Medium-modified fragmentation functions: overview

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Workshop on Parton fragmentation processes: in the vacuum and in the medium
ECT* Trento - February 2008

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

Increase energy density

simple systems

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

→ **Increase energy density**

simple systems

Collective properties of the fundamental interactions

→ **Increase <u>extended</u> energy density**

"less simple" systems

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Collective properties of the fundamental interactions → **Increase <u>extended</u> energy density**

"less simple" systems

What are the building blocks and how they organize?

- Spectroscopy
- Heavy-ion collisions

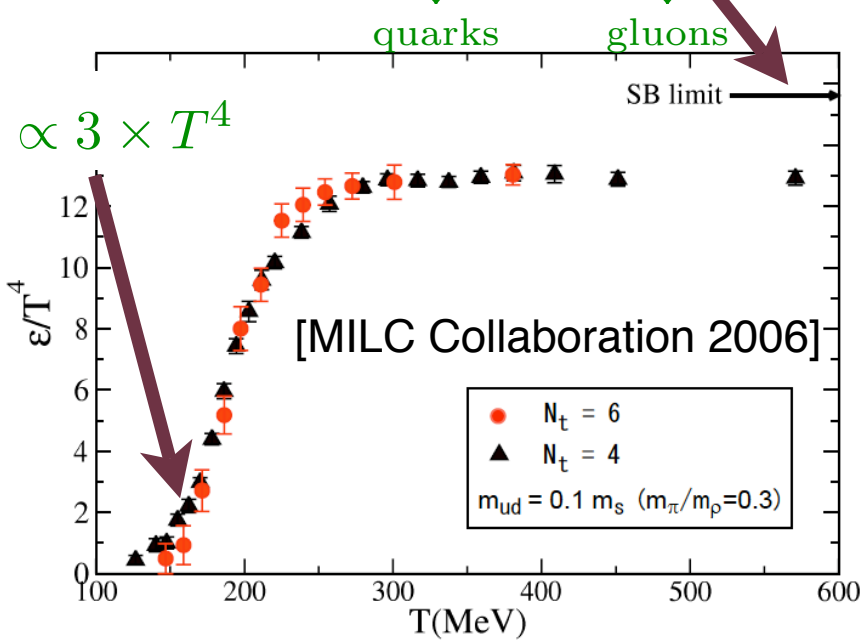
QCD has a rich dynamical structure

- Two broken symmetries in the QCD vacuum
  - confinement
  - chiral symmetry is broken
- Restored at high-temperatures ← asymptotic freedom

Equation of state

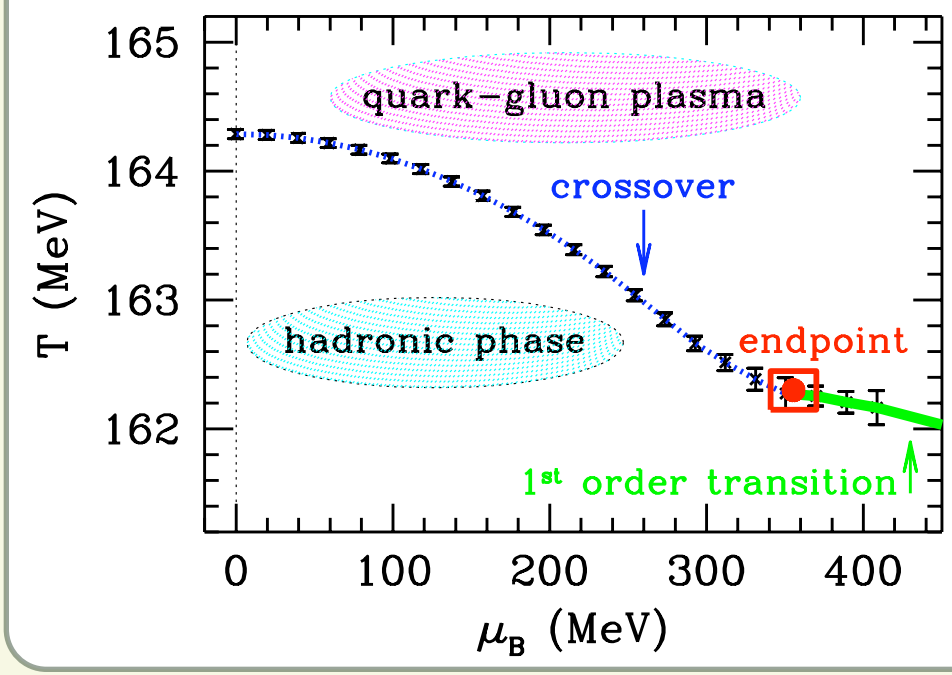
$$P_{QGP} \propto (\underbrace{2 \times 2 \times 3}_{\text{quarks}} + \underbrace{2 \times 8}_{\text{gluons}}) \times T^4$$

$$P_\pi \propto 3 \times T^4$$



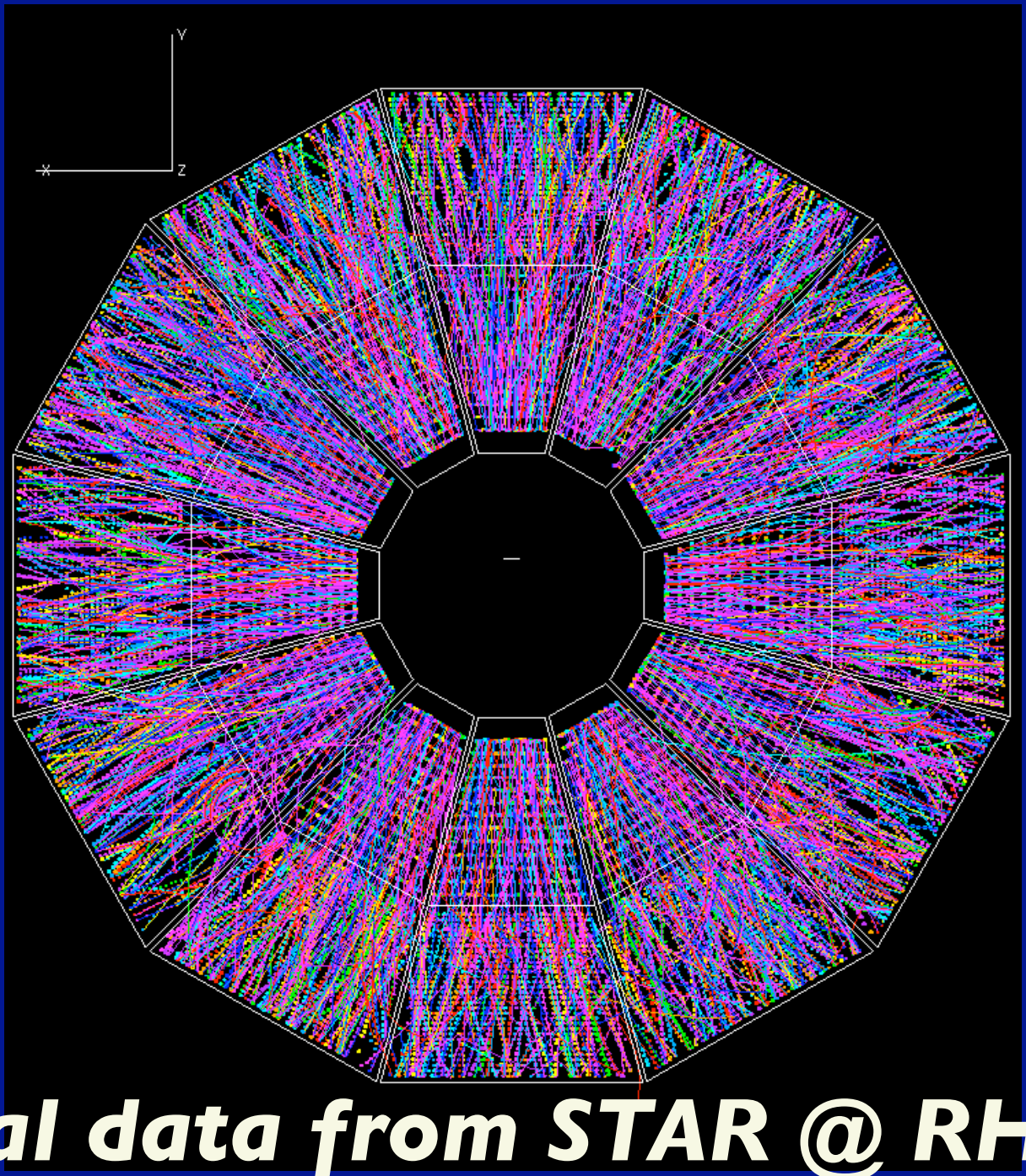
Phase diagram

[Fodor, et al. 2004]

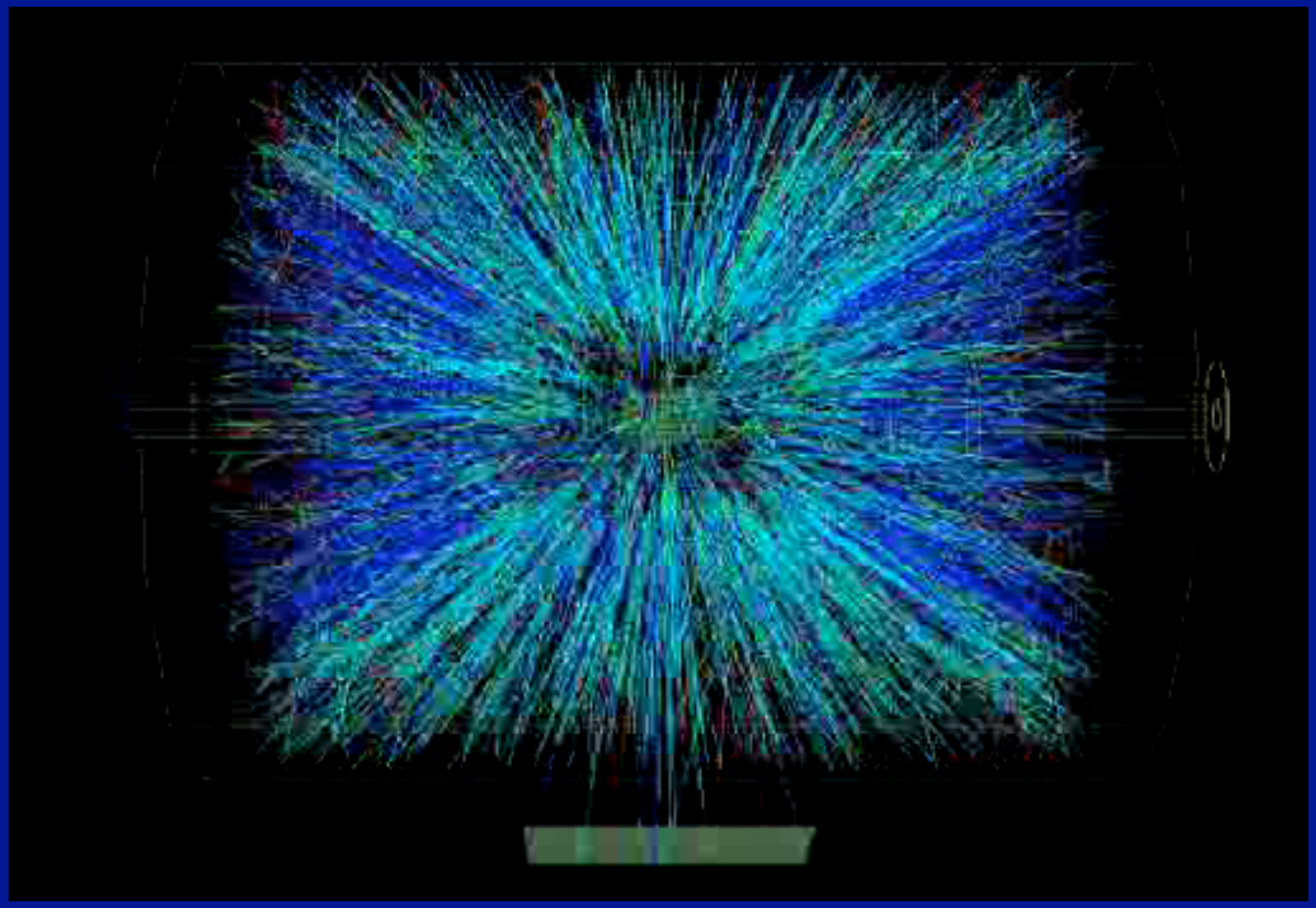


Where?

- SPS at CERN.
  - Have collided pA at $p_{\rm lab} = 450$ GeV/c, SU at $p_{\rm lab} = 200$ AGeV/c and PbPb at $p_{\rm lab} = 158$ AGeV/c.
  - The program is almost finished now
- RHIC at BNL
  - pp, dAu, AuAu and CuCu at $\sqrt{s} = 20 \ldots 200$ AGeV
  - RHIC II will improve detectors for rare processes and enhance statistics
- LHC at CERN
  - Will collide PbPb at $\sqrt{s} = 5500$ AGeV also pPb or dPb (under discussion) at $\sqrt{s} = 8200$
  - ALICE is a dedicated HI experiment
  - CMS and ATLAS have own programs of heavy ion collisions



real data from STAR @ RHIC



real data from STAR @ RHIC

What do we expect to learn?

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?

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Today's talk

Hard probes

Hard probes in heavy-ion collisions

- 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

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

LHC

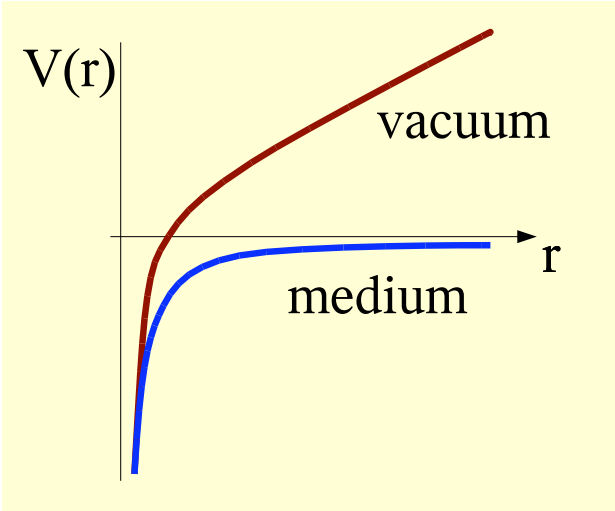
- The extension of the medium modifies the long-distance terms
  - New evolution equations for $f_A(x, Q^2); D(z, Q^2)$
- Kinematical access to evolution: large-Q^2, small-x $\rightarrow$ LHC

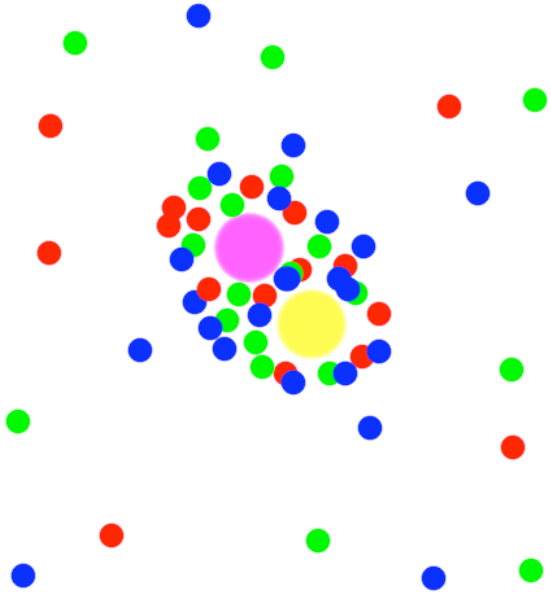
A conceptually simple example, J/Ψ suppression

- A J/Ψ is a $c\bar{c}$ bound state.

