Fragmentation Functions in-Medium Two Particle Correlations and Jets in PHENIX at RHIC

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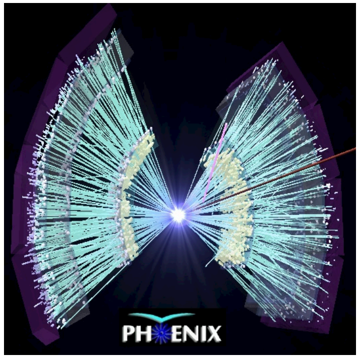
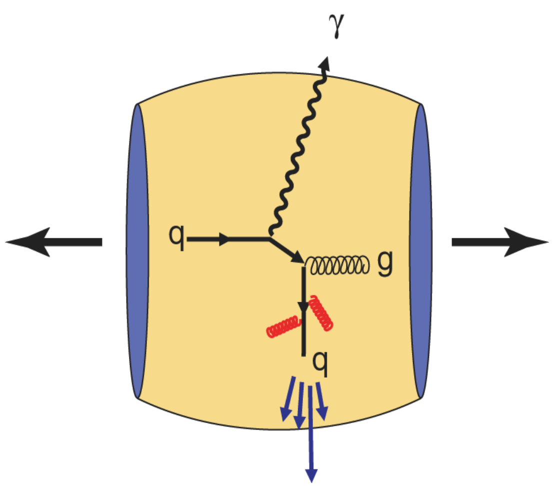
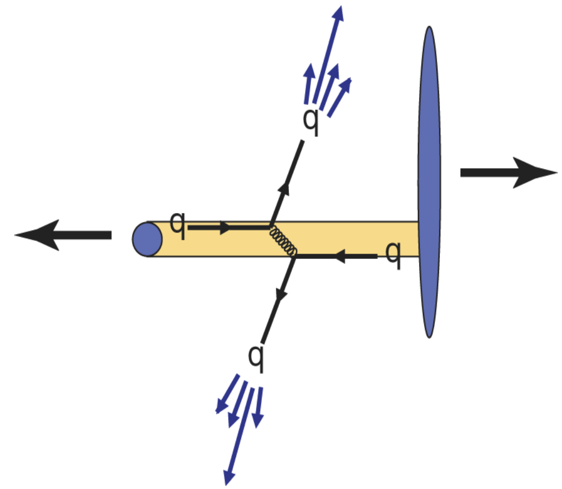


PANIC11
July 24-29, 2011
MIT, Cambridge, MA

Hard scattering as a probe of the medium: Hot (AA) vs Cold pA Nuclear Matter Effects



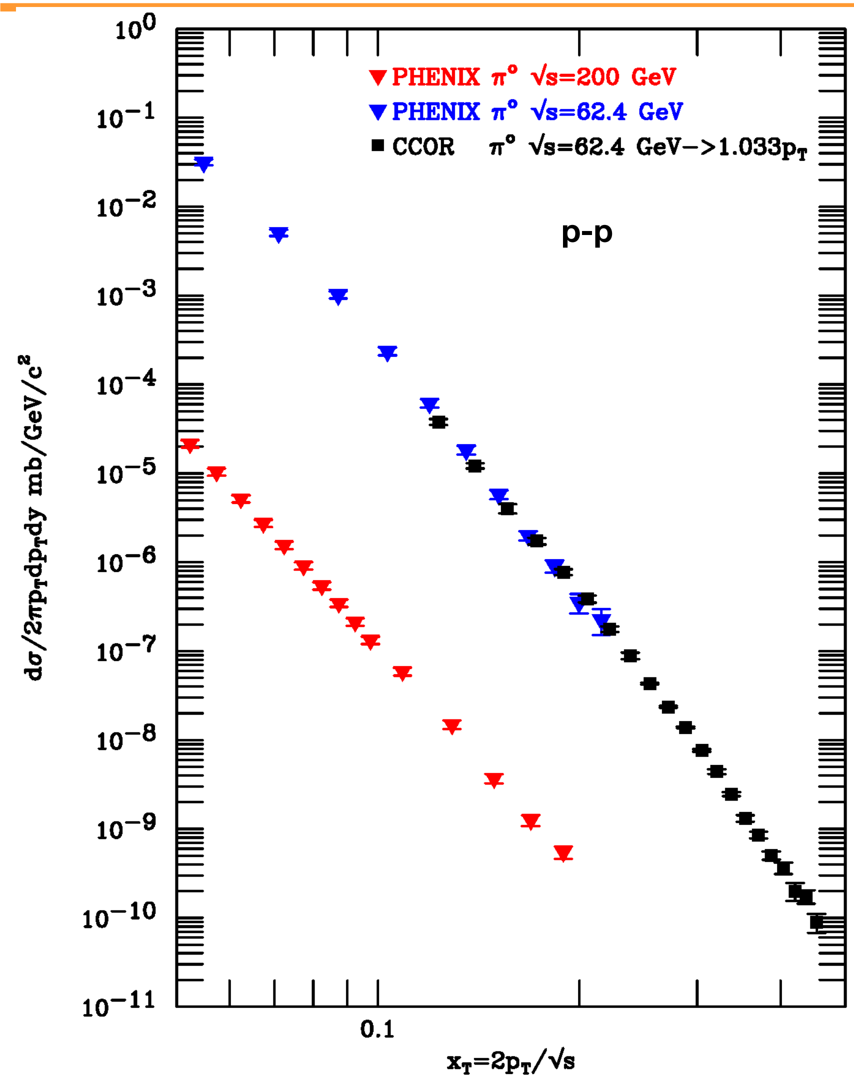


Hard scattering of partons in the initial collision is in-situ internal probe of medium. Do quarks and gluons lose energy in the medium? If so exactly how?

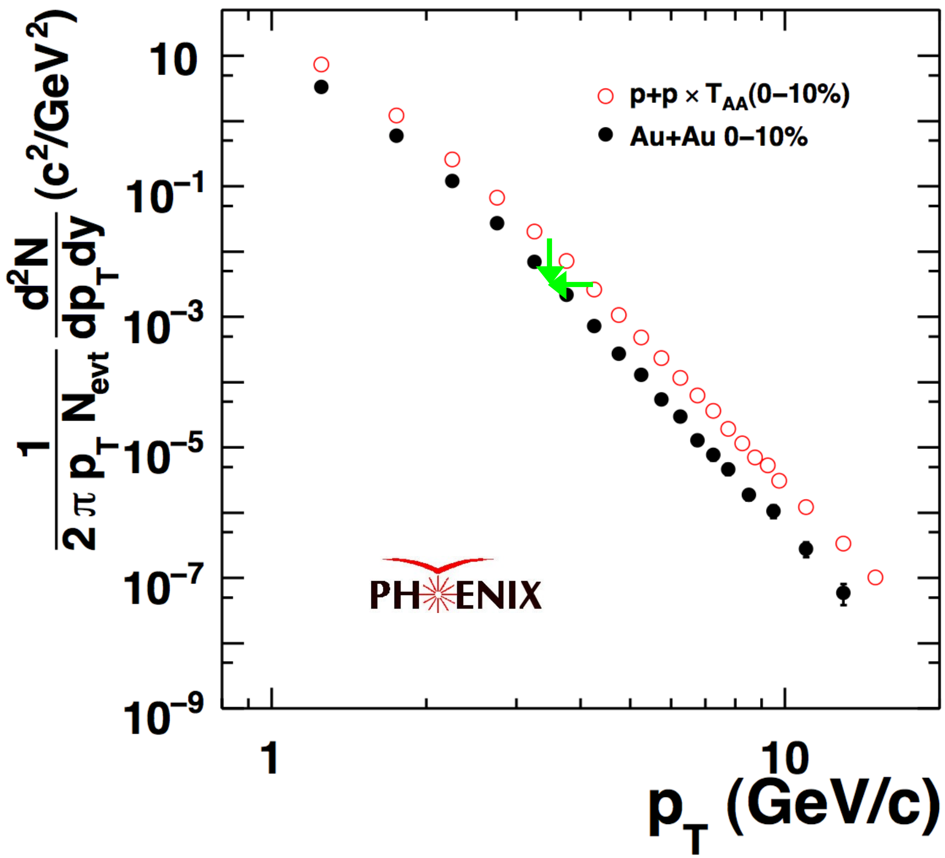
In p+A or d+A, medium is small, (1 nucleon wide) or non-existent. This is baseline for any cold nuclear matter effect in initial collision

- RHIC is versatile
  - ✓ Can collide any nuclear species on any other

ISR π^0 vs RHIC p-p $\Rightarrow$ RHIC pp vs AuAu



π^0 are suppressed in Au+Au eg 200 GeV

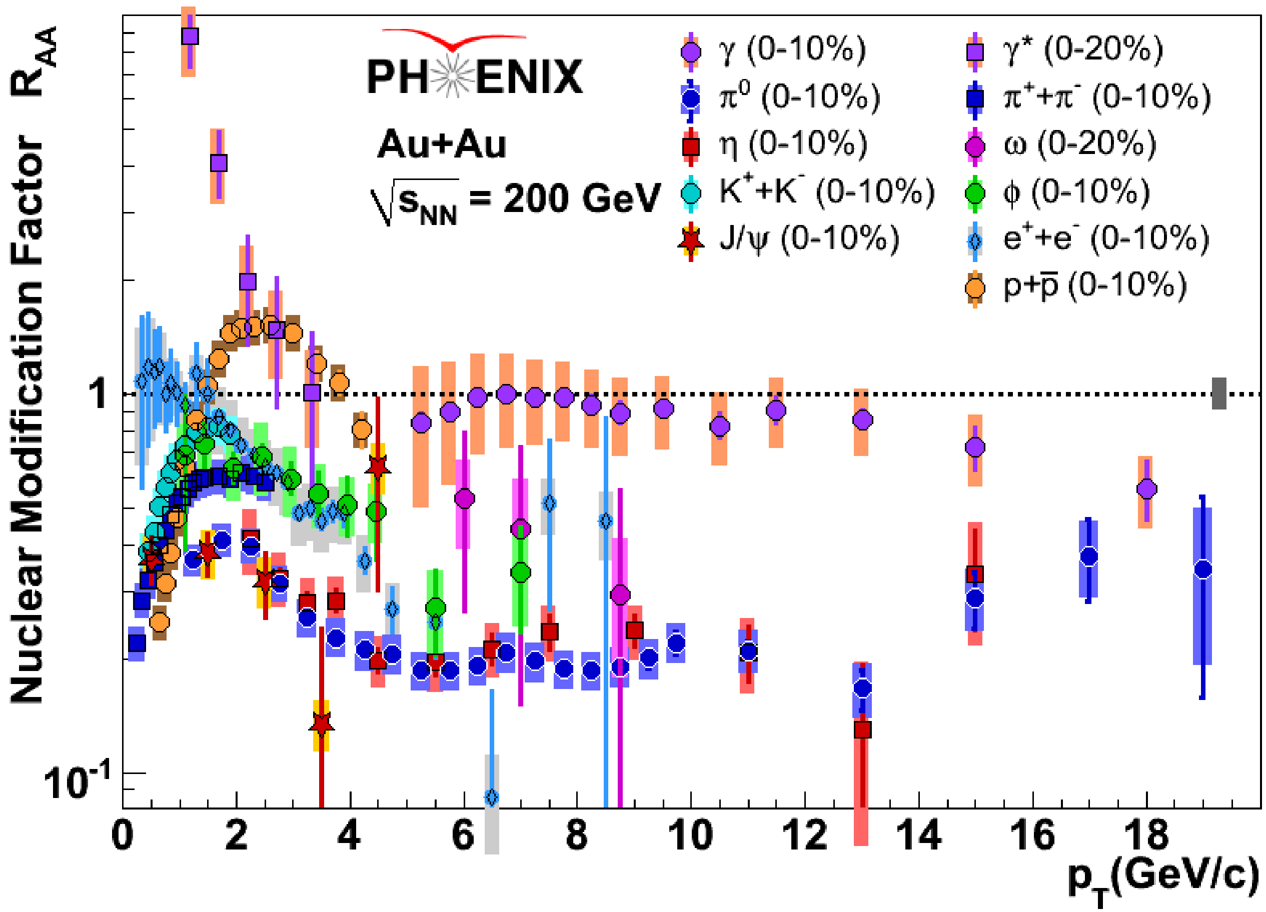


π^0 invariant cross section in p-p at $\sqrt{s}$=200 GeV is a pure power law for $p_T > 3$ GeV/c, n=8.1±0.1

Nuclear Modification Factor

$$R_{AA}(p_T) = \frac{d^2N^{\pi}_{AA} / dp_T dy N^{inel}_{AA}}{\langle T_{AA} \rangle d^2\sigma^{\pi}_{pp} / dp_T dy}$$

Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV QM11



particle ID is crucial different particles behave differently

Exponential enhancement of direct-γ as $p_T \rightarrow 0$ is unique. No other particle is enhanced except in the region of the 'baryon anomaly'. This suggests new physics, *i.e*. thermal-γ. For p_T>4 GeV/c direct-γ (color neutral) are not suppressed; all hadrons are suppressed, indicating that suppression is a medium-effect on outgoing color-charged partons.

