Physics with first fb^{-1}

at Large Hadron Collider

Today:

- **Machine status**
- **Detectors**
- **Physics results**
  - **Highlights from 2010**
  - **Where we stand with searches?**

LHC at CERN laboratory

- CERN: the world's largest particle physics laboratory
  - International organisation created in 1953/1954, initial membership: 12 countries
  - Poland is a member starting from year 1991
  - About 10000 active physicists, computing scientists, engineers

Situated between

Jura mountains

and Geneva

(France/Swiss)

http://public.web.cern.ch

A brief historical overview: toward LHC

1984: Glimmerings of LHC and SSC

1987: First comparative studies of physics potential of hadron colliders (LHC/SSC) and e^+e^- linear colliders (CLIC)

1989: First collisions in LEP and SLC
Precision tests of the SM and search for the Higgs boson begin in earnest
R&D for LHC detectors begins

1993: Demise of the SSC

1994: LHC machine is approved (start in 2005)

1995: Discovery of the top quark at Fermilab by CDF (and D0)
Precision tests of the SM and search for the Higgs boson continue at LEP2

Approval of ATLAS and CMS

2000: End of LEP running

2001: LHC schedule delayed by two more years

2008: LHC started but after few days of operating with single beam very serious accident

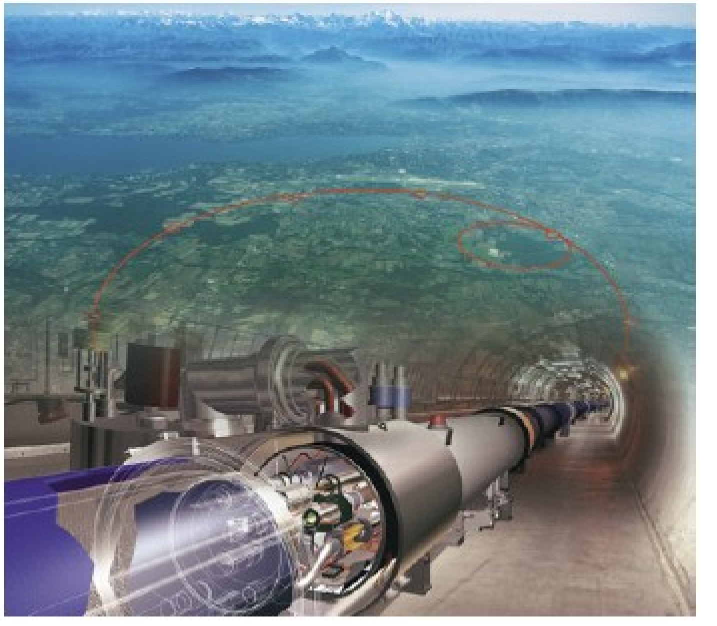
2009: Restarted back just before Xmass with 900 GeV collision

2010: Since March collecting data at 7 TeV pp collision.

The Large Hadron Collider

pp collisions at $\sqrt{s}$ = 7 TeV (and PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV)

	2010	Nominal
Energy [TeV]	3.5	7
β* [m] (IP1,IP2,IP5,IP8)	3.5, 3.5, 3.5, 3.5	0.55, 10, 0.55, 10
Emittance [μm] (start of fill)	2.0 – 3.5	3.75
Transverse beam size at IP1&5 [μm]	60	16.7
Bunch population	1.2×10^{11} p	1.15×10^{11} p
Number of bunches	368	2808
Number of collisions (IP1 & IP5)	348	-
Stored energy [MJ]	28	360
Peak luminosity [$cm^{-2}s^{-1}$]	2×10^{32}	1×10^{34}
Max delivered luminosity (1 fill) [pb^{-1}]	6.23	-
Longest Stable Beams fill [hrs]	12:09	-



Experiments

Four (five) large-scale experiments:

ATLAS, CMS — general-purpose pp experiments

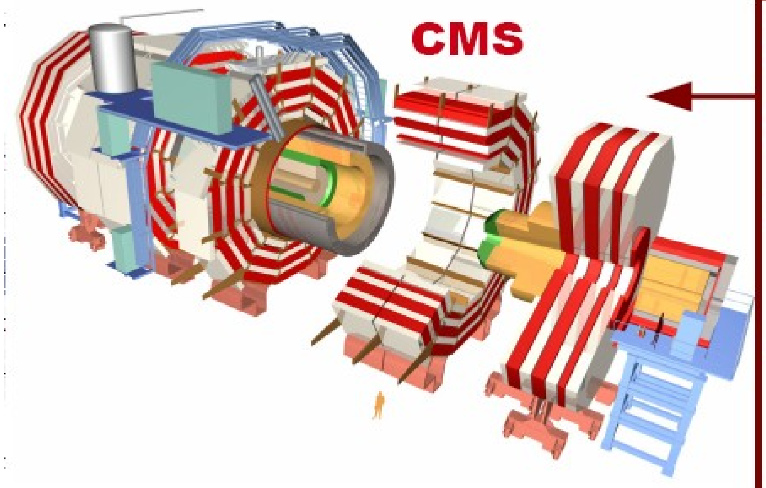
LHCb — pp experiment dedicated to b-quark physics and CP violation

ALICE — heavy-ion experiment (Pb-Pb collisions) at 5.5 TeV/nucleon $\rightarrow \sqrt{s} \cong$ 1000 TeV
Quark-gluon plasma studies.

TOTEM (in CMS cavern) — Total Cross-Section, Elastic Scattering and Diffraction Dissociation

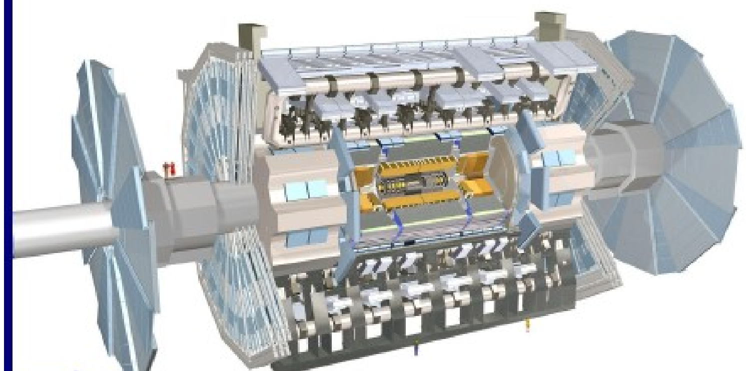
The ATLAS and CMS Detectors: same goals, different choices

Both detectors are already close to their nominal performance

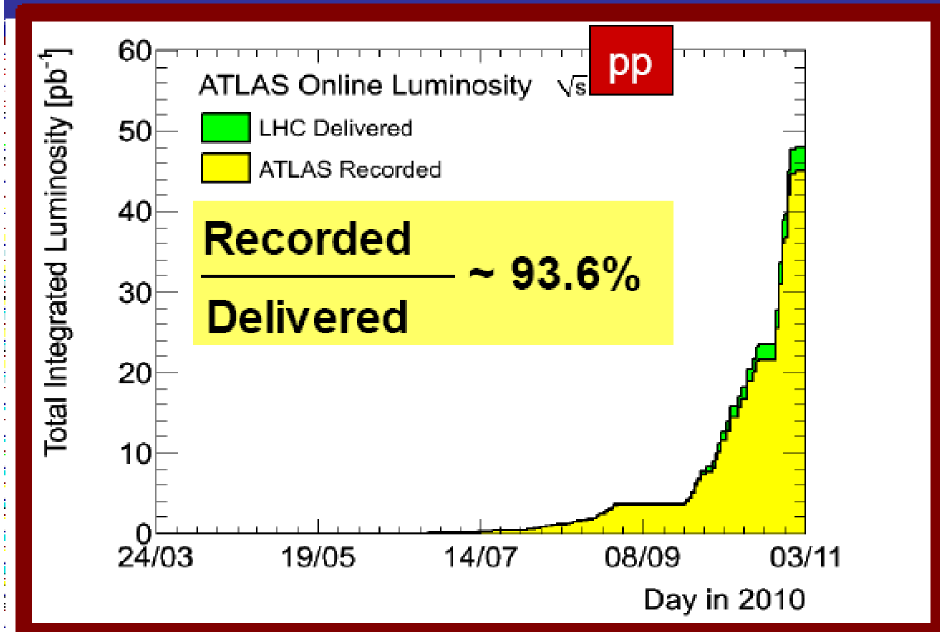


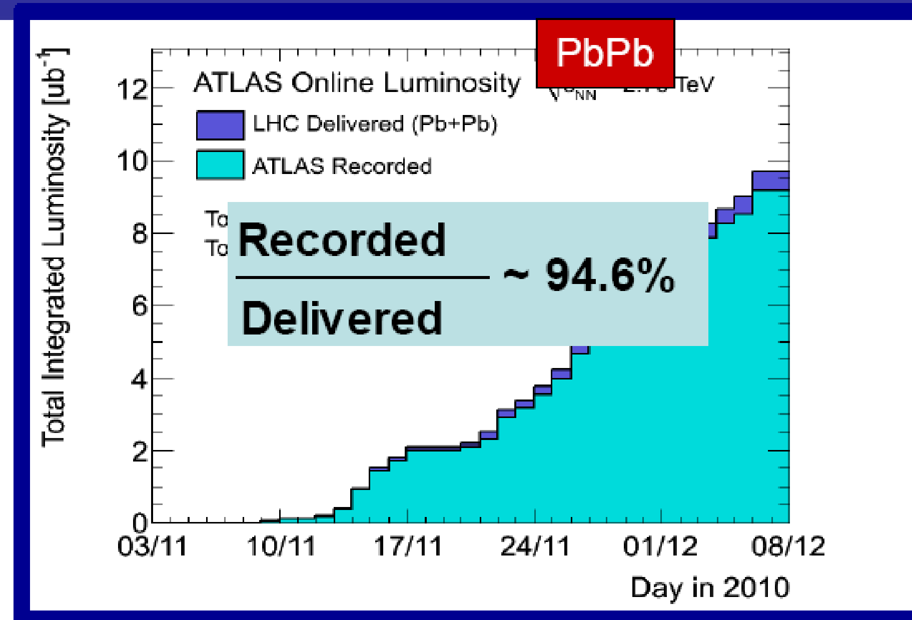
- 3.8T solenoid containing calorimeters
- Silicon tracker: $\sigma(p_T)/p_T \sim 15\%$ at 1TeV
- EM cal: homogeneous Lead-Tungstate crystal, $\sigma_E/E \sim 3\%/\sqrt{E[GeV]} \oplus 0.5\%$
- HAD cal: Brass-scint., $\geq 7\lambda_0$ $\sigma_E/E \sim 100\%/\sqrt{E[GeV]} \oplus 5\%$
- Iron return yoke muon spectrometer

- 2T solenoid inside calorimeters
- Silicon+TRT tracker + electron ID
- EM cal: Longitudinally segmented Lead-Ar: $\sigma_E/E \sim 10\%/\sqrt{E[GeV]} \oplus 0.7\%$
- HAD cal: Fe-scint + Cu-Ar, $\geq 11\lambda_0$ $\sigma_E/E \sim 50\%/\sqrt{E[GeV]} \oplus 3\%$
- Air-toroid muon sp.: $\int \sqrt{B}.dl$ = 1 to 7 T.m



2010 Recorded Data



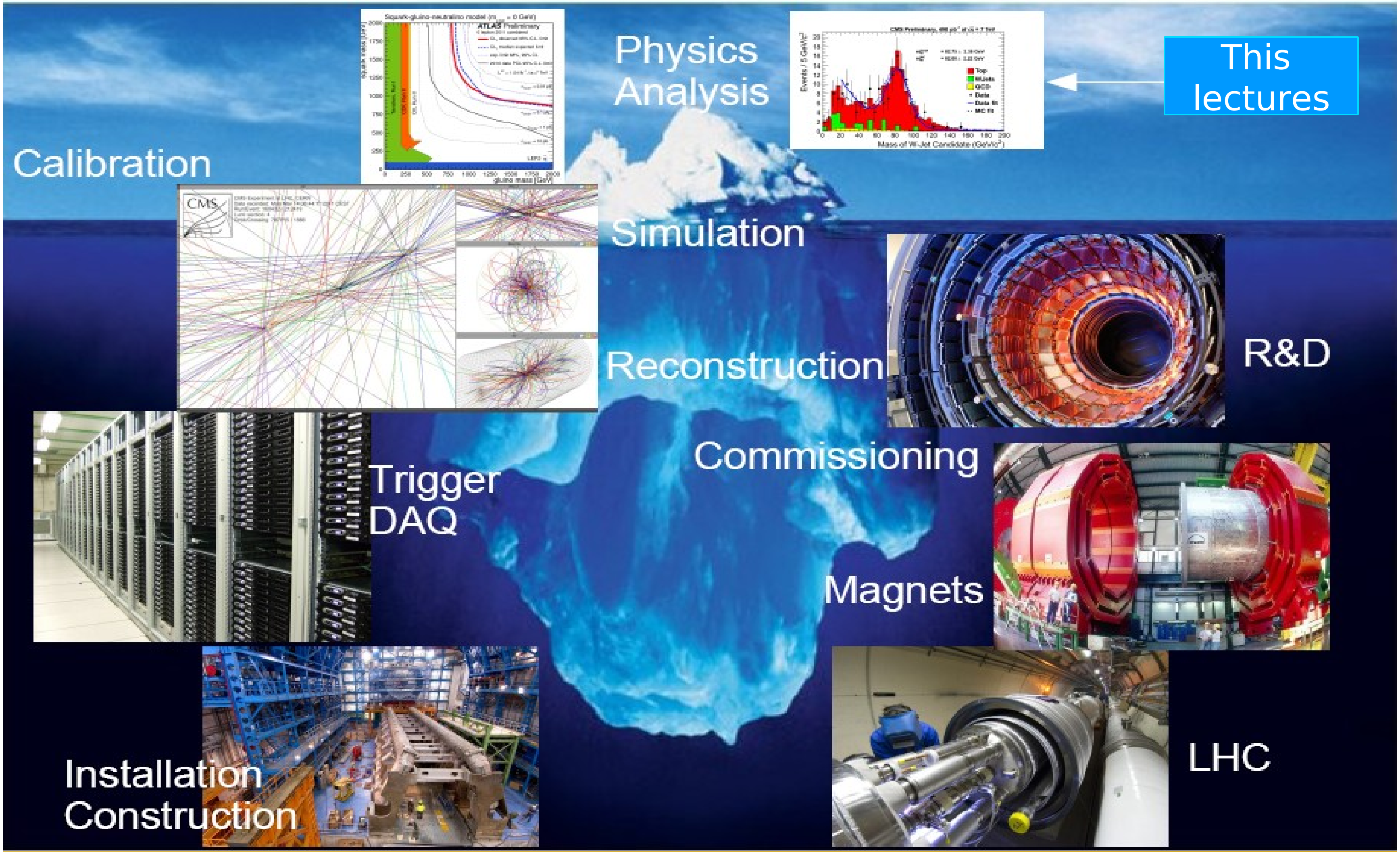


2010 pp run

Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.1	99.9	100	90.7	96.6	97.8	100	99.9	99.8	96.2	99.8

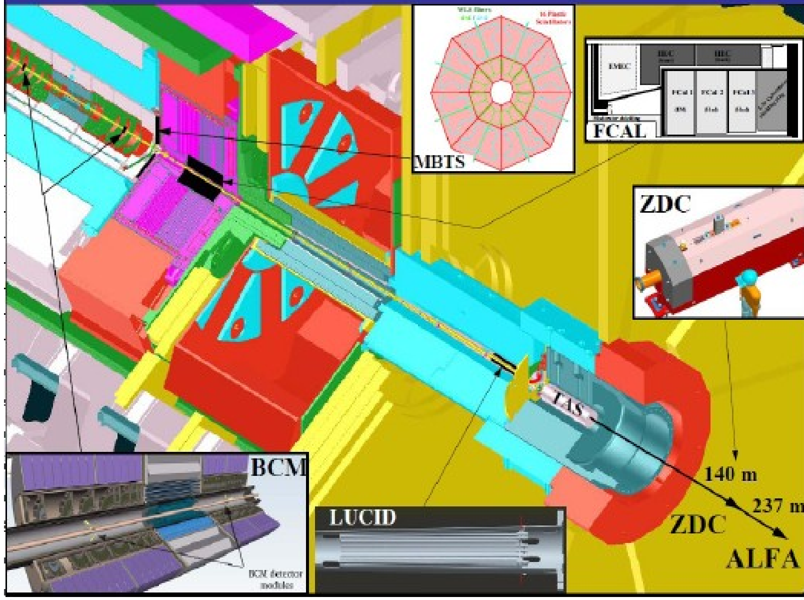
Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in pp collisions at $\sqrt{s}$=7 TeV between March 30th and October 31st (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future.

Acknowledgement



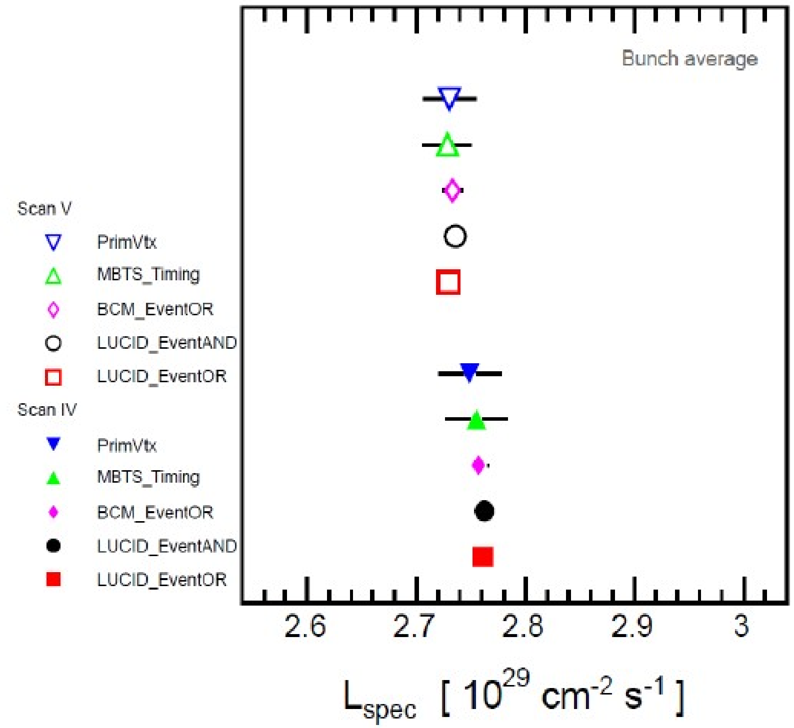
Improved Luminosity Measurement

ATLAS-CONF-2011-011



van der Meer Scans

5 lumi detectors and up to 5 algorithms



Thanks to LHC team and ATLAS efforts

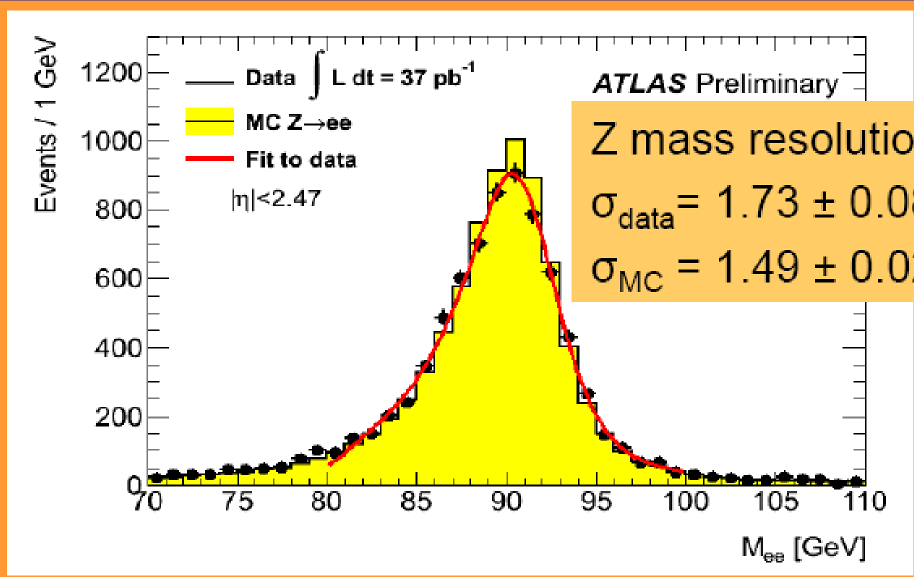
- Improved determination
  - LHC bunch currents: 10% -> 2.9%
- ATLAS vdM scan analysis
  - length scale: 2%→0.3%
  - emittance growth: 3%→0.5%
  - mu dependence: 2%→0.5%
  - fit model: 1%→0.1%
  - beam centering: 2%→0.1%

Uncertainty reduced 11% → 3.4%

Electron Performance Results (2010 data)

Calibrated at Z peak

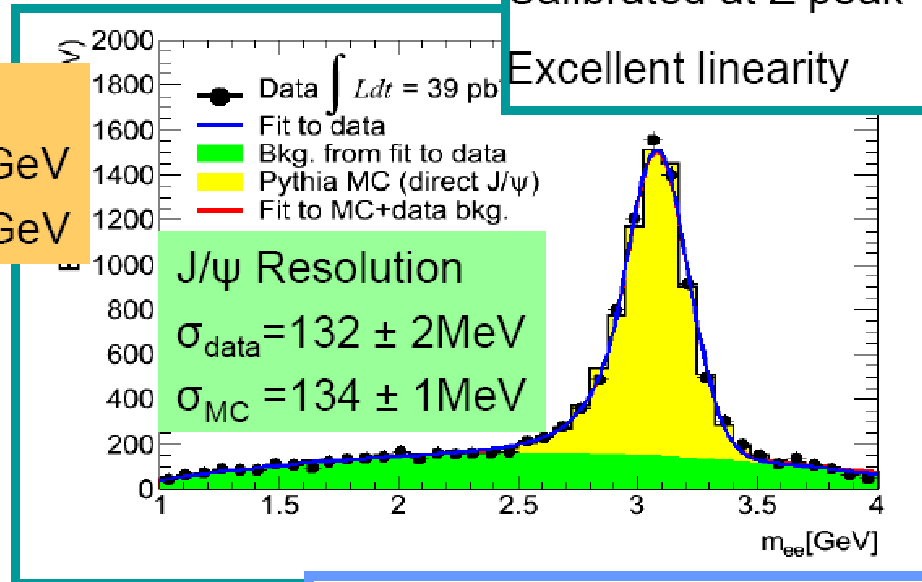
Excellent linearity



Z mass resolution

σ_{data} = 1.73 ± 0.08 GeV

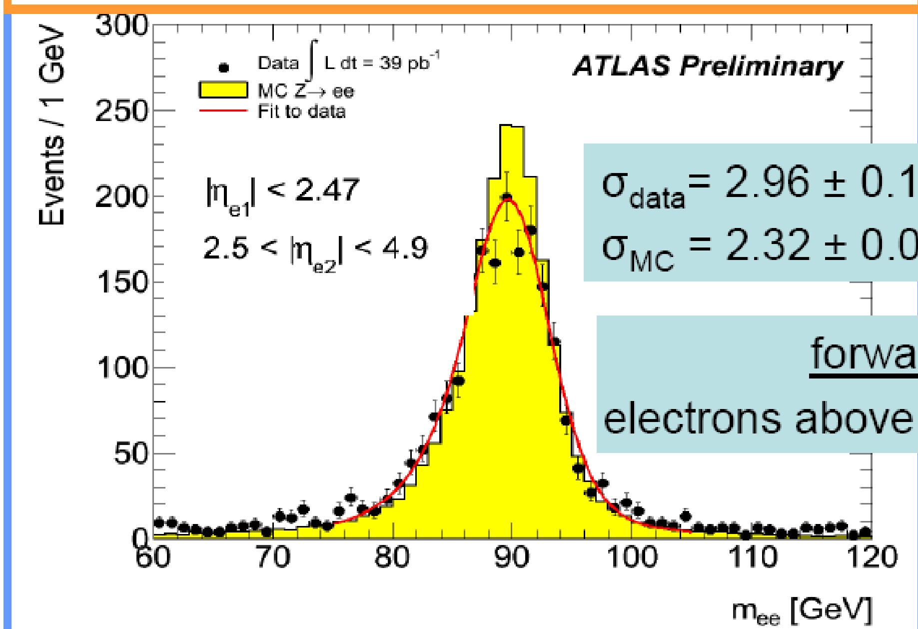
σ_{MC} = 1.49 ± 0.02 GeV



J/ψ Resolution

σ_{data}=132 ± 2MeV

σ_{MC} =134 ± 1MeV

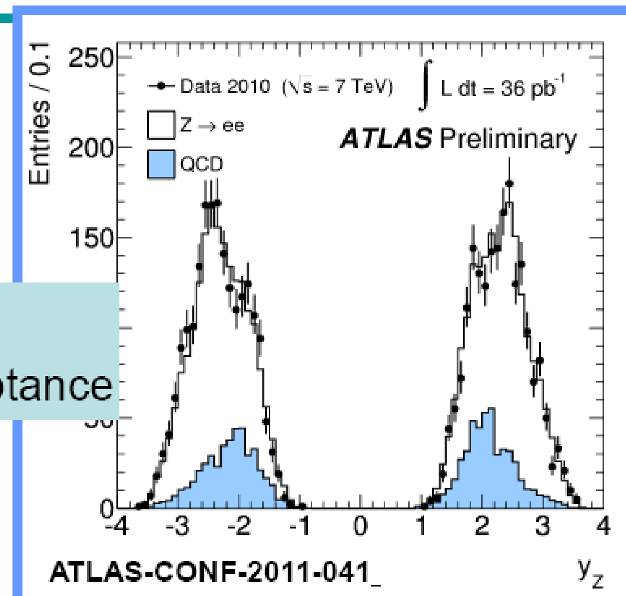


σ_{data}= 2.96 ± 0.1 GeV

σ_{MC} = 2.32 ± 0.03 GeV

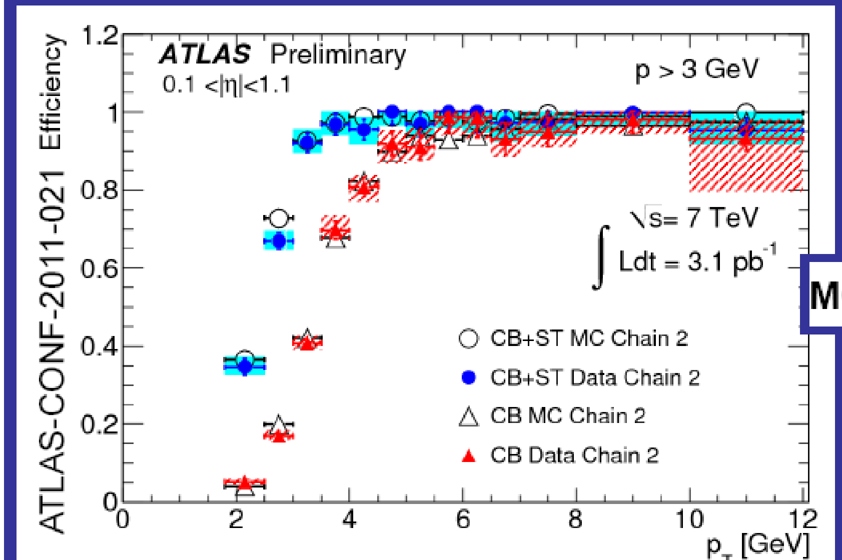
forward-central Zs

electrons above the tracker acceptance

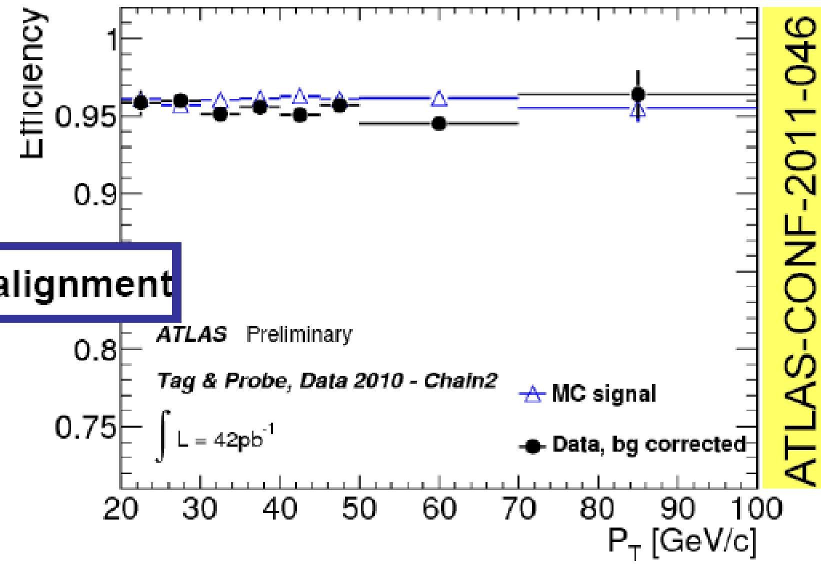


ID and Muon Combined Performance Results (2010 data)

