High-energy heavy-ion collisions.

Selected phenomenological aspects

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Joint B-D-NL graduate school, Texel, September 2008

High-energy heavy-ion collisions.
Selected phenomenological aspects

- Lecture I. Introduction – First steps
- Lecture II. "Collective flow"
- Lecture III. "Hard probes": high-p_T particles
  - Why study high-p_T particles / jets in heavy-ion collisions?

    ☞ "jet quenching"
  - How can one show collectivity in the high-p_T sector?
  - Models of jet quenching
  - Some RHIC data! and a hint of phenomenology

“Hard probes” of high-energy heavy-ion collisions

Some processes involve an energy scale Q that is much larger than the typical energy scale (≈ T≈200-400 MeV) of the created medium:

- creation of heavy quark-antiquark pairs ($Q = 2m_{\mathrm{Q}}$);
- interactions at high momentum transfer, in particular the production of high-p_{T} particles ($Q \approx p_{\mathrm{T}}$)...

The corresponding length scale $\simeq 1/Q$ of such processes is thus much smaller than the length scale of typical medium excitations, so that they are sufficiently point-like to be unaffected by the medium.

Additionally, such processes are to a large extent calculable from first principles, i.e., using perturbative QCD.

☞ “hard probes”

"Hard probes"
of high-energy heavy-ion collisions

Why are hard probes interesting?

- The creation process is to a large extent calculable within pQCD: the "benchmark" over which collective / medium effects might appear is easy to establish.

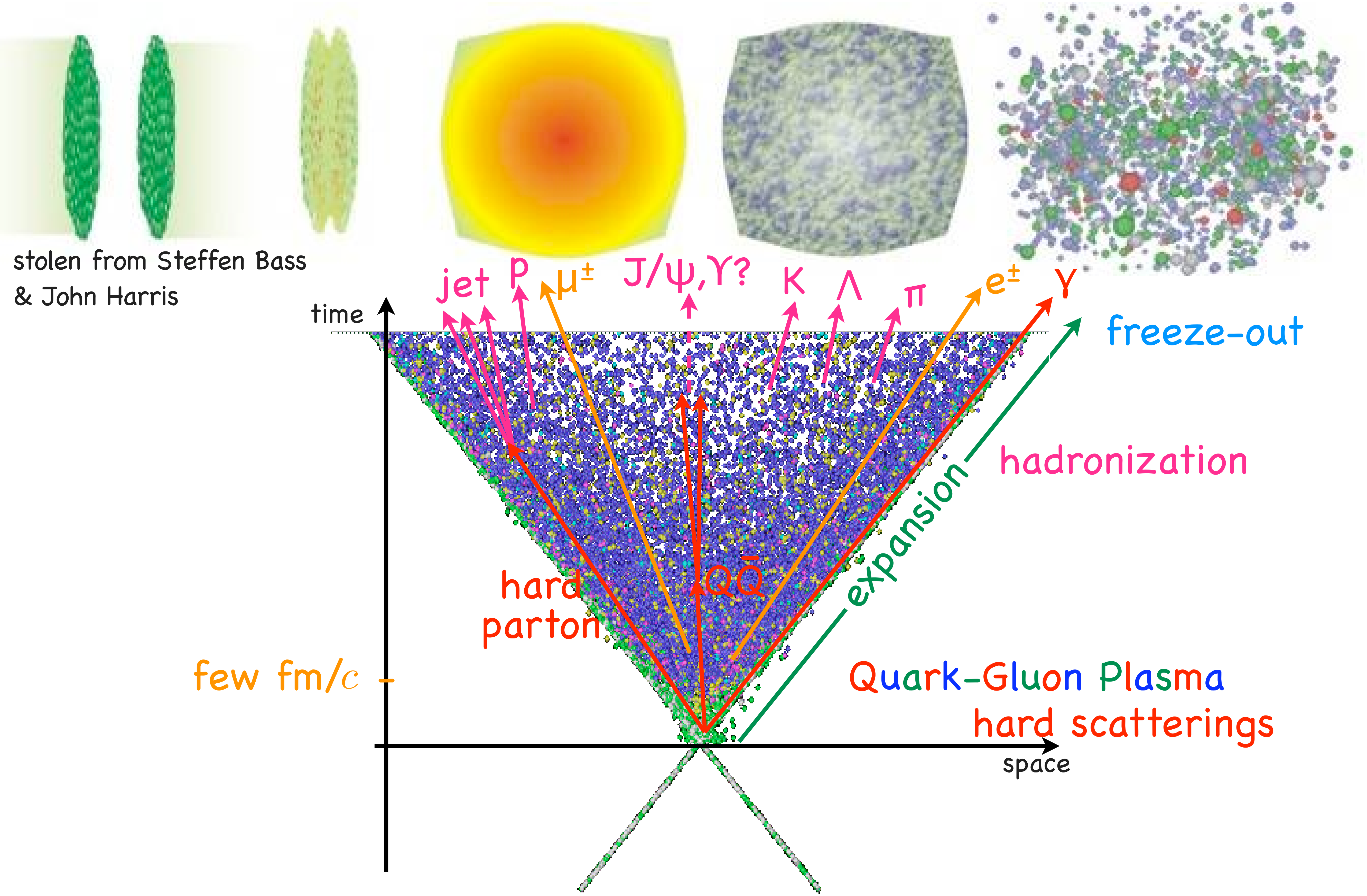
- While the production (of a high-p_T particle, a heavy $Q\bar{Q}$-pair) is insensitive to the presence of a medium, however the probe then has to travel through the medium, and possibly be modified at that stage.

(Celebrated example: the medium-induced screening of the $Q\bar{Q}$ potential observed in lattice QCD computations lead Matsui & Satz to predict that quarkonia, in particular the J/ψ, are dissociated and thus suppressed in a QGP)

- Eventually, before the hard process, its "progenitors" had to travel through the medium: here as well, some modification is possible.

From now on, I shall focus on high-p_T particles.

Time evolution of a heavy-ion collision



stolen from Steffen Bass
& John Harris

Establishing a benchmark

... is rather easy!

Consider the single-particle yield.

If the nucleus-nucleus collision A-B is an incoherent superposition ($\Leftrightarrow$ no collective effect) of $N_{\rm coll}^{A\text{-}B}$ nucleon-nucleon N-N collisions, then the yield in A-B equals $N_{\rm coll}^{A\text{-}B}$ times the yield in an N-N collision.

☞ To establish and quantify collectivity, one only need compare the yields in A-B and N-N, and use a proper estimate of $N_{\rm coll}^{A\text{-}B}$ (e.g., using Glauber theory).

In practice, one does not measure the “reference” yield in N-N, but rather in pp collisions.

"Jets" in nucleus-nucleus collisions: experimental aspects

Basic one-particle "observable": nuclear modification factor R_{AB}

$$R_{AB} = \frac{\text{yield in } A\text{-}B \text{ collisions}}{\text{equivalent number of } pp \text{ collisions} \times \text{yield in } pp \text{ collisions}}$$

= 1 if A-B collision is a superposition of independent pp collisions*

$$R_{AB} \equiv \frac{1}{N_{\rm coll}^{AB}} \frac{\frac{{\rm d}^2 N_{AB}}{{\rm d}P_T\,{\rm d}y}}{\frac{{\rm d}^2 N_{pp}}{{\rm d}P_T\,{\rm d}y}}$$

---

* up to isospin corrections...

Characterizing the medium with high-p_T particles

A basic principle:

Review of Particle Properties, chap.27 ("Passage of particles through matter"):

☞ Measure the energy deposited by a particle as it travels through some well-calibrated medium ⇝ particle type and velocity

(electromagnetic energy loss)

Characterizing the medium with high-p_T particles

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☞ Measure the energy deposited by a particle as it travels through some well-calibrated medium ⇝ particle type and velocity

(electromagnetic energy loss)

By analogy, in heavy-ion collisions (theorist's view!):

Measure the energy deposited by a quark/gluon with (known) high p_T as it travels through the dense medium ⇝ medium properties

(here, QCD energy loss)

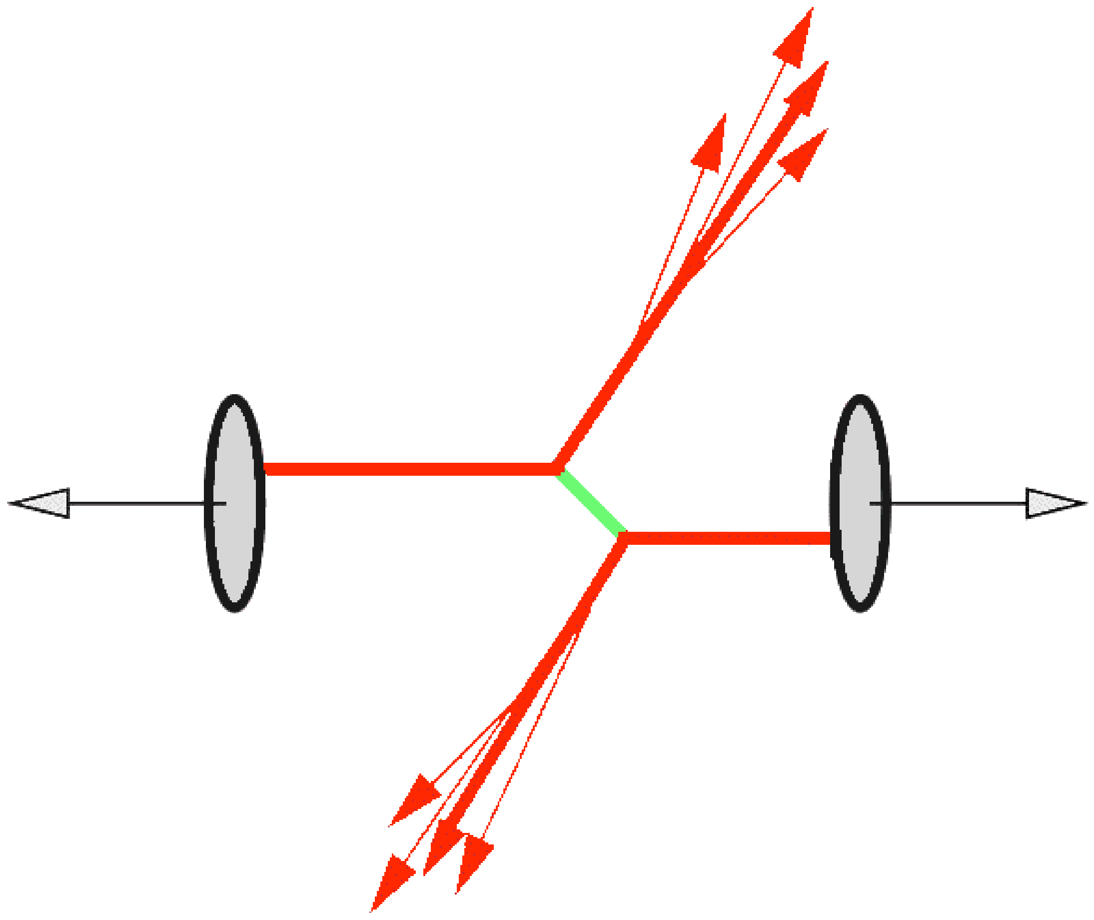
"jet quenching"

"Jet quenching": basic picture

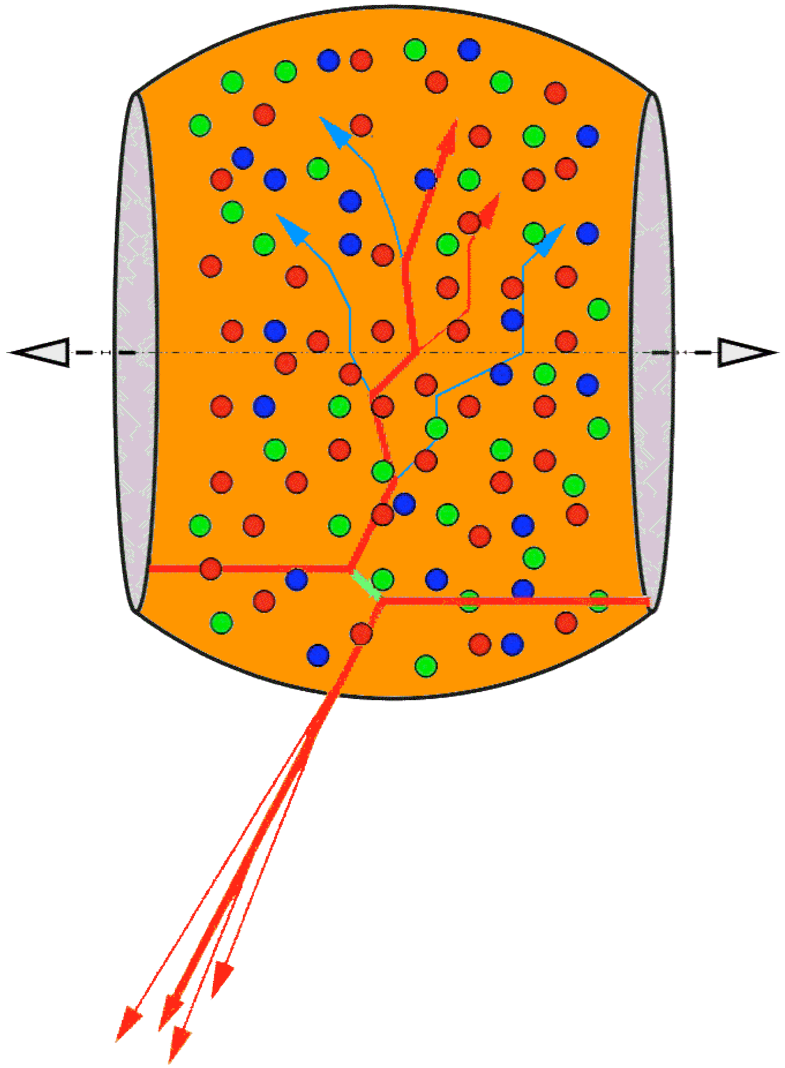
A fast quark/gluon propagating through a dense medium will "lose" part of its energy-momentum.