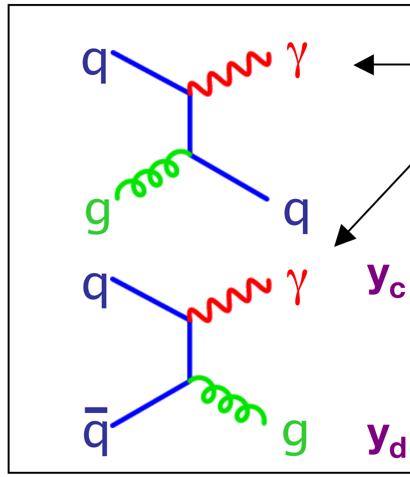
Direct photon production-simple theory hard experiment

See the classic paper of Fritzsch and Minkowski, PLB **69** (1977) 316-320

Compton

Annihilation

small-ignore



isolated photons

q is 8/1 u/d quark in p-p

Analytical formula for γ-jet cross section for a <u>photon</u> at p_T, y_c (and *parton* (<u>jet</u>) at p_T, y_d):

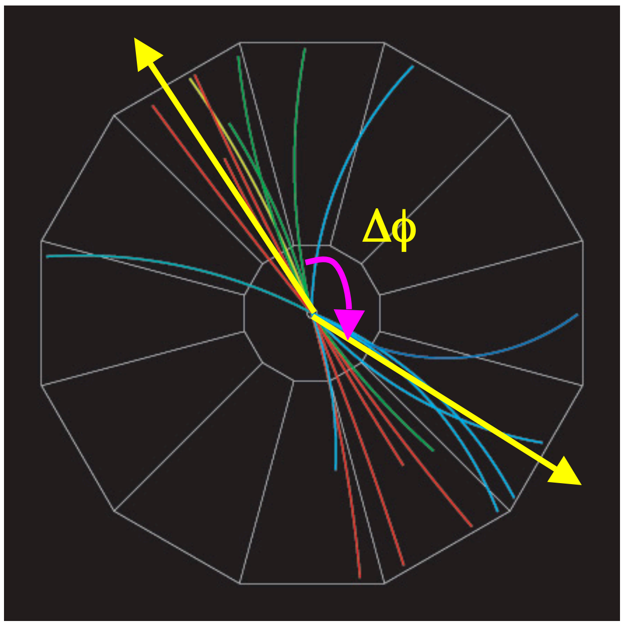
$$\frac{d^3\sigma}{dp_T^2\, dy_c\, dy_d} = x_1 f_g^A(x_1)\, F_{2B}(x_2, Q^2) \frac{\pi\alpha\alpha_s(Q^2)}{3\hat{s}^2} \left(\frac{1+\cos\theta^*}{2} + \frac{2}{1+\cos\theta^*}\right)$$
$$+ \; F_{2A}(x_1, Q^2)\, x_2 f_g^B(x_2) \frac{\pi\alpha\alpha_s(Q^2)}{3\hat{s}^2} \left(\frac{1-\cos\theta^*}{2} + \frac{2}{1-\cos\theta^*}\right)$$

$$\cos\theta^* = \tanh\frac{(y_c - y_d)}{2}$$

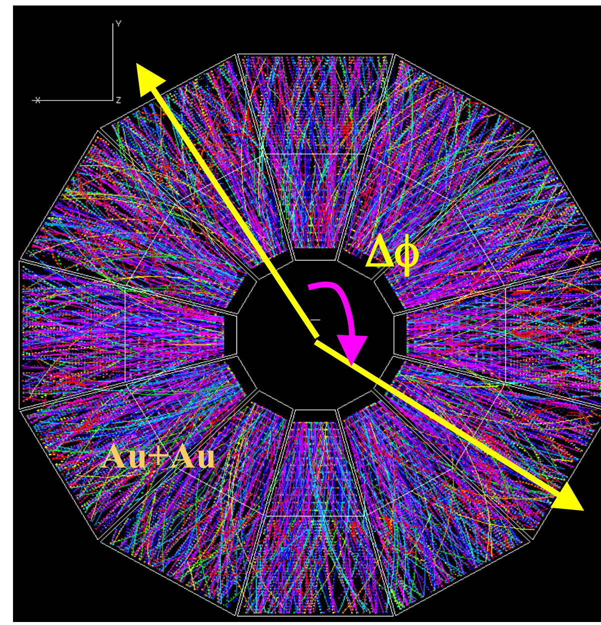
$$x_{1,2} = x_T \frac{e^{\pm y_c} + e^{\pm y_d}}{2}$$

$f_g(x)$ and $F_2(x)$ are g and q pdf's in nuclei A,B

Correlations



e.g. p + p → jet + jet

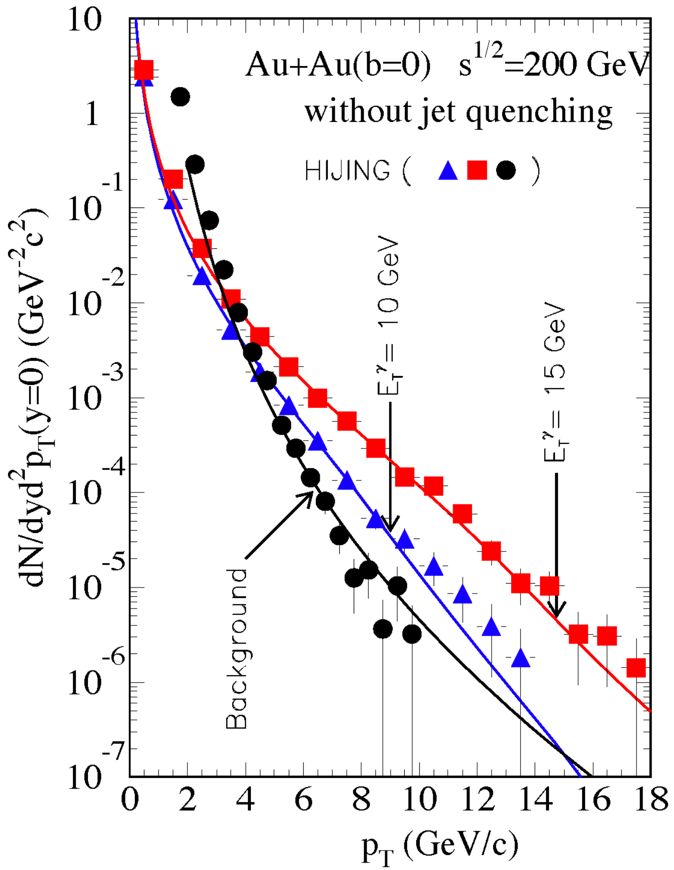


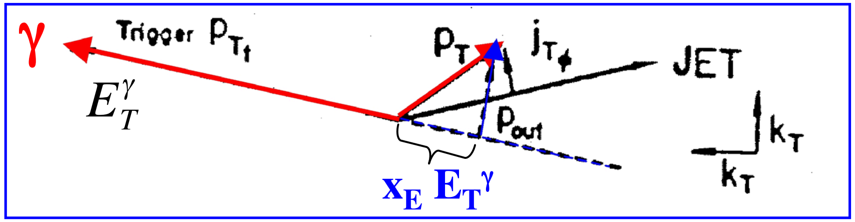
c.f. Au + Au → jet + jet
+ flow

The Holy Grail: γ-h correlations in Au+Au

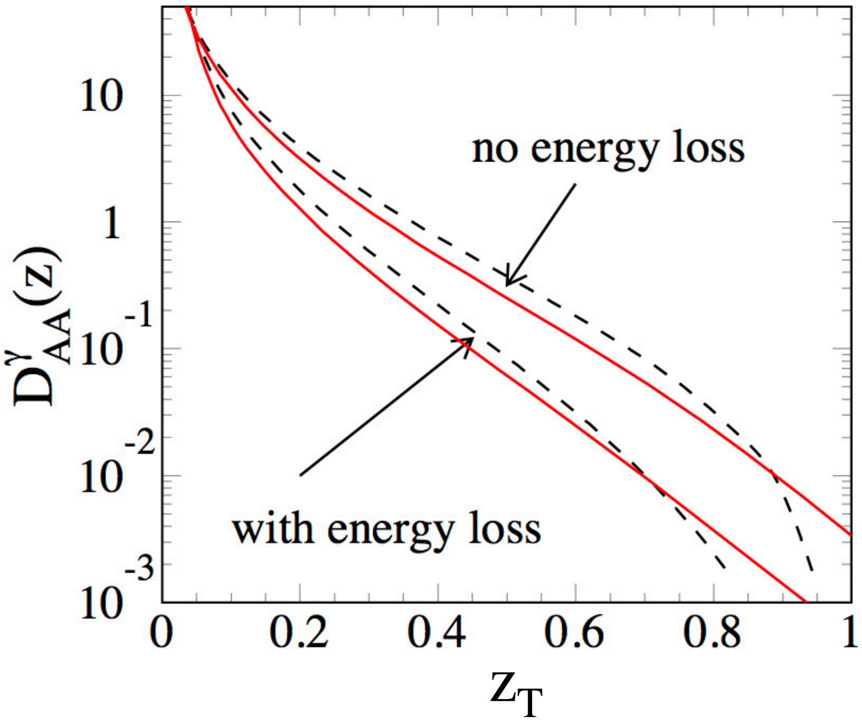
X-N. Wang and Z. Huang PRC 55, 3047 (1997)

Trigger on direct-γ with E^{γ}_{T} measure away jet fragment p_T distribution





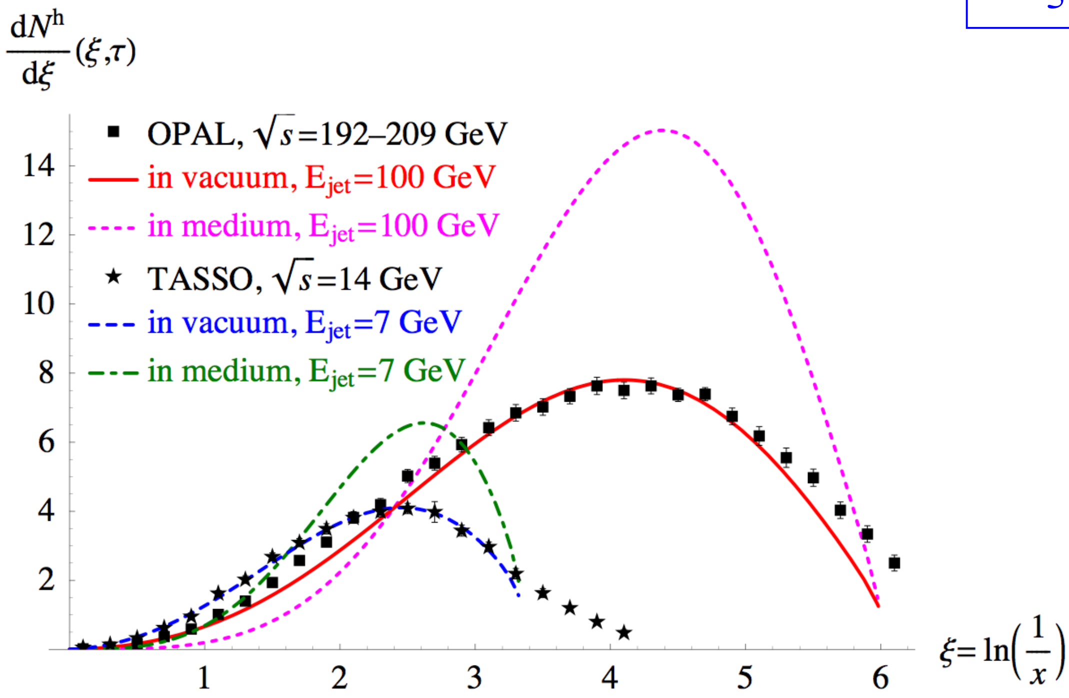
$x_E = p_T^h \cos(\Delta\phi)/E_T^{\gamma} \sim z_T = p_T^h/E_T^{\gamma}$



Prediction of Jet shape in vacuum and medium

Borghini & Wiedemann, hep-ph/0506218

Why use the Hump-backed distribution?
Is ξ=ln(1/z) better than z?



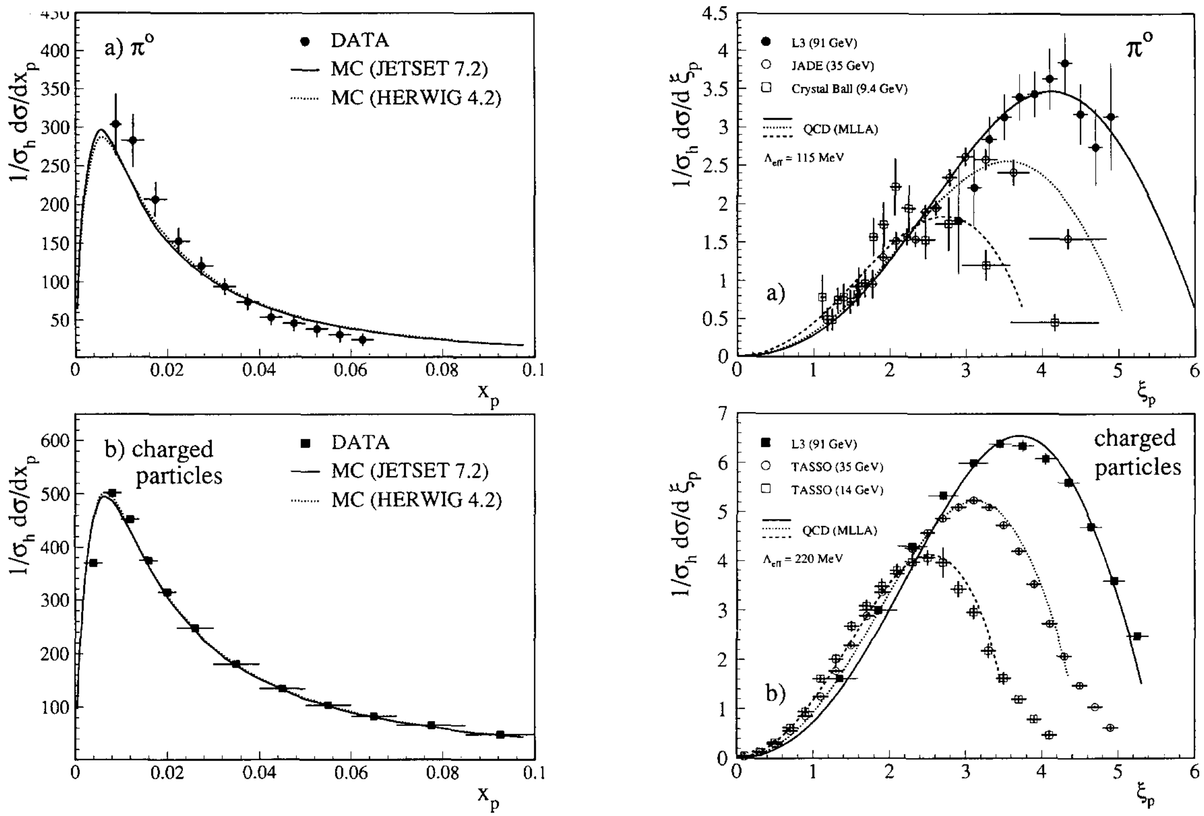
- Evolution is predictable in MLLA QCD and is signature for coherence for small values of z<0.1 (Large values of ξ>2.3). [Dokshitzer, et al, RMP60, 373(1988)]
- Emphasizes the increase in emission of fragments at small z due to the medium induced depletion of the number of fragments at large z.

Borghini and Wiedemann thought that reconstruction of jets would be required to measure this distribution. However, it was shown at LEP that if the energy of the jet were known, e.g. for dijet events at a precisely known √s in e^+e^- collisions, then both z and ξ=ln(1/z) distributions could be obtained without jet reconstruction.