Low p_T efficiency from J/ψ→μμ decays

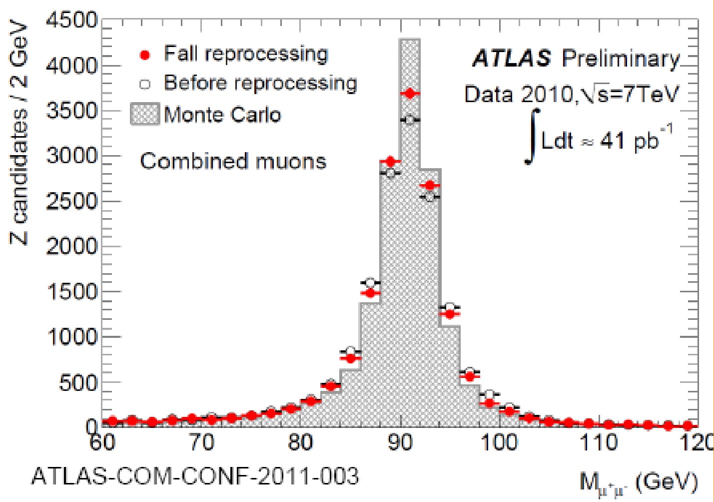


High p_T efficiency from Z→μμ decays



MC: perfect alignment

Efficiency understood down to very low p_T



Smear MC hit uncertainties

$$\sigma = a * \sigma \oplus c$$

$$a = 1$$

Present understanding of ID alignment

Detector type	coordinate	Barrel	End-caps
		c [μm]	
Pixel	local x	4	7
	local y	18	35
SCT	local x	10	11
TRT		0	0

Improved momentum scale and resolution

muon scale uncertainty is < 1%

dimuon mass resolution 1.8% barrel and 3% end-cap

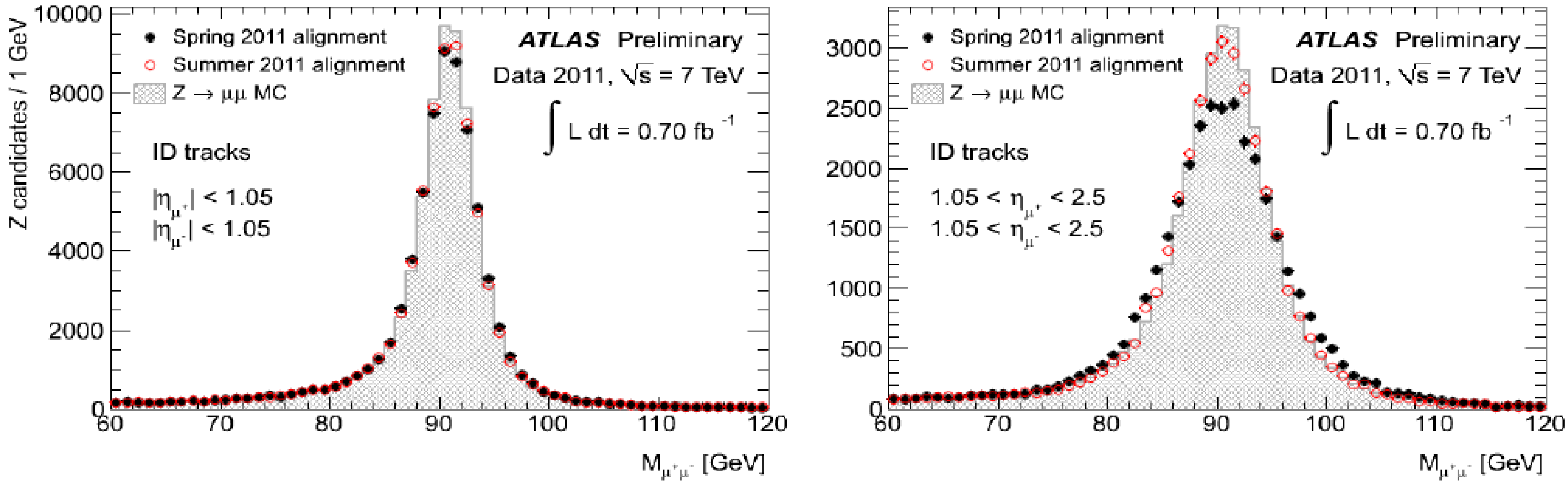
ATLAS alignment and calibration: inner detector

- Unfortunately, alignment work for "light-weight" inner detector does not stop at minimising residuals
- Need to eliminate distortions which affect track parameters, especially impact parameter and momentum measurements (residuals are insensitive to a number of these possible distortions). Use E/p measurement for electrons and apply to muons!
- This has led to large improvement on Z to μμ experimental resolution, a factor three in end-caps (much weaker initial constraints from cosmics)

Exp. resolution expected from MC (GeV)

Additional contribution to exp. resolution from data (to be added quadratically)

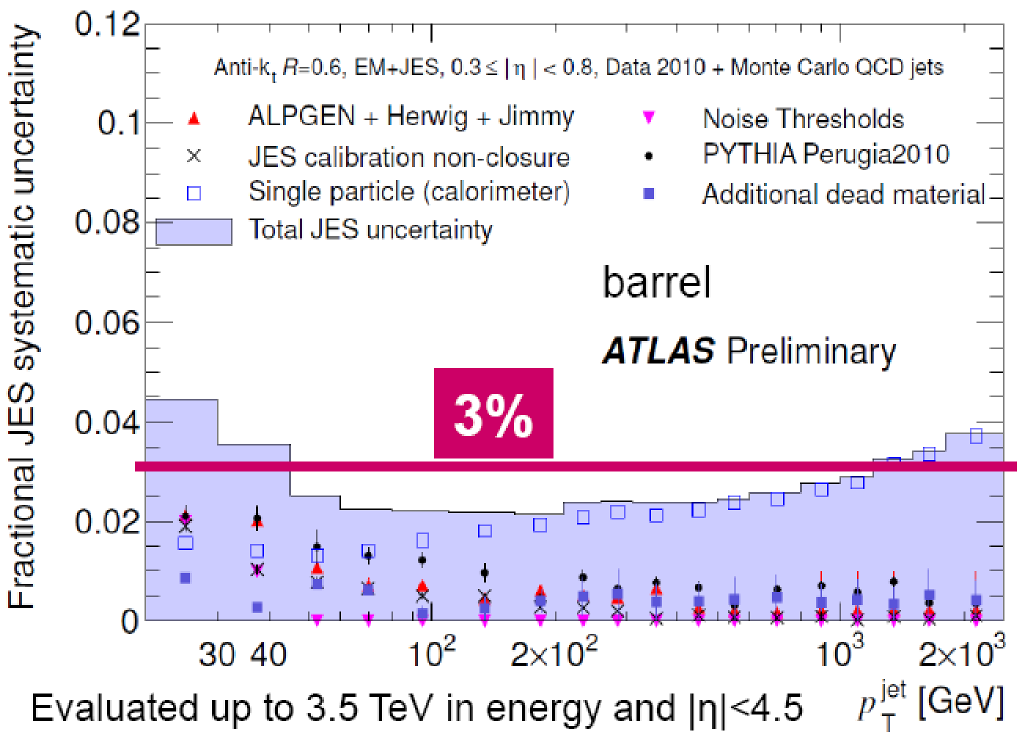
Z to μμ in ID only (250k events)	Ideal	Only residuals used in minim.	Add E/p constraint from e^+ vs e^-
Both μ in barrel ID	1.60	0.98 ± 0.01	0.71 ± 0.01
Both μ in same end-cap ID	3.42	3.03 ± 0.03	1.16 ± 0.01



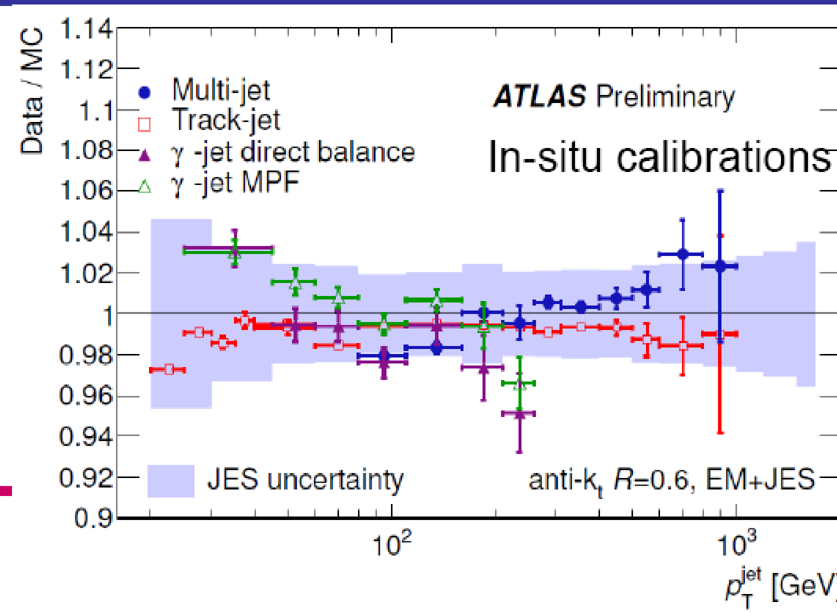
Jet Energy Scale

ATLAS-CONF-2011-032

(2010 data)



Evaluated up to 3.5 TeV in energy and |η|<4.5



Improved by factor of 2

η region	Maximal relative JES uncertainty		
	P_T^{jet} = 20 GeV	P_T^{jet} = 200 GeV	P_T^{jet} = 1.5 TeV
|η|<0.3	4.6%	2.3%	3.1%
2.1<|η|<2.8	7.1%	2.5%	
3.6<|η|<4.5	12.6%	2.9%	

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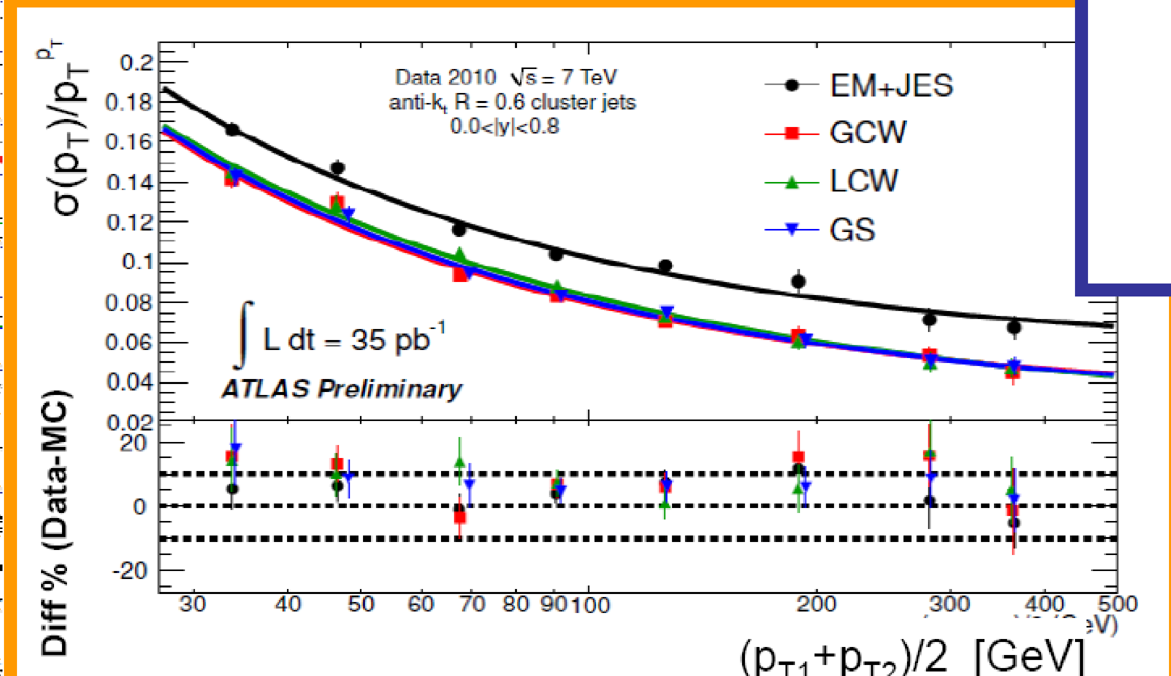
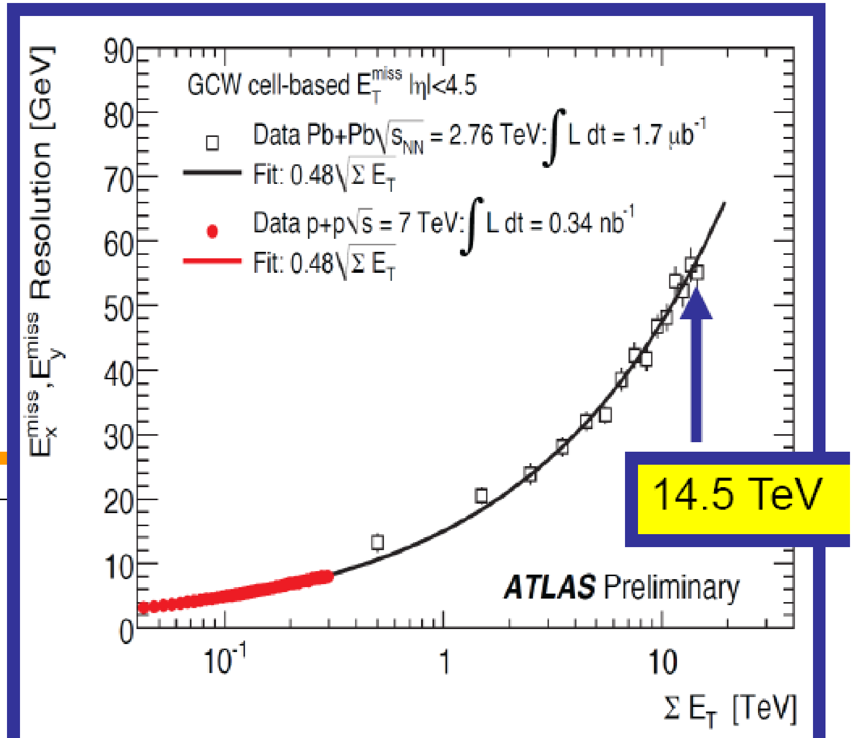
Jet Energy and Etmiss Resolutions (2010 data)

Advanced calibrations →
improve resolution by 10-30%

Monte Carlo agrees with data within 10%

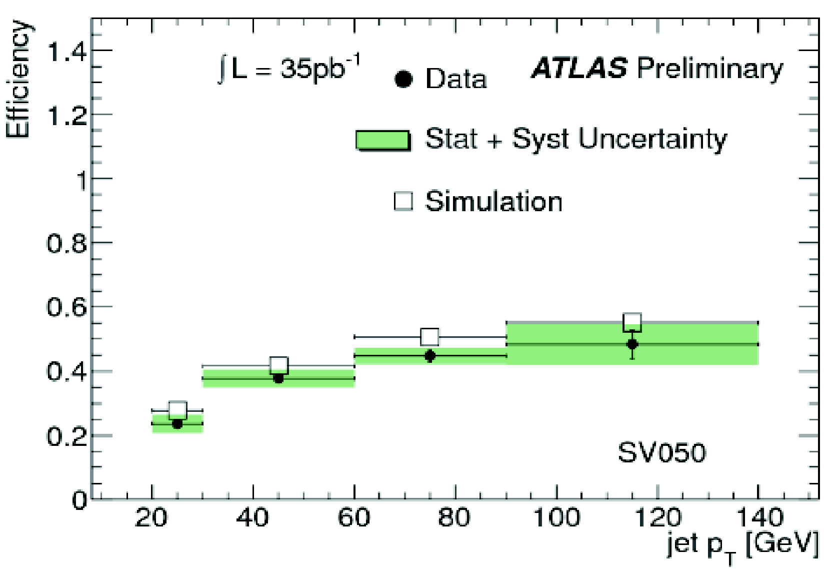


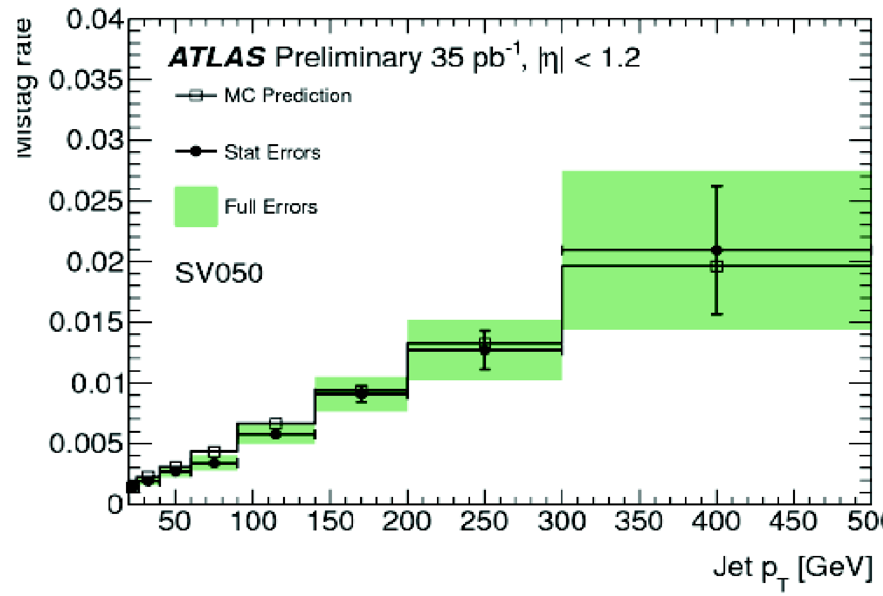


PbPb data only sample reaching this high in $\sum E_T$

Tracking and b-tagging

- B-tagging performance measured with 3 complementary methods for several taggers:
  - $p_T^{rel}(\mu)$, D*+μ, top
  - Consistent results
- Mistag rate also well controlled
- Understanding and calibration of advanced taggers in progress

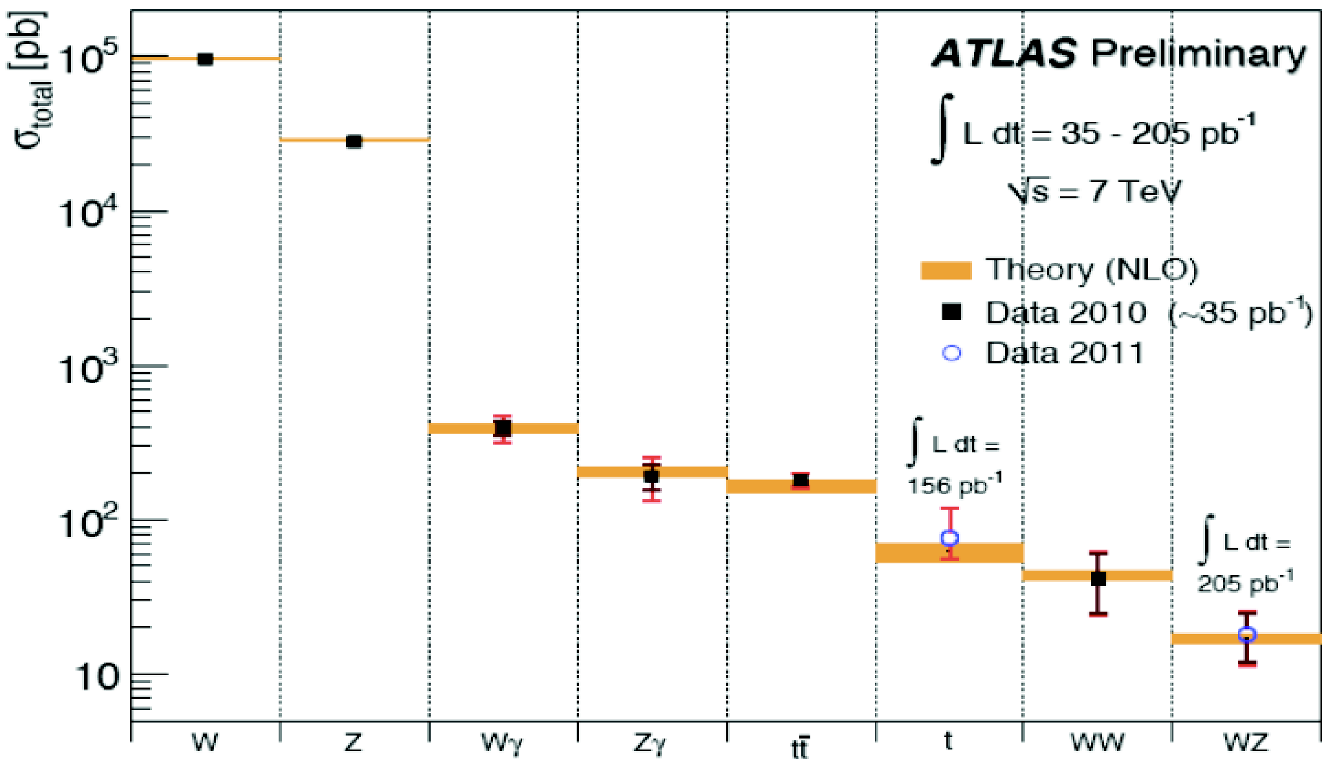




- Tracking p_T cut was increased to 400 MeV in 2011
  - Mainly affects vertexing but well understood

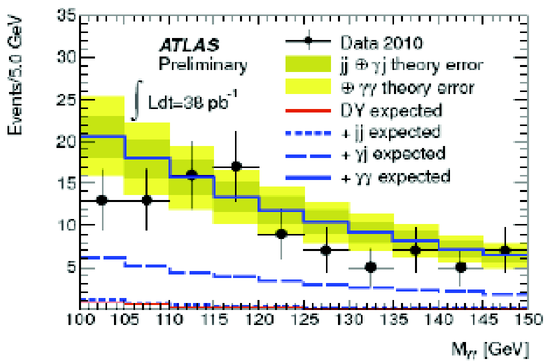
ATLAS-CONF-2011-089

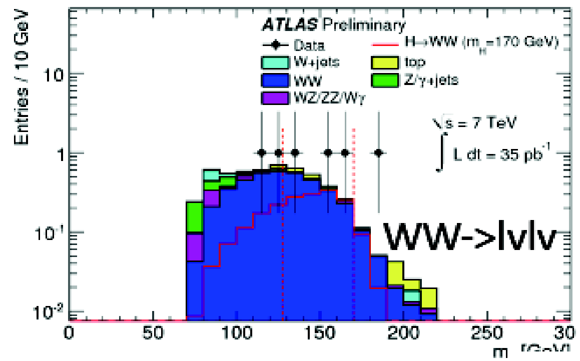
Summary of Electroweak Boson and Top Quark Cross Sections

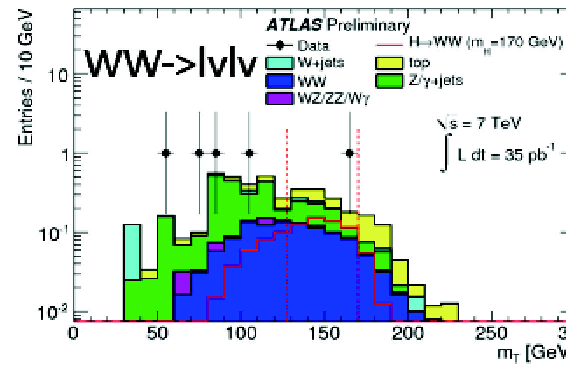


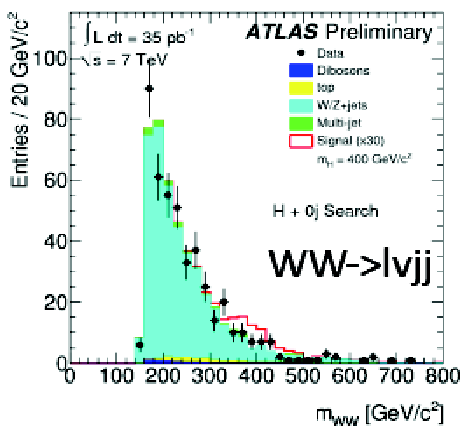
- All measurements agree with SM expectation (so far)
- Measuring cross sections of ~10 pb

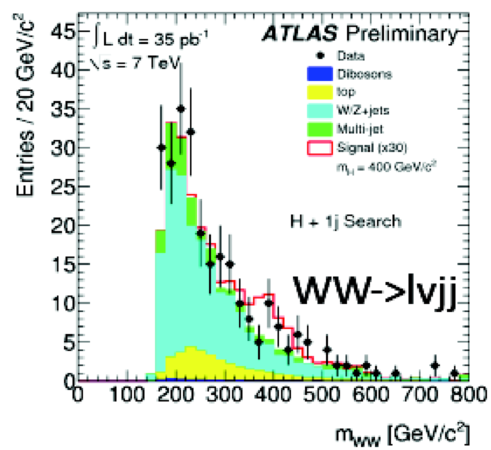
2010 Higgs Search Results

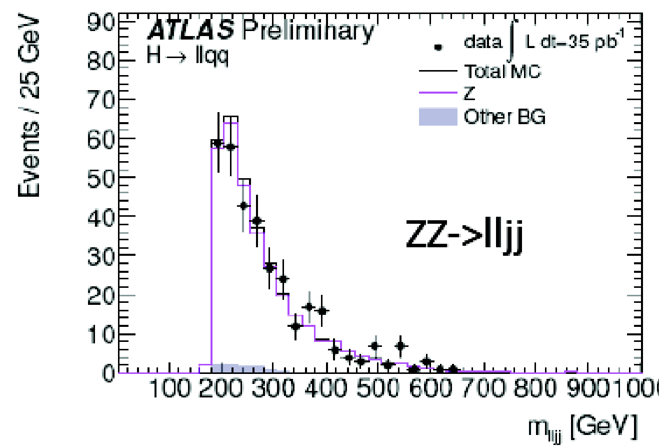


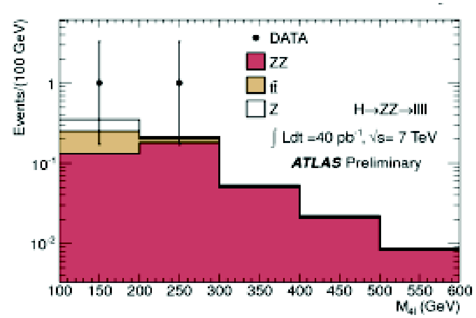


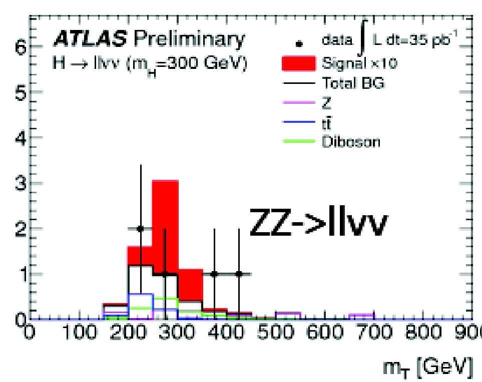






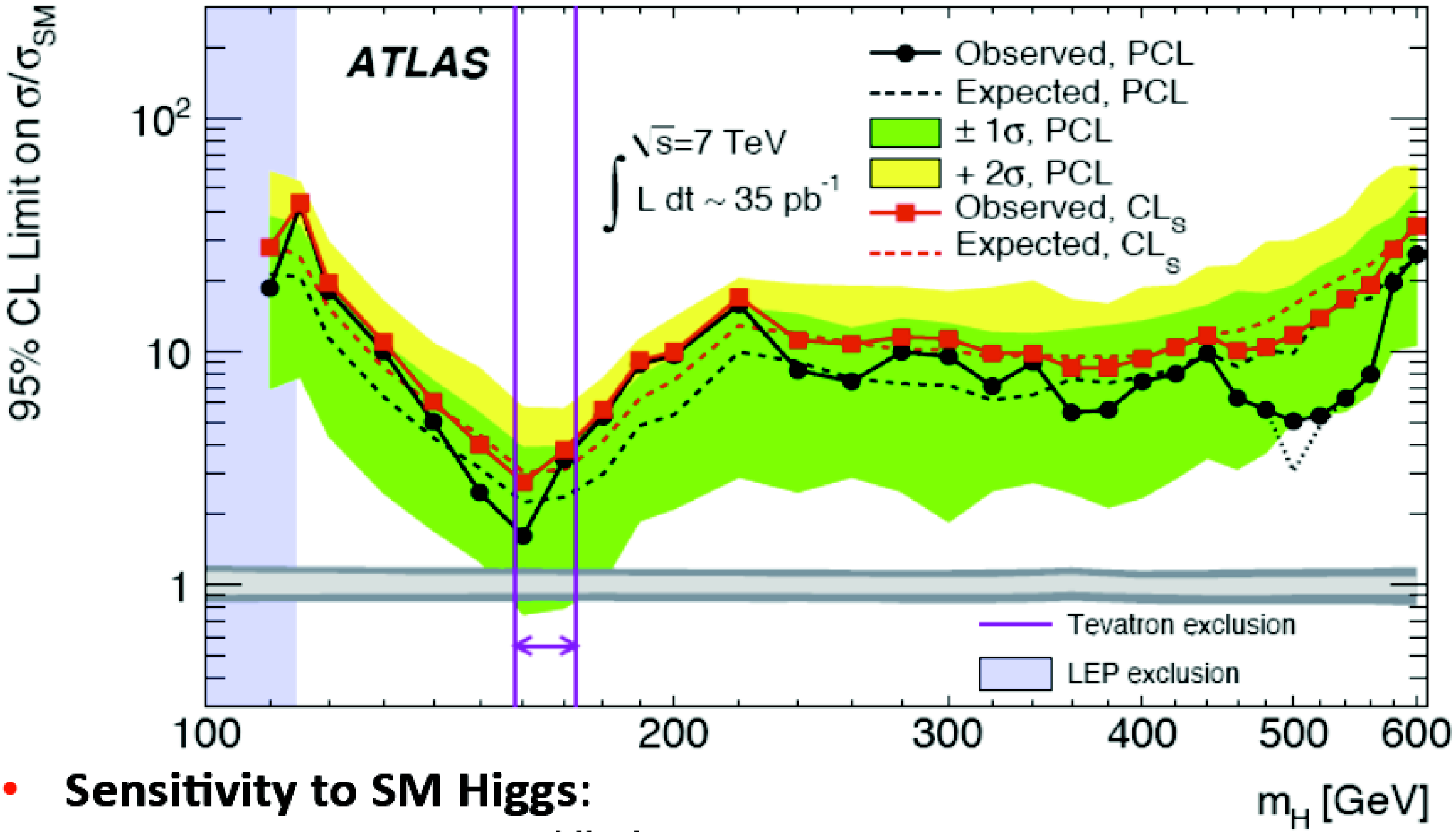






- 2010 data analyses complete
  - H->γγ
  - H->WW: both lvlv and lvjj
  - H->ZZ: llll, llvv and ll jj
- All analyses simple/cut-based
  - Room for improvement!

