Phenomenology of heavy-ion collisions: two topics

Nicolas BORGHINI

Universität Bielefeld

DESY Theory workshop, September 29 - October 2, 2009

Phenomenology of heavy-ion collisions: two topics

- Experimental heavy-ion programs at colliders: RHIC & LHC
- Theoretical motivation 1: "condensed matter of QCD"
- Hard probes of the created medium: "jets"
  - Phenomenological / theoretical ideas
  - RHIC results (a biased personal choice!)
- Theoretical motivation 2: "local" strong parity violation
  - RHIC results(?)

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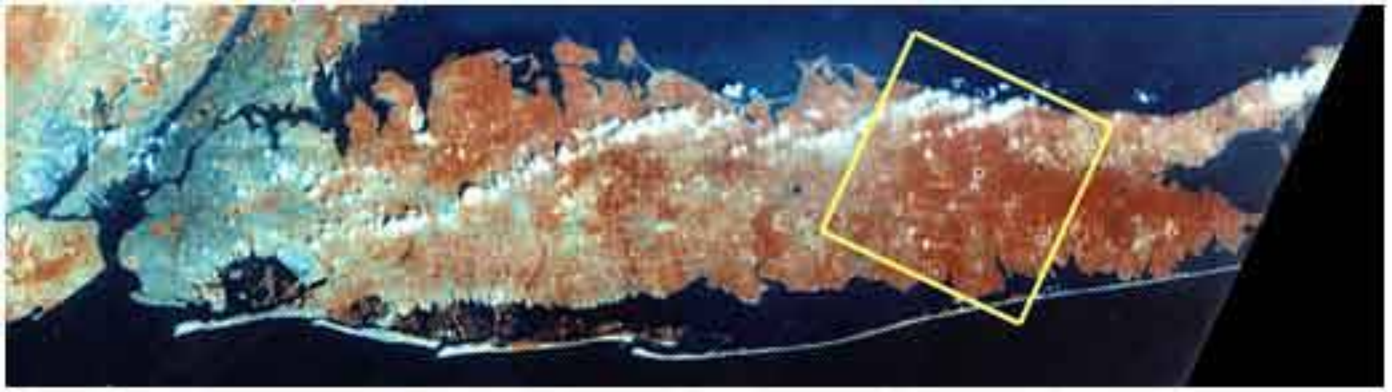
A dedicated collider: RHIC

RHIC (Relativistic Heavy Ion Collider) at Brookhaven Nat. Lab.



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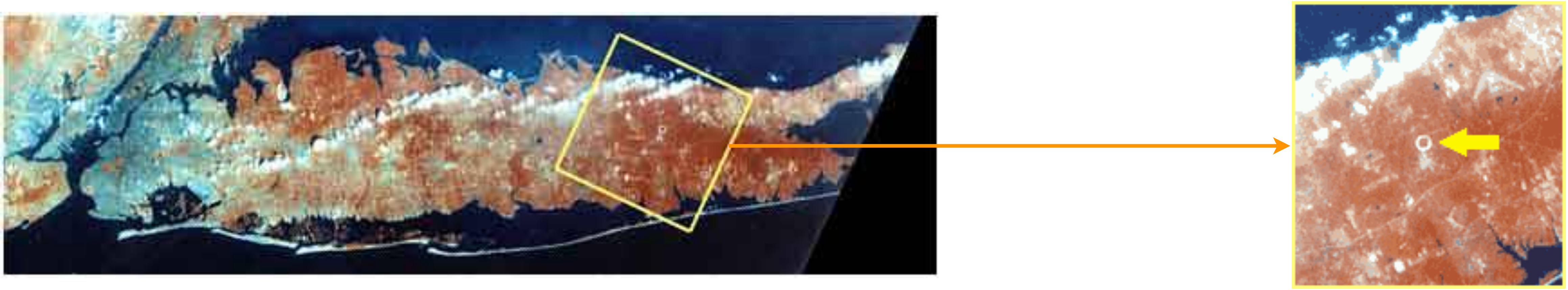

A dedicated collider: RHIC

RHIC (Relativistic Heavy Ion Collider) at Brookhaven Nat. Lab.

4 km-long collider, in service since 2000:

☞ Au-Au & Cu-Cu collisions at $\sqrt{s_{NN}}$ = 9.2, NEW (19.6), 62.4, 130 & 200 GeV (+ pp & d-Au)

4 experiments (BRAHMS, PHENIX, PHOBOS, STAR)

Heavy-ion collisions at the LHC

LHC to run at 3.5 TeV for early part of 2009-2010 run rising later

PR13.09
06.08.2009

Geneva, 6 August 2009. CERN's[1] Large Hadron Collider will initially run at an energy of 3.5 TeV per beam when it starts up in November this year. This news

⋮

The procedure for the 2009 start-up will be to inject and capture beams in each direction, take collision data for a few shifts at the injection energy, and then commission the ramp to higher energy. The first high-energy data should be collected a few weeks after the first beam of 2009 is injected. The LHC will run at 3.5 TeV per beam until a significant data sample has been collected and the operations team has gained experience in running the machine. Thereafter, with the benefit of that experience, the energy will be taken towards 5 TeV per beam. At the end of 2010, the LHC will be run with lead ions for the first time. After that, the LHC will shut down and work will begin on moving the machine towards 7 TeV per beam.

Original plan: Pb+Pb @ $\sqrt{s_{NN}}$ = 5.5 TeV, one month per year.

New plan?

Heavy-ion collisions at the LHC

IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **34** (2007) 2307–2455 doi:10.1088/0954-3899/34/11/008

149 pages

CMS Physics Technical Design Report: Addendum on High Density QCD with Heavy Ions

The CMS Collaboration

D d'Enterria[1], M Ballintijn[2], M Bedjidian[3], D Hofman[4], O Kodolova[5], C Loizides[2], I P Lokthin[5], C Lourenço[1], C Mironov[4], S V Petrushanko[5], C Roland[2], G Roland[2], F Sikler[6] and G Veres[2] (editors)

Heavy-ion collisions at the LHC

CERN/LHCC/2004-009
LHCC I-013
22 March 2004

Heavy Ion Physics with the ATLAS Detector

ATLAS Collaboration

Letter of Intent

Heavy-ion collisions at the LHC

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **30** (2004) 1517–1763 PII: S0954-3899(04)83684-3

247...

ALICE: Physics Performance Report, Volume I

ALICE Collaboration[5]

F Carminati[1], P Foka[2], P Giubellino[3], A Morsch[1], G Paic[4], J-P Revol[1], K Šafařík[1], Y Schutz[1] and U A Wiedemann[1] (editors)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **32** (2006) 1295–2040 doi:10.1088/0954-3899/32/10/001

+ 746 pages

ALICE: Physics Performance Report, Volume II

ALICE Collaboration[14]

B Alessandro[1], F Antinori[2], J A Belikov[3], C Blume[4], A Dainese[2], P Foka[5], P Giubellino[1], B Hippolyte[6], C Kuhn[6], G Martínez[7], M Monteno[1], A Morsch[3], T K Nayak[3], J Nystrand[8], M López Noriega[3], G Paić[9], J Pluta[10], L Ramello[11], J-P Revol[3], K Šafařík[3], J Schukraft[3], Y Schutz[3], E Scomparin[1], R Snellings[12], O Villalobos Baillie[13] and E Vercellin[1] (editors)

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+ 746 pages There must be some reason!

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Hints from lattice QCD

PHYSICAL REVIEW D **80,** 014504 (2009)

Equation of state and QCD transition at finite temperature

A. Bazavov,[1] T. Bhattacharya,[2] M. Cheng,[3] N. H. Christ,[4] C. DeTar,[5] S. Ejiri,[8] Steven Gottlieb,[6] R. Gupta,[2] U. M. Heller,[7] K. Huebner,[8] C. Jung,[8] F. Karsch,[8,9] E. Laermann,[9] L. Levkova,[5] C. Miao,[8] R. D. Mawhinney,[4] P. Petreczky,[8,10] C. Schmidt,[9] R. A. Soltz,[3] W. Soeldner,[11] R. Sugar,[12] D. Toussaint,[1] and P. Vranas[3]

[1]*Physics Department, University of Arizona, Tucson, Arizona 85721, USA*
[2]*Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*
[3]*Physics Division, Lawrence Livermore National Laboratory, Livermore California 94550, USA*
[4]*Physics Department, Columbia University, New York, New York 10027, USA*
[5]*Physics Department, University of Utah, Salt Lake City, Utah 84112, USA*
[6]*Physics Department, Indiana University, Bloomington, Indiana 47405, USA*
[7]*American Physical Society, One Research Road, Ridge, New York 11961, USA*
[8]*Physics Department, Brookhaven National Laboratory, Upton, New York 11973, USA*
[9]*Fakultät für Physik, Universität Bielefeld, D-33615 Bielefeld, Germany*
[10]*RIKEN-BNL Research Center, Brookhaven National Laboratory, Upton, New York 11973, USA*
[11]*ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, Planckstr. 1, D-64291 Darmstadt, Germany*
[12]*Physics Department, University of California, Santa Barbara, California 93106, USA*

(Received 4 April 2009; published 17 July 2009)

We calculate the equation of state in 2 + 1 flavor QCD at finite temperature with physical strange quark mass and almost physical light quark masses using lattices with temporal extent $N_\tau = 8$. ...

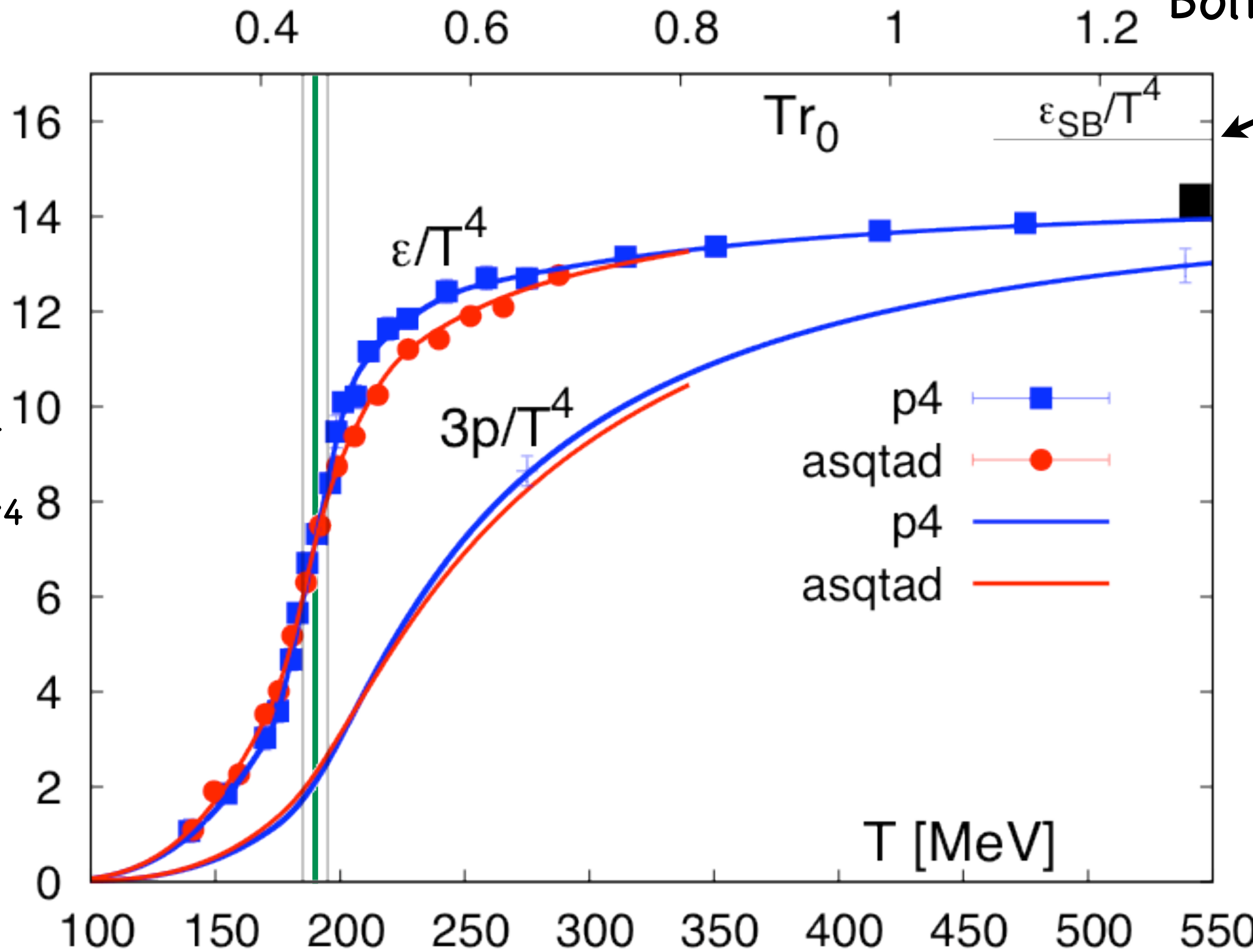
"2+1" flavors, $m_\pi \approx 220$ MeV, $m_K \approx 500$ MeV

Hints from lattice QCD

Energy density ε & pressure p:

ideal Stefan-Boltzmann limit

ε/T^4
$3p/T^4$



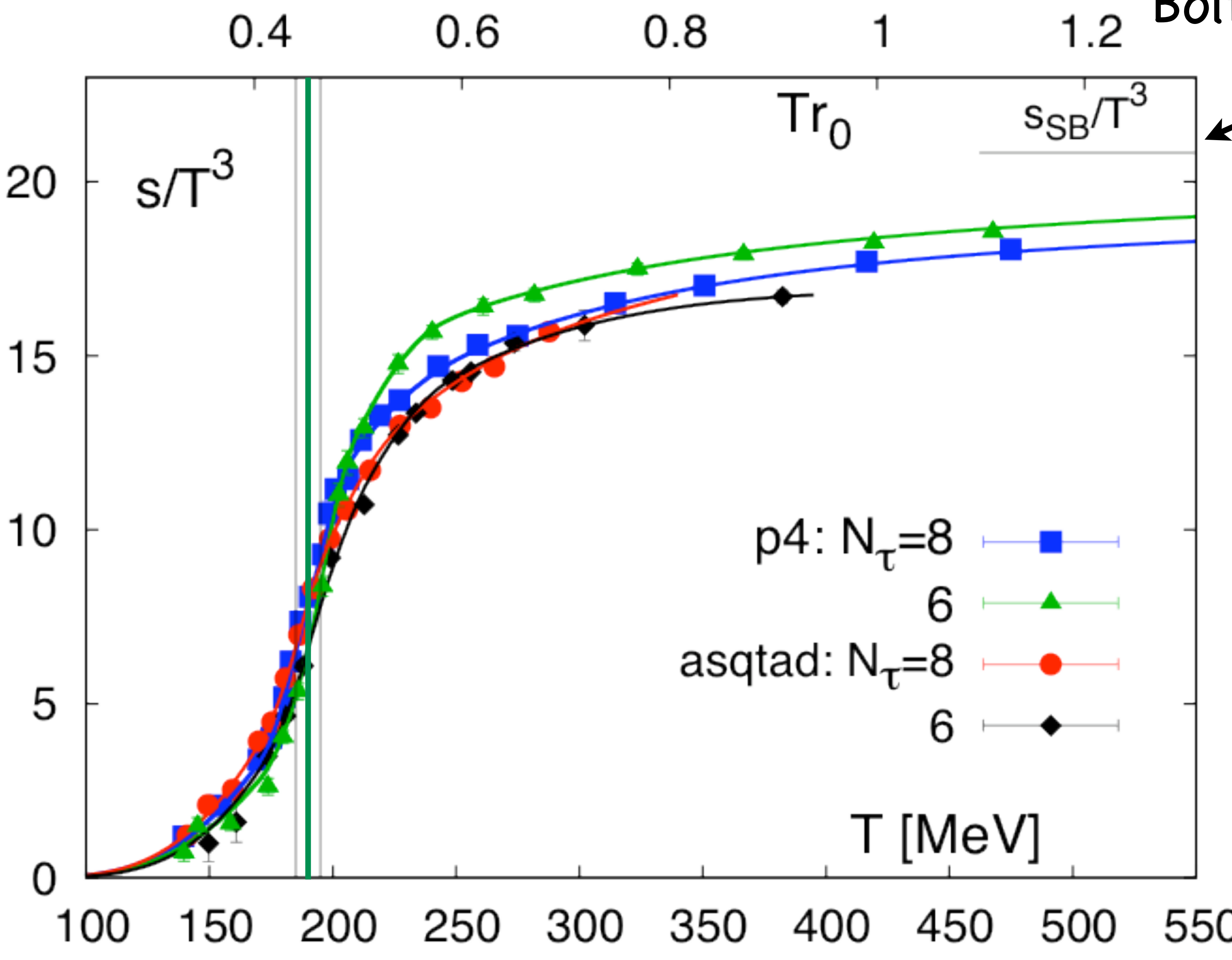
PRD 80 (2009) 014504

Hints from lattice QCD

Entropy density s

ideal Stefan-Boltzmann limit

s/T^3



PRD 80 (2009) 014504

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:

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

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- 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?)

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☞ Heavy-ion experiments (and phenomenology)

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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.

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...
Hereafter, with the help of "high-p_T probes".

Review of Particle Properties, chapter 27 on the "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

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Review of Particle Properties, chapter 27 on the "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"

“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 ...

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Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

(unfortunately, effect overestimated by a factor ≈100)

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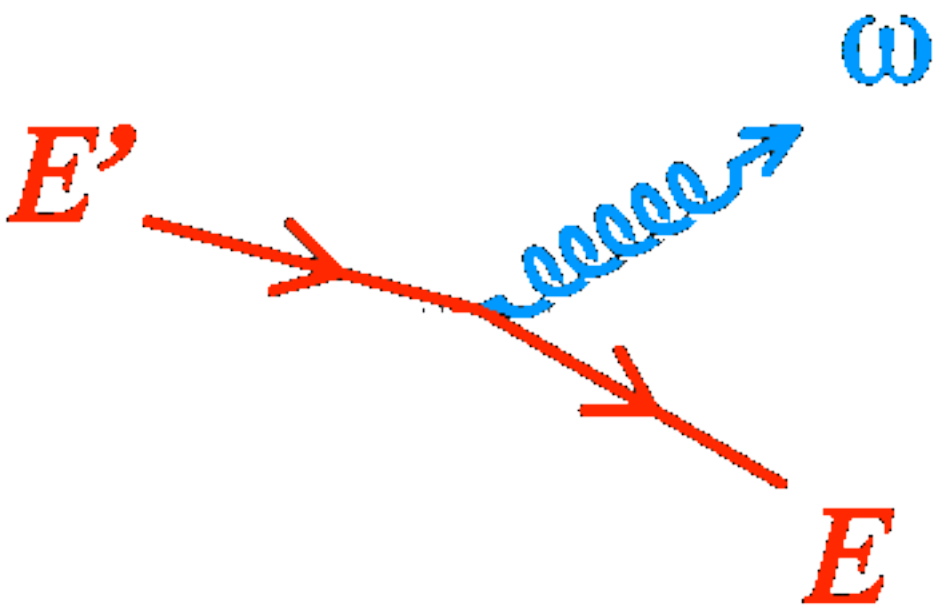
[...] a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed ...