ξ from single inclusive π^0 at Z^0--L3. Thank you Sam Ting

L3, PLB 259 (1991)199-208

PHYSICS LETTERS B 18 April 1991



$$\boxed{dN/d\xi = z\ dN/dz}$$

$$\boxed{dN/d\xi \approx x_E\ dN/dx_E}$$

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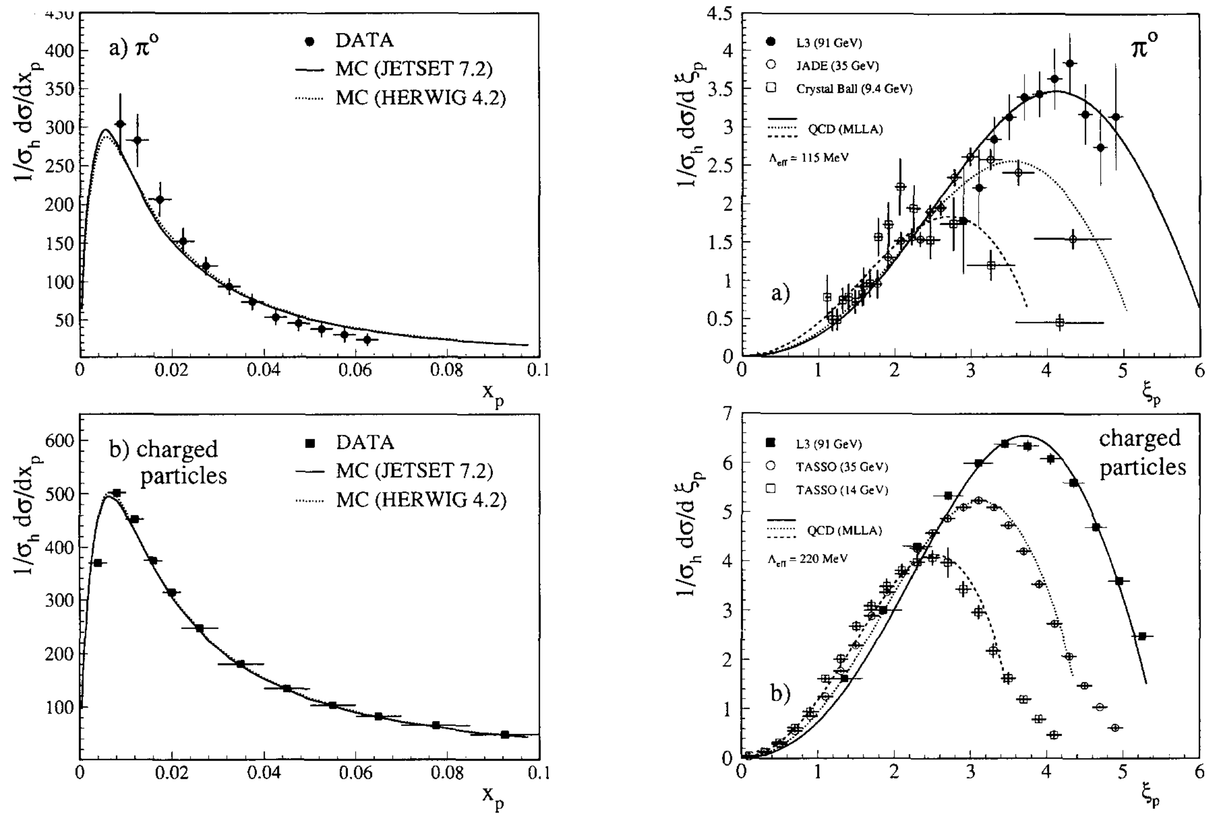
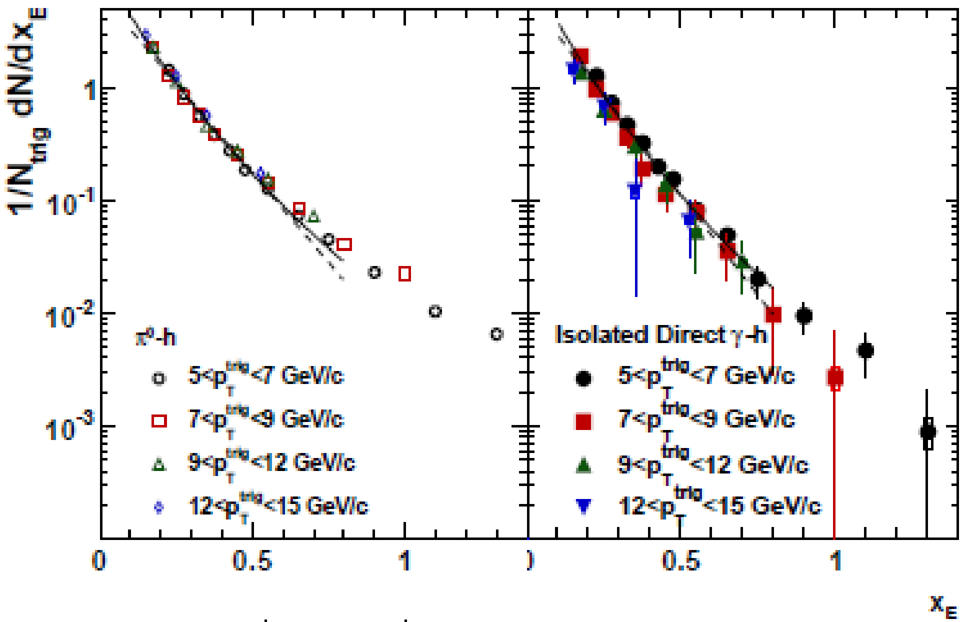


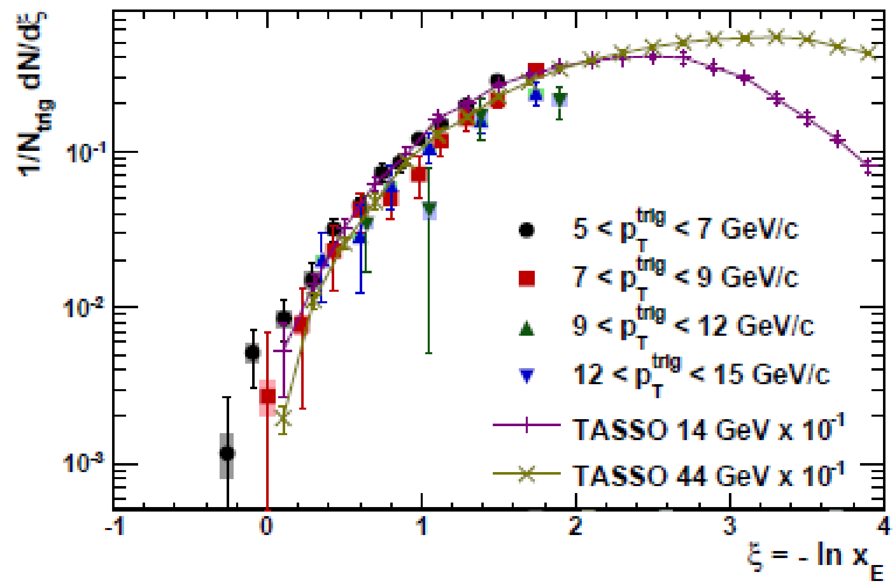
$$\boxed{dN/d\xi = z\ dN/dz}$$

$$\boxed{dN/d\xi \approx x_E\ dN/dx_E}$$

The key to this measurement is that the jet energy be precisely known. This is true for the jet opposite to the direct-γ. Thus we can do this from γ-π^0 or γ-h away side correlations in p-p and Au+Au (convert $x_E \approx z_T$ plot to ξ) with semi-log ordinate to make the whole fragmentation fn. visible

Direct-γ-*h* correlation measures (~u quark) fragmentation function in p-p





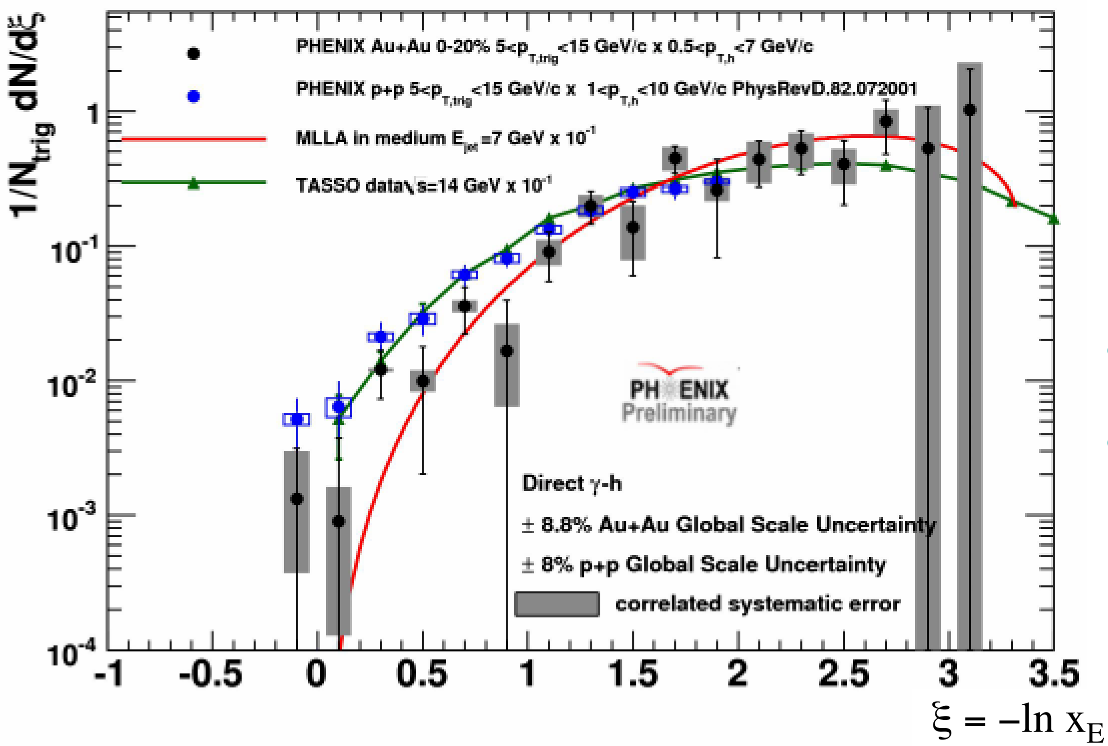
- $x_E = |p_T{}^h/p_T{}^\gamma| \cos(\Delta\phi) \sim z_T$
- γ-h is steeper than π^0-h!
- x_E universal scaling vs. p_{Tt} in γ-h
- b=8.2±0.3

$$\frac{dN}{dx_E} = Ne^{-bx_E}$$

- Plot with MLLA variable $\xi = -\ln x_E$
- Good agreement with TASSO measurement (e^+e^-)
- Baseline for E-loss in Au+Au

PHENIX, PRD **82** (2010) 072001

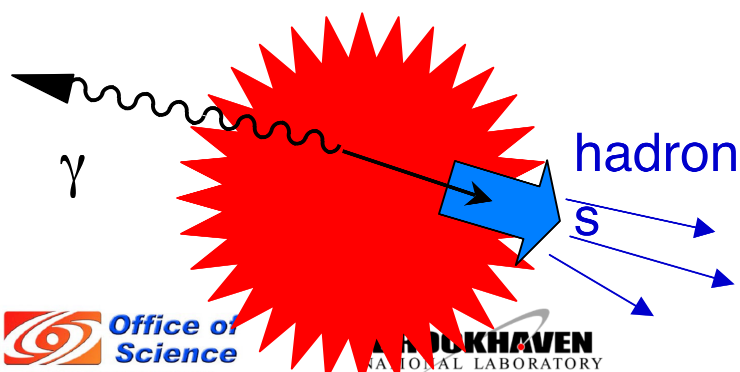
Direct-γ-h correlation measures (~u quark) fragmentation function in Au+Au



Tasso:
Braunschweig et al. , Z. Phys. 320 C47, 187
MLLA:
Borghini, Wiedemann, hep-ph/0506218

$$\xi = -\ln(x_E) \approx -\ln(|p_{Th}/p_{T\gamma}|)$$

- p+p consistent with e^+e^-
- Au+Au consistent with E loss model; but need more statistics to be definitive



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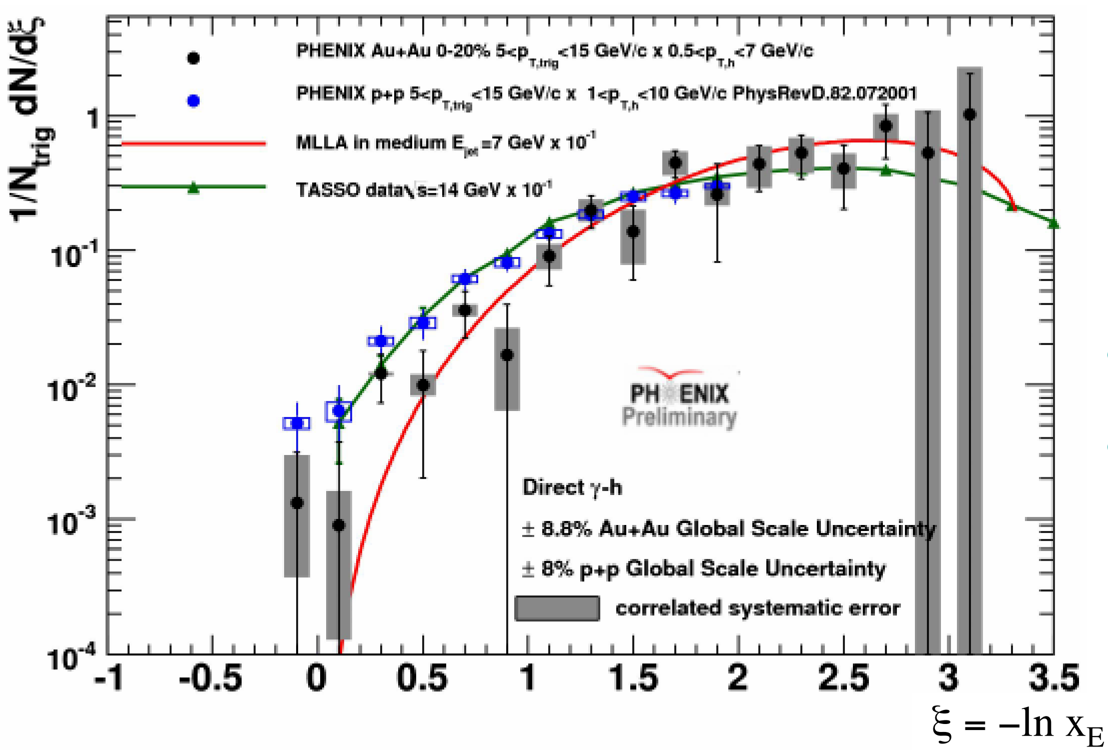