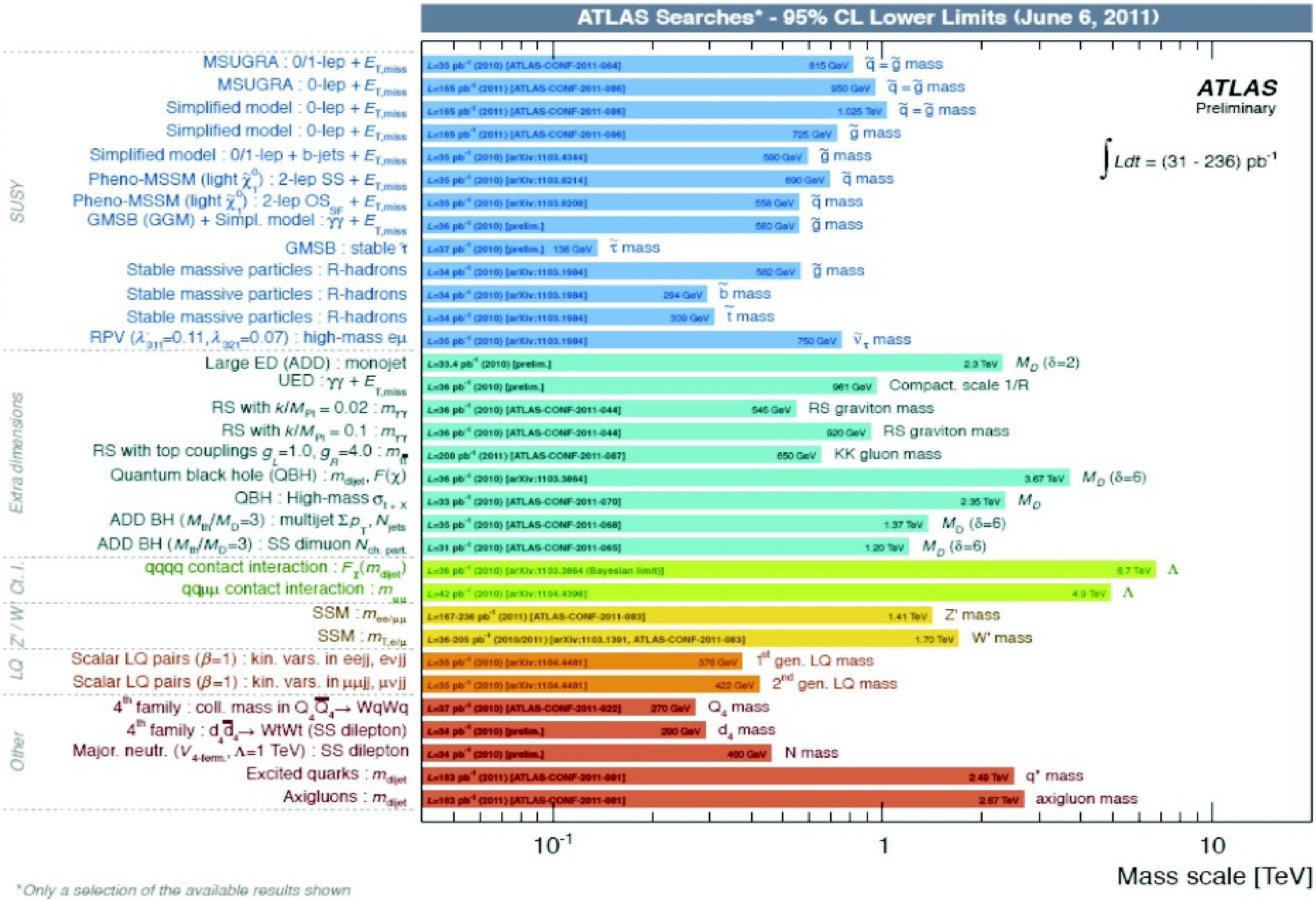
Combined Limit for 2010 Data on SM Higgs Cross Section



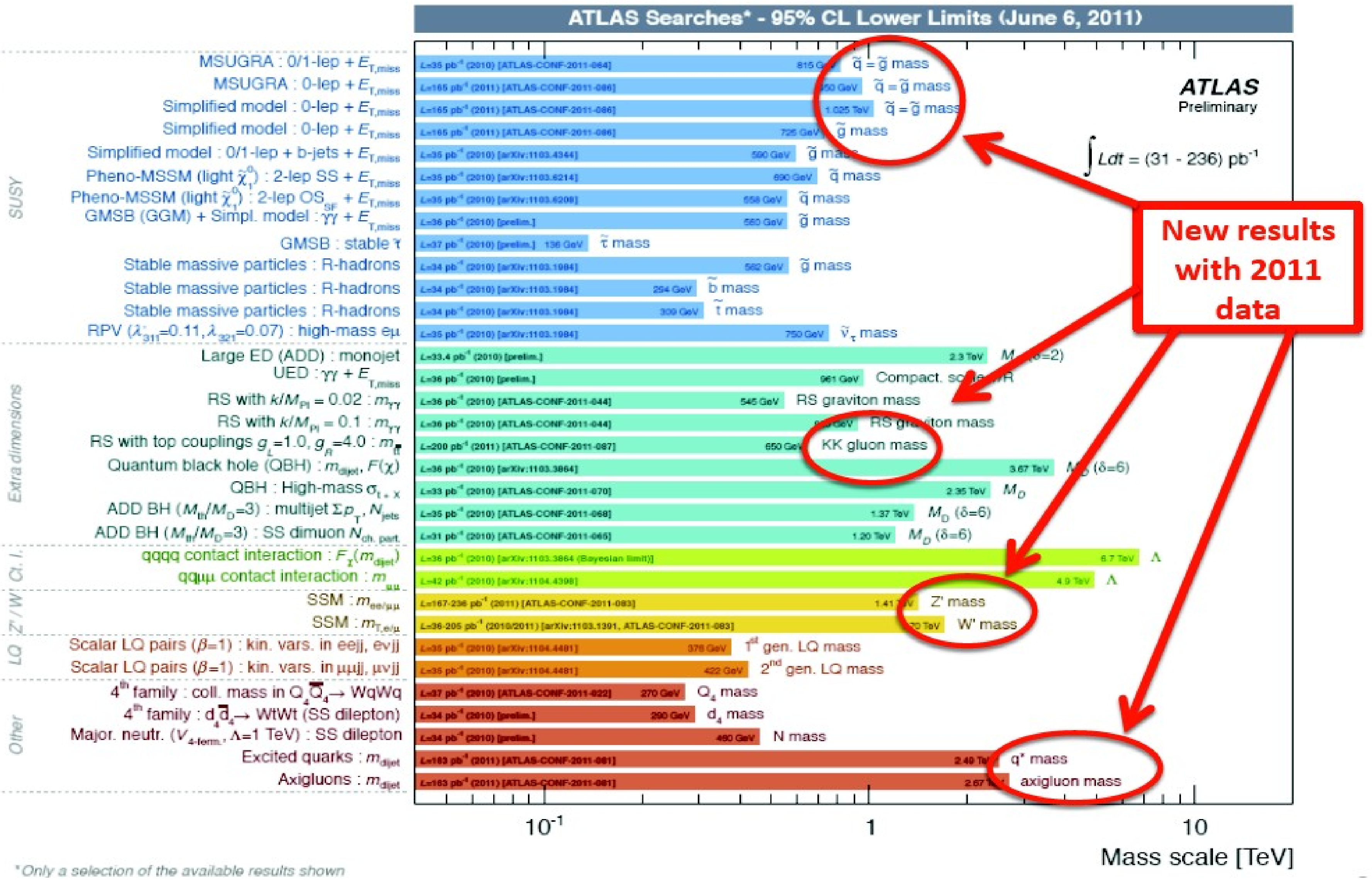
- **Sensitivity to SM Higgs:**
  - m_H=120 GeV: expected limit 11.4 x σ_{SM}
  - m_H=160 GeV: expected limit 2.3 x σ_{SM}
  - m_H=300 GeV: expected limit 7.2 x σ_{SM}
- **Exclude 140<m_H<185 GeV in models with 4th generation**
  - Assuming no other new physics is present
  - Expected exclusion 136<m_H<208 GeV

arXiv:1106.2748

Physics Beyond the Standard Model

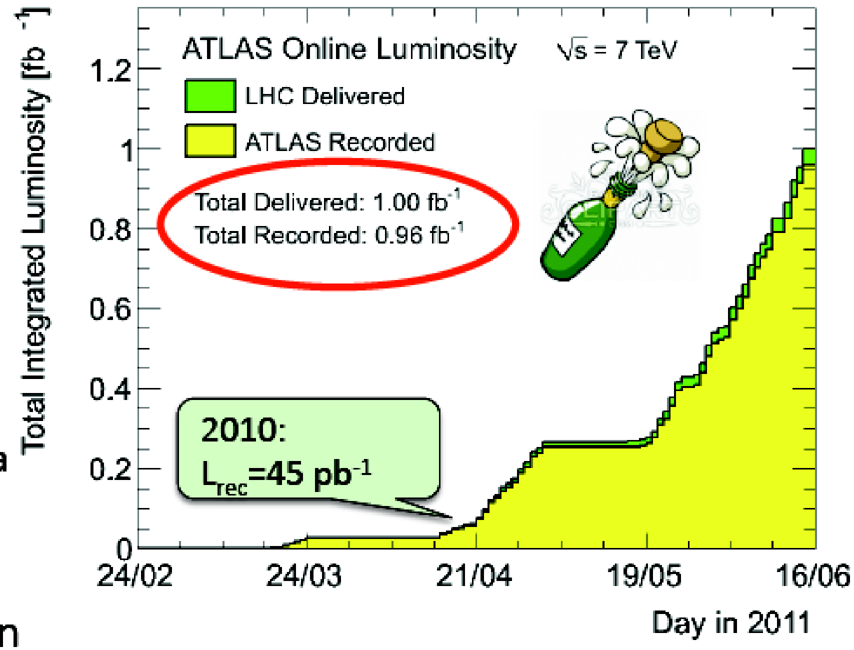


Physics Beyond the Standard Model



2011 Luminosity and Data Taking

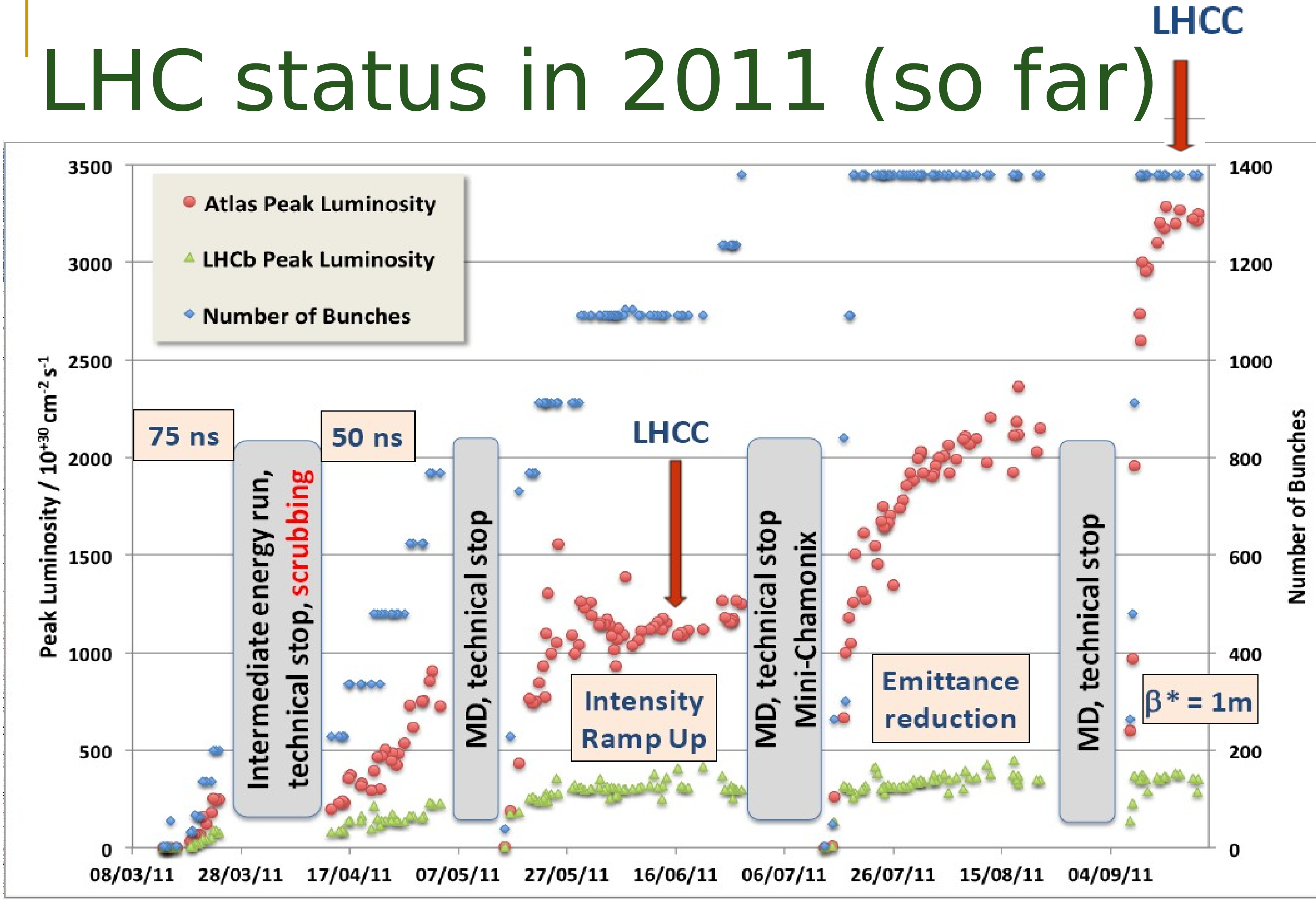
- ATLAS is recording the amazing amount of LHC data efficiently: **1.0 fb^{-1} delivered by LHC**
  - 95.8% data-taking efficiency
  - Inefficiency due to:
    - Turn-on at start of stable beams: 1.6%
    - Deadtime: 2.6%
  - Uncertainty on luminosity: 4.5%
    - Will improve with recent vdM scan data
- Quality of data generally very high
  - LAr calorimeter DataQuality inefficiency will largely be recovered in reprocessing by Fall 2011



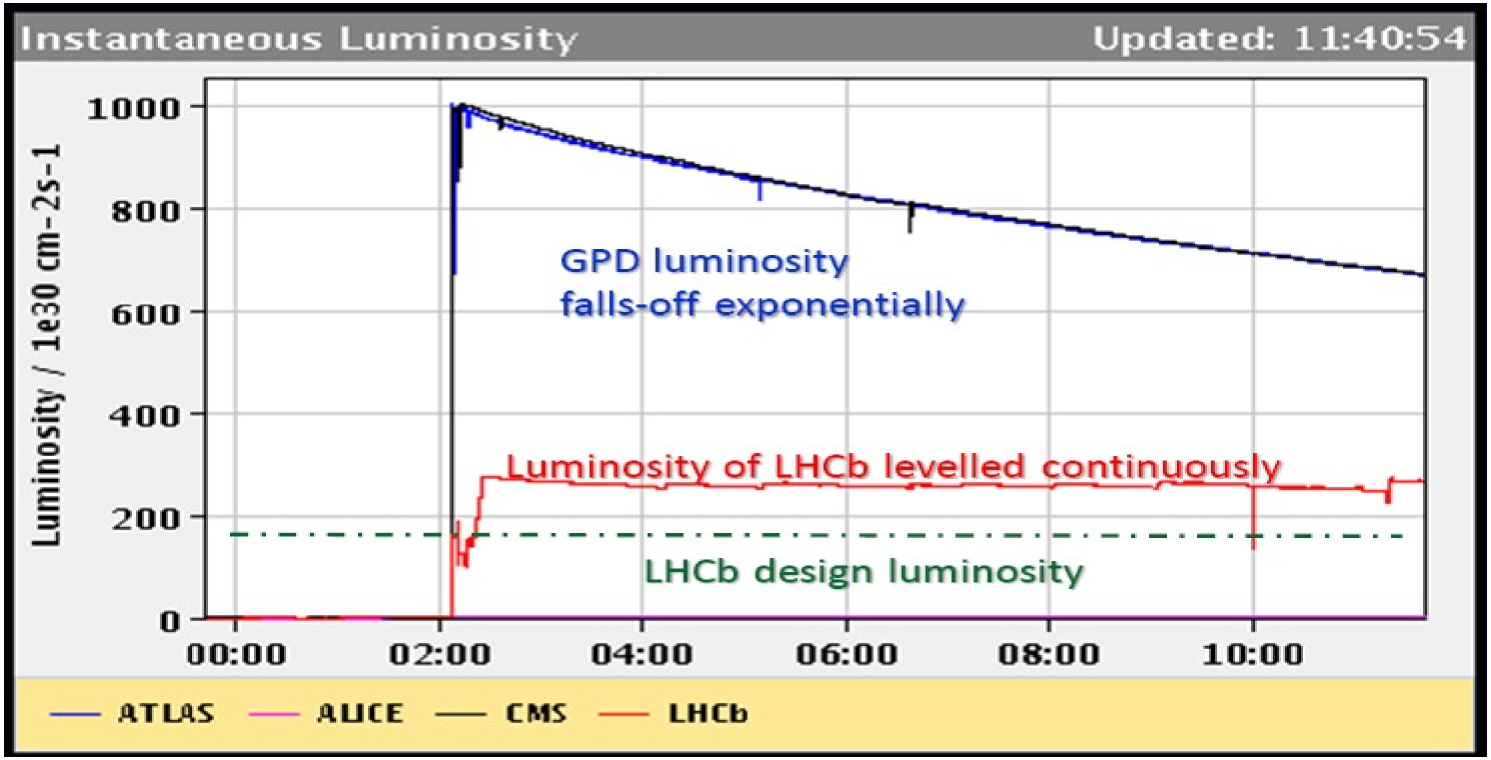
Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.5	100	89.3	92.7	94.3	99.5	100	99.5	100	99.9	98.5	97.9

Luminosity weighted relative detector uptime and good quality data delivery during 2011 stable beams in pp collisions at √s=7 TeV between March 13th and June 6th (in %). The inefficiencies in the LAr calorimeter will partially be recovered in the future. The magnets were not operational for a 3-day period at the start of the data taking.

LHC status in 2011 (so far)



Luminosity leveling

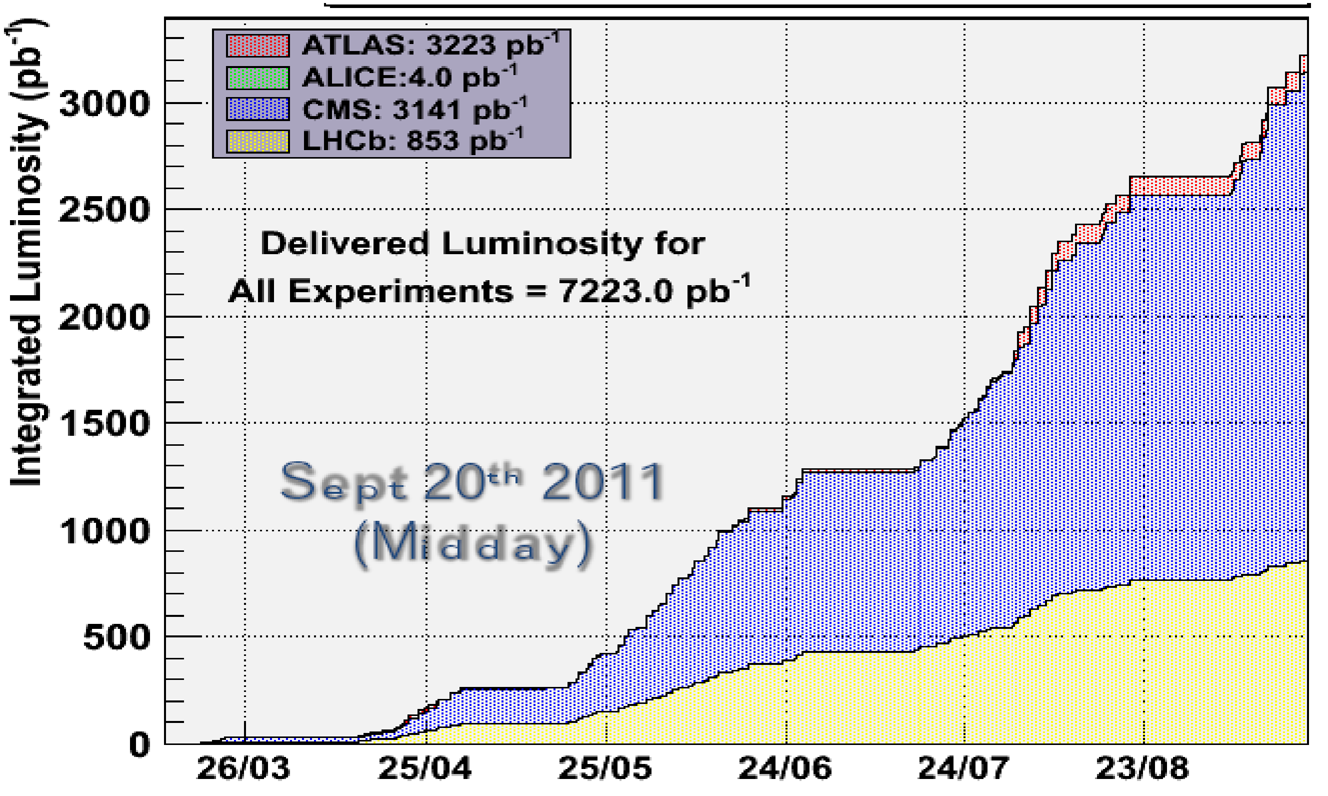


- Since end of May LHCb is taking data with constant $L \sim 3\text{-}3.5\ 10^{32}\ cm^{-2}\ s^{-1}$ with $\mu \sim 1.5$

Parameters of the LHC machine

	2010	2011	Nominal
Energy [TeV]	3.5	3.5	7
β* [m] (IP1,IP2,IP5,IP8)	3.5, 3.5, 3.5, 3.5	1.0, 10,1.0,3.0	0.55, 10, 0.55, 10
Emittance [μm] (start of fill)	2.0 – 3.5	**1.5 – 2.2**	3.75
Transverse beam size at IP1&5 [μm]	60	23	16.7
Bunch population	1.2×10^{11} p	$1.4\text{x}10^{+11}$ p	1.15×10^{11} p
Number of bunches	368	1380	2808
Number of collisions (IP1 & IP5)	348	1318	-
Stored energy [MJ]	28	110	360
Peak luminosity [$cm^{-2}s^{-1}$]	2×10^{32}	$3.3\text{x}10^{+33}$	1×10^{34}
Max delivered luminosity (1 fill) [pb^{-1}]	6.23	116 130.7	-
Longest Stable Beams fill [hrs]	12:09	25:59	-

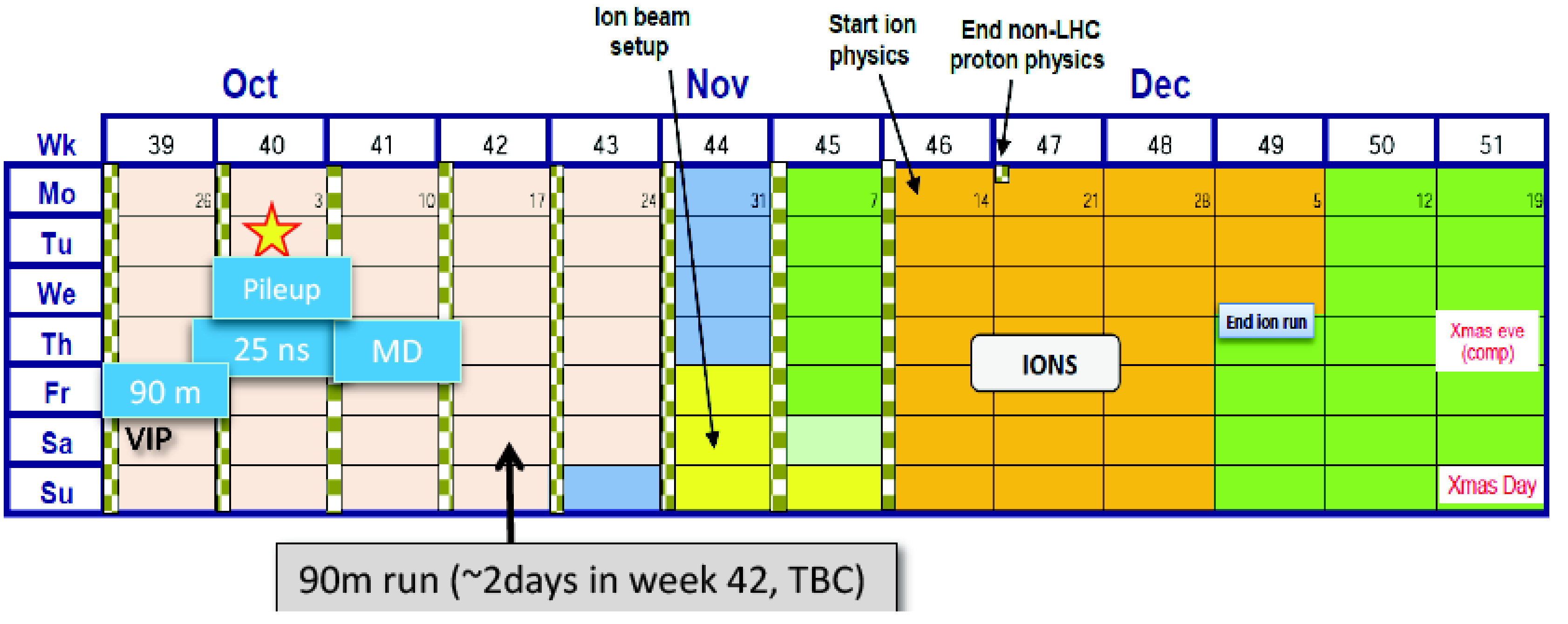
2011 luminosity production



- As of today about 4fb^{-1} for Atlas and CMS, 1fb^{-1} for LHCb
- Maximum delivered during 1 day (2.10): 130.7pb^{-1}

Prospects for rest of the year

- Increasingly difficult to meet needs of different experiments.