$$\sigma^{hh\to J/\Psi} = f_i(x_1,Q^2)\otimes f_j(x_2,Q^2)\otimes\sigma^{ij\to[c\bar{c}]}(x_1,x_2,Q^2)\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle$$

- The potential is screened by the medium
  - The long-distance part is modified $\langle\mathcal{O}([c\bar{c}]\to J/\Psi)\rangle\to 0$
- The J/Ψ production is suppressed [Matsui, Satz 1986]





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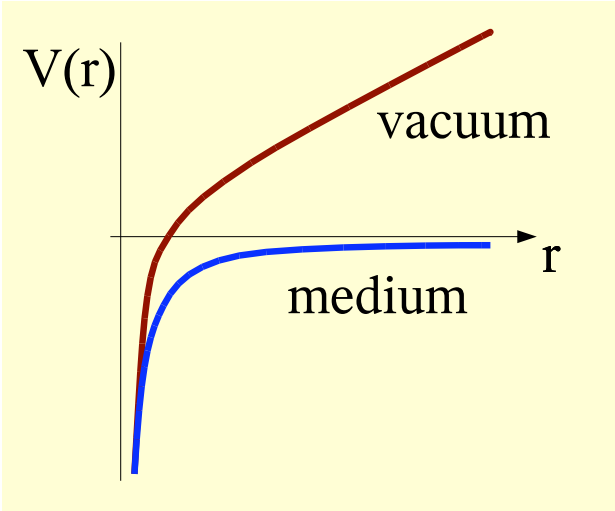
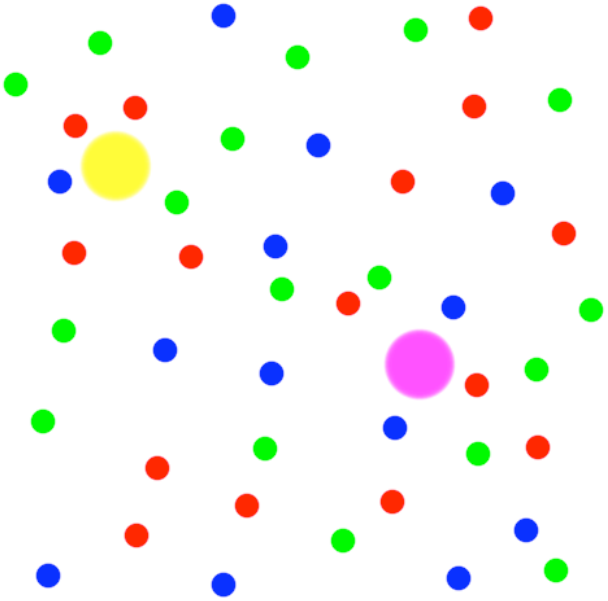
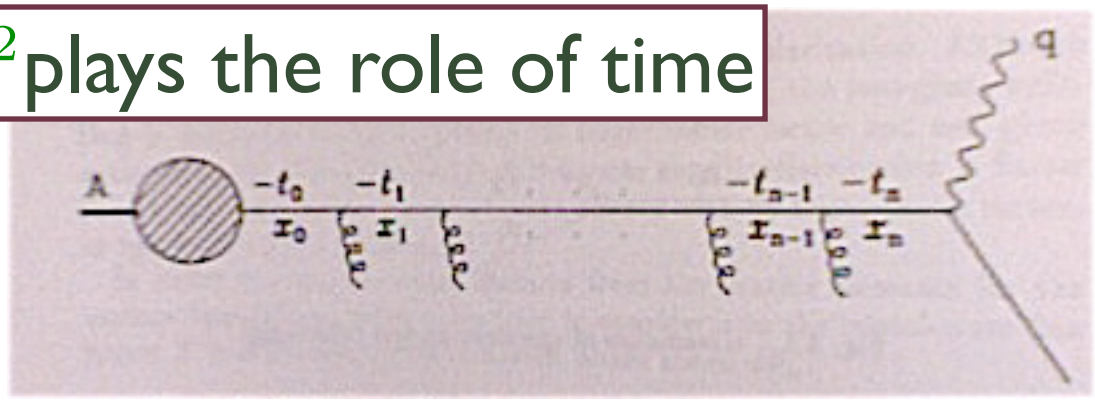




DGLAP evolution in vacuum

$t = Q^2$ plays the role of time



Ordered gluon splitting given by DGLAP

$$\frac{\partial f(x,t)}{\partial \log t} = \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) f(x/z,t)$$

splitting function

f(x,t) are the PDFs or the FF

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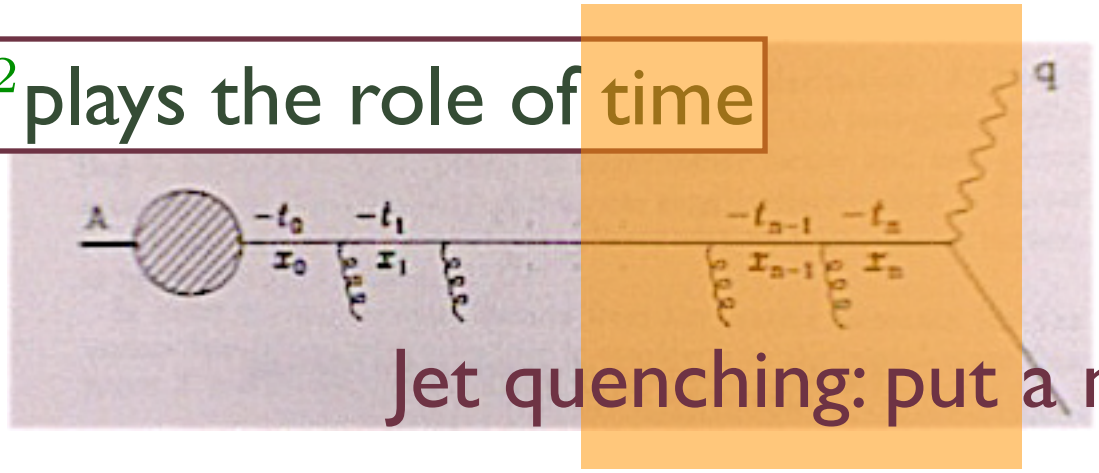

Jet quenching: put a medium here

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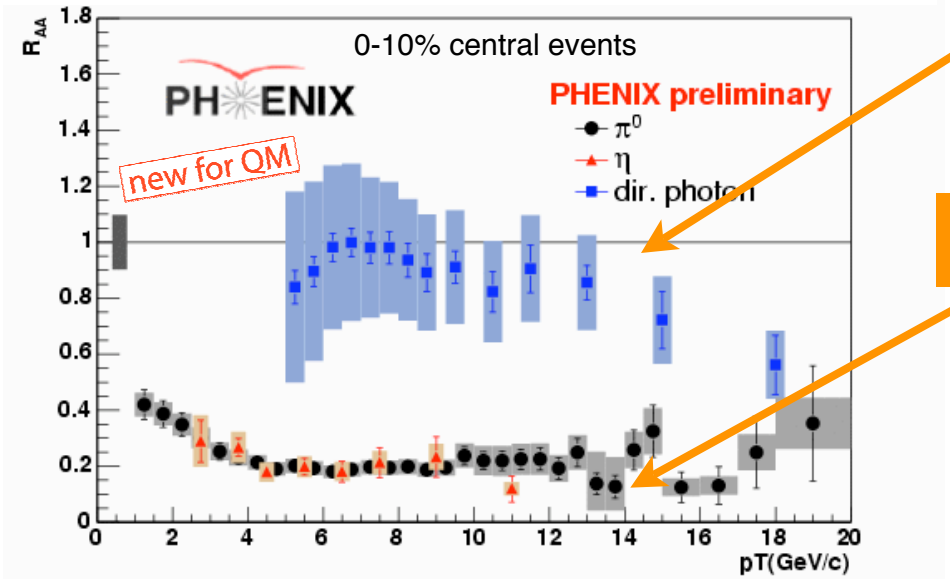
Experimental observations

$$R_{AA} = \frac{dN^{AA}/dp_t}{N_{\rm coll} dN^{pp}/dp_t}$$



photons

mesons

Photons don't interact with the medium quarks and gluons do

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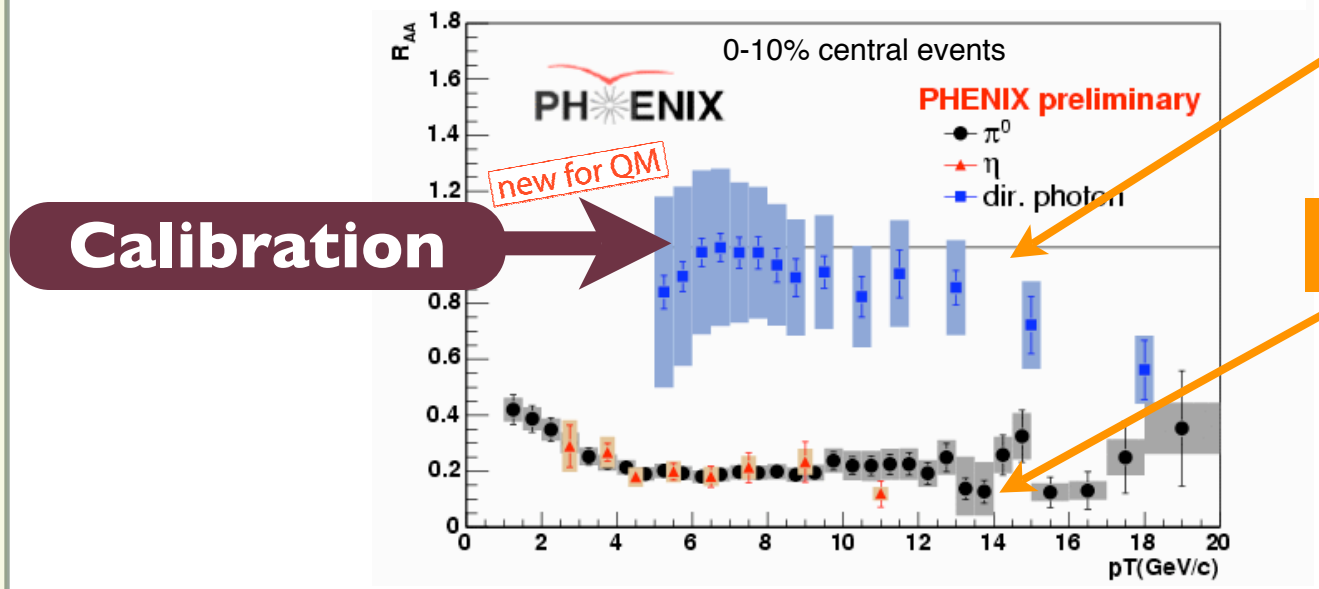
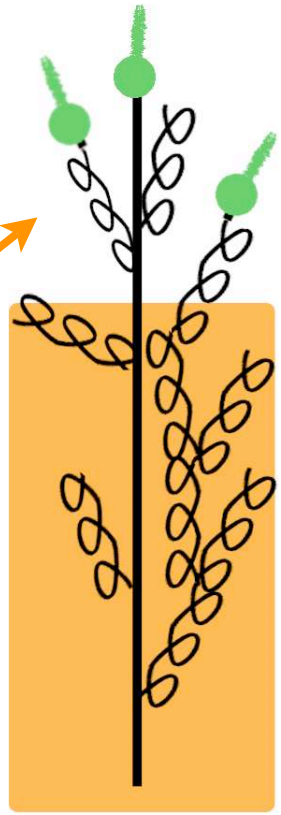
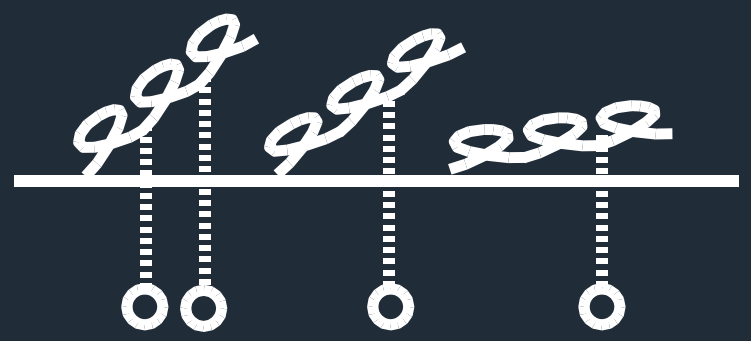


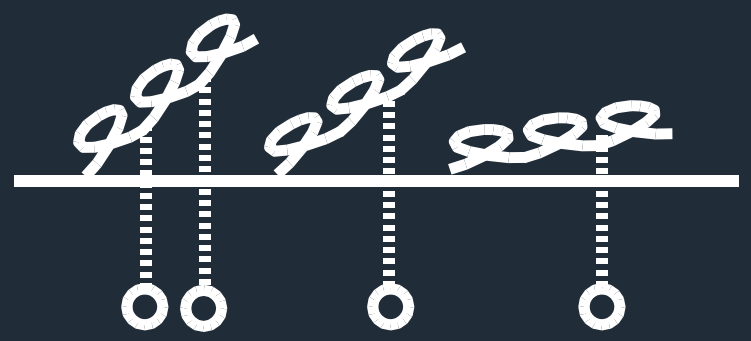


Photons don't interact with the medium quarks and gluons do

⇒ Well calibrated and abundant probes of the medium



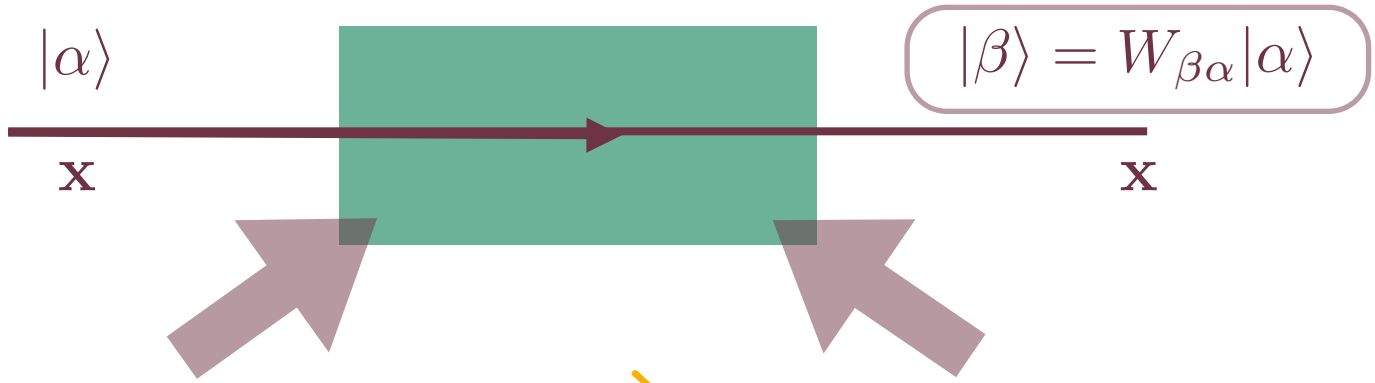
QCD at high densities



- Modification of the PDFs
- Modification of the jet evolution

Particle propagation in matter: Eikonal limit

⇒ At high energies → Eikonal approximation $E \gg k_\perp$



⇒ Particle does not change its direction of propagation

⇒ The medium rotates the color of the probe

$$W(\mathbf{x}) = P\,\exp\left\{ i \int dz^- T^a A_a^+(\mathbf{x}, z^-) \right\}$$

Wilson line

⇒ Recoil is neglected → medium is a background field

[See e.g. J. Casalderrey-Solana and C.A. Salgado arXiv:0712.3443]

