High transverse momentum physics in heavy-ion collisions

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High transverse momentum physics in heavy-ion collisions

- Motivation
- Hard probes of the created medium: jets
- Theoretical / phenomenological ideas
- Time evolution of an ultra-relativistic heavy-ion collision
- RHIC results (a biased personal choice!)

Hints from lattice QCD

PHYSICAL REVIEW D **77**, 014511 (2008)

QCD equation of state with almost physical quark masses

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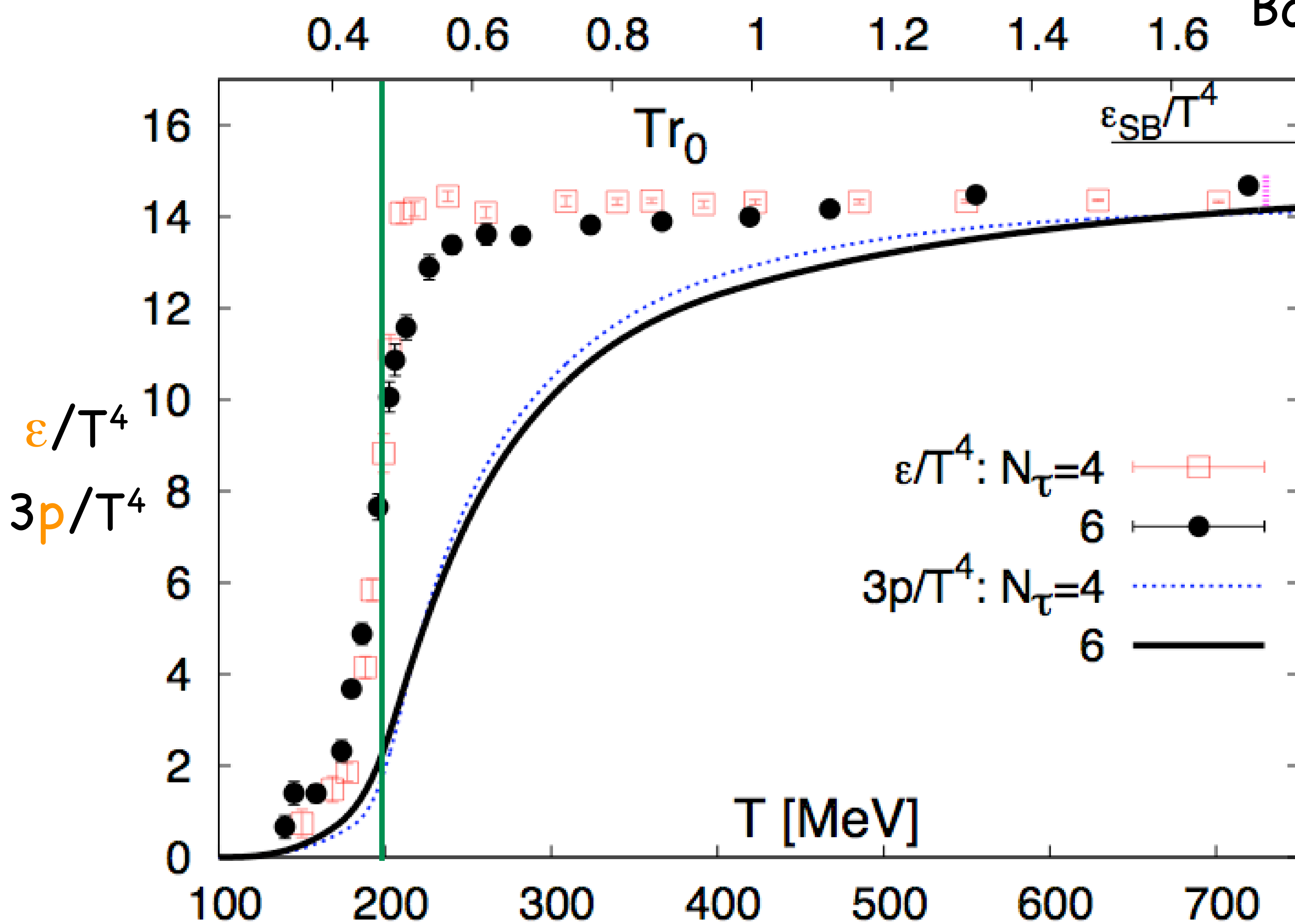
We present results on the equation of state in QCD with two light quark flavors and a heavier strange quark. Calculations with improved staggered fermions have been performed on lattices …

"2+1" flavors, $m_\pi \approx 220$ MeV, $m_K \approx 500$ MeV

Hints from lattice QCD

Energy density ε & pressure p:

ideal Stefan-Boltzmann limit

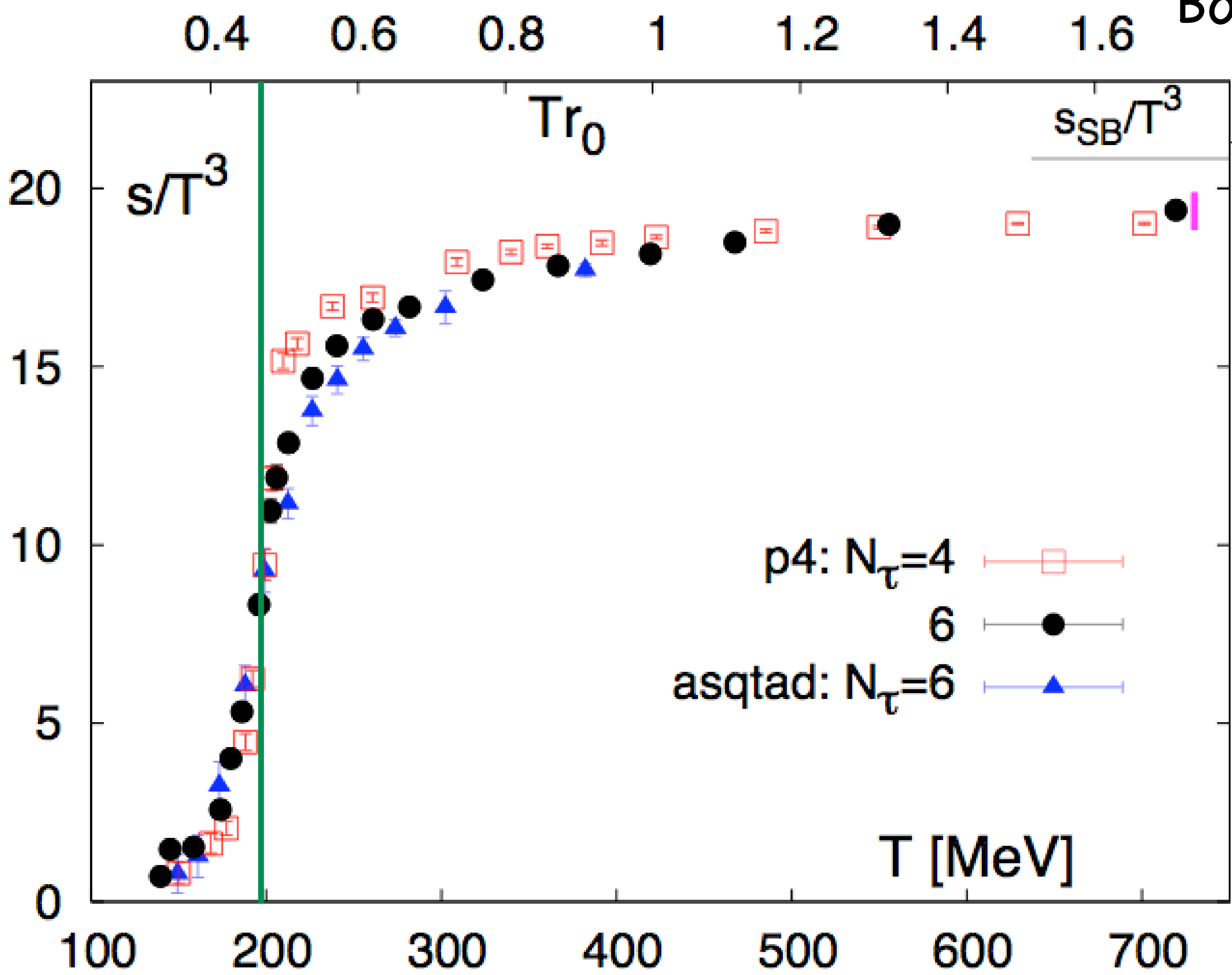


PRD 77 (2008) 045511

Hints from lattice QCD

Entropy density s

ideal Stefan-Boltzmann limit



s/T^3

PRD 77 (2008) 045511

Hints from lattice QCD

- Rapid change of thermodynamic quantities (energy density, pressure, entropy density...) ☞ transition / crossover between two states:

hadron gas vs. Quark-Gluon Plasma

around a "critical" temperature $T_c = 196 \pm 4$ MeV.

- (not shown here: screening of the heavy-quark potential in the high-temperature phase; equation of state; susceptibilities...)

Hints from lattice QCD

- Rapid change of thermodynamic quantities (energy density, pressure, entropy density…) ☞ transition / crossover between two states:

hadron gas vs. Quark-Gluon Plasma

around a "critical" temperature $T_c \approx 150\text{–}200$ MeV.

