RHIC physics Short overview

Anna Staśto
Penn State University, USA
and
Institute of Nuclear Physics, Poland

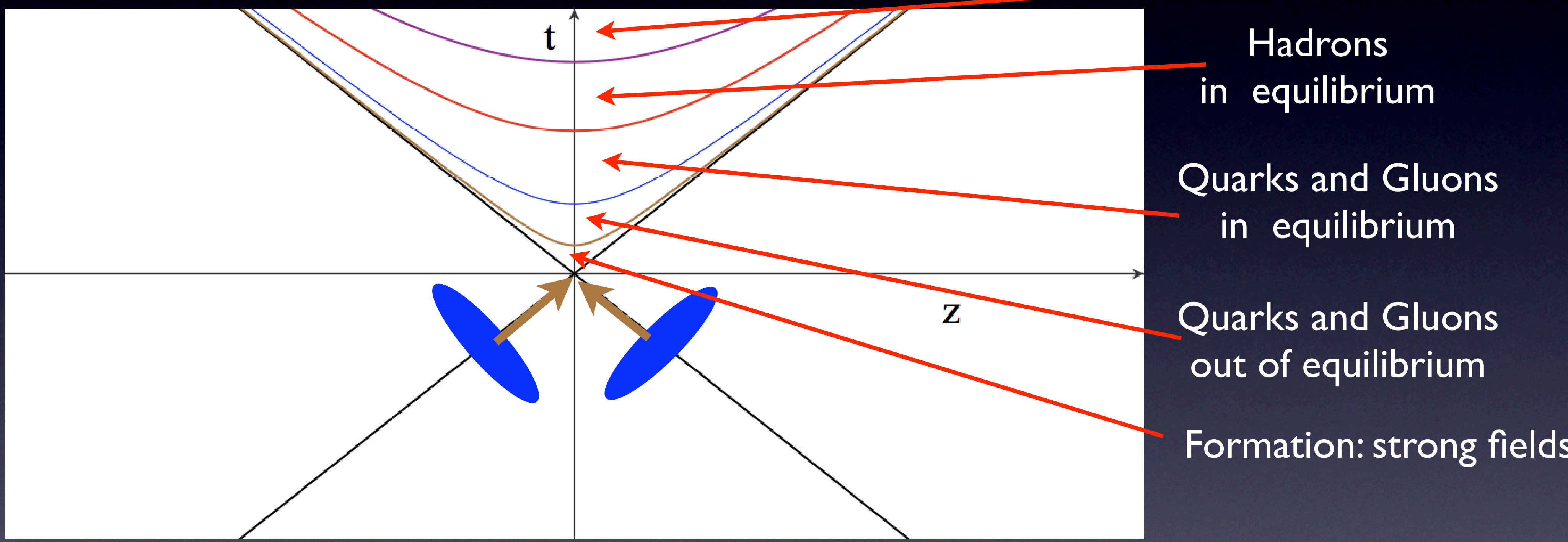
Forward Physics and QCD, 21 May 2007, Hamburg

Heavy Ion collisions

- High energy pp or ee collisions: search for new physics (SUSY or extra dimensions, ...)
- High energy AA collisions: create the high energy density over a larger region.
- Investigate a collective dynamics of the strong interactions.
- RHIC is a versatile, powerful machine
  - AA, (AuAu, CuCu), pp, dA
  - Different energies: 19.6, 62.4,130,200 GeV
  - Polarized beams

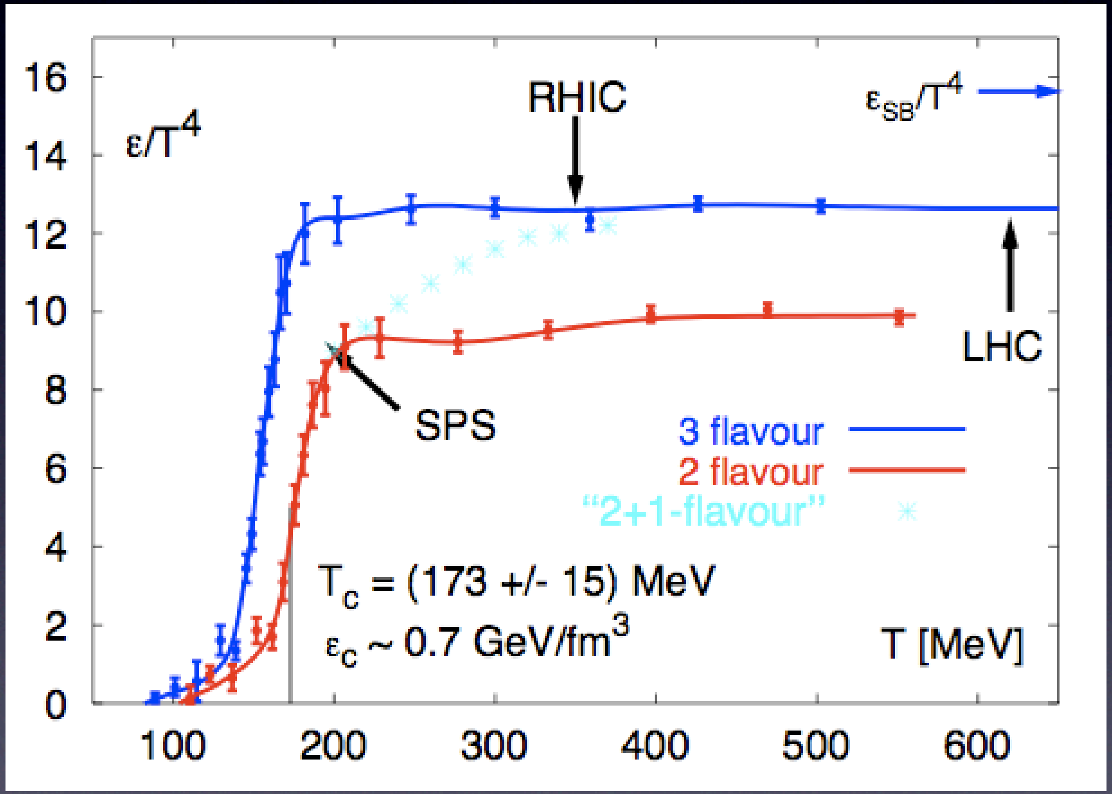
Space-time picture of heavy-ion collisions