Jet quenching: underlying processes

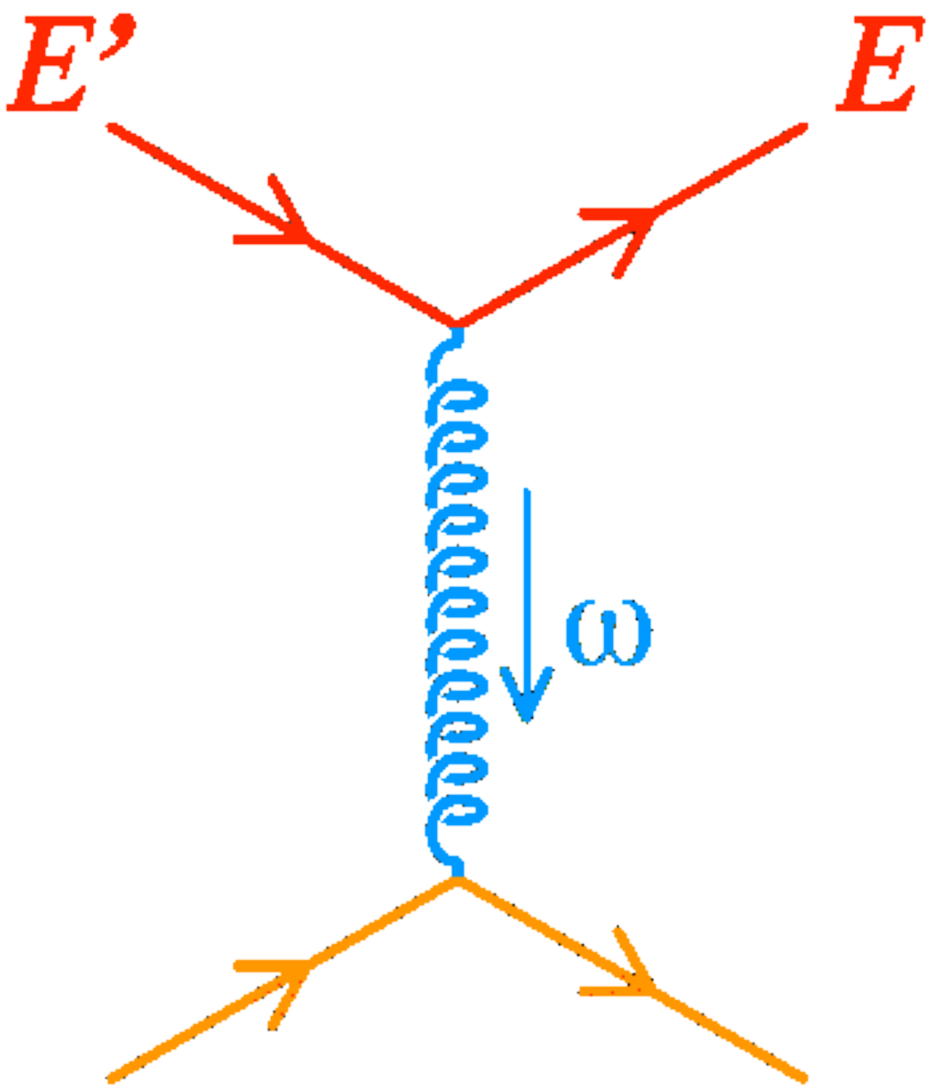
Two different processes lead to the loss of energy by a fast parton:

"radiative" process (Bremsstrahlung)



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

"collisional" process



Jet quenching: underlying processes

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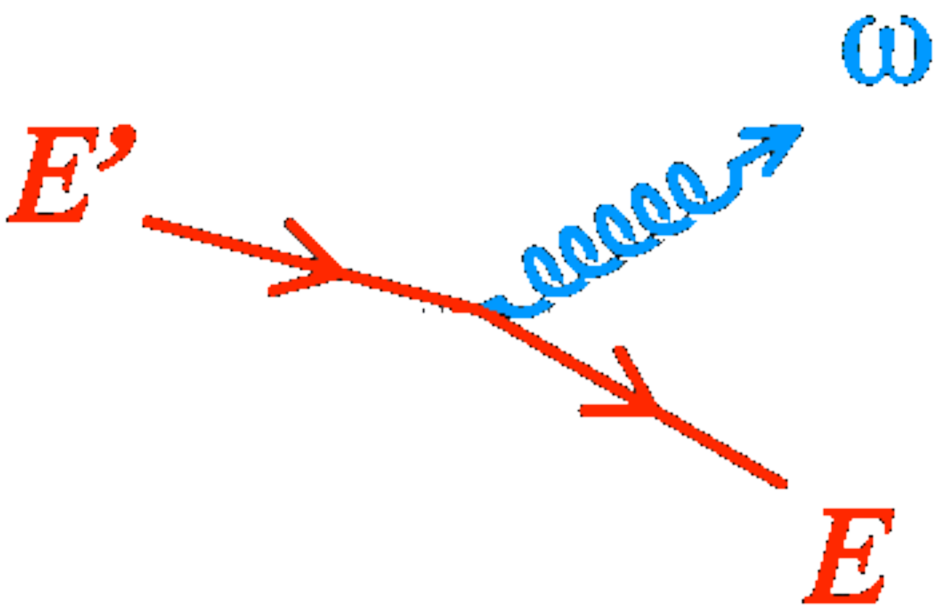
inelastic

"~~radiative~~" process (Bremsstrahlung)

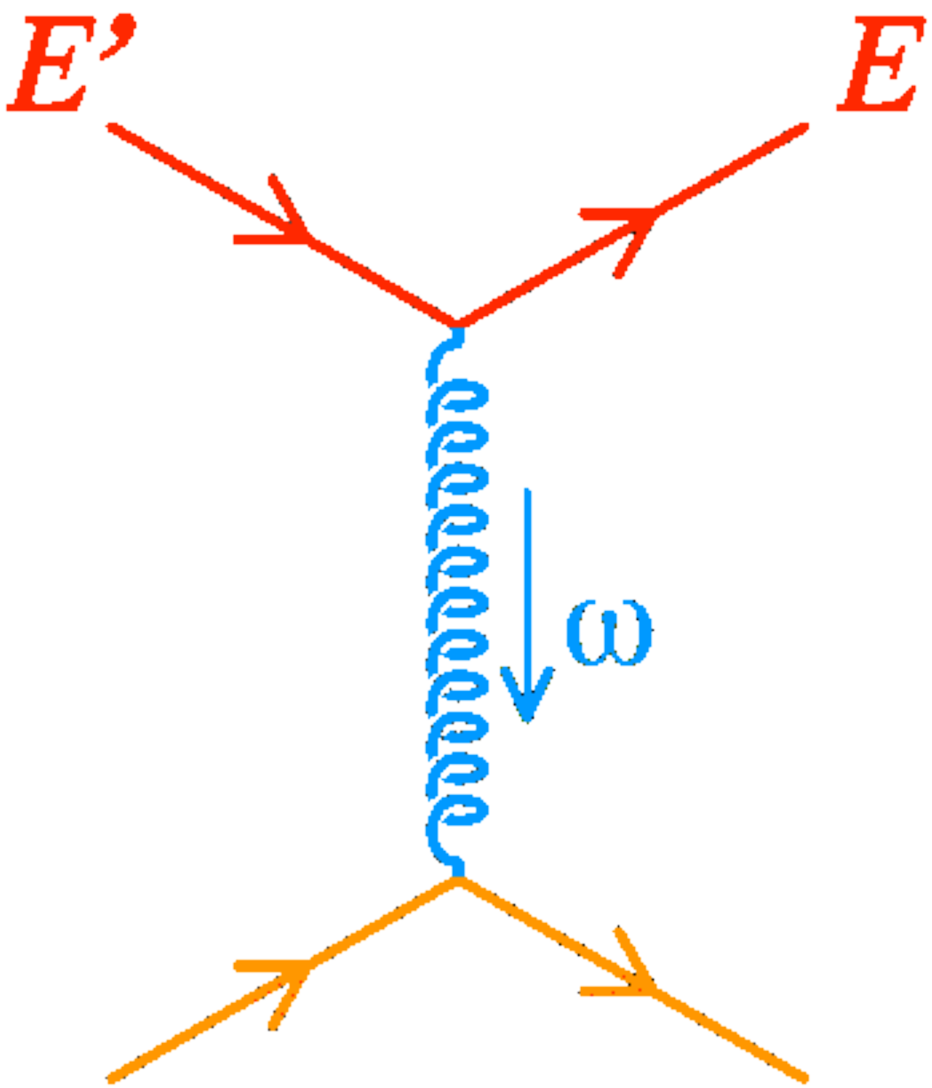


also "in vacuum" (DGLAP evolution), yet modified by the presence of a (colored) medium

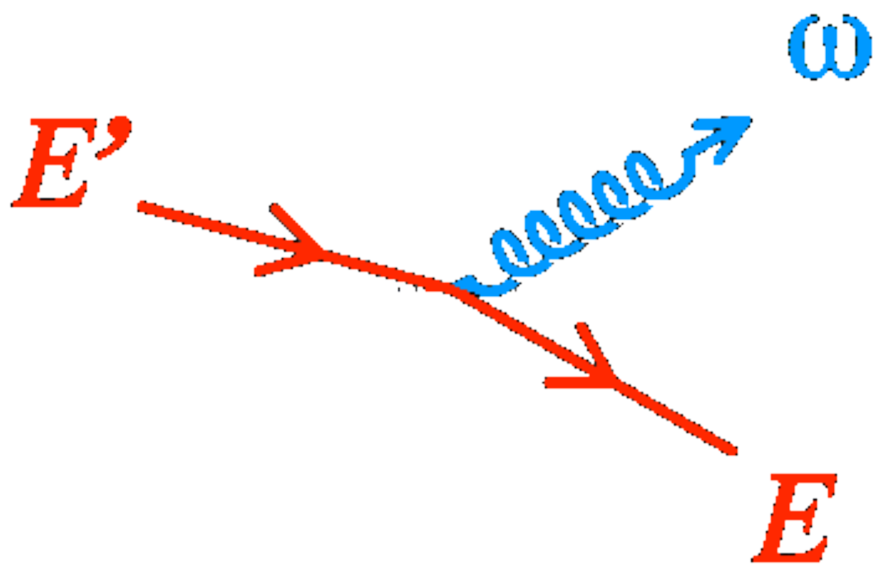
collisions!

elastic

"~~collisional~~" process



Inelastic energy loss



The spectrum of 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 ($\mathrm{d}I^{\mathrm{vac}}$)

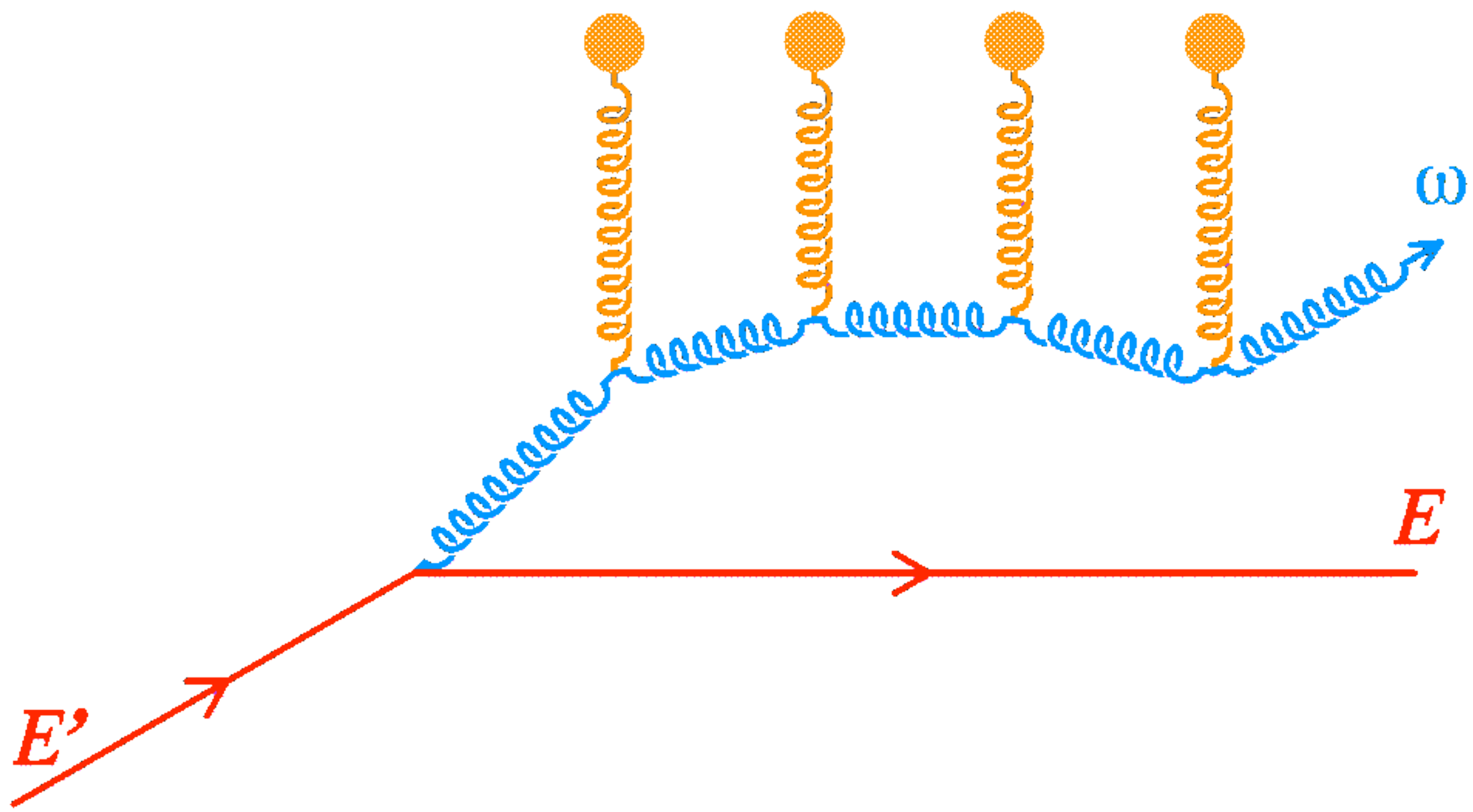
depends on the modeling of the medium ($\mathrm{d}I^{\mathrm{med}}$)

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**.

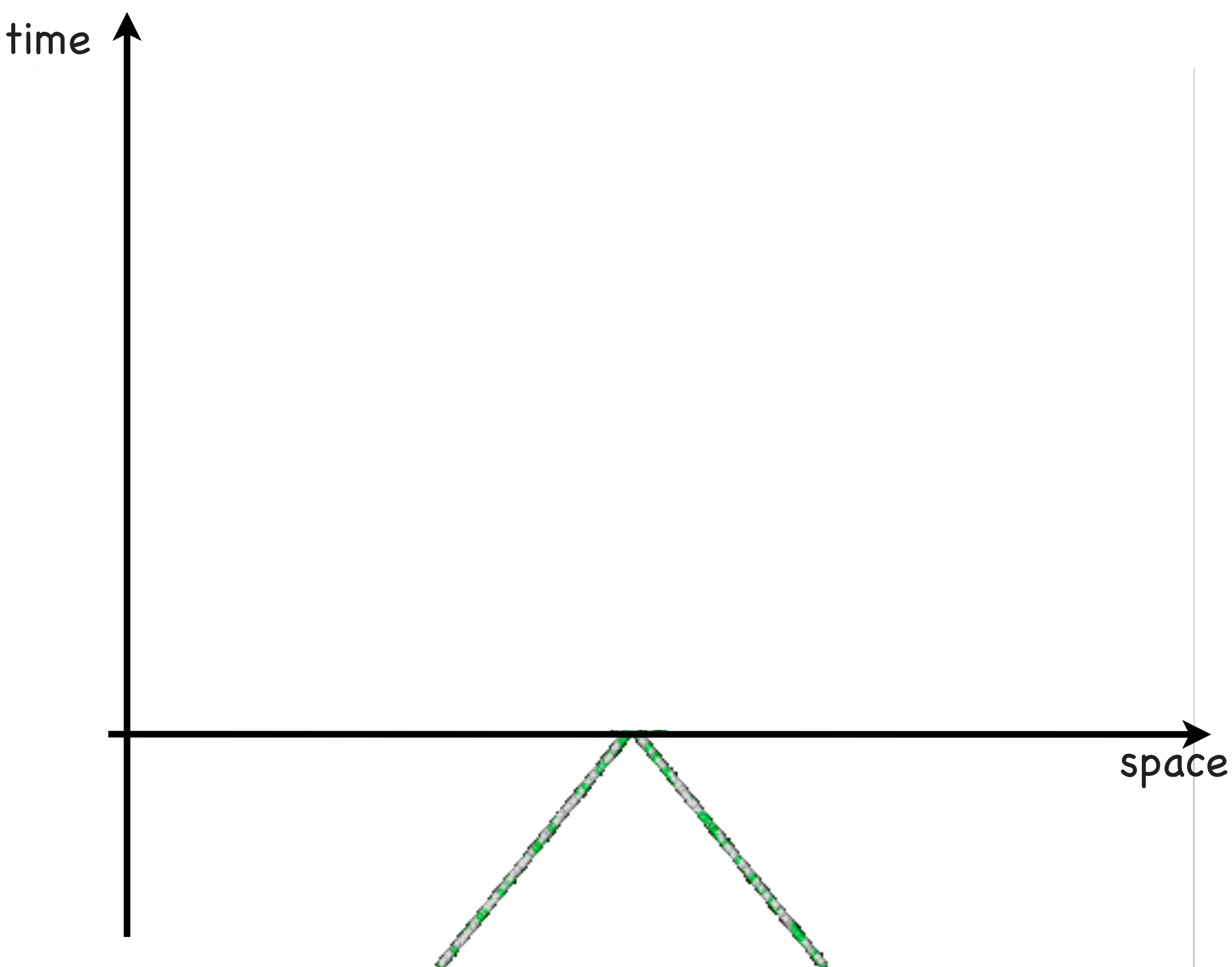


It radiates soft gluons, which scatter **coherently** on independent color charges in the medium, resulting in a medium-modified gluon spectrum.

