

Jets in heavy ion collisions

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Fundamental interactions
Searches – Higgs, SUSY, extra-dimensions...

pp @ LHC, LC??



Increase energy density

Fundamental interactions
Searches – Higgs, SUSY, extra-dimensions...

pp @ LHC, LC??

Increase energy density

Increase extended energy density

AA @ RHIC and LHC

Collective properties
of the fundamental interactions

How?

Specific questions in heavy-ion collisions

- ⇒ What is the initial state of the system and how is it produced?
 - ↪ What is the structure of the colliding objects?
 - ↪ What is the asymptotic limit of QCD?
- ⇒ What is the mechanism of thermalization?
 - ↪ How is thermal equilibrium reached?
 - ↪ What is the temperature of the created system?
- ⇒ What are the properties of the produced medium?
 - ↪ How to measured them? – signals
 - ↪ What is the relation with lattice QCD?

Hard Probes

Provide a general framework
to answer these questions

Hard probes: heavy ion experiments

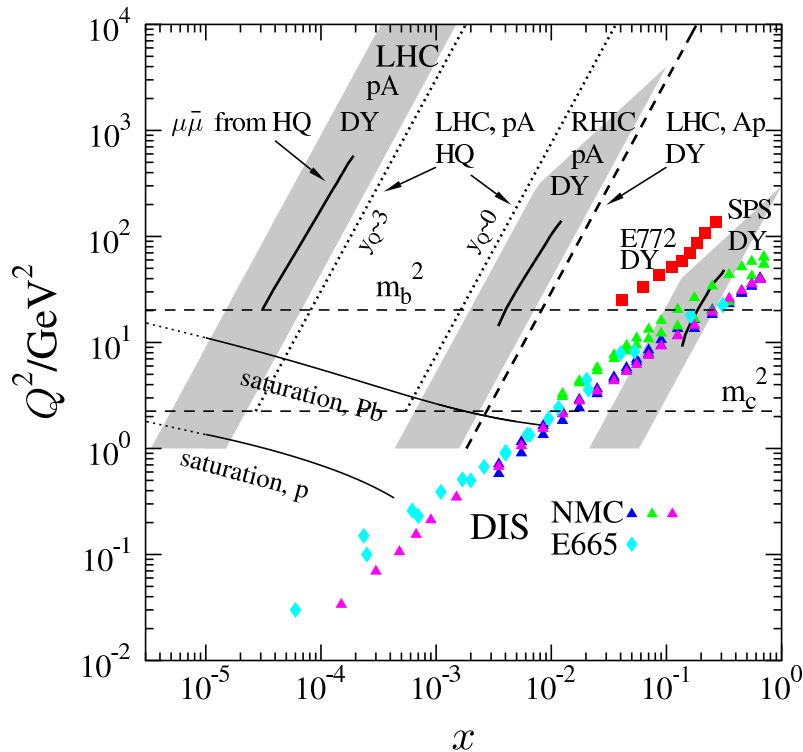
- ⇒ SPS $\sqrt{s} = 20$ GeV ($Q \sim 1$ GeV) → marginal access to HP
- ⇒ RHIC $\sqrt{s} = 200$ GeV ($Q \sim 10$ GeV) → access to HP
- ⇒ LHC $\sqrt{s} = 5500$ GeV ($Q \gtrsim 100$ GeV) → HP and QCD evolution

$$\sigma^{pp \rightarrow h} = f_p(x_1, Q^2) \otimes f_p(x_2, Q^2) \otimes \underbrace{\sigma(x_1, x_2, Q^2)}_{\text{RHIC}} \otimes D(z, Q^2) + \left(\frac{1}{Q^2}\right)^n$$

The diagram illustrates the mapping of experimental facilities to the components of the cross-section formula. Red arrows point from 'LHC' to the first two $f_p(x, Q^2)$ terms, from 'RHIC' to the $\sigma(x_1, x_2, Q^2)$ term, and from 'SPS' to the $\left(\frac{1}{Q^2}\right)^n$ term.

- ⇒ $Q^2 \gg 1 \implies$ short distance pieces not affected by the medium
- ⇒ Modification of long-distance parts $f_p(x, Q^2)$ and $D(z, Q^2)$
 - ↪ new dynamics (evolution eqs.) → properties of the medium.

Kinematical regions studied

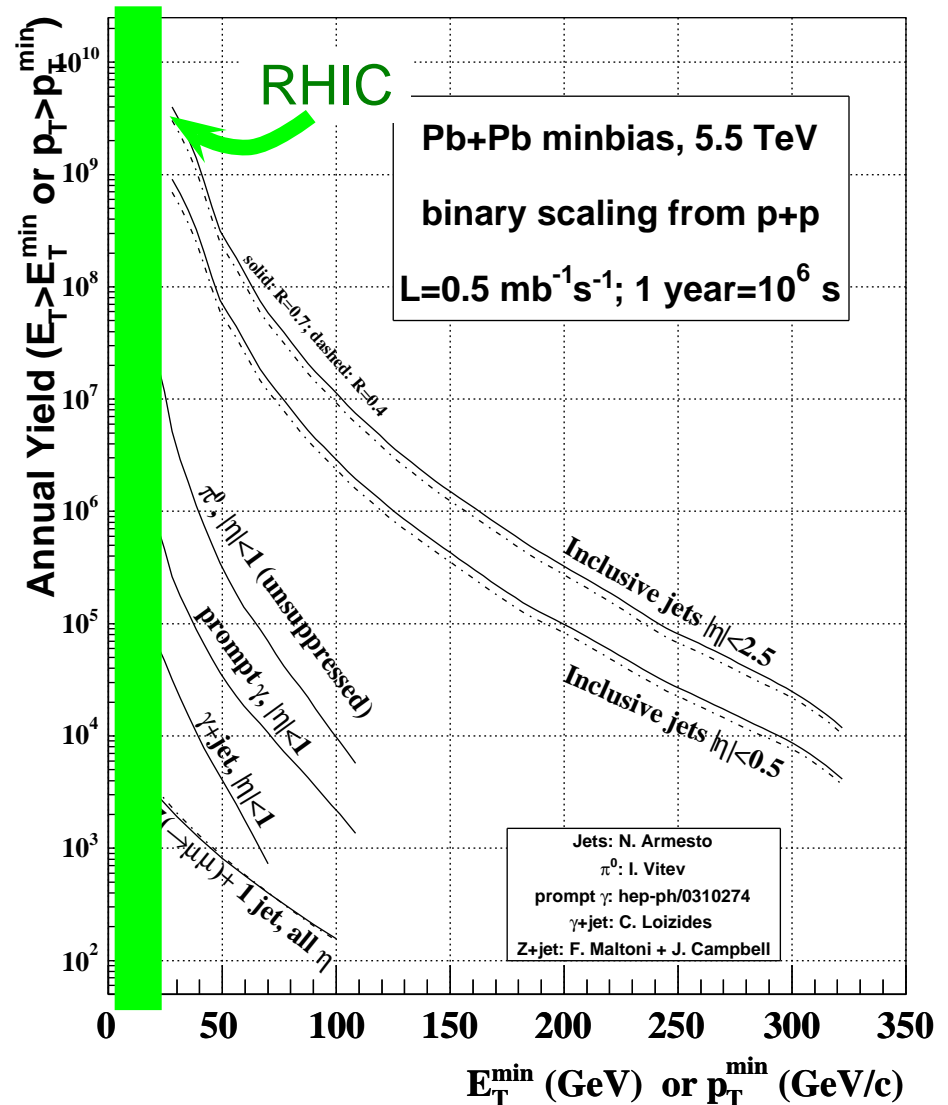


Eskola *et al.* hep-ph/0302170

➔ New regimes at the LHC

➔ In-medium QCD-evolution

Annual hard process yields



P. Jacobs, M. van Leeuwen 2005

Why high- p_t ?