- (not shown here: screening of the heavy-quark potential in the high-temperature phase; equation of state; susceptibilities…)

Hints from lattice QCD

- Rapid change of thermodynamic quantities (energy density, pressure, entropy density...) ☞ transition / crossover between two states:

hadron gas vs. Quark-Gluon Plasma

around a "critical" temperature $T_c \approx 150$–200 MeV.

- (not shown here: screening of the heavy-quark potential in the high-temperature phase; equation of state; susceptibilities...)

- However lattice simulations of QCD at finite temperature are not (yet) performed with "physical" light-quark masses.

- They do not provide any phase diagram (finite quark density!),

- nor transport coefficients. (yet?)

☞ Heavy-ion experiments (and phenomenology)

Experimental results

THE result

(first seen at SPS, at RHIC? in the end, it doesn't matter)

In heavy-ion collisions at ultra-relativistic energies, something "new" is created, namely a "mesoscopic" region (size ≈ several fm, much larger than that of a hadron) in which the acting degrees of freedom carry a color charge.

Should it be called a quark-gluon plasma?

(issues about thermal equilibrium...)

In any case, what is formed has to be characterized quantitatively.

Characterizing the medium

A priori, many possibilities...
In this talk, with the help of "high-p_T probes".

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)

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)

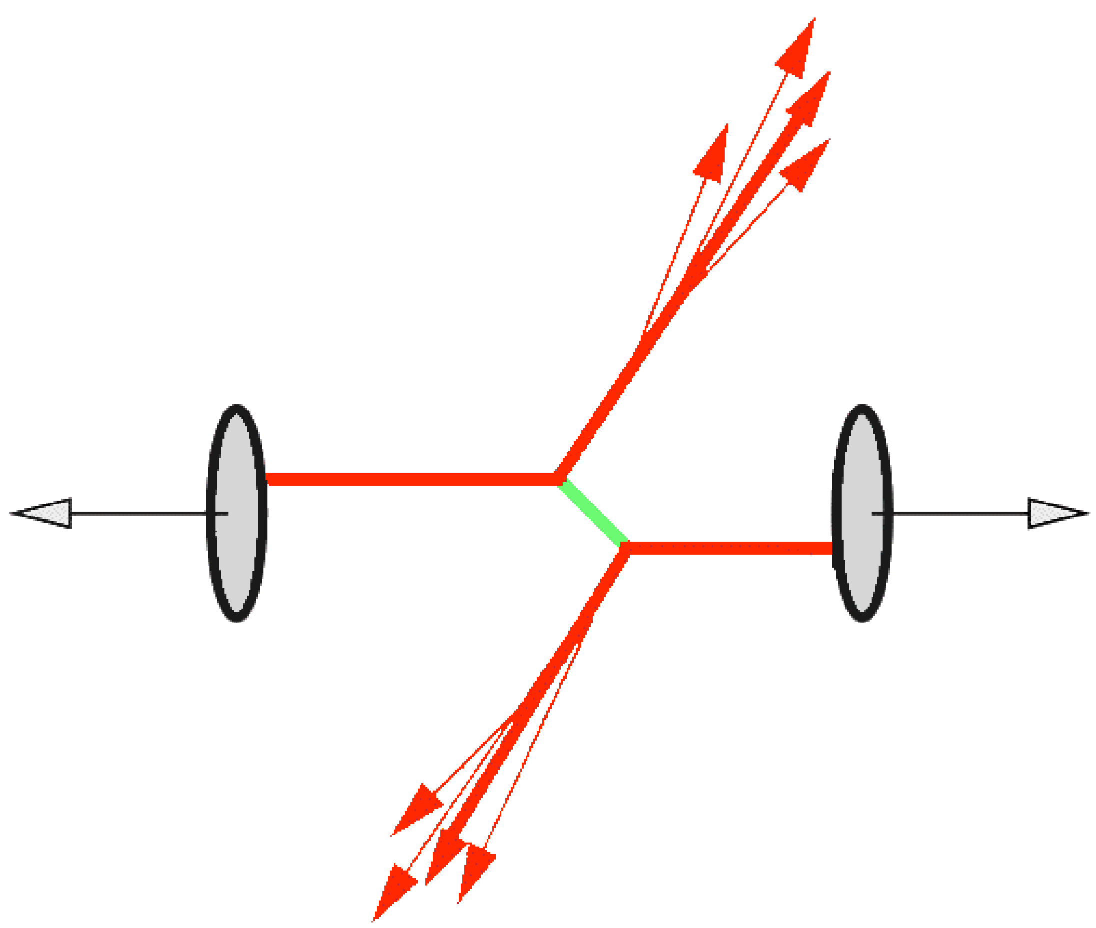
"jet quenching"

"Jet quenching": basic picture

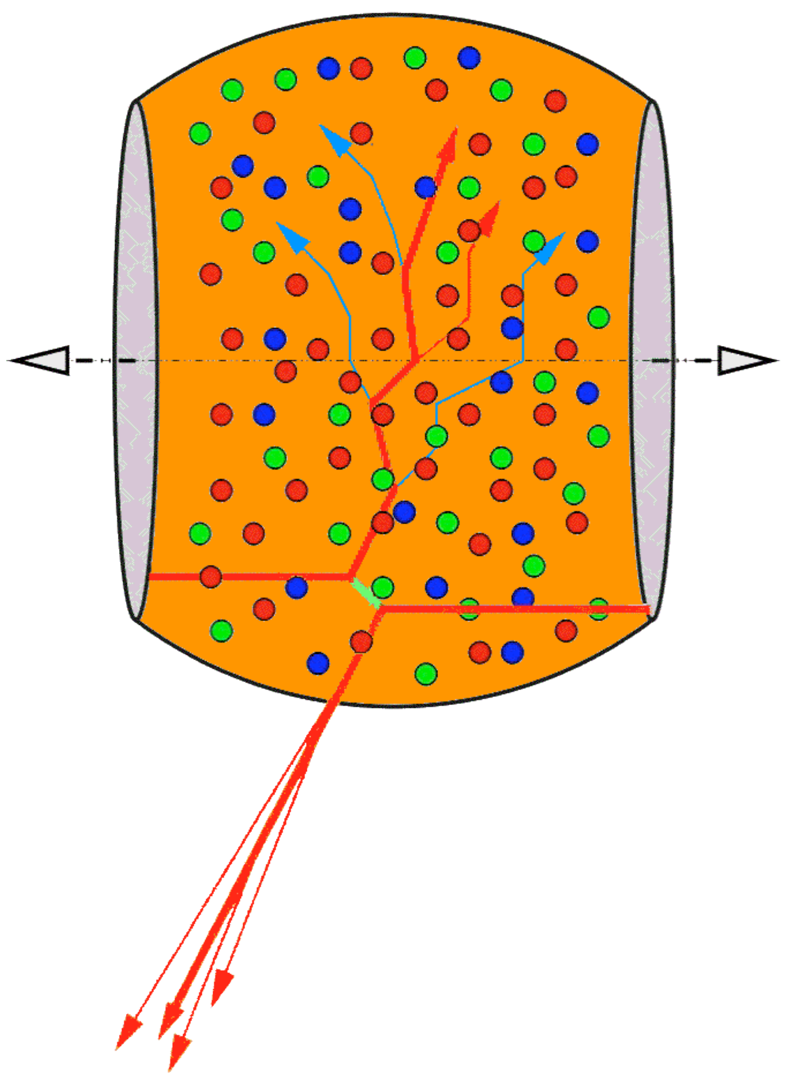
A fast quark/gluon propagating through a dense medium will "lose" part of its energy-momentum.

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

in vacuum



in medium



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.

(unfortunately, effect overestimated by a factor ≈100)

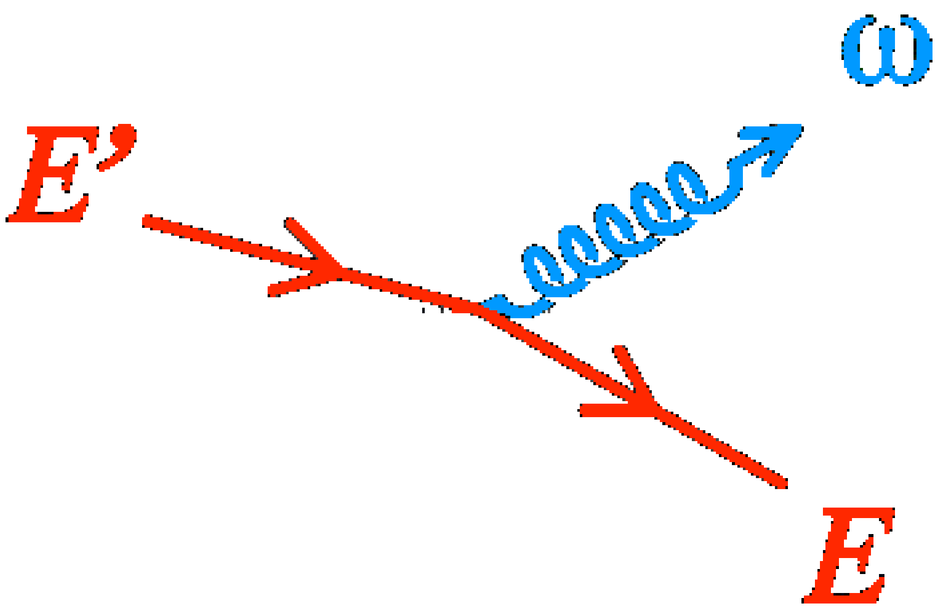
J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

[...] 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 ...

