Status and Prospects of Jet Quenching

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CATHIE-TECHQM Workshop

BNL - 14-18 December 2009

Topics

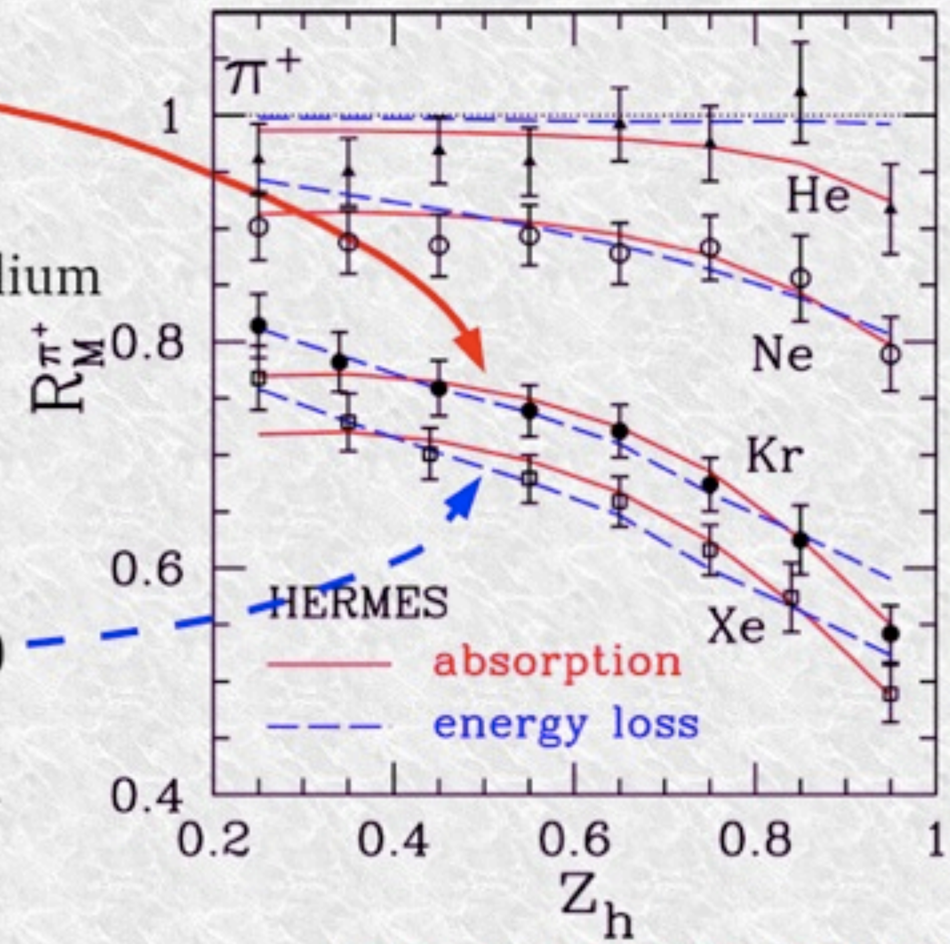
- TEC-HQM: Understanding the limitations of the current theoretical approaches to jet quenching (Verweij, Horowitz, ...)
- MC implementations (Schenke, Corcella)
- Parton energy loss in cold nuclear matter (Arcadi, Majumder)
- Heavy quark / open heavy flavor mesons (Sharma)

Cold nuclear matter

1) Hadron quenching in nDIS

- **Prehadron absorption**
  [Accardi *et al.*;
  Falter *et al.*; Kopeliovich, *et al.*]
  - color neutralization inside the medium
  - prehadron-nucleon scatterings

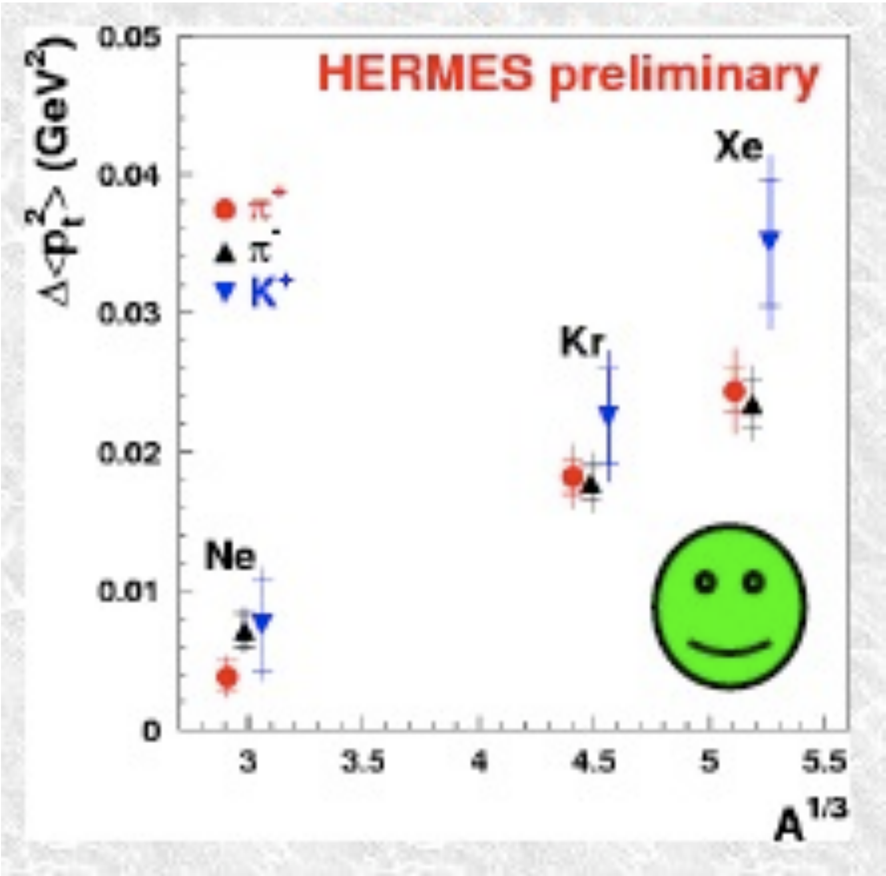
- **Energy loss (gluon bremsstrahlung)**
  [Arleo; Wang *et al.*; Accardi]
  - hadronization outside the medium
  - gluon radiation off struck quark



