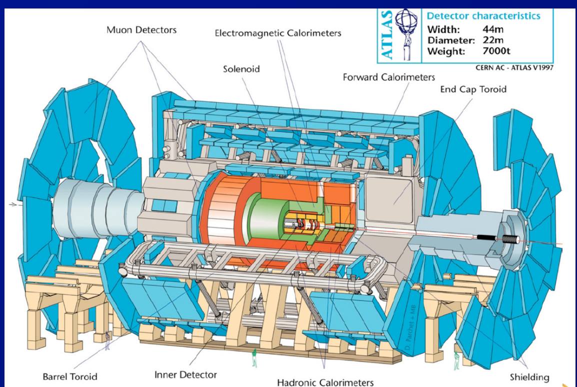
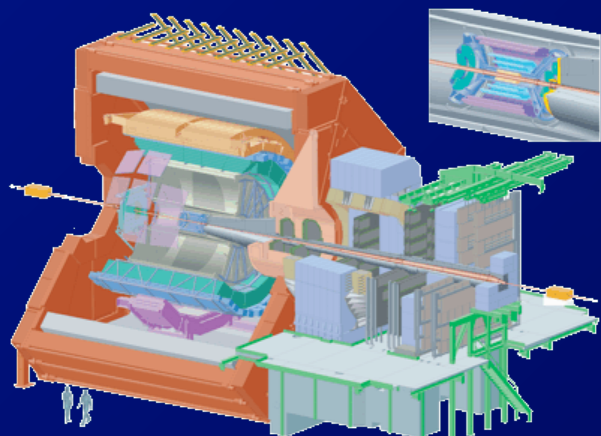
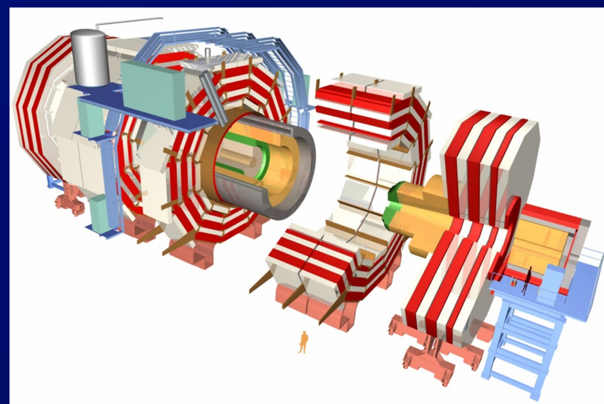
The LHC heavy ion program: results, prospects, and implications

Brian A. Cole
Columbia University

Riken High-Energy QCD workshop







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 (?)

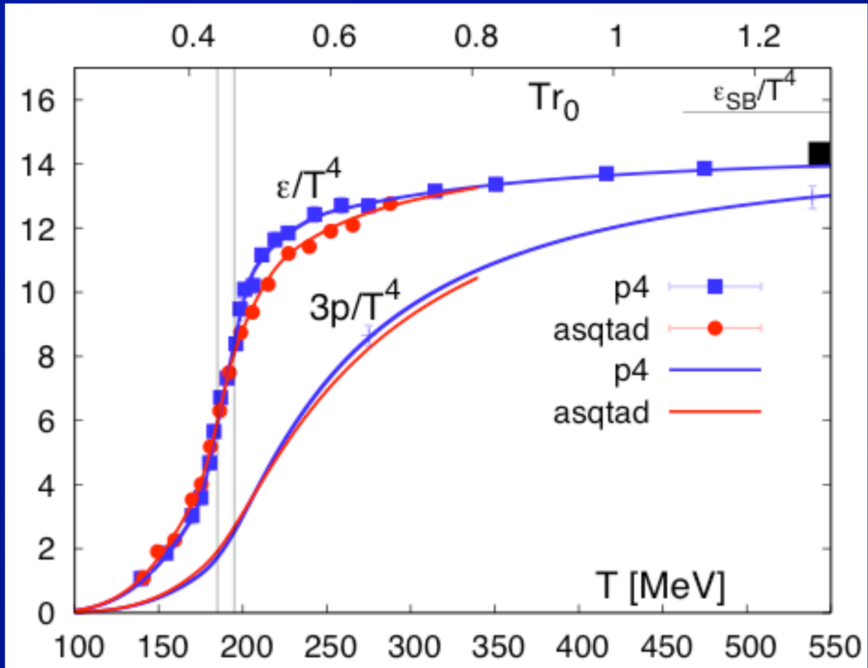
  - High gluon field strength, saturation

    ⇒ Unitarity in fundamental field theory

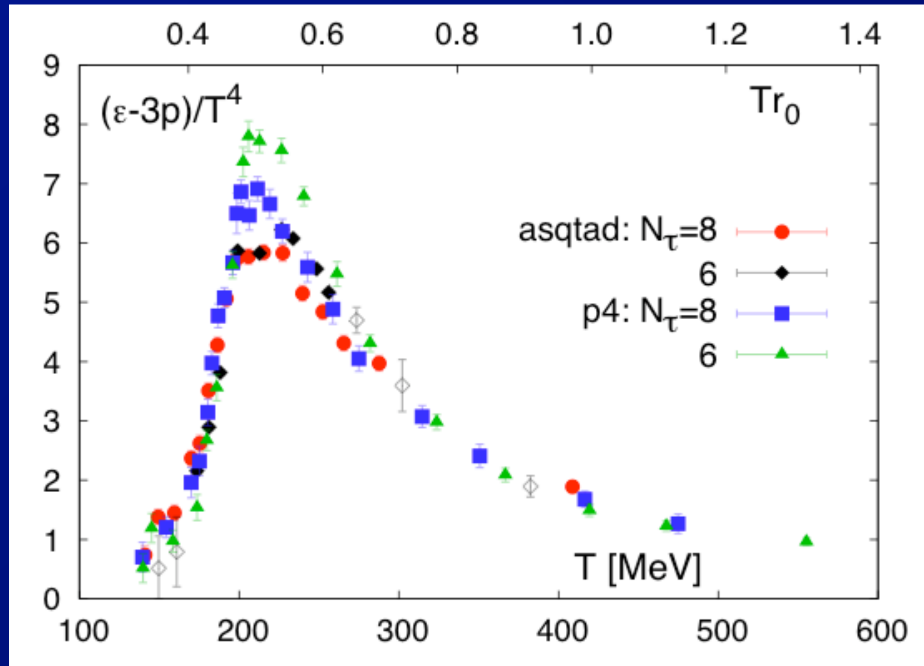
- Only non-Abelian FT whose phase transition & multi-particle behavior we can study in lab.

QCD Thermodynamics on Lattice

Energy Density or pressure



QCD trace anomaly

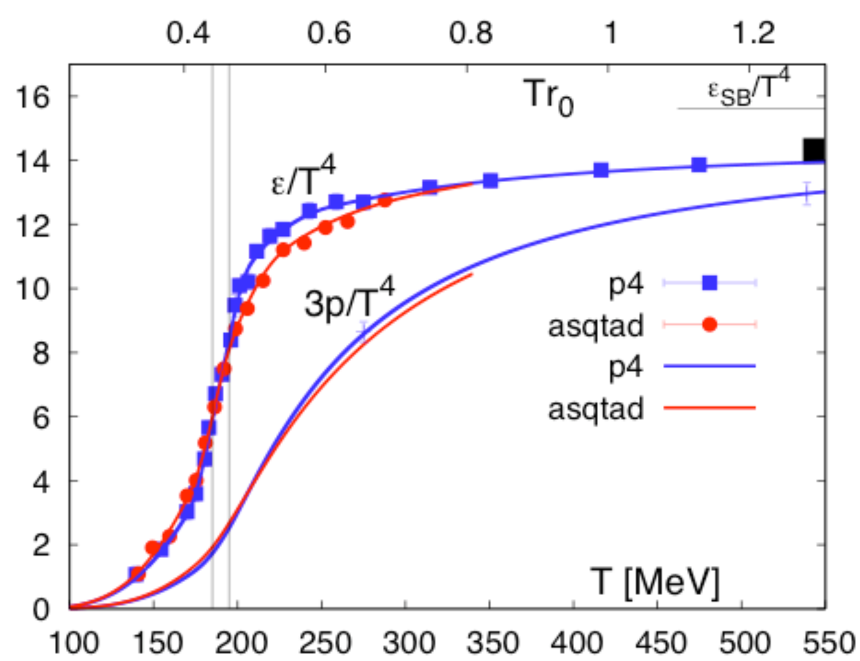


- Lattice thermodynamics from hotQCD group
  - Trace anomaly $(\varepsilon-3p)/T^4$, an "interaction measure"

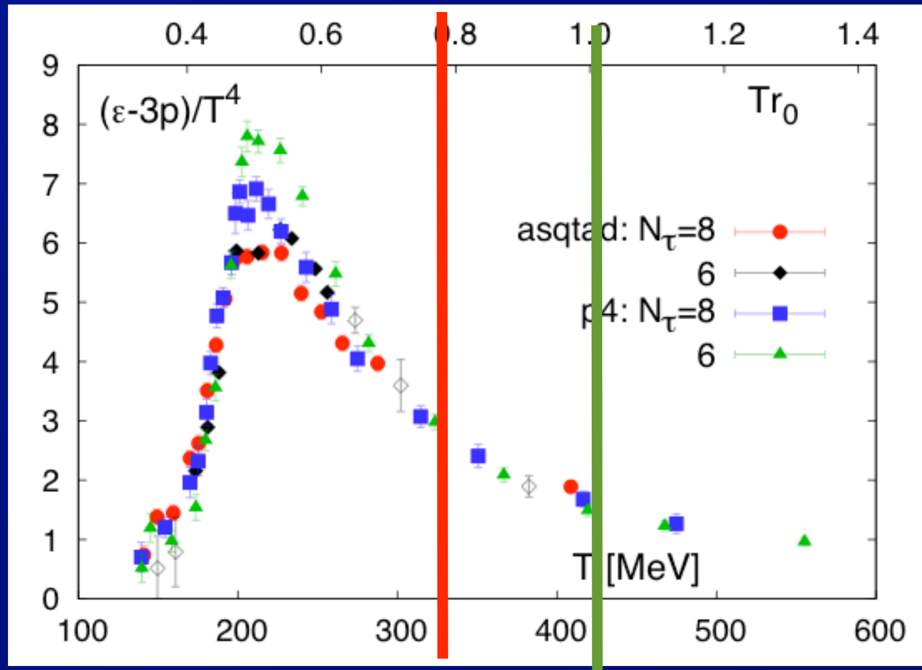
    ⇒ Strong coupling already evident near T_C (?)

QCD Thermodynamics on Lattice

Energy Density or pressure

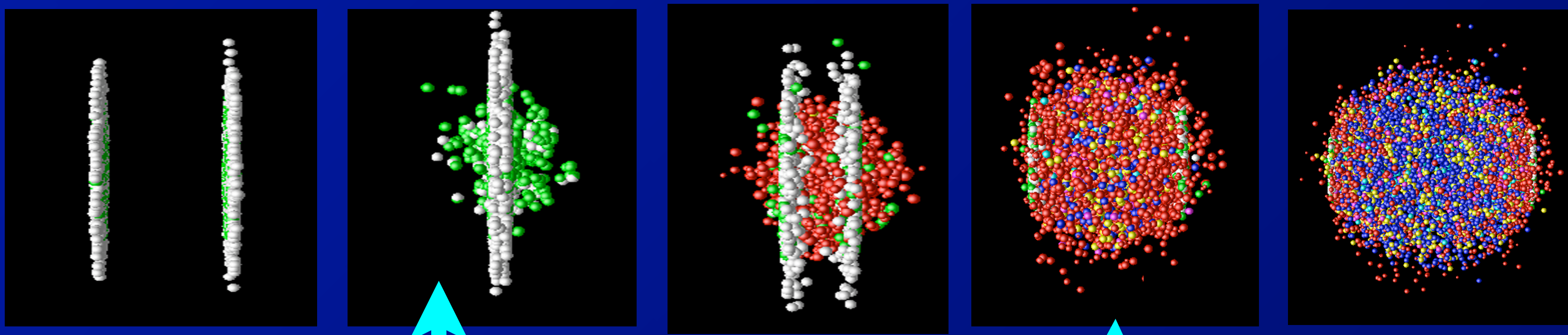


T_{RHIC} (τ =1fm) T_{LHC} (τ =1fm)



- Lattice thermodynamics from hotQCD group
  - Trace anomaly $(\varepsilon\text{-}3p)/T^4$, an “interaction measure”
    - ⇒Strong coupling already evident near T_C (?)
- Can we observe any consequences of the increase of the (initial) temperature between RHIC and LHC?

Heavy Ion Collision Time History



Initial entropy (gluon) production

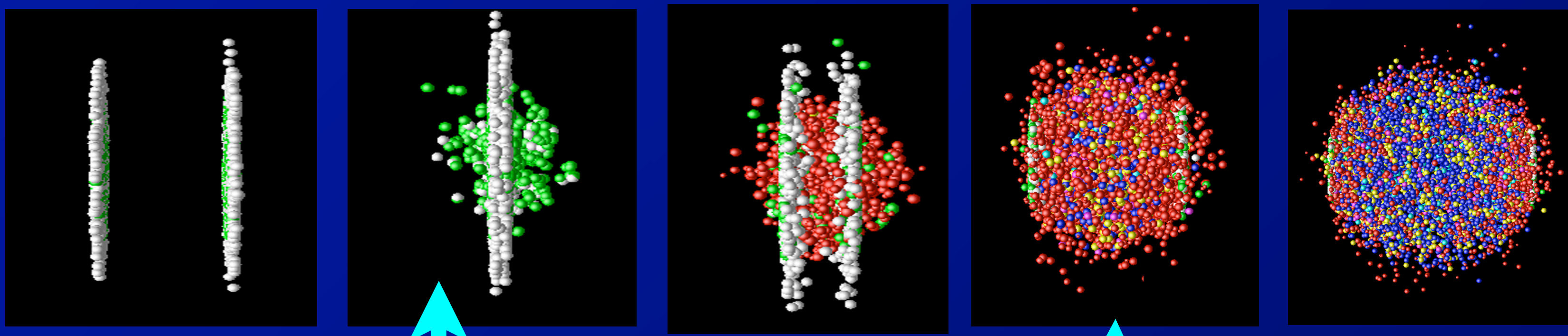
Rapid Thermalization

Collective Evolution

Hadronization

- Conclusions from RHIC program
  - ⇒Initial particle production influenced by strong gluon fields in the incident nuclei.
  - ⇒Created particles rapidly thermalize into a strongly coupled quark gluon plasma.
  - ⇒Quark gluon plasma efficiently attenuates high-energy quarks and gluons.

Heavy Ion Collision Time History



Initial entropy (gluon) production

Rapid Thermalization

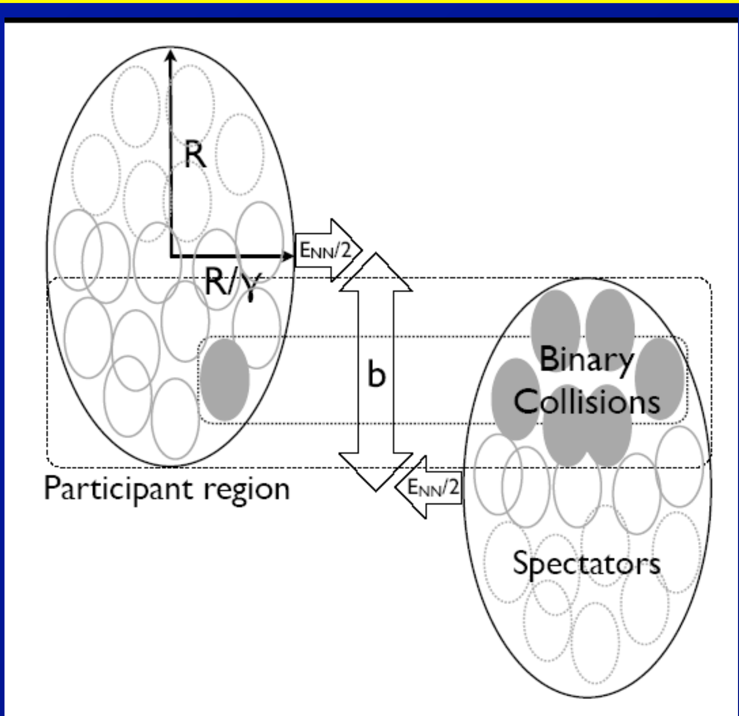
Collective Evolution

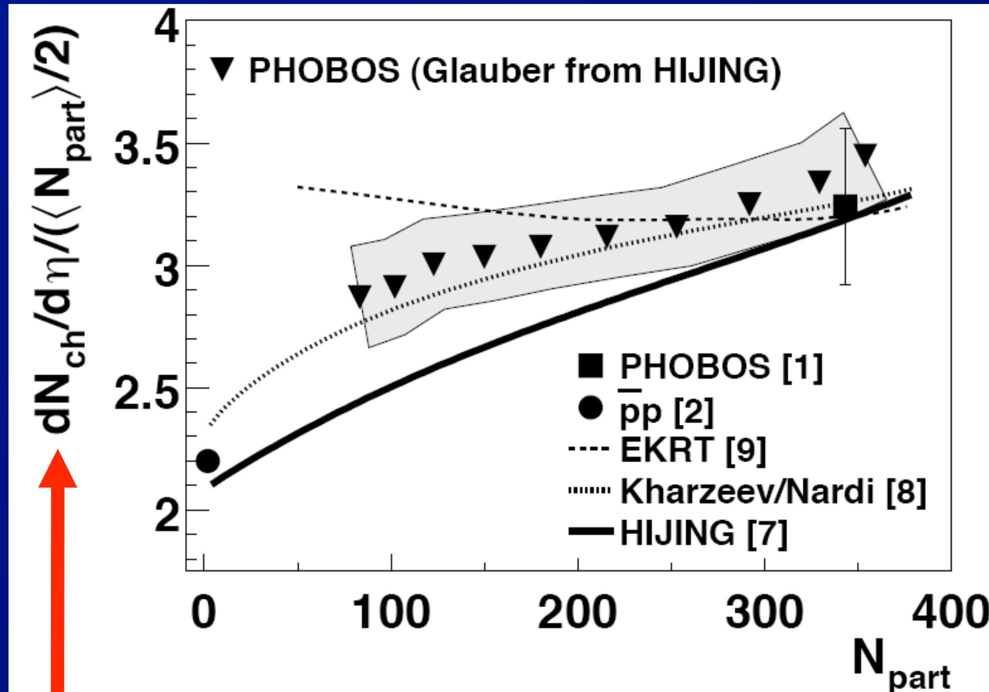
Hadronization

- Conclusions from RHIC program
  - ⇒Initial particle production influenced by strong gluon fields in the incident nuclei.
  - ⇒Created particles rapidly thermalize into a strongly coupled quark gluon plasma.
  - ⇒Quark gluon plasma efficiently attenuates high-energy quarks and gluons.

Test in Pb+Pb collisions @LHC

RHIC Particle Multiplicities

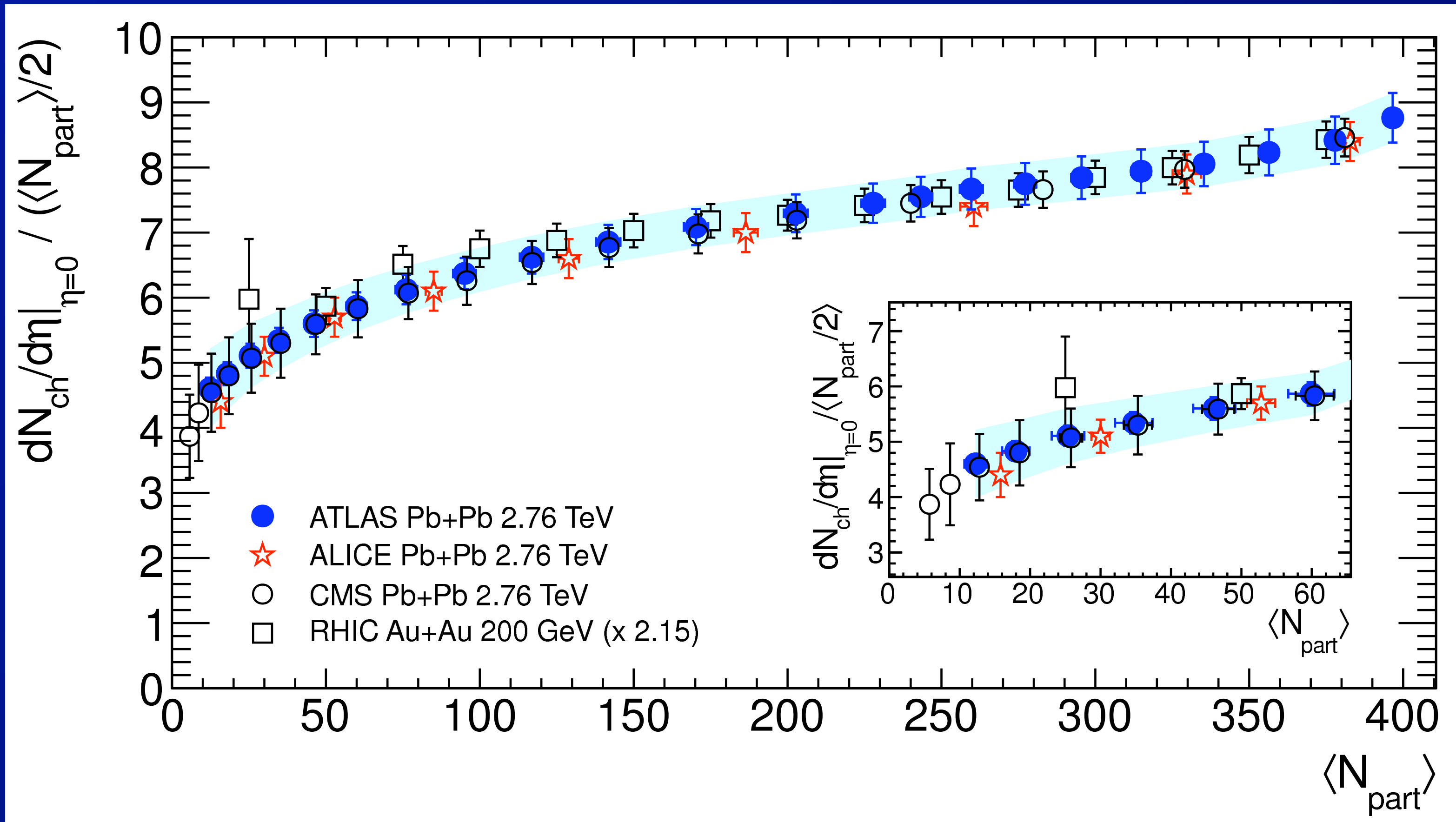




Multiplicity per colliding nucleon pair

- Multiplicity @ RHIC on low end of predicted range, slow growth with N_{part}
  - Suppression of expected hard contribution
    - ⇒"Saturation" via gluon recombination?
    - ⇒Test by going to LHC where saturation effects are expected to be stronger.

