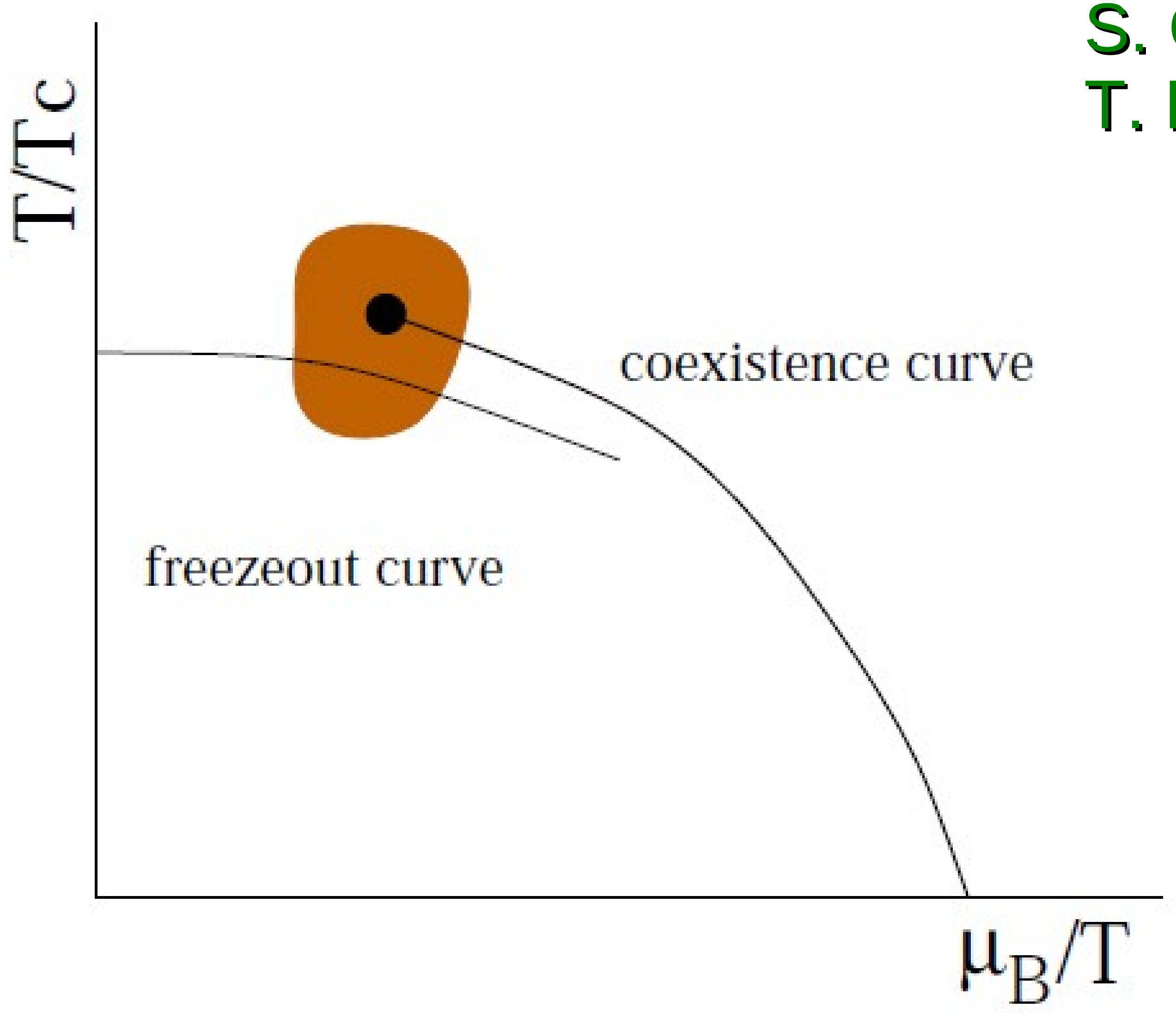
(Some of the) Theory presented at ISMD 2011

Adrian Dumitru

RIKEN BNL Research Center
&
Baruch College / CUNY

Phase diagram of QCD

S. Gupta
T. Kunihiro



Lattice setup

Lattice simulations impossible at finite baryon density: **sign problem**. Basic algorithmic problem in all Monte Carlo simulations: no solution yet.

Bypass the problem; make a Taylor expansion of the pressure:

$$P(T,\mu) = P(T) + \chi_B^{(2)}(T)\frac{\mu^2}{2!} + \chi_B^{(4)}(T)\frac{\mu^4}{4!} + \cdots$$

Series expansion coefficients evaluated at $\mu = 0$.
Implies

$$\chi_B^2(T,\mu) = \chi_B^{(2)}(T) + \chi_B^{(4)}(T)\frac{\mu^2}{2!} + \chi_B^{(6)}(T)\frac{\mu^4}{4!} + \cdots$$

Series fails to converge at the critical point.

, Gavai, SG, hep-lat/0303013 (2003)

What to compare with QCD

The cumulants of the distribution are related to Taylor coefficients—

$$[B^2] = T^3 V \left(\frac{\chi^{(2)}}{T^2}\right), \quad [B^3] = T^3 V \left(\frac{\chi^{(3)}}{T}\right), \quad [B^4] = T^3 V \chi^{(4)}.$$

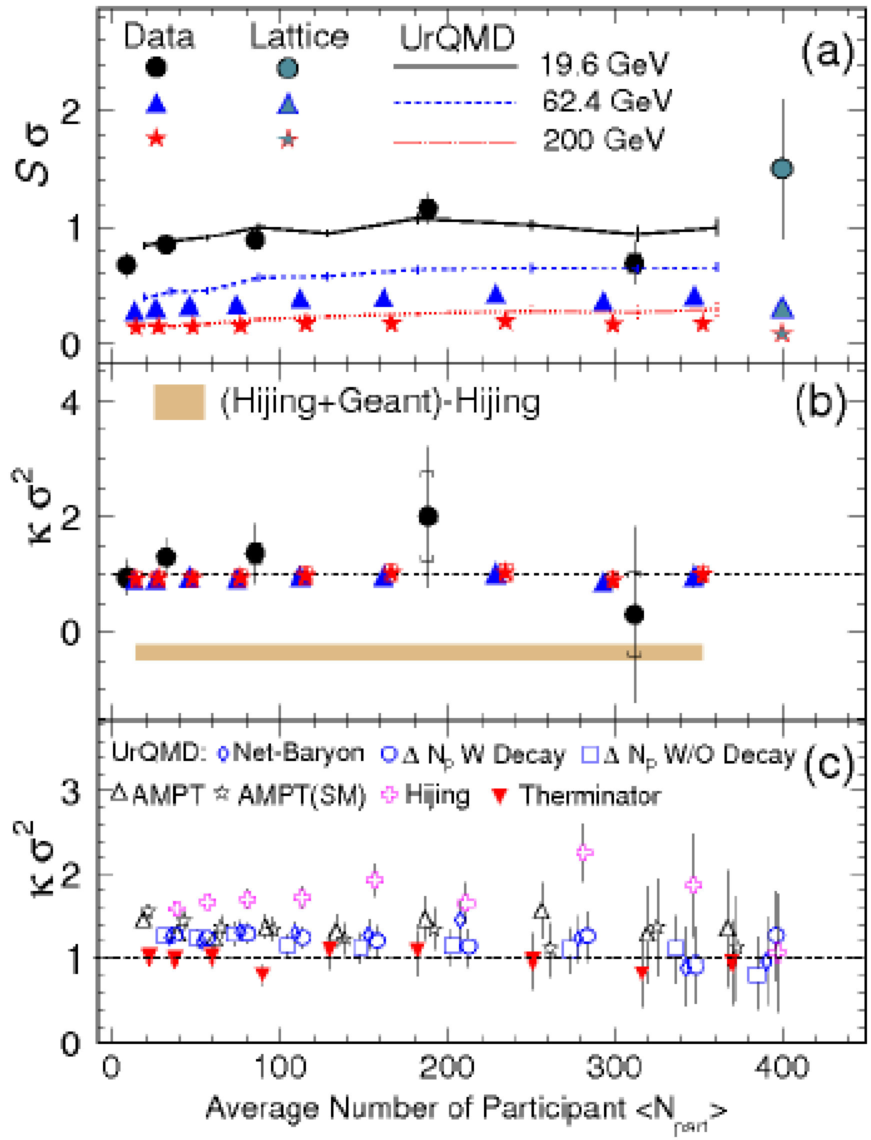
T and V are unknown, so direct measurement of QNS not possible (yet). Define variance $\sigma^2 = [B^2]$, skew $\mathcal{S} = [B^3]/\sigma^3$ and Kurtosis, $\mathcal{K} = [B^4]/\sigma^4$. Construct the ratios

$$m_1 = \mathcal{S}\sigma = \frac{[B^3]}{[B^2]}, \qquad m_2 = \mathcal{K}\sigma^2 = \frac{[B^4]}{[B^2]}, \qquad m_3 = \frac{\mathcal{K}\sigma}{\mathcal{S}} = \frac{[B^4]}{[B^3]}.$$

These are comparable with QCD provided all other fluctuations removed.

SG, 0909.4630 (2009)