The resulting jet of hadrons (if any!) is distorted: "quenching".

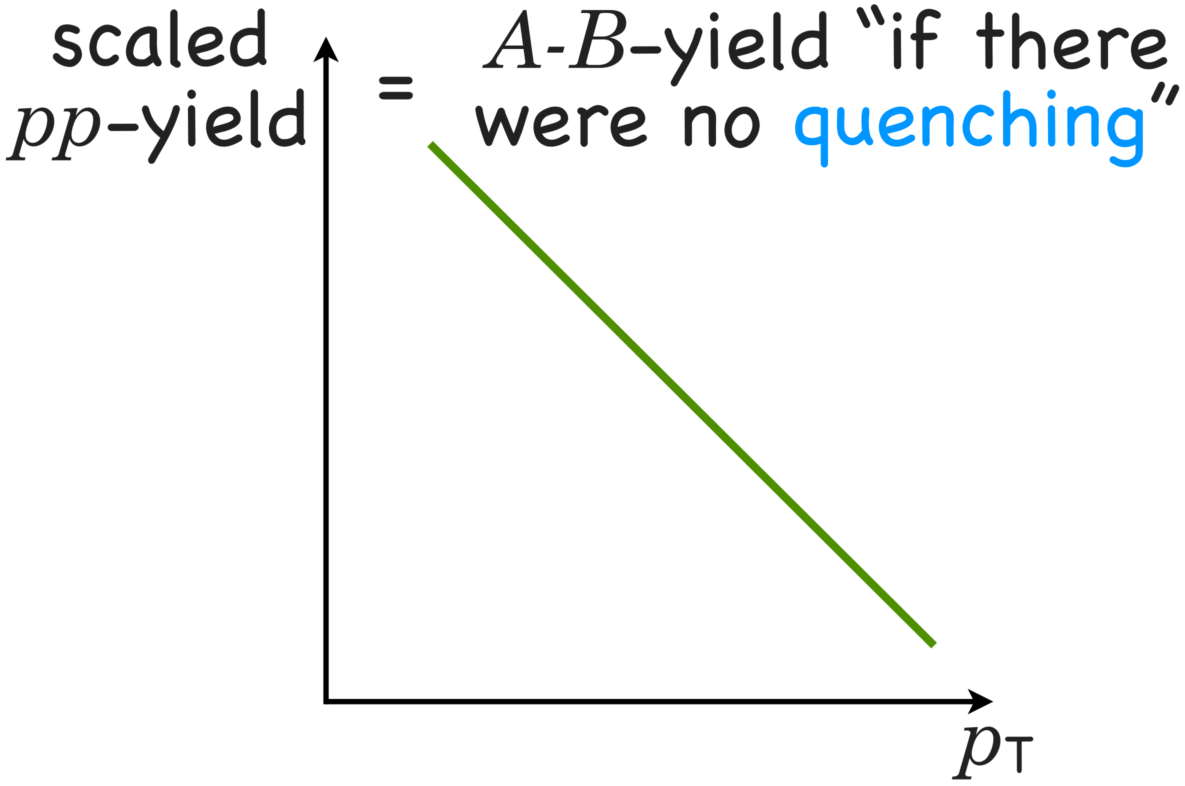
in vacuum



in medium



"Jet quenching": consequence for R_{AB}



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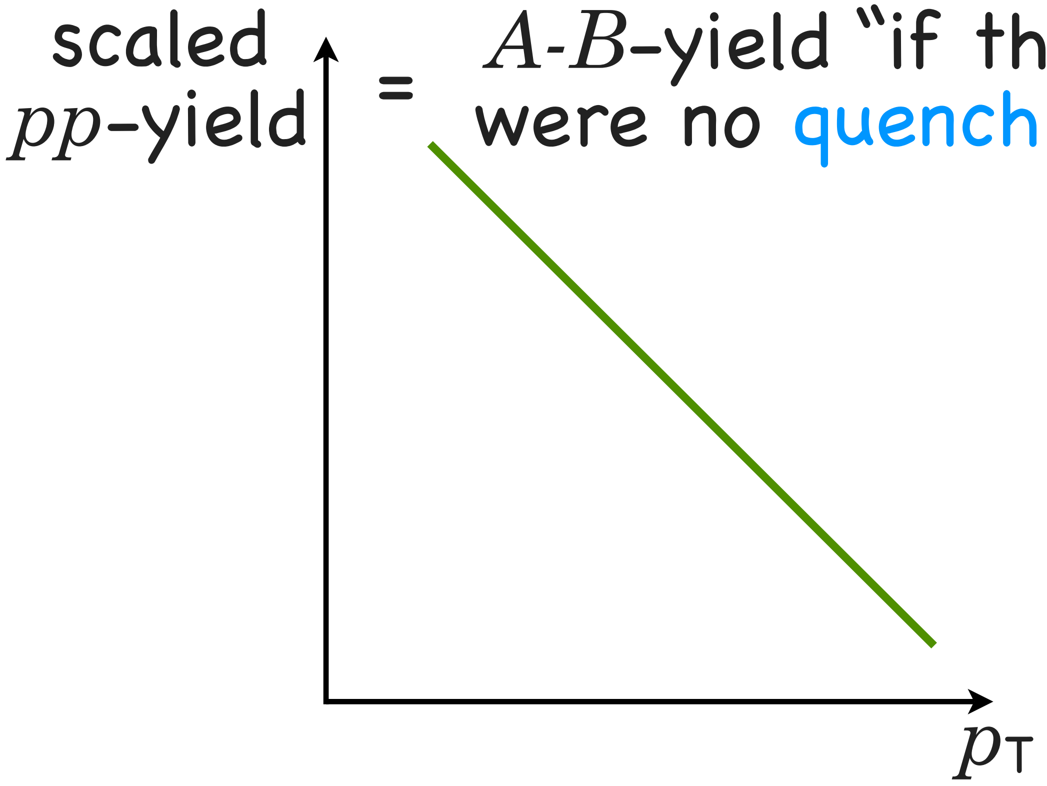

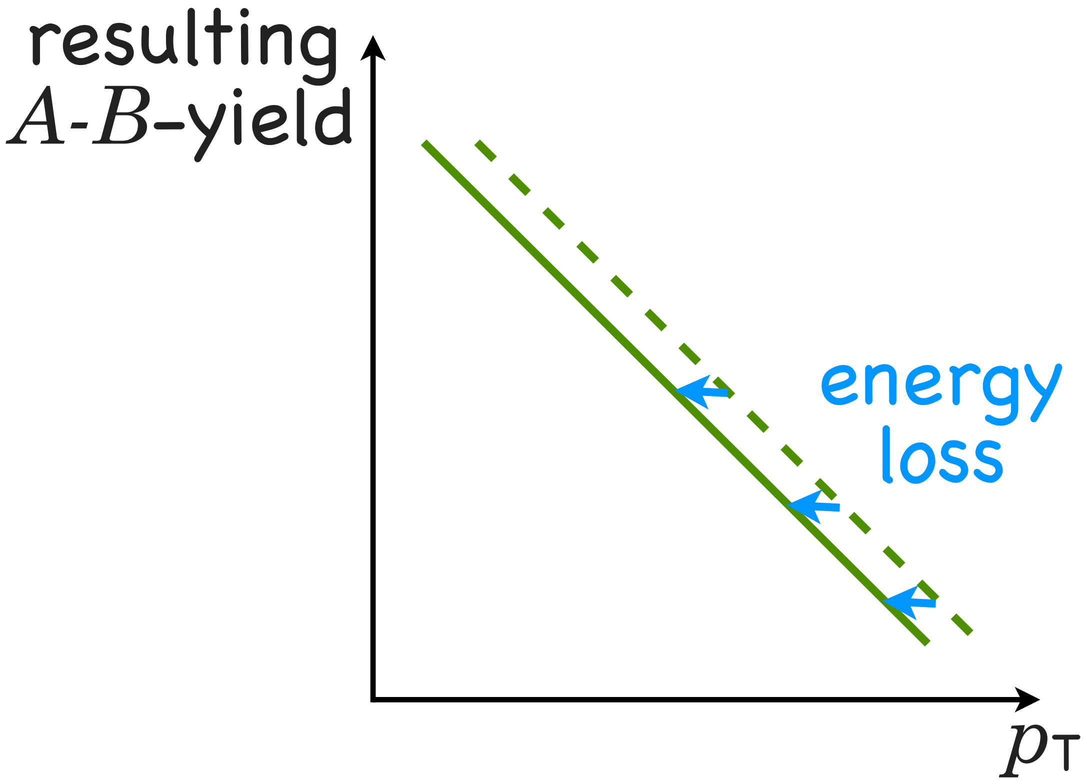

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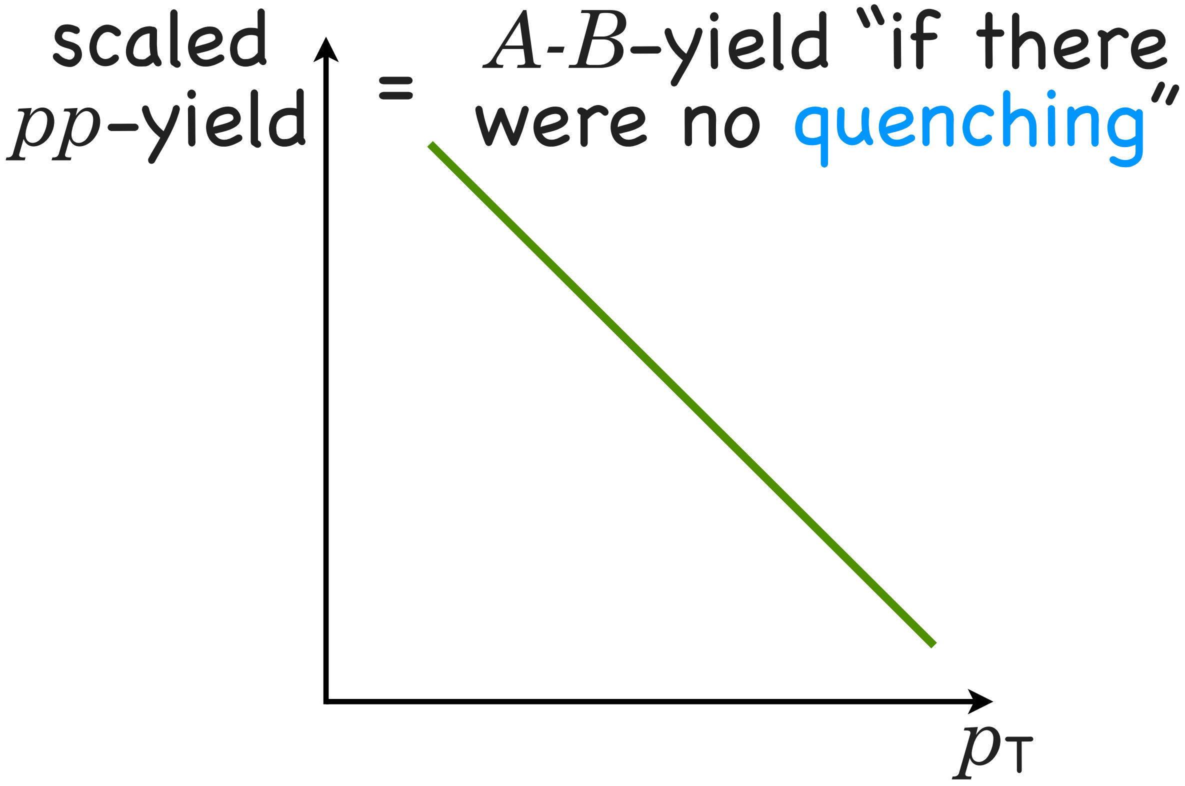
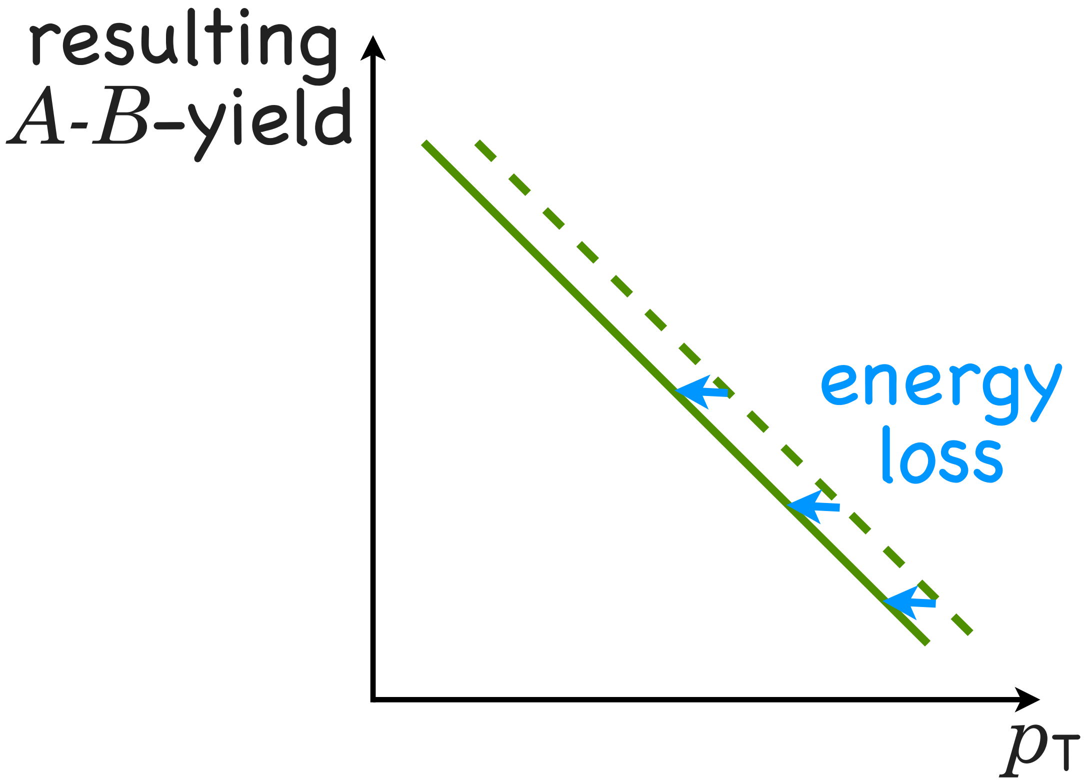


