XIII Mexican School of Particles and Fields
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Hard probes in heavy-ion collisions at RHIC

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1. Introduction: hard probes and the medium at RHIC.

2. Elliptic flow.

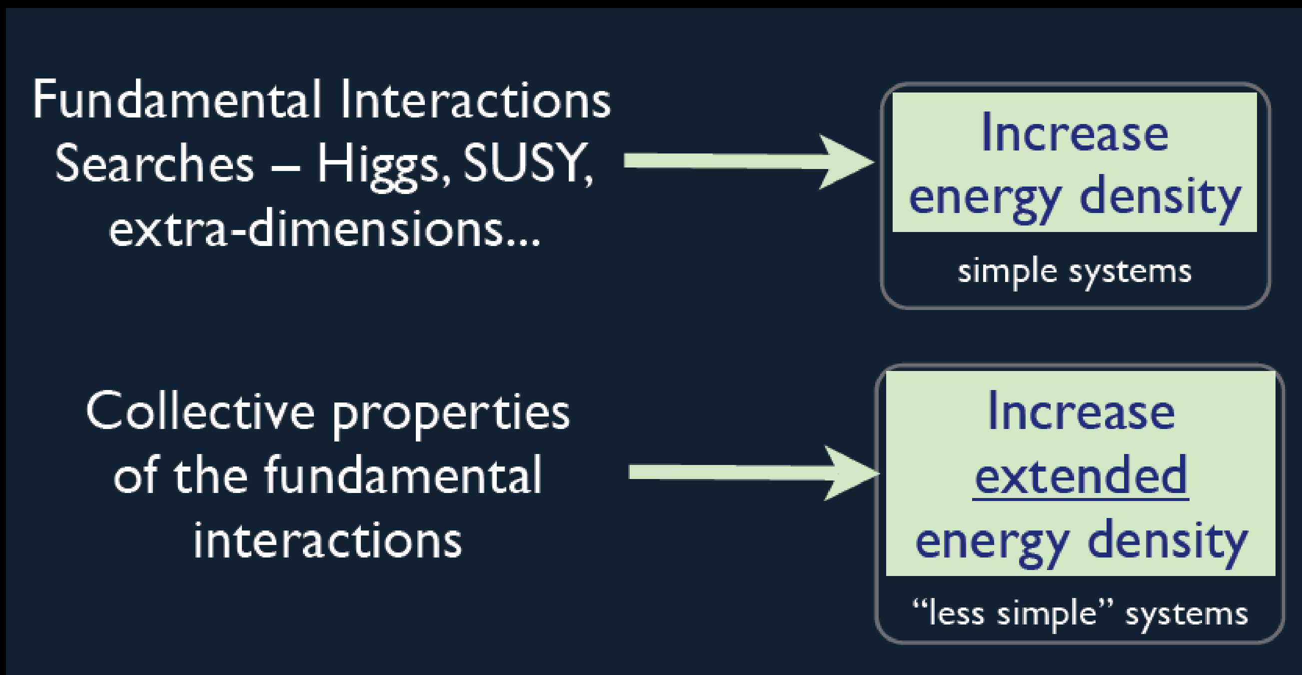
3. Hard probes: jet quenching, quarkonium suppression, photon and dilepton production.

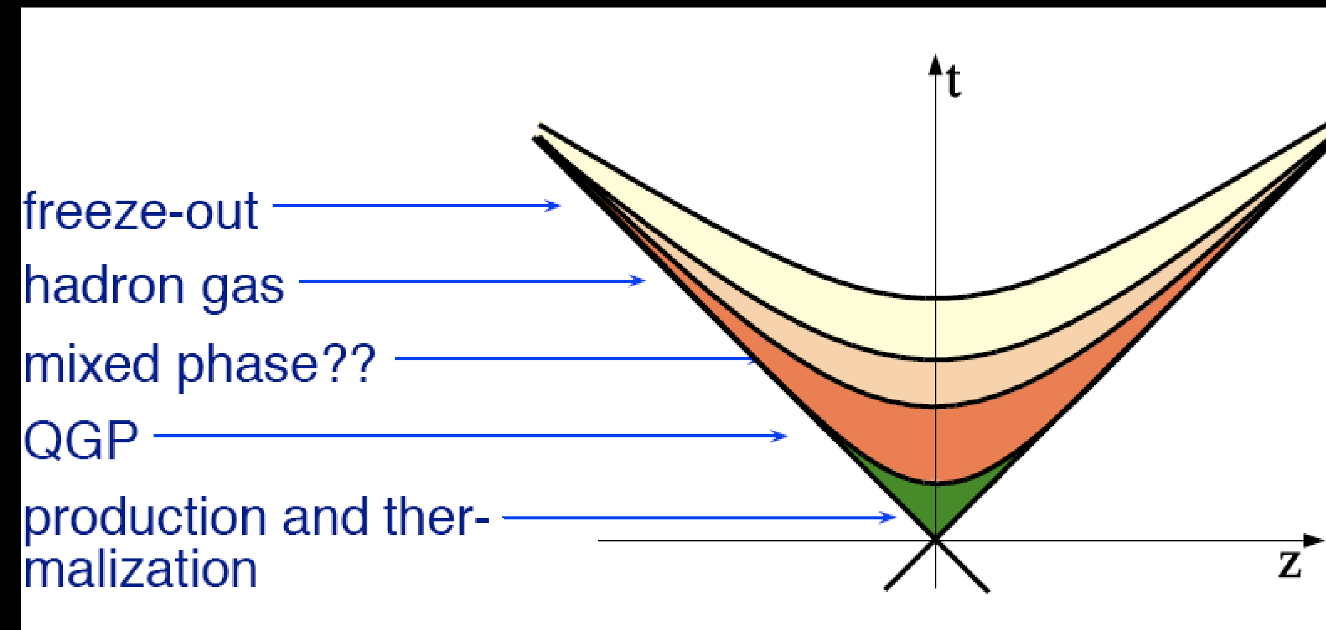
4. Perspectives for the LHC.

5. Summary.

See the talks by J. Edelstein, A. Buchel, H. Caines, J. Jalilian-Marian, G. Paic and S. Brodsky, and the thematic session on Relativistic Heavy Ions; see also the talks at Hard Probes 2008.

Heavy-ion collisions:





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

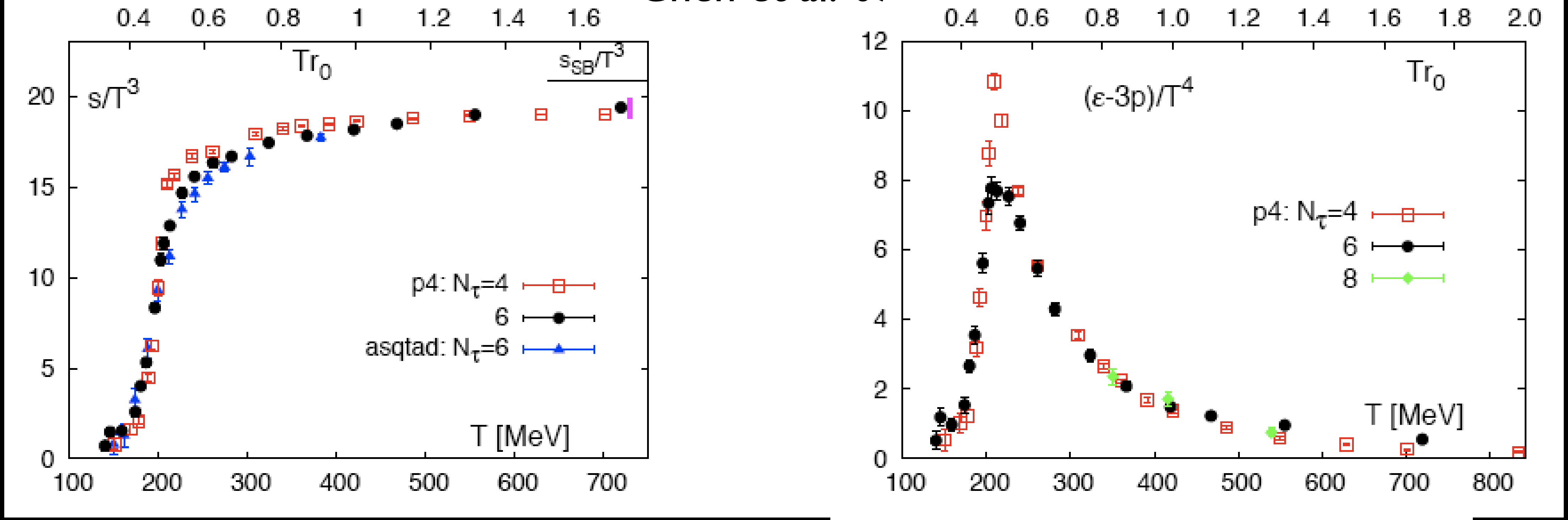
HIC is an interdisciplinary field, whose goal is the understanding of confinement through the study of systems with high parton densities. Using asymptotic freedom, high densities lead to quasi-free partons: Quark-Gluon Plasma?

The phase diagram of QCD:

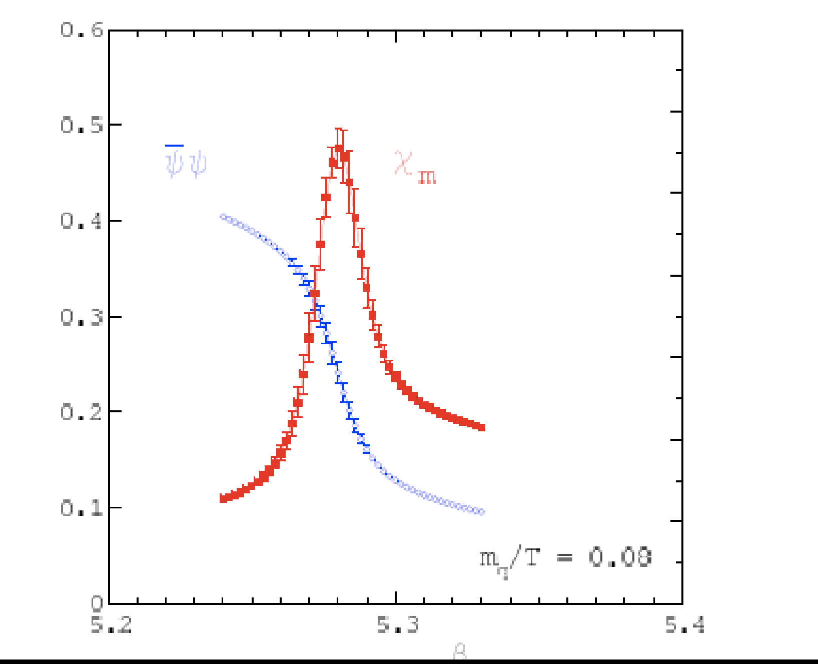
$$\epsilon_{\rm HG} = \frac{\pi^2}{30} 3\, T^4 \simeq T^4$$

$$\epsilon_{\rm QGP} = \frac{\pi^2}{30}\left[2\times 8 + \frac{7}{8}\times 2(3)\times 2\times 2\times 3\right] T^4 = \frac{\pi^2}{30}\left[16+21(31.5)\right] T^4$$

Chen et al. '07



$$\langle 0|\bar q_L q_R|0\rangle \neq 0 \quad \xrightarrow[T\to\infty]{} \quad \langle 0|\bar q_L q_R|0\rangle = 0$$



Until very recently, simulations for μ=0. See Schmidt at HP2008.

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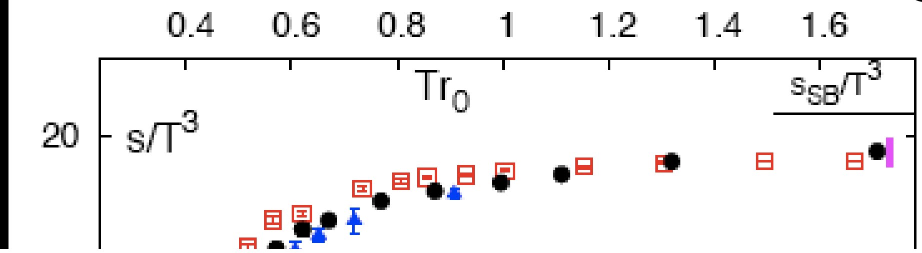
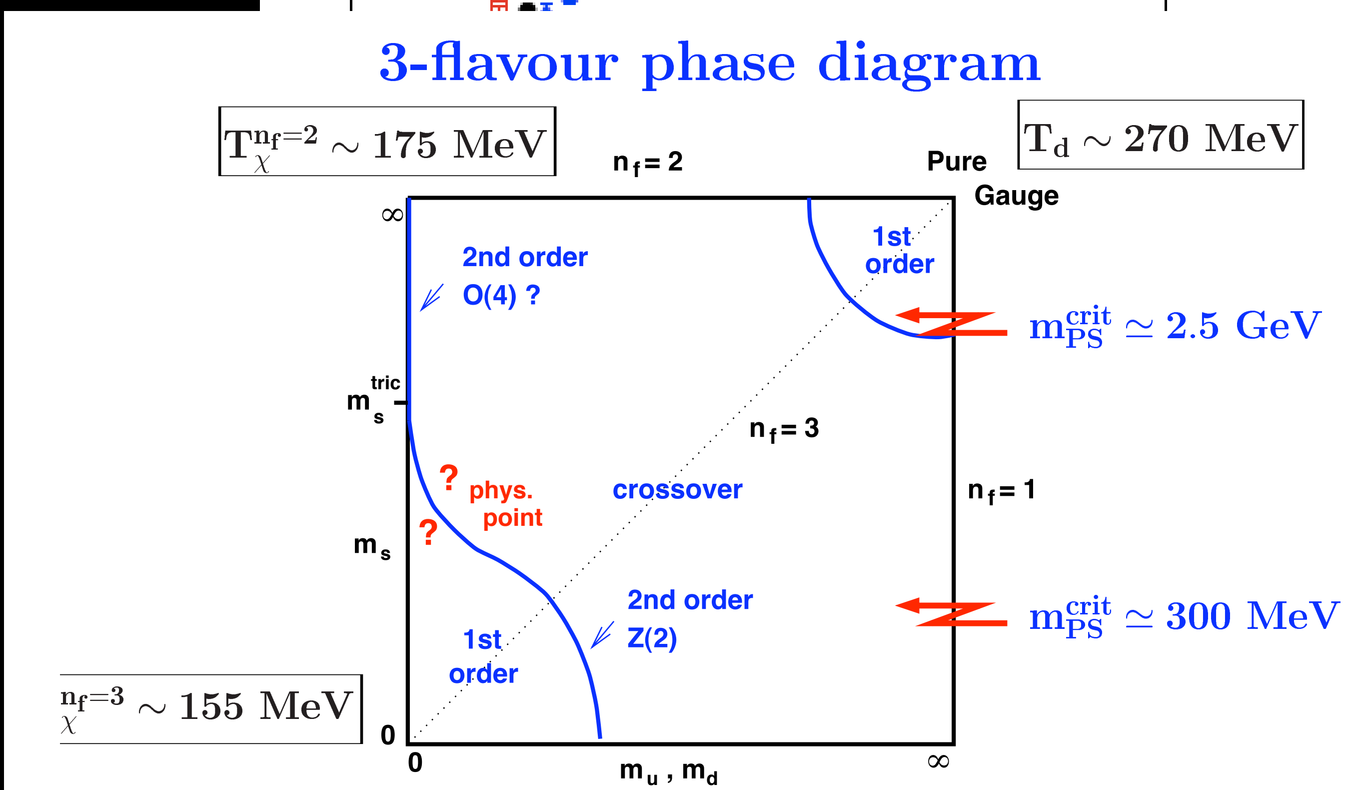
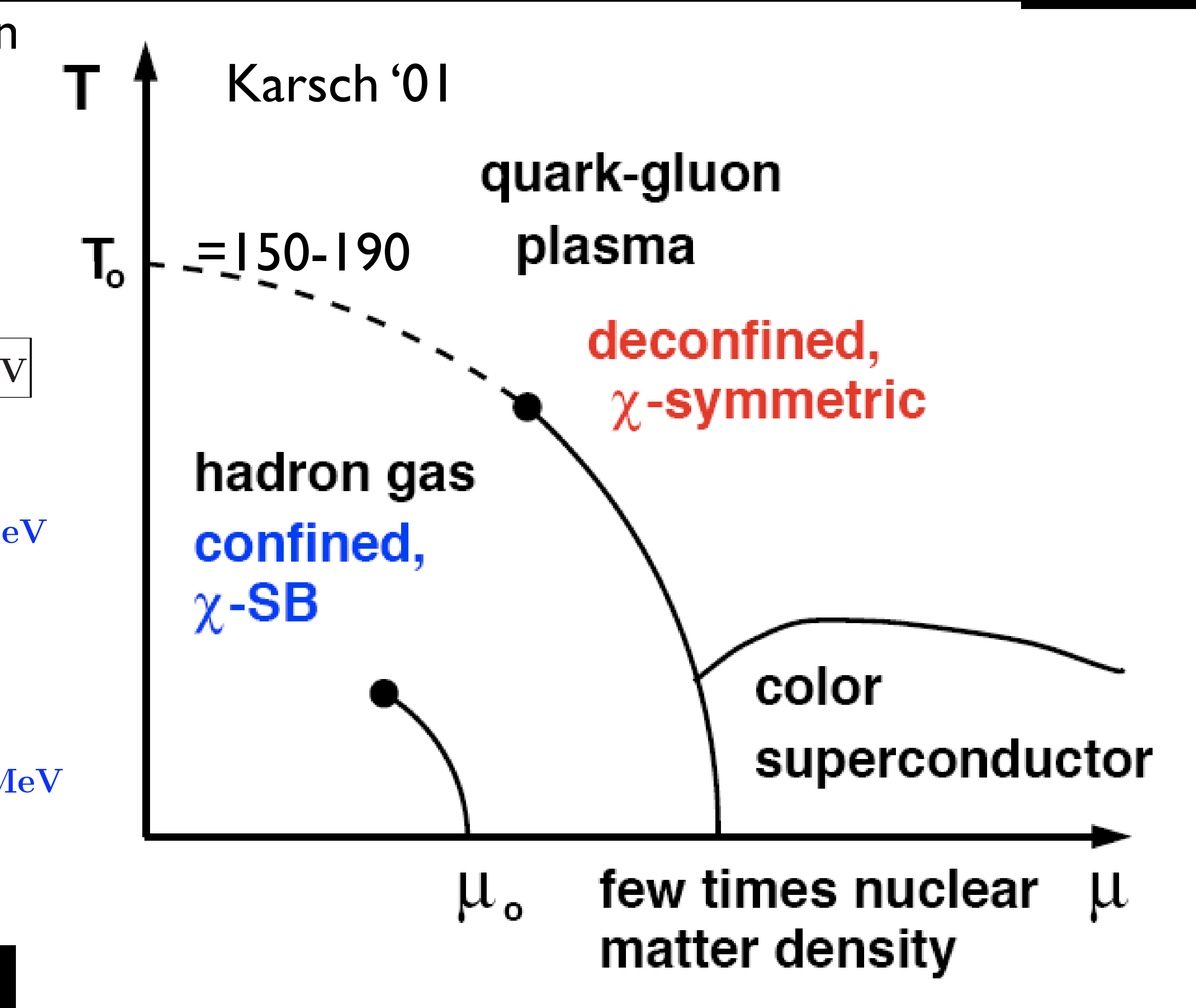


Chen





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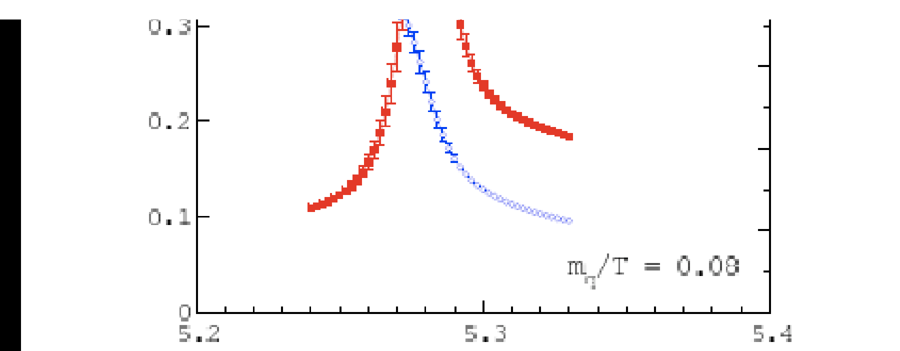

Probes of the medium:

Signatures which would allow to identify the medium created in URHIC with a phase of matter built of quasi-free partons:

1) Signatures from the medium itself (soft, momenta ~ T):

☛ Thermalization/collective behavior: elliptic flow, thermal photon/dilepton emission, statistical hadronization.

☛ Chiral-symmetry restoration: strangeness enhancement, broadening of resonances (ρ).

☛ Phase transition: fluctuations.

2) Probes whose comparison measured/expected (in perturbative QCD - $p \gg \Lambda_{QCD}, T$; hard) characterizes the medium:

☛ Suppression of QQbar bound states: quarkonium linear potential becomes Debye screened.

☛ Suppression of high energy particles: jet quenching.

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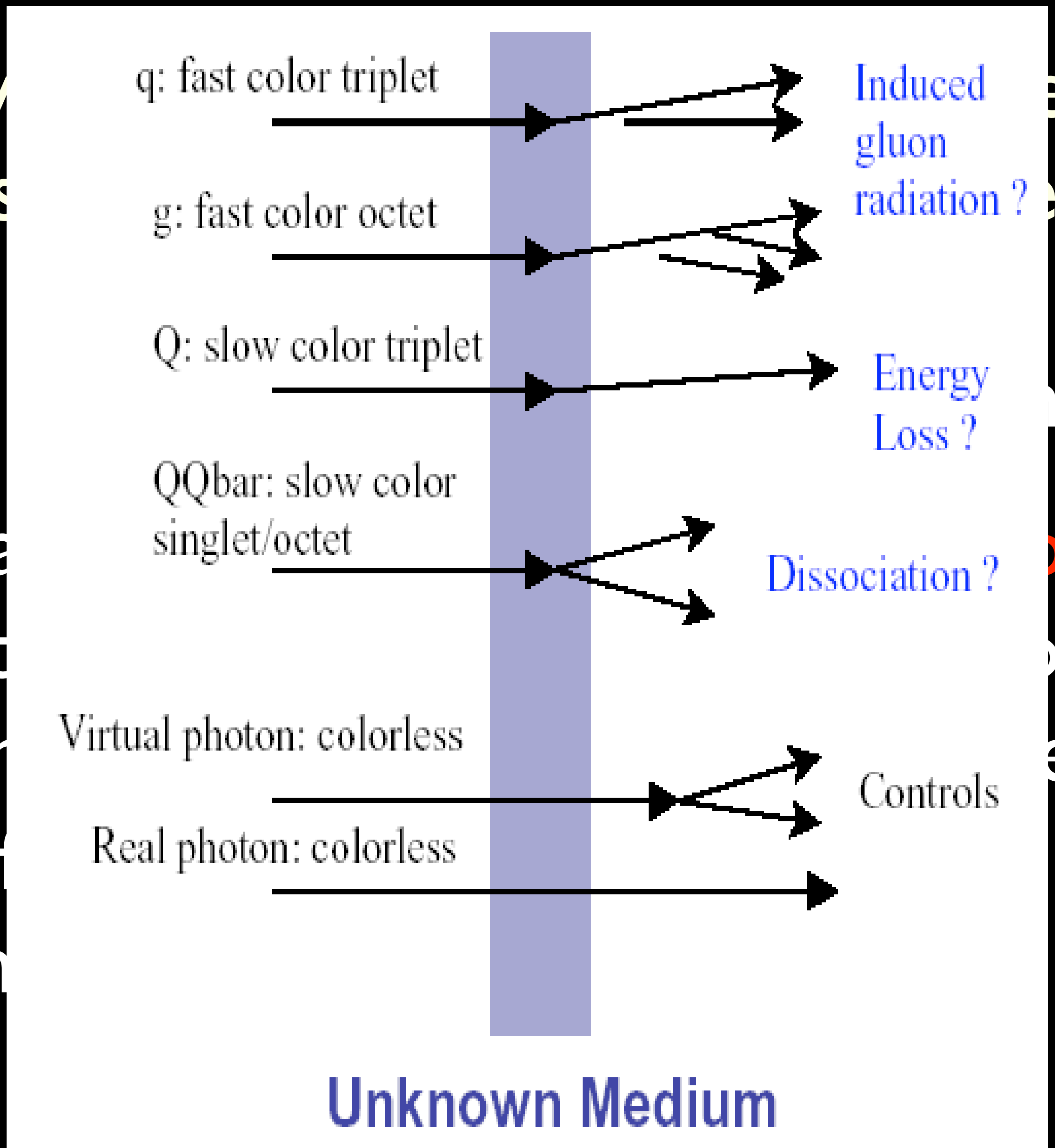

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'Standard' claim at RHIC:

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

➪ Highlights from RHIC: the medium created in the collisions is dense, ~10 GeV/fm^3, partonic and behaves very early like a quasi-ideal fluid; strong collectivity: scQGP. New theoretical developments:

A) Why the medium gets thermalized so early (τ<1 fm)? Instabilities, perturbative HO processes, strong coupling phenomena (studied in N=4 SYM using the AdS/CFT (*) correspondence), CGC.

B) The value of qhat is? too large for pQCD: strong coupling? (*)

C) Why the viscosity is so low? (*). How to do viscous hydro?

D) Differential observables; and jet-medium interactions? (*).

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2. Elliptic flow:

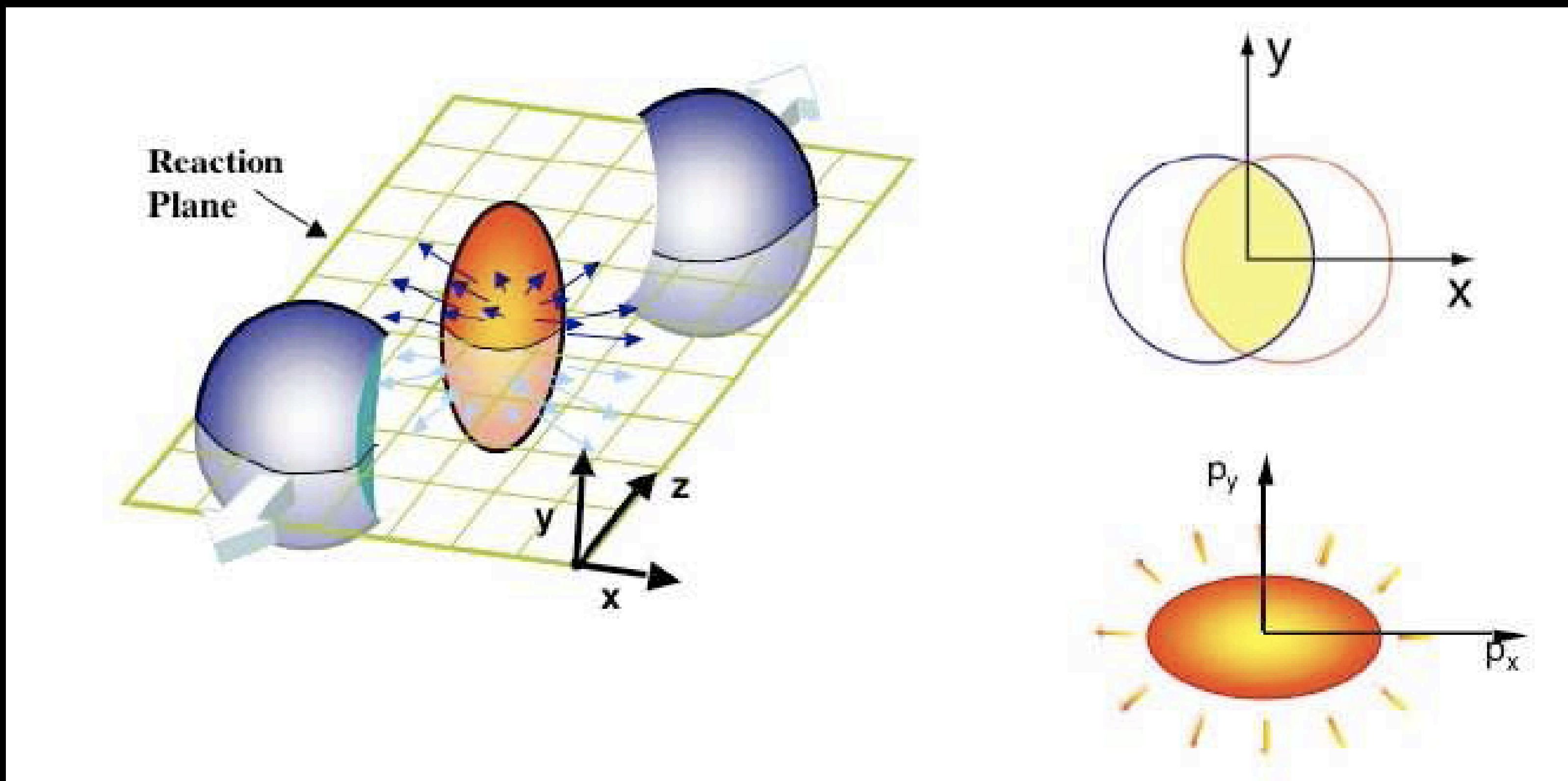
2.1. Definition.

