High p_T measurements by ATLAS in Pb+Pb Collisions at the LHC

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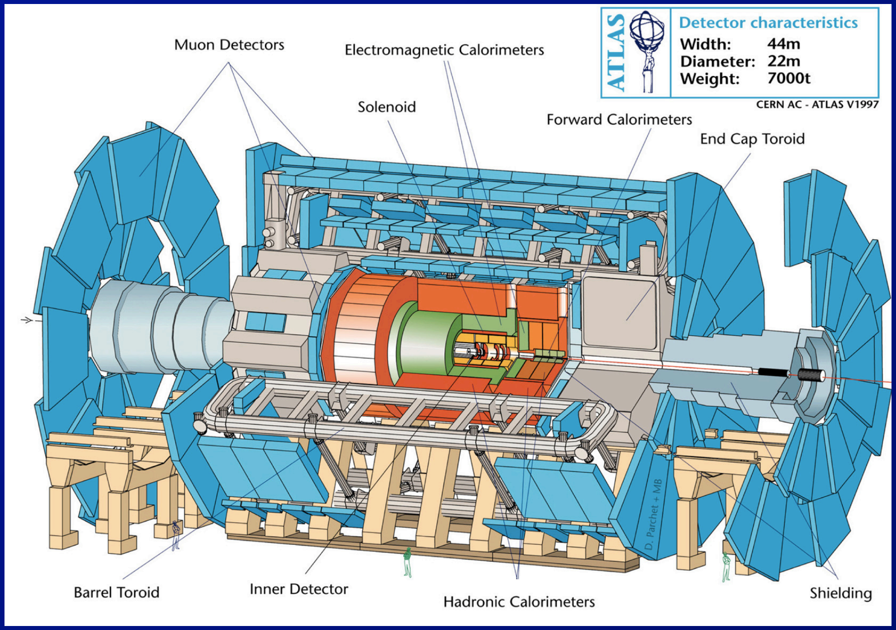
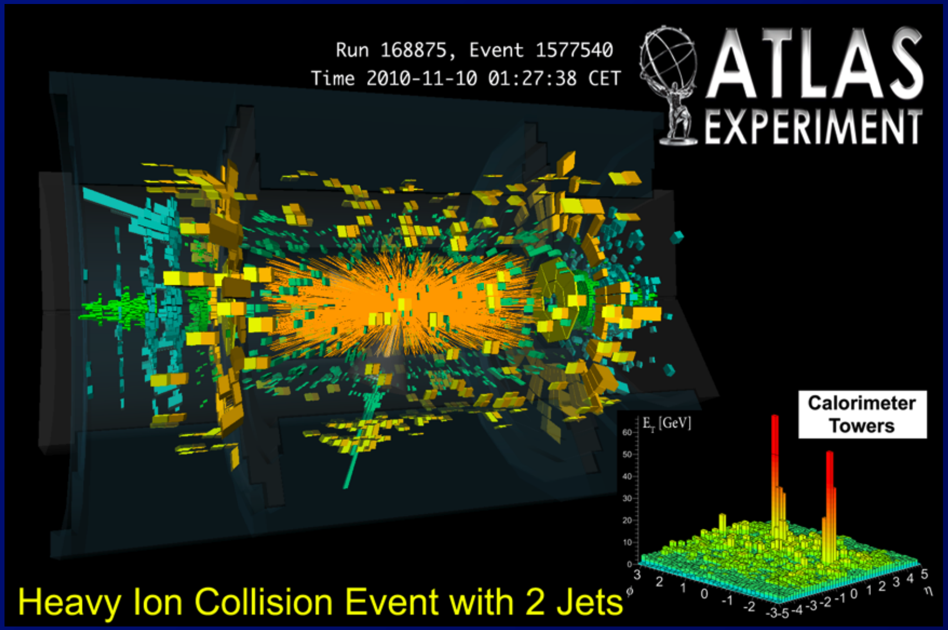




Introduction

The Big Picture

- We know that strong interactions are well described by the QCD Lagrangian:

$$L_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a - \sum_n \bar{\psi}_n \left(\not{\partial} - i g \gamma^\mu A^a_\mu t_a - m_n \right) \psi_n$$

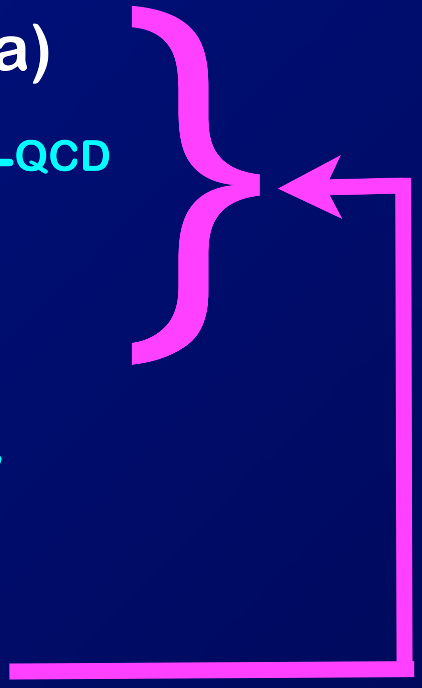
⇒Perturbative limit well studied

- Nuclear collisions provide a laboratory for studying QCD outside the large Q^2 regime:
  - Deconfined matter (quark gluon plasma)

    ⇒"Emergent" physics not manifest in L_{QCD}

    ⇒ Strong coupling ⇒ AdS/QCD (?)
  - High gluon field strength, saturation

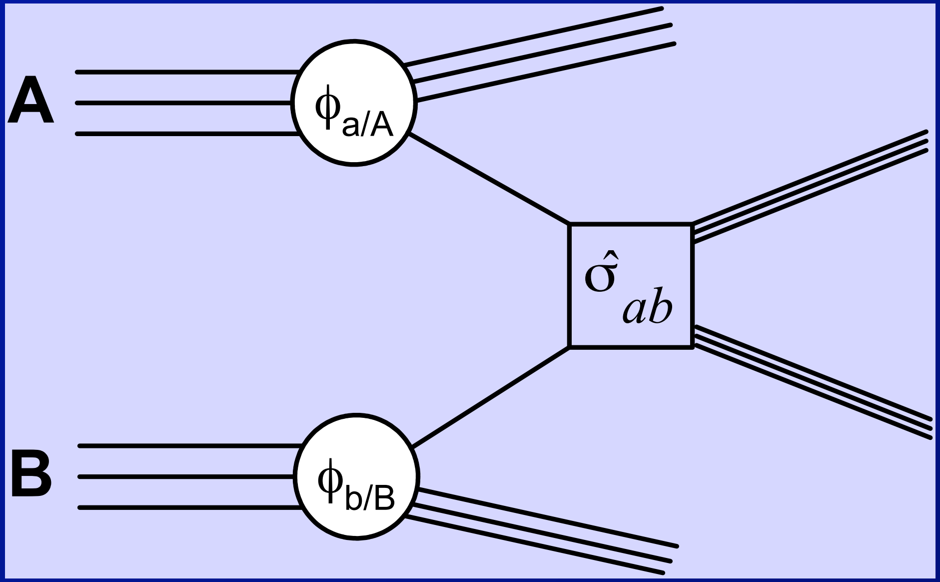
    ⇒ Unitarity in fundamental field theory

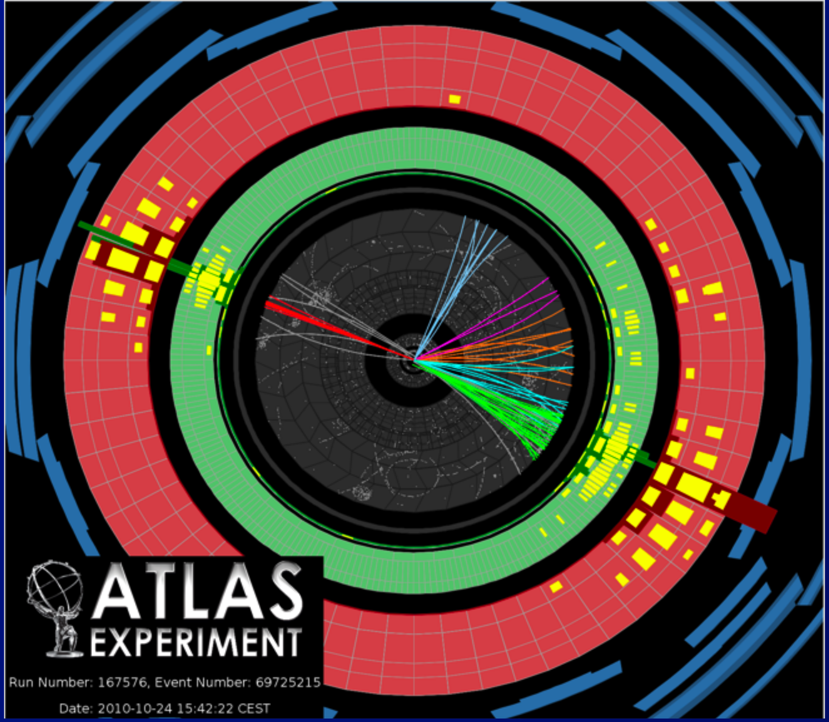


- In this talk:

⇒Using large Q^2 processes to probe

Hard Scattering in p-p Collisions



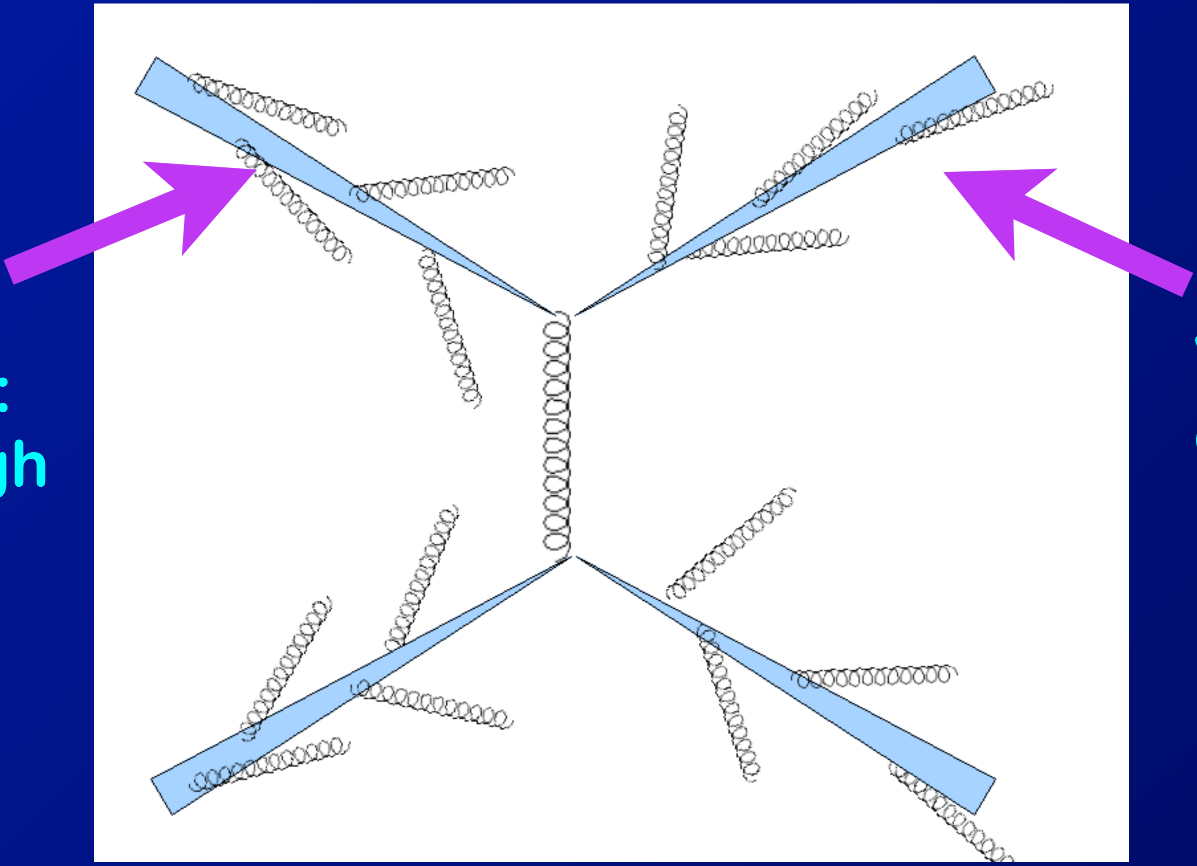


From **Collins, Soper, Sterman**
Phys. Lett. B438:184-192, 1998

$$\sigma_{AB} = \sum_{ab} \int dx_a dx_b \, \phi_{a/A}(x_a, \mu^2) \, \phi_{b/B}(x_b, \mu^2) \, \hat{\sigma}_{ab}\left(\frac{Q^2}{x_a x_b s}, \frac{Q}{\mu}, \alpha_s(\mu)\right) \left(1 + \mathcal{O}\left(\frac{1}{Q^P}\right)\right)$$

- Factorization: separation of σ into
  - Short-distance physics: σ_{ab}
  - Long-distance physics: φ's

Hard Scattering & parton showers

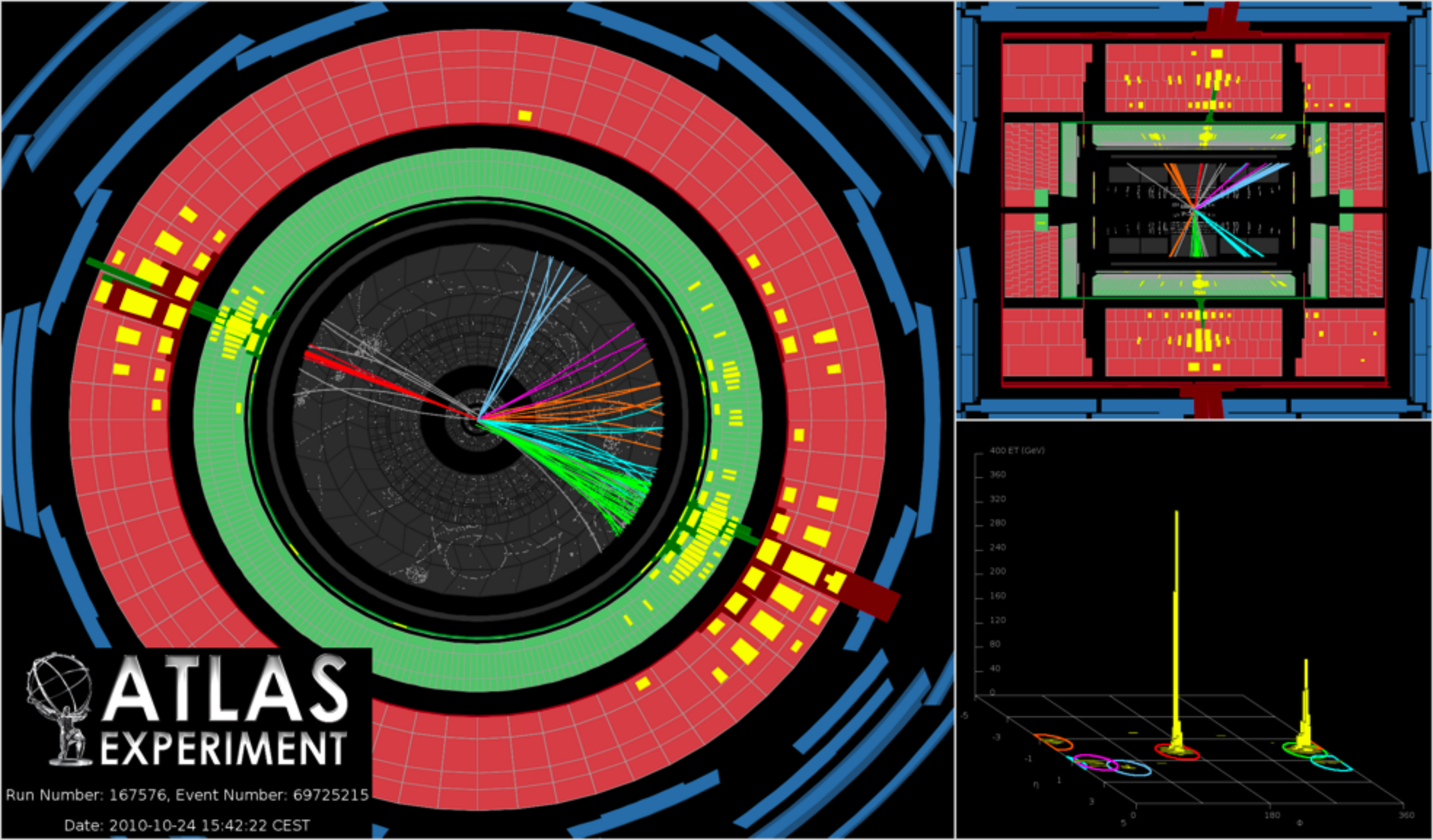


Virtuality
evolution:
low → high

Virtuality
evolution:
high → low

- Initial and final state parton showers
  - Angular ordered (initial and) final state showers as by-product of virtuality evolution.

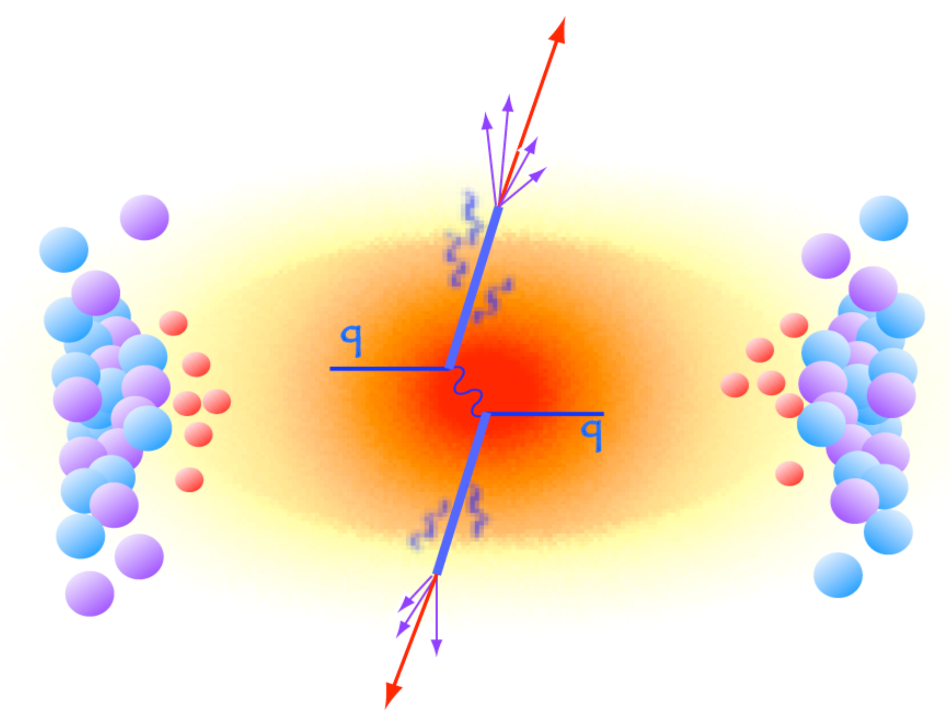
“Baseline”: jets in p-p



- ➡ Leading jet : p_T= 670 GeV, η = 1.9, φ = -0.5
- ➡ Sub-leading jet: p_T = 610 GeV, η = -1.6, φ = 2.8

Jet probes of the quark gluon plasma

- Use jets from hard scattering processes to directly probe the quark gluon plasma (QGP)

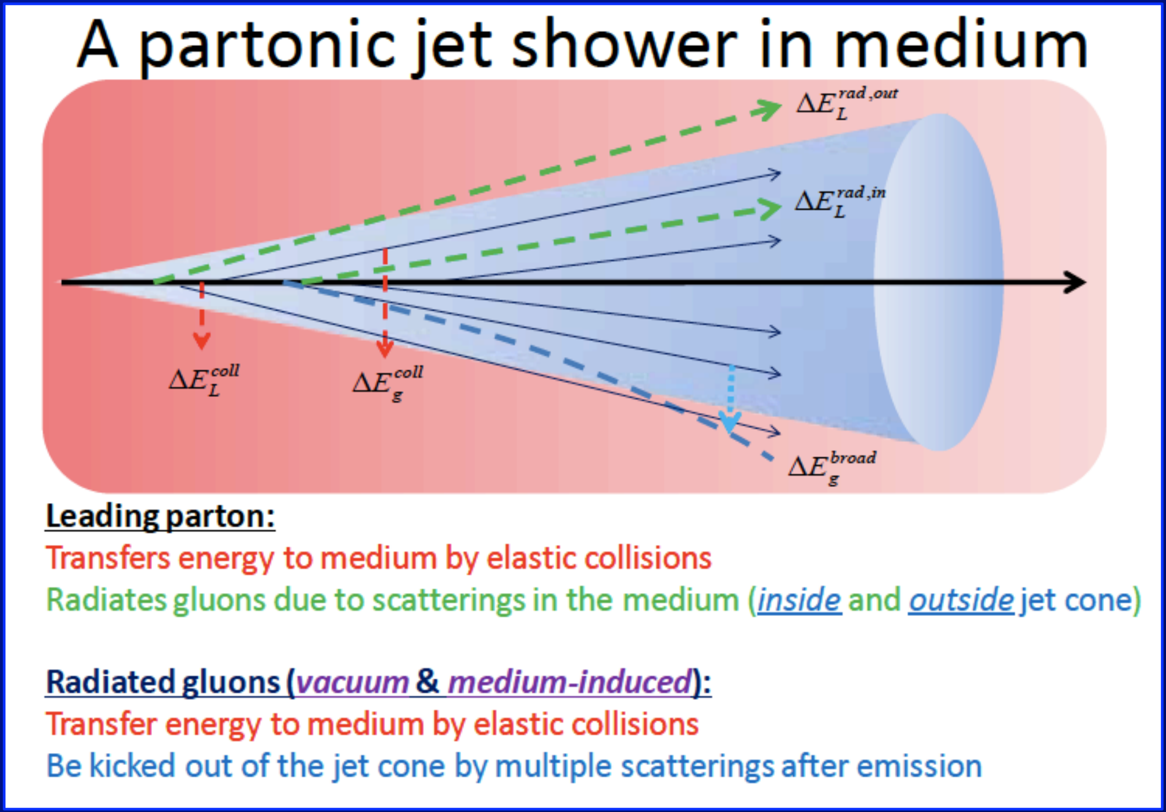


- Key experimental question:
  - ⇒How do parton showers in quark gluon plasma differ from those in vacuum?
- Use vector bosons -- for which the QGP is transparent -- to calibrate hard scattering rates in Pb+Pb collisions.

