Theoretical Overview Quark Matter 2004

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The Main Goal:

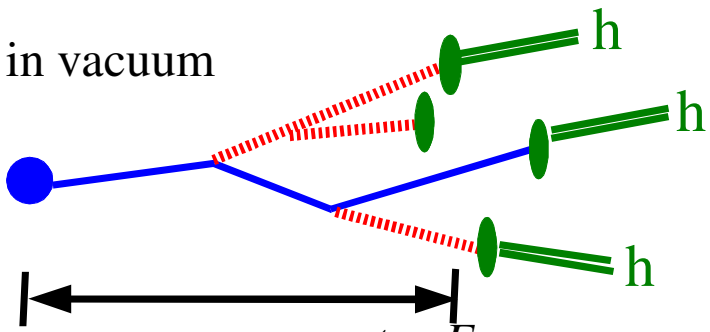
to produce the Quark Gluon Plasma
and to study its properties

The underlying Questions:

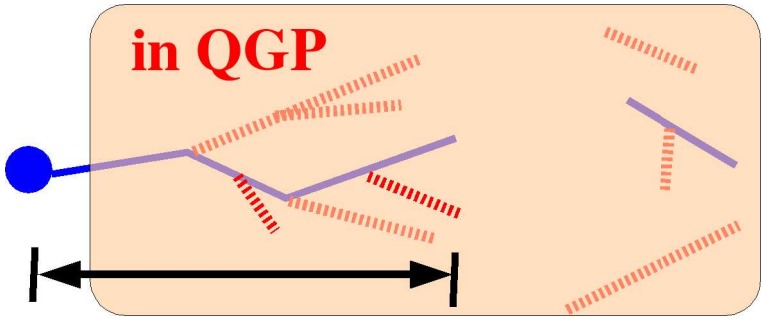
- What determines the initial energy density created in nucleus-nucleus collisions ?
- What is the nature of equilibration processes and what is their time scale ?
- What is the dynamics of hadronization and how does it depend on system size ?

Focus of this talk

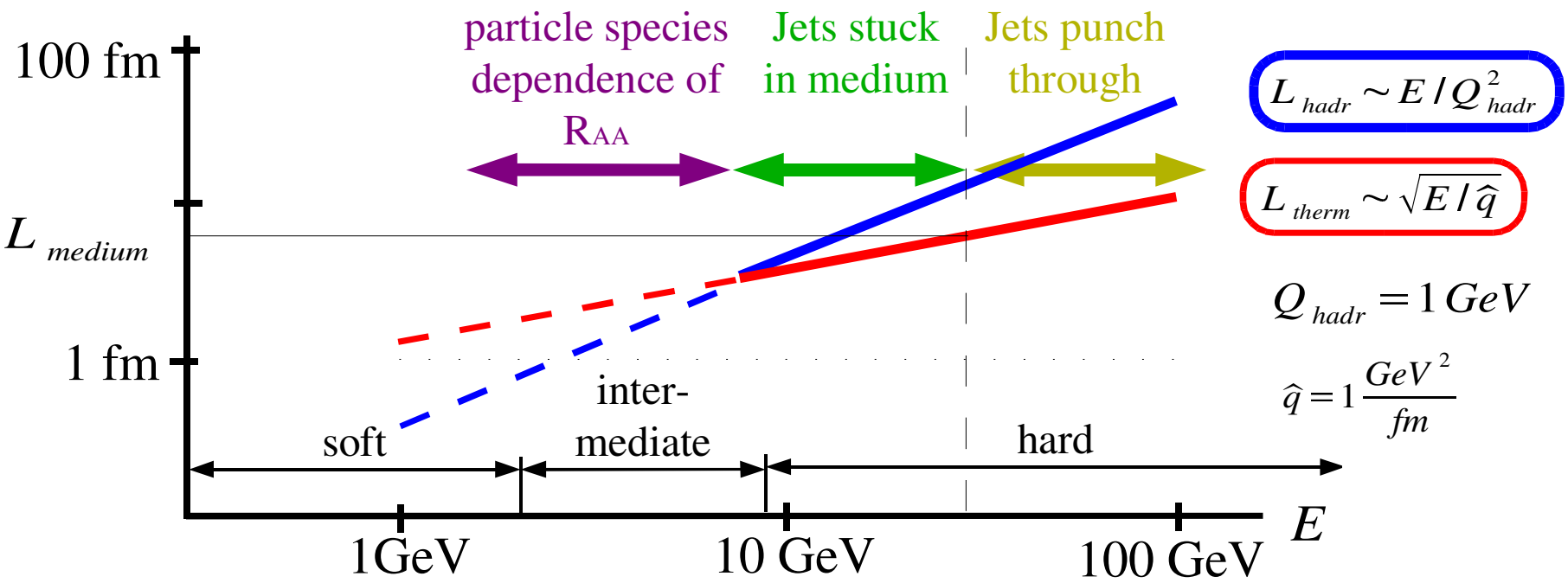
Hadronization versus Thermalization of Jets



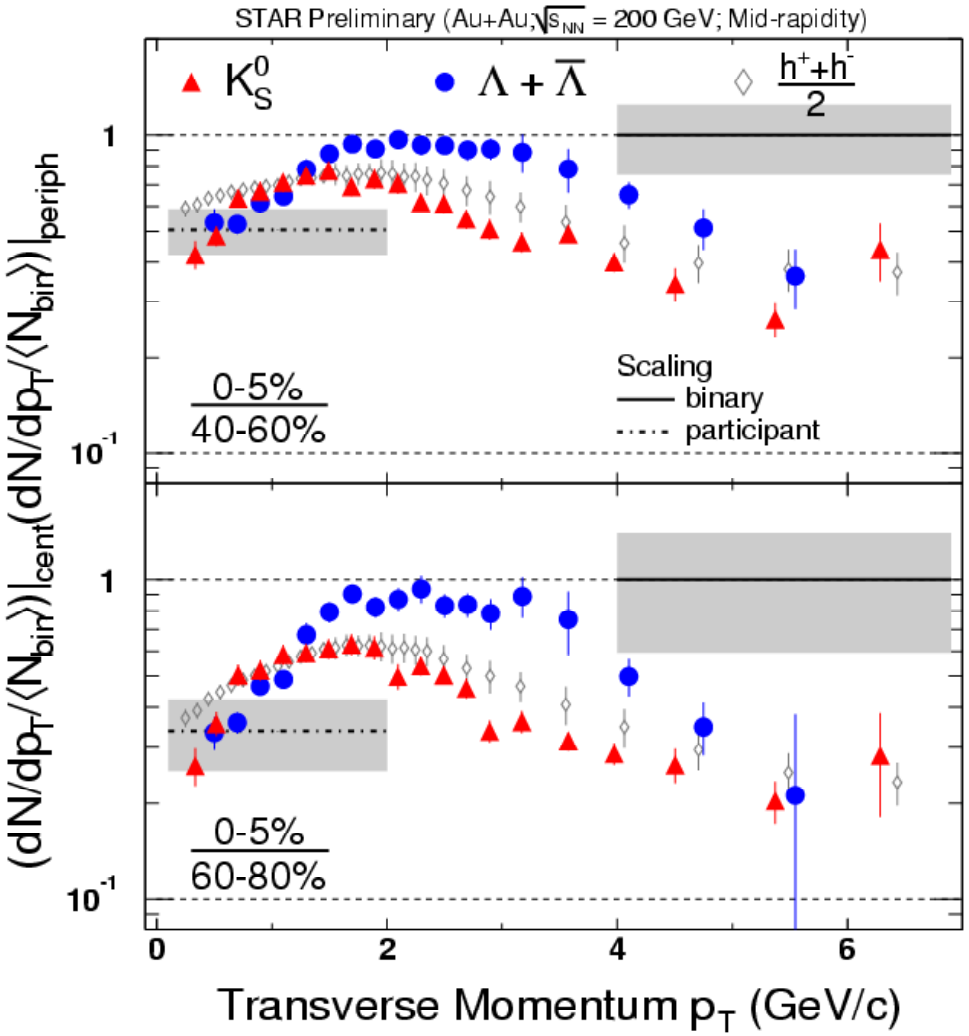
$$L_{hadr} \sim \frac{const}{Q_{hadr}} \frac{E}{Q_{hadr}}$$



$$E \approx \Delta E = \frac{\alpha_s C_R}{4} \hat{q} L^2_{therm}$$



Setting the Transverse Momentum Scales



- <u>High p_T</u> $L_{hadr} > L_{therm}$

  $p_T^{hadr} > 6-7\,GeV \Rightarrow p_T^{parton} > 8-10\,GeV$

  <u>jet tomography</u>

  <u>parton thermalization</u>

- <u>Intermediate p_T</u> $L_{hadr} \sim L_{therm} \sim L_{med}$

  $3\,GeV < p_T^{hadr} < 6-7\,GeV$

  <u>dynamics of hadronization</u>

- <u>Soft p_T</u>

  $p_T^{hadr} < 2-3\,GeV$

  <u>bulk dynamics</u>

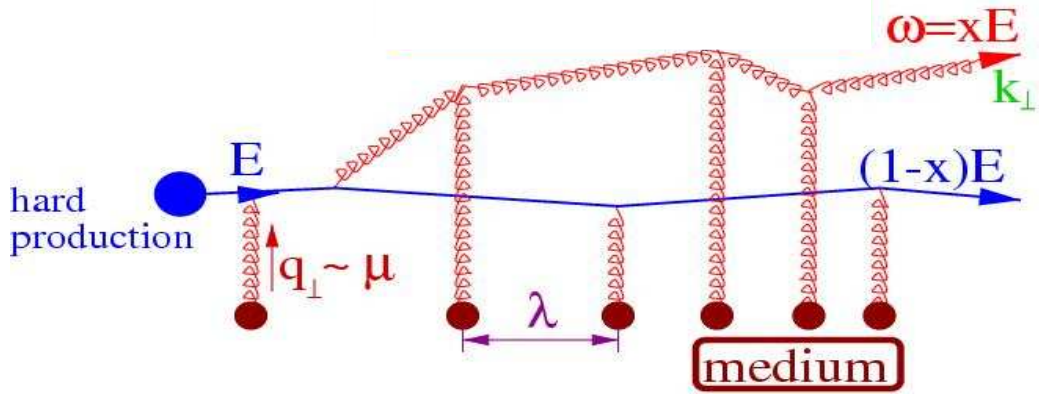
High pt

Testing the medium with high pt probes

Testing the onset of parton equilibration via 'jet heating'

The medium-modified Final State Parton Shower

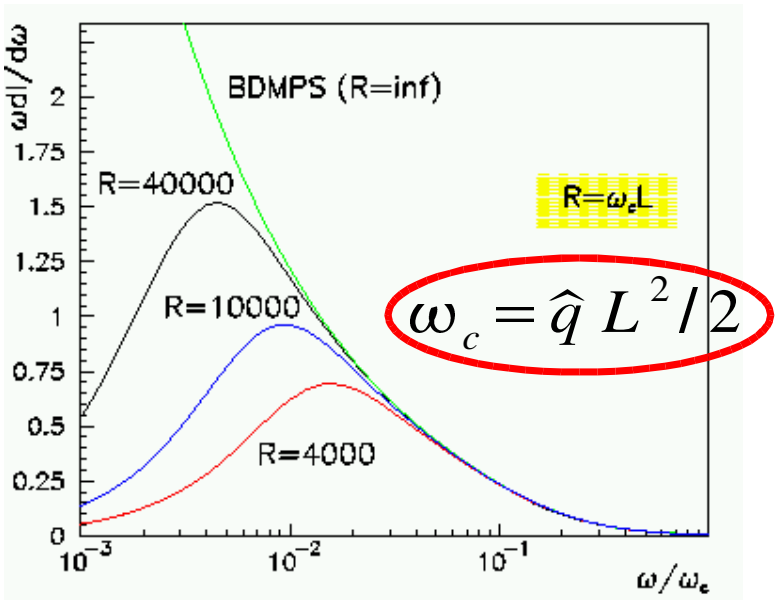
Baier, Dokshitzer, Mueller, Peigne, Schiff (1996); Zakharov (1997); Wiedemann (2000); Gyulassy, Levai, Vitev (2000); Wang ...



