Lessons from RHIC for the LHC and Vice Versa

M. J. Tannenbaum
Brookhaven National Laboratory
Upton, NY 11973 USA

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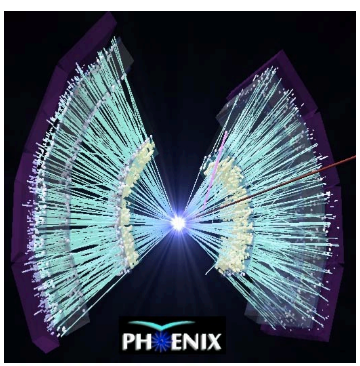
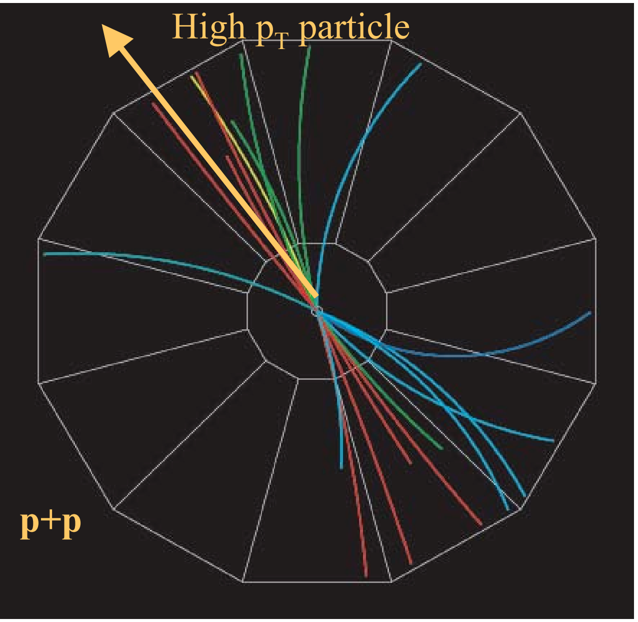
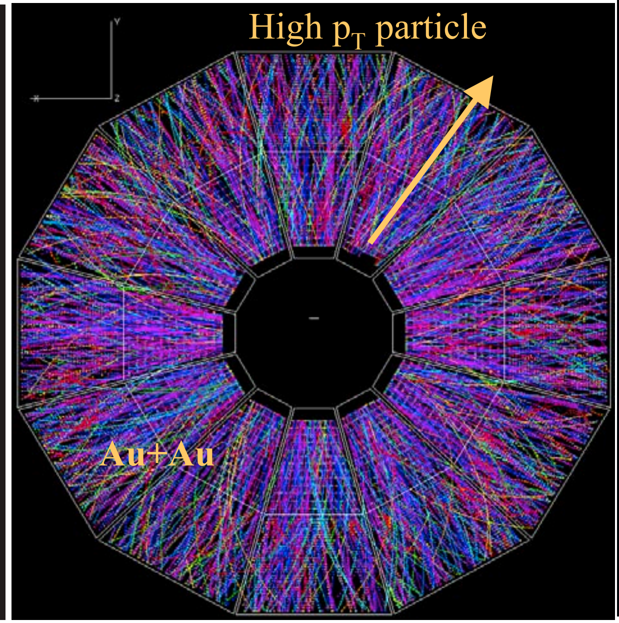


AuAu Central Collisions cf. p-p

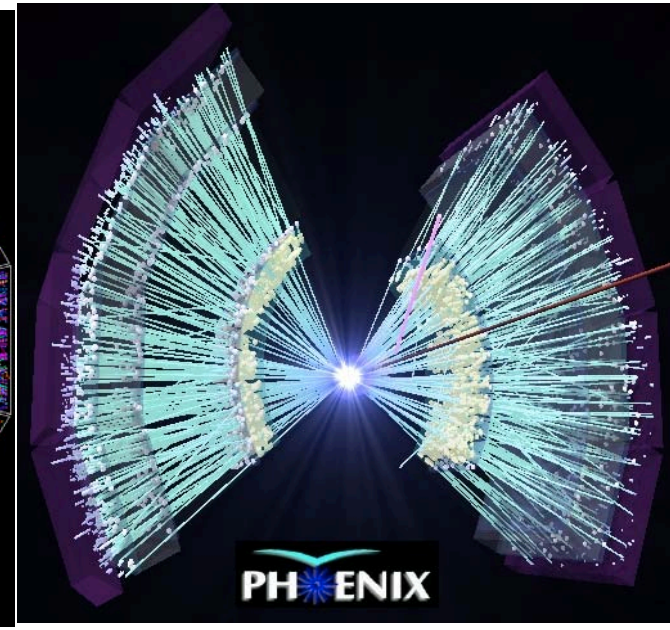
STAR-Jet event in pp

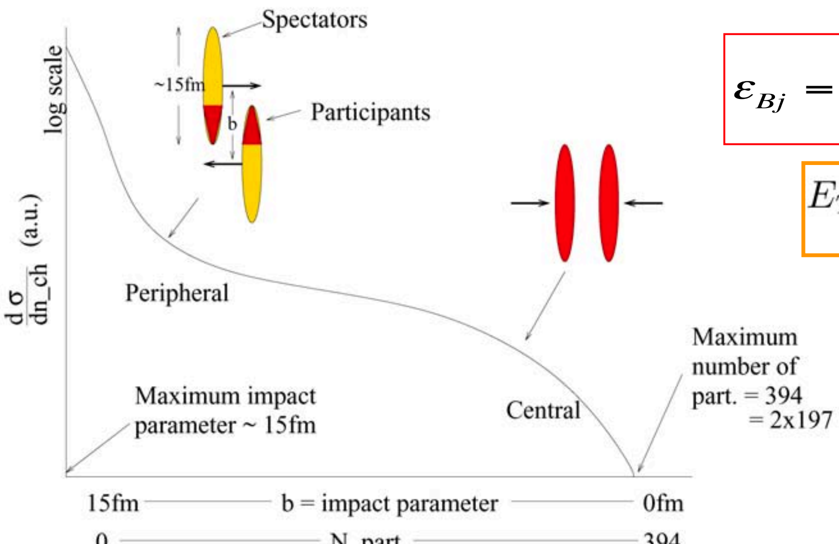


STAR Au+Au central



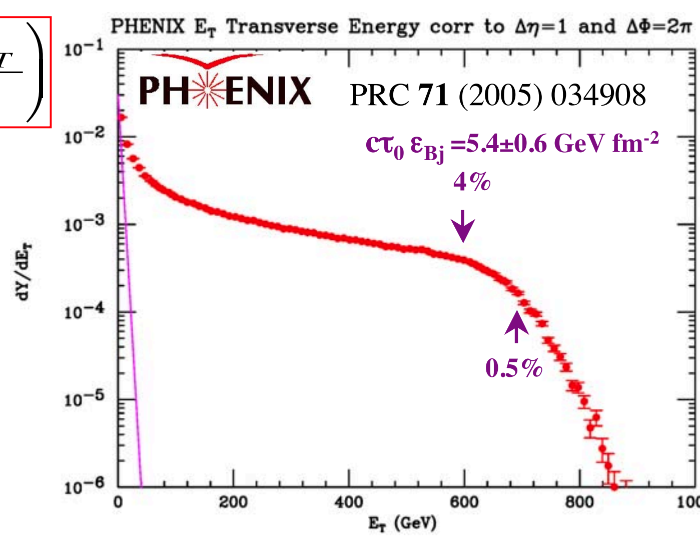
PHENIX Au+Au central



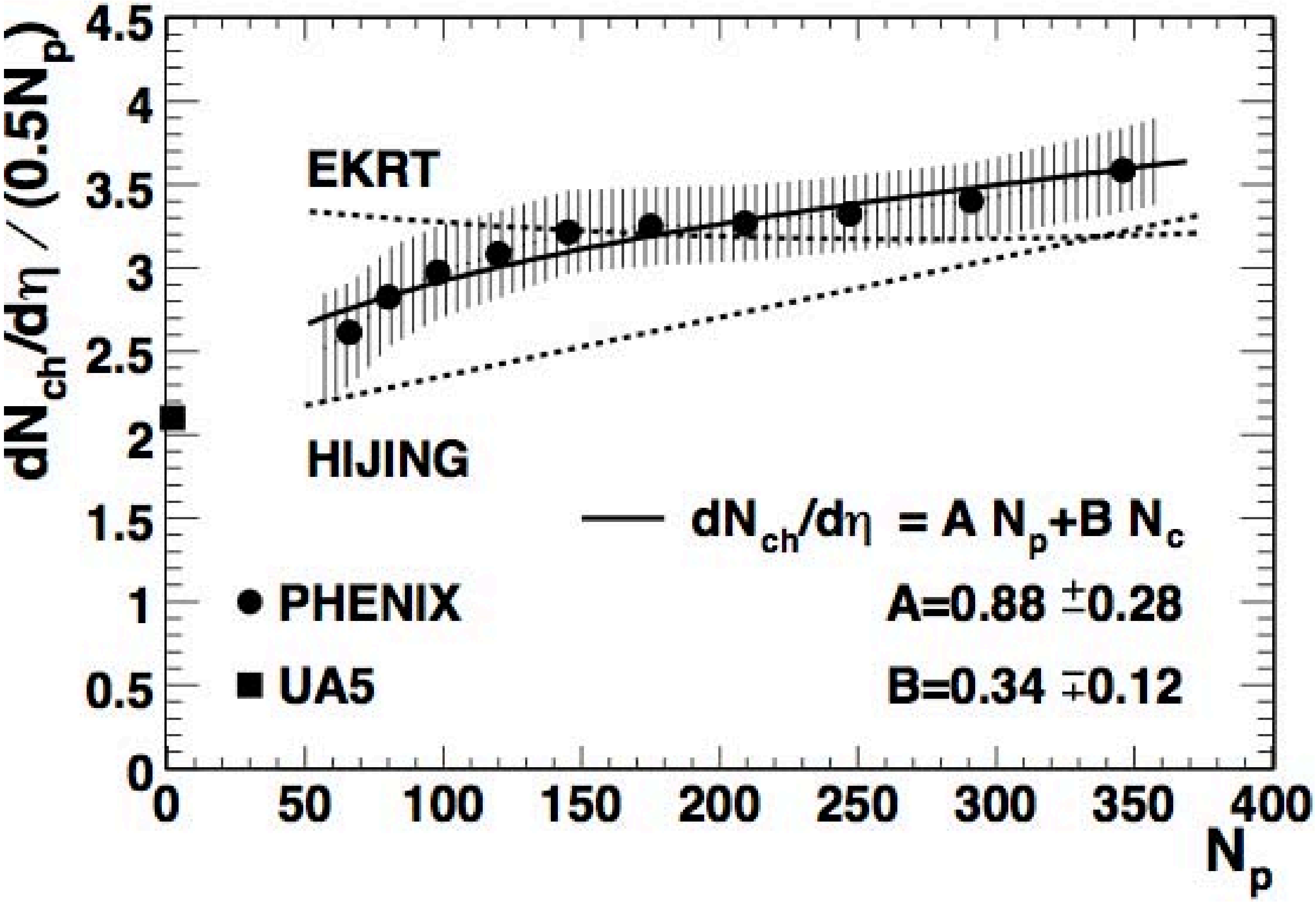


$$\boxed{\varepsilon_{Bj} = \frac{1}{\pi R^2}\frac{1}{c\tau_0}\left(\frac{dE_T}{dy}\right)}$$

$$\boxed{E_T \equiv \sum_i E_i \sin\theta_i}$$



From RHIC to LHC to RHIC evolution of multiplicity with centrality, N_{part}



PHENIX $\sqrt{s_{NN}}$=130 GeV, PRL 86, 3500 (2001); ALICE $\sqrt{s_{NN}}$=2.76 TeV PRL 106,032301(2011)