Different scales studied

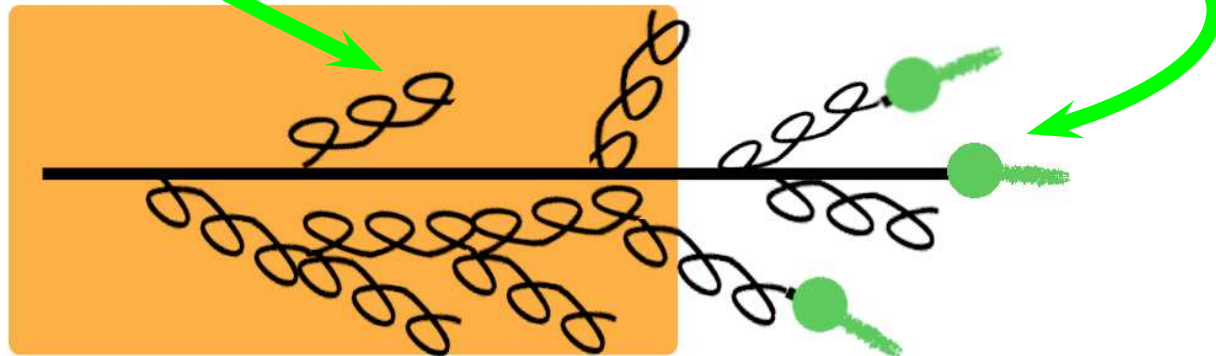
Unique property of jet quenching as a probe of the medium

Radiation formation time

$$t_{\text{form}} \sim \frac{\omega}{k_t^2} \sim \frac{1}{p_t^{\text{assoc}} \sin \theta}$$

Hadronization time

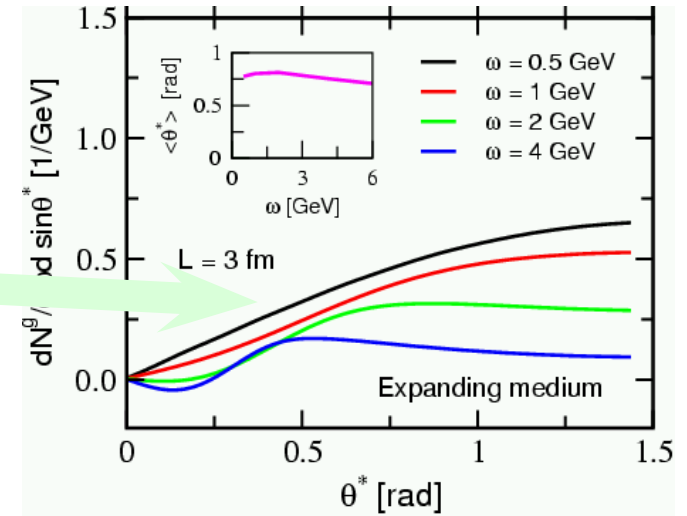
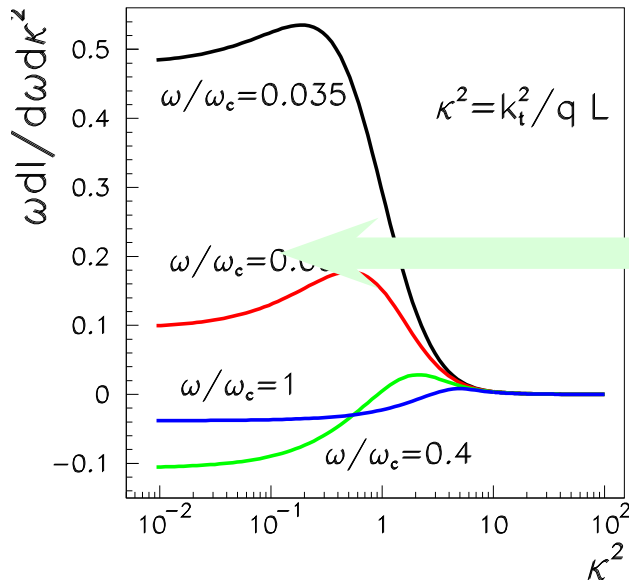
$$t_{\text{had}} \sim \frac{E}{m} R_{\text{had}} \sim \frac{p_t^{\text{lead}}}{m} R_{\text{had}}$$



- ⇒ $t_{\text{form}} \leq L \implies$ shower in a medium
- ⇒ R_{had} not known for a medium
- ⇒ Intermediate $p_t \longrightarrow$ interplay radiation–thermalization–hadronization
- ⇒ Which part of the spectrum is thermalized?

The Medium-induced gluon radiation spectrum

[BDMPS (1996); Zakharov (1997); Wiedemann (2000); GLV (2000)]



Coherence/
Formation time

⇒ Collinear singularity regularized

[Salgado, Wiedemann 2003]

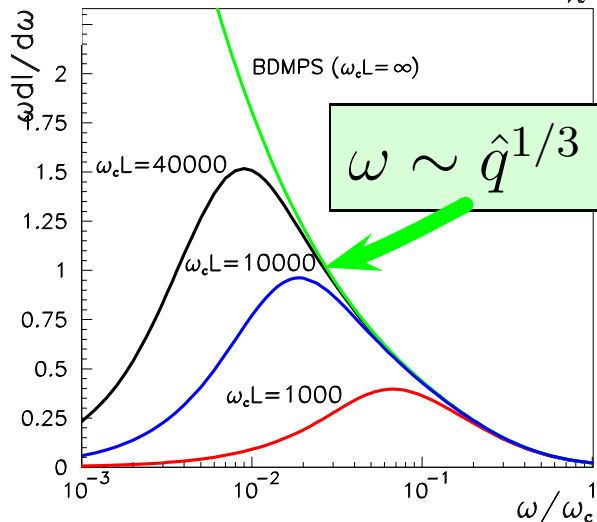
⇒ Spectrum softer than in the vacuum

⇒ Medium: transport coefficient

$$\hat{q} \simeq \frac{\langle k_t^2 \rangle}{\lambda} \propto n(\xi)$$

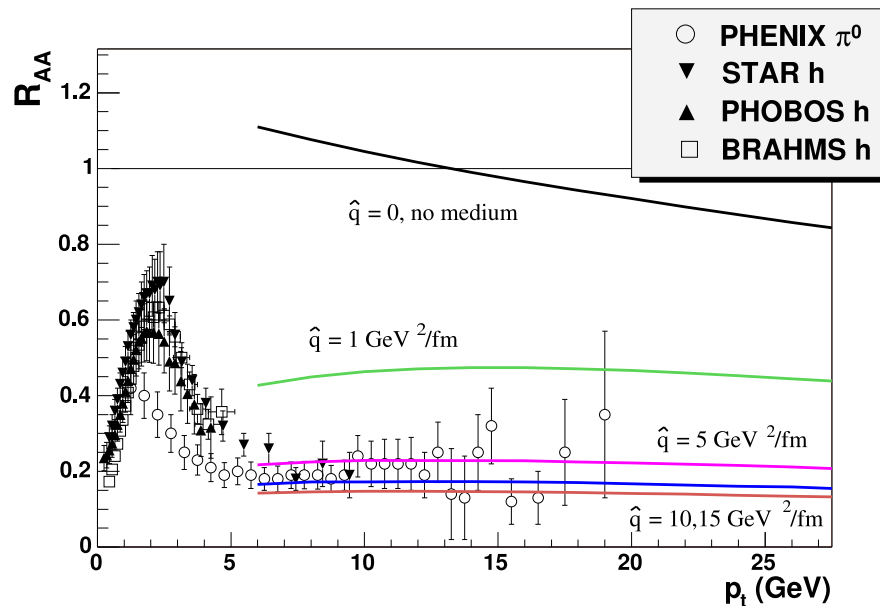
⇒ High- p_t suppression: $\Delta E \sim \alpha_S \hat{q} L^2$

