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and Related Subjects - DIS 2009
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Theoretical Progress in Heavy-Ion Collisions

Néstor Armesto
Departamento de Física de Partículas and IGFAE
Universidade de Santiago de Compostela

See the previous talk by David d'Enterria.

Contents:

Accelerator	Collisions
SPS	pp to PbPb at E_{cm}=17-30 AGeV
RHIC	pp to AuAu at E_{cm}=20-200 AGeV
LHC	pp to PbPb at E_{cm}=5.5-14 ATeV

Not a full review, see e.g. the contributions to QGP4 in arXiv '09.

Introduction (I):

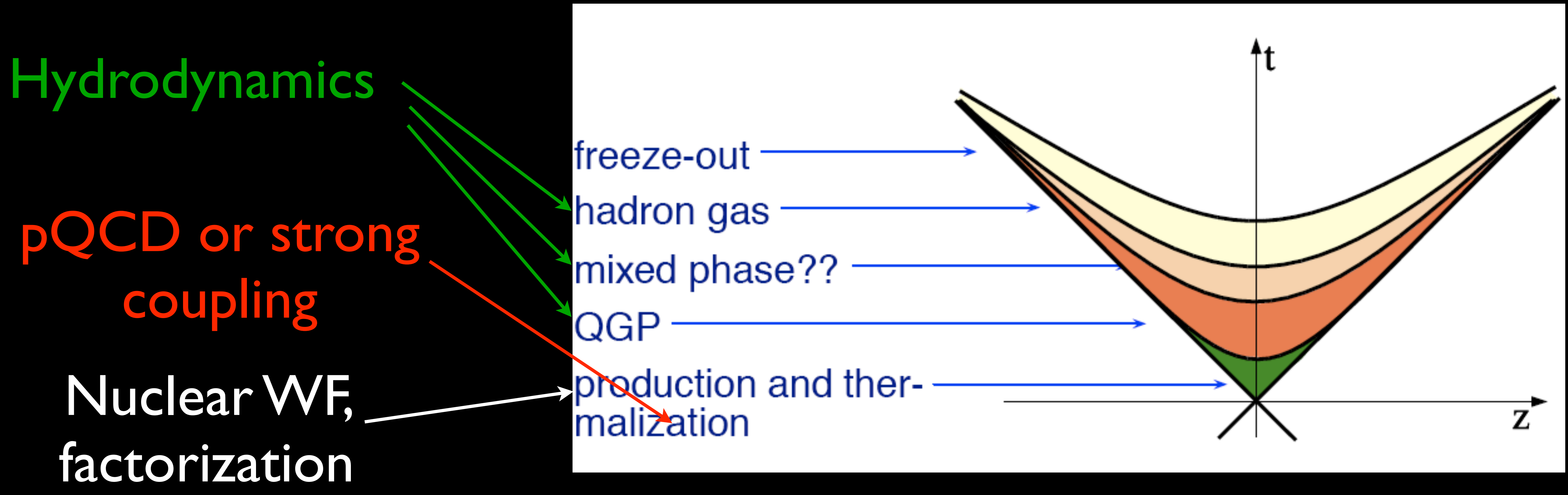
• URHIC is an interdisciplinary field, whose goal is the understanding of confinement through the study of matter at high parton densities → through asymptotic freedom → QGP.

• Experiments at RHIC claim (NPA757 '05): the creation of partonic matter with $\epsilon > \epsilon_{crit}$(HM→QGP), with large coherence in soft particle production, very early behaving like a quasi-ideal fluid and extremely opaque to energetic partons traversing it.

Observable at RHIC	Standard interpretation
Low multiplicity compared to pre-RHIC expectations	Strong coherence in particle production
v_2 in agreement with ideal hydro	Almost ideal fluid
Strong jet quenching	Opaque medium

Introduction (II):

- ‘Medium’: particles with momenta momenta ~ <p> (T).
- Hard probes: those pQCD-computable in vacuum, whose medium-modification characterizes it.
- At variance with other fields, here the space-time evolution has to be considered: interplay between usual evolution (momentum) variables and dimensions of the ‘medium’.



2. Initial conditions:

2.1. Nuclear wave function.

2.2. Factorization.

See the talk by Jochen Bartels.

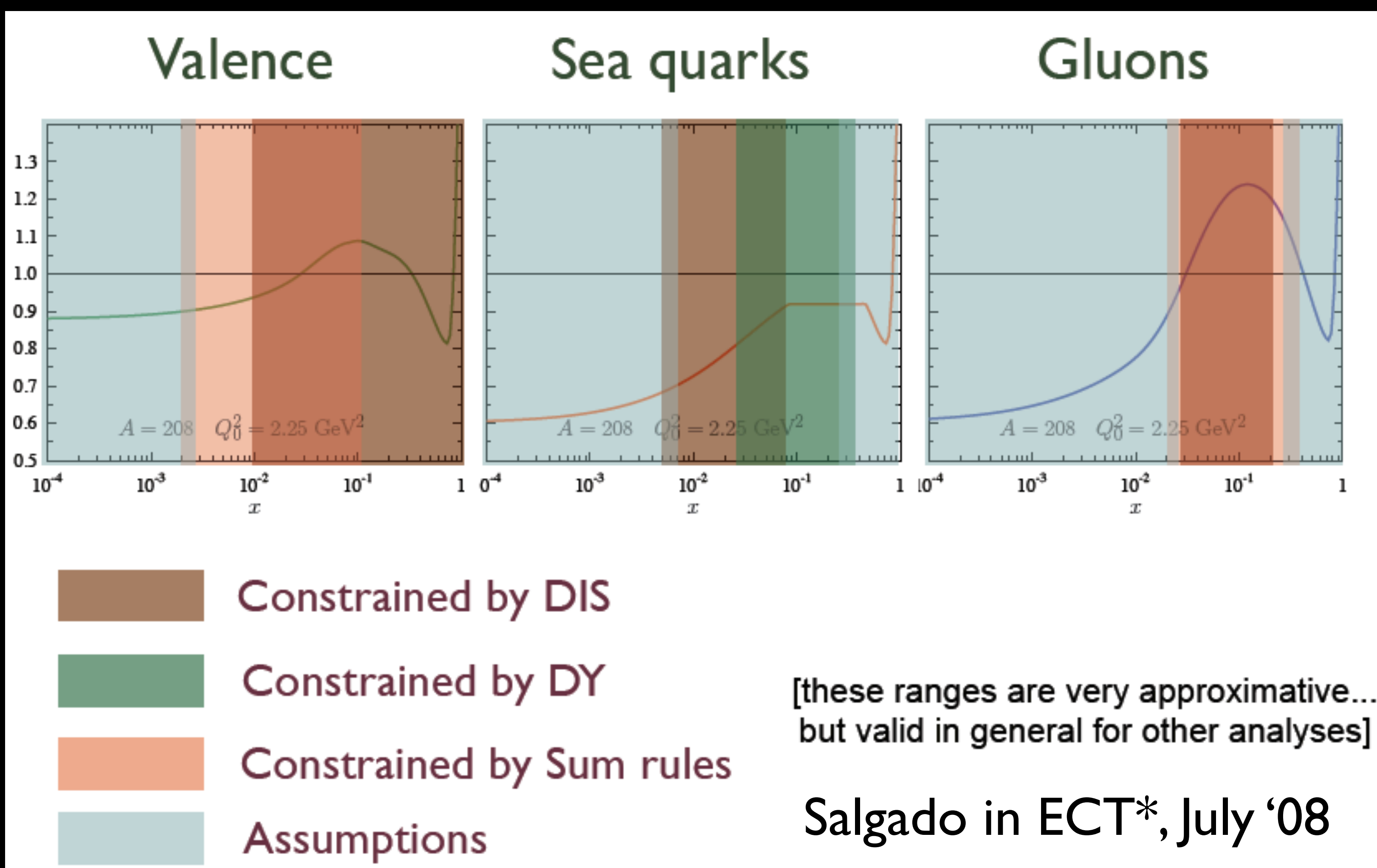
$$R = \frac{\text{Measured (on nuclei)}}{\text{Expected if no nuclear effects}}$$

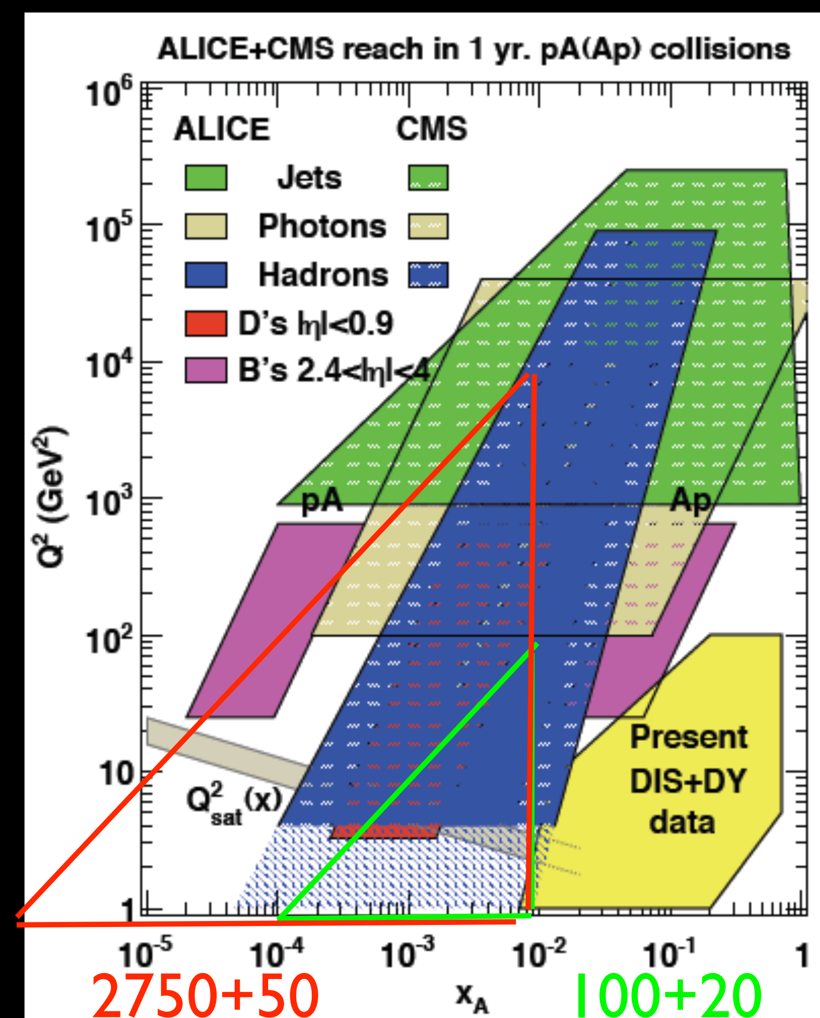
$$R_{F_2}^A(x, Q^2) = \frac{F_2^A(x, Q^2)}{A F_2^{\text{nucleon}}(x, Q^2)}$$

$$R_{dAu} = \frac{\frac{dN^{dAu}}{d\eta d^2b d^2p}}{N_{coll}\frac{dN^{pp}}{d\eta d^2b d^2p}}$$

Nuclear WF - DGLAP analysis

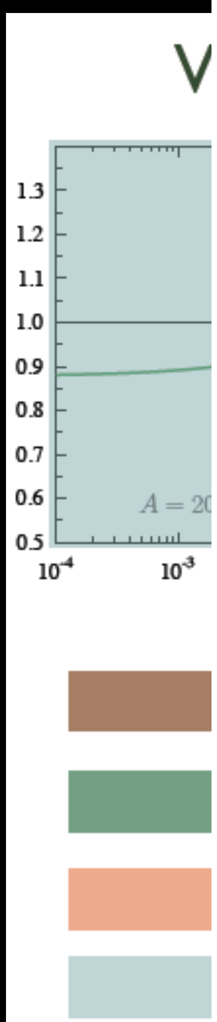
- DGLAP analysis at LO (EPS08) and NLO (HKN07,dFS, EPS09) and with error analysis through the Hessian method available: HKN, EPS.
- Limitation: existing data do not cover the LHC kinematics: pA@LHC and future eA colliders (talks on EIC and LHeC; Lappi).

