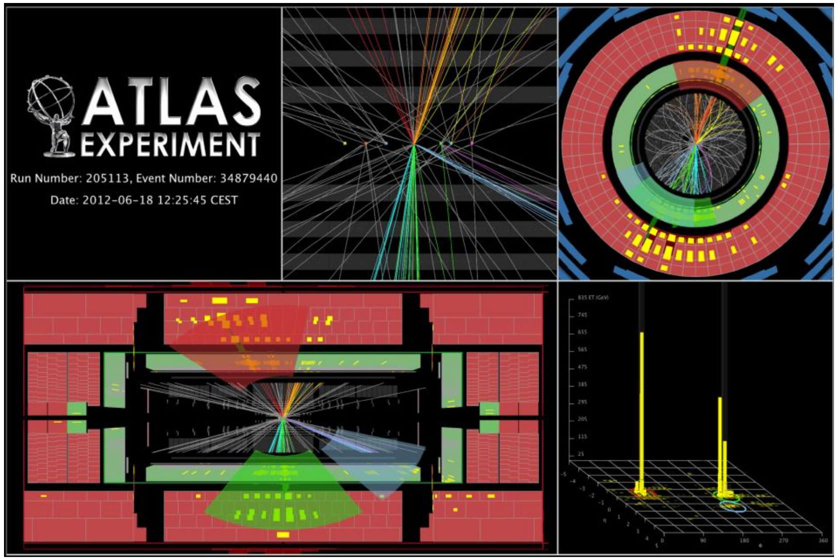
Model independent cross section limit

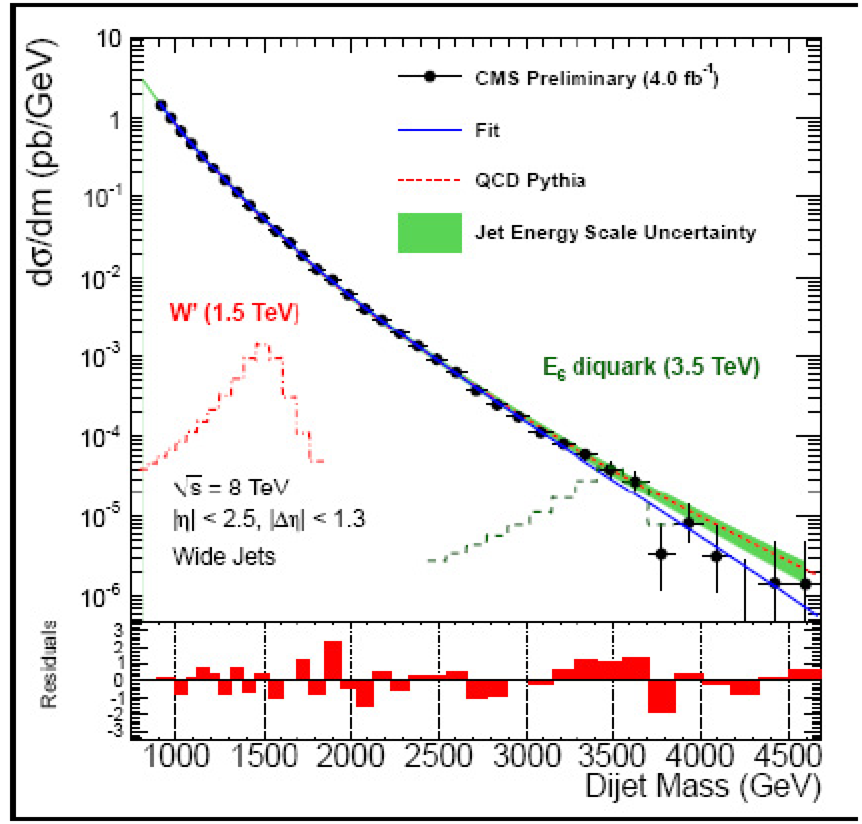


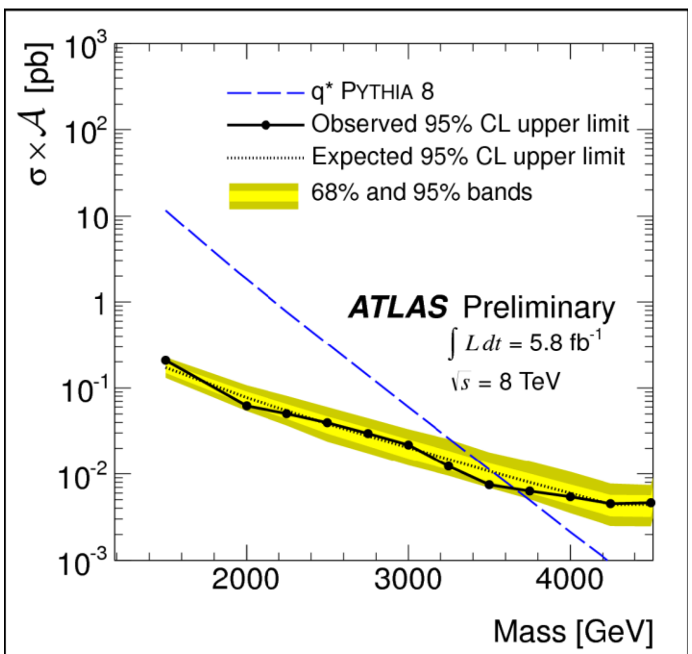
Good agreement data/QCD in the full mass range and full 2011 statistics

