lecture 2, jet quenching and the QGP

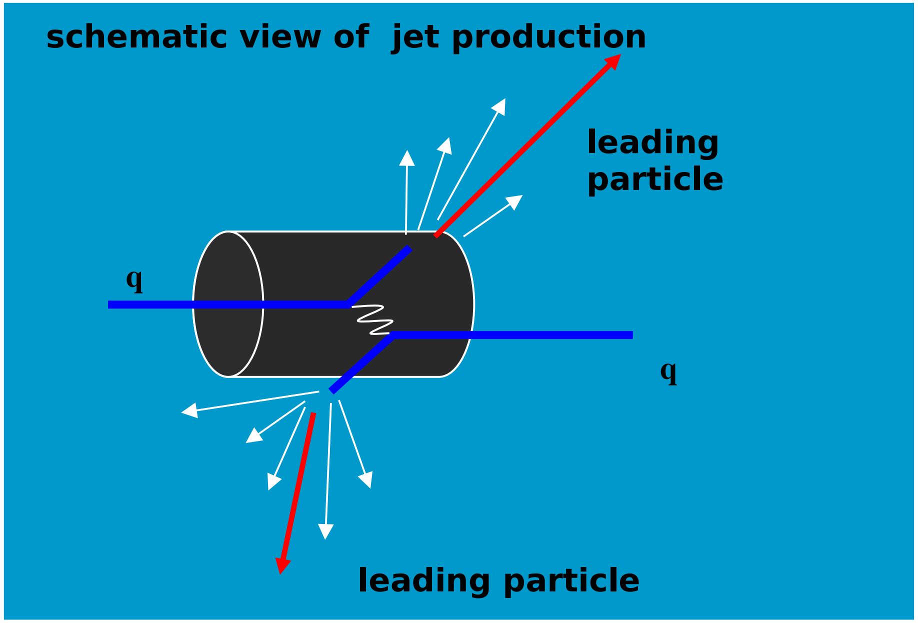
- suppression of high p_t particles in AA relative to pp collisions
- disappearance of jet-like correlations
- connected to large gluon density in hot (QGP) fireball
- fragmentation in the medium?

Ecole Joliot-Curie
Villa Clythia
Frejus, Oct. 2-4, 2013

Peter Braun-Munzinger

Jets of hard partons as probe of the hot medium

- Hard parton scattering observed via leading particles
- Expect strong $\Delta\phi$ π azimuthal correlations



However, the scattered partons may loose energy (~ several GeV/fm) in the colored medium

$\longrightarrow$ momentum reduction (fewer high p_T particles in jet)

$\longrightarrow$ no jet partner on other side

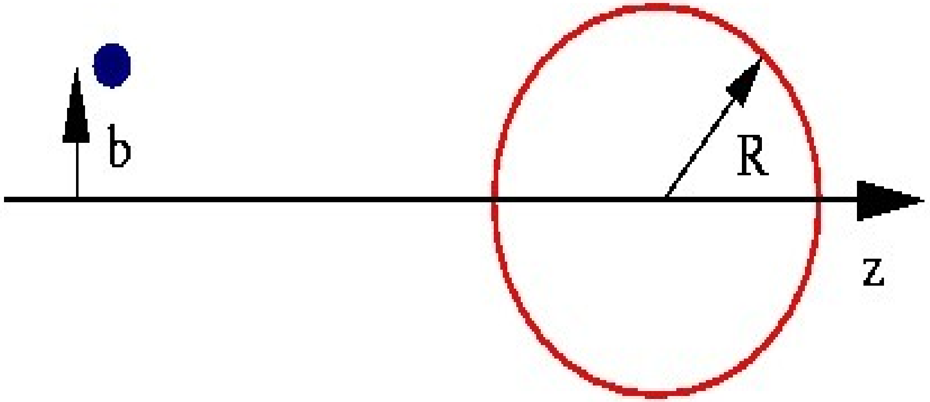
Jet Quenching

From pp to AA collisions

all valid for hard scattering only

start with normalized nuclear density, $\rho(b, z)$

$$\int \rho(b, z)\mathrm{d}z\mathrm{d}b \cdot 2\pi b = A$$



$$R = r_0 A^{1/3}$$

Thickness function continued

Thickness function:

- pA collisions:

$$T_A(b) = \int_{-\infty}^{+\infty} \mathrm{d}z\, \rho(b,z)$$

with $\int \mathrm{d}^2 b T_A(b) = \int_0^\infty 2\pi b \mathrm{d}b T_A(b) = A$

Note: $\sigma_{NN} \cdot T_A(b) = \langle N_{coll}^{pA}(b) \rangle$

sharp spheres: $T_A(0) = \frac{3}{2} \frac{A}{\pi R_A^2}$

Thickness function continued

- AB collisions:

$$T_{AB}(b) = \int d^2b_1 d^2b_2 \delta^{(2)}(\vec{b} - \vec{b_1} - \vec{b_2}) T_A(b_1) T_B(b_2)$$

with $\int d^2b T_A(b) = A \cdot B$

$$\sigma_{NN} \cdot T_{AB}(b) = \langle N_{coll}^{AB}(b) \rangle$$

sharp spheres: $T_{AB}(0) = \frac{9}{8}\frac{A^2}{\pi R_A^2}$

Thickness function continued

Implications:

$$\frac{\mathrm{d}\sigma^{AB}}{\mathrm{d}y}(\Delta b = b_2 - b_1) = \frac{\mathrm{d}\sigma^{NN}}{\mathrm{d}y} \int_{b_1}^{b_2} \mathrm{d}^2 b T_{AB}(b)$$

for minimum bias ($b = [0, R_A + R_B]$):

$$\frac{\mathrm{d}\sigma^{AB}}{\mathrm{d}y} = \frac{\mathrm{d}\sigma^{NN}}{\mathrm{d}y} \cdot A \cdot B$$

also:

$$\frac{\mathrm{d}N^{AB}}{\mathrm{d}y} = \frac{\mathrm{d}N^{NN}}{\mathrm{d}y} \cdot \sigma^{NN}_{inelastic} \cdot \frac{\int_{b_1}^{b_2} \mathrm{d}^2 b T_{AB}(b)}{\pi(b_2^2 - b_1^2)}$$

Thickness function continued

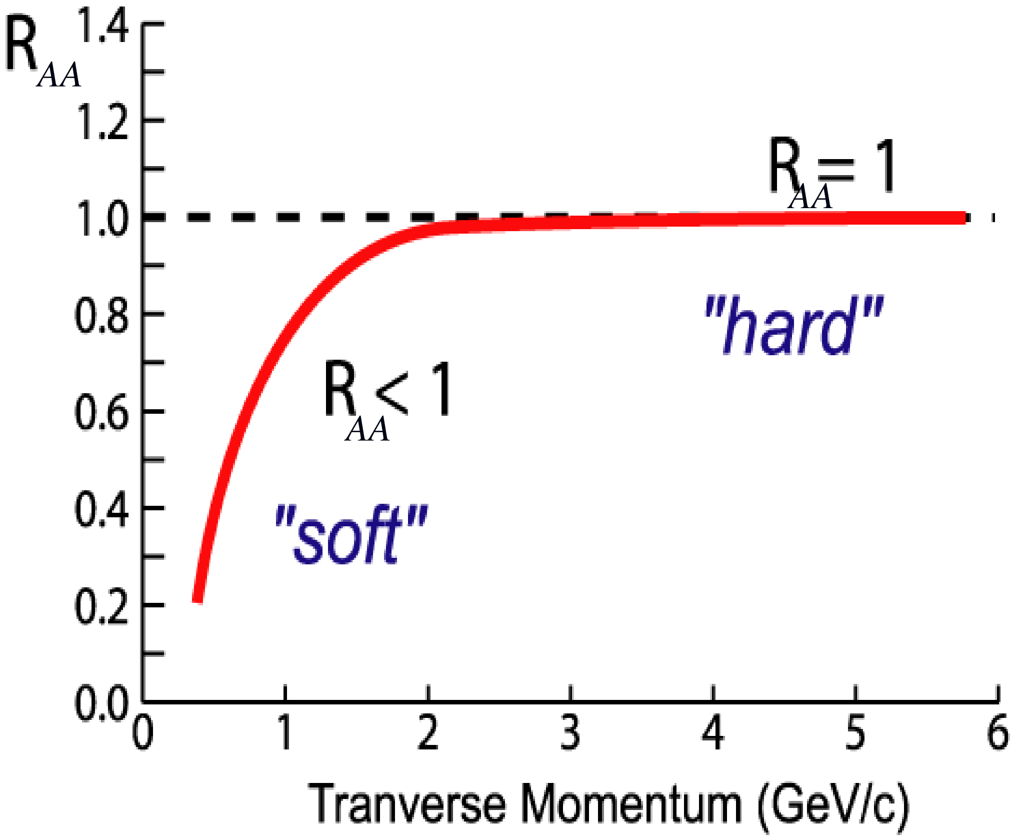
The R_{AA} function:

$$R_{AA}(b) = \frac{\frac{d^2N^{AA}}{dp_t^2dy}}{N_{coll}^{AA}(b) \cdot \frac{d^2N^{NN}}{dp_t^2dy}}$$

if hard scattering only:

$$R_{AA}(b) = 1$$

Qualitative expectations



no medium effects:

$R_{AA} < 1$ in regime of soft physics

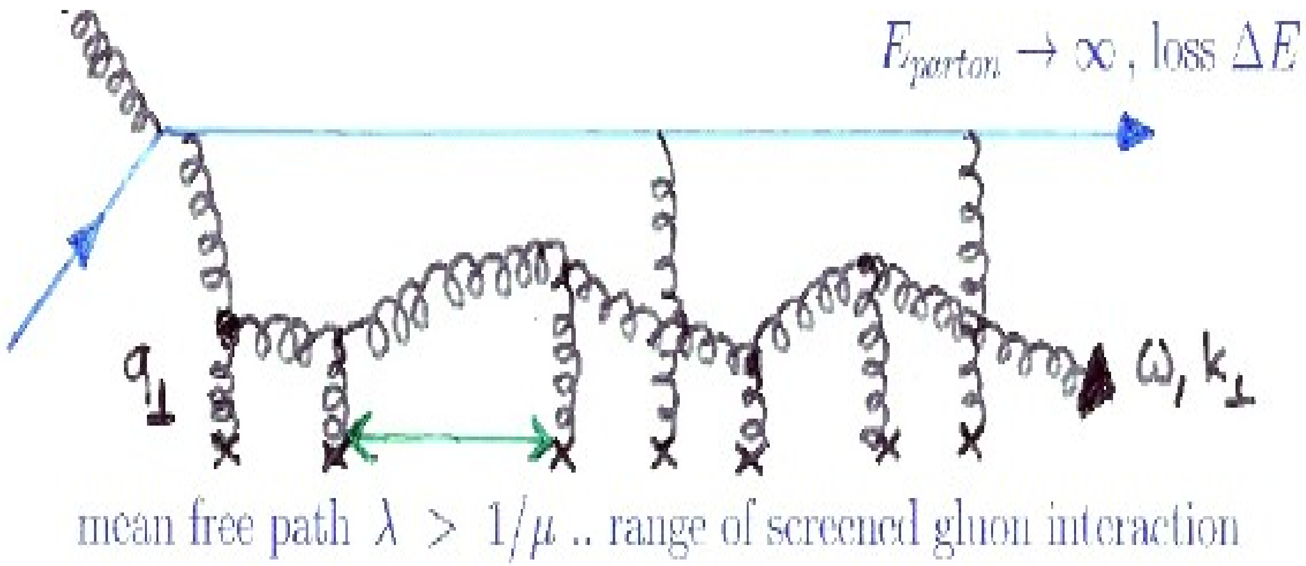
$R_{AA} = 1$ at high-p_T where hard scattering dominates

Suppression:

$R_{AA} << 1$ at high-p_T

The fireball is opaque for high momentum partons

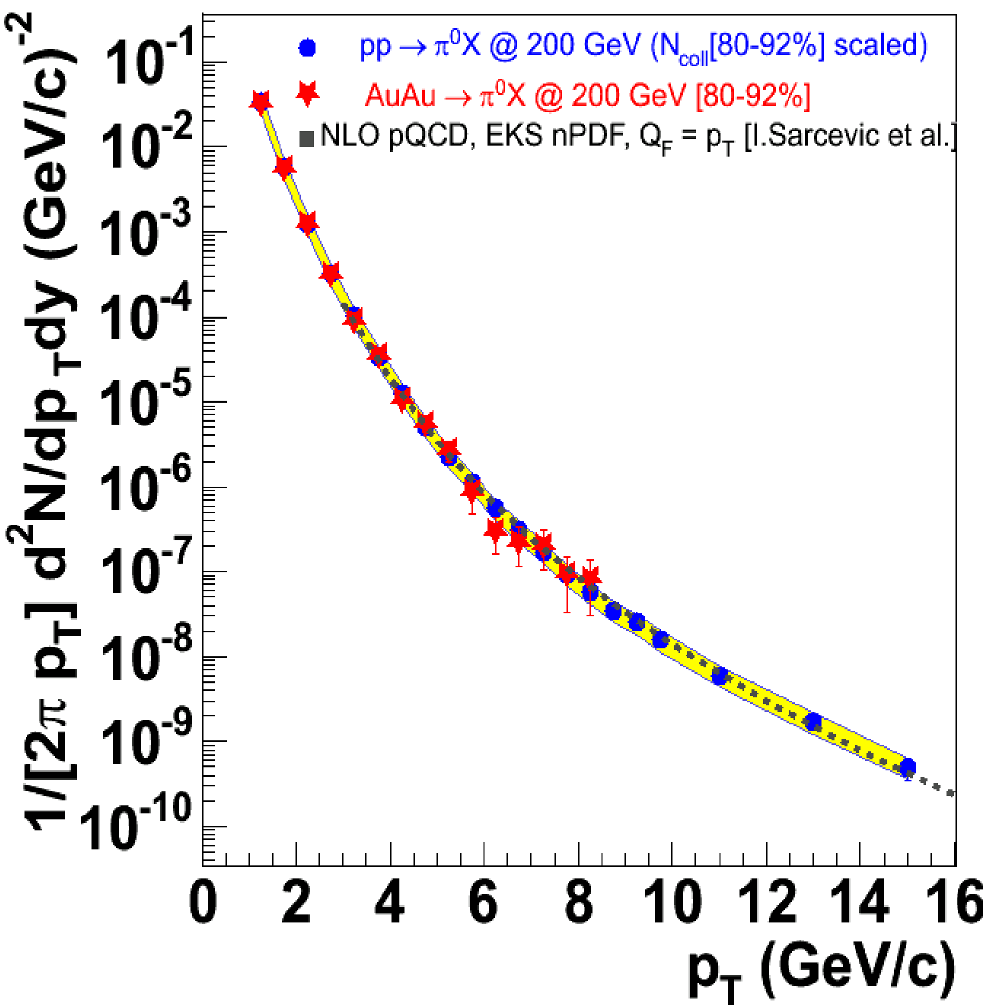
- suppression of high p_t particles in AA relative to pp collisions
- disappearance of jet-like correlations
- connected to large gluon density in hot (QGP) fireball