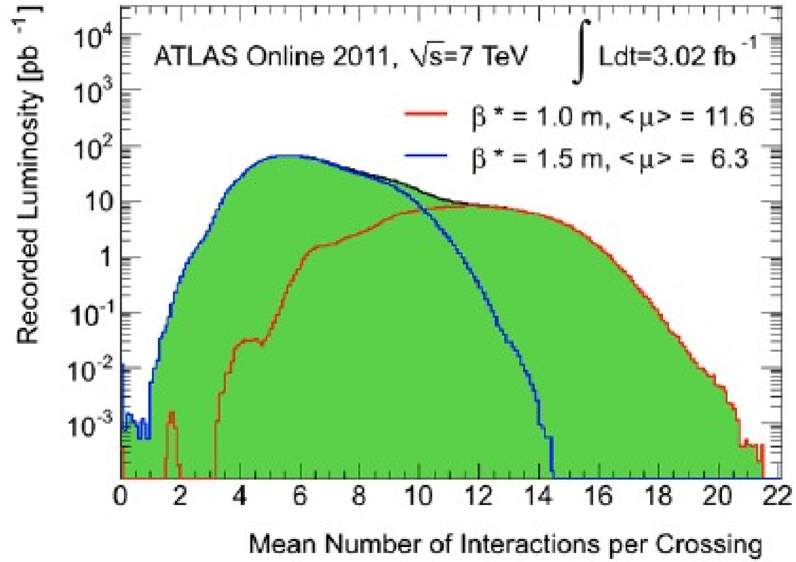
ATLAS trigger: preserve performance and trigger

Difficult to keep inclusive single lepton trigger at 20 GeV

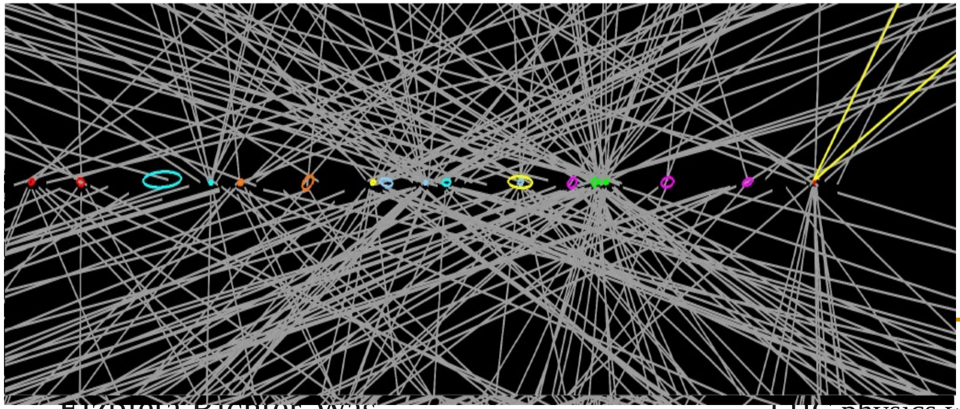
Trigger objects	Offline Selection (p_T thresholds)	Trigger Selection		L1 Rate (kHz) at 3 10^{33}	EF Rate (Hz) at 3 10^{33}
		L1	EF		
Single leptons	Single muon > 20 GeV	11 GeV	18 GeV	8	100
	Single electron > 25 GeV	16 GeV	22 GeV	9	55
Two leptons	2 muons > 4 GeV	11 GeV	15,10 GeV	6	5
	2 electrons, > 15 GeV	2x10 GeV	2x12 GeV	2	1.3
	2 $\tau \rightarrow h$ > 45, 30 GeV	15,11 GeV	29,20 GeV	7.5	15
Two photons	2 photons, > 25 GeV	2x12 GeV	2x20 GeV	3.5	5
E_T^{miss}	E_T^{miss} > 170 GeV	50 GeV	70 GeV	0.6	5
Multi-jets	5 jets, > 55 GeV	5x10 GeV	5x30 GeV	0.2	9
Single jet plus E_T^{miss}	Jet p_T > 130 GeV & E_T^{miss} > 140 GeV	50 GeV & 35 GeV	75 GeV & 55 GeV	0.8	18
Total rate (peak)				55 kHz	550 Hz

ATLAS reconstruction: impact of pileup

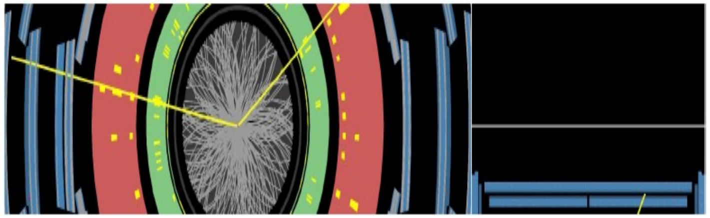
- Do not expect a significant impact on tracking, nor muons, nor even electrons and photons
- But sizable impact on jets ($+E_T^{miss}$) and τ's



Example of Z → μμ decay with 20 reconstructed vertices
Total scale along z is ~ ± 15 cm, p_T threshold for track reco is 0.4 GeV
(ellipses have size of 20σ for visibility)

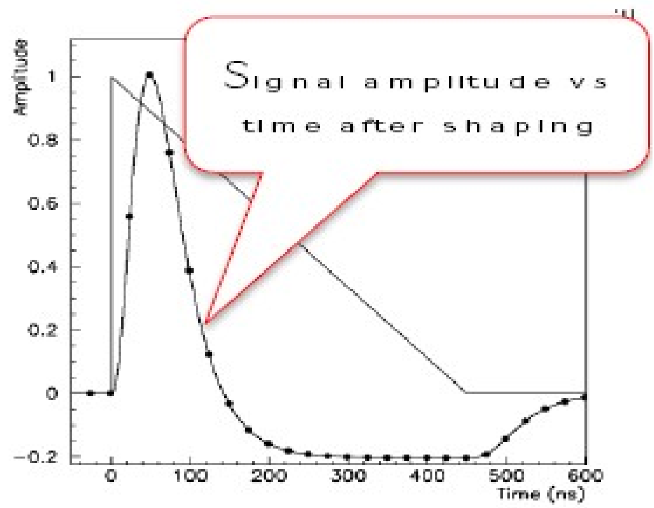


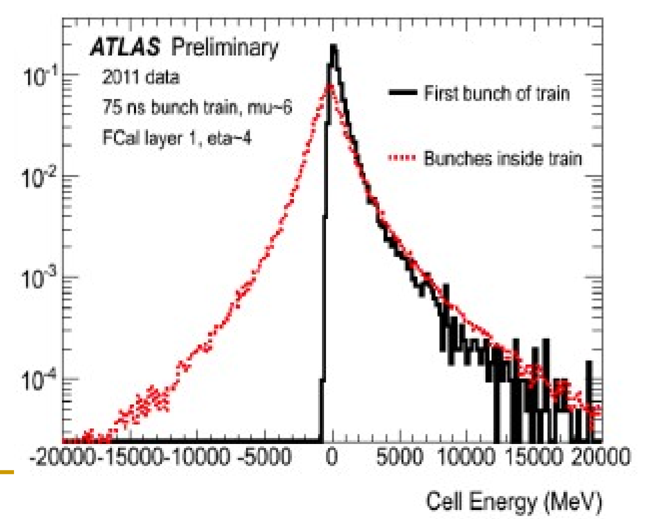
Now have <pile-up> ~ 14 per bunch crossing,
a challenge for tracking and for low-p_T jets!



ATLAS reconstruction: Lar

- LAr drift-time is ~500ns and out-of-time bunches have impact on measurement. Bipolar pulse shaping designed so that $<E_T>\sim0$ for 25ns beam spacing and uniform intensity per BX
- Uniform performance will require correction per cell type in η-bins as a function of luminosity to set $<E_T>$ to zero.
- At the moment increased scale uncertainty for low p_T jets in forward calo.



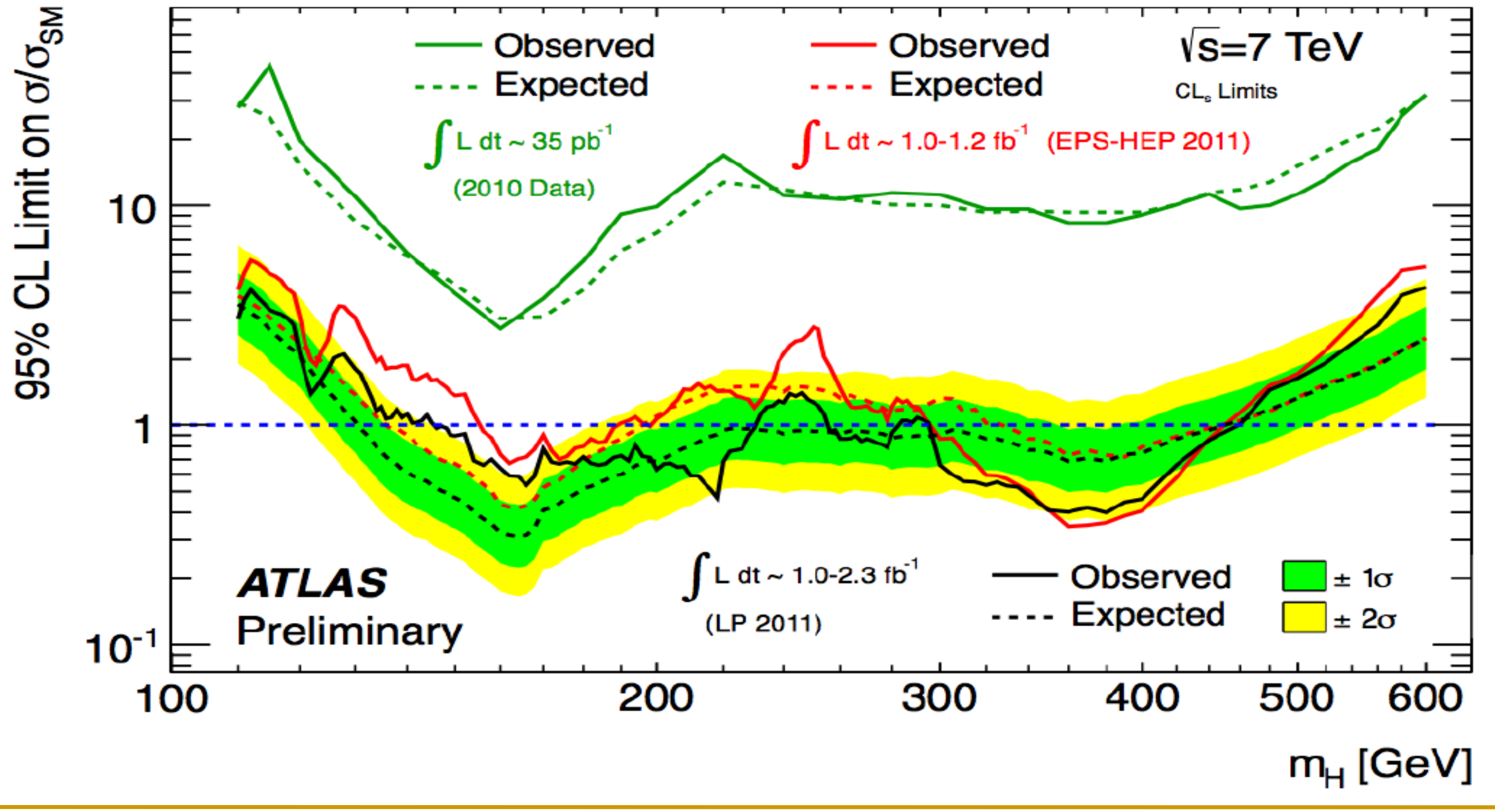


Luminosity error

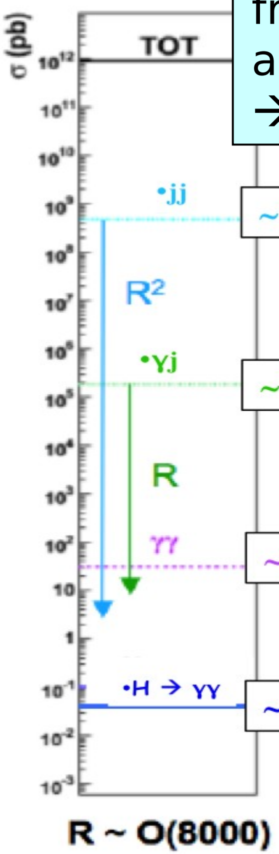
- Luminosity error quoted at summer conferences 2011
  - D0 6.5%
  - CDF 5.9%
  - CMS 4.5% (4.0% for 2010)
  - ATLAS 3.7% (3.4% for 2010)
- At present error dominated by LHC current
  - 3.0% possible scenario to reduce to 1.5%
- Discussion about VDM scan before the end of 2011 data taking, it will cost ~4% of integrated luminosity but could reduce error to ~ 2.0 – 2.5%
  - nb. similar lost may occur if unexpected “power cut” and perturbations to recover from it

Search for the Higgs boson

- Huge progress over 2011, more to come.

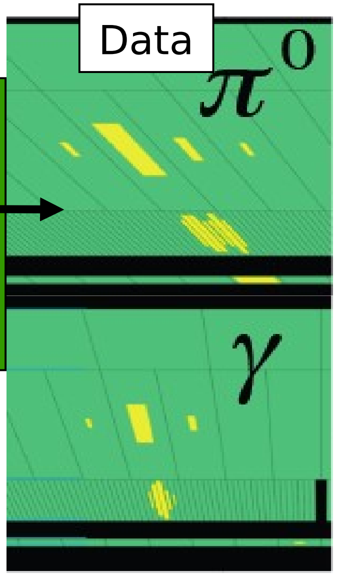


Photon measurements: physics and commissioning of H->γγ search



Potentially huge background from jets fragmenting into a single hard π^0
→ π^0 fakes single photon

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



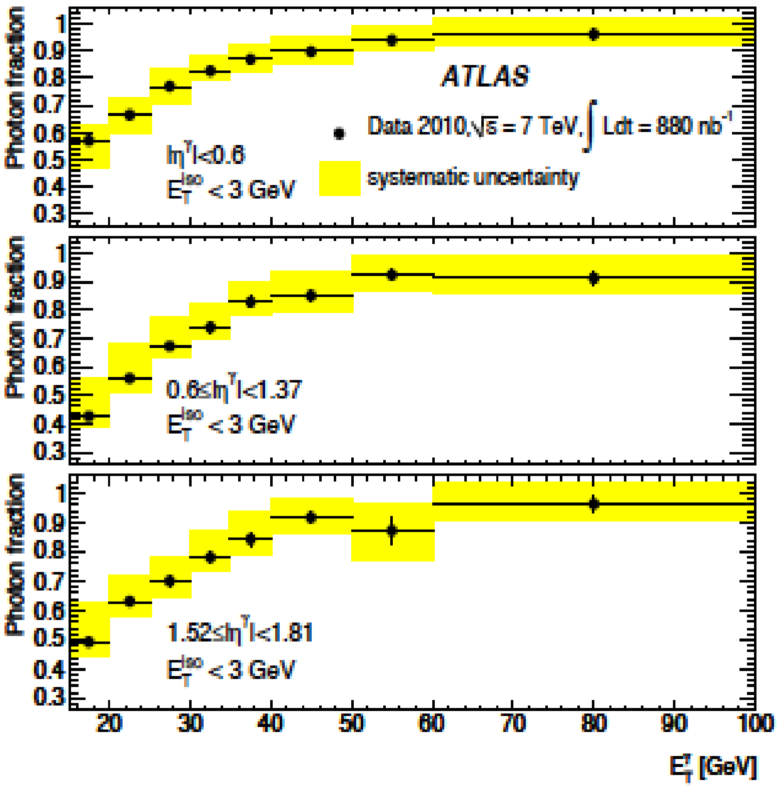
η-strips

σ (γj, jj): huge uncertainties !!
Not clear γj, jj could be suppressed until measured with data.

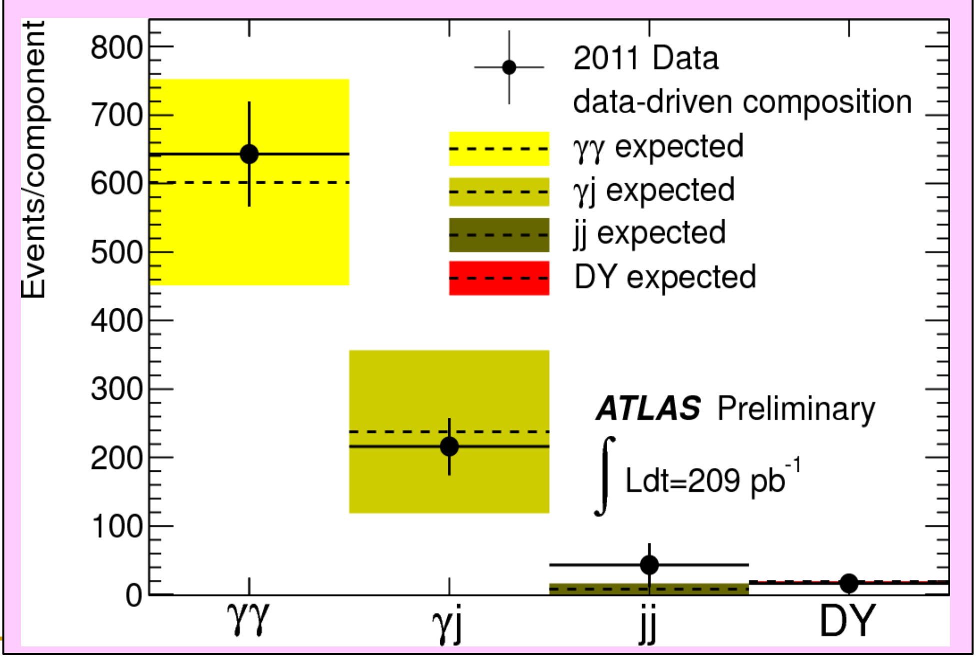
Photon measurements: physics and commissioning of H->γγ search

Photon purity versus E_T:

- around 70-80% in H to γγ range (25-40 GeV)
- above 90% at high E_T

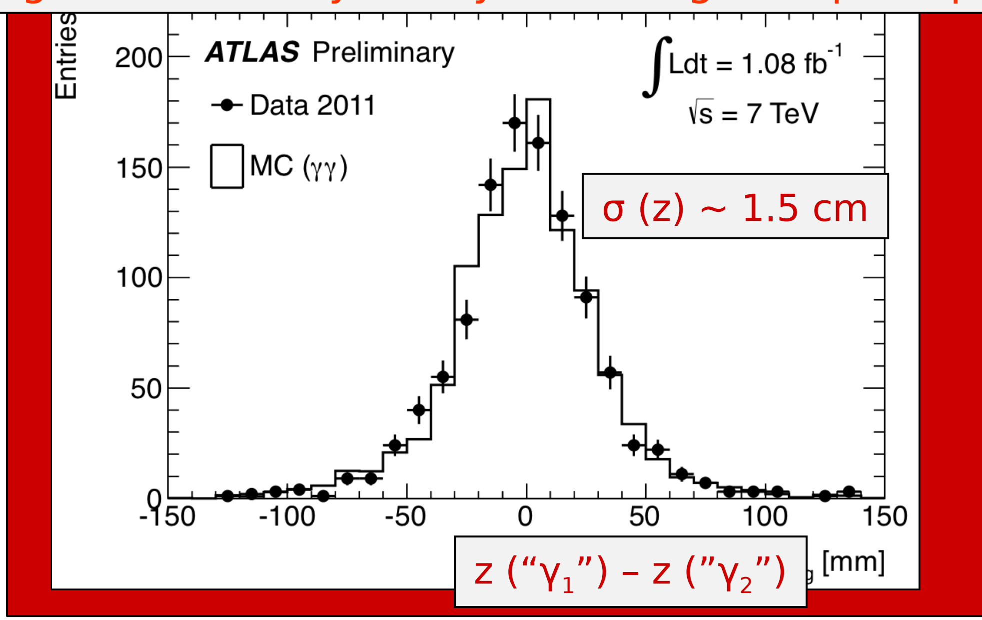


γγ, γj, jj backgrounds estimated from data using control samples → γj + jj << γγ irreducible



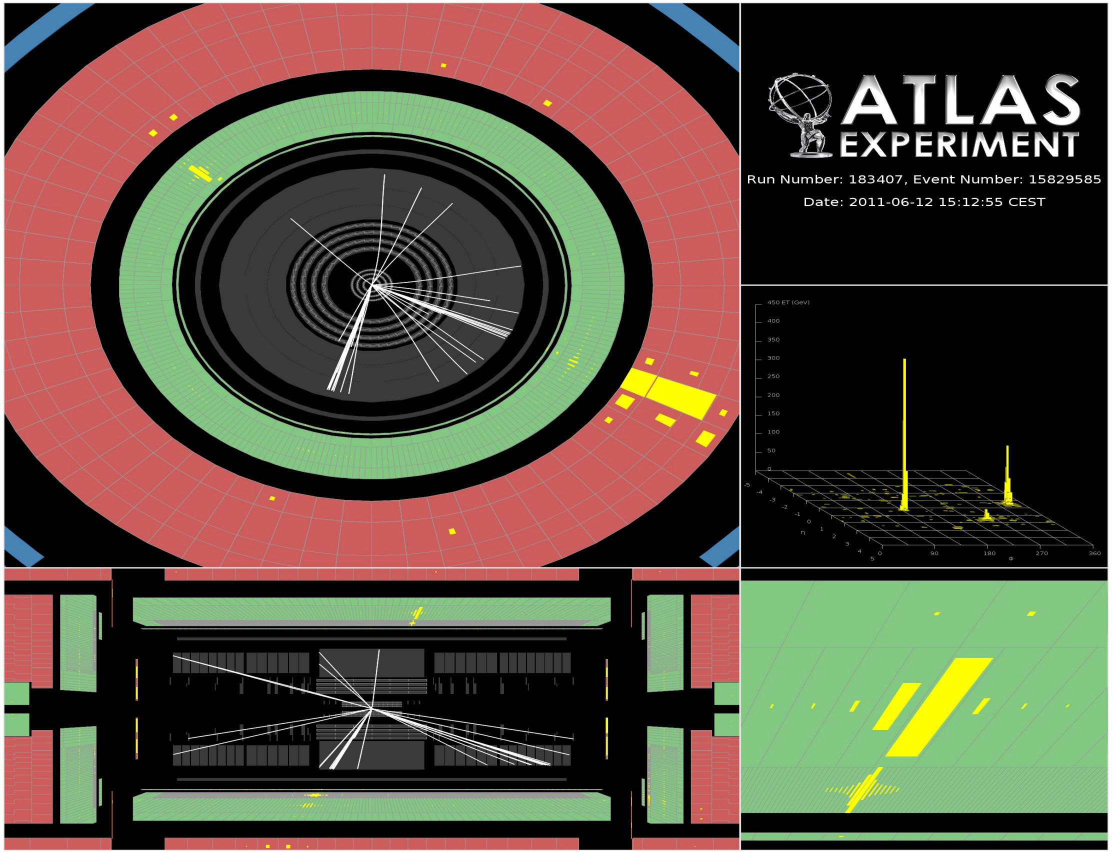
Photon measurements: physics and commissioning of H->$\gamma\gamma$ search

z-vertex measurement from calorimeter "pointing" using Z → ee decays: very robust against pile-up



Photon measurements: reach also TeV scale by now

Highest E_T (960 GeV) unconverted photon observed to-date



Prospects for Higgs boson searches

- More data
  - ~4-5 fb^{-1} by the end of 2011, > 10fb^{-1} by the end of 2012
- Refined understanding of the detector
  - Alignment, calibration, comparison with simulation
  - Smaller systematic uncertainties, better efficiency for rare channels
- More precise measurements of SM processes
  - Additional constraints on the MC generators
- More sophisticated analyses
  - Multivariate techniques and additional discriminating variables p_T, angular distributions)
  - Exclusive channels (VBF channel)
  - Higher statistics leading to sharper observables (eg. $H\rightarrow\tau\tau$ mass reconstruction for non back-to-back pairs)