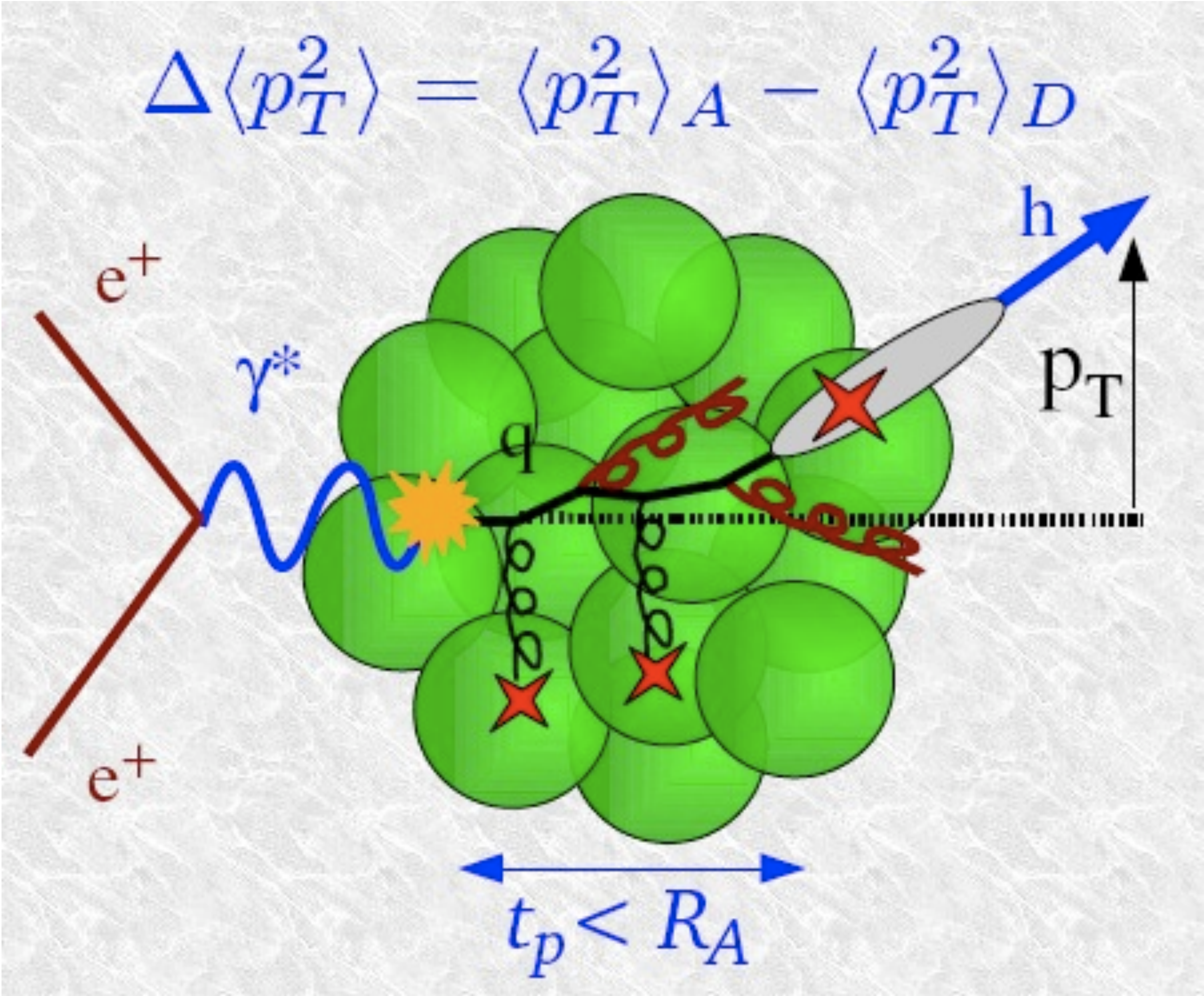
[A.A., et al., NPA 761(05)67]
[A.A., Acta.Phys.Hung. '06 & PRC '07]

