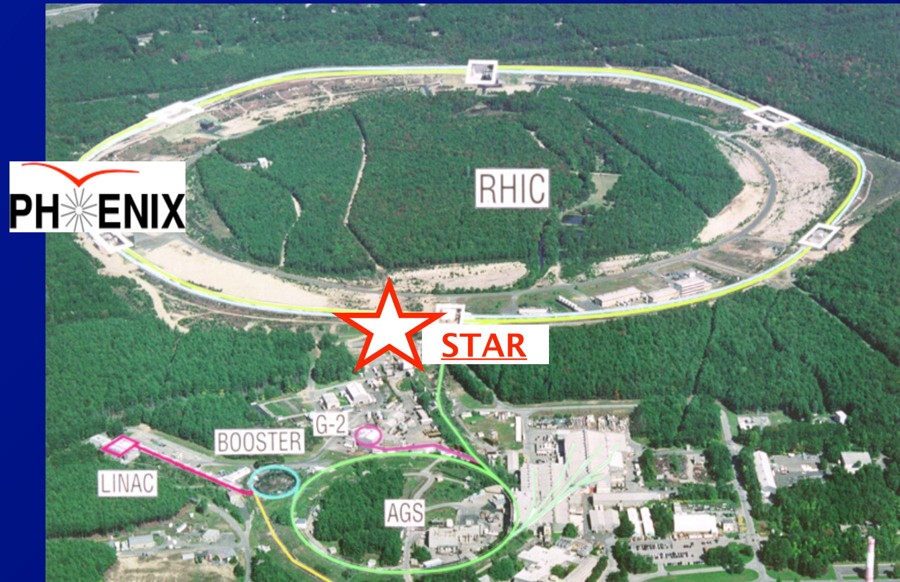
High p_T Physics at

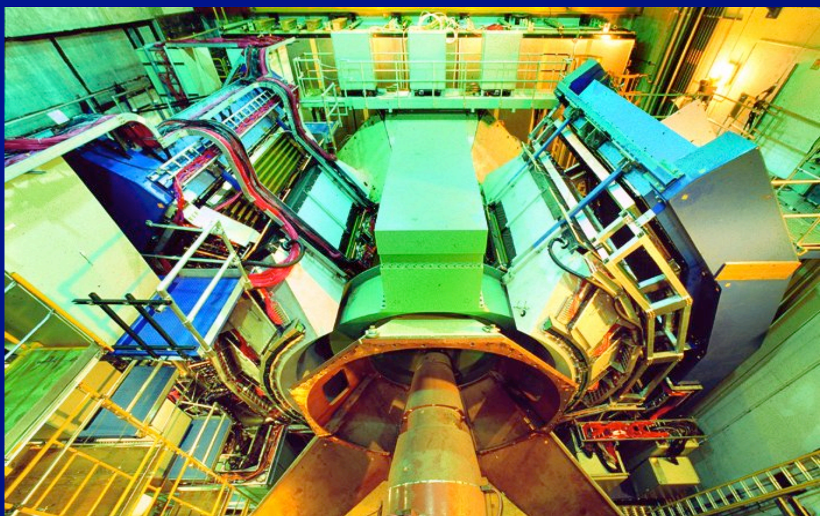
Brian A. Cole
Columbia University

HCP 2011
November 14, 2011

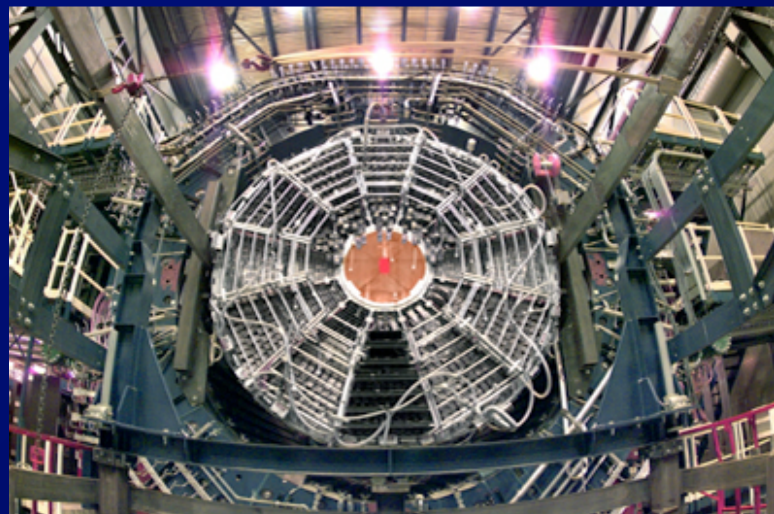


7-200 GeV/A Au+Au, d+Au, Cu+Cu
32-500 GeV p+p, ...

PHENIX



STAR



The Big Picture

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

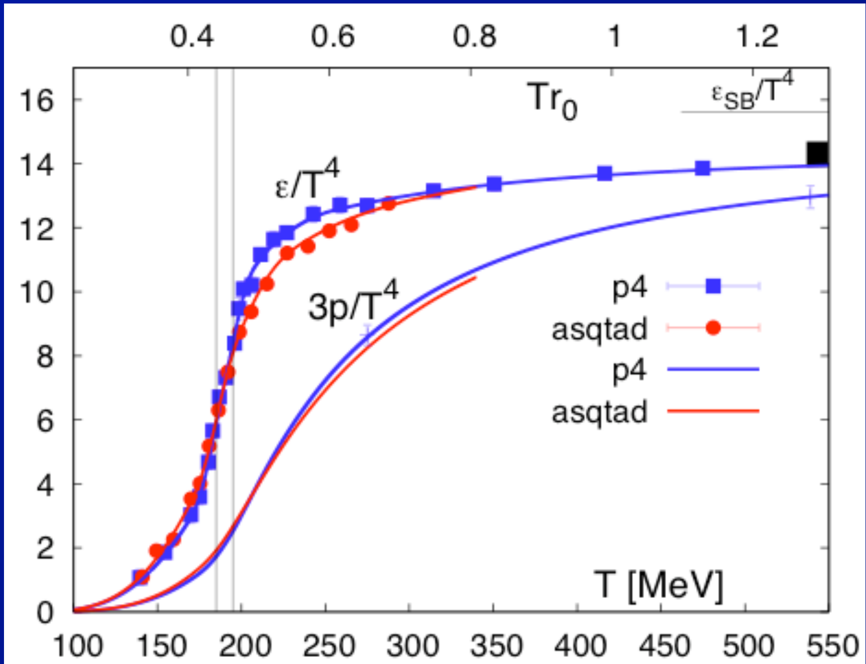
$$L_{QCD} = -\frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu} - \sum_n \bar{\psi}_n \left(\not{\partial} - ig\gamma^\mu A^a_\mu t_a - m_n \right) \psi_n$$

  ⇒Perturbative limit well studied

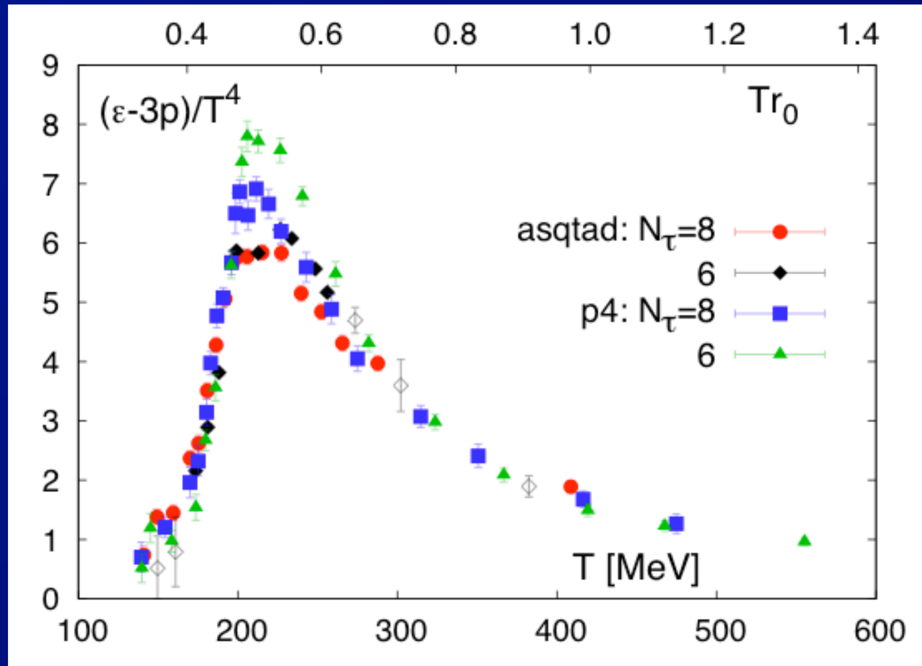
- Nuclear collisions provide a laboratory for studying QCD outside the large Q^2 regime:
  - Deconfined matter (quark gluon plasma)
    ⇒"Emergent" physics not manifest in L_{QCD}
    ⇒ Strong coupling ⇒ AdS/QCD (?)
  - High gluon field strength, saturation
    ⇒ Unitarity in fundamental field theory
- Only non-Abelian FT whose phase transition & multi-particle behavior we can study in lab.

QCD Thermodynamics on Lattice

Energy Density or pressure



Thermodynamic trace anomaly

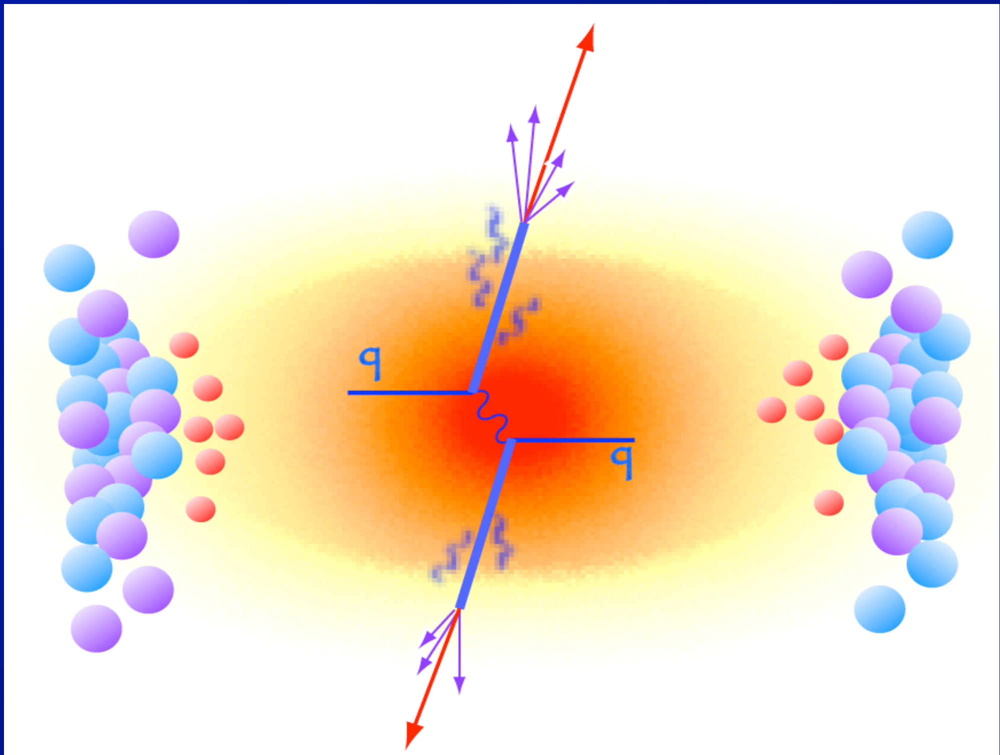


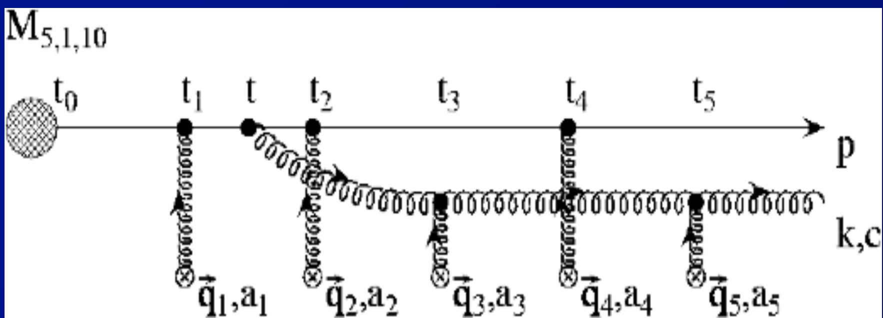
- Lattice thermodynamics from hotQCD group
  - Cross-over transition at ~ 170 MeV

    ⇒ to "quark-gluon plasma"
- Trace anomaly $(\varepsilon-3p)/T^4$ an interaction measure
  - Strong coupling already evident near T_C.

    ⇒ Confirmed experimentally (QGP → sQGP)

Jet Quenching

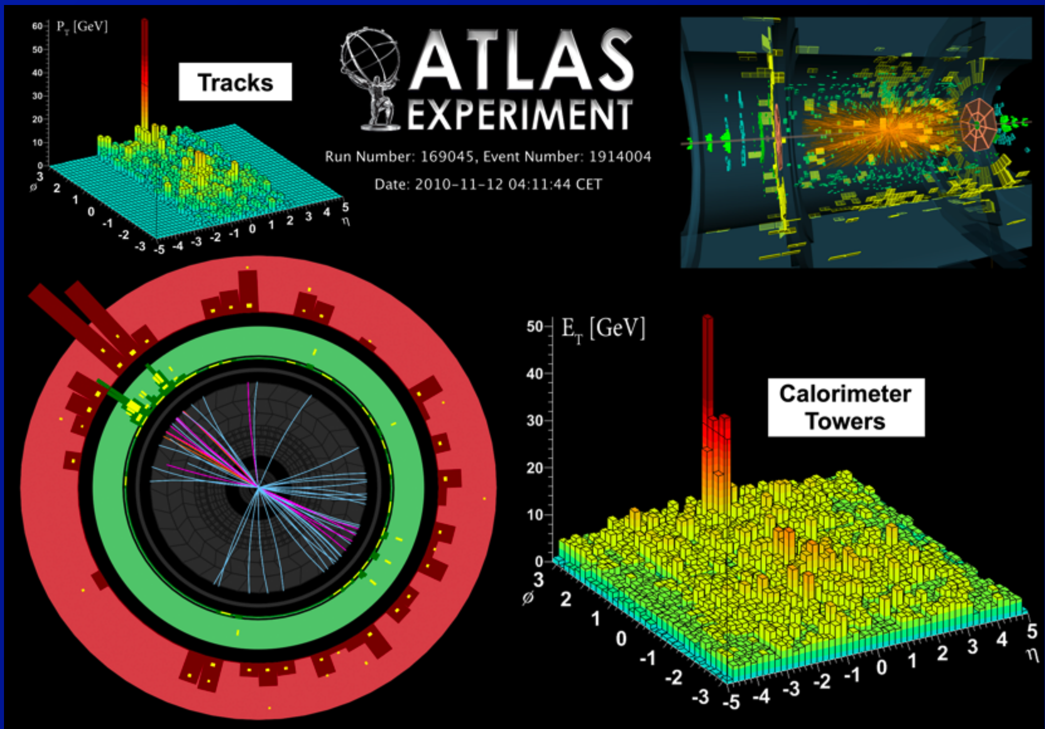


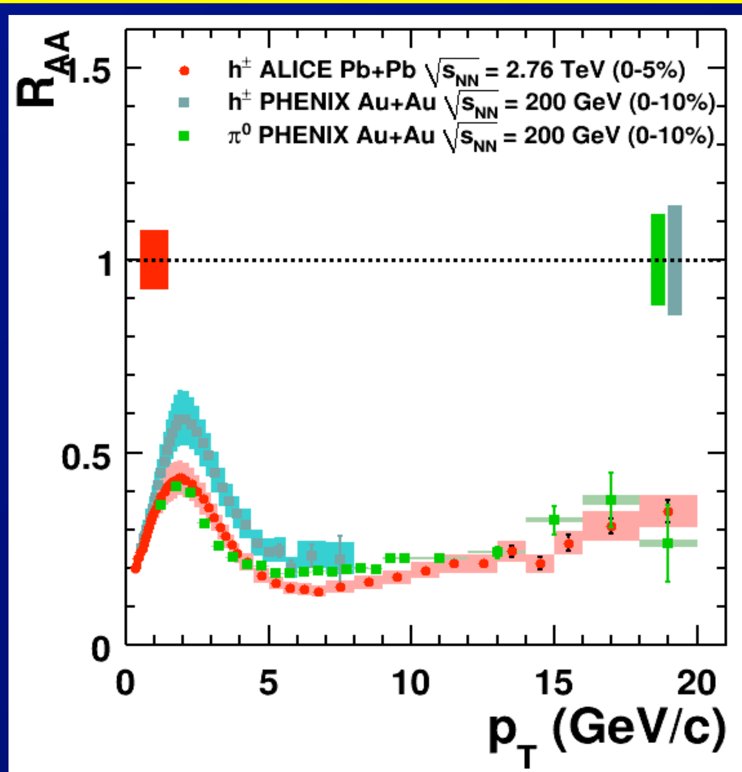


Opacity expansion diagram for medium induced gluon radiation

- Direct measurement of interaction of colored particle(s) with sQGP
- Key questions:
  - How do parton showers in sQGP differ from those in vacuum?
  - Do partons in the shower have weakly or strongly coupled interactions with the sQGP?

