Jets at RHIC and LHC heavy-ion collisions

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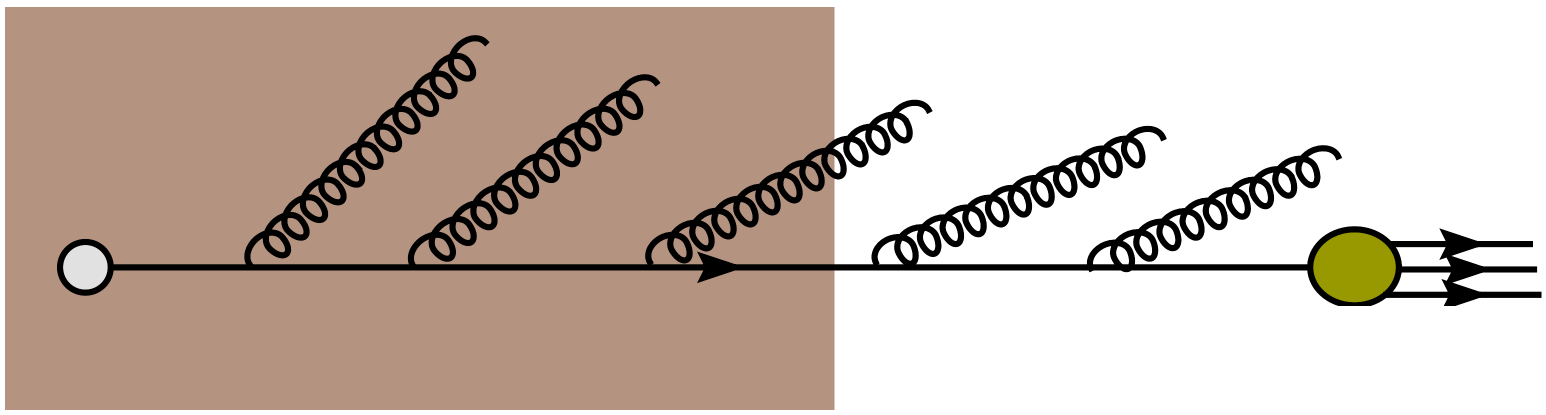
- ***Jet quenching has been established at RHIC as a fundamental tool in the study of hot matter in heavy-ion collisions***
    - *Single inclusive suppression*
    - *Two- and three-particle correlations*
    - *Particle species dependence: Specially heavy-quarks*

RHIC phenomenology - Quenching Weights

- Vacuum and medum-induced gluon radiation treated separately
  - Medium-radiation first
  - Medium produces only energy loss

    (no modification of the evolution)
  - Independent gluon emission approximation - Poisson distribution



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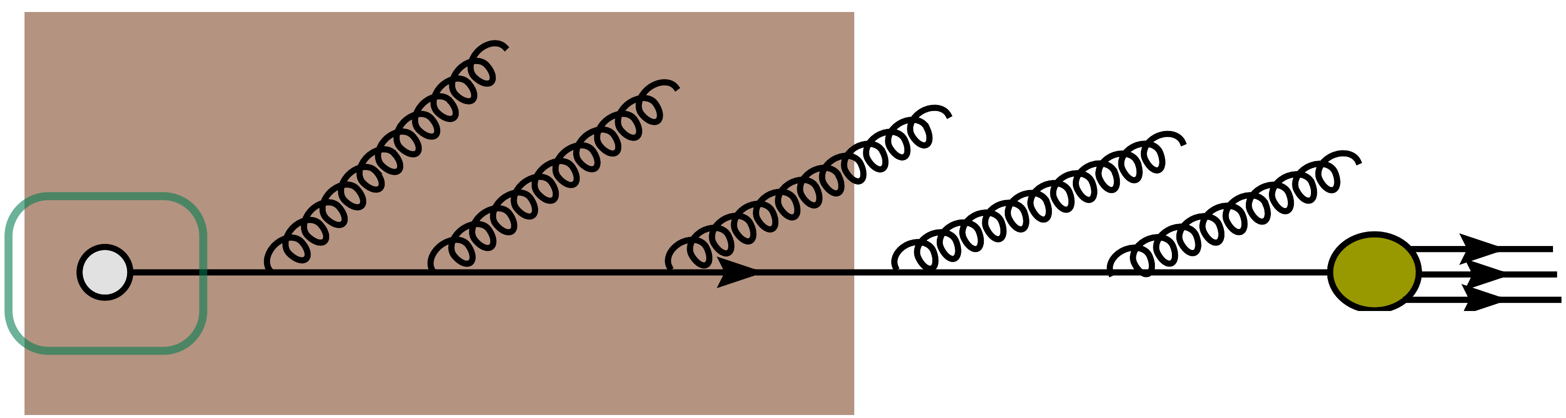
Hard Process



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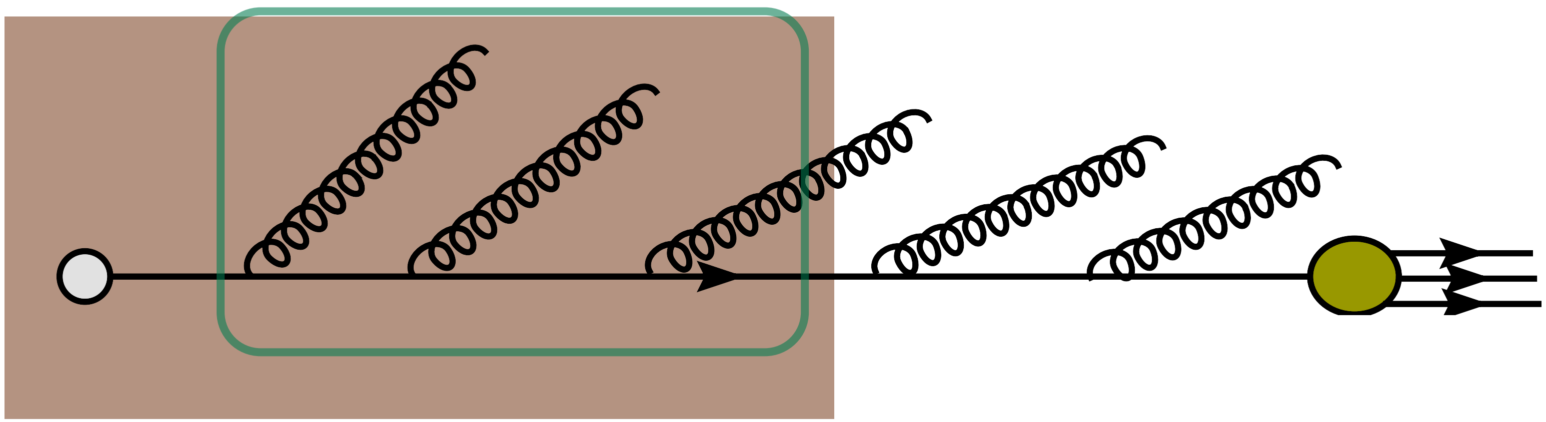
Medium-induced gluon radiation



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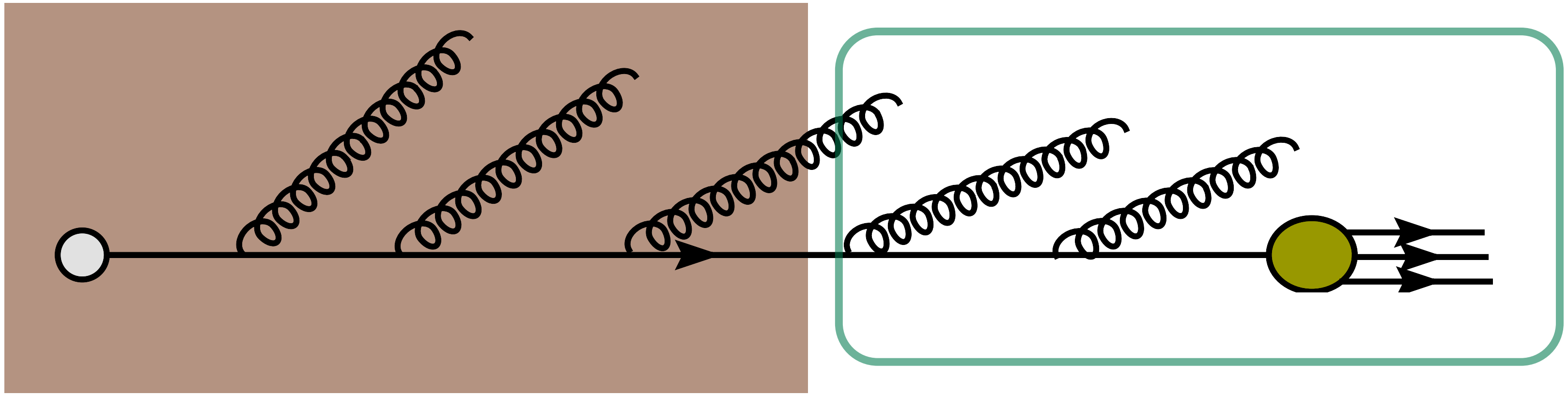
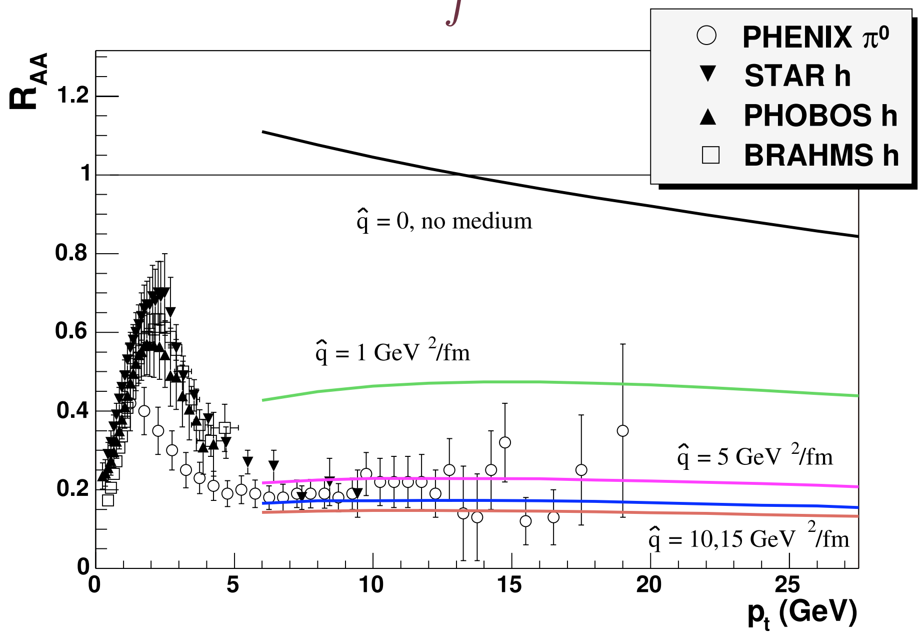
DGLAP vacuum evolution and hadronization