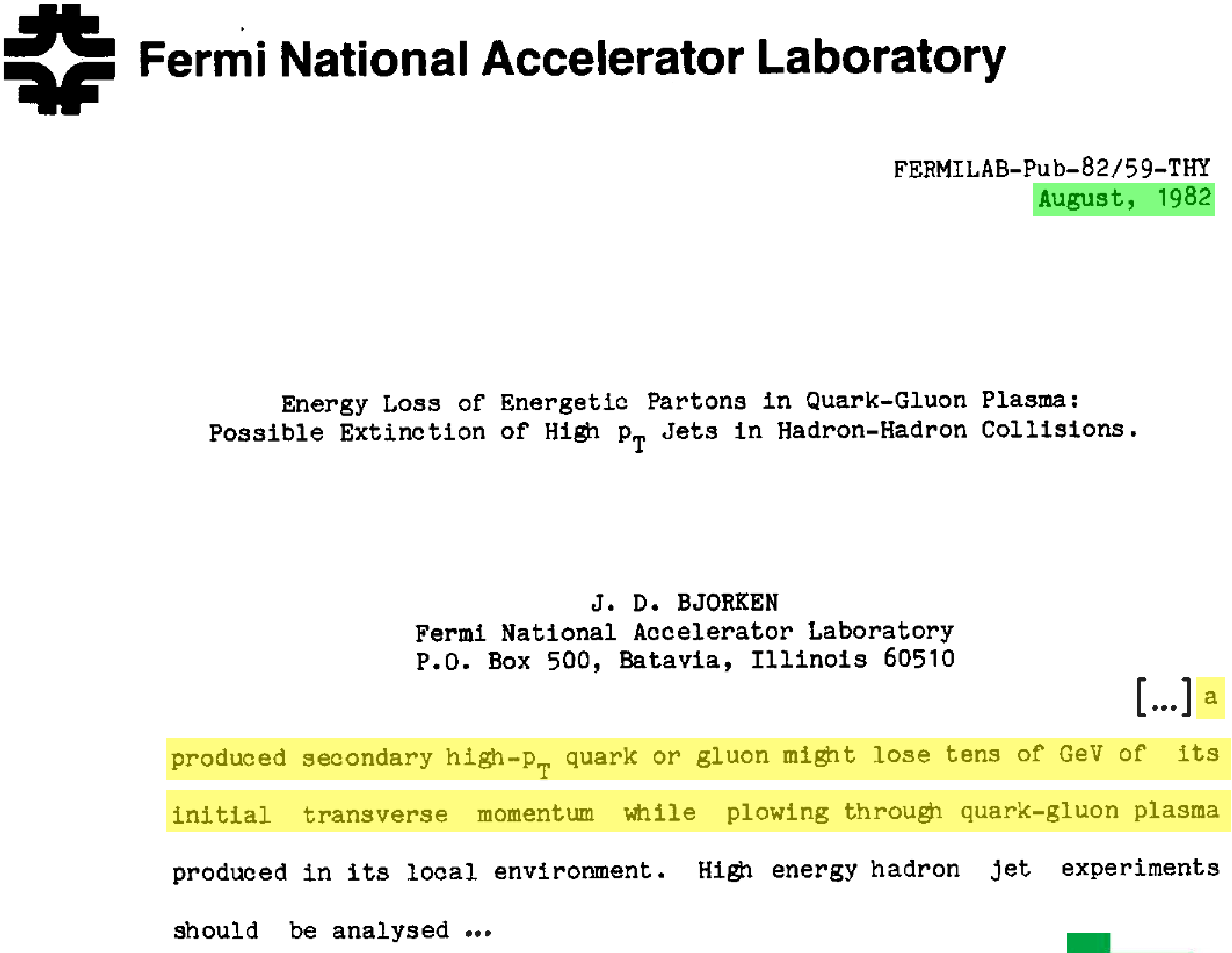


At a given large transverse momentum, the “quenched” A-B-yield is smaller than the scaled pp-yield.

☞ expect $R_{AB} < 1$ at large p_T

Various models of jet quenching...

Jets in heavy-ion collisions



Fermi National Accelerator Laboratory

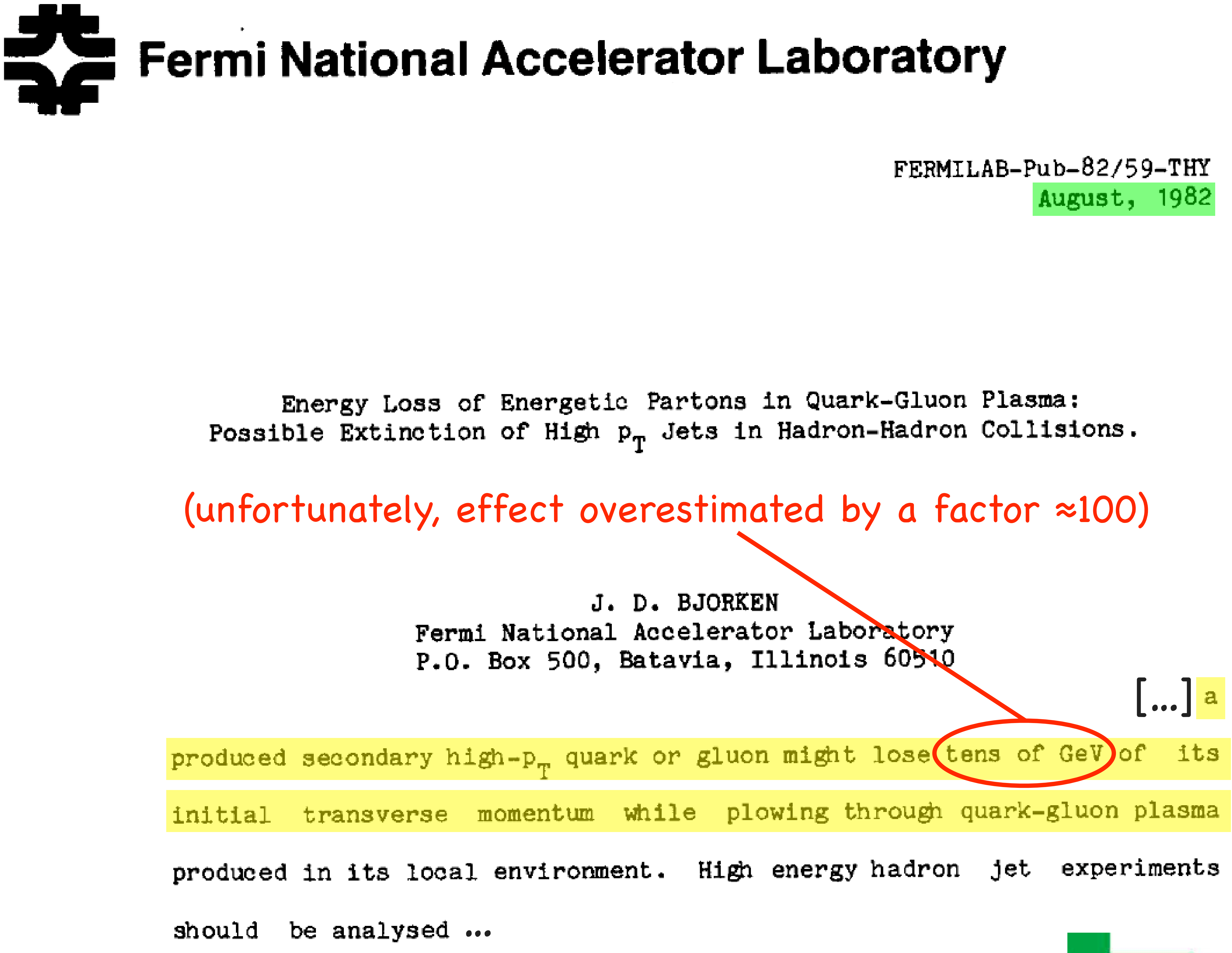
FERMILAB-Pub-82/59-THY
August, 1982

Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

[...] a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed ...

Jets in heavy-ion collisions



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(unfortunately, effect overestimated by a factor ≈100)

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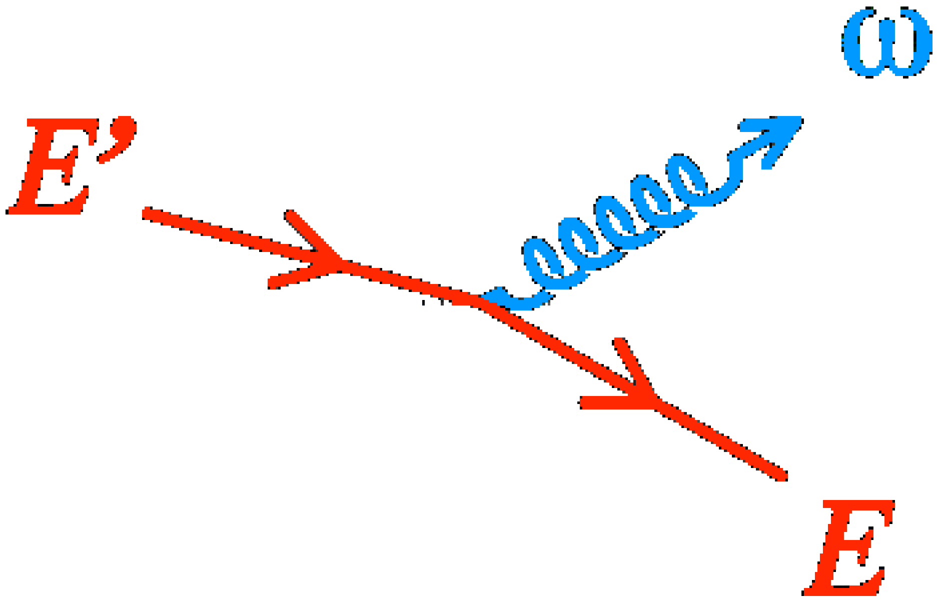
Jet quenching: underlying processes

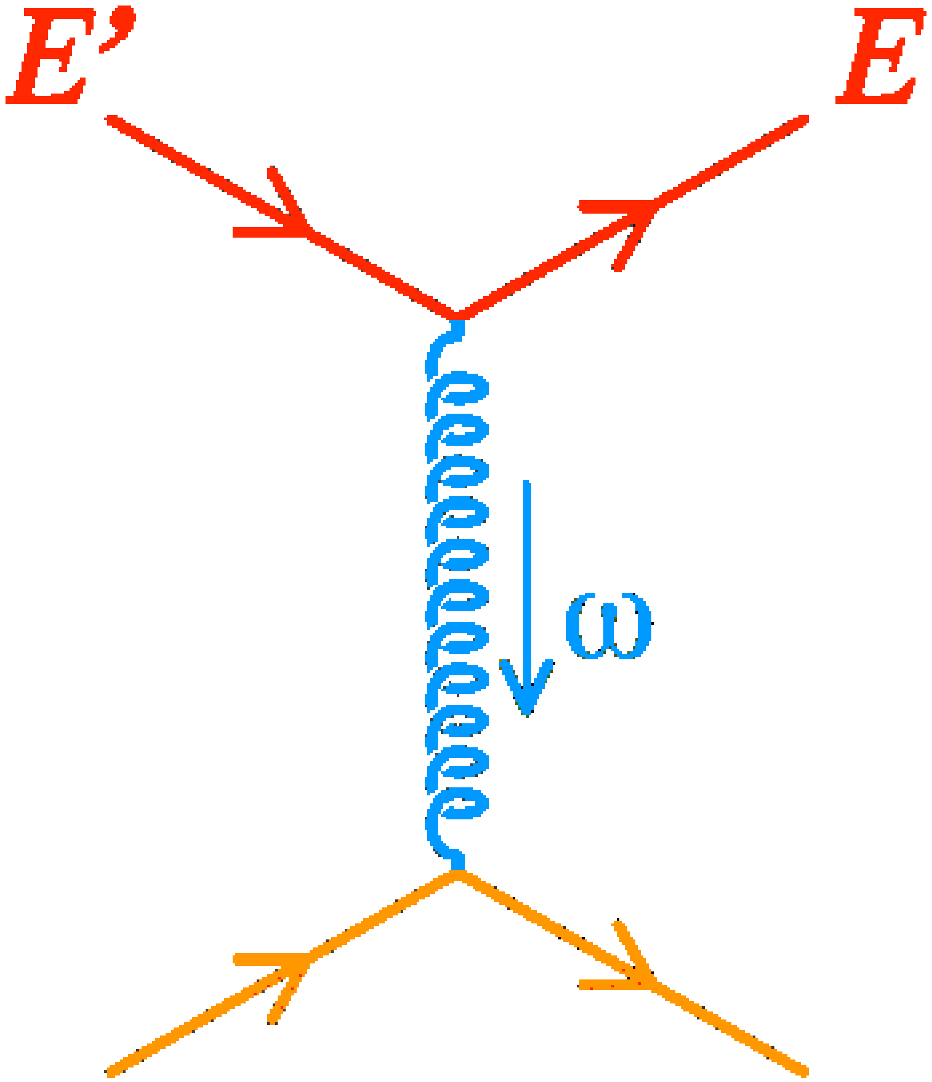
Two different processes lead to the loss of energy by a fast parton:

"radiative" process (Bremsstrahlung)



also "in vacuum" (DGLAP evolution), yet modified by the presence of a (colored) medium