Jet probes of the quark gluon plasma (2)

Jet - QGP interactions schematically

From Quark Matter 2011 talk by B. Muller



A partonic jet shower in medium

Leading parton:
Transfers energy to medium by elastic collisions
Radiates gluons due to scatterings in the medium (*inside* and *outside* jet cone)

Radiated gluons (*vacuum* & *medium-induced*):
Transfer energy to medium by elastic collisions
Be kicked out of the jet cone by multiple scatterings after emission

- **QGP can modify jets in multiple ways:**
  1. Collisional energy loss (analog of Bethe-Bloch)
  2. Radiative energy loss (enhanced splitting)
  3. Broadening of parton shower

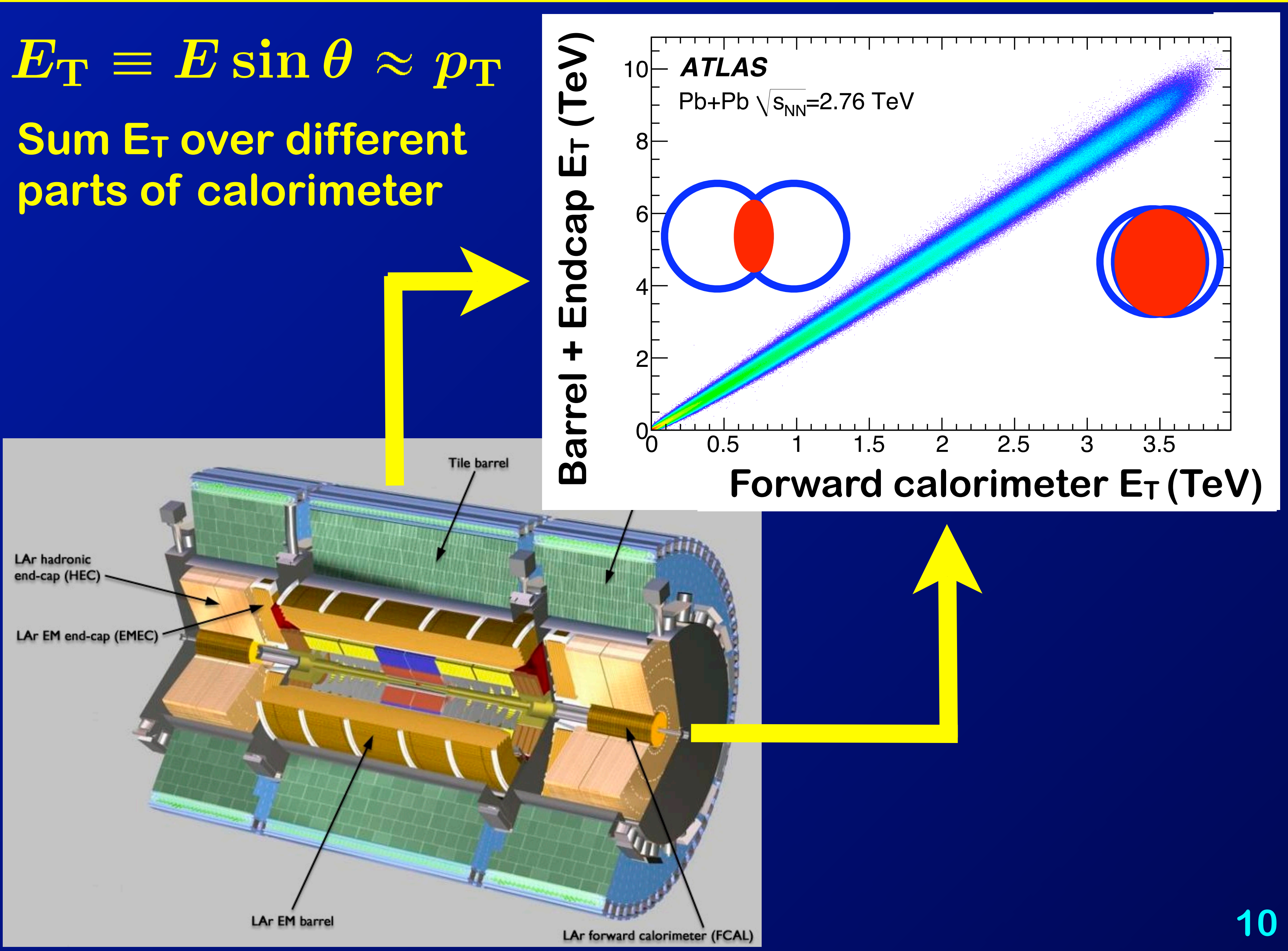
  ⇒ 2 & 3 will depend on jet radius

Centrality, geometry, and hard scattering rates

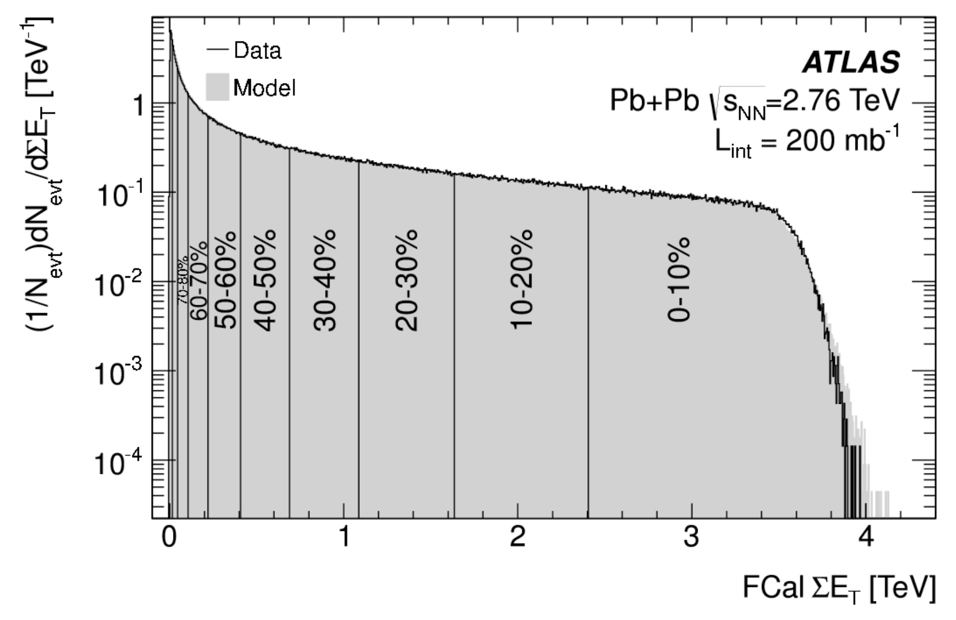
Pb+Pb (transverse) energy measurement

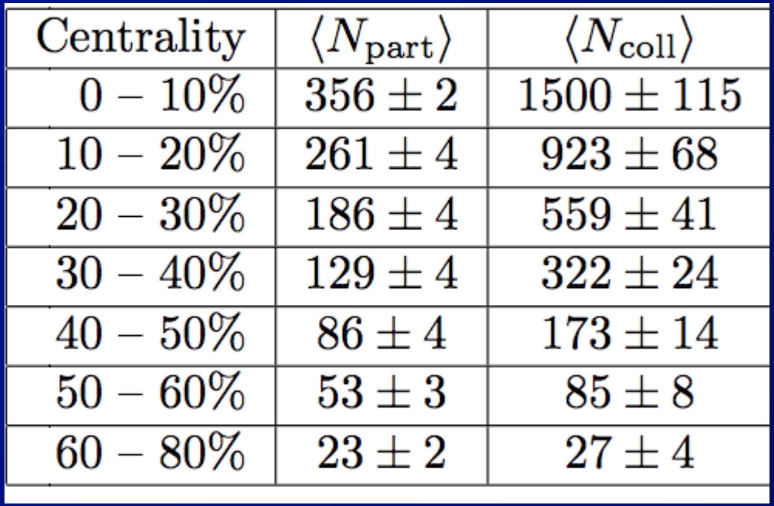
$$E_T \equiv E \sin\theta \approx p_T$$

Sum E_T over different parts of calorimeter



ATLAS: Pb+Pb centrality





Centrality	$\langle N_{\rm part} \rangle$	$\langle N_{\rm coll} \rangle$
$0 - 10\%$	356 ± 2	1500 ± 115
$10 - 20\%$	261 ± 4	923 ± 68
$20 - 30\%$	186 ± 4	559 ± 41
$30 - 40\%$	129 ± 4	322 ± 24
$40 - 50\%$	86 ± 4	173 ± 14
$50 - 60\%$	53 ± 3	85 ± 8
$60 - 80\%$	23 ± 2	27 ± 4

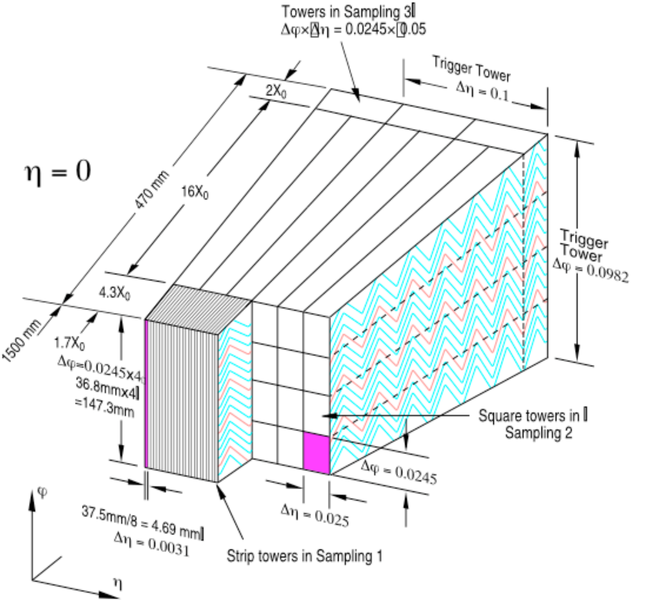
- Pb+Pb collision centrality characterized by ΣE_T in forward calorimeters ($3.2 < |\eta| < 4.9$).
  - Also quantified using number of participants (N_{part})
  - Pb+Pb partonic luminosity expressed in terms of “number of nucleon-nucleon collisions” (N_{coll}) or T_{AA}

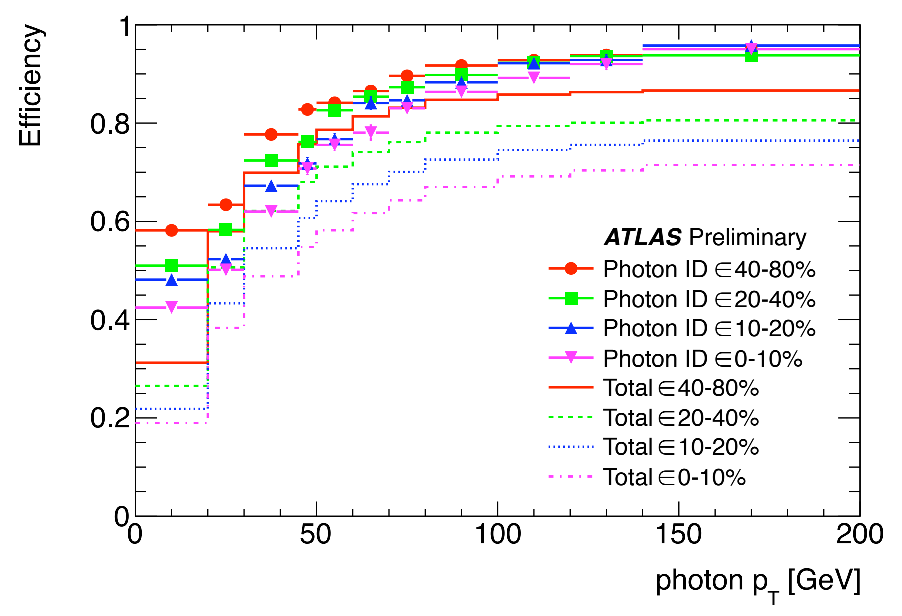
    ⇒Calculated using standard Glauber Monte Carlo.

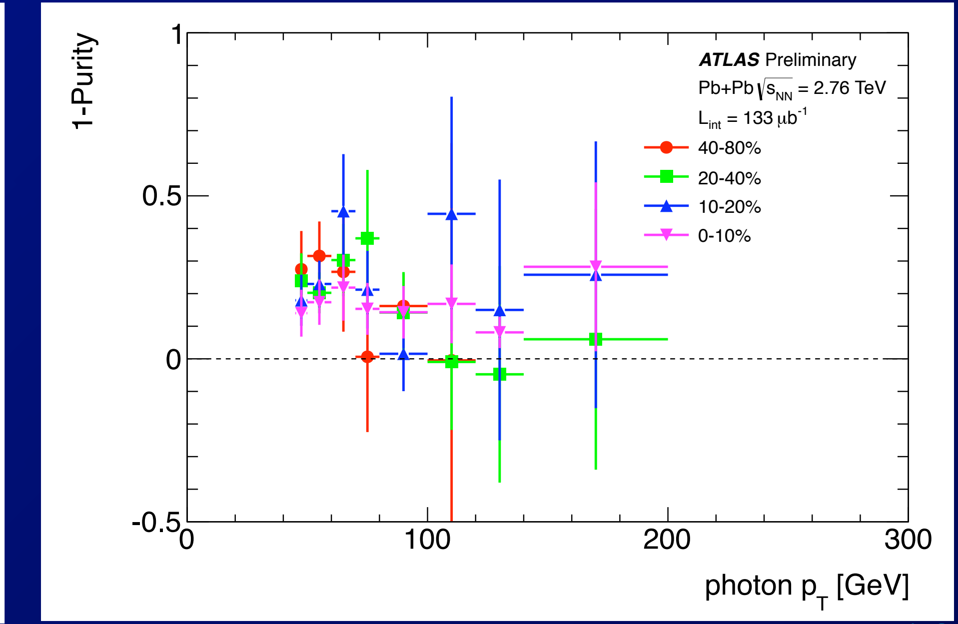
Prompt photon production

- Transverse segmentation of ATLAS EM calorimeter allows rejection of photons from π^0, η decay
- Also use isolation cuts

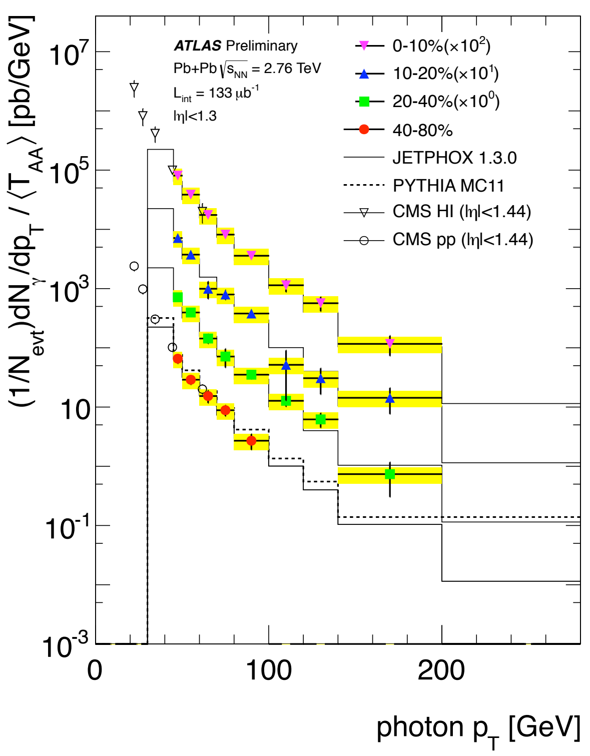
$\Rightarrow$Purity > 70%

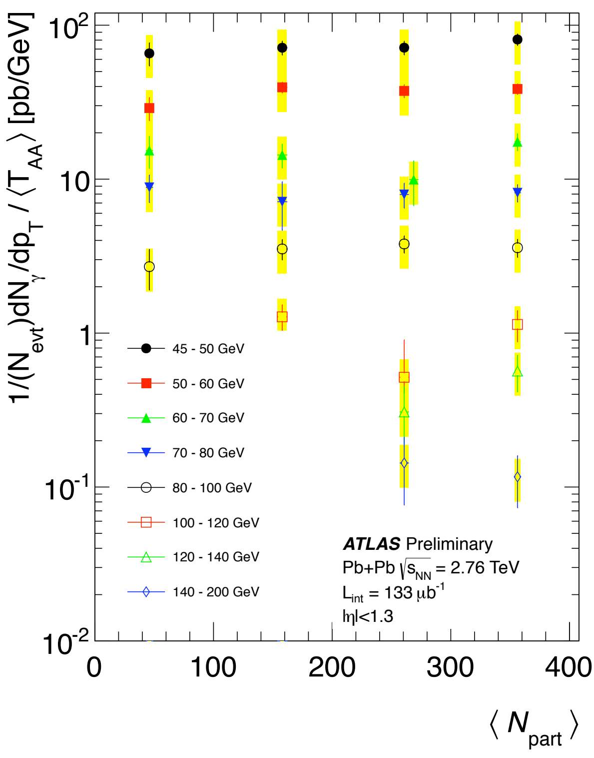


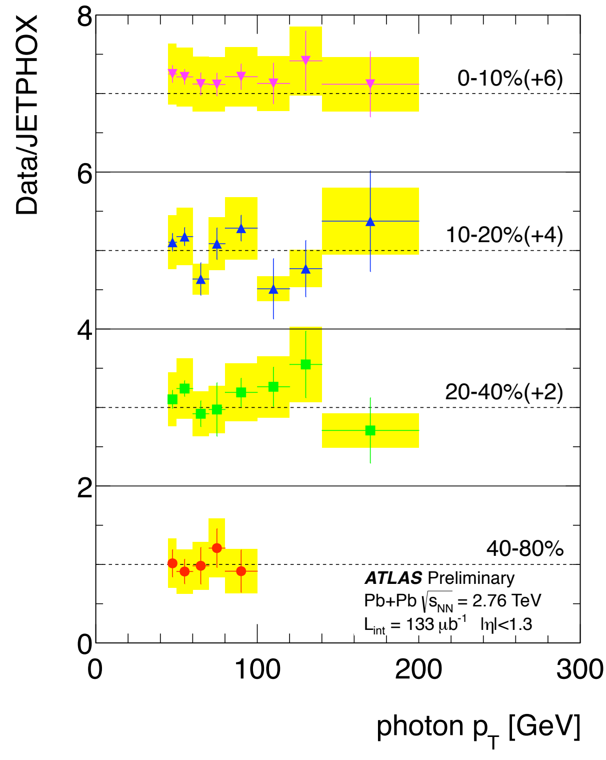




Prompt photon production (2)





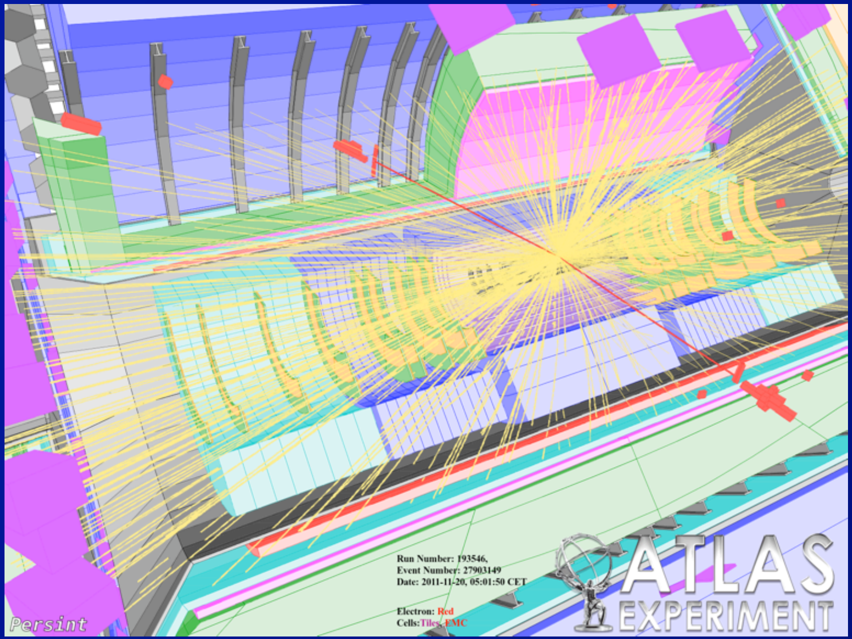


- Photon spectra over $40 < p_T < 200$ GeV
  - well described by JETPHOX multiplied by T_{AA}
  - Yield / T_{AA} ~ independent of centrality

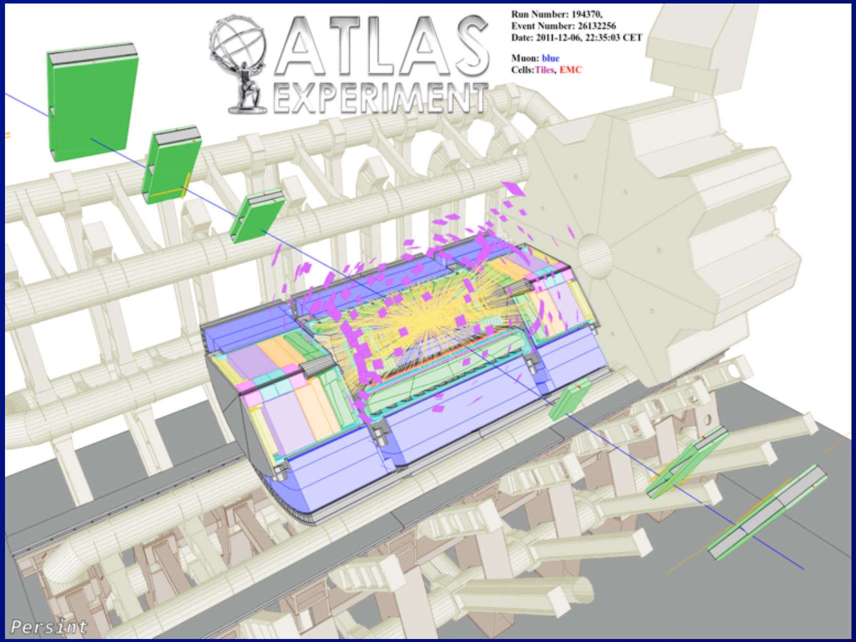
    ⇒Hard QCD photon production varies with Pb+Pb centrality as expected

