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Jets in Heavy Ion Collisions

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V International Conference on
Perspectives in Hadronic Physics

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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

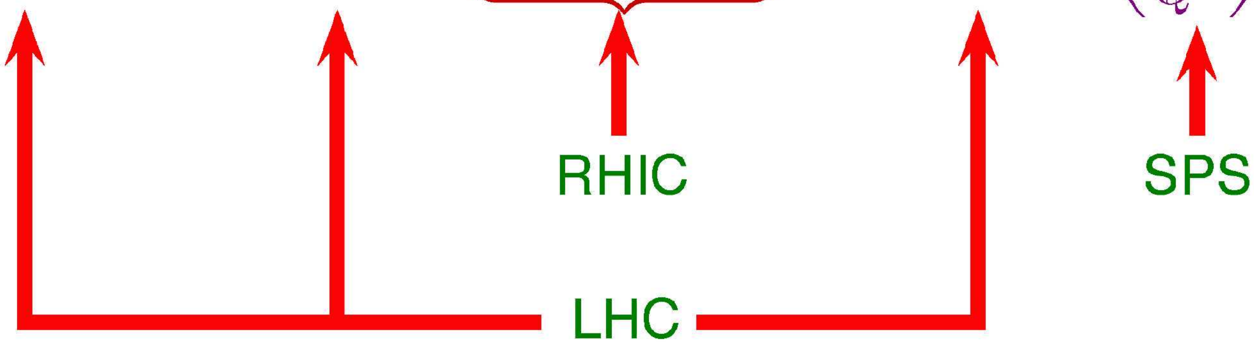
Provide a general framework

to answer these questions

Hard probes: heavy ion experiments

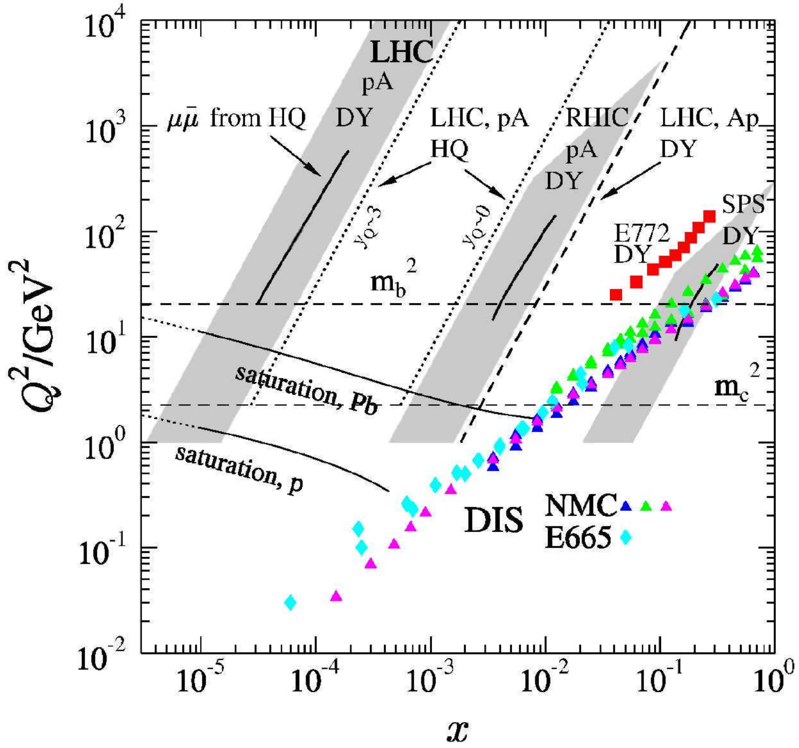
- ⇛ SPS $\sqrt{s} = 20$ GeV ($Q \sim 1$ GeV) $\longrightarrow$ marginal access to HP
- ⇛ RHIC $\sqrt{s} = 200$ GeV ($Q \sim 10$ GeV) $\longrightarrow$ access to HP
- ⇛ LHC $\sqrt{s} = 5500$ GeV ($Q \gtrsim 100$ GeV) $\longrightarrow$ HP and QCD evolution

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



- ⇛ $Q^2 \gg 1 \implies$ short distances 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.) $\longrightarrow$ properties of the medium.

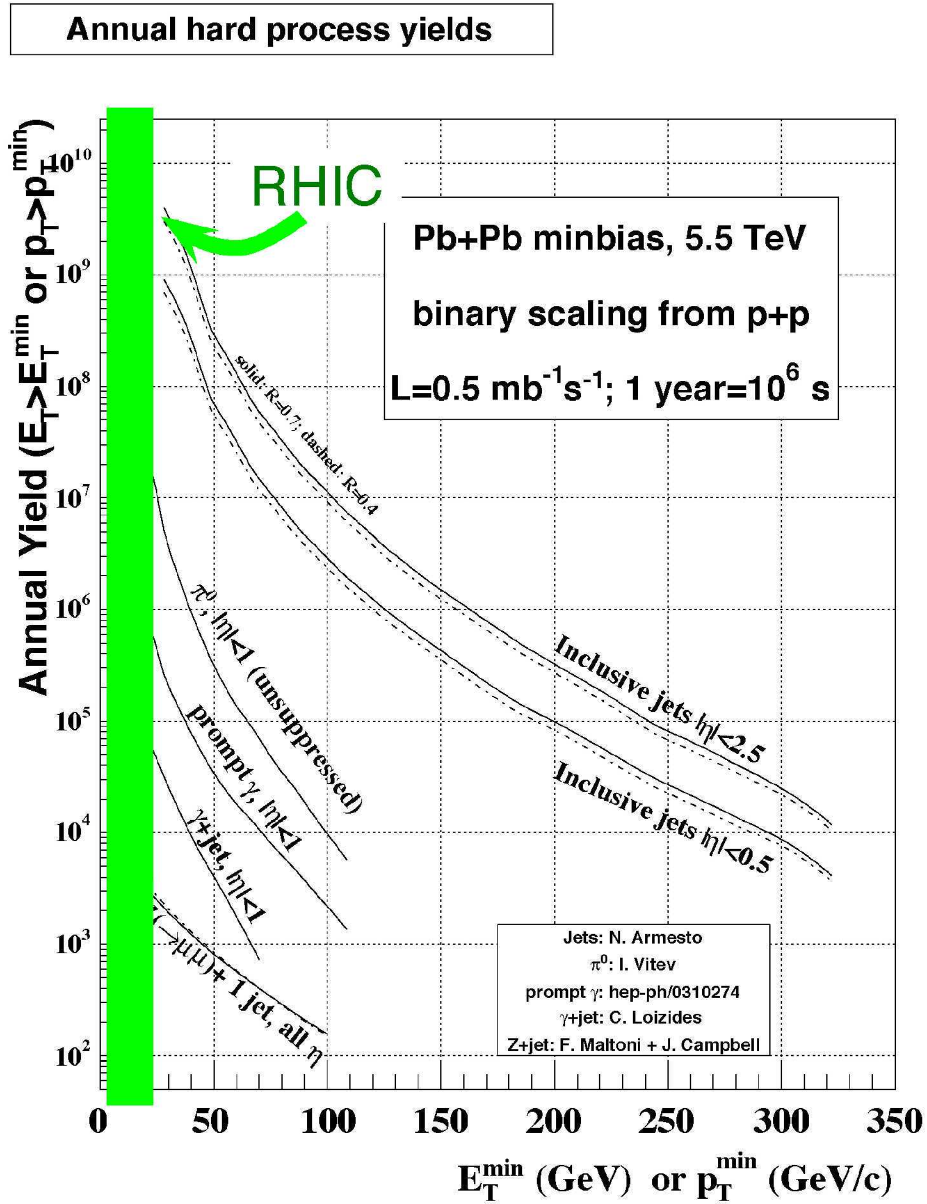
Kinematical regions studied



Eskola *et al.* hep-ph/0302170

⇒ New regimes at the LHC

In-medium QCD-evolution



P. Jacobs, M. van Leeuwen 2005

Why high-p_t?