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

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

Time evolution of a heavy-ion collision



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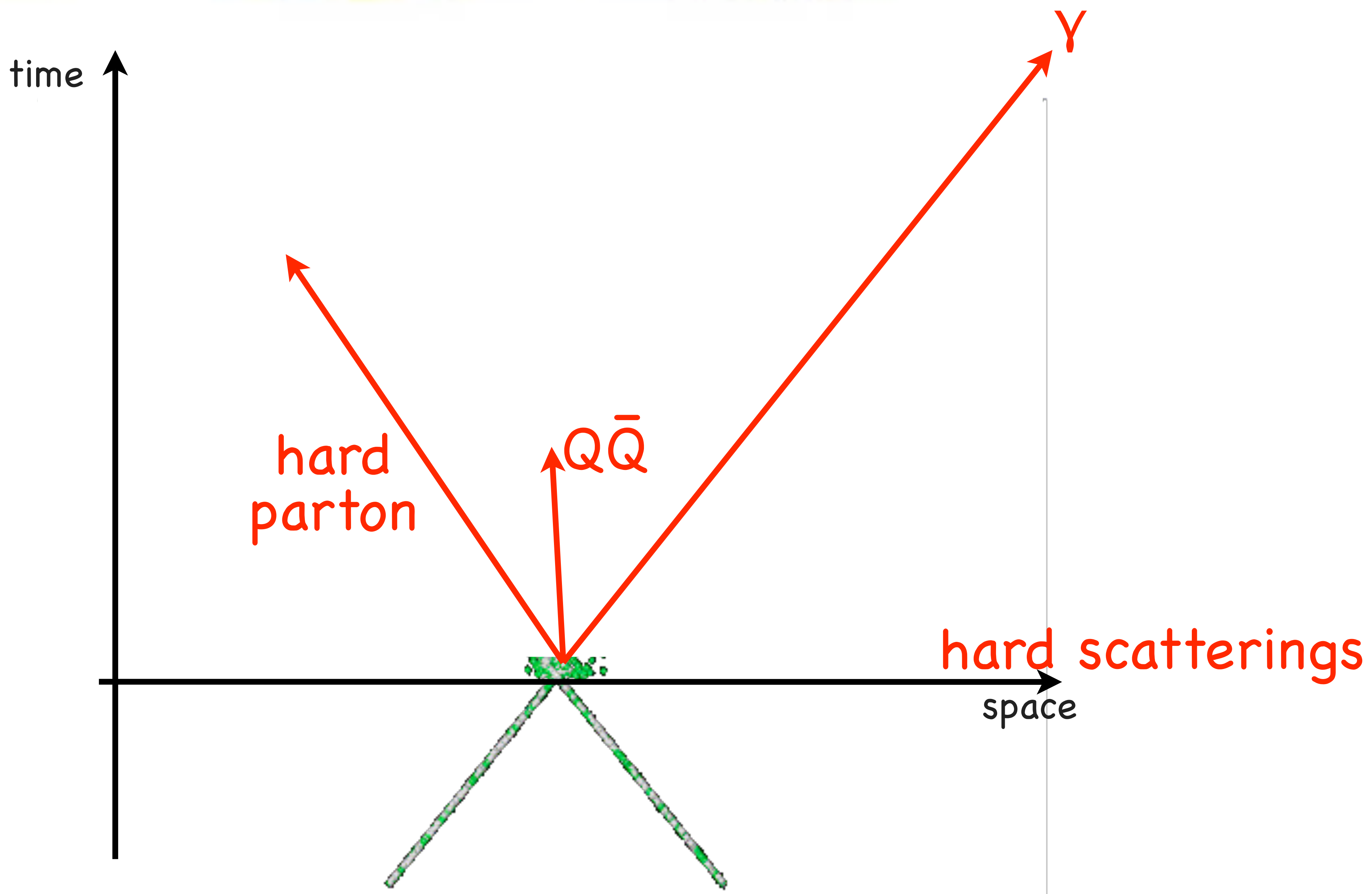

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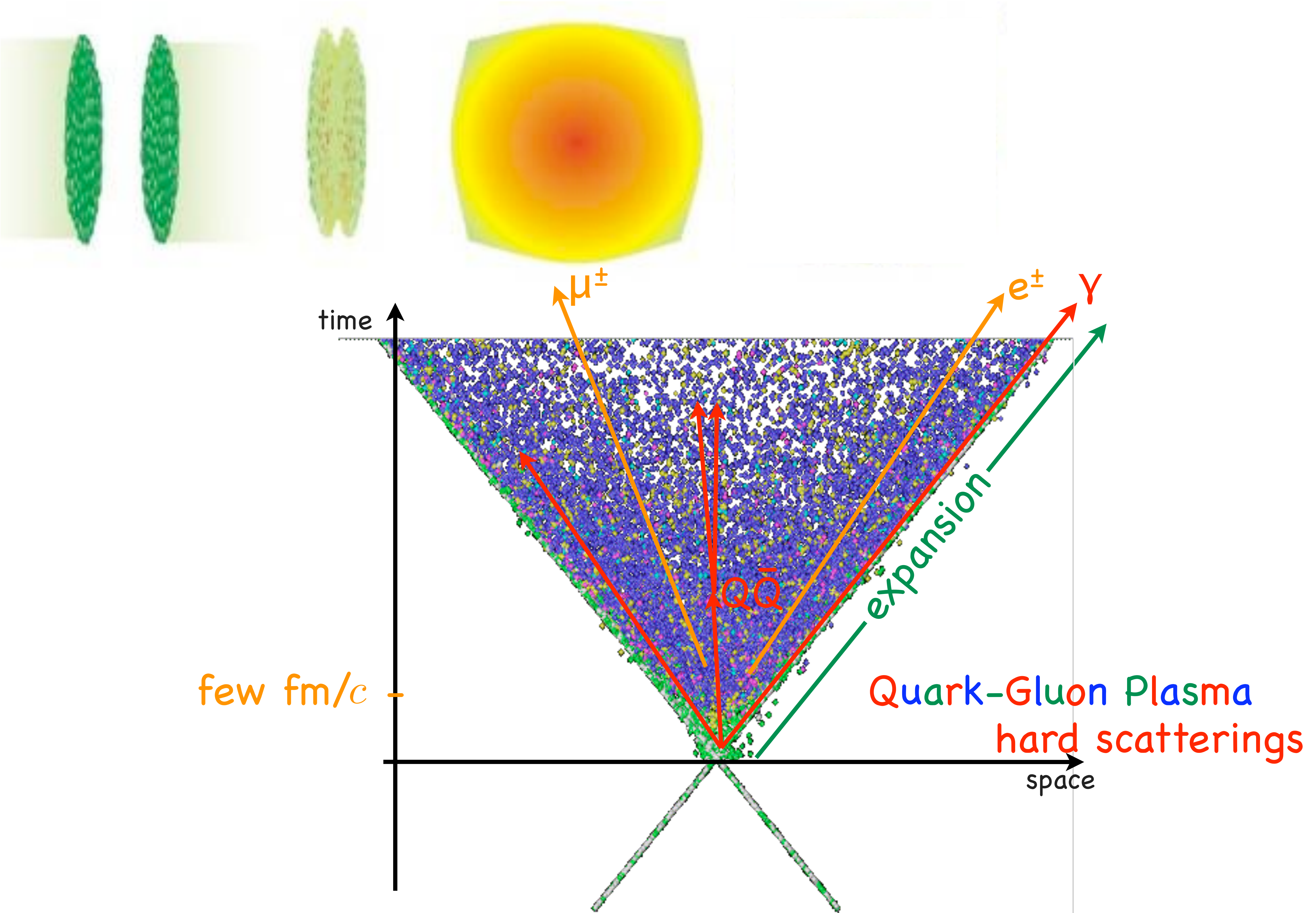

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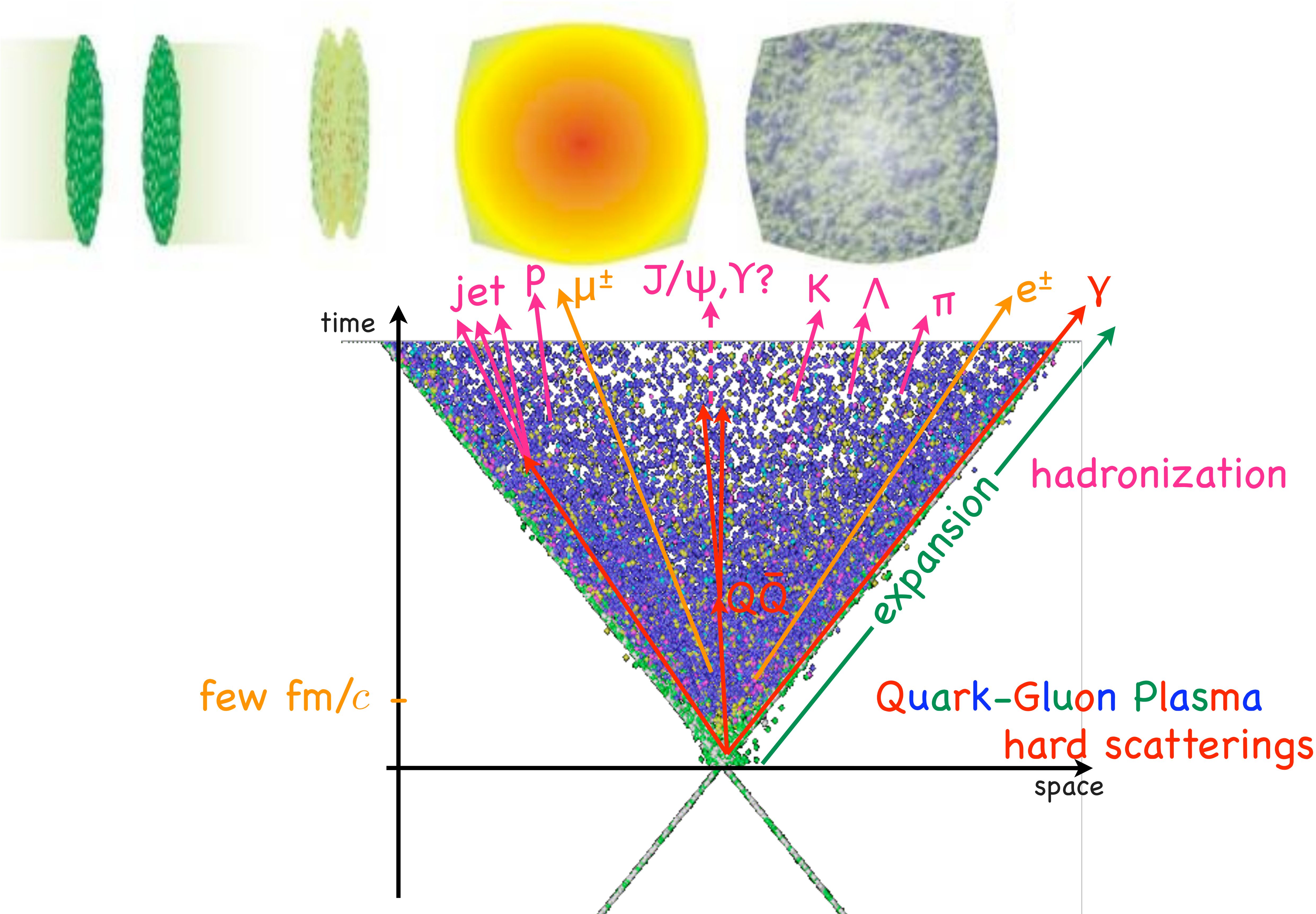

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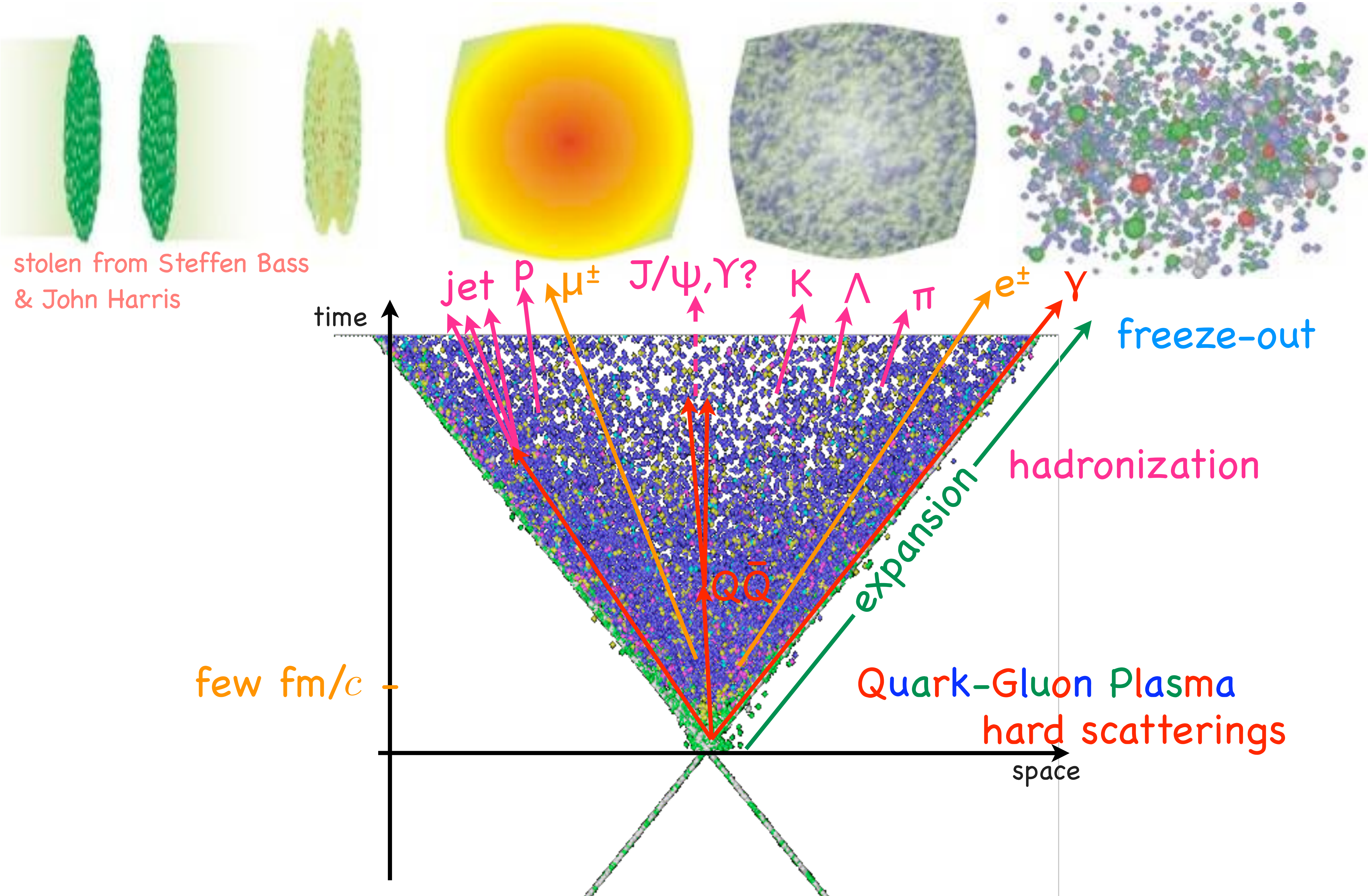
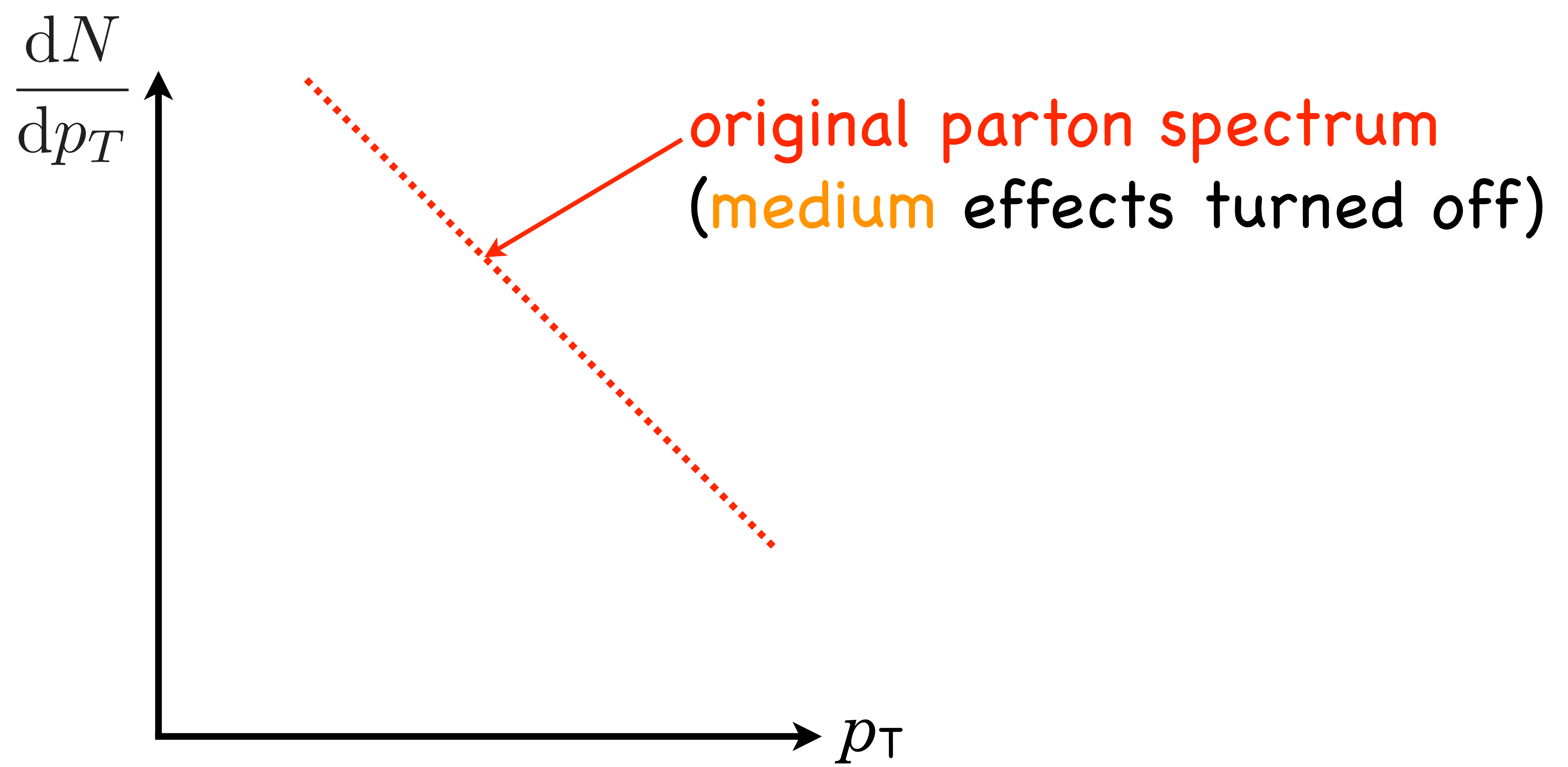


Jet quenching affects the p_T spectrum

Medium-enhanced gluon radiation or elastic scatterings, which degrade the energy of a high-p_T parton, modify the steeply falling transverse momentum distribution of emitted hadrons.



