Beyond the Standard Model with ATLAS at the LHC

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(TRIUMF)

On behalf of the ATLAS Collaboration

CAP Congress 2011

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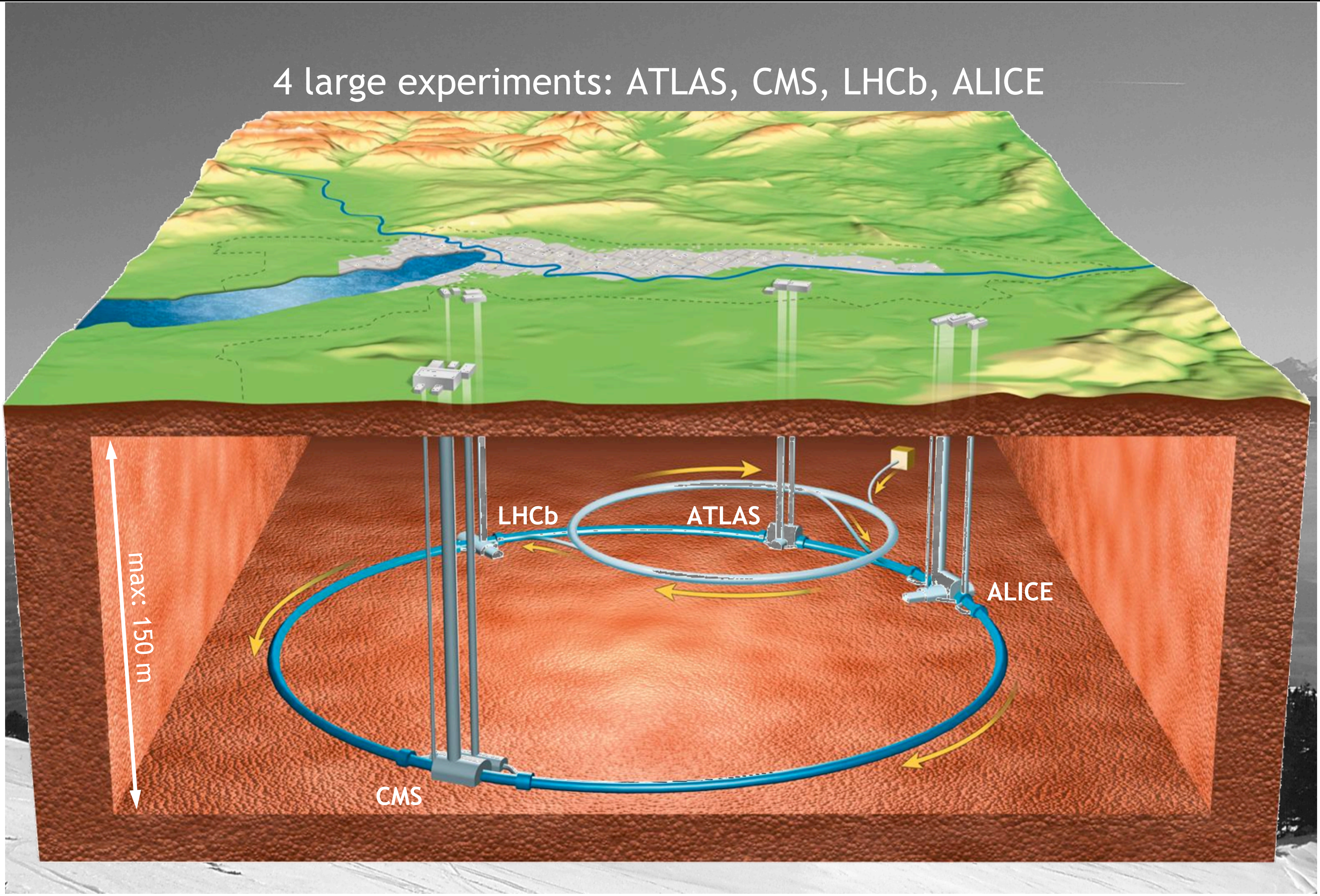
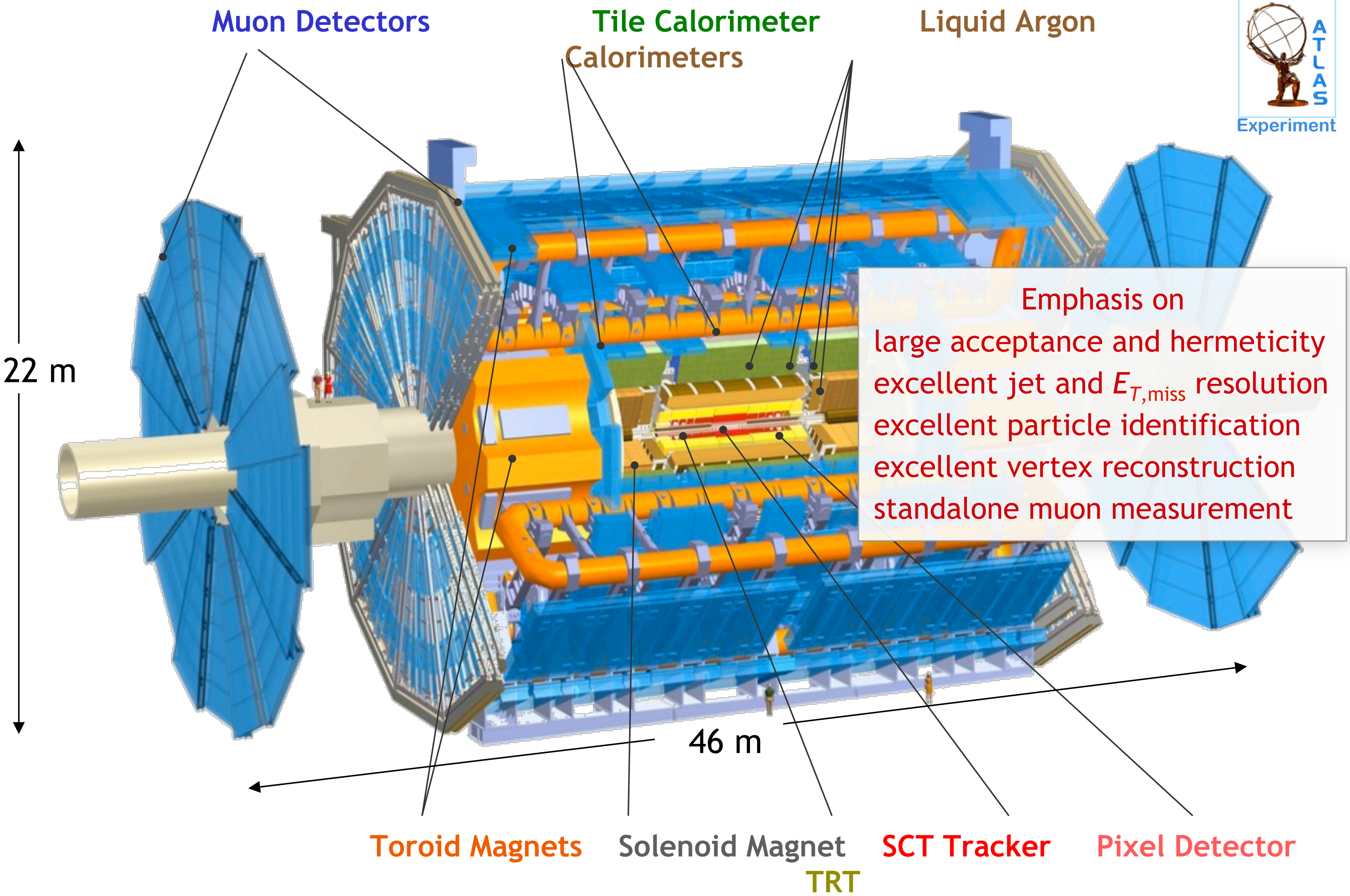
The LHC at CERN



ATLAS

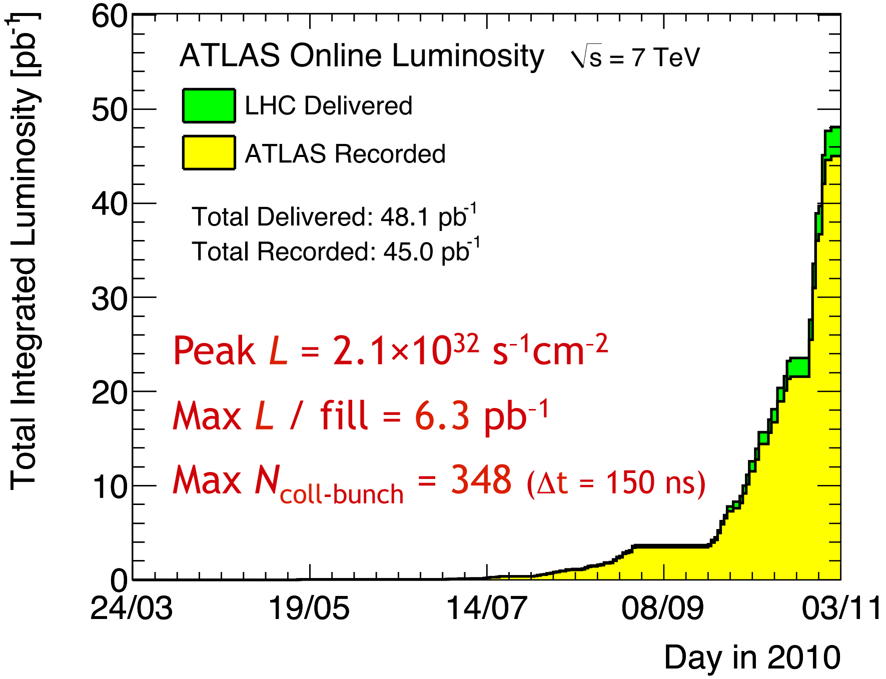


Emphasis on

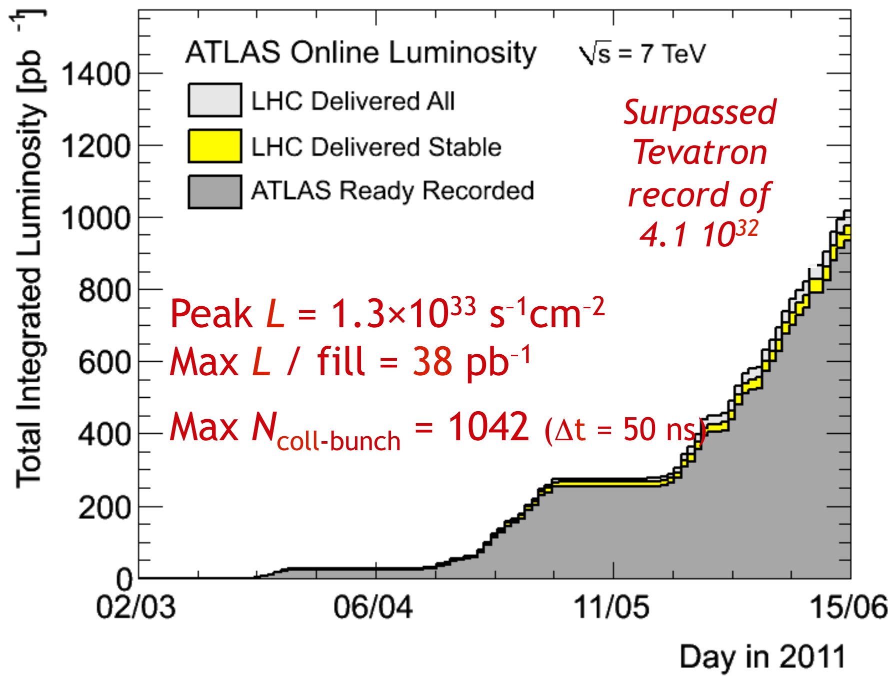
- large acceptance and hermeticity
- excellent jet and $E_{T,miss}$ resolution
- excellent particle identification
- excellent vertex reconstruction
- standalone muon measurement

Recorded Luminosity

ATLAS integrated luminosity vs time in **2010**



ATLAS integrated luminosity vs time in **2011**



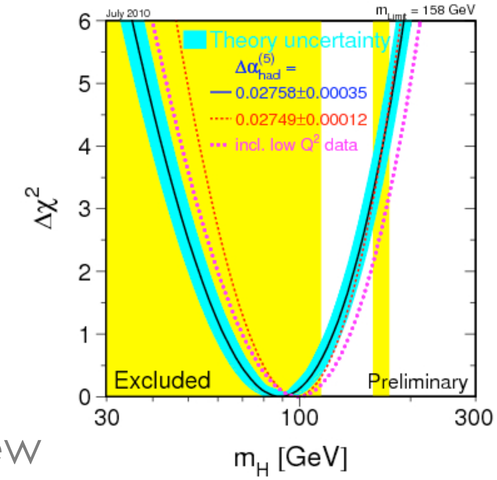
As of today: over 930 pb^{-1} of data recorded!

Outline

- *Large fraction of results shown today, based on 2010 dataset of 35 - 43 pb^{-1}*
- *Several analysis already looked at 2011 data, based on 165 - 236 pb^{-1}*
- *Exotic Searches*
- *SUSY Searches*
- *Higgs Searches*
- *Conclusion/Summary*

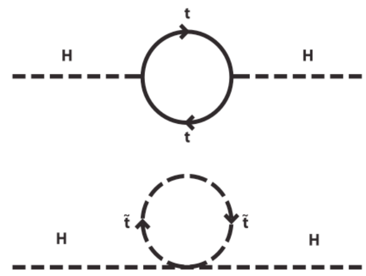
Introduction

Why we expect new physics at the Terascale



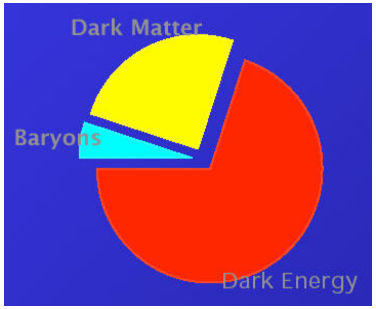
Electroweak Symmetry is broken at the EWK scale and requires a Standard Model Higgs or New Physics

Gauge Hierarchy:
Nature is fine-tuned or Higgs mass must be stabilized by New Physics, e.g. SUSY or KK towers in extra dimensional models



Dark Matter:
Weakly Interacting Massive Particle must have mass around the TeV scale to reproduce observed DM density

Vacuum Expectation Value:
The scale v=246 GeV could indicate the W, the Z, and the top quark are the only known particles with the masses on the 'correct' scale



GUT theories and extra dimensional models with KK excitations predict new resonances possibly at the Terascale

…

Exotic Searches

- ✓ Excited Quarks
  - *Dijet mass, angular distribution*
- ✓ New gauge bosons
  - *dilepton, diphoton, ttbar*
- ✓ Leptoquarks, Extra dimensions
- ✓ Black Holes, HIPs

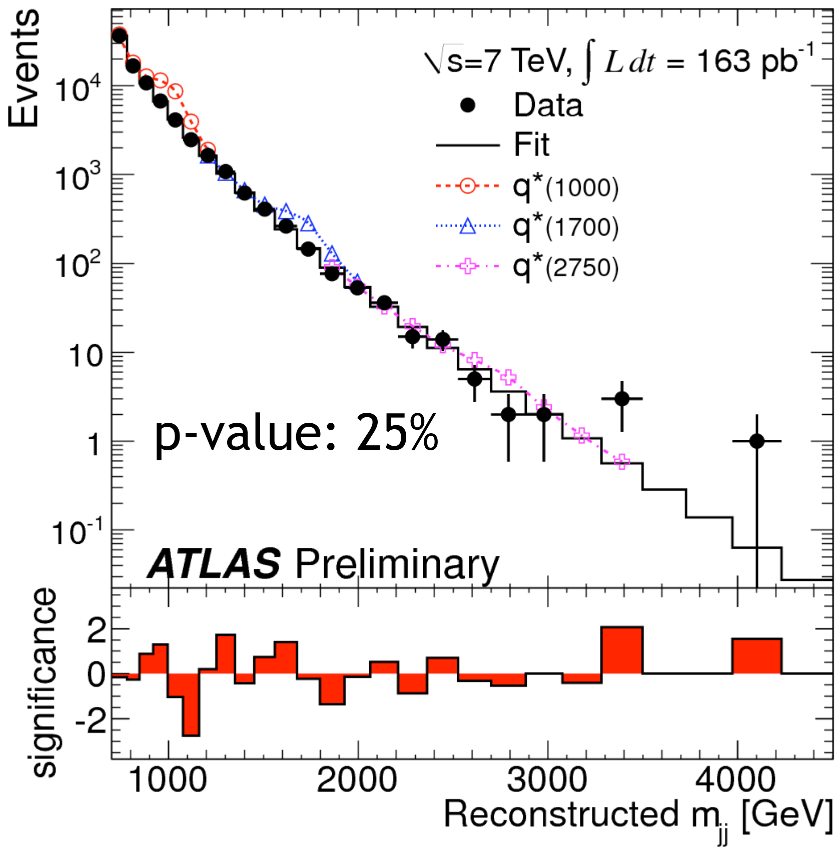
Resonances in Dijets

Dijet mass and angular distributions as probes of New Physics

Smooth QCD background prediction from fit to the data

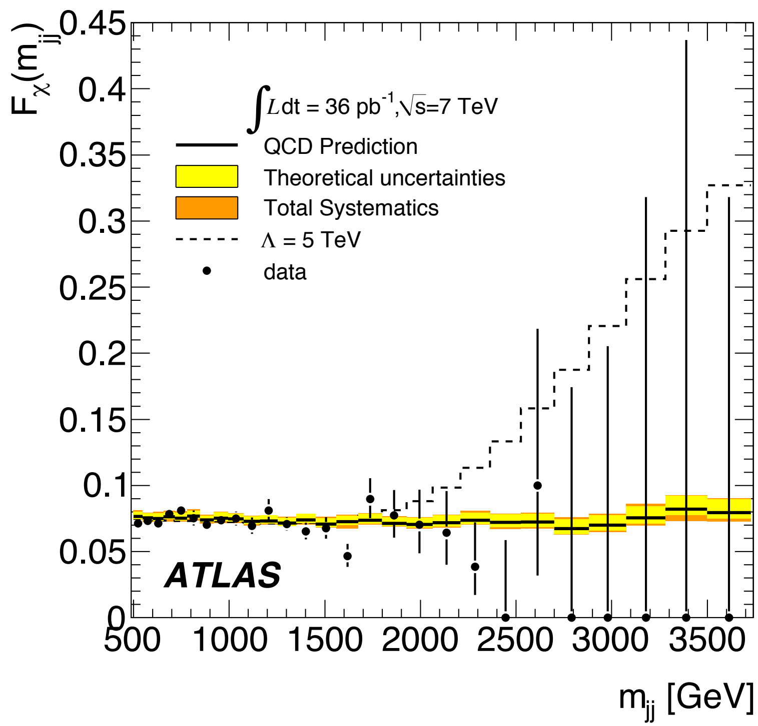
Excited quarks, contact interactions, axigluons, strong gravity, …

