# RHIC results from LHC perspectives

Carlos A. Salgado

Physics Department
CERN, TH-Division

## Studying the medium with high-$p_t$ particles

carlos.salgado@cern.ch, http://home.cern.ch/csalgado

# Why high-$p_t$?

Different scales studied

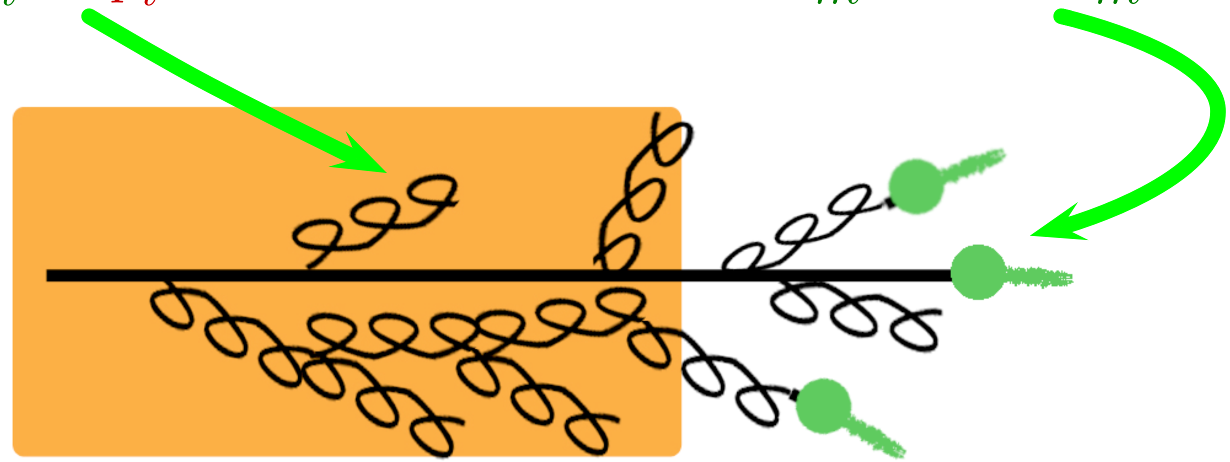
Unique property of jet quenching as a probe of the medium

Radiation formation time

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

Hadronization time

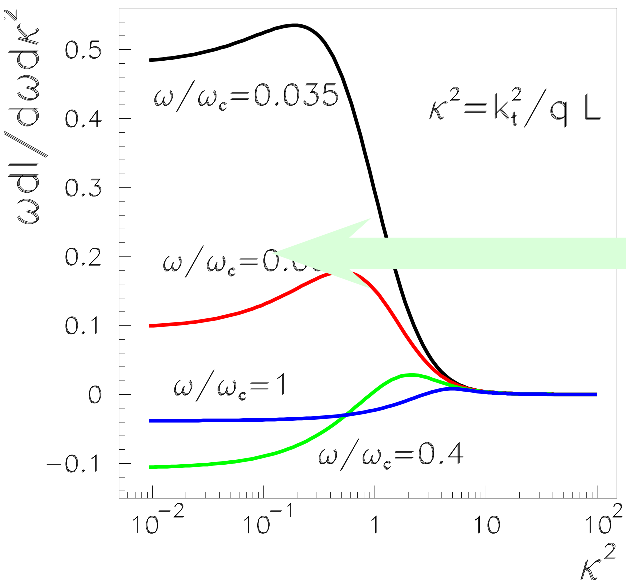
$$t_{\text{had}} \sim \frac{E}{m} R_{\text{had}} \sim \frac{p_t^{\text{lead}}}{m} R_{\text{had}}$$



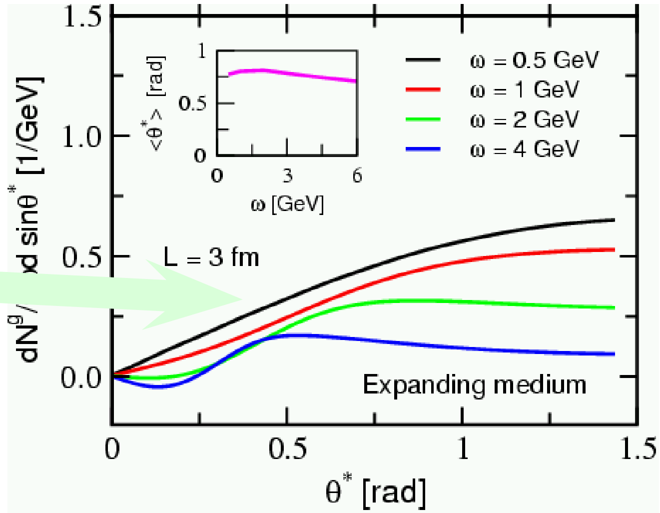
- $t_{\text{form}} \leq L \Longrightarrow$ shower in a medium
- $R_{\text{had}}$ not known for a medium
  - Conservative estimate [meson/baryon in AuAu] $\Longrightarrow p_t \gtrsim$ 6 GeV
- Intermediate $p_t \longrightarrow$ interplay radiation–thermalization–hadronization

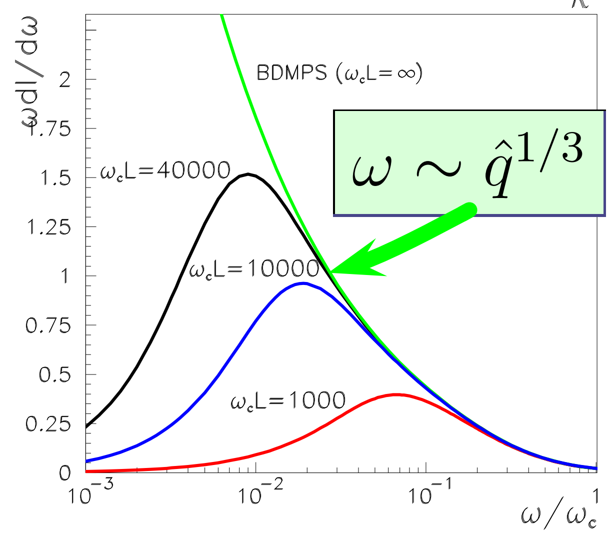
# The Medium-induced gluon radiation spectrum

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




Coherence/
Formation time




$\omega \sim \hat{q}^{1/3}$

⇛ Spectrum IR and collinear finite

[Salgado,Wiedemann 2003; Vitev 2005]