Jet quenching: underlying processes

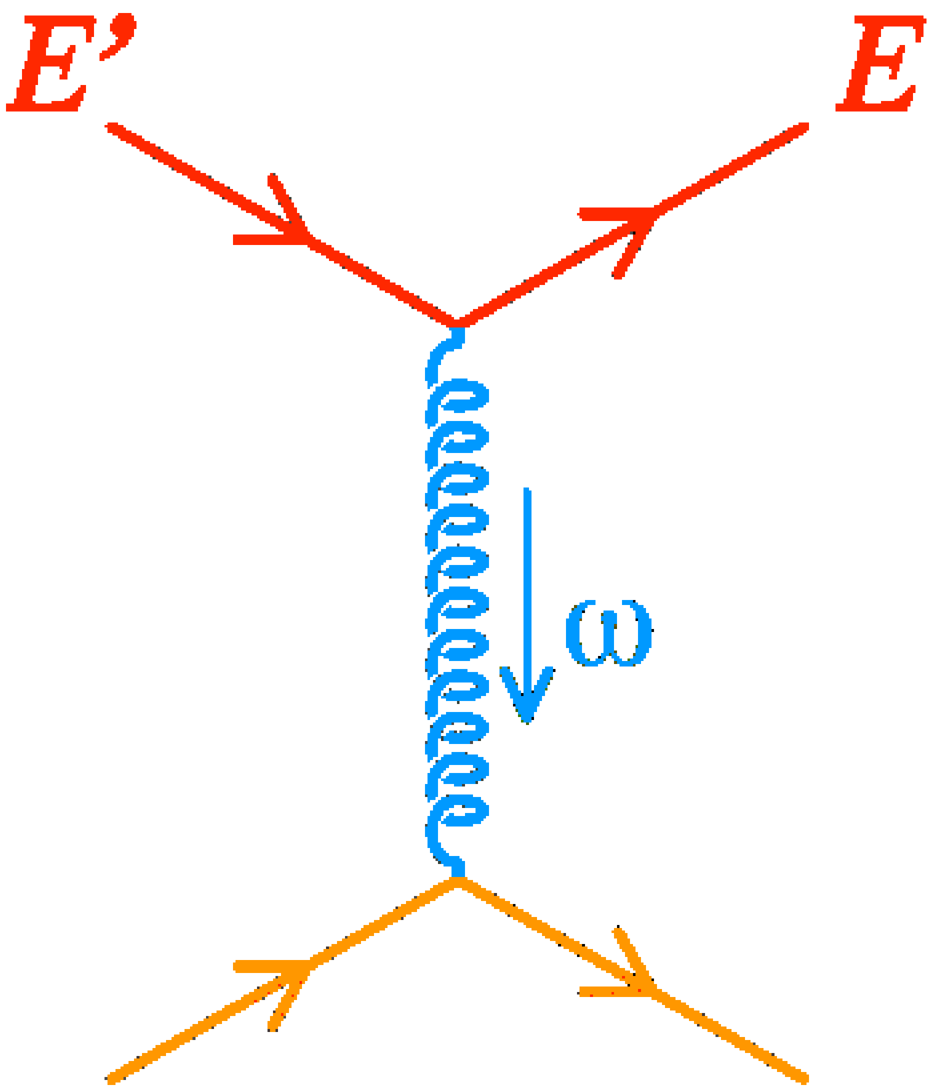
Two different processes lead to the loss of energy by a fast parton:

"radiative" process (Bremsstrahlung)



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

"collisional" process

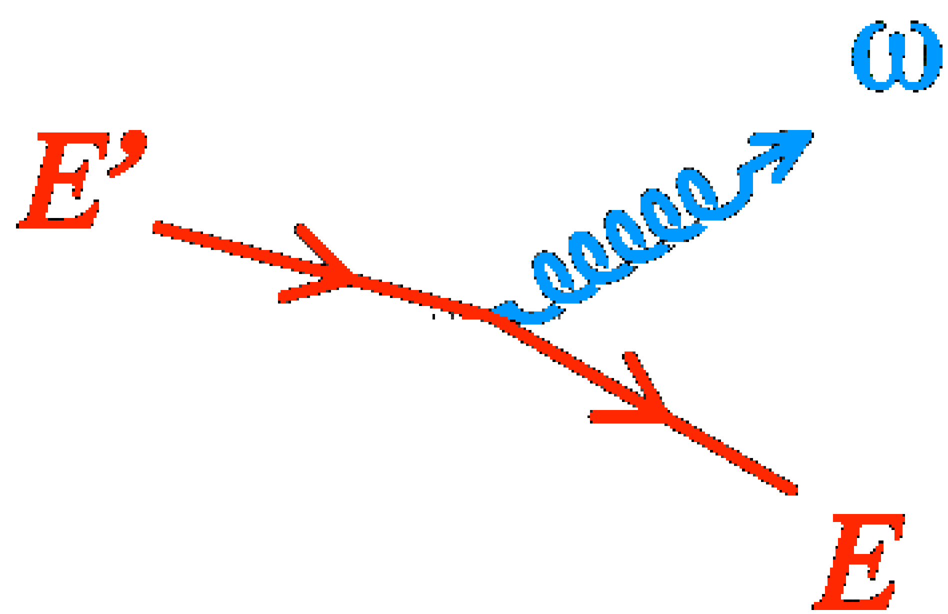


Jet quenching: underlying processes

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

inelastic

"~~radiative~~" process (Bremsstrahlung)

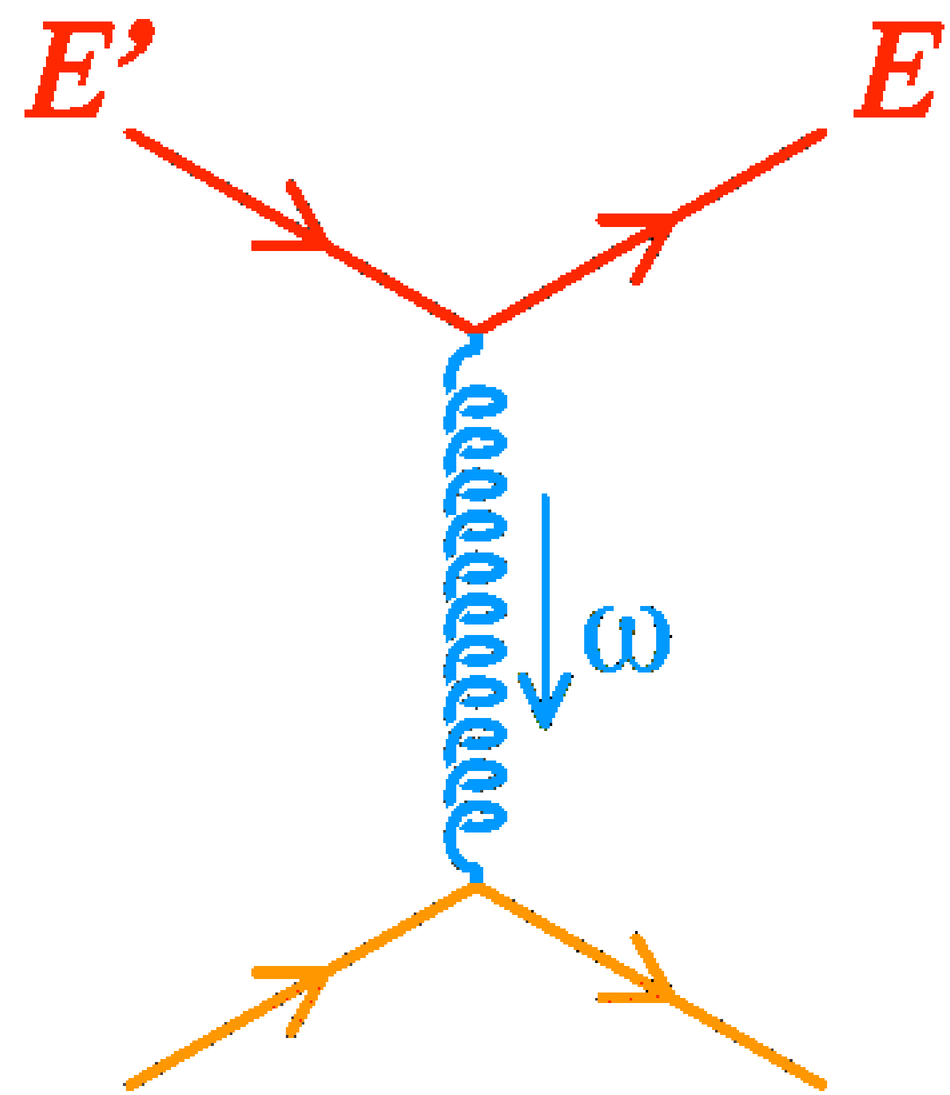


also "in vacuum" (DGLAP evolution), yet modified by the presence of a (colored) medium

