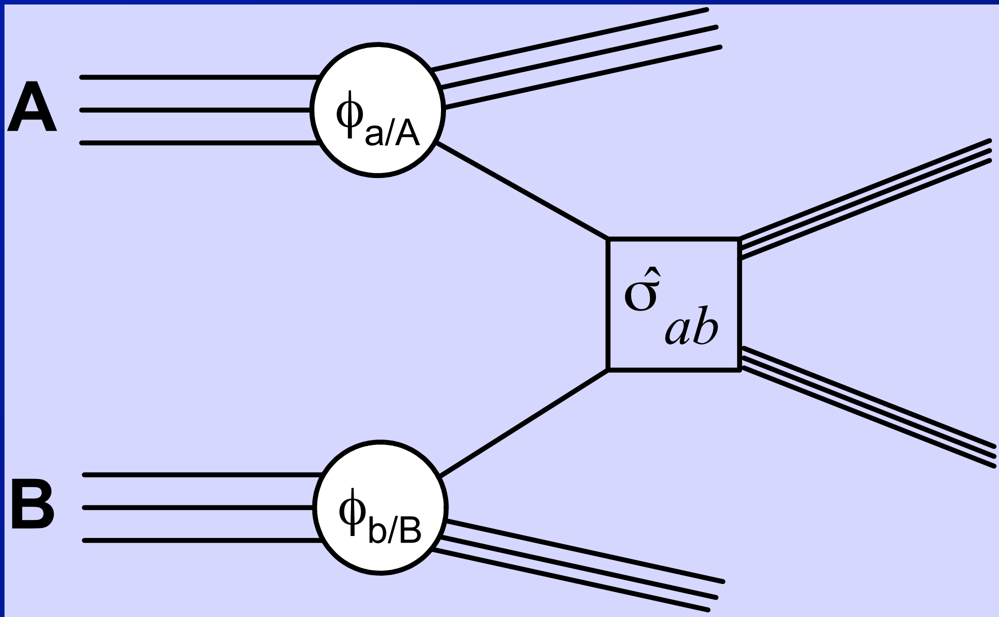
RHIC: a new regime

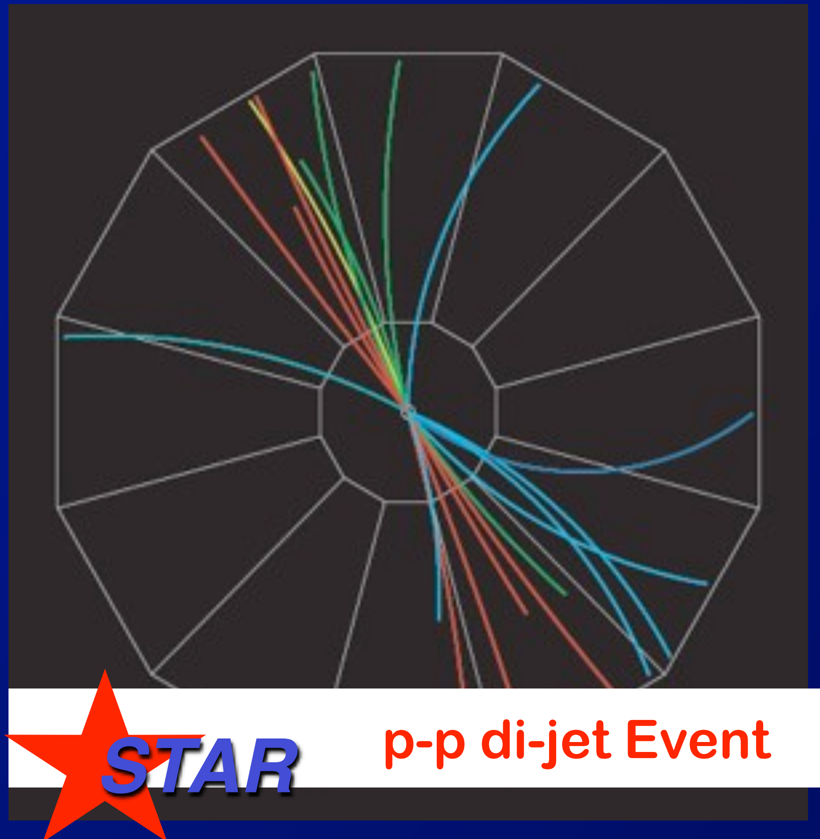
7-200 GeV/A Au+Au, d+Au, Cu+Cu
32-500 GeV p+p, ...

PHENIX

STAR

Hard Scattering in p-p Collisions



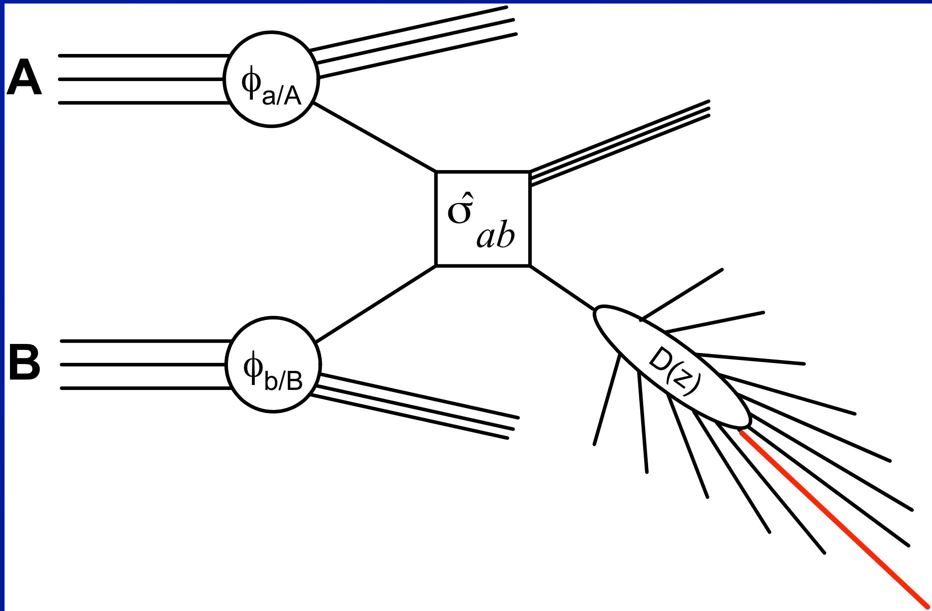


From **Collins, Soper, Sterman**
Phys. Lett. B438:184-192, 1998

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

- **Factorization: separation of σ into**
  - Short-distance physics: $\hat{\sigma}$
  - Long-distance physics: φ's (universal)

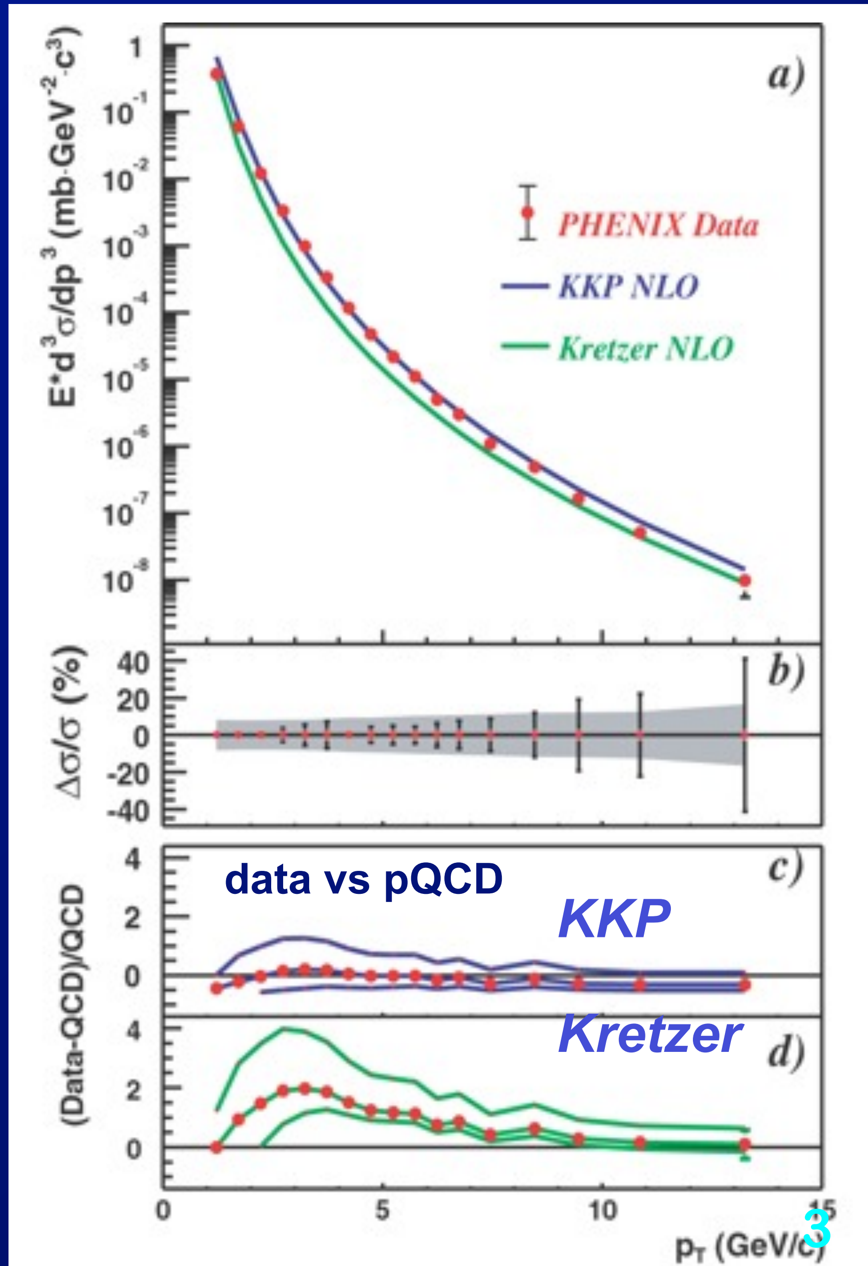
Single High-pt Hadron Production



$$E\frac{d^3\sigma}{dp^3} = \sum_{abc}\int dx_a dx_b\, \phi_{a/A}(x_a,Q^2,\mu)\phi_{b/B}(x_a,Q^2,\mu)$$

$$\times \frac{D_{\pi^0/c}(z,Q^2,\mu)}{z\pi}\frac{d\hat{\sigma}}{dt}$$

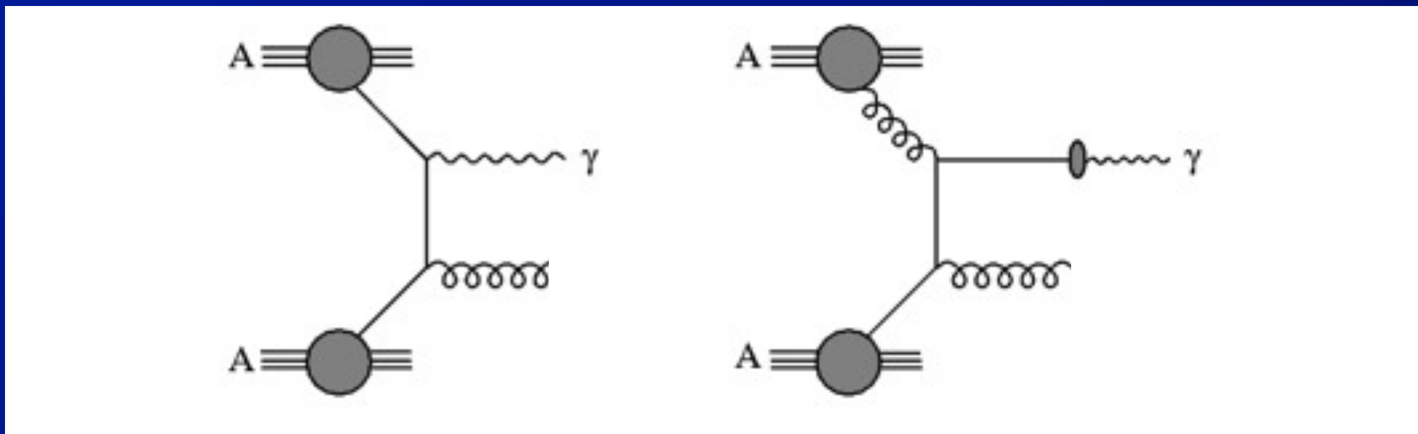
Phys. Rev. Lett. 91, 241803 (2003



- NLO calculation agrees well with PHENIX π^0 spectrum (!?)
  - BUT, FF dependence ?
  - Lore: KKP better for gluons

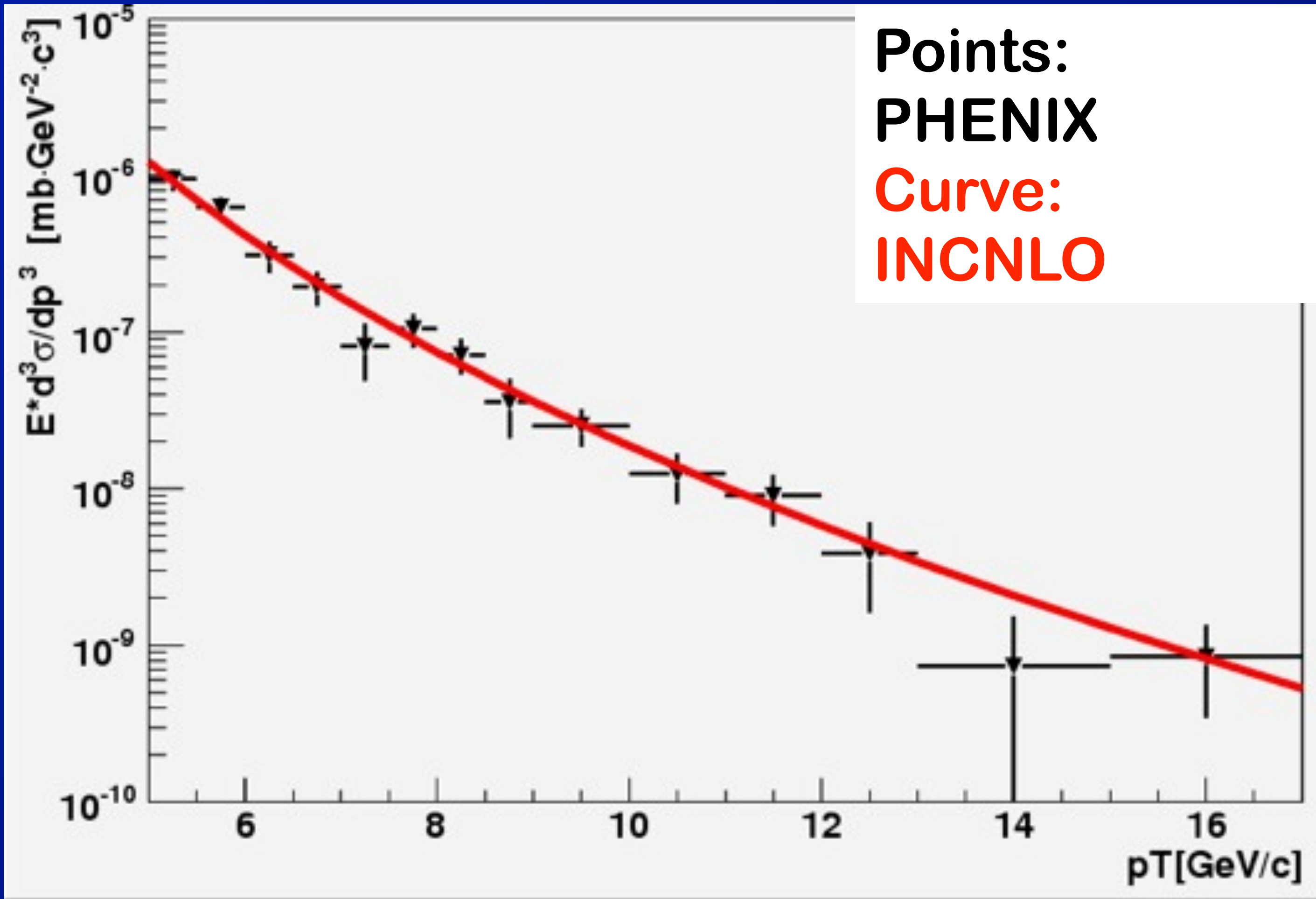
Hard Photon Production in pQCD

- @ LO in pQCD, photon production is simple.
- Two contributions:
  - "partonic" photons: direct from hard scattering
  - "Fragmentation" photons – from fragmentation of jet(s)



- But, @ NLO things are much more complicated
  - Distinction between partonic & fragmentation contributions becomes ambiguous.
  - In principle, "isolation" cuts possible – but matching those cuts with pQCD is difficult (infrared sensitivity).