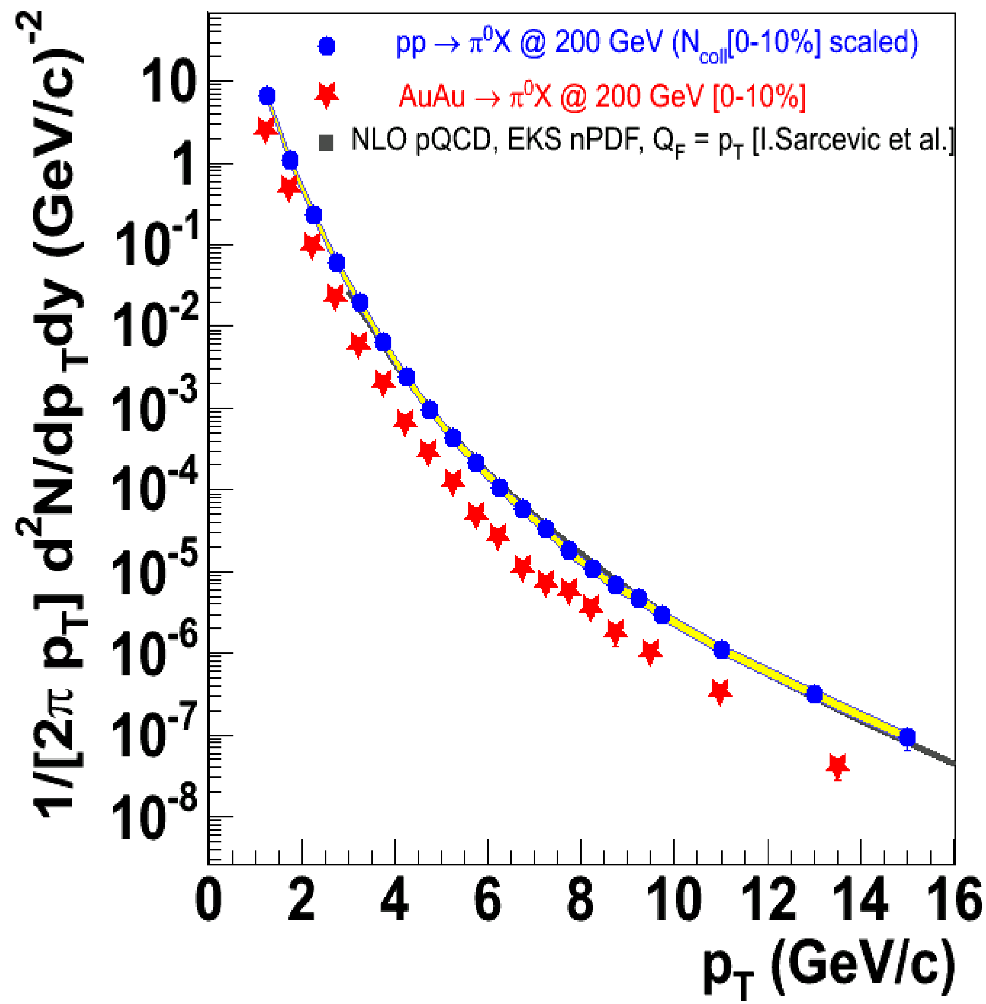


schematic picture of energy loss of a fast parton

spectra suppressed at high p_t in AuAu relative to pp

proton data scaled to AuAu with appropriate number of binary collisions

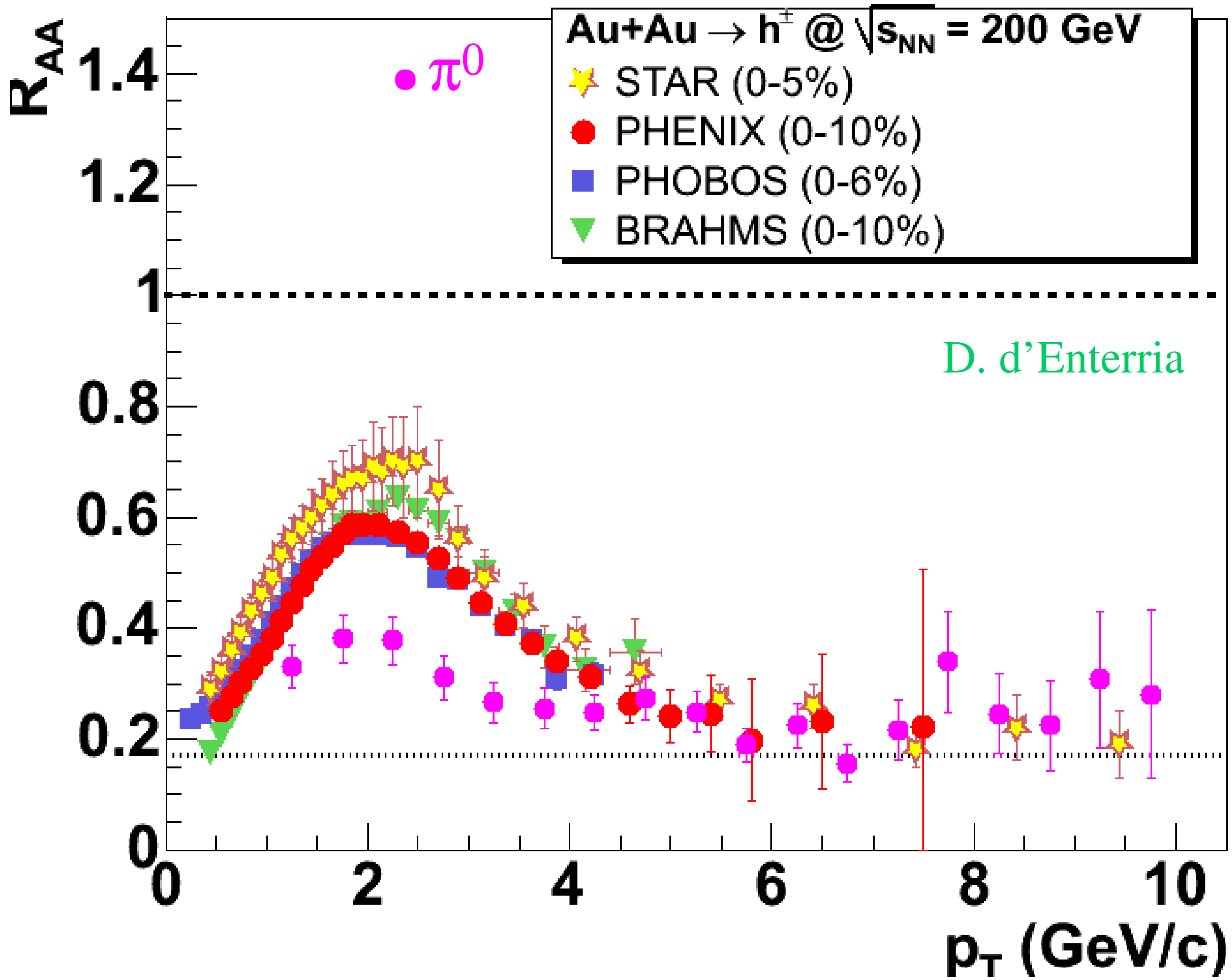




PHENIX PRL 91 (2003) 072305 and 241803

high p_t suppression seen by all RHIC experiments

R_{AA}=yield(AuAu)/N_{coll} yield(pp)

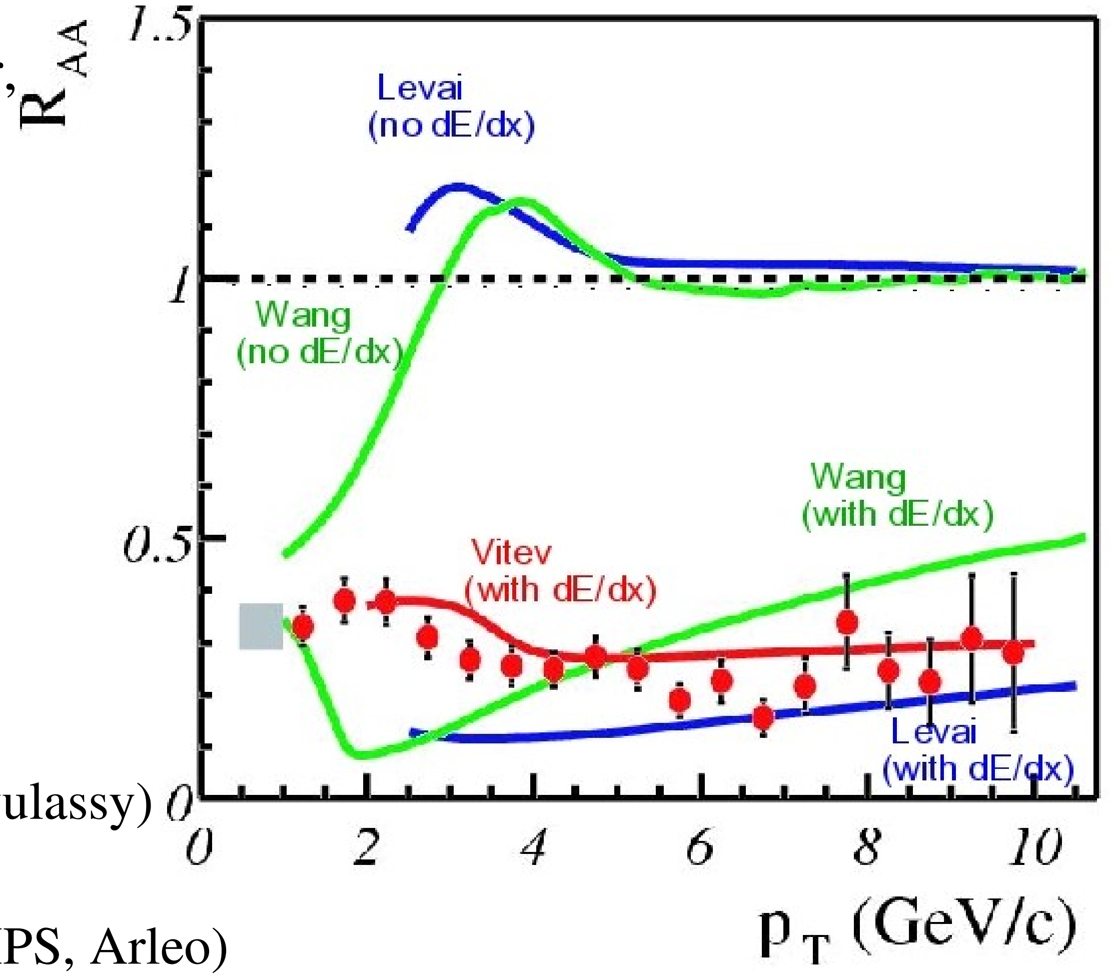


- all expts. see large suppression in AuAu
- π^0 lower than $h^\pm$
- no suppression in dAu rather Cronin enhancement
  → medium effect, not incoming partons

- reasonable agreement between 4 experiments

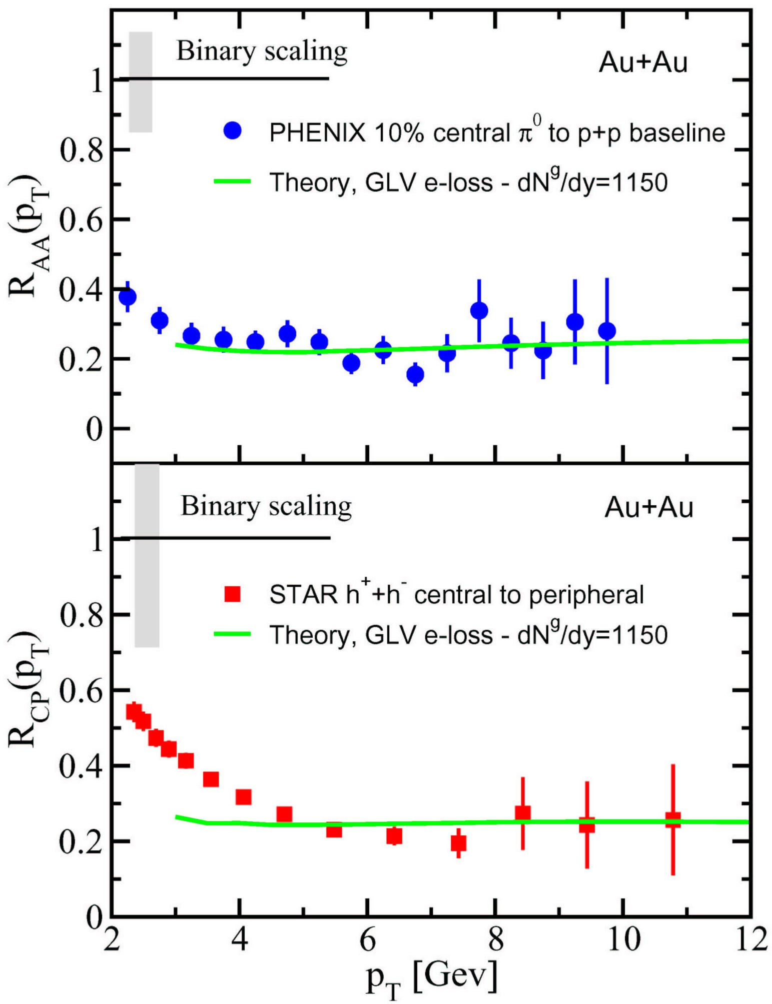
Suppression predicted due to energy loss of partons in hot matter "jet quenching"