⇛ 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

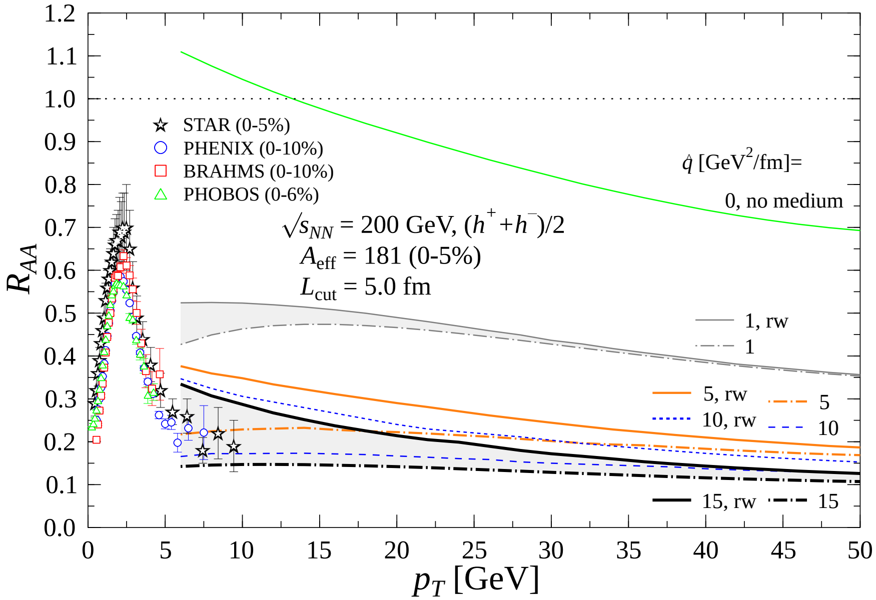
# Inclusive particle suppression

$\longrightarrow$ light mesons

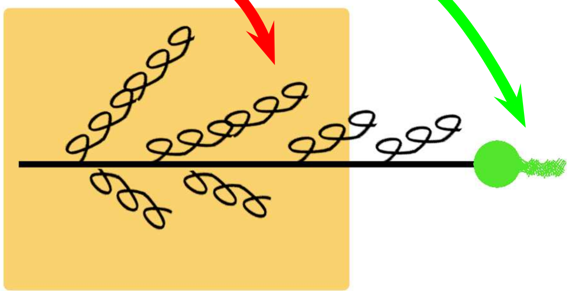
$\longrightarrow$ heavy quarks

# $R_{AA}$ 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

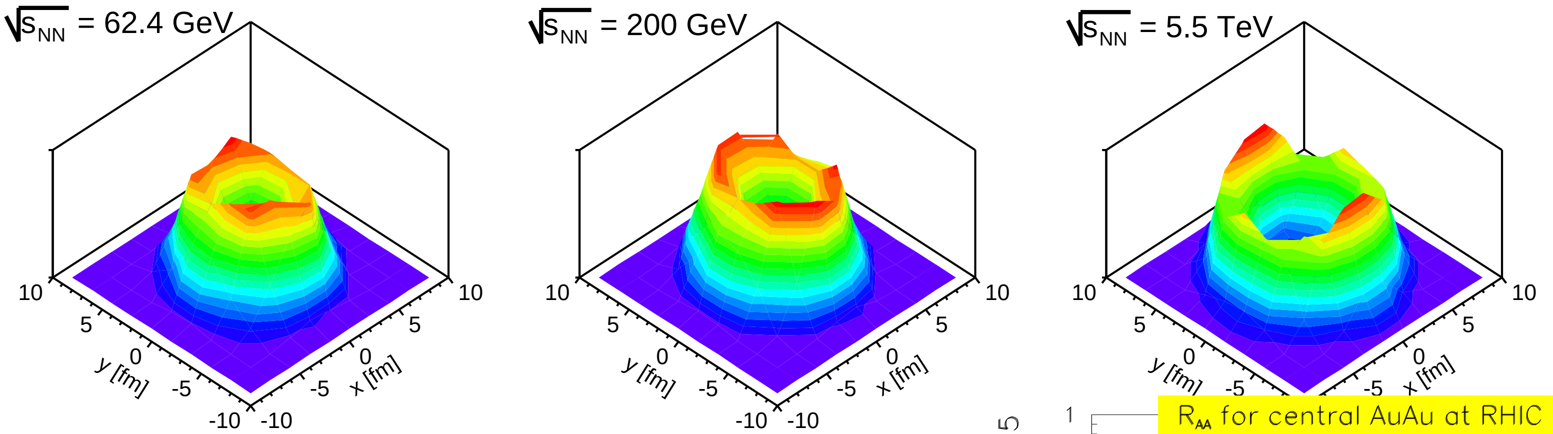
$$\boxed{\hat{q} \sim 5 \ldots 15 \frac{GeV^2}{fm}}$$

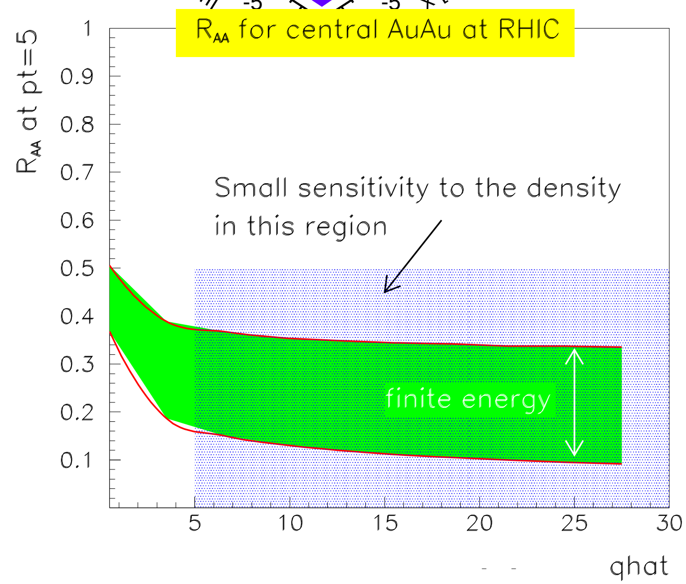
[Gyulassy, Levai, Vitev 2002; Arleo 2002; Dainese, Loizides, Paic 2004; Wang, Wang 2005; Drees, Feng, Jia 2005; Turbide, Gale, Jeon, Moore 2005...]

# 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)]



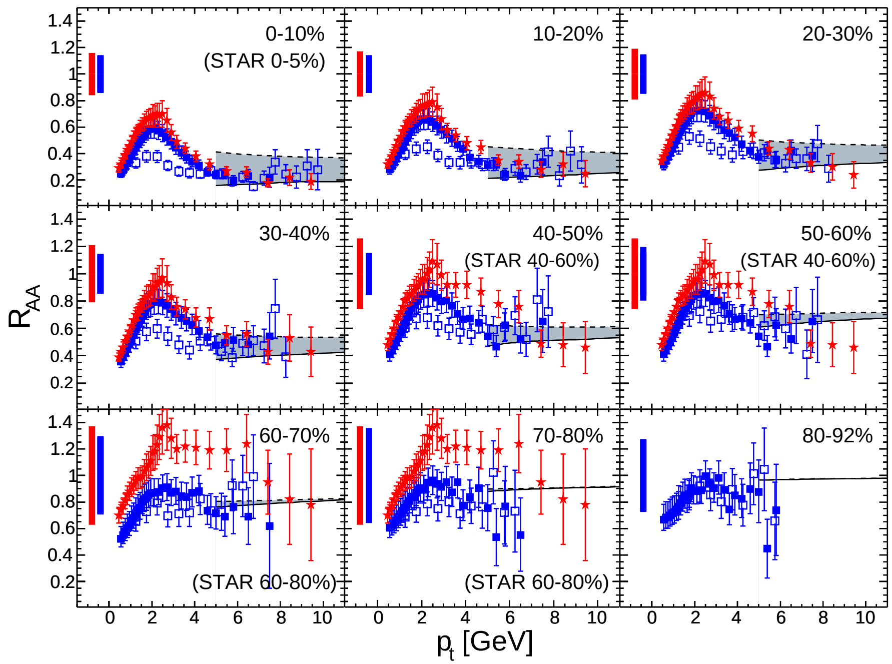




⇒ Perturbative spectrum $\sim 1/p_t^n$, $n \sim 7$

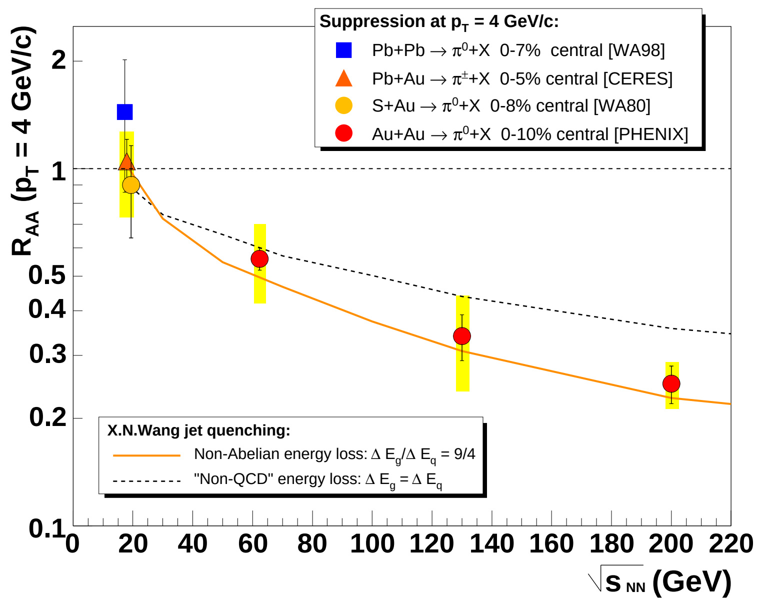
- Trigger bias to small energy loss
- Trigger bias to surface emission
- Sensitivity to $\hat{q}$ small (affect determination of medium density)

# Energy and centrality dependence

$\hat{q} \propto$ density




[Dainese, Loizides, Paic (2005)]

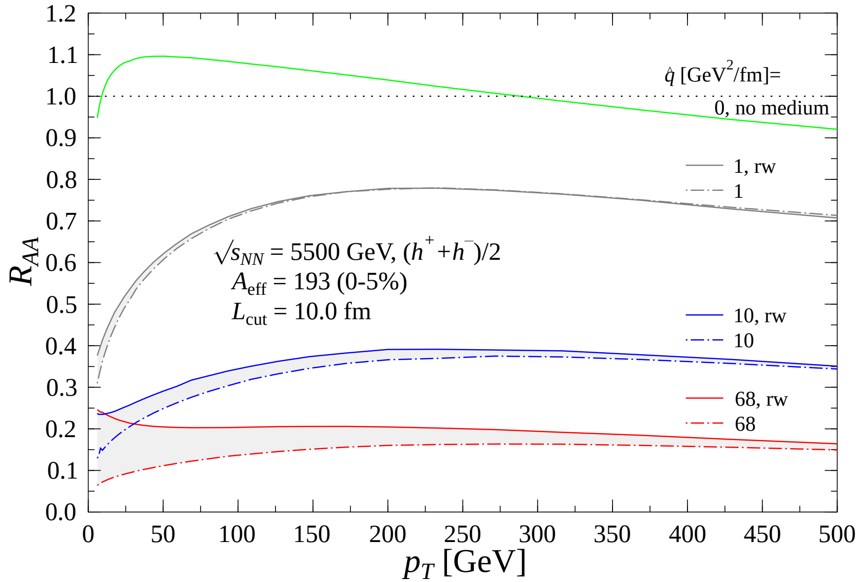



[Fig. from D'Enterria (2005)]