Microscopic non-Gaussianity



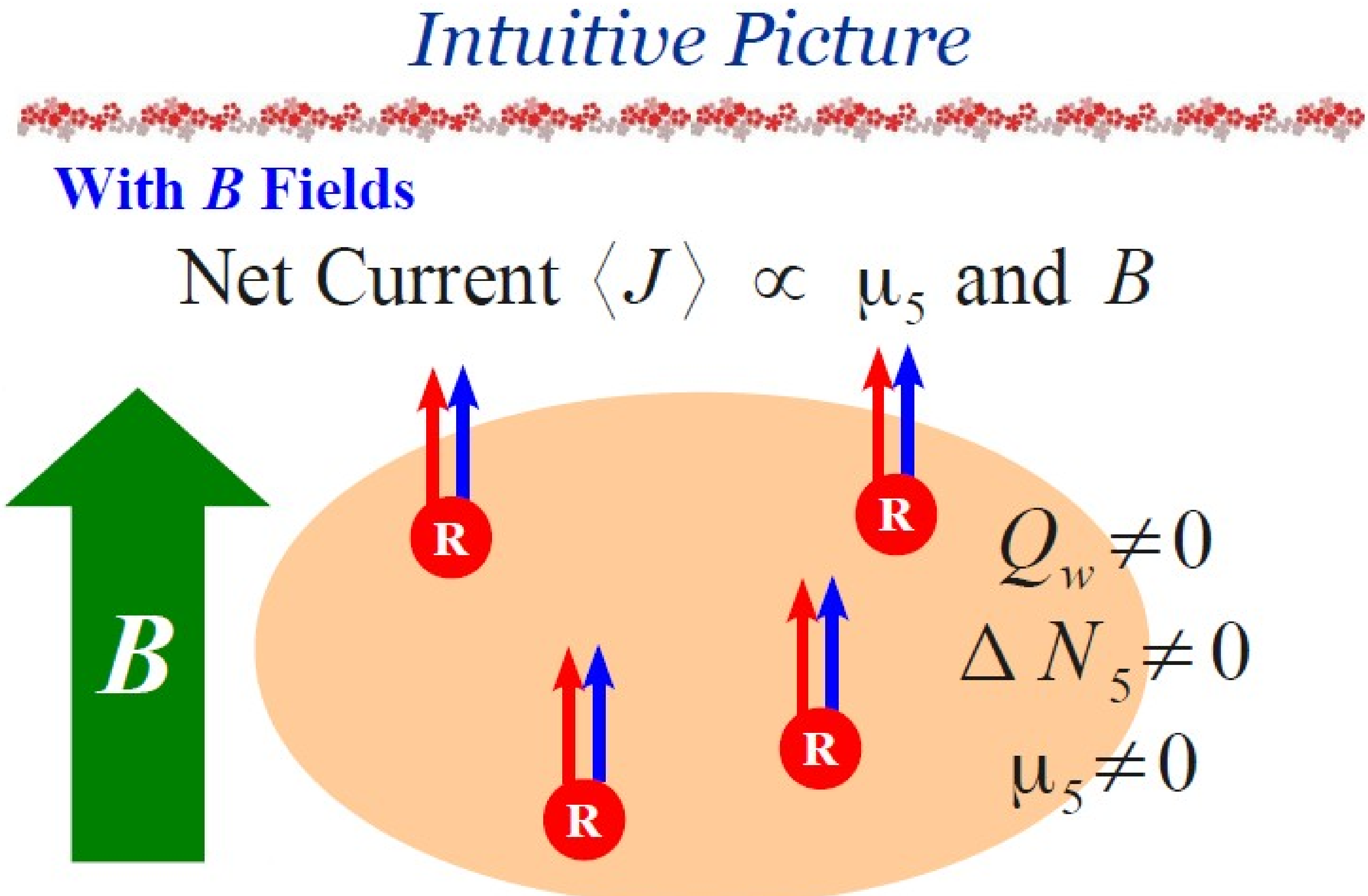
STAR Collaboration, 1004.4959 (2010)

Surprising agreement with lattice QCD: implies non-thermal sources of fluctuations are very small; temperature does not vary across the freezeout surface.

Gavai, SG, 1001.3796 (2010)

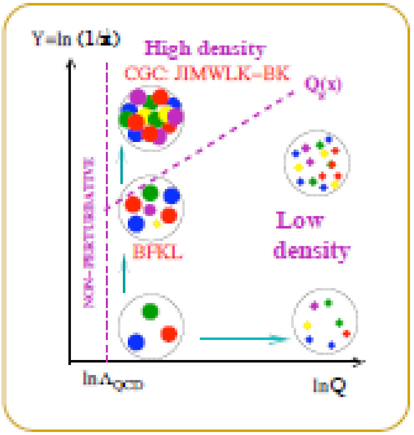
Lattice prediction: $\mathcal{K}\sigma^2 = 0.88 \pm 0.0$

Chiral Magnetic Effect



K. Fukushima

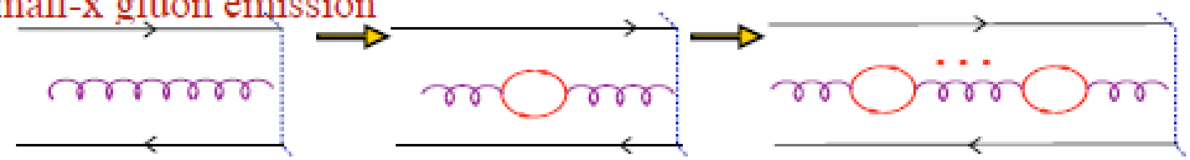
High-energy scattering, small x, gluon saturation, Color Glass Condensate



"BK-JIMWLK" $$\frac{\partial \phi(\mathbf{x}, \mathbf{k_t})}{\partial \ln(\mathbf{x_0}/\mathbf{x})} \approx \mathcal{K} \otimes \phi(\mathbf{x}, \mathbf{k_t}) - \phi(\mathbf{x}, \mathbf{k_t})^2$$

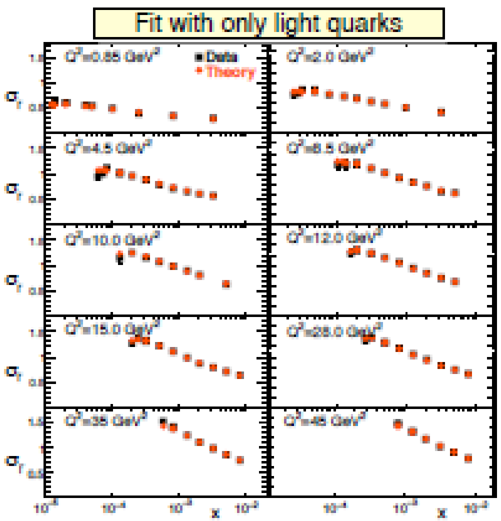
radiation recombination

LO: $\alpha_s \ln(1/x)$ small-x gluon emission — NLO — Running coupling

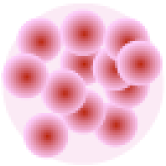


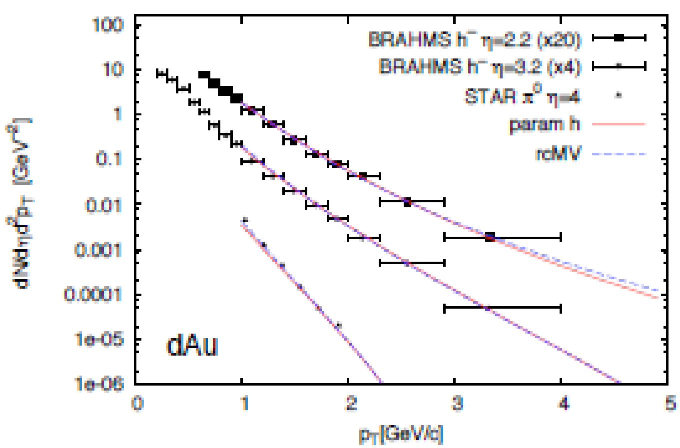
CGC: NLO corrections allow for successful description of data in different collision systems

e+p structure functions
HERA

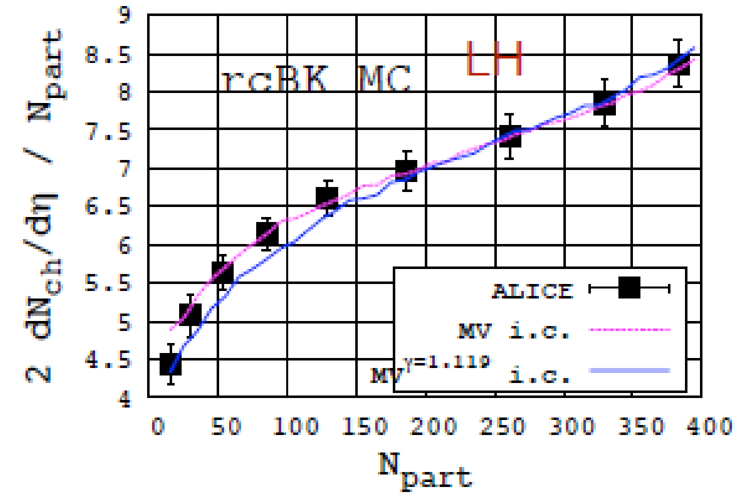


d+Au forward production
RHIC





A+A multiplicities
RHIC LHC



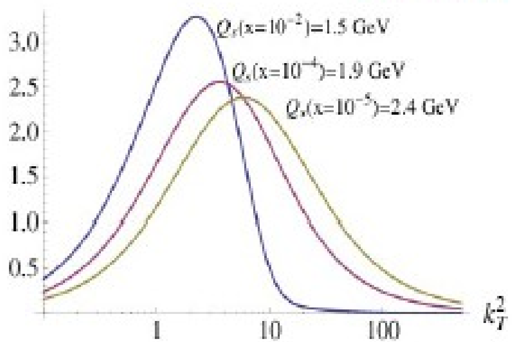
J. Albacete

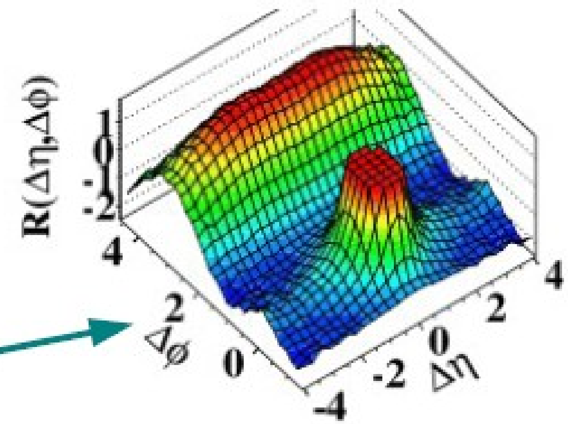
Forward physics way to constrain gluon both at small and large pt

Possible determination of shape of gluon?
Finally with LHC we can probe gluon

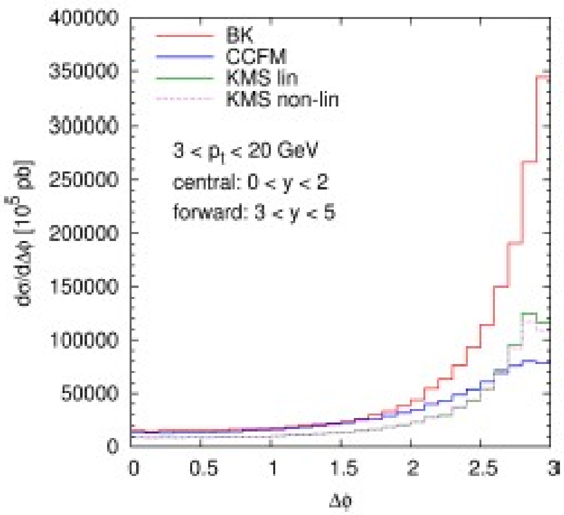
Ridge observed at CMS in 2010

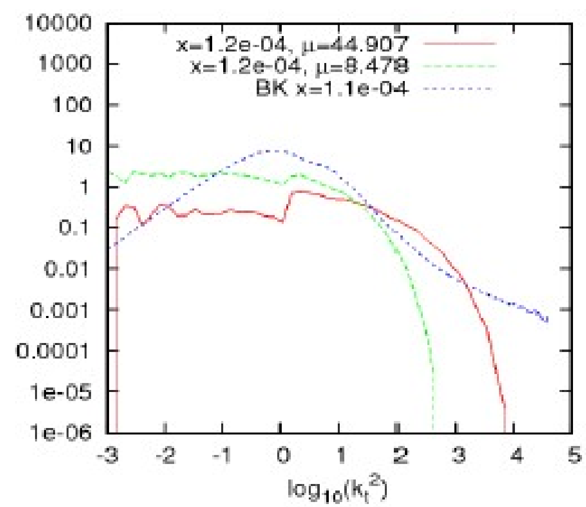
Dumitru, Venugopalan, Gellis McLerran, Lapp '10