"collisional" process

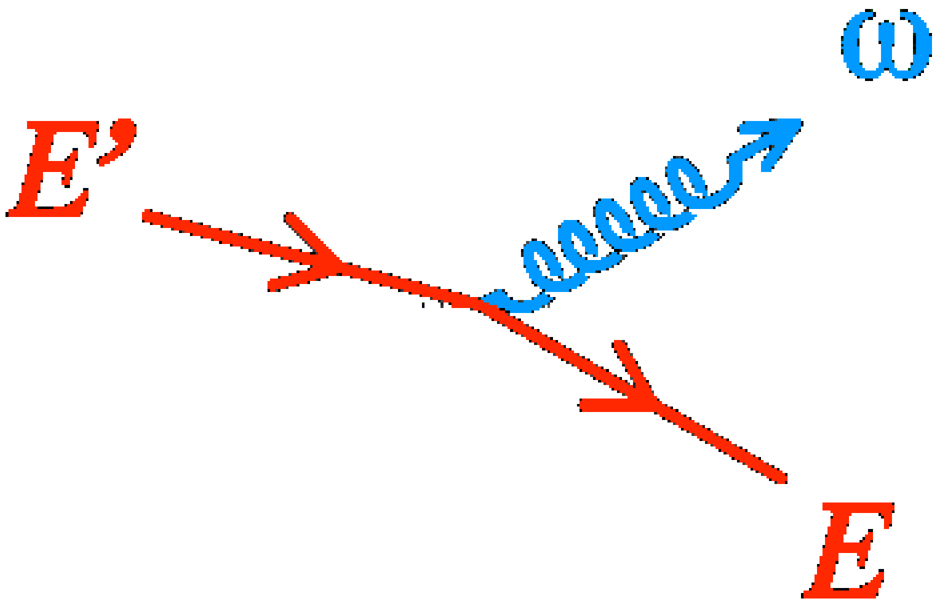


Jet quenching: underlying processes

Two different processes lead to the loss of energy by a fast parton:

inelastic

“~~radiative~~” process (Bremsstrahlung)

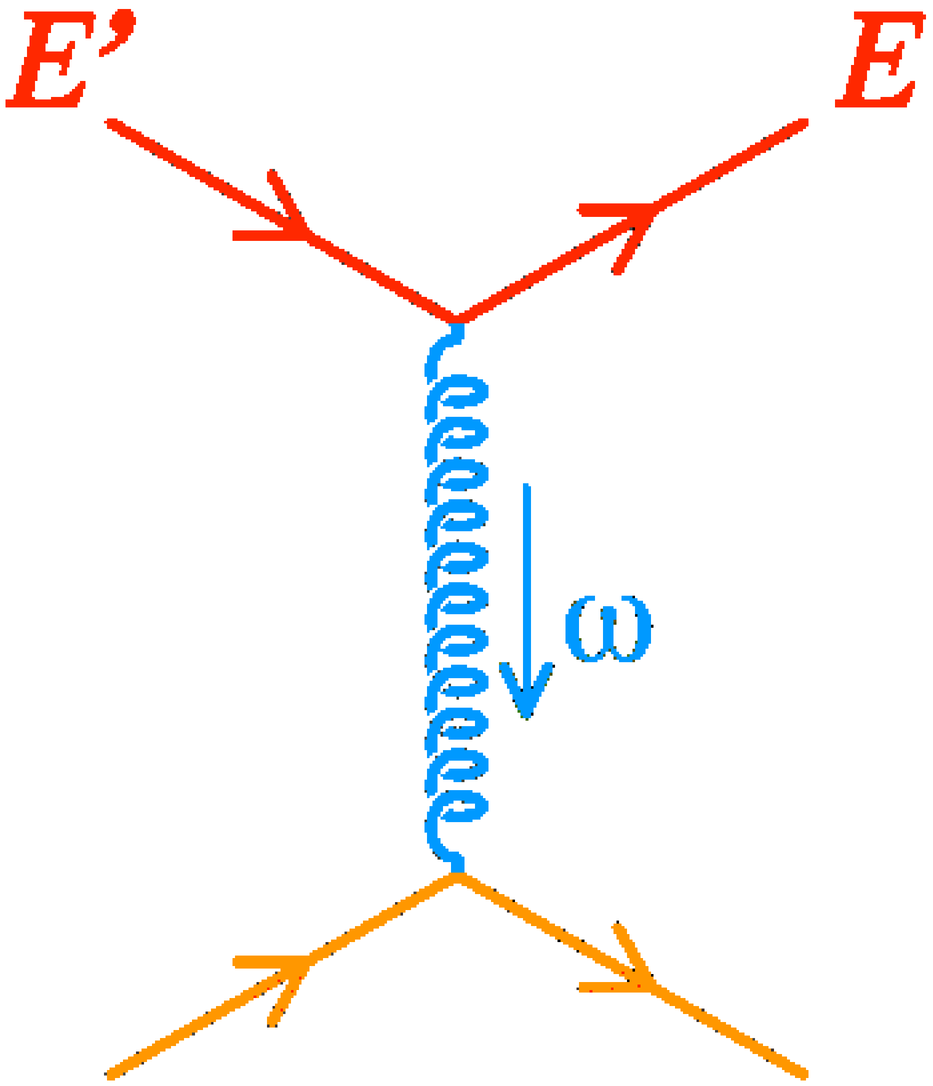


also “in vacuum” (DGLAP evolution), yet modified by the presence of a (colored) medium

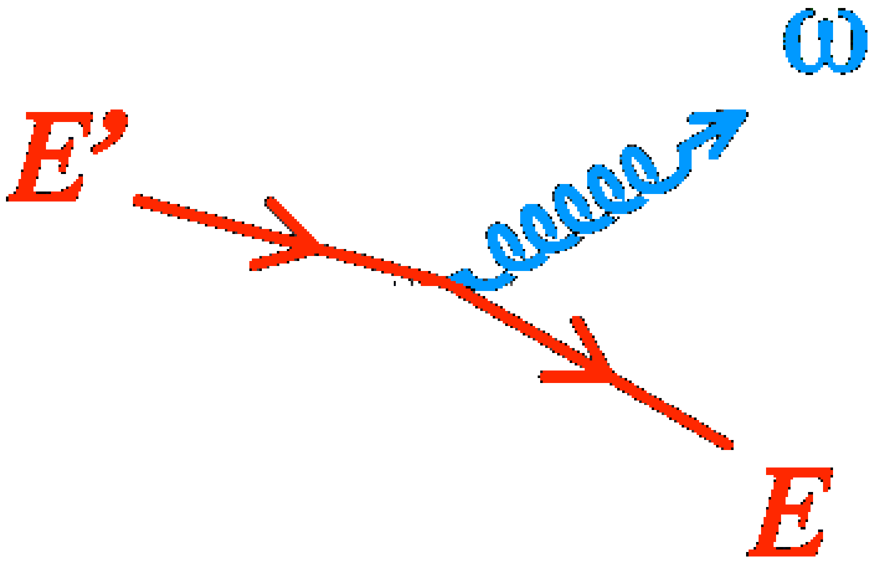
collisions!

elastic

“~~collisional~~” process



Inelastic energy loss



The spectrum of (mostly) gluons radiated by a high-p_T quark/gluon 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

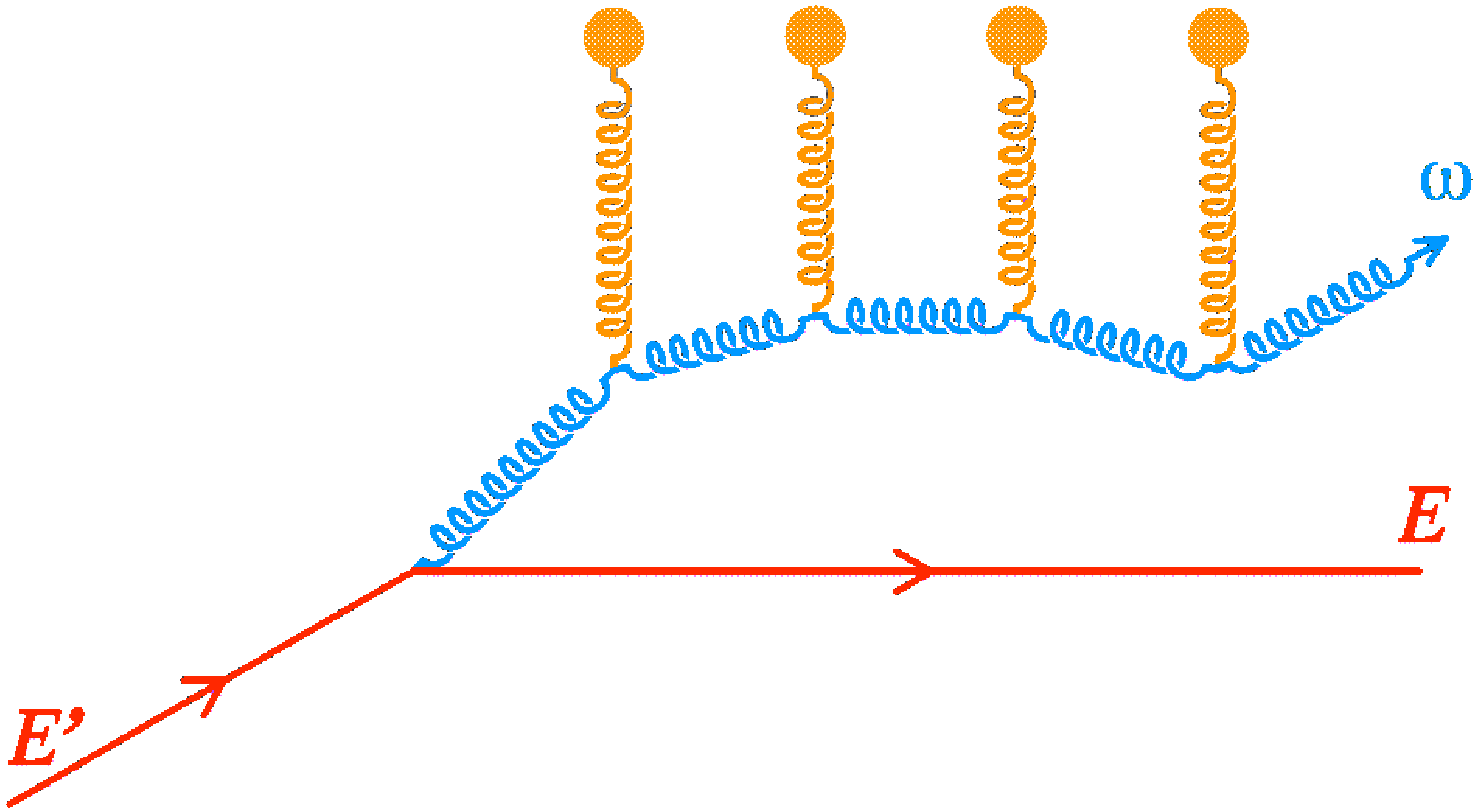
depends on the modeling of the medium

Various implementations, with emphasis on different physics aspects…

Inelastic energy loss

Landau-Pomeranchuk-Migdal effect: Multiple soft scattering limit

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



Through coherent scatterings on independent color charges in the medium, a soft gluon from the wave-function of the high-p_T parton becomes real carrying away some energy of its parent.

☞ $\Delta E \propto$ transport coefficient $\hat{q}$

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

Inelastic energy loss

Landau-Pomeranchuk-Migdal effect: Multiple soft scattering limit

Modeling the medium:

Independent scattering centers: $\underbrace{\lambda}_{\text{mean free path}} \gg 1/\underbrace{\mu}_{\text{screening mass}}$

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Modeling the medium:

Independent scattering centers: $\underbrace{\lambda}_{\text{mean free path}} \gg 1/\underbrace{\mu}_{\text{screening mass}}$

In each collision on a scattering center in the medium, the gluon receives a momentum kick ≈ μ .

After N_{coh} collisions (random walk!), it has acquired a transverse* momentum $k_\perp$ given by $(k_\perp)^2 \simeq N_{\text{coh}}\mu^2$.

* with respect to the parent fast parton

Inelastic energy loss

Landau-Pomeranchuk-Migdal effect: Multiple soft scattering limit

The time the gluon takes to acquire its transverse momentum $k_\perp$ (to decohere from its parent) is $1/k_\perp$ in the gluon frame, i.e. $\omega/(k_\perp)^2$ in the lab frame (more precisely $2\omega/(k_\perp)^2$).

This duration corresponding to a "coherence length" for the emission of the gluon $\ell_{\rm coh}$, i.e. the path length traveled by the high-momentum parent parton during the emission.

Along this path, the parton undergoes $N_{\rm coh}$ collisions on the medium scattering centers, so that $\ell_{\rm coh} = N_{\rm coh}\lambda$.

... And to make sense, the in-medium path length of the fast parton should be smaller than the size L of the medium!