Z production

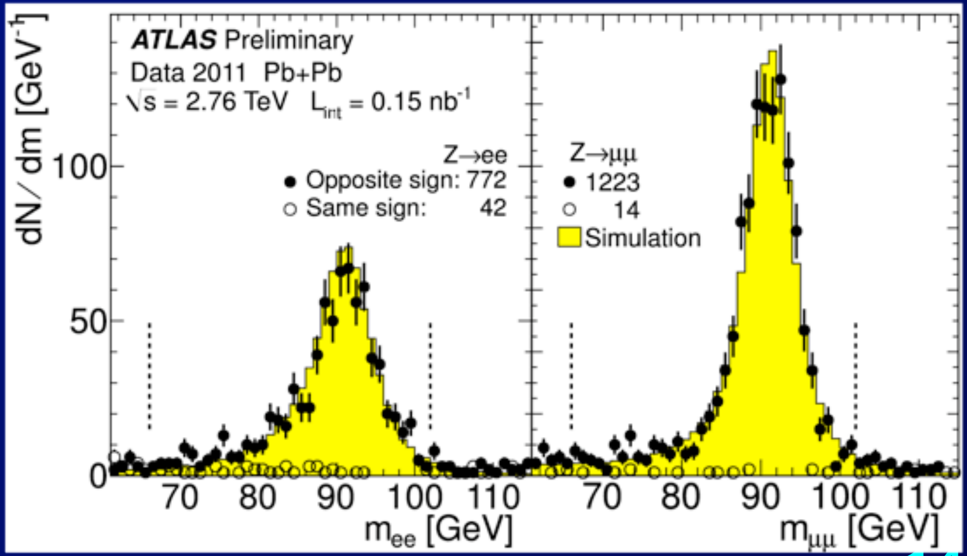
$Z \rightarrow e^+e^-$ event display



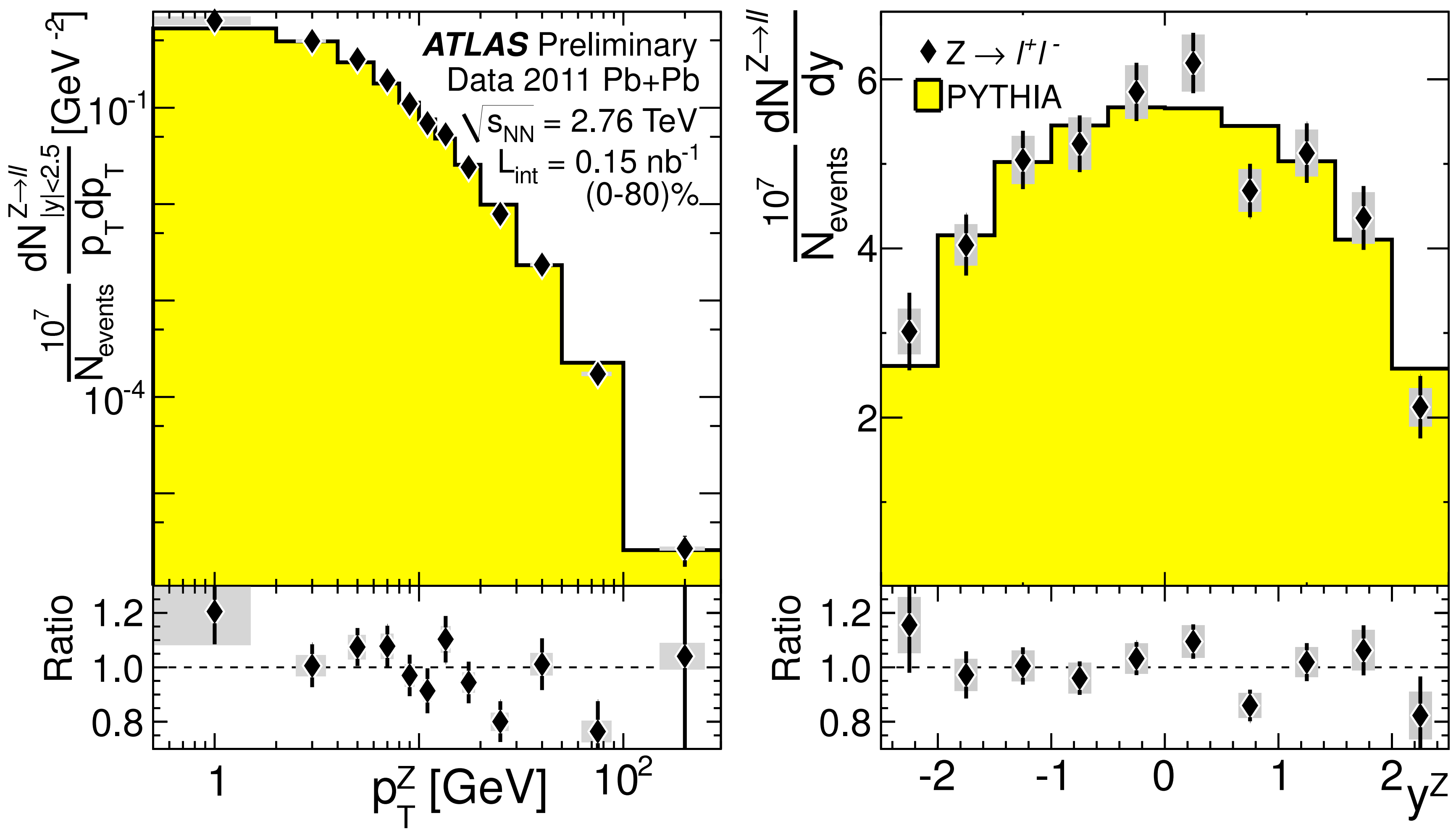
$Z \rightarrow \mu^+\mu^-$ event display



- **Measured in both electron and muon channels**
  - different efficiency
  - consistent results

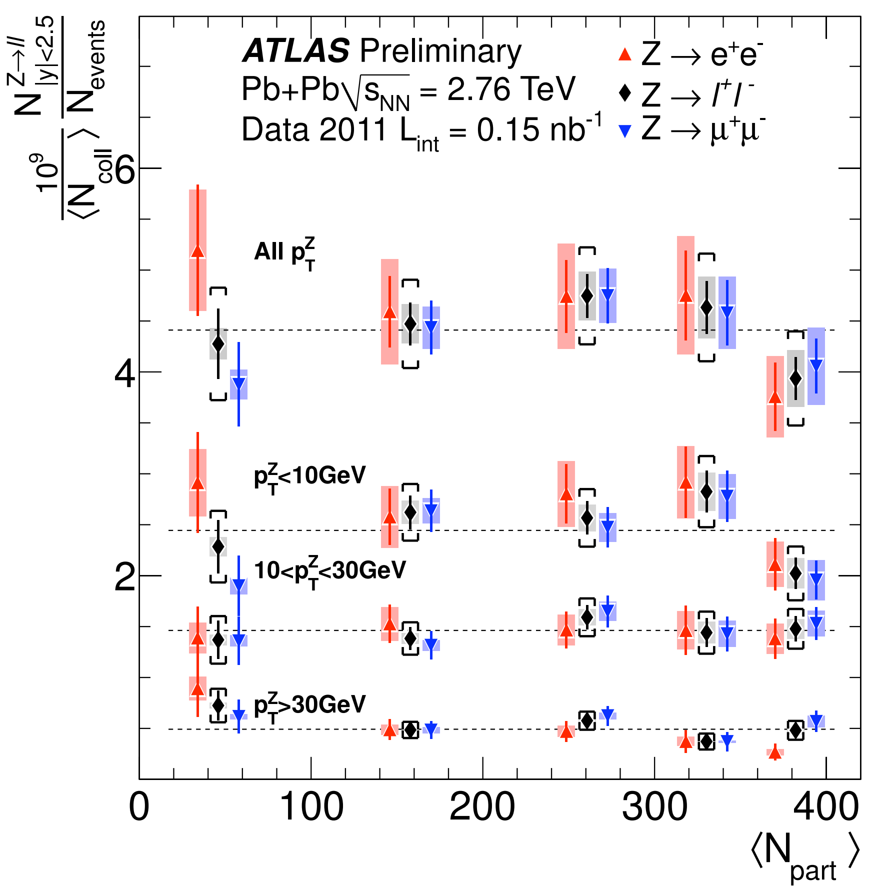


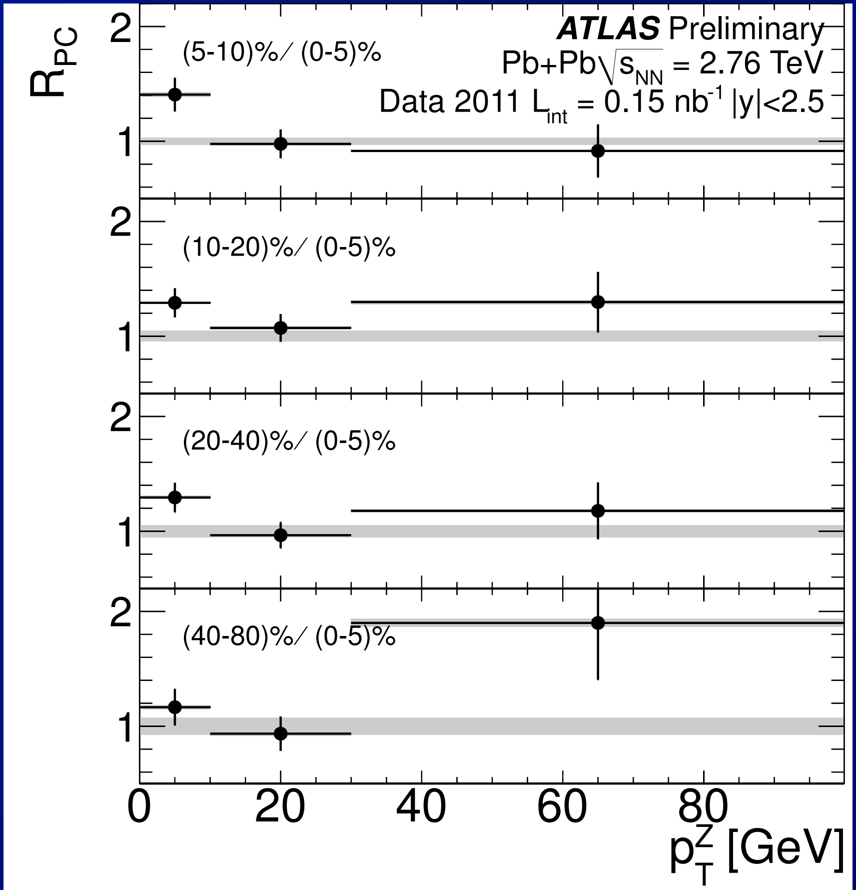
Z production (2)



- Minimum-bias Pb+Pb Z p_T and rapidity distributions well-described by PYTHIA

Z production (3)

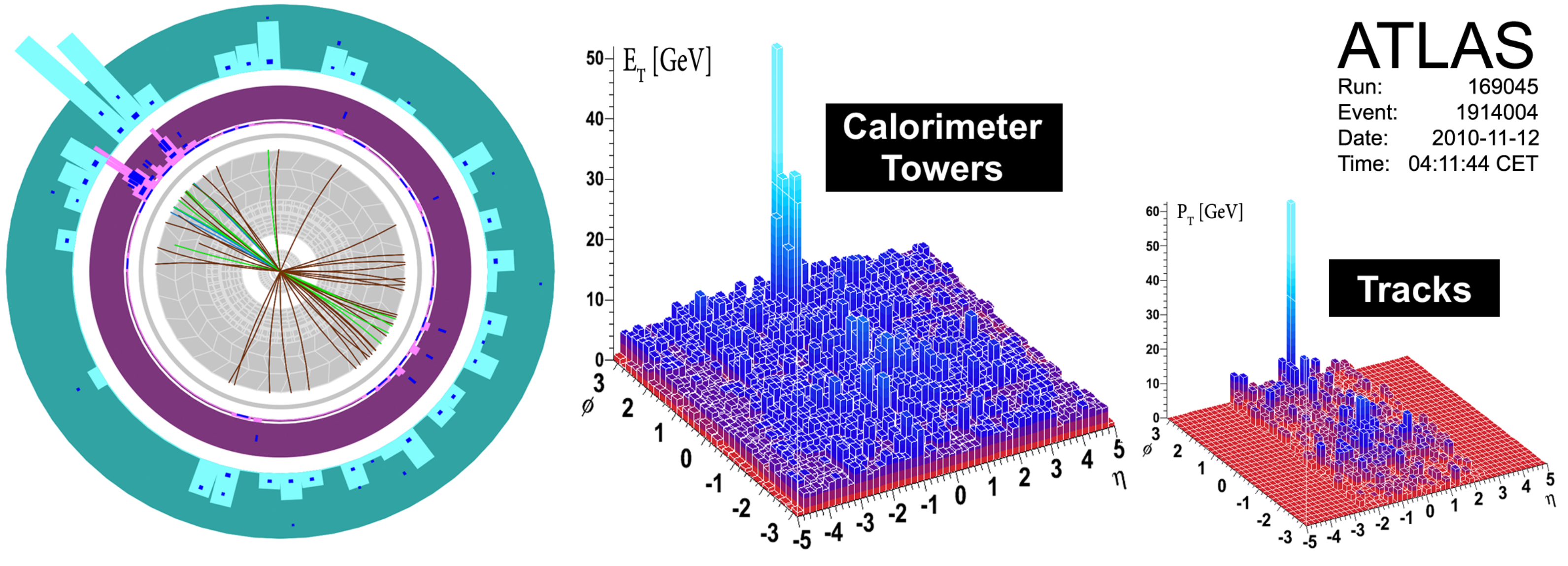


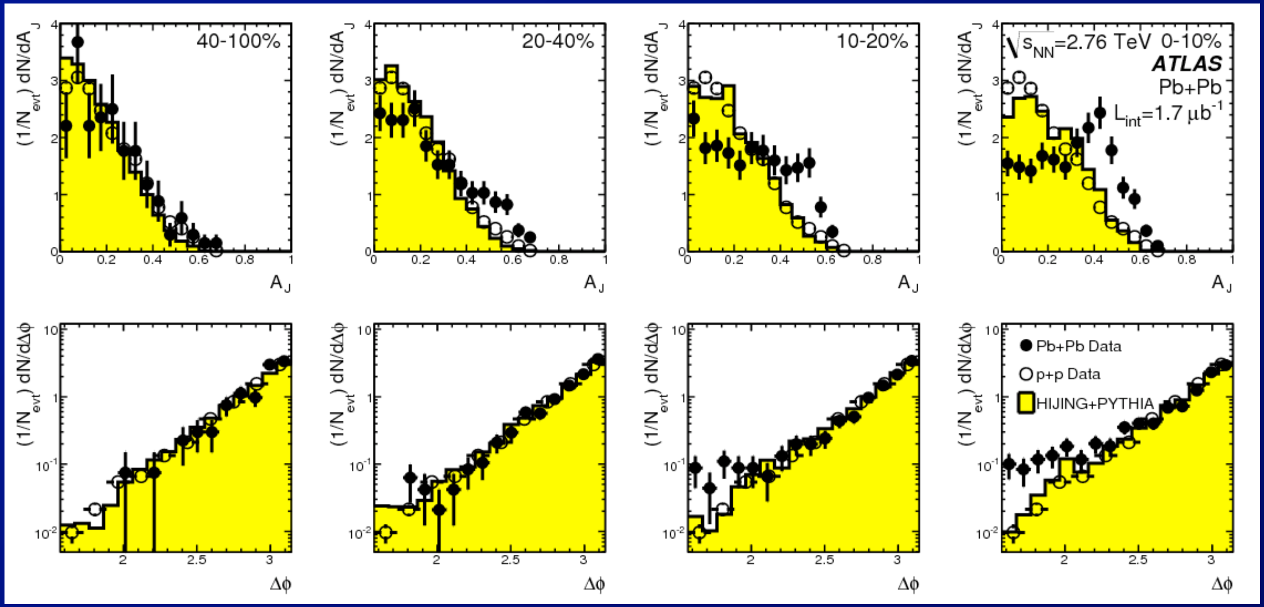


- Z yield / N_{coll} independent of centrality.
- R_{PC} (peripheral/central) ~ 1
  - –though possible reduction of low-p_T Z yield in more central collisions

Jet measurements

ATLAS dijet asymmetry measurement





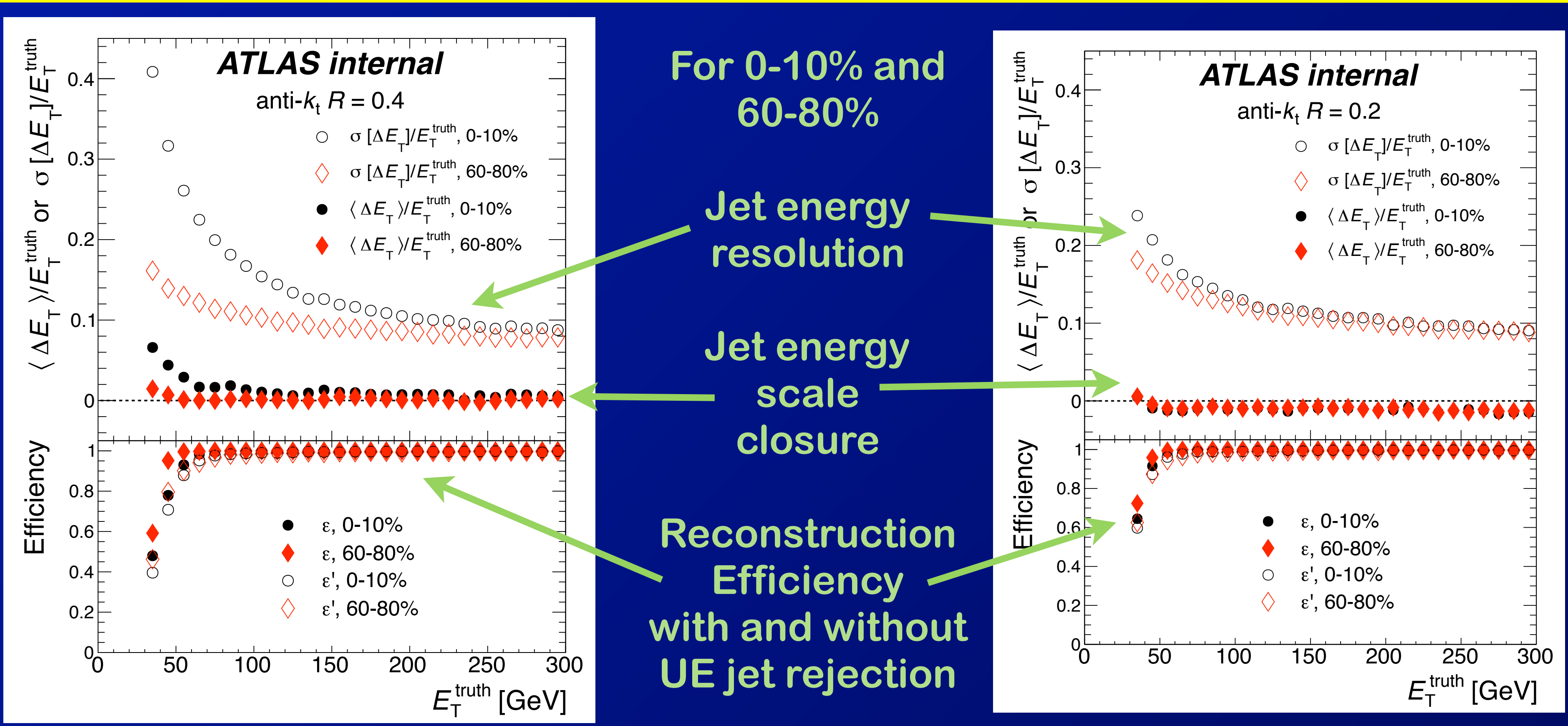
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

$$E_{T1} > 100\ GeV$$

$$E_{T2} > 25\ GeV$$

1st indication of medium modifications of jets @ LHC

ATLAS Pb+Pb Jet Performance



For 0-10% and 60-80%

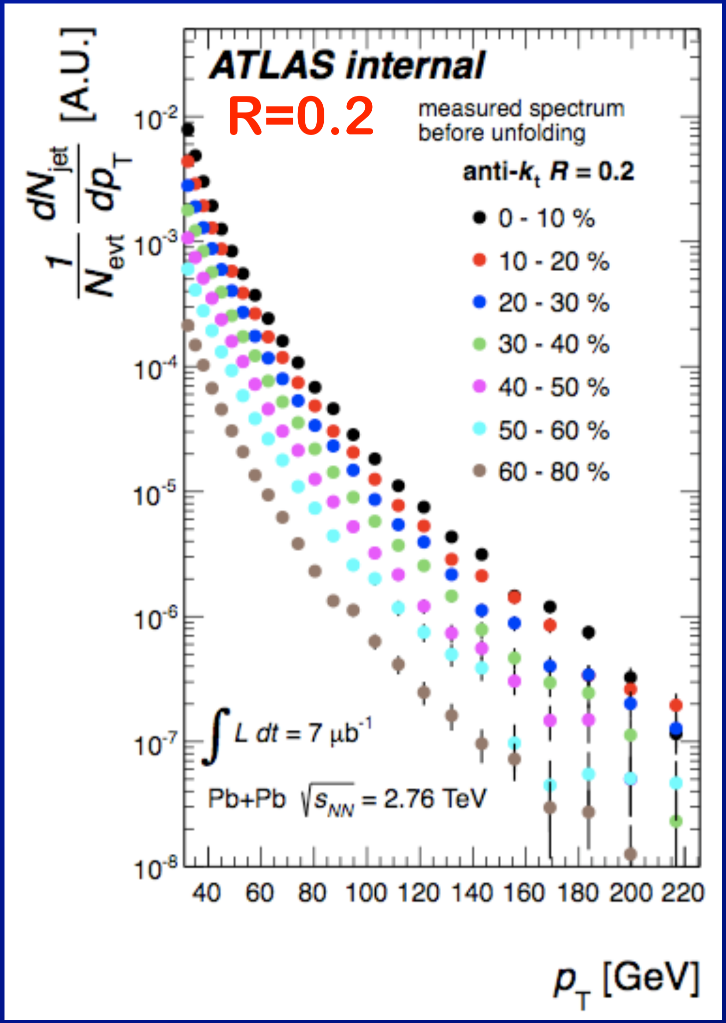
Jet energy resolution

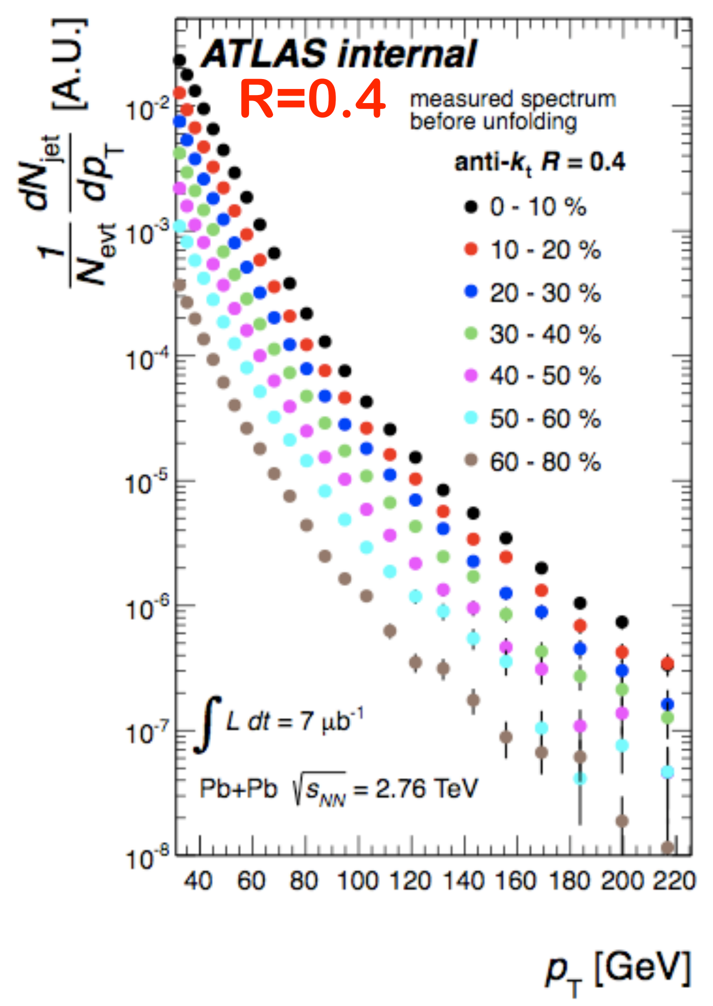
Jet energy scale closure

Reconstruction Efficiency with and without UE jet rejection

- Evaluated first using 5 million PYTHIA dijet events overlayed on 10^6 HIJING Pb+Pb events
  - More recently, also evaluated using PYTHIA overlaid onto 10^6 minimum-bias Pb+Pb data events