H. Baier, Y.L. Dokshitzer, A.H. Mueller, S. Peigne, D. Schiff, Nucl. Phys. B483 (1997) 291 and 484 (1997) 265
energy loss of high energy parton traversing color charged medium ->
medium induced gluon radiation
in high energy limit
$\Delta E \approx \alpha_s \mu^2 L^2/\lambda\ (1 + O(1/N))$



implemented in models in different ways:
high initial densities dN_g/dy=1100 (Vitev/Gyulassy)
large opacities <n> = $L/\lambda \approx$ 3-4 (Levai et al.)
transport coefficients q_0=3.5 GeV/fm^2 (BDMPS, Arleo)
plasma temperature T = 400 MeV (G. Moore)
medium induced radiative energy loss
dE/dx(expanding)=0.25 GeV/fm or dE/dx(static source)=14 GeV/fm (X.N.Wang)

suppression of hadron yields at high p_t in central AuAu collisions

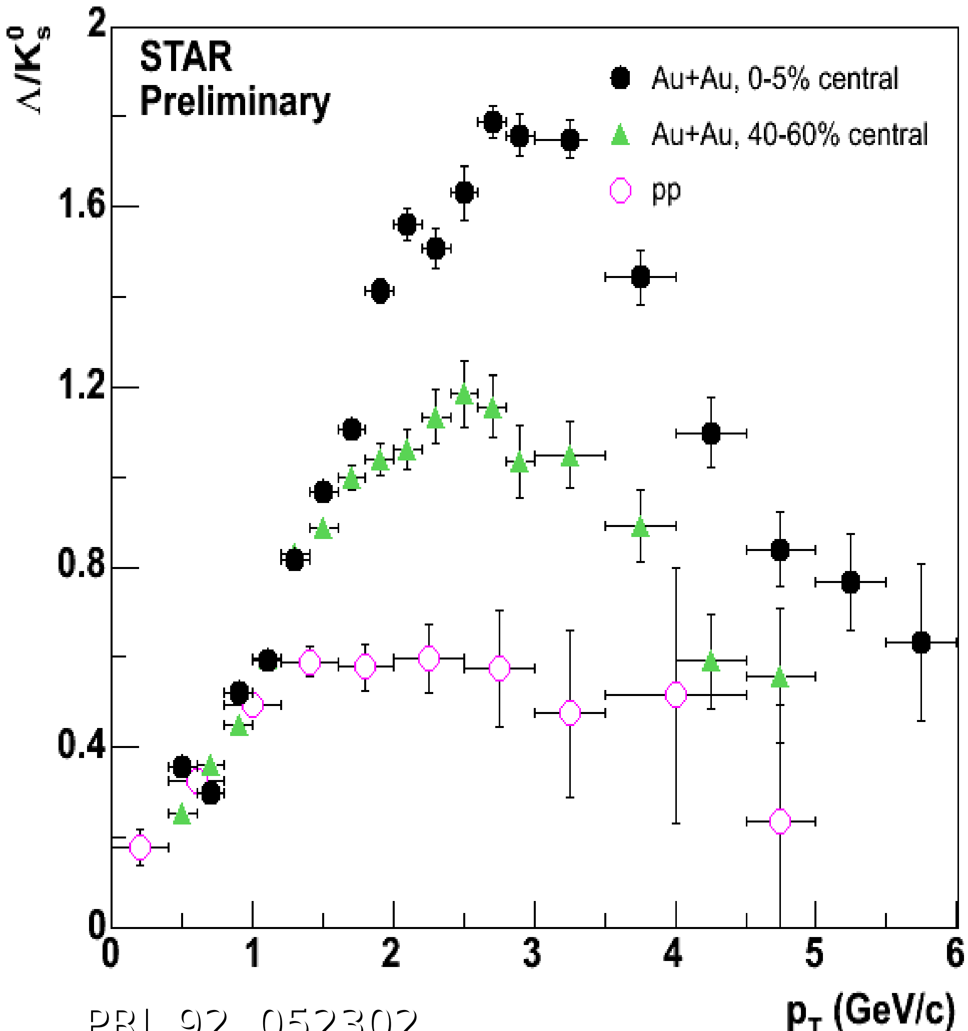


AuAu compared to pp scaled with number of binary collisions

AuAu central collisions compared to peripheral collisions scaled with number of binary collisions

in central collisions hadron yields suppressed indicative of jet quenching due to parton energy loss due to high gluon density

suppression pattern depends on hadronic species



observed early on: protons exceed number of pions at 2 GeV/c

general feature for all baryons?

very cleanly shown recently for Λ as compared to $K^0{}_s$ while pp shows normal fragmentation

coalescence of valence quarks? 3:2

Duke model...

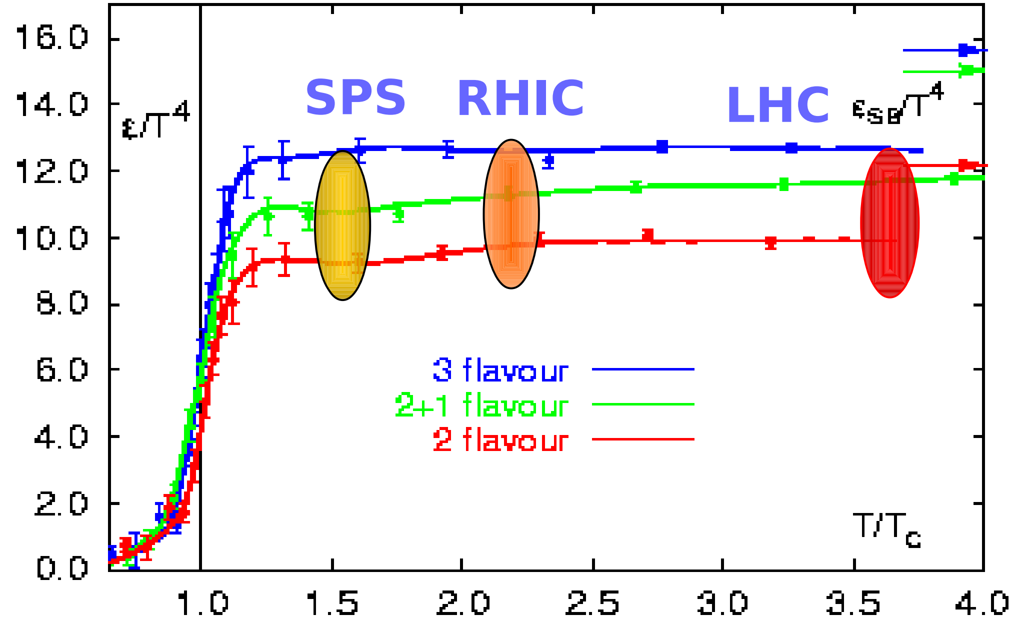
PRL 92, 052302 (2004)
J.Phys. G30, S963 (2004)

jet quenching indicative of gluon rapidity density prediction before LHC start

	$\tau_0[\,fm]$	$T[MeV]$	$\varepsilon[GeV\,/\,fm^3]$	$\tau_{tot}[\,fm]$	$dN^g\,/\,dy$
SPS	0.8	210-240	1.5-2.5	1.4-2	200-350
RHIC	0.6	380-400	14-20	6-7	800-1200
LHC	0.2	710-850	190-400	18-23	2000-3500