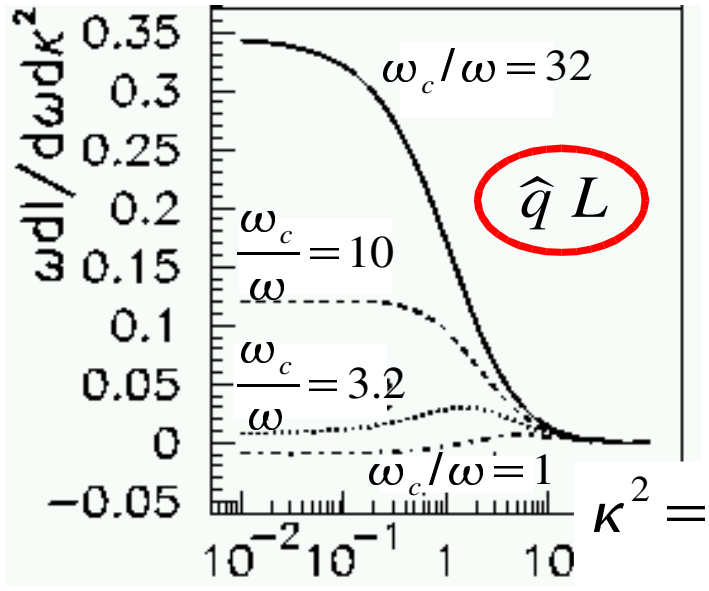
Medium characterized by transport coefficient:

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

- energy loss of leading parton



- pt-broadening of shower



$$\kappa^2 = \frac{k_t^2}{\hat{q} L}$$

Salgado,Wiedemann PRD68:014008 (2003)

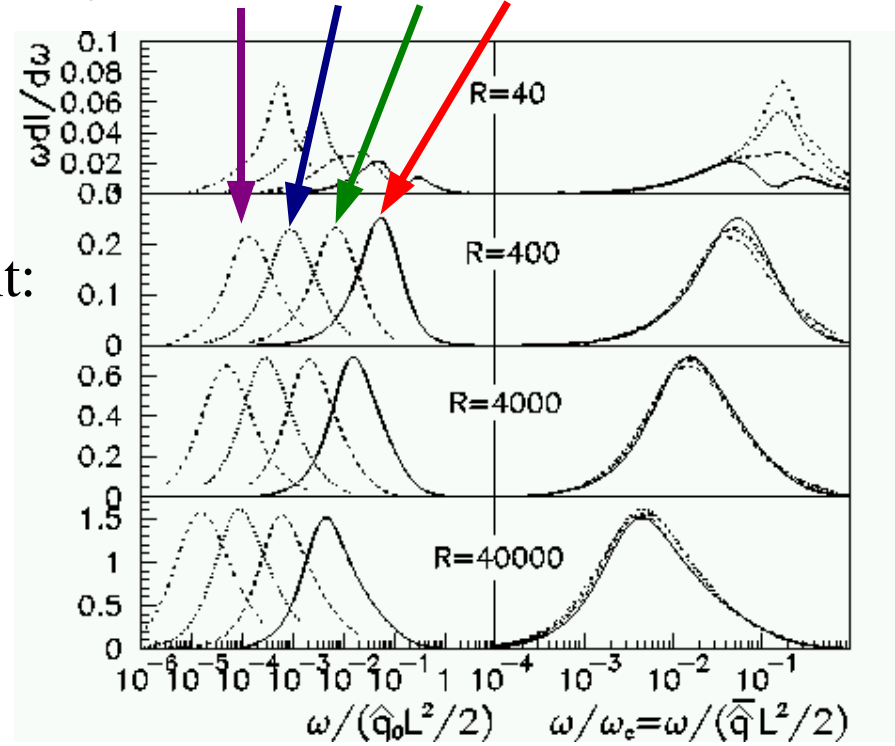
Energy Loss in a Strongly Expanding Medium

- In A-A collisions, the density of scattering centers is time-dependent:

$$\hat{q}(\tau) = \hat{q}_0 \left(\frac{\tau_0}{\tau} \right)^{\alpha}$$

Salgado, Wiedemann PRL 89, 092303 (2002)

α = 1.5, 1.0, 0.5, 0



- Dynamical Scaling Law:
  same spectrum obtained for equivalent static transport coefficient:

$$\bar{\hat{q}} \equiv \frac{2}{L^2} \int_{\tau_0}^{\tau_0 + L} d\tau \left(\tau - \tau_0 \right) \hat{q}(\tau)$$

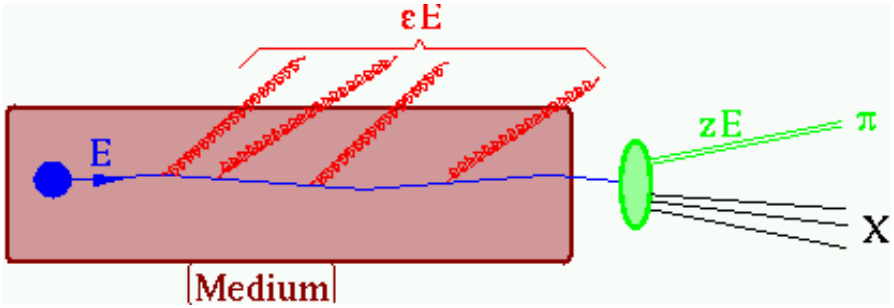
- Calculations for a static medium apply to expanding systems

Baier, Dokshitzer, Mueller, Schiff PRC58 (1998) 1706
Gyulassy, Vitev, Wang, PRL86 (2001) 2537

Rescaled spectrum

'DIS of the QGP': Jet Tomography

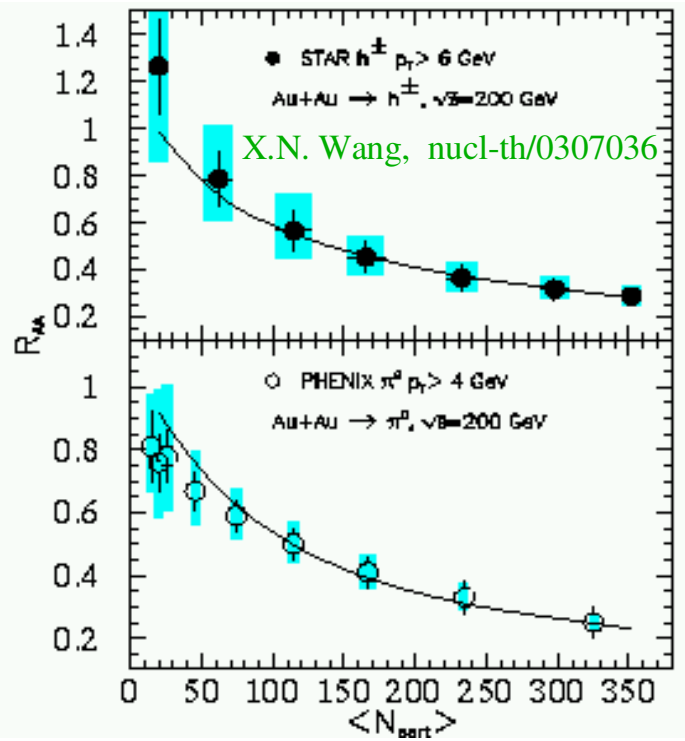
E.Wang, X.N. Wang, PRL 89 (2002) 162301; Gyulassy, Vitev, Wang PRL 89 (2002) 252301; Salgado, Wiedemann PRL 89 (2002) 092303



suppression of leading hadrons governed by

$$\hat{q} L^2$$

Centrality dependence tests interplay of density and geometry



suppression implies X.N. Wang, nucl-th/0307036

$$\epsilon\,|_{\tau=0.2fm/c} \sim 15\,\frac{GeV}{fm^3}$$

scaling → $\tau_{QGP}^{life} = 4 \pm 2 \pm ?\ fm/c$

Uncertainties:

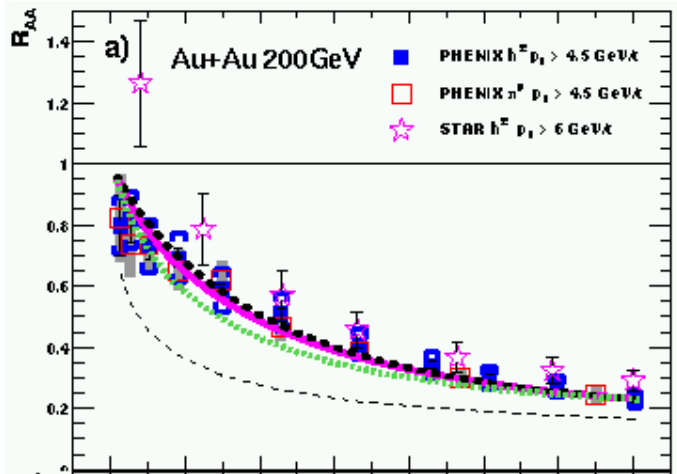
- modelling of dynamics and geometry
- finite energy constraints

Talk: Vitev

Poster: Honkanen

Sensitivity of Leading Hadron Spectra

nucl. mod. factor



A. Drees, H. Feng, J. Jia, nucl-th/0310044

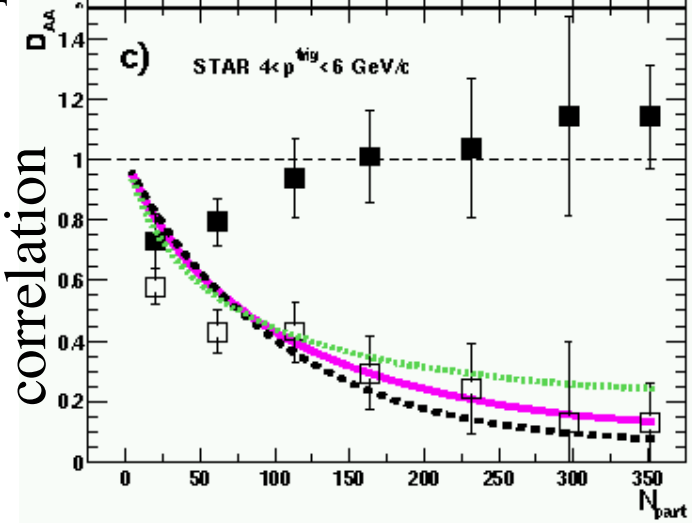
E-loss models:

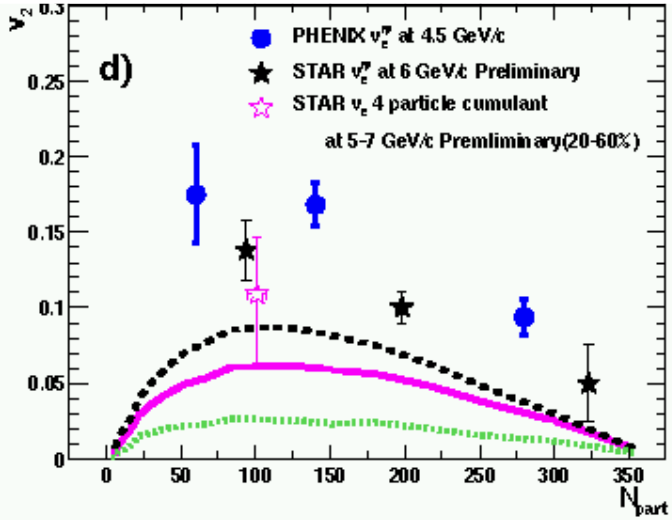
$\propto L^2$, 1-dim expansion

$\propto L$, 1-dim expansion

$\propto L^2$, static

back-to-back correlation





elliptic flow

More direct tests of the energy loss mechanism ?

