Berndt Müller

BNL Users Workshop
on RHIC Future Strategy

BNL, 21-24 June 2011

Compelling open and Quantitatively addressable Questions requiring a Next generation of RHIC

Take 1

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Overview

- The Liquid QGP
  - Transport coefficients
  - Fluctuations
  - Equation of state
- The Opaque QGP
  - Quark energy loss
  - Jet quenching
  - Color screening
- The Flavored QGP
  - Susceptibilities
  - Critical region

Phases of exploration

Phases of exploration

Charting
the Territory
Phase

Smoking Gun
Phase

Tourist Attraction Phase

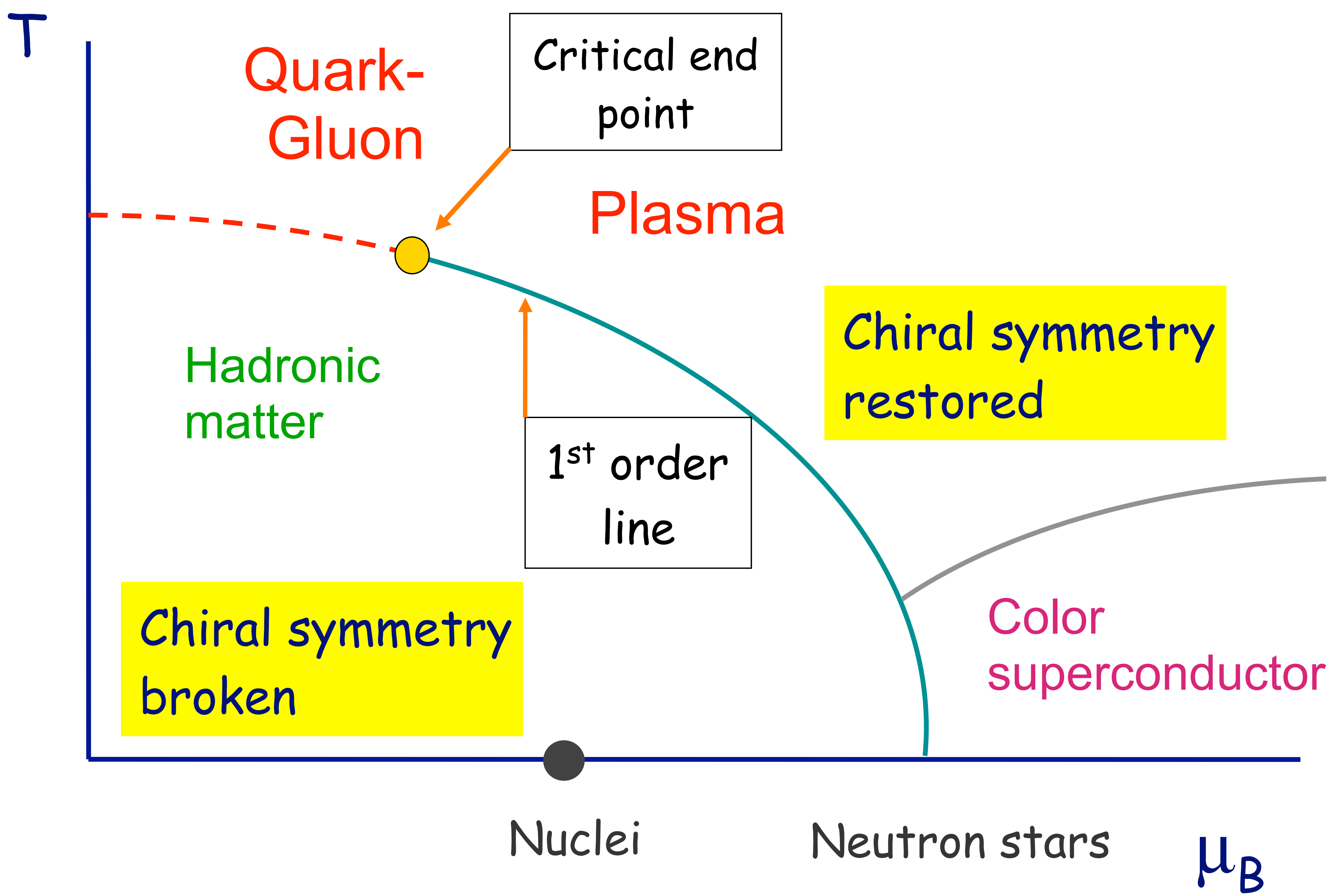
Precision
Measurement
Phase

A Grand Challenge

- How can we clarify the understanding of fluids without quasiparticles, whose nature is a central mystery in so many areas of science?
- We are developing more, and better, ways of studying the properties and dynamics of Liquid QGP — "our" example of a fluid without quasiparticles.
- At some short length scale, a quasiparticulate picture of the QGP must be valid, even though on its natural length scales it is a strongly coupled fluid. It will be a challenge to see and understand *how* the liquid QGP emerges from short-distance quark and gluon quasiparticles.

