High-p_T physics at RHIC and prospects for LHC

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High transverse momentum physics in heavy-ion collisions

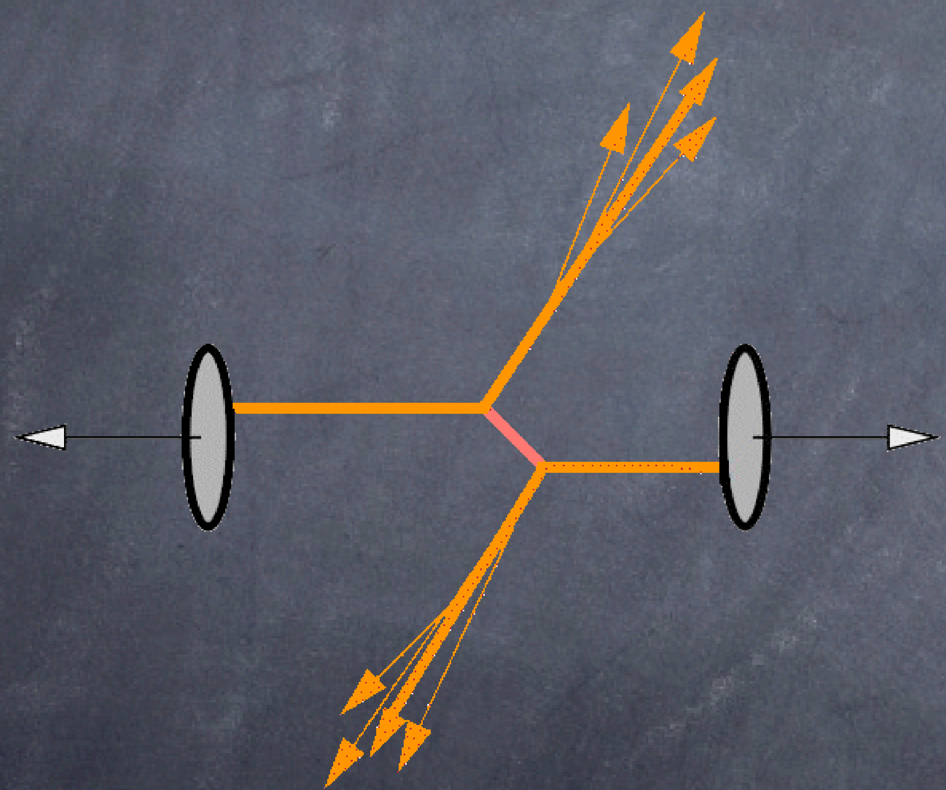
- A 5-plot overview of high-p_T results from RHIC
- Radiative vs. collisional energy loss
- Models of radiative energy loss
  - energy loss due to the (non-Abelian) LPM effect
  - opacity expansion
  - medium-modified MLLA
- (Models of collisional energy loss)
- "Predictions" for LHC

High transverse momentum physics in heavy-ion collisions

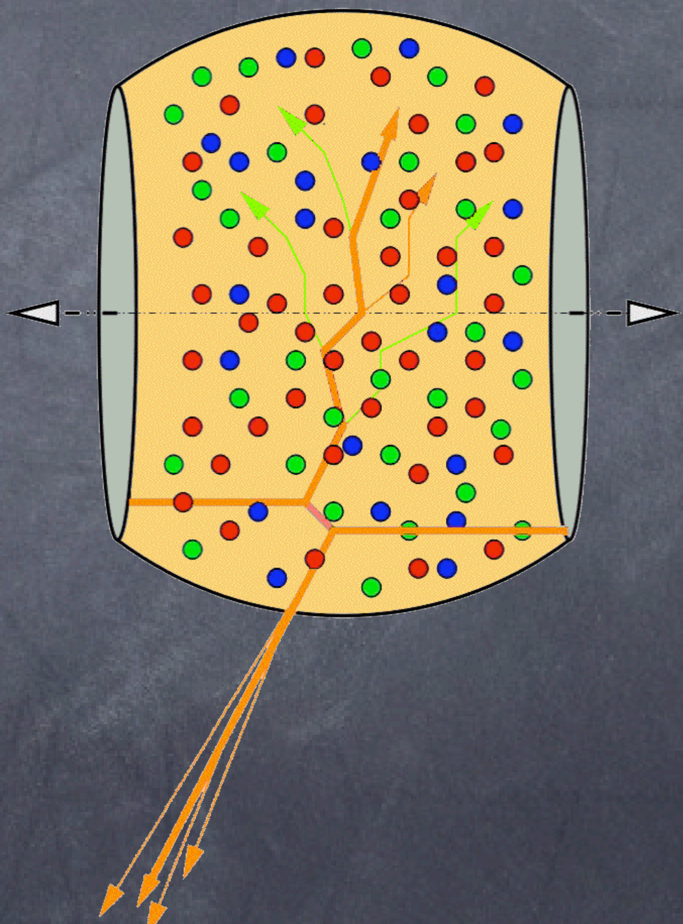
Prediction (Bjorken, 1984):

a high-p_T parton traversing a dense colored medium loses energy

proton-proton:



nucleus-nucleus:



The "jet" is quenched and does not escape the medium

(a photon, a $W^{\pm}$ or a Z^0 boson are not affected)

High transverse momentum physics in heavy-ion collisions

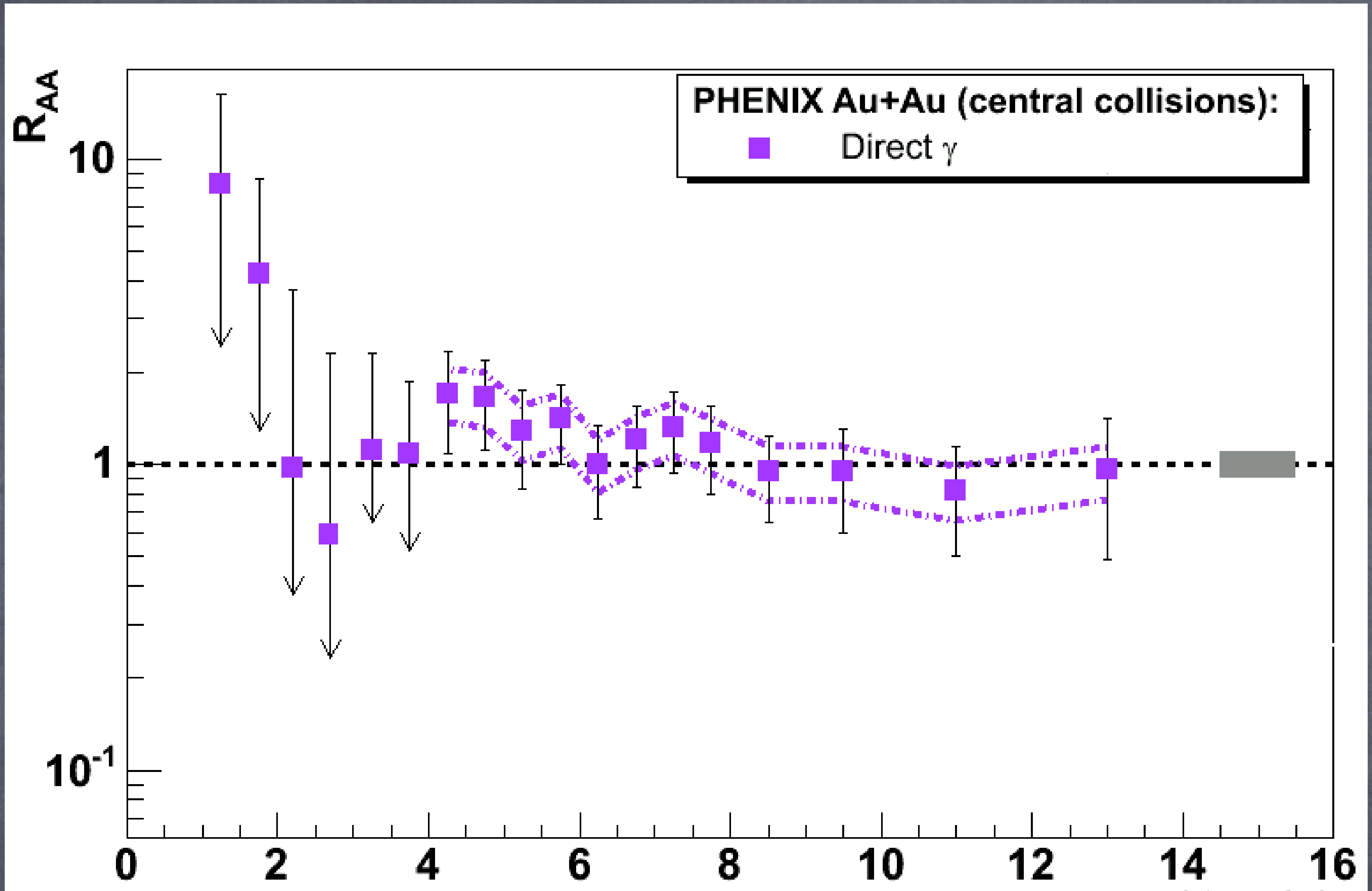
To quantify the amount of jet quenching, compare the yield in high-p_T particles in nucleus-nucleus with that in proton-proton collision:

"nuclear modification factor" $R_{AB} \equiv \frac{\text{yield in } AB}{N_{\text{coll.}} \times \text{yield in } pp}$

number of binary collisions → $N_{\text{coll.}}$

If the nucleus-nucleus collision amounts to the superposition of $N_{\text{coll.}}$ independent nucleon-nucleon collisions, $R_{AB} = 1$.