⇒ Jet-broadening: $k_t^2 \sim \Delta E / \alpha_S L$ BDMPS 97

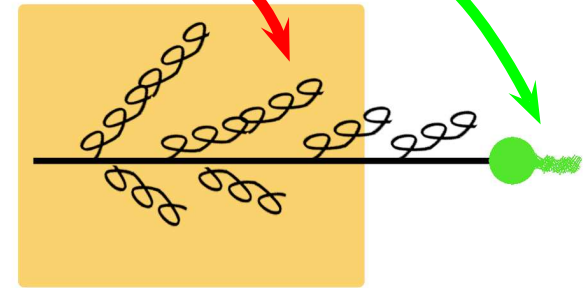


R_{AA} for light mesons at RHIC

$$d\sigma_{(\text{med})}^{AA \rightarrow h+X} = \sum_f d\sigma_{(\text{vac})}^{AA \rightarrow f+X} \otimes P_f(\Delta E, L, \hat{q}) \otimes D_{f \rightarrow h}^{(\text{vac})}(z, \mu_F^2).$$



[Eskola, Honkanen, Salgado, Wiedemann (2004)]



- ⇒ Multiple emission:
Poisson distribution
- ⇒ Hadronization in vacuum
at high- p_t

⇒ Data favors a large time-averaged transport coefficient

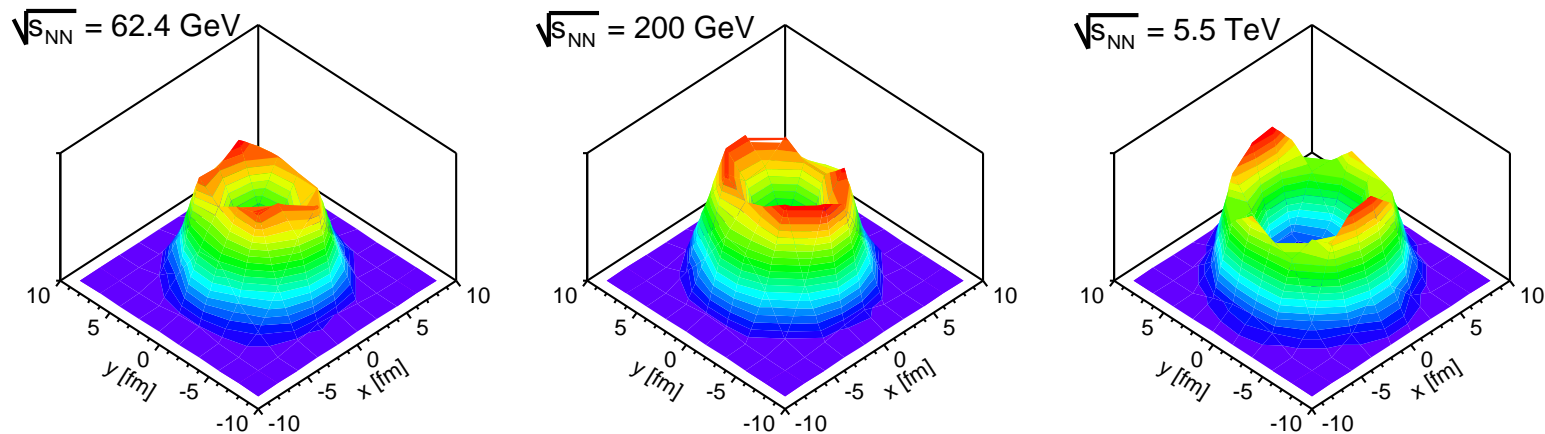
$$\hat{q} \sim 5 \dots 15 \frac{\text{GeV}^2}{\text{fm}}$$

[Gyulassy, Levai, Vitev 2002; Arleo 2002; Dainese, Loizides, Paic 2004; Wang, Wang 2005; Drees, Feng, Jia 2005; Turbide, Gale, Jeon, Moore 2005...]

Surface emission

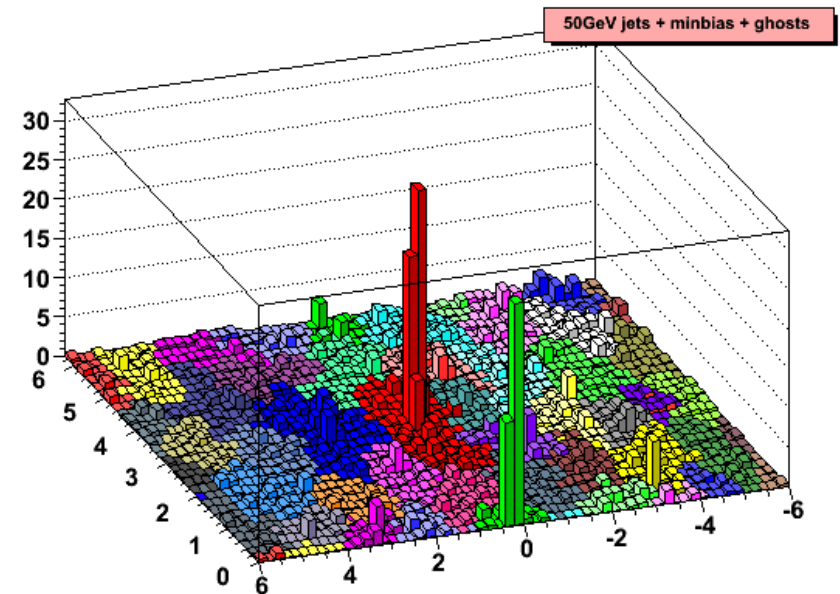
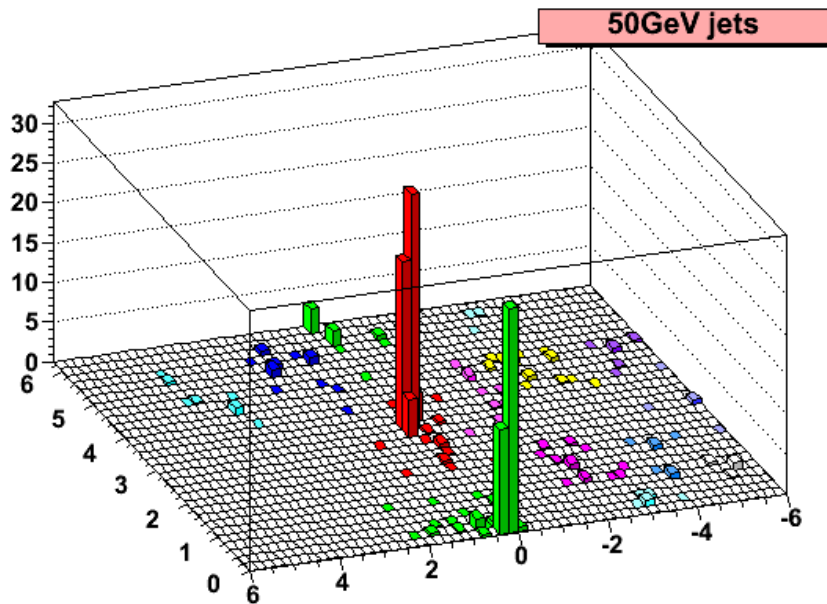
The medium produced at RHIC is so dense that only particles produced close to the surface can escape [Muller (2003)]

[Dainese, Loizides, Paic (2004); Eskola, Honkanen, Salgado, Wiedemann (2004)]



- ⇒ Inclusive particle production dominated by surface effects at RHIC
 - Complementary study of the underlying dynamics needs of additional well established observables
- ⇒ Change particle identity – heavy quarks → novel opportunities
 - Different energy loss $\Delta E_g > \Delta E_q^{m=0} > \Delta E_q^{m \neq 0}$
- ⇒ Study the structure of the radiated gluons → jets

