Searches for physics beyond the Standard Model using dijet distributions in ATLAS

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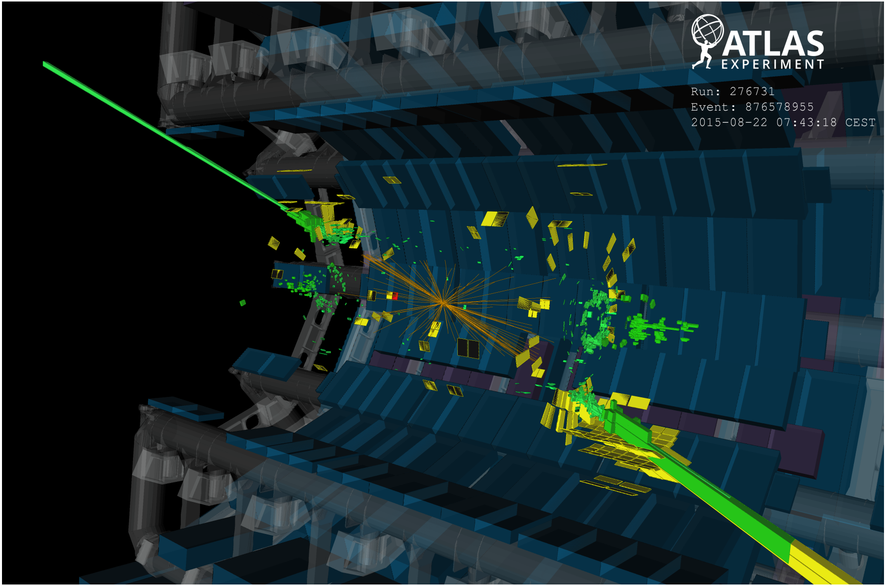
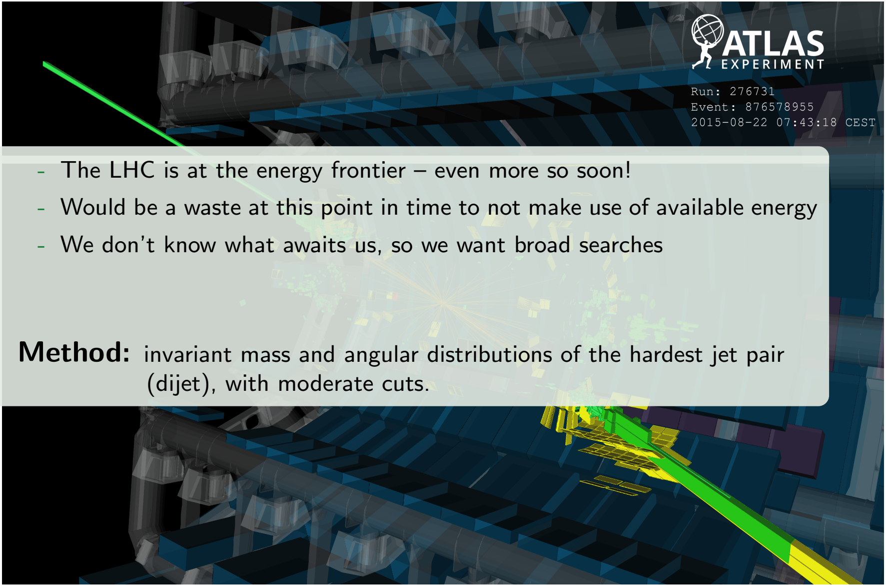
Uppsala, October 1

Analysis idea



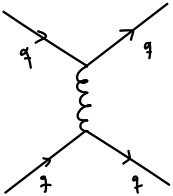
Analysis idea

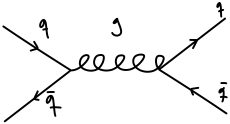


- The LHC is at the energy frontier – even more so soon!
- Would be a waste at this point in time to not make use of available energy
- We don't know what awaits us, so we want broad searches

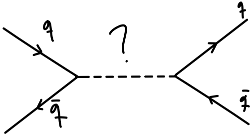
Method: invariant mass and angular distributions of the hardest jet pair (dijet), with moderate cuts.

