Jets in heavy-ion collisions

Nicolas BORGHINI

Universität Bielefeld

Teilchenkolloquium, Heidelberg, July 8, 2008

Jets in heavy-ion collisions

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

Hints from lattice QCD

Volume 113B, number 5 PHYSICS LETTERS 1 July 1982

THE HIGH-TEMPERATURE BEHAVIOUR OF LATTICE QCD WITH FERMIONS

J. ENGELS, F. KARSCH and H. SATZ
Fakultät für Physik, Universität Bielefeld, Bielefeld, Germany

Received 29 March 1982

By Monte Carlo simulation on the lattice, we calculate the high-temperature behaviour of the energy density ϵ in SU(2) and SU(3) QCD with Wilson fermions. From the leading term of the hopping parameter expansion, we find that ϵ converges very rapidly to the Stefan–Boltzmann limit of an asymptotically free quark–gluon gas. ...

Hints from lattice QCD

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

QCD equation of state with almost physical quark masses

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(Received 2 October 2007; published 22 January 2008)

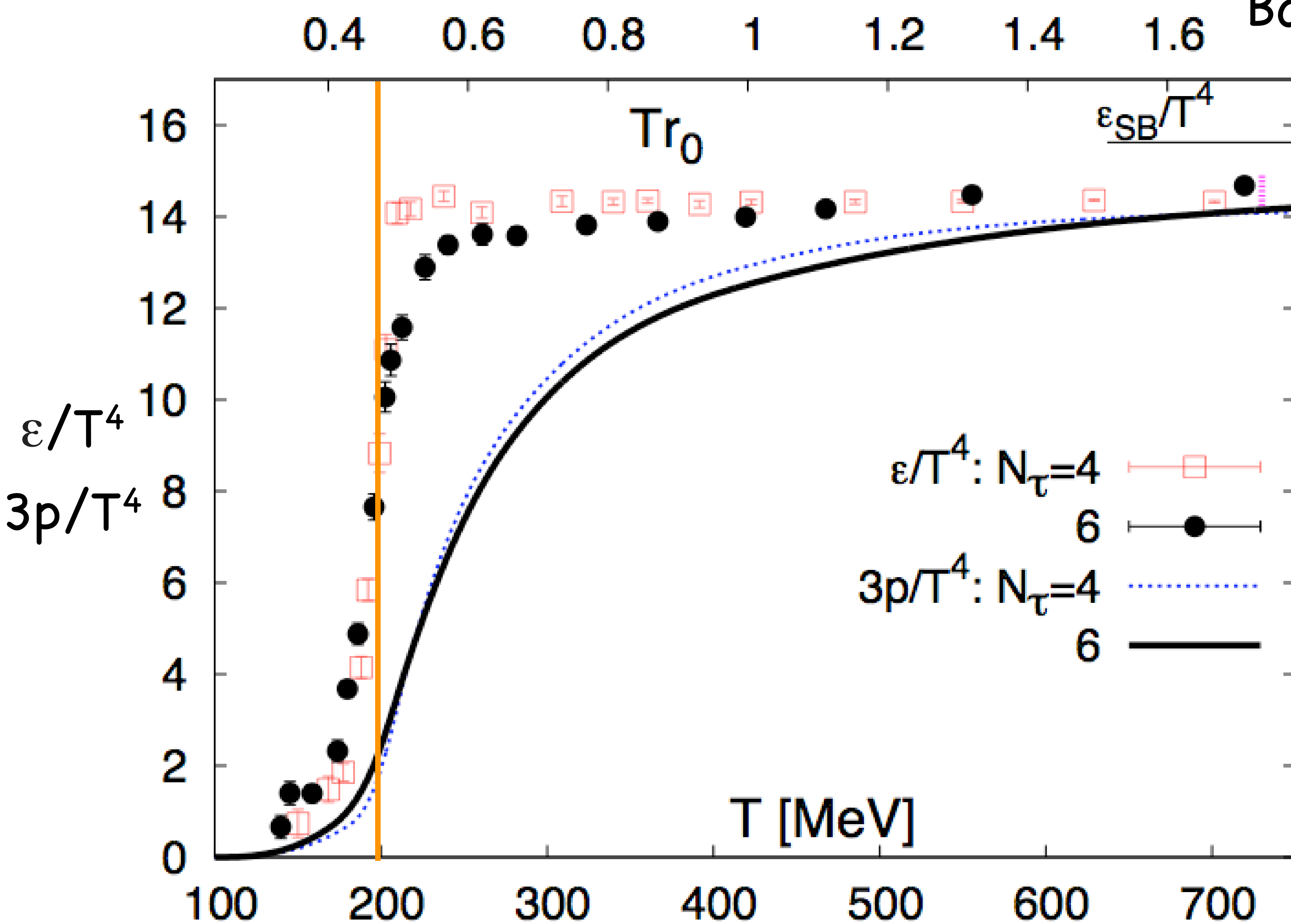
We present results on the equation of state in QCD with two light quark flavors and a heavier strange quark. Calculations with improved staggered fermions have been performed on lattices ...