K. Rajagopal, Opening Theory Talk QM2011

QCD phase diagram



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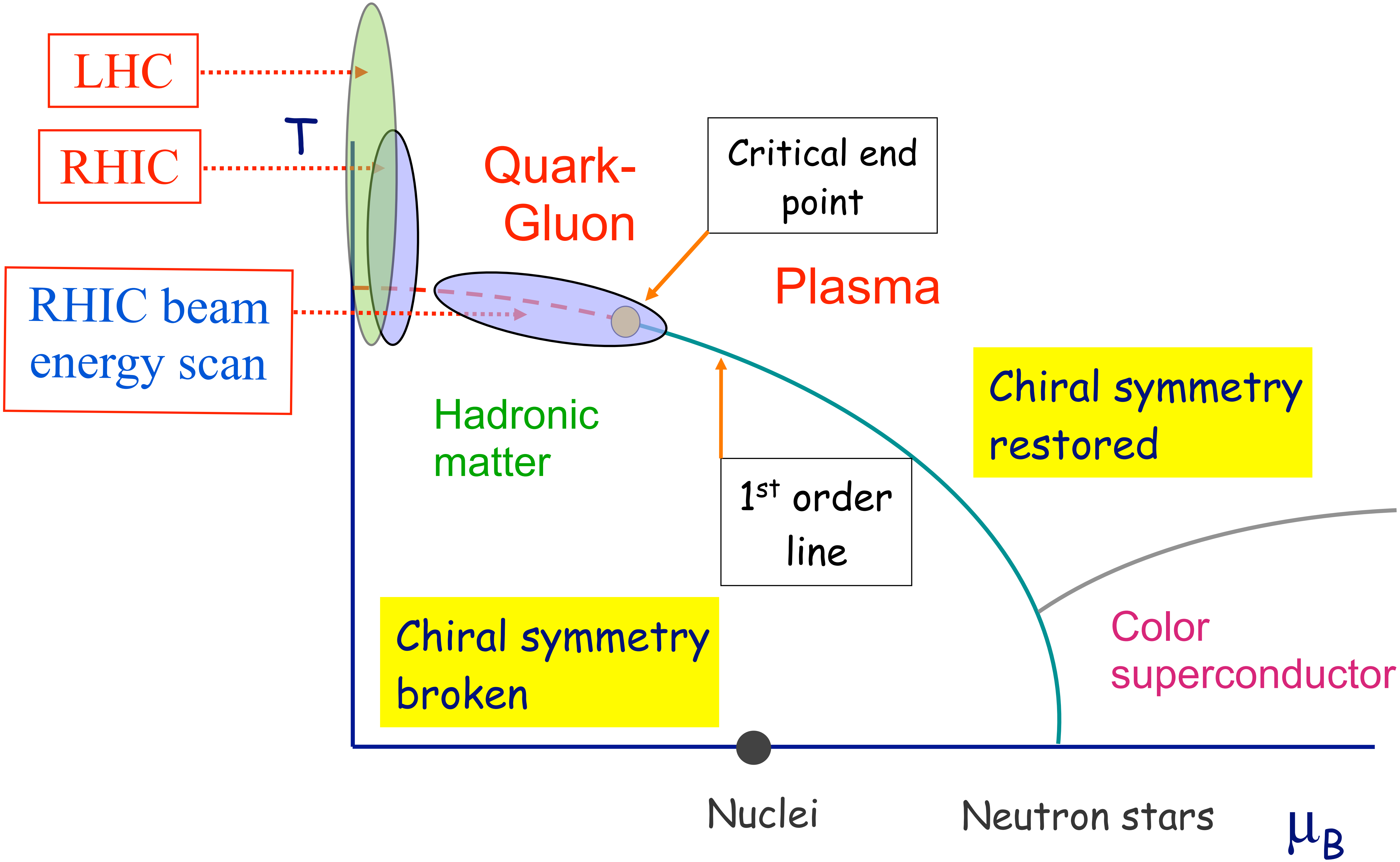


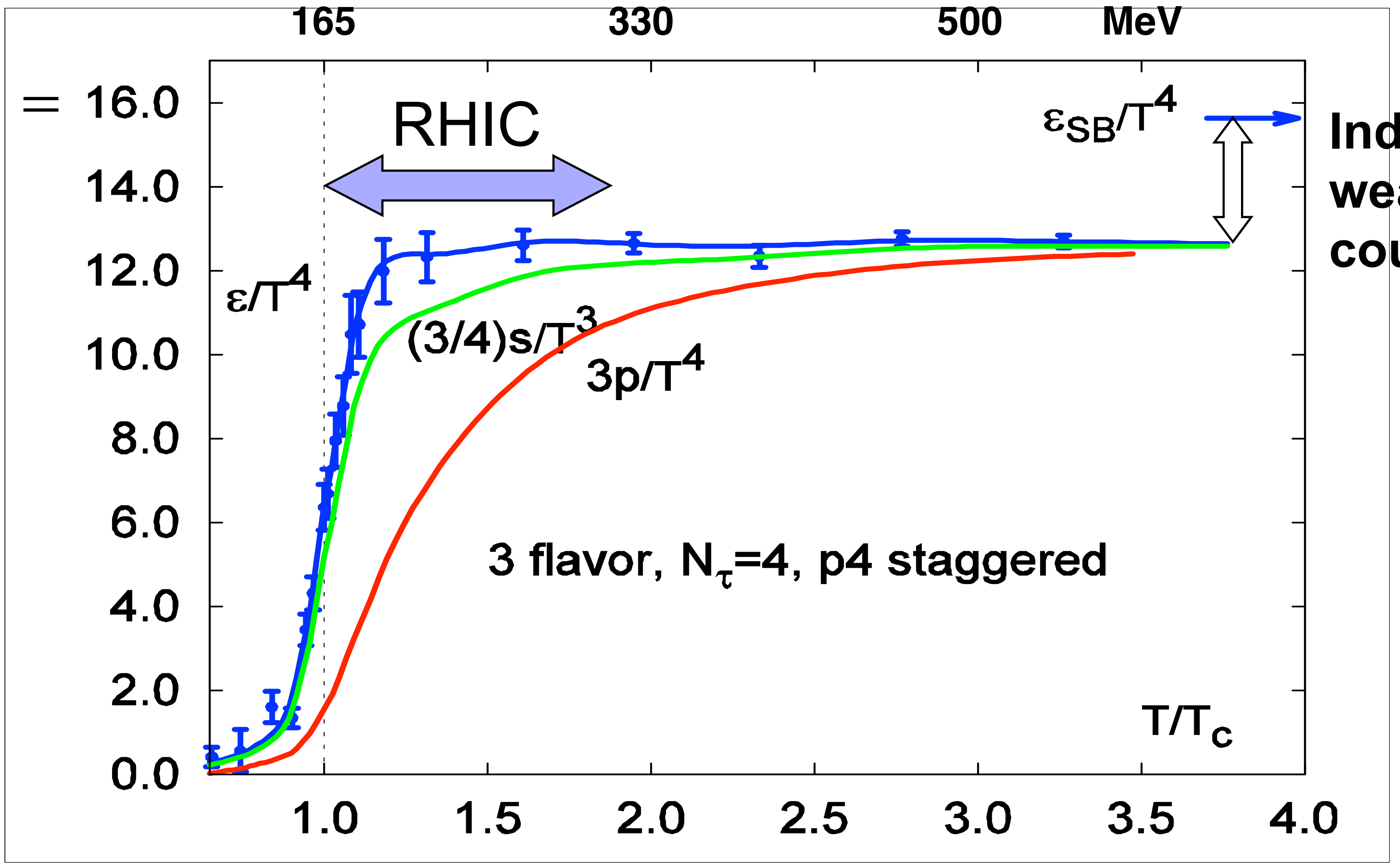
QCD equation of state

gluons quarks

Degrees of freedom : $\nu = \left[\left(\underbrace{2}_{\text{spin}} \times \underbrace{8}_{\text{color}} \right) + \frac{7}{4} \times \left(\underbrace{2}_{\text{spin}} \times \underbrace{3}_{\text{color}} \times \underbrace{N_f}_{\text{flavor}} \right) \right] \times \left(1 - O(g^2) \right)$

$\frac{\pi^2}{30}\nu =$

Lattice QCD



Indication of weak or strong coupling?