Observed and fitted ***m*(jet-jet)** distributions



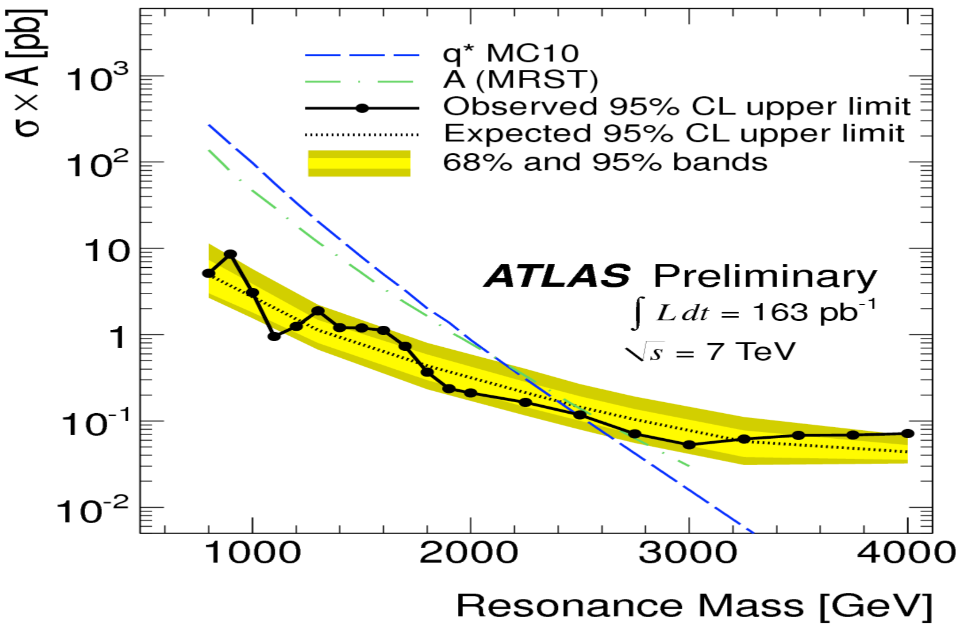
2 jets p_T>30 GeV, |η|<2.5, |Δη|<1.3

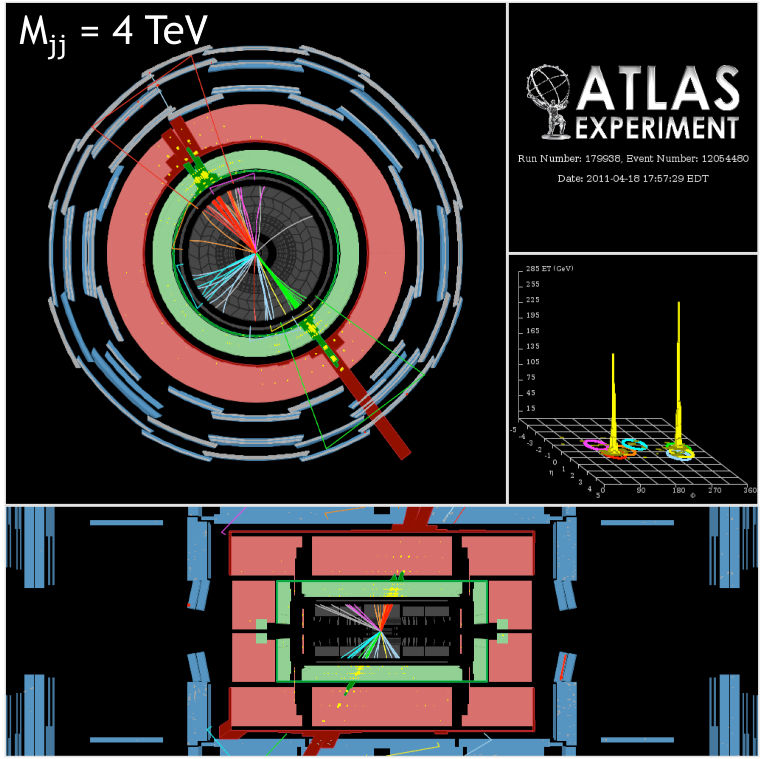
Observed and predicted **jet centrality vs. *m*(jj)**



No deviations from SM seen → set limits

Resonances in Dijets

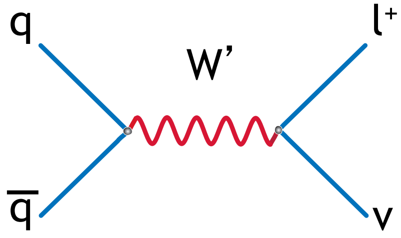




	Benchmark model	Observed (expected) limit at 95% CL
Resonant 2011 data	Excited quarks	$m(q^*)$ > 2.49 (2.40) TeV
	Axigluons	m > 2.67 (2.48) TeV
Nonresonant	RM quantum black hole (δ = 6)	M_D > 3.67 (3.64) TeV
	4-quark contact interactions	Λ > 6.7 (5.7) TeV

New Heavy Bosons: $W' \rightarrow \mu\nu$

Search based on transverse mass spectrum

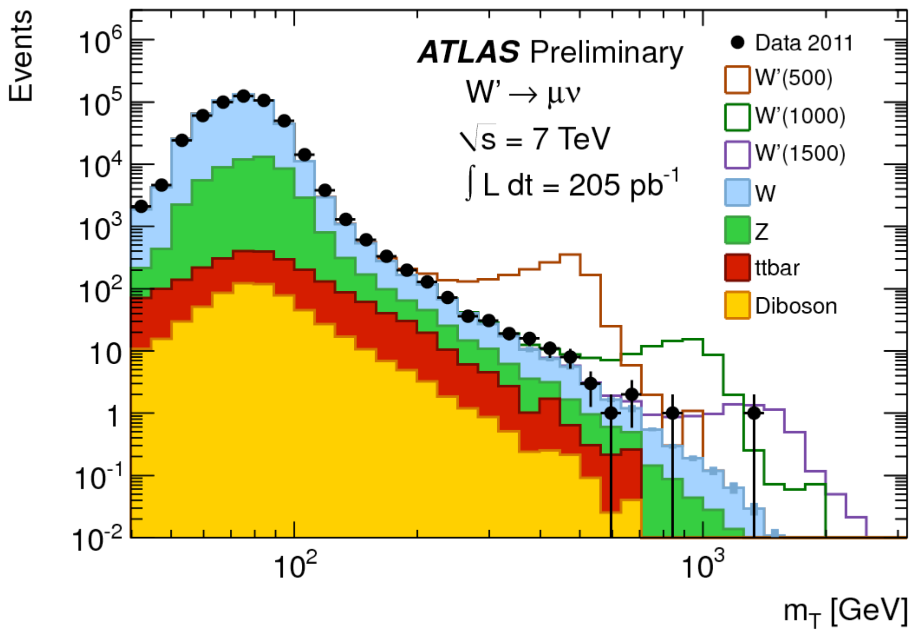


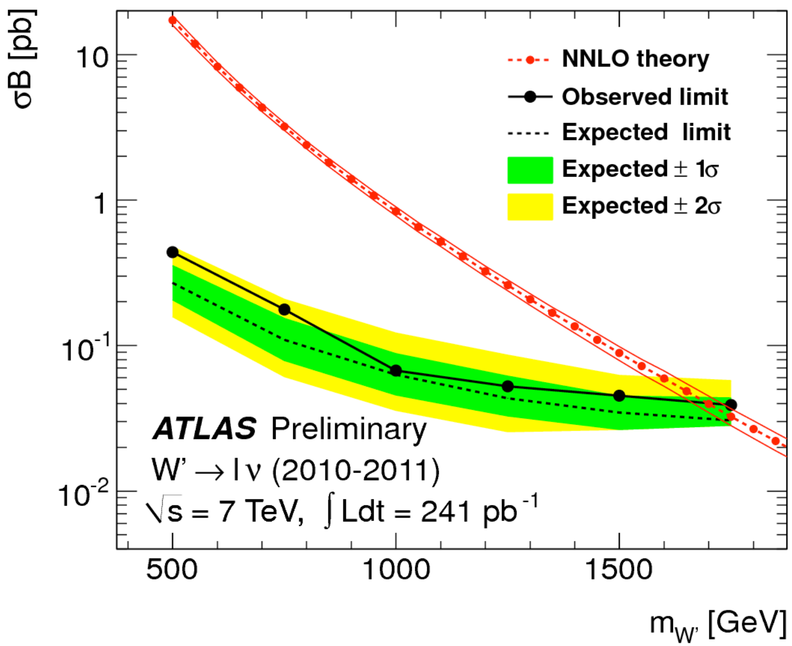
$p_T > 25$ GeV, $E_T^{miss} > 25$ GeV

$$m_T = \sqrt{2 p_T E_T^{miss}(1 - \cos\varphi_{l\nu})}$$

Need to understand E_{Tmiss} and leptons at very high momentum

Quoted limits are obtained in the sequential Standard Model

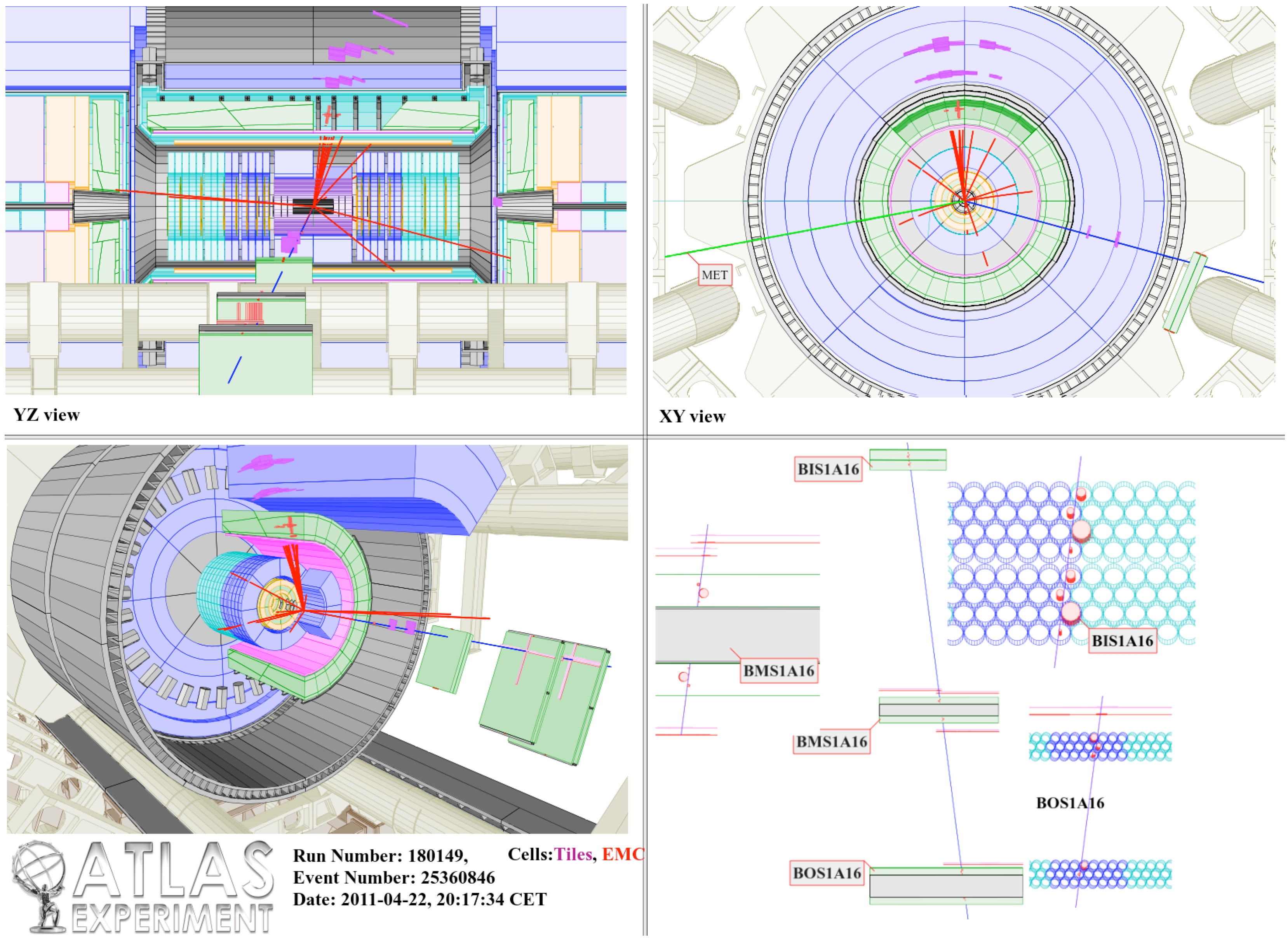




Limit improved combining the 2010 electron and muon with the 2011 muon result

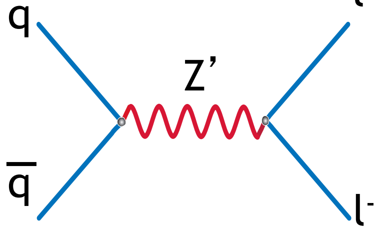
$M_{W'} > 1.70$ TeV at 95% C.L. (1.77 TeV expected)

Highest Transverse Mass: M_T = 1.35 TeV

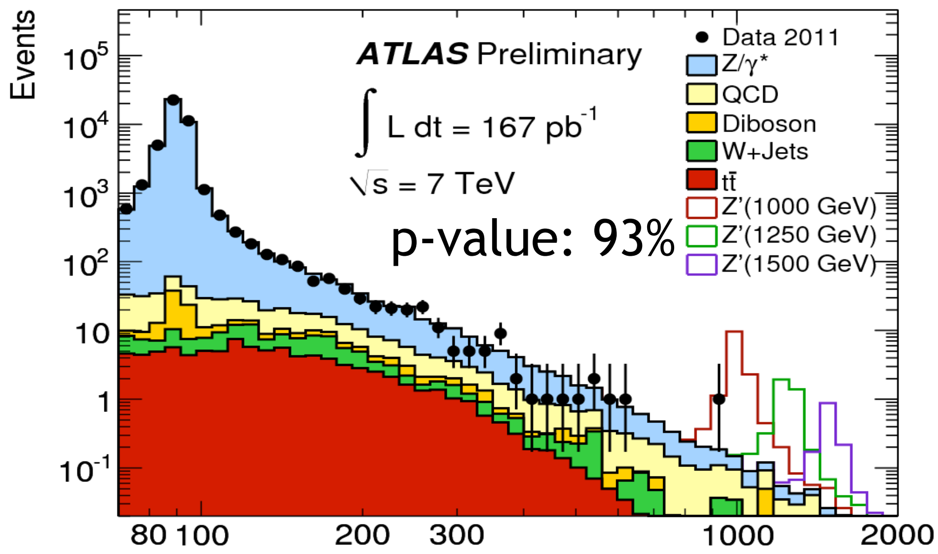


Search for Dilepton Resonances: Z'→ ll

See Simon Viel's talk in EF 3

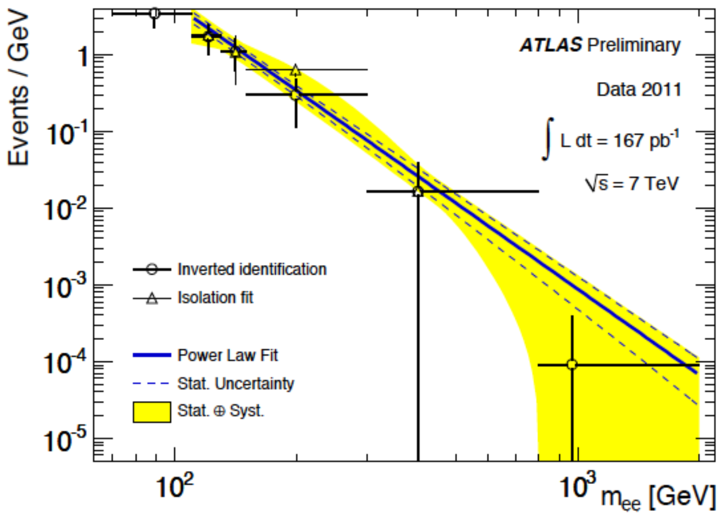


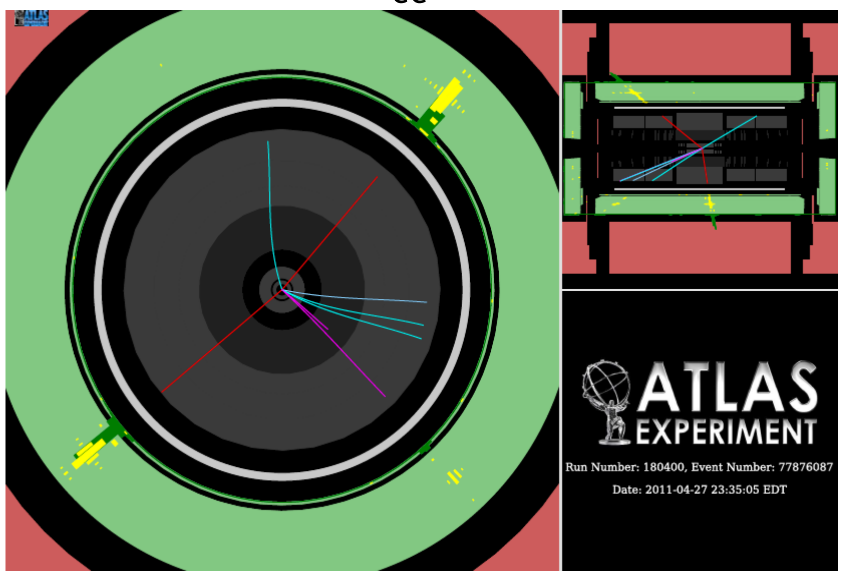
Signal template scan in dilepton mass spectrum