Different scales studied

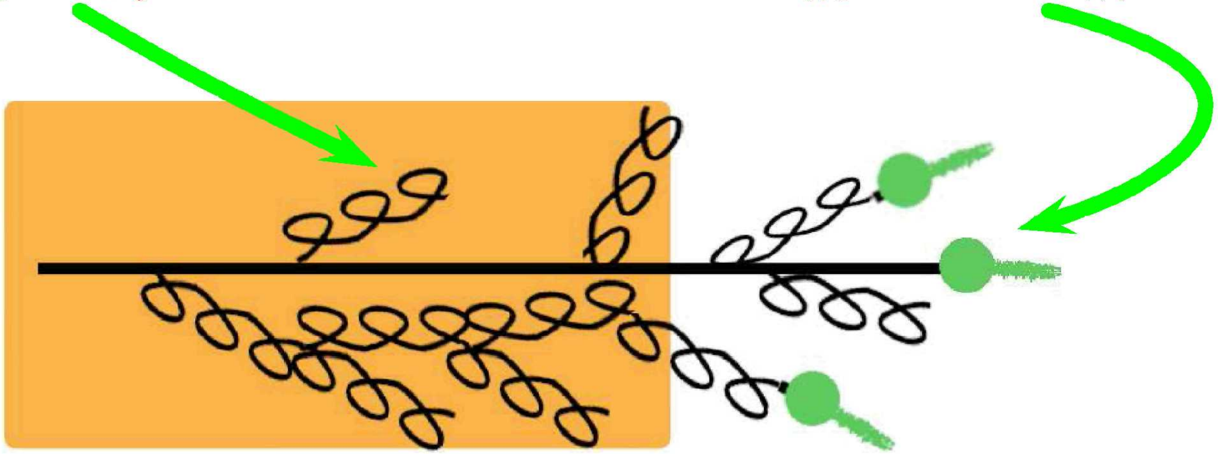
Unique property of jet quenching as a probe of the medium

Radiation formation time

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

Hadronization time

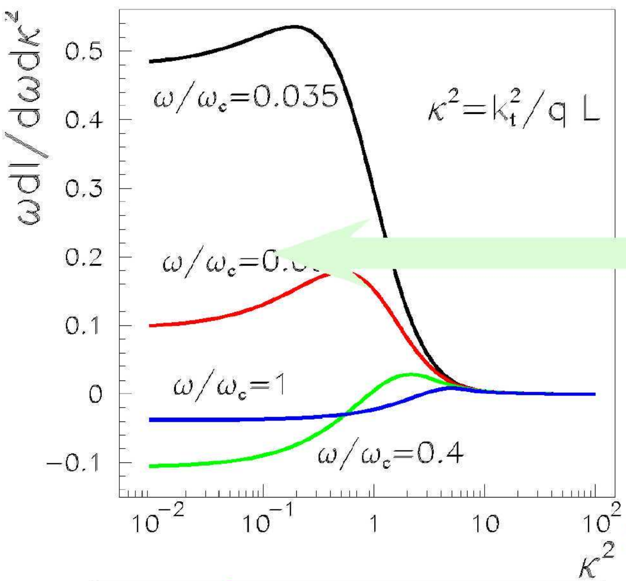
$$t_{\rm had} \sim \frac{E}{m} R_{\rm had} \sim \frac{p_t^{\rm lead}}{m} R_{\rm had}$$



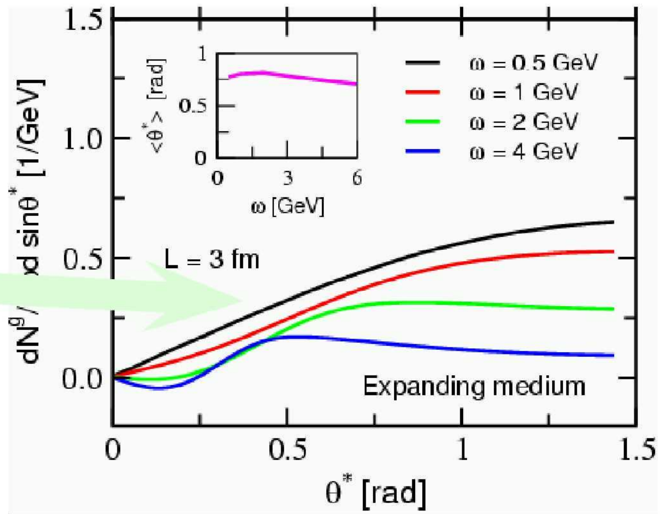
- ⇒ $t_{\rm form} \leq L \Longrightarrow$ shower in a medium
- ⇒ $R_{\rm had}$ not known for a medium
- ⇒ Intermediate $p_t \longrightarrow$ interplay radiation–thermalization–hadronization
- ⇒ Which part of the spectrum is thermalized?

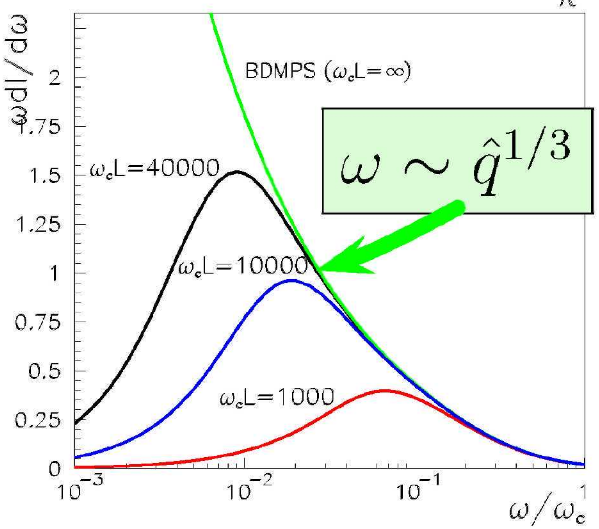
The Medium-induced gluon radiation spectrum

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



Coherence/
Formation time





⇒ Collinear singularity regularized

[Salgado,Wiedemann 2003]