accardi@jlab.org BNL, 14-18 December 2009 18

p_T broadening data

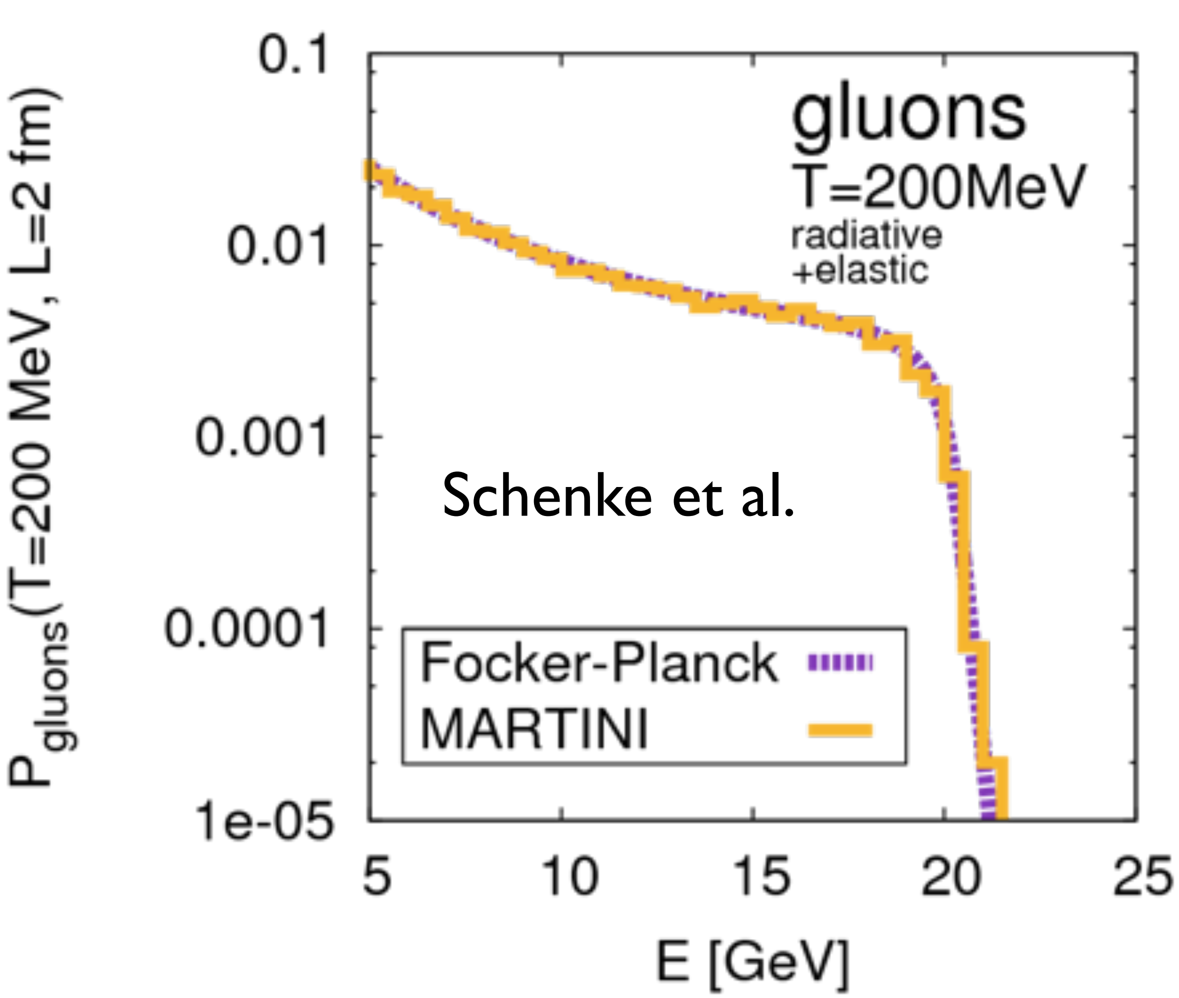


A. Accardi

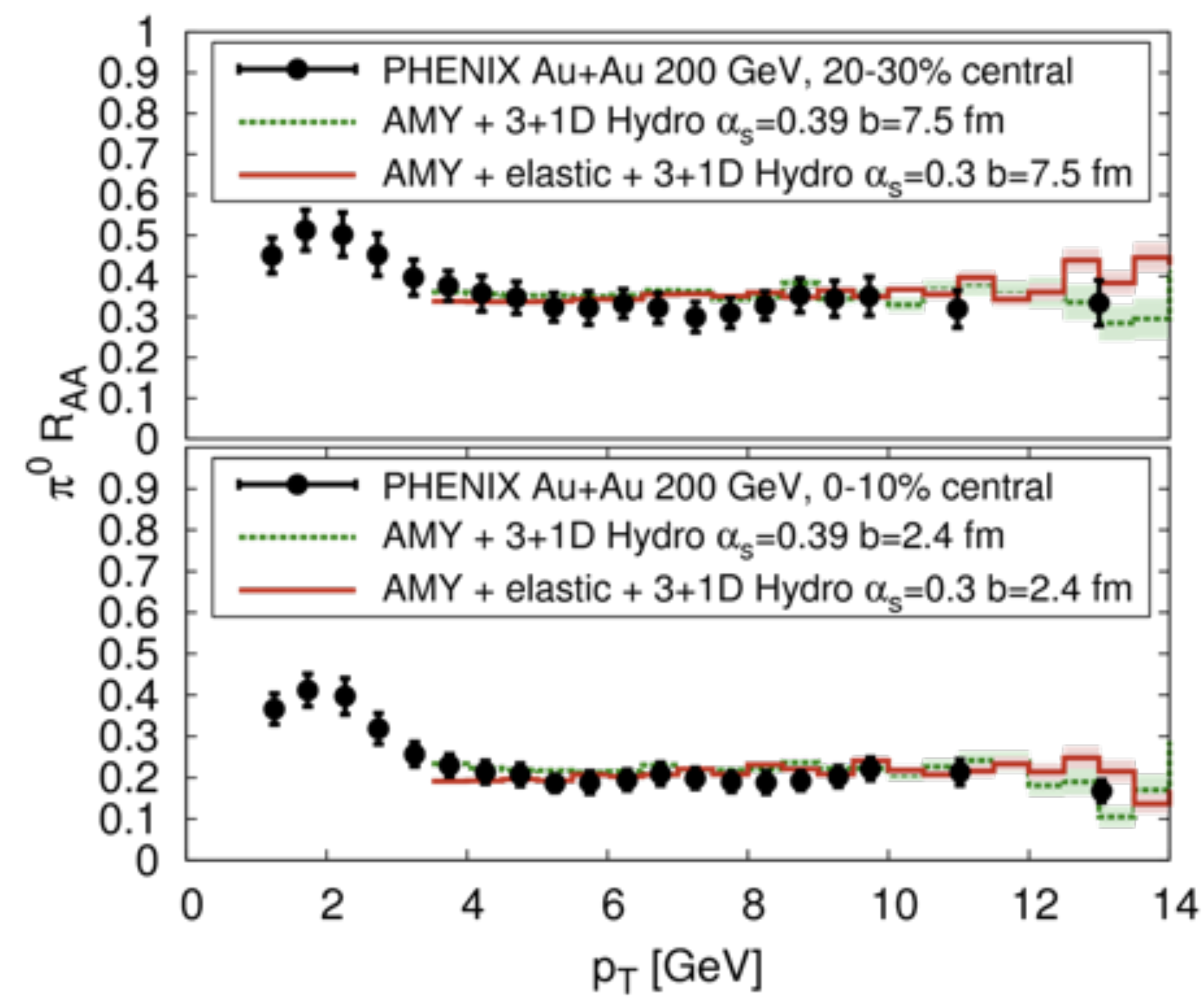


MC schemes

MARTINI:
Monte Carlo for QGP brick



MARTINI:
Au+Au collisions



Formalisms

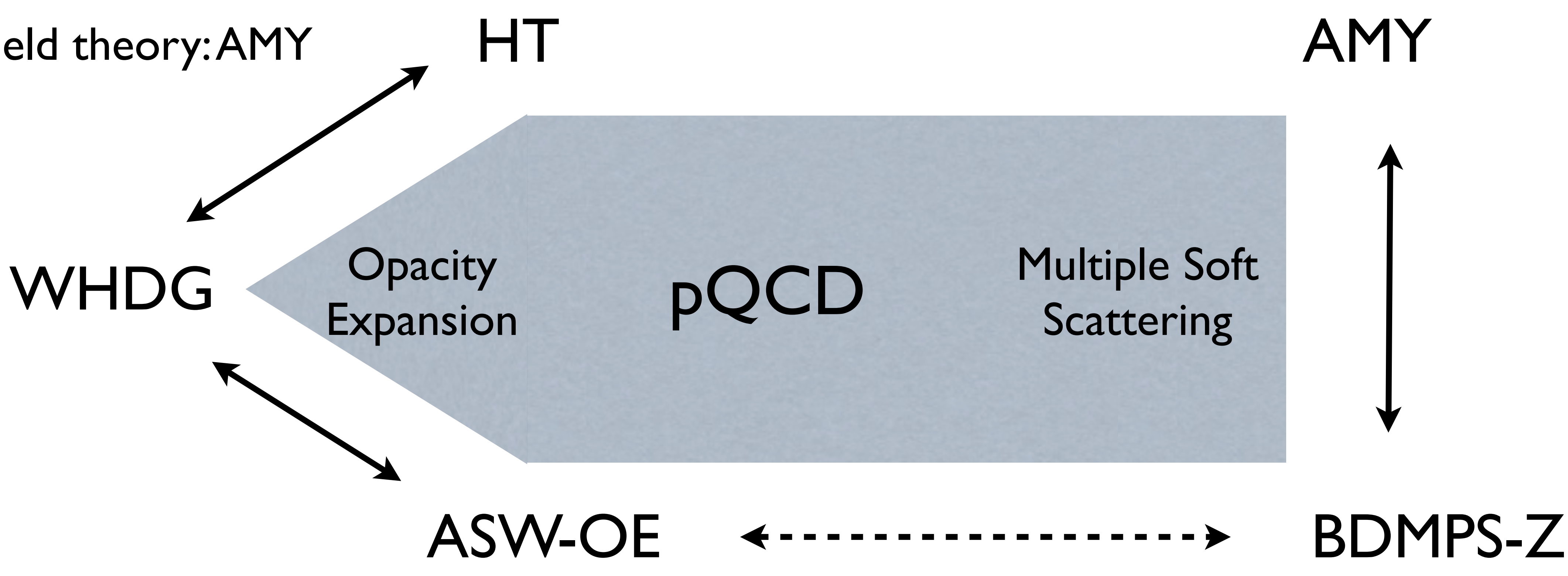
Four major pQCD based formalisms of jet quenching:

★ Opacity expansion: GLV (DGLV), WHDG, ASW-SH

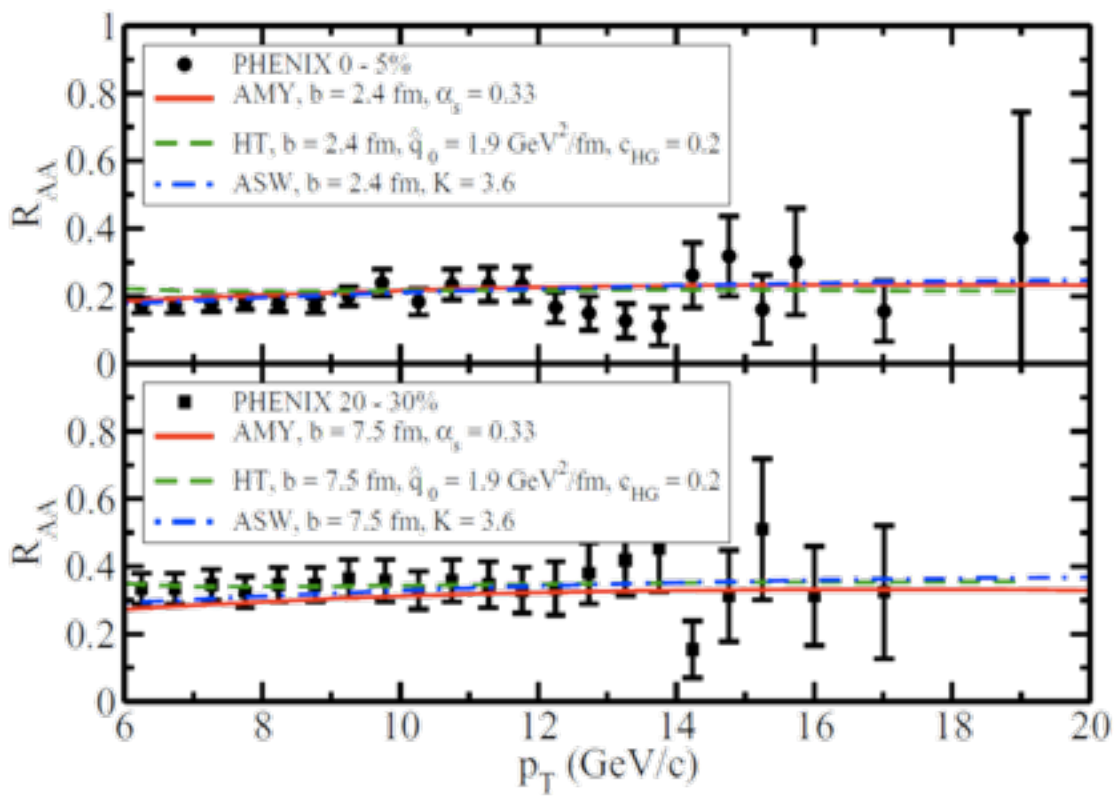
★ Multiple soft scattering: BDMPS, ASW-MS

