Advanced Topics in Particle Physics: LHC Physics

Part III: Heavy-Ion Physics

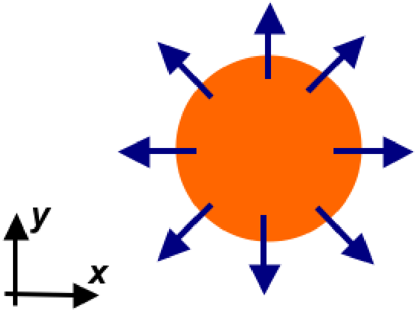
PD Dr. Klaus Reygers
Physikalisches Institut
Universität Heidelberg

Contents

6 Collective Flow

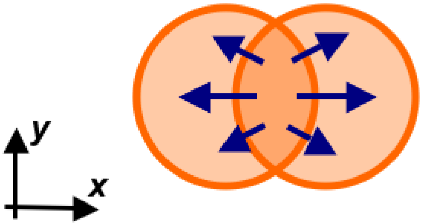
Types of Collective Flow

Radial flow



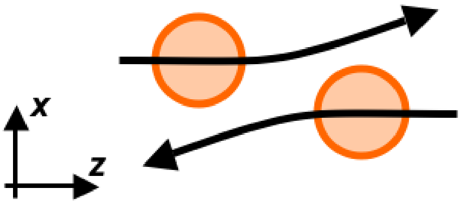
- The only type of collective flow in A+A collisions with impact parameter $b = 0$
- Affects the shape of particle spectra at low p_T

Elliptic flow



- Caused by anisotropy of the overlap zone ($b \neq 0$)
- Requires early thermalization of the medium

Directed flow



- Is produced in the pre-equilibrium phase of the collision
- Gets smaller with increasing $\sqrt{s}_{NN}$

m_T Spectra from a Stationary Thermal Source

Stationary thermal source:

$$E\frac{d^3n}{d^3p} = \frac{1}{m_T}\cdot\frac{dn}{dm_T\,dy\,d\phi} = \frac{gV}{(2\pi)^3}Ee^{-(E-\mu)/T}$$

$V = \text{volume}$

$g = \text{spin/isospin-degeneracy factor}$

$\mu = b\mu_b + s\mu_s = \text{chemical potential from baryon and strangeness quantum numbers}$

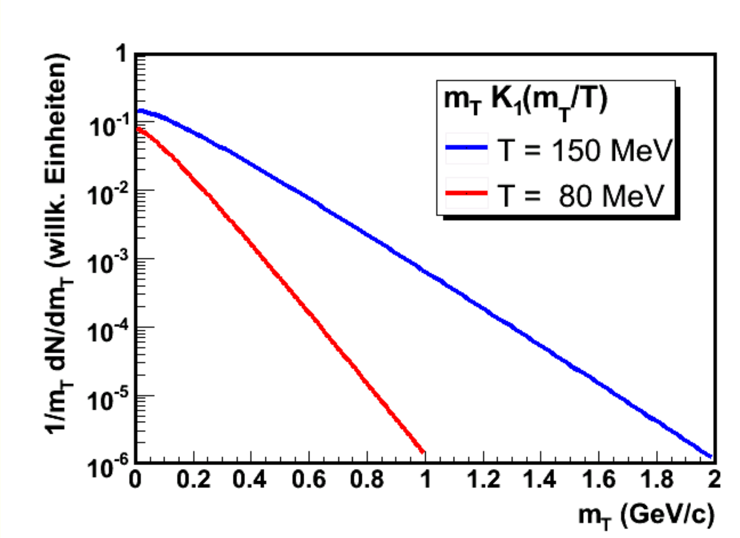
The corresponding transverse mass spectrum can be obtained by integrating over rapidity:

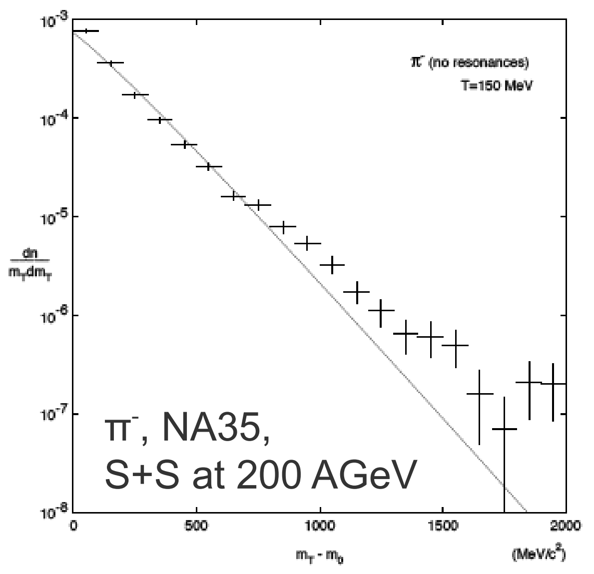
$$\frac{1}{m_T}\frac{dn}{dm_t} = \frac{V}{2\pi^2}m_T K_1\left(\frac{m_T}{T}\right) \xrightarrow{m_T \gg T} V'\sqrt{m_T}e^{-m_T/T}$$

$K_1 = \text{Modified Bessel functions of 2nd kind}$

Schnedermann, Sollfrank, Heinz,
Phys.Rev.C48:2462-2475,1993

Relation between Temperature and Slope





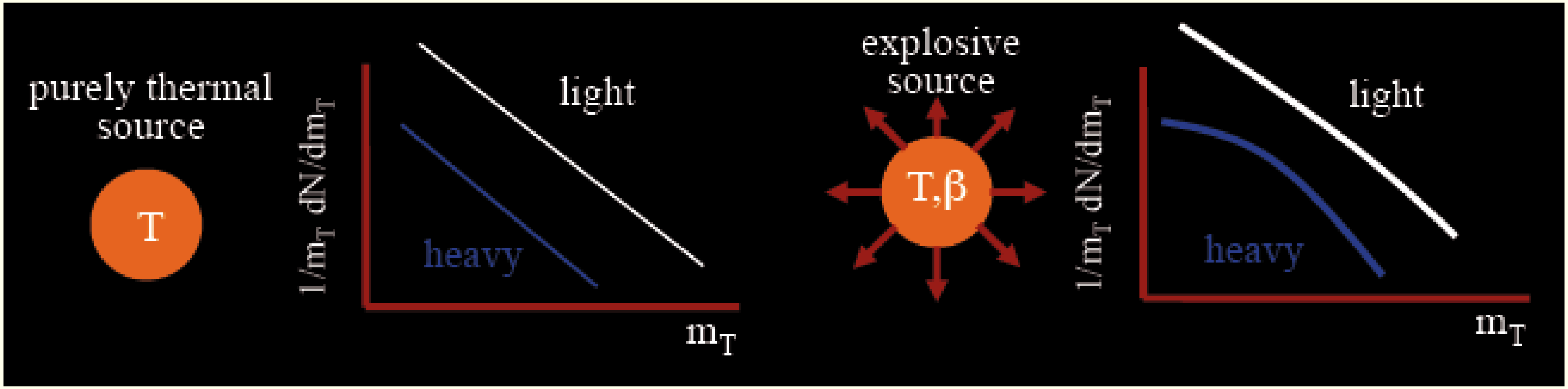
Slope of the m_T (or p_T) spectrum reflects the temperature of the fireball

- However, other effects like collective flow and resonance decays affect the slope as well and make the extraction of the temperature more difficult

- m_T spectra are indeed approximately exponential with an almost uniform slope $1/T$
- However, clear deviation are visible:
  A stationary thermal source clearly is an oversimplification

Schnedermann, Sollfrank, Heinz,
Phys.Rev.C48:2462-2475,1993

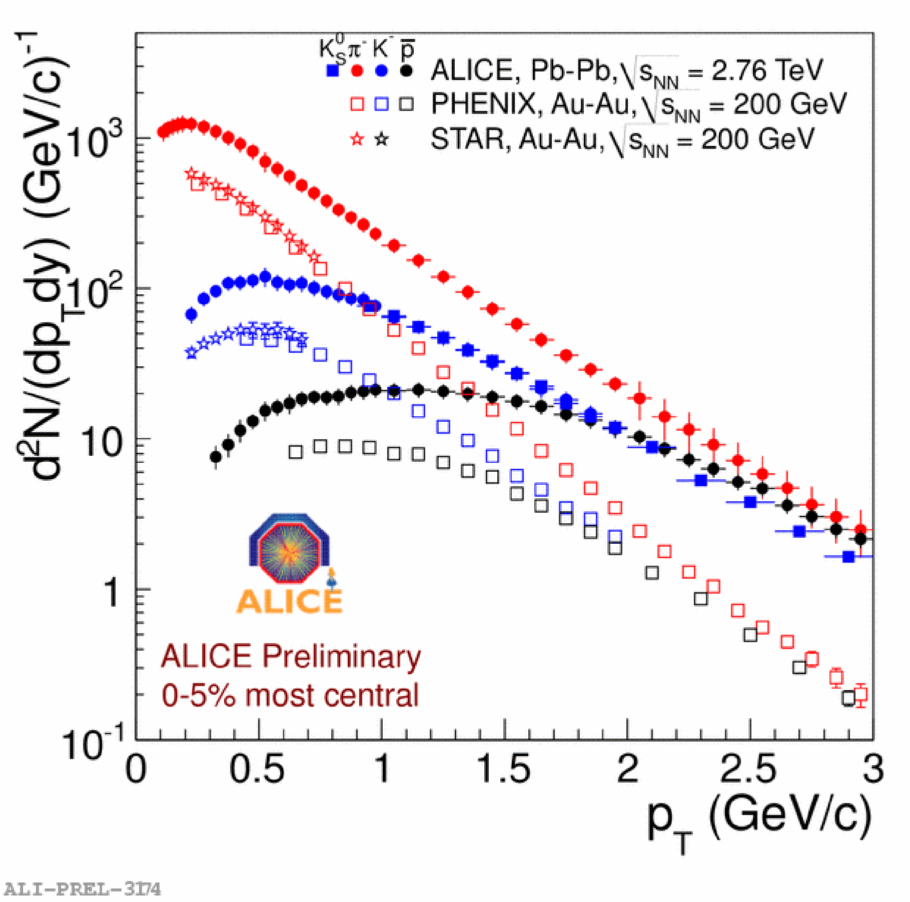
Radial Flow

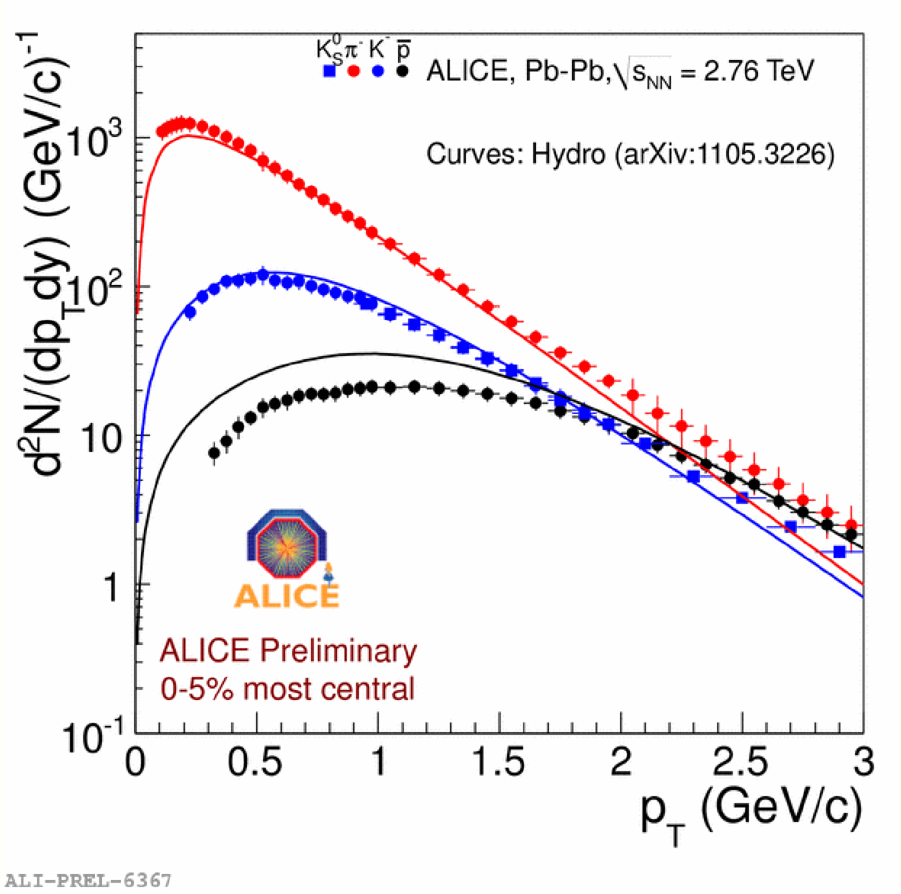


Heavier particles profit more from collective flow than the light ones:

$$\langle E\rangle \approx \langle E_{\mathrm{th}}\rangle + \frac{m_0}{2} v^2_{\mathrm{collective}}$$

Identified Particle p_T Spectra in Pb+Pb at 2.76 TeV





Inverse slope (“effective temperature”) at LHC larger than at RHIC

Hydro predictions quite good for pions and Kaons, some discrepancies for protons

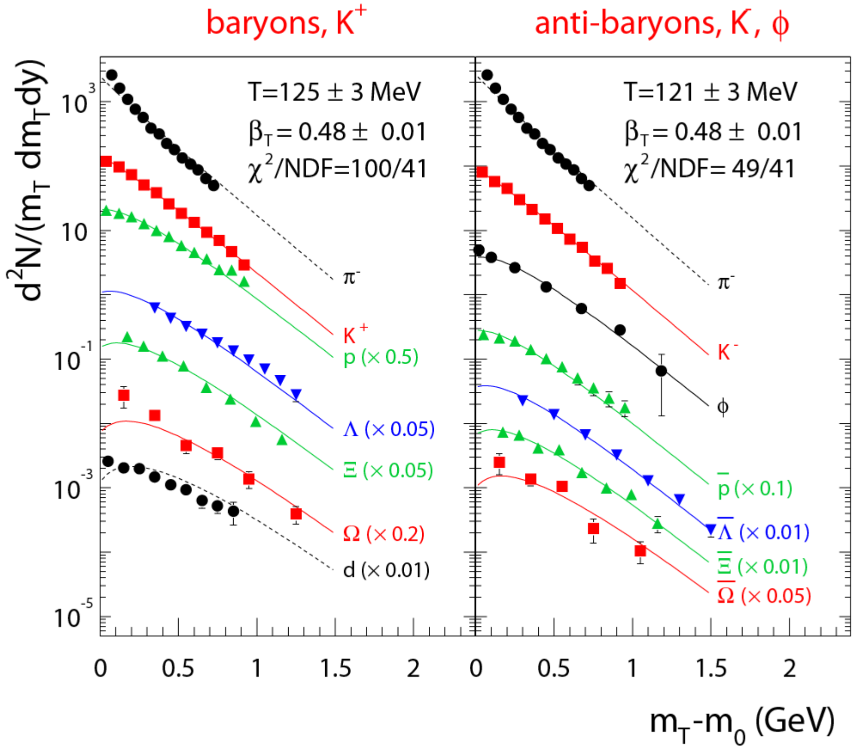
Blast Wave Fit of Particle Spectra

Schnedermann, Sollfrank, Heinz,
Phys.Rev.C48:2462-2475,1993

Transverse velocity profile: $$\beta_T(r) = \beta_s \left(\frac{r}{R}\right)^n$$

This leads to: $$\frac{1}{m_T}\frac{dn}{dm_T} \propto \int_0^R r\,dr\,m_T I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{p_T \cosh\rho}{T}\right)$$

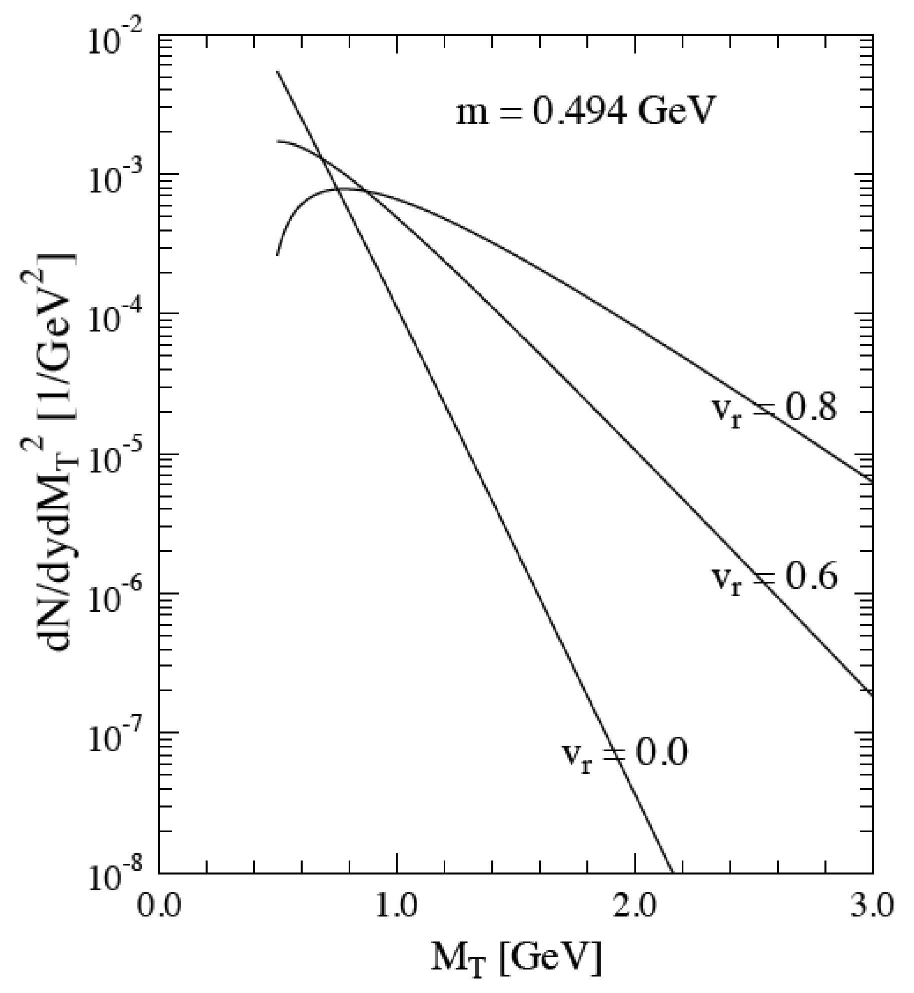
$$\rho := \mathrm{arctanh}(\beta_T) \quad \text{"transverse rapidity"}$$



Blast wave fits capture the essence of full-blown hydro calculations.