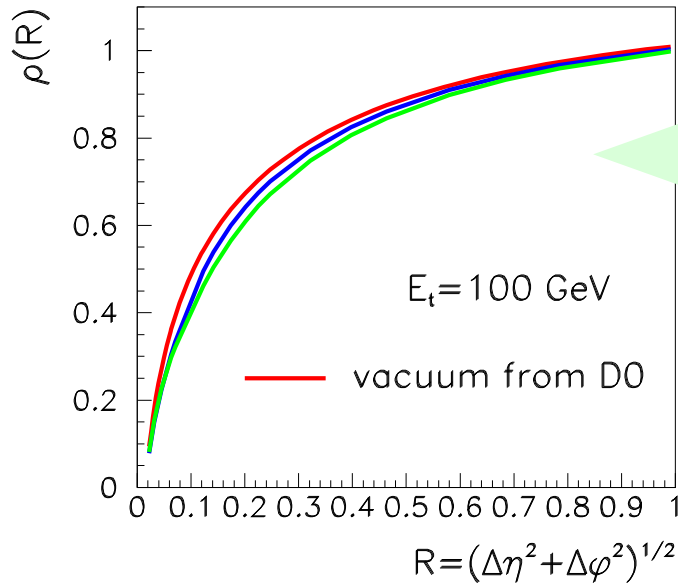
Jets in HIC



- ⇒ Large multiplicity background in HIC
- ⇒ Intrinsic uncertainties for jet-energy calibration
 - ↘ Out-of-cone fluctuations — decrease with R
 - ↘ Background fluctuations — increase with R
- ⇒ Compromise, LHC, $R \sim 0.3 \div 0.5$ + small- p_t cuts + different methods of background subtraction
- ⇒ k_t jet algorithm → New fast implementation [Cacciari, Salam 2005]

Medium-modification of jet shapes

Jet heating at the LHC, $E_t=100$ GeV [Salgado, Wiedemann 2004]



⇒ Fraction of the energy inside a cone

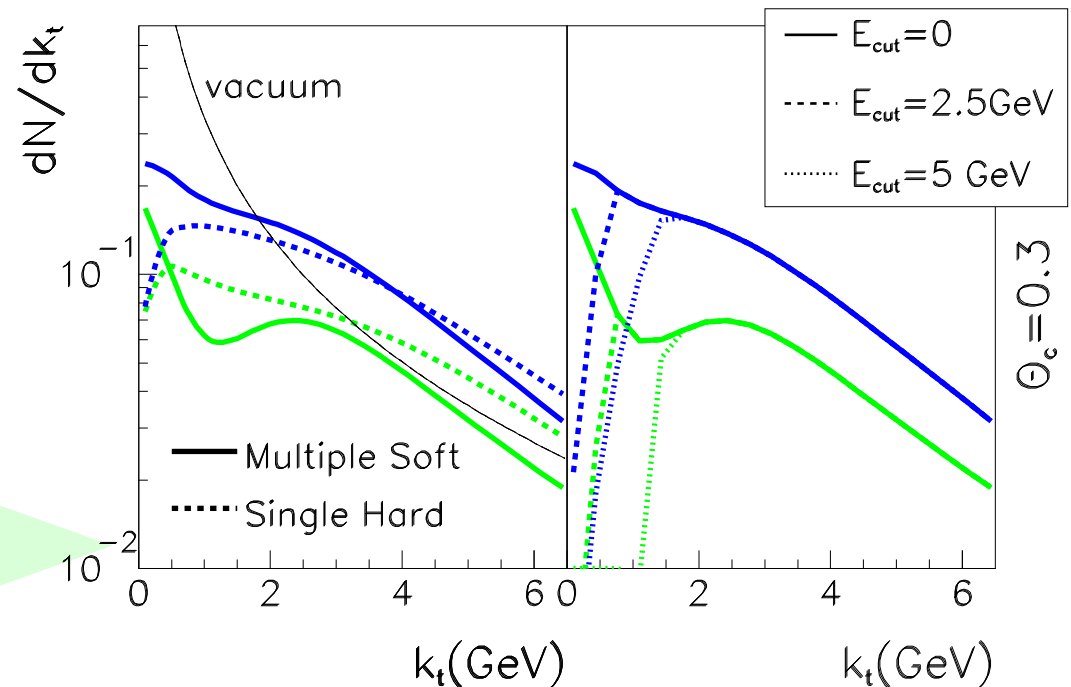
$$R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

$$\rho(R) = \frac{1}{N_{\text{jets}}} \sum_{\text{jets}} \frac{E_t(R)}{E_t(R=1)}$$

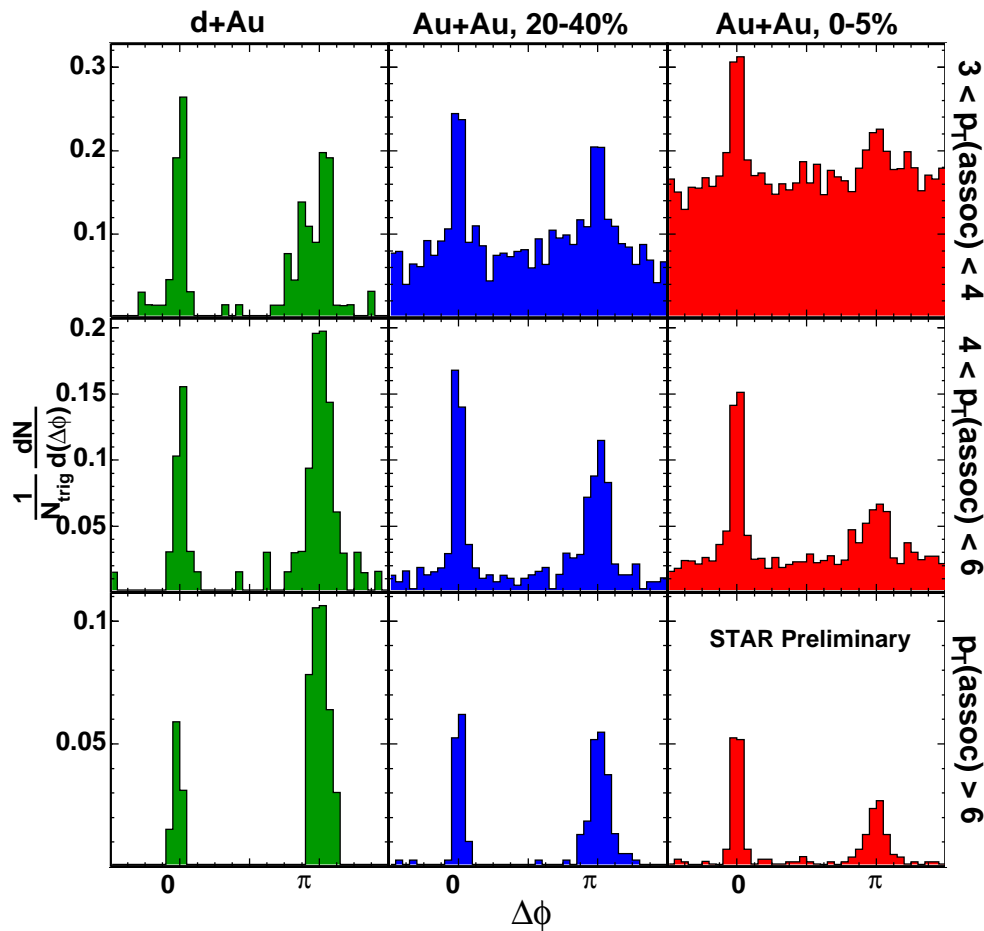
⇒ Jet energy calibration for $R \sim 0.3$