Charged Particle Multiplicity

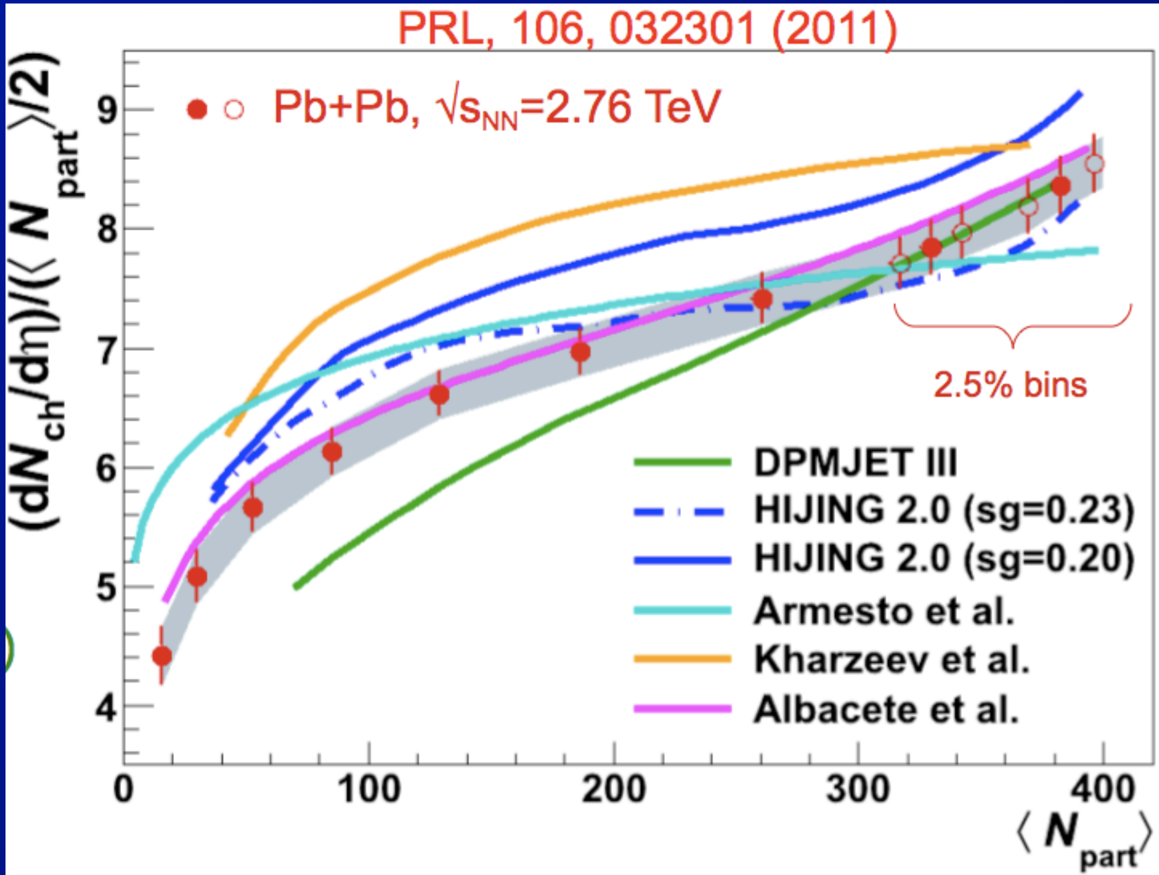


- Weak variation of $dN_{chg}/d\eta$ with centrality
  - Consistent results between ALICE, ATLAS, CMS
- Same centrality variation @ RHIC and LHC

  ⇒(Naturally) consistent with saturation?

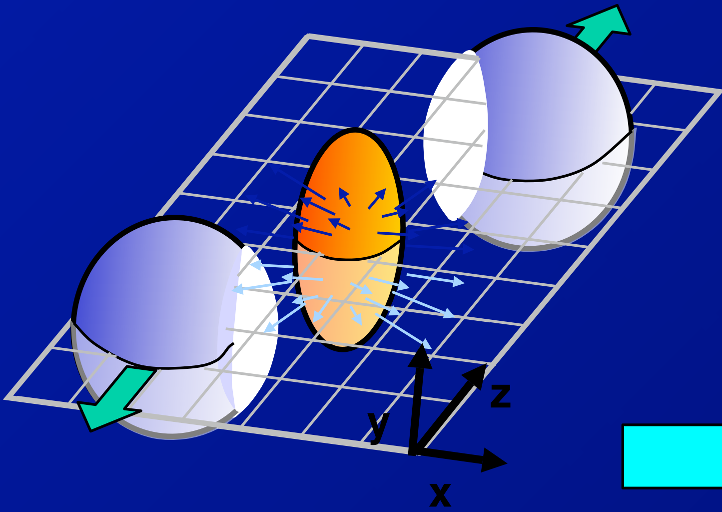
  ⇒Where is the hard contribution?

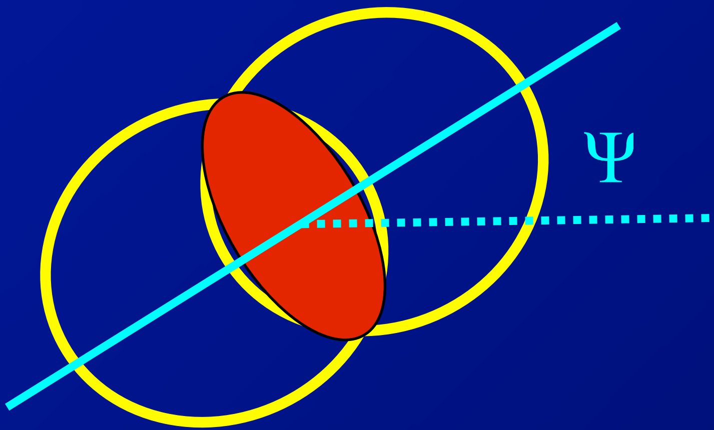
Charged Particle Multiplicity (3)

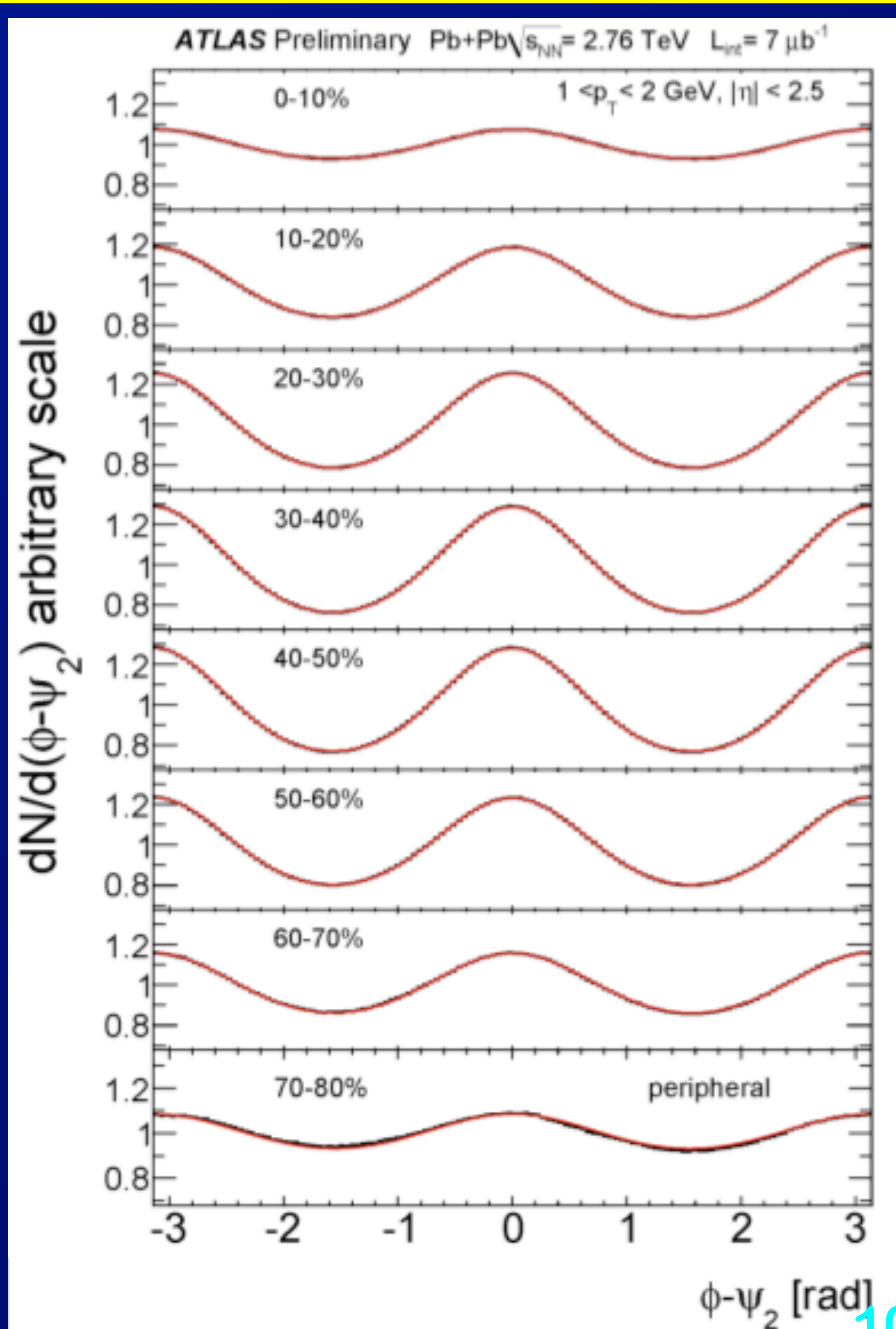


- Generically, saturation models too flat
  - Except for Albacete et al (BK saturation + k_T fact. ++)
    - ⇒ role of late entropy production in central (~10%)??
- HIJING: hard + soft can describe central growth
  - But then why same shape for RHIC & LHC?

Collective Motion: Elliptic Flow

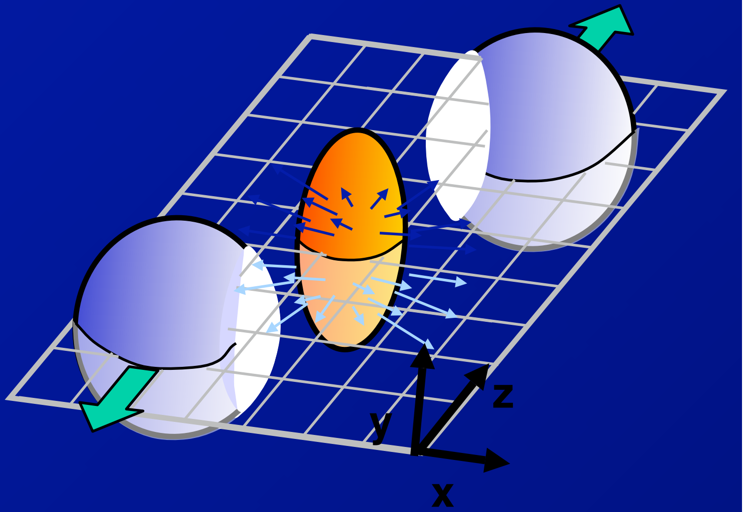


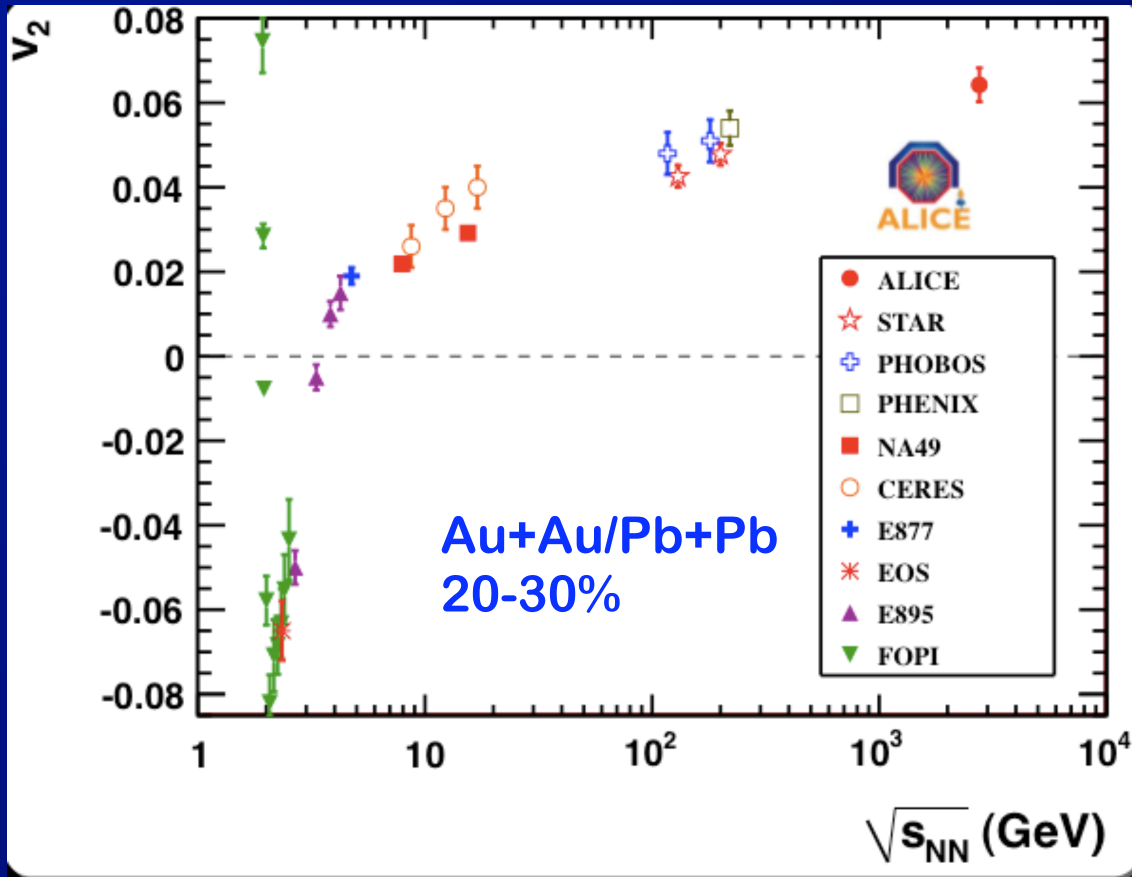




- Pressure converts spatial anisotropy to momentum anisotropy.

Collectivity: Elliptic Flow

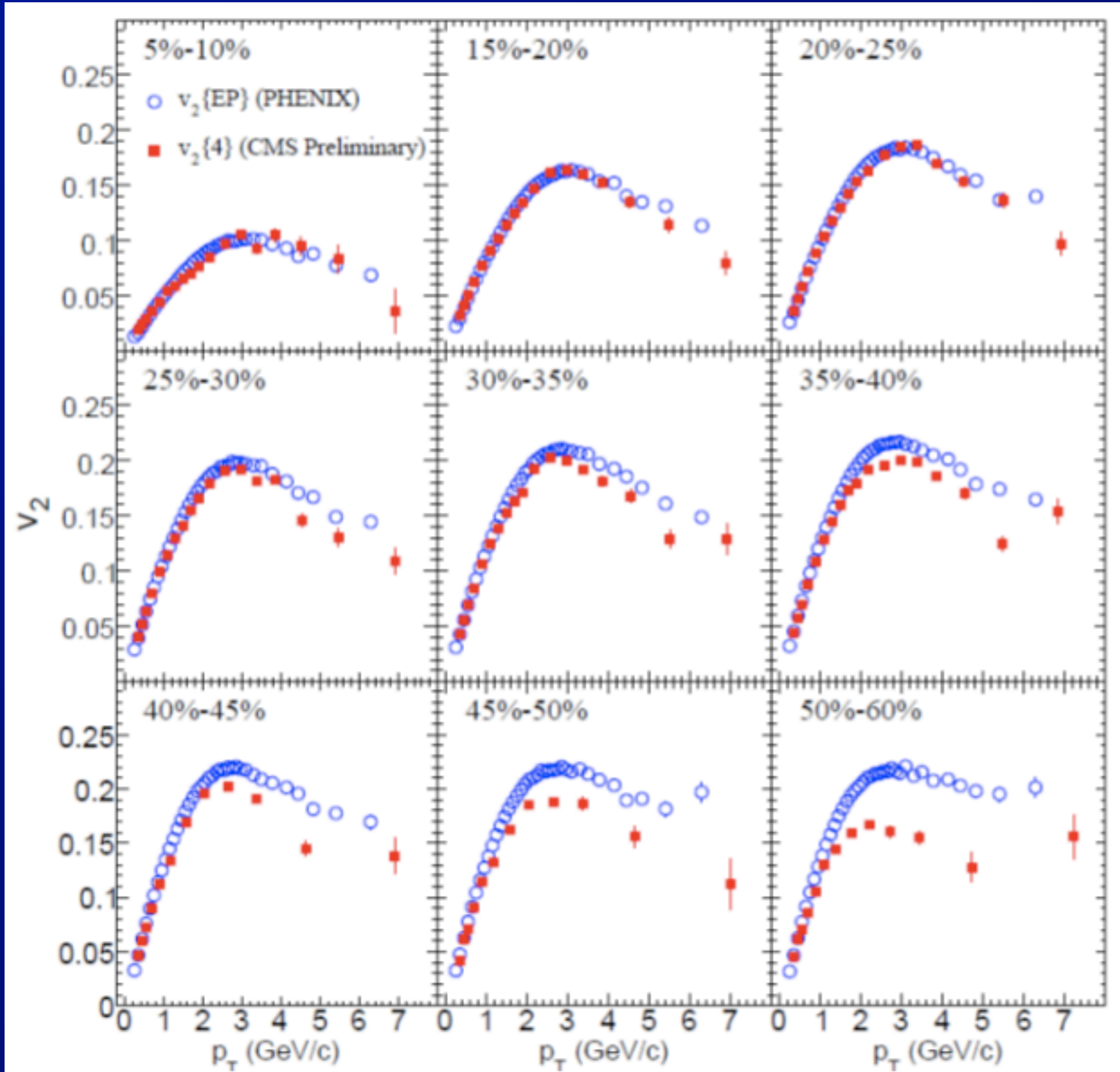




- Logarithmic variation of v_2 with $\sqrt{s}$ above 10 GeV
  - Change from RHIC to LHC is comparable to change from SPS to RHIC
    - ⇒But, beware, integral v_2 can be misleading.
    - ⇒Though it may be most directly related to η/s