Pb+Pb Jet Spectra





Unfolded (SVD) and efficiency corrected

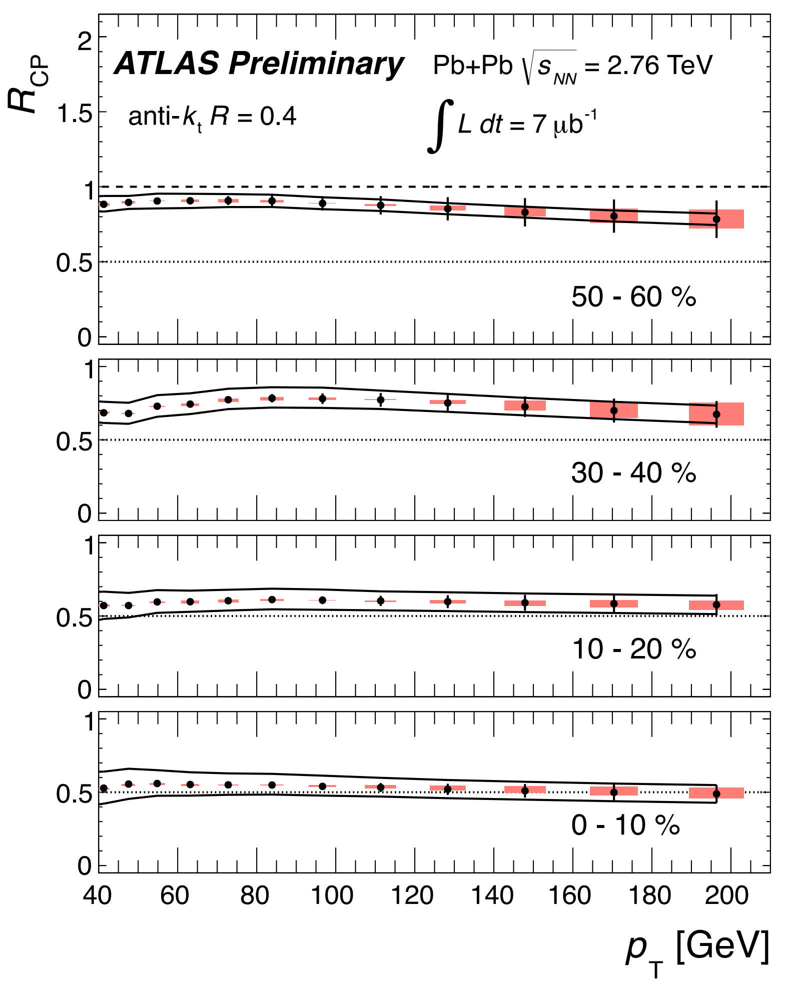
- Absolute normalization awaiting final Pb+Pb absolute jet energy scale.

Jet yields: centrality dependence

- If factorization holds jet yields should vary with centrality $\propto N_{\text{coll}}$
- Compare yields between centrality bins using "R_{cp}"

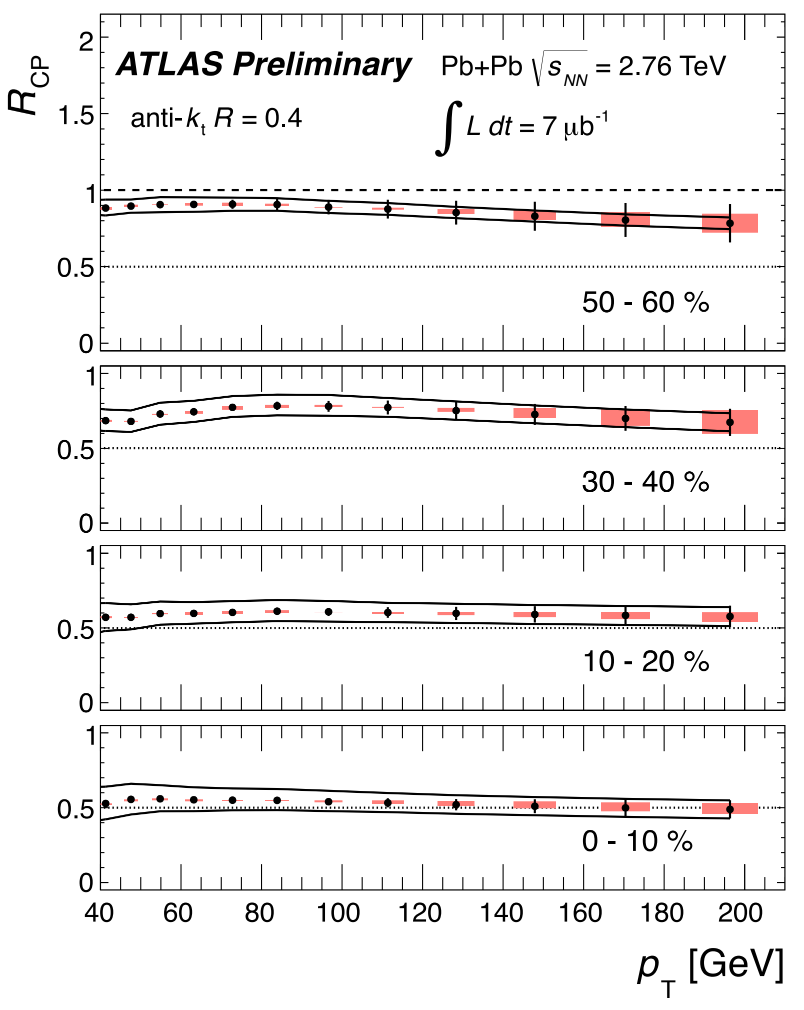
$$R_{CP} = \frac{\left.\frac{1}{N_{\text{coll}}}\frac{1}{N_{\text{evt}}}\frac{dN}{dp_T}\right|_{\text{cent}}}{\left.\frac{1}{N_{\text{coll}}}\frac{1}{N_{\text{evt}}}\frac{dN}{dp_T}\right|_{60-80}}$$

  - Overall jet energy scale divides out in ratio



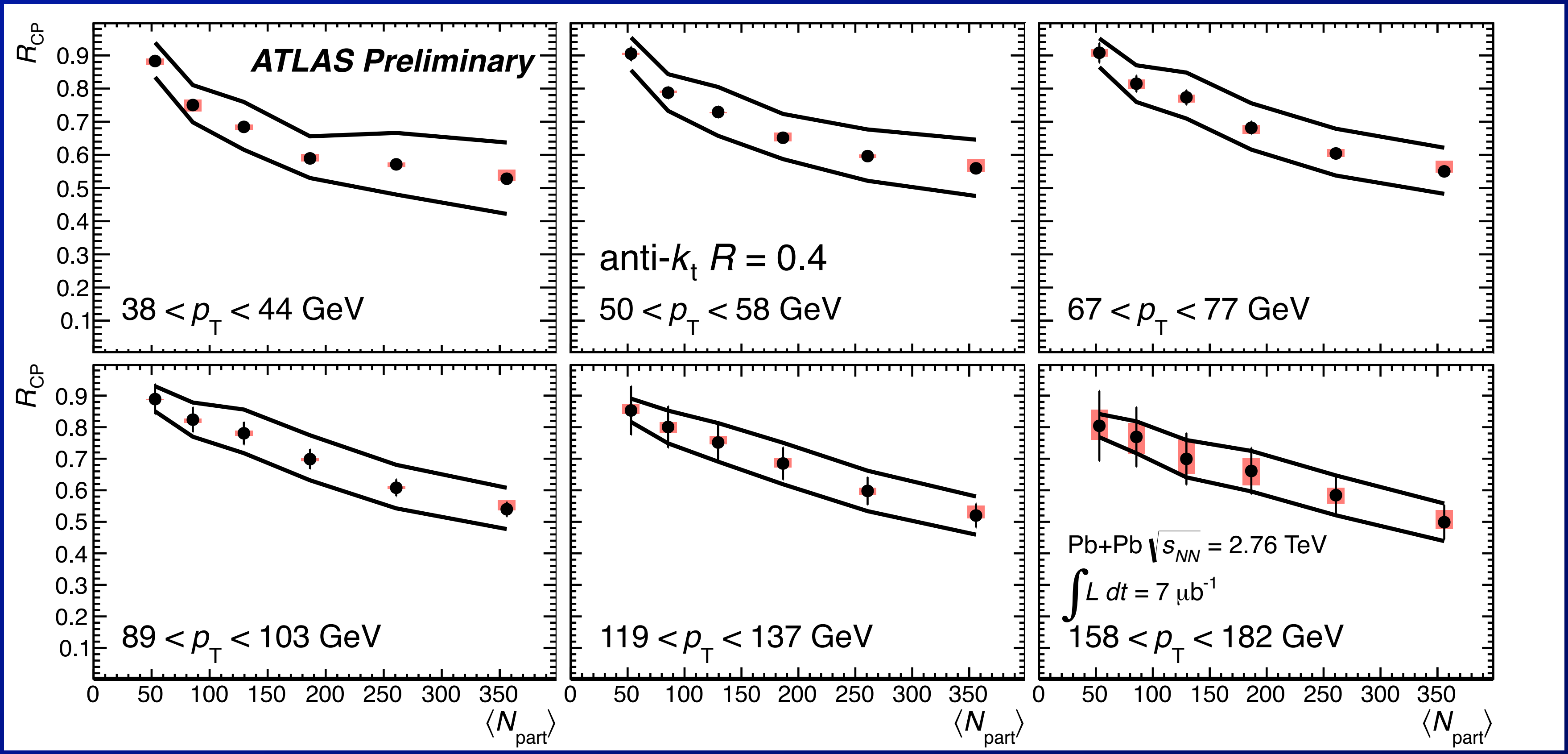
Jet yields: centrality dependence (2)

- Systematic errors
  - Black band: fully correlated systematics
    - ➡ all points move up/down together
    - ➡ JES, JER, efficiency, x_{ini}, R_{coll}
  - Red boxes: partially correlated systematics
    - ➡ unfolding
- Error bars: square root of diagonal elements of covariance matrix
- No significance to horizontal width of error bars



- Jet yield/Ncoll reduced in central collisions
  - ⇒for 0-10% by factor of ~2
  - ⇒Suppression only weakly dependent on p_T

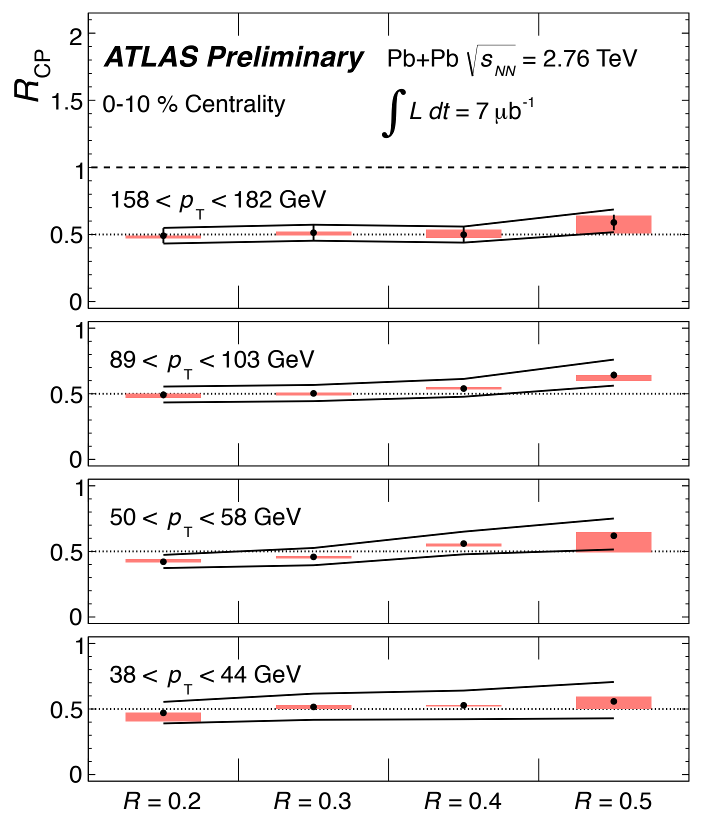
Centrality dependence of jet R_{cp}



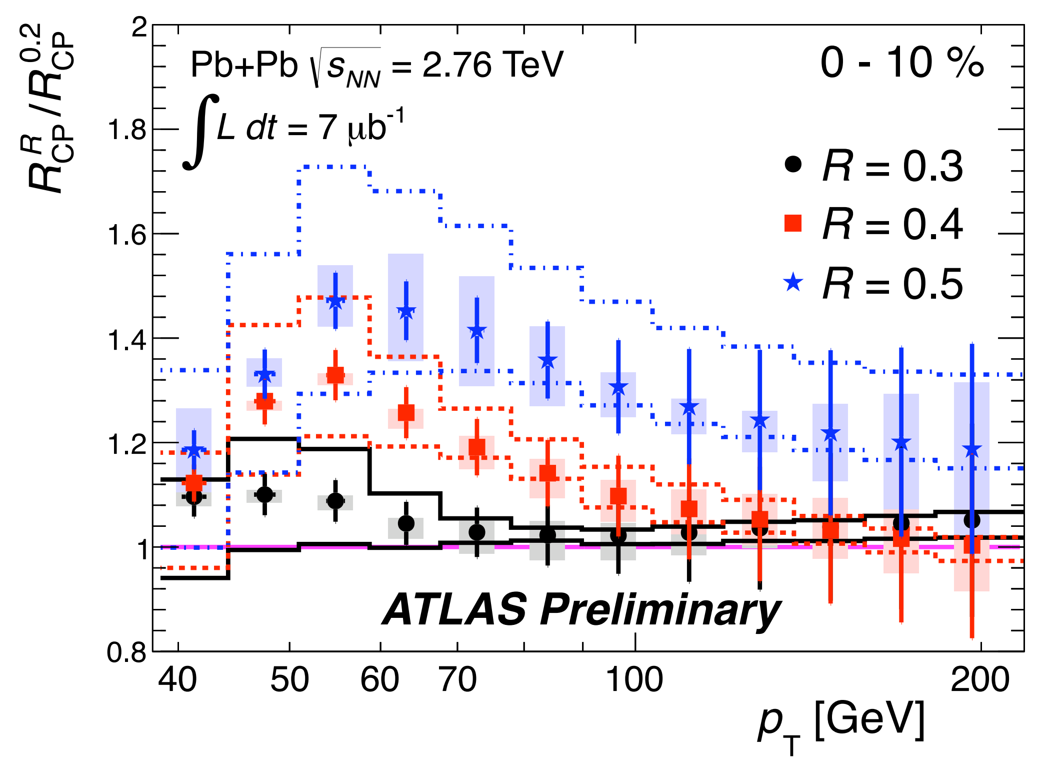
- **Study centrality evolution for fixed jet p_T**
  - R_{cp} vs N_{part}

    ⇒Smooth turn on of jet suppression between peripheral and central collisions.

Jet radius dependence of R_{cp}



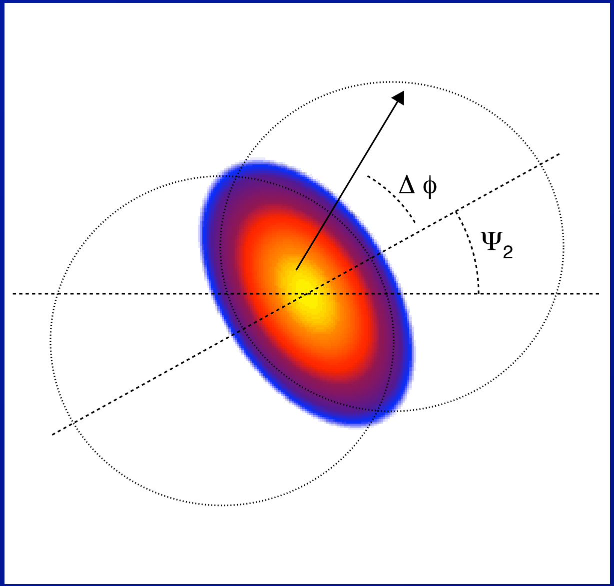
Significant cancellation of correlated errors

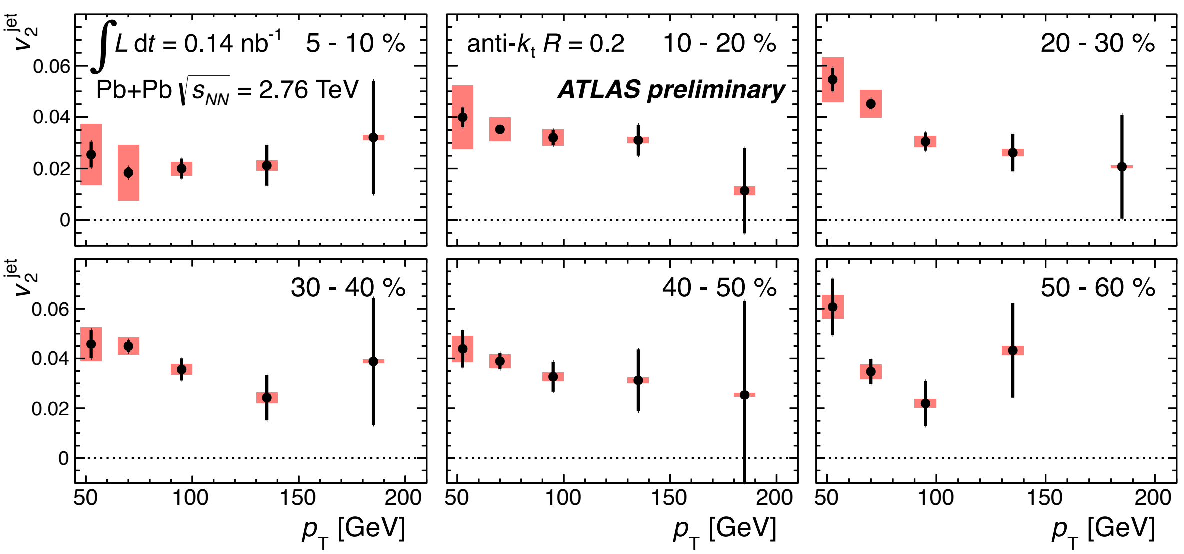


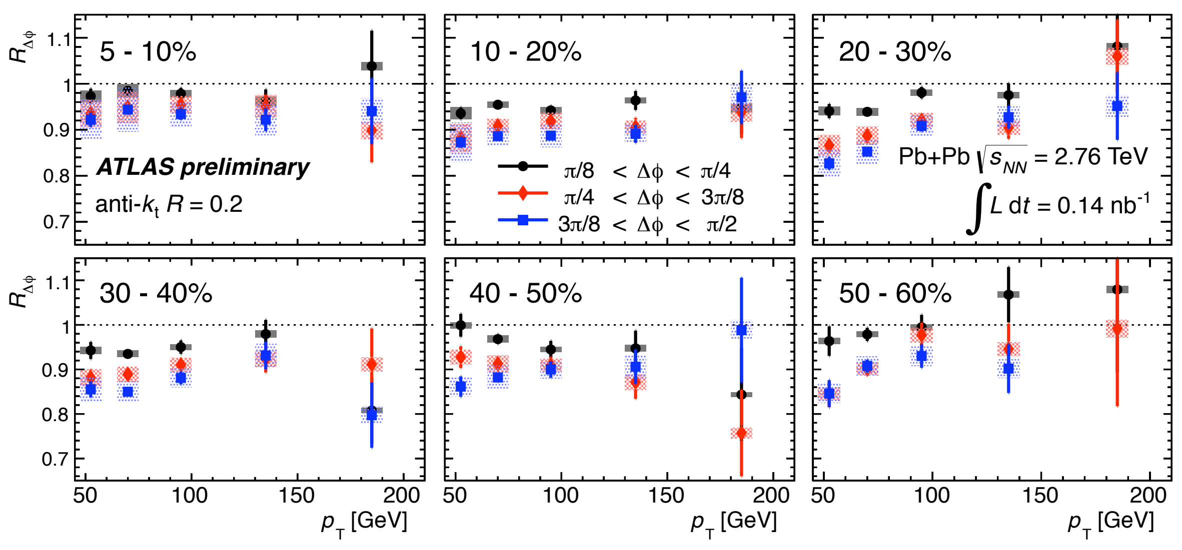
- Evaluate jet radius dependence of R_{cp}
  - Modest but significant variation of R_{cp}
  - Less suppression for larger R

⇒An indication of jet broadening?

