Exotics Searches in Jet Final States with the ATLAS Detector

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Outline, Motivation

- Jet signatures probe the highest energies directly accessible at the LHC
- Test popular models like those with extra dimensions

- Model-independent, signature-based, searches for new physics
- Limits set on particular models including
  - Dijet resonances
  - Extra Dimensions, strong gravitational scenarios (ADD, black holes)
  - Compositeness models (e.g. excited quarks) and contact interactions
  - Model-independent limits

- Multi-jet searches (≥ 5 jets)
- Dijet searches (≥ 2 jets)
- Monojet searches (== 1 jet)

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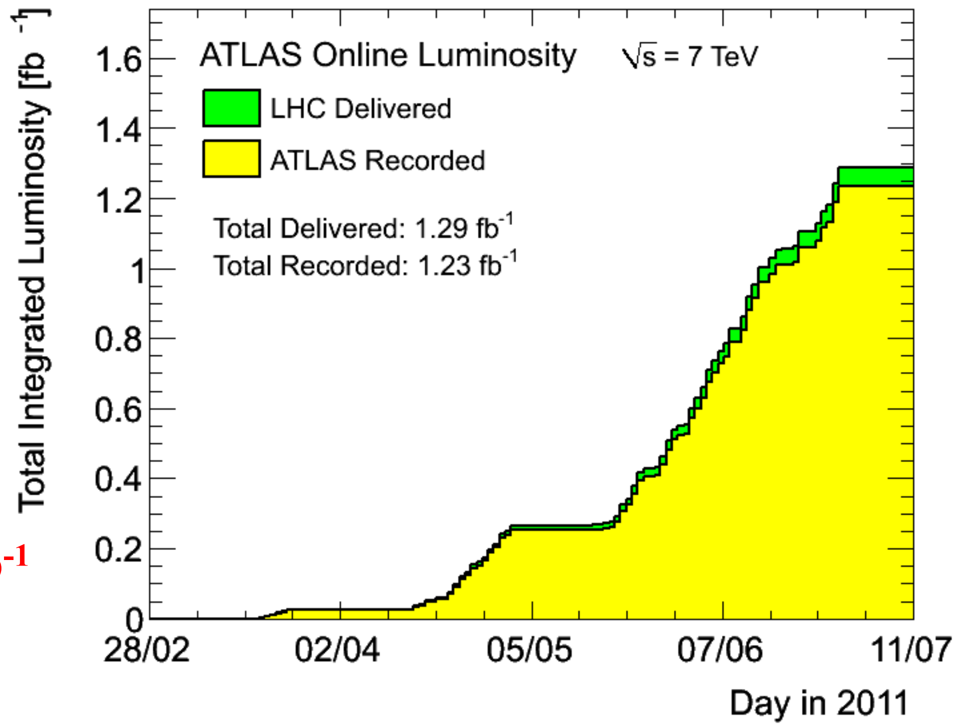
- **Monojet searches (== 1 jet)**

New results:
Presented for the first time, today!

LHC and ATLAS Operations

- 2010: A solid start to physics operations
  - ATLAS papers with e.g. 36 pb^{-1}
- LHC has continued remarkable performance in 2011
- ATLAS subdetectors record good quality data
- ATLAS and LHC operations have already supported excellent physics in 2011
  - **Brand new results with 0.81 and 1.0 fb^{-1}**



Subdetector fraction of good data for 593 pb^{-1} recorded

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.