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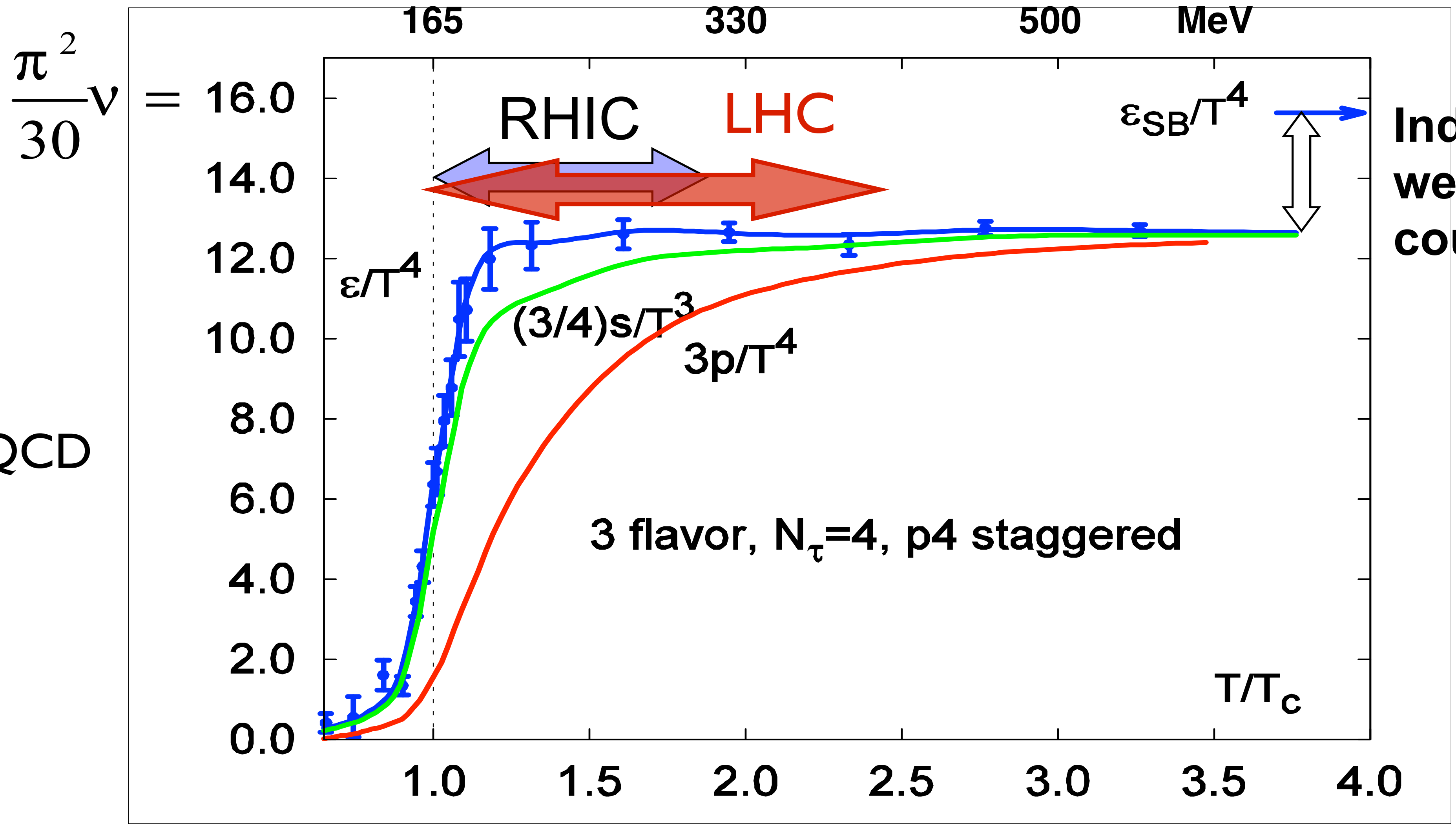

Lattice QCD

Indication of weak or strong coupling?

Hot QCD matter properties (I)

Which **properties of hot QCD matter** can we hope to determine from relativistic heavy ion data ?

$T_{\mu\nu} \quad \Leftrightarrow \quad \varepsilon, p, s$ **Equation of state**: spectra, coll. flow, fluctuations

$c_S^2 = \partial p / \partial \varepsilon$ **Speed of sound**: correlations

$\eta = \frac{1}{T} \int d^4x \left\langle T_{xy}(x) T_{xy}(0) \right\rangle$ **Shear viscosity**: anisotropic collective flow

$$\left.\begin{aligned}
\hat{q} &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle F^{a+i}(y^-) F_i^{a+}(0) \right\rangle \\
\hat{e} &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \int dy^- \left\langle i\partial^- A^{a+}(y^-) A^{a+}(0) \right\rangle \\
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\end{aligned}\right\}$$

Momentum/energy diffusion: parton energy loss, jet fragmentation

$m_D = -\lim_{|x|\to\infty} \frac{1}{|x|} \ln \left\langle E^a(x) E^a(0) \right\rangle$ **Color screening**: Quarkonium states

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Color screening: Quarkonium states