Why dijets?





- Access to energy frontier
  - highest mass reach
  - smallest scales
- Hadron collider: partons in – partons out



But aren't jets just too messy?

What is a jet? The output of a jet finding algorithm.

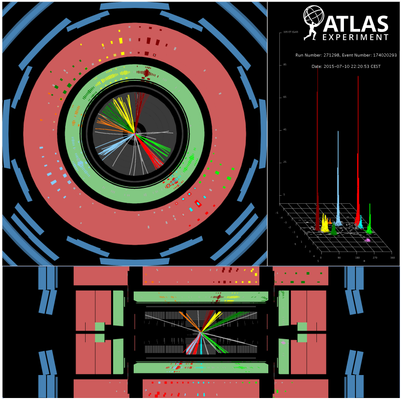
⇒ need to be defined such that they sensibly find something corresponding to a collimated spray of particles with partonic origin

Jets (or jet algorithms) are the bullies of the event!

Don't need to worry about

- isolation
- charge
- fakes
- vertex distance parameter

⇒ dijets are in fact a very clean topology!



But is this really true??

Jets should be intrinsically sensitive to pile-up.

- 10-20 simultaneous proton collisions in 2012 and 2015
- signal from these events piles up in the calorimeter read-out
  - contributes energy (positive or negative) within the jet
  - distorts p_{T} measurement (scale and resolution)
  - distorts mass (and other single jet structure) measurement(s)
  - contributes extra jets

⇒ pile-up is a potential hurdle; suddenly "isolation", fakes and vertex reconstruction could start to matter!

Solution: correct for pile-up

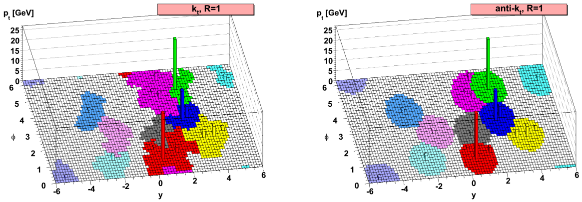
Imagine we could measure

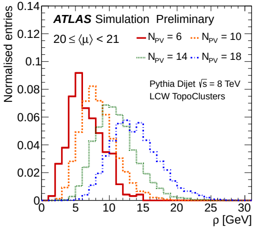
- how much pile-up there is in a given event
- how susceptible each individual jet is to pile-up

Then we could correct for it!

Solution: correct for pile-up

... and in fact we can:





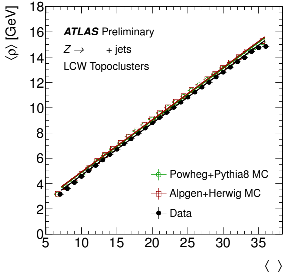
The Anti-k_t jet clustering algorithm, M. Cacciari, G. P. Salam, G. Soyez JHEP 0804 (2008) 063

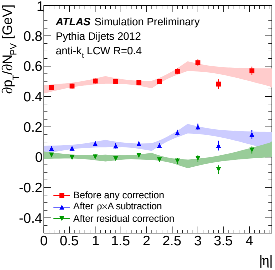
- measure the median p_T density (ρ) in the event
  - this is dominated by low-p_T "jets" as found by the k_t algorithm
- the area A is a measure of how much pile-up a jet will contain

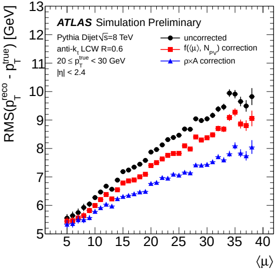
$\Rightarrow$ subtract $\rho \times A$ from the jet p_T.