2.2. The room for viscosity.

2.3. The role of initial conditions.

See Heinz's talk at HP2008.

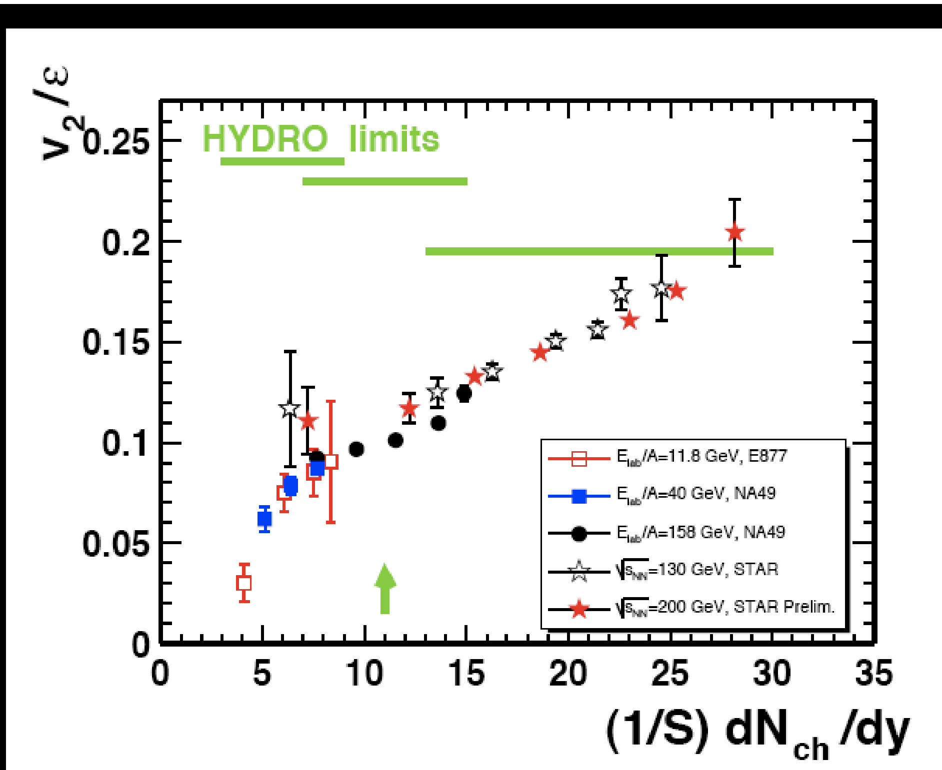
2.1. Definition:



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

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

$$\epsilon = \left\langle\frac{y^2-x^2}{y^2+x^2}\right\rangle \qquad v_2 \propto \epsilon\,\frac{1}{S}\frac{dN_{charged}}{dy}$$



v_2, also called elliptic flow, is usually interpreted in terms of a final momentum anisotropy dictated by an initial space anisotropy. The most appealing frame to describe the data is in terms of relativistic hydrodynamics.

2.2. The room for viscosity:

Ideal hydro (no viscous corrections), see Heinz et al '03

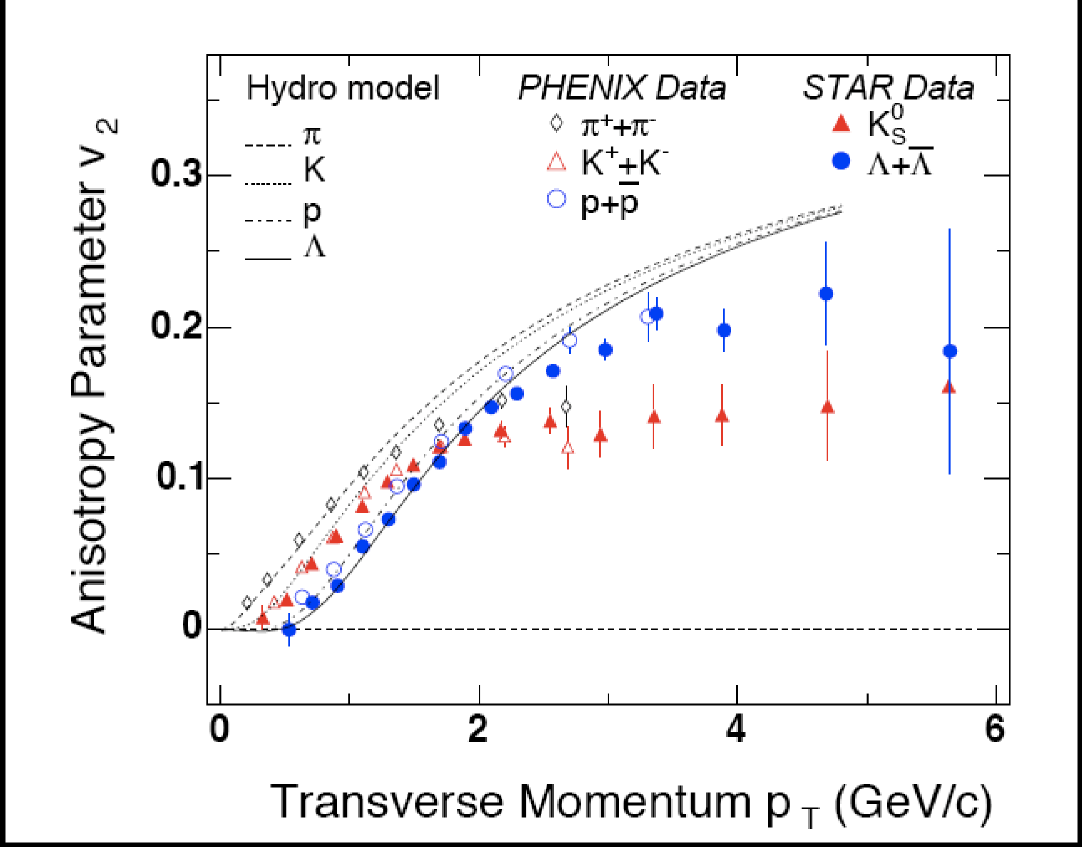
$$u^\mu = \gamma\,(1, v_x, v_y, v_z)$$

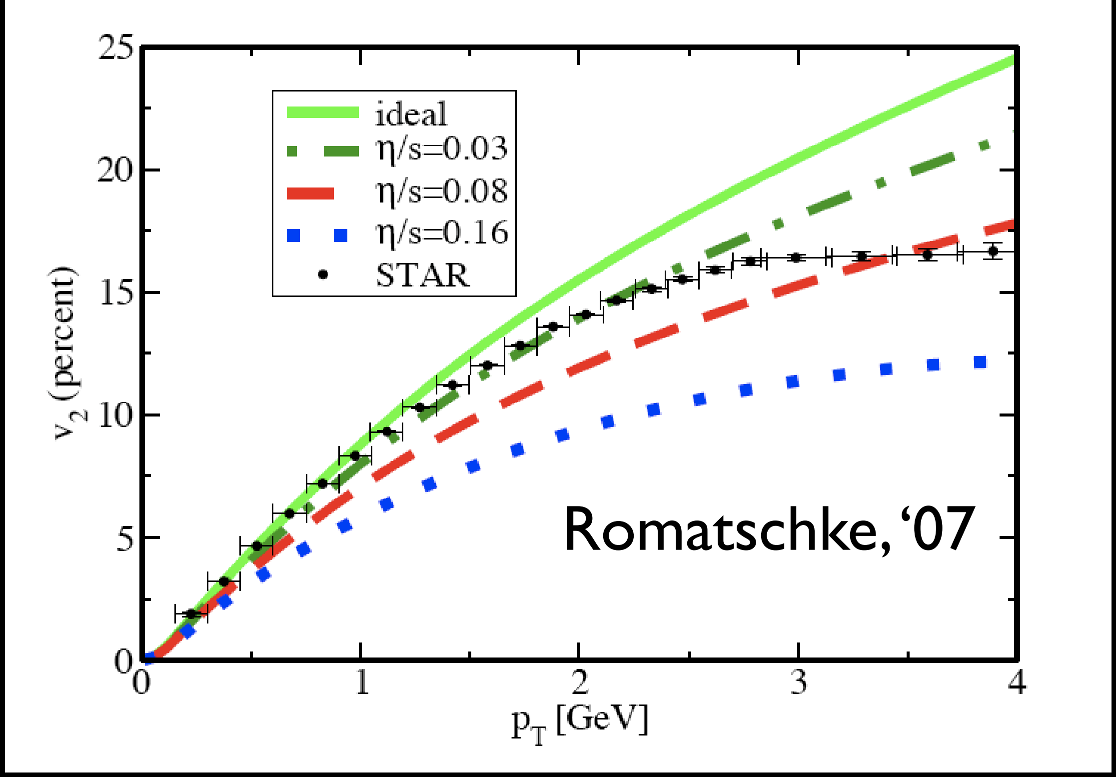
$$T^{\mu\nu}(x) = \Big(e(x) + p(x)\Big)u^\mu(x)u^\nu(x) - p(x)\,g^{\mu\nu}$$

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

$$\partial_\mu j_i^\mu(x) = 0, \qquad i = 1, \dots, M$$

With an EOS (5+M variables, 4+M equations), a set of initial conditions and a hadronization prescription:





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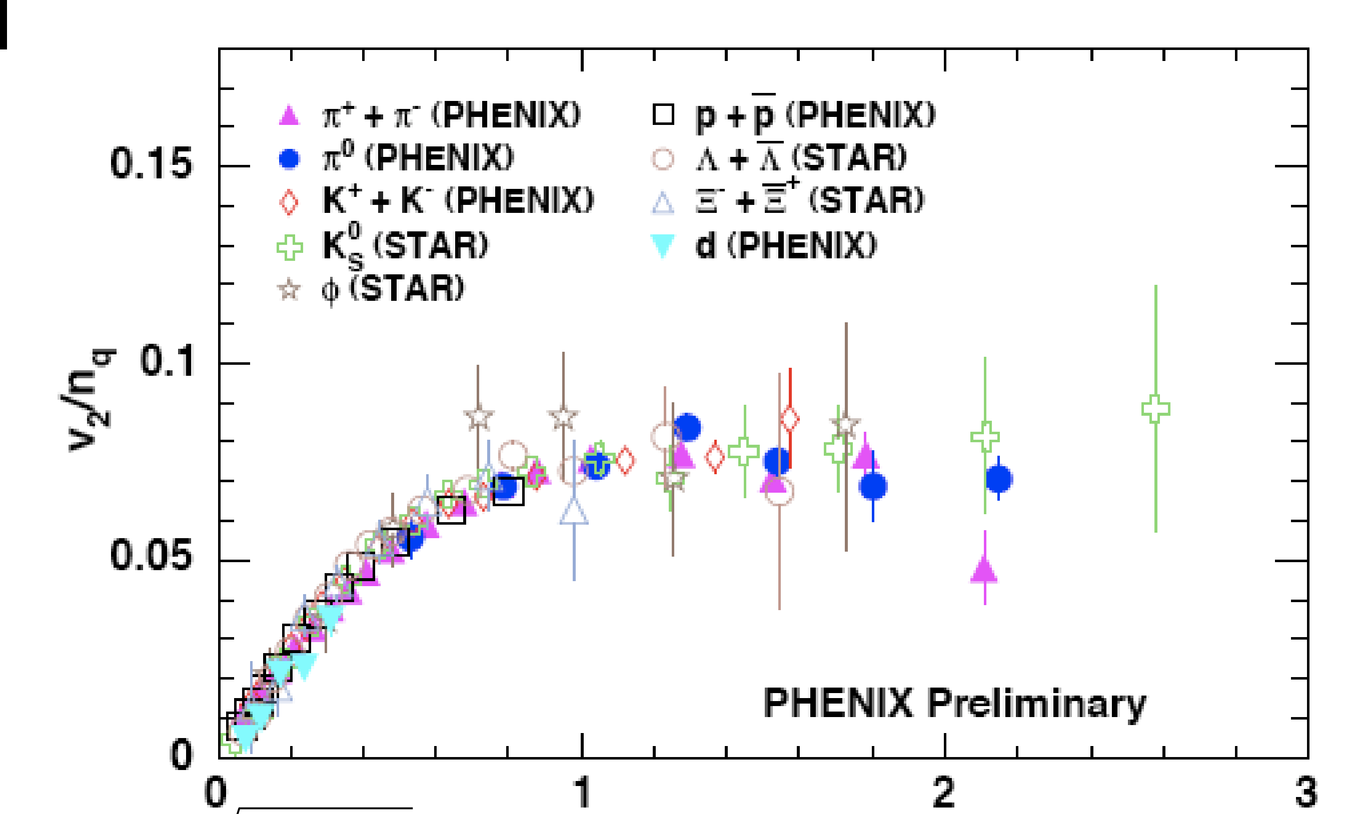
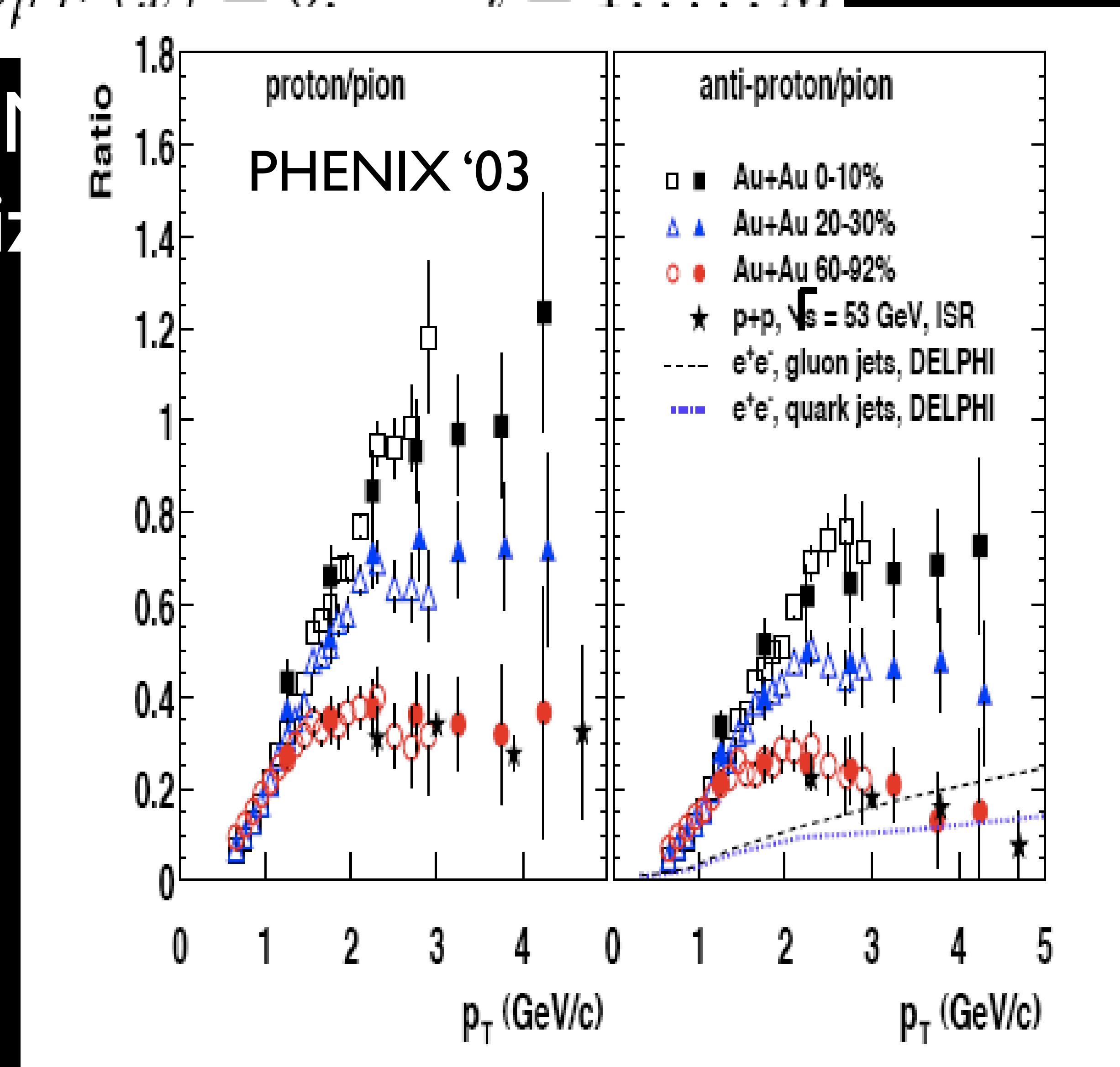
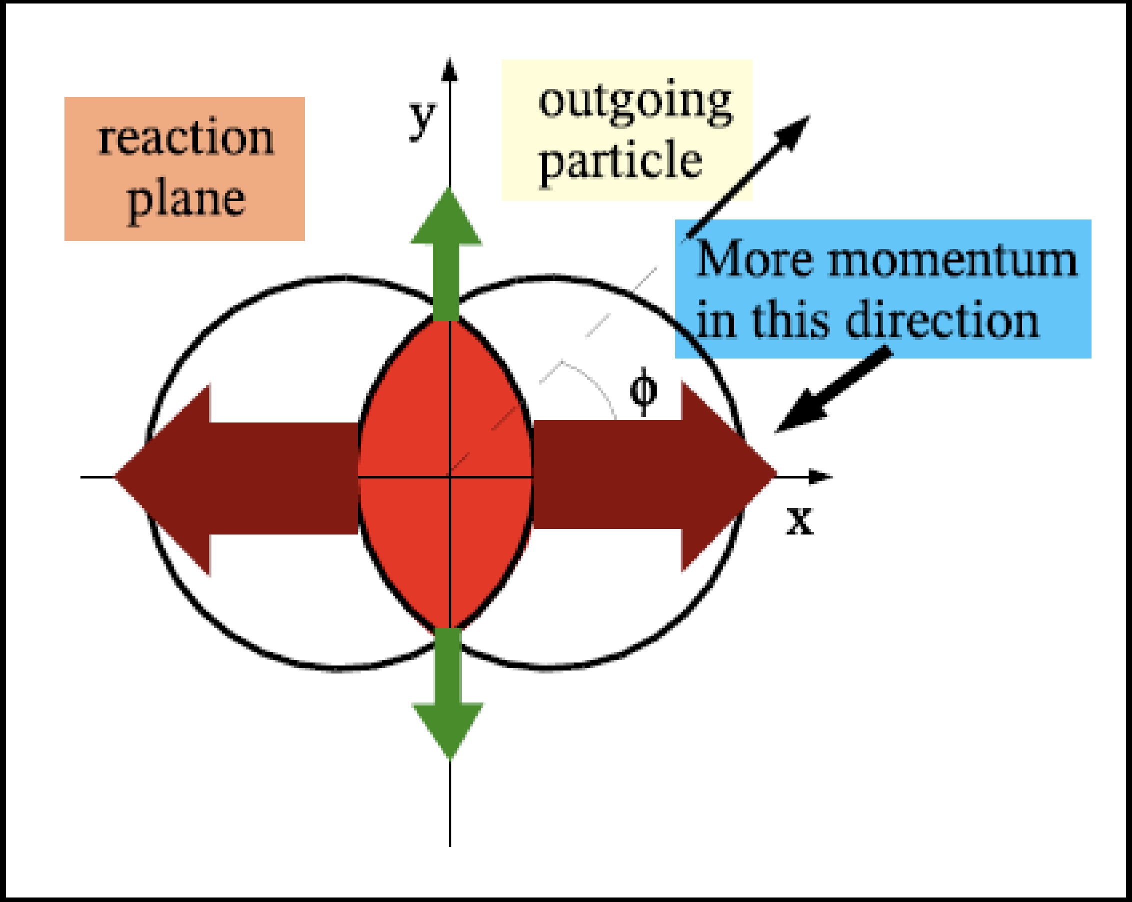


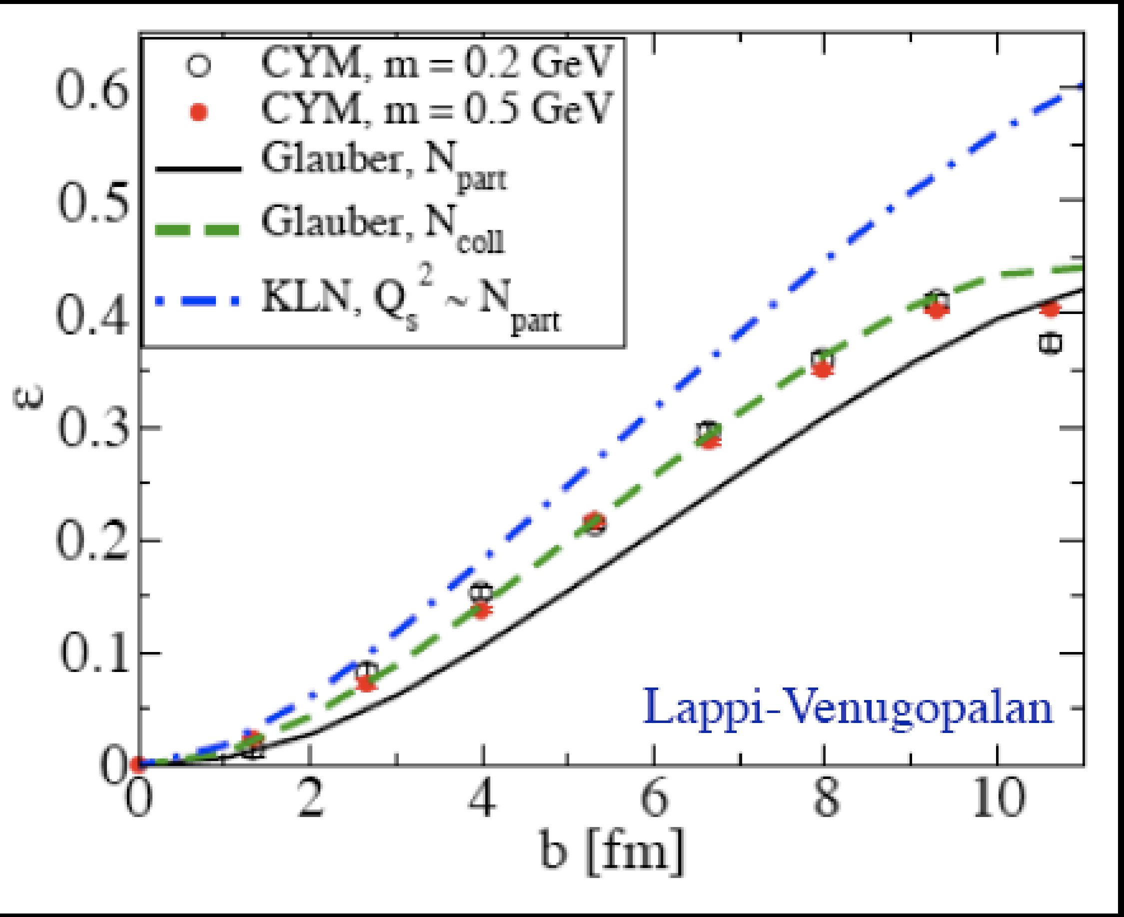
$$KE_T = \sqrt{p_T^2 + m^2} - m$$



2.3. The role of initial conditions:

Hydro is initialized when thermodynamical equilibrium (isotropization) is achieved: very soon, to produce more particles in the direction where there was less matter ⇒ τ_{eq}<1 fm/c.





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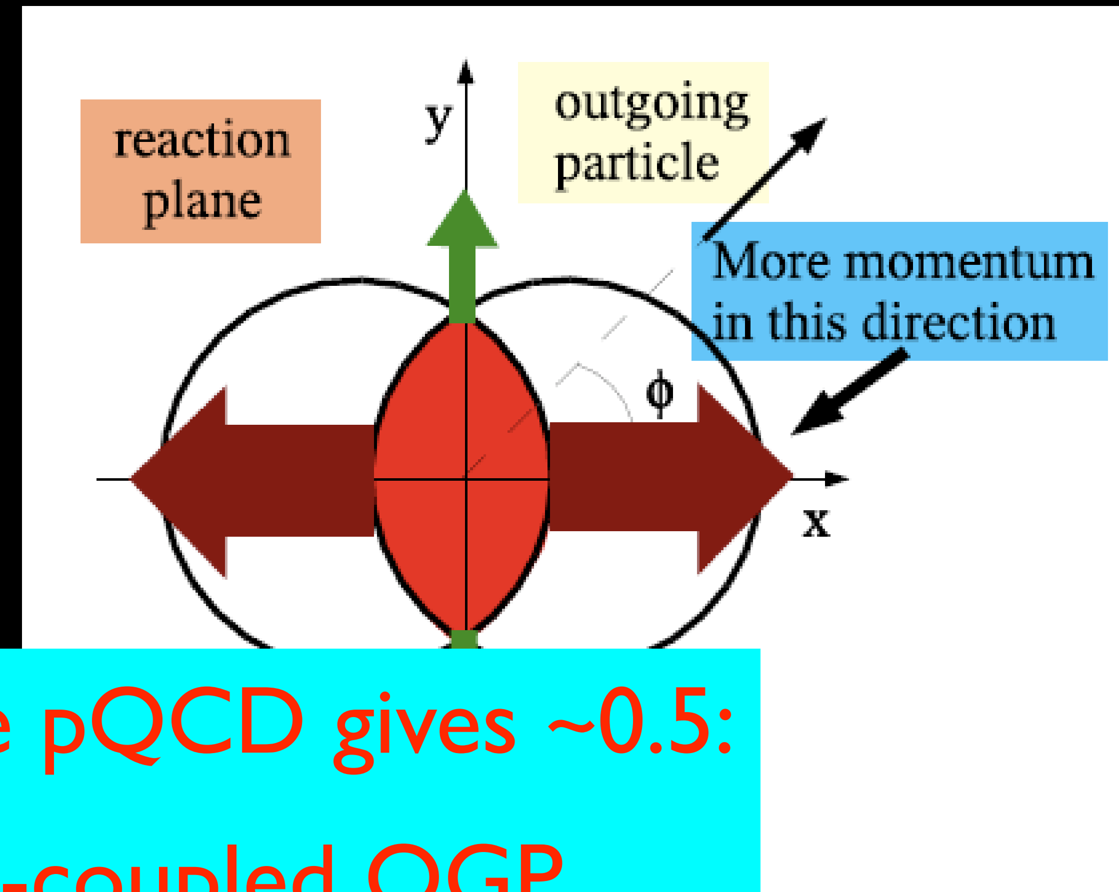
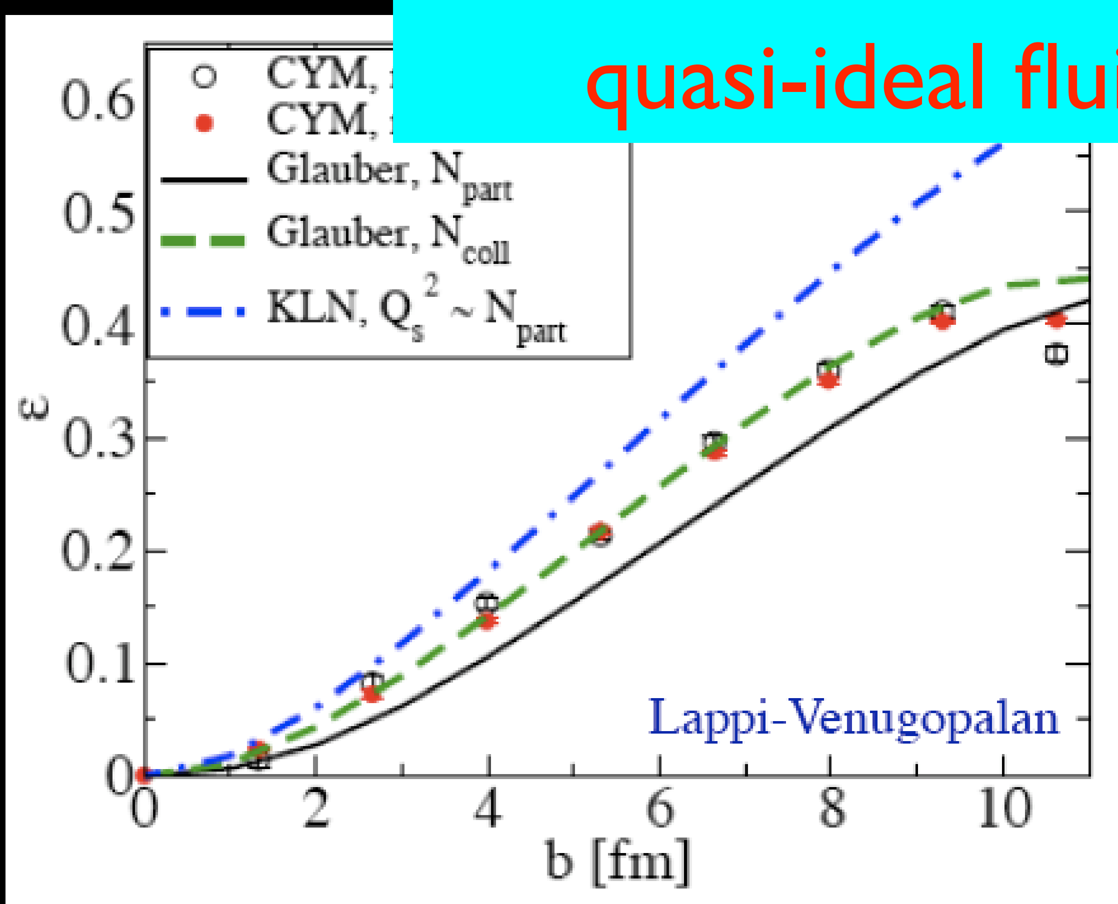


Data suggest η/s~<0.1, while pQCD gives ~0.5: quasi-ideal fluid, strongly-coupled QGP.