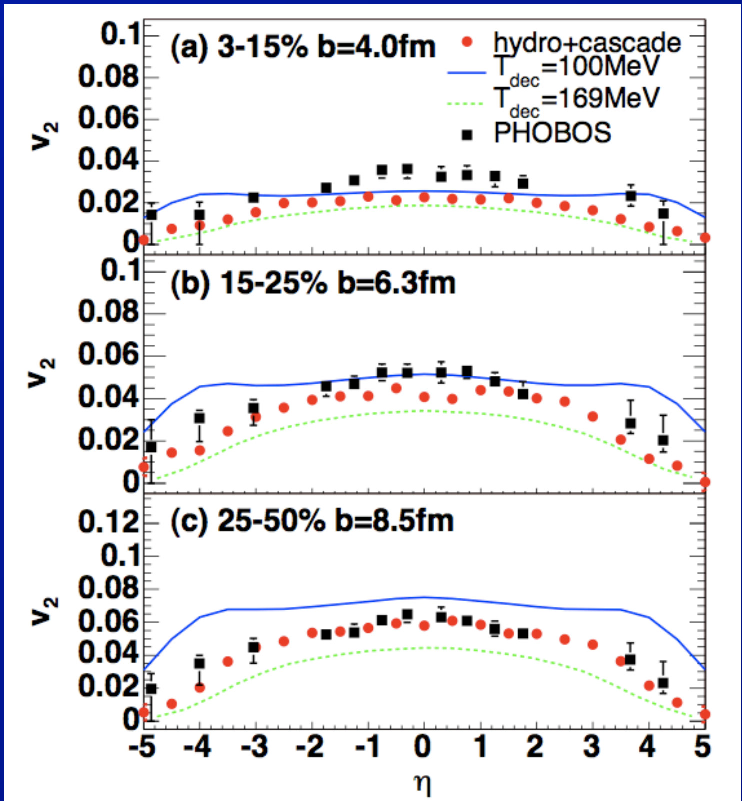
Collectivity: Elliptic Flow (2)

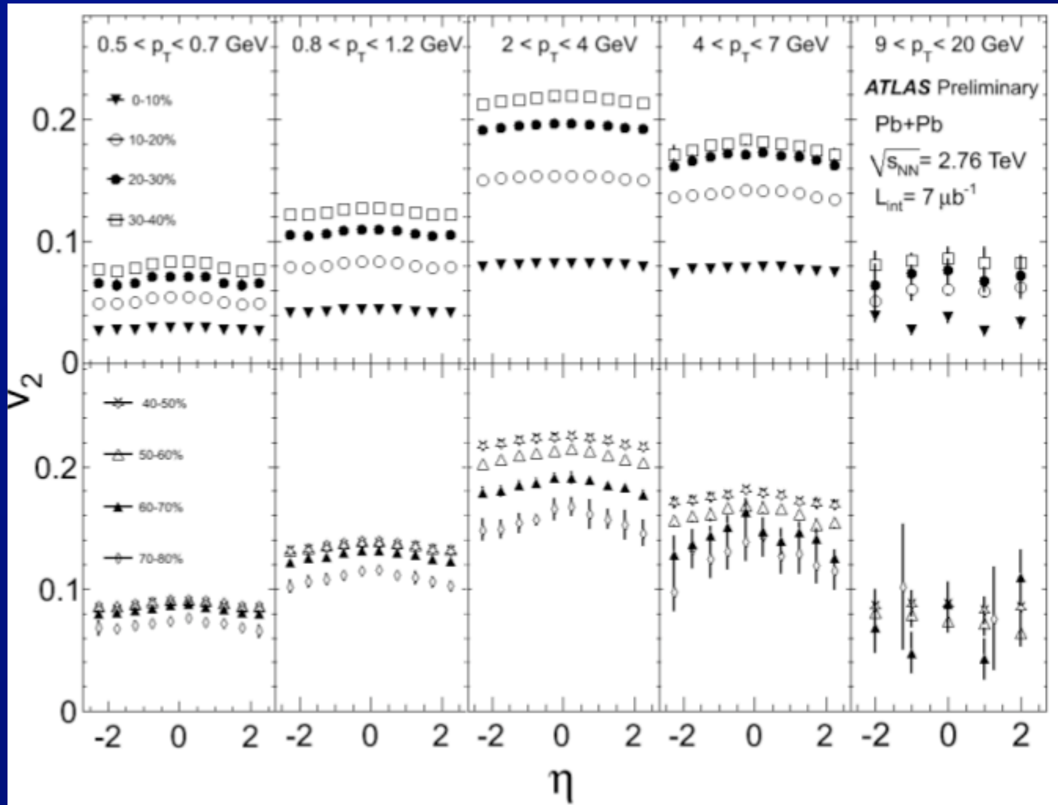
- Identical results for $v_2(p_T)$ @ RHIC & LHC
  - Except for peripheral
    - ⇒Likely EP vs cumulant
- How?
  - Same initial eccentricity + same collectivity?
- Or
  - Accident?



Collectivity: Elliptic Flow (3)

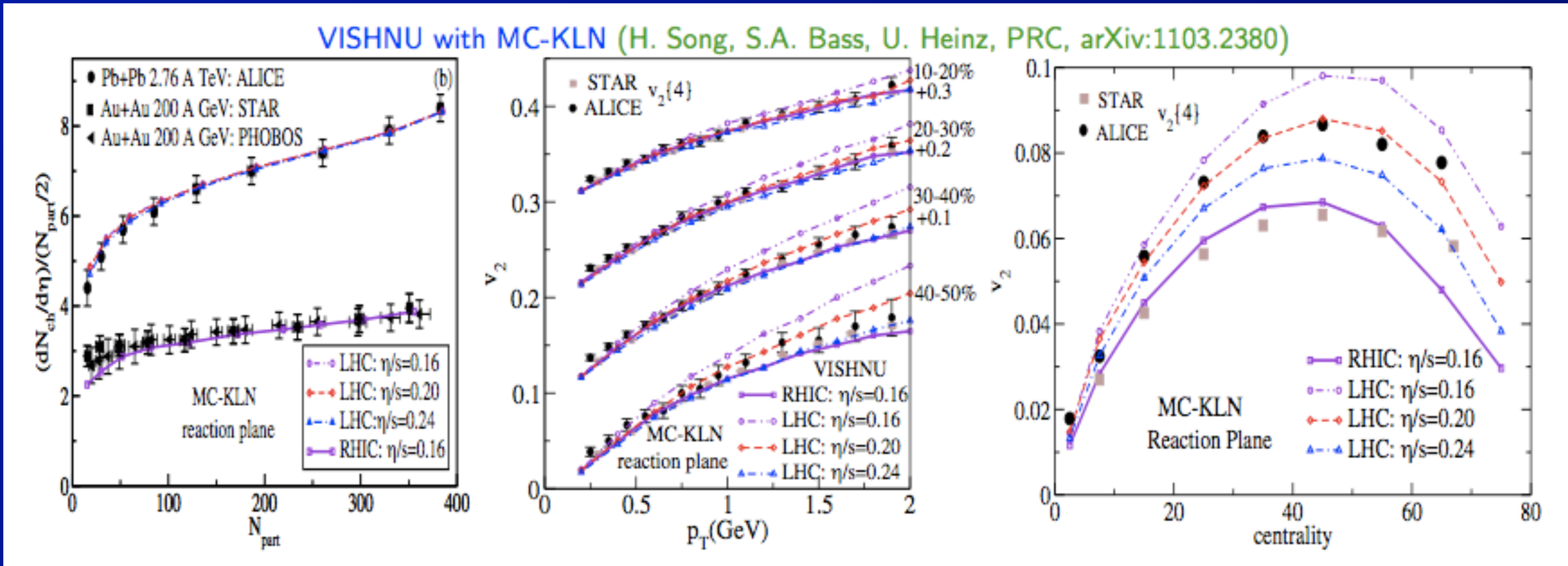
RHIC (PHOBOS) v2(η) LHC (ATLAS) v2(η)





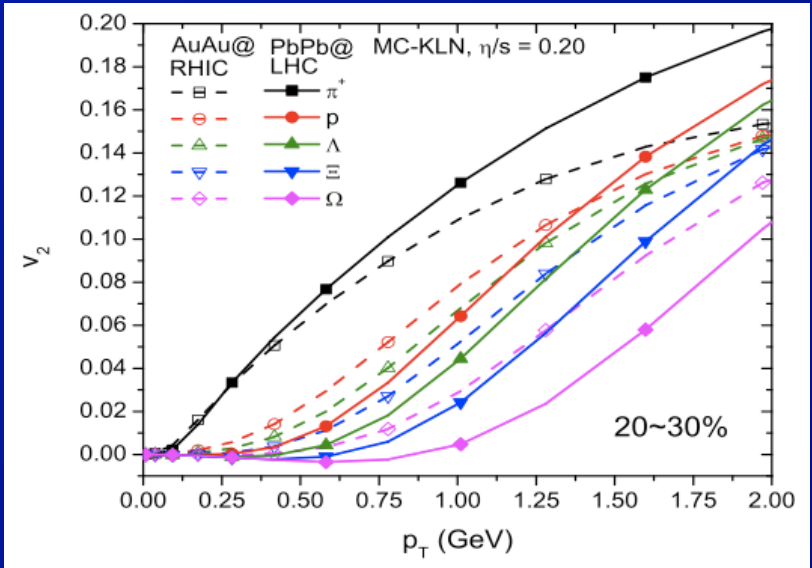
- Weak variation of v_2 with η for p_T > 500 MeV
  - In contrast to RHIC results.
    - ⇒Saturation of v_2 due to longer lifetime @ LHC?

Collectivity: Elliptic Flow (4)



- Viscous hydro + hadronic cascade (VISHNU)
  - Compare to RHIC and LHC $dN_{chg}/d\eta$, $v_2(p_T)$, v_2(cent)
  - Using CGC initial conditions (KLN)
- Possibly higher η/s @ LHC
  - But, caveats re: initialization of $\pi^{\mu\nu}$
- Important to remember that longer lifetime of sQGP @ LHC should have consequences for v_2

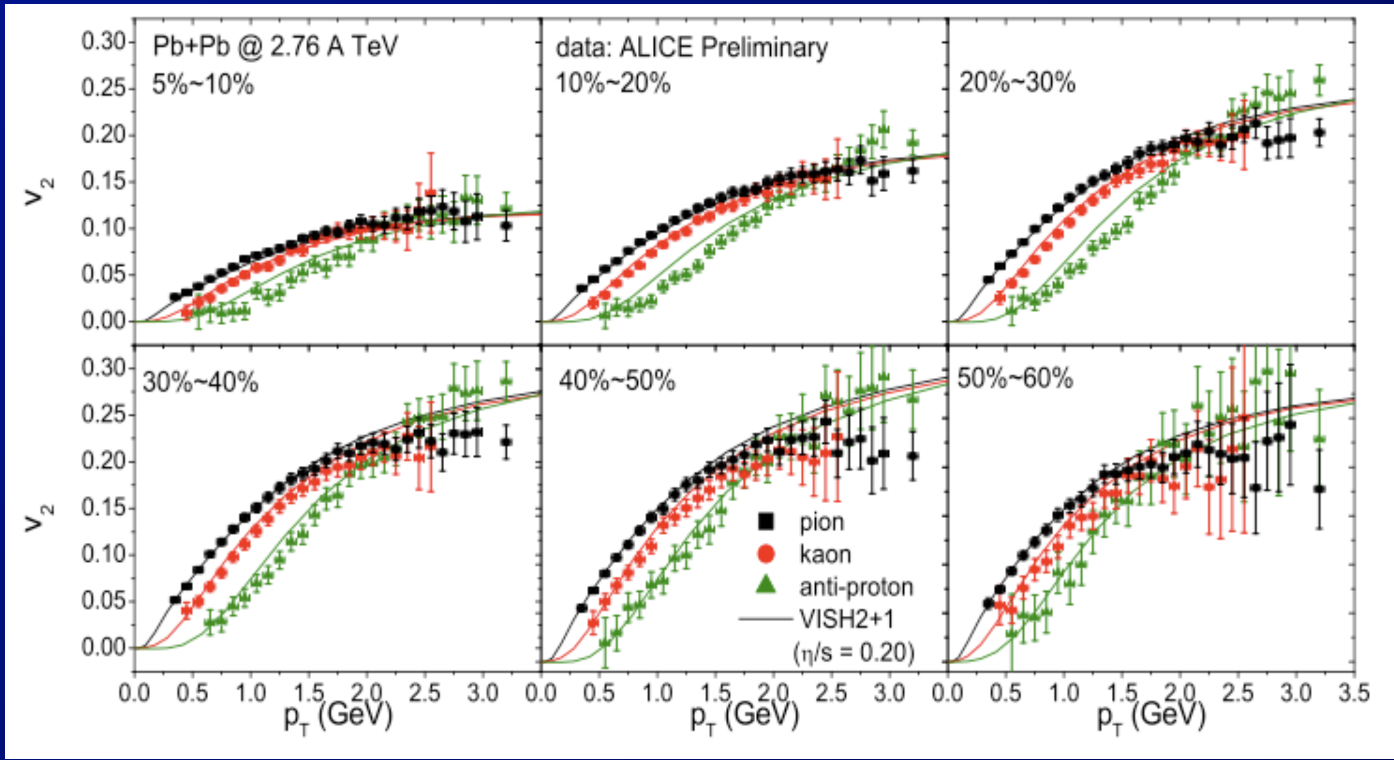
Collectivity: Elliptic Flow (5)



- **Heinz:**
  - charged particle $v_2(p_T)$ agreement between RHIC & LHC is largely an accident
    - ⇒π, K, p differ between RHIC and LHC in Hydro

Heinz et al:

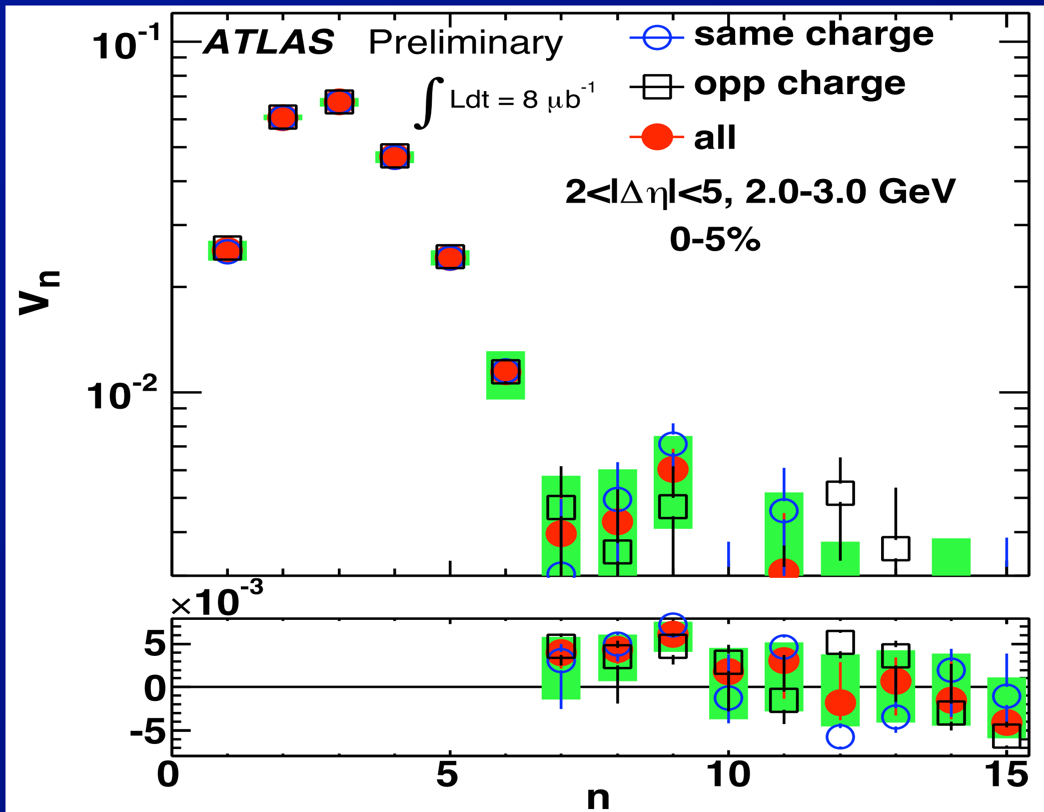
Hydro + cascade (VISHNU) describes mass (π, K, p) splitting

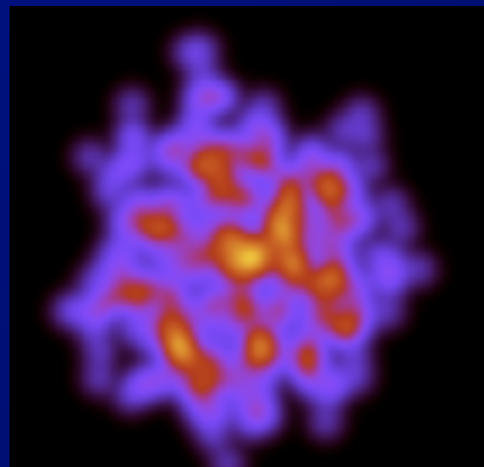


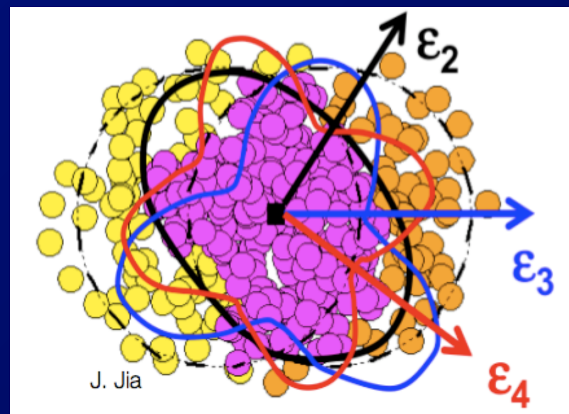
Higher Flow Harmonics

- **Major paradigm shift in the field in the last year**
  - Higher flow harmonics arising from initial-state fluctuations in transverse positions of participants

$$\frac{dN}{d\phi\, dp_T\, d\eta} = \frac{dN}{2\pi\, dp_T\, d\eta}\left(1 + \sum_m 2v_m \cos\left[m(\phi - \psi_m)\right]\right)$$