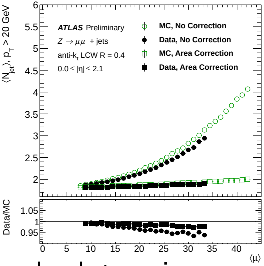
This is the jet-area based pile-up correction implemented in ATLAS and used in most analyses since 2012 data taking.

Performance





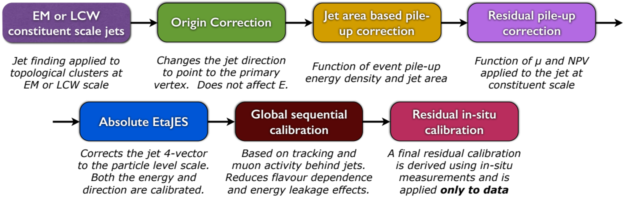




- correction goes to 0 in limit of no pile-up
- reduced dependence of jet p_T on pile-up
- removes some of the resolution smearing introduced by pile-up
- brings the number of pile-up jets down

After correction we can safely go back to using the bullying jets!

Jets in ATLAS



EM or LCW constituent scale jets

Jet finding applied to topological clusters at EM or LCW scale

Origin Correction

Changes the jet direction to point to the primary vertex. Does not affect E.

Jet area based pile-up correction

Function of event pile-up energy density and jet area

Residual pile-up correction

Function of μ and NPV applied to the jet at constituent scale

Absolute EtaJES

Corrects the jet 4-vector to the particle level scale. Both the energy and direction are calibrated.

Global sequential calibration

Based on tracking and muon activity behind jets. Reduces flavour dependence and energy leakage effects.

Residual in-situ calibration

A final residual calibration is derived using in-situ measurements and is applied ***only to data***

The other steps in the calibration chain:

- bring the jets to “particle level” energy (Jet Energy Scale, JES)
- ensure that different energy response in different detector regions is compensated for
- makes use of a number of *in-situ* techniques (using a reference object in data to restore p_{T} balance)

The dijet search

Search strategy

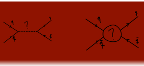
Recall the method: invariant mass and angular distributions of the hardest jet pair (dijet), with moderate cuts.

QCD is an overwhelming background! Make use of the knowledge:

QCD

- No new scales above top mass – **smooth** mass distributions
- Incoming partons predominantly undergo **small-angle scattering** (*t*-channel)

BSM



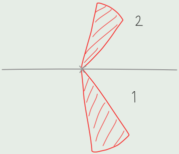
- A new scale (particle mass, interaction) – **feature** in the mass spectrum
- New particle production or new interaction predominantly **isotropic** (*s*-channel like)

- Probe the scale: bin in dijet mass
- Find the isotropic events: bin in jet rapidity difference

$$y_B = \frac{y_1 + y_2}{2}$$

$$y^* = \frac{y_1 - y_2}{2}$$

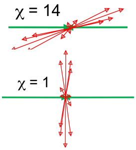
$$\chi = e^{2|y^*|}$$



- Use lowest unprescaled single jet trigger $\Rightarrow$ dictates leading jet $p_\mathrm{T} > 410$ GeV
- Two or more anti-k_t 0.4 jets (pile-up dictates second jet $p_\mathrm{T} > 50$ GeV)
- m_{jj} cut for unbiased kinematics

- The distribution in χ (or y^*) is our isotropy measure
- Rapidity is additive – measure in the dijet frame

more QCD-like



more BSM-like

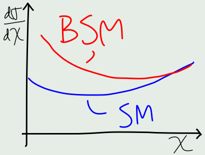
This talk refers to two searches:

Search for New Phenomena in the Dijet Angular Distributions in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector,
Phys. Rev. Lett., 114:221802, 2015. arXiv link

Search for New Phenomena in Dijet Mass and Angular Distributions with the ATLAS Detector at $\sqrt{s} = 13$ TeV,
ATLAS-CONF-2015-042, Aug 2015. CDS link