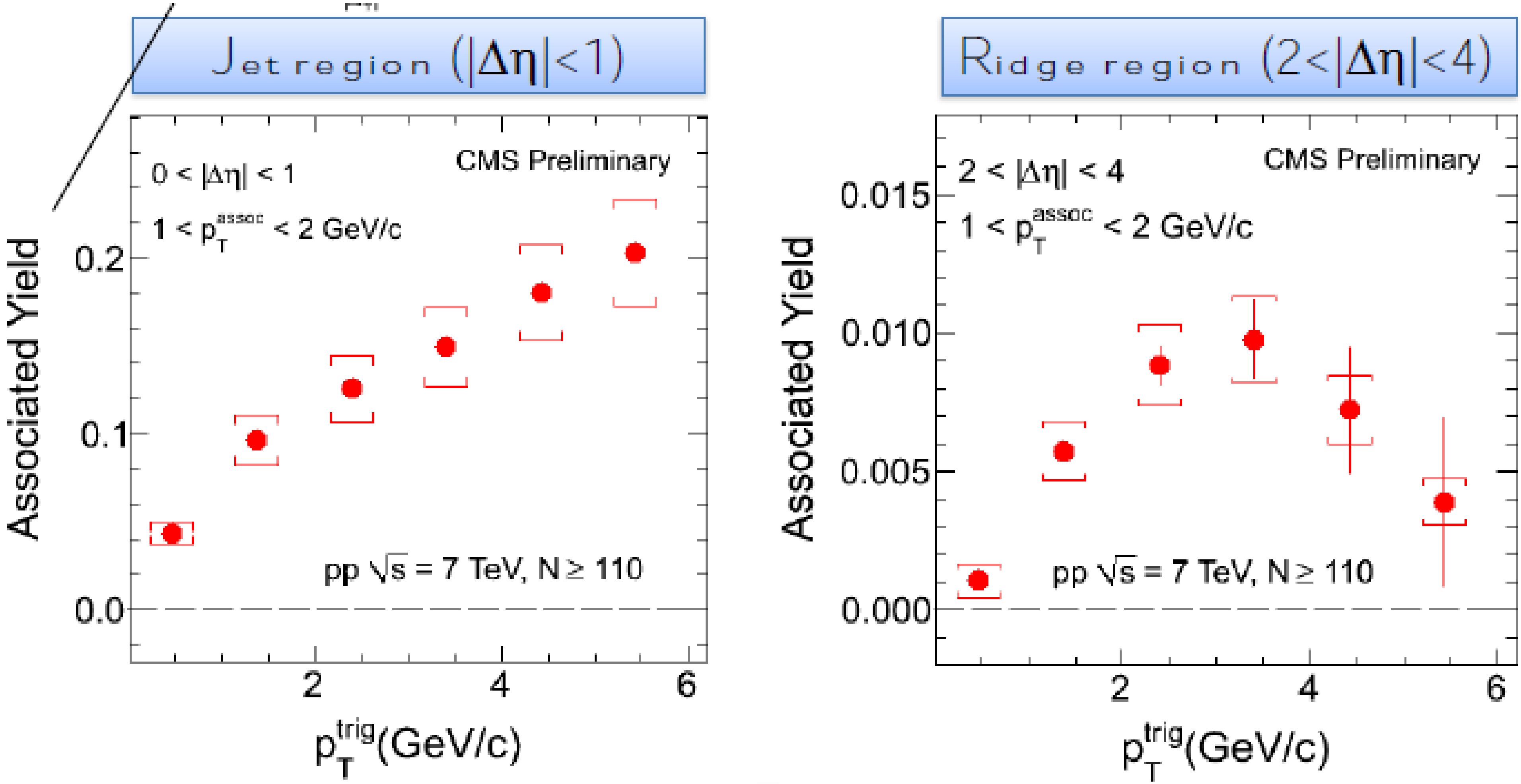
The maximum of glue essential for



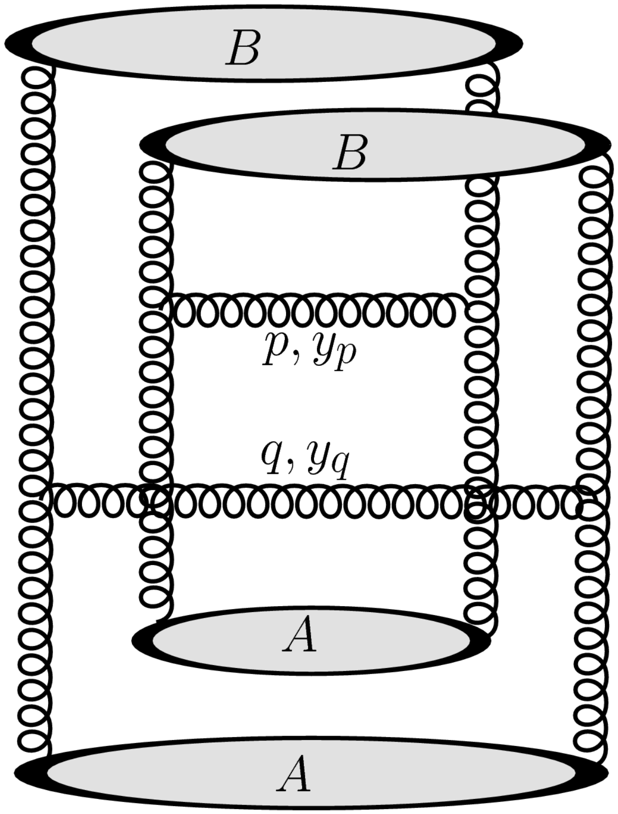


Kutak, Sapeta
in preparation

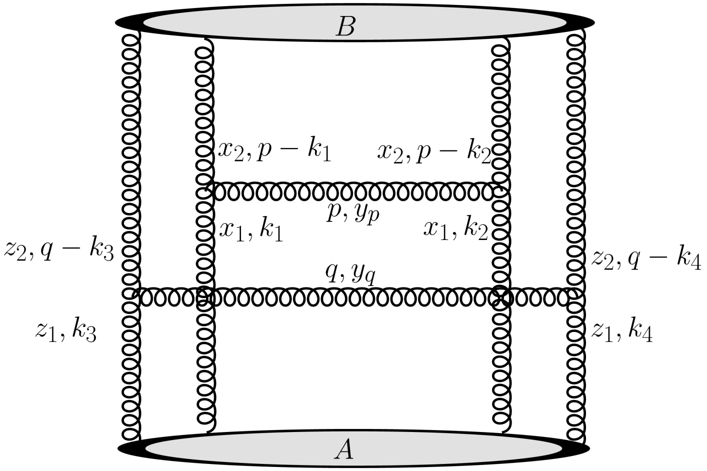
CMS: ridge sees a scale! Possibly ~Qs



Semi-hard scale, assume main contribution from two-gluon production with Δη>1, ΔΦ«π



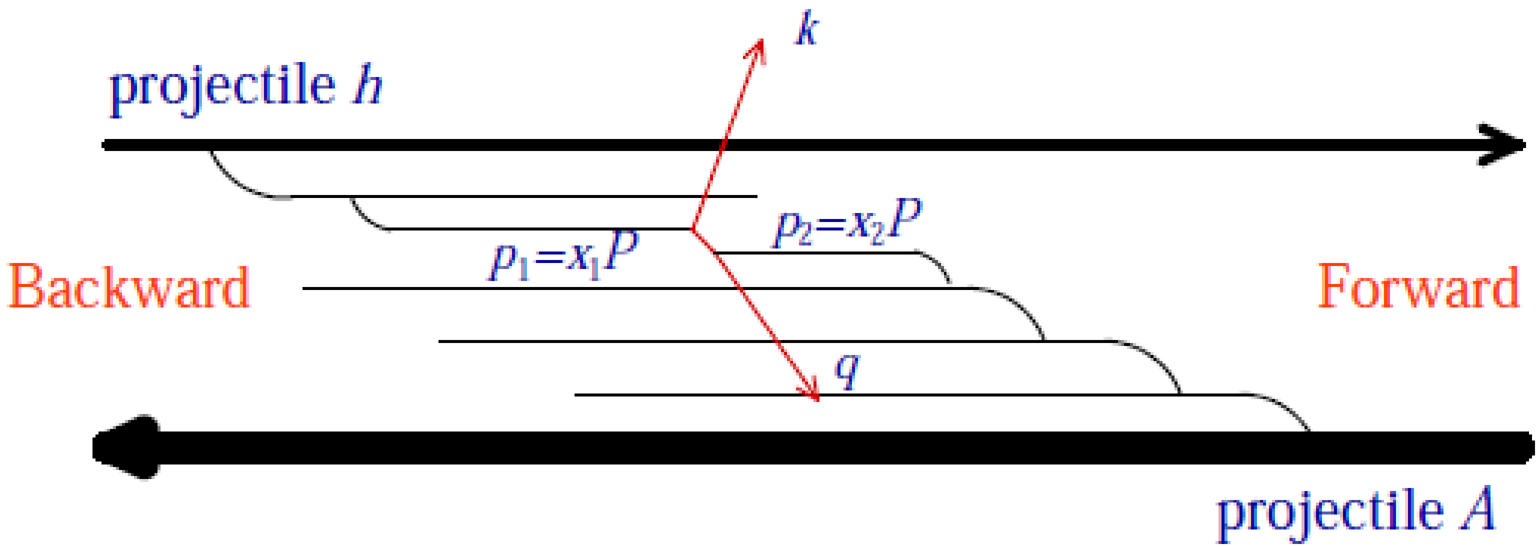
more generally:



“multi-parton interaction”