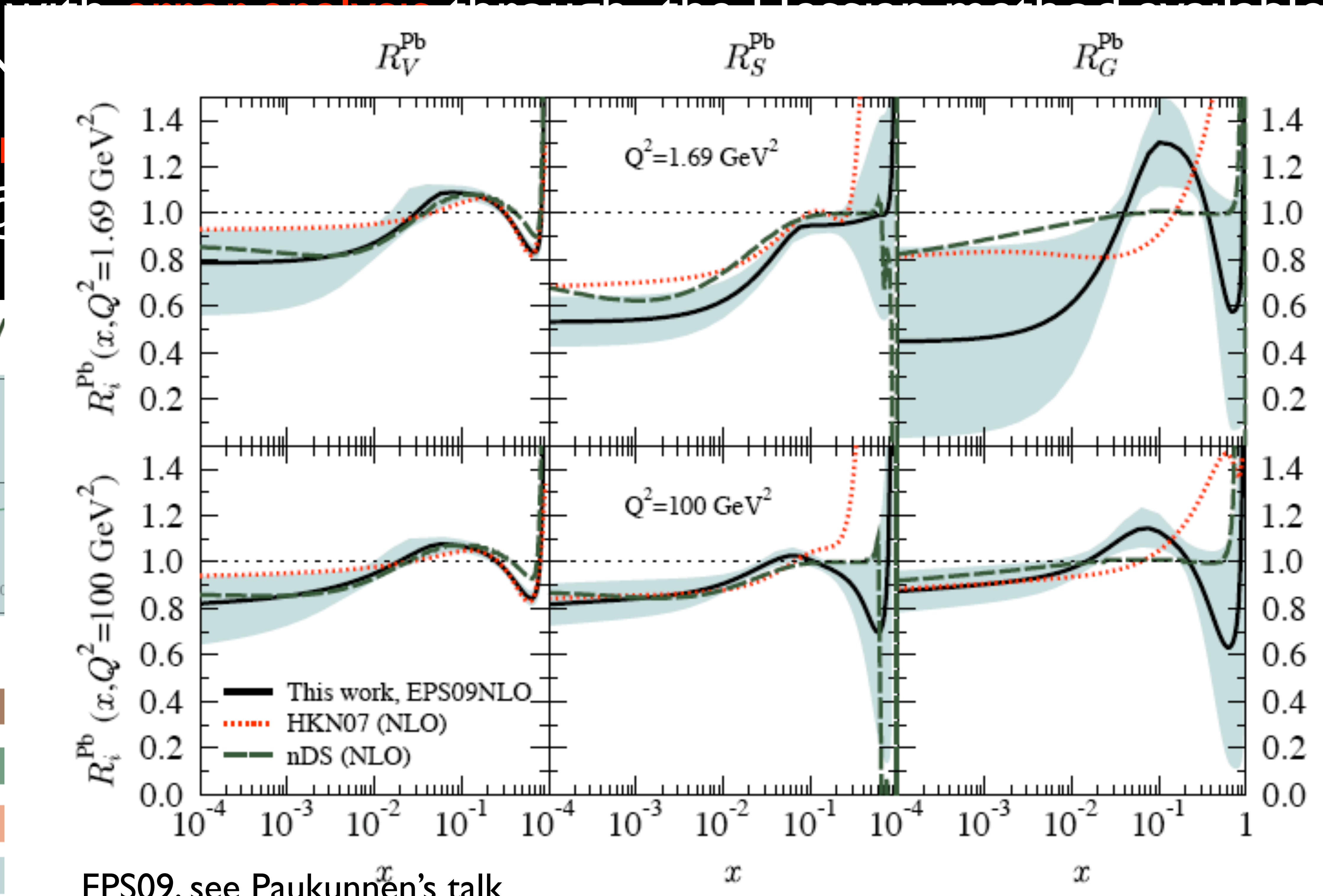


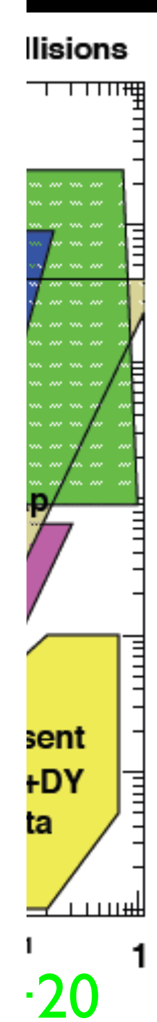


Nuclear WF - DGLAP analysis

• DGLAP analysis at LO (EPS08) and NLO (HKN07,dFS, EPS09)
and
HKN
• Li
pA@ ppi).







EPS09, see Paukunnen's talk

Nuclear WF - models

- For ep, several models including saturation exist: dipole (GBW and descendants), Regge,... Geometric scaling is the striking feature (only suggestive, DGLAP also leads to it!).

$$x \ll \frac{1}{2m_N R_A} \simeq 0.1 A^{-1/3}$$

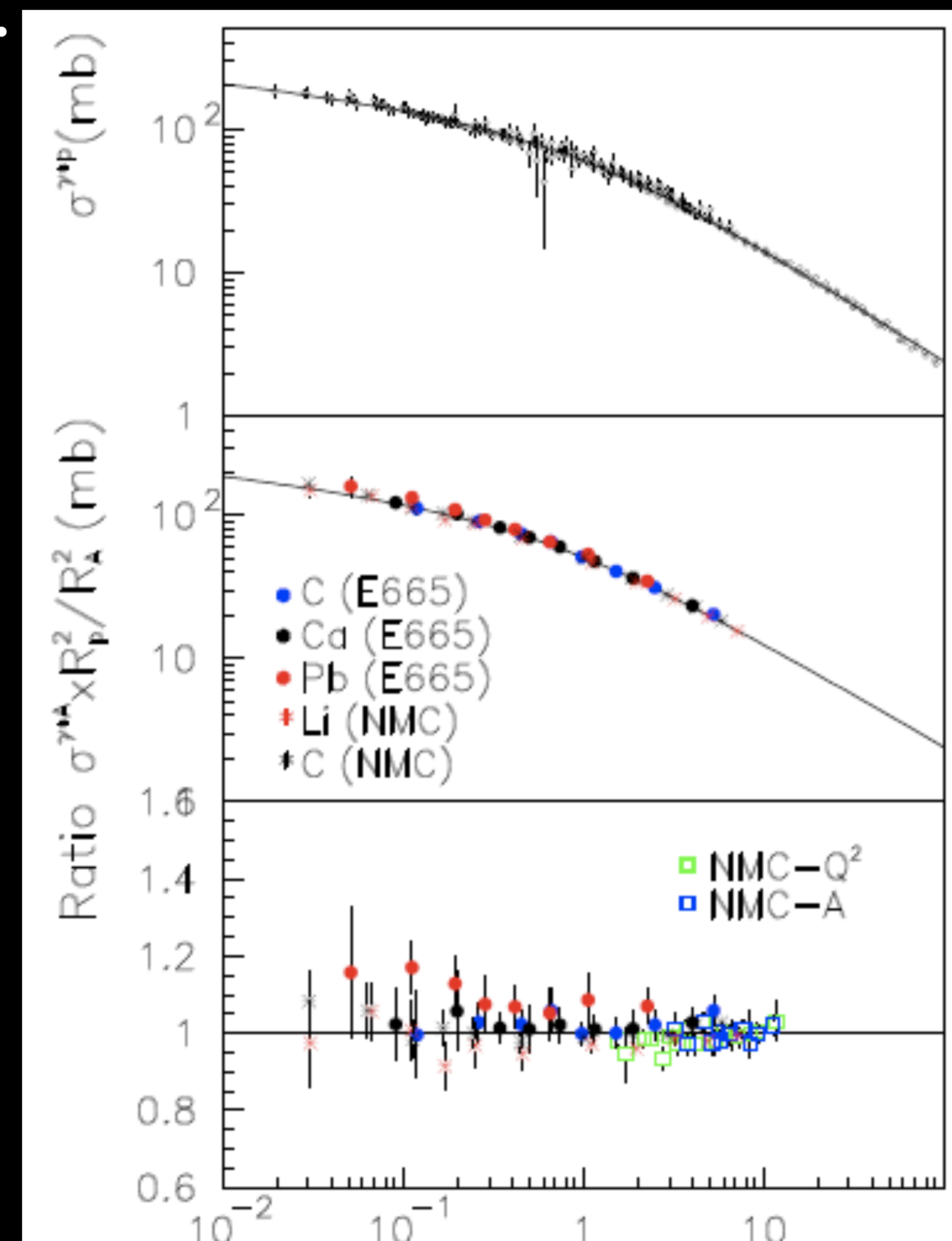
- Geometric scaling also works for nuclei for x<0.02 (Rummukainen et al '03, NA et al '04):

$$\frac{\sigma^{\gamma^* A}(\tau_A)}{\pi R_A^2} = \frac{\sigma^{\gamma^* p}(\tau_A)}{\pi R_p^2}$$

$$\frac{Q^2_{\rm s,A}}{Q^2_{\rm s,p}} = \left(\frac{A\pi R_p^2}{\pi R_A^2}\right)^{\frac{1}{\delta}} \Rightarrow \frac{\tau_A}{\tau_p} = \left(\frac{\pi R_A^2}{A\pi R_p^2}\right)^{\frac{1}{\delta}}$$

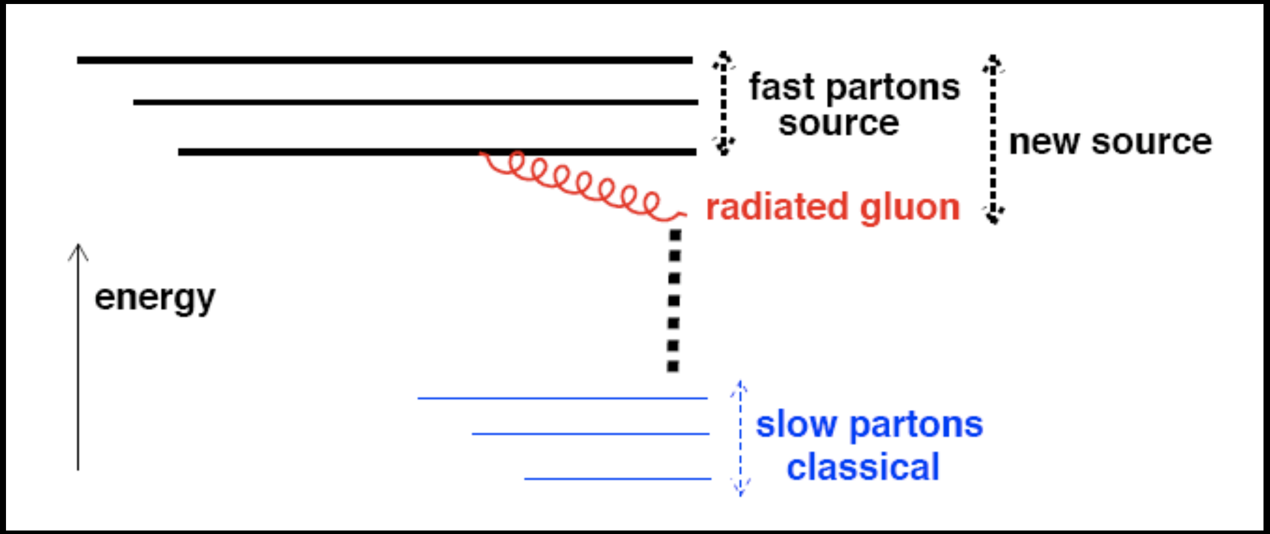
$\delta = 0.79 \pm 0.02$ $(x < 0.02)$.

$$Q_s^2 \propto x^{-\lambda} A^{\beta}$$



NA et al '04

Nuclear WF - theory



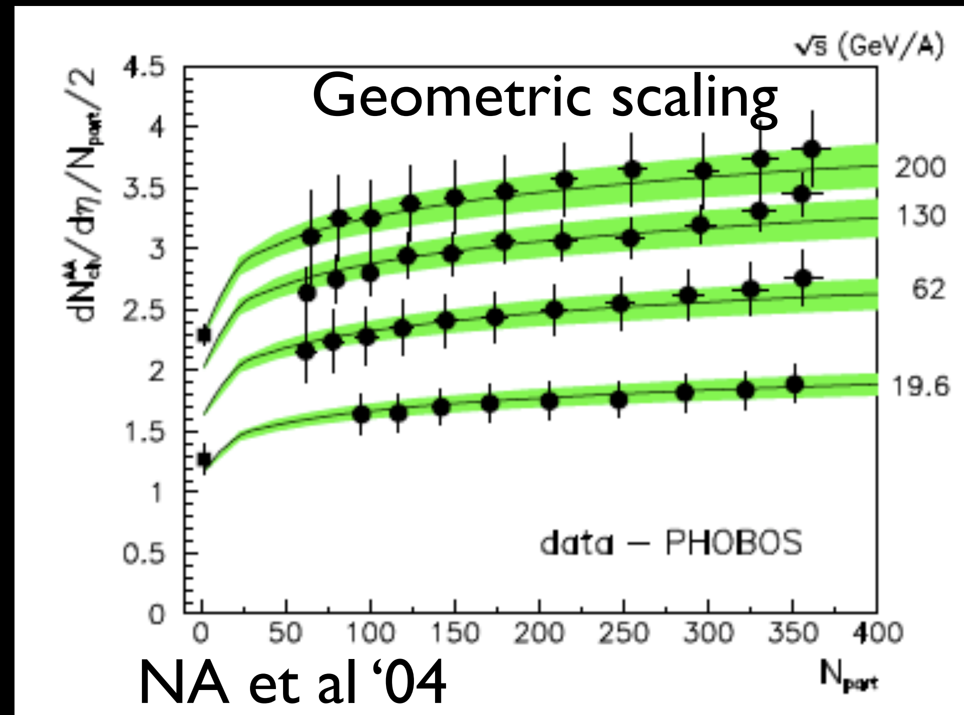
- RG functional equation: JIMWLK, $\rho_P \sim O(1)$, $\rho_t \sim O(1/\alpha_s)$, mean field version: BK, from LL to NLL (talks: Balitsky, Albacete, Weigert, Avsar).