Testing the Mechanism: E-Loss of Heavy Quarks

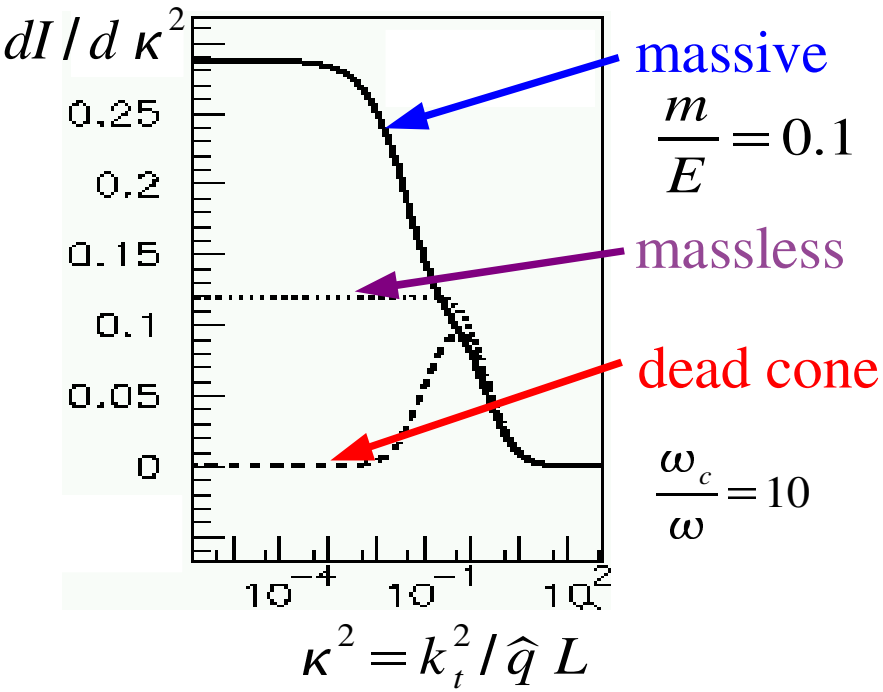
- vacuum radiation suppressed in the dead-cone $\theta < m/E$

  Dokshitzer, Kharzeev, PLB 519 (2001) 199

$$\frac{1}{k_t^2} \Rightarrow \frac{k_t^2}{\left(k_t^2 + \omega^2 m^2/E^2\right)^2}$$

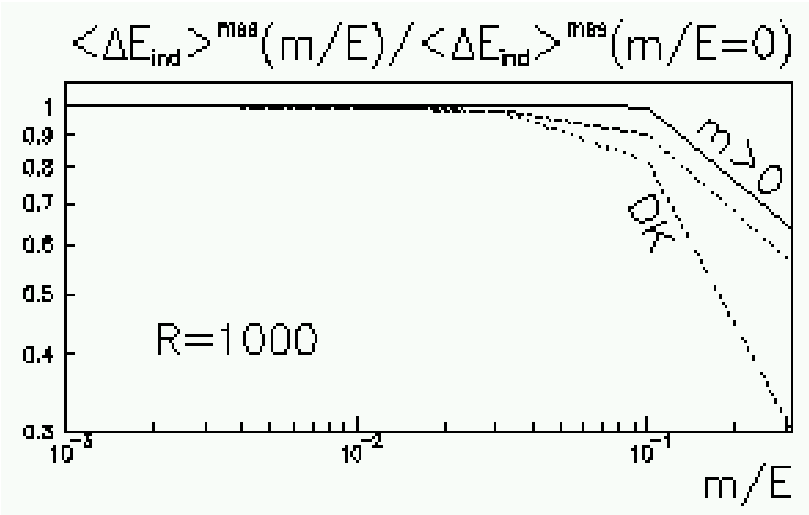
- medium-induced radiation fills the dead-cone

  Armesto, Salgado, Wiedemann, hep-ph/0312106



- total energy loss comparable but smaller than in the massless case

  Armesto, Salgado, Wiedemann, hep-ph/0312106



Uncertainties:

- massive quarks are slower

  (hadronization inside medium relevant for higher pt)

- finite energy corrections large

Talks: Djordjevic, B.W. Zhang

Djordjevic, Gyulassy, nucl-th/0310076

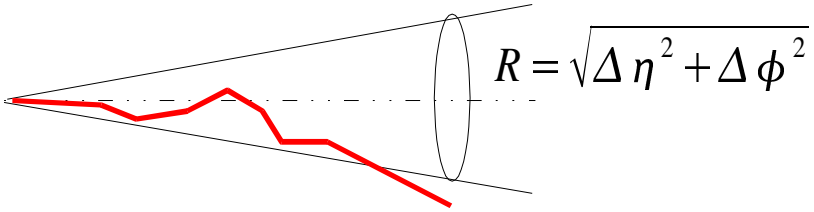
B.W. Zhang, E. Wang, X.N. Wang, nucl-th/0309040

'Jet Heating': Jet Shapes and Jet Multiplicities

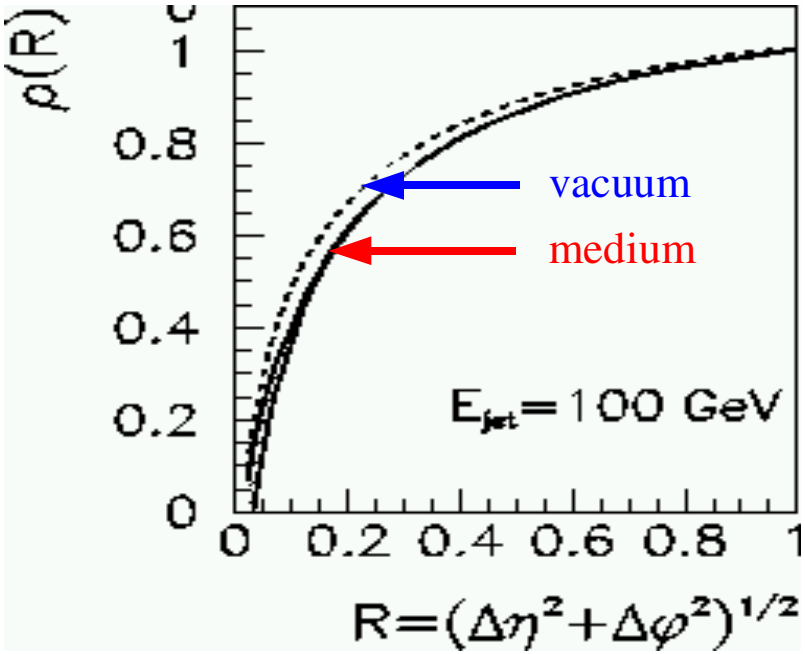
Salgado, Wiedemann, hep-ph/0310079

- Energy fraction in fixed jet cone

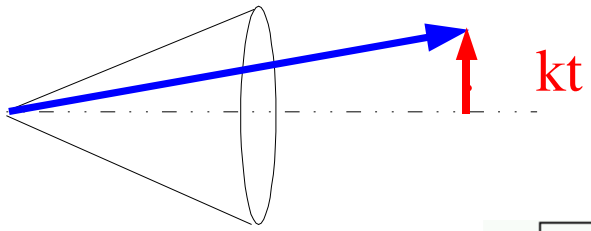
$$\rho_{vac}(R) = \frac{1}{N_{jets}} \sum_{jets} \frac{E_t(R)}{E_t(R=1)}$$

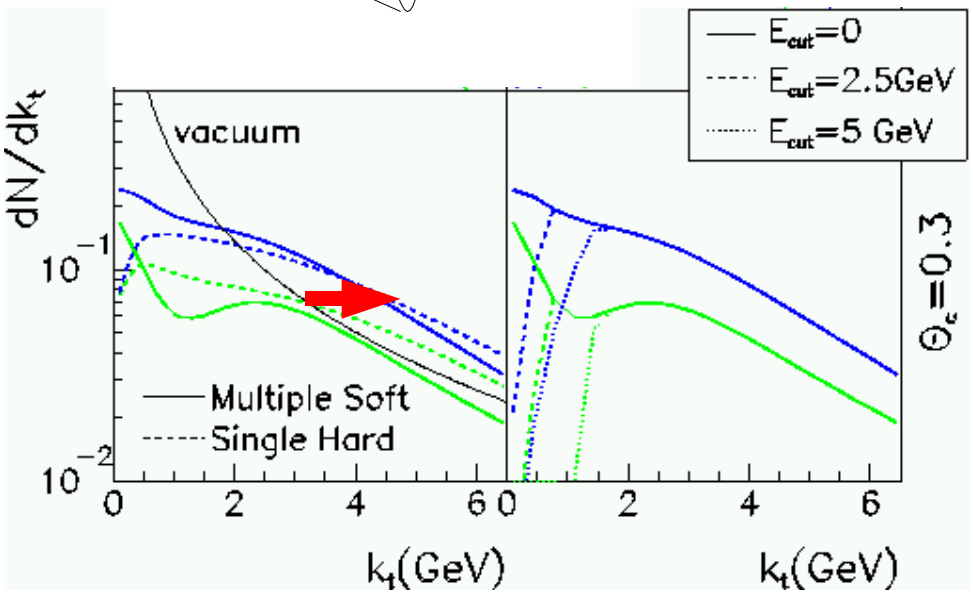


weakly dependent on medium



- Multiplicity within small jet cone broadens significantly

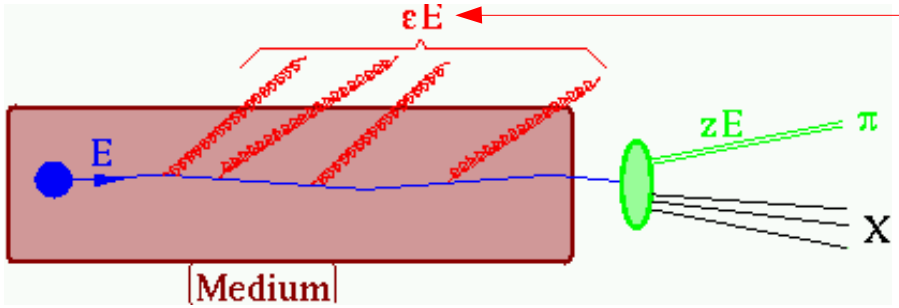




unaffected by high-multiplicity background ! Talk: C. Salgado

Going beyond Leading Hadron Spectra

How does the medium-induced radiation evolve towards thermal and chemical equilibrium ?



Where does this associated radiation go to ?

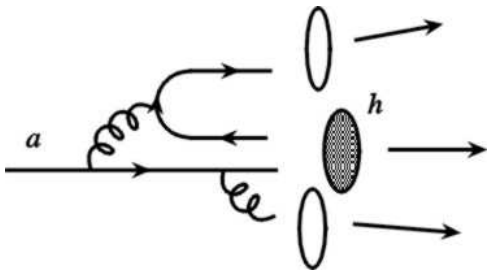
Associated radiation:

- How to distinguish from a high-multiplicity background ?
- What is the angular distribution of the radiated energy ?
- What is its spectrum ? Exponential or powerlaw ?
- Does it induce high-pt hadronic correlations ?
- What is its chemical composition ?