In general good description
of particle spectra
(example from NA49)

Effect on Radial Flow on m_T Spectra

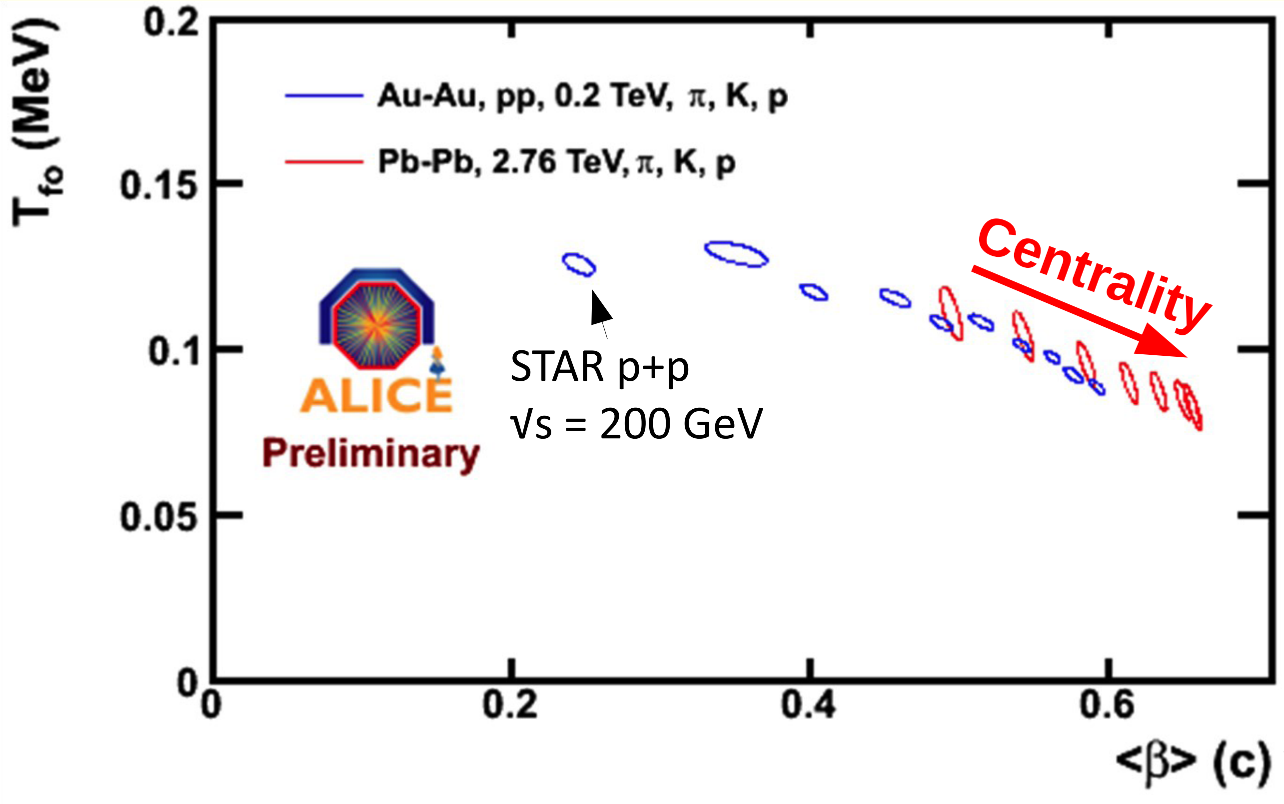


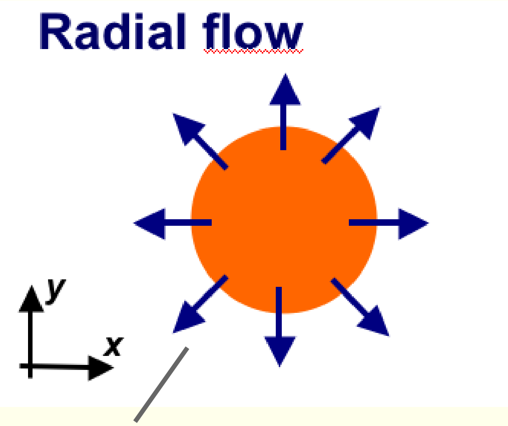
review: Huovinen, Ruuskanen, arXiv:nucl-th/0605008

The apparent temperature, i.e., the inverse slope at high m_T, is larger than the original temperature by a blue shift factor:

$$T_{\text{eff}} = T\sqrt{\frac{1+\beta_r}{1-\beta_r}}$$

Radial Flow Velocities as a Function of $\sqrt{s}_{NN}$

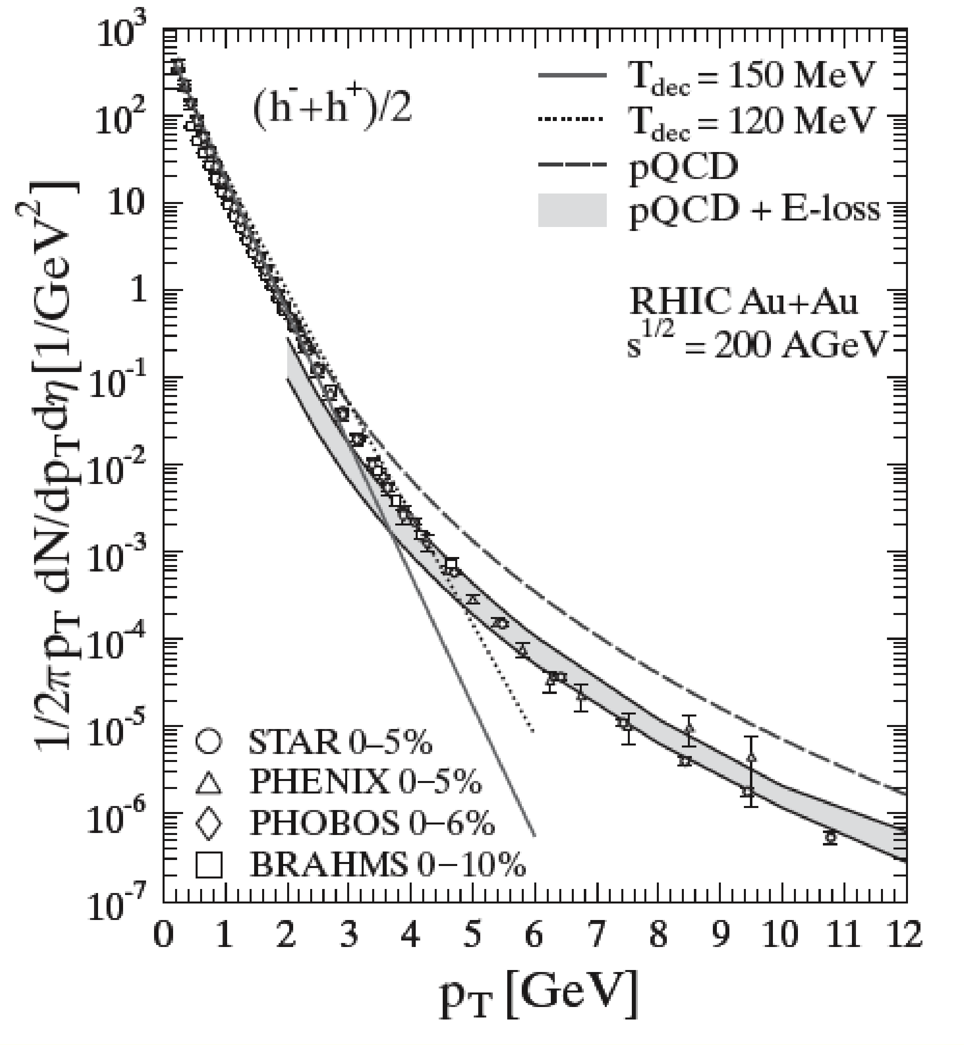




Radial flow velocity β

LHC: Strong radial flow, ~10% higher in most central collisions than at RHIC

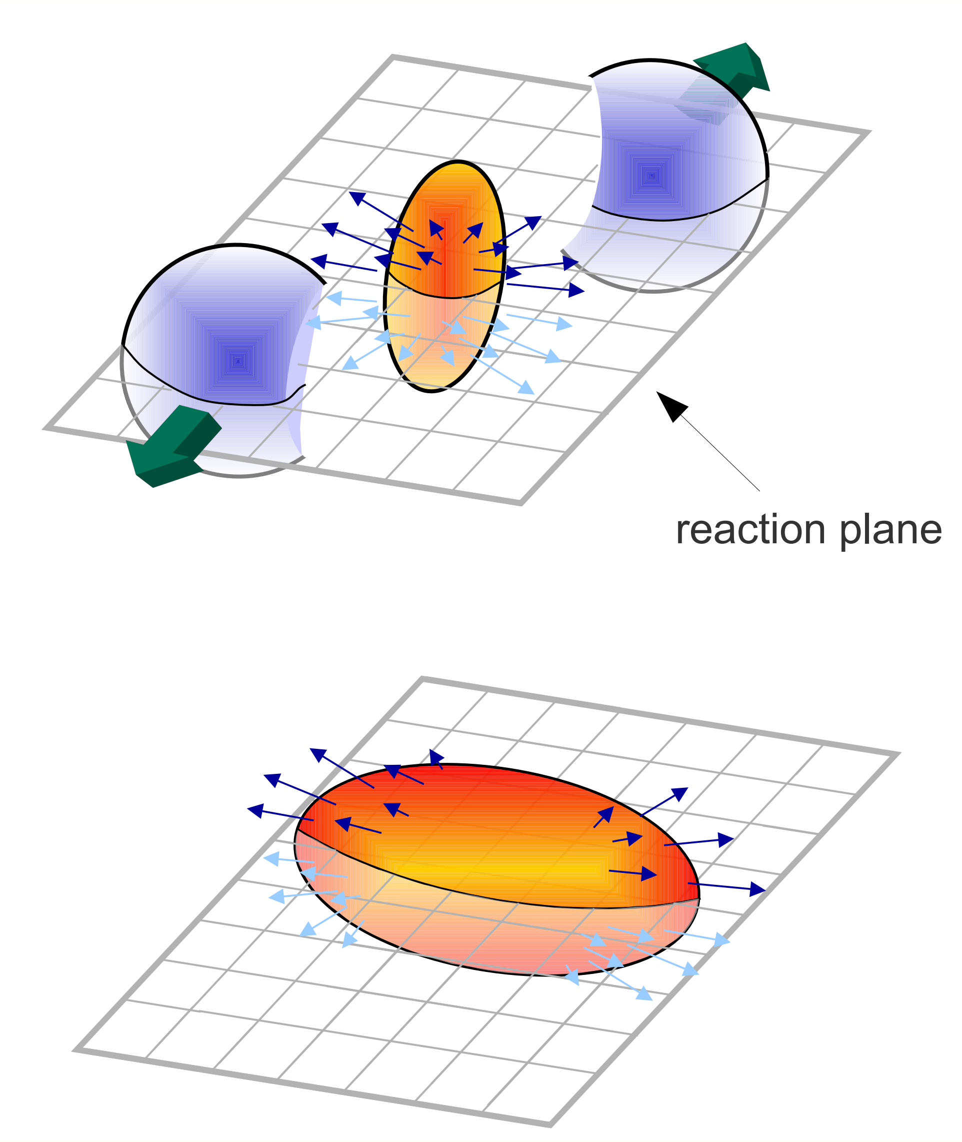
Transition from Soft to Hard Physics Around p_T= 2 - 3 GeV/*c*



At large p_T the hydro description yields exponential spectra

However, around p_T = 2 – 3 GeV/c the measured spectra start to follow a power law shape: hard scattering of partons becomes relevant

The Reaction Plane

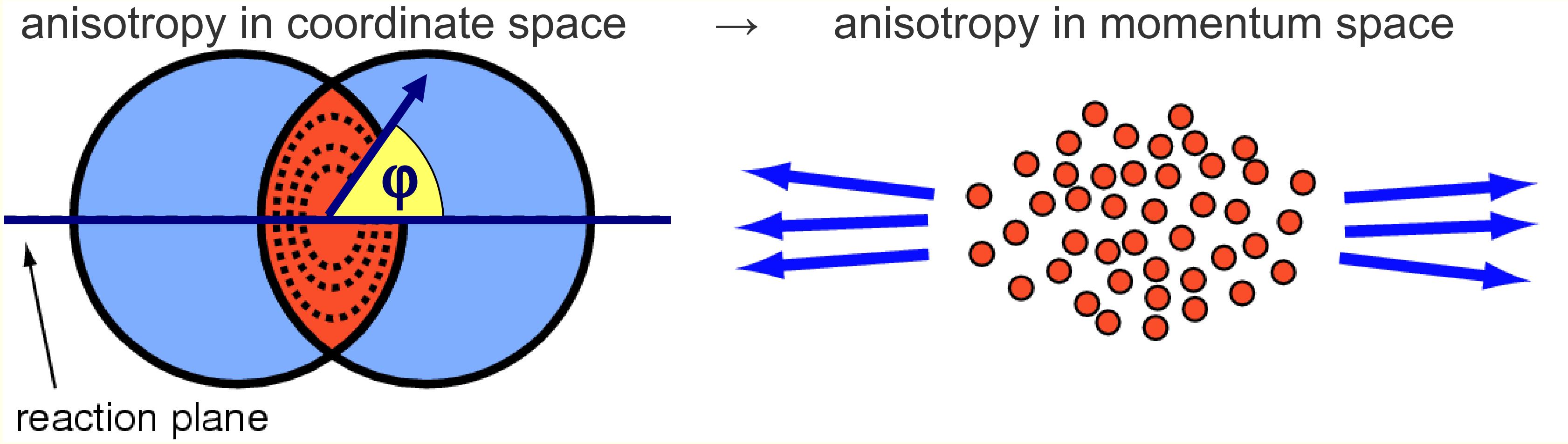


The impact parameter vector ***b*** and the beam axis span the reaction plane

Experimentally, the reaction plane can be measured (with some finite resolution) on an event-by-event basis

One can then study particle production as a function of the emission angle w.r.t. the reaction plane

Fourier Decomposition of the Azimuthal Particle Distribution



$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3\mathbf{p}} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{t}\mathrm{d}p_\mathrm{t}\mathrm{d}y}\left(1+2\sum_{n=1}^{\infty} v_n \cos[n(\varphi-\Psi_\mathrm{RP})]\right)$$

The sine terms in the Fourier expansion vanish because of the reflection symmetry with respect to the reaction plane.

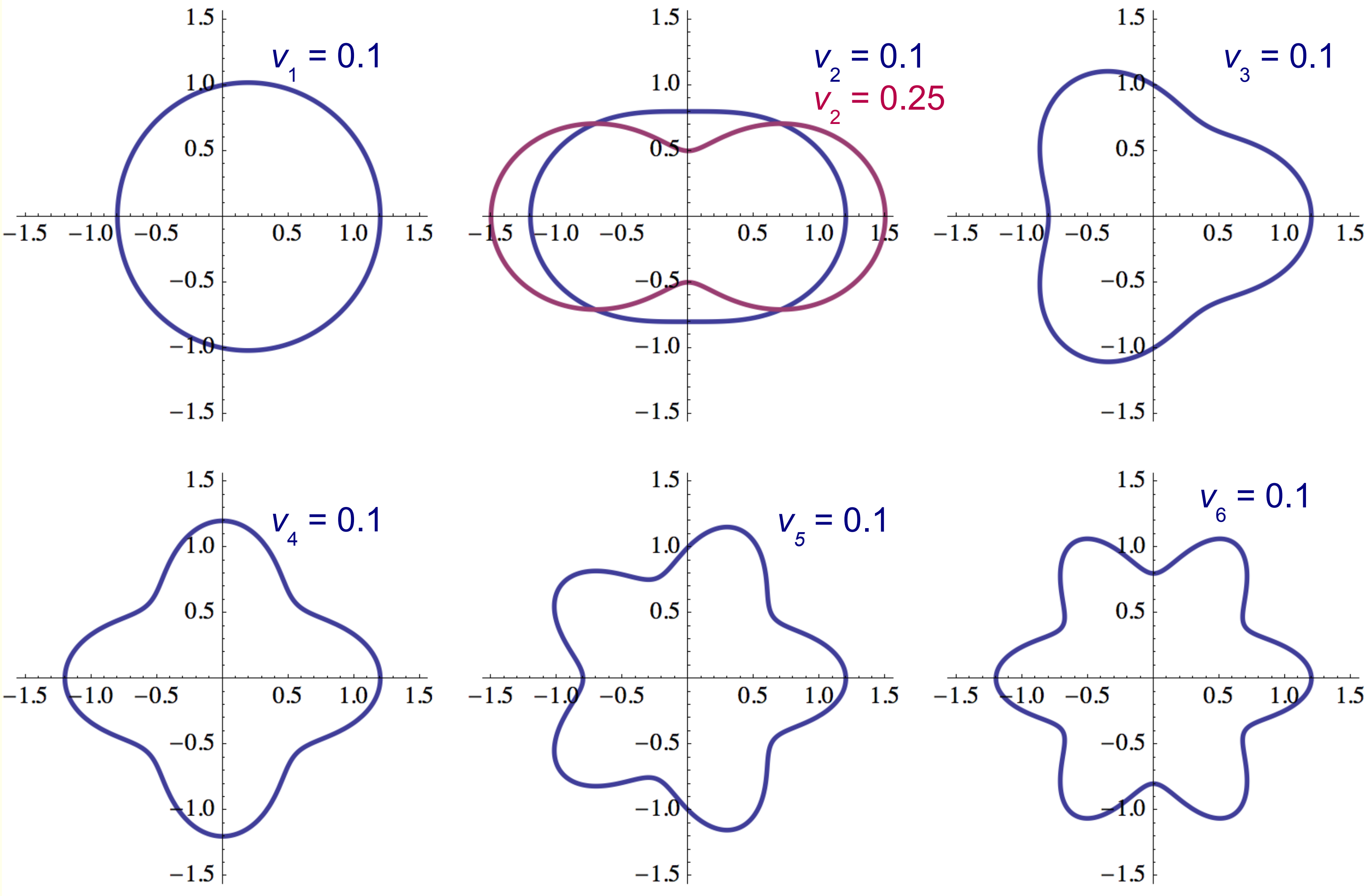
Fourier coefficients: $v_n(p_T, y) = \langle \cos[n(\varphi-\Psi_\mathrm{RP})]\rangle$