Dijets resonance search at 8TeV

Highest-mass central dijet event, mjj=4.1 TeV



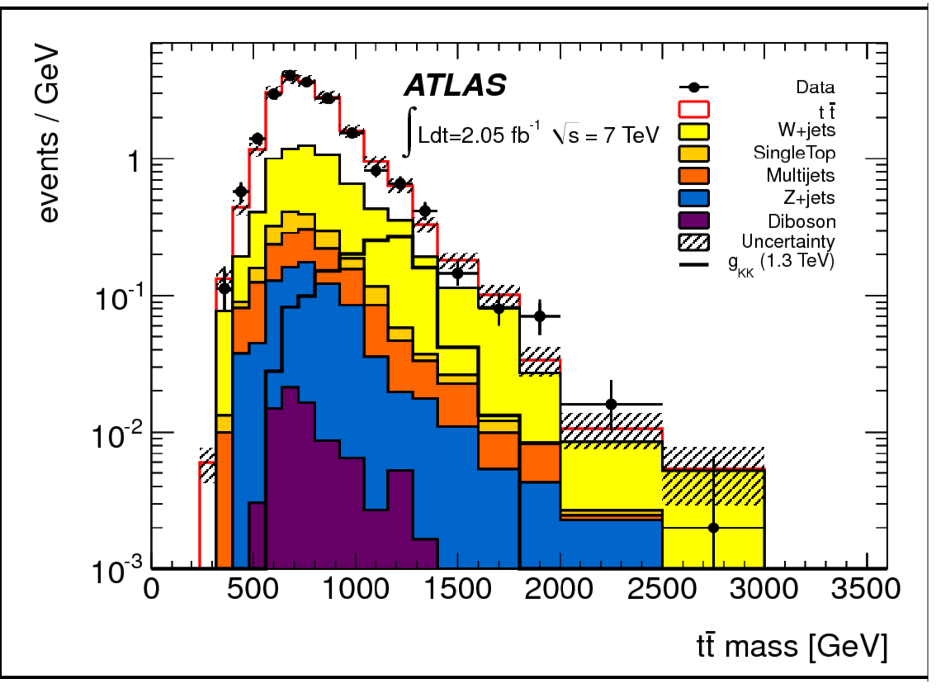


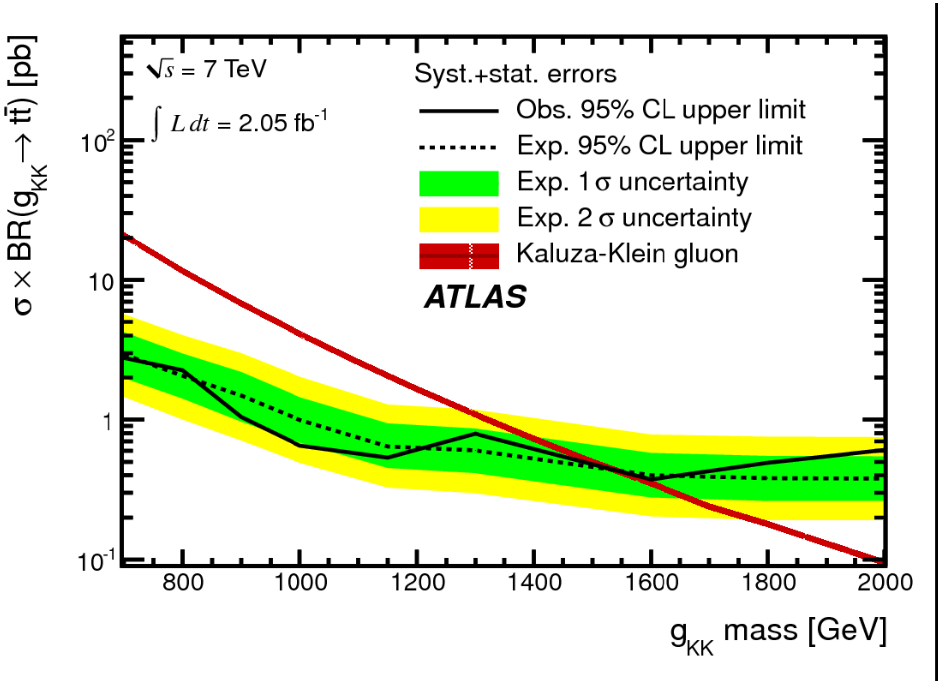


Limit on exicited quark mass enlarged from 3.35 TeV (2011) to 3.51 TeV (2012)