Event selection

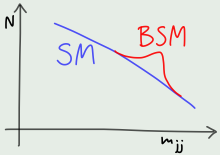
Angular distribution search:



At high m_{jj}

- $|y^*| < 1.7$
- $|y_B| < 1.1$
- $m_{jj} > 2.5$ TeV

Mass resonance search:



- $|y^*| < 0.6$ (suppress QCD)
- $m_{jj} > 1.1$ TeV

- Bin (coarsely) in m_{jj}
- *Prediction* for SM shape (lowest order: flat!) – relies on modelling
- Deviation at low χ for some m_{jj} $\Rightarrow$ discovery (or else, limit setting)

$\Rightarrow$ sensitive to *wide or non-resonant* phenomena

- Cut on y^*
- Fit to smooth SM background – relies "only" on good fit function choice
- BumpHunt for most discrepant region in m_{jj} $\Rightarrow$ discovery, or, limit setting

$\Rightarrow$ sensitive to *narrow resonances* (fit swallows other deviations)

Maximise discovery potential by exploiting this complementarity!

The search: (angular) 8 and 13 TeV

Spring:

- Used 17.3 fb^{-1} of 8 TeV data
- Mature data set, collected since a long time
- Partial data set to validate search

Why this rush?

Summer:

- Used 80 pb^{-1} of 13 TeV data
- The first approved ATLAS search
- Lots of validation work on-the-fly within the group
- Analysis strategy, cuts etc already set in stone before data taking started

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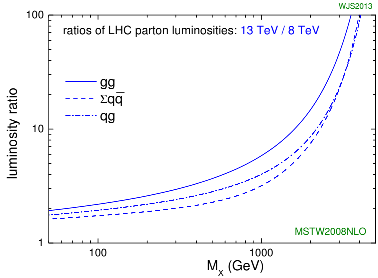
W.J. Stirling, private communication



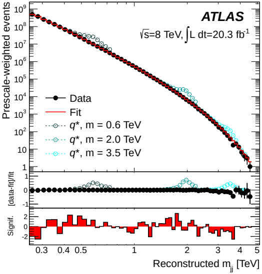
Discovery potential!

SM prediction: mass spectrum

The fit is an evolution of a semi-ad hoc function
$f(x) = p_1(1-x)^{p_2} x^{p_3 + p_4 \log(x) + p_5 \log(x)^2}$, where $x = m_{jj}/\sqrt{s}$

Historically, as mass reach/luminosity has increased, more parameters added

8 TeV mass search: realised after unblinding that five parameters were needed



This time around, we have

- narrower mass region
- smaller luminosity
- but still no ways to change strategies after looking at data!

Solution: start with 3 parameters, use a pre-defined figure of merit for when to add more

SM prediction: angular distribution

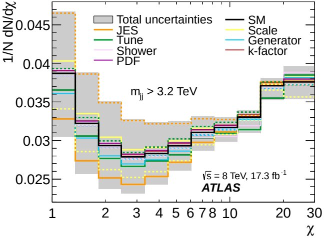
Use Pythia8, which gives a leading order prediction
Normalise it to the data integral – this is a shape comparison!

- NLO: QCD *K*-factors derived using NLOjet++
- EW corrections from Dittmaier et. al

Dominant theory uncertainties: renormalisation and factorisation scale uncertainty

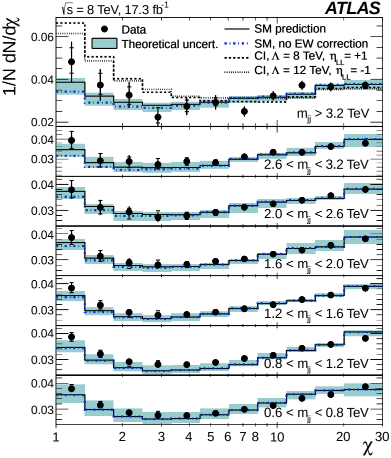
PDF uncertainty largely vanishes in the normalisation!