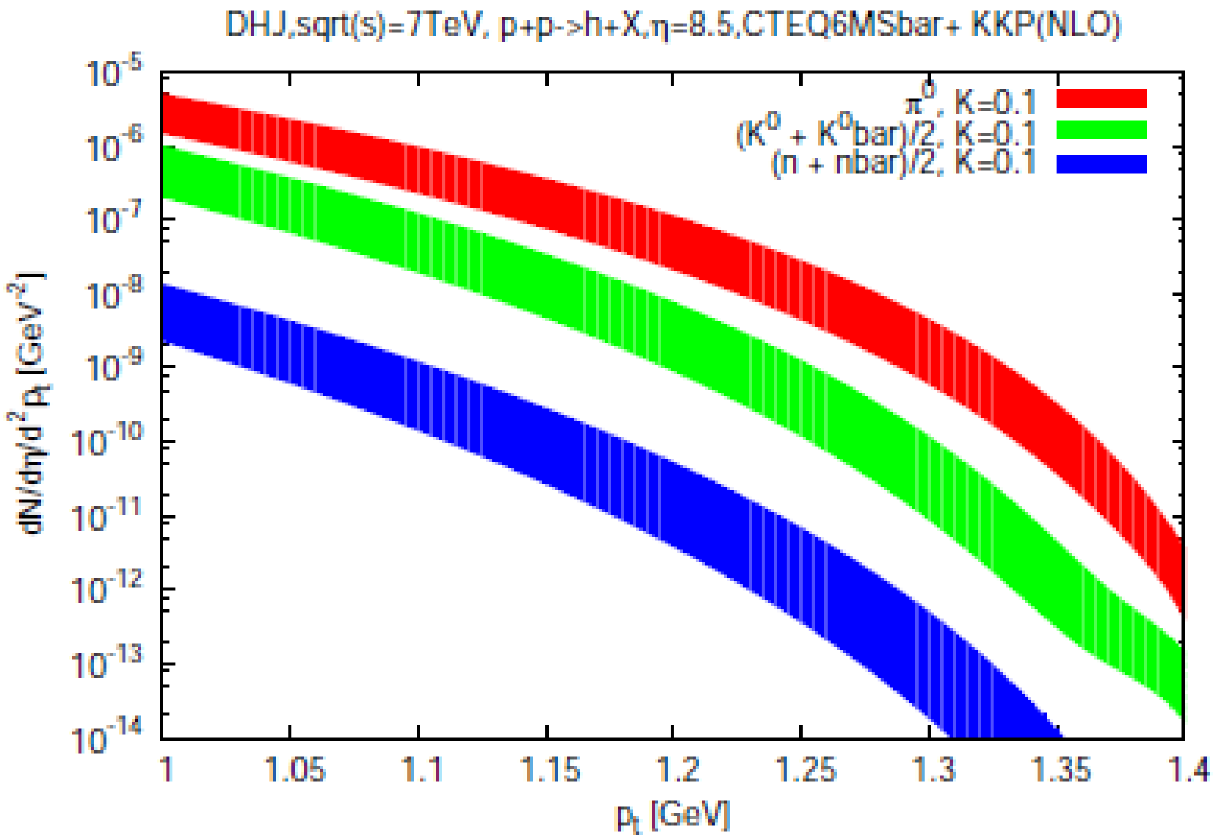
forward pA @ LHC:

- Collider energies $\sqrt{s} \gg k_\perp$ in forward region $y > 0$,
  = kinematic regime of $x_2 = \frac{|k_\perp| e^{-y_k} + |q_\perp| e^{-y_q}}{\sqrt{s}} \ll 1$



- many gluons emerge due to BFKL cascade
- atomic number $A > 1$ enhances the gluon density

H. Fujii



- Hadron productions (π^0, K^0 and n) at $\eta = 8.5$ at 7 TeV (LHCf) is being studied in this framework

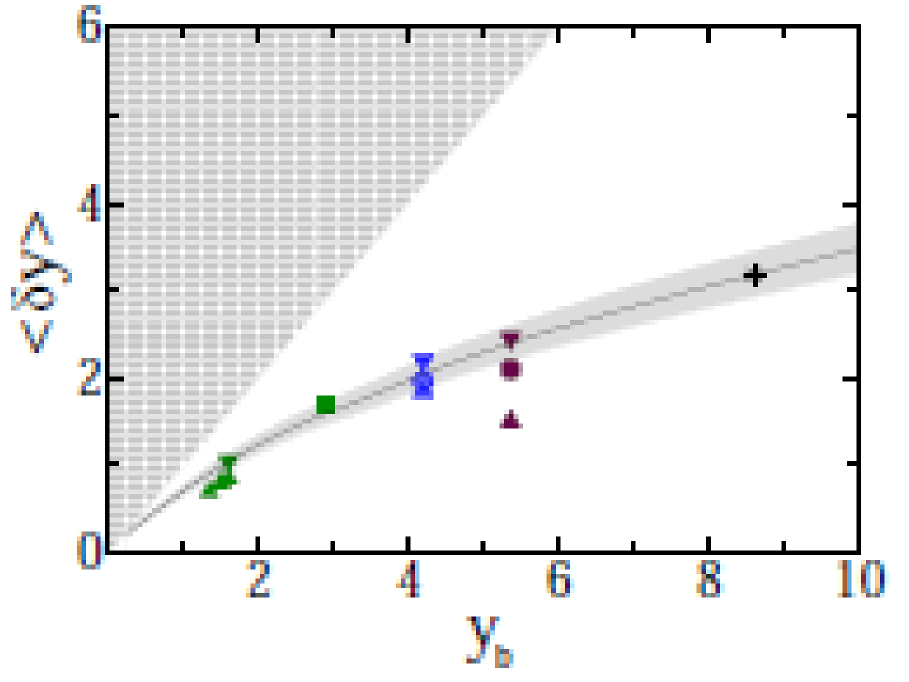
“stopping” of large-xF charges:

important for cosmic ray airshower simulations

S. Ostapchenko

net baryon distribution G. Wolschin

$$y_{\text{peak}} = \frac{y_B - \log A^{1/6}}{1+\lambda}$$



very forward bremsstrahlung photons ? ($\vartheta \sim 1/\gamma$)

→ deceleration of electric charges

$E_\gamma \sim \Delta y$

LHCf

B. Kopeliovich

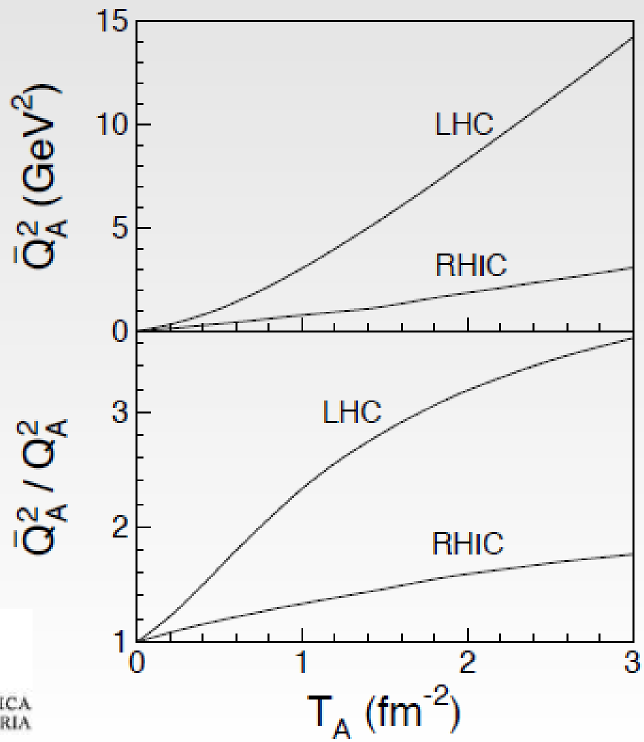
Boosted saturation scales

The usual relations for the gluon saturation scales Q^2_{sA} (Q^2_{sB}) in $pA(pB)$ collisions, in the case of collision of two nuclei A and B are replaced by the system of reciprocity equations,

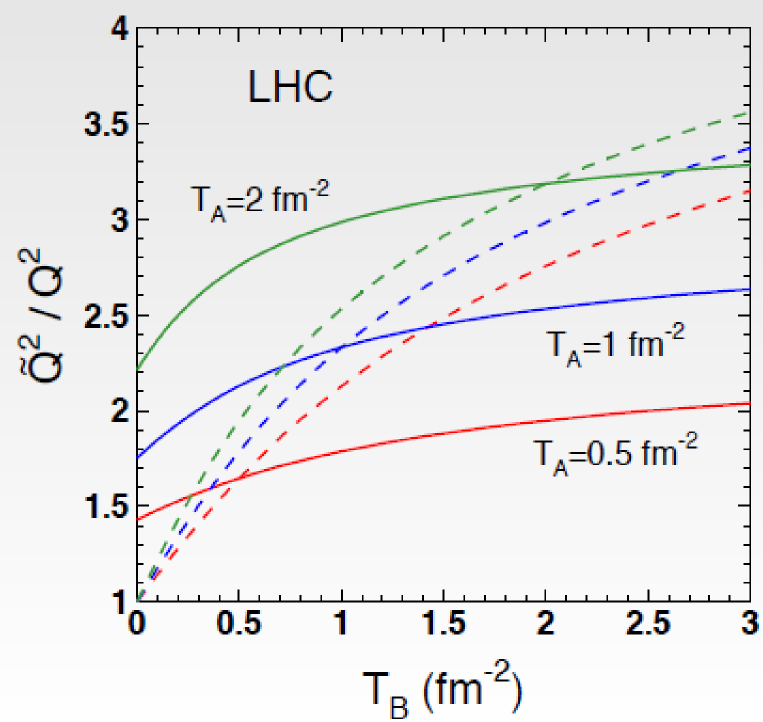
$$\tilde{Q}^2_{sB}(x_B) = \frac{3\pi^2}{2}\,\alpha_s(\tilde{Q}^2_{sA} + Q^2_0)\, x_B g_N(x_B, \tilde{Q}^2_{sA} + Q^2_0)\, T_B$$

$$\tilde{Q}^2_{sA}(x_A) = \frac{3\pi^2}{2}\,\alpha_s(\tilde{Q}^2_{sB} + Q^2_0)\, x_A g_N(x_A, \tilde{Q}^2_{sB} + Q^2_0)\, T_A$$