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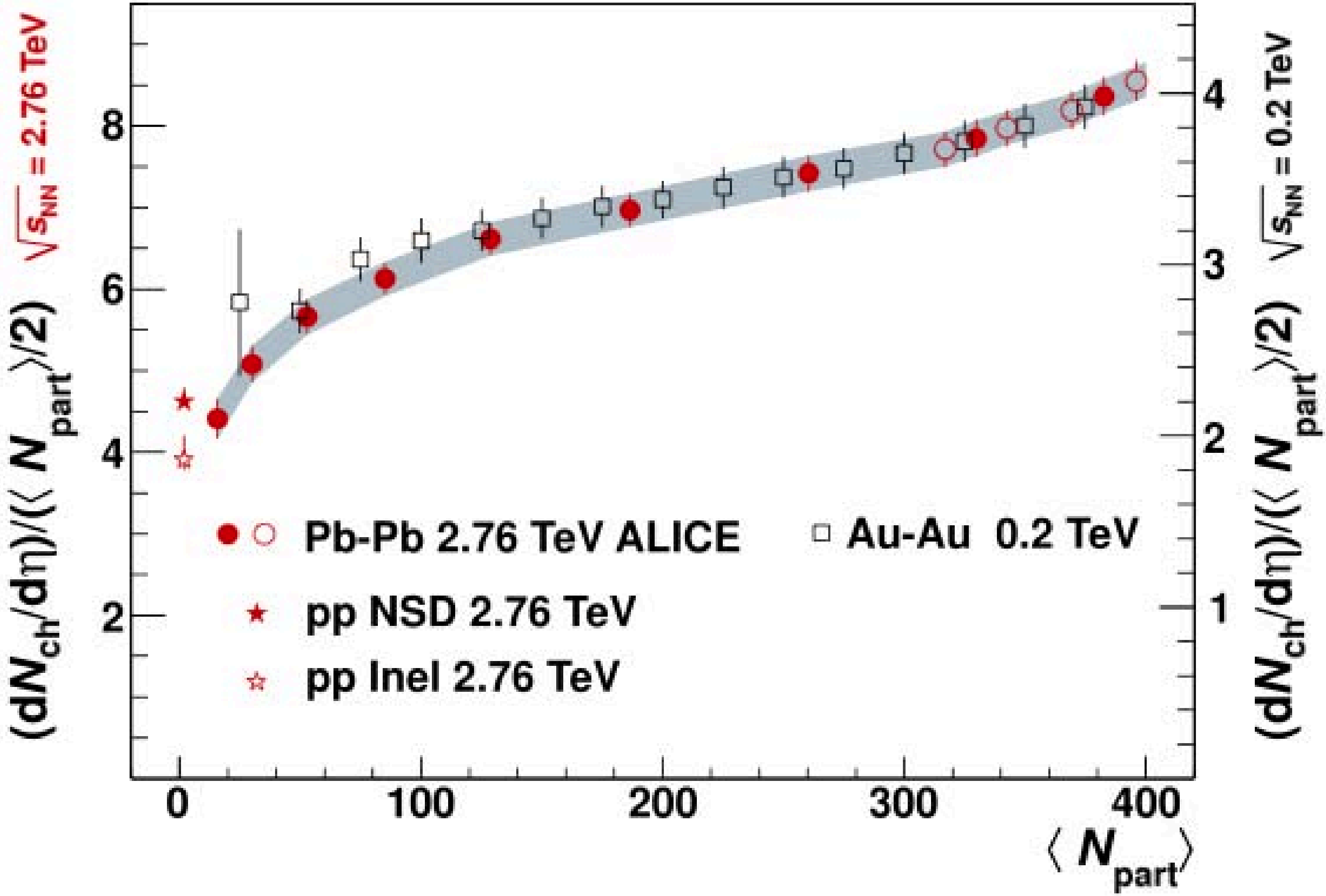

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Identical shape of distributions indicates a nuclear-geometrical effect

The geometry is the number of quark participants/nucleon participant

Eremin&Voloshin, PRC 67, 064905(2003) ; De&Bhattacharyya PRC 71; Nouicer EPJC 49, 281 (2007)

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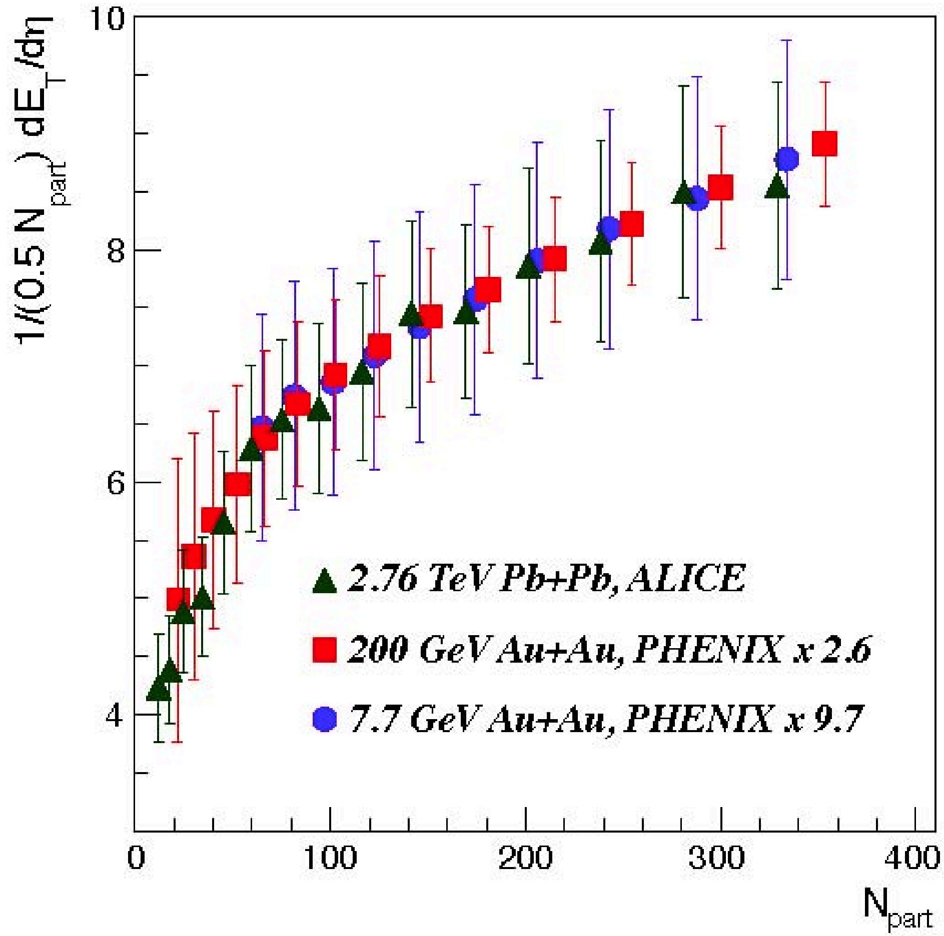

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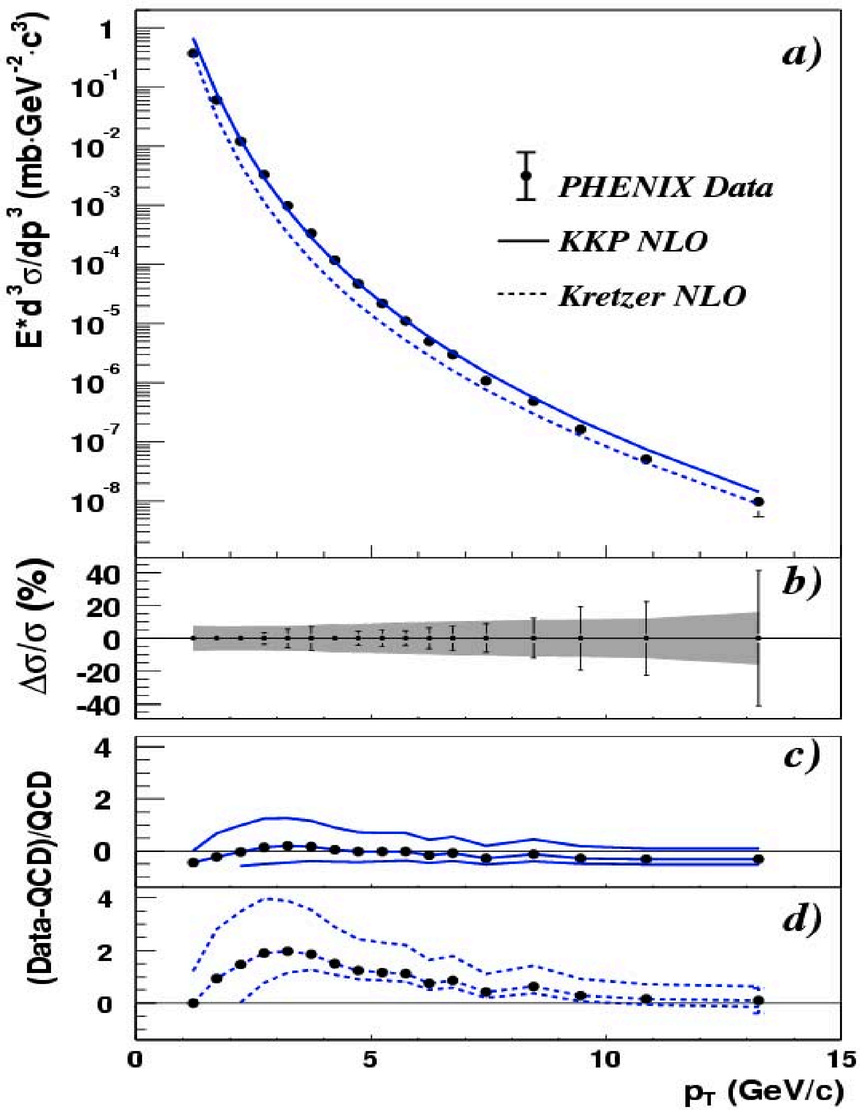
π^0's in p+p $\sqrt{s}$=200 GeV:Soft vs Hard production

- Result published from run2 -a classic
  - ✓ PHENIX PRL91 (2003) 241803

Soft production p_T<2 GeV/c dominates $dN_{ch}/d\eta$



Hard scattering-Inclusive invariant π^0 spectrum is pure power law for $p_T \geq 3$ GeV/c n=8.1±0.1

NLO-pQCD describes very well down even to $p_T \sim 1$ GeV/c

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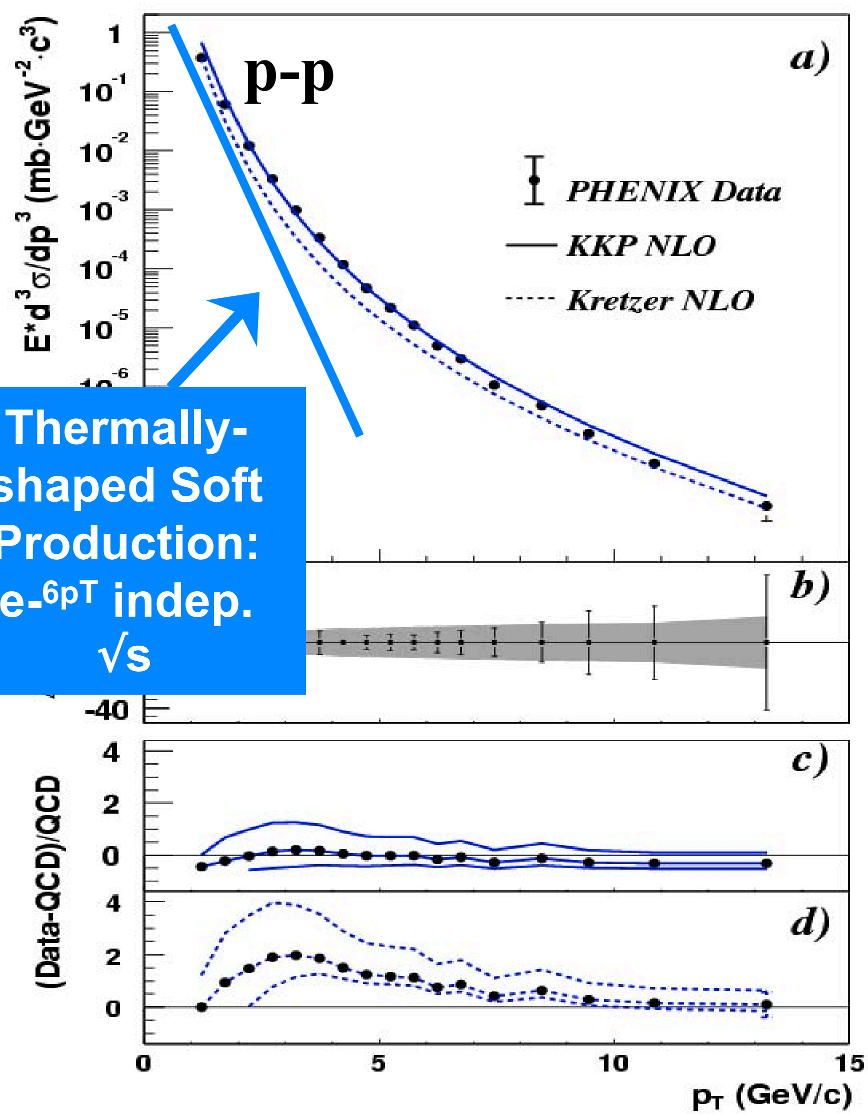

