Lecture 3:
Results of jet measurements in p-p and heavy ion collisions

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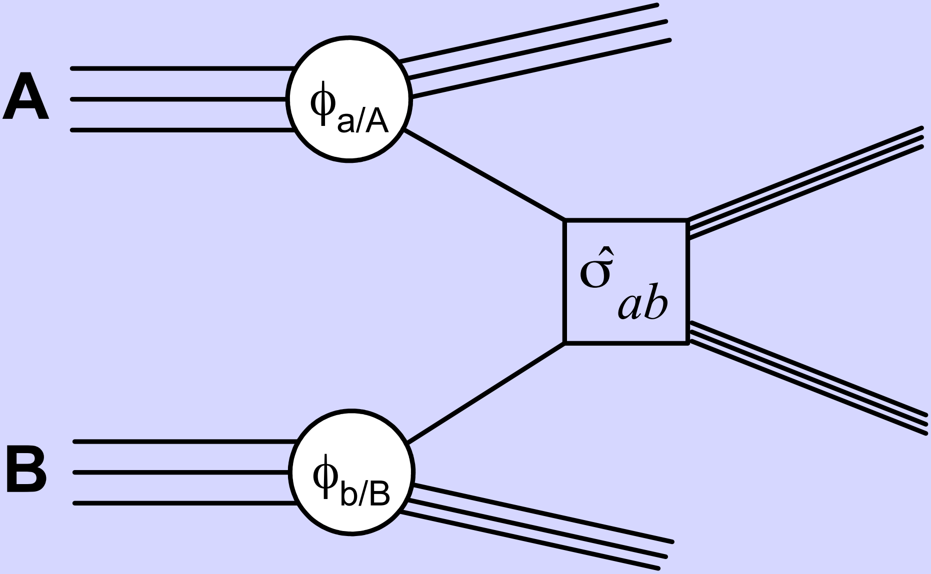
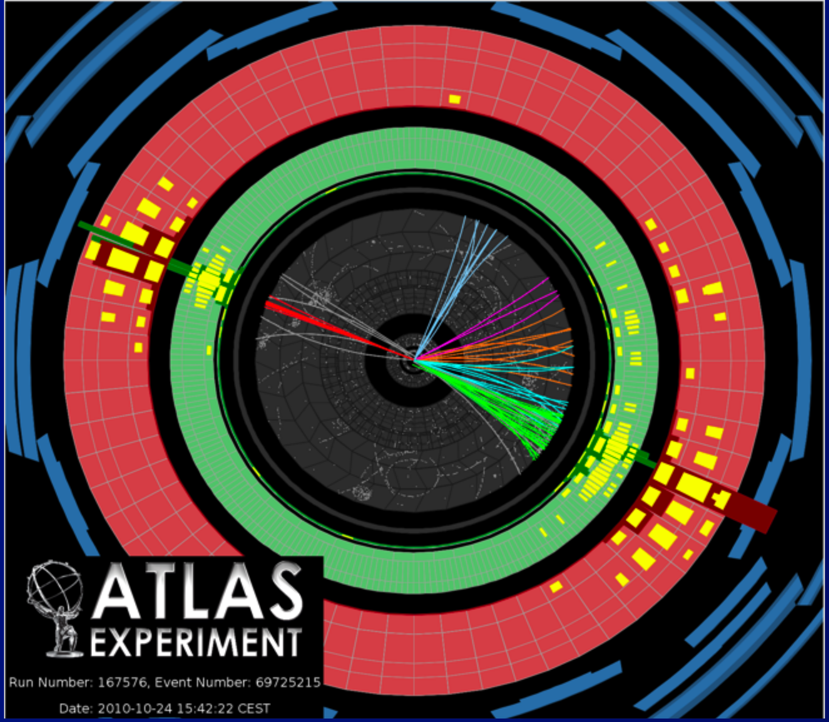
June 14, 2013

Hard Scattering in p-p Collisions





Run Number: 167576, Event Number: 69725215

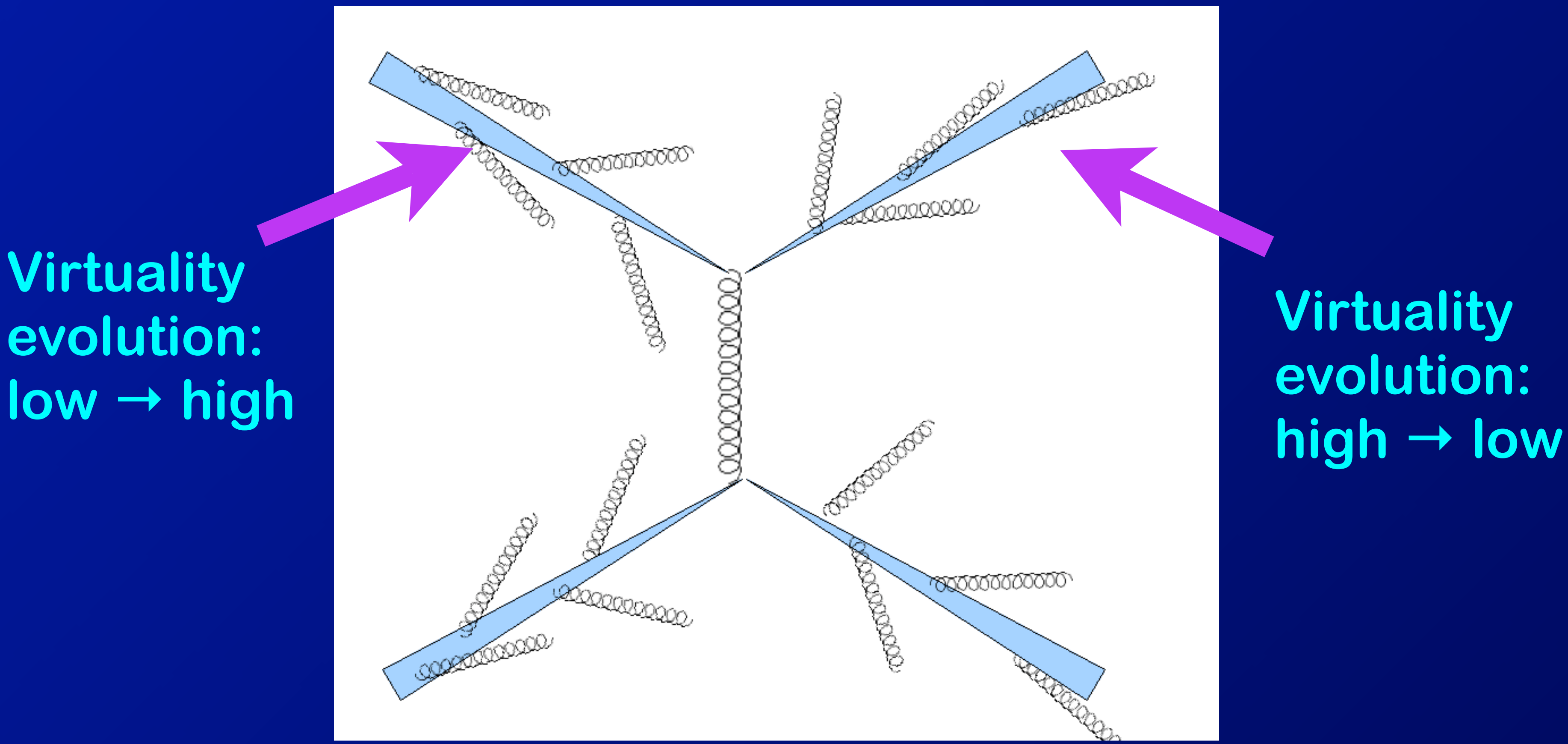
Date: 2010-10-24 15:42:22 CEST

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

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

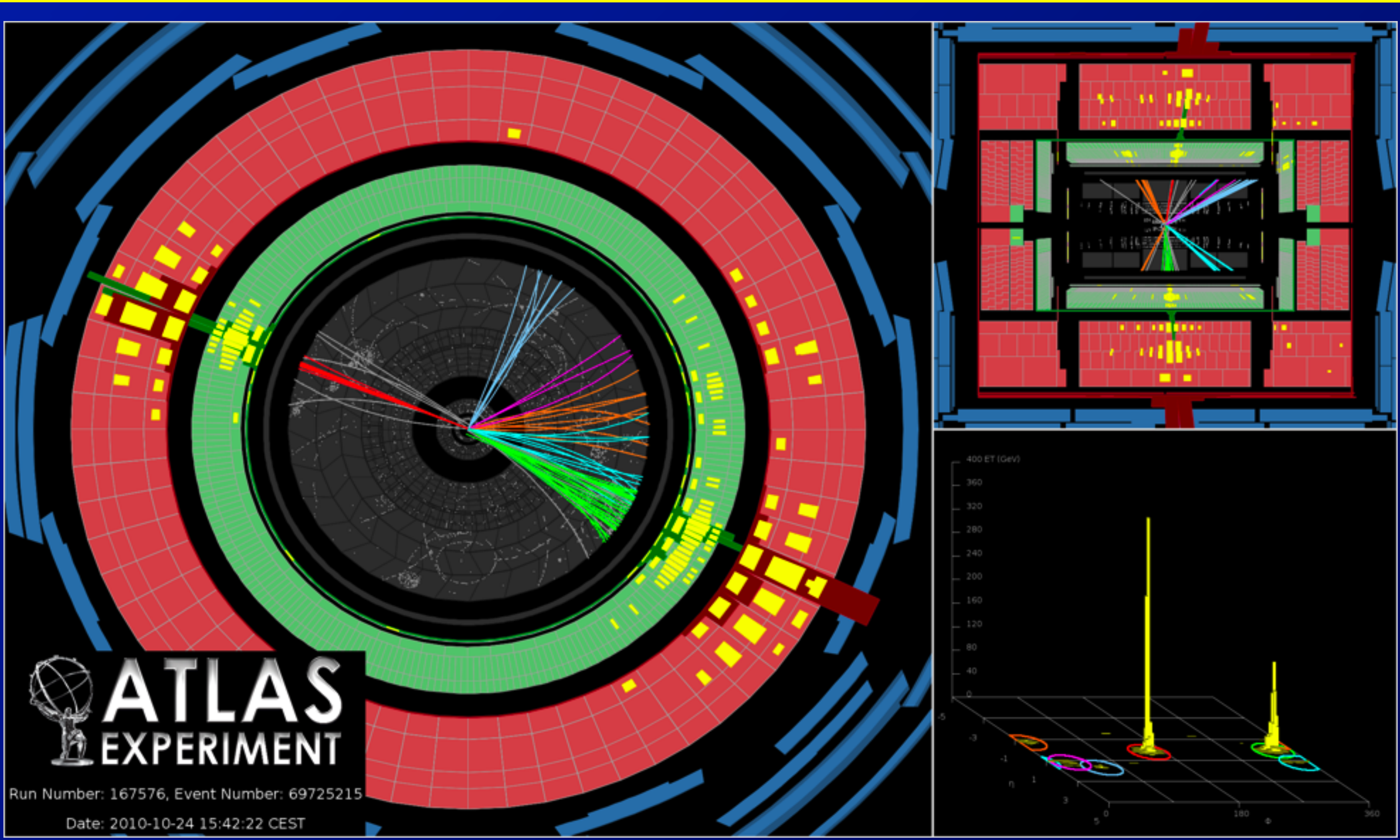
- Factorization: separation of σ into
  - Short-distance physics: σ_{ab}
  - Long-distance physics: φ's

Hard Scattering & parton showers



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

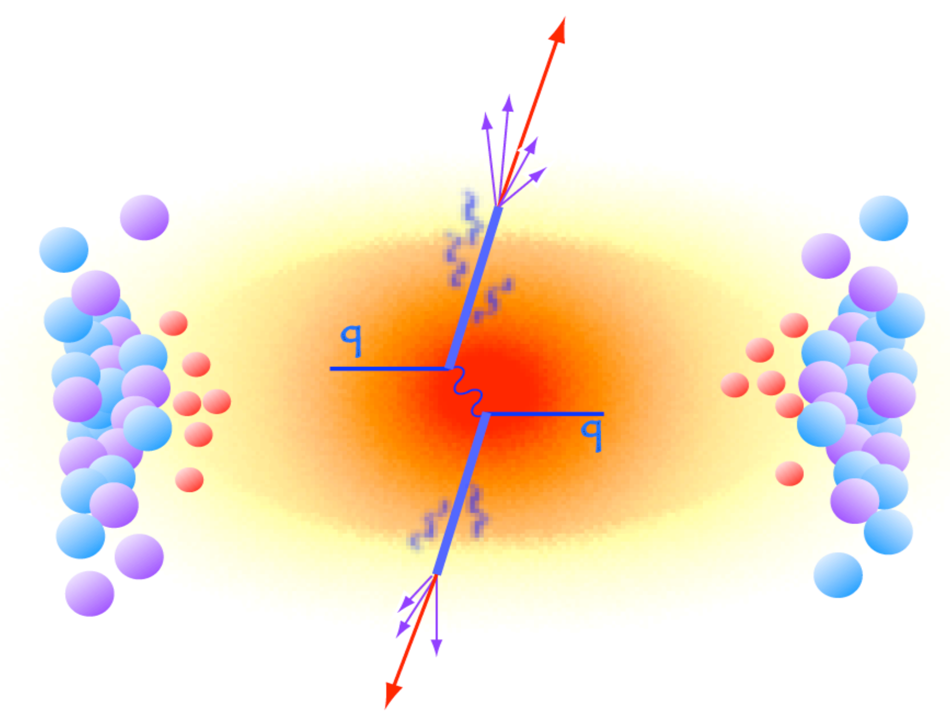
“Baseline”: jets in p-p



- ➡ 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)



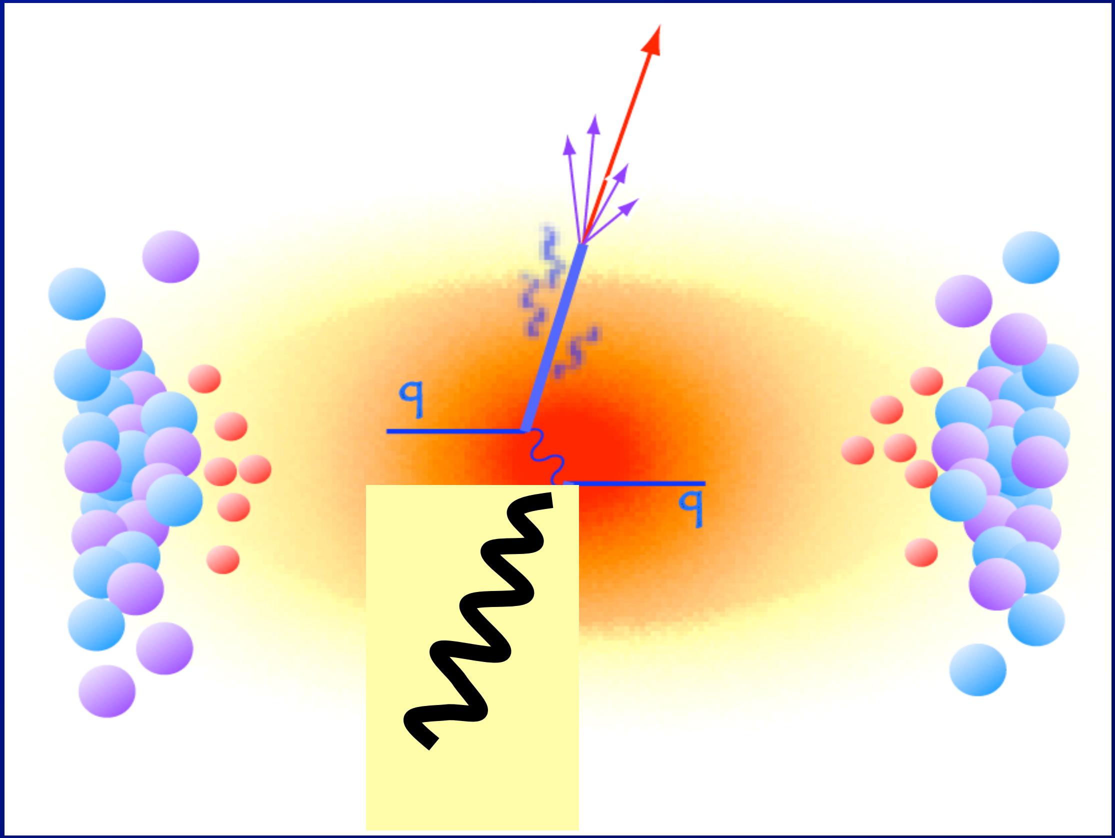
- Key experimental question:

  ⇒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

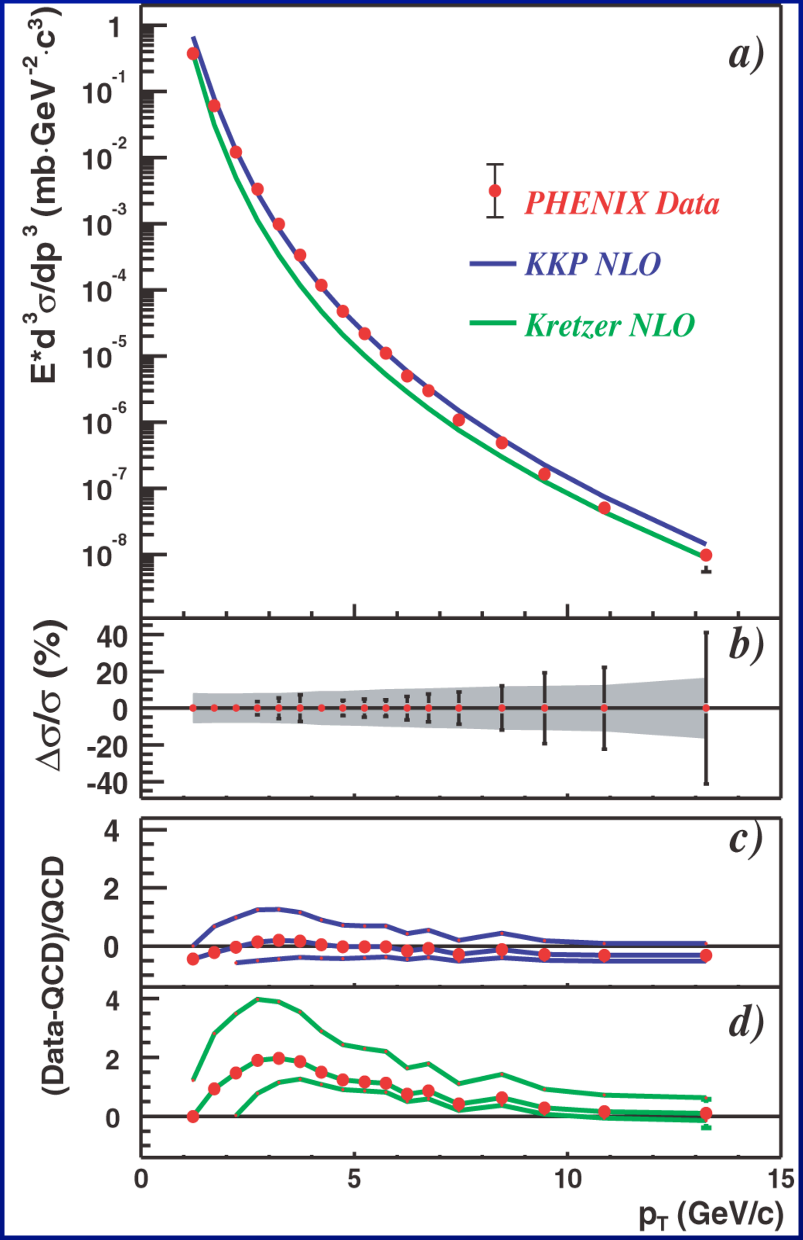
- Use γ-jet pairs to directly probe the quark gluon plasma (QGP)

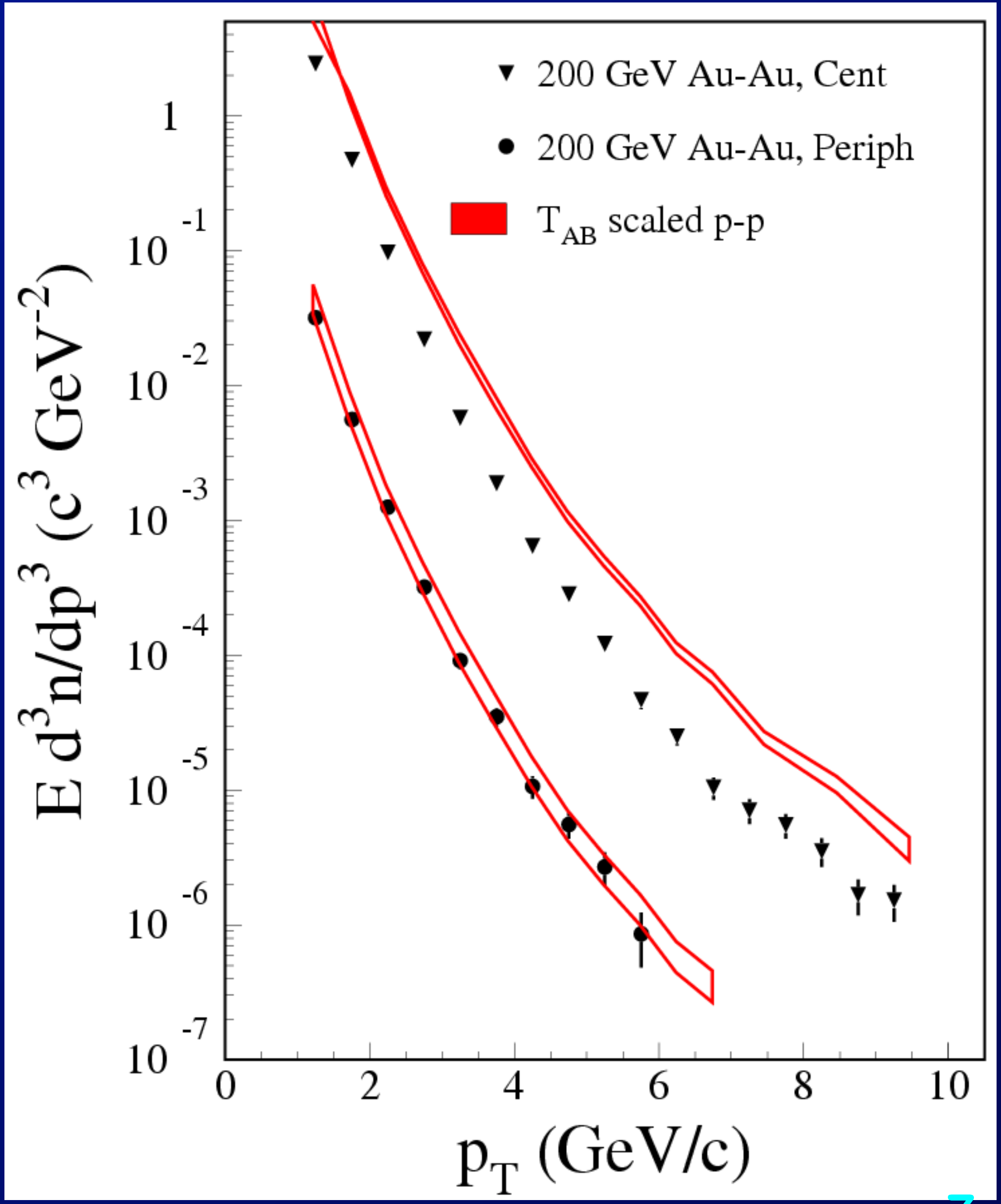


- Key experimental question:
  - ⇒How do parton showers in quark gluon plasma differ from those in vacuum?
    - » Where the photon provides a reference energy scale for the jet.