Dominant experimental uncertainty: JES

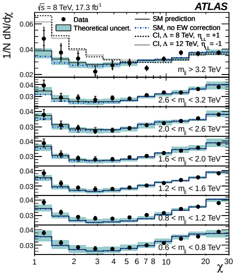


Uncertainty breakdown, 8 TeV angular search

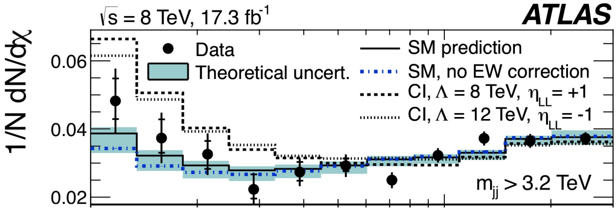
The 8 TeV lesson



The 8 TeV lesson: EW corrections



Zoom in:

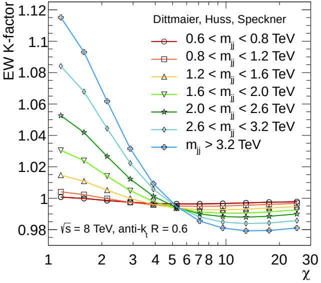


- Significant improvement in data/MC agreement with EW corrections

EW corrections

- Combination (cancellation) of tree-level effects and loop corrections
- increasingly important at high m_{jj}, low χ
- this is our search region

EW corrections to the angular distribution, 8 TeV



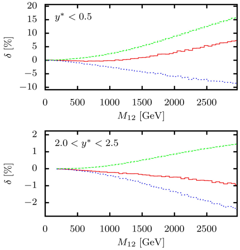
$$\mathrm{pp} \longrightarrow jj + X \text{ at } \sqrt{s} = 8 \text{ TeV}$$

$\delta^{\text{1-loop}}_{\text{weak}}$

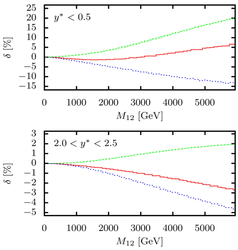
$\delta^{\text{tree}}_{\text{EW}}$

$\delta^{\text{tree}}_{\text{EW}} + \delta^{\text{1-loop}}_{\text{weak}}$

Weak radiative corrections to dijet production at hadron colliders, Dittmaier et. al, arXiv:1210.0438



EW corrections, 8 TeV

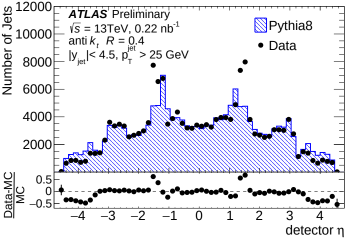


EW corrections, 14 TeV

Even more important at 13 TeV!

Jet Energy Scale uncertainties

- Dominated by η intercalibration uncertainty
- η intercalibration: use dijet p_T balance to calibrate jets in the forward region
- residual correction applied to data
  - corrects scale and reduces uncertainty
  - very important for the angular search!



Properties of jets and inputs to jet reconstruction and calibration with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ *TeV* ATL-PHYS-PUB-2015-036

An aside on SM prediction methods

Dijet mass spectrum fit: data driven

- small uncertainties, “early” search
- angular search uses MC; historically a little later
- First Run2 result: made public together as one search

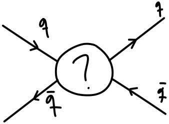
We have shown that the understanding of the ATLAS detector is already good enough for an early first-Run2 data angular result!