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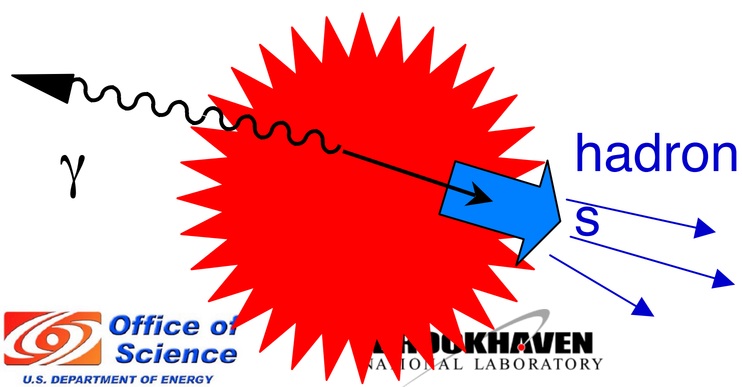
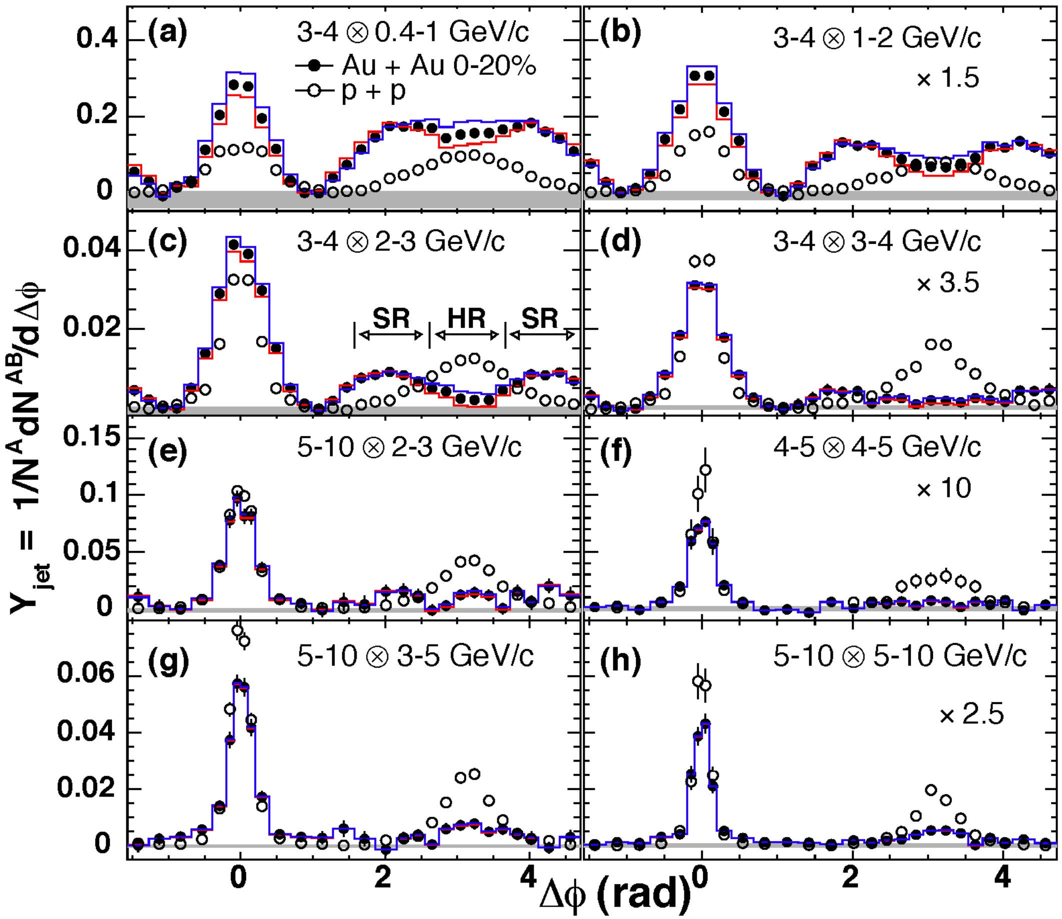


N.B. h-h correlations where both h are jet fragments does NOT measure the fragmentation function

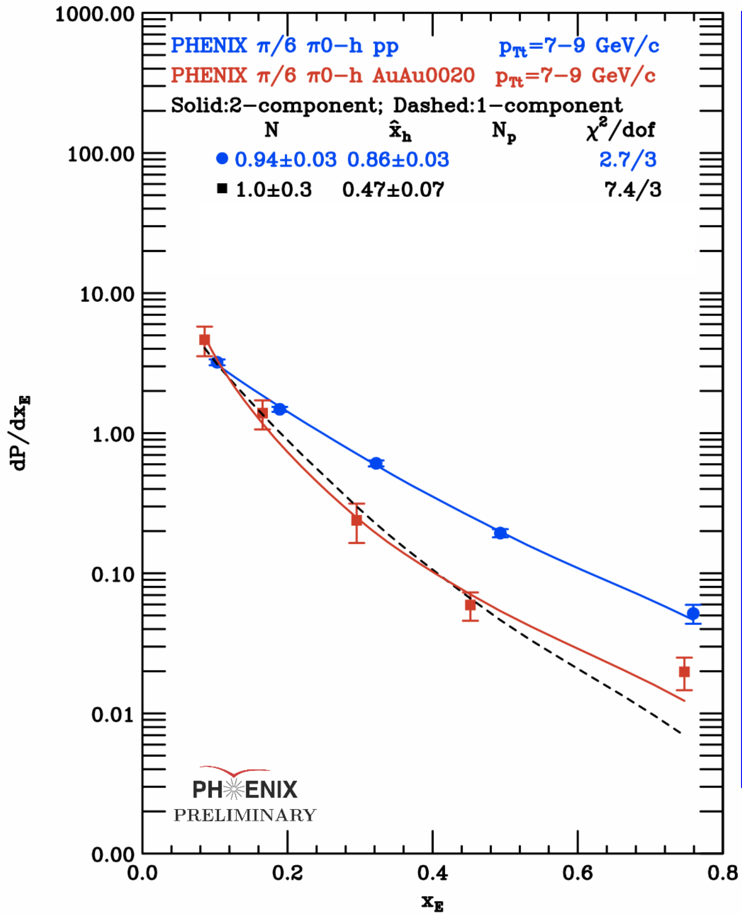
PRC 77,011901(R)(2008)-h±-h± correlations



Away side correlation in Au+Au is generally wider than p-p with complicated structure. This structure found (2011) to be due to not correcting for v_3. To avoid this use high p_{Tt}.

Define Head region (HR) and Shoulder regions (SR) for wide away side correlation.

h-h or π^0-h correlations in Au+Au: Away-side yield vs $x_E \approx p_{Ta}/p_{Tt}$ is steeper in Au+Au than p-p indicating energy loss



The away side $p_{Ta}/p_{Tt} \approx x_E$ distribution triggered by a leading particle with p_{Tt} was thought to be equal to the fragmentation function but we found that it is NOT sensitive to the shape of the fragmentation function but only to the shape of the inclusive p_{Tt} spectrum with power n (=8.1). Formula derived in PRD 74 (2006) 072002 works for pp and AA

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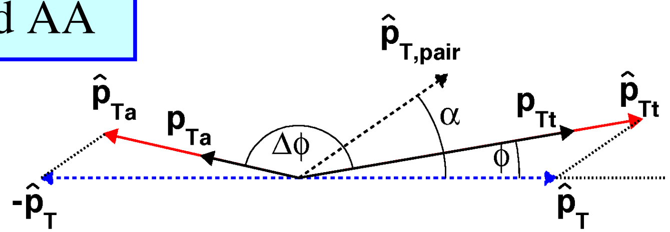
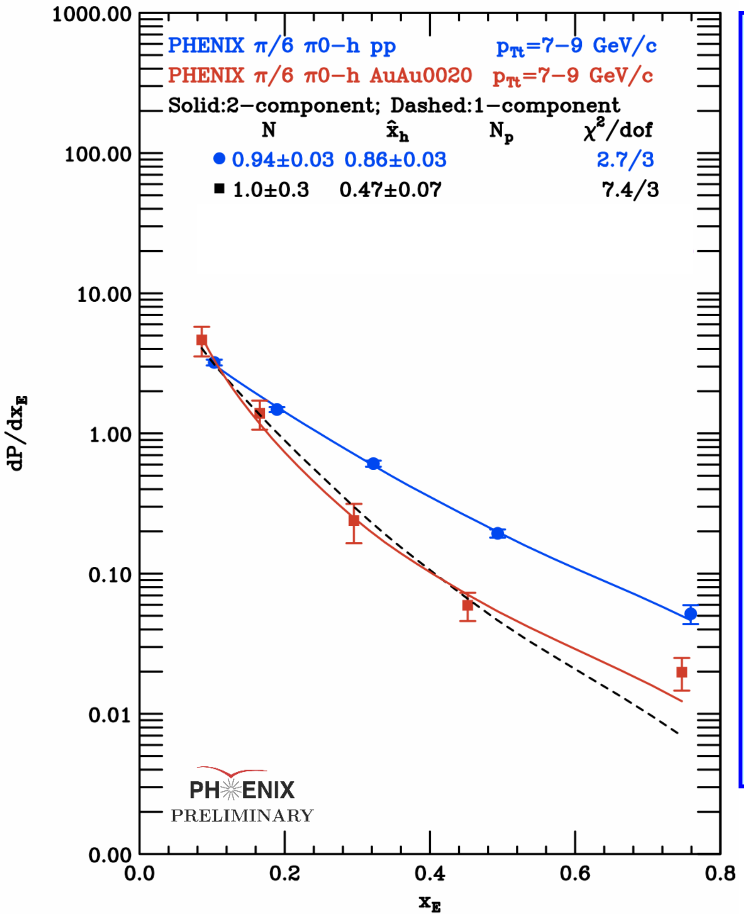
π^0-h correlations
PRL104(2010)252301



Measured ratio of particle $p_{Ta}/p_{Tt} \approx x_E \Rightarrow$ Ratio of jet transverse momenta $\boxed{\hat{p}_{Ta} / \hat{p}_{Tt} \equiv \hat{x}_h}$

$\hat{x}_h = 0.47 \pm 0.07$ in Au+Au indicates that away jet has lost energy relative to trigger jet

h-h or π^0-h correlations in Au+Au: Away-side yield vs $x_E \approx p_{Ta}/p_{Tt}$ is steeper in Au+Au than p-p indicating energy loss



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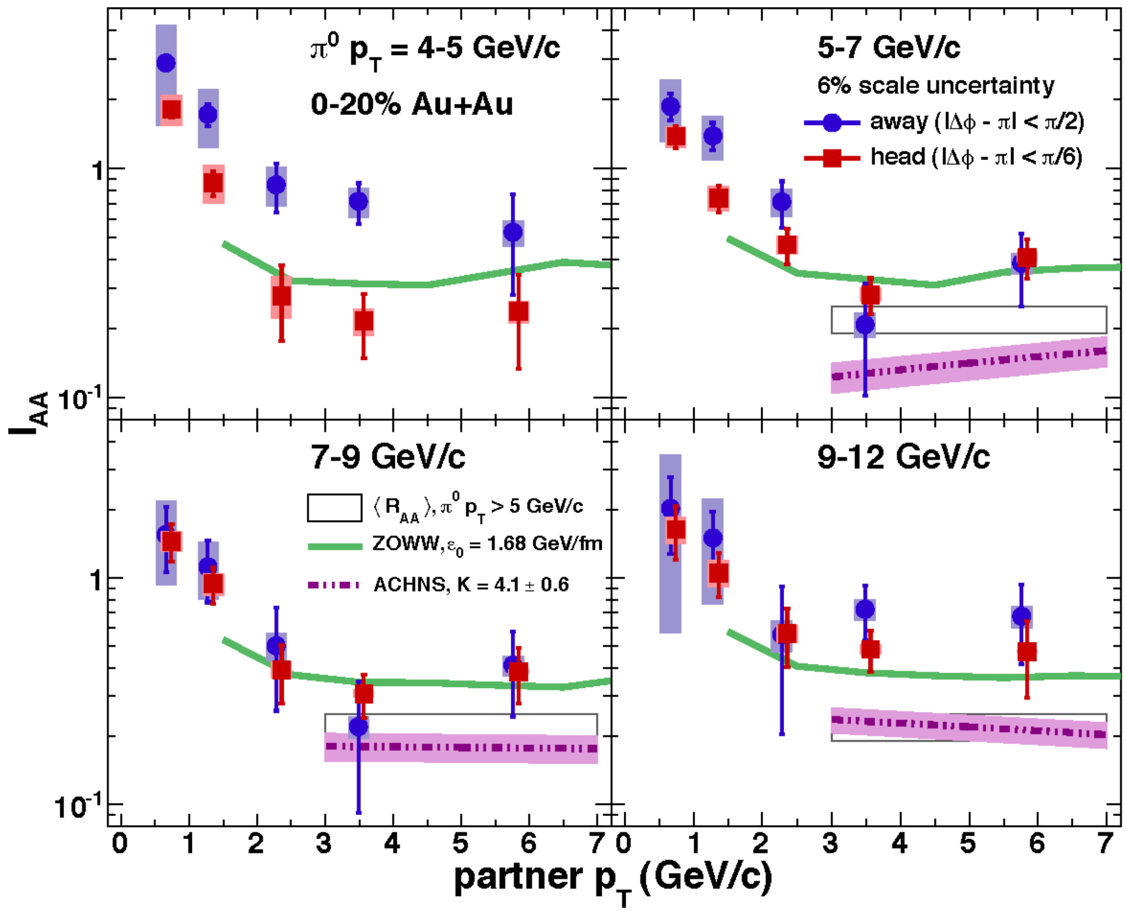
PHENIX
π^0-h correlations
PRL104(2010)252301

$$\left.\frac{dP_\pi}{dx_E}\right|_{p_{T_t}} \approx N\,(n-1)\frac{1}{\hat{x}_h}\frac{1}{(1+\frac{x_E}{\hat{x}_h})^n}$$

Measured ratio of particle $p_{Ta}/p_{Tt} \approx x_E \Rightarrow$ Ratio of jet transverse momenta $\boxed{\hat{p}_{Ta}/\hat{p}_{Tt} \equiv \hat{x}_h}$

$\hat{x}_h = 0.47 \pm 0.07$ in Au+Au indicates that away jet has lost energy relative to trigger jet

Typically experiments only show I_{AA}, the ratio of the AA and pp $x_E \approx z_T = p_{Ta}/p_{Tt}$ distributions