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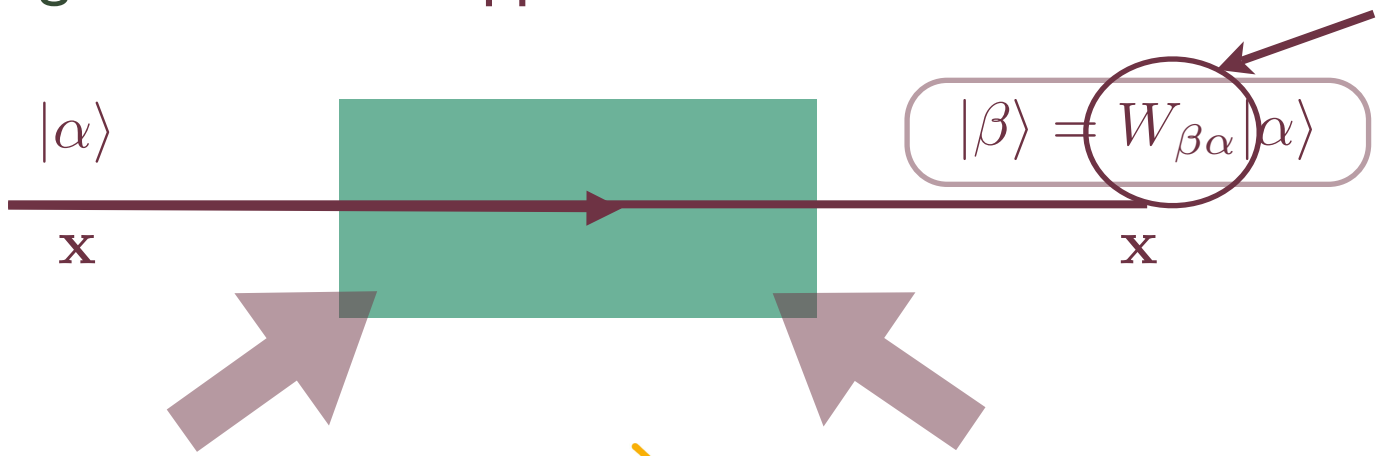
S-matrix



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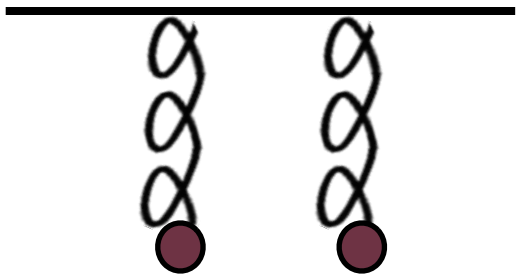
A simple model: potential scattering

⇒ The contribution from 2 scattering centers to the S-matrix



$$S_2(p',p) = \int \frac{d^4k}{(2\pi)^4} \left\{ -ig(k_\mu + p'_\mu) \int d^4x_2 A^\mu(x_2) \mathrm{e}^{ix_2(p'-k)} \right\}$$
$$\frac{i}{k^2 + i\epsilon} \left\{ -ig(p_\mu + k_\mu) \int d^4x_1 A^\mu(x_1) \mathrm{e}^{ix_1(k-p)} \right\}$$

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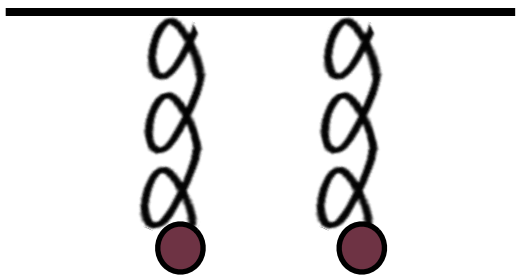

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⇒ Taking the eikonal limit $p_+ \to \infty$

$$S_2 = 2\pi\delta(p'_+ - p_+) 2p_+ \int \frac{d^2\mathbf{k}_\perp}{(2\pi)^2} \int d^3\mathbf{x_1} \left[-igA_-(\mathbf{x_1})\right] \int d^3\mathbf{x_2} \left[-igA_-(\mathbf{x_2})\right] \times$$
$$\times \exp\left\{i\mathbf{k}_\perp(\mathbf{x_1}_\perp - \mathbf{x_2}_\perp)\right\} \exp\left\{i(\mathbf{x_2}_\perp \mathbf{p_2}_\perp - \mathbf{x_1}_\perp \mathbf{p_1}_\perp)\right\} \exp\left\{ i\frac{\mathbf{k}_\perp{}^2}{p_+}(x_{1+} - x_{2+}) \right\}$$

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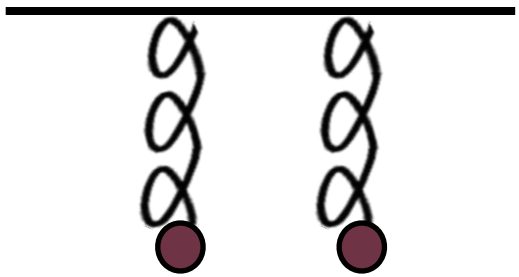

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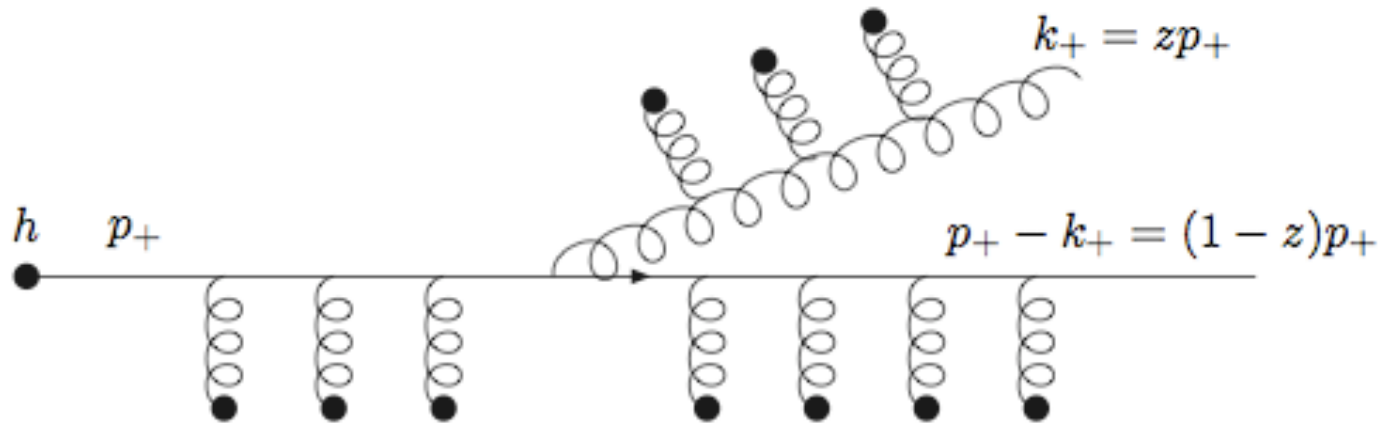
⇒ Resumming an arbitrary number of scattering centers

$$S = \int d^2\mathbf{x}_\perp \mathrm{e}^{-i\mathbf{x}_\perp(\mathbf{p}'_\perp - \mathbf{p}_\perp)} \boxed{P \exp\left\{-\frac{ig}{2} \int dx_+ A_-(x_+, x_\perp)\right\}}$$

The medium-induced gluon radiation I

$$G(\mathbf{x}_\perp, x_+; \mathbf{y}_\perp, L_+)$$



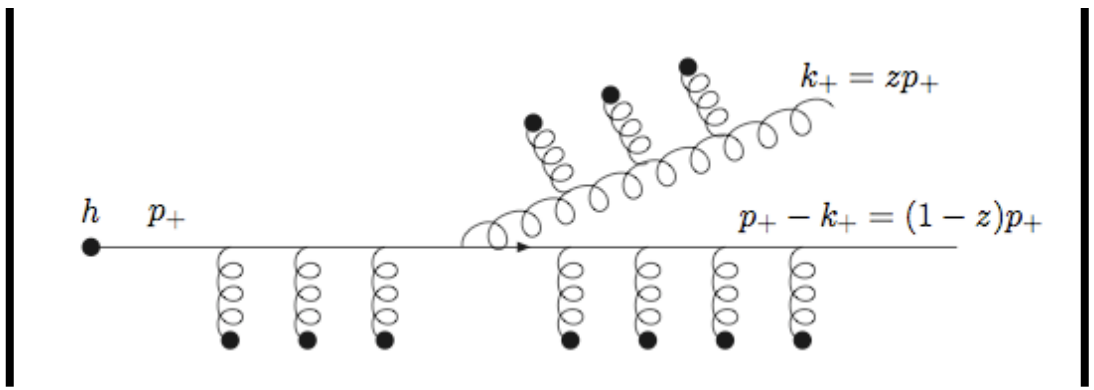
$$W(\mathbf{x}_\perp, x_{0+}, x_+) \qquad W(\mathbf{x}_\perp, x_+, L_+)$$

⇒ Takes into account non-eikonal corrections for the gluon

$$G(\mathbf{x}_\perp, x_+; \mathbf{y}_\perp, L_+) = \int \mathcal{D}\mathbf{r}(x_+) \exp\left\{ i\frac{p_+}{2} \int dx_+ \left[\frac{d\mathbf{r}}{dx^+}\right]^2 \right\} W(\mathbf{r})$$

The medium-induced gluon radiation II

2



$$\langle|\mathcal{M}_{a\to bc}|^2\rangle = \frac{g^2}{N^2-1}2\mathrm{Re}\Bigg[\frac{1}{k_+^2}\int_{x_{0+}}^{L_+} dx_+ \int_{x_+}^{L_+} d\bar{x}_+ \int d\mathbf{x}d\bar{\mathbf{x}}\; e^{i\mathbf{k}_\perp(\mathbf{x}-\bar{\mathbf{x}})}\times$$

$$\Big\langle W_{aa_1}(\mathbf{0},x_{0+},x_+)T^{c_1}_{a_1b_1}\frac{\partial}{\partial\mathbf{y}}G_{c_1c}(\mathbf{y}=0,x_+;\mathbf{x},L_+)W_{b_1b}(\mathbf{0},x_+,L_+)\times$$

$$W^\dagger_{b\bar{b}_1}(\mathbf{0},\bar{x}_+,L_+)\frac{\partial}{\partial\bar{\mathbf{y}}}G_{c\bar{c}_1}(\bar{\mathbf{x}},L_+;\bar{\mathbf{y}}=0,\bar{x}_+)T^{\bar{c}_1}_{\bar{b}_1\bar{a}_1}W^\dagger_{\bar{a}_1a}(\mathbf{0},x_{0+},\bar{x}_+)\Big\rangle -$$

$$-\frac{2}{k_+}\frac{\mathbf{k}_\perp}{k_\perp^2}\int_{x_{0+}}^{L_+} dx_+\int d\mathbf{x}e^{i\mathbf{k}_\perp\mathbf{x}}\Big\langle W_{aa_1}(\mathbf{0},x_{0+},x_+)T^{c_1}_{a_1b_1}\frac{\partial}{\partial\mathbf{y}}G_{c_1c}(\mathbf{y}=0,x_+;\mathbf{x},L_+)\times$$

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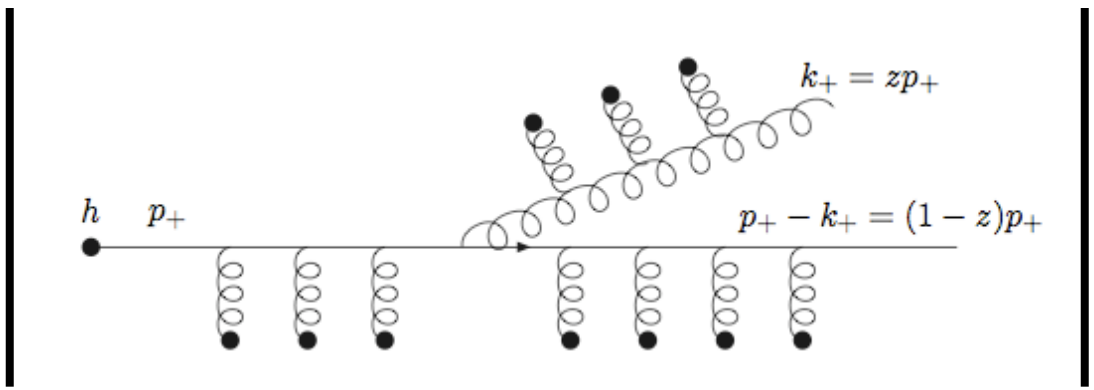
The medium-induced gluon radiation II



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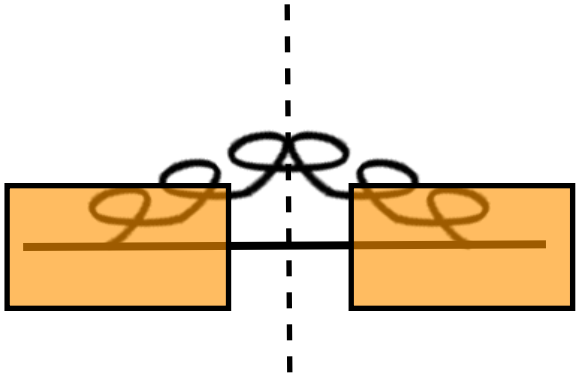

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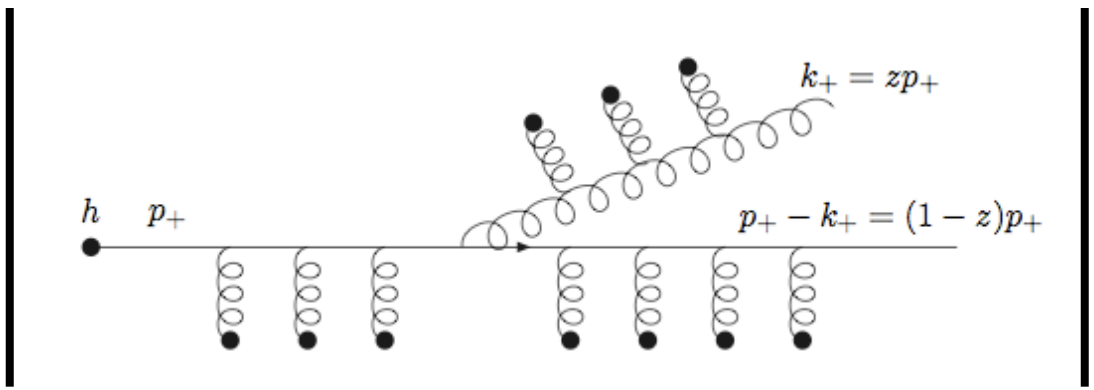

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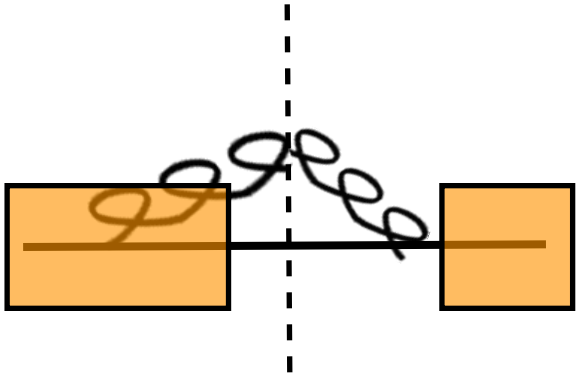


$$\langle|\mathcal{M}_{a\to bc}|^2\rangle = \frac{g^2}{N^2-1}2\mathrm{Re}\Bigg[\frac{1}{k_+^2}\int_{x_{0+}}^{L_+} dx_+ \int_{x_+}^{L_+} d\bar{x}_+ \int d\mathbf{x}d\bar{\mathbf{x}}\; e^{i\mathbf{k}_\perp(\mathbf{x}-\bar{\mathbf{x}})}\times$$