Inelastic energy loss

Landau-Pomeranchuk-Migdal effect: Multiple soft scattering limit

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

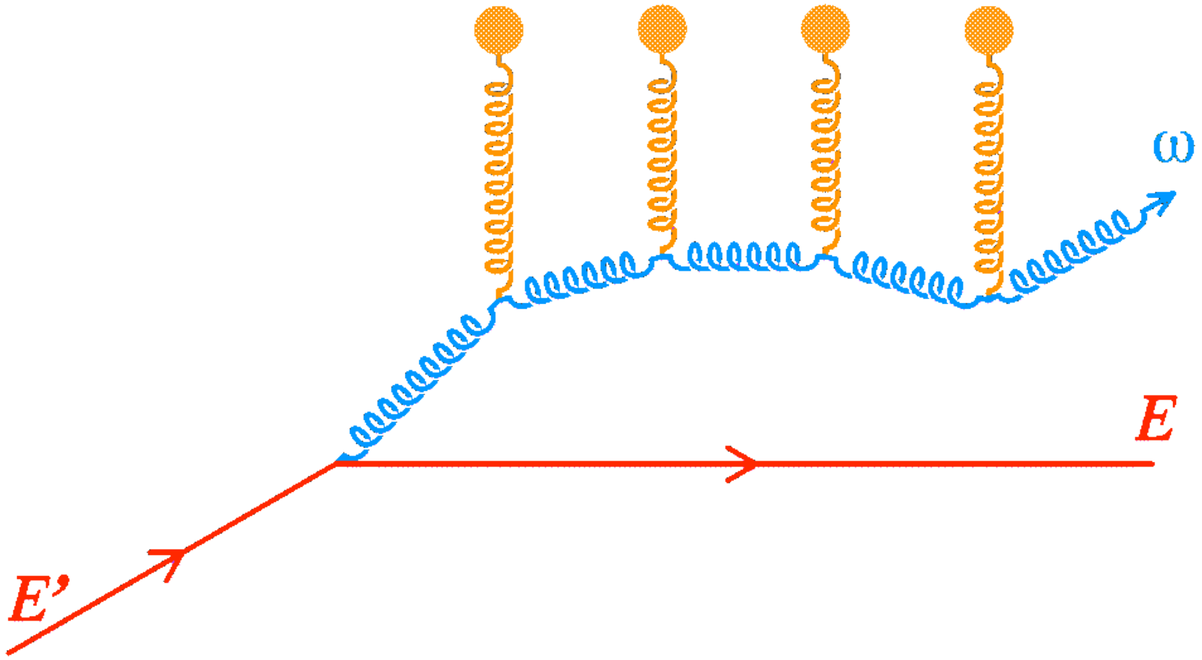
coherence length of the emitted gluon

$$\underbrace{\ell_{\rm coh} \sim \frac{2\omega}{(k_\perp)^2} \leq L \qquad (k_\perp)^2 \simeq N_{\rm coh}\mu^2} \quad \Rightarrow \quad \ell_{\rm coh} = \sqrt{\frac{2\omega\lambda}{\mu^2}}$$

LPM-produced gluons have $\omega \lesssim \omega_c \equiv \frac{1}{2}\hat{q}L^2$

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

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



Inelastic energy loss

Landau–Pomeranchuk–Migdal effect: Multiple soft scattering limit

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

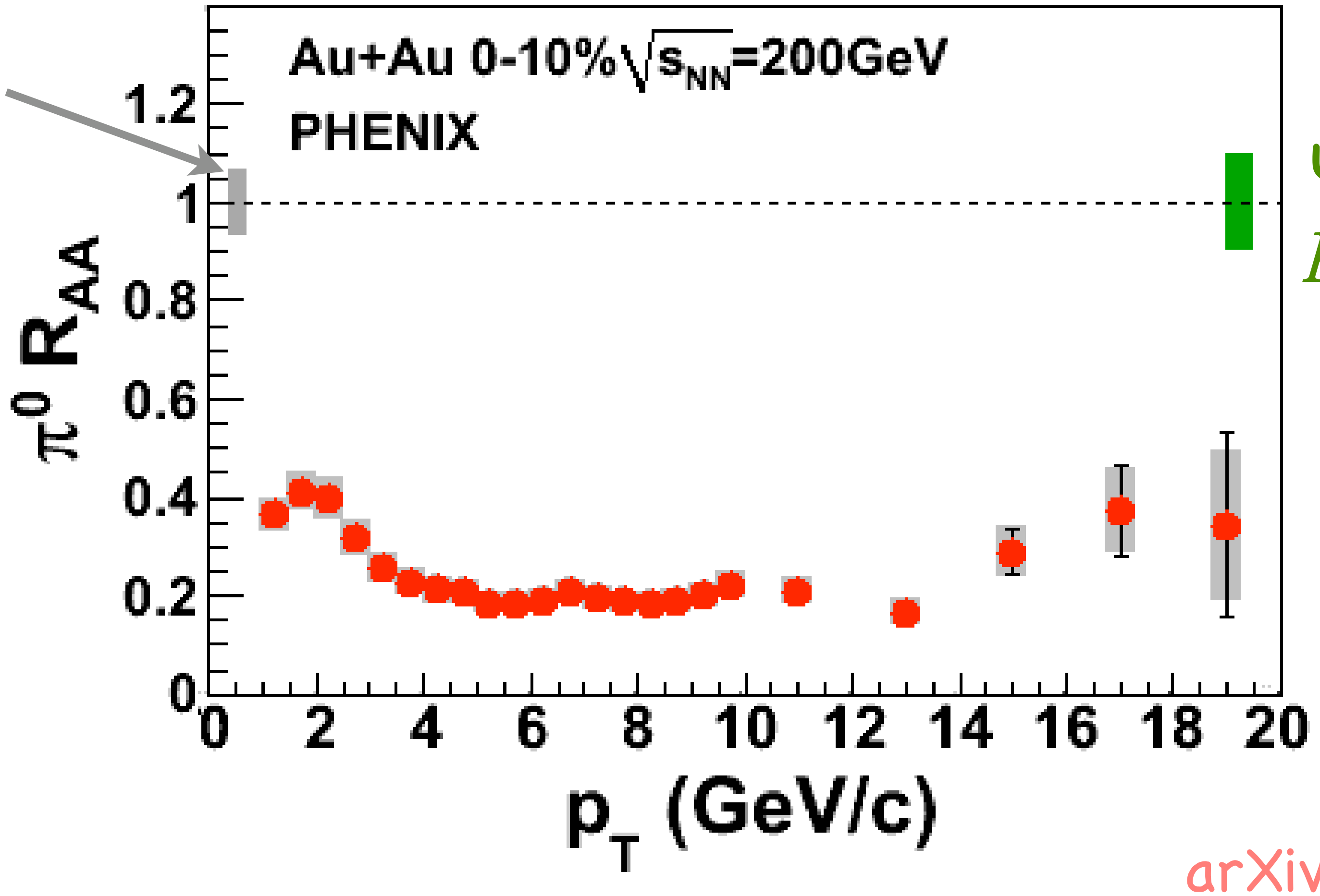
$\Rightarrow$ gluon energy spectrum per unit path length $\omega\frac{{\rm d}I}{{\rm d}\omega{\rm d}z} \simeq \frac{\alpha_s}{\ell_{\rm coh}} \simeq \alpha_s\sqrt{\frac{\hat{q}}{\omega}}$

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

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

"Jets" in Au-Au collisions at RHIC (1)

Nuclear modification factor $R_{AA} \equiv \dfrac{1}{N_{\rm coll}} \dfrac{\frac{{\rm d}^2 N_{AA}}{{\rm d}P_T\,{\rm d}y}}{\frac{{\rm d}^2 N_{pp}}{{\rm d}P_T\,{\rm d}y}}$



$N_{\rm coll}$ uncertainty

uncertainty on pp-normalization

arXiv:0801.4020 [nucl-ex]

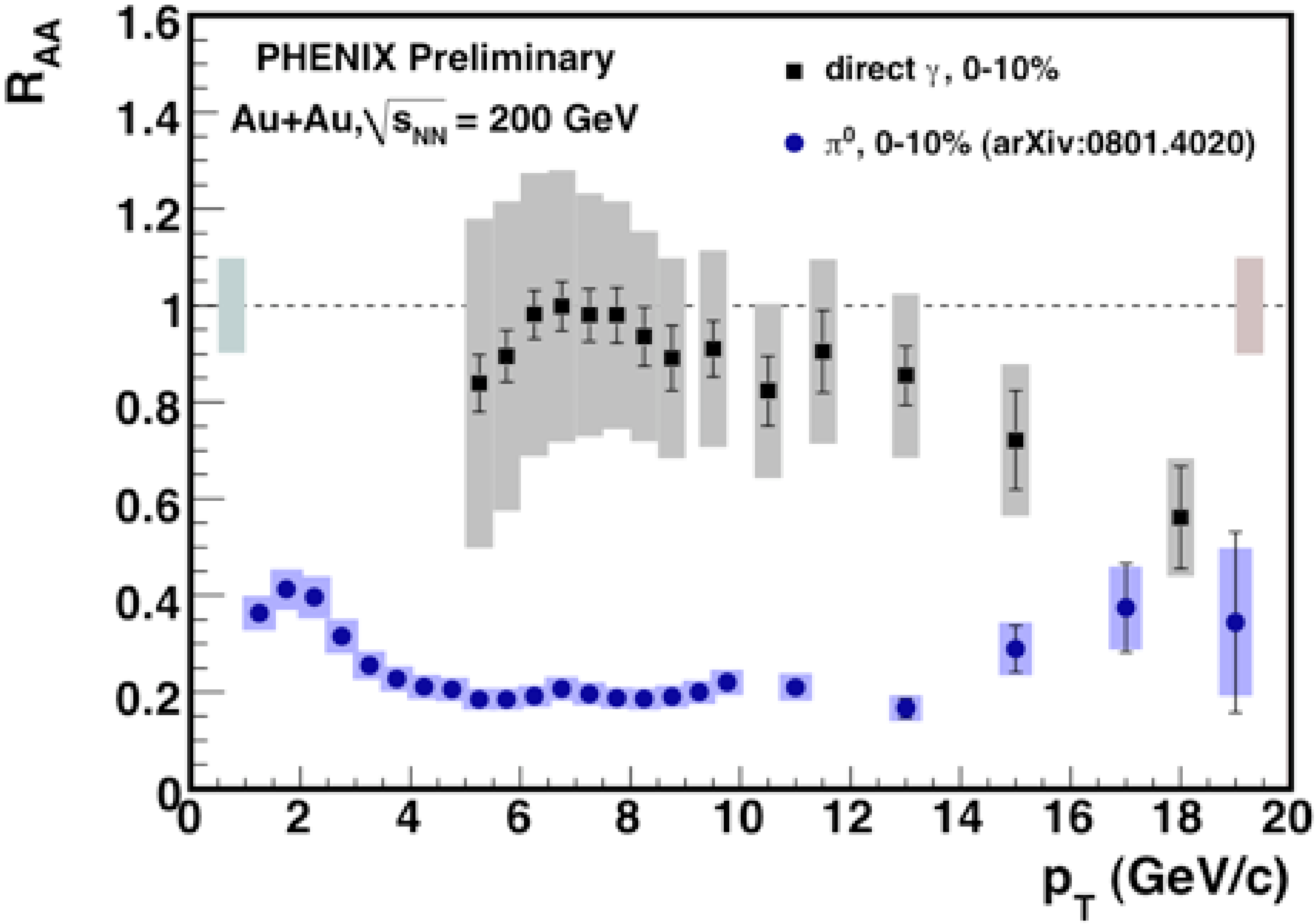
In central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, one misses 80% of the high-transverse-momentum hadrons!

(no pathology in the pp reference! perfectly described in pQCD)

Jet quenching vs. initial-state effect

$$R_{AA} \equiv \frac{1}{N_{\rm coll}} \frac{\frac{{\rm d}^2 N_{AA}}{{\rm d}P_T\,{\rm d}y}}{\frac{{\rm d}^2 N_{pp}}{{\rm d}P_T\,{\rm d}y}}$$ < 1: is $N_{\rm coll}$ well under control?

☞ Photons should not dissipate energy like colored particles*: $R_{AA} \approx 1$



* yet photon production is modified: Bremsstrahlung, photons from parton fragmentation...

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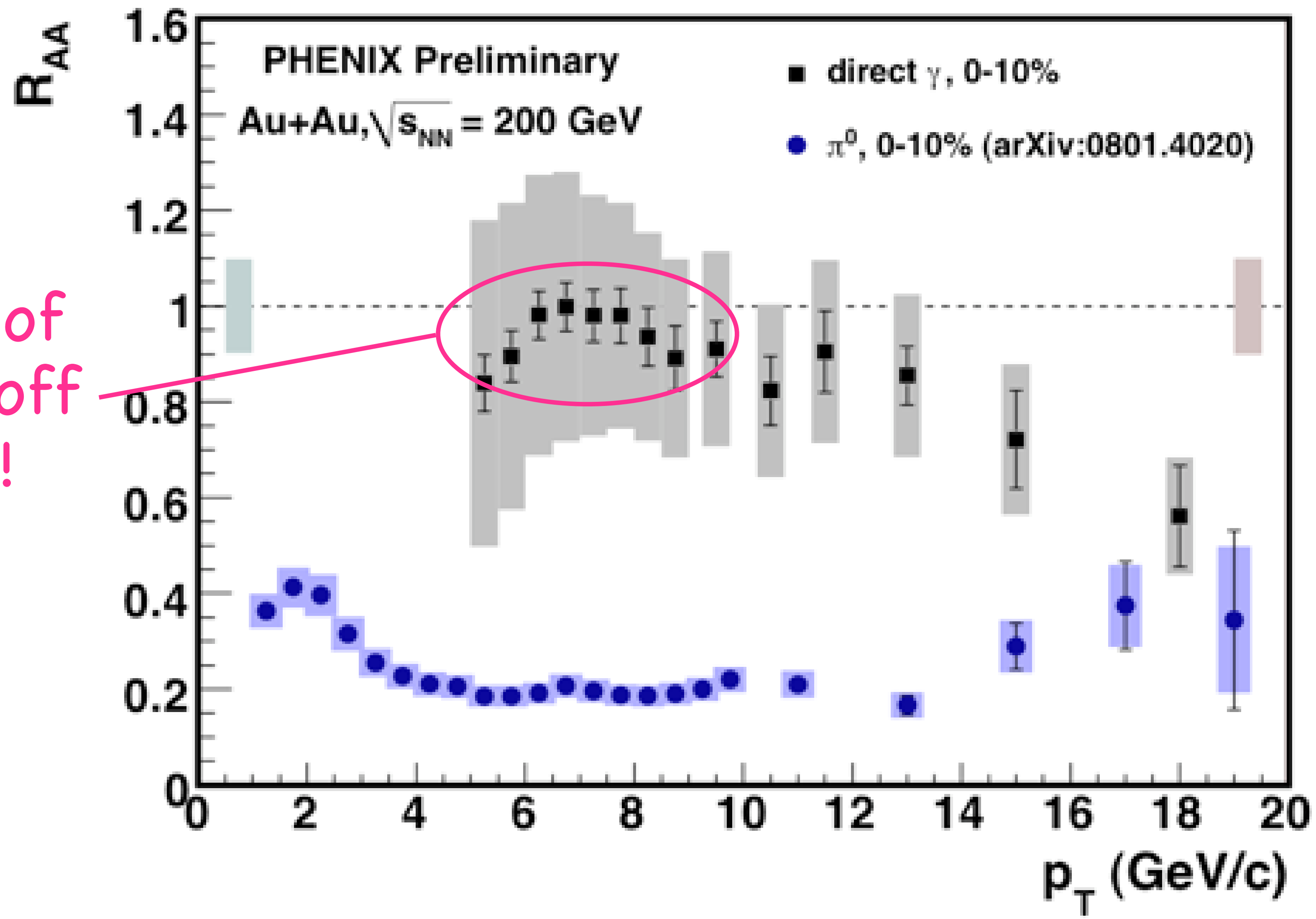

computations of $N_{\rm coll}$ are not off by a factor 5!