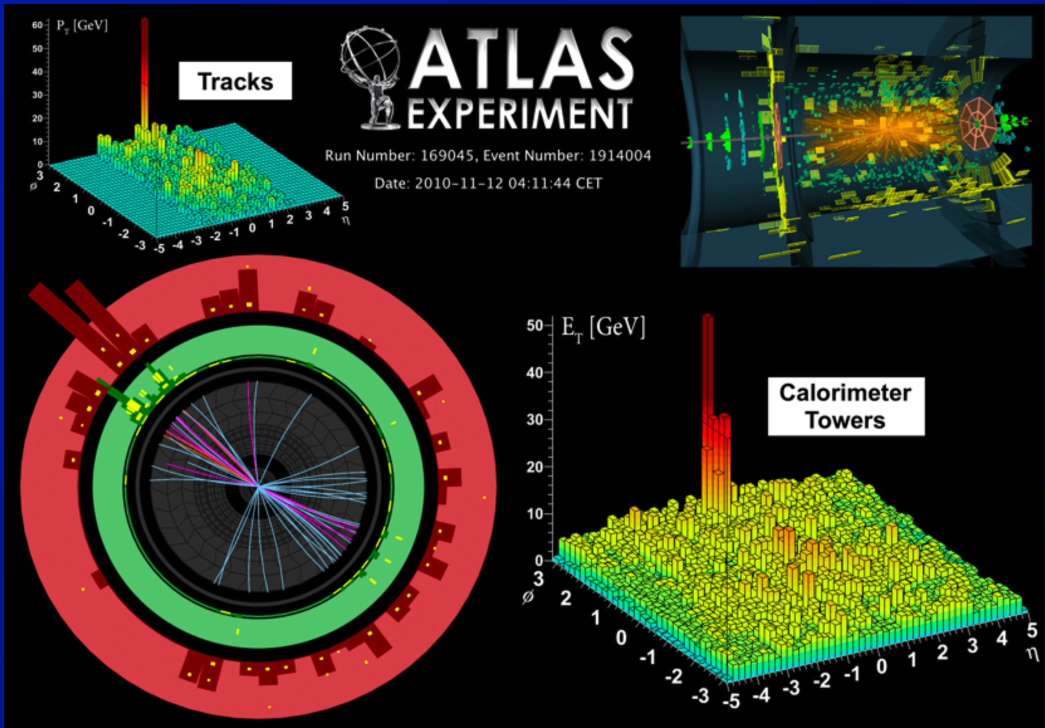
High pT @ RHIC in LHC era

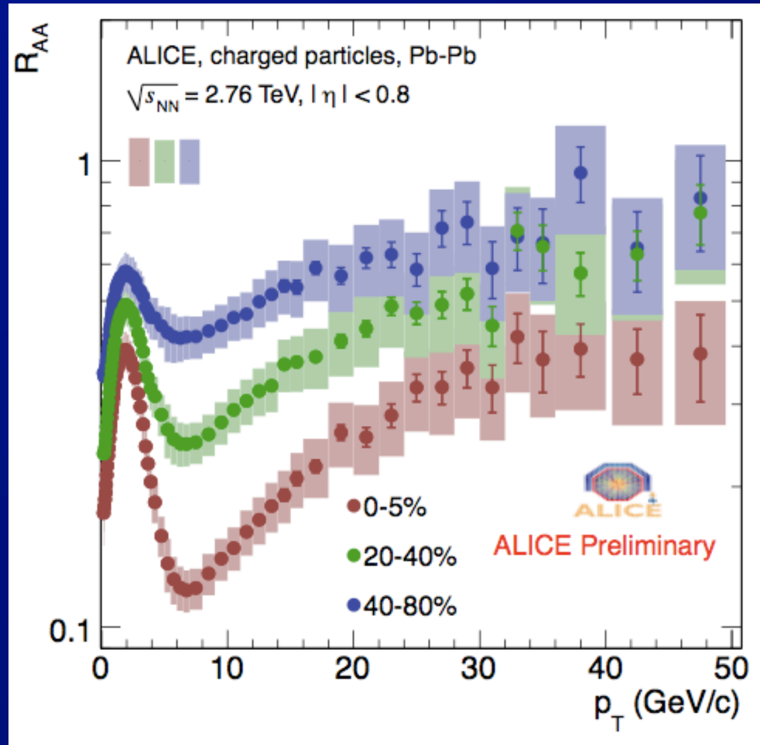




- The start of the Pb+Pb jet/high-pT program @ LHC has dramatically altered the landscape of RHIC high-pT physics program
  - Demonstrates importance of full jet measurements
  - Answers some important open questions
  - Emphasizes need to focus on decisive measurements

High p_T @ RHIC in LHC era





- The start of the Pb+Pb jet/high-p_T program @ LHC has dramatically altered the landscape of RHIC high-p_T physics program
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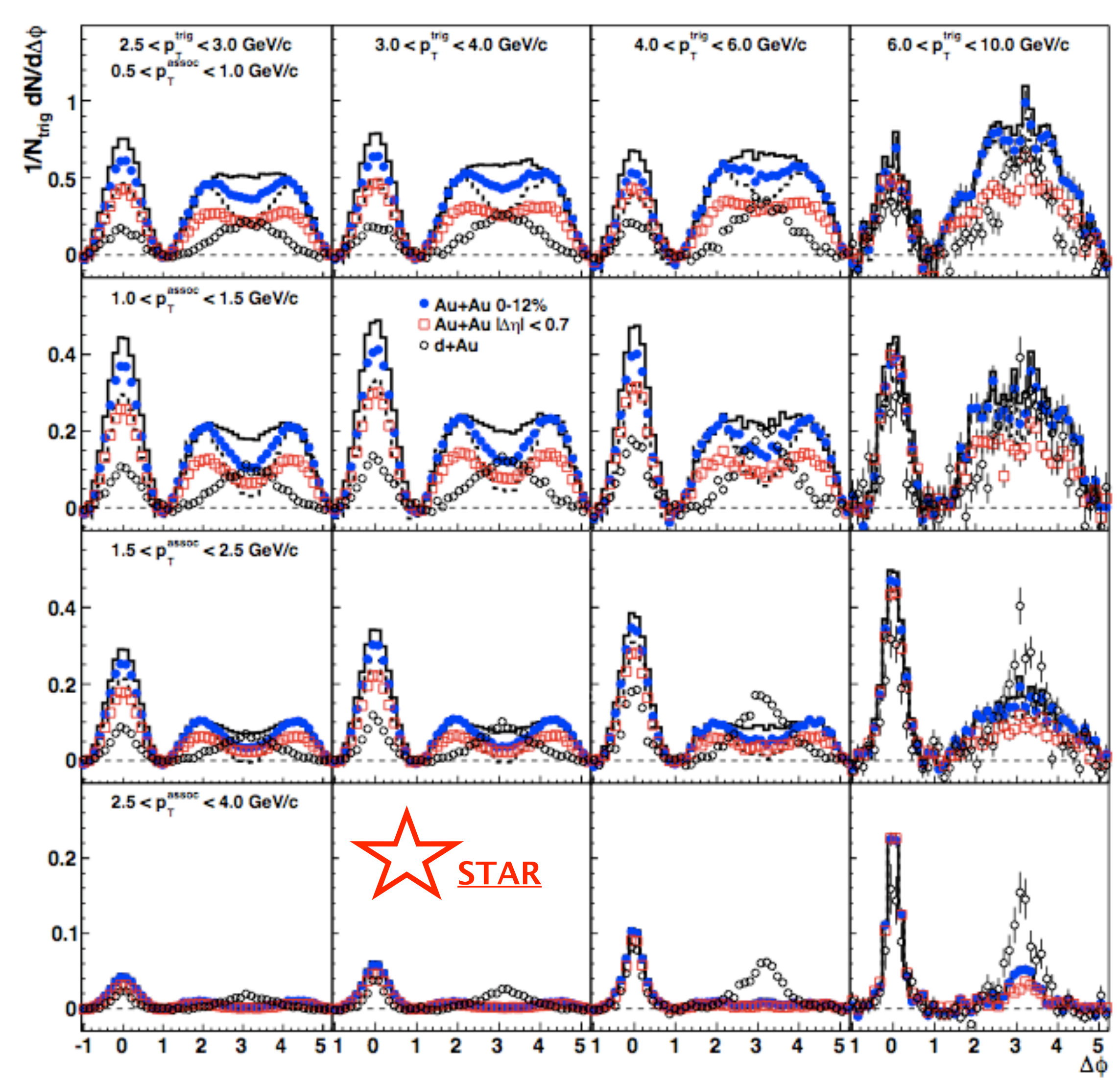
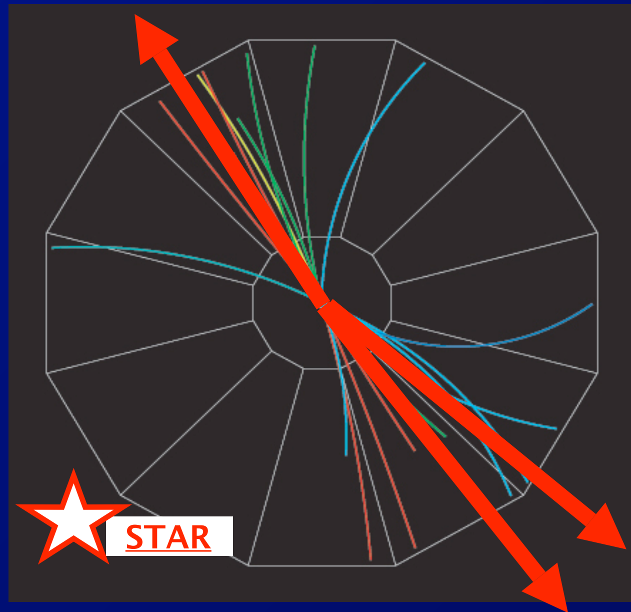
Signs of progress ...



Indirect dijet measurement via dihadron correlations

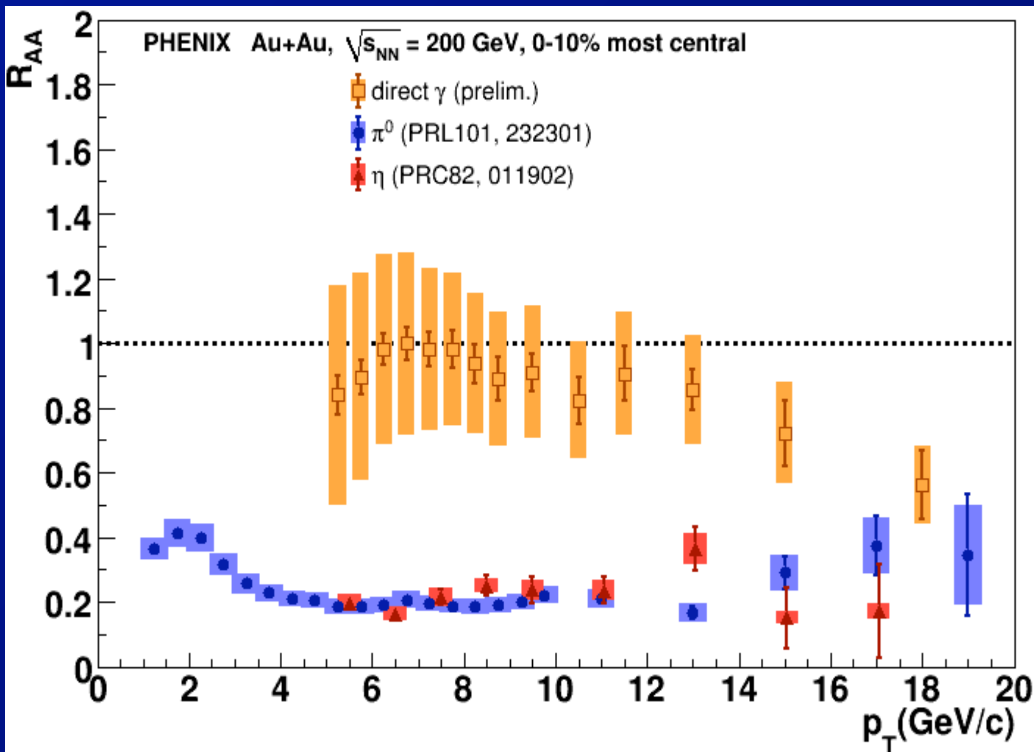


STAR, Phys. Rev. C82 (2010) 024912

- 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

Single hadron suppression

- In absence of nuclear modifications
  - $dN^{\mathrm{A-A}} = T_{\mathrm{AA}}\ d\sigma^{p-p}$
  - T_{AA} is analogous to a per- bunch crossing (integrated) luminosity @ LHC
- Define $R_{AA} = \frac{1}{T_{\mathrm{AA}}} \frac{dN^{\mathrm{A-A}}}{d\sigma^{p-p}}$
  - Characterizes initial & final state modifications



Single hadron suppression

- In absence of nuclear modifications
  - $dN^{\mathrm{A-A}} = T_{\mathrm{AA}}\, d\sigma^{p-p}$
  - T_{AA} is purely geometric factor analogous to a per-bunch crossing (integrated) luminosity @ LHC
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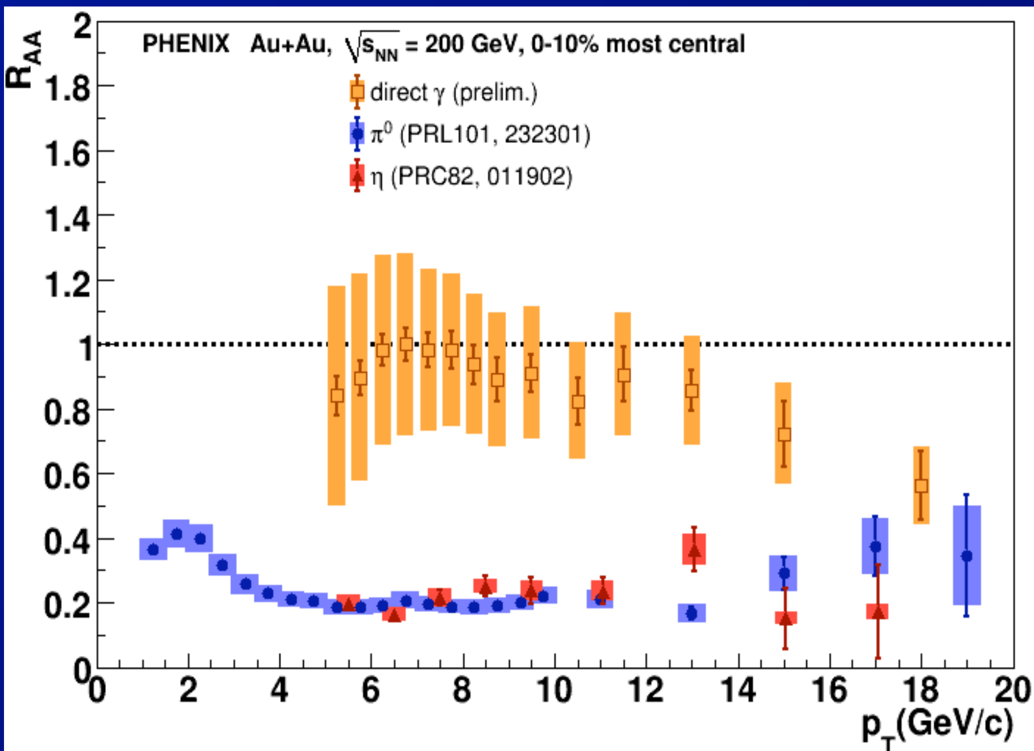
  - Characterizes initial & final state modifications



Single π^0 and η suppression but no photon suppression:

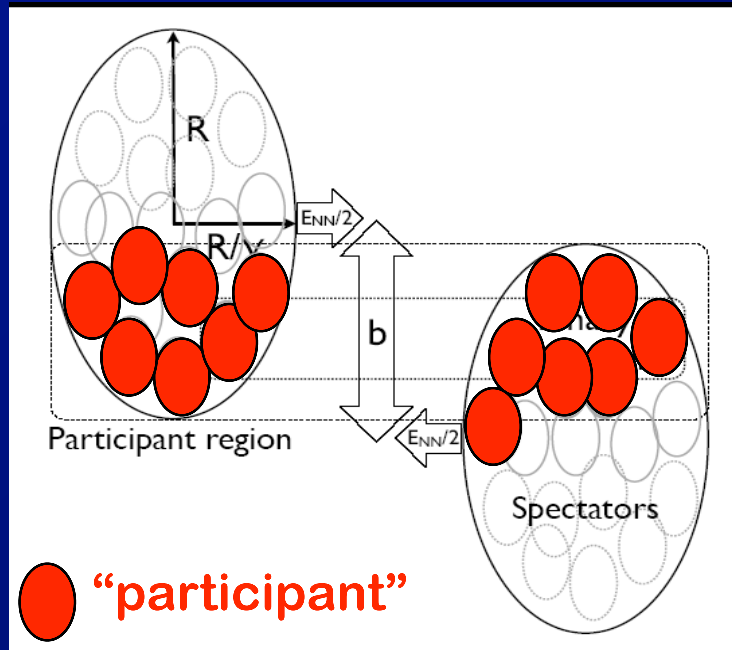
Requires large unscreened color charge density

GLV: dN_g/dy > 1000 (±?)

$\varepsilon \geq 10$ (±?) GeV/fm^3

Single hadron suppression

- But, modification depends on nuclear geometry
  - Characterized by "number of participants", N_{part}
- With increasing N_{part}:
  - higher temperatures
  - Longer path lengths



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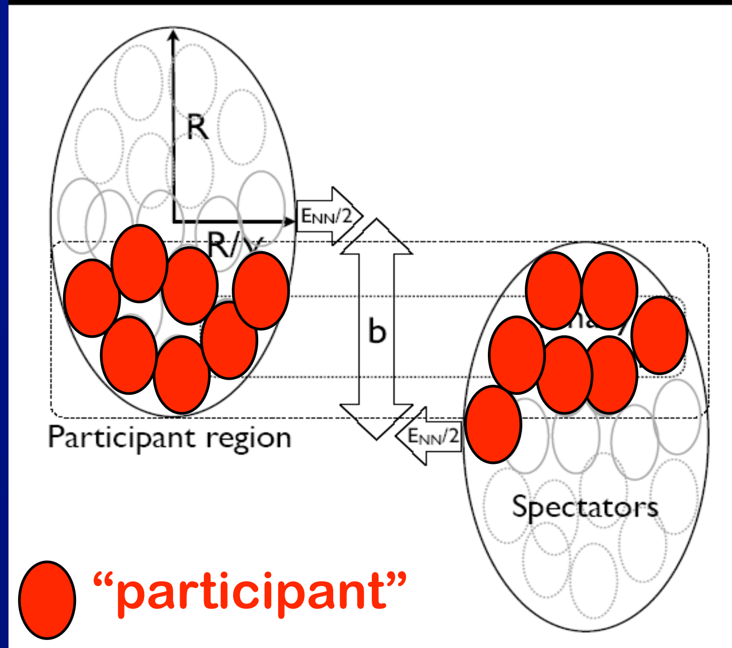
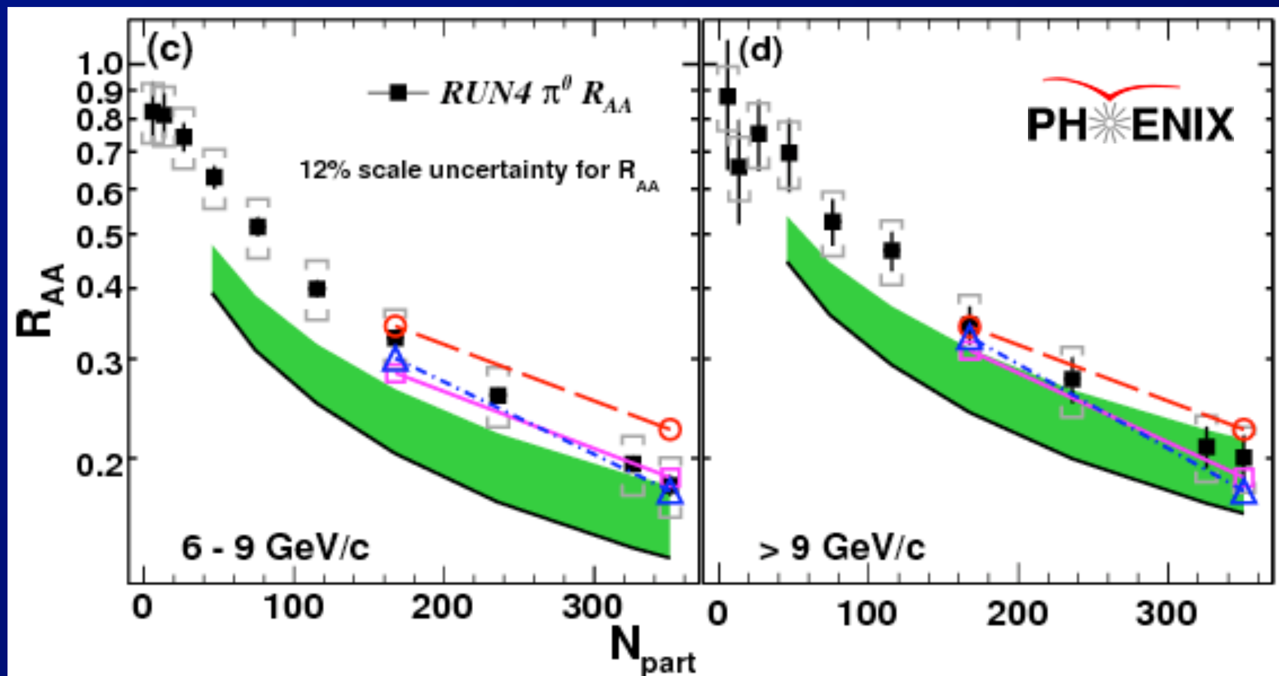


