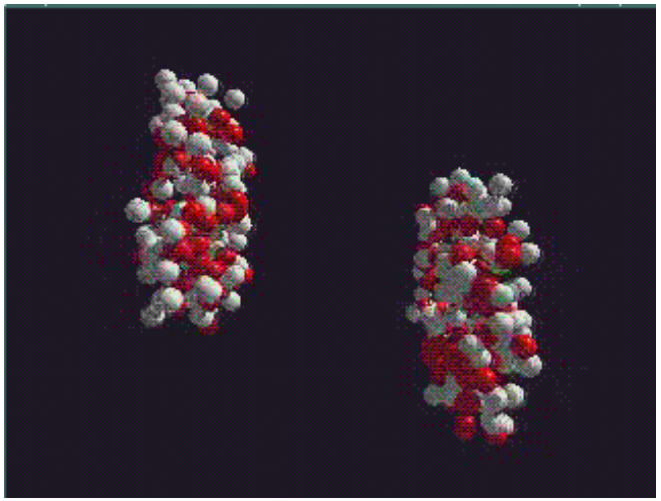
More is different

Selected theoretical aspects
of the upcoming LHC heavy ion programme



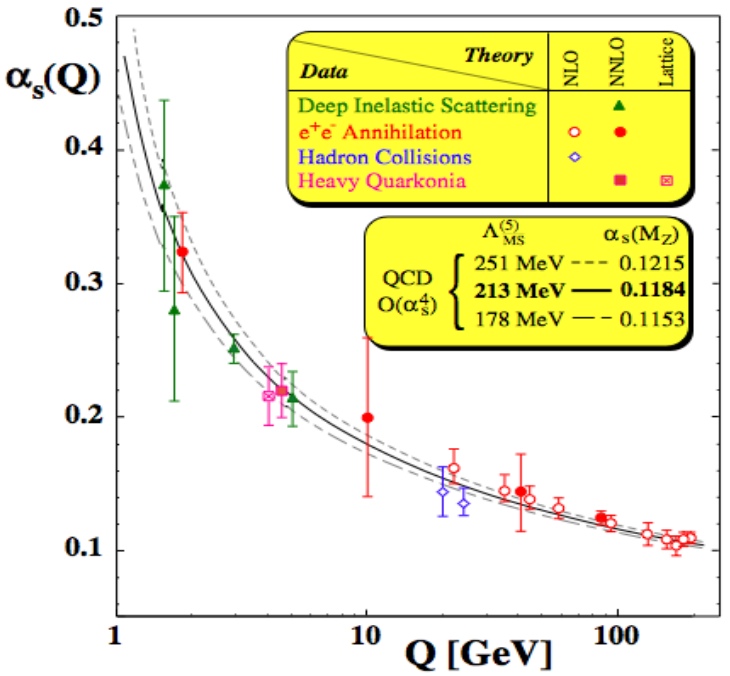
Urs Achim Wiedemann
CERN PH-TH

From elementary interactions to collective phenomena

1973: asymptotic freedom

⇒ QCD = quark model
+ gauge invariance

Today: mature theory with
a precision frontier



How do collective phenomena and macroscopic properties of matter emerge from fundamental interactions?

⇒ QCD much richer than QED:

- non-abelian theory
- degrees of freedom change with Q^2

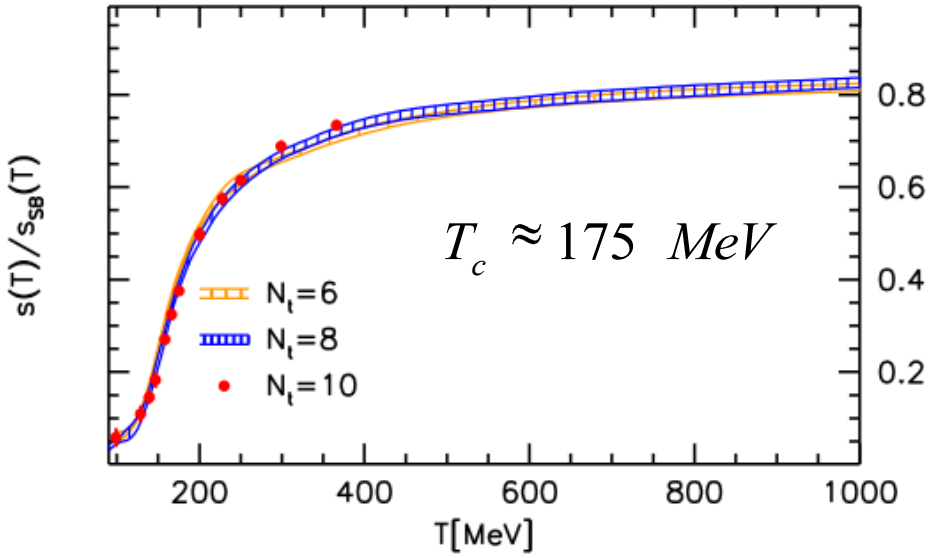
From 1st principles: QCD @ high temperature