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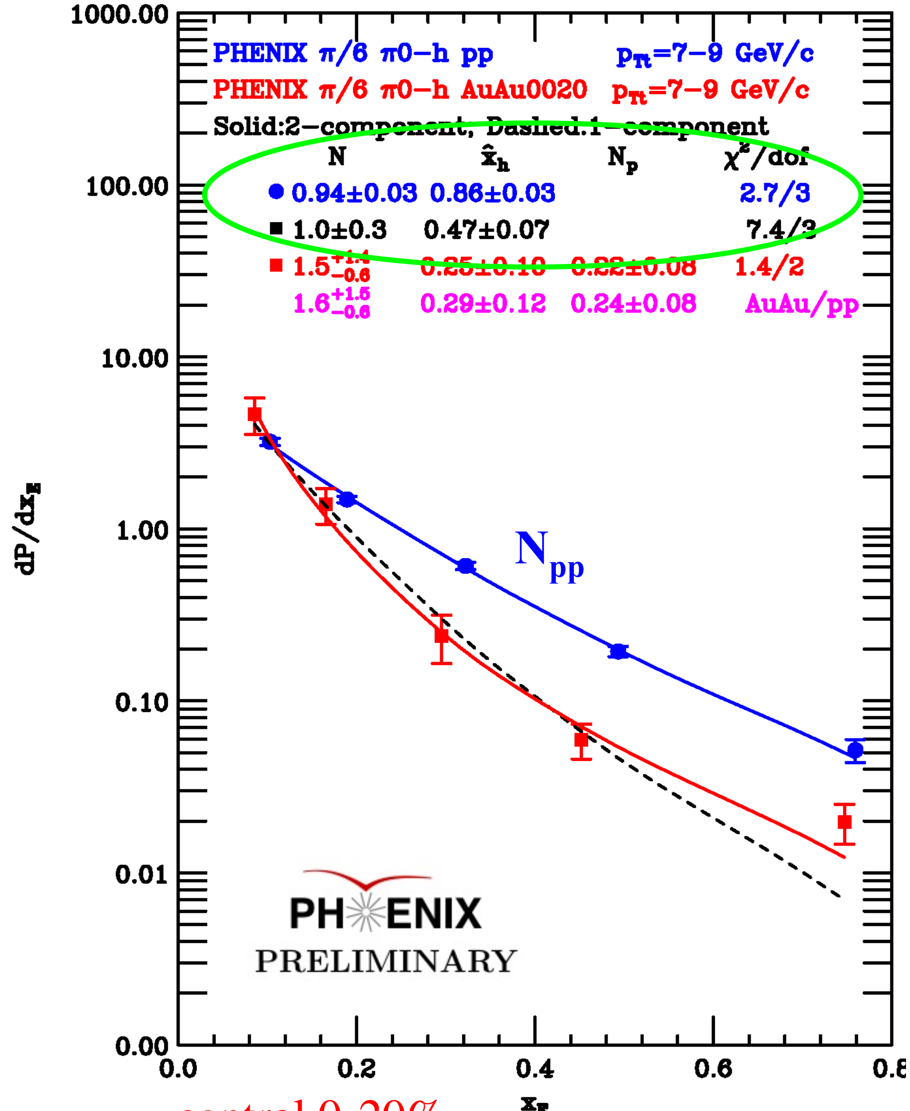
π^0-h correlations
PRL104(2010)252301

n.b for $p_{Tt} \geq 7$ GeV/c no difference between whole away side and head because background under peaks is greatly reduced, with no shoulder, since effect of v3 modulation is negligible

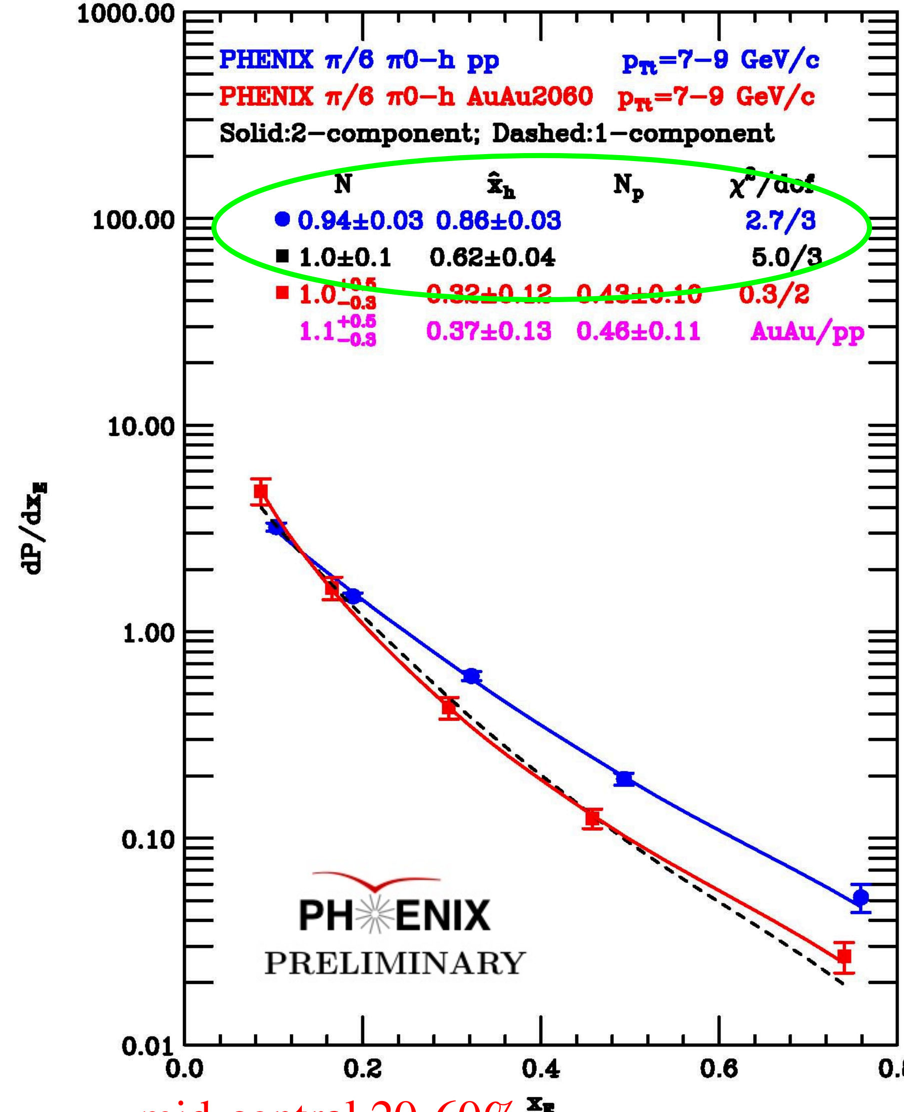
$I_{AA} = [dN^{AA}/dx_E] / [dN^{pp}/dx_E] \approx [dN^{AA}/dz_T] / [dN^{pp}/dz_T]$

Separately fit pp and AuAu $x_E(z_T)$ distributions

First, use 1 component fit



central 0-20%



mid-central 20-60%

$$\left.\frac{dP_\pi}{dz_T}\right|_{p_{T_t}} = N_{pp}\,(n-1)\frac{1}{\hat{x}_h^{pp}}\frac{1}{(1+\frac{z_T}{\hat{x}_h^{pp}})^n}$$

$$\left.\frac{dP_\pi}{dz_T}\right|_{p_{T_t}} = N_{1AA}\,(n-1)\frac{1}{\hat{x}_h^{AA}}\frac{1}{(1+\frac{z_T}{\hat{x}_h^{AA}})^n}$$

Separately fit pp and AuAu $x_E(z_T)$ distributions

First, use 1 component fit

p_{T_t}	N_{1AA}/N_{pp}	$\hat{x}_h^{AA}/\hat{x}_h^{pp}$	$AA\chi^2$/dof
4-5 GeV/c	2.1 ± 0.7	0.44 ± 0.06	3.0/3
5-7 GeV/c	1.1 ± 0.2	0.58 ± 0.06	10.1/3
7-9 GeV/c	1.1 ± 0.3	0.54 ± 0.08	7.4/3
9-12 GeV/c	1.0 ± 0.4	0.65 ± 0.14	5.2/3

Table 2: 00-20 Centrality. 1 component fits to Au-Au data (Eq. 1). Fitted parameters N_{1AA}/N_{pp} $\hat{x}_h^{AA}/\hat{x}_h^{pp}$

p_{T_t}	N_{1AA}/N_{pp}	$\hat{x}_h^{AA}/\hat{x}_h^{pp}$	$AA\chi^2$/dof
4-5 GeV/c	1.2 ± 0.2	0.68 ± 0.06	7.7/3
5-7 GeV/c	1.0 ± 0.1	0.72 ± 0.05	11.1/3
7-9 GeV/c	1.1 ± 0.1	0.72 ± 0.05	5.0/3
9-12 GeV/c	1.0 ± 0.1	0.74 ± 0.07	3.8/3

Table 3: 20-60 Centrality. 1 component fits to Au-Au data (Eq. 1). Fitted parameters N_{1AA}/N_{pp} $\hat{x}_h^{AA}/\hat{x}_h^{pp}$

central 0-20%

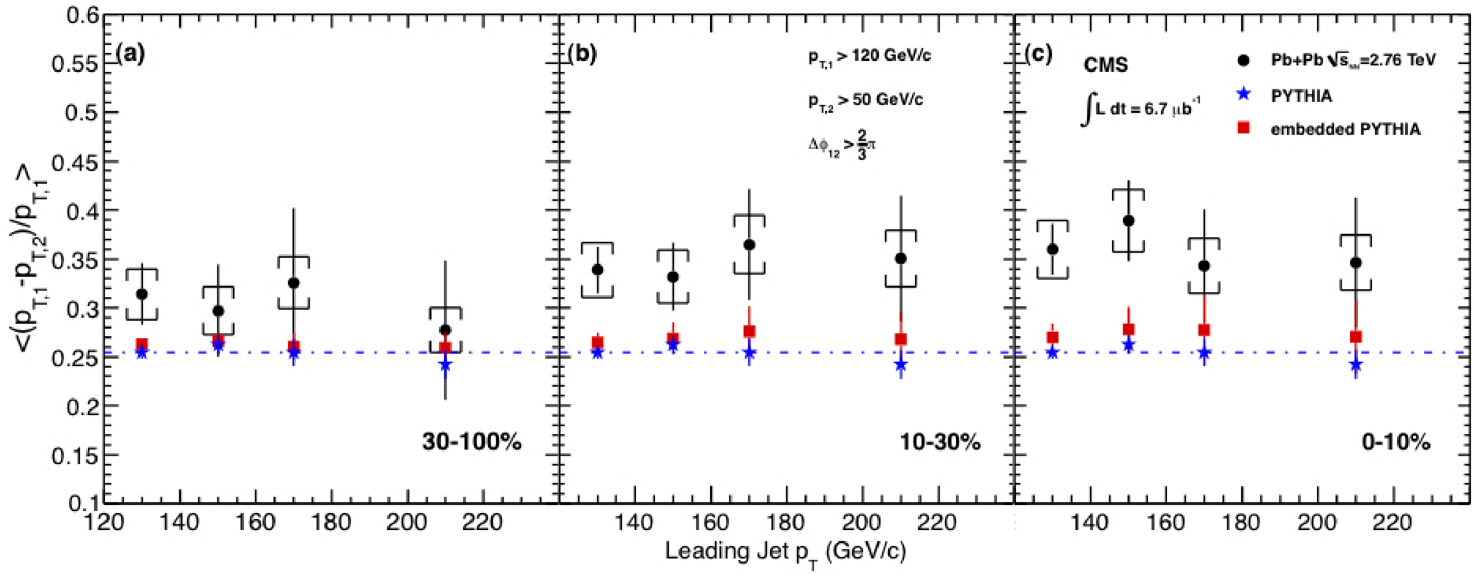
mid-central 20-60%

$$\left.\frac{dP_\pi}{dz_T}\right|_{p_{T_t}} = N_{pp}\,(n-1)\frac{1}{\hat{x}_h^{pp}}\frac{1}{(1+\frac{z_T}{\hat{x}_h^{pp}})^n}$$

$$\left.\frac{dP_\pi}{dz_T}\right|_{p_{T_t}} = N_{1AA}\,(n-1)\frac{1}{\hat{x}_h^{AA}}\frac{1}{(1+\frac{z_T}{\hat{x}_h^{AA}})^n}$$

Comparison with CMS-fractional jet imbalance

arXiv:1102.1957v2



Need to correct for the large non-zero effect in p-p collisions

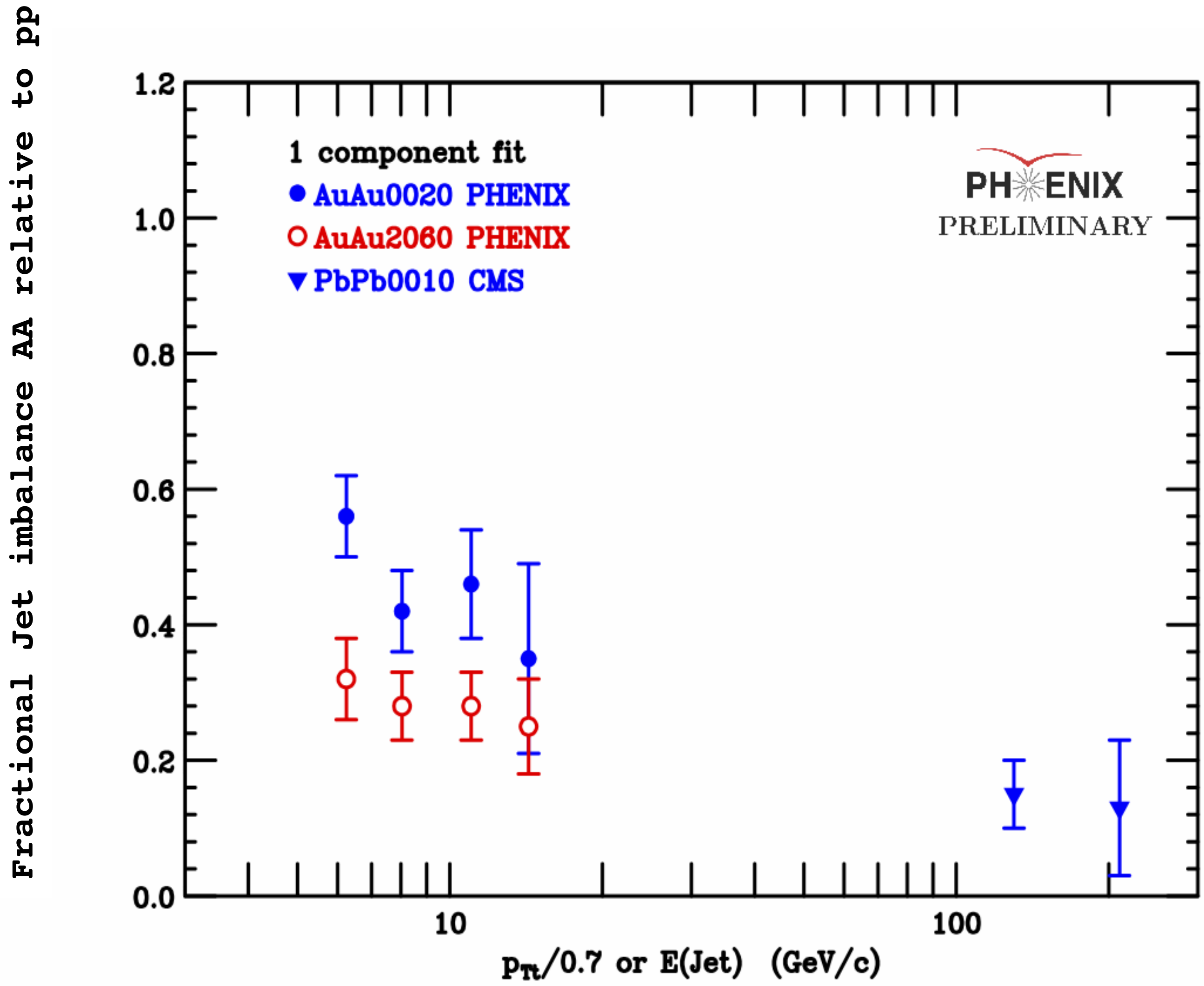
$$(p_{T1} - p_{T2})/p_{T1} = 1 - \hat{x}_h$$