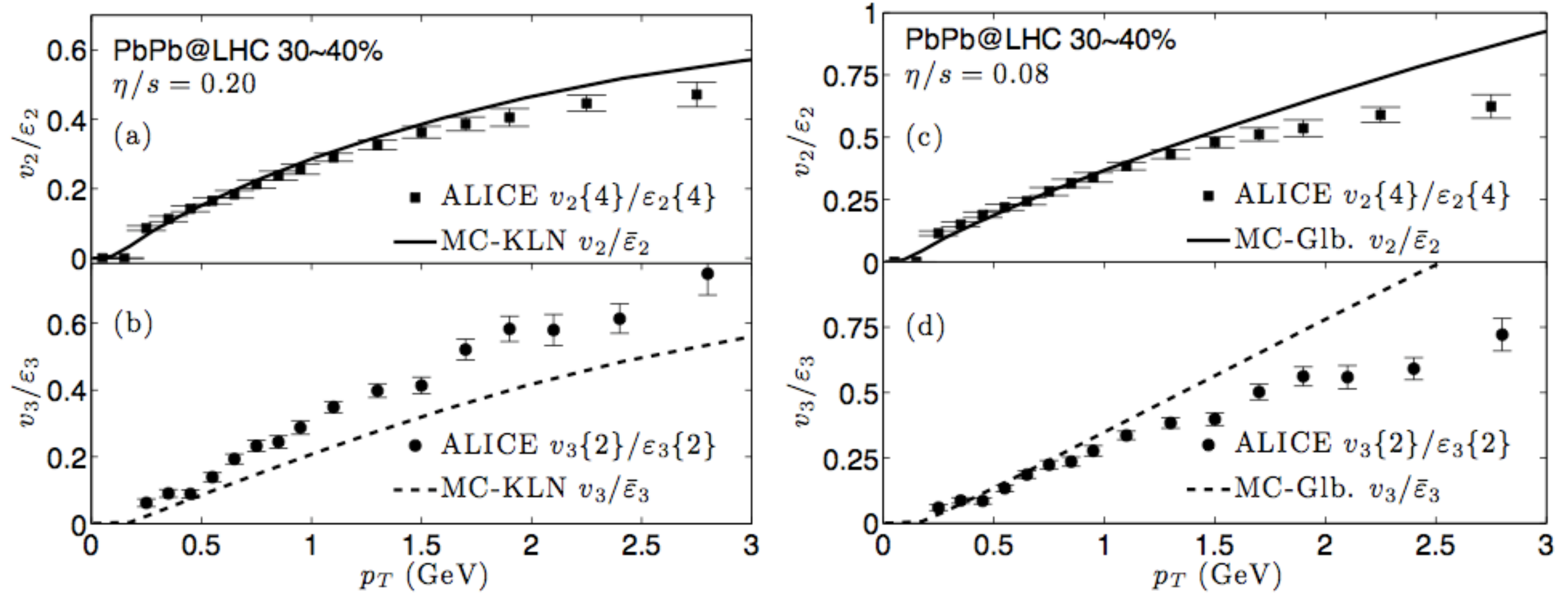






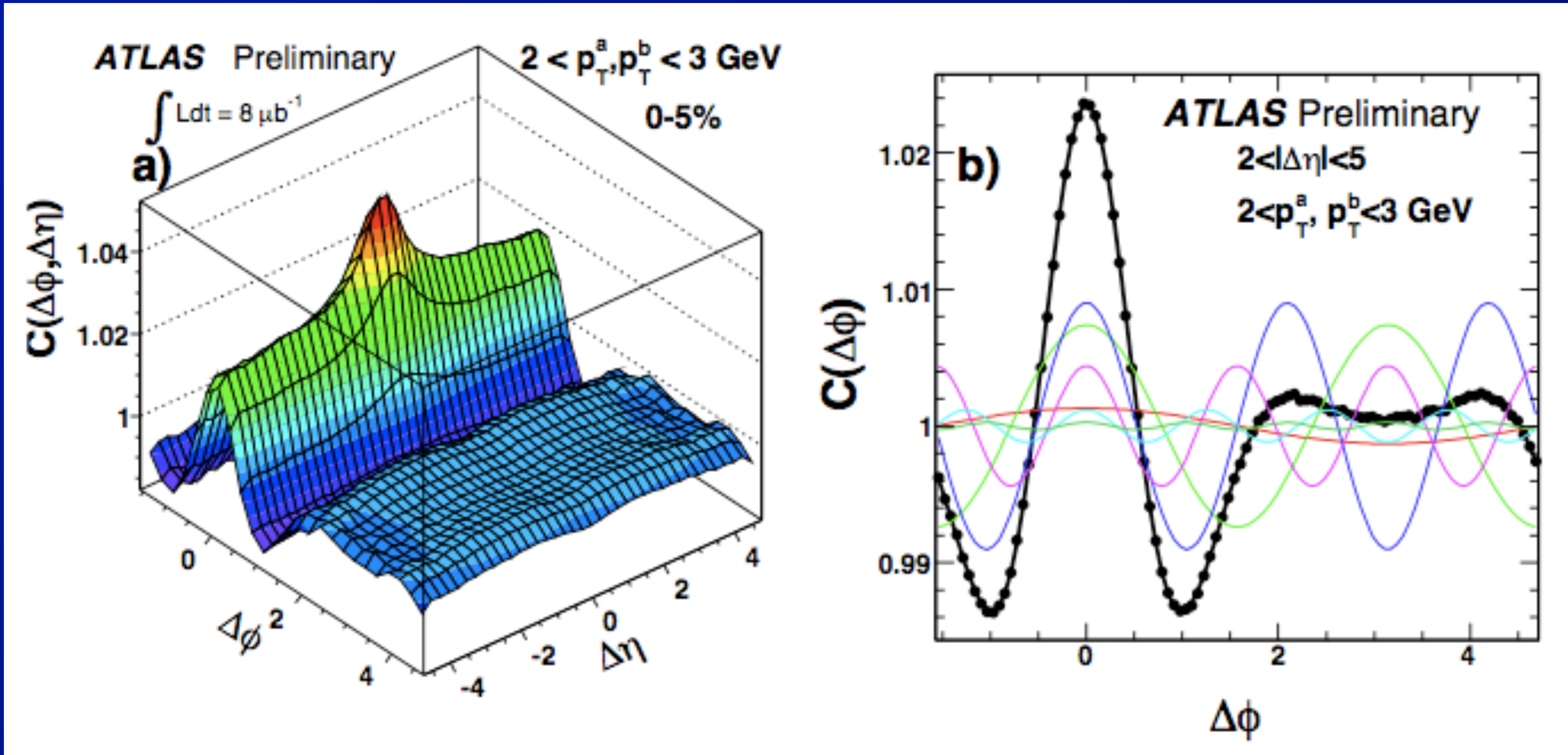
Significant results up to n = 6

Higher Flow Harmonics (2)



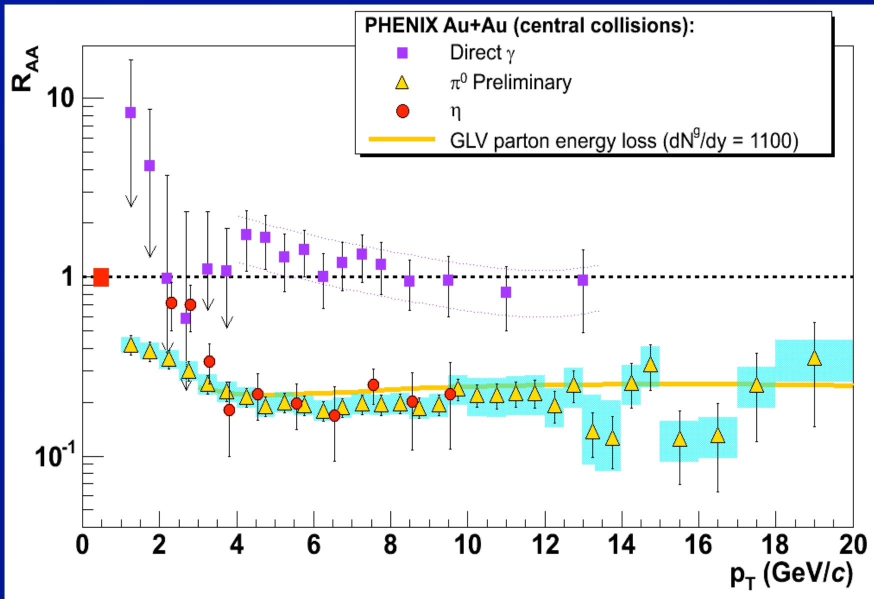
- Combination of v_2 and v_3 provide more stringent tests of hydrodynamic calculations
- Heinz *et al*: (preliminarily)
  - LHC data prefer ordinary "Glauber" initial conditions (MC-Glb) over CGC *a la* MC-KLN
    - ⇒$\eta/s \approx 1/4\pi$
    - ⇒rules out saturation? or just KLN

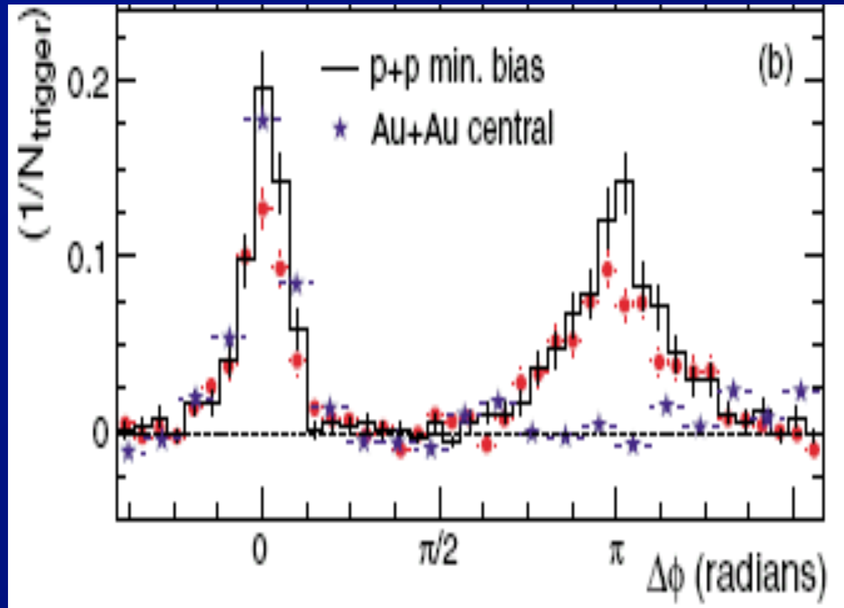
Higher Flow Harmonics (3)

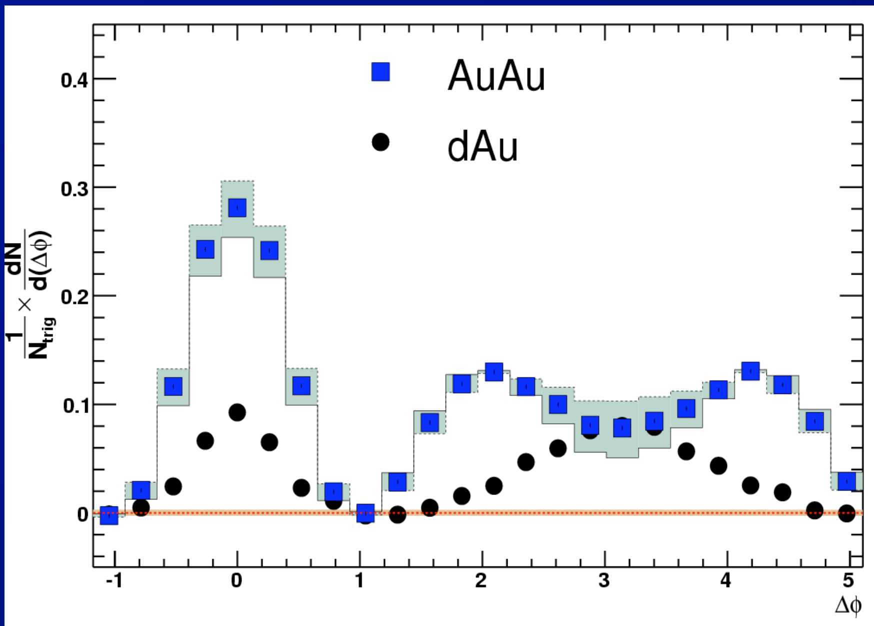


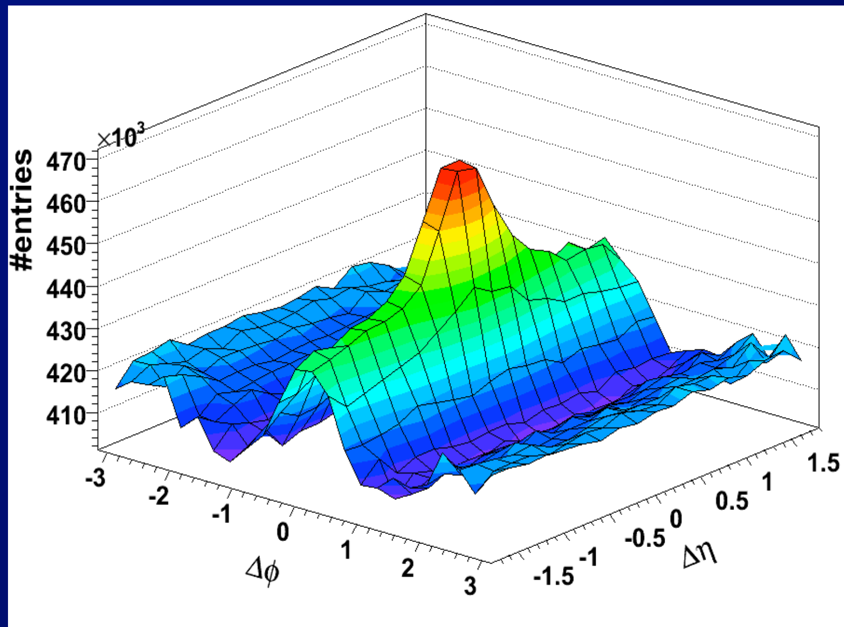
- Higher harmonics also studied using 2-particle correlations at large Δη
  - Sum of harmonic contributions sufficient to explain the "ridge" and the "mach(?) peaks"
    - ⇒Resolves two important "problems" in the field