Central collisions $T_A = T_B$

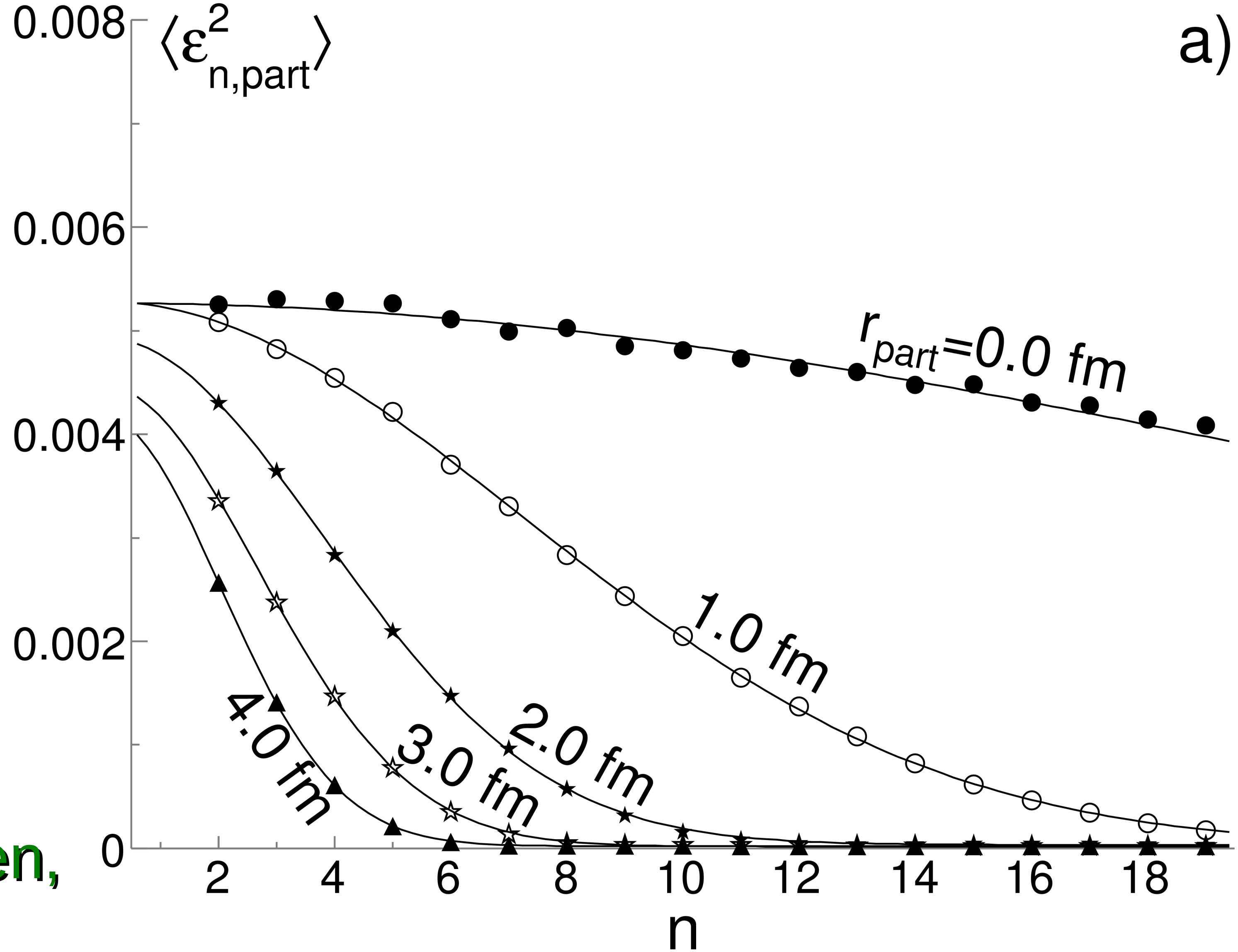


Non-central collisions, $T_A \neq T_B$



Initial state fluctuations in heavy-ion collisions, and their hydrodynamical evolution

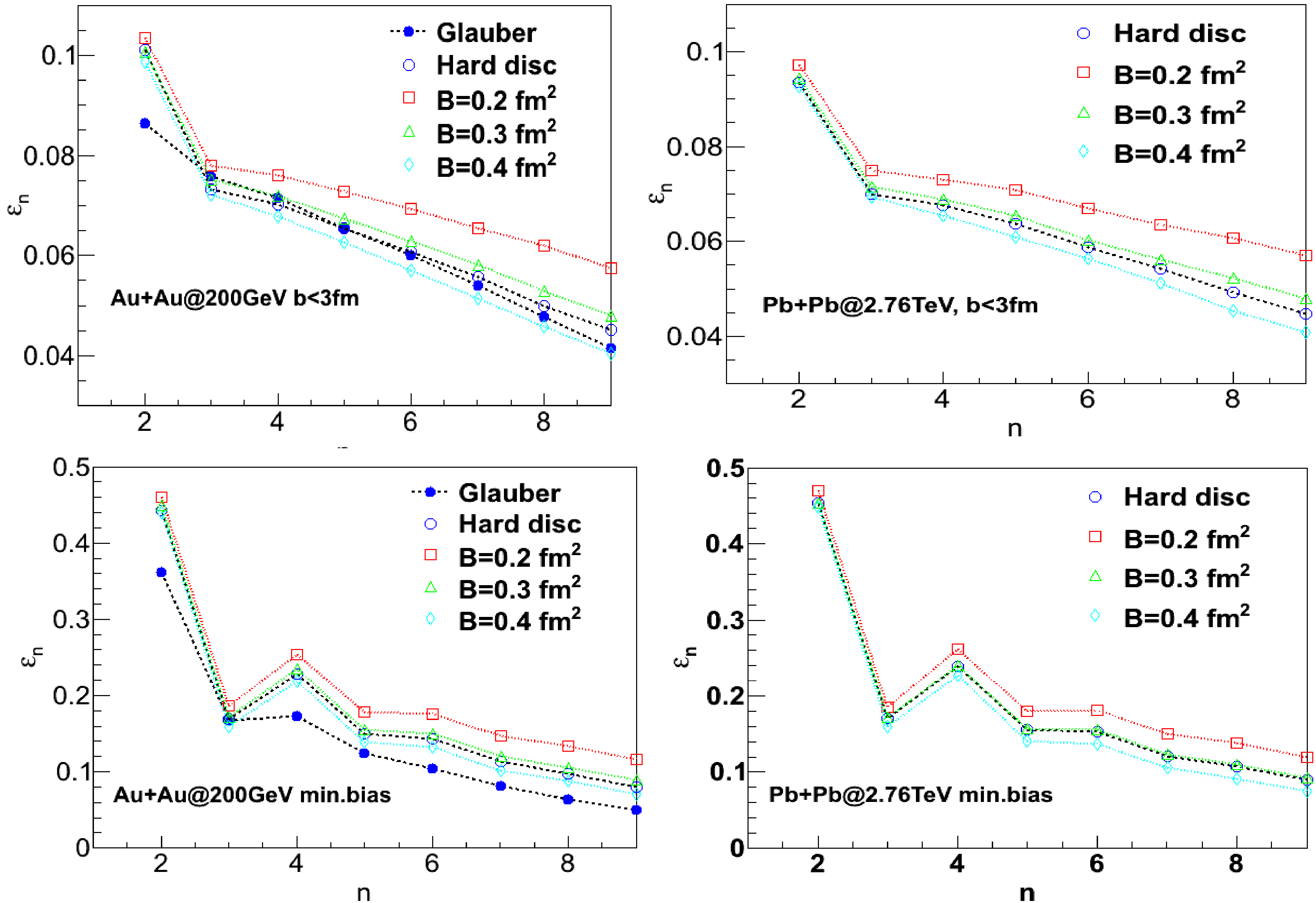
Higher-order moments and the length scale of fluctuations (analogy: CMB)



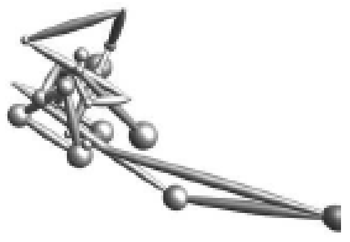
P. Sorensen,
A. Mocsy

Y. Nara

Eccentricity as a function of order

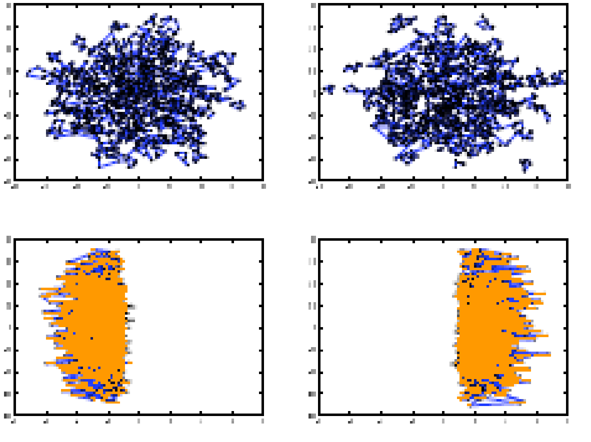


DIPSY: a BFKL Dipole Event Generator



- Colour dipoles in transverse space, evolved in rapidity.
- Saturation, NLL corrections, confinement, ...
- σ_{tot}, σ_{el}, $\sigma_{\text{diff ex}}$ in $\gamma^* p$ and pp, Minimum Bias pp.

- Extends to AA without extra model dependence.
- Similar to CGC, but with all fluctuations and correlations.
- Larger ε_3 than Glauber MC and KLN. Shows that flux tubes are not independent.

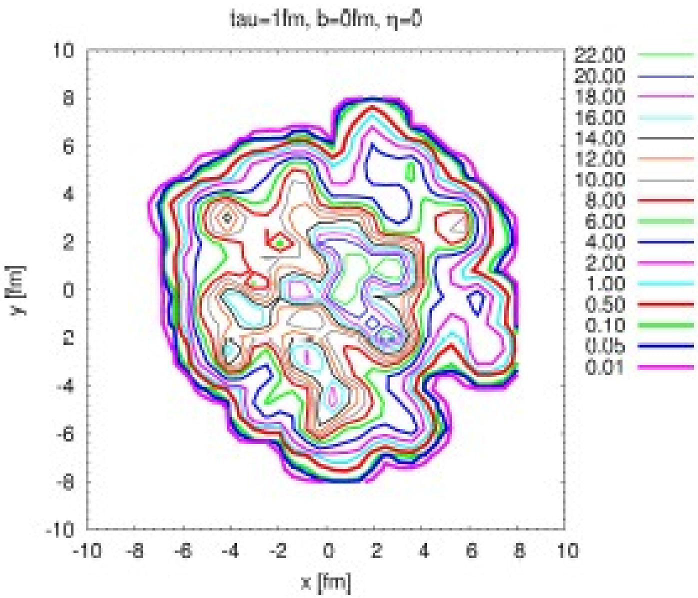


Summary

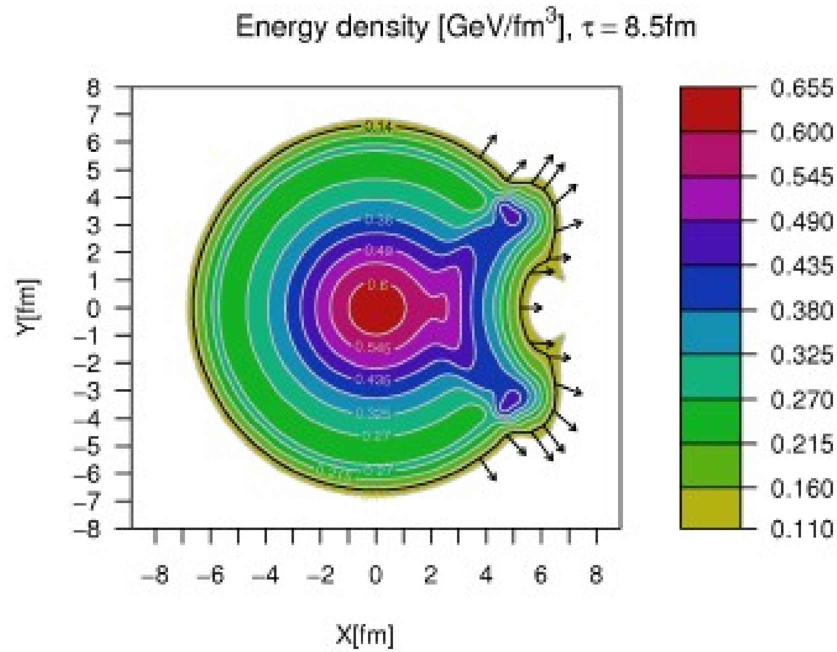
One-tube model to study the dynamics of ridge formation.