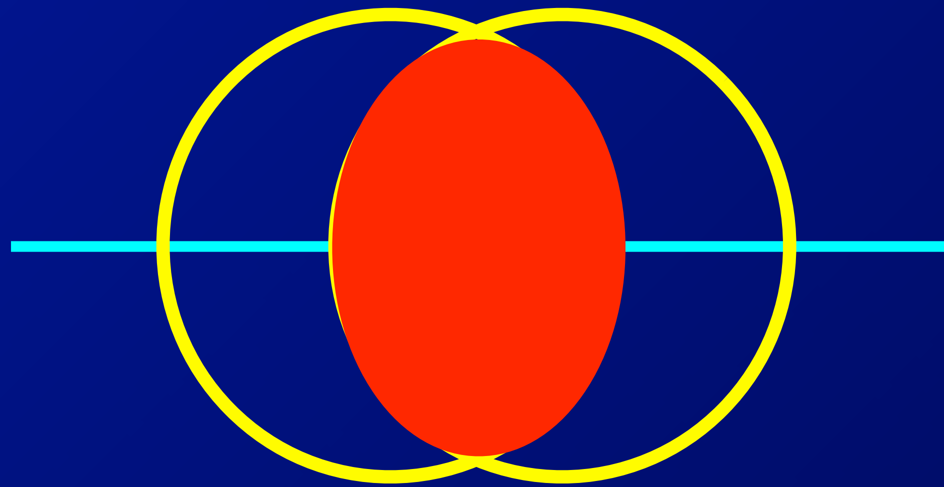
PHENIX Collaboration
Phys. Rev. Lett. 105 (2010) 142301

Theory calculations referenced on slide 16



Single hadron suppression

- How to disentangle two contributions?
  - Use spatial asymmetry of medium @ non-zero impact parameter



Single hadron suppression

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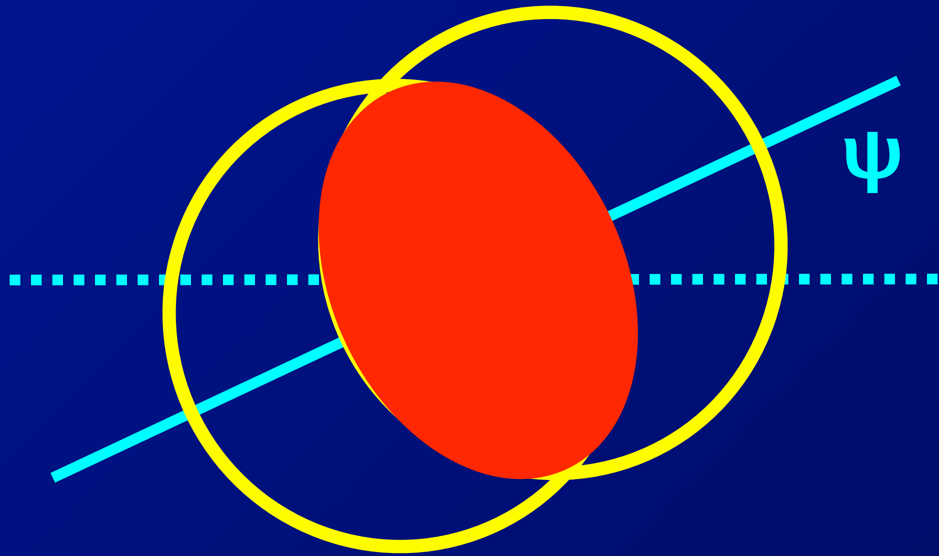
  - Measure orientation (ψ) event-by event



Single hadron suppression

- How to disentangle two contributions?
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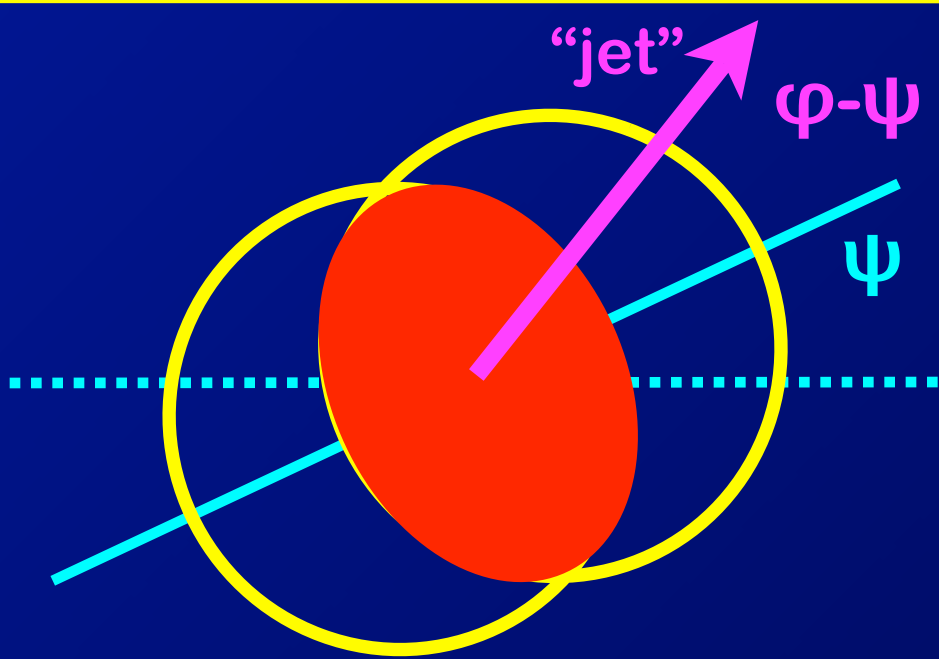
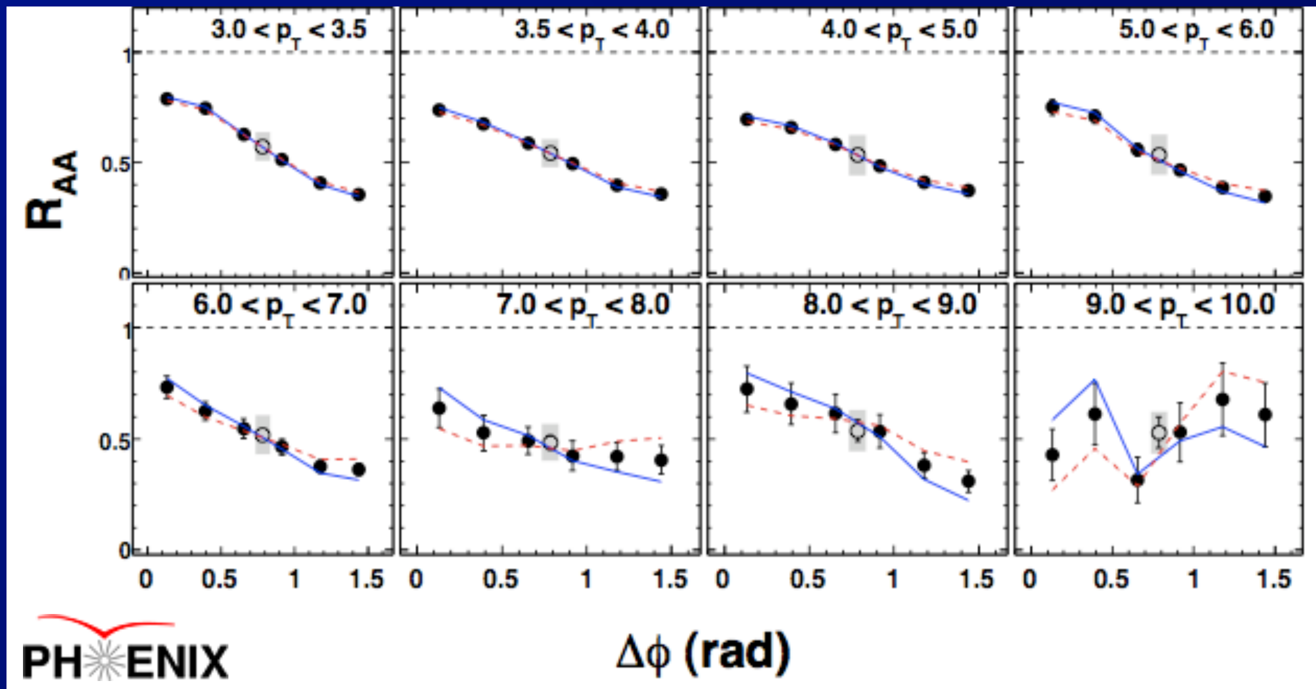
  - Measure orientation (ψ) event-by event
- Measure R_{AA} vs $\Delta\varphi = \varphi - \psi$





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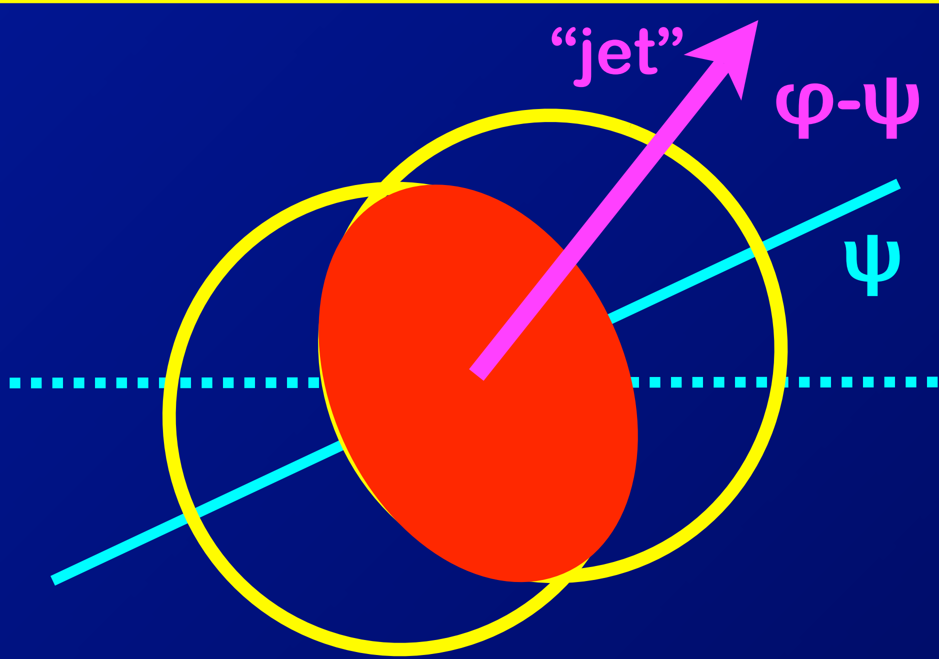

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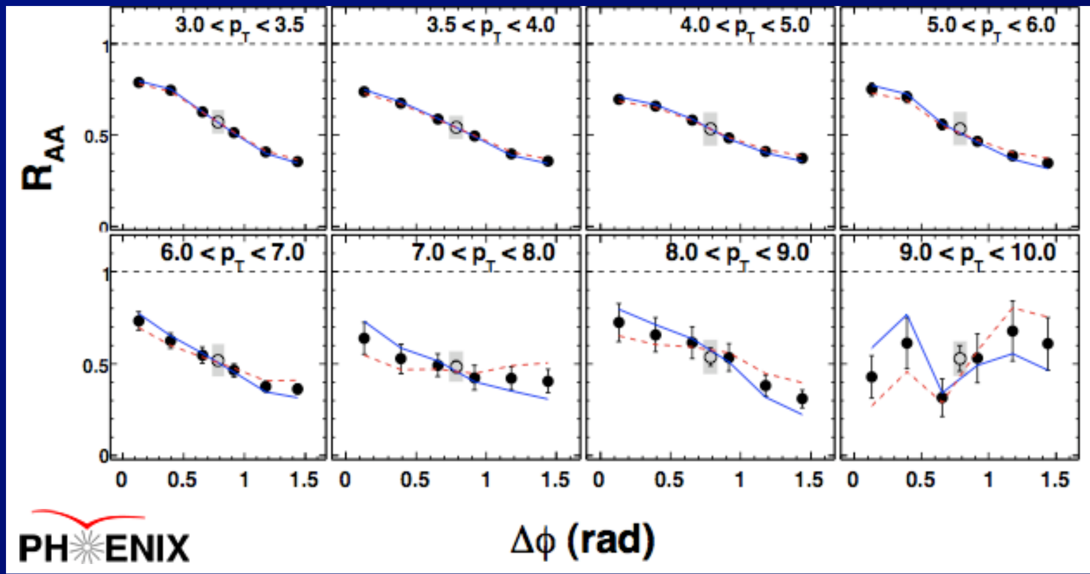
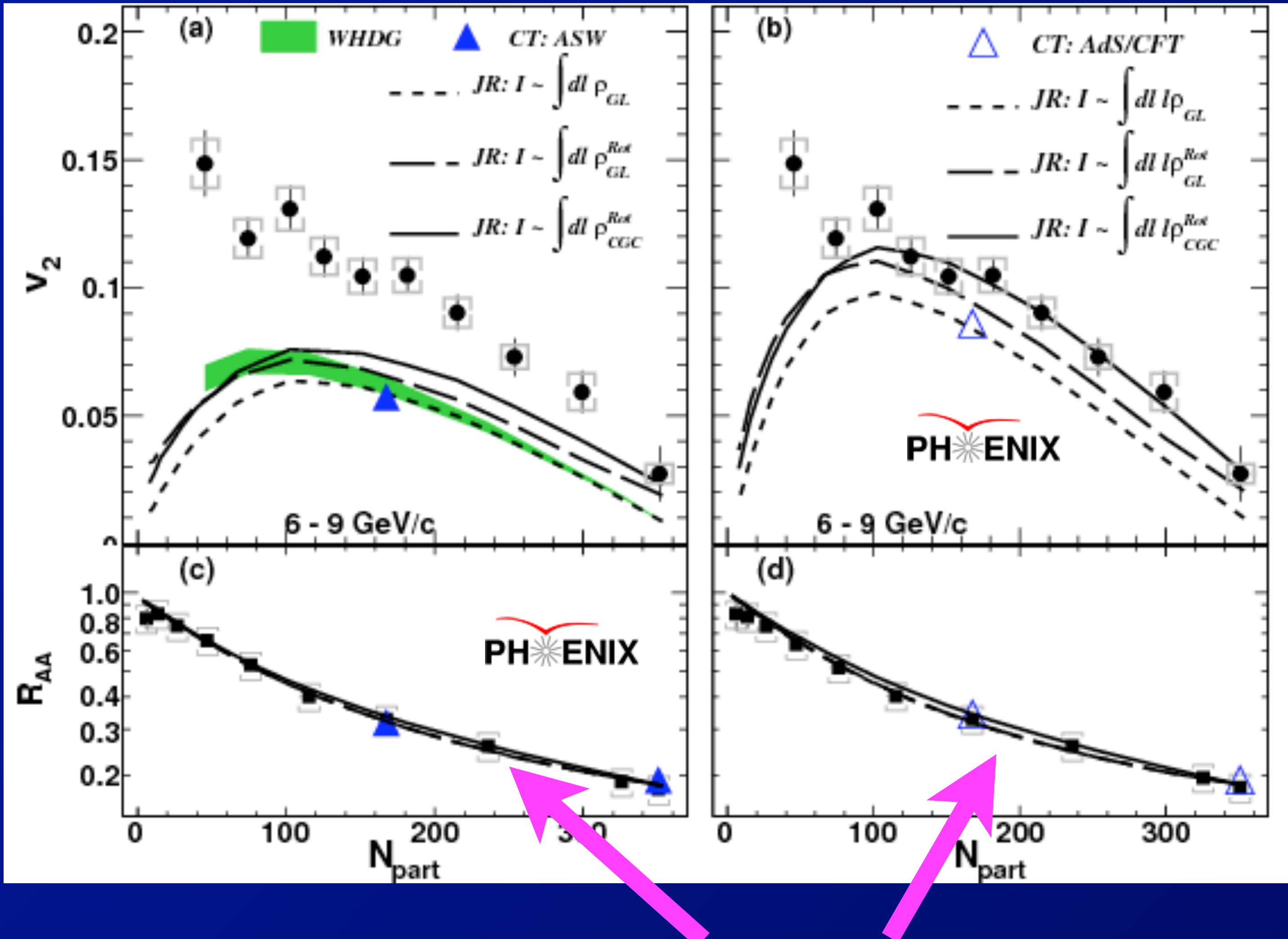


- Characterize by amplitude of Δφ modulation:

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

Single hadron suppression

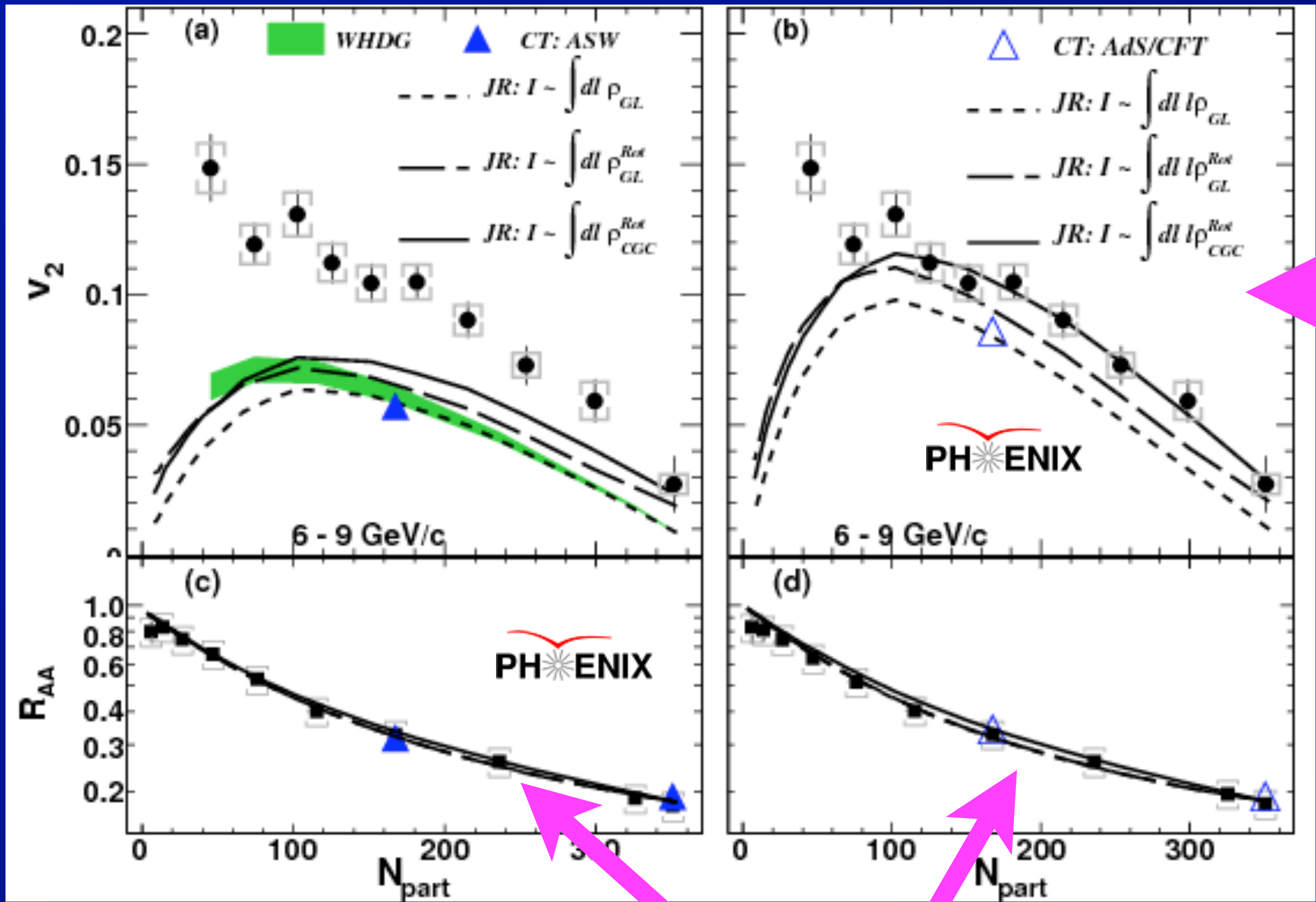


Calculations:

- 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 v_2 (modulation vs $\Delta\varphi$) prefers strong coupling

Single hadron suppression



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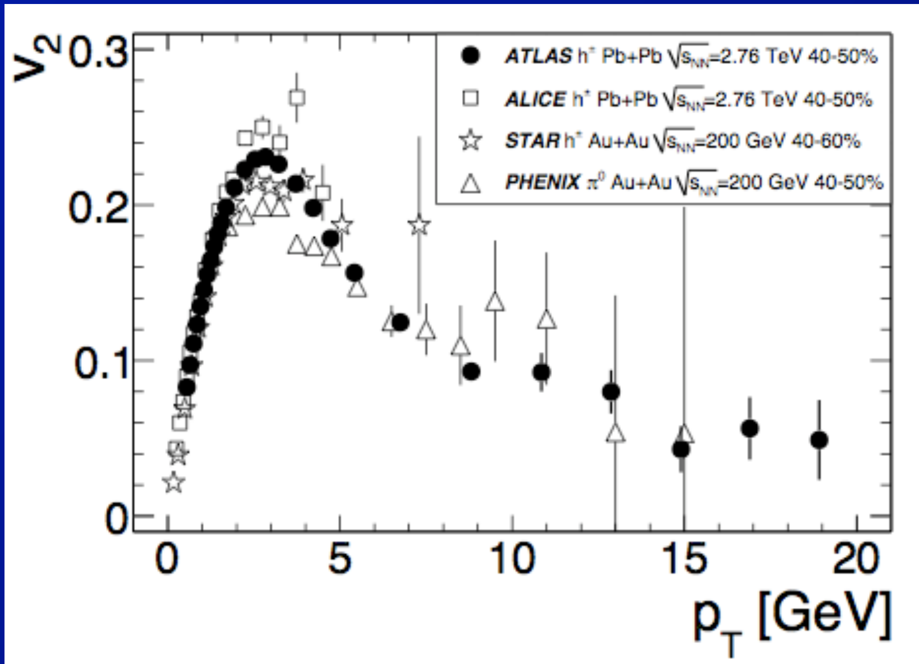
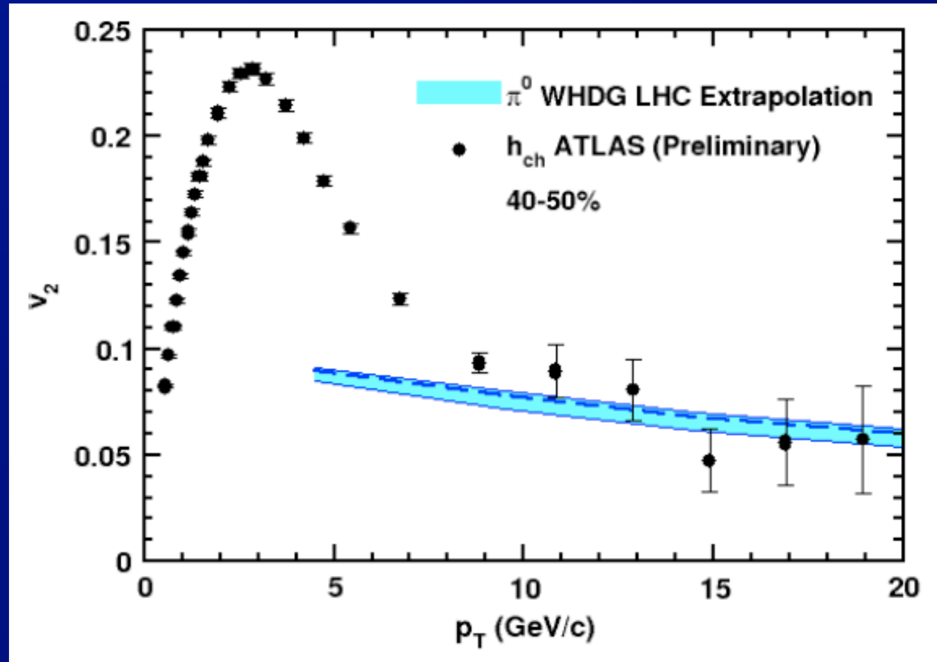
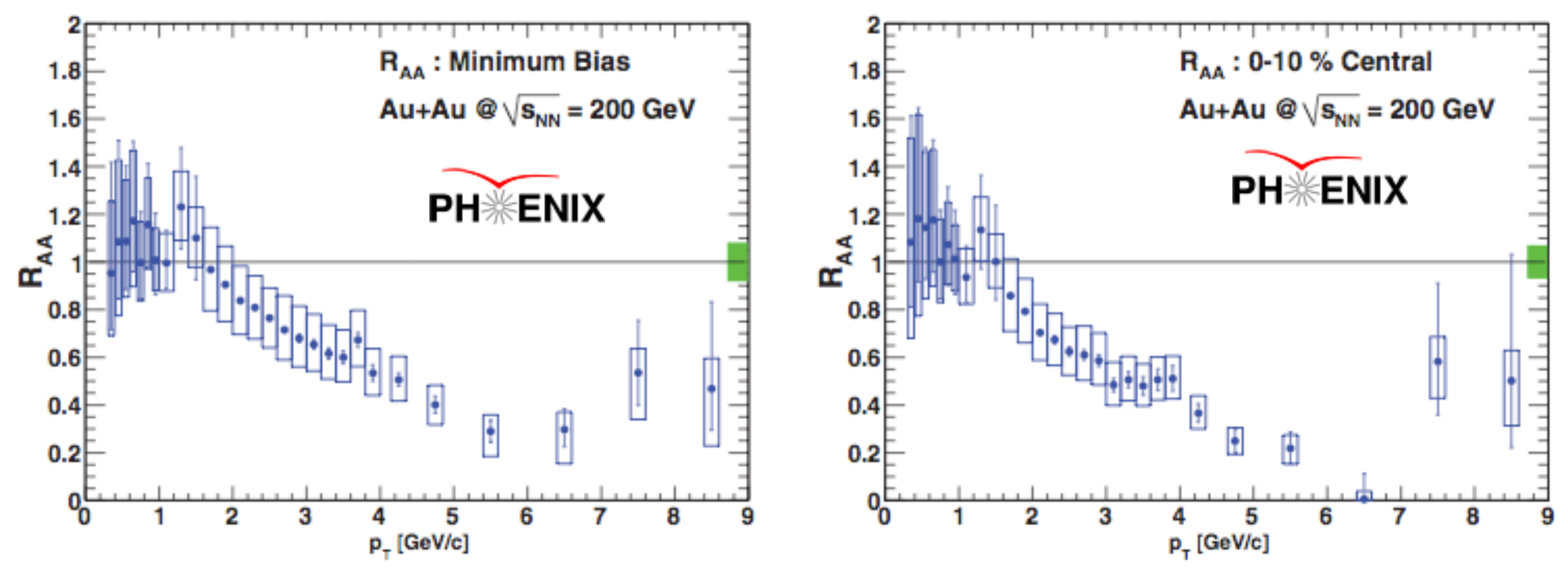
ATLAS: Charged particle $v_2(p_T)$





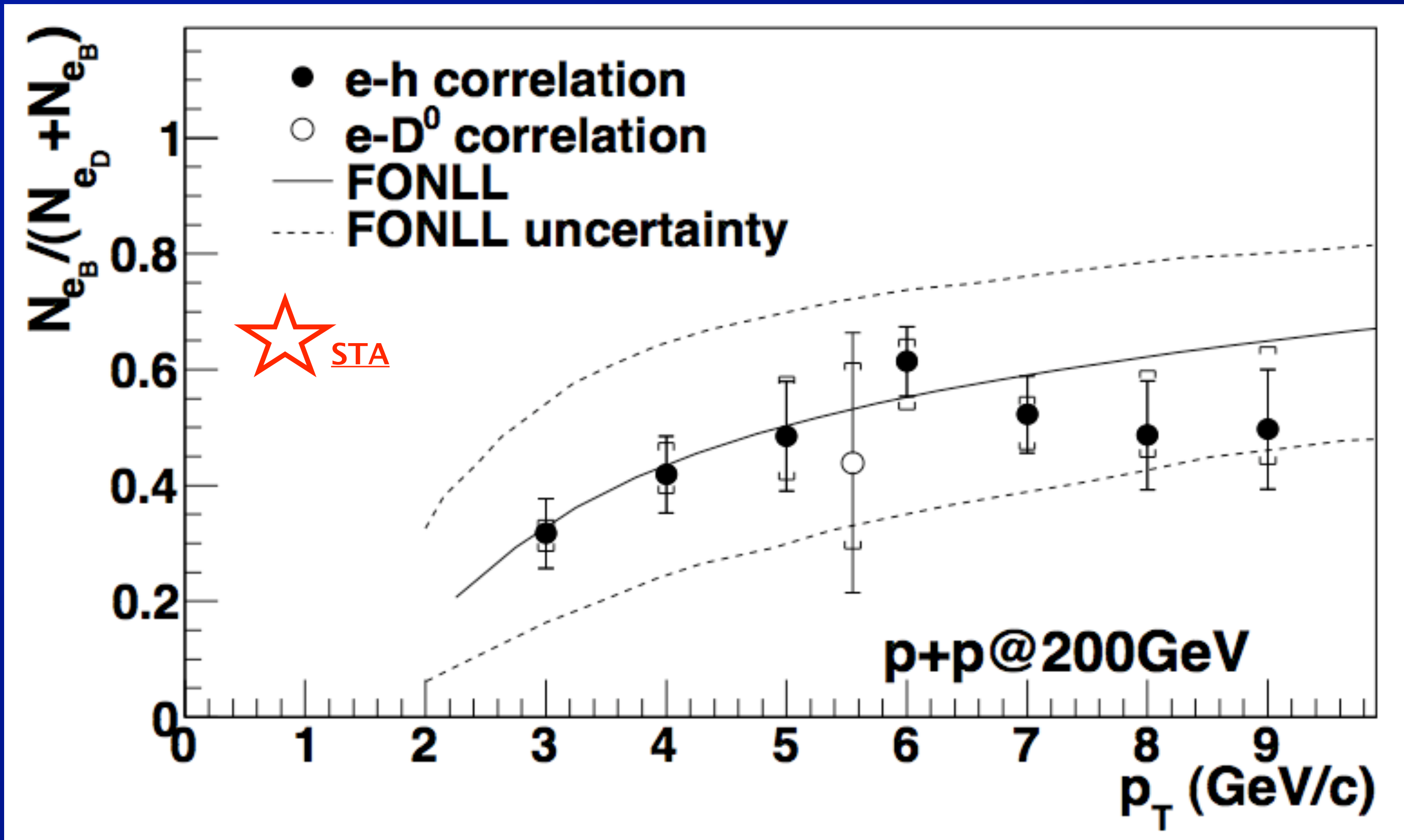
- **Surprising agreement between RHIC and LHC $v_2(p_T)$, but beware "apples and oranges"**
  - Charged (ATLAS, STAR), π^0 (PHENIX)
- **Weak coupling energy loss OK for $p_T > 10$?!**
  - ⇒Do we understand geometry of quenching?
  - ⇒Or is PHENIX measurement contaminated by underlying event modulation?

Heavy quark suppression



- Measure heavy quark production via semi-leptonic decays (B+D) to electrons
  - See suppression comparable to light mesons
    - ⇒Unexpected due to mass suppression of radiative contributions, especially for b quark.
- More evidence for strong coupling?
    - ⇒ Not clear.

Heavy quark: b contribution

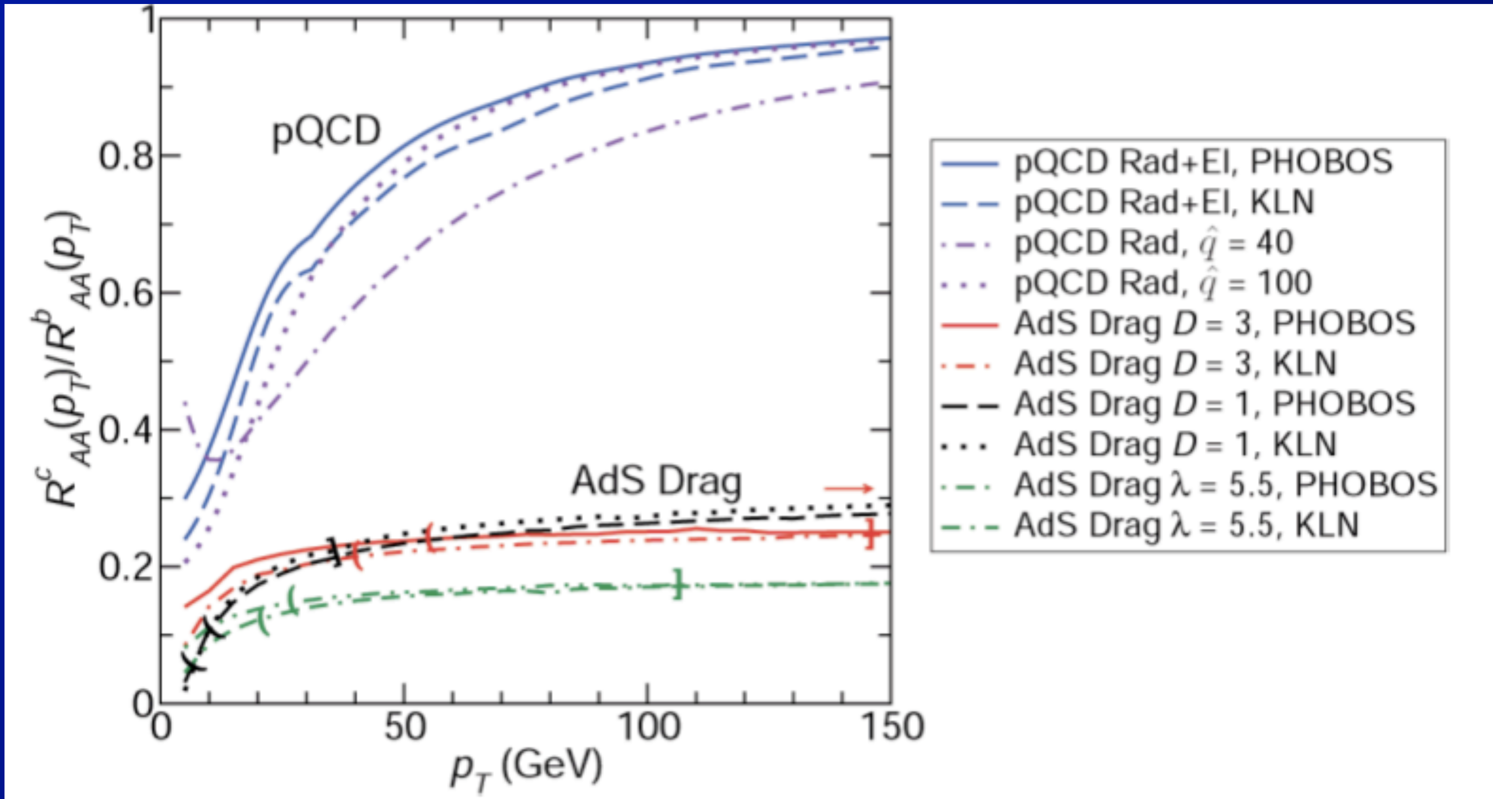


STAR, PRL 105 (2010) 202301

- (Unquenched) b contribution to electron spectrum consistent with pQCD
  - heavy quark suppression results cannot be “explained” by small b contribution

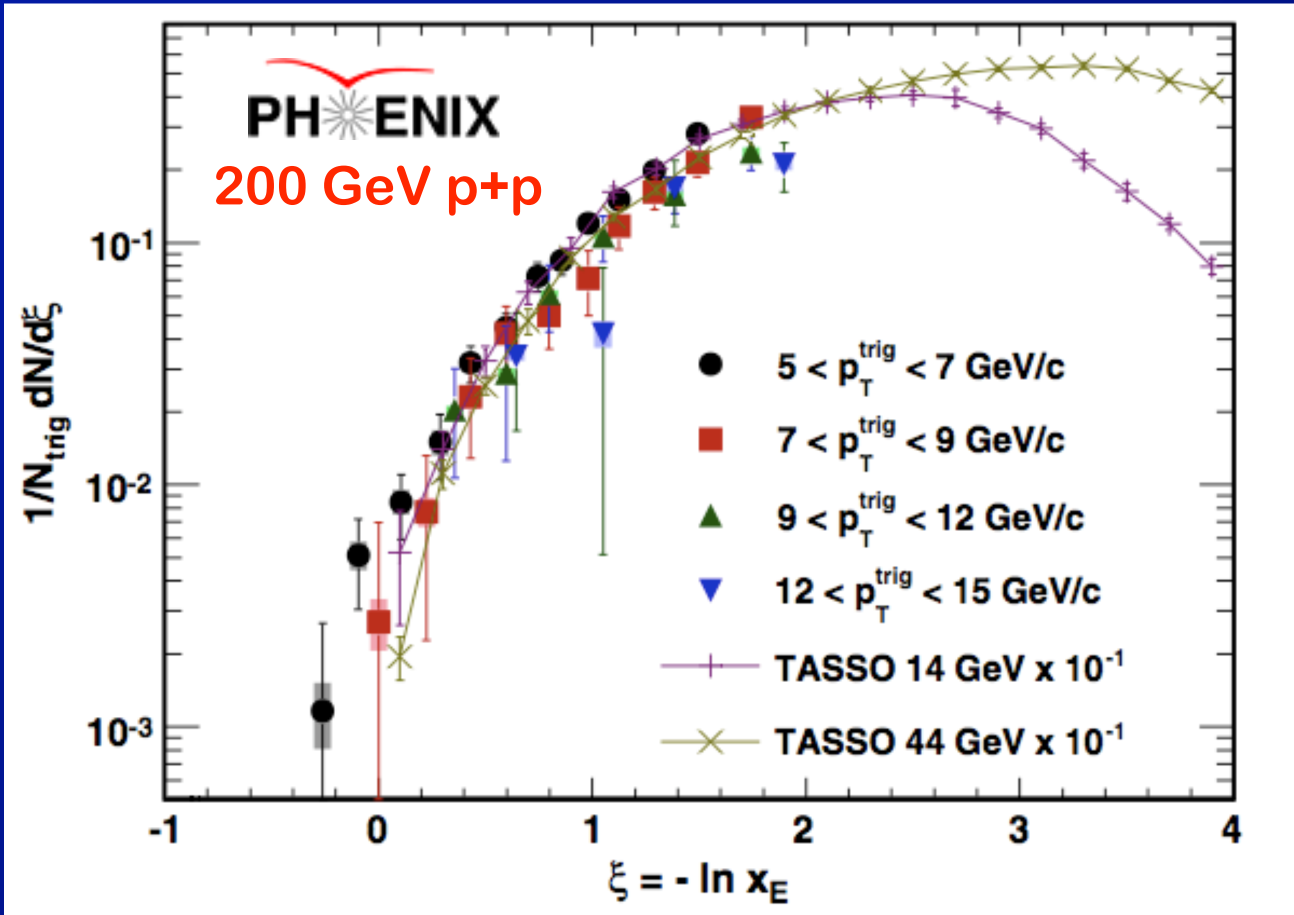
Heavy Q quenching: pQCD vs AdS/CFT

Gyulassy and Horowitz, J. Phys. G G35 (2008) 104152

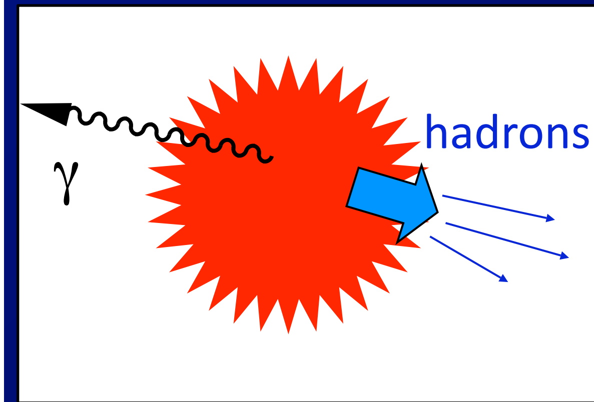


- Use c&b together to test strong/weak coupling.
- Motivation to push heavy quark measurements at RHIC to higher p_T & separate b, c.
  - Goal of silicon detector upgrades for both PHENIX (underway) and STAR (starting)