QCD background data driven and extrapolated to high mass

Highest Mass Event M_{ee}=920 GeV



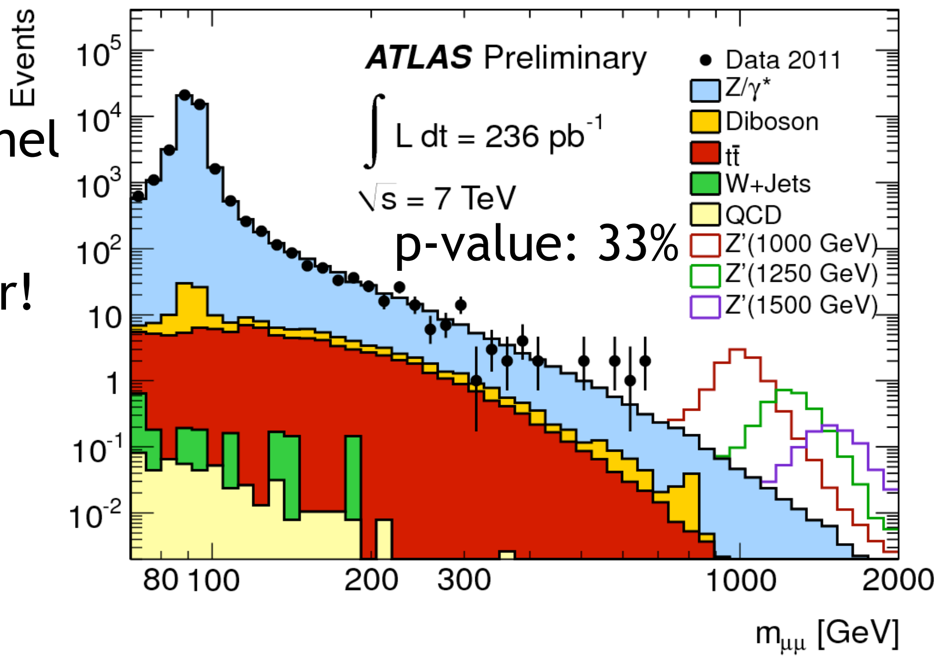


Search for Dilepton Resonances: Z'→ ll

2 lepton p_T>25 GeV

Equivalent search in the dimuon channel

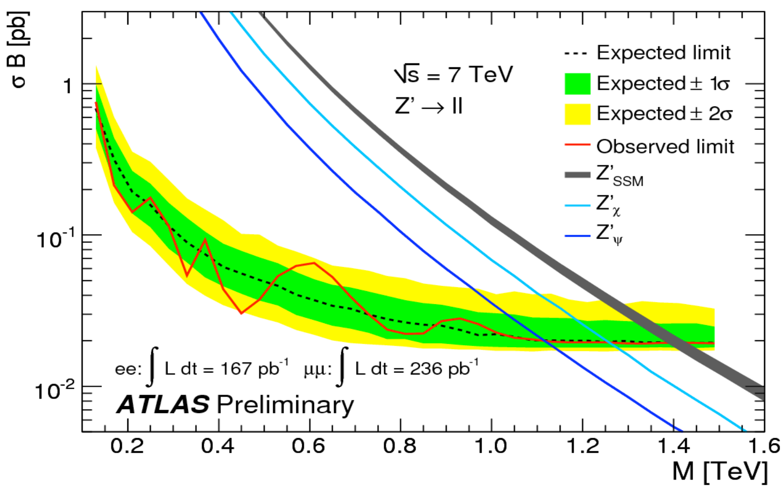
Largest analyzed ATLAS dataset so far!



Combine results

Limits in the sequential SM

	Observed limit mass [TeV]	Expected limit mass [TeV]
$Z'_{SSM} \to e^+e^-$	1.275	1.275
$Z'_{SSM} \to \mu^+\mu^-$	1.222	1.231
$Z'_{SSM} \to \ell^+\ell^-$	1.407	1.407



and GUT inspired E6

Model	Z'_{ψ}	Z'_{N}	Z'_{η}	Z'_{I}	Z'_{S}	Z'_{χ}
Mass limit [TeV]	1.116	1.142	1.150	1.203	1.230	1.259

Extra Dimensions: KK Gravitons

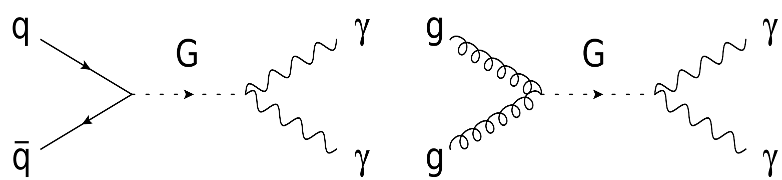
Search for extra dimensions

Randall-Sundrum KK graviton $G \rightarrow \gamma\gamma$

Diphoton background extrapolated

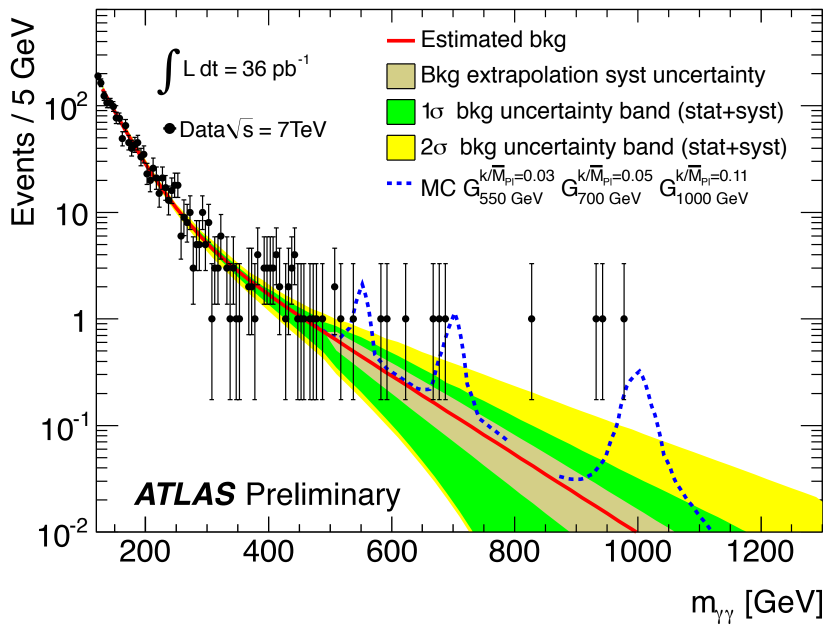
to high mass using data

See Bertrand Brelier's talk in EF 3

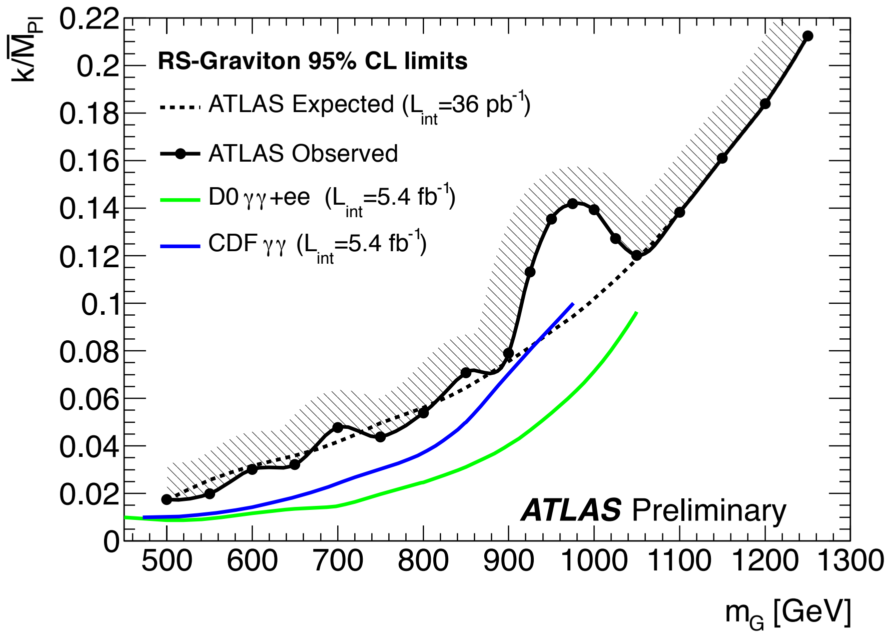


2 photons E_T>25 GeV

Observed and fitted **diphoton mass**



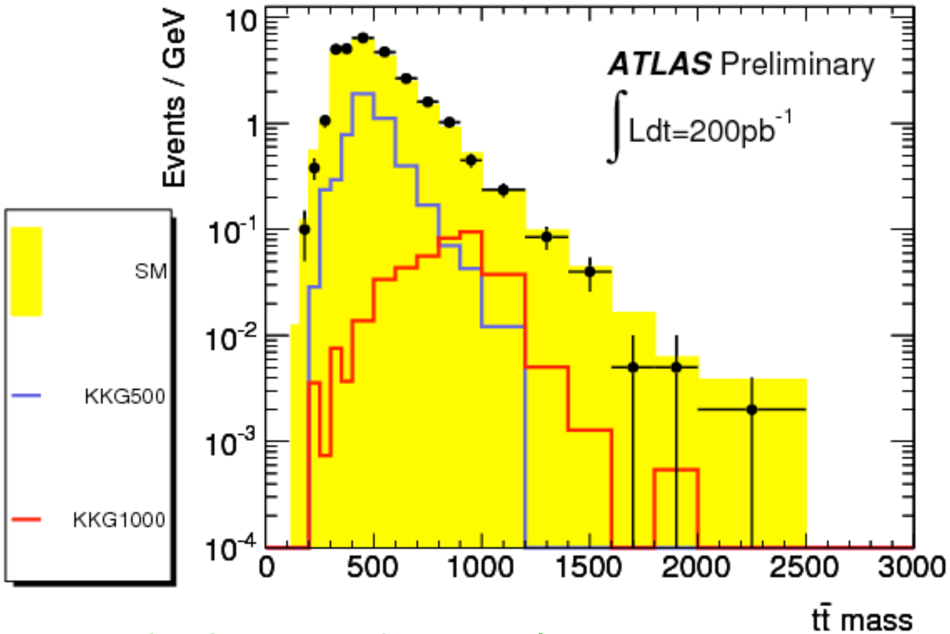
Observed and expected **RS graviton limit**

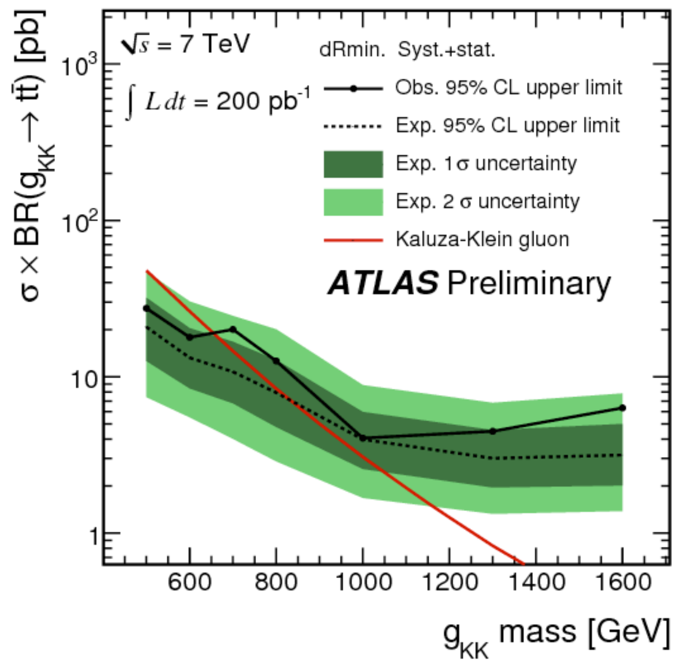


95% CL_s limit: M_G > 545 (920 GeV) for k / M_{Pl} = 0.02 (0.1)

Resonances Decaying to Top Quark Pairs

Search for new resonances decaying to top quark pairs
3^{rd} generation can be special eg. Leptophobic Z' or
Kaluza-Klein gluons in Randall-Sundrum models of extra dimensions



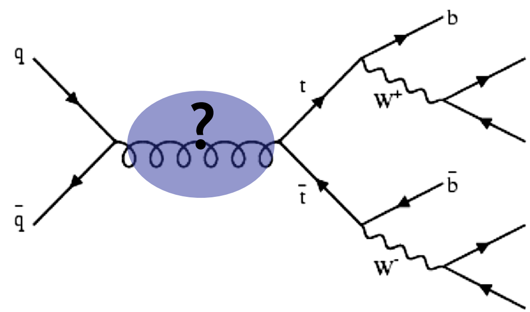


4 jets E_T>25 GeV, |η|<2.5, one b-tag
Electrons: E_T >25 GeV, E_T^{miss} >35 GeV, M_T>25 GeV
Muons: p_T >20 GeV, E_T^{miss} +M_T>60 GeV

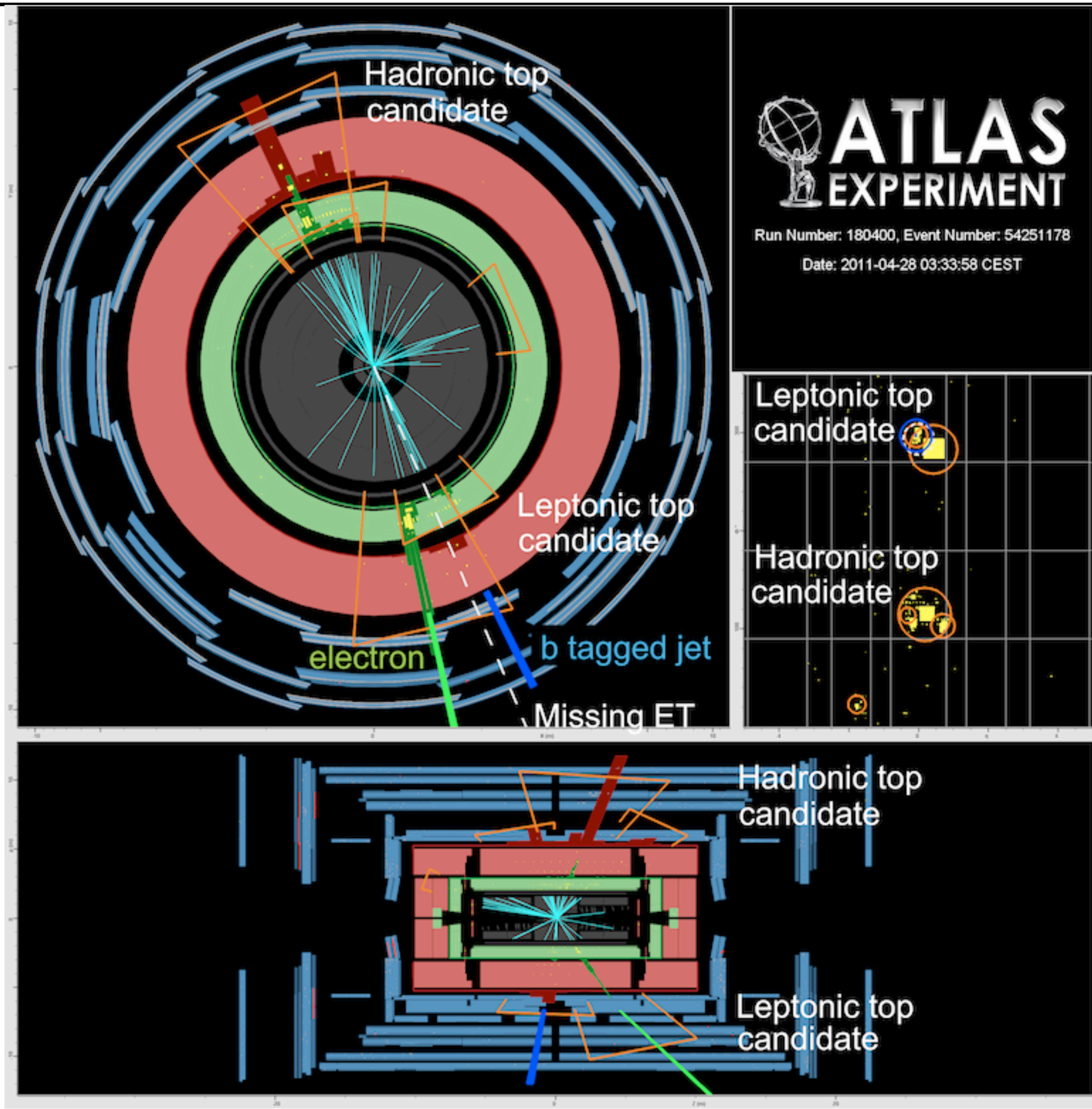
Final states: e+jets+E_{tmiss} and μ+jets+E_{tmiss}

Template Fit in invariant mass distribution

$M_{KK\ gluon}$ > 0.65 TeV at 95% C.L.