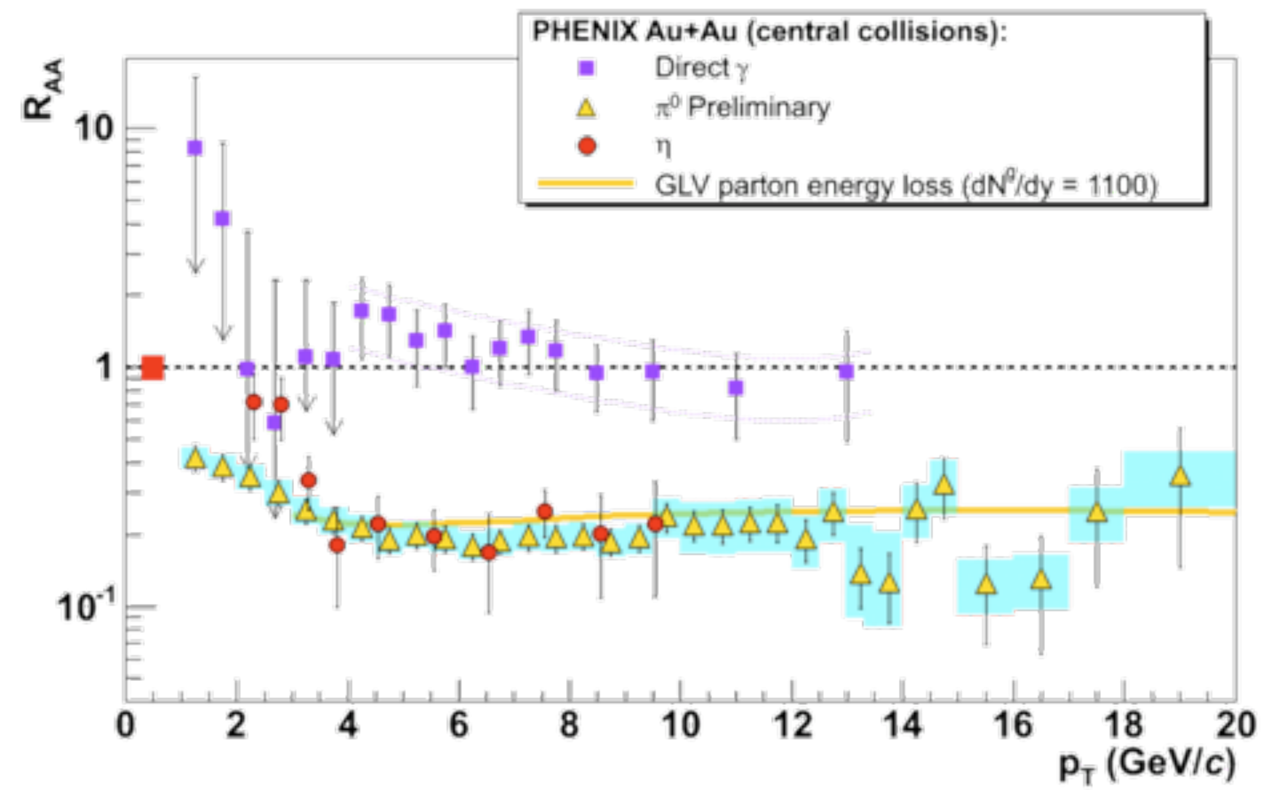
★ Higher twist expansion: HT

★ Thermal field theory: AMY

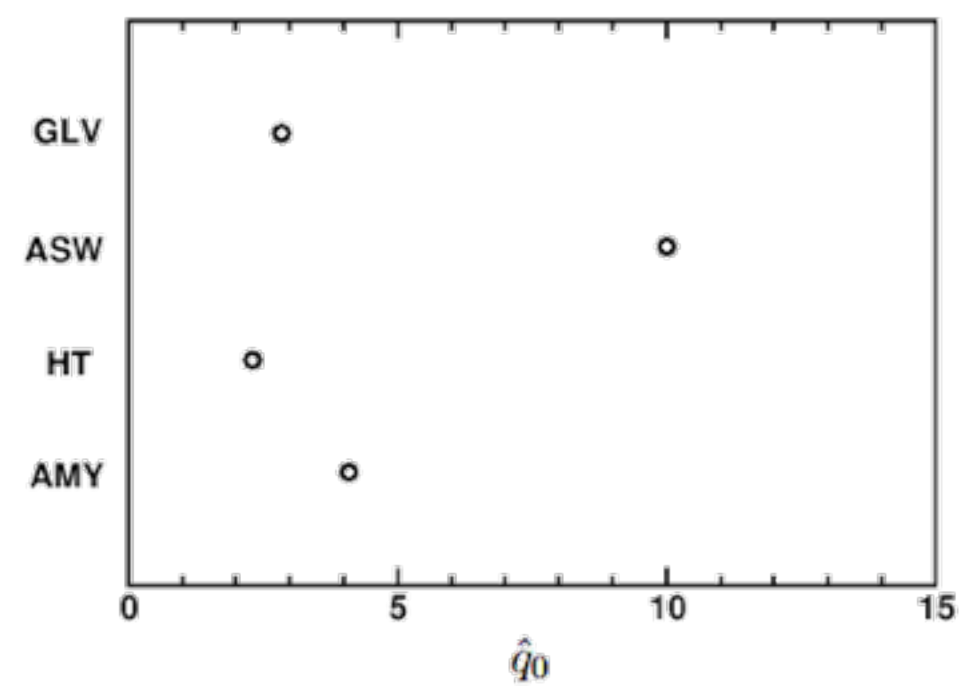


q^ puzzle





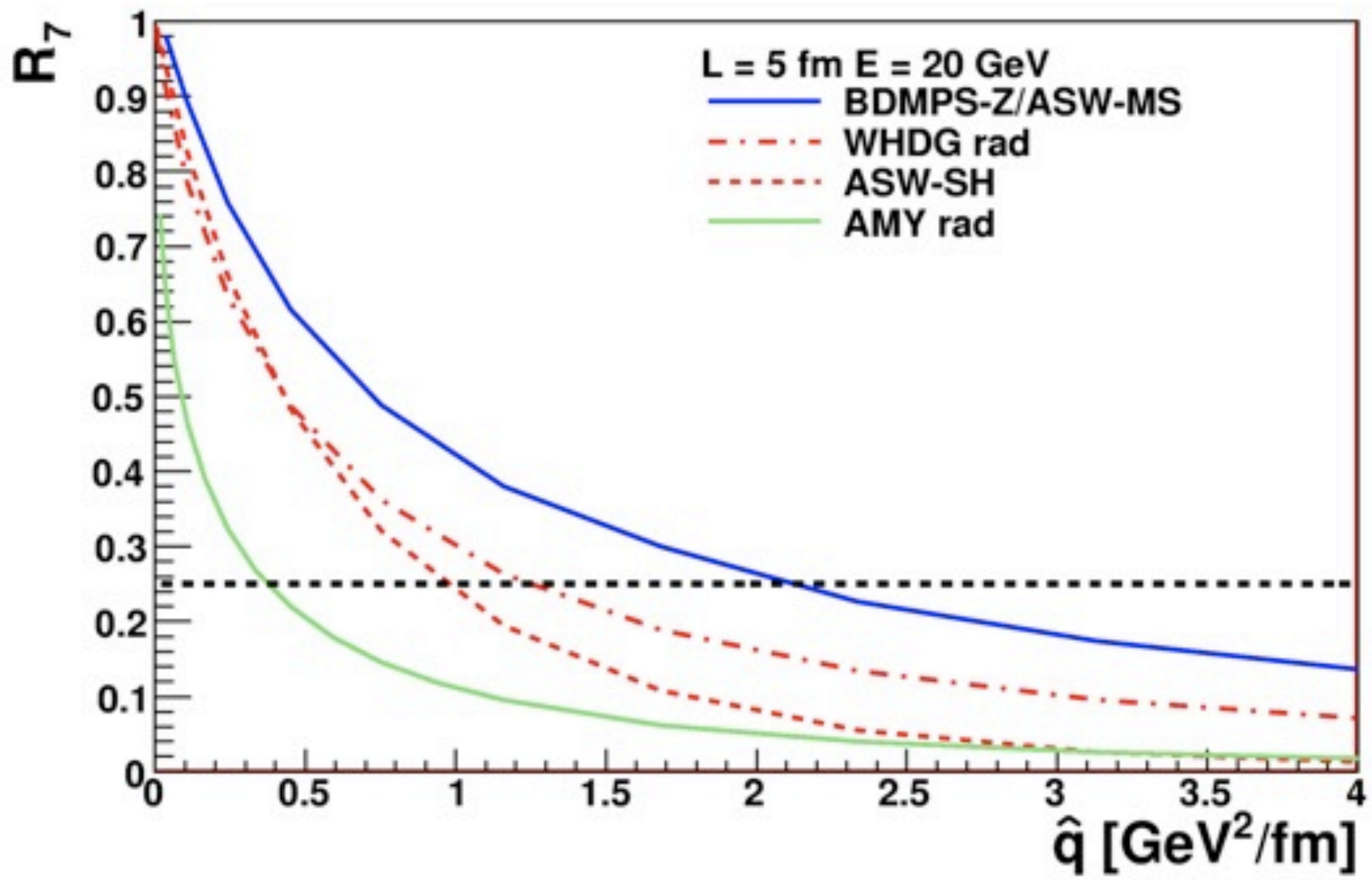
All formalisms describe the RHIC data very well, but...



$$\hat{q} = \rho \int q^2 \, dq^2 \, \frac{d\sigma}{dq^2} = \frac{\langle q_\perp^2 \rangle}{\lambda}$$