The early days of jet quenching

PHENIX, Phys. Rev. Lett. 91, 241803 (2003)

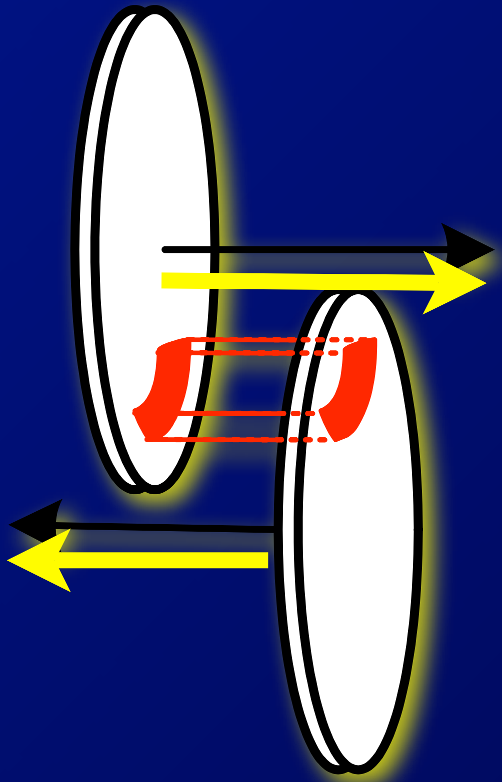




A-A Hard Scattering Rates

- For “partonic” scattering or production processes, rates are determined by T_{AB}

$$T(r_t) = \int_{-\infty}^{\infty} dz\, \rho_A^{nucleon}(z, r_t)$$



$$T_{AB}(b) = \int d\vec{r}\; T_A(|\vec{r}|)\; T_B(|\vec{b} - \vec{r}|)$$

  - t-integrated A-A parton luminosity
  - Normalized relative to p-p
- If factorization holds, then

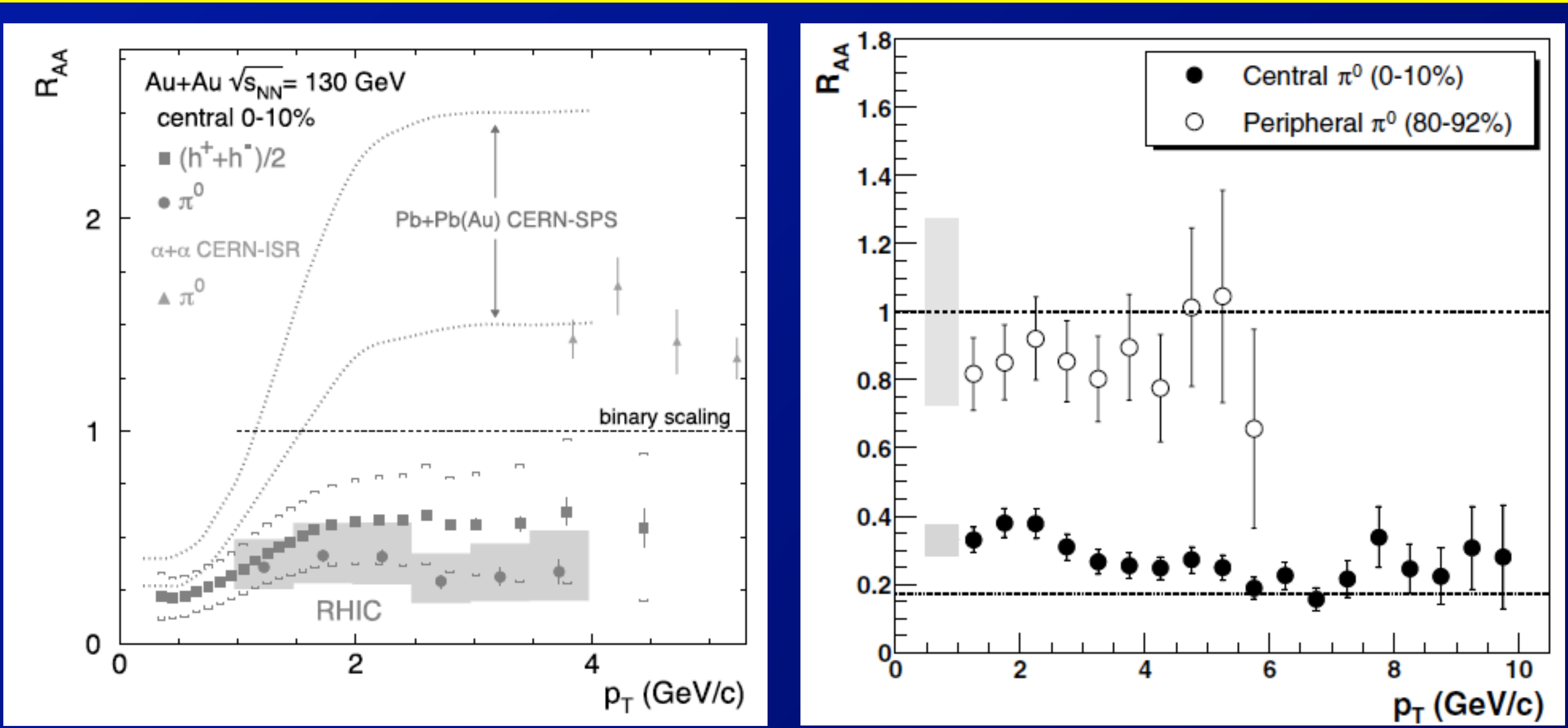
$$\frac{dn^{AB}_{hard}}{dp_\perp^2} = \frac{d\sigma^{NN}_{hard}}{dp_\perp^2} T_{AB}(b)$$

  - Define ratio R_{AA}

$$R_{AA} = \frac{dn^{AB}_{hard}}{dp_\perp^2} \Bigg/ \frac{d\sigma^{NN}_{hard}}{dp_\perp^2} T_{AB}(b)$$

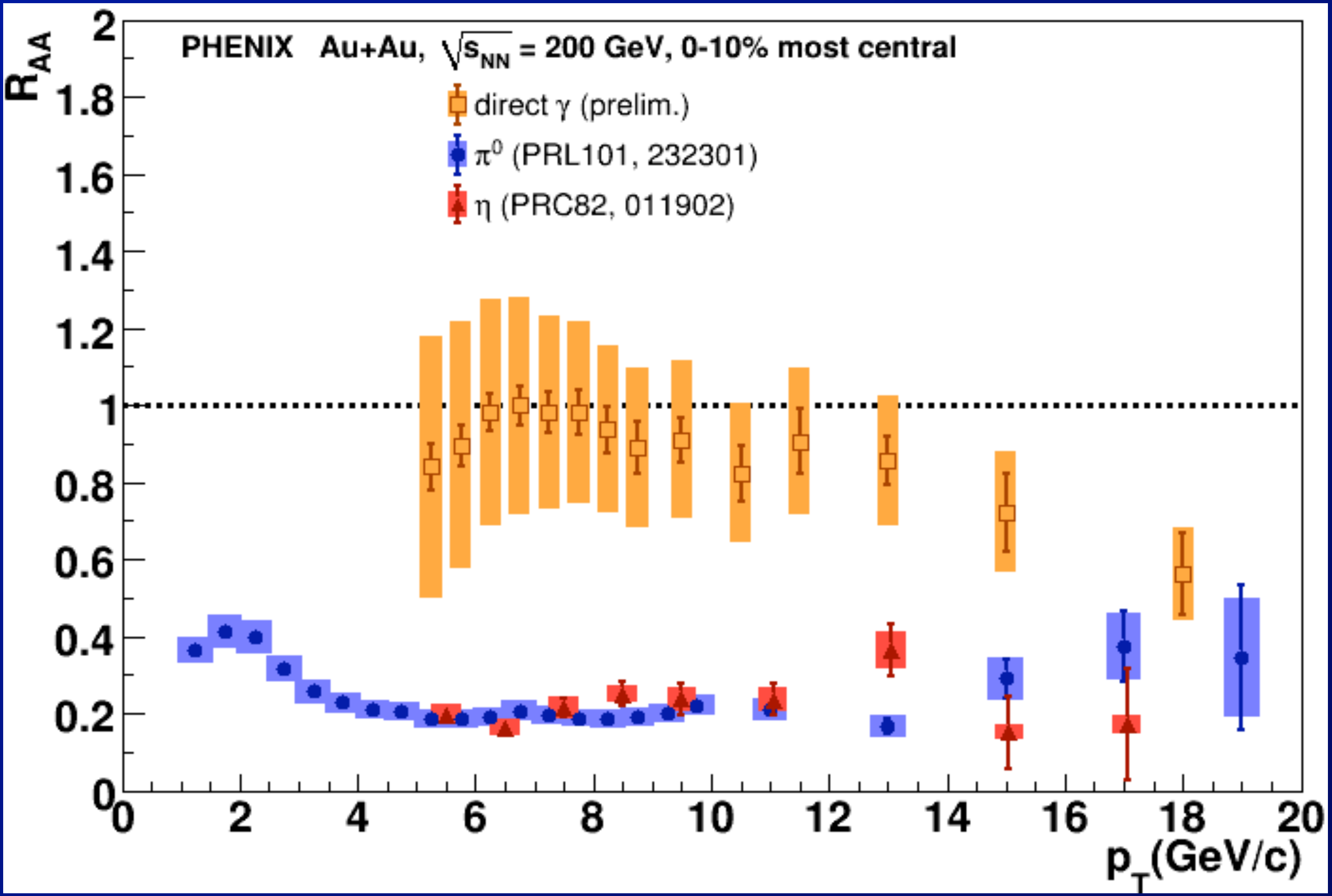
  - Note: $N_{coll} = \sigma_{NN}\, T_{AB}$

PHENIX: “jet” quenching @ 130, 200 GeV



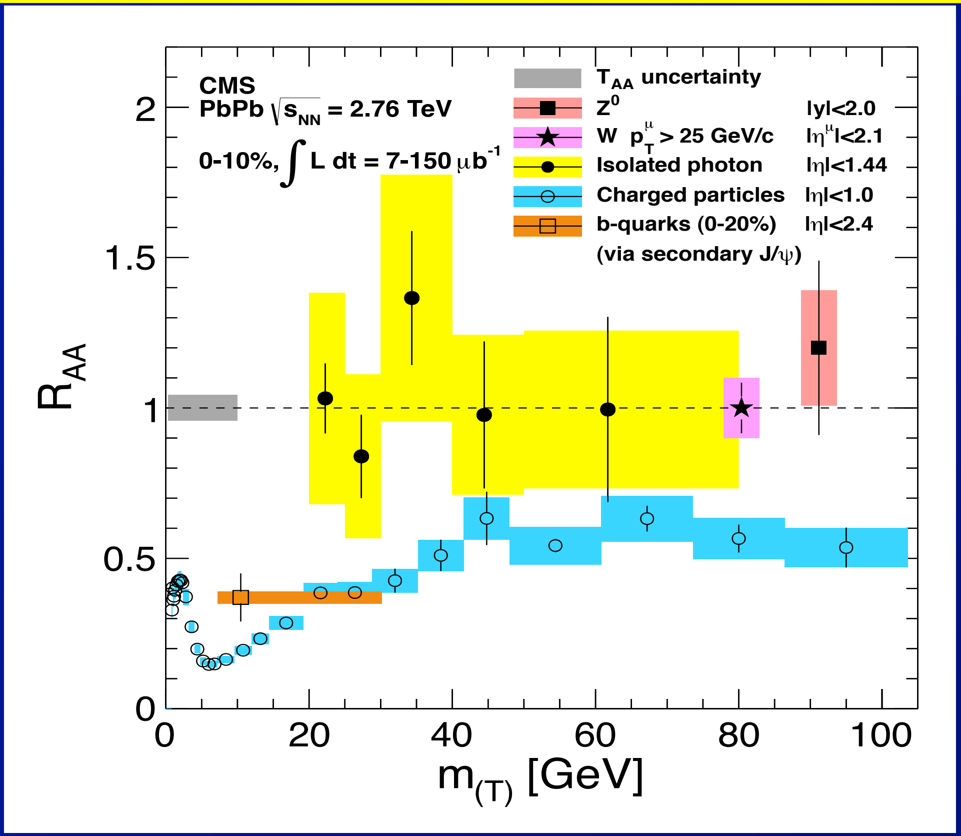
- Limited reach in pT compared to what we are used to in the LHC era.
  - Qualitative features of single hadron suppression already established in 2003.
    - ⇒In particular, apparent weak p_T variation

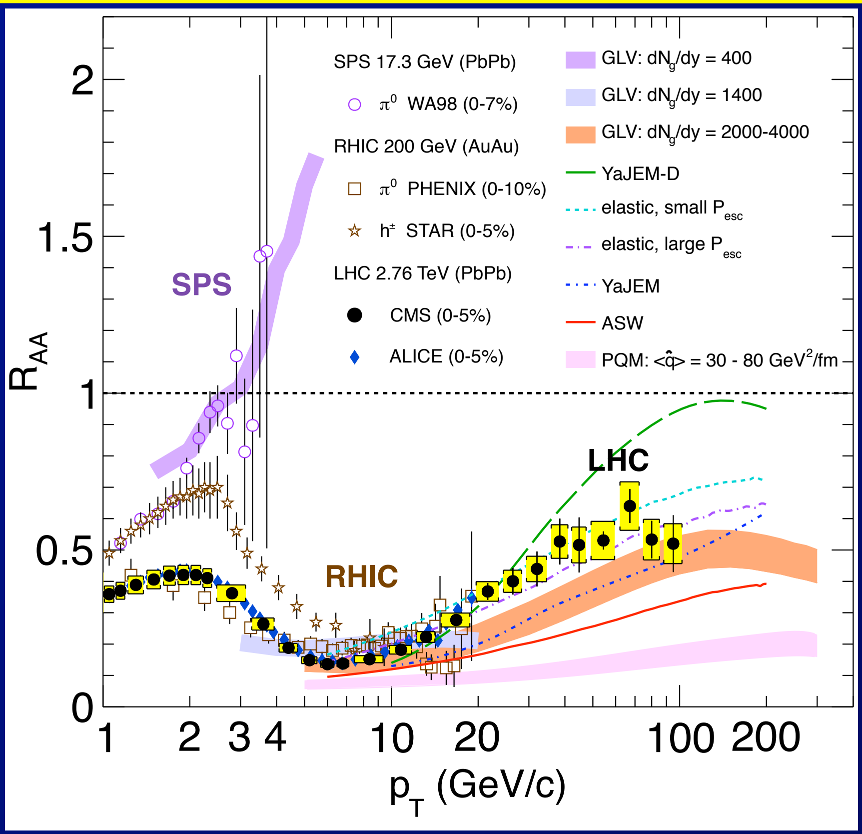
Single hadrons, photon



- “State of the art” in single hadron suppression measurements @ RHIC.

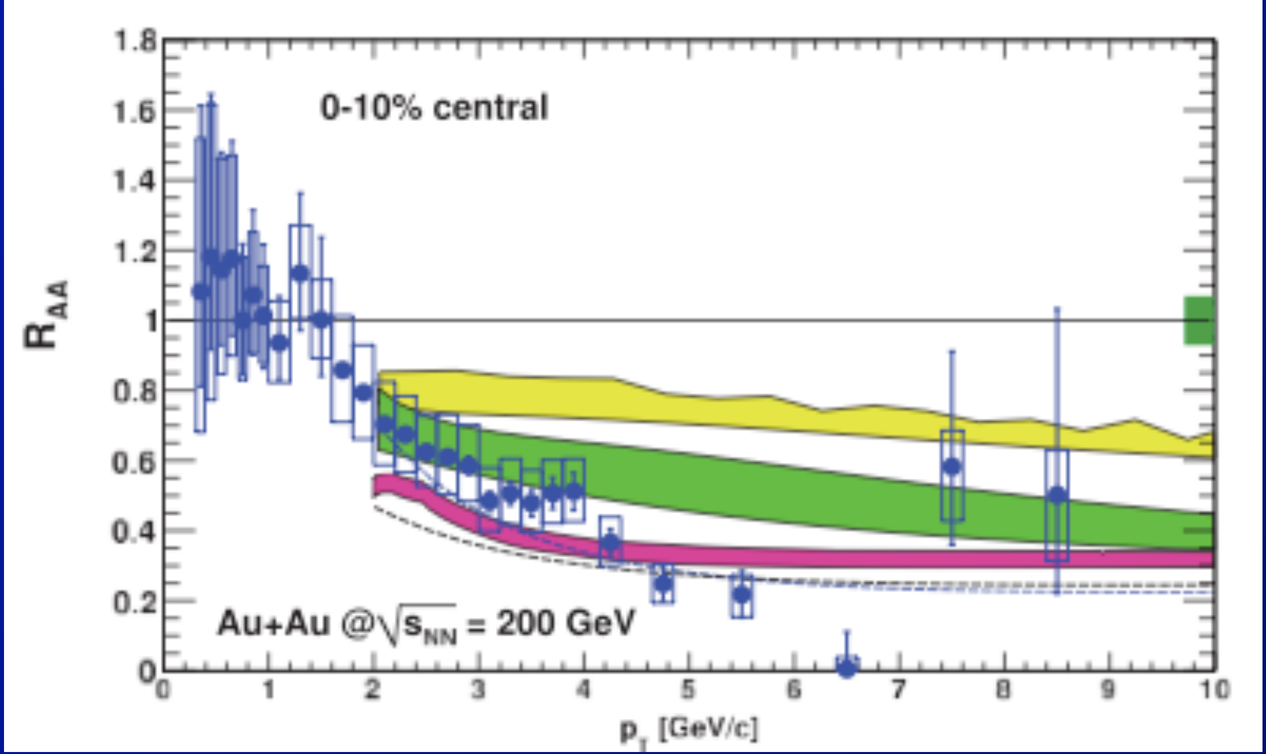
Hadron suppression @ LHC

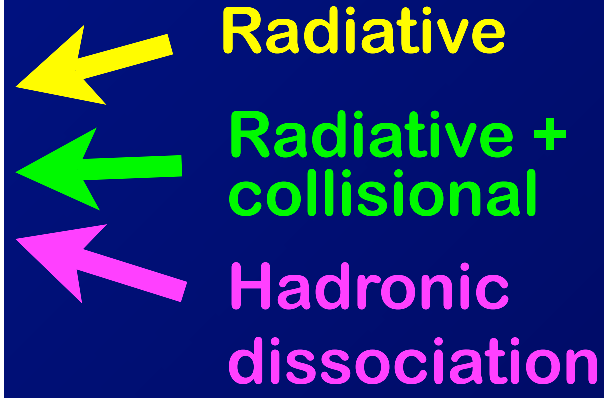




- At high p_T, see factor of 2 suppression in charged hadron yield.
  - photons, W's, Z rates show no suppression
- p_T dependence matches RHIC measurements

Heavy quark suppression

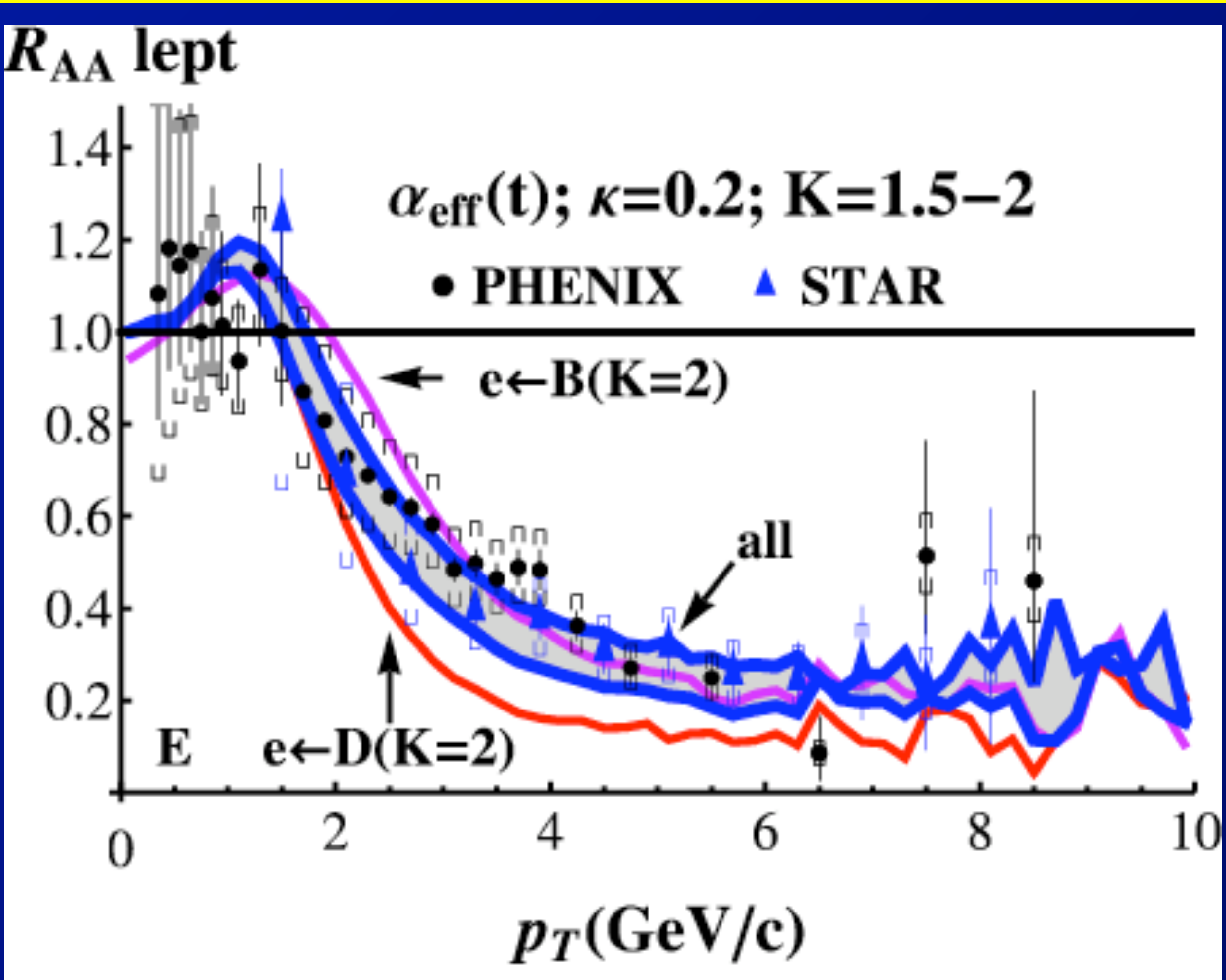




- Heavy quarks provide a valuable test of our understanding of energy loss
  - Large mass changes contribution of collisional and radiative energy loss

    ⇒But RHIC semi-leptonic decay data proved challenging to describe theoretically.

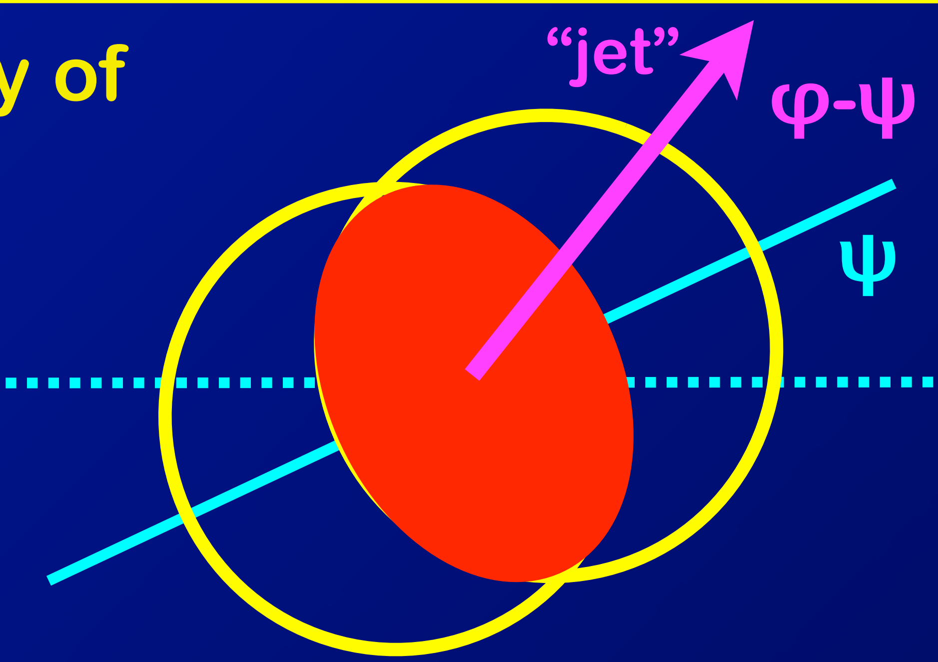
Heavy quark suppression



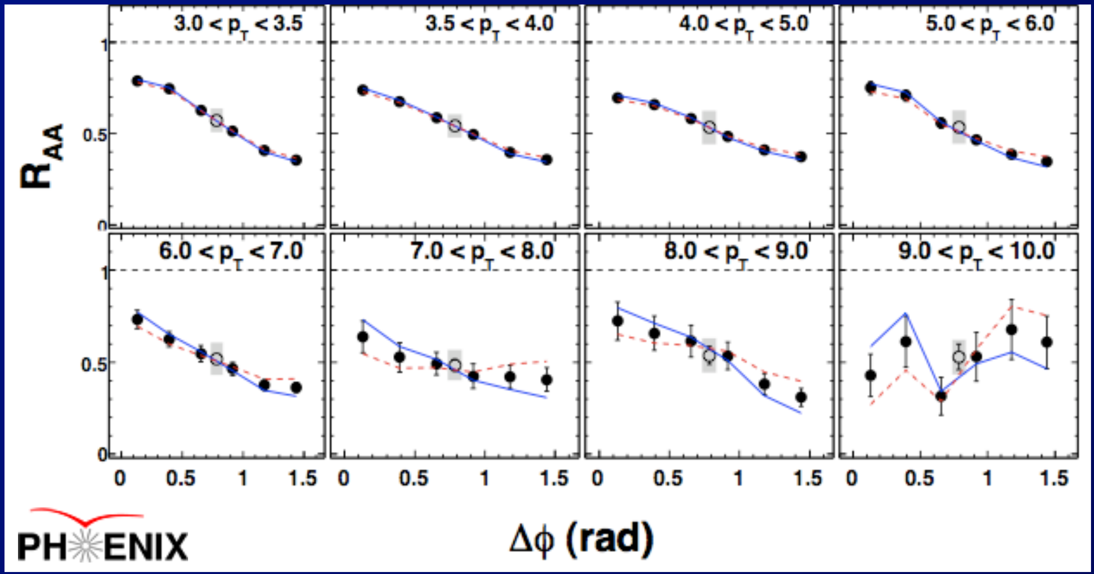
- Recent calculations by Aichelin et al are able to describe RHIC results
  - But only by scaling up the collisional interaction rates by a factor of 1.5-2

Jet tomography

- How to probe geometry of the initial state?
  - Use spatial asymmetry of medium @ non-zero impact parameter
  - Measure orientation (ψ) event-by event