Differential jet suppression



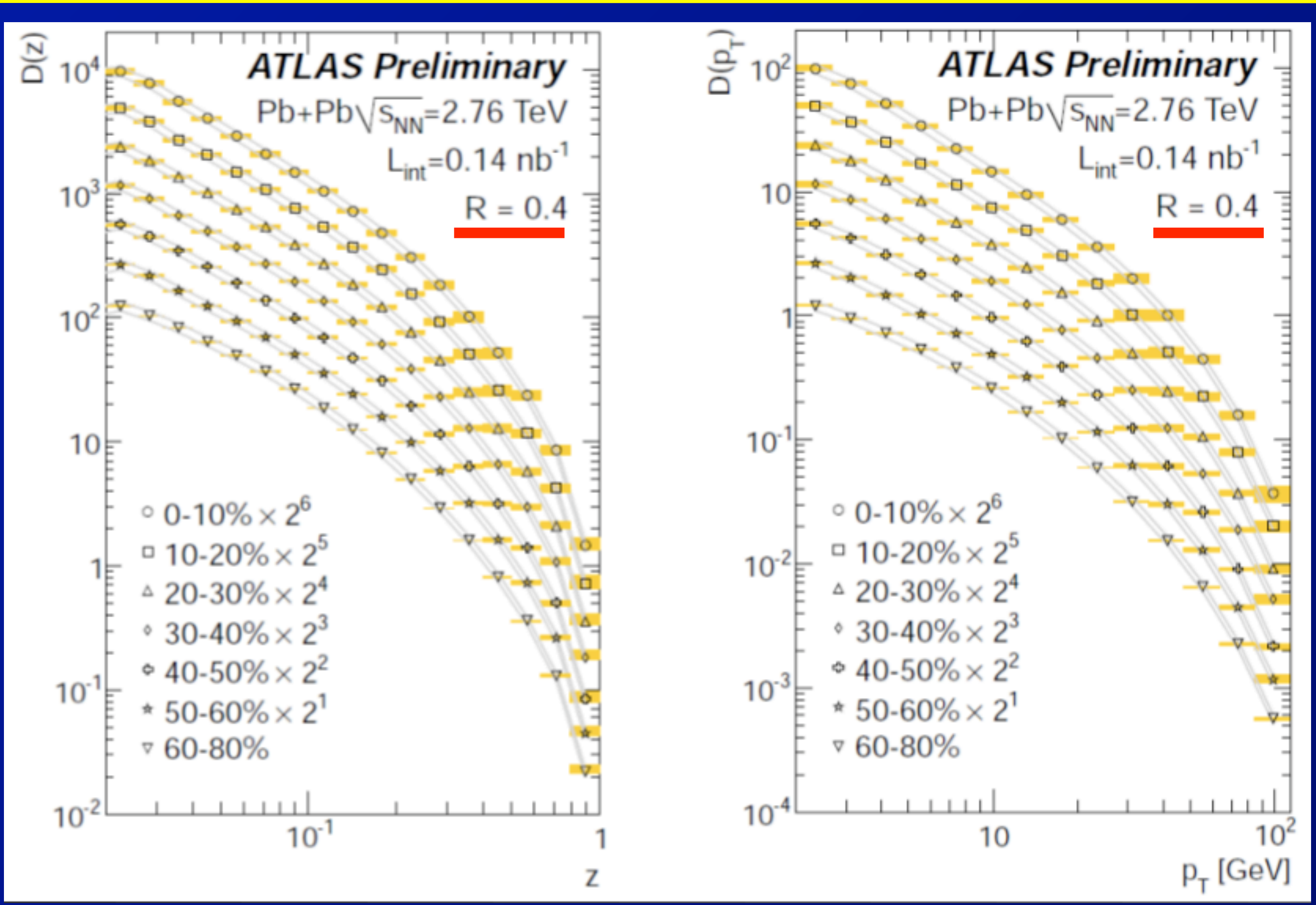




- **Measure:**
  - Jet v_2
  - Ratios of jet yields in Δφ bins

⇒1st measurement of differential jet quenching using jets.

Inclusive jet fragmentation

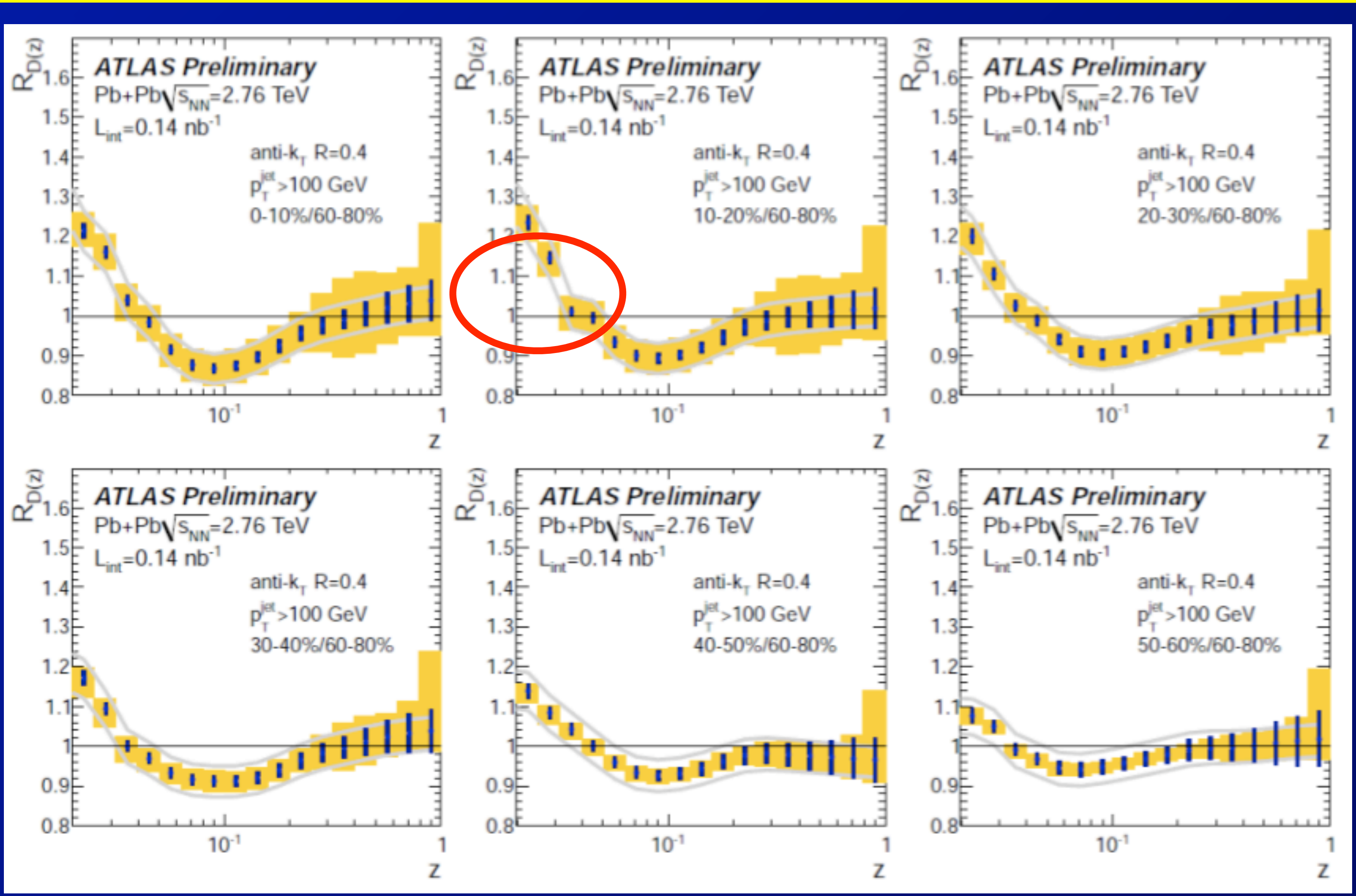


Unfolded for jet and charged particle resolution

$$D(z) = \frac{1}{N_{jet}} \frac{dN_{chg}}{dz}, z = \vec{p}_{chg} \cdot \vec{p}_{jet} / \left| \vec{p}_{jet} \right|$$

$$D(p_T) = \frac{1}{N_{jet}} \frac{dN_{chg}}{dp_T}$$

Inclusive jet fragmentation (2)

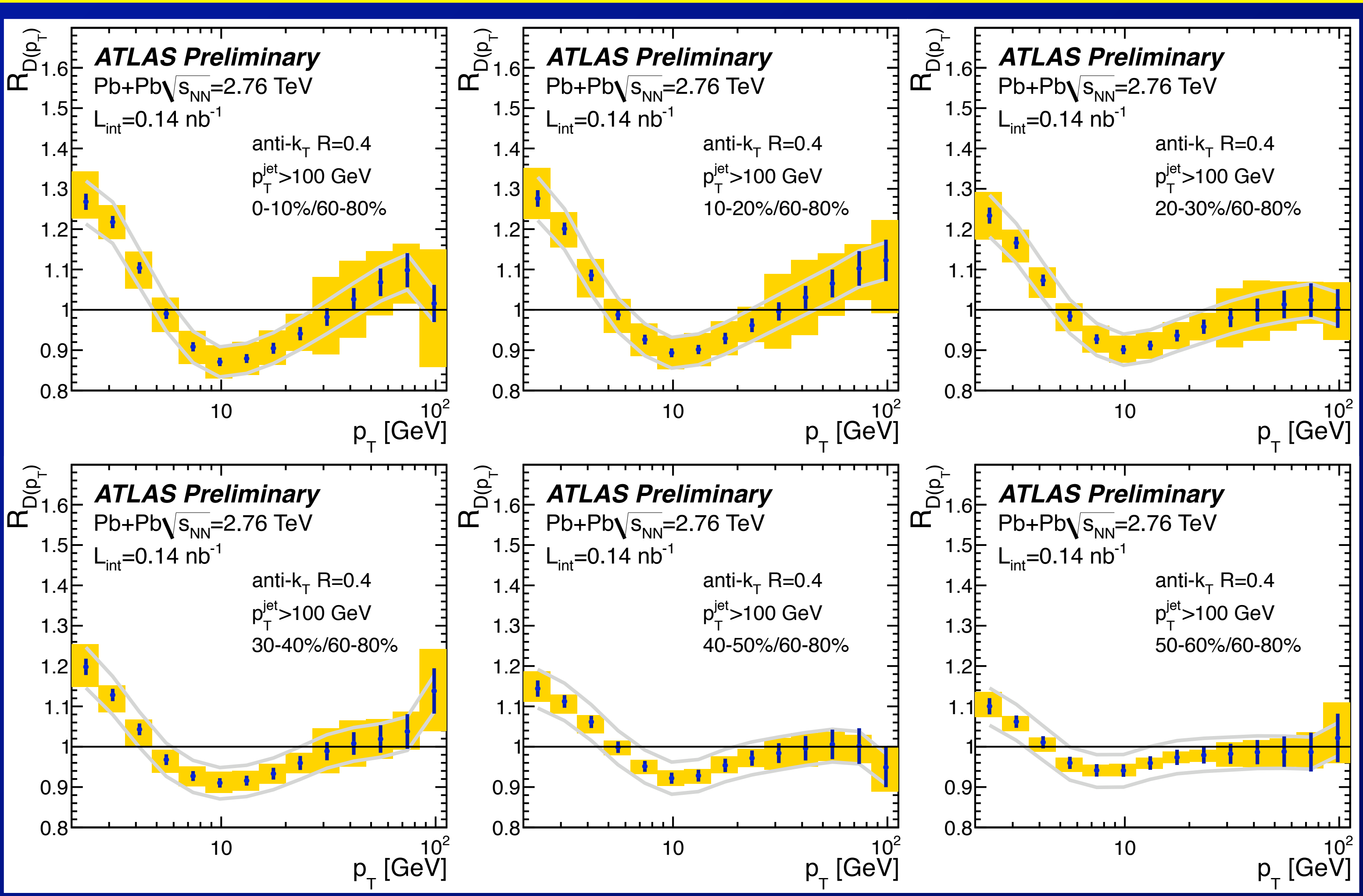


R = 0.4

- First observation of modified parton shower in inclusive jets

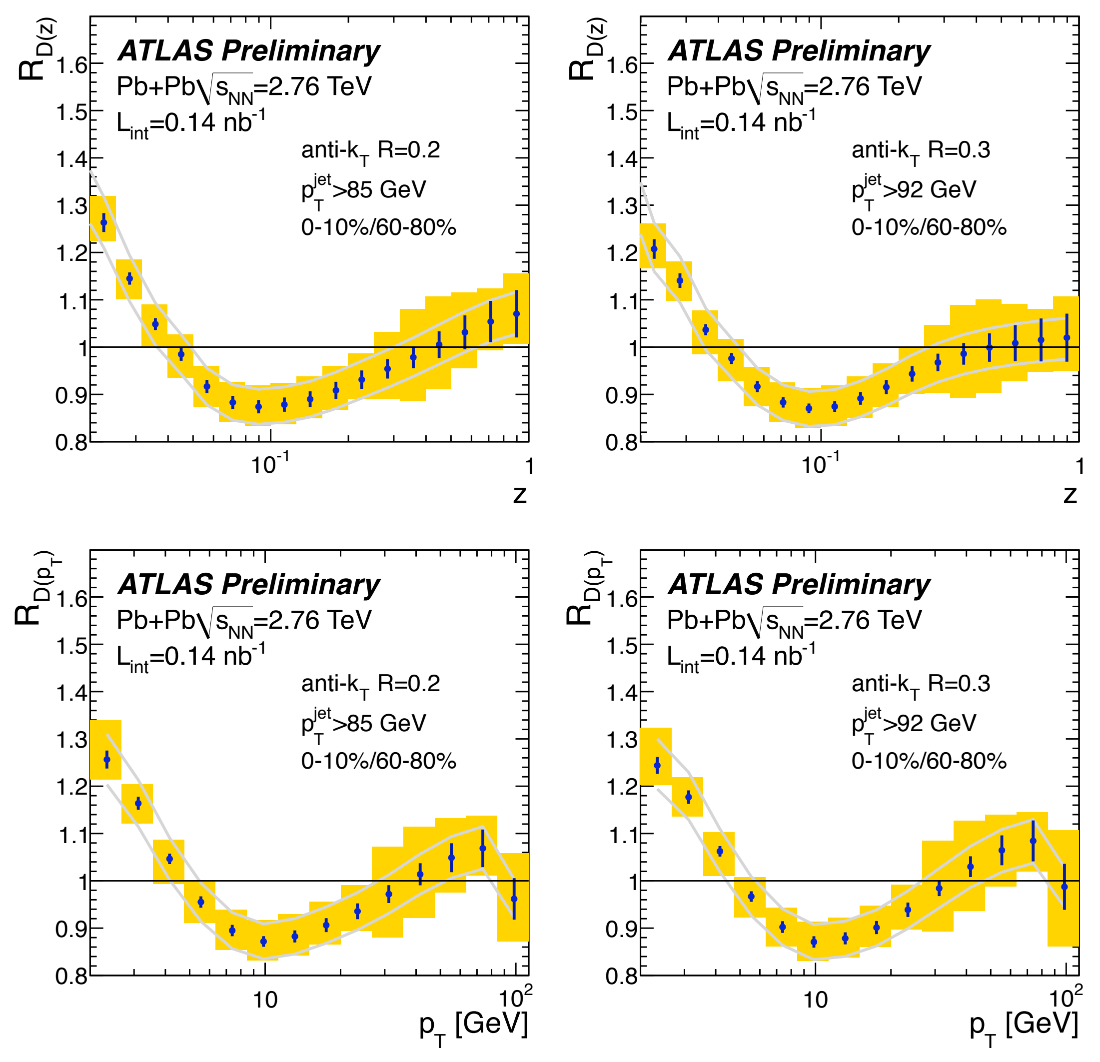
⇒Not only seeing “left over” unquenched jets.

Inclusive jet fragmentation (3)



- Check that the modification is not due to the measurement of jet p_T ⇒ $D(p_T)$
  - ⇒$D(p_T)$ shows similar modifications

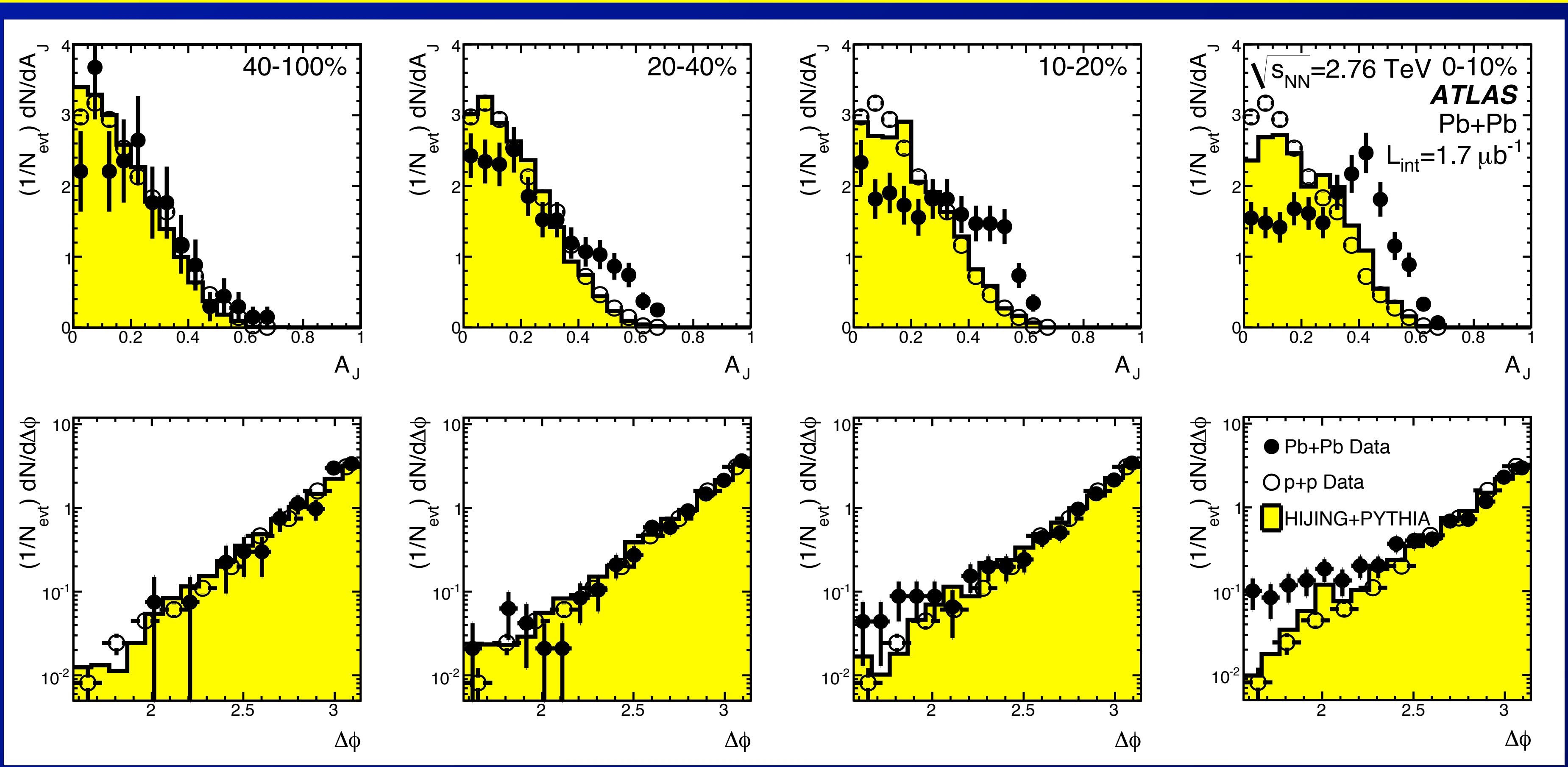
Jet fragmentation: R depdendence



- Check that the modification is not due to underlying event fluctuations
  - Use different jet sizes: R = 0.2, 0.3
- Obtain the same results as R = 0.4

⇒Observed modifications are robust

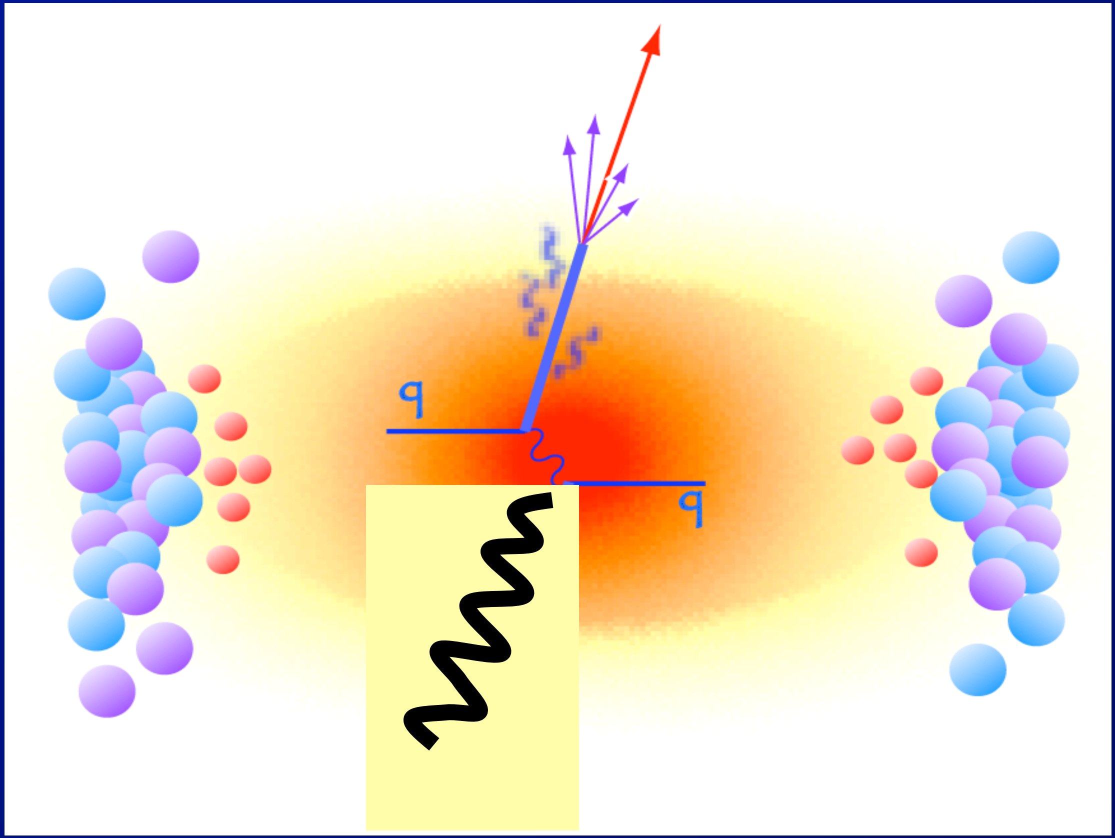
Di-jet asymmetry & acoplanarity



- **For more central collisions, see:**
  - Change in distribution of dijet asymmetry
  - While no change in the distribution of Δφ
    - ⇒Except for combinatoric pairs in central

Jet probes of the quark gluon plasma

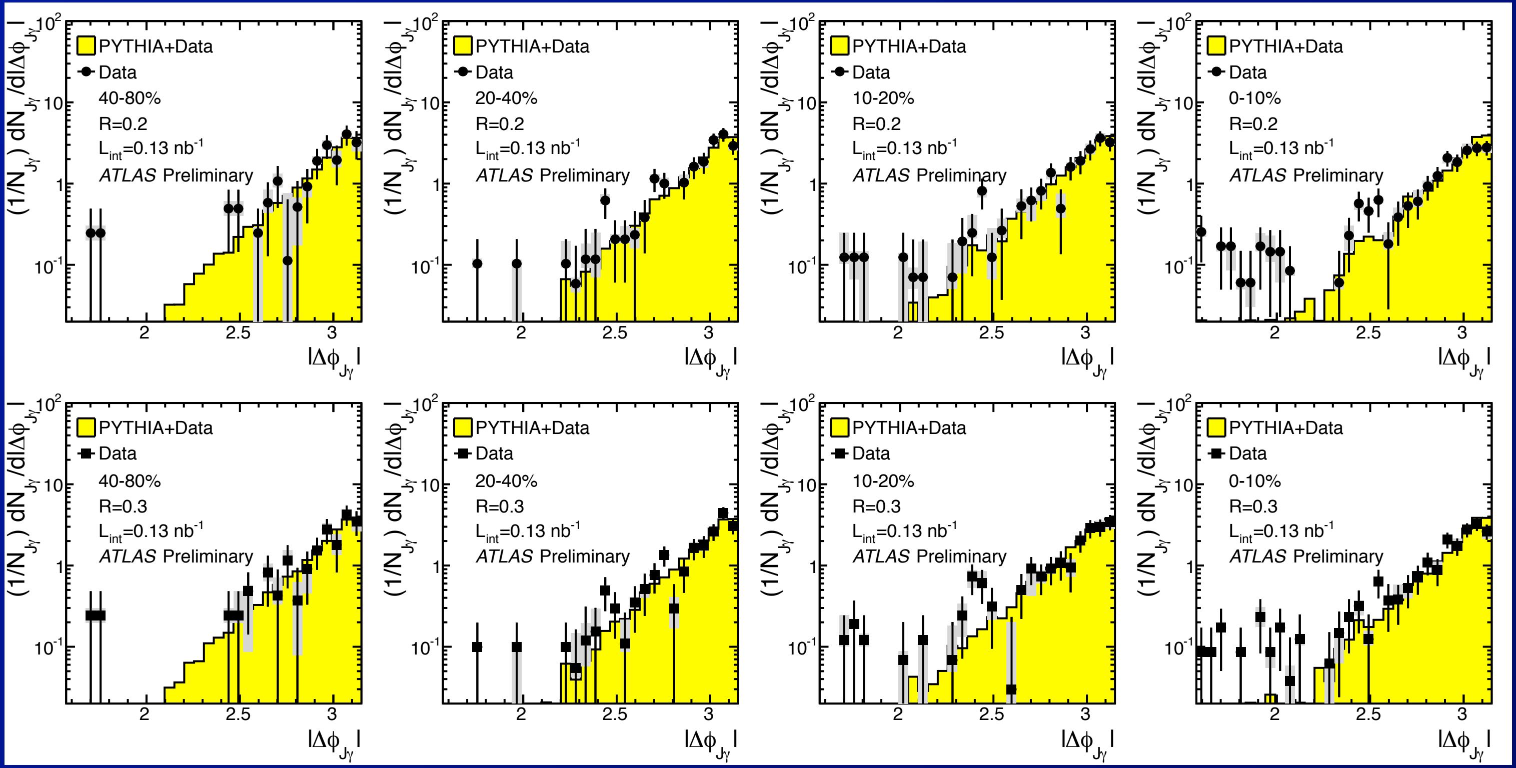
- Use γ-jet pairs to directly probe the quark gluon plasma (QGP)



- Key experimental question:
  - ⇒How do parton showers in quark gluon plasma differ from those in vacuum?
    - » Where the photon provides a reference energy scale for the jet.