⇒ Spectrum softer than in the vacuum

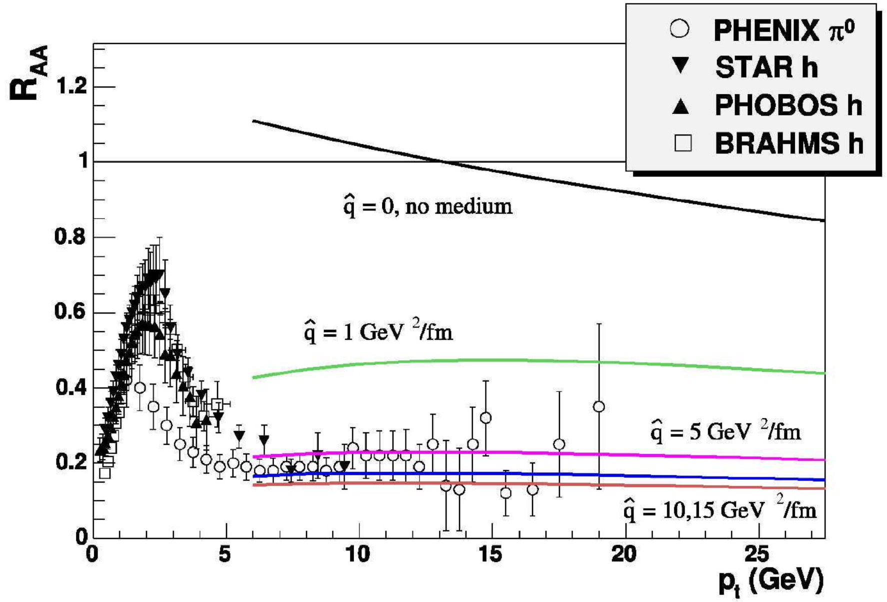
⇒ Medium: transport coefficient

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

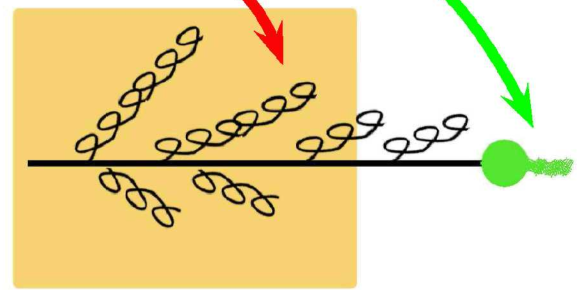
- High-p_t suppression: $\Delta E \sim \alpha_S \hat{q}\, L^2$
- Jet-broadening: $k_t^2 \sim \Delta E/\alpha_S L$ BDMPS 97

R_{AA} for light mesons at RHIC

$$d\sigma^{AA\to h+X}_{(\mathrm{med})} = \sum_f d\sigma^{AA\to f+X}_{(\mathrm{vac})} \otimes \boxed{P_f(\Delta E, L, \hat{q})} \otimes D^{(\mathrm{vac})}_{f\to h}(z,\mu_F^2)\,.$$



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



⇛ Multiple emission: Poisson distribution

⇛ Hadronization in vacuum at high-p_t

⇛ Data favors a large time-averaged transport coefficient

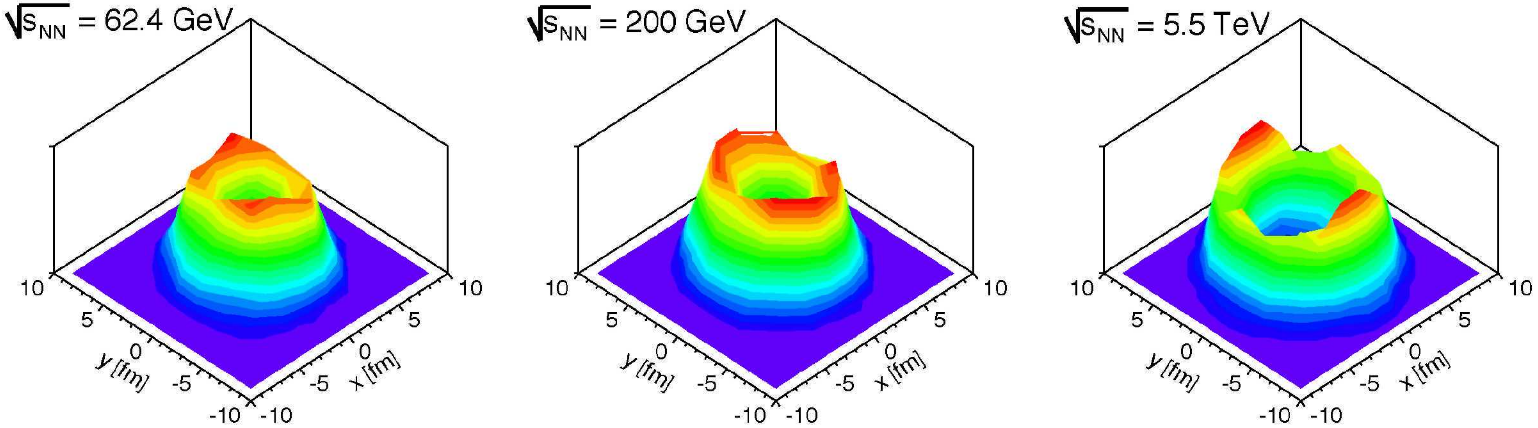
$$\hat{q} \sim 5\ldots 15 \frac{GeV^2}{fm}$$

[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

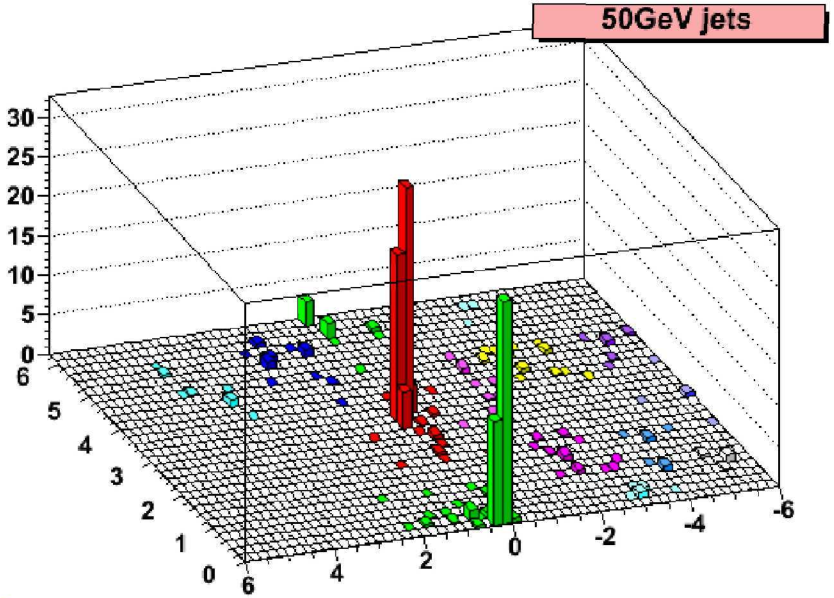
- Complementary study of the underline dynamics needs of additional well established observables

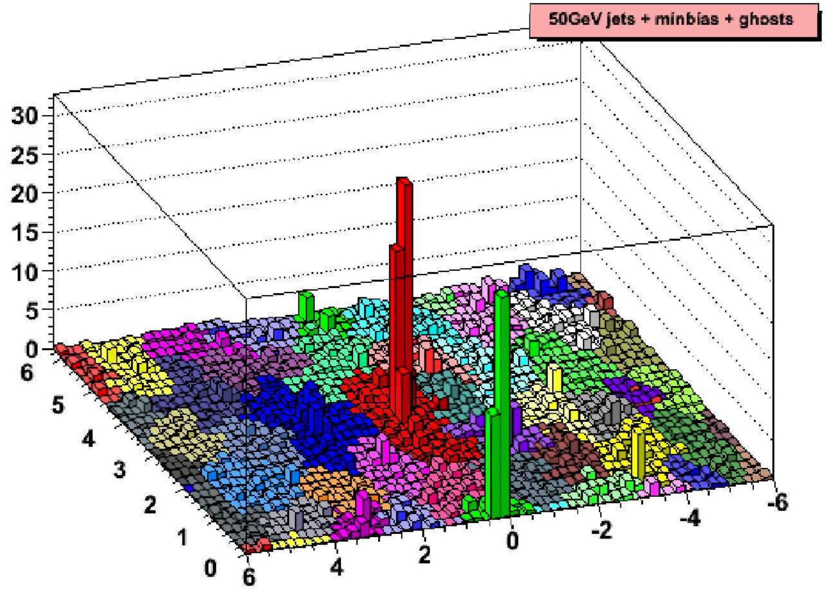
⇛ Change particle identity – heavy quarks ⟶ novel opportunities