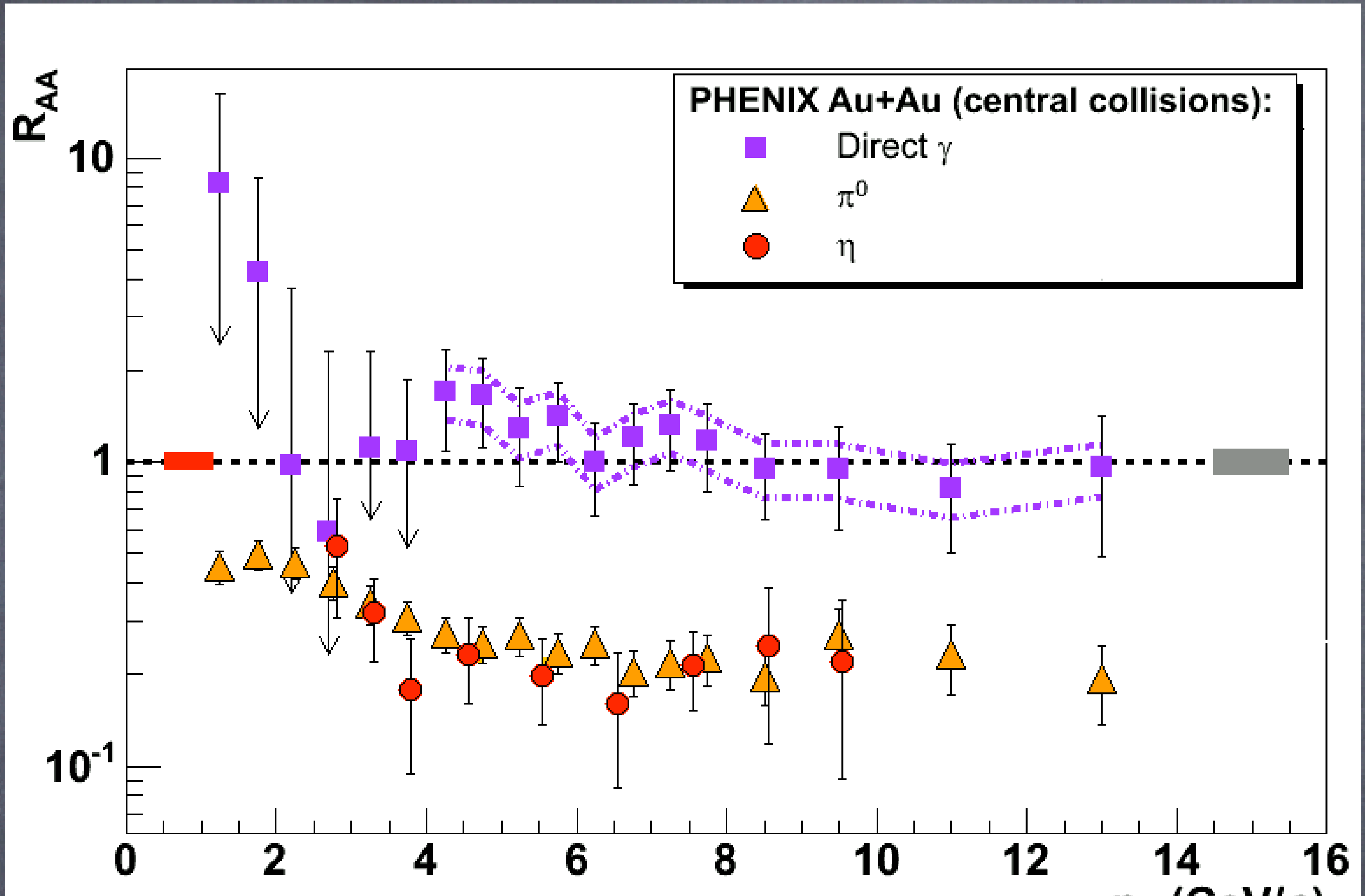
Nuclear modification factor at RHIC



Phys. Rev. Lett. **96** (2006) 202301

For photons, $R_{\rm AuAu} \simeq 1$ at high p_T: no medium effect (and $N_{\rm coll}$ is calculated properly).

Nuclear modification factor at RHIC

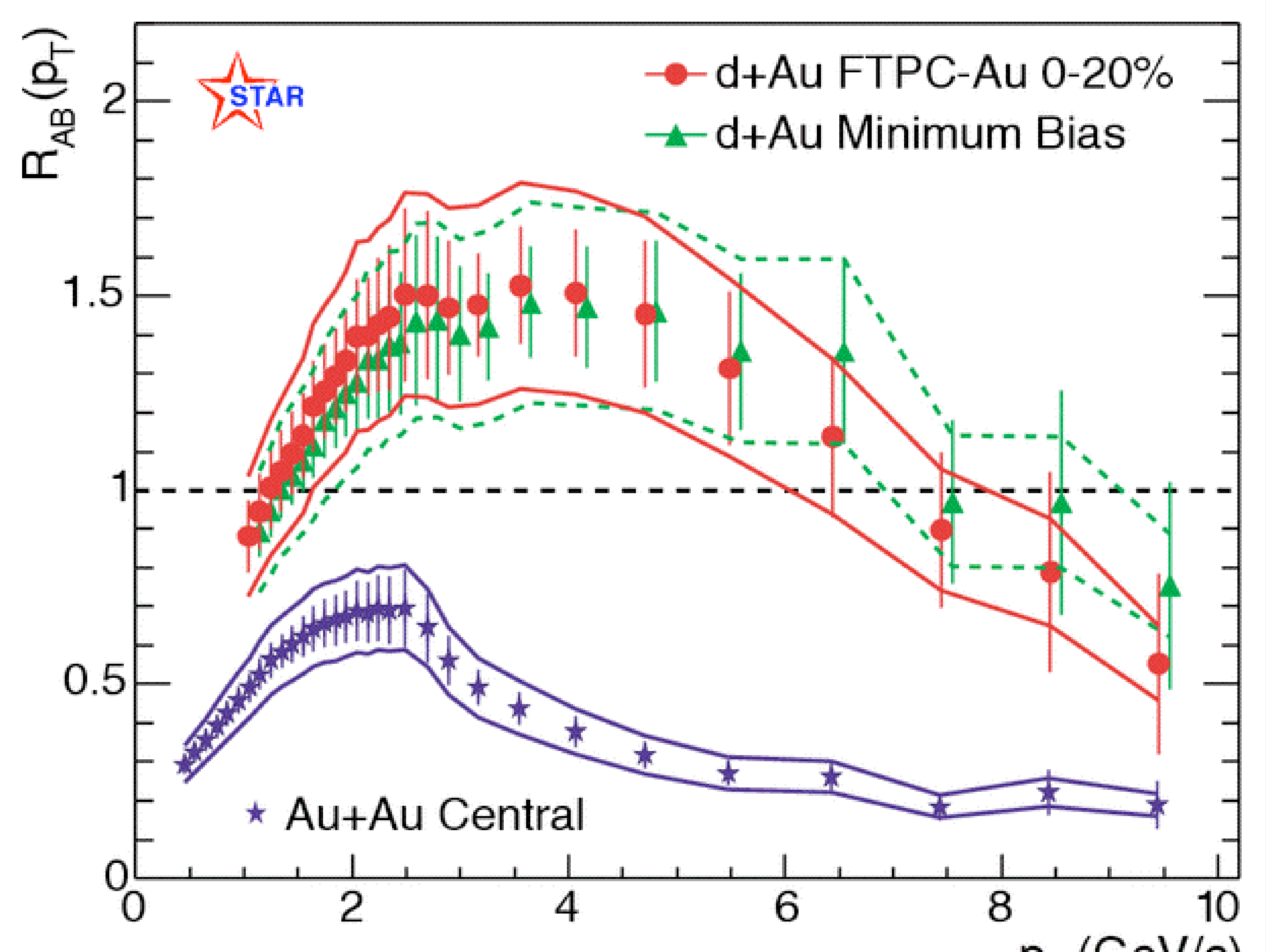


Phys. Rev. Lett. **96** (2006) 202301

For photons, $R_{\rm AuAu} \simeq 1$ at high p_T: no medium effect (and $N_{\rm coll}$ is calculated properly).

In contrast, high-momentum π^0 and η are suppressed by a factor ≈5.