z: beam axis



Lattice results for QCD at finite T

Energy density for 2 and 3 flavors



F. Karsch

Lattice calculations indicate phase transition at critical temperature T=173 MeV

Critical density

$$\epsilon_c \sim 0.7\,\mathrm{GeV/fm^3}$$

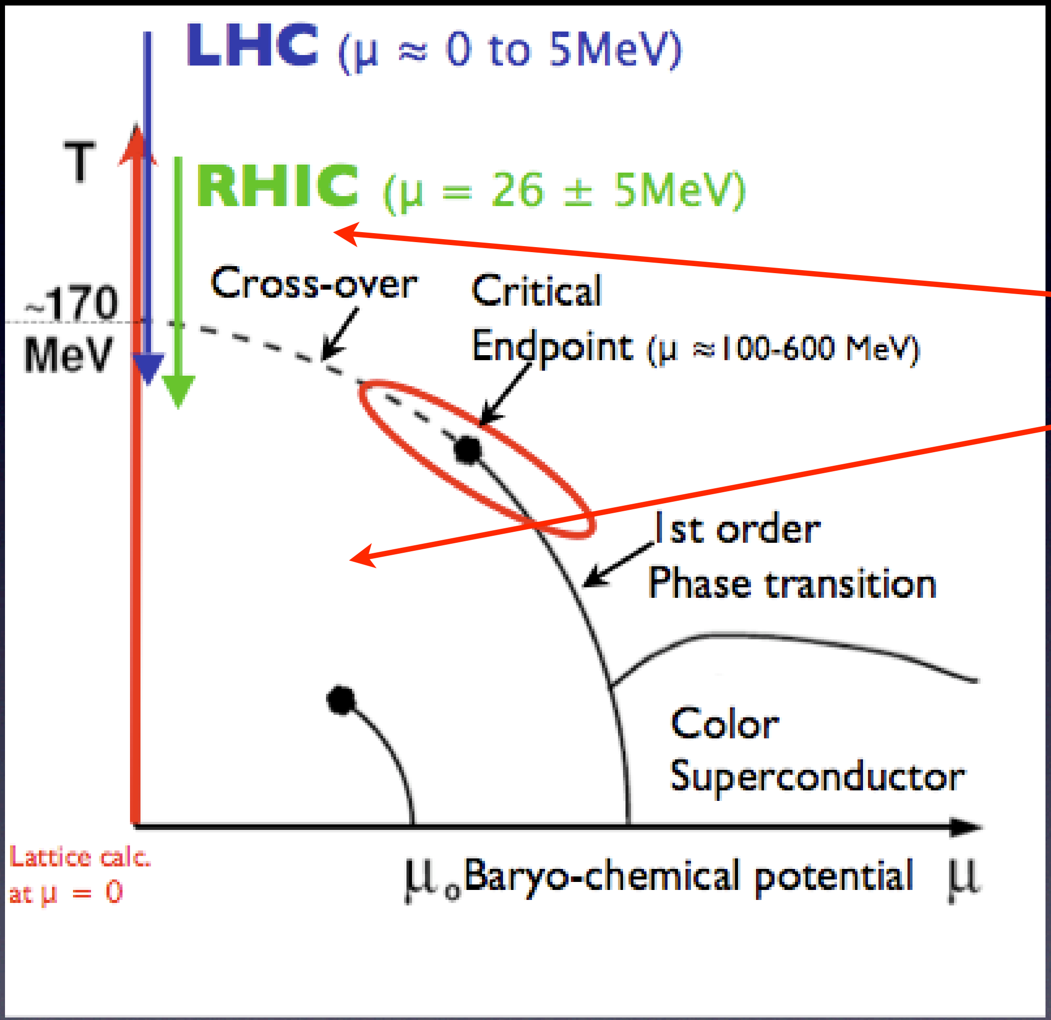
Energy density in RHIC

$$\langle\epsilon\rangle = \frac{1}{\tau\pi R^2}\frac{dE_T}{dy} \sim 5-10\,\mathrm{GeV/fm^3}$$

Much larger (>30x) than cold nuclear matter

$$\epsilon_{NM} \simeq 0.15\,\mathrm{GeV/fm^3}$$

Phase diagram

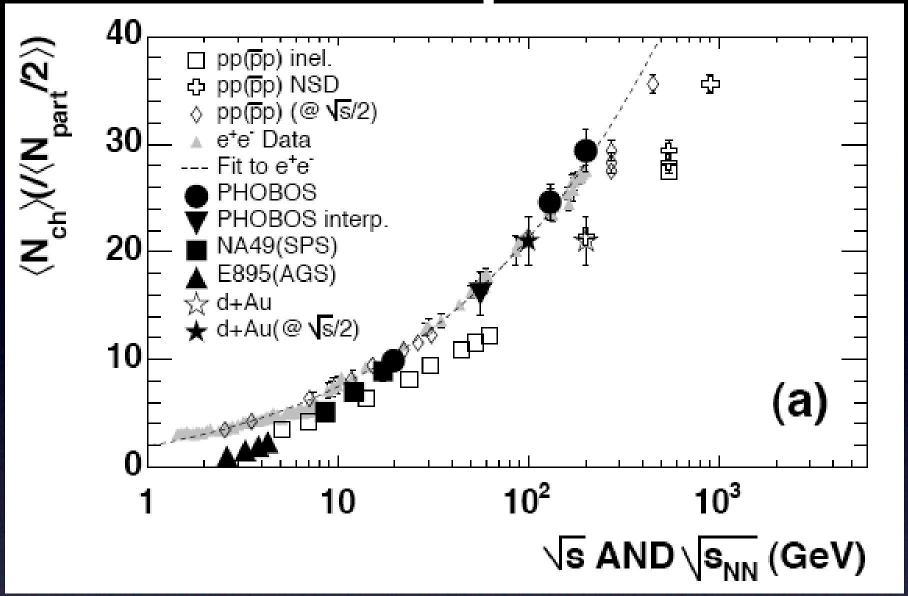


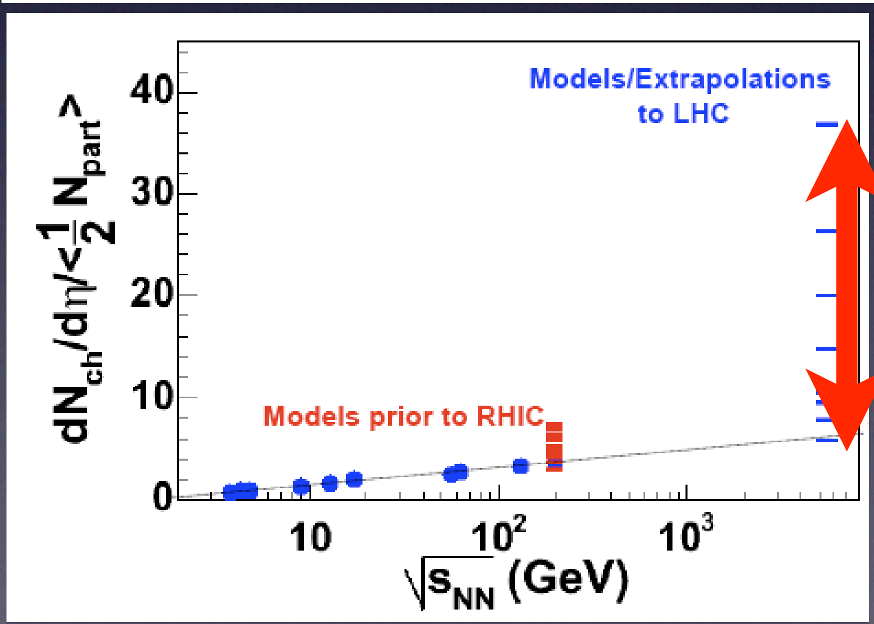
- Quark gluon plasma
- Hadron phase
- Deconfinement, chiral symmetry restoration
- Positions of the phase boundaries not known in detail
- Investigate experimentally

- Muliplicities
- Initial state
- Final state: Hard probes

Multiplicities

Multplicities in Heavy Ion collisions





Plot from G.Roland's talk 2006

Increase with energy

AuAu similar to e+e-

Multiplicities depend only on energy of the system (and N(part))

pp lower: leading particle effect

Multiplicity at mid-rapidity

⟶ energy density

Consistent with *ln s* dependence

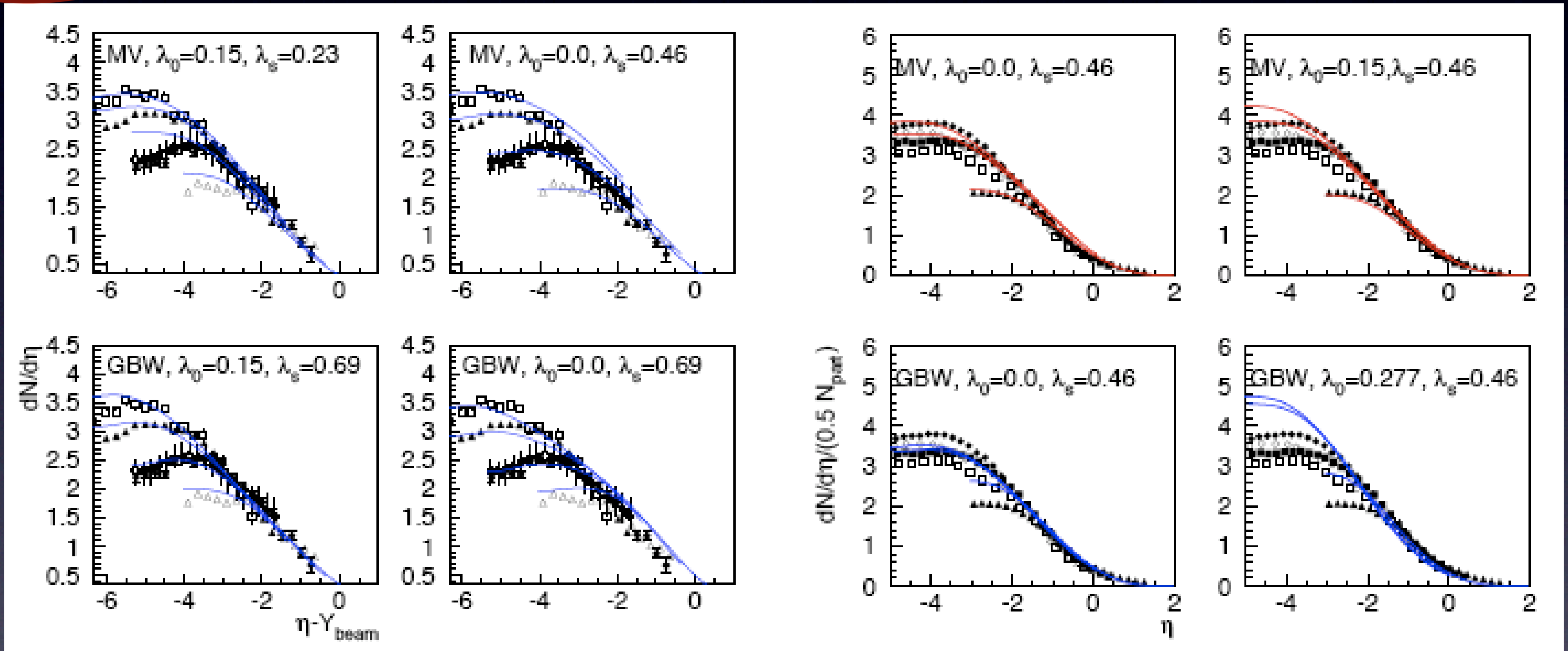
Huge uncertainties of theoretical predictions for LHC!