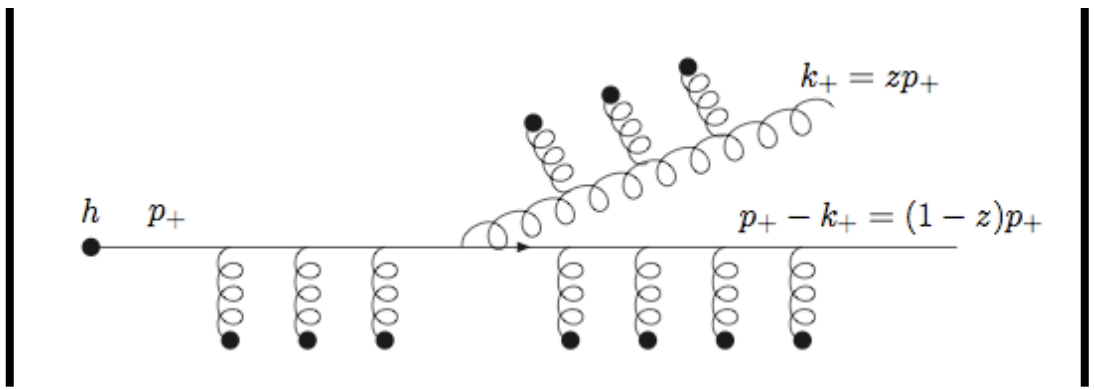
$$\Big\langle W_{aa_1}(\mathbf{0},x_{0+},x_+)T^{c_1}_{a_1b_1}\frac{\partial}{\partial\mathbf{y}}G_{c_1c}(\mathbf{y}=0,x_+;\mathbf{x},L_+)W_{b_1b}(\mathbf{0},x_+,L_+)\times$$

$$W^\dagger_{b\bar{b}_1}(\mathbf{0},\bar{x}_+,L_+)\frac{\partial}{\partial\bar{\mathbf{y}}}G_{c\bar{c}_1}(\bar{\mathbf{x}},L_+;\bar{\mathbf{y}}=0,\bar{x}_+)T^{\bar{c}_1}_{\bar{b}_1\bar{a}_1}W^\dagger_{\bar{a}_1a}(\mathbf{0},x_{0+},\bar{x}_+)\Big\rangle -$$

$$-\frac{2}{k_+}\frac{\mathbf{k}_\perp}{k_\perp^2}\int_{x_{0+}}^{L_+} dx_+\int d\mathbf{x}e^{i\mathbf{k}_\perp\mathbf{x}}\Big\langle W_{aa_1}(\mathbf{0},x_{0+},x_+)T^{c_1}_{a_1b_1}\frac{\partial}{\partial\mathbf{y}}G_{c_1c}(\mathbf{y}=0,x_+;\mathbf{x},L_+)\times$$

$$W_{b_1b}(\mathbf{0},x_+,L_+)T^{c_1}_{b\bar{a}_1}W^\dagger_{\bar{a}_1a}(\mathbf{0},x_{0+},L_+)\Big\rangle\Bigg] + \frac{4g^2C_R}{k_\perp^2}$$

The medium-induced gluon radiation II



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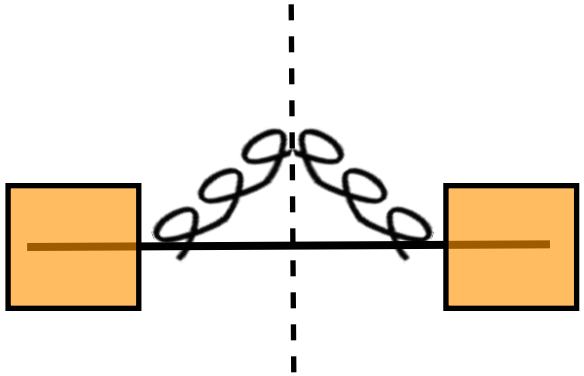

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What are the $\langle \ldots \rangle$??

- All the medium properties are encoded in the medium-averages of the Wilson lines.

- Several prescriptions used
  - Opaque medium, many scatterings

$$\frac{1}{N}\mathrm{Tr}\left\langle W^{A}(\mathbf{x}_\perp)W^{A\dagger}(\bar{\mathbf{x}}_\perp)\right\rangle \approx \exp\left\{-\frac{1}{4}\hat{q}L(\mathbf{x}_\perp-\bar{\mathbf{x}}_\perp)^2\right\}$$

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[See e.g. J. Casalderrey-Solana and C.A. Salgado arXiv:0712.3443; Kovner and Wiedemann, PRD64 (2001)114002]

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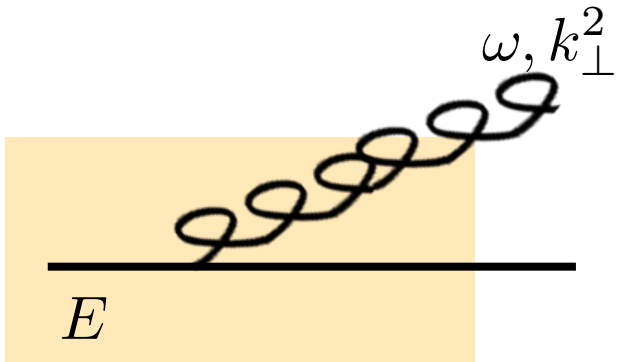
Medium-induced gluon radiation spectrum

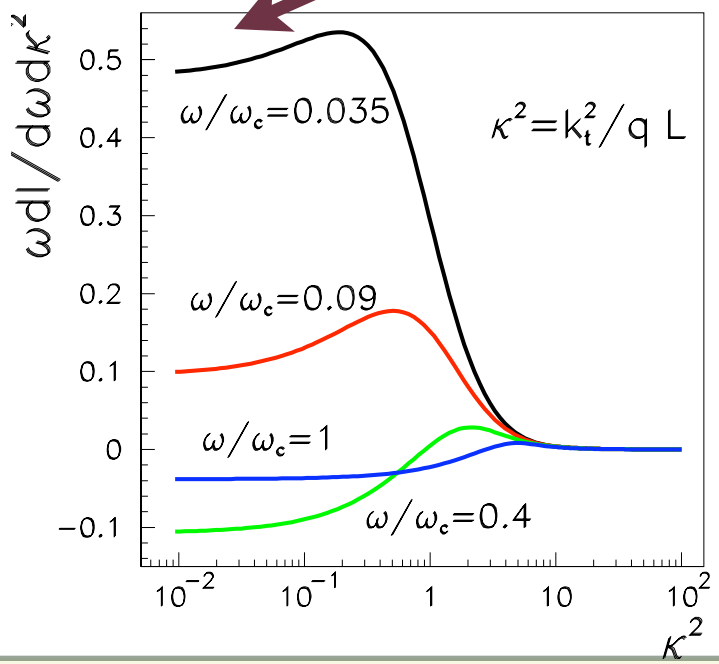
Medium-modification of the jet evolution



- Gluon formation time

$$t_{\rm form} \sim \omega / k_\perp^2$$

- Radiation suppressed for $t_{\rm form} \geq L$



- Transport coefficient

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

- Two main predictions
  - Energy loss $\Delta E \sim \alpha_s \hat{q} L^2$
  - Jet broadening $\langle k_t \rangle \sim \hat{q} L$

Medium-modification of the evolution

- Total spectrum: vacuum+medium

$$\frac{dI}{dz dk_t^2} = \frac{\alpha_s}{2\pi}\frac{1}{k_t^2}P(z) + \frac{dI^{\rm med}}{dz dk_t^2}$$

- Take as a model $P^{\rm tot}(z) = P(z) + \Delta P(z)$

- Two main modifications w.r.t. vacuum
  - Modified radiation structure
  - Enhanced number of splittings $\longrightarrow$ faster evolution

- Previous related approaches
  - Medium-effects as higher-twist corrections to IA DIS find similar modification of the splitting function [Guo-Wang-Majumder]
  - Constant factor $P(z) \to (1 + f_{\rm med})P(z)$ [Borghini, Wiedemann 2005]

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Sudakov prescription

- The probability of no radiation between two scales

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

- The probability of one splitting

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

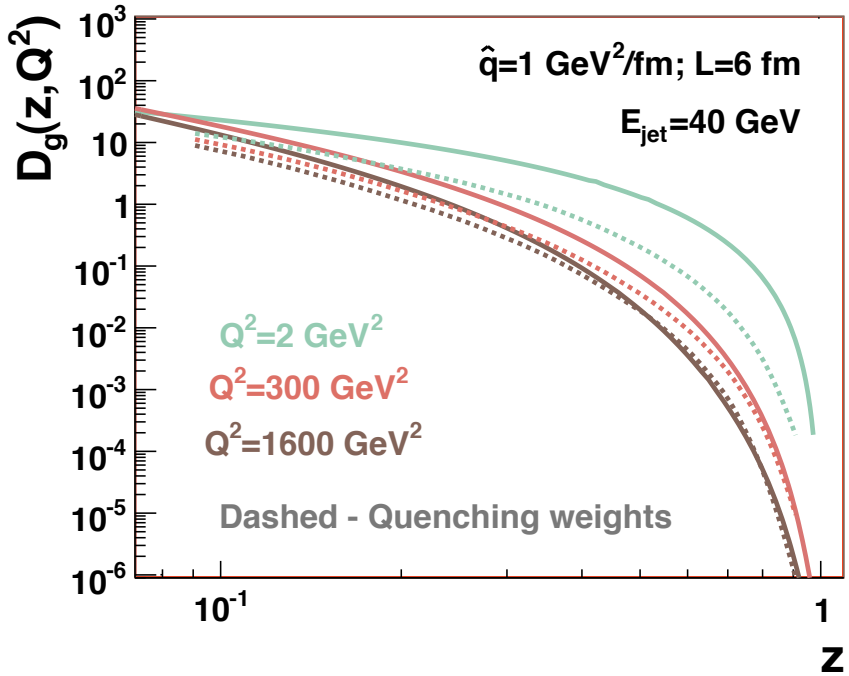
- Iterating, an equivalent to DGLAP is obtained (at LO in α_s)

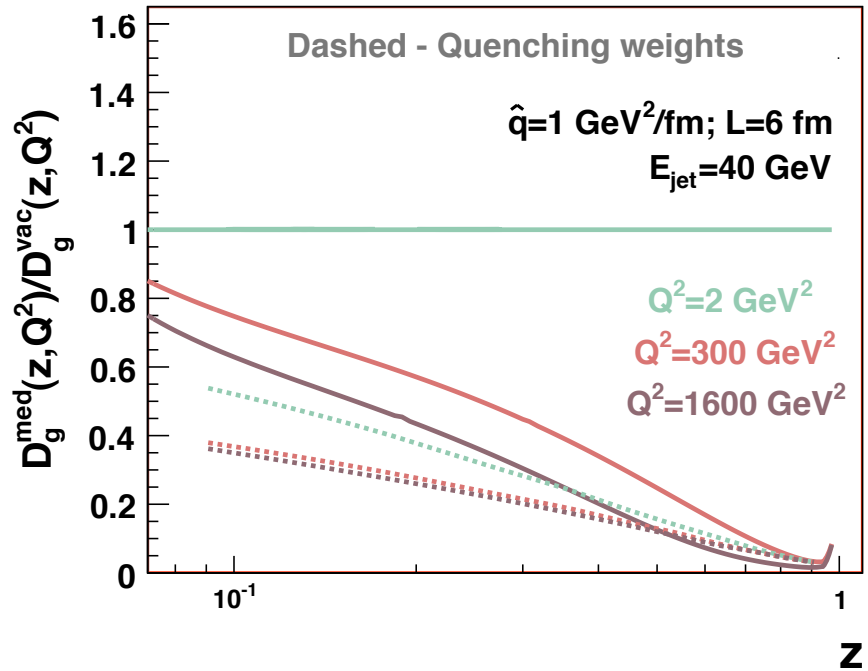
$$f(x,t) = \Delta(t) f(x,t_0) + \int \frac{dt'}{t'} \frac{\Delta(t)}{\Delta(t')} \int \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) f(x/z,t')$$

- Probabilistic interpretation well suited for MC event generators

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]

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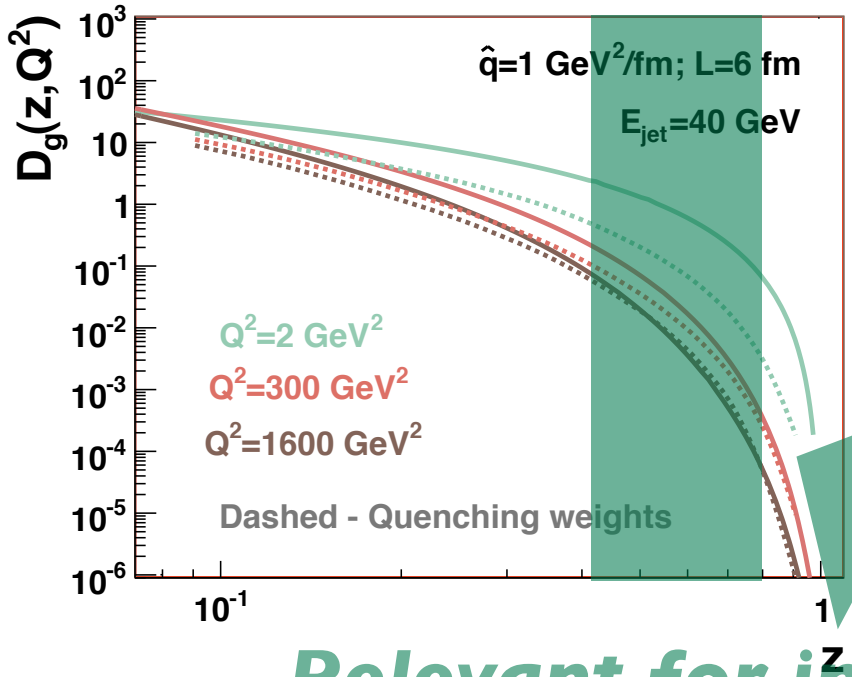
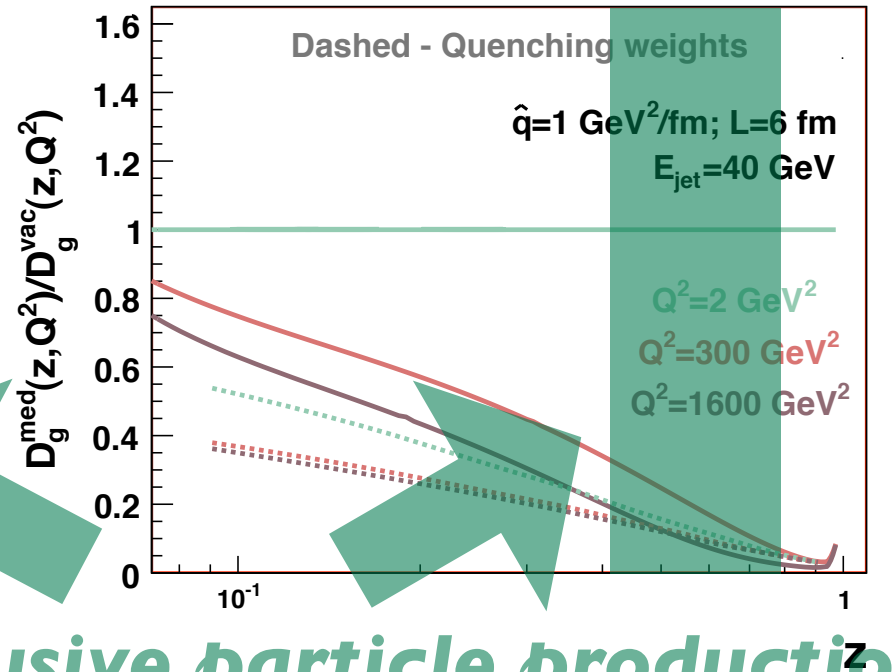




Relevant for inclusive particle production

- 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]