$$\hat{x}_h = 1 - (p_{T1} - p_{T2})/p_{T1}$$

130: pp = 0.255, PbPb=0.36 $\Rightarrow$ $\hat{x}_h$: pp = 0.745, PbPb=0.64

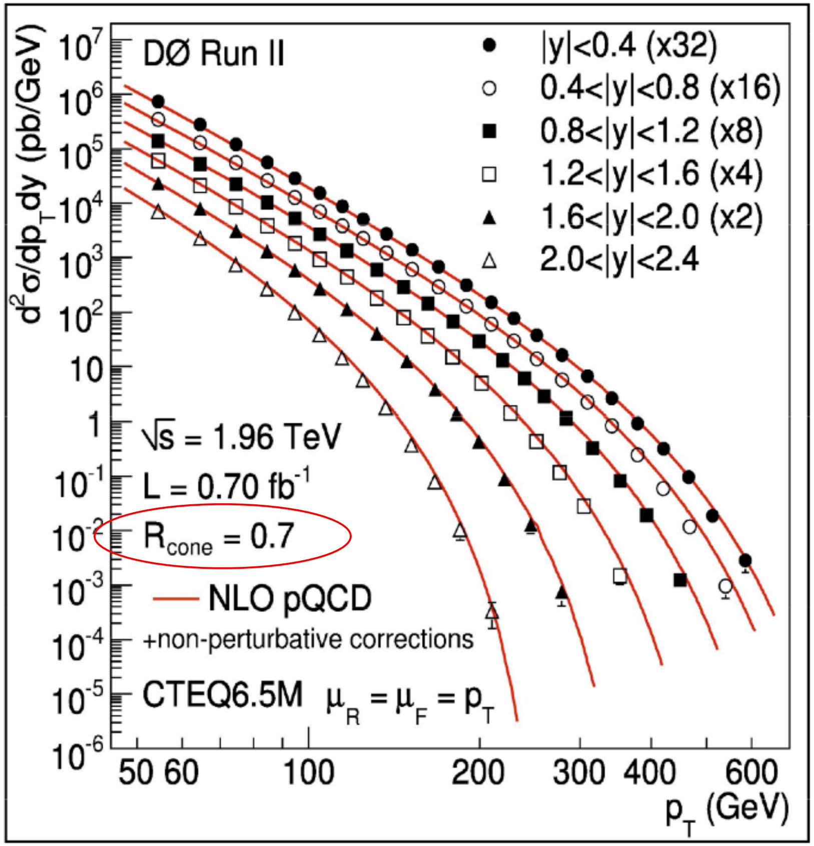
$$1 - \hat{x}_h^{AA}/\hat{x}_h^{pp} = 0.141 \Leftarrow \hat{x}_h^{AA}/\hat{x}_h^{pp} = 0.64/0.745 = 0.859$$

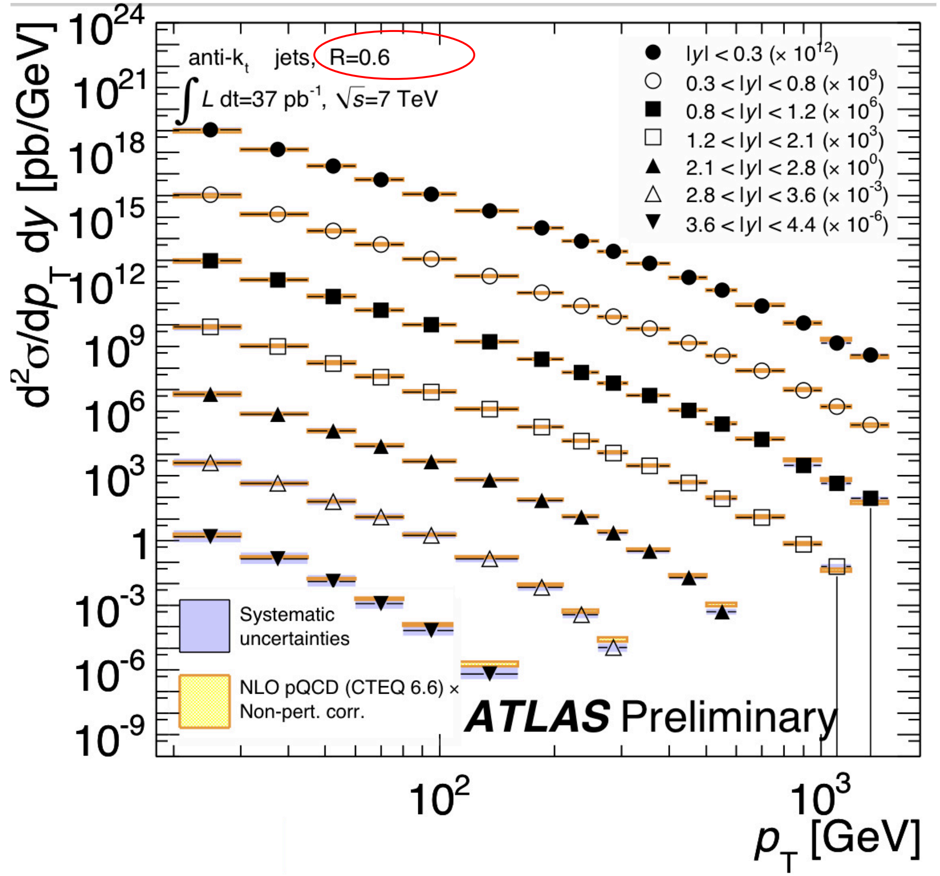
PHENIX 00-20, 20-60 cf CMS central



Big difference between RHIC and LHC in this analysis

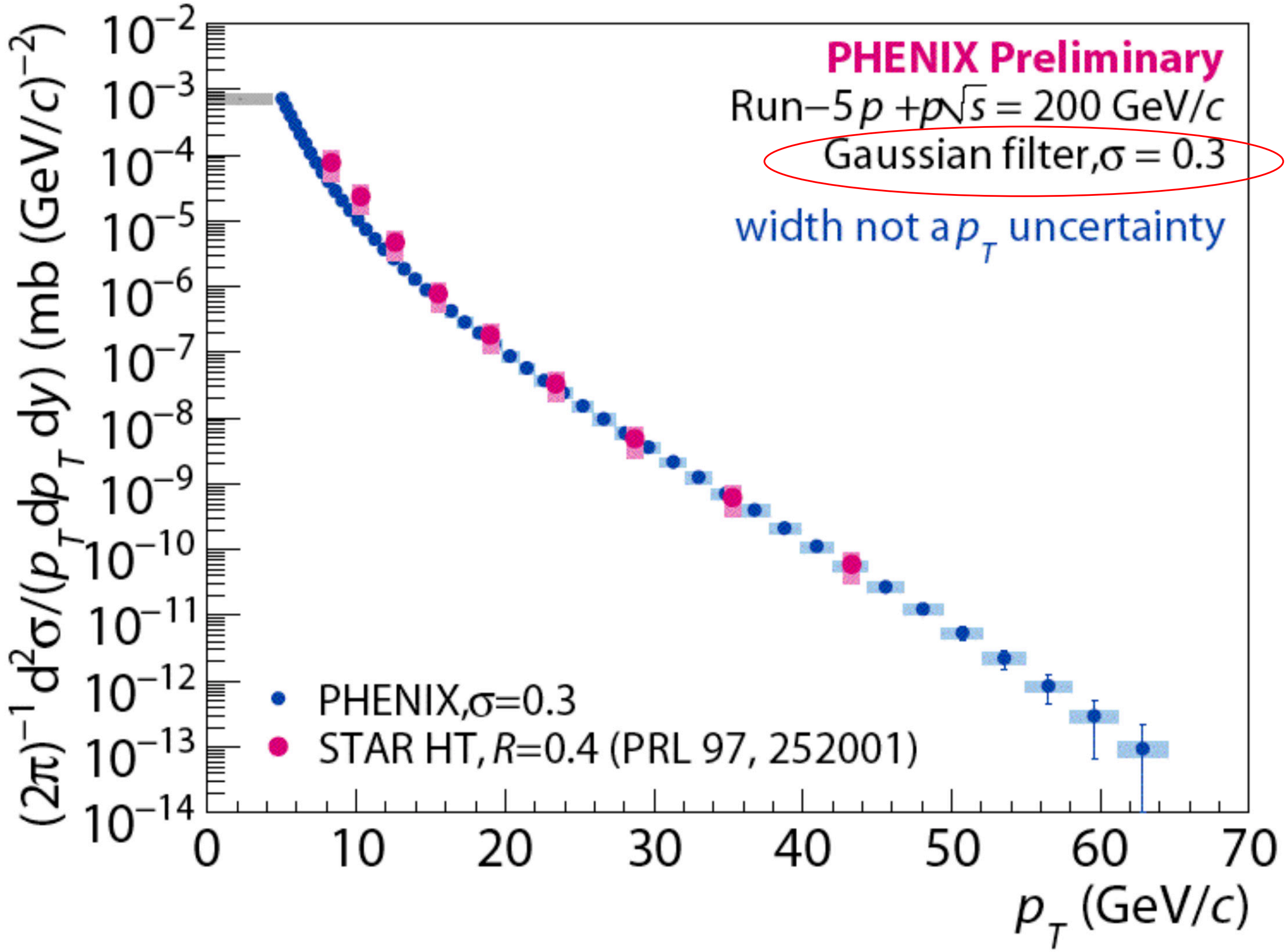
Jets are the workhorse of High Energy Physics





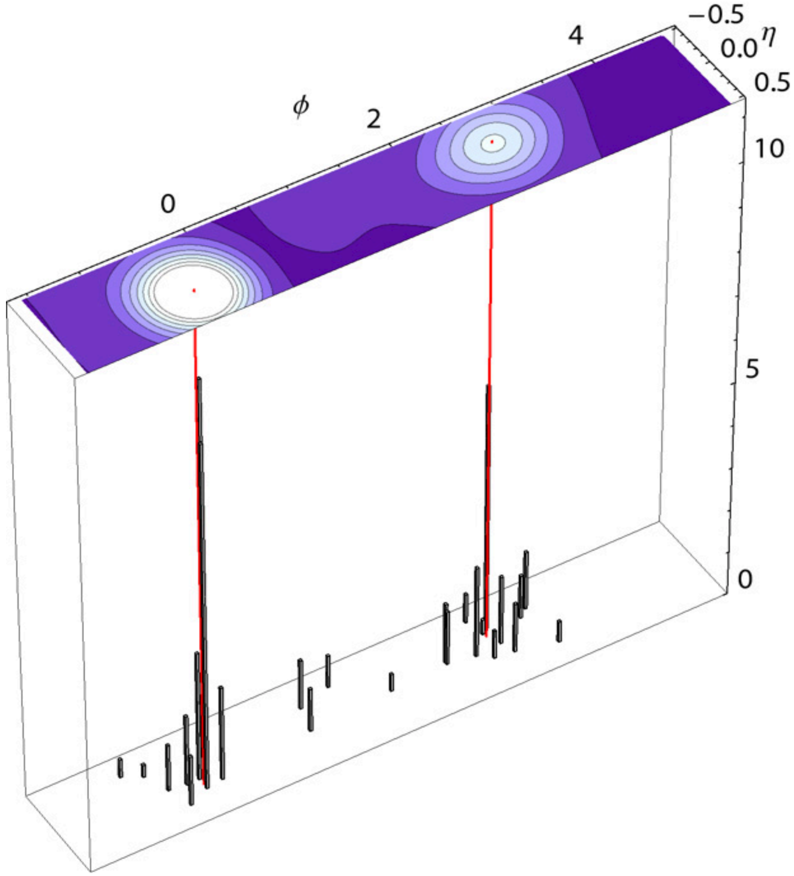
To find out how jets are defined, be prepared look through many pages of text because, IMHO, a jet is not a physical quantity but a legal contract between experimentalists and theorists. In central AuAu collisions at RHIC ($\sqrt{s_{NN}}$=200 GeV) in a cone R=0.7, the expected energy is 150 GeV, c.f. maximum jet energy 100 GeV. After 11 years at RHIC still no refereed jet publication in A+A collisions; but:

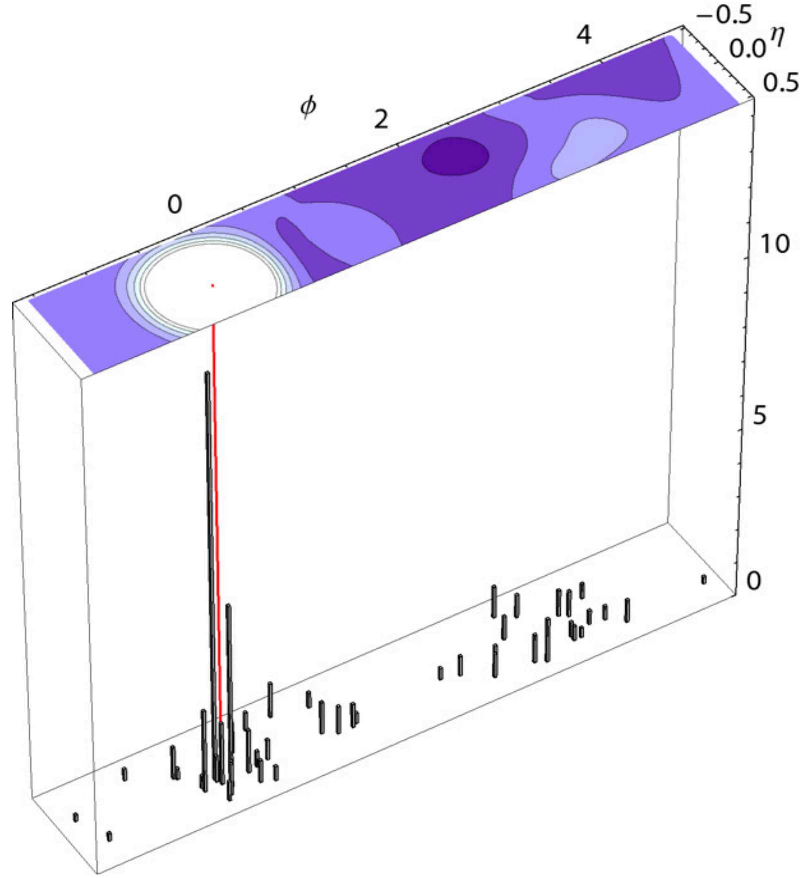
First Jet Reconstruction in PHENIX p-p



new method

PHENIX Cu+Cu Event Display

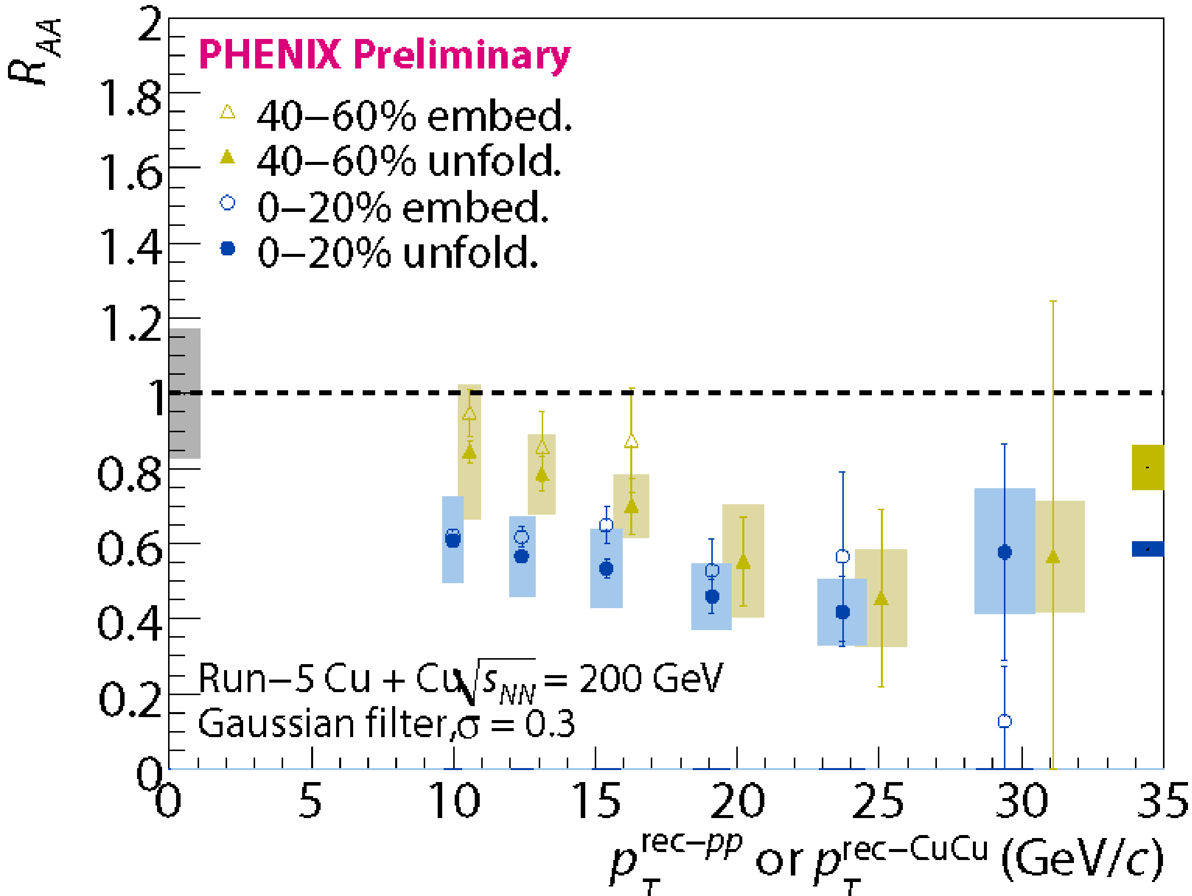




✓Event display of two Cu+Cu events

- Di-jet event
- Single-jet event, other outside acceptance (?)

Two methods to calculate Cu+Cu effect on jet p_T

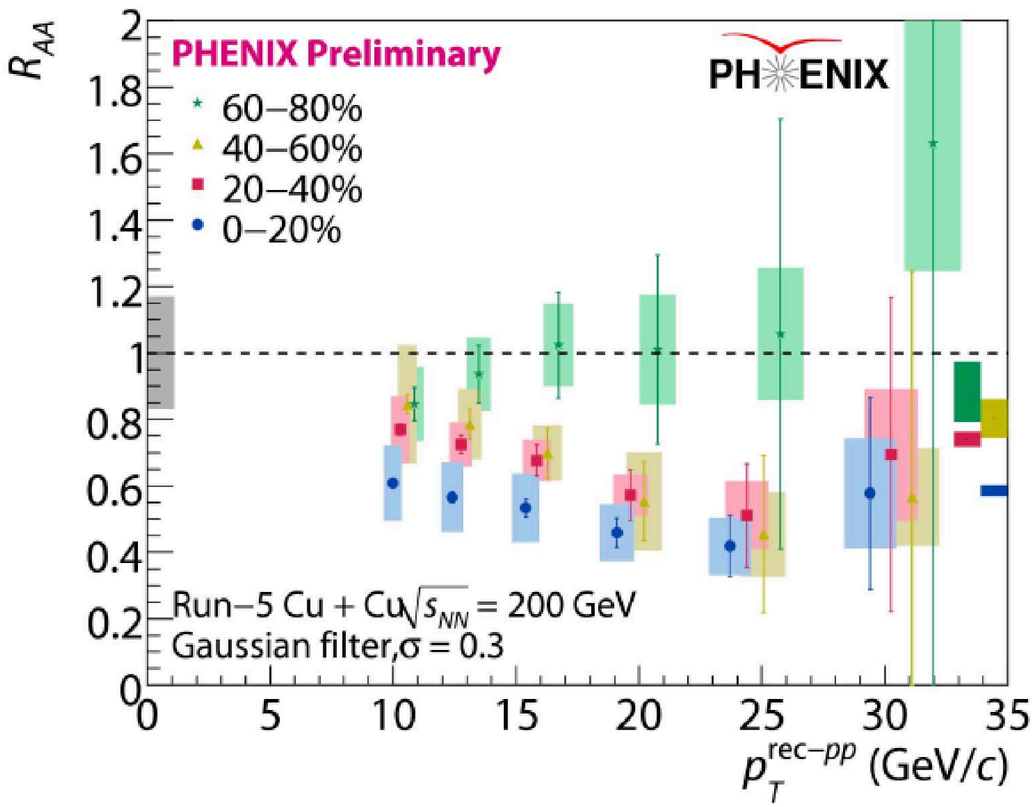


1) Unfold CuCu response from known background and fluctuations and correct the measured p_T in Cu+Cu to the correct p_T scale ($p_T^{rec\text{-}pp}$)

2) Embed known p-p jets into Cu+Cu events to measure the $p_T^{rec\text{-}CuCu}$ and using this value for the p_T of the p-p jet to compare with Cu+Cu jet p_T.

Jet R_{AA} in 200 GeV Cu-Cu

R_{AA} of fully reconstructed jets



Centrality-dependent suppression of jet yields observed comparable to π^0 but goes to much larger p_T

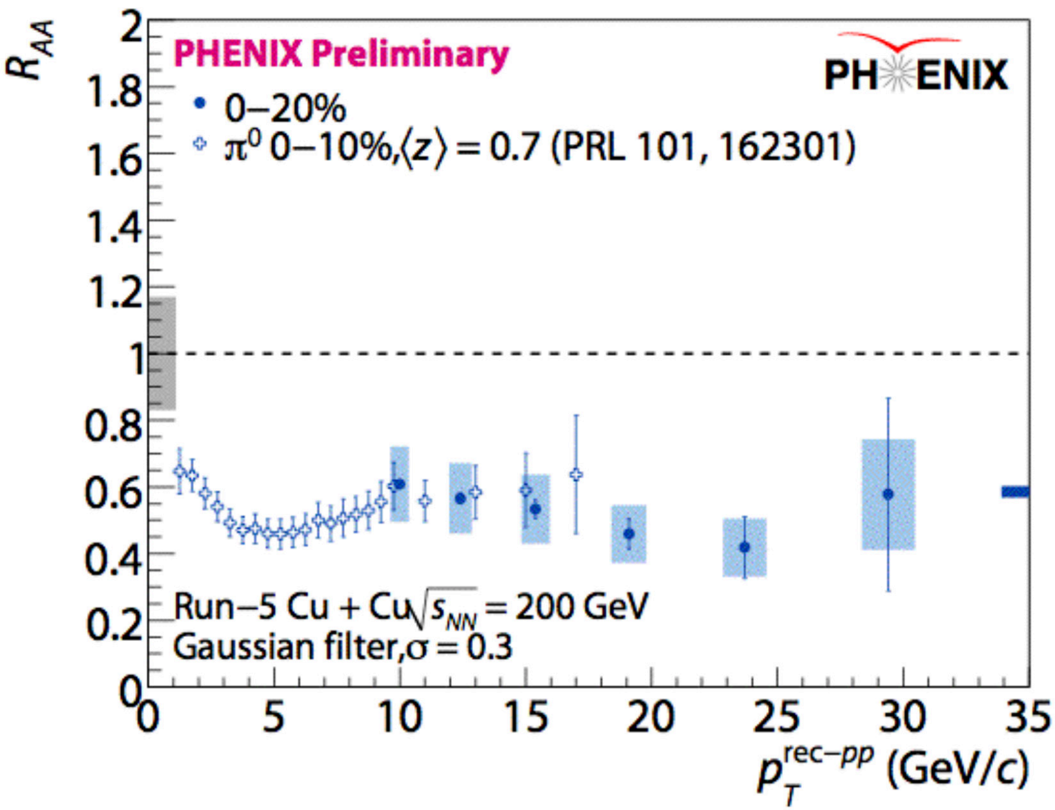
Could be out-of cone radiation from medium interaction

Or the jet shape or other properties are modified and makes the jet fail the rejection cut

Either one would be a *really* interesting result

Jet R_{AA} in 200 GeV Cu-Cu

R_{AA} of fully reconstructed jets



Centrality-dependent suppression of jet yields observed comparable to π^0 but goes to much larger p_T

Could be out-of cone radiation from medium interaction

Or the jet shape or other properties are modified and makes the jet fail the rejection cut

Either one would be a *really* interesting result

Conclusion

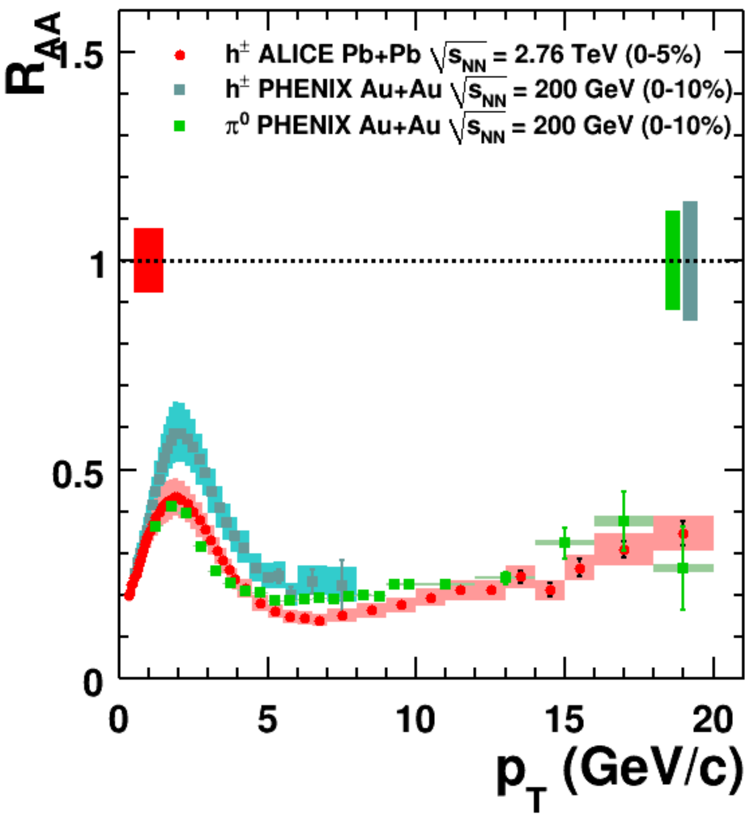
RHIC and LHC jet imbalance

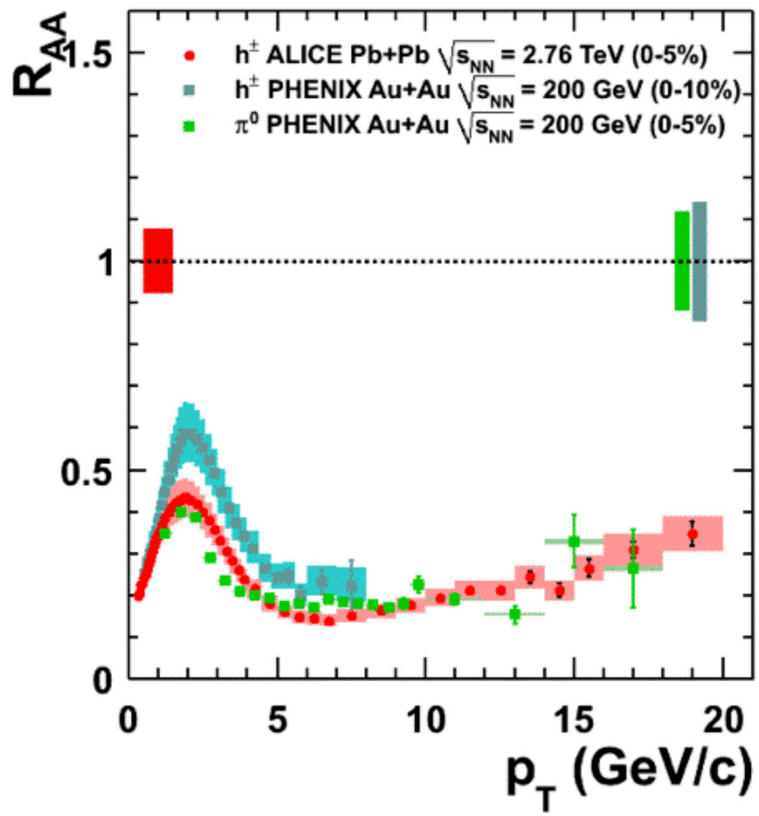
(= fractional energy loss?)