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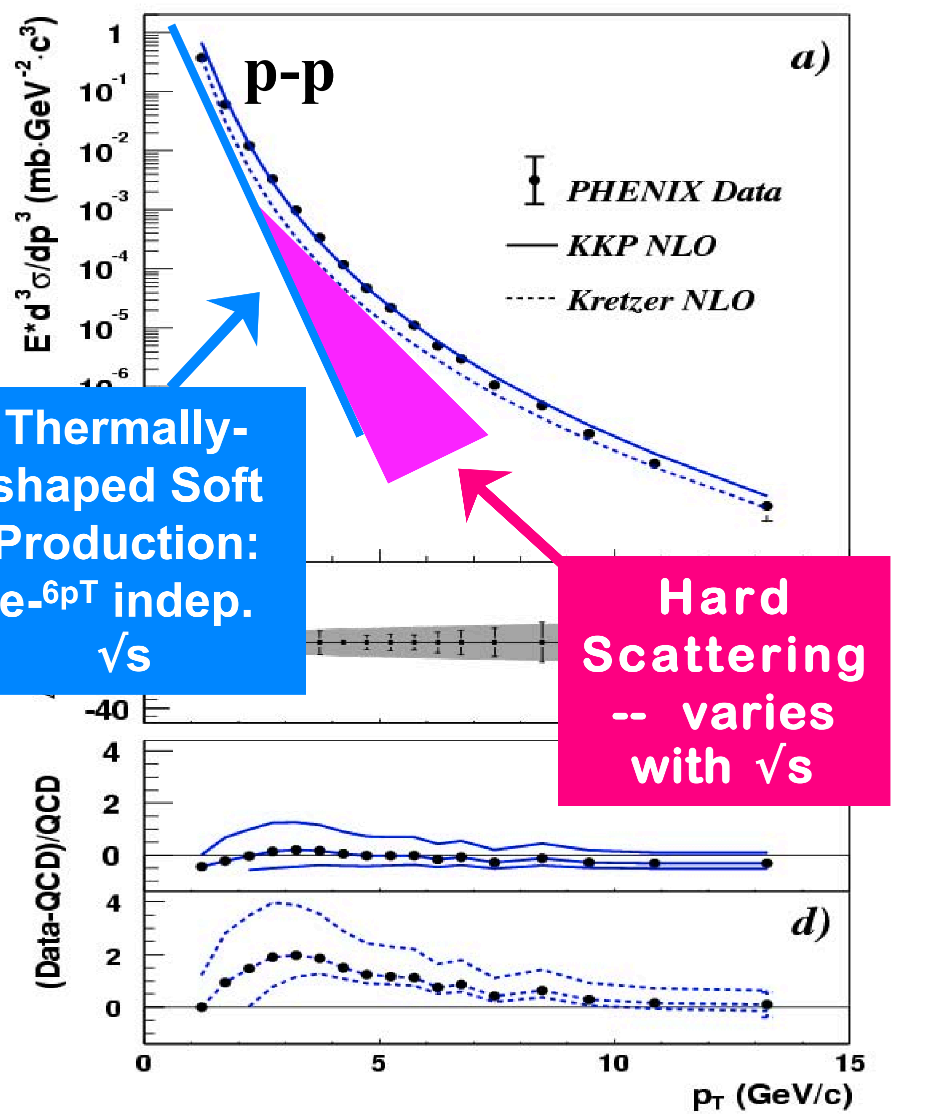

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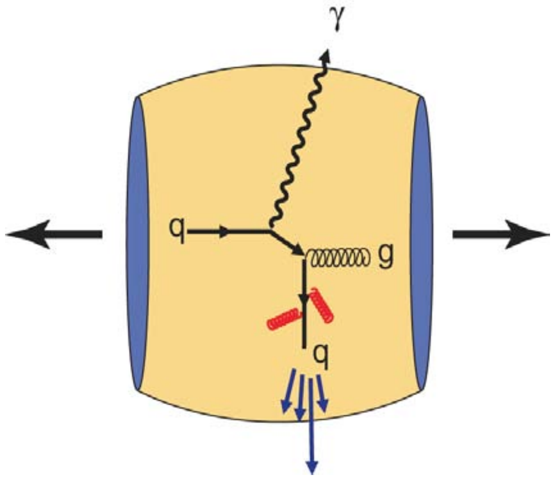
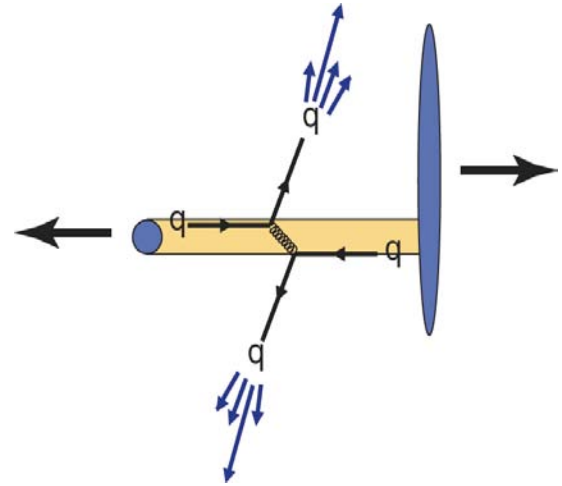
Hard scattering as a probe of the medium: Hot (AA) vs Cold pA Nuclear Matter Effects



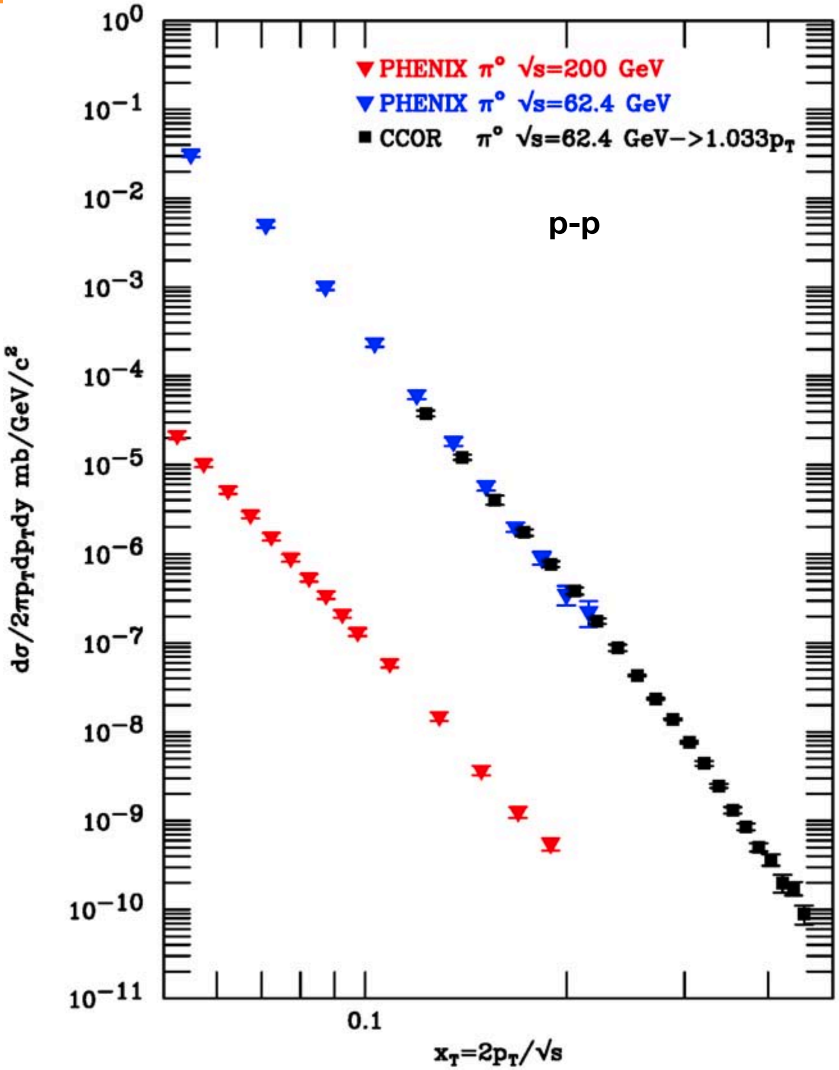


Hard scattering of partons in the initial collision is in-situ internal probe of medium. Do quarks and gluons lose energy in the medium? If so exactly how?

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

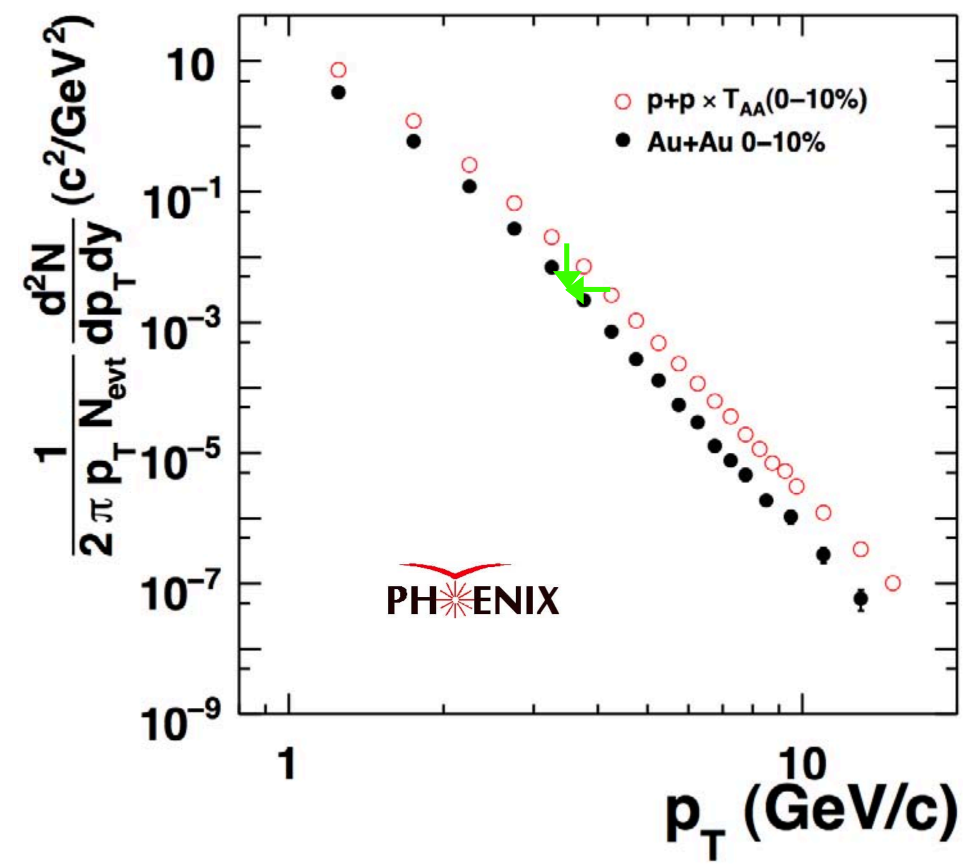
- RHIC is versatile
  - ✓ Can collide any nuclear species on any other

ISR π^0 vs RHIC p-p ⇒ RHIC pp vs AuAu



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

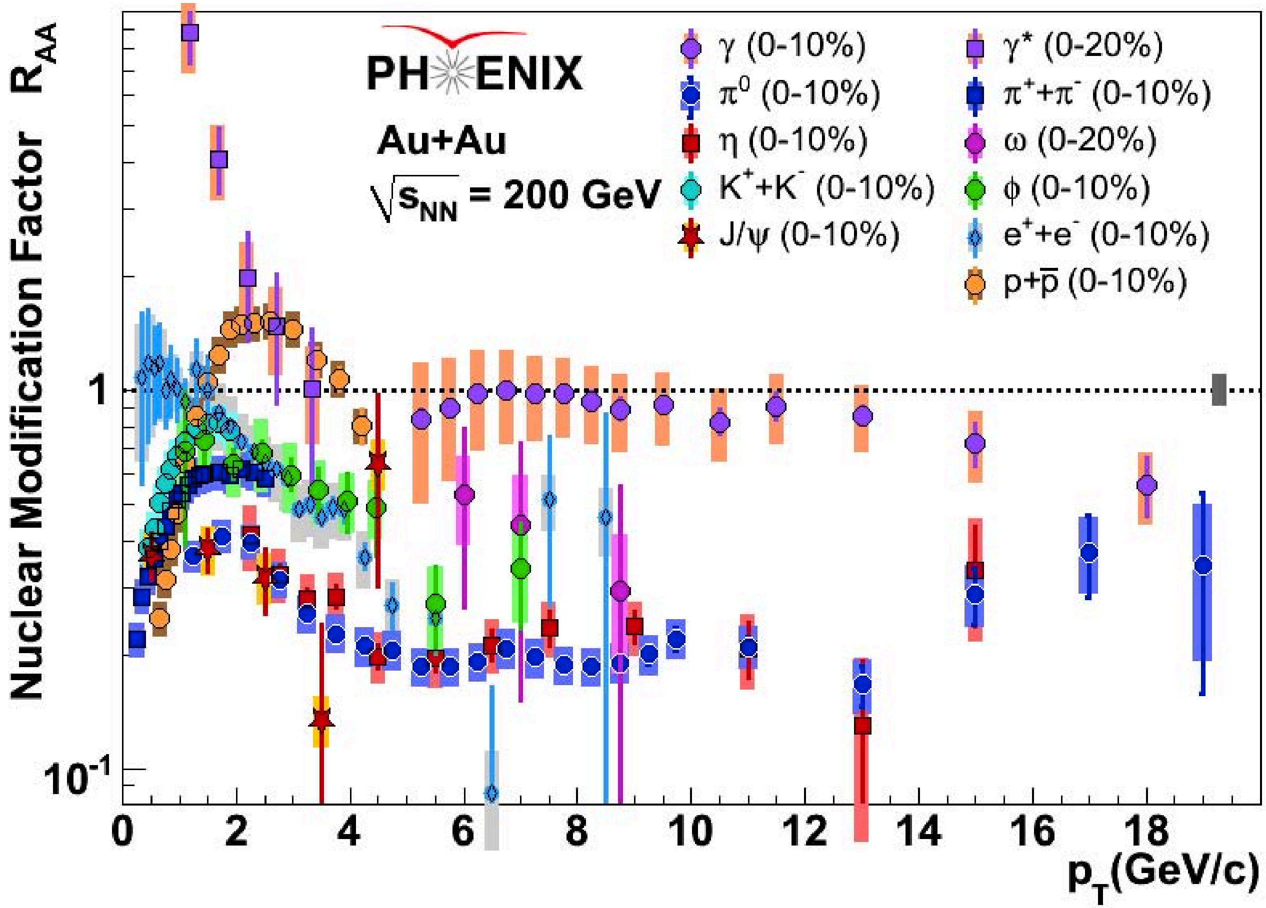
π^0 are suppressed in Au+Au eg 200 GeV



Nuclear Modification Factor

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

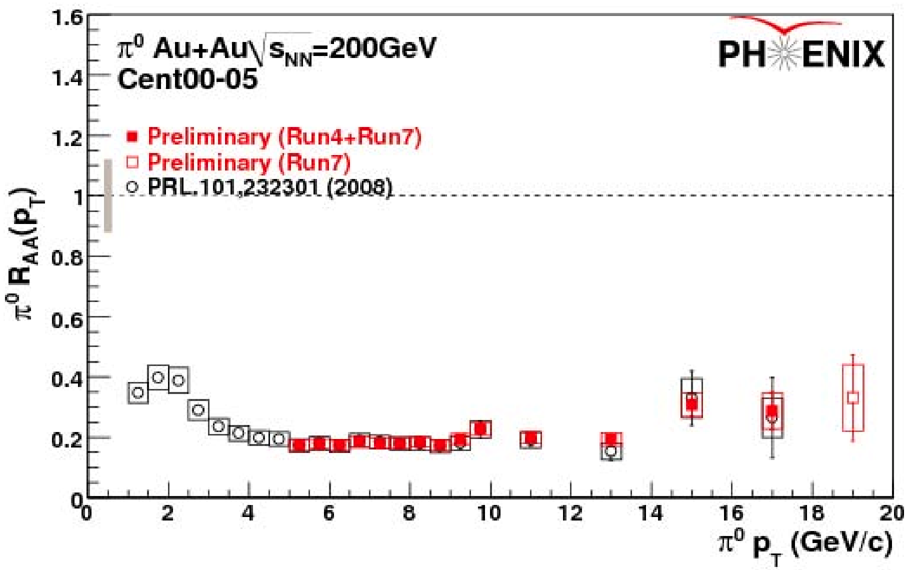
Status of R_{AA} in AuAu at $\sqrt{s_{NN}}$=200 GeV QM11