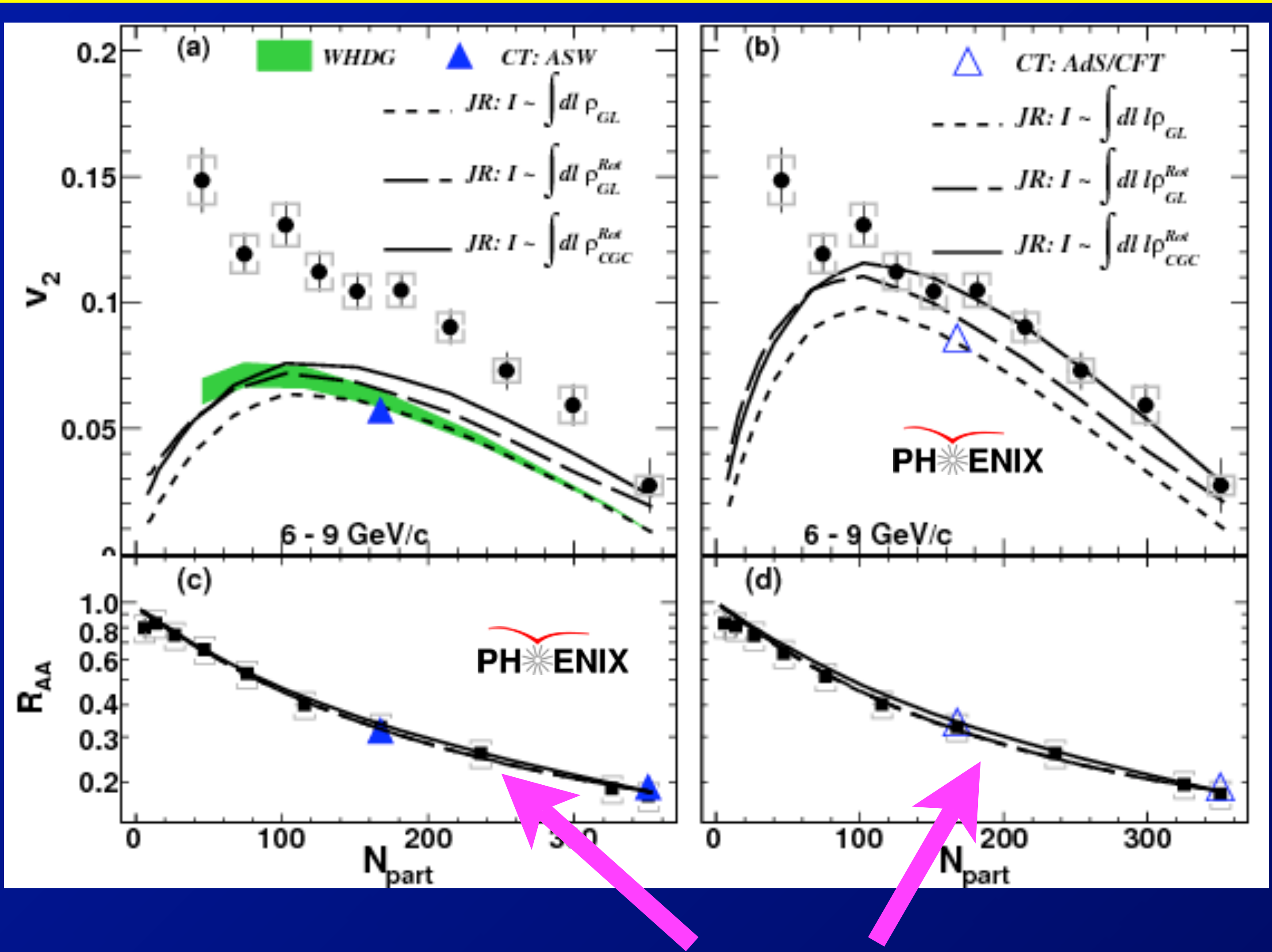
- Measure R_{AA} vs $\Delta\varphi = \varphi-\psi$



- Characterize by amplitude of Δφ modulation:

$$\frac{dN}{d\phi} = C\left[1 + 2\underline{v_2}\cos\left(2\Delta\phi\right)\right]$$

Single hadron suppression



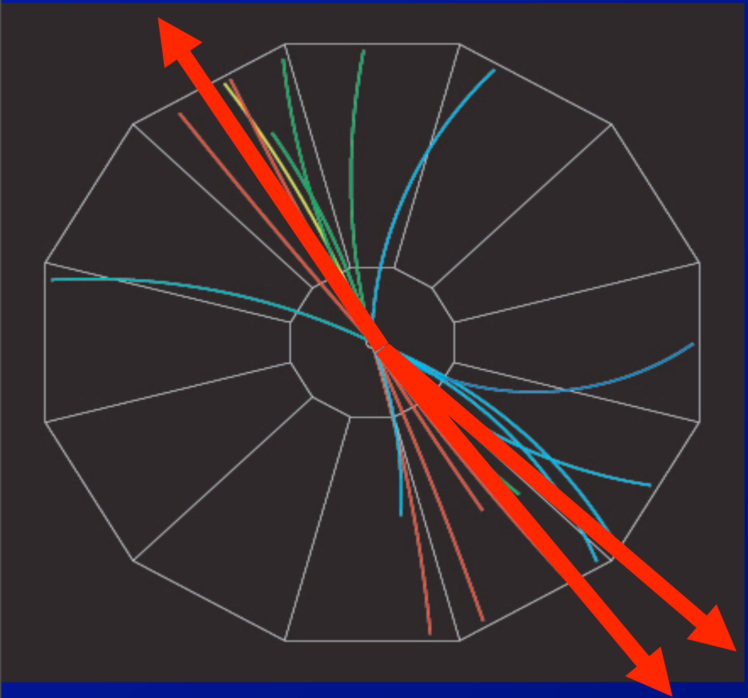
Calculations:

- Wicks *et al.*, NPA784, 426
- Marquet, Renk, PLB685, 270
- Drees, Feng, Jia, PRC71, 034909
- Jia, Wei, arXiv: 1005.0645

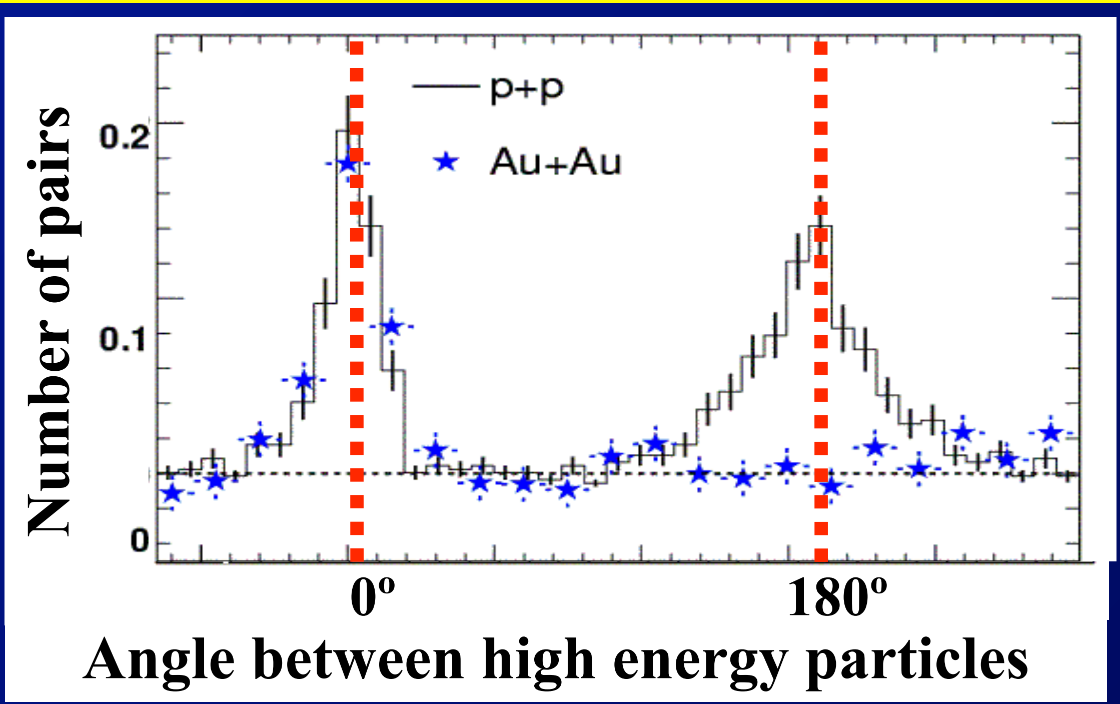
- Two calculations: weak, strong coupling
  - N_{part} dependence same for both
  - But data prefer strong coupling

STAR Experiment: “Jet” Observations

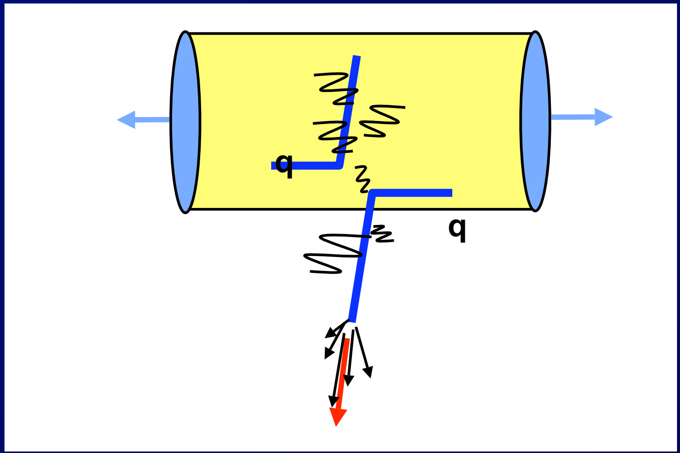
proton-proton jet event



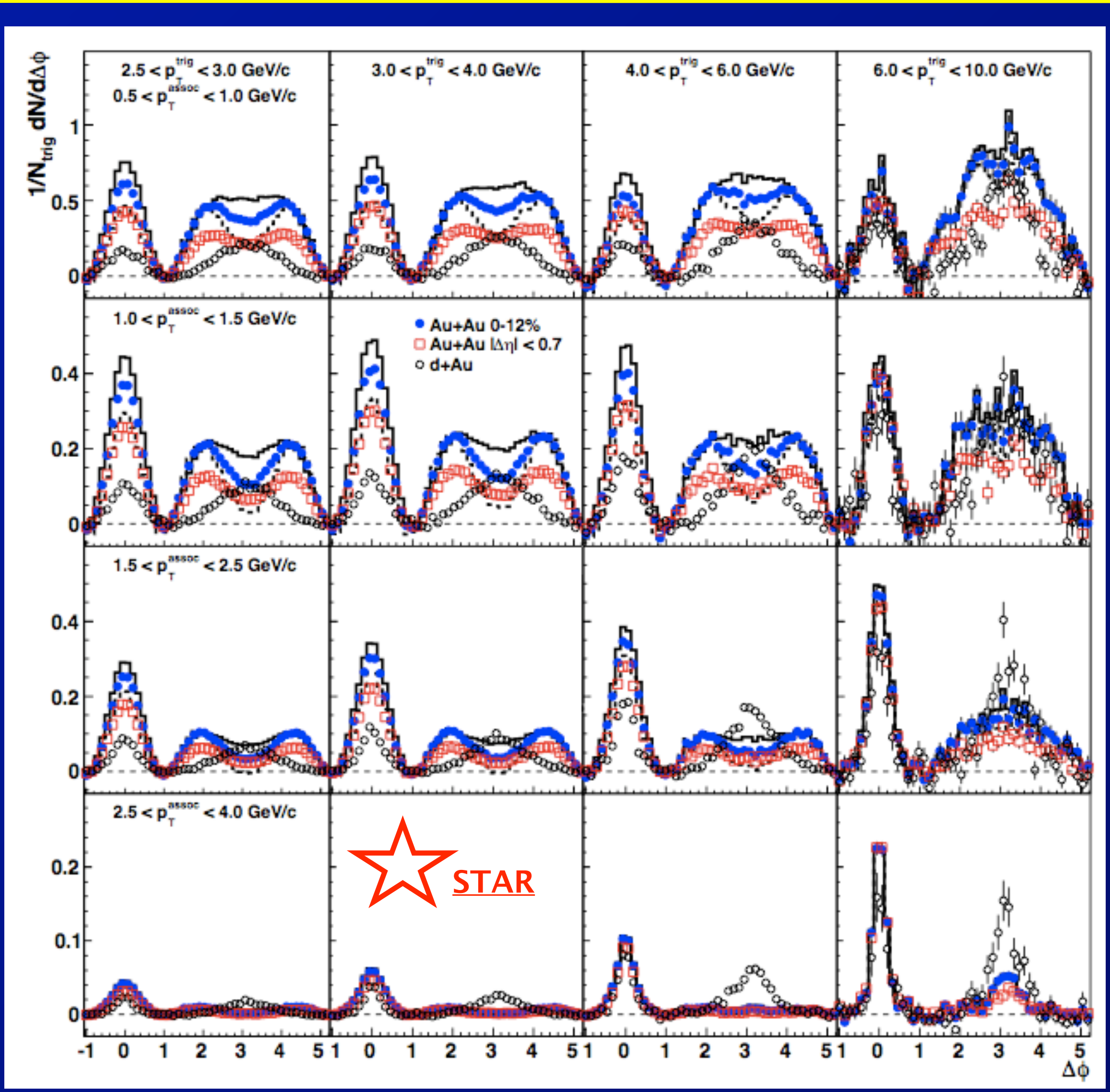
Analyze by measuring (azimuthal) angle between pairs of particles



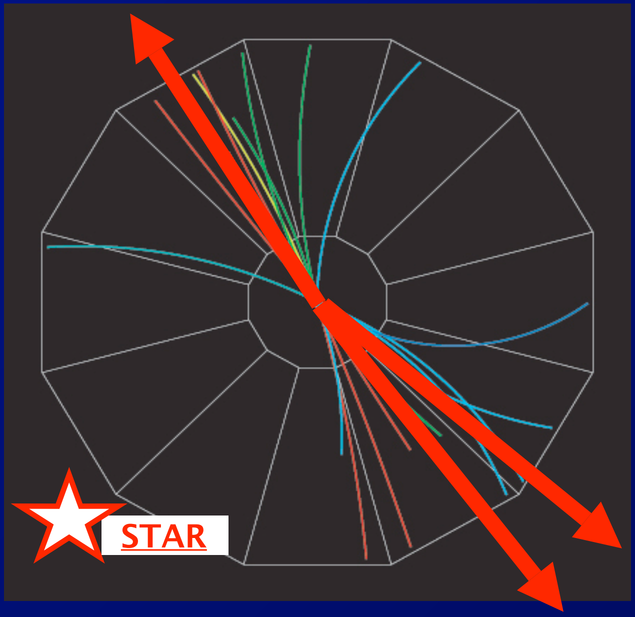
- In Au-Au collisions we see one “jet” at a time
- Strong jet quenching
- Enhanced by surface bias



Two-particle correlations



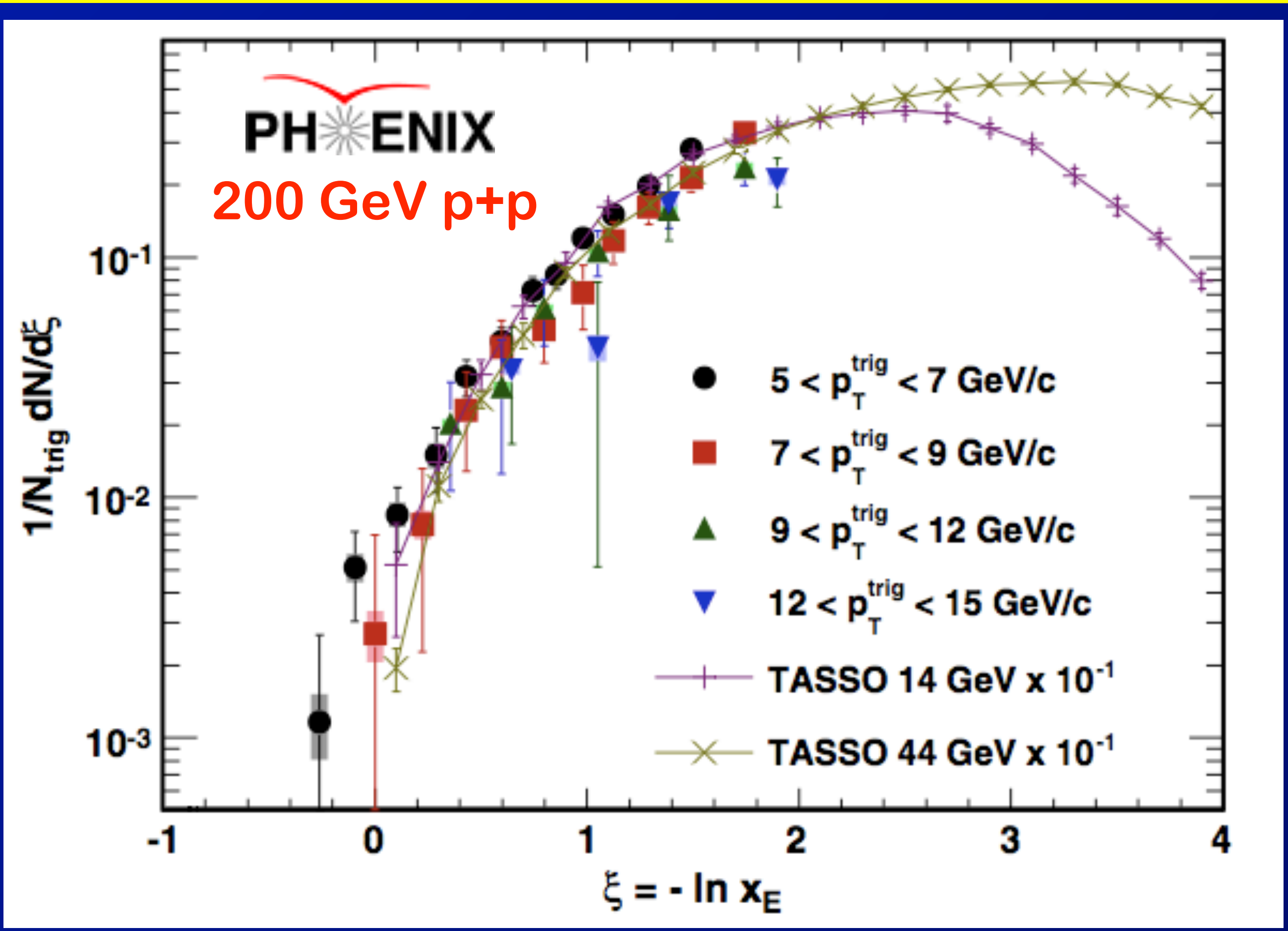
Indirect dijet measurement via dihadron correlations



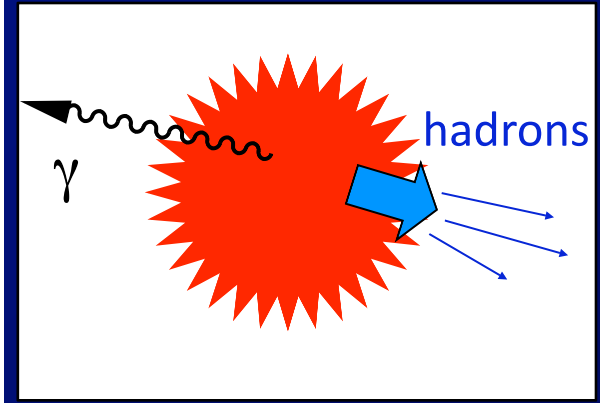
STAR,
Phys. Rev. C82
(2010) 024912

- Through very detailed measurements from STAR and PHENIX we’ve learned that most of this has little to do with high-p_T physics, though it is very interesting

First step towards jets: γ-hadron



PHENIX,
Phys. Rev. D82
(2010) 072001

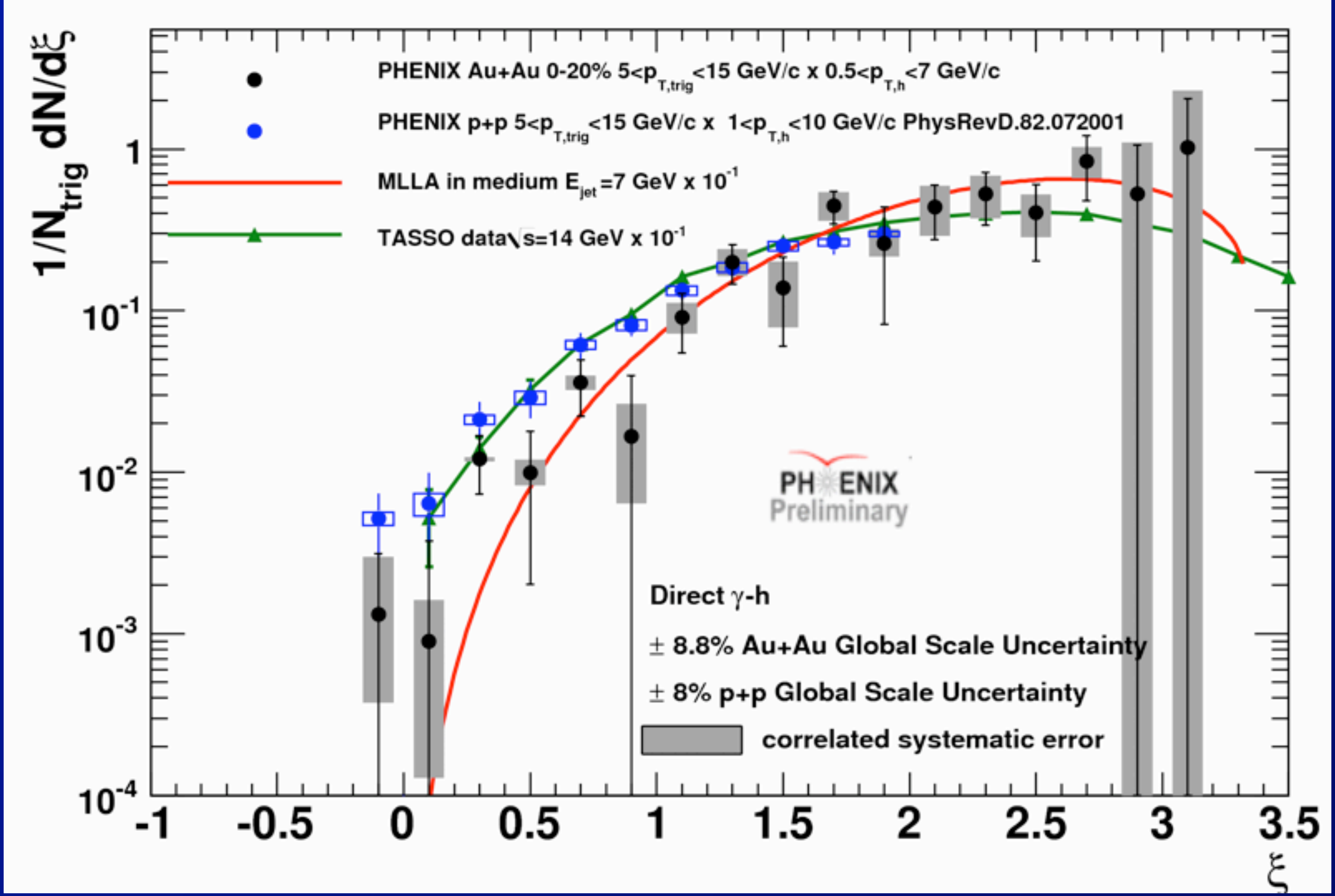


$$\xi = -\ln\left(\frac{p_T^h}{p_T^\gamma}\right)$$

- Measure jet fragmentation using γ-jet events but measuring “jet” via single hadrons
  - Compare to measurements from TASSO

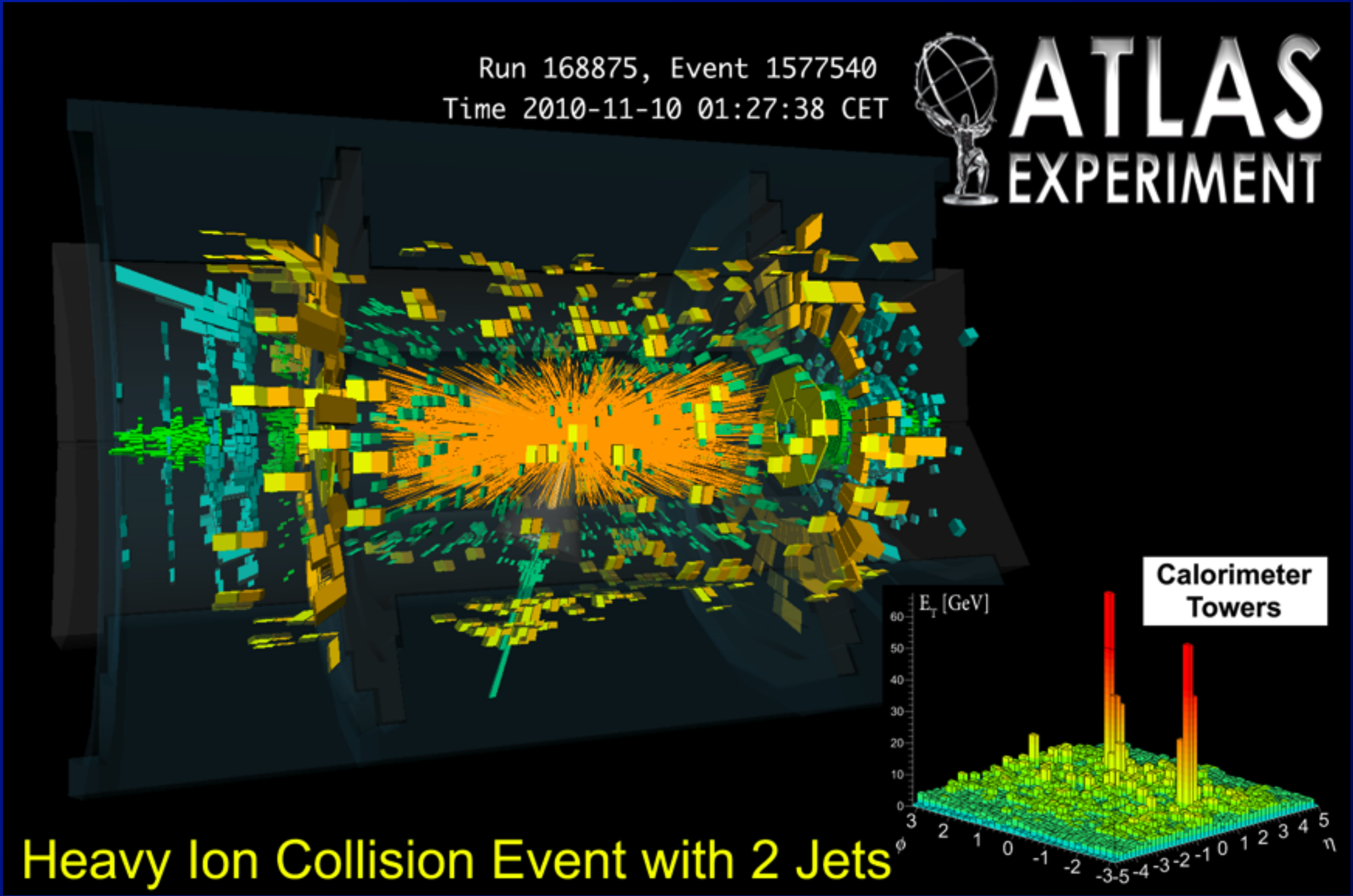
    ⇒Good agreement

First step towards jets: γ-hadron (2)



- Observe suppression in yield of large z (small ξ) fragments in (central) Au+Au collisions