Jet Quenching @ RHIC: 1 slide summary

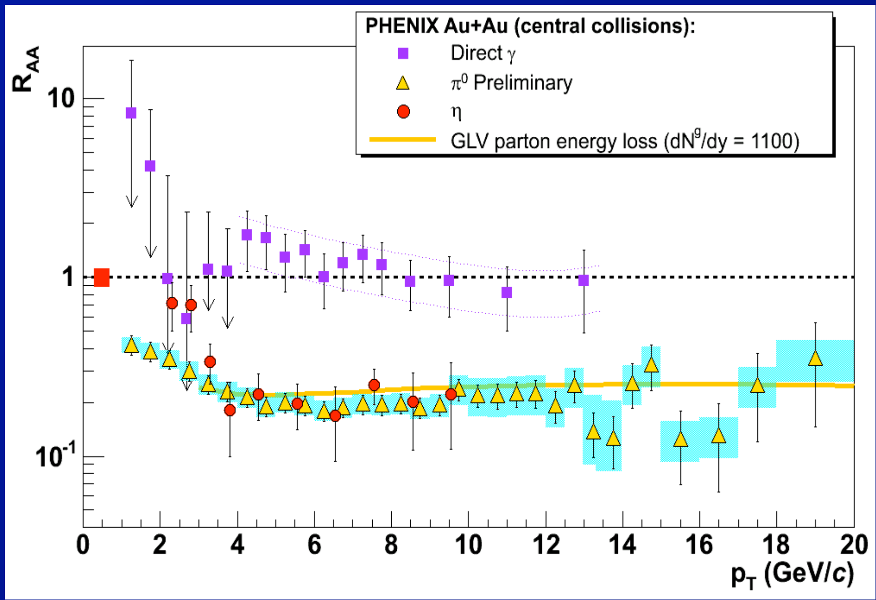


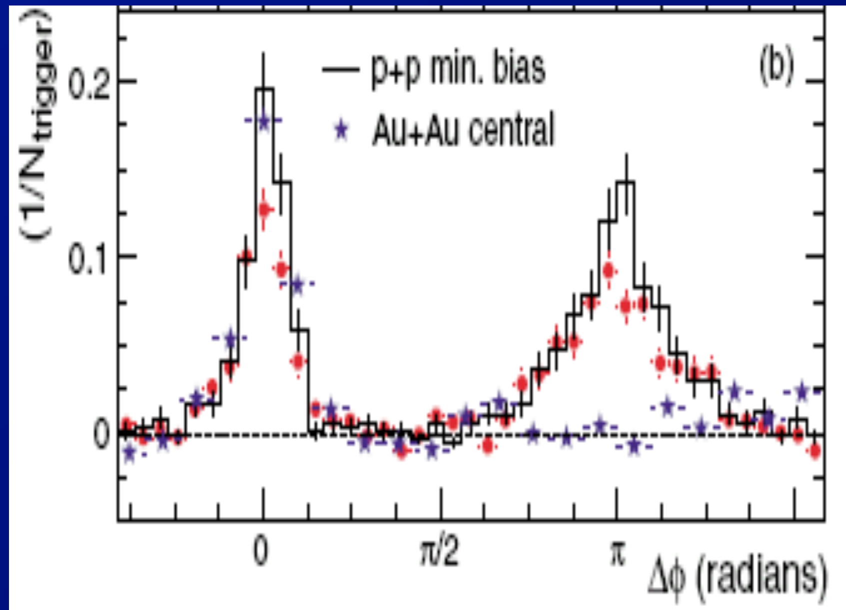


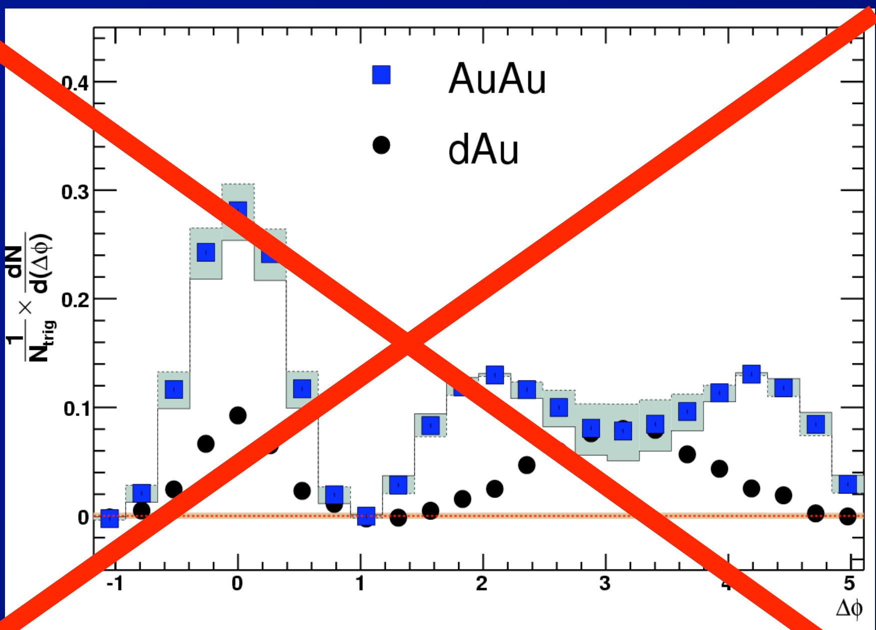


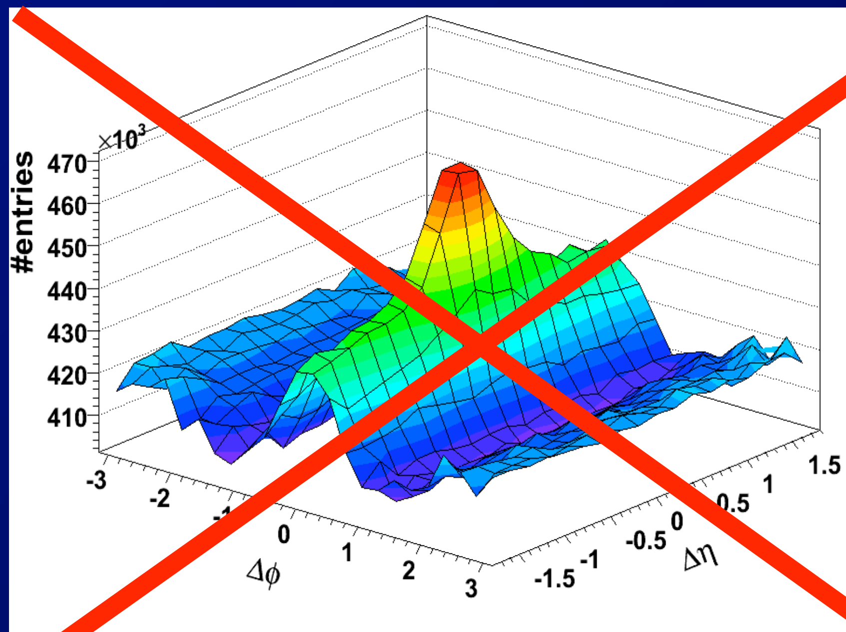


Jet Quenching @ RHIC: 1 slide summary

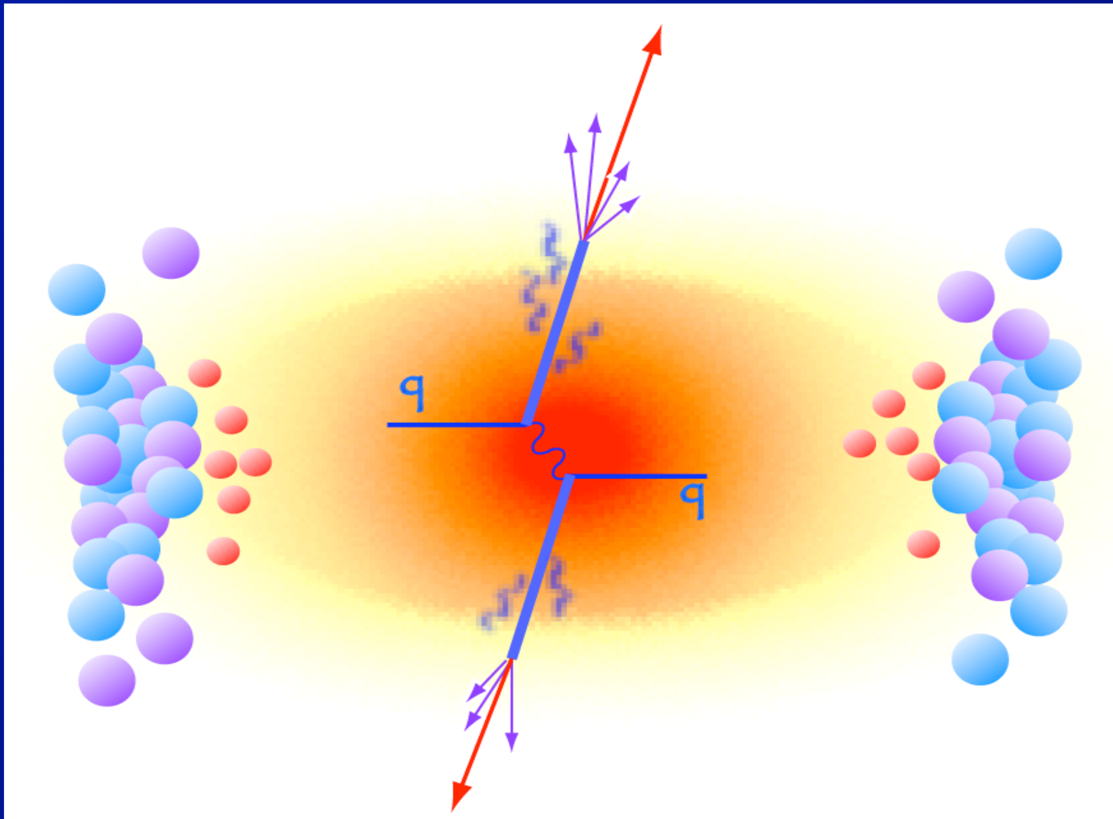




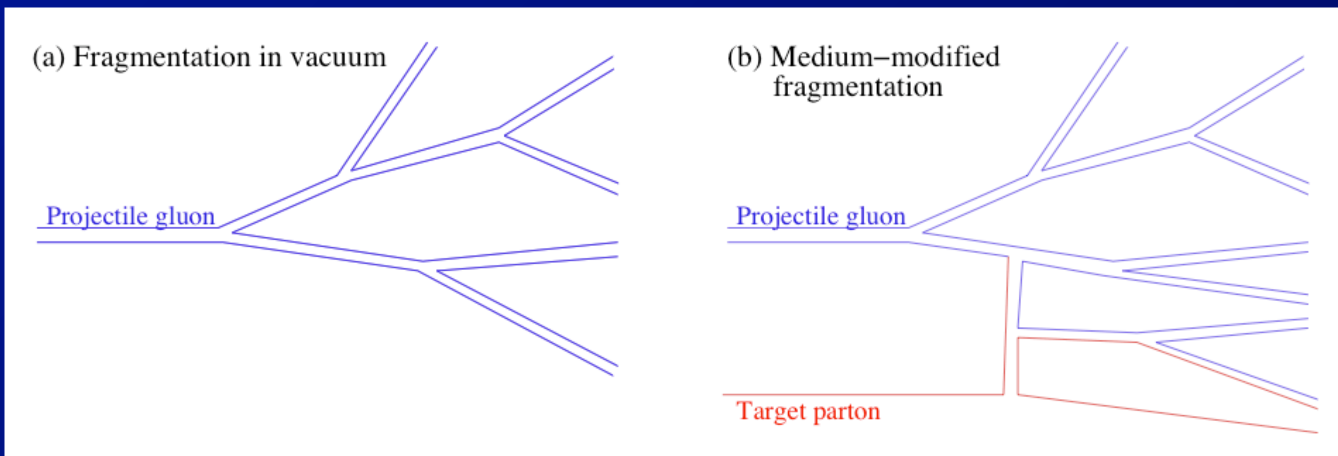




Jet Quenching

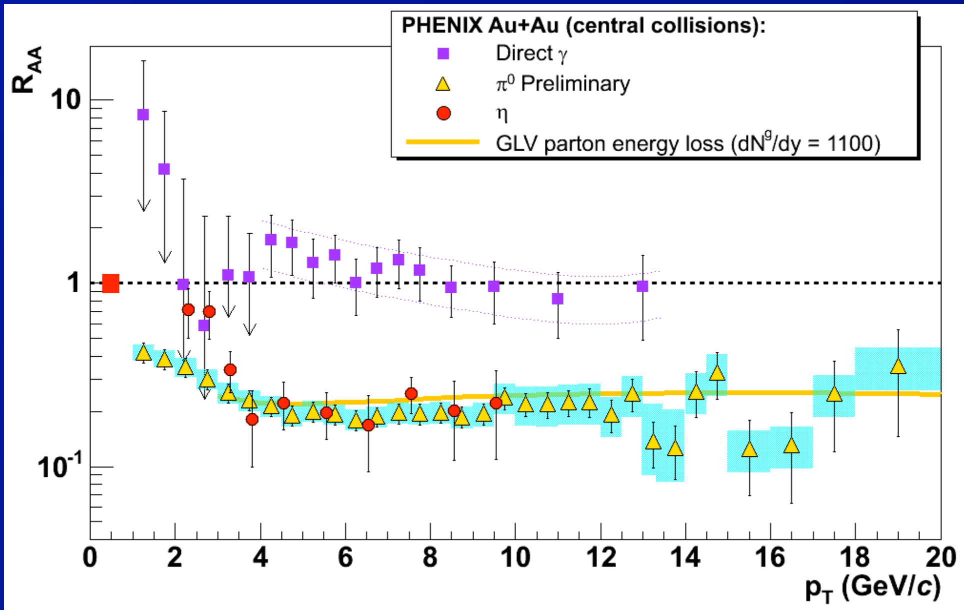


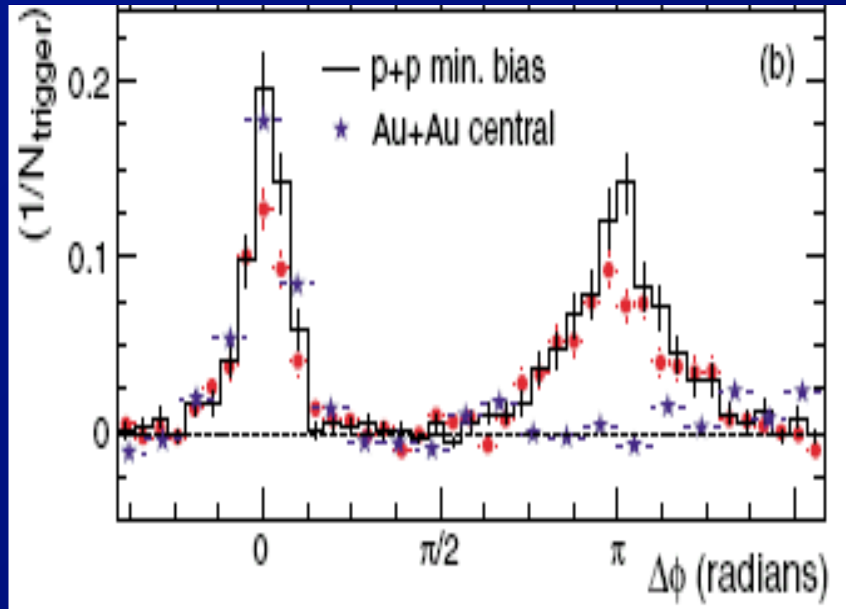
- **Key question:**
  - How do parton showers in hot medium (quark gluon plasma) differ from those in vacuum?



From "Jet Quenching in Heavy Ion Collisions", U. Wiedemann, arXiv:0908.2306

Light “Jet” Quenching @ RHIC





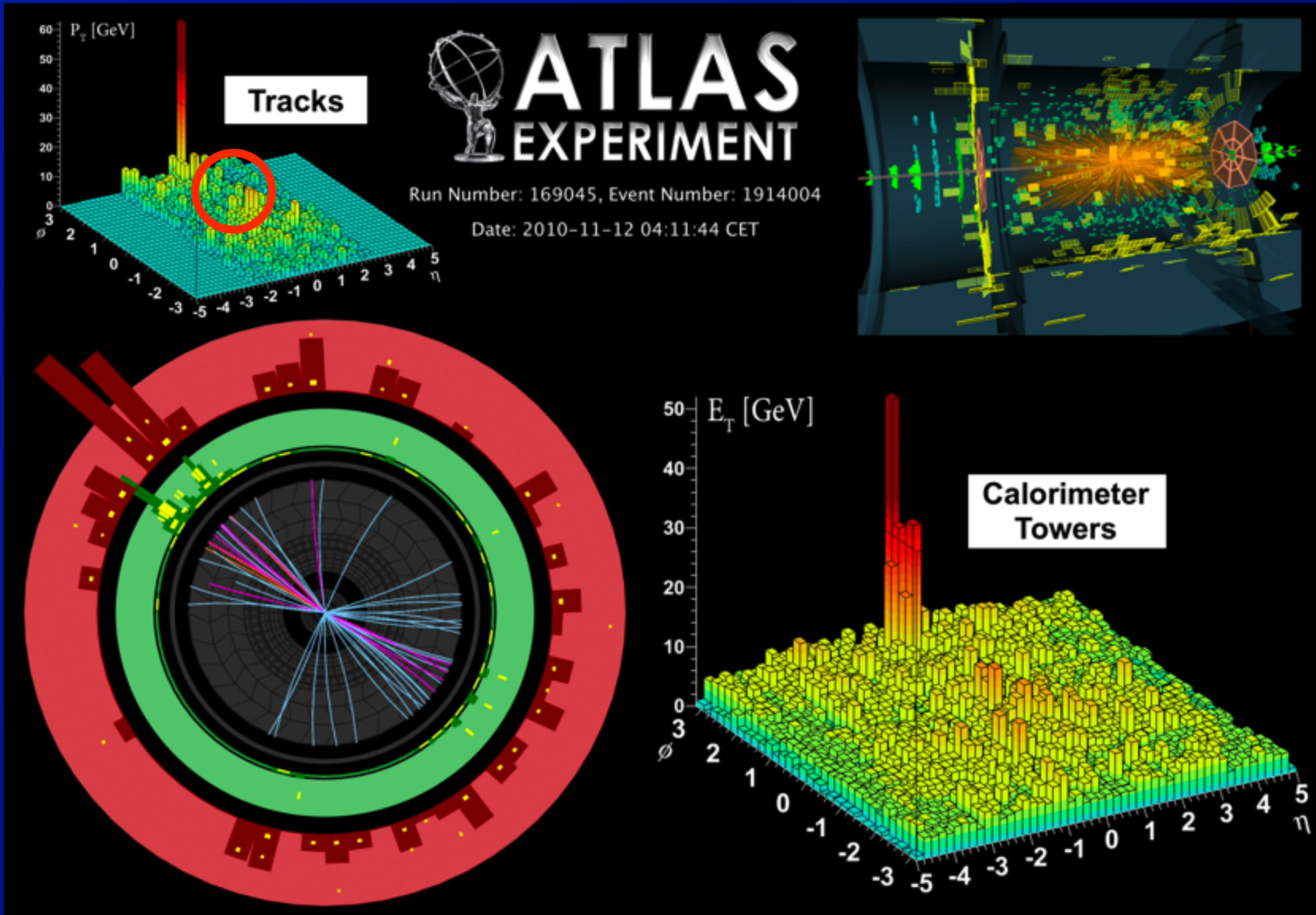
Indirect measurement of jet quenching via single particles

Indirect measurement of di-jet imbalance via pairs of particles

- We do not yet have a unique quantitative understanding of jet quenching @ RHIC

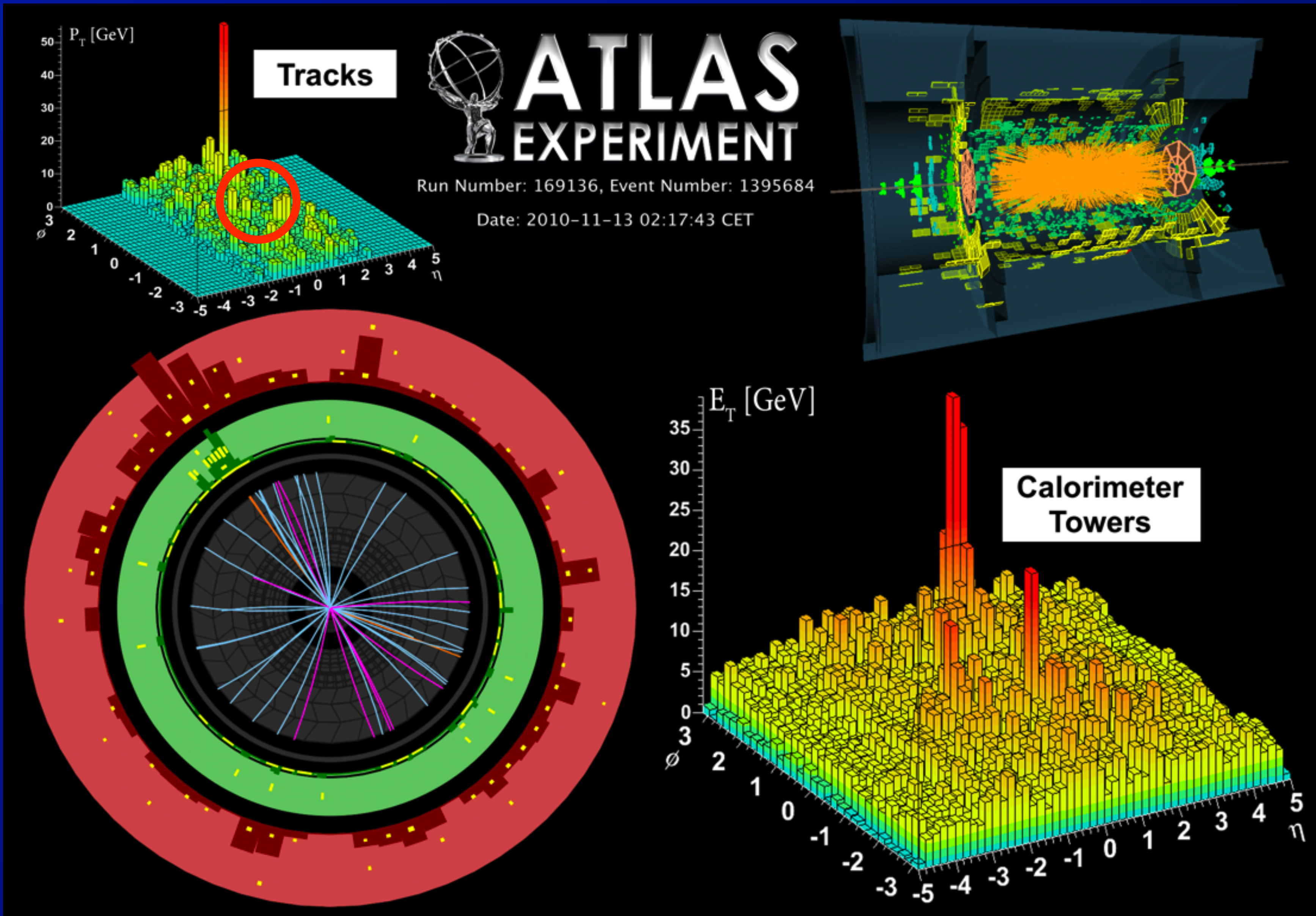
  ⇒Lack of jet measurements a serious limitation

ATLAS: asymmetric dijet in Pb+Pb



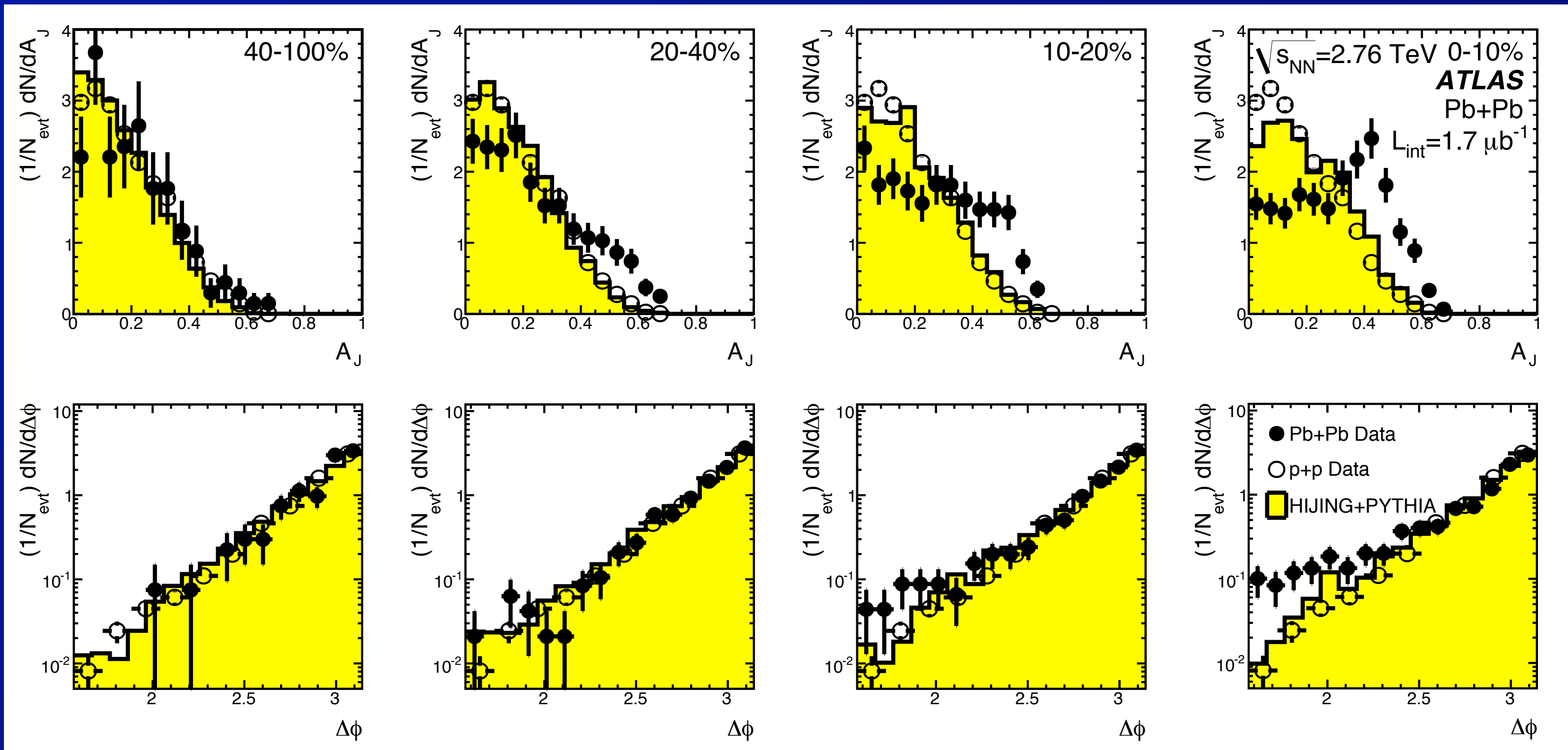
Central collision, highly asymmetric dijet