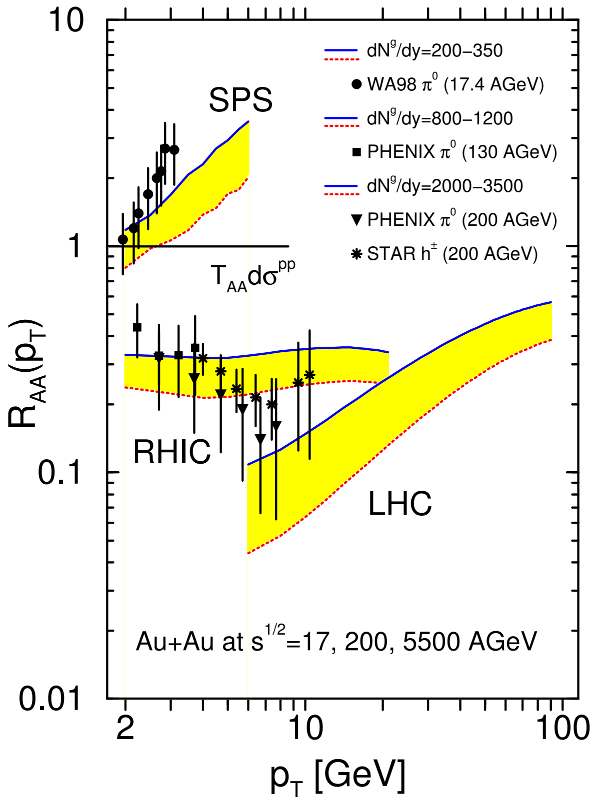
Talk by X-N Wang; A. Adil Poster+talk

# Extrapolation to the LHC

Scale $\hat{q}$ by the expected density at the LHC




[Eskola, Honkanen, Salgado, Wiedemann 2004]



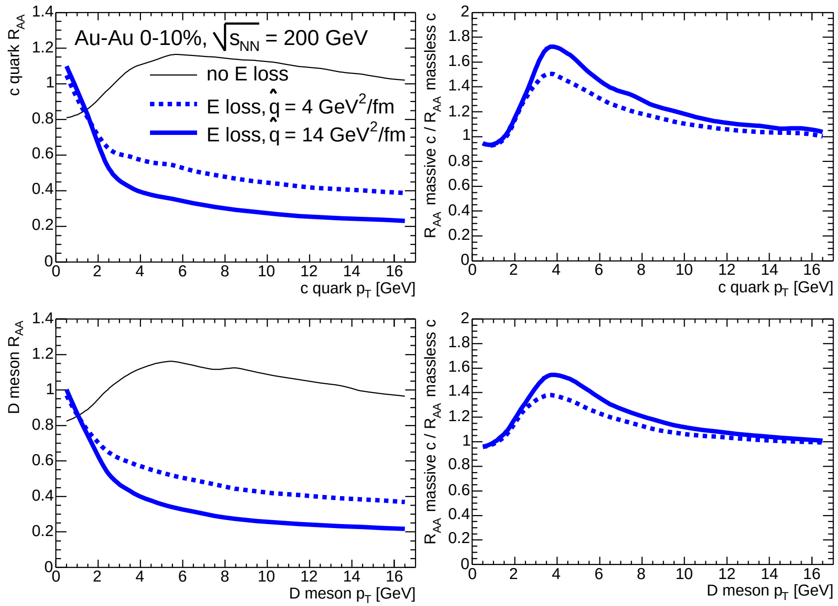

[Gyulassy, Vitev 2002]

High-$p_t$ hadrons are fragile objects even at the LHC

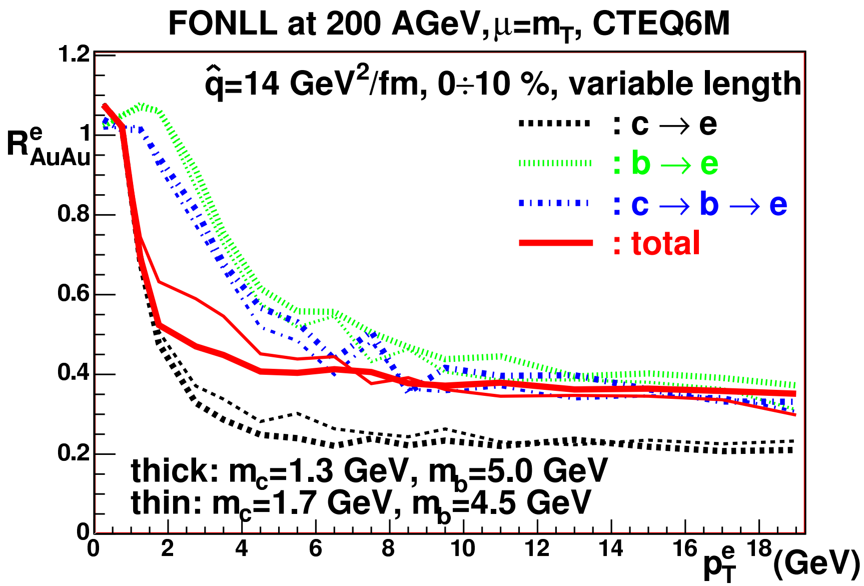
# Heavy flavor at RHIC

[Dokshitzer, Kharzeev 2001; Djordjevic, Gyulassy 2003; Zhang, Wang, Wang 2003; Armesto, Salgado, Wiedemann 2004]

Flavor + mass hierarchy: $\Delta E_g > \Delta E_q^{\mathrm{m}=0} > \Delta E_Q^{\mathrm{m}\neq 0}$




[Armesto, Dainese, Salgado, Wiedemann 2005]



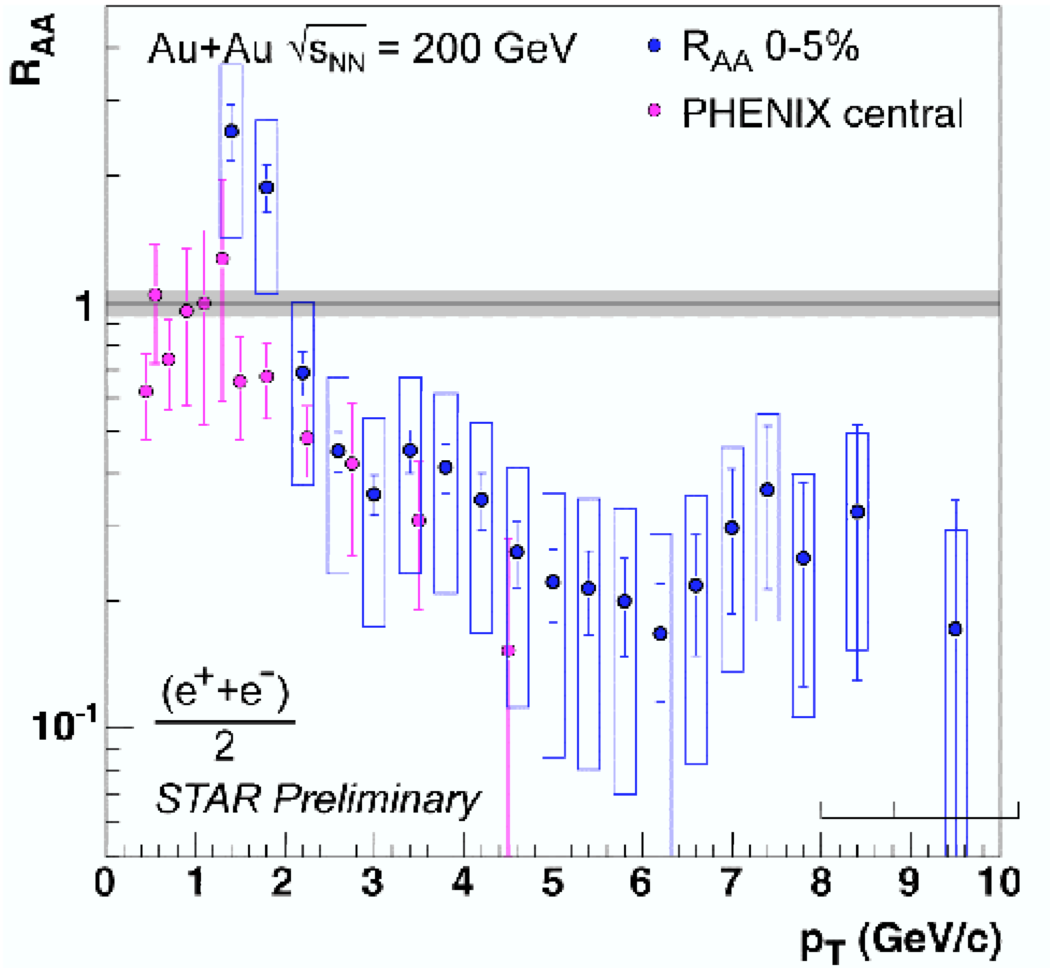

[Armesto, Cacciari, Dainese, Salgado, Wiedemann, Preliminary; Djordjevic, Gyulassy, Vogt, Wicks 2005]

Constrain $b/c \rightarrow e^-$ with pp!