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3. Hard probes:

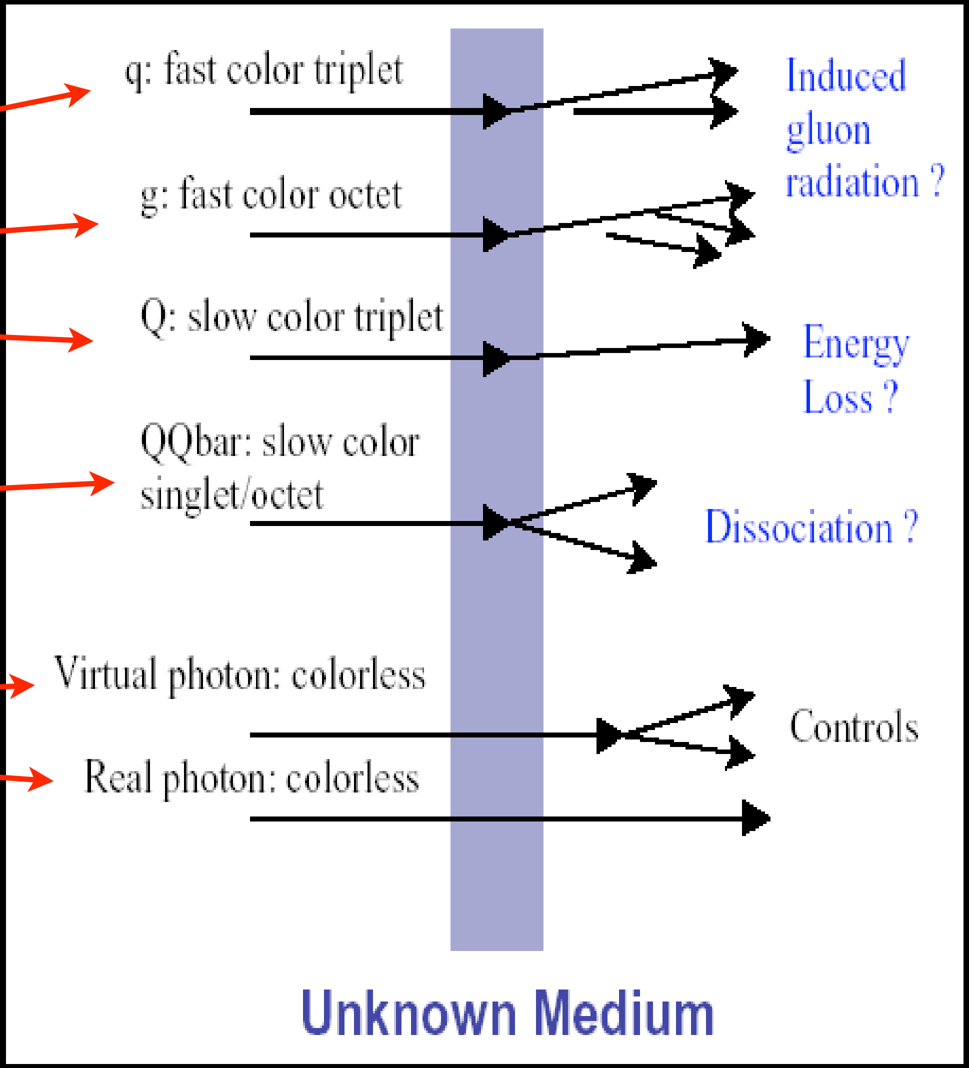
3.0. Benchmark.

3.1. Jet quenching.

3.2. Quarkonium suppression.

3.3. Photon and dilepton production.

I will touch small-intermediate p_T (< 6 GeV/c) very briefly.



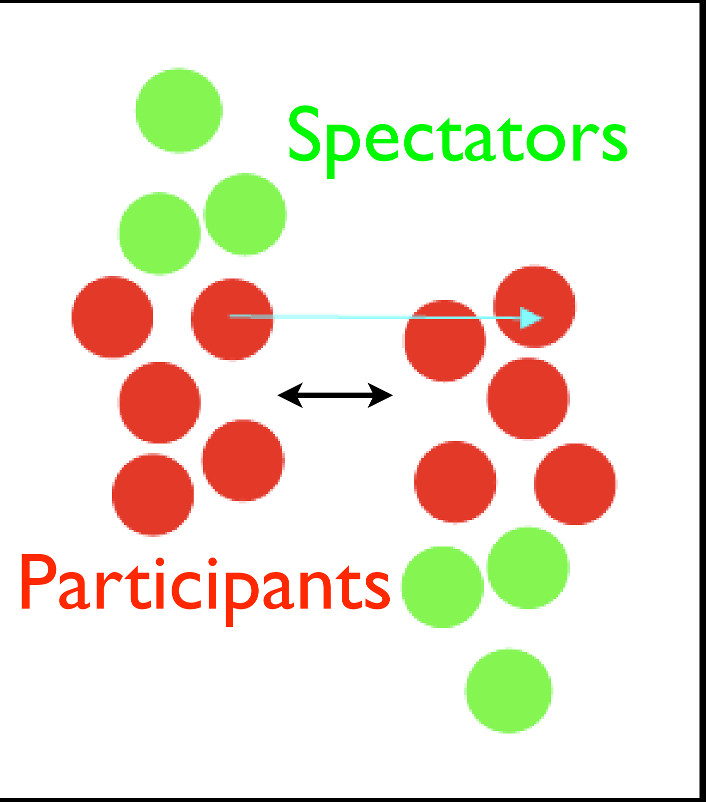
3.0. Benchmark (I):

- The usual tool to compute particle production is collinear factorization (for $Q \sim E_{cm} >> \Lambda_{QCD}$):

$$\sigma^{pp\to h} = f_p(x_1,Q^2) \otimes f_p(x_2,Q^2) \otimes \sigma(x_1,x_2,Q^2) \otimes D(z,Q^2) + \left(\frac{1}{Q^2}\right)^n$$

Quantum evolution — LHC — RHIC — SPS — Marginal

- Nuclear corrections - no medium, QGP or not - to parton densities and fragmentation functions poorly known.

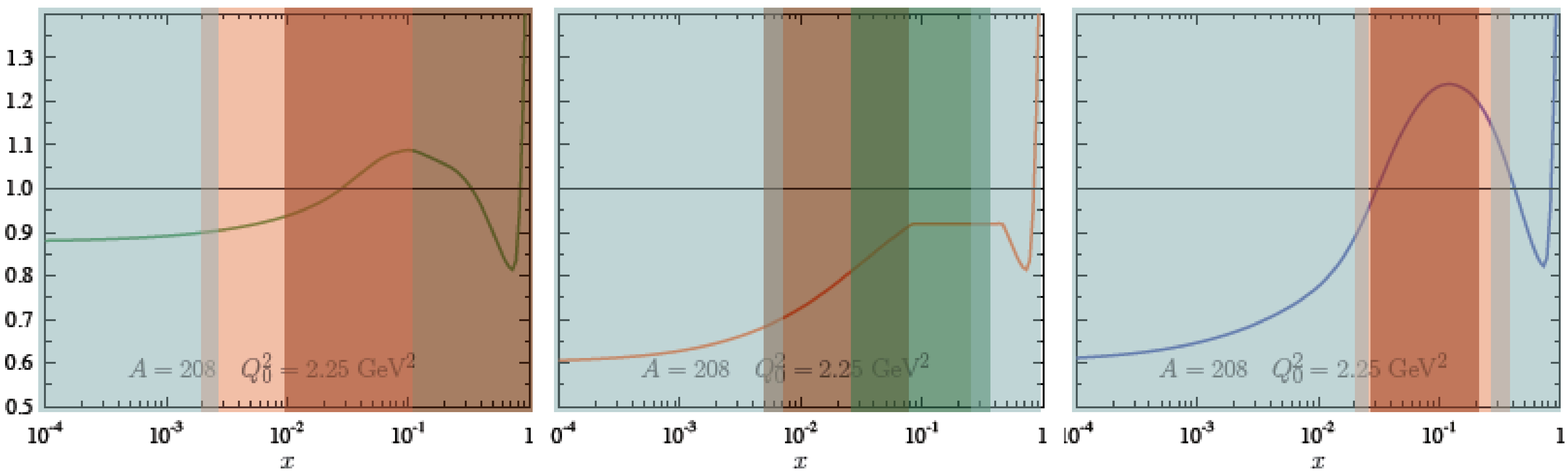


- Nuclear effects usually discussed through the ratio measured/expected: nuclear modification factor, =1 in absence of nuclear effects.

$$R^k_{AB}(y,p_T) = \frac{\frac{dN^k_{AB}}{dydp_T}}{\langle N_{coll}\rangle \frac{dN^k_{pp}}{dydp_T}}$$

3.0. Benchmark (II):

Valence | Sea quarks | Gluons



- Constrained by DIS
- Constrained by DY
- Constrained by Sum rules
- Assumptions

[these ranges are very approximative... but valid in general for other analyses]

$$\frac{f_i^A}{A f_i^p}$$

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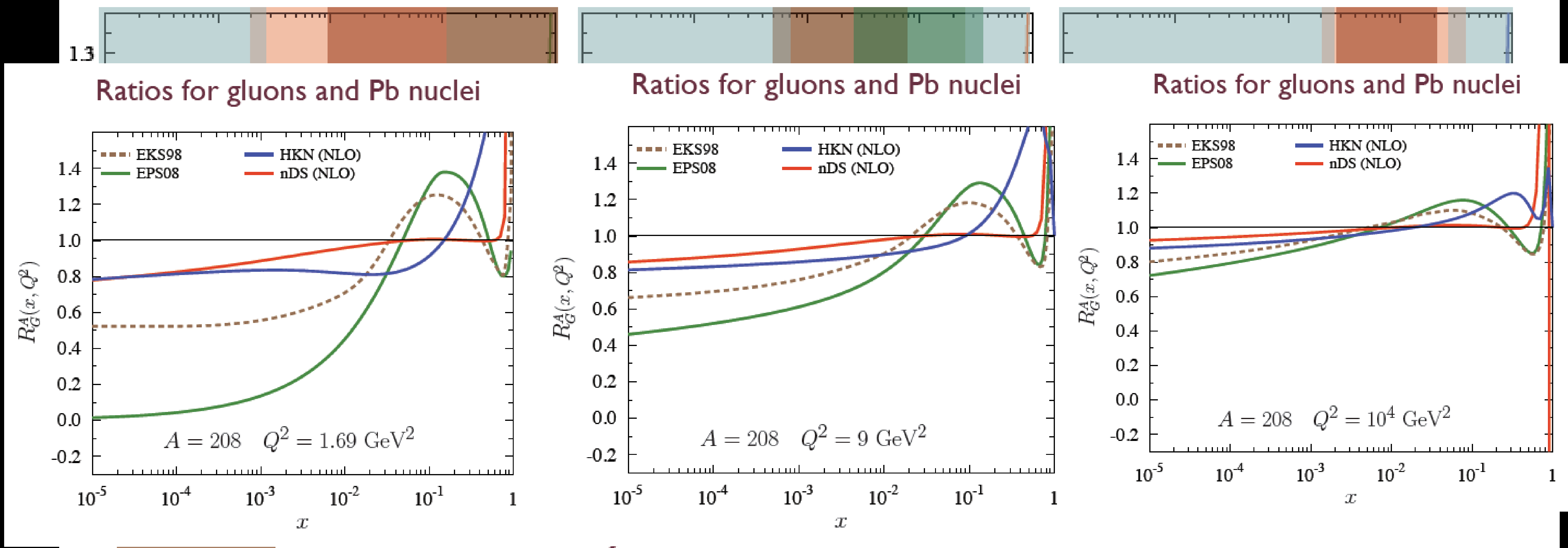

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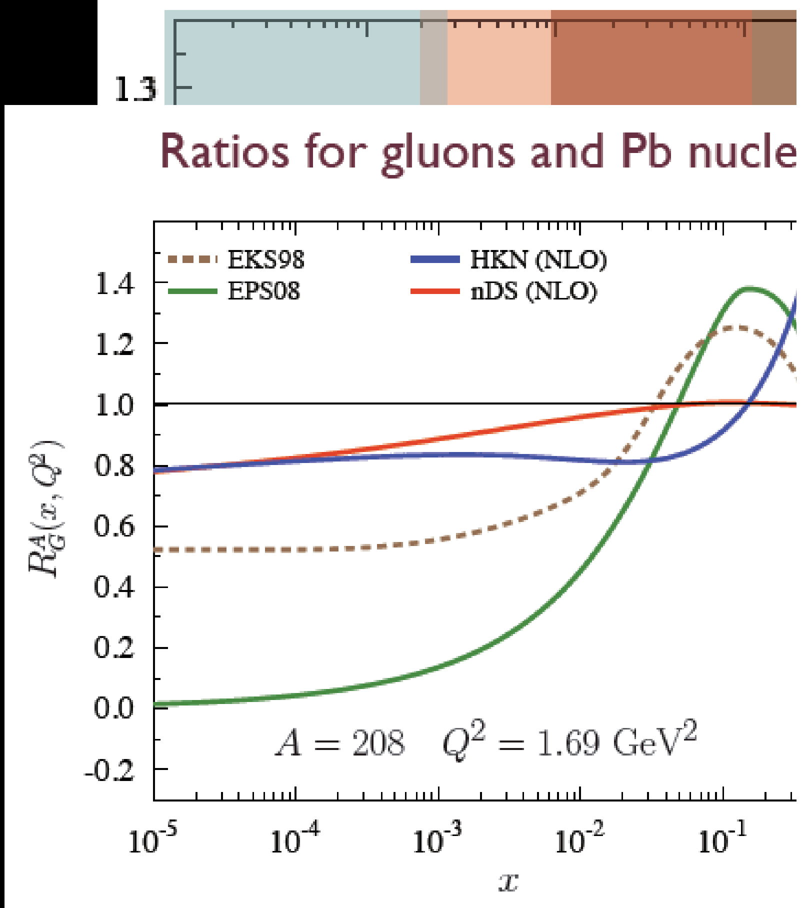

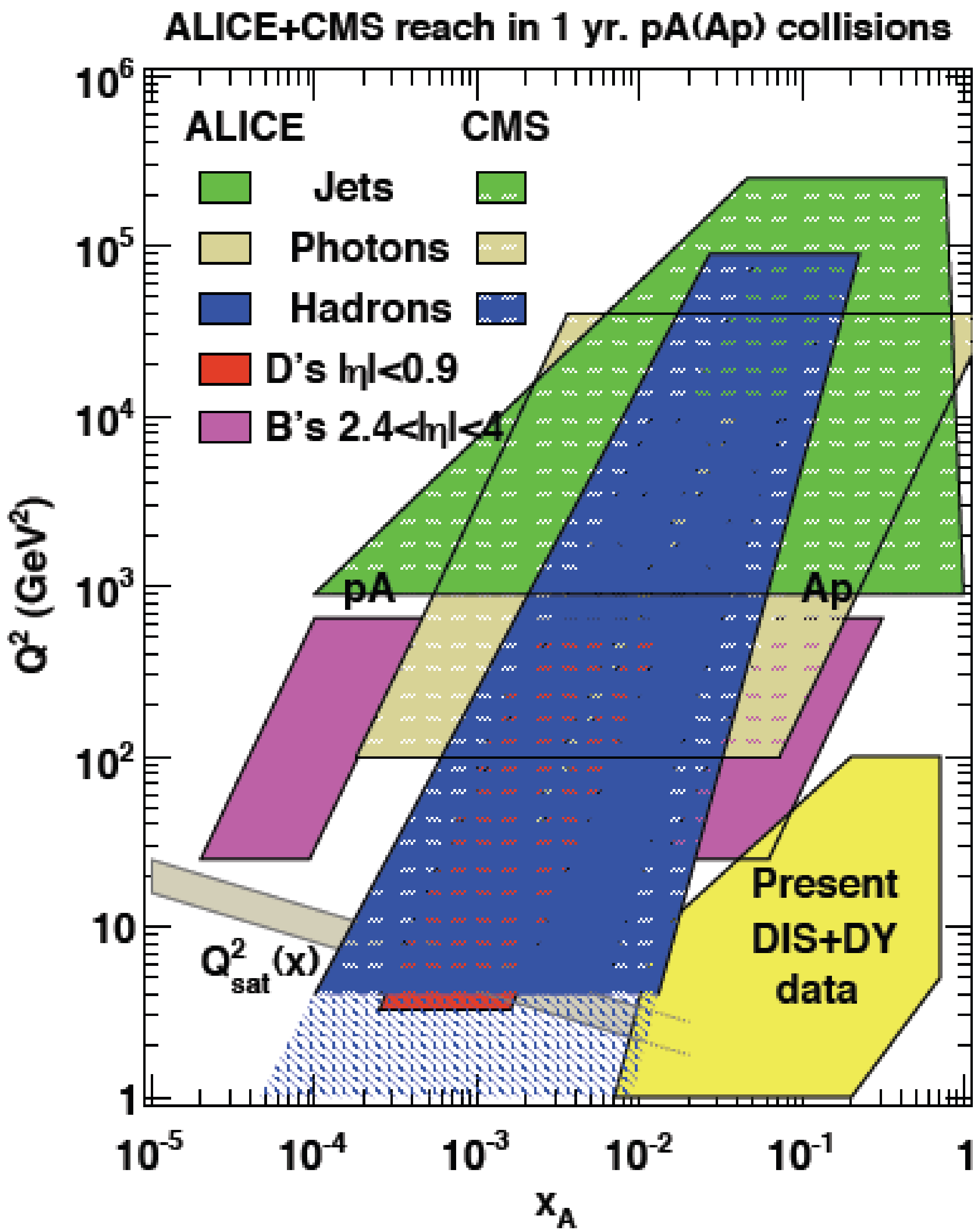

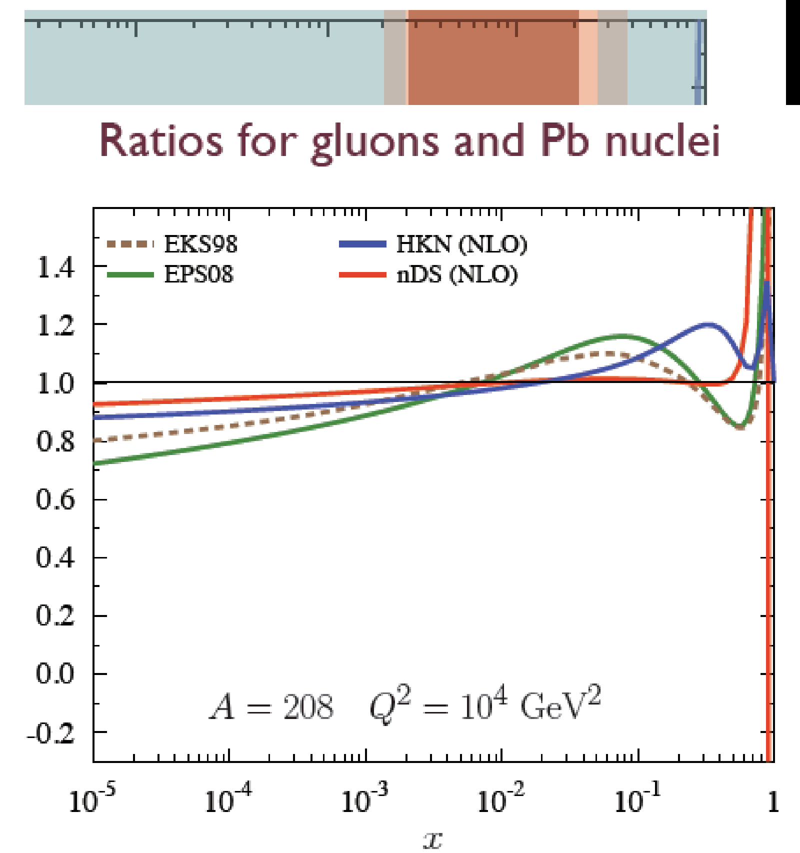

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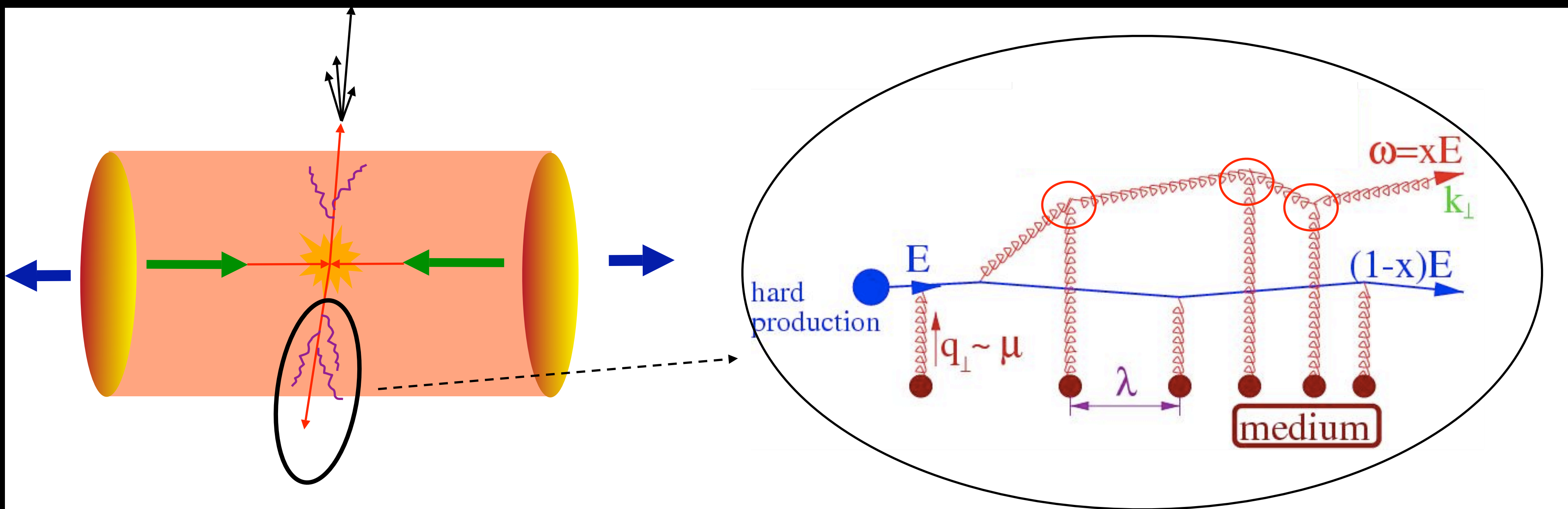
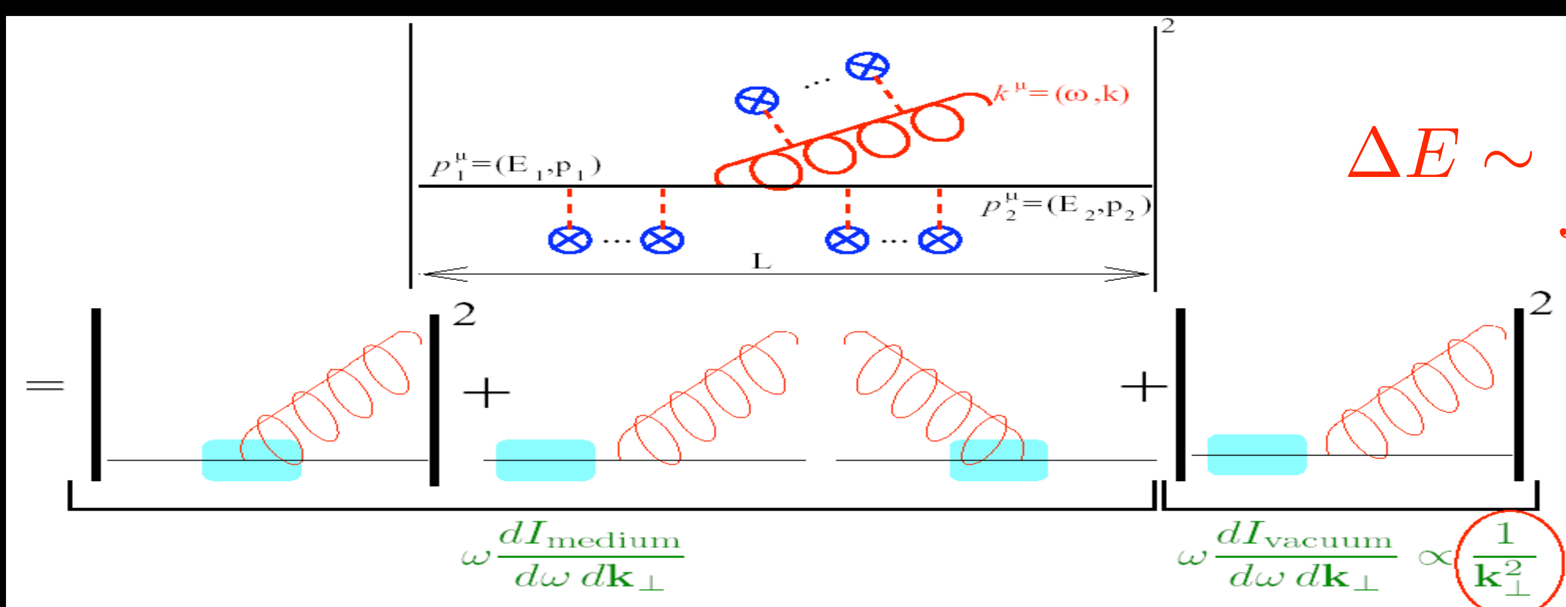
Radiative energy loss:



Medium-modified gluon radiation through interference of production and rescattering.



$$\Delta E \sim \int d\omega \omega \frac{dI}{d\omega} \sim \alpha_s C_R \omega_c = \frac{1}{2} \alpha_s C_R \hat{q} L^2$$