v_1 : Strength of the directed flow (small at midrapidity)

v_2 : Strength of the elliptic flow

Visualization of v_n

$$f(\varphi) = 1 + 2v_n \cos(n\varphi)$$



Hydrodynamic Models

Ingredients of hydrodynamic models

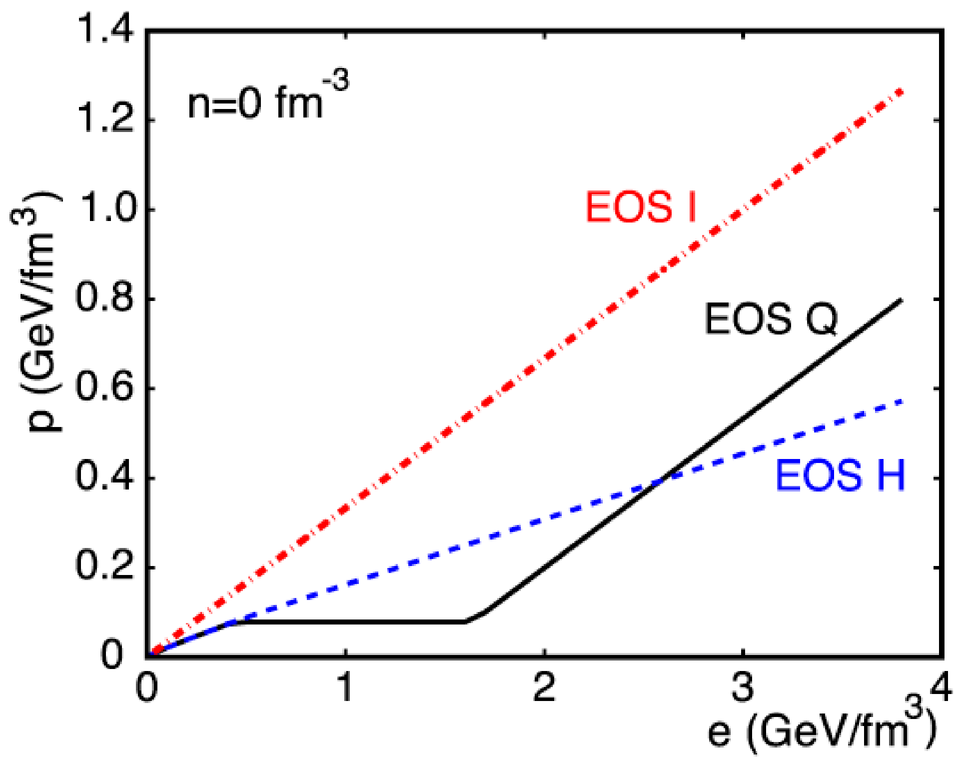
- Equation of motion and baryon number conservation:

  $$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu j^\mu_\mathrm{B}(x) = 0$$

  5 equations for 6 unknowns:

  $$(u_x, u_y, u_z, \varepsilon, P, n_\mathrm{B})$$

- Equation of state: $P(\varepsilon, n_\mathrm{B})$ (needed to close the system)
- Ideal hydro: Zero viscosity (zero mean free path)
- Initial conditions, e.g., from Glauber calculation
- Freeze-out condition



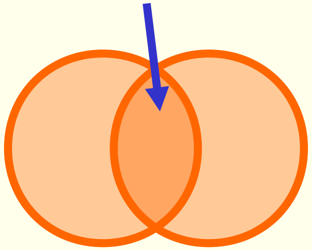
EOS I: ultra-relativistc gas $P = \varepsilon/3$

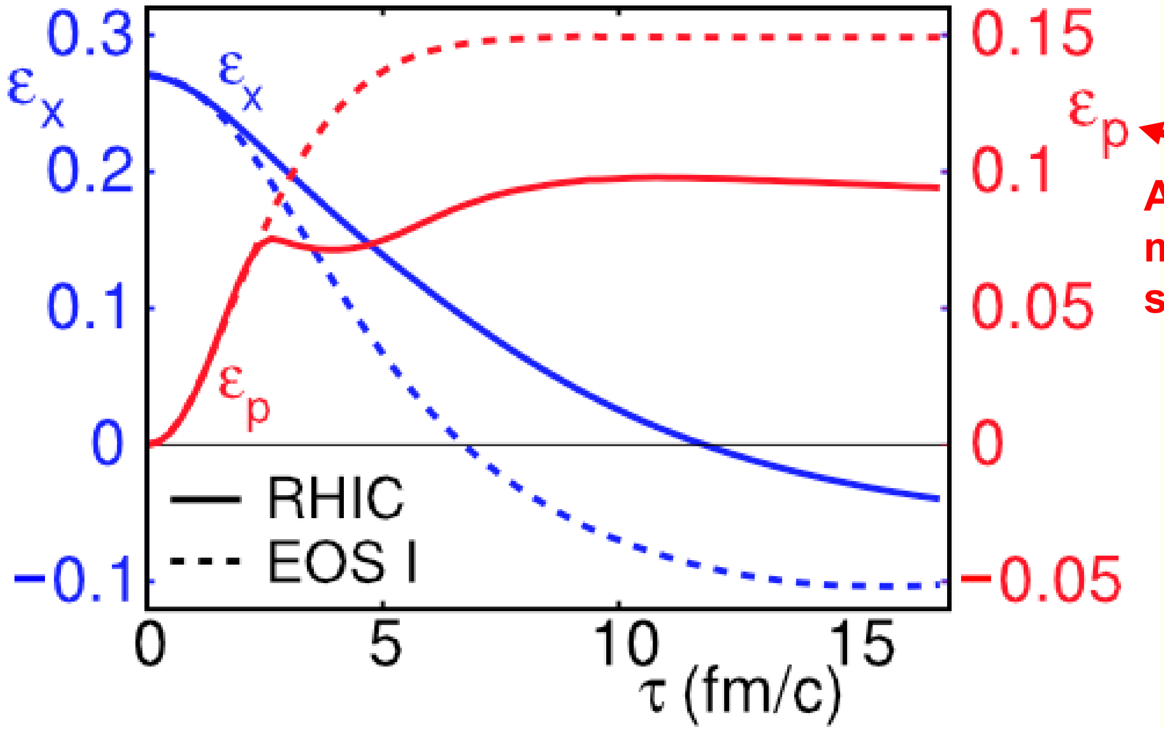
EOS H: resonance gas, $P \approx 0.15\ \varepsilon$

EOS Q: phase transition, QGP ↔ resonance gas

Time Dependence of the Momentum Anisotropy

Anisotropy in coordinate space





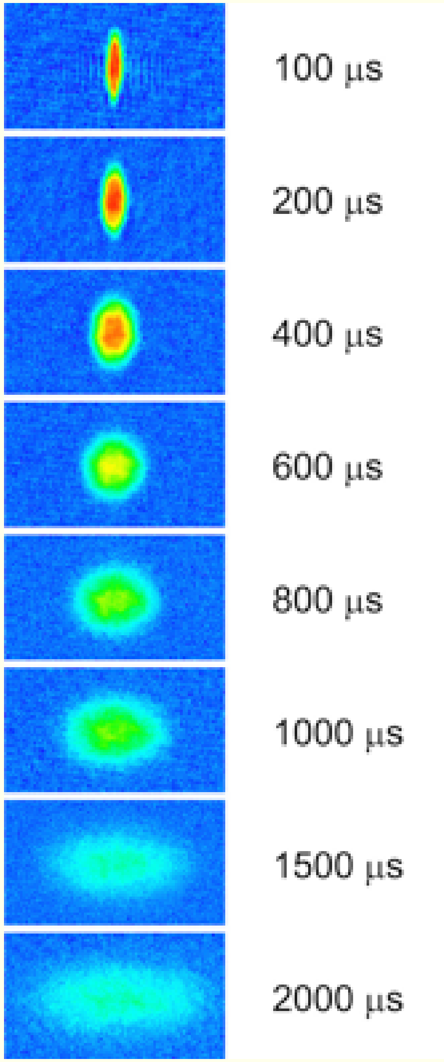
Ulrich Heinz, Peter Kolb, arXiv:nucl-th/0305084

Anisotropy in momentum space

In hydrodynamic models the momentum anisotropy develops in the early (QGP) phase of the collision. Thermalization times of less then 1 fm/*c* are needed to describe the data.

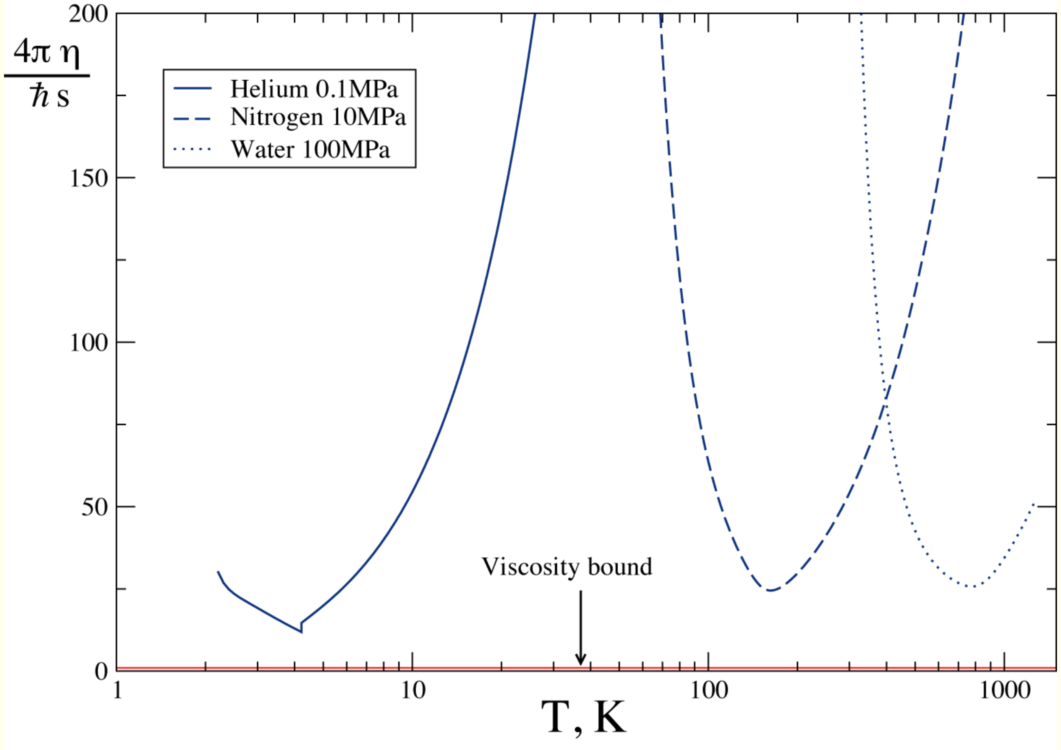
An Interesting Connection: Elliptic Flow of Cold Atoms in a Trap

- 200 000 Li-6 atoms in an highly anisotropic trap (aspect ratio 29:1)
- Very strong interactions between atoms (Feshbach resonance)
- Once the atoms are released the one observed a flow pattern similar to elliptic flow in heavy-ion collisions



Sensitivity of v_2 to Viscosity

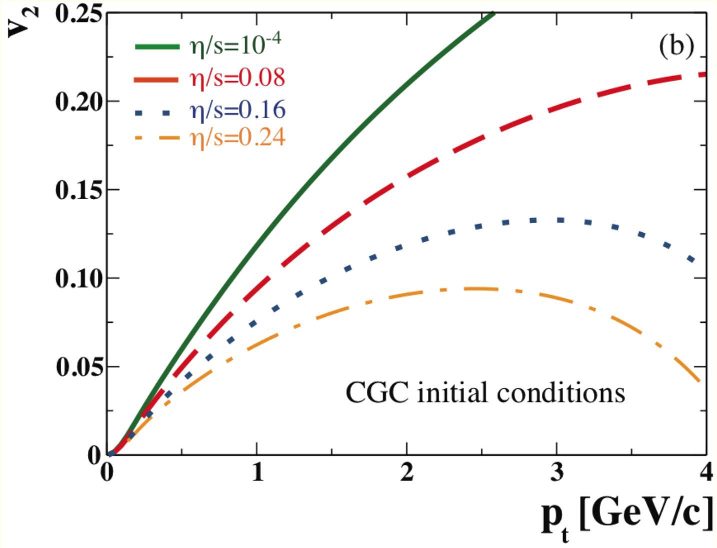
Kovtun, Son, Starinets,
PRL 94 (2005) 111601



Based on a correspondence between string theory and quantum field theory (“AdS/CFT correspondence”) Kovtun, Son, and Starinets argued that there is a lower limit for the viscosity of any fluid:

$$\frac{\eta}{s} = \frac{\hbar}{4\pi k_B}$$

v_2 is sensitive to the viscosity of the quark-gluon plasma. The larger η/*s*, the smaller is the resulting v_2



Event Plane Method (I)

S. A. Voloshin, A. M. Poskanzer, R. Snellings, arXiv:0809.2949

Event flow vector Q_n:

$$Q_{n,x} = \sum_i w_i \cos(n\phi_i) = Q_n \cos(n\Psi_n)$$

$$Q_{n,y} = \sum_i w_i \sin(n\phi_i) = Q_n \sin(n\Psi_n)$$

The optimal choice for w_i is to approximate $v_n(p_T; y)$. $w_i = p_{T,i}$ is often used as a good approximation.

Event plane angle:

$$\Psi_n = \frac{1}{n}\mathrm{atan2}(Q_{n,y}, Q_{n,x})$$

atan2(y, x) is defined such that $(r, \mathrm{atan2}(y, x))$ are the polar coordinates of the cartesian coordinates (x, y); $r := \sqrt{x^2 + y^2}$. atan2 is a C/C++ function.

Event Plane Method (II)

Fourier coefficient w.r.t. the event plane (not the reaction plane):

$$v_n^{\text{observed}}(p_T, y) = \langle \cos[n(\varphi - \Psi_{\text{RP}})] \rangle$$

To remove auto-correlations one has to subtract the Q-vector of the particle of interest from the total event Q-vector, obtaining ψ_n to correlate with the particle.

Alternatively, one determines the reaction plane at forward rapidities and correlates this event plane with particles measured at mid-rapidity.

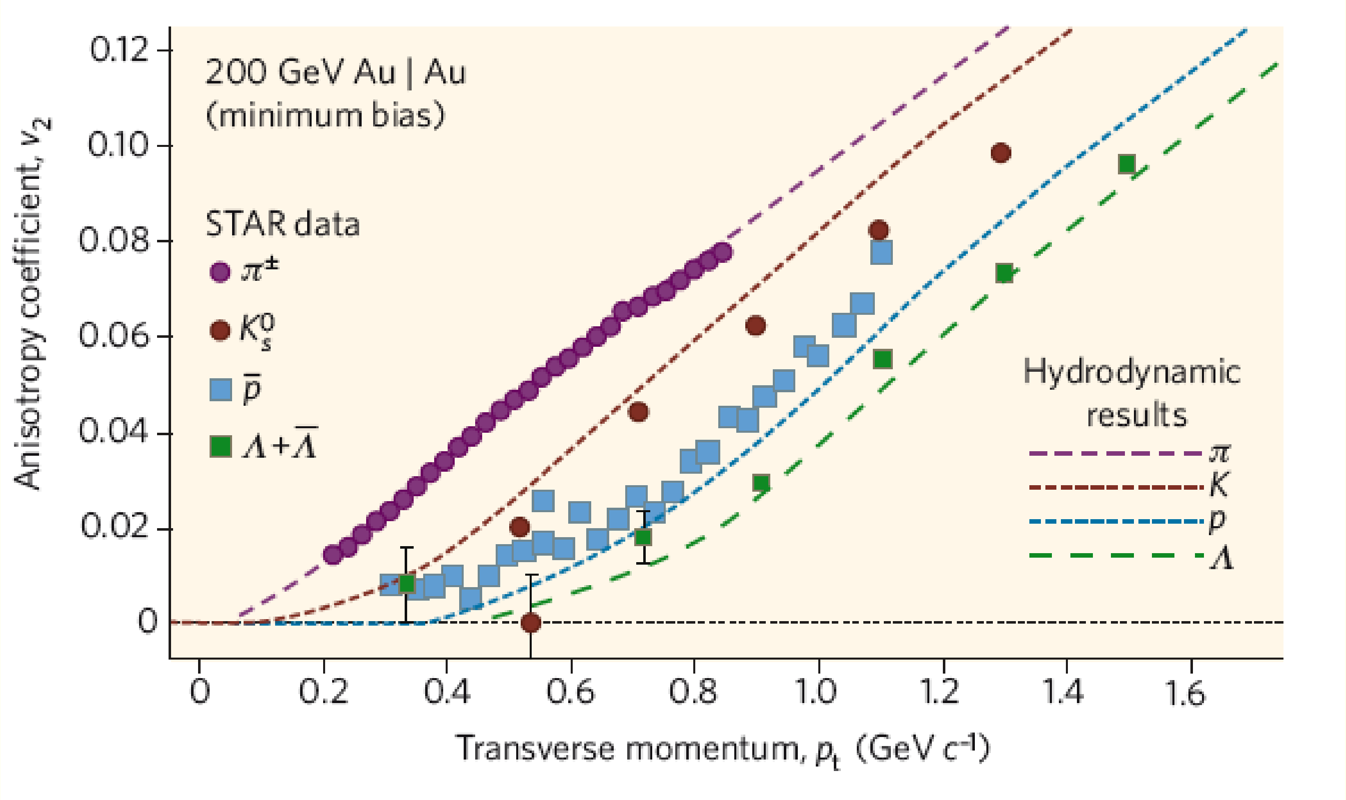
Since finite multiplicity limits the estimation of the angle of the reaction plane, the v_n have to be corrected for the event plane resolution for each harmonic:

$$v_n = \frac{v_n^{\text{observed}}}{R_n}, \qquad R_n = \langle \cos[n(\Psi_n - \Psi_{\text{RP}})] \rangle$$