Rapidity distributions limiting fragmentation

Similar pattern observed in multiplicities e+e- when plotted vs y-Y(jet)

proton-proton

Au-Au



curves from Gelis, Stasto, Venugopalan

Data scale when plotted vs $\eta' = \eta - Y_{\rm beam}$

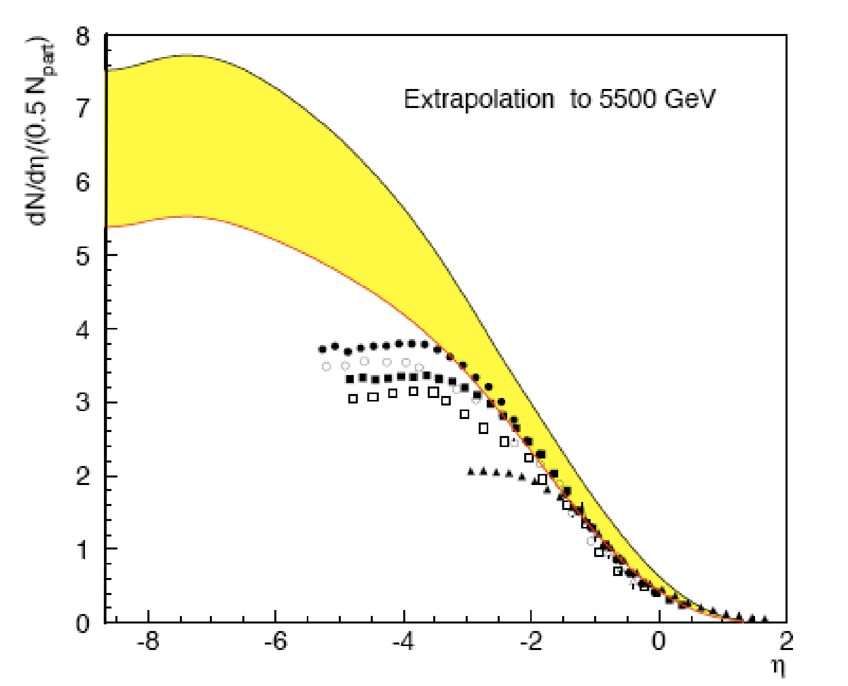
Limiting distribution is that of the broken target: momentum and quantum number transfer between the projectile and the target does not change when the energy is further increased.

Limiting fragmentation

- Gluon production evaluated using Kt factorized formula.
- Parton density from nonlinear evolution equation.
- Limiting fragmentation: target density (large x) approximately flat in rapidity and independent of scale (Bjorken scaling).
- Rapidity distributions seem to be determined very early in the collisions, by the initial state.

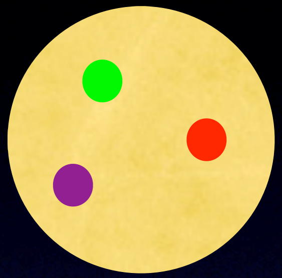
Extrapolations to LHC: approximately factor 1.5-1.9 increase of dN/dy at y=0

Gelis, Stasto, Venugopalan



Initial state

Initial state: saturation of gluon density



Low energy - large x
Dilute system

High energy - small x
Dense system

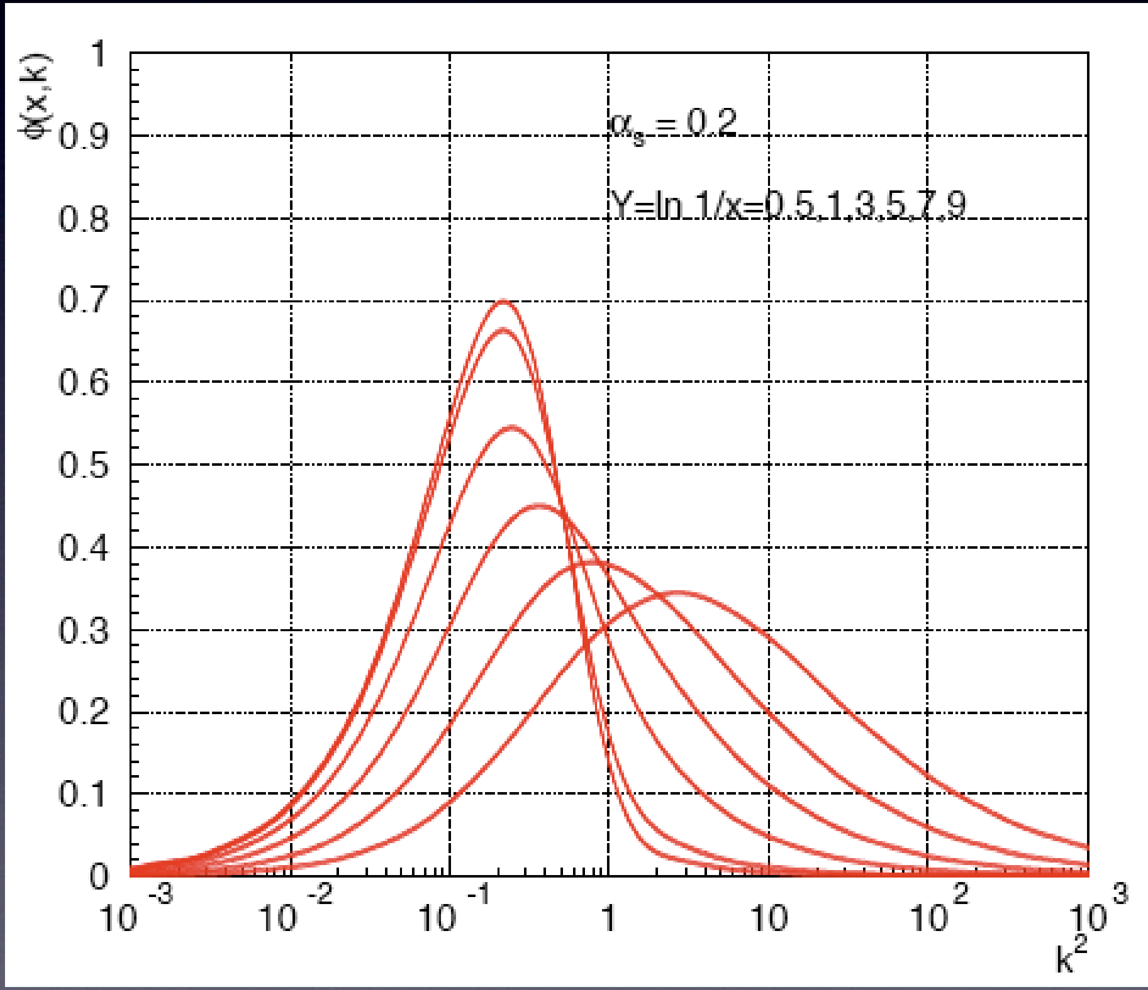
$$\frac{\alpha_s(Q_s^2)}{Q_s^2} xg(x, Q_s^2) \sim 1$$

- Small coupling, but high density
- Saturation of gluon density
- Saturation scale Qs
- Nonlinear evolution equation

Gribov, Levin, Ryskin; Bartels, Wusthoff; Mueller, Qiu; McLerran, Venugopalan, Kovner, Weigert, Jalilian-Marian, Leonidov; Kovchegov, Balitsky; Lipatov; ...