BDMPS $\quad \hat{q} = \dfrac{\mu^2}{\lambda}$

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

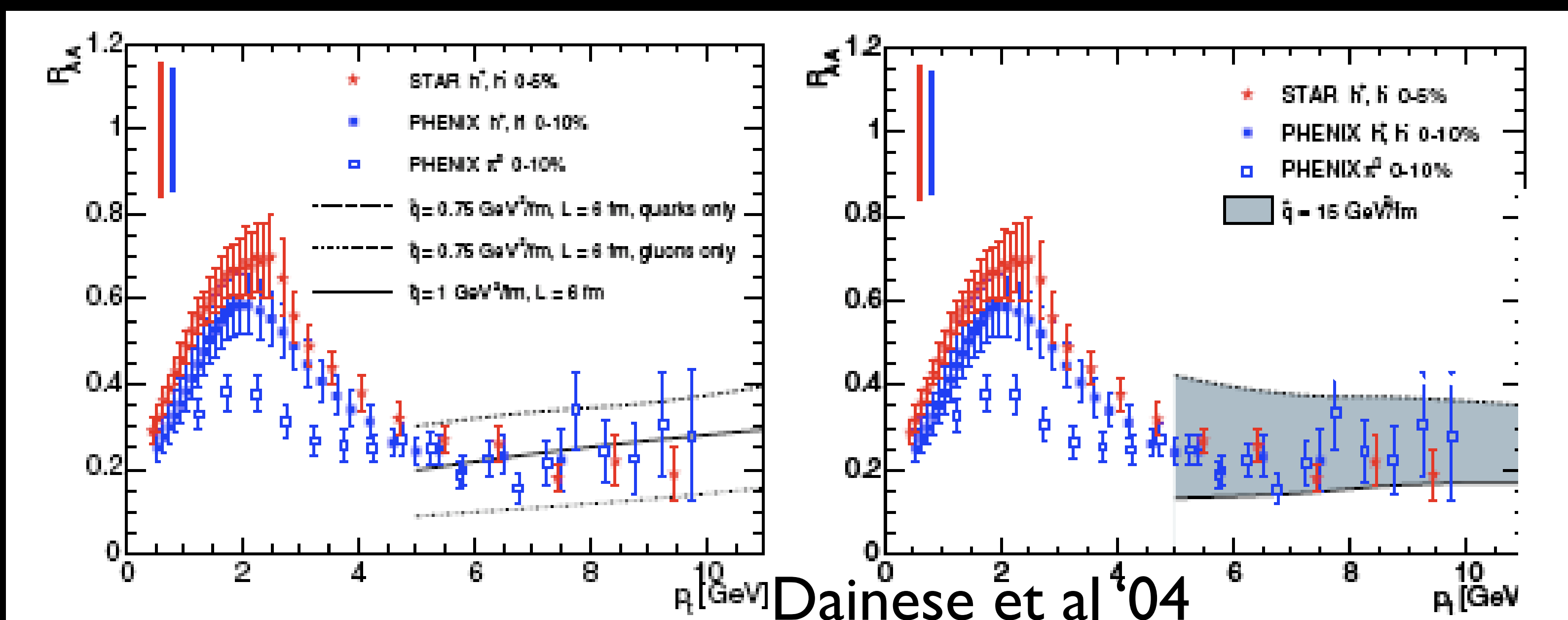
Radiative eloss: light hadrons

$$Q(p_\perp) = \frac{d\sigma^{\mathrm{med}}(p_\perp)/dp_\perp^2}{d\sigma^{\mathrm{vac}}(p_\perp)/dp_\perp^2} = \int d\Delta E\, P(\Delta E) \left(\frac{d\sigma^{\mathrm{vac}}(p_\perp + \Delta E)/dp_\perp^2}{d\sigma^{\mathrm{vac}}(p_\perp)/dp_\perp^2} \right)$$

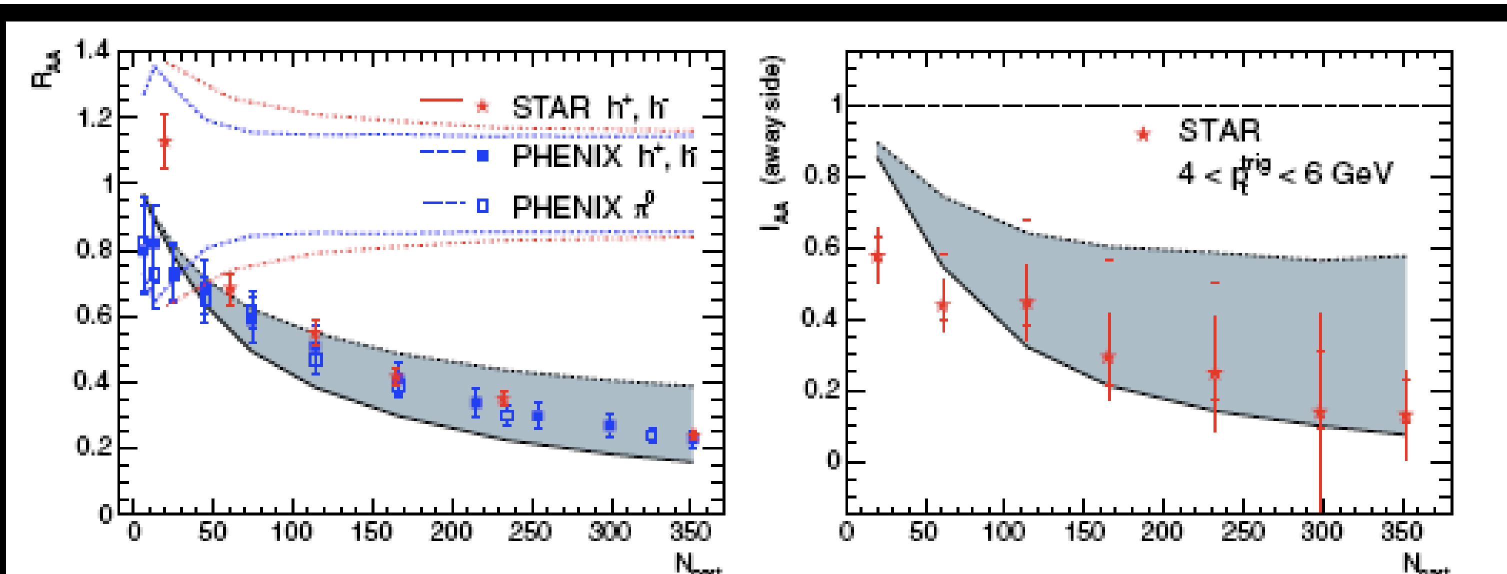
$$D^{(\mathrm{med})}_{h/q}(x, Q^2) = \int_0^1 d\epsilon\, P(\epsilon) \frac{1}{1-\epsilon} D_{h/q}\left(\frac{x}{1-\epsilon}, Q^2 \right)$$

BDMS '01; Wang et al '96

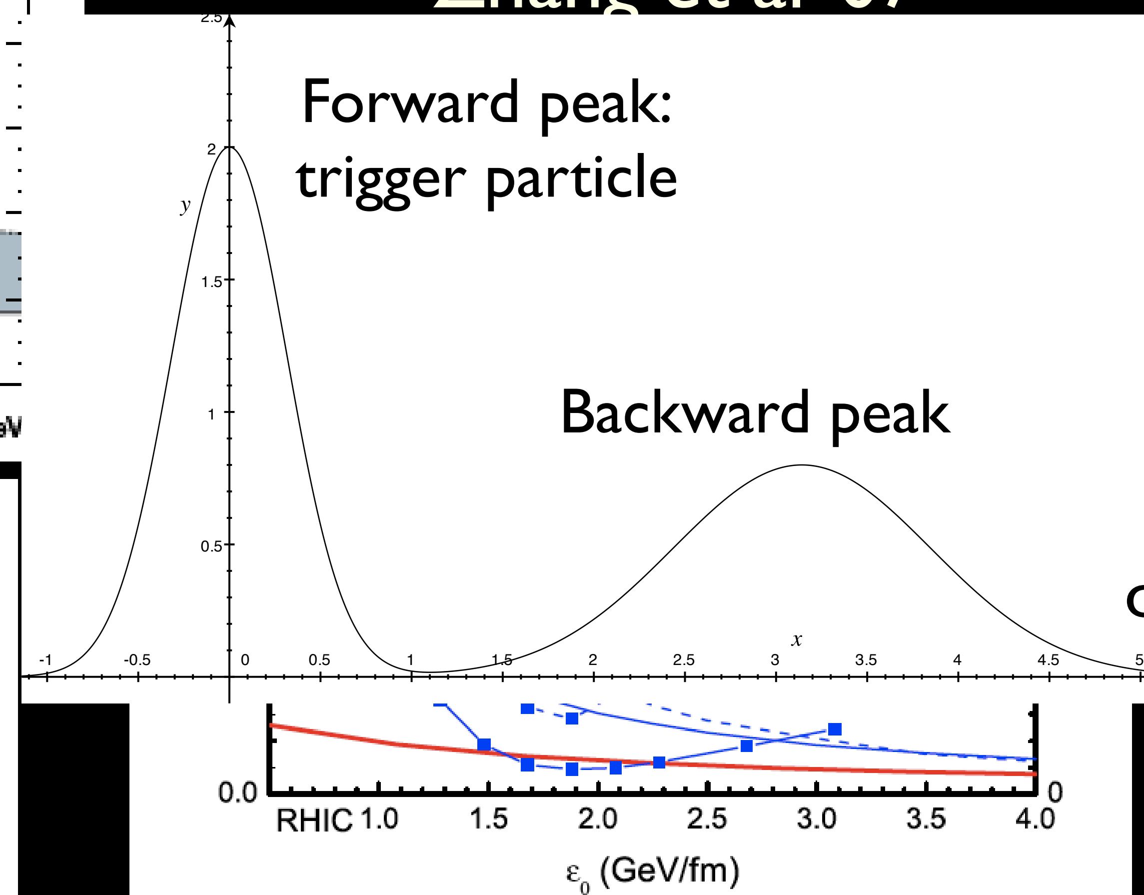
Medium modeling → $<\tau_0\,\hat{q}(\tau_0)>=1\text{-}15\,\mathrm{GeV}^2$



Dainese et al '04



Zhang et al '07



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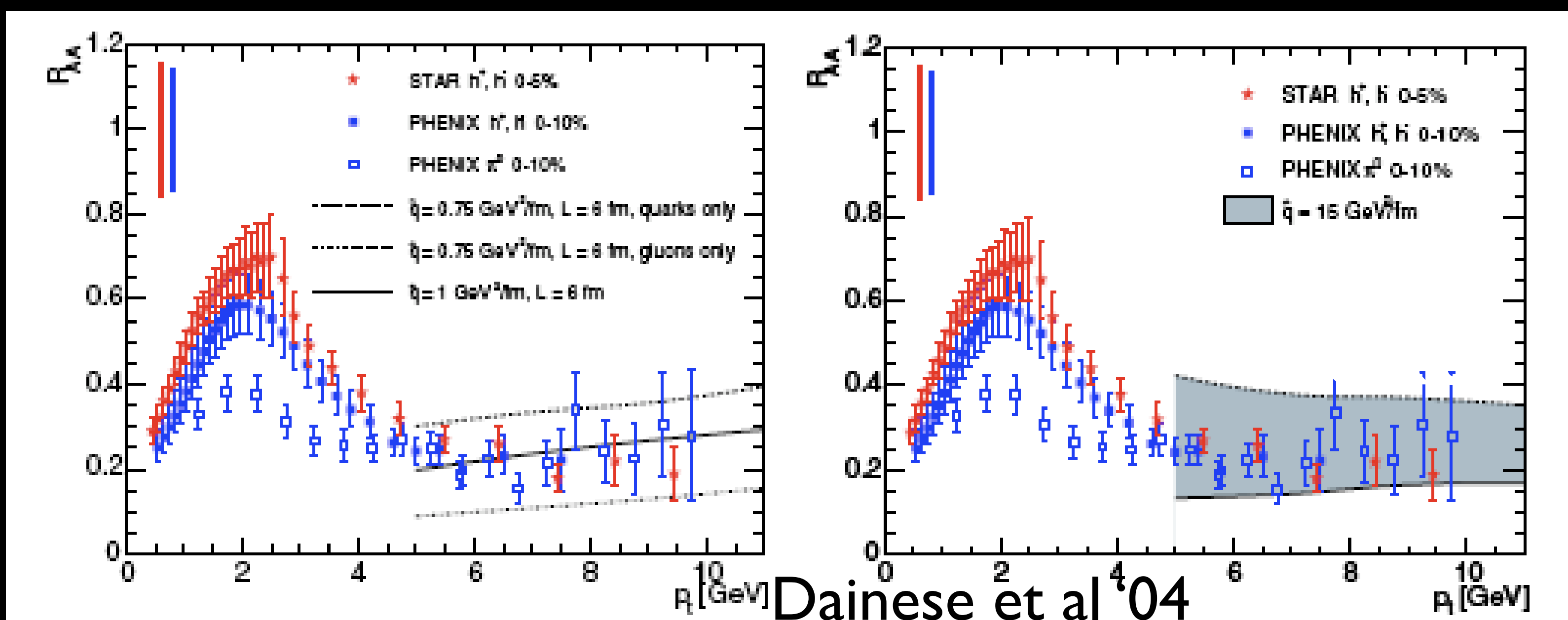
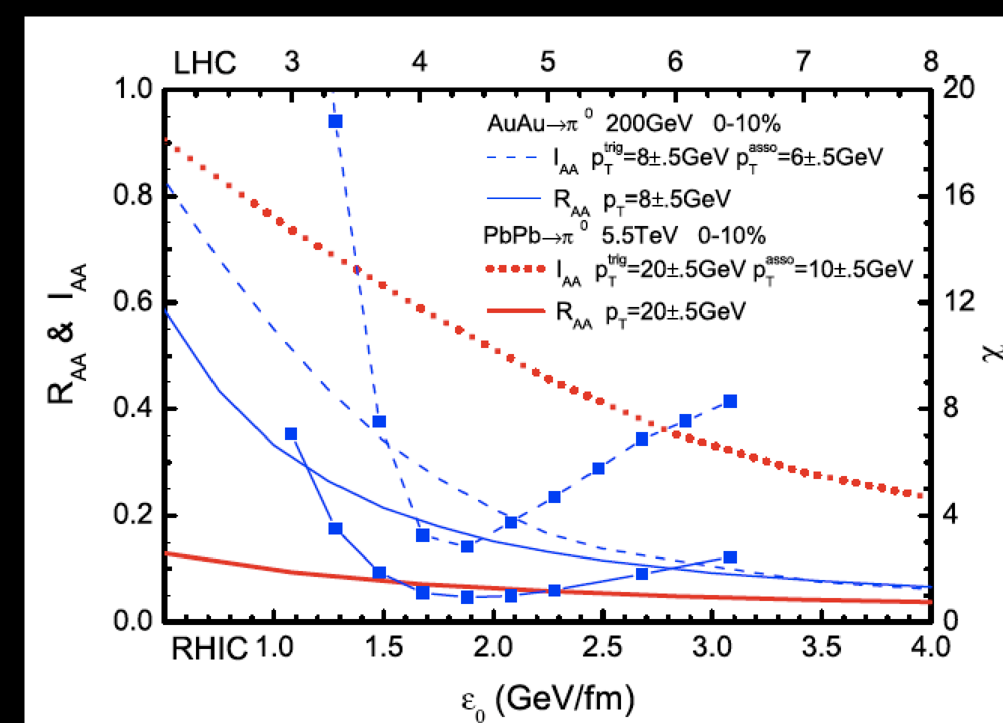
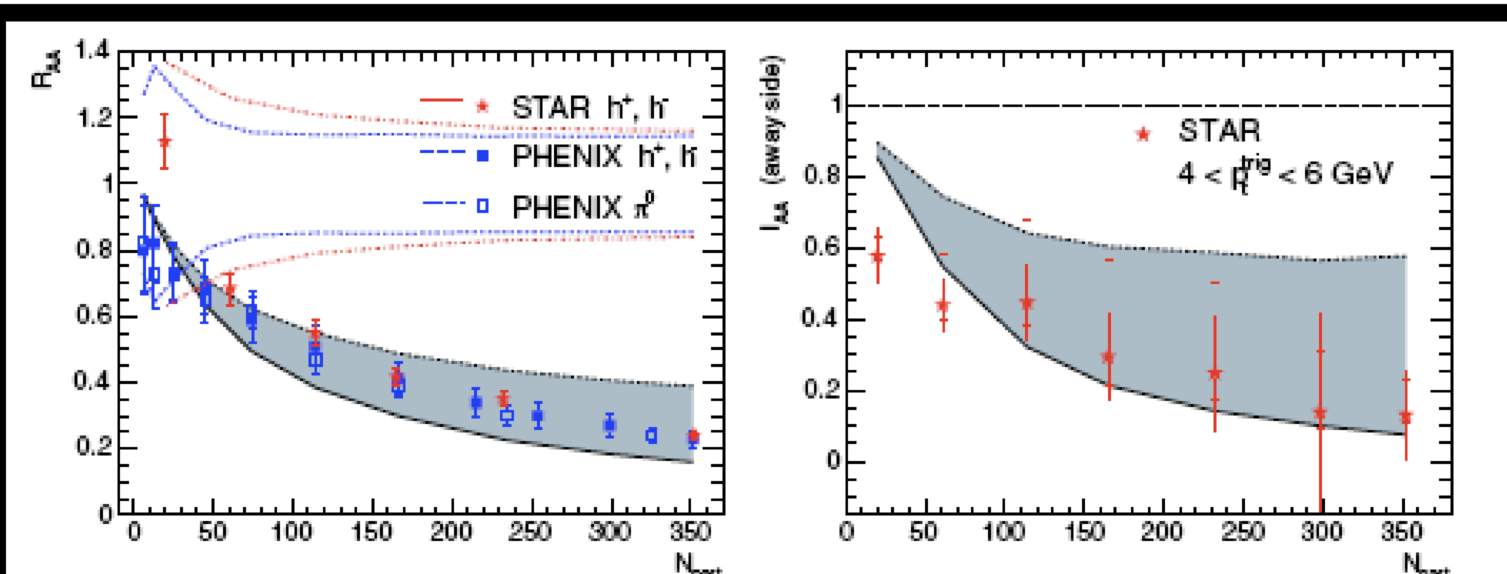


Dainese et al '04

Zhang et al '07

$$\langle \hat{q}_0\tau_0\rangle \approx 2 \div 3\ \ \mathrm{GeV}^2$$





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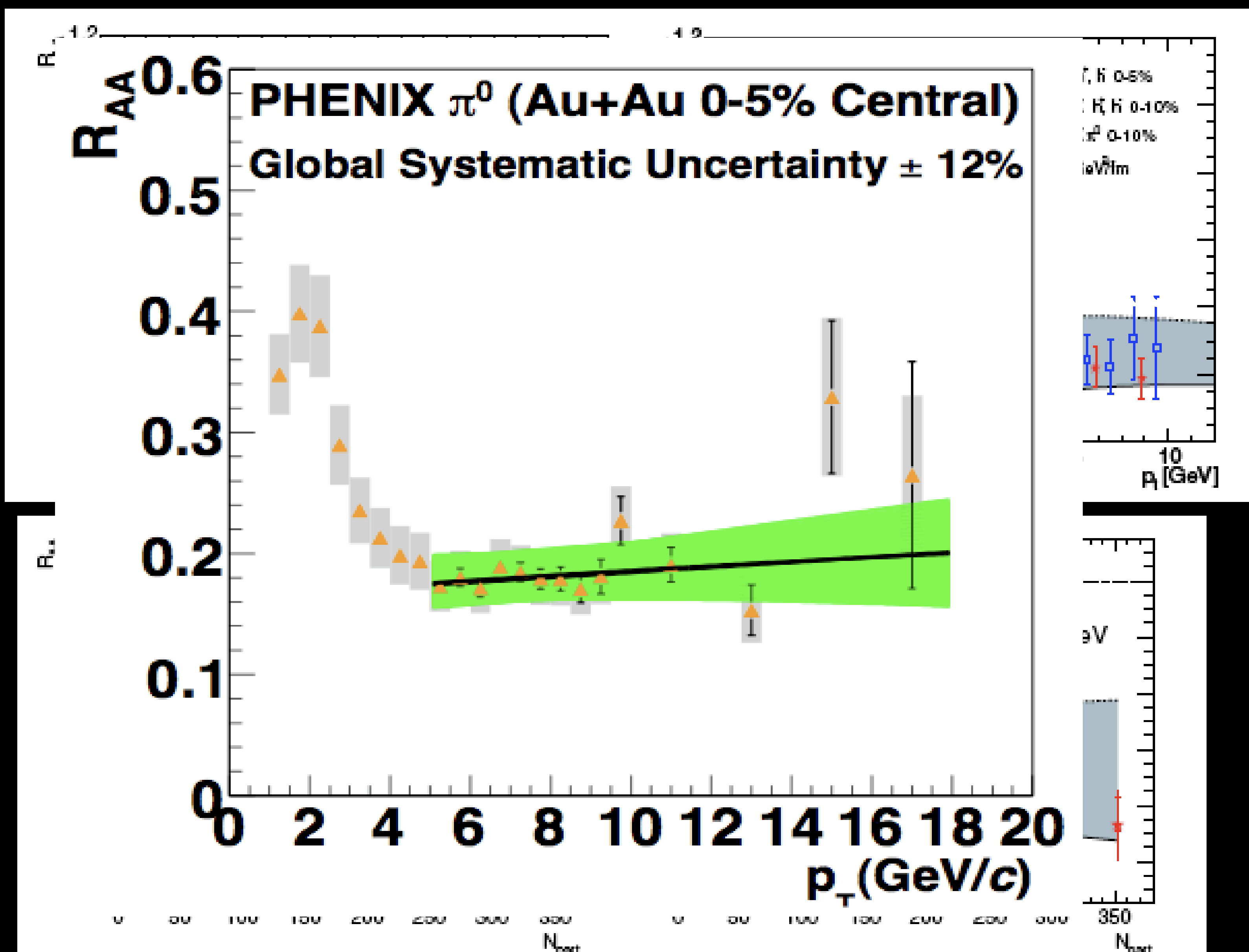

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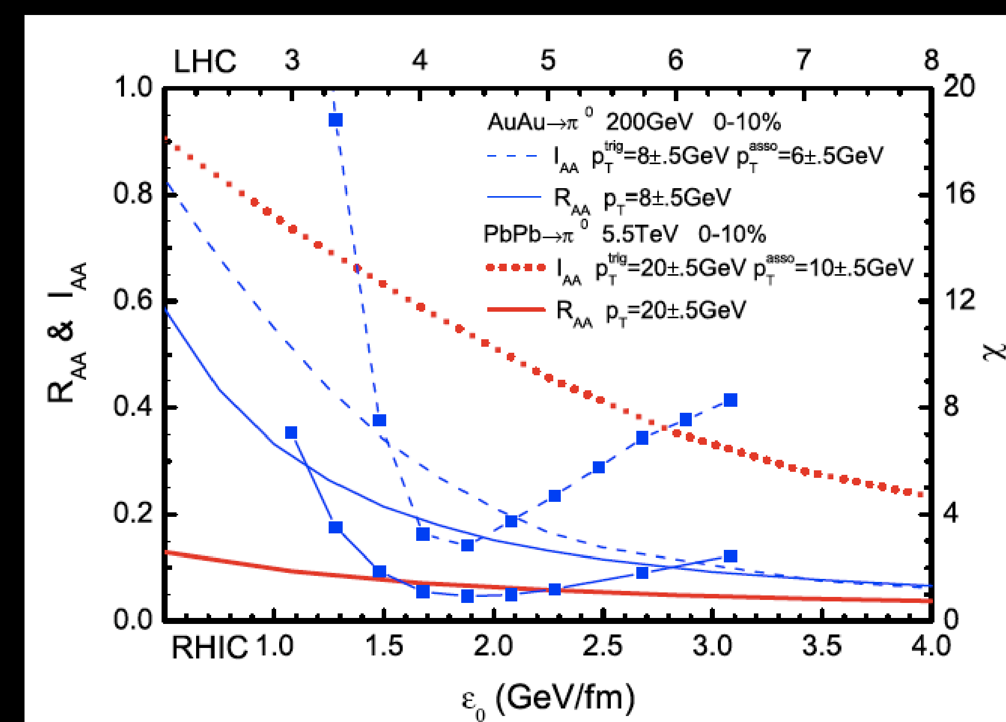
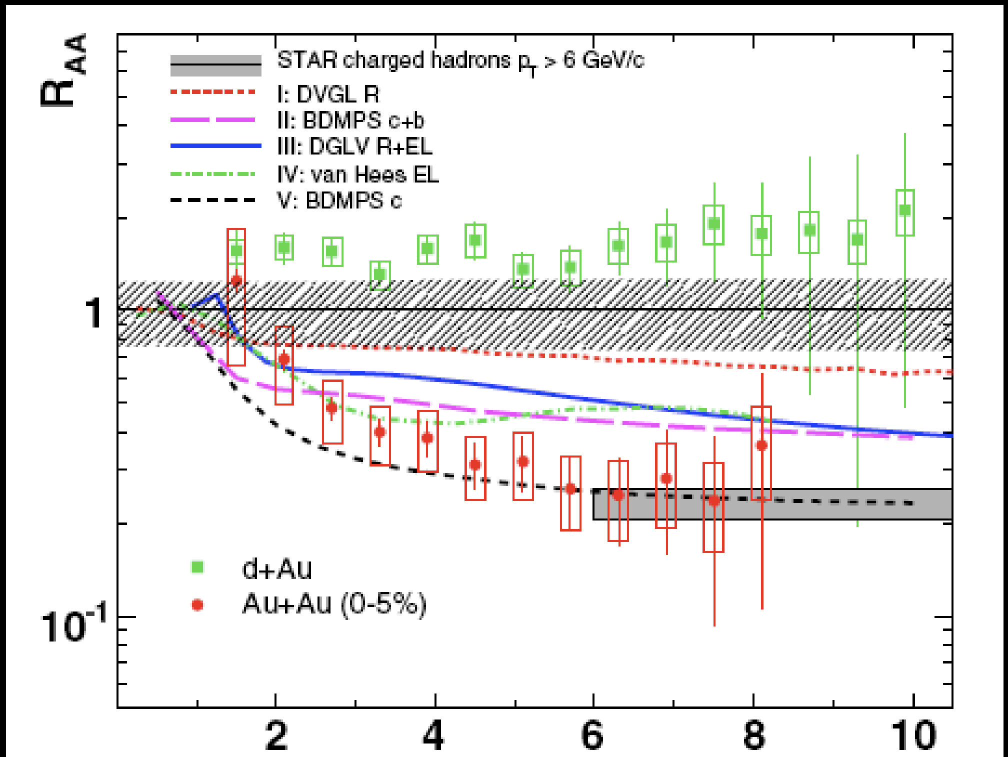


Radiative eloss: e's, differential observ.

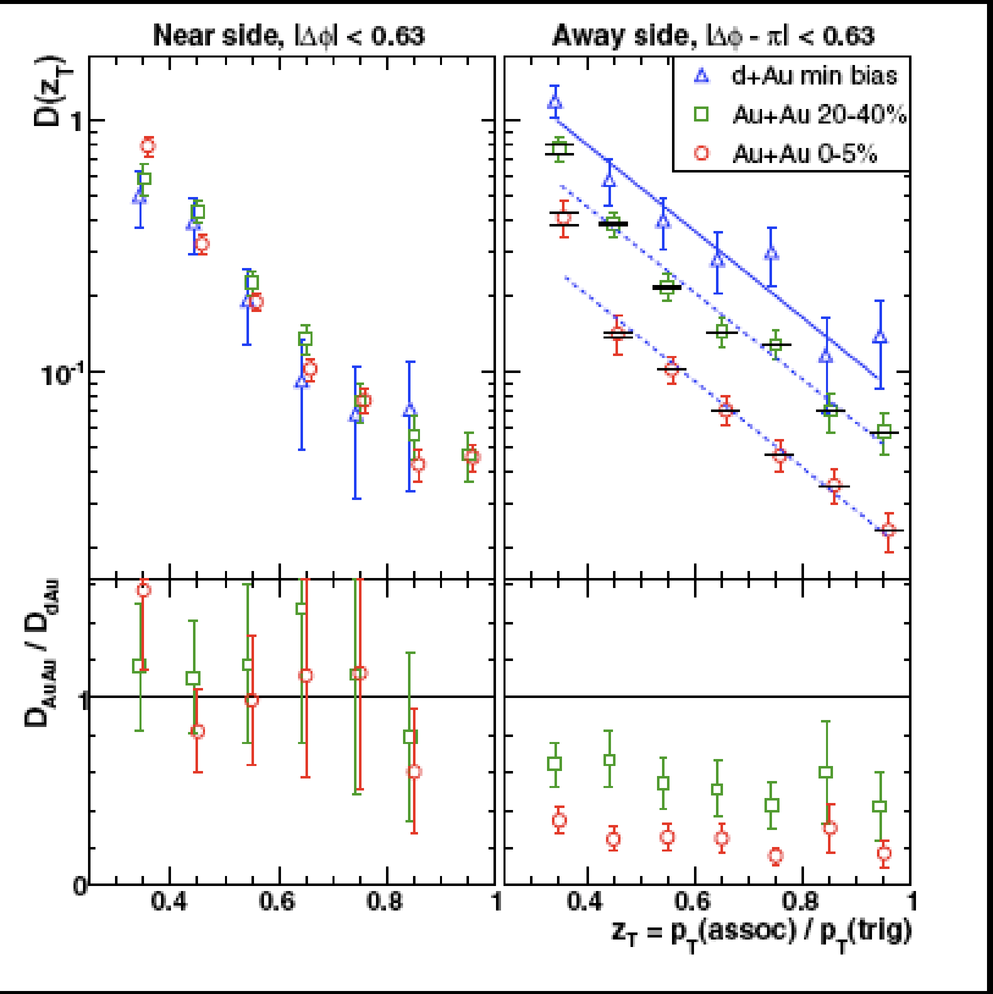
- ΔE(g)>ΔE(q)>ΔE(Q). Non-photonic electrons not conclusive: benchmark (Armesto et al '05), hadronization (Adil et al '06), collisional (Djordjevic et al '06, Ayala et al '06), resonances (van Hees et al '06), dynamical medium (Djordjevic et al. '08),...