- ⇛ Charm quark suppression similar to light mesons
- ⇛ Possibility to further constrain $\hat{q}$

Parallel talks by N. Armesto and M. Djordjevic

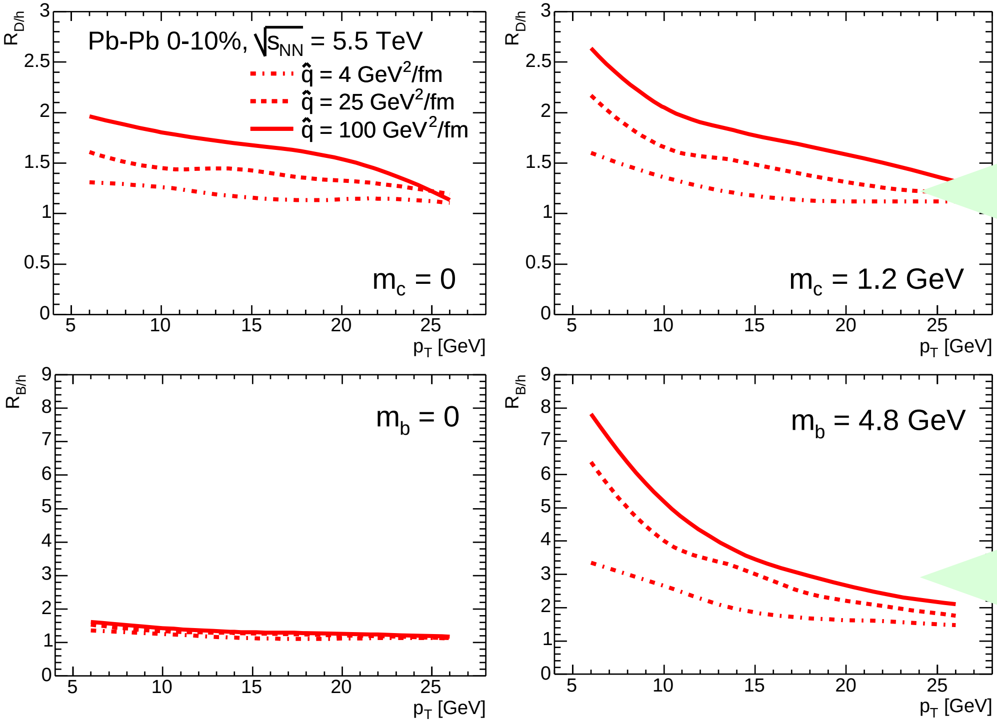
# New data




Talks by J. Dunlop (STAR) & V. Greene (PHENIX)

# Heavy-to-light ratios at the LHC

$D/h$ and $B/h$ ratios for the LHC

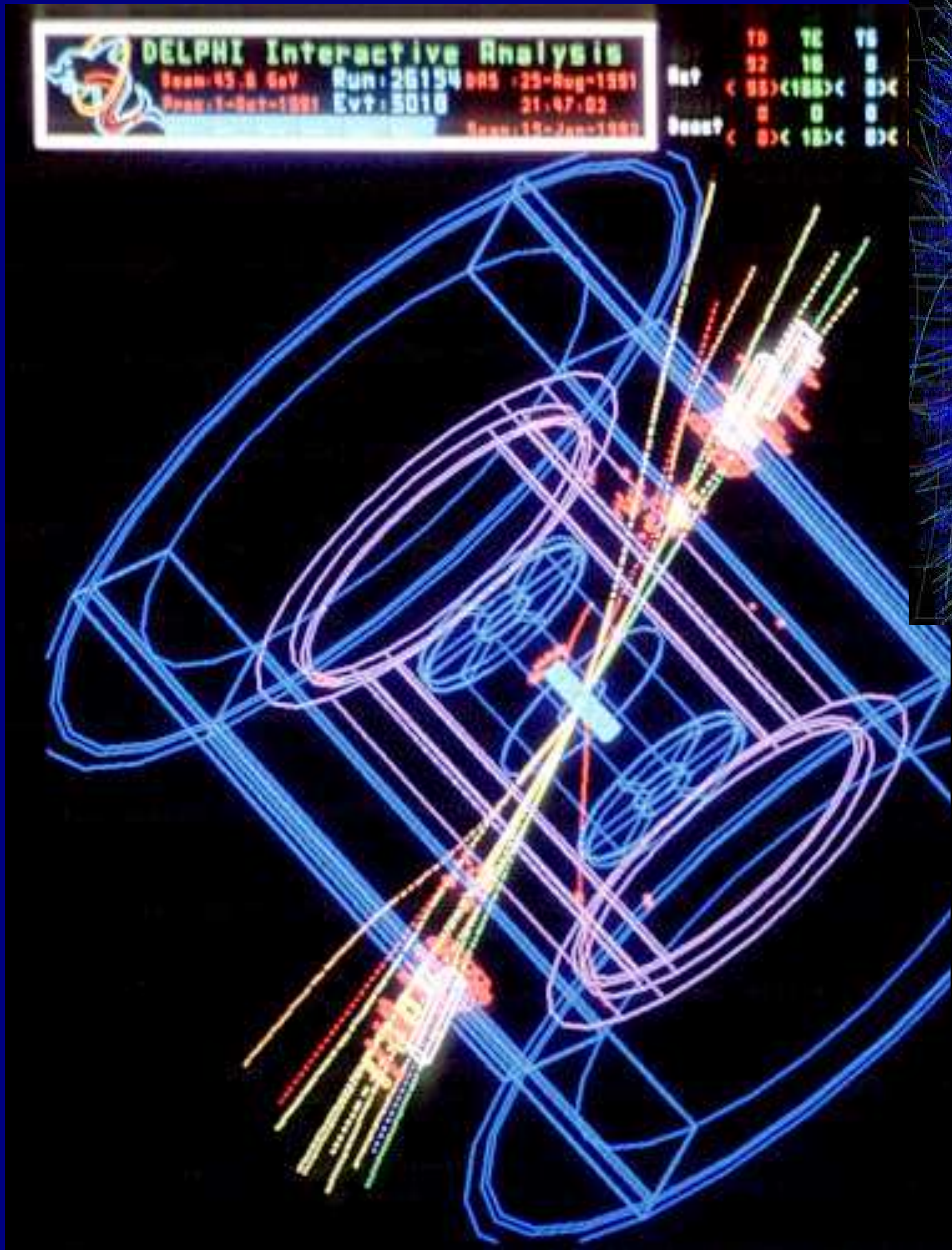


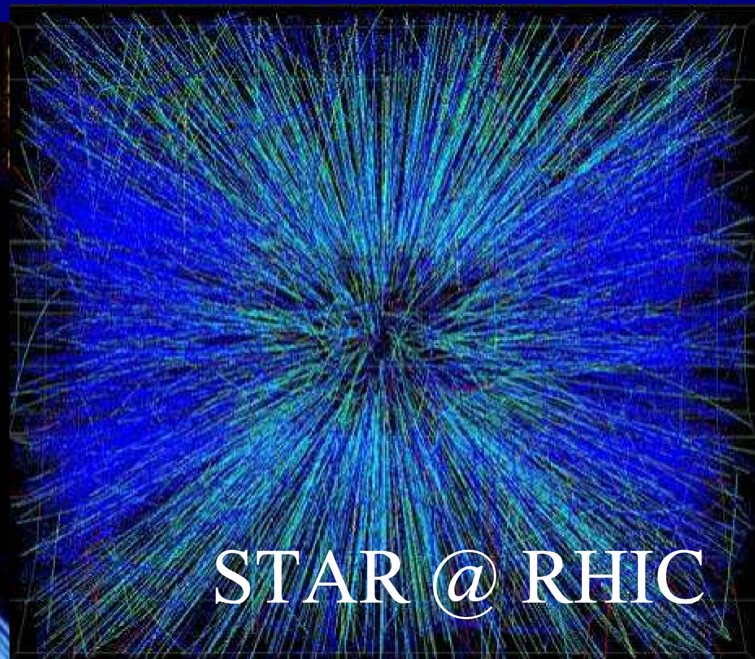

charm
gluon/quark dominates

beauty
Mass effect dominates

[Armesto, Dainese, Salgado, Wiedemann (2005)]

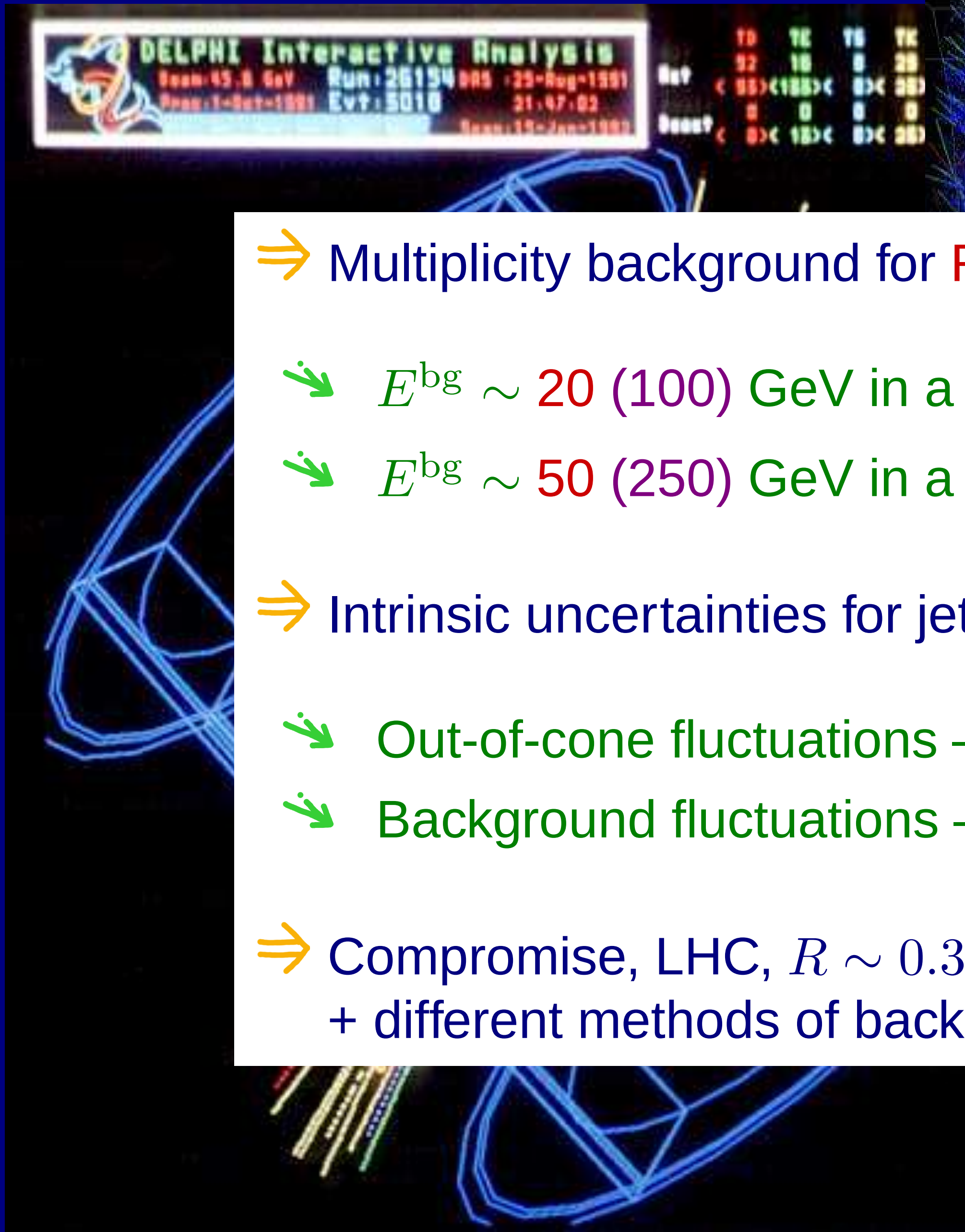
# Jets in HIC???