High Mass m_{ttbar}=1.6 TeV Event

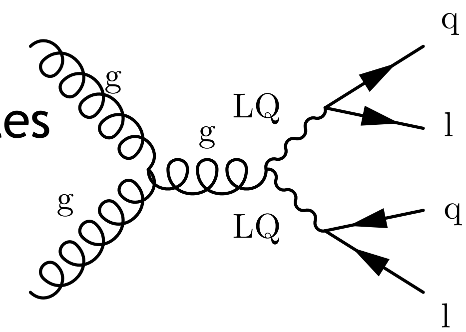


Leptoquarks

Search for 1st and 2nd generation leptoquarks

Study scalar LQ pair production to *lljj* and *lνjj* final states

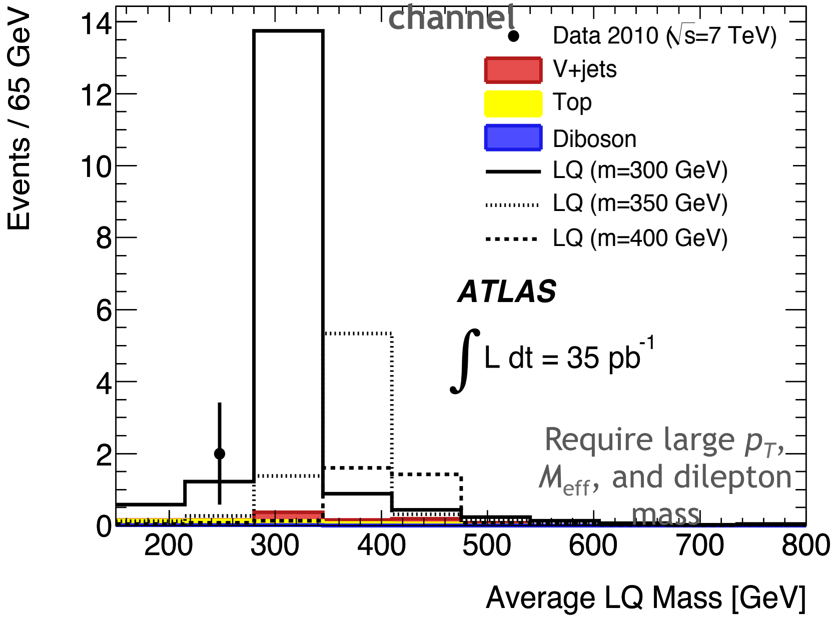
Average LQ mass or transverse mass is discriminant



2 jets E_T>20 GeV, |η|<2.8

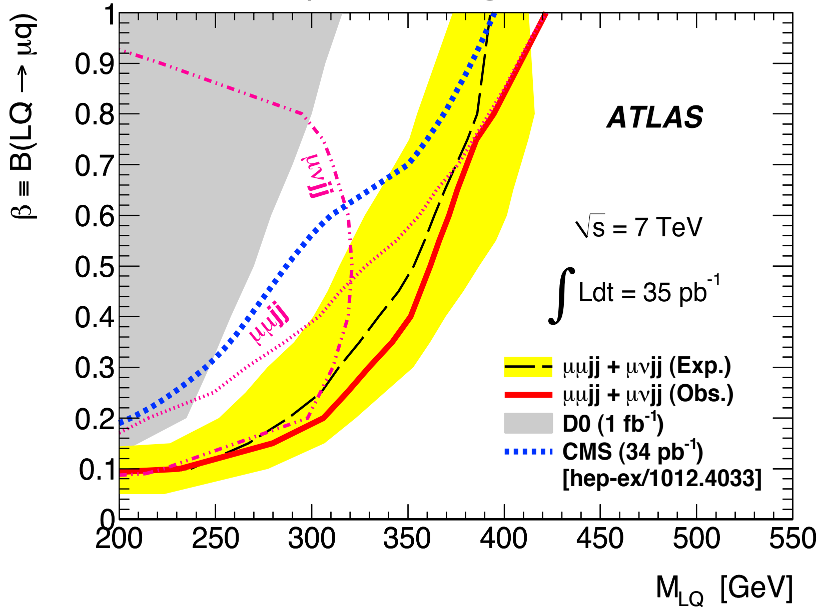
Dilepton: E_T >20 GeV; Single Lepton: E_T >20 GeV, E_t^{miss}>25 GeV

Observed and predicted **ave. *M*(LQ) in *eejj* channel**



Require large p_T, M_{eff}, and dilepton mass

Observed and expected **2nd generation LQ limit**



Validate background model in dedicated control regions

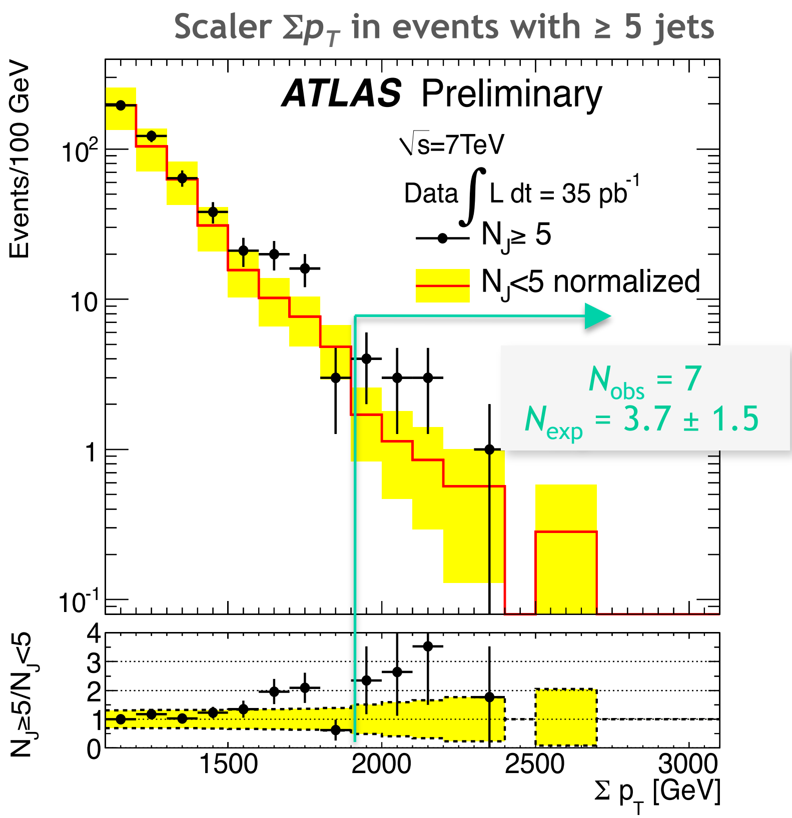
95% limits on M_{LQ} for 1st gen: > 376 (319) GeV

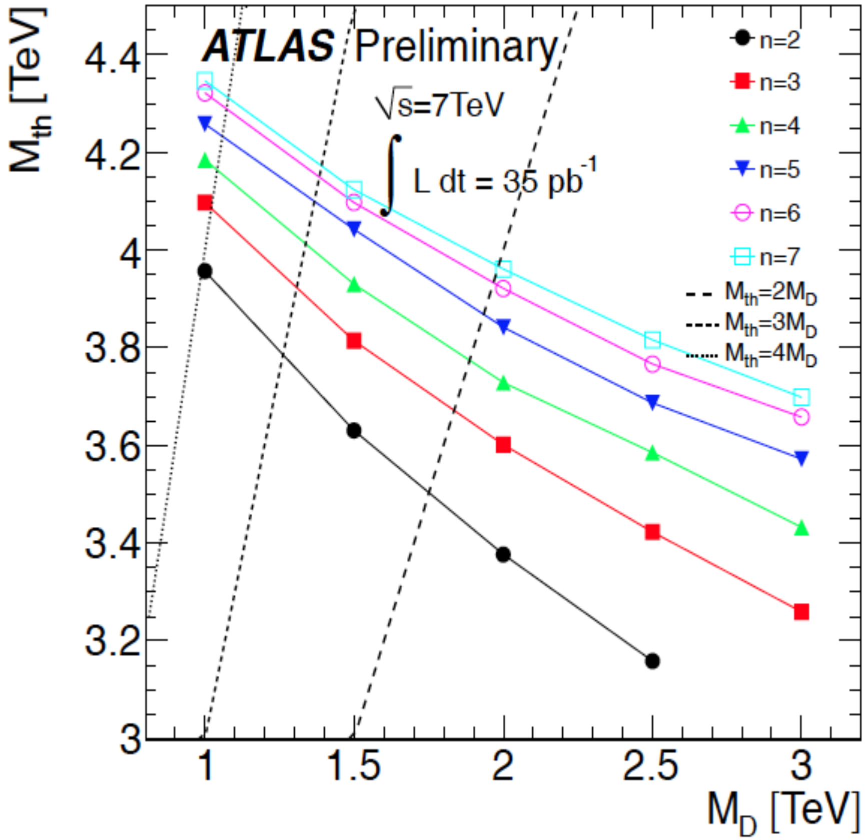
2nd gen > 422 (362) GeV for β = 1.0 (0.5)

Trans-Planck Physics

Quantum black hole search in multijet and same-sign dimuon events

Jets with E_T>50 GeV, $|\eta|$<2.8, Leading jet E_T >250 GeV





Background estimate from N_J sideband largest systematic from resulting uncertainty

Fiducial non-SM cross section limits :

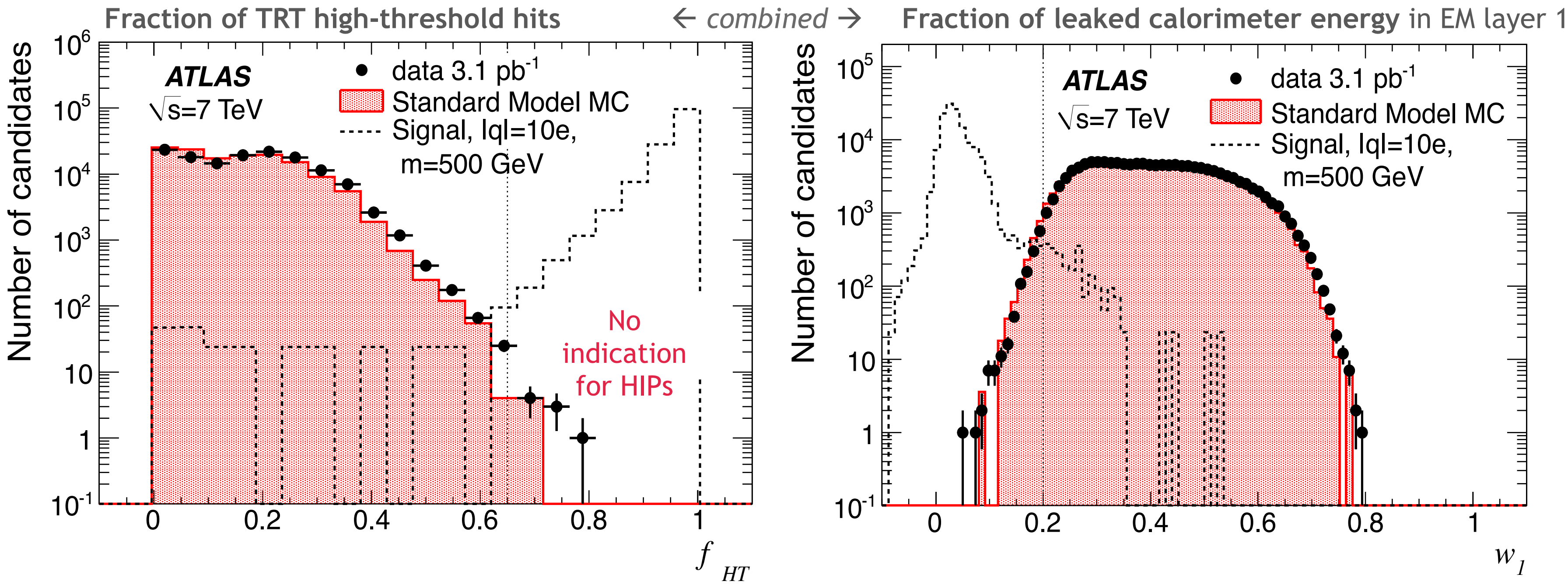
- Multijet analysis: $\sigma \times BR \times A$ < 0.29 (0.19) pb
- SS dimuon analysis: $\sigma \times BR \times A$ < 0.18 (0.28) pb

Search for Long-Lived Highly Ionizing Particles (HIP)

See Wendy Tailor's talk

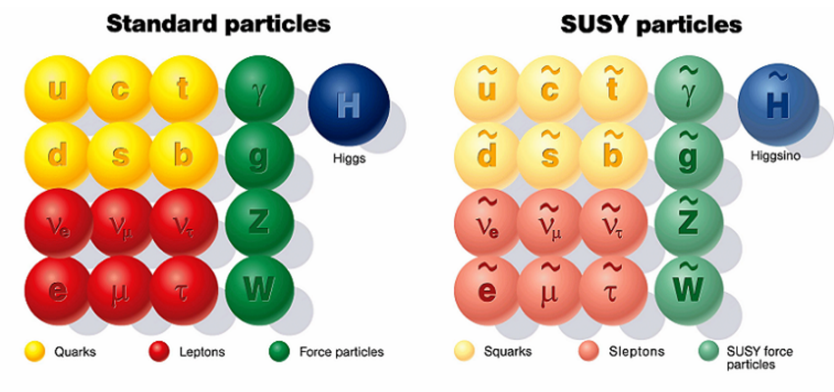
Heavy particle with $Q_{electric}$~O(10e)

→ large specific energy loss in detector



95% CL limits: σ < 3−12 pb for 6e ≤ $|Q_e|$ ≤ 17e and 0.2 < m_{HIP} < 1 TeV

SUperSYmmetry Searches



Predicts a boson for every fermion

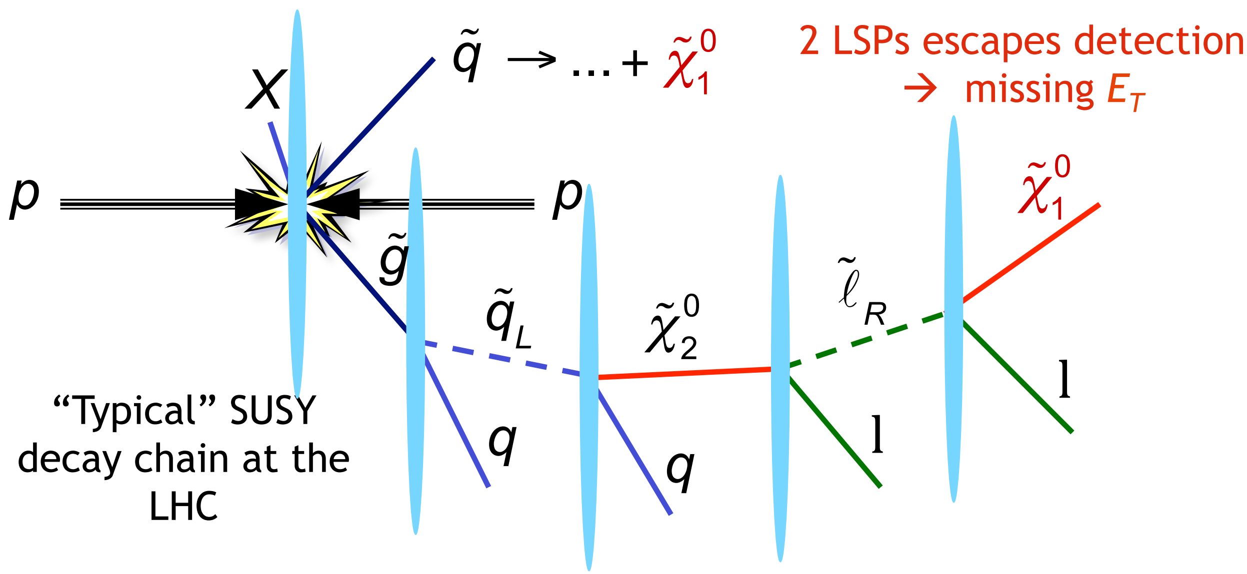
- ✓ Solution to hierarchy problem
  - *Removes fine-tuning, UV complete*
- ✓ Cold dark matter candidate
  - *If R-parity is conserved, lightest SUSY particle (LSP) is stable*

Characteristic SUSY Decay Cascades

R-parity requires existence of a lightest stable SUSY particle (LSP)→ WIMP

Typical **LSP is spin-½ neutralino**

With *R* parity: SUSY production in pairs which requires energy 2 × SUSY mass !