⇒ k_t -dependence of the multiplicity inside a cone

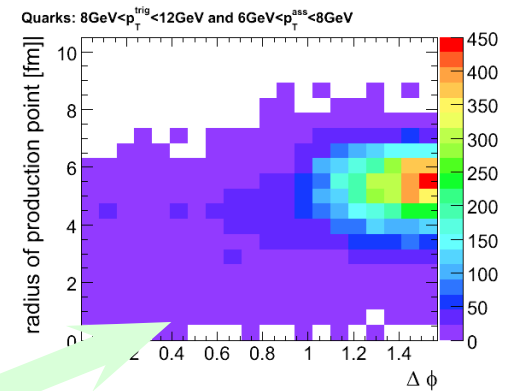
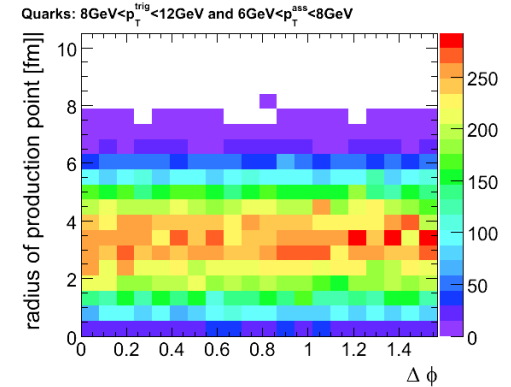
⇒ Large broadening



News from RHIC



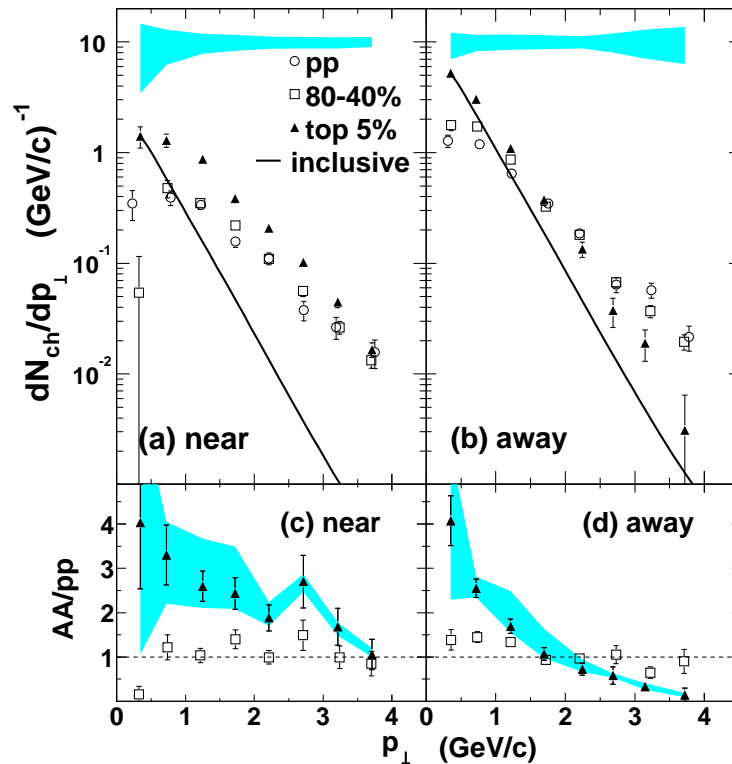
$p_t^{\text{trigg}} > 8 \text{ GeV}$, No background subtraction
 [STAR: D. Magestro QM05]



⇒ Data can be understood in the formalism [Dainese, Loizides 2005]

Removing the cut-off at RHIC

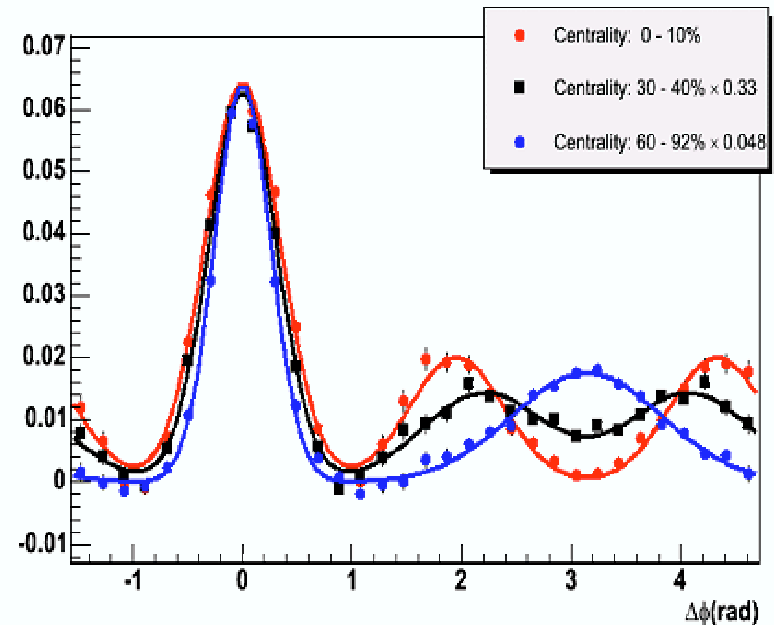
Interplay between the soft bulk and high- p_t



[STAR Collaboration 2005]

$$4 \leq p_t^{\text{trig}} \leq 6 \text{ GeV}$$

2.5 - 4 GeV/c × 2 - 3 GeV/c, All Charge



[PHENIX Collaboration 2005]

⇒ Associated particles are softer

⇒ Large broadening (two-peaks?) in the away side

Removing the cut-off at RHIC: Interpretations

⇒ Shock waves: **measure sound velocity in the medium**

[Satarov,Stoeker,Mishustin 2005; Casalderrey-Solana,Shuryak,Teaney 2004; Ruppert,Muller 2005]

⇒ Cherenkov radiation [Dremin 2005; Koch, Majumder, Wang 2005]

⇒ Initial state effect [Baier, Kovner, Nardi, Wiedemann 2005]

⇒ Jet quenching + flow [Armesto, Salgado, Wiedemann 2004]

Experimental data not conclusive

⇒ Is this a kinematic effect?

↪ The structure of the peaks depend on the p_t -cuts

⇒ Uncertainties in background subtraction

++ These data is stimulating important theoretical developments

Improving the shower evolution

⇒ Beyond the independent (Poisson) gluon emission

↘ Include energy constraints

↘ Include possibility of secondary branching...

⇒ In the vacuum DGLAP evolution equations, or implemented in MC by Sudakov form factors

$$\Delta(t_0, t) \equiv \exp \left[- \int_{t_0}^t \frac{dt'}{t'} \int dz \frac{\alpha_s}{2\pi} P_{j,i}(z) \right],$$

giving the probability of no-branching

⇒ Medium-modified fragmentation functions computed as higher-twist corrections in nuclear-DIS [Guo, Wang 2000–2003]

$$\tilde{P}_{ji}(z, x, x_L, l_T^2) = P_{ji}(z) + \Delta P_{ji}(z, x, x_L, l_T^2)$$

⇒ $\Delta P_{ji}(z, x, x_L, l_T^2)$ is the medium modification

Parton Shower for opaque media

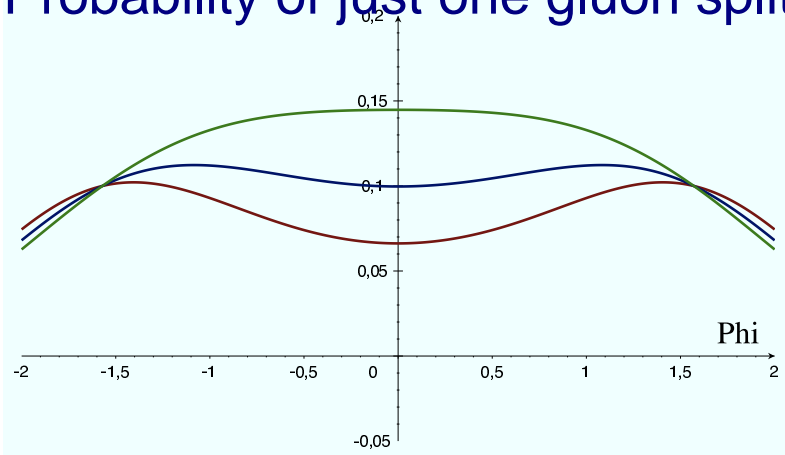
⇒ When $p_t \sim \omega \lesssim \hat{q}^{1/3} \sim 3 \text{ GeV} \rightarrow$ totally coherent limit and large angle radiation.