SUSY searches: progress on understanding SM background

1 lepton+jets+E_T^{miss}

at least 3 jets

$p_T^{j1} > 130$ GeV,

$p_T^{j} > 40$ GeV

0 lepton+b-jet+E_T^{miss}

at least 3 jets

$p_T^{j1} > 130$ GeV,

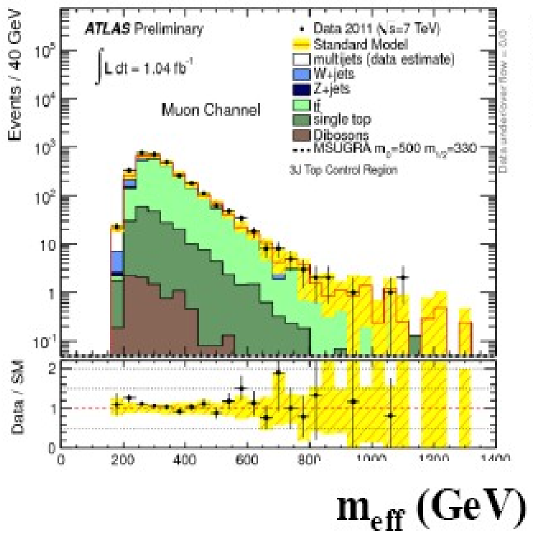
one tagged b,

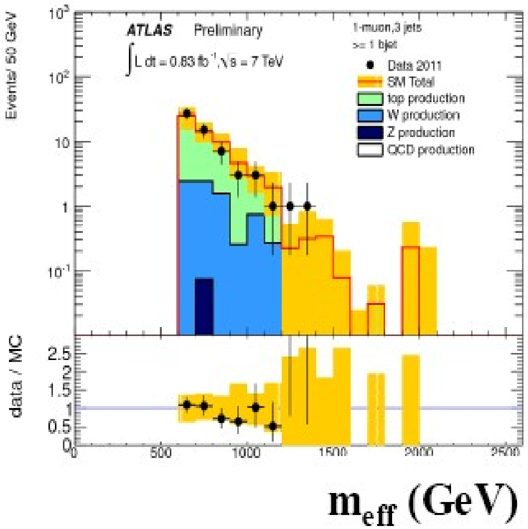
1 lepton+b-jet+E_T^{miss}

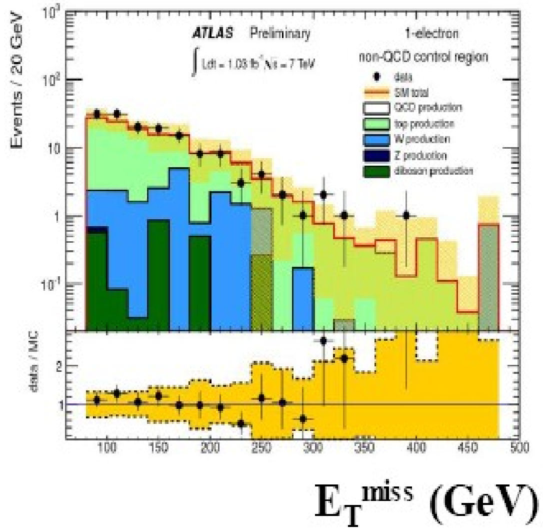
at least 4 jets

$p_T^{j1} > 130$ GeV,

one tagged b,







Yellow band in ratio plots show good agreement between data and MC

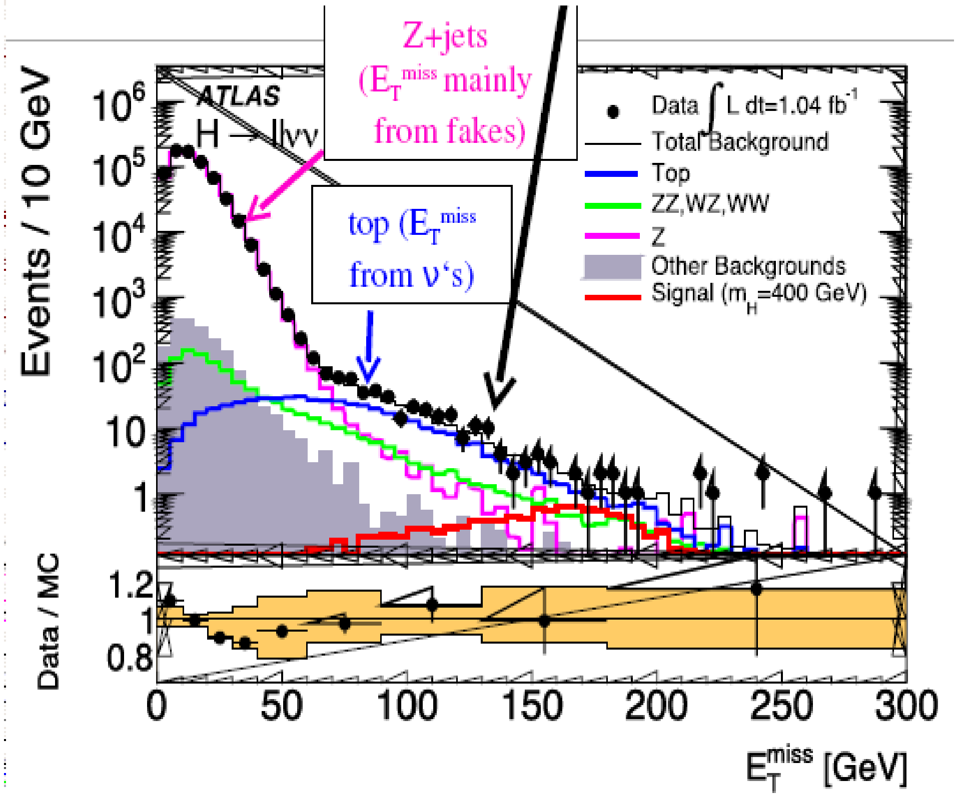
ATLAS reconstruction: E_t^{miss}

(with pile-up of EPS data)

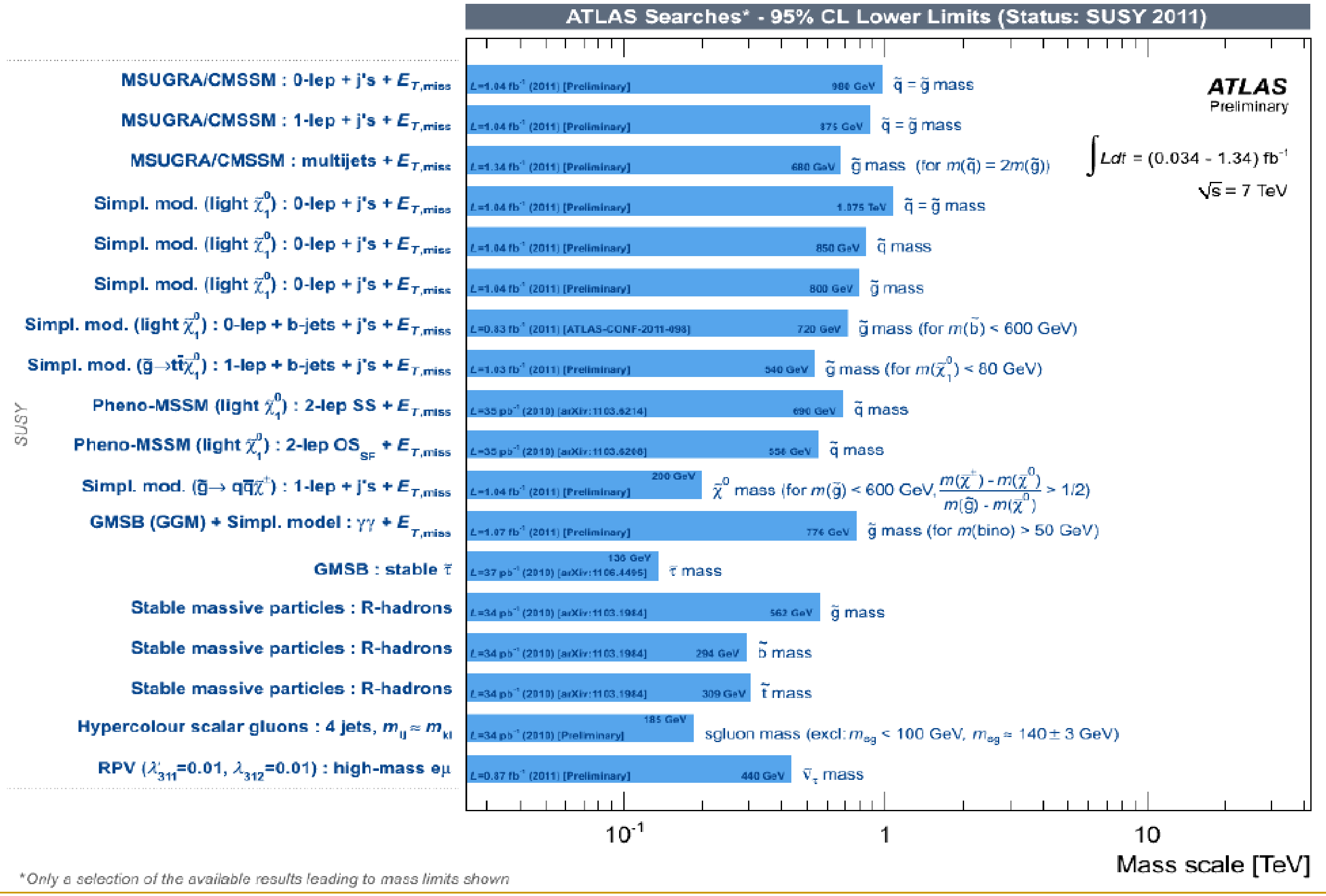
E_T^{miss} spectrum in data for events with a lepton pair with $m_{ll} \sim m_Z$ well described (over 5 orders of magnitude !) by various background components.

Note: dominated by real E_T^{miss} from ν's already for $E_T^{miss} \sim 50$ GeV

→ little tails from detector effects !



SUSY searches



Exotic searches: progress on understanding SM background

Long-lived neutralino

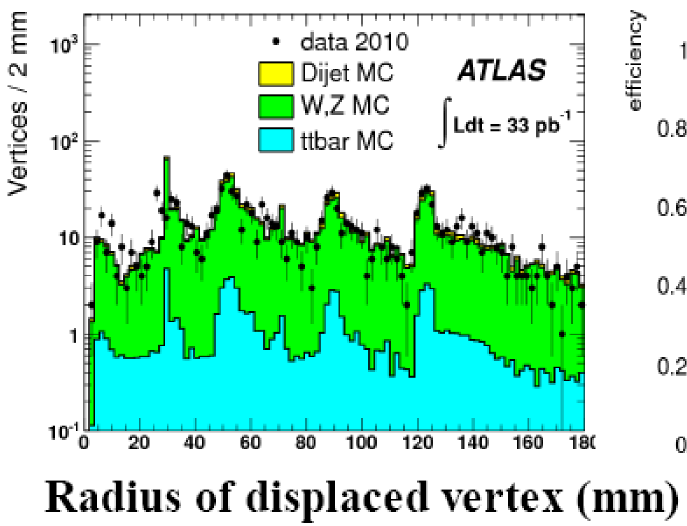
decay to two jets, displaced vertex with high track multiplicity (tracking, vertex reco)

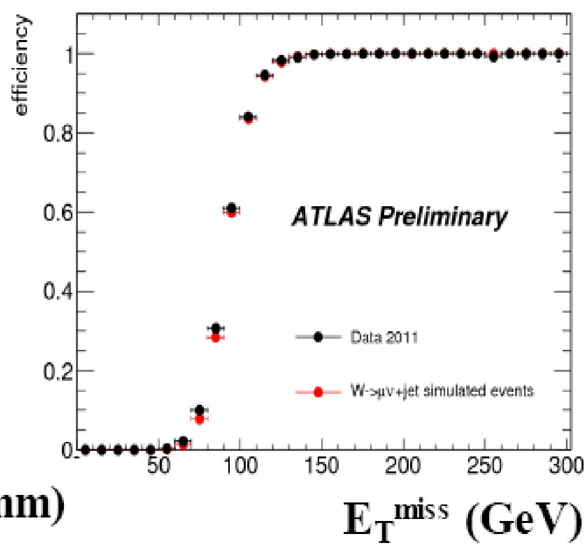
Monojets

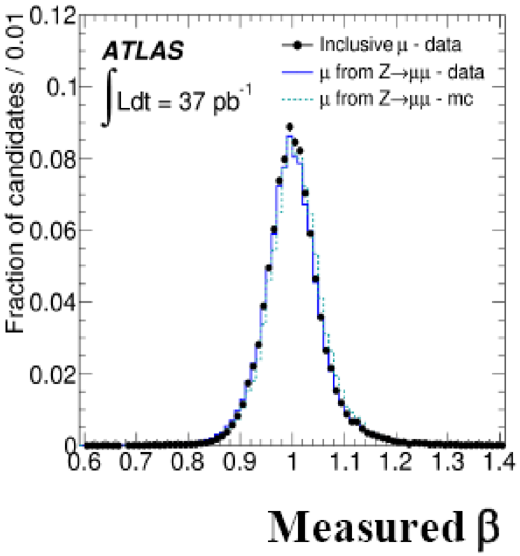
efficiency of E_T^{miss} turn-on curve for trigger

Long-lived isolated slepton:

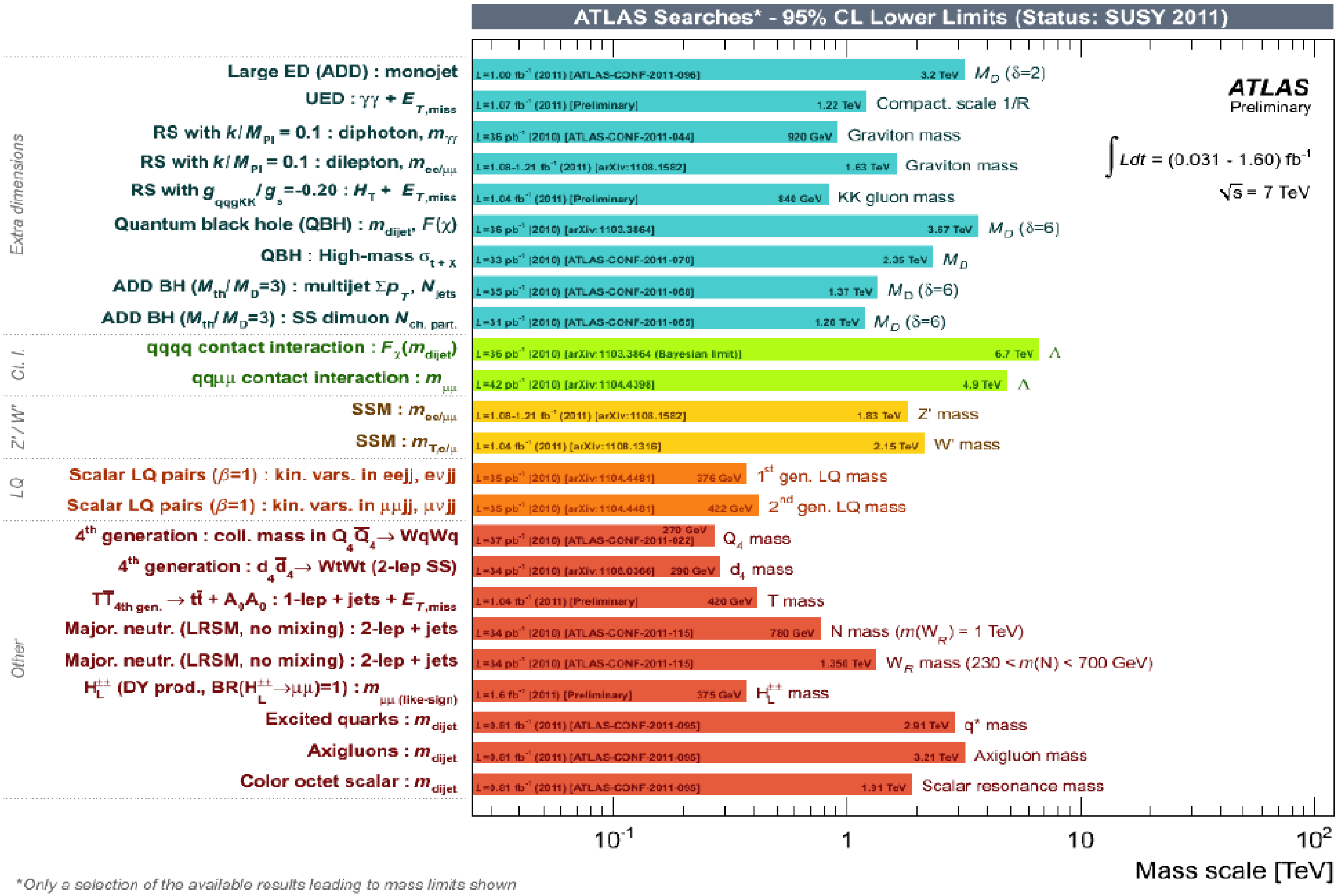
timing of muon spectrometer







Exotic searches



Summary

- Experiments are happily learning about proton-proton physics at 7 TeV.
- The accelerator and detector are continuously delivering beautiful data. This together with emerging state-of-the-art MC tools opens the possibility of doing precision measurements in both the EW and QCD sectors of the SM.
- With 3-5 fb^{-1} in 2011 we are experiencing a hugely exciting period of the data analysis.
- For discoveries, no promises can be made. But the past year has shown that the potential is undoubtedly there.
- A special moment with large dataset both from LHC and Tevatron.
  Tevatron: up to 9fb^{-1} analysed so far.

Plan

- Amazing how much could have been done with only 36pb^{-1} data accumulated in 2010: numbers of results are still in the pile-line but already theory is being tested quantitatively.... and is holding its own (unfortunately)

  5.10 BSM searches

  19.10 QCD jet physics

  9.11 W,Z inclusive, asymmetry, W/Z + heavy flavours

  23.11 Top physics

  7.12 Diboson production and TGS couplings

  21.12 Analysis techniques

  4.01 B-physics and heavy ions

  18.01 What's new from searches?

Beyond the Standard Model

Supersymmetry (with MET)

→ Jets + MET

→ Lepton(s) + MET

→ 3rd generation + MET

→ Photon(s) + MET

Strong Gravity

→ Monojet

→ Monophoton

→ Dilepton spectrum

→ Black-hole

Heavy Resonances

→ Heavy gauge bosons

→ Diphoton

→ Dijet

→ Doubly-charged Higgs

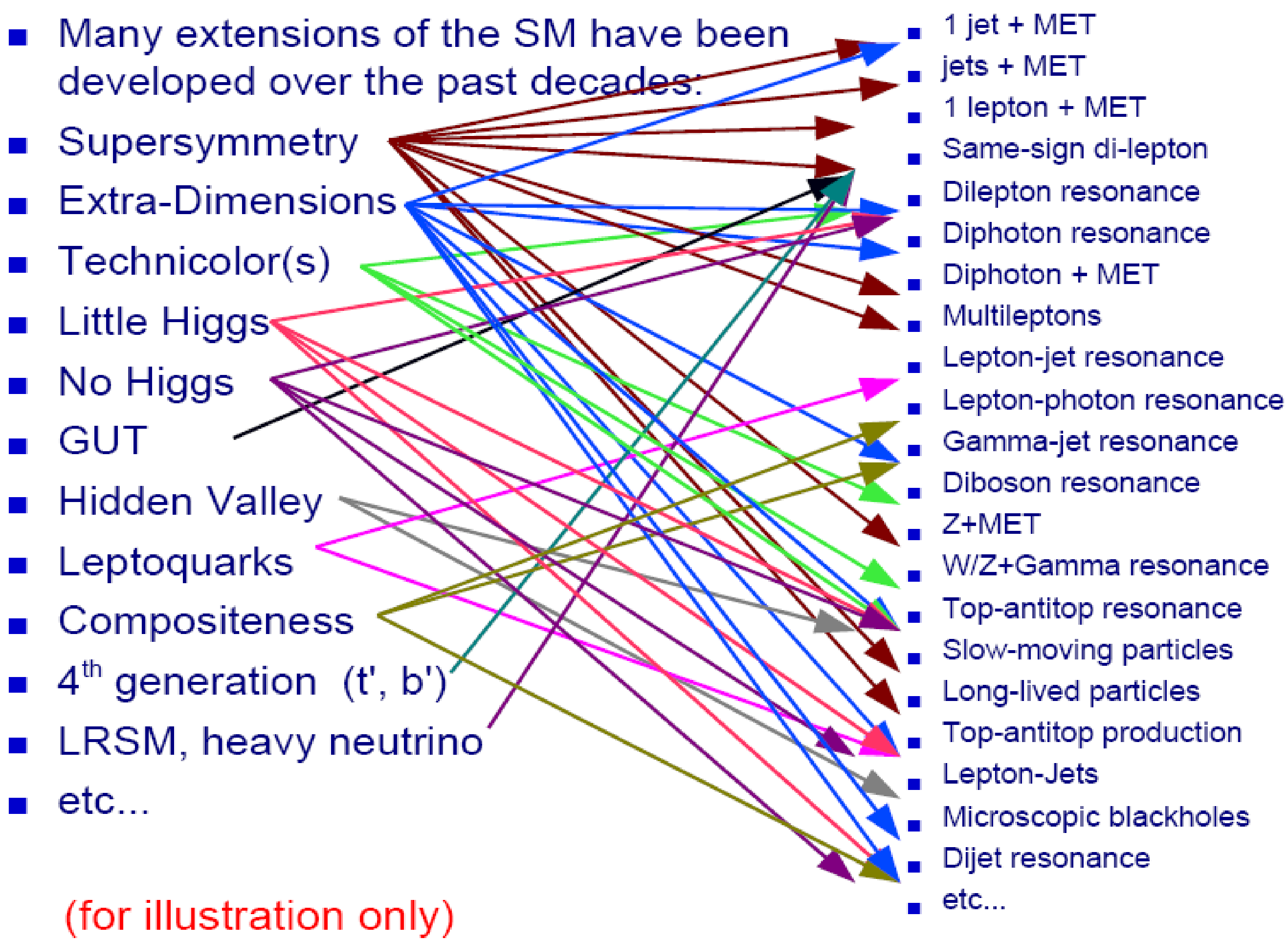
Long-Lived Particles

→ Displaced vertices

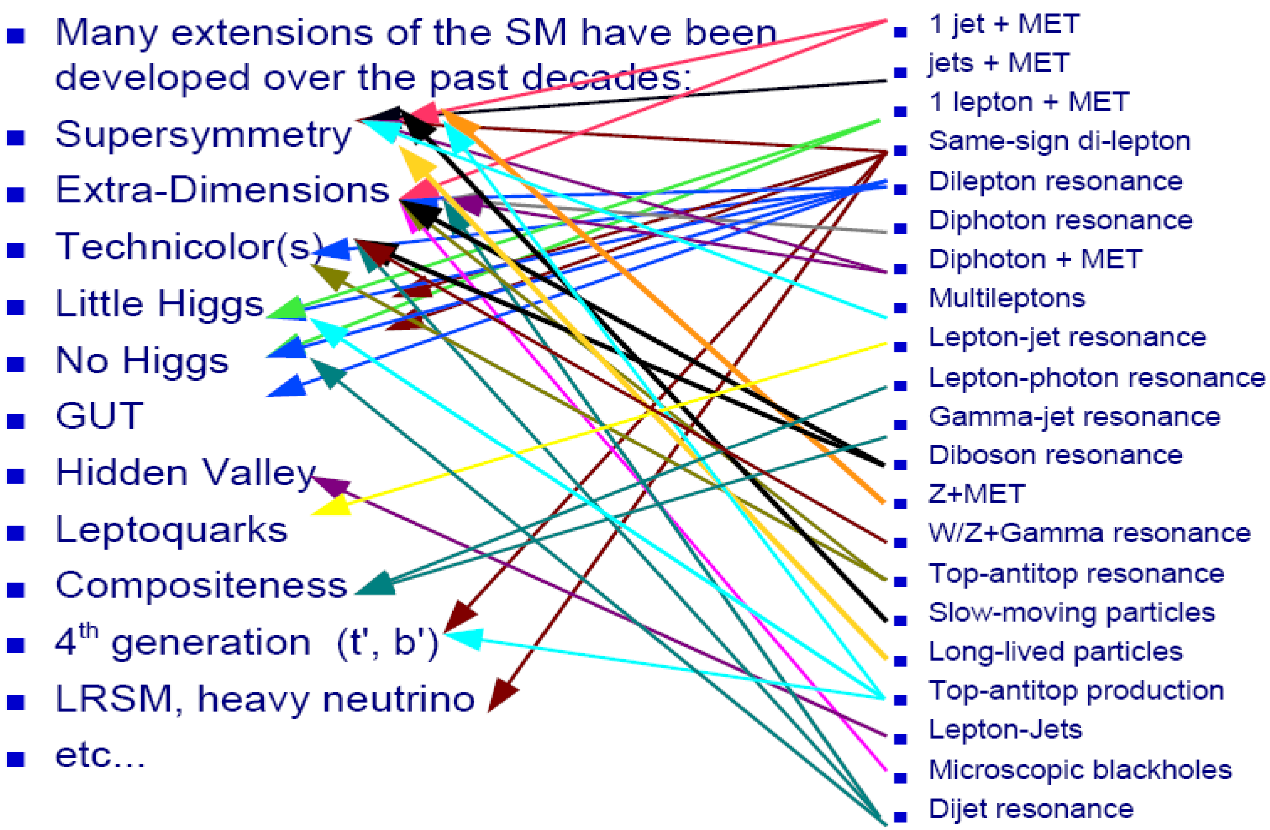
→ Slow particles

→ Out-of-time decays

A very long list of models x signatures



A very long list of models x signatures

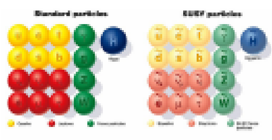


(for illustration only)

A complex 2D problem

Experimentally, a **signature standpoint** makes a lot of sense:

- → Practical
- → Less model-dependent
- → Important to cover every possible signature

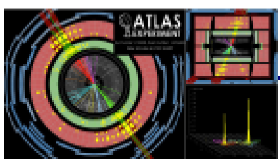


Supersymmetry (with MET)

- → Jets + MET
- → Lepton(s) + MET
- → 3rd generation + MET
- → Photon(s) + MET

Strong Gravity

- → Monojet
- → Monophoton
- → Dilepton spectrum
- → Black-hole



Heavy Resonances

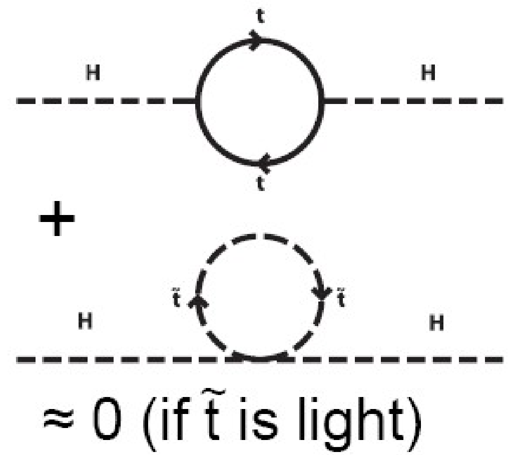
- → Heavy gauge bosons
- → Diphoton
- → Dijet
- → Doubly-charged Higgs

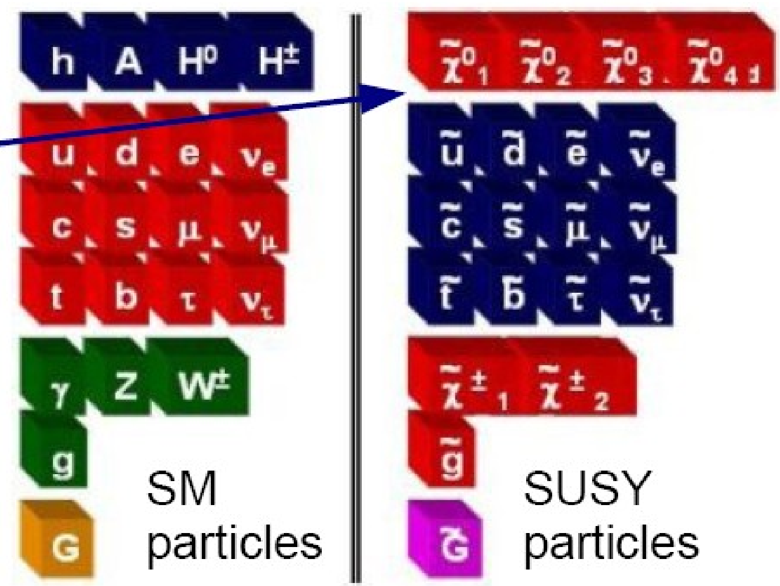
Long-Lived Particles

- → Displaced vertices
- → Slow particles
- → Out-of-time decays

Supersymmetry

- Extension of the Poincaré algebra
- Fermion ↔ Boson symmetry
- Solves many problems of the SM, esp. stabilizes Higgs sector
- If R-parity ($R = (-1)^{3(B-L)+2s}$) is conserved, Lightest SUSY Particle (LSP) is an excellent Dark Matter candidate
- Phenomenology is **very** diverse





Supersymmetry (with MET)

Cascade ending with LSP
→ large MET

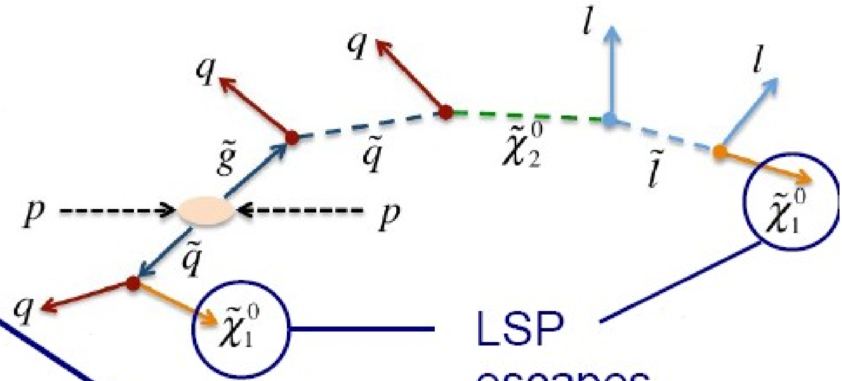
1 Jets+MET: Gluino and Squark prod. dominate