Characteristic SUSY Decay Cascades

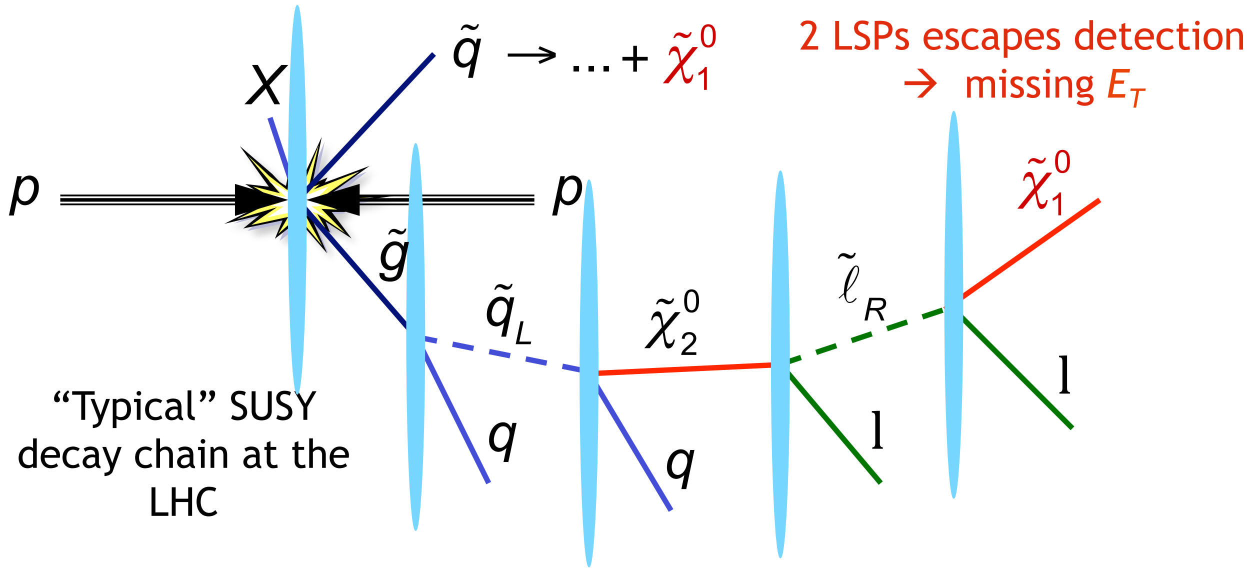
SUSY cascades produce high-p_T jets + leptons + $E_{T,\mathrm{miss}}$

→ **Incomplete event reconstruction**

- SUSY evidence in tails of distributions

Analysis concentrates on understanding backgrounds (top, W/Z+jets, QCD)

Each background component is taken from / verified in control regions



"Typical" SUSY decay chain at the LHC

Various Scenarios

Channel	Signature	Main backgrounds
0 leptons + jets + $E_{T,\mathrm{miss}}$	≥ 2–4 jets, large $E_{T,\mathrm{miss}}$, m_{eff}	W / Z + jets, top, QCD
1 lepton + jets + $E_{T,\mathrm{miss}}$	≥ 3 jets, large $E_{T,\mathrm{miss}}$, m_{eff}, m_T	top, W / Z + jets
2 leptons (SS / OS) + jets + $E_{T,\mathrm{miss}}$ (also “flavour subtraction” OS analysis)	large $E_{T,\mathrm{miss}}$	SS: Fakes, diboson; OS: top, Z + jets, also cosmics ($\mu\mu$)
≥ 3 leptons + jets + $E_{T,\mathrm{miss}}$	≥ 2 jets, $E_{T,\mathrm{miss}}$, $m_{l+l-} \neq m_Z$	top, Z + jets
0(1) lepton + *b*-jets + $E_{T,\mathrm{miss}}$	≥ 3(2) jets, $E_{T,\mathrm{miss}}$, m_{eff}, (m_T)	top, W / Z + jets
2 photons + $E_{T,\mathrm{miss}}$	$E_{T,\mathrm{miss}}$	QCD, top, $W(\gamma)$ + jets

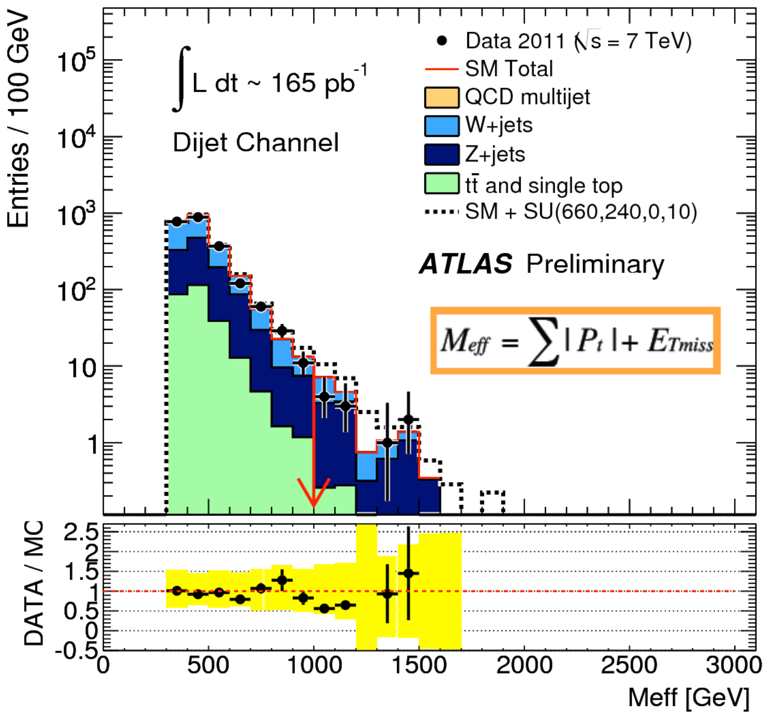
+ more targeted analyses for SUSY scenarios with features not covered by above inclusive searches

Incomplete list

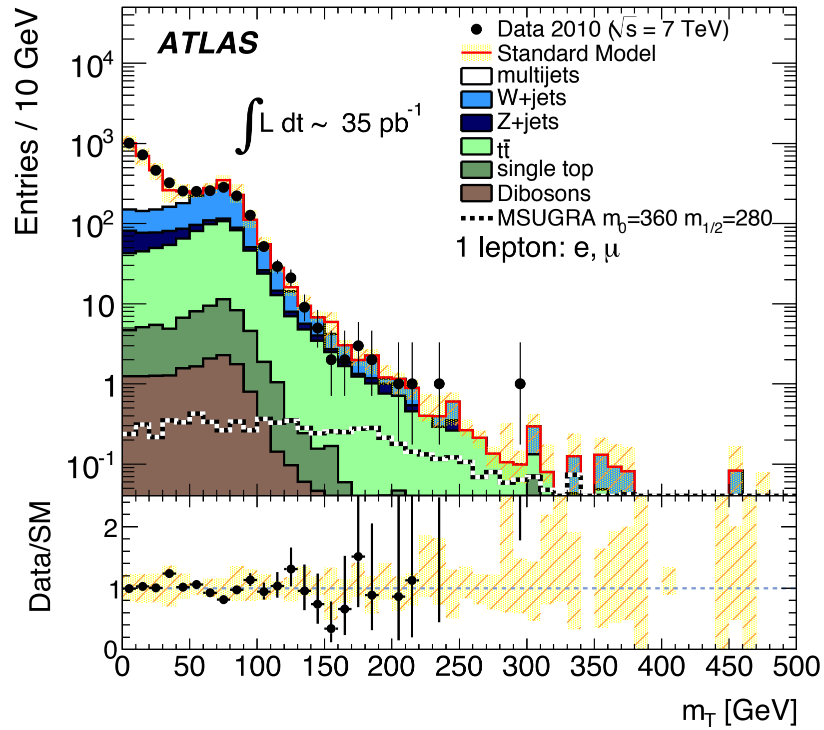
0 and 1 lepton channel

Data-driven background determination using background-enhanced control regions (*anti-cuts*) Extrapolation into signal region(s) using MC

0-lepton channel, M_{eff}
Subdivided into 2, 3, 4 jet



1-lepton channel, transverse mass

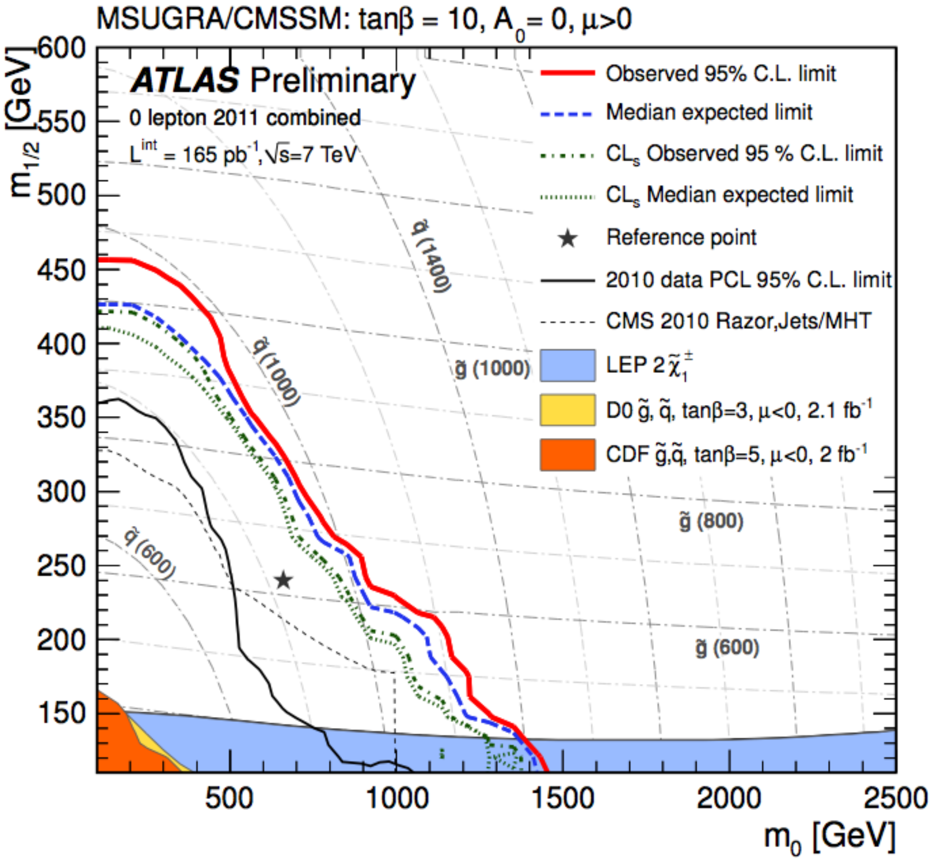


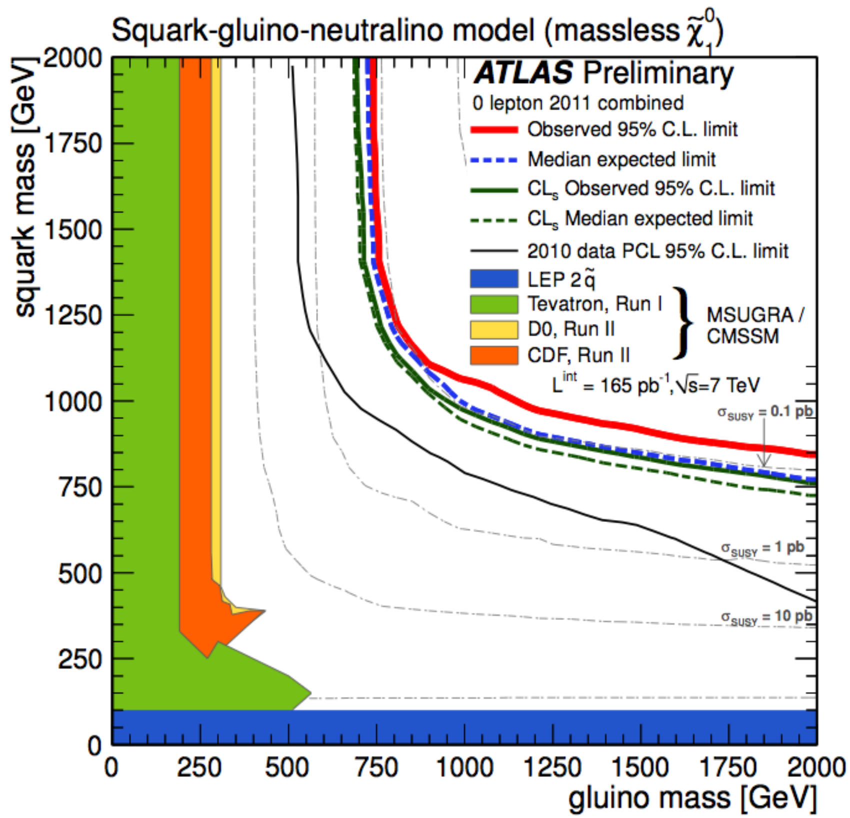
Example for observed and predicted events in signal regions		2011 data 0-lepton (>= 2j)	2010 data 1-lepton (e)	2010 data 1-lepton (μ)
	Observed	**10**	**1**	**1**
	Total SM background	12.1 ± 2.8	1.81 ± 0.75	2.25 ± 0.94

SUSY Exclusion

No signal evidence found → exclusion limits using MSUGRA and simplified models

In MSUGRA: combined 0 + 1-lepton analyses has best sensitivity
(1-lepton not updated, yet for 2011)





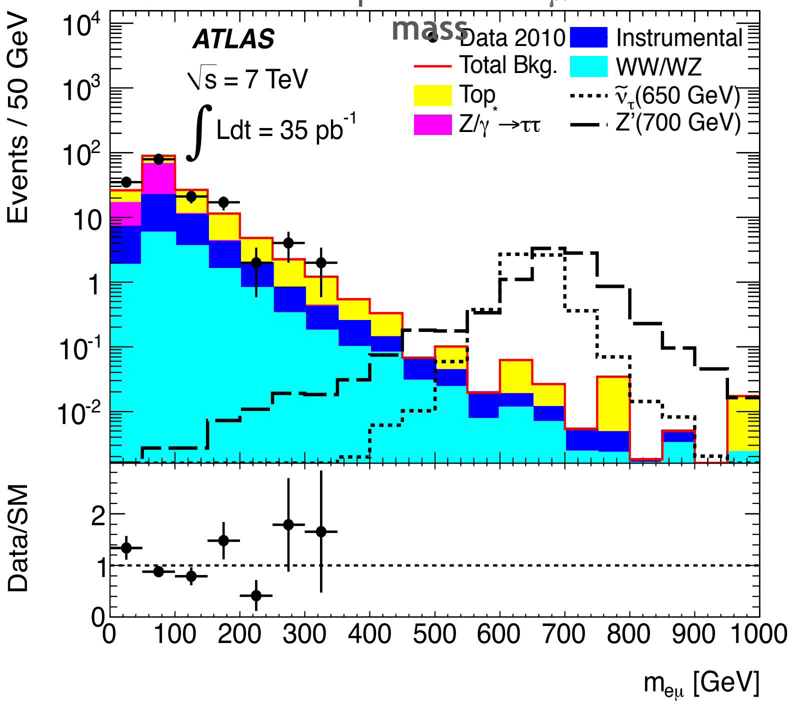
Exclude equal squarks and gluino masses of 950 GeV at 95% CL

Limit on the gluino mass is 725 GeV, raising to 1025 GeV at 95% CL assuming degeneracy

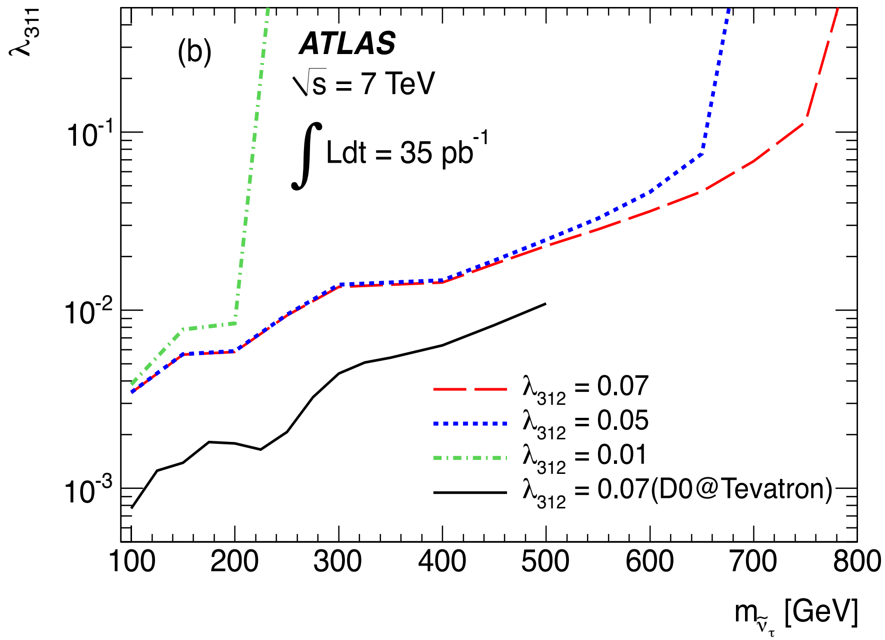
R-Parity Violating SUSY

Consider: $d\bar{d} \xrightarrow[\lambda'_{311}]{} \tilde{\nu}_\tau \xrightarrow[\lambda_{321}]{} e\mu$, search for high mass $e\mu$ signature

Observed and predicted **e-μ invariant mass**



Limits on **RPV couplings vs. sneutrino mass**



Analysis also sensitive to Z' bosons
with non-diagonal flavour coupling allowing LFV

Limits on RPV coupling: at 95% CL exclude:

$m(\tilde{\nu}_\tau) < 750$ GeV for $\lambda'_{311} = 0.11,\ \lambda_{321} = 0.07$