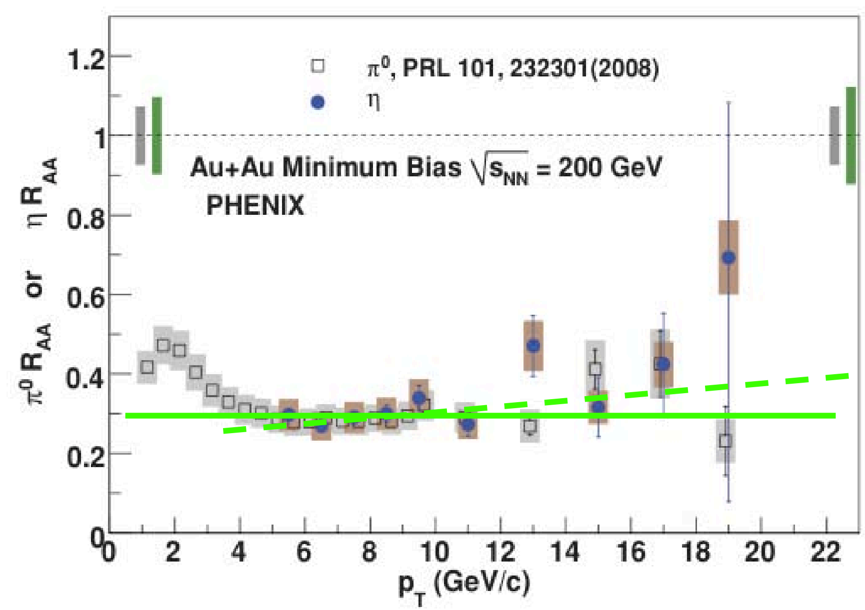
particle ID is crucial different particles behave differently

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.

Does R_{AA} increase with p_T? Comparison to ALICE



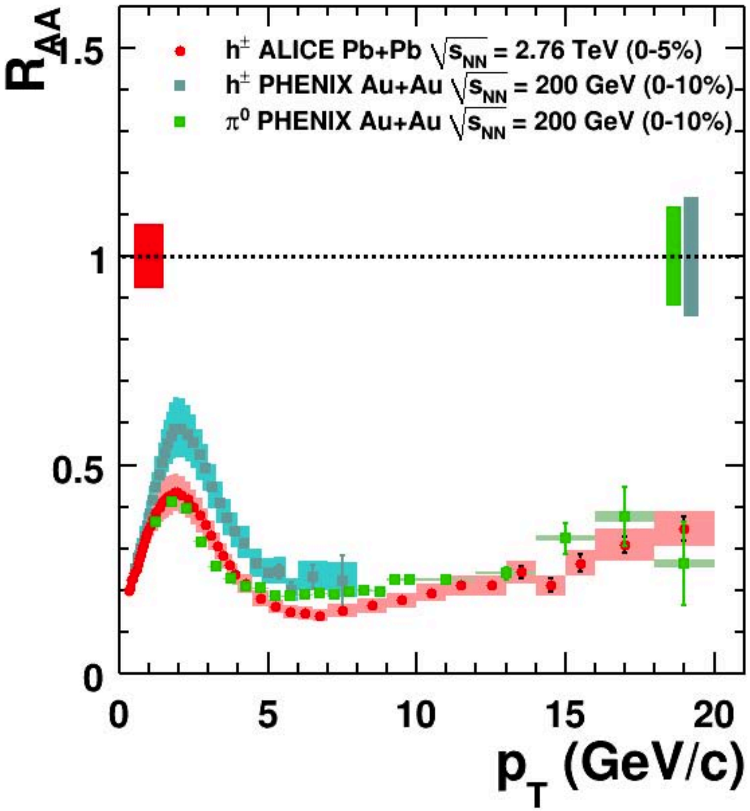
A. ADARE *et al.*

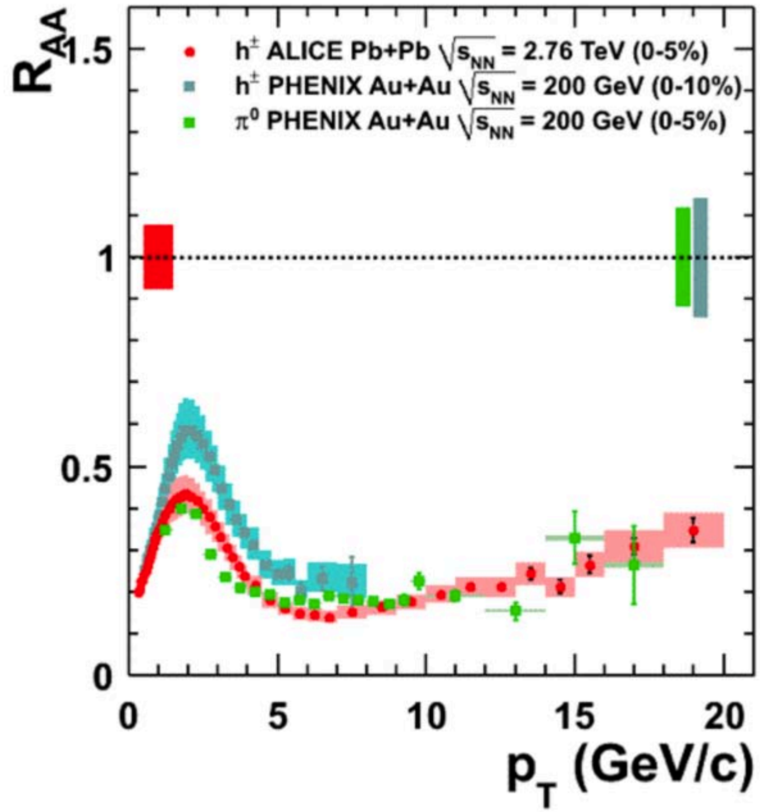


PHENIX **minimum bias** $\pi 0$ R_{AA}
PRL 101, 232301 (2008)
η R_{AA} PRC82, 011902(R)(2010)
new PRELIMINARY 0-5%

Contour lines for fit to η R_{AA} rising linearly with p_T are consistent with zero slope, i.e. constant. PRC82, 011902(R)(2010) same as for $\pi 0$.

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





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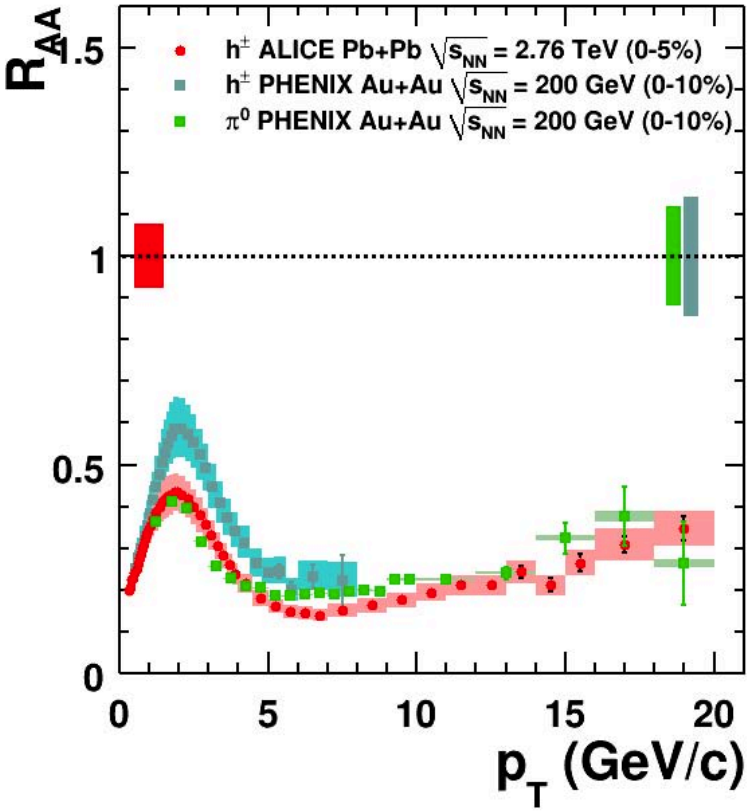

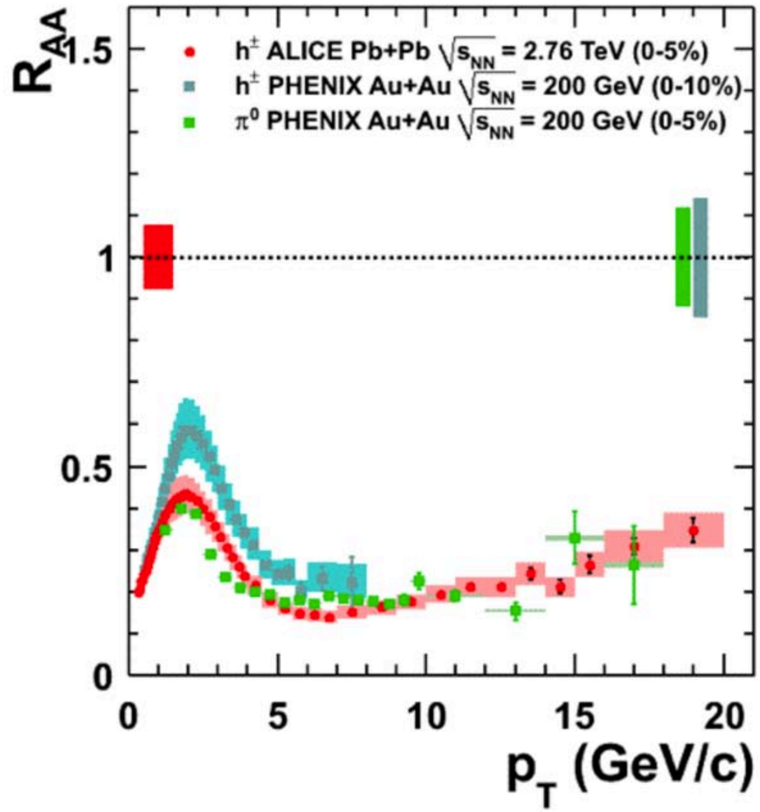

- Despite more than a factor of 20 higher $\sqrt{s_{NN}}$, the R_{AA} looks nearly identical for RHIC and LHC for 5<pT< 20 GeV/c
- ALICE data show significant upward trend but PHENIX upward trend not significant.