"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

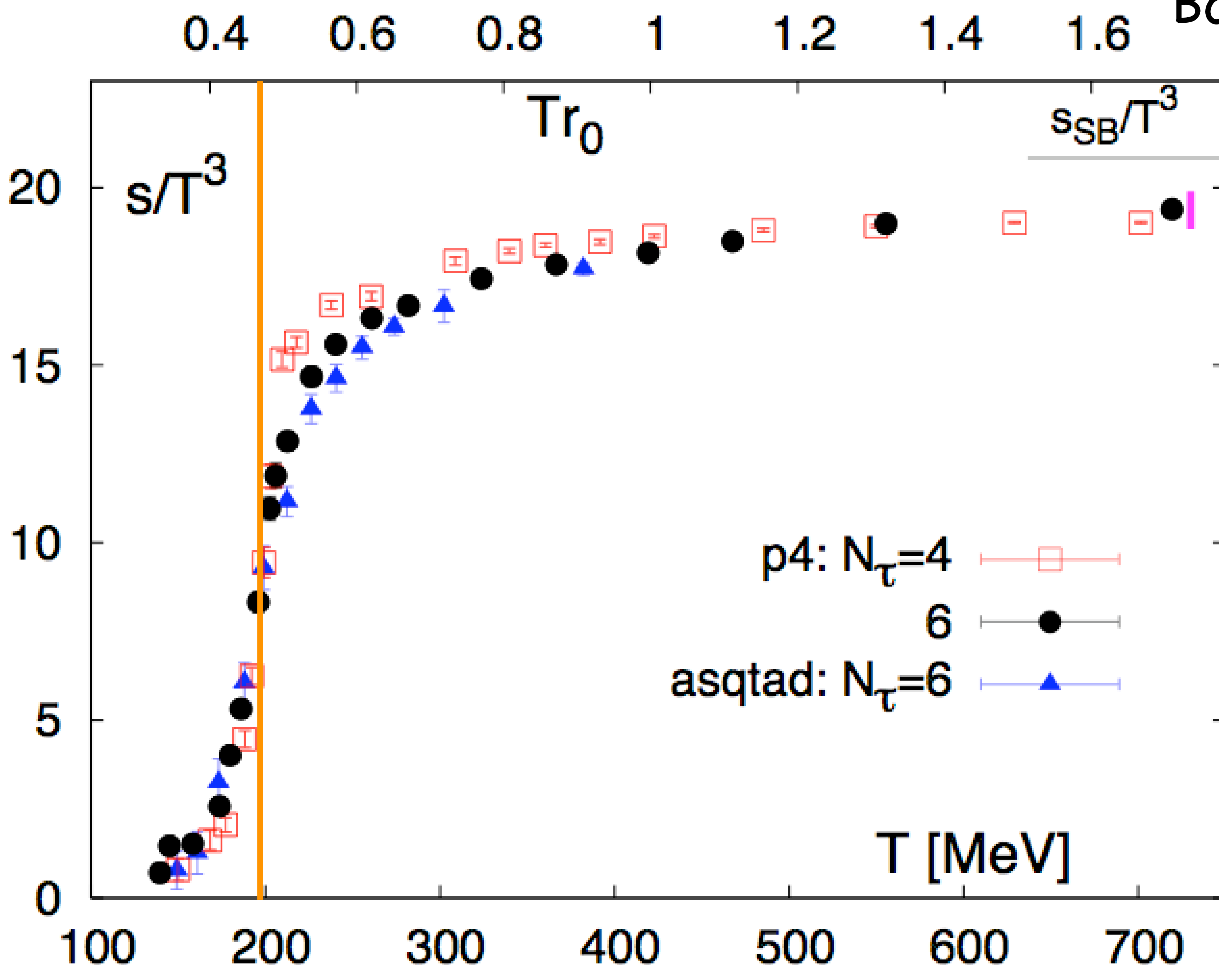


PRD 77 (2008) 045511

Hints from lattice QCD

Entropy density s

ideal Stefan-Boltzmann limit

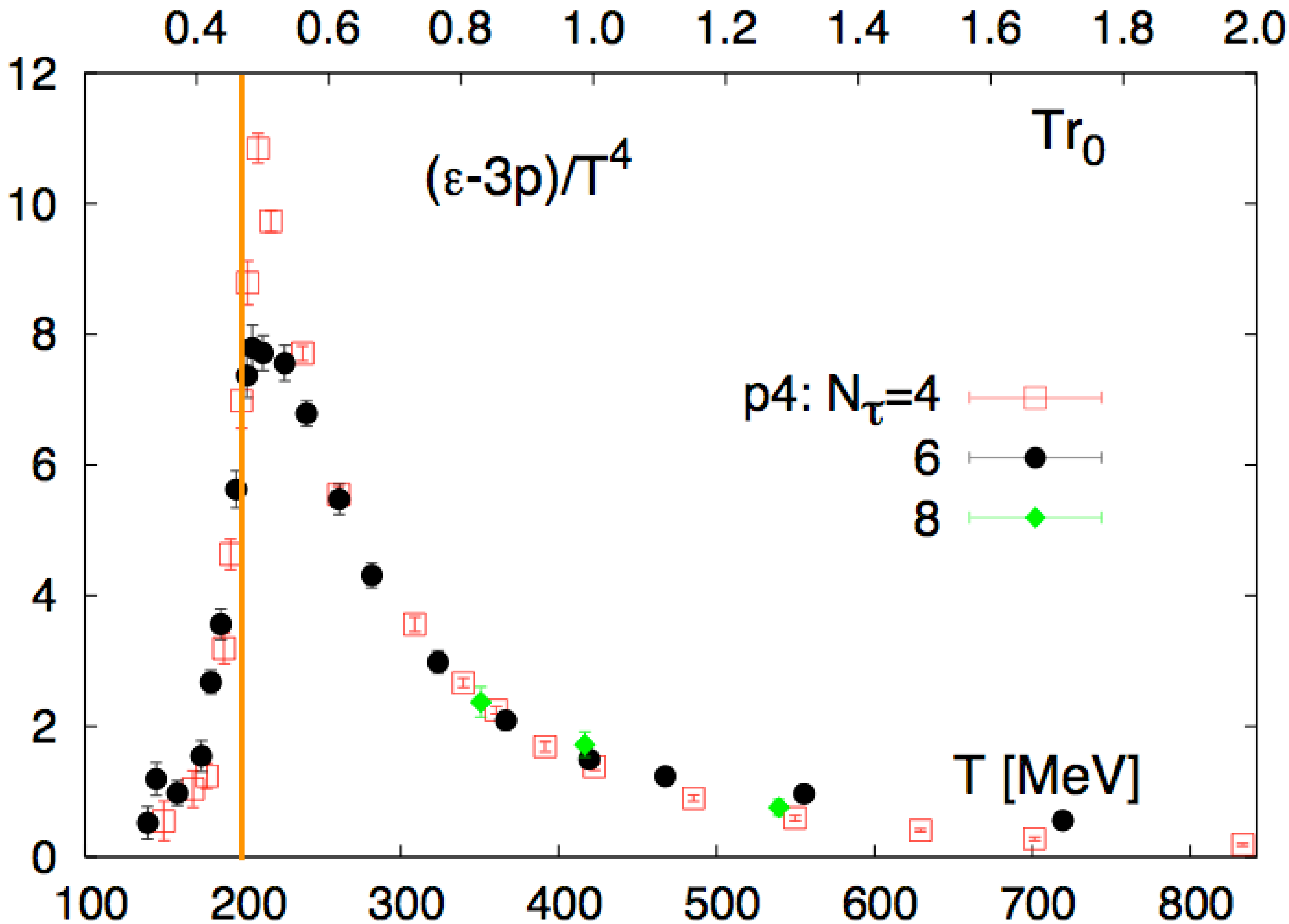


s/T^3

PRD 77 (2008) 045511

Hints from lattice QCD

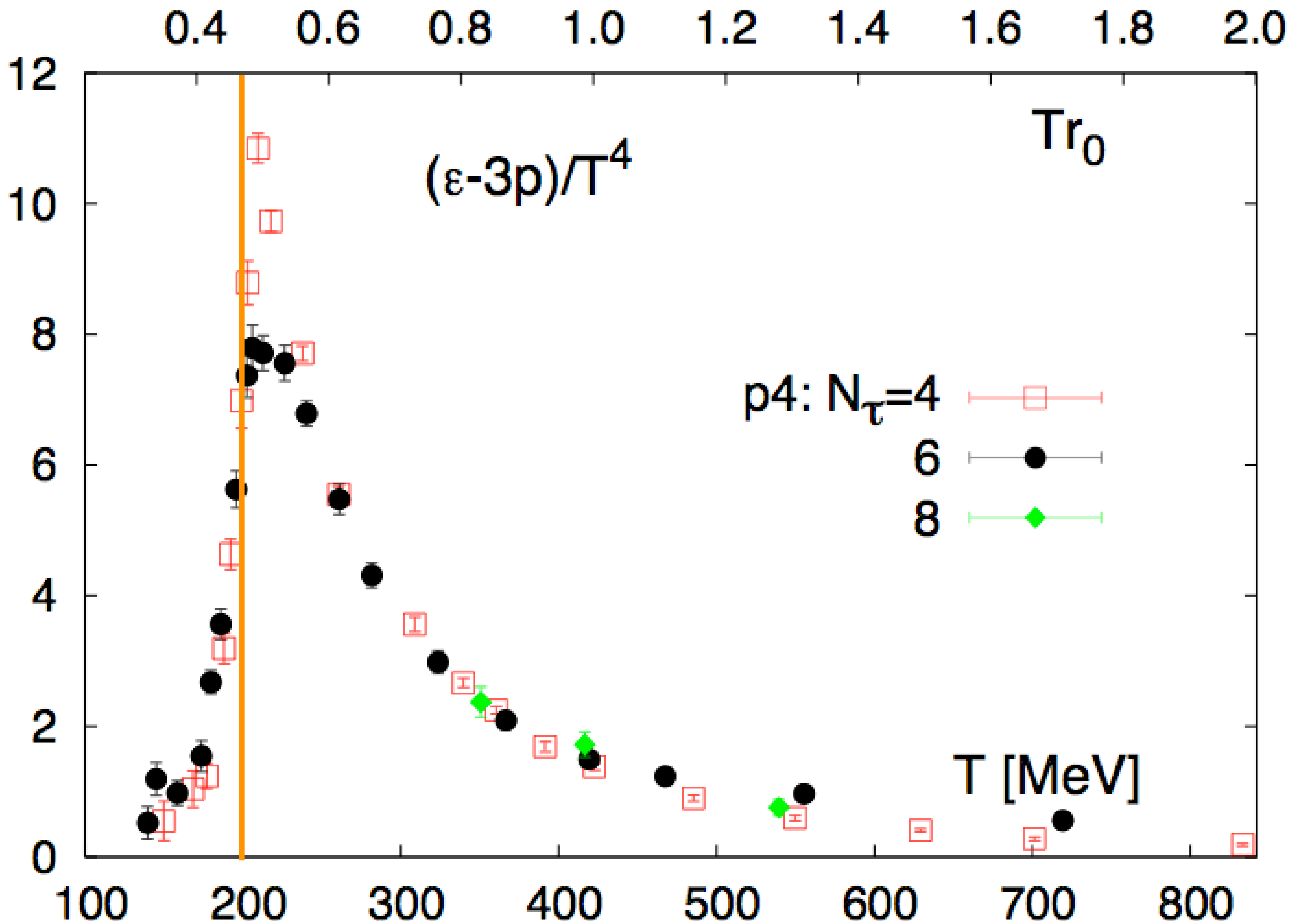
"Critical" temperature T_c=196±4 MeV



PRD 77 (2008) 045511

Hints from lattice QCD

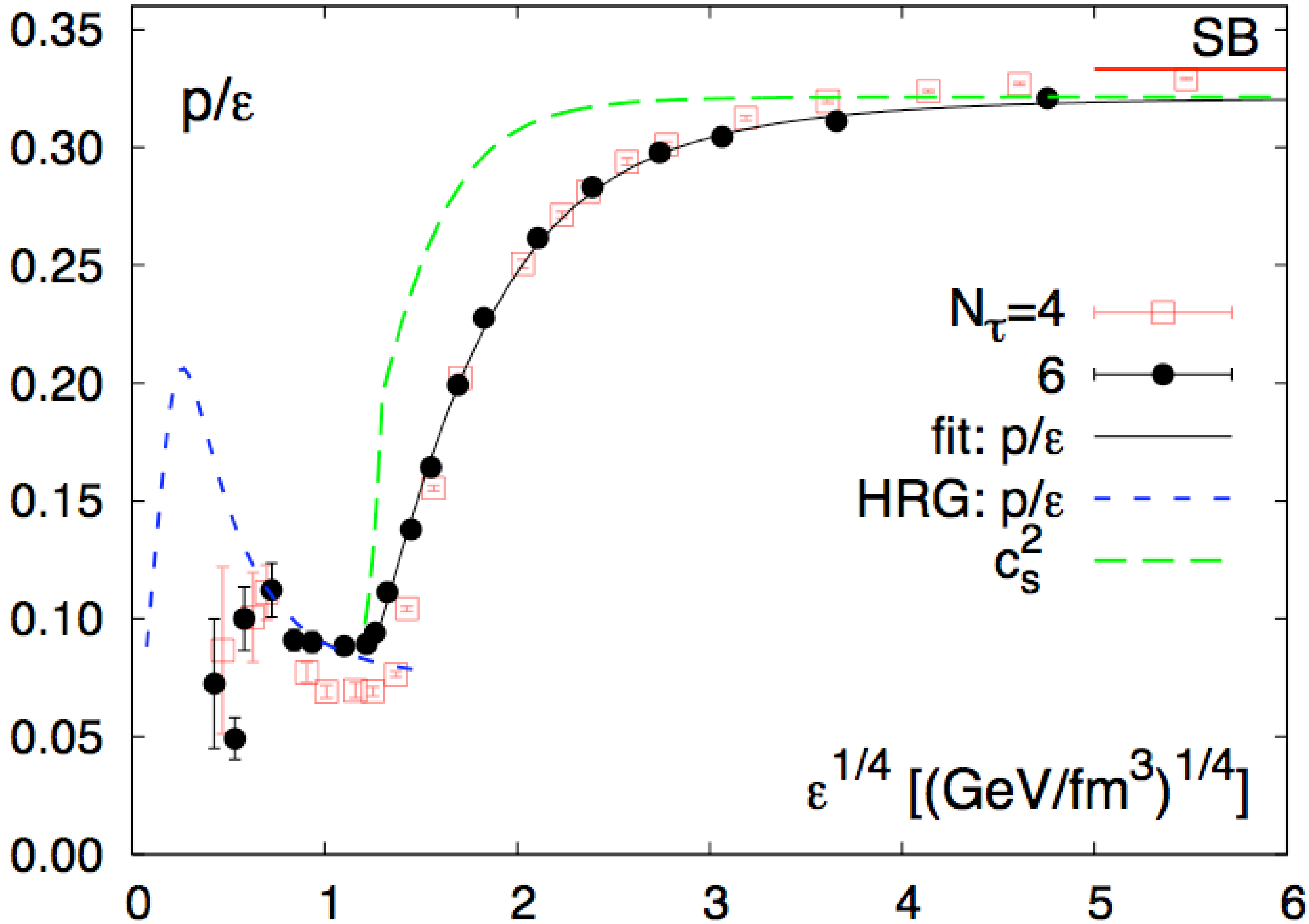
"Critical" temperature $T_c \approx$150-200 MeV



PRD 77 (2008) 045511

Hints from lattice QCD

$\frac{\mathrm{d}p}{\mathrm{d}\varepsilon}$ ☞ sound velocity c_s: $\quad c_s^{\,2} = \frac{\mathrm{d}p}{\mathrm{d}\varepsilon} = \varepsilon\frac{\mathrm{d}(p/\varepsilon)}{\mathrm{d}\varepsilon} + \frac{p}{\varepsilon}$



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

- (Screening of the heavy-quark potential in the high-temperature phase.)

- Equation of state, sound velocity...

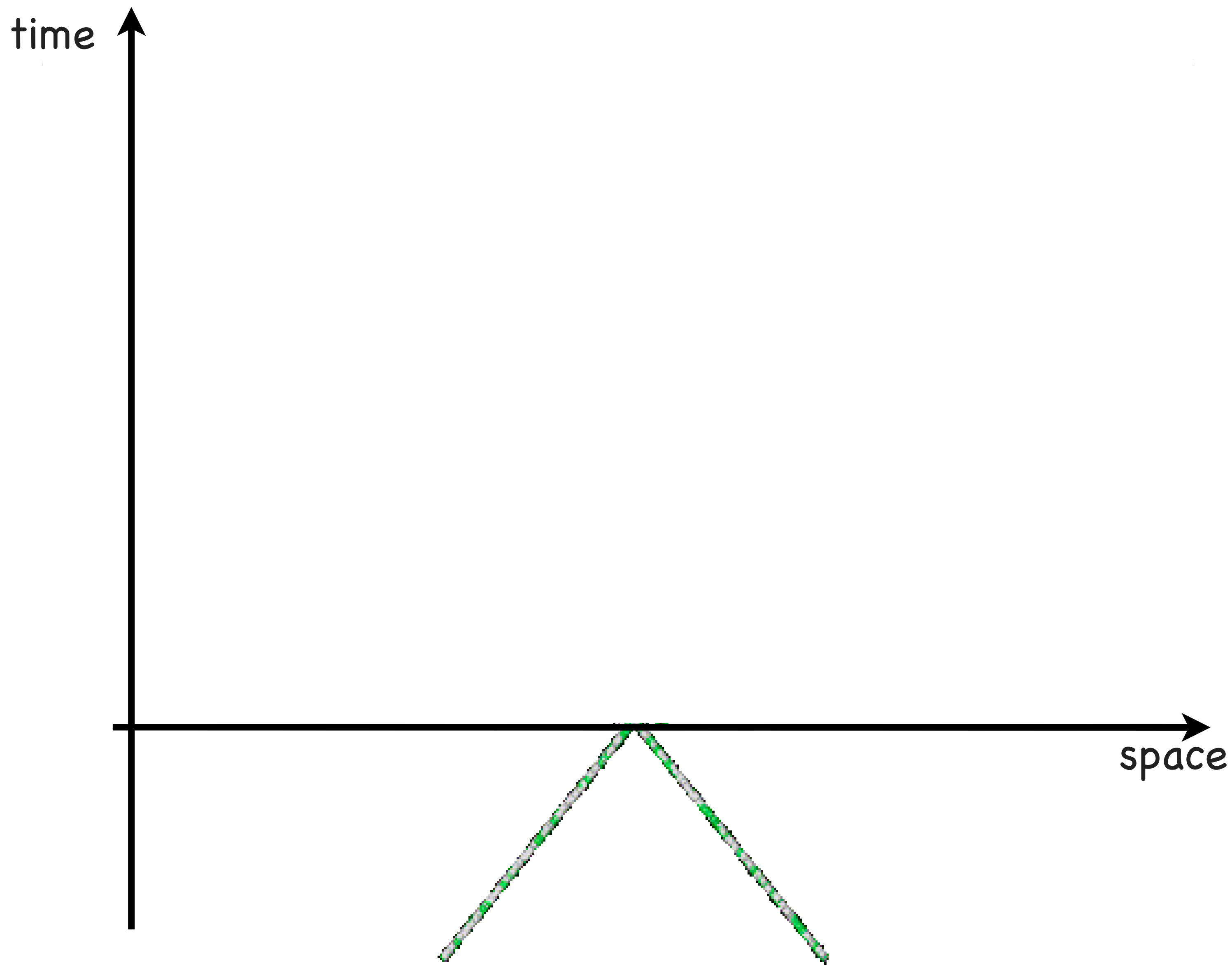
- However lattice simulations of QCD at finite temperature are not (yet) performed with "physical" light-quark masses.

- They do not provide any phase diagram,

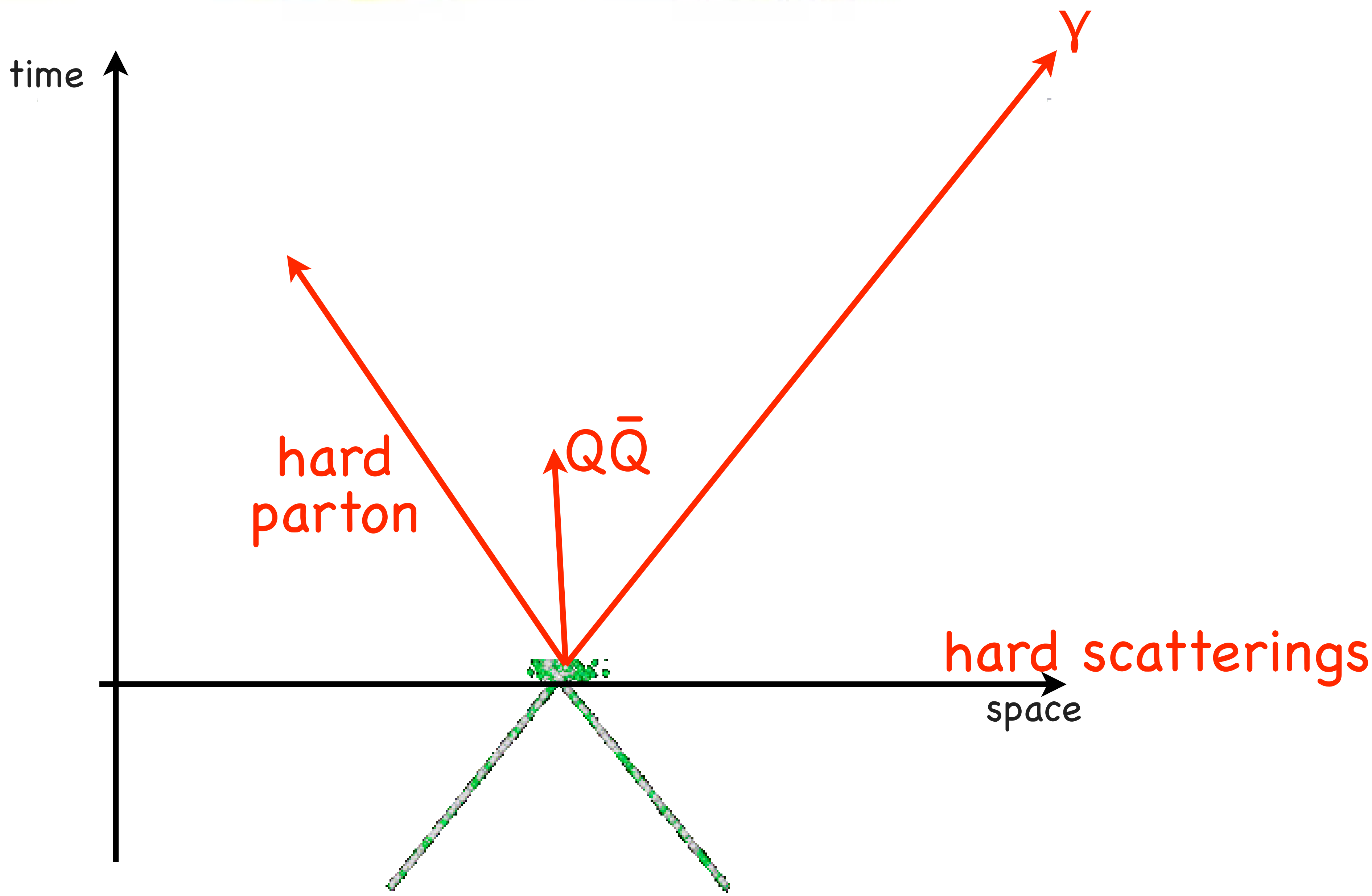
- nor transport coefficients.