$$\tilde{P}(z) \sim E L \sin^2 \theta P(z)$$

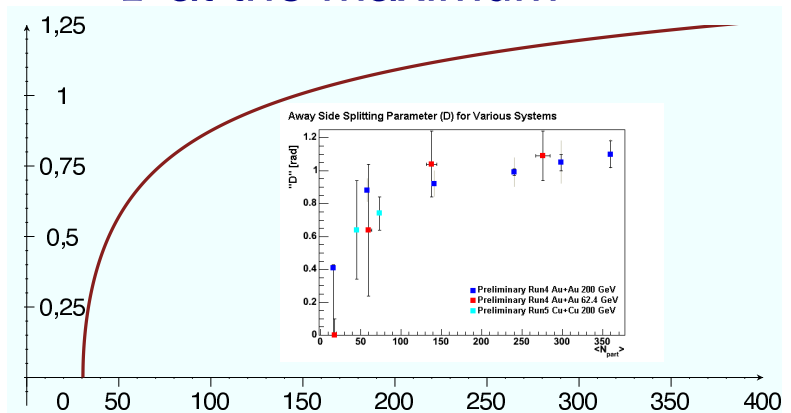
⇒ The probability of only one splitting

$$d\mathcal{P} \sim dz d\theta \sin \theta (1 + \cos \theta) \exp \left\{ -A \left[\cos \theta + \frac{\cos^2 \theta}{2} \right] \right\}$$

Probability of just one gluon splitting



Φ at the maximum



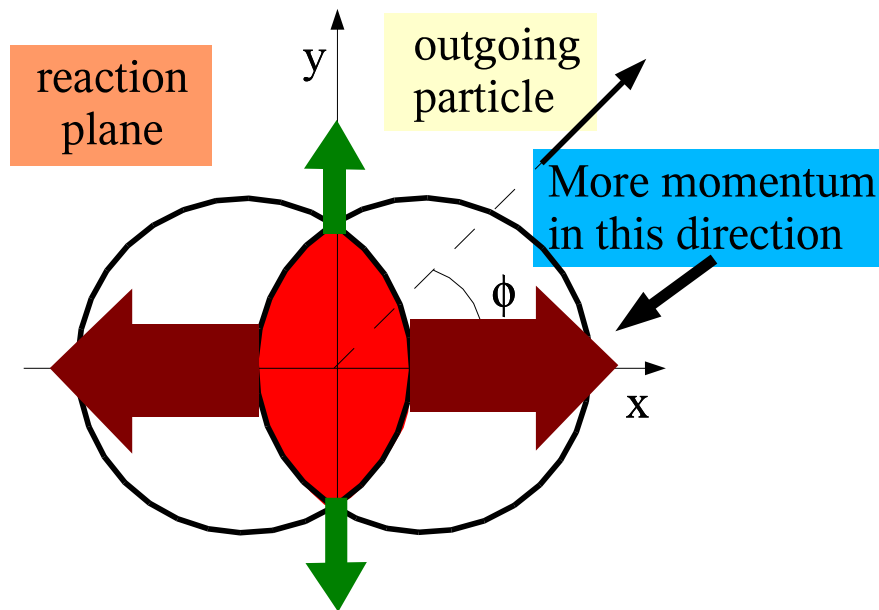
Preliminary

N_{part}

Description of the medium as a fluid

⇒ In a fluid, the acceleration is given by the Euler equation

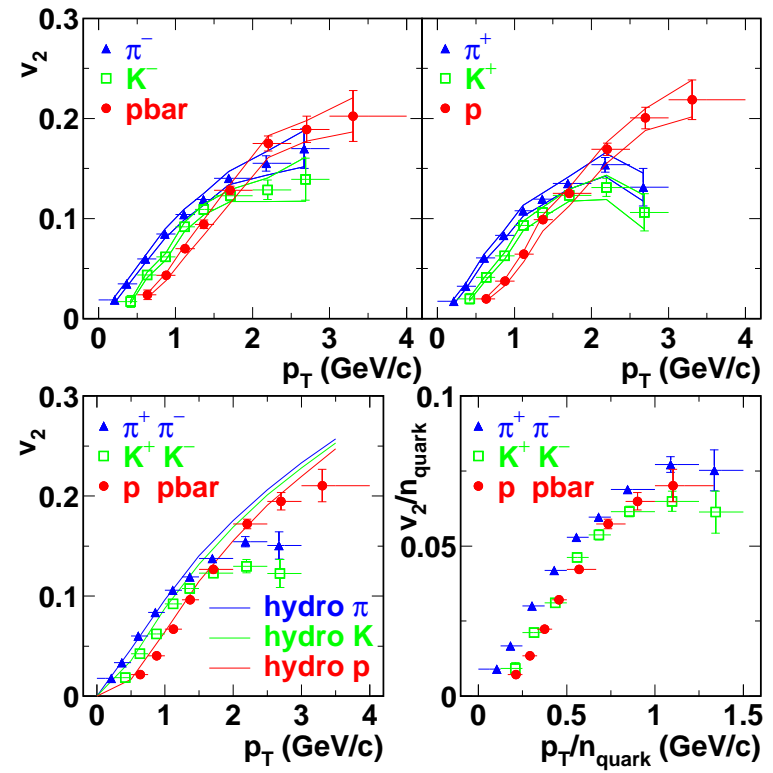
$$\frac{d\beta}{dt} = \frac{1}{\rho} \nabla P \quad \text{for an ideal gas} \quad \epsilon = 3P$$



⇒ Developing idea

⇒ Early thermalization $\tau_0 < 1\text{fm}$

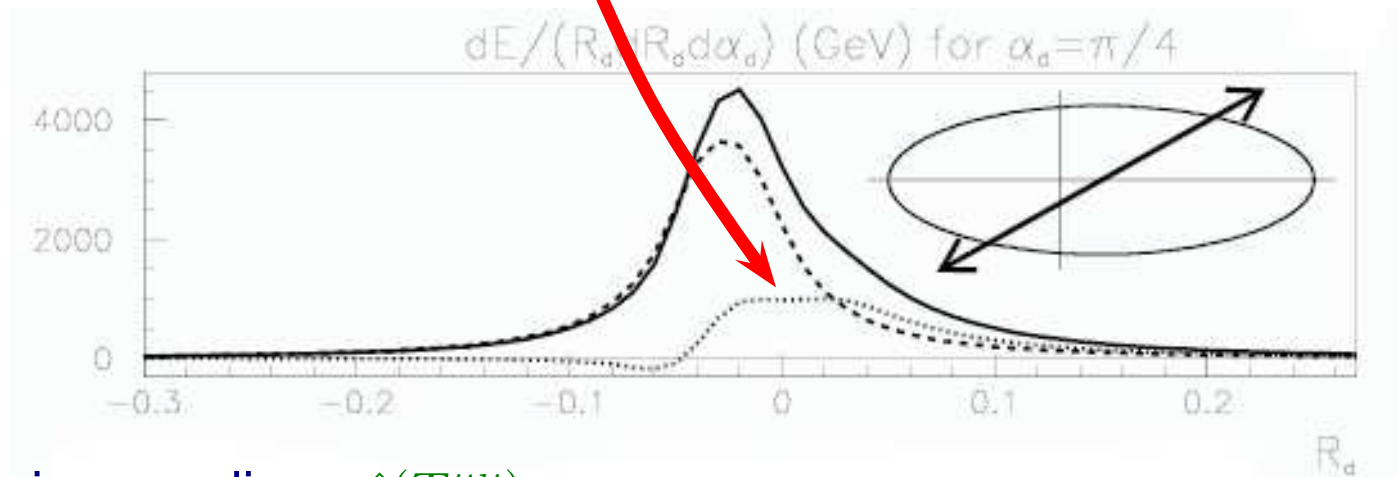
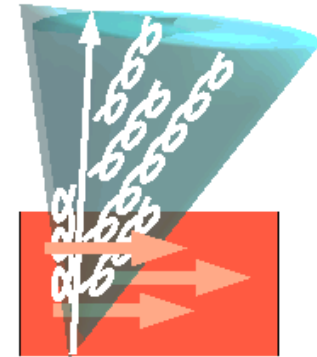
⇒ Ideal liquid



Can u^μ be measured with jets?