Poisson approximation for the medium

- The Sudakov form factor contains now the vacuum and medium

$$\Delta^{\rm tot}(t) = \exp\left[-\int_{t_0}^{t}\frac{dt'}{t'}\int dz\frac{\alpha_s}{2\pi}\left[P(z)+\Delta P(z,t)\right]\right] = \Delta^{\rm vac}(t)\Delta^{\rm med}(t)$$

- Ignoring virtuality, i.e. setting the limits to the kinematical ones

$$\Delta^{\rm med}(t) = p_0 \equiv \exp\left[-\int d\omega\, dk_t^2\,\frac{dI^{\rm med}}{d\omega dk_t^2}\right]$$

- For $Q \sim E \gg 1$ and $x = 1 - z \ll 1$ $\longrightarrow$ Quenching Weights

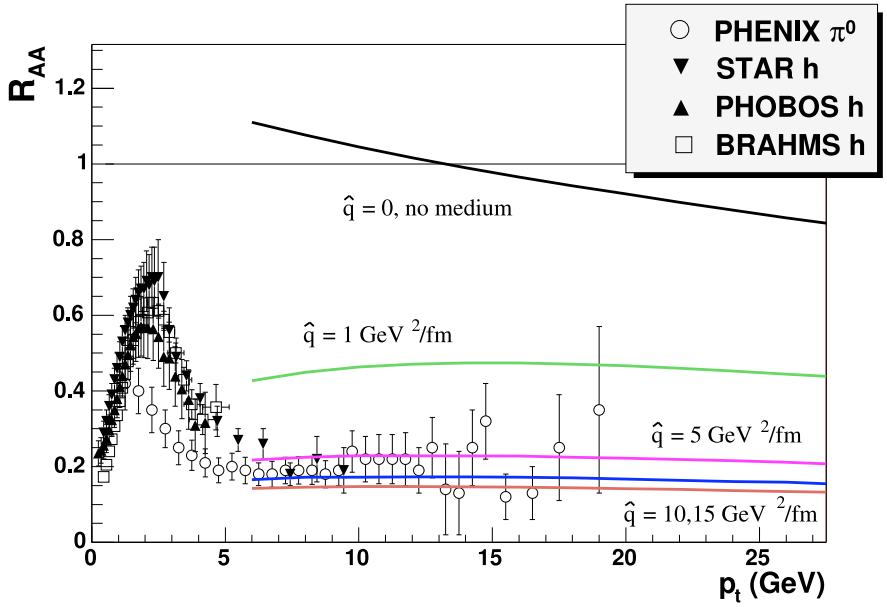
$$D(x,t) \simeq \Delta^{med}(t)D^{vac}(x,t) + \Delta^{med}(t)\int\frac{d\epsilon}{1-\epsilon}\sum_{n=1}^{\infty}\frac{1}{n!}\prod_{i=1}^{n}\int_{t_0}^{t}\frac{dt_i}{t_i}\int dz_i\, P^{med}(z_i)$$

$$\times\,\delta\left(\epsilon-\sum_{j=1}^{n}x_j\right)D^{vac}\left(\frac{x}{1-\epsilon},t\right),$$

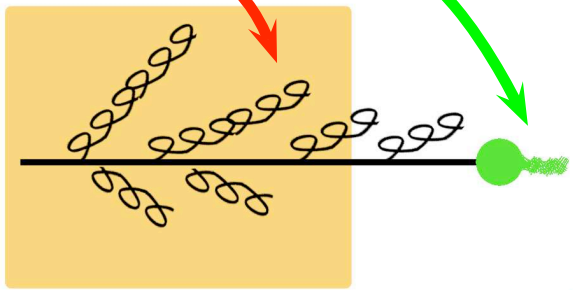
[Armesto, Cunqueiro, Salgado, Xiang 2007]

Description of the suppression

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



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



⇒ Virtuality neglected

⇒ Poisson distribution for multiple gluon radiation

⇒ 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; Renk, Ruppert, Nonaka, Bass 2007...]

This approach provides a straightforward implementation in Monte Carlo codes

- Just change the vacuum splitting by the medium+vacuum one in the shower algorithm

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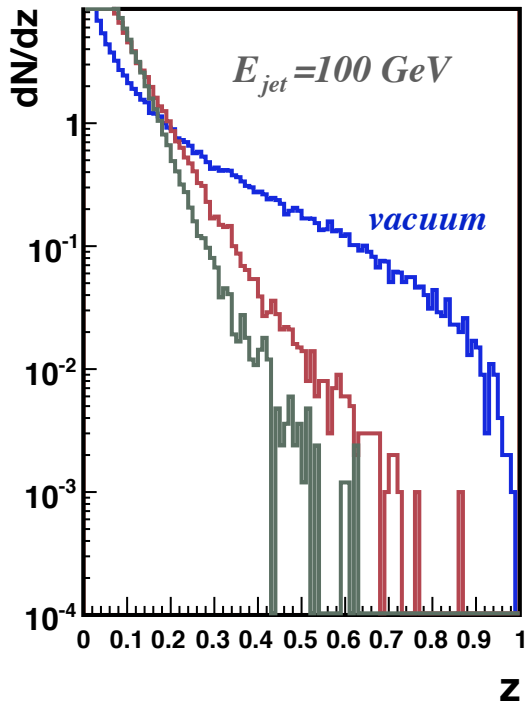
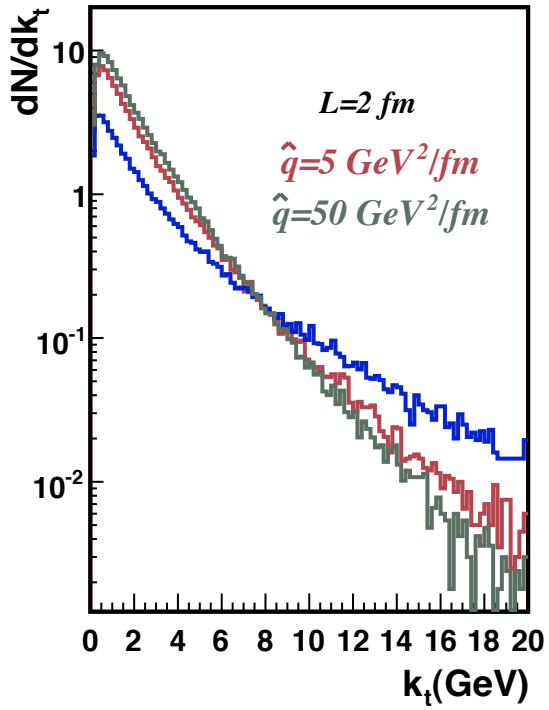
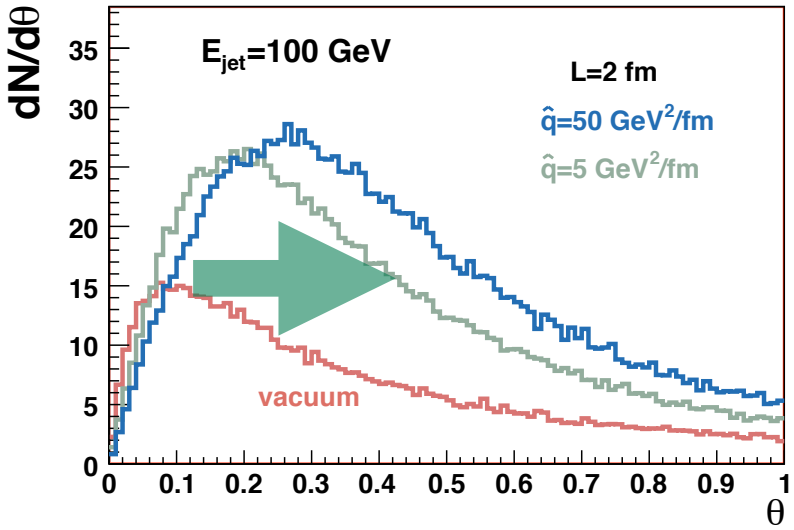
Results from an implementation in Pythia

Fragmentation function





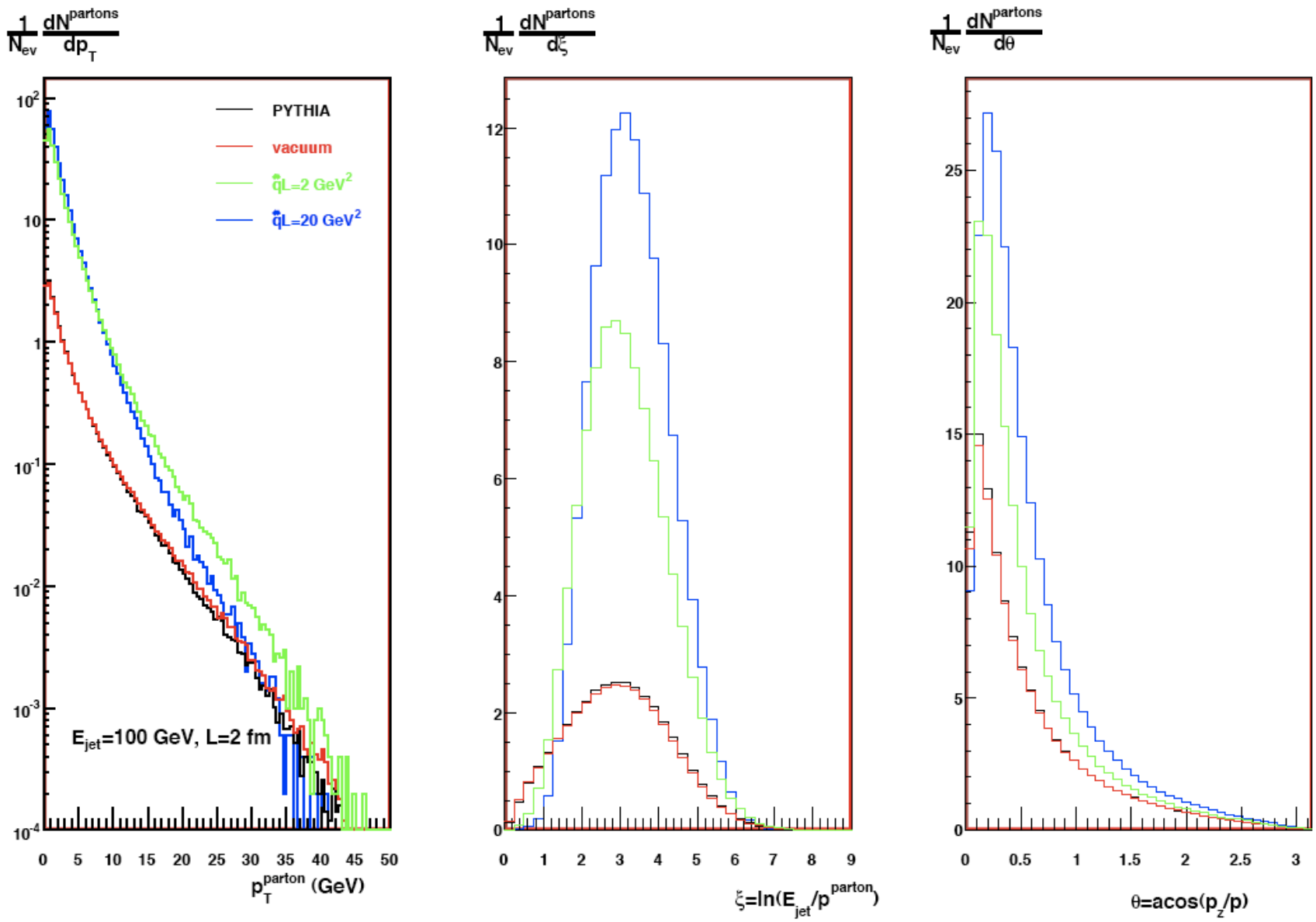
Angular distribution



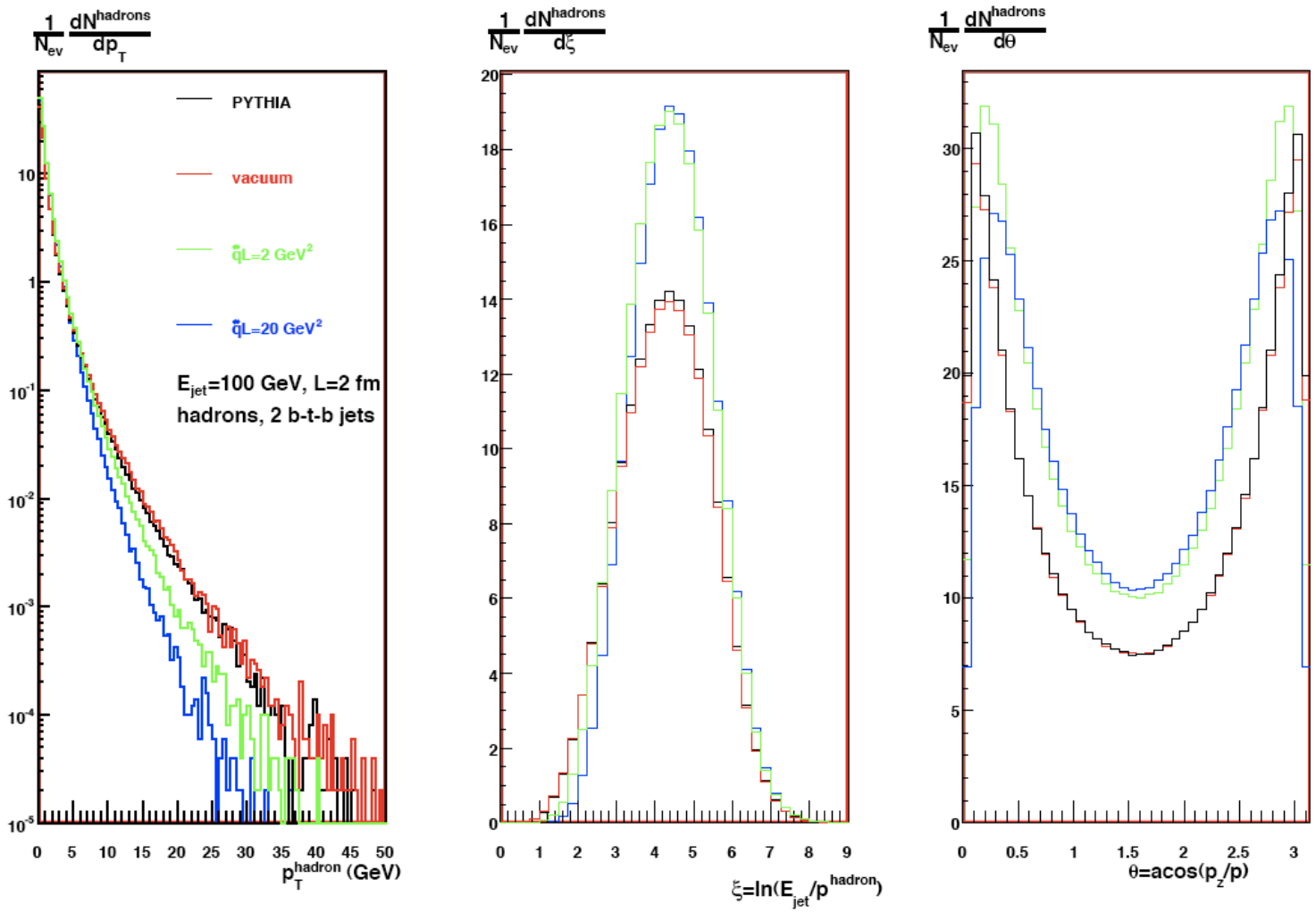
- Main medium-modifications in agreement with expectations
  - Particle spectrum softens (energy loss)
  - Larger emission angles (jet broadening)
  - Larger multiplicity

[Armesto, Cunqueiro, Salgado in preparation]