To estimate the event plane resolution one divides the full event up into two independent sub-events of equal multiplicity

$$R_n = \sqrt{\langle \cos[n(\Psi_n^A - \Psi_n^B)] \rangle}$$

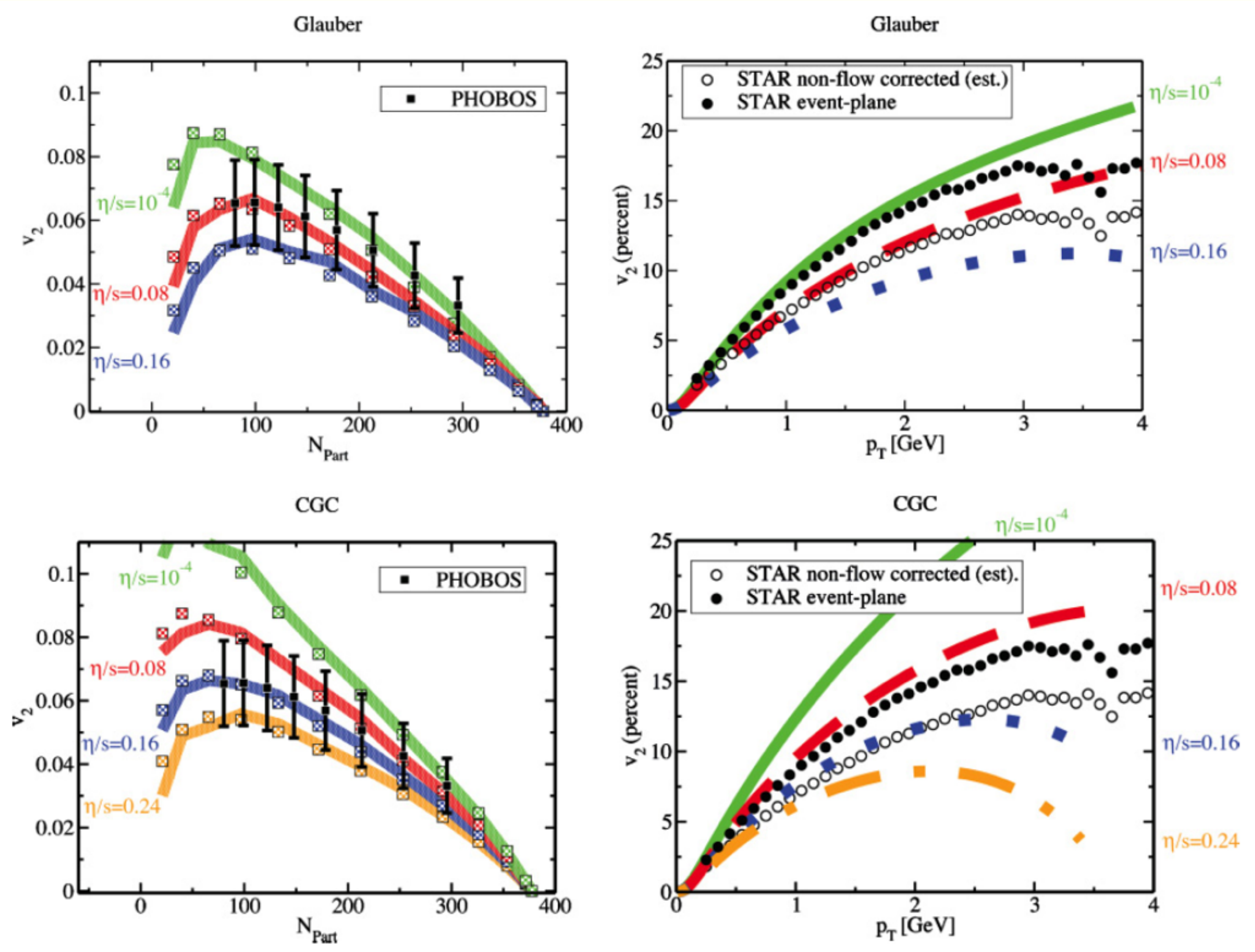
Elliptic Flow at RHIC



Plot from
Braun-Munzinger, Stachel,
Nature 448:302-309,2007

- Measured v_2 in good agreement with ideal hydro
- Hydro predicts mass ordering: $v_2 \sim \frac{1}{T}(p_T - v m_T), \quad v = \text{average flow velocity}$
- Indeed observed!
- “Perfect liquid” created at RHIC

How Perfect is the QGP Fluid at RHIC?



Luzum, Romatschke, Phys.Rev.C78:034915,2008

Glauber initial cond.

$$\Rightarrow \quad 0 < \eta/s < 0.1$$

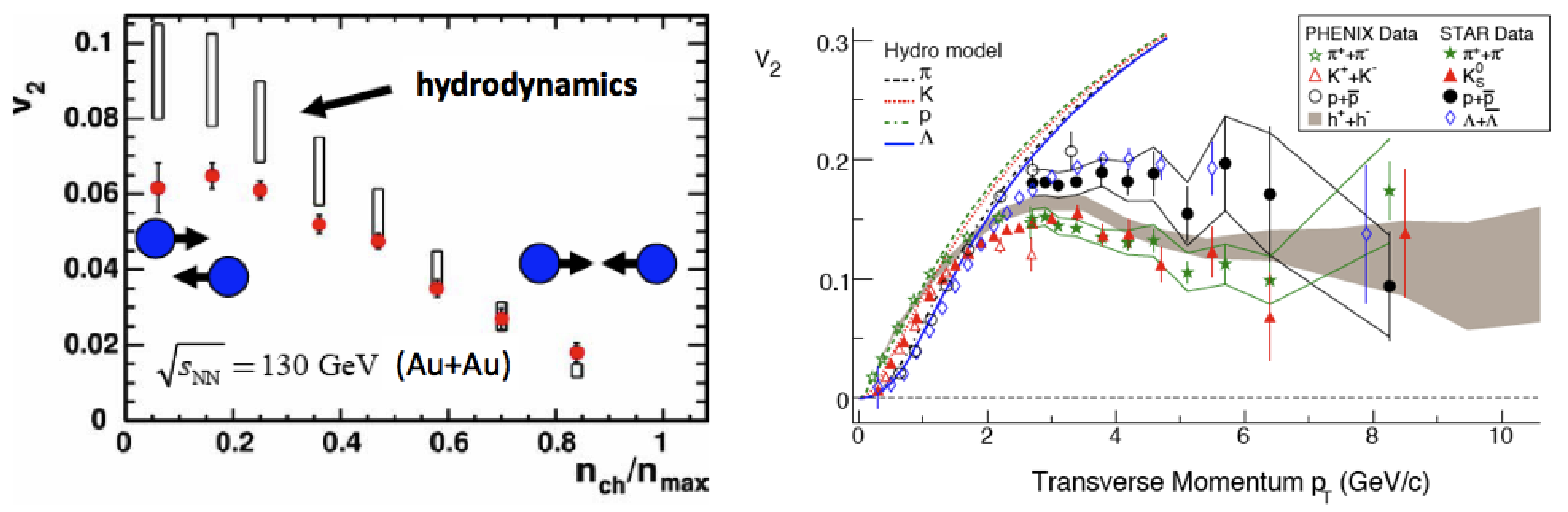
CGC initial cond.

$$\Rightarrow \quad 0.08 < \eta/s < 0.2$$

Conservative estimate for the QGP (taking into account e.g. effects of EOS variations, bulk viscosity, ...):

$$\begin{aligned} \eta/s \quad &< \quad 5 \times \left.\frac{\eta}{s}\right|_{\mathrm{KSS}} \\ &= \quad 5 \times \frac{1}{4\pi} \end{aligned}$$

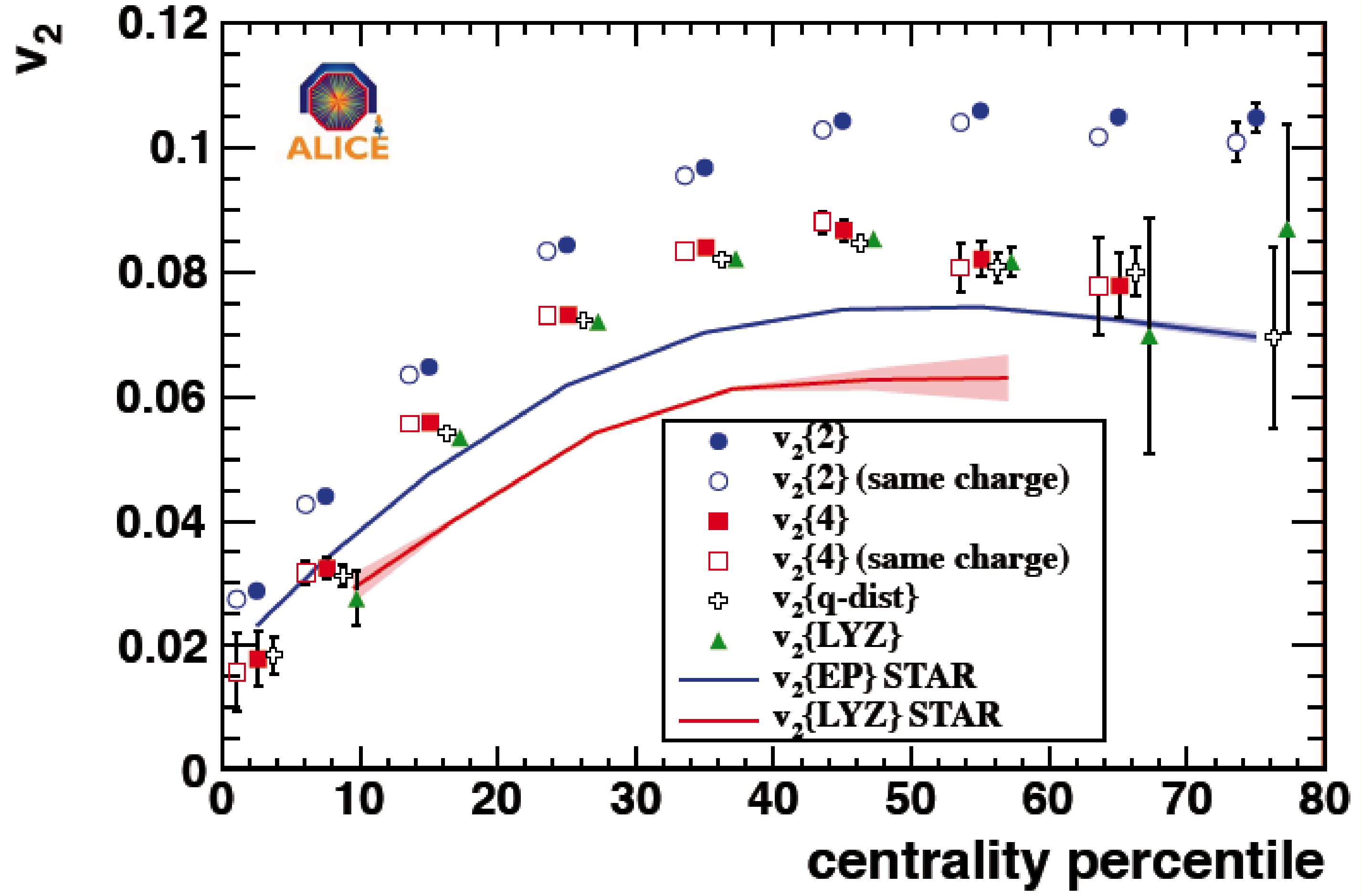
Breakdown of Ideal Hydro



Hydro description for Au+Au at RHIC only works in central collisions and for $p_T < 1.5$ GeV/c

$v_2(p_T)$ in Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 TeV from ALICE Compared to v_2 at RHIC (I)

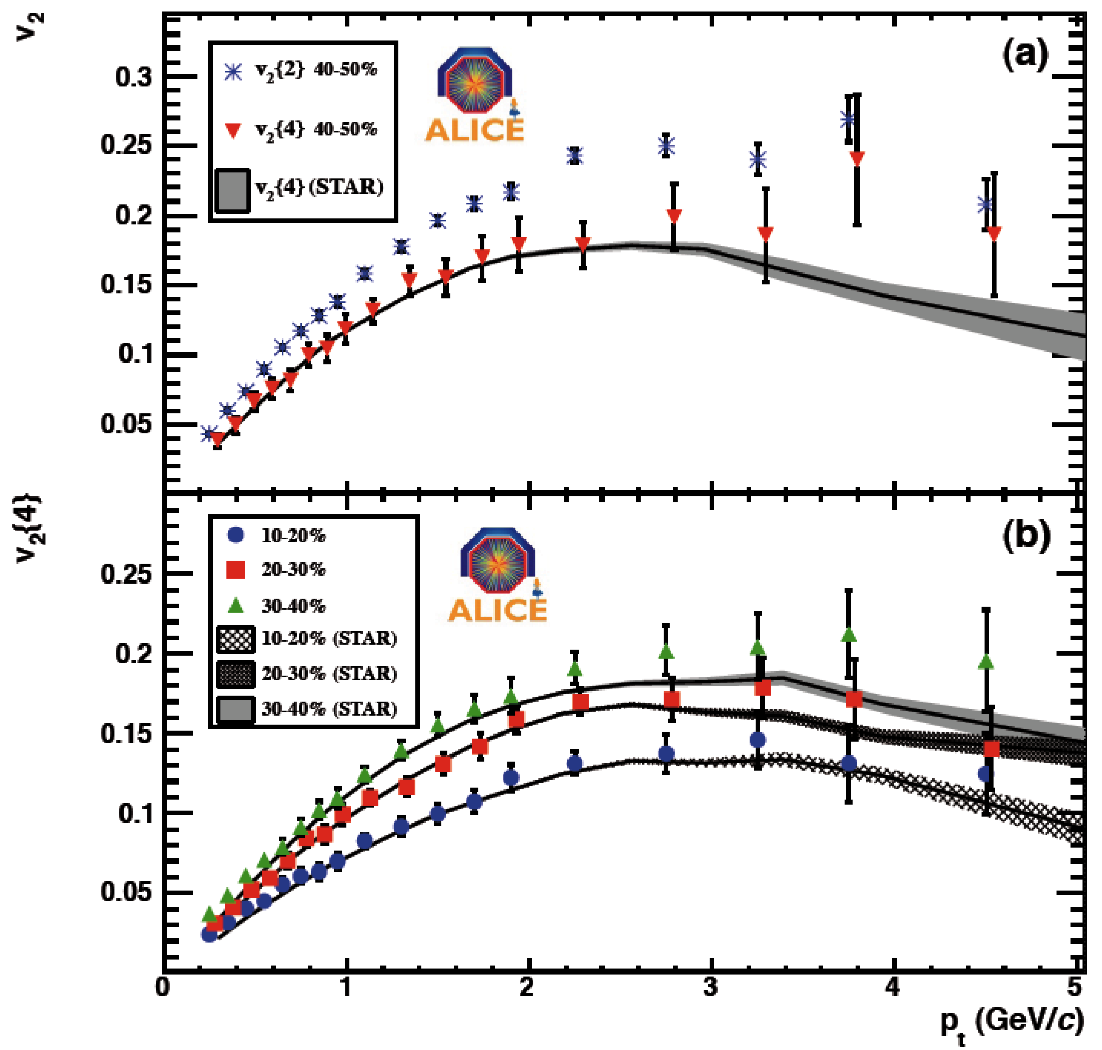
ALICE, Phys. Rev. Lett. 105, 252302 (2010)



v_2 increases up to 30% (for more peripheral collisions)

$v_2(p_T)$ in Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 TeV from ALICE Compared to v_2 at RHIC (II)

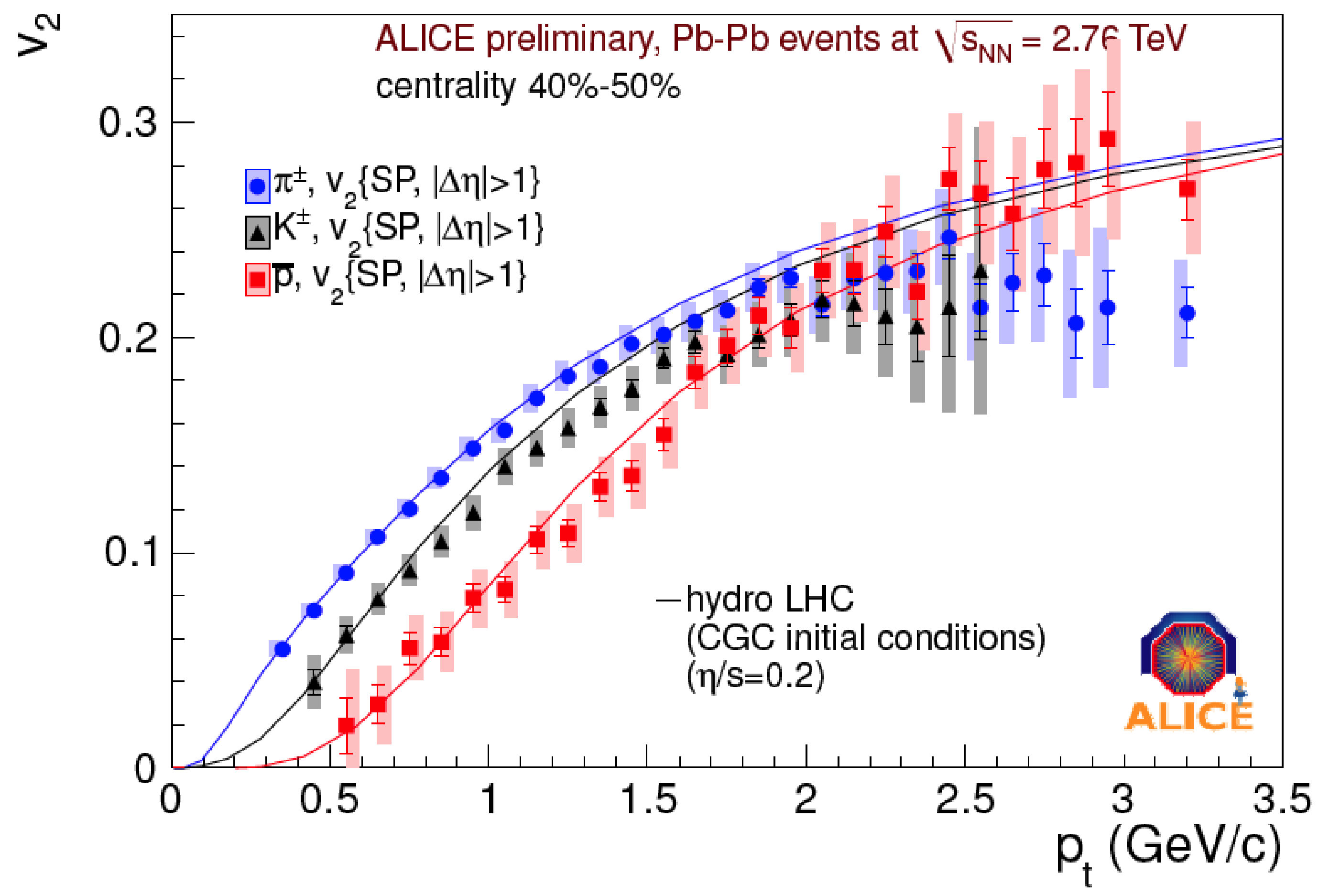
ALICE, Phys. Rev. Lett. 105, 252302 (2010)



$v_2(p_T)$ at LHC and RHIC is virtually identical.