PHENIX Prompt γ: Comparison to pQCD



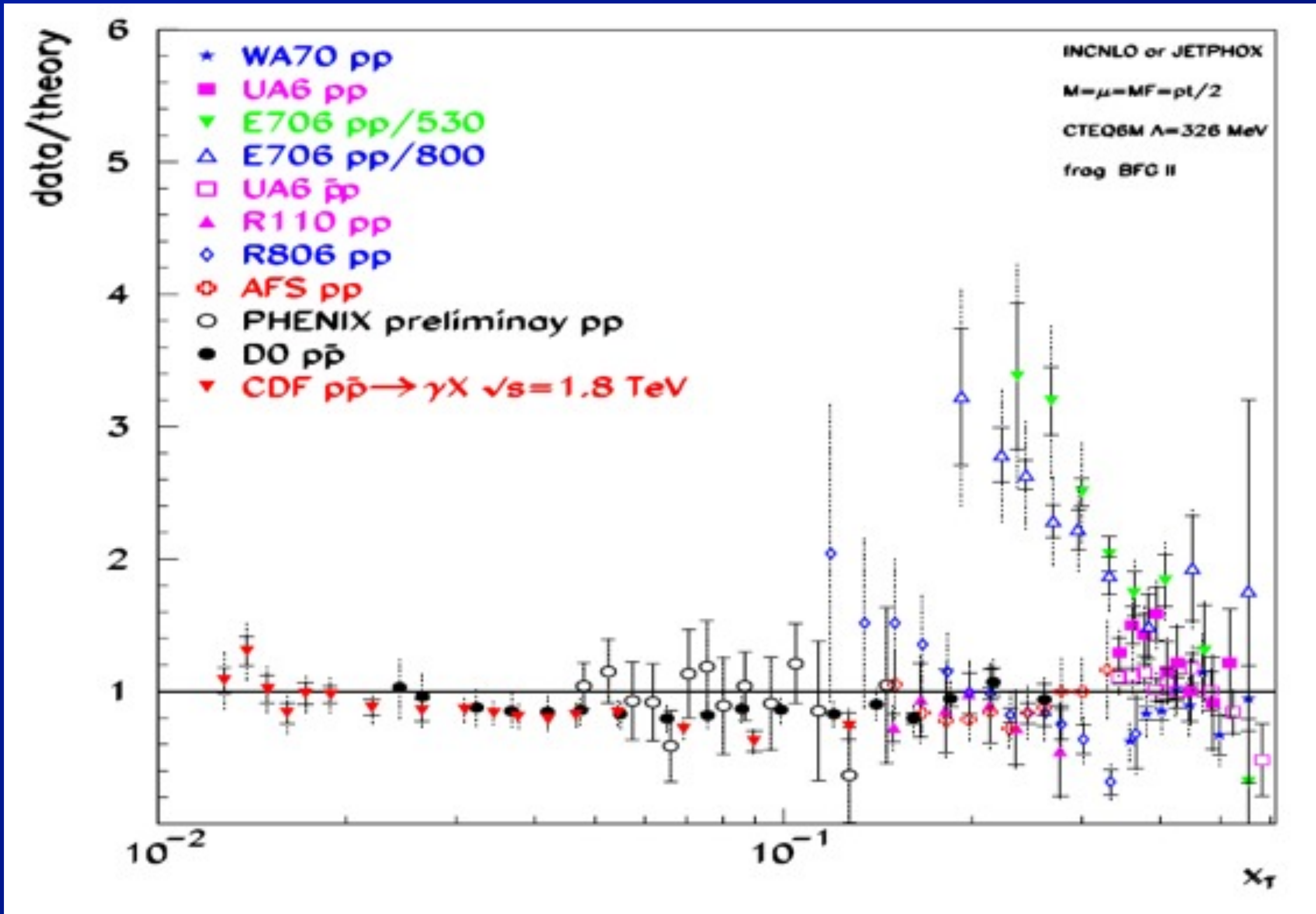
INCNLO (1.4):

NLO pQCD + NLL photon frag. func.

- No K factors, no fudge factors, absolute comparison
- Completely independent calculation.
  - Good control over pQCD prompt photon calculation @ RHIC.

p-p Prompt Photon – Comparison w/ QCD

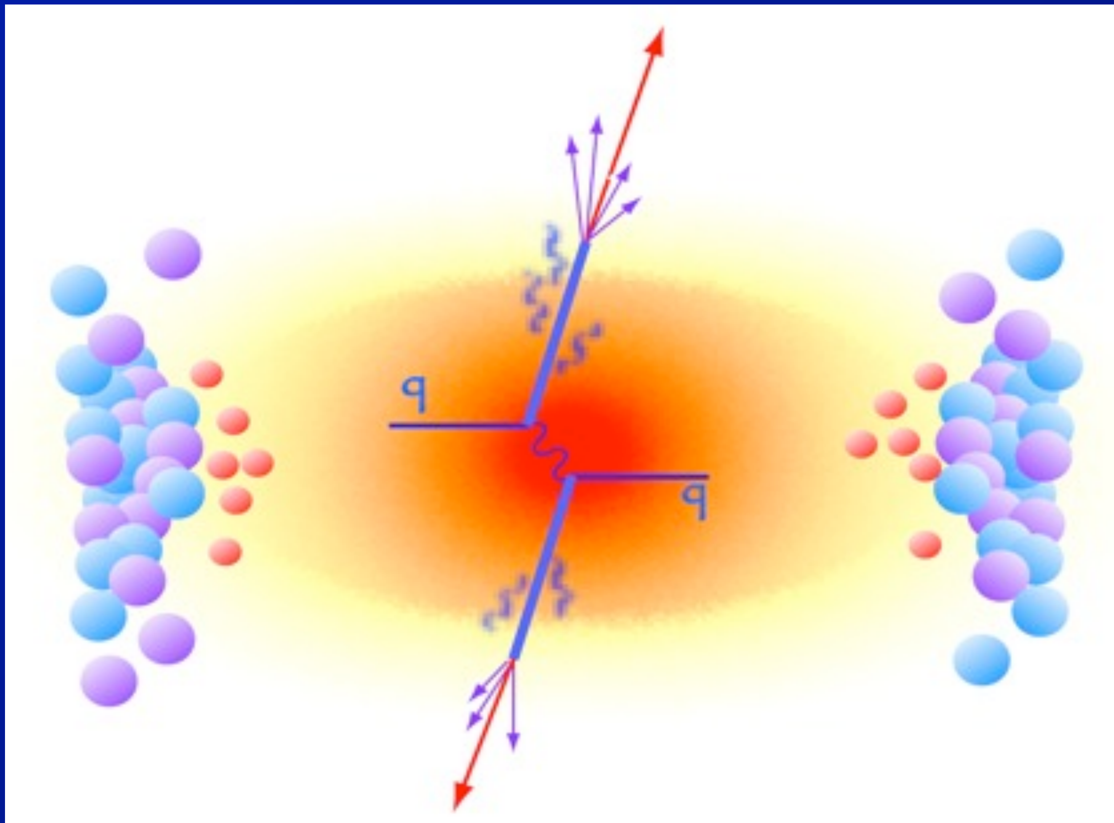
Aurenche *et al.*, PRD73, 094007(2007)



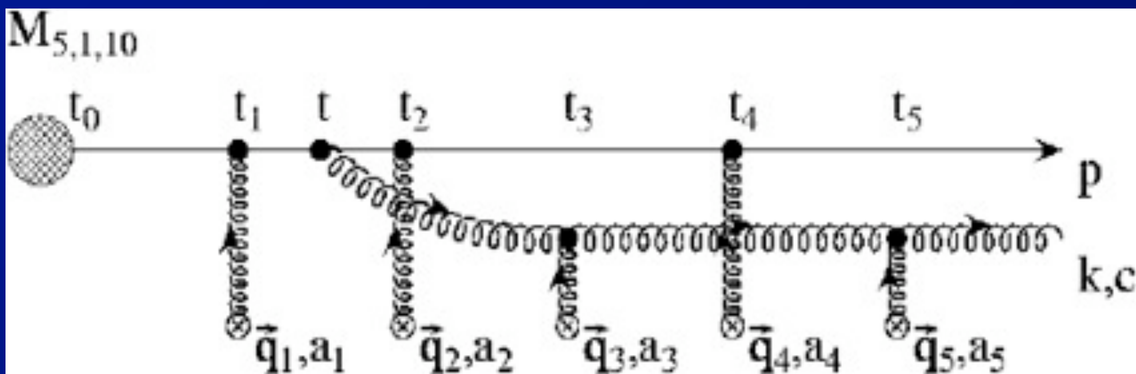
$$x_T = \frac{2\,p_T}{\sqrt{s}}$$

- **PHENIX prompt photon spectra consistent w/ other collider data (vs x_T) and QCD**

Jet Quenching: RHIC perspective



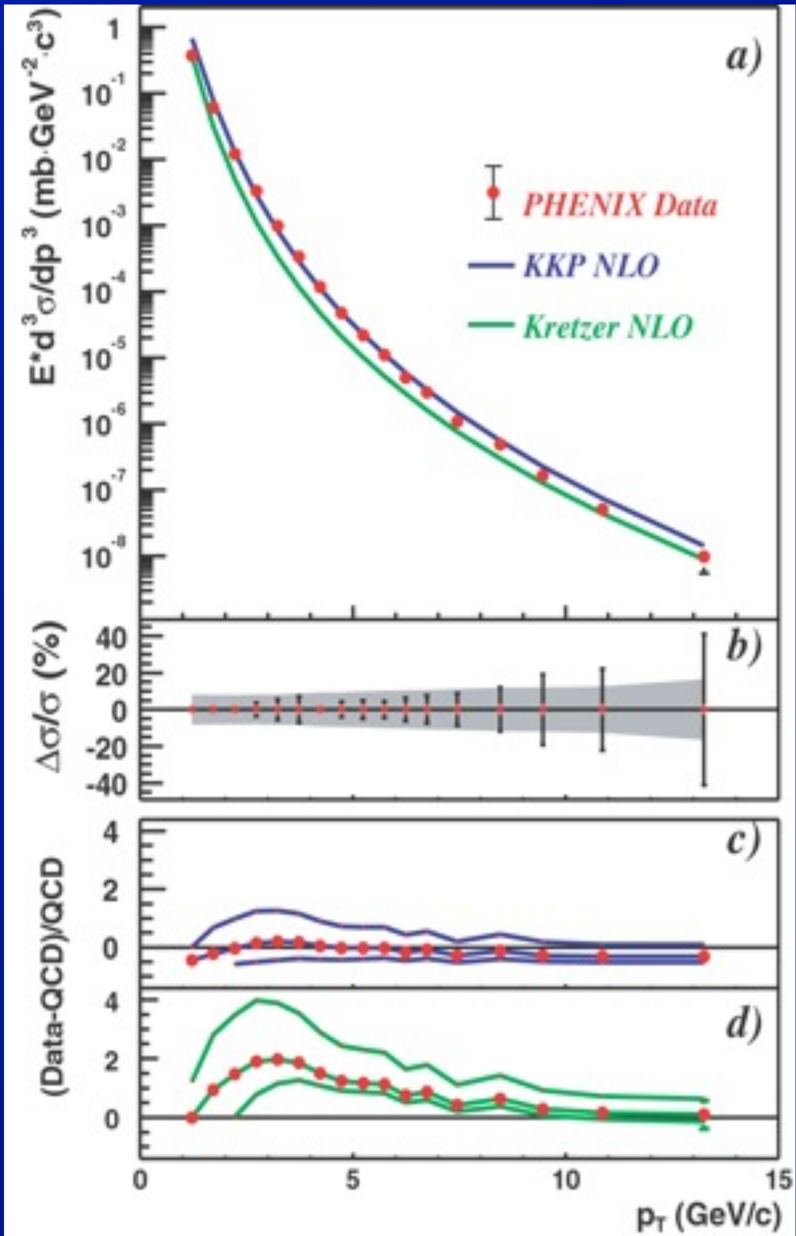
- Key question:
  - How quarks (and gluons) lose energy in the quark gluon plasma?

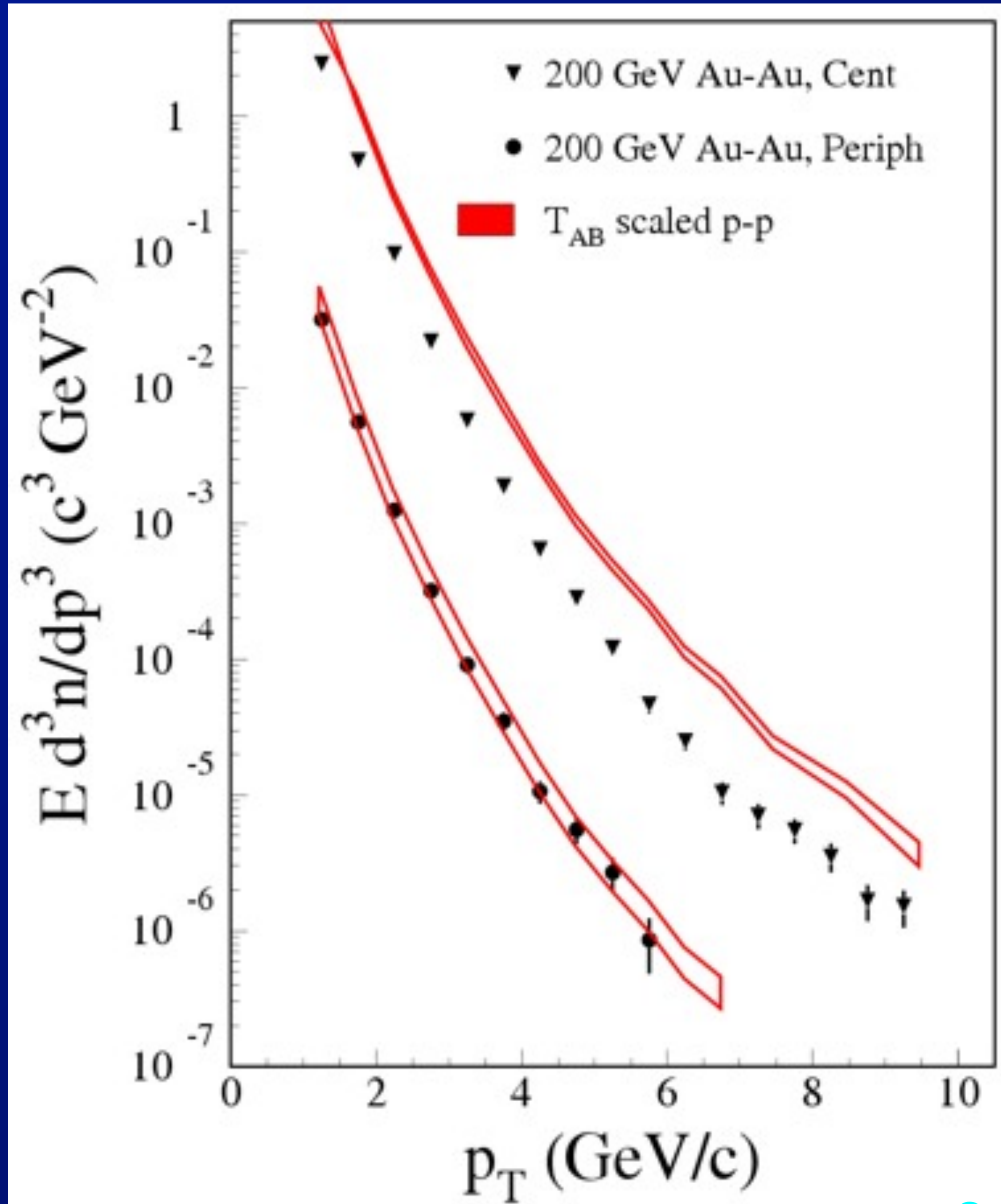


One diagram in a calculation of QGP induced radiative energy loss

The early days of jet quenching

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



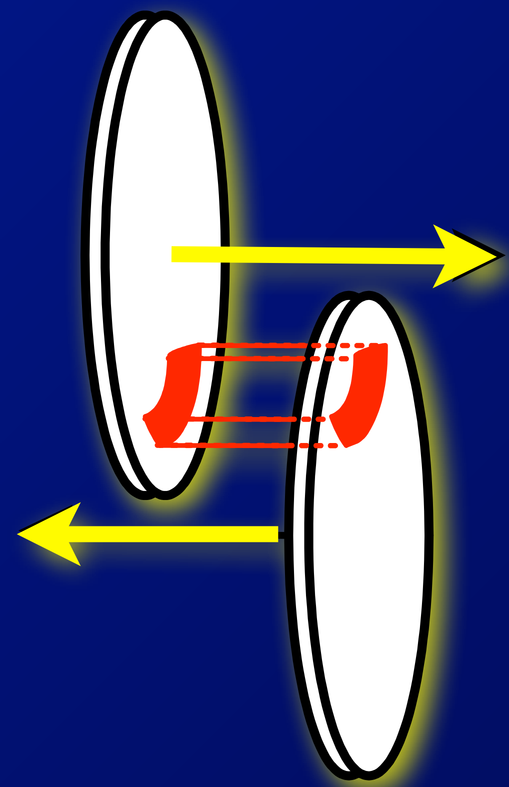


Geometry, again

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

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

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



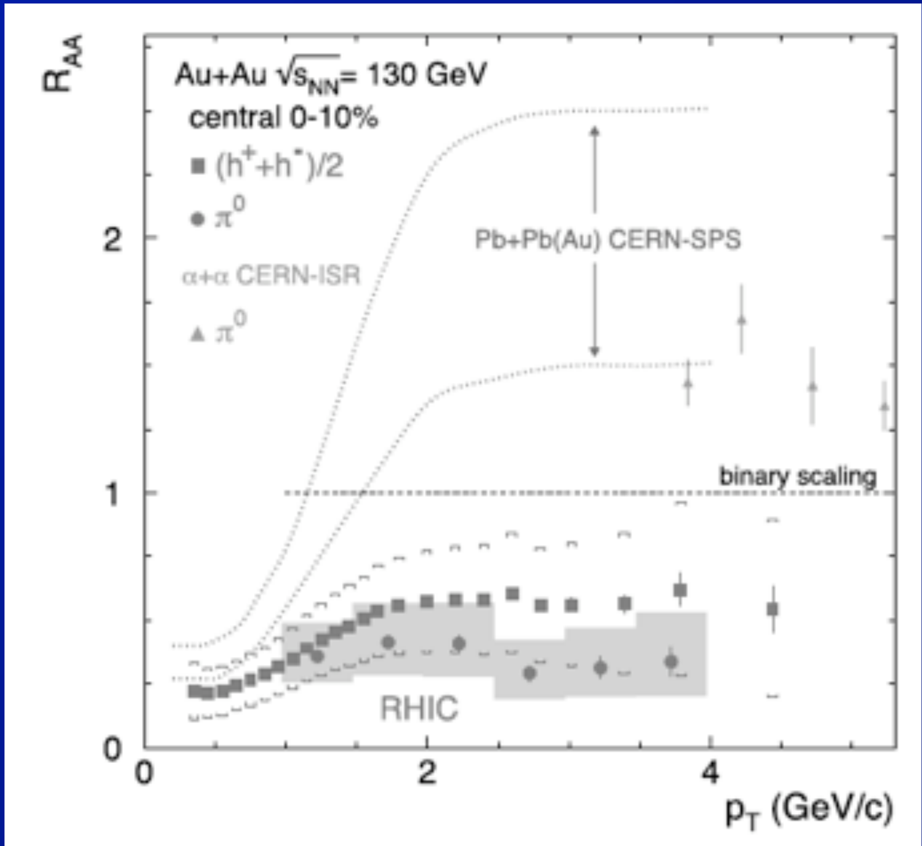
  - t-integrated A-A parton luminosity
  - Normalized relative to p-p
- If factorization holds, then