STAR '06, '07

$$z(\text{ff}) = \frac{p_{had}}{p_{jet}} \neq z(\text{pff}) = \frac{p_{had}}{p_{trigger}}$$

- PseudoFF not well understood: no broadening at high p_t in the near side, trigger bias?



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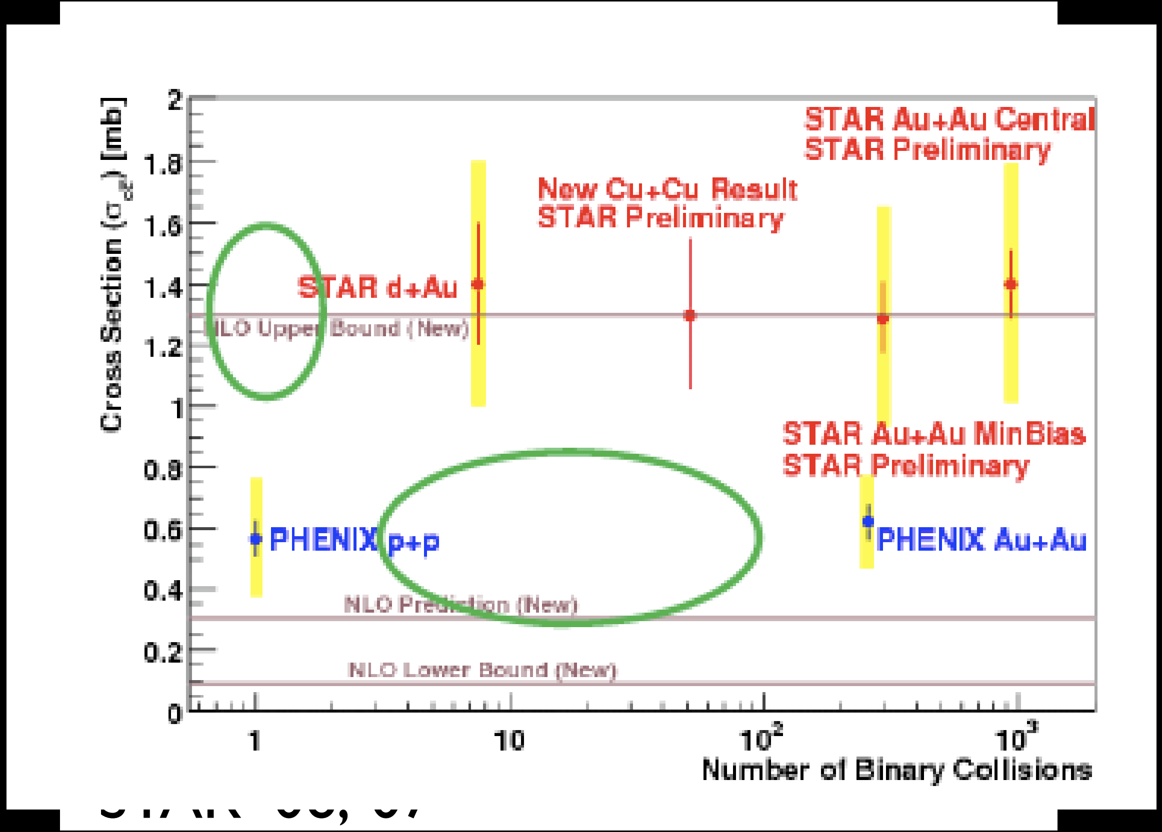
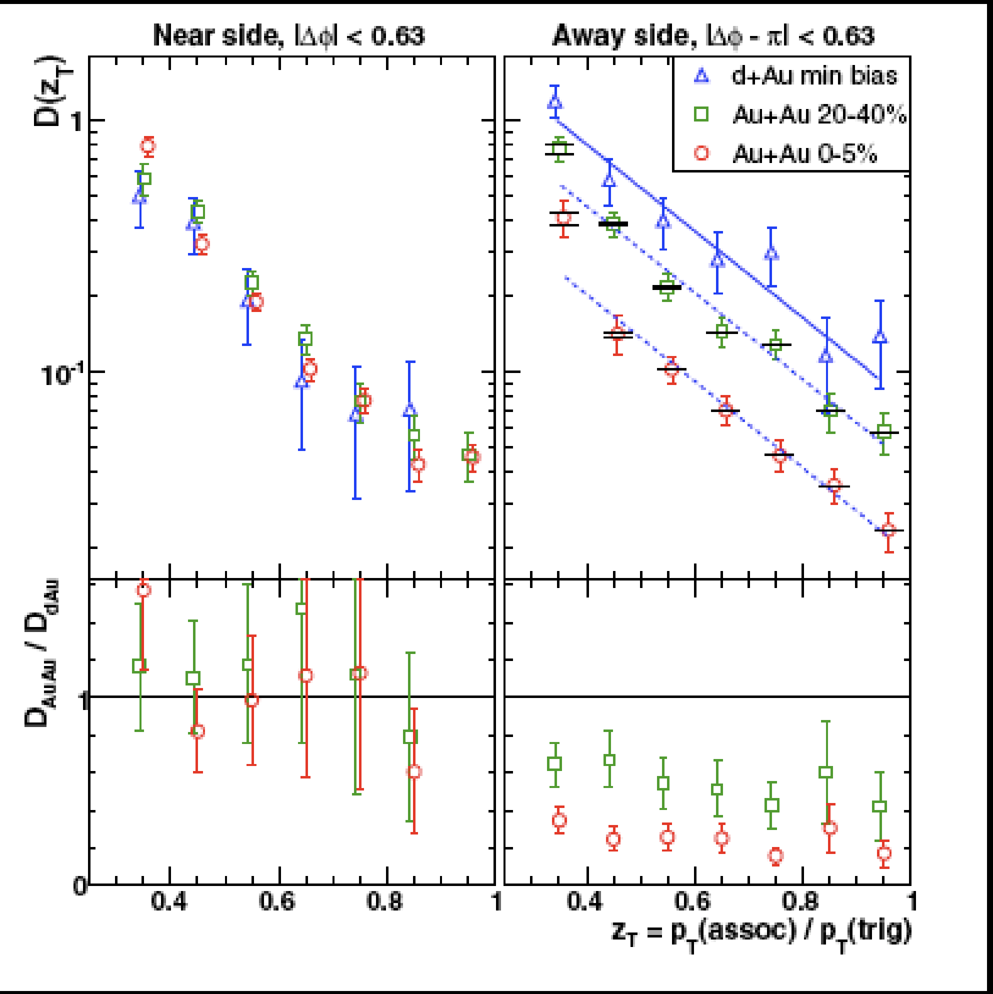
- $\Delta E(g) > \Delta E(q) > \Delta E(Q)$. Non-photonic electrons not conclusive: benchmark (Armesto et al '05), hadronization (Adil et al '06), collisional (Djordjevic et al '06, Ayala et al '06), resonances (van Hees et al '06), dynamical medium (Djordjevic et al. '08),...



$$z(\text{ff}) = \frac{p_{had}}{p_{jet}} \neq z(\text{pff}) = \frac{p_{had}}{p_{trigger}}$$

- PseudoFF not well understood: no broadening at high p_t in the near side, trigger bias?



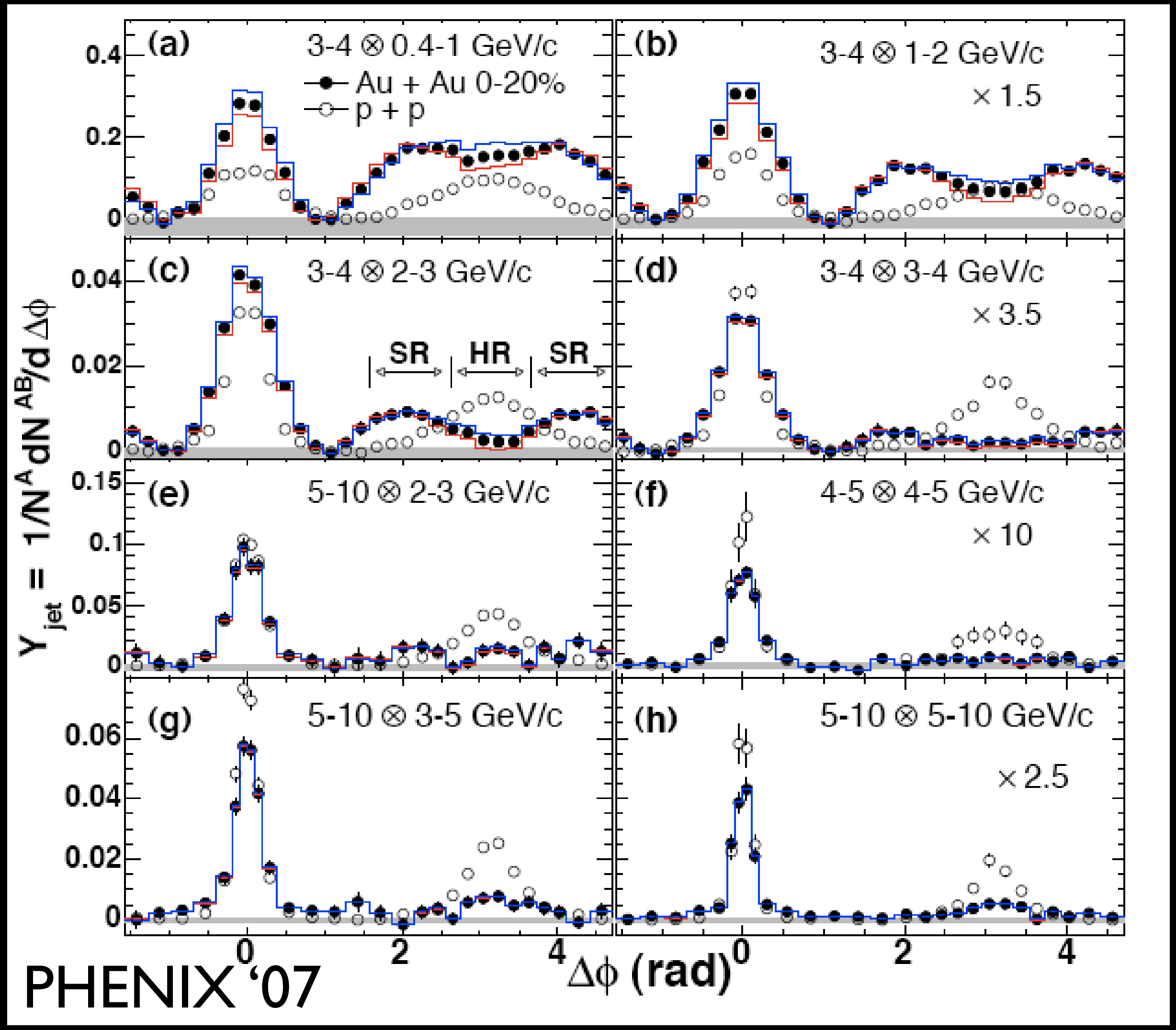
Radiative eloss: limitations

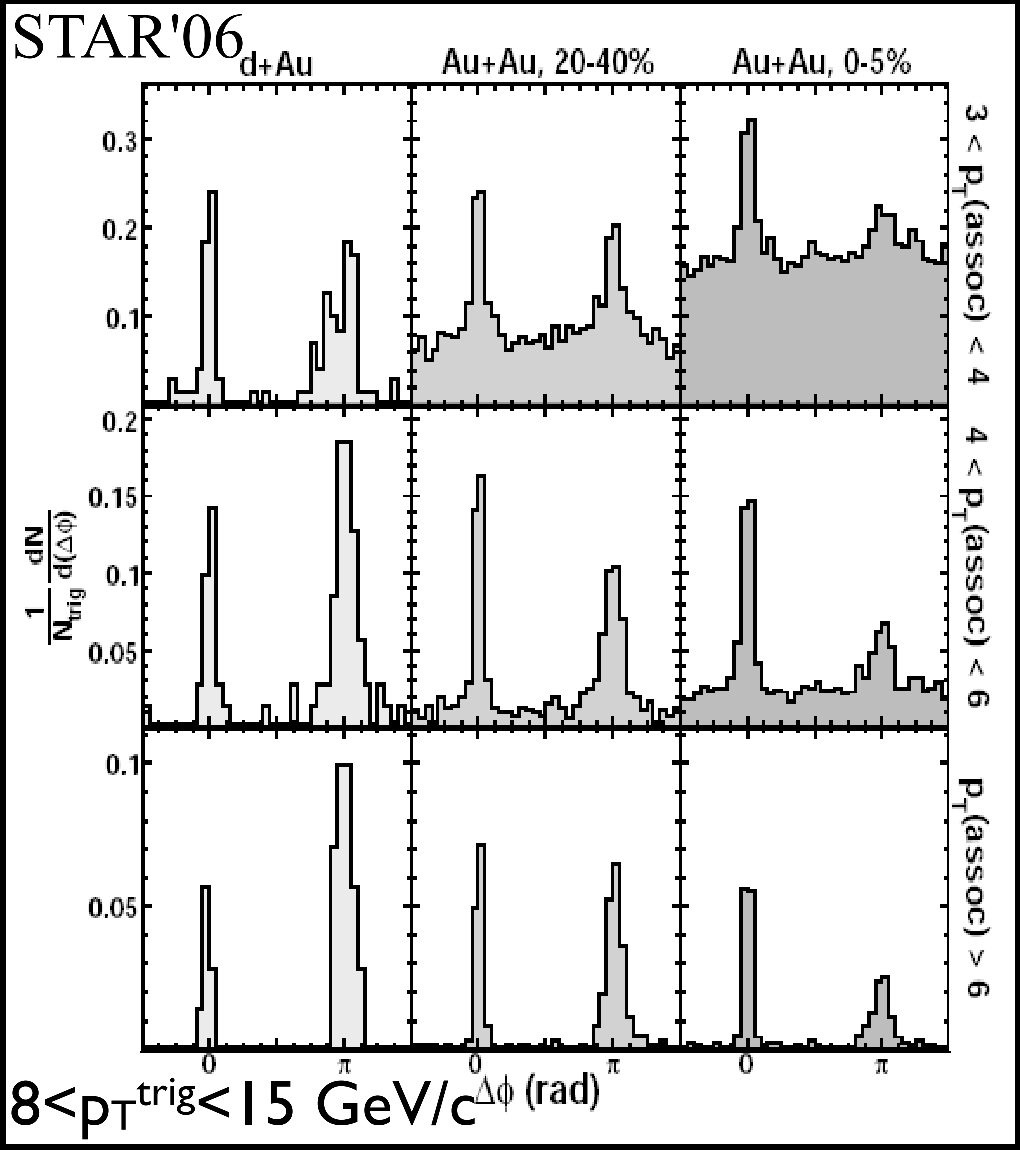
- The extracted value of qhat depends on medium model: 1<qhat<15 GeV^2/fm ⇒ interface with realistic medium (TECHQM).
- Calculations done in the high-energy approximation: only soft emissions, energy-momentum conservation imposed a posteriori ⇒ Monte Carlo.
- Multiple gluon emission: Quenching Weights (BDMS ‘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 (GMW ’01, Salgado et al ’06, Armesto et al ‘07).

Medium response: backward peak

- Starting from a trigger, and increasing the p_T for the associate, we go from a double-bump structure to nothing to a reappearance of the backward peak (tangential emission).

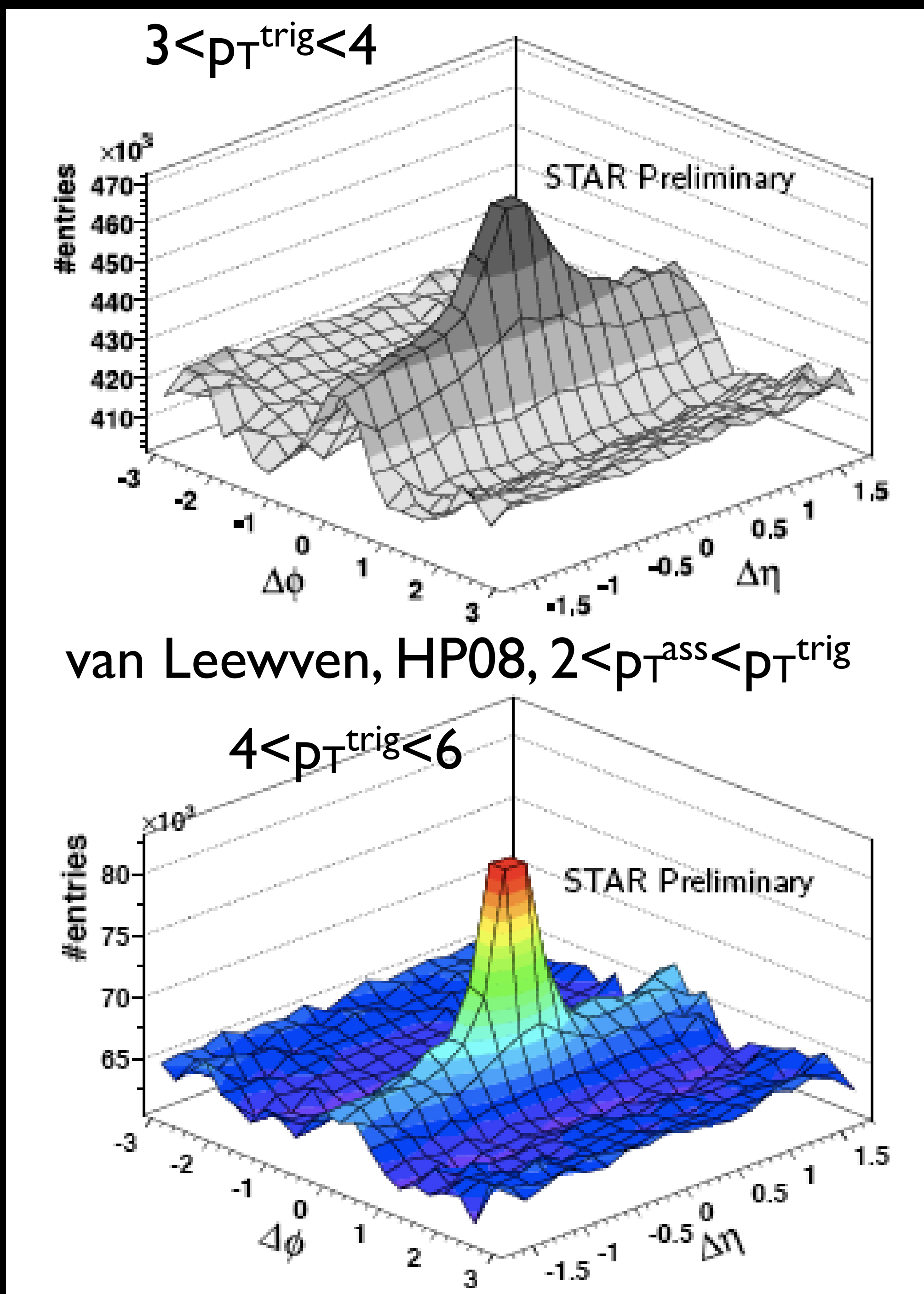
- Double bump: Mach cone (Stöcker et al, Shuryak et al), Cherenkov gluons (Dremin, Koch et al), radiation (Salgado et al, Vitev),...



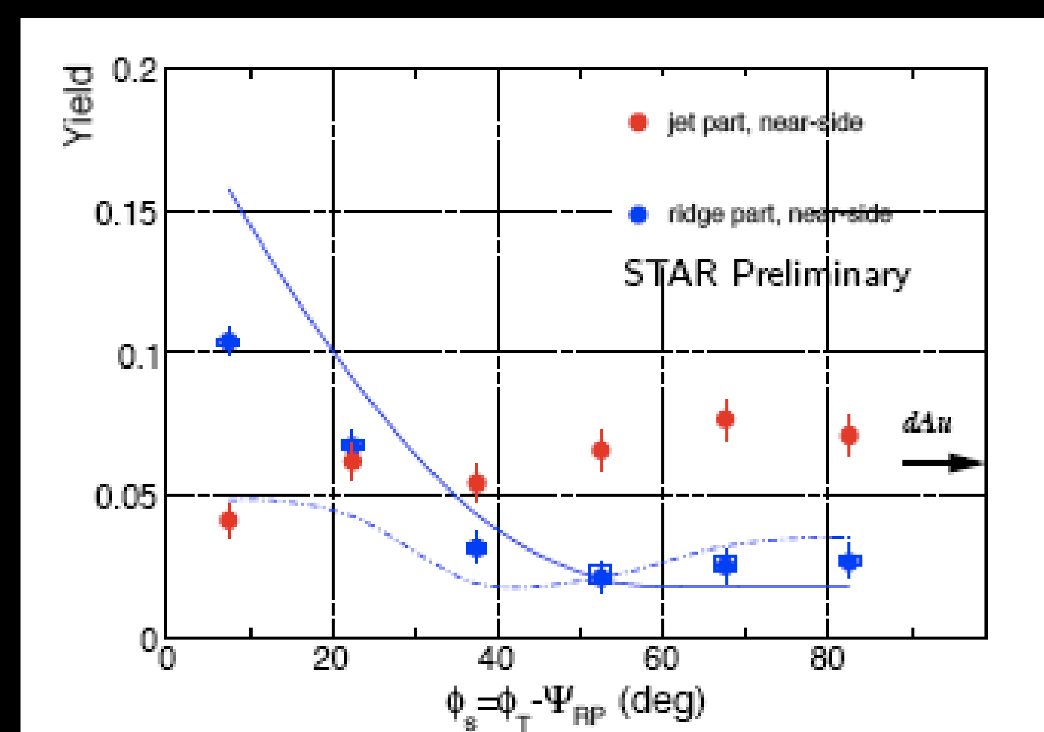


Medium response: the ridge

- A structure, elongated along $\eta=-\ln tg(\theta/2)$, appears in the near side of a trigger, called the ridge. It can be divided in 'jet' and 'shoulder'.



- The 'jet' structure is jet-like (pp) in composition and transverse momentum spectrum; the shoulder is bulk-like ⇒ excitation of the medium due to the jet? Several features look strange...



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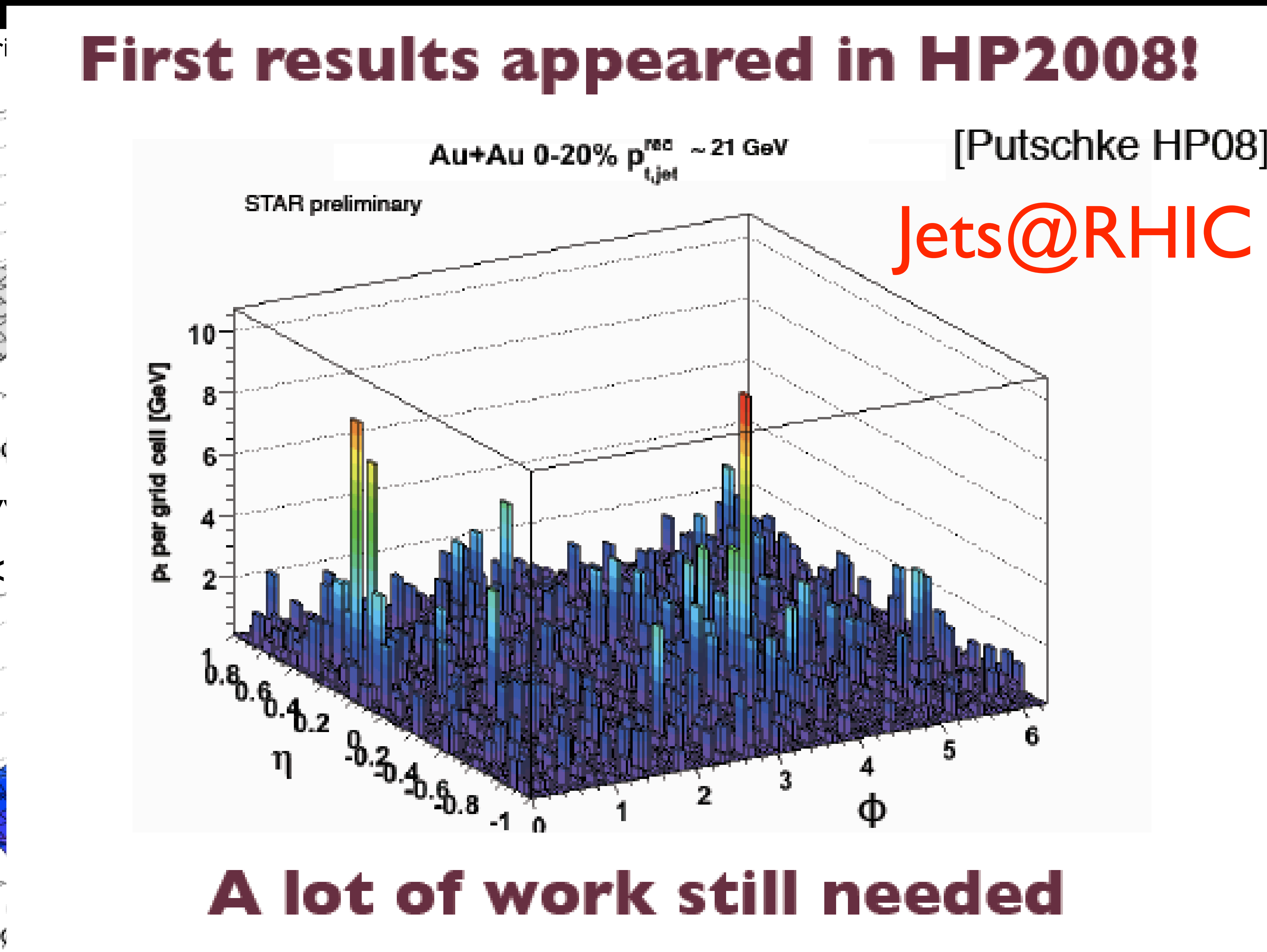
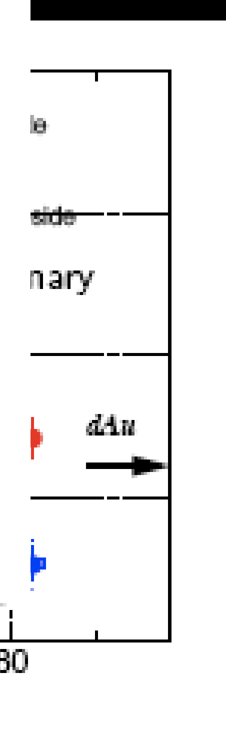
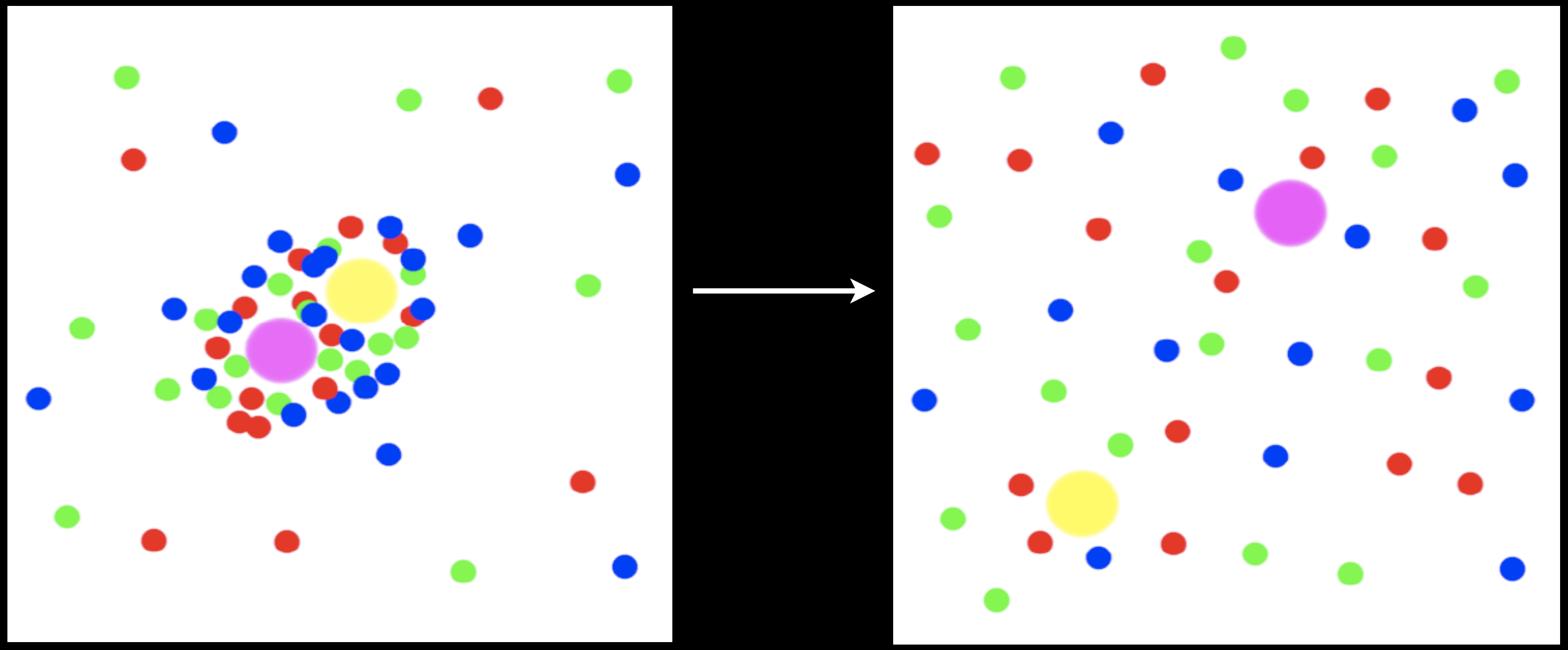