$$\text{Opacity} = L / \lambda$$

The QGP brick



$$\frac{dN}{dp_T} \propto \frac{1}{p_T^n} \qquad p_T \to (1-x)\,p_T$$

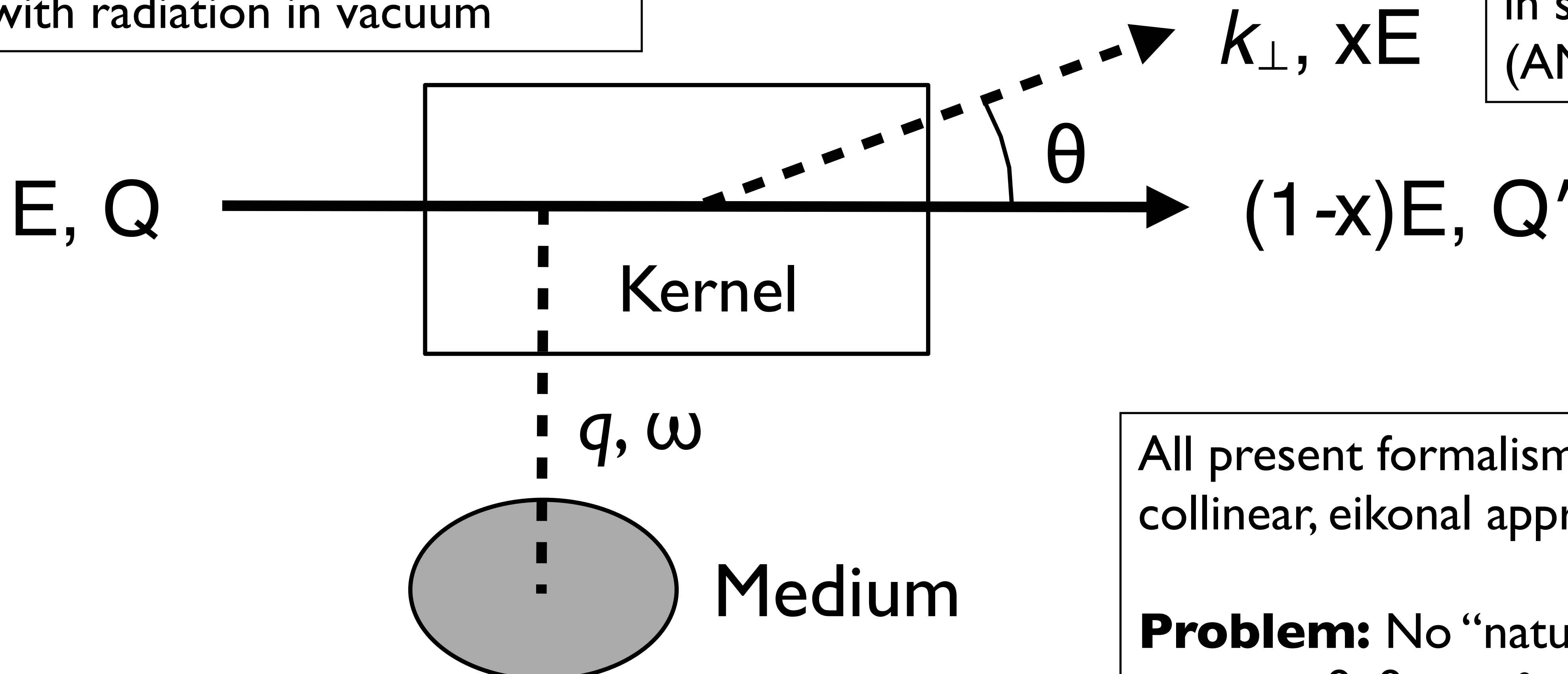
$$R_{AA} \Rightarrow R_n = \int_0^1 dx\,(1-x)^{n-1}\,P(x)$$

R7=0.25	qhat (GeV^2/fm)			
	BDMPS	WHDG rad	ASW-SH	AMY
L = 2 fm	23.1	17.8	8.4	2.7
L = 5 fm	2.13	1.25	0.98	0.4

Ingredients

Most formalisms (except AMY) treat virtuality and interference with radiation in vacuum

Quarks and gluons are medium modified in some formalisms (AMY, DGLV)



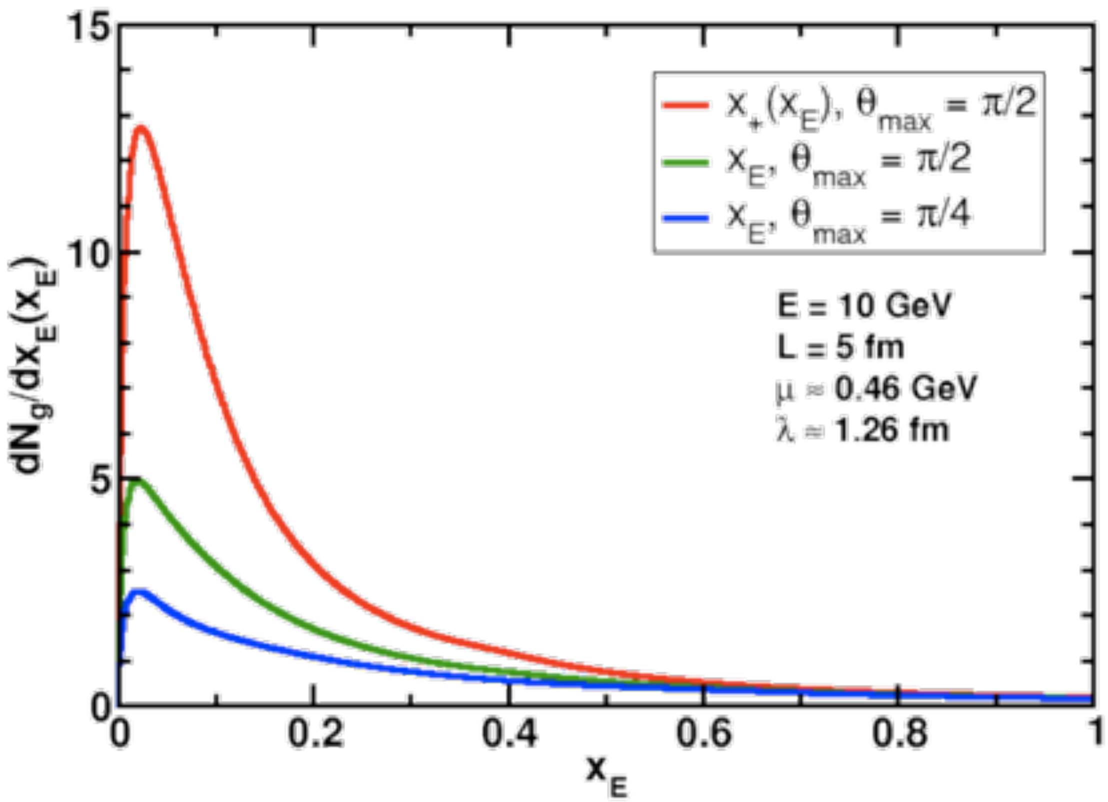
All present formalisms make the collinear, eikonal approximation.

Problem: No "natural" constraint on angle θ: θ > 45° region found to significantly contribute in GLV, ASW.