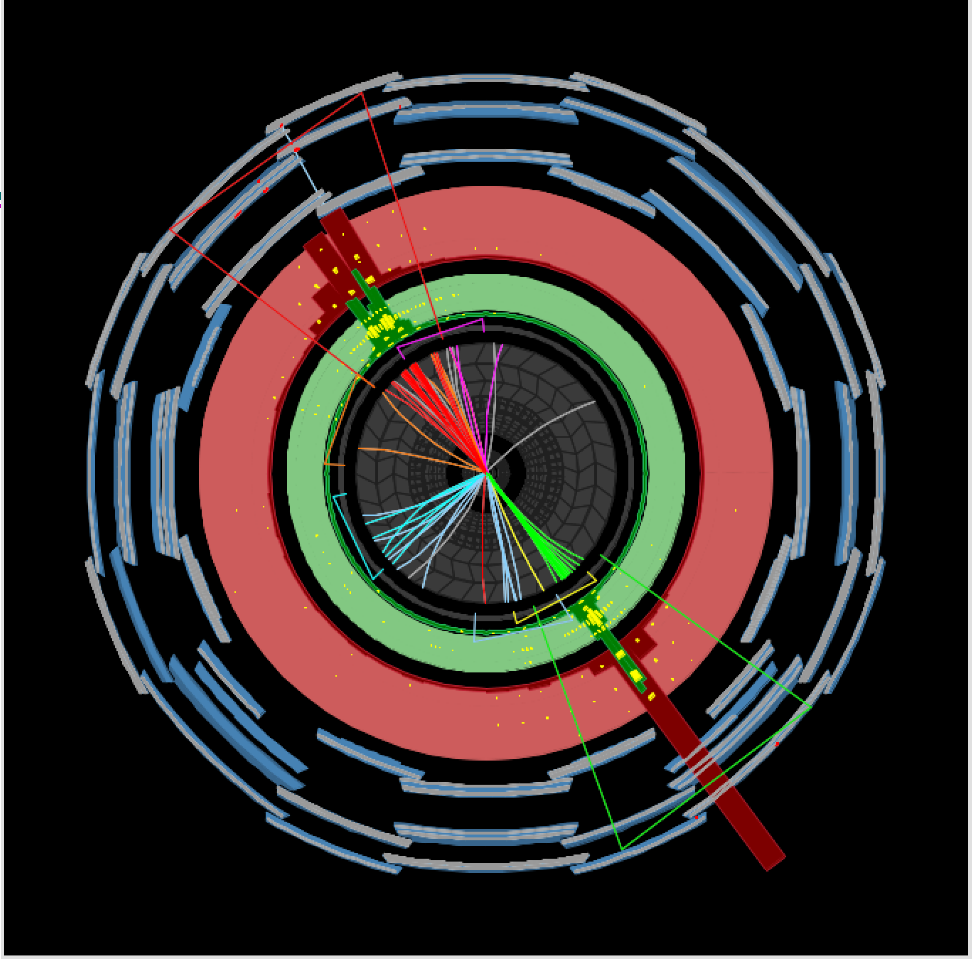
Very high energy jet event

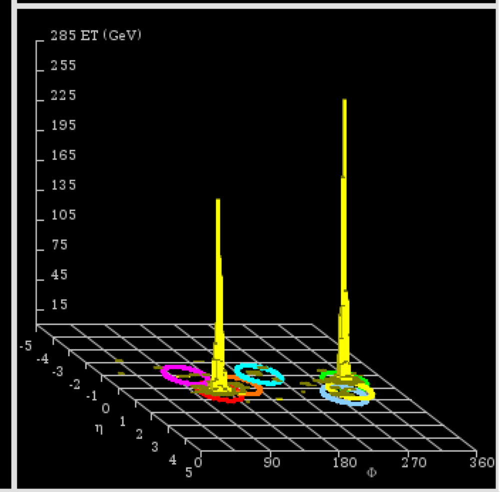
m_{jj} = 4040 GeV

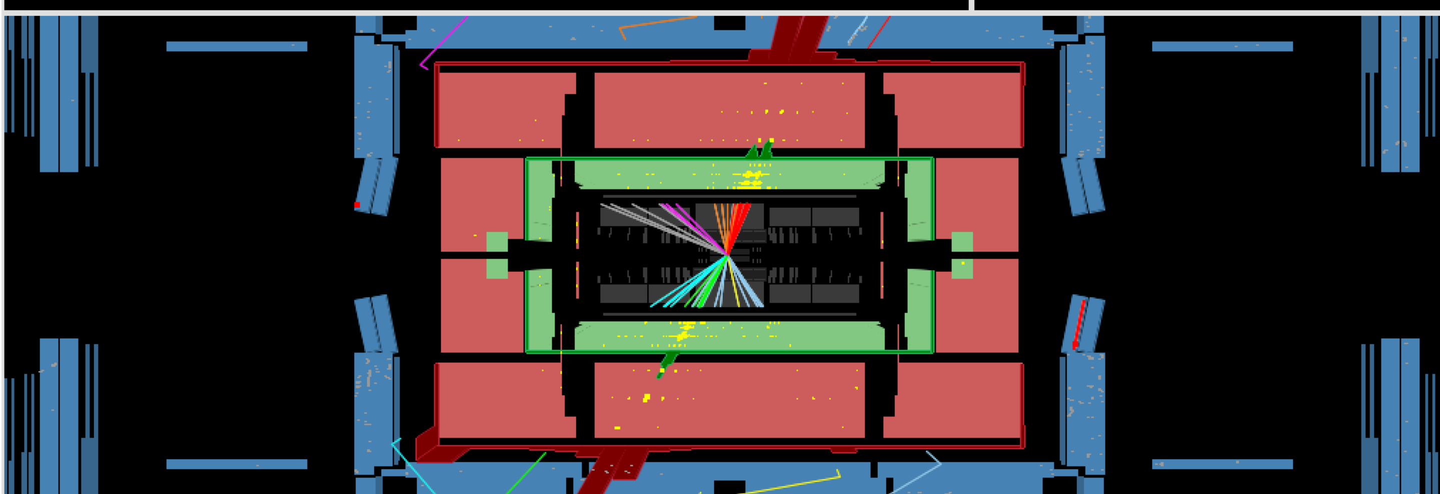
p_T^{j1} = 1850 GeV

p_T^{j2} = 1840 GeV

ATLAS-CONF-2011-081

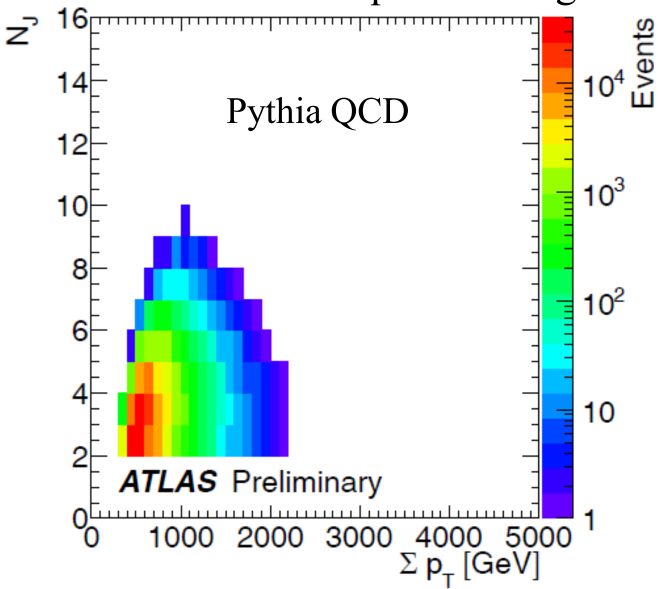






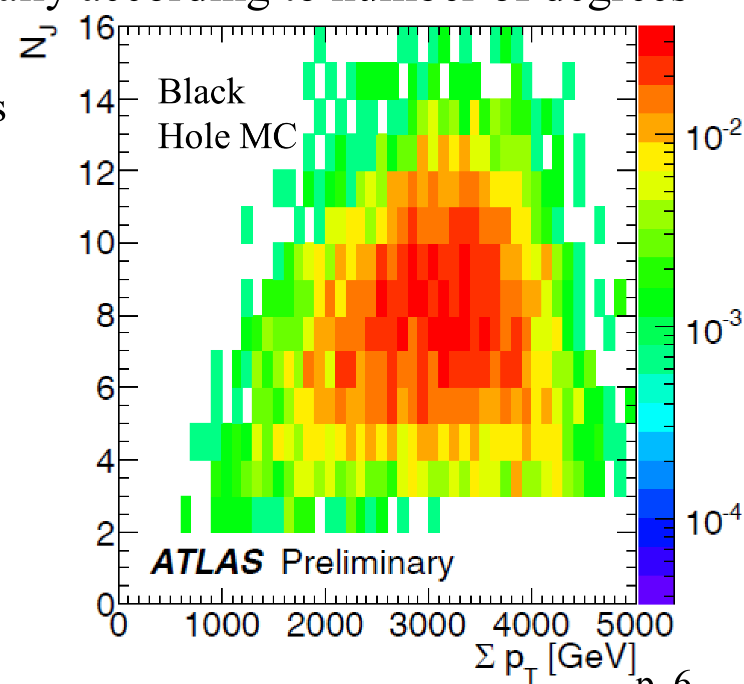
Search in Multi-Jet Final State: Black Holes?

- What if the Planck scale is approximately the same as the EW scale?
  - Large, flat, extra dimensions can allow it (ADD)
  - Gravity can become strong at the TeV scale, perhaps we'll abundantly produce microsopic black holes at the LHC
- Assume classical black hole production, and semi-classical decays
  - (For this analysis.) Expected to hold well above the reduced Planck scale, M_D.
    - We set the signal cross section to zero below a threshold mass $M_{th} > M_D$.
  - Black hole quickly evaporates, decaying democratically according to number of degrees of freedom
    - Lots of quarks and gluons (jets), also all other particles

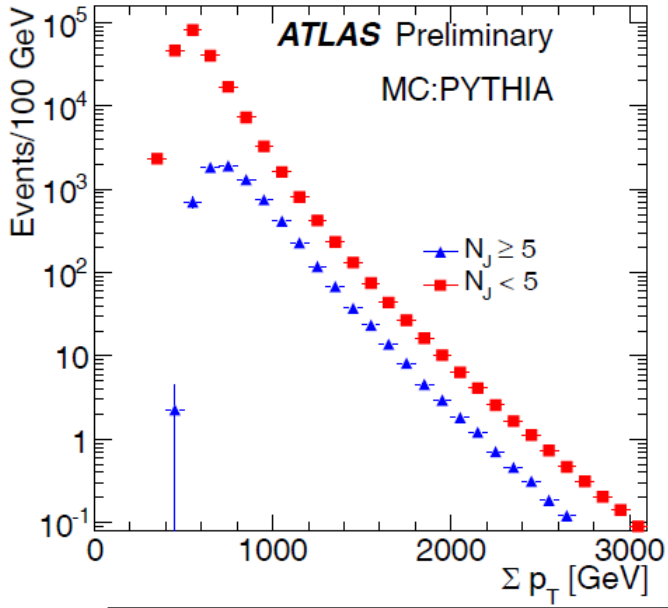


QCD peaks at low numbers of jets (N_J), and low Σp_T

Black hole scenarios peak at high N_J and high Σp_T (here Blackmax M_D = 1 TeV, M_{th} = 4.3 TeV, n = 2 extra dimensions)



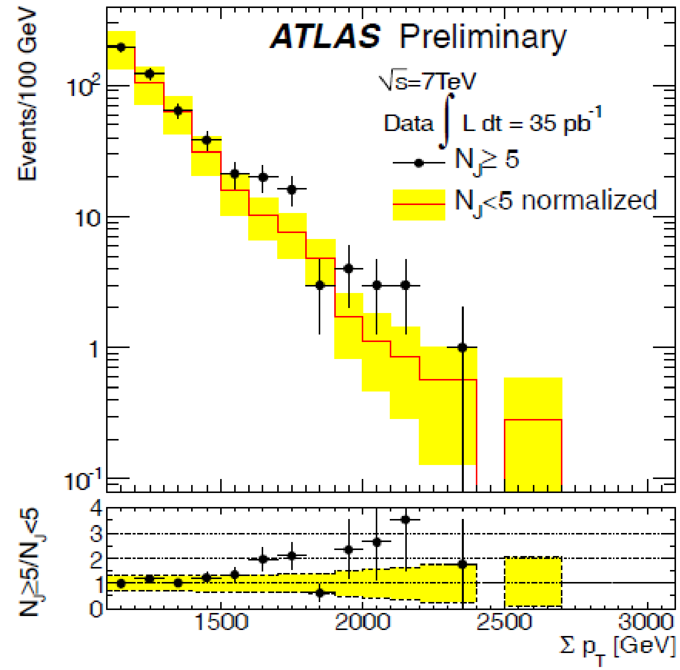
Multi-Jet **Search**: New Physics? Or Set Limits

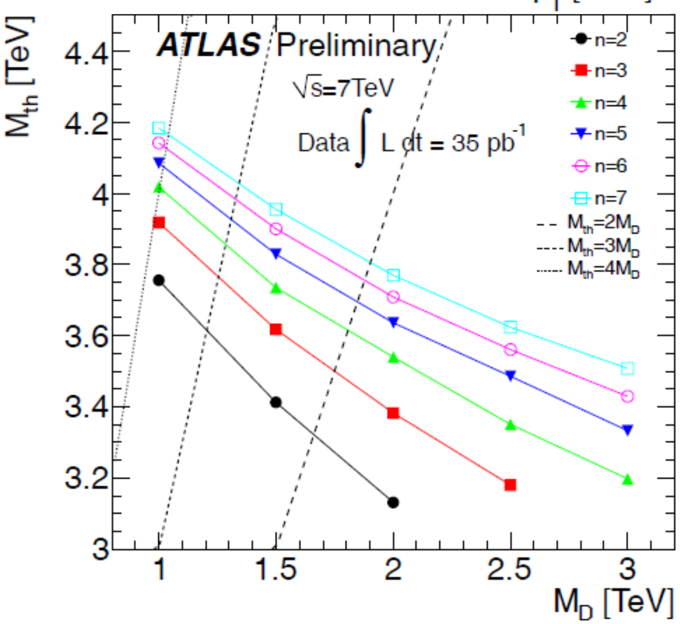


Require $E_T^{j1} > 250$ GeV for good trigger efficiency

For N_J, count jets with $p_T > 50$ GeV

To good approximation, the shape of Σp_T is the same in QCD for $N_J < 5$ and $N_J \geq 5$.