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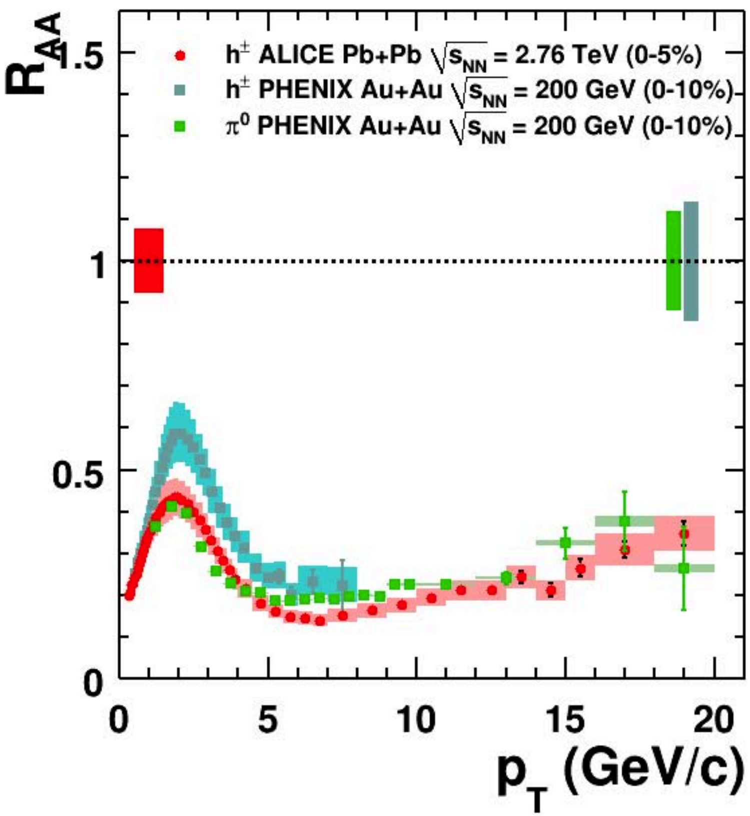

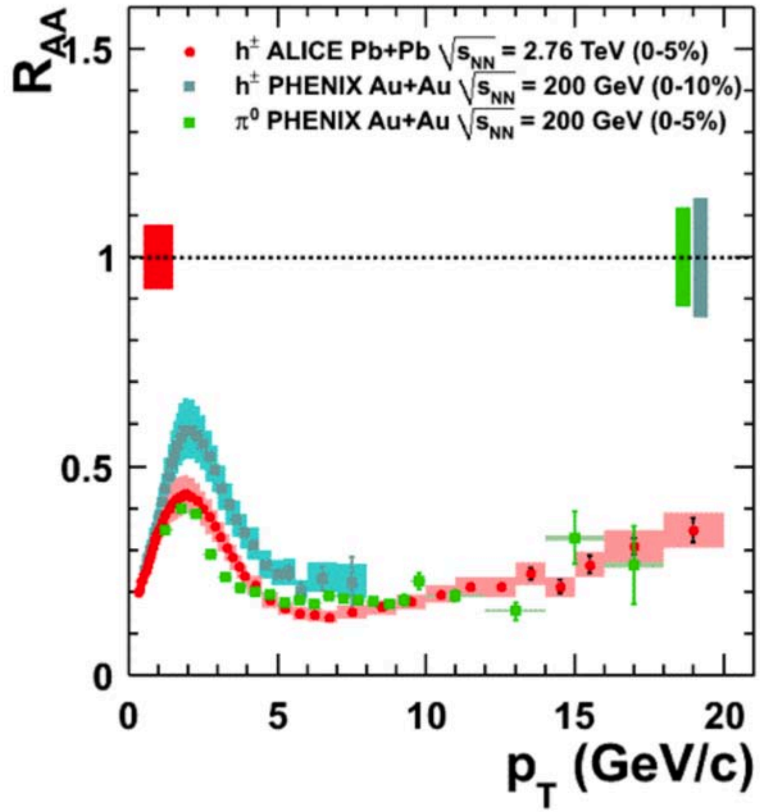

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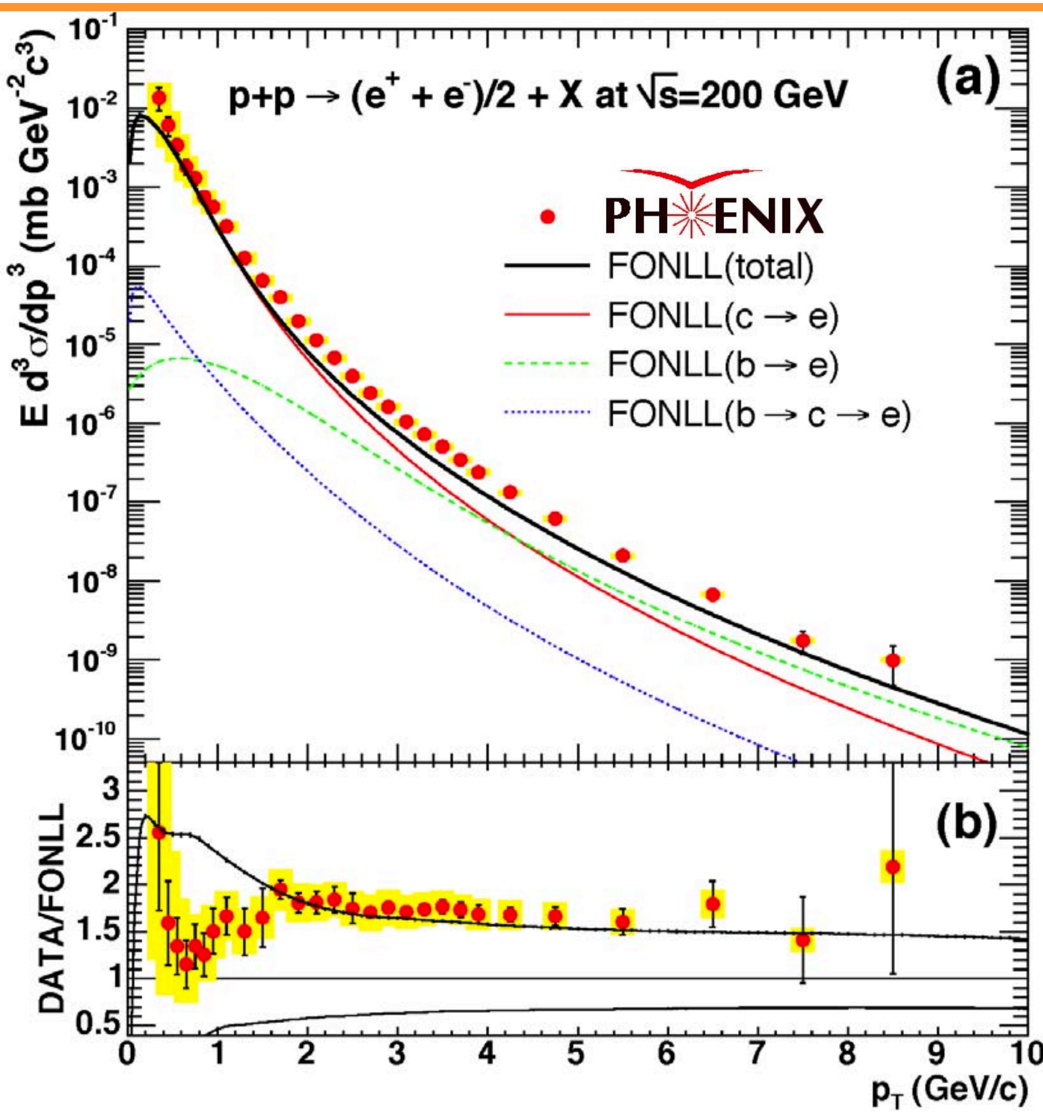
Don't be tempted to conclude that the fractional jet energy loss is the same at RHIC and LHC: the inclusive spectra are flatter at LHC n~6 cf. RHIC n=8.1, which implies 50% more $\Delta E/E$ at LHC than at RHIC

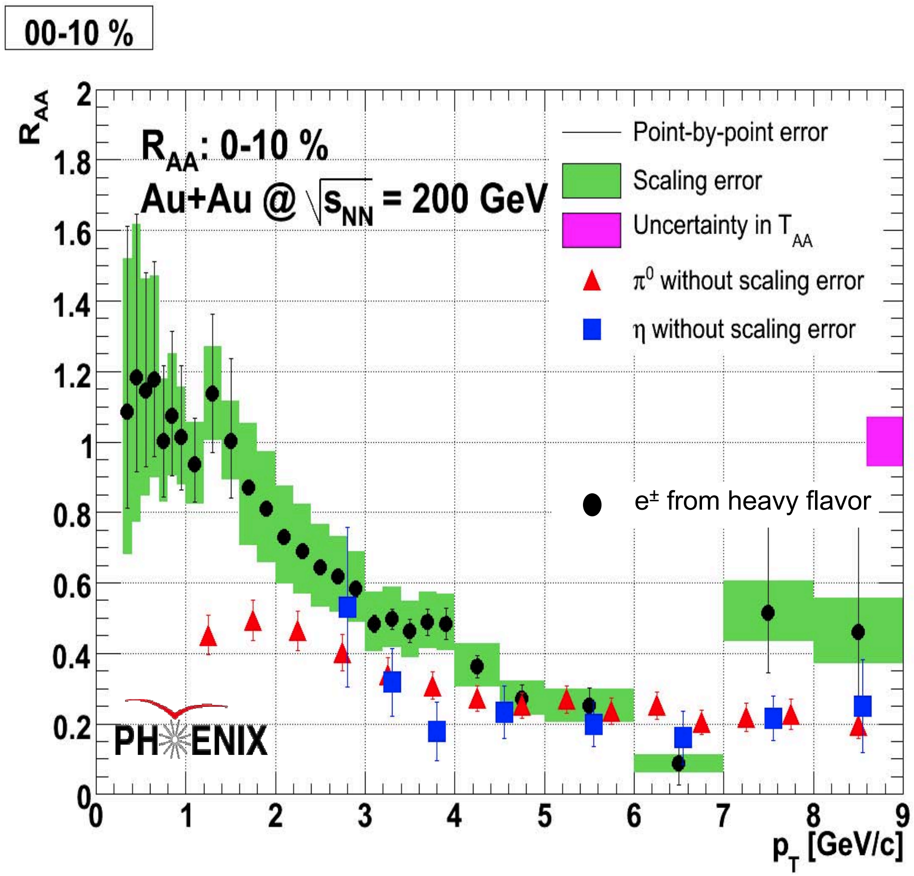
Charm via direct single e in p-p collisions



PHENIX PRL**97**(2006)252002

Beautiful agreement of e± with *c b* production in p-p

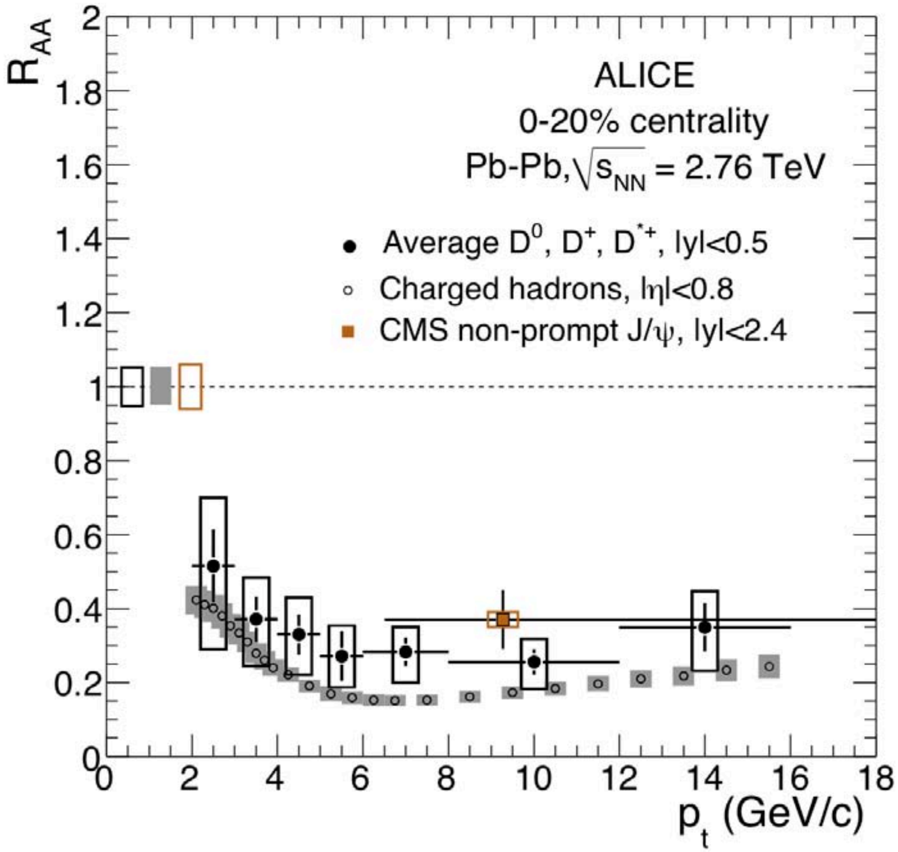
Direct e± in Au+Au indicate a theoretical crisis



Au+Au PHENIX
PRL **98** (2007)172301

- heavy quarks suppressed the same as light quarks, and they flow, but less.
- This disfavors the hypothesis of energy loss by gluon bremsstrahlung in medium
- but brings string theorists into the game, see references in PRL 98 (2007) 172301.
- However, I think that Nino Zichichi had a better explanation.

Confirmed at LHC



D meson from c quarks (ALICE arXiv:1203.2160v1); non-prompt J/Psi from b quarks [CMS arXiv:1201.5069v1 suppressed the same as charged hadrons $R_{AA}\approx 0.3$-0.4

From CERN Courier, September 2007

- I read an article "Yukawa's gold mine" by Nino Zichichi taken from his talk at INPC 2007 in Tokyo, Japan, in which he noted that the Higgs doesn't need to give Fermions mass for Electro-Weak unification, the Yukawa coupling is put in by hand.

S. Weinberg, PRD 19, 1277 (1979); L. Susskind, PRD20, 2619 (1979)

"However, since the origin of the quark masses is still not known, it cannot be excluded that in a QCD coloured world (i.e. QGP), the six quarks are all nearly massless and that the colourless condition is 'flavour' dependent."