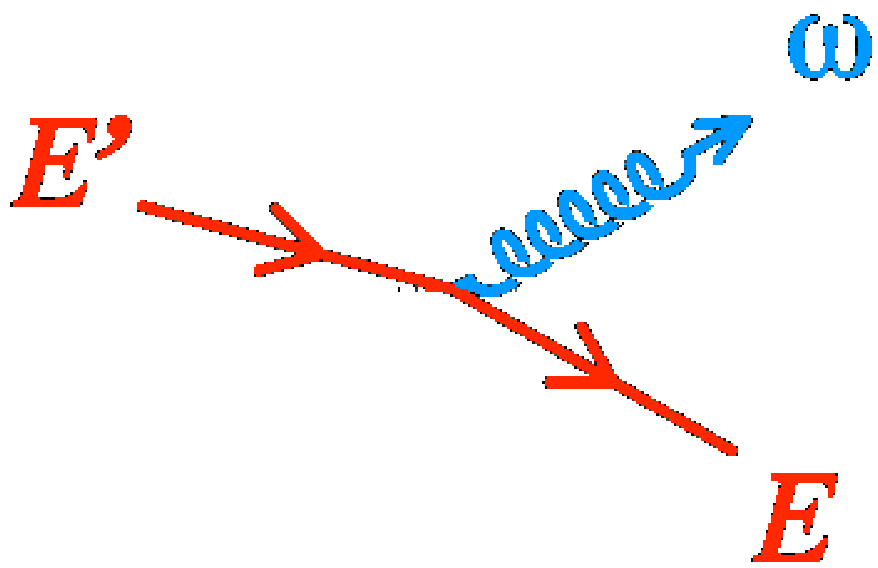
collisions!

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

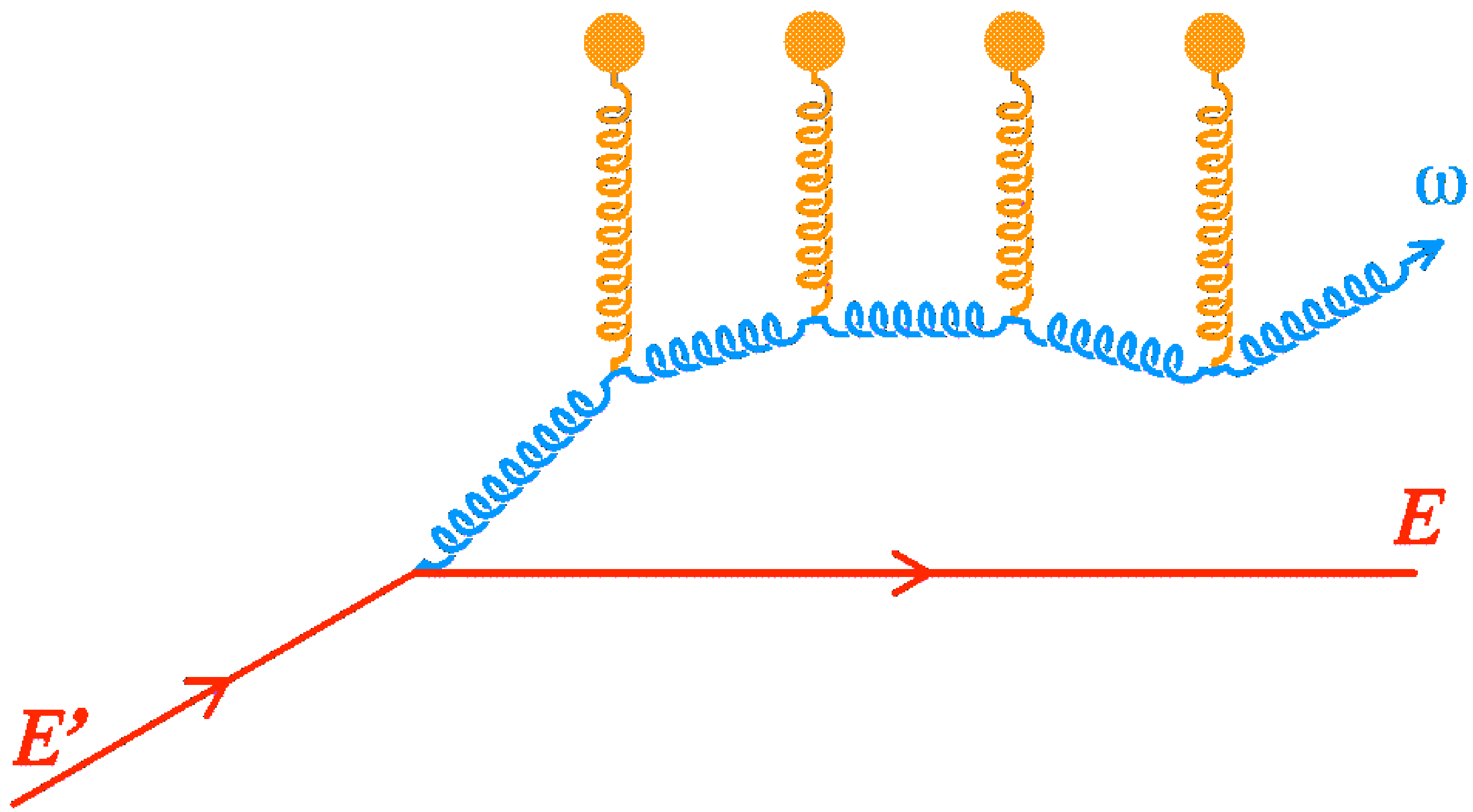
depends on the modeling of the medium

Various implementations, with emphasis on different physics aspects...

Jet quenching: coherent gluonstrahlung

Landau–Pomeranchuk–Migdal effect: Multiple soft scattering limit

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



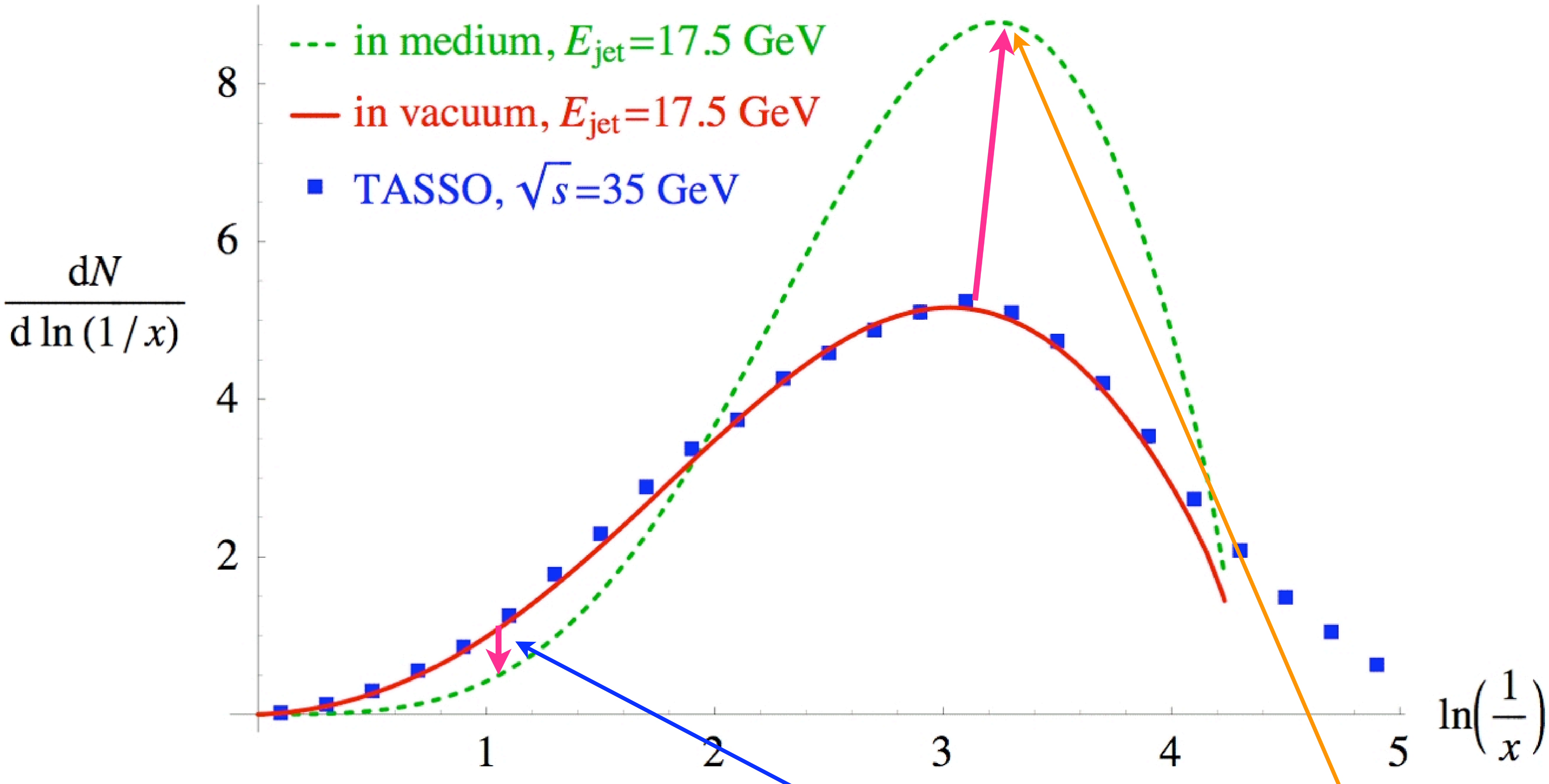
It radiates soft gluons, which scatter **coherently** on independent color charges in the medium, resulting in a medium-modified gluon spectrum.