I. Vitev, JPG 30 (2004) S791

- **Consistent estimate with hydrodynamic analysis**



hard probes at RHIC and the LHC

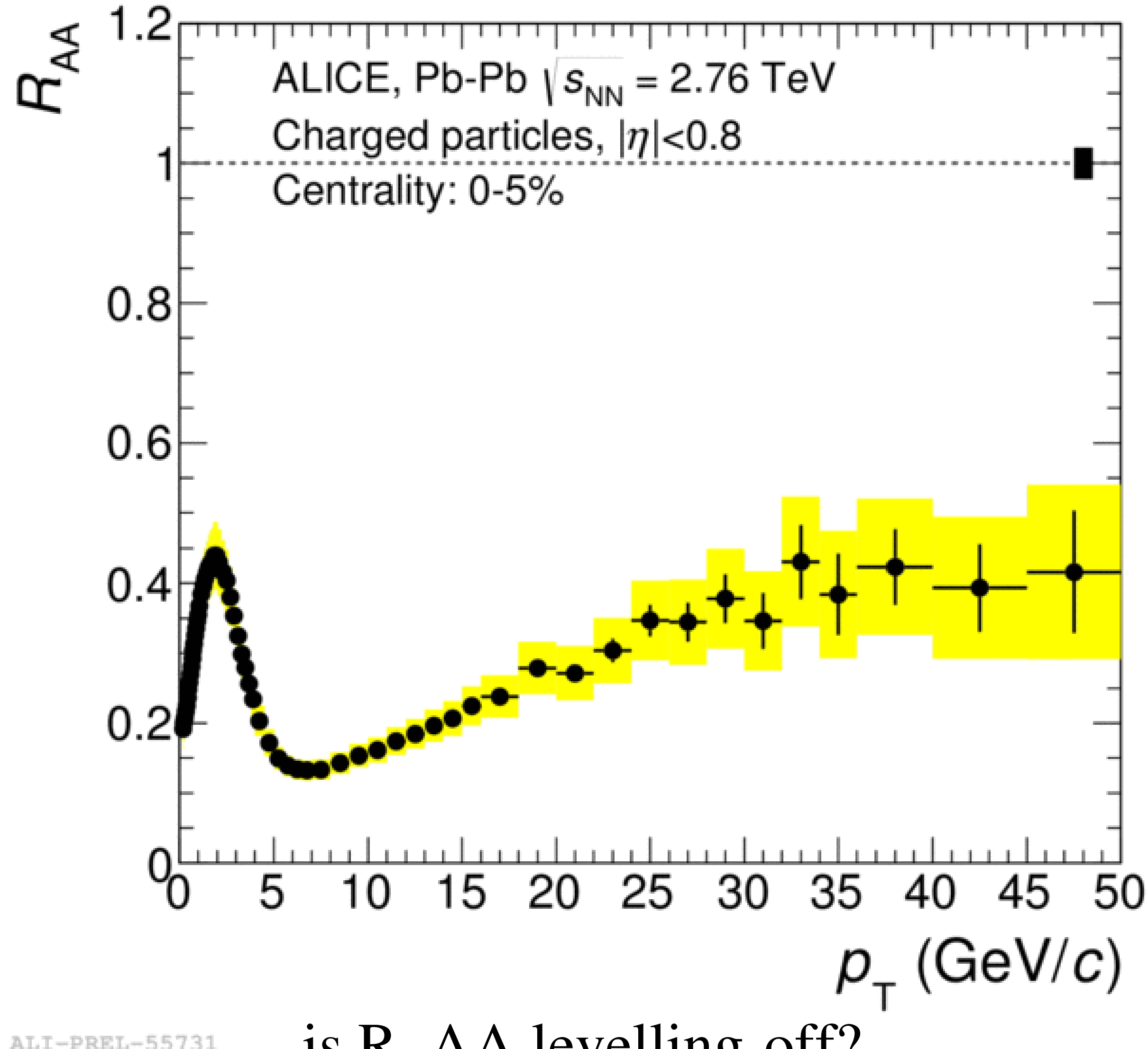
R_AA = medium/vacuum

R_AA = 1 if no dense medium is formed

or

if one looks at electro-weak probes

R_AA for charged particles

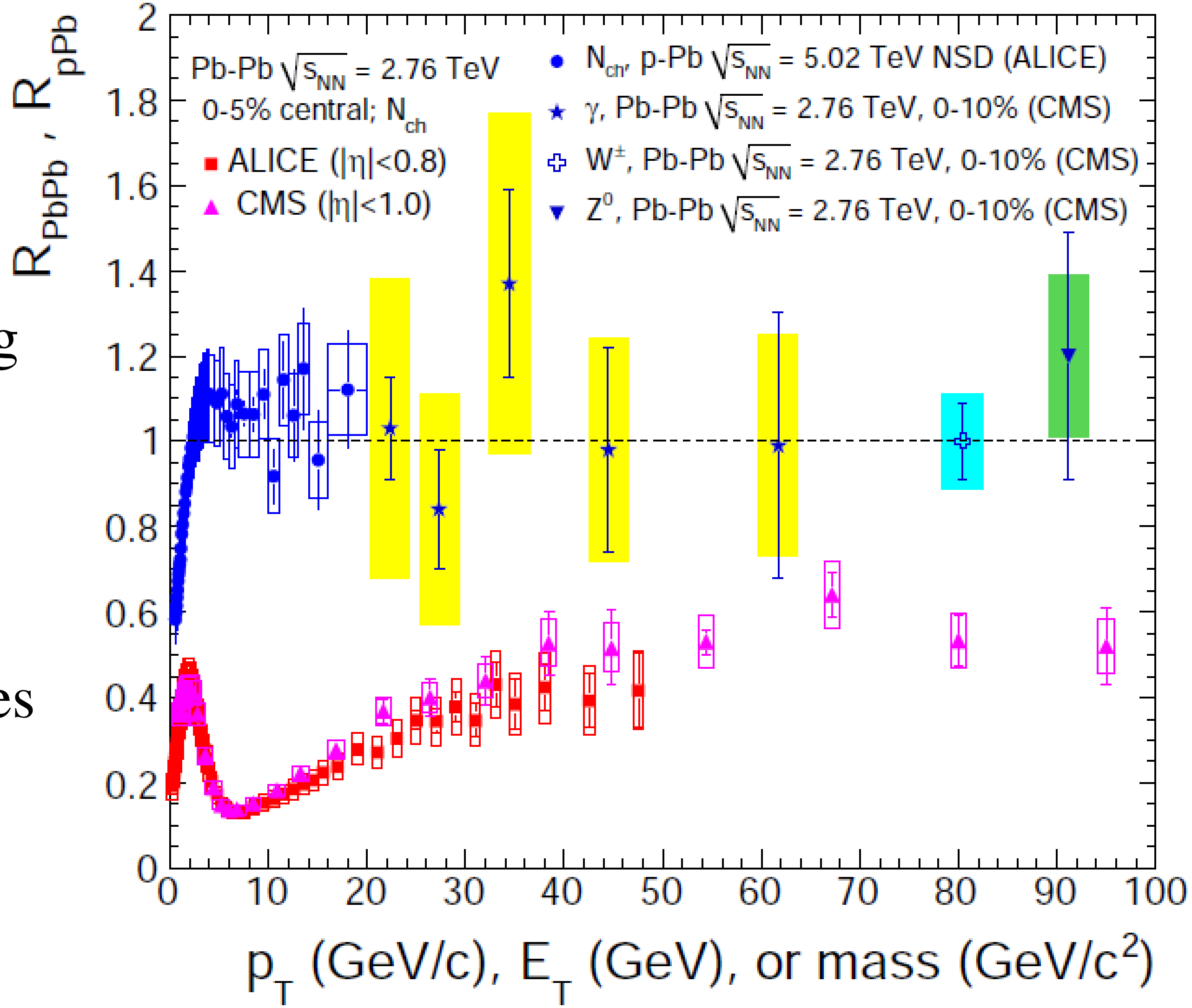


is R_AA levelling-off?

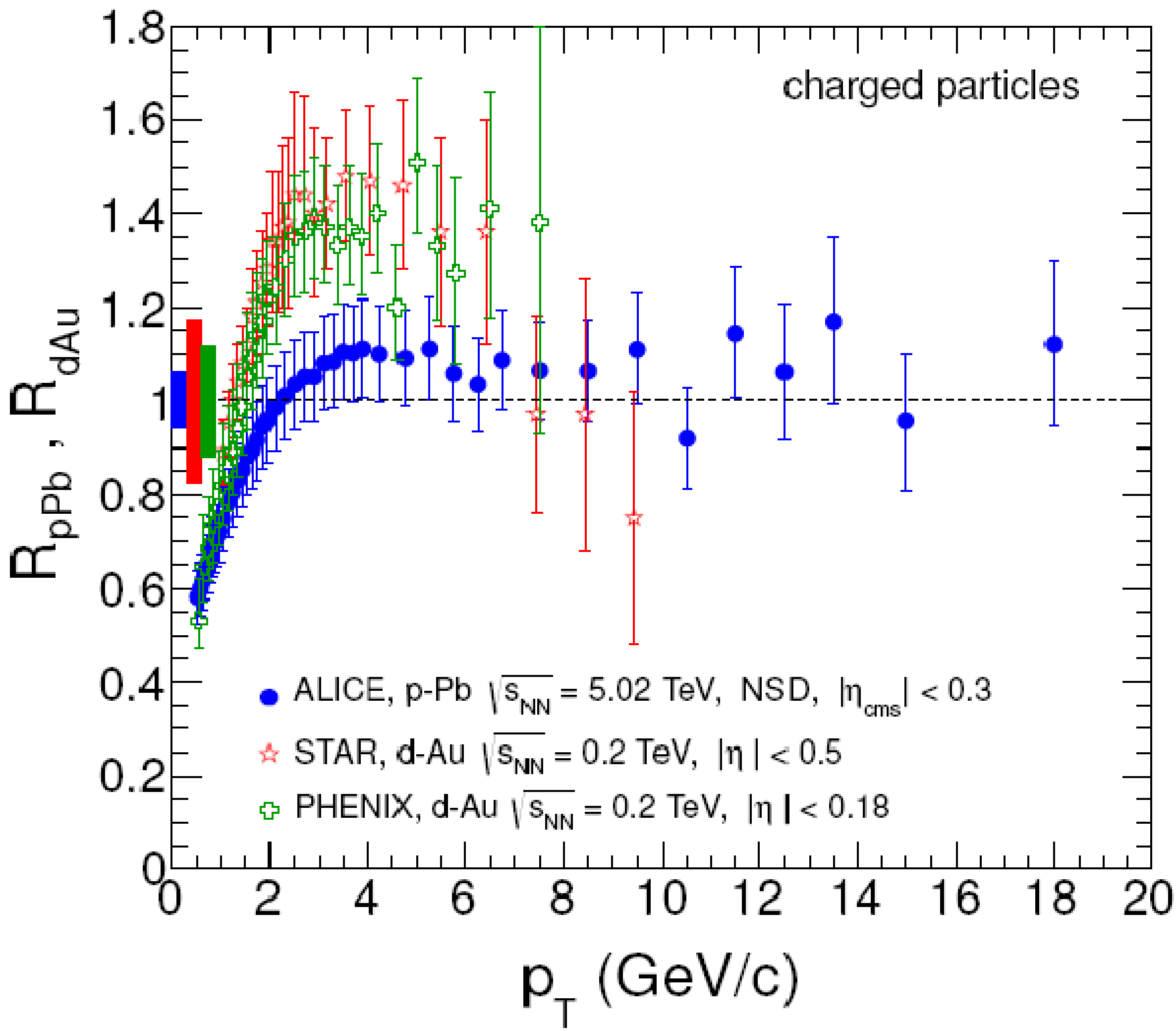
Nuclear Modification Factor

R_AA << 1 for strongly interacting probes, even for large transverse momenta,

electro-weak probes don't
see the dense medium

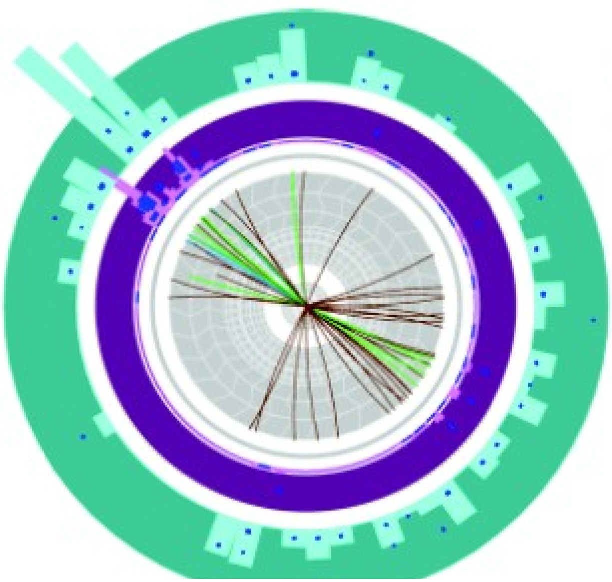


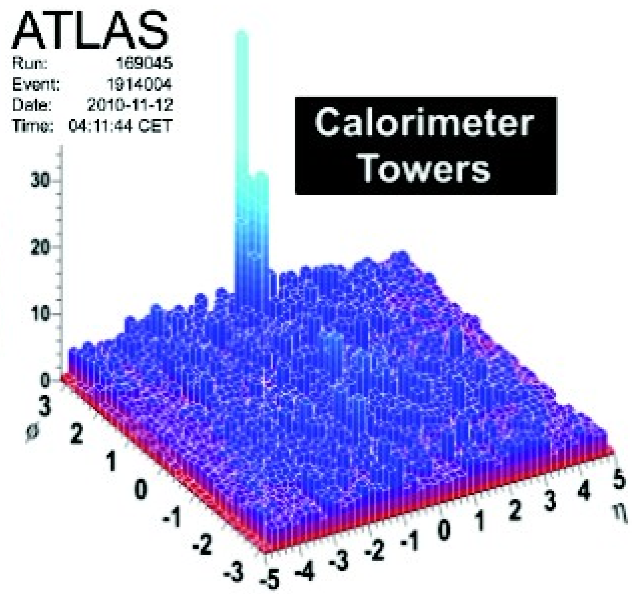
Hot off the press: p-Pb collisions from LHC vs d-Au collisions from RHIC

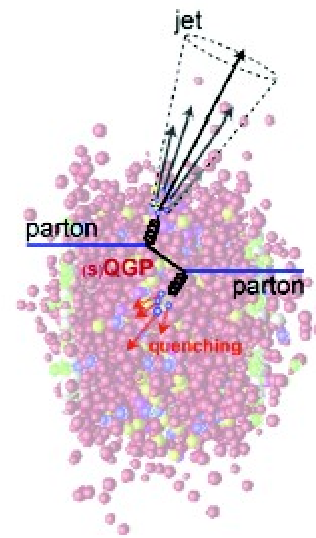


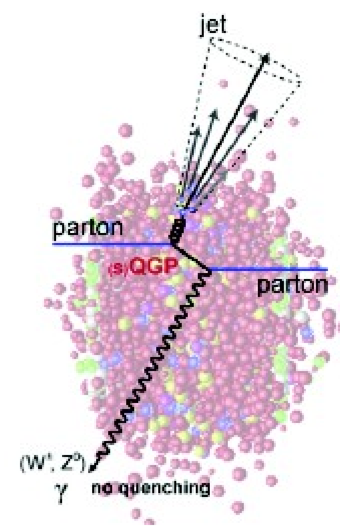
R_AA = 1 for pPb collisions at LHC (p_T > 3 GeV)