Transverse momentum distribution of partons

Gluon density from nonlinear equation:



Gelis, Stasto, Venugopalan

- Typical transverse momentum of the gluon from nonlinear equation
- Peak shifts to higher momenta as energy increases
- Saturation scales increases with energy
- Nonlinearity provides with a natural cutoff at lower scales

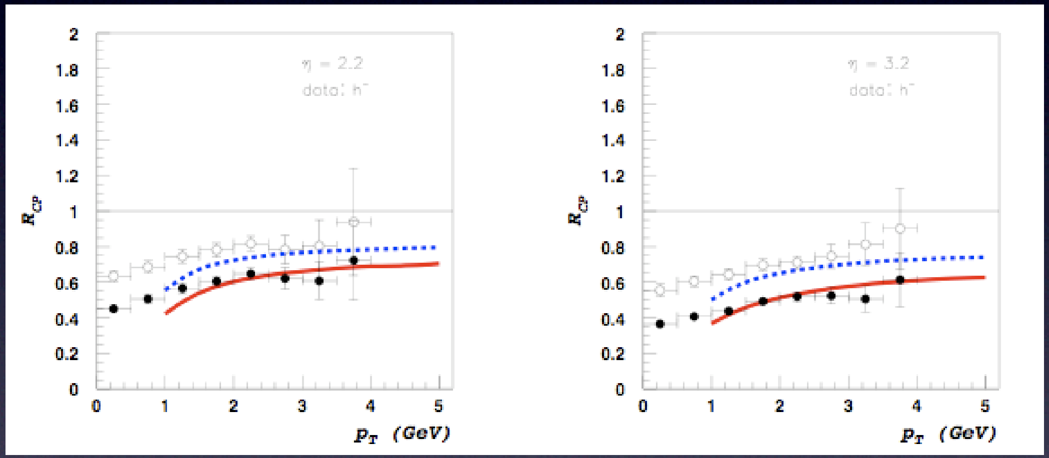
Saturation

- Very attractive approach :
  - Natural cutoff at infrared.
  - Small coupling but non-perturbative (even though from Feynman diagrams).
- Does it work?
  - RHIC lower energy than HERA, not always small x, need to go to forward rapidities. But, presence of nucleus helps: $Q_s^2 \sim A^{1/3} x^{-\lambda}$
  - Saturation scale rather small, <1 GeV at HERA.
  - Only gluons are consistently taken into account in this framework.

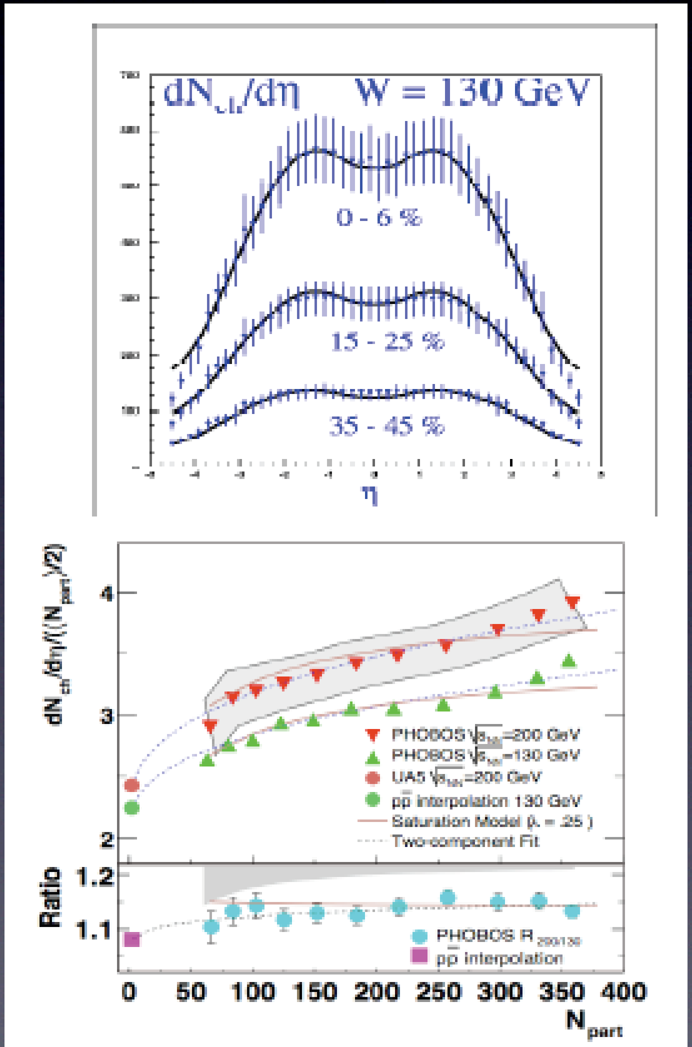
Saturation: phenomenology at RHIC

Rapidity distributions

$\eta = 2.2$ $\eta = 3.2$



Kharzeev, Kovchegov, Tuchin



dAu : suppression of the transverse momentum distribution at forward rapidities

Very good agreement with the data!

Kharzeev, Levin, Nardi

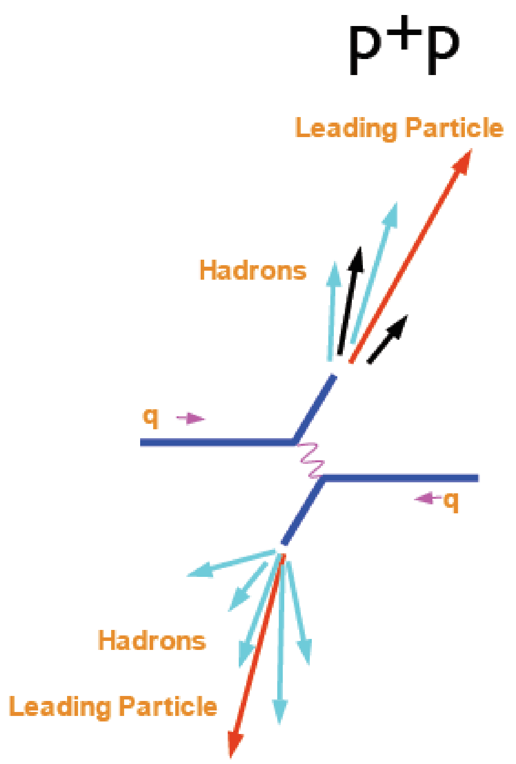
Final state:
Hard probes

Hard probes

- High Pt light quarks/gluons
- Heavy quarks
- Provide an excellent measure of the properties of a dense medium
- Due to a presence of a hard scale, it is possible to use perturbative theory
- Compare with the pp cross sections

Transport properties of the medium

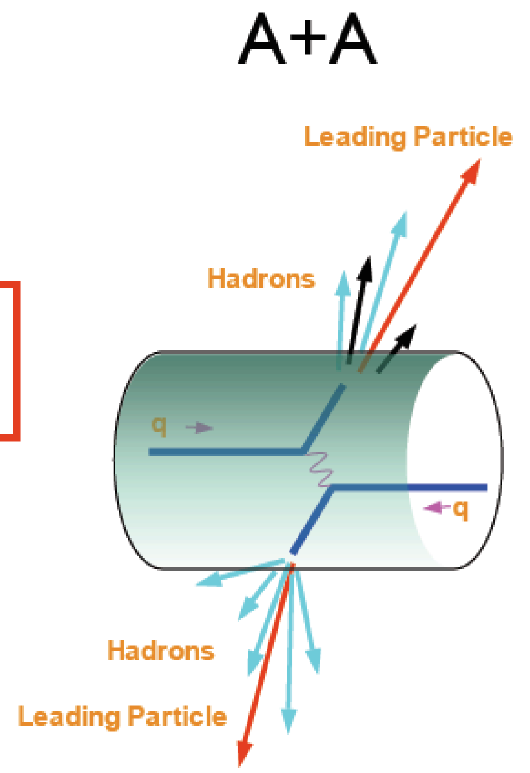
By comparing momentum distributions to the pp benchmark we obtain information about the medium created at heavy-ion collisions



Jet-like high pT hadron production

$$R_{AA} = \frac{\sigma_{pp}^{inel}}{\langle N_{coll} \rangle} \frac{d^2 N_{AA}/dp_T d\eta}{d^2 \sigma_{pp}/dp_T d\eta}$$