Remarkable understanding of

- detector
- jet calibration
- simulation

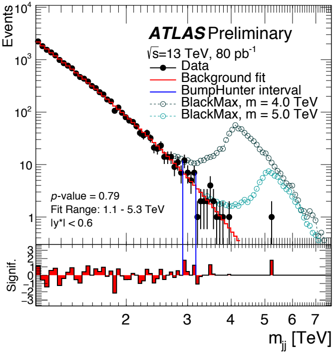
This understanding builds from the 8 TeV experience.

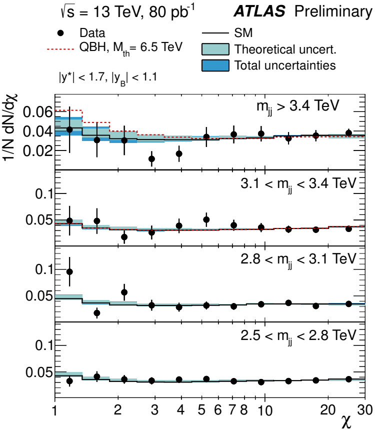
Benchmark models



- Contact Interactions (CI)
  - effective four-point interaction model
  - characterised by compositeness scale Λ
  - and by constructive or destructive interference with the QCD process $q\bar{q} \rightarrow q\bar{q}$
  - generated together with QCD in Pythia8 and brought to NLO using CIJET
- (non-thermal) Quantum Black Holes
  - ADD scenario with fundamental quantum gravity scale $M_D = M_{th}$ (threshold mass), $n = 6$
  - two generators: BlackMax and QBH
  - different modelling but final distributions mostly differ by cross section

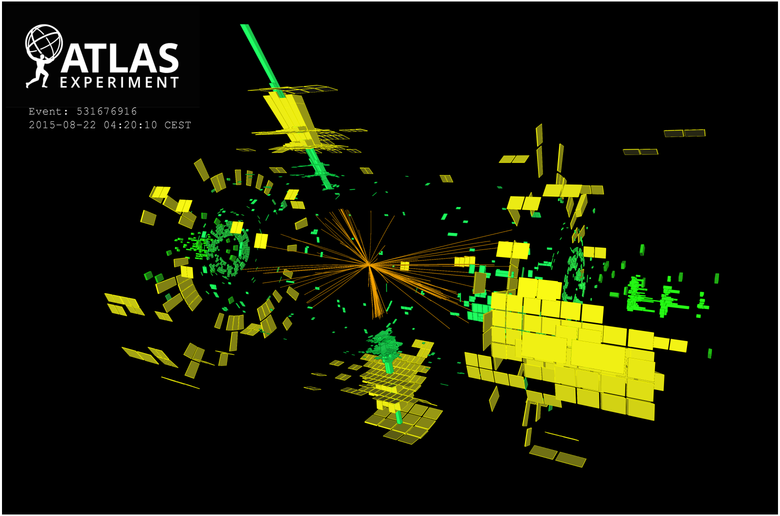
13 TeV results





- No significant deviations from the background predictions
- *p*-values of 0.79 and 0.57 respectively

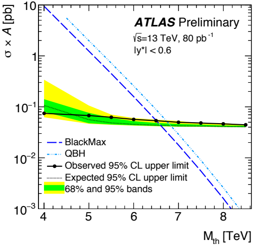
13 TeV results: highest m_{jj} signal-like event



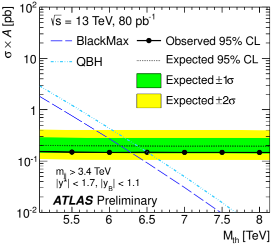
95% CL lower limits

For CI, 13 TeV data set too small to be competitive. 8 TeV limits on constructive interference best to date: $\Lambda > 12.0$ TeV

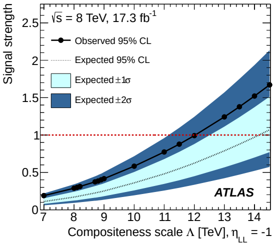
13 TeV, resonance, QBH and BlackMax



13 TeV, angular, QBH and BlackMax



8 TeV, angular, constr. int. CI



- Resonance limits: $M_{th} > 6.5$ (6.8) TeV for BlackMax (QBH)
- Angular limits: 6.4 (6.5) TeV
- Angular distributions only slightly less sensitive to these resonant phenomena!