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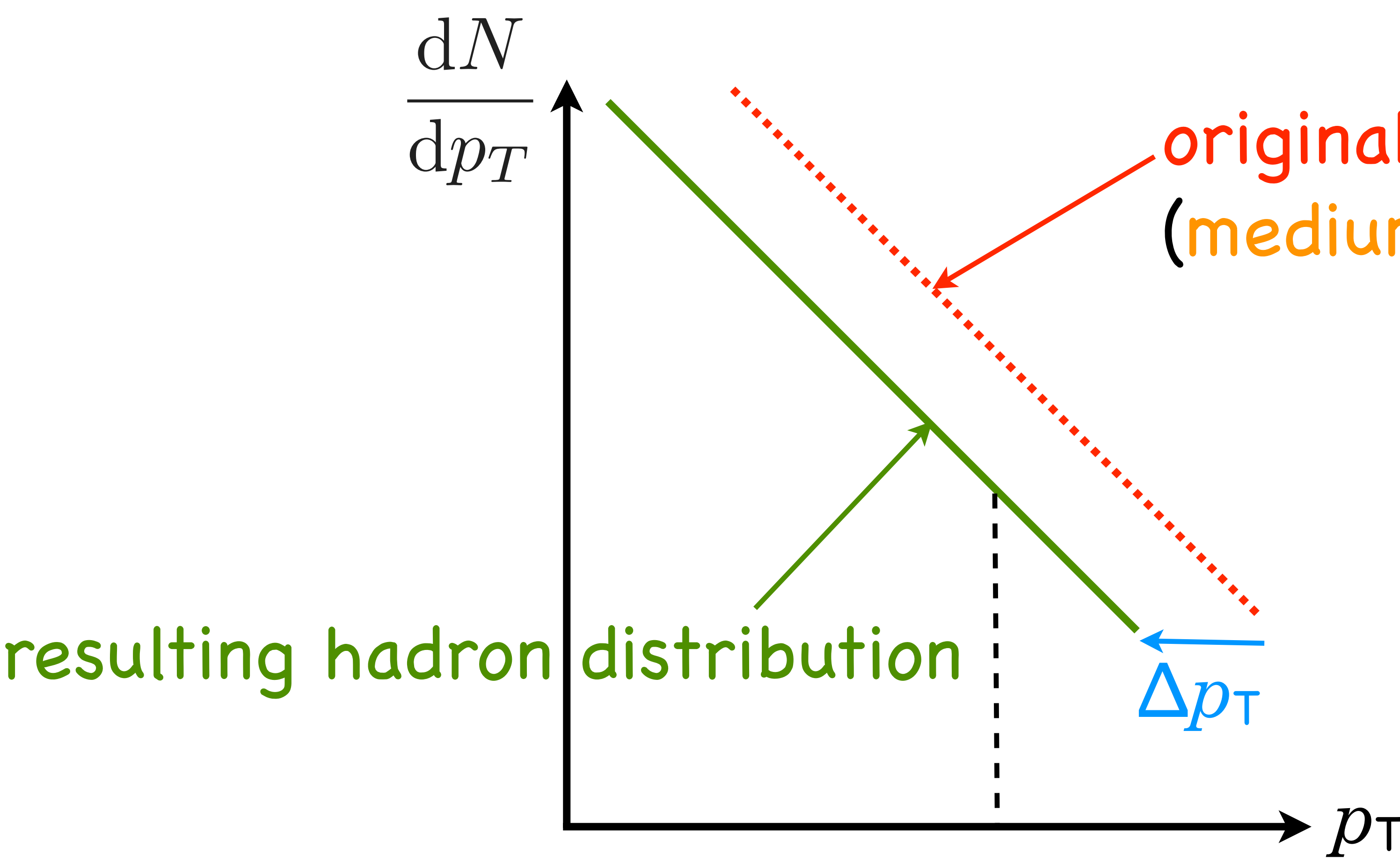
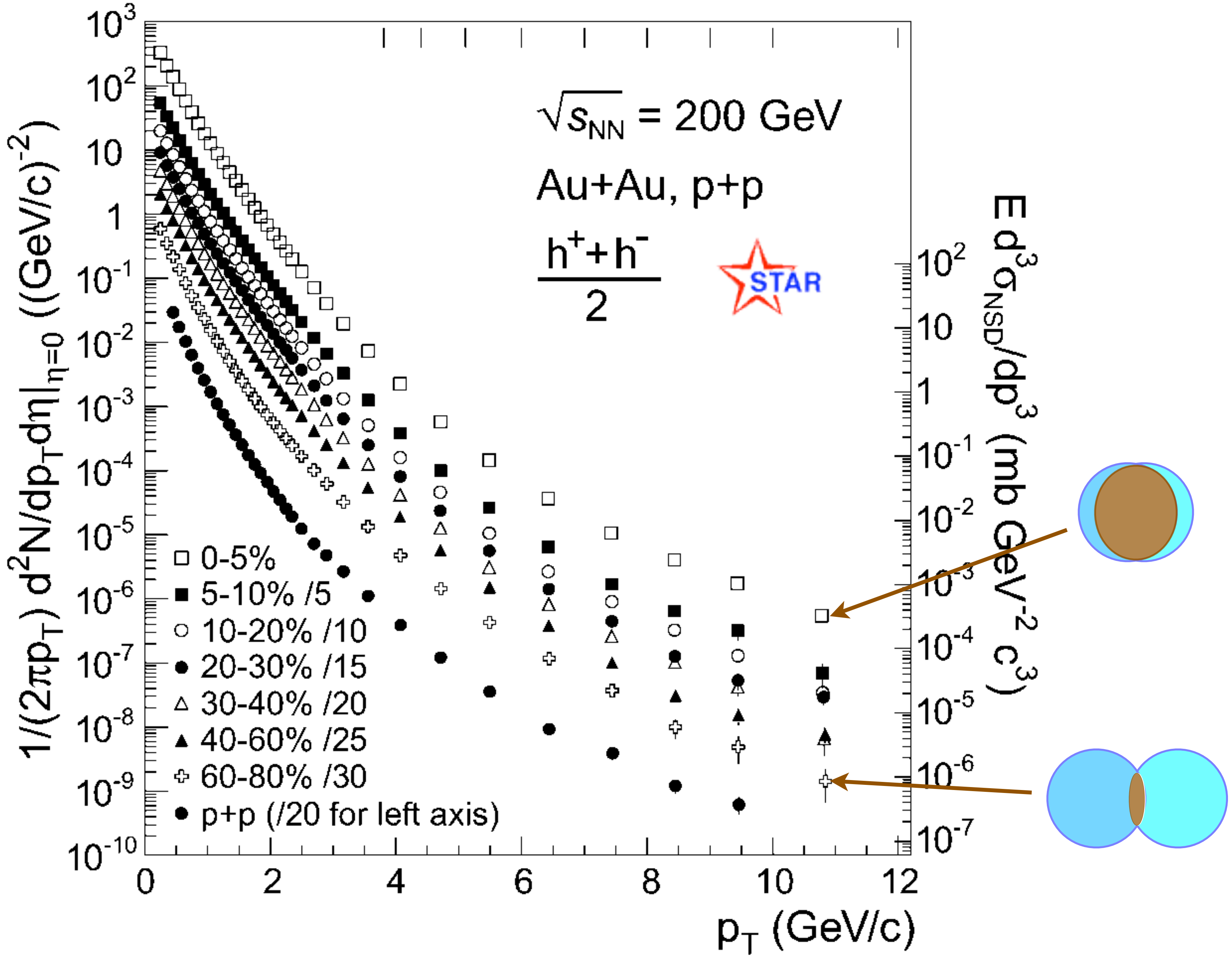


hadrons measured with p_T were partons with $p_\mathrm{T}+\Delta p_\mathrm{T}$:
lower yield at fixed momentum

(The actual convolution with a parton fragmentation function is ignored for simplicity.)

Jet quenching affects the p_T spectrum



STAR Collaboration, Phys. Rev. Lett. **91** (2003) 172302

"Jets" in nucleus-nucleus collisions: experimental aspects

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

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

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

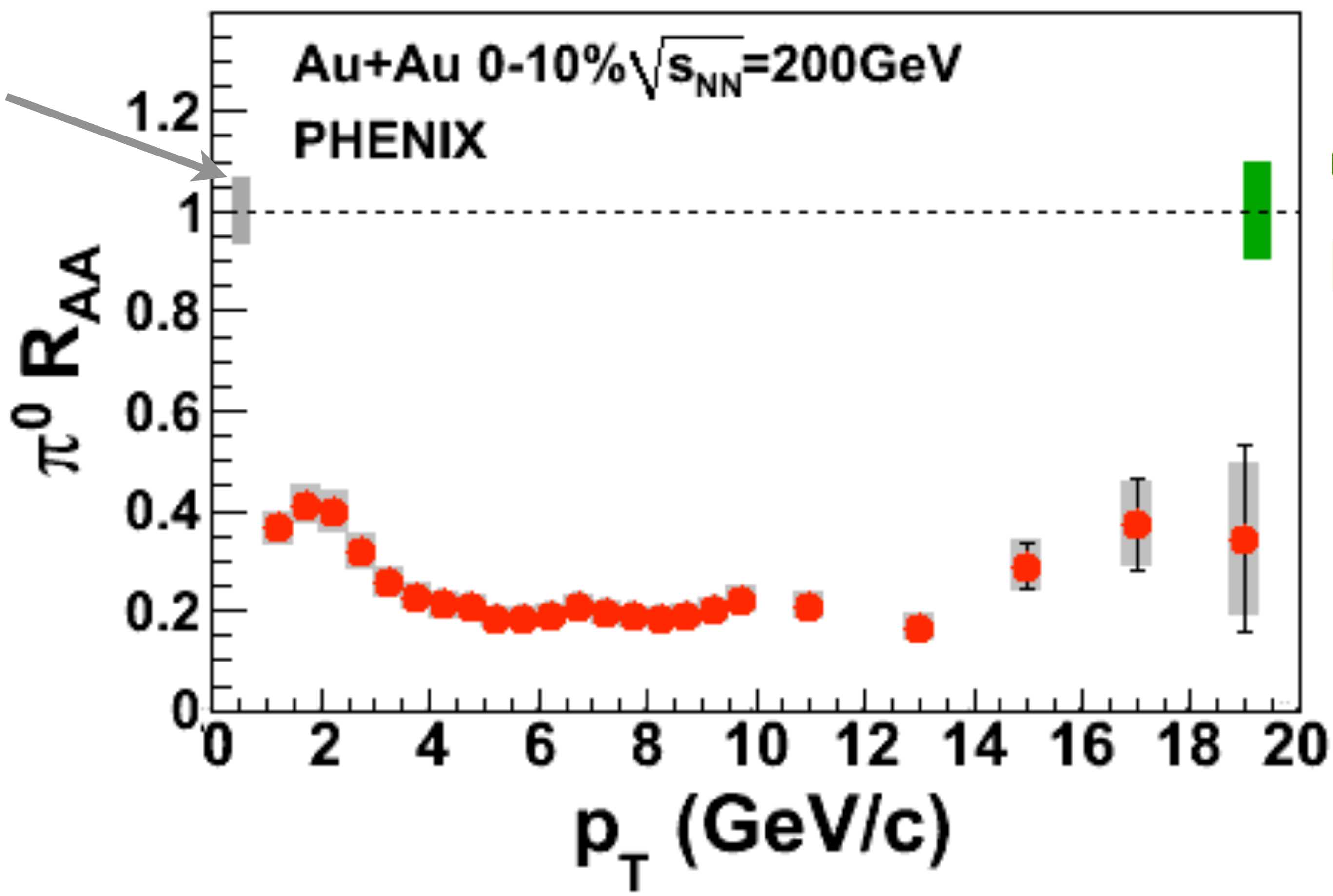
$$R^{h}_{AB} \equiv \frac{1}{\langle N^{AB}_{coll} \rangle} \frac{\frac{dN^{h}_{AB}}{d\mathbf{p}_T\, dy}}{\frac{dN^{h}_{pp}}{d\mathbf{p}_T\, dy}}$$

* up to isospin corrections...

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

Nuclear modification factor $R_{AA} \equiv \frac{1}{\langle N_{\rm coll}^{\rm AA}\rangle} \frac{\frac{{\rm d}N_{\rm AA}}{{\rm d}\mathbf{p}_T\,{\rm d}y}}{\frac{{\rm d}N_{\rm pp}}{{\rm d}\mathbf{p}_T\,{\rm d}y}}$

$\langle N_{\rm coll}^{\rm AA}\rangle$ uncertainty



uncertainty on pp-normalization

PHENIX Coll., Phys. Rev. Lett. **101** (2008) 232301

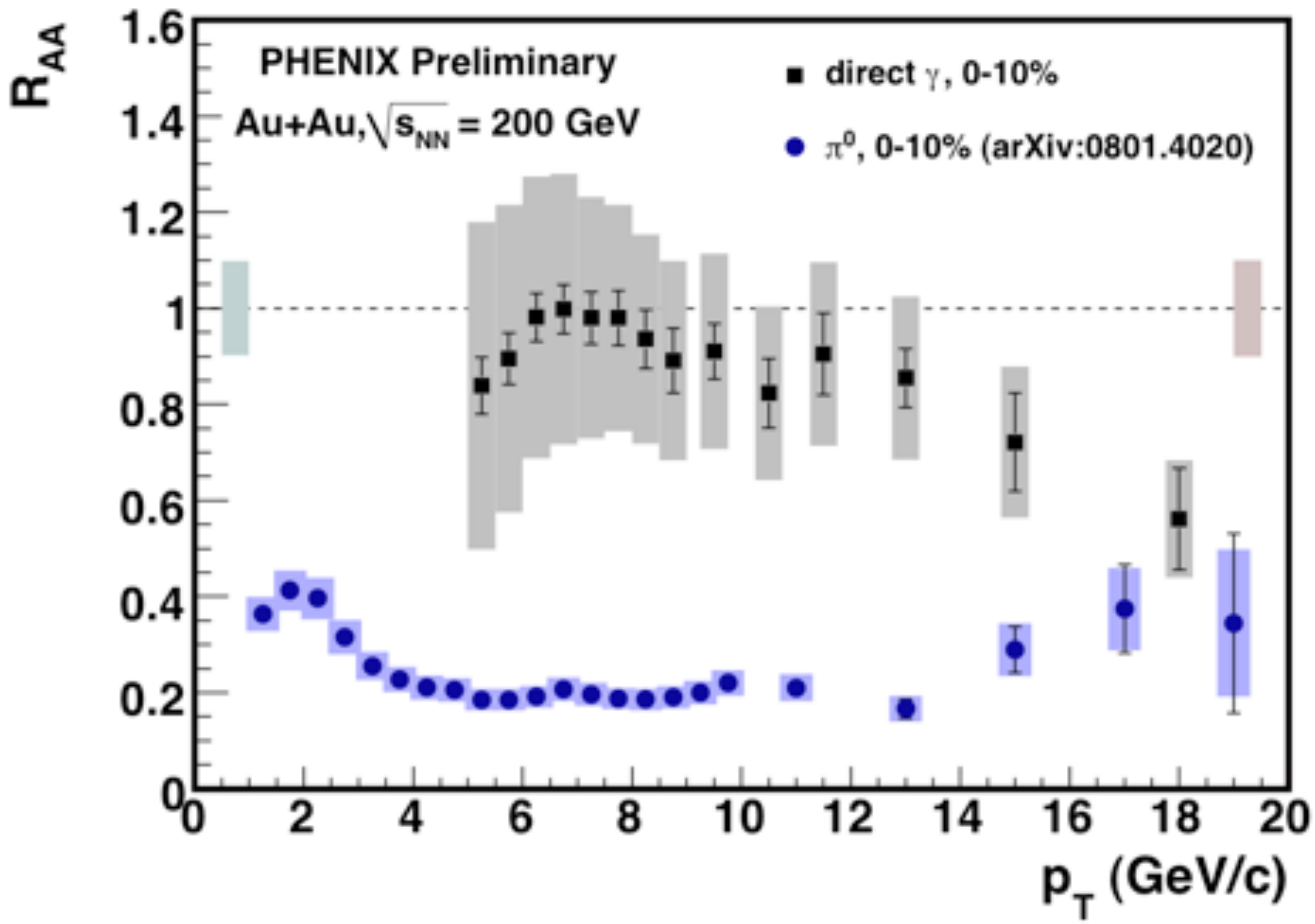
In central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV, one misses 80% of the high-transverse-momentum hadrons!

(no pathology in the pp reference!)