Jet measurements at the LHC



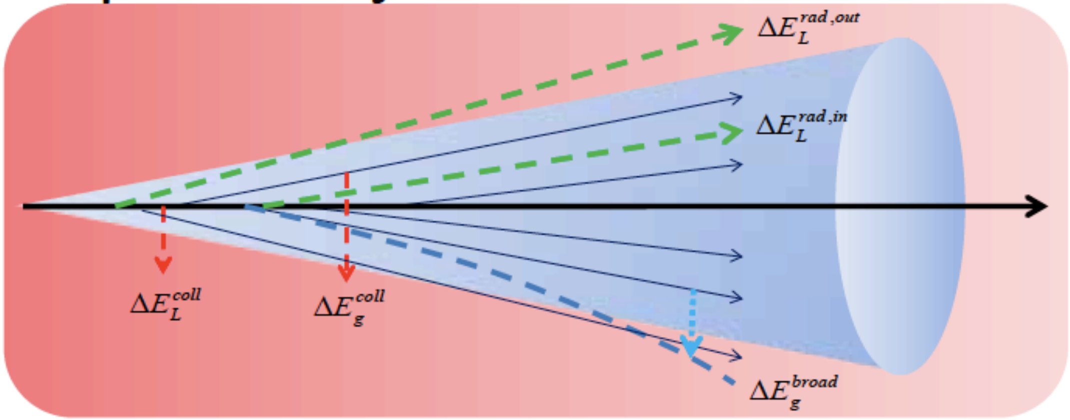
Heavy Ion Collision Event with 2 Jets

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

Successive recombination algorithms

- Start with “proto-jets”
  - Particles, towers, clusters, ...
- Define angular distance measure:
  - $D_{ij} = \min\left({p_T}_i^{2p}, {p_T}_j^{2p}\right) \frac{\Delta R_{ij}^2}{R^2}$, p = -1, 0, 1.
  - $\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$
- Also, define single-jet “cutoff”, $D_i = {p_T}_i^{2p}$
- From all pairs select minimum of $\{D_{ij}, D_i\}$
  - If *D*D_i is minimum, jet *i* is final
  - Otherwise combine *i* and *j* (below)
- Iterate until all jets are final

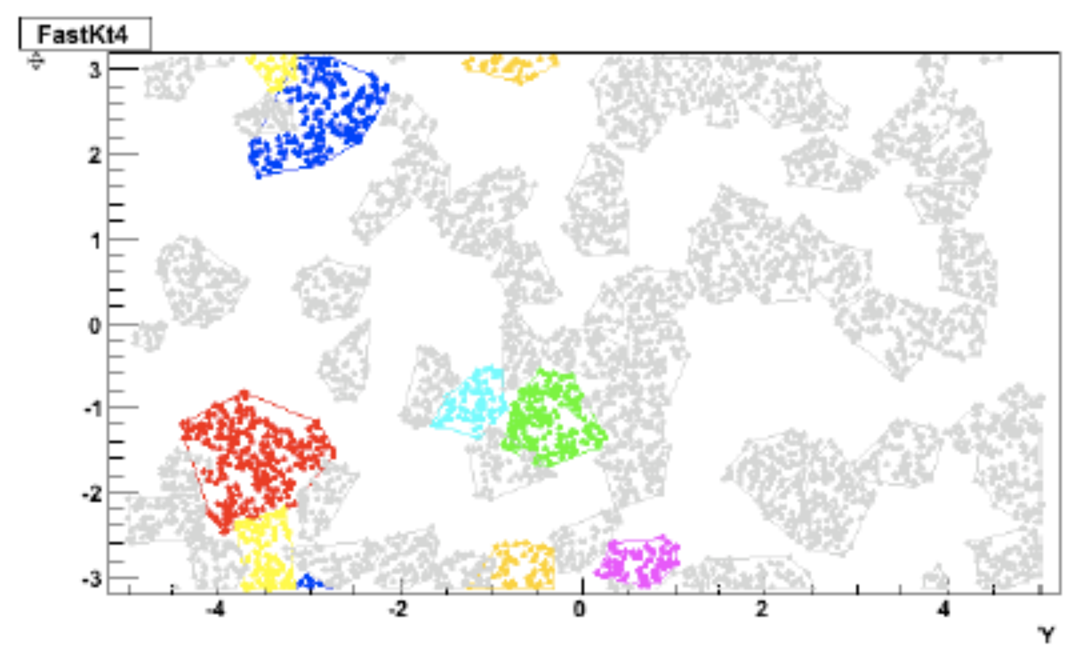
k_T algorithm

- k_T algorithm, p = 1
  - k_T of pair measured with respect to the higher energy parton

$$\Rightarrow \quad D_{ij} = \min\left({p_T}_i^{2p}, {p_T}_j^{2p}\right) \frac{\Delta R_{ij}^2}{R^2} \rightarrow min(k_T^2)$$

$$\Rightarrow \quad k_T \approx p_T \, \Delta R$$

- designed to reverse pQCD splitting
  - tends to make large, lumpy jets



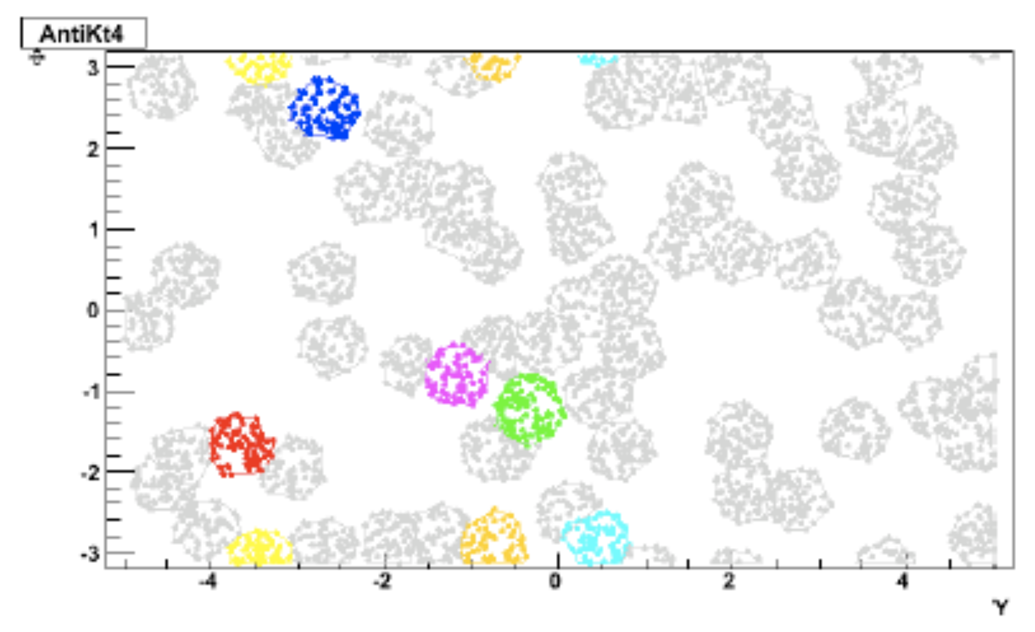
From 2009 talk by P.A. Delsart

anti-k_T algorithm

- k_T algorithm, $p = -1$
  - High p_T proto-jets provide minimum $1/p_T^2$

    ⇒define stable points around which D_{ij} is measured

    ⇒Proto-jets get clustered to the local maximum proto-jet out to a radius R.



- anti-k_T algorithm behaves like an IR and collinear safe cone algorithm.

  ⇒Most commonly used algorithm

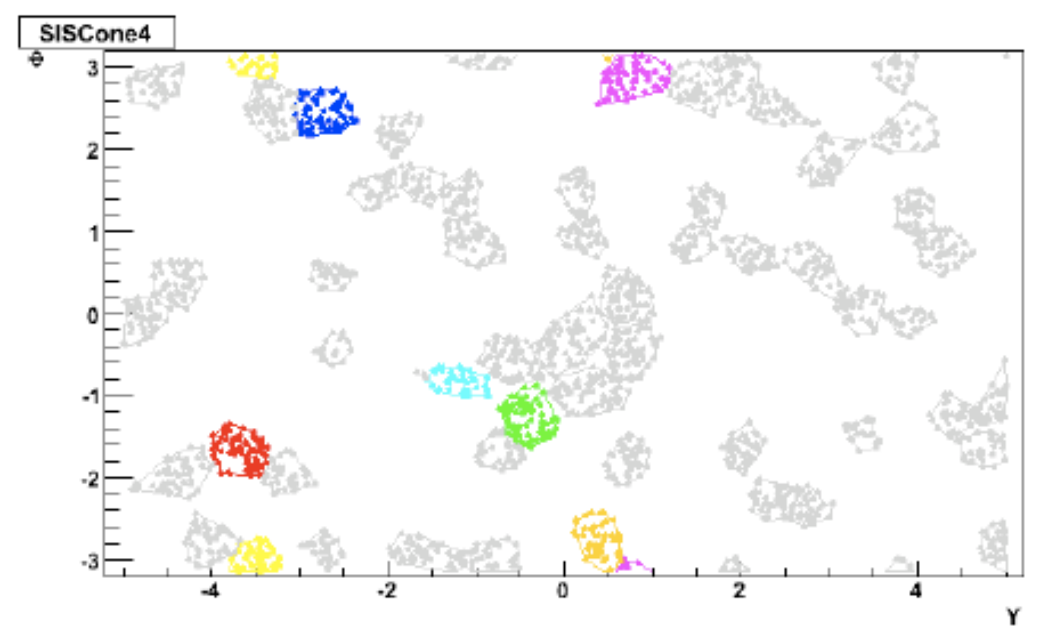
From 2009 talk by P.A. Delsart

Cambridge-Aachen, SIScone

- Cambridge-Aachen algorithm, p = 0
  - Clusters proto-jets that are closest in angle

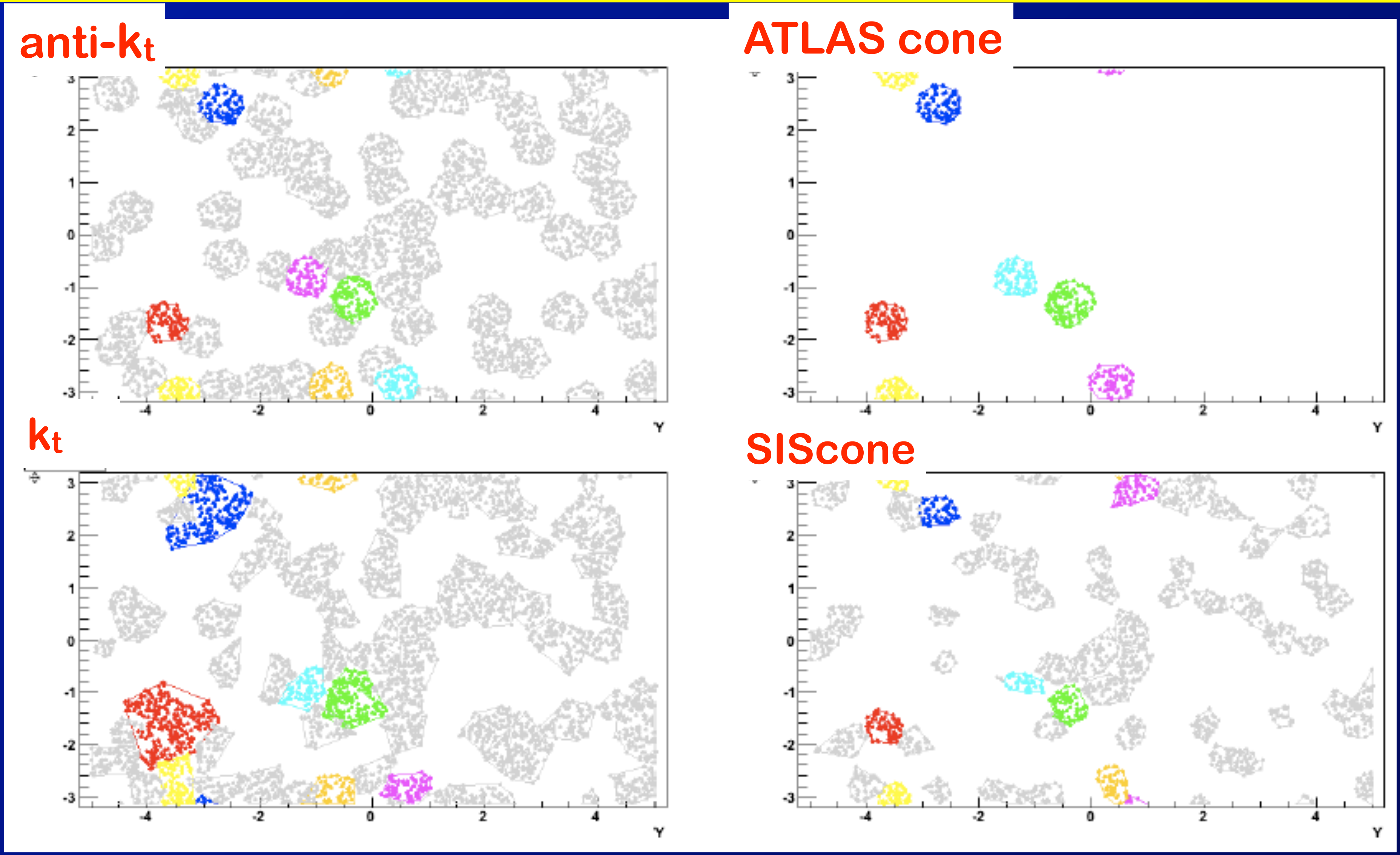
$$\Rightarrow \quad D_{ij} \to \frac{\Delta R_{ij}^2}{R^2}$$

  - Similar in behavior to k_T algorithm
- SISCone
  - Seedless, infrared safe cone algorithm by Soyez



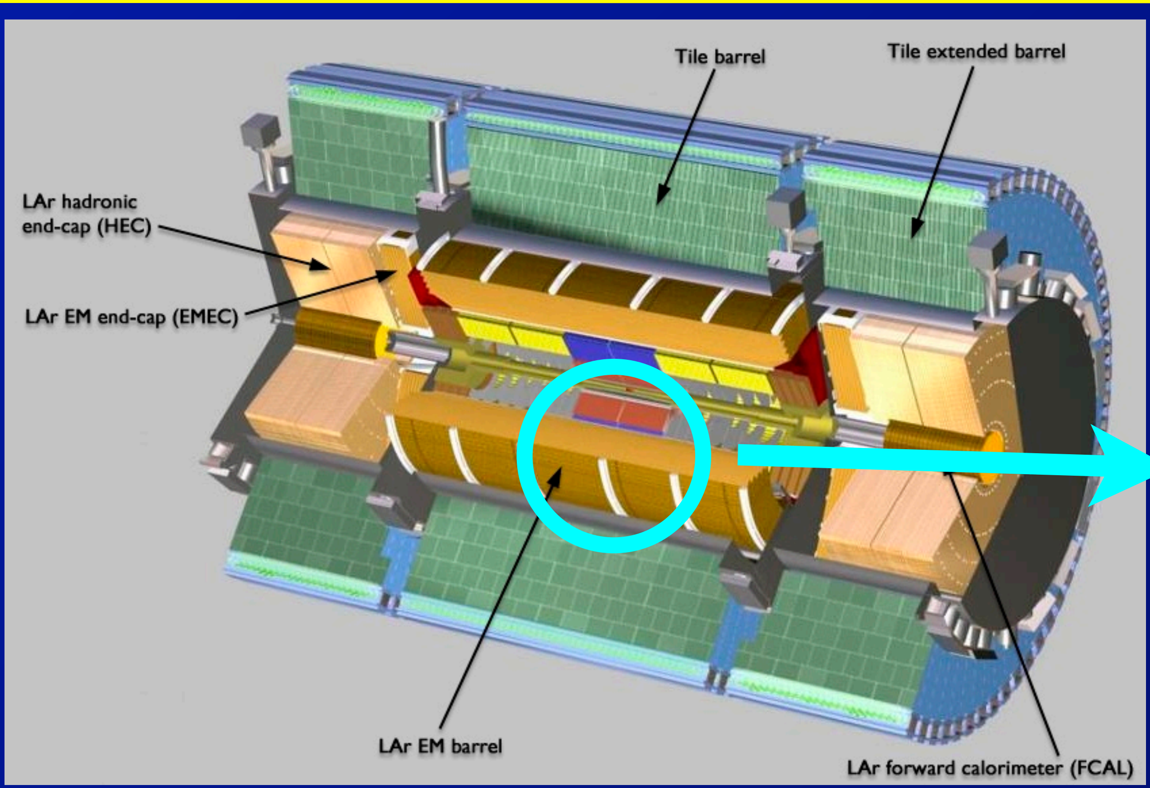
From 2009 talk
by P.A. Delsart

Comparison of jet algorithms

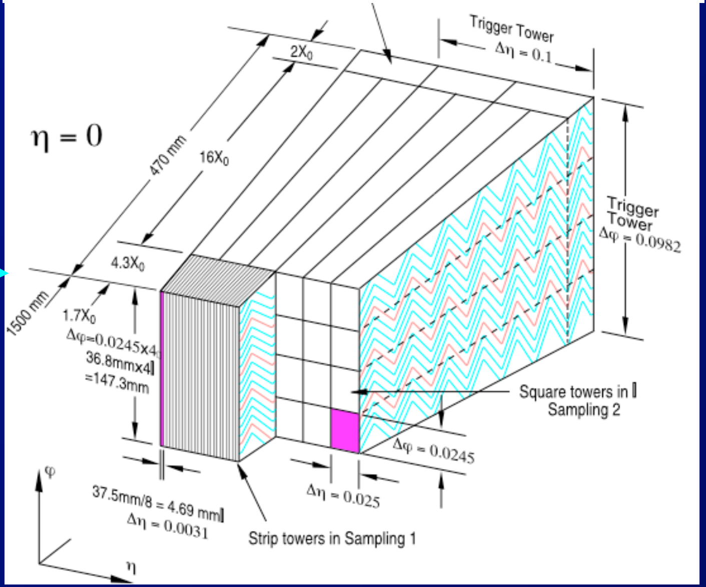


- Four algorithms, one event.
  - k_t, anti-k_t, and SIScone are collinear, IR safe

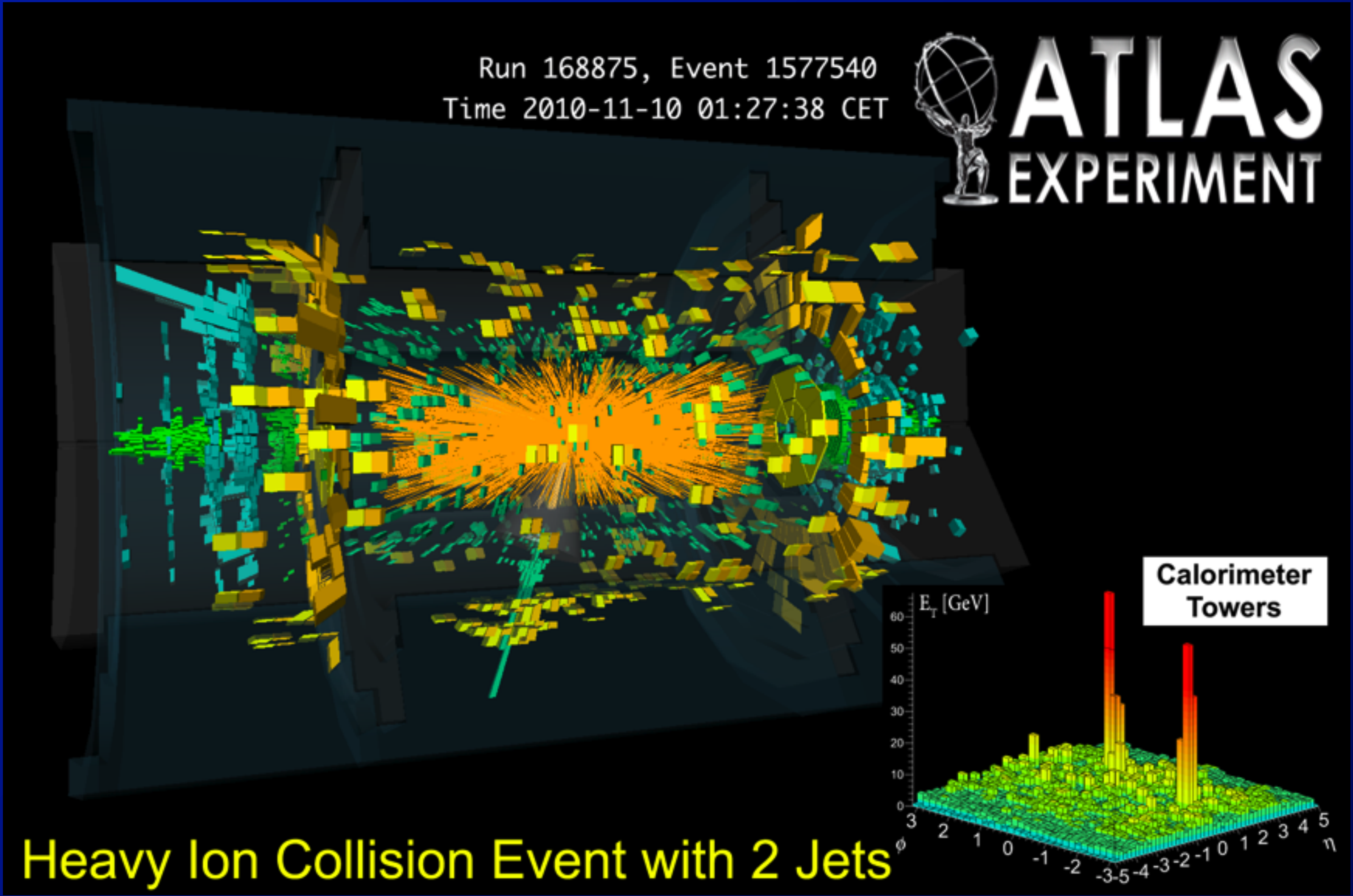
Jet reconstruction: reality



EM Longitudinal Segmentation

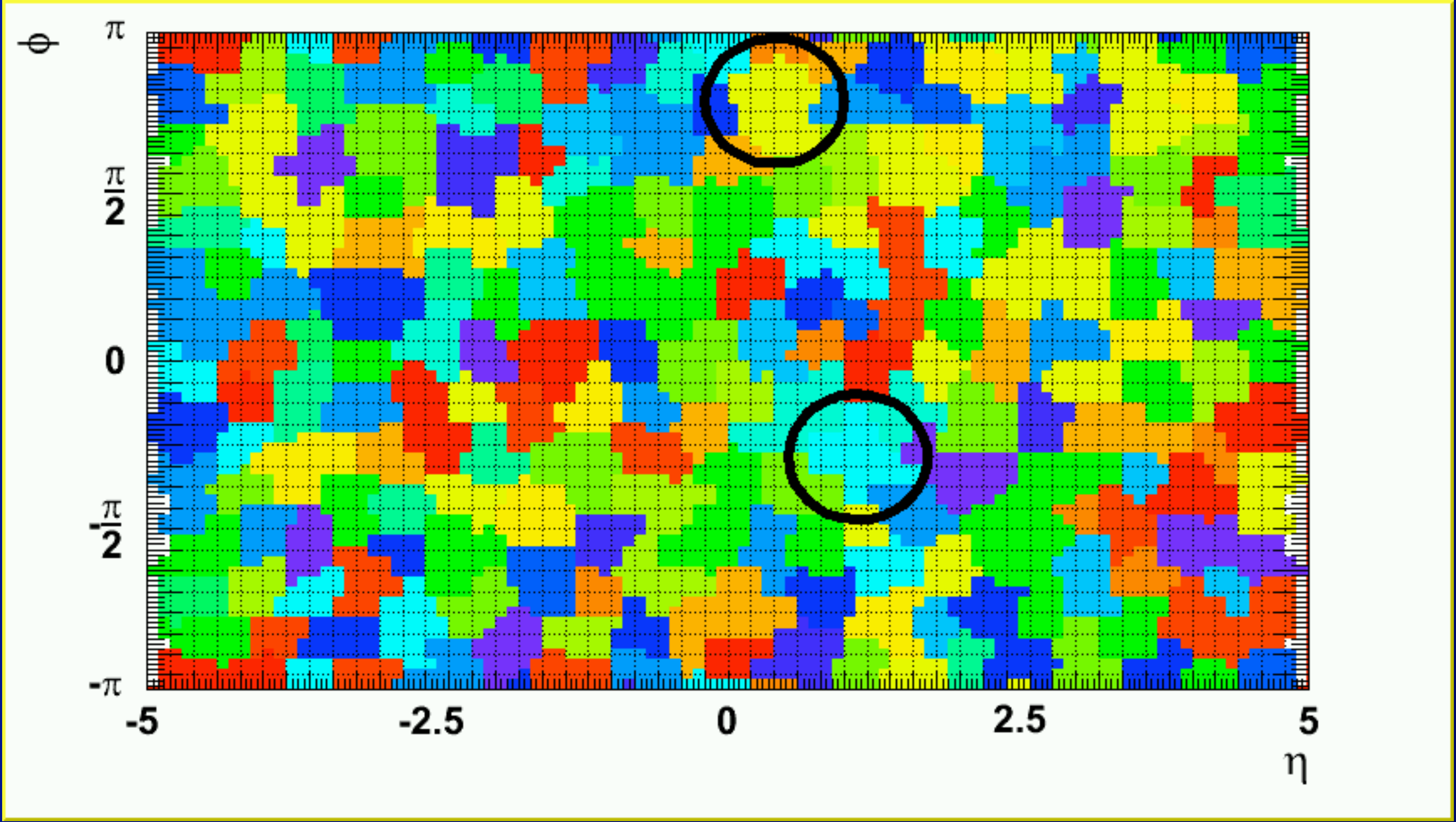


- **Details that matter for all calorimeters:**
  - Technology
  - Longitudinal, transverse segmentation
  - Hadronic vs electromagnetic response
  - Electronic noise
  - Dead material



Heavy Ion Collision Event with 2 Jets

The starting point



- Reconstruct (unsubtracted) Pb+Pb event
  - Here, for demonstration, with k_t algorithm
    - ⇒But the kt algorithm is problematic because the background jets “eat” edges of real jets

The underlying event

- ~ universal starting point for UE subtraction
  - $E_{\mathrm{T}}^{\mathrm{subtr}} = E_{\mathrm{T}}^{\mathrm{unsubtr}} - \rho A$

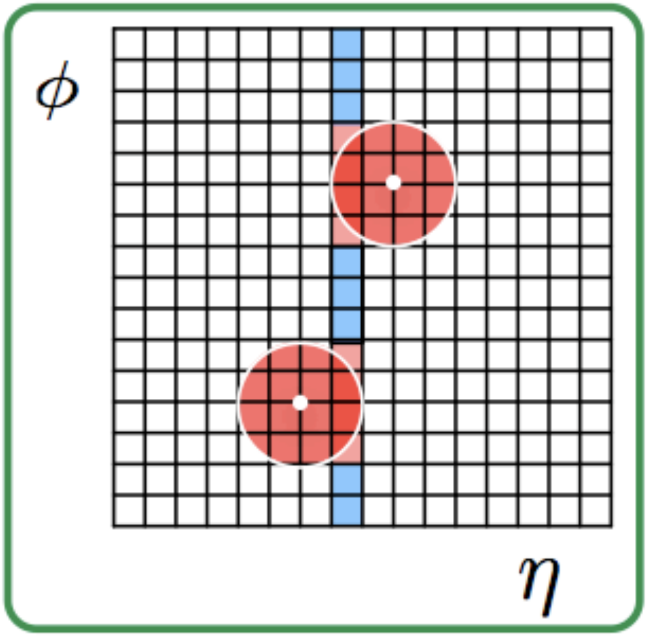
    ➡ But the details are critical
- Important considerations:
  - What kind of objects is subtraction applied to?