- ⇒ Hydrodynamical models provide a consistent description of small- p_t RHIC data with an EoS and

$$T^{\mu\nu} = (\epsilon + p) u^\mu u^\nu - p g^{\mu\nu}$$



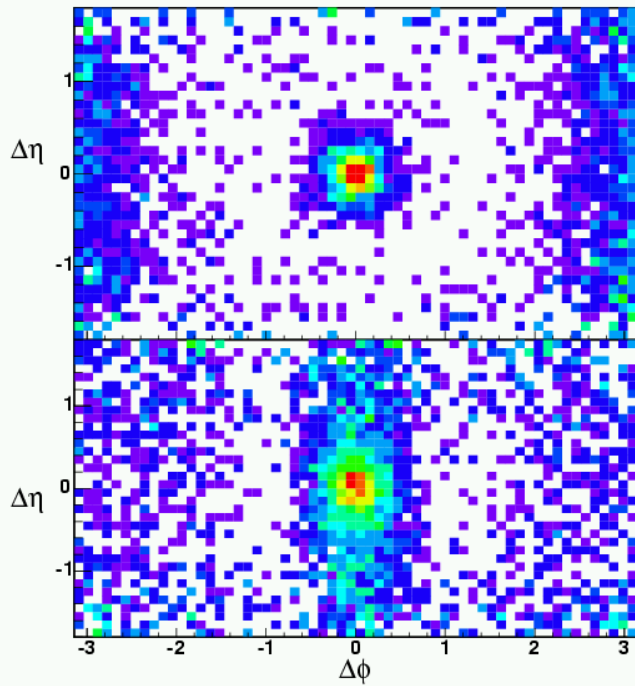
- ⇒ Flow in a medium $\hat{q}(T^{\mu\nu})$
- ↘ Additional source of energy loss
 - ↘ Assymmetric jet shapes

Measuring collective flow with jets?

Longitudinal flow

Space-time picture of collision

[STAR preliminary, D. Magestro HP04]

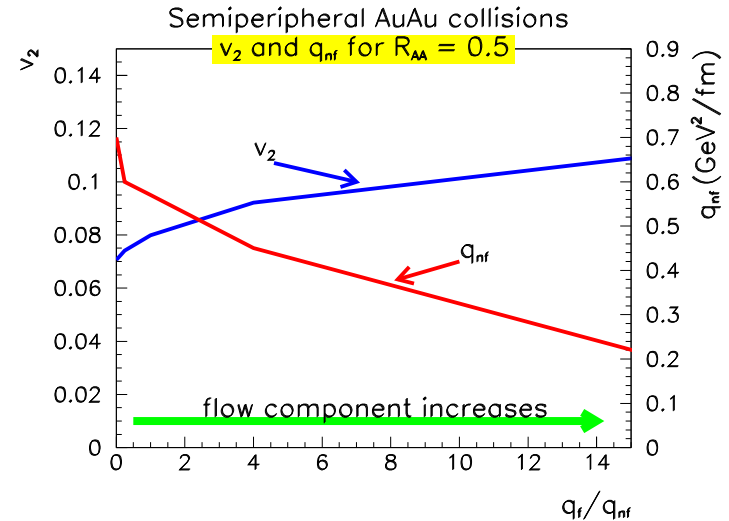


$$3 \text{ GeV} < p_t^{\text{trigg}} < 6 \text{ GeV};$$

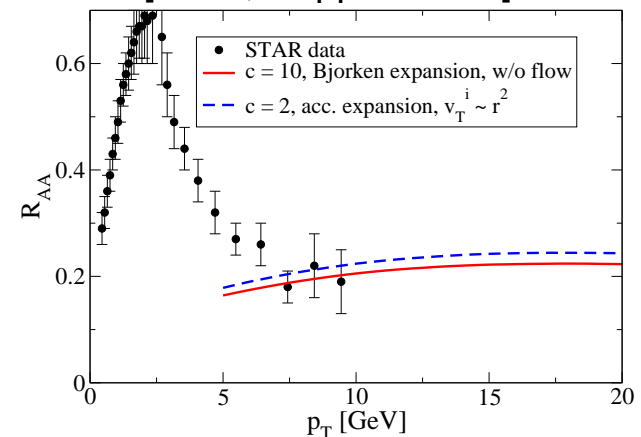
$$2 \text{ GeV} < p_t^{\text{assoc}} < p_t^{\text{trigg}}$$

Transverse flow

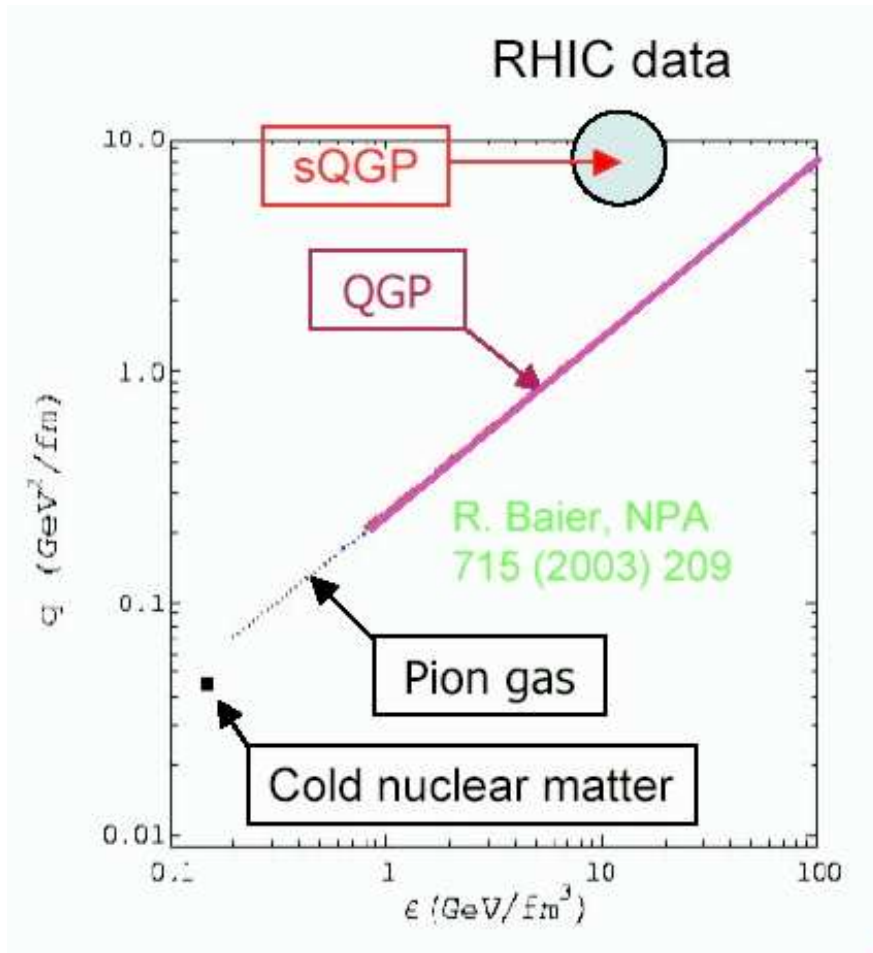
[Armesto, Salgado, Wiedemann 2004]



[Renk, Ruppert 2005]



Interpretation of the value of \hat{q}



⇒ Opacity problem

$$\hat{q} = c \epsilon^{3/4}, \quad c_{\text{ideal}}^{QGP} \simeq 2$$

$$c > 5c_{\text{ideal}}^{QGP}$$

Why??