One peripheral tube is chosen.
The complex background is replaced by a smooth average distribution.
Boost-invariant longitudinal expansion.

NEXUS initial conditions



Particle emission in one-tube model



Y. Hama, P. Mota, F. Gardim, T. Kodama, W. Broniowski

- Azimuthal distibution with two symmetrical peaks with respect to the tube position is prouced. $\Rightarrow$ Two-particle correlation with three-ridge structure.
- In-plane/out-of-plane effect can be understood in terms of this model. Due to the multiplicity fluctuation, the mixed-event procedure does not subtract completely the background v_2 , givig an additional trigger-dependent contribution to the resultant two-particle correlation.

Extracting Science from Data & Models

MADAI Collaboration:

a multi-institutional and multi-disciplinary collaboration to develop next generation tools for complex model-to-data knowledge extraction

Michigan State University
RHIC Physics: Scott Pratt
Supernova: Wolfgang Bauer
Astrophysics: Brian O'Shea and Mark Voit
Atmospheric Modeling: Sharon Zhong
Statistics: Dan Dougherty

Duke University
RHIC Physics: Steffen A. Bass and Berndt Müller
Statistics: Robert Wolpert

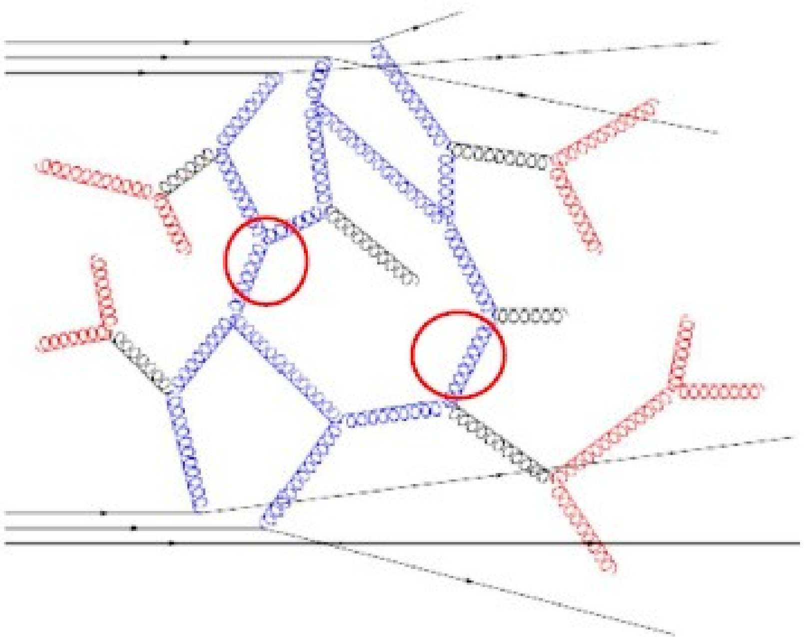
UNC & RENCI
Visualization: Xunlei Wu and Russell M. Taylor

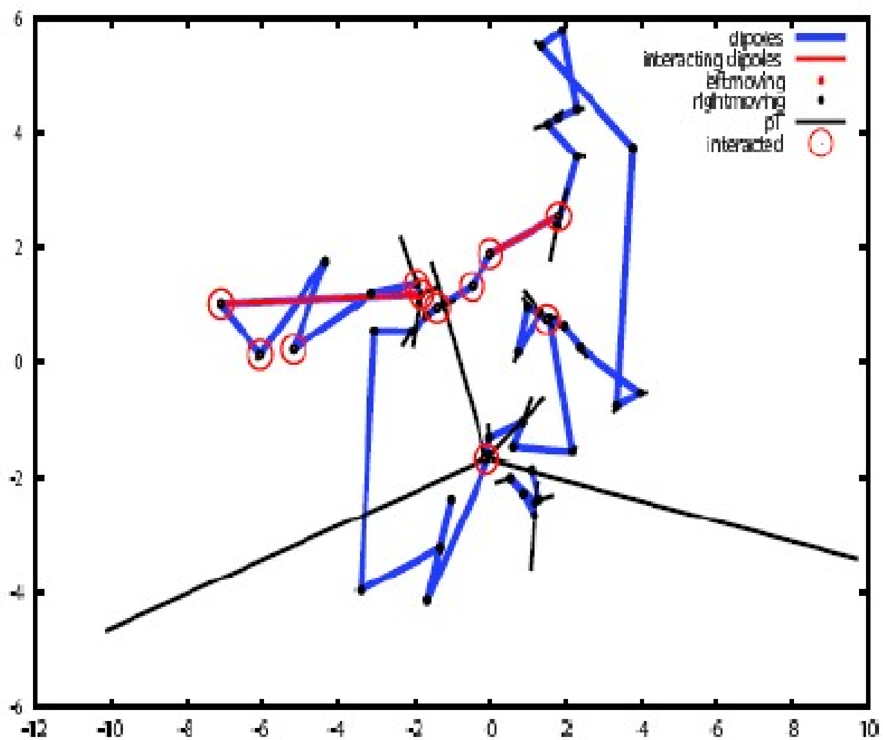
Funded by NSF CDI program (Cyber-Enabled Discovery Initiative)
- US$ 1,800,000 over 4 years

- develop a comprehensive transport framework, capable of describing the full time-evolution of a heavy-ion collision at RHIC and LHC
- identify the relevant physics parameters (EoS, QCD transport coefficients, matrix elements etc.) which are sensitive to the observables measured at RHIC & LHC
- develop a statistical tool set to determine the compatibility of a chosen set of parameters with experimental data
- conduct a systematic study in that multi-dimensional parameter-space and via comparison to data to determine the properties of the QCD medium created at RHIC & LHC

Y. Hatta
C. Flensburg

Deconstructing high-multiplicity events





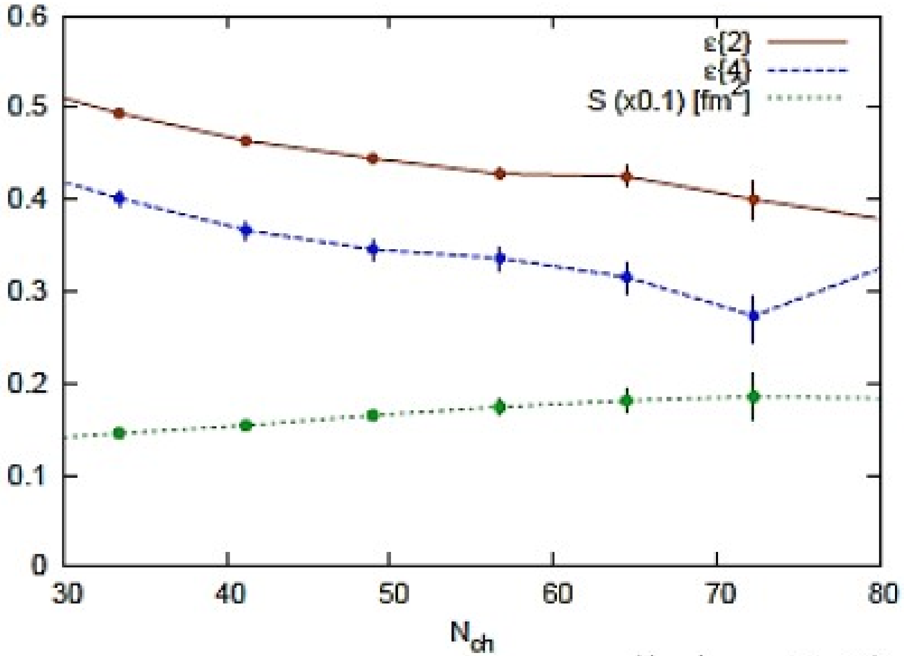
High-multiplicity pp events

= Upward fluctuation in the gluon number in proton's w.f.

+ Multiple (more than 10) parton-parton interactions

Eccentricity in pp at 7 TeV

Shape of the area occupied by the "liberated" gluons.



$(|\eta| < 0.9)$

$$\epsilon_{\rm part} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

$$\epsilon\{2\} = \sqrt{\langle \epsilon_{\rm part}^2 \rangle}$$

$$\epsilon\{4\} = \left(2\langle \epsilon_{\rm part}^2 \rangle^2 - \langle \epsilon_{\rm part}^4 \rangle\right)^{\frac{1}{4}}$$

$v_2\{4\}$ ALICE data vs. DIPSY

Avsar et al., 1106.4356 [hep-ph]

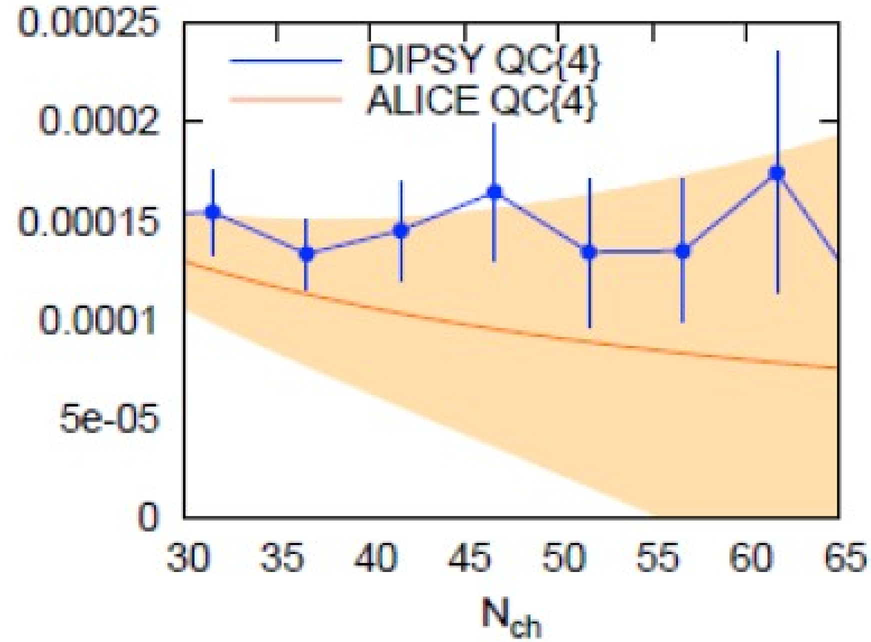
$(v_2\{4\})^4$ negative in the data and in MCs (no flow)

$(v_2^{\text{flow}}\{4\})^4$

$$\sim (\epsilon\{4\})^4 = 2\langle\epsilon_{\text{part}}^2\rangle^2 - \langle\epsilon_{\text{part}}^4\rangle$$

positive in the flow scenario

$-(v_2\{4\})^4$



Sign change at large Nch → Possible signature of flow.