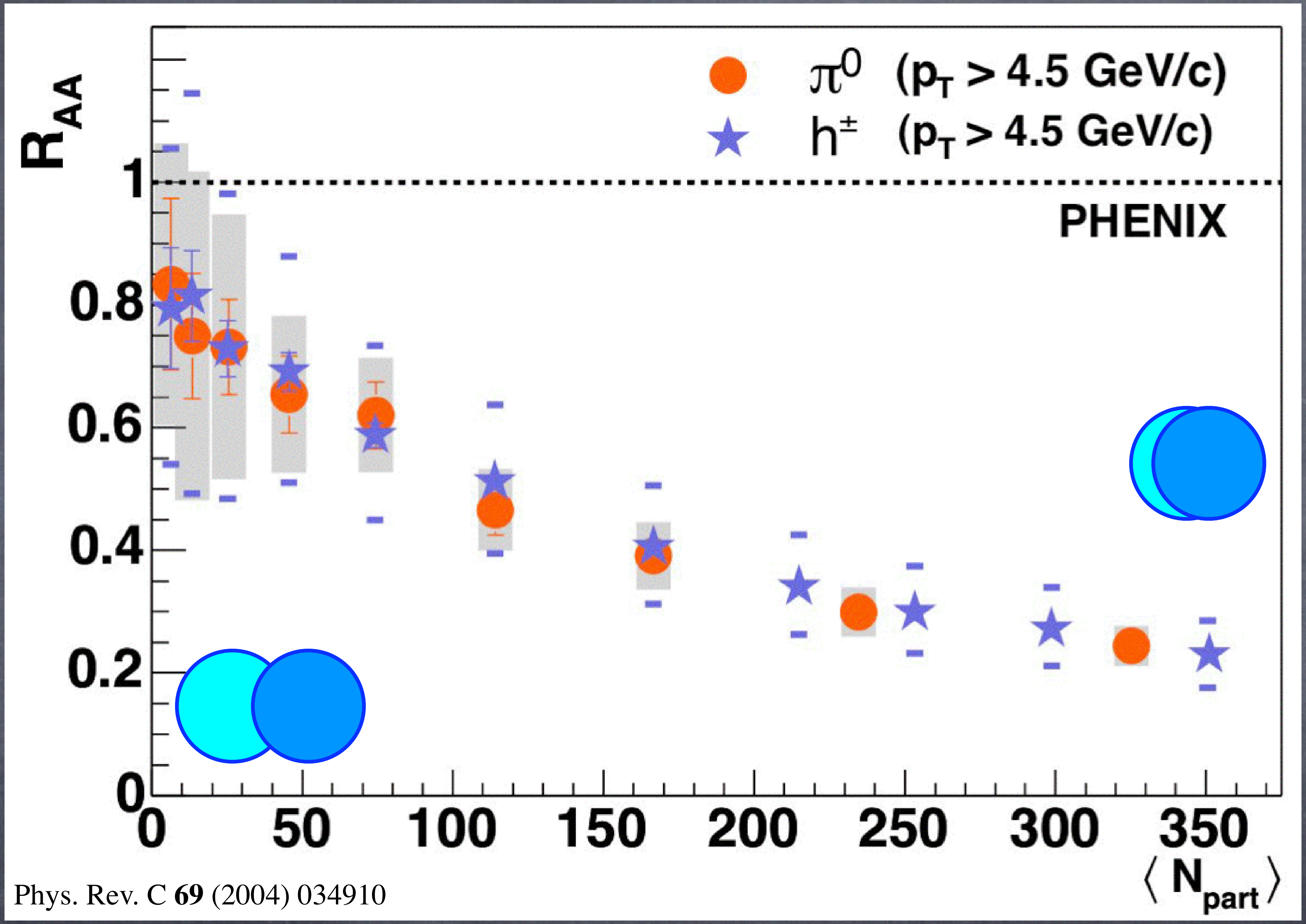
Nuclear modification factor at RHIC



Phys. Rev. Lett. **91** (2003) 072304

High-p_T charged hadrons are suppressed in central Au-Au collisions as well, by the same amount (≠ no suppression in d-Au).

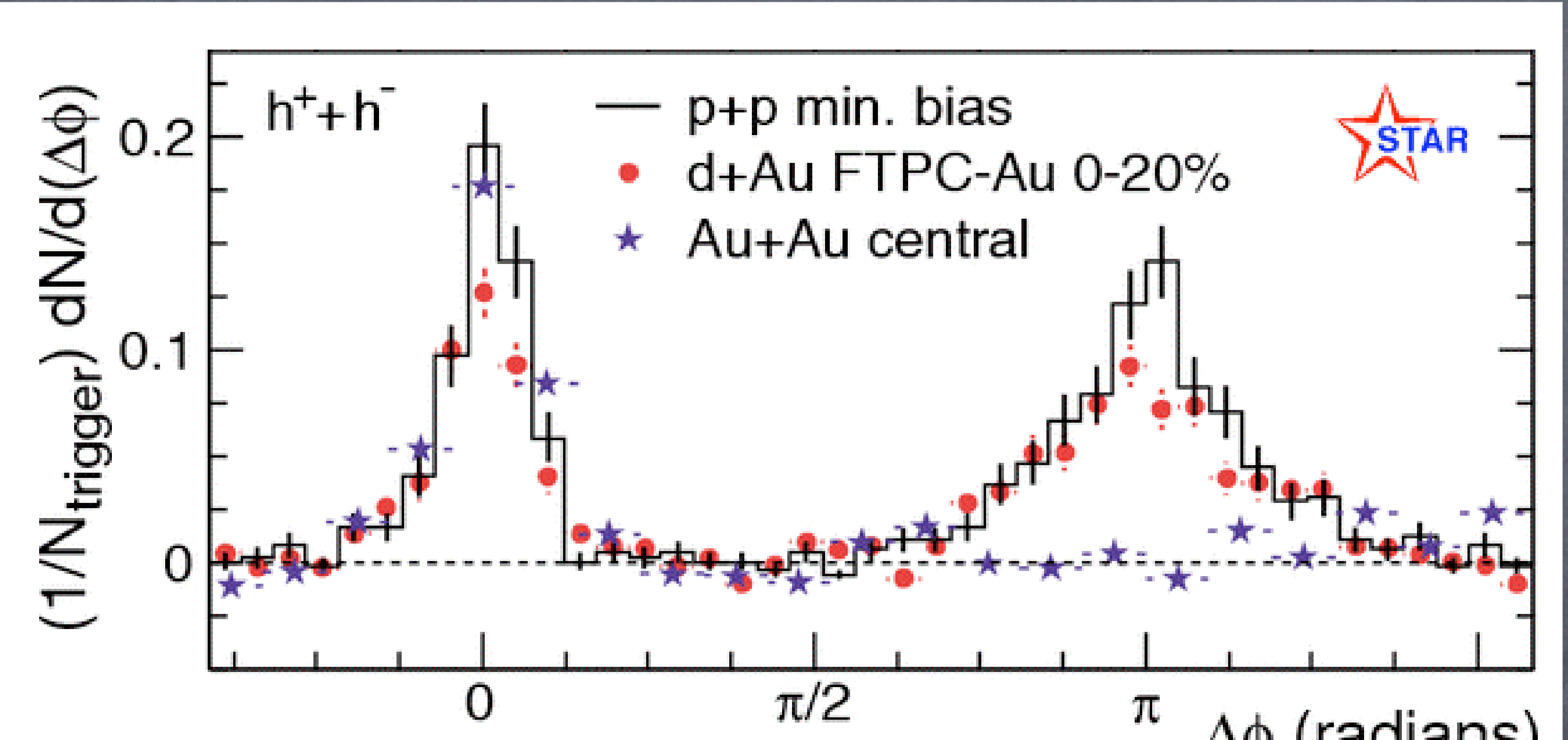
Nuclear modification factor at RHIC



The more peripheral the collision (the smaller the medium size), the smaller the suppression.

Two-particle correlations

Count, as a function of the angular separation $\Delta\phi$, the multiplicity of particles (above a given p_T cut) "associated" with the particle with highest transverse momentum in the event ("trigger particle").



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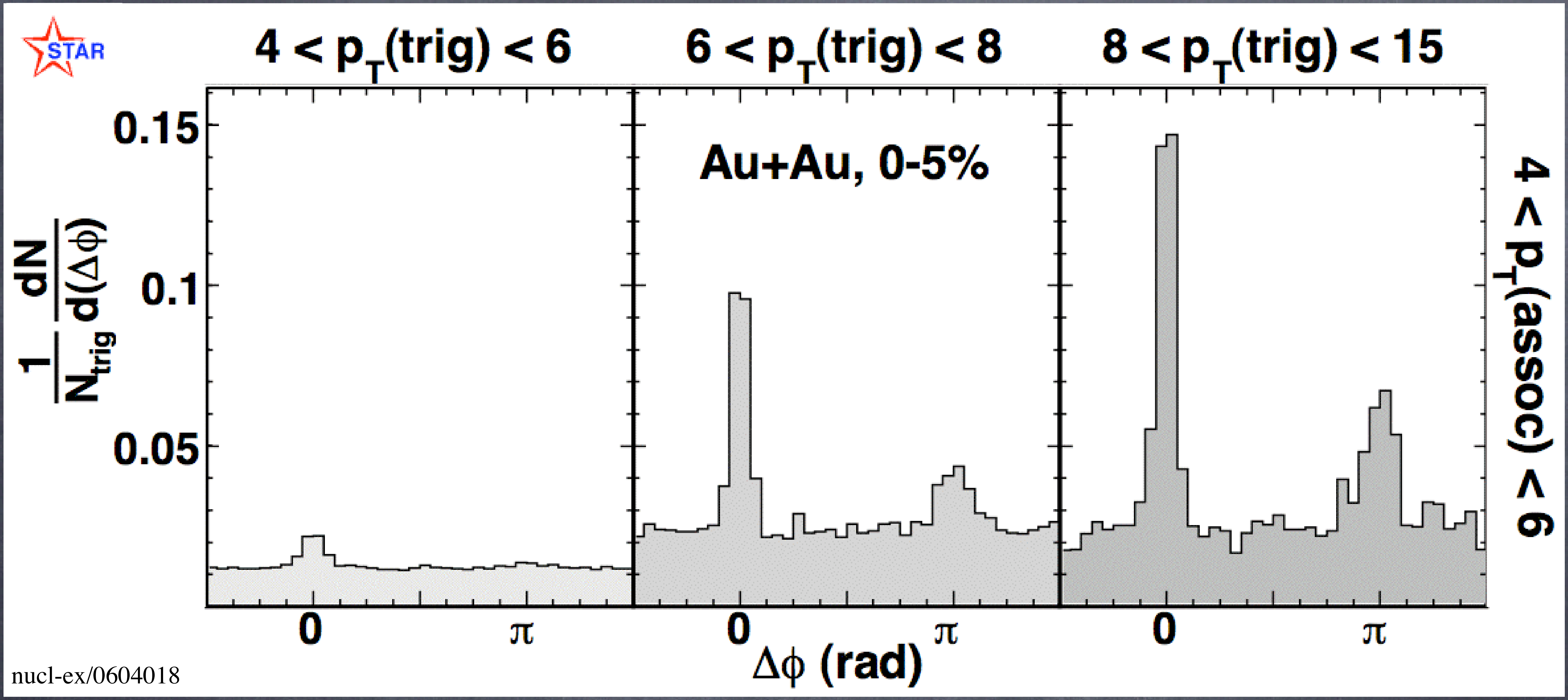
In central Au-Au collisions, the back jet at 180° disappears