More results



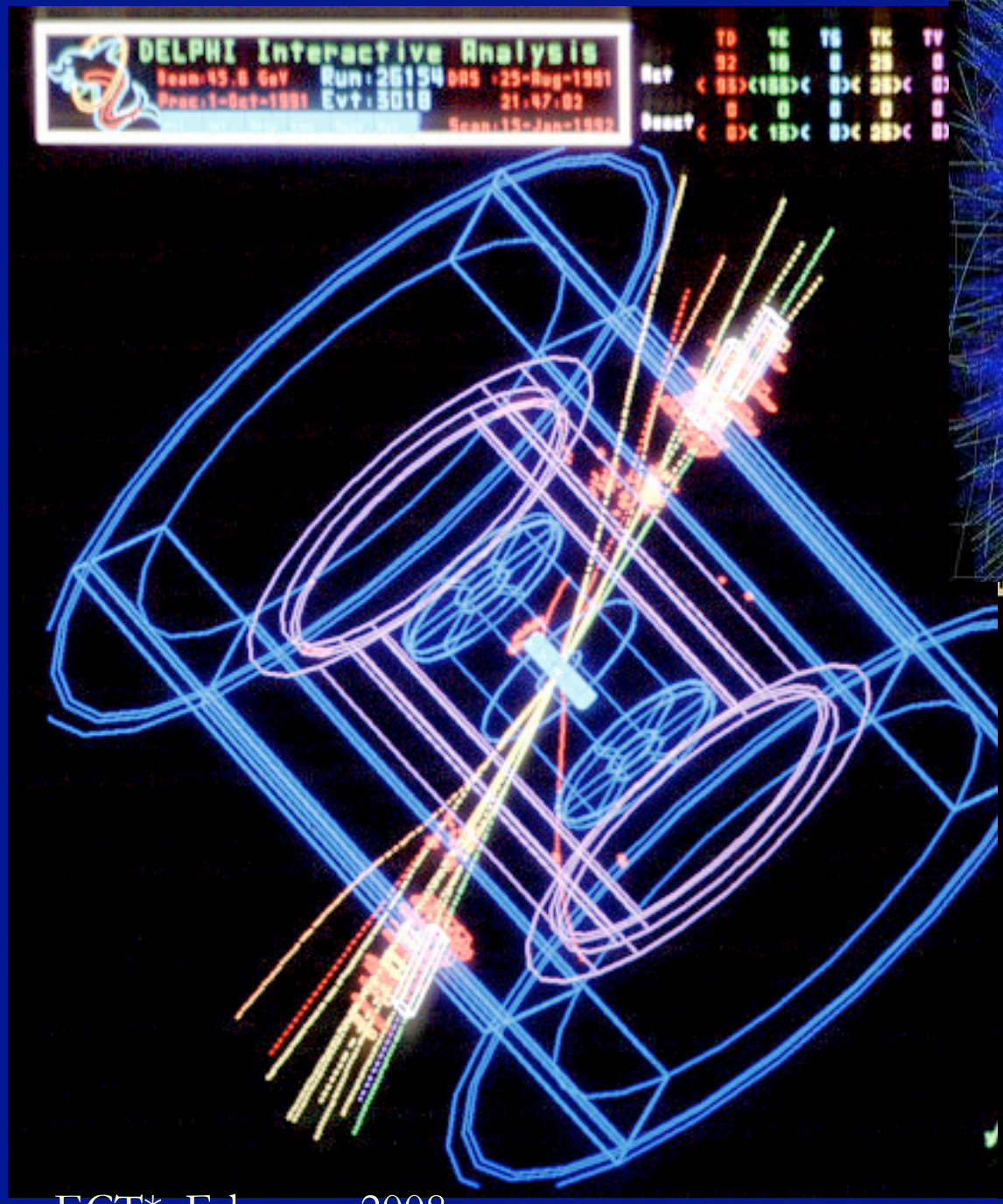
Effect of hadronization

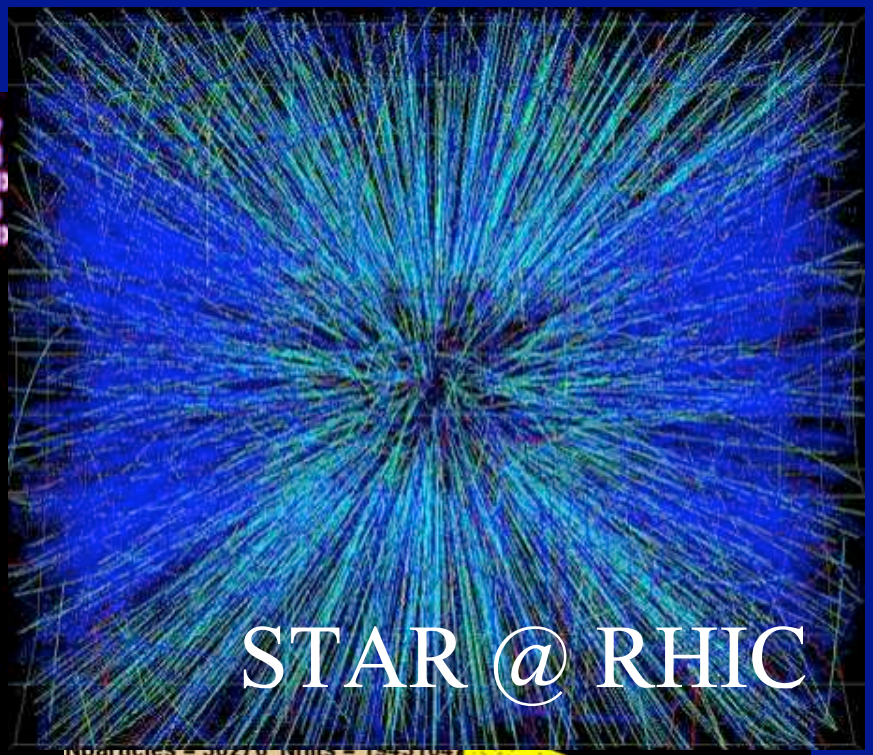


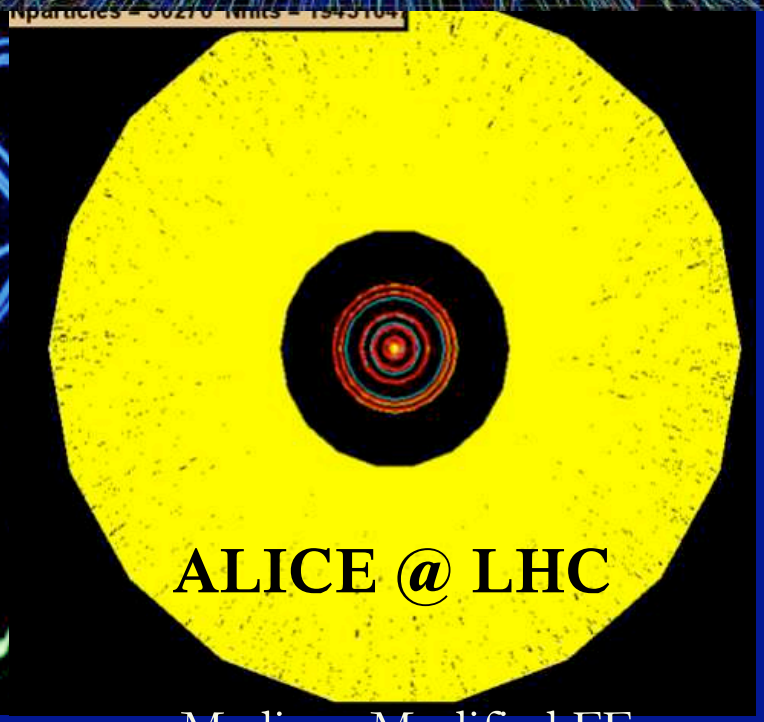
⇒ Preliminary results. Role of hadronization to be clarified

[Armesto, Corcella, Cunqueiro, Salgado]

Jets in HIC







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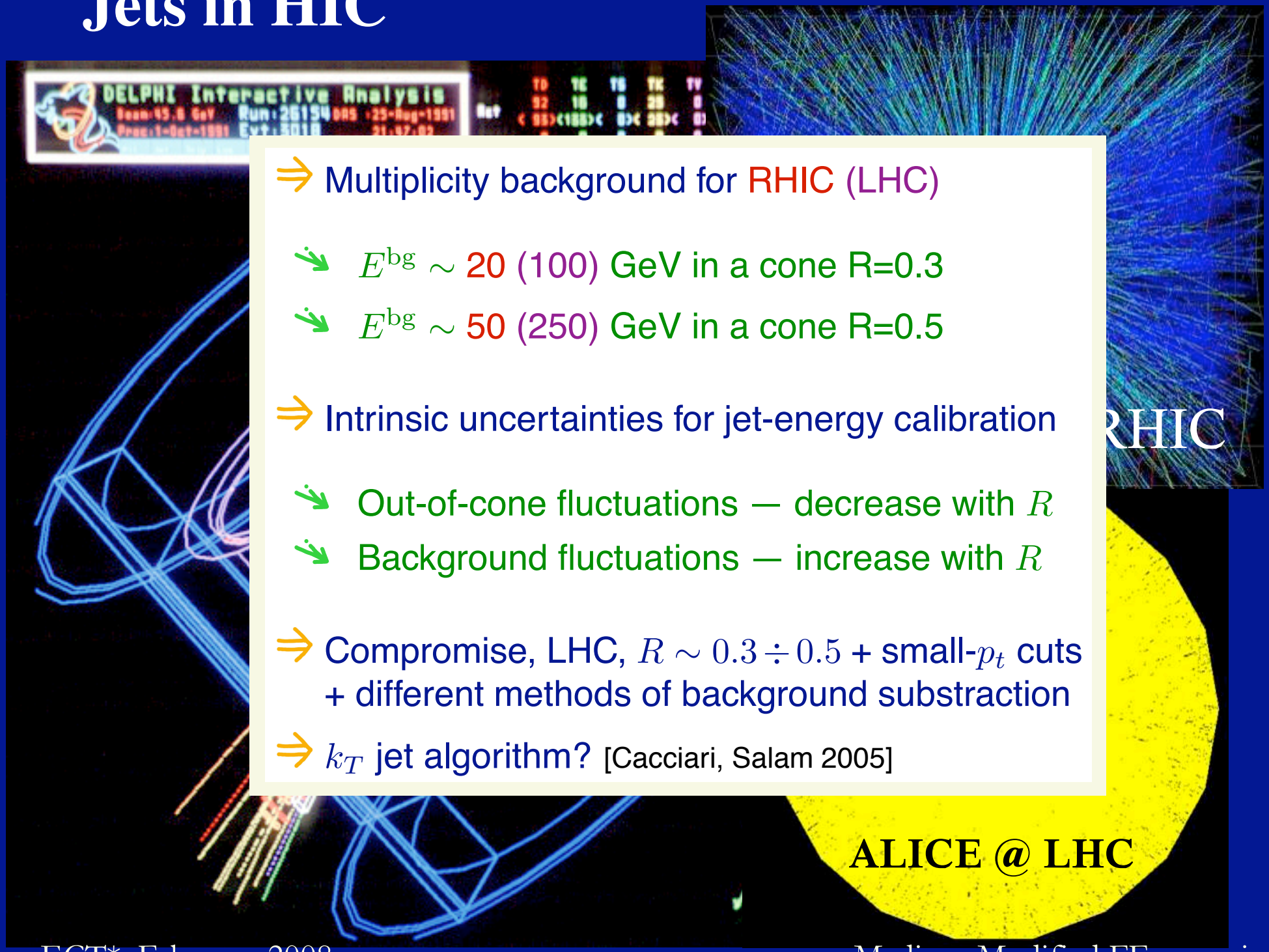
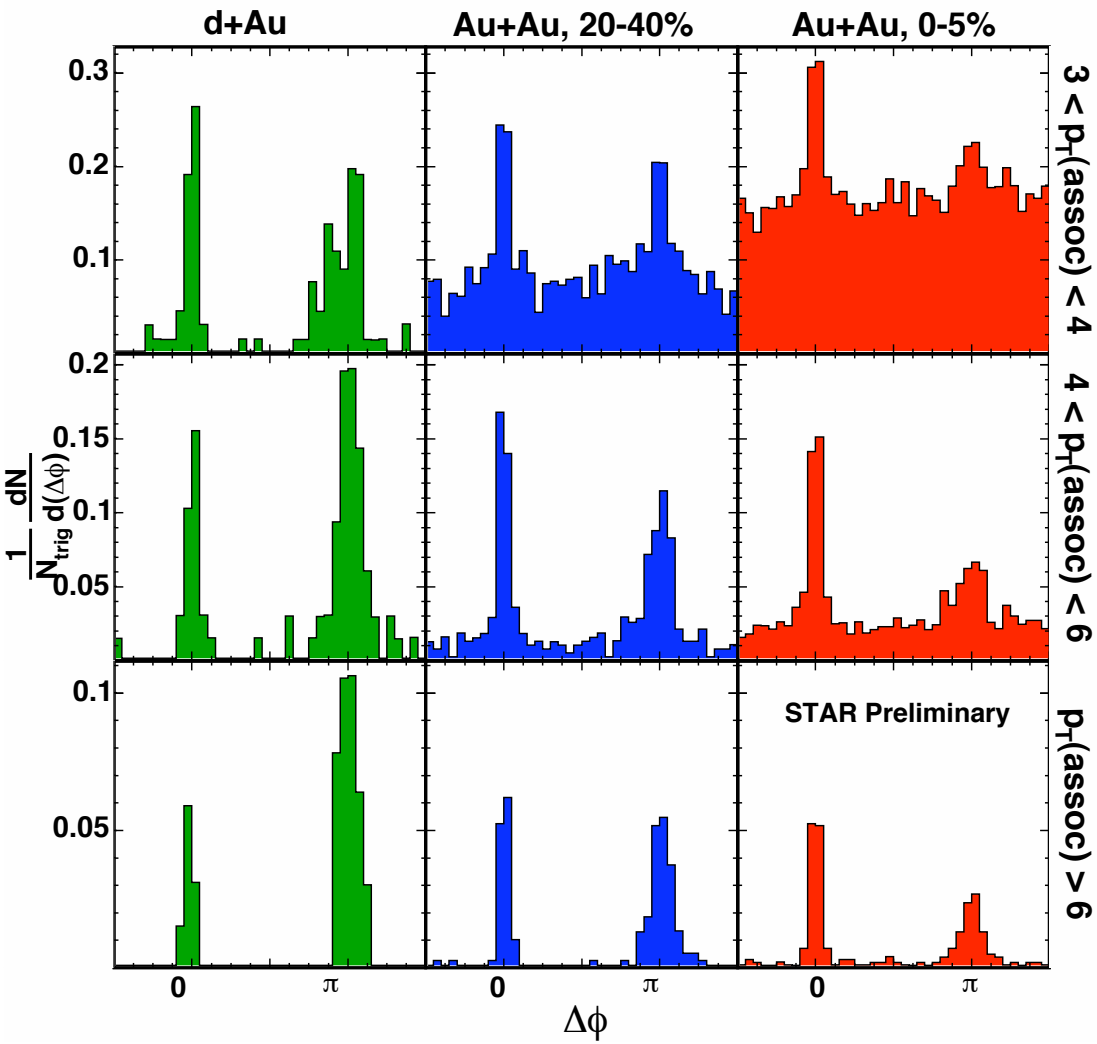
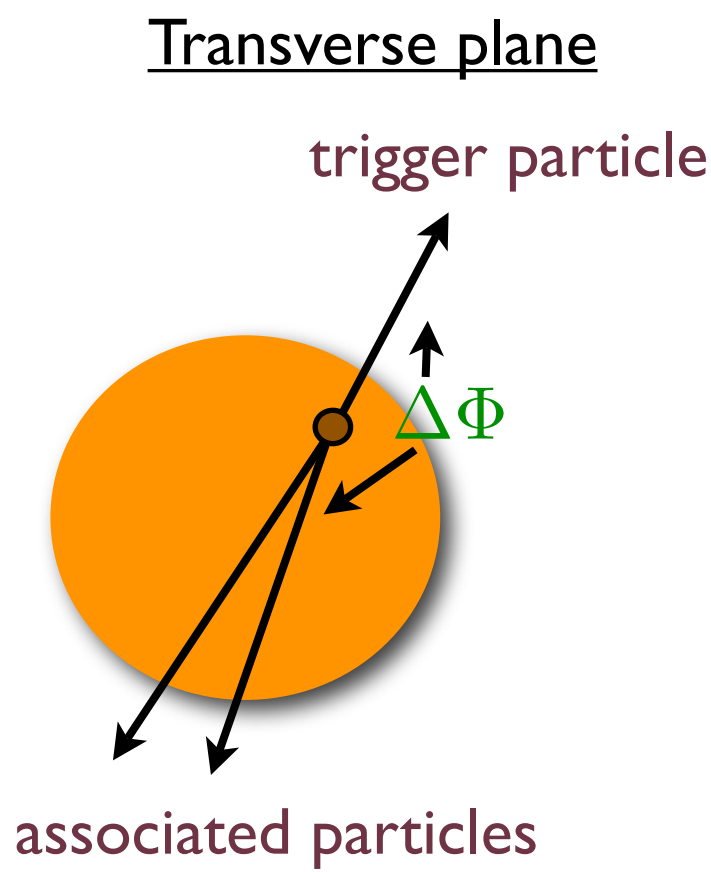