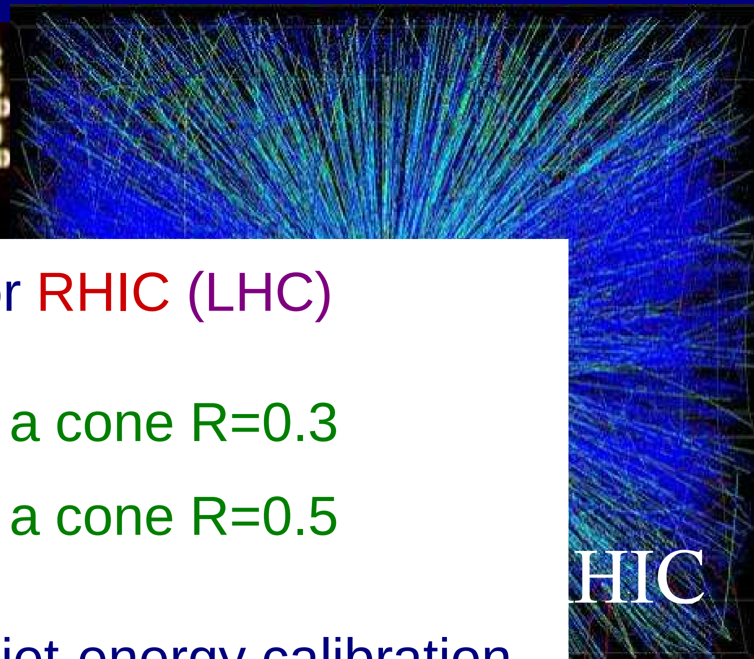

DELPHI Interactive Analysis
Run: 26154
Evt: 5010

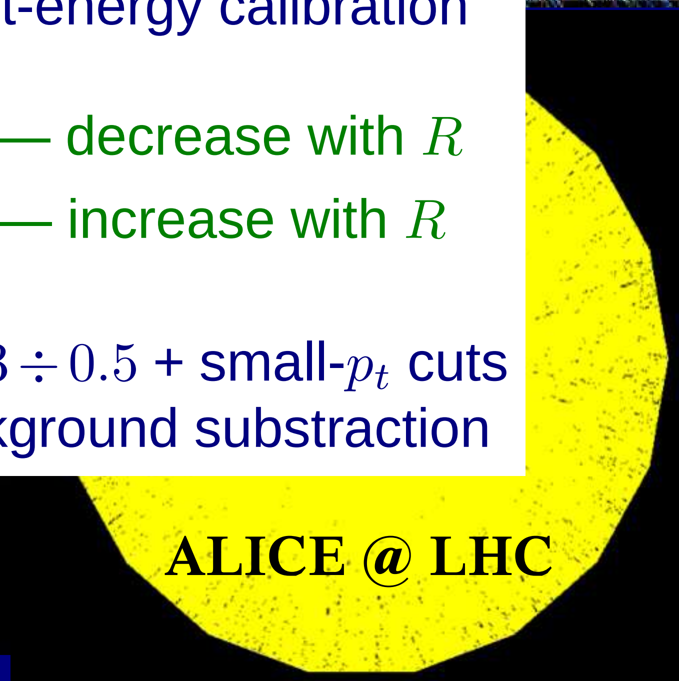

STAR @ RHIC


Alice event: 0, Run:0
Nparticles = 36276 Nhits = 19431047
ALICE @ LHC

# Jets in HIC???



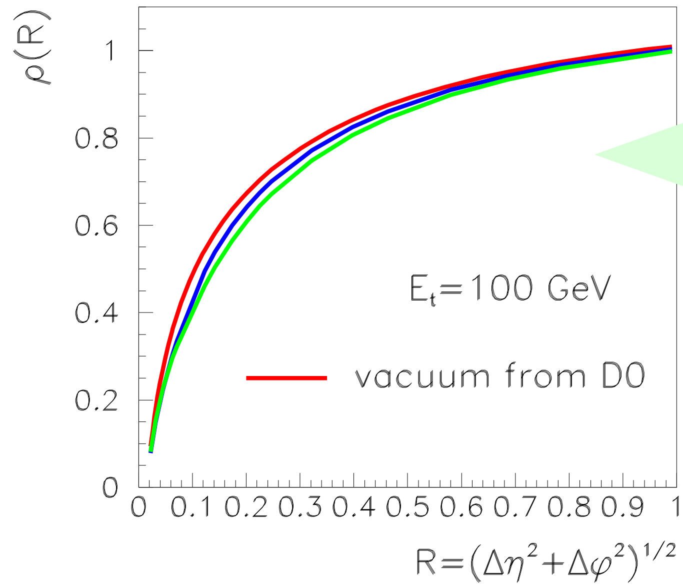




- ⇒ Multiplicity background for RHIC (LHC)
  - $E^{\mathrm{bg}} \sim$ 20 (100) GeV in a cone R=0.3
  - $E^{\mathrm{bg}} \sim$ 50 (250) GeV in a cone R=0.5
- ⇒ Intrinsic uncertainties for jet-energy calibration
  - Out-of-cone fluctuations — decrease with $R$
  - Background fluctuations — increase with $R$
- ⇒ Compromise, LHC, $R \sim 0.3 \div 0.5$ + small-$p_t$ cuts + different methods of background substraction

# Medium-modification of jet shapes

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



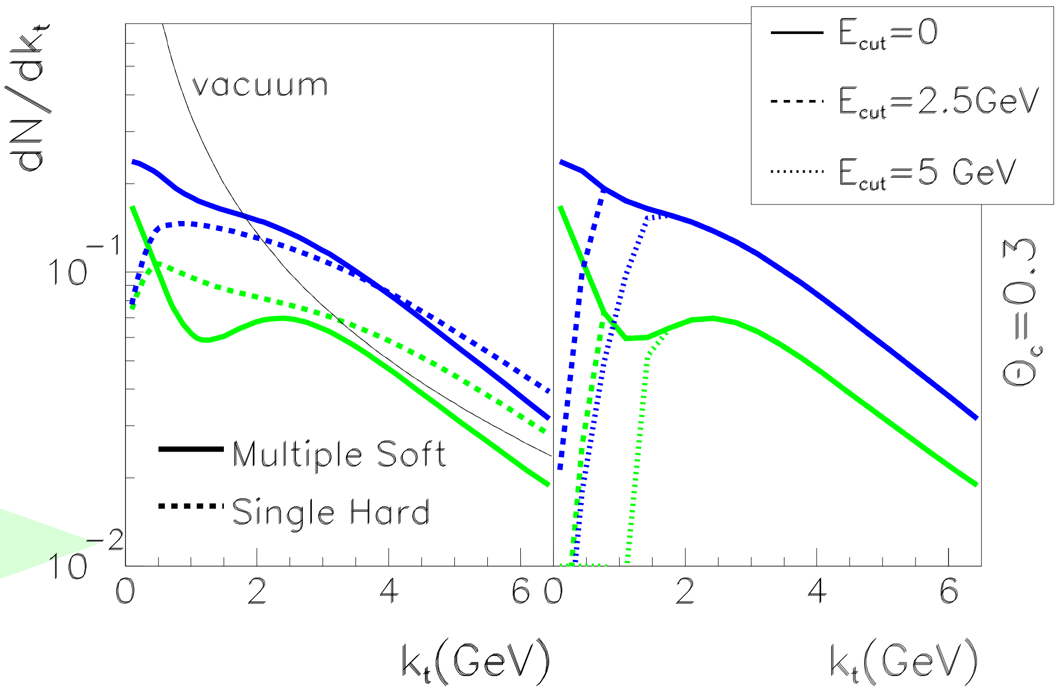

⇛ Fraction of the energy inside a cone $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