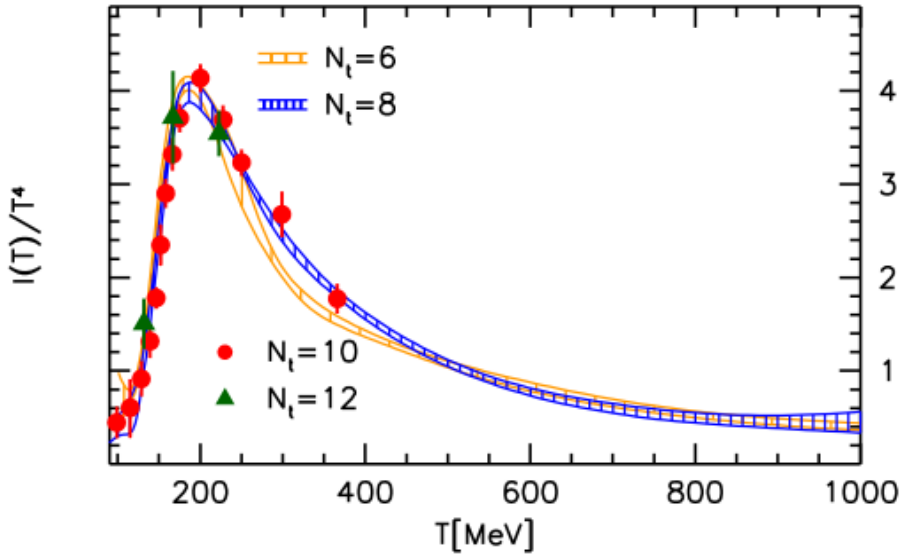
- QCD 'phase transition' at

$$\varepsilon_c \approx (3-5)\,\varepsilon^{cold}_{nuclear\ \ matter}$$

Wuppertal-Budapest, arXiv:1005.3508, arXiv:1007.2580

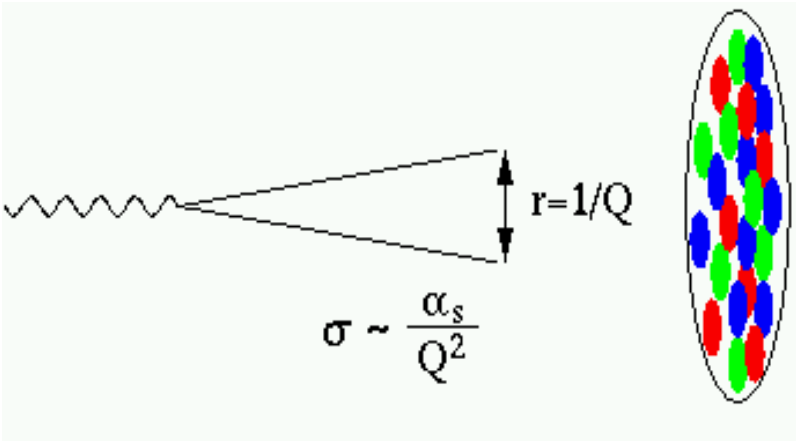
- Characteristic dependencies above T_c





- Recent progress in lattice QCD:
  - + fluctuation measures (susceptibilities)
  - + transport properties

From 1st principles: QCD @ high parton density



$\sigma\,\rho \ll 1$ "hard"
$\sigma\,\rho \gg 1$ "soft"

$\rho \sim \frac{Q_s^2}{\alpha_s(Q_s^2)}$

At high $\sqrt{s_{NN}}$, standard distinction between **hard** and **soft** breaks down:

- At small-x, parton densities $\rho \sim Q_s^2/\alpha_s(Q_s^2)$ are **saturated**

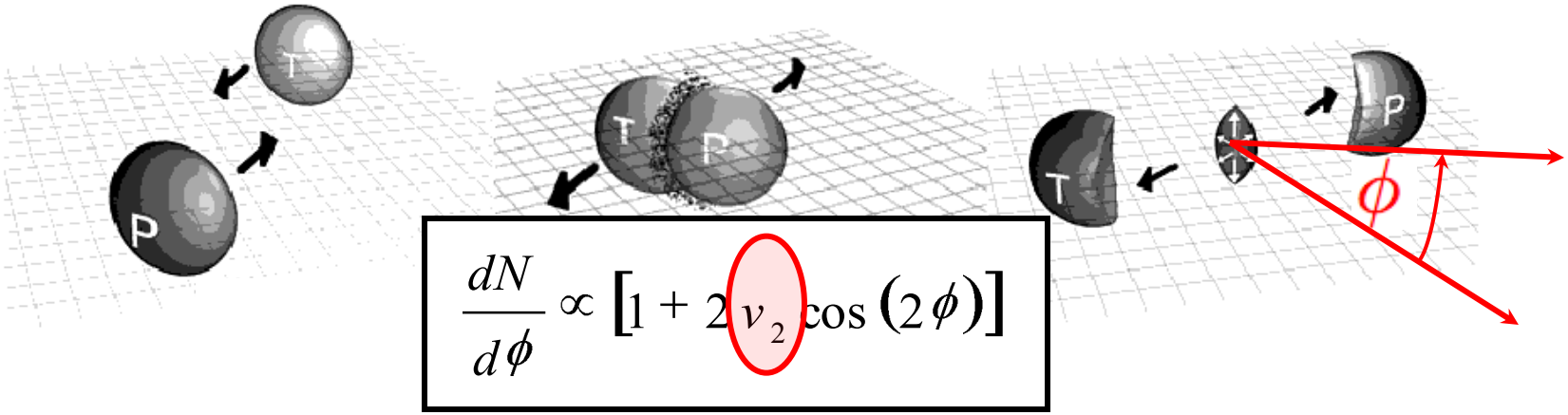
  up to large scales $Q^2 < Q_{sat}^2(\sqrt{s})$ $\qquad Q_{sat}^{2\ A} = A^{1/3}\, Q_{sat}^{2\ p}$

- Coupling constant is small $\alpha_s(Q_{sat}^2(x) \gg \Lambda_{QCD})$

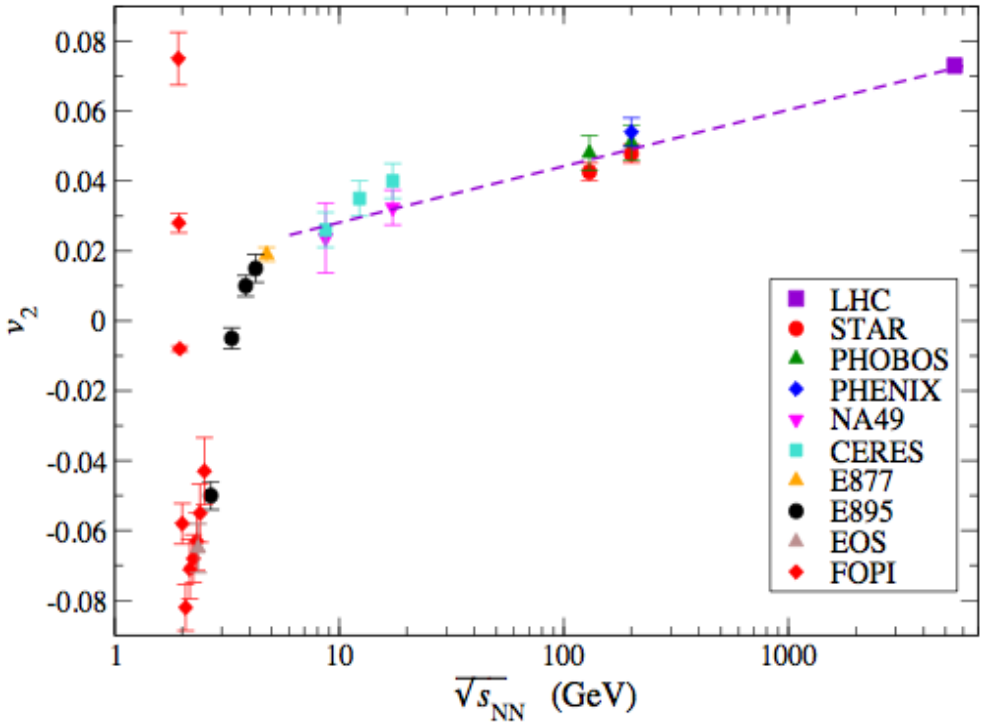
⇒ Non-linear QCD evolution in perturbative regime.