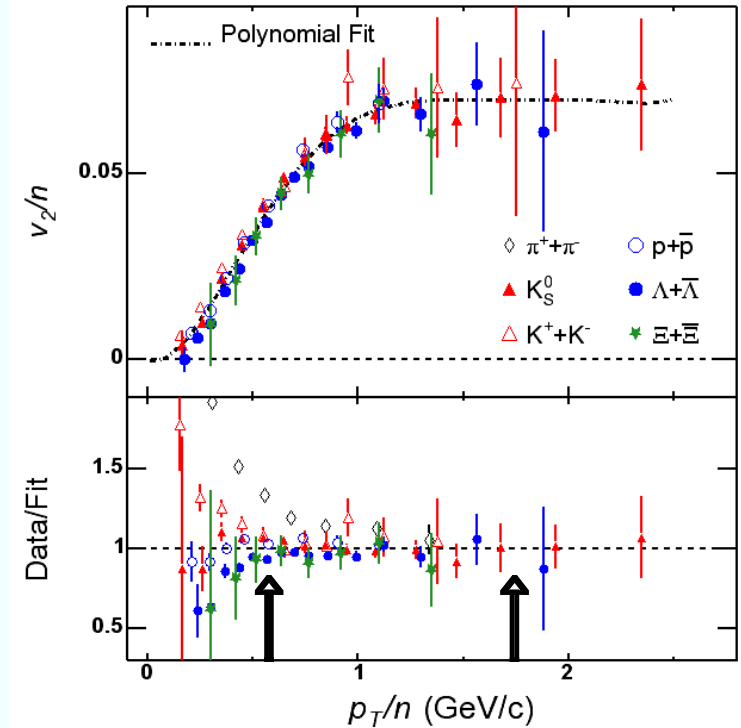
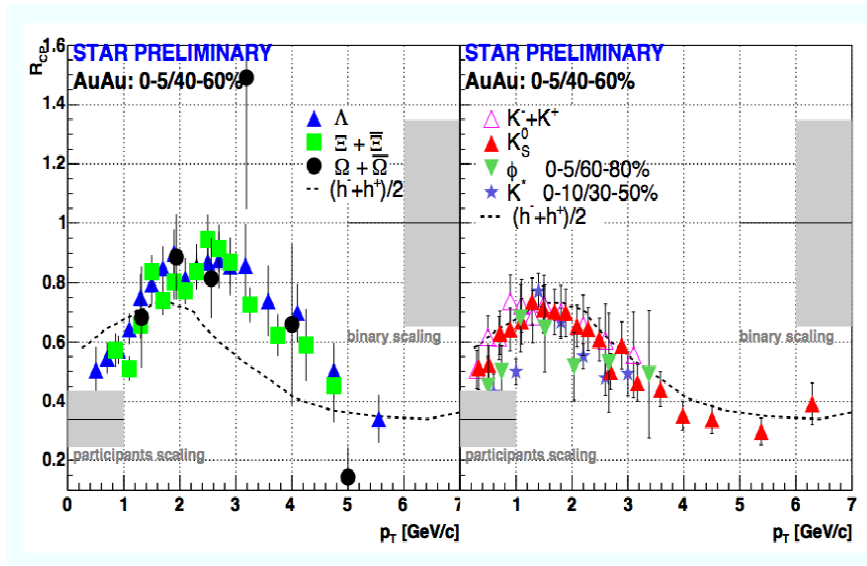
⇒ Interaction much stronger than in an ideal gas

⇒ sQGP hypothesis

⇒ \hat{q} sensitive to flow

⇒ Theory needs to be improved

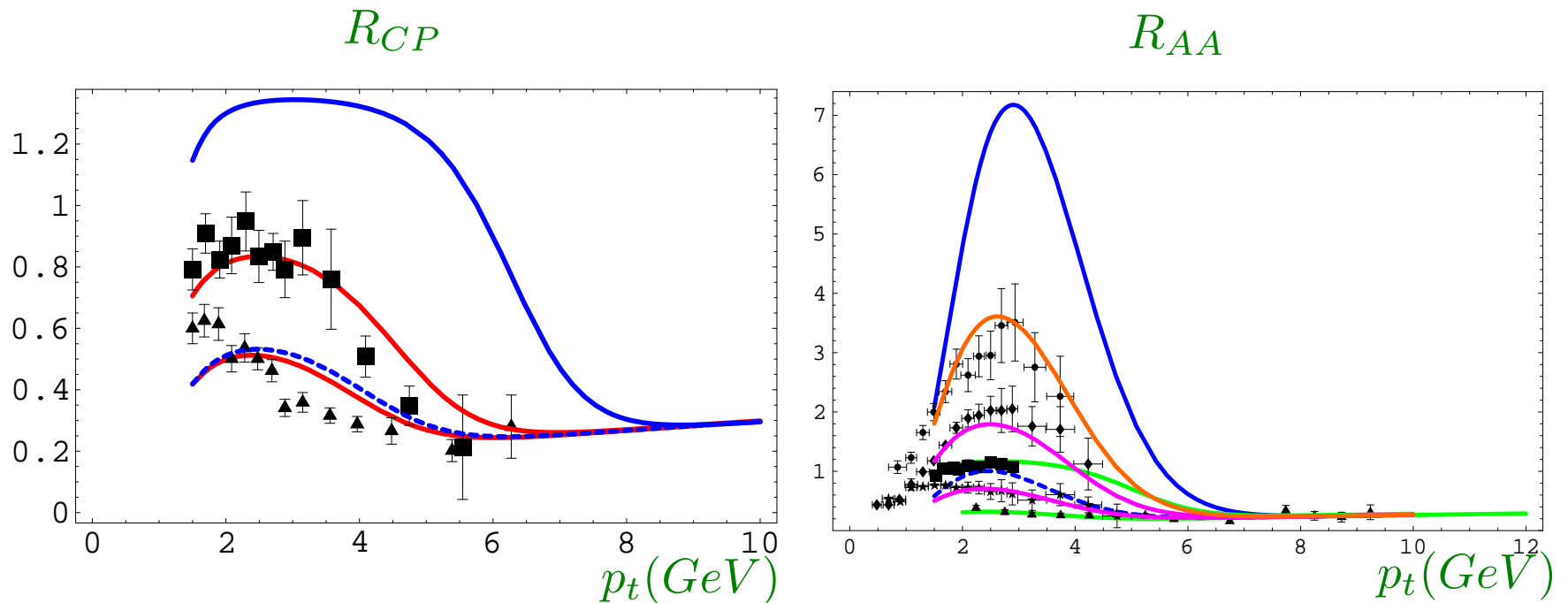
Counting quarks in HIC



⇒ high- p_t observables sensitive to the quark content of the hadron for $p_t \lesssim 5 - 6$ GeV

f_0 resonance at high- p_t

⇒ A strong probe for the quark structure of f_0 : $[qq][\bar{q}\bar{q}]$ vs $q\bar{q}$



[Preliminary: Maiani, Polosa, Riquer, Salgado]

⇒ Measure v_2 for $f_0(980)$ [Nonaka et al. (2003) for pentaquarks]

⇒ Measure R_{CP} and R_{AA} for $f_0(980)$

Summary

- ⇒ New regimes where QCD evolution is dominant are accessible
 - ↪ Hard probes provide the general framework
- ⇒ High- p_t studies ideal probes of the medium
- ⇒ Induced radiation is the dominant medium mechanism at high- p_t
- ⇒ Very dense medium created at RHIC
 - ↪ Open question: why is \hat{q} so large?
- ⇒ Jet quenching sensitive to flow fields in the medium
- ⇒ Include virtuality evolution in the parton shower
 - ↪ Is this the origin of the double peak in the away side?
- ⇒ Decisive check for the (exotic) structure of resonances – e.g. $f_0(980)$ at intermediate- p_t are possible.