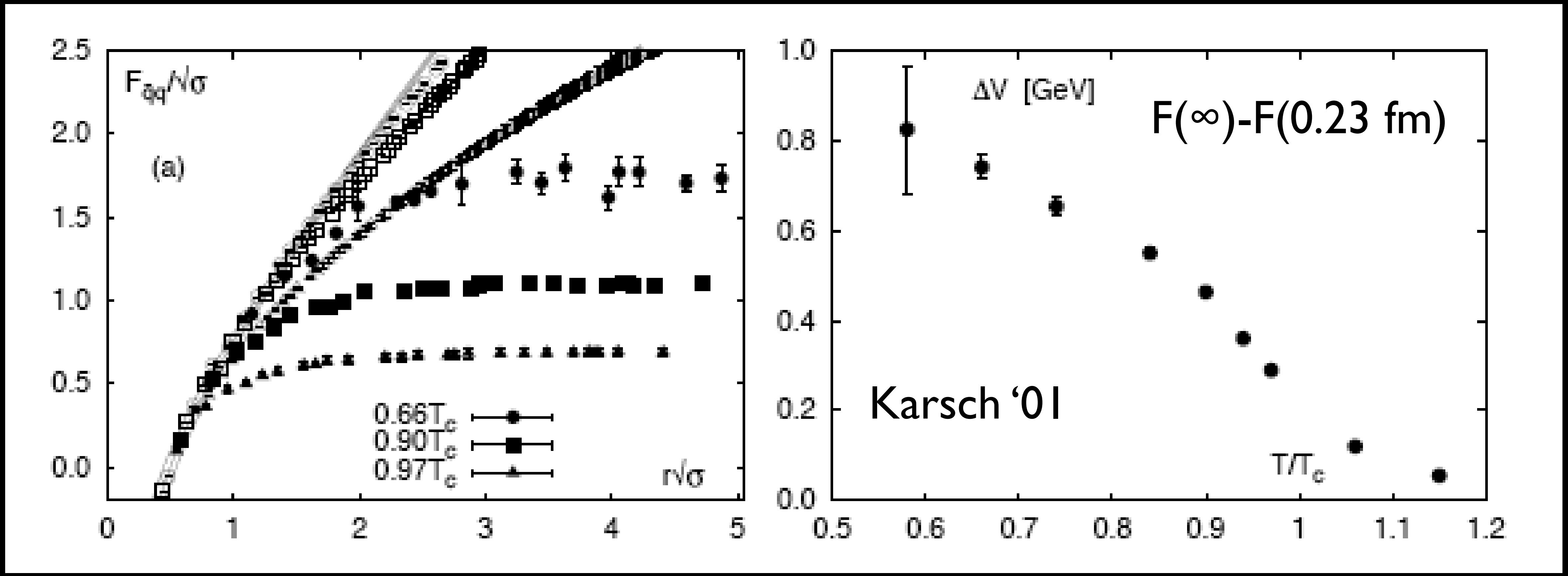


Quarkonium

- From Matsui and Satz's proposal ('86), the suppression of QQbar bound states plays a central role in the discussion of QGP formation.

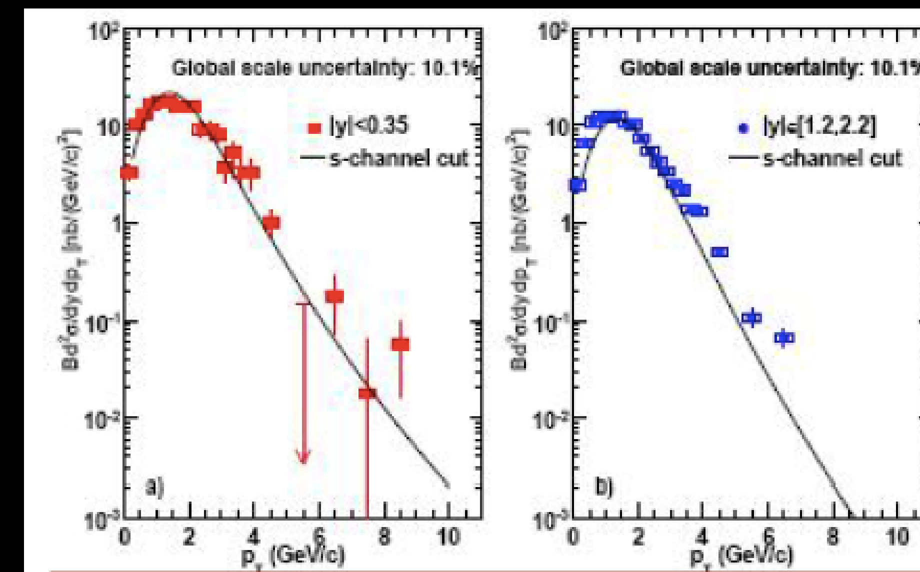
- Debye screening due to the free color charge in the plasma modifies the linear part of the QQbar potential.

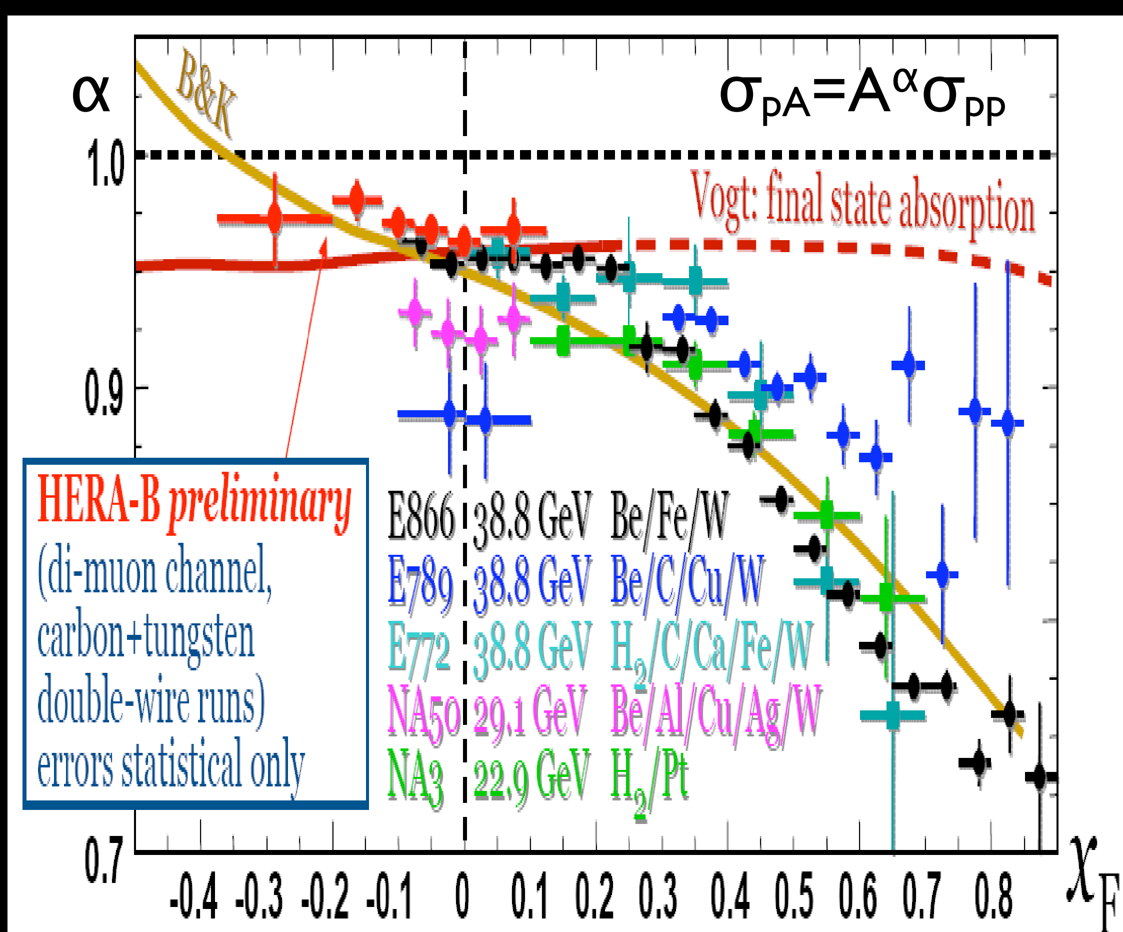


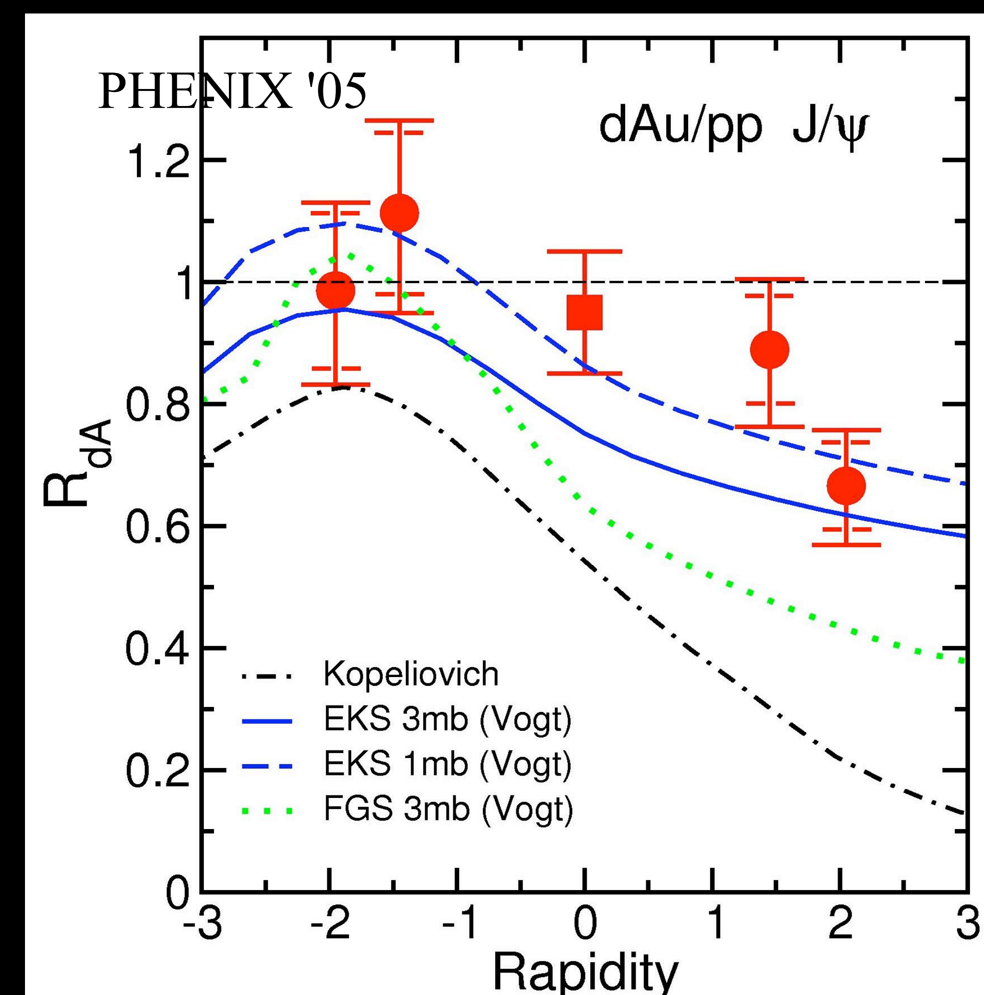


Quarkonium: the baseline

- e^+e^-: 60-80 % of J/psi produced with more charm (Belle, BaBar): higher orders in NRQCD?, additional mechanisms (Kaidalov '03).
- pp(bar): polarization puzzle goes on: NRQCD? (Nayak et al '05, Lansberg '08).
- pA: smaller absorption at RHIC than at SPS, negative x_F (HERA-B).

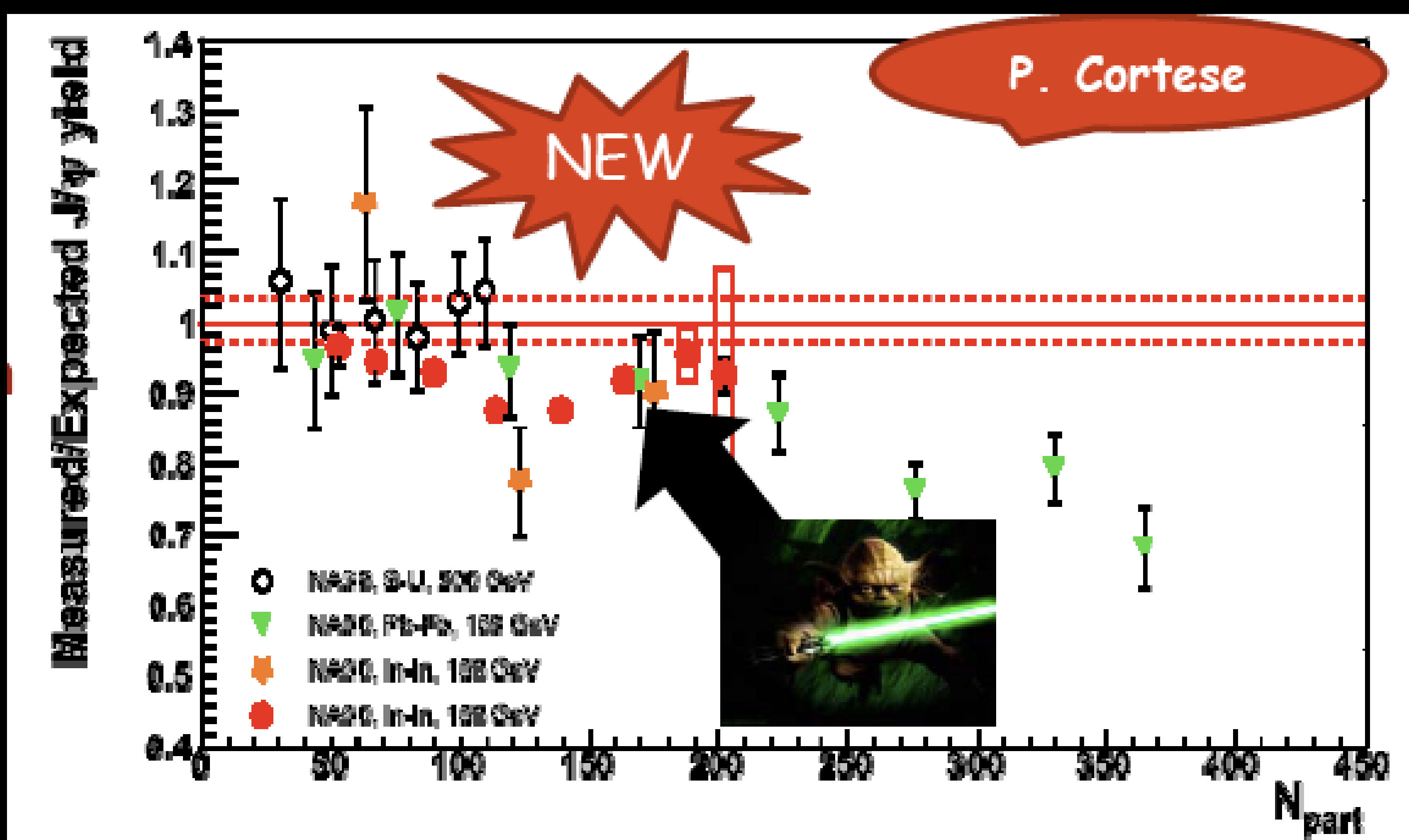


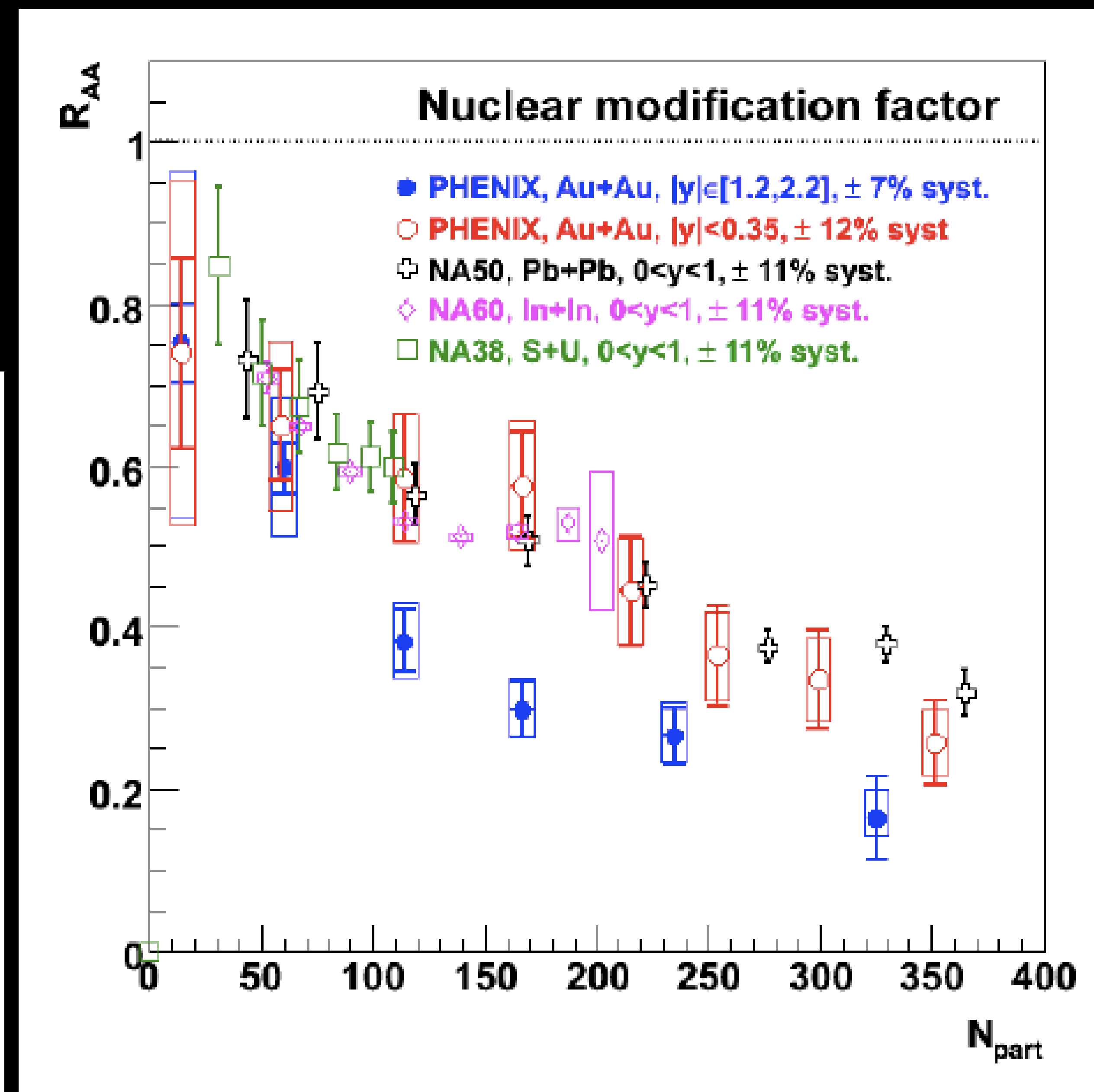




Quarkonium: HI data

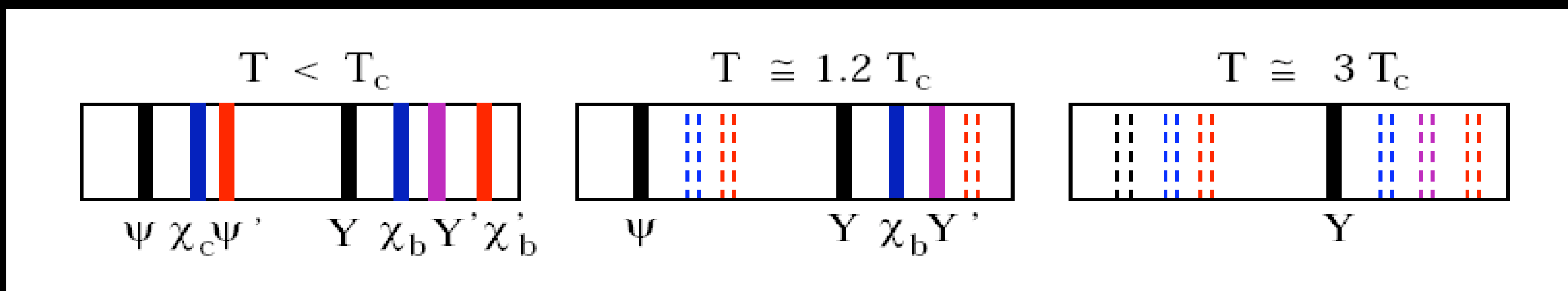
- SPS data show anomalous suppression.
- Data show 'scaling' versus the number of participants.
- At RHIC, larger suppression at forward rapidities, opposite to expected from a density effect.





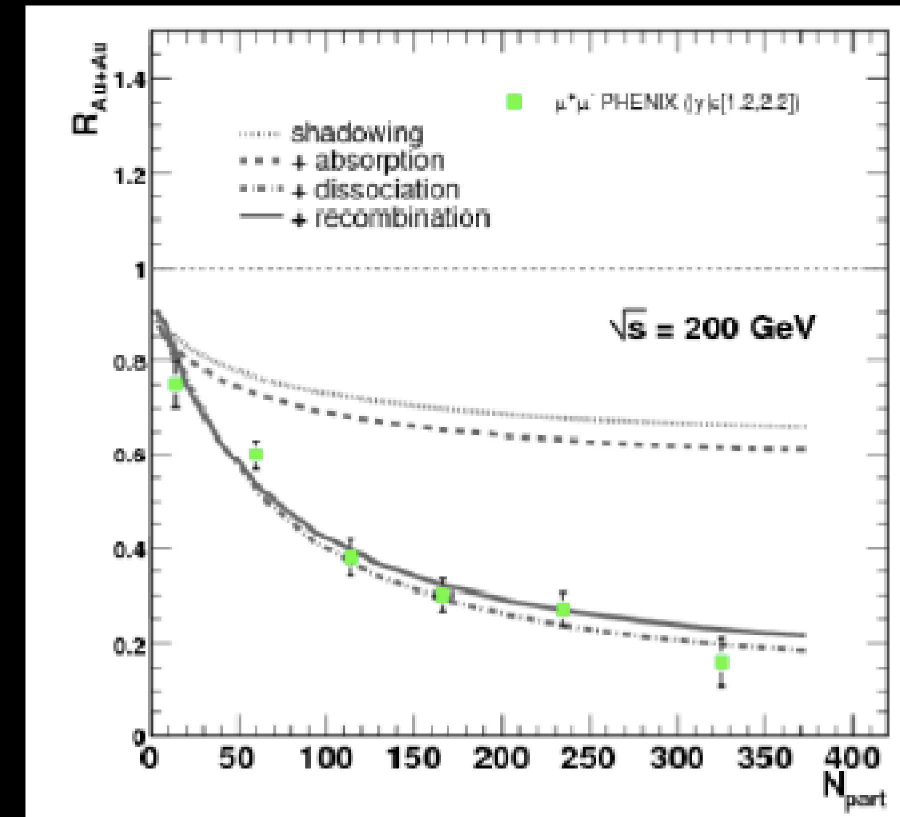
Quarkonium: theoretical interpretation

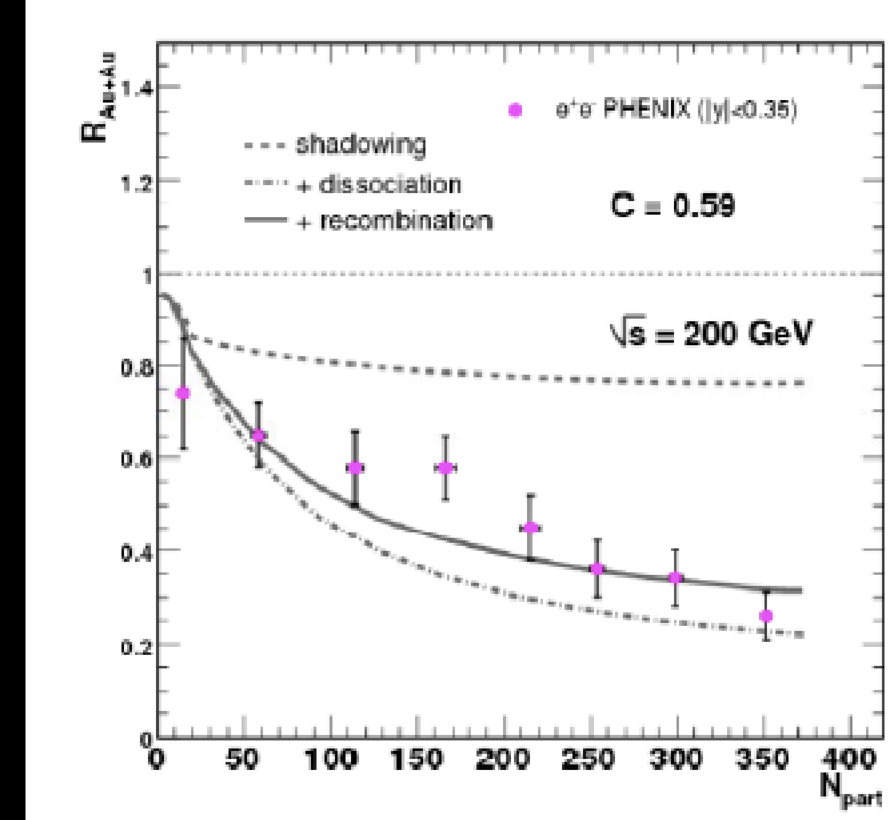
- Lattice suggests a sequential picture of quarkonia melting (but see Mocsy et al ‘07).



- Other explanations rely on dissociation + recombination of Q’s and Qbar’s in a deconfined medium, eventually combined with shadowing (Andronic et al ’05, Thews et al ’05, Tywoniuk et al ‘08).