γ-jet angular distribution

Peripheral ⟶ central



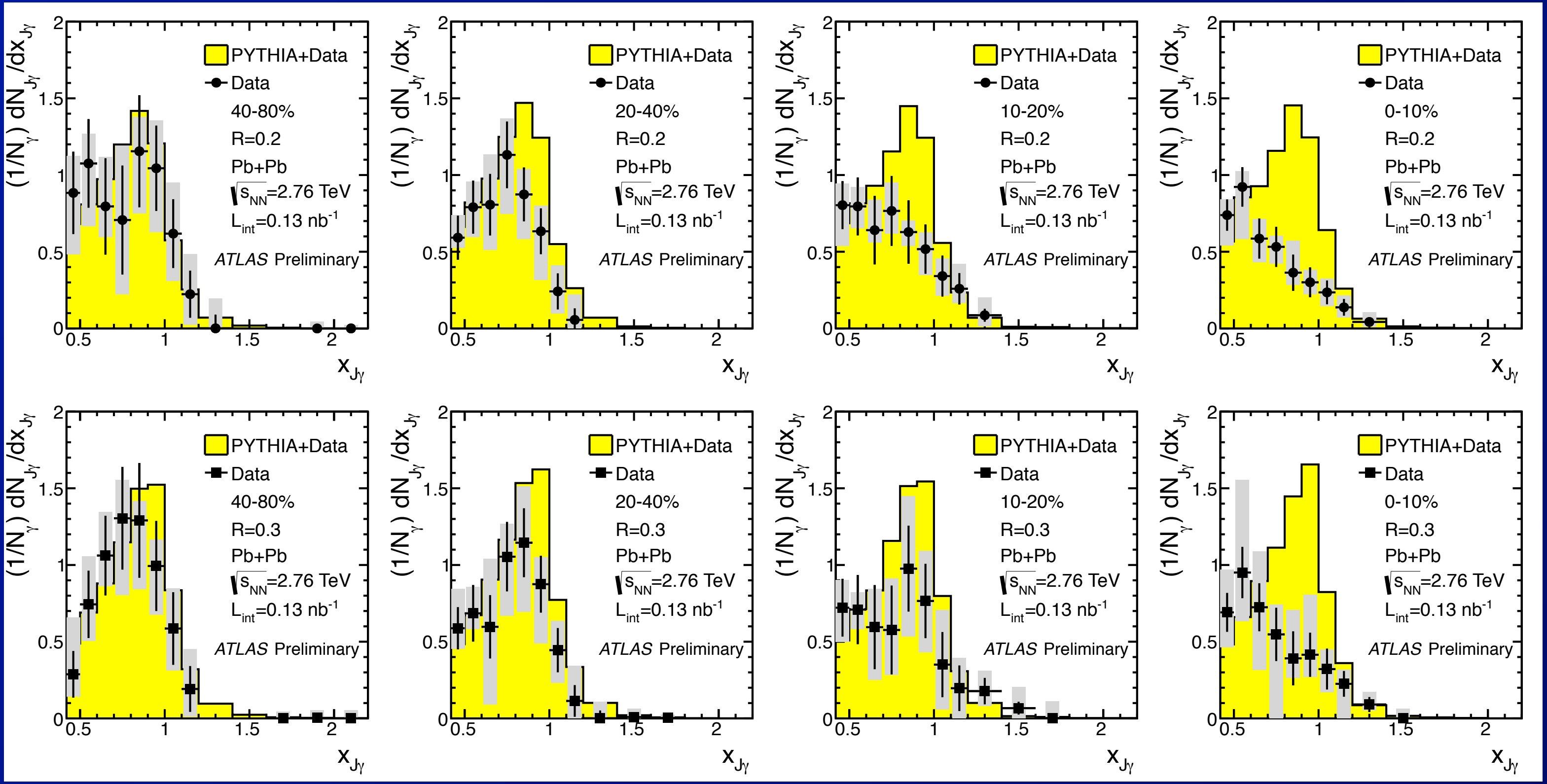
R = 0.2

R = 0.3

- Take leading jet in hemisphere opposite photons with $60 < p_T < 90$ GeV
  - Jets with $p_T > 25$ GeV, R = 0.2 and 0.3
    - ⇒Distribution of Δφ peaked at π
    - ⇒For following, apply cut $|\Delta\phi - \pi| < 7\pi/8$

γ-jet momentum balance

Peripheral ⟶ central



R = 0.2

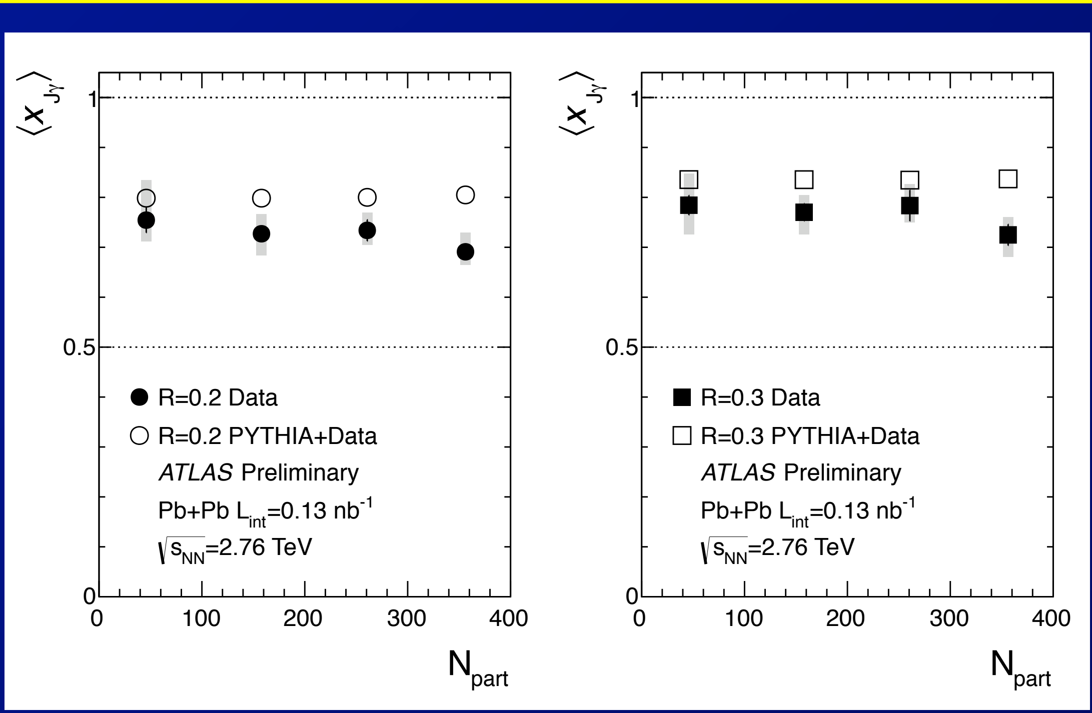
R = 0.3

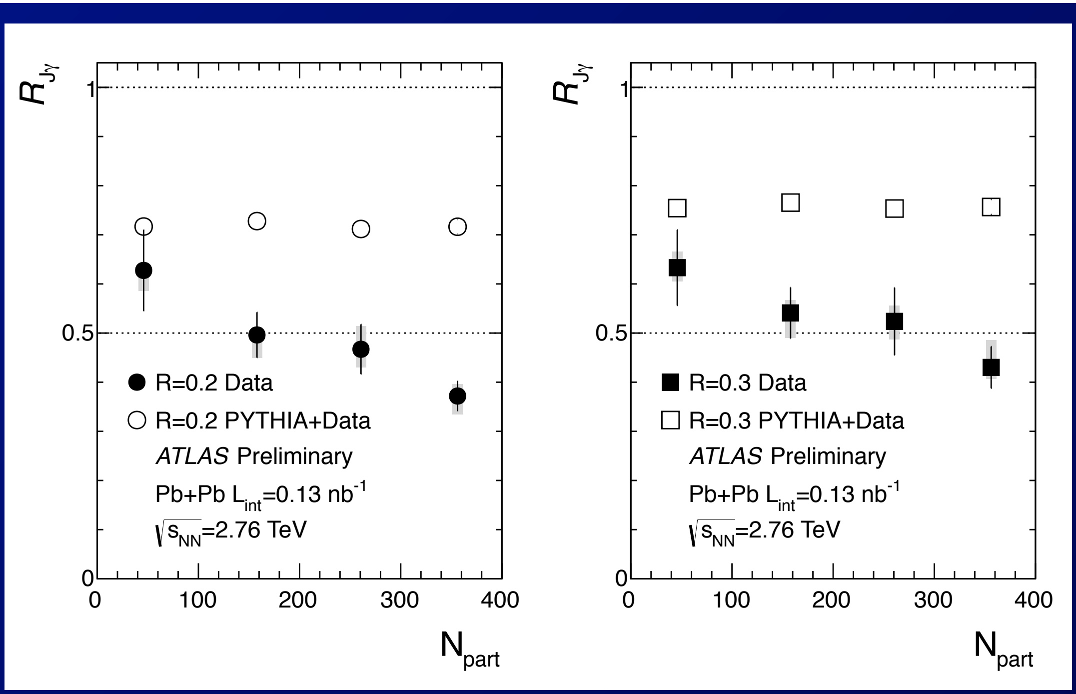
- Plot distribution of $x_J = p_T^{\mathrm{jet}} / p_T^{\gamma}$
  - photon background pairs subtracted
  - unfolded for jet energy resolution

⇒Substantial change in γ-jet balance

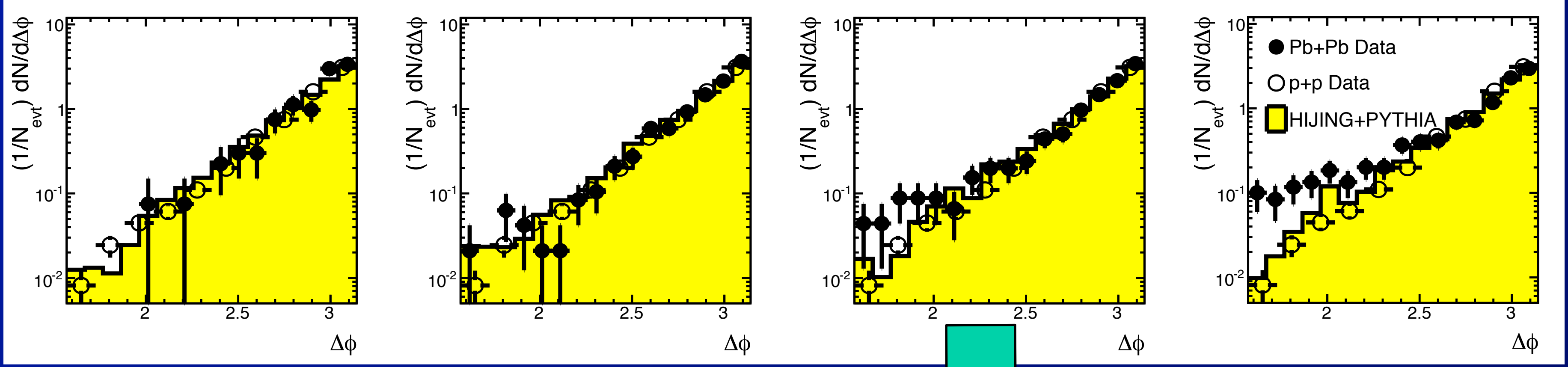
γ-jet momentum balance

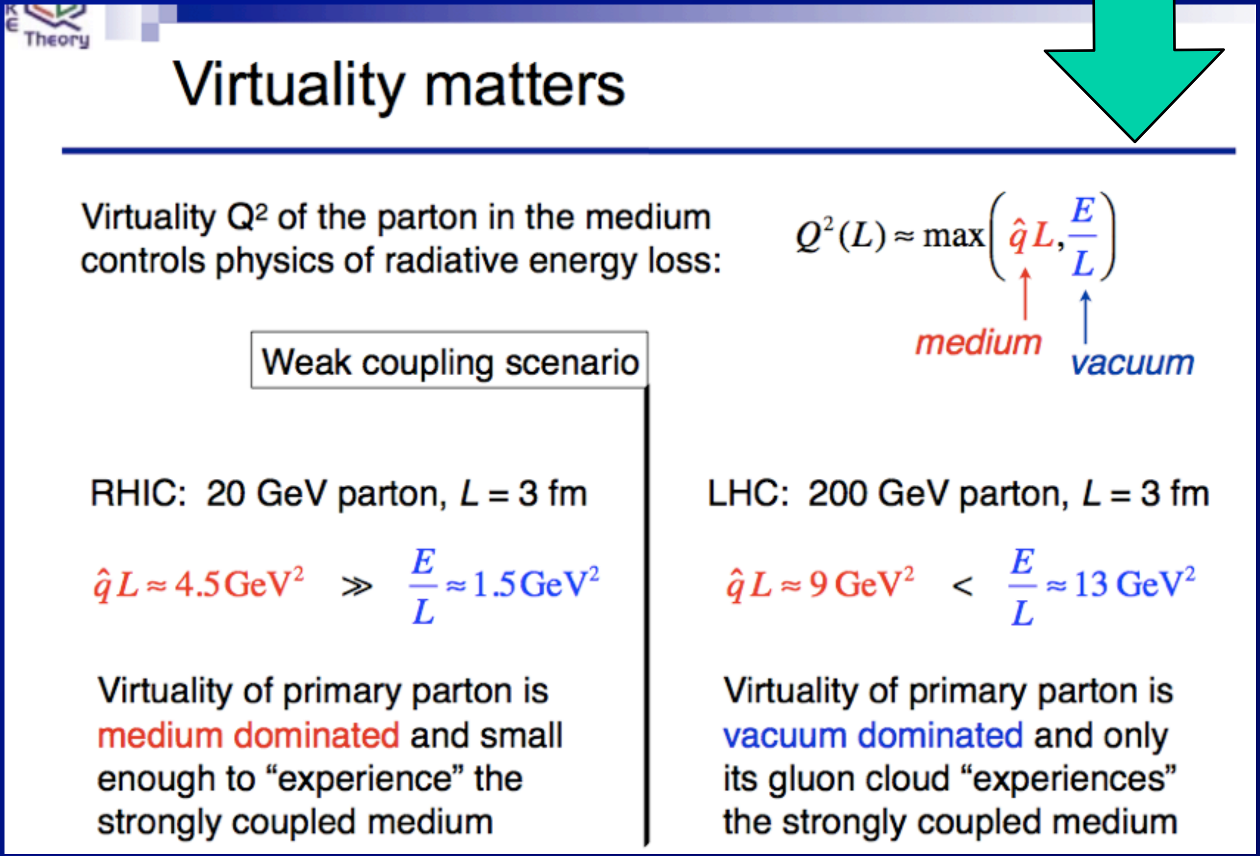
- Quantify the behavior seen in the x_J distributions
  - Evaluate $\langle x_J \rangle$ and R -- fraction of photons with jet passing cuts
    - ⇒$\langle x_J \rangle$ limited by acceptance
    - ⇒Significant change in R in central events





Dijet (and gamma-jet) acoplanarity





Virtuality matters

Virtuality Q^2 of the parton in the medium controls physics of radiative energy loss:

$$Q^2(L) \approx \max\left(\underset{\uparrow \atop \text{medium}}{\hat{q}L}, \underset{\uparrow \atop \text{vacuum}}{\frac{E}{L}}\right)$$

Weak coupling scenario

RHIC: 20 GeV parton, *L* = 3 fm

$$\hat{q}L \approx 4.5\,\mathrm{GeV}^2 \gg \frac{E}{L} \approx 1.5\,\mathrm{GeV}^2$$

Virtuality of primary parton is medium dominated and small enough to "experience" the strongly coupled medium

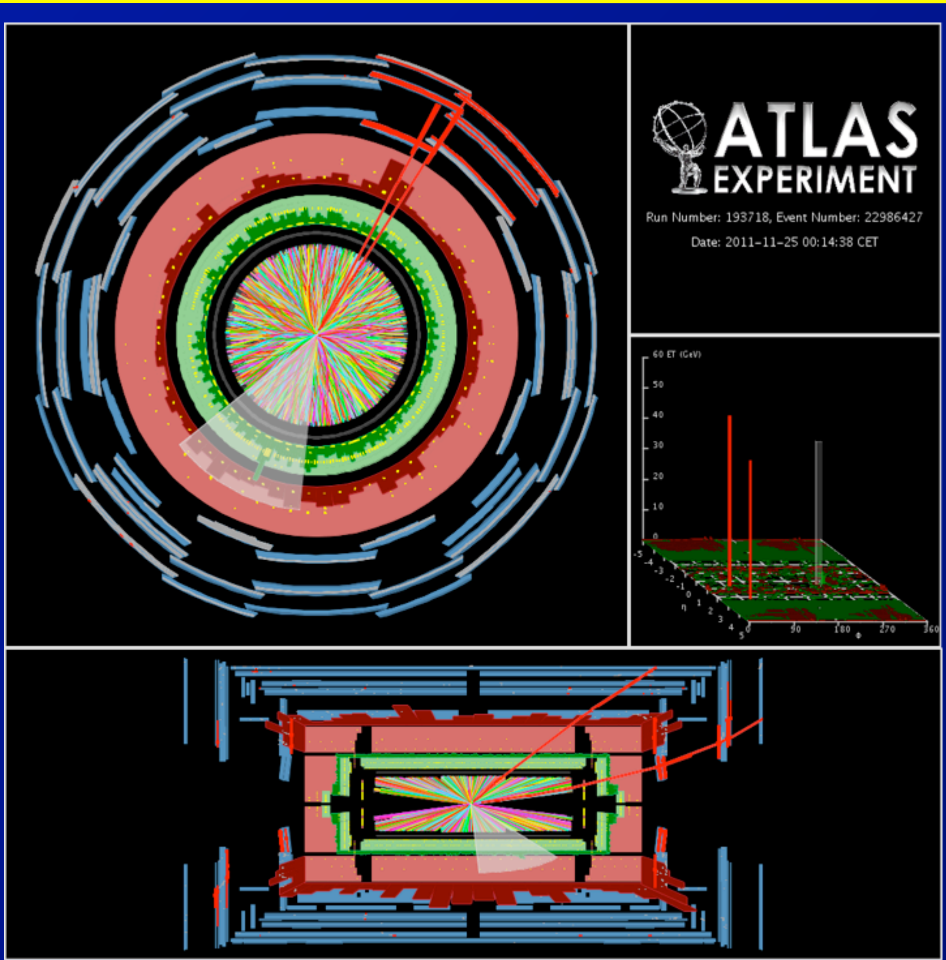
LHC: 200 GeV parton, *L* = 3 fm

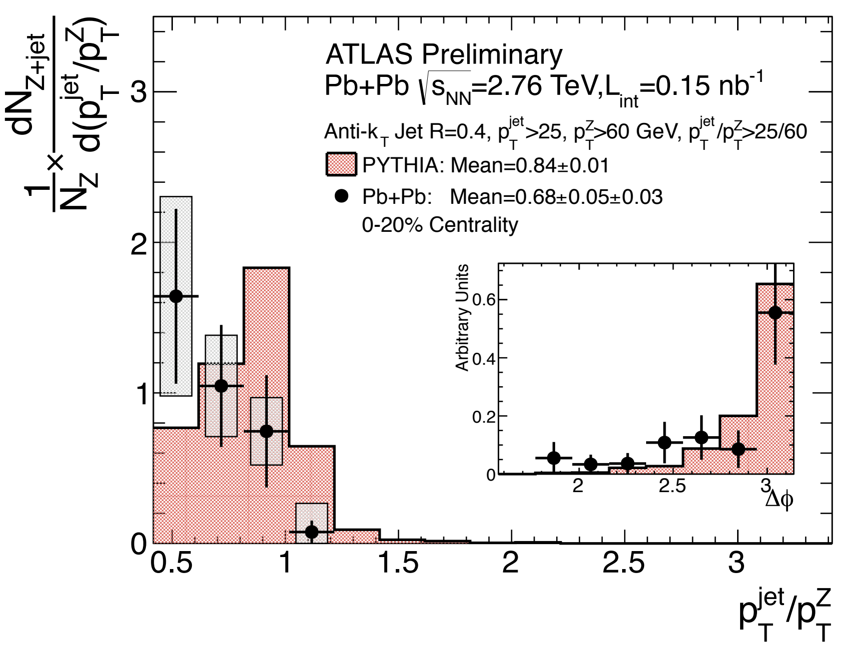
$$\hat{q}L \approx 9\,\mathrm{GeV}^2 < \frac{E}{L} \approx 13\,\mathrm{GeV}^2$$

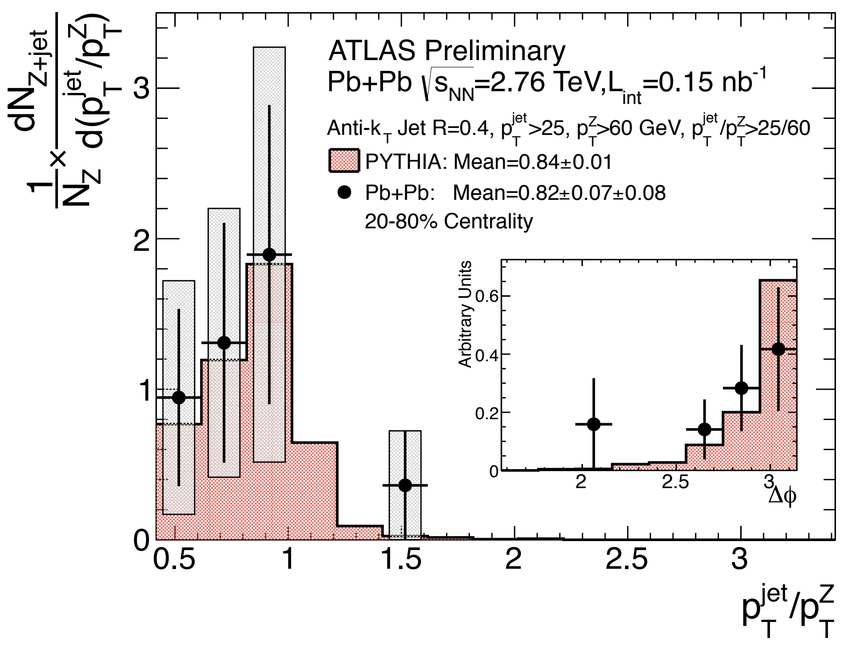
Virtuality of primary parton is vacuum dominated and only its gluon cloud "experiences" the strongly coupled medium

Is the lack of k_T broadening in the presence of significant quenching a death knell for "leading parton" models of energy loss?