Outlook: extensions

Startup of Run2 – exciting times!

...but what if we don't find anything?

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- we don't stop looking

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- we try harder

Outlook: extensions

Startup of Run2 – exciting times!

...but what if we don't find anything?

- we don't stop looking
- we try harder
- we add in more information!

Strengths that can get stronger

The dijet analysis is sensitive to scale and isotropy.

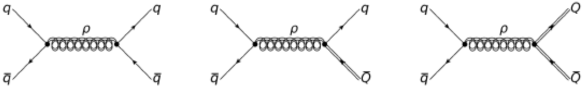
- Dijet/event properties
- Add in single jet properties to enhance discovery potential
- One example model: 4-jet final state

Example model

Compositeness of light right-handed quarks

as outlined in
"Strong Signatures of Right-Handed Compositeness",
by M. Redi, V. Sanz, M. de Vries and A. Weiler, arXiv:1305.3818

- compatible with constraints from precision SM tests and flavour physics
- large cross sections for production of resonances coupled to light quarks
- focus: spin-1 gluon partner, colour octet with mass m_ρ



Dominant production and decay modes

… why dijets?

We don't know the mass of the mediator or the composite quarks!

Imagine $m_\rho >> m_Q$

- we get very boosted Q which subsequently decay to quarks
- the single jet mass picks up m_Q
- the dijet mass picks up m_ρ
- decays distinct from the t-channel QCD both in angle and scale

Imagine $m_\rho \sim 2m_Q$

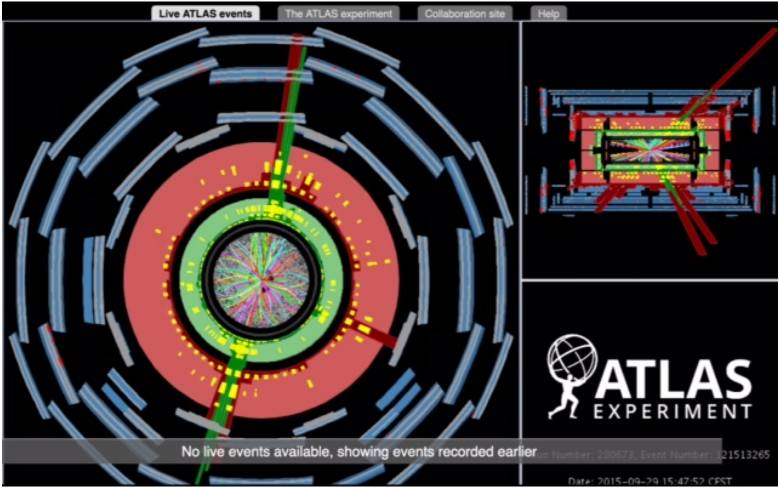
- Q decays to quarks at rest
- the dijet mass picks up m_Q
- the four-jet mass picks up m_ρ
- decays distinct from the t-channel QCD both in angle and scale

These are the extremes of the spectrum. Ideally a resolved and a boosted analysis is done together.

Conclusions

- Dijets probe the energy frontier
- Broad search for new phenomena
- I have shown first results from the 13 TeV data taking
    - We see good agreement between data and our background modelling
    - We set new limits on the threshold mass of Quantum Black Holes
- Fast results possible due to preparation and experience – in the team and in ATLAS
- Longer term: extend with larger sensitivity to single-jet properties

Thank you



No live events available, showing events recorded earlier

un Number: 280673, Event Number: 121513265

Date: 2015-09-29 15:47:52 CEST

Two or four jets? in the ATLAS Live event stream (very raw!!)