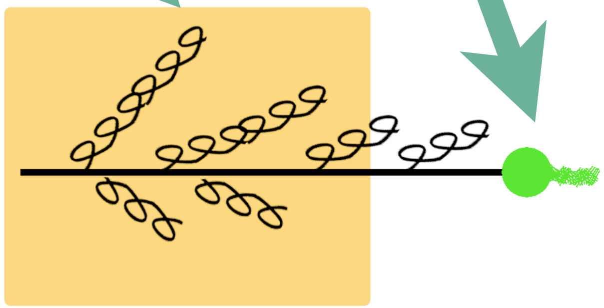


The inclusive particle suppression

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



[Eskola, Honkanen, Salgado, Wiedemann 2005]



⇛ Transport coefficient

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

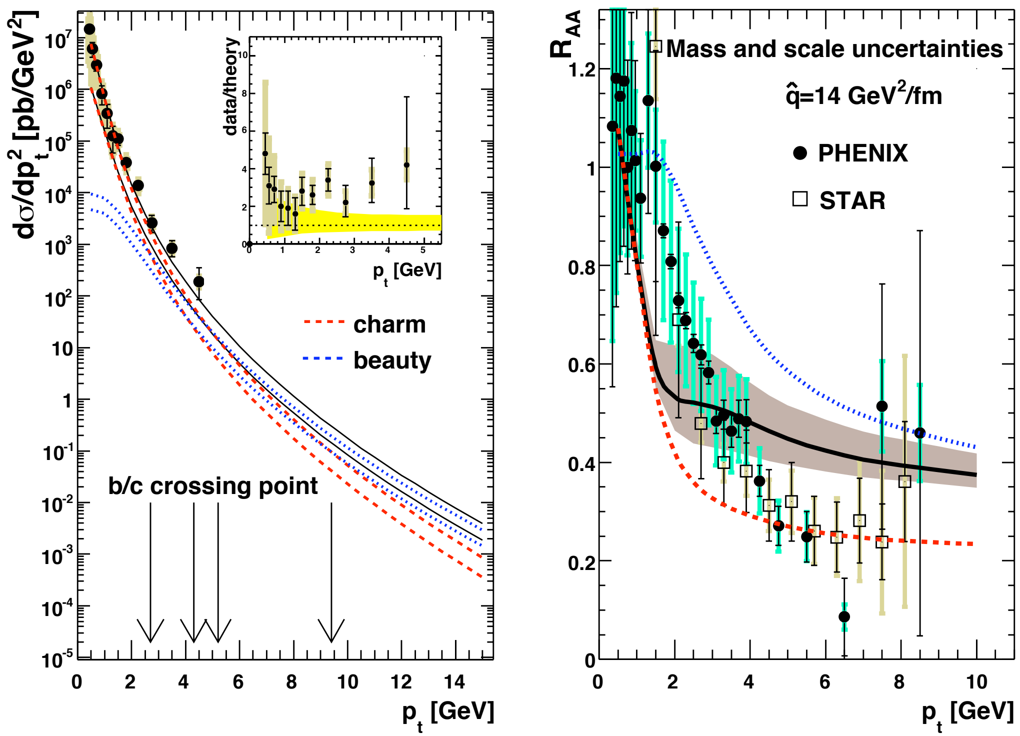
⇛ Data favor a large transport coefficient

$$\boxed{\hat{q} \simeq 5...15 \ {\rm GeV}^2/{\rm fm}}$$

[Gyulassy, Levai, Vitev 2002; Arleo 2002; Dainese, Loizides, Paic 2004; Wang, Wang 2005; Drees, Feng Jia 2005; Turbide, Gale, Jeon, Moore 2005; Renk, Ruppert, Nonaka, Bass 2007...]

The single electron puzzle at RHIC

⇛ Suppression of charm and bottom at RHIC



[Armesto, Cacciari, Dainese, Salgado, Wiedemann 2005]

⇛ Only non-photonic electrons measured

- Do not distinguish between charm and bottom
- Large theoretical uncertainty in the c/b ratio

⇛ Measure charm and bottom separately

- ***Improve the static medium assumption***
- ***Hydrodynamics to describe the medium evolution***
  - *Scaling law from dynamical to static scenario is known*

    [Salgado, Wiedemann 2002; also BDMS, Gyulassy, Vitev, Wang]
  - *Define medium properties as*

$$\langle \hat{q} L \rangle = \int d\xi \hat{q}(\xi) \qquad \langle \omega_c \rangle = \int d\xi (\xi - \xi_0) \hat{q}(\xi)$$

  - *where*

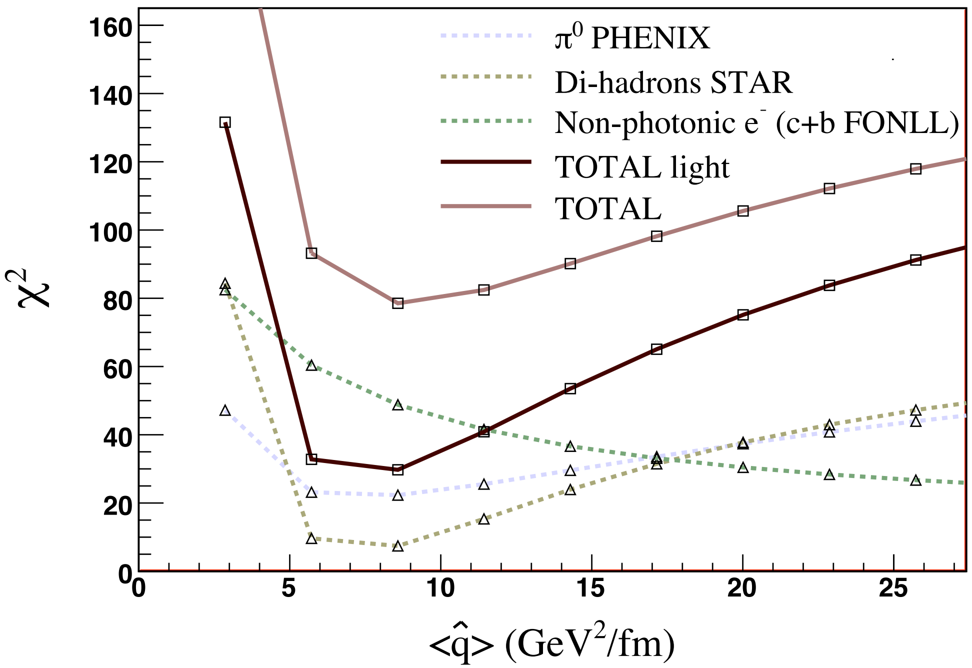
$$\hat{q}(\xi) = K \hat{q}_{\rm ideal}(\xi) = K \; 2\epsilon^{3/4}(\xi)$$

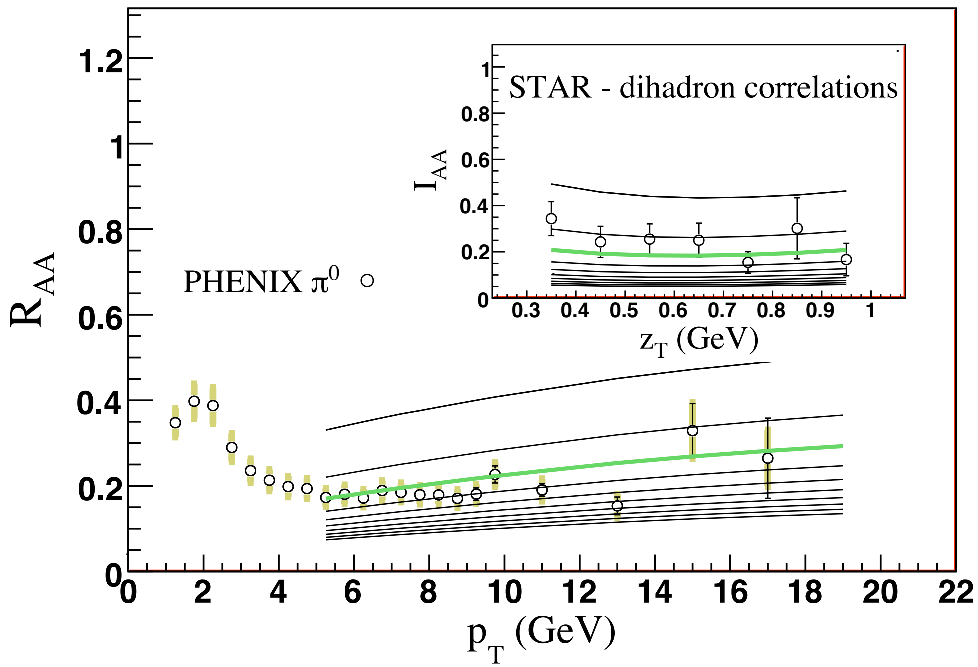
  - *and energy density taken from a hydro calculation*

    [Renk, Ruppert, Nonaka, Bass, Gale, Majumder, Qin]

Global fit to data using a hydrodynamical medium

⇛ A common fit of several observables to obtain the value of $\hat{q}$





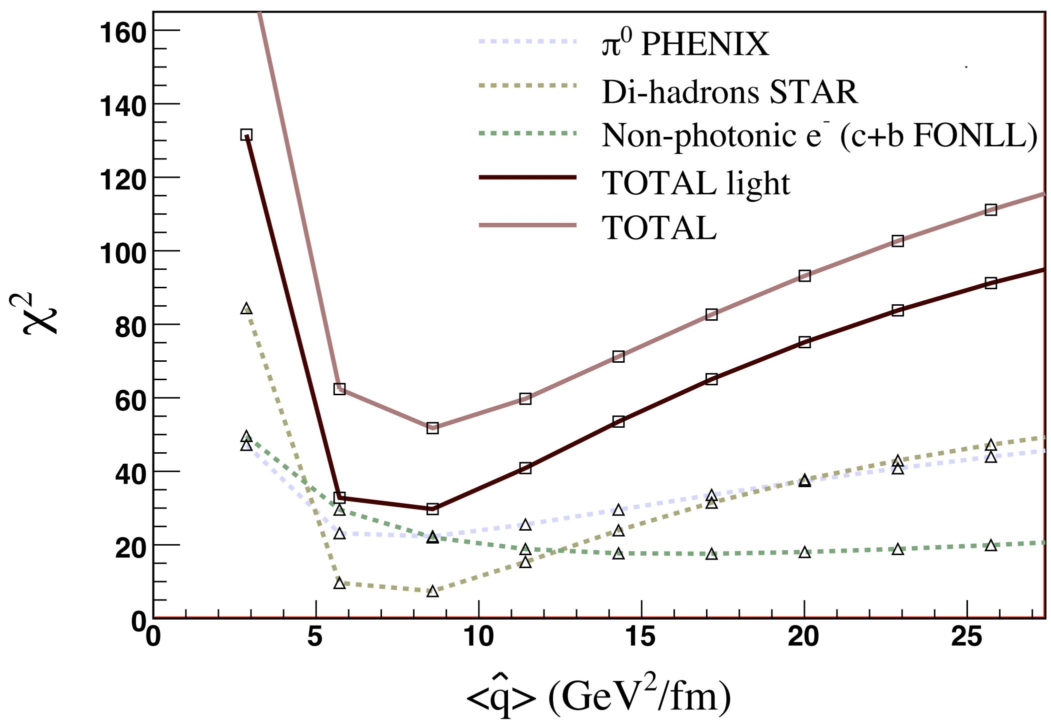
$$\langle \hat{q} \rangle = 8.6^{+0.8}_{-1.6} \mathrm{GeV}^2/\mathrm{fm} \longrightarrow K = 4.1^{+0.38}_{-0.77}$$