- Different energy loss $\Delta E_g > \Delta E_q^{\mathrm{m}=0} > \Delta E_q^{\mathrm{m}\neq 0}$

⇛ Study the structure of the radiated gluons ⟶ jets

Jets in HIC





⇛ Large multiplicity background in HIC

⇛ Intrinsic uncertainties for jet-energy calibration

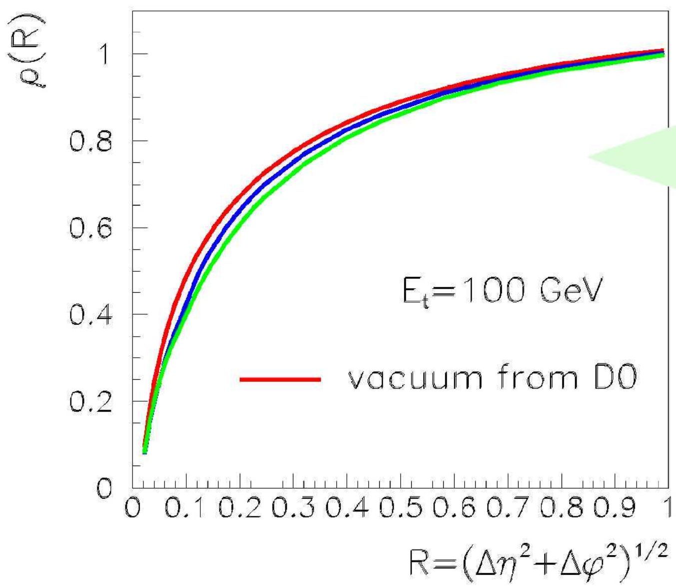
- Out-of-cone fluctuations — decrease with R
- Background fluctuations — increase with R

⇛ Compromise, LHC, $R \sim 0.3 \div 0.5$ + small-p_t cuts + different methods of background substraction

⇛ k_t jet algorithm $\longrightarrow$ New fast implementation [Cacciari, Salam 2005]

Medium-modification of jet shapes

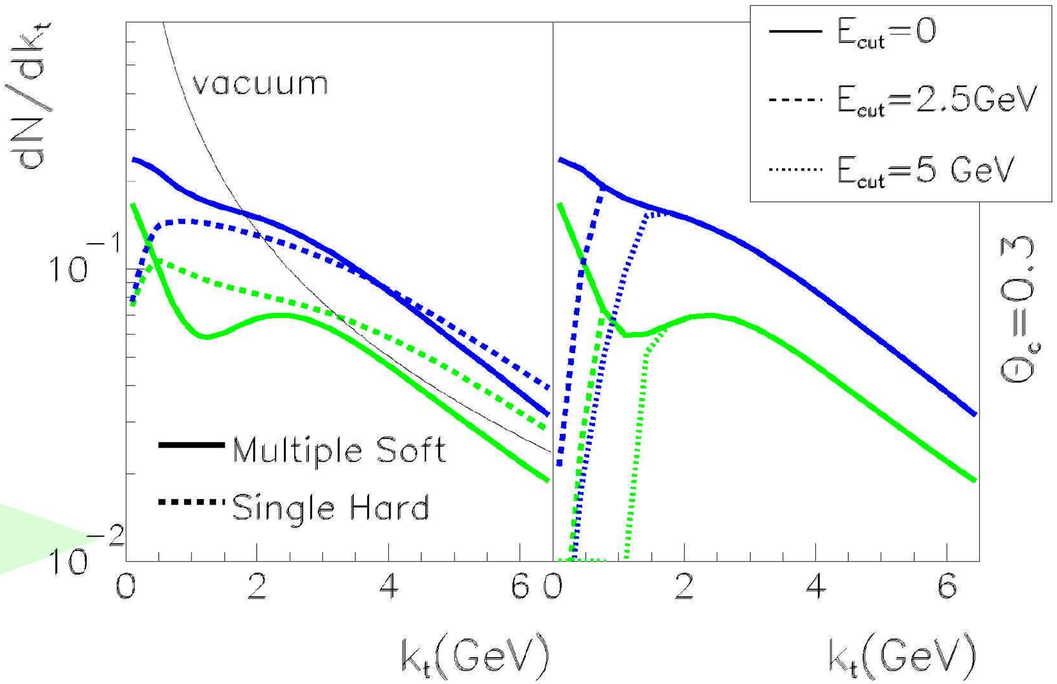
Jet heating at the LHC, E_t=100 GeV [Salgado, Wiedemann 2004]



⇛ Fraction of the energy inside a cone $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

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

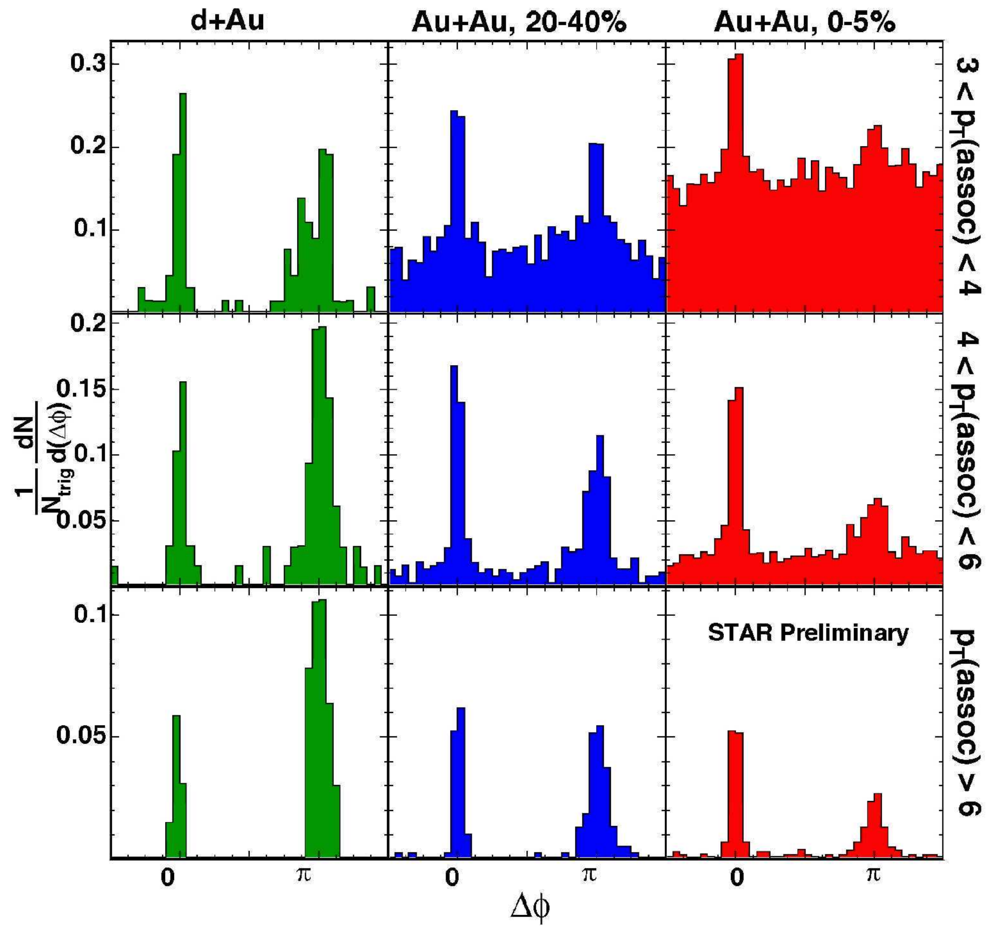
⇛ Jet energy calibration for $R \sim 0.3$