≠ in pp or in d-Au collisions

Two-particle correlations

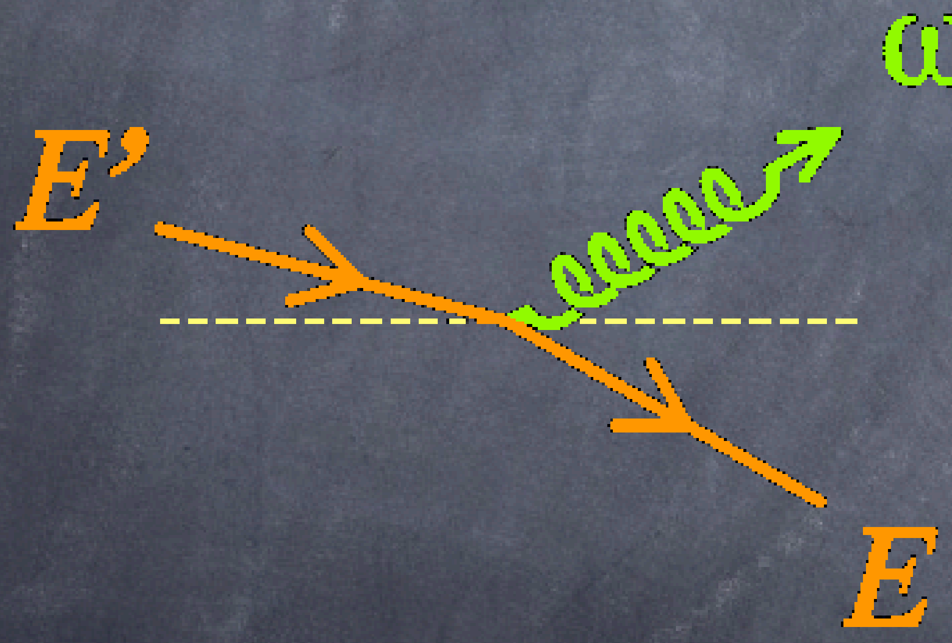


When increasing the transverse momentum threshold (= triggering on jets of increasing energy), the back jet reappears.

Models of high-p_T parton energy loss

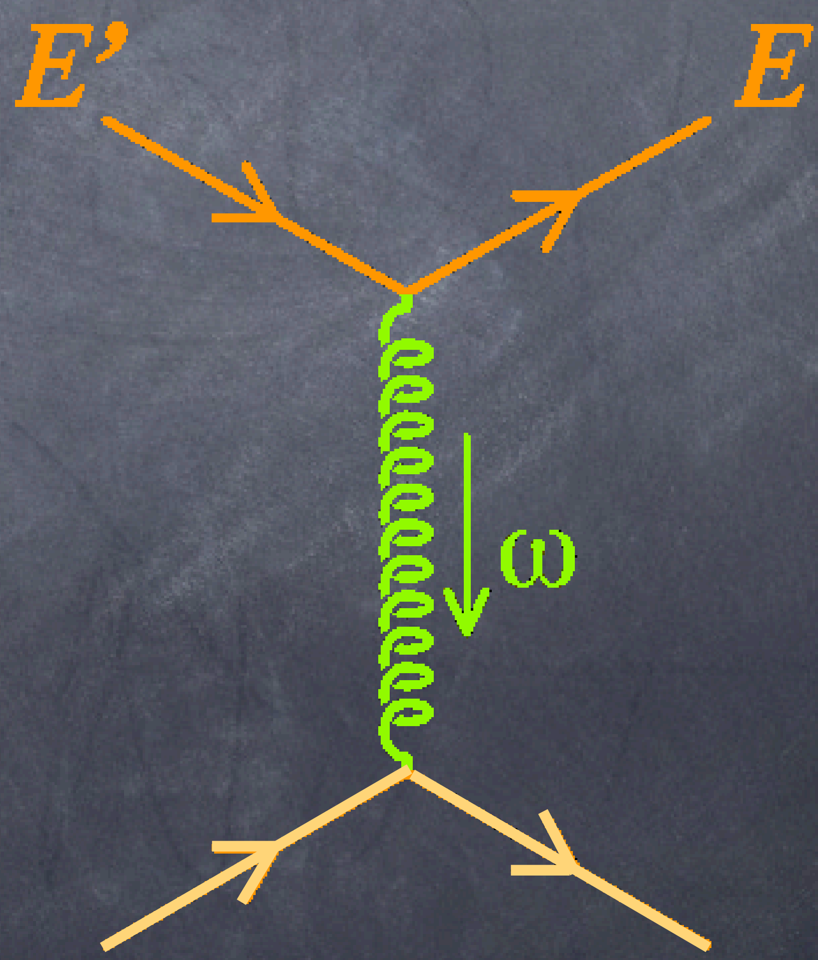
Two different "categories" of models of parton energy loss, depending on the basic underlying process:

"radiative" process (Bremsstrahlung)



also "in vacuum", but controlled by the presence of a medium

"collisional" process

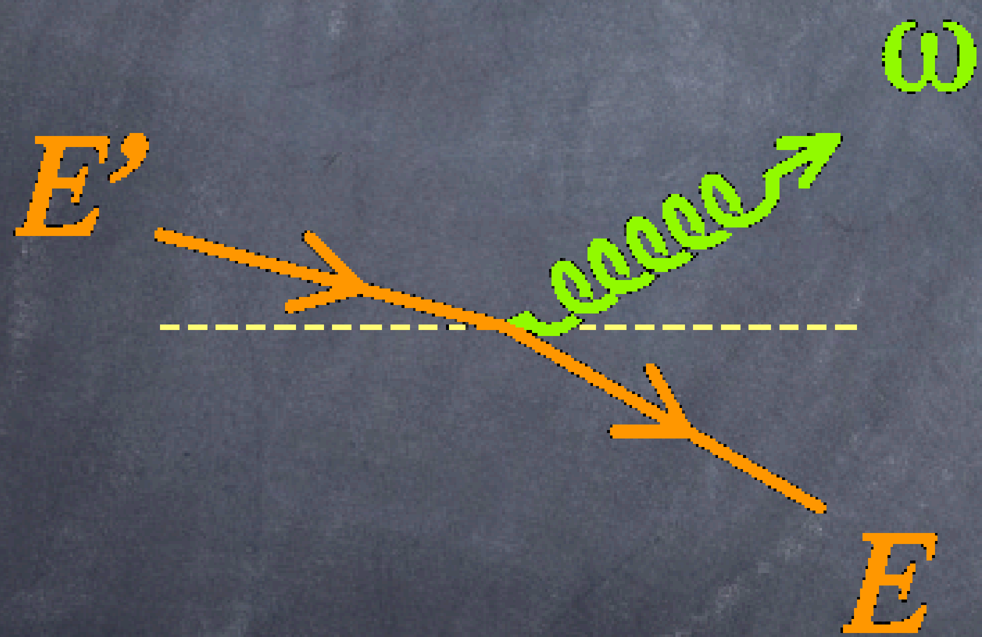


Models of high-p_T parton energy loss

Two different "categories" of models of parton energy loss, depending on the basic underlying process:

inelastic

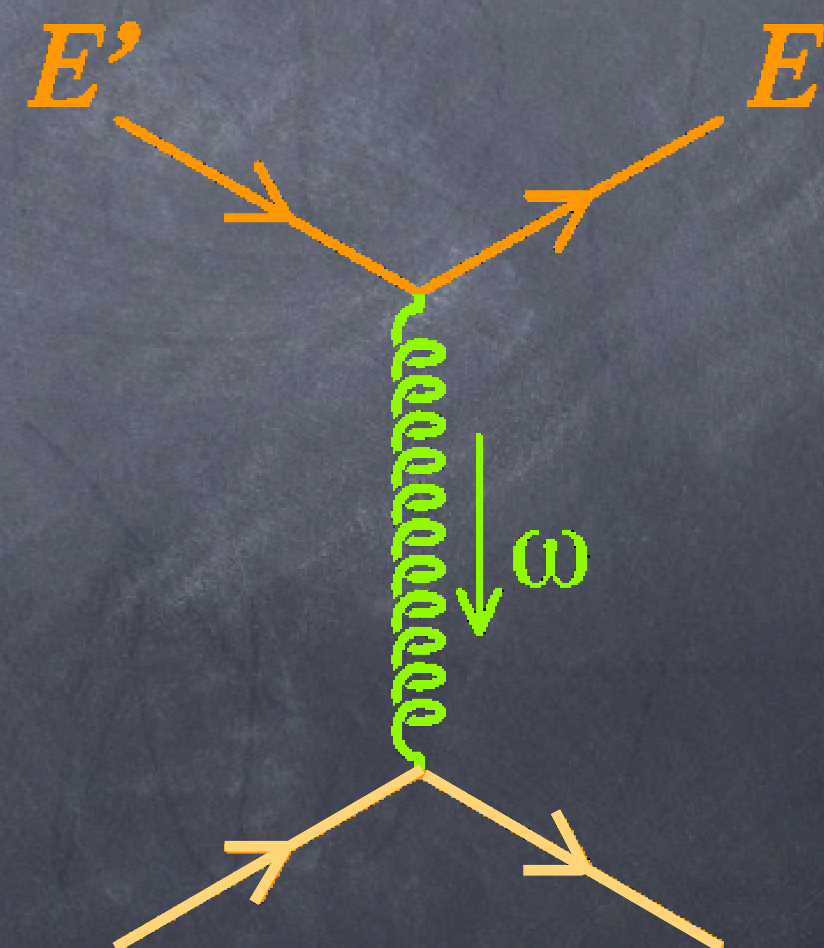
"~~radiative~~" process (Bremsstrahlung)