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

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

"Medium-modified" MLLA

Idea: describe the effect of the medium on the whole parton shower, recovering the MLLA hump-backed plateau "in the vacuum".
(here, emphasis on energy-momentum conservation)

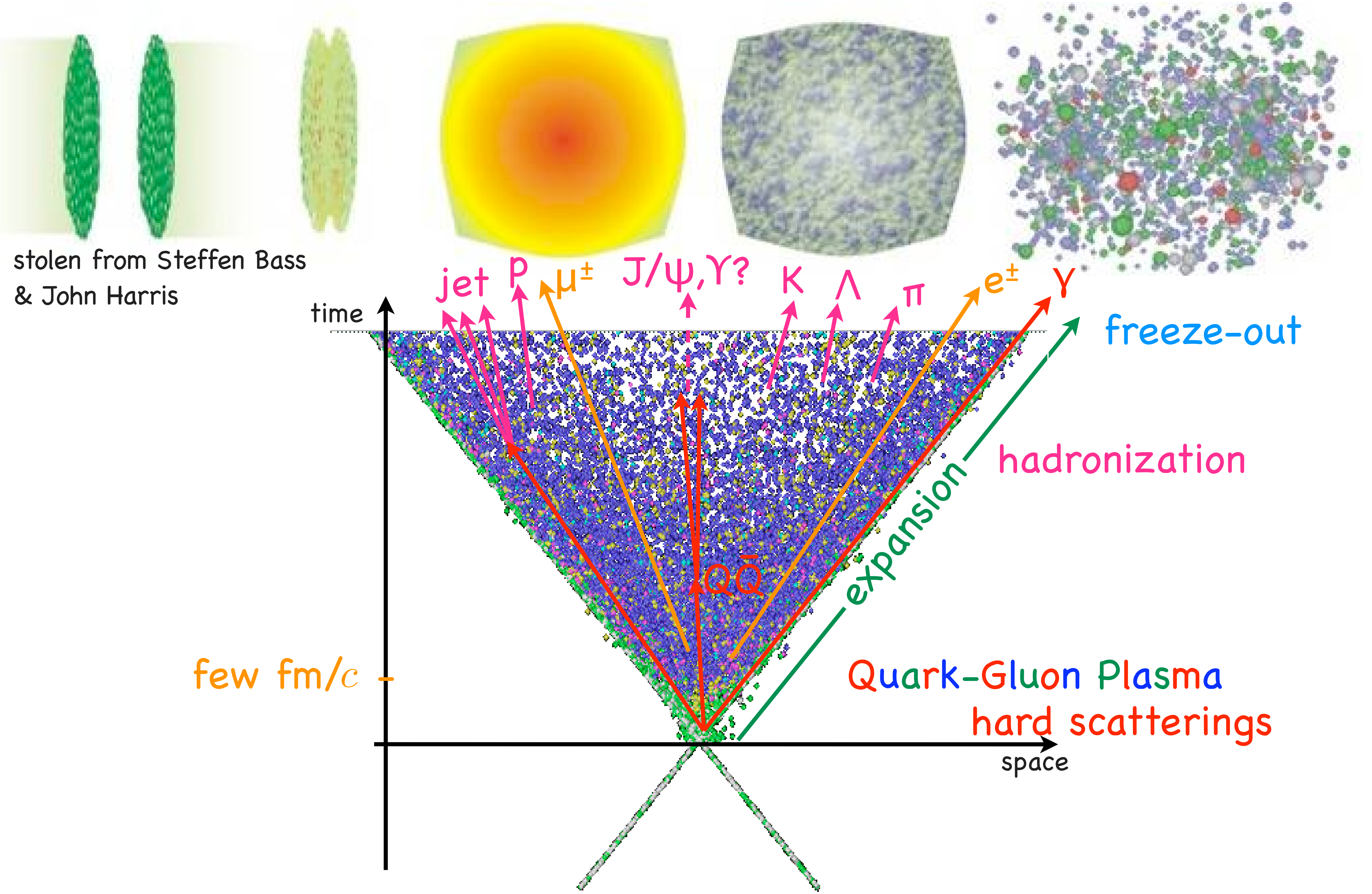


Partons are redistributed from high p_T (large x) to low p_T (small x)
Describing a whole jet becomes feasible!

NB & Wiedemann

(Corresponding Monte-Carlo implementations are appearing.)

Time evolution of a heavy-ion collision



stolen from Steffen Bass
& John Harris

"Jets" in nucleus-nucleus collisions: experimental aspects

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

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

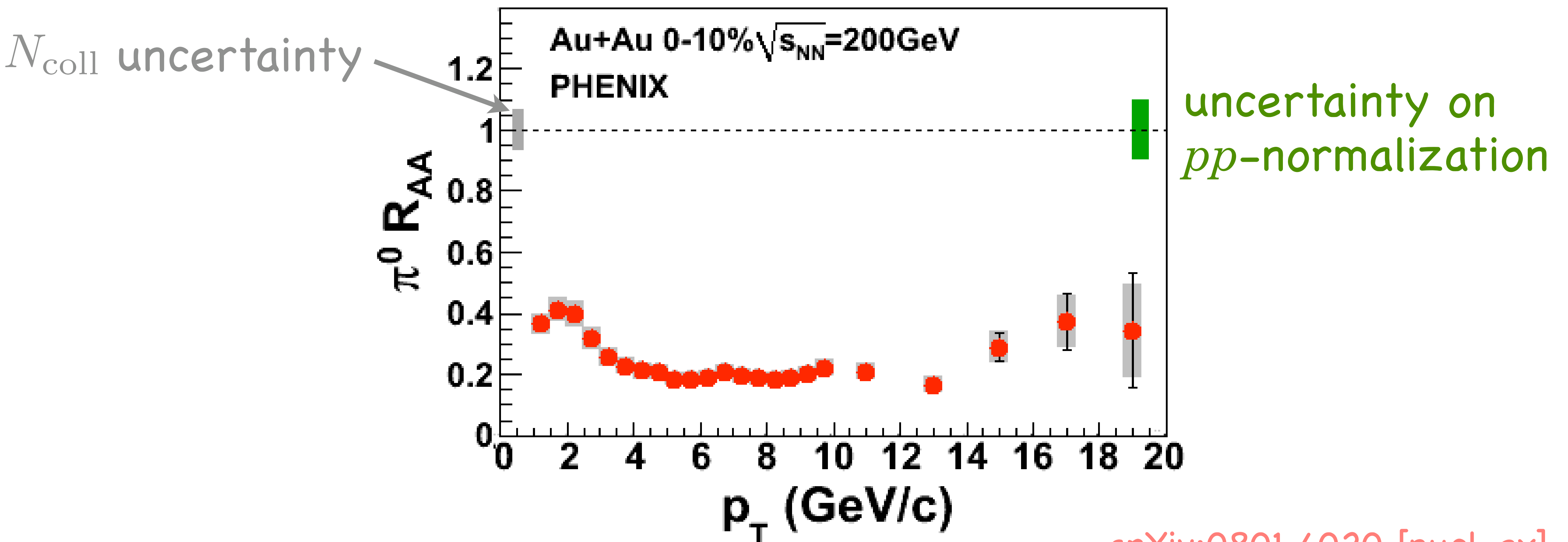
= 1 if A-A collision is a superposition of independent pp collisions*

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

* up to isospin corrections...