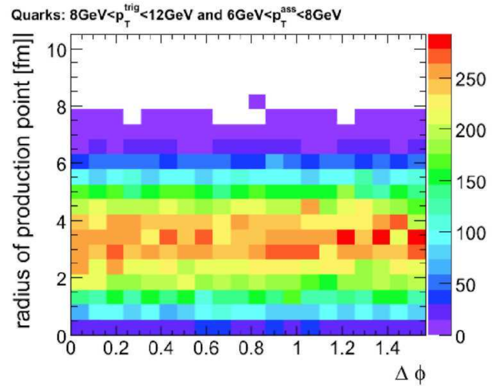


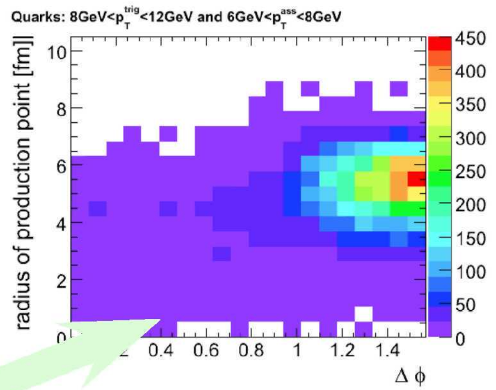
⇛ k_t-dependence of the multiplicity inside a cone

⇛ Large broadening

News from RHIC







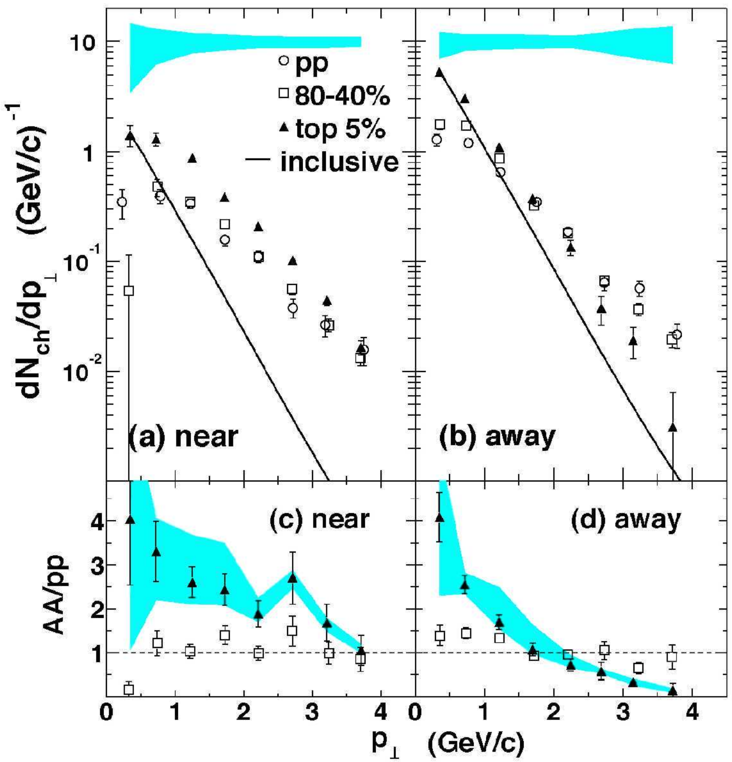
$p_t^{\rm trigg} > 8$ GeV, No background substranction

[STAR: D. Magestro QM05]

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

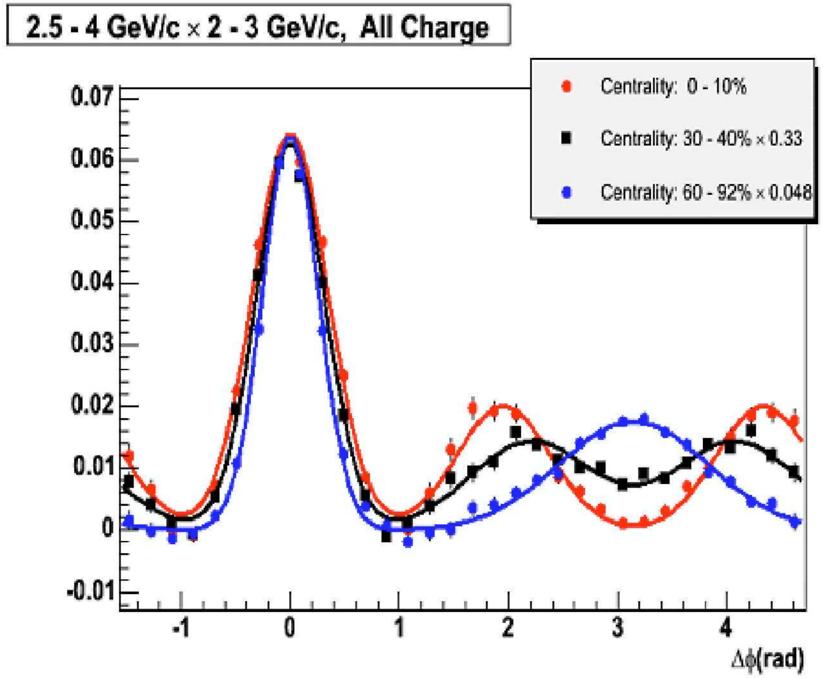
Removing the cut-off at RHIC

Interplay between the soft bulk and high-p_t



[STAR Collaboration 2005]

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



[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

⇛ Uncentainties in background substraction

++ 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

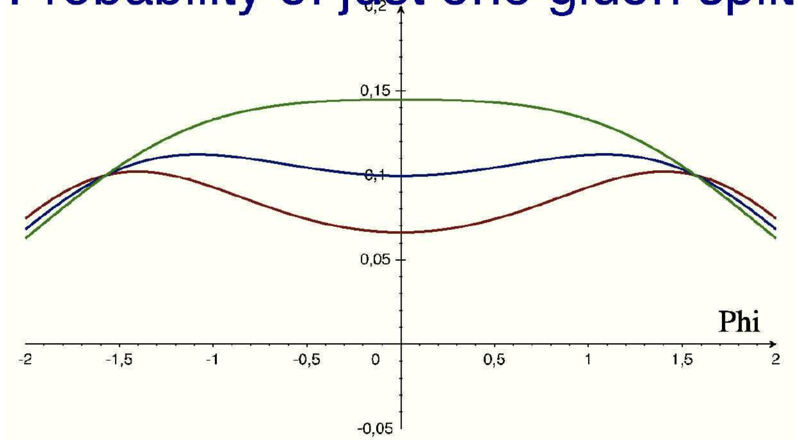
⇛ When $p_t \sim \omega \lesssim \hat{q}^{1/3} \sim$ 3 GeV$\longrightarrow$ totally coherent limit and large angle radiation.