- Multiplicity background for RHIC (LHC)
  - $E^{\rm bg} \sim$ 20 (100) GeV in a cone R=0.3
  - $E^{\rm bg} \sim$ 50 (250) GeV in a cone R=0.5
- Intrinsic uncertainties for jet-energy calibration
  - Out-of-cone fluctuations — decrease with R
  - Background fluctuations — increase with R
- Compromise, LHC, $R \sim 0.3 \div 0.5$ + small-p_t cuts + different methods of background substraction
- k_T jet algorithm? [Cacciari, Salam 2005]

RHIC: two particle correlations



[STAR 2006]



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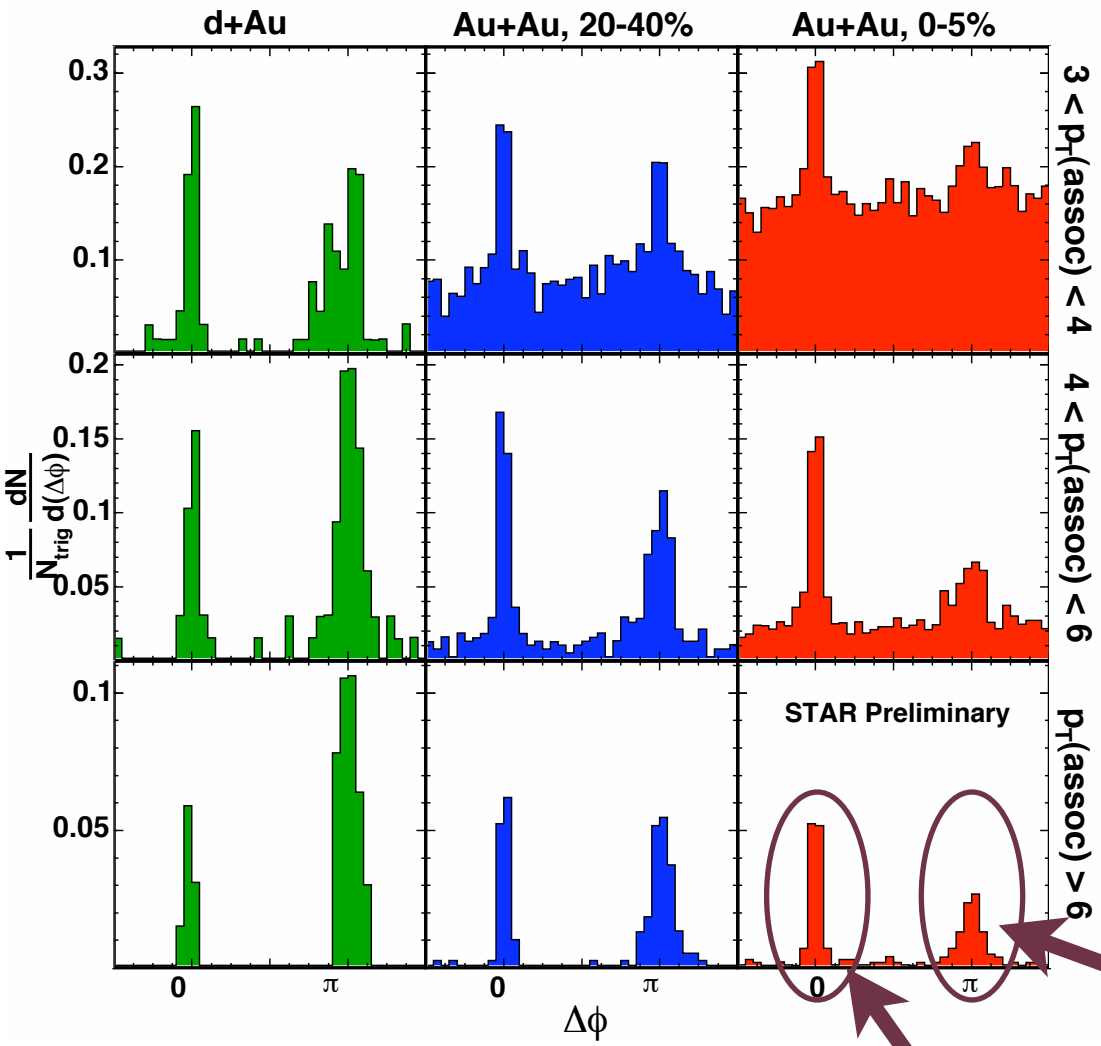
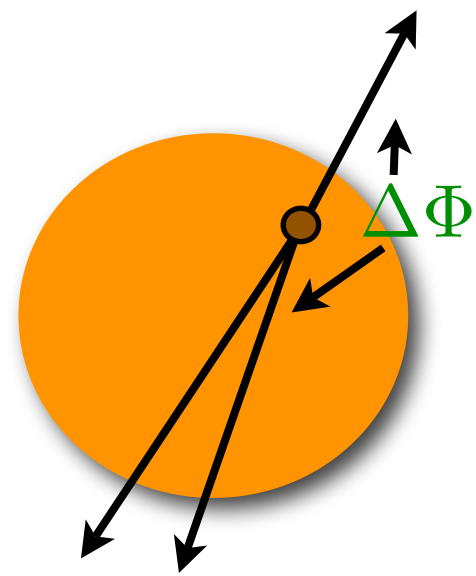


[STAR 2006]

Unchanged

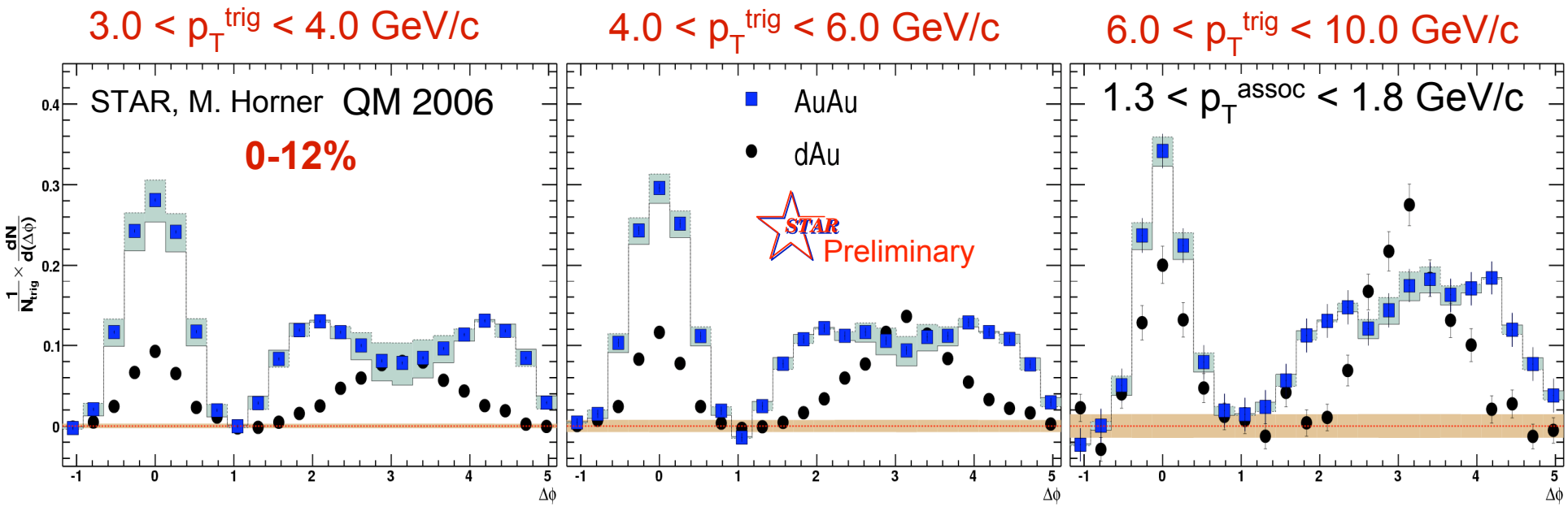
Suppression but no broadening

Transverse plane



Removing the cut-off at RHIC

[Similar results for PHENIX and also SPS (Ceres)]



- Nontrivial angular dependences in the away-side
  - Large broadening
  - Two-peaks when $p_t^{\mathrm{trigg}} \sim p_t^{\mathrm{assoc}}$

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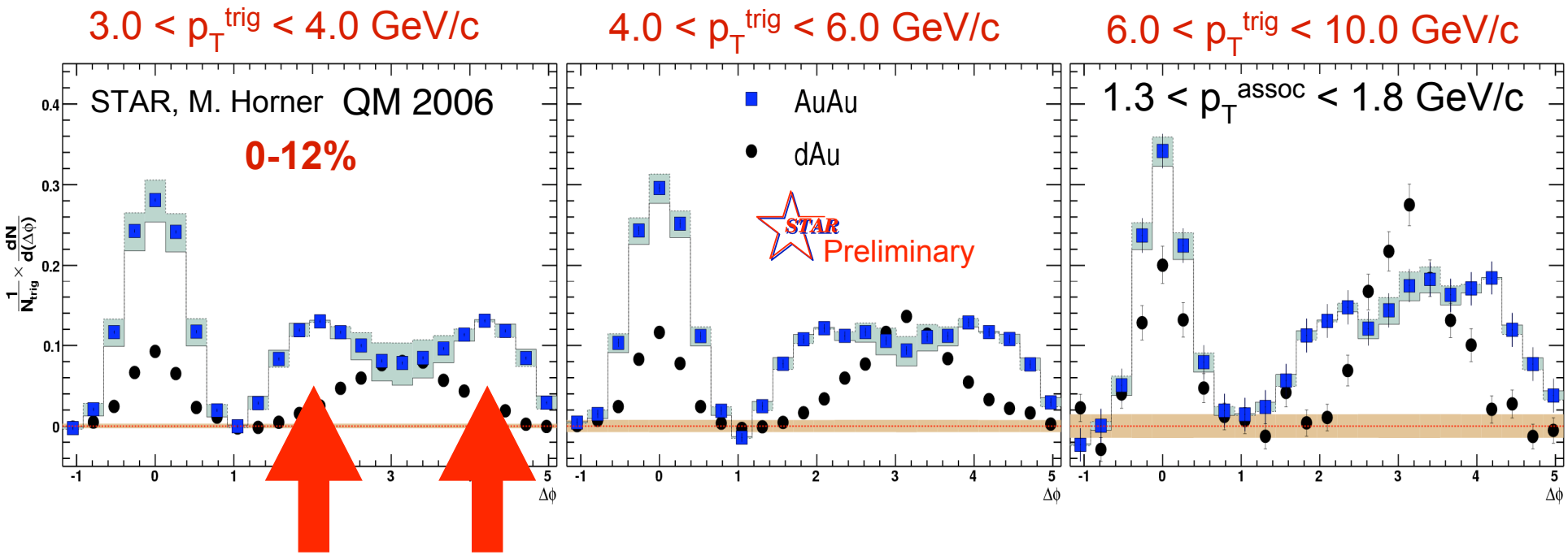

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Two opposite assumptions:

- All energy deposited in the medium +hydrodynamical evolution
- Recoil-less medium-induced radiation

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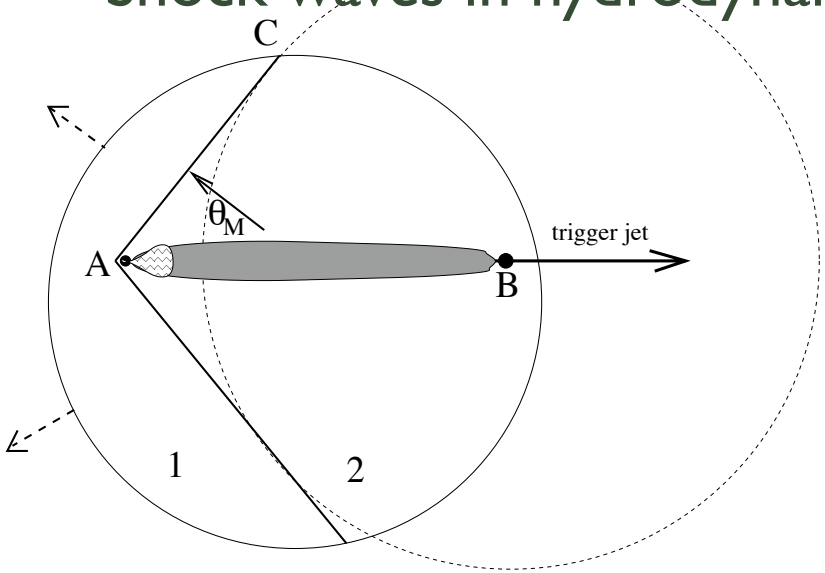
- All energy deposited in the medium +hydrodynamical evolution
- Recoil-less medium-induced radiation

A way to understand the energy deposition in the medium

Interpretations...

Shock waves in hydrodynamical medium

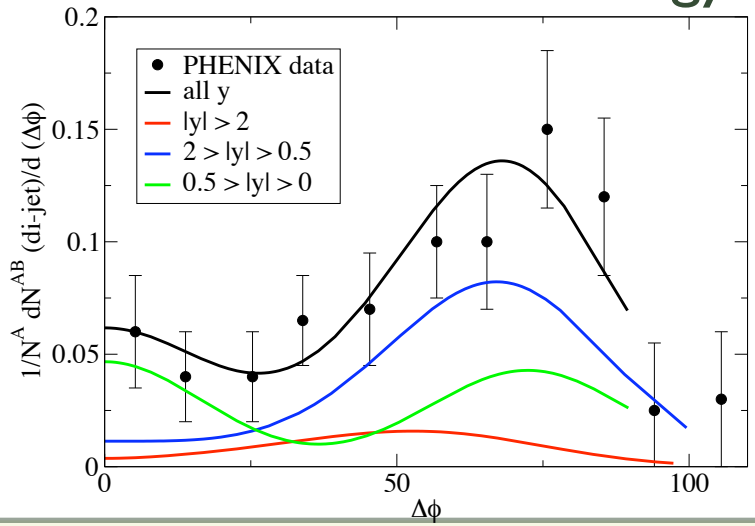


⇒ A hydrodynamical medium produces shock waves IF the energy is deposited fast enough

[Casalderrey-Solana, Shuryak, Teaney; Stoeker; Muller, Renk, Ruppert; Manuel, Mannarelli ...]