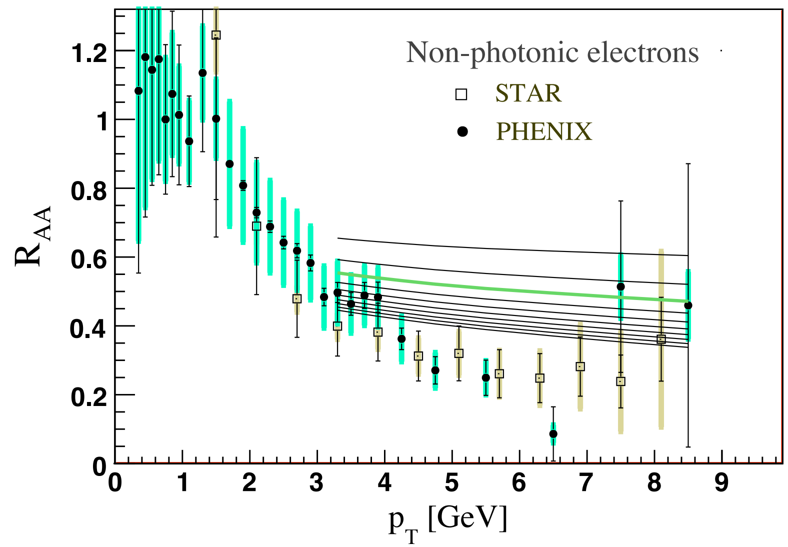
(Only light quarks in the fit)

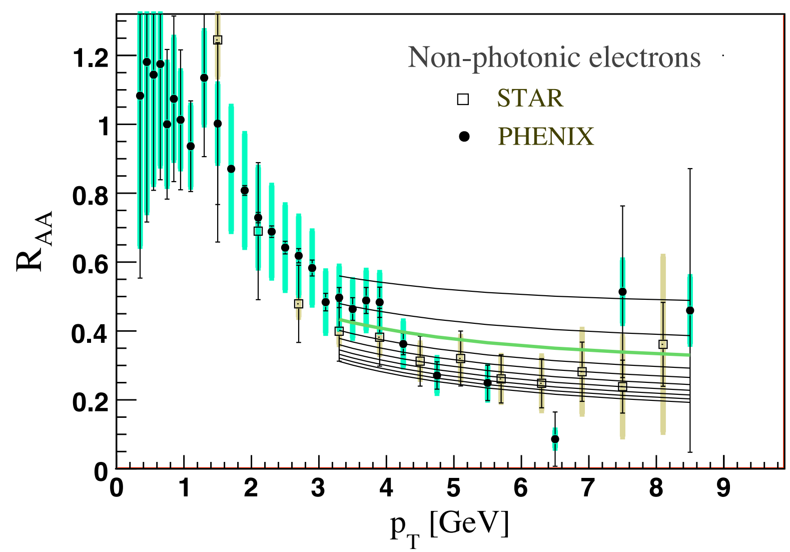
[Armesto, Cacciari, Hirano, Salgado, in preparation]

The single electron puzzle at RHIC II

The charm and botton contributions







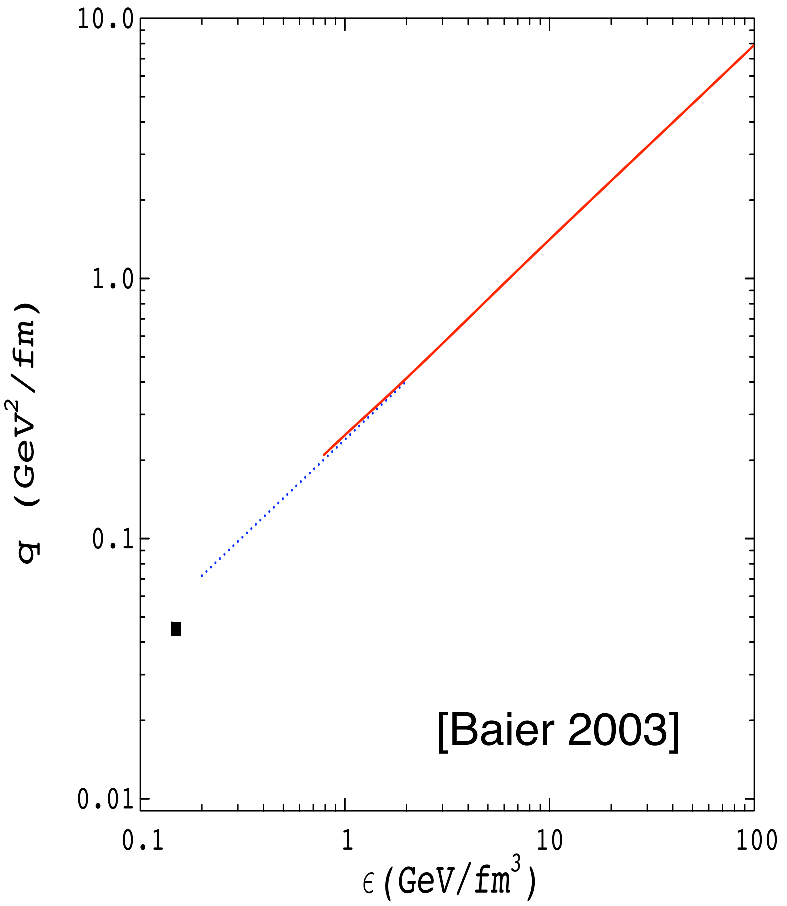
⇛ Conclusions unchanged

measure charm and bottom

⇛ Room for additional effects

[Talks by Aichelin and Peshier]

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



- Transport coefficient for an ideal quark-gluon gas

$$\hat{q}_{\mathrm{ideal\ gas}} \simeq \frac{72}{\pi}\xi(3)\alpha_s^2 T^3 \simeq \boxed{2\epsilon^{3/4}}$$

[Baier and Schiff 2006]

- Fits to the data

$\hat{q} > 5\ \hat{q}_{\mathrm{ideal\ gas}}$ [Eskola et al. 2004]

$\hat{q} \simeq 4.2\ \hat{q}_{\mathrm{ideal\ gas}}$ [Renk et al. 2007; Armesto et al 2008]

- Geometry plays a crucial role
- Model of the medium? sQGP?

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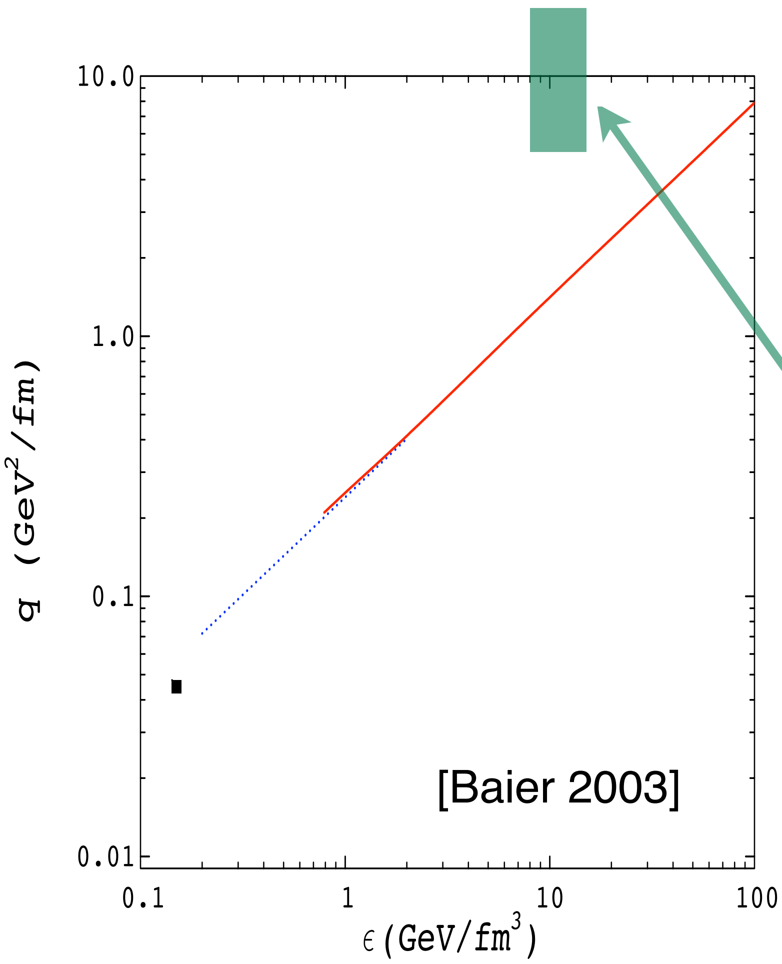

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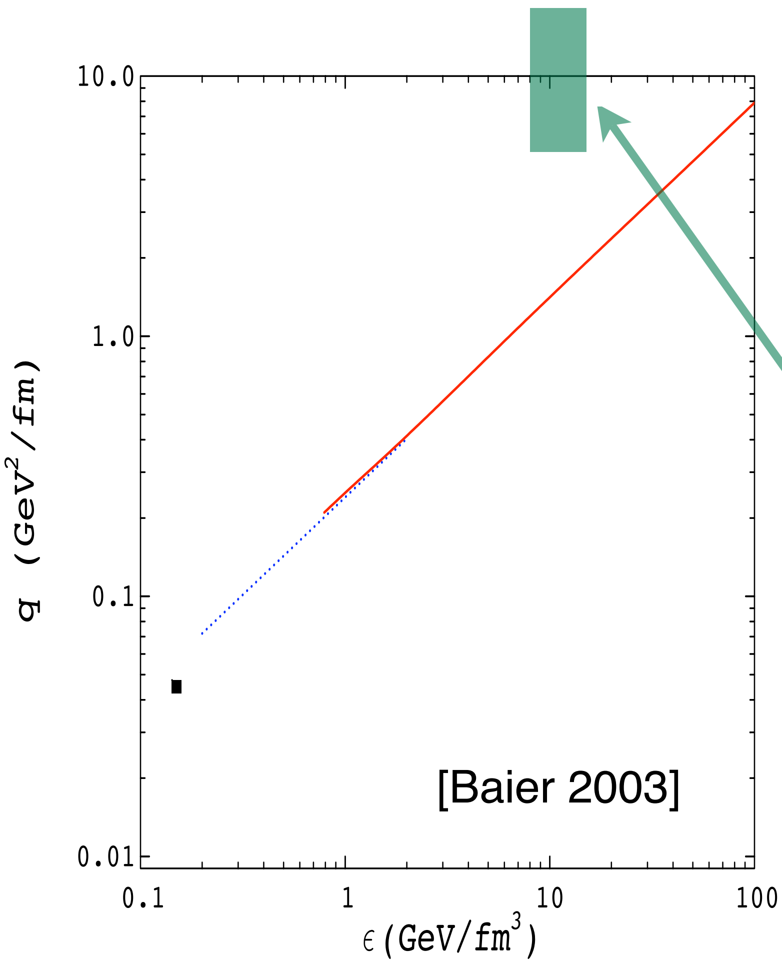

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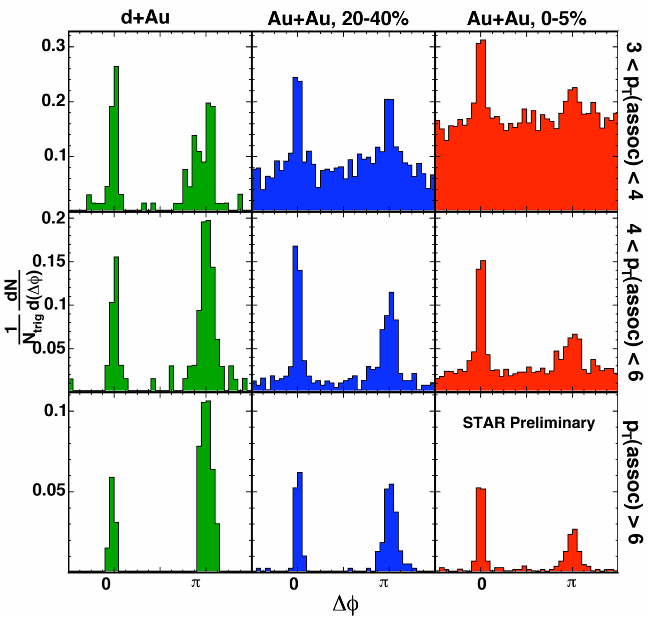
Signals large cross sections (much larger than perturbative ones?)