jet quenching at LHC







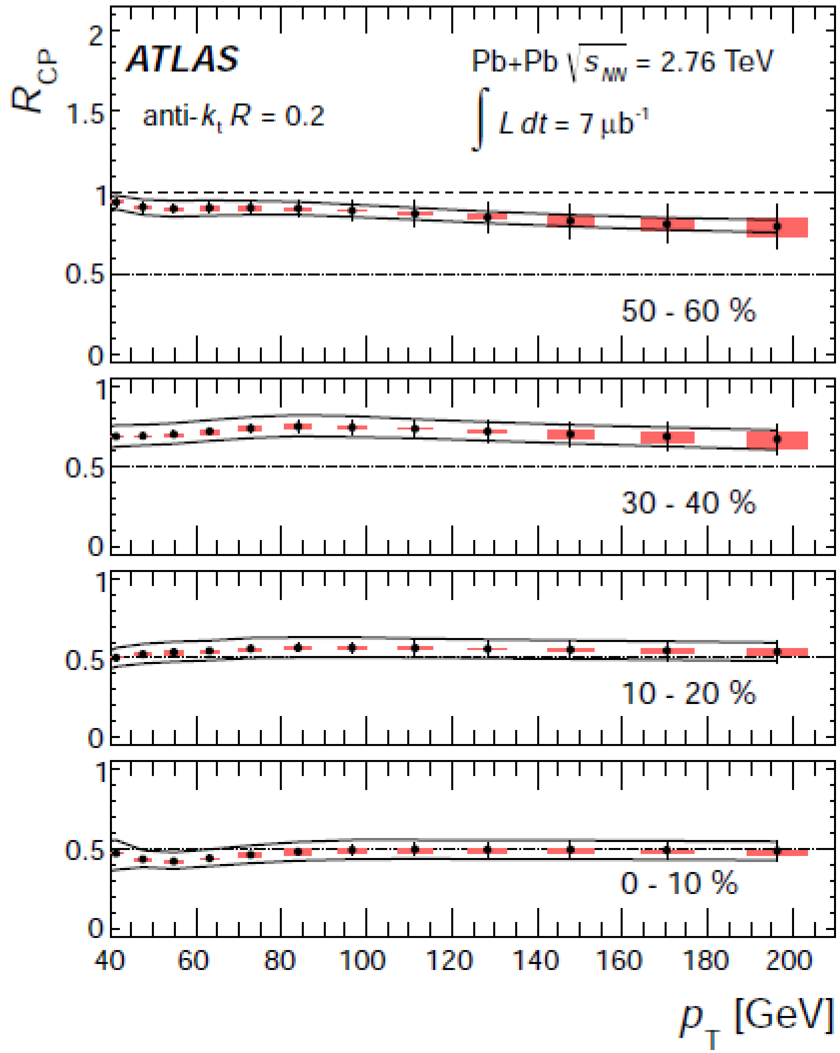


Direct observation of in-medium parton energy loss

quantitative jet analysis
very complicated

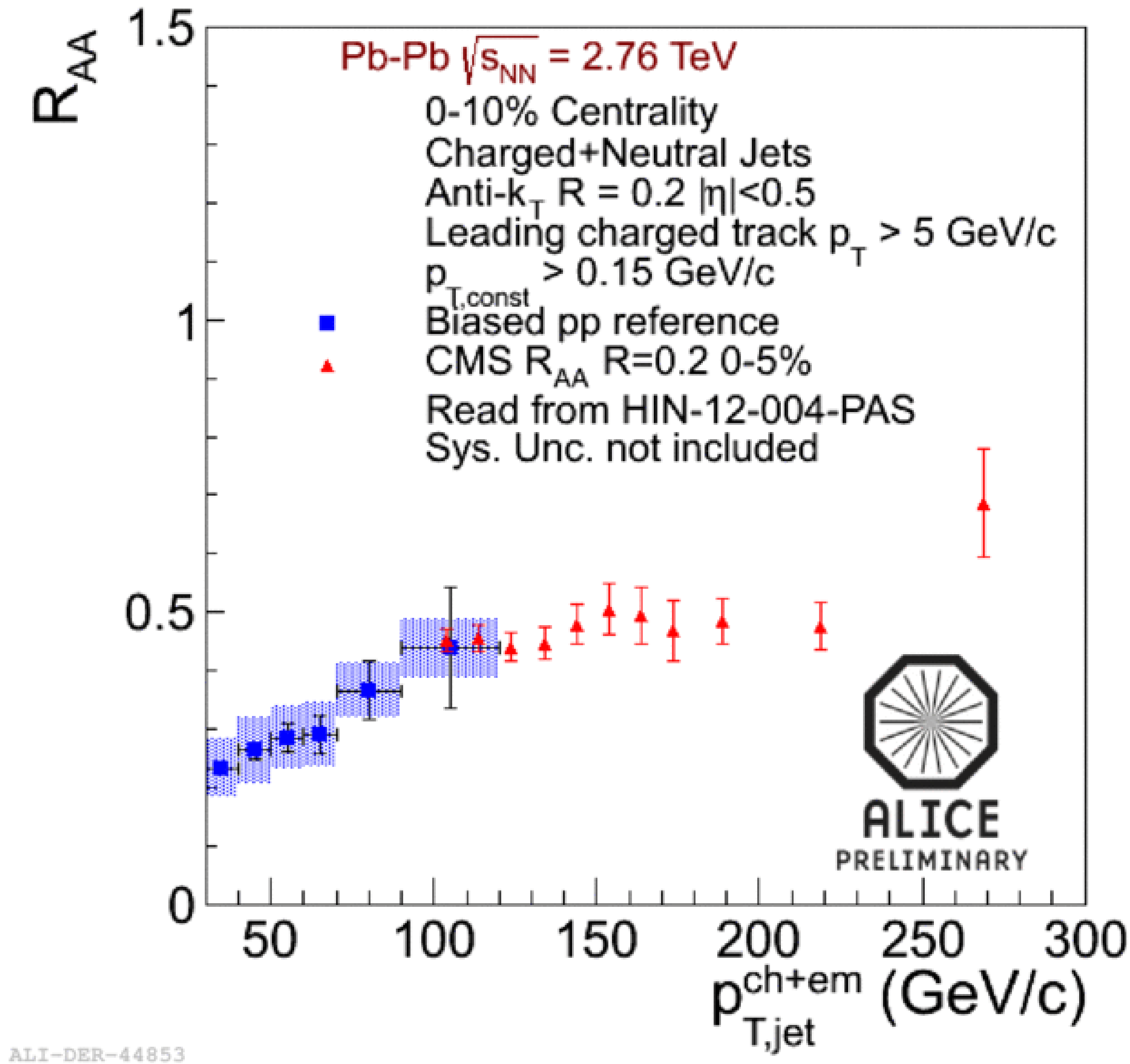
ATLAS, PRL105 (2010) 252303
CMS, PLB712(2012) 176

Jet quenching at the LHC



R_AA never reaches unity

reconstructed jets from ALICE and CMS



comparison to data of Jewel+Pythia calculations

Zapp, Kraus, Wiedemann, arXiv:1212.1599

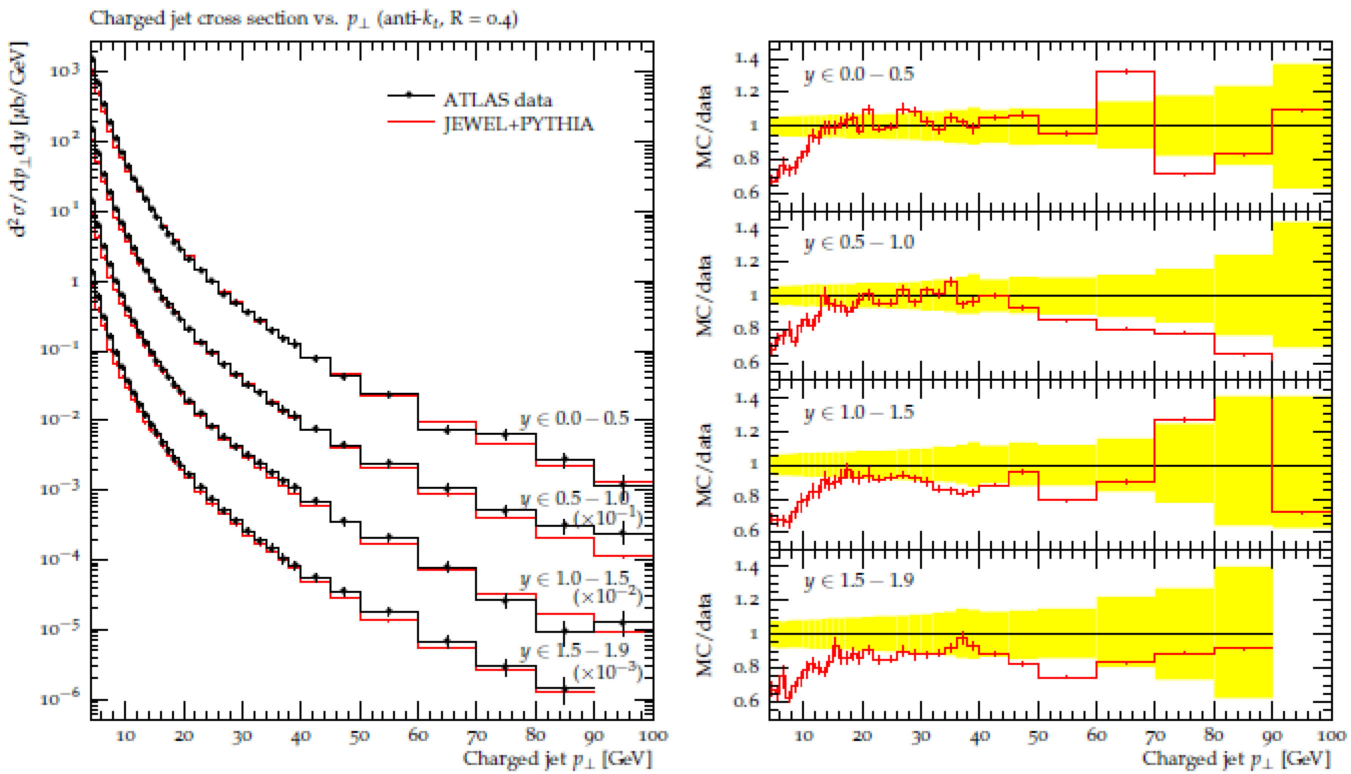
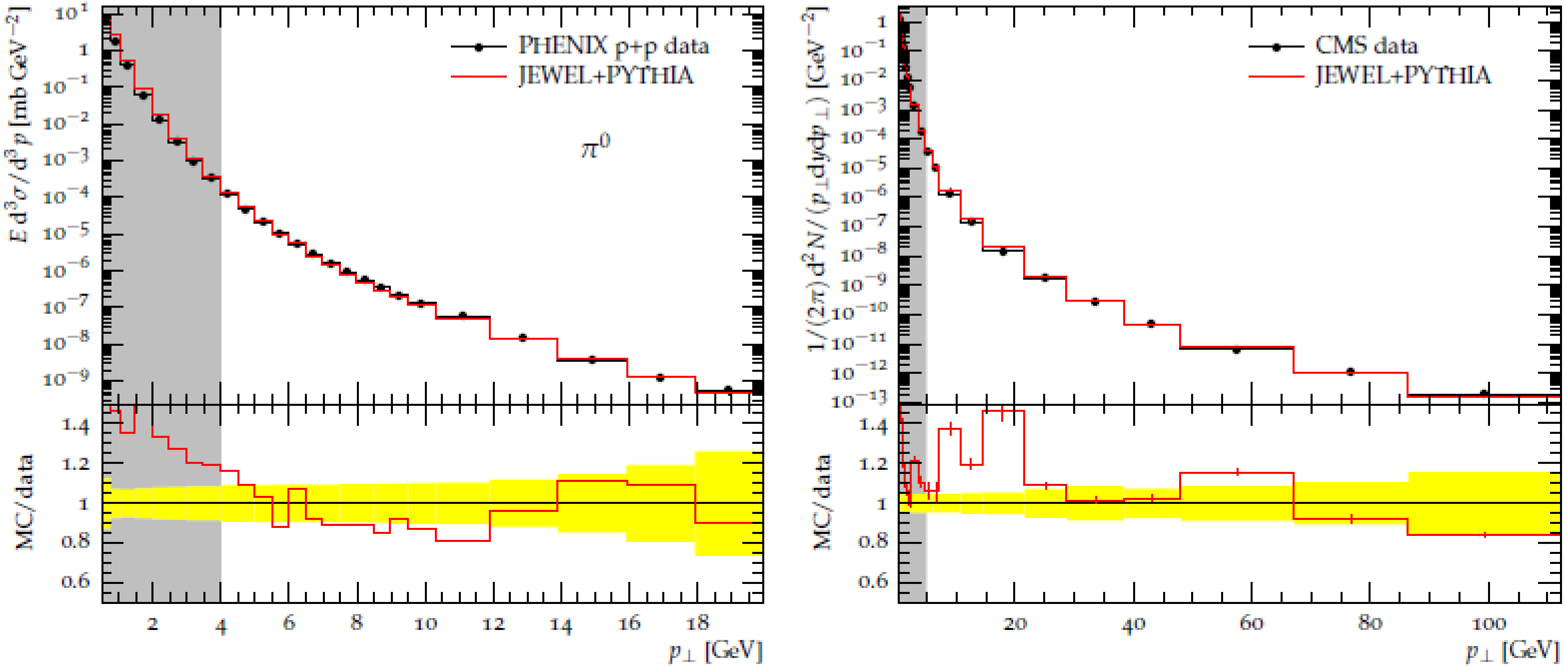


Figure 2. JEWEL+PYTHIA results for the inclusive jet cross section in different rapidity bins compared to ATLAS data [71] in p+p at $\sqrt{s} = 7\,\text{TeV}$. Jets are reconstructed using the anti-$k_\perp$ algorithm with R=0.4 on tracks.

first comparison to pp baseline for inclusive jet production
excellent agreement

comparison to leading hadron production in pp collisions

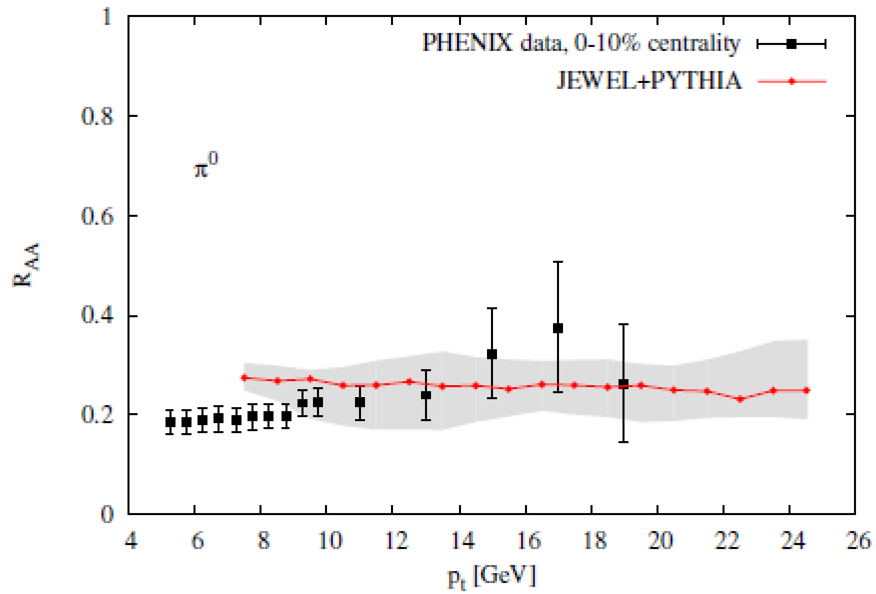
Zapp, Kraus, Wiedemann, arXiv:1212.1599



Au-Au collisions at RHIC energy

both collisional and radiative energy loss included

Zapp, Kraus, Wiedemann, arXiv:1212.1599



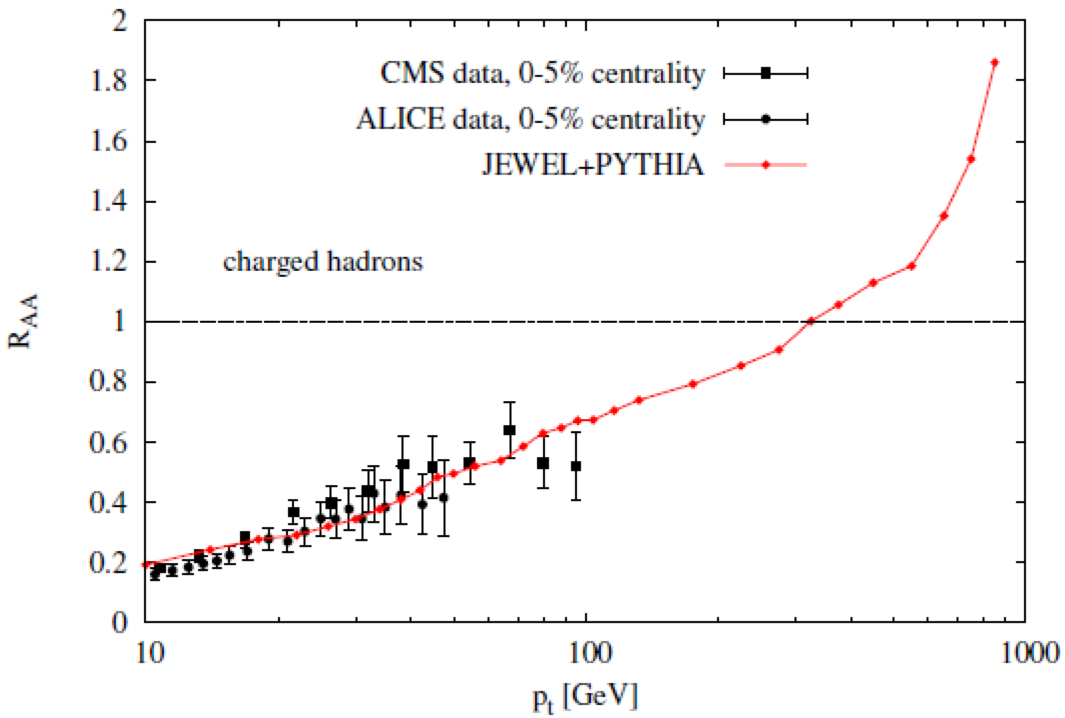
the medium is described in a Bjorken approach with boost-invariant longitudinal expansion with energy density prop. to the density of wounded nucleons

$$\epsilon(x, y, b, \tau_\mathrm{i}) = \epsilon_\mathrm{i} \frac{n_\mathrm{part}(x, y, b)}{\langle n_\mathrm{part}\rangle(b=0)} \qquad \text{with} \qquad \langle n_\mathrm{part}\rangle(b=0) \approx \frac{2A}{\pi R_A} 2$$