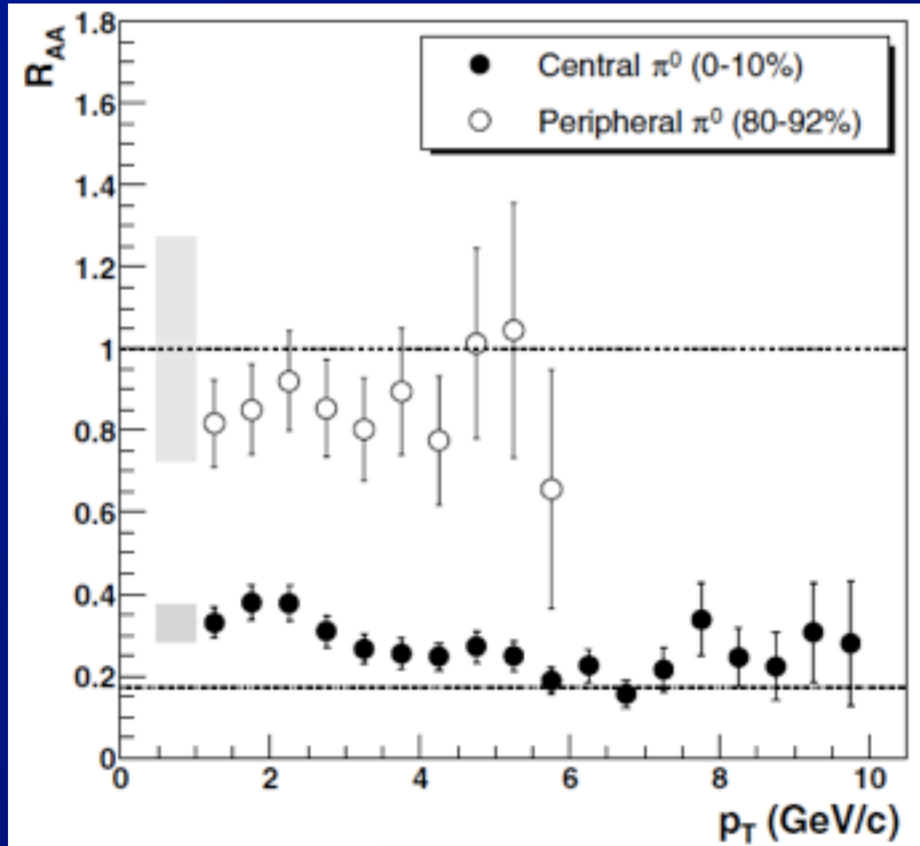
$$\frac{dn_{hard}^{AB}}{dp_\perp^2} = \frac{d\sigma_{hard}^{NN}}{dp_\perp^2} T_{AB}(b)$$

- Define R_{AA}
  - Degree to which factorization is violated

$$R_{AA} = \frac{dn_{hard}^{AB}}{dp_\perp^2} \Big/ \frac{d\sigma_{hard}^{NN}}{dp_\perp^2} T_{AB}(b)$$

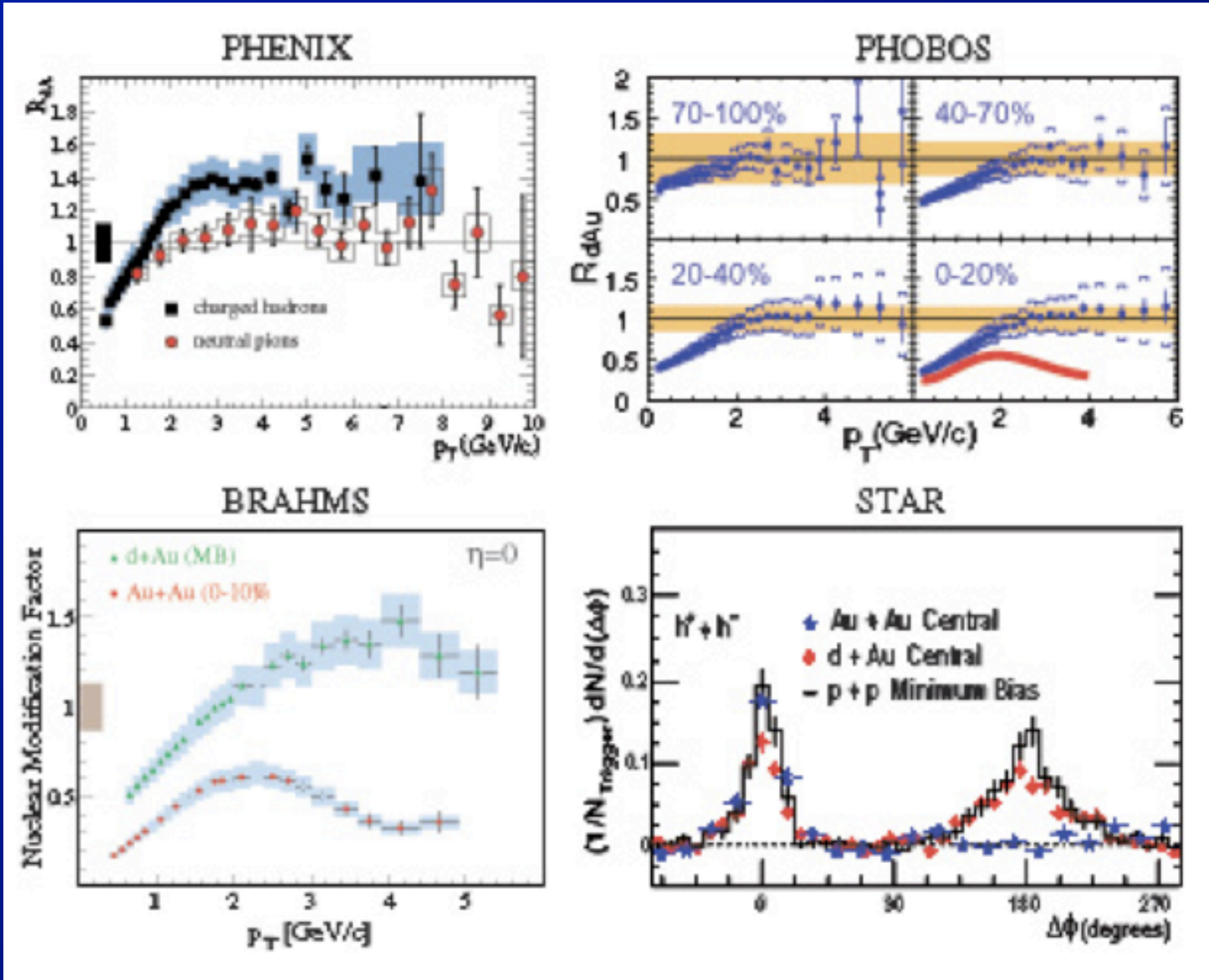
PHENIX: "jet" quenching @ 130, 200 GeV



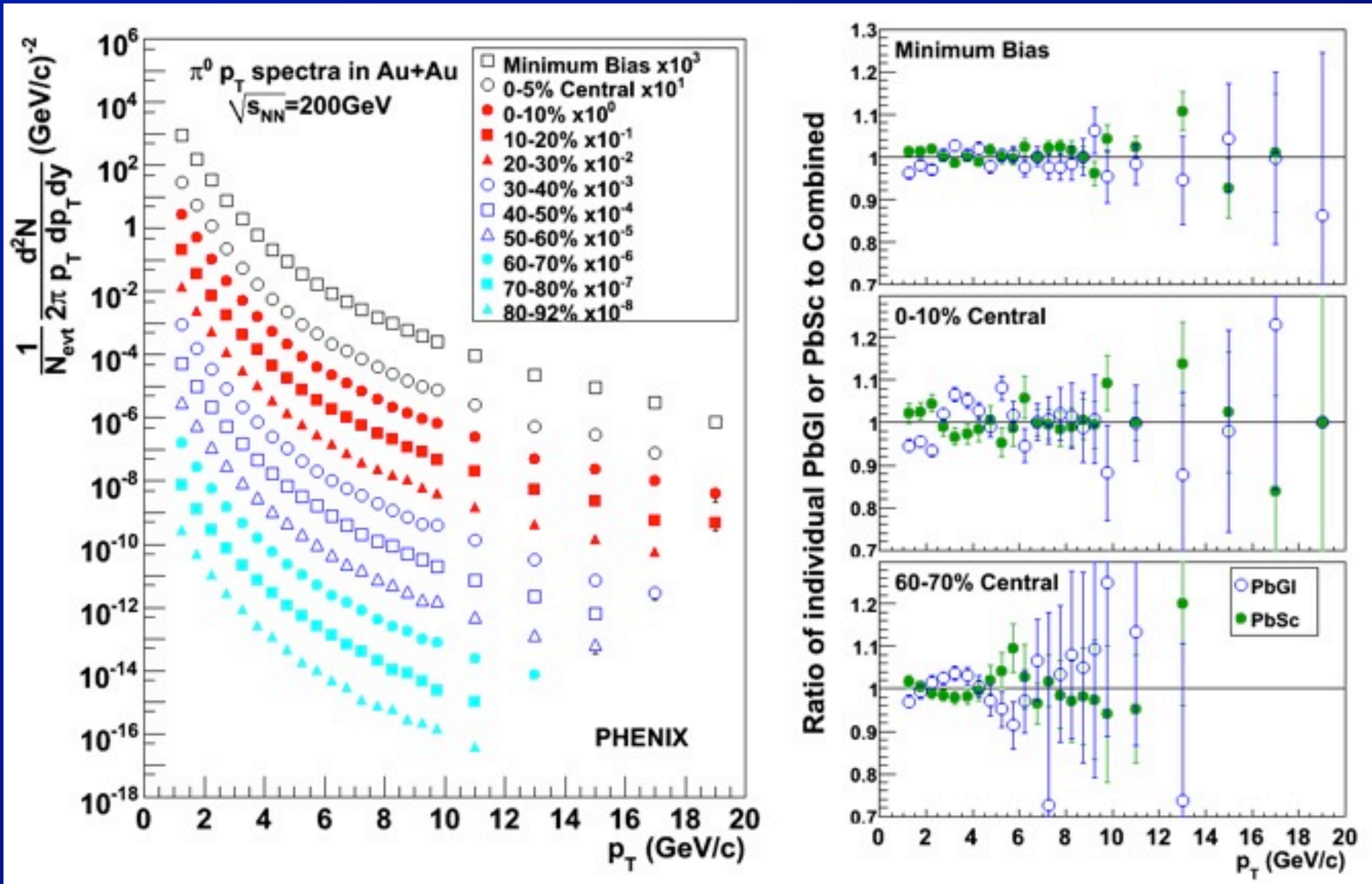


- Limited reach in pT compared to what we are used to in the LHC era.
  - Qualitative features of single hadron suppression already established in 2003.
    - ⇒In particular, apparent weak p_T variation

Single/di-hadron suppression w/ control

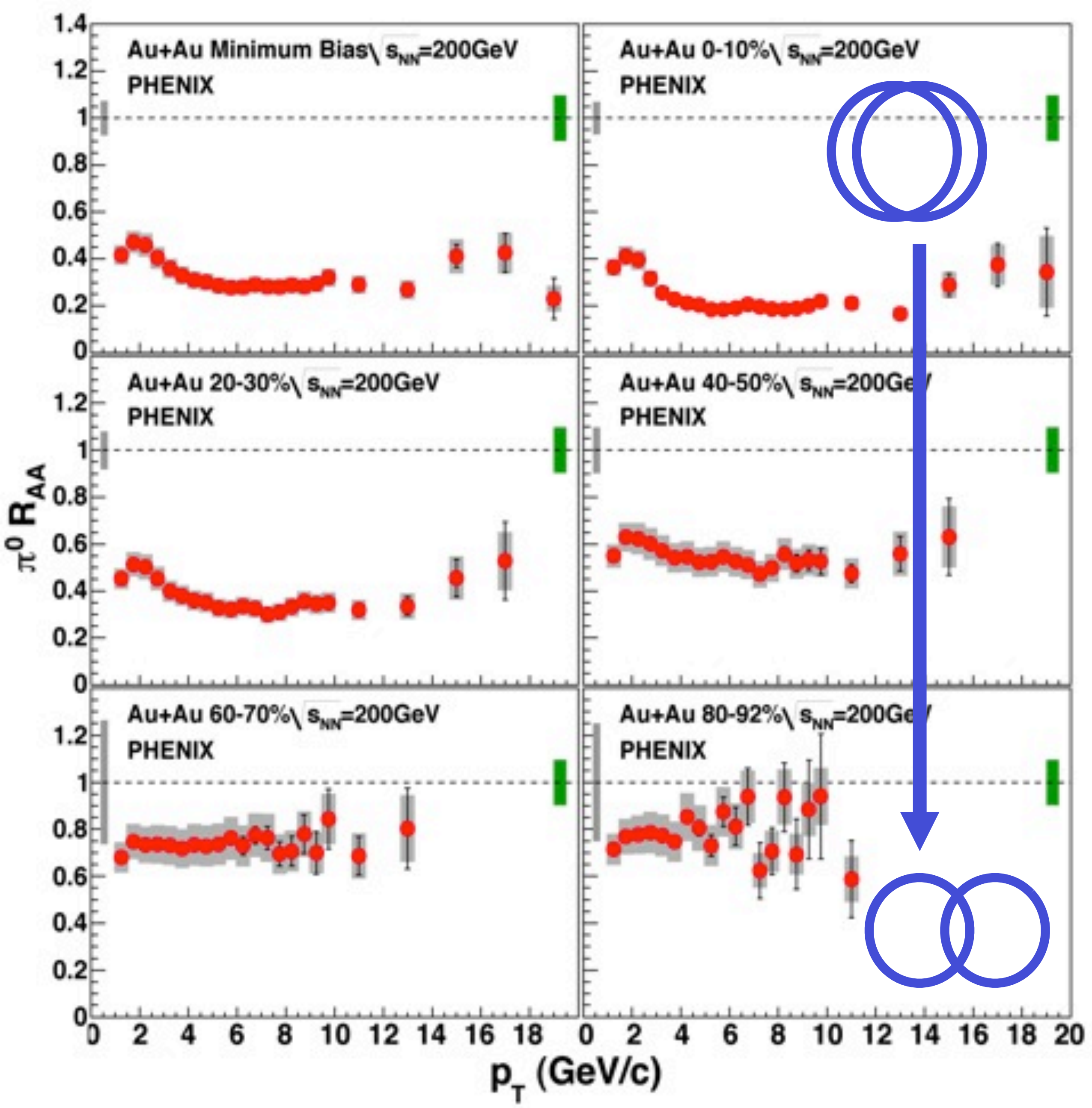


PHENIX Au+Au π^0 Spectra



- Control over systematic errors w/ two measurements using different electromagnetic calorimeter