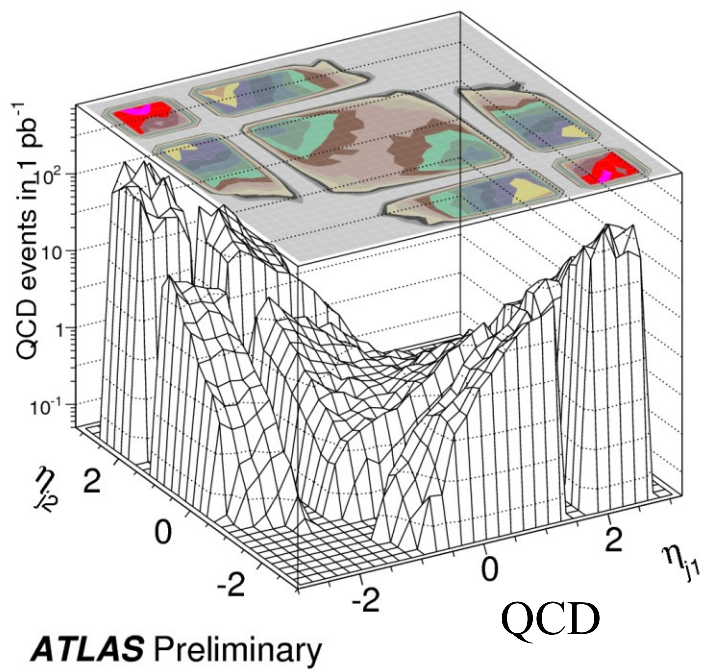
- Use 1.1 TeV < Σp_T < 1.2 TeV region for normalization, then compare the $N_J < 5$ shape to $N_J > 5$ data
- Predict number of events in **signal region: $N_J \geq 5$, $\Sigma p_T > 2$ TeV**
  - 3.7 ± 1.0 (stat) ± 1.1 (syst) compared to 7 data
  - Largest syst is 24% due to QCD modelling
- At **95% CL cross section × acceptance < 0.29 pb**
- Set model-dependent limits in M_D, M_{th}, n space

Searches with a Dijet Signature, and Some Nuts and Bolts

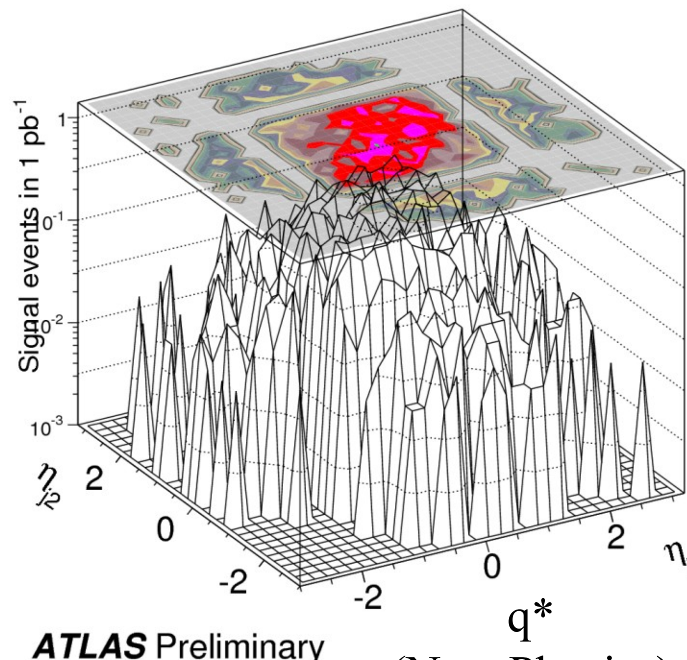
- Also perform sensitive searches for new physics at highest pt using dijet events
  - ≥ 2 jets, instead of ≥ 5
- Look for "bumps" in the m_{jj} distribution, and discrepancies in the dijet angular distributions
  - First published search for new physics at LHC, Phys. Rev. Lett. **105 (2010) 161801,** 315 nb^{-1}
- Results presented today with 36 pb^{-1}
  - New Journal of Physics **13 (2011)** 053044
- And **new results, for the Dijet Mass Distributions, with 0.81/fb**
  - ATLAS-CONF-2011-095
  - Expand on the experimental details for this latest search
- Require two high pt jets
  - Reconstructed with anti-k_T algorithm, R = 0.6
  - Calibrated with MC-derived p_T and η dependent function
  - Apply "cleaning cuts" to remove events affected by non-collision backgrounds
  - Require $|y_1 - y_2| < 1.2$ and $|\eta| < 2.8$ to suppress QCD
  - For jet trigger efficiency, require $m_{jj} > 717$ GeV (effectively, $p_T^{j2} > 150$ GeV)
- 2011 data-taking brings a few new challenges
  - Significant in-time and out-of-time pileup; modeled in MC and MC re-weighted to match data
  - Small hole in central EM calorimeter (6 front end boards, O[1%]) warrants fiducial cut

Importance of Dijet Angular Information

- Both the resonance search and the angular search **take advantage of the angular distribution of dijets in background (QCD, relatively forward)** vs. **many signal hypothesis (e.g. q*, relatively central)**
  - Resonance analysis cuts on $|y_1 - y_2| < 1.2$
  - Angular analysis analyzes the angular distribution
    - Or analyzes F_χ, the fraction of events with small $|y_1\text{-}y_2|$, in bins of m_{jj}



QCD



q*
(New Physics)

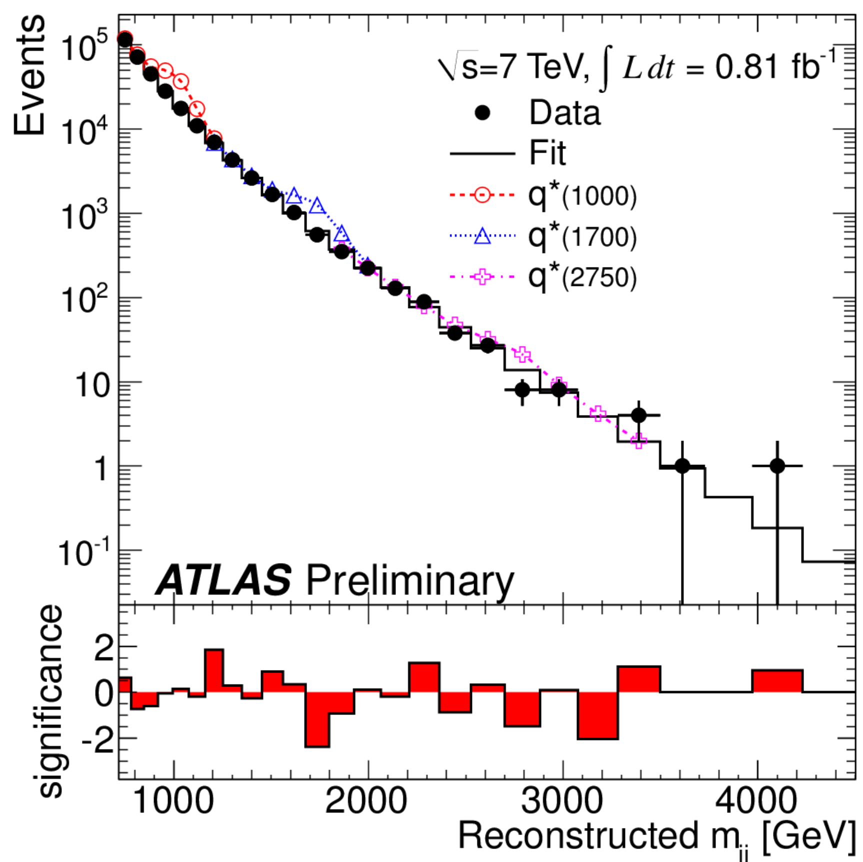
Dijet Resonance Search: Data and Background Fit

ATLAS-CONF-2011-095; 0.81 fb^{-1} of 2011 data

- Model-independent search for new physics
  - Do we see any bumps in m_{jj}, on top of a smooth background?
- Data fit well by the same QCD-compatible function in use for some time at the LHC and Tevatron

$$f(x) = p_1(1-x)^{p_2}x^{p_3+p_4 \ln x}$$

  - Use χ^2 test statistic, throw pseudo-experiments to evaluate p value in data, p = 0.35; reasonable background fit