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

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



arXiv:0801.4020 [nucl-ex]

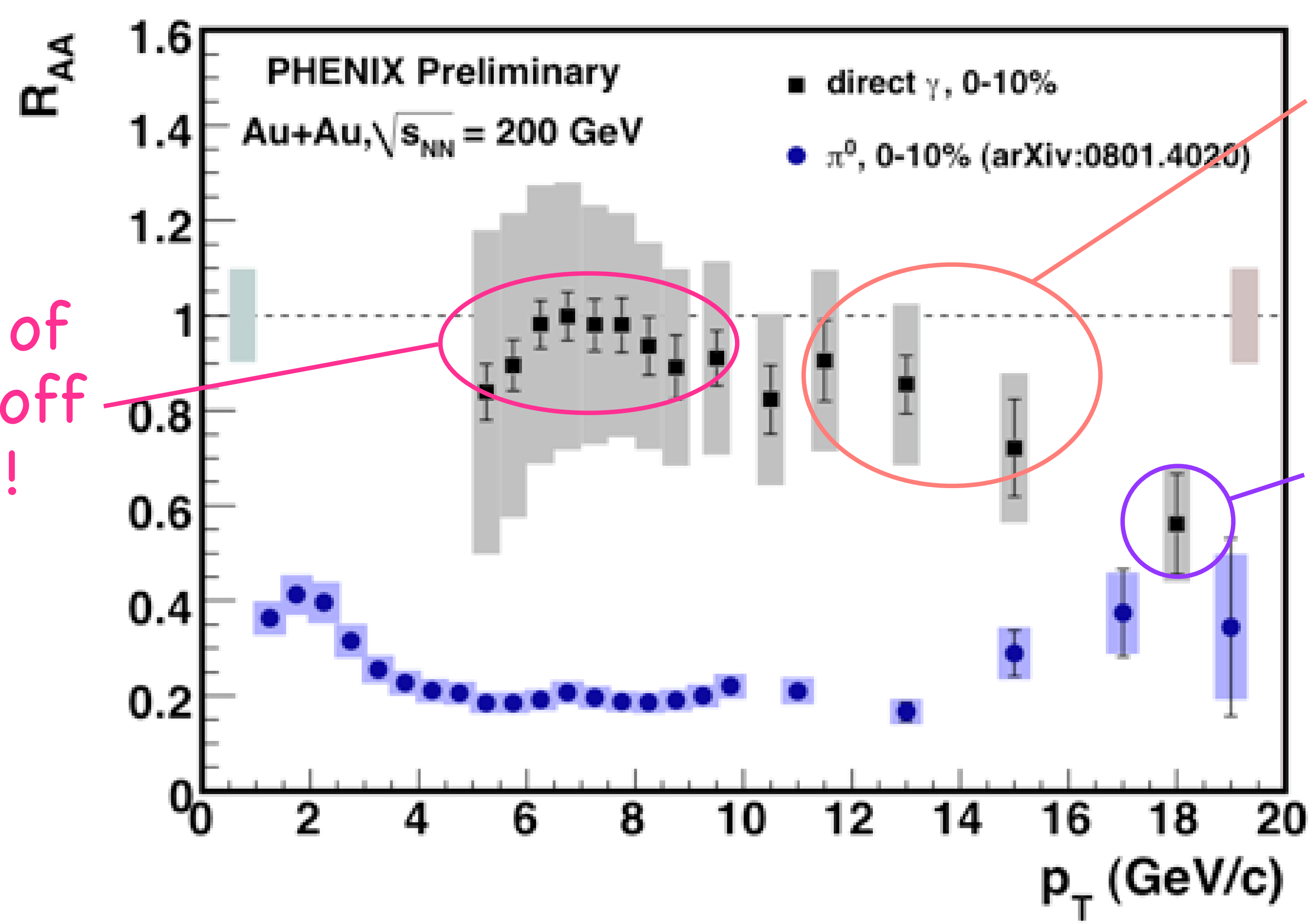
In central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, one misses 80% of the high-transverse-momentum hadrons!

(no pathology in the pp reference! cf. plot in E.Leader's talk)

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*: $R_{AA} \approx 1$



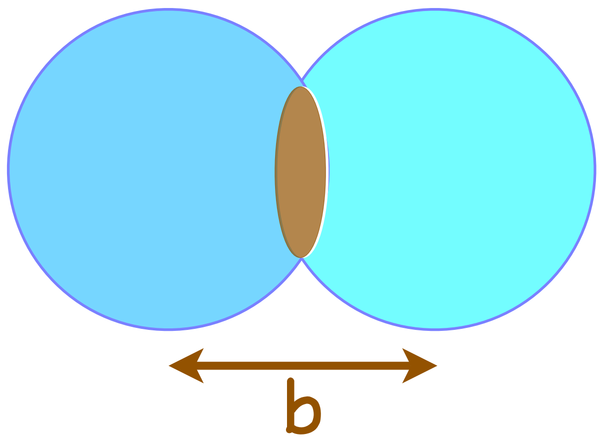
* yet photon production is modified: Bremsstrahlung, photons from parton fragmentation...

Heavy-ion collisions: geometry

Heavy nuclei have a finite radius!

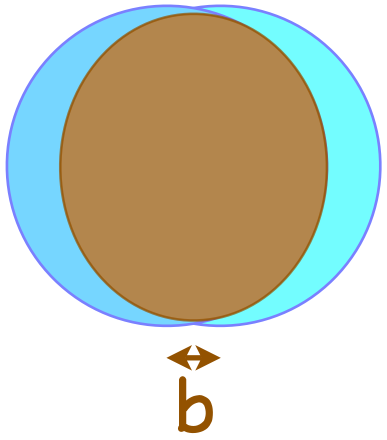
☞ In a collision the impact parameter plays a role:

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



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)

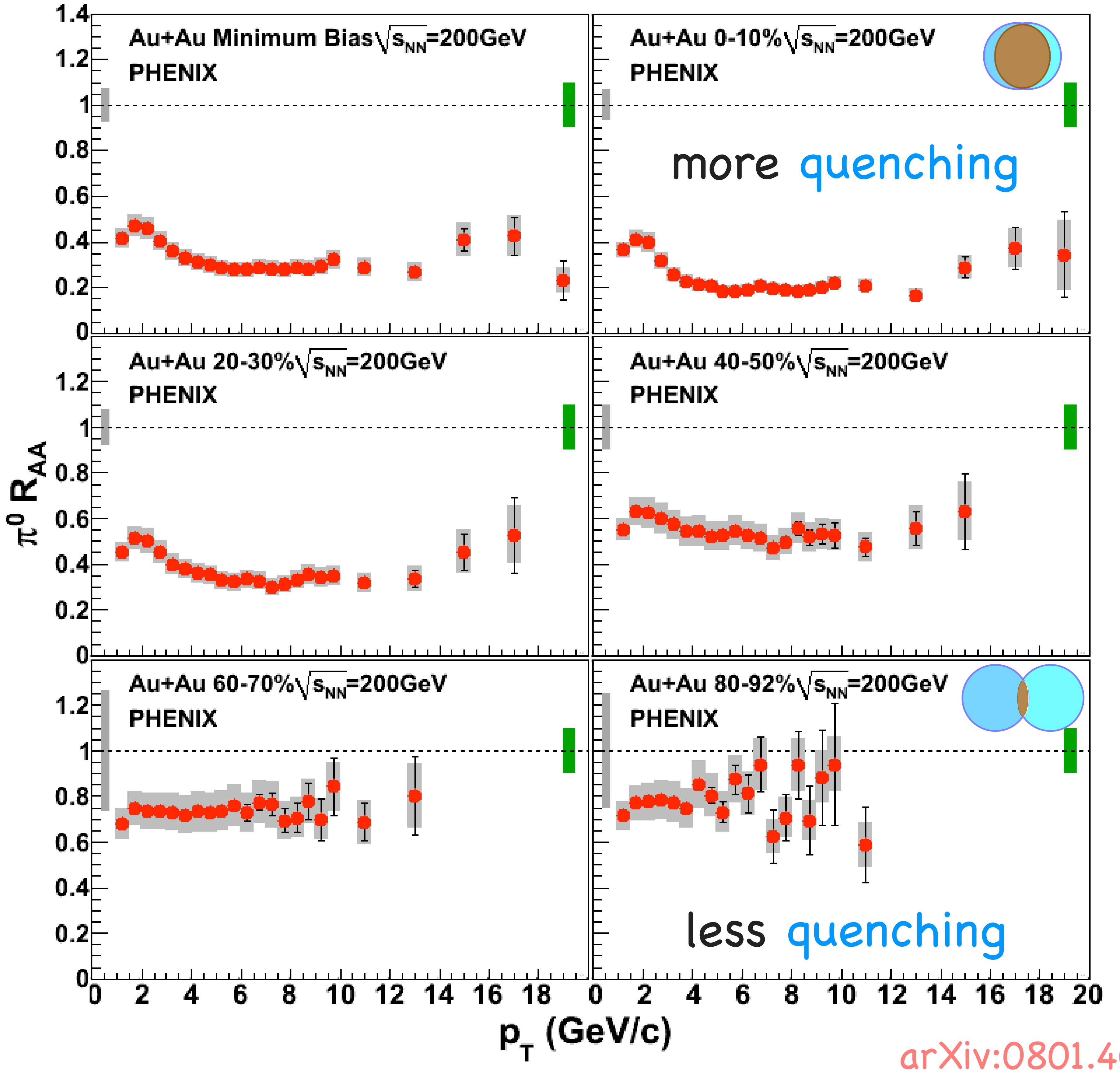


High-p_T partons have larger in-medium path-lengths, thus lose more energy (in average).