Talks: Majumder, Rak, Salgado, Vitev, F. Wang

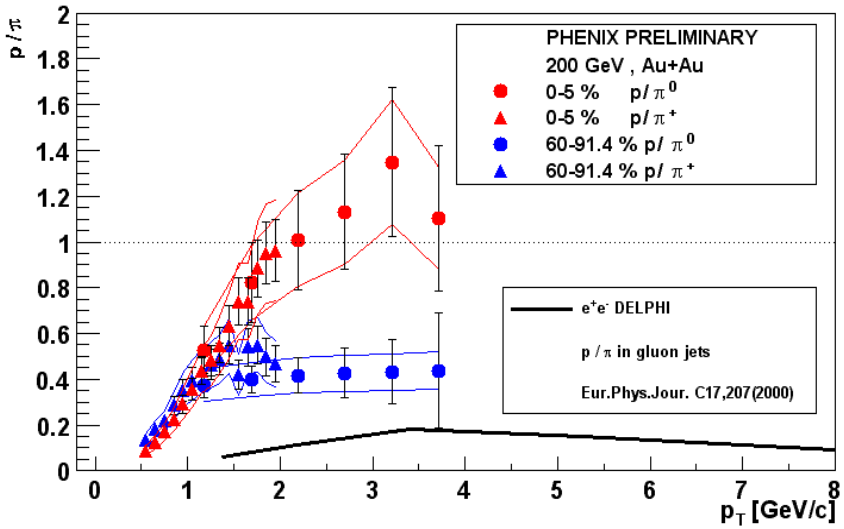
Intermediate pt

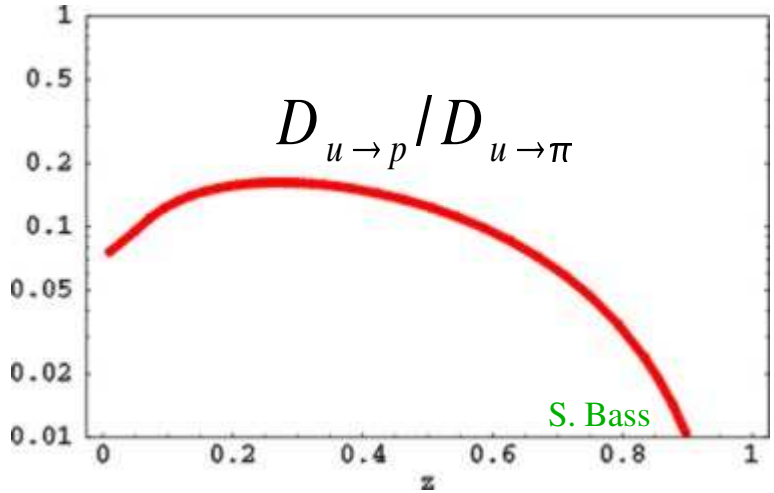
Testing the Dynamics of Hadronization



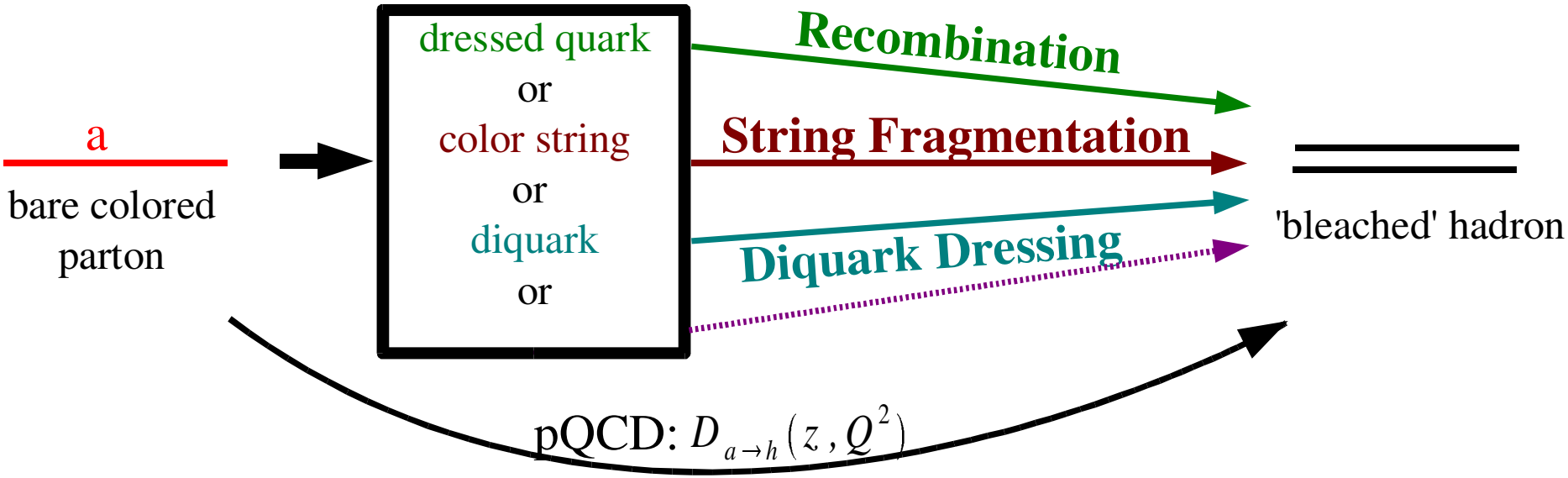
Breakdown of Independent (pert.) Fragmentation

- Jet quenching does not affect ratio $D_{q\to p}/D_{q\to\pi}$ in contrast to observation





- How does the bleaching of color charges proceed dynamically ?



Fragmentation versus Recombination

start from quark spectrum: $w_\alpha(P/z)$

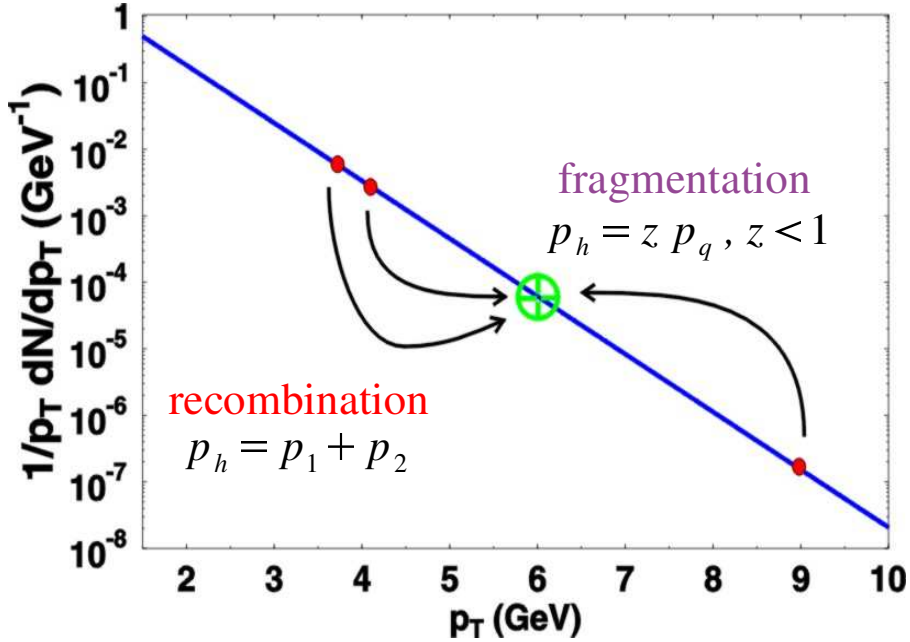
- Fragmentation:

$$E\frac{dN_h}{d^3P} = \int_0^1 \frac{dz}{z^2} w_\alpha(P/z) D_{\alpha\to h}(z)$$

- Recombination

$$E\frac{dN_M}{d^3P} \sim C_M [w_\alpha(P/2)]^2 \int d^3q \left|\phi_M(q)\right|^2$$

$$E\frac{dN_B}{d^3P} \propto C_B [w_\alpha(P/3)]^3$$



Range of applicability: intermediate pt

Exp. spectrum: recombination dominates

Powerlaw tail: fragmentation dominates

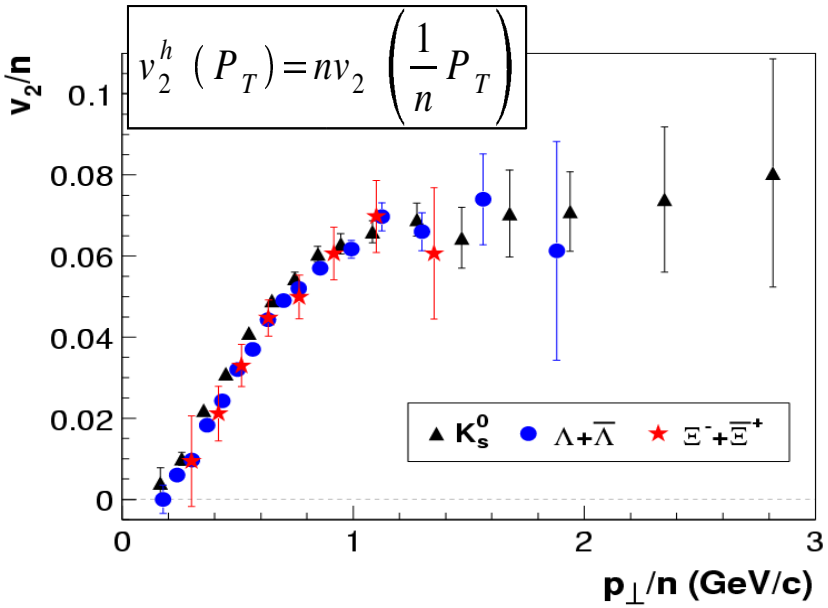
→ upper bound on pt

Biro, Levai, Zimanyi, PLB 347 (1995) 6 [ALCOR]
Voloshin, QM2002, nucl-ex/0210014
Hwa, Yang, PRC 66 (2002) 025205
Fries, Muller, Nonaka, Bass PRL 90 (2003) 202303
Greco, Ko, Levai, PRL 90 (2003) 202302
Molnar, Voloshin PRL 91 (2003) 092301