    ➡ Towers, topoclusters, cells, ...
  - How to estimate UE energy density, ρ ?
  - With what granularity?
  - Event -by-event or event-averaged?

    ➡ But if averaged, need separate measure of μ
  - How to exclude jets, photons, ... from ρ ?

The underlying event (ATLAS)

$$\rho(\eta) = \left\langle \frac{E_{\mathrm{T}}^{i}}{\Delta\eta^{i}\Delta\phi^{i}} \right\rangle_{i \notin \mathrm{jet},\, |\eta^{i}-\eta|<0.05}$$



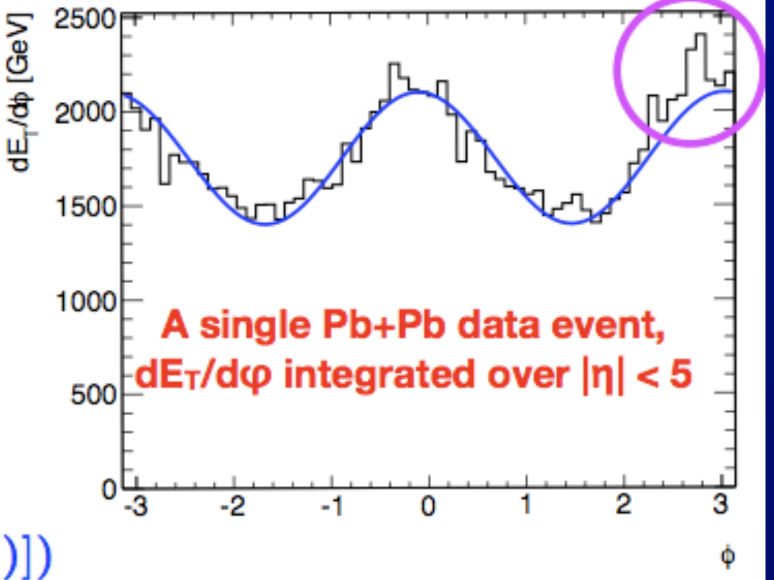
- For each Pb+Pb event:
  - For each calorimeter layer:
    - ➡ Calculate an AVERAGE (not median!) cell E_T density in $\Delta\eta = 0.1$ intervals
    - ➡ Excluding cells that lie within $\Delta R = 0.4$ of seeds
- Then, apply $E_{\mathrm{T}}^{\mathrm{subtr}} = E_{\mathrm{T}}^{\mathrm{unsubtr}} - \rho A$ to each cell within tower constituents of reconstructed jets

The underlying event (ATLAS)

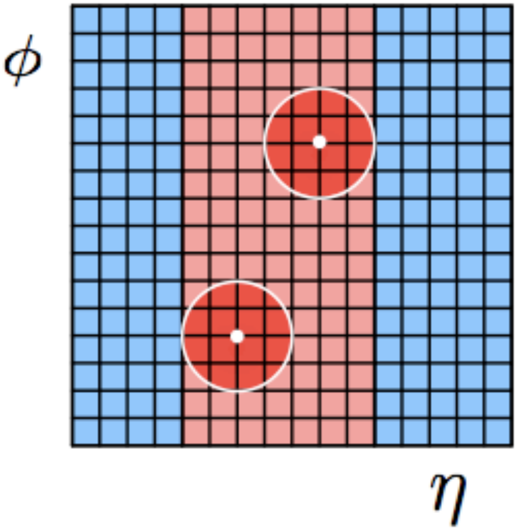
- **Pb+Pb collisions present additional complications**
  - collective flow in the UE
    - ➡ as large as ± 20%
    - ➡ fluctuates event to event
- **Accounted for in subtraction**
  - $\rho^{\mathrm{Pb+Pb}}(\eta,\phi) = \rho(\eta)(1 + 2v_2^{\mathrm{UE}}\cos[2(\phi - \Psi_2)])$
- **With amplitude of modulation (v2) determined event-by-event**

$$\boxed{v_2^{\mathrm{UE}} = \langle E_{\mathrm{T}}^{i}\cos[2(\phi^{i} - \Psi_2)]\rangle_{i\notin \mathrm{jet}}}$$

- ➡ excluding any η interval containing a seed



A single Pb+Pb data event, $dE_T/d\varphi$ integrated over $|\eta| < 5$

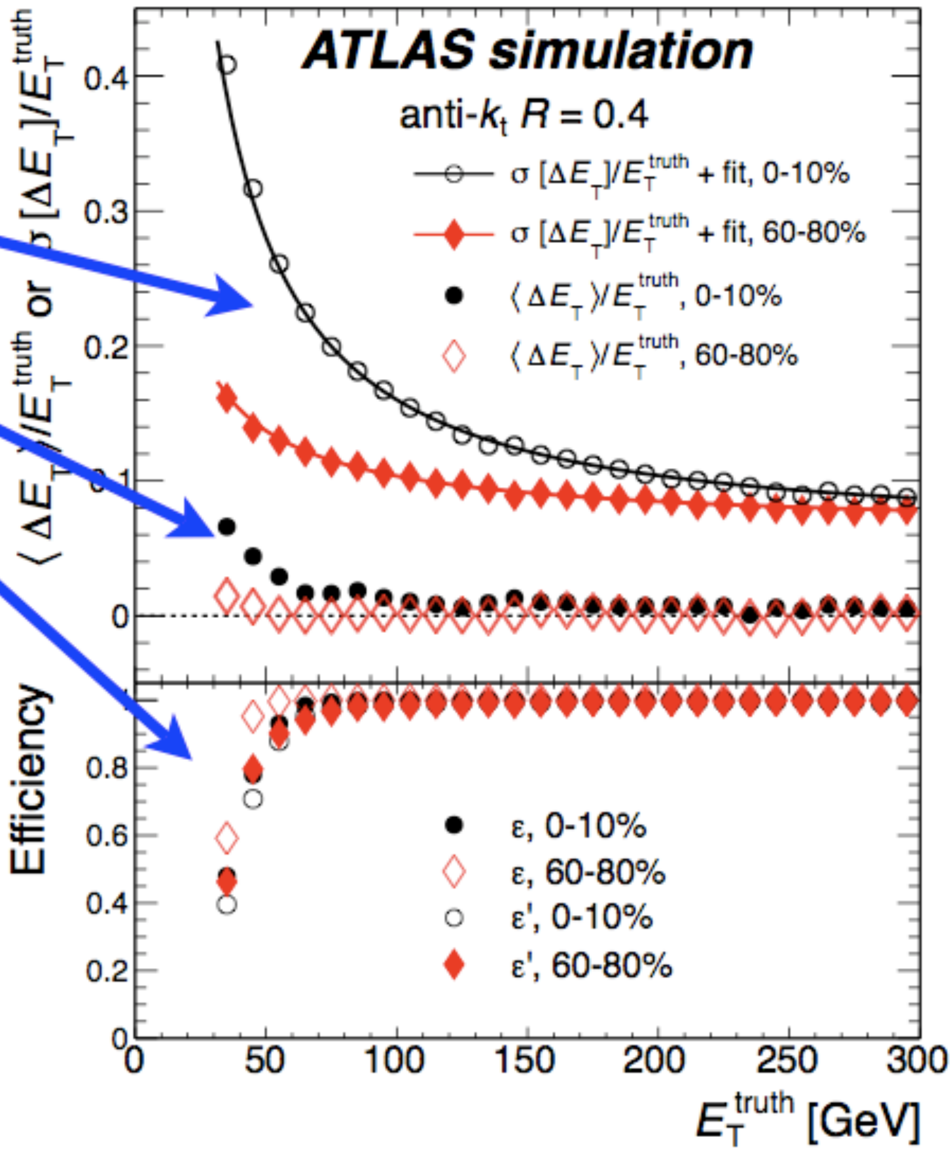


ATLAS jet performance

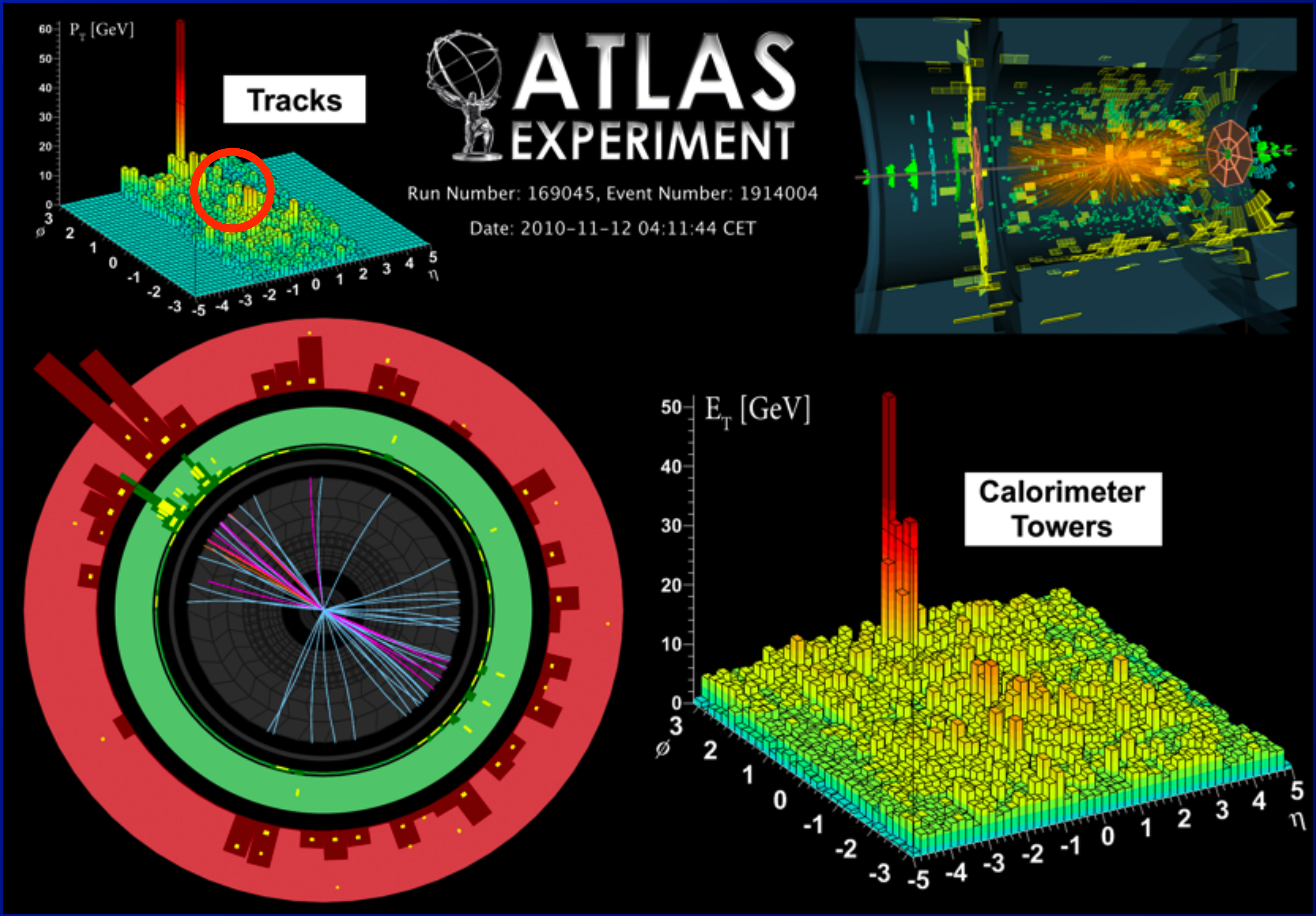
- **Three metrics**
  - Jet energy resolution
  - Jet energy scale
  - Jet reconstruction efficiency

  ➡ with (ε') and without (ε) fake rejection
- **Of these, we only have control over JES**

  ➡ Sensitive test of background subtraction

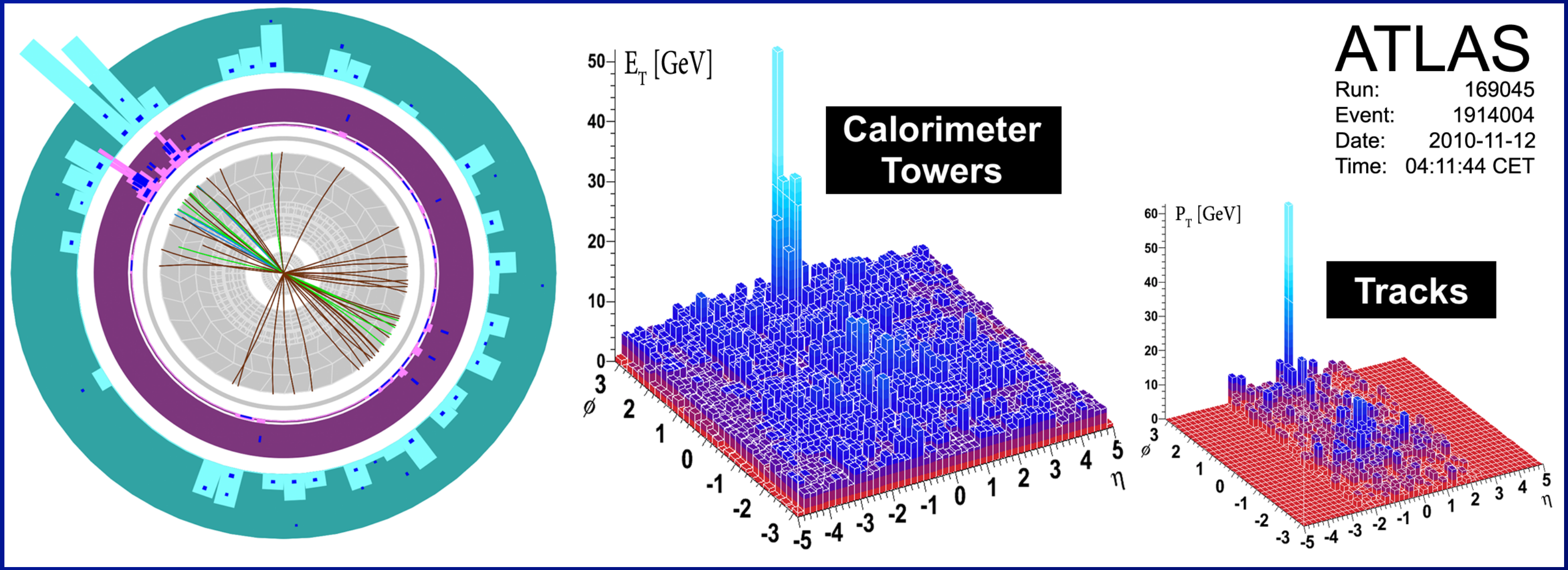


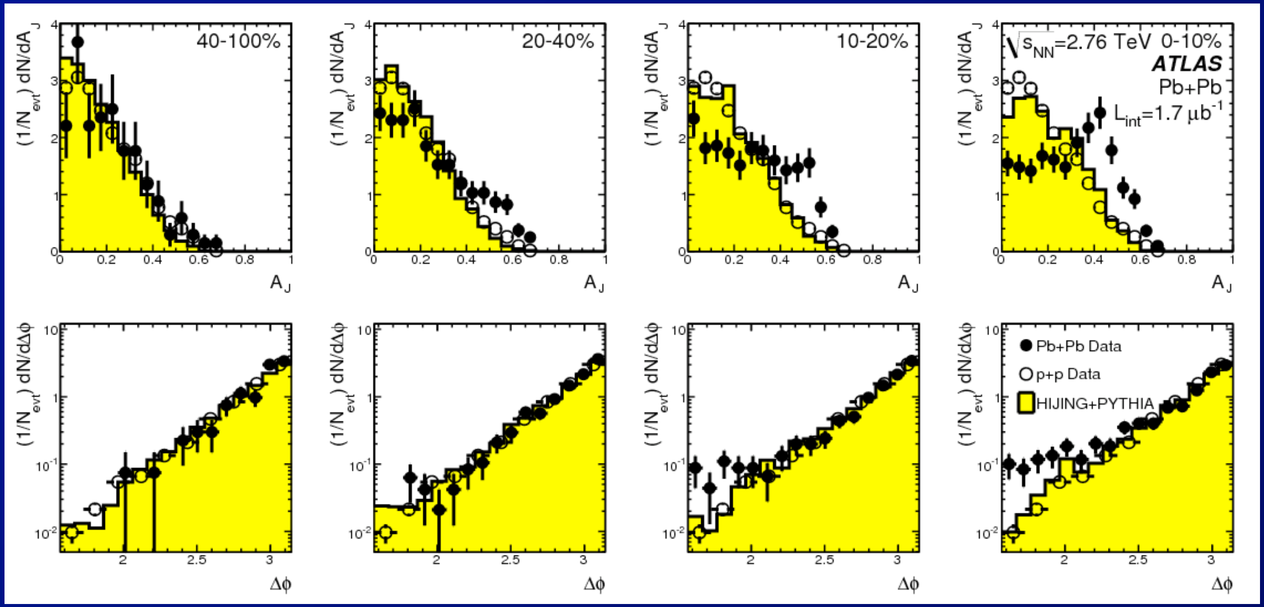
An example Pb+Pb jet event



Even more central collision, more asymmetric dijet

ATLAS dijet asymmetry measurement





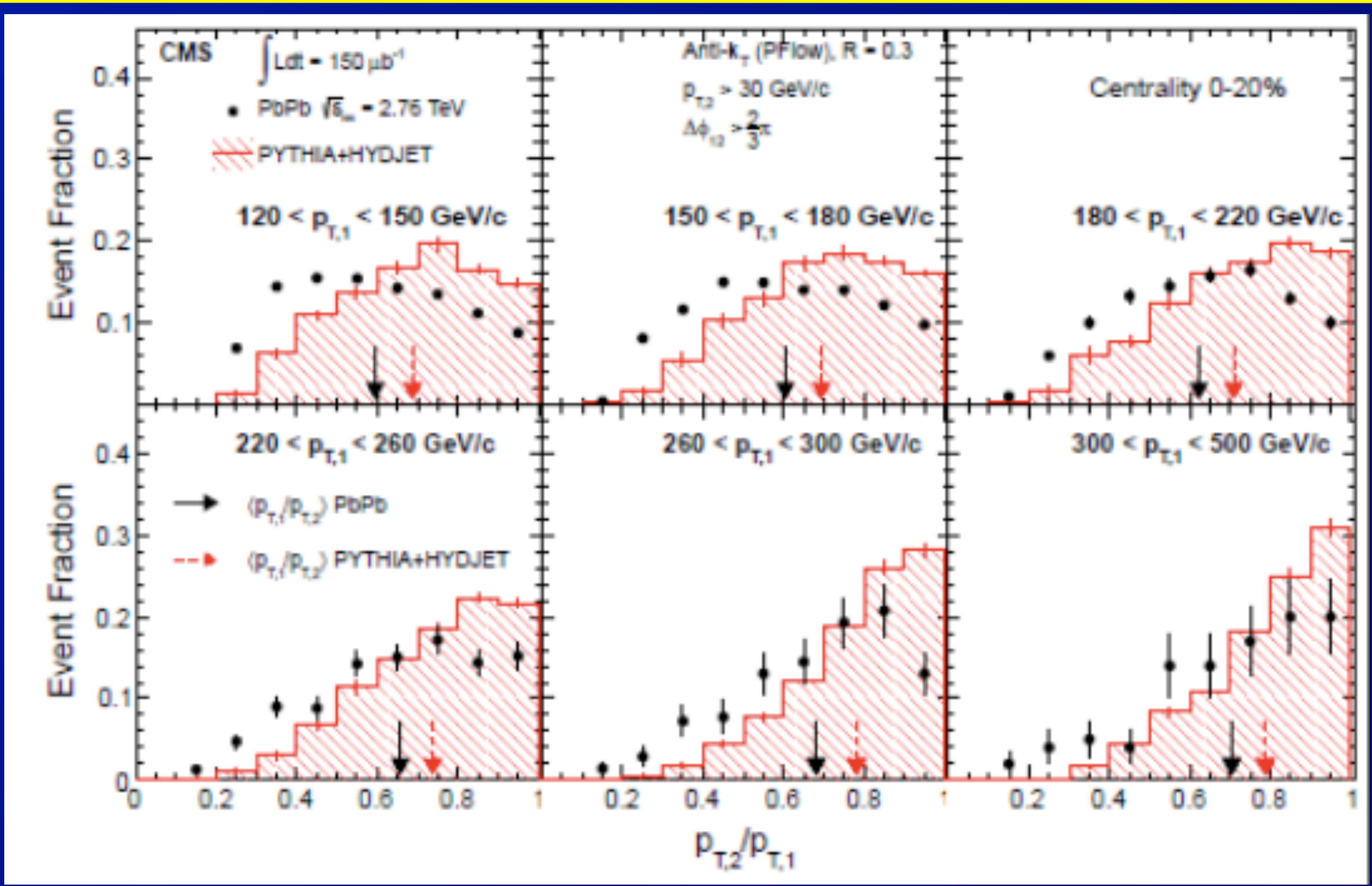
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

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

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

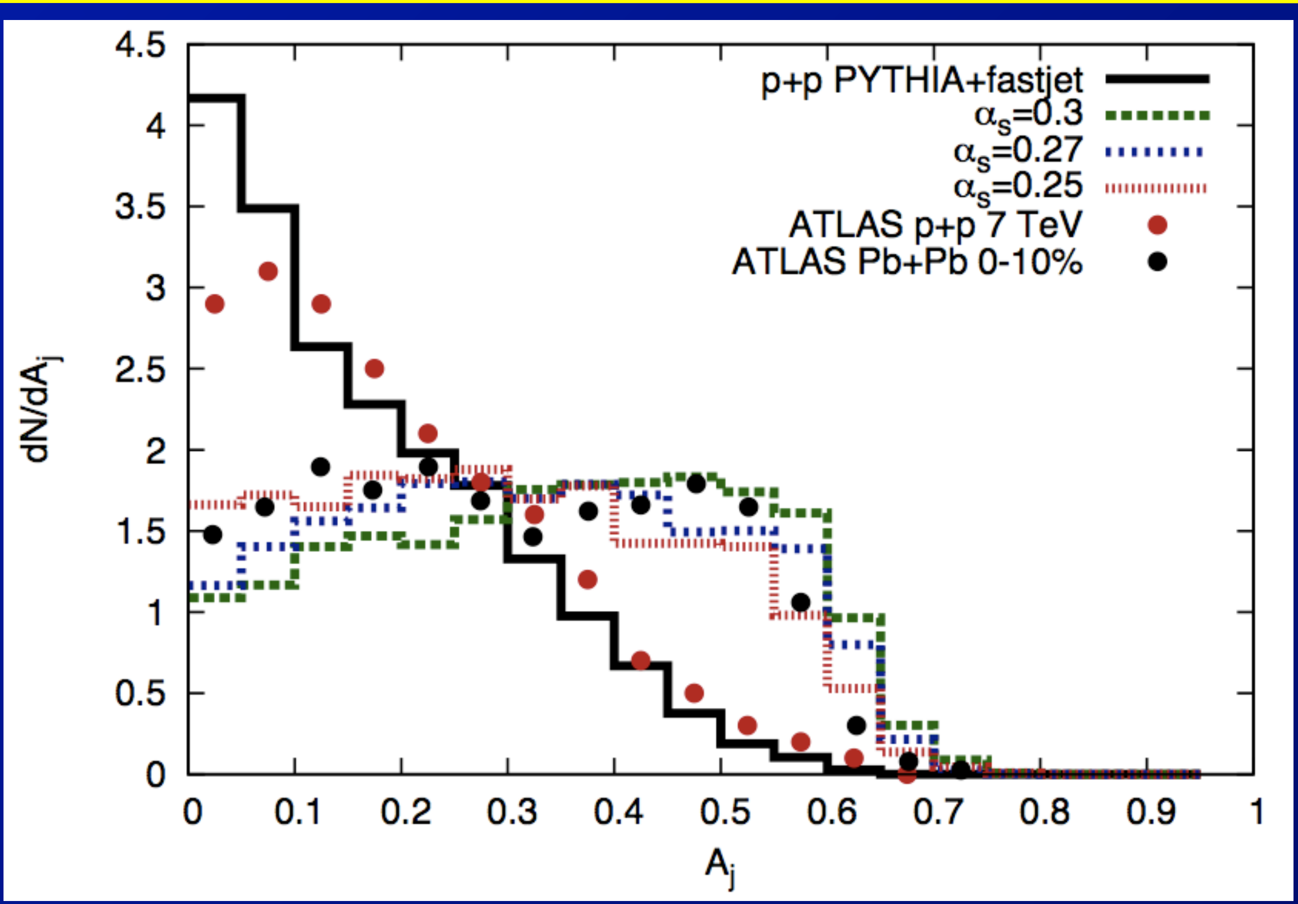
1st indication of medium modifications of jets @ LHC

Dijets: CMS 2011 data



- Clear demonstration that the effects of differential quenching extend to high p_T
  - –what is role of jet flavor (quark, gluon, heavy)?
    - ⇒In particular, gg vs qg.