T_i = 350 MeV tau_i = 0.8 fm eps_i = 10 GeV/fm^3

now to LHC data
strongly increased p_t reach

Zapp, Kraus, Wiedemann, arXiv:1212.1599

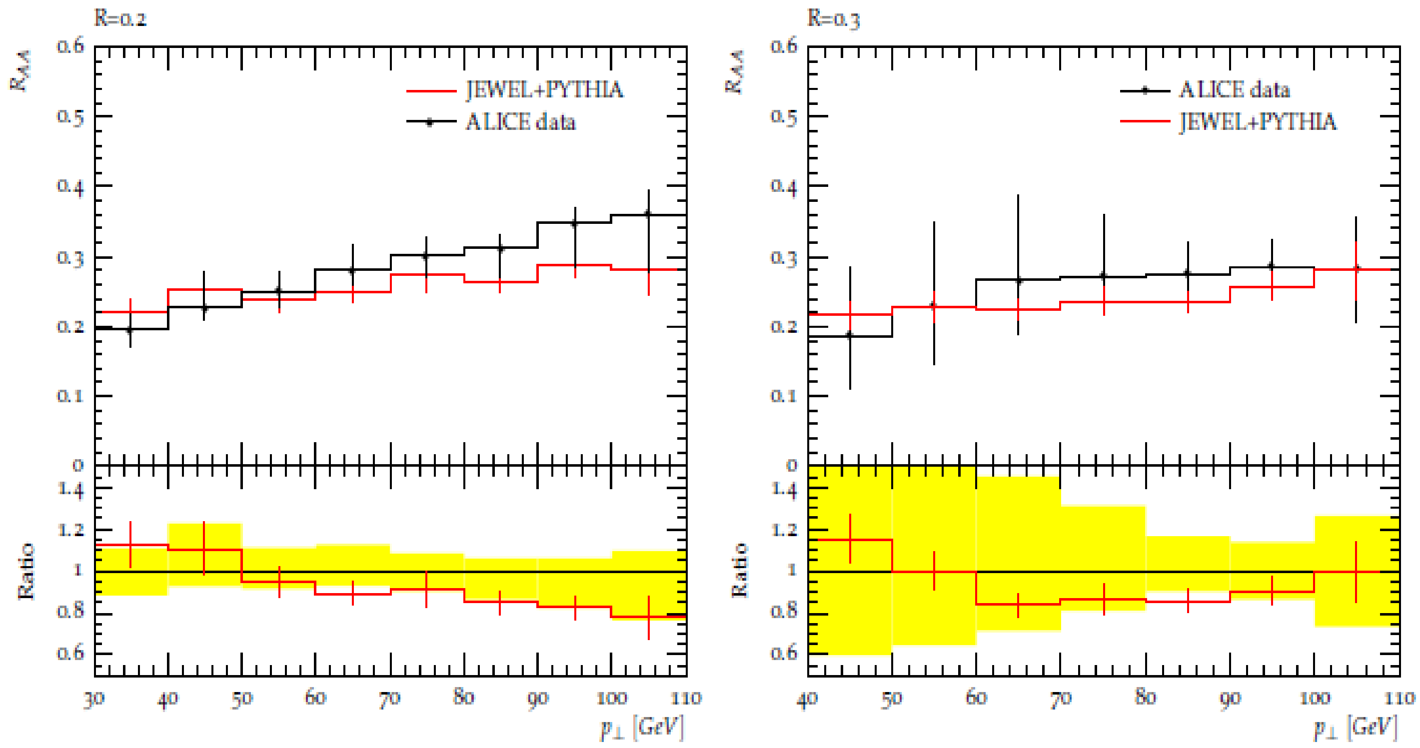


at LHC: T_i = 530 MeV, tau_i = 0.5 fm eps_i = 53 GeV/fm^3

this is about 100 times the critical energy density at T_c = 165 MeV!

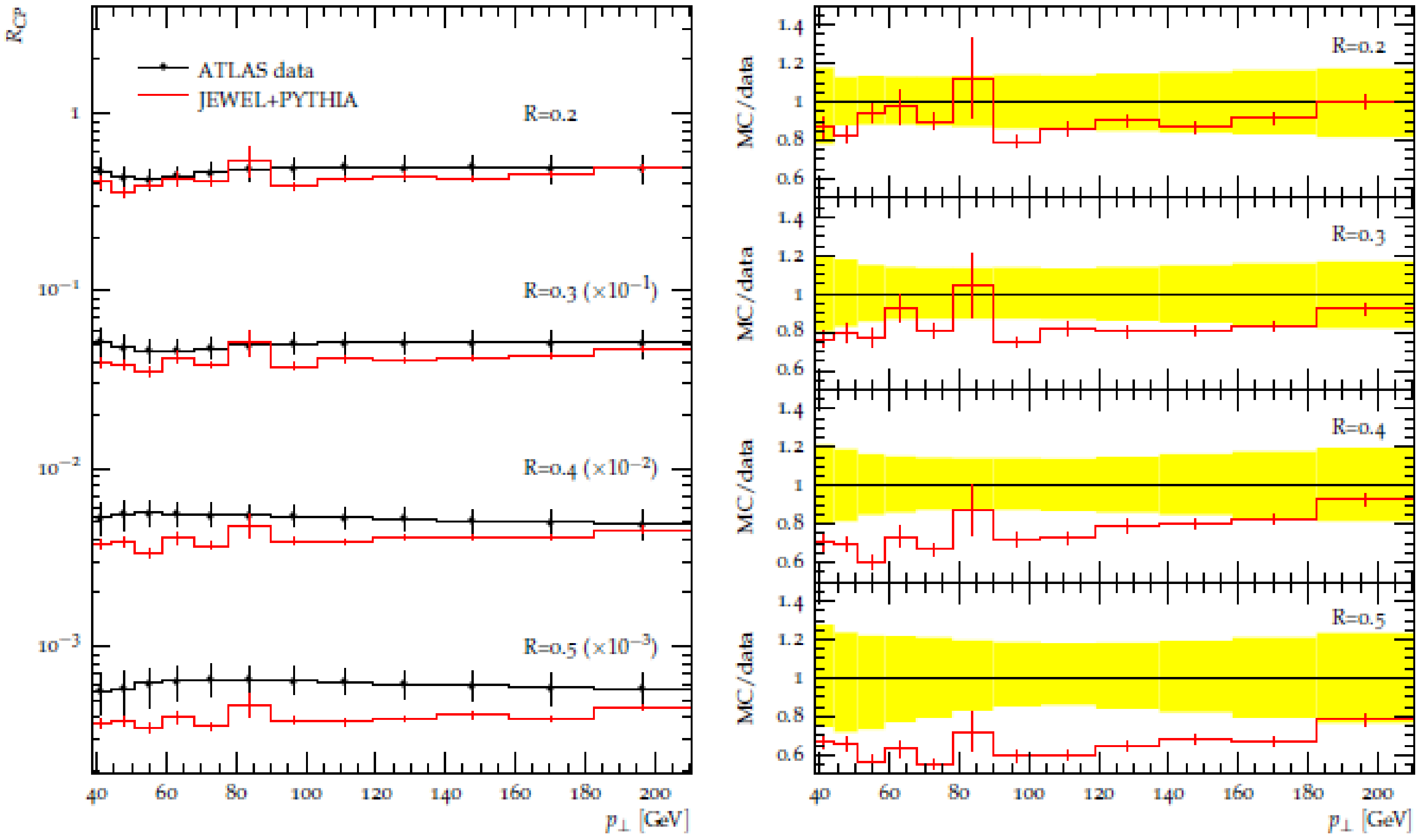
comparison to reconstructed jets

Zapp, Kraus, Wiedemann, arXiv:1212.1599



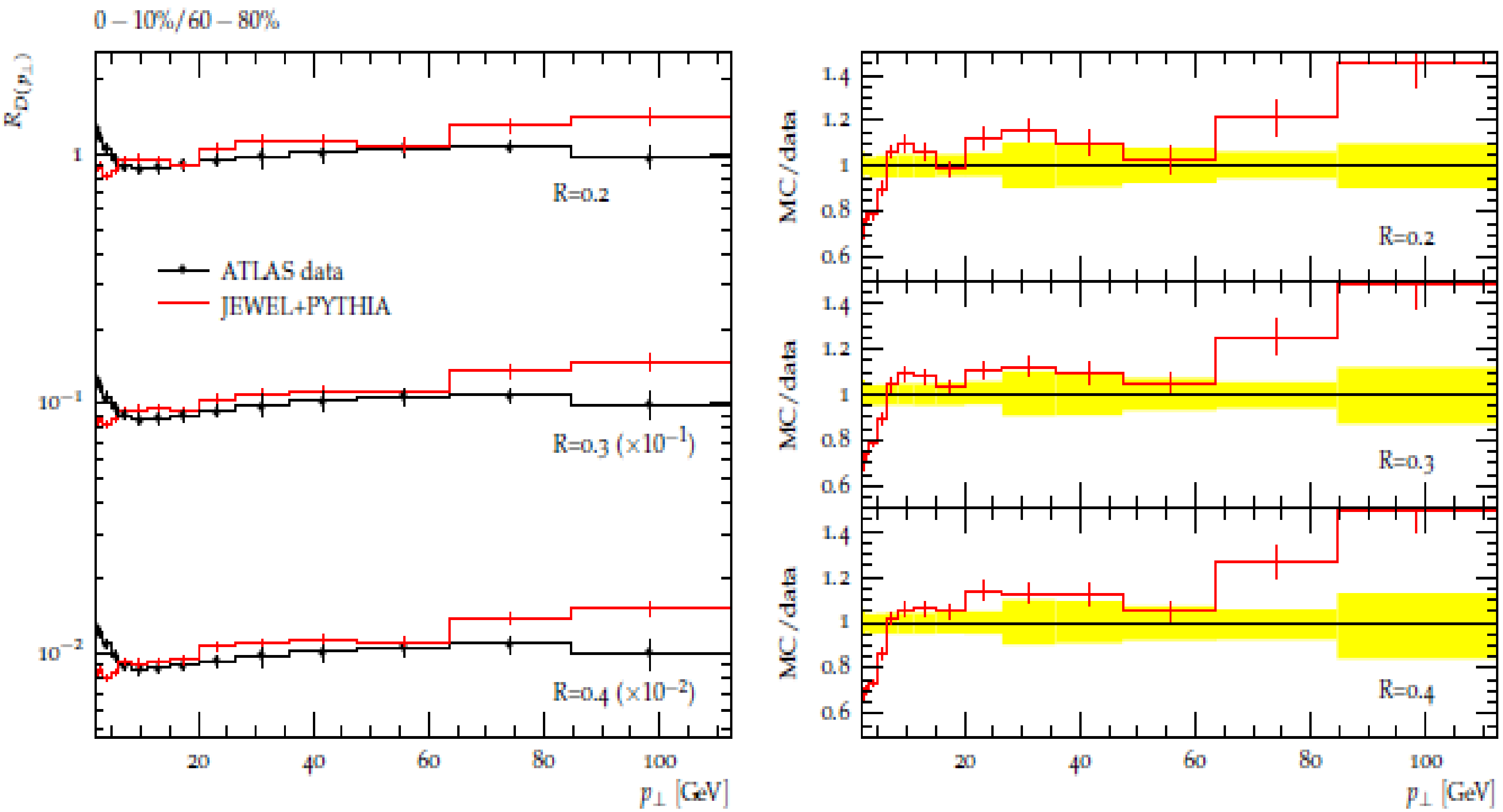
comparison to reconstructed jets continued