ATLAS: asymmetric dijet in Pb+Pb

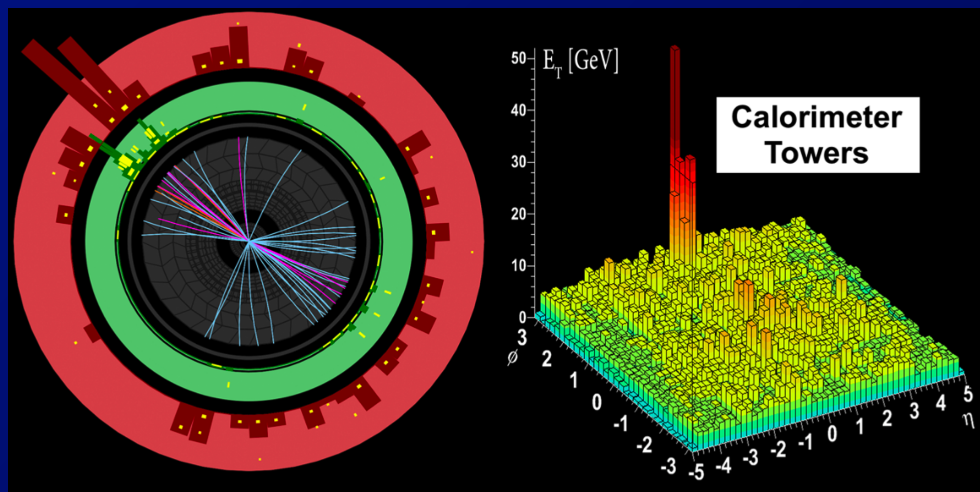


Central event, with split dijet + additional activity

Di-jet asymmetry - ATLAS PRL

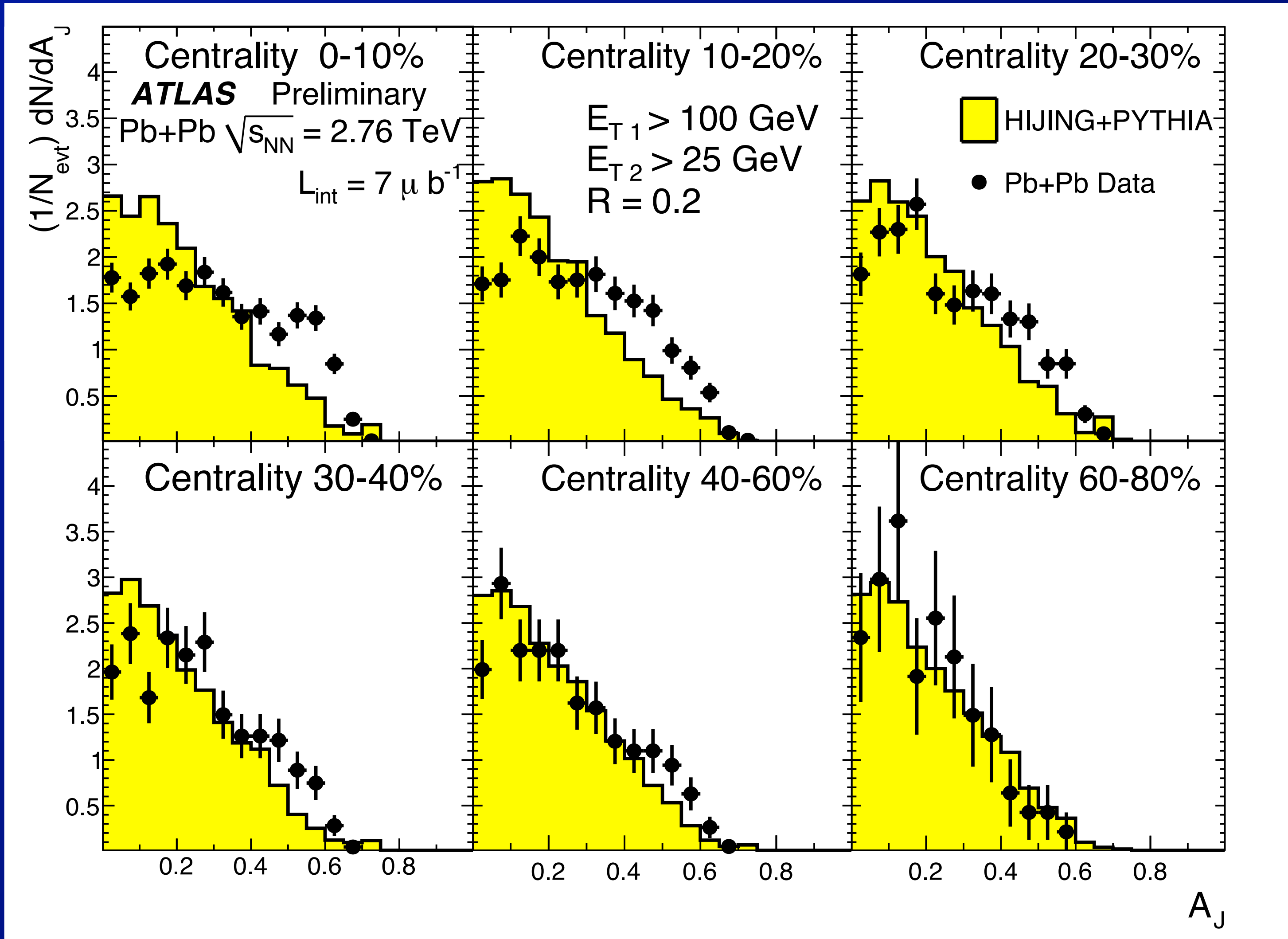


$$A_J \equiv \frac{E_{T1} - E_{T2}}{E_{T2} + E_{T1}}$$



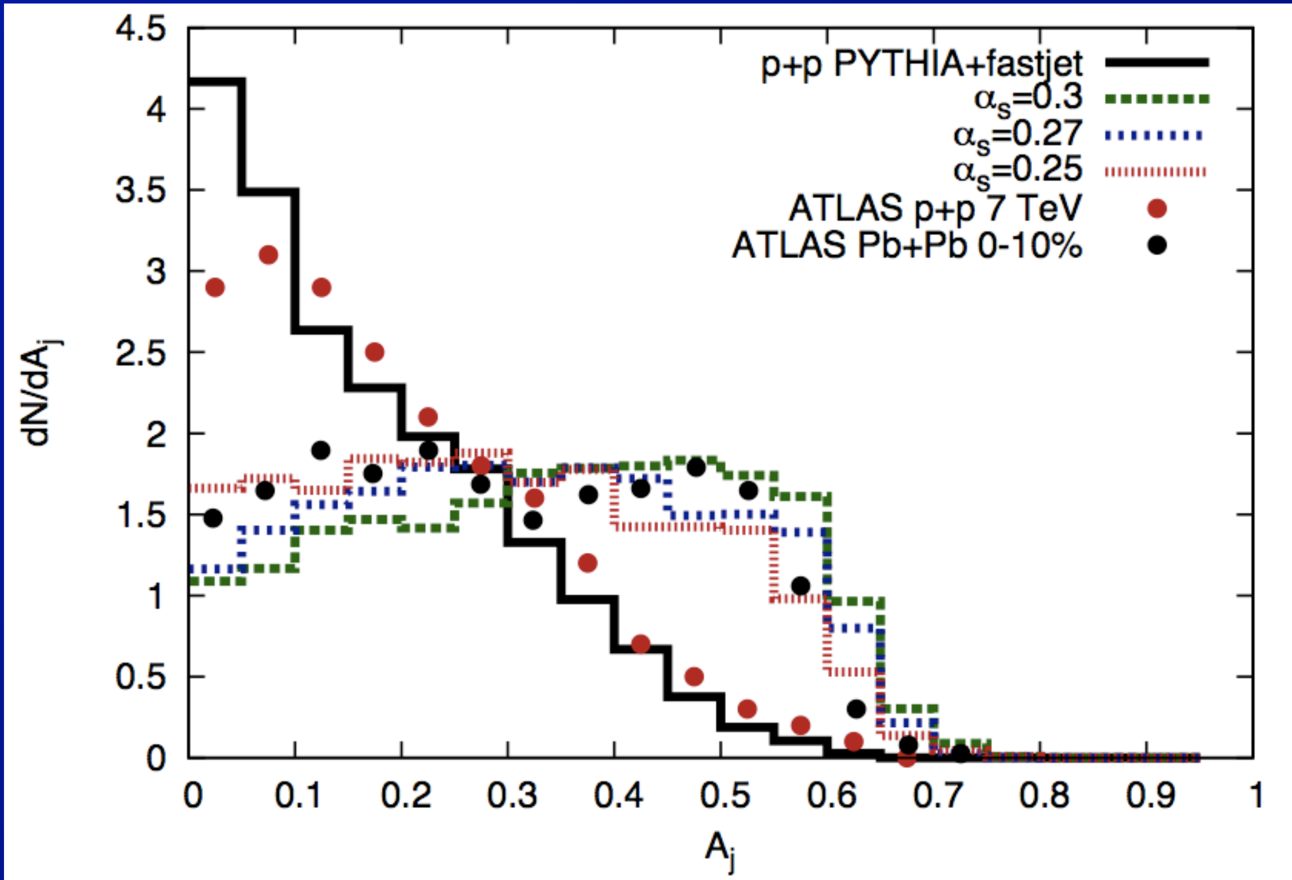
- "Holy grail" of jet quenching
  - But, due to quenching or underlying event?

ATLAS: Di-jet Asymmetry, R = 0.2



- **Strong modification of di-jet asymmetry in R = 0.2 jets (1/4 area of R = 0.4)**
  - ⇒ **Asymmetry not due to underlying event**

Dijet asymmetry: Theory comparisons



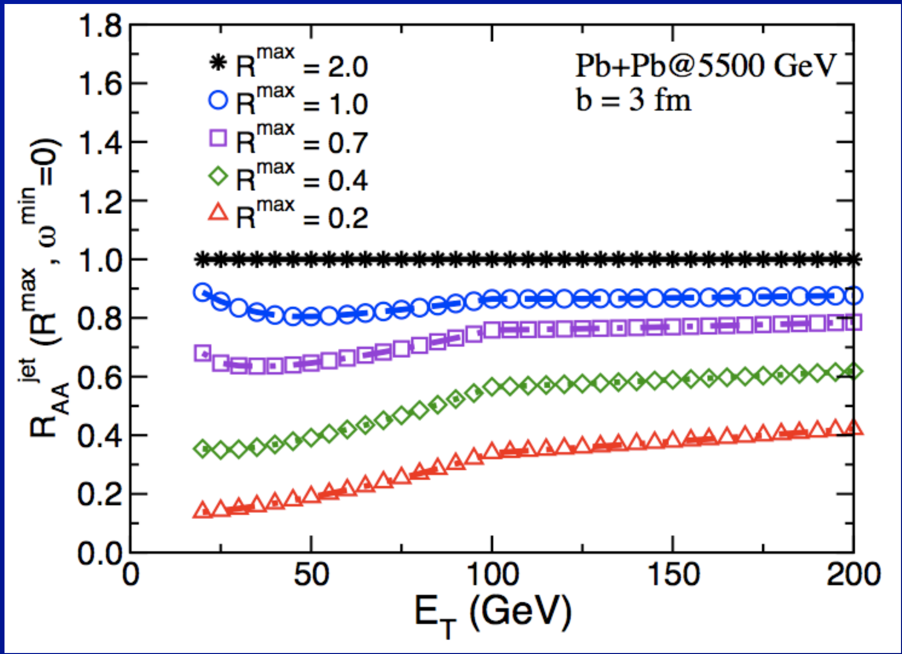
Young et al, arXiv 1103.5769 [nucl-th]

AMY energy loss formalism

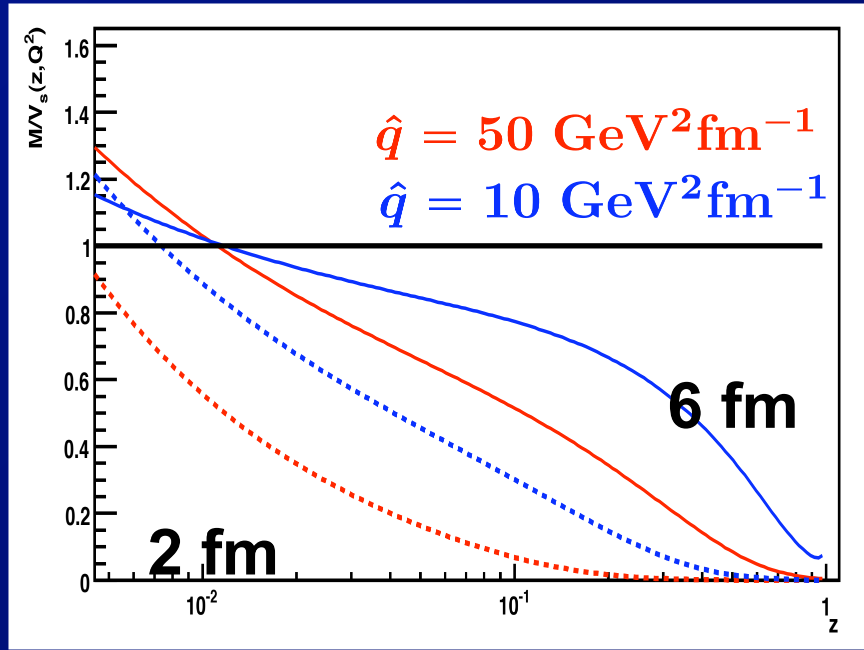
- AMY energy loss with 1 free parameter (α_s)
  - Good description of modified asymmetry distribution
    - ⇒Decisive test of energy loss calculations
    - ⇒1st step towards quantitative probe of jet + sQGP interactions using jets

Jet Quenching: Inclusive Observables

Vitev, Wicks, Zhang, JHEP 0811 (2008) 093



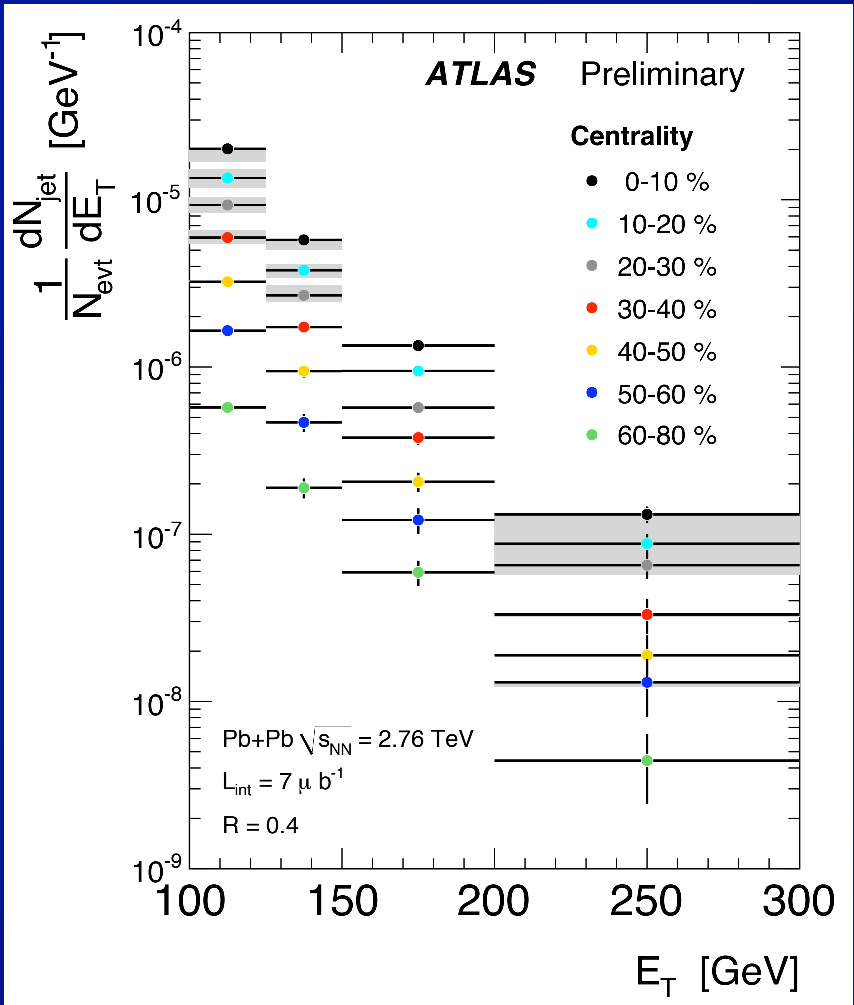
Armesto, Salgado, *et al*, JHEP 0802 (2008) 048



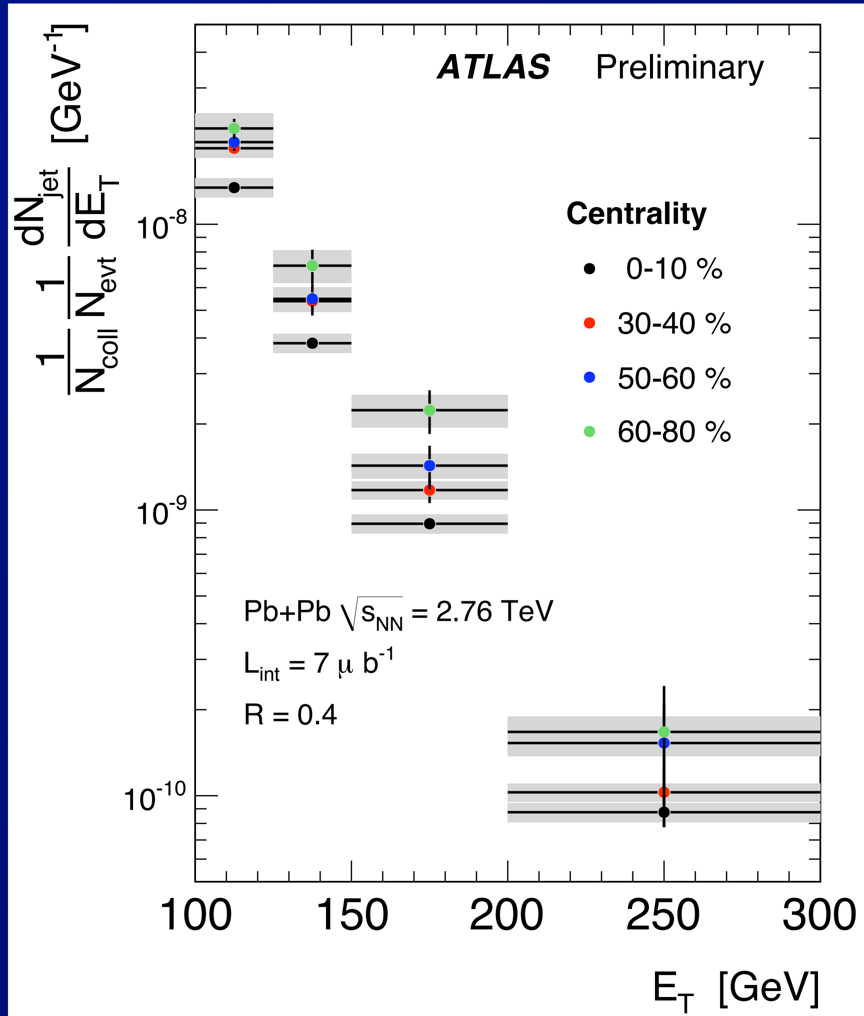
- **Key questions:**
  - ⇒ (How much) Is the jet yield suppressed?
  - ⇒ How does suppression depend on jet radius?
  - ⇒ Is the fragmentation function D(z) modified?
  - ⇒ Is the hadron angular distribution broadened?

Single Jet Rates, R = 0.4

Single jet spectra



Single jet spectra/N_{coll}



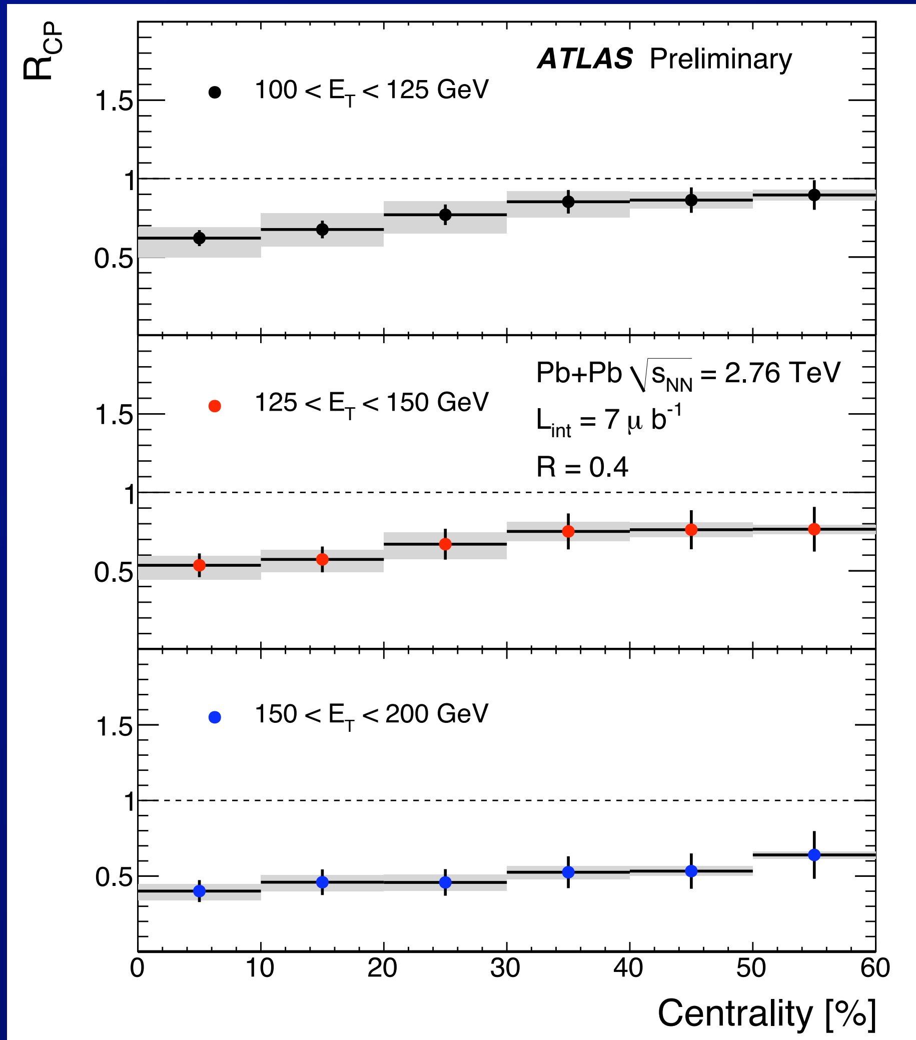
- For single jet spectra
  - Centrality independent 22% systematic error on normalization due to 4% jet energy scale uncertainty.