Is more different
in heavy ion collisions at
collider energies?

I. Elliptic Flow:
Hallmark of a collective phenomenon



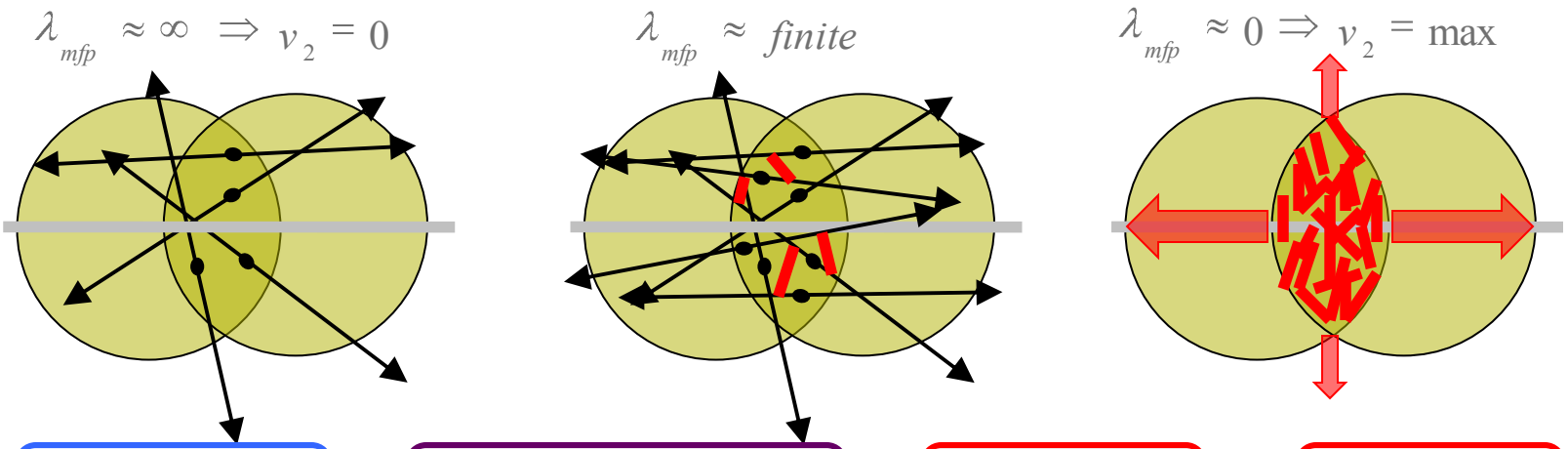
$$\frac{dN}{d\phi} \propto \left[1 + 2 v_2 \cos(2\phi)\right]$$



??

Elliptic Flow: insights from RHIC

Mean free path vs. collectivity



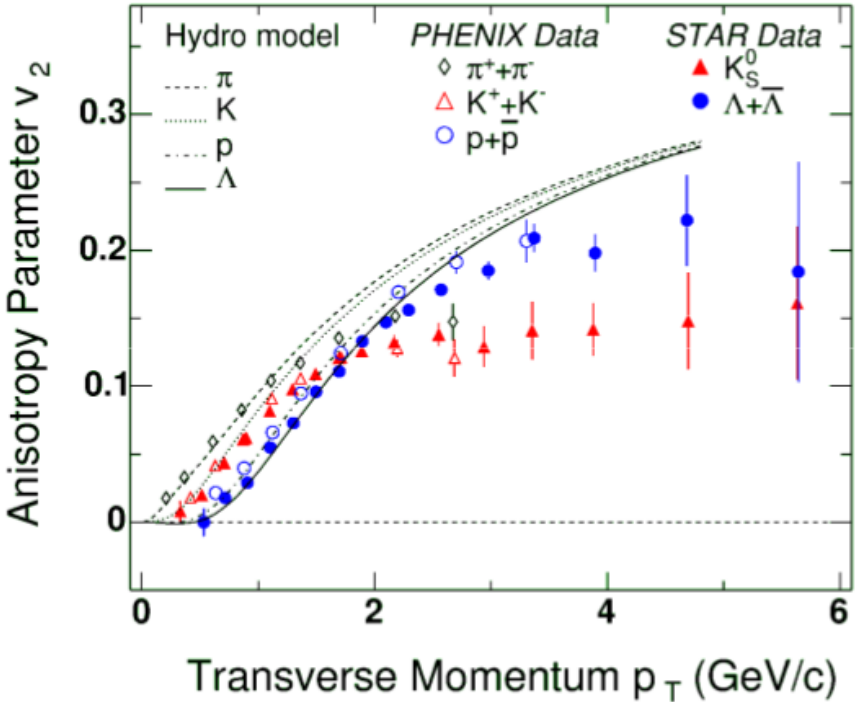
Theory tools:

Free streaming → Particle cascade (QCD transport theory) → Dissipative fluid dynamics → Perfect fluid dynamics

RHIC:
- v2 close to maximal
- characteristic mass-dependence (common flow for all hadrons)
- v_2 satisfies quark number counting rules
- fluid dynamic simulations agree with size of v2, dependence on pT, PID and centrality at midrapidity
- constrain dissipative properties