- MJT: "Wow! Massless *b* and *c* quarks in a color-charged medium would be the simplest way to explain the apparent equality of gluon, light and heavy quark suppression indicated by the equality of R_{AA} for π^0 and direct-single $e^{\pm}$ in regions where both *c* and *b* quarks dominate." Test by measuring b-dijet imbalance in $b-\bar{b}$ correlations

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- Higgs doesn't give quarks mass
- QCD isn't flavor-blind

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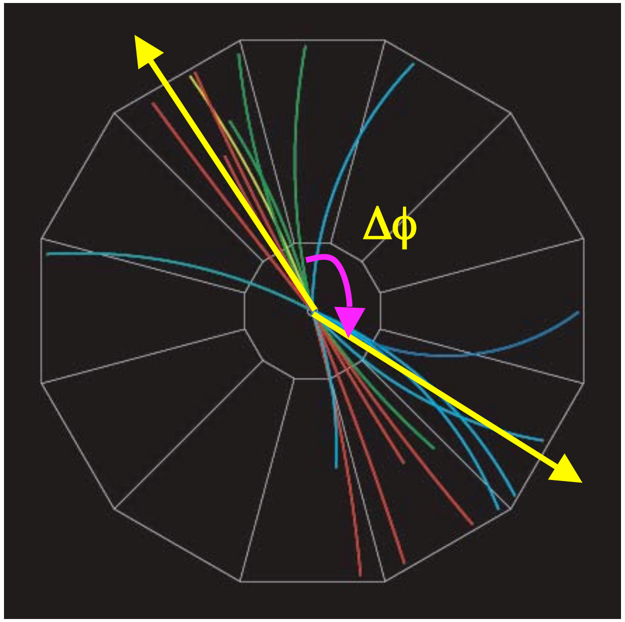
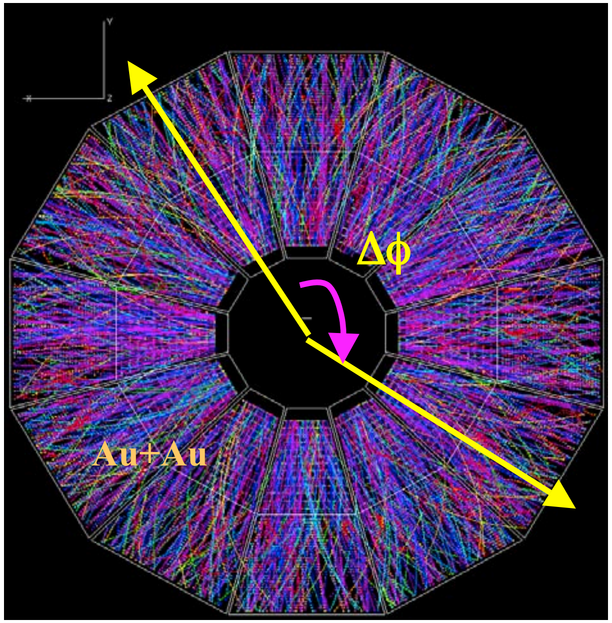
Correlations

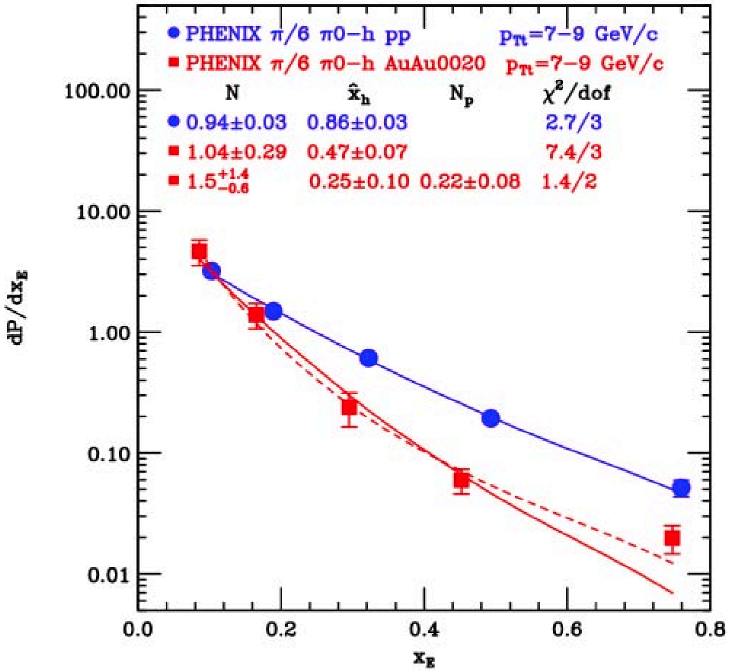




e.g. p + p → jet + jet

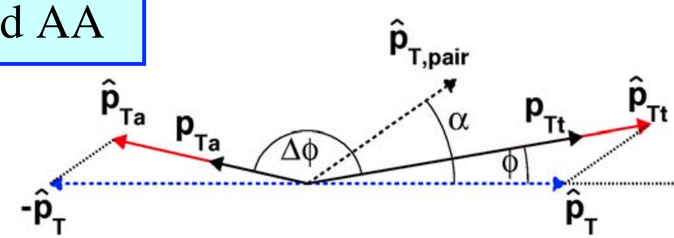
c.f. Au + Au → jet + jet
+ flow

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

PHENIX
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

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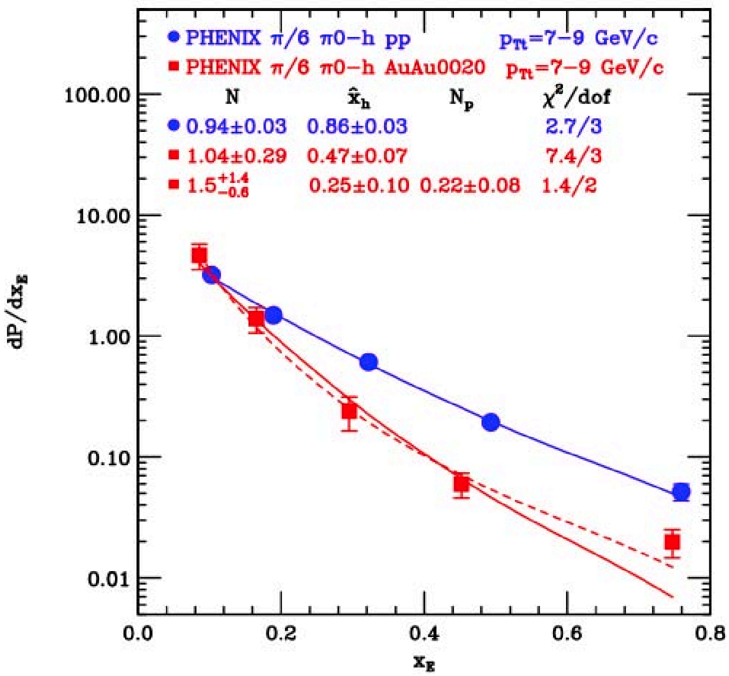

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PHENIX
π^0-h correlations
PRL104(2010)252301

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

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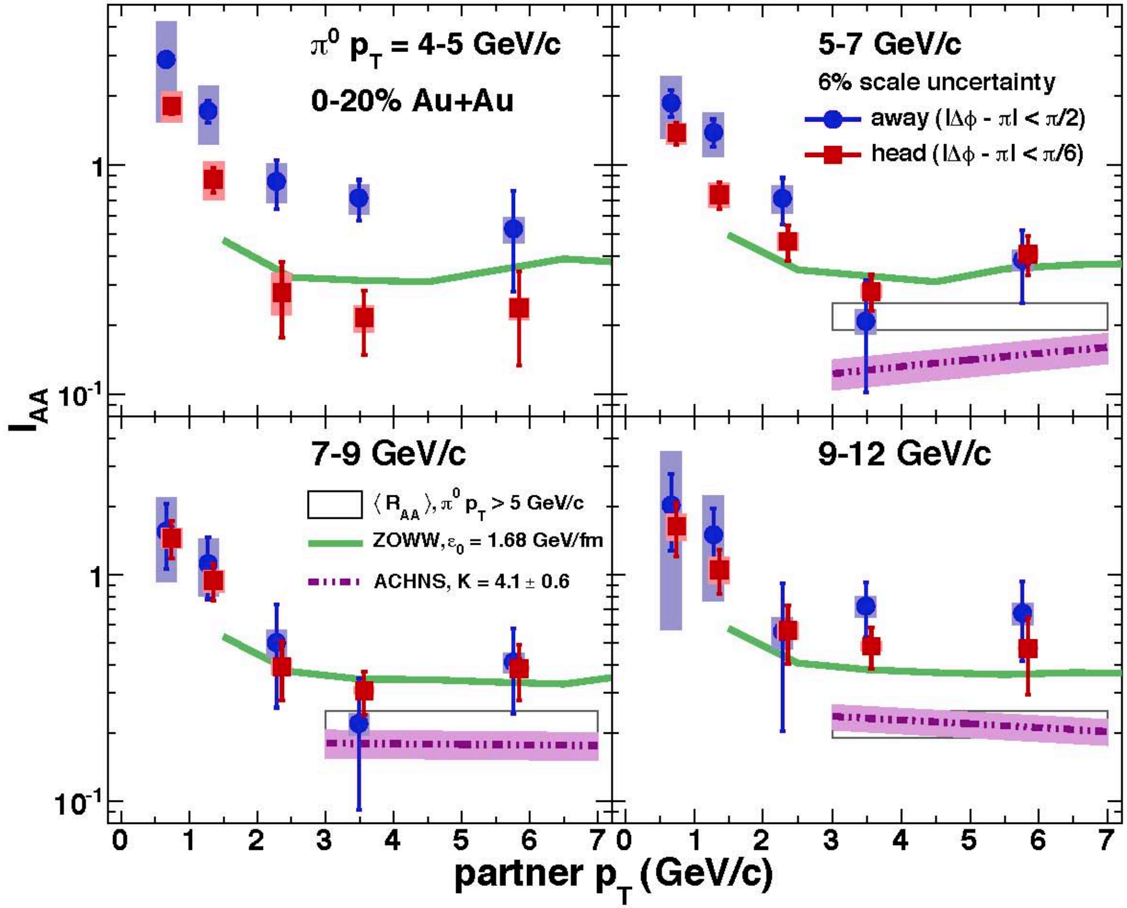
Typically experiments only show I_{AA}, the ratio of the AA and pp $x_E \approx z_T = p_{Ta}/p_{Tt}$ distributions

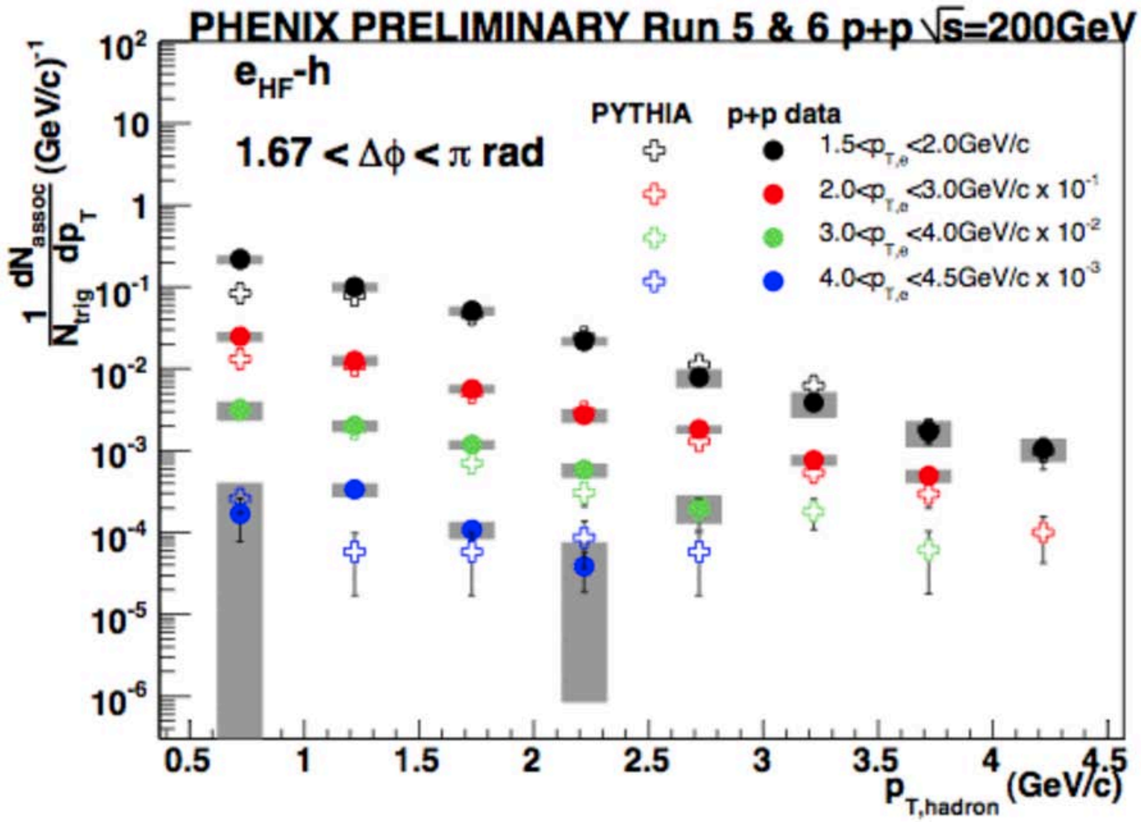


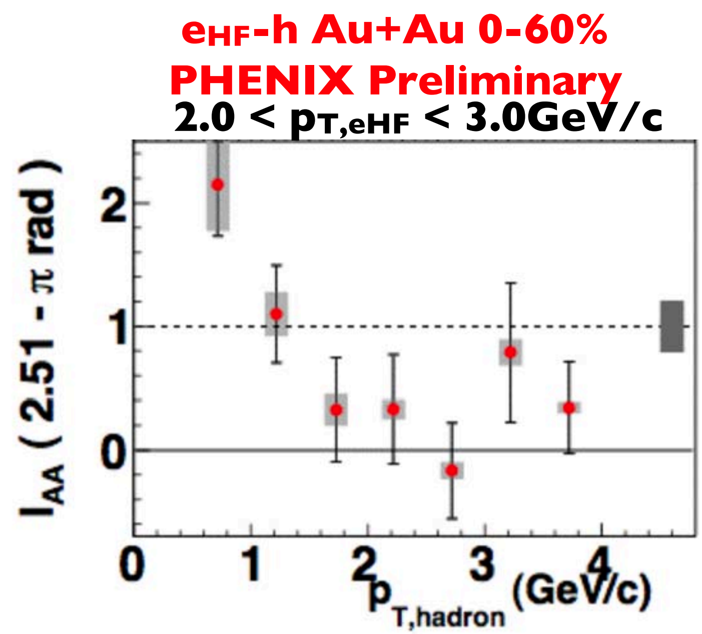
PHENIX
π^0-h correlations
PRL104(2010)252301