⇒ Also Cherenkov radiation proposed

[Dremin; Majumder, Wang]



Parton shower for opaque media

- When $\omega \lesssim \hat{q}^{1/3}$
  - totally coherent limit and large angle radiation

$$\frac{dI^{\rm med}}{d\omega\, dk_t^2} \simeq \frac{\alpha_s C_R}{16\pi}\, L\, \frac{1}{\omega^2} \quad \Longrightarrow \quad \frac{dI^{\rm med}}{dz\, dk_t^2} \simeq \frac{\alpha_s C_R}{16\pi}\, L\, \frac{1}{E\, z^2}$$

- The probability of only one splitting

$$d\mathcal{P} = dz\, d\theta\, \frac{\alpha_s C_R}{8\pi}\, E\, L\, \sin\theta\, \cos\theta \exp\left\{-\frac{\alpha_s C_R}{16\pi}\, E\, L\, \cos^2\theta\right\}$$

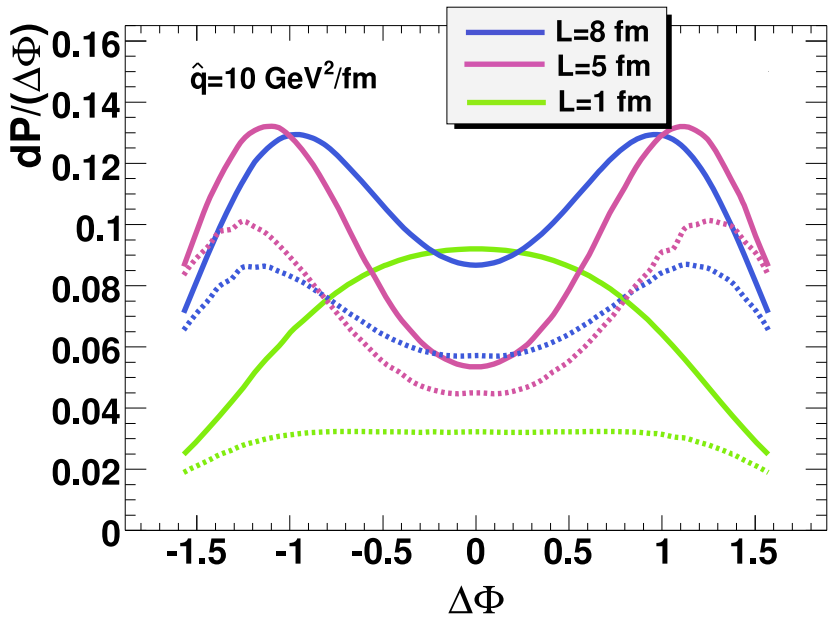
- Non-trivial angular dependence for the medium-induced gluon radiation. Two peaks in the laboratory variables η, Φ for ($\eta \simeq 0$)

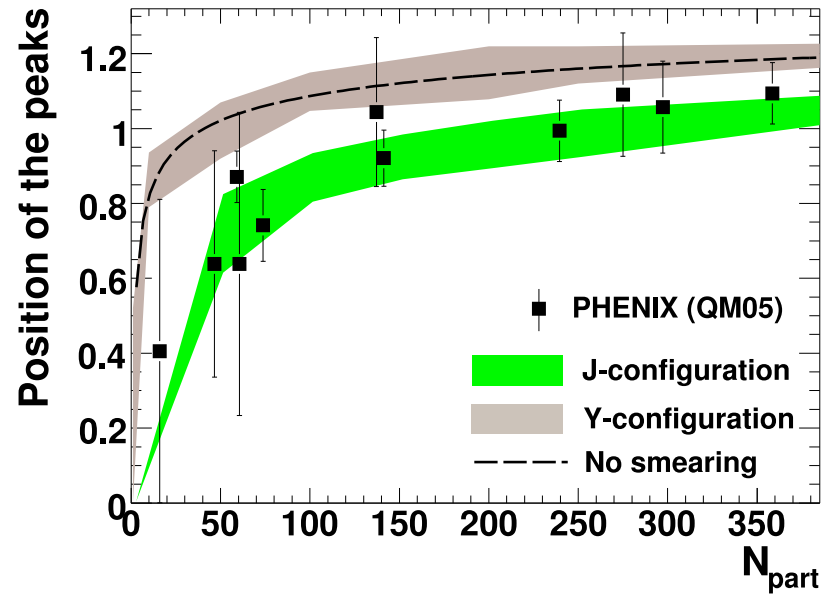
$$\Phi_{\rm max} = \pm \arccos\sqrt{\frac{8\pi}{E\, L\, \alpha_s\, C_R}}$$

A simple model to compare with data

- Smearing in longitudinal (η) and transverse (Φ) variables

$$\frac{dP}{d\Delta\Phi dz} = \frac{1}{N}\int_{-\Delta\eta}^{\Delta\eta} d\eta \int d\Phi' \frac{d\mathcal{P}}{d\Phi' dz d\eta} \mathrm{e}^{-\frac{(\Delta\Phi-\Phi')^2}{2\sigma^2}}$$

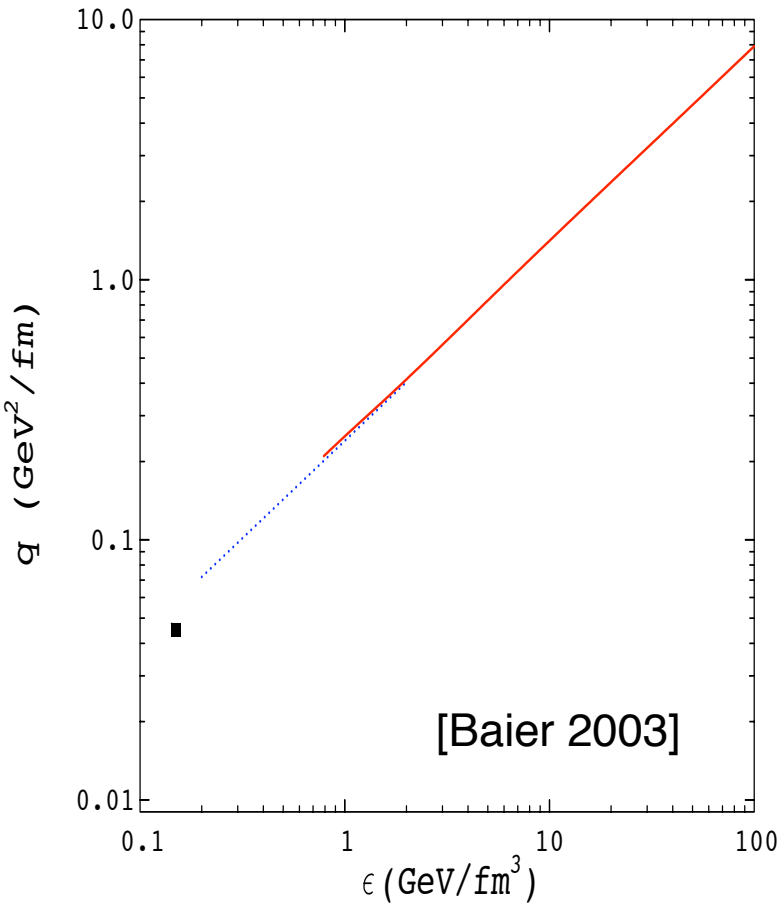




[Polosa, Salgado hep-ph/0607295]

- A perturbative mechanism, the medium-induced gluon radiation, is able to reproduce the observed 2-peak structure in the away side jet.

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



- Transport coefficient for an ideal quark-gluon gas

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

[Baier and Schiff 2006]

- Fits to the data

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

$$\hat{q} \simeq 4.2\ \hat{q}_{\text{ideal gas}}$$ [Renk et al. 2007]

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

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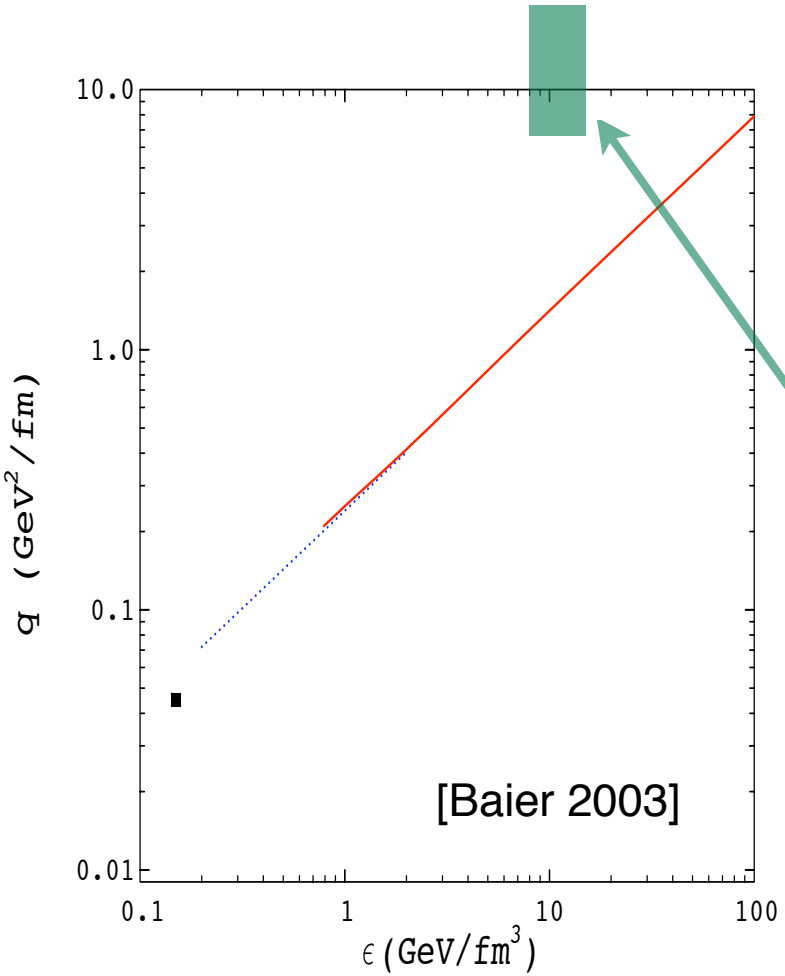

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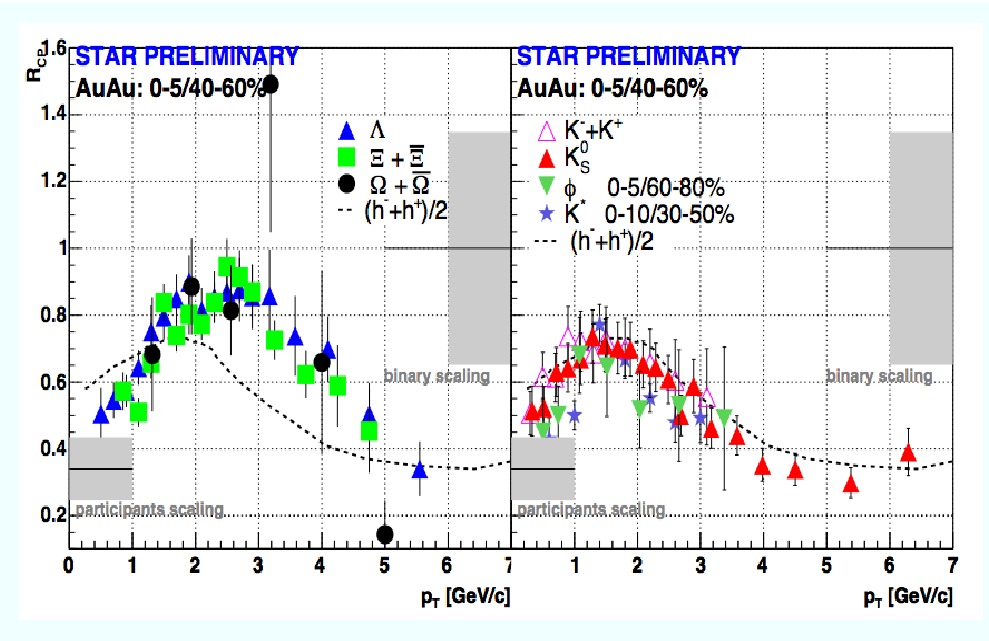
What is the order of magnitude of the NLO correction?

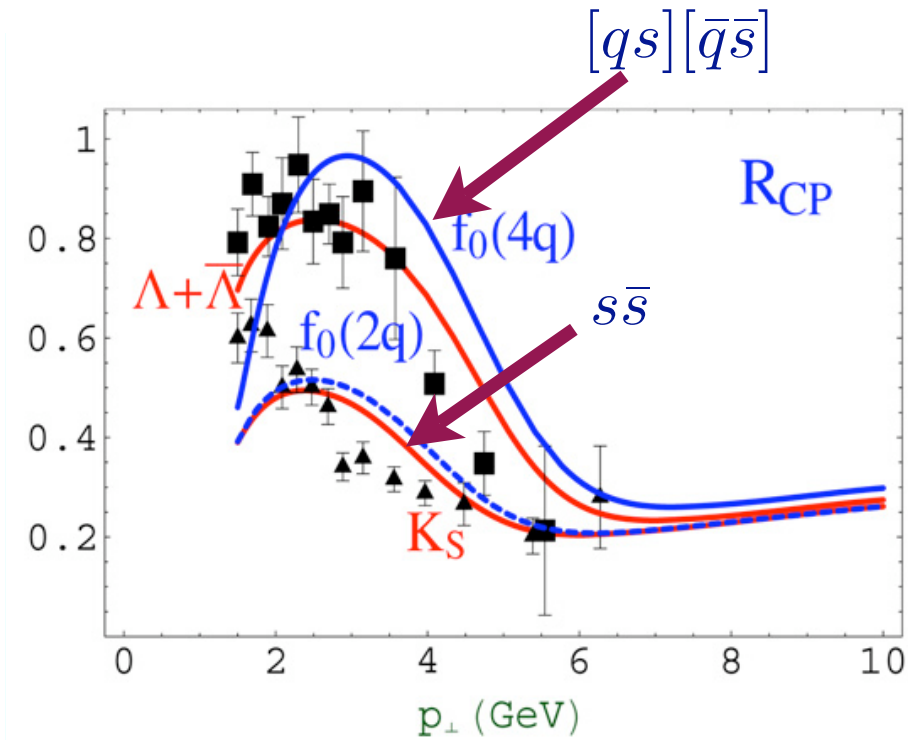
What are the degrees of freedom?

- Above 3Tc quark and gluon quasiparticles (pert. QCD)
- Below 3Tc (where experiments are)
  - Possible existence of bound states (lattice)
  - Large Interaction cross sections (viscosity, jet quenching)
  - Still unclear → several proposals
  - Ideal fluid formed by colored bound states, diquarks...?
  - Strongly coupled Quark Gluon Plasma (sQGP)?

Exotic meson spectroscopy and HIC

Baryon/meson hierarchy of suppressions observed at RHIC





A nice possibility for a clean measurement of the exotic structure

$$f_0(980) = s\bar{s} \quad \text{OR} \quad [qs][\bar{q}\bar{s}] \ ?$$

[Maiani, Polosa, Riquer, Salgado (2007)]

[Nonaka, Muller, Asakawa, Bass, Fries 2004; Chen, Ko, Liu, Nielsen, Greco, Lee, Liu 2004, 2007]

Summary

- Successful phenomenology of jet-quenching at RHIC
  - Improvements needed for jets at the LHC
- A new implementation of medium-effects presented
  - Modification of the splitting function taken from medium-induced gluon radiation
  - Consistent treatment of vacuum+medium splittings, energy conservation and virtuality evolution
  - Implemented in PYTHIA and HERWIG (work in progress)
- Some points to be clarified
  - Length evolution
  - Hadronization
  - Virtuality

Title