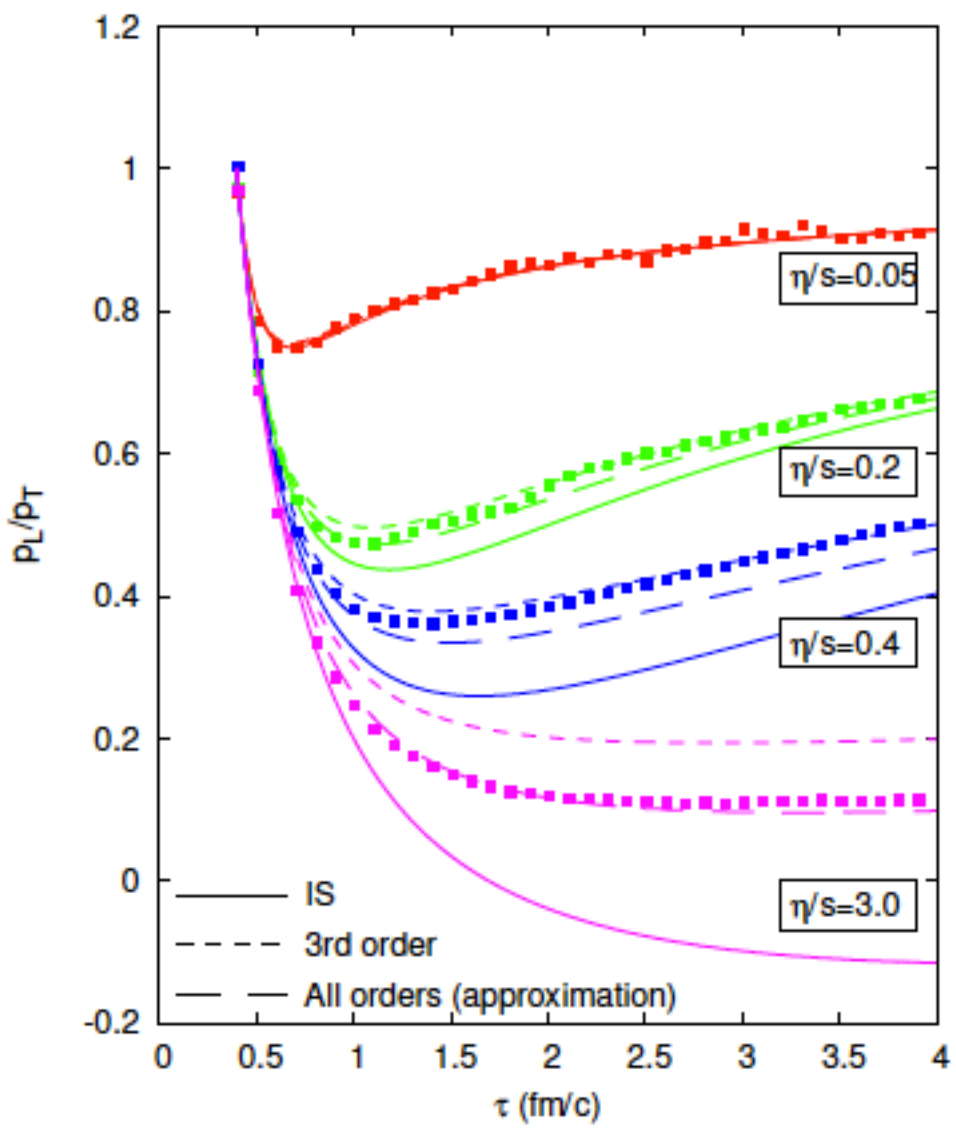
The Liquid QGP

Viscous FD under control

$$\partial_\mu T^{\mu\nu} = 0 \quad \text{with} \quad T^{\mu\nu} = (\varepsilon + P)u^\mu u^\nu - P g^{\mu\nu} + \Pi^{\mu\nu}$$

boost inv. expansion: $$\frac{d\Pi}{d\tau} = -\frac{\Pi}{\tau_\pi} + \frac{8\varepsilon}{27\tau} - \frac{4\Pi}{3\tau} - \frac{a\Pi^2}{\varepsilon\tau}$$

El, Xu & Greiner,
PRC 81 (2010) 041901



Excellent approximation of kinetic theory (Boltzmann transport).

Main input parameters:

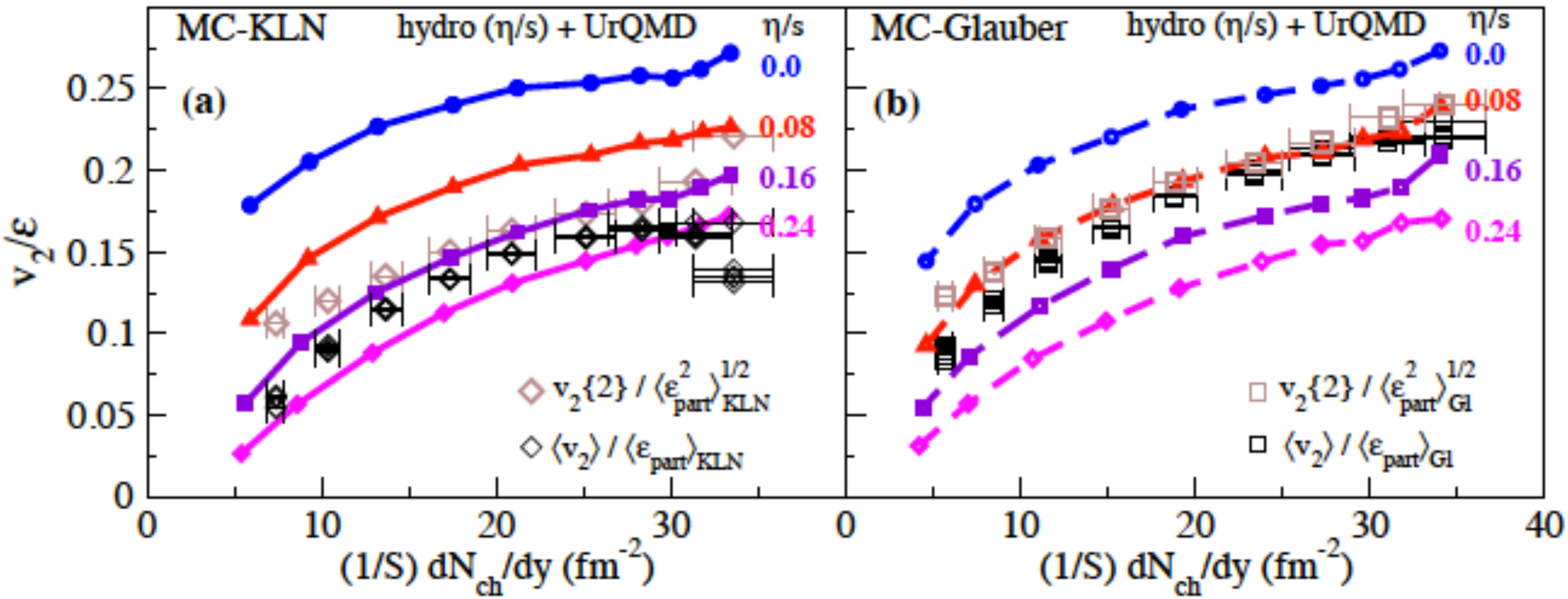
- η/s
- Initial energy density profile
- Equilibration time τ_0

Small uncertainties arising from:

- Bulk viscosity
- QCD Equation of state

Shear viscosity

Song, Bass, Heinz, Hirano, Shen, PRL 106 (2011) 192301

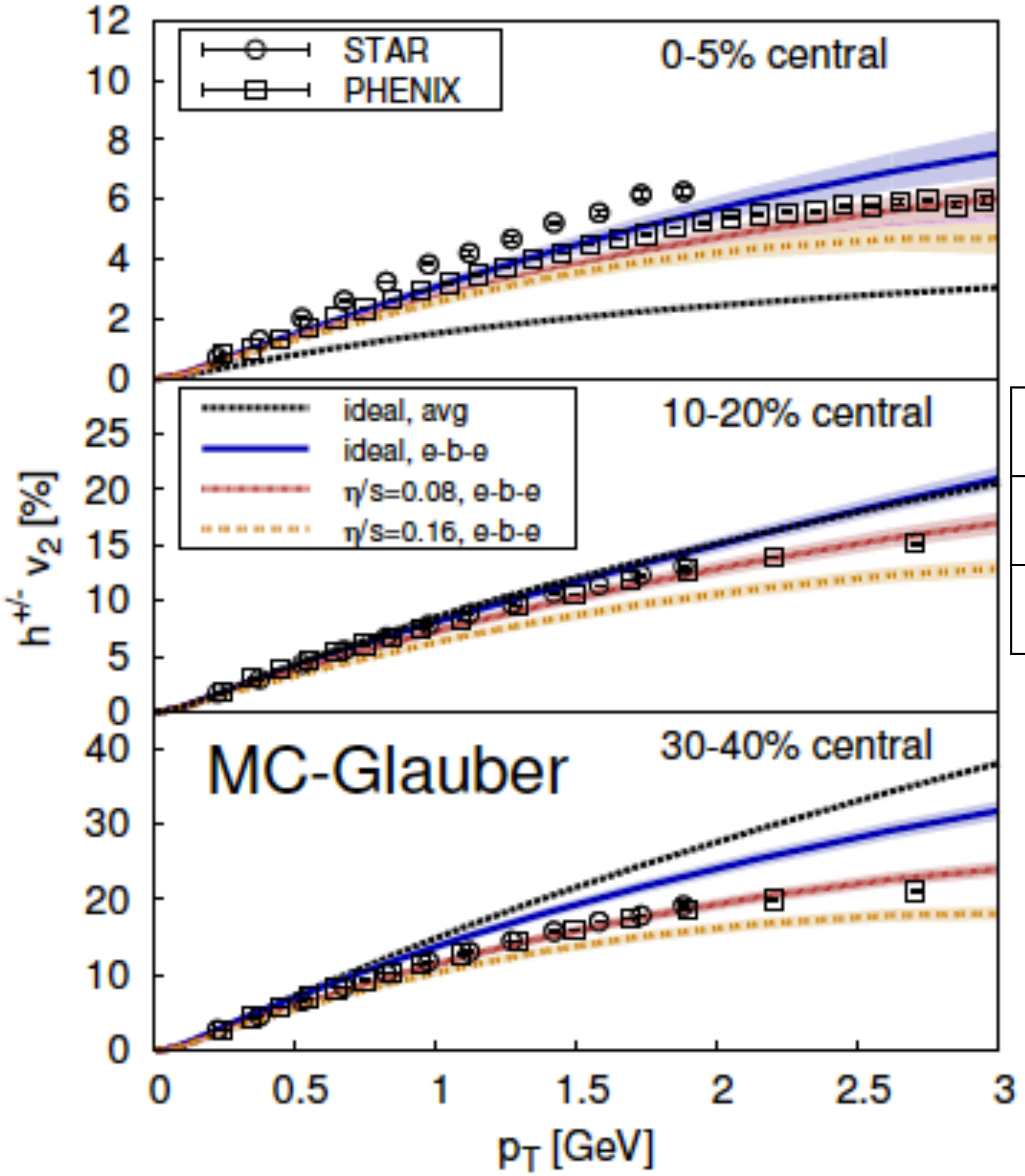


Conclusion: $1 \leq 4\pi\eta/s \leq 2.5$

Remaining uncertainty mainly due to initial density profile

Elliptic flow "measures" η_{QGP}

Schenke, Jeon, Gale, PRL 106 (2011) 042301



$\eta/s = 0$

$\eta/s = 1/4\pi$

$\eta/s = 2/4\pi$

Universal strong coupling limit of non-abelian gauge theories with a gravity dual:

$\eta/s \longrightarrow 1/4\pi$

aka: the "perfect" liquid

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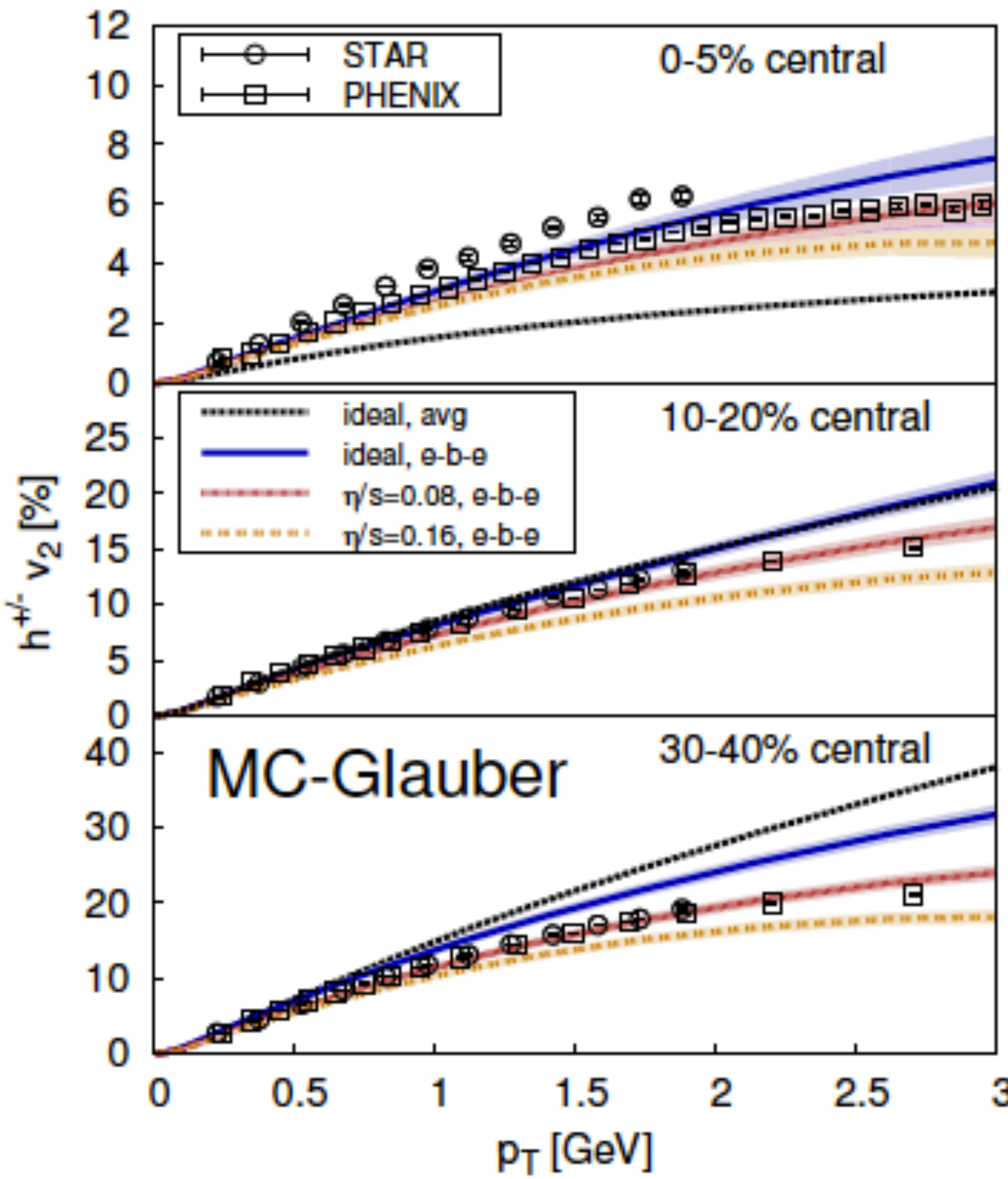
Schenke, Jeon, Gale, PRL 106 (2011) 042301



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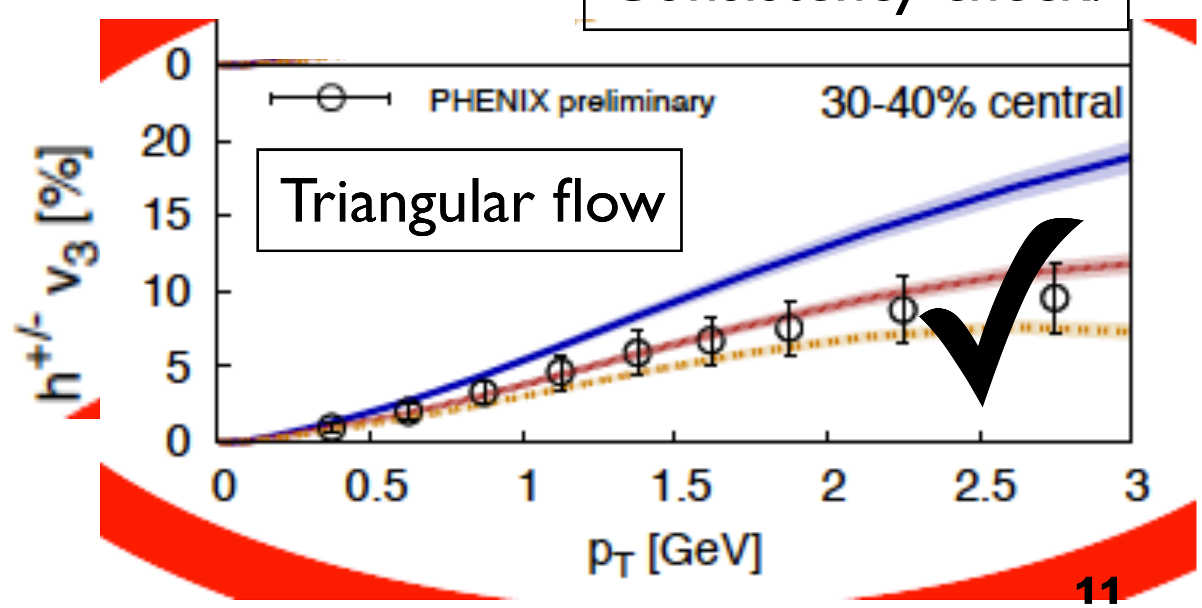
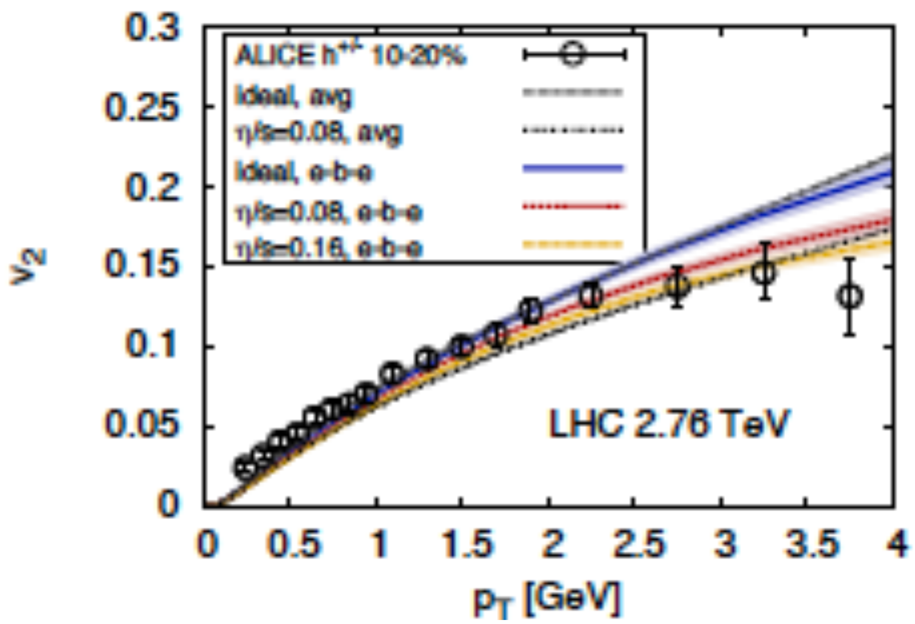
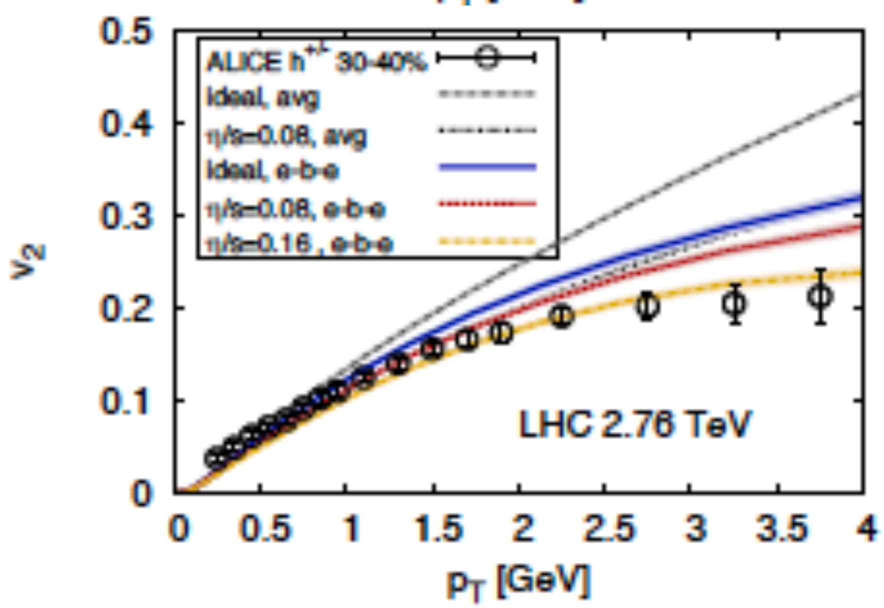
Consistency check:

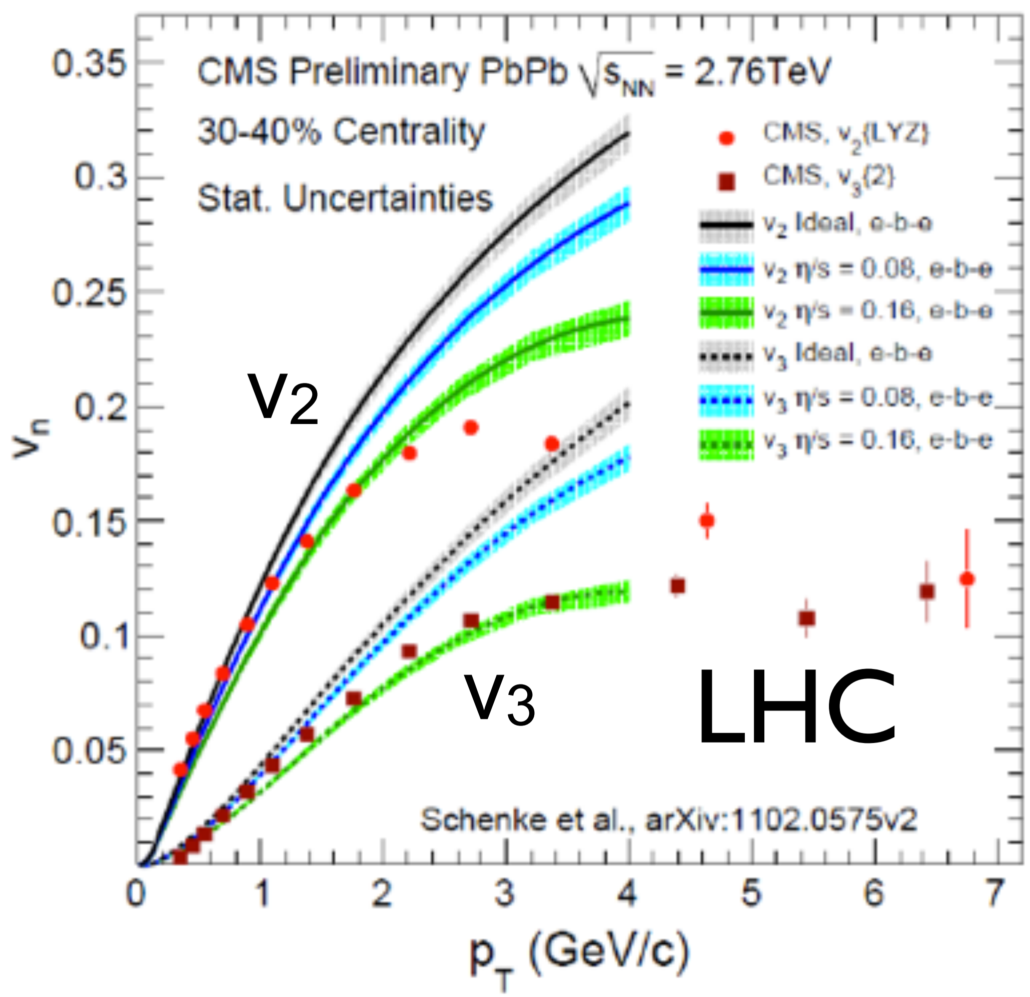


v_2 & v_3 @ LHC

Results agree almost perfectly with RHIC

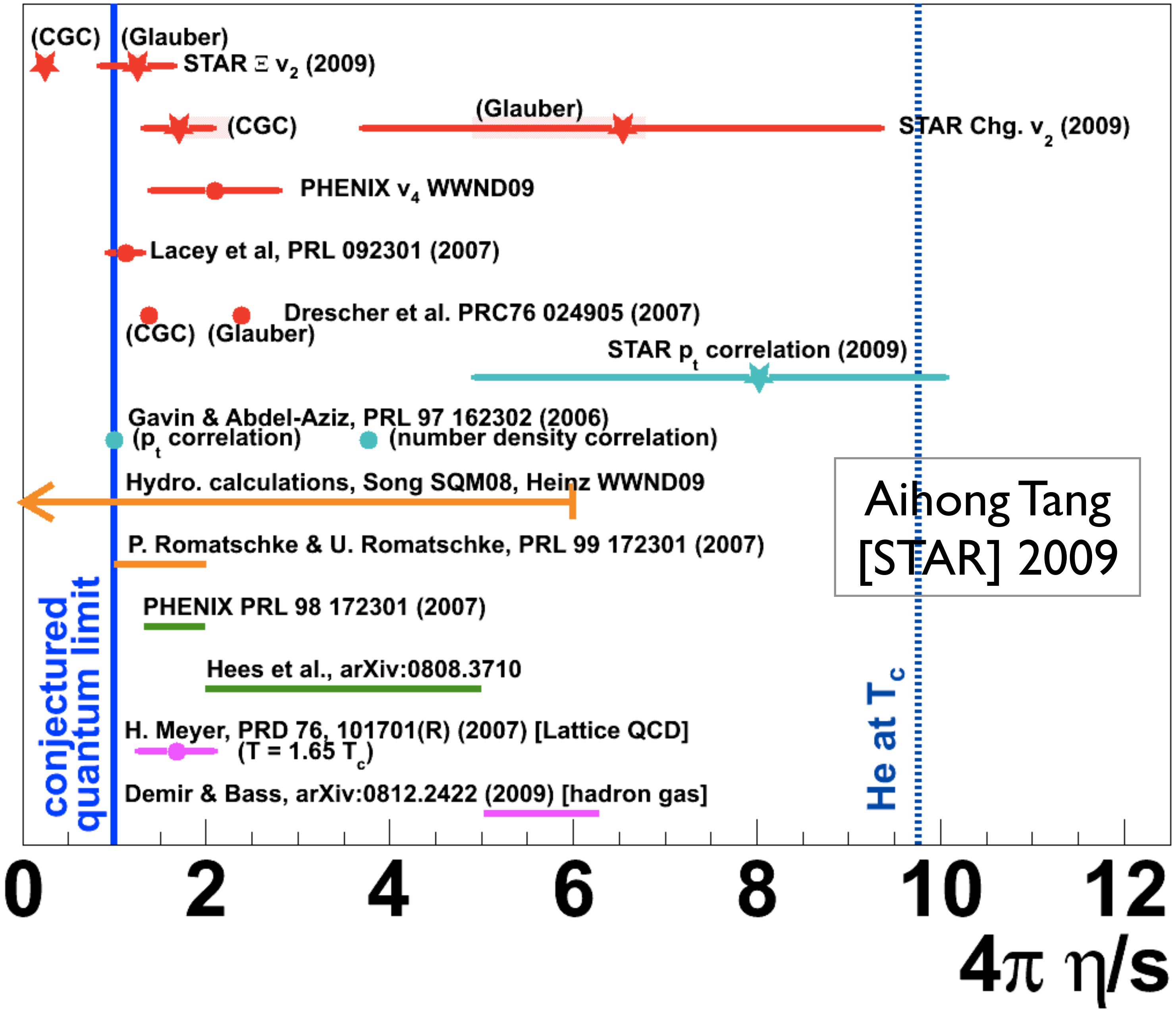






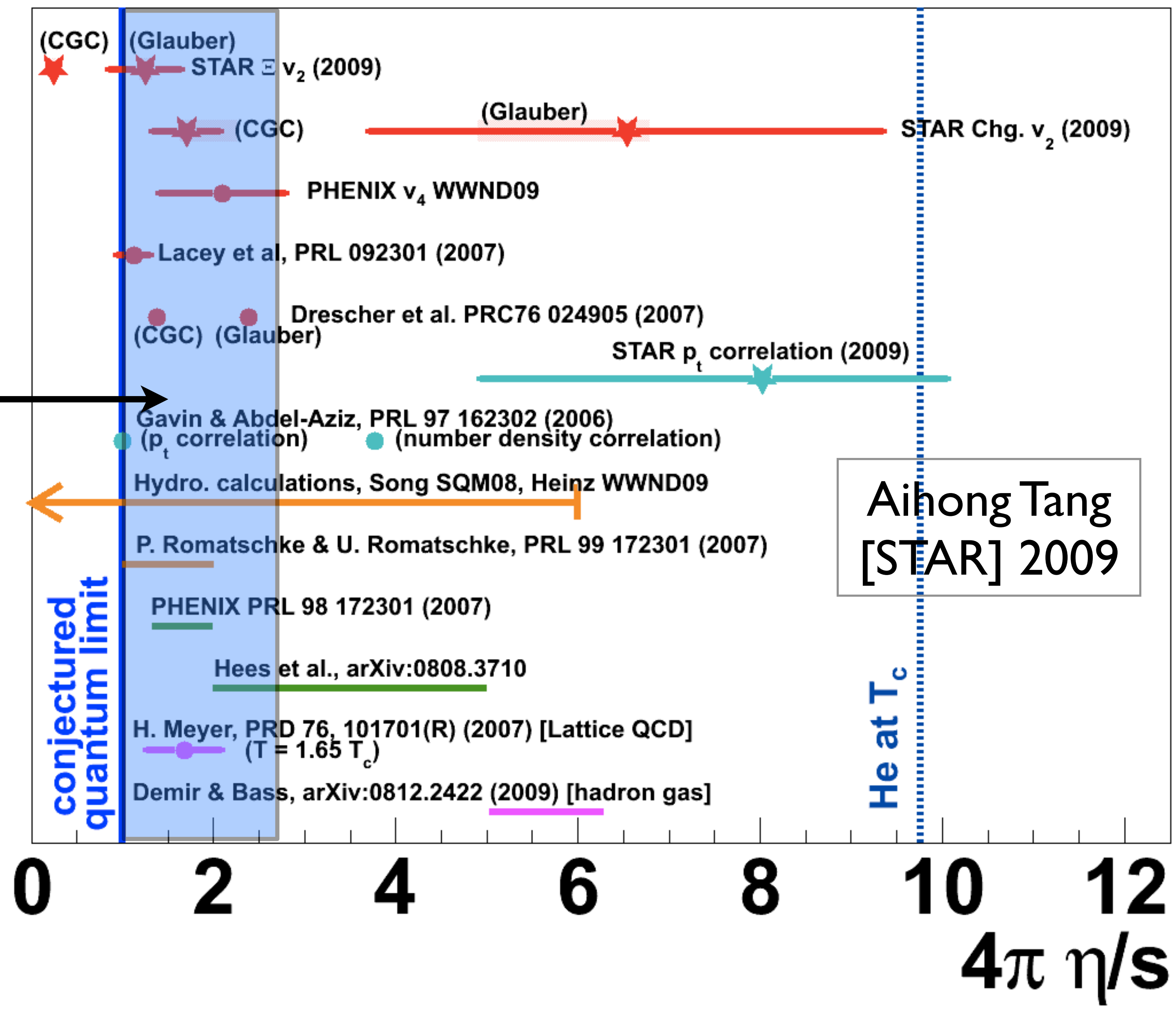
η/s from v_3 might be slightly larger than η/s from v_2. If true, this could indicate a momentum dependence of η, because events with large v_3 are more granular than on average.

Closing