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] ≈ [dN^{AA}/dz_T]/ [dN^{pp}/dz_T]

First e±-h heavy flavor correlation-no VTX



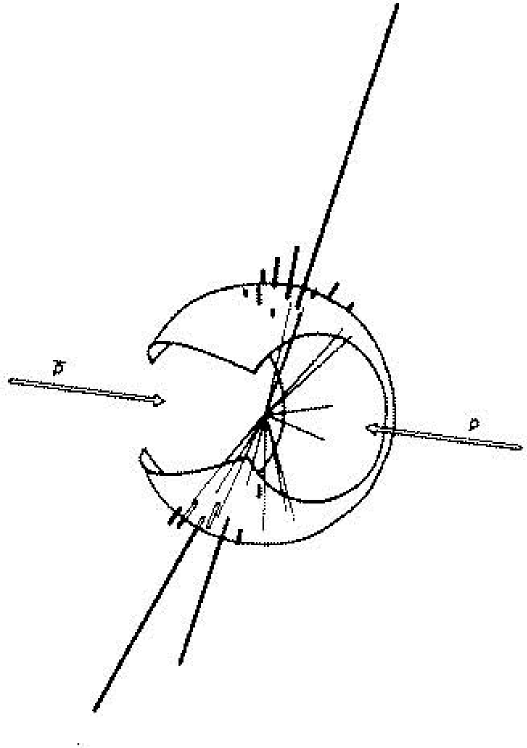


- heavy flavor tagged correlations: NLO important--e_{HF} not necessarily balanced by back-to-back heavy quark

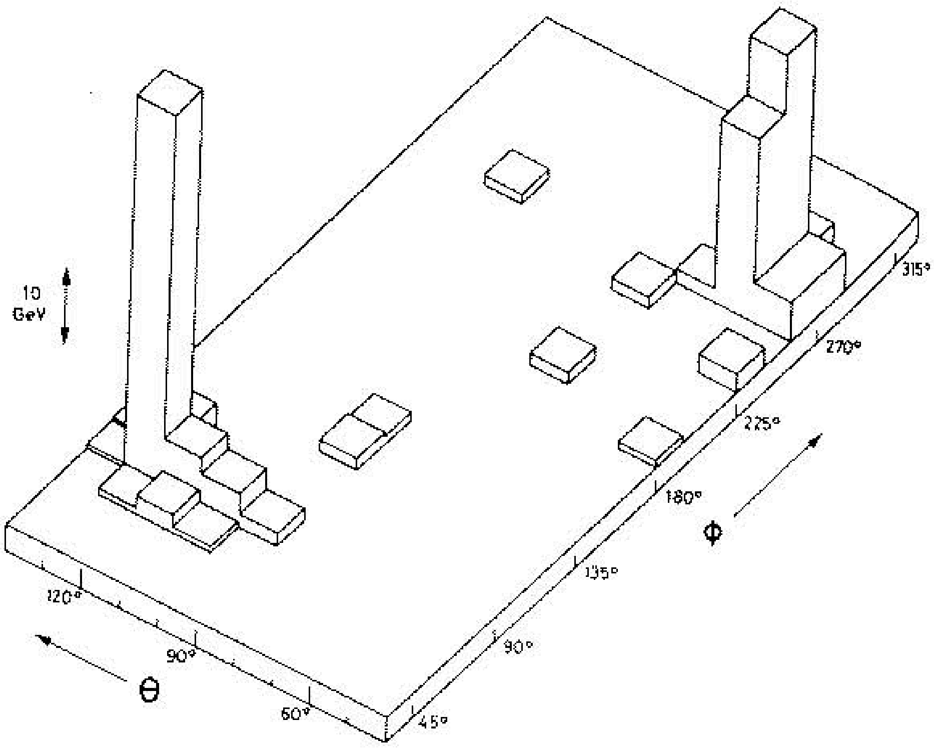
Quark Matter 2009 Anne M. Sickles March 31, 2009

THE UA2 Jet-Paris 1982

From 1980--1982 most high energy physicists doubted jets existed because of the famous NA5 E_T spectrum which showed NO JETS. This one event from UA2 in 1982 changed everybody's opinion.



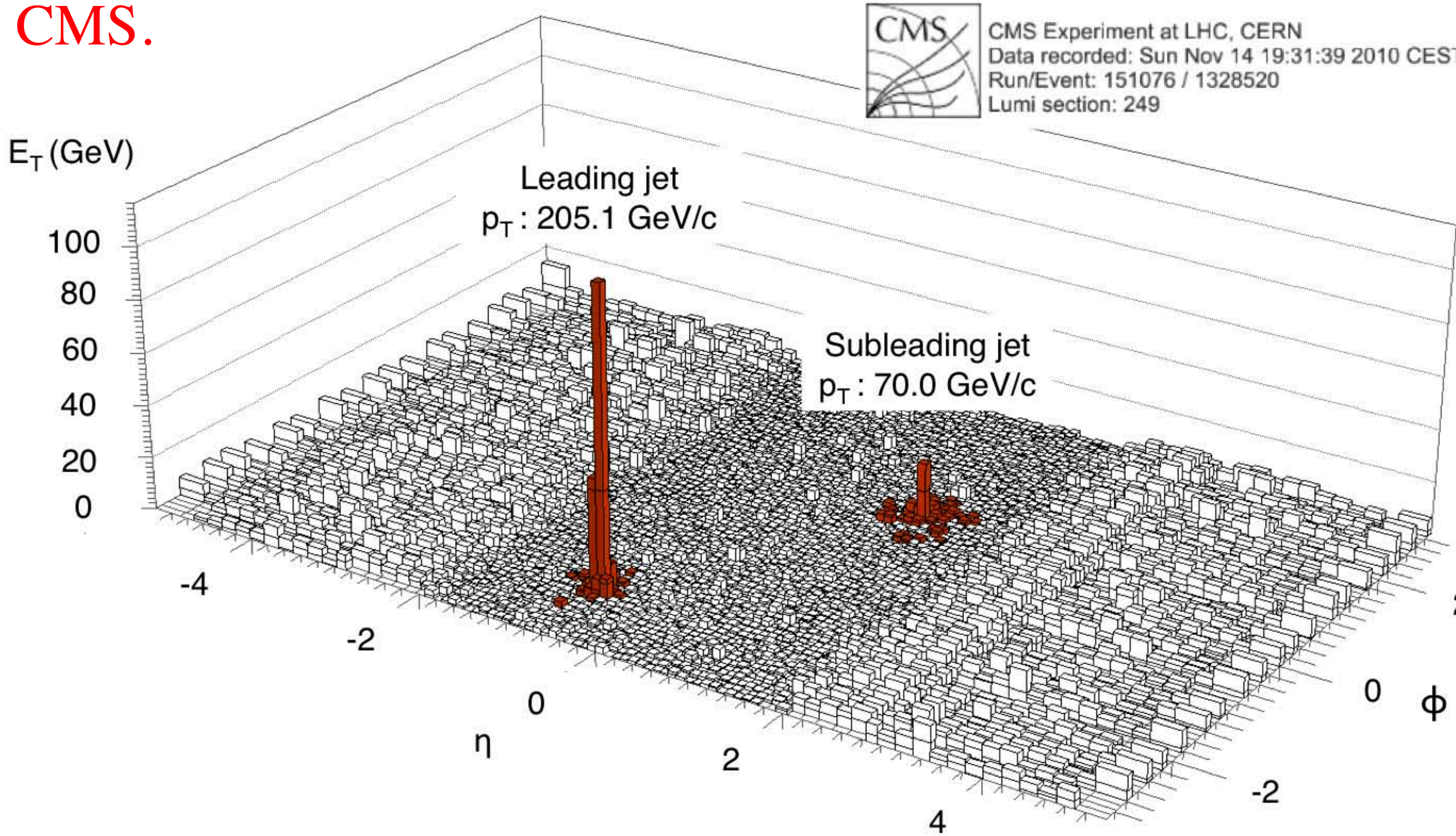
(a)



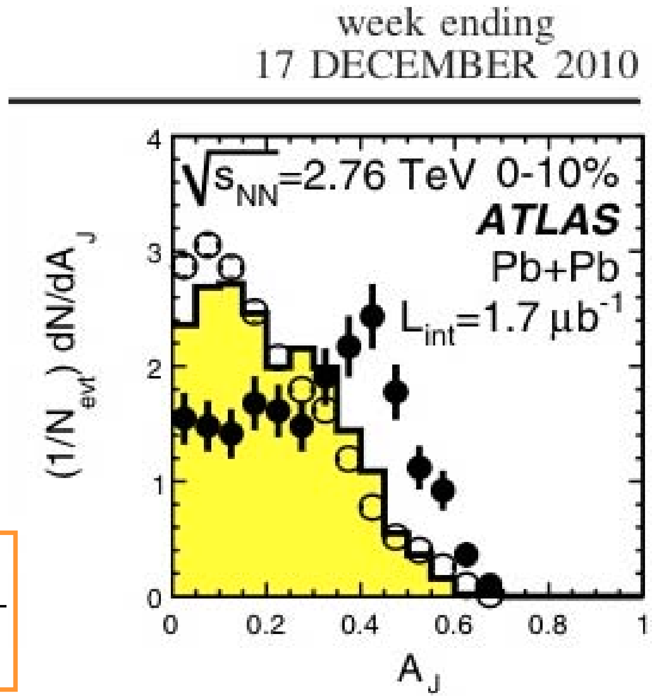
(b)

THE LHC Jet Pb+Pb-CERN 2010

In 2010, following a long p-p run at the LHC, with event displays of di-jets of roughly equal energy, the first Pb+Pb collisions showed events with strikingly asymmetric di-jets, as seen first by ATLAS and then by CMS.



Comparison with ATLAS



$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}} \approx \frac{1-\hat{x}_h}{1+\hat{x}_h}$$

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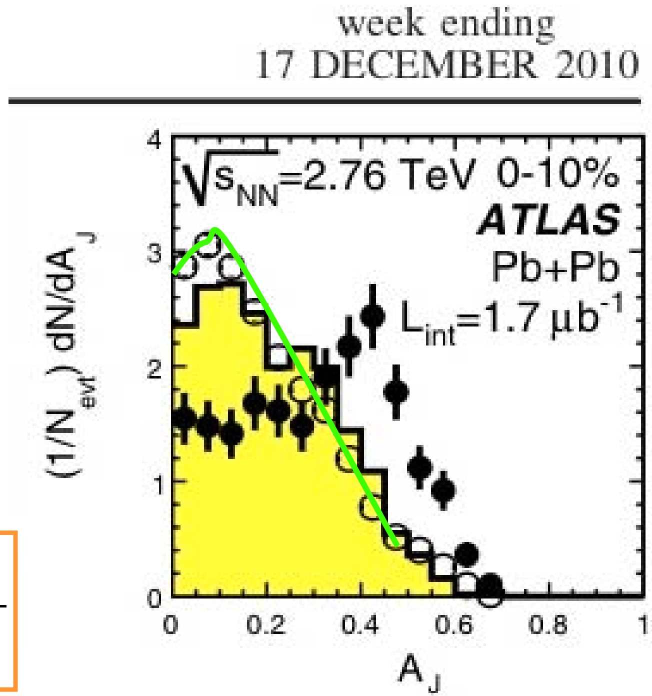