Ratio of AA/pp scaled by
# of binary NN collisions



Partons propagate through medium
before fragmentation

Plot from G. Roland ‘ Physics at LHC ’ 2006

General framework

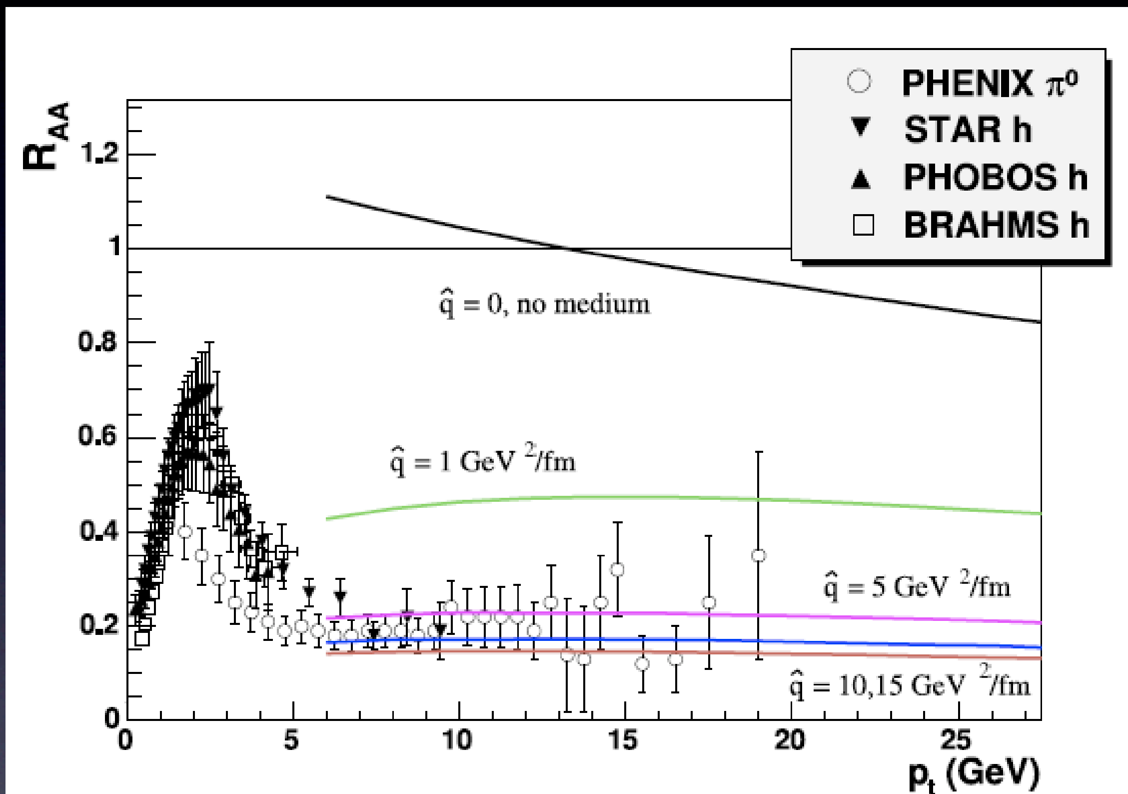
- Use collinear factorization formula
- Assume that the hadronization takes place outside the medium (time formation)
- Supplement it with the additional parton energy loss function: quenching weight P
- Transport coefficient: average transverse momentum transfer in the gluon scattering in medium

$$\sigma_{\rm med}^{AB\rightarrow h} = \sigma_{\rm vac}^{AB\rightarrow f} \otimes P(\Delta E, L, \hat{q}) \otimes D_{\rm vac}^{f\rightarrow h}(z, \mu_F^2)$$

$$\sigma_{\rm vac}^{AB\rightarrow h} = f_A(x_1, Q^2) \otimes f_B(x_2, Q^2) \otimes \hat{\sigma}(x_1, x_2, Q^2)$$

Transport coefficient: $\hat{q} \simeq 4 - 14 \ {\rm GeV/fm^2}$

Nuclear modification for hadrons



Eskola, Honkanen, Salgado, Wiedemann

- Quenching weight P: probability for parton to loose medium-induced energy as it propagates through the medium of length L
- Data favor large transport coefficient
- Flat spectrum for R_{AA} at high p_T
- The medium is so dense that the *shell* emission dominates
- Expect that the suppression will persist at LHC even for highest momenta (100 GeV)

Heavy flavors

Factorization theorem for production of heavy quarks in hadron-hadron collisions *(Collins, Soper, Sterman)*

$$\sigma_{AB\to QX}(s, m_Q^2) \;=\; \sum_{i,j} \int dx_1 dx_2\, \hat{\sigma}_{ij\to QX}\, f_{i/A}(x_1,\mu_F)\, f_{j/B}(x_2,\mu_F) + \mathcal{O}\left(\frac{\Lambda}{m_Q}\right)^p$$

Partonic cross section

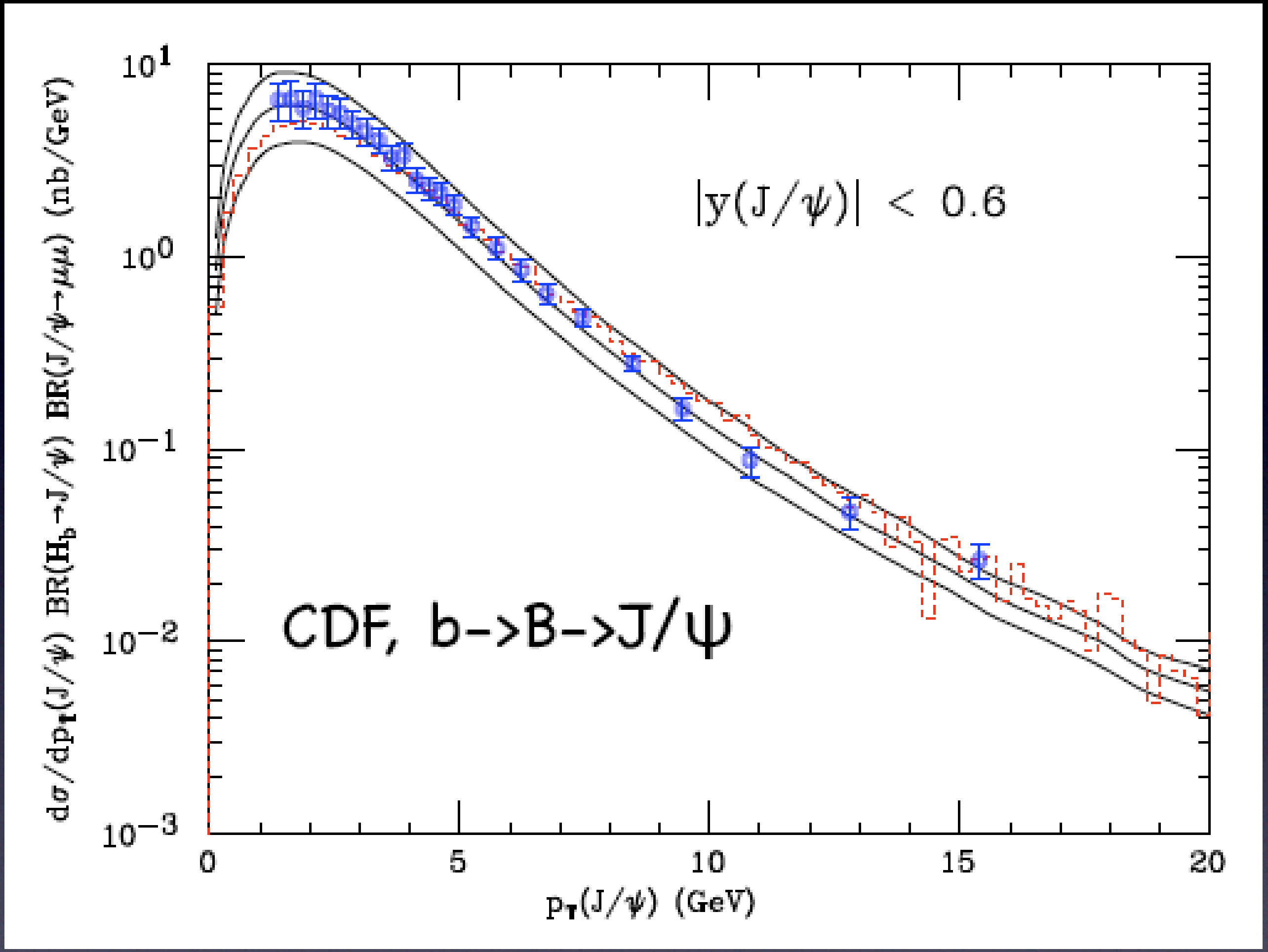
$$\hat{\sigma}_{ij\to QX}(x_1 x_2 s, m_Q^2; \alpha_s(\mu_R^2); \mu_F^2, \mu_R^2)$$