First step towards jets: γ-hadron



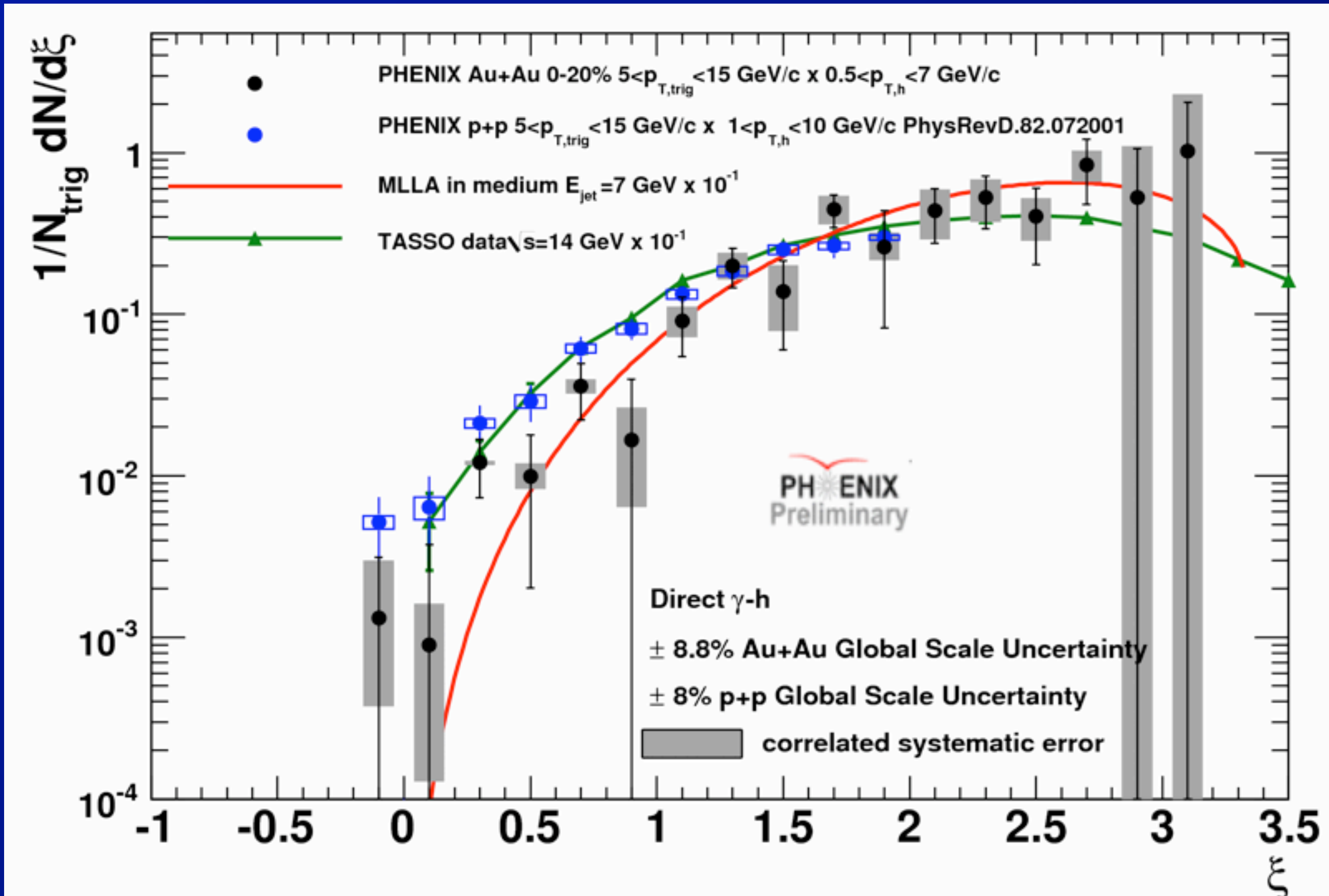
PHENIX,
Phys. Rev. D82
(2010) 072001



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

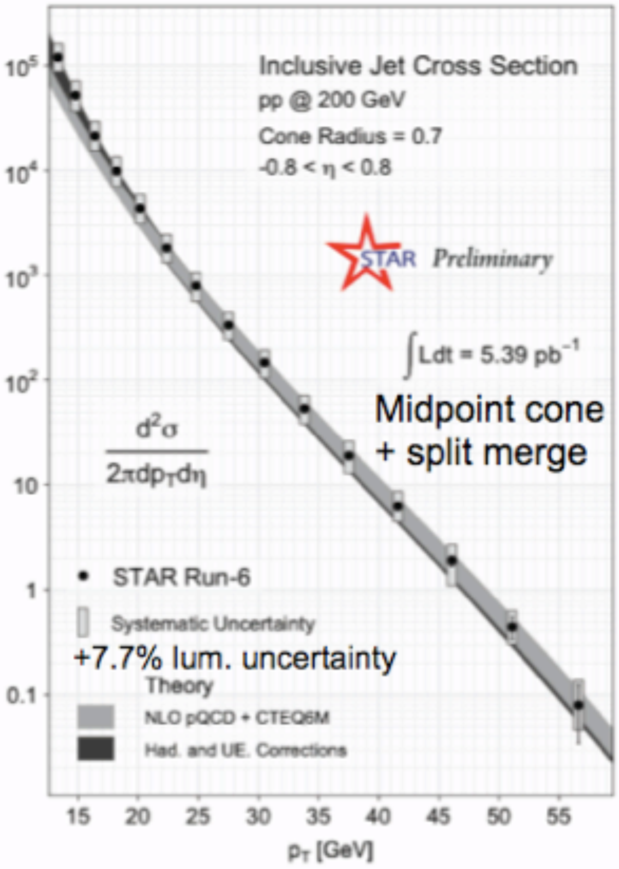
- Measure jet fragmentation using γ-jet events but measuring “jet” via single hadrons
  - Compare to measurements from TASSO
    - ⇒Good agreement

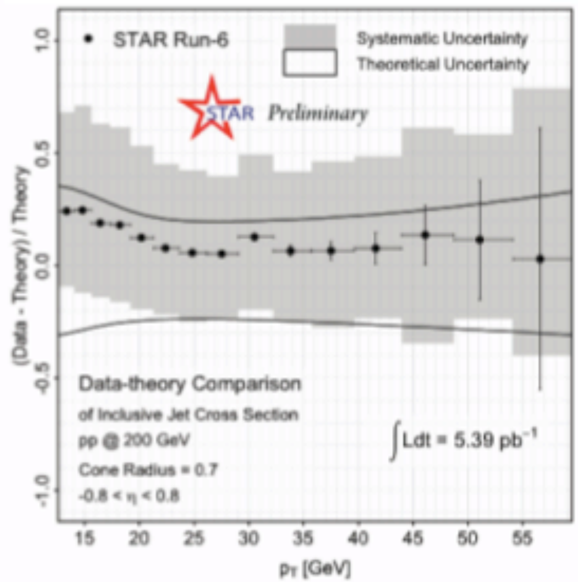
First step towards jets: γ-hadron (2)

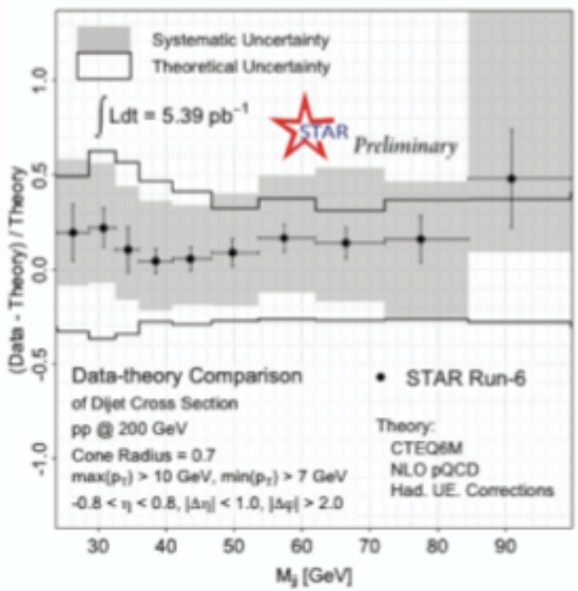


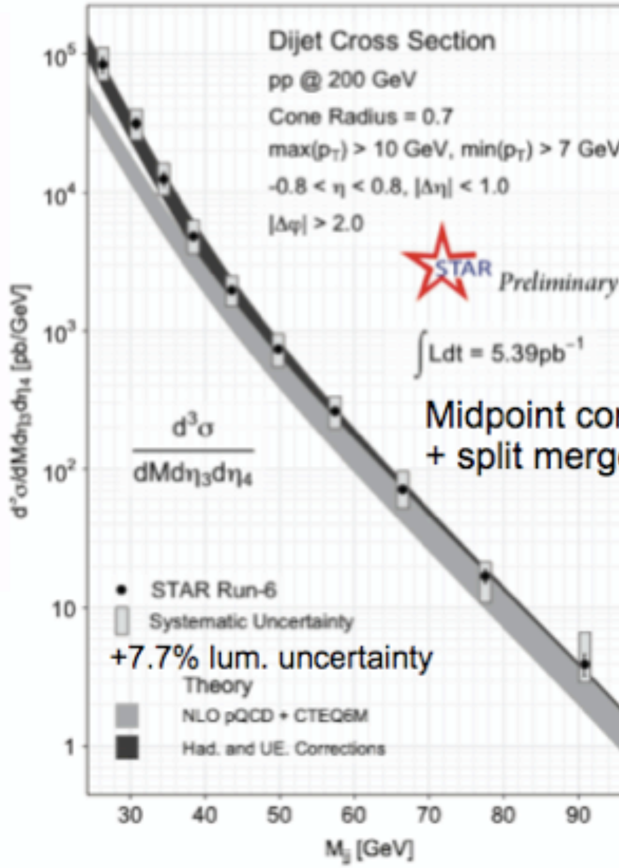
- Observe suppression in yield of large z (small ξ) fragments in (central) Au+Au collisions
  - Red curve shows medium-modified MLLA calculations by Borghini and Wiedemann.

p-p jet measurements: STAR







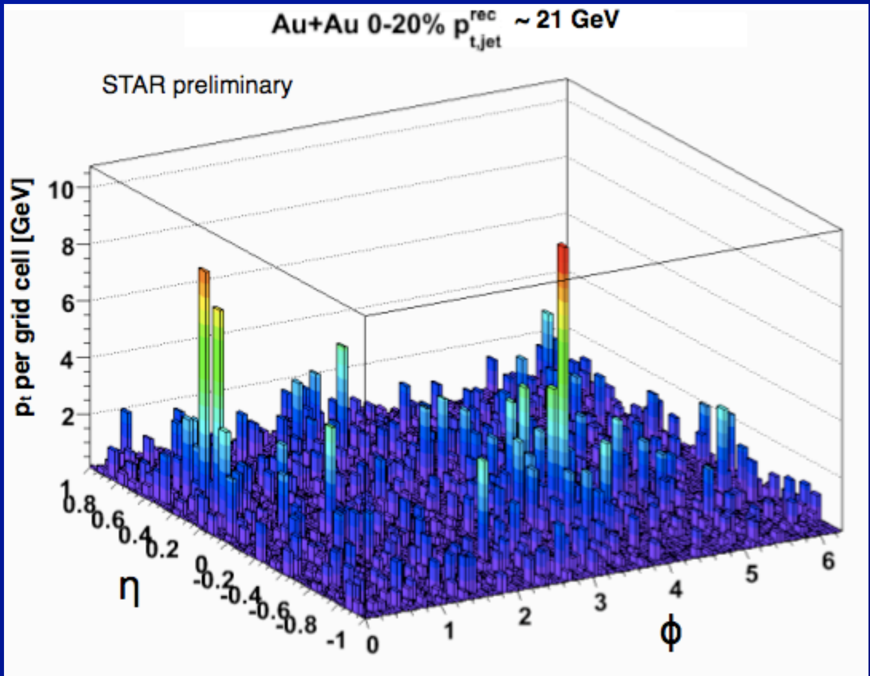


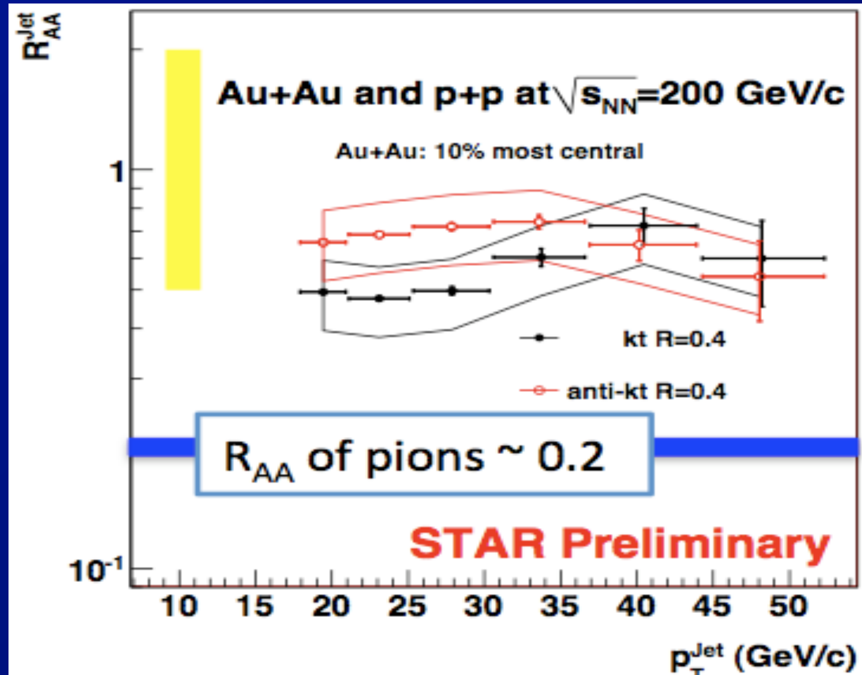
Hadronization and UE correction applied to theory

Jet and di-jet cross-section well described by NLO

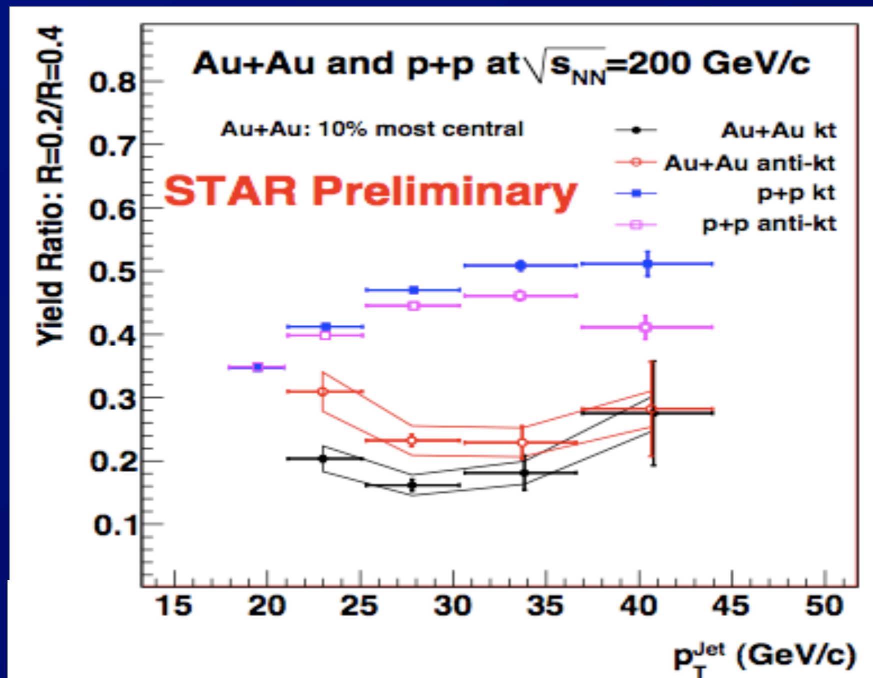
- From H. Caines Quark Matter 2011 plenary talk.

Au+Au jet measurements: STAR



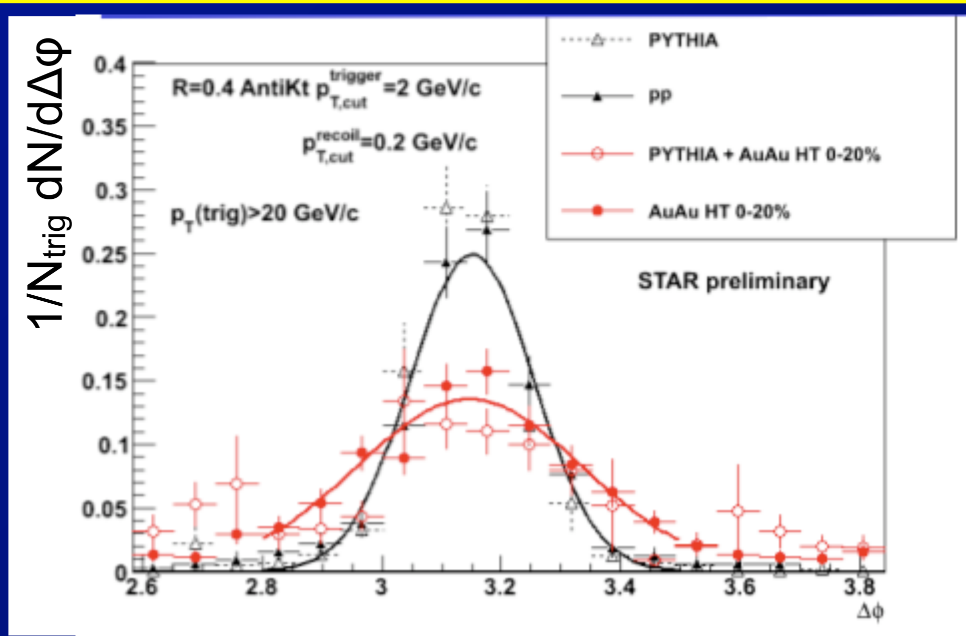


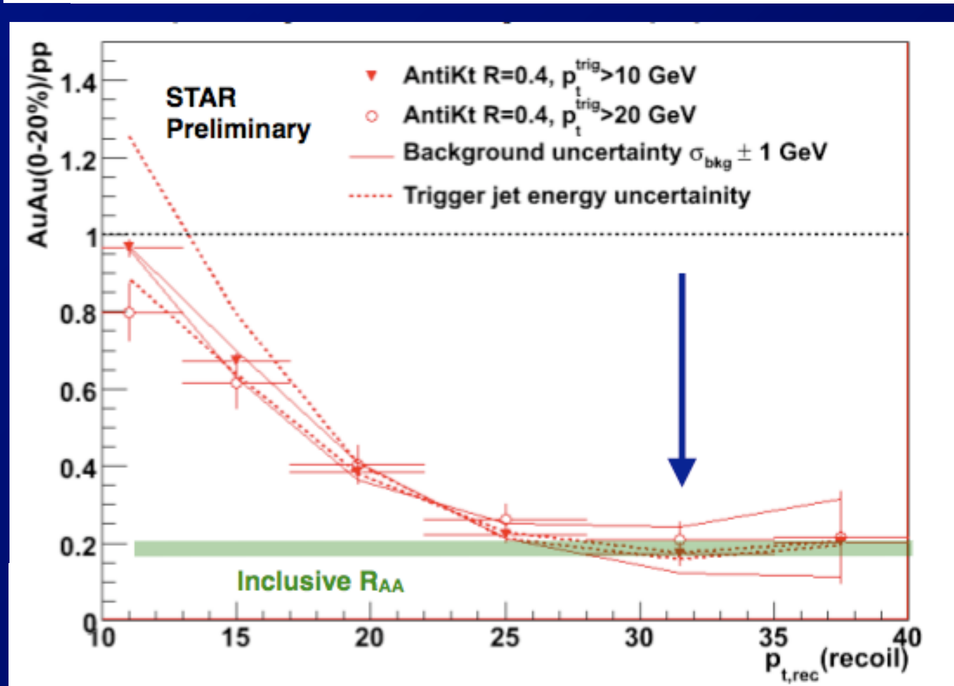
- STAR central Au+Au R_{AA} ~ 0.4
  - but consistent with 1 within syst. errors
- Ratio of R = 0.2, 0.4 yields differs between p-p, Au+Au. Physics?