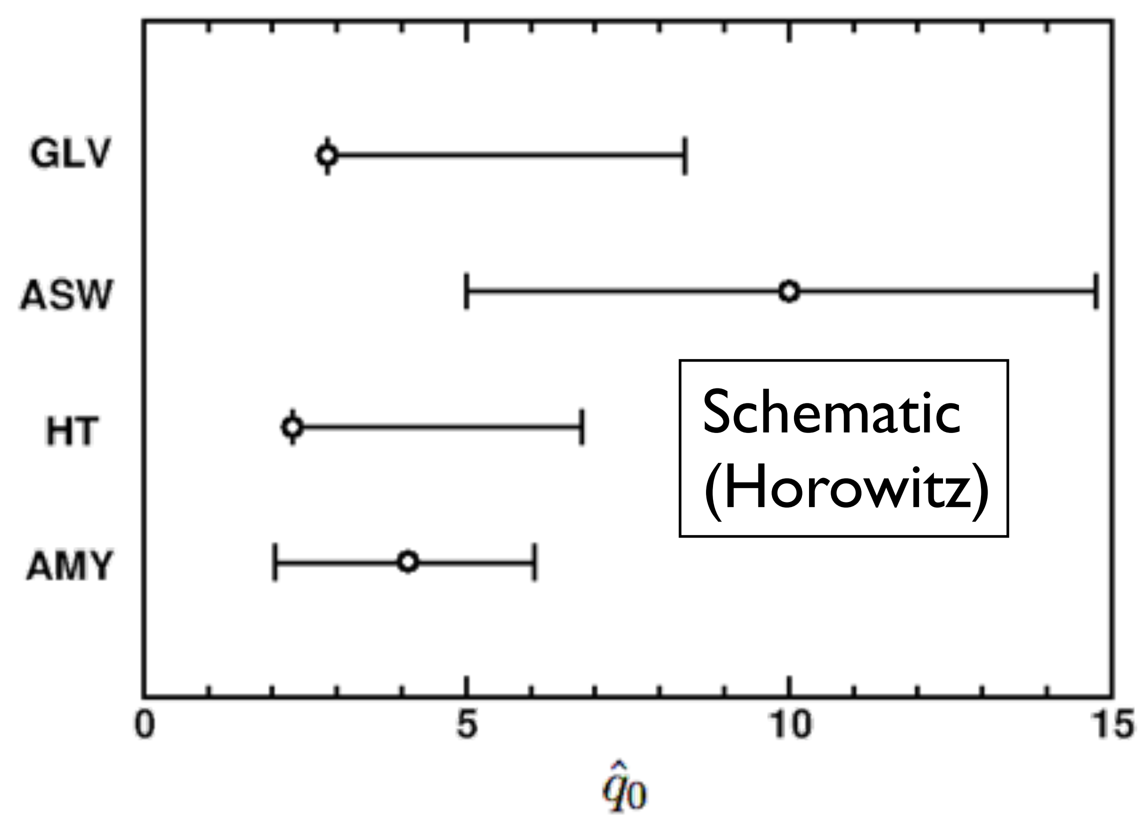
Medium treated differently in different formalisms: static in GLV, ASW, BDMPS; dynamic in HT, AMY.

Revelation

Ad hoc cuts in $k_\perp$ (θ) cause differences of factors 2-3 in ASW and GLV.



Dependence on uncontrolled parameters explains large difference between values of $\hat{q}_0$ required in different formalisms.



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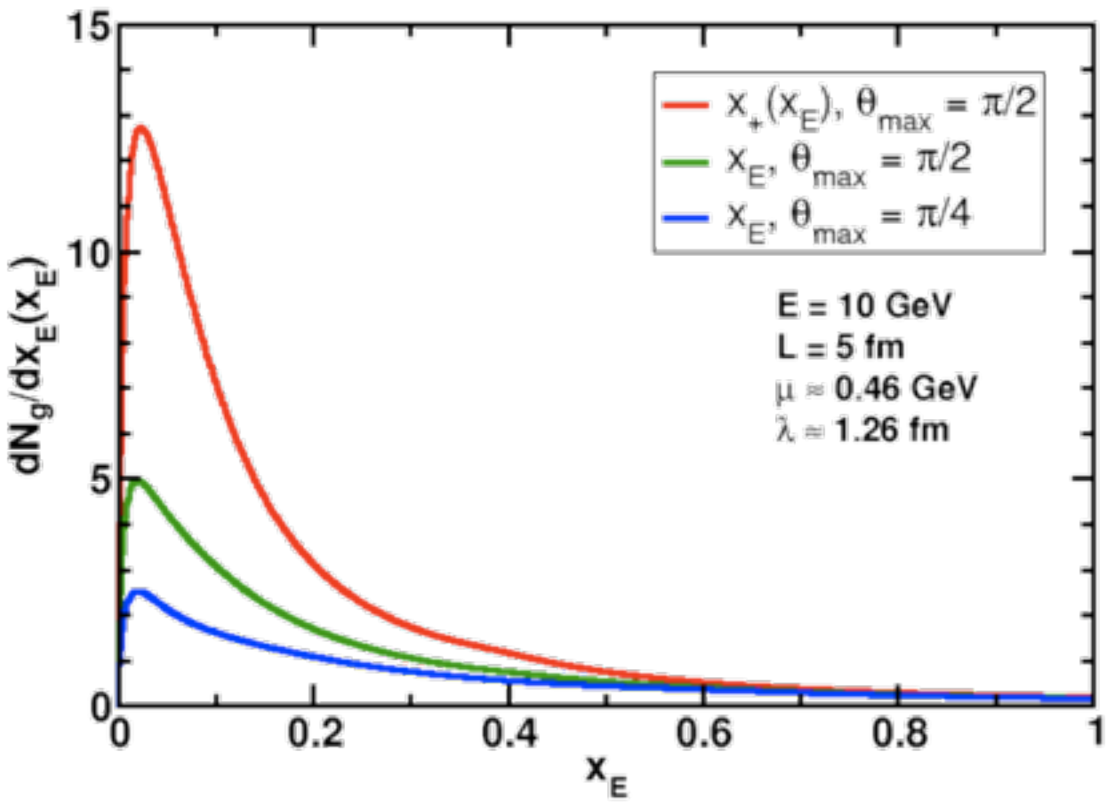

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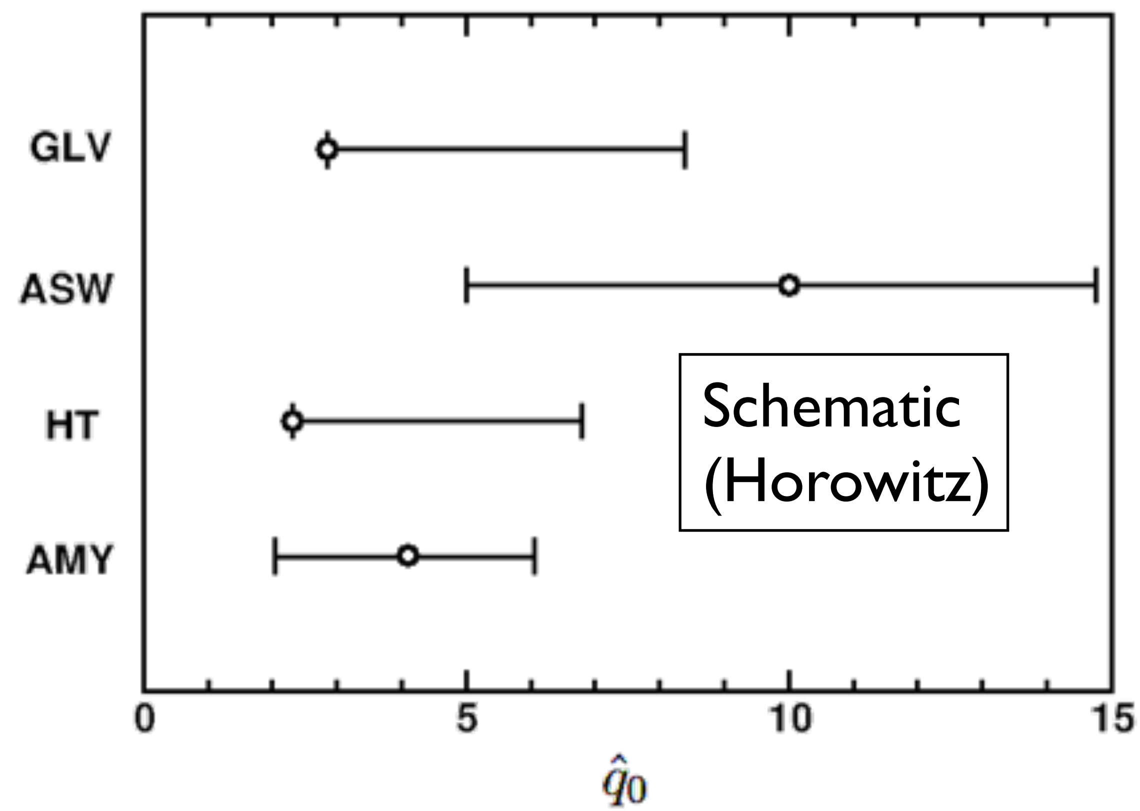