Dijet asymmetry: Theory comparisons



Young et al,
arXiv 1103.5769
[nucl-th]

AMY energy loss
formalism

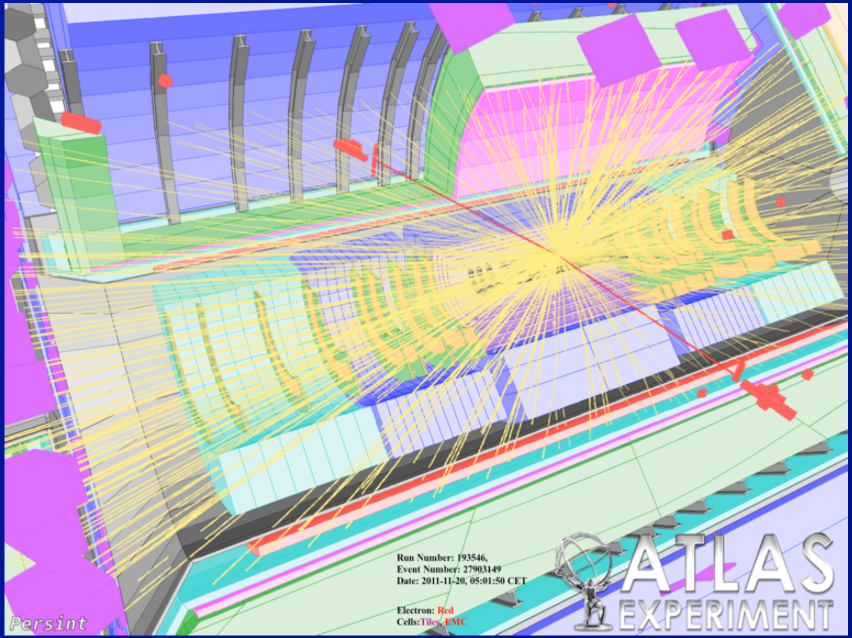
- AMY energy loss with 1 free parameter (α_s)
  - Good description of modified asymmetry distribution

    ⇒Decisive test of energy loss calculations

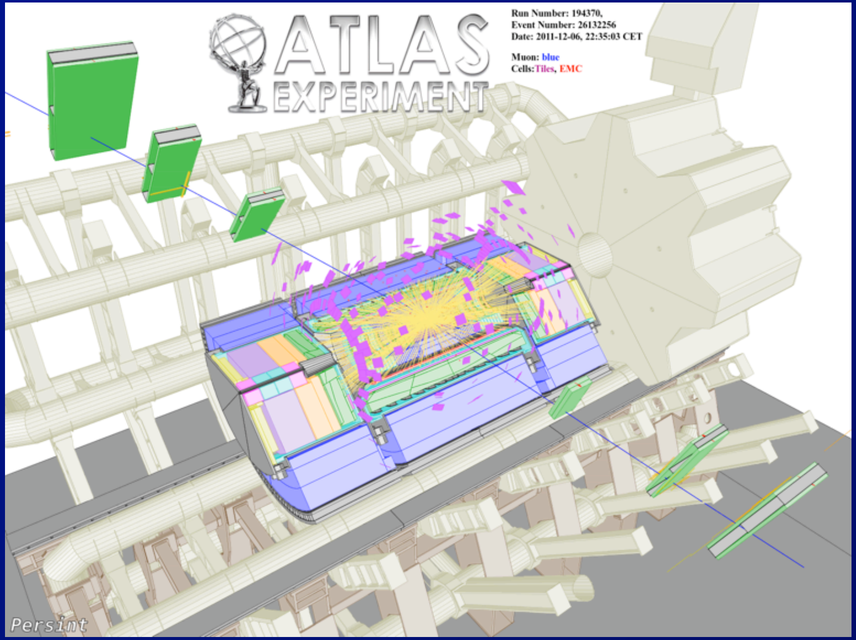
    ⇒1st step towards quantitative probe of jet + sQGP interactions using jets

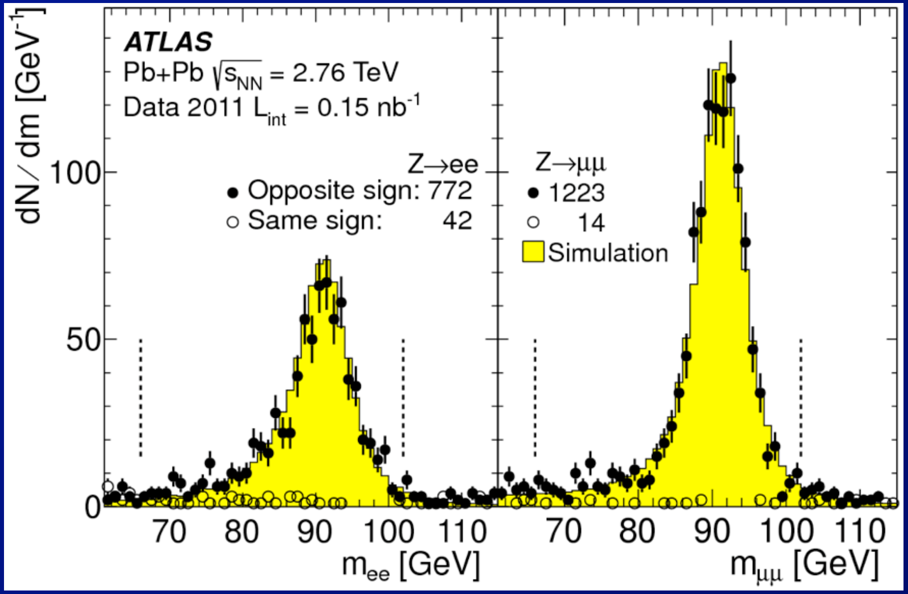
Hard scattering rate control: Z

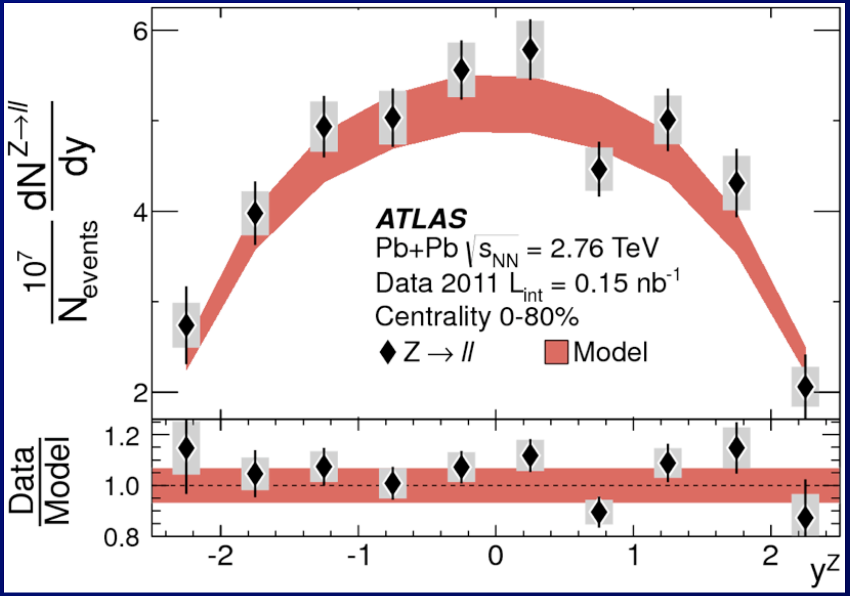
Z→e^+e^- event display



Z→$\mu^+\mu^-$ event display

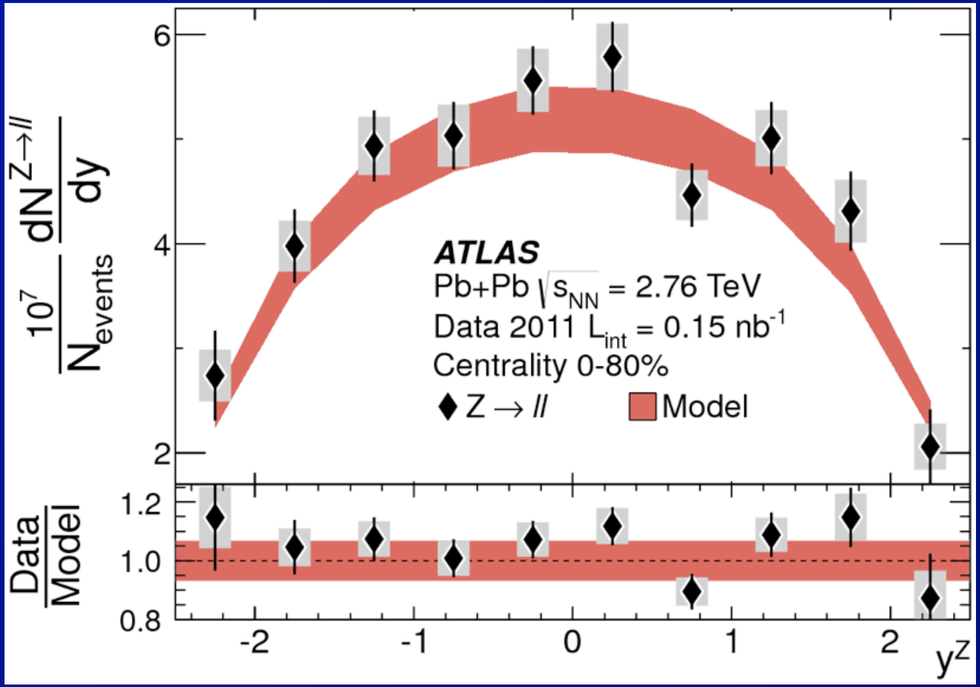


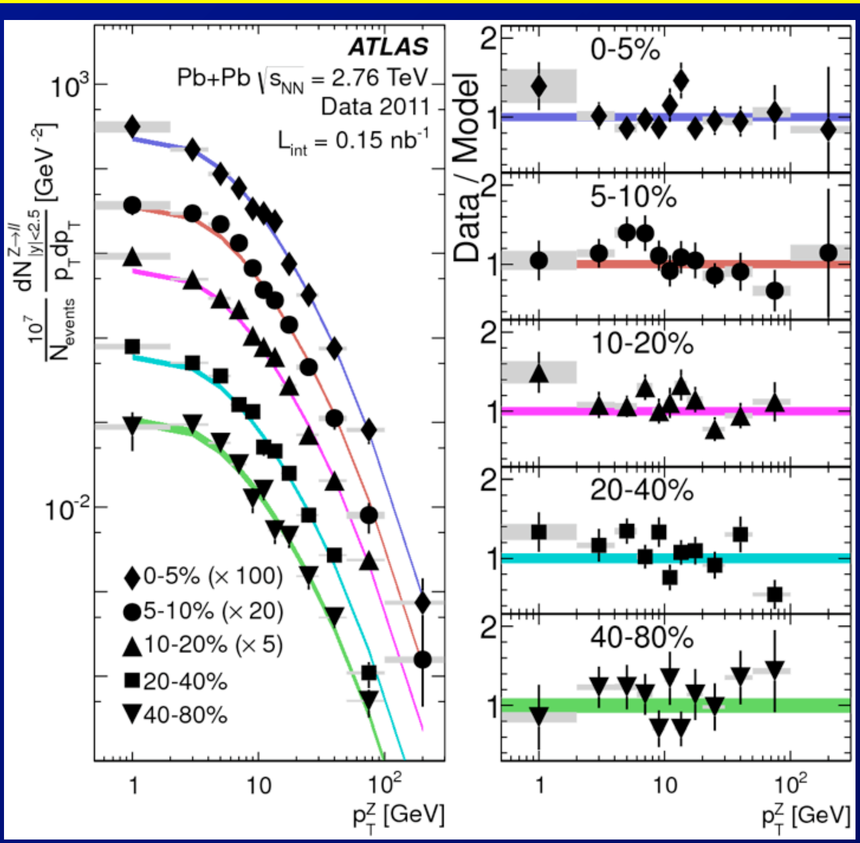




Hard scattering rate control: Z

Phys. Rev. Lett. 110, 022301 (2013)

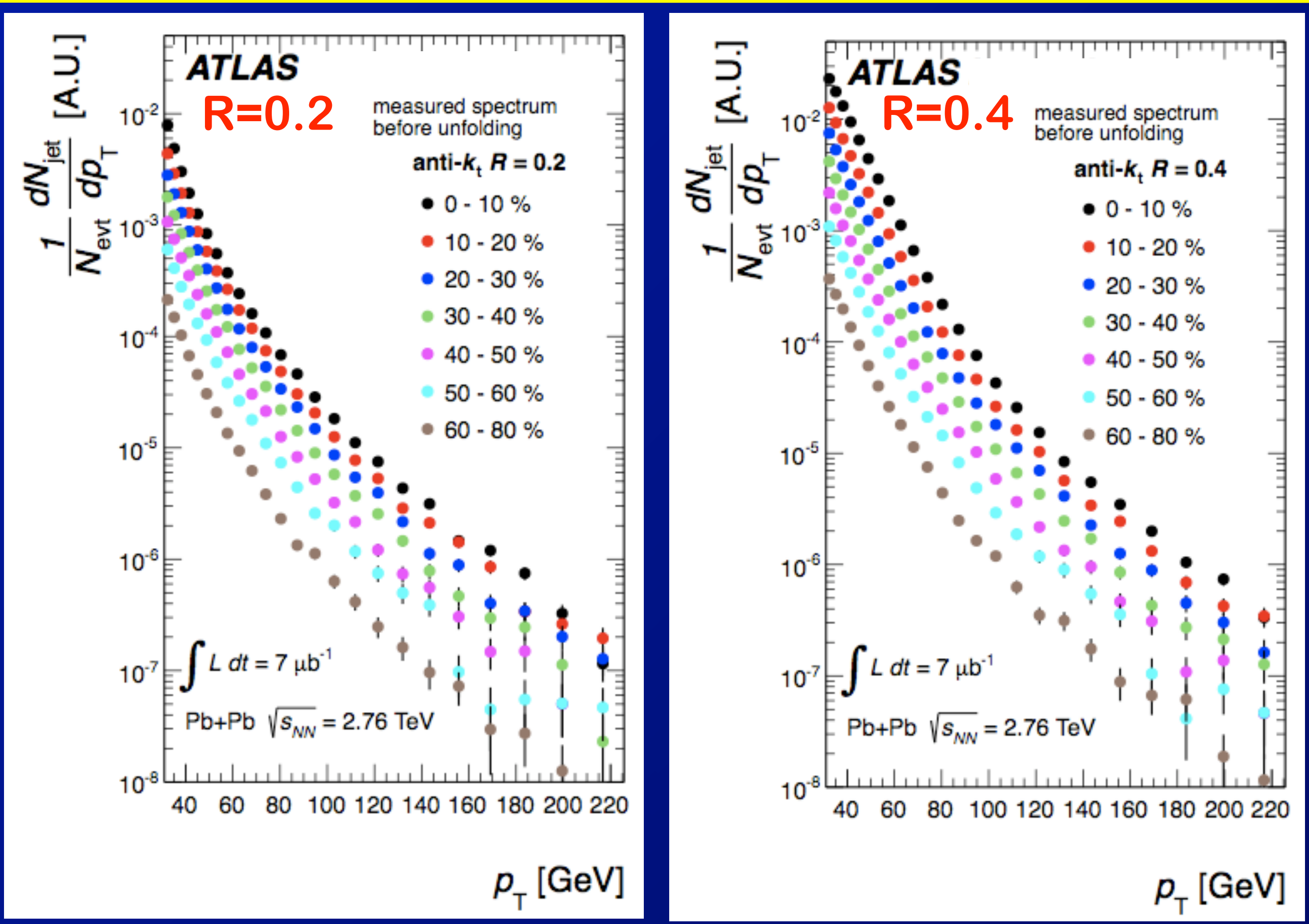




- Compare Pb+Pb Z rapidity distributions (minimum-bias) and p_T spectra to PYTHIA scaled to NNLO calculations
  - Pb+Pb Z production rates consistent with MC

    ⇒hard scattering rates under control

Pb+Pb Jet Spectra



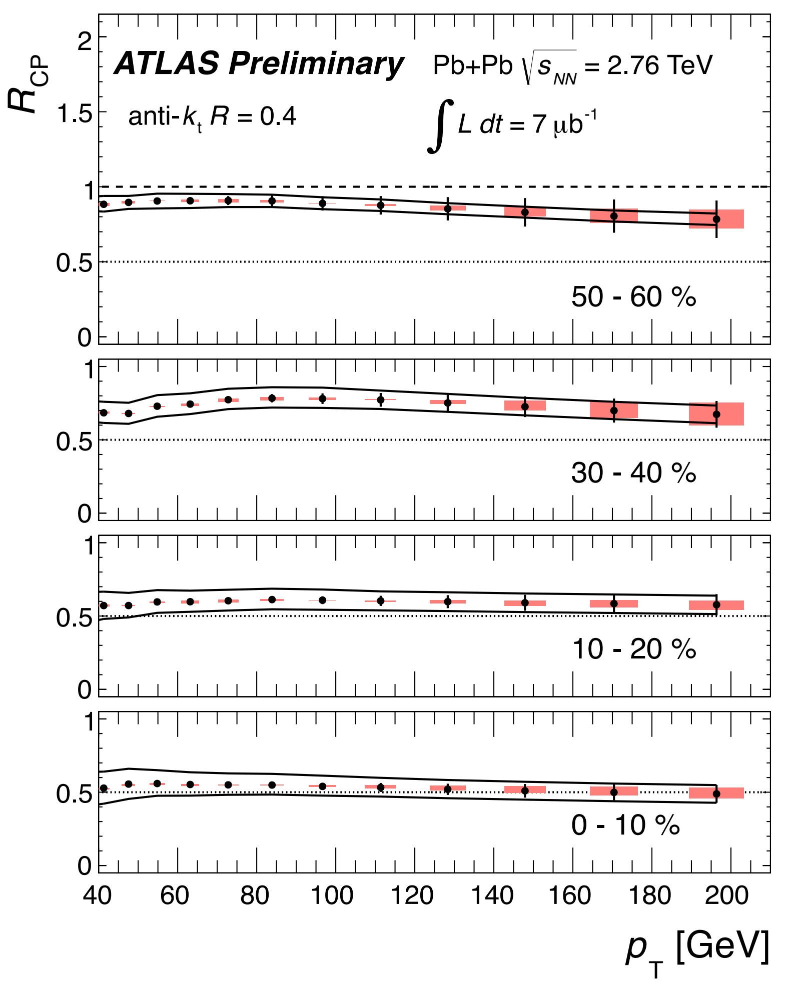
Unfolded (SVD) and efficiency corrected

- For these results, no absolute normalization
  - awaiting absolute jet energy scale uncertainty

Jet yields: centrality dependence

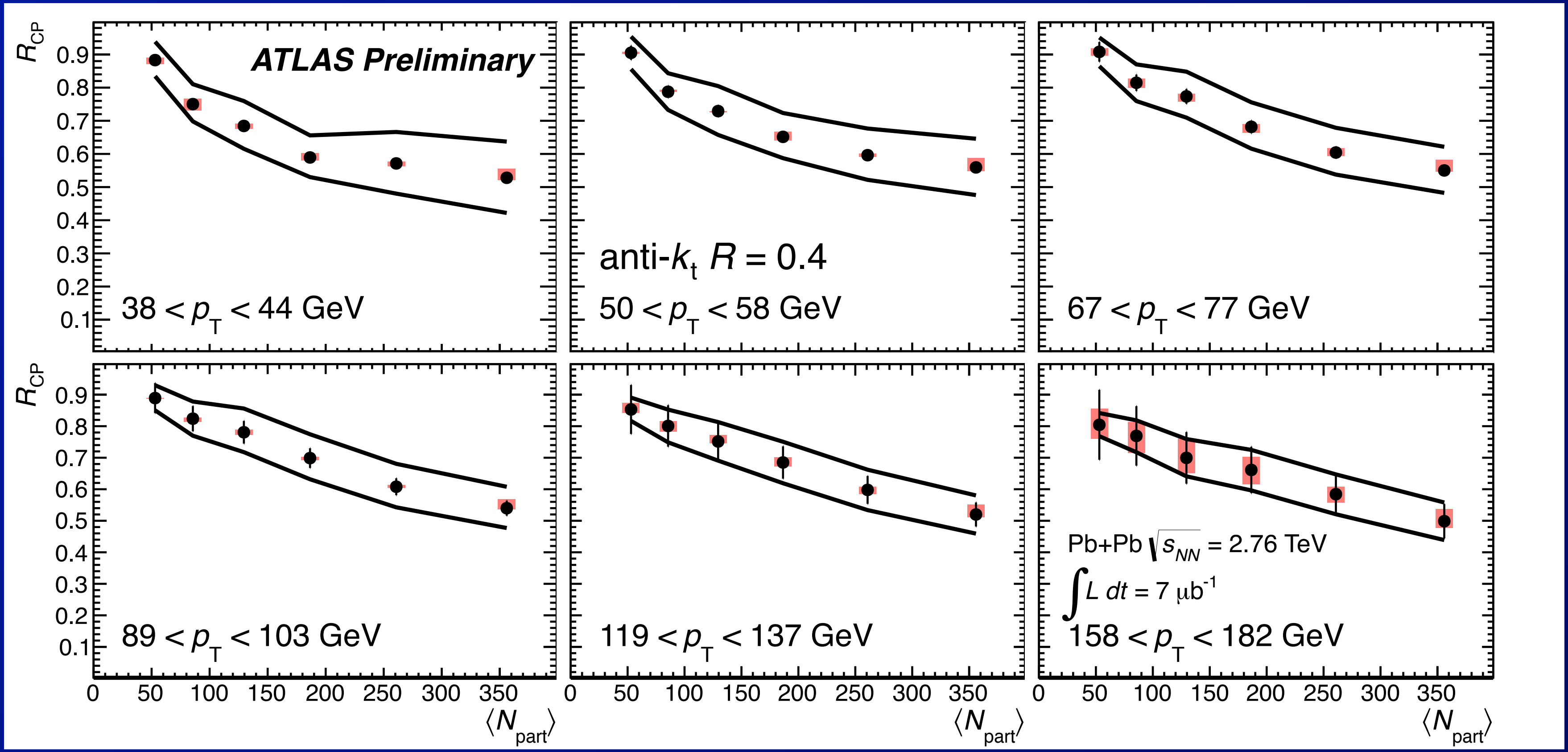
- If factorization holds jet yields should vary with centrality $\propto N_{\rm coll}$
- Compare yields between centrality bins using "$R_{\rm cp}$"

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



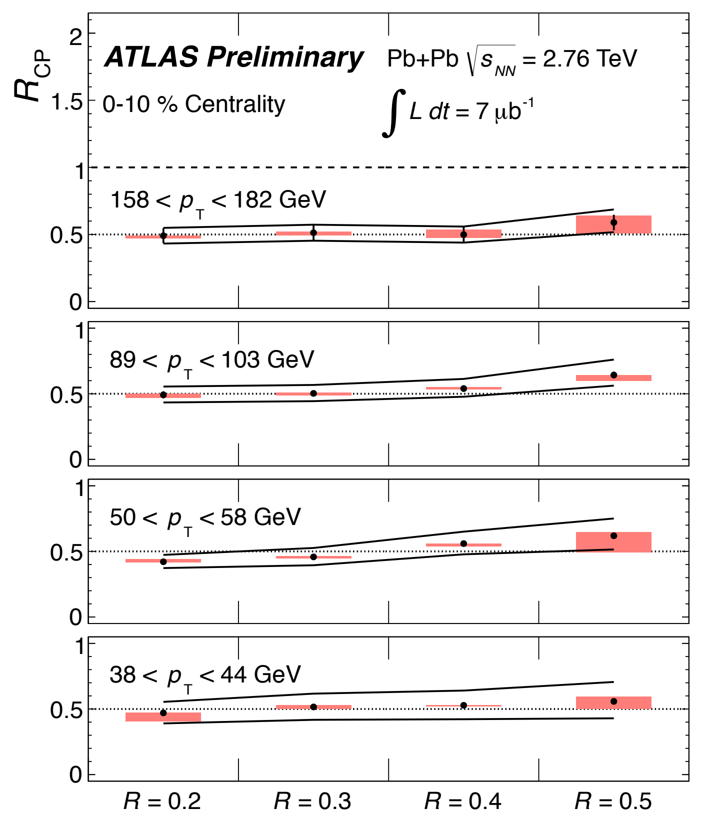
  - Overall jet energy scale divides out in ratio

Centrality dependence of jet R_{cp}

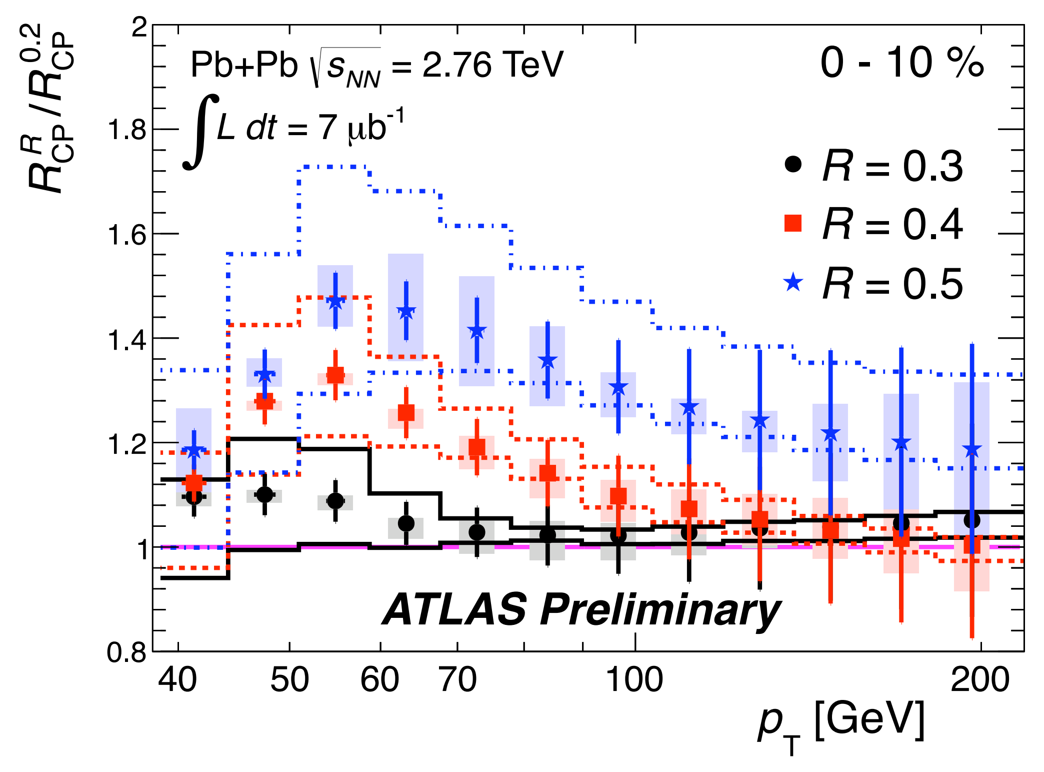


- Study centrality evolution for fixed jet p_T
  - R_{cp} vs N_{part}
    - ⇒Smooth turn on of jet suppression between peripheral and central collisions.