(yet?)

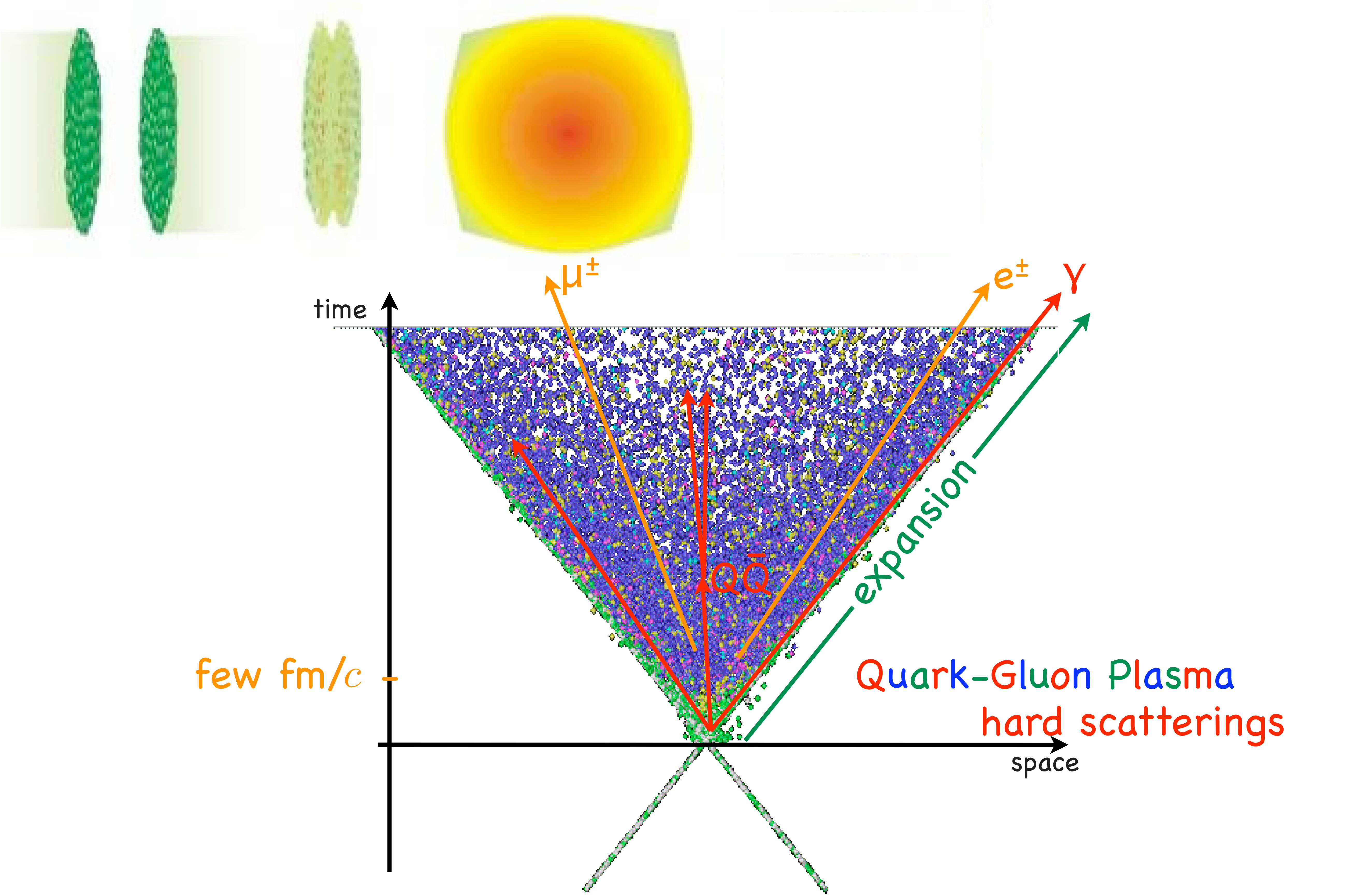
Time evolution of a heavy-ion collision



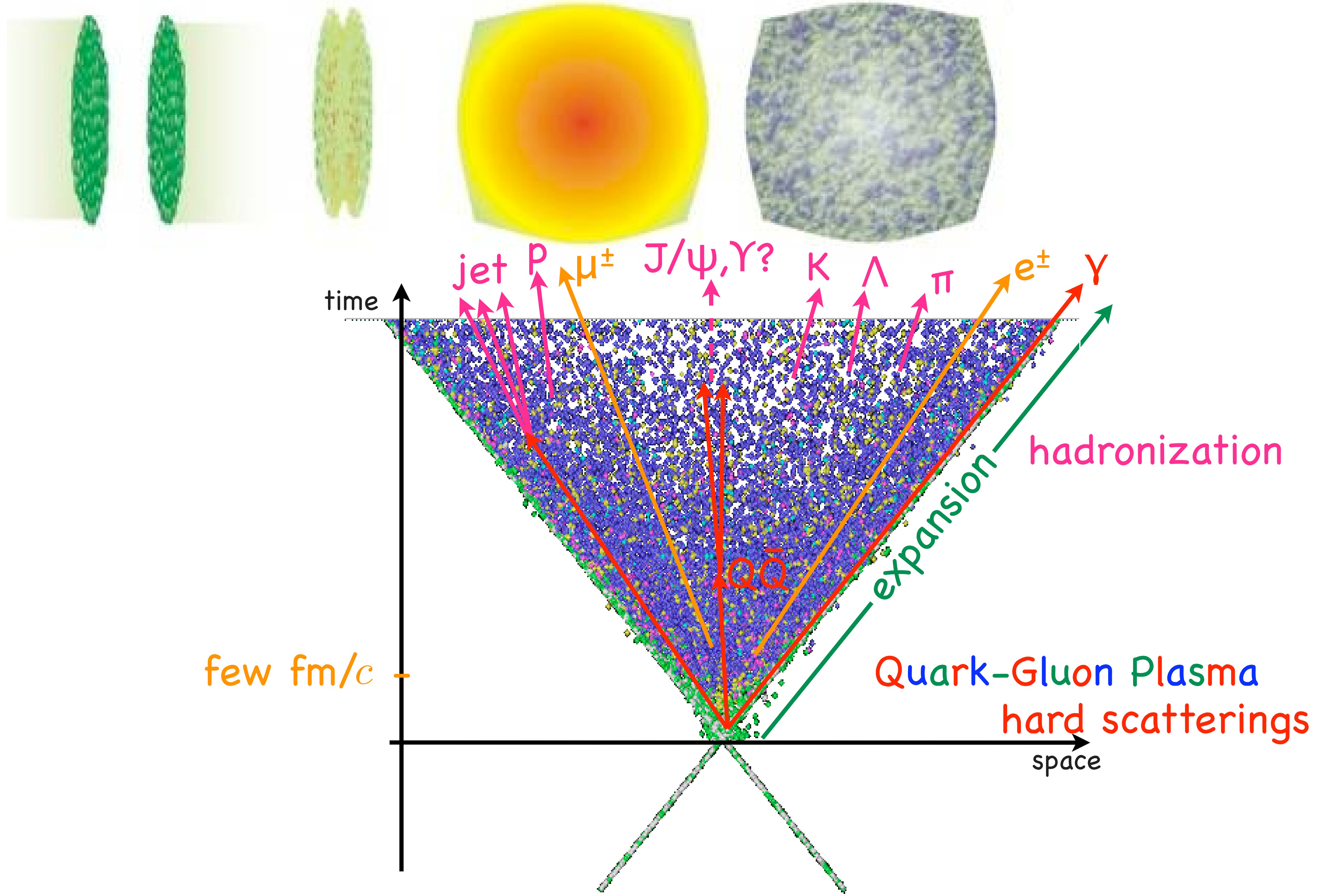
Time evolution of a heavy-ion collision



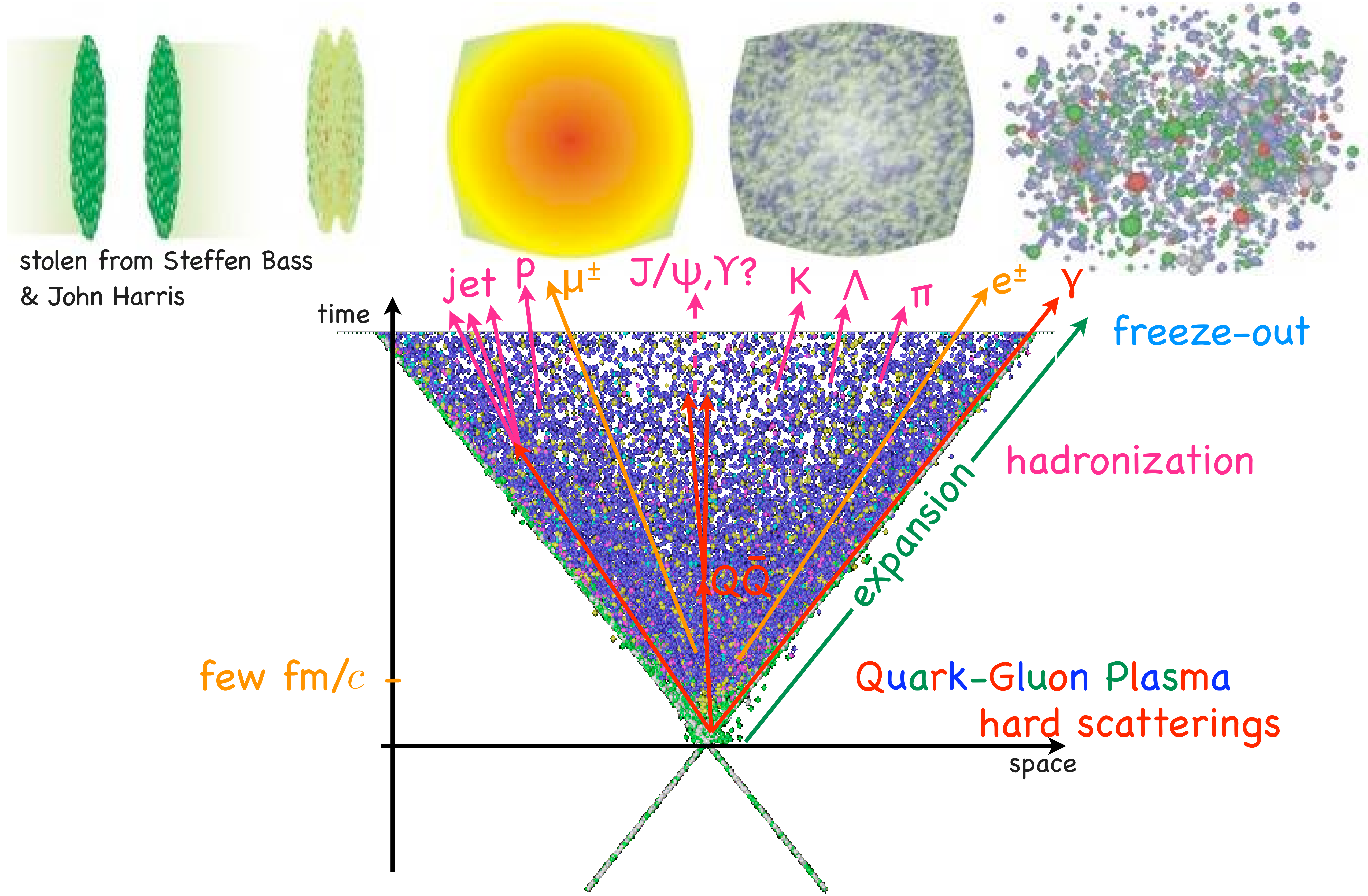
Time evolution of a heavy-ion collision



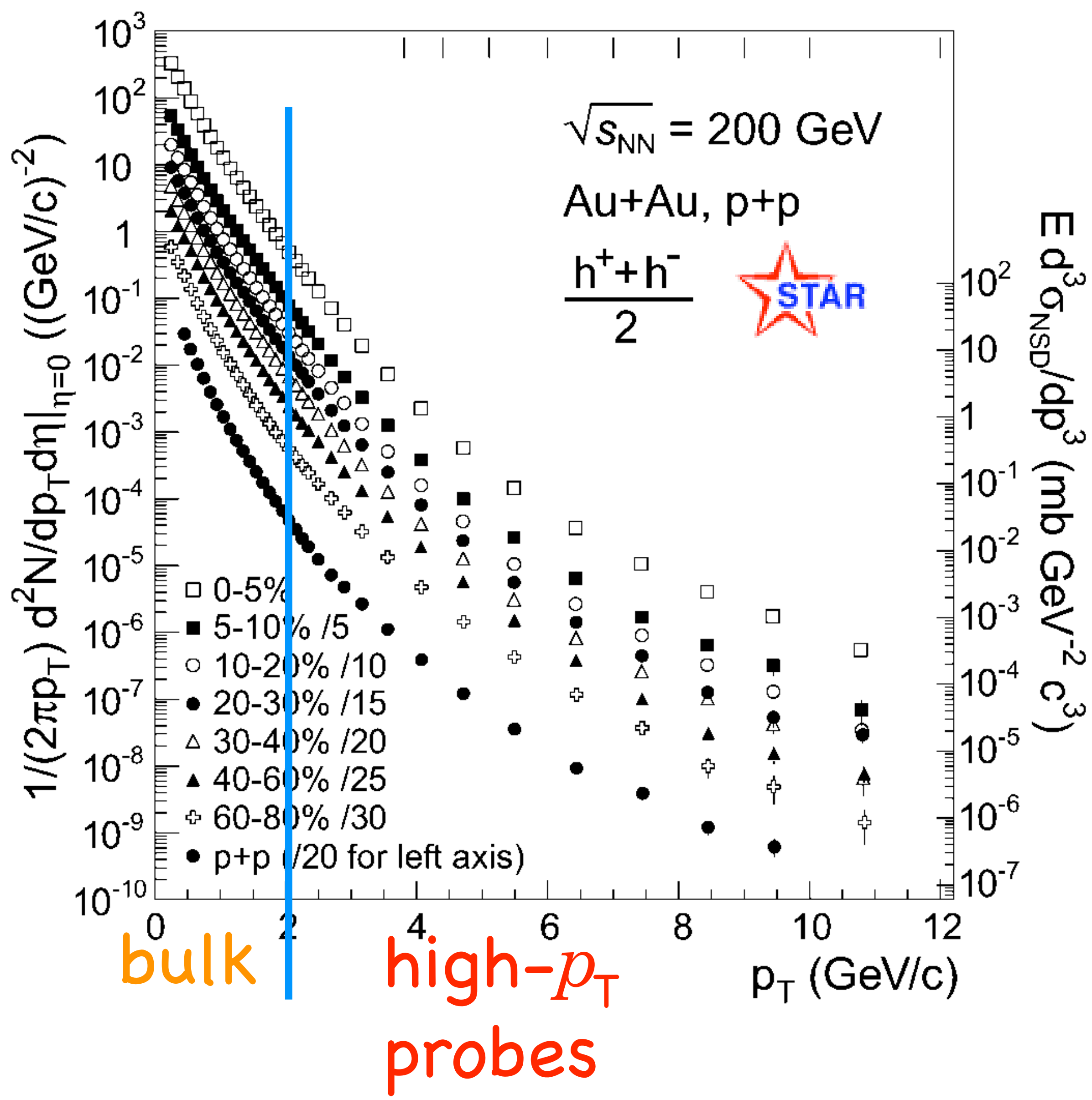
Time evolution of a heavy-ion collision



Time evolution of a heavy-ion collision



Bulk observables vs. hard probes



Only few particles with high transverse momenta (or containing heavy quarks), but their production mechanism is a priori better understood (perturbative QCD) ☞ can probe their environment ≡ the "bulk".

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)

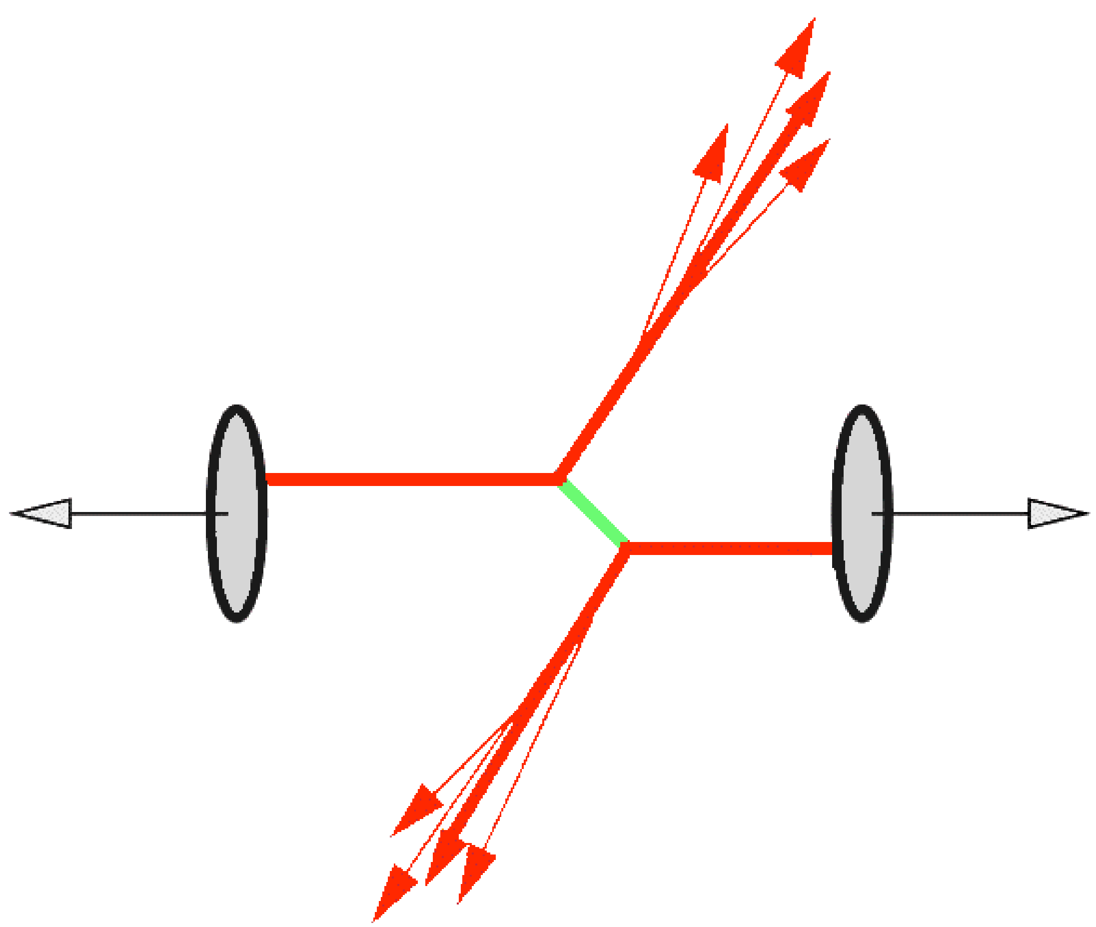
J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

[...] 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 ...

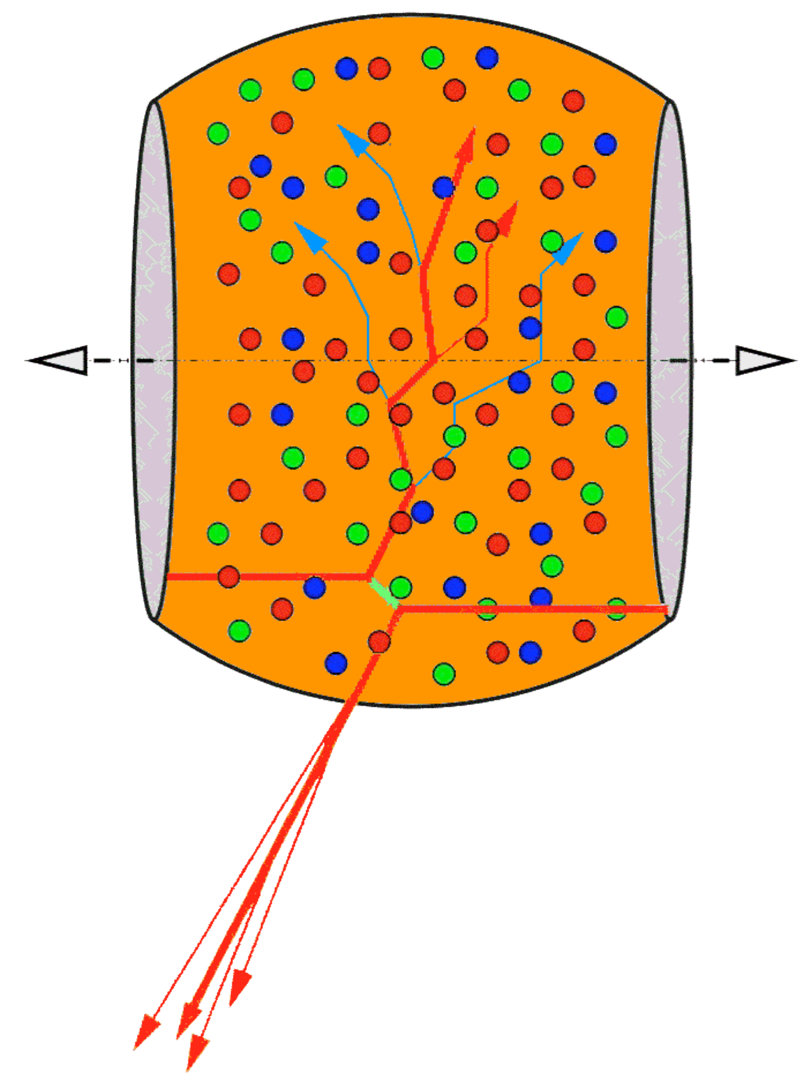
"Jet quenching": basic picture

A fast parton propagating through a dense medium will "lose" part of its energy-momentum.