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Jet quenching vs. initial-state effect

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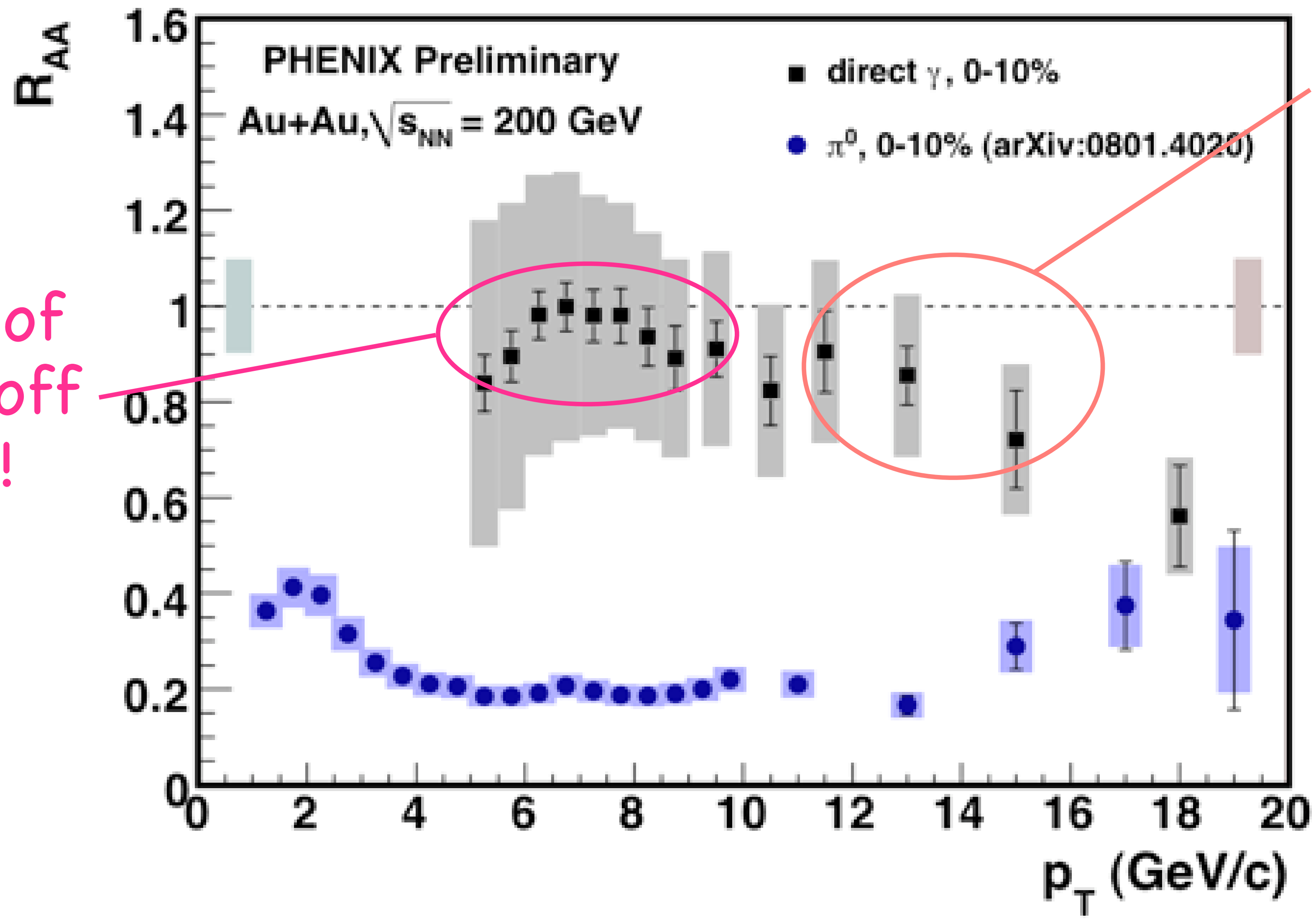

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deviation from 1 not unexpected (isospin…)

---

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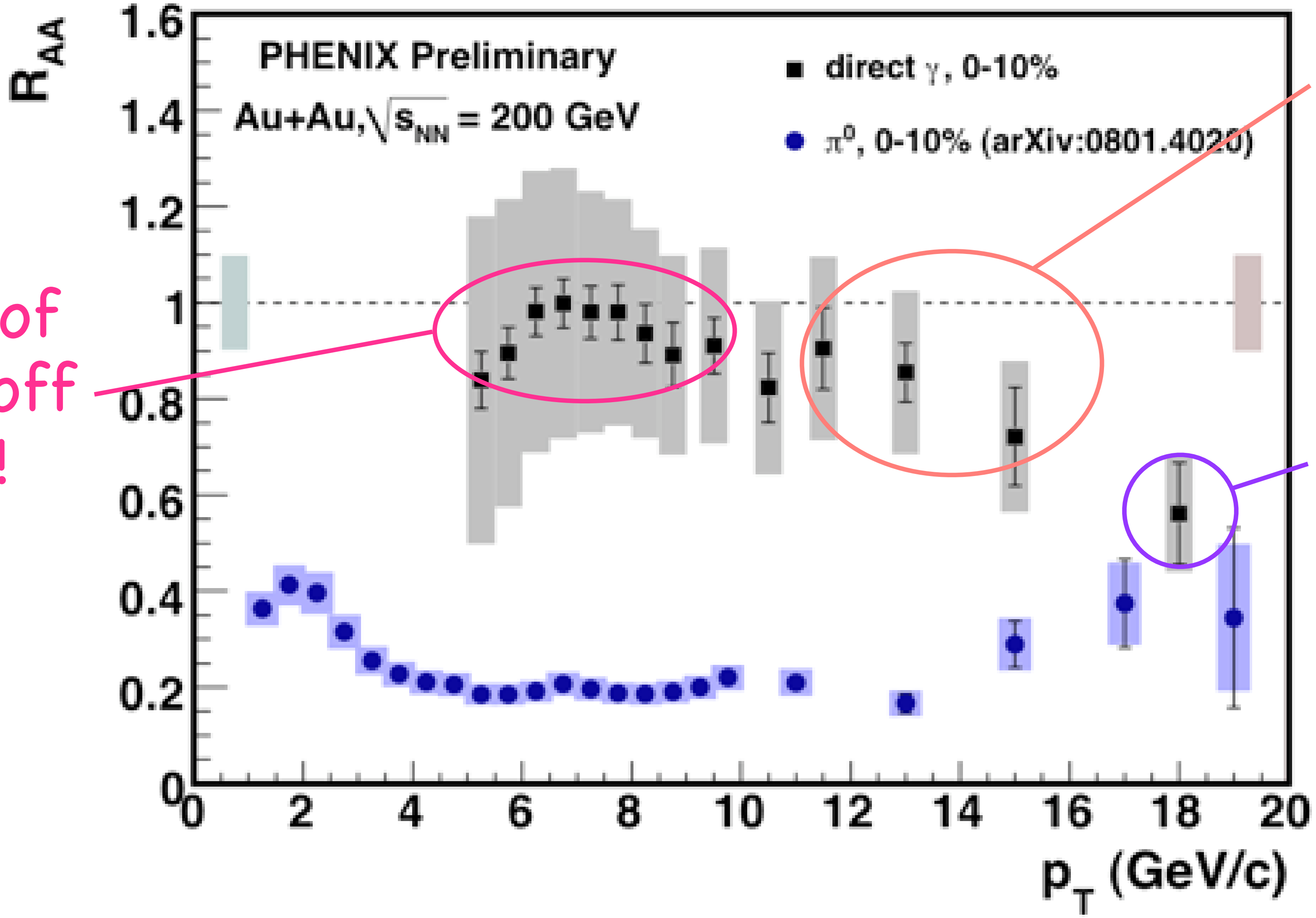


computations of $N_{\rm coll}$ are not off by a factor 5!

deviation from 1 not unexpected (isospin...)

embarrassingly close to the pion value?

---

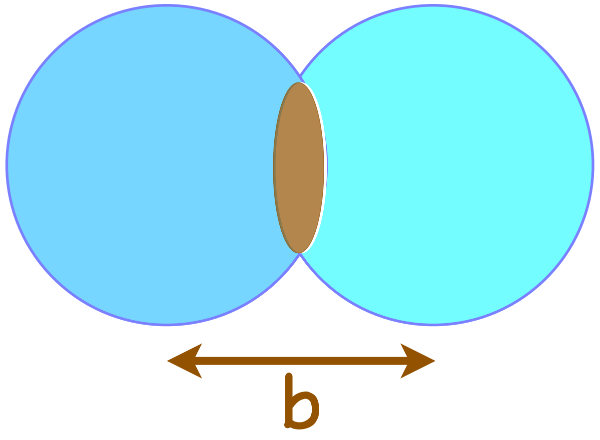
* yet photon production is modified: Bremsstrahlung, photons from parton fragmentation...

Heavy-ion collisions: geometry

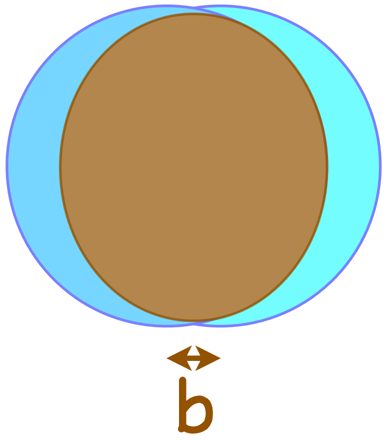
Heavy nuclei have a finite radius!

☞ In a collision the impact parameter plays a role:

- the nuclei might barely graze each other (large impact parameter, “peripheral” collision)



- or the collision might be almost head-on (small impact parameter, “central” collision)



The (almond-shaped) overlap regions of the nuclei are different in either case (size, eccentricity...).

Heavy-ion collisions: geometry

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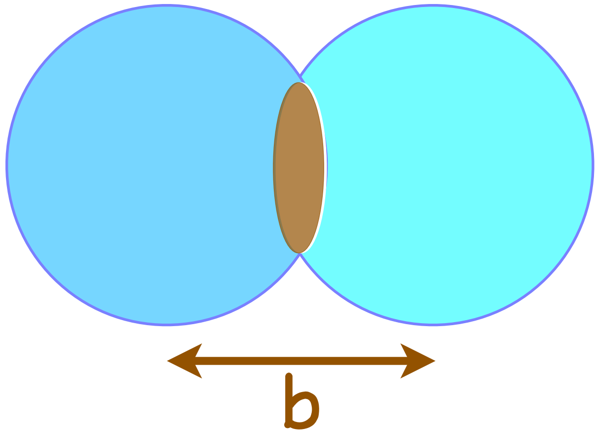
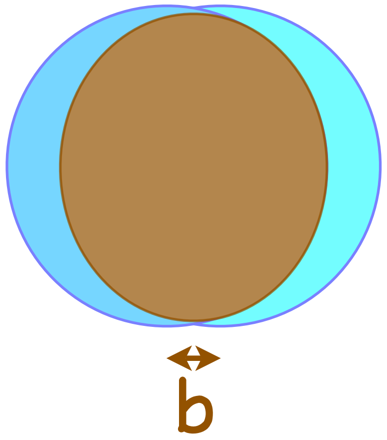


- the nuclei might barely graze each other (large impact parameter, "peripheral" collision)

A high-p_T parton quickly escapes the medium: it emerges after losing less energy.