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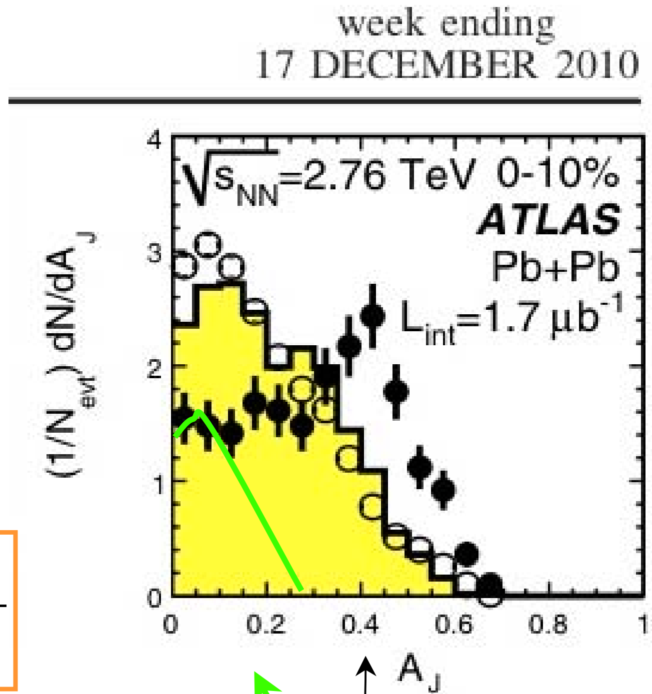

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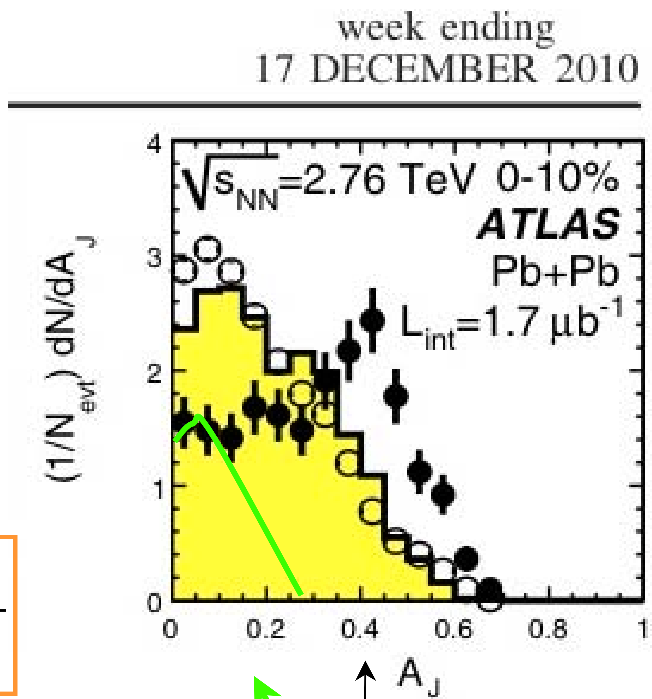
Punchthrough?

Energy Loss

Comparison with ATLAS



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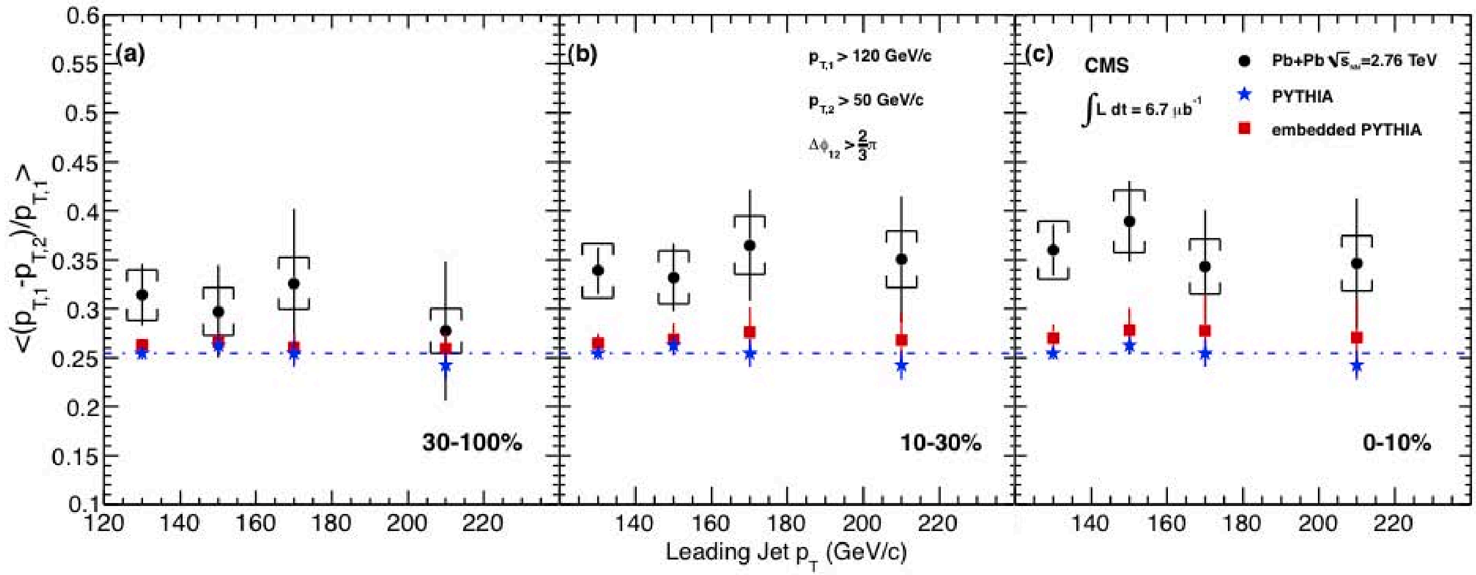
Punchthrough?

Energy Loss

ATLAS didn't agree. Can one tell punchthrough, i.e. pp jets, from jets with the correct energy but with modified fragmentation function.
Need to look at fragments, not only Jets

Comparison with CMS-fractional jet imbalance

arXiv:1102.1957v2



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

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

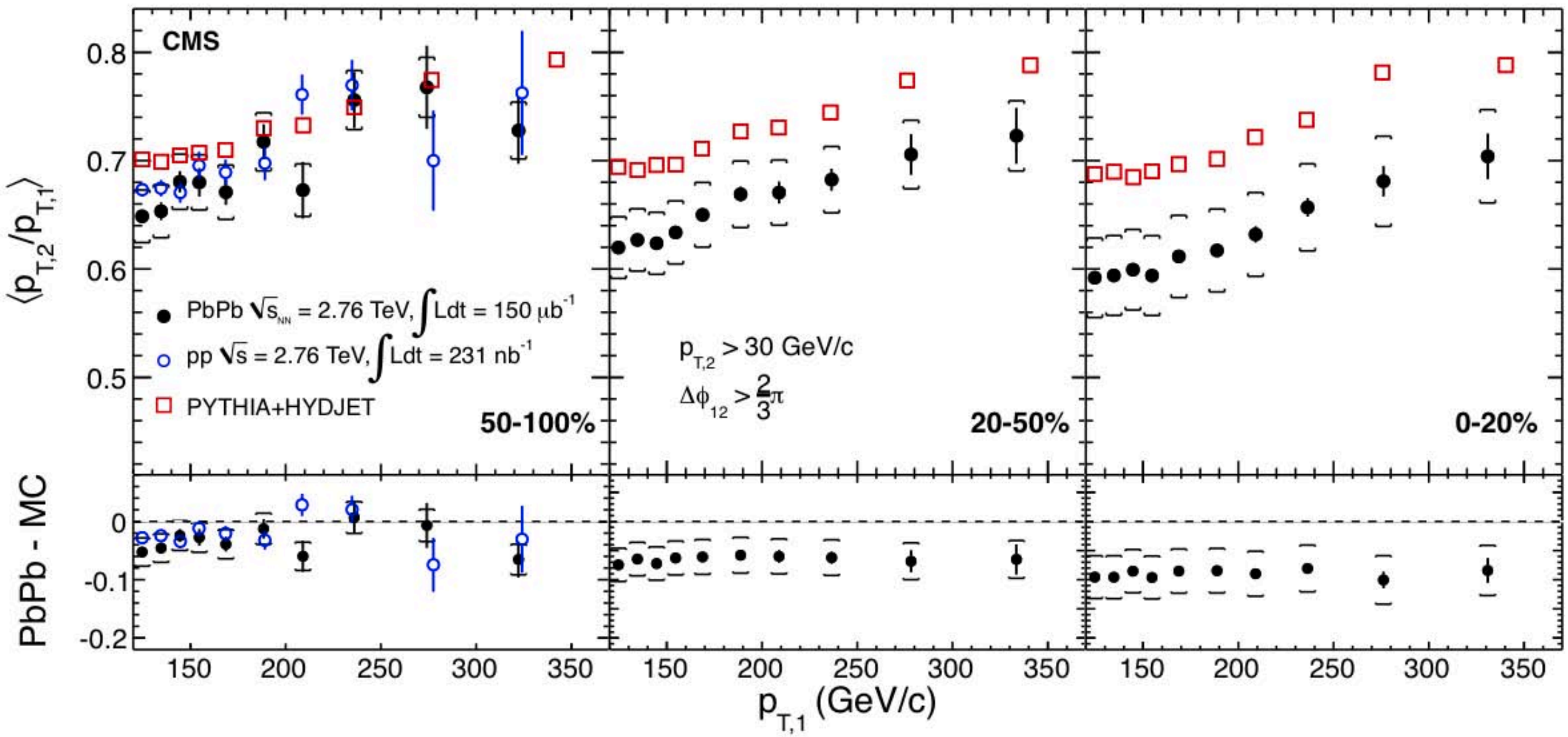
$$\hat{x}_h = 1 - (p_{T1} - p_{T2})/p_{T1}$$

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

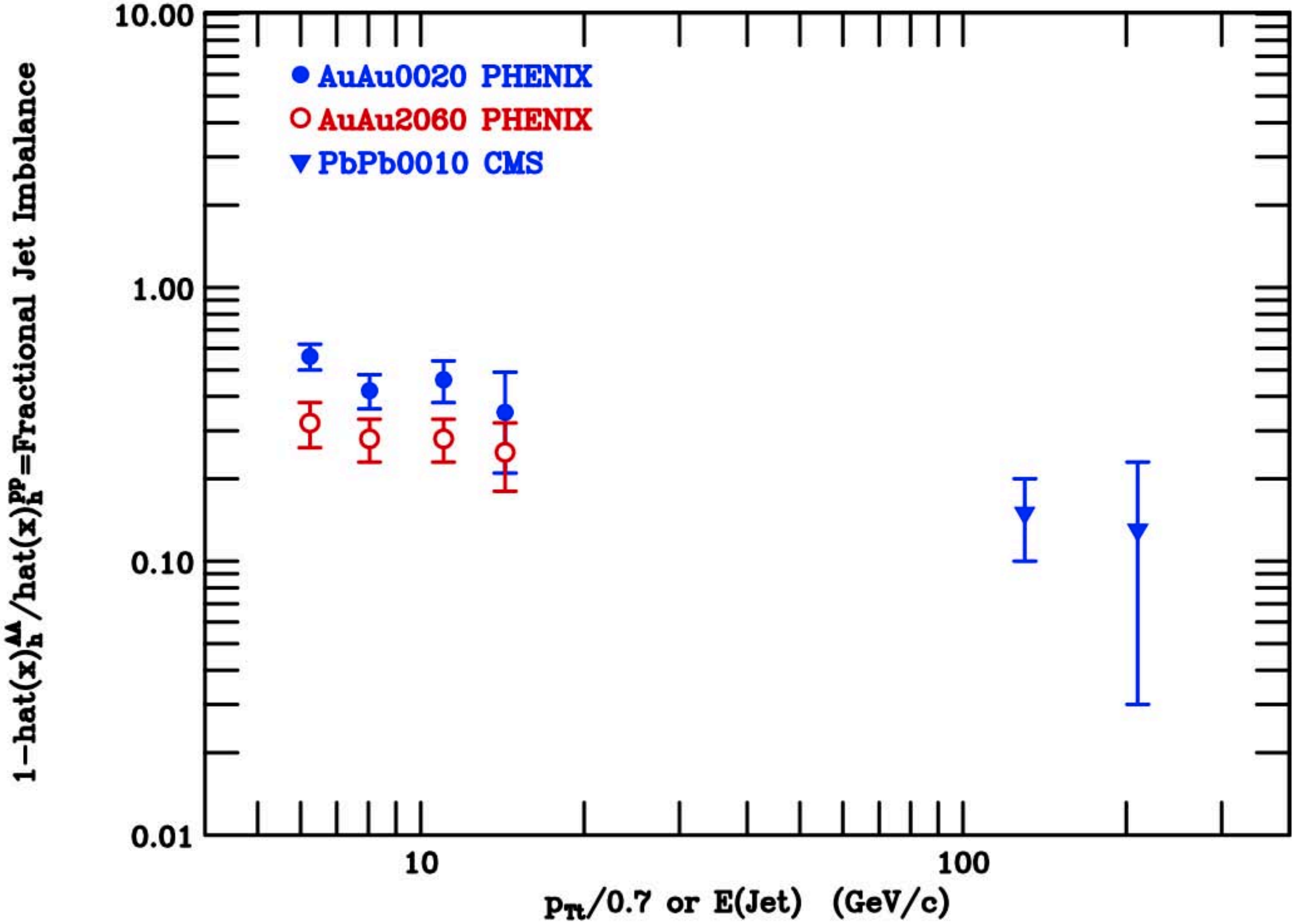
$$1 - \hat{x}_h^{AA} / \hat{x}_h^{pp} = 0.141 \Longleftarrow \hat{x}_h^{AA} / \hat{x}_h^{pp} = 0.64/0.745 = 0.859$$

CMS new result confirms my idea

ratio of
away
jet
totrigge



PHENIX cf. CMS corrected for pp



PHENIX cf. CMS corrected for pp