(cf. energy loss of electrically charged particles in matter: Bethe-Bloch...)
The resulting jet of hadrons (if any!) is distorted: "quenching".

in vacuum



in medium



"Jet quenching": note the analogy!

Review of Particle Properties, chap.27 ("Passage of particles through matter"), Bethe-Bloch equation (27.1) (for massive particles):

$$-\frac{\mathrm{d}E}{\mathrm{d}\ell} = K\frac{z^2}{\beta^2}\frac{Z}{A}\left[\frac{1}{2}\ln\frac{2m_ec^2\beta^2\gamma^2T_{\mathrm{max}}}{I} - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right]$$

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

(here, electromagnetic energy loss)

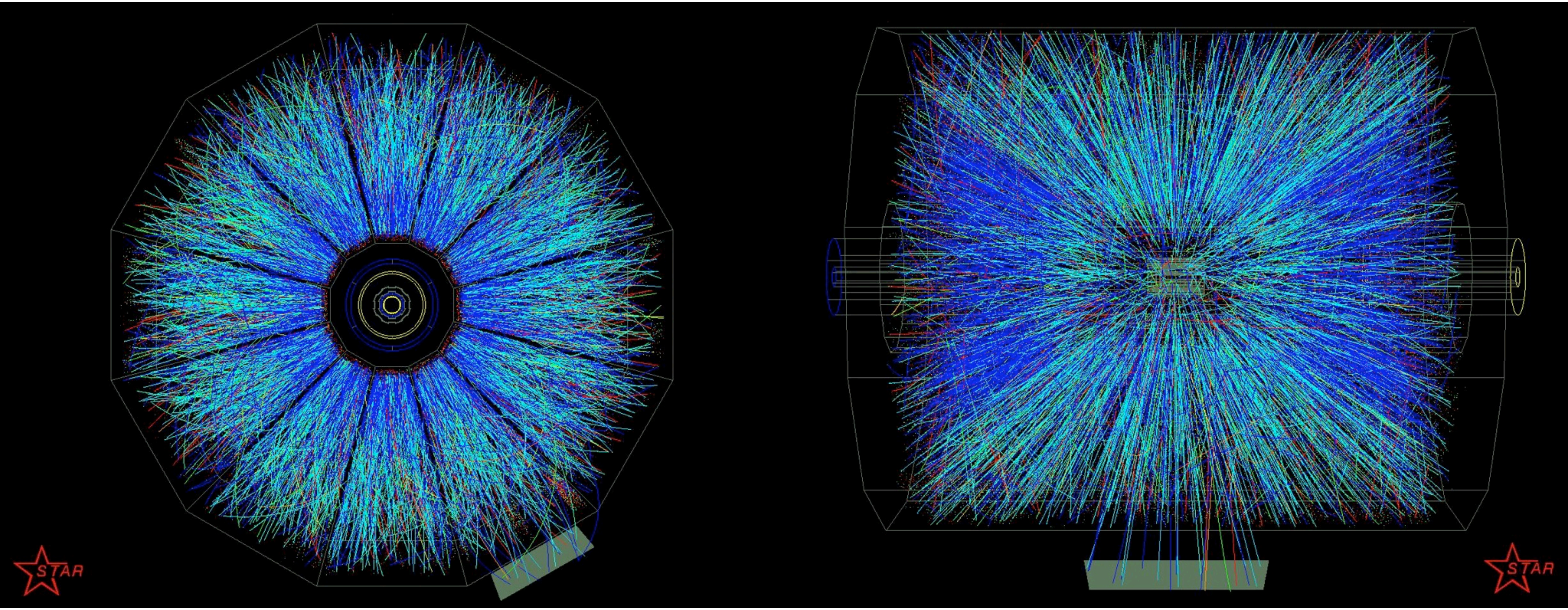
Use of jet quenching in heavy-ion collisions (theorist's view!):
Measure the energy deposited by a quark/gluon with (known) high p_T as it travels through the dense medium ⇝ medium properties

(here, QCD energy loss)

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:



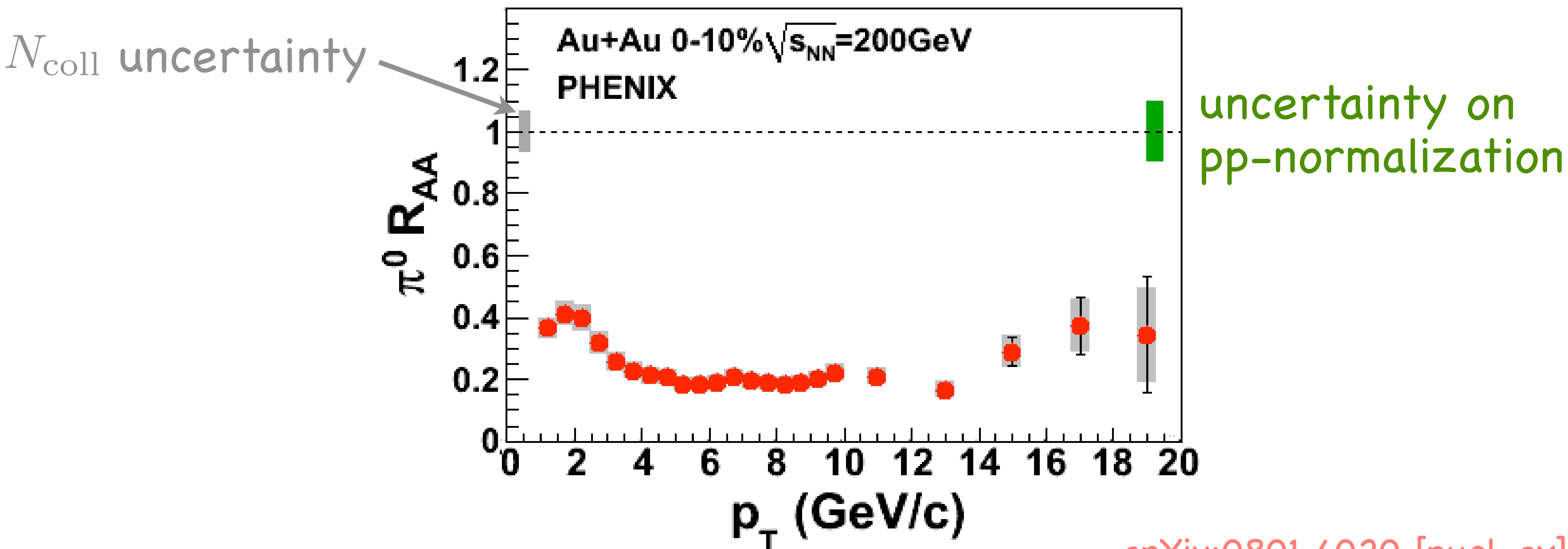
Common lore: forget about identifying jets in RHIC heavy-ion collisions.