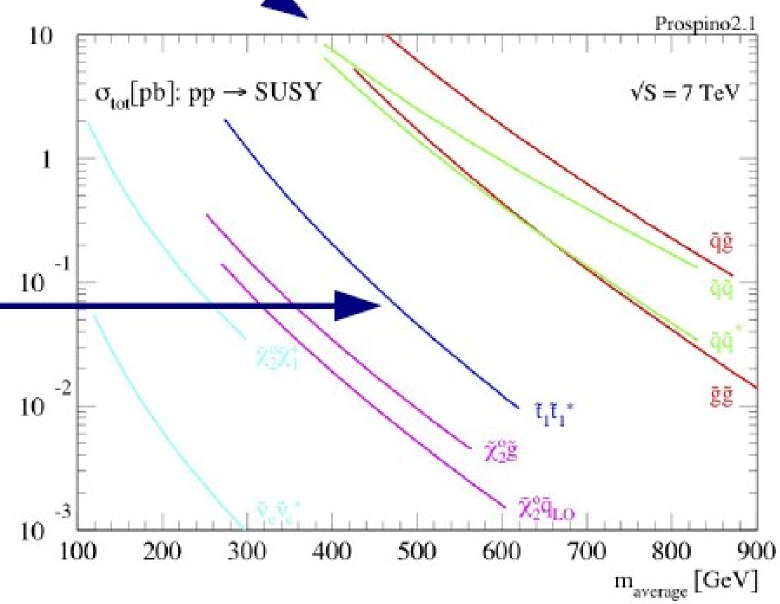
2 Leptons(+jets)+MET: lower branching ratio/cross-section but complementary

3 3rd generation (b or t):

- → in cascade
- → direct production requires > 1 fb^{-1}
  → coming soon

4 Photon(s)+MET: GMSB models





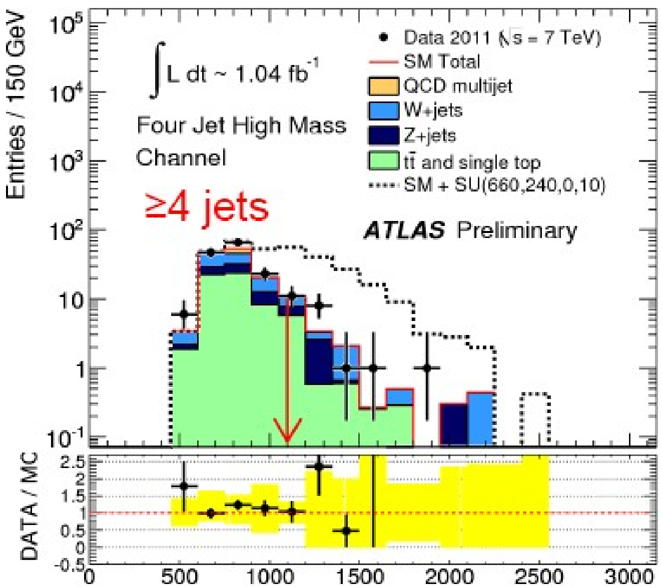
1. SUSY: Jets + Missing E_T

$\tilde{q} \to q\tilde{\chi}_1^0$

$\tilde{g} \to qq\tilde{\chi}_1^0$

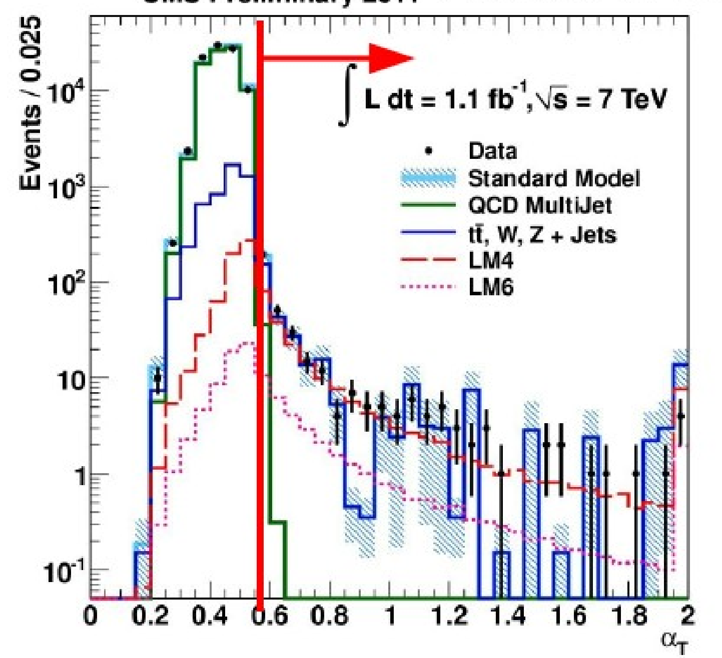
- "Workhorse" of SUSY search
- ATLAS:
  - → Cut on MET and m_{eff}
  - → Combine exclusive channels
- CMS explores various techniques:
  - → α_T = 2nd jet E_T / Trans. Mass

H_T = scalar sum of all jet E_T



m_{eff} = H_T + Missing E_T [GeV]

PAS-SUS-11-003

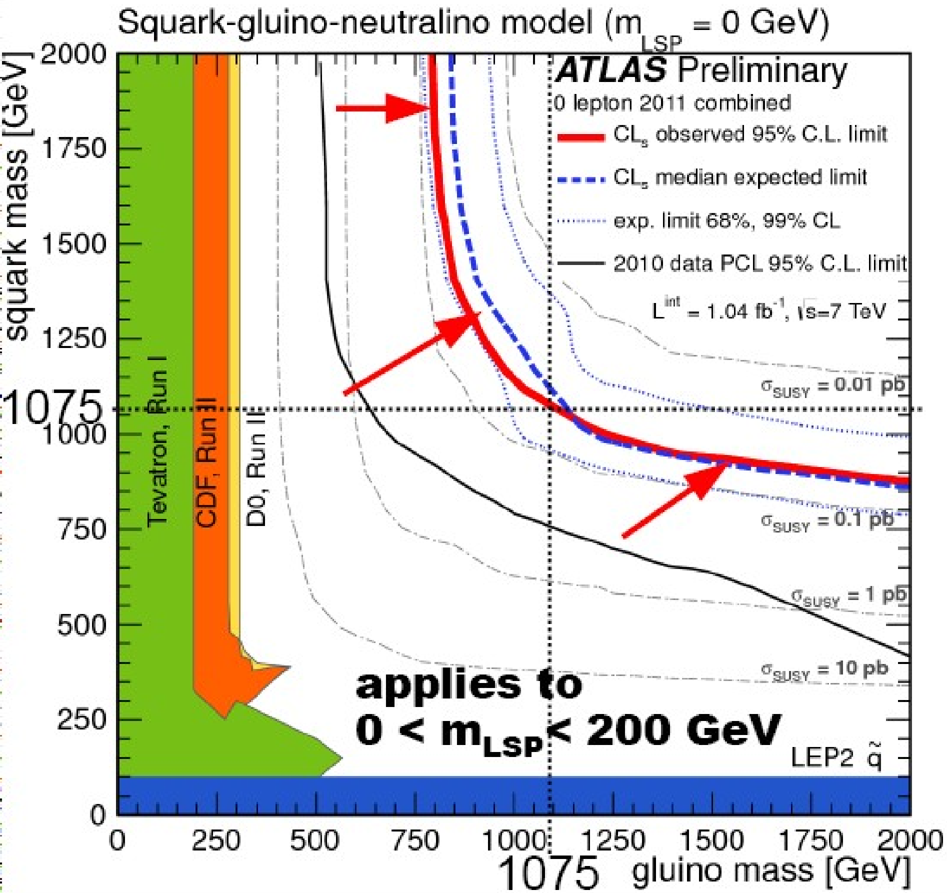


1. SUSY: Jets + Missing E_T

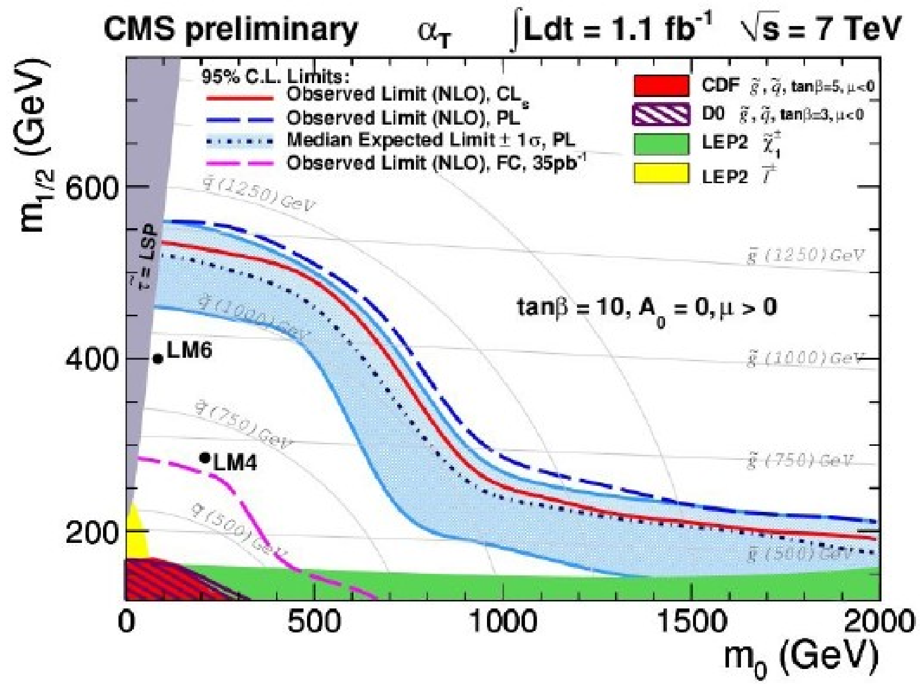
$\tilde{q} \rightarrow q\tilde{\chi}_1^0$

$\tilde{g} \rightarrow qq\tilde{\chi}_1^0$

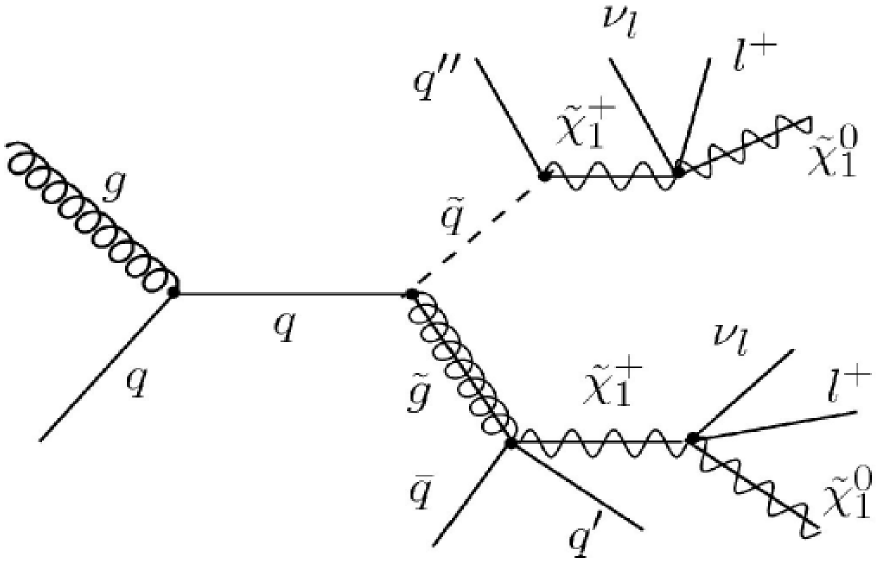
- Exclude up to ~ 1 TeV for m(squark) = m(gluino)



CMS-SUS-11-003



2. SUSY: Lepton(s) + Jets + Missing ET

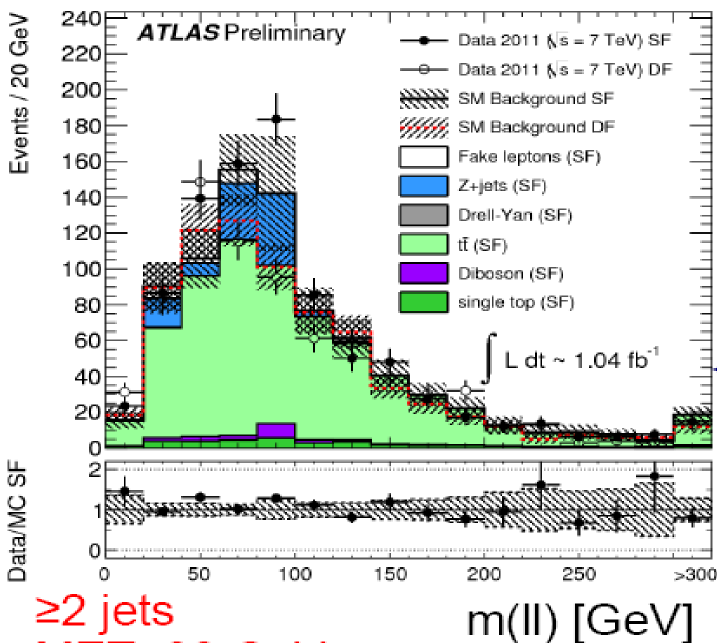


- Leptons arise from slepton or charginos or W/Z decays
- Due to smaller Branching Ratio, less stringent limits than fully hadronic but complementary
- Look for 1, 2 (same-sign or opposite sign) or more leptons
- Flavor subtraction selects flavor-correlated decays
- Can also look explicitly for heavy boson decay

2. SUSY: Lepton(s) + Jets + Missing ET

Dilepton (+jets) + MET, ATLAS 1 fb^{-1}

		Background	Obs.
opposite sign	OS-SR1	$15.5 \pm 1.2 \pm 4.4$	13
	OS-SR2	$13.0 \pm 1.8 \pm 4.1$	17
	OS-SR3	$5.7 \pm 1.1 \pm 3.5$	2
same sign	SS-SR1	$32.6 \pm 4.4 \pm 4.4$	25
	SS-SR2	$24.9 \pm 4.1 \pm 6.6$	28



ee + μμ - eμ

≥2 jets
MET>80 GeV

- Leptons arise from slepton or charginos or W/Z decays
- Due to smaller Branching Ratio, less stringent limits than fully hadronic but complementary
- Look for 1, 2 (same-sign or opposite sign) or more leptons
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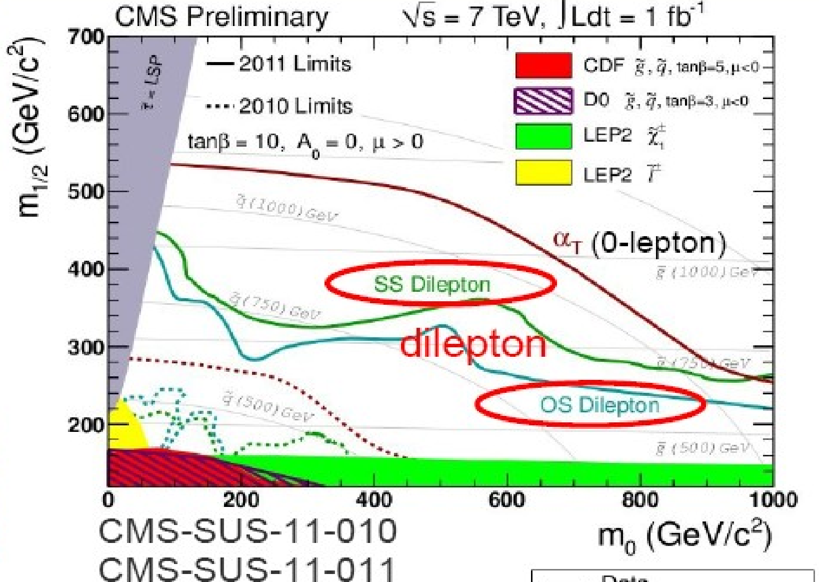
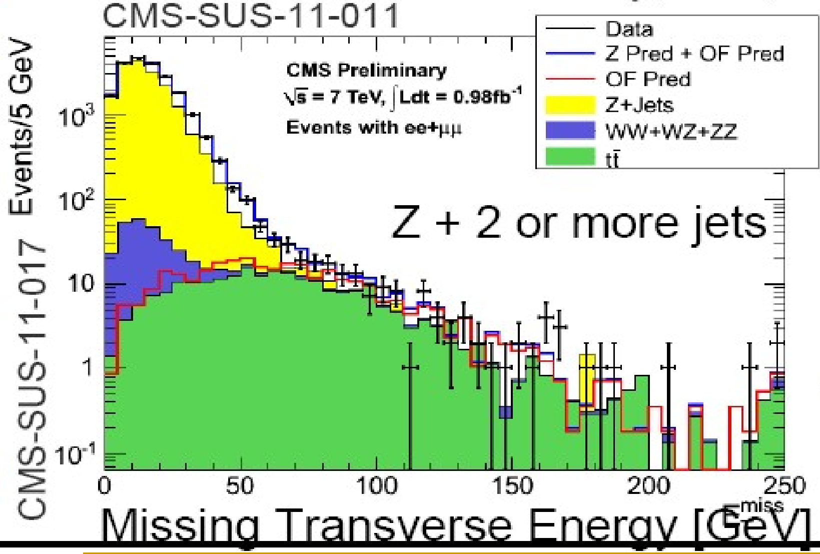
2. SUSY: Lepton(s) + Jets + Missing ET





- Leptons arise from slepton or charginos or W/Z decays
- Due to smaller Branching Ratio, less stringent limits than fully hadronic but complementary
- Look for 1, 2 (same-sign or opposite sign) or more leptons
- Flavor subtraction selects flavor-correlated decays
- Can also look explicitly for heavy boson decay

3. SUSY: b-Jets + lepton + Missing E_T

- What if gluinos decay preferentially to 3rd generation?
- Consider several pheno. scenarii, such as:

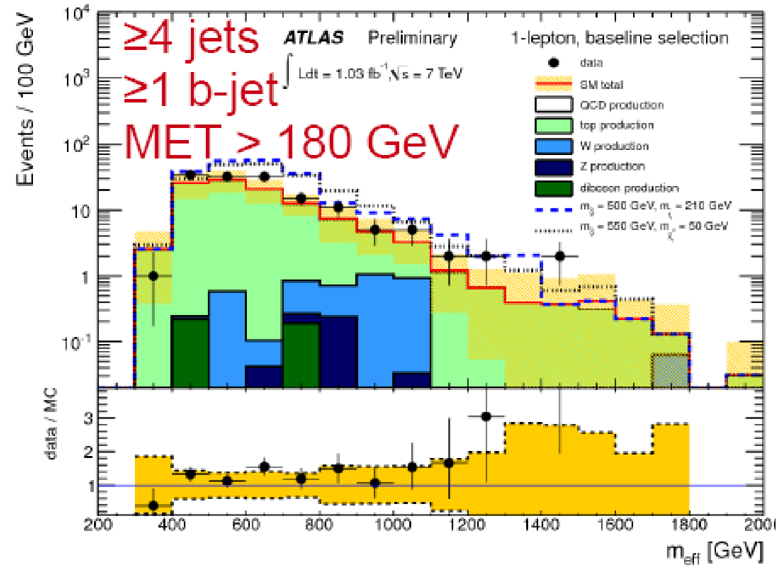
  Assume $m(\tilde{g}) > m(\tilde{t}_1) > m(\tilde{\chi}_1^{\pm}) > m(\tilde{\chi}_1^{0})$ (and everything else heavier)

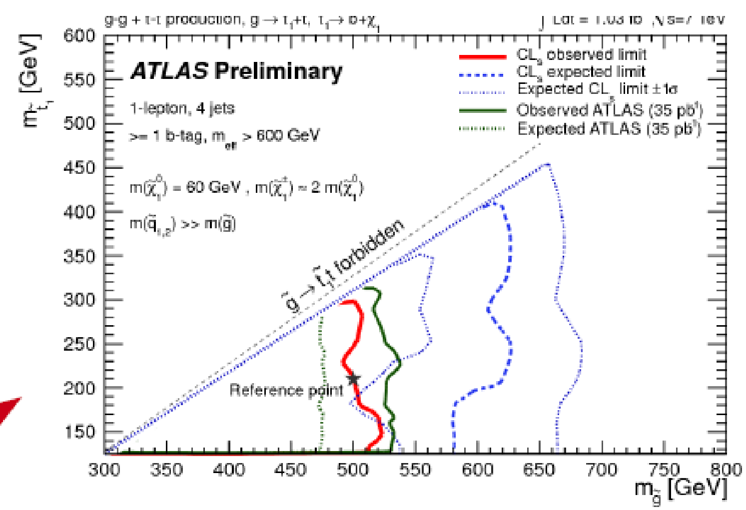
  Consider only the following decays:

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

  and $\tilde{\chi}_1^{\pm} \rightarrow W^* \tilde{\chi}_1^{0}$
- Complex final states with lepton(s) and b-jets
- Limit on gluino mass:

  m(gluino) > 500 GeV at 95% C.L.





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3. SUSY: b-Jets + lepton + Missing E_T

- What if gluinos decay preferentially to 3rd generation?
- Consider several pheno. scenarii, such as:

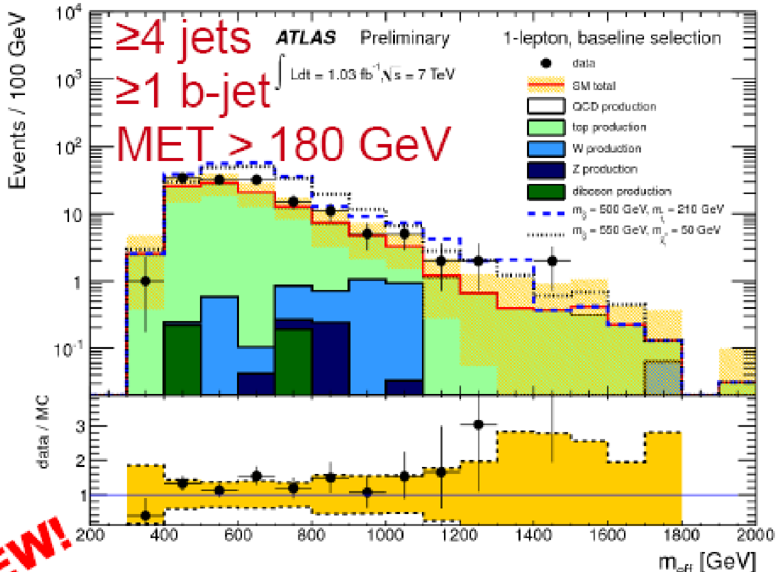
  Assume $m(\tilde{g}) << m(\tilde{t}_1) << m(\tilde{q}_{1,2}) \approx m(\tilde{b}_1)$

  Consider only gluino-gluino production followed by decay through off-shell stop:

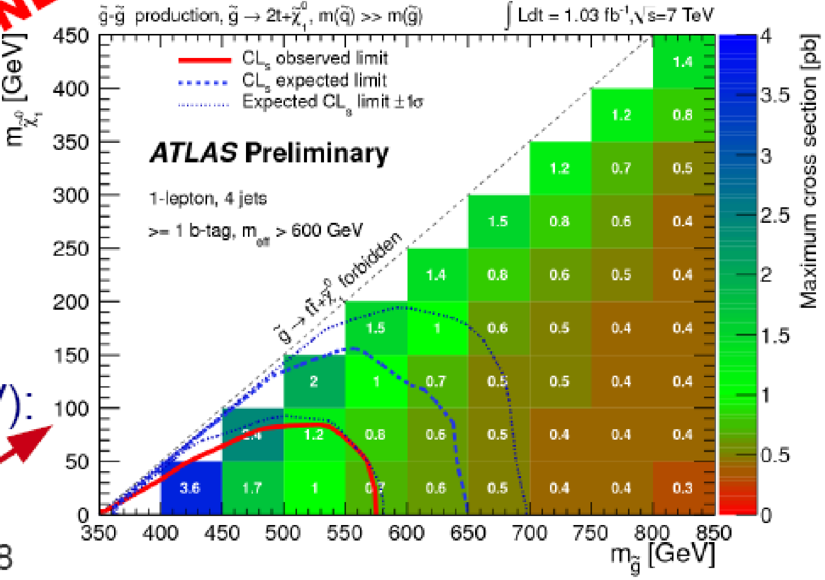
  $\tilde{g} \rightarrow \tilde{t}_1{}^* t \rightarrow t t \tilde{\chi}_1^0$

- Complex final states with lepton(s) and b-jets
- Limit on gluino mass ($m(\chi_1^0) < 80$ GeV):

  m(gluino) > 540 GeV at 95% C.L.



NEW!



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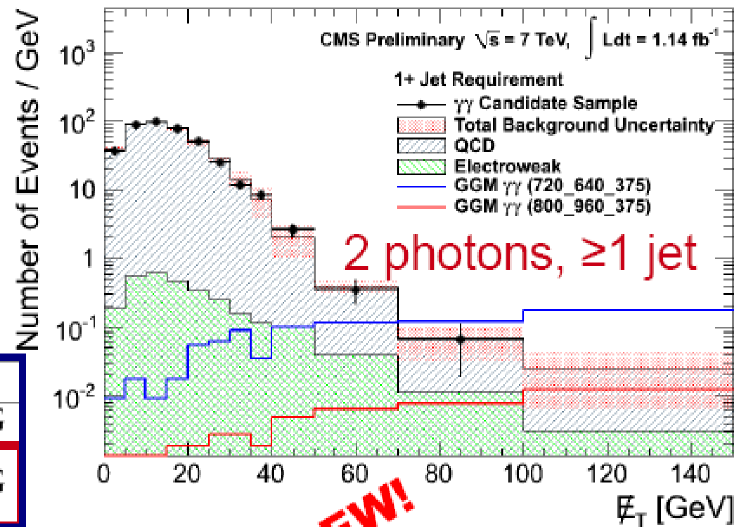
4. SUSY: diphoton + jet + Missing E_T

- Gauge-Mediated SUSY Breaking:
  - → LSP = Gravitino
  - → NLSP = Neutralino (and Chargino)
  - → NLSP → LSP + Photon or W or Z

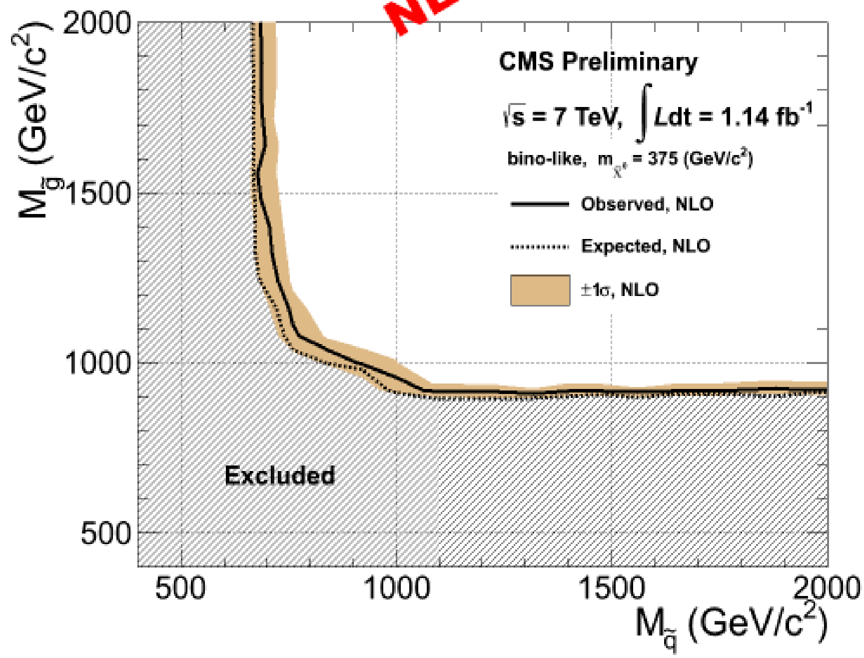
NLSP type	γ + 3 jets + E_T^{miss}	$\gamma\gamma$ + jet + E_T^{miss}
Bino	jets + $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow$ jets + $\gamma + Z + \tilde{G}\tilde{G}$	jets + $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow$ jets + $\gamma\gamma + \tilde{G}\tilde{G}$
Wino	jets + $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow$ jets + $\gamma + Z + GG$ jets + $\tilde{\chi}_1^0\tilde{\chi}_1^\pm \rightarrow$ jets + $\gamma + W^\pm + \tilde{G}\tilde{G}$	jets + $\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow$ jets + $\gamma\gamma + \tilde{G}\tilde{G}$

$m(\chi_1^0) \approx m(\chi_1^\pm)$
co- NLSP's

- Consider both final states:
  - → Diphoton
  - → Single photon (next slide)



NEW!