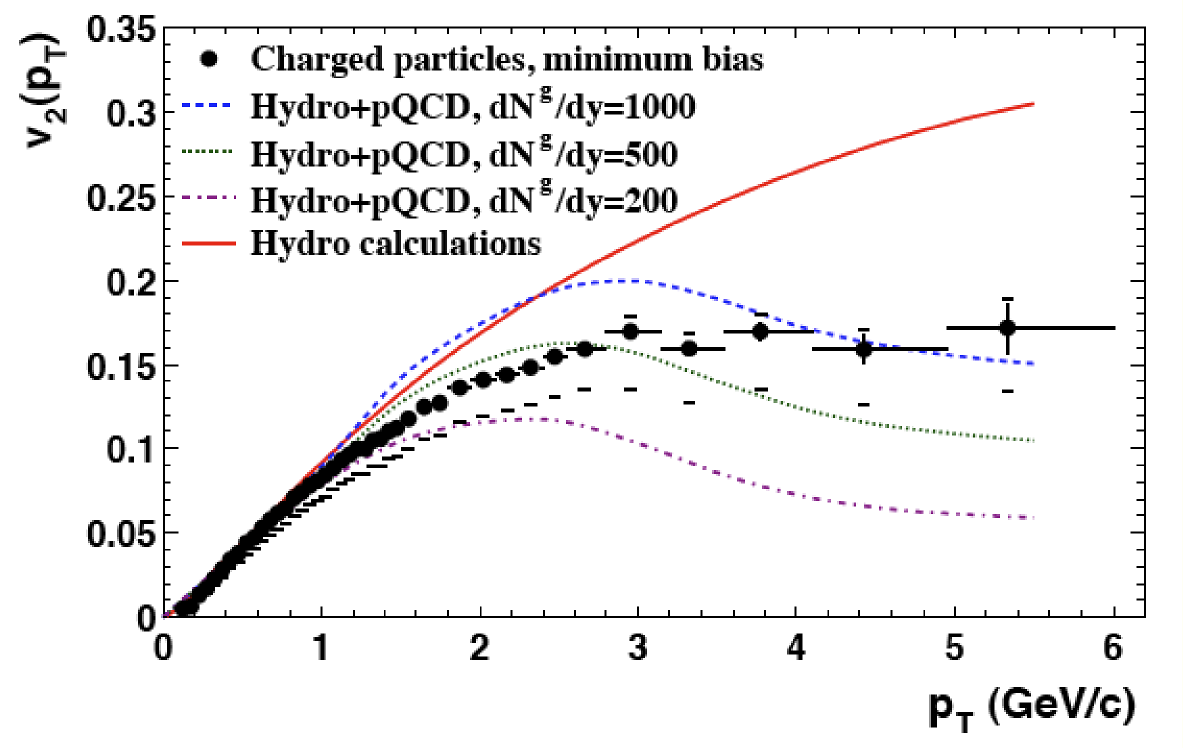
The increase of the mean p_T at the LHC can explain the increase of the p_T-integrated v_2 value.

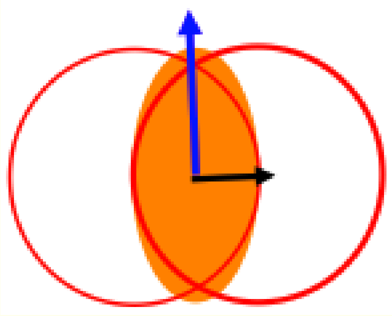
v_2 of Identified Particles in Pb+Pb at 2.76 TeV



Hydrodynamic model predictions are able to describe the data

v_2 and Jet Quenching





For p_T > 4-6 GeV/*c* particle production is dominated by jet fragmentation. Jets, i.e, energetic quark and gluons, are expected to lose energy in the QGP ("jet quenching"). The shorter path length for jets in the reaction plane compared to jets perpendicular to the reaction plane is expected to result in a positive v_2 at hight p_T.

Points to Take Home

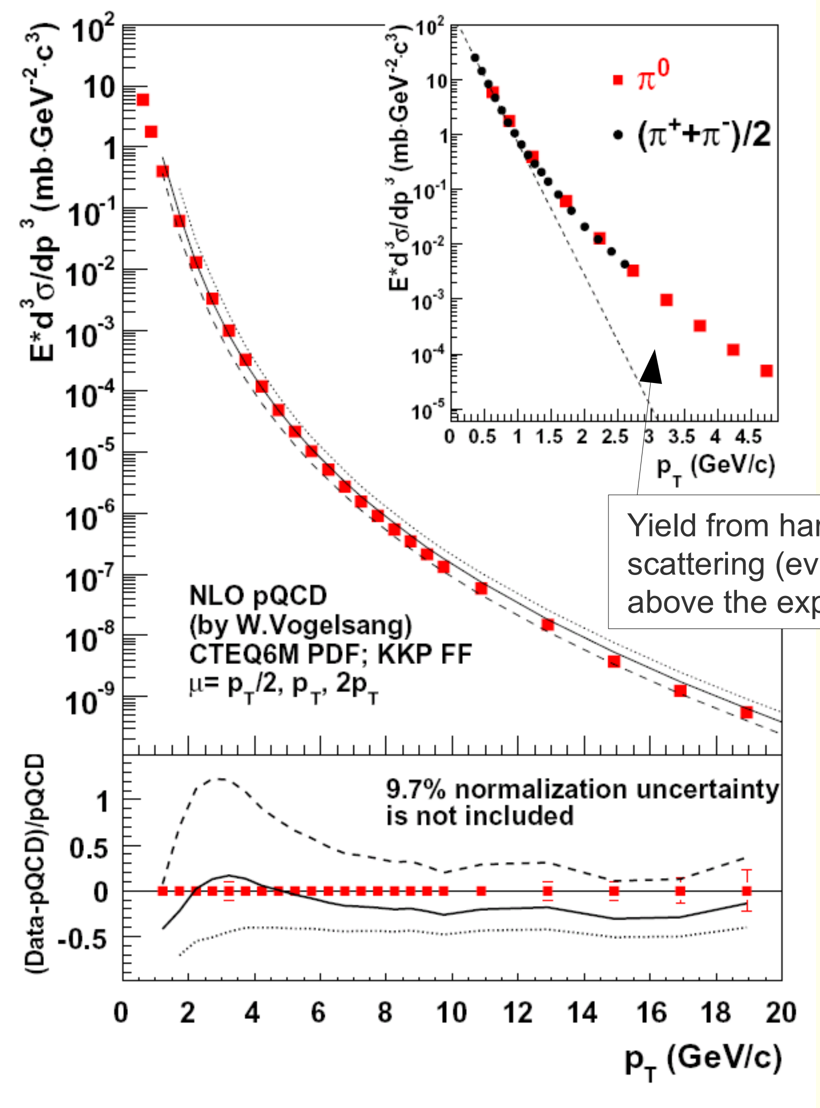
- QGP at RHIC and LHC is close to an ideal fluid (close to KSS bound)
- Elliptic flow coefficient v_2 sensitive to viscosity of the QGP (viscosity reduces v_2)
- Largest systematic uncertainty in the extraction of η/s is the unknown initial eccentricity ($\varepsilon_{\mathrm{CGC}} > \varepsilon_{\mathrm{Glauber}}$)
- Similar η/s for RHIC and LHC
- Upper limit from data/theory comparison (ca. 2009):

$$\eta/s < 5 \times \left.\frac{\eta}{s}\right|_{\mathrm{KSS}} = 5 \times \frac{1}{4\pi}$$

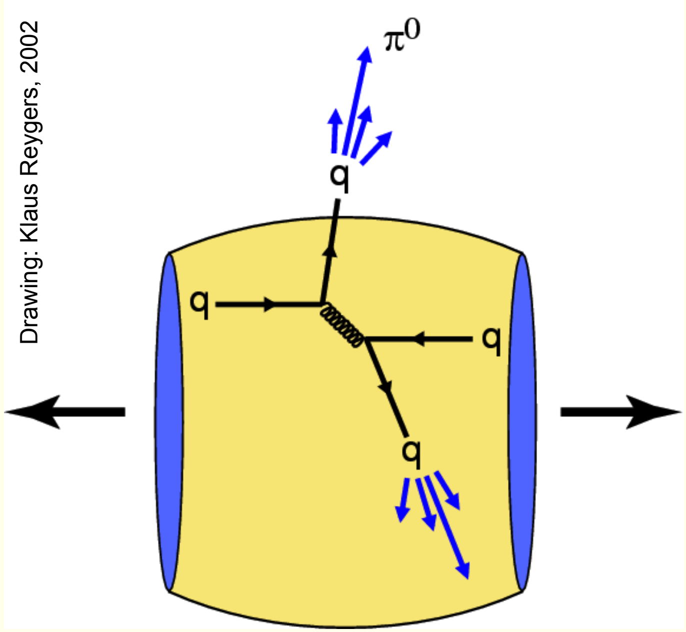
- At Quark Matter 2011 somewhat tighter bounds of $\eta/s < 3/(4\pi)$ were reported

7 Jet Quenching

Hard Scattering



Yield from hard scattering (everything above the exponential)

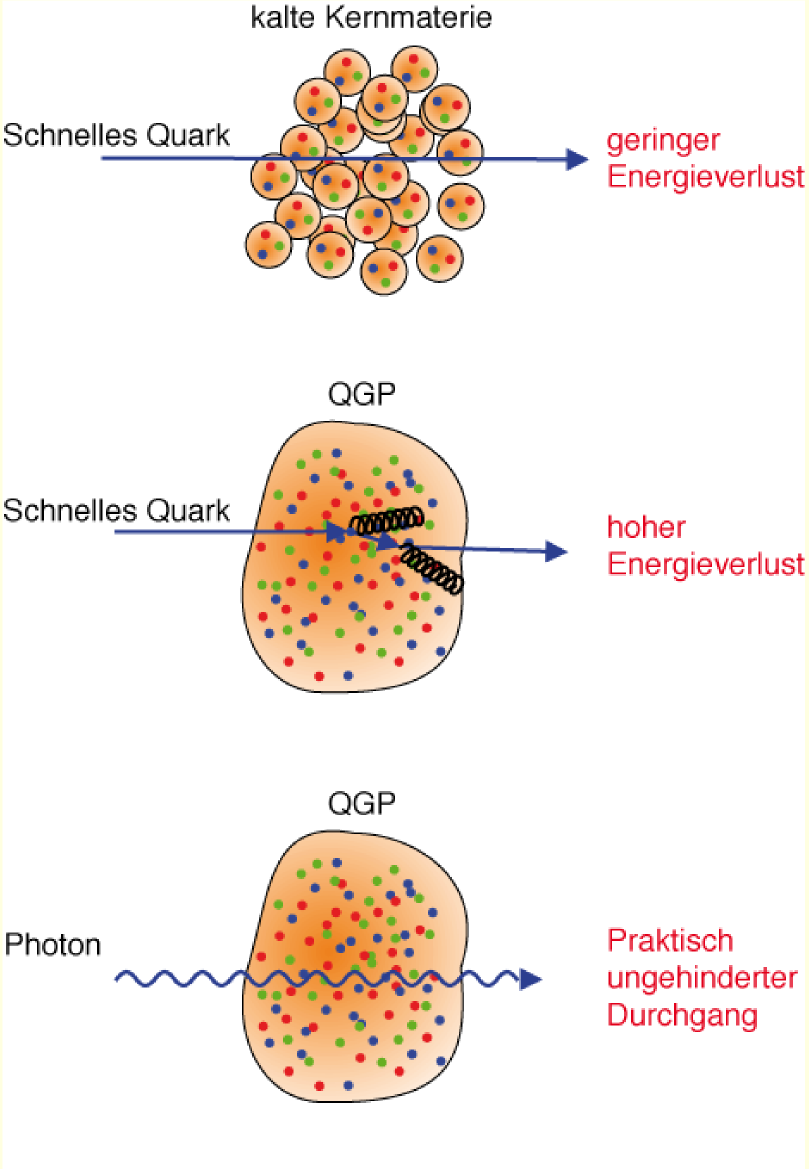


Drawing: Klaus Reygers, 2002

More than 99% of all particles (the bulk) have transverse momenta less than 2 GeV/c.

High-p_T particles in A+A can be used as a probe of the created medium

Jet Quenching: Basic Idea



Expectation:
Simple scaling from
p+p to p+A
(no suppression)

Expectation:
Pion suppression in A+A

Expectation:
Simple scaling from
p+p to A+A for direct photons
(no suppression)

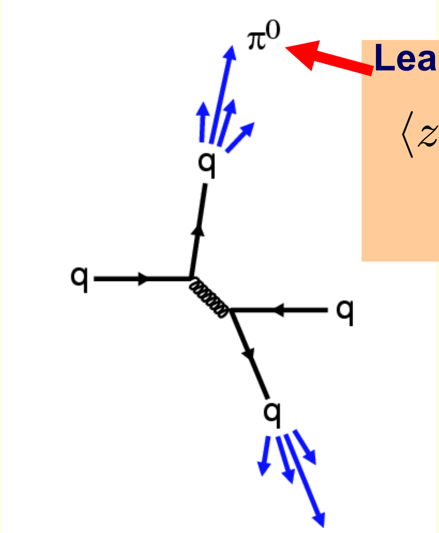
What Can We Hope to Learn from Particles at High p_T and Jets?

- In heavy-ion physics, particles at high p_T and jets are of great interest because
  - they are produced in the early stage of a heavy-ion collisions, prior to the formation of the quark-gluon plasma
  - their initial production rate can be calculated with perturbative QCD

- Observables related to jet quenching may help to
  - characterize the new state of matter above T_c
  - understand the mechanism of parton energy loss

Theoretical Description of High-p_T Particle Production: Perturbative QCD

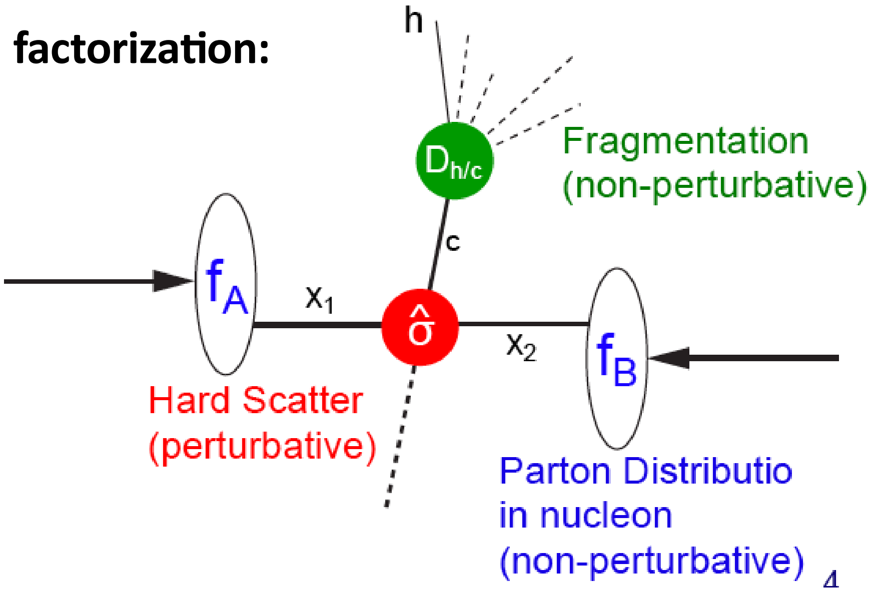
- Scattering of pointlike partons described by QCD perturbation theory (pQCD)
- Soft processes described by universal, phenomenological functions
  - Parton distribution function from deep inelastic scattering
  - Fragmentation functions from e^+e^- collisions



Leading hadron:

$$\langle z \rangle = \langle \frac{p_{\text{hadron}}}{p_{\text{parton}}} \rangle \approx 0.25$$

factorization:



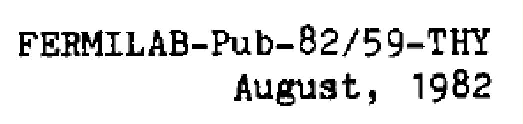
Fragmentation (non-perturbative)

Hard Scatter (perturbative)