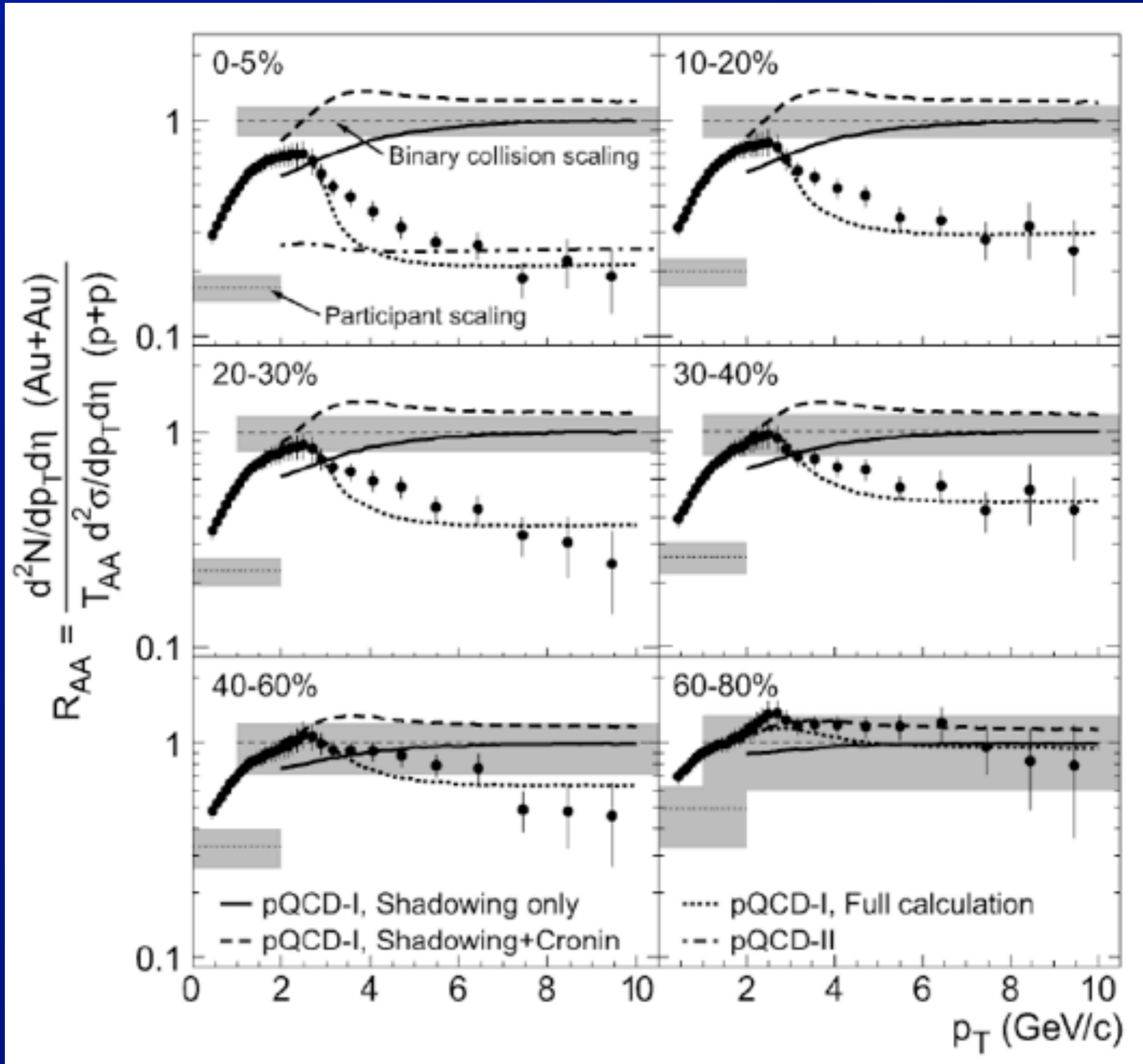
PHENIX Au+Au π^0 R_{AA}



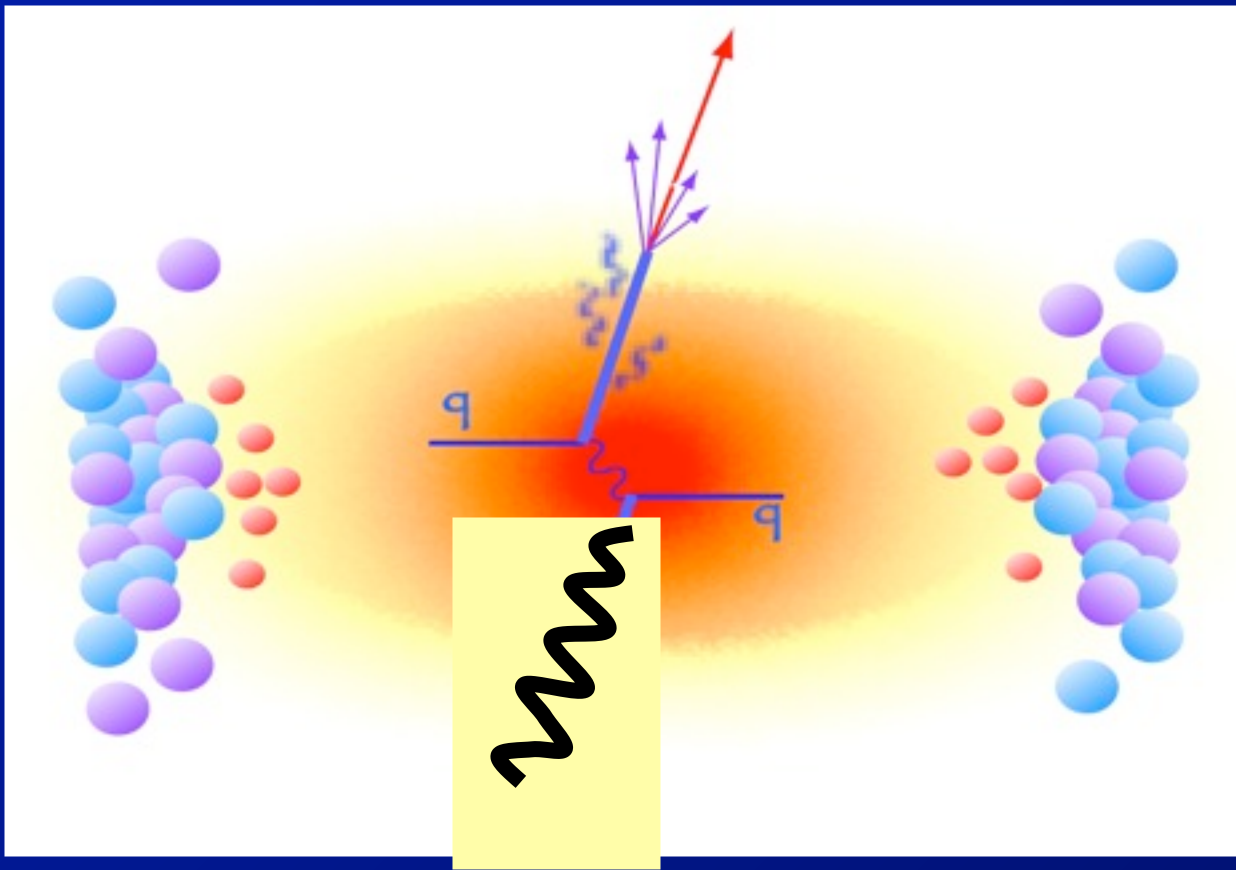
- Factor of ~ 5 violation of factorization in central Au +Au
- Smooth evolution of high-p_T π^0 suppression with centrality.
- ≈ constant for p_T > 4 GeV/c (more)

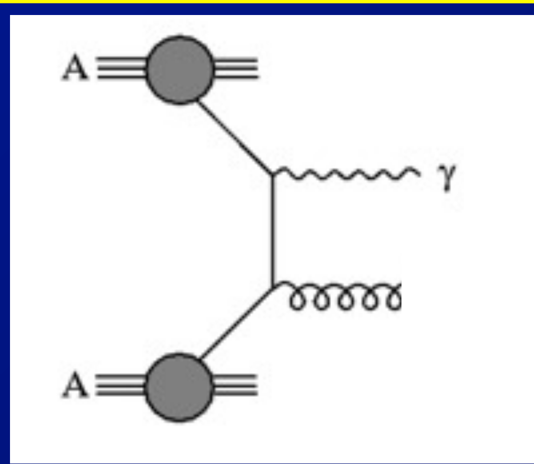
STAR charged hadron suppression

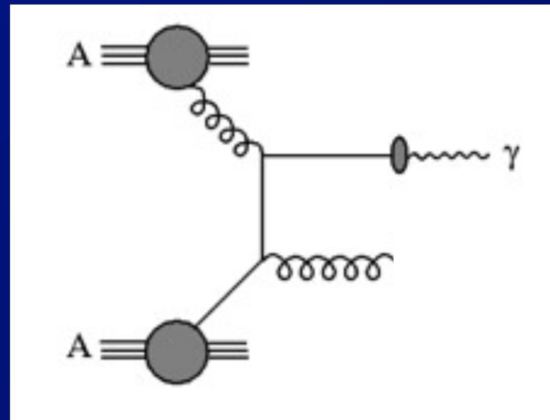
STAR, PRL 91 (2003) 172302



Prompt Photon Production

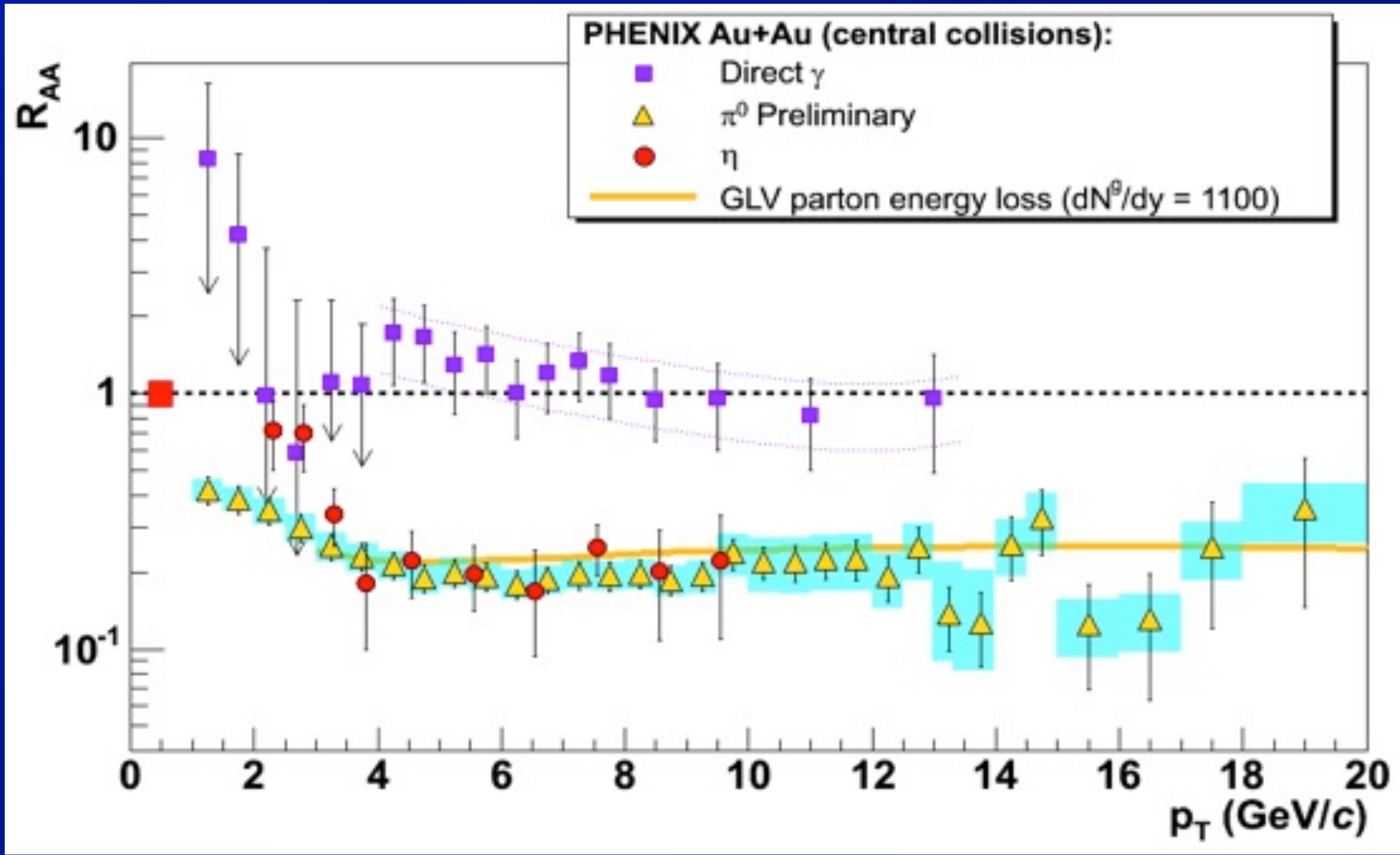






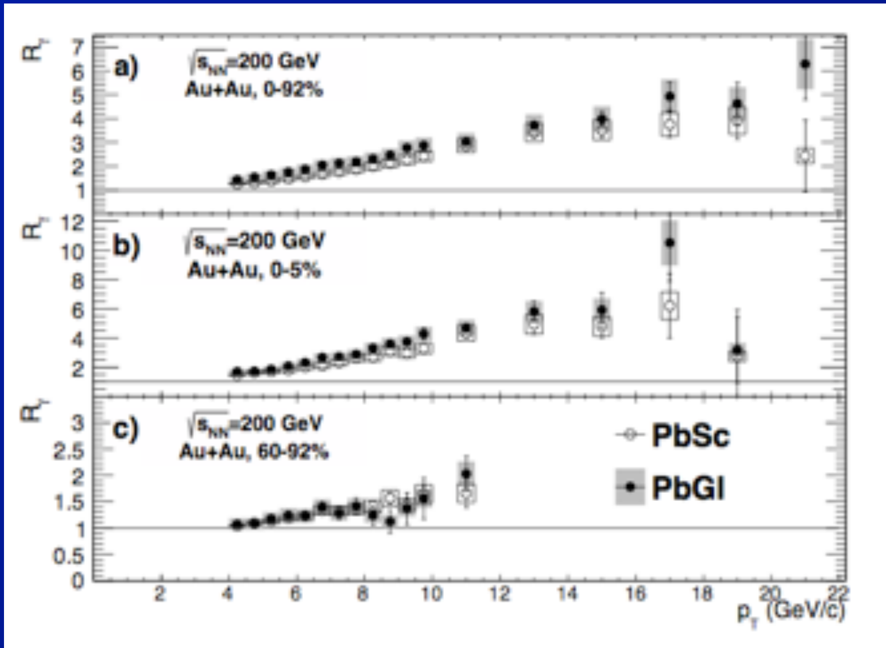
- Prompt photons provide an independent control measurement for jet quenching.
  - Produced in hard scattering processes
  - But, no final-state effects (naively)

Au+Au photon vs hadron R_{AA}

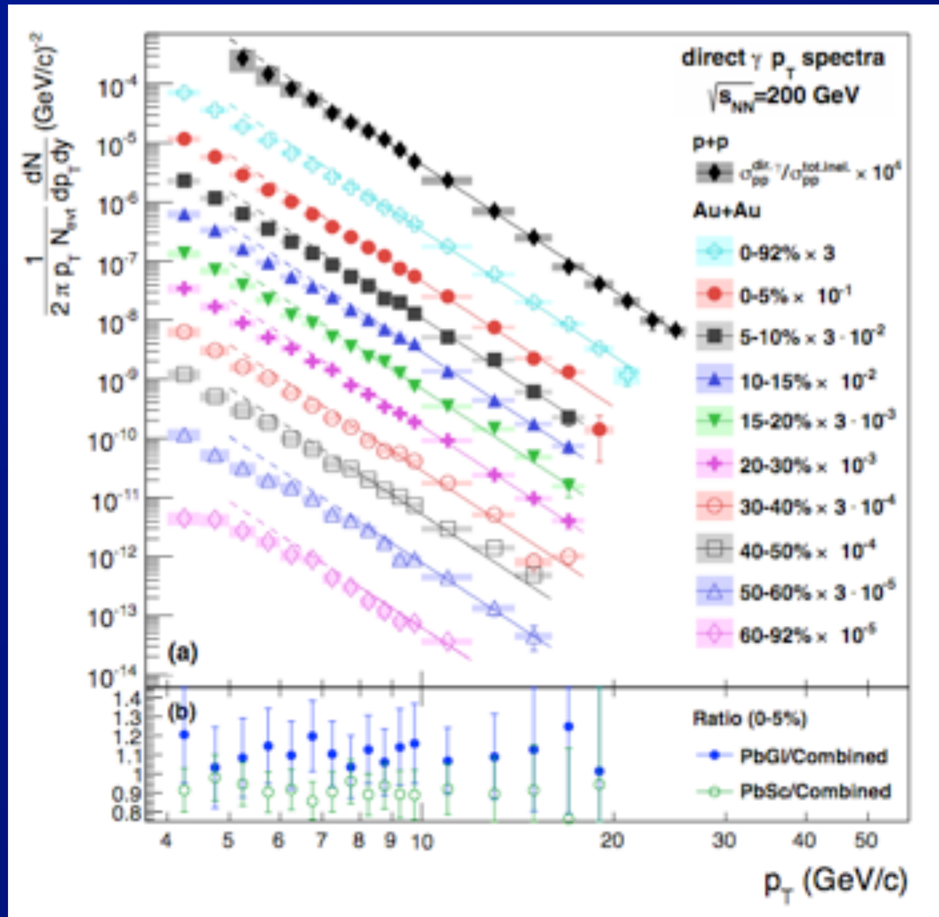


- **Prompt photons in Au+Au consistent with TAB scaling of p+p (factorization)**
  - ⇒**Important test of understanding of hard processes in A+A.**

Photons @ RHIC: more recent



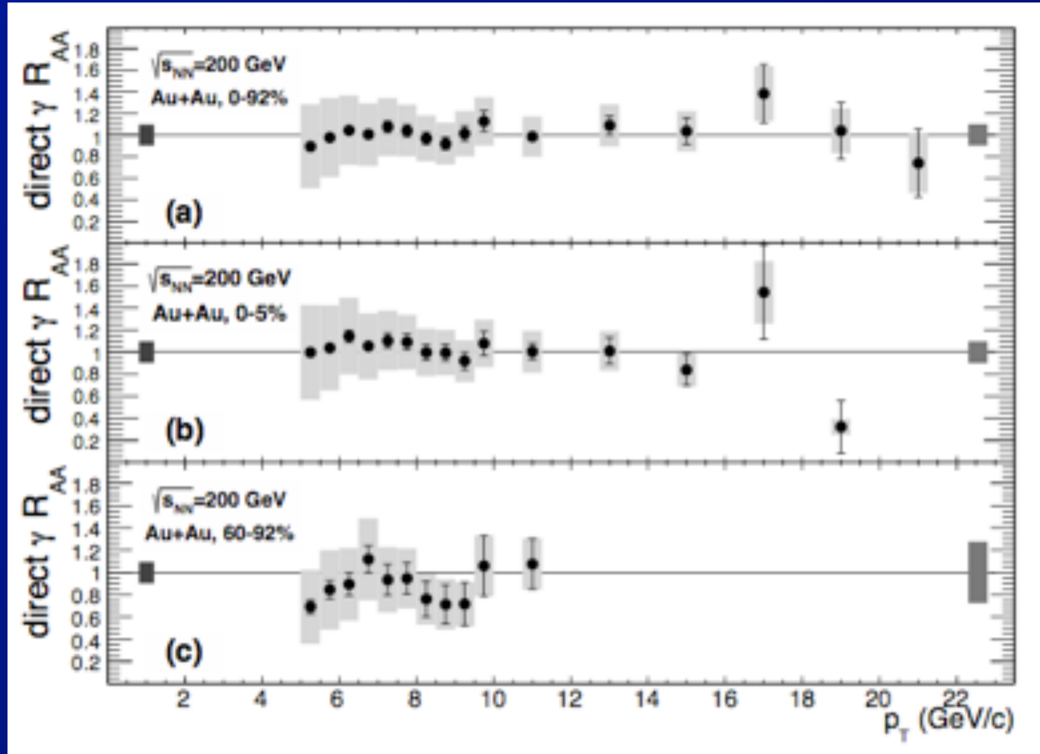
Ratio of total photon to decay photon yields vs p_T