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

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

One-particle observable: nuclear modification factor $R_{AA} \equiv \frac{1}{N_{\rm coll}} \frac{\frac{{\rm d}^2 N_{AA}}{{\rm d}P_T\,{\rm d}y}}{\frac{{\rm d}^2 N_{pp}}{{\rm d}P_T\,{\rm d}y}}$

(=1 if AA collision is a superposition of independent NN collisions*)



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!

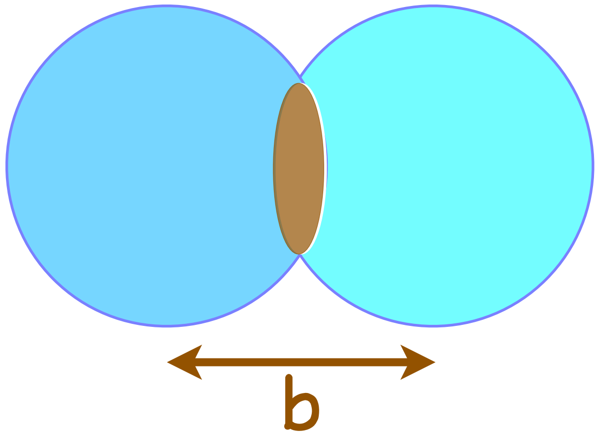
* up to isospin corrections...

Heavy-ion collisions: geometry

Heavy nuclei have a finite radius!

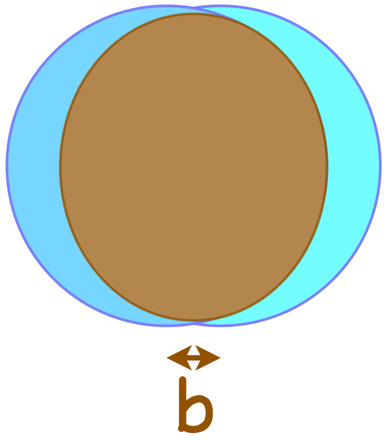
☞ In a collision the impact parameter plays a role:

- 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)

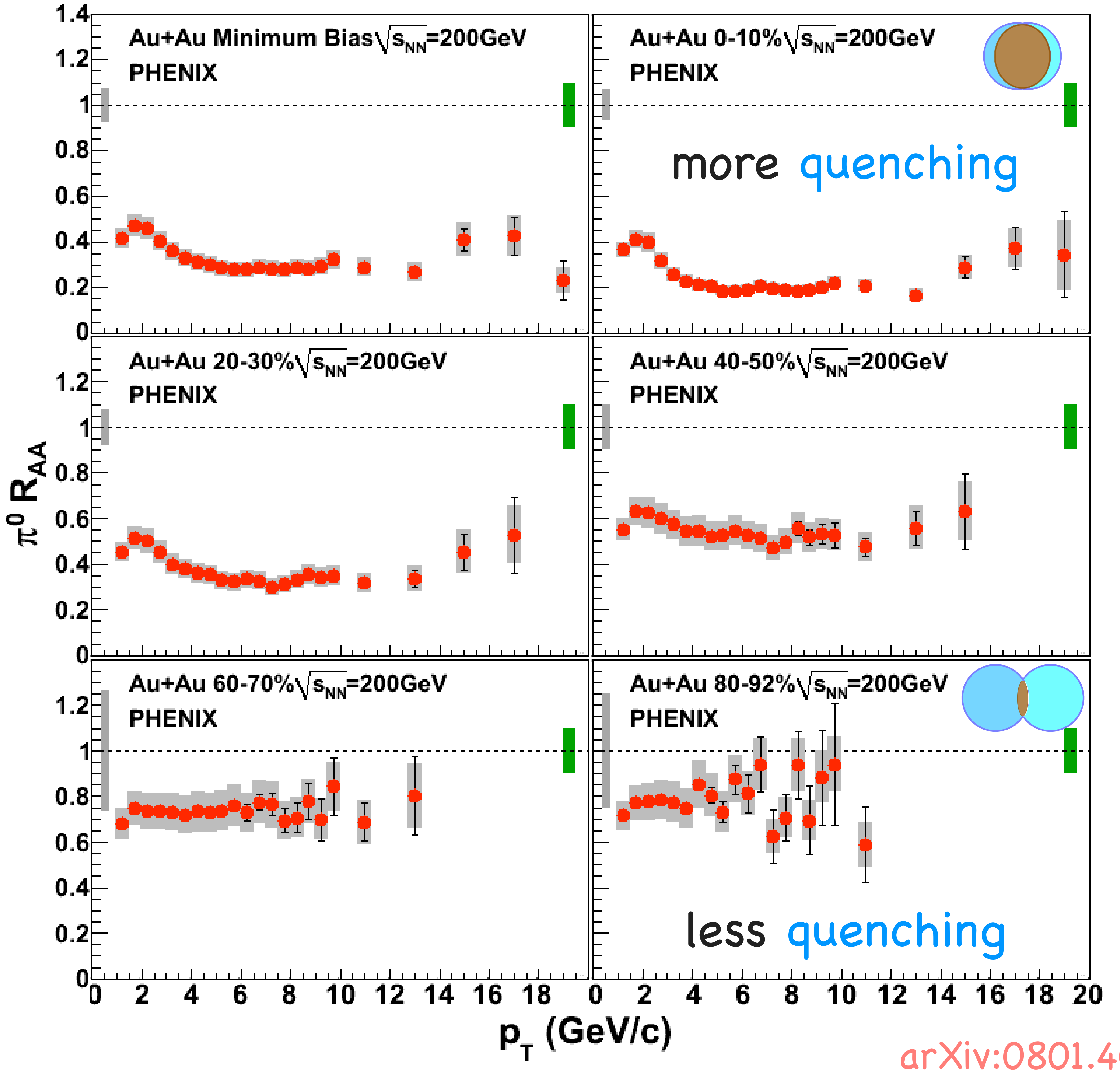


High-p_T partons have larger in-medium path-lengths, thus lose more energy (in average).

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

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

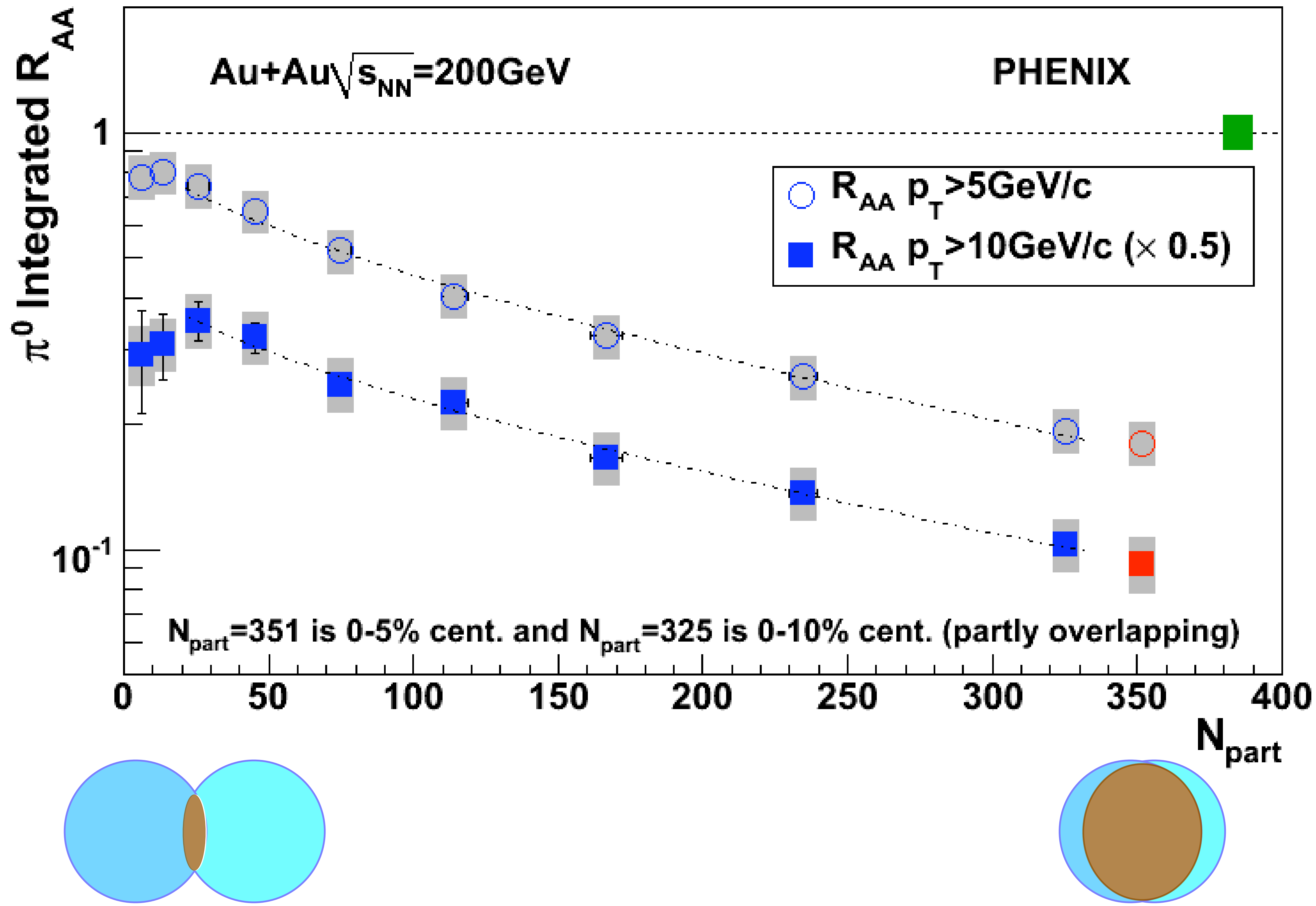
$$R_{AA} \equiv \frac{1}{N_{\rm coll}} \frac{\frac{d^2 N_{AA}}{dP_T\,dy}}{\frac{d^2 N_{pp}}{dP_T\,dy}}$$



arXiv:0801.4020 [nucl-ex]

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

The scaled yield of high-p_T hadrons decreases with growing centrality: increasing quenching



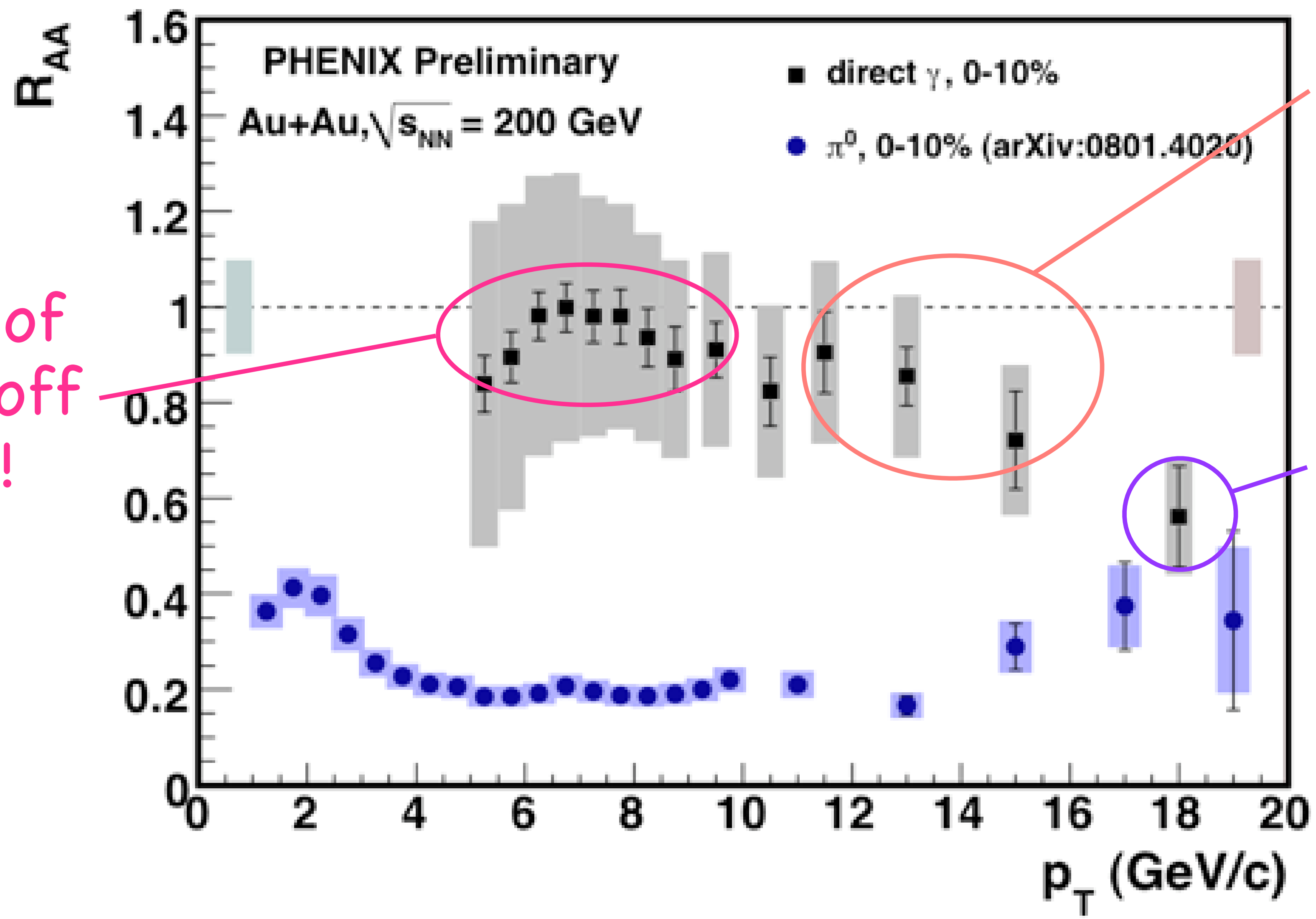
arXiv:0801.4020 [nucl-ex]

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*: $R_{AA} \approx 1$

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



deviation from 1 not unexpected (isospin...)

embarrassingly close to the pion value?