Jet quenching vs. initial-state effect

$R_{AA} \equiv \frac{1}{\langle N_{coll}^{AA}\rangle} \frac{\frac{dN_{AA}}{d\mathbf{p}_T\, dy}}{\frac{dN_{pp}}{d\mathbf{p}_T\, dy}}$ < 1: is $\langle N_{coll}^{AA}\rangle$ 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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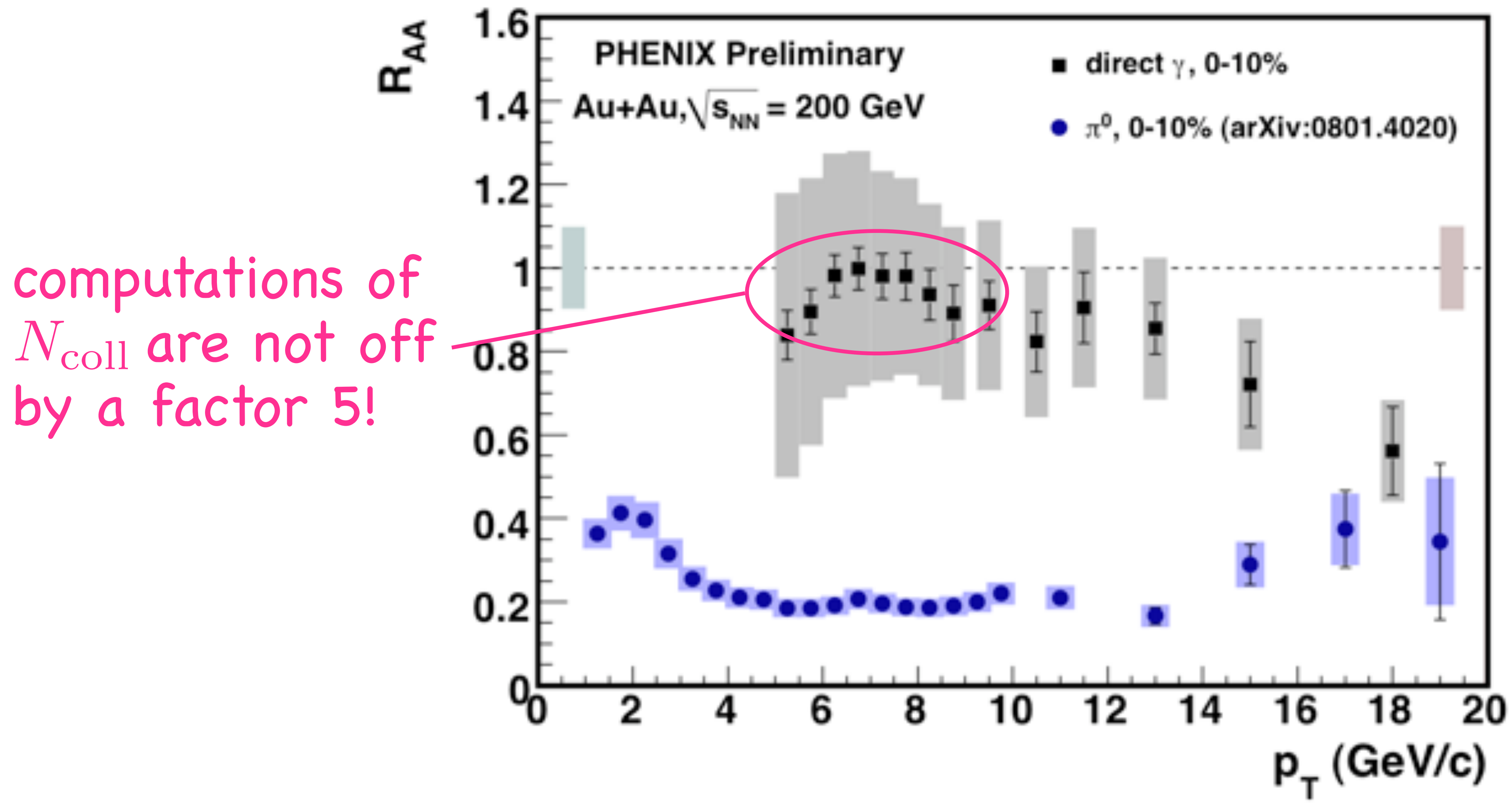

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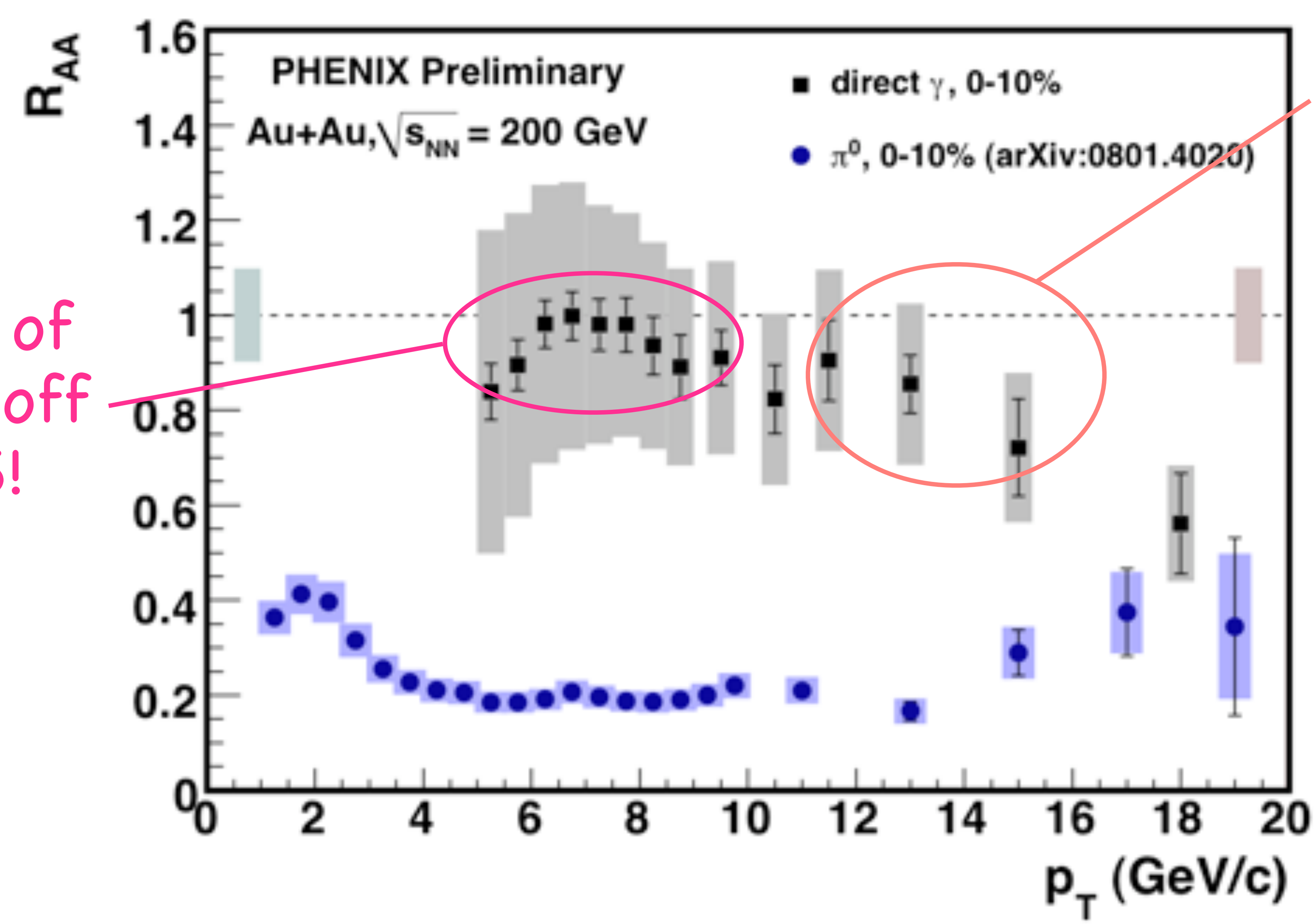

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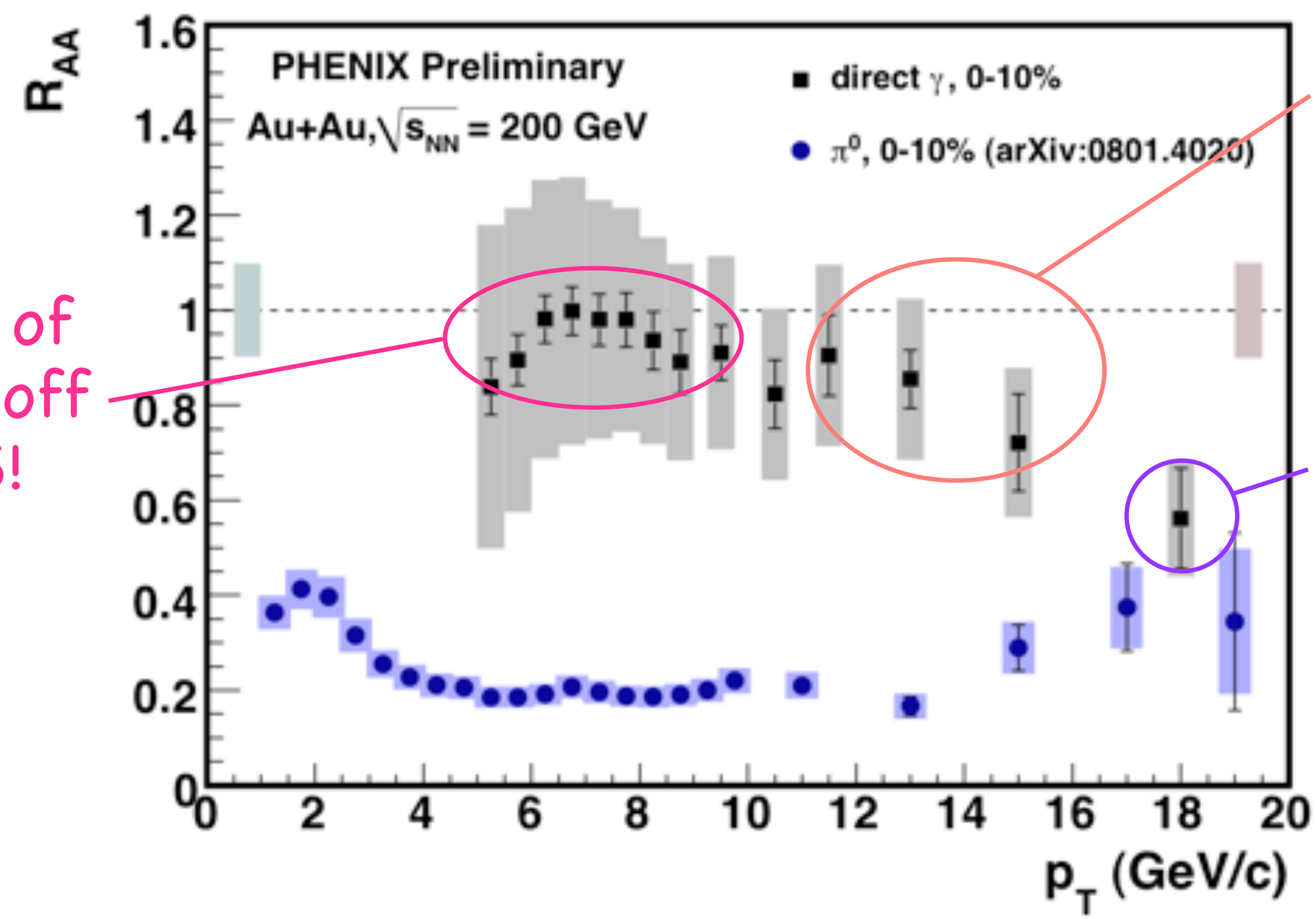
computations of $N_{\rm coll}$ are not off by a factor 5!



deviation from 1 not unexpected (isospin...)

embarrassingly close to the pion value?

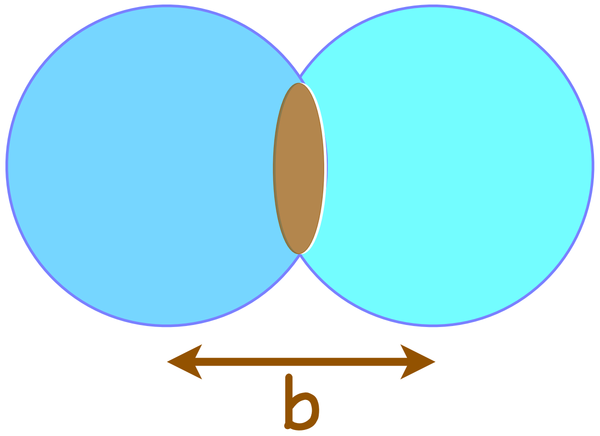
* yet photon production is modified: Bremsstrahlung, photons from parton fragmentation...

Heavy-ion collisions: geometry

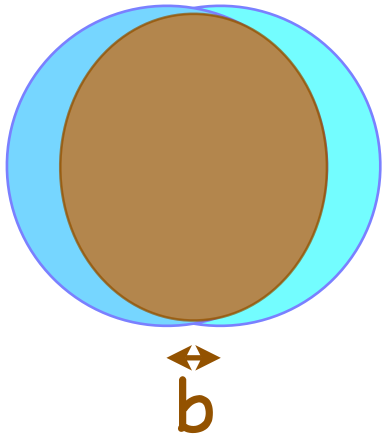
Heavy nuclei have a finite radius!

☞ 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...).

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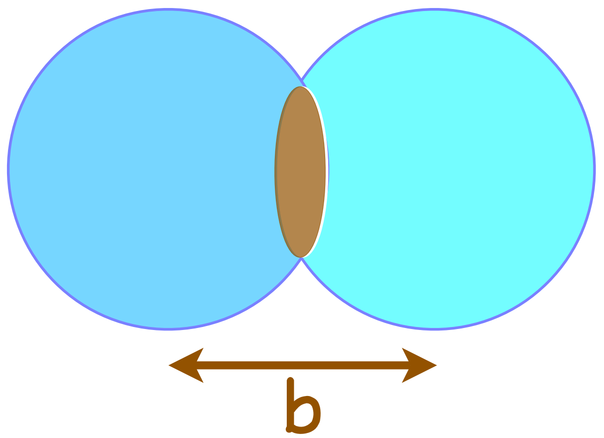
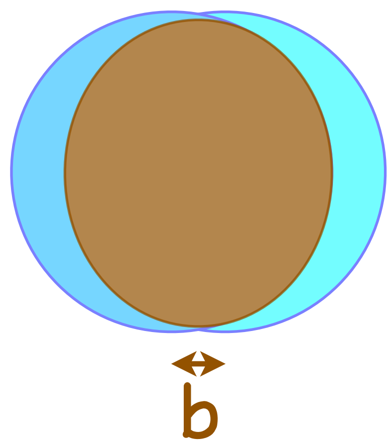


A high-p_T parton quickly escapes the medium: it emerges after losing less energy.

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

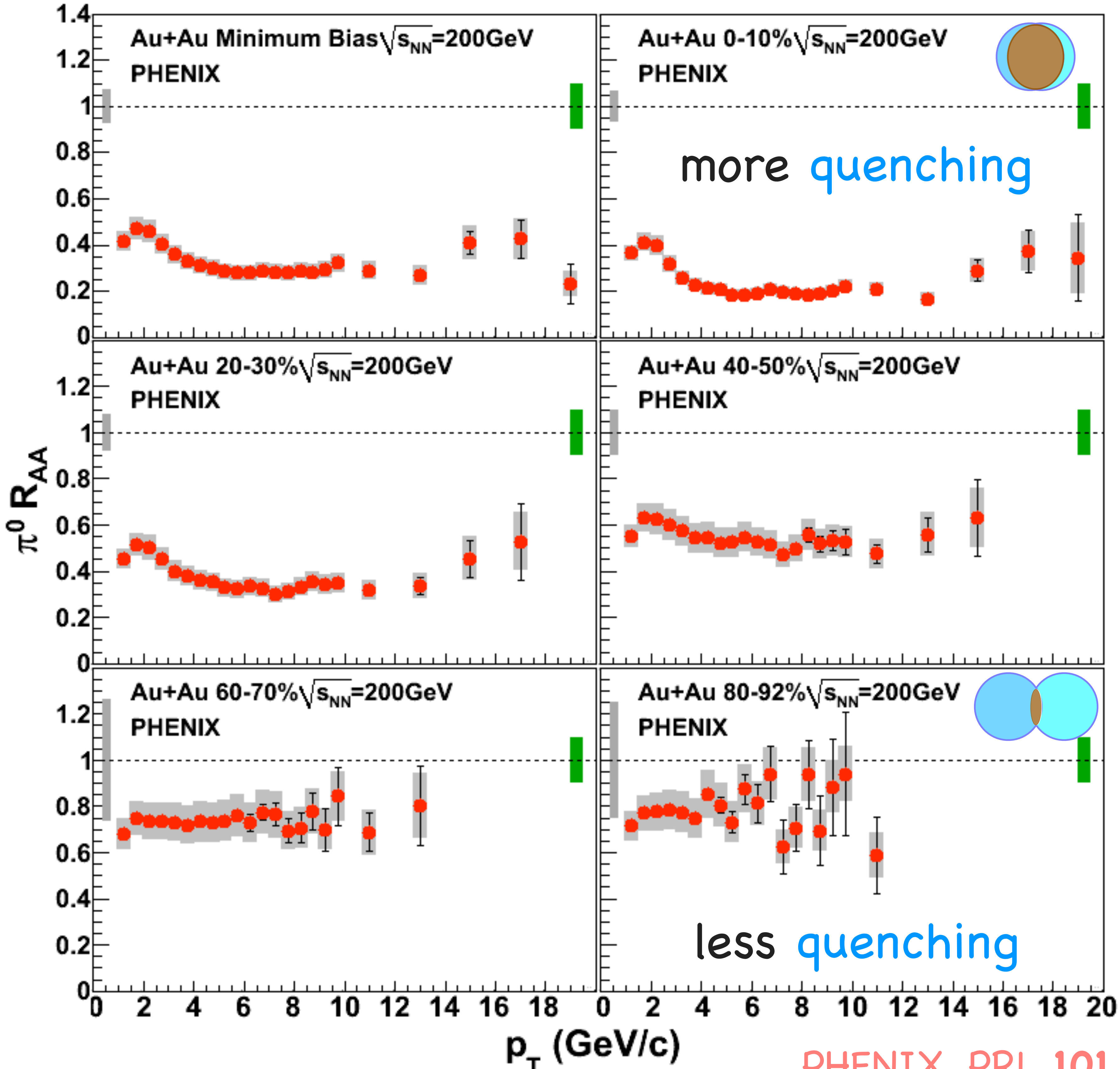


High-p_T partons have larger in-medium path-lengths, thus lose more energy (in average).