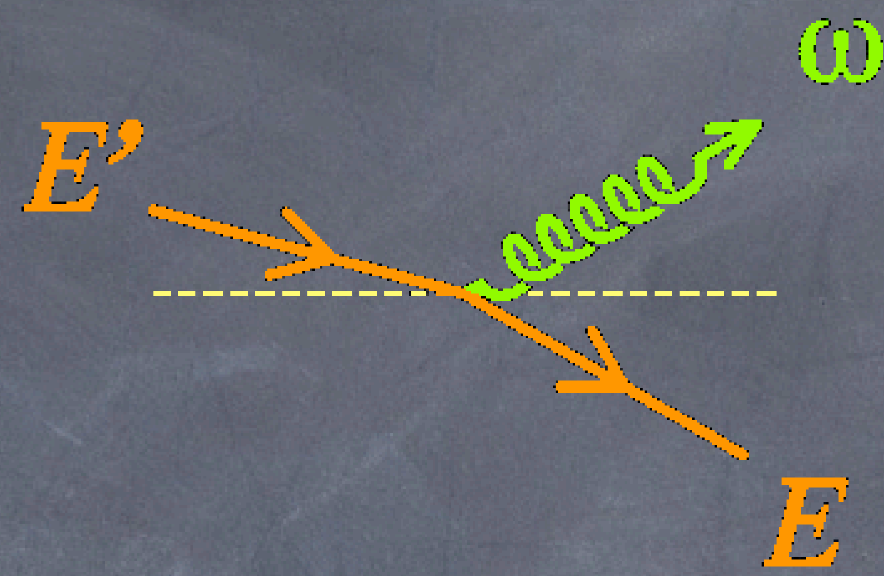
also "in vacuum", but controlled by the presence of a medium → collisions!

elastic

"~~collisional~~" process



Inelastic energy loss



The spectrum of (mostly) gluons radiated by a fast parton is modified by the presence of the medium:

$$\mathrm{d}I^{\mathrm{tot}} = \mathrm{d}I^{\mathrm{vac}} + \mathrm{d}I^{\mathrm{med}}$$

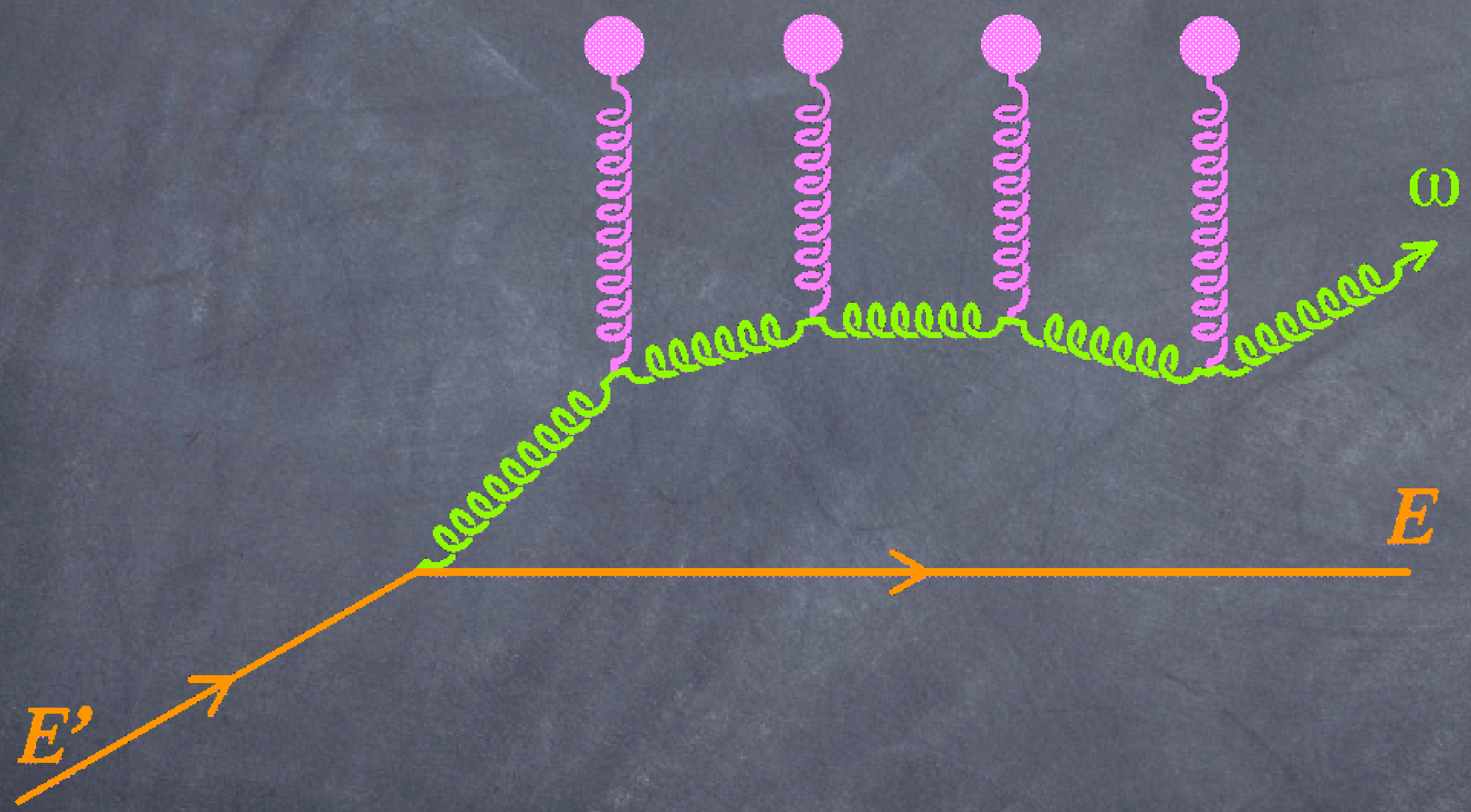
given by the normal DGLAP evolution ($\mathrm{d}I^{\mathrm{vac}}$)

depends on the modeling of the medium ($\mathrm{d}I^{\mathrm{med}}$)

Inelastic energy loss

Models based on the Landau-Pomeranchuk-Migdal effect [1/4]

The propagating high-p_T parton traverses a **thick target**.



It radiates soft gluons, which scatter **coherently** on independent color charges in the medium, resulting in a medium-modified gluon energy spectrum.

Multiple soft scattering limit

Inelastic energy loss

Models based on the Landau-Pomeranchuk-Migdal effect [2/4]

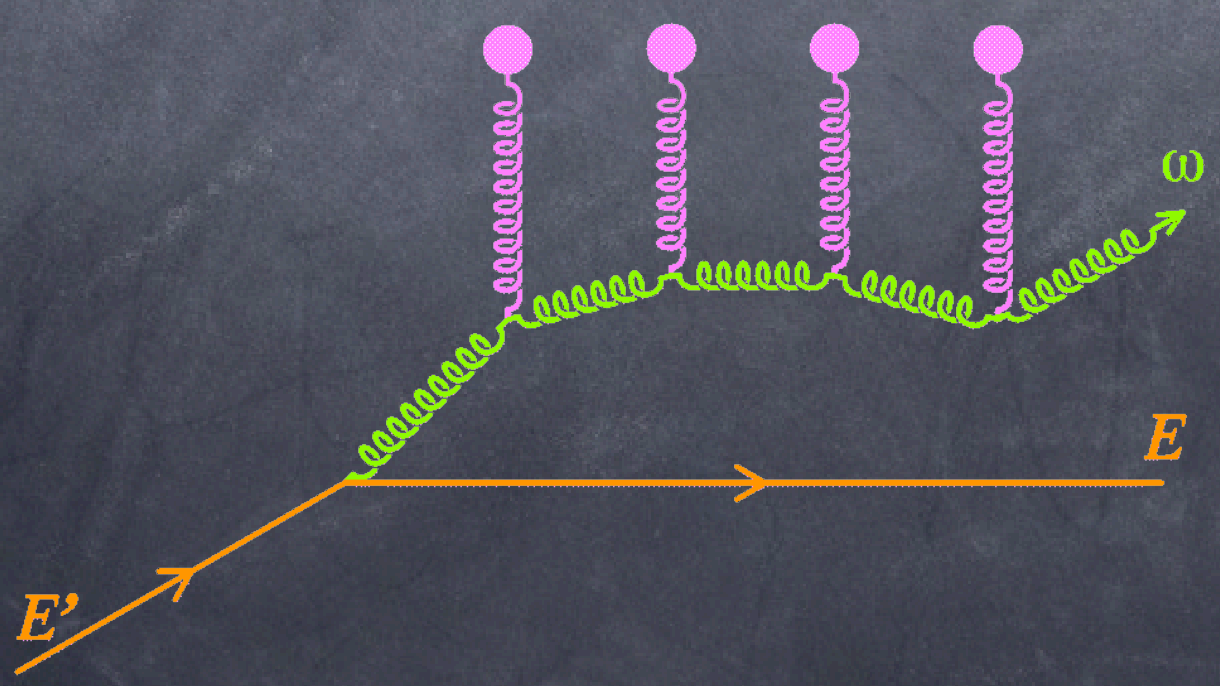
Coherent scatterings: $\ell_{\rm coh} \sim \frac{2\omega}{k_\perp^2} \leq L$ (medium length)

coherence length of the emitted gluon ← $\ell_{\rm coh}$; $k_\perp^2 \simeq N_{\rm coh}\mu^2$ $\Rightarrow$ $\ell_{\rm coh} = \sqrt{\frac{2\omega\lambda}{\mu^2}}$