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

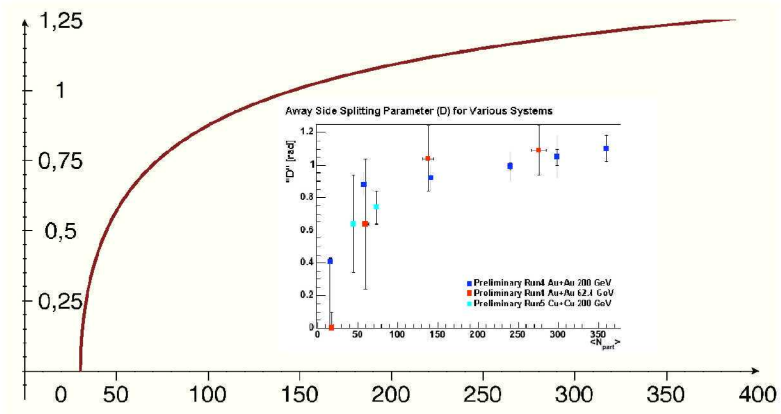
⇛ The probability of only one splitting

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

Probability of just one gluon splitting



Φ at the maximum



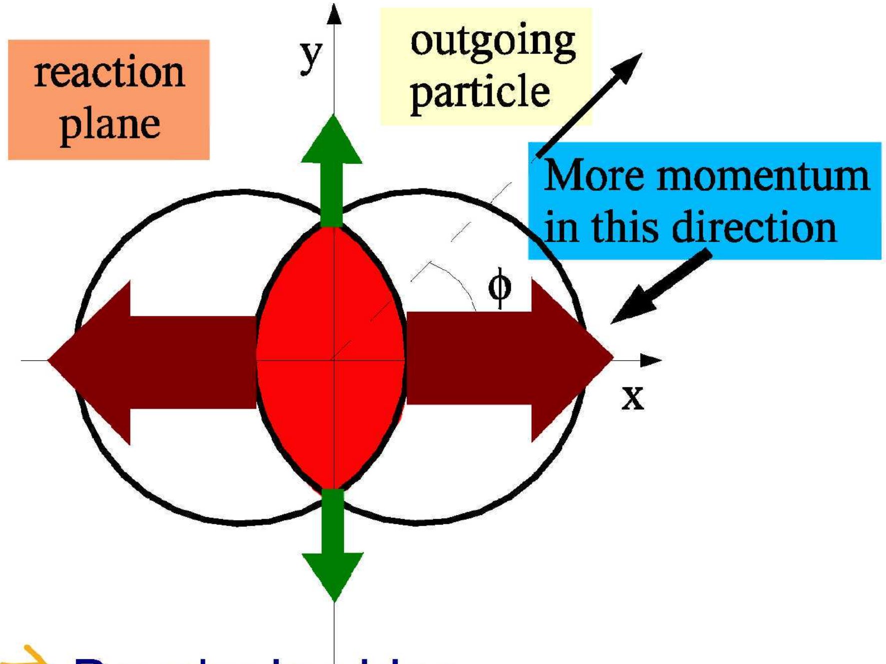
N_{part}

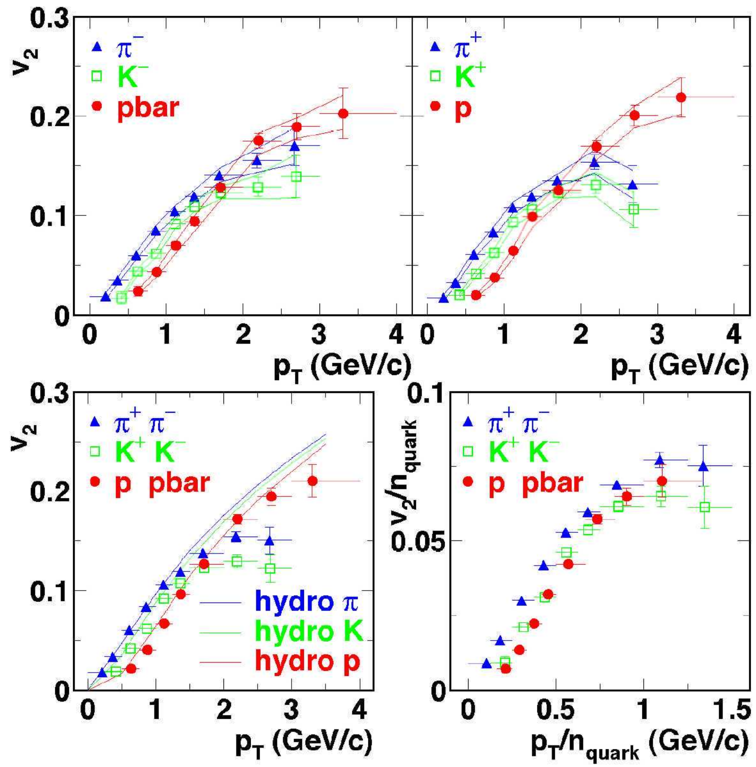
Preliminary

Description of the medium as a fluid

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

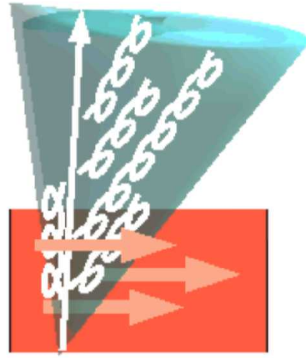
$$\frac{d\beta}{dt} = \frac{1}{\rho}\nabla P \quad \text{for an ideal gas} \quad \epsilon = 3P$$





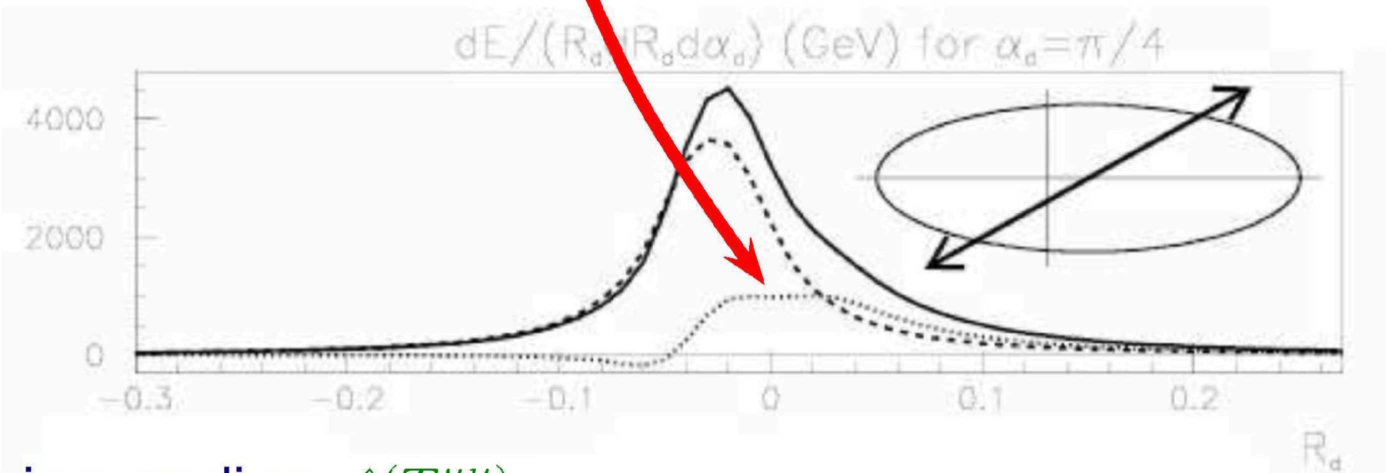
- ⇒ Developing idea
  - Early thermalization $\tau_0 < 1$fm
  - Ideal liquid

Can u^μ be measured with jets?