Parton distribution functions

Power suppressed corrections

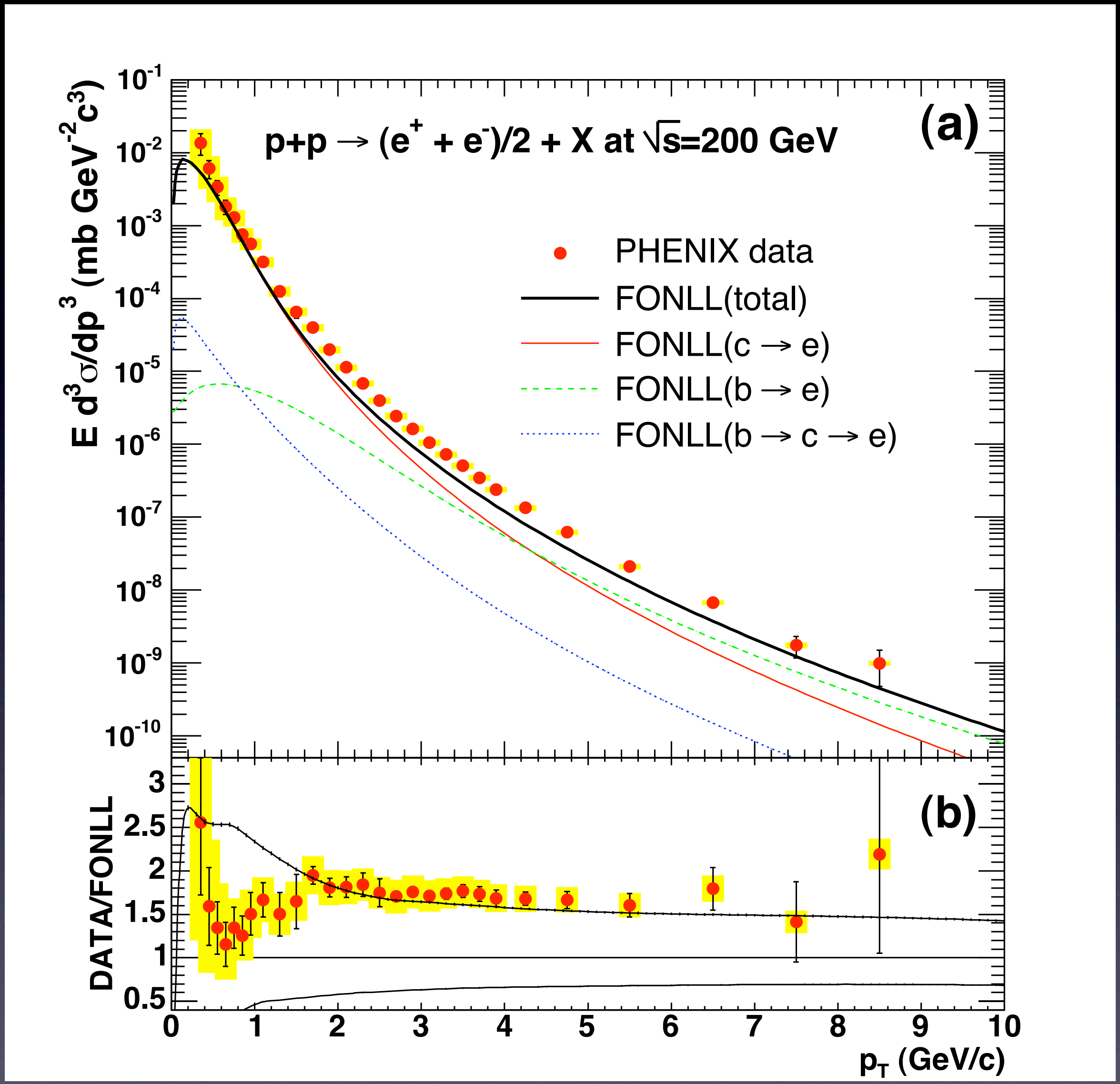
For this process factorization is a conjecture: not proven.

Heavy quark production in pp collisions



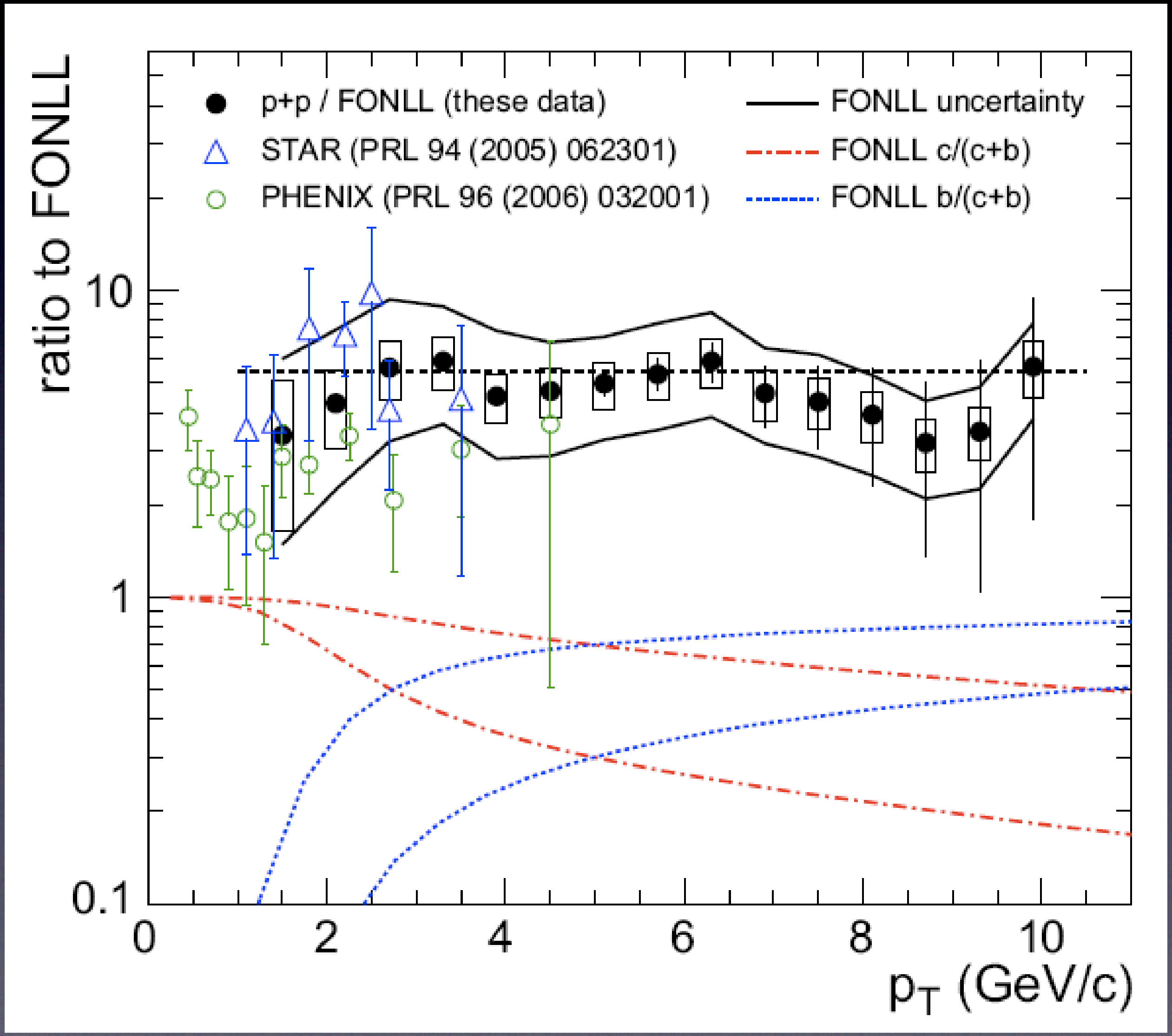
Bottom production at Tevatron: Run II
Very good agreement (after *proper* extraction of the fragmentation function from LEP data) *M.Cacciari*

Heavy flavor production in pp collisions at RHIC



- PHENIX pp data
- Electrons from semi-leptonic decays of heavy flavors
- Charm+Beauty
- FONLL pQCD *M.Cacciari*
- $|y|<0.35$
- $0.3<p_T< 9.0$ GeV
- DATA/THEORY=1.72
- Shape of distribution correct (except at low momenta)

Heavy flavor production in pp collisions at RHIC



- STAR pp data, electron
- $1.2<p_T<10$ GeV
- DATA/THEORY=5.5
- Excess more significant than for PHENIX
- FONLL curves with scale uncertainty
- B decay significant fraction at high p_T

Heavy flavor production in pp collisions not well understood at lower energies

Radiation off heavy quarks

- Radiation from heavy quarks differs from light quarks: *dead cone effect*
- Gluon radiation suppressed at angles smaller than the ratio $\theta_0 = \frac{m_Q}{E}$

$$dP_{m_q=0} \simeq \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{dk_T^2}{k_T^2}$$