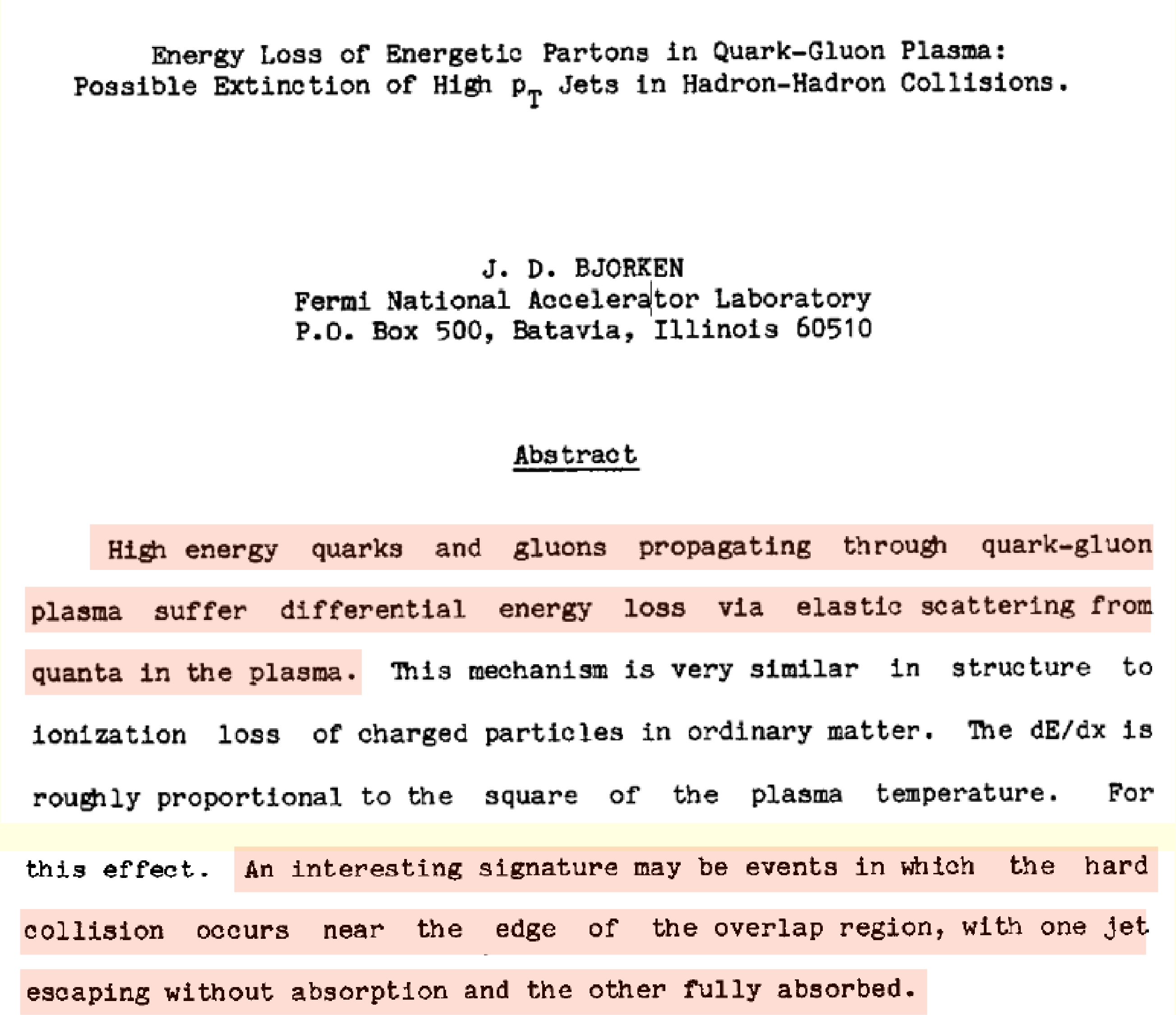
Parton Distributio in nucleon (non-perturbative)

$$d\sigma = \sum_{a,b,c} f_a \otimes f_b \otimes d\hat{\sigma}^{c}_{ab} \otimes D_c^{Hadron}$$

Jet Quenching History



FERMILAB-Pub-82/59-THY
August, 1982



Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

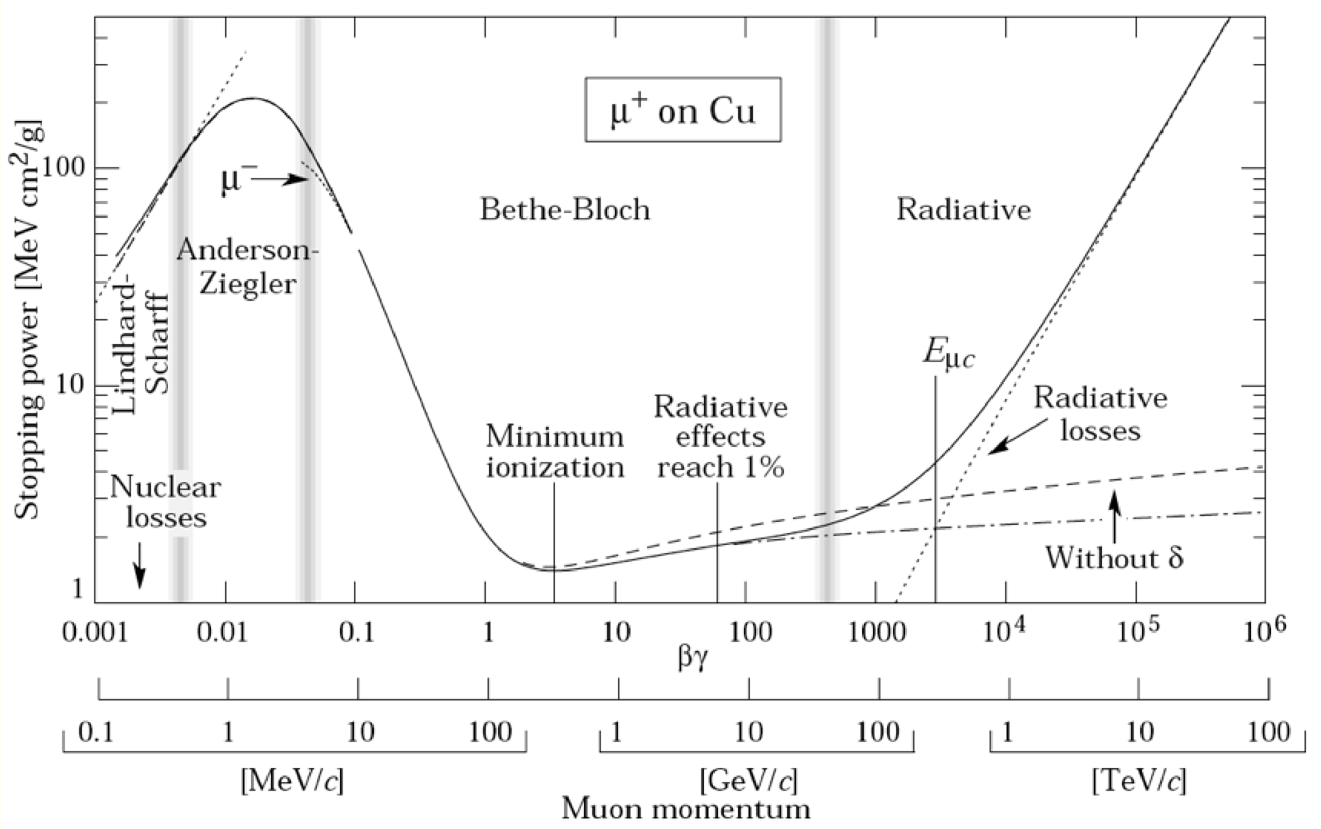
Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For

this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

- Energy loss via elastic scattering was later believed to have only a minor effect on jets
- Radiative energy loss was discussed in the literature from 1992 on by Gyulassy, Pluemer, Wang, Baier, Dokshitzer, Mueller, Peigne, Schiff, Levai, Vitev, Zhakarov, Wang, Salgado, Wiedemann, …

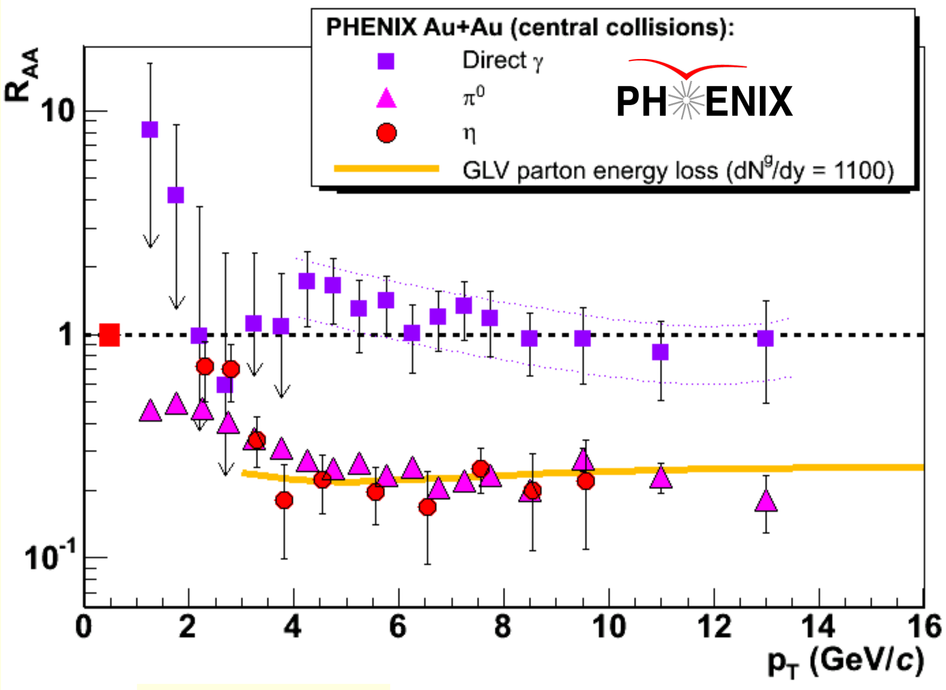
Analogy:
Energy loss of Charged Particles in Normal Matter



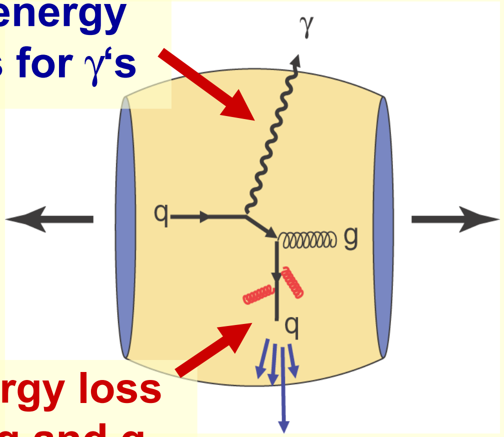
- μ^+ on Cu: Radiational energy loss („bremsstrahlung“) starts to dominate over collisional energy loss („Bethe-Bloch formula“) for *p* >> 100 GeV/c
- For energetic quarks and gluons in QCD matter, radiative energy loss via induced gluon emission is/was expected to be the dominant process

The Discovery of Jet Quenching at RHIC

Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (I)



No energy loss for γ's



energy loss for q and g

$$R_{AB} = \frac{\mathrm{d}N/\mathrm{d}p_T|_{\mathrm{A+B}}}{\langle T_{\mathrm{AB}}\rangle \times \mathrm{d}\sigma_{\mathrm{inv}}/\mathrm{d}p_{\mathrm{T}}|_{\mathrm{p+p}}},$$

$$\text{where} \quad \langle T_{\mathrm{AB}}\rangle = \langle N_{\mathrm{coll}}\rangle / \sigma_{\mathrm{inel}}^{\mathrm{NN}}$$

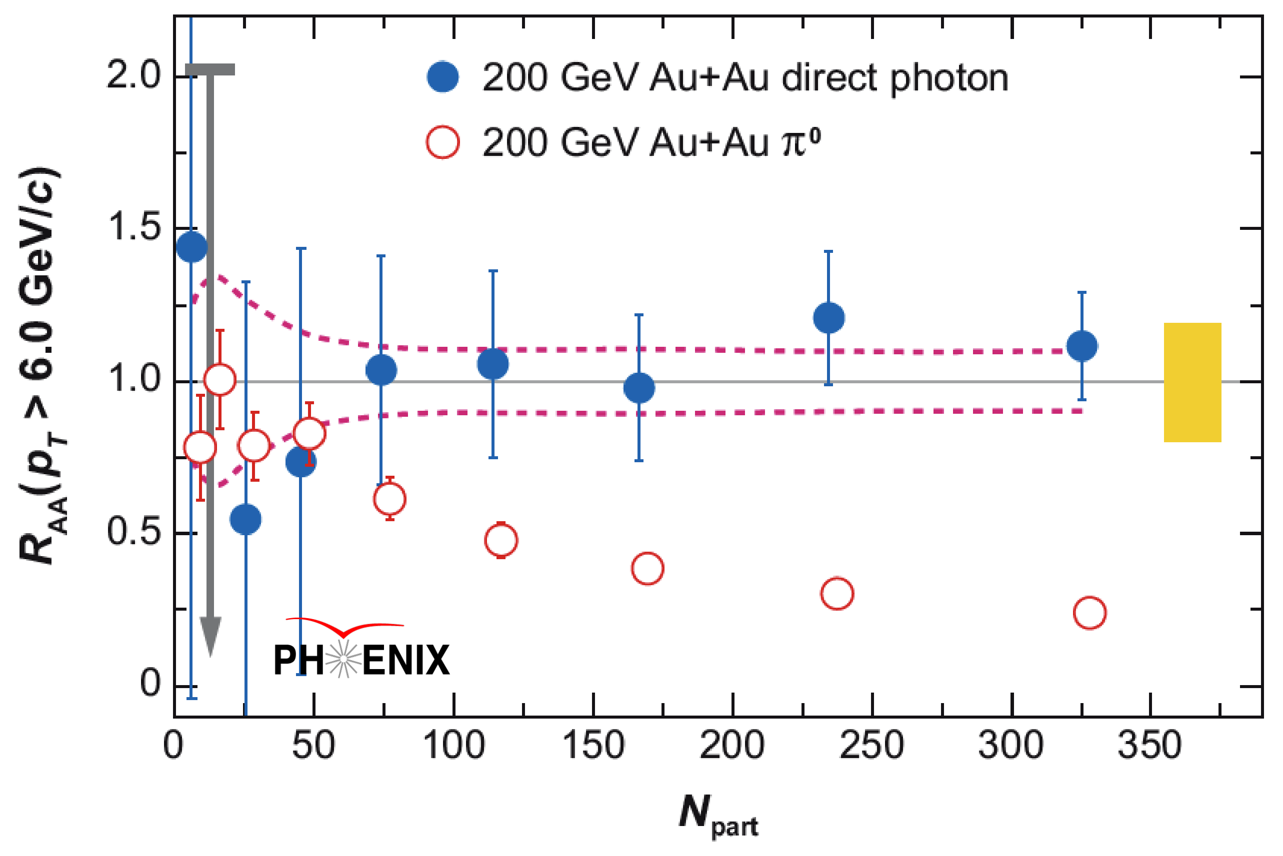
- Hadrons are suppressed, direct photons are not
- No suppression in d+Au (see slide 22)
- Evidence for parton energy loss

PHENIX: Phys.Rev.Lett.88:022301, 2002
PHENIX: Phys.Rev.Lett.91:072301, 2003
PHENIX: Phys.Rev.Lett.94:232301, 2005

STAR: Phys.Rev.Lett.89:202301,2002
STAR: Phys.Rev.Lett.90:082302,2003
STAR: Phys.Rev.Lett.91:172302,2003

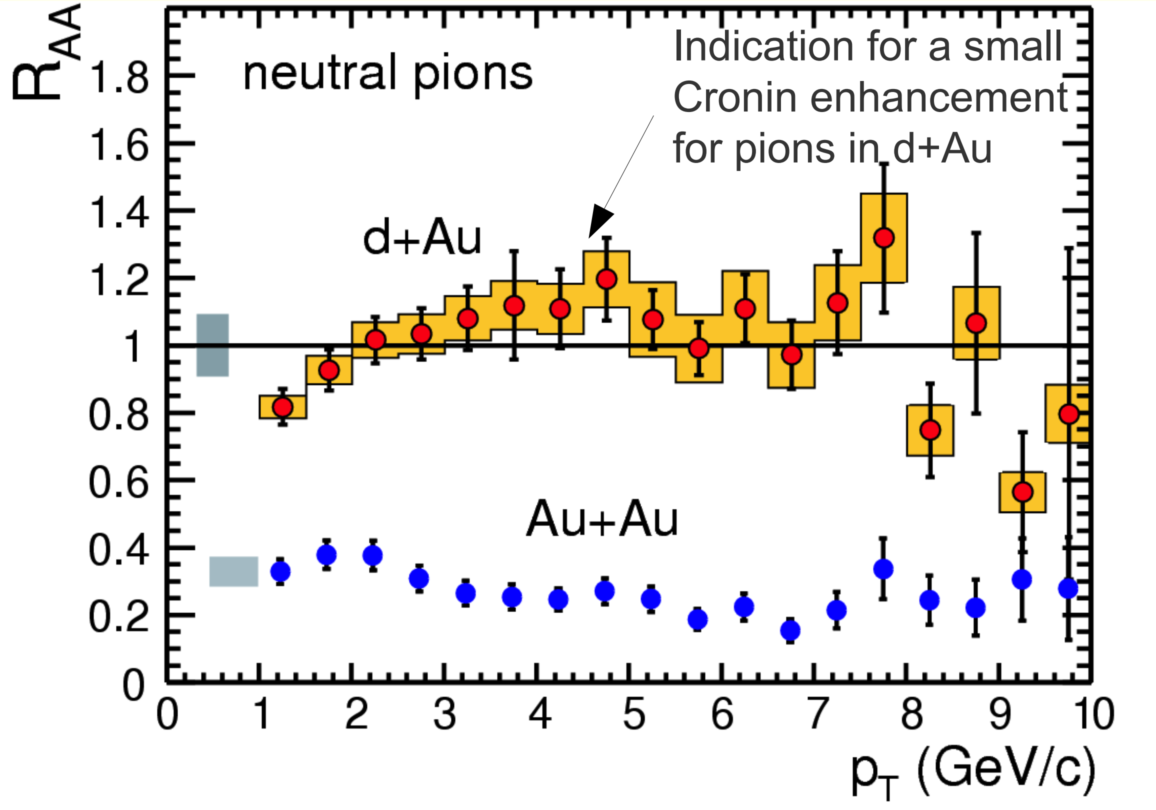
Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (II)

Centrality Dependence of the π^0 and direct γ R_{AA}:

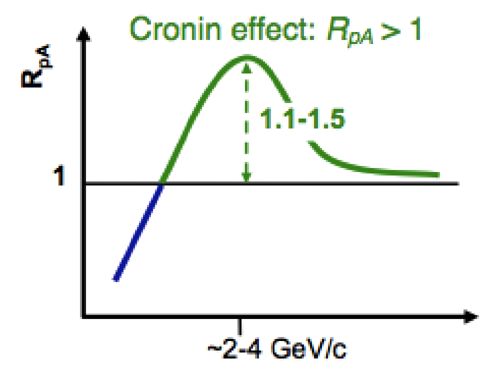


Direct photons follow T_{AB} scaling as expected for a hard probe not affected by the medium

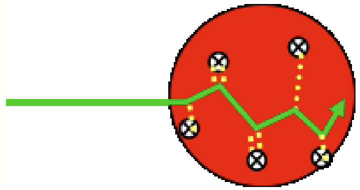
Discovery of Jet Quenching at RHIC (ca. 2000 - 2003) (III)