Appear to be different in this analysis.

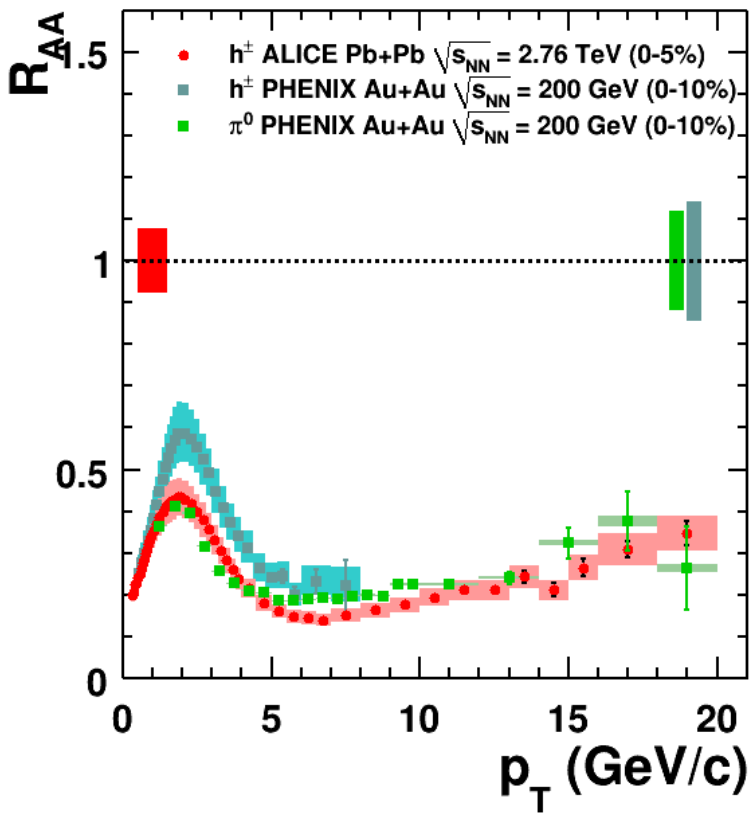
Is it due to a difference in the medium or to the different p_T range?

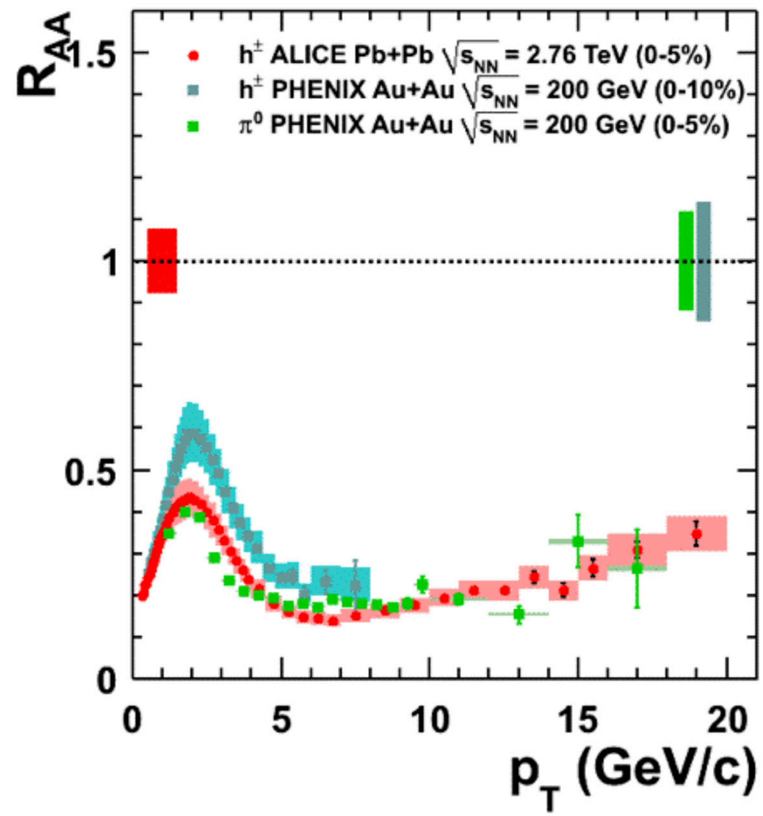
Comparison RHIC π^0 to ALICE $h^{\pm}$ at LHC





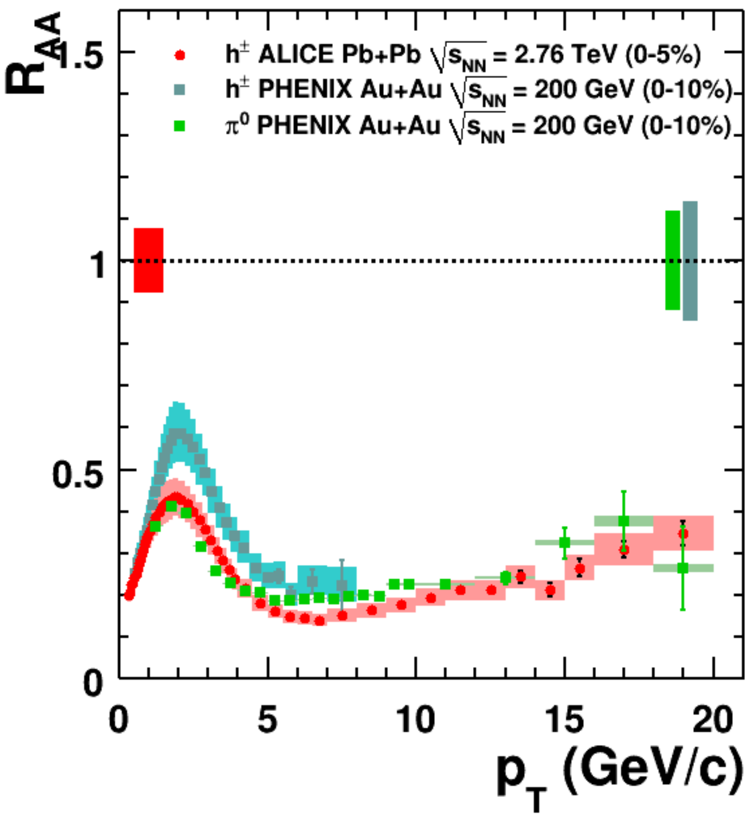
Comparison RHIC π^0 to ALICE $h^{\pm}$ at LHC

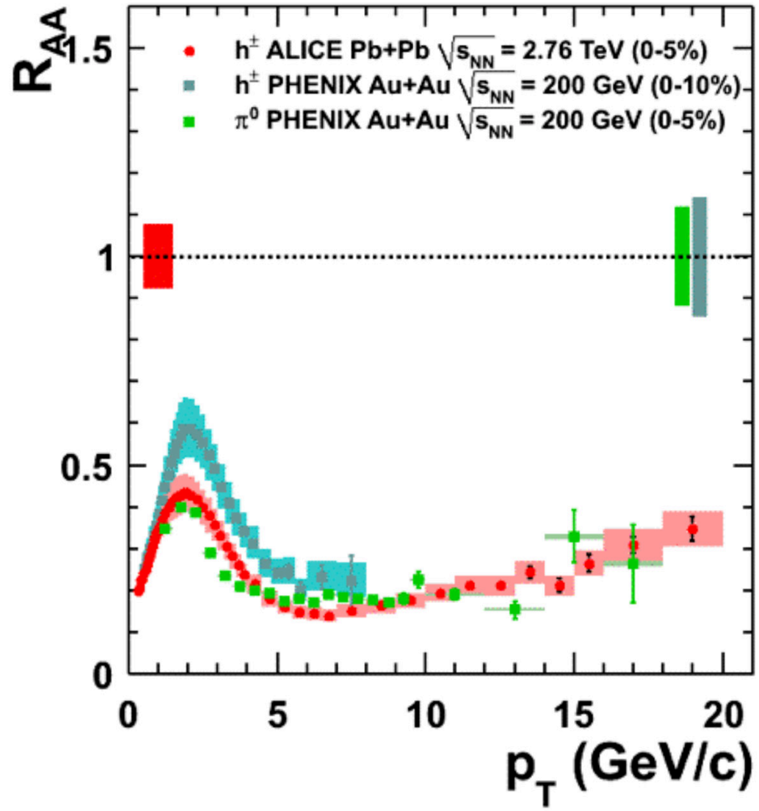




- **Despite more than a factor of 20 higher $\sqrt{s_{NN}}$, the R_{AA} looks nearly identical for RHIC and LHC for 5<pT< 20 GeV/c**
- **ALICE data show significant upward trend but PHENIX upward trend not significant.**

Comparison RHIC π^0 to ALICE $h^\pm$ at LHC

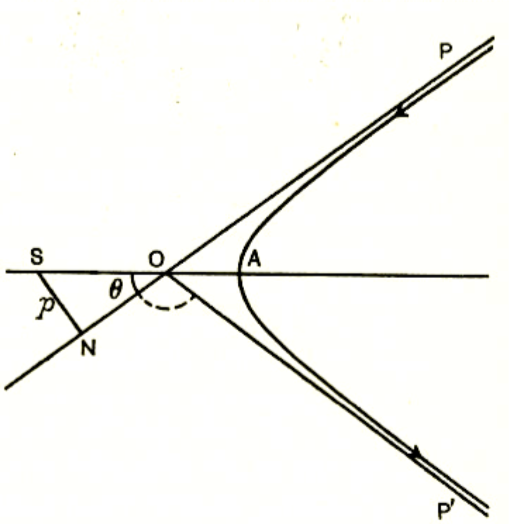




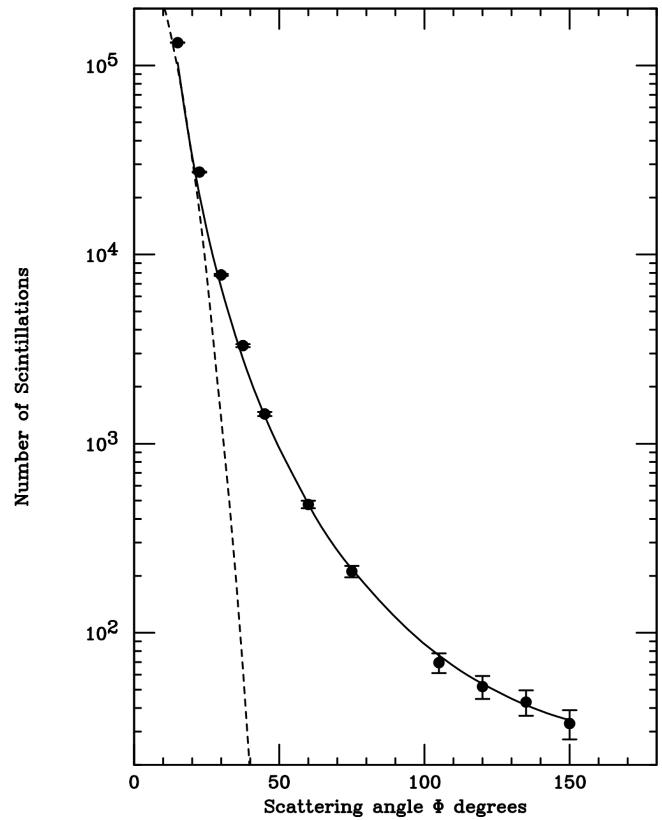
- Despite more than a factor of 20 higher $\sqrt{s_{NN}}$, the R_{AA} looks nearly identical for RHIC and LHC for 5<pT< 20 GeV/c
- ALICE data show significant upward trend but PHENIX upward trend not significant.

Don't be tempted to conclude that the fractional jet energy loss is the same at RHIC and LHC: the inclusive spectra are flatter at LHC n~6 cf. RHIC n=8.1, which implies 50% more $\Delta E/E$ at LHC than at RHIC

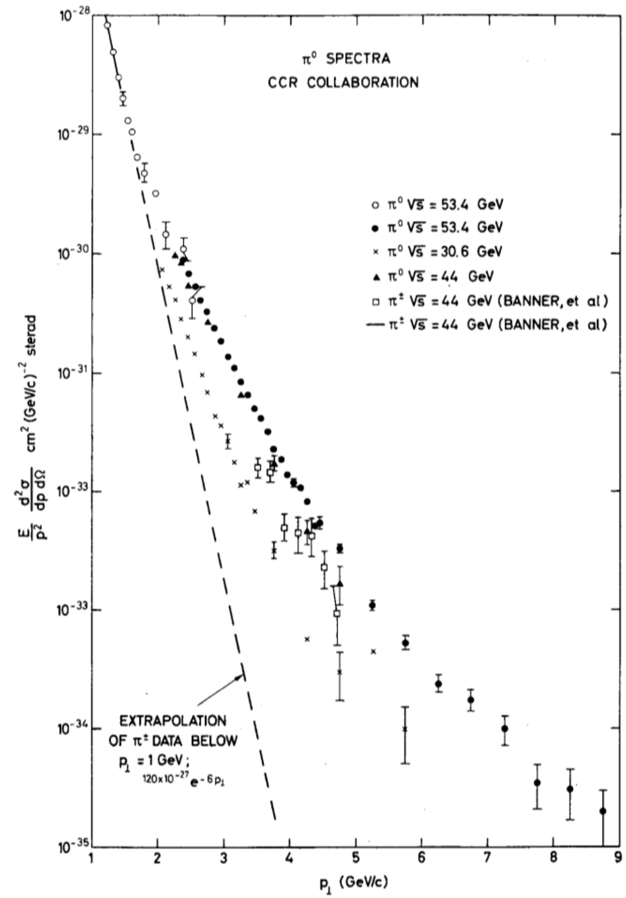
Rutherford to ISR to RHIC



Rutherford scattering
Phil. Mag 21(1911)669



Geiger & Marsden
α+Au→ α+Au
Phil.Mag 25(1913)604



CCR ICHEP 1972
$p+p\rightarrow\pi^0+X$
Hard scattering of partons