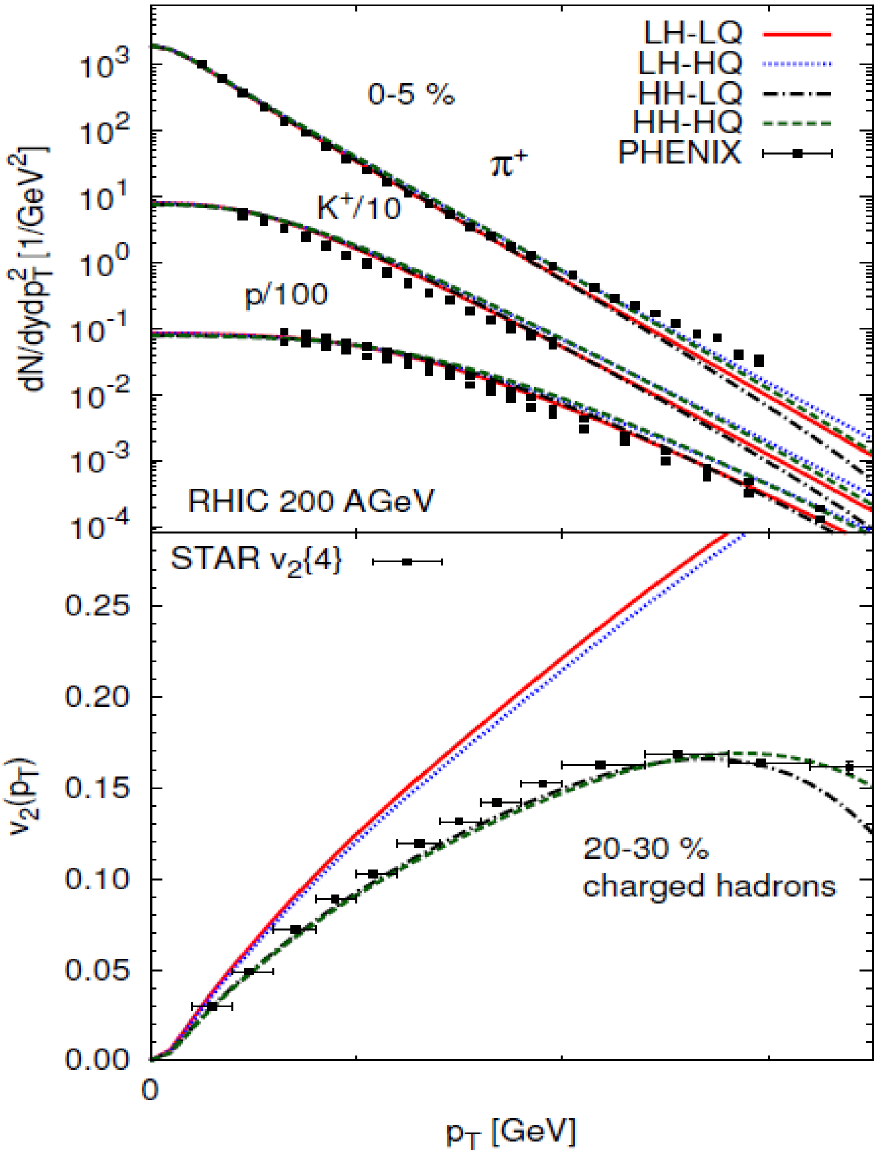
Dissipative relativistic hydrodynamics of heavy-ion collisions

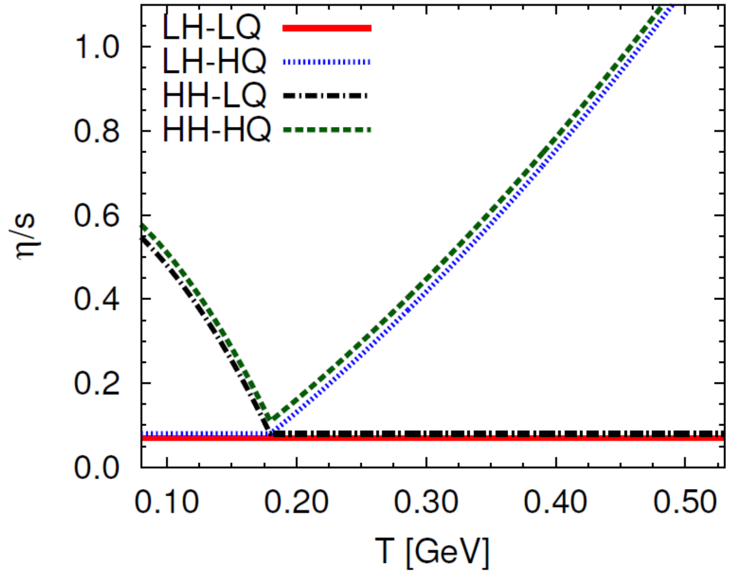
S. Muroya
G. Denicol

Israel Stewart theory etc...

transport coefficients: viscosity η,
stress relaxation time τ

Results - RHIC





- elliptic flow is **independent** of high temperature η/s

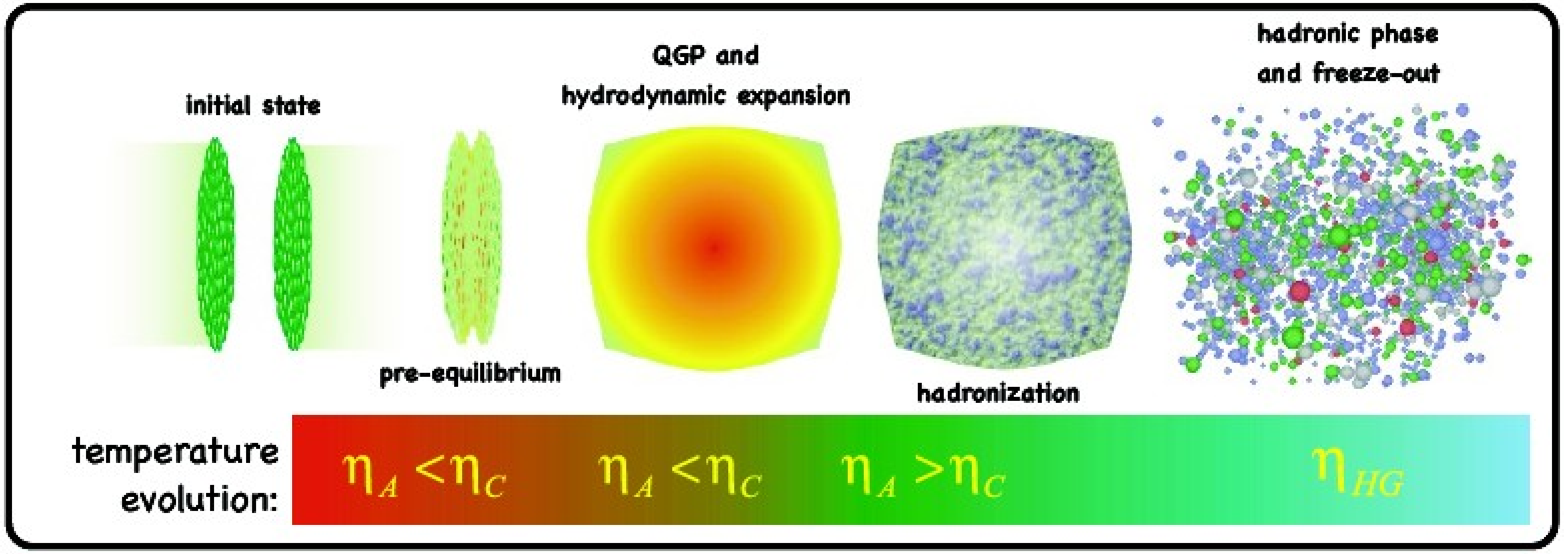
G. Denicol

Collisional vs. Anomalous Viscosity

- sum-rule for system w/ 2 viscosities: (derived from variational principle)

$$\frac{1}{\eta} = \frac{1}{\eta_A} + \frac{1}{\eta_C}$$

- smaller viscosity dominates in system w/ 2 viscosities!
- for reasonable values of g: $\eta_A < \eta_C$



- anomalous viscosity dominates total shear viscosity during early QGP evolution
- a small viscosity does not necessarily imply strongly interacting matter!

S.A. Bass

High e-density QCD probes

- R_{AA} and N_{coll}
- Quarkonium
- Jet energy loss
- Heavy Q energy loss

N_{coll} beyond the Glauber model

- Glauber single-channel model: $$\mathbf{n^{Gl}_{coll}(b) = \frac{\sigma^{hN}_{in} T_A(b)}{P^{Gl}_{in}(b)}}$$

$$\mathbf{P^{Gl}_{in}(b) = \frac{d\sigma^{hA}_{tot}}{d^2b} - \frac{d\sigma^{hA}_{el}}{d^2b} - \frac{d\sigma^{hA}_{qel}}{d^2b} = 1 - e^{-\sigma^{hN}_{in} T^h_A(b)}}$$

If diffractive excitation of the proton and/or the nucleus escape detection, their cross sections should be subtracted as well. However, diffraction cannot be treated self-consistently within the Glauber model.

- Gribov multi-channel approach: $$\mathbf{n^{Gr}_{coll}(b) = \frac{(\sigma^{hN}_{in} - \sigma^{hN}_{diff}) T_A(b)}{P^{Gr}_{in}(b)}}$$

$$\mathbf{P^{Gr}_{in}(b) = \frac{d\sigma^{hA}_{tot}}{d^2b} - \frac{d\sigma^{hA}_{el}}{d^2b} - \frac{d\sigma^{hA}_{qel}}{d^2b} - \frac{d\sigma^{hA}_{diff}}{d^2b} - \frac{d\sigma^{hA}_{qsd}}{d^2b} - \frac{d\sigma^{hA}_{tsd}}{d^2b} - \frac{d\sigma^{hA}_{dd}}{d^2b}}$$

All these cross sections haven't been measured, can be only calculated.