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

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

$$R_{AA} \equiv \frac{1}{\langle N_{\rm coll}^{\rm AA}\rangle} \frac{\frac{{\rm d}N_{\rm AA}}{{\rm d}p_T\,{\rm d}y}}{\frac{{\rm d}N_{\rm pp}}{{\rm d}p_T\,{\rm d}y}}$$



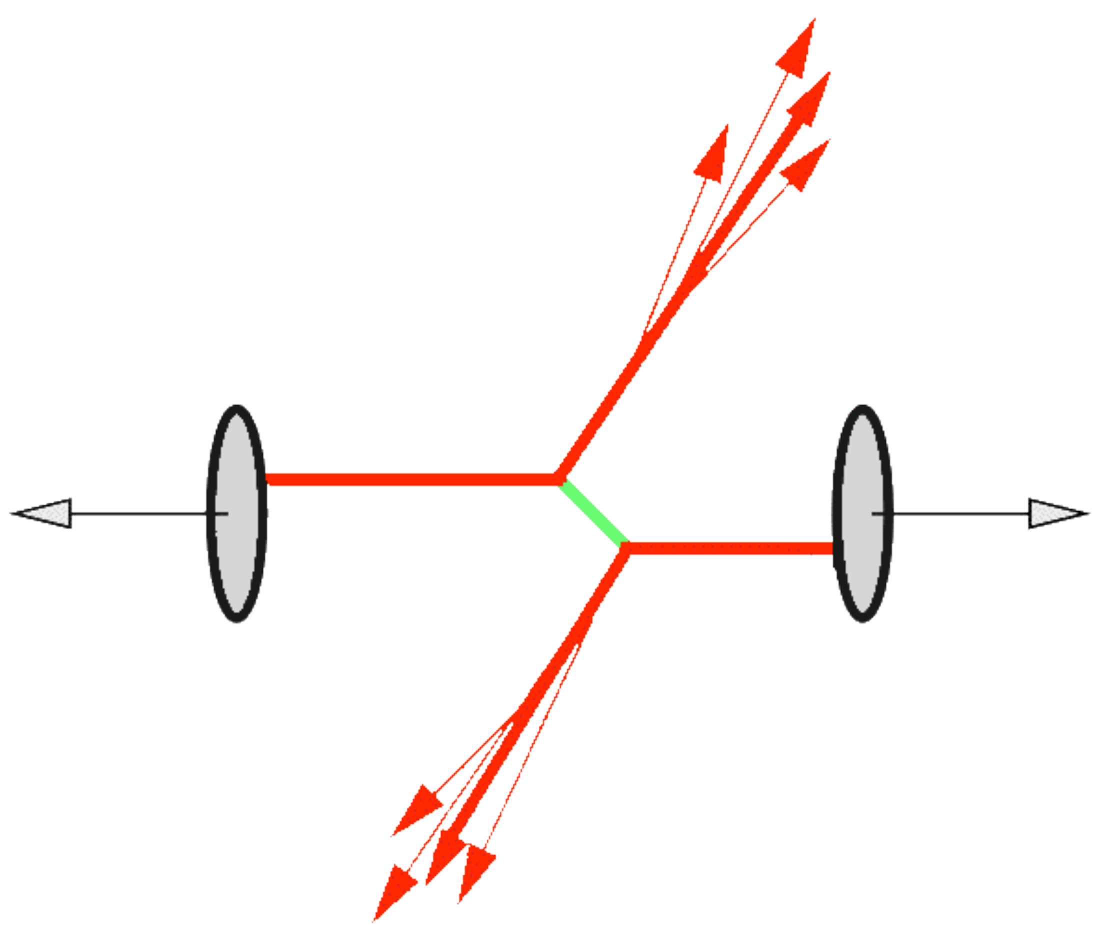
PHENIX, PRL **101** (2008) 232301

"Jet quenching": basic picture

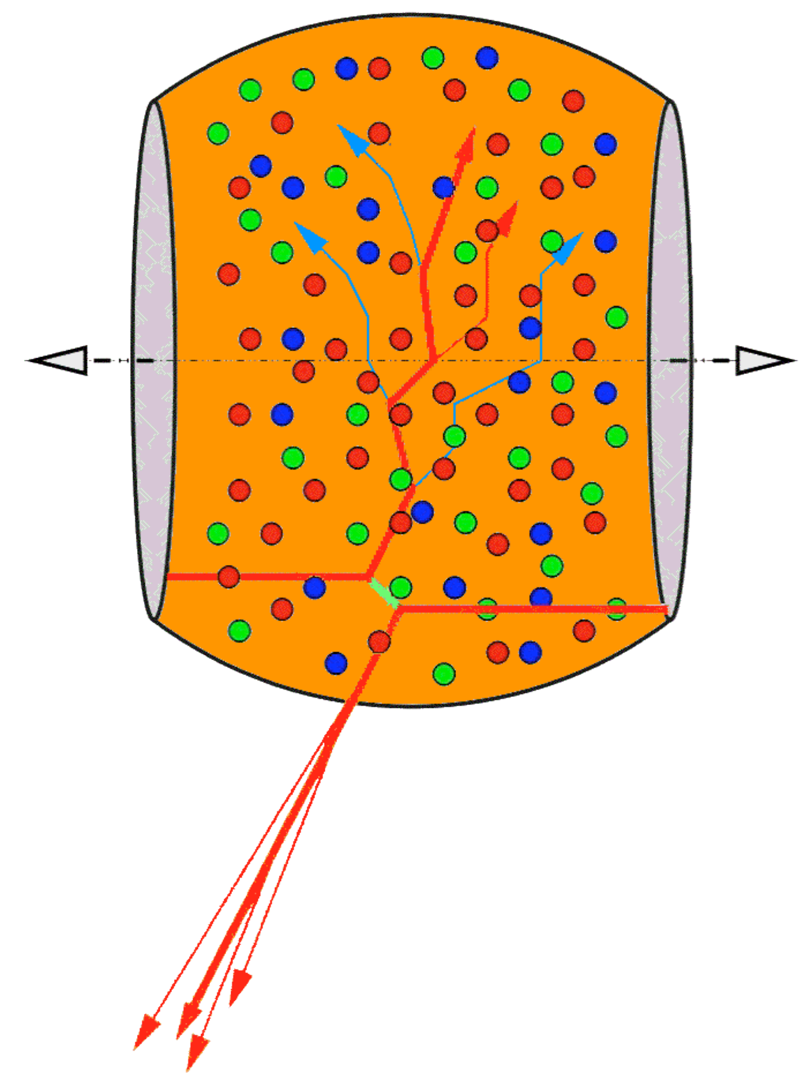
A fast quark/gluon propagating through a dense medium "loses" part of its energy-momentum ☞ suppression of hadron yield at high p_T.

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

in vacuum



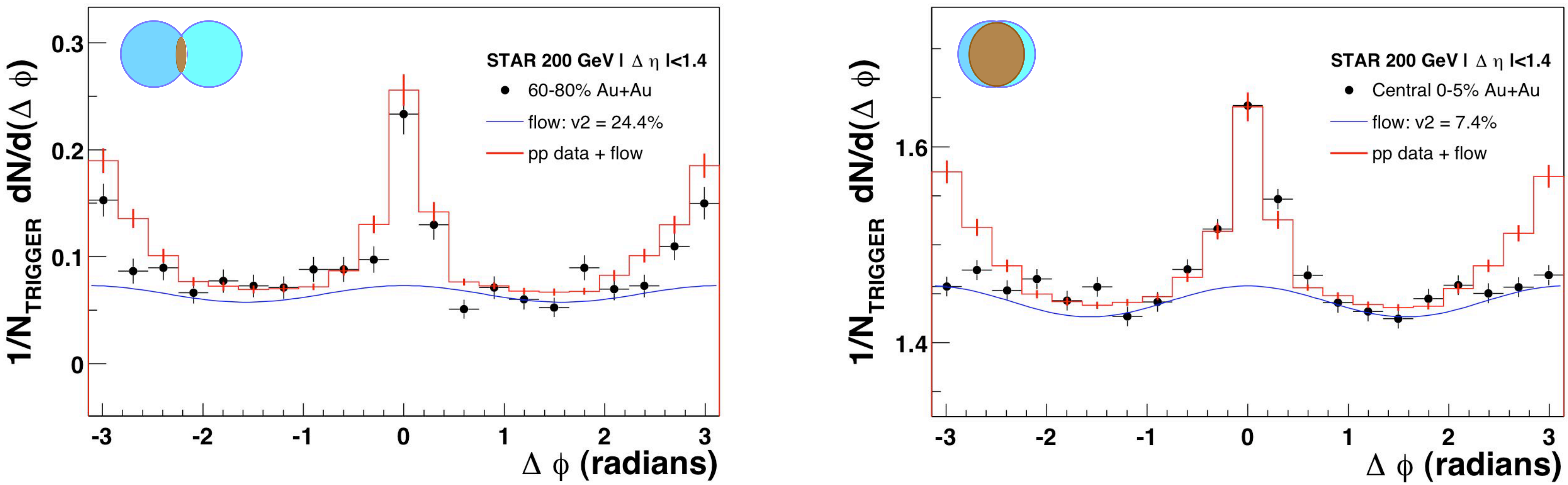
in medium



"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 $P_{T\,\mathrm{cut}} < P_T < P_{T\,\mathrm{max}}$.



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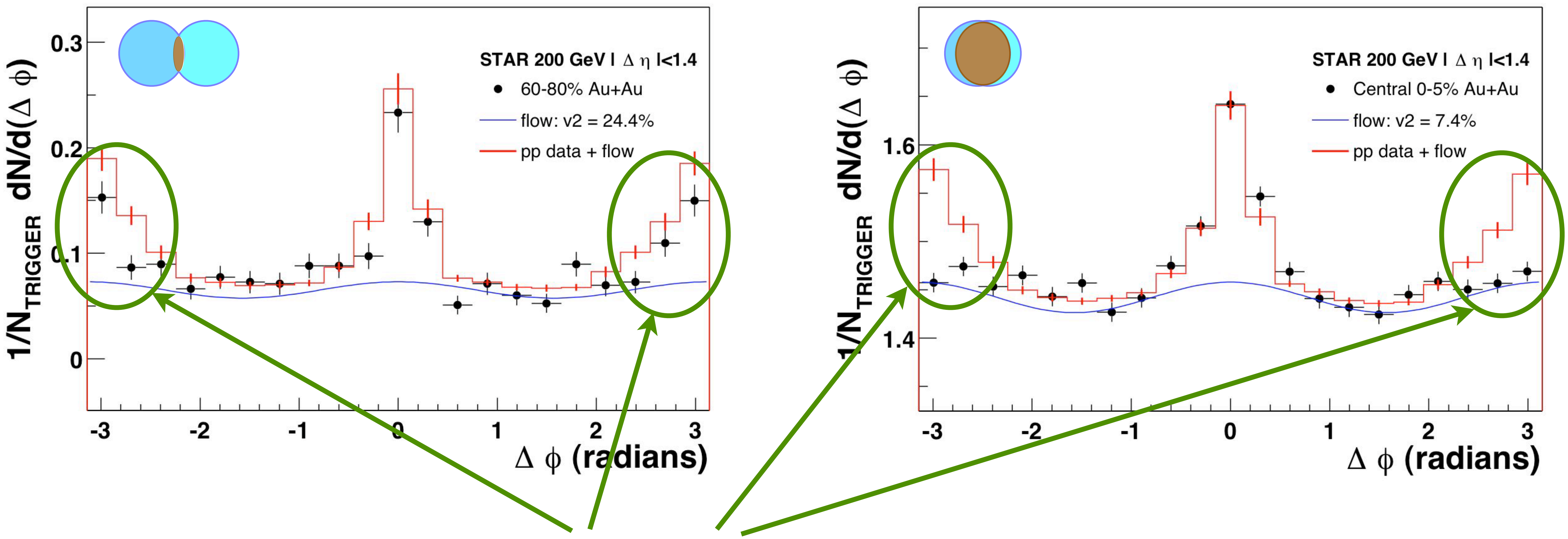


In central collisions, the "back jet" (= peak at 180° from the trigger particle) disappears.

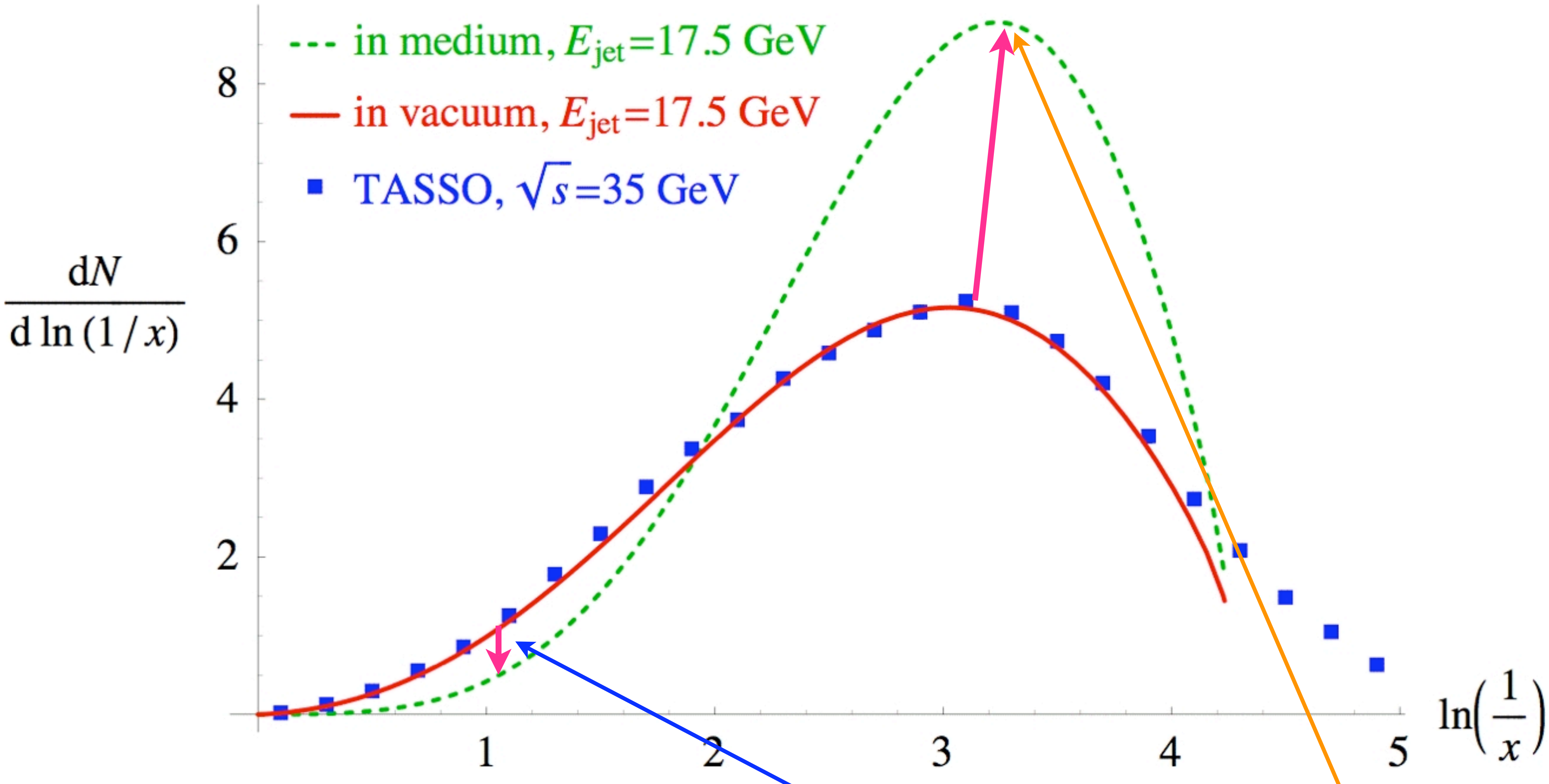
High transverse momentum physics in heavy-ion collisions

- 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

“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)



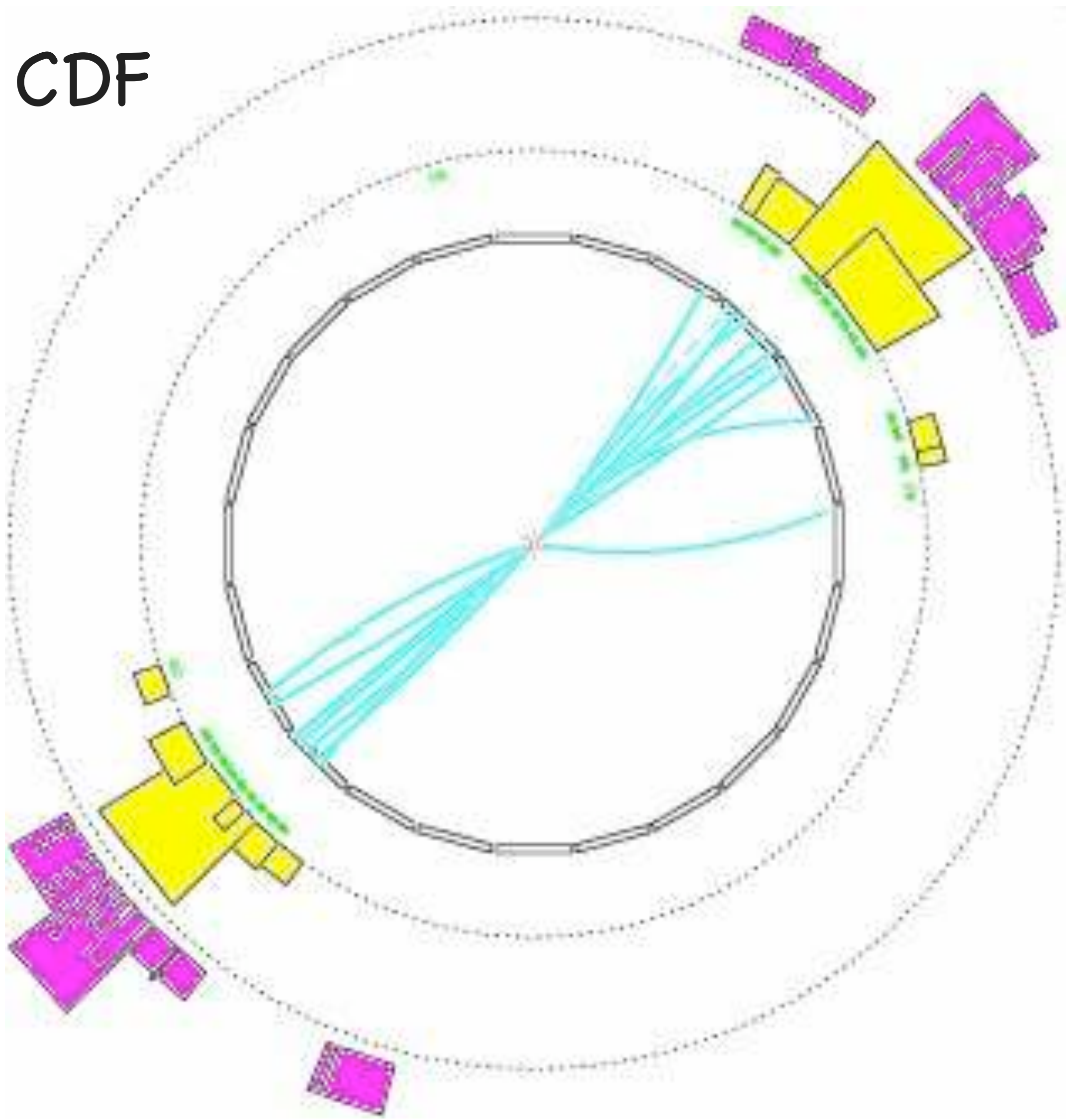
Partons are redistributed from high p_T (large x) to low p_T (small x)
Describing a whole jet becomes feasible!