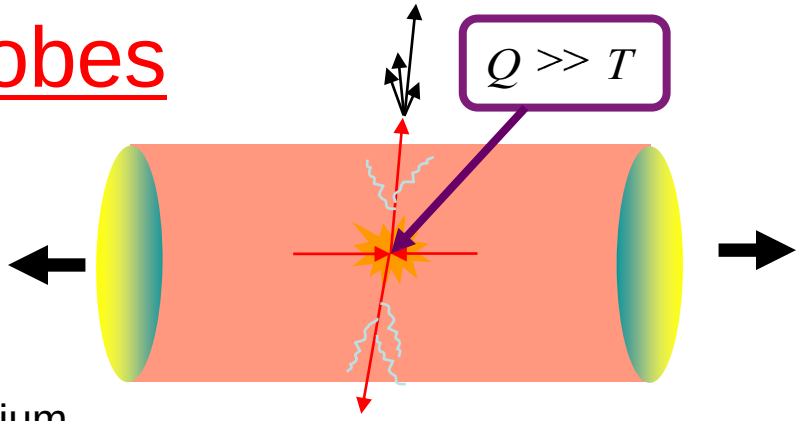
Strong claims at RHIC: perfect liquid

Physics in reach with ~10^6 Pb+Pb events!

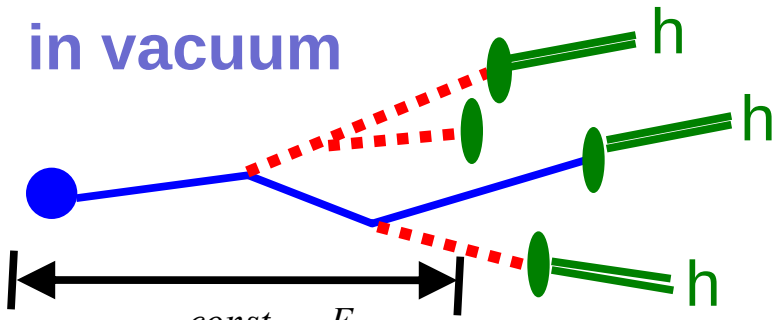


II. Hard Probes

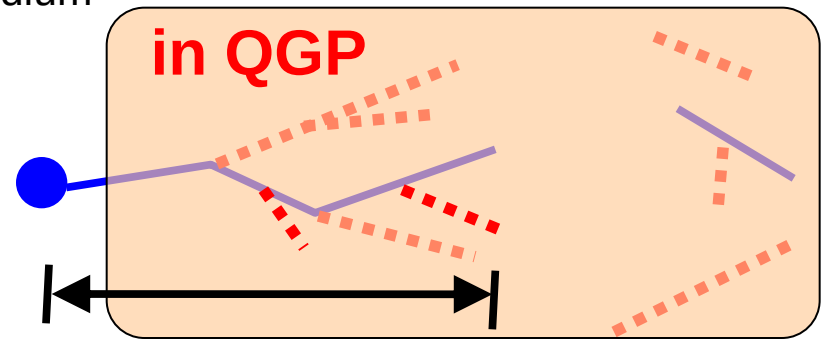
- In Pb+Pb @ LHC embed hard processes in dense nuclear environment



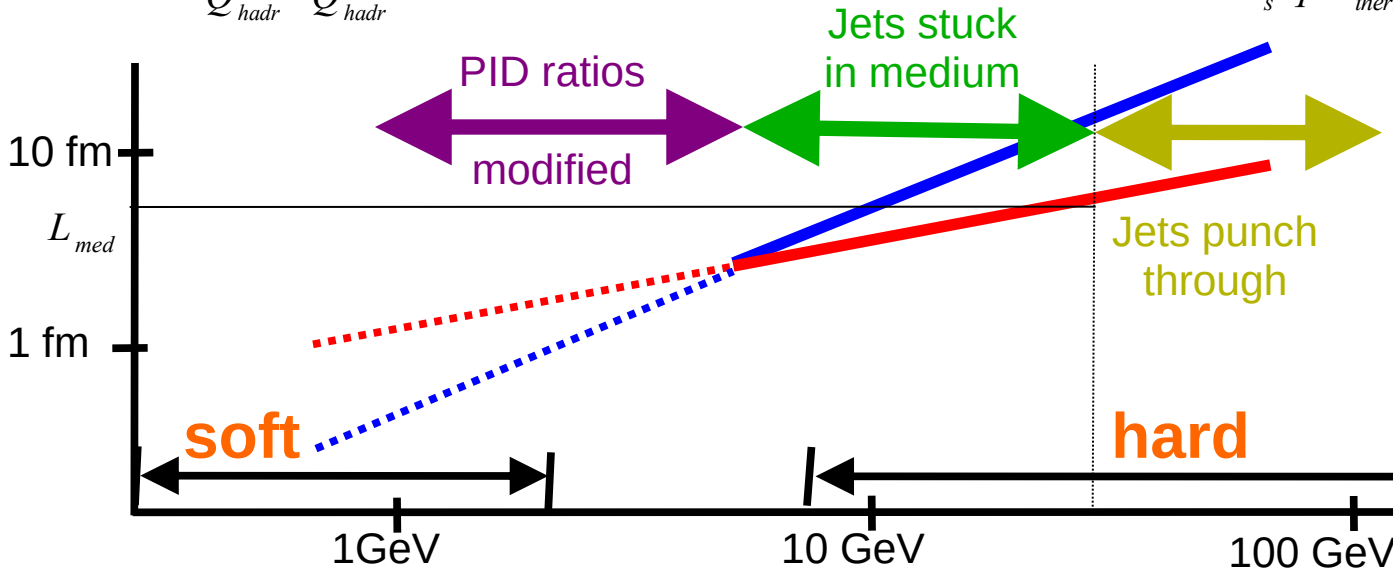
- Hadronization in vacuum vs. thermalization in medium