Zapp, Kraus, Wiedemann, arXiv:1212.1599

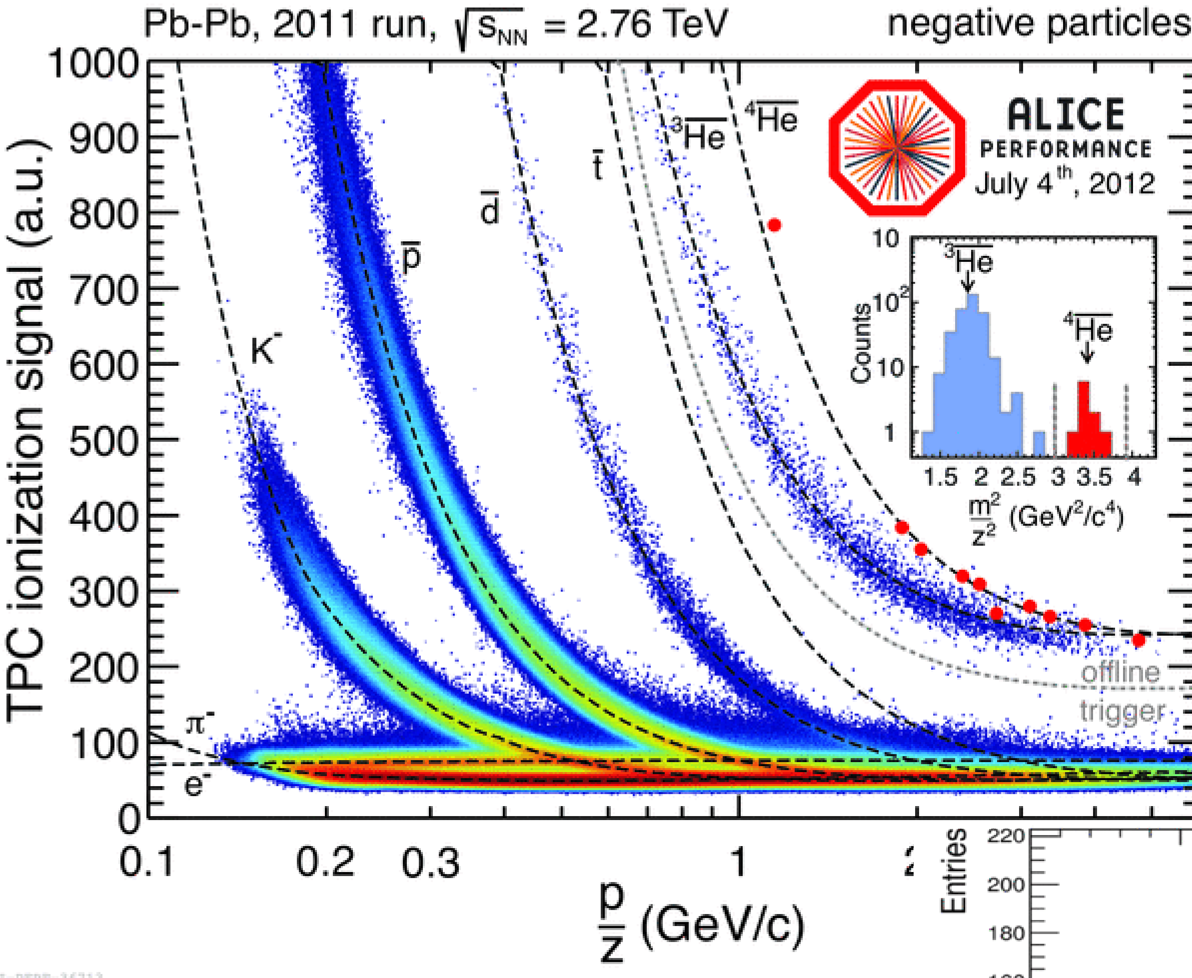


comparison to reconstructed jets continued

Zapp, Kraus, Wiedemann, arXiv:1212.1599

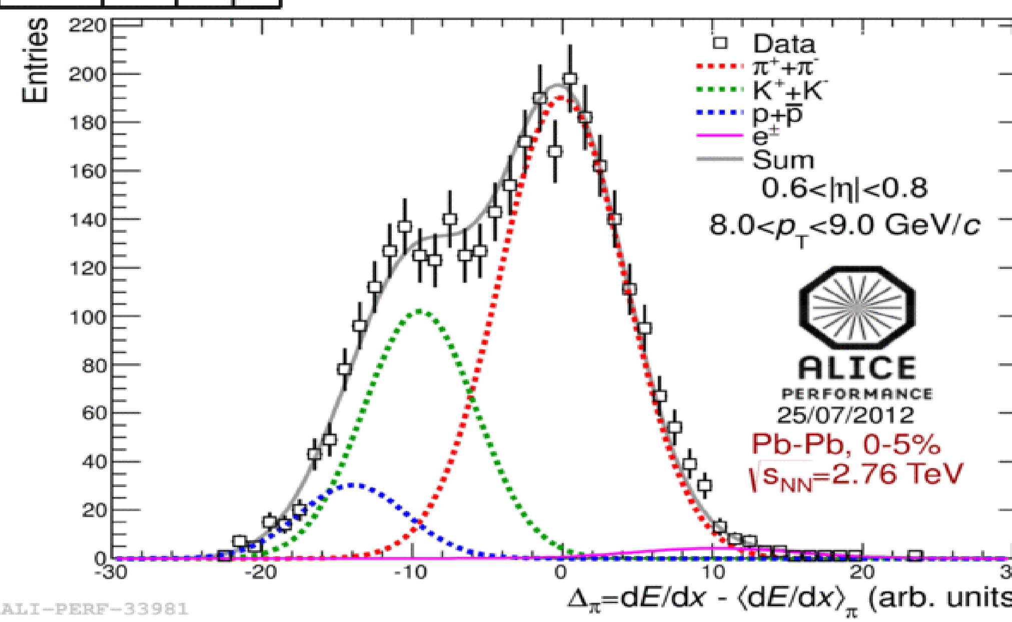


now with identified particles

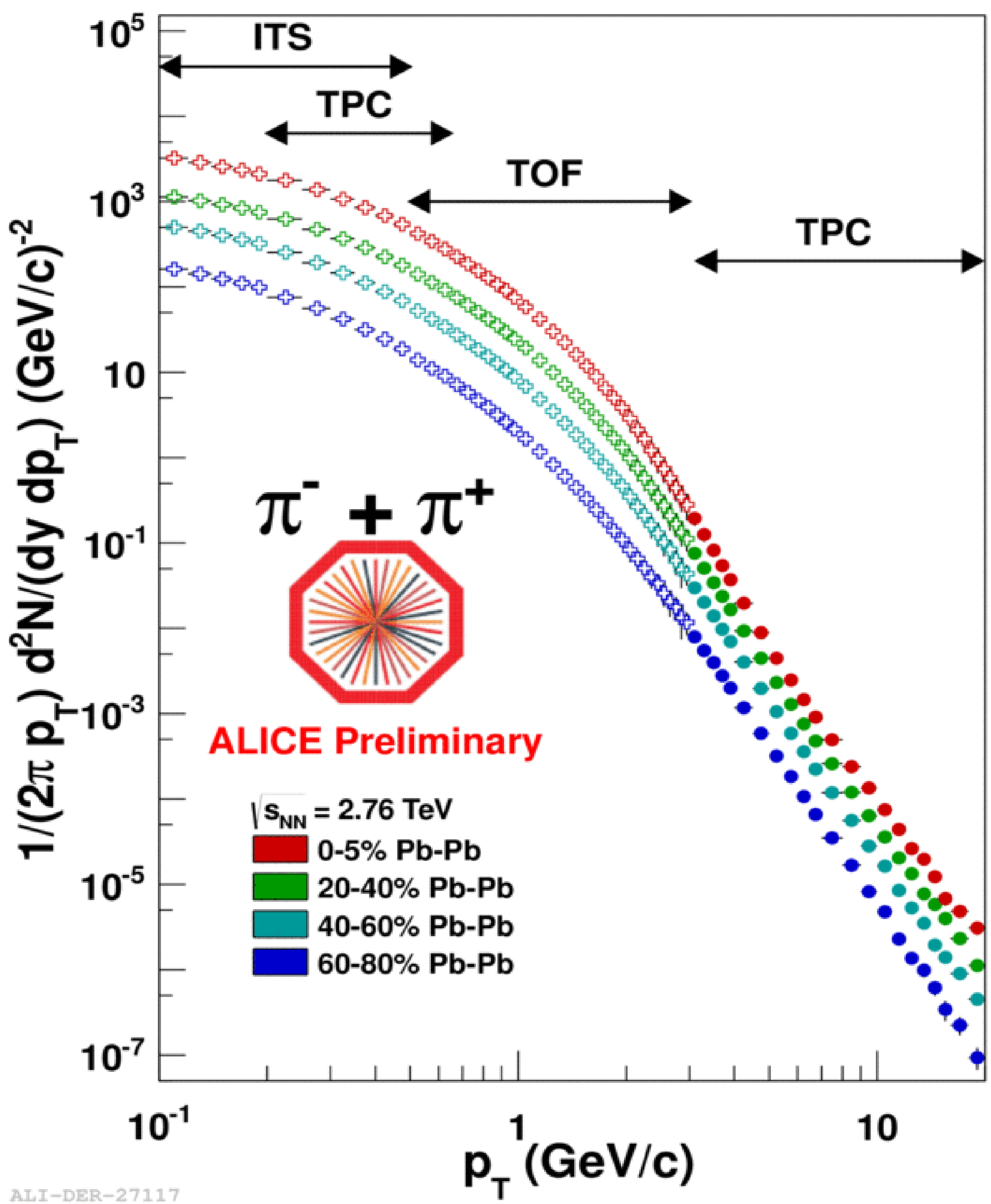


particle identification with ALICE TPC

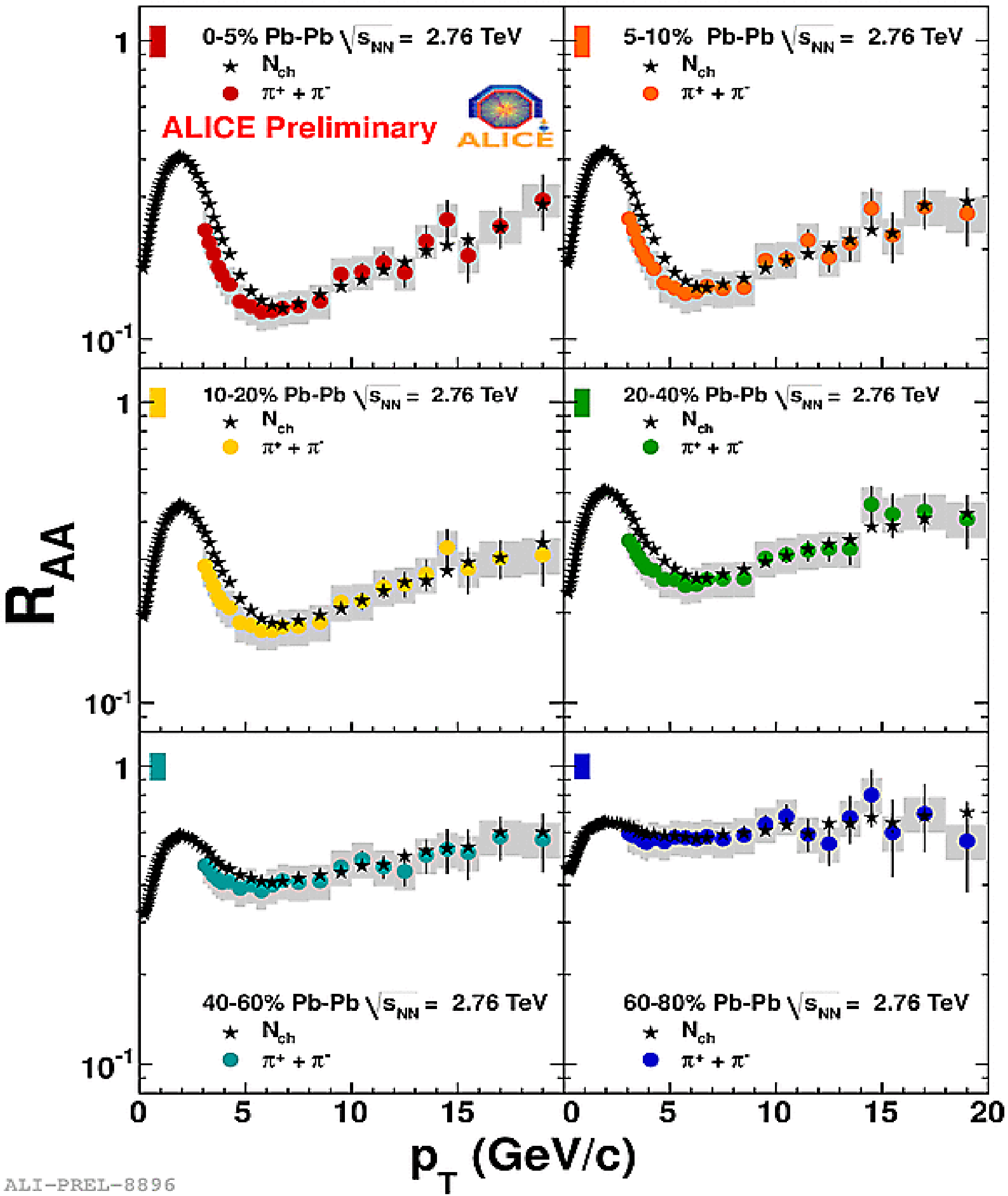
pi, k, p separation up to 30 GeV/c



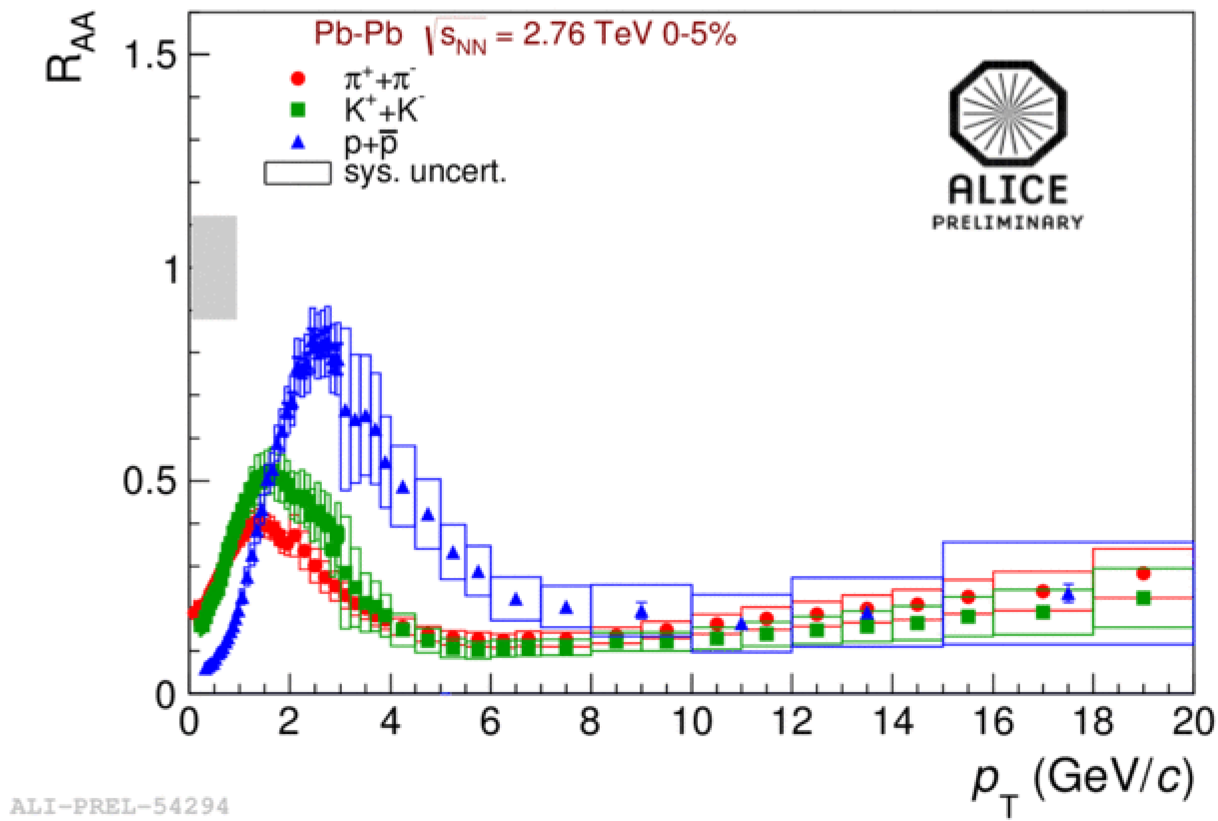
Jet quenching visible by 'naked eye'



R_AA as function of centrality for charged particles and identified pions

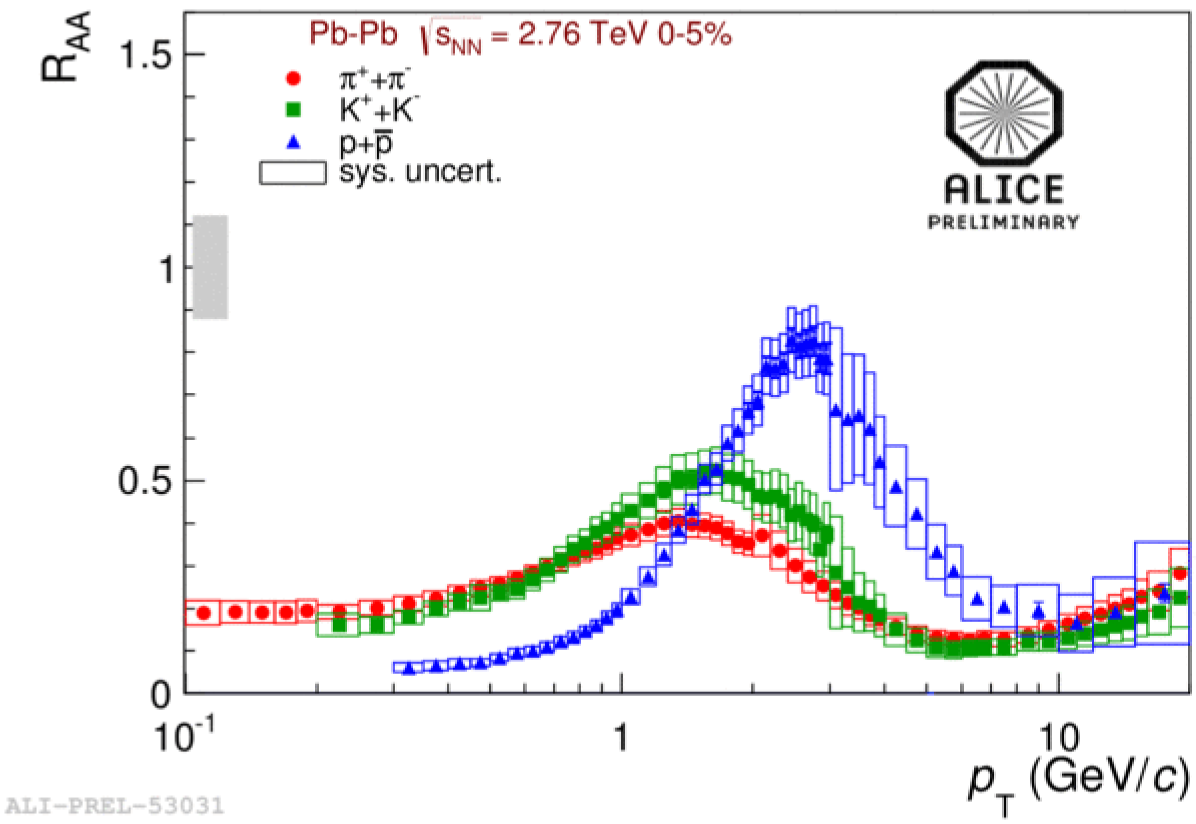


R_AA for pions, kaons, and protons



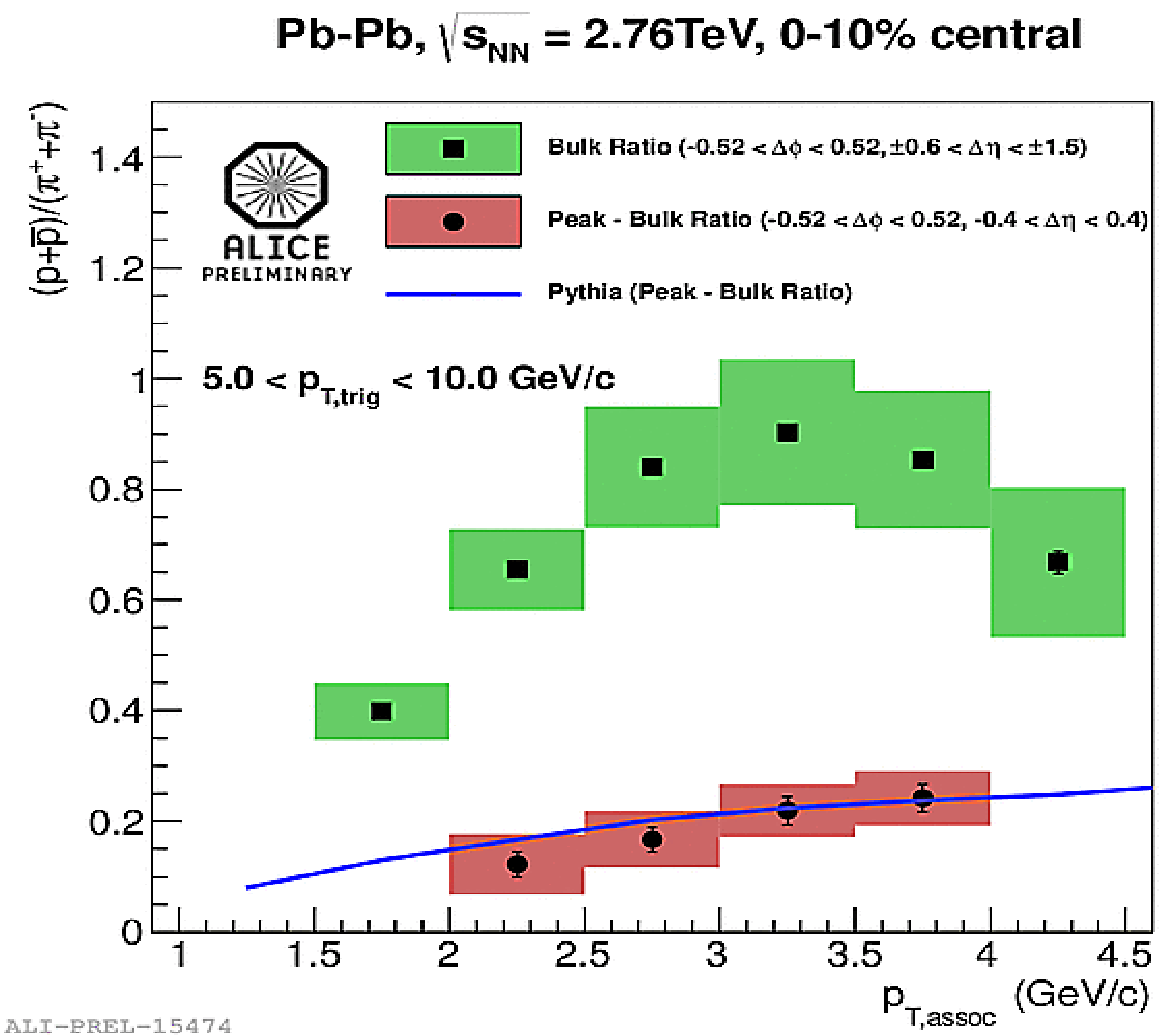
above 7 GeV/c in p_T, no difference is observed → medium does not change the fragmentation function!