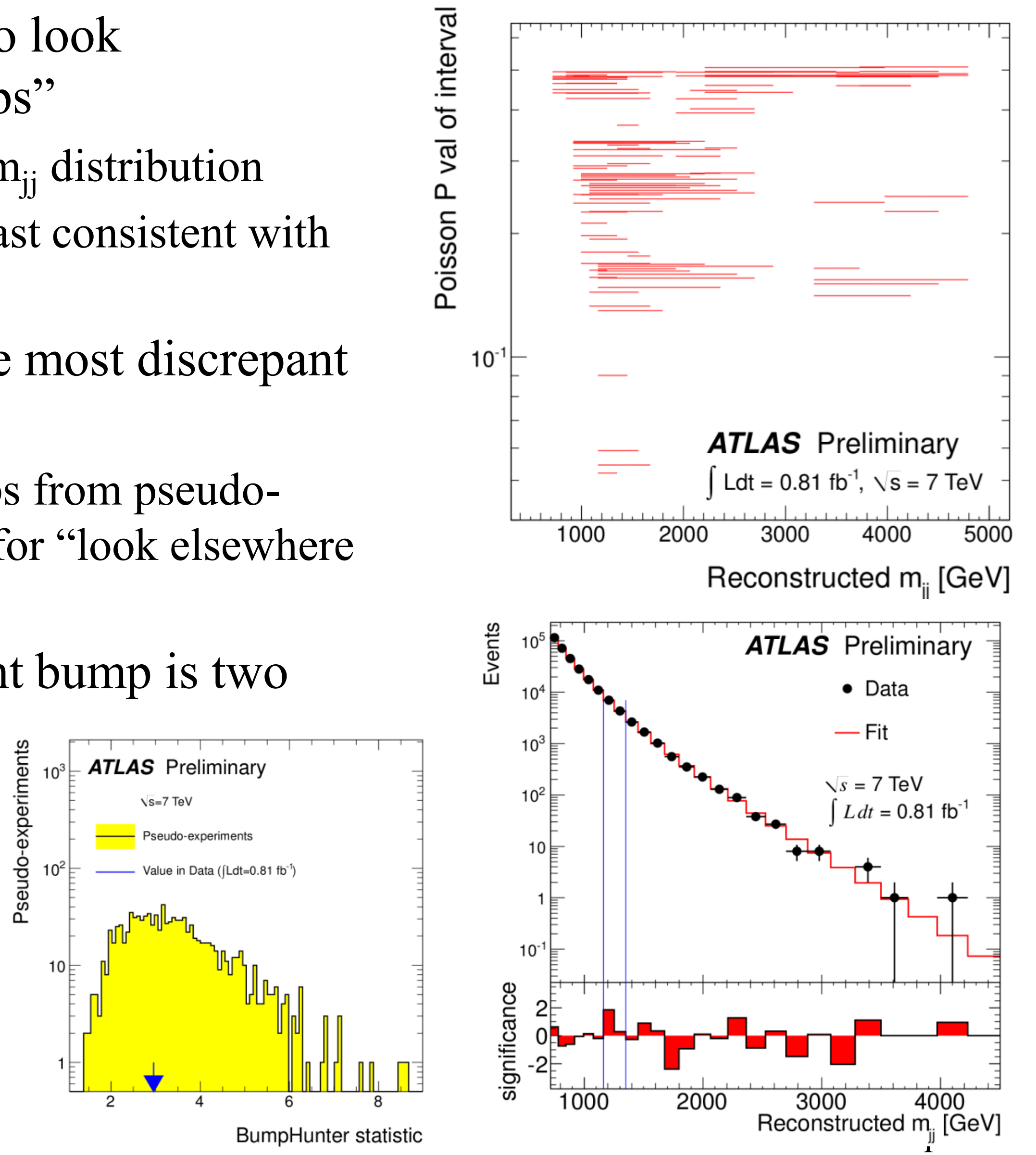


– Pseudo-experiments are Poisson fluctuations around background fit

- Can the fit absorb a signal?
  - Not easily, for a resonance
  - But, if $p < 0.01$ we exclude most discrepant region
  - Improves sensitivity, and greatly improves the fit if there's a large signal

Do we find a dijet resonance? Ask BumpHunter

- Use BumpHunter (arXiv:1101.0390) to look systematically for candidate "bumps"
  - Two bins to half the width of the m_{jj} distribution
  - Look for the candidate "bump" least consistent with smooth background
- Consider the Poisson p value of the most discrepant bump
  - Compare to most discrepant bumps from pseudo-experiments (PE's); thus account for "look elsewhere effect"
- In 2011 dataset, the most discrepant bump is two bins wide, 1162-1350 GeV
  - p value of 0.62
  - Perfectly likely to get a bump as significant from a Poisson fluctuation of smooth bkgrd
  - No evidence for new physics ☹

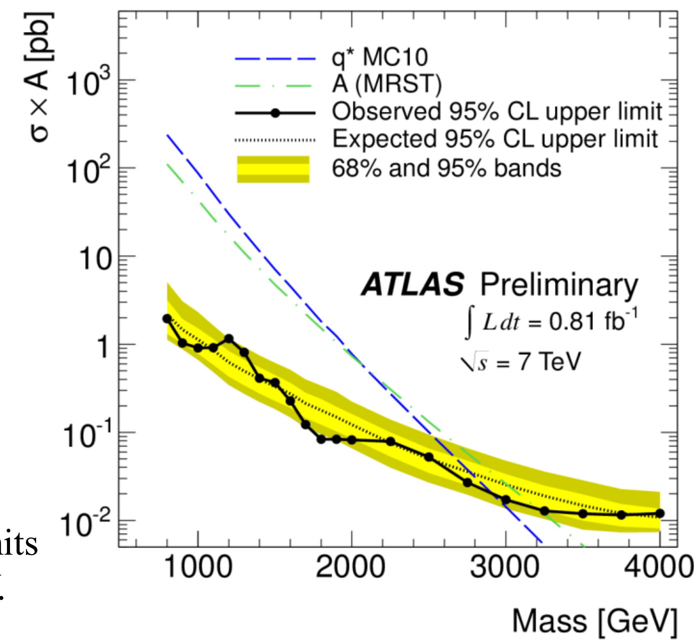


No Evidence for New Physics in Dijet Mass Distribution: Set Limits

- For the "limit setting phase" we have specific models in mind (one theory, with fixed parameters, e.g. 2 TeV q*)
- Signal events with full detector simulation for m_{jj} templates
  - Background fit for limit setting uses signal template on top of smooth background function
- Bayesian limits: prior flat in signal cross-section
- Set limits on various models
  - **q* and axigluon limits nearly 1 TeV better than best published limits**
  - New: scalar color octets
    - T. Han et al JHEP **12 (2010) 085**

Model	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

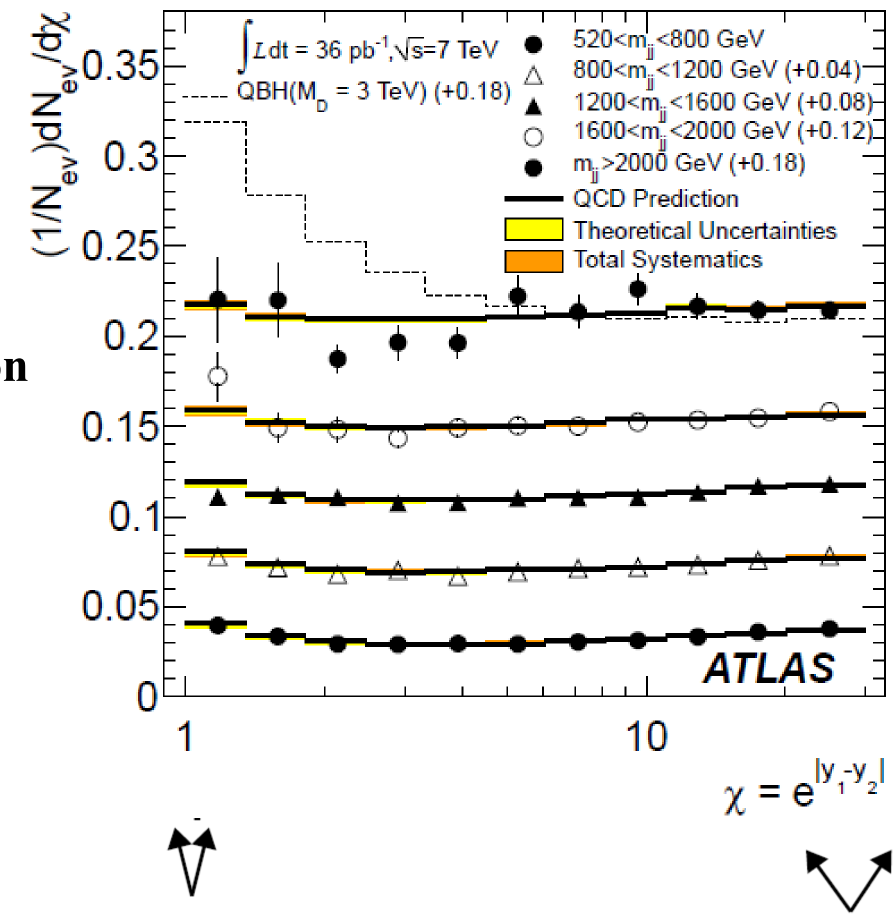
Systematics included. Degrade limits by ~60 GeV.