Successes and Suggestive Features of Recombination

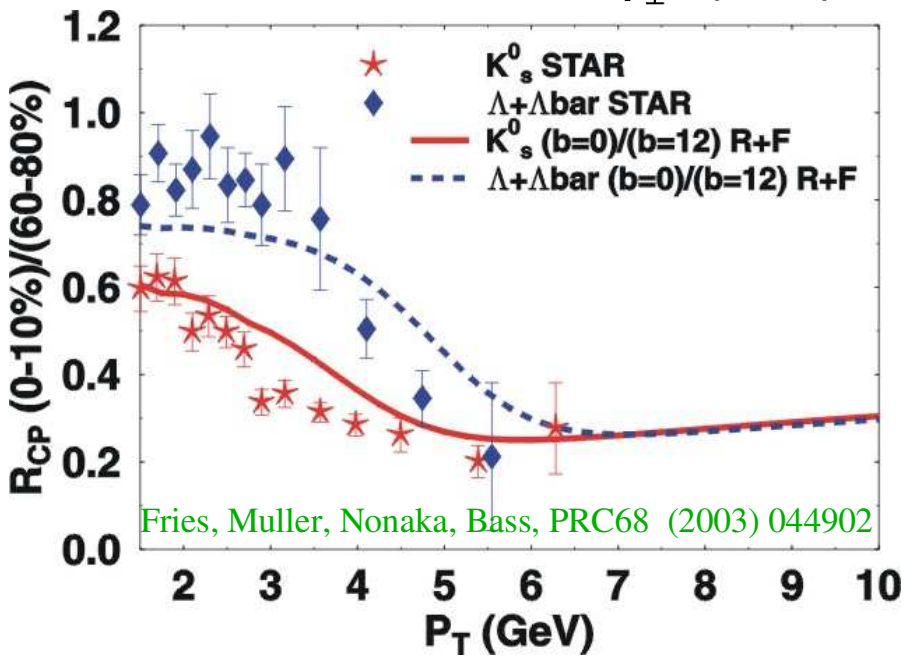
- Quark number scaling of v2

  Voloshin, QM2002, nucl-ex/0210014



- Explanation of large baryon/meson ratio at intermediate pt

  Talks: Fries, Hwa, Molnar

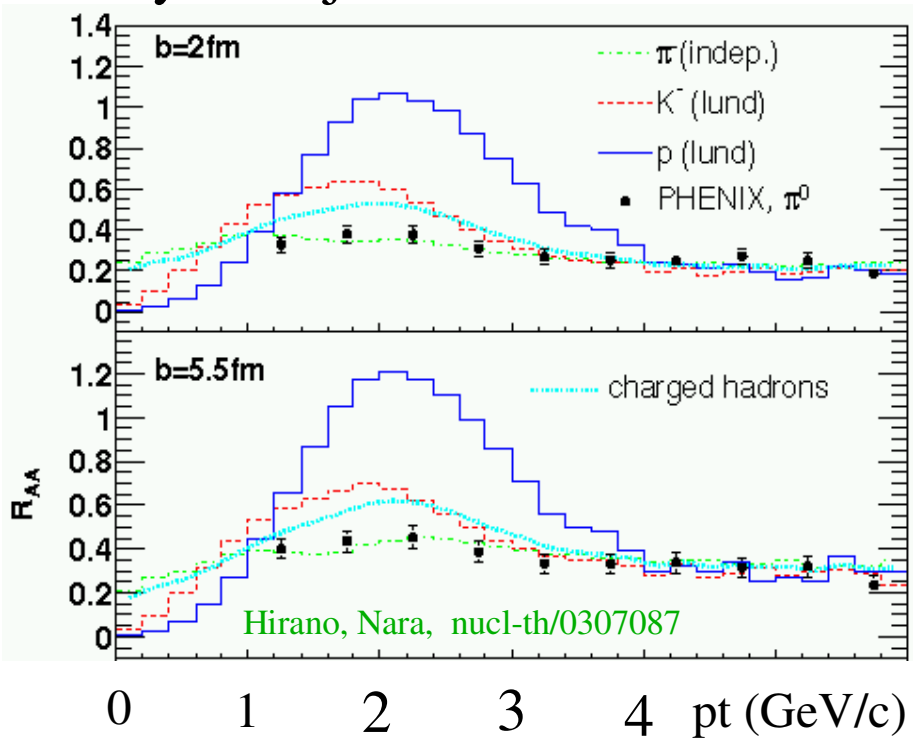


Many open questions:

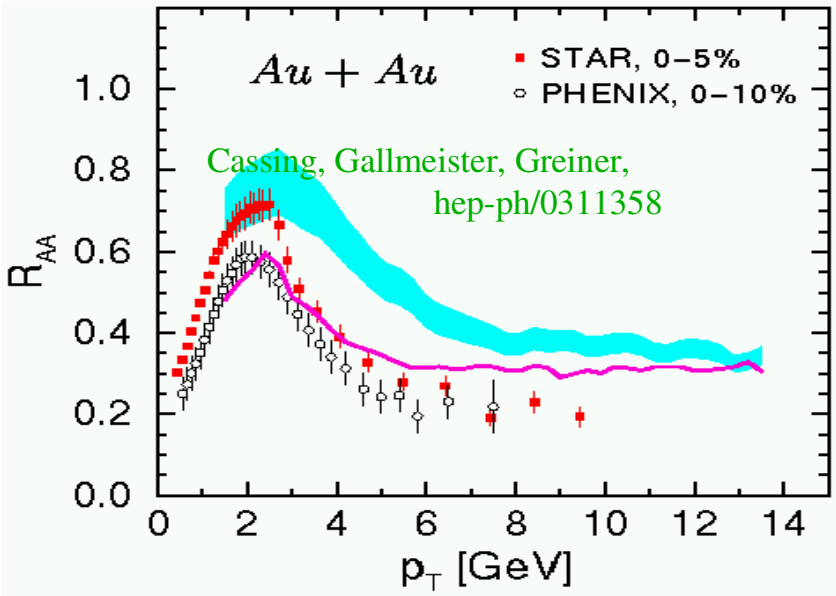
- Recombination violates entropy conservation
- Realistic coalescence conditions: momentum vs. phase space
- Dynamical understanding:
  - where does the initial glue go ?
  - how is baryon number transported ?
  - particle correlations ?

Alternatives to Recombination

- Hydro + jets Talk: Hirano



- Strings (HSD) Talk: Greiner



Hadronic FS interactions negligible above pt = 6 GeV

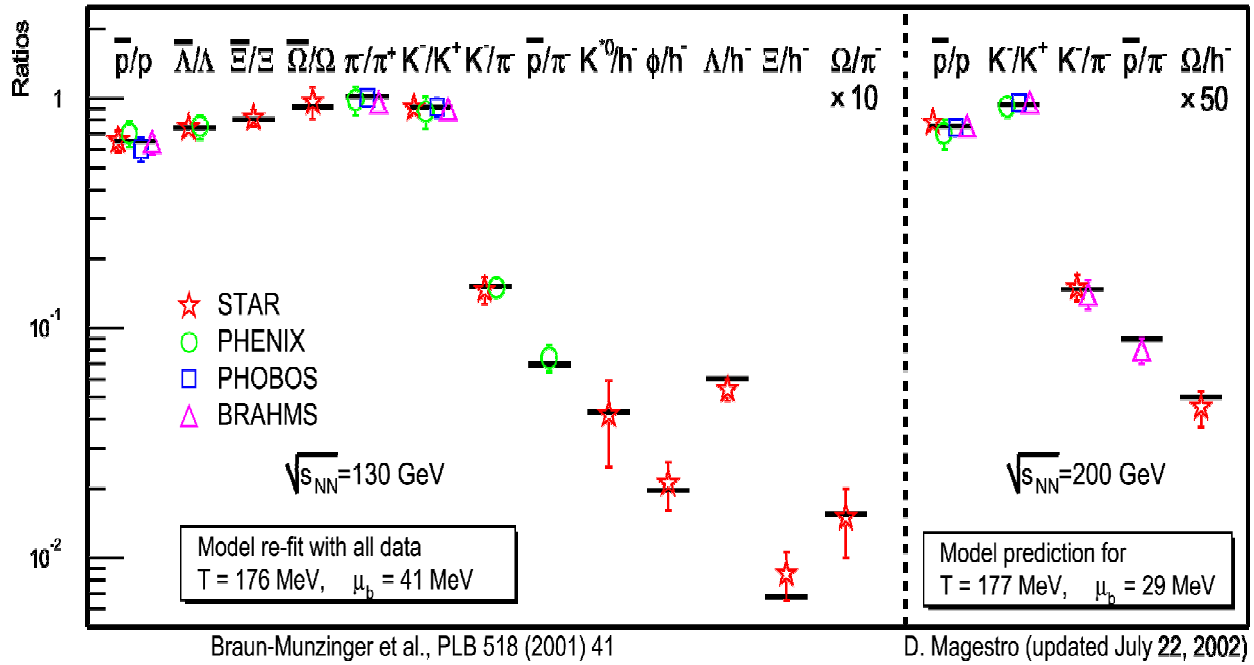
How to decide between different hadronization scenarios ?

Soft pt

Statistics and Dynamics of the Bulk

Hadronization in the Grand Canonical Ensemble

- Hadron yields and ratios fitted by statistical model in terms of (T, μ)

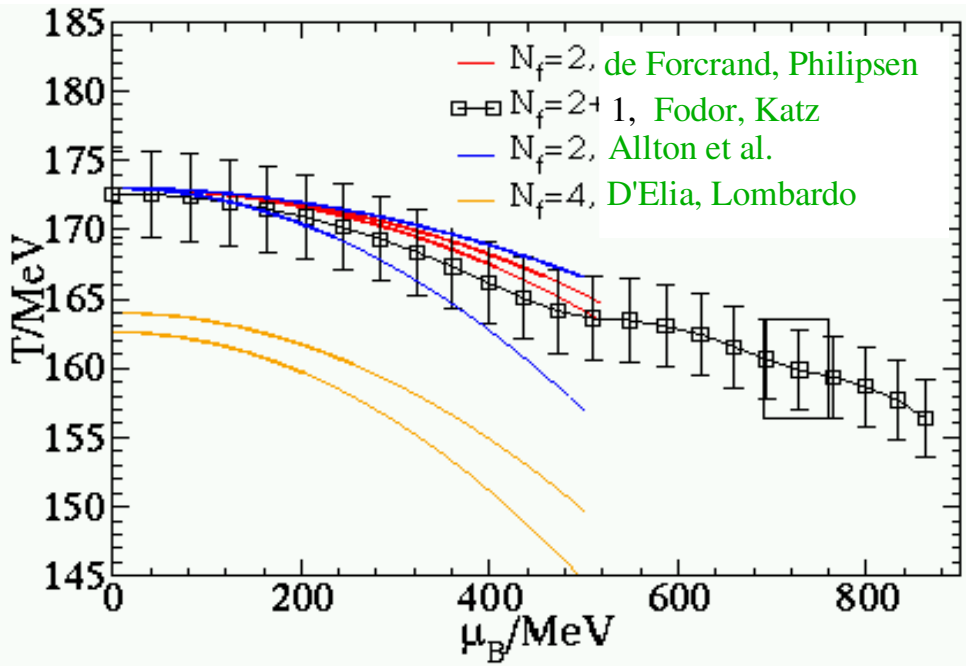


- Recent refinements:
  - system size dependence
  - hadronization of charm

  Talk: Redlich

- Hadronization of a QGP in chemical equilibrium at (T, μ) ?

  Talk: Karsch, Petreczky



Which microscopic dynamics turns quarks and gluons into hadrons ?

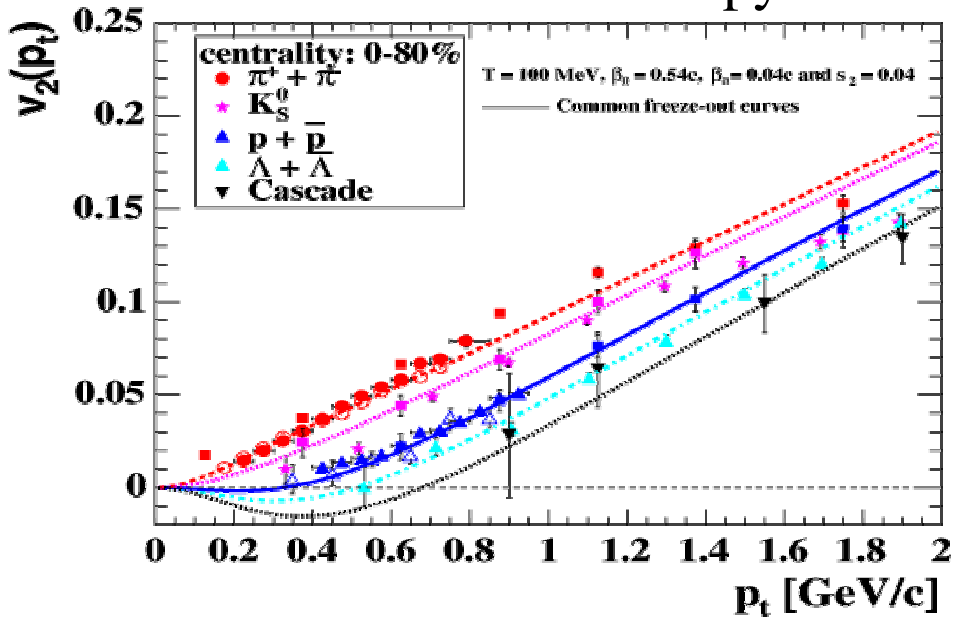
'Blastwave Model': Snapshot at Freeze-out