Au+Au jet measurements: STAR

- No broadening of di-jet Δφ distribution
  - After accounting for broadening due to Au+Au underlying event
- Di-jet yield obtained using high-tower trigger shows x5 reduced rate
  - Evaluation of UE effects on this measurement not yet available





PHENIX jet measurements, p-p, Cu-Cu

- Filter Jet: seedless, infrared and collinearly safe algorithm with angular weighting (Lai and Cole arXiv:0806:1499)
- Calculate

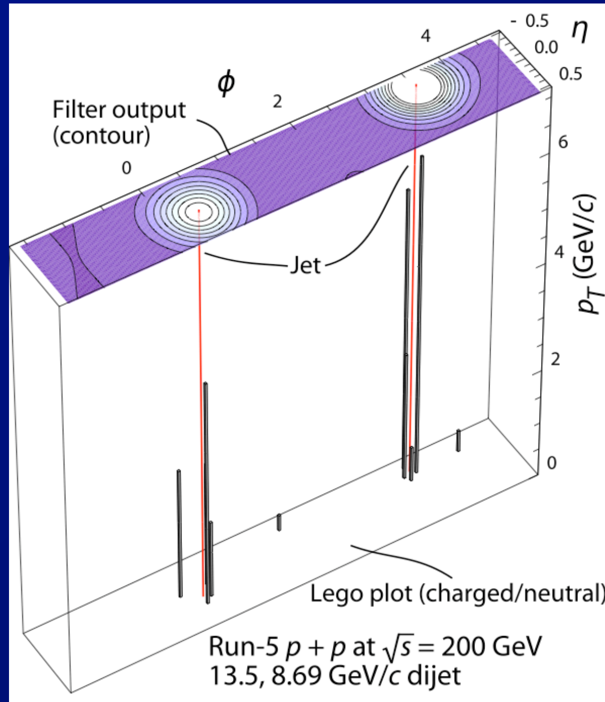
$$\tilde{p}_T(\eta,\phi) = \iint d\eta'\, d\phi'\, p_T(\eta,\phi)\, h(\eta,\phi,\eta',\phi')$$

where

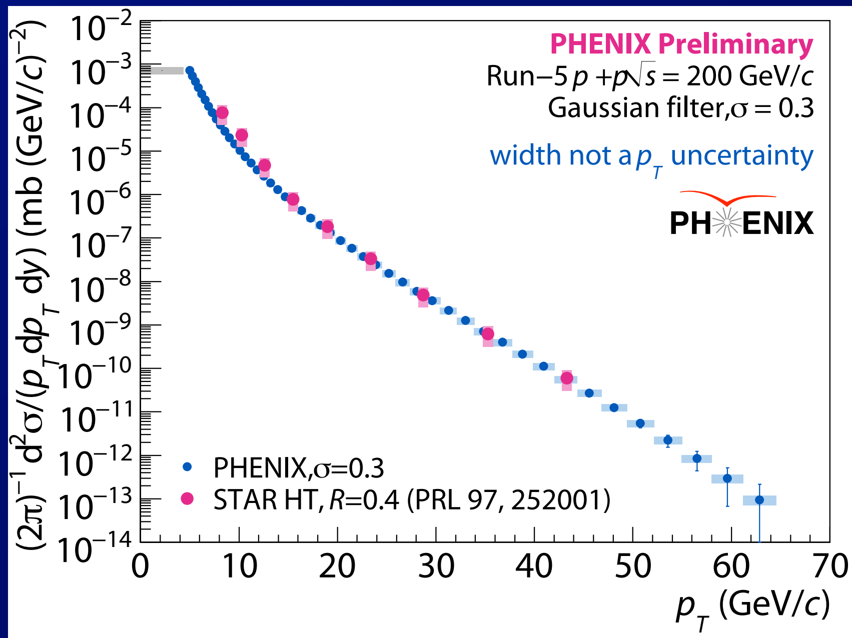
$$p_T(\eta,\phi) = \sum_{i \in \text{particles}} p_{T,i}(\eta,\phi)$$

and

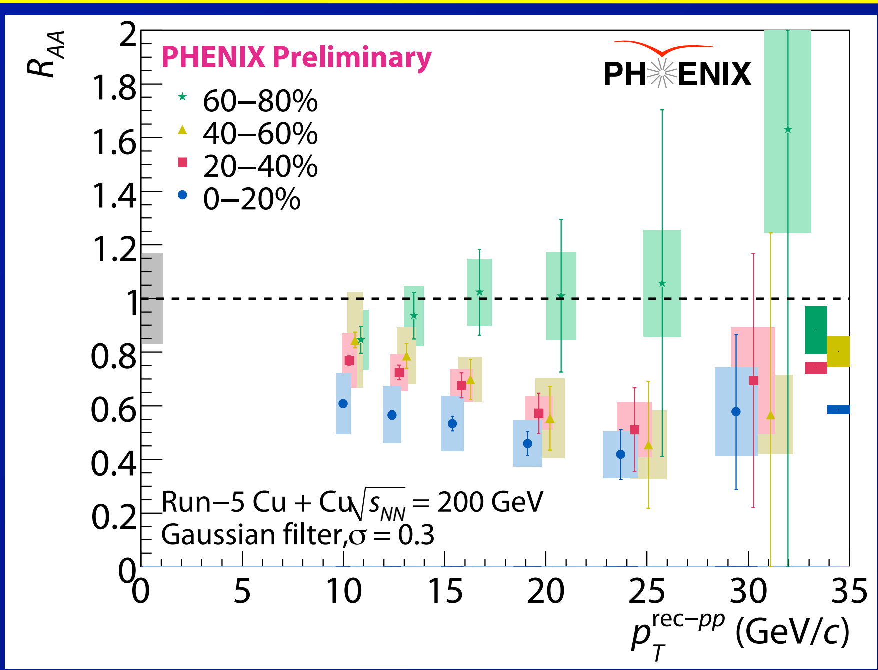
$$h(\eta,\phi,\eta',\phi') = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(\eta-\eta')^2 + (\phi-\phi')^2}{2\sigma^2}\right]$$



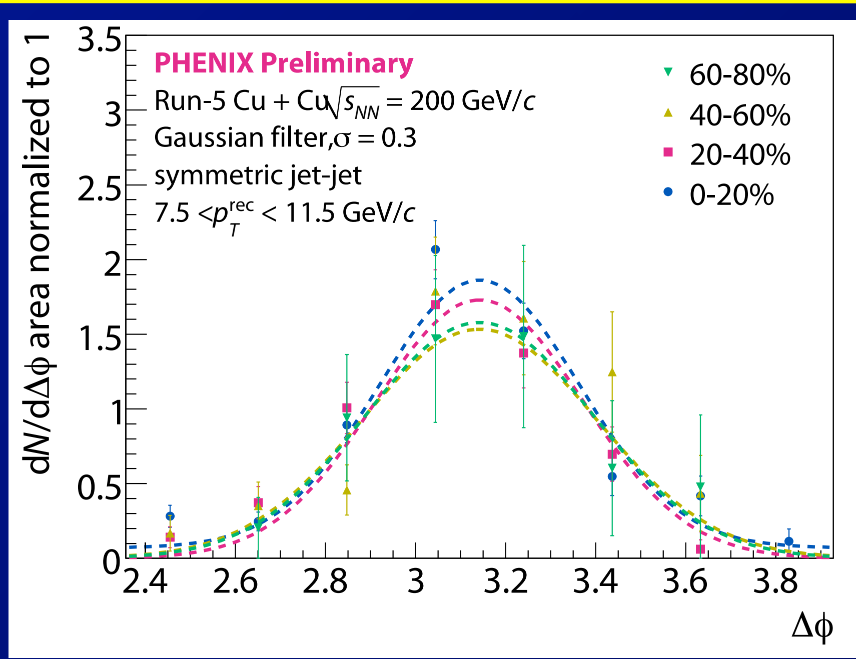
- **Gaussian filter jet finder suited to PHENIX acceptance, large UE**
  - Filter output analogous to energy flow variable
- **For maxima in $\tilde{p}_T(\eta,\phi)$**
  - good proxy for jet energy



PHENIX jet measurements, p-p, Cu-Cu



More central

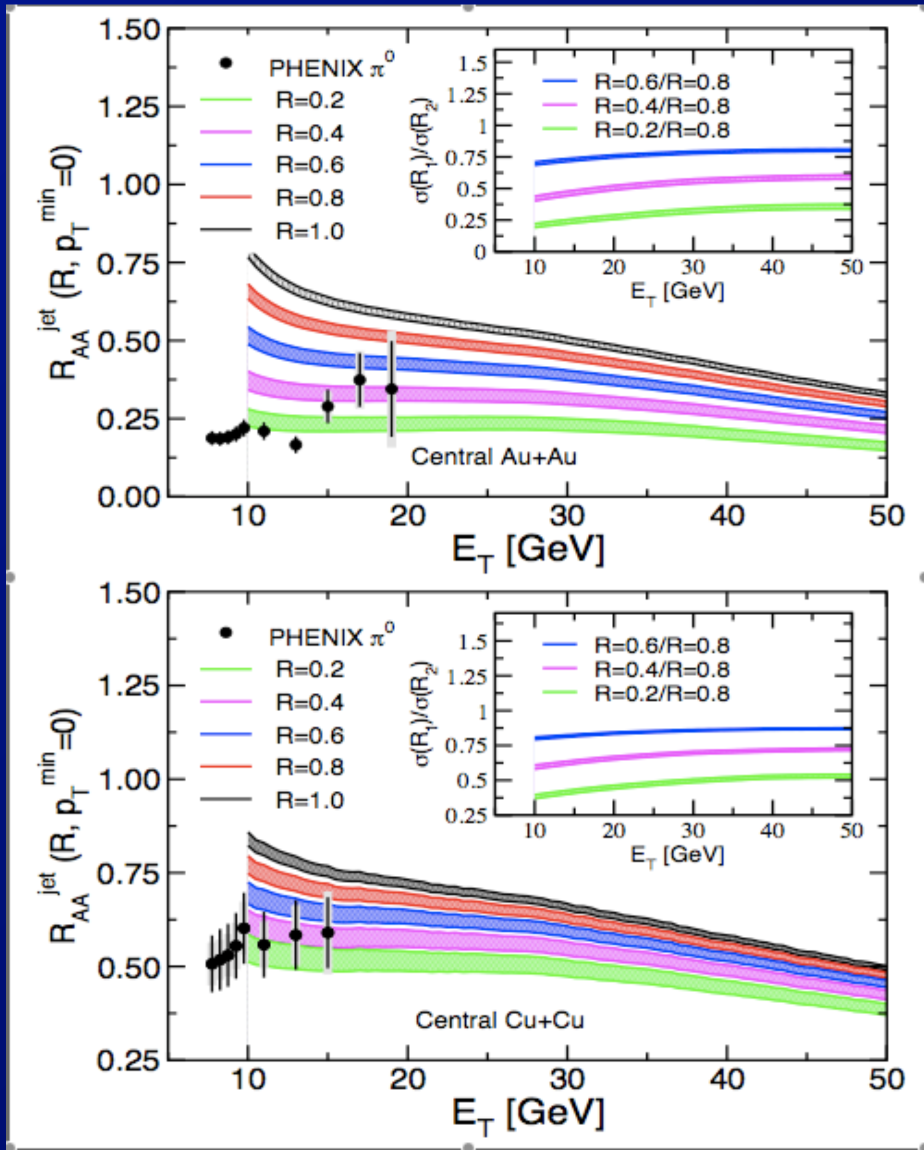


- PHENIX observes significant jet suppression in lighter ion collisions
  - But no modification of the dijet Δφ distribution
    - ⇒Consistent story @ RHIC and LHC
- The amount of jet suppression is expected to depend on the jet definition (size)

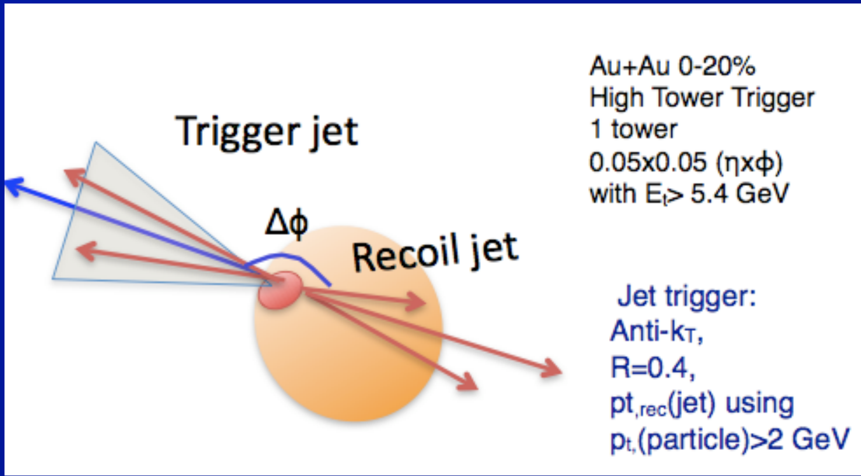
Jet Suppression: theory

- Calculation of jet R_{AA} at NLO including medium-induced gluon radiation
  - Medium parameters matched to single hadron suppression
- For radiative quenching,
  - R_{AA} depends on jet size due to out of "cone" radiation.
- With final data from PHENIX, STAR quantitative test of radiative quenching possible

Vitev and Zhang, Phys. Rev. Lett. 104 (2010) 132001



Au+Au jet measurements: STAR



$$D_{AA}(p_T^{assoc}) = Y_{AA}(p_T^{assoc}) \cdot p_{T,AA}^{assoc} - Y_{pp}(p_T^{assoc}) \cdot p_{T,pp}^{assoc}$$

$$\Delta B = \int dp_T^{assoc} D_{AA}(p_T^{assoc})$$

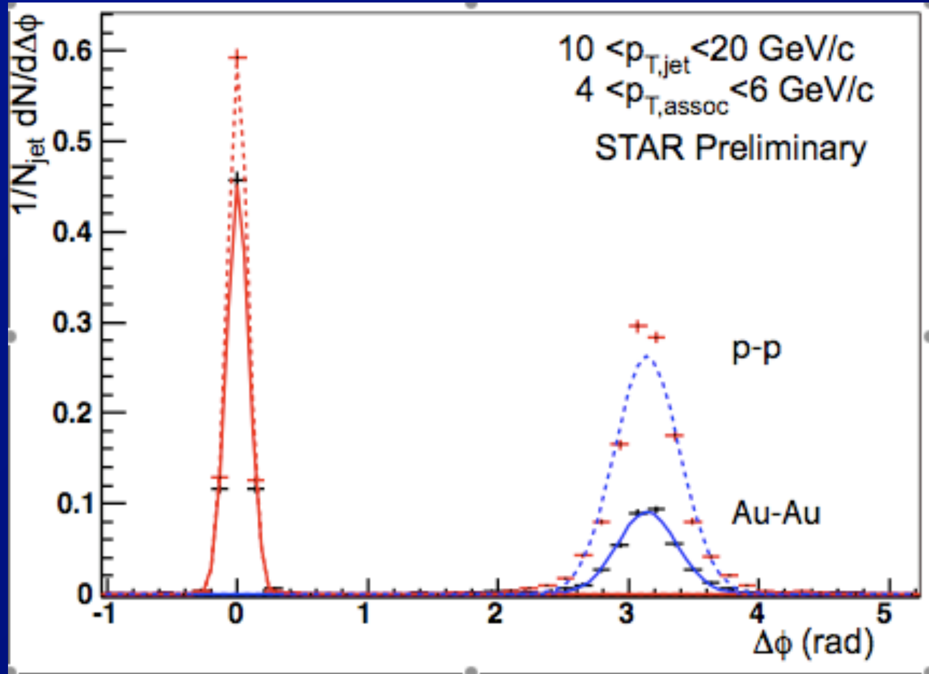
Near-side:

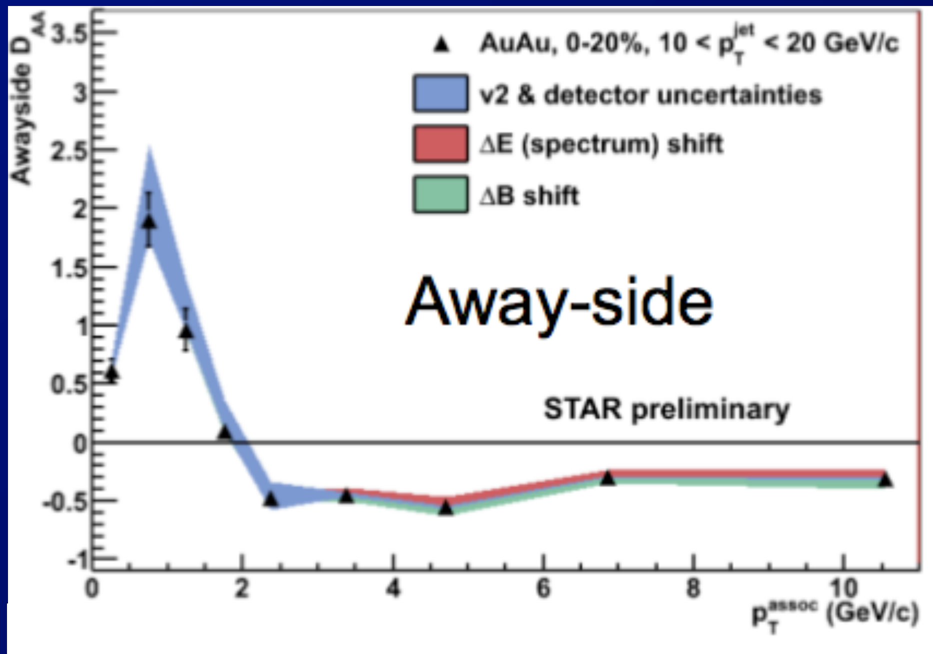
$\Delta B = 0.6 \, ^{+1.9}_{-1.0} \, ^{+0.5}_{-0.4}$ (sys) GeV/c

Away-side:

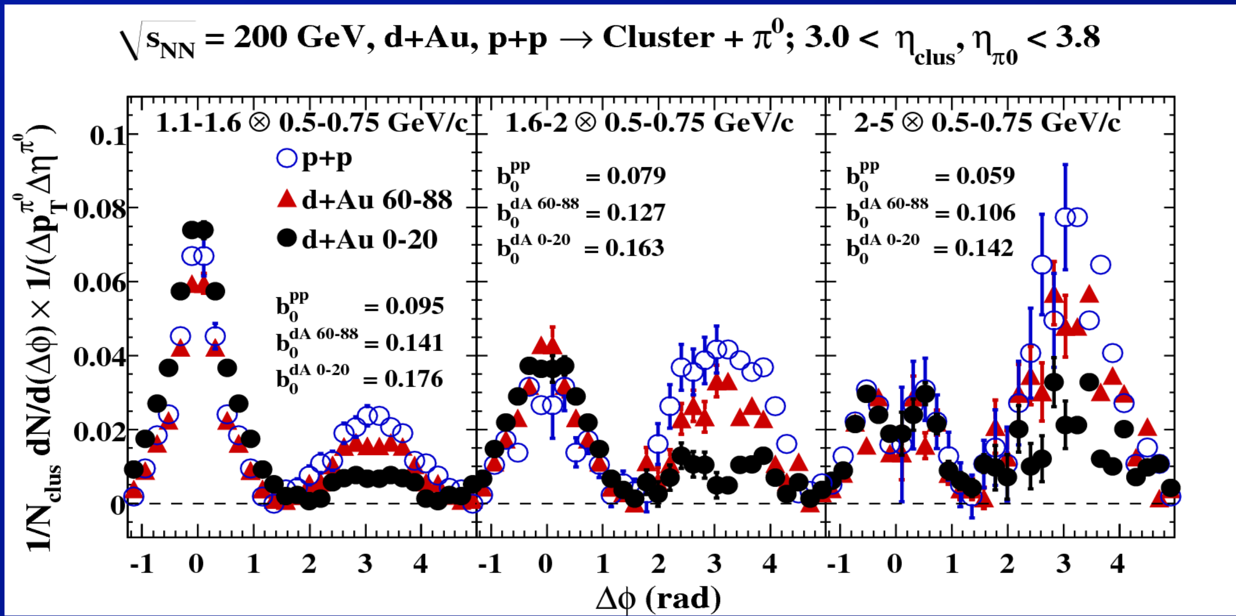
$\Delta B = 1.5 \, ^{+1.7}_{-0.4} \, ^{+0.5}_{-0.4}$ (sys) GeV/c

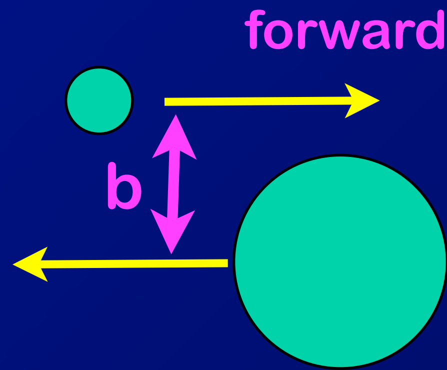
In balance jet, energy shifted to softer hadrons

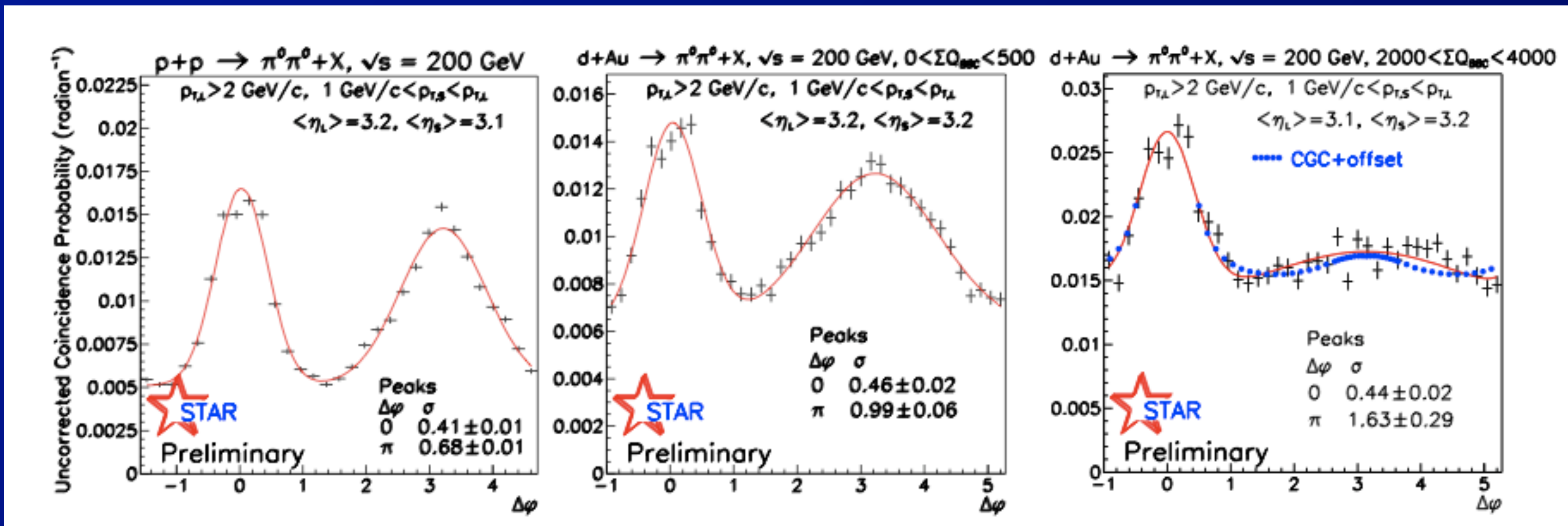




Initial-state effects: forward dijets







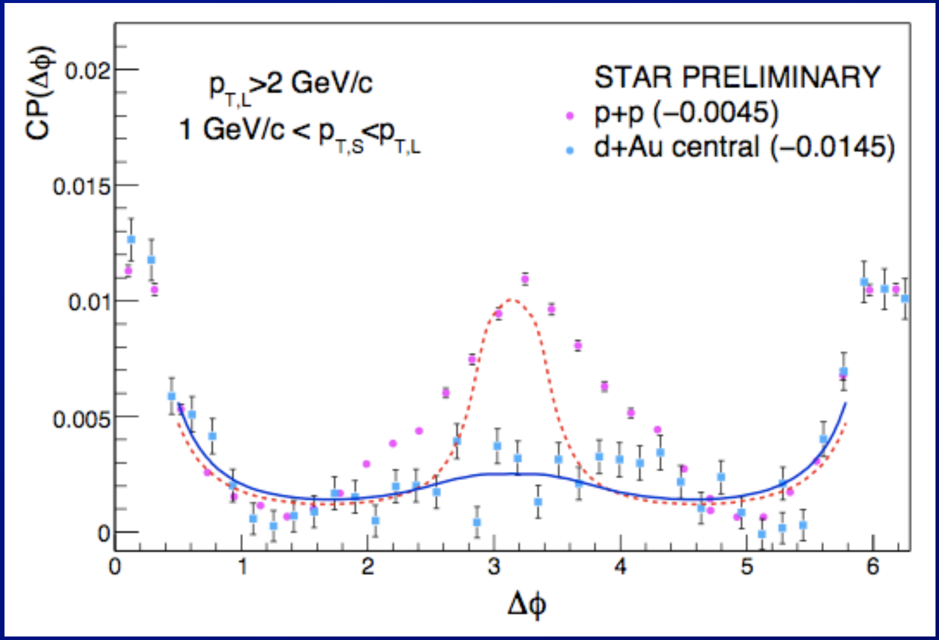
• Suppressed forward dijet yield

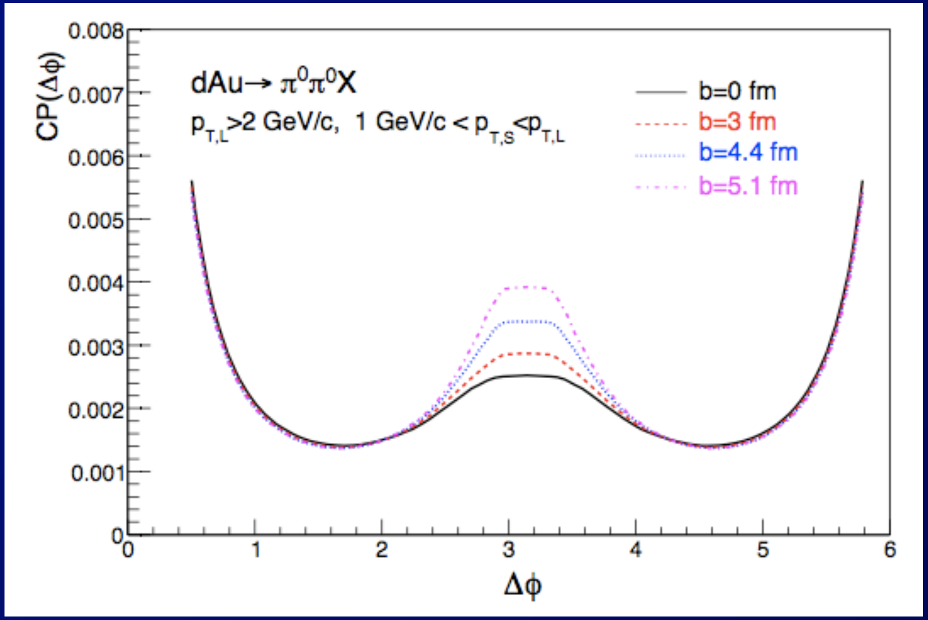
di-hadron forward correlations: theory

- Calculation using BFKL evolution to small x
  - But with non-linear term describing gluon recombination

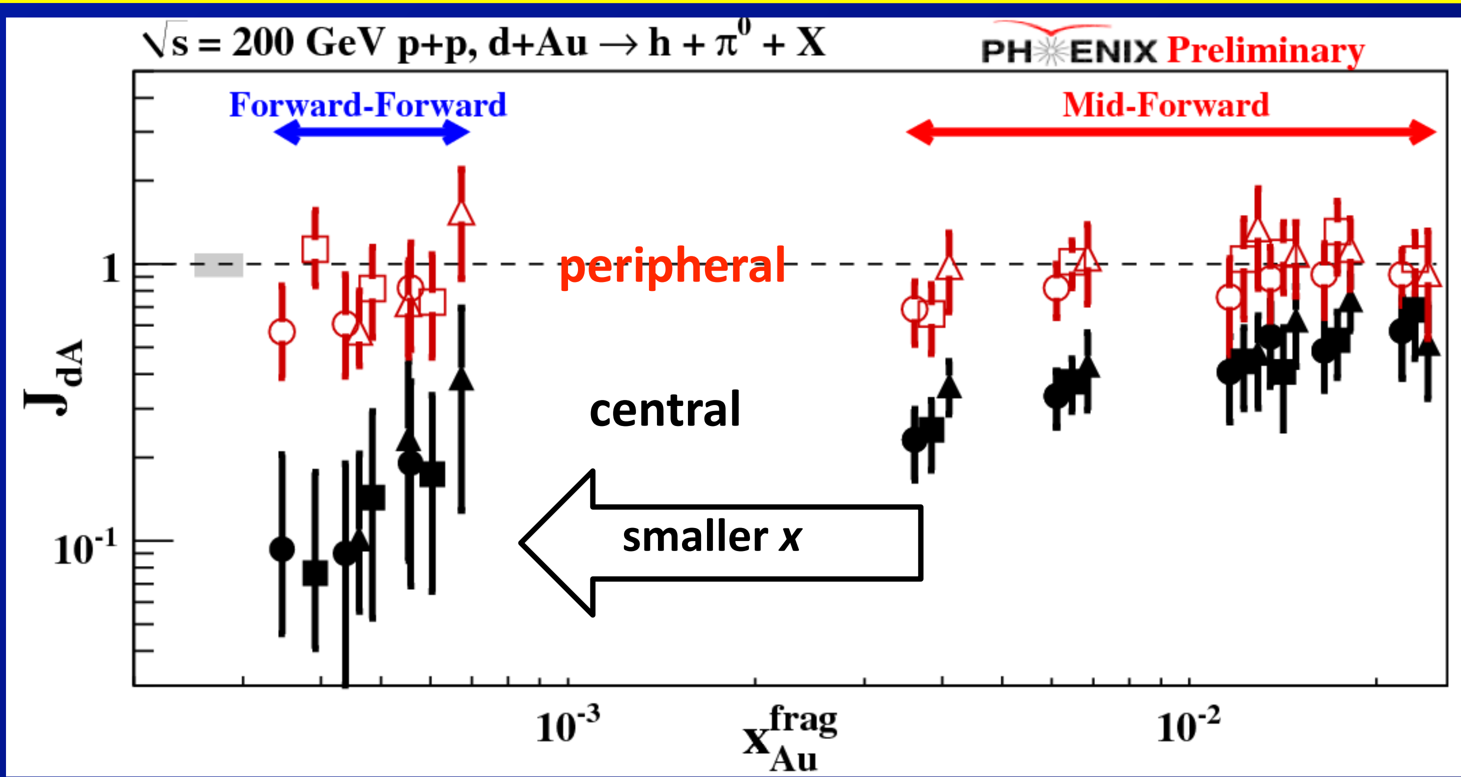
$$\frac{\partial \mathcal{N}(x,r)}{\partial \ln(x_0/x)} = \int d^2r_1\ K^{\mathrm{run}}(r,r_1,r_2)\,[\mathcal{N}(x,r_1) + \mathcal{N}(x,r_2) - \mathcal{N}(x,r) - \underline{\mathcal{N}(x,r_1)\,\mathcal{N}(x,r_2)}]$$

- Properly:
  - Running coupling "BK"evolution
  - Approximation to full set of non-linear evolution eqn's.





Initial-state effects: forward dijets



PHENIX, Phys. Rev. Lett. 107, 172301 (2011)

- See x10 suppression in forward di-jet yield for small impact parameters, $x < 10^{-3}$
  - Strongly suggestive of high parton density effect
    - ⇒Also known as "saturation"
  - Very important for understanding initial conditions of heavy ion collisions
    - ⇒Interesting QCD physics in its own right

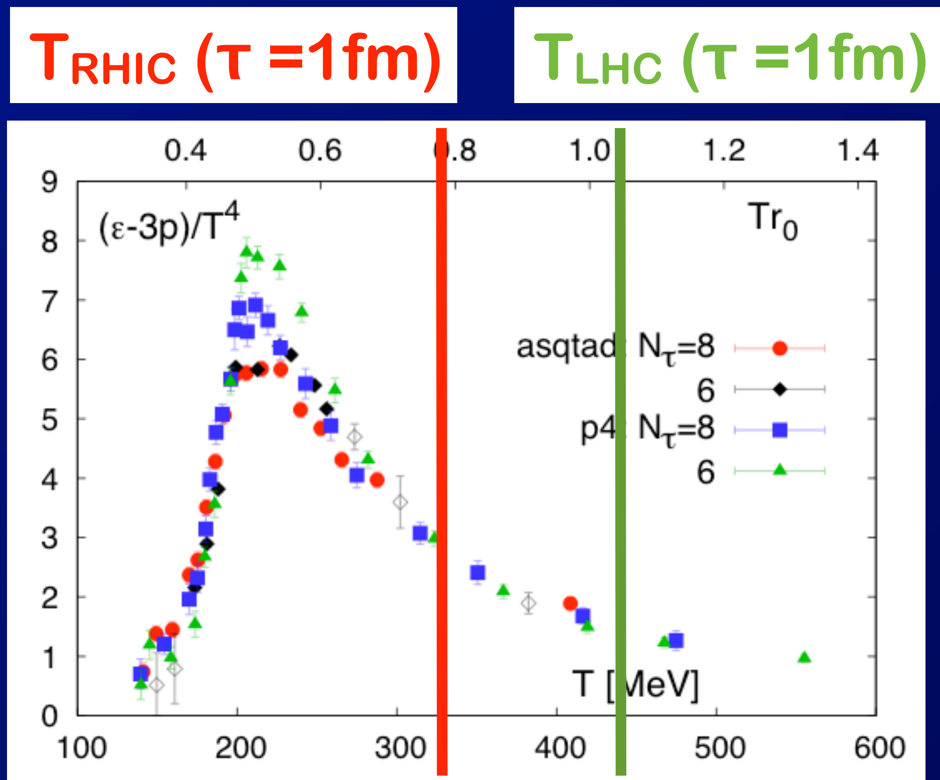
Summary, conclusions

- Jet quenching, observed indirectly, is well established at RHIC
  - But, unique quantitative explanation not available.
  - Still don't know (for sure) if quenching is weak or strong coupling phenomena.

    ⇒ Likely a mixture depending on virtuality of probe
  - Theoretical approximations still not under control
- But, much recent progress
  - Understanding the role of azimuthal modulation of the underlying event.
  - Photon-hadron measurements (luminosity!).
  - heavy quark measurements ⇒ upgrade program
  - Full jet measurements, but still all preliminary.
  - Insight from LHC measurements.

Summary, conclusions (2)

- May be observing high parton density effects in d+Au collisions via (e.g.) forward jets
  - Within 2 days will have first p+A (p+Pb) data @ LHC
    - ⇒ Expect to probe higher parton densities -- test!
- More Generally:
  - If we are to do quantitative science, need to be able to answer questions like:
  - "can we see difference between interaction strength at RHIC and LHC QGP temperatures"
    - ⇒ Jet quenching still best hope for answering IMHO.



PHENIX upgrade

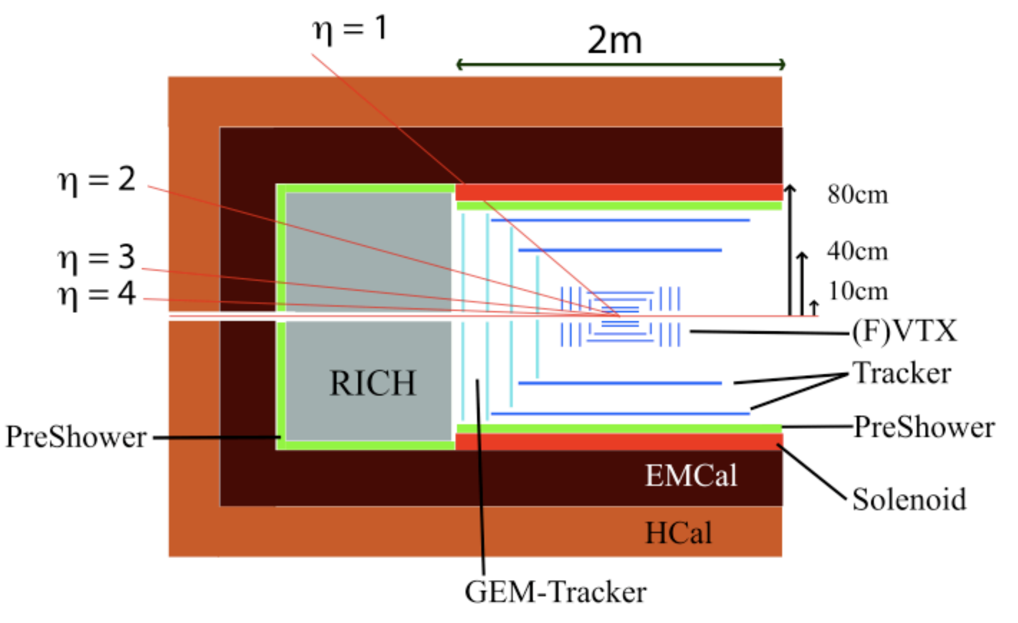
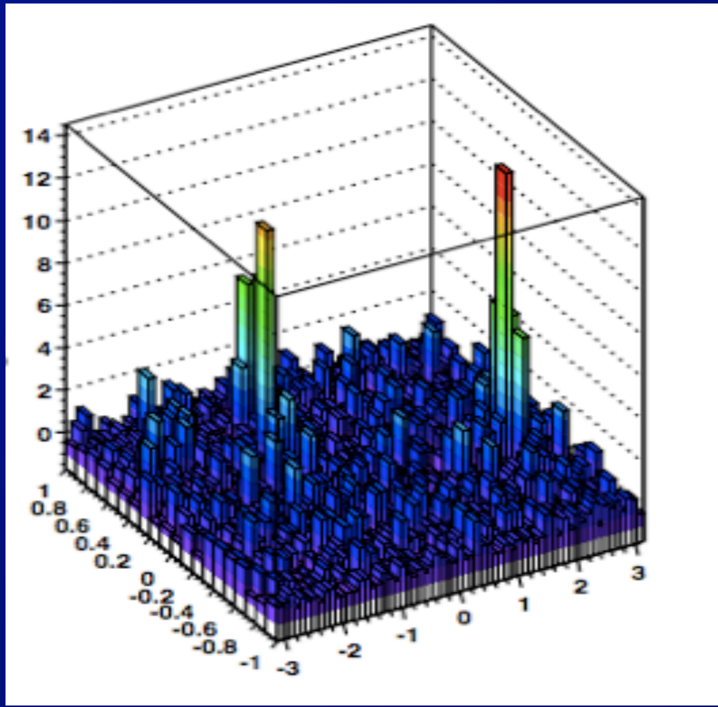


Figure 1. A strawman sketch of the sPHENIX detector. Some features of the detector are discussed in the text.