Jet radius dependence of R_{cp}

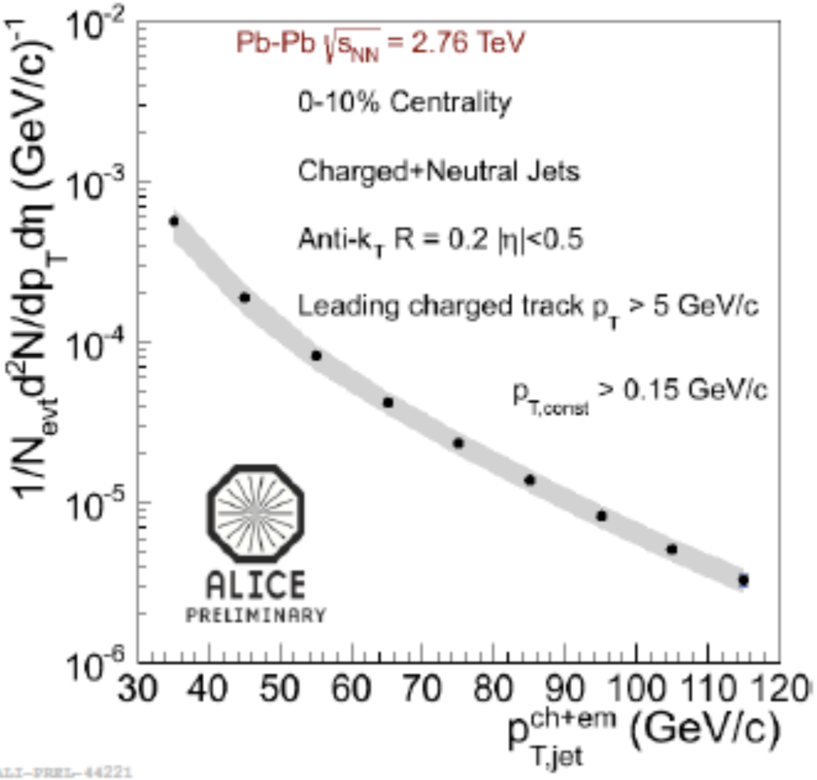


Significant cancellation of correlated errors

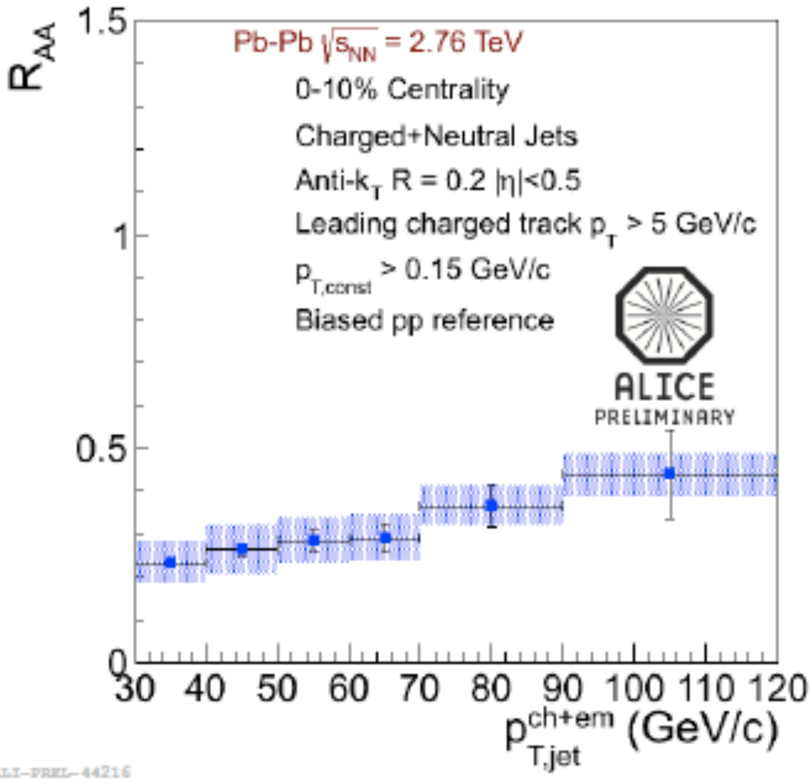


- Evaluate jet radius dependence of R_{cp}
  - Modest but significant variation of R_{cp}
  - Less suppression for larger R
    ⇒An indication of jet broadening?

ALICE: jet suppression



ALI-PREL-44221



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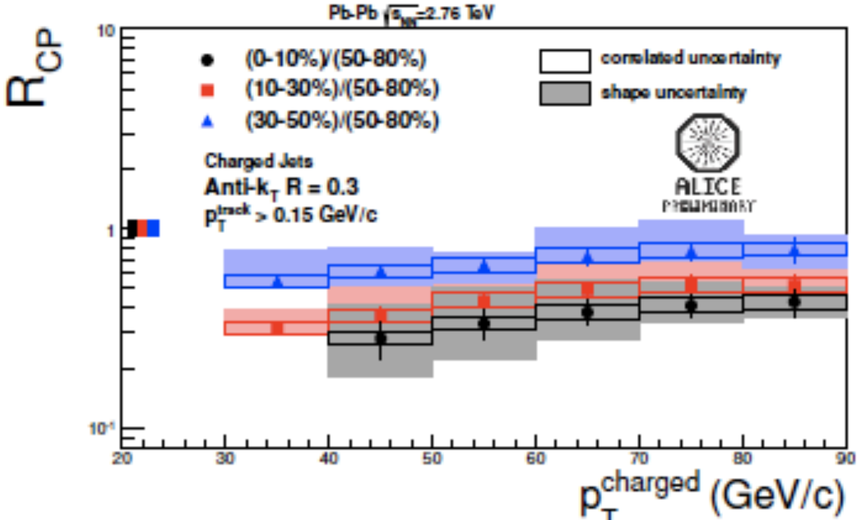
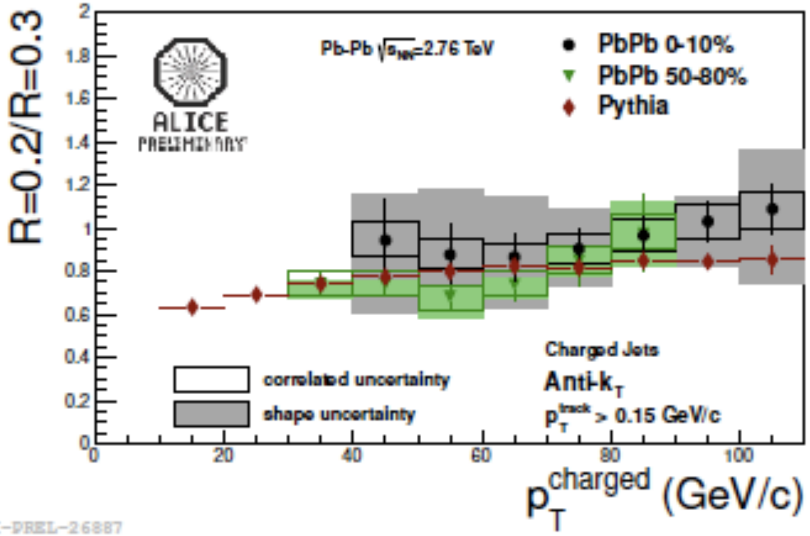
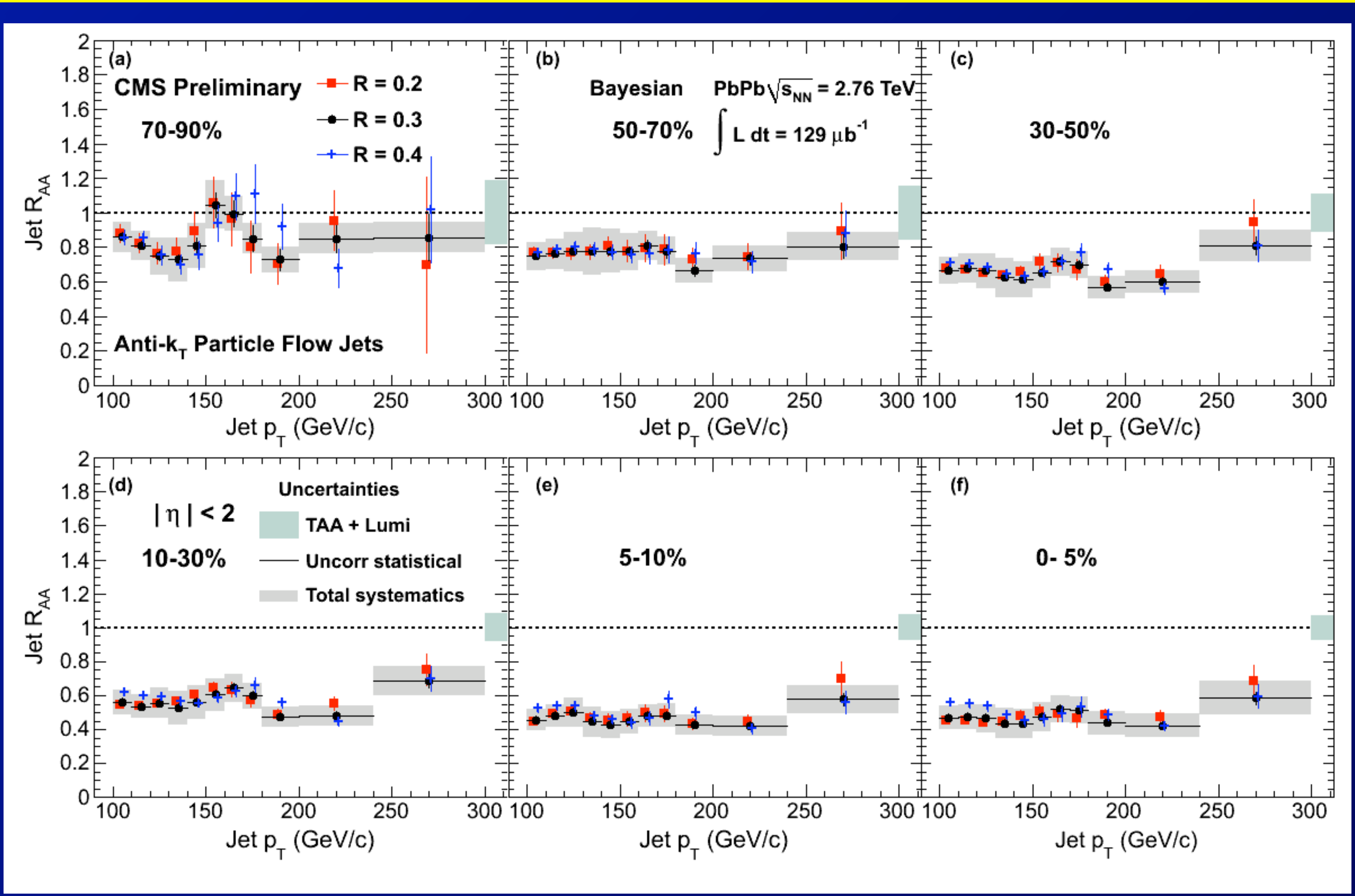


ALI-PREL-16490



ALI-PREL-26887

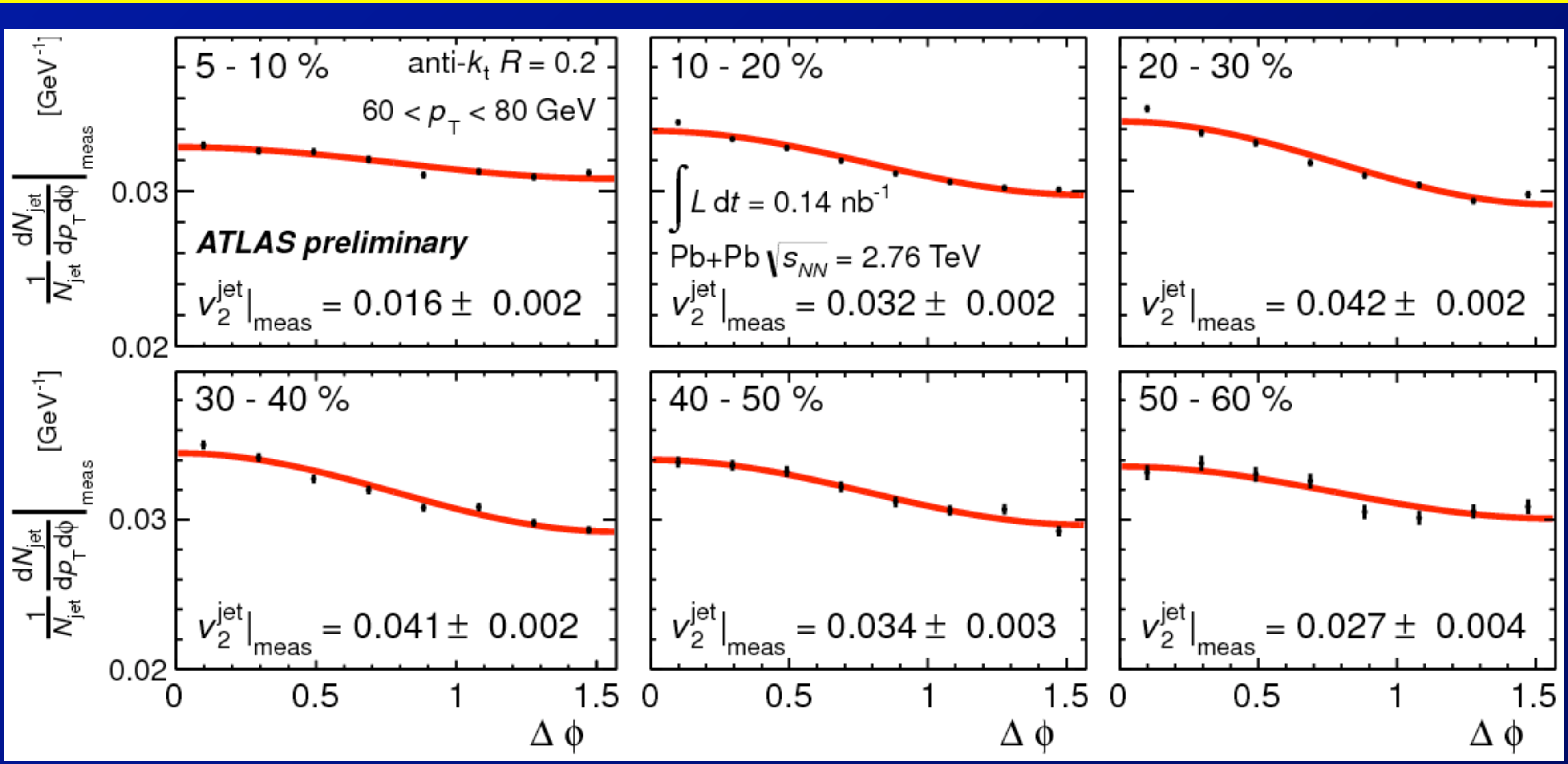
CMS jet R_{AA}



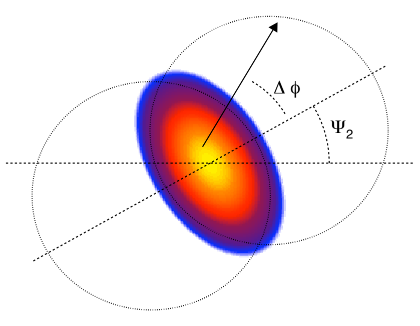
- First results on jet R_{AA} @ LHC

  ⇒ Consistent behavior with ATLAS R_{cp}

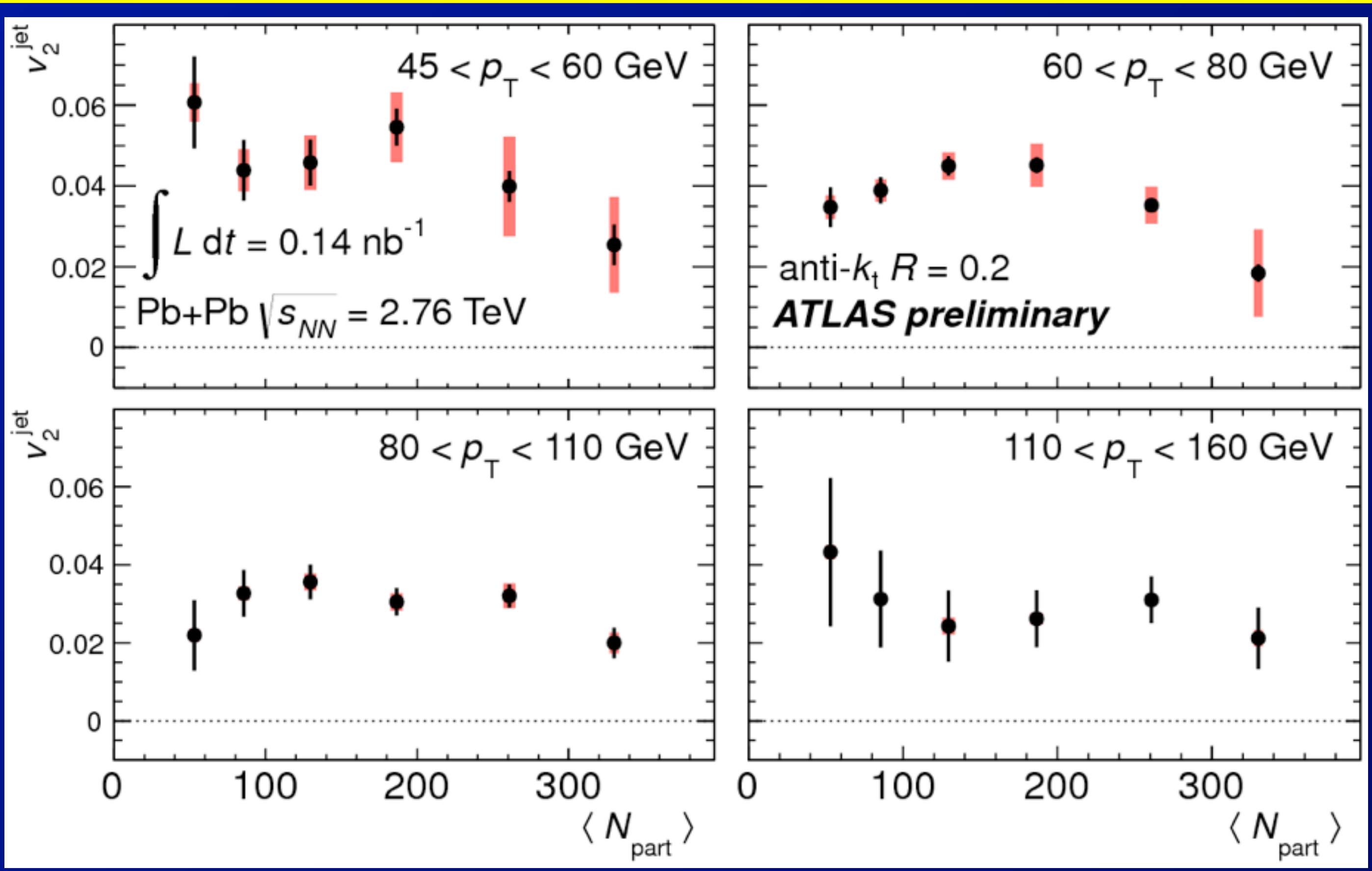
Differential jet suppression



- Measure jet yields in 8 bins of Δϕ with respect to the elliptic event plane
  - Here for R = 0.2 jets, 60 < p_T < 80 GeV
    - ⇒UE subtraction corrected for elliptic flow modulation in calorimeter



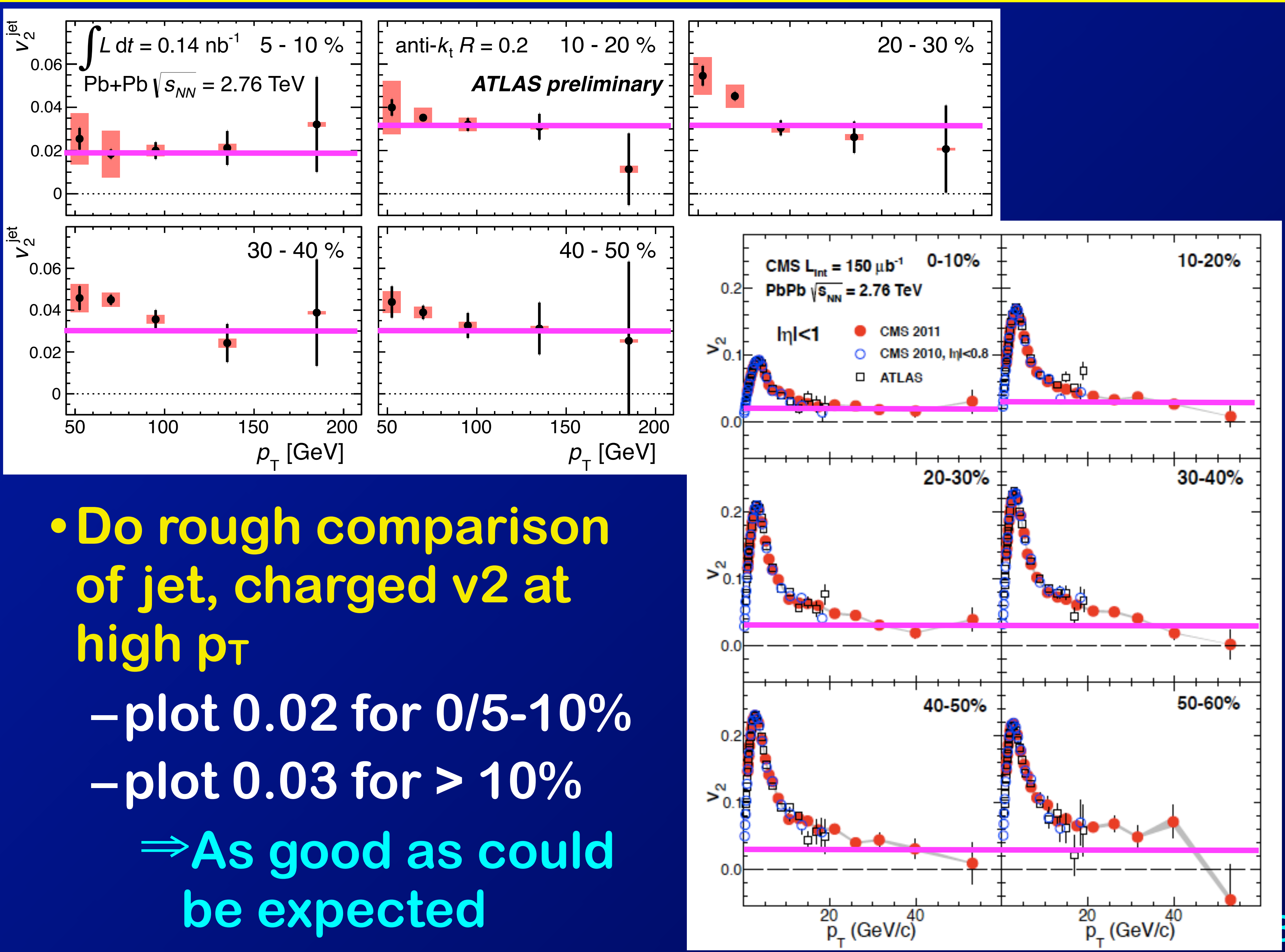
Differential jet suppression



- Observe non-zero jet v_2 for (R = 0.2) p_T values > 100 GeV

  ⇒jet quenching clearly sensitive to initial geometry out to very high p_T

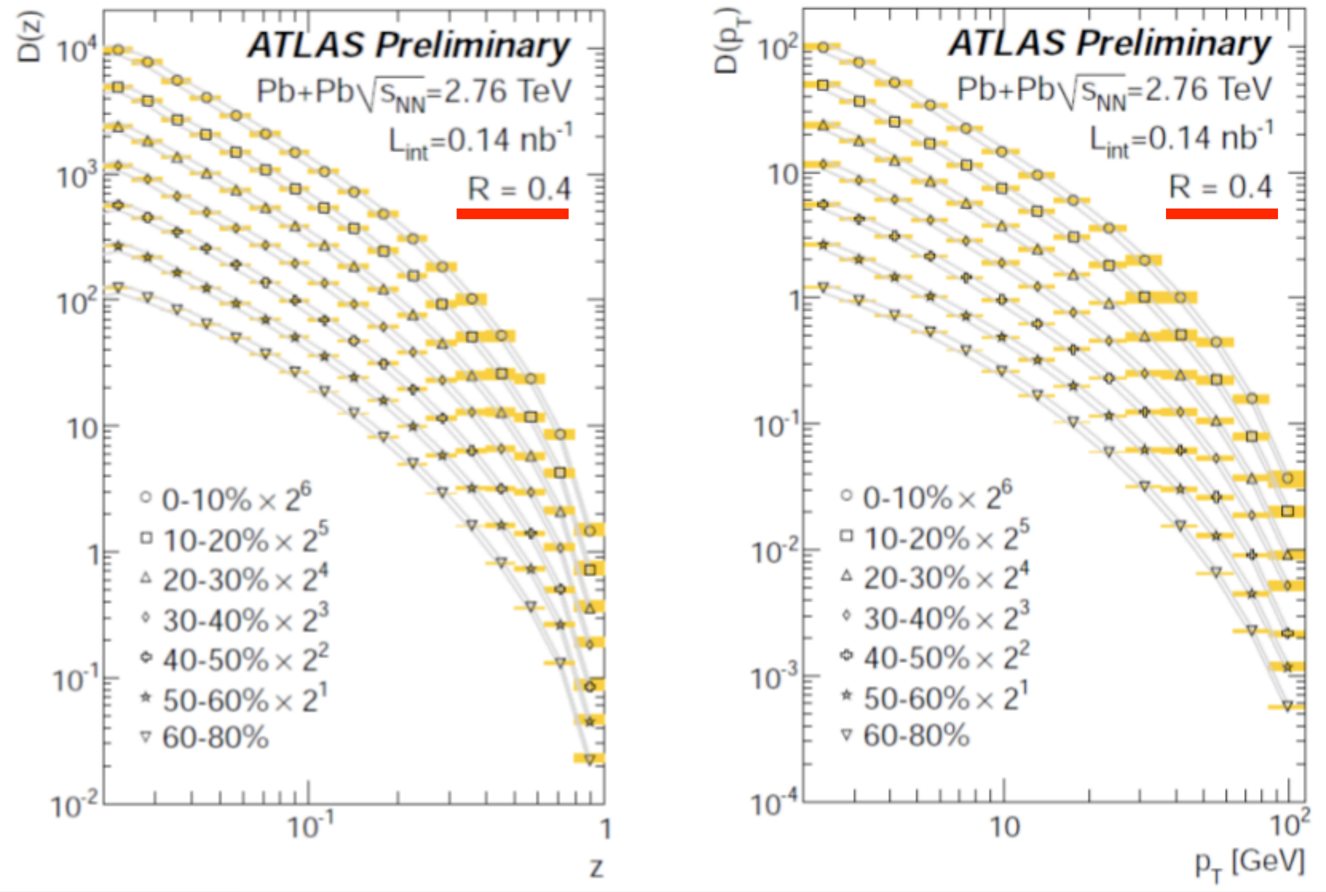
Jet $v_2(p_T)$



- Do rough comparison of jet, charged v2 at high p_T
  - plot 0.02 for 0/5-10%
  - plot 0.03 for > 10%