- Low pt Hadron Spectra fitted by
  - local thermal equilibrium $T(\eta, b)$
  - collective flow u_ν

$$T_{fo} \sim 100\,MeV \qquad v_{trans} > 0.5\,c$$

Talks: Retiere, Heinz, Magestro

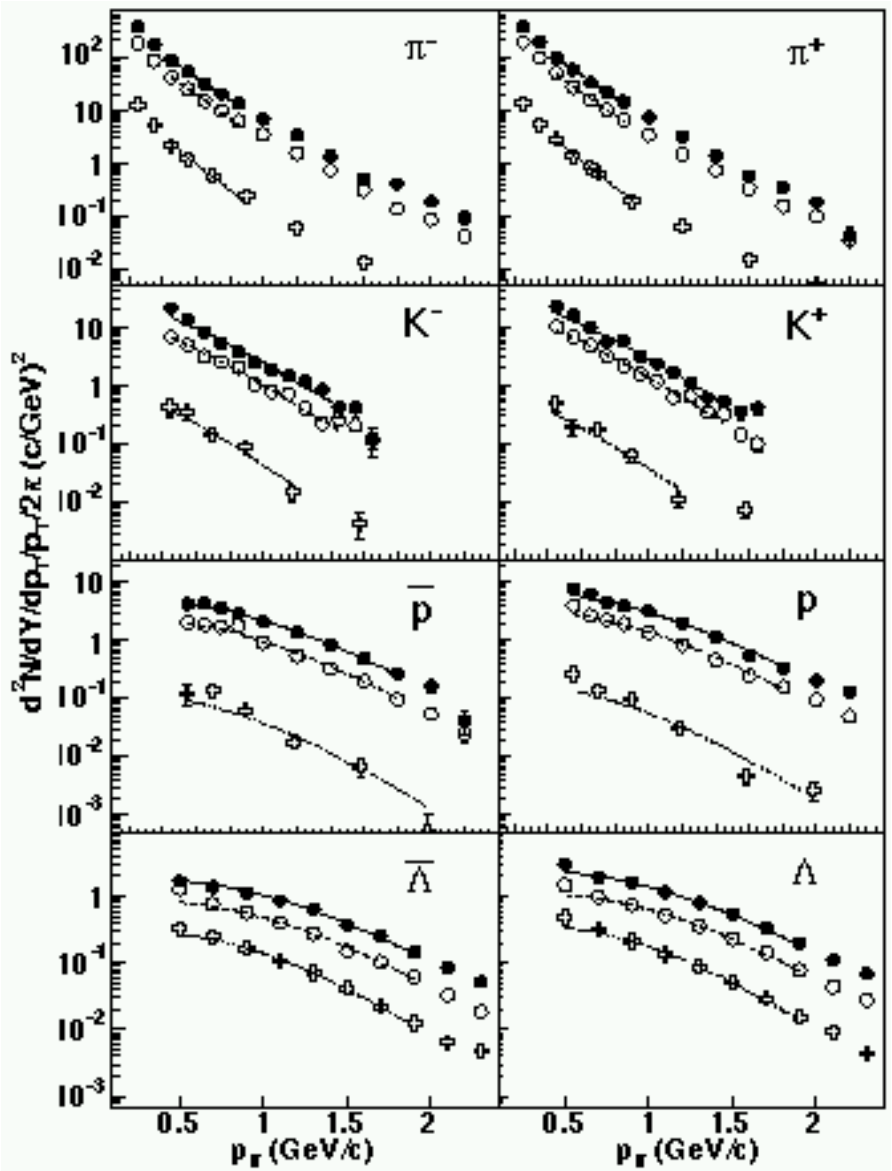
- Recent refinements: anisotropy



space-time geometry: HBT ?, asHBT !

Talk: Magestro

Lisa, Retiere, nucl-th/03122024



What is the microscopic dynamics determining these distributions ?

Hydro: Learning from Agreements or Deviations ?

- Hydrodynamics + statistical hadronization works up to $p_t \sim 1-2\,GeV$ for

Hirano, Nara, nucl-th/0307015

  - pt -spectra
  - rapidity distribution
  - elliptic flow

Talks: Hirano, Shuryak, Teaney

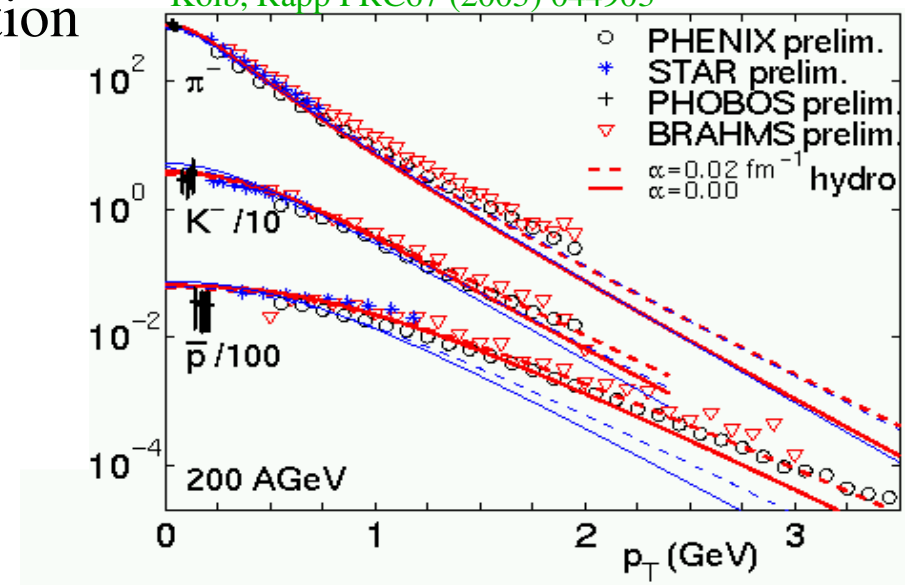
- How to understand the range of validity of hydrodynamics ?
  - hadronization may change flow by by a large factor (2-3)

    Molnar, Voloshin PRL 91 (2003) 092301
  - realistic freeze-out condition (beyond Cooper-Frye) needed for some data, e.g. HBT

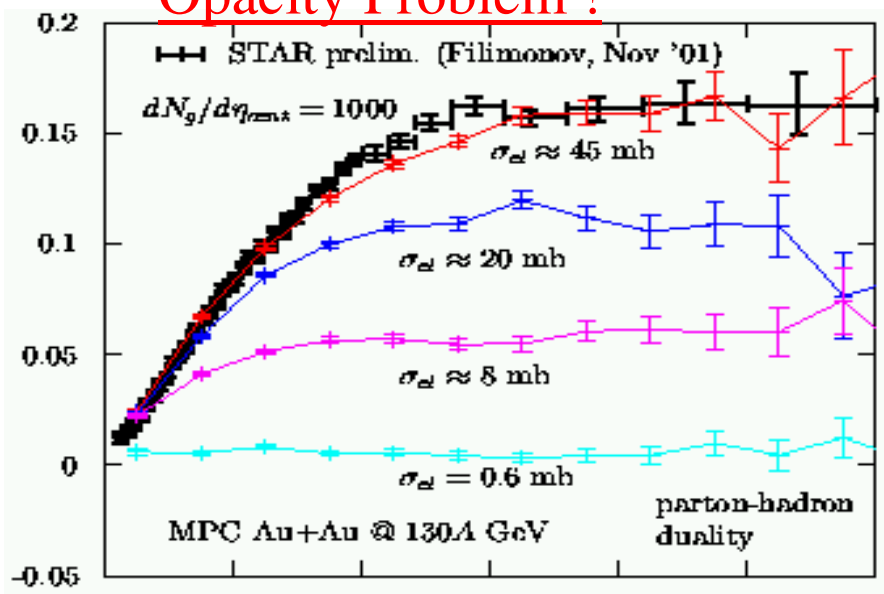
Sinyukov, Akkelin, Hama, PRL 89 (2002) 052301
Akkelin, Braun-Munzinger, Sinyukov, NPA710 (2002) 439
Tomasik, Wiedemann PRC68 (2003) 034905

→ Hadronization matters !

Kolb, Rapp PRC67 (2003) 044903

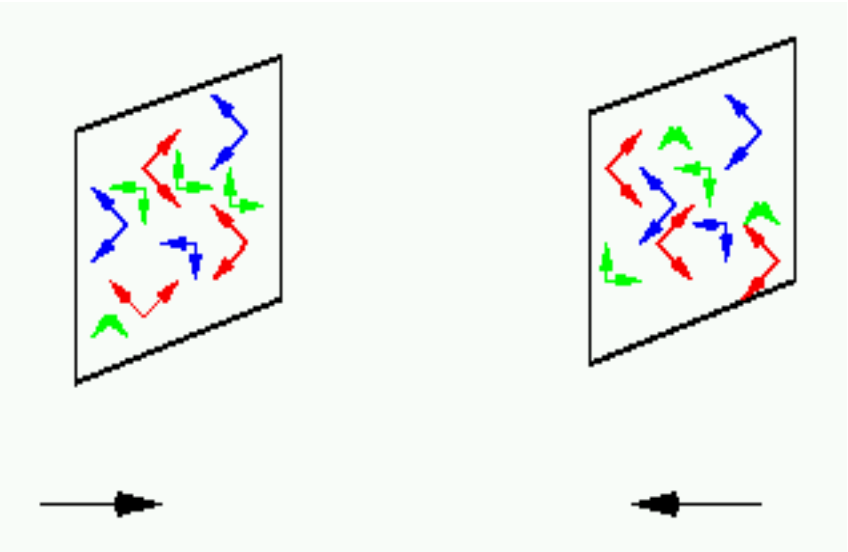


Opacity Problem !