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

⇛ Jet energy calibration for $R \sim$ 0.3

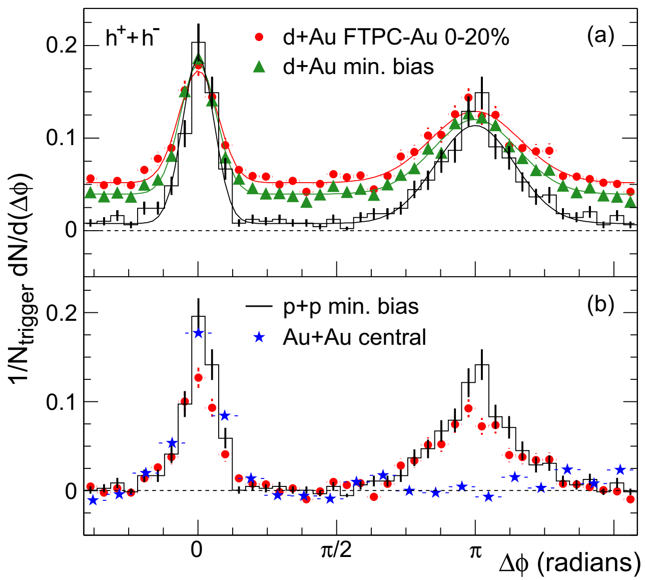
⇛ $k_t$-dependence of the multiplicity inside a cone

⇛ Large broadening



# Two-particle correlations $\longrightarrow$ jets at RHIC

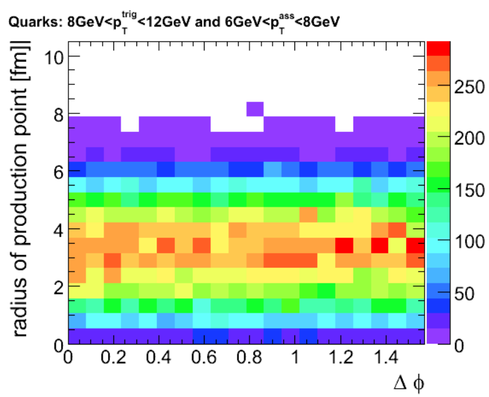
## Small-$p_t$ cuts at RHIC

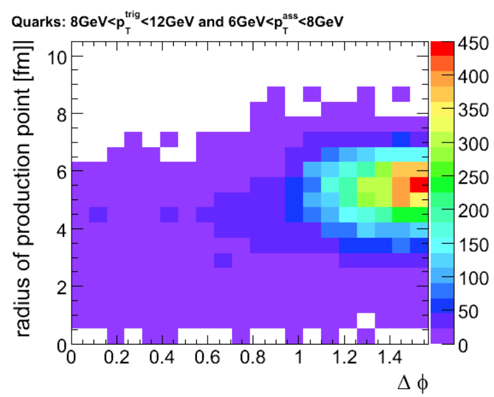



STAR; $4 \leq p_t^{\mathrm{trig}} \leq 6$; $2 \leq p_t^{assoc}$

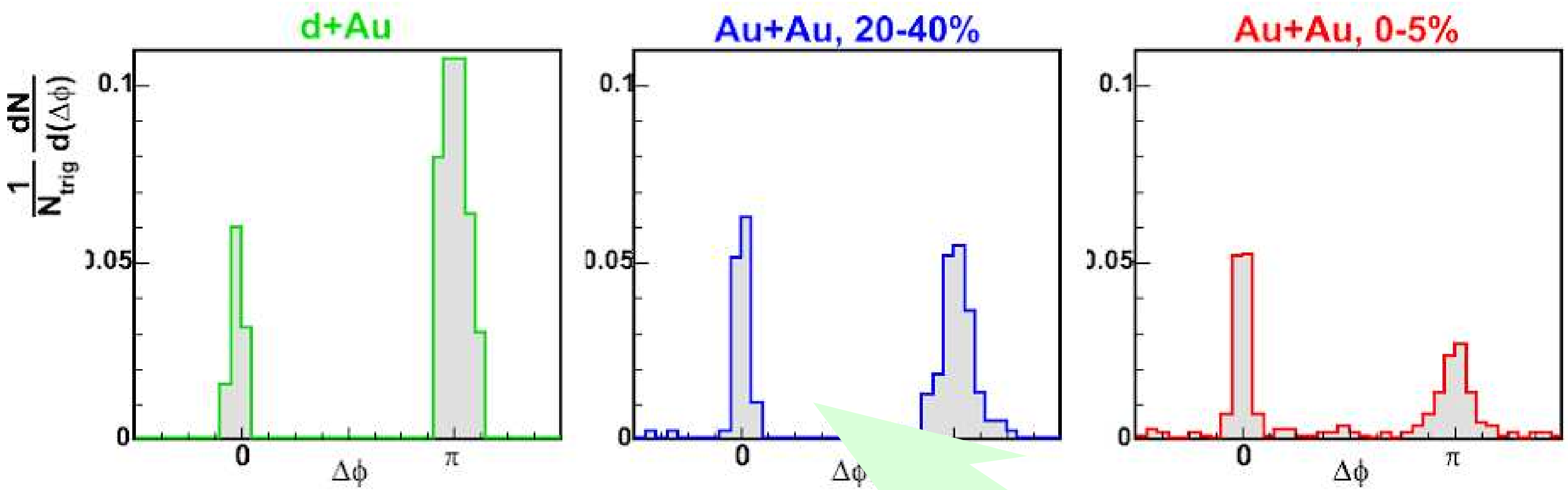
- Trigger bias $d\sigma/dp_t \sim 1/p_t^n$
  - Small energy loss for trigger particle
  - Small energy loss for assoc. for large $p_t^{\mathrm{assoc}}$
- Trigger bias $\Longrightarrow$ Surface and tangential emission
  - Small broadening

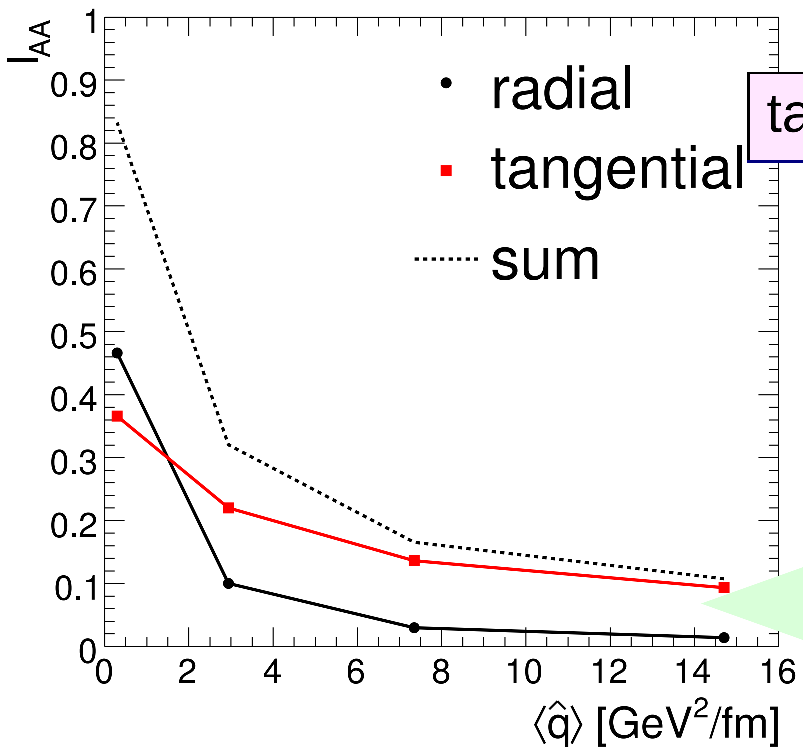
Poster by C. Loizides



# New data




talks by J. Dunlop and D. Magestro (STAR)

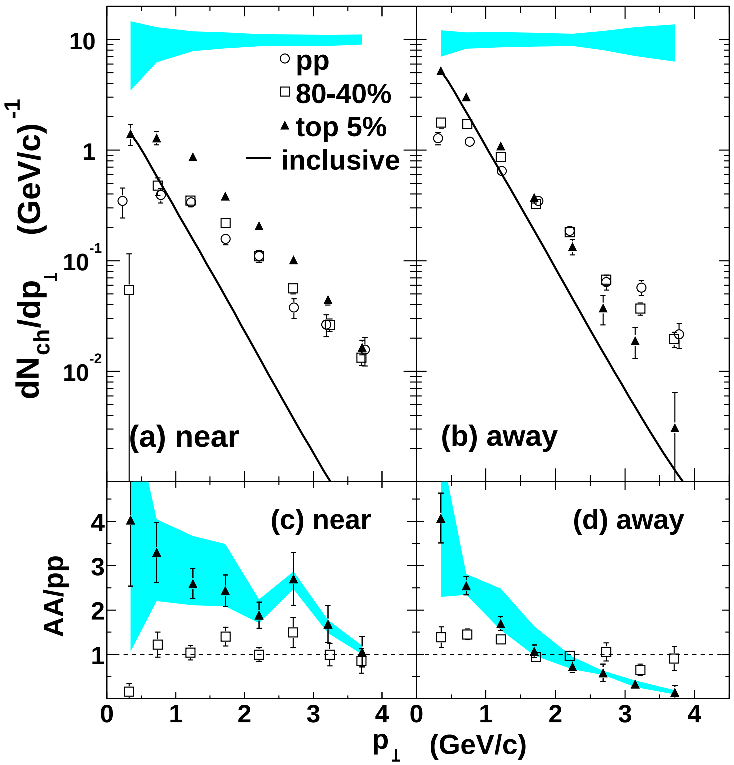
$8 < p_t^{\mathrm{trig}} < 15 GeV; p_t^{\mathrm{assoc}} > 6$