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

"Jets" in Au-Au collisions at RHIC (2)

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

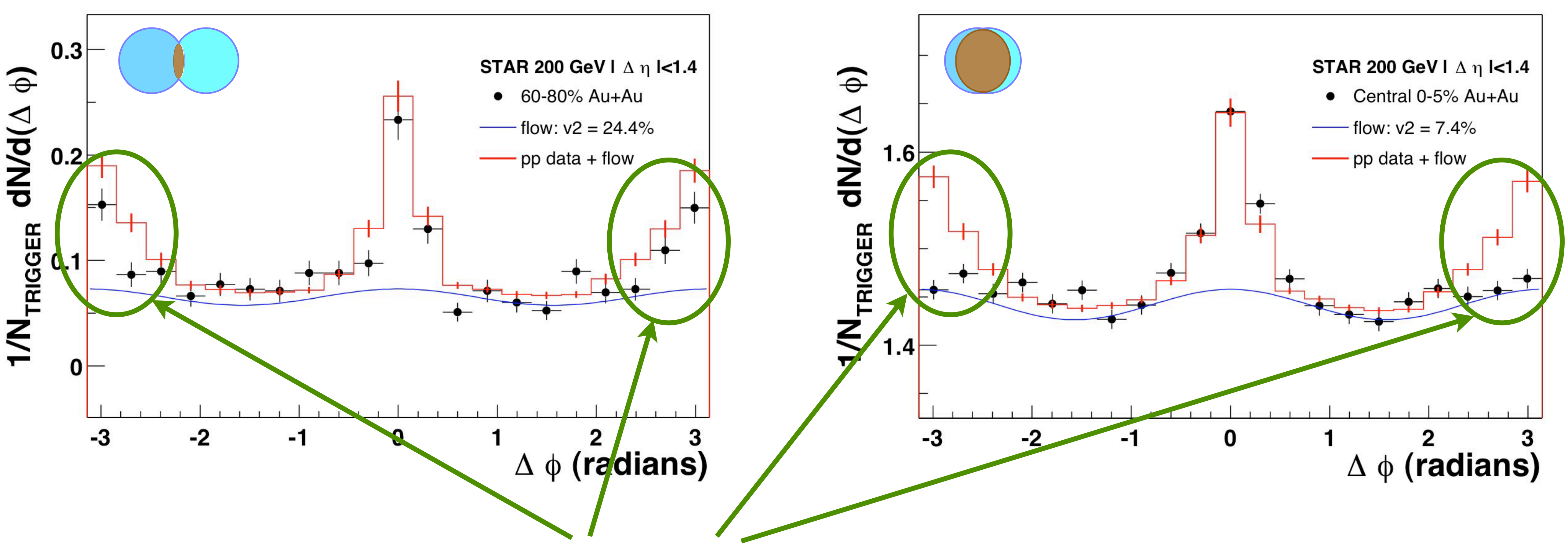


arXiv:0801.4020 [nucl-ex]

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

Beyond single-particle yields...

Study of "azimuthal correlations" between ① a reference, "trigger" particle (leading particle) with momentum $P_{T\,\mathrm{max}}$, and ② "associated particles" with momenta $P_{T\,\mathrm{cut}} < P_T < P_{T\,\mathrm{max}}$.



In central collisions, the "back jet" (= peak at 180° from the trigger particle) disappears.

High transverse momentum physics in heavy-ion collisions

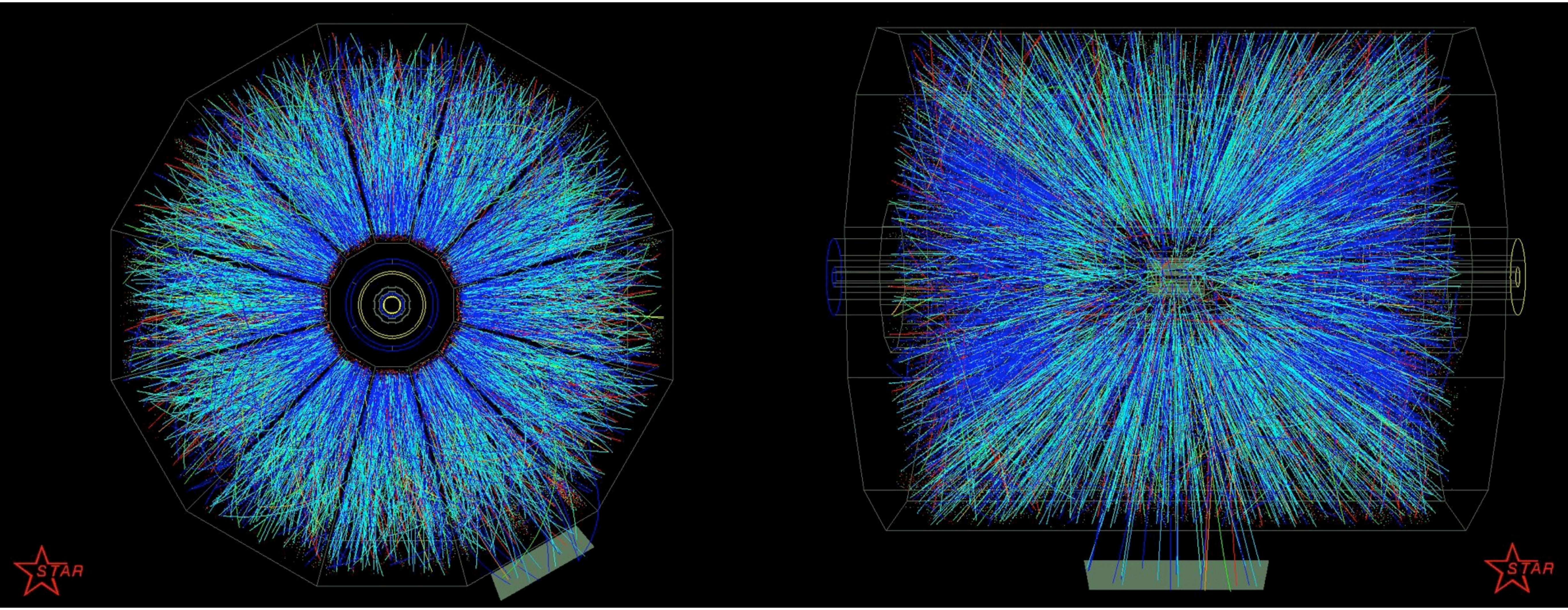
- Jets supposedly a good tool to extract information on the medium created in ultra-relativistic collisions of heavy nuclei: energy loss
  - transport coefficient $\hat{q}$: medium density + mean free path
- Already a wealth of experimental data: high p_{T} physics
  - single-particle spectra

    80% suppression of hadrons requires large $\hat{q}$: $\approx 10^2$ times larger than the value for a hot pion gas
  - two-particle correlations in azimuth
- A handful of models available, with emphasis on different aspects
  - approaches focusing on the leading hadron
  - 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:



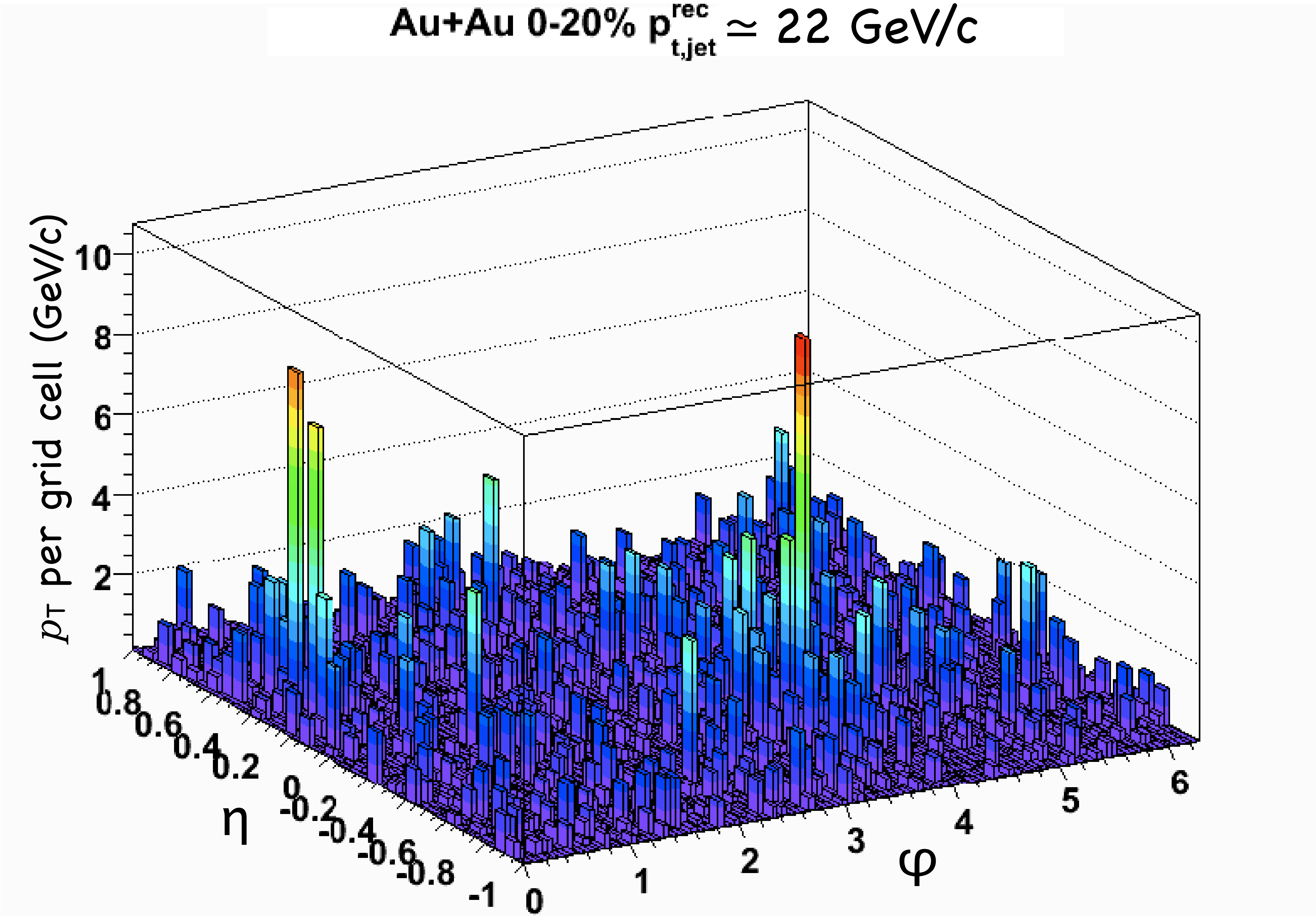
Common lore: forget about identifying jets in RHIC heavy-ion collisions.