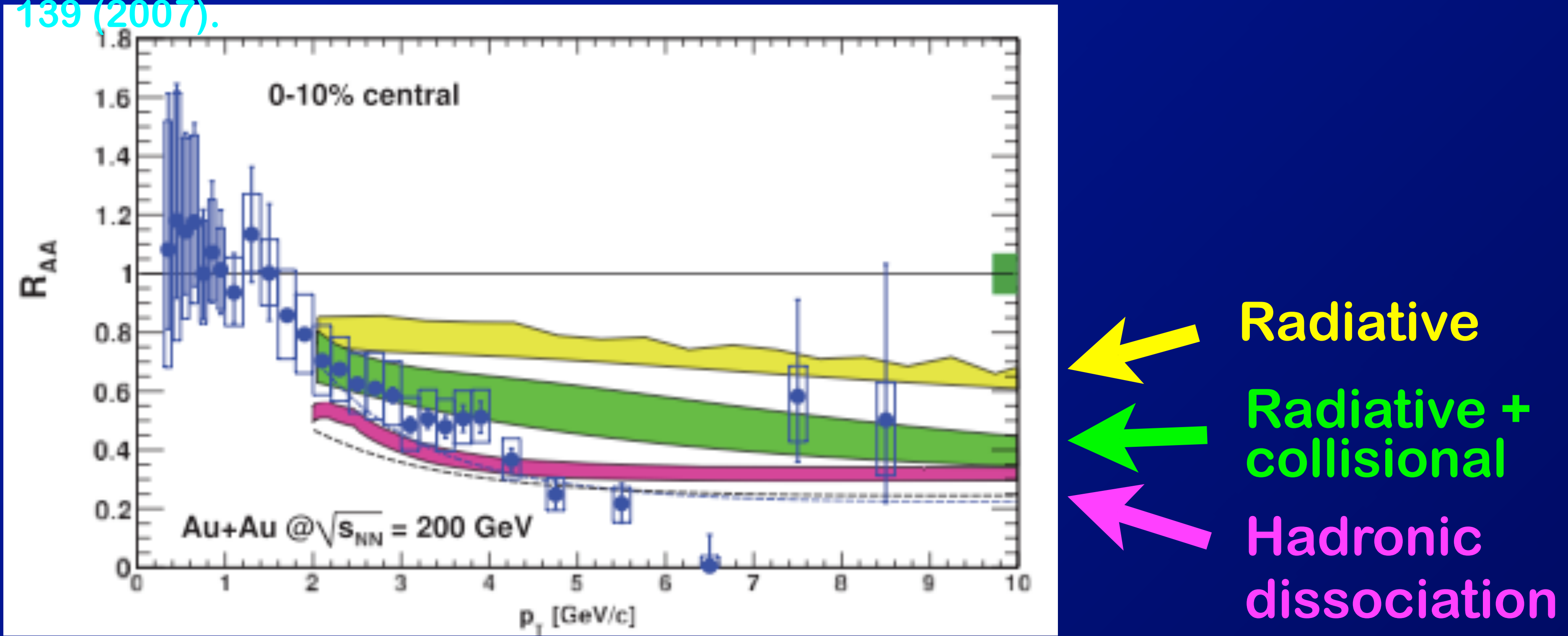


- **Both STAR and PHENIX are pursing A+A jet measurements @ RHIC**
  - But, PHENIX detector is not optimal for jets
    - ⇒So, PHENIX has proposed major upgrade (sPHENIX) with goal of performing jet measurements *a la* ATLAS & CMS

Backup

Heavy quark suppression

S. Wicks et al., Nucl. Phys. A 784, 426 (2007), A. Adil and I. Vitev, Phys. Lett. B 649, 139 (2007).



- **Wicks *et al*:**
  - Radiative or radiative + collisional matched to light quark quenching cannot explain heavy quark data.
- **Adil and Vitev:**
  - Formation of hadron-like states (short formation time) + dissociation?

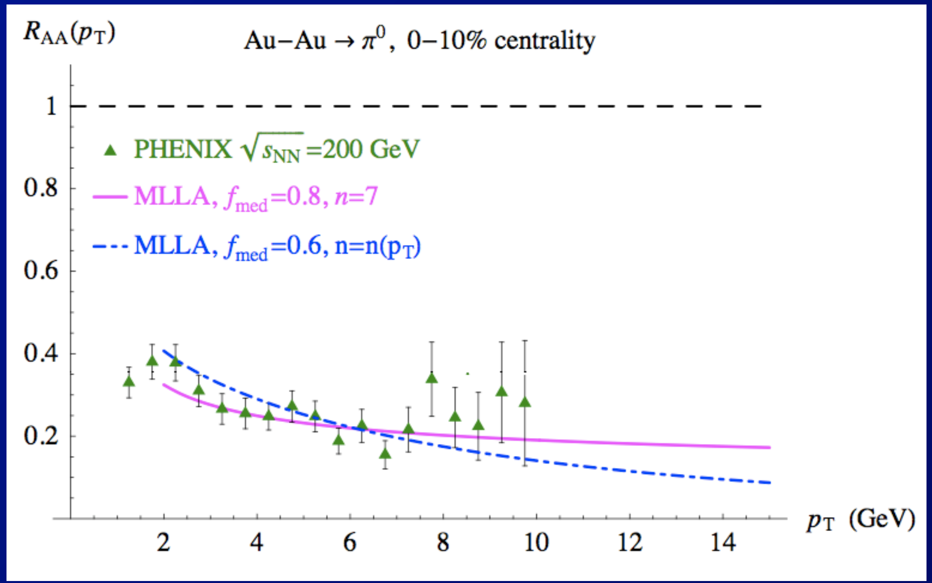
Medium modified parton shower

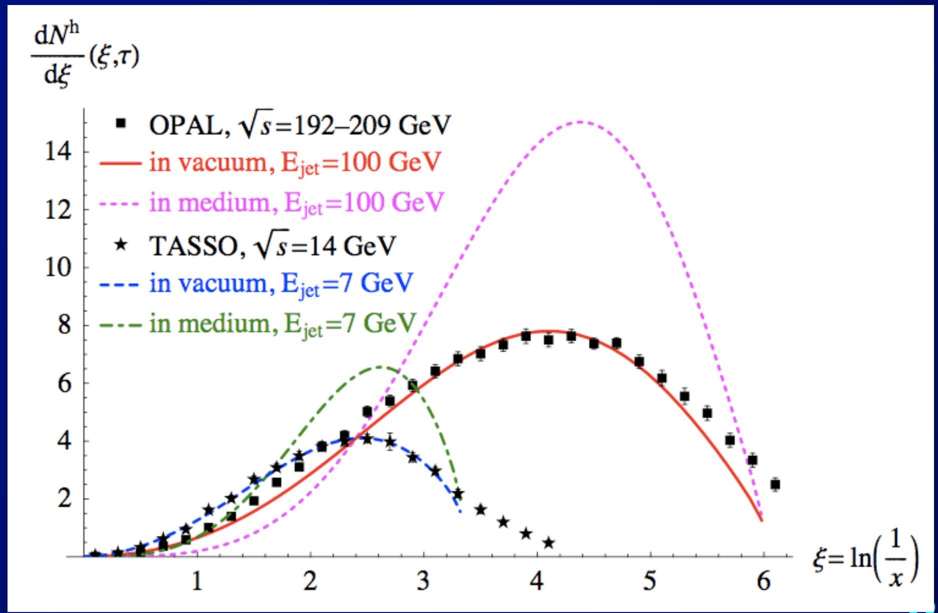
- Described quenching via enhanced gluon emission in MLLA
  - Included in splitting function "by hand"

$$P_{qq}(z) = C_F \left(\frac{2\,(1+f_{\rm med})}{(1-z)_+} - (1+z) \right)$$

  - Fit to PHENIX data
- Clearly naive
  - Doesn't "know" about medium scales, path length, etc.
- But, implemented consistent with pQCD

Borghini, Wiedemann





One slide quarkonia summary

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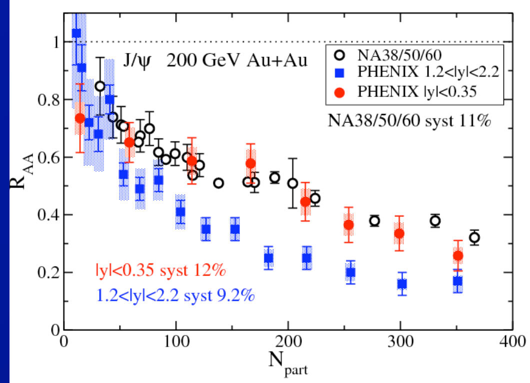
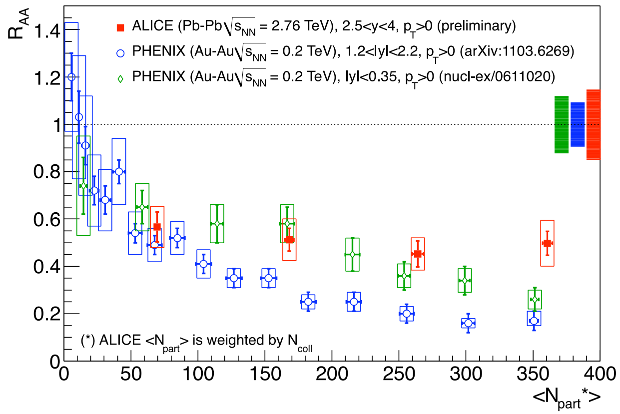
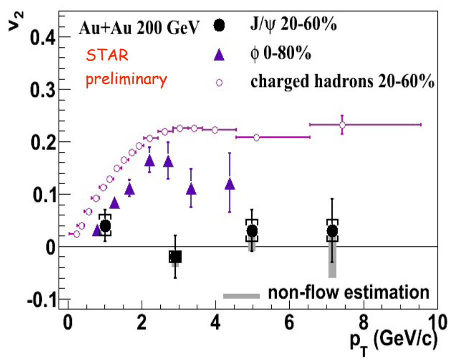
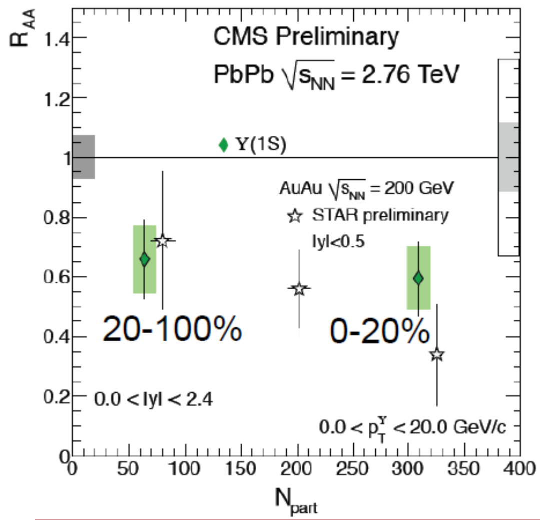




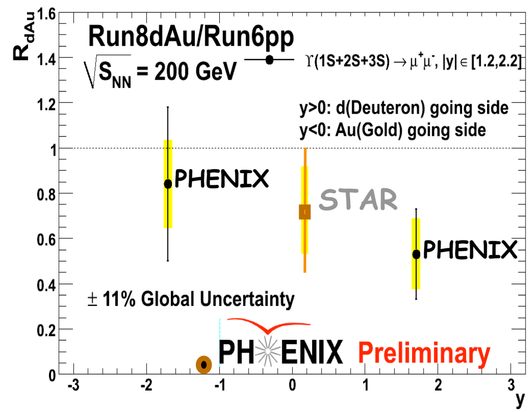
- J/ψ suppression almost same at all energies
- Stronger at forward rapidity!
- Regeneration?



- But: flow very small at RHIC
- Regeneration dead?



Upsilon suppression at RHIC & LHC similar



Strong CNM effects for Upsilon too

CNM measurements needed
FVTX upgrade

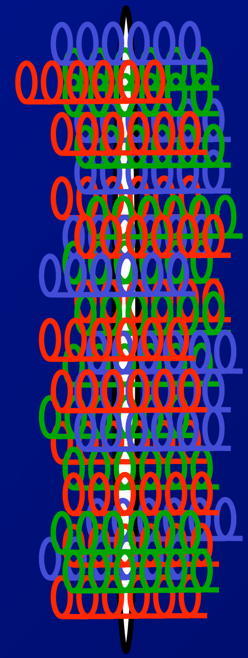
Shamelessly borrowed from excellent talk by S. Bathe at RIKEN QCD workshop

“Saturation” @ low x

- @ High energy nuclei are highly Lorentz contracted

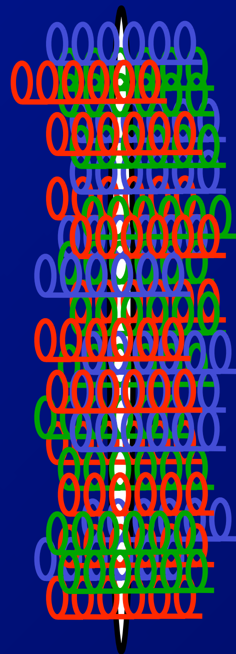
"Saturation" @ low x

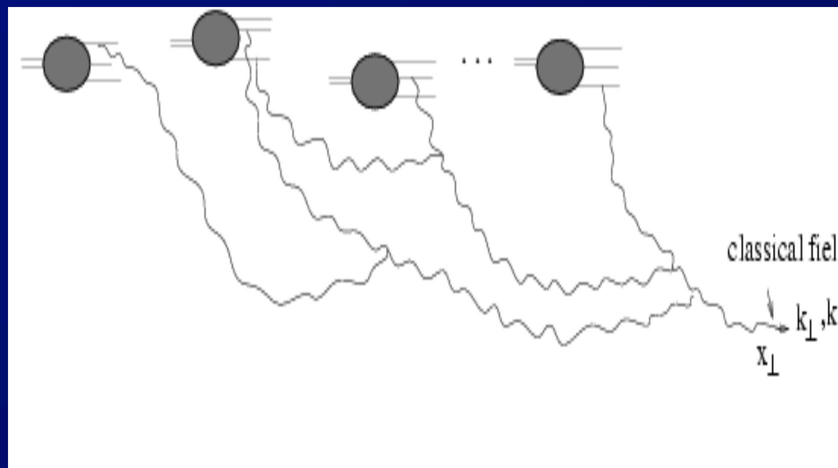
- @ High energy nuclei are highly Lorentz contracted
  - Except for low-momentum gluons which have spatial spread $\Delta z \geqslant \hbar / p_z$
    - $\Rightarrow$ Gluons from many nucleons overlap



"Saturation" @ low x

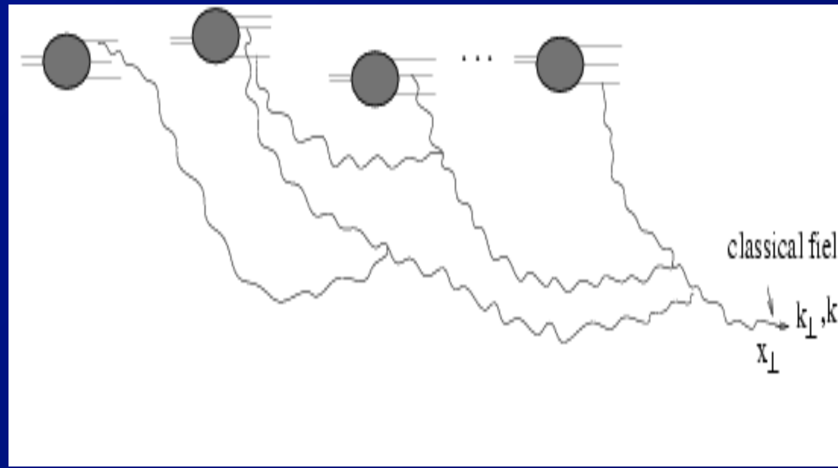
- @ High energy nuclei are highly Lorentz contracted
  - Except for soft gluons
  - Which overlap longitudinally
  - And recombine

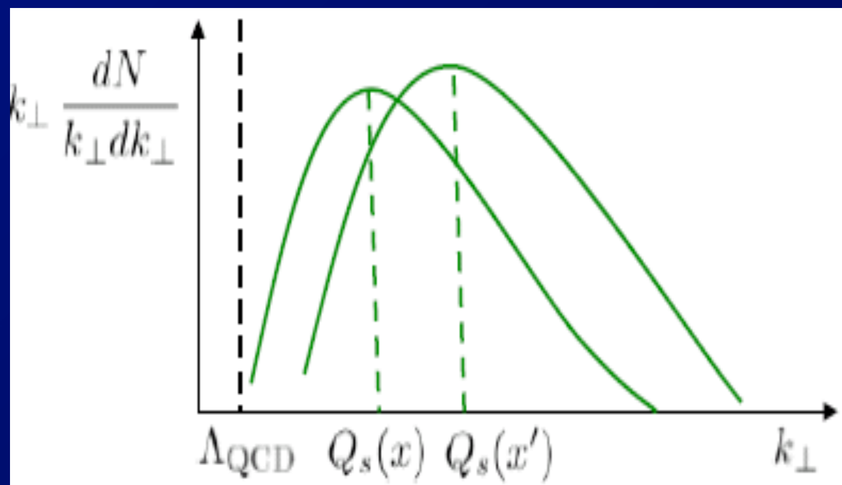




"Saturation" @ low x

- @ High energy nuclei are highly Lorentz contracted
  - Except for soft gluons
  - Which overlap longitudinally
  - And recombine
  - Broadening k_T distribution
    - $\Rightarrow$ Generates a new scale: Q_s





"Saturation" @ low x

- @ High energy nuclei are highly Lorentz contracted
  - Except for soft gluons
  - Which overlap longitudinally
  - And recombine
  - Broadening k_T distribution
    - ⇒Generates a new scale: Q_s
- Naively, for $Q_s >> \Lambda_{QCD}$, perturbative calculations
  - ⇒Large occupation #s for $k_T<Q_s$ ⇒ classical fields
- Saturation a result of unitarity in QCD