Jet studies in HIC



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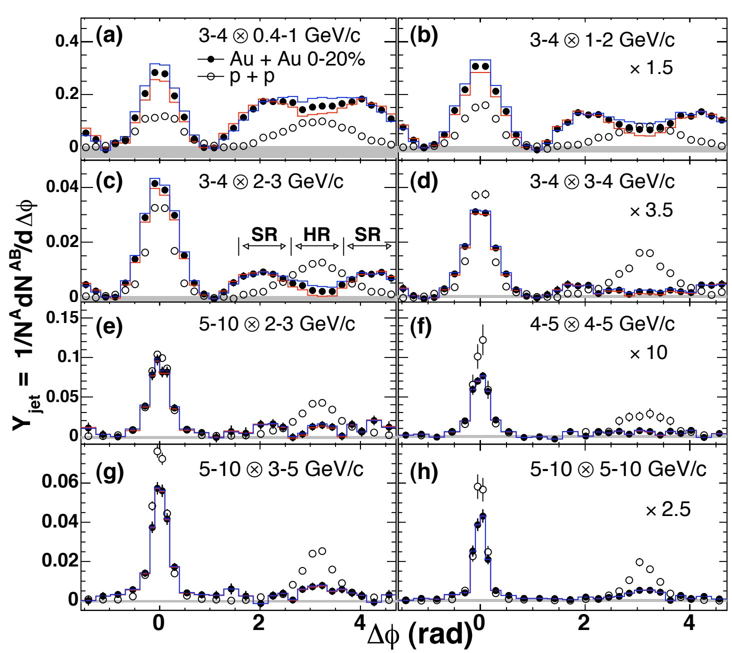
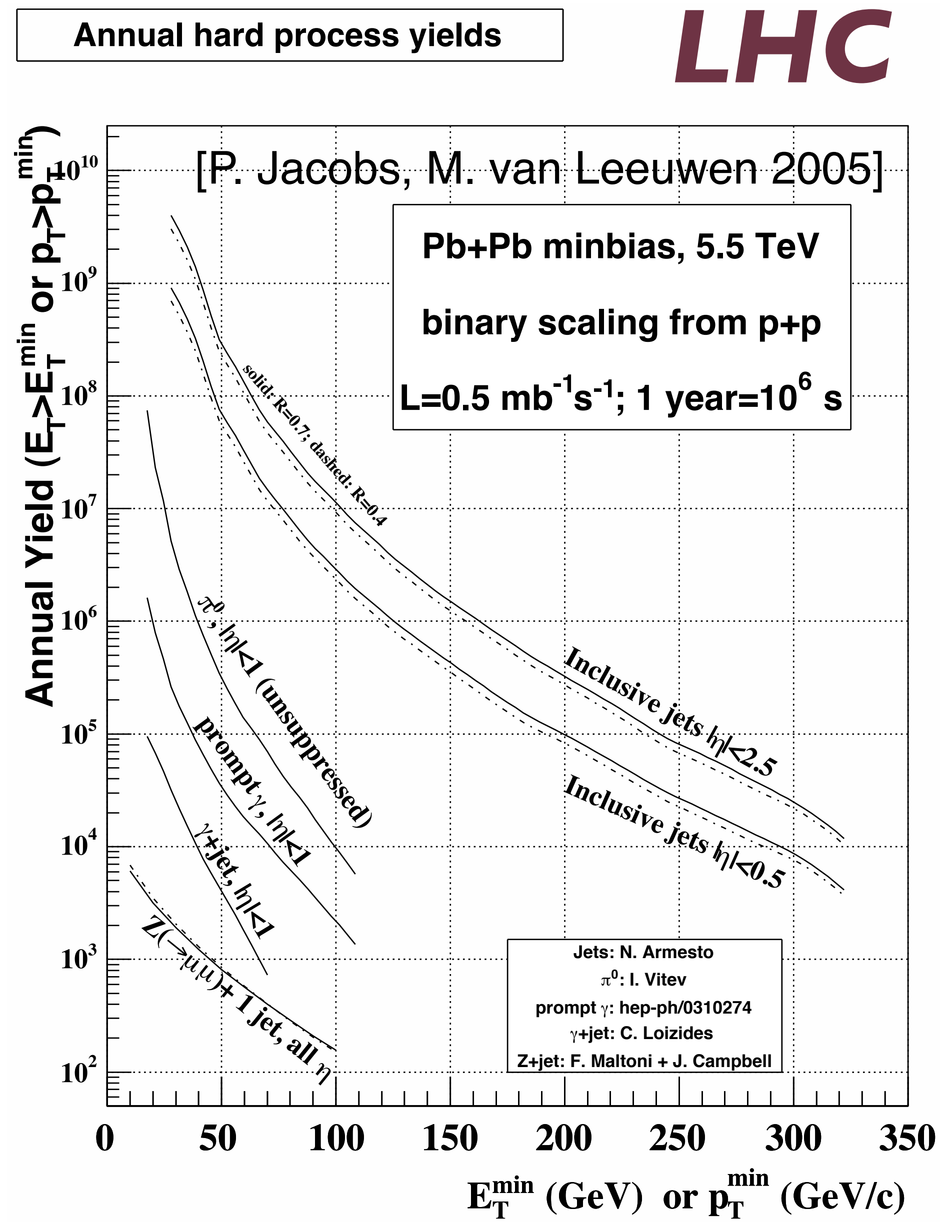


[PHENIX]



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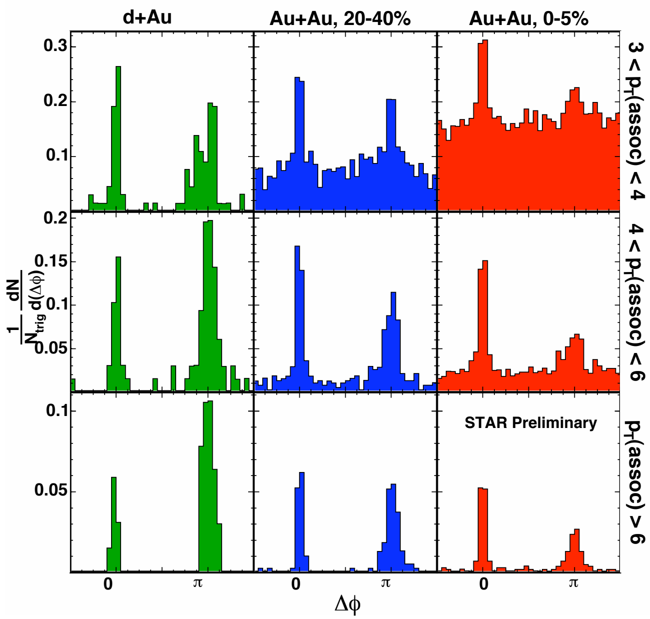

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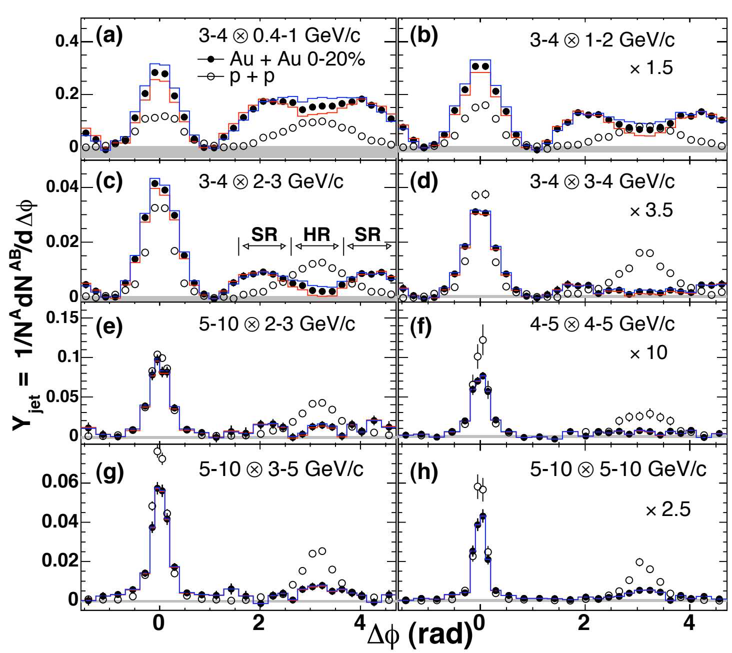