LPM only affects gluons with $\omega \lesssim \omega_c \equiv \frac{1}{2}\hat{q}L^2$

Medium characterized by the transport coefficient $\hat{q} \equiv \frac{\mu^2}{\lambda}$

Baier, Dokshitzer, Mueller, Peigné, Schiff (BDMPS); Zakharov



Inelastic energy loss

Models based on the Landau-Pomeranchuk-Migdal effect [3/4]

Gluon coherence length $\ell_{\rm coh} = \sqrt{\dfrac{2\omega\lambda}{\mu^2}}$

$\Rightarrow$ gluon energy spectrum per unit path length $\omega\dfrac{{\rm d}I}{{\rm d}\omega{\rm d}z} \simeq \dfrac{\alpha_s}{\ell_{\rm coh}} \simeq \alpha_s\sqrt{\dfrac{\hat{q}}{\omega}}$

For a path length L: $\omega\dfrac{{\rm d}I}{{\rm d}\omega} \simeq \alpha_s\sqrt{\dfrac{\hat{q}L^2}{\omega}}$

2

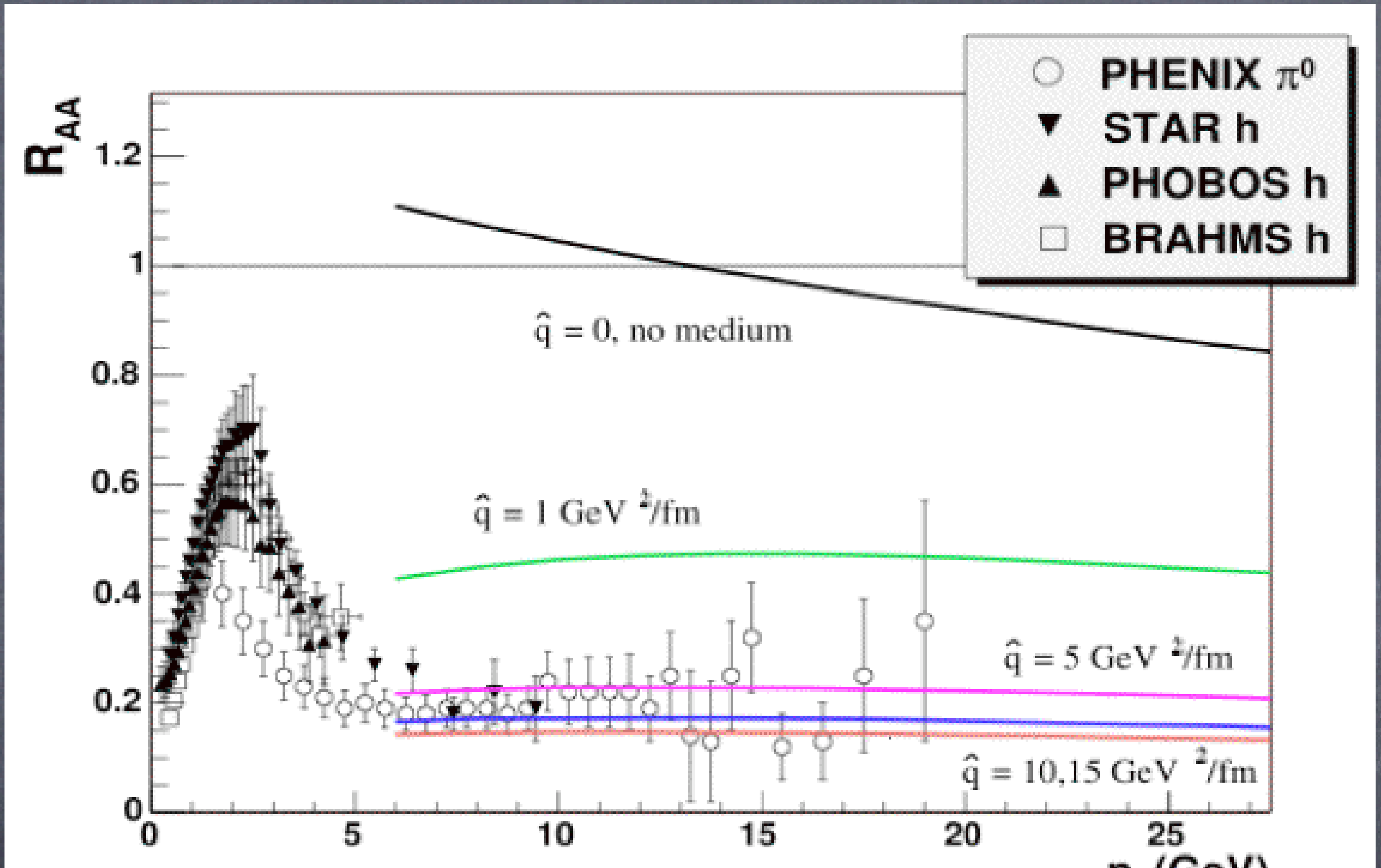
Average medium-induced energy loss: $\Delta E = \displaystyle\int^{\omega_c} \omega\frac{{\rm d}I}{{\rm d}\omega}\,{\rm d}\omega \simeq \alpha_s\omega_c \propto \alpha_s\hat{q}L^2$

☞ BDMPS-Z, only two parameters: $\hat{q}$ & L

Inelastic energy loss

Models based on the Landau-Pomeranchuk-Migdal effect [4/4]

BDMPS-Z approach gives a good description of the data:



Nucl. Phys. A **747** (2005) 511

...but "R_{AA} is fragile" (Eskola, Honkanen, Salgado, Wiedemann):

data cannot allow to distinguish between $\hat{q} =$ 5 or 15 GeV ^{2}/fm.

Inelastic energy loss

Models based on an opacity expansion [1/2]

The high-p_T parton interacts with a thin target:

the energy loss results from an incoherent superposition of very few $\chi \equiv L/\lambda$ single hard scattering processes along the path length L.

χ ⟶ "opacity" (= number of collisions)

⇒ gluon energy spectrum per unit path length

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega\,\mathrm{d}z} \simeq \left(\frac{L}{\lambda}\right) \frac{\alpha_s}{\ell_{\mathrm{coh}}} \simeq \left(\frac{L}{\lambda}\right) \alpha_s \frac{\mu^2}{\omega} \qquad \neq \alpha_s \sqrt{\frac{\hat{q}}{\omega}} \text{ within LPM}$$

leads to an average energy loss $\Delta E \propto L^2$ (for a static medium)

Gyulassy, Lévai, Vitev (GLV); Wiedemann

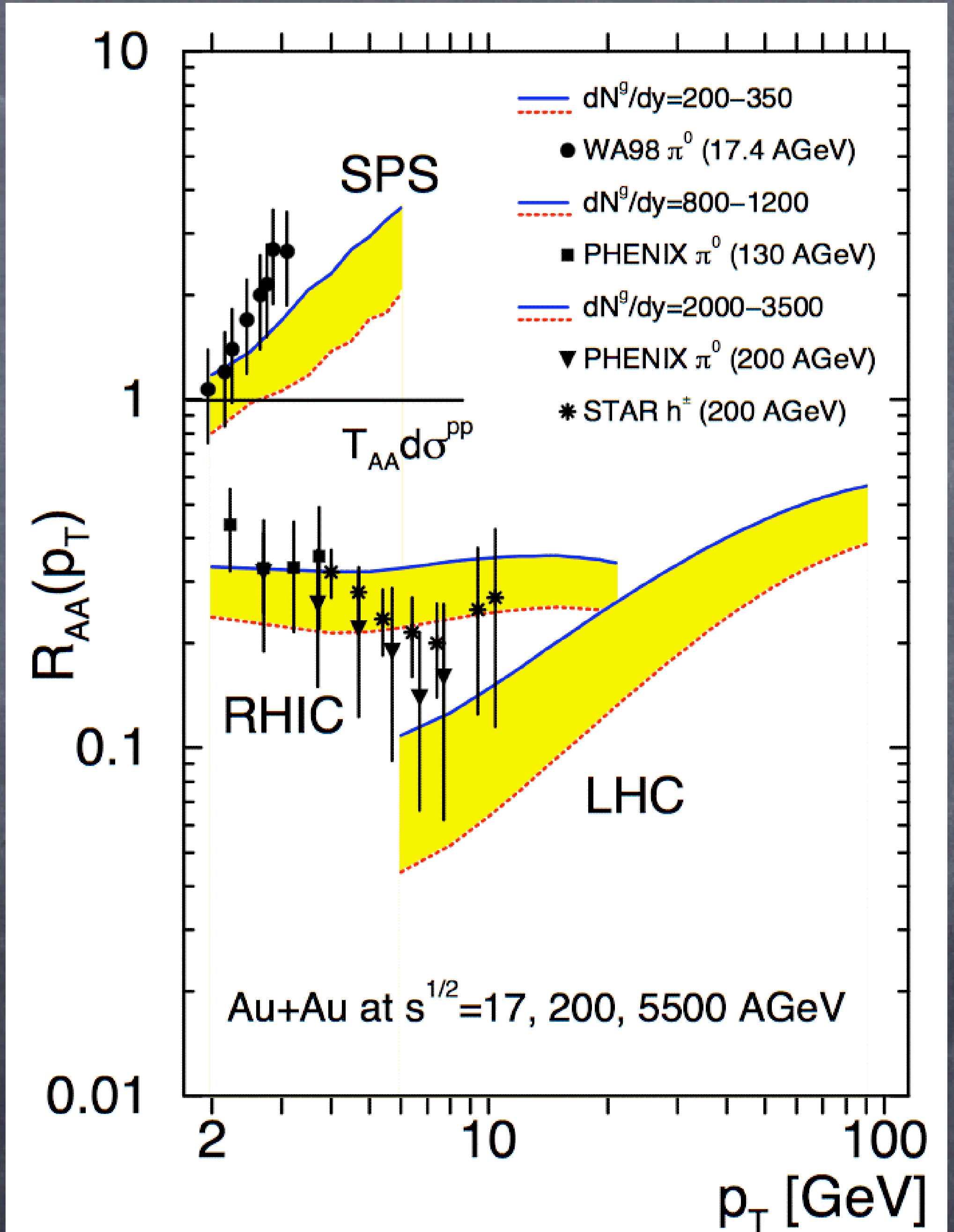
☞ three parameters: $\left(\frac{L}{\lambda}\right)$, μ & L