Search for ttbar resonances

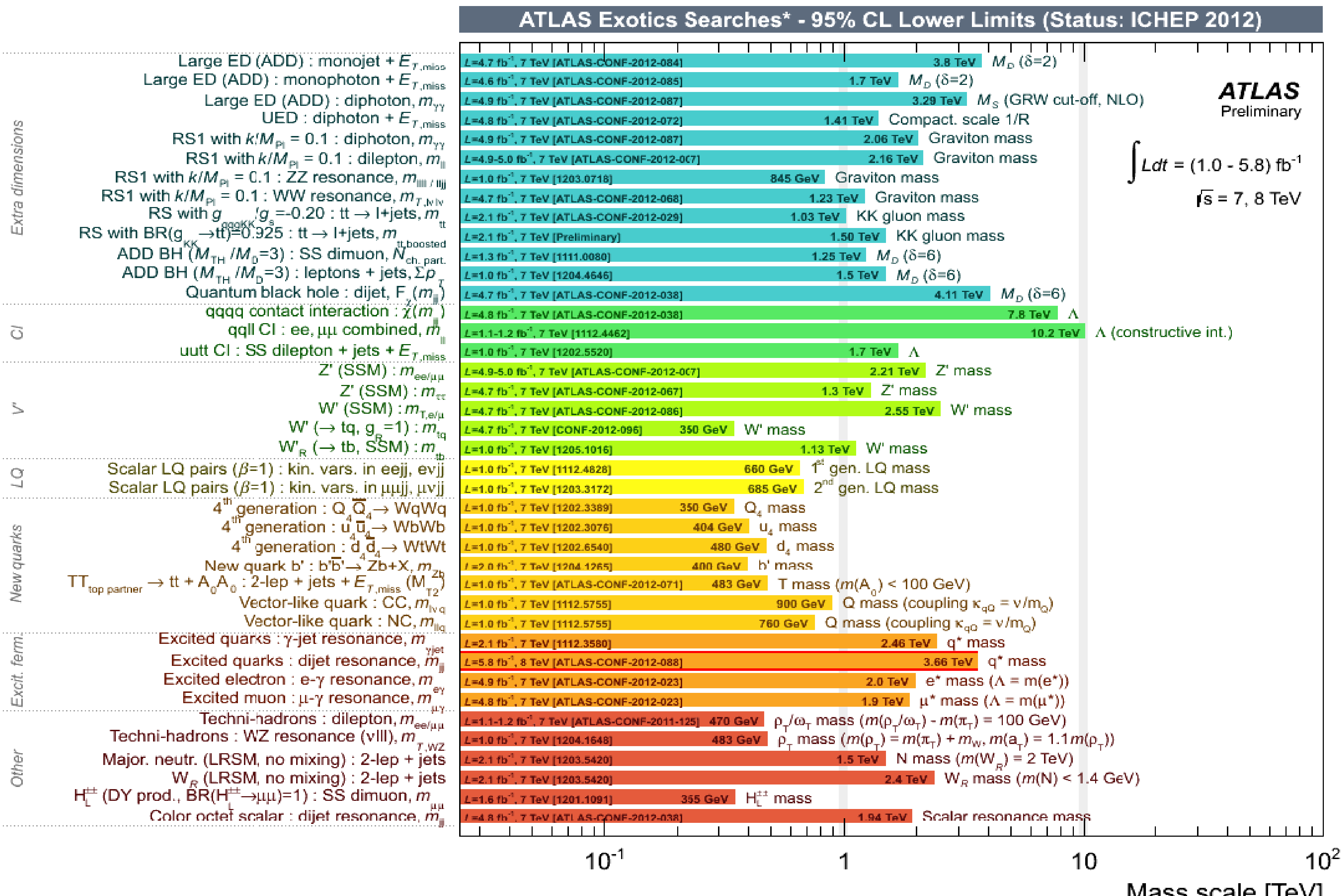
Search in the semi-leptonic final state





95% CL limit on the mass of the Kaluza-Klein gluon: 1.5 TeV

Exotics searches overview



Summary on BSM searches

- What if there is no SUSY?
  - Maybe SUSY is hidden ?
    - Close the gaps, e.g. low mass splittings, long decay chains
    - Search for a initial state radiation + NOTHING Monojets
  - Or SUSY is a bit heavier ?
    - For electroweak symmetry breaking not all SUSY particles have to be close to the 1 TeV scale, light stop and heavy 1st and 2nd gen. fermions
    - If the Higgs is around 125 GeV, usually stop heavier, also other **SUSY particles expected to be >1 TeV ?**
  - **Or SUSY looks a bit different ?**
    - **Extend searches to non-standard SUSY scenarios**
- **Many models BSM are tested are exclusion limits are provided already.**
  - **Analysis limited by available center-of-mass energy**
    - **more possibilities at 14TeV**

We have Opened the door to real understanding of EW symmetry breaking:

And finally...

We have Opened the door to real understanding of EW symmetry breaking:

Is this signal the SM Higgs?

Then what else? Are we done with the SM?

Or a BSM Higgs ?

A much more exciting scenario!

Thank you