OK, but what now ?

The JET Collaboration

Quantitative Jet and Electromagnetic Tomography
of Extreme Phases of Matter in Heavy-Ion Collisions

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V. Koch, A. Majumder, D. Molnar, B. Müller, I. Vitev, R. Vogt, X.N. Wang, F. Yuan.

(LBNL, LANL, LLNL, Columbia U, Duke U, Mc. Gill U, Ohio State U, Purdue U, Texas A&M U)

Co-Spokespersons: B. Müller & X.N. Wang

External Associates:

F. Arleo (LAPTH), N. Armesto (Santiago), R. Baier (Bielefeld), B. Cole (Columbia), K. J. Eskola (Jyväskylä), E. Frodermann (Minnesota), C. Greiner (Frankfurt), T. Hirano (Tokyo), P. Huovinen (Frankfurt), Z. Lin (ECU), A. H. Mueller (Columbia), J. Owens (Florida State), J.W. Qiu (Iowa State / BNL), D. Rischke (Frankfurt), C. Salgado (Santiago), J. Stachel (Heidelberg), G. Sterman (Stony Brook), E. Wang (CCNU), U. Wiedemann (CERN), B. Zhang (CCNU).

Goals

In order to perform a quantitative characterization of properties of the quark-gluon plasma by means of hard probes of QCD matter, the Jet Collaboration will:

(a) extend the theoretical framework for jet-medium interaction beyond soft and collinear approximations and thereby reduce uncertainties intrinsic to the current theoretical studies;

(b) develop new and powerful Monte-Carlo algorithms for jet propagation and evolution inside a dynamic medium;

(c) implement in the jet-medium interaction a realistic space-time evolution of the bulk medium as described by a combination of viscous hydrodynamics with parton and hadron cascades;

(d) carry out systematic phenomenological studies of experimental data on single hadron (including heavy flavors) and photon spectra, multi-hadron and gamma-hadron correlations and jet shapes.

Research program 1

2010

- Complete a comparative study of modified fragmentation functions from four different approaches to jet quenching and identify the sources of discrepancy among these model calculations.
- Begin development of a Monte Carlo description of jet evolution and propagation in a dense medium. (➔ B. Schenke's, G. Corcella's talk)
- Start of a NLO pQCD calculation of jet shape study.
- Formulate a unified description of parton recombination and fragmentation.
- Incorporate radiative processes in the covariant parton transport calculation for the evolution of bulk matter.
- Implement a realistic EOS in hydrodynamic simulations and develop a viscous hydrodynamics - hadron cascade interface.
- Carry out a precision study of the cold nuclear matter effect in direct photon production in $p + A$ collisions.

Research program 2

2011

- Study the interplay between collinear and hard medium-induced radiation and matching between them.
- Continue to develop a Monte Carlo description of jet evolution and propagation in a dense medium, including jet-field interaction, rescattering of radiated gluons and the recoil of thermal medium partons.
- Complete the formulation of a unified description of parton recombination and fragmentation for the hadronization of jets.
- Develop a covariant parton transport description of the evolution of bulk matter, including both elastic and inelastic processes and the LPM effect.
- Test the hydro - cascade interface and explore the sensitivity to the switching temperature within a hydro-cascade model.
- Develop realistic source terms to account for energy and momentum transferred to the medium by hard probes and begin to study the collective response to such source terms.
- Consider hadron formation and interaction in the effective modified fragmentation for heavy flavor hadrons.

Research program 3

2012

- Complete the development of a Monte Carlo description of jet evolution and propagation in a dense medium with consistent description of both collinear and hard medium-induced gluon emission, including both elastic and inelastic processes, flavor conversion, recoil of the thermal medium partons.
- Systematically investigate intermediate-p_T hadron spectra within the developed parton recombination formalism.
- Investigate the consequences of radiative processes in the evolution of bulk partonic matter within the parton transport model.
- Compare the hydro-cascade model with soft hadron data to extract shear and bulk viscosity of hot QCD matter.
- Calculate EM emission from jet-medium interaction and the EM radiation from the evolving medium.
- Employ the FONLL scheme to calculate heavy quark spectra incorporating both elastic and inelastic parton energy loss.

Research program 4

2013

- Complete the integration of the parton recombination model with parton energy loss in a dynamic medium as described by the hydro-cascade model to calculate hadron spectra in the full range of transverse momenta.
- Use the resulting modified fragmentation functions to calculate single and di-hadron spectra and gamma-hadron correlation in NLO pQCD.
- Conduct phenomenological studies of the available data (both from RHIC and LHC) on large transverse momentum hadrons, di-hadron and gamma-hadron correlations, direct photon, heavy quarks and jet shape within the developed framework.
- Develop Jet and Electromagnetic Tomography (JET) program packages of Monte Carlo simulation of jet propagation and evolution in the form of open source codes and algorithmic routines (OSCAR) for use in phenomenological analyses of experimental data.

Research program 5

2014

- Complete the comprehensive phenomenological analysis of experimental data on various hard and electromagnetic probes from RHIC and LHC using the JET program packages.
- Establish values of the medium properties, e.g. jet transport parameter (qhat), temperature and shear viscosity, and their space-time profile with both theoretical and experimental error bands.
- Release the JET program package to the public domain for use in RHIC and LHC experiment analysis.

Other Activities

The JET Collaboration will hold annual summer schools with pedagogical lectures on perturbative QCD in elementary hard processes and multiple scattering in a medium, thermal field theory, jet and electromagnetic tomography, experimental heavy-ion physics and other related and relevant topics.

Outlook

A prediction:

When we meet for the (next-to-next-...-to-next) CATHIE-TECHQM Workshop in 2014, we will have much better pQCD based theories of jet quenching. We will also have experimental data that test these theories over a much larger kinematic range.

Goal: Determination of $q^\wedge$ from data to a precision comparable to the determination of η/s from elliptic flow data.

Reason for optimism: Much hard work is necessary, but we now understand much better than 18 months ago what the required improvements of jet quenching theory are. The work has been commissioned; please, contribute or stay (patiently) tuned.