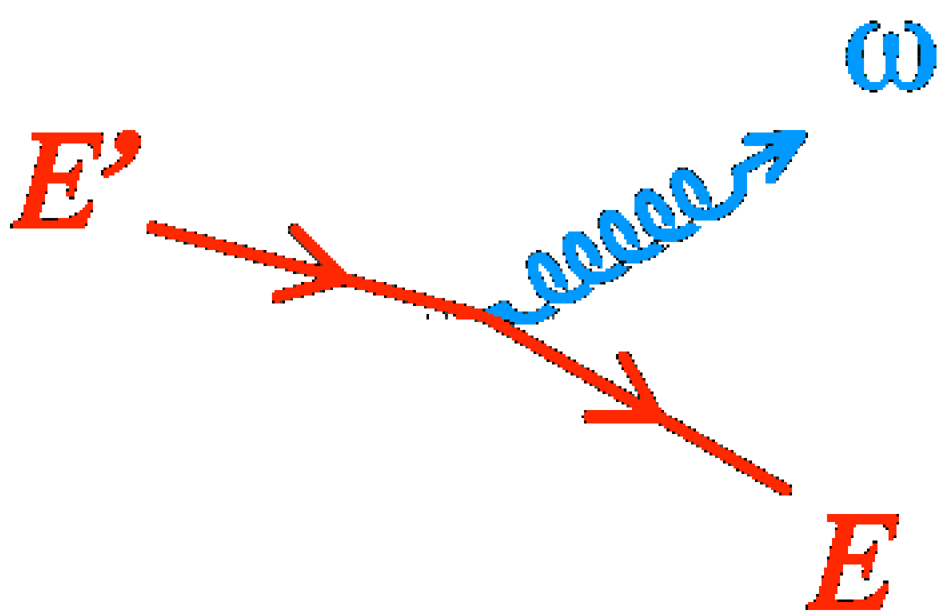
* yet photon production is modified: Bremsstrahlung, photons from parton fragmentation...

Jet quenching: underlying processes

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

inelastic

"~~radiative~~" process (Bremsstrahlung)

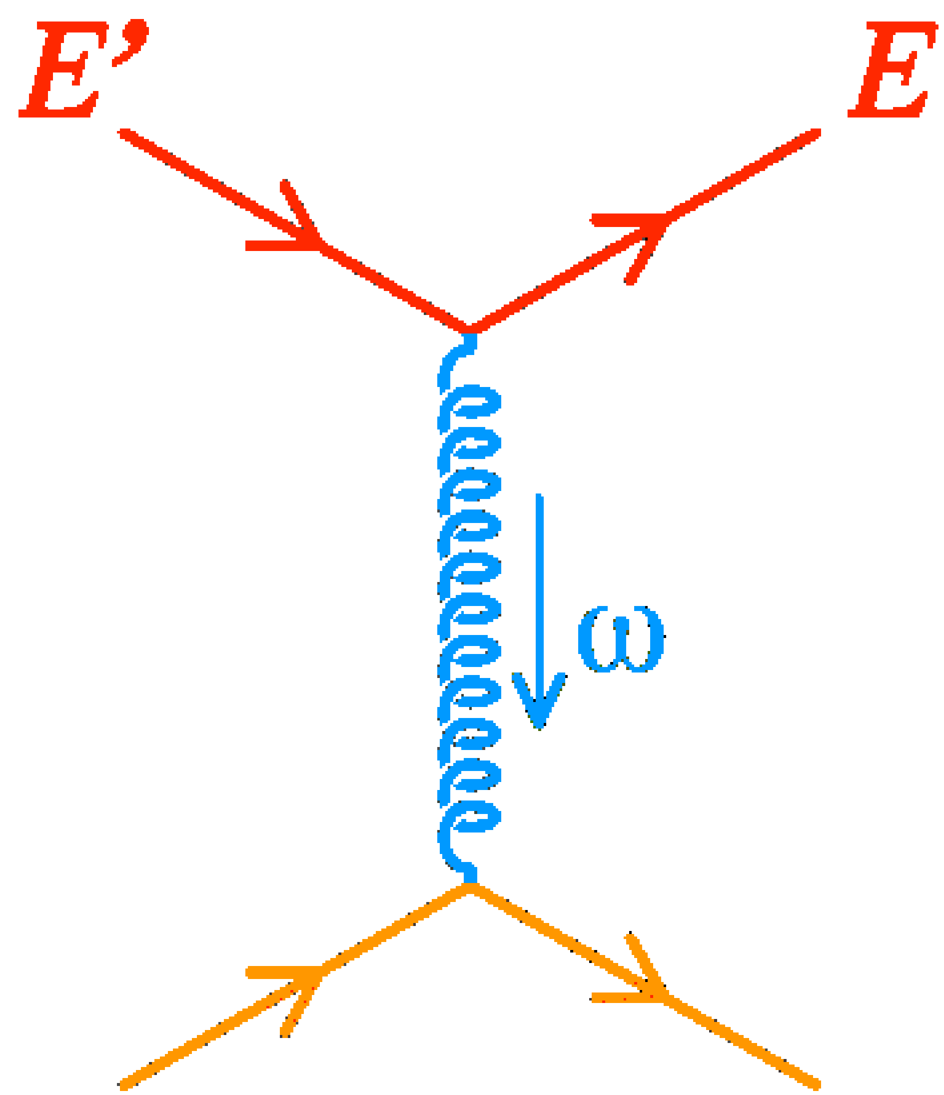


also "in vacuum" (DGLAP evolution), yet modified by the presence of a (colored) medium

collisions!

elastic

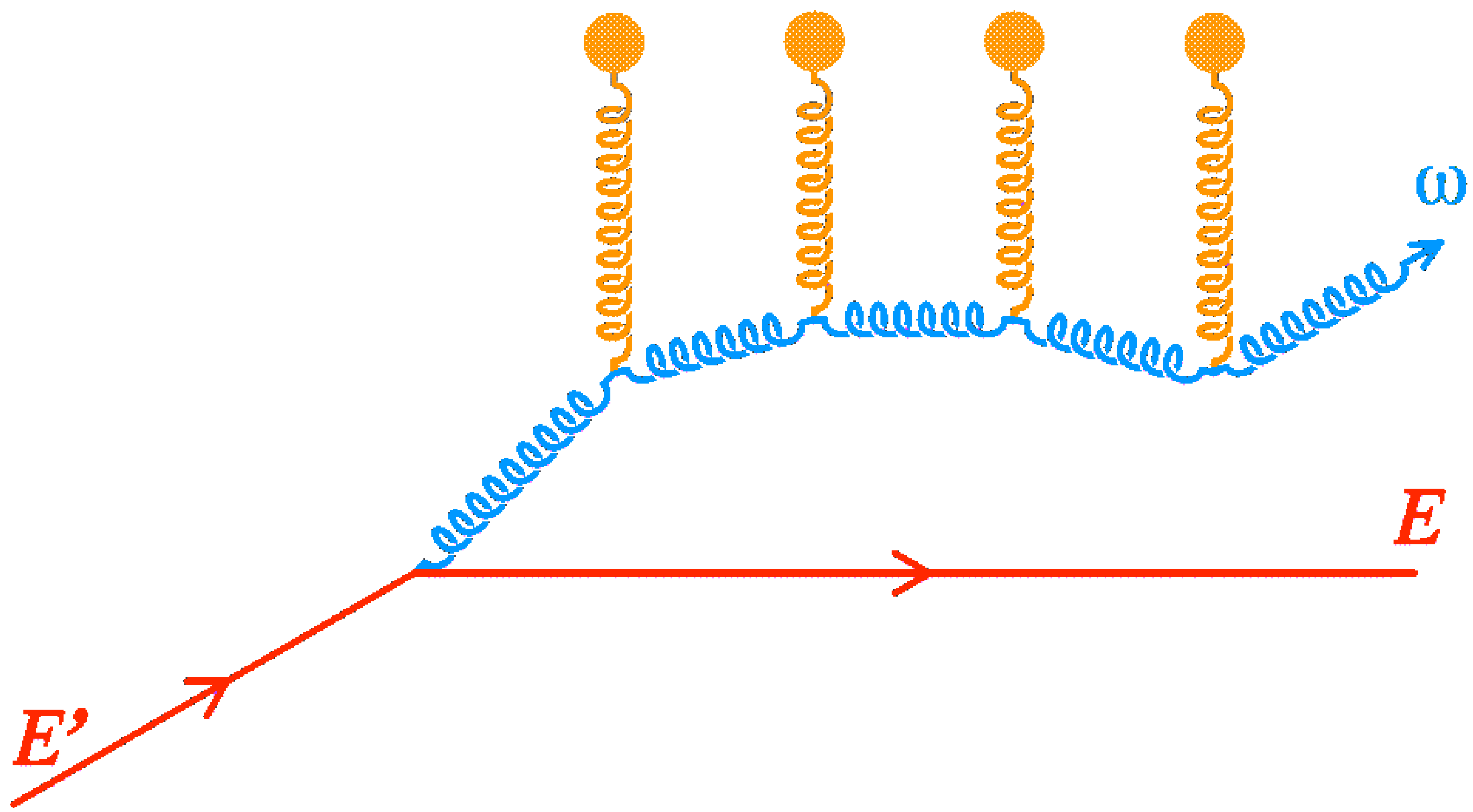
"~~collisional~~" process



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.

☞ transport coefficient $\hat{q}$

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

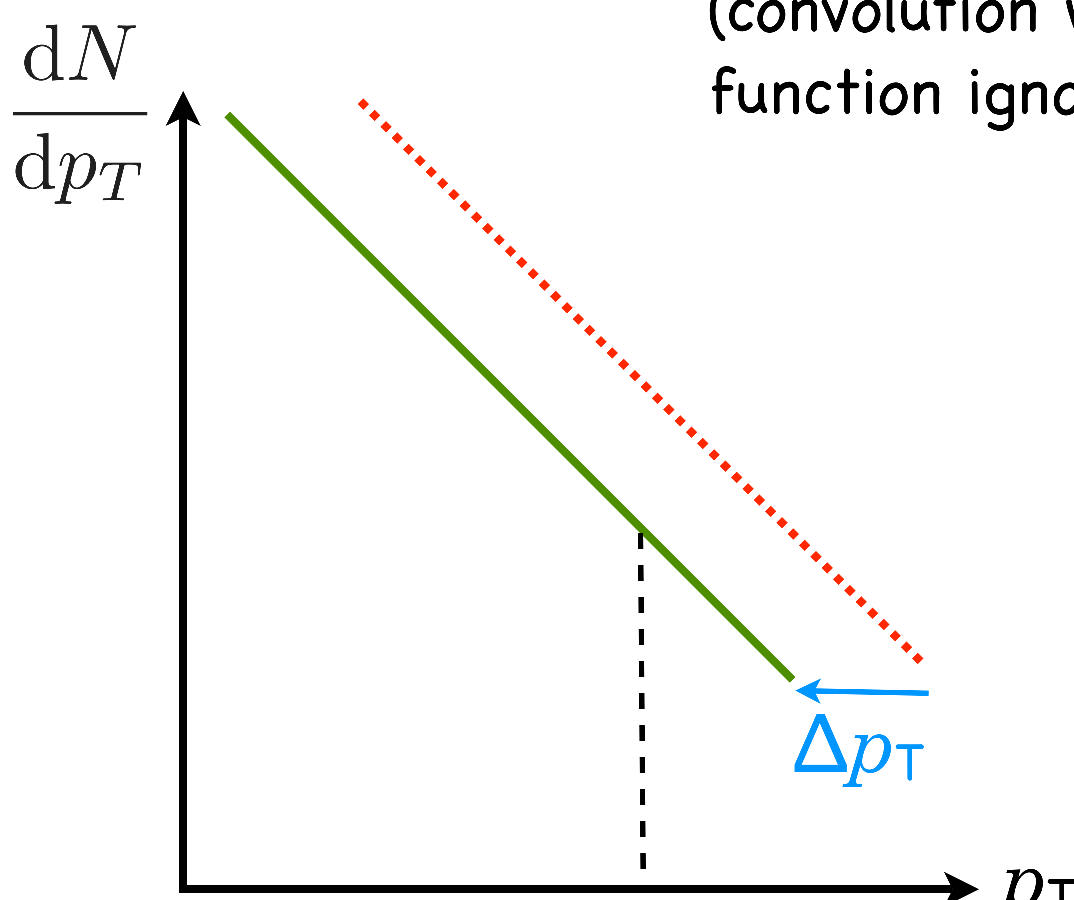
Jet quenching: a stochastic process

Medium-enhanced gluon radiation or elastic scatterings, which degrade the energy of the high-p_T parton, are stochastic processes:

a few lucky quarks/gluons might escape the medium unscathed.