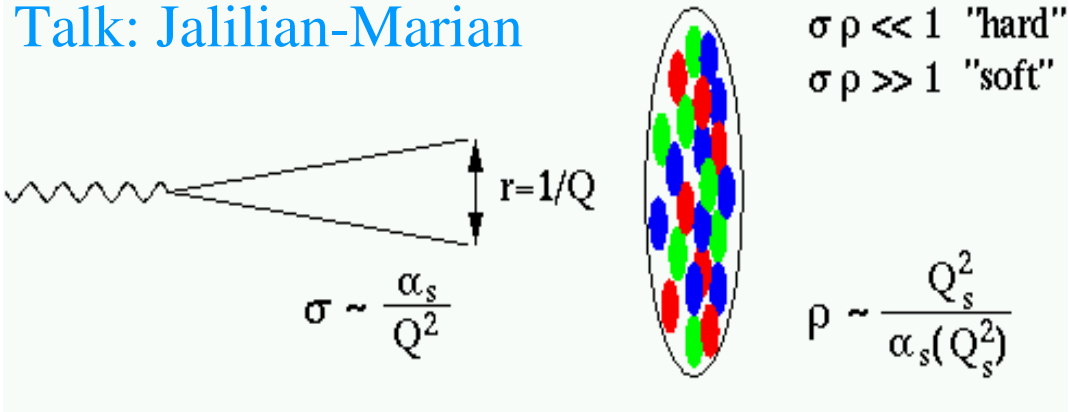
Molnar, Gyulassy, NPA 697 (2002) 495

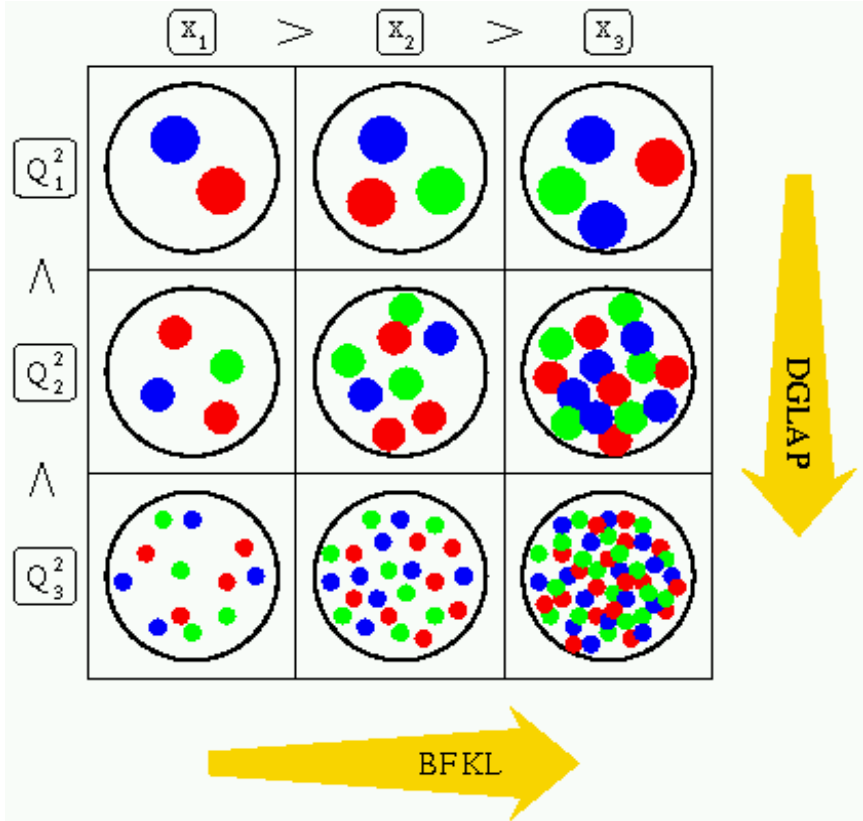
Saturation Physics – a complementary View



Saturation Physics: Theory

Talk: Jalilian-Marian





High density: $\sigma\ \rho \geqslant 1$ but $\alpha_s(Q_s^2) \ll 1$

→ non-linear small-x evolution perturbatively calculable

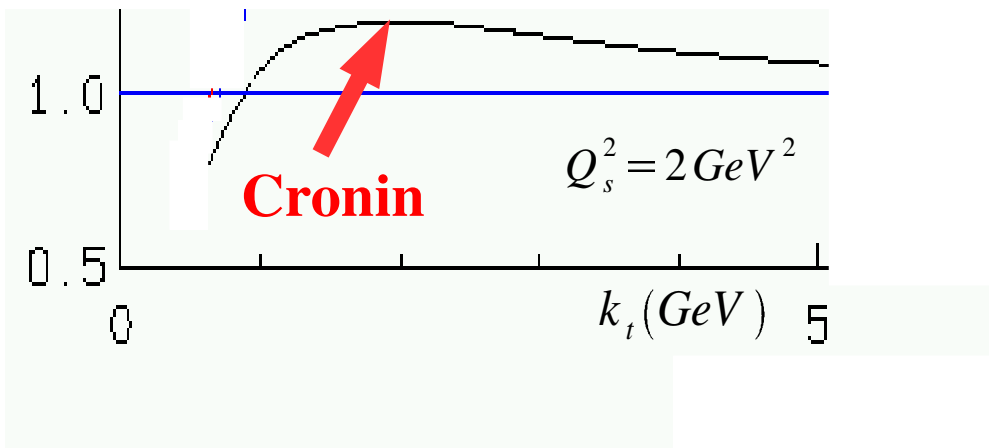
Balitsky; Kovchegov; Jalilian-Marian,Kovner, Leonidov, Weigert; ...

- kt-differential gluon distribution:
  (typical initial condition) McLerran, Venugopalan; Golec-Biernat, Wusthoff

$k_t < Q_s$ saturated

$k_t > Q_s$ Cronin-enhanced

$\Phi(k_t)/\Phi^{pert}(k_t)$

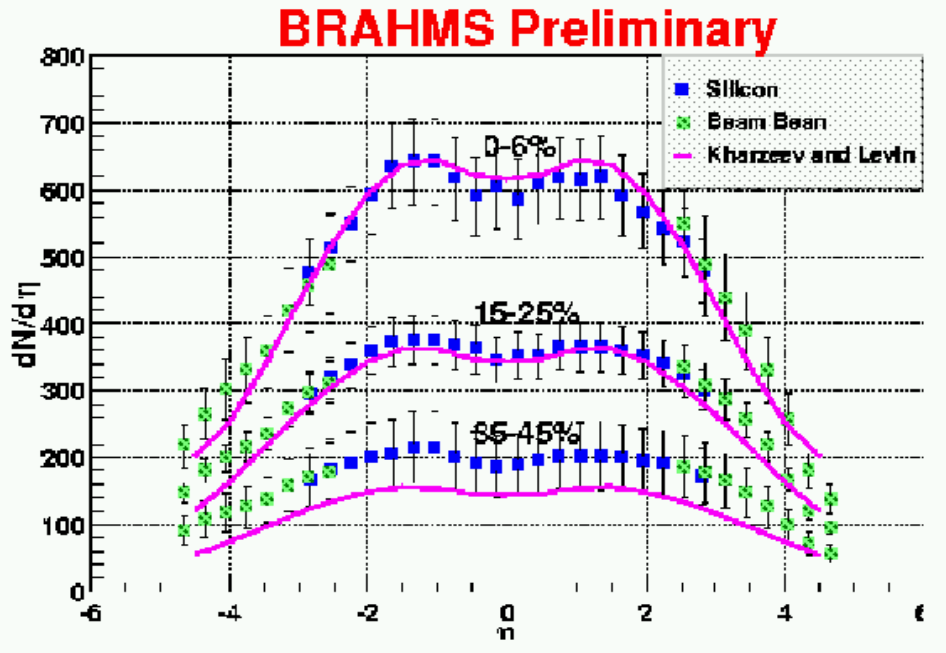


What determines the onset of saturation physics ?

Saturation Models consistent with Bulk Observables

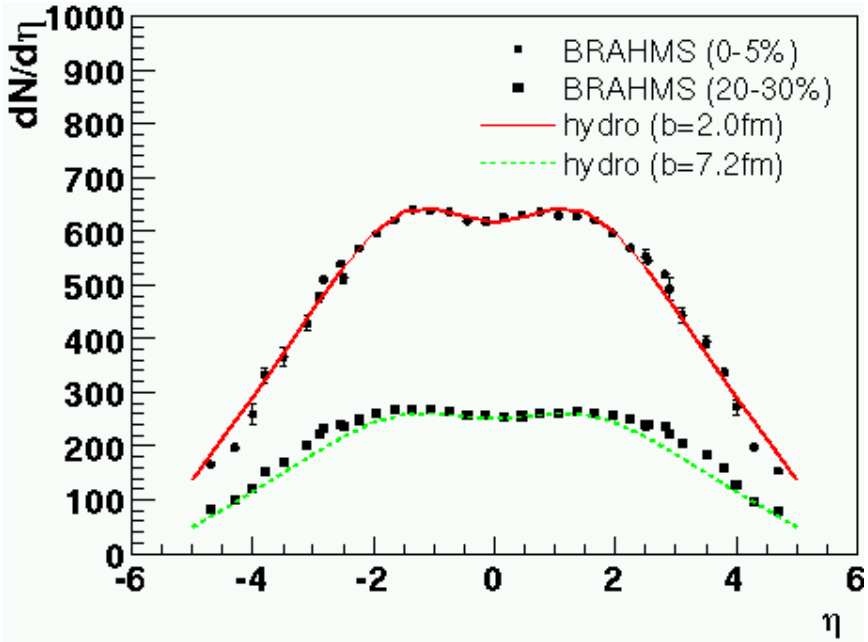
- Saturation Model

  Kharzeev, Levin, nucl-th/0108006



- Hydrodynamics

  Hirano, Nara, nucl-th/0307015



Are there more direct probes of saturation physics ?

Are there tests at intermediate and high pt ?

Small-x evolution generates 'intermediate -pt' region

Iancu, Itakura, McLerran, NPA 708 (2002) 327 Mueller, Triantafyllopoulos NPB 640 (2002) 331

1. Saturation region: $k_t^2 < Q_s^2$ $\Phi(k_t) \sim \ln(Q_s^2/k_t^2)$
2. Scaling window: $Q_s^2 < k_t^2 < \frac{Q_s^4}{Q_0^2}$ $\Phi(k_t) \sim \left(Q_s^2/k_t^2\right)^{\gamma}$ $0.5 < \gamma < 1$
3. Perturbative region: $\frac{Q_s^4}{Q_0^2} < k_t^2$ $\Phi(k_t) \sim \frac{1}{k_t^2}$

Talks: Itakura, Jalilian-Marian

Observable consequences ?

- Intermediate pt suppression

  Kharzeev, Levin, McLerran, PLB 561 (2003) 93

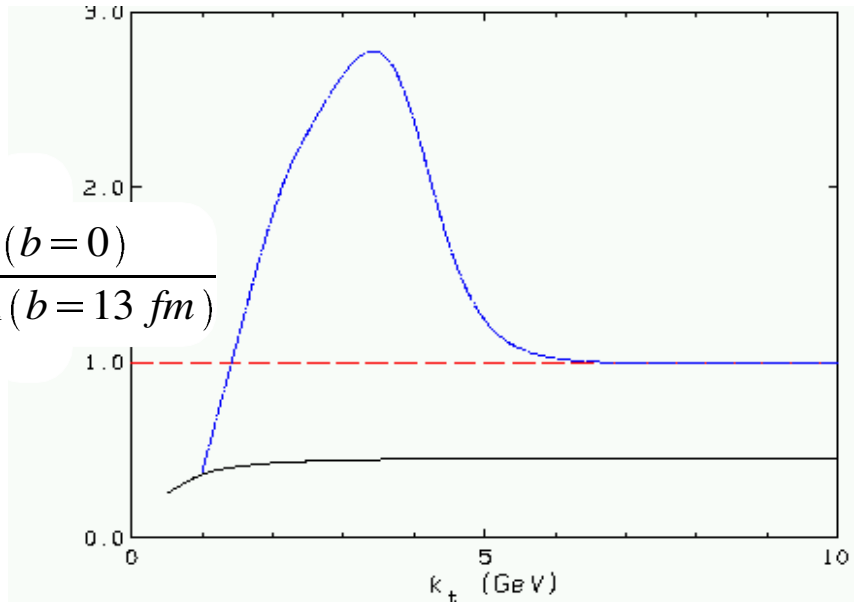
- Evolution of Cronin enhancement

  Baier, Kovner, Wiedemann, PRD 68 (2003) 054009

No analytical control of transition from scaling window to pert. region,

$$R^{periph}(k_t) = \frac{\Phi(b=0, k_t)/\rho_{part}(b=0)}{\Phi(b=13\ fm, k_t)/\rho_{part}(b=13\ fm)}$$

but this matters !