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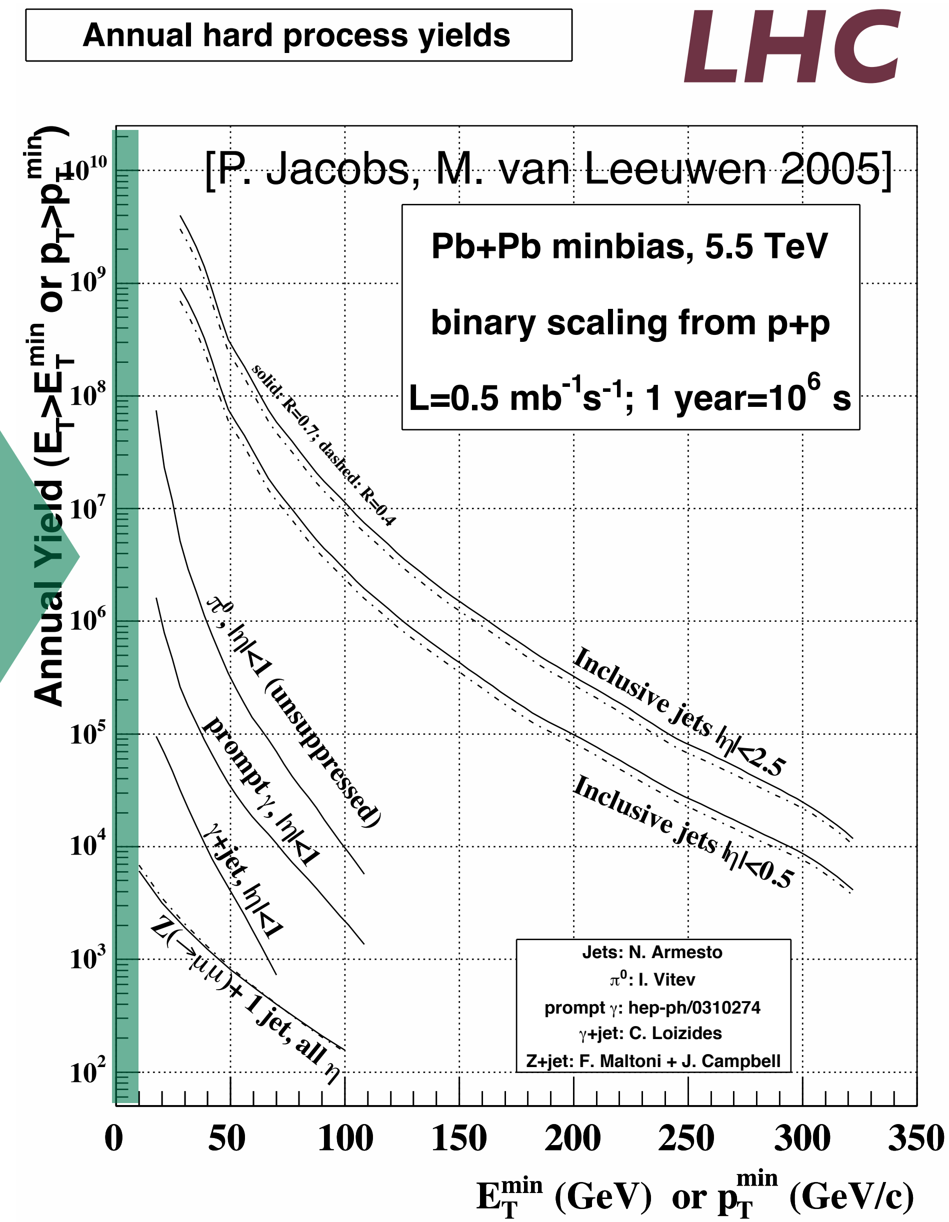
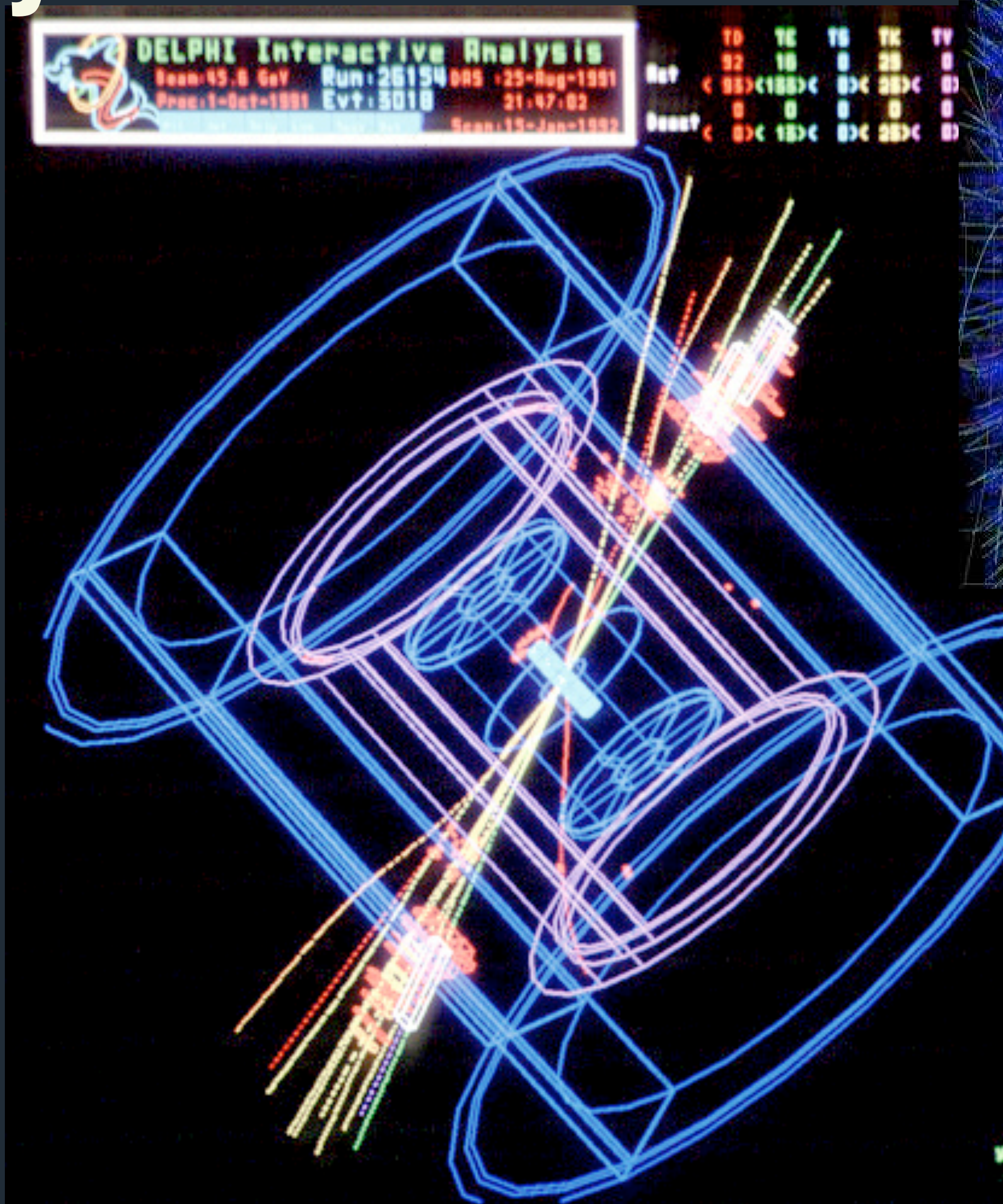
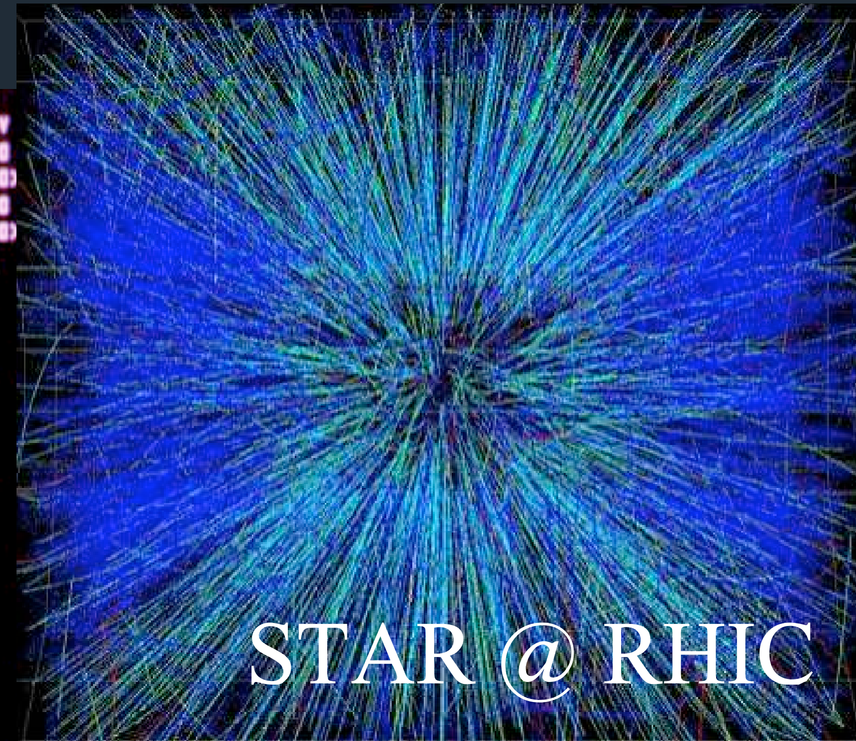


Jets in HIC



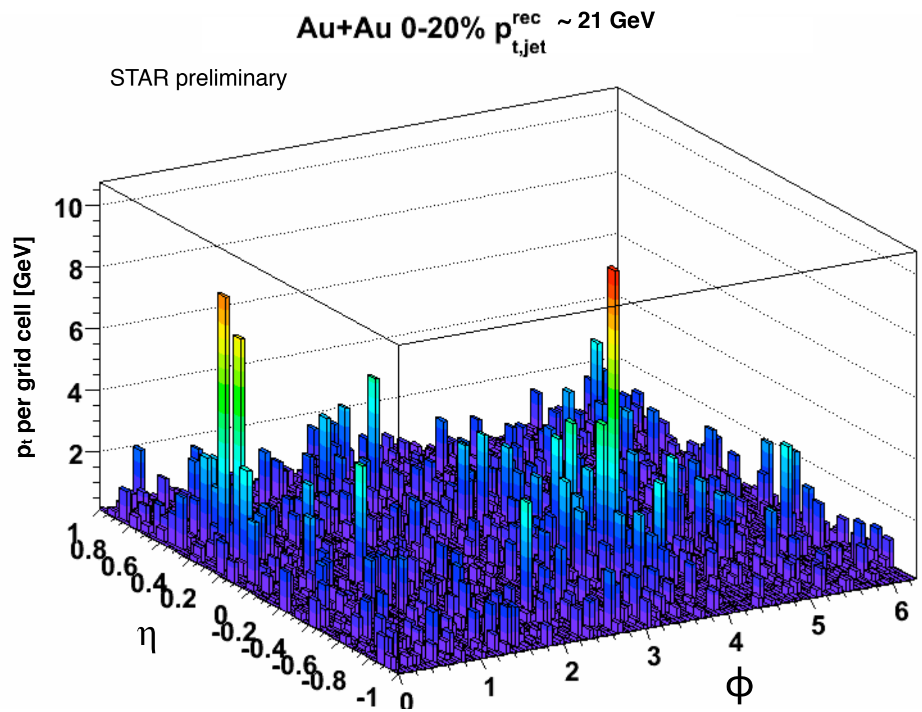


Jets in HIC

DELPHI Interactive Analysis

RHIC

First results appeared in HP2008!