☞ the corresponding hadrons will dominate the steeply falling p_T spectrum ⇔ R_{AA}.

(convolution with parton fragmentation function ignored for simplicity)



hadrons measured with p_T were partons with $p_T+\Delta p_T$

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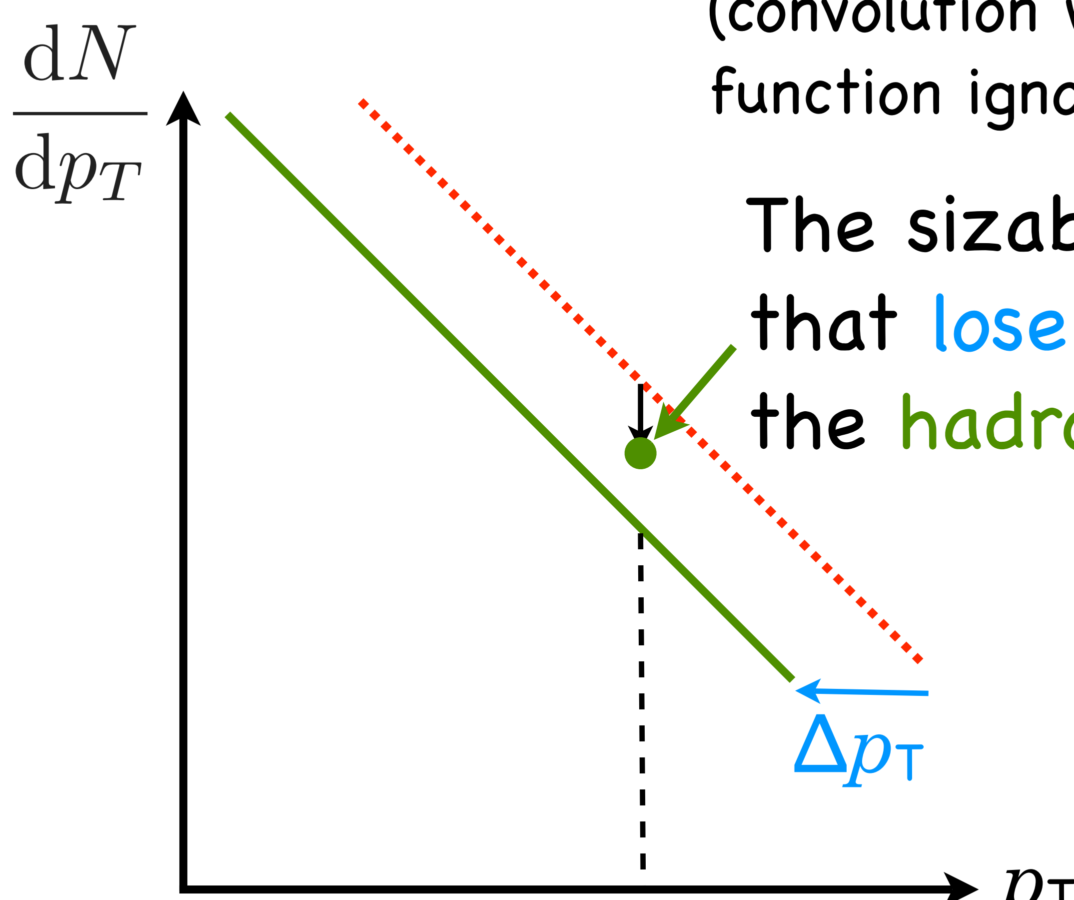


hadrons measured with p_T were partons with $p_T + \Delta p_T$

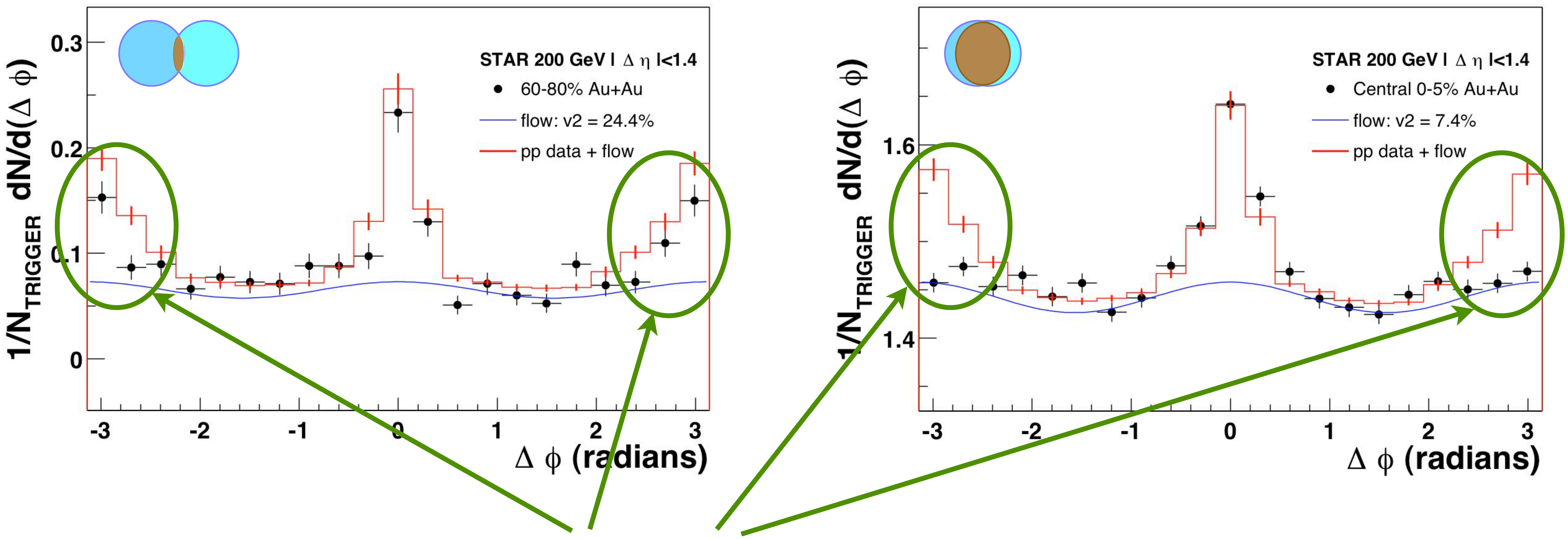
Limited discriminative power of single-particle yields. (under debate!)

"Jets" in Au–Au collisions at RHIC (4)

Beyond single-particle yields...

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

* in fact, conditional yields...



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

Models of jet quenching

There exist a handful of models that implement some degradation of the energy of a high-p_T quark / gluon traversing a dense medium.

☞ Generally, success* in fitting the nuclear modification factor R_{AA}.

However, difficulties when going to more detailed predictions:

- Energy-momentum conservation is not automatically ensured at each step (a parton can radiate more energy than it has initially!)

⇒ conservation is imposed a posteriori, globally ("quenching weights").

- The formalisms deal differently with the leading parton (for which medium-enhanced radiation is considered) and the subleading ones

⇒ cannot address intra-jet correlations.

* modulo the introduction of initial conditions + some dynamical evolution of the medium, of characteristics of the parton spectra (shadowing, p_T-broadening)...

Modeling the medium influence: a suggestion

Nice description of jets in e^+e^- / $p\bar{p}$ collisions through MLLA: emphasis on momentum conservation (more on next slide)

- The hump of the MLLA "limiting spectrum" is mostly due to the singular parts of the splitting functions.
- In medium, the emission of a soft gluons by a fast parton increases.
- Accounting properly for momentum conservation is more important than using the "correct" spectrum of extra gluons (choice!)

☞ One can model medium-induced effects by modifying the parton splitting functions $P_{ji}(z)$... see e.g. Guo & Wang, PRL **85** (2000) 3591

... and especially their singular parts:

$$P_{qq}(z) = \frac{4}{3}\left[\frac{2(1+f_{\rm med})}{(1-z)_+} - (1+z)\right]$$

$f_{\rm med} > 0 \quad \Rightarrow$ Gluonstrahlung increases

NB & Wiedemann, hep-ph/0506218

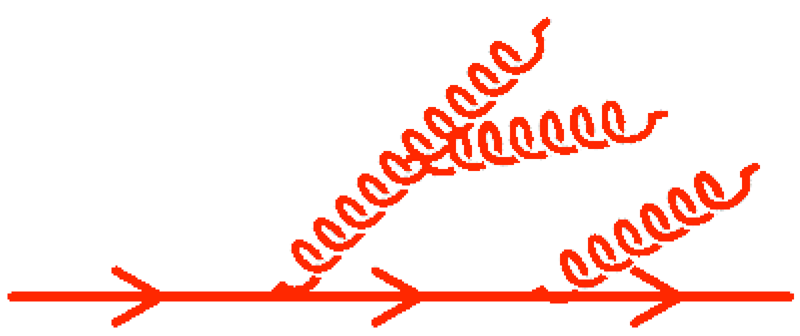
MLLA: some theory

Modified Leading Logarithmic Approximation (of QCD)

Main ingredients:

- Resummation of double- and single-logarithms in $\ln\frac{1}{x}$ and $\ln\frac{E_{\rm jet}}{\Lambda_{\rm eff}}$;
- Takes into account the running of α_s along the parton shower evolution;
- Probabilistic interpretation (results from intra-jet color coherence):
  - independent successive branchings $g\to gg$, $g\to q\bar{q}$, $q\to qg$;
  - with angular ordering of the sequential parton branchings:

    at each step in the evolution, the angle between father and offspring partons decreases.



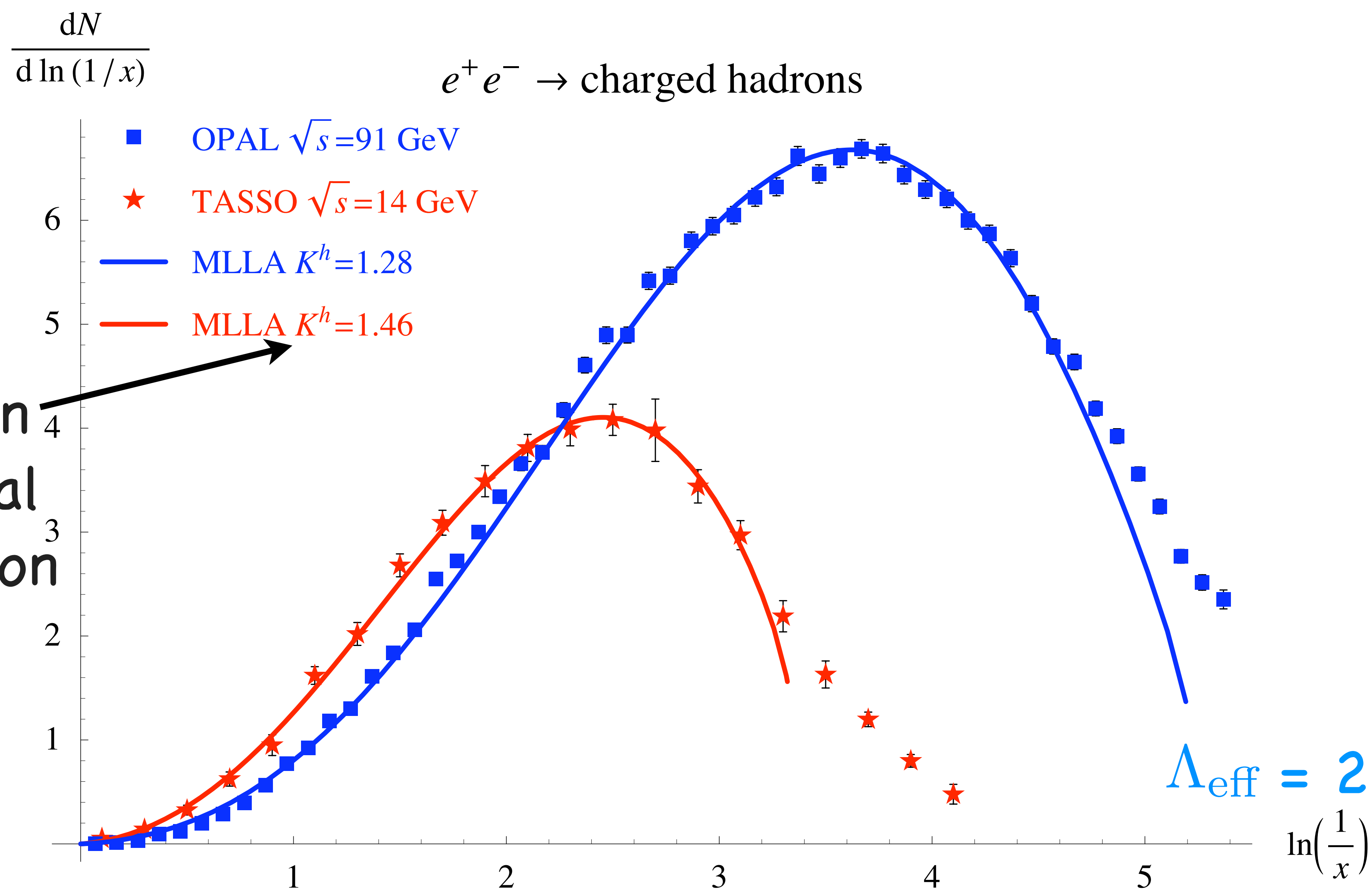
- Includes in a systematic way next-to-leading-order corrections.