dramatic changes at low p_T



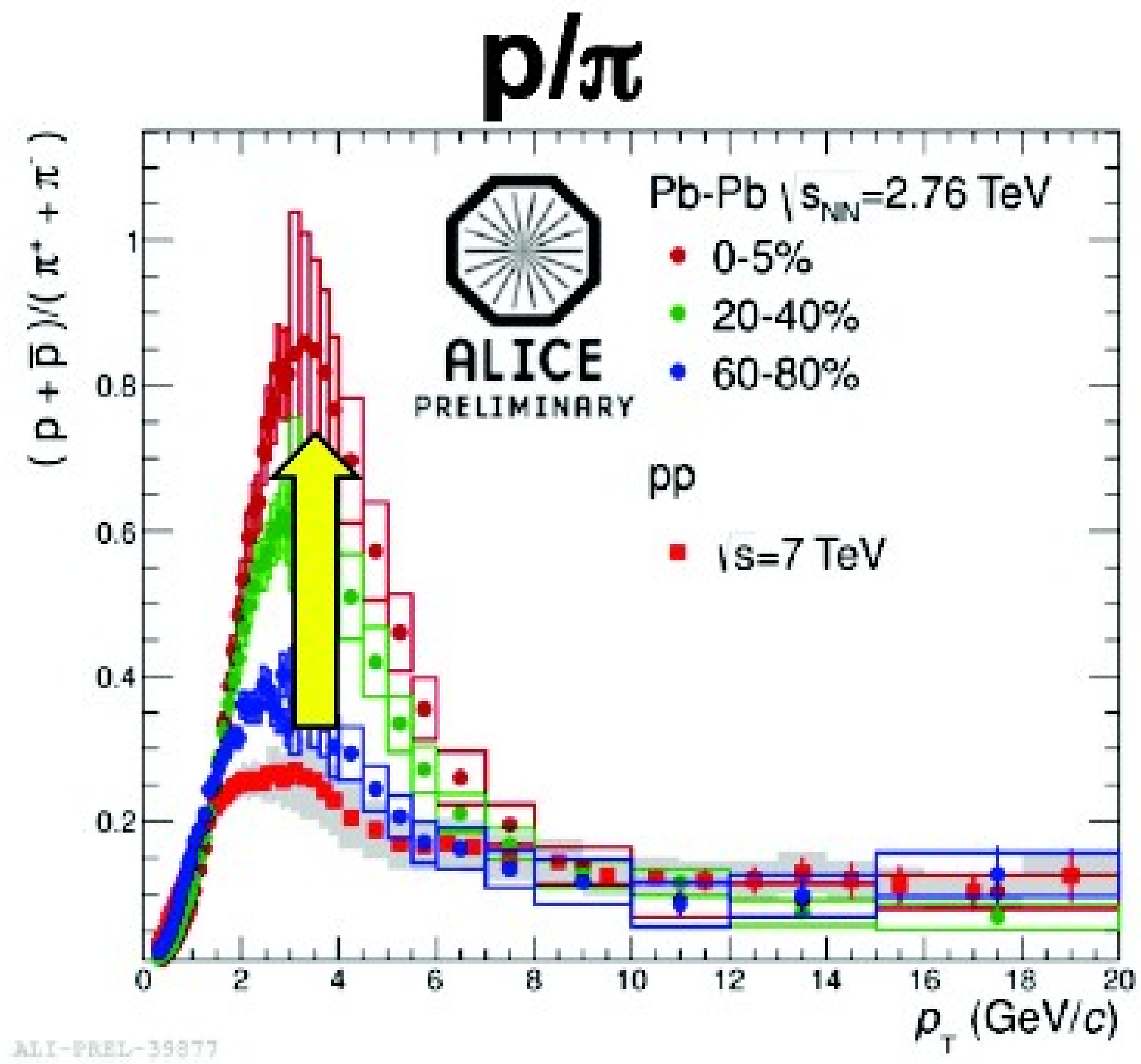
Evidence for hydrodynamic effects and interaction of jet with the medium at a few GeV/c

Particle production in a jet and in the 'bulk' is very different



separation of jet-like and bulk-like features via 2 particle correlation with particle indentification

centrality dependence of proton/pion ratio



summary, high p_t and jet phenomena

- hadron production in Pb—Pb at high p_t is strongly suppressed compared to collision scaling from pp, even up to 100 GeV
- jets are quenched up to 300 GeV
- current data are well described within the Zapp/Krauss/Wiedemann approach
- what is the high p_t limit in the jet suppression?
- the fireball is dense enough to affect high p_t partons but not as dense as presumed in AdS/CFT scenarios