$$L_{hadr} \cong \frac{const}{Q_{hadr}} \frac{E}{Q_{hadr}}$$



$$\Delta E \equiv E \approx \alpha_s \hat{q} L^2_{therm}$$



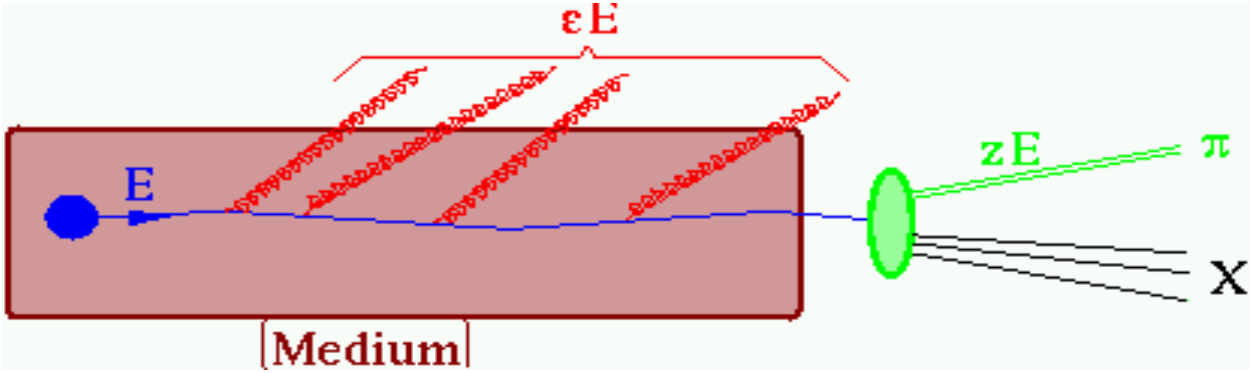
$$L_{hadr} \propto E / Q^2_{hadr}$$

$$L_{therm} \propto \sqrt{E/\hat{q}}$$

$$Q_{hadr} \approx 1\ GeV$$

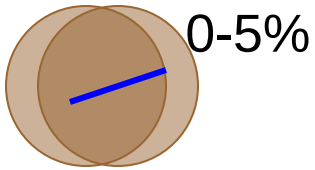
$$\hat{q} \approx 10\ GeV^2 / fm$$

High pT Hadron Spectra at RHIC …

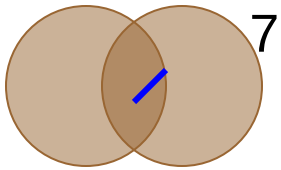


$$R_{AA}(p_T,\eta) = \frac{dN^{AA}/dp_T d\eta}{n_{coll}\ dN^{NN}/dp_T d\eta}$$

Centrality dependence:



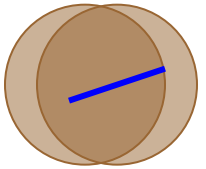
L large

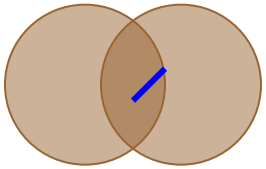


L small

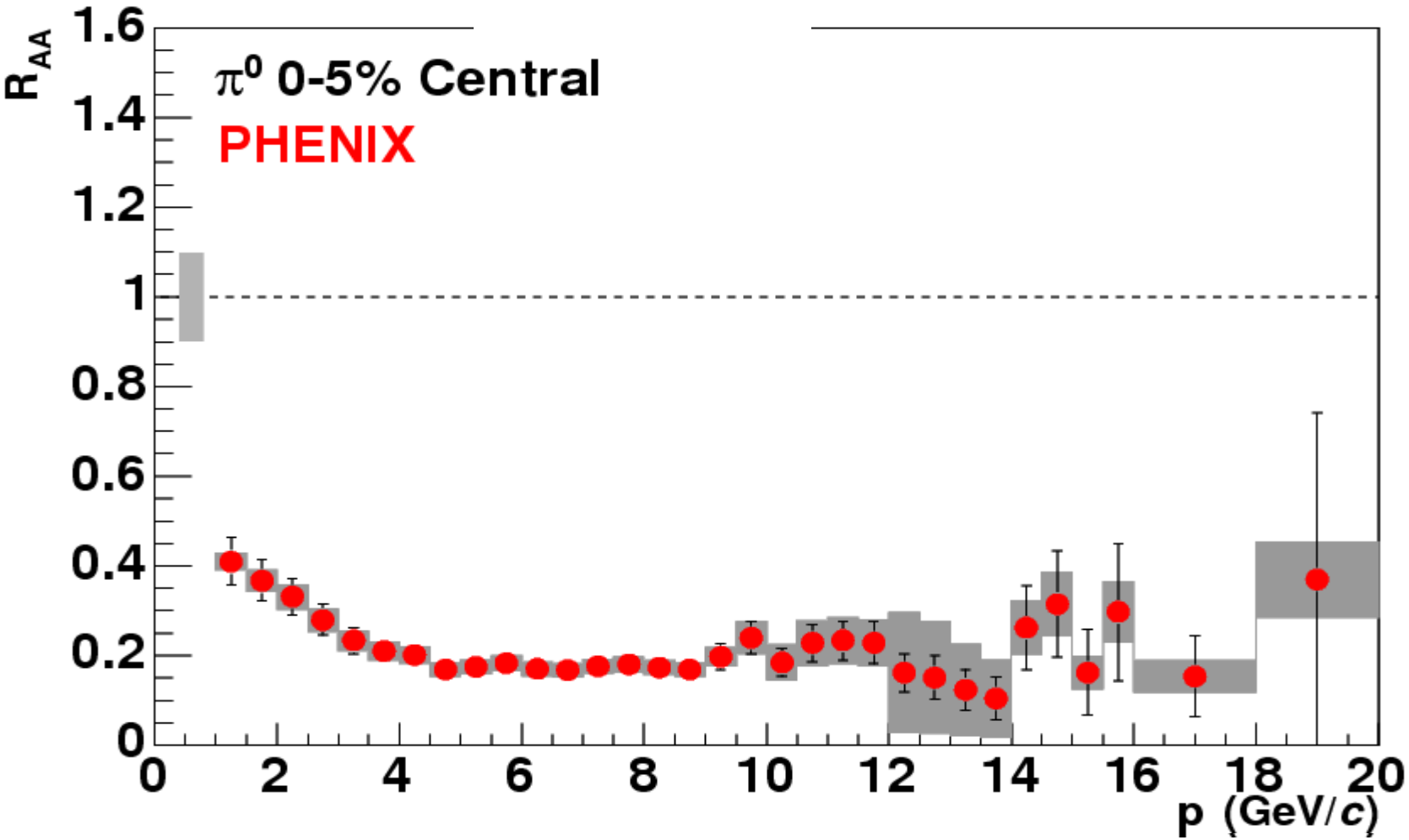
… are suppressed => implications for LHC

Centrality dependence:





L large **L small**



Enhanced

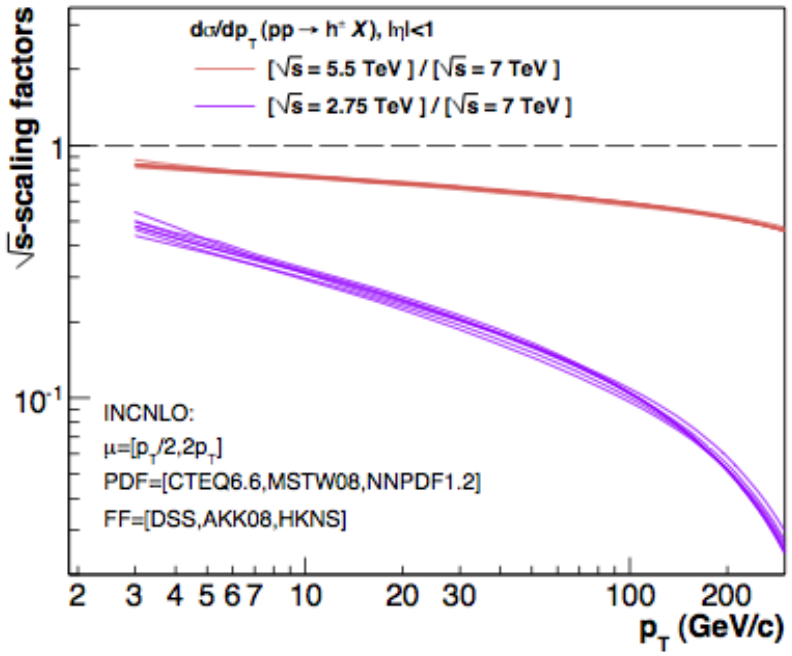
Suppressed

The pp baseline for R_{AA}

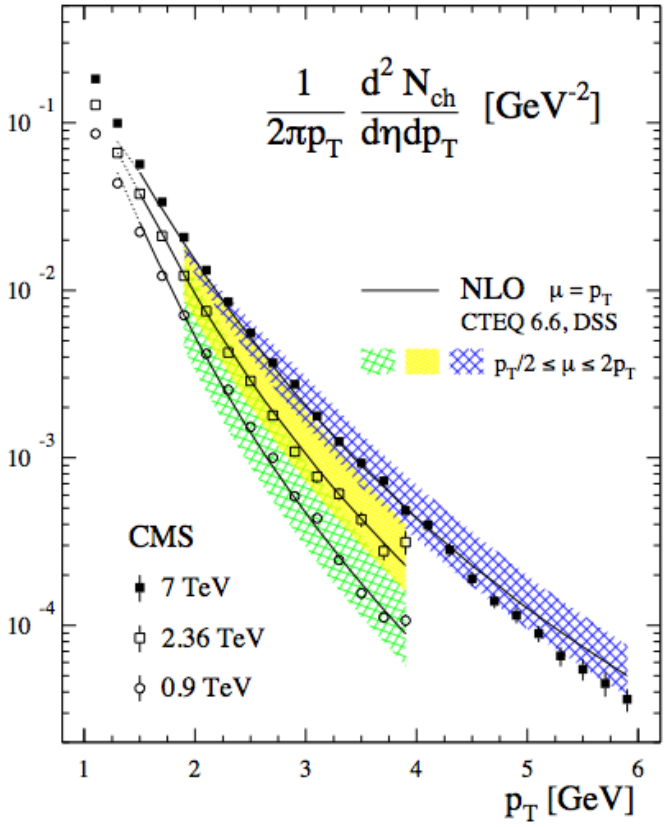
- Quantifying nuclear modification requires control of normalization
  - + pp-reference spectrum at same $\sqrt{s_{NN}}$
    - a) interpolating between .9 and 7 TeV pp (uncertainties at low p_T ?)
    - b) measuring pp @ 2.76 TeV
  - + testing Glauber theory (n_{coll})
  - + alternative tests: e.g. photon spectra

$$R_{AA}(p_T,\eta) = \frac{dN^{AA}/dp_T d\eta}{n_{coll}\, dN^{NN}/dp_T d\eta}$$

F. Arleo et al. , arxiv.org/1003.2963



R. Sassot et al. arxiv.org/1008.0540



The role of p-Pb

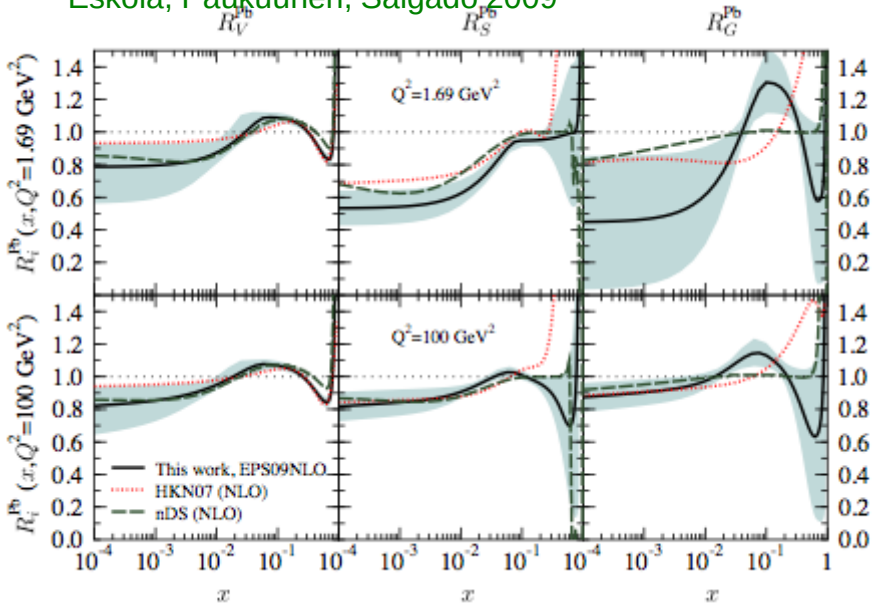
- Refined baseline for heavy ion programme
  Ex: theory of R_{AA} relies on factorization

$$nPDFs(A) \otimes HARD \otimes D_{frag}(A)$$

but collinear factorization of A-dependence is assumed, pA@LHC provides decisive tests