Indication for a small Cronin enhancement for pions in d+Au



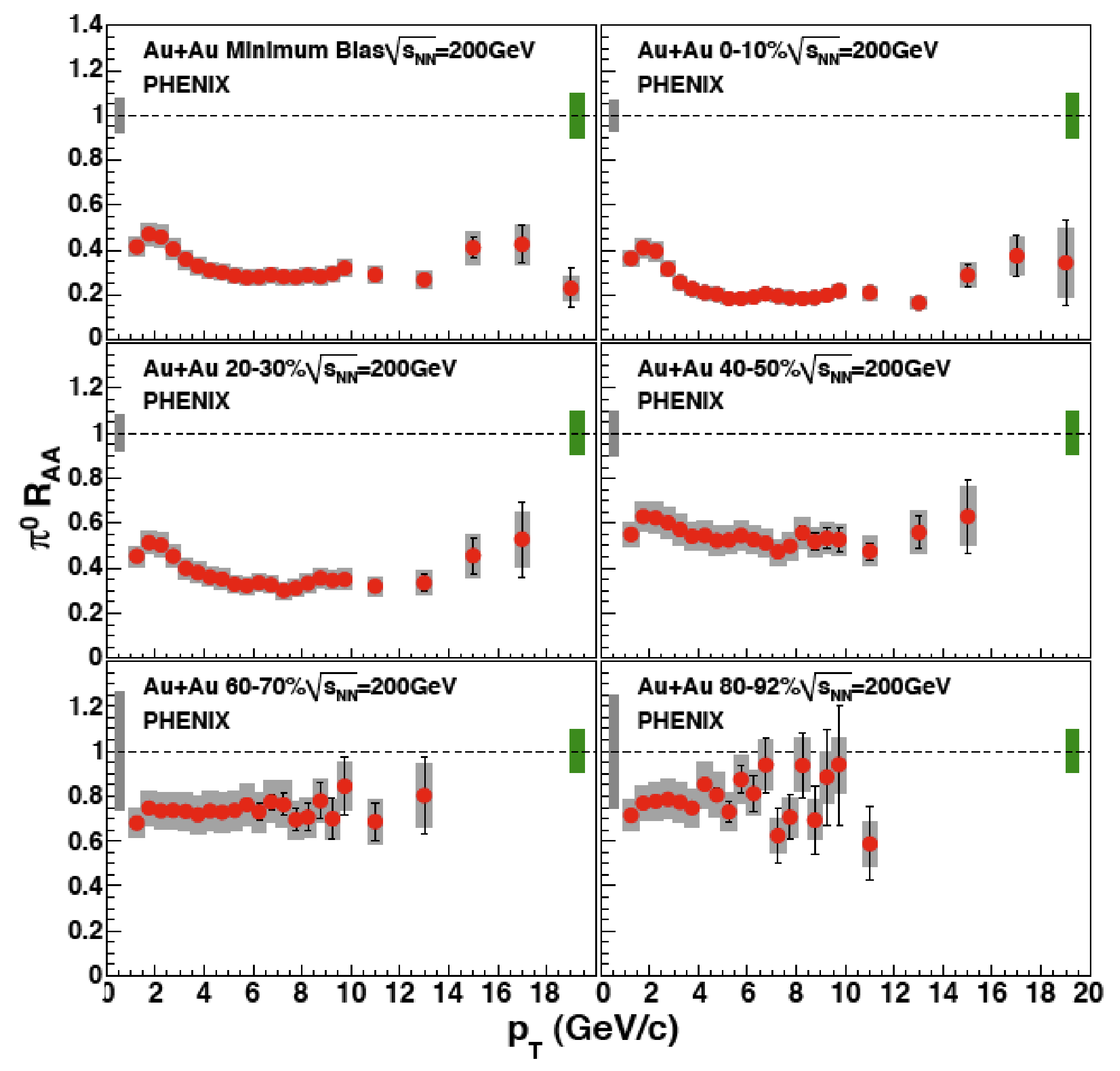
Likely explanation for the Cronin effect: multiple soft scattering in the initial state



No pion suppression in min. bias d+Au collisions
⇒ pion suppression is a final state effect caused by the created medium

π^0 R_{AA} with Higher Statistics (Run 4)

Phys. Rev. Lett. 101, 232301 (2008)



$$R_{AB} = \frac{dN/dp_T|_{A+B}}{\langle T_{AB}\rangle \times d\sigma_{inv}/dp_T|_{p+p}},$$

$$\text{where} \quad \langle T_{AB}\rangle = \langle N_{coll}\rangle / \sigma_{inel}^{NN}$$

Simple Interpretation of the Constant R_{AA}

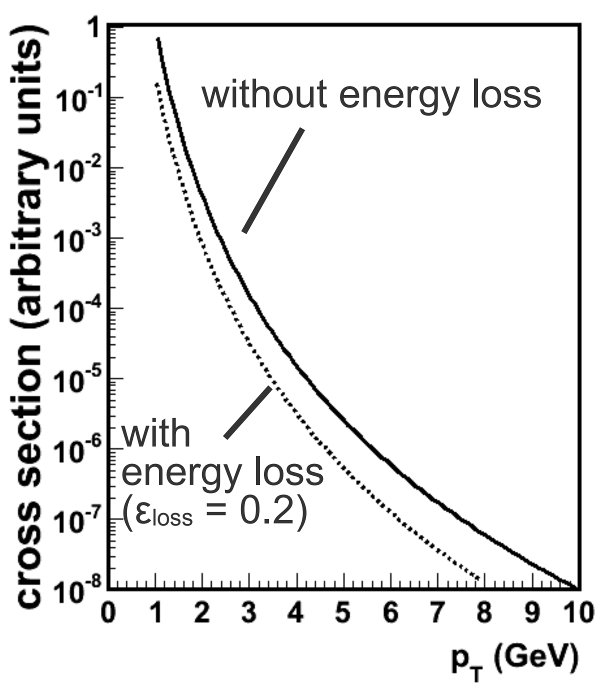
π^0 spectrum without energy loss: $$\frac{1}{p_T}\frac{dN}{dp_T} \propto \frac{1}{p_T^n}$$

π^0 spectra at RHIC energy ($\sqrt{s_{NN}}$ = 200 GeV) described with $n \approx 8$

Constant fractional energy loss:

$$\varepsilon_\text{loss} := -\frac{\Delta p_T}{p_T} \text{ , i.e., } p'_T = (1-\varepsilon_\text{loss})p_T$$

(However, QCD expectation is $\varepsilon_\text{loss} \sim \log(p_T)/p_T$)



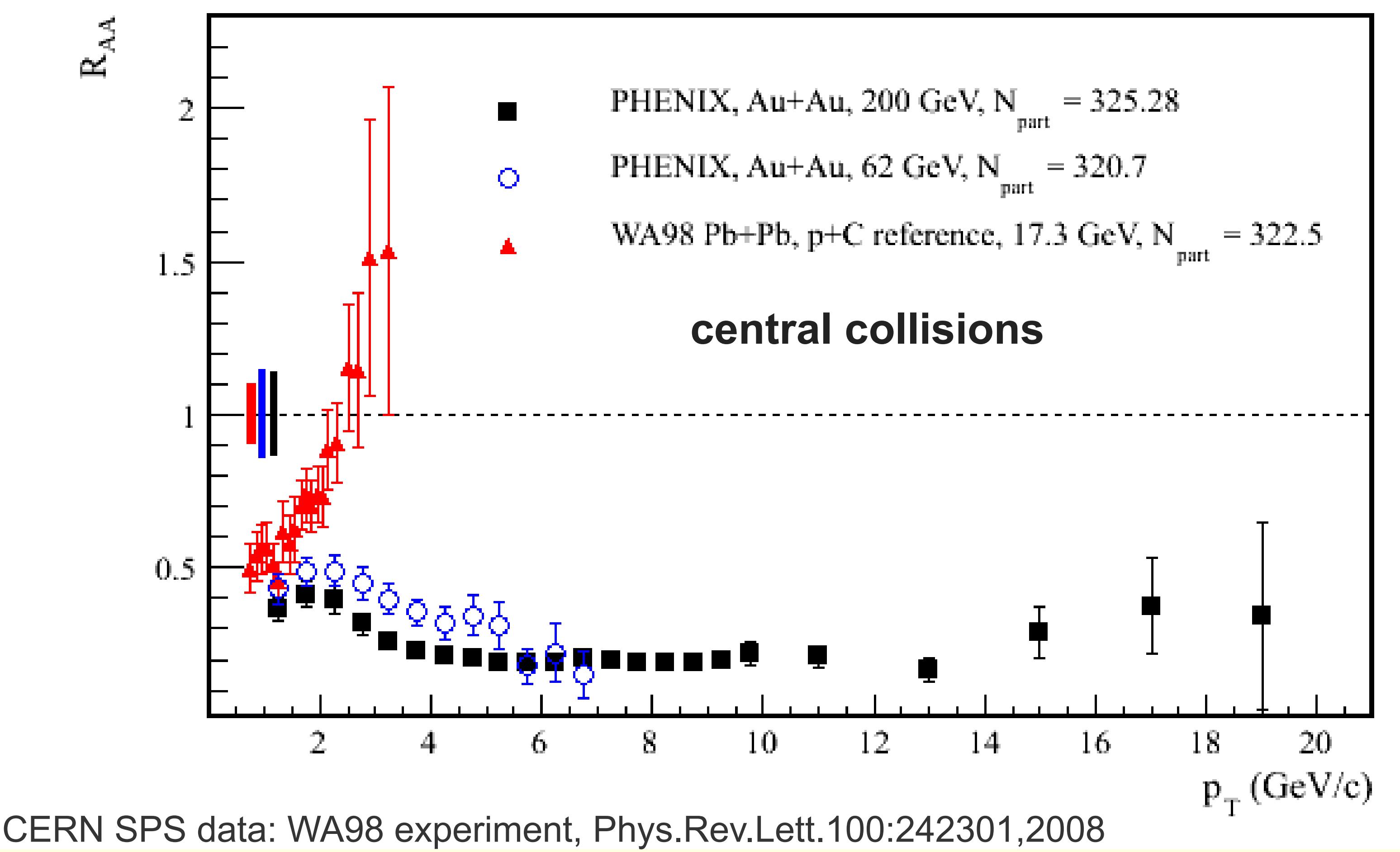
This leads to:

$$R_{AA} = (1-\varepsilon_\text{loss})^{n-2} \quad \Rightarrow \quad \varepsilon_\text{loss} = 1 - R_{AA}^{1/(n-2)} \approx 0.2 \text{ for } R_{AA} \approx 0.25$$

R_{AA} depends on the parton energy loss *and* the shape of the p_T spectrum

In this simplistic view the constant $R_{AA} \approx 0.25$ implies a constant fractional energy loss of about 20% in central Au+Au collisions at 200 GeV

$\sqrt{s_{NN}}$ Dependence: π^0 R_{AA} for Heavy Nuclei at $\sqrt{s_{NN}}$ = 17.3, 62.4, and 200 GeV

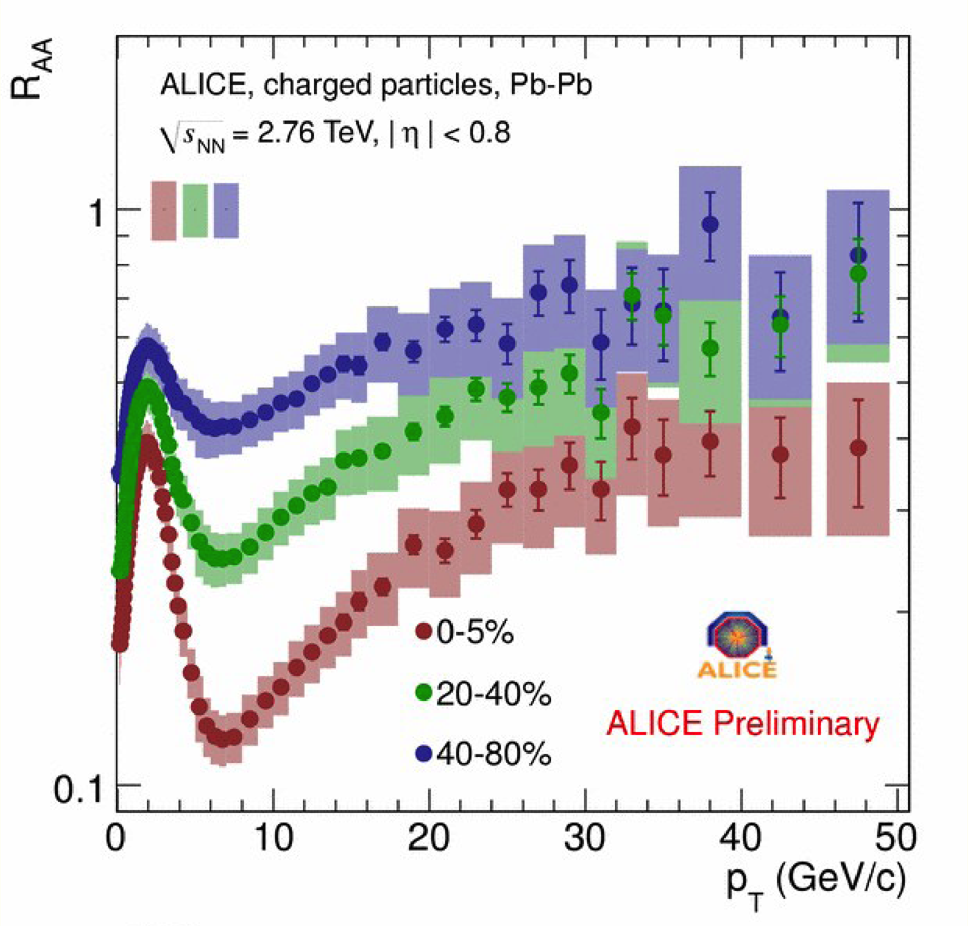


CERN SPS data: WA98 experiment, Phys.Rev.Lett.100:242301,2008

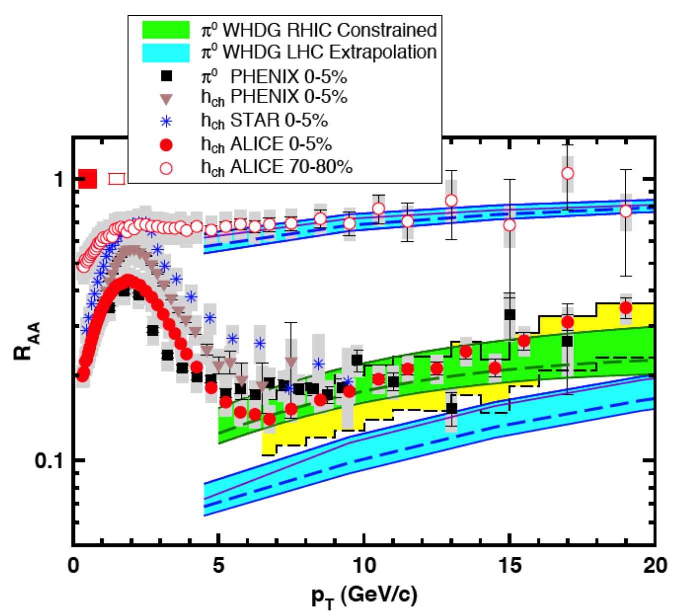
Onset of suppression between $\sqrt{s_{NN}}$ = ~ 20 GeV and 62.4 GeV

Results from the LHC: 1. Spectra

R_{AA} for Charged Particles in Pb+Pb at $\sqrt{s}_{NN}$ = 2.76 TeV



ALI-PREL-10239

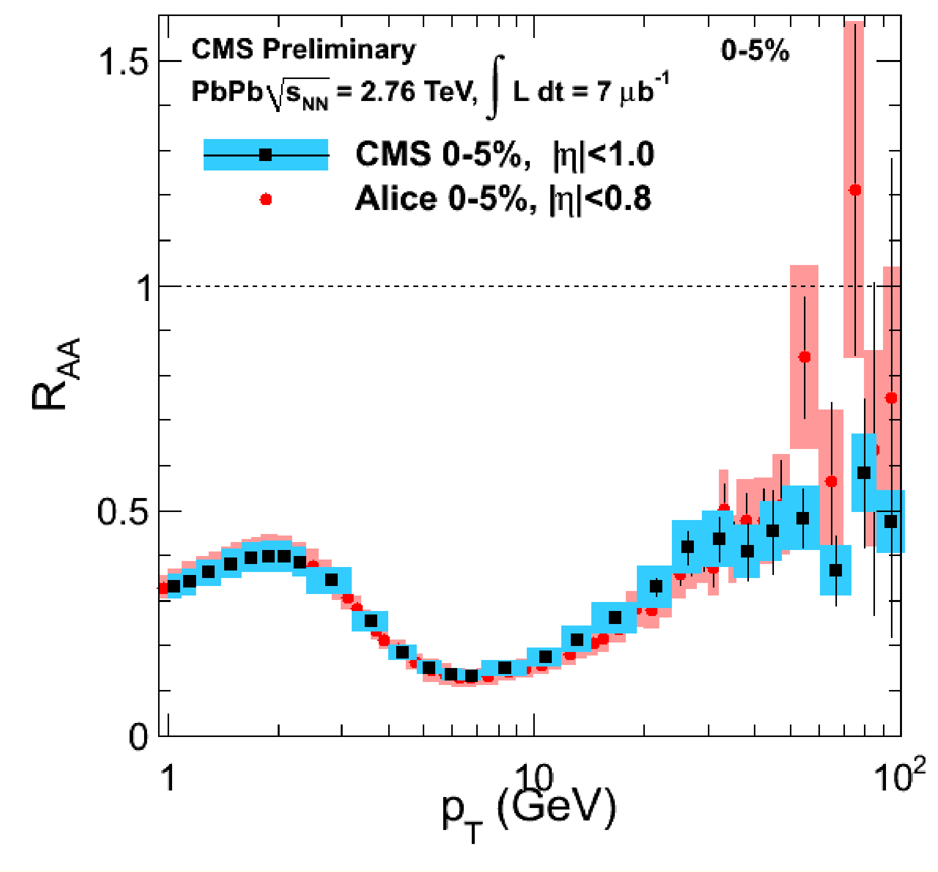


Horowitz, Gyulassy, arXiv:1104.4958

Data test density dependence of light quark and gluon energy loss: $dN_{ch}/d\eta_{PbPb@2.76TeV} \approx 2\ dN_{ch}/d\eta_{AuAu@0.2TeV}$

The relatively small difference between R_{AA} at RHIC and LHC is a challenge to theory