Higgs Searches

Origin of Mass

✓ Standard Model

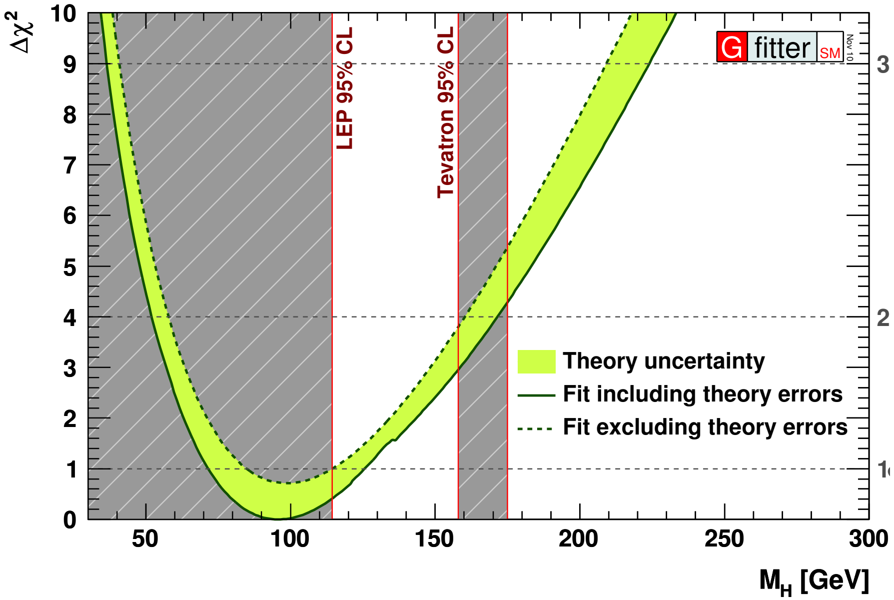
– *Indirect constraints point to small M_H*

✓ Beyond the Standard Model

– *Need to scan full mass range, expect multiple Higgses*

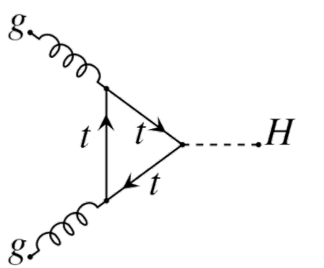
Standard Model Higgs

EW fit not including direct Higgs searches

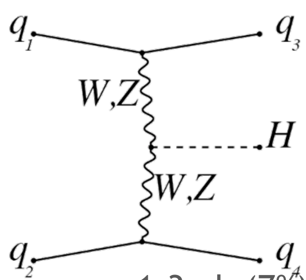


$M_H = 96^{+30}_{-25}$ GeV

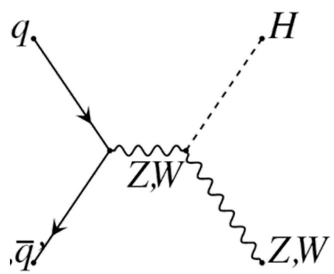
95% CL upper limit: 170 GeV



$\sigma_{M=120}$ = 16.6 pb (87%)

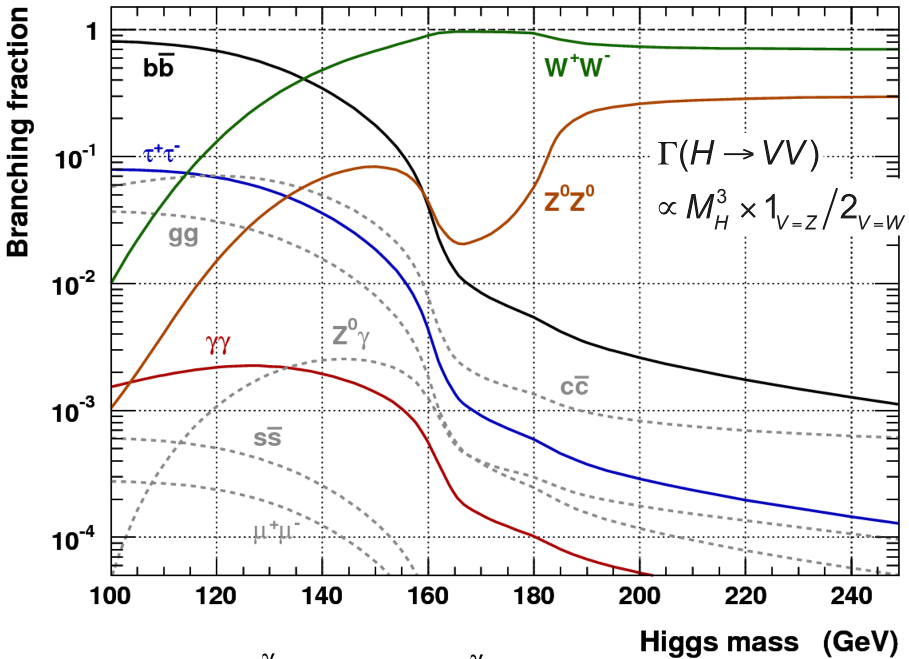


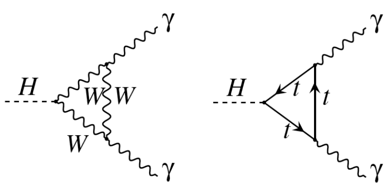
$\sigma_{M=120}$ = 1.3 pb (7%)



$\sigma_{M=120}$ = 1.0 pb (5%)

Dependence of Branching Fraction drives Search Strategy





For heavy Higgs:

- Lepton final states via $WW^{(*)}$, $ZZ^{(*)}$

For light Higgs:

- Lepton final states via WW^*, ZZ^*
- Di-photon final state
- Di-tau final state

The dominant $H \to bb$ mode is only exploitable in association with W/Z or tt, also with strong Higgs boost

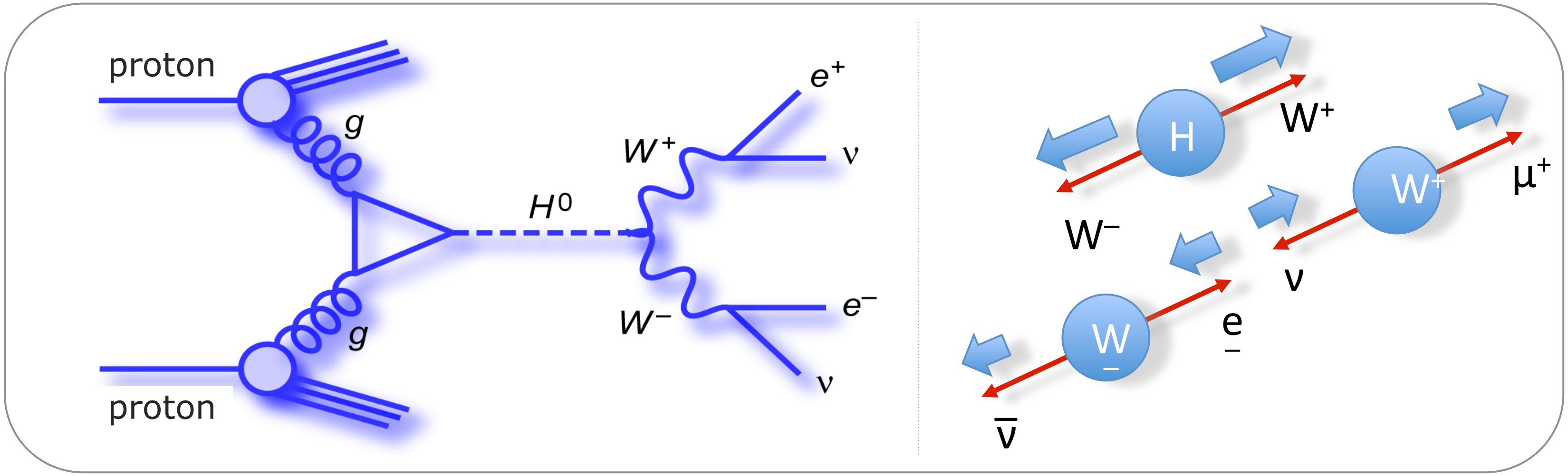
Higgs Searches

Relatively clean channel and large $\sigma \times$ BR

Leptonic mode ($\ell\nu\ell\nu$) used for $120 < M_H < 220$ GeV, semi-leptonic mode ($\ell\nu qq$) for $220 < M_H < 600$ GeV

Signal selection: leptons, $M_T^2 = (E_{T,ll} + E_{T,\text{miss}})^2 - (\mathbf{p}_{T,ll} + \mathbf{p}_{T,\text{miss}})^2 \sim M_H^2$, exploit W polarisation, separate jets

$p\bar{p} \to H + X \to W^+W^- + X \to \ell^+\nu\ell^-\bar{\nu} + X$: leptons + E_T^{miss} + small $\Delta\phi_{\ell\ell}$

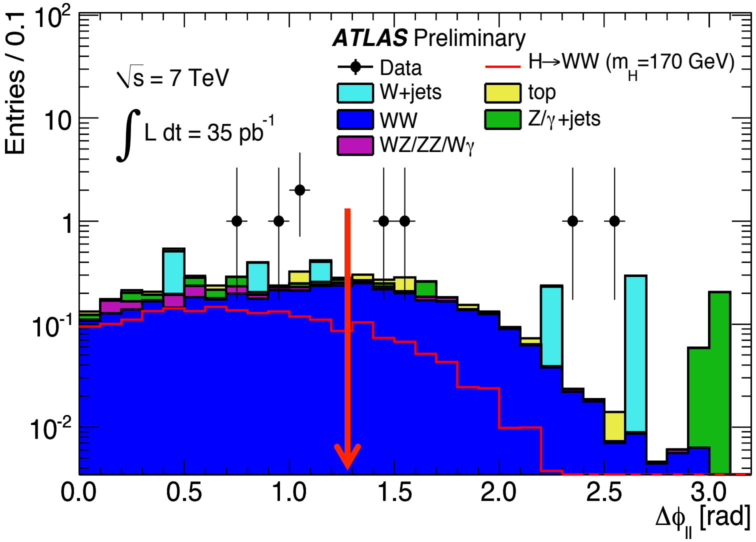


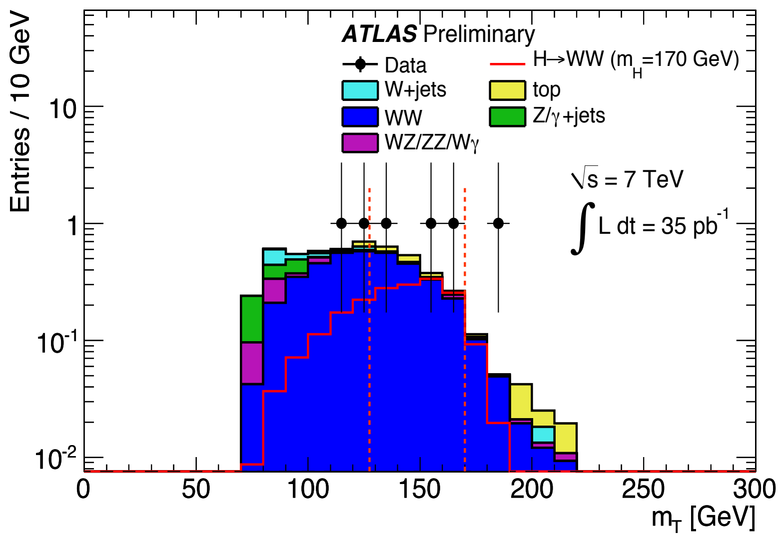
Dominant backgrounds from WW continuum, W + jets, top…

W polarisation: correlated lepton emission
Dilepton opening angle is discriminant

Higgs Searches

Data-driven background determination using bkg-enhanced control regions (*anti-cuts*)
0-jet channel: S/B ~ 0.7 at M_H = 170 GeV, after cuts on $\Delta\phi_{ll}$, m_{ll}, m_T, $E_{T,\mathrm{miss}}$





Separate in *ee*, *eμ and μμ* channel, as well as 0, 1 and 2 jet bins

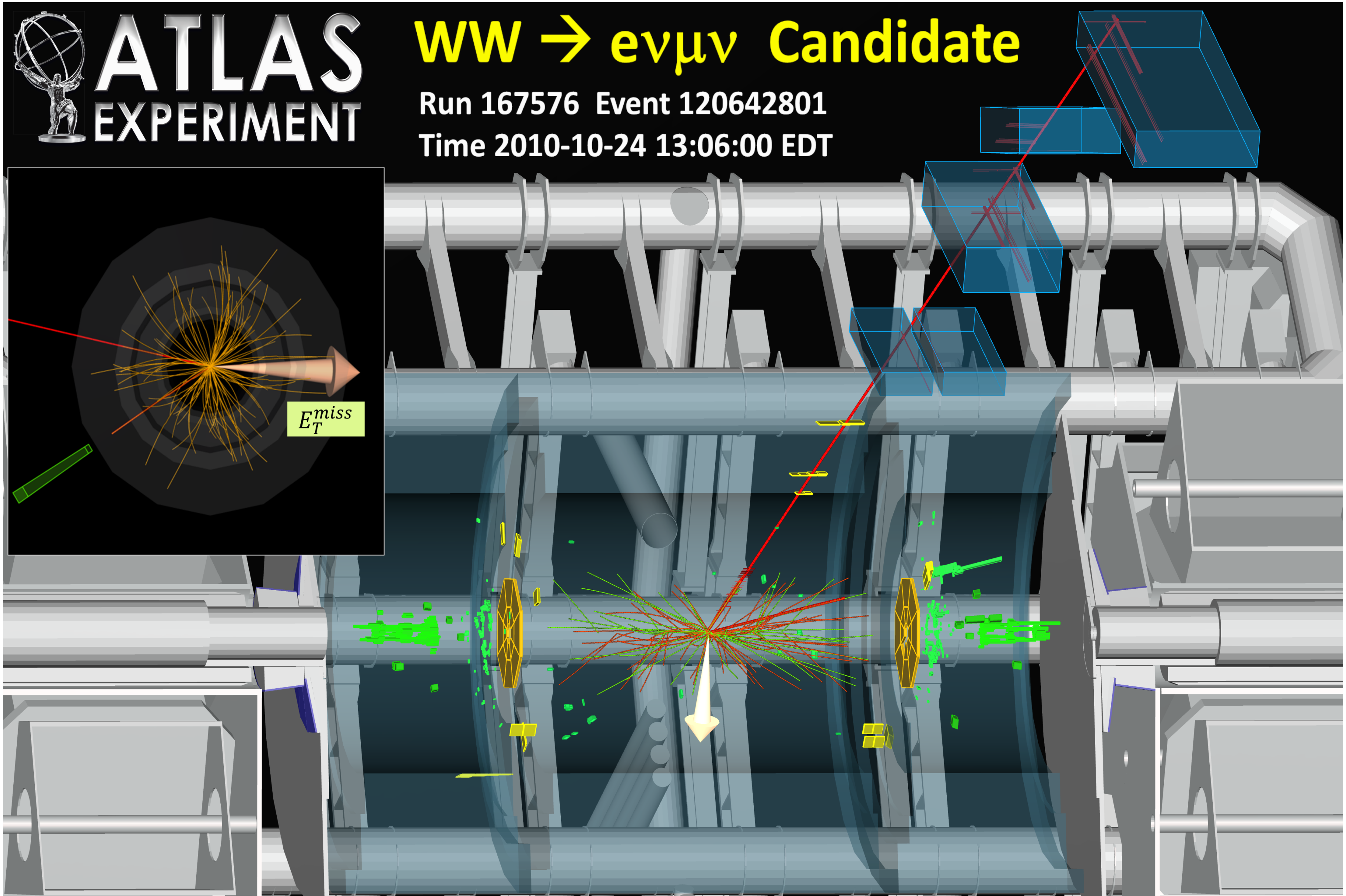
Higgs detection requires good understanding of *WW* background

Recent ATLAS measurement finds:

$\sigma(pp \rightarrow W^+W^-) = (41^{+20}_{-16} \pm 5)$ pb

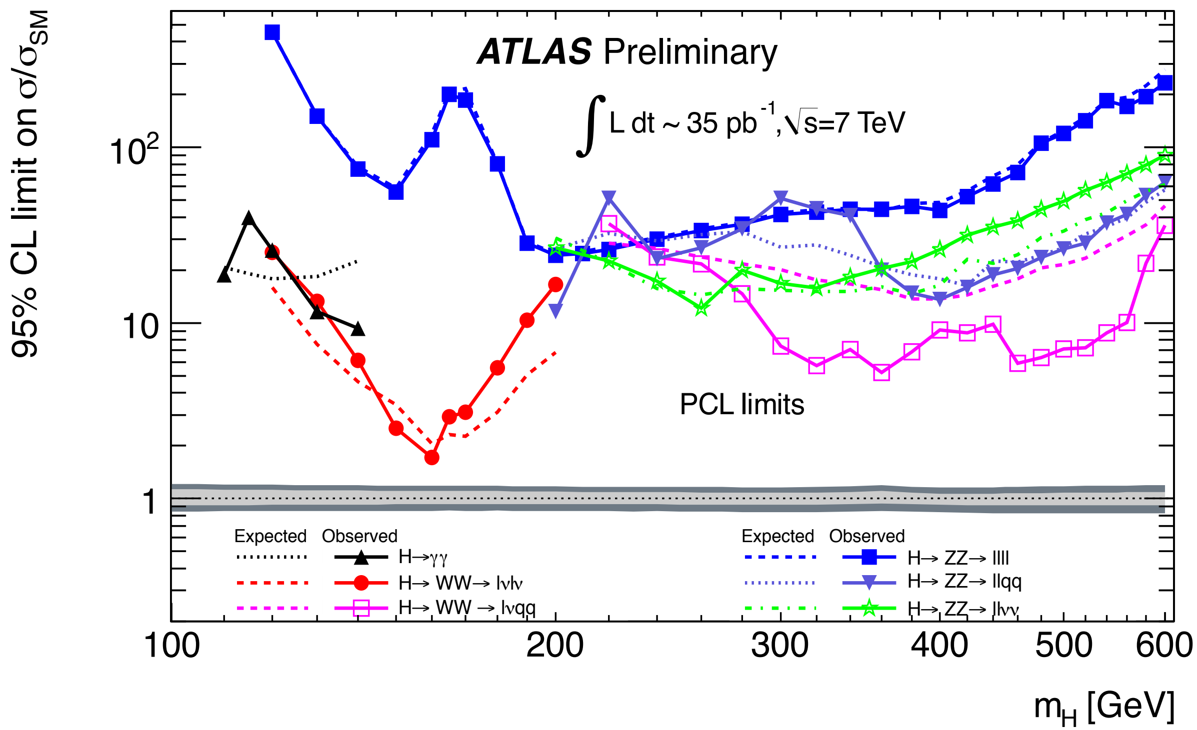
agreeing with NLO SM: (44 ± 3) pb

WW Event Display



Higgs Exclusions

Observed and expected 95% CL exclusion limits in units of SM cross section



At M_H = 120 GeV, *WW* competitive with γγ

Almost 95% exclusion at M_H ~ 160 GeV

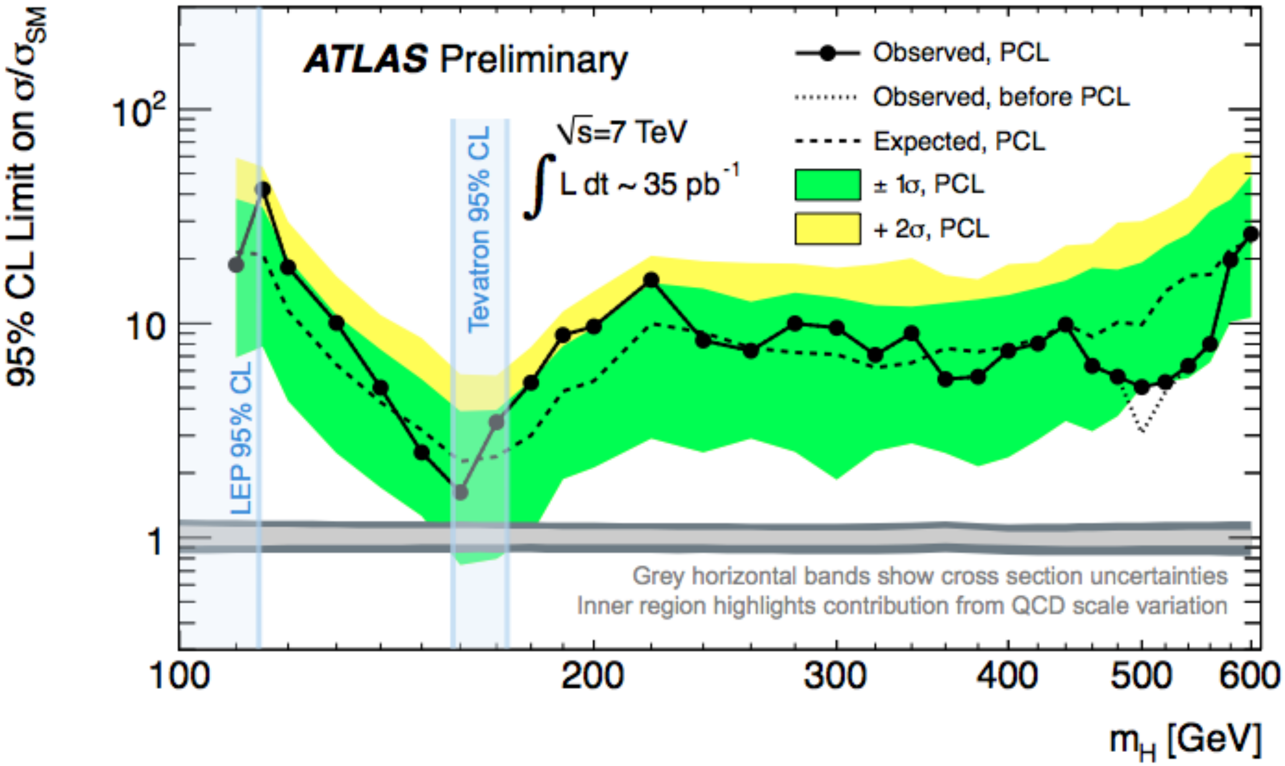
Between M_H ~ 210 and 290 GeV $ZZ \to ll\nu\nu$ most sensitive

Above M_H ~ 290 GeV $WW \to l\nu qq$ dominant

Above M_H ~ 400 GeV $ZZ \to llqq$ competitive

ATLAS Combination

ATLAS combination of individual channels for 2010 data

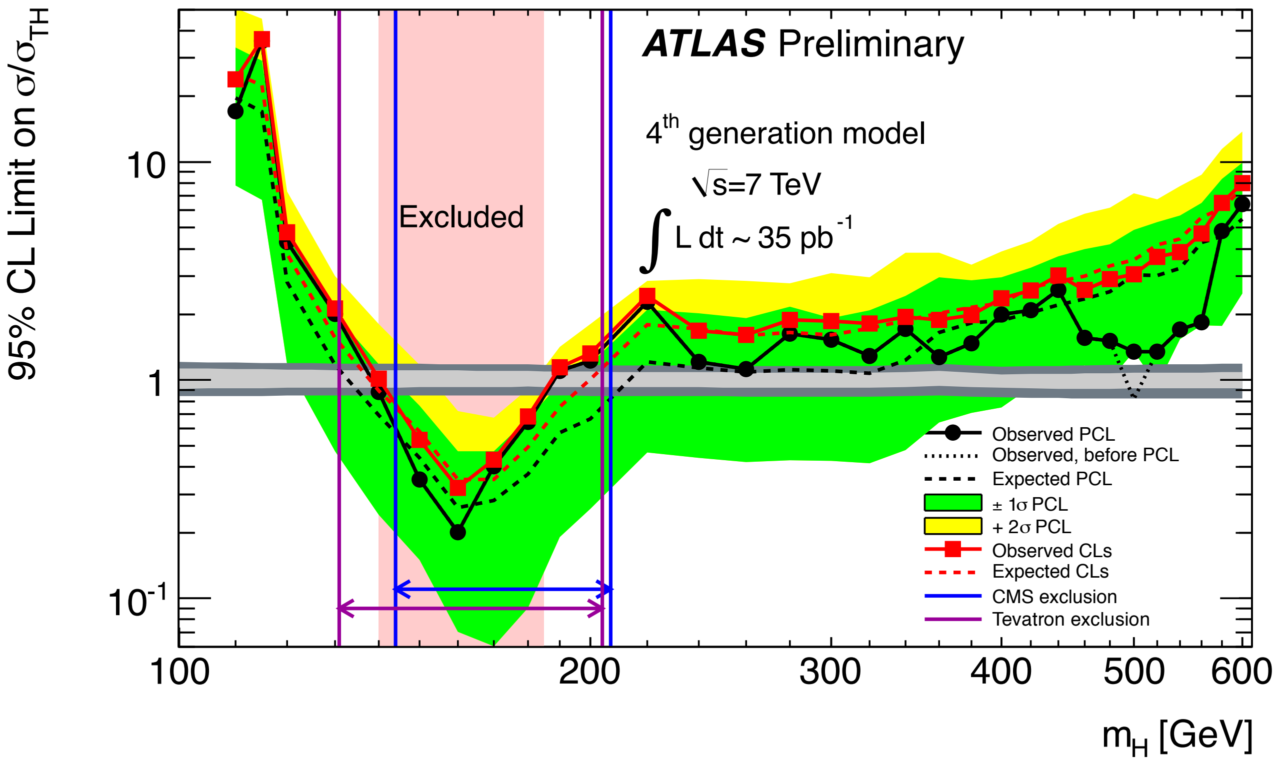


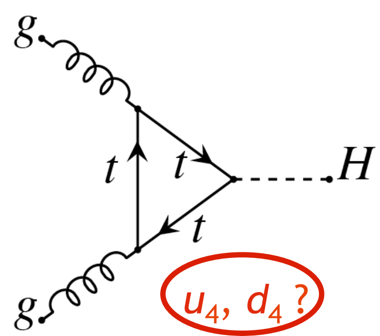
Combination using maximum likelihood fit taking into account correlated nuisance parameters

Not yet reached at Tevatron which exclude 158–173 GeV at 95% CL

ATLAS Combination 4th Generation

Gluon fusion to Higgs via triangular heavy-quark loop sensitive to 4th generation





4th generation ? K-factor of ~3^2 = 9 using sequential model

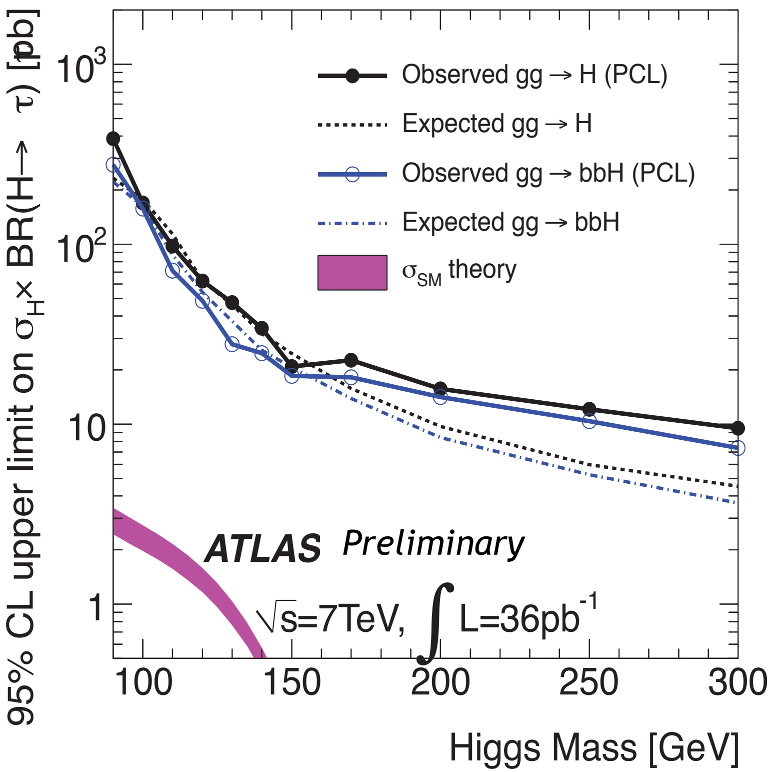
95% CL exclusion of 140 < M_H < 185 GeV in "SM with 4th generation"

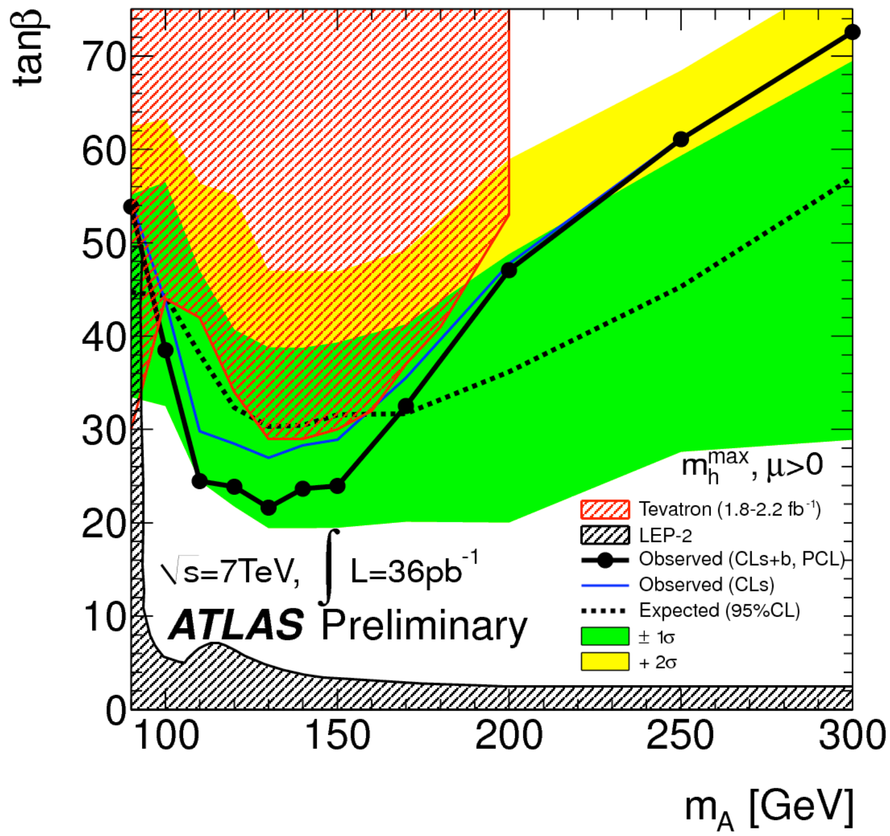
SM / SUSY Higgs to ττ

2 Higgs doublets required in MSSM, leading to 5 Higgs bosons: *h*, *H*, *A*, $H^{\pm}$

Higgs coupling to down-type fermions can be strongly enhanced depending on $\tan\beta = \upsilon_d / \upsilon_u$ and m_A

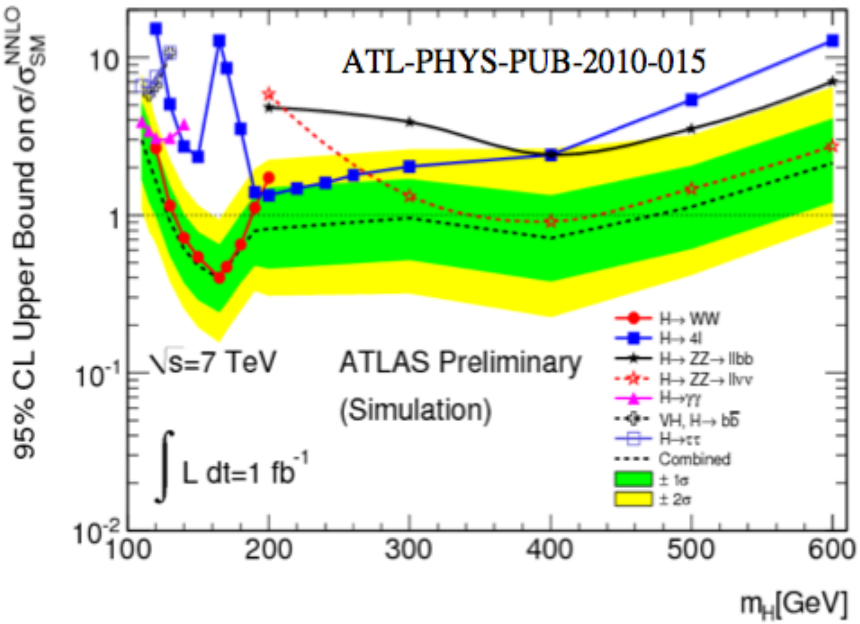
Search for *h*, *H*, *A* → $\tau\tau$ decays in e–μ & e/μ–had channels, require $E_{T,miss}$ > 20 GeV and low M_T