- current uncertainties in NLO nPDF-fits

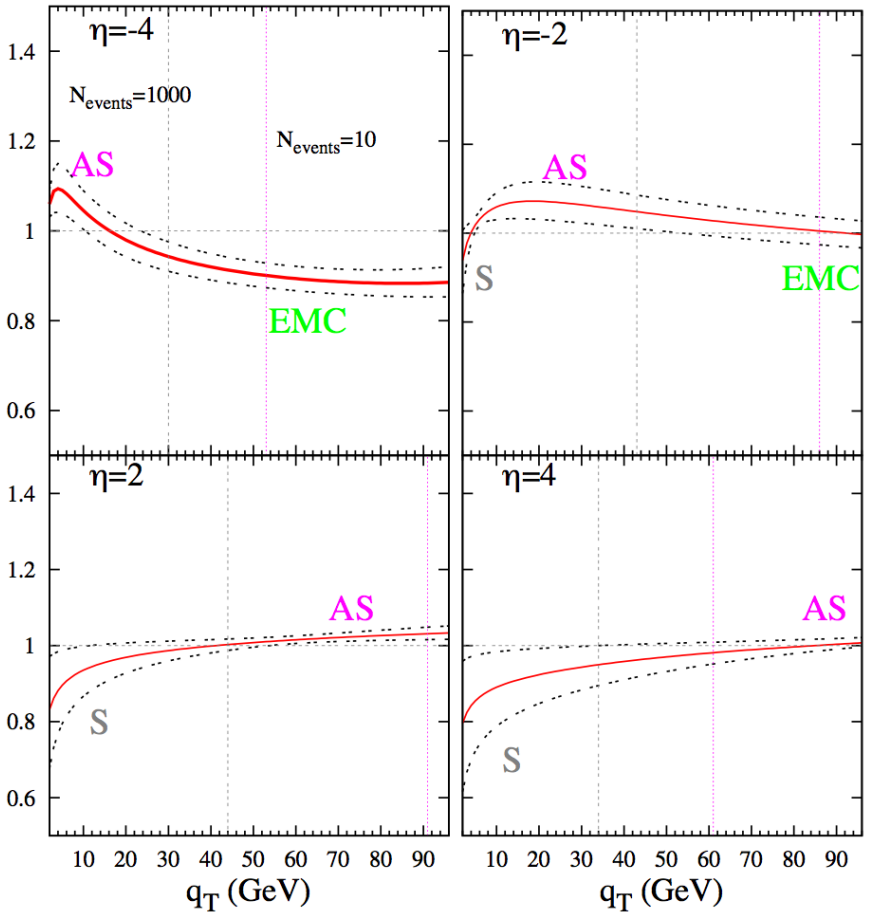
Eskola, Paukuunen, Salgado 2009



- a study of the physics potential of pA@LHC is currently in preparation (ed. Salgado), including a discussion of tests of saturation physics

- sensitivity of R_{pPb} on nPDFs

Quiroga et al, 2010

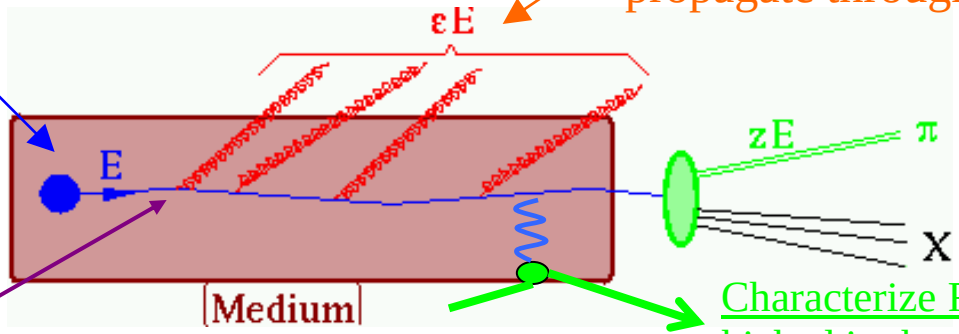


- strong arguments to initiate a feasibility study of all aspects of pA @ LHC

Going beyond single inclusive spectra

How does this parton thermalize?

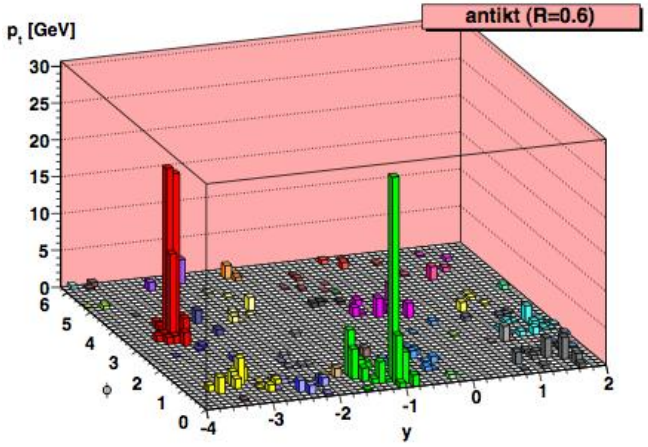
How does this radiation fragment/ propagate through the medium?

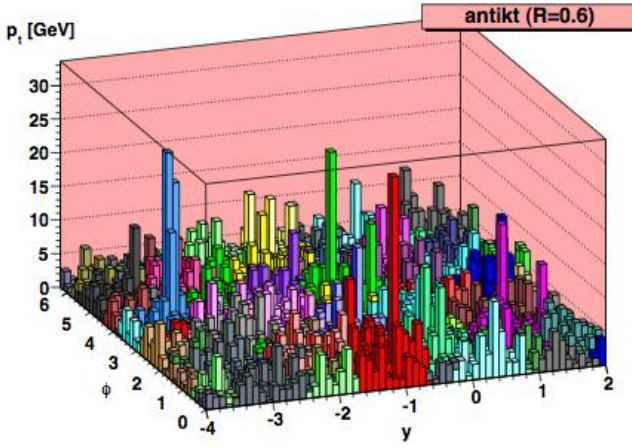


What is the dependence on parton identity?

Characterize Recoil: What is kicked in the medium?