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"

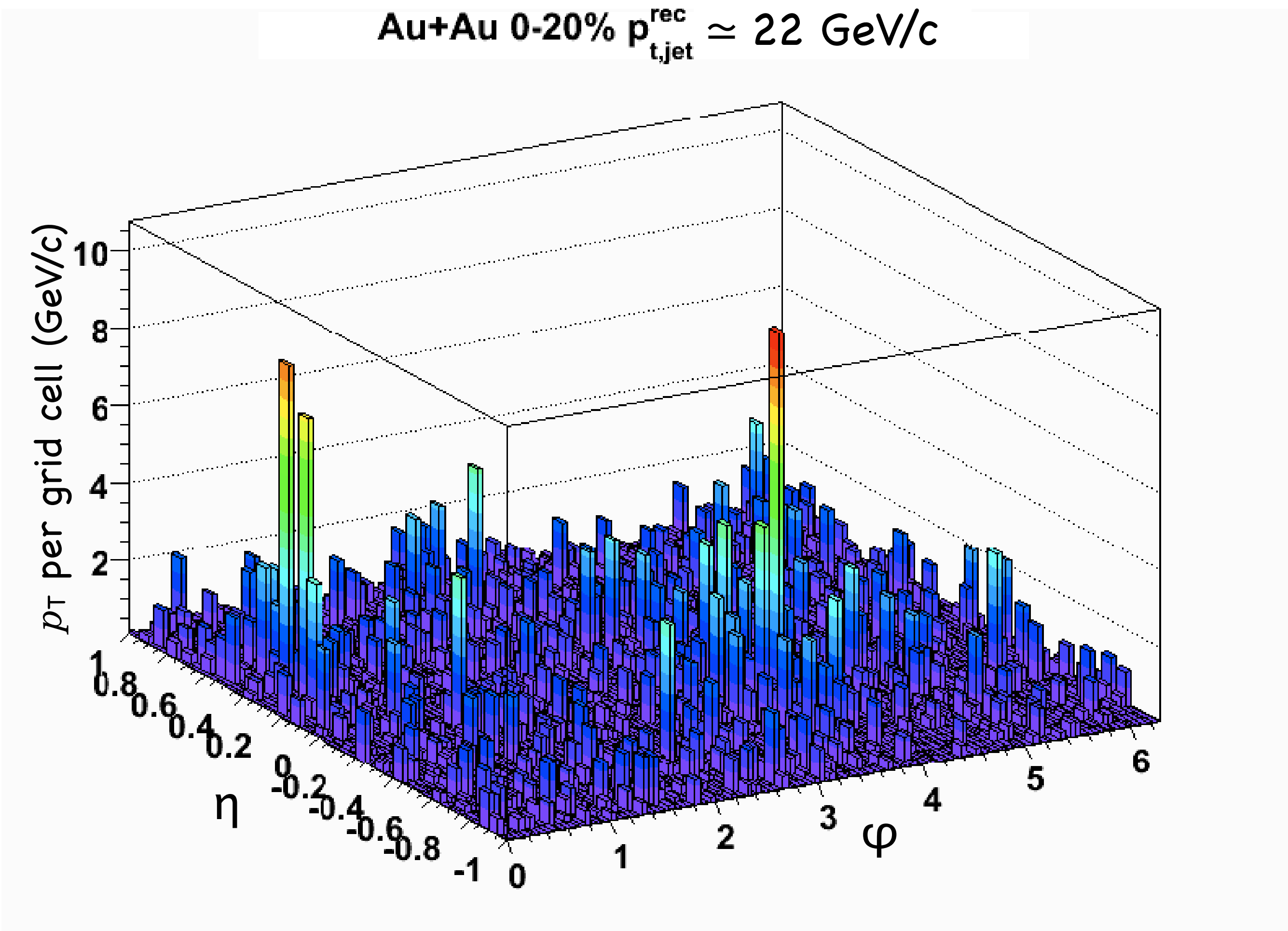


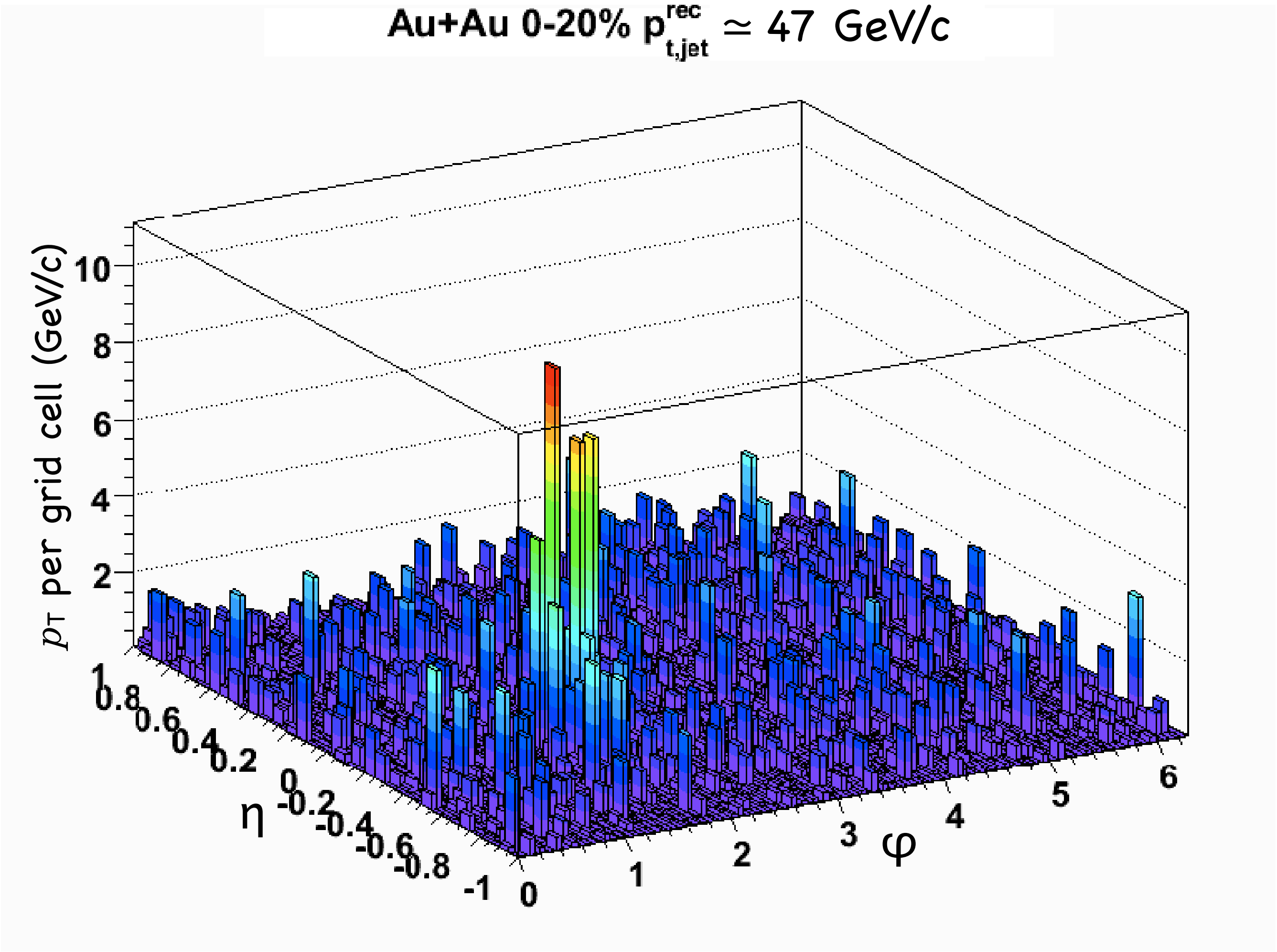
talks by J.Putschke & S.Salur @ Hard Probes 2008

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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