$\gamma \to 1$, rapidly for $\frac{Q_s^4}{Q_0^2} < k_t^2$

$\gamma = 0.64$
$k_t^2 > Q_s^2$

BK and BFKL evolution erase Cronin enhancement

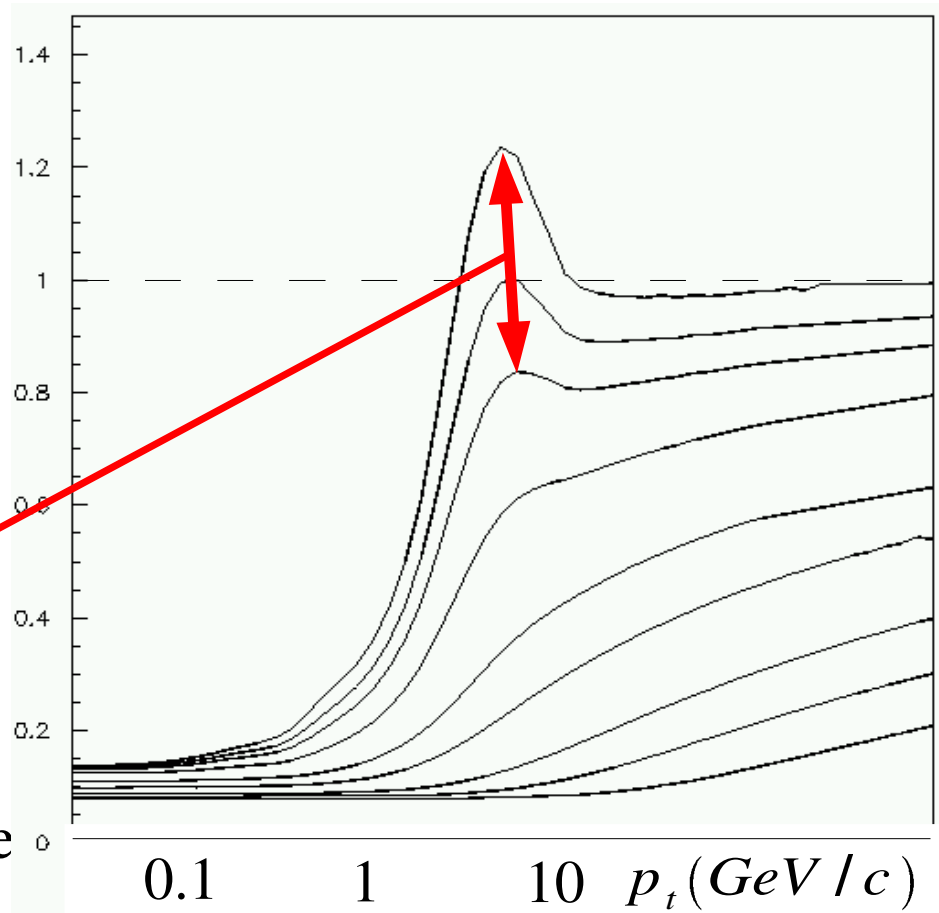
numerical control: Albacete, Armesto, Kovner, Salgado, Wiedemann, hep-ph/0307179, PRL in press

- Ratio of spectra:

$$\frac{dN_{AA}}{dy\,d^2p_t} \sim \frac{A^{2/3}}{p_t^2}\int d^2k_t\,\phi^Q(k_t,y)\,\phi^Q(p_t-k_t,y)$$

$$R_{AA} = \frac{\dfrac{dN_{AA}}{dy\,d^2p_t\,db}}{A^{4/3}\dfrac{dN_{pp}}{dy\,d^2p_t\,db}}$$

$\sqrt{s} = 130\,GeV \rightarrow \sqrt{s} = 200\,GeV$,
corresponds to $\delta y = 0.1$, $\alpha_s = 0.2$



- Running coupling slows down decrease

Poster: J.L. Albacete

Forward rapidity at RHIC becomes testing ground for BK

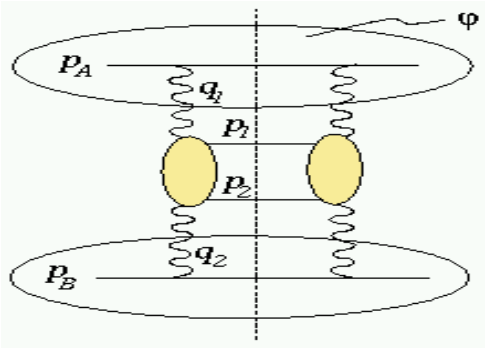
Talks: Kovchegov, Venugopalan, Accardi

Kharzeev, Kovchegov, Tuchin, hep-ph/0307037 v1

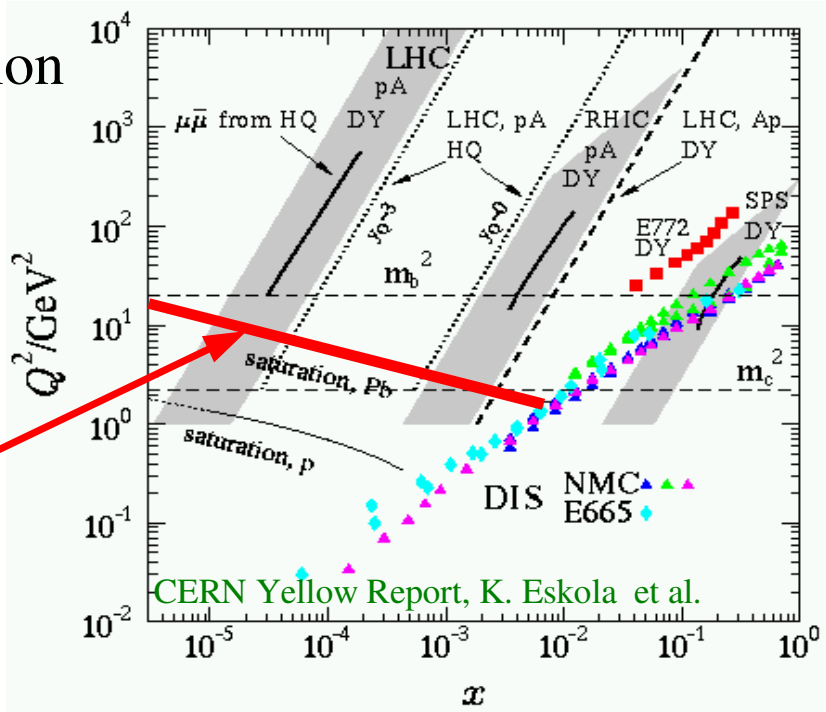
Jalilian-Marian, Nara, Venugopalan, nucl-th/0307035

Probing Saturation via Heavy Quark Production

- HQ production tests gluon distribution



at unprecedented low x.
Direct test of saturation

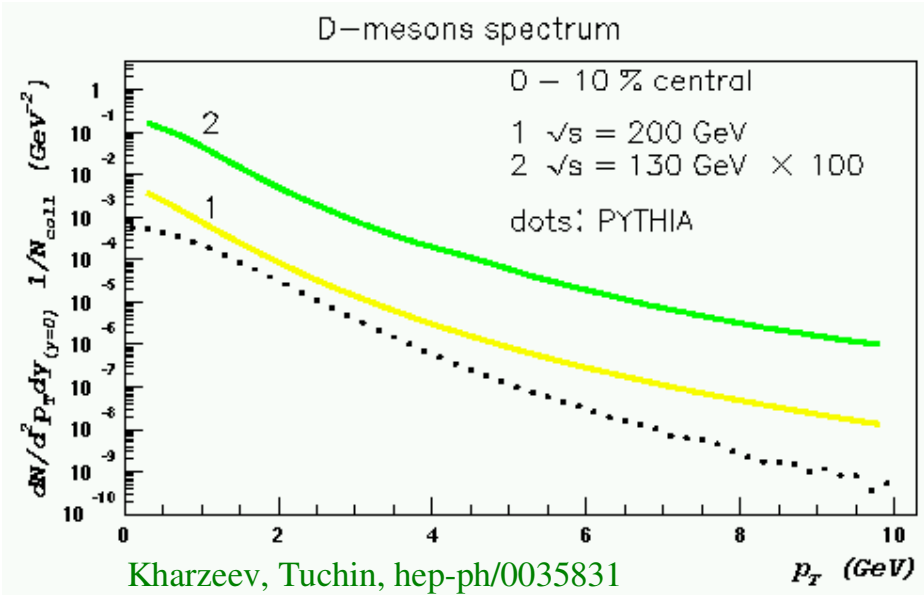


- Interesting predictions:

- hardening of open charm pt-spectra ?
- N_{coll} - scaling at mid-rapidity ?
- N_{part}- scaling at forward rapidity ?

Talks: Kolhinen, Tuchin, Raufeisen

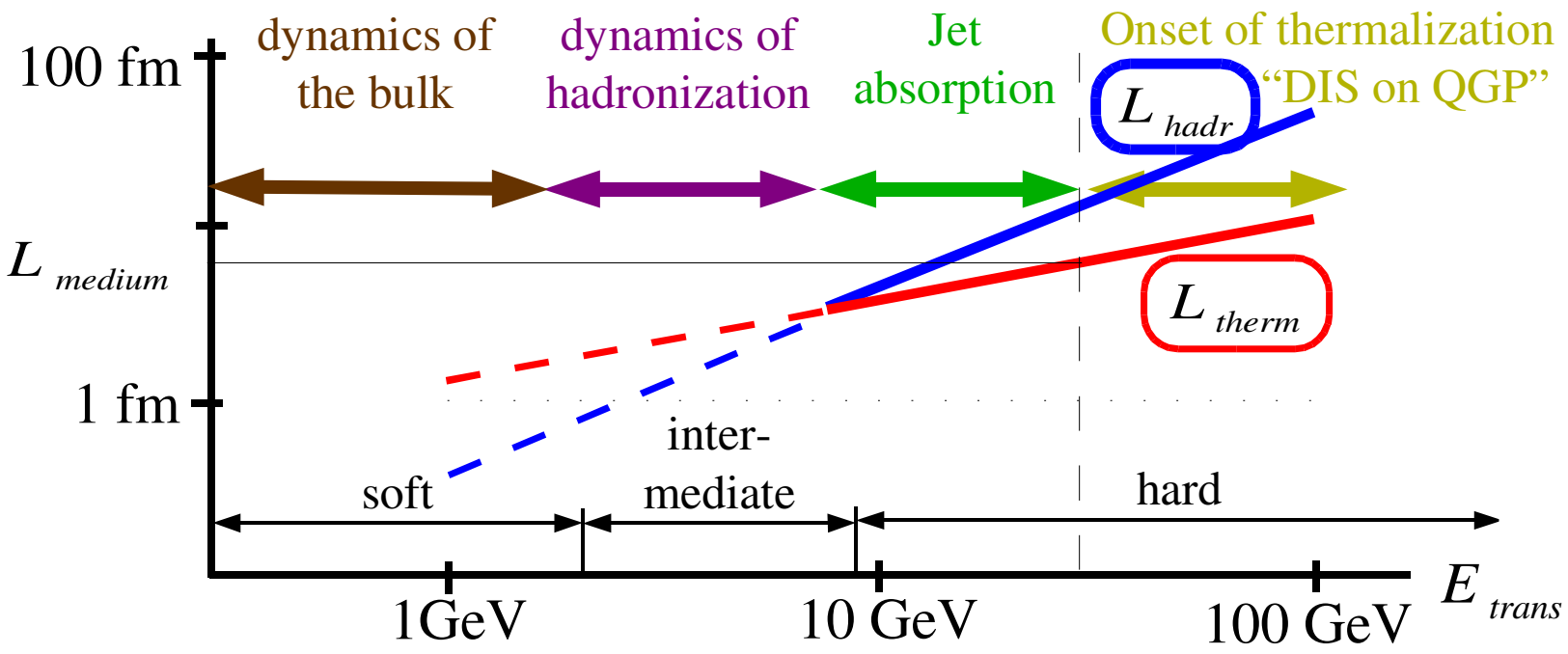
Eskola, Kolhinen, Vogt, hep-ph/0310111



Kharzeev, Tuchin, hep-ph/0035831

- Control of final state energy loss is important

The RHIC-ness of accessible Scales



+ A-dependence
+ $\sqrt{s}$ - dependence
+ d-Au collisions
+ LHC

→

- What determines the initial energy density created in nucleus-nucleus collisions ?
- What is the nature of equilibration processes and what is their time scale ?
- What is the dynamics of hadronization and how does it depend on system size ?
- ...