$\mathcal{O}(\sqrt{\alpha_s})$!

Dokshitzer, Khoze, Troian

MLLA vs. e^+e^- data

Longitudinal distribution of hadrons inside a jet:



hadronization through Local Parton-Hadron Duality

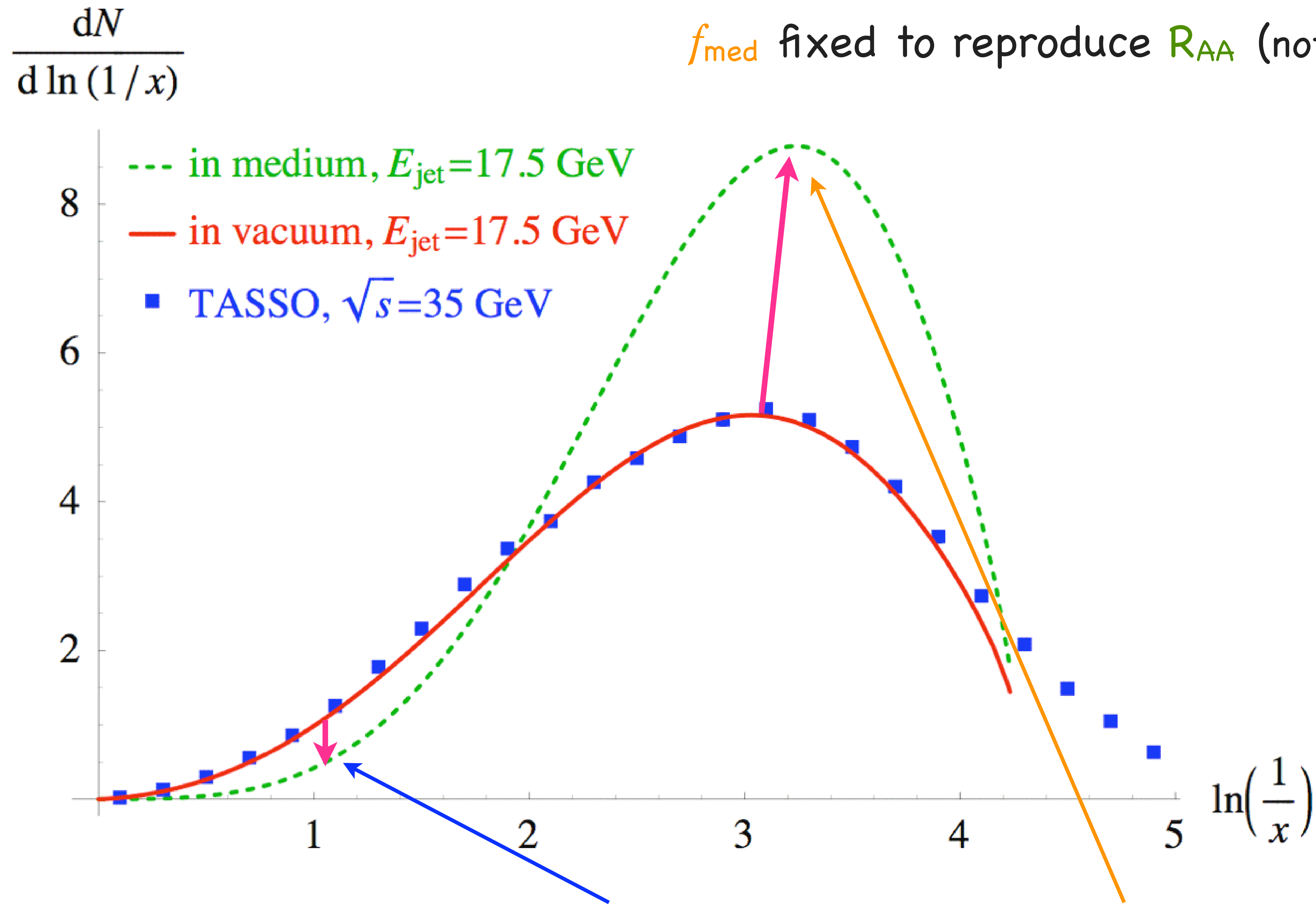
Λ_{eff} = 253 MeV

Good description of data also in $p\bar{p}$ collisions (CDF):

MLLA is reliable! (also at large x...)

“Medium-modified” MLLA

f_{med} fixed to reproduce R_{AA} (not shown here)



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

Describing a whole jet becomes feasible!

NB, U.A.Wiedemann, hep-ph/0506218

Monte-Carlo implementations are appearing.

Zapp, Ingelmann, Rathsman, Stachel & Wiedemann, arXiv:0804.3568 [hep-ph]

Jets 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 $\hat{q}$ / $f_{\rm med}$: medium density + mean free path
- Already a wealth of experimental data from RHIC: high p_T physics
  - single-particle spectra
  - 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
    new formalism, that reduces to MLLA in the absence of a medium: analytical computations feasible (oversimplified medium influence), as a benchmark for the emerging Monte Carlo codes with more realistic medium modeling.

Jets in heavy-ion collisions

topics not mentioned here (1)

- Many theoretical ideas
  - gluon vs. light quark vs. heavy quark: different energy losses
  - photon (resp. Z^0)-jet correlations
  - response of the medium to the excitation by a jet...
- Phenomenology
  - successful in reproducing single-hadron spectra... but meaningful? (many additional ingredients enter the fits)
  - extrapolations to / predictions for LHC...

Jets in heavy-ion collisions

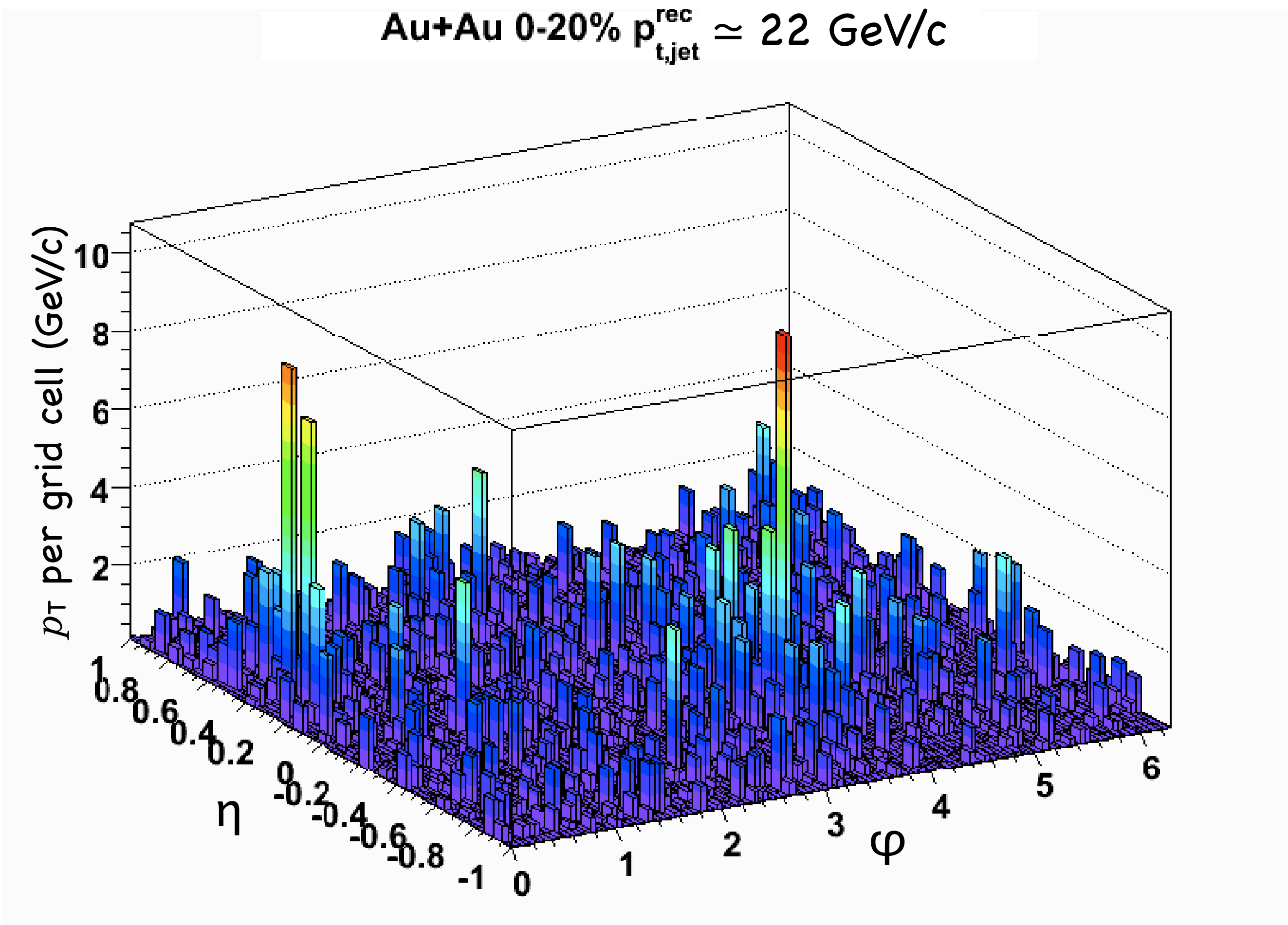
topics not mentioned here (2)

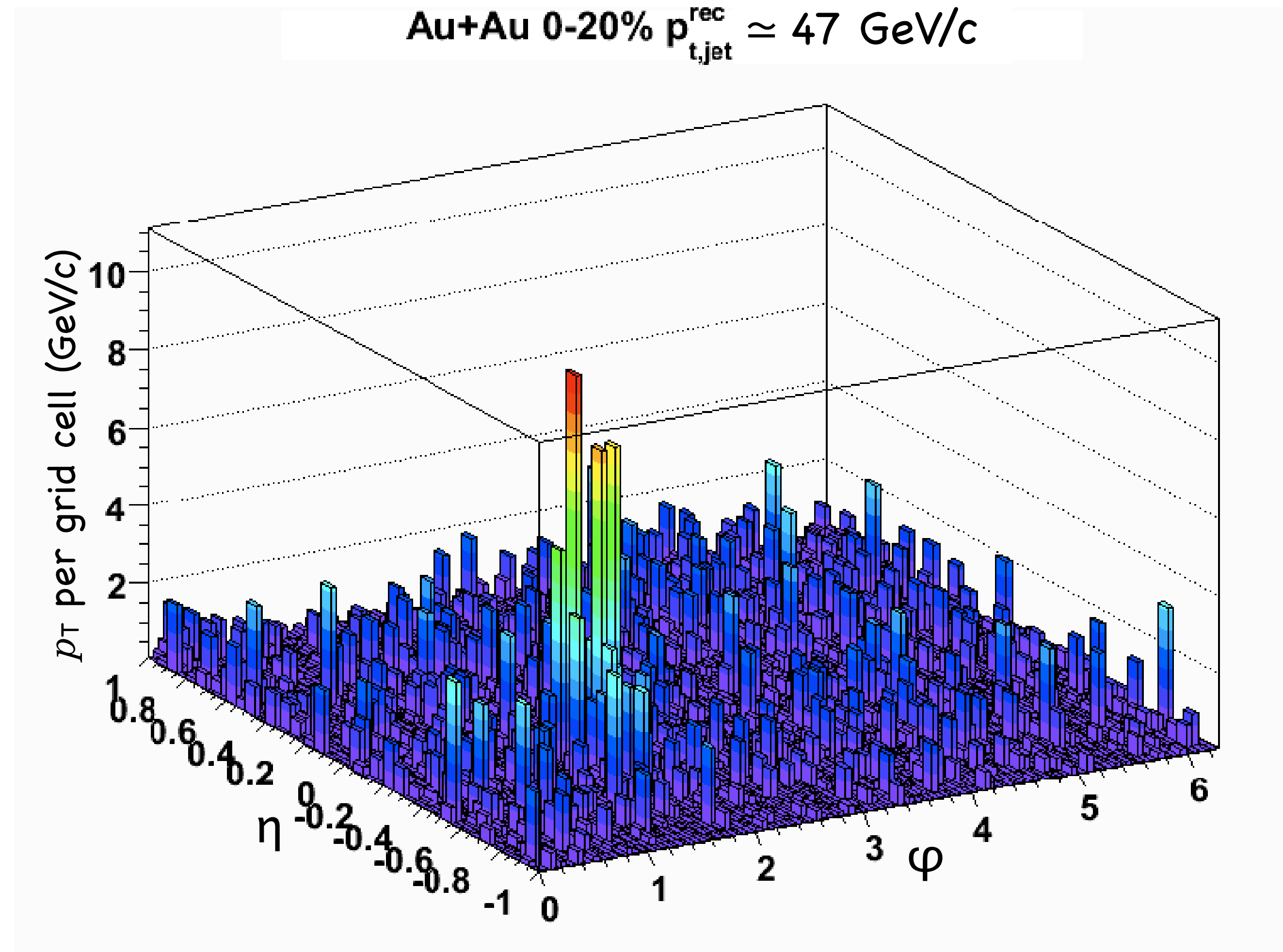
- Challenges for LHC studies!
  - 3 experiments with different / complementary capabilities (common saying: "jets, at last!")
  - no pp collision at $\sqrt{s_{NN}}$ = 5.5 TeV: some rethinking will be needed!
- Already existing experimental data from RHIC
  - "two-particle correlations" in rapidity
  - dependence on particle type / on azimuth (with respect to the reaction plane) / on energy / on the colliding system (Au+Au vs. Cu+Cu) of single-hadron spectra & azimuthal two-hadron correlations...
  - preliminary photon-jet correlation studies

Jets in Au-Au collisions at RHIC (5)

Audaces fortuna juvat... STAR very preliminary "results"

(with cone or k_T reconstruction algorithms)





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