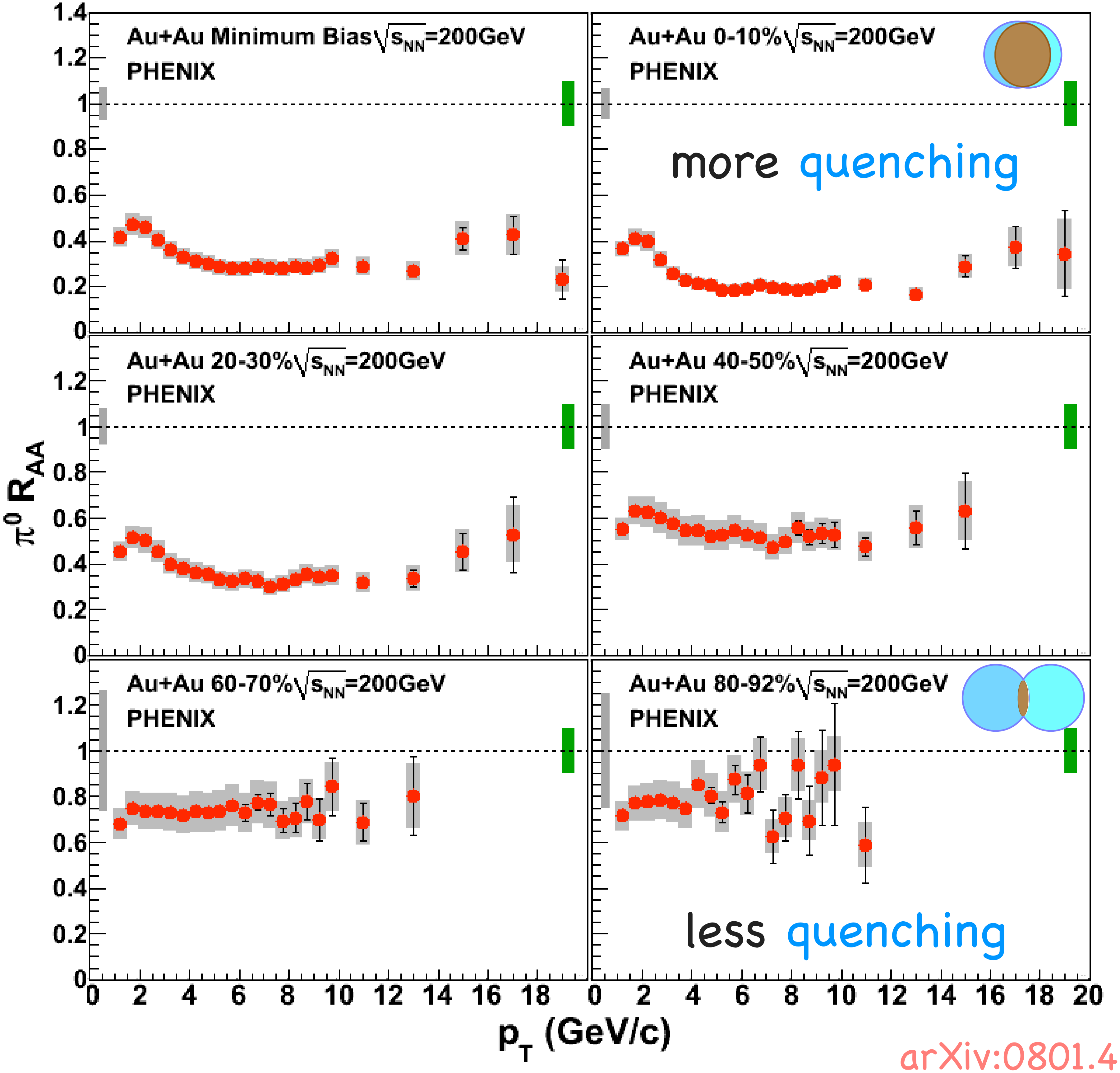
- or the collision might be almost head-on (small impact parameter, "central" collision)

High-p_T partons have larger in-medium path-lengths, thus lose more energy (in average).

The (almond-shaped) overlap regions of the nuclei are different in either case (size, eccentricity…).

“Jets” in Au-Au collisions at RHIC (2)

$$R_{AA} \equiv \frac{1}{N_{\rm coll}} \frac{\frac{{\rm d}^2 N_{AA}}{{\rm d}P_T\,{\rm d}y}}{\frac{{\rm d}^2 N_{pp}}{{\rm d}P_T\,{\rm d}y}}$$



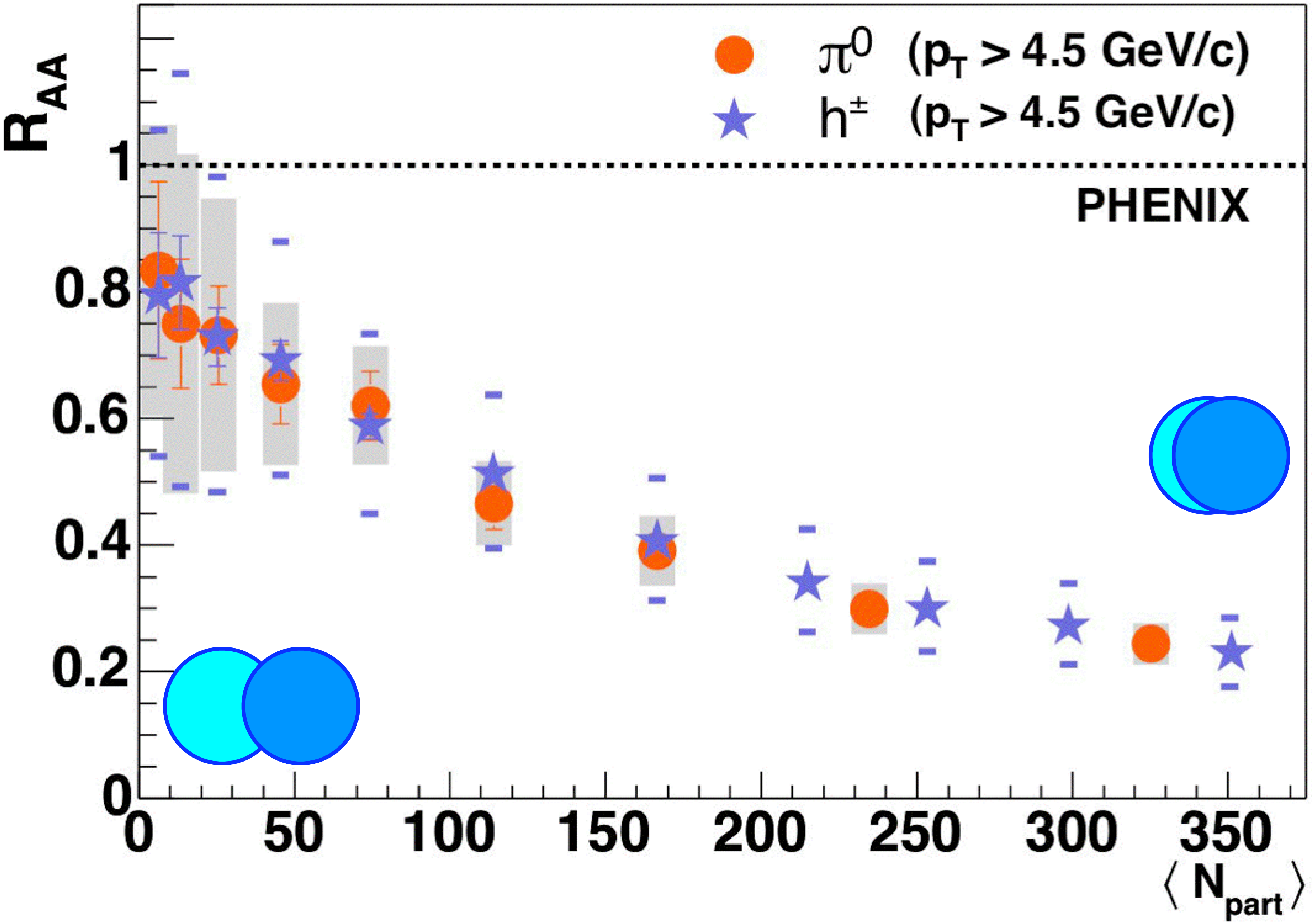
more quenching

less quenching

arXiv:0801.4020 [nucl-ex]

"Jets" in Au-Au collisions at RHIC (3)

Suppression of yields at high-p_T in Au-Au collisions also for charged hadrons: similar suppression as for π^0:



PRC 69 (2004) 034910

High-p_{T} hadrons
in Au-Au collisions at RHIC

- No suppression for photons... as expected!

- Similar suppression (≈ 80%) above $p_{\mathrm{T}} \approx 7$ GeV for all hadron species

  ☞ hard to explain with energy loss only at the hadronic level, the suppression took place in a deconfined medium.

- Phenomenology: from the measured R_{AuAu} one extracts larges values of $\hat{q}$, about 10^2 larger than the value for a hot pion gas: hints once again at "jet quenching" in a colored medium.

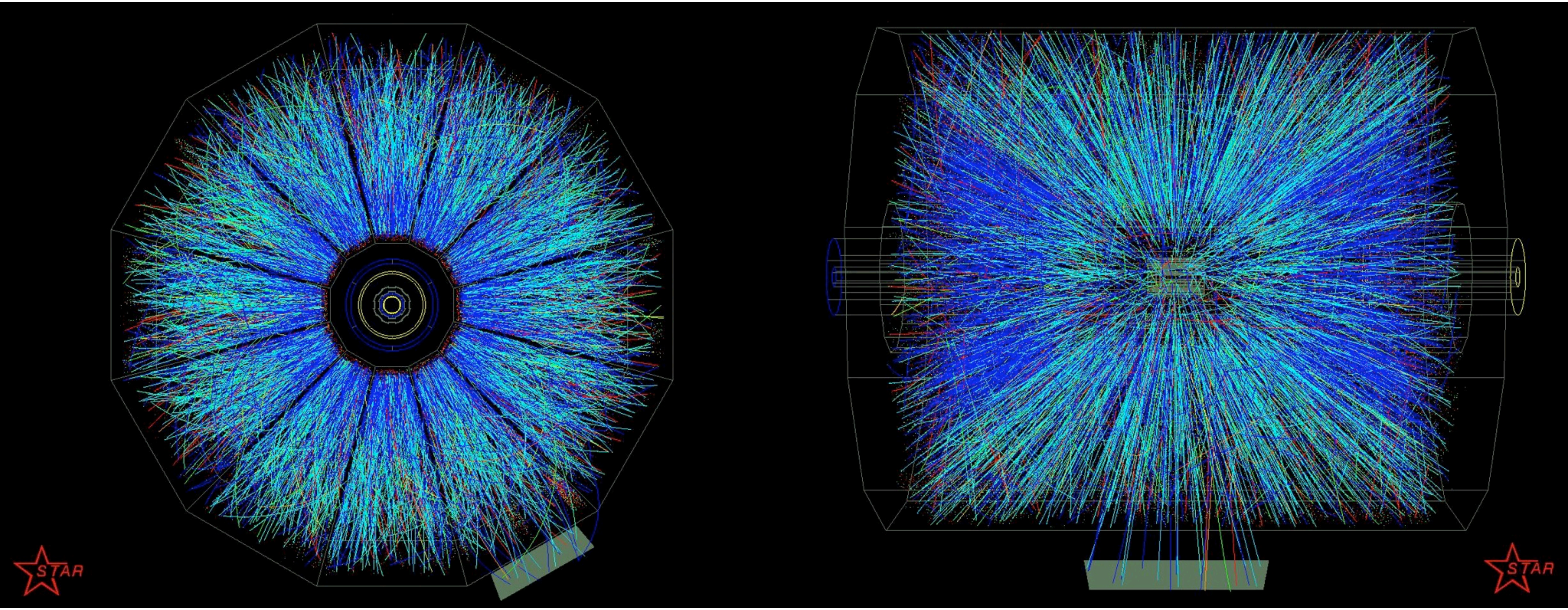
High transverse momentum physics in heavy-ion collisions

- Jets are a good tool to extract information on the medium created in ultra-relativistic collisions of heavy nuclei: energy loss
  - transport coefficient $\hat{q}$: medium density + mean free path
- Already a wealth of experimental data: high p_{T} physics
  - single-particle spectra
  - (not shown: two-particle correlations in azimuth...)
- A handful of models available, with emphasis on different aspects
  - approaches focusing on the leading parton
  - description of whole parton shower / jet might be useful

Observing jets in heavy-ion collisions

Needle in a haystack...

About 8000 hadrons in a central Au+Au collision at $\sqrt{s_{NN}}$ = 200 GeV:



Common lore: forget about identifying jets in RHIC heavy-ion collisions.

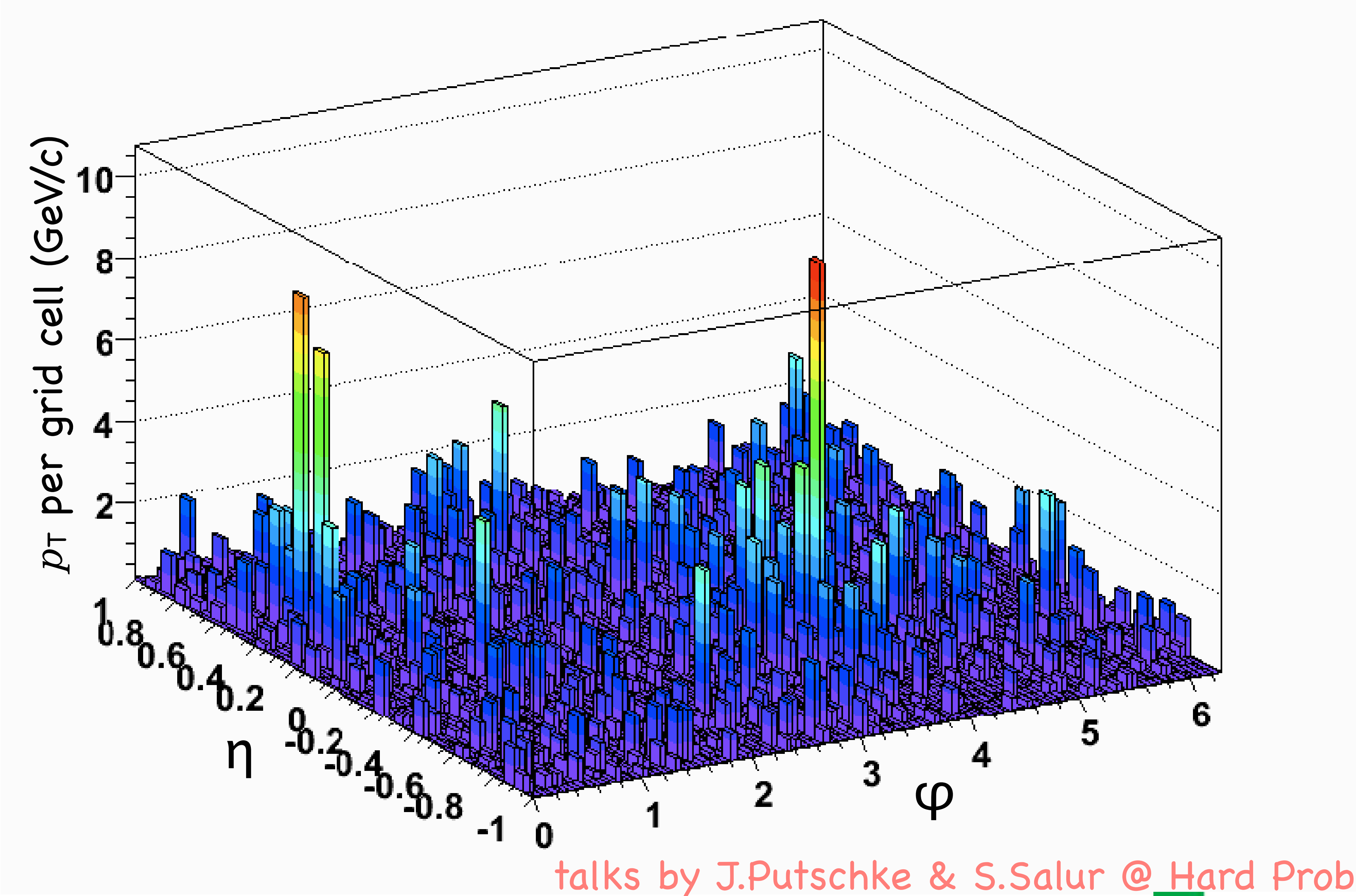
Investigate high-p_{T} hadrons instead (and wait for LHC events)!