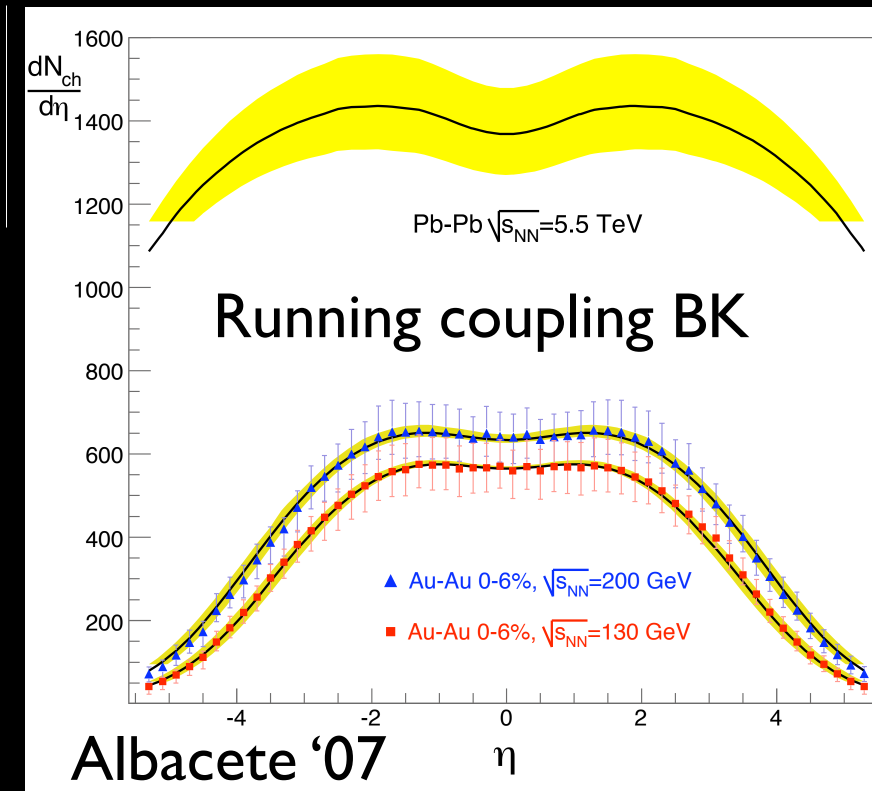
- Beyond JIMWLK: $\rho_P \sim \rho_t \sim O(1/\alpha_s)$ (Kovner; Triantafyllopoulos '05)
  - → Beyond tree diagrams: Pomeron loops, H_{RFT} (Kovner et al '09).
  - → Statistical mechanics analogies: sFKPP, important for large E.
  - → Corrections to BK within JIMWLK: small! (Kovchegov et al '08).

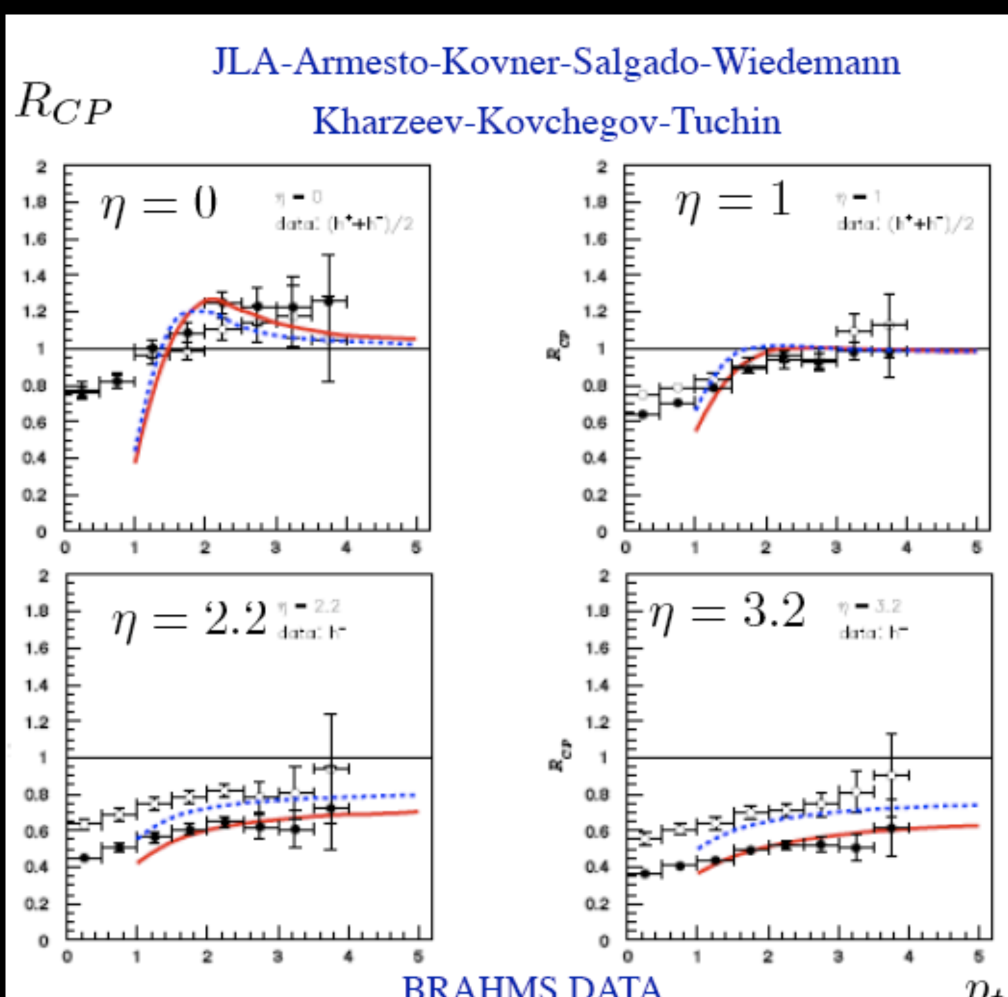
BK vs. ep/eA data	λ	β	slope of tail
Data	0.25-0.3	≥1/3	0.75
fixed coupling	$4.88\alpha_s$	initial conditions	0.63
running coupling	OK	small evolution	?

Factorization (I):

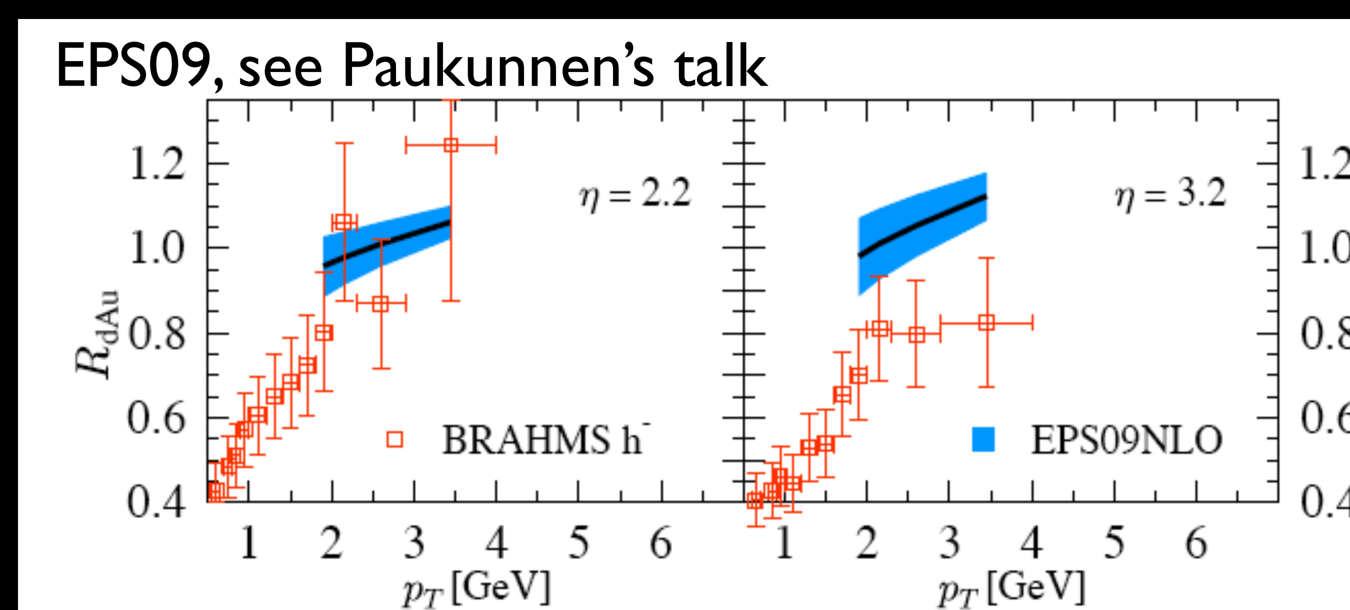
- k_T-factorization + LPHD (or DGLAP FF) used in nuclear collisions, for low-intermediate p_T particle production.







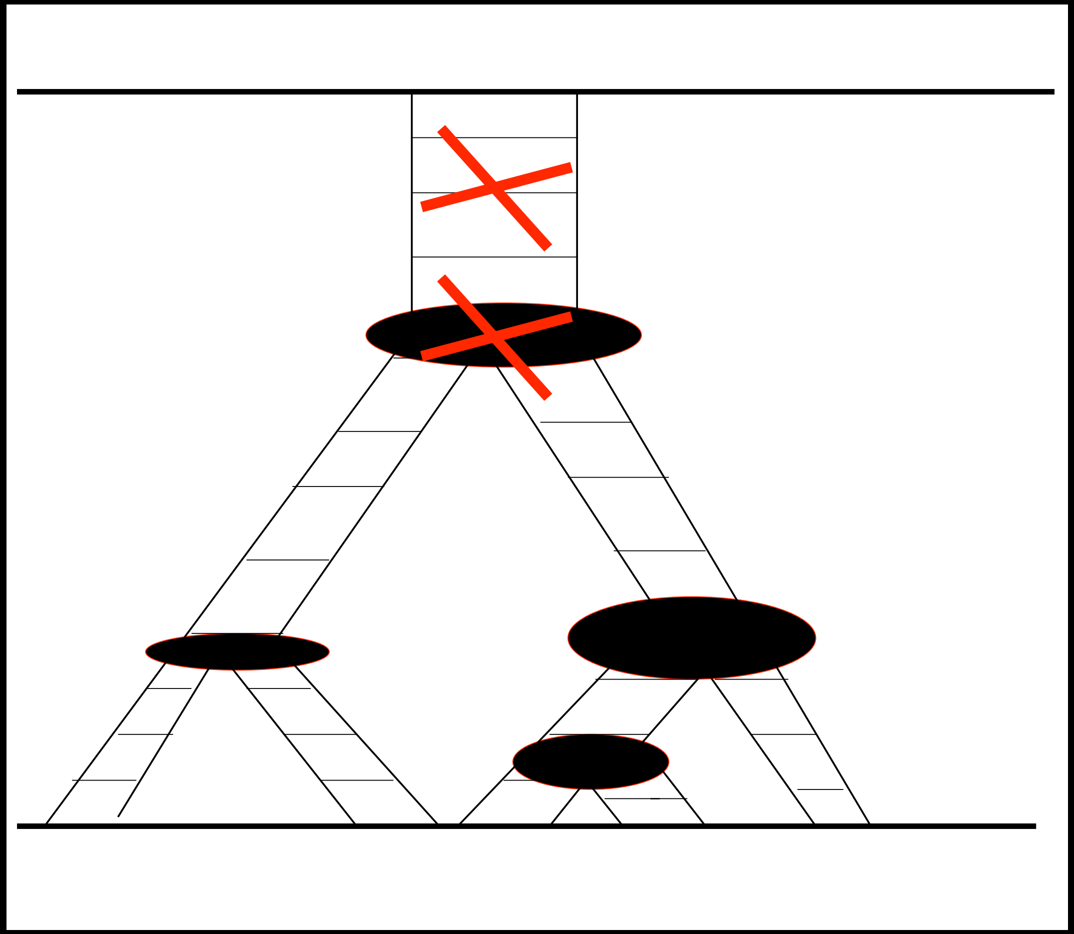
- Suppression in pA at forward rapidities constrains gluon shadowing.



Factorization (II):

- Analysis of k_T-like factorization or particle production in CYM, and of the validity of DGLAP-FF are under development. Several groups attempt to prove factorization for gluon or quark production:
  - → In momentum space, the BFKL Pomeron language (Braun, Bartels et al).
  - → In the dipole model (Kovchegov et al).
  - → In classical gluodynamics: expansion in projectile and target densities (Gelis et al, Balitsky et al, McLerran et al, Marquet, Fukushima et al).
  - → Hadron wave function (Nikolaev et al, Kovner et al).

- In dilute-dense: k_T-factorization OK? for single gluon, not for quark or for 2 gluons. Several pieces evolving BK-like.



- In dense-dense, usual k_T-factorization not valid (quantitative inaccuracy?); factorization becomes more involved.

3. Collective behavior:

3.1. Elliptic flow.

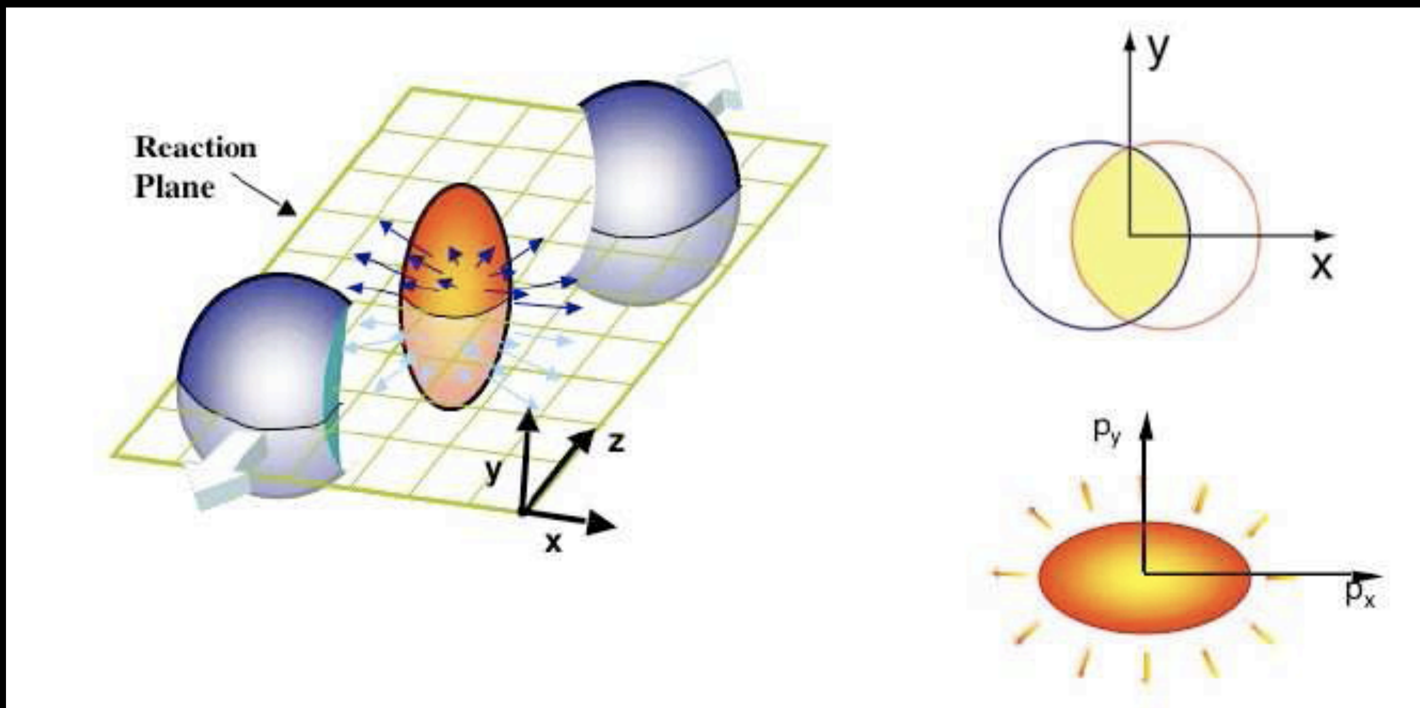
3.2. Hydrodynamical modeling.