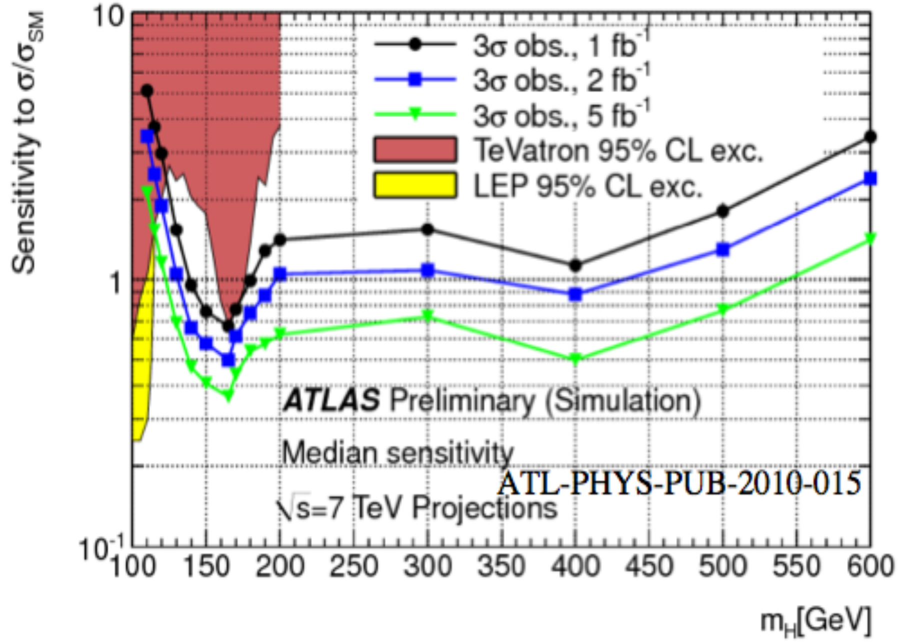




Higgs Prospects

With 1 fb^{-1} sensitivity to exclude SM
Higgs in range m_H=130-450 GeV

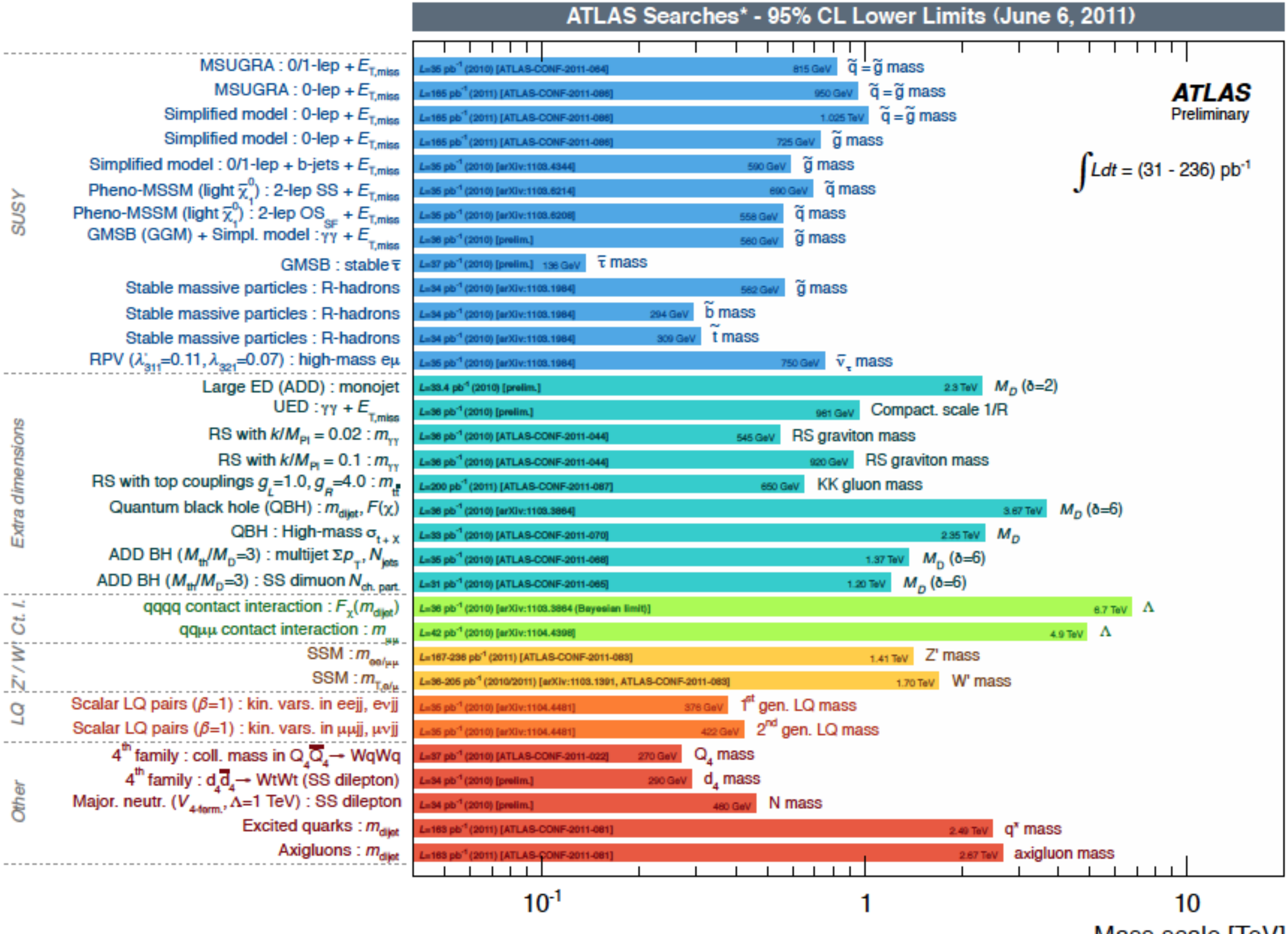




3 σ evidence possible with 5 fb^{-1} above m_H=~123 GeV

Combination ATLAS+CMS :
LHC Higgs Combination Group aiming for LP2011

Summary *... after (only) one year of 7 TeV data taking*



*Only a selection of the available results shown

Conclusion

ATLAS is taking data at high rate (>930 pb^{-1} on tape) and is in discovery mode

Data analyses are proceeding at high speed: 36 papers and 190 conference notes have been published with 2010 and 2011 data

Entering unchartered territory (could only cover a selection of results)

https://twiki.cern.ch/twiki/bin/view/AtlasPublic

Due to higher CM, surpassed Tevatron constraints on many New Physics models with relatively small dataset

In the next day, 1 fb^{-1} will be available, by the end of 2011 double or more

2011 can be the year of a (real!) new discovery: Higgs, SUSY, Exotics

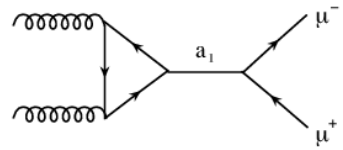
Big thanks to the LHC accelerator and LHC computing grid!

Backup

SUSY Higgs: $a_1 \rightarrow \mu\mu$

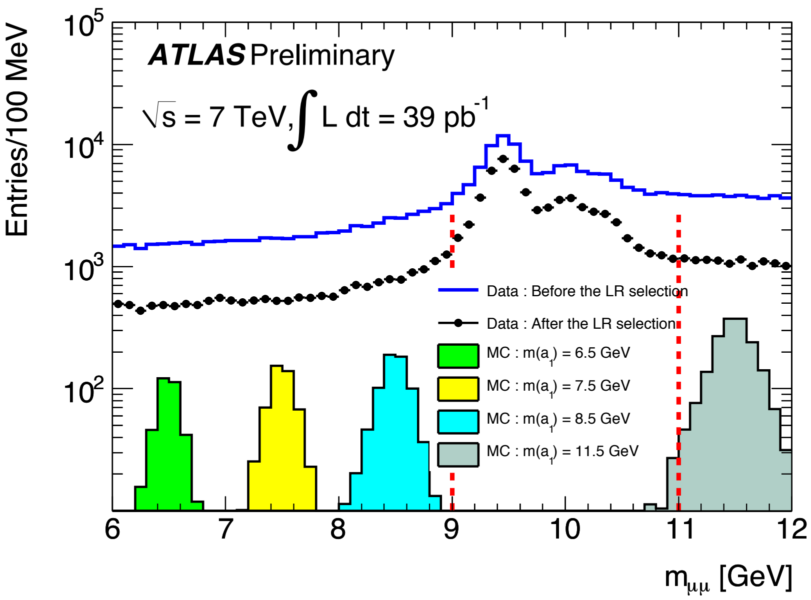
NMSSM expands Higgs sector by scalar singlet

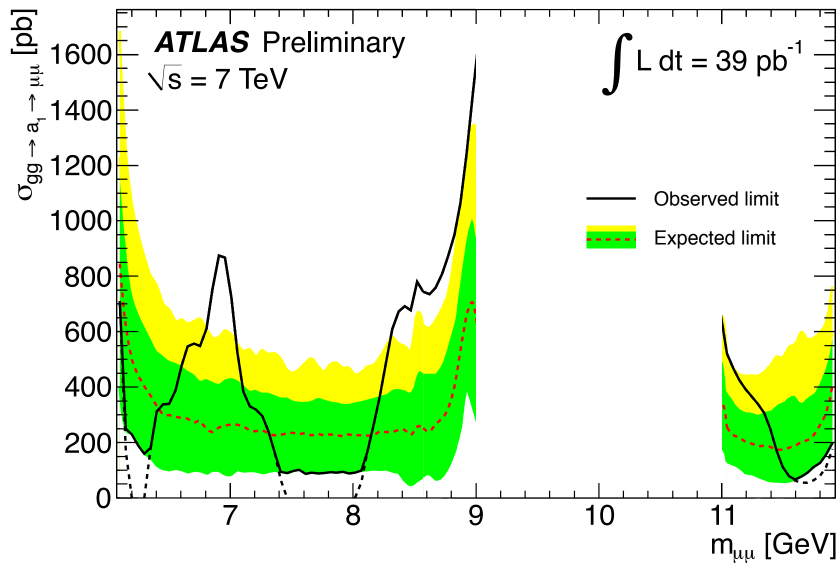
→ adds h_1, a_1 (*CP*-even/odd) fields



Higgs phenomenology dramatically altered if $h_1 \rightarrow a_1 a_1$ dominant. $\sigma \times$ BR depends on tanβ and a_1–a_2 mixing

Search for $a_1 \rightarrow \mu\mu$ (BR ~ 0.5%) in mass ranges 6–9 and 11–12 GeV (cut out $\Upsilon_{1..3S}$), tight muon-pair





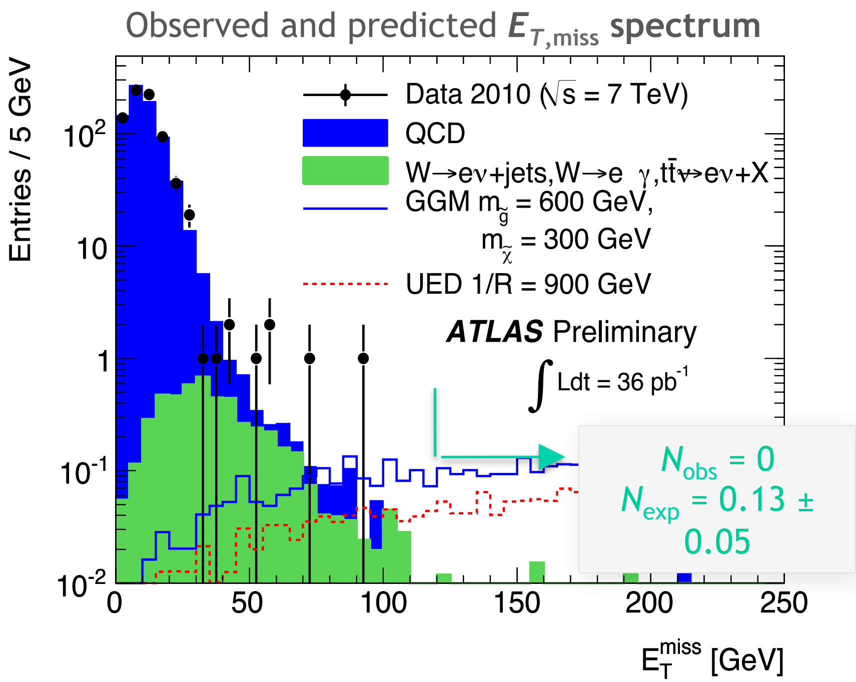
Upper limit on $\sigma(gg \rightarrow a_1 \rightarrow \mu\mu)$

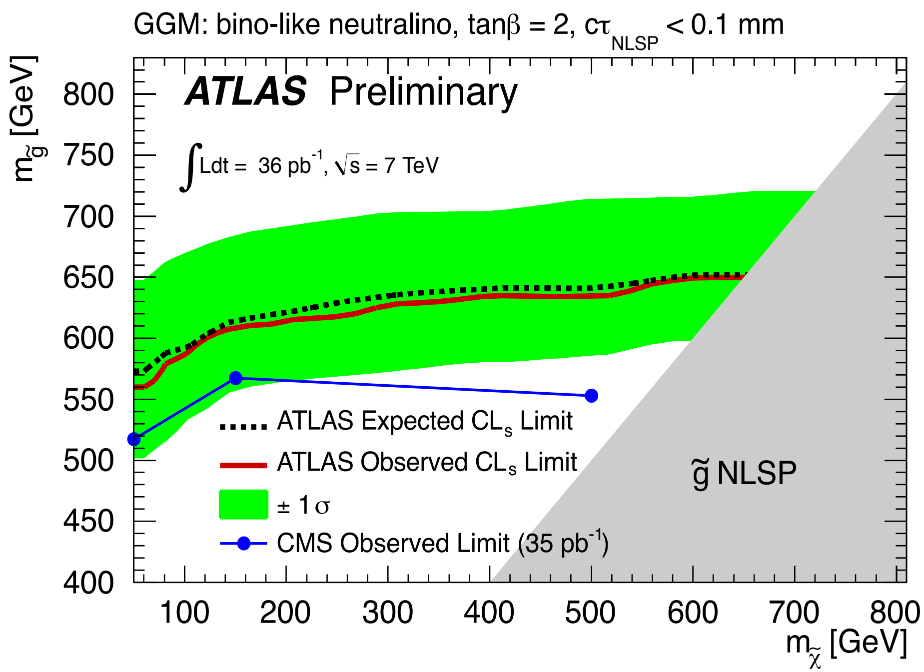
Example:
σ×BR ~ 3 pb for *m*(*a*)=8 GeV, tanβ=10, cosθ =0.1

Inclusive Search with 2 Photons and E_{Tmiss}

See Bertrand Brelier's talk in EF 3

Sensitive to gauge-mediated SUSY breaking and also UED models





Cut $E_{T,miss}$ > 125 GeV sets 95% CL$_s$ limits:

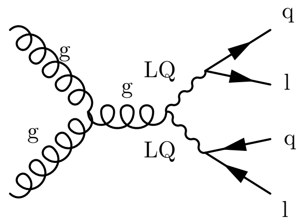
GGM gluino mass > 560 GeV; UED compactification scale: $1/R_{UED}$ > 960 GeV

Leptoquarks

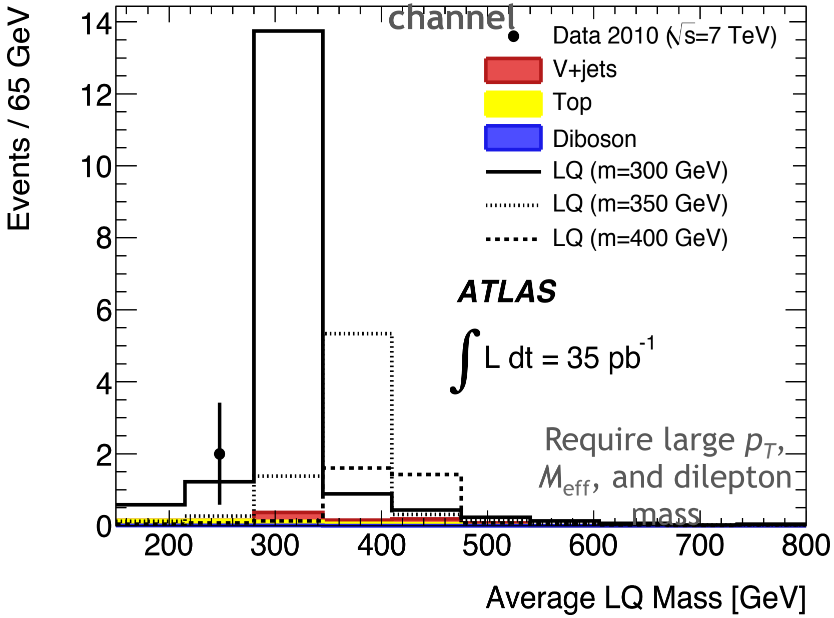
Search for 1st and 2nd generation leptoquarks

Study scalar LQ pair production to *lljj* and *lνjj* final states

Average LQ mass or transverse mass is discriminant



Observed and predicted **ave. *M*(LQ)** in ***eejj* channel**



Require large p_T, M_{eff}, and dilepton mass

Validate background model in control regions

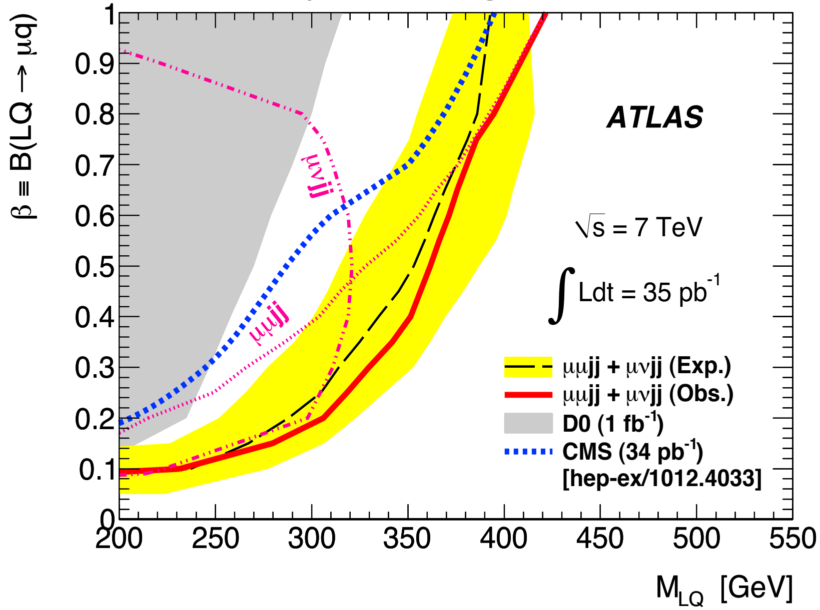
Event Source	$\mu\mu jj$ Control Region $Z+\geq 2$ jets	$\mu\mu jj$ Control Region $t\bar{t}$	$\mu\nu jj$ Control Region $W+2$ jets	$\mu\nu jj$ Control Region $W+\geq 3$ jet	$\mu\nu jj$ Control Region $t\bar{t}$
V+jets	190 ± 24	0.3 ± 0.1	3300 ± 1100	900 ± 300	250 ± 80
Top	2.7 ± 0.5	24 ± 4	14 ± 3	53 ± 1	260 ± 50
Diboson	0.2 ± 0.1	0.8 ± 0.1	28 ± 6	14 ± 3	3.0 ± 0.7
QCD	$6.0^{+11.0}_{-6.0}$	$0.0^{+0.1}_{-0.0}$	300 ± 100	130 ± 50	54 ± 32
Total Bkg	200 ± 25	25 ± 4	3600 ± 1100	1100 ± 330	570 ± 120
Data	216	22	3588	1120	547

2 jets E_T>20 GeV, |η|<2.8

Dilepton: E_T >20 GeV

Single Lepton: E_T >20 GeV, E_t^{miss}>25 GeV

Observed and expected **2nd generation LQ limit**



95% limits on M_{LQ} for 1st gen: > 376 (319) GeV

2nd gen > 422 (362) GeV for β = 1.0 (0.5)