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

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



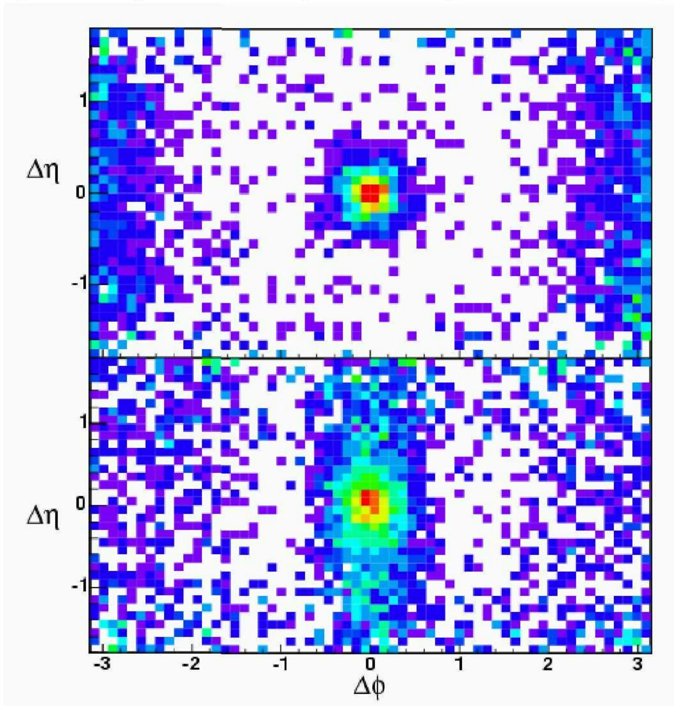
- Flow in a medium $\hat{q}(T^{\mu\nu})$
  - Additional source of energy loss
  - Assymetric jet shapes

Measuring collective flow with jets?

Longitudinal flow

Space-time picture of collision

[STAR preliminary, D. Magestro HP04]

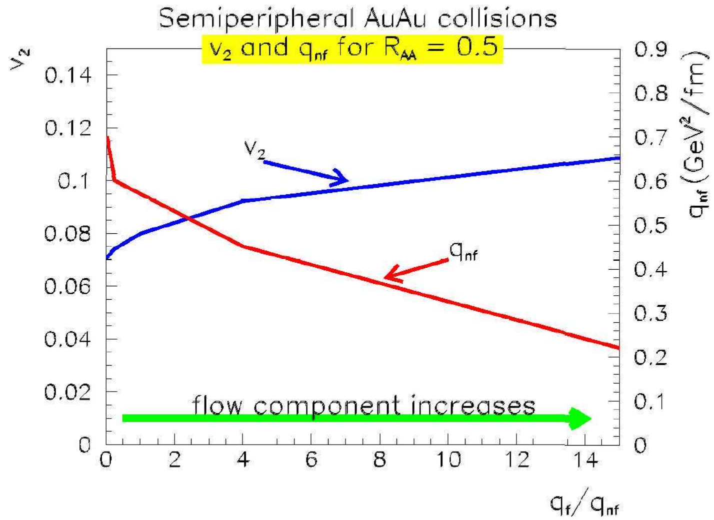


$$3\,\mathrm{GeV} < p_t^{\mathrm{trigg}} < 6\,\mathrm{GeV};$$

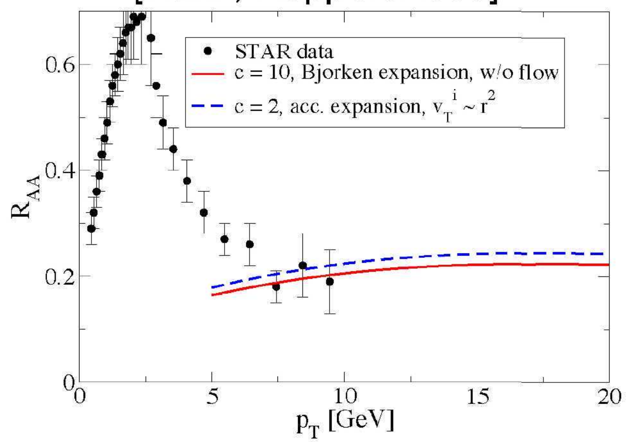
$$2\,\mathrm{GeV} < p_t^{\mathrm{assoc}} < p_t^{\mathrm{trigg}}$$

Transverse flow

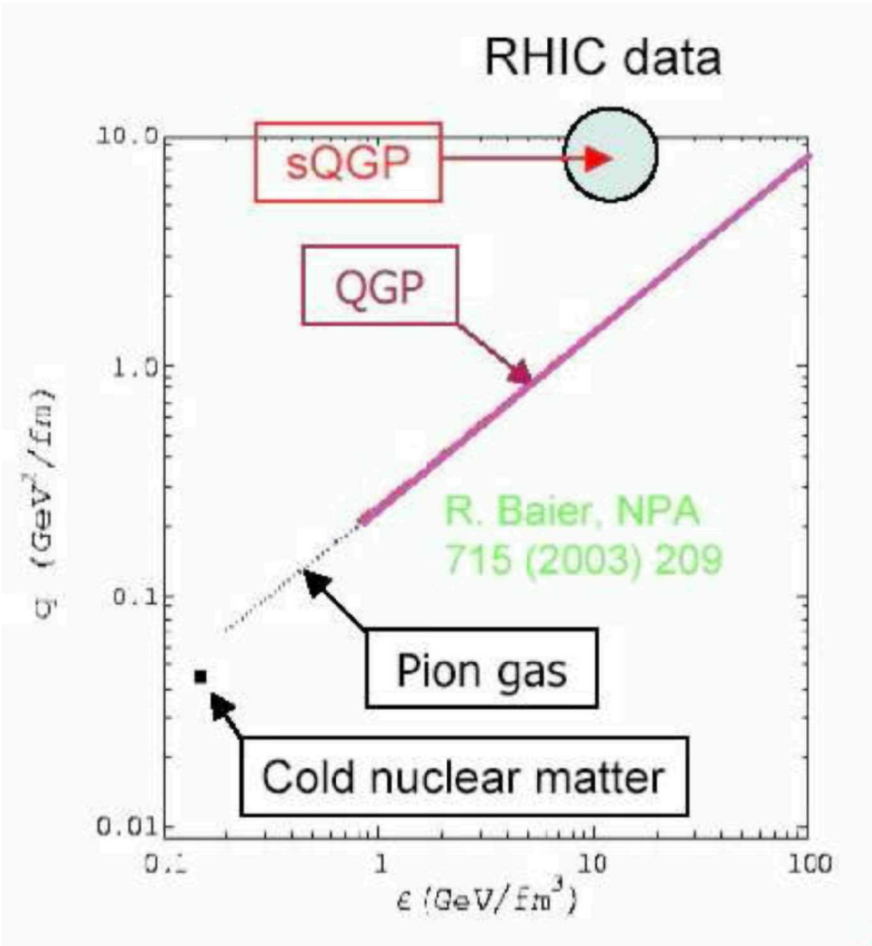
[Armesto, Salgado, Wiedemann 2004]



[Renk, Ruppert 2005]



Interpretation of the value of $\hat{q}$



⇒ Opacity problem

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

$$\boxed{c > 5c_{\rm ideal}^{QGP}}$$

Why??