Pb+Pb Z-jet measurement







- Z-jet measurements have less background than γ-jet, but smaller rate

⇒1st results

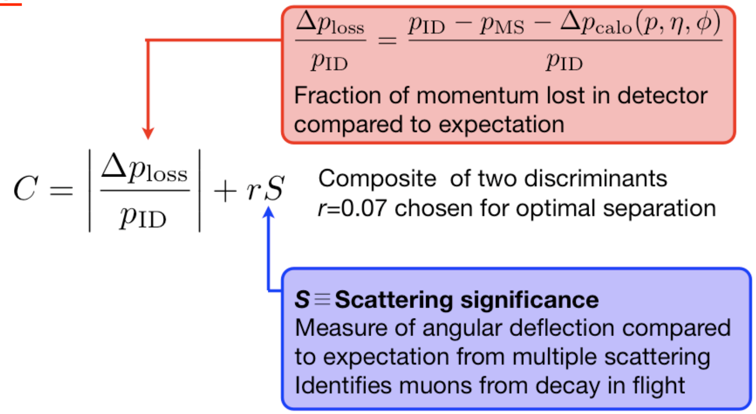
Heavy flavor

Single muons from heavy quark decays

https://cdsweb.cern.ch/record/1451883

- Calculate discriminant between π/K decay muons and signal
- Perform template fit to data

$$\frac{dP}{dC} = f_s \frac{dP}{dC}\bigg|_S + (1 - f_s)\,\frac{dP}{dC}\bigg|_B$$



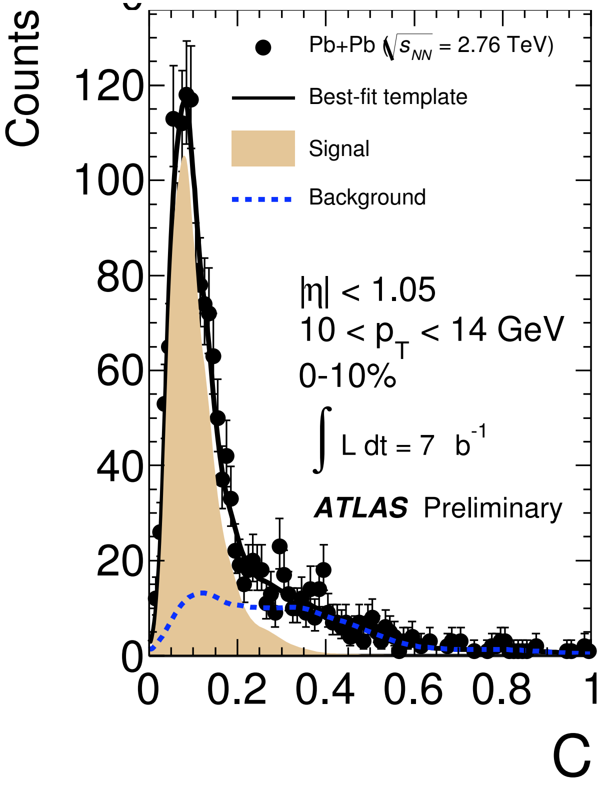
$$\frac{\Delta p_{\mathrm{loss}}}{p_{\mathrm{ID}}} = \frac{p_{\mathrm{ID}} - p_{\mathrm{MS}} - \Delta p_{\mathrm{calo}}(p,\eta,\phi)}{p_{\mathrm{ID}}}$$

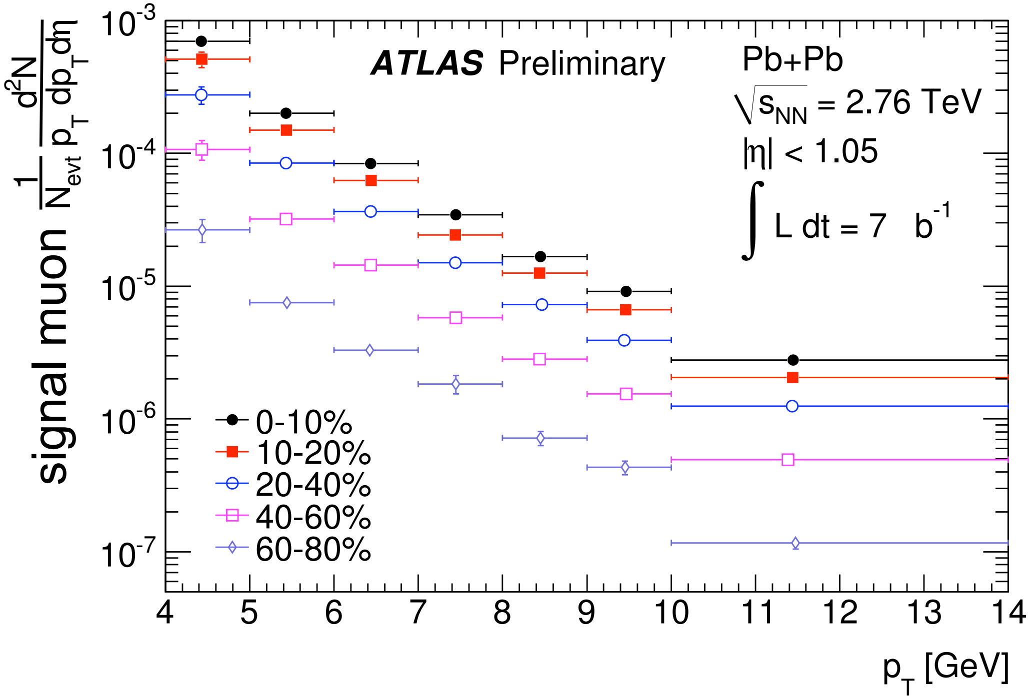
Fraction of momentum lost in detector compared to expectation

$$C = \left|\frac{\Delta p_{\mathrm{loss}}}{p_{\mathrm{ID}}}\right| + rS$$

Composite of two discriminants
r=0.07 chosen for optimal separation

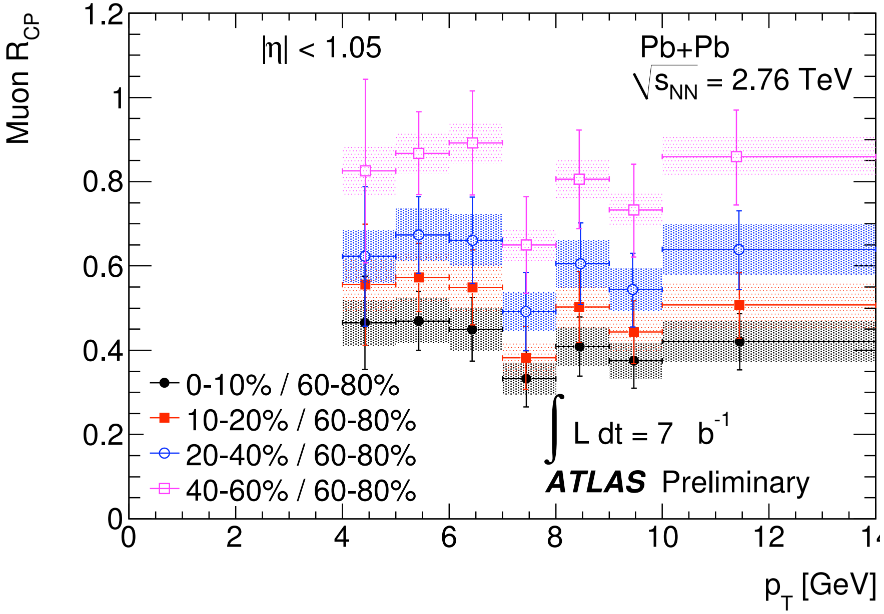
S≡**Scattering significance**
Measure of angular deflection compared to expectation from multiple scattering
Identifies muons from decay in flight

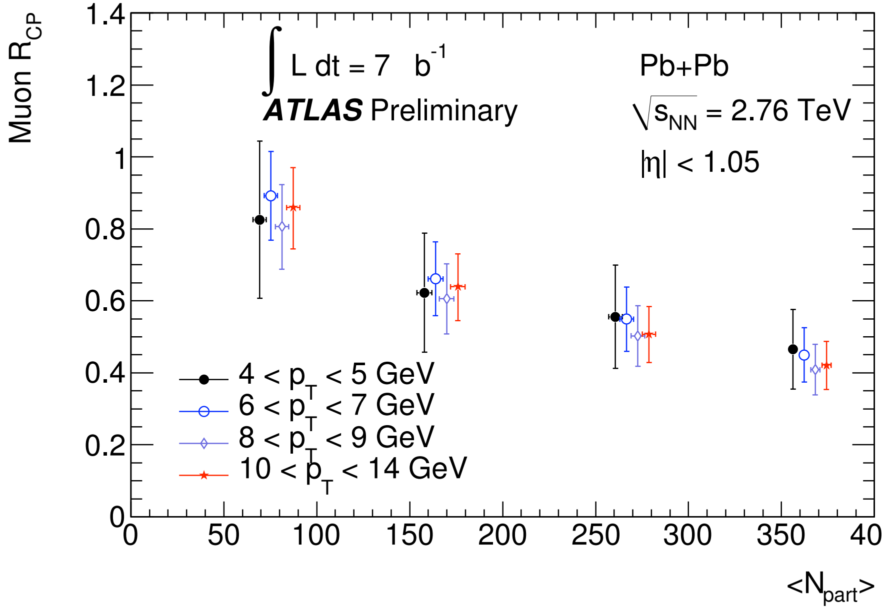




Error bars: combined stat+syst

Single muons from heavy quark decays





- **In measured p_T range, muons primarily from c, b decays.**
  - **J/ψ contribution ~ 1%**
- **Evaluate R_{cp} using 60-80% peripheral reference**

➡ **Factor of 2.5 suppression in 0-10% relative to 60-80%**

➡ **Independent of muon p_T within errors**

➡ **Evolution with N_{part} consistent between p_T bins**

Summary, perspectives

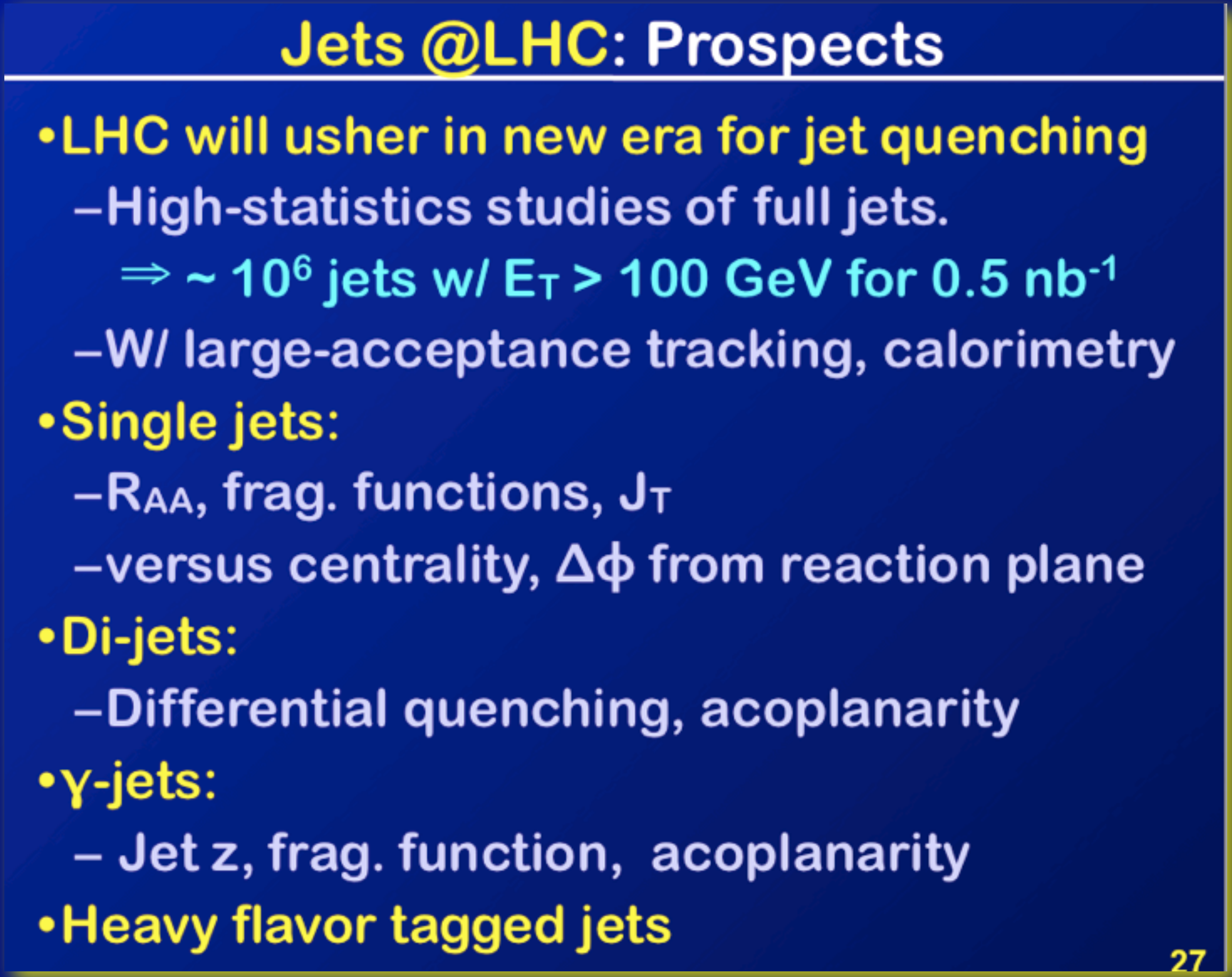
Summary

- Multiple observations of medium effects on parton showers:
  - Suppression of inclusive jet rate
  - Modification of jet fragmentation function
  - Modified dijet asymmetry distributions
  - Modified Z/γ-jet momentum balance
    - ⇒But the azimuthal directions of jets unaffected by the medium.
  - Suppressed production of heavy flavor
- Jet quenching calculations able to describe some of the above observations
  - Progress towards quantifying medium properties using jet measurements
    - ⇒But, we are only just getting started.

Historical perspective (2)

From talk by BAC at Intersections 2009

We are well along or started on all of these



Jets @LHC: Prospects

- LHC will usher in new era for jet quenching
  - High-statistics studies of full jets.
    - ⇒ ~ 10^6 jets w/ $E_T > 100$ GeV for 0.5 nb^{-1}
  - W/ large-acceptance tracking, calorimetry
- Single jets:
  - R_{AA}, frag. functions, J_T
  - versus centrality, $\Delta\phi$ from reaction plane
- Di-jets:
  - Differential quenching, acoplanarity
- γ-jets:
  - Jet z, frag. function, acoplanarity
- Heavy flavor tagged jets

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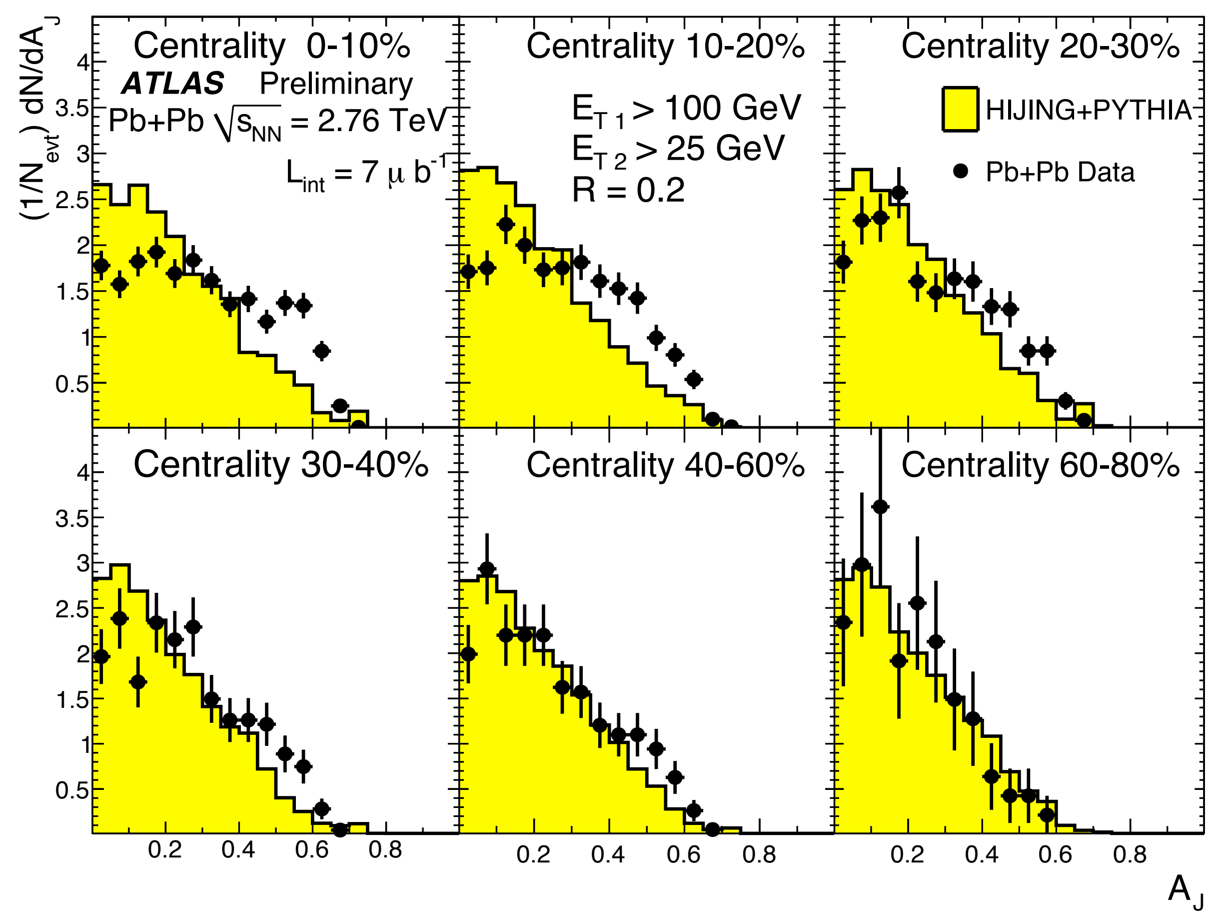
Backup