Jet Suppression via R_{cp}

R = 0.4

Use 60-80% centrality as peripheral reference for R_{cp}

$$Rcp = \frac{\frac{1}{N_{coll}^{cent}}\frac{1}{N_{evt}^{cent}}\frac{dN_{jet}^{cent}}{dE_T}}{\frac{1}{N_{coll}^{60-80}}\frac{1}{N_{evt}^{60-80}}\frac{dN_{jet}^{60-80}}{dE_T}}$$

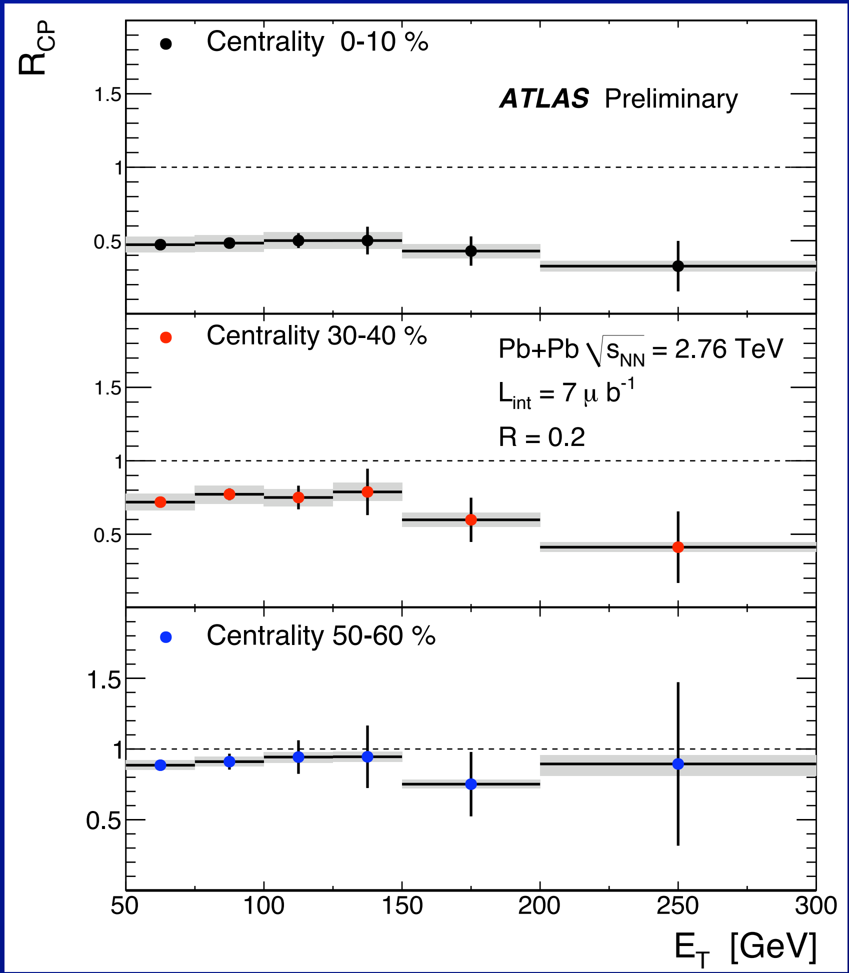


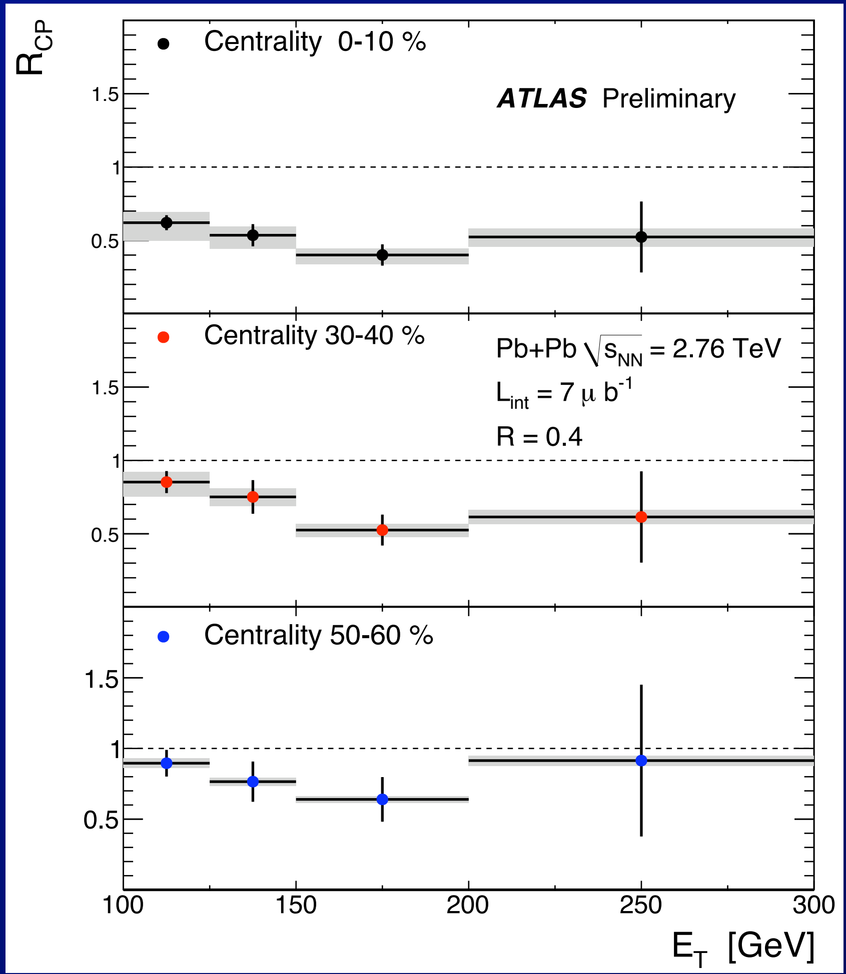
- **Observe:**

⇒Factor of ≈ 2 suppression of jet yield/N_{coll} in central (0-10%) collisions relative to 60-80% collisions.

Jet Suppression via R_{cp} (2)

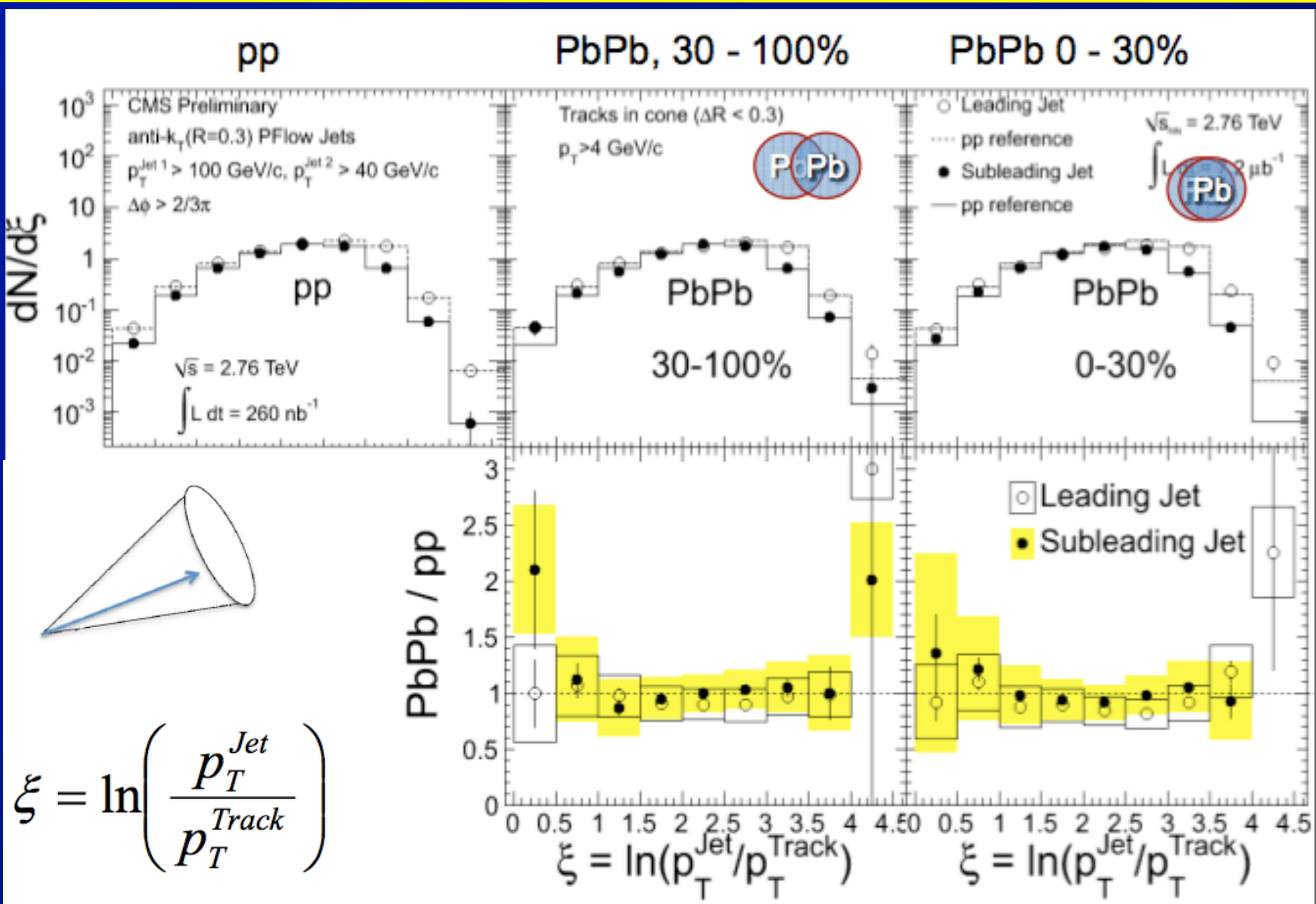
R = 0.2 | **R = 0.4**





- **Observe**
  - ⇒ Suppression E_T independent within errors
  - ⇒ Same for R = 0.2 and R = 0.4 within errors

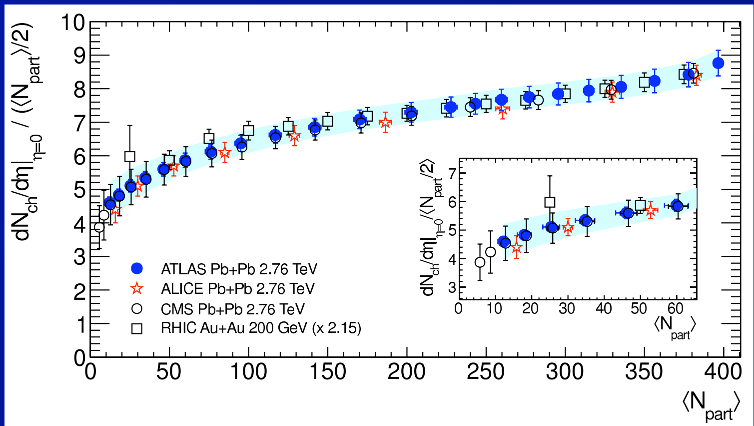
Jet Fragmentation

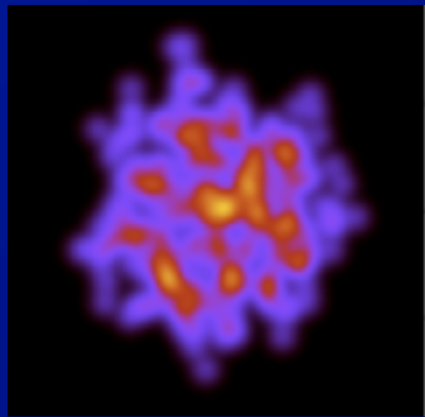


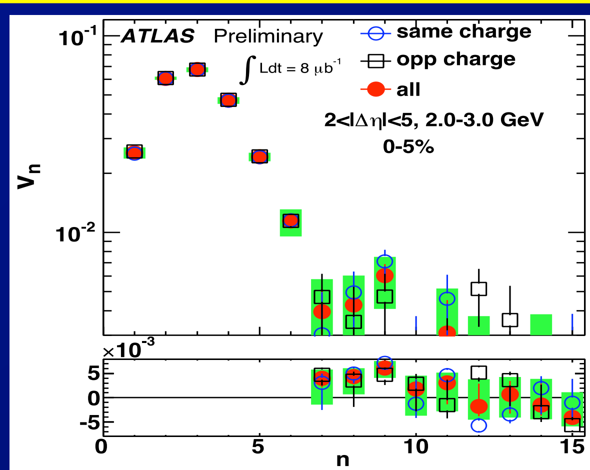
$$\xi = \ln\left(\frac{p_T^{Jet}}{p_T^{Track}}\right)$$

- No apparent modifications of (longitudinal) jet fragmentation function.

Summary & Comments/Questions

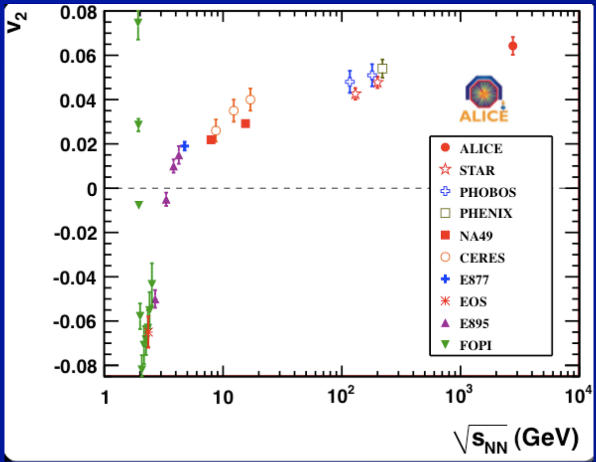


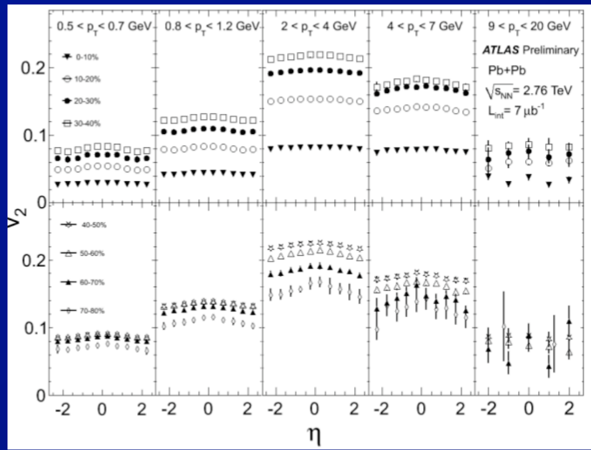


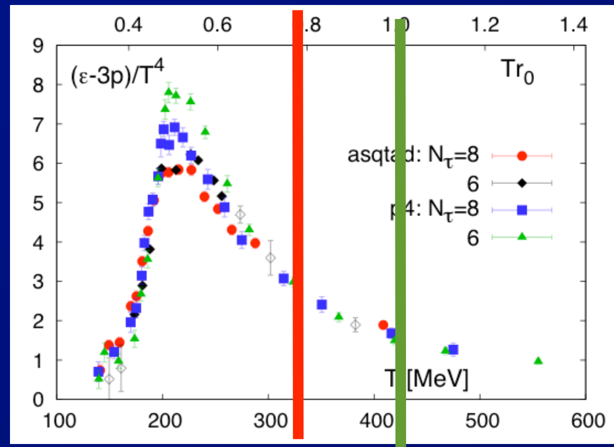


- LHC multiplicity (and E_T) results provide key data on LHC initial conditions
  - ⇒But insight on the physics?
- Physics of bulk particle production also determines initial state geometry & fluctuations
  - ⇒Possibility for v_n to constrain theoretical descriptions of the initial conditions
  - ⇒But, do we have the correct physical picture?
- Additional insight from p+A, e+A needed

Summary & Comments/Questions (2)

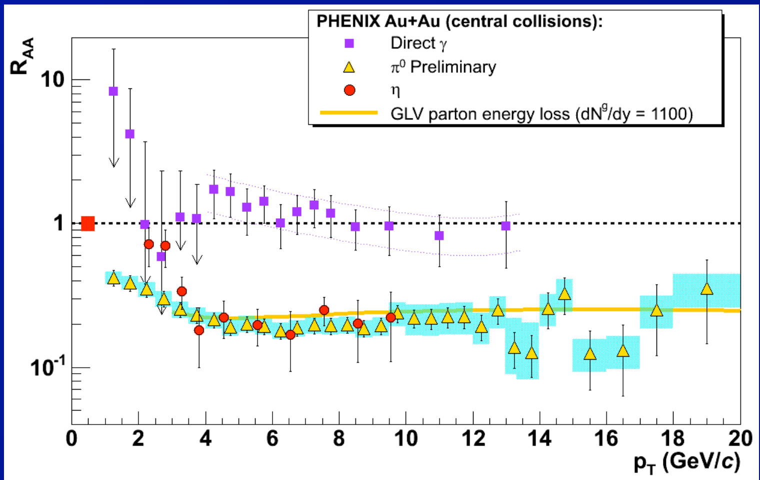


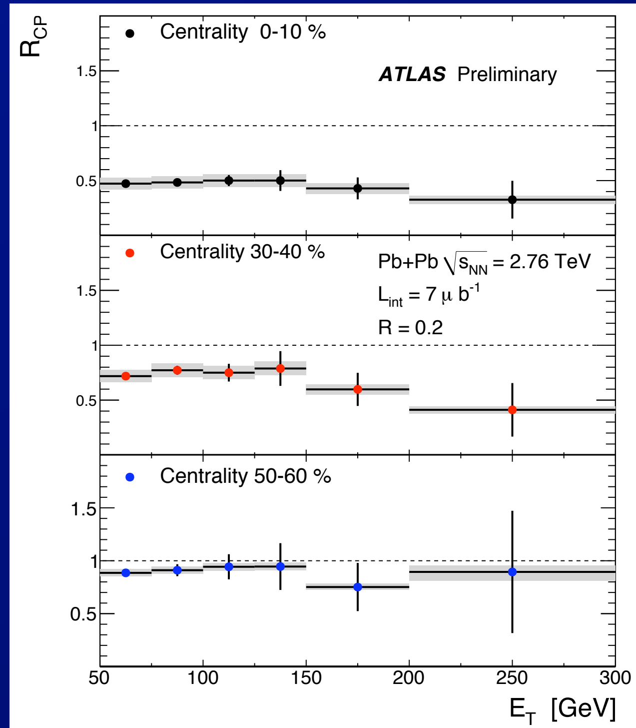




- Collective flow physics qualitatively similar at RHIC and the LHC
  - But, longer lifetime of sQGP at LHC results in less sensitivity to hadronic stage.
- For both RHIC, LHC v_n physics will revolutionize study of collective flow
  - ⇒Precision determination of transport coefficients?
  - ⇒Constrain descriptions of initial state
- Sensitivity to weaker coupling at higher T?

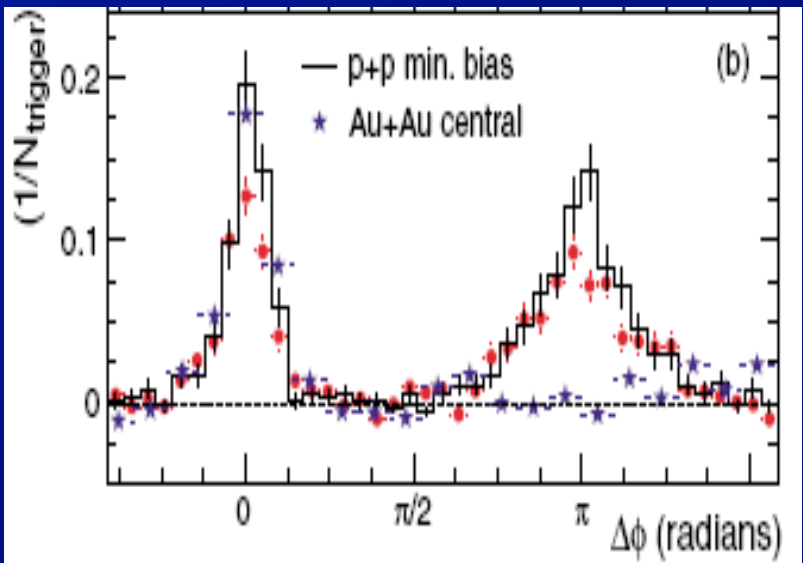
Summary & Comments/Questions (3)