$\left(\frac{L}{\lambda}\right)$ ⟶ ⇔ the (linear) density of scattering centers

Inelastic energy loss

Models based on an opacity expansion [2/2]

GLV reproduce the data with ≈1000-1200 gluons per rapidity unit:



Phys. Rev. Lett. **89** (2002) 252301

Inelastic energy loss

A model based on modified parton splitting functions [1/3]

The above-mentioned approaches to inelastic energy loss are only applied to the leading parton.
However, the parton virtuality does not enter present comparisons to experimental data.
In addition, momentum conservation is not implemented at each parton splitting, but only globally.

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→ can be done analytically, modulo an extra approximation, namely neglecting the ω-dependence of the medium-induced spectrum of radiated gluons:

$$\frac{\mathrm{d}I^{\mathrm{med}}}{\mathrm{d}\omega} = f_{\mathrm{med}}$$

(reasonable in the kinematic regime at RHIC).

Inelastic energy loss

A model based on modified parton splitting functions [2/3]

Assuming a constant medium-induced radiation spectrum amounts to modifying the Altarelli-Parisi parton splitting functions, e.g.

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

where $f_{\rm med} = 0$ in the absence of a medium. ($f_{\rm med}$ only parameter)

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MLLA: Modified Leading Logarithmic Approximation (of QCD)

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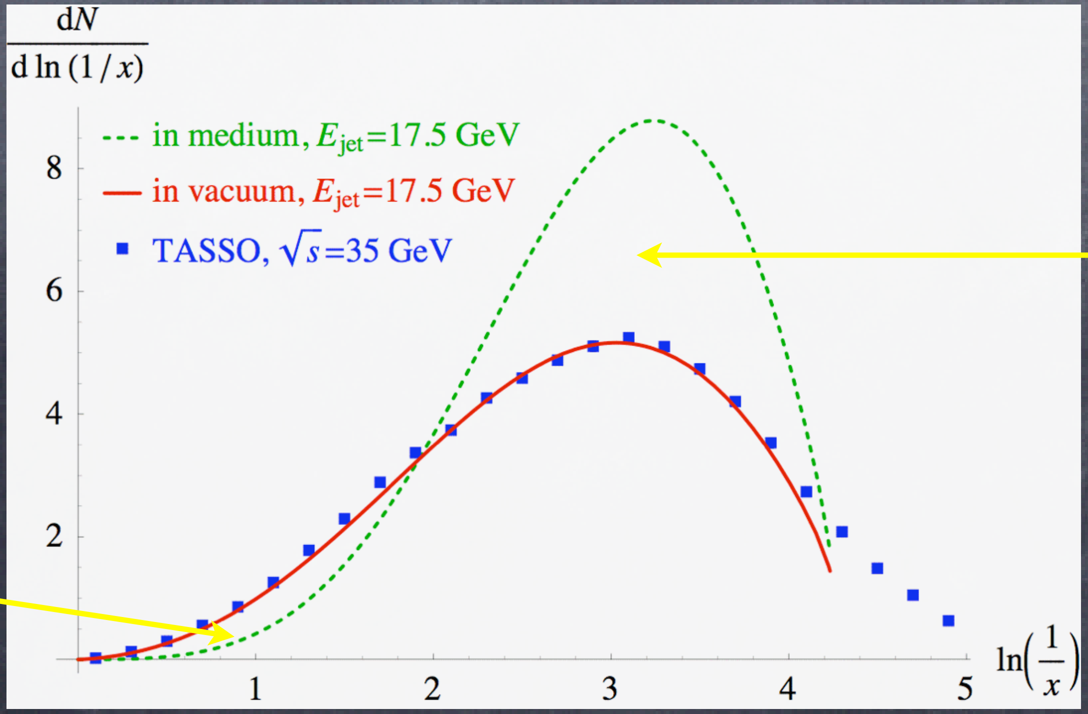


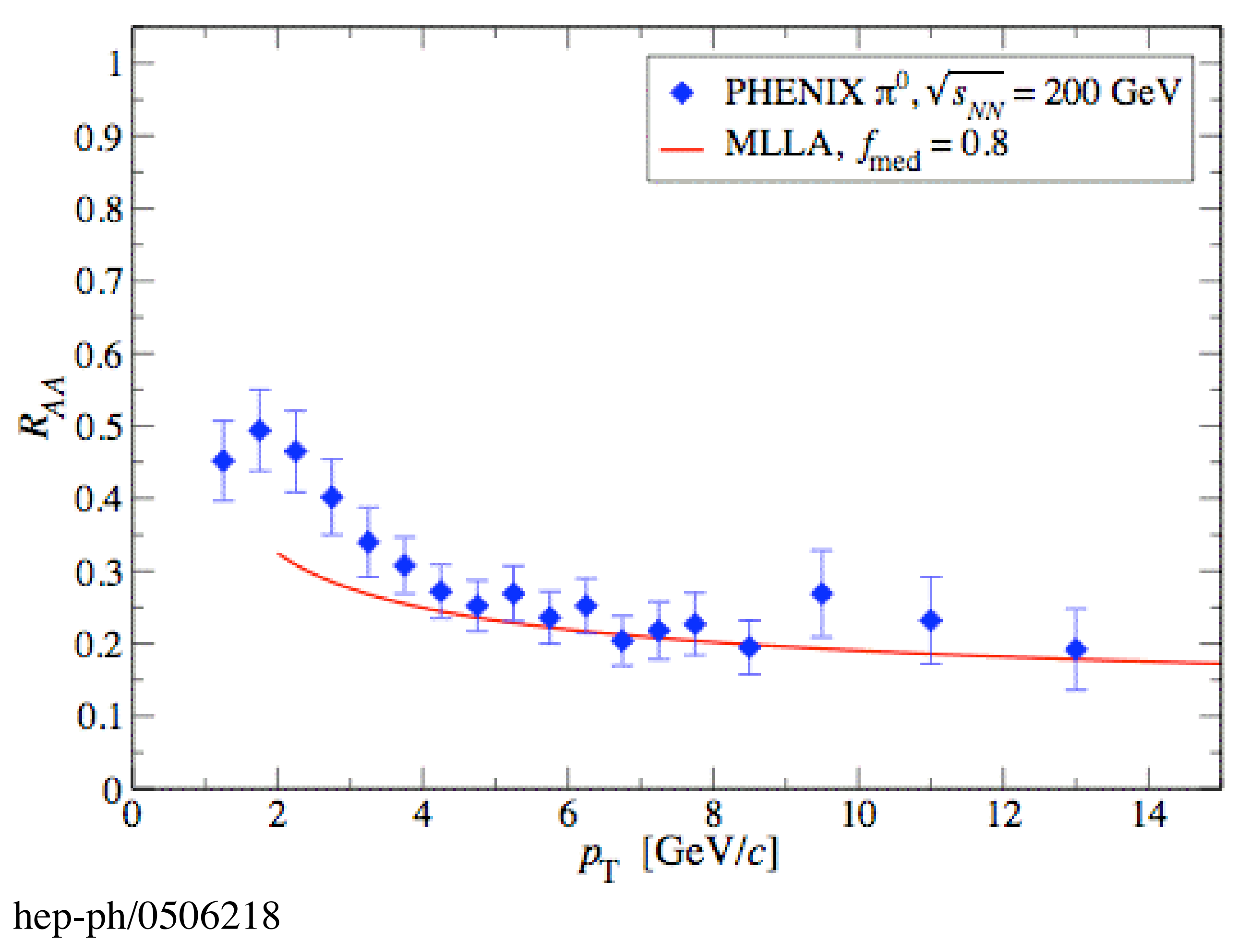
enhancement at small x

depletion at large x

Inelastic energy loss

A model based on modified parton splitting functions [3/3]

The agreement with the data is also satisfactory:



However, several realistic features are not included in the calculation...