See the reviews: Heinz et al '03, Hirano et al '08, Romatschke '09.

3.3. Strong coupling calculations.

See the review Edelstein et al '09.

Elliptic flow:

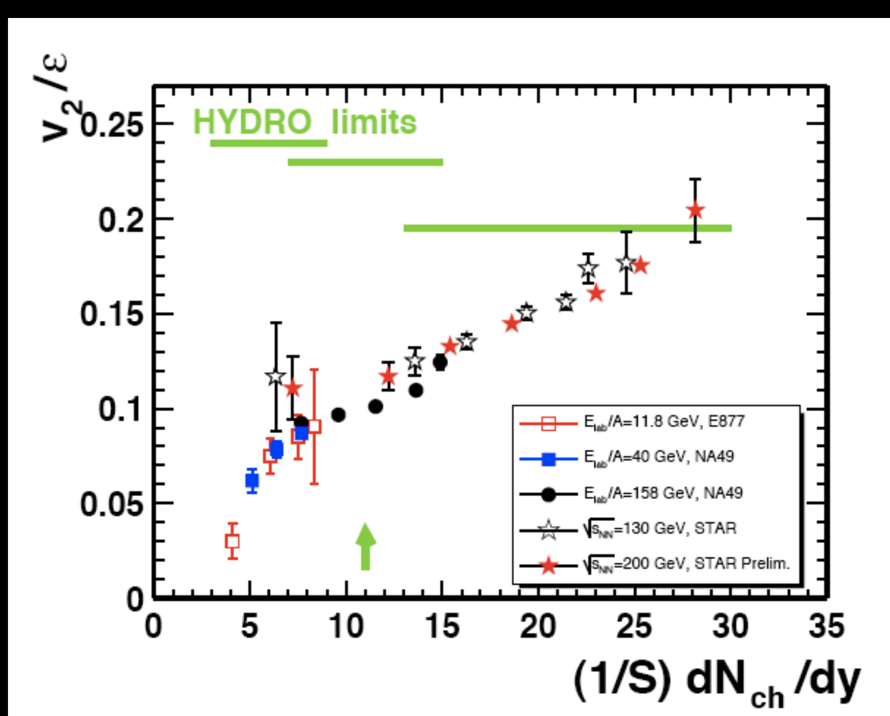


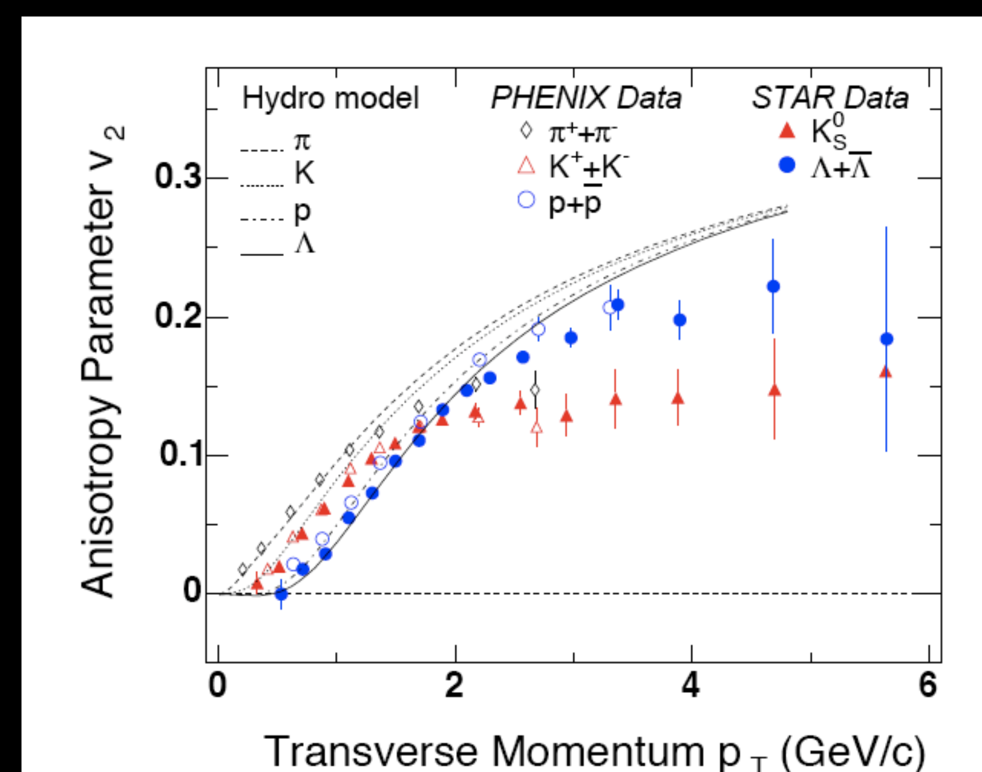
$$\frac{dN_k}{dy\,dp_T^2\,d\phi} = \frac{dN_k}{dy\,dp_T^2}\frac{1}{2\pi}\left[1 + 2v_1\cos\left(\phi-\phi_R\right) + 2v_2\cos 2\left(\phi-\phi_R\right) + \ldots\right]$$

$$v_2 = \langle\cos 2\left(\phi-\phi_R\right)\rangle = \left\langle\frac{p_x^2-p_y^2}{p_T^2}\right\rangle$$

$$\epsilon_x = \frac{\langle y^2 - x^2\rangle}{\langle y^2 + x^2\rangle}$$

- v_2, also called elliptic flow, is usually interpreted in terms of a final momentum anisotropy dictated by an initial space anisotropy.





Hydrodynamical behavior:

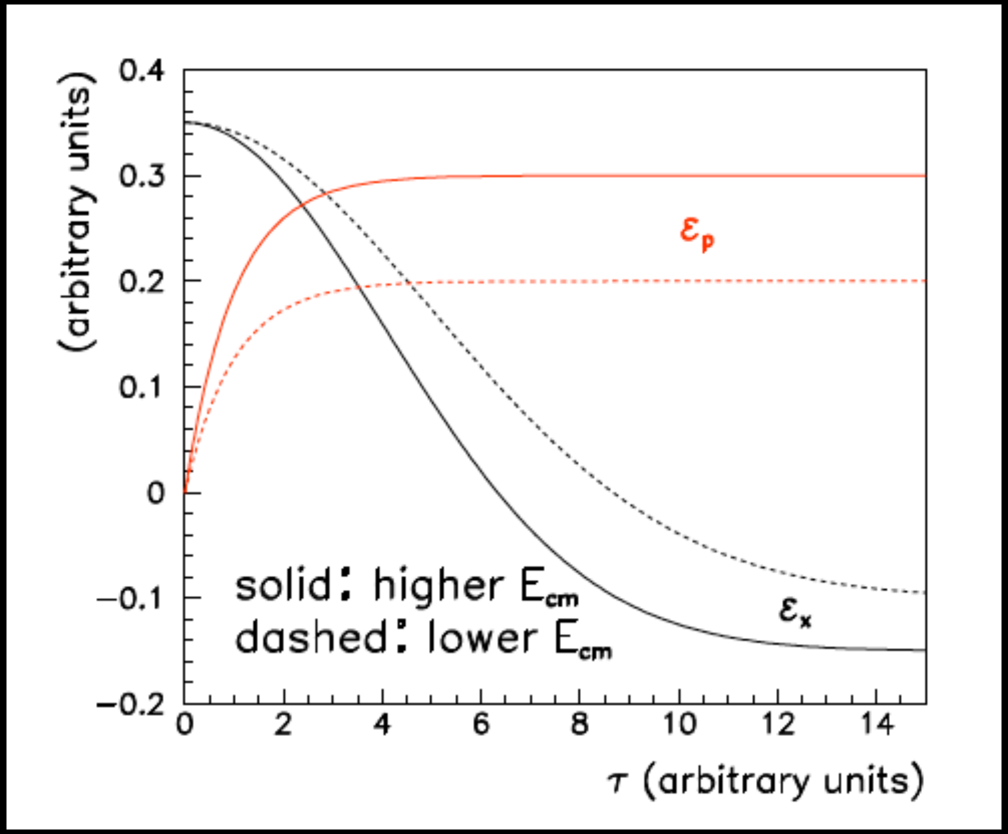
- Ideal hydro: plus an (lattice) EOS, initial conditions and a hadronization prescription.

$$u^\mu = \gamma\,(1, v_x, v_y, v_z)$$

$$T^{\mu\nu}_{(0)}(x) = \Big(e(x) + p(x)\Big)u^\mu(x)u^\nu(x) - p(x)\,g^{\mu\nu}$$

$$\partial_\mu\, T^{\mu\nu}_{(0)}(x) = 0\,, \qquad (\nu = 0, \ldots, 3)$$

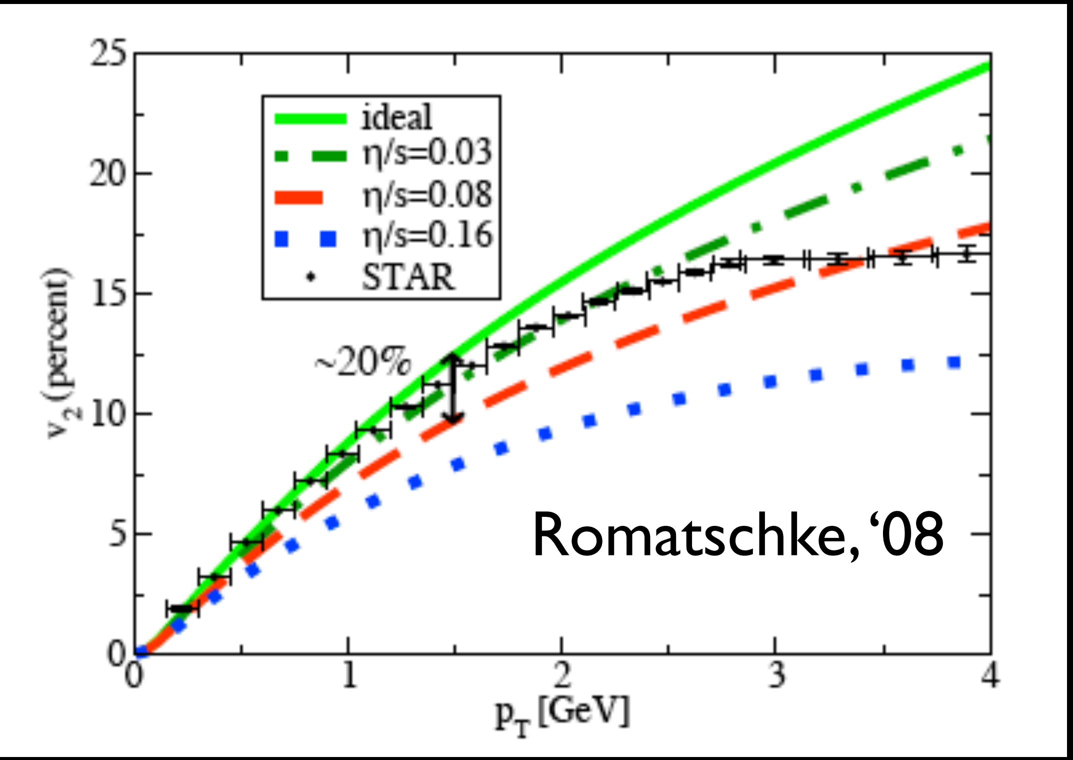
$$\partial_\mu j^\mu_i(x) = 0, \qquad i = 1, \ldots, M$$



- Non-ideal hydro: dissipative (viscous) corrections.