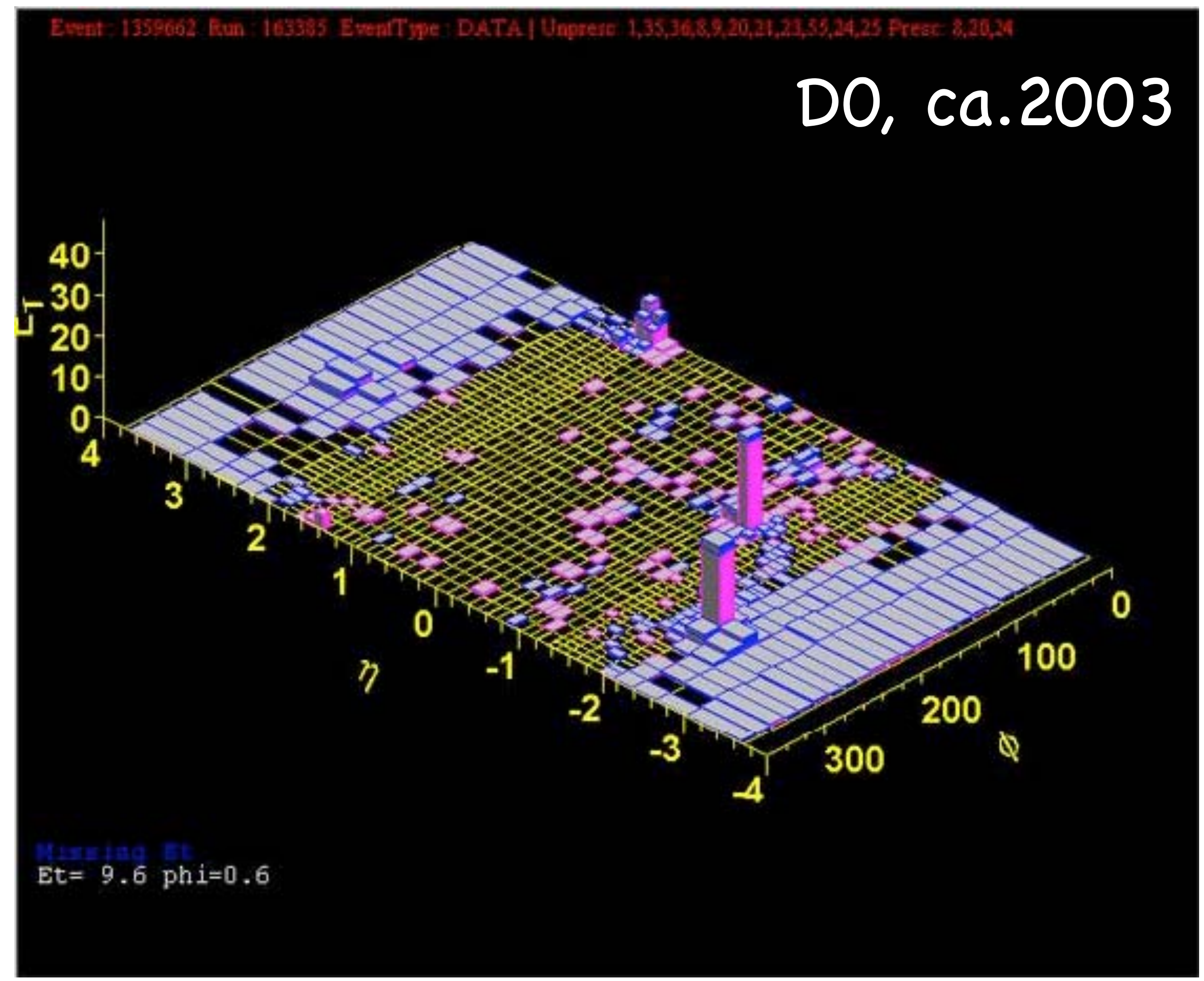
Borghini & Wiedemann, 2005

(Corresponding Monte-Carlo implementations are appearing.)

Jets?

“Clear signal” in e^+e^- / e^-p / $p\overset{(-)}{p}$ collisions (remember, I’m a theorist!)



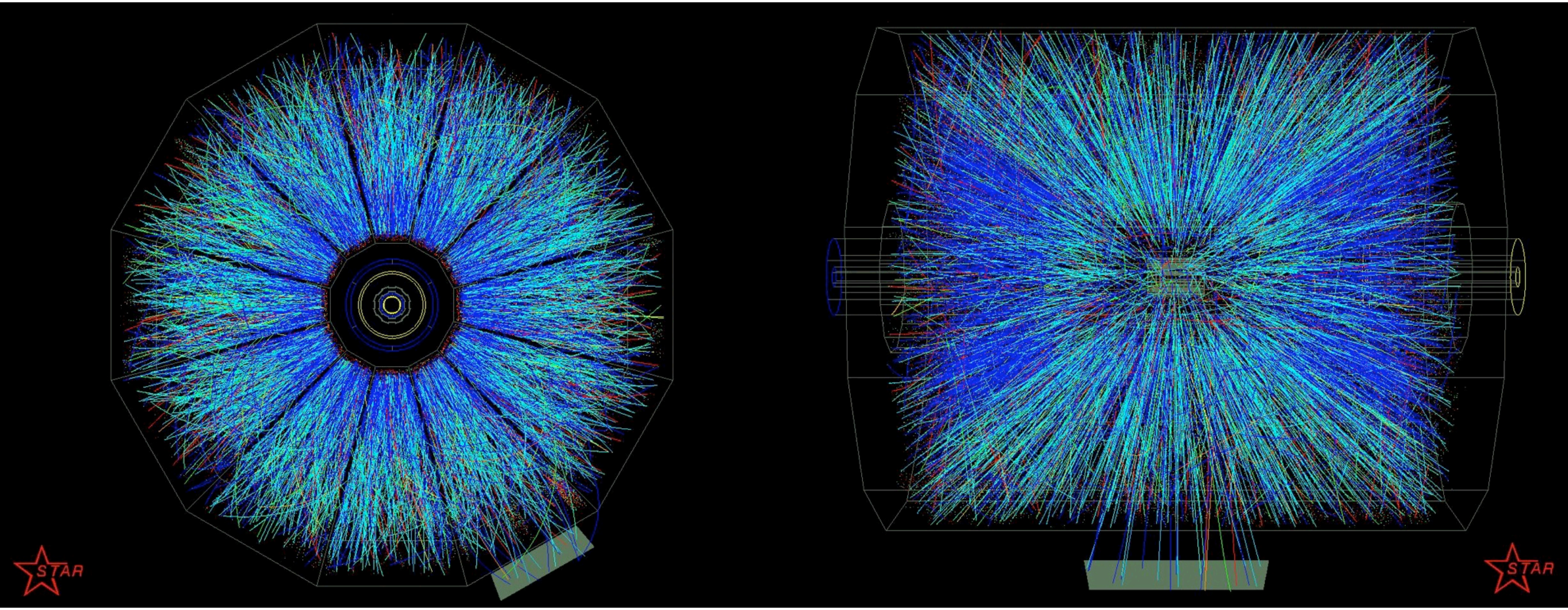


pictures taken from T.Ullrich’s student lecture at Quark Matter 09

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:

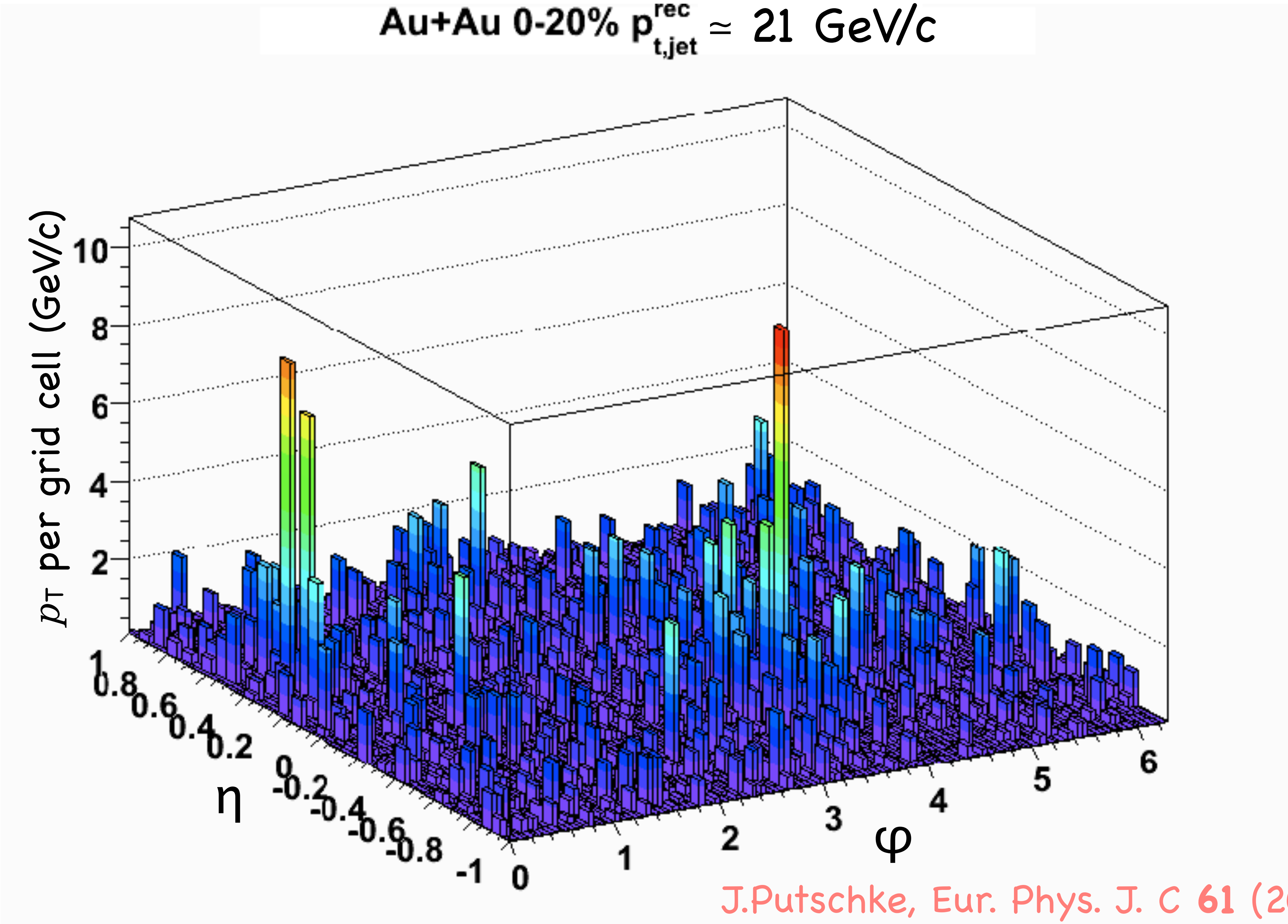


Common lore: forget about identifying jets in RHIC heavy-ion collisions.

Investigate high-p_T hadrons instead (and wait for LHC events)!

Jets in Au-Au collisions at RHIC (4)

Audaces fortuna juvat... STAR preliminary results

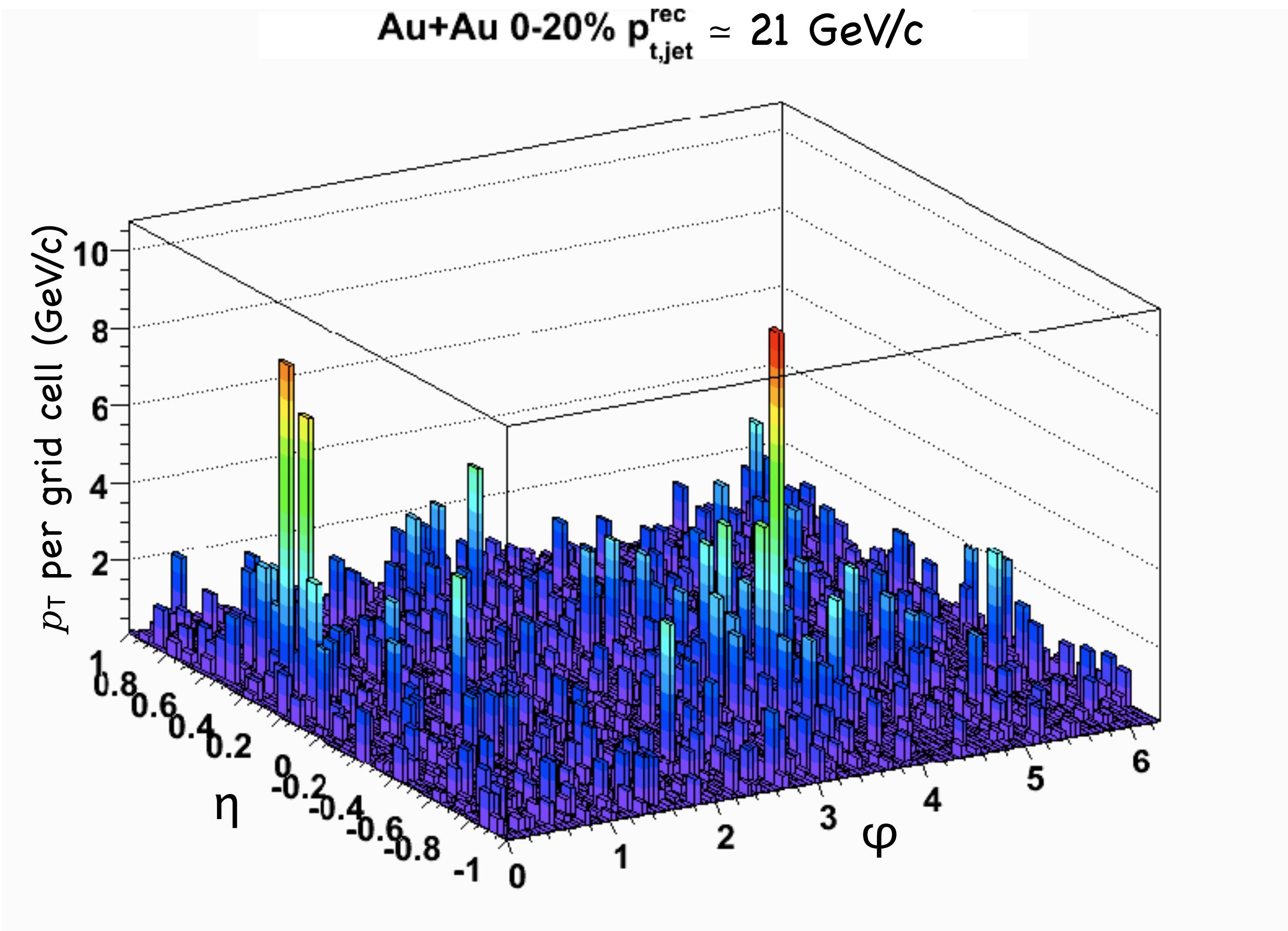


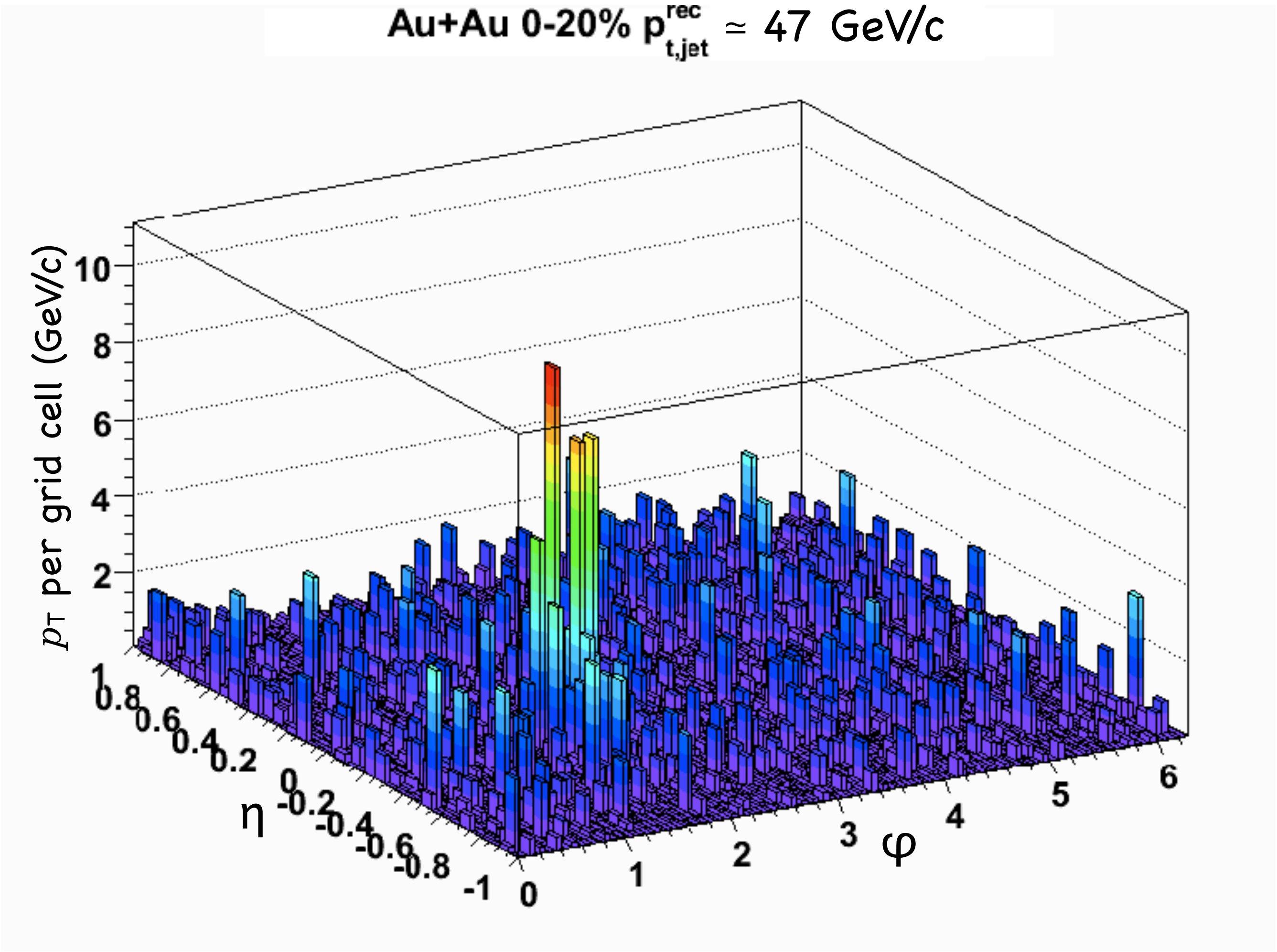
J.Putschke, Eur. Phys. J. C **61** (2009) 629

Jets in Au-Au collisions at RHIC (4)

Audaces fortuna juvat... STAR preliminary results

(with cone or k_T reconstruction algorithms)





J.Putschke, Eur. Phys. J. C **61** (2009) 629

Jets in nucleus-nucleus collisions...