Inelastic energy loss

A few model-independent remarks [1/2]

actually also valid for models of elastic energy loss

- Independent scattering centers: $\lambda \gg 1/\mu$.
  mean free path (λ) — screening mass (μ)

- All partons do not lose the same amount of energy, even when they traverse the same in-medium path length L
  ⇒ nuclear modification factor R_{AA} mostly reflects the few partons which have lost little energy.
  ☞ use of "quenching weights" (= probability to lose a given energy)

Inelastic energy loss

A few model-independent remarks [2/2]

- A model of partonic energy loss has to be supplemented by several other elements to allow comparison with the data:
  - parton distribution functions inside the nuclei (shadowing, Cronin effect...);
  - production cross-sections.

- The medium traversed by the parton is not static, but in expansion!

  ☞ model-builders introduce dynamics (most often, à la Bjorken), which may lead to a redefinition ($\hat{q} \longrightarrow \hat{q}_{\rm eff}$) of the parameters, to the introduction of new ones (τ_0 , T_0), or to a change in scaling properties ($\Delta E_{\rm GLV} \propto L$ instead of L^2).

Elastic energy loss

The elder (Bjorken, 1984), yet still in its infancy...

Until 2003, it was commonly accepted that the amount of energy dissipated by the fast parton through elastic processes

$$\frac{\mathrm{d}E_{\mathrm{el.}}}{\mathrm{d}z} \approx 0.3 - 0.5 \text{ GeV/fm}$$

was negligible with respect to the inelastic energy loss.

Since then, many models are emerging, stating that it is actually sizable...

— because of the running of the coupling constant α_s ;

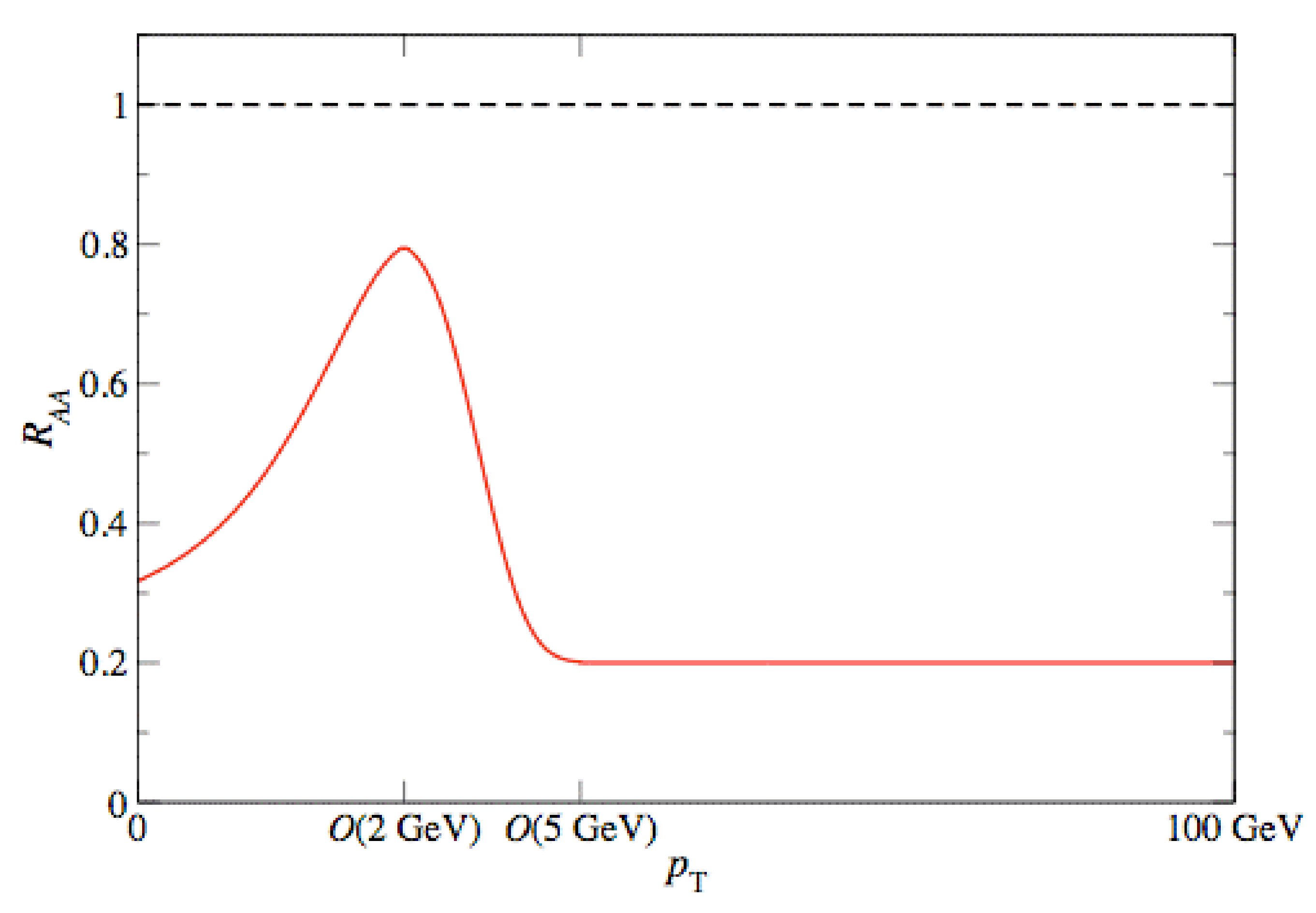
— for heavy quarks only;

— for c quarks only;

— because of "soft QCD processes".

Wait and see...

Nuclear modification factor at LHC...



Should one anticipate that R_{PbPb} remain constant at **high p_T**?

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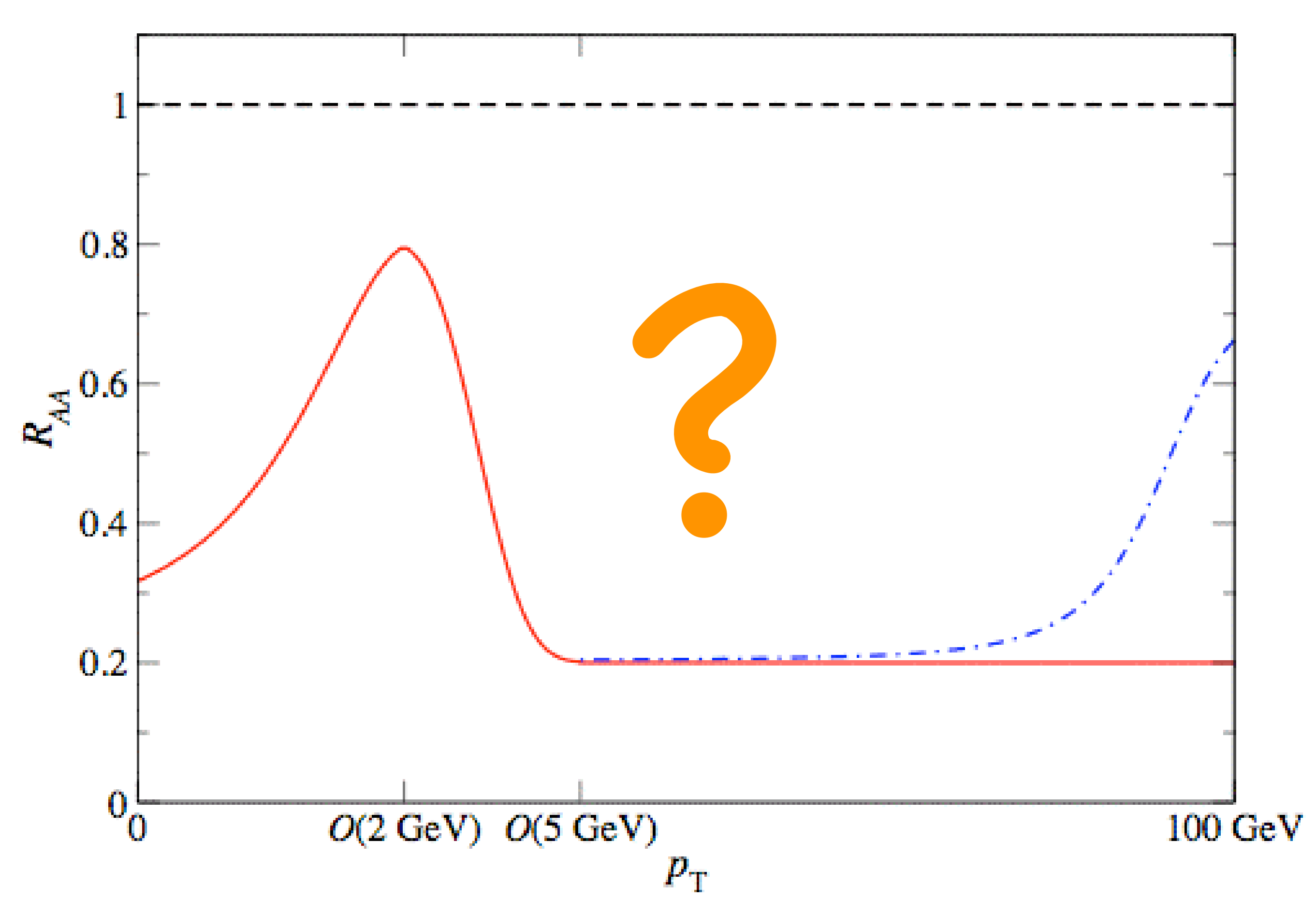

Should one anticipate that R_{PbPb} remain constant at high p_T?

Or rather, that it will increase?
(for instance, because virtuality effects kick in: a high-Q parton will degrade its virtuality on a time scale $\sim E/Q^2$, so quick that it does not feel the presence of the medium.)

The answer comes in 2008!