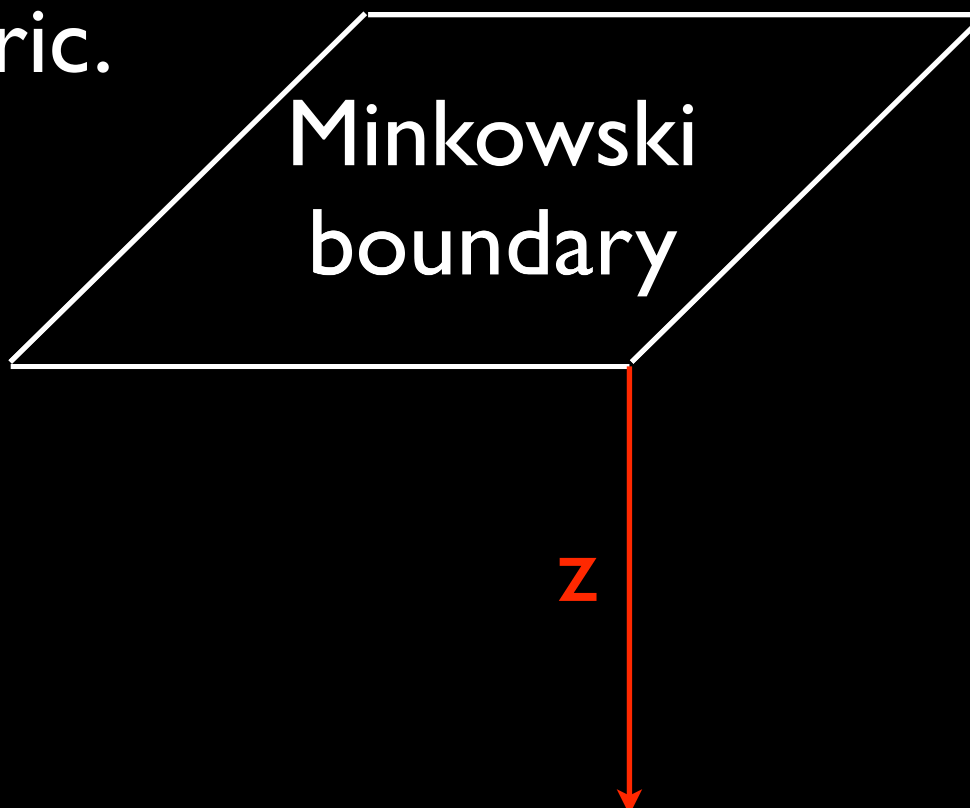
$$T^{\mu\nu} = T^{\mu\nu}_{(0)} + \Pi^{\mu\nu}$$

- $\Pi^{\mu\nu}$ introduces bulk viscosity plus gradients of u: 1st order (shear viscosity), 2nd order (5 constants for a CFT),...



Strong coupling calculations (I):

- Strong coupling is suggested by:
  → The quasi-ideal fluid behavior ($\lambda=(\rho\sigma)^{-1}<<R$).
  → The early isotropization/thermalization, difficult to explain in pQCD (Romatschke et al '04, Xu et al '05).
  → The strong quenching of high-energy particles.
- AdS/CFT correspondence: dynamics of N=4 SUSY QCD for $N_c,\lambda=g^2N_c\to\infty$ can be computed using classical gravity in $AdS_5\times S^5$.
  → Temperature through black-hole metric.
  → No confinement, no asymptotic freedom, no quarks,...



$$\mathcal{Z}_{\rm string}\left[\Phi_i(z,x^\mu)\Big|_{z=0}=\varphi_i(x^\mu)\right]=\left\langle \exp\left(\int d^4x\, \varphi_i \mathcal{O}_i\right)\right\rangle_{\rm SYM}$$

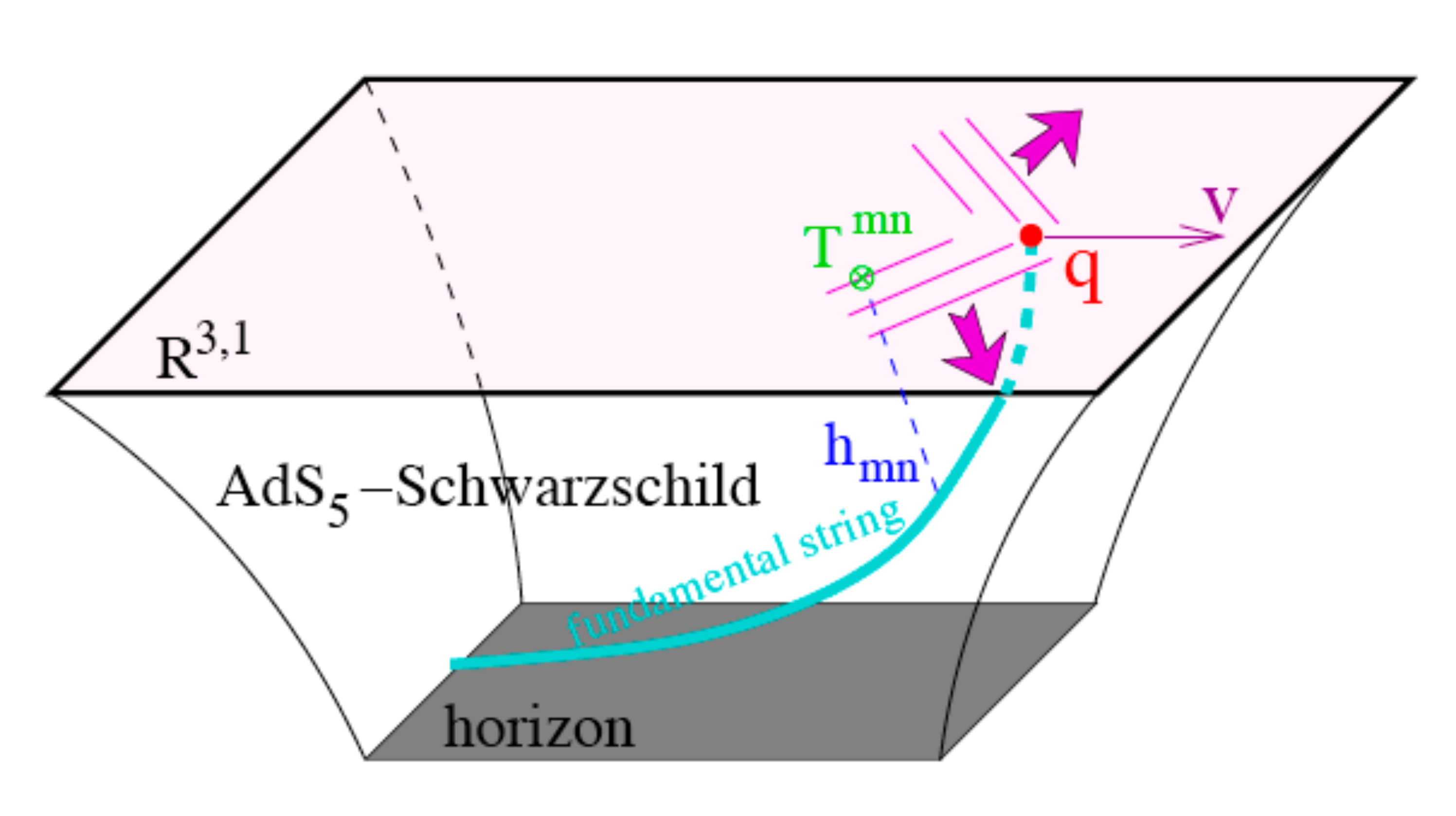
O_i is the SYM associated with the supergravity field Φ_i.

Strong coupling calculations (II):

- AdS/CFT has been applied to several aspects of HIC:

→ The energy loss of fast (Liu et al ’06) and slow partons (Gubser et al ’09).

→ The energy deposition and medium disturbance created by the energetic particle.



→ The early isotropization/thermalization problem.

→ The hydrodynamical behavior (Janik et al ’07; Kovchegov ’07).

$$\tilde{g}_{\mu\nu}(x,z) = \tilde{g}^{(0)}_{\mu\nu}(x) + z^2\,\tilde{g}^{(2)}_{\mu\nu}(x) + z^4\,\tilde{g}^{(4)}_{\mu\nu}(x) + \dots$$

$$\langle T_{\mu\nu}\rangle = \frac{N_c^2}{2\,\pi^2}\,\tilde{g}^{(4)}_{\mu\nu}(x)$$

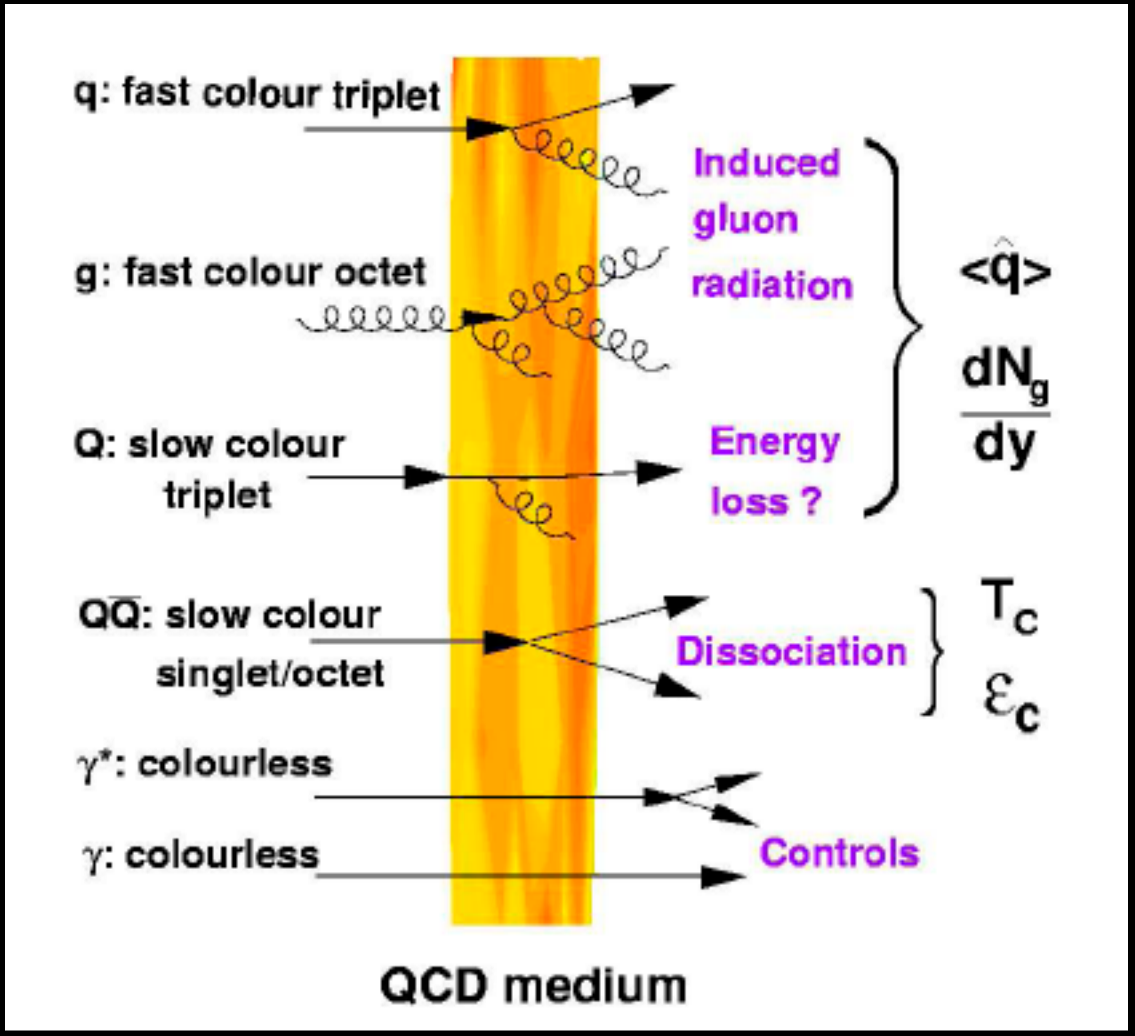
→ The initial conditions for a HIC (Albacete et al ’08).

4. Hard probes: high-p_T particles and jets:

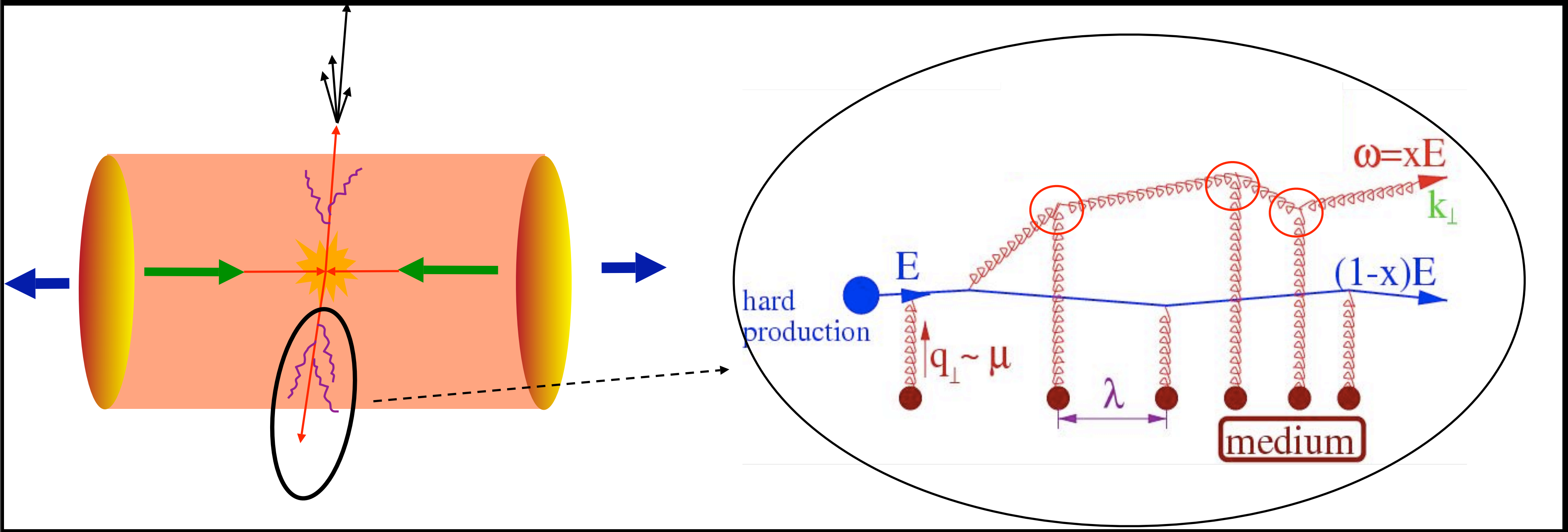
4.1. Successes and problems in radiative energy loss.