  - Also limits on simplified Gaussian models, for various means, widths – w/ systematics
    - Intended to ease application to other models

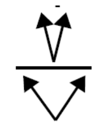
Dijet Angular Analysis: Chi

- **Normalized spectra of $\chi = \exp(|y_1 - y_2|)$**
  - Finely resolve angular distributions, coarse mass bins
  - Normalized so that systematics cancel (luminosity, bulk of jet energy scale)
  - Highest mass bin acts as a search bin
- Event selection very similar to m_{jj} search
  - Consider also higher rapidity, lower p_T jets and lower m_{jj}
- "Discovery Phase"
  - **Compare data with NLO QCD prediction**
  - Use χ^2 as a test statistic, compare with pseudo-experiments
    - p values 0.44, 0.33, 0.64, 0.89, 0.44
    - **No evidence for new physics ☹**

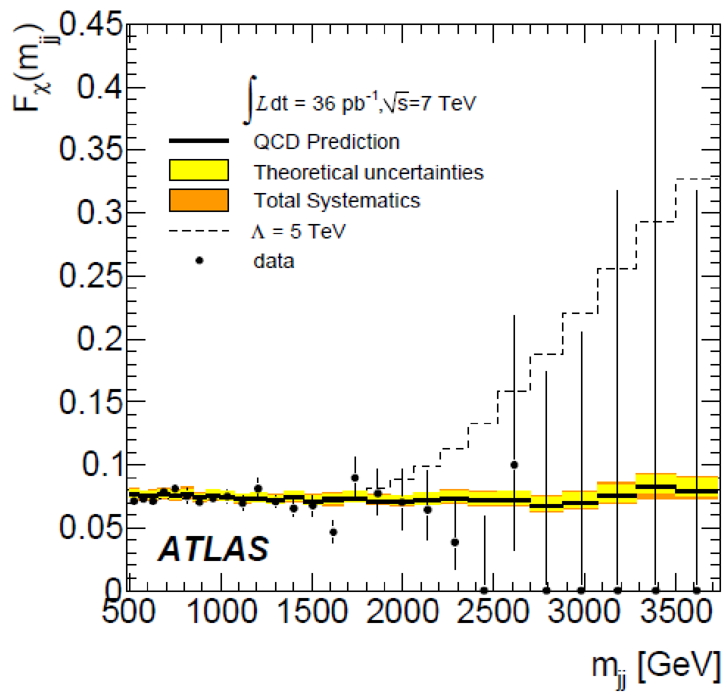


New Dijet Angular Observable: $f\chi(m_{jj})$

- $F\chi\ (m_{jj})$: $N(\ |y_1-y_2| < 1.2) / N(\ |y_1-y_2| < 3.4)$



  - Coarse use of angular information: chi fraction $F\chi$
    - Roughly, the fraction of events with central, “new physics”-like, jets
  - Resolve angular deviations with fine bins of m_{jj}; $F\chi\ (m_{jj})$
  - Combine some strengths of the resonance analysis and the chi analysis
- Use bin-by-bin analysis to **compare with NLO QCD prediction**
  - Calculate p value from PE’s (0.28)
    - In QCD pseudo-experiments we see something more discrepant 28% of the time
    - Our data is consistent with statistical fluctuations around QCD
  - **No evidence for new physics ☹**
- Set limits using Bayesian and/or Frequentist approaches (likelihood ratio)



Summarizing ATLAS searches with dijets

- Several analysis techniques that make complementary use of dijet m_{jj} and angular distributions
  - Unfortunately, no evidence for new physics
  - So, we set the world's best limits instead (for q*, axigluons, low multiplicity QBH)
- New $F\chi(m_{jj})$ observable combines advantages of what were fairly separate methods
  - Continue to explore the best ways to slice this 2D space of observables (m_{jj} and angular information)
- Limits on q* as a manifestation of quark compositeness
- Also consider contact interactions, as a low energy proxy for quark compositeness
- And low multiplicity Quantum Black Holes (QBH)
  - Near the Planck mass, M_D, it has been suggested that gravitational interactions might be dominantly _low_ multiplicity, e.g. dijets

Limits from 0.81 fb[-1]

Model	95% CL Limits (TeV) Expected	95% CL Limits (TeV) Observed
Excited Quark q^*	2.77	2.91
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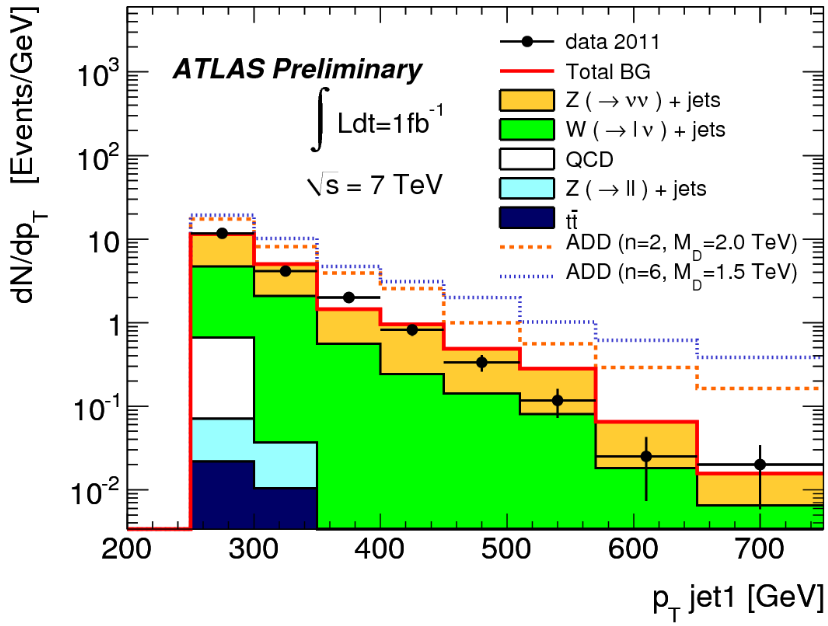
Limits from 36 pb[-1]

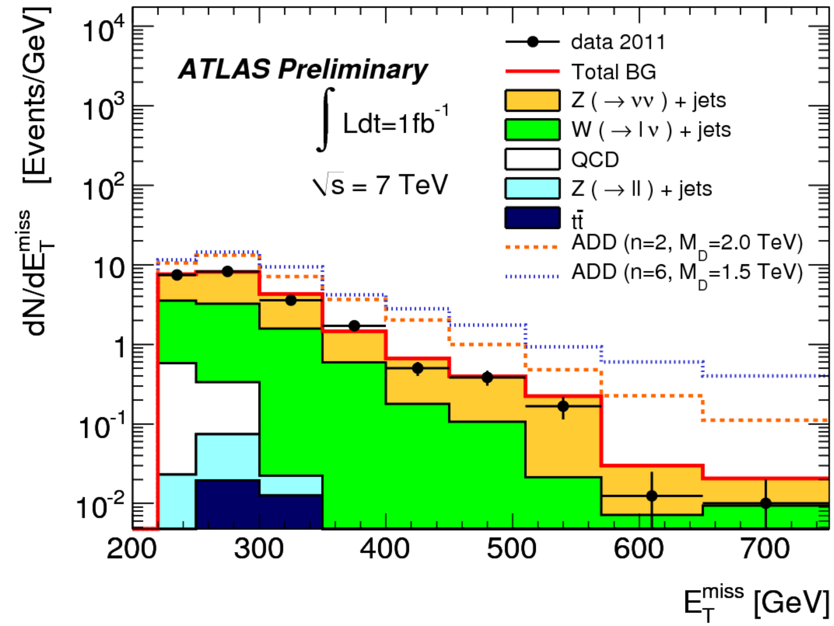
Model and analysis strategy	95% CL limits (TeV) Expected	95% CL limits (TeV) Observed
QBH for $n = 6$		
Resonance in m_{jj}	**3.64**	**3.67**
$F_\chi(m_{jj})$	3.49	3.78
θ_{np} parameter for $m_{jj} > 2$ TeV	3.37	3.69
11-bin χ distribution for $m_{jj} > 2$ TeV	3.36	3.49
Contact interaction Λ $F\chi(m_{jj})$ Bayesian	5.7	6.5
$F_\chi(m_{jj})$	**5.7**	**9.5**
F_χ for $m_{jj} > 2$ TeV	5.2	6.8
11-bin χ distribution for $m_{jj} > 2$ TeV	5.4	6.6

Monojets: a single jet plus missing E_T

- Another possible consequence of large extra dimensions (e.g. ADD)
  - Produce jet + Graviton, graviton disappears into the extra dimension
  - Observe a single (high p_T) jet and missing E_T
- Submitted to PLB based on 33 pb^{-1} (http://arxiv.org/abs/1106.5327)
  - ***Search for new phenomena with the monojet and missing transverse momentum signature using the ATLAS detector in $\sqrt{s}$ = 7 TeV proton-proton collisions***
  - Updated CONF note with 1 fb^{-1}
  - **First presented in public today!**
- Missing E_T trigger
- Signal region ("HighPt")
  - $p_T^{j1} > 250$ GeV, missing $E_T > 220$ GeV,
  - $p_T^{j2} < 60$ GeV, $\Delta\varphi$(j2, missing E_T) > 0.5
  - No reasonable e's, μ's
- Missing E_T calculated from locally calibrated clusters of calorimeter cells
- Anti-k_T 0.4 jets (calibration, cleaning much as in dijet search)
- Consider control regions with electrons or muons, and cross-check with "lowPt" and "veryHighPt" cuts