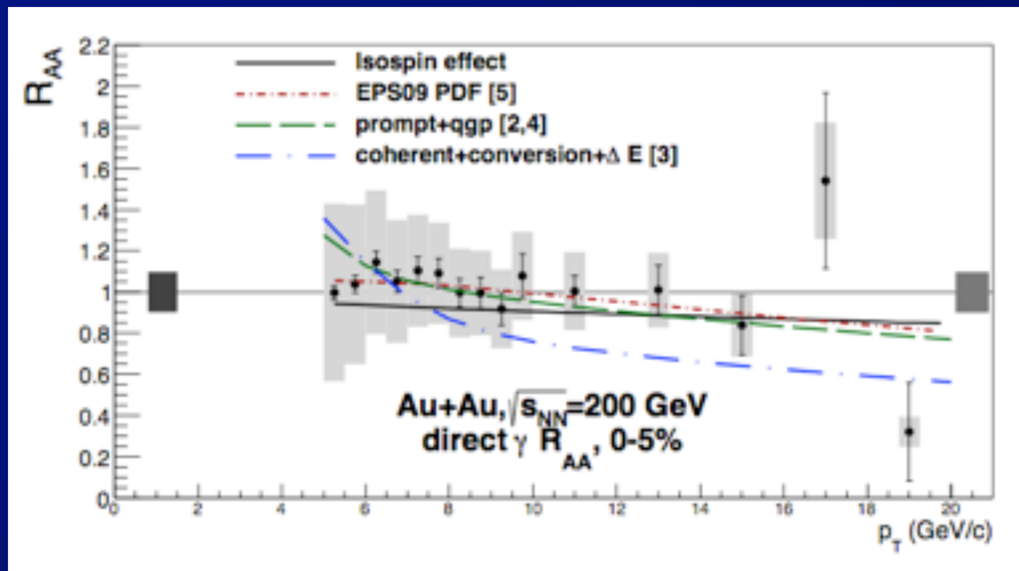


- @RHIC (so far) direct photons measured by subtracting decay photons from π^0, η decay from total photons.

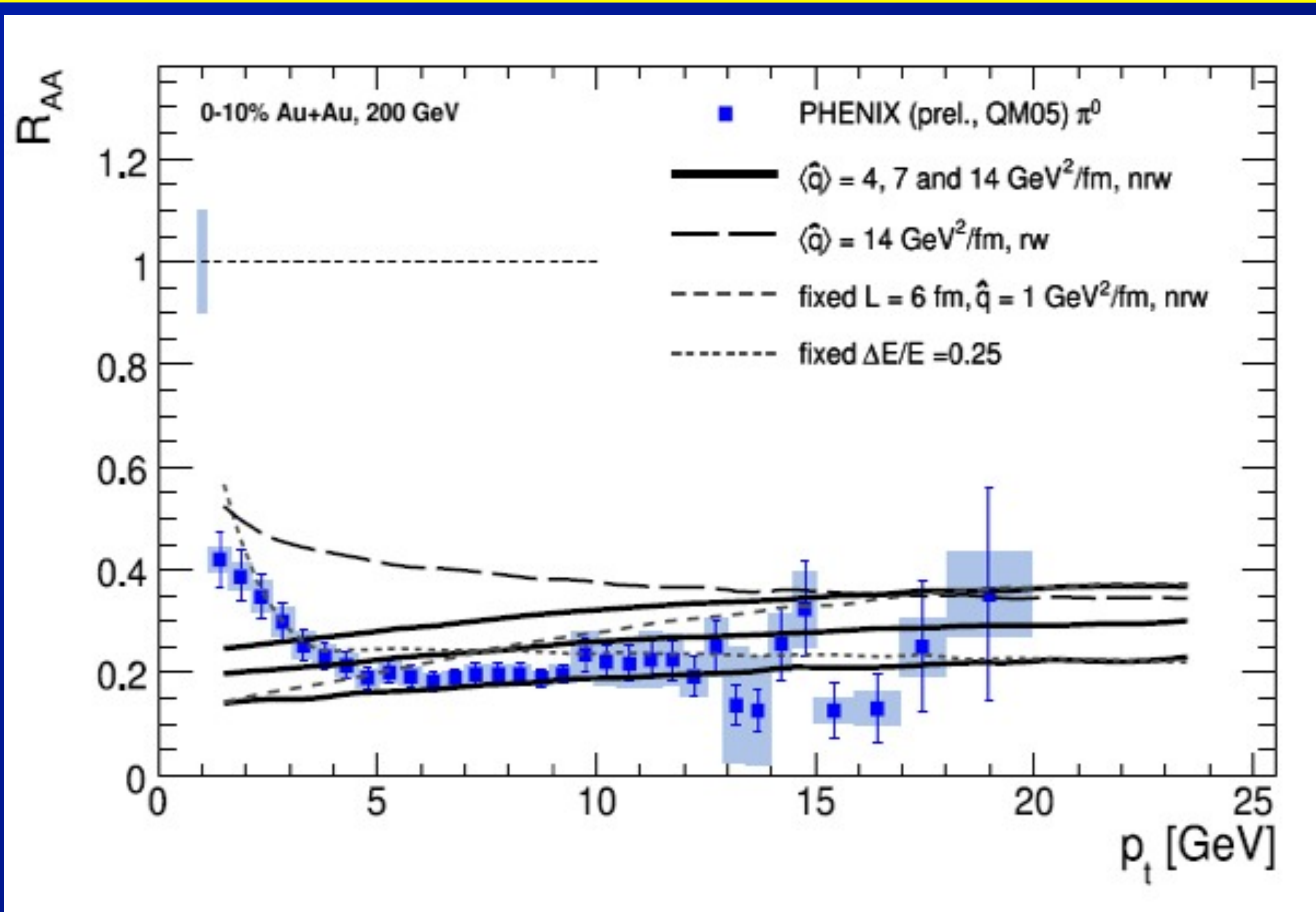
Photons R_{AA} RHIC: more recent

- With improved systematics, extend photon R_{AA} to higher p_T
  - ⇒Consistent with factorization
- But, expect deviations at high p_T
  - Isospin
  - Nuclear PDFs
  - other
  - ⇒Unable to test experimentally





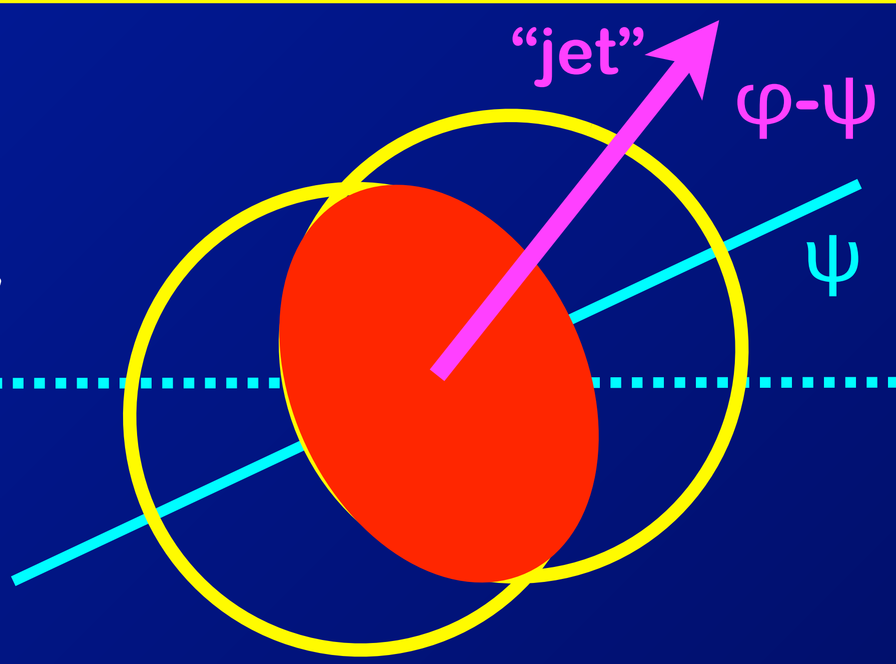
Single hadron and quenching "theory"



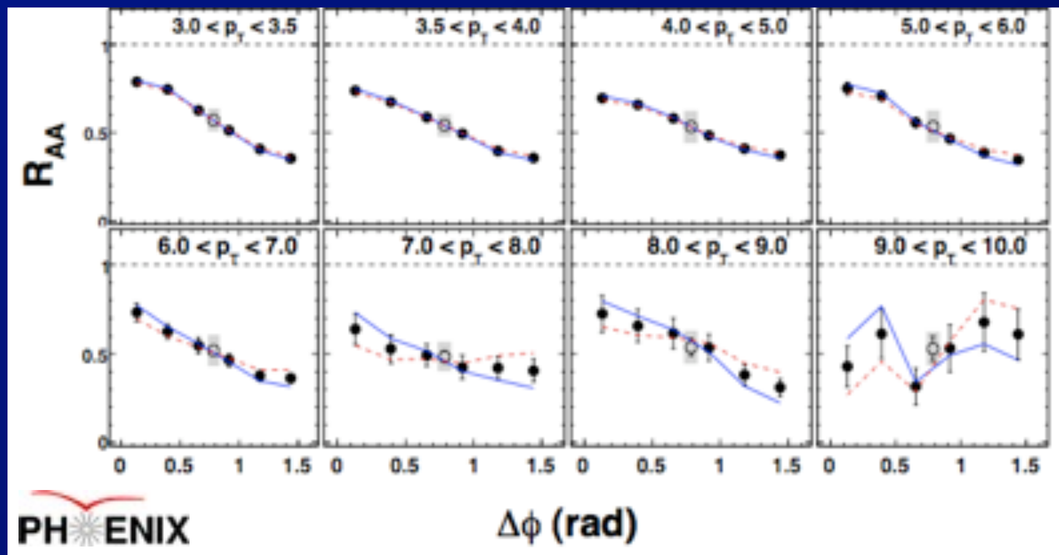
- suggests qhat values >> larger than ones we currently think are appropriate (~ 1

Jet tomography

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

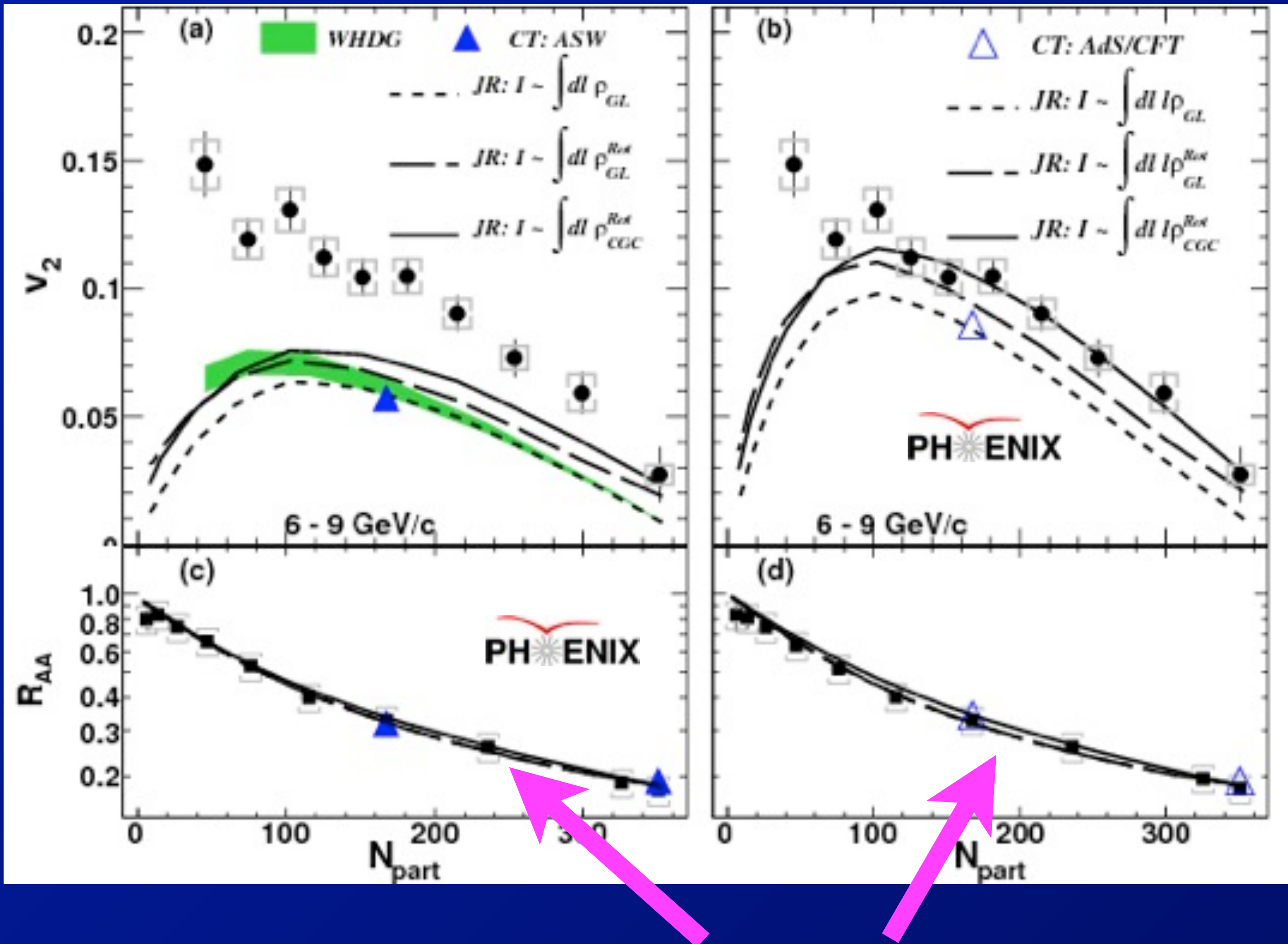


- Measure R_{AA} vs $\Delta\varphi = \varphi - \psi$
- Characterize by amplitude of $\Delta\varphi$ modulation:



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

Single hadron suppression

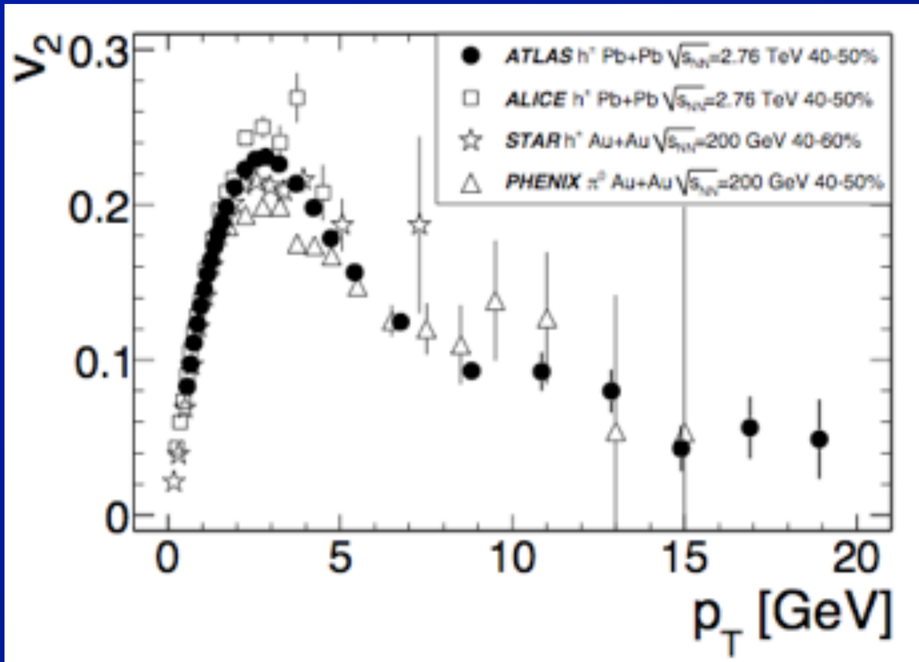


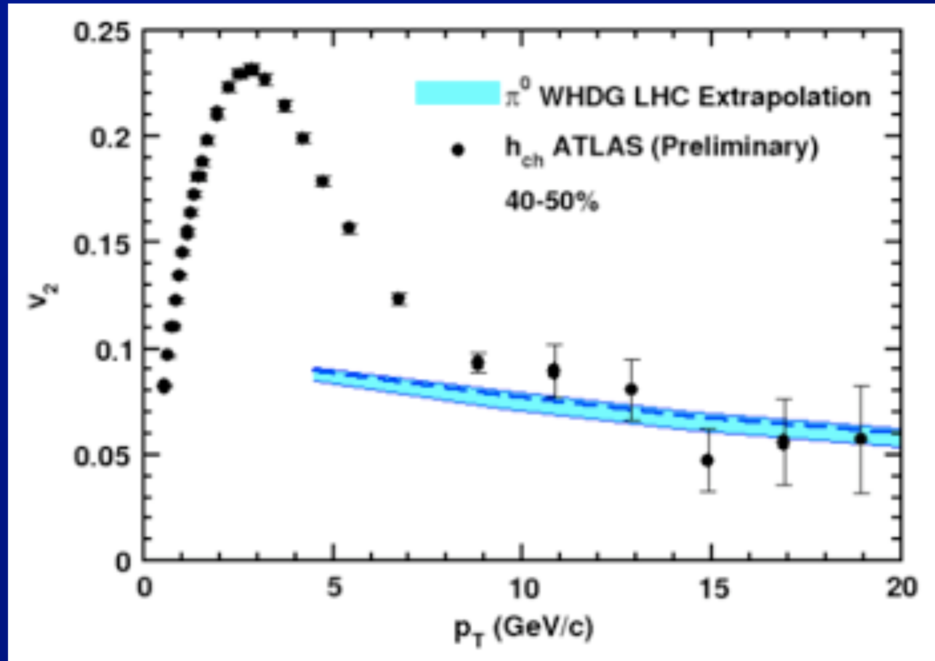
Calculations:

- 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

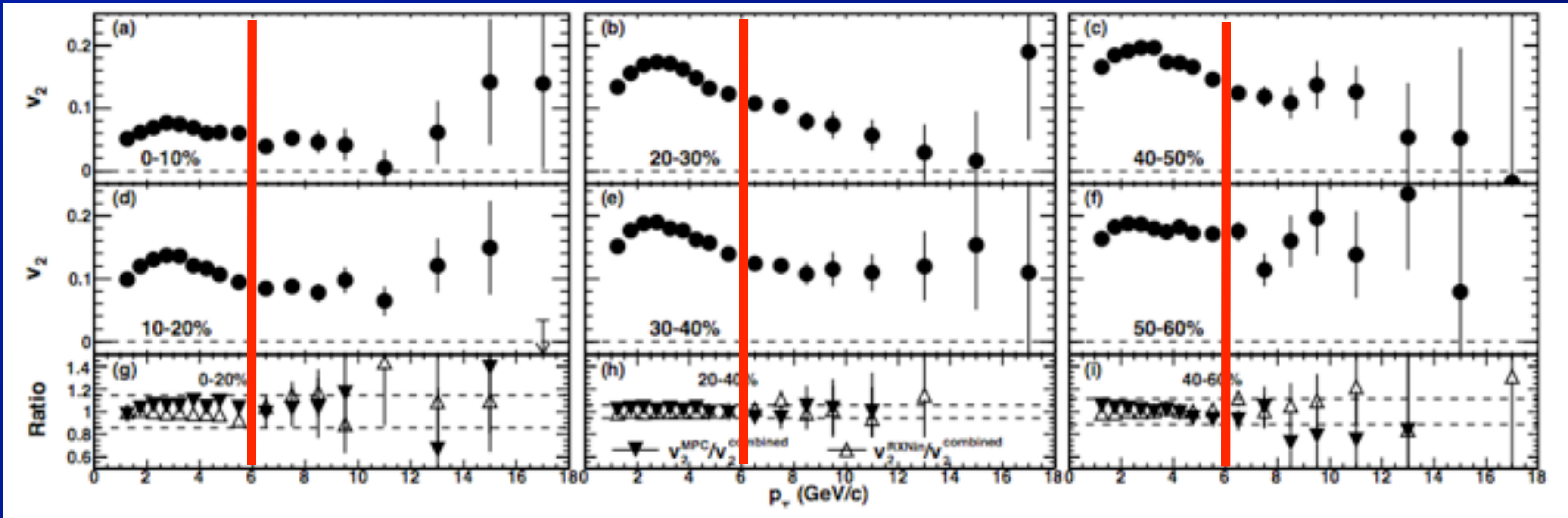
Fast forward … hadron v_2 @ LHC



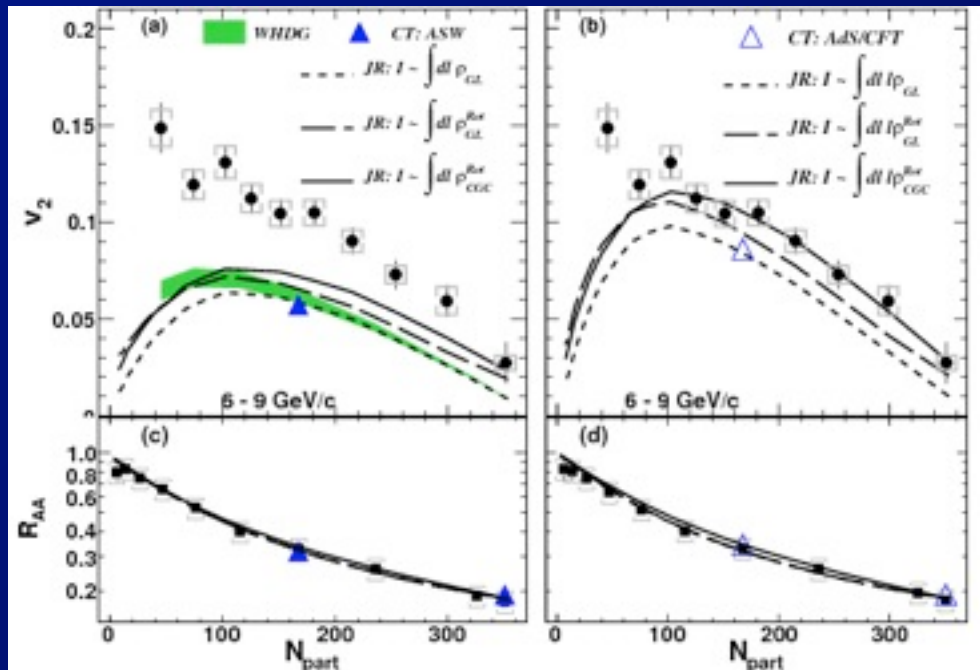


- **Charged hadron $v_2(p_T)$ from ATLAS**
  - Compared to PHENIX π^0 results (beware)
    - ⇒ Surprising agreement
- **Compared to energy loss calculation**
  - Reasonable agreement for $p_T > 10$ GeV
    - ⇒ Likely contamination of $v_2(p_T)$ from strong elliptic flow in underlying event for lower p_T

PHENIX $v_2(p_T)$

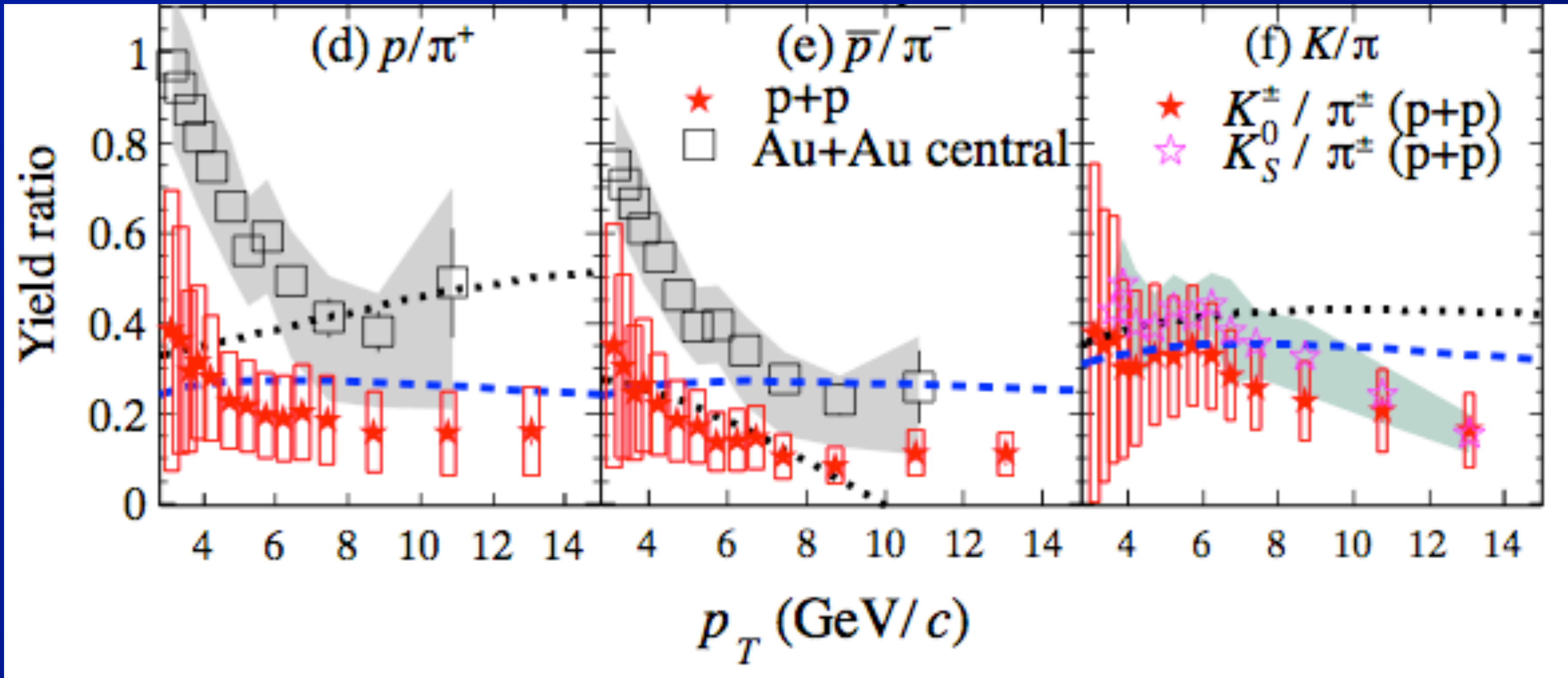


- PHENIX "strong coupling" result dominated by yield at 6 GeV/c.
  - ⇒ Likely from p_T region contaminated by flow



Single hadron R_{AA}, PID

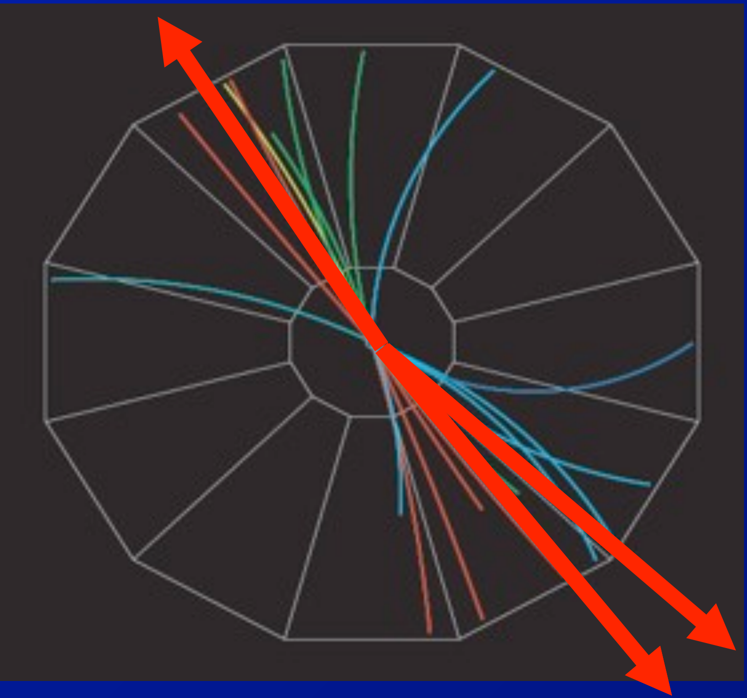
STAR, PRL 108 (2012) 072302



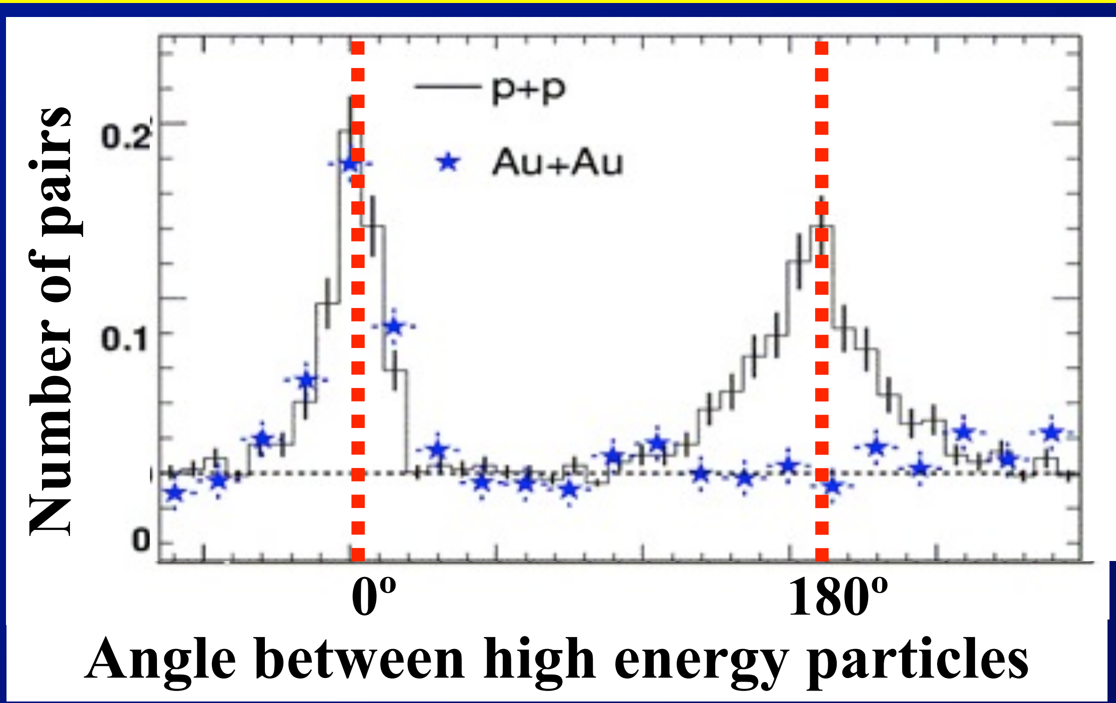
- Indications that the yield ratios at high p_T are approaching "vacuum" values
  - In contrast to earlier results.
    - ⇒But, important to evaluate hadron species composition within jets at low p_T

STAR Experiment: “Jet” Observations

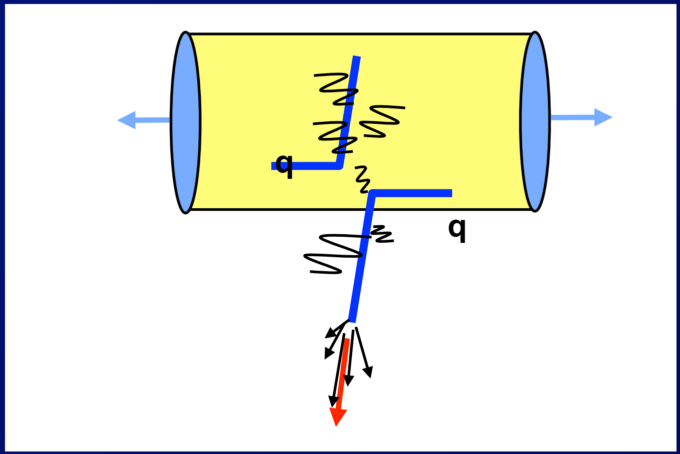
proton-proton jet event



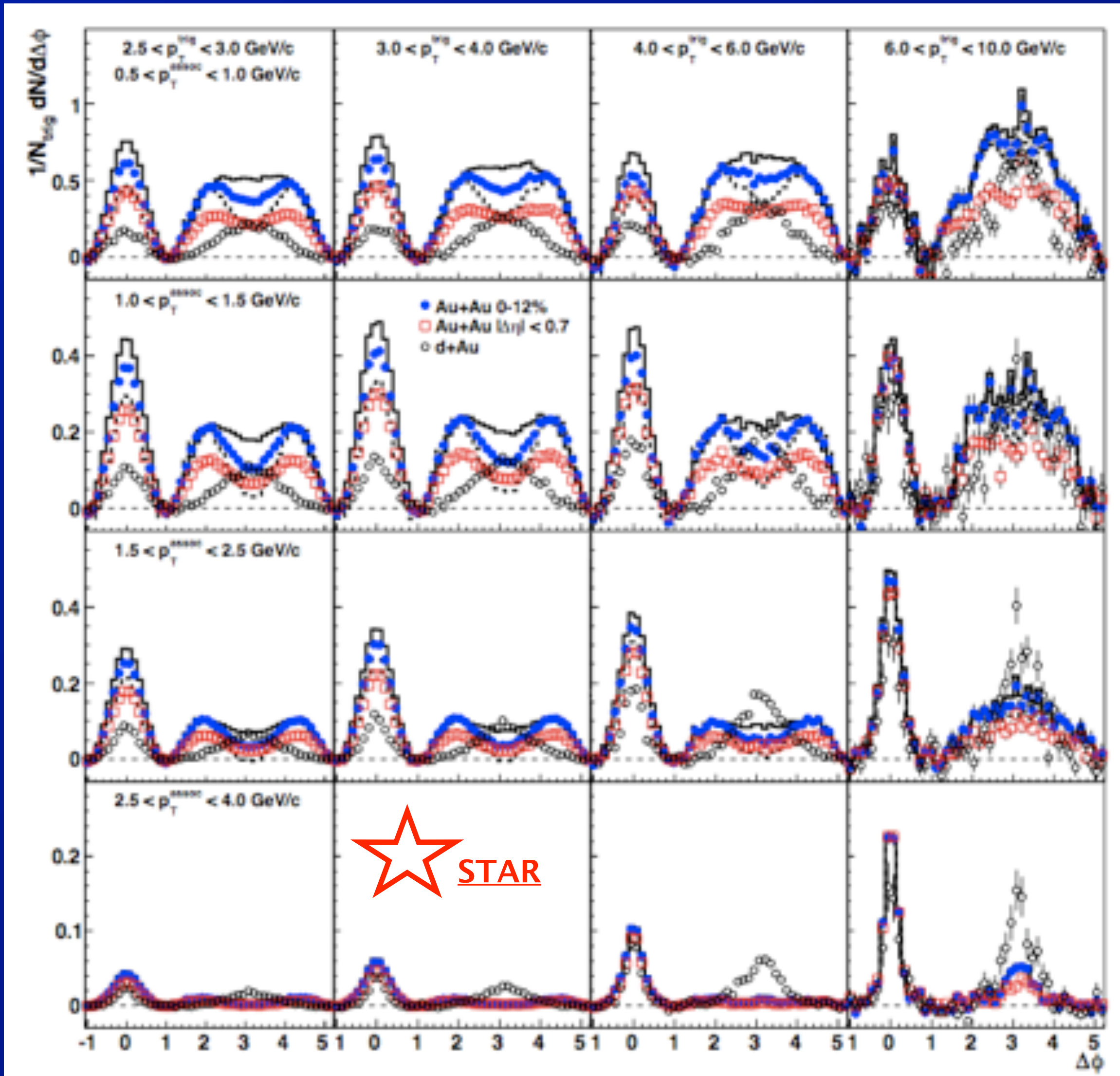
Analyze by measuring (azimuthal) angle between pairs of particles