4.2. In-medium parton showers.

See the reviews: d’Enterria ’09; Casalderrey-Solana et al ’07; Yellow Report on Hard and EM Probes ‘04.



Radiative eloss - successes:

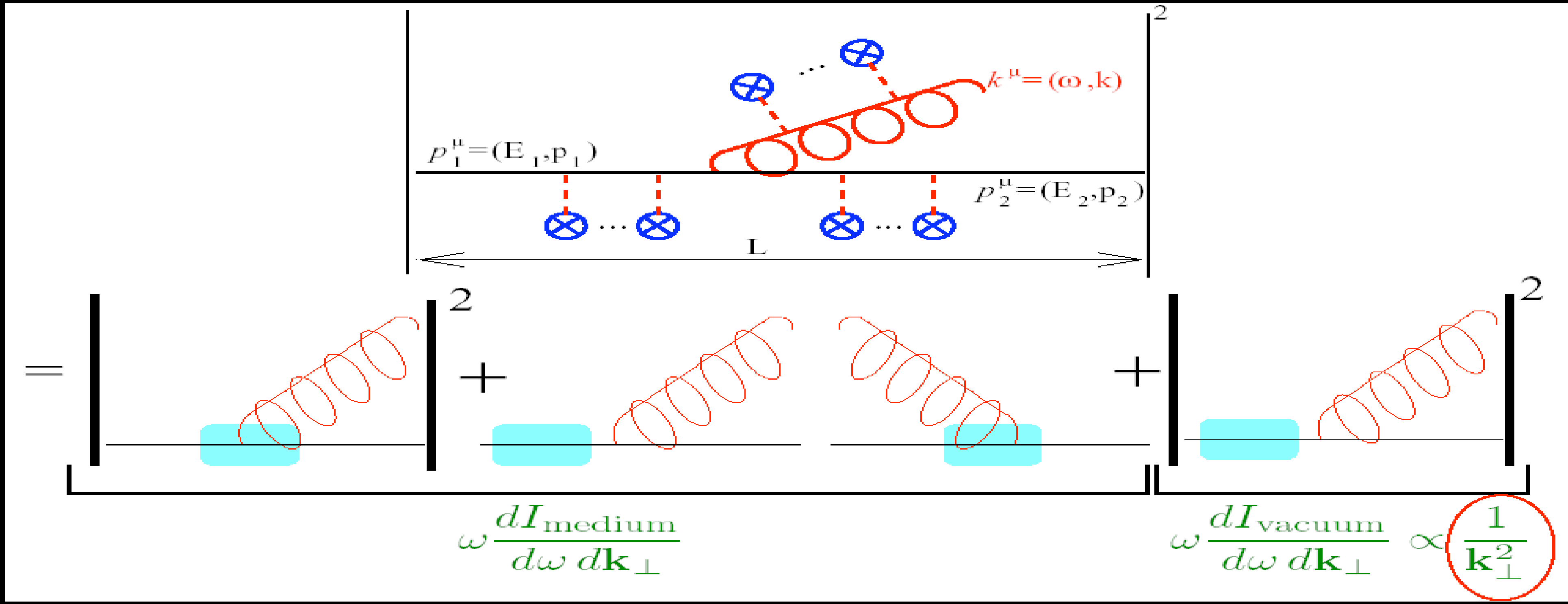


$$\hat{q} = \frac{\mu^2}{\lambda}$$

BDMPS

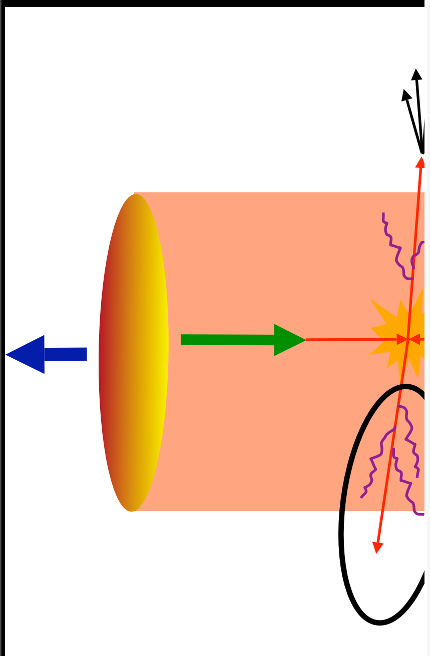
$$\Delta E \propto C_R \alpha_s \hat{q} L^2$$

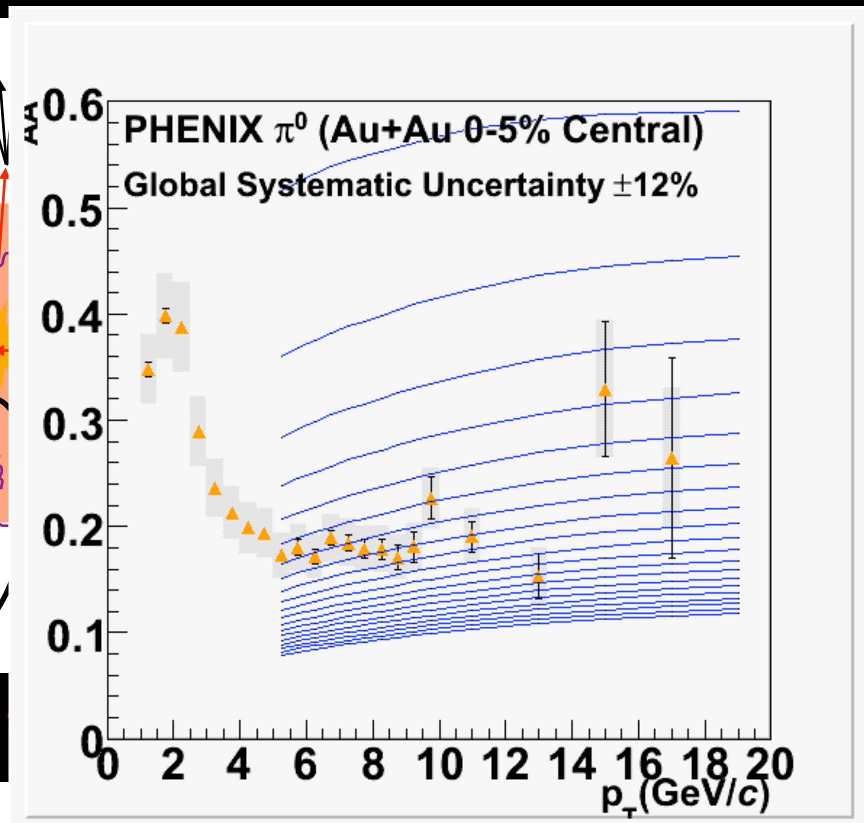
- Medium-modified gluon radiation: production/rescattering.

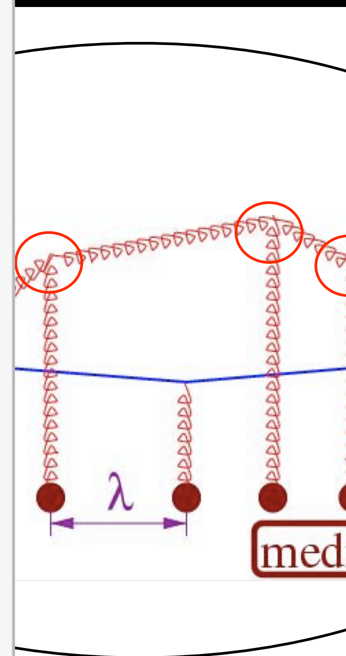


- Two medium parameters: qhat or gluon density plus mean free path, and length (geometry, dynamical expansion).

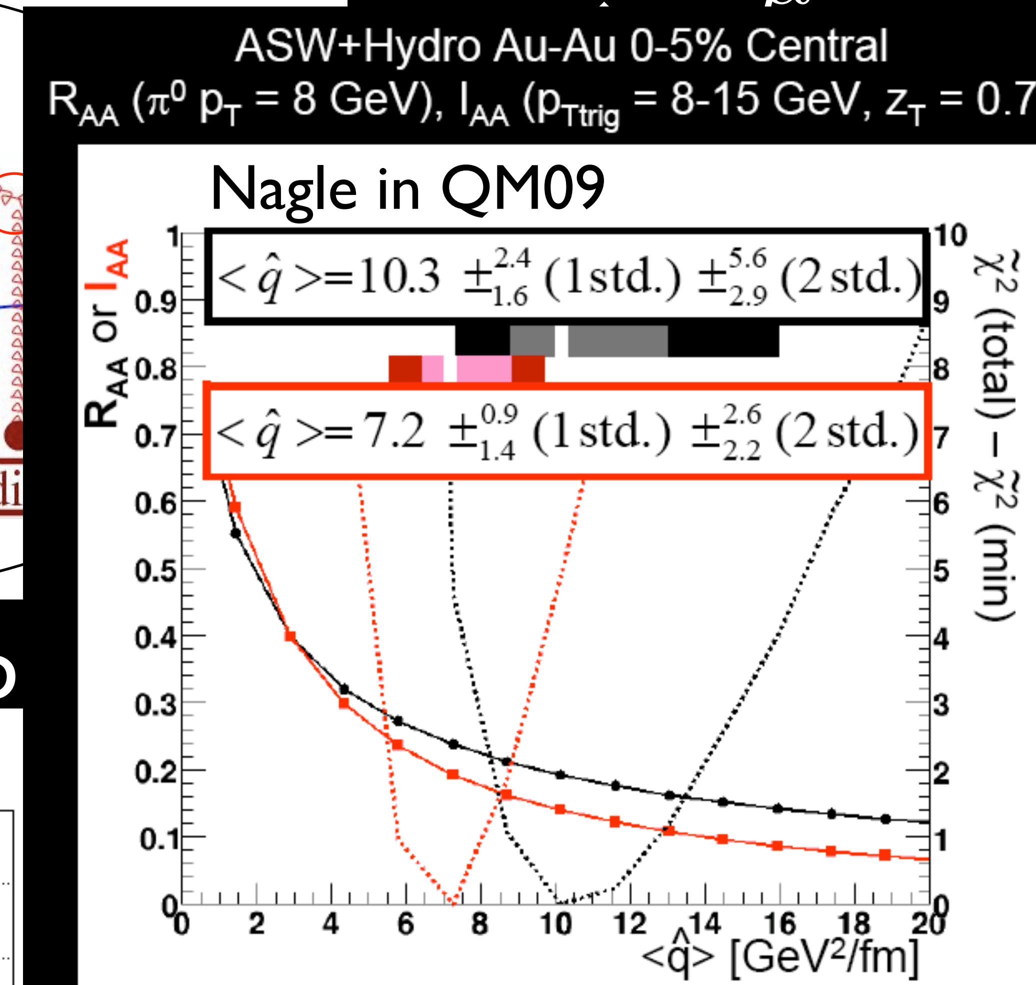
Radiative eloss - successes:



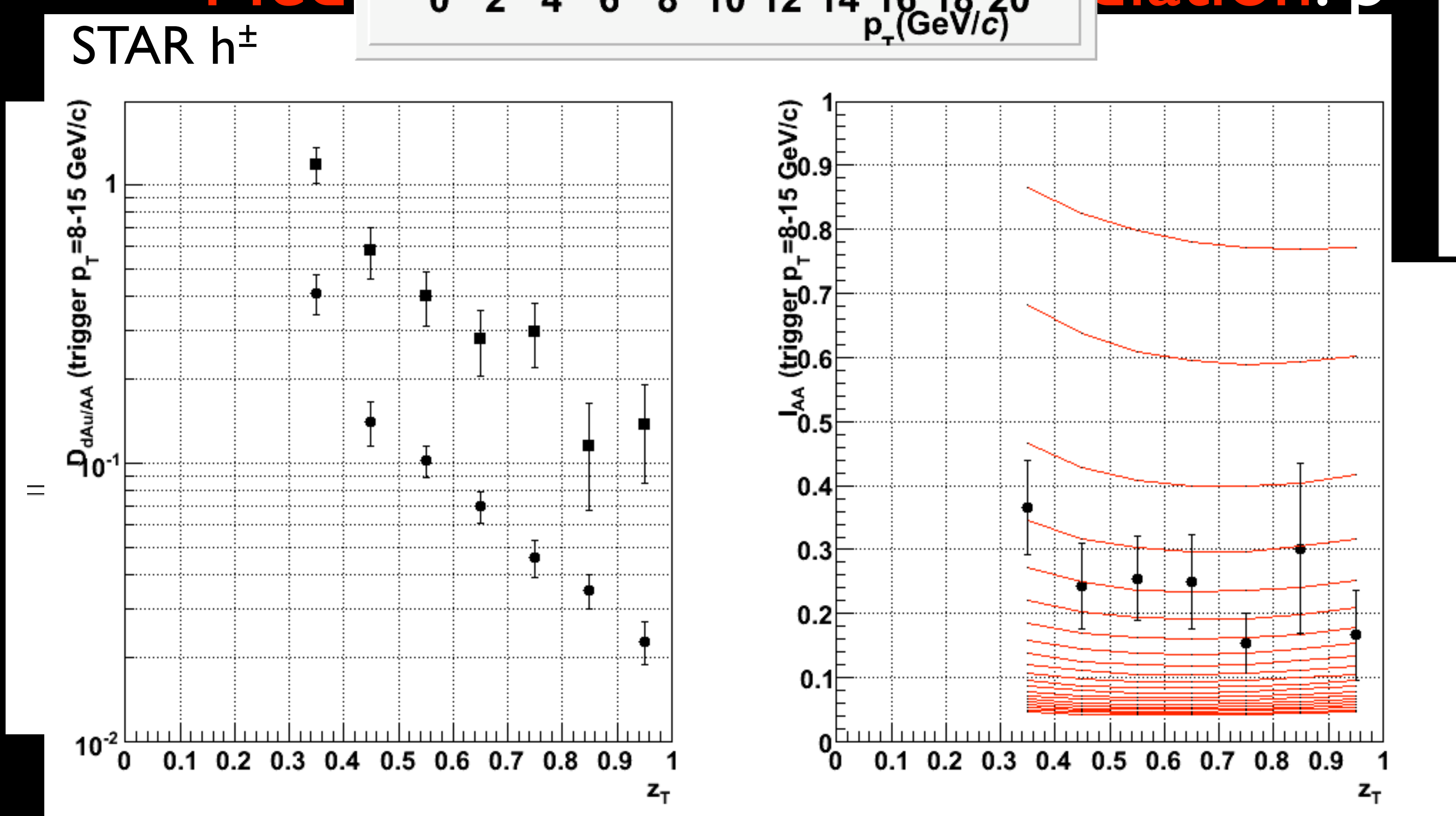


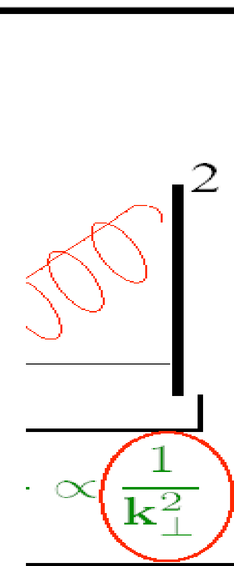


μ^2



• Med... ...diation: p





or gluon density plus mean free path, and length (geometry, dynamical expansion).