Monojet Background Predictions



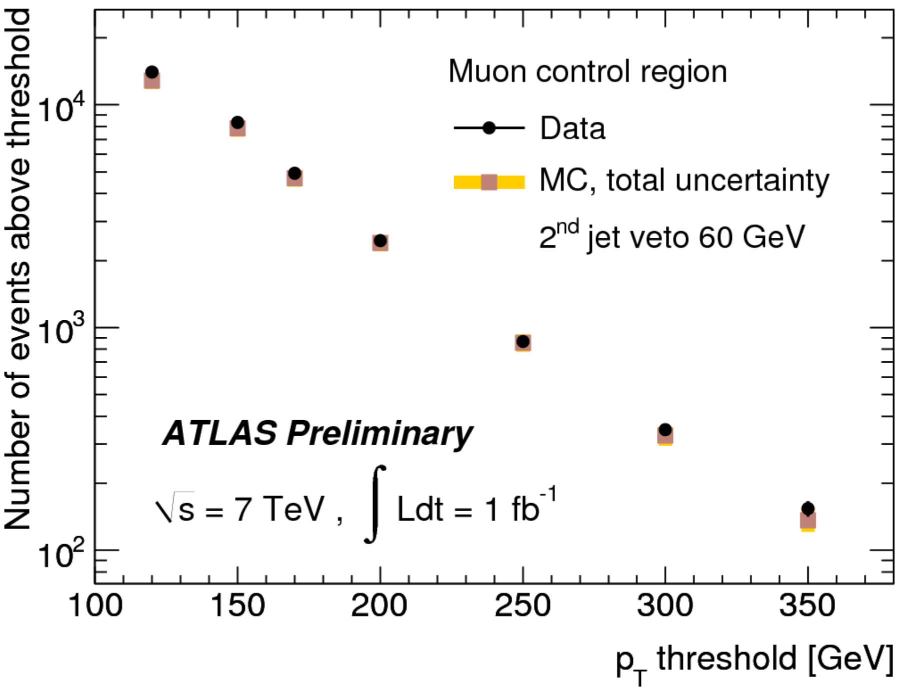


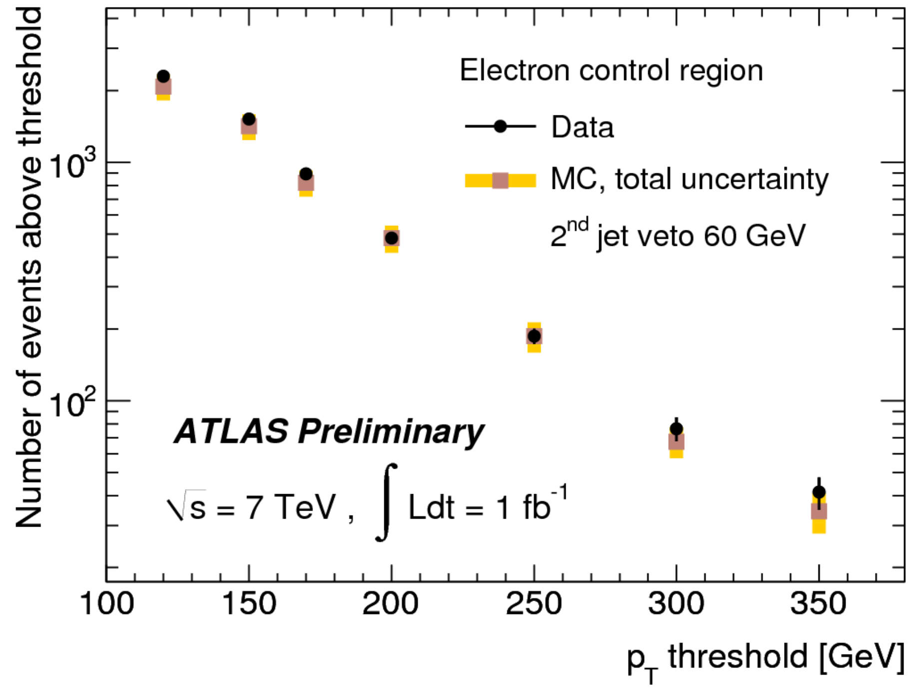
	Background Predictions ± (stat.) ± (syst.)
	HighPt Selection
$Z(\rightarrow \nu\bar{\nu})$+jets	$610 \pm 27 \pm 47$
$W(\rightarrow \tau\nu)$+jets	$180 \pm 16 \pm 22$
$W(\rightarrow e\nu)$+jets	$68 \pm 10 \pm 8$
$W(\rightarrow \mu\nu)$+jets	$113 \pm 14 \pm 9$
Multi-jets	$30 \pm 6 \pm 11$
$Z/\gamma^*(\rightarrow \tau^+\tau^-)$+jets	$2.0 \pm 0.6 \pm 0.2$
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$+jets	$2.0 \pm 0.6 \pm 0.1$
$t\bar{t}$	$1.7 \pm 0.3 \pm 0.3$
γ+jet	-
$Z/\gamma^*(\rightarrow e^+e^-)$+jets	-
Non-collision Background	$8.0 \pm 3.3 \pm 4.1$
Total Background	$1010 \pm 37 \pm 65$
Events in Data (1.00 fb^{-1})	965

- Dominant background is EW
  - "Irreducible" (Z→ νν + jets) and single lepton + jets
  - EW normalization taken from data, applied to MC samples
- Multi-jet background estimated in data by reversing delta-phi cut and allowing a 2nd jet

Monojets: Determining the EW normalization

- Use a control sample, with one or more electrons or muons to normalize the EW background prediction
- Test the shape of the ALPGEN + NNLO k factor prediction vs. leading-jet p_T threshold

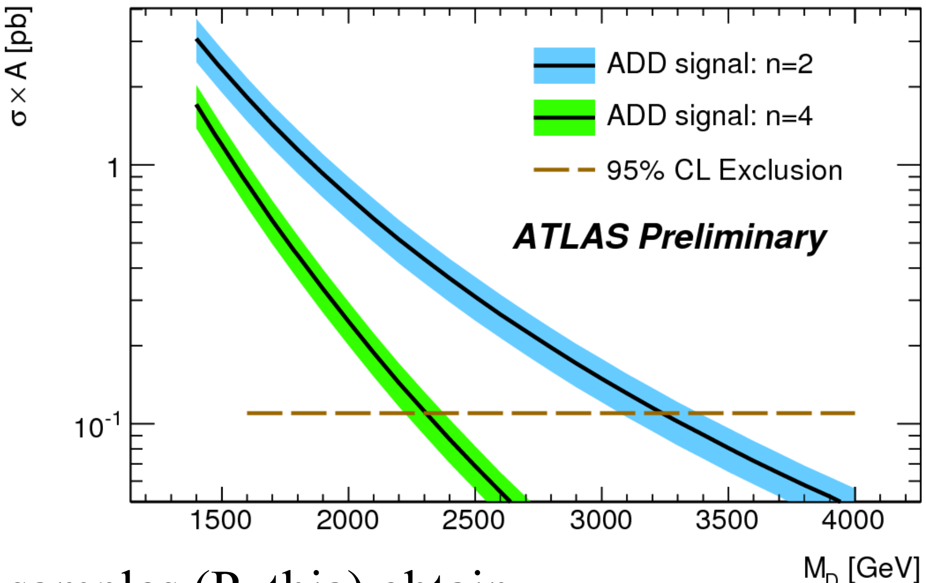




- Normalization factors
  - 0.87 ± 0.05 for muons (used also for $Z \rightarrow \nu\nu$)
  - 0.81 ± 0.09 for electrons