A lot of work still needed

ALICE @ LHC

Jets and new developments

- **Exploratory studies up to now**
  - *Several effects might appear. We have only a partial knowledge*
- **One main goal: to have a Monte Carlo implementation**
  - *Armesto, Corcella, Cunqueiro, Salgado (also Xiang) **

** JHEP0802 (2008) 048; arXiv:0809.4433 [hep-ph] and in preparation*

  - *Zapp, Ingelman, Rathsman, Stachel, Wiedemann*

    (also Borghini, Sapeta)
  - *Lokhtin, Petrushanko, Snigirev, Teplov ...*
  - *Renk*

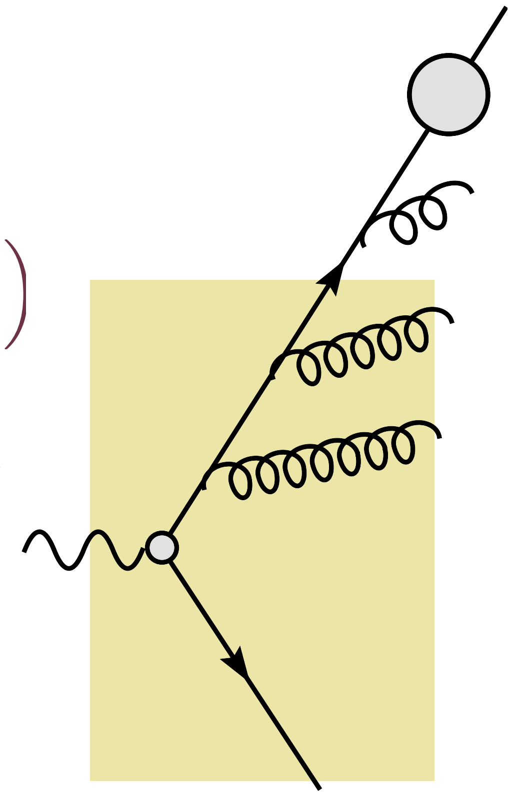
An improved in-medium evolution?

⇛ DGLAP evolution for FF in vacuum

$$\frac{\partial D_i^h(x,Q^2)}{\partial \log Q^2} = \sum_j \int_x^1 \frac{dz}{z}\frac{\alpha_s}{2\pi} P_{ji}(z) D_j\left(\frac{x}{z}, Q^2\right)$$

⇛ Define a medium-modified splitting probability

$$P^{\rm tot}(z) = P^{\rm vac}(z) + \Delta P(z)$$



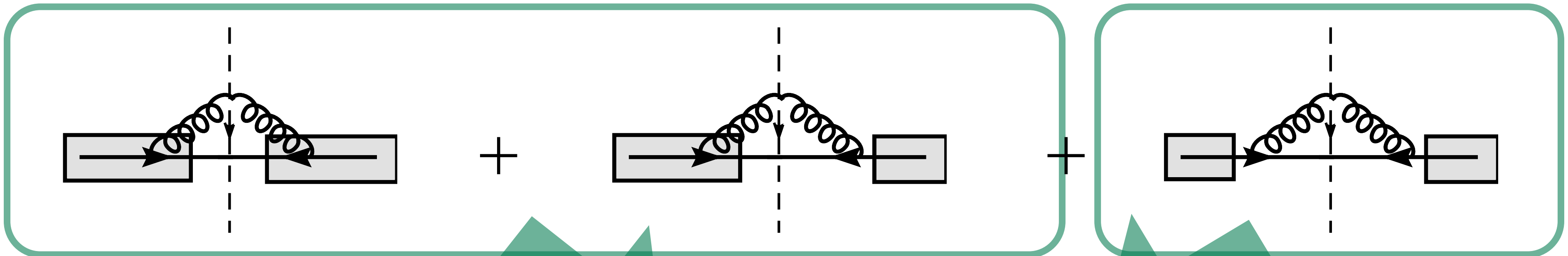
⇛ Improvements with respect to QW:

- Vaccum and medium-radiation treated on the same footing
- Energy conservation at each individual splitting
- Virtuality is included

[Wang, Guo 2001; Borghini, Wiedemann 2005; Polosa, Salgado 2006; Armesto, Cunqueiro, Salgado, Xiang 2007]

Medium-modified splittings

⇛ Remember that the total gluon radiation has vacuum+medium



$$\frac{dI}{dz\,dk_\perp^2} = \boxed{\frac{dI^{\rm med}}{dz\,dk_\perp^2}} + \boxed{\frac{\alpha_s}{2\pi}\frac{1}{k_\perp^2}P(z)}$$

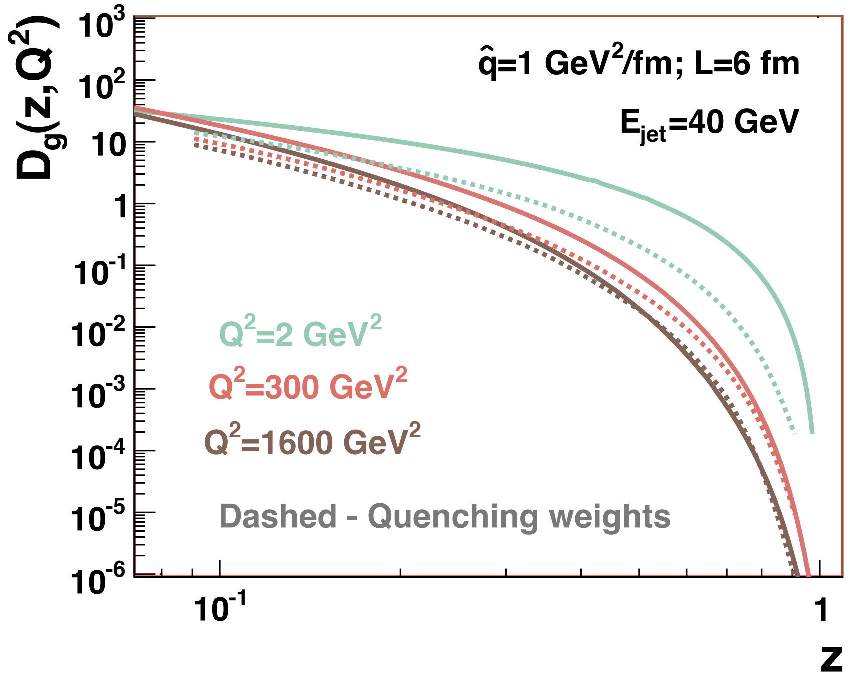
⇛ So, define the medium-modified part of the splitting probability as

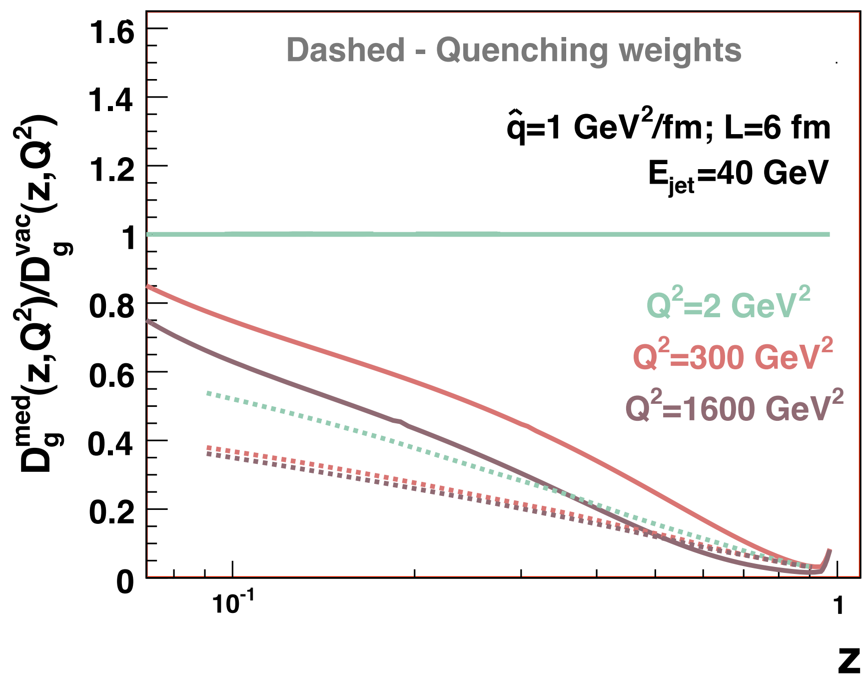
$$\frac{dI}{dz\,dk_\perp^2} = \frac{\alpha_s}{2\pi}\frac{1}{k_\perp^2}\Delta P^{\rm med}(z) + \frac{\alpha_s}{2\pi}\frac{1}{k_\perp^2}P(z) \quad \Longrightarrow \quad \boxed{\Delta P(z) \equiv \frac{2\pi k_\perp^2}{\alpha_s}\frac{dI^{\rm med}}{dz\,dk_\perp^2}}$$

⇛ We take the spectrum from BDMPS/AWS

Results

- Initial conditions: no effect at $Q_0 = 2$ GeV - vacuum KKP FF taken





- Softening of the fragmentation functions - energy loss
- Agreement with QW framework when $Q^2 \simeq E_{\rm jet}^2$
- QW overestimates suppression when $Q^2 \ll E_{\rm jet}^2$

[Armesto, Cunqueiro, Salgado, Xiang 2007]

Monte Carlo implementation

The vacuum

PYTHIA, HERWIG, ...

Sudakov prescription

- Integral formulation of DGLAP (equivalent at LO in α_s)

$$f(x,t) = \Delta(t) f(x,t_0) + \int \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \int \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) f(x/z, t')$$

- Probability of no radiation between two scales
  - Sudakov form factor

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

- The probability of one splitting

$$d\mathcal{P}(t,z) = \frac{dt}{t} dz \frac{\alpha_s}{2\pi} P(z) \Delta(t)$$

- Probabilistic interpretation well suited for MC event generators

Monte Carlo implementation

⇛ This probabilistic approach is the basis of most MC codes

HERWIG, PYTHIA, SHERPA, ...

How does it work?

1) First, decide whether there is branching from an initial t_1 to t_2

i) $\Delta(t_2)/\Delta(t_1)$ is the probability of no (resolvable) branching

ii) $\mathcal{R}$ is a random number generated by the program

iii) Generate t_2 with

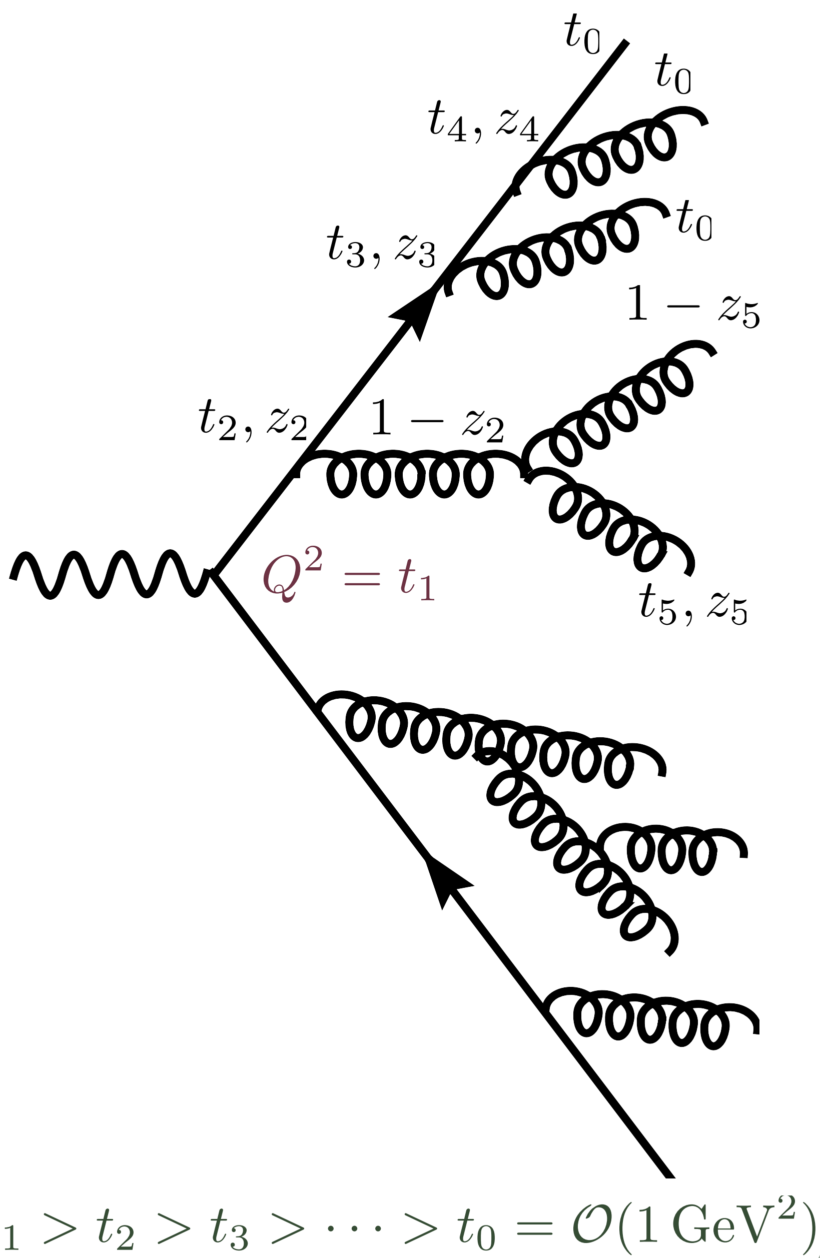
$$\frac{\Delta(t_2)}{\Delta(t_1)} = \mathcal{R}$$