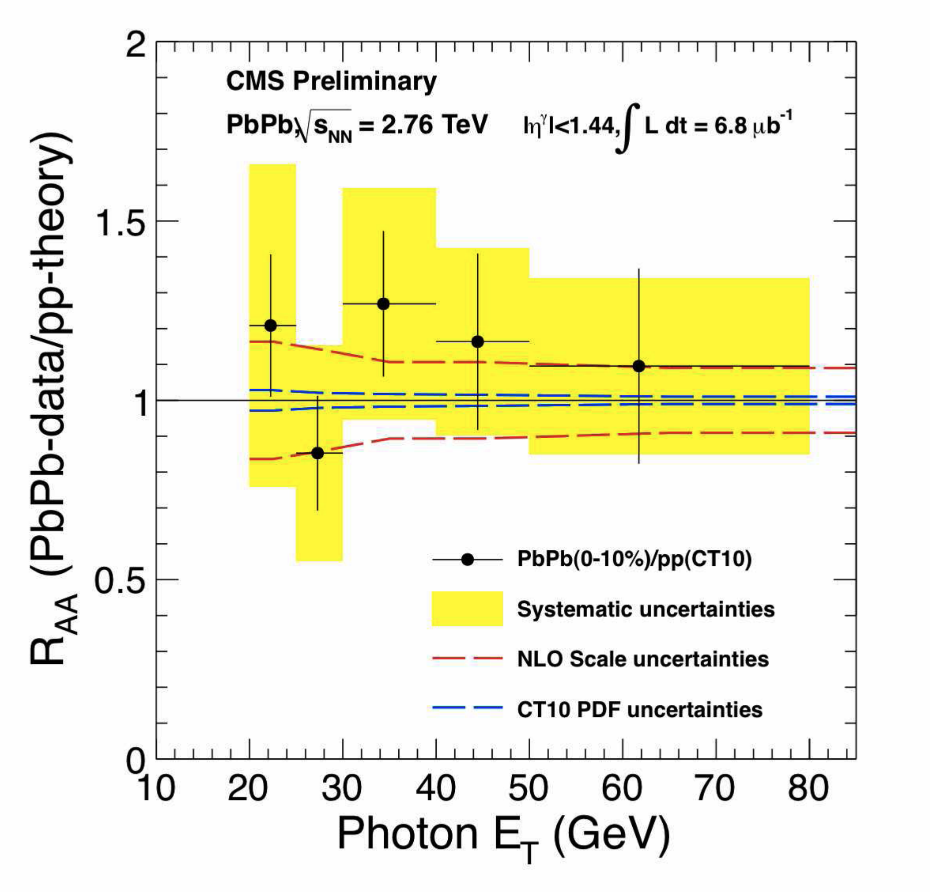
R_{AA} for Charged Particles up to p_T = 100 GeV/*c*

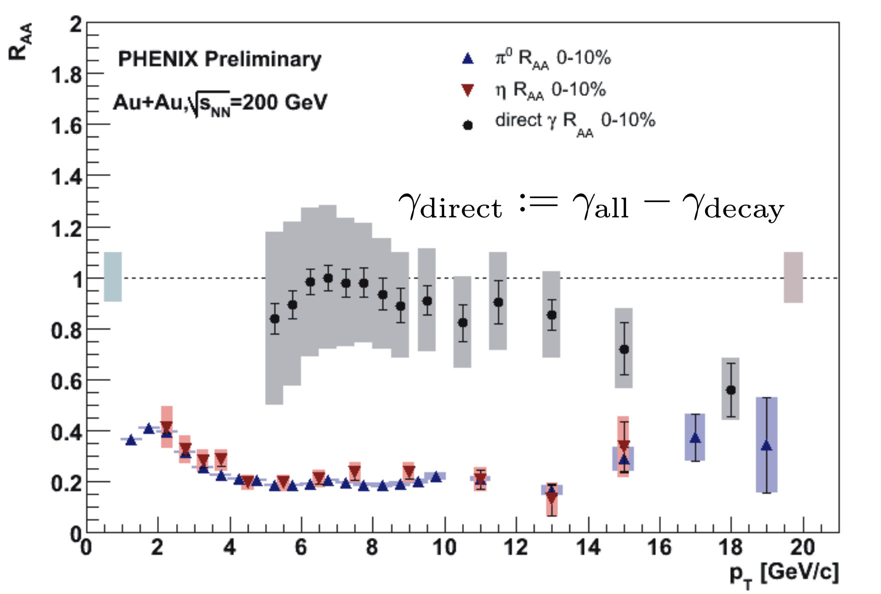


R_{AA} rises with p_T up to $R_{AA} \approx 0.5$.

The increase of R_{AA} is consistent with the expected $p_{T,f}/p_{T,i} \sim \log(p_T)/p_T$

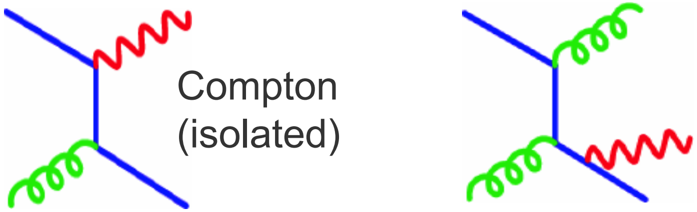
Verification of T_{AB} Scaling with Hard Photons



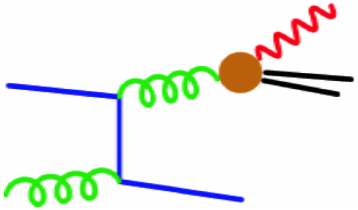


$$\gamma_{\text{direct}} := \gamma_{\text{all}} - \gamma_{\text{decay}}$$

R_{AA} ≈ 1 for isolated photons (CMS) verifies the expected T_{AB} (or N_{coll}) scaling for hard processes

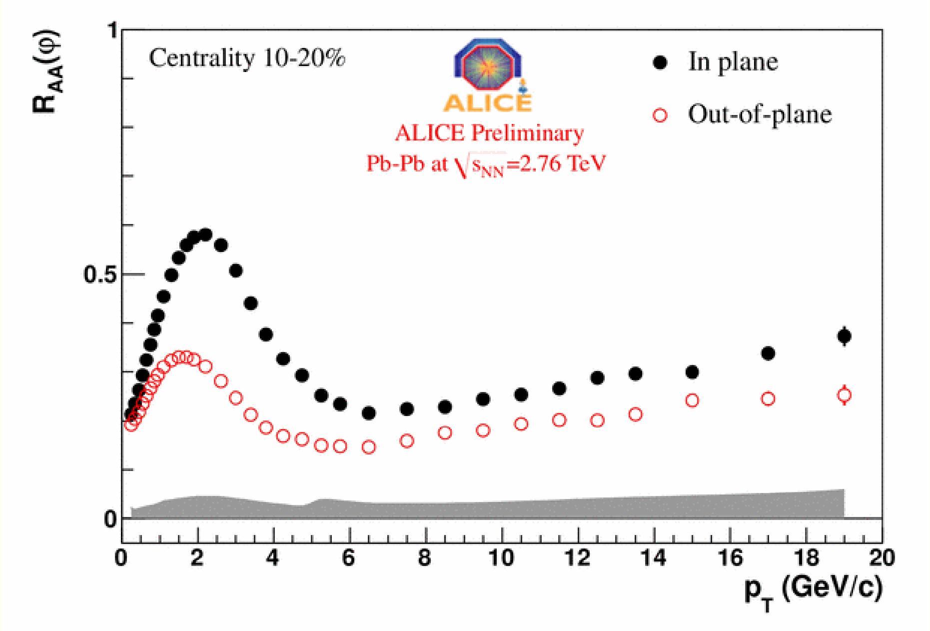


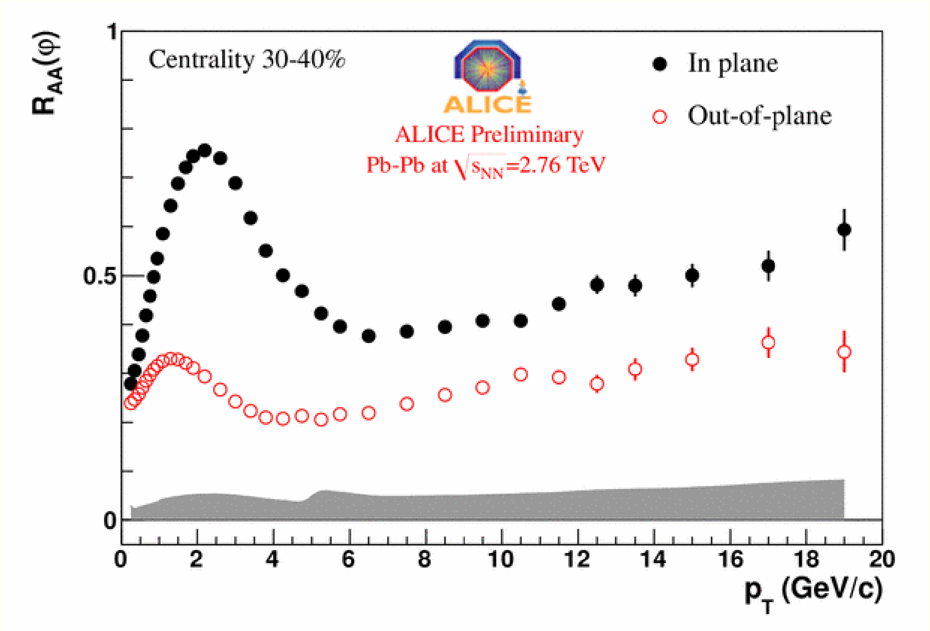
Compton
(isolated)

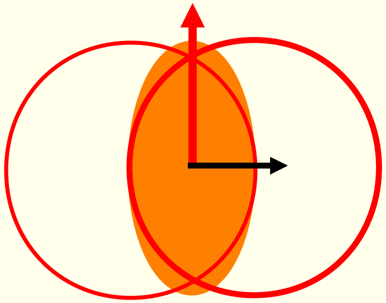


bremsstrahlung, fragmentation
(not isolated)

Reaction Plane Dependence of R_{AA}







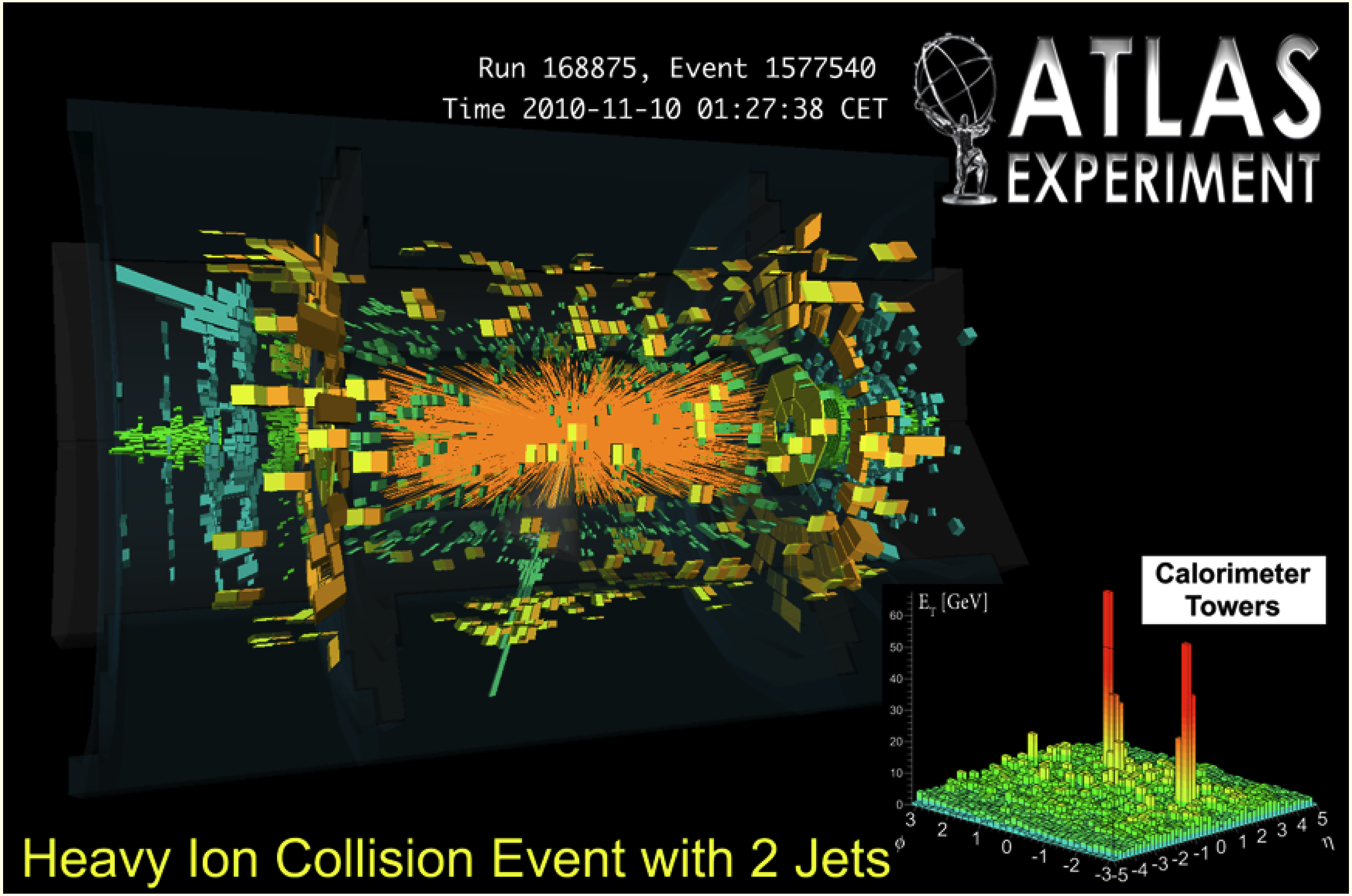
in plane
out-of-plane

The reaction plane dependence of R_{AA} constrains the path length dependence of parton energy loss

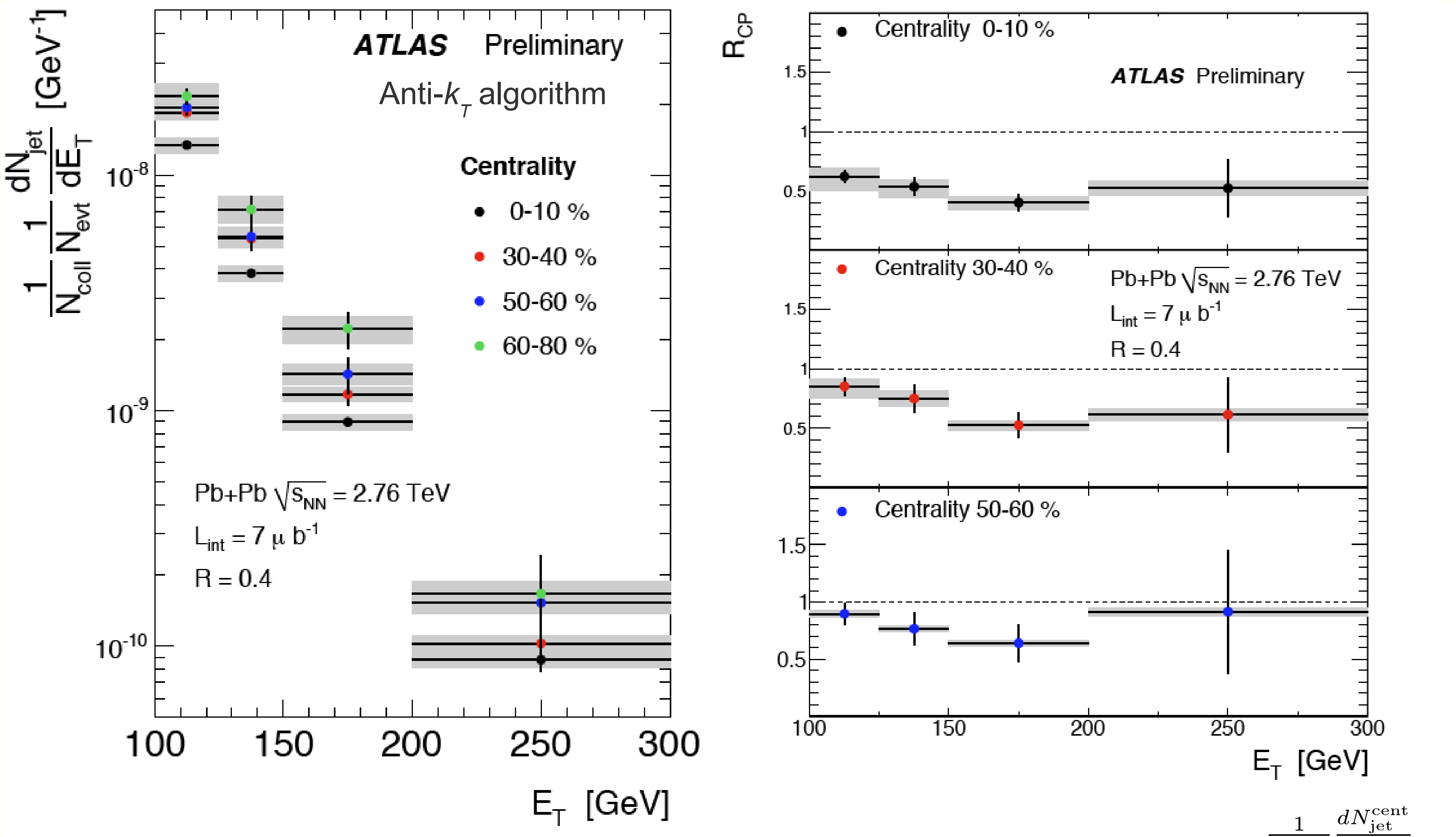
The reaction plane dependence of R_{AA} at RHIC poses a problem to perturbative energy loss models (PHENIX, Phys.Rev.Lett.105:142301,2010)

Results from the LHC: 2. Jets

Two-Jet Event in Pb+Pb at $\sqrt{s}_{NN}$ = 2.76 TeV (ATLAS)



Jet-E_T Spectrum and Jet R_{AA} in Pb+Pb at $\sqrt{s_{NN}}$ = 2.76 TeV



$$R_{CP} = \frac{\frac{1}{N_{\mathrm{coll}}^{\mathrm{cent}}} \frac{dN_{\mathrm{jet}}^{\mathrm{cent}}}{dE_T}}{\frac{1}{N_{\mathrm{coll}}^{60-80\%}} \frac{dN_{\mathrm{jet}}^{60-80\%}}{dE_T}}$$

Jet R_{CP} ≈ 0.5 in central Pb+Pb (R = 0.4)

Points to Take Home

- High-p_T particles can be regarded as a probe of the medium created in heavy-ion collisions
- The suppression of high-p_T particles in A+A collisions can be described by parton energy loss in a medium of high color charge density
- Many open issues in parton energy loss theory:
    - Reaction plane dependence of R_{AA}
    - Heavy-quark energy loss
    - Similar R_{AA} at RHIC and LHC
    - ...
- Full jet reconstruction is challenging at RHIC due to large backgrounds
- The increased jet cross section allows to study parton energy loss in Pb+Pb collisions with full jet reconstruction at the LHC