Massless quarks

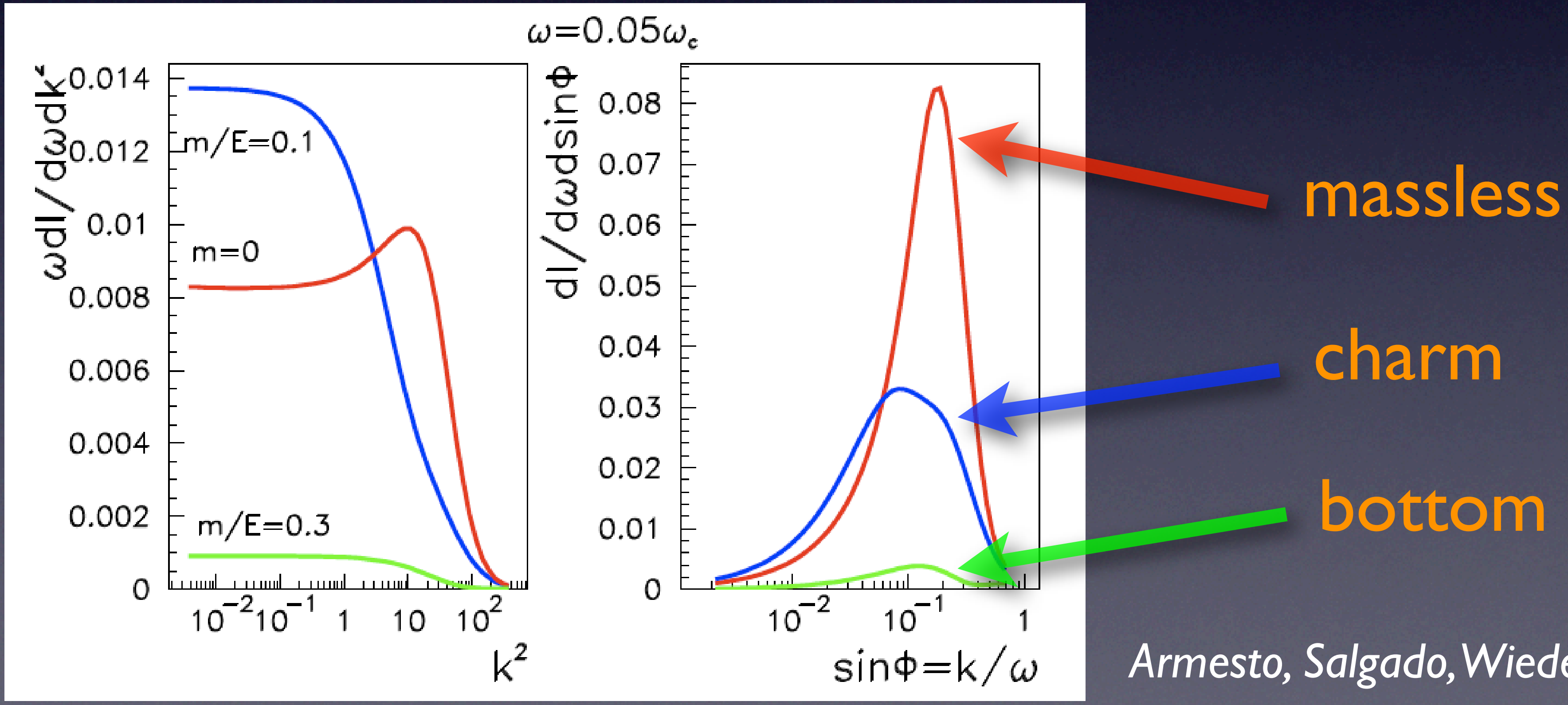
$$dP_{m_q \neq 0} \simeq \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_T^2 dk_T^2}{[k_T^2 + \omega^2 \theta_0^2]^2}$$

Massive quarks

- One expects less suppression than for light quarks

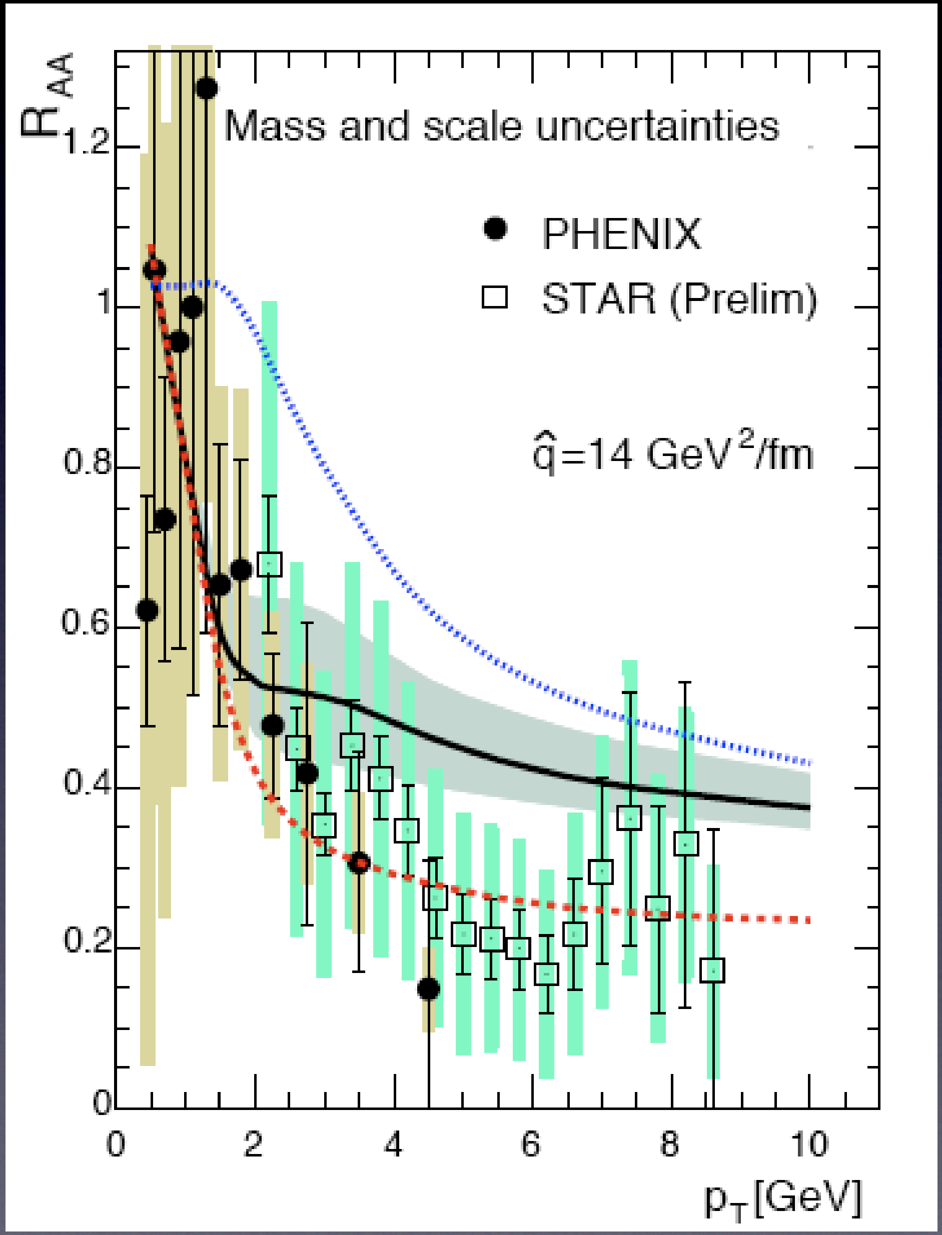
Heavy quarks in medium

- Situation in medium more complicated: suppression at large angles, (moderate) enhancement at small angles
- Another effect: shorter formation time in case of heavy quarks
- Net effect: smaller energy loss than light quarks



Armesto, Salgado, Wiedemann

Heavy quarks in medium



Armesto, Cacciari, Dainese, Salgado, Wiedemann

$$R^e_{AA}(p_T) = \frac{\frac{d^2N^{AA\to e}}{dp_T dy|_{y=0}}}{\langle N^{AA}_{\rm coll}\rangle \frac{d^2N^{pp\to e}}{dp_T dy|_{y=0}}}$$

- Large suppression observed in electron spectra in AA collisions
- Calculations do not quite predict that strong suppression
- b/c ratio not known. Large sensitivity of calculations to that ratio.
- Sensitivity to transport coefficient $\hat{q}$
- pp cross section not well under control

Heavy quarks in medium

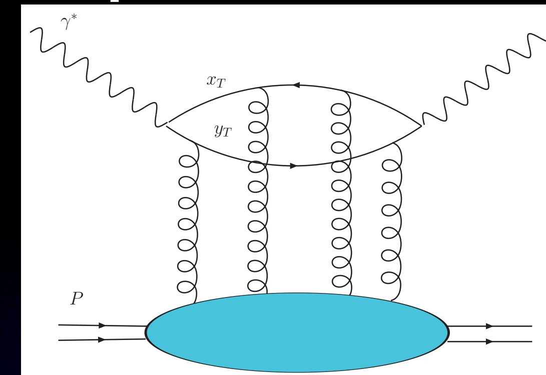
Other effects:

- Collisional energy loss of the heavy quark? Not sufficient to explain the large suppression.(*Djordjevic, Gyulassy*)
- Fragmentation does not occur outside? Final state interactions of D mesons? (*Strikman*)
- Is the use of (generalized) factorization justified in AA? Breakdown of the factorization formula for hadroproduction (two transverse momenta, kt dependent distributions) in proton-proton. (*Collins, Qiu*)

$$E_3 E_4 \frac{d\sigma^{AB\to h_3 h_4}}{d^2 p_{3T} d^2 p_{4T}} = \sum_{ijkl} f_{A/i} \otimes f_{B/j} \otimes \hat{\sigma}_{ij\to kl} \otimes D_{k\to h_3} \otimes D_{l\to h_4}$$