    ⇒As good as could be expected

Inclusive jet fragmentation

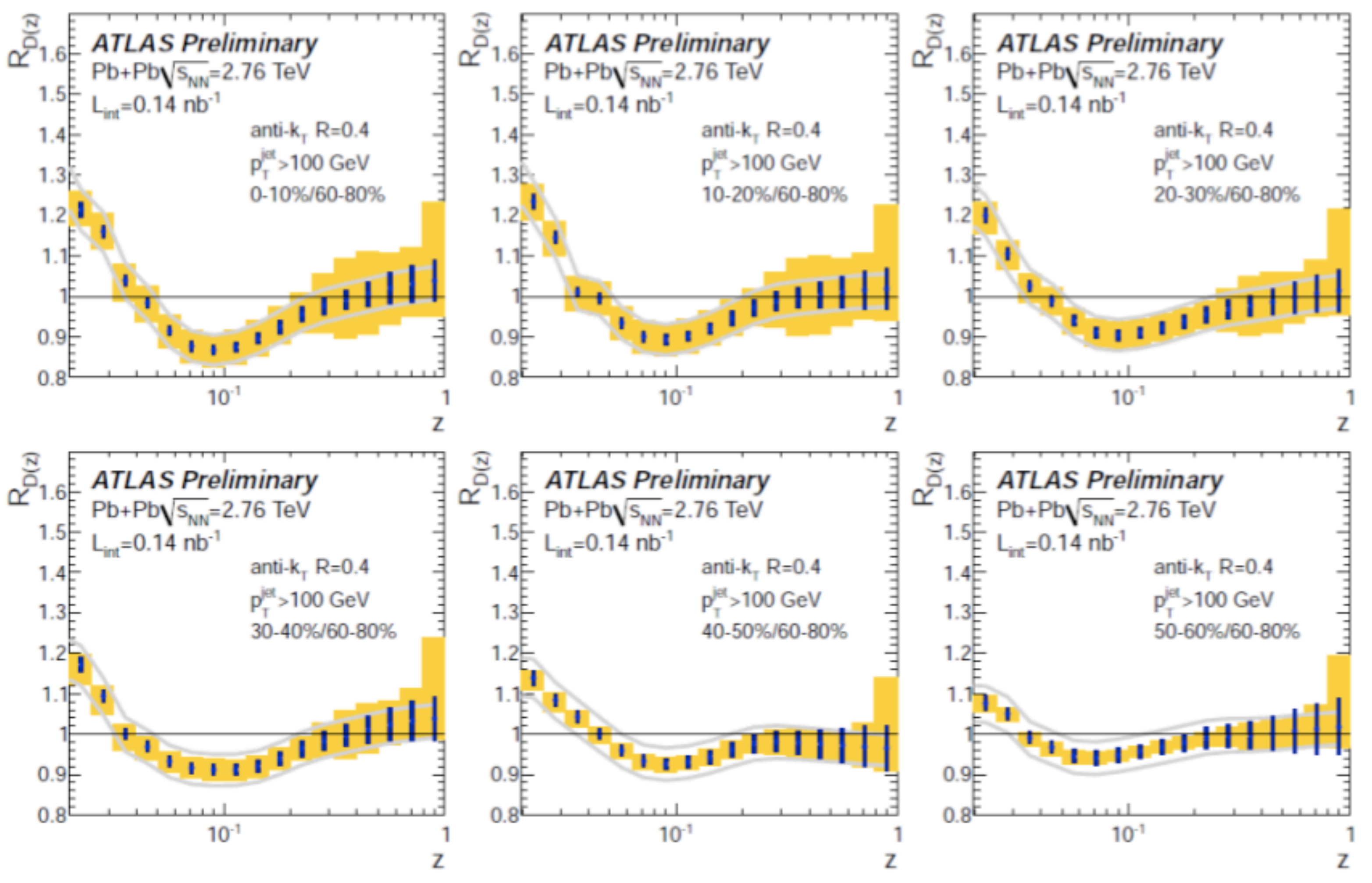


Unfolded for jet and charged particle resolution

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

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

Inclusive jet fragmentation (2)

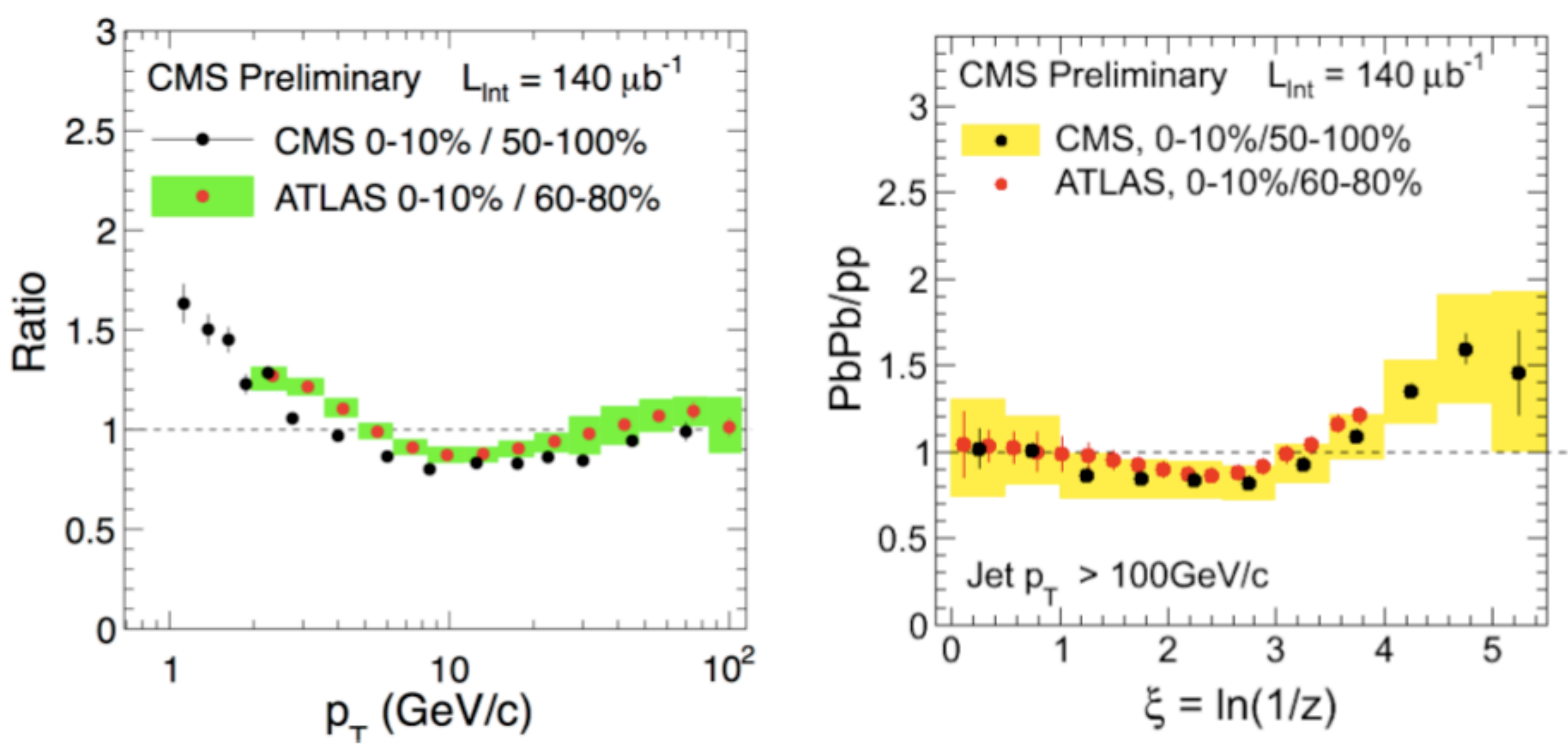


R = 0.4

- First observation of modified parton shower in inclusive jets

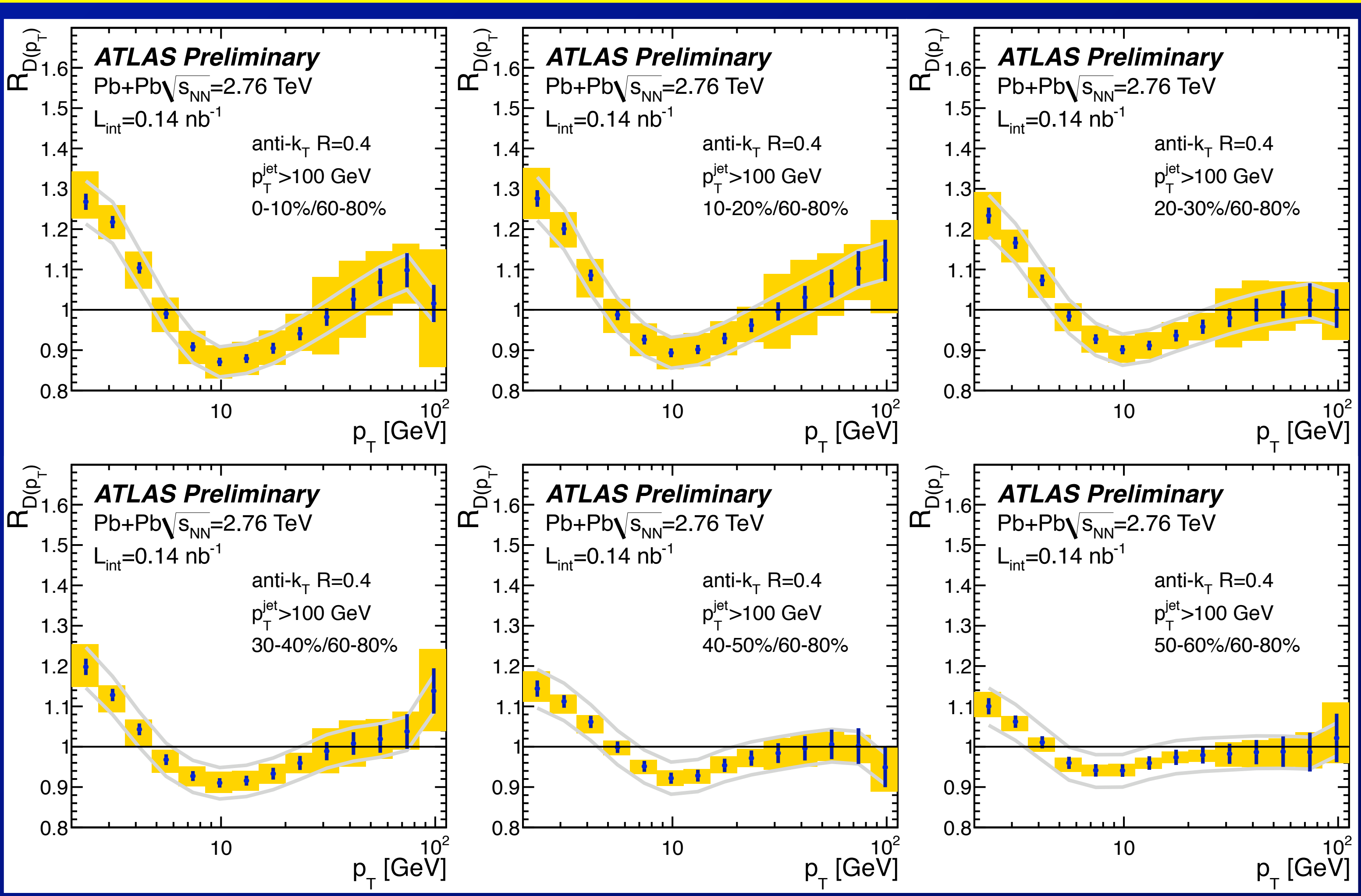
  ⇒Not only seeing “left over” unquenched jets.

Inclusive jet fragmentation



- First direct handle on the p_T dependence of modifications of the parton shower.
  - ⇒Important to determine whether modification is p_T or z dependent.
  - ⇒How to determine whether low-p_T enhancement is from PS or from medium?

Inclusive jet fragmentation (3)



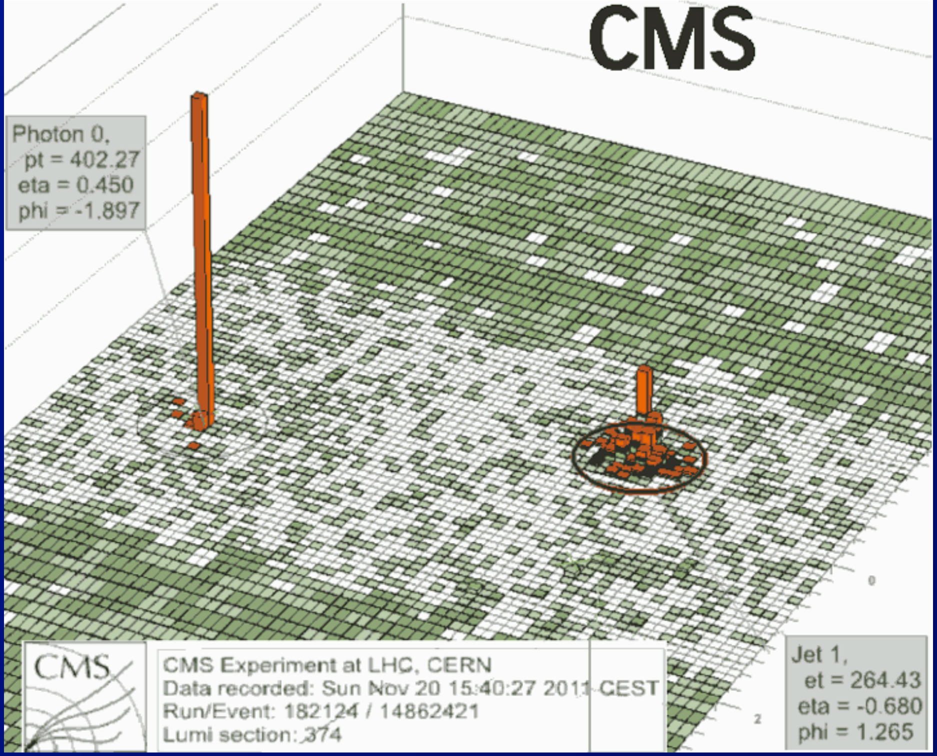
- Check that the modification is not due to the measurement of jet $p_T \Rightarrow D(p_T)$

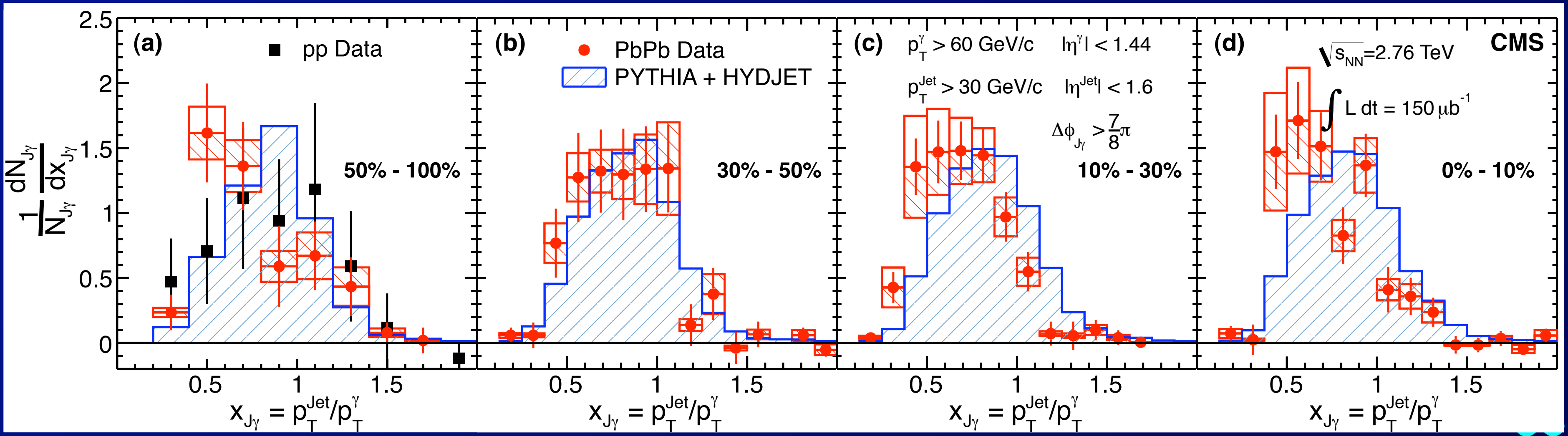
  $\Rightarrow D(p_T)$ shows similar modifications

CMS gamma-jet

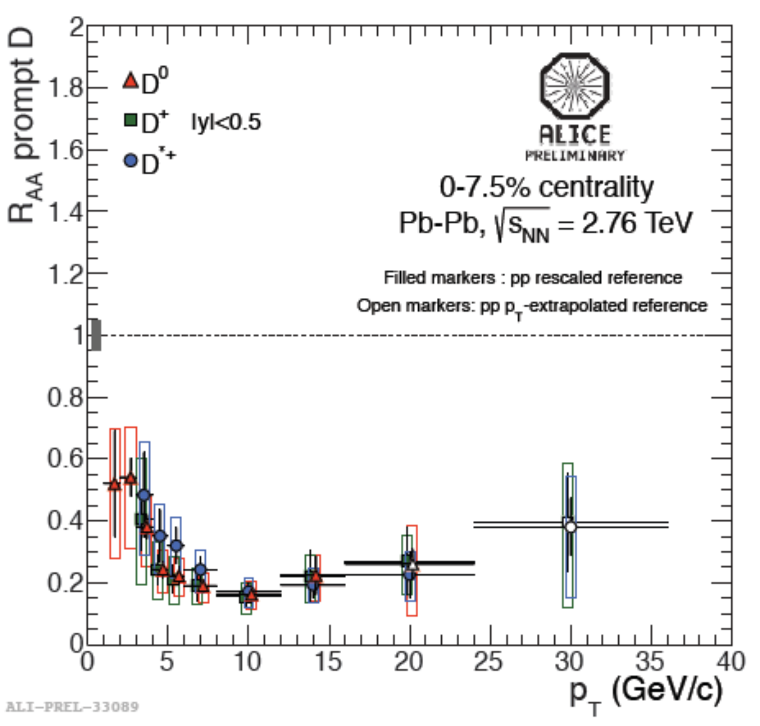
- **Analogous to dijet measurement but with “clean” photon**
  - – See clear shift in fraction of photon energy carried by jet

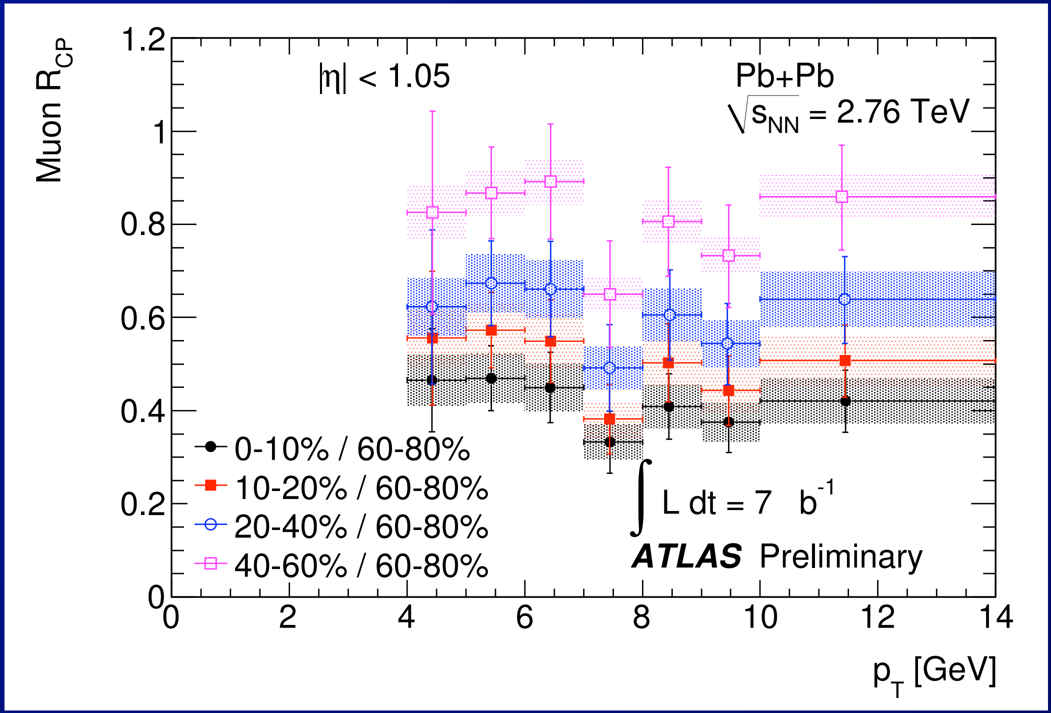
⇒But beware, photon is not proxy for unquenched jet (p-p)

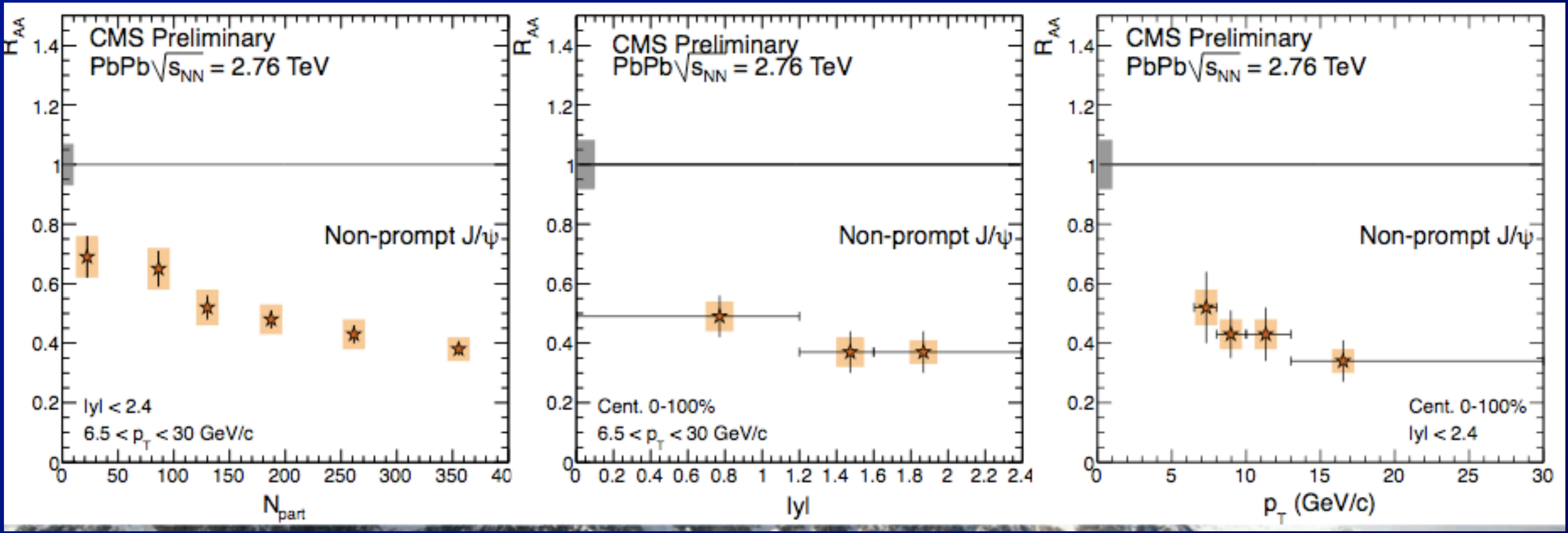




Heavy flavor @ moderate p_T







Summary

- Extensive set of measurements at RHIC and the LHC showing that high-pT quarks and gluons lose energy in the quark gluon plasma.
- Non-trivial theoretical problem
  - Controlling approximations
  - Role of collisional and radiative energy loss
  - Parton shower not single quark
  - Description of the time-evolving medium
- Data prior to start of the LHC program was not sufficiently discriminating to sufficiently constrain theory
  - More rapid progress with jet measurements

    ⇒Stay tuned