No evidence for new physics: set limits

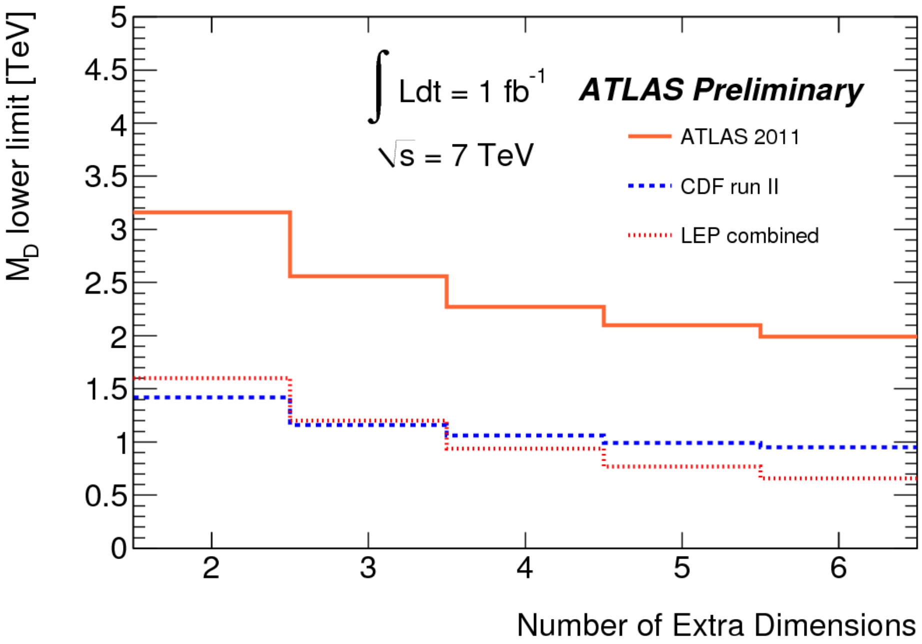
- Excellent agreement between data and the background prediction
  - 965 events vs. 1010 ± 37 (stat) ± 65 (syst);
  - Dominant systematic is normalization of EW background, a "good" systematic
- So, we set limits
  - Using the total number of events in the signal region
  - CLs, modified frequentist, statistical analysis
- **Model-independent limit on cross section times acceptance**
  - **0.11 pb , at 95% CL**



- Using the acceptance from ADD signal samples (Pythia) obtain
  - 95% CL limit on fiducial cross section: 0.13 pb

Limits on Planck Scale, MD, for ADD extra dimensions

- Comparing to the ADD cross section, set limits as a function of the number of extra dimensions
  - Additional theory uncertainties 20%
  - ISR/FSR, scale, etc.
- Using (Pythia) low-energy effective theory version of ADD
  - Invalid for sqrt(s-hat) > M_D
  - So, we interpret it carefully
- Extend the reach of previous limits
  - ATLAS, CMS, CDF, LEP



	95% CL limits on M_D for the ADD model	
	HighPt selection	
n	expected [TeV]	observed [TeV]
2	2.98	3.16
3	2.44	2.56
4	2.18	2.27
5	2.03	2.10
6	1.92	1.99

Conclusions

- LHC and ATLAS performing well!
- Sensitive searches for new physics with jet signatures
  - Multi-jet, Dijet, and Monojet
  - Probing the highest energies directly accessible at the LHC
  - And probing popular models, like those with extra dimensions
- Unfortunately, no evidence yet for new physics
  - Instead, set excellent limits on particular models, and model-independent limits
  - q*, axigluons, scalar octets, contact interactions, Planck scale for black holes and extra dimensions
- Looking forward to lots of data and excellent discovery possibilities this year
- LHC center of mass energy can make a big difference for searches at high p_T
  - Especially for dijet searches
  - Would be great to run at 8 TeV, 9 TeV, or of course 14 TeV center of mass
- Hopefully some surprises, and new physics, are on the horizon!

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic
- https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/

Related Presentations at EPS-HEP 2011

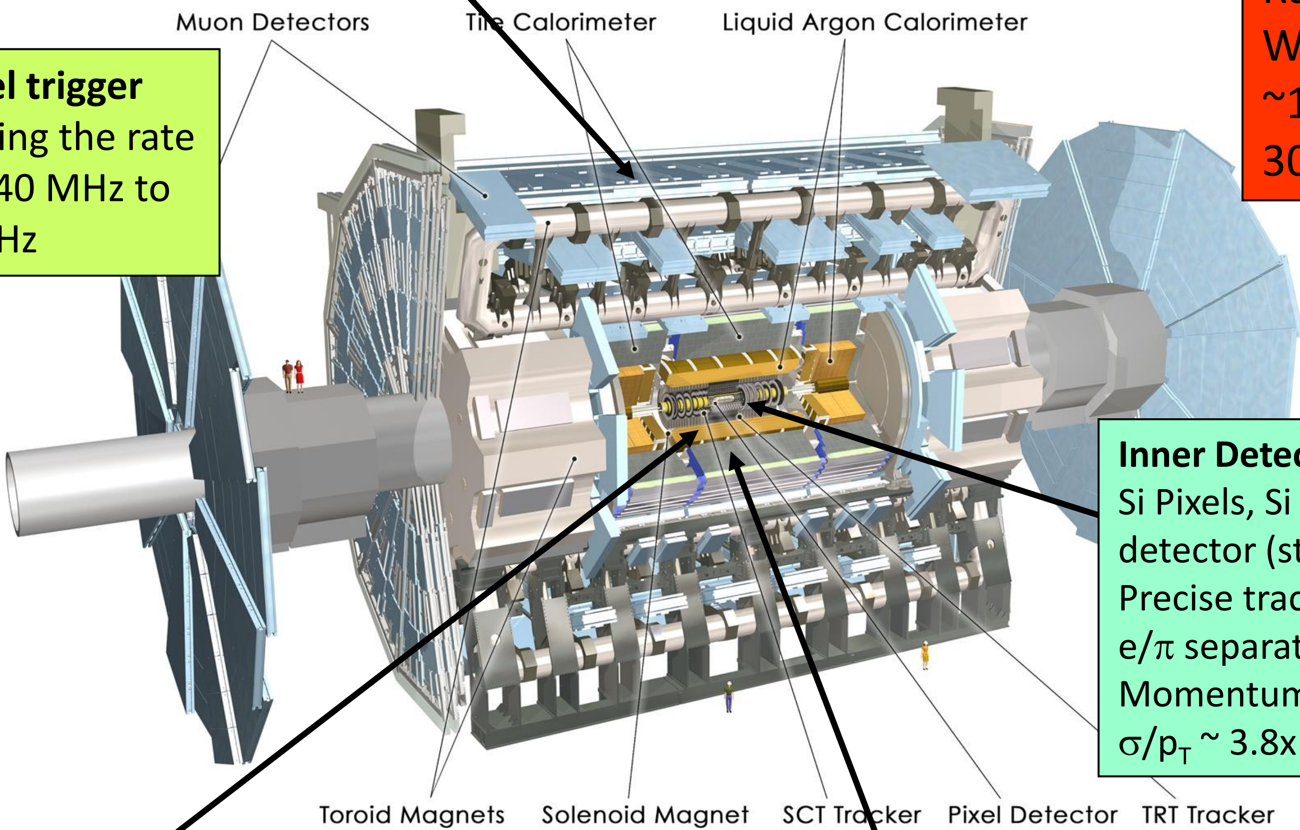
- Thorsten Alexander Dietzsch, poster
  - ***Search for New Physics in Dijet Mass and Angular Distributions in pp Collisions at sqrt(s) = 7 TeV measured with the ATLAS Detector***
- Valerio Rossetti, poster
  - ***Search for new physics in events with monojet and large MET with ATLAS detector***
- Dave Charlton (Monday plenary)
  - ***Searches for new physics and highlights from ATLAS***
- Thorsten Kuhl (earlier today)
  - ***Exotics Searches in Top, Top-like and Diboson Final States with the ATLAS Detector***
- Tetiana Hryn'ova (coming soon, in this session)
  - ***Exotics Searches in Photon and Lepton Final States with the ATLAS Detector***
- Paolo Francavilla
  - ***Measurement of single and multi-jet cross sections in proton-proton collisions at 7 TeV centre-of-mass energy with ATLAS***
- Dag Gillberg, poster
  - ***Jet performance and inclusive jet cross section measurement in ATLAS***
- Caterina Doglioni
  - ***Jet resolution and energy scale uncertainty in ATLAS***
- Andreas Salzburger
  - ***Heavy Flavor Production in ATLAS***

Additional Material

Muon Spectrometer ($|\eta|<2.7$): air-core toroids with gas-based muon chambers
Muon trigger and measurement with momentum resolution < 10% up to E_μ ~ 1 TeV

Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons
~10^8 electronic channels
3000 km of cables