Radiative eloss - problems:

• $\Delta E(g)>\Delta E(q)>\Delta E(Q)$; but e^- from c,b are too suppressed: collisional contributions, hadronization, problems in pQCD?

• The extracted value of qhat depends on medium model: $1<\hat{q}<15$ GeV^2/fm ⇒ interface with realistic medium (TECHQM).

• Calculations done in the high-energy approximation: only soft emissions, energy-momentum conservation imposed a posteriori ⇒ Monte Carlo.

• Multiple gluon emission: Quenching Weights (Baier et al '01), independent (Poissonian) gluon emission: assumption! ⇒ Monte

Carlo (PQM, PYQUEN, YaJEM, JEWEL, Q-PYTHIA).

• No role of virtuality in medium emissions; medium and vacuum treated differently ⇒ modified DGLAP evolution (Guo et al '01-...,

Salgado et al '06, Armesto et al '07).

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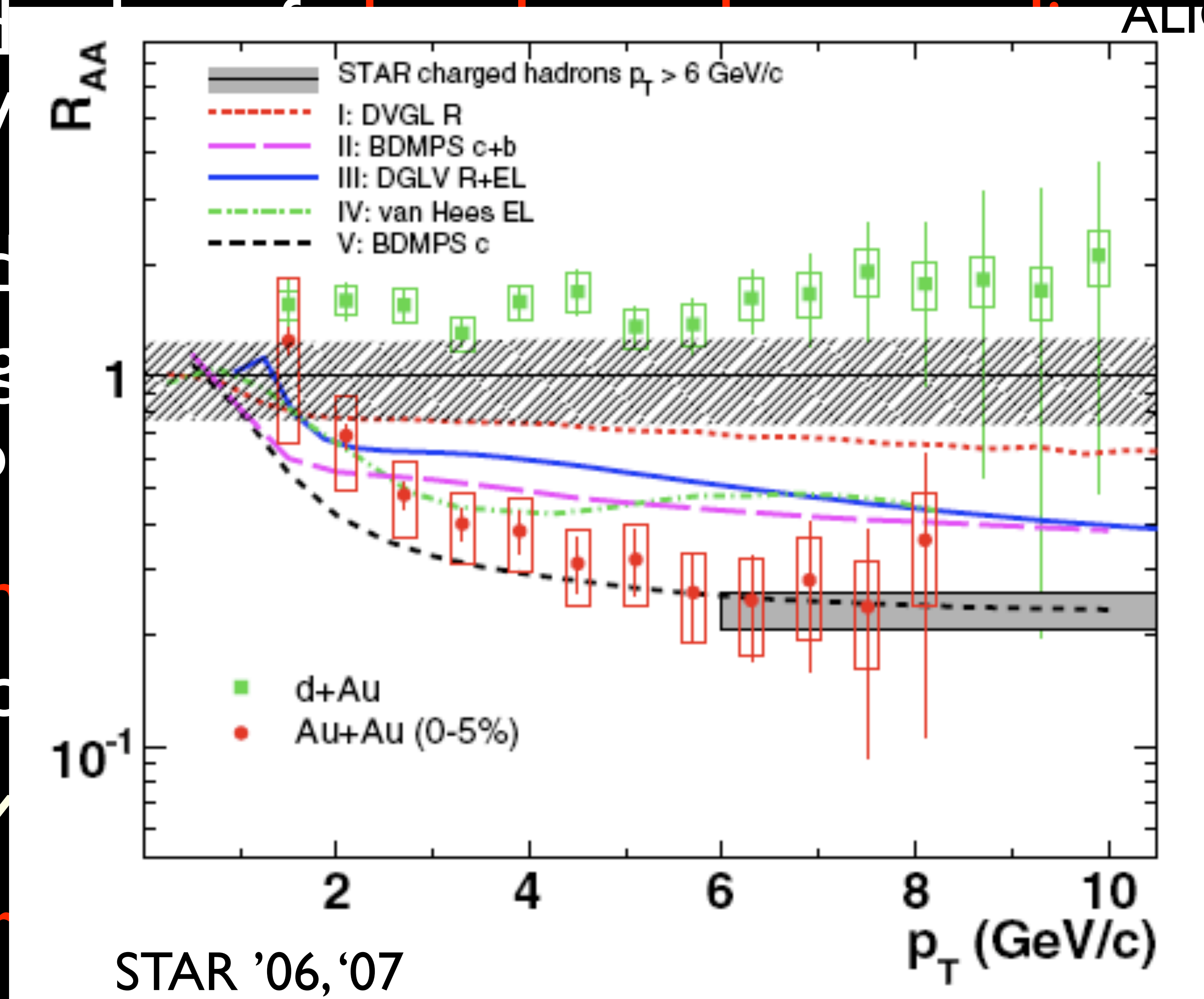

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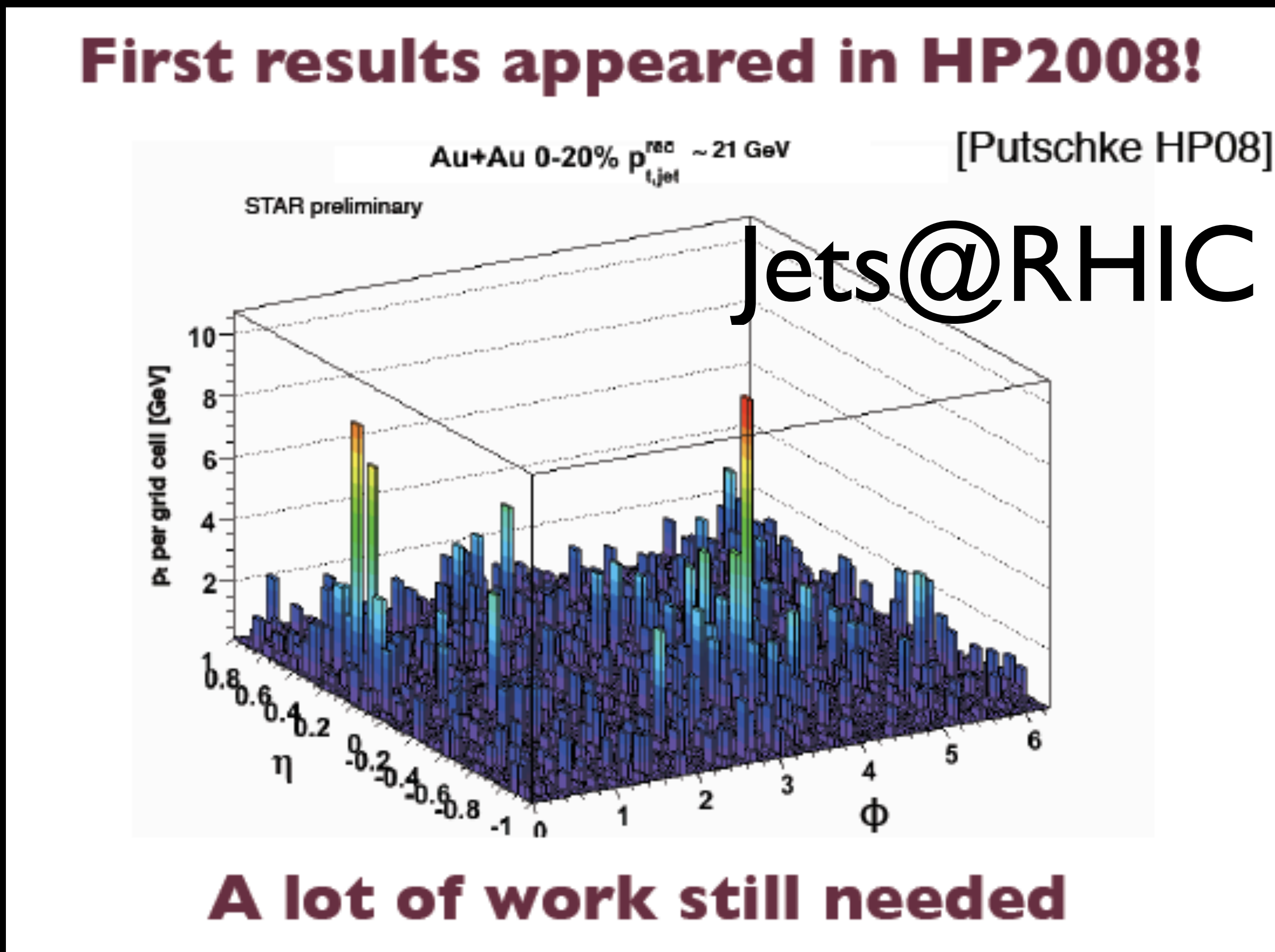
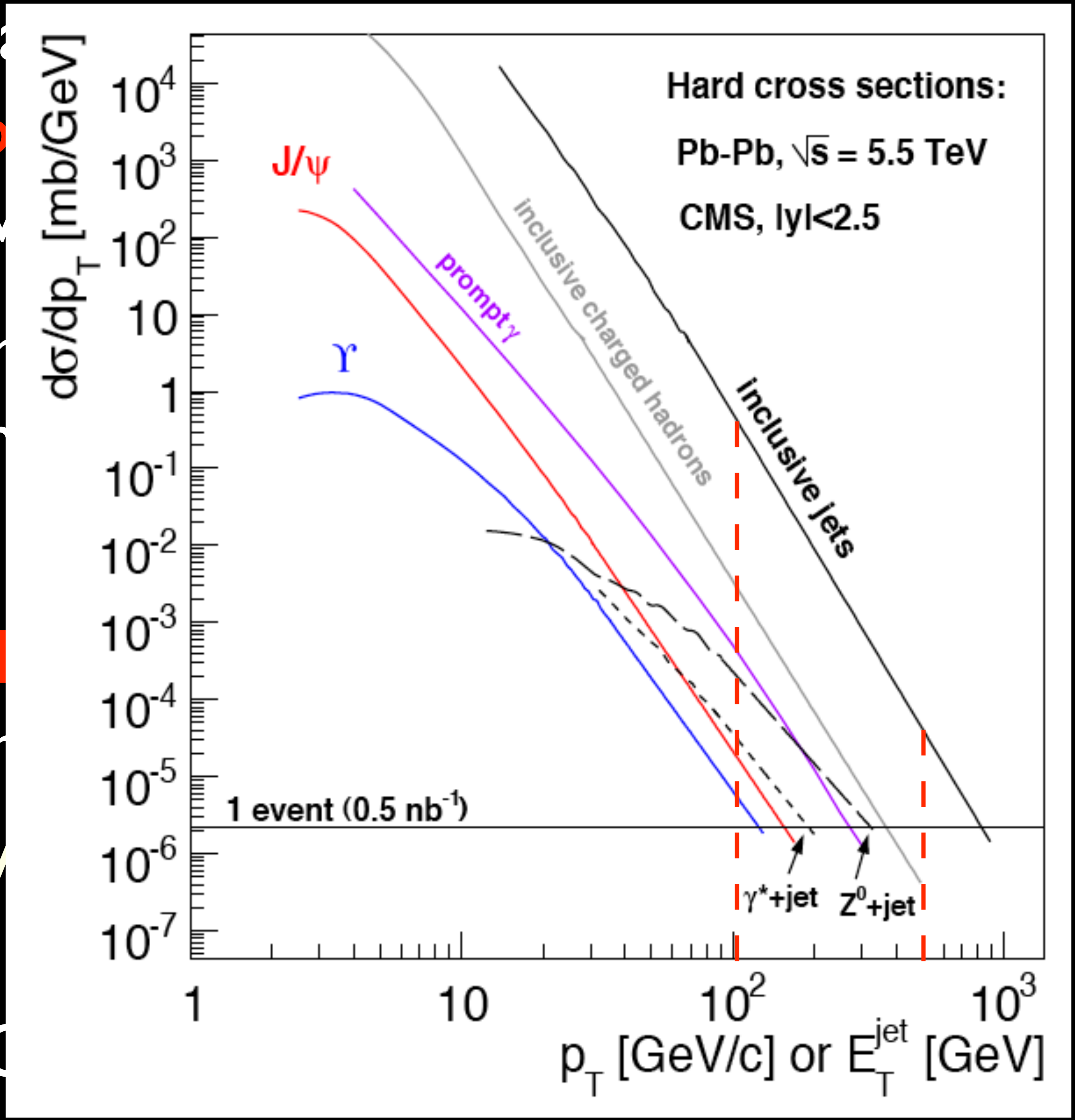
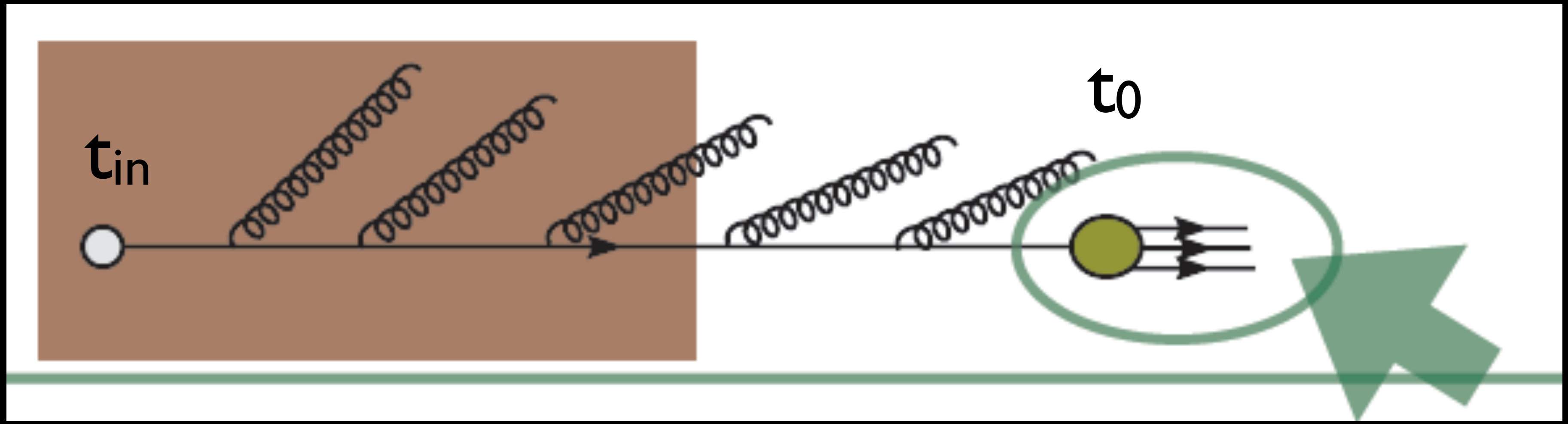