- Requires jet reconstruction in high multiplicity environment



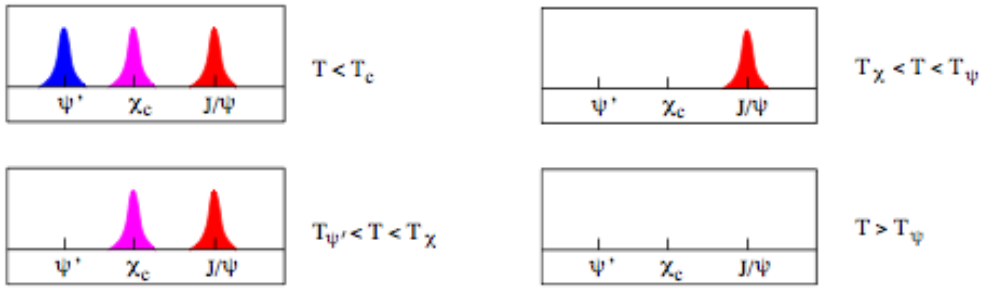


- Significant recent progress:
  - modern jet finding algorithms (FastJet)
  - MC models of medium-modified jets
  - prelim. analyses at RHIC (E_T < 40 GeV)

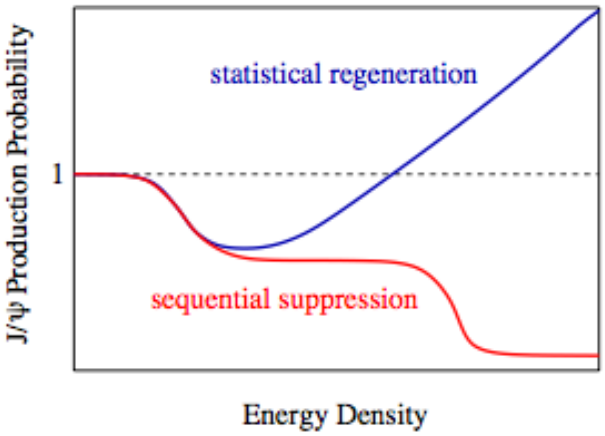
- Interplay between TH and EXP clearly needed:
  - strong motivation to aim for "several" 10^7 events in first LHC Pb+Pb run

Quarkonium in heavy ion collisions @ LHC

- schematic motivations for studying charmonium
  charmonium as a thermometer



- Dissociation vs regeneration



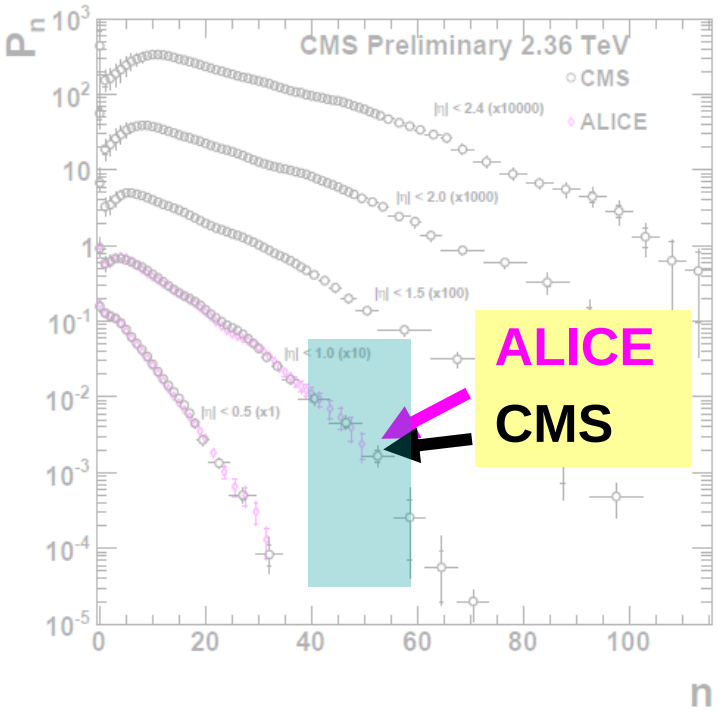
- With a few x 10^7 min. bias events, only marginal conclusions possible
  (but dramatic enhancements predicted by some regeneration models should be visible.)

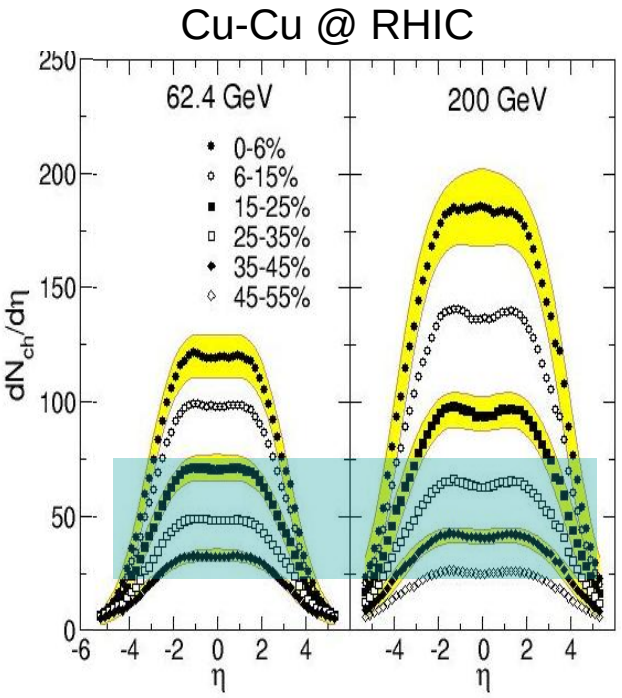
- Study of charmonium and bottomonium physics in heavy ion collisions requires maximal luminosity.

- Benchmarking needs may differ significantly from those for R_{AA} and jets
  (open charm measurements in A-A provide baseline on top of which regeneration effects could be quantified)

pp as mini-AA?

- Tails of multiplicity distributions in pp @ LHC comparable to charged multiplicities in semi-peripheral Cu-Cu collisions at RHIC (J. Schukraft, QM08 Jaipur).
- But energy densities are vastly different!!





- To what extent does event multiplicity determine collectivity?
  - hadrochemistry
  - flow (elliptic flow)
  - ...

Instead of a conclusion

$$\sqrt{s}\Big|_{LHC} > 10\ \sqrt{s}\Big|_{RHIC}$$

First Pb beam will help shape the LHC heavy ion programme.