Our experimental friends are performing measurements...

Yet there is no theoretical counterpart (in pQCD?) to the object they are extracting (yet???).

And it is not clear that the "vacuum" Monte-Carlo codes can be meaningfully extended to the propagation in a medium.

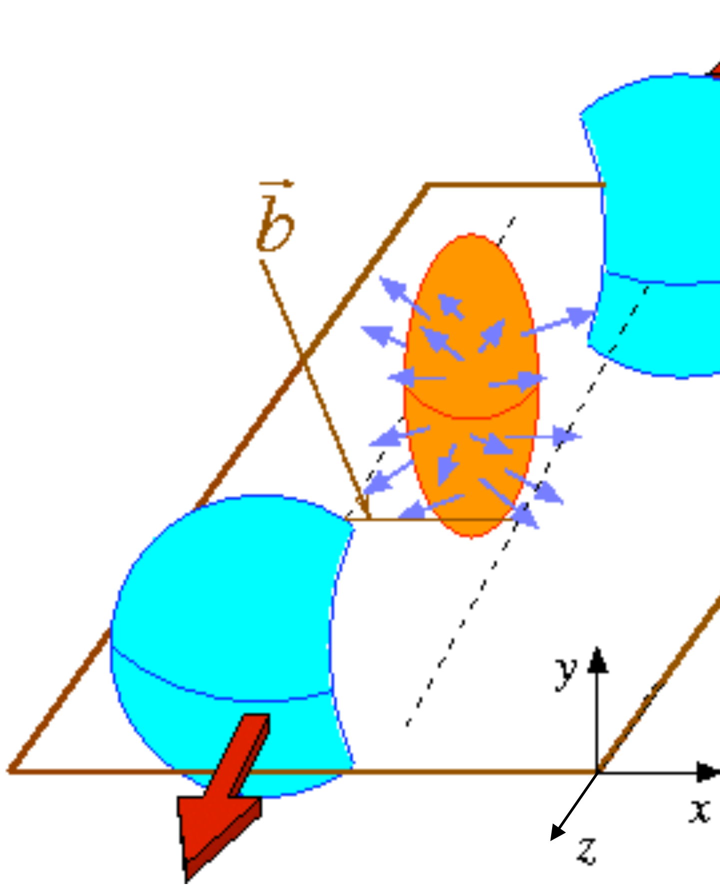
theoretical work needed!

Phenomenology of heavy-ion collisions: two topics

- Experimental heavy-ion programs at colliders: RHIC & LHC
- Theoretical motivation 1: "condensed matter of QCD"
- Hard probes of the created medium: "jets"
  - Phenomenological / theoretical ideas
  - RHIC results (a biased personal choice!)
- Theoretical motivation 2: "local" strong parity violation
  - RHIC results(?)

Azimuthal dependence of particle emission

In a collision at finite impact parameter, the latter breaks the isotropy in the transverse plane ☞ anisotropic particle emission



in the lab frame: varies from event to event

z-axis: fixed in the lab frame
y-axis: along the angular momentum

$$\frac{\mathrm{d}N}{\mathrm{d}\mathbf{p}_T} = \frac{\mathrm{d}N}{2\pi p_T\,\mathrm{d}p_T}\left(1 + 2\sum_{n\geq 1}\left[v_{n,c}\cos n(\varphi - \Phi_R) + 2v_{n,s}\sin n(\varphi - \Phi_R)\right]\right)$$

A crazy suggestion...

Imagine that due to some mechanism, positively charged particles are preferentially emitted above the x-z plane ($0 < \varphi - \Phi_R < \pi$), negatively charged particles below ($-\pi < \varphi - \Phi_R < 0$).

☞ parity violation!?

Then $v_{1,s} \equiv \langle \sin(\varphi - \Phi_R) \rangle$ is positive for positively charged particles, negative for negatively charged ones!

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☞ parity violation!?

Then $v_{1,s} \equiv \langle \sin(\varphi - \Phi_R) \rangle$ is positive for positively charged particles, negative for negatively charged ones!

Let's assume that the effect is "spontaneous" and changes handedness randomly from event to event, with equal probability to be left- or right-handed.

Then, averaging over many events ($\langle \cdots \rangle$) one eventually finds for both positively and negatively charged particles $v_{1,s}(+) = v_{1,s}(-) = 0$.
That's sad!

A crazy suggestion... (continued)

OK, keep the same scenario, but look at $\langle\cos(\varphi_1+\varphi_2-2\Phi_R)\rangle$ for pairs of particles (1,2) then:

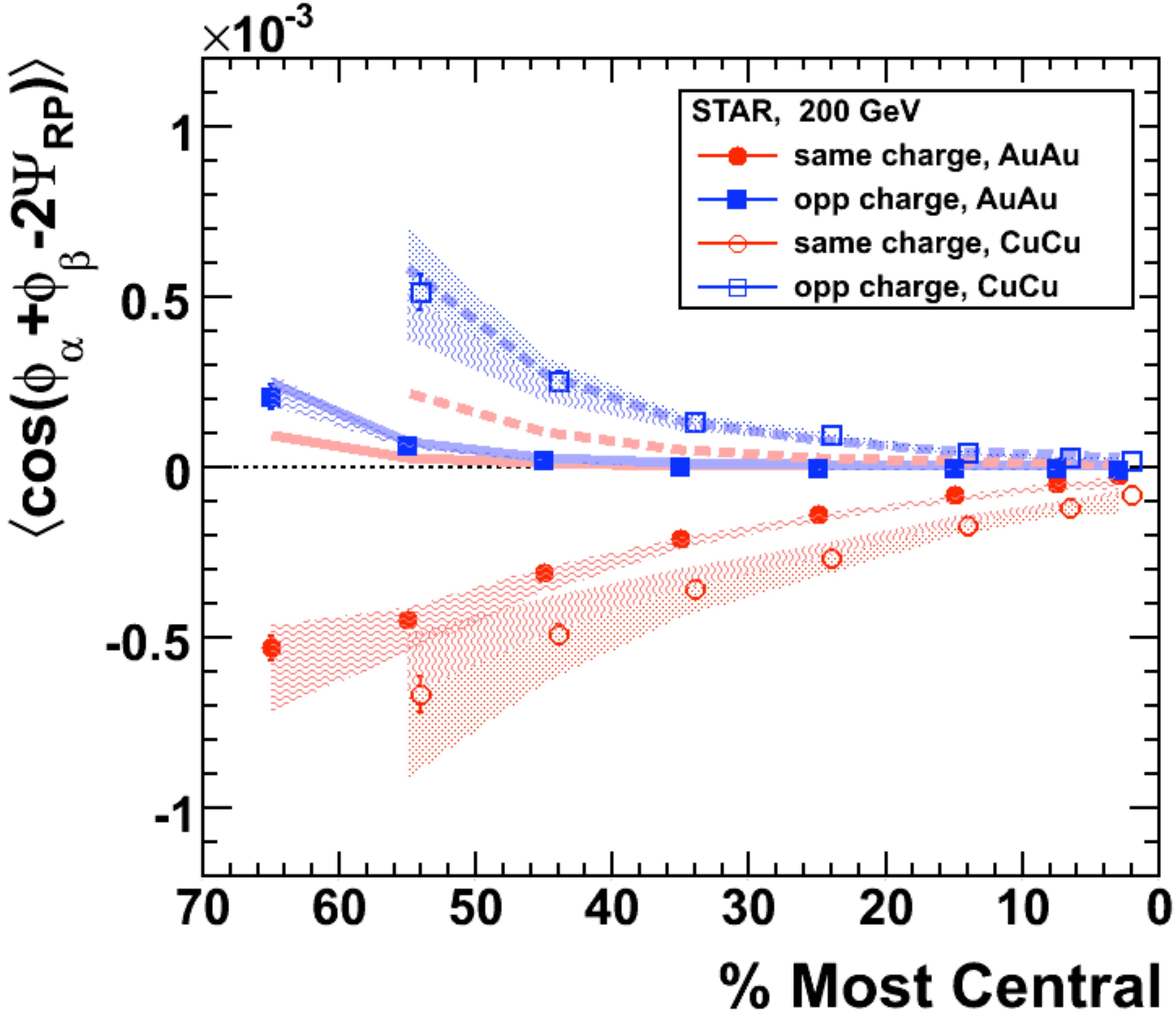
$$\langle\cos(\varphi_1+\varphi_2-2\Phi_R)\rangle = \langle\cos(\varphi_1-\Phi_R)\cos(\varphi_2-\Phi_R) - \sin(\varphi_1-\Phi_R)\sin(\varphi_2-\Phi_R)\rangle$$

- $\langle\cos(\varphi_1-\Phi_R)\cos(\varphi_2-\Phi_R)\rangle$ vanishes if one averages over a region symmetric with respect to midrapidity in collisions of identical nuclei;
- $\langle\sin(\varphi_1-\Phi_R)\sin(\varphi_2-\Phi_R)\rangle$ is positive for like-sign pairs, negative for pairs of particles with opposite charge.

This remains true even if the (unknown!) mechanism responsible for charge separation changes sign from event to event.

☞ $\langle\cos(\varphi_1+\varphi_2-2\Phi_R)\rangle$ $\begin{cases} \text{negative for (+,+) or (-,-) pairs,} \\ \text{positive for (+,-) pairs} \end{cases}$

Some recent data from RHIC...



STAR Coll., arXiv:0909.1717 & arXiv:0909.1739 [nucl-ex]

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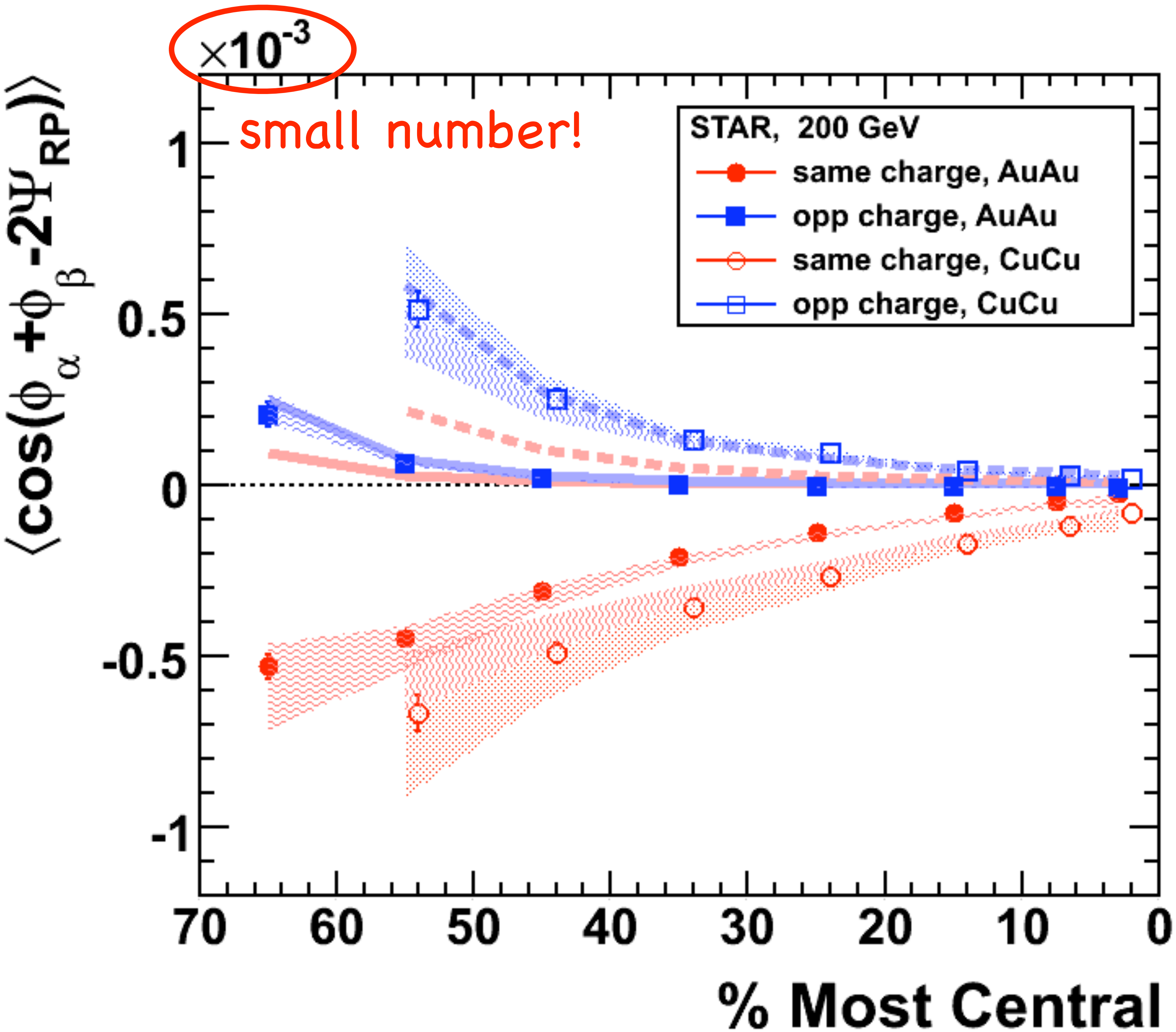
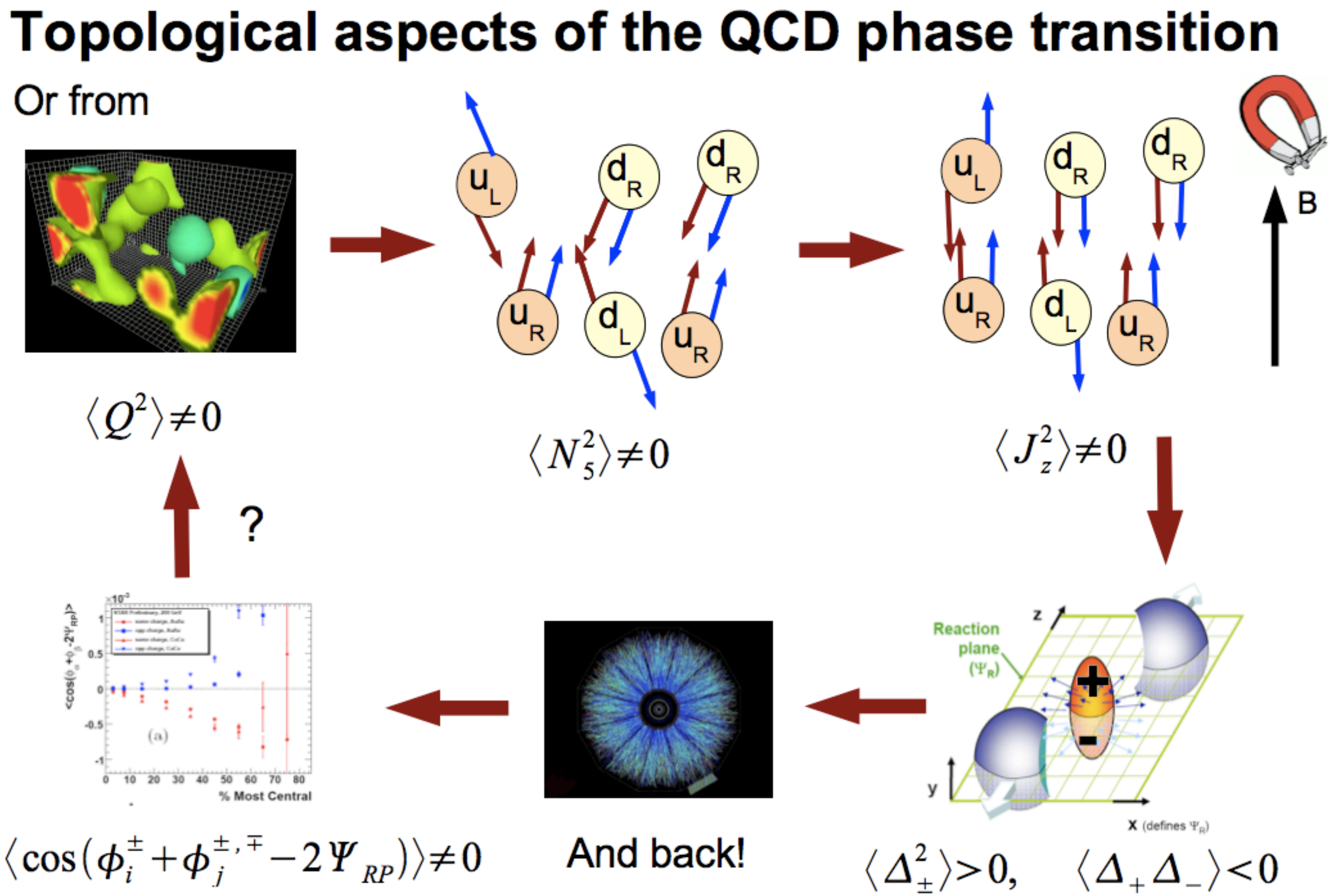


STAR Coll., arXiv:0909.1717 & arXiv:0909.1739 [nucl-ex]

Can one explain these data with "standard" effects?

A crazy suggestion...

... or must one invoke some mechanism like this?



taken from a set of lectures by H.Warringa on parity violation in heavy-ion collisions, available at http://www.physik.uni-bielefeld.de/igs/schools/Spring2009/warringa-topqcd.pdf

Phenomenology of heavy-ion collisions: two topics

- Experimental heavy-ion programs at colliders provide us with plenty of data: a phenomenologist's dream (or nightmare?)

- These data should mostly be in the realm of QCD:
  - pQCD... needs no confirmation!
    Where does it fail? (controversy around $\hat{q}$)
  - topological aspects of the QCD vacuum?
  - can we learn something on the confinement mechanism?