treated differently ⇒ modified DG

Salgado et al '06, Armesto et al '07).

In-medium FSR (I):



- Assumption: hadronization is not affected by the medium: looks OK at RHIC for pT>7-10 GeV.
- The splittings are modified: either radiatively (Q-PYTHIA) or radiative+collisionally (JEWELL, PYQUEN); or the evolution is enlarged due to momentum broadening (YaJEM).

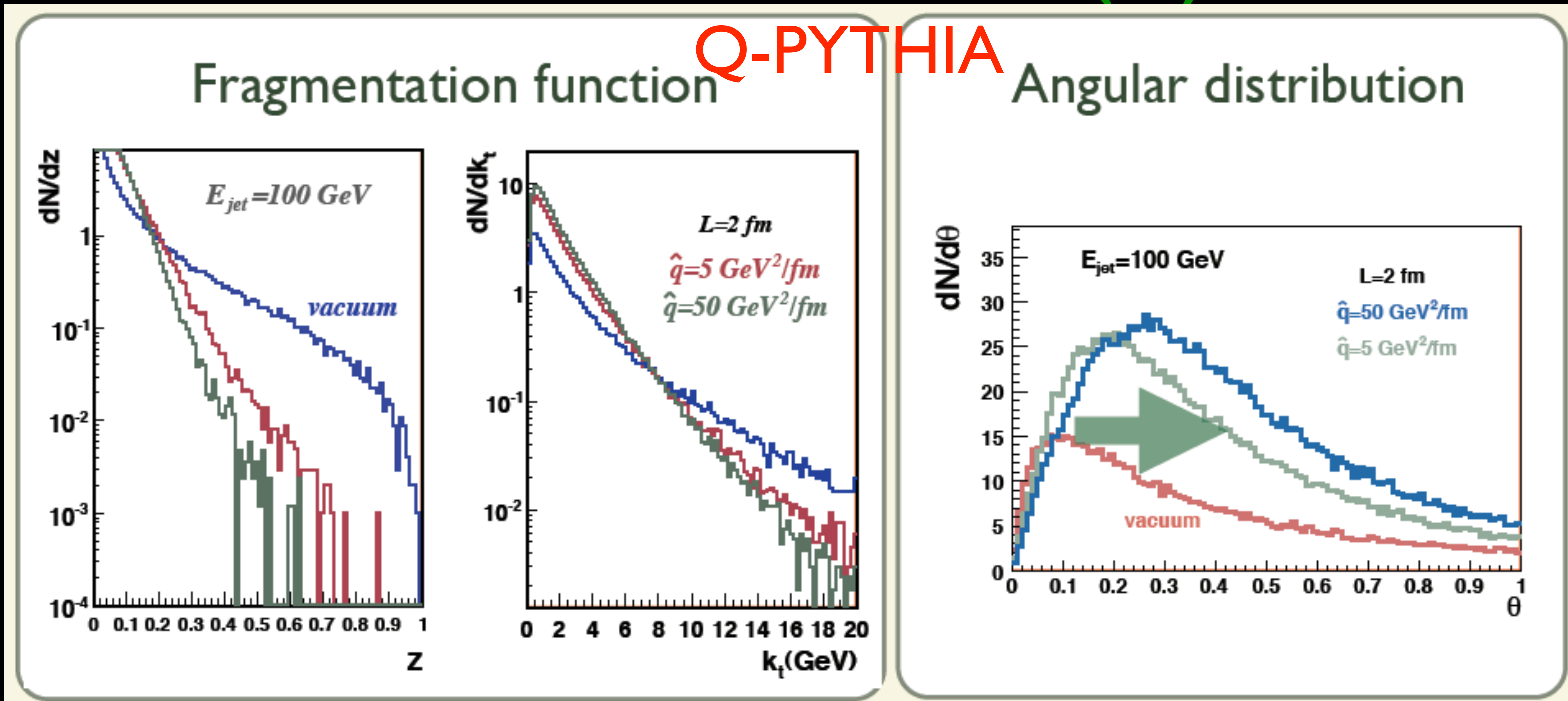
$$P_{i\to j}(z) \longrightarrow P_{i\to j}(z) + \Delta P_{i\to j}(z,t,E,L,\hat{q})$$

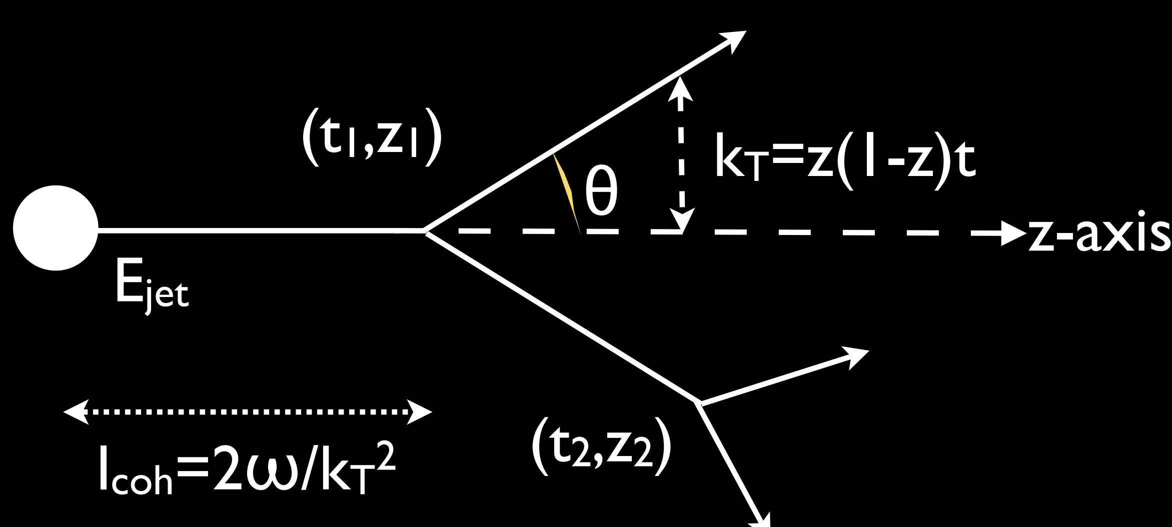
- Underlying ingredients: factorization no emission/emission/no emission/... (Sudakov/splitting/Sudakov/...) holds in the medium, and the evolution scale (t,k_T,Θ) can be related with the medium length → both to be proved (Jet Calculus in a medium).

In-medium FSR (II):

- The MC's generically reproduce the expectations:
  - → Particle spectrum softens (jet quenching).
  - → Larger emission angles (jet broadening).
  - → Intra-jet multiplicity enlarges.

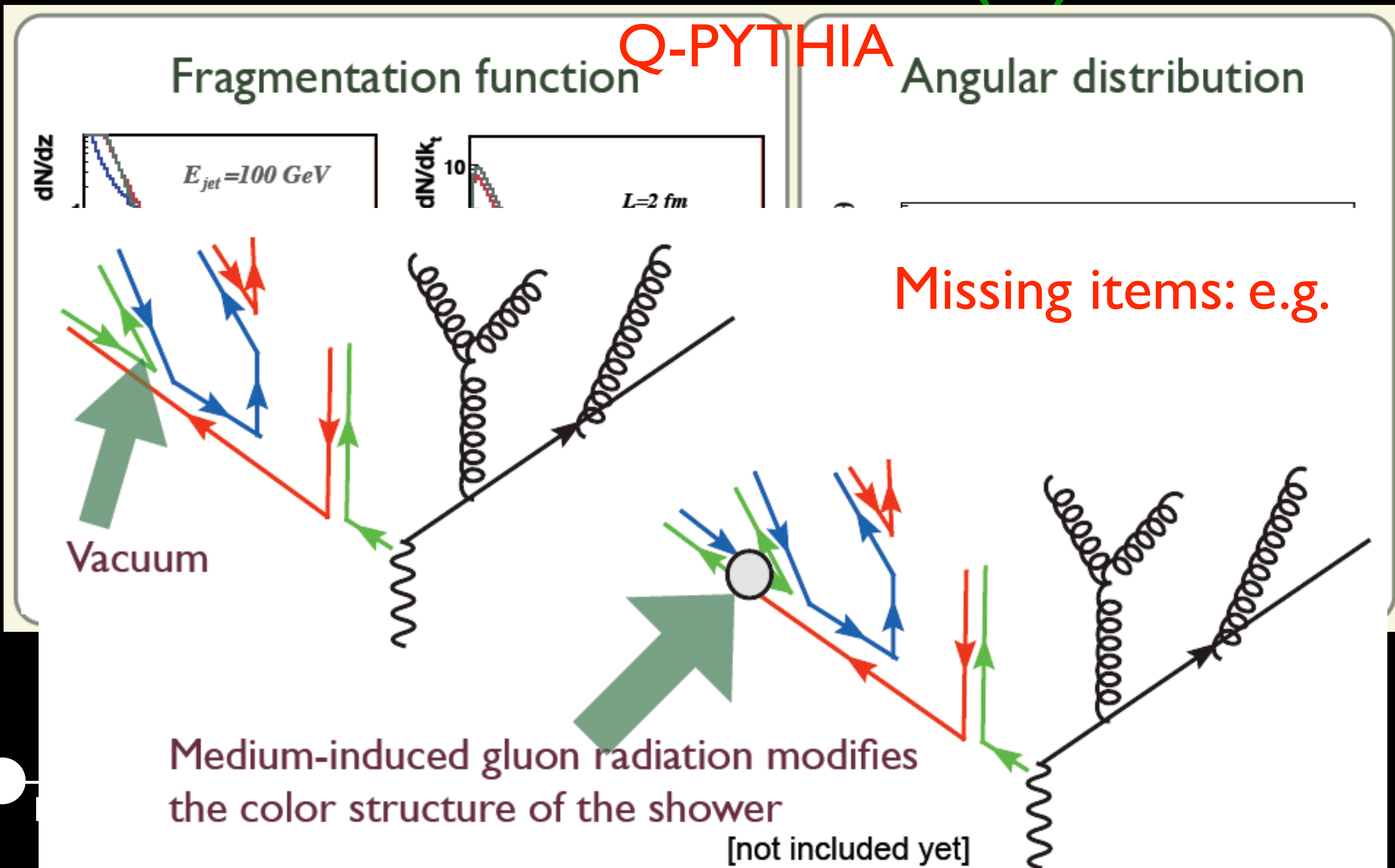
In-medium FSR (II):





- Intense activity at RHIC and the LHC: jet reconstruction in a large background (small clustering parameters versus out-of-'cone' medium modification).

In-medium FSR (II):



medium modification).

Summary:

- The interpretations of the three main observables at RHIC (low multiplicity, collective flow, jet quenching) have triggered a lot of ongoing theoretical activity on (to mention just a few):
  - A) Small-x physics and particle production in nuclear collisions.
  - B) Early thermalization and viscous hydrodynamics.
  - C) Strong coupling computations: AdS/CFT for HIC.
  - D) New formalisms for eloss: correlations, jets, Monte Carlo,...

- The LHC and RHIC-II offer huge possibilities to verify or falsify the picture arising from RHIC with new observables: jets, identified heavy flavor, EW boson production,... Much work has been done but much remains to be done.

- Points A) and D) in the list above have clear connections with pp and DIS: link with plans on future eA colliders.