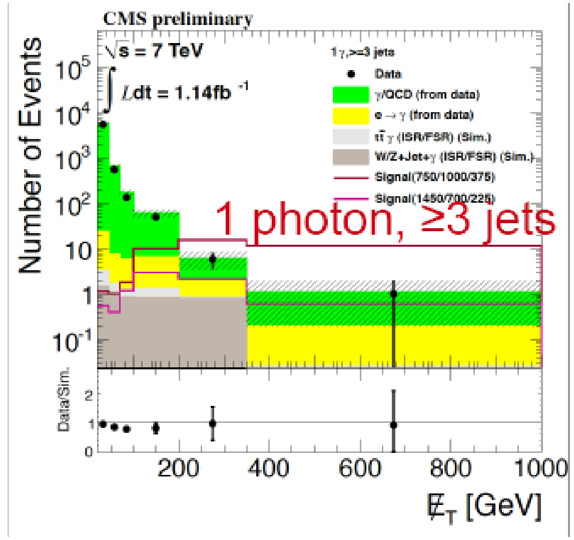


4. SUSY: photon + jets + Missing E_T

- Gauge-Mediated SUSY Breaking:
  - → LSP = Gravitino
  - → NLSP = Neutralino (and Chargino)
  - → NLSP → LSP + Photon or W or Z

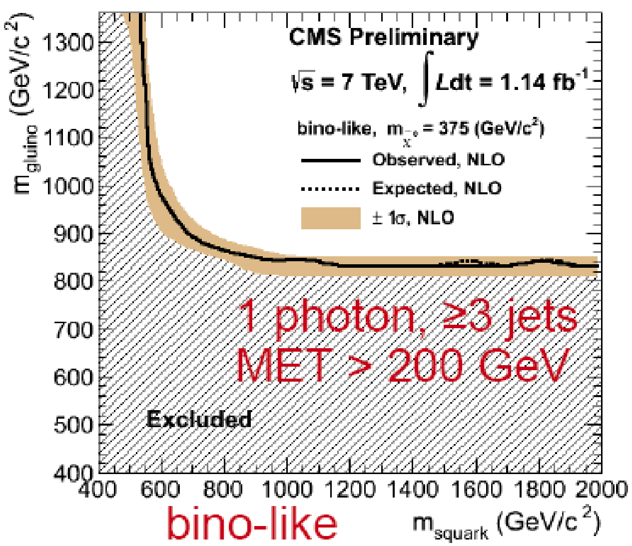
NLSP type	$\gamma + 3\text{ jets} + E_T^{miss}$	$\gamma\gamma + \text{jet} + E_T^{miss}$
Bino	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \text{jets} + \gamma + Z + \tilde{G}\tilde{G}$	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \text{jets} + \gamma\gamma + \tilde{G}\tilde{G}$
Wino	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \text{jets} + \gamma + Z + GG$ $\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^\pm \rightarrow \text{jets} + \gamma + W^\pm + \tilde{G}\tilde{G}$	$\text{jets} + \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \text{jets} + \gamma\gamma + \tilde{G}\tilde{G}$

$m(\chi_1^0) \approx m(\chi_1^\pm)$
co- NLSP's

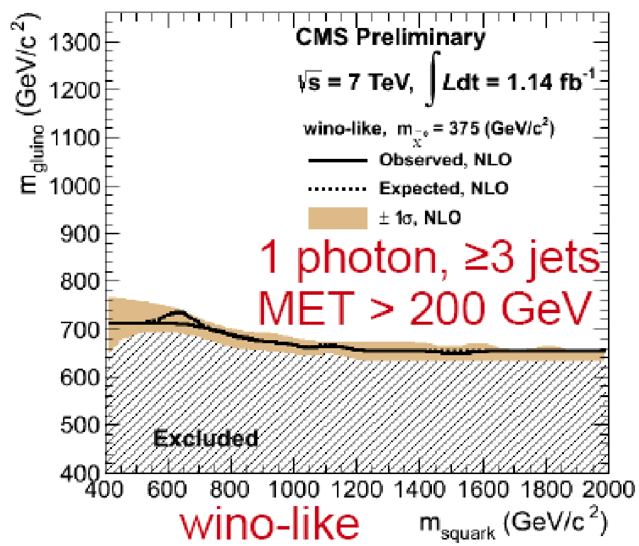


1γ, >=3 jets, MET> 200 GeV

NEW!



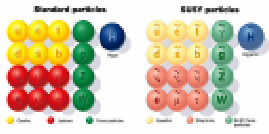
bino-like



wino-like

Supersymmetry: Summary

- SUSY in its most hoped for incarnation is starting to be in trouble
  - → Of course we will continue looking and increasing our reach
- What if SUSY were hiding? (e.g. no Missing E_T)
  - → "Split", "low-MET", "squashed", "mashed?"
  - → Even if very soft cascade at tree level, Initial State Radiation still creates MET, but this needs to be studied further
- With >1 fb^{-1}, other SUSY prod. mechanisms open up → exclusive chargino/neutralino and 3rd generation production

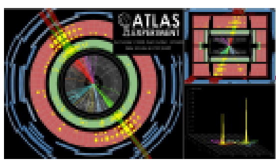


Supersymmetry (with MET)

- → Jets + MET
- → Lepton(s) + MET
- → 3rd generation + MET
- → Photon(s) + MET

Strong Gravity

- → Monojet
- → Monophoton
- → Dilepton spectrum
- → Black-hole



Heavy Resonances

- → Heavy gauge bosons
- → Diphoton
- → Dijet
- → Doubly-charged Higgs

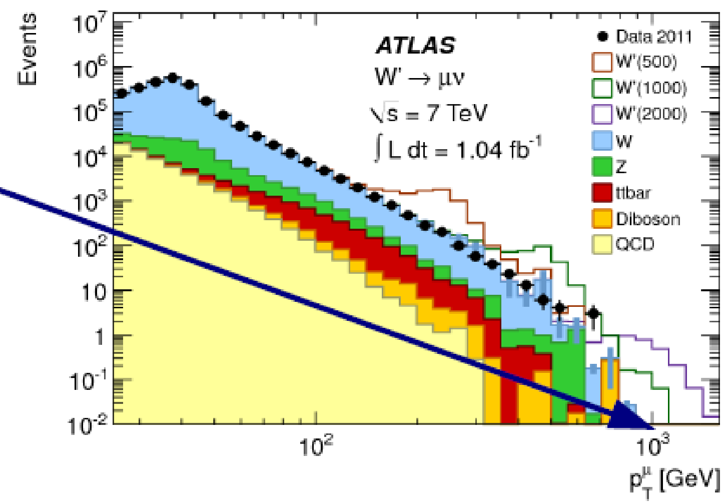
Long-Lived Particles

- → Displaced vertices
- → Slow particles
- → Out-of-time decays

Search for Heavy Resonance

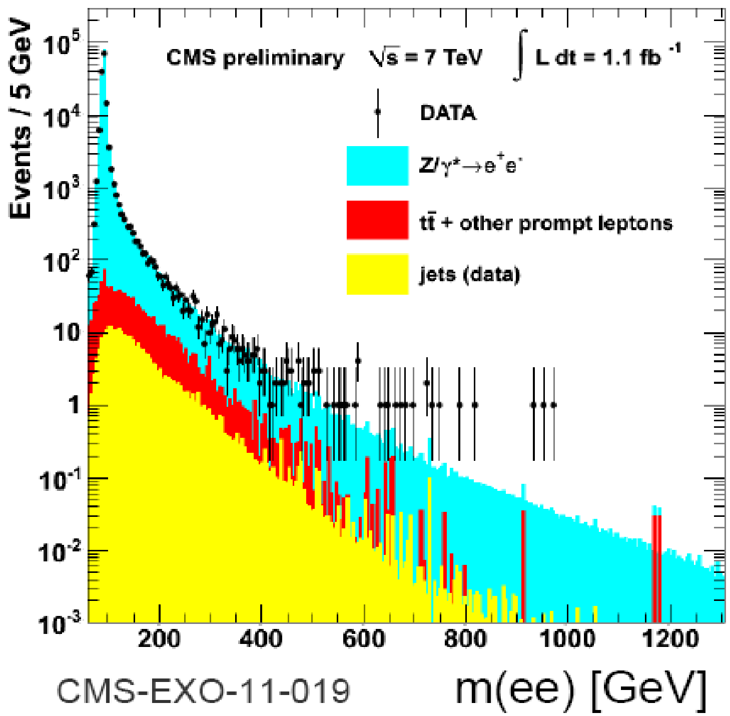
- Predicted by numerous extensions of the Standard Model:
  - → GUT-inspired theories, Little Higgs → heavy gauge boson(s) Z' (W')
  - → Technicolor → narrow technihadrons
  - → Randall-Sundrum ED → Kaluza-Klein graviton
- Experimental challenge: understand detector performance (resolution, efficiency) for a signal with (almost) no control sample at very high momentum → confidence in alignment, simulation, etc...
- Electrons and muons:

  Rapidly approaching 1 TeV!

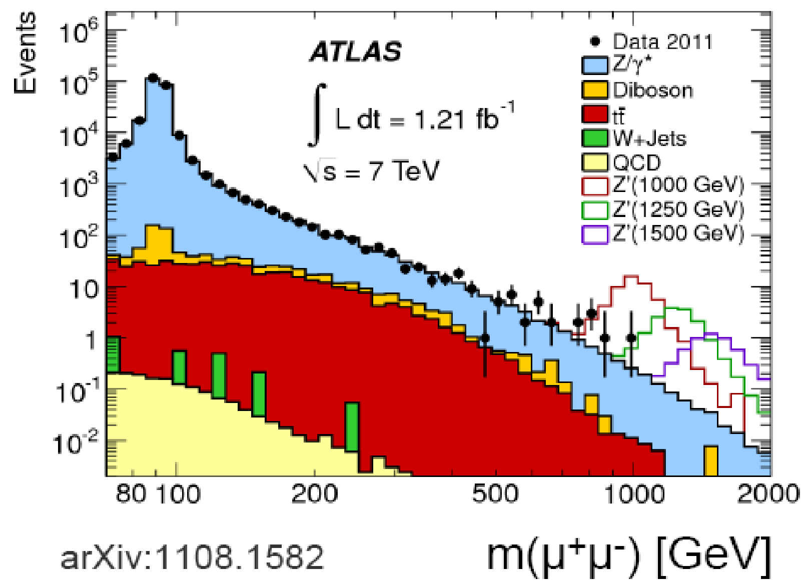


Search for Heavy Resonance: dilepton channel

- Randall-Sundrum KK graviton excitation
- Neutral heavy gauge boson
- Technihadron



CMS-EXO-11-019



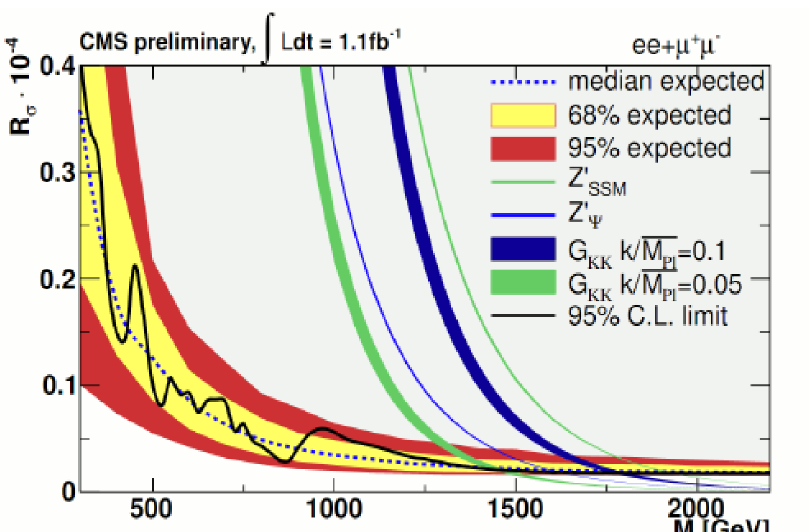
arXiv:1108.1582

Search for Heavy Resonance: dilepton channel

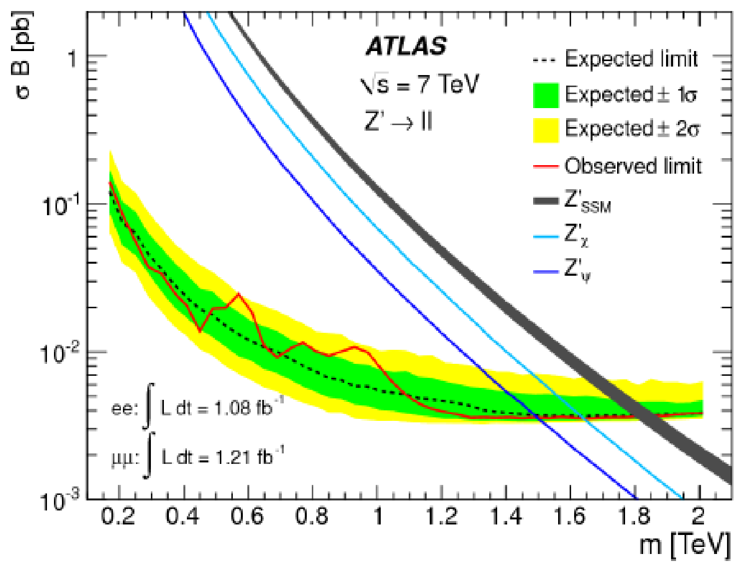
- Randall-Sundrum KK graviton excitation
- Neutral heavy gauge boson
- Technihadron

Sequential SM:
m(Z') > 1.9 TeV at 95% C.L.

RS graviton (k/M_{Pl} = 0.1):
m(G) > 1.8 TeV at 95% C.L.



CMS-EXO-11-019

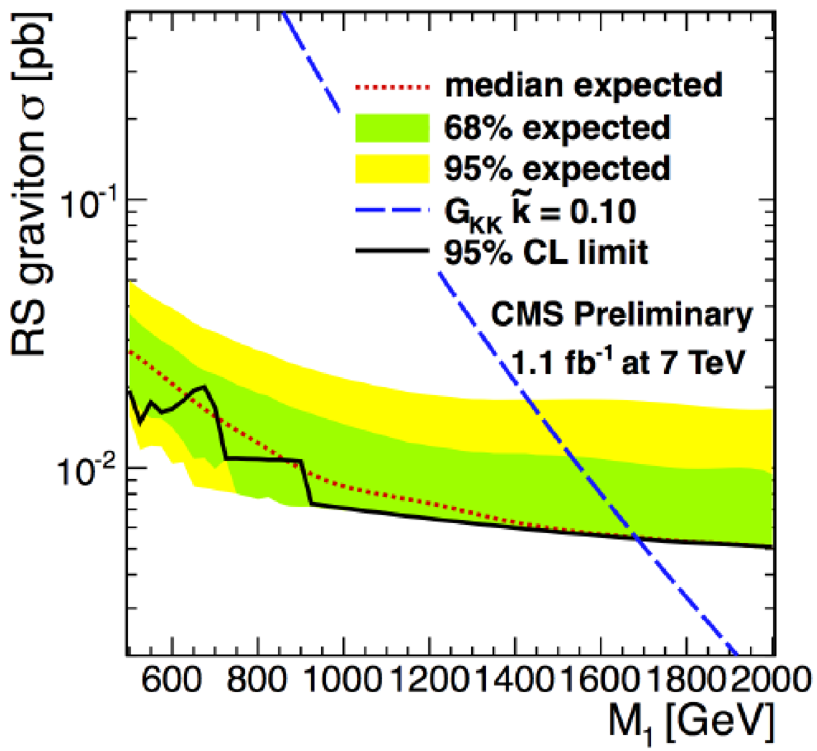


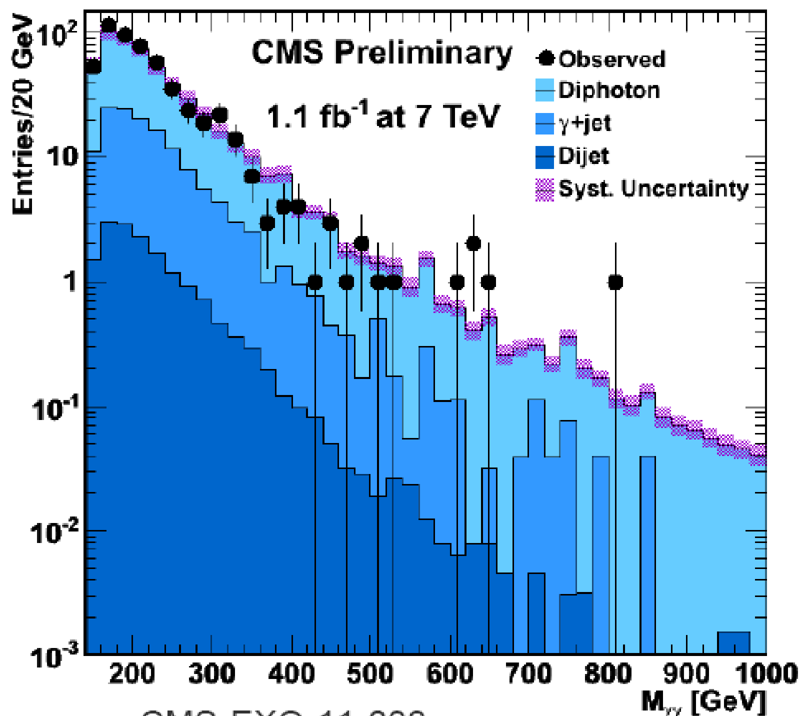
arXiv:1108.1582

Search for Heavy Resonance: diphoton channel

- Randall-Sundrum KK graviton excitation

RS graviton (k/MPl = 0.1): m(G) > 1.7 TeV at 95% C.L.





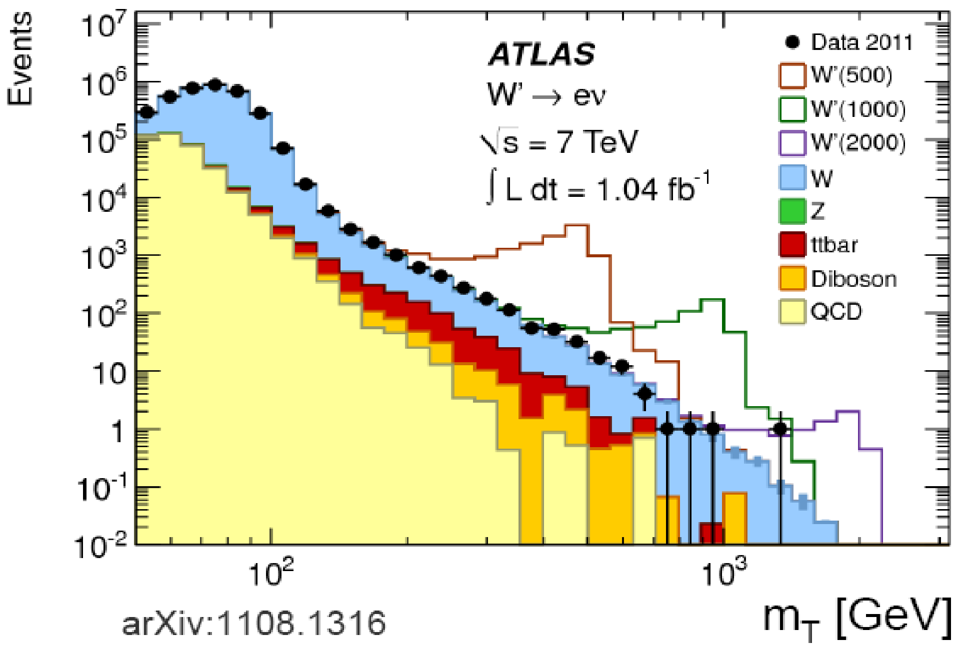
CMS-EXO-11-038

Search for Heavy Resonance: W' → lν

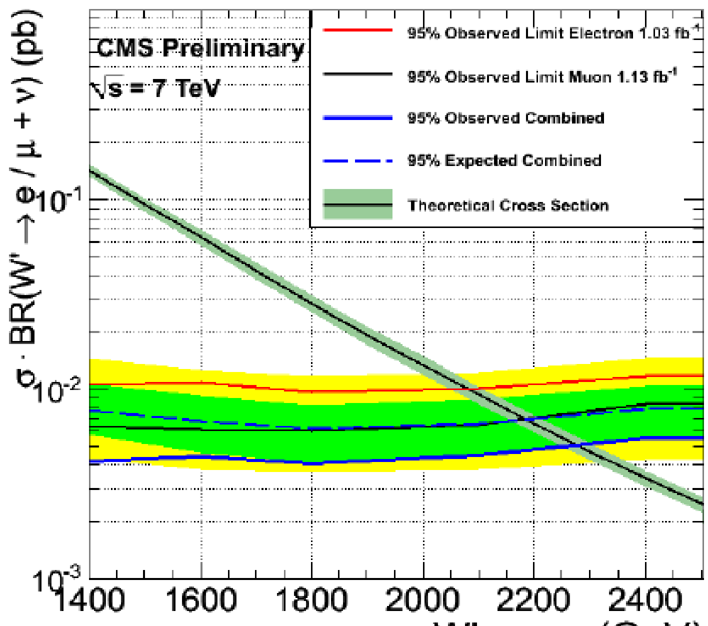
- Heavy charged gauge boson
- Technirho, Little Higgs
- 1 lepton + Missing E_T
- Look for Jacobian peak

$$m_T = \sqrt{2 p_T \not{E}_T (1 - \cos\Delta\phi_{\ell,\not{E}_T})}$$

Sequential SM:
m(W') > 2.3 TeV at 95% C.L.



arXiv:1108.1316



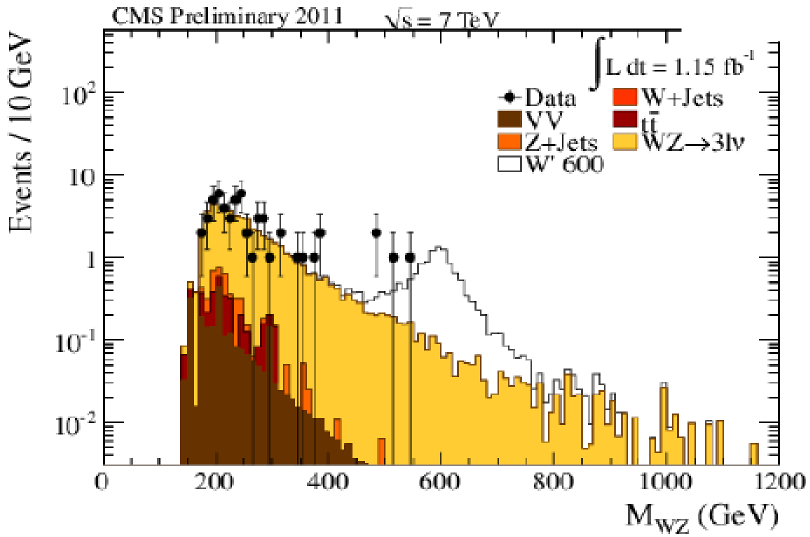
CMS-EXO-11-024

Search for Heavy Resonance: WZ

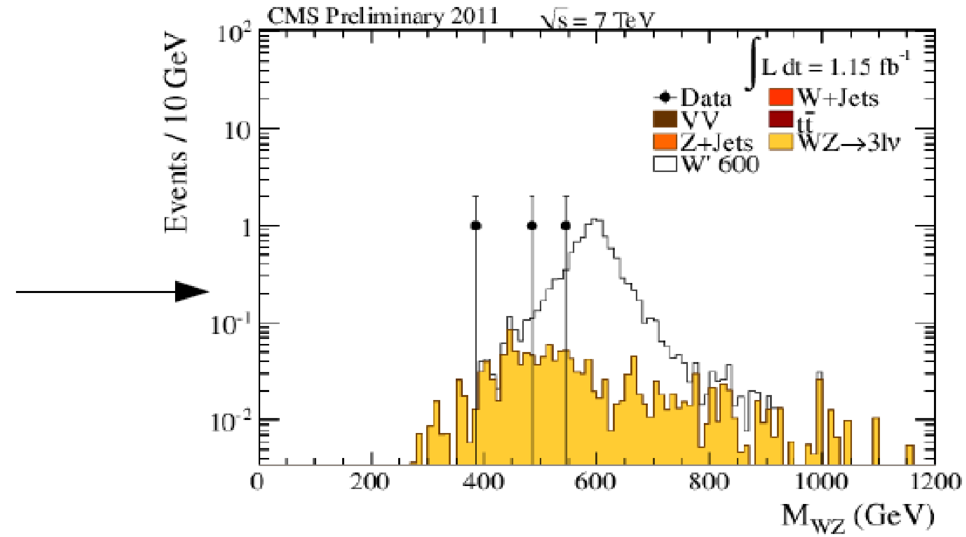
- W' or $\rho_{TC} \rightarrow WZ$
- All-leptonic channel:

  $W \rightarrow l^{\pm}\nu$ and $Z \rightarrow l^{+} l^{-}$

- Reconstruct m(WZ) by constraining $m(l^{\pm}\nu)$ to m_W



Pre-selection



Final selection

CMS-EXO-11-041

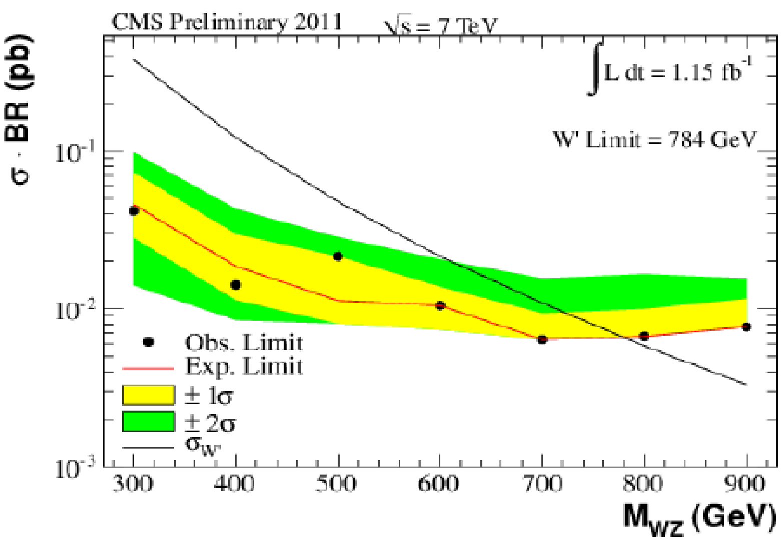
Search for Heavy Resonance: WZ

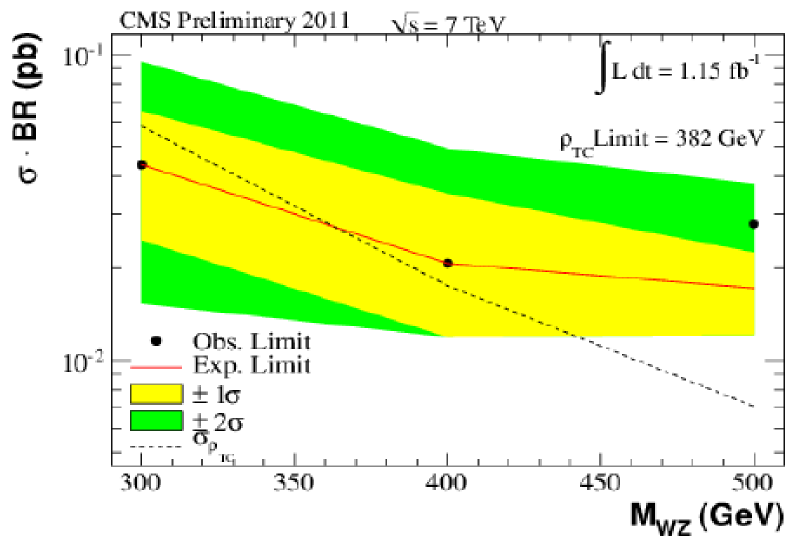
- W' or $\rho_{TC} \rightarrow WZ$
- All-leptonic channel:

  $W \rightarrow l^{\pm}\nu$ and $Z \rightarrow l^{+} l^{-}$

Sequential SM:
m(W') > 784 GeV at 95% C.L.

Technicolor:
ρ_{TC} > 382 GeV at 95% C.L.