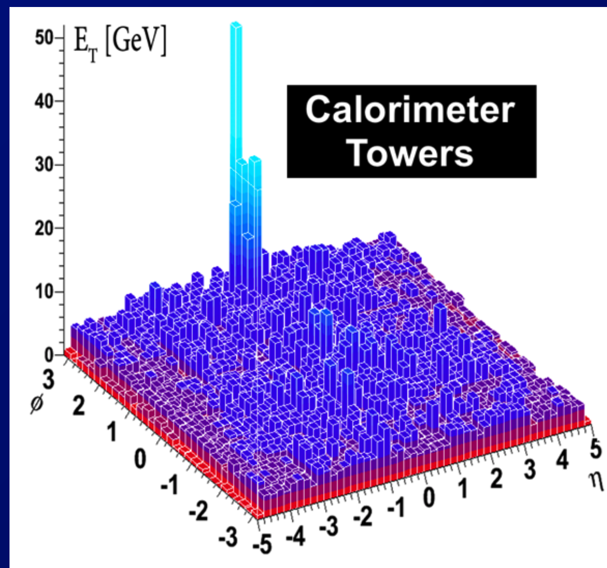




Single/di-hadron measurements replaced by jet measurements

➡ **on our way to sQGP tomography**





Jet Measurements @ RHIC

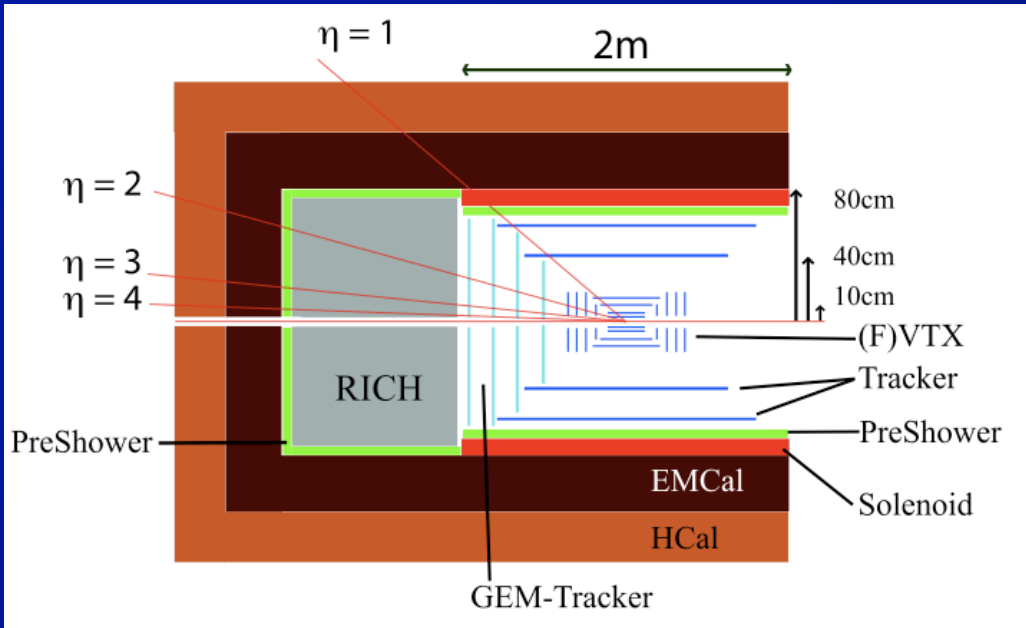
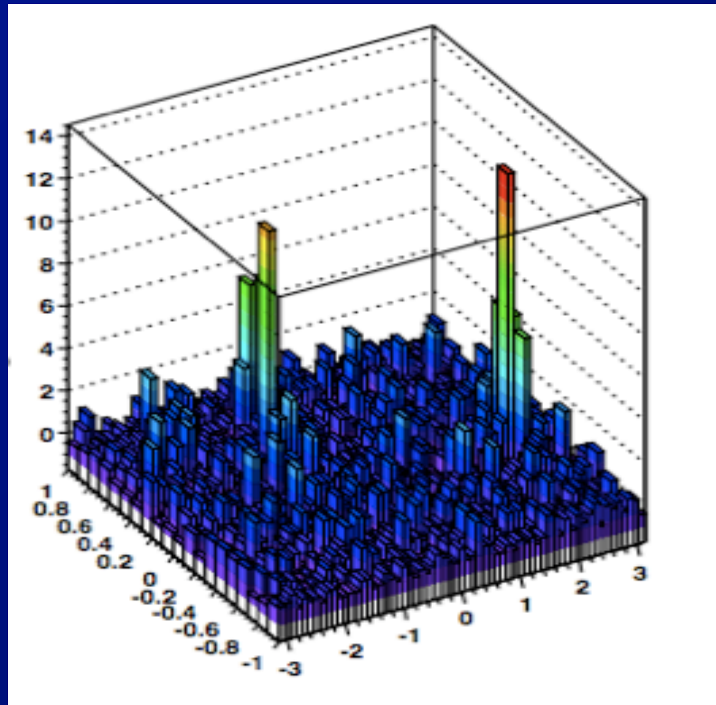
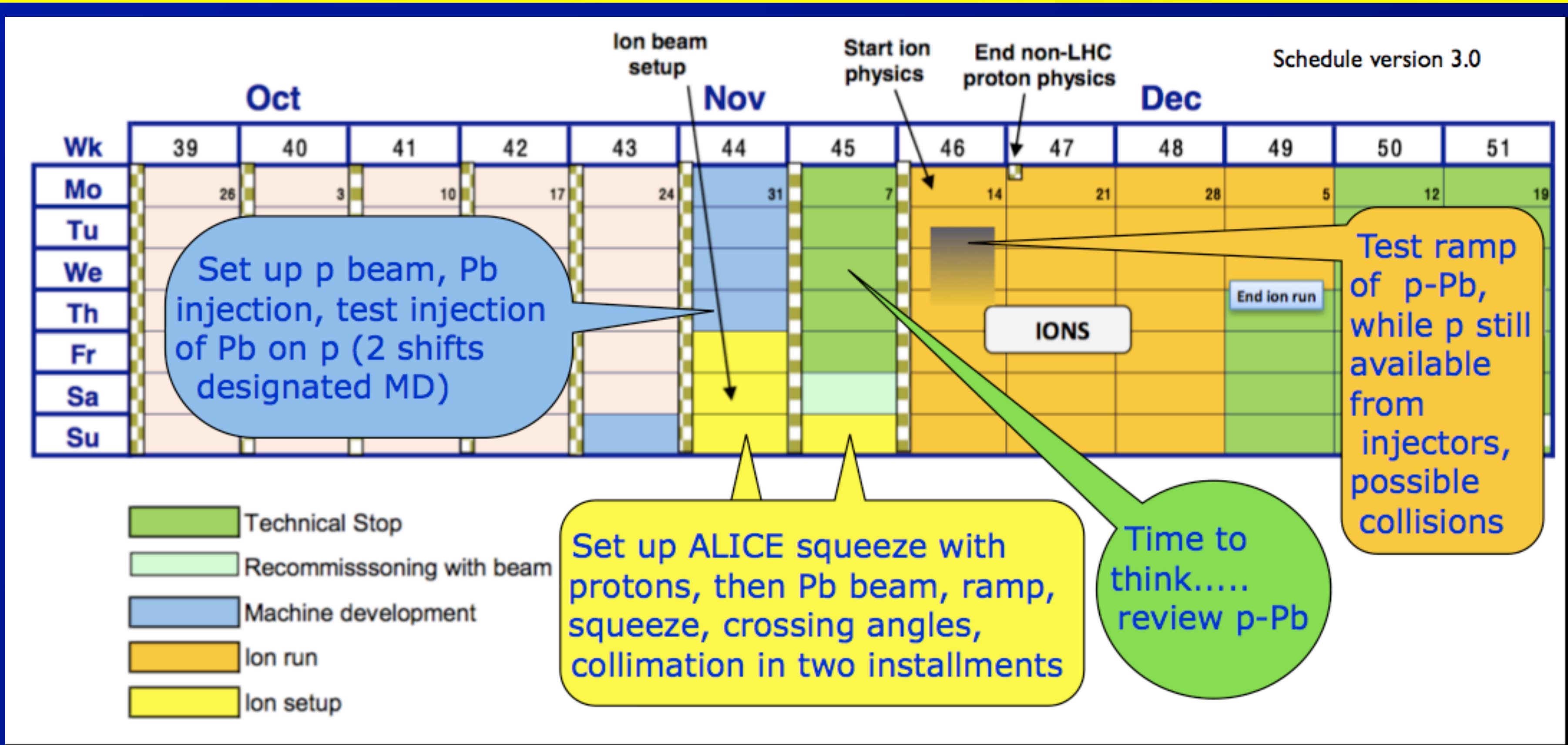


Figure 1. A strawman sketch of the sPHENIX detector. Some features of the detector are discussed in the text.



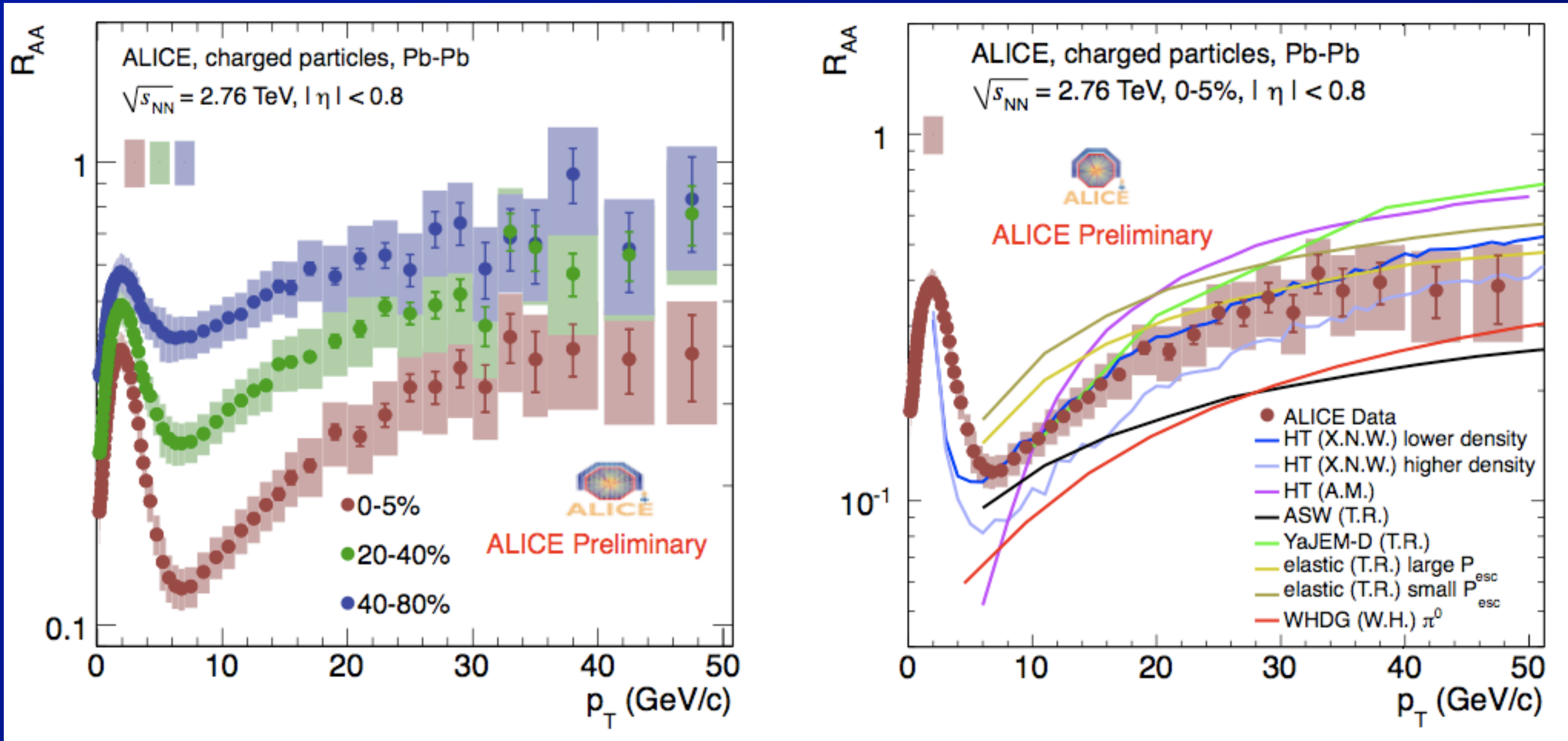
- Both STAR and PHENIX are pursing A+A jet measurements @ RHIC
  - ⇒But, neither detector is optimal for jets in A+A
- So, PHENIX has proposed major upgrade (sPHENIX) with goal of performing jet measurements similar to ATLAS & CMS

LHC Heavy Ion Program: prospects



- In Nov. 2011, 3 week Pb+Pb run
  - expect x10 increase in $\int \mathcal{L}\, dt$ over 2010 run
    - $\Rightarrow$ Important for jet, γ, γ-jet, b jet, W, Z, J/ψ, Υ
- Hopefully, a first low-statistics p+Pb data set
  - As a test for a high-statistics p+Pb run in 2012

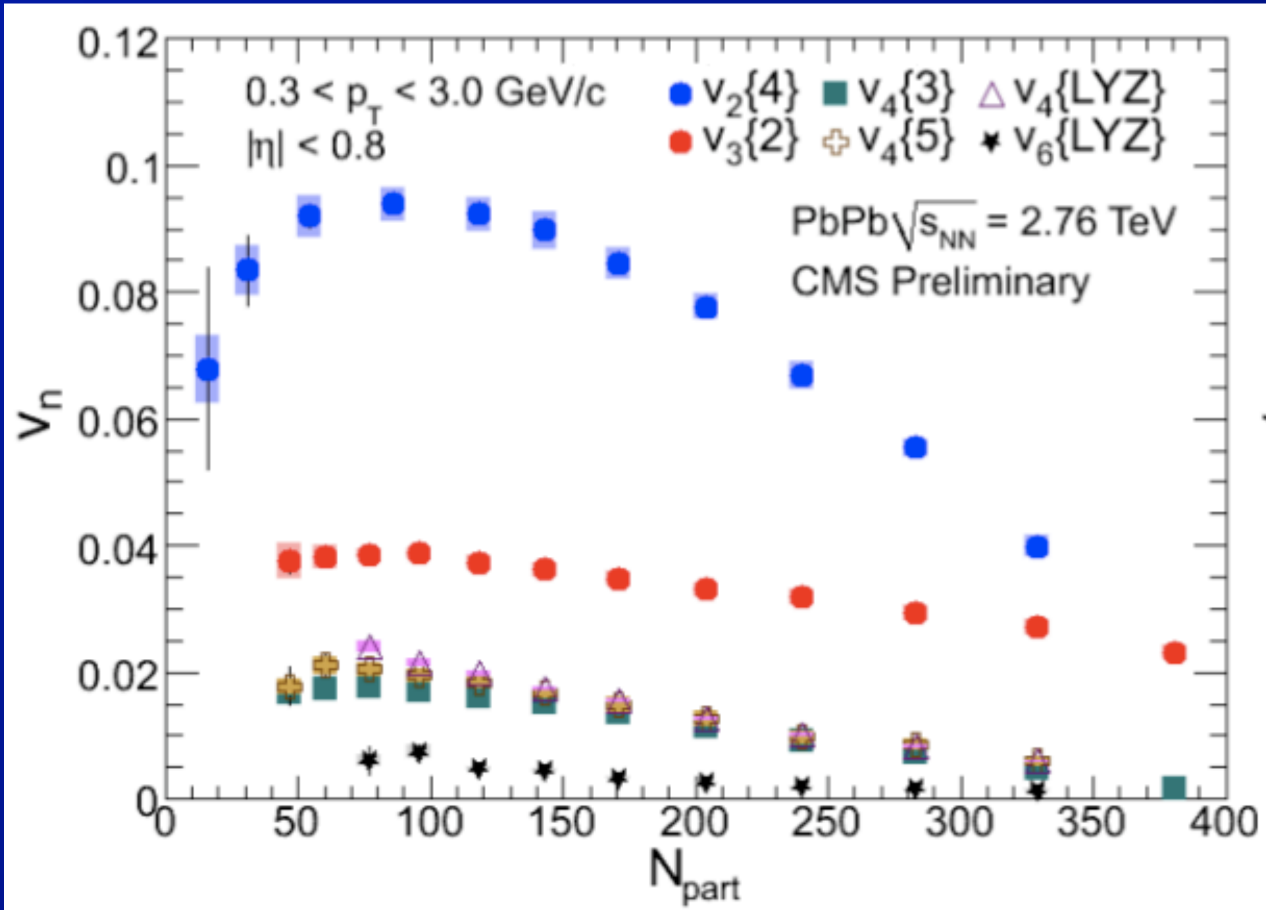
Charged Particle Suppression

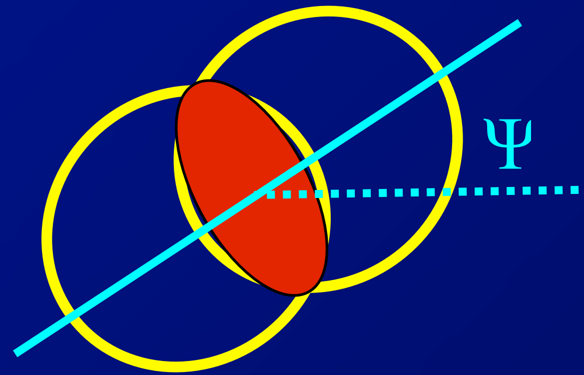


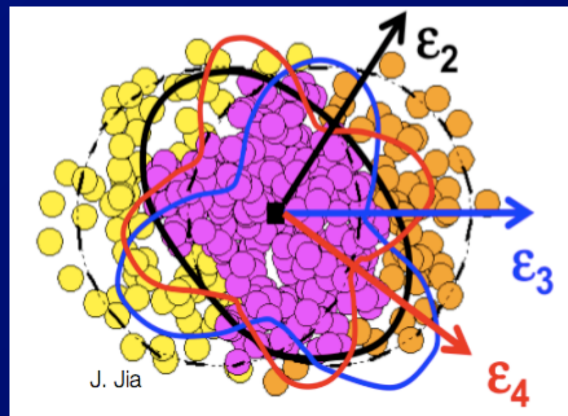
- Charged particle R_{AA} vs p_T up to 50 GeV/c
  - Below ~ 6 GeV, dominated by soft physics
  - Gradual reduction in suppression with increasing p_T
    - ⇒Long sought indications of radiative energy loss?
    - ⇒Measurements starting to discriminate models?

Backup

Higher Flow Harmonics (2)

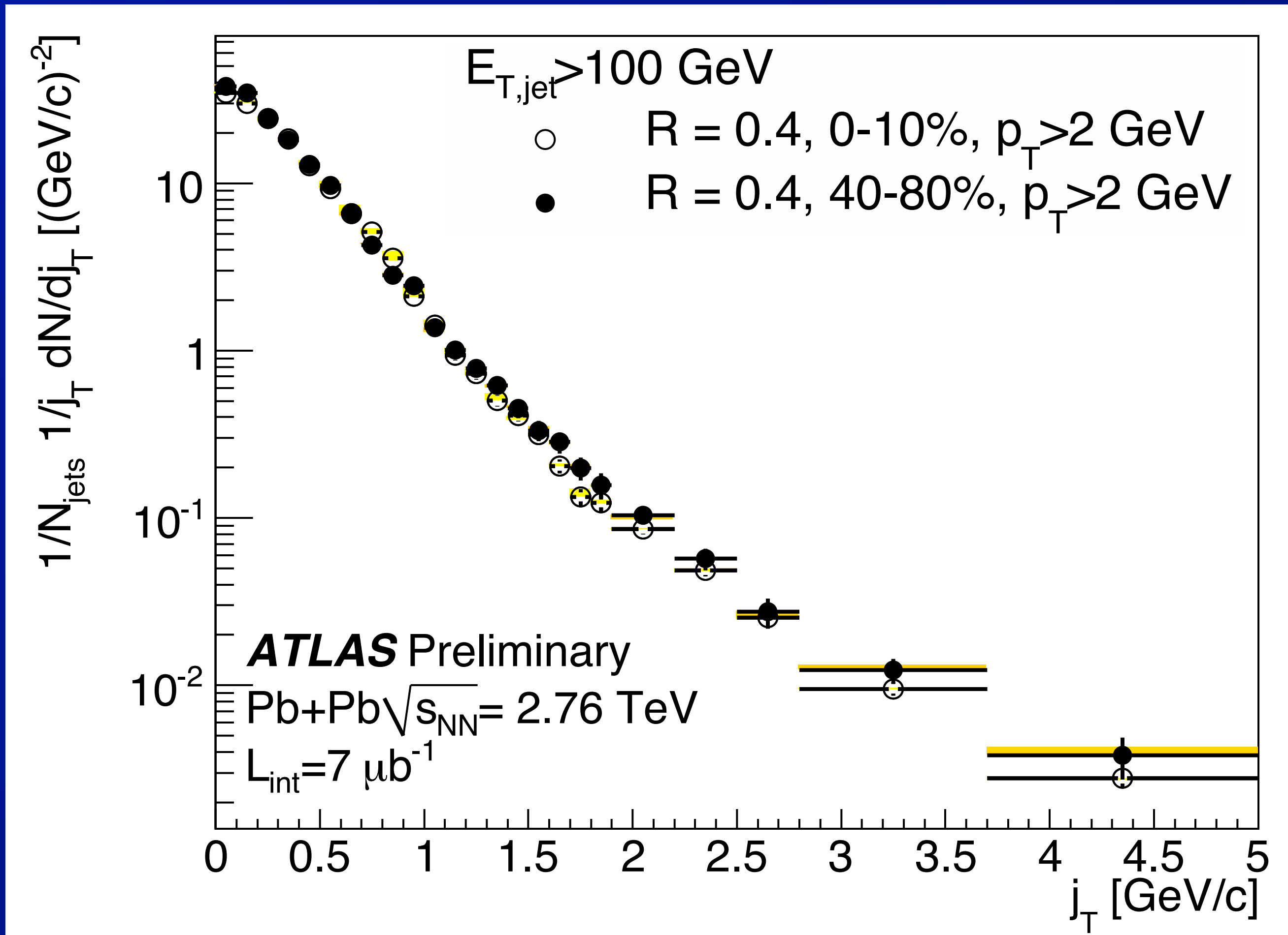


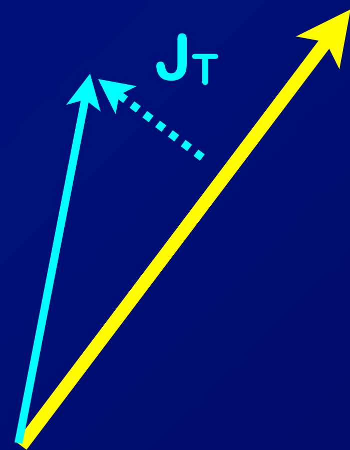




- Elliptic (v_2) flow dominates except in central collisions where $\varepsilon_2 = 0$ without fluctuations
  - v_3 has much weaker centrality dependence
    - $\Rightarrow$ consistent with participant fluctuations

Jet Fragmentation (Transverse)





- **Measure distribution of fragment p_T normal to jet axis:** $j_T \equiv p_T^{had} \sin \Delta R = p_T^{had} \sin\left(\sqrt{\Delta\eta^2 + \Delta\phi^2}\right)$
  - **Compare central (0-10%) to peripheral (60-80%)**

    ⇒**No substantial broadening observed.**