2) For this branching, decide the fraction of momentum $z = x_2/x_1$

$$\int_\epsilon^{x_2/x_1} dz\, \frac{\alpha_s}{2\pi}\, P(z) = \mathcal{R}' \int_\epsilon^{1-\epsilon} dz\, \frac{\alpha_s}{2\pi}\, P(z)$$

3) Repeat 1) and 2) until a cut-off scale t_0 is reached

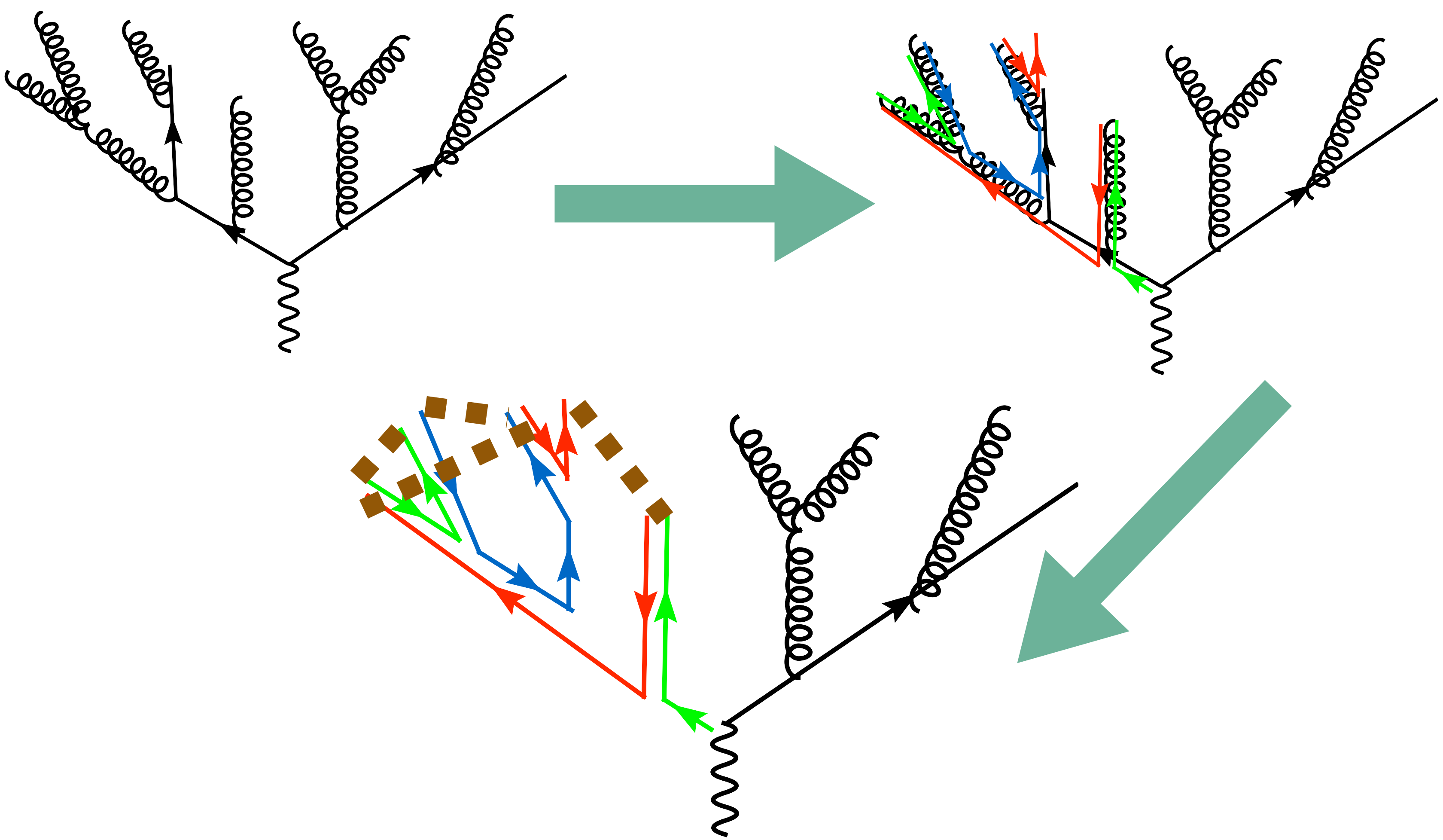
Branching process done by PYSHOW in PYTHIA



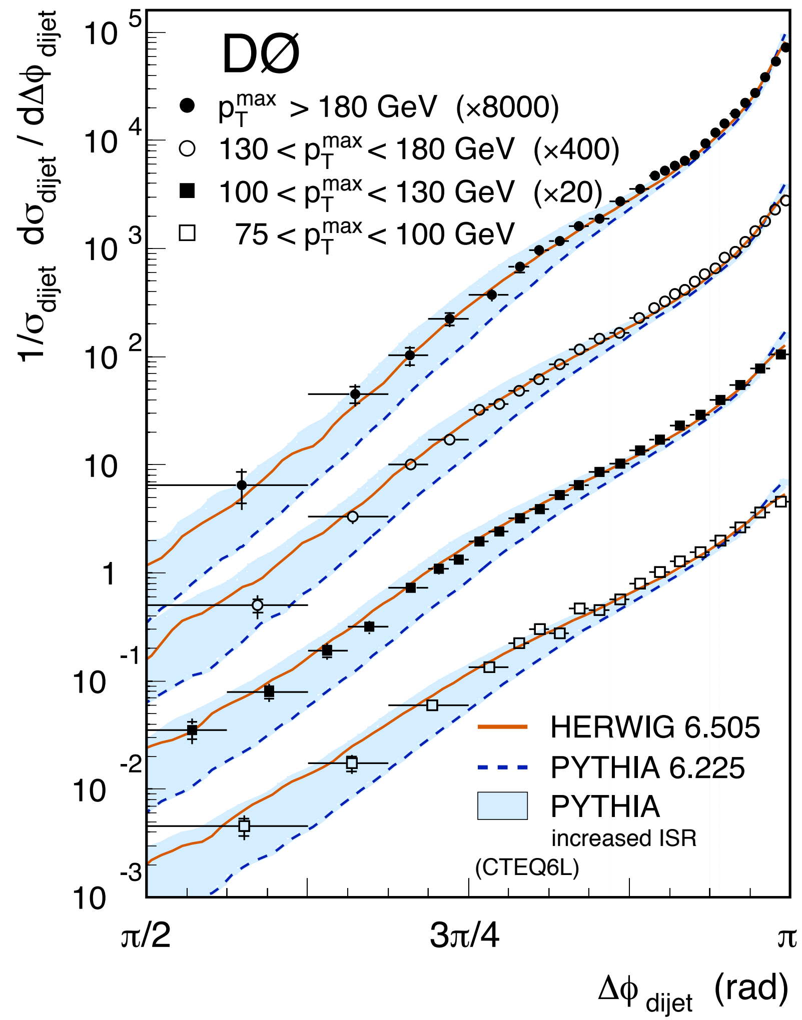
1) The hard process is generated
   - i) Virtuality $Q^2 = t_1$
2) Resolvable branching at (t_2, z_2)
   - i) Gives qg with fract. of momentum z_2
   - ii) q branches again at (t_3, z_3)
   - iii) q branches again at (t_4, z_4)
   - iv) No branching is found with $t < t_0$
     - → Branching stops
3) Gluon branches at (t_5, z_5)
   - i) No branching is found with $t < t_0$
     - → Branching stops
4) Distribution of gluons in the final state has to be hadronized

Color connections

- Each parton splitting modifies the color structure
  - PYTHIA then reconnects the colors to form and decay strings



Comparison with data



Di-jet azimuthal decorrelation at the Tevatron

Monte Carlo implementation

The medium

Armesto, Corcella, Cunqueiro, Salgado:

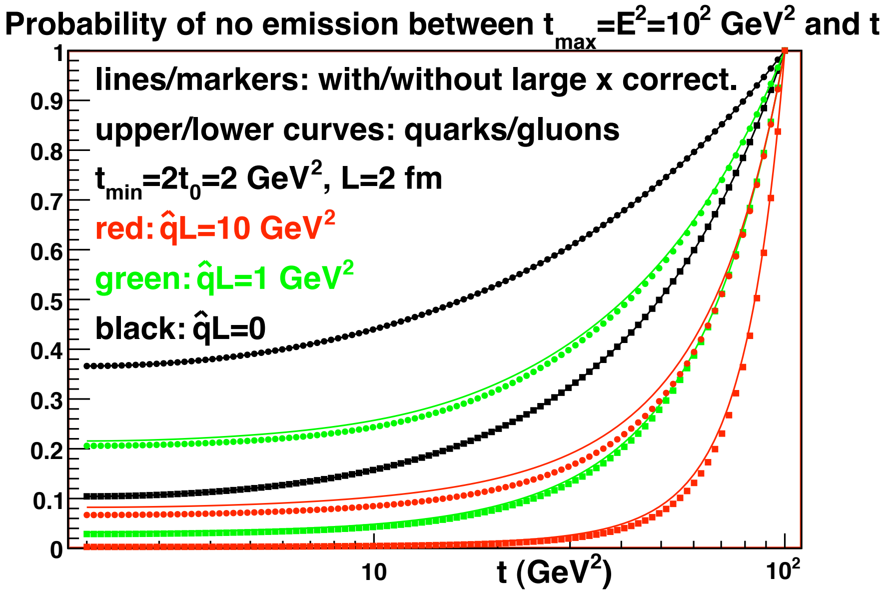
Q-PYTHIA; Q-HERWIG

Including the medium terms

- Sudakov form factor with medium-modified splitting probability

$$\Delta(t) \equiv \exp\left[-\int_{t_0}^{t} \frac{dt'}{t'} \int dz \frac{\alpha_s}{2\pi} \left[P(z) + \Delta P(z, t', \hat{q}, L)\right]\right]$$