Jet quenching:
Wilson loops in AdS/CFT

Jet quenching and Wilson loops



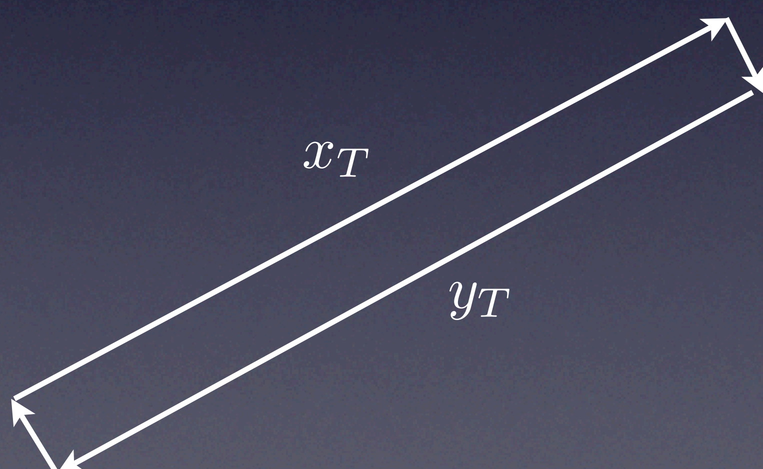
Recall DIS on cold nucleus

$$\sigma^{DIS} = \int d^2x_T d^2y_T\, dz\, |\psi(x_T, y_T; z)|^2 P^{q\bar{q}}(x_T, y_T)$$

Dipole cross section

$$P^{q\bar{q}} = 2\langle 1 - \frac{1}{N_c}\mathrm{Tr}[W^F(x_T)W^{F\dagger}(y_T)]\rangle = 2(1 - \langle W(C_{light-like})\rangle)$$

Correlator of two Wilson lines averaged over the field configurations of the target nucleus



$$\langle W(C_{light-like})\rangle \simeq \exp(-r^2 Q_s^2)$$

Dipole size

$$r = |x_T - y_T|$$

Wilson loops in AdS/CFT

Quark-gluon plasma

$$\langle W^F(C)\rangle_{\text{plasma}} = \exp(-\hat{q}r^2L^-)$$

$\hat{q}$ energy loss of a hard parton when traversing QGP

L^- light-cone distance (longitudinal distance)

In AdS/CFT

$$\langle W^F(C)\rangle = \exp(i\mathcal{S}(\mathcal{C}) - i\mathcal{S}_0)$$

where S is the Nambu-Goto action

$$\mathcal{S} = -\frac{1}{2\pi\alpha'}\int d\sigma d\tau \sqrt{-\det[G_{\mu\nu}\partial_\alpha X^\mu \partial_\beta X^\nu]}$$

with the metric on the 4+1 dimensional AdS space

Wilson loops in thermal background

In the nonzero temperature T:

The metric is given by the AdS Schwarzschild black hole

Taking the limit:

$$N_c, \lambda = R^4/\alpha'^2 \to \infty$$

Problem becomes classical: finding the extremum of the action

Can evaluate the jet quenching parameter:

$$\hat{q}_{SYM} \simeq 5\mathrm{GeV}^2/\mathrm{fm}$$

Liu, Rajagopal, Wiedemann

Summary I

- Total multiplicities grow as $\ln^2 s$.
- Multiplicities in ee the same as in AA per participating pair.
- pp are systematically lower due to effect of leading particle.
- Limiting fragmentation visible for various systems and centralities.
- This universality of rapidity distributions suggest that they are determined very early in the collisions, essentially by the initial state.
- At high energies and for heavy nuclei, one expects the saturation of the gluon density.
- But RHIC does not quite reach quite very values of Bjorken x; need to consider forward rapidity. Saturation effects enhanced by the mass number A.
- Saturation applied to the initial state provides with the reasonable description of the data: rapidity distributions, dA pt distributions.

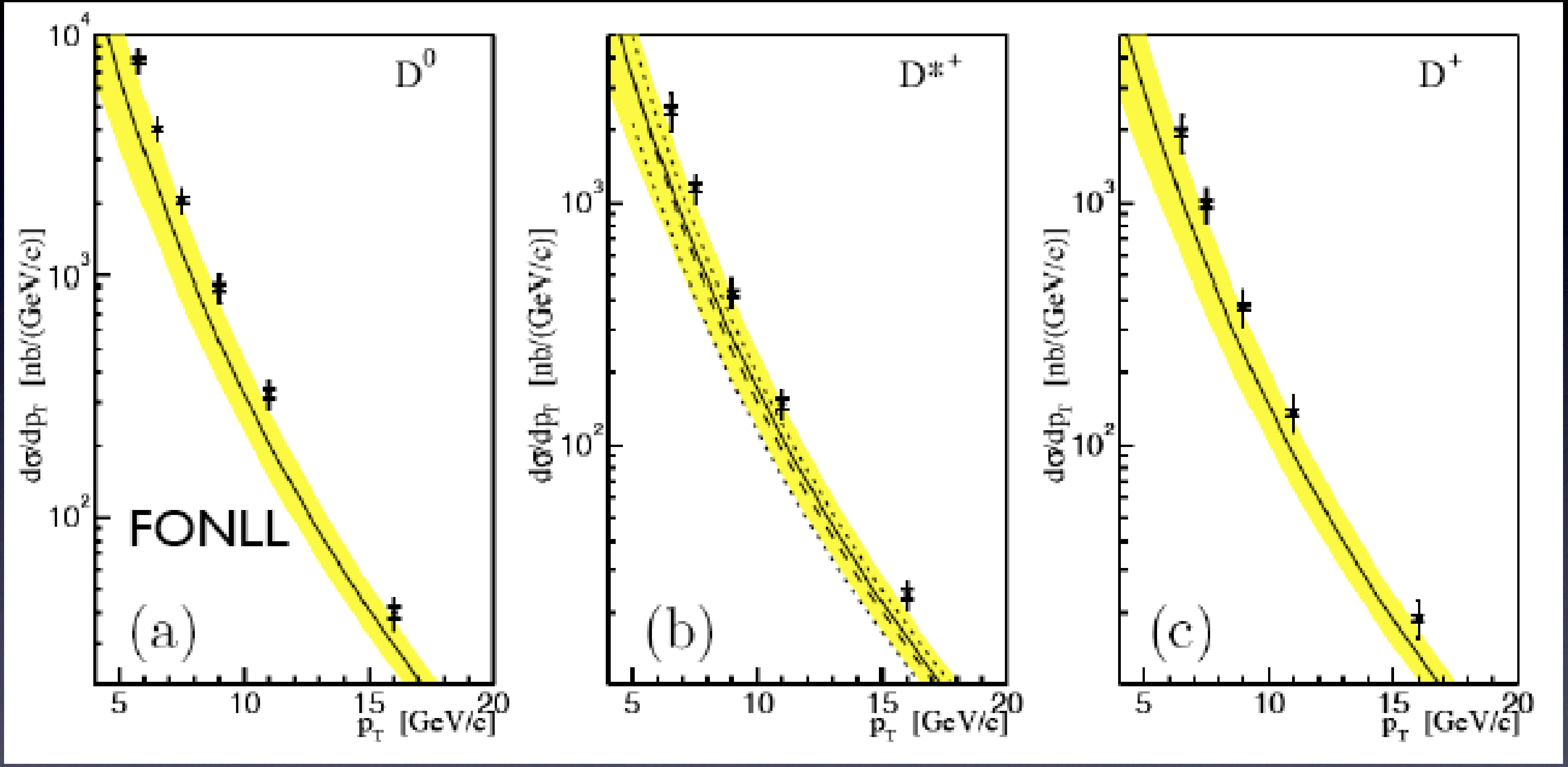
Summary II

- Heavy quarks and pt jets are excellent hard probes of the medium produced.
- Significant attenuation observed, up to transverse momenta of about 10 GeV.
- Theoretical calculations based on a generalized factorization framework with the rescattering effects for the fast particle (pt jet/ heavy quark) in medium.
- The spectrum of heavy quarks not quite well reproduced by the theory. In pp deficit of the overall cross section. In AA the predicted attenuation is too small.
- Possible effects: collisional energy loss, fragmentation inside medium, factorization formula too simplistic.
- Interesting approach to jet quenching using AdS/CFT. Many uncertainties (N=4 SYM vs QCD).

Backup slides

Charm production in pp collisions

CDF Run II: c to D data



Good agreement. Theory systematically little bit lower.