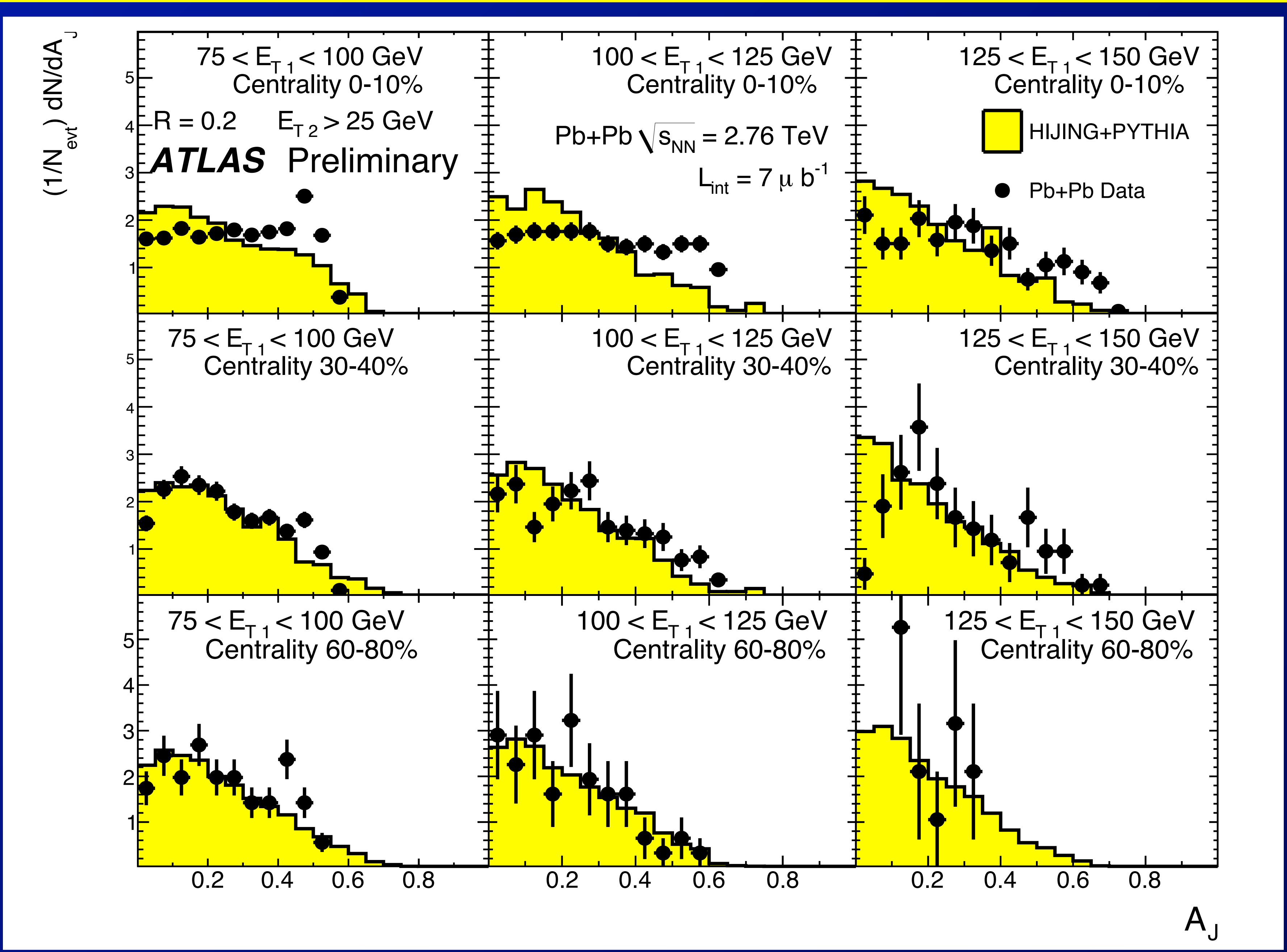
Dijet asymmetry, R = 0.2



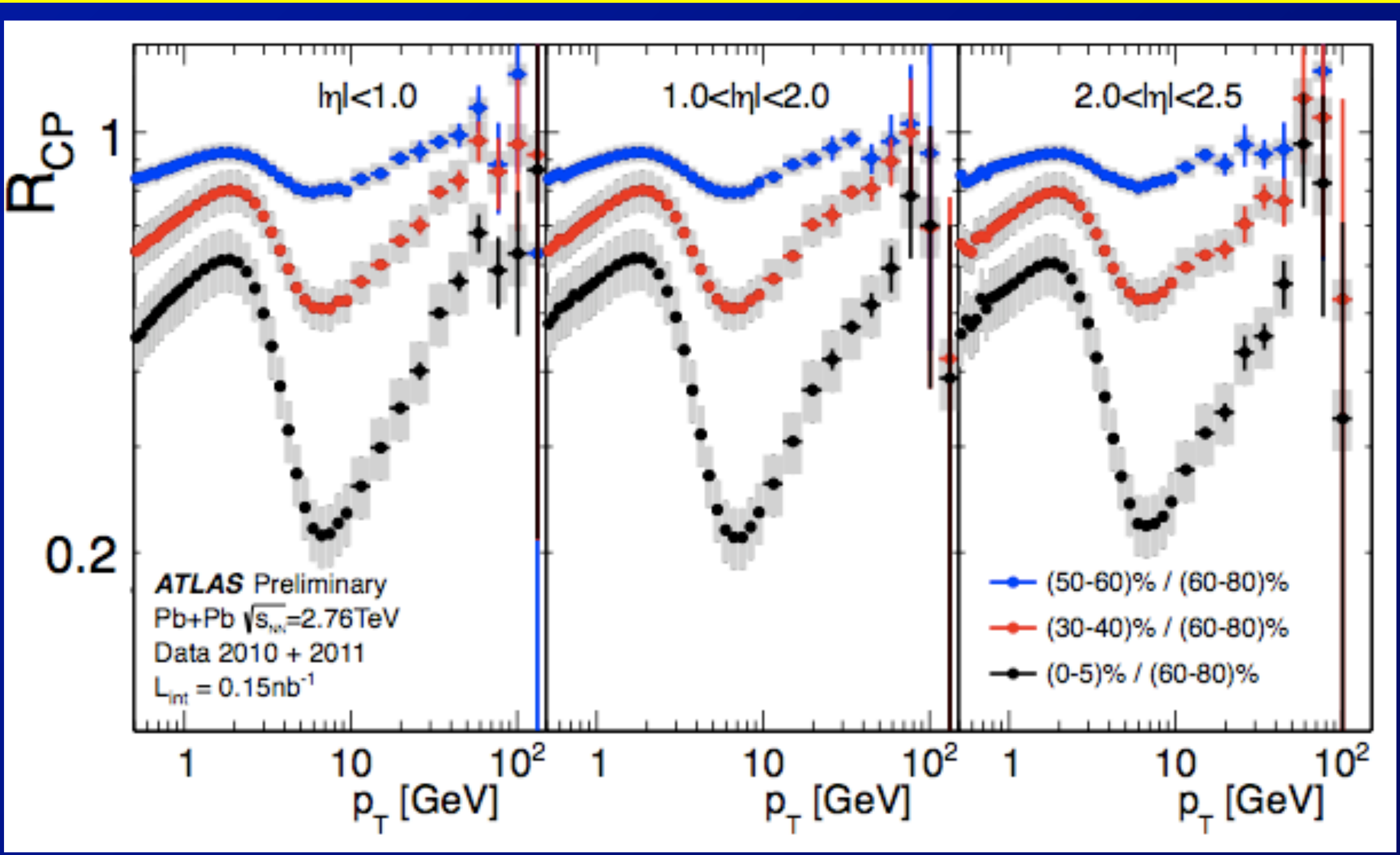
- Underlying event fluctuations in R = 0.2 factor of 2 smaller than for R = 0.4
  - Yet, modification of asymmetry persists

    ⇒NOT due to underlying event

Dijet asymmetry p_T dependence



Fast forward 12 years



- one of several single hadron suppression measurements (for ATLAS, preliminary)
  - Work of Weizmann ATLAS heavy ion group

Single muons from heavy quark decays

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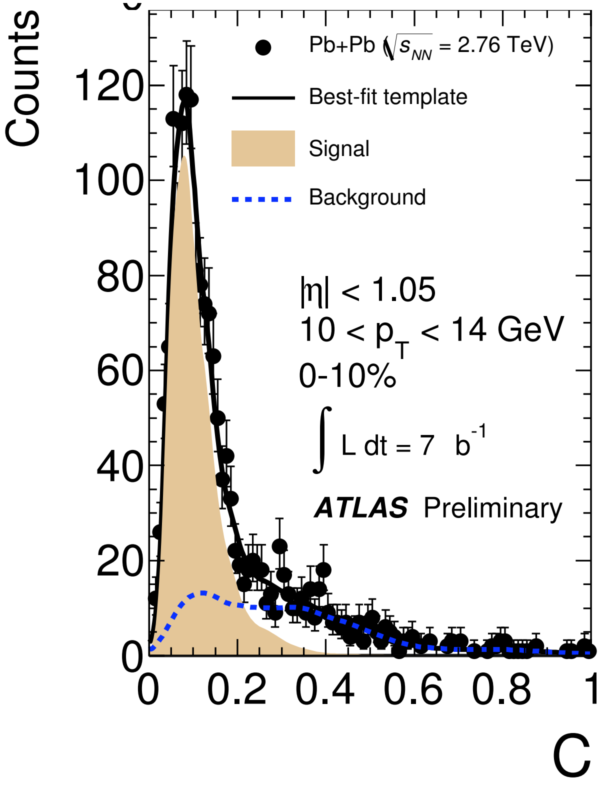
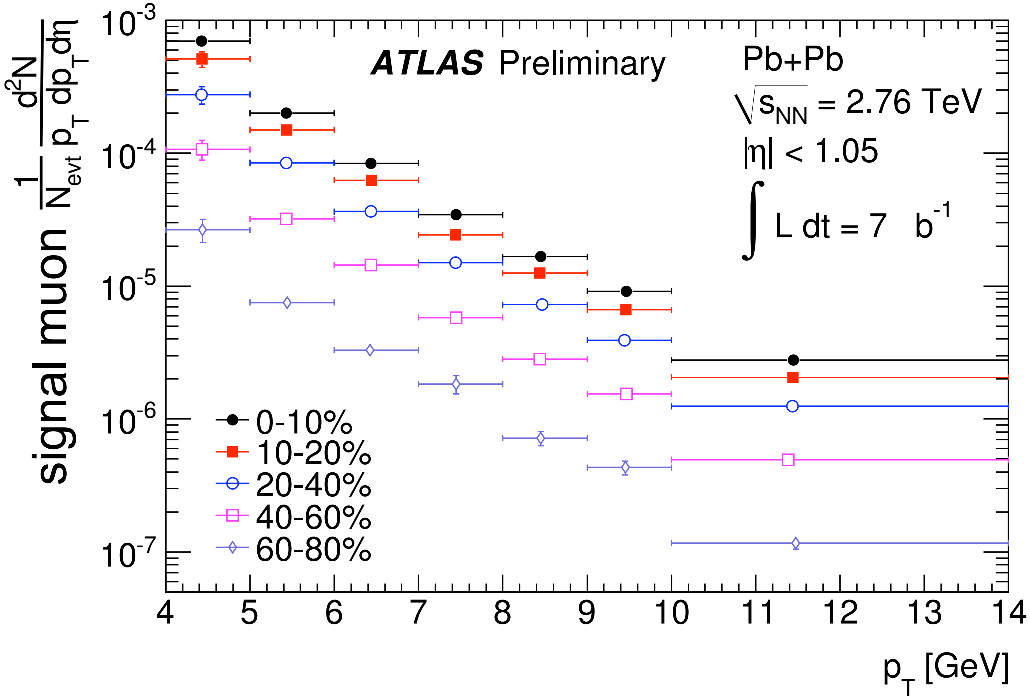
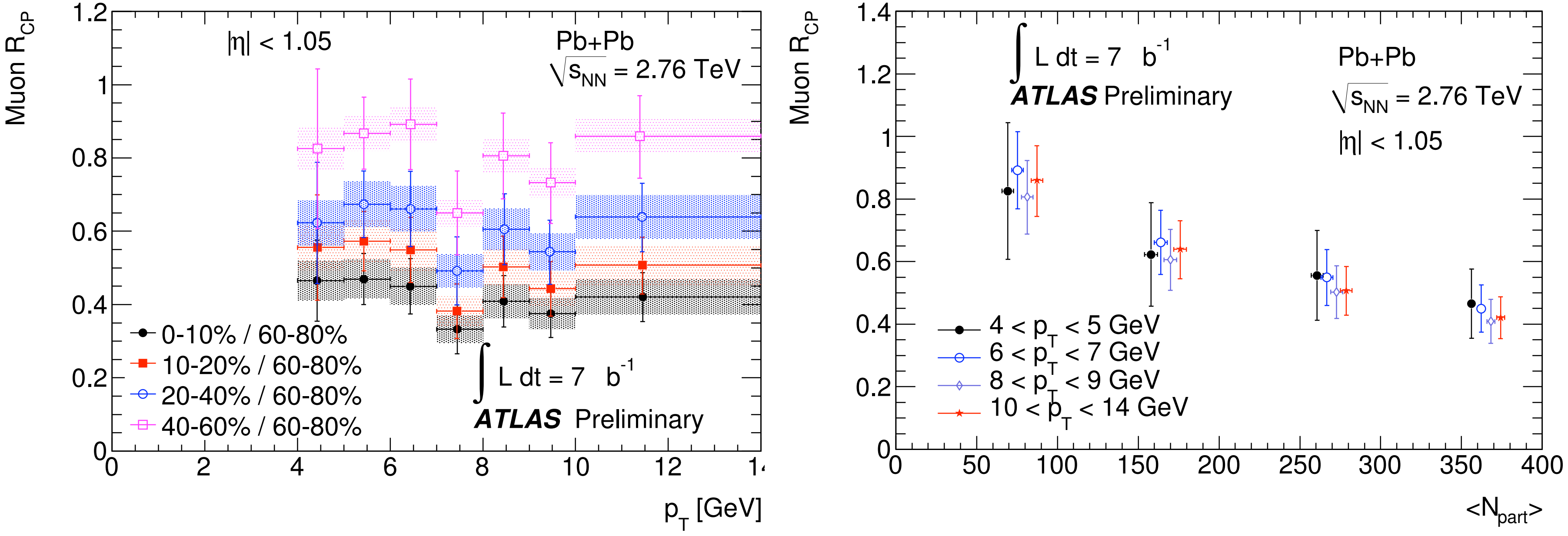




Error bars: combined stat+syst

Single muons from heavy quark



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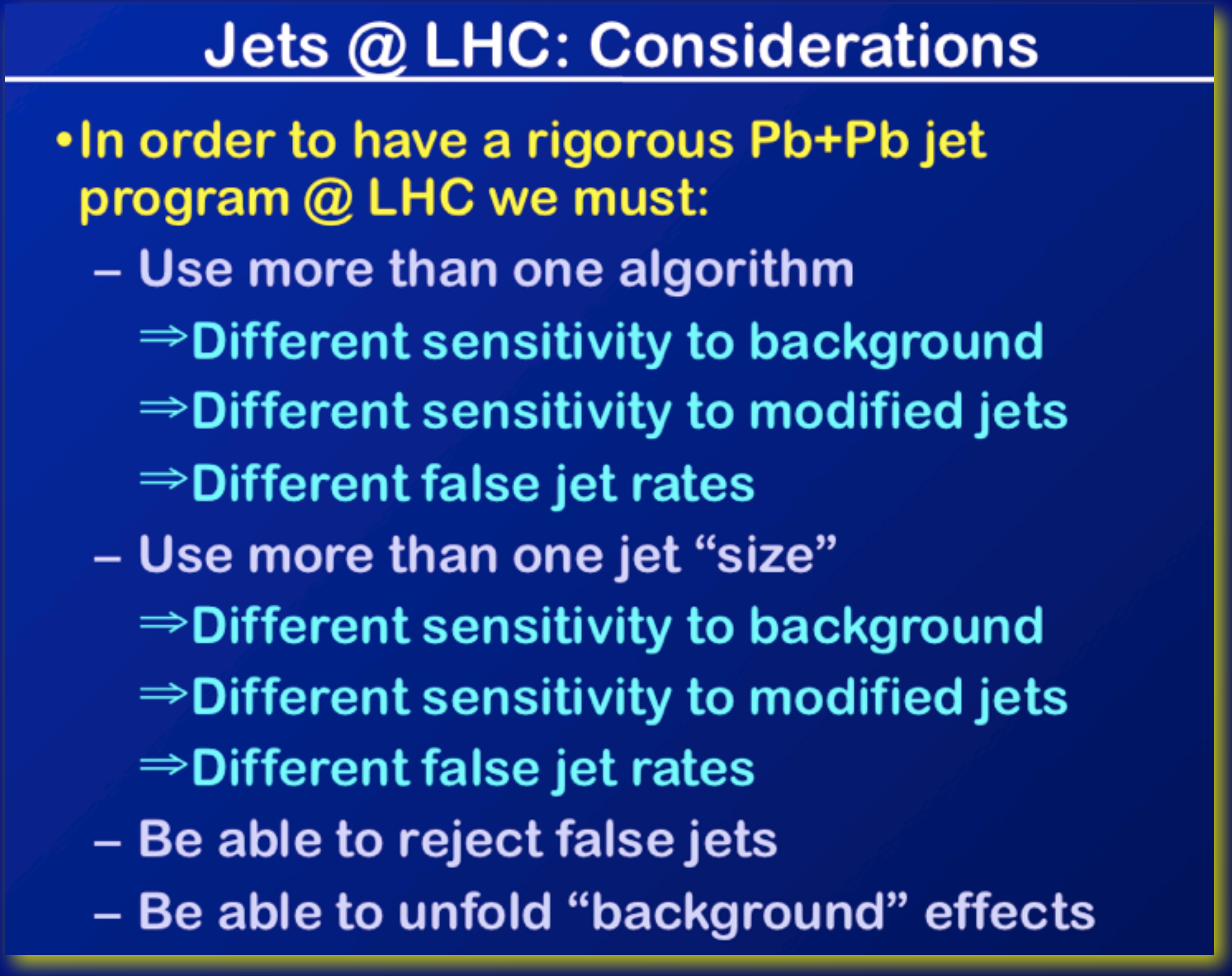
Historical perspective (3)

From talk by BAC at Intersections 2009

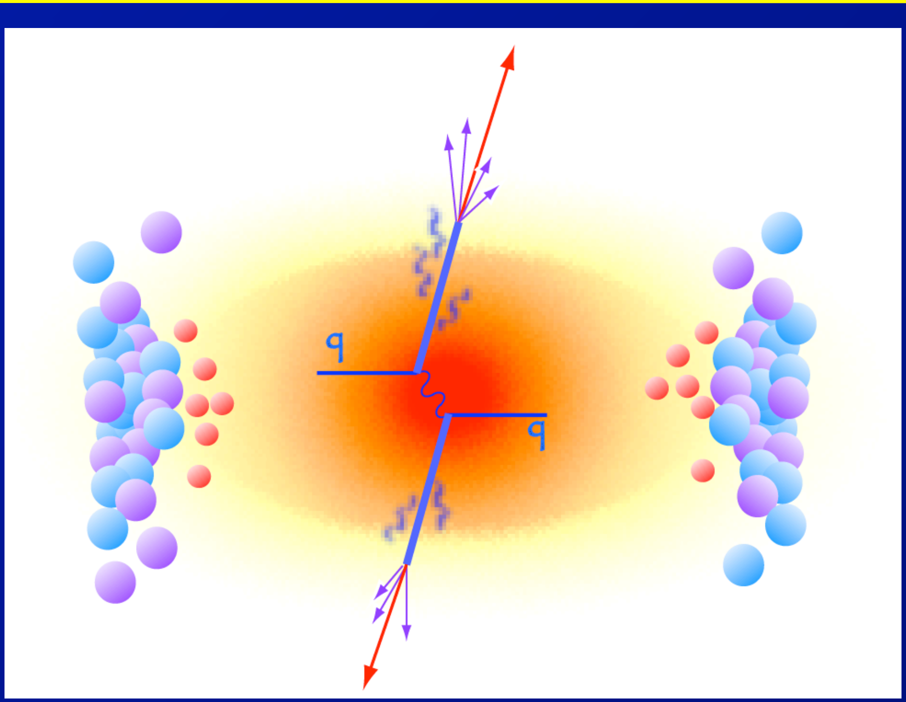
Done except for more than one algorithm



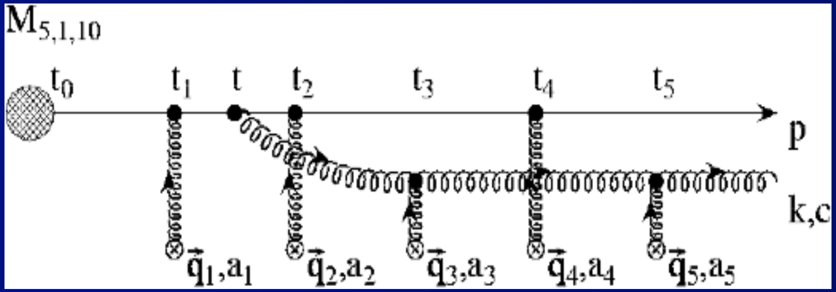
Jets @ LHC: Considerations

- In order to have a rigorous Pb+Pb jet program @ LHC we must:
  - Use more than one algorithm
    - ⇒Different sensitivity to background
    - ⇒Different sensitivity to modified jets
    - ⇒Different false jet rates
  - Use more than one jet "size"
    - ⇒Different sensitivity to background
    - ⇒Different sensitivity to modified jets
    - ⇒Different false jet rates
  - Be able to reject false jets
  - Be able to unfold "background" effects

20.1th century view of jet quenching



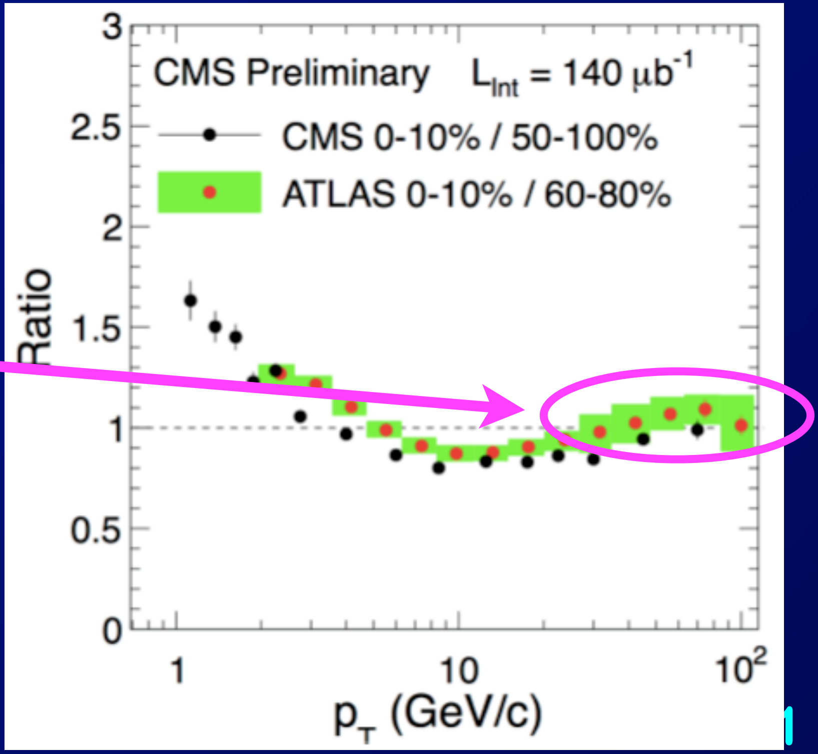
e.g. opacity expansion
a la GLV



- High-p_T quarks or gluons propagate through and scatter in the QGP
  - with collisional and radiative energy loss
  - interference between vacuum and medium-induced radiation + LPM interference of multiple emissions
  - Fragmentation in vacuum

Inclusive jet fragmentation

- What are the consequences of using quenched jet p_T for fragmentation?
- A simple toy model:
  - Jet loses energy via collimation.
    - ⇒Modes (hadrons) with $p_T > x$ are unaffected.
    - ⇒Jet energy is reduced
- This toy model would yield an ENHANCEMENT in $D(p_T)$ or $D(z)$ for $p_T > x$ when using reduced jet energy.
    - ⇒Critical to control



- Are we seeing at large z Kopeliovich’s pre-hadrons?
    - ⇒Can they survive QGP?