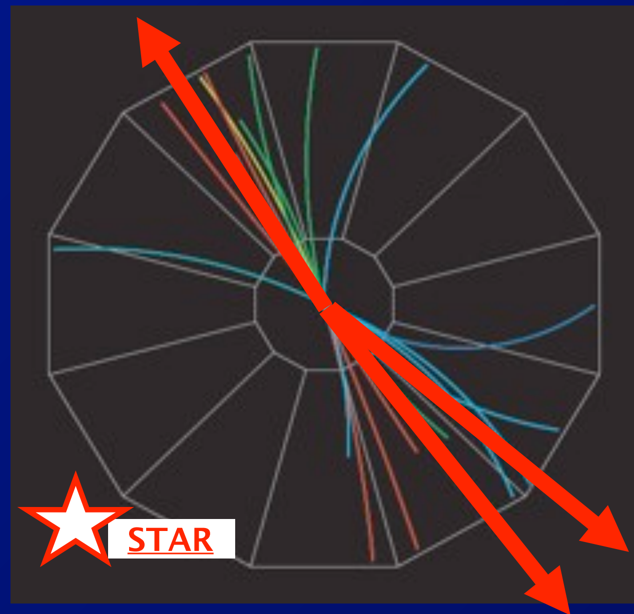
- In Au-Au collisions we see one “jet” at a time
- Strong jet quenching
- Enhanced by surface bias



Two-particle correlations



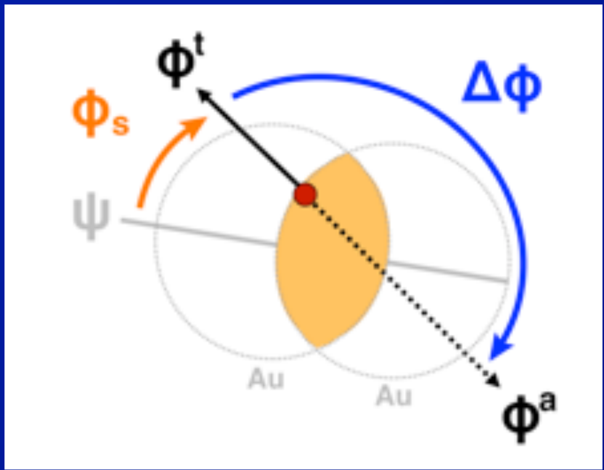
Indirect dijet measurement via dihadron correlations

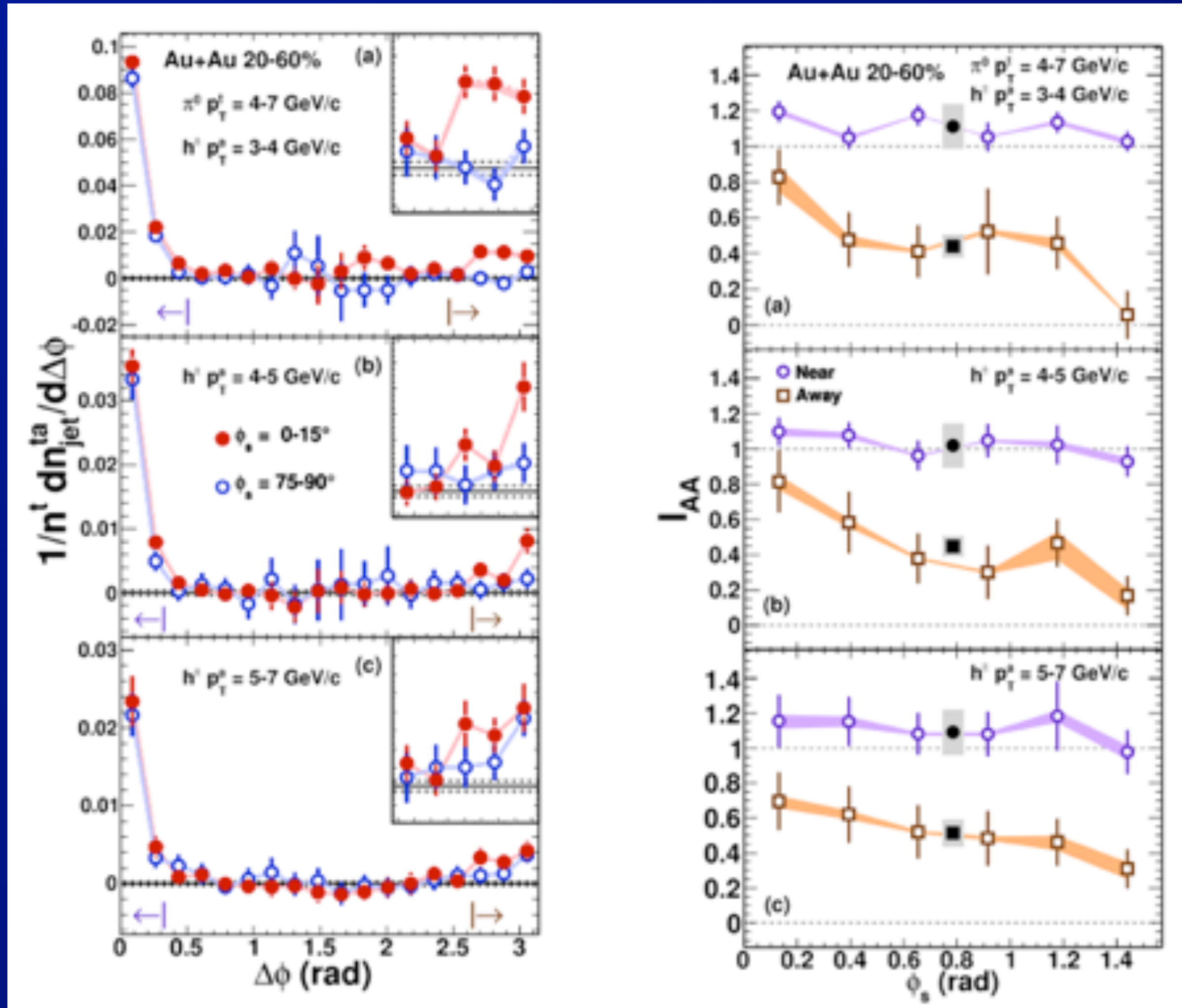


STAR,
Phys. Rev. C82 (2010) 024912

- 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

Most differential measurement @ RHIC?

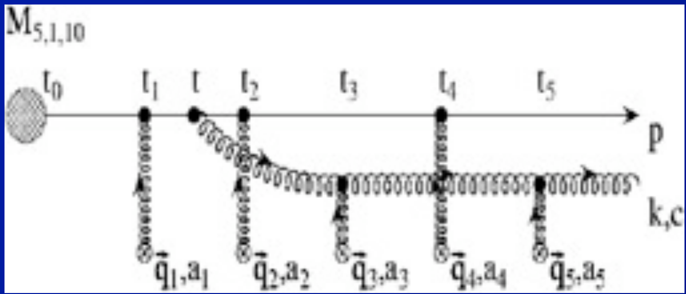




- Detailed, time consuming (~ 4 man-years) analysis. No theoretical comparisons.

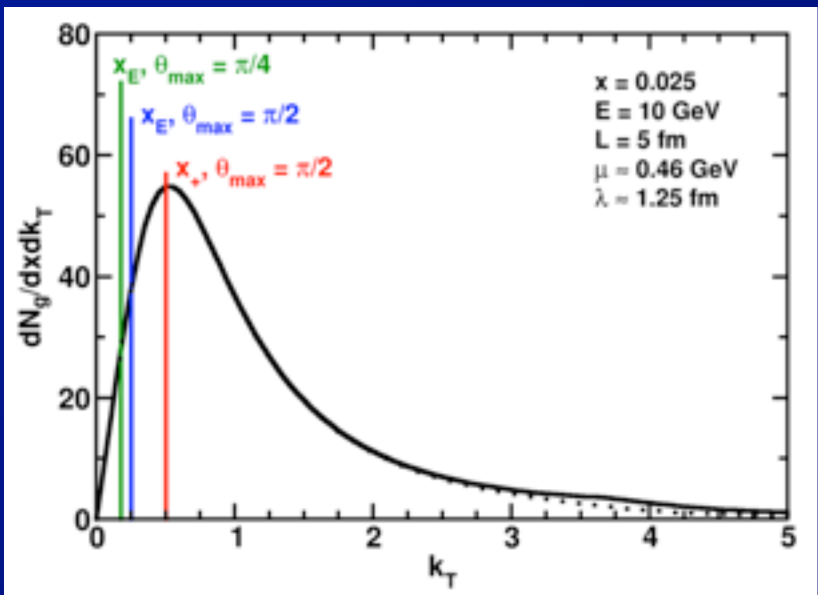
⇒Why?

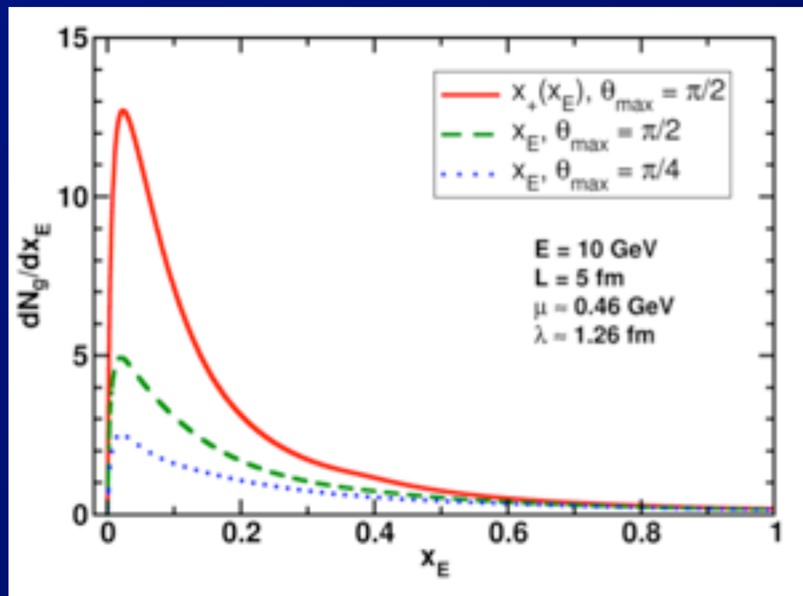
Theoretical problems (e.g.)



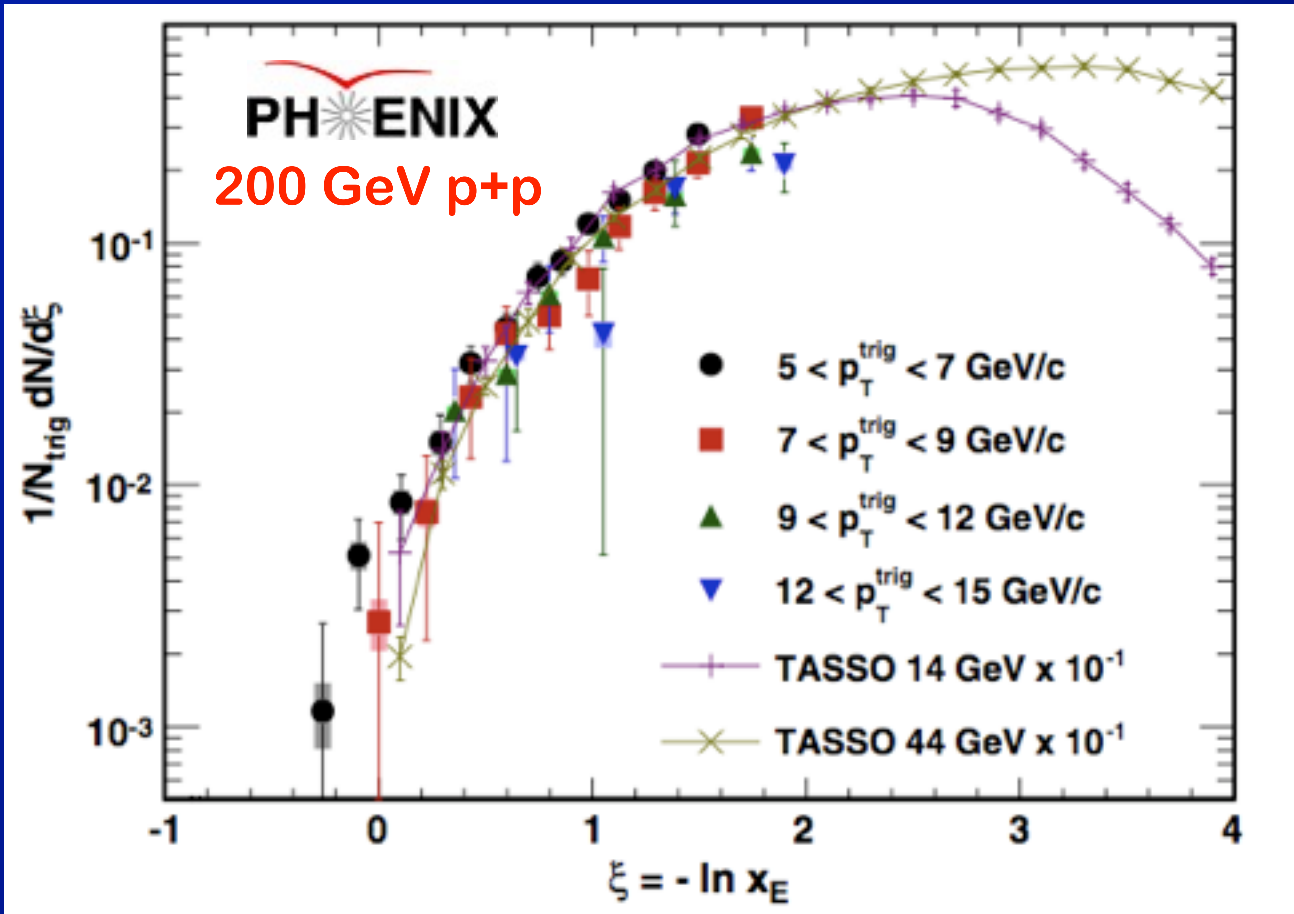
$$\frac{dN_g}{dx} = \frac{8C_R\alpha_s\mu^2}{\pi\,x}\frac{L}{\lambda}\int dq_T dk_T \frac{q_T^3}{(4xE/L)^2+(q_T^2+\beta^2)^2} \times \frac{k_T}{k_T^2+\beta^2}\frac{k_T^2(k_T^2+\mu^2-q_T^2)+\beta^2(q_T^2+\mu^2-k_T^2)}{\left((k_T-q_T)^2+\mu^2\right)^{3/2}\left((k_T+q_T)^2+\mu^2\right)^{3/2}}$$

- **Gluon emission kernel used in many energy loss calculations (from collinear approximation)**
  - But application violates approximation
  - Collinear approximation not unique
    - ⇒Different versions yield very different results