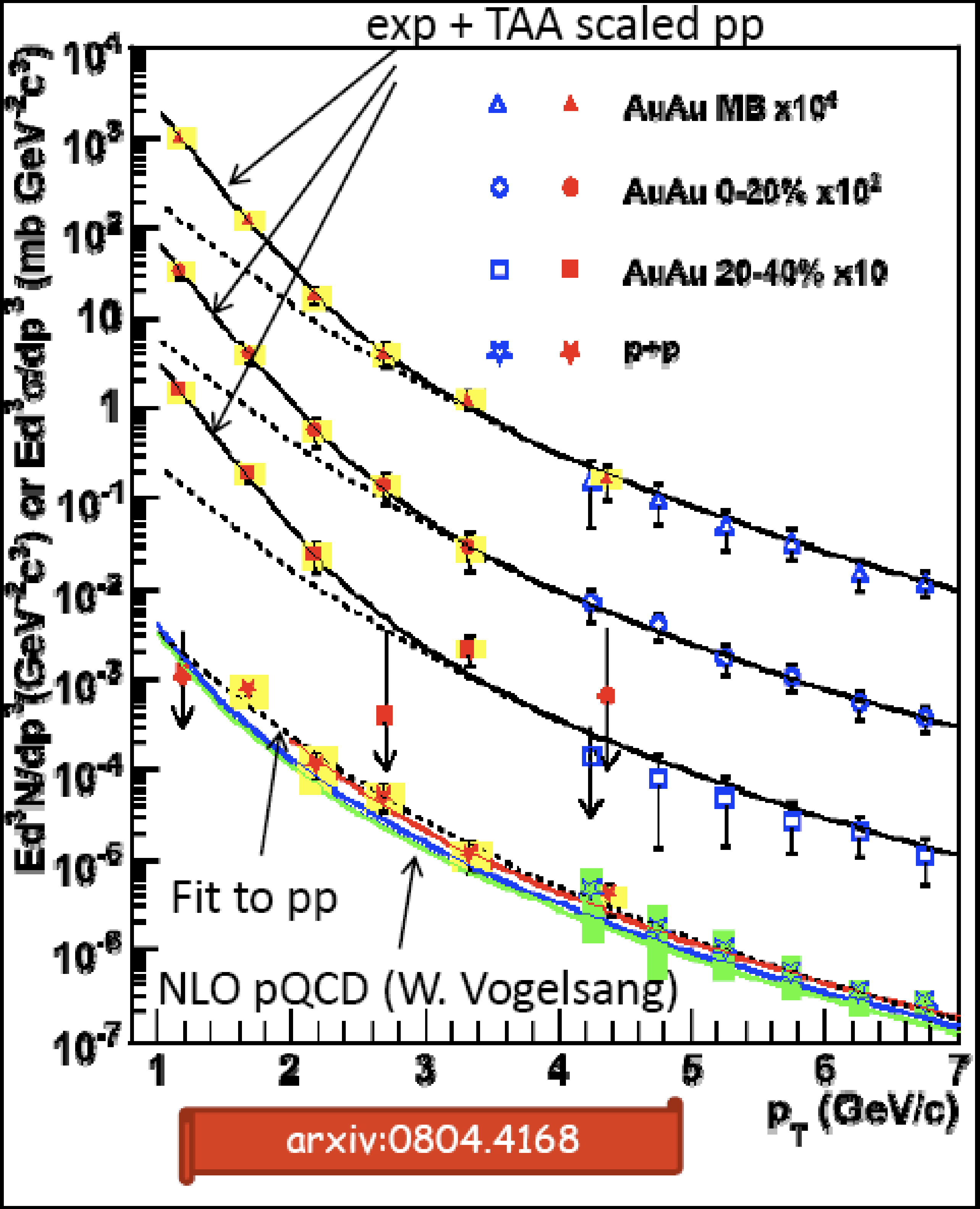
- Initial state effects may also explain the larger suppression at higher rapidities (Ferreiro et al ’08, Kharzeev et al ‘08).



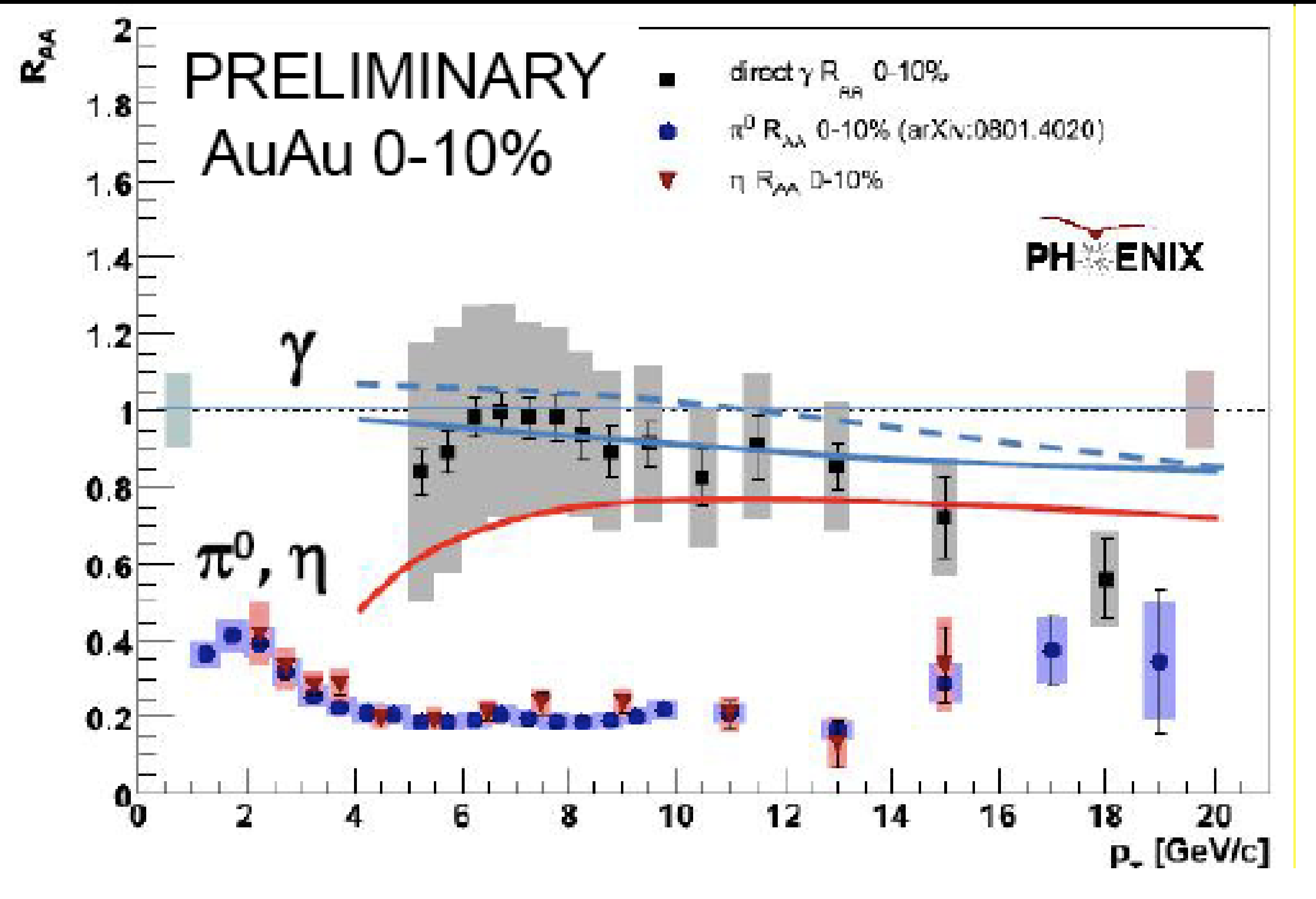


Photons: baseline in pQCD

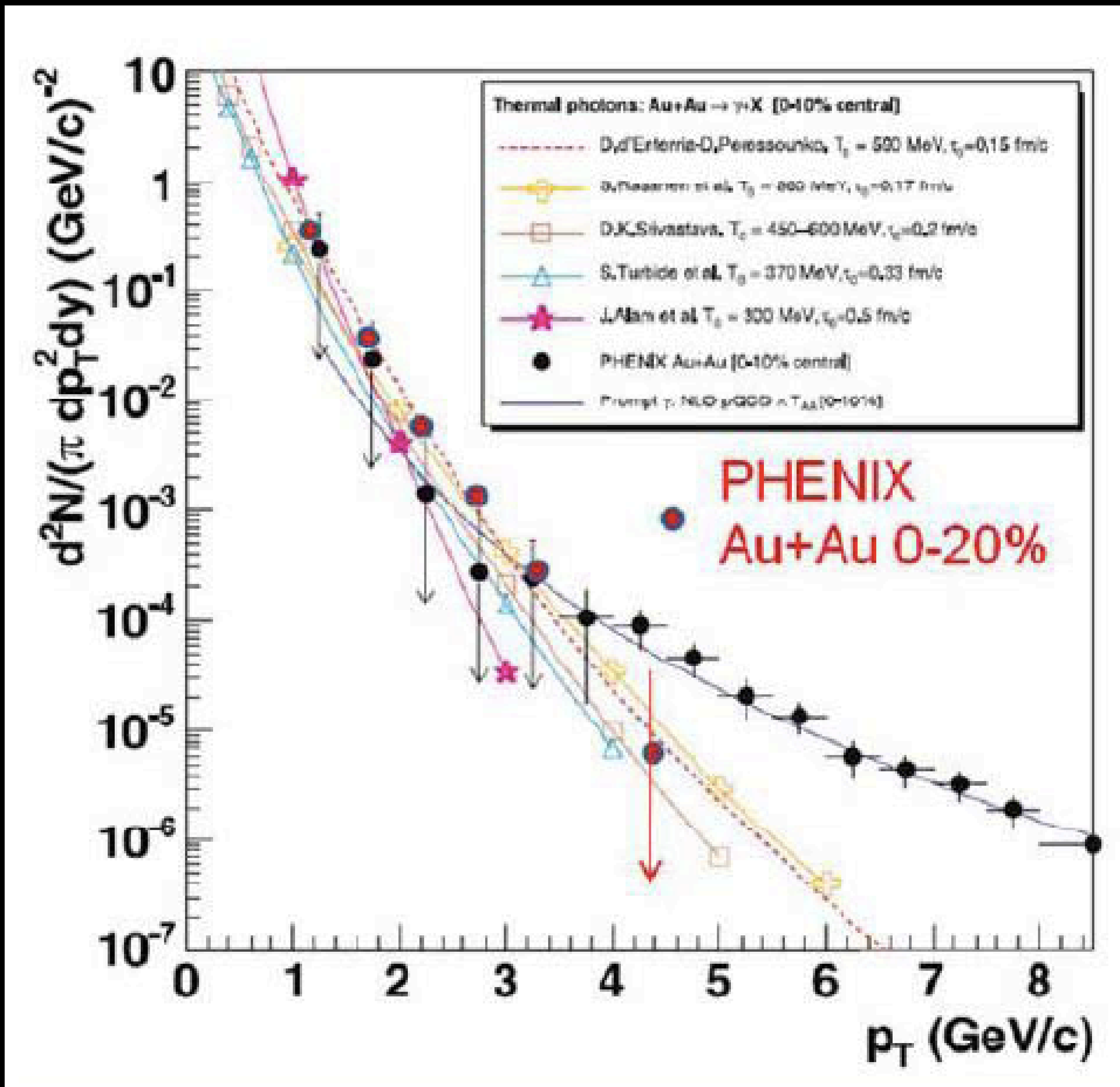
- pQCD works very well for photons with p_T>1 GeV/c.



- Photons show nuclear effects even at quite large p_T: initial state effects and quenching for photons from fragmentation.



Photons: low p_T excess



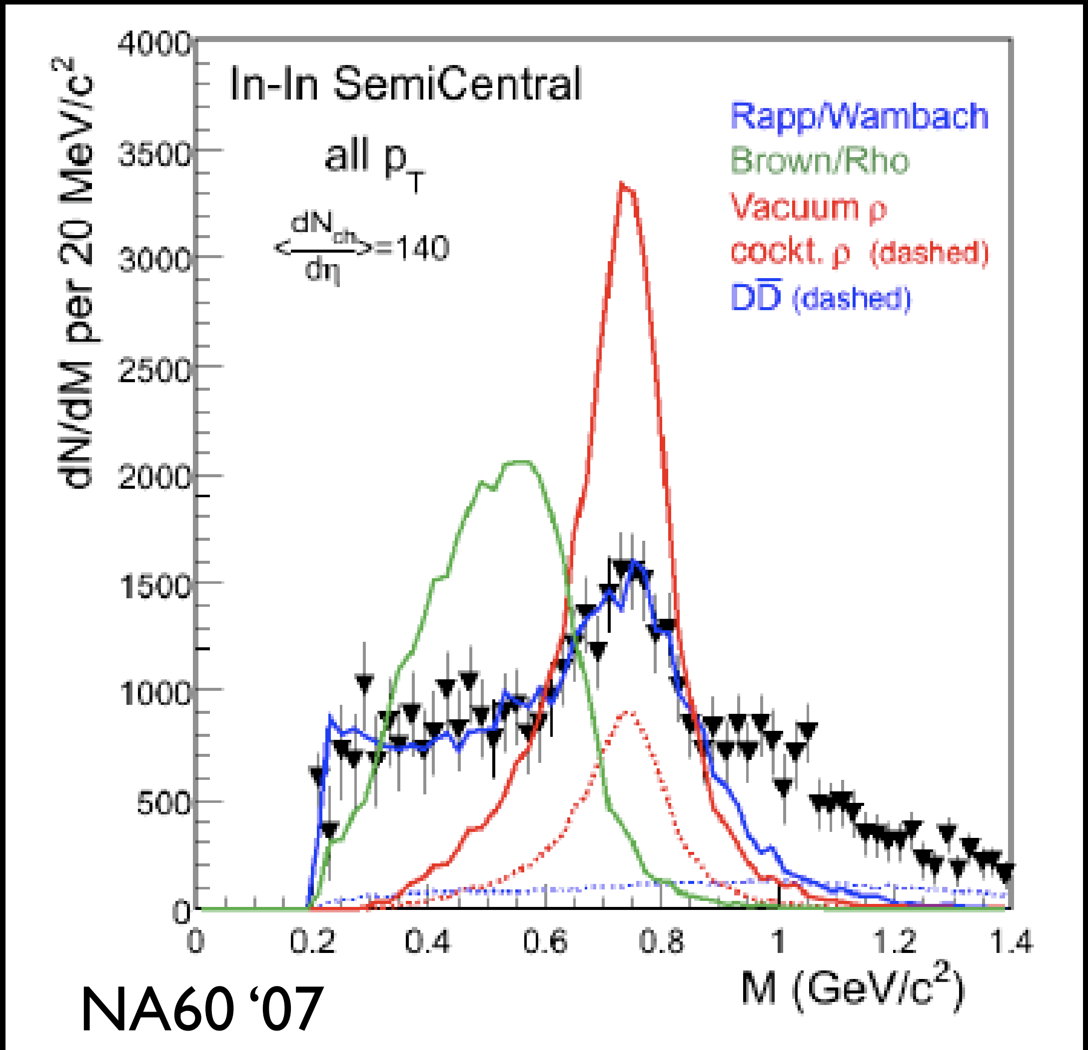
- Small-p_T excess compatible with thermal production:

  * T_{in}=300-600 MeV.

  * τ_0=0.15-0.5 fm/c.

  Early thermalization and high temperature, well about deconfinement.

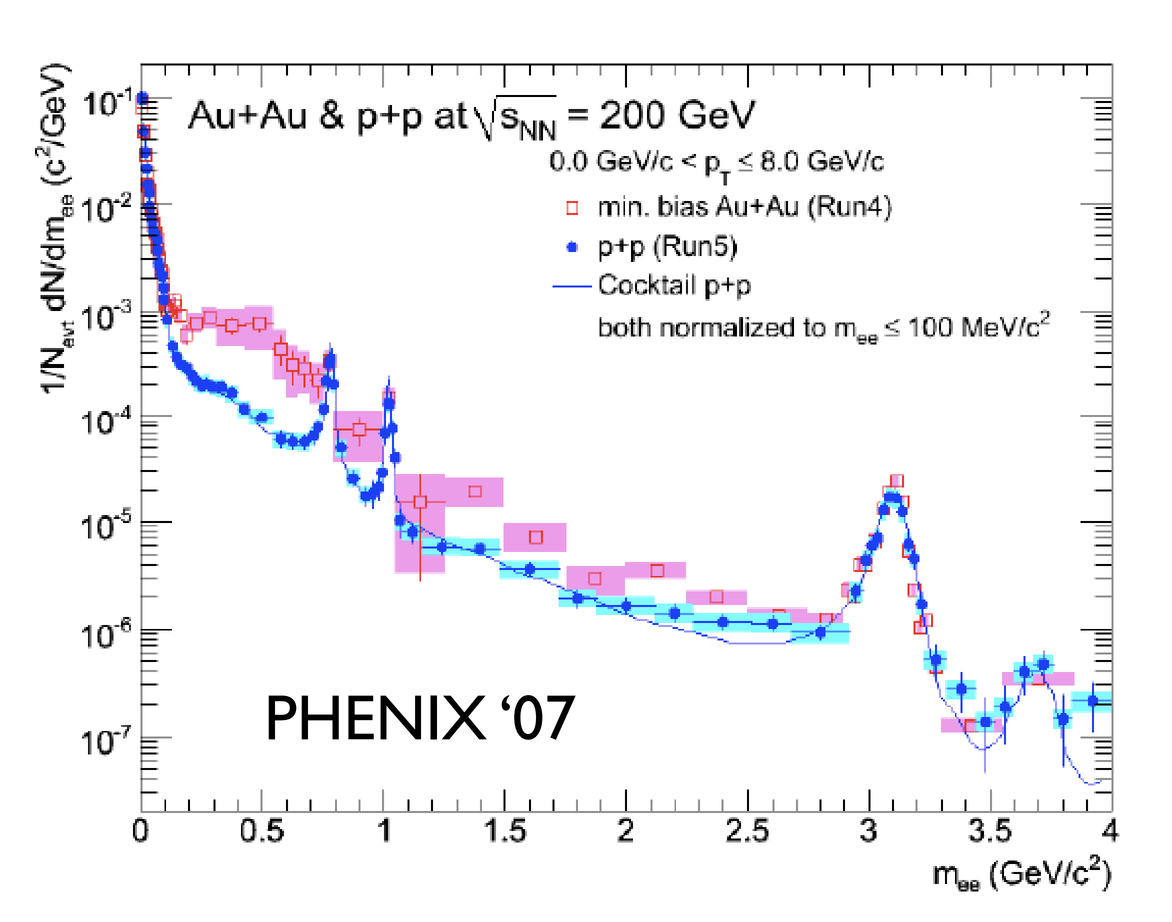
Dileptons:



- NA60 sees an excess in the region M<1 GeV/c², compatible with ρ-broadening (but no mass shift).

- NA60 sees an excess in the region 1<M<1.5 GeV/c² which is not charm: thermal?

- PHENIX sees an excess in the region M<1 GeV/c².



4. Perspectives for the LHC:

4.1. What is new?

4.2. Predictions for multiplicities.

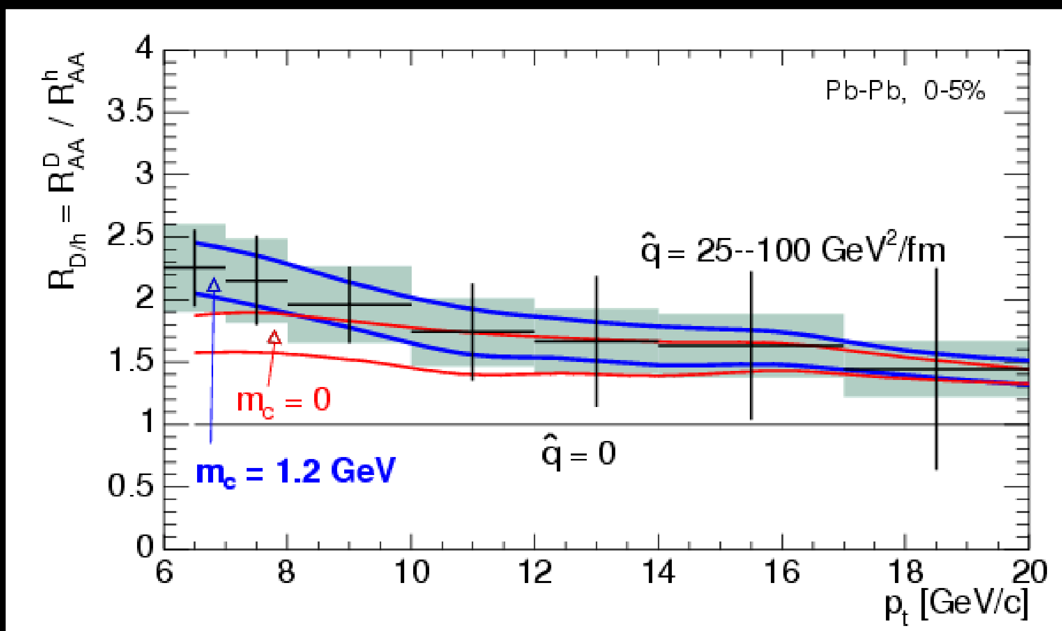
4.3. Predictions for elliptic flow.

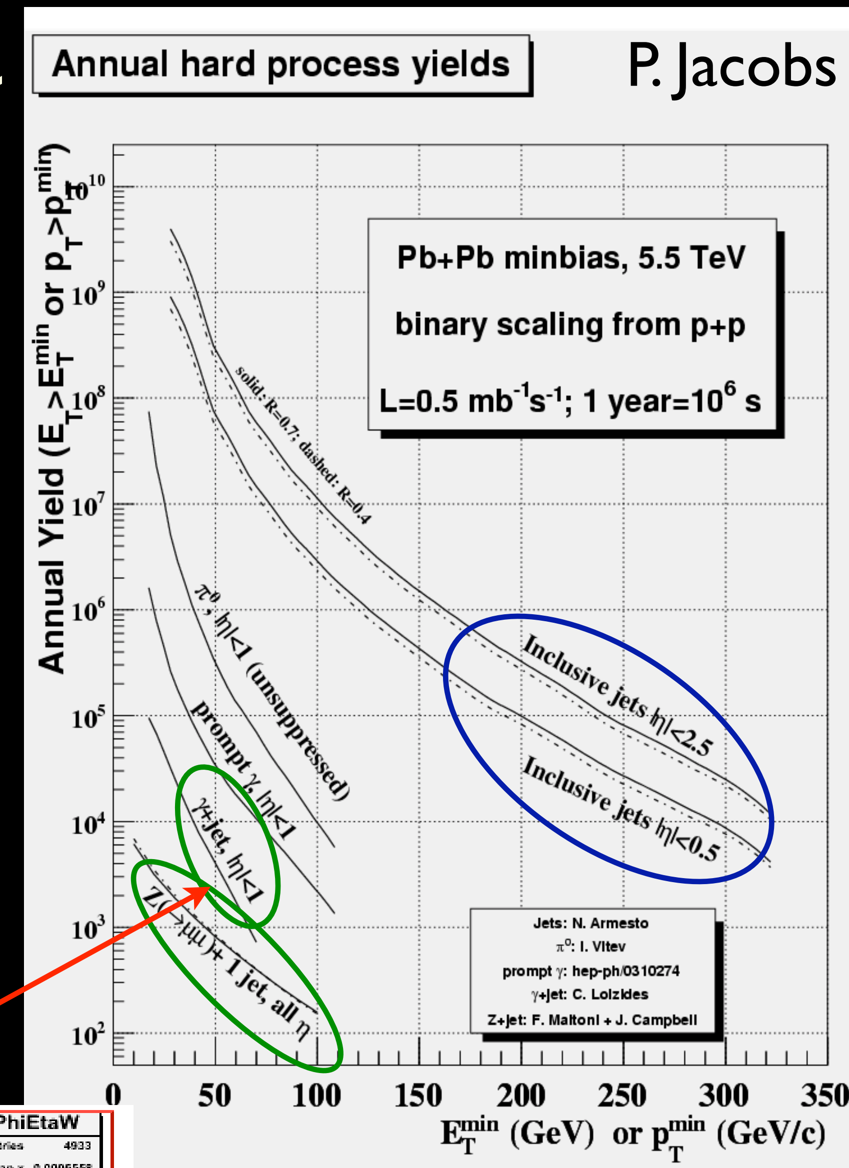
4.4. Predictions for R_{AA}.

See Last Call..., arXiv:0711.0974.

4.1. What is new?

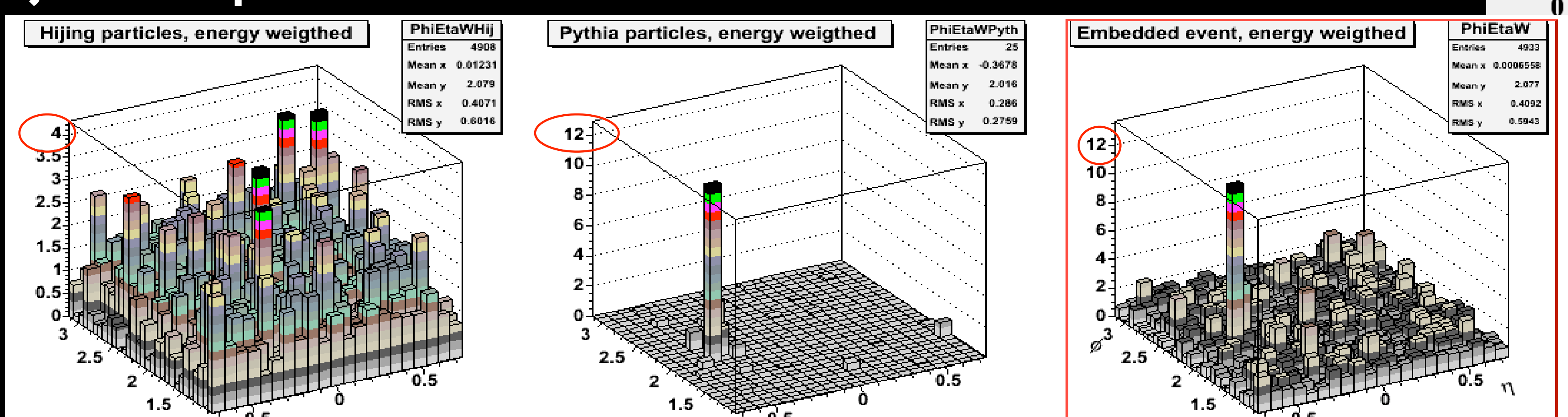
Abundant yield of hard probes (Yellow Report '04); reconstruction of higher quarkonium states, and of D (B) mesons.