The medium is here



E=10 GeV

[Armesto, Cunqueiro, Salgado, Xiang 2007]

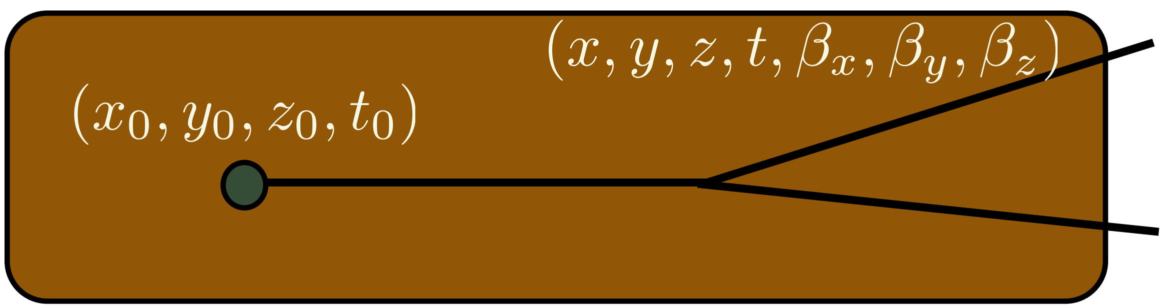
- The medium terms suppress the Sudakov
  - **More radiation in medium than in vacuum**

The program

- Fortran program, uses PYTHIA-6.4.18 defaults.
  - We modify *only* PYSHOW, providing additional auxiliary routines: black box for the user.
  - So, Q-PYTHIA is usual PYTHIA with a modified parton shower

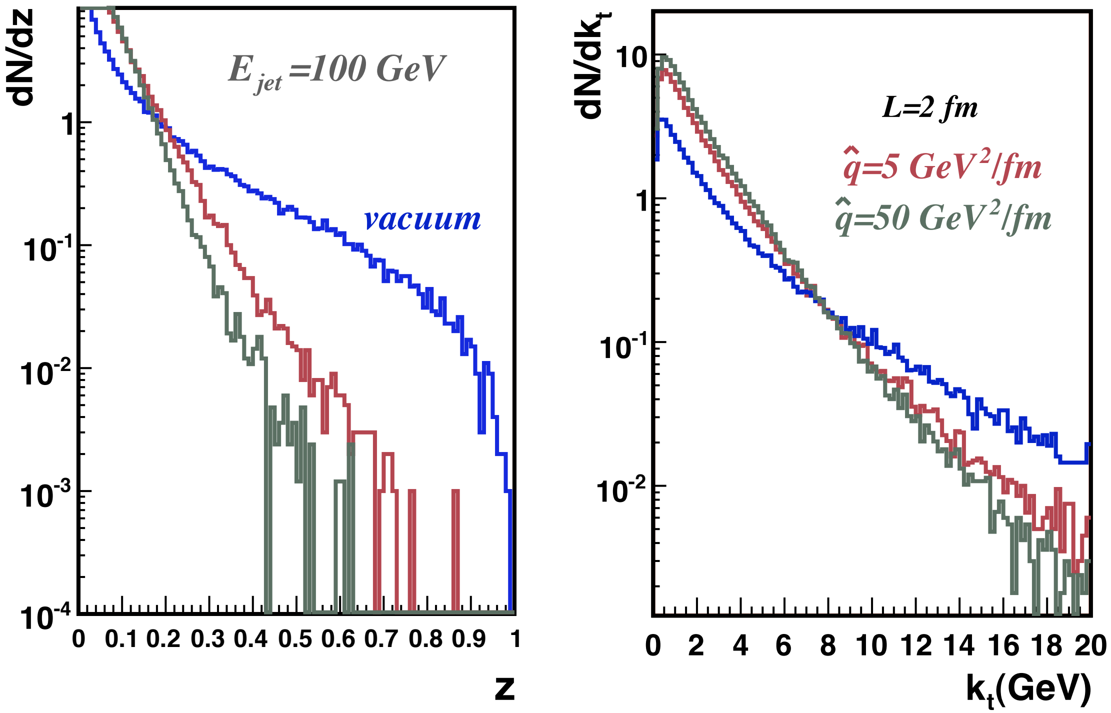
[Notice, however, that this is not an official PYTHIA release]

- User-defined:
  - **QPYGIN**: Position of hard scattering - jet origin - (x_0, y_0, z_0, t_0)
  - **QPYGEO**, which contains medium modelling: Values of $\hat{q}L$ and $\omega_c = \hat{q}L^2/2$ at point of branching $(x, y, z, t, \beta_x, \beta_y, \beta_z)$

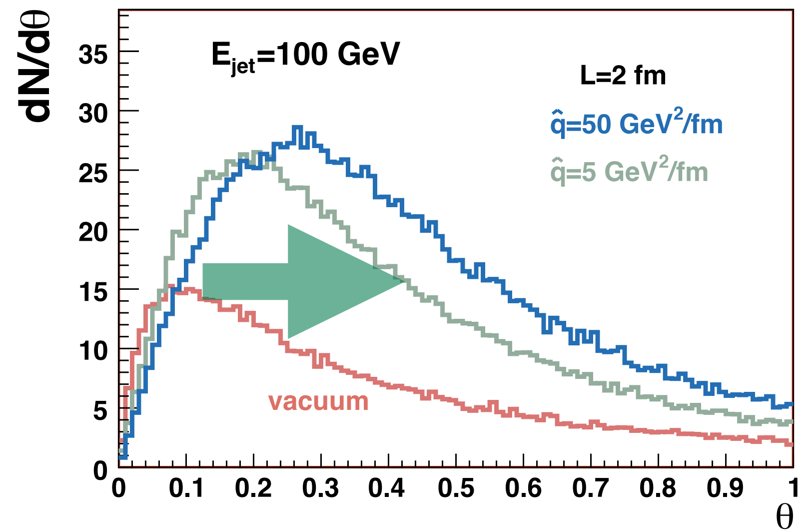


Results at parton level: Q-PYTHIA

Fragmentation function



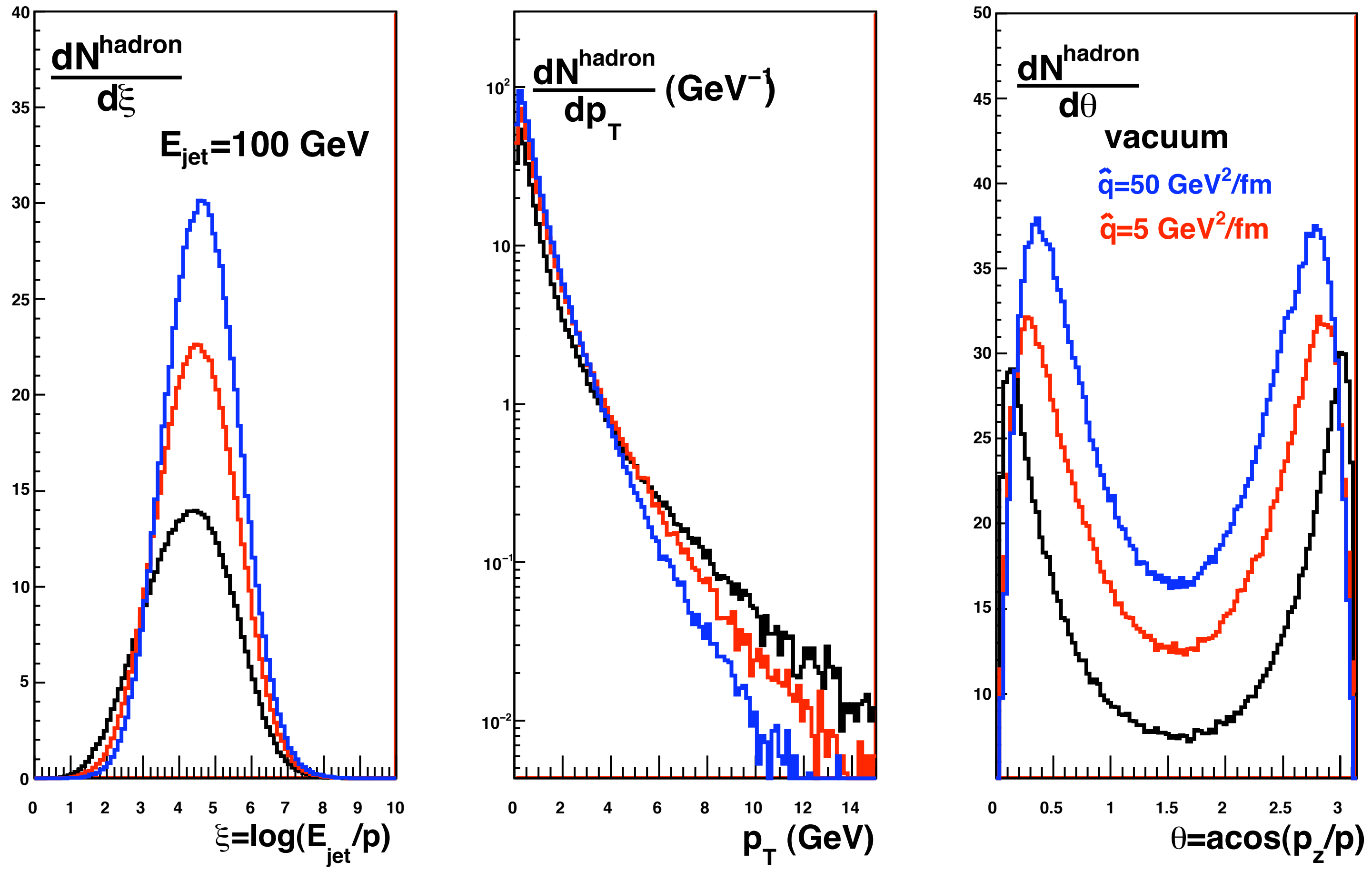
Angular distribution



⇒ Main medium-modifications in agreement with expectations

- Particle spectrum softens (energy loss)
- Larger emission angles (jet broadening)
- Multiplicity enhancement

Results including hadronization



- ⇛ Effects are reduced by hadronization
- ⇛ Comparison of different hadronization models is important:

PYTHIA (string fragmentation) vs HERWIG (cluster hadronization)

Future work

- Color structure of the shower
- Finite energy corrections to splitting functions
  - Elastic energy loss
- Interplay between virtuality and length
  - Space-time picture of the parton shower
  - Ordering variable in the medium case
- Role of hadronization: different models
- Energy flow from/to the medium
- Jet reconstruction in realistic environment

Summary

- High-pt studies are essential tools in HI phenomenology
  - RHIC shows a large energy loss by opaque media
- New opportunities with real jet studies
  - Formalism needs to be improved for less inclusive observables
  - We present a Monte Carlo implementation
- Publicly available code Q-PYTHIA v1.0 at Q@MC site:

  http://igfae.usc.es/QatMC