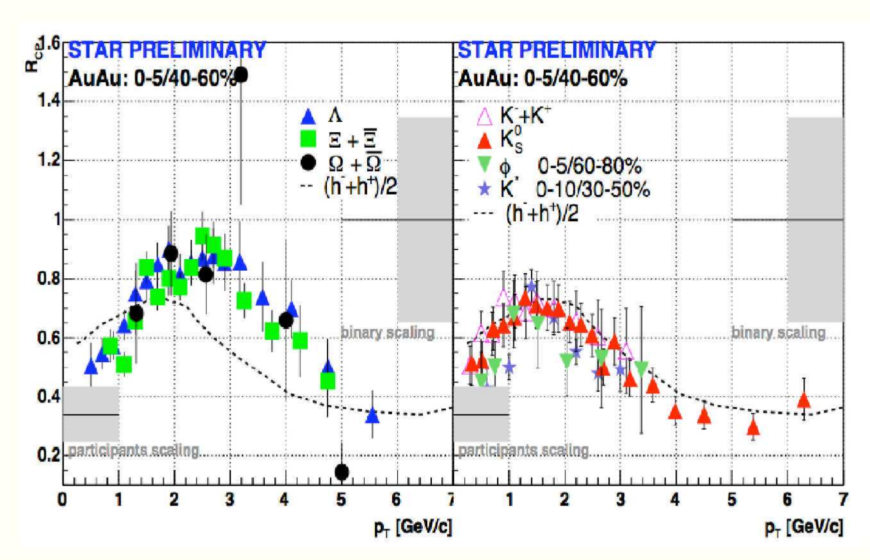
⇒ Interaction much stronger than in an ideal gas

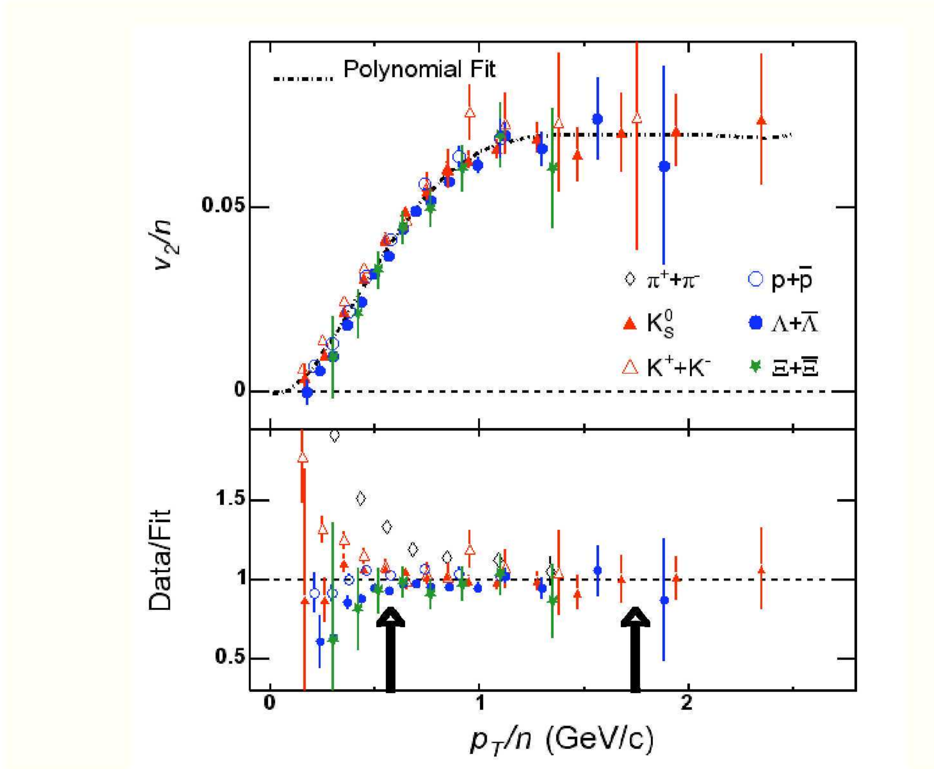
↘ sQGP hypothesis

⇒ $\hat{q}$ sensitive to flow

⇒ Theory needs to be improved

Counting quarks in HIC



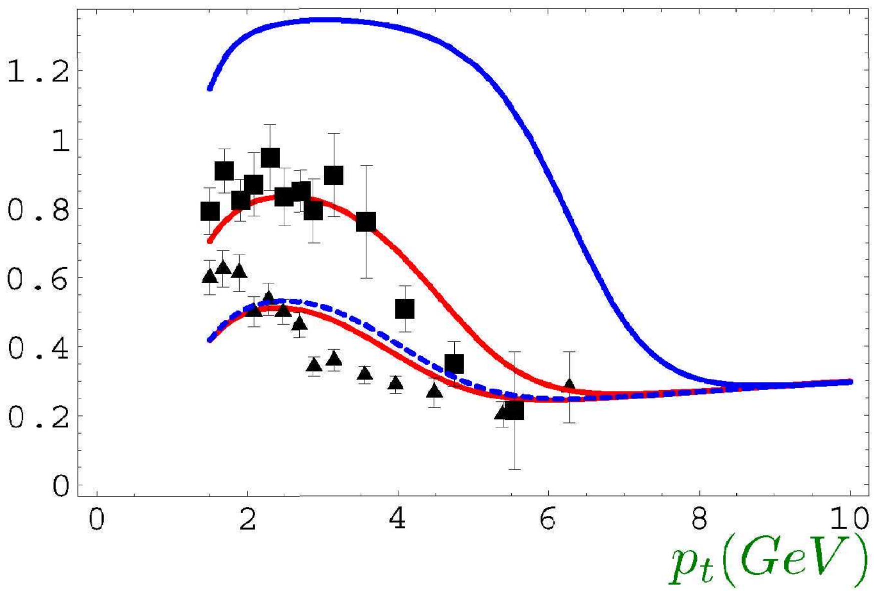


⇒ high-p_t observables sensitive to the quark content of the hadron for $p_t \lesssim 5-6$ GeV

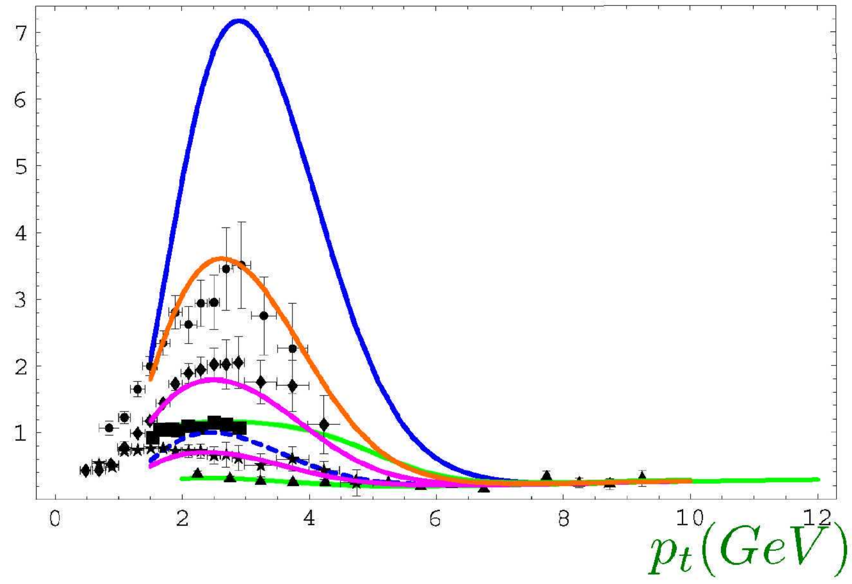
f_0 resonance at high-p_t

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

R_{CP}



R_{AA}



[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.