3-level trigger
reducing the rate from 40 MHz to ~200 Hz

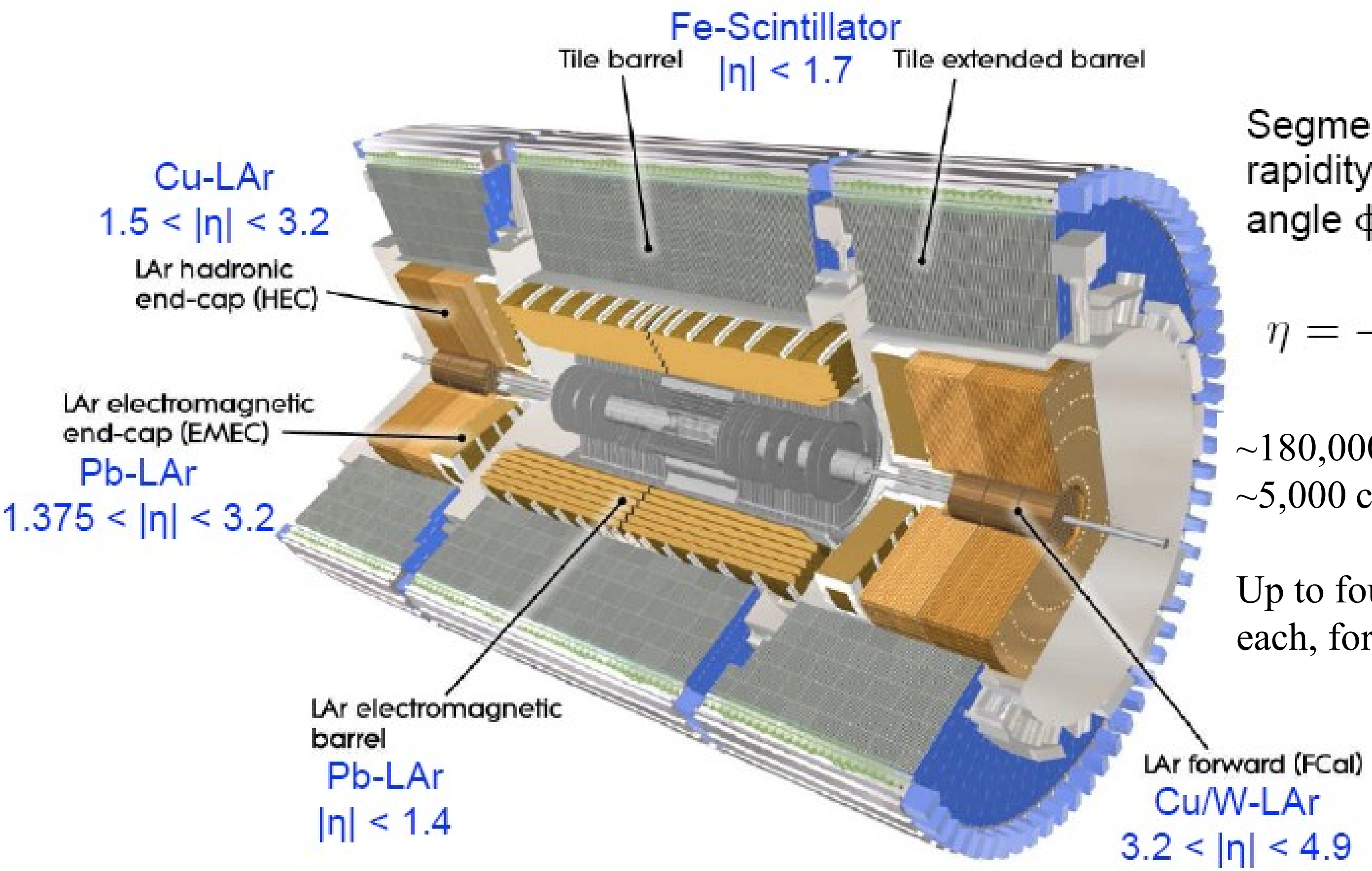


Inner Detector ($|\eta|<2.5$, B=2T):
Si Pixels, Si strips, Transition Radiation detector (straws)
Precise tracking and vertexing,
e/π separation
Momentum resolution:
$\sigma/p_T \sim 3.8\text{x}10^{-4}\ p_T(\text{GeV}) \oplus 0.015$

EM calorimeter: Pb-LAr Accordion
e/γ trigger, identification and measurement
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

HAD calorimetry ($|\eta|<5$): segmentation, hermeticity
Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution: $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

ATLAS Calorimeters



Segmented in pseudo-rapidity η and azimuthal angle ϕ

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

~180,000 cells in LAr calorimeter
~5,000 cells in Tile calorimeter

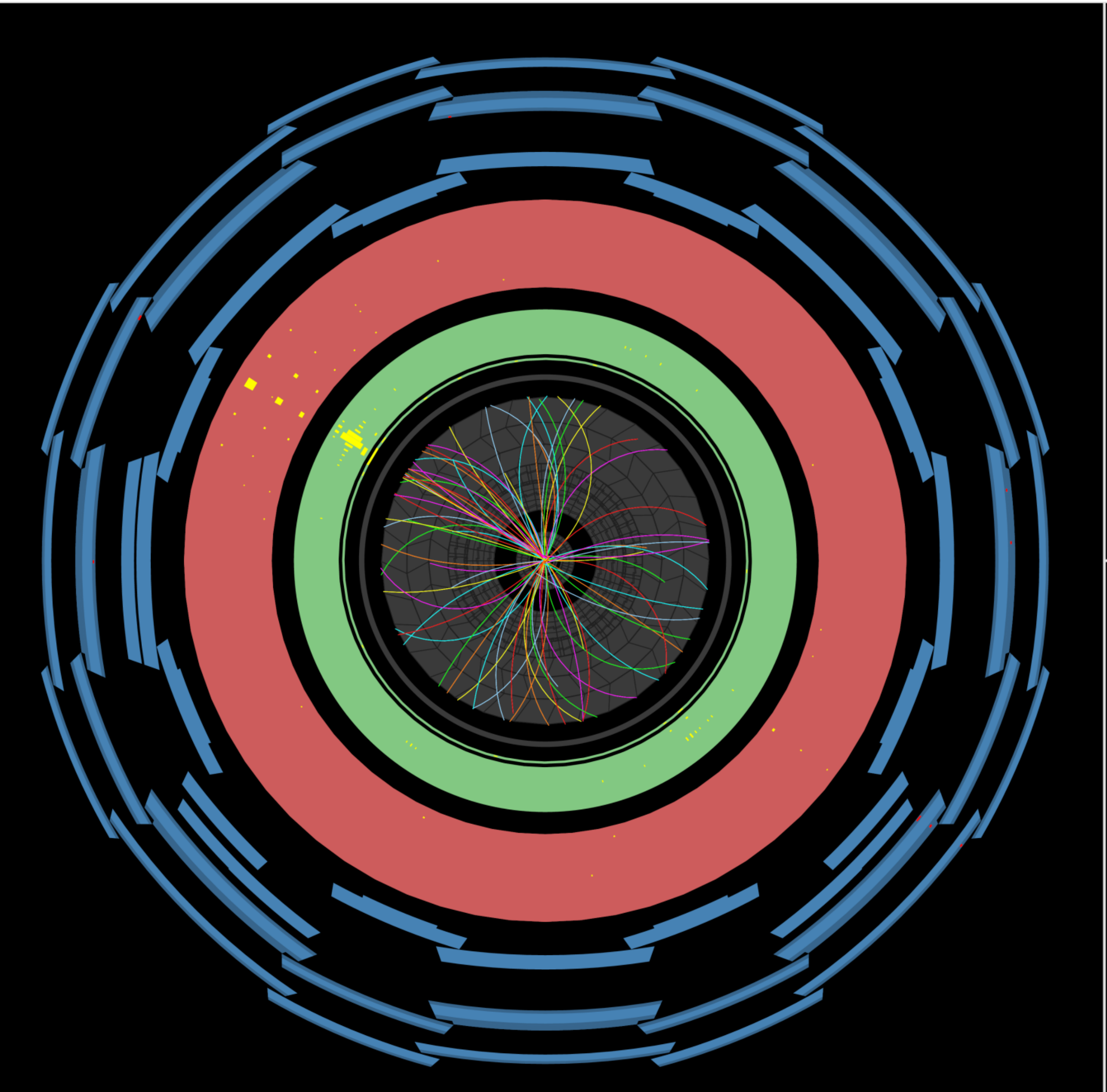
Up to four longitudinal samplings, each, for EM and hadronic.

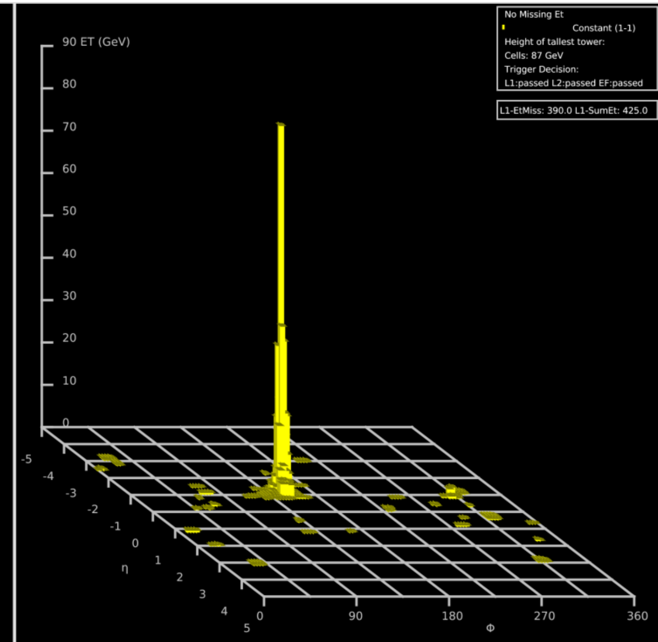
Fine transverse and longitudinal segmentation.

Very high energy mono-jet event

$p_T^{j1} = 600$ GeV; $p_T^{j2} < 30$ GeV; Missing $E_T = 520$ GeV

ATLAS-CONF-2011-096





ATLAS EXPERIMENT

Run Number: 180309, Event Number: 36060682

Date: 2011-04-27 02:33:15 CEST