Jets in Au-Au collisions at RHIC (4)

Audaces fortuna juvat...

STAR very preliminary "results"

Au+Au 0-20% $p_{t,jet}^{rec} \simeq 22$ GeV/c

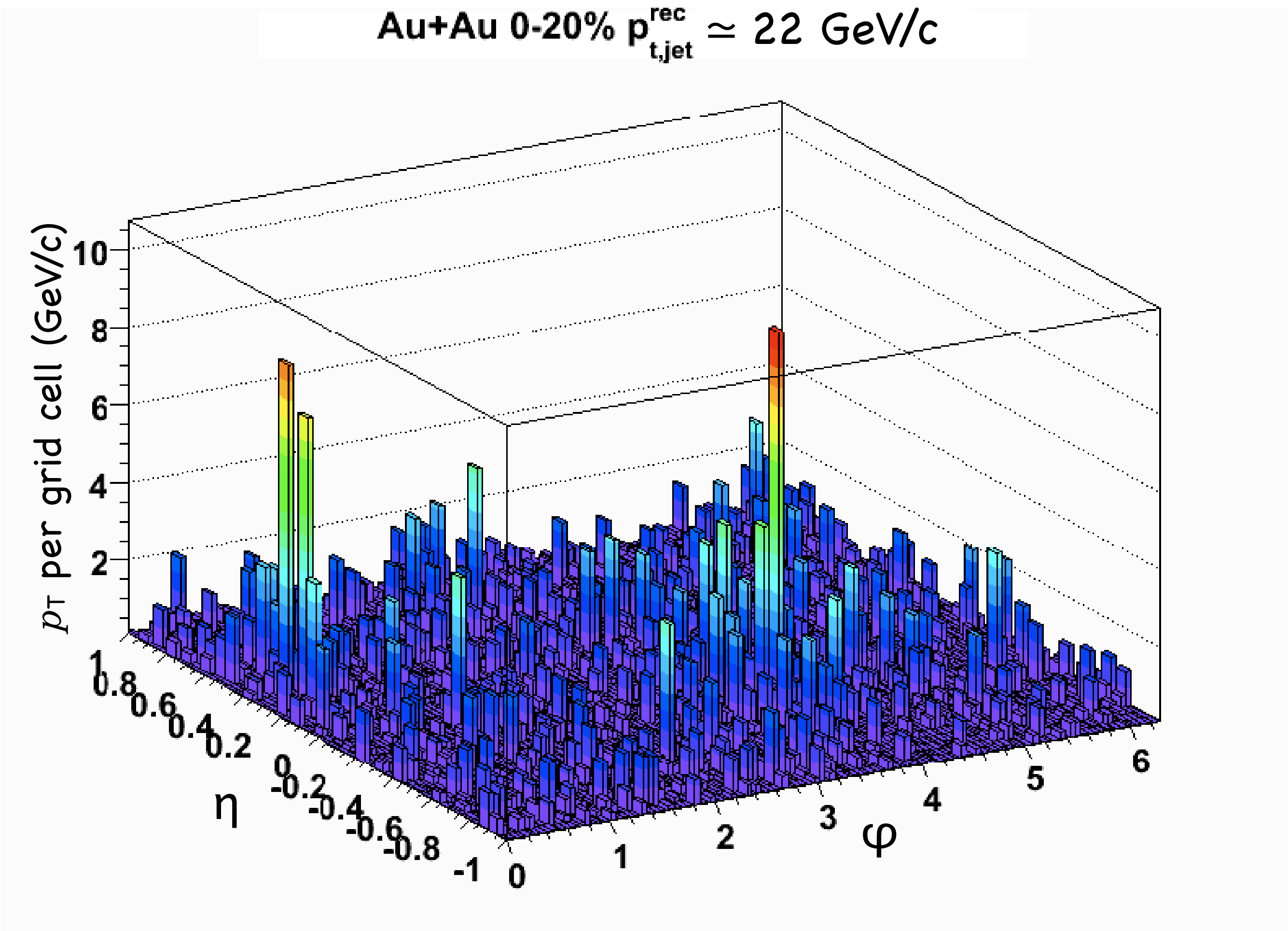


talks by J.Putschke & S.Salur @ Hard Probes 2008

Jets in Au-Au collisions at RHIC (4)

Audaces fortuna juvat… STAR very preliminary “results”

(with cone or k_T reconstruction algorithms)



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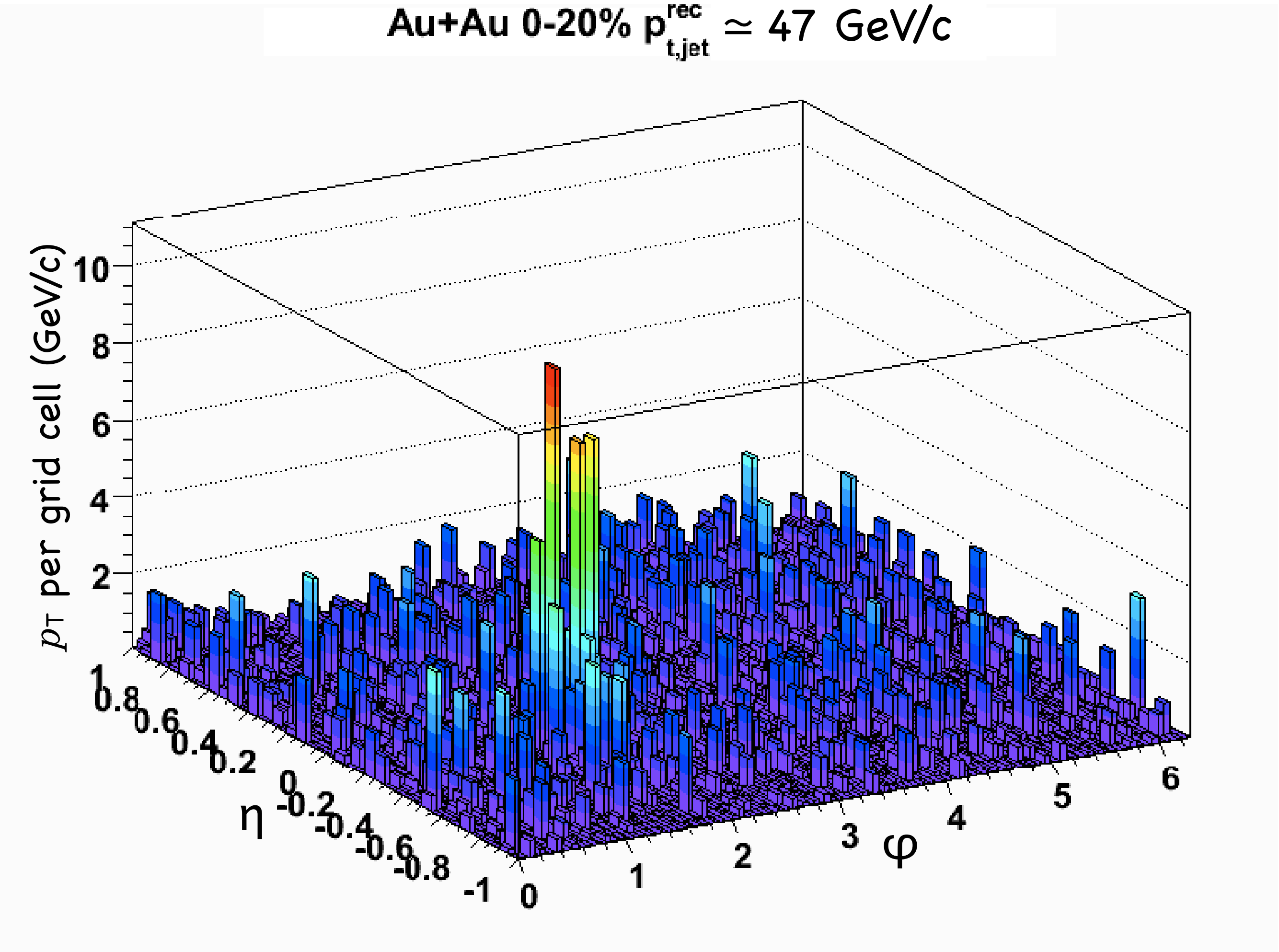


Au+Au 0-20% $p_{t,jet}^{rec} \simeq 47$ GeV/c

talks by J.Putschke & S.Salur @ Hard Probes 2008

Medium-induced distortion of a jet

Idea: the effect of the medium is to redistribute part of the energy from a high-p_T parton as some low-p_T radiation (gluon-strahlung).

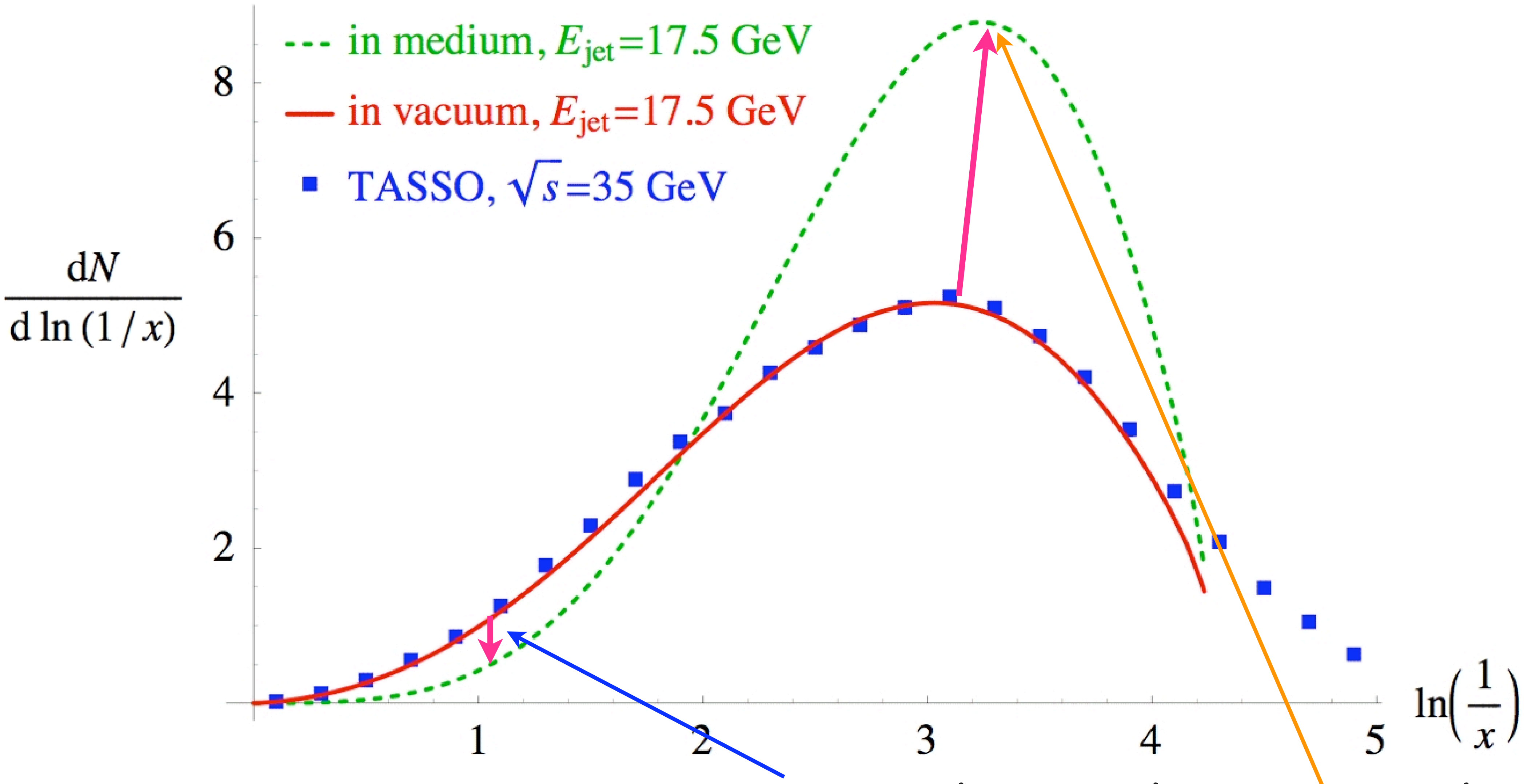
At level of the parton shower, this means some distortion of the jet.
☞ emphasis on energy-momentum conservation inside the shower.

Jets in vacuum are well described by pQCD (especially, within its Modified Leading Logarithmic Approximation, MLLA): "hump-backed plateau" of the longitudinal distribution of hadrons inside a jet.

... let us investigate the expected distortion of the jet shape due to a medium.

“Medium-modified” MLLA

Idea: describe the effect of the medium on the whole parton shower, recovering the MLLA hump-backed plateau “in the vacuum”.



Partons are redistributed from high p_T (large x) to low p_T (small x)

Describing a whole jet becomes feasible!

NB & Wiedemann

(Corresponding Monte-Carlo implementations are appearing.)