$\Rightarrow$ New data from high-$p_t$ azimuthal correlations constrain $\hat{q}$ further

Poster C. Loizides

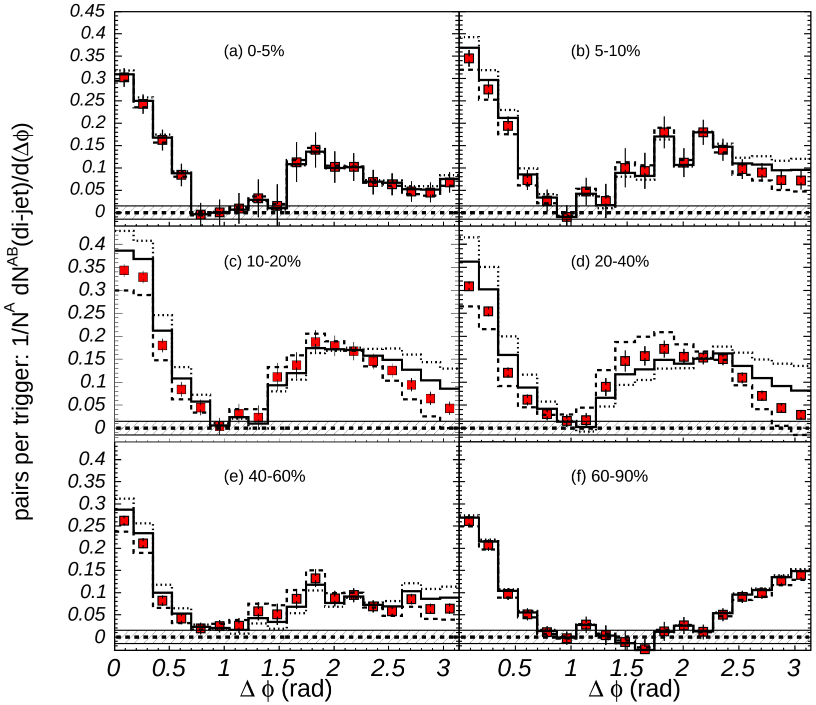
# Removing the cut-off at RHIC

## Interplay between the soft bulk and high-$p_t$




[STAR Collaboration 2005]

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



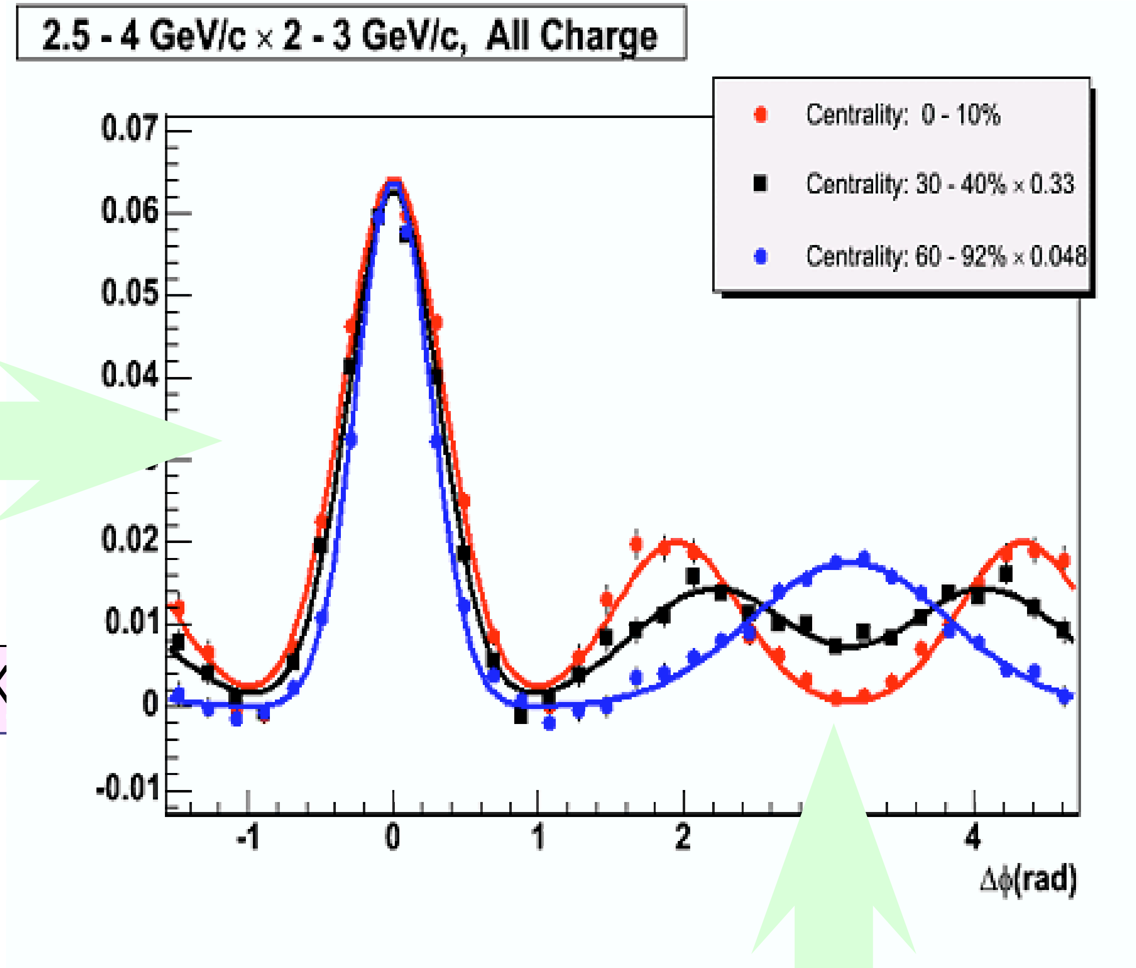

[PHENIX Collaboration 2005]

$2.5 \leq p_t^{\mathrm{trig}} \leq 4$ GeV; $1 \leq p_t^{\mathrm{assoc}} \leq 2.5$ GeV

⇛ Associated particles are softer

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

# New data




- ⇒ Moderate broadening in near side
- ⇒ dissappears for larger $p_t^{\text{trigg}}$

Talk H. Büsching, PHENIX

$p_t$ and centrality dependence

# 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]

Parallel talks: A. Majumder, J. Casalderrey-Solana

## Medium–induced gluon radiation

- Softer than vacuum $\longrightarrow$ maximum at $\omega \sim \hat{q}^{1/3} \sim 1...3$ GeV
- Small-energy radiation $\Longrightarrow$ Large angle
  - Possibility of secondary radiation for large angle
- Effect disappears for increasing $p_t^{\rm assoc} \gtrsim \hat{q}^{1/3}$

# Limitations/future developments

$\longrightarrow$ Medium

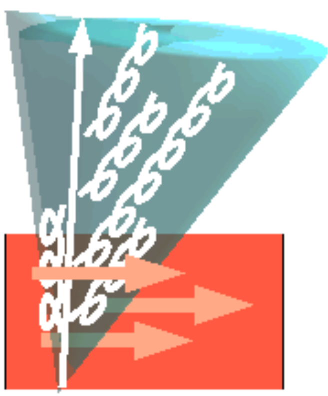
$\longrightarrow$ Shower evolution

# Improving the model of the medium

Beyond the medium as a collection of static scattering centers

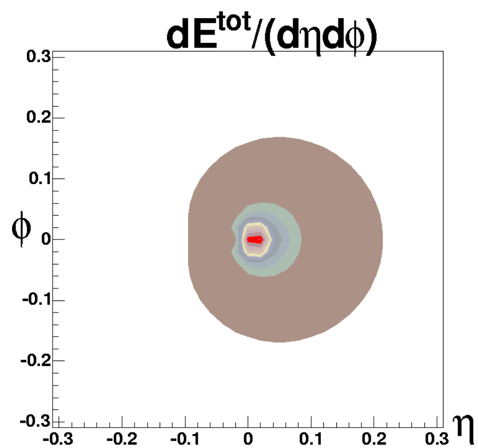
- Hydro: consistent picture of low-$p_t$ RHIC data given by $T^{\mu\nu}$ + E.o.S.
  - $T^{\mu\nu} = (\epsilon + p)\, u^\mu u^\nu - p\, g^{\mu\nu}$ is the fundamental object describing the medium $\Longrightarrow \quad \hat{q}(T^{\mu\nu})$
  - Example, longitudinal flow $\hat{q} = c\,\epsilon^{3/4} \rightarrow c\,(T^{zz})^{3/4} = c\,(p + \Delta p)^{3/4}$

$$\Delta p = (\epsilon + p)u^z u^z = 4p\frac{\beta^2}{1-\beta^2}$$



- Flow: additional source of induced radiation
- Asymmetric jet shapes in the $\eta \times \phi$ plane