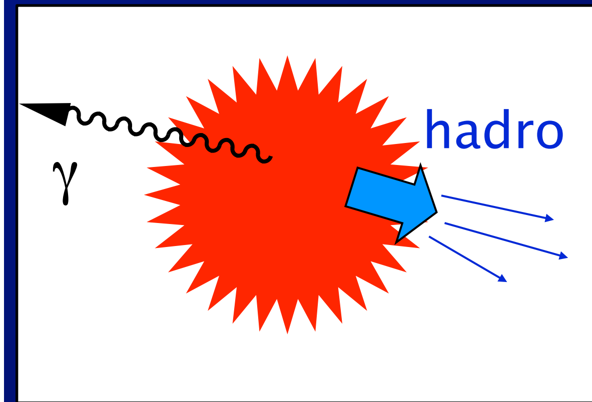




First step towards jets: γ-hadron



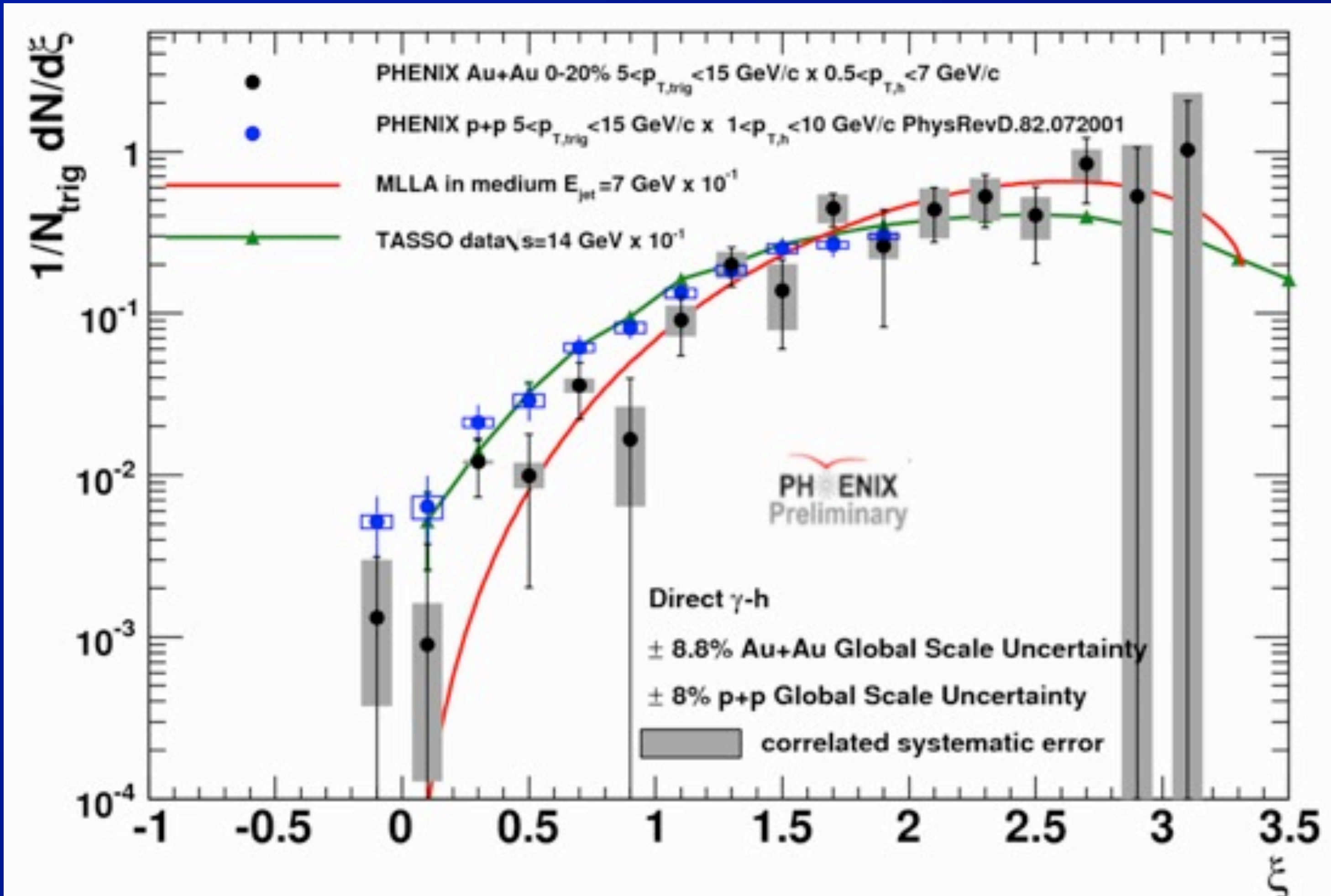
PHENIX,
Phys. Rev. D82
(2010) 072001



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

- 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)

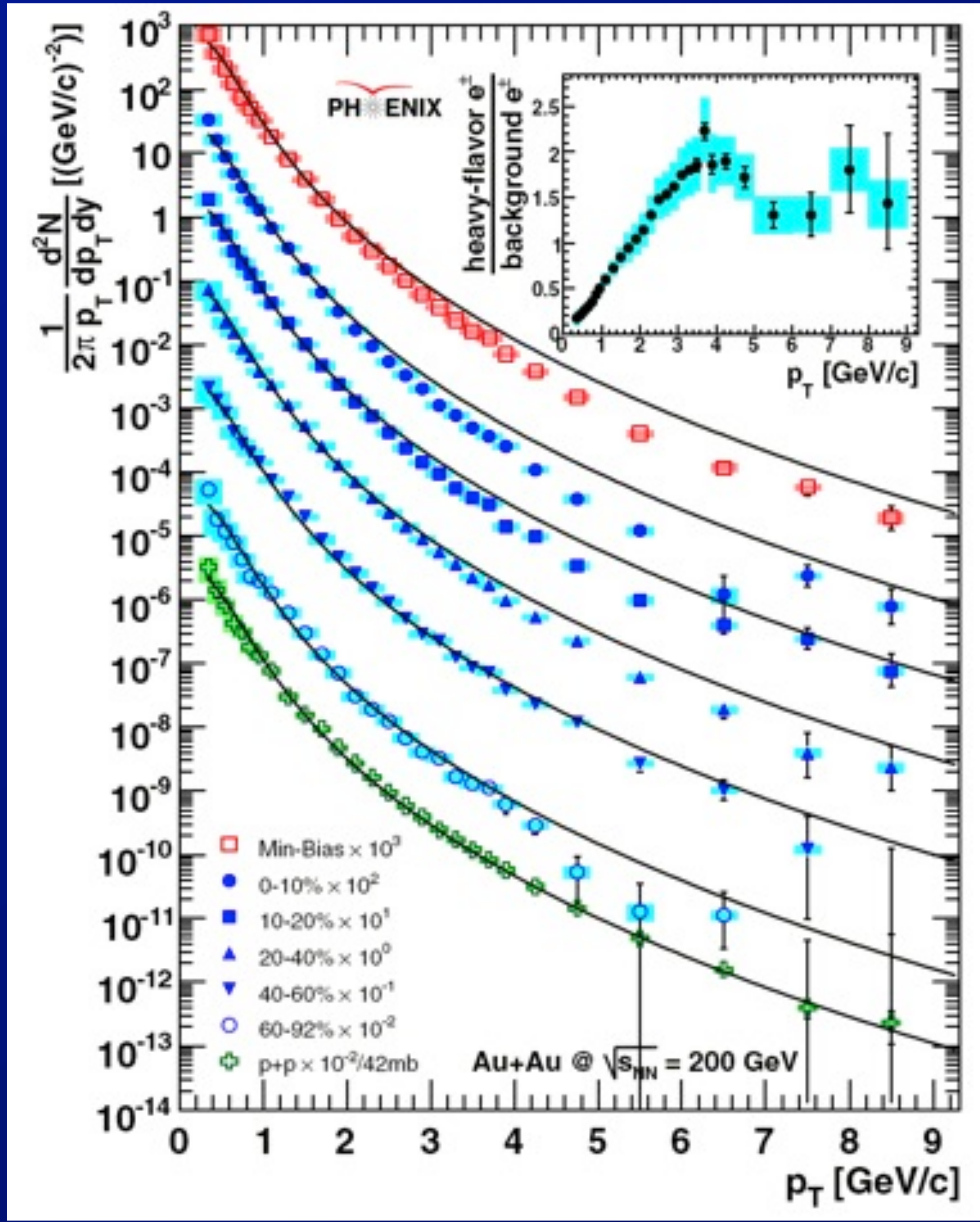


- Observe suppression in yield of large z (small ξ) fragments in (central) Au+Au collisions
  - Red curve shows medium-modified MLLA calculations by Borghini and Wiedemann.

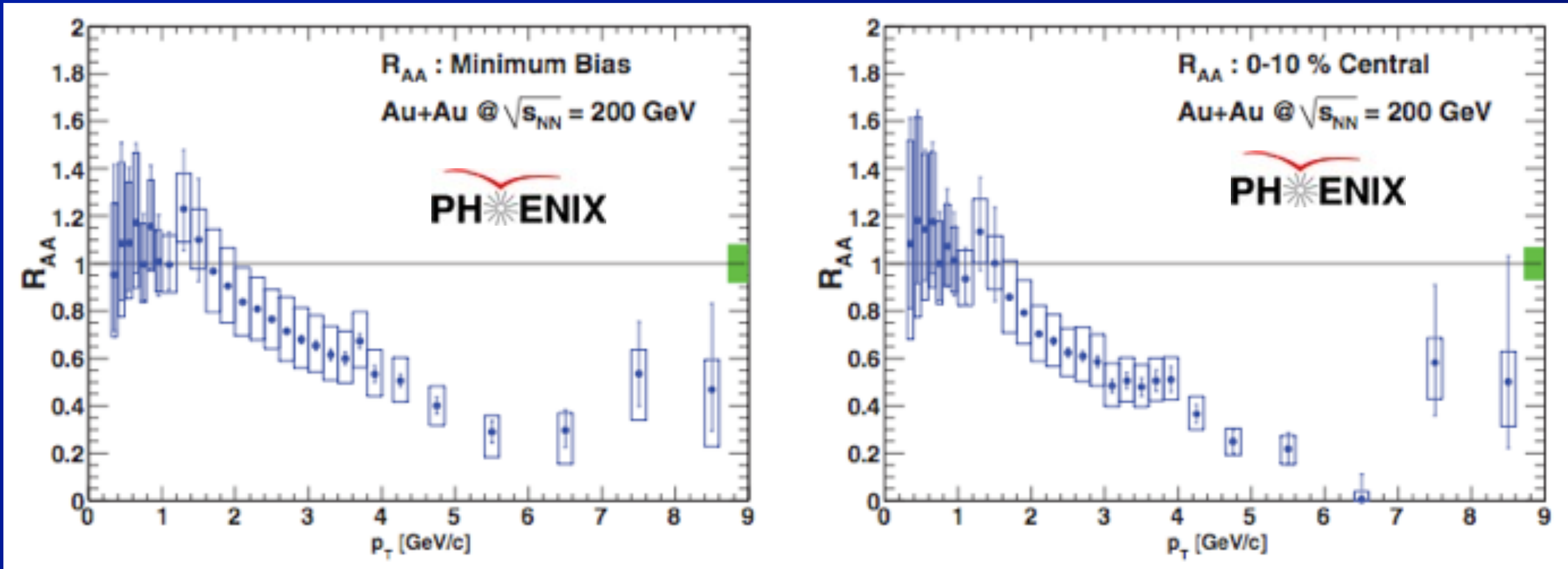
PHENIX: Heavy Quark Quenching

- Measure via semi-leptonic decays
  - Single $e^+ + e^-$ spectrum
- 2 methods to estimate (large) backgrounds
  - Direct estimate of backgrounds (cocktail)
  - Data taken with extra converter material

  ⇒Directly measure

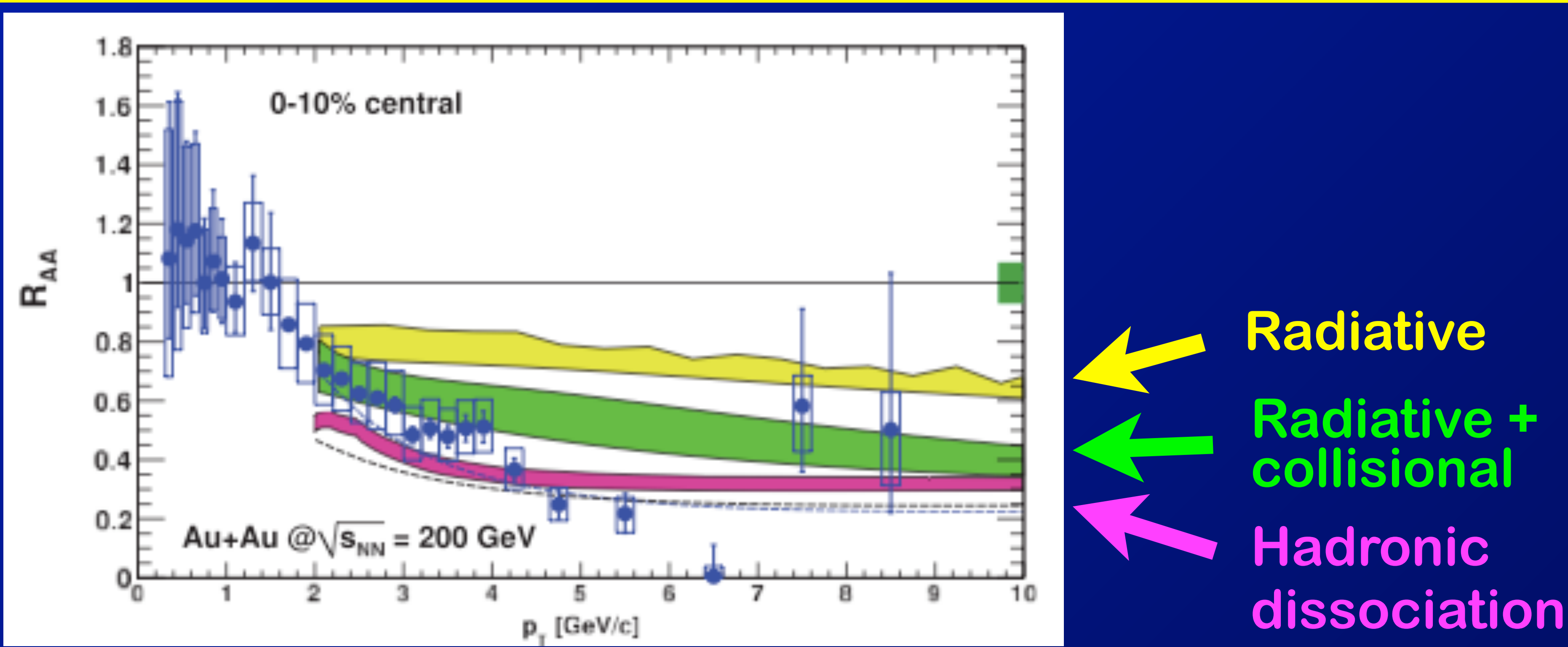


Heavy quark suppression



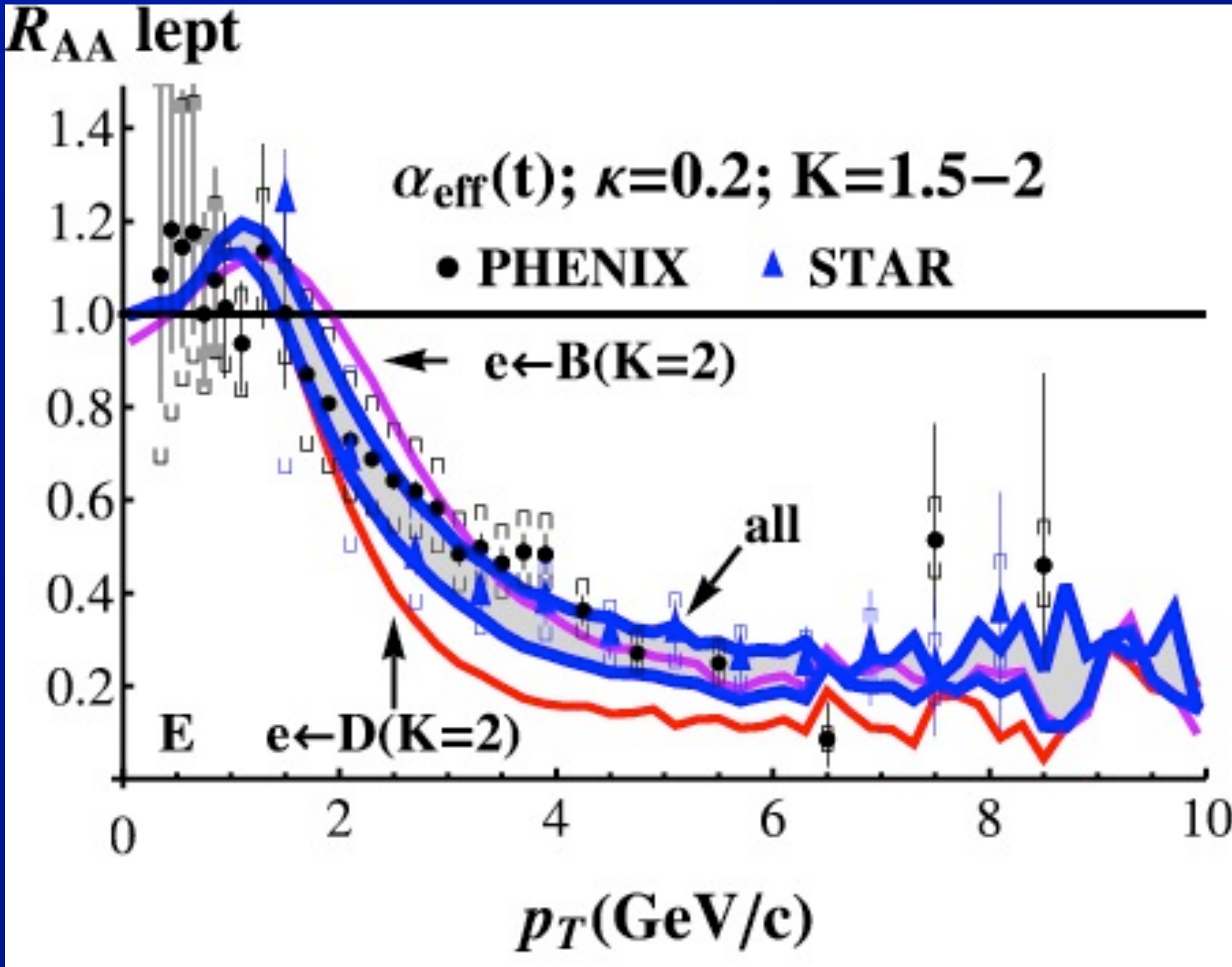
- Measure heavy quark production via semi-leptonic decays (B+D) to electrons
  - See suppression comparable to light mesons
    - ⇒Unexpected due to mass suppression of radiative contributions, especially for b quark.

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

RHIC – Where We Stand

- Unequivocal observation of substantial quark/gluon energy loss in plasma.
  - Significant theoretical uncertainties
    - ⇒Role of collisional energy loss.
    - ⇒Differences in approximations.
    - ⇒Choice of strong coupling constant.
    - ⇒Description of medium
    - ⇒ …
- 13 years after start of RHIC operation, we still do not have unique, complete understanding of energy loss physics.
    - ⇒Need more complete empirical understanding of quenched jets.