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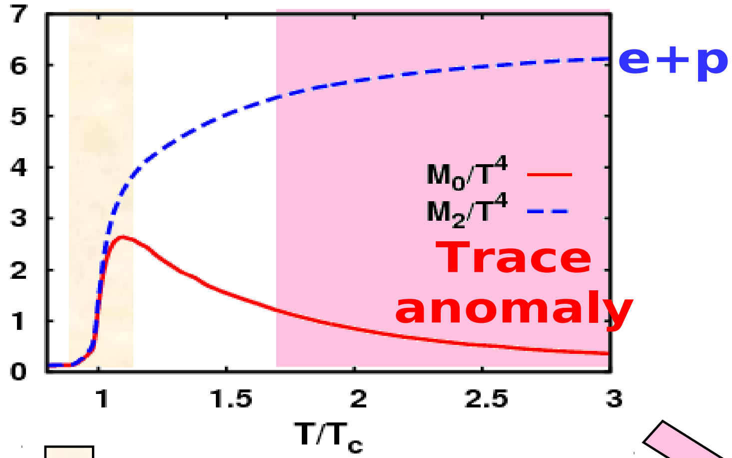
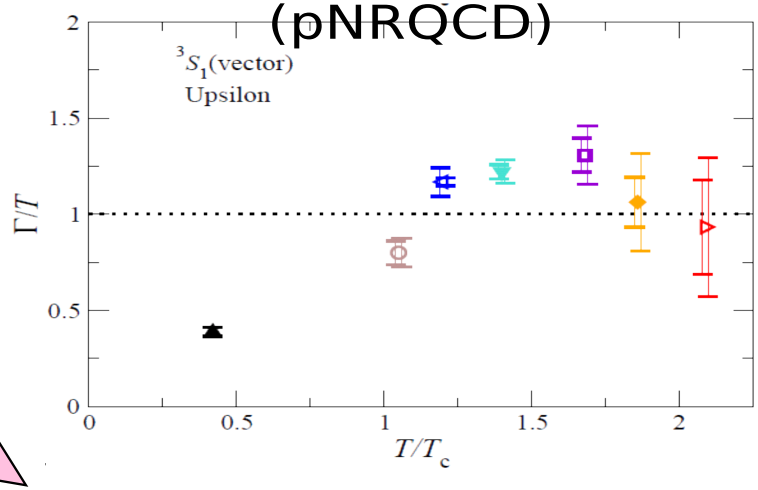
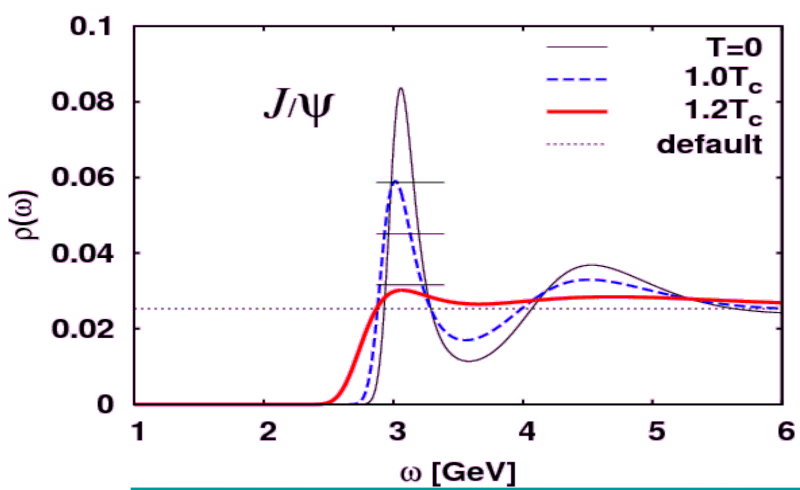
Charmonium: T~ Tc   Bottomonium : T >> Tc

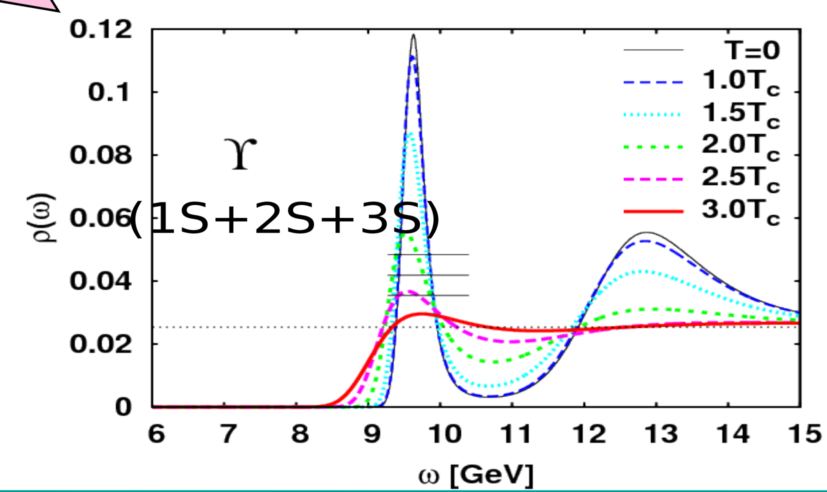


Lattice NRQCD vs EFT (pNRQCD)

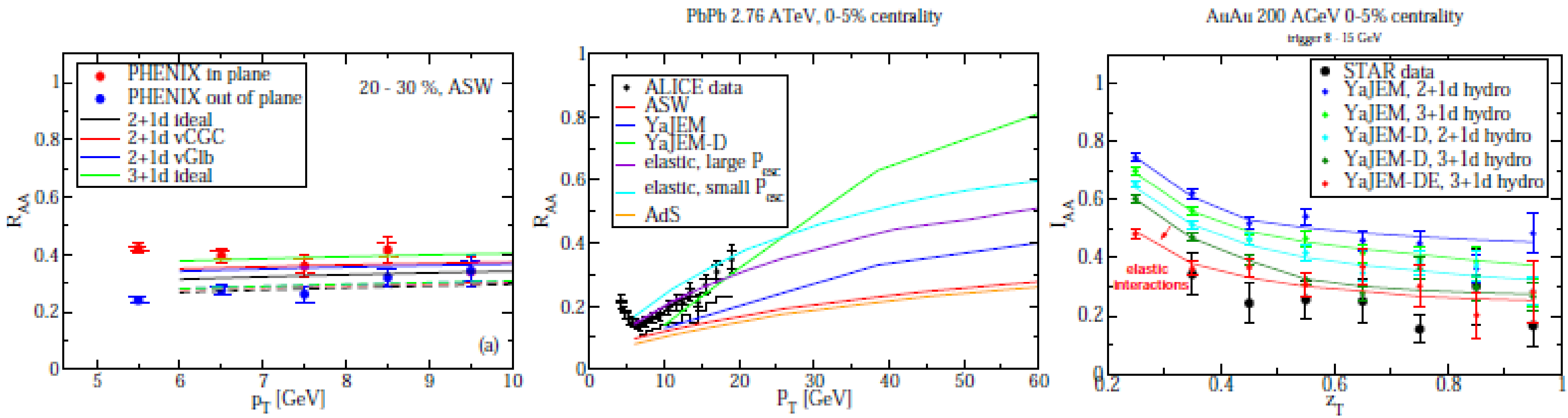


OPE+Sum Rule+MEM





Jets in medium



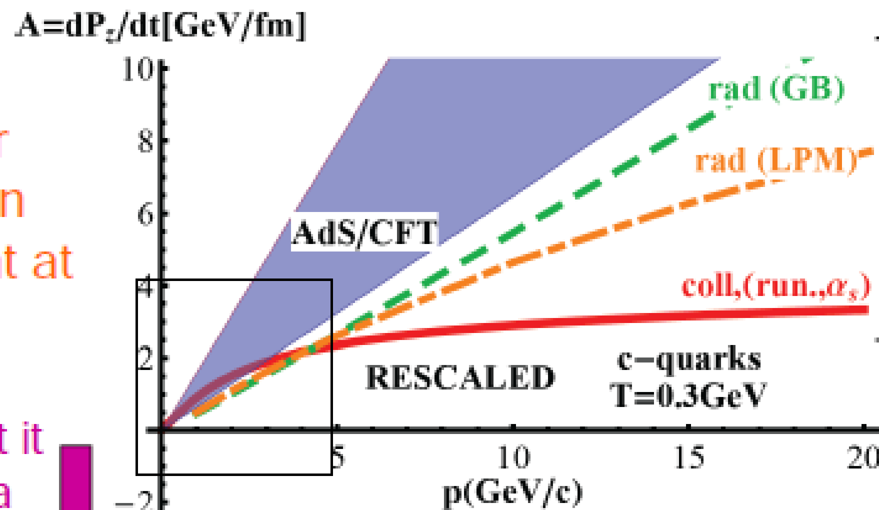
- assuming the best choice of hydro model for each parton-medium interaction model: (all models tuned to describe R_{AA} in central 200 AGeV AuAu collisions)

	R_{AA}@RHIC (centrality)	R_{AA}@LHC (P_T)	I_{AA}@RHIC	I_{AA}@LHC
elastic	**fails!**	works	**fails!**	fails
ASW	works	fails	marginal	works
AdS	works	**fails!**	marginal	works
YaJEM	fails	fails	fails	fails
YaJEM-D	works	works	marginal	marginal
YaJEM-DE	works	works	works	works

T. Renk

QGP properties: update on stopping power

Gathering all *rescaled* models (*coll. and radiative*) compatible with RHIC R_{AA}:



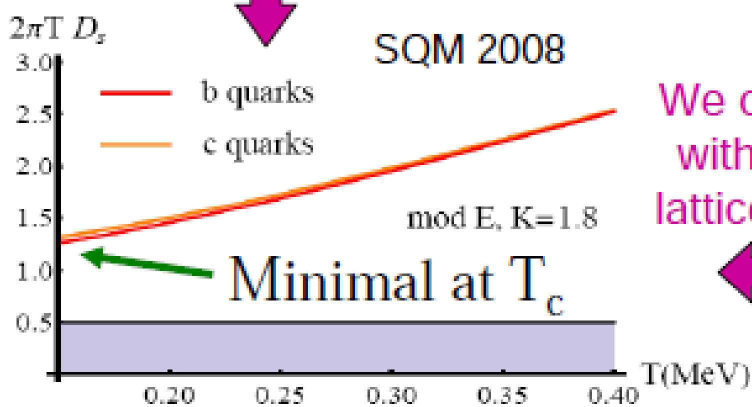
Similar diffusion coefficient at low p

Present RHIC experiments cannot resolve between those various trends

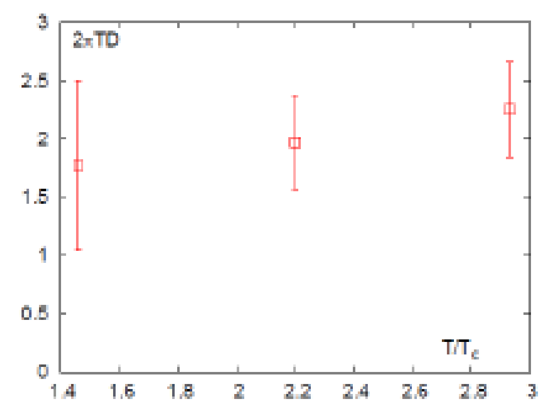
quite consistent as the drag coefficient reflects the average momentum loss (per unit time) => large weight on x ~ 1

Hope that LHC will do !!!

We extract it from data



We compare with recent lattice results



Kaczmarek Bad Honnef 2011

Lesson n°3: Yes, it is really possible to reveal some fundamental property of QGP using HQ probes

P.B. Gossiaux

- Physics of intense laser fields / QED in strong field
  K. Homma, Y. Suto, Y. Fujii
- pQCD jet showers   Z. Nagy
- Higgs   Y. Okada
- ...

ISMD 2011
featured a broad and up
to date theory program !

QCD, QED, BSM

Many thanks to the organizers !

どうもありがとうございました