Armesto, Salgado, Wiedemann 2004



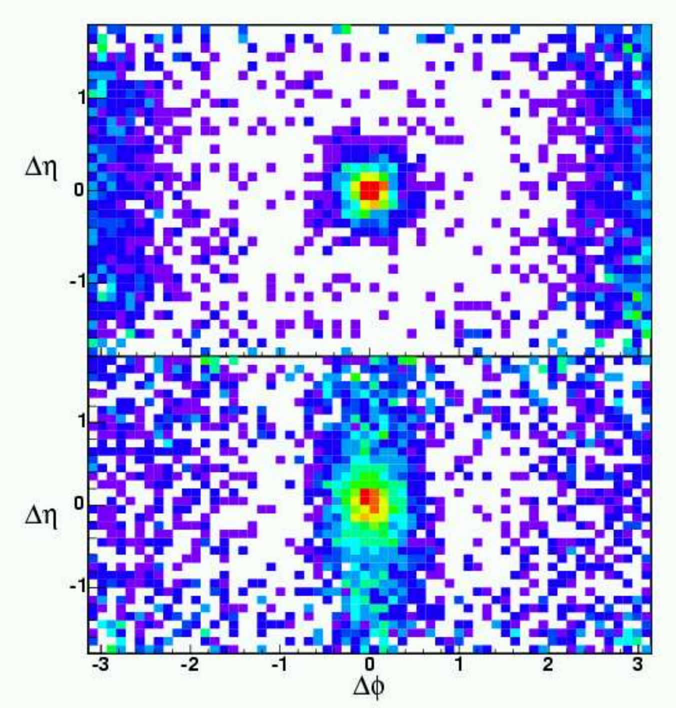

- Full 3-D hydrodynamical simulation coupled to jet-quenching needed

# Measuring collective flow with jets

## Longitudinal flow

Space-time picture of collision

[STAR preliminary, D. Magestro HP04]

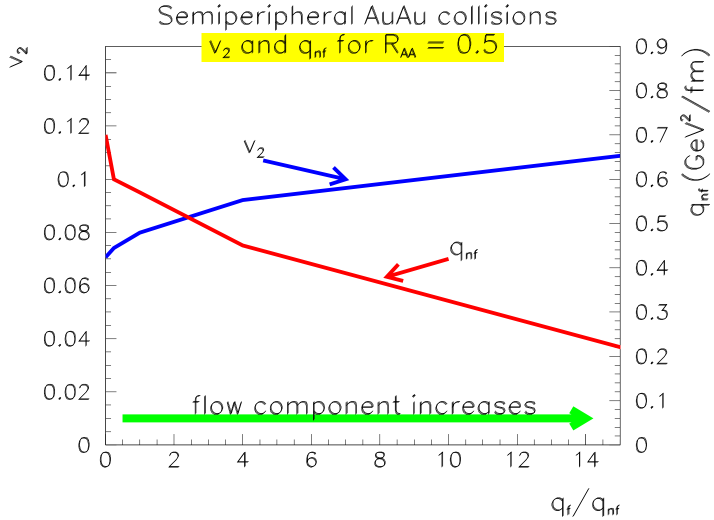



$$3\,\mathrm{GeV} < p_t^{\mathrm{trigg}} < 6\,\mathrm{GeV};$$
$$2\,\mathrm{GeV} < p_t^{\mathrm{assoc}} < p_t^{\mathrm{trigg}}$$

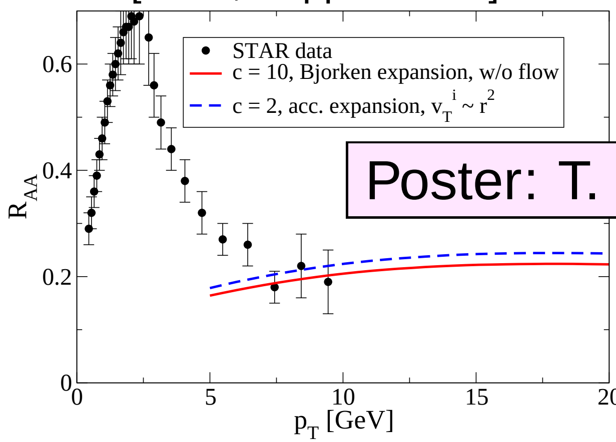
Poster: D. Magestro

## Transverse flow

[Armesto, Salgado, Wiedemann 2004]




[Renk, Ruppert 2005]




Poster: T. Renk

# 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
- Can this be generalized to the medium?

$$\omega\frac{dI^{\rm vac}}{d\omega dk_t^2}\sim\frac{1}{k_t^2} \qquad\qquad \omega\frac{dI^{\rm med}}{d\omega dk_t^2}\sim\frac{1}{k_t^4}\left(\frac{\omega_c}{\omega}\right)^n ; n=\frac{1}{2}....2$$

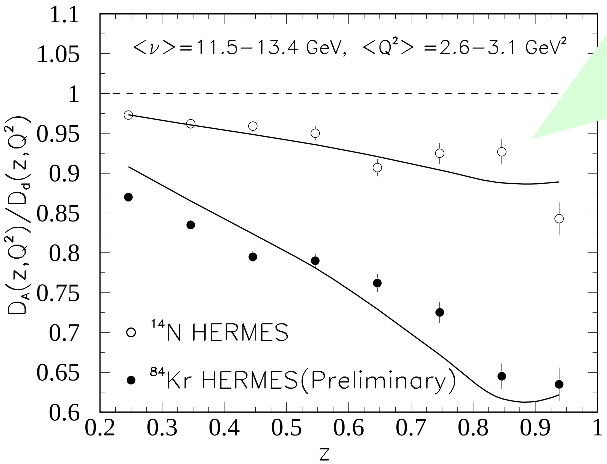
  - With formation time effects regularizing the divergences

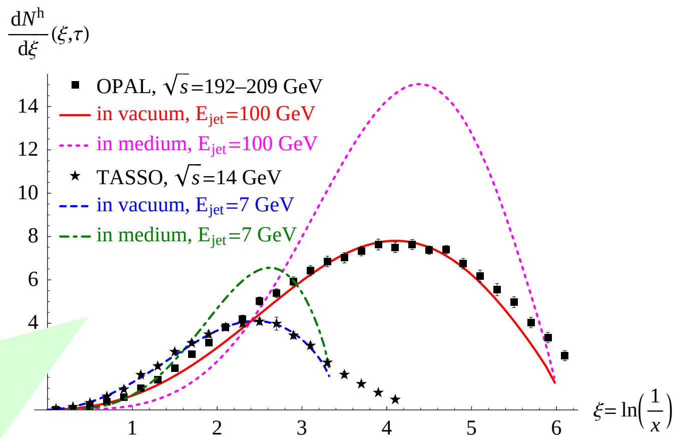
# Toward an evolution equation

Is there a $Q^2$-dependence on the energy loss?

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

$$\tilde{P}_{ji}(z,x,x_L,l_T^2) = P_{ji}(z) + \Delta P_{ji}(z,x,x_L,l_T^2)\,; \quad \Delta P_{ji}(z,x,x_L,l_T^2) \propto \frac{1}{l_T^2}$$




⇛ Enhance the singular parts of the vacuum splitting functions in the Modified-Leading-Log-Approximation [Borghini, Wiedemann 2005]

$$P_{qq}(z) = C_F \left( \frac{2(1+f_{\rm med})}{(1-z)_+} - (1-z) \right)$$

Parallel talk N. Borghini

# Jet quenching and the sQGP

- Very large value of $\hat{q} \sim$ 5...15 GeV$^2$/fm obtained from fit to the data
  - Taking $\hat{q} = c\,\epsilon^{3/4} \Rightarrow c \gtrsim 5\; c_{\rm ideal}^{QGP}$ [estimation for ideal QGP: Baier 2002]
  - Expectations from relation to CGC: $Q^2_{\rm sat} \sim \hat{q}\,L \gtrsim \mathcal{O}(10$ GeV$^2)$

$\hat{q} \gtrsim$ 5 times larger than expected

- Why? Several possibilities
  - Formalism not quantitatively reliable? (incomplete)
  - Scattering cross sections $\gtrsim$ 5 times larger than perturbative estimates $\Longrightarrow$ relation with sQGP hypothesis
  - Flow effects very significant: $\hat{q}$ measures $\epsilon$ AND flow
- Jet quenching has the potential to give answer to these questions and study the medium properties with a quantified effect.

$\Longrightarrow$ New data presented at this Conference!

# Summary

Messages from RHIC

- Jet quenching is the dominant medium mechanism at high-$p_t$ $\Longrightarrow$ Very dense medium produced at RHIC
- Heavy quarks able to constrain energy loss $\longrightarrow$ reference for $e^-$!
- Trigger bias effects make it difficult to quantify broadening
  - High-$p_t$ $\longrightarrow$ fragmentation in the vacuum
  - Moderate/Small-$p_t$ $\longrightarrow$ extreme broadening in away side
  - Small $\Delta\phi$-broadening in near side, but dissappears with $p_t$?
  - New constrains to energy loss ($\hat{q}$)

Lessons for the LHC

- High-$p_t$ particles still fragile objects $\longrightarrow$ Study true jets
  - Experiment: Remove trigger bias, study associated radiation
- Open mind in the (wider) intermediate-$p_t$ $\longrightarrow$ measure flow with jets?
- Theory: Improve model for medium and shower – $Q^2$-dependence