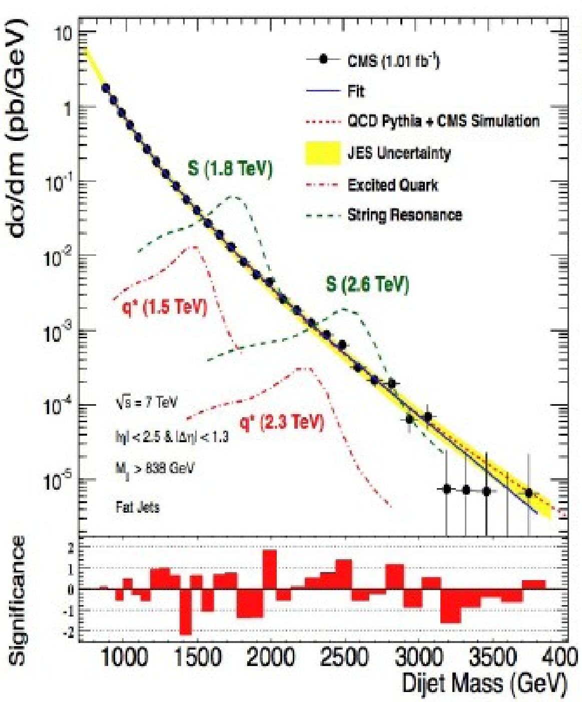
CMS-EXO-11-041

Search for Heavy Resonance: Dijet

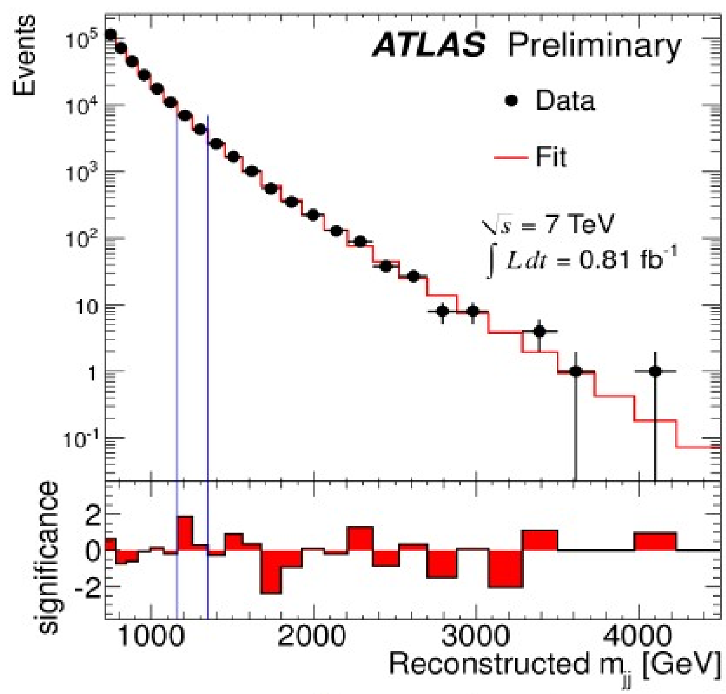
- Excited quarks, strong gravity, contact interaction
- Look for resonance above phenomenological fit of the data

Probing the quark structure beyond 4 TeV

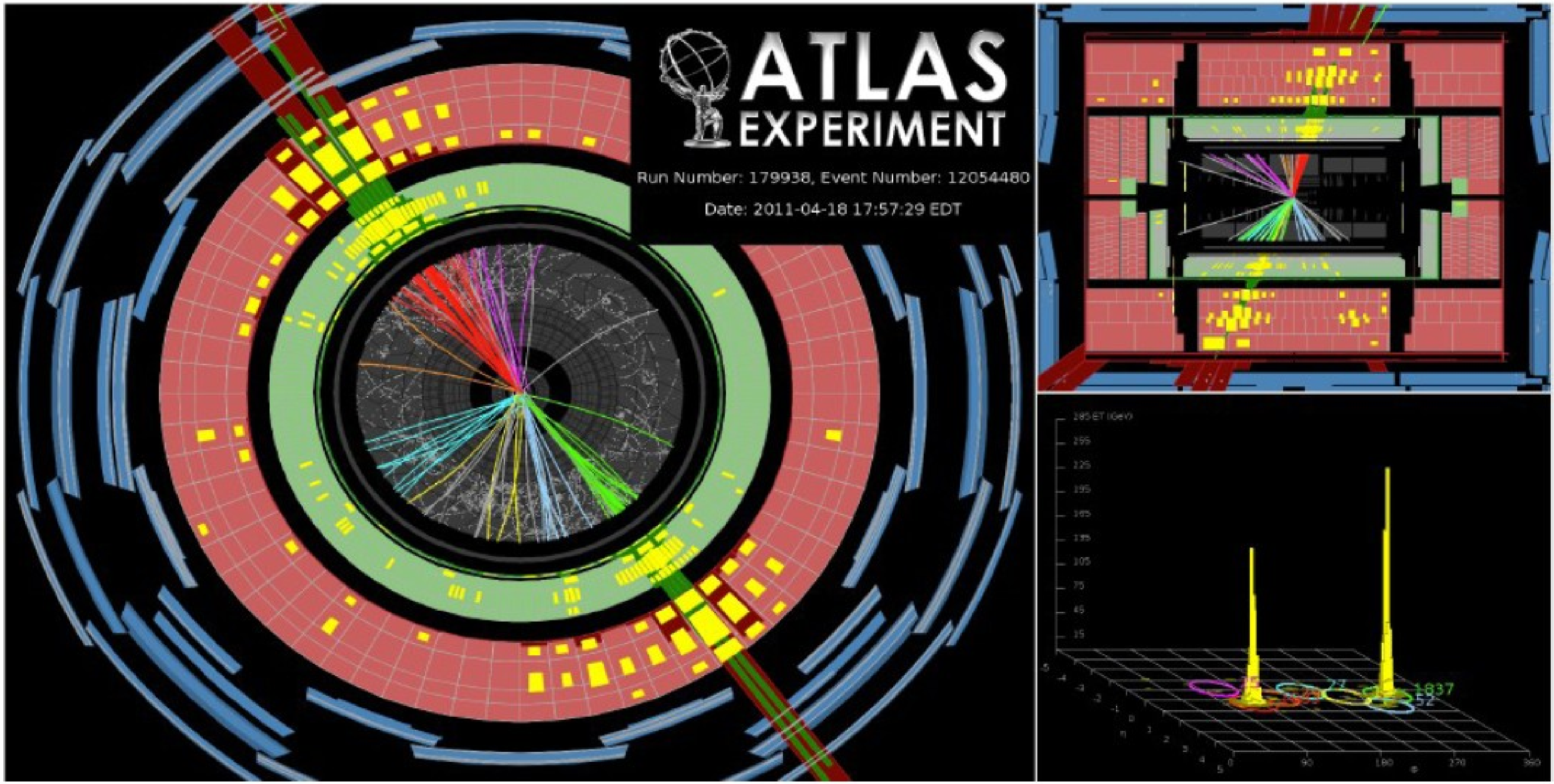
arXiv.1107.4771



ATL-CONF-2011-095



Search for Heavy Resonance: Dijet



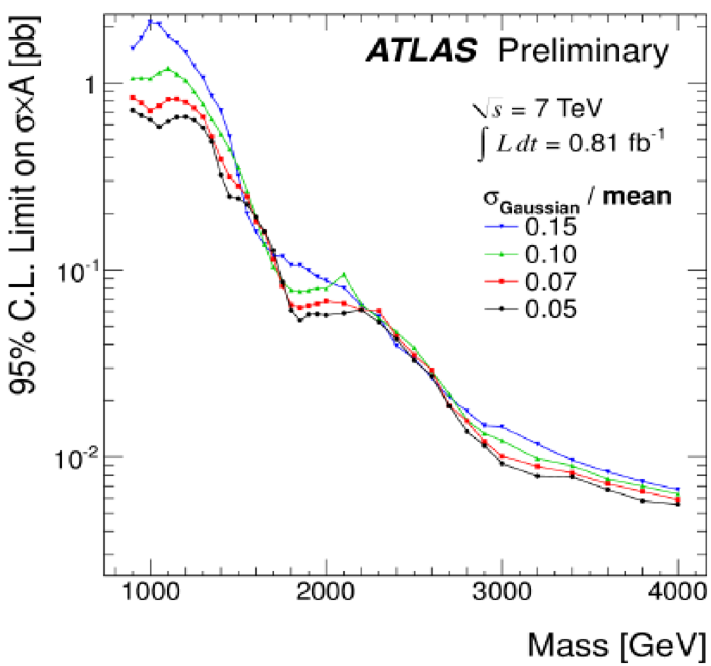
m(jet-jet) = 4.0 TeV **Missing E_T = 100 GeV**

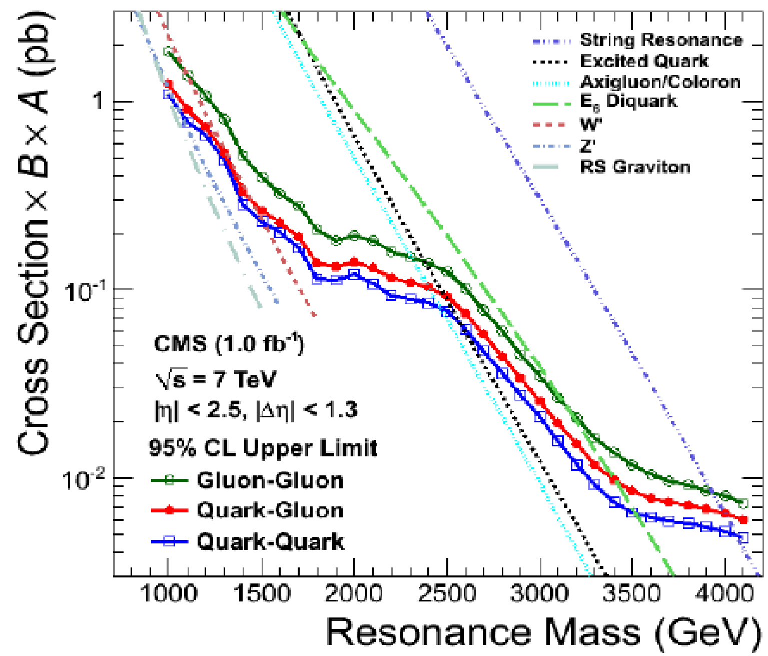
Search for Heavy Resonance: Dijet

Model ATL-CONF-2011-095	95% CL Limits (TeV) Expected	 Observed
Excited Quark q^*	2.77	2.91
Axigluon	3.02	3.21
Color Octet Scalar	1.71	1.91

Model CMS arXiv.1107.4771	Excluded Mass (TeV) Observed	 Expected
String Resonances	4.00	3.90
E_6 Diquarks	3.52	3.28
Excited Quarks	2.49	2.68
Axigluons/Colorons	2.47	2.66
W' Bosons	1.51	1.40

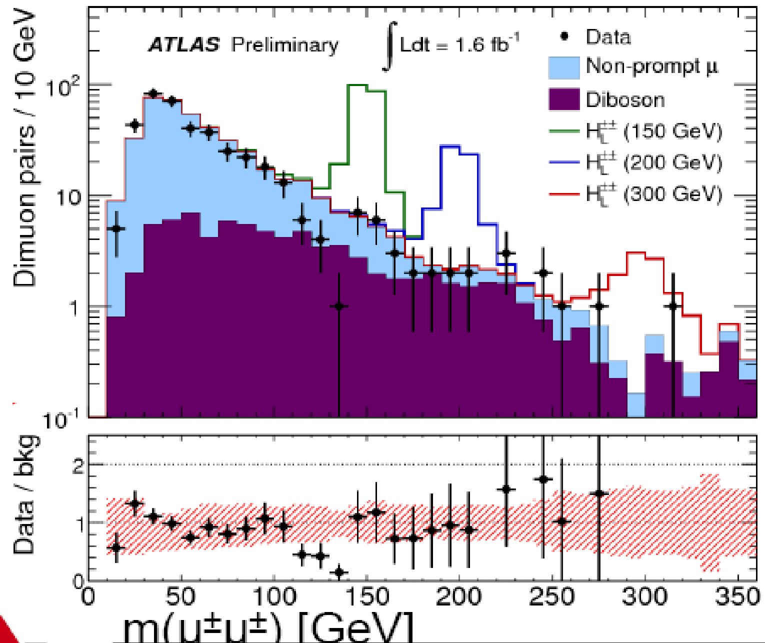
- Also providing model-independent limits:





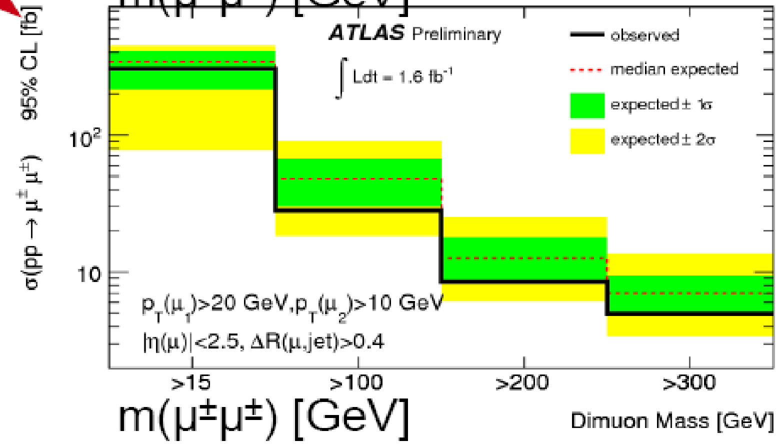
Search for ~~Heavy Resonance~~ Inclusive search: Same-Sign Dilepton

- Predicted by many models
- Very clean signature
- Inclusive, model-independent search:
  - Fiducial cross-section limit as function of m(μ±μ±)



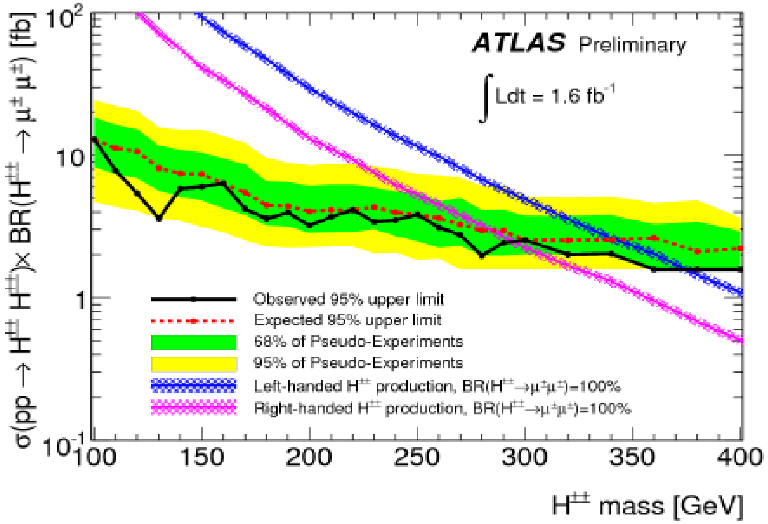
Mass range [GeV]	95% C.L. limit on dimuon pair σ [fb]	
	expected	observed
$m_{\mu\mu} > 15$ GeV	341^{+67}_{-125}	304
$m_{\mu\mu} > 100$ GeV	48^{+20}_{-18}	28
$m_{\mu\mu} > 200$ GeV	$12.6^{+5.3}_{-4.2}$	8.5
$m_{\mu\mu} > 300$ GeV	$7.0^{+2.5}_{-2.0}$	5.0

ATL-CONF-2011-126



Search for Heavy Resonance: Same-Sign Dilepton

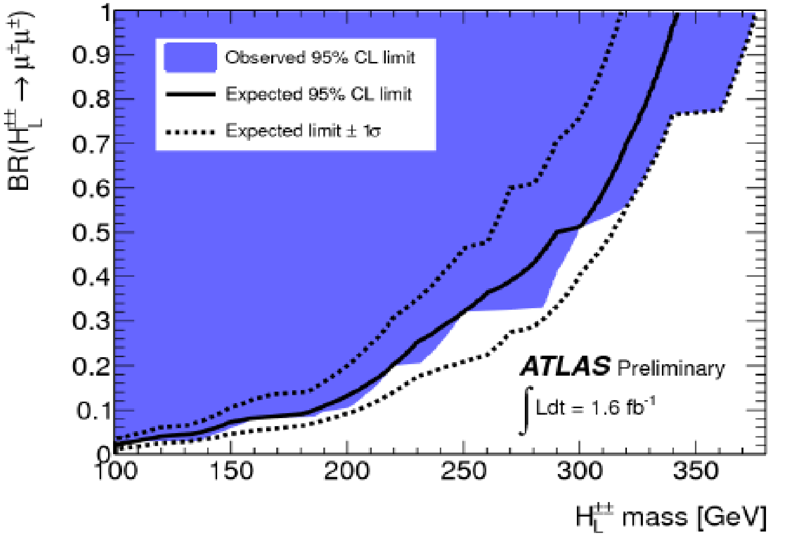
- Doubly-charged Higgs search
  - → based on same analysis as inclusive search
  - → window 10% around Higgs mass



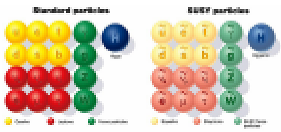
Assuming $BR(\mu^\pm\mu^\pm) = 100\%$:

$m(H_L) > 375$ GeV (exp. 342 GeV)

$m(H_R) > 295$ GeV (exp. 286 GeV)



ATL-CONF-2011-127

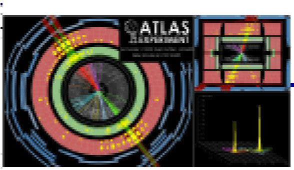


Supersymmetry (with MET)

- → Jets + MET
- → Lepton(s) + MET
- → 3rd generation + MET
- → Photon(s) + MET

Strong Gravity

- → Monojet
- → Monophoton
- → Dilepton spectrum
- → Black-hole



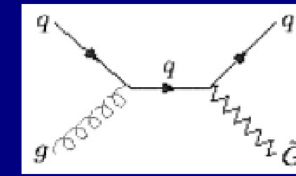
Heavy Resonances

- → Heavy gauge bosons
- → Dijet
- → Diphoton
- → Right-handed W
- → Doubly-charged Higgs

Long-Lived Particles

- → Displaced vertices
- → Slow particles
- → Out-of-time decays

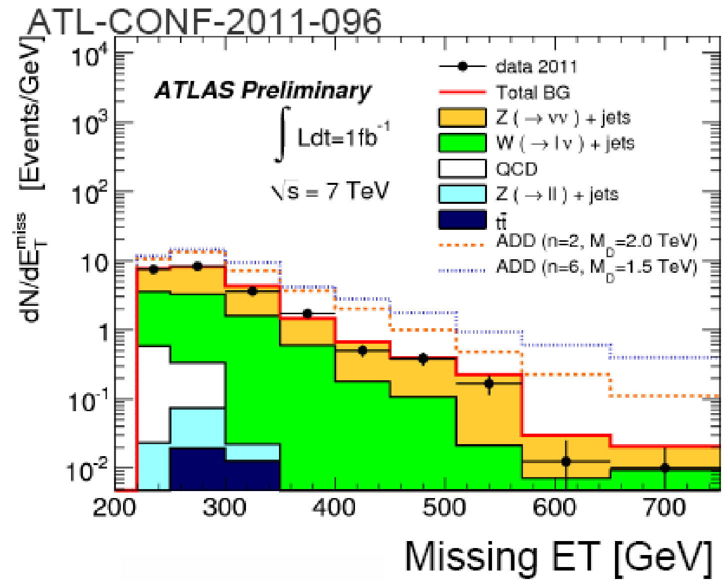
Search for Monojets

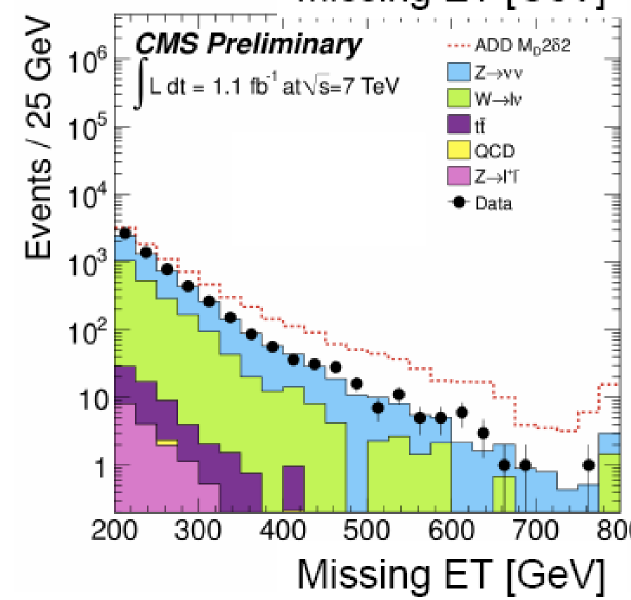


- **Large Extra-D (ADD):**
  - → Brings the Plank scale down to the TeV scale:

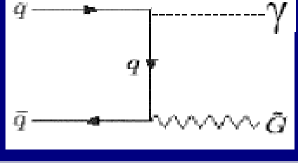
$$M_{Pl}{}^2 \sim M_D{}^{2+n} R^n$$

  - → Graviton escapes detector
- **Also Split SUSY**
- **Look for a jet and ~ nothing else**
- **Challenge:**
  - → Instrumental background
  - → Understanding Z(→ νν) + jets





Search for Monophoton

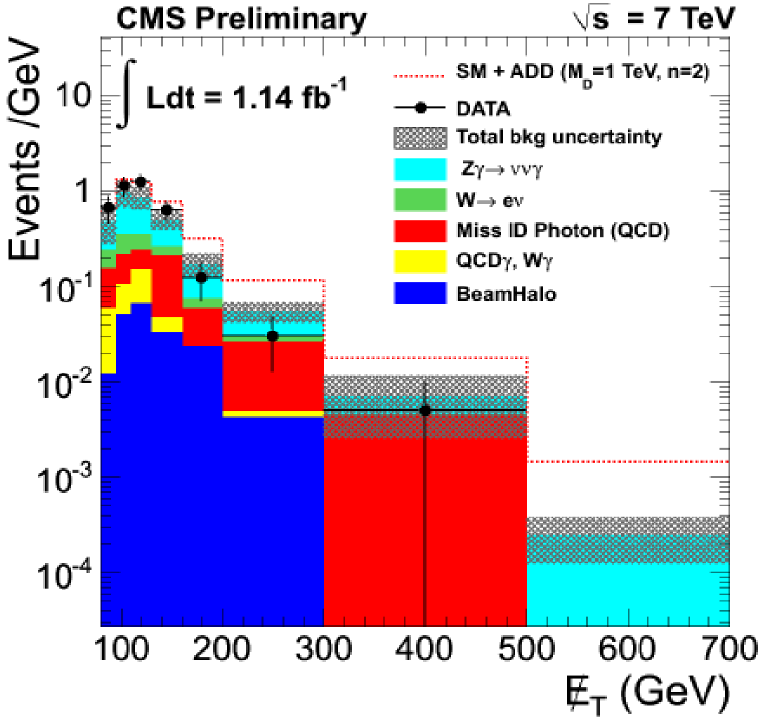


- Large Extra-D (ADD):
  - → Graviton escape detector
- Similarly to monojet:

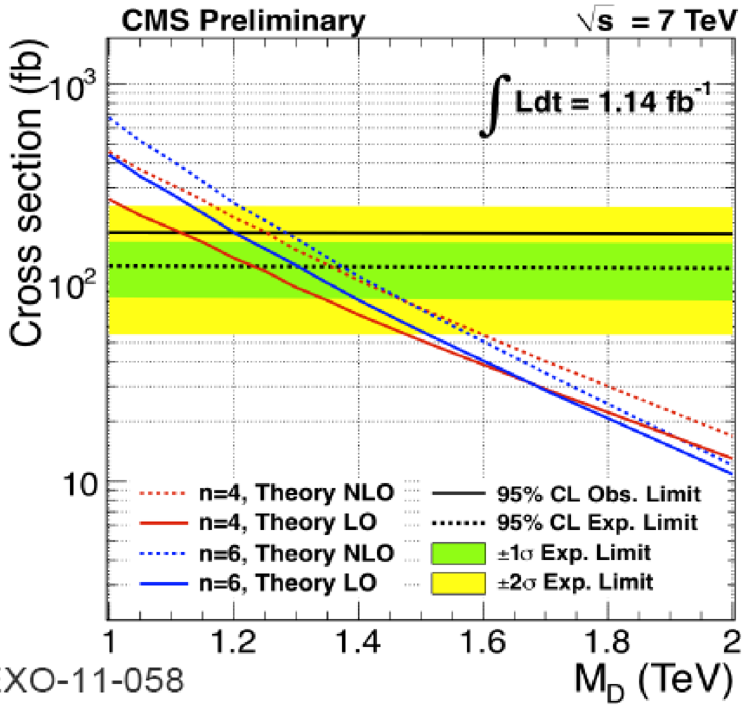
  Look for a photon and ~ nothing else

For n = 2-6:

M_D > 1.25 – 1.31 TeV



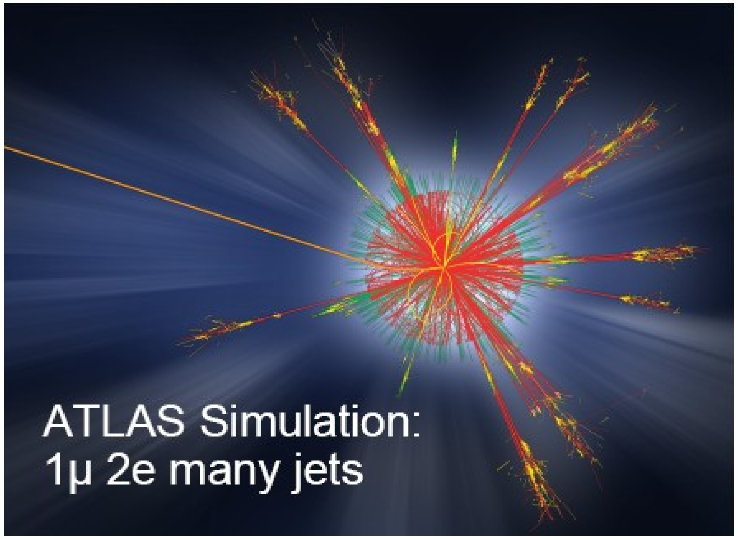
NEW!

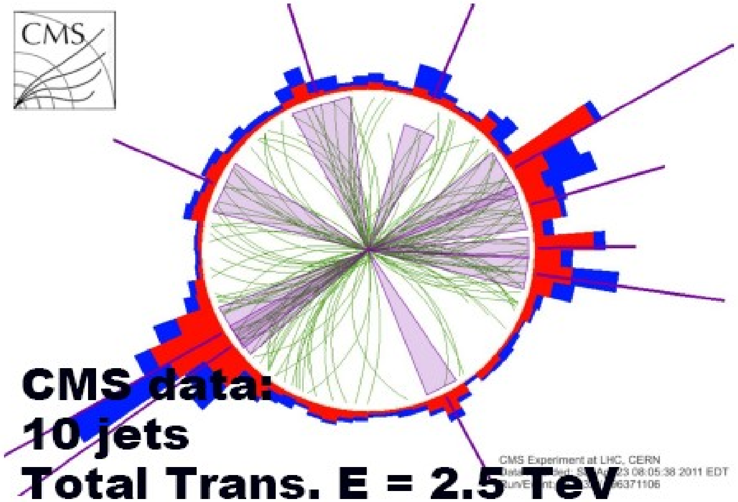


CMS-EXO-11-058

Black Holes: Multi-Object, Multi-Jets, Same-Sign

- Microscopic black-holes decaying through Hawking radiation
- Large uncertainty on models due to our ignorance of quantum gravity
- Semi-classical models only for m(B.H.) >> m(threshold)
- A safe bet: decay is democratic and isotropic. Likely large multiplicity of particles → **look for (many) jets and leptons at high mass**





Conclusion and Outlook

- Thanks to the LHC for delivering so well and so fast

  An impressive number of results from ATLAS and CMS
- Unfortunately, New Physics was not “around the corner”
- Experimental challenges as we enter further the Multi-TeV world:
  - → TeV leptons
  - → Boosted objects (W, top)
  - → Investigate less obvious signatures
- It's only the beginning!

	Lower Limit (95% C.L.)
SUSY ($m_{\tilde{q}} = m_{\tilde{g}}$)	1 TeV
Gauge bosons (SSM)	2 TeV
Excited quark	3 TeV