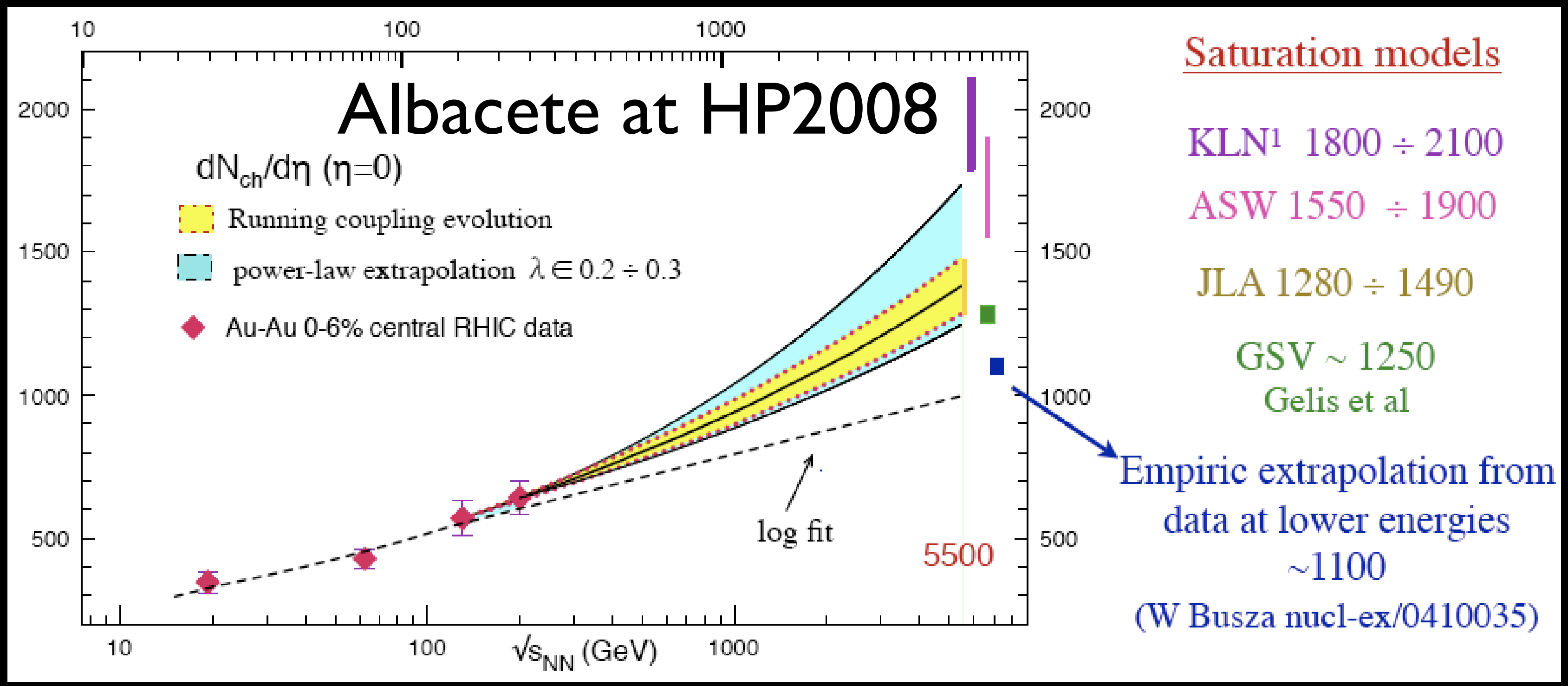
New theoretical tools required!!!

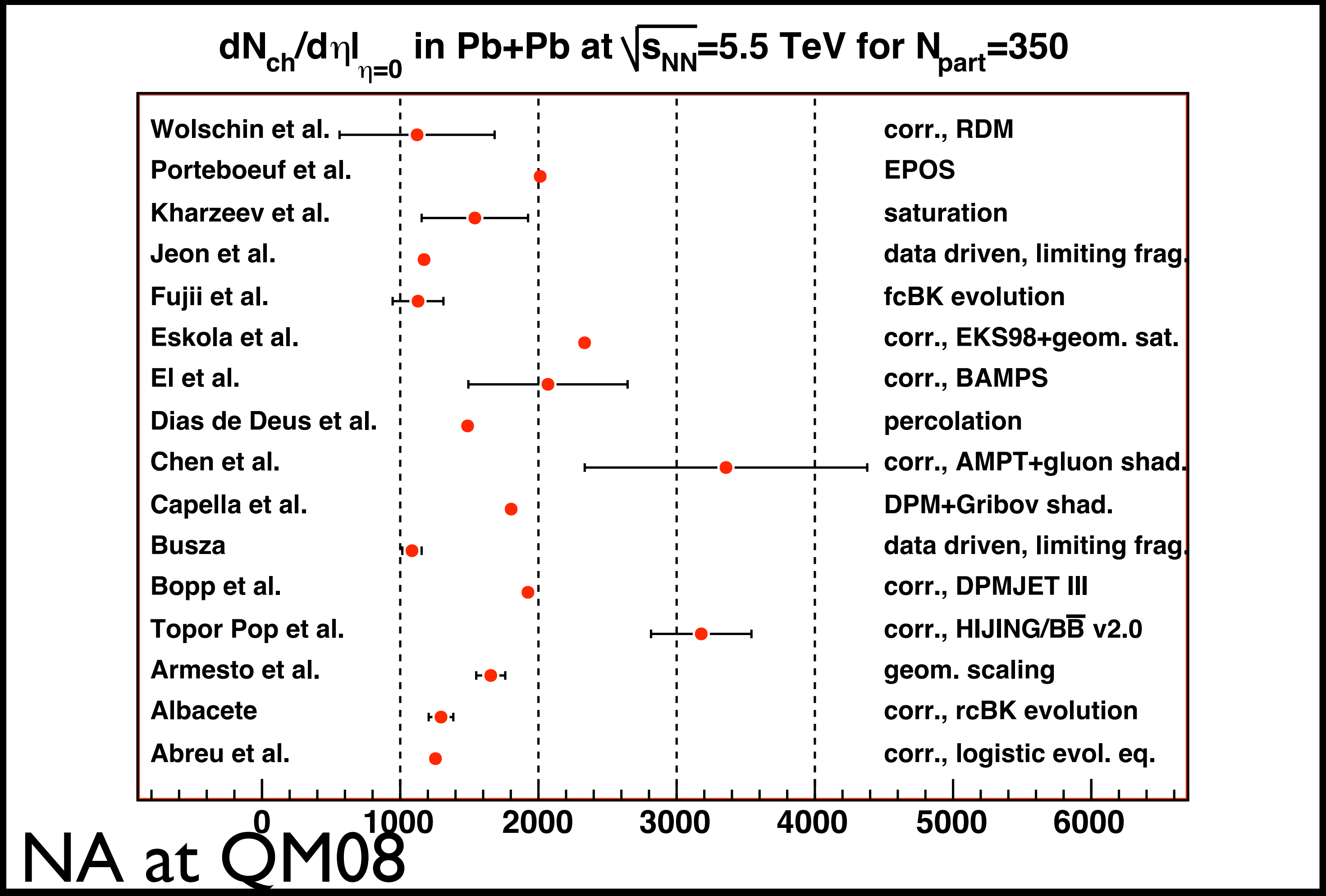
Possibility of jet reconstruction and study of jet shapes: check of the eloss mechanism.



50 GeV jet (Pythia) + central Pb+Pb background (Hijing)

4.2. Predictions for multiplicties:





➪ A 1st day observable: charged mutiplicity at midrapidity, will have discriminating power on models.

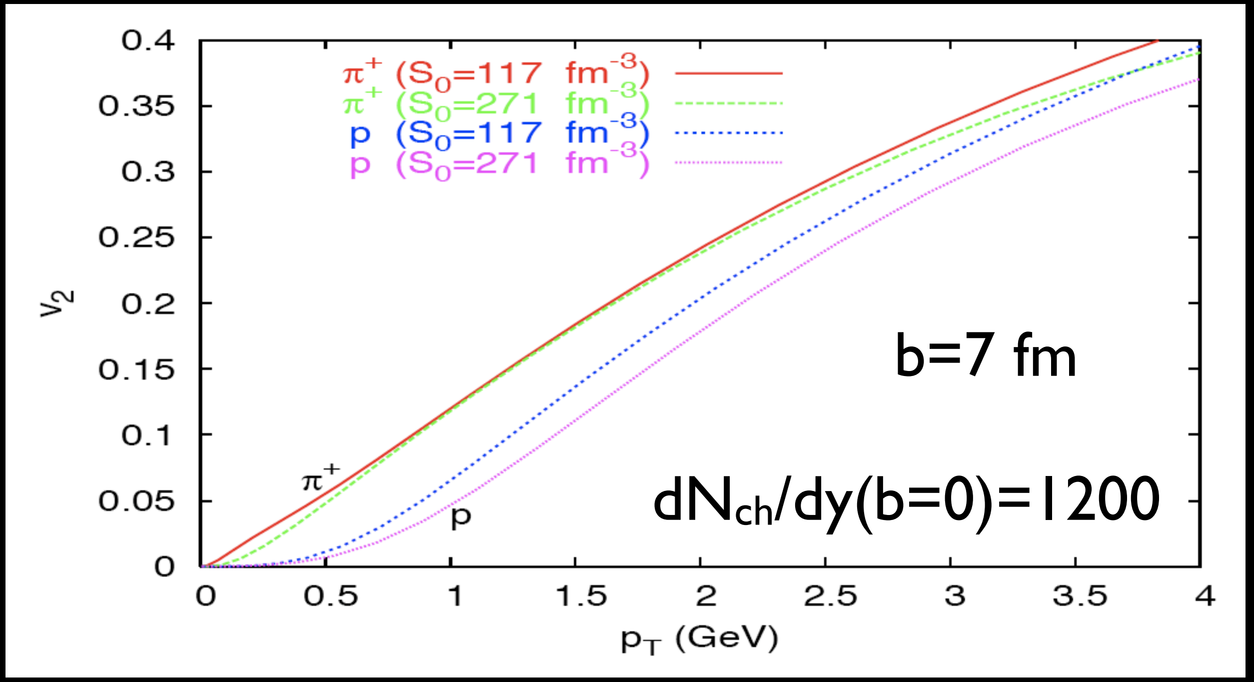
➪ $dN_{ch}/d\eta|_{\eta=0}>2000$ will be a challenge for saturation physics.

4.3. Predictions for elliptic flow:

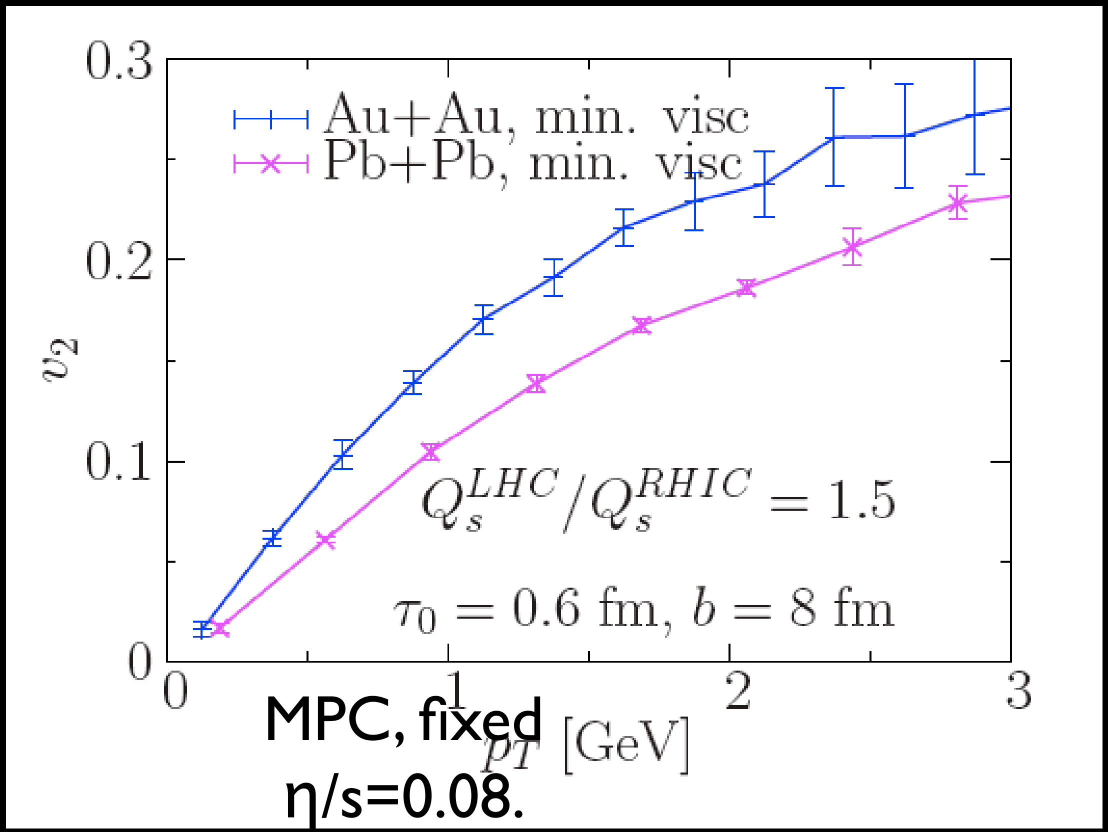
- Ideal hydro is expected to work better and until larger p_T<4 GeV/c.

- With respect to RHIC, v_2 at fixed p_T decreases, but p_T-integrated v_2 increases, though in ideal hydro less than naive expectations (Borghini et al '07).

- These trends remain if a fixed viscosity is considered (MPC) (actually the system should become closer to a gas than at RHIC, and then viscosity should increase - so v_2 decrease even more).

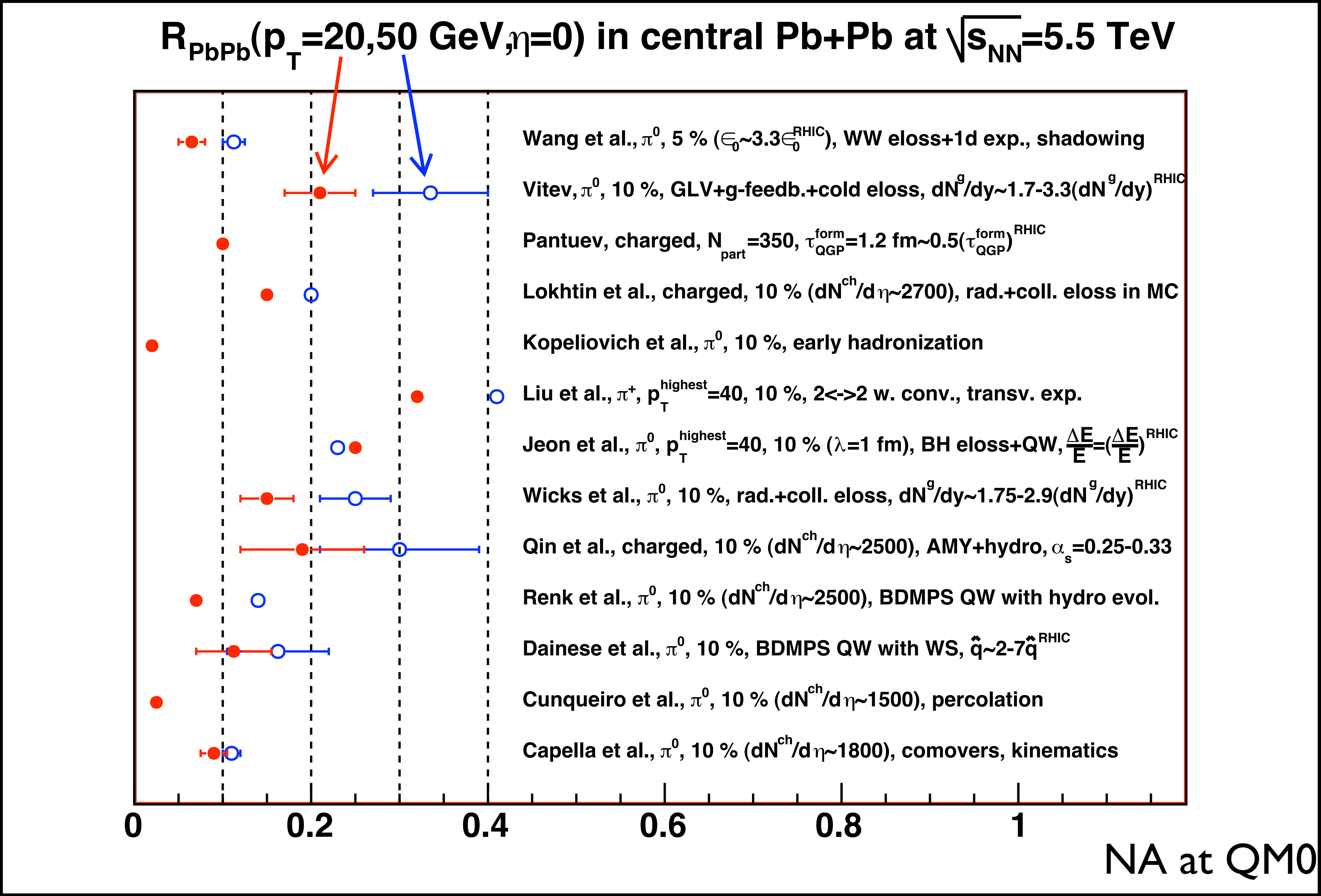


Kestin et al.; ideal hydro.



MPC, fixed η/s=0.08.

4.4. Predictions for R_{AA}:



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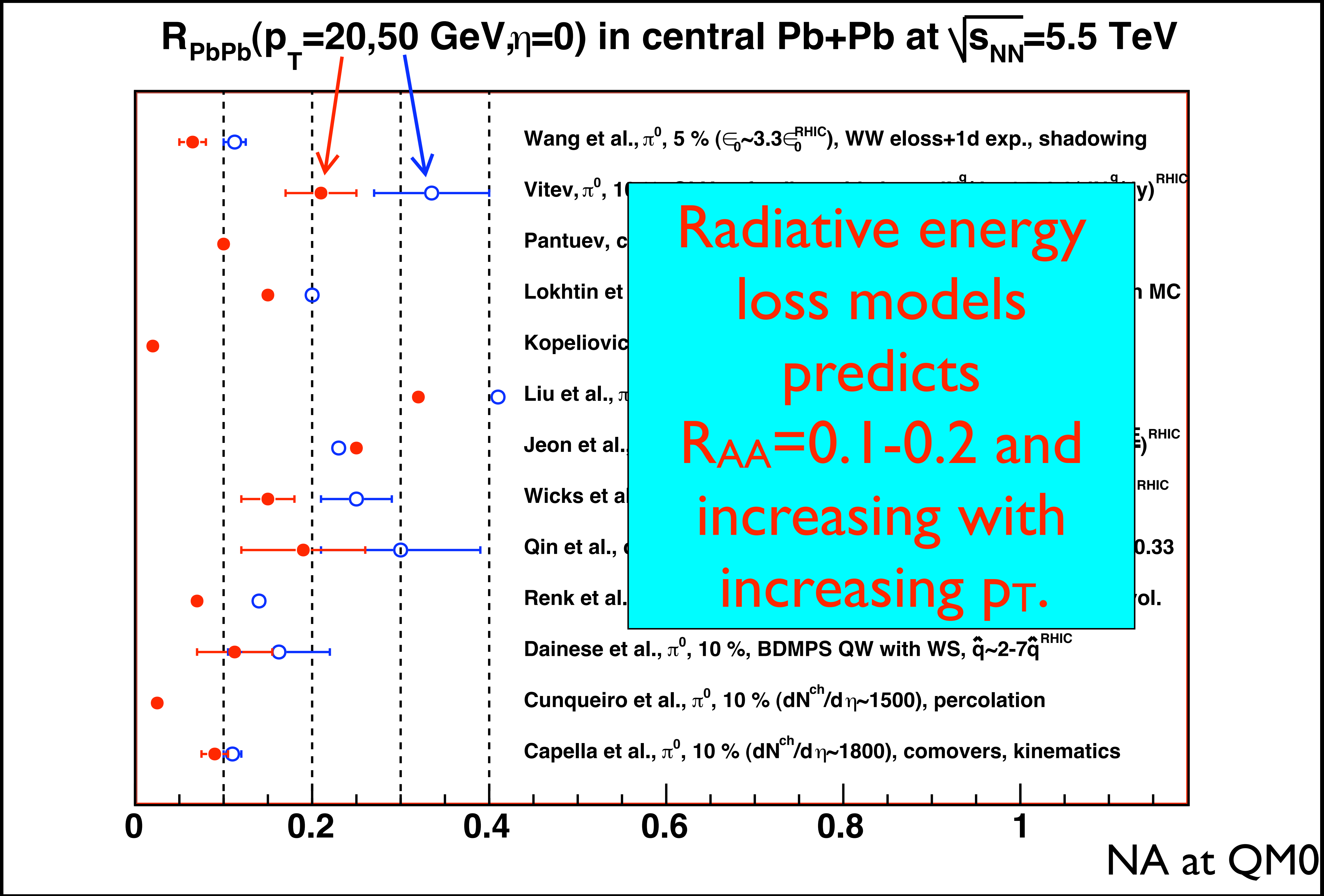

Radiative energy loss models predicts R_{AA}=0.1-0.2 and increasing with increasing p_T.

From RHIC to the LHC:

Observable at RHIC	Standard interpretation	Prediction for the LHC
Low multiplicity	Strong coherence in particle production	$dN_{ch}/d\eta\|_{\eta=0}<2000$ for central collisions
v_2 in agreement with ideal hydro	Almost ideal fluid	Similar or smaller $v_2(p_T)$
Strong jet quenching	Opaque medium	R_{AA}(20 GeV)~0.1-0.2 for π^0

* Major deviations from expectations will enlarge our understanding of Ultra-Relativistic Heavy-Ion Collisions: naive extrapolations tend to disagree with those from successful models at RHIC (Borghini et al '07).

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4. Summary:

- The standard claims at RHIC is that a very opaque medium is produced which behaves very quickly like an almost ideal fluid. Both play a central role in our understanding of non-perturbative QFTs.

- These claims are supported on the success of models for energy loss and of ideal hydro, respectively.

- To check these claims, much work is demanded:
  * Theory: understanding of the mechanism of energy loss through differential observables; early thermalization and viscous corrections.
  * Experiment: heavy flavors, quarkonia and more differential measurements, both from RHIC-II and from the LHC.

- Hard Probes: the control of the benchmark is crucial⇒pp and pA.

4. Summary:

- The standard claims at RHIC is that a very opaque medium is produced which behaves very quickly like an almost ideal fluid. Both play a central role in our understanding of non-perturbative QFTs.

MANY THANKS to the organizers for their invitation to this BEAUTIFUL place!!!

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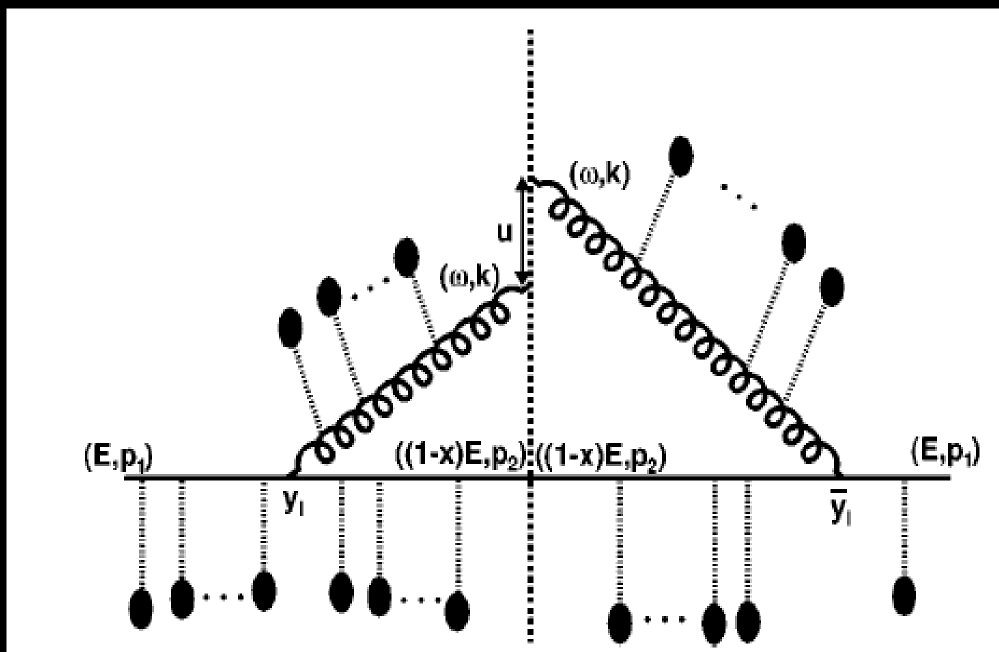
corrections.

* Experiment: heavy flavors, quarkonia and more differential measurements, both from RHIC-II and from the LHC.

- Hard Probes: the control of the benchmark is crucial⇒pp and pA.

Models for radiative eloss:

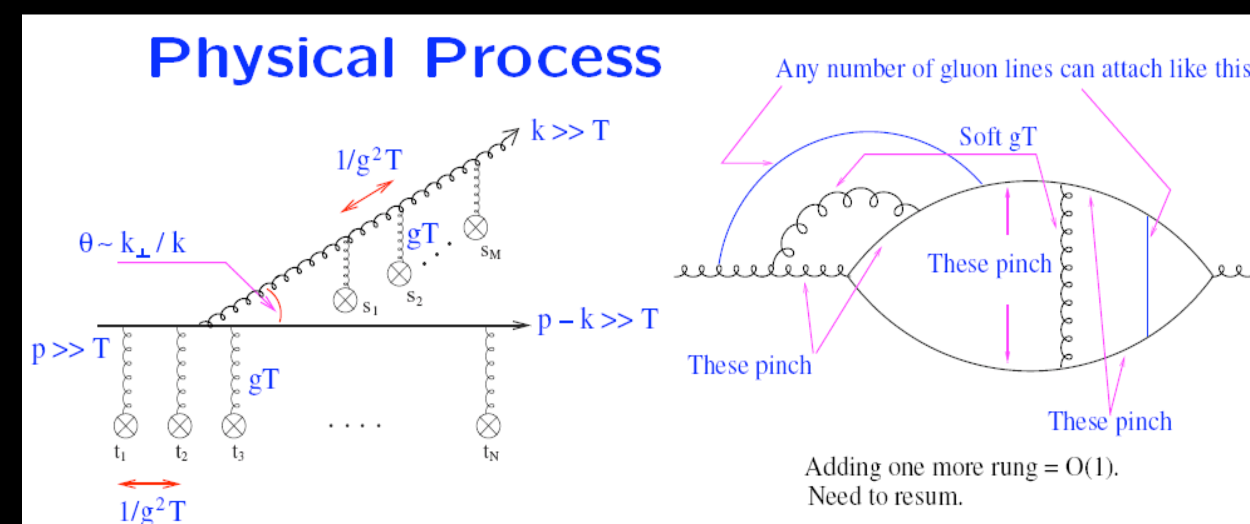
1/2. BDMPS/GLV: static medium.



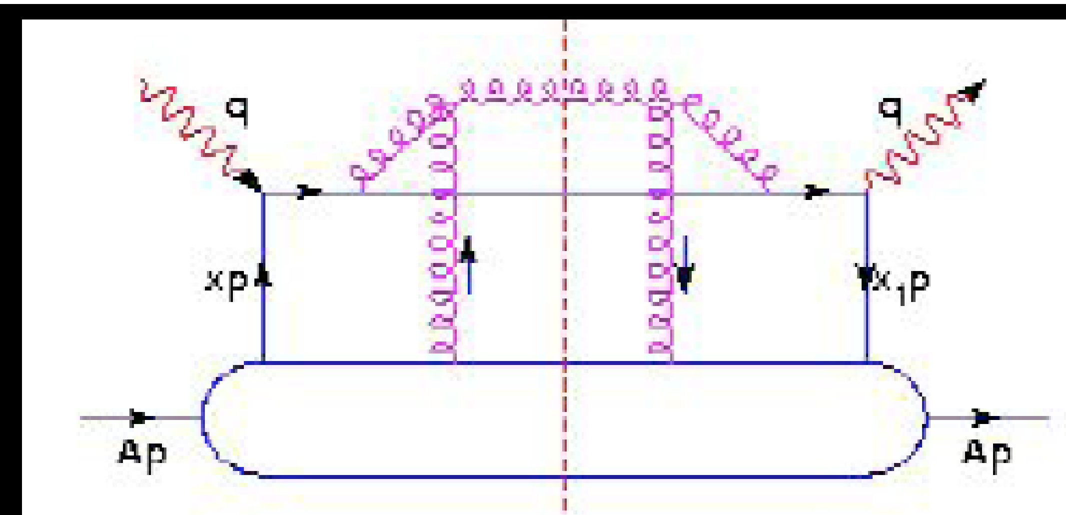
1. BDMPS: Multiple soft scatterings (Brownian motion).

2. GLV: single hard scattering, corrects Brownian motion.

3. AMY: HTL calculation, dynamical medium, rates order α_s .



4. GW(M): FF in DIS on nuclei, first corrections in L/k_T^2 .



Radiative eloss: medium modeling

$$\hat{q}(\xi) = K \cdot 2 \cdot \epsilon^{3/4}(\xi)$$

$$\langle \hat{q} \rangle = \frac{2}{L^2 - \tau_0^2} \int_{\tau_0}^{L} d\tau \tau \hat{q}_0 \frac{\tau_0}{\tau} \simeq \frac{2\tau_0 \hat{q}_0}{L} \approx \frac{\hat{q}_0}{2 \div 5}$$

Gyulassy et al. '01, Salgado et al. '02

Phenomenological implementation	qhat (GeV^2/fm)
fixed length	<~1 (average)
Woods-Saxon (PQM)	4-14 (average)
dilution	increases, factor 2-5
dynamical medium (Djordjevic et al.)	decreases
flow (Armesto et al., Baier et al.)	no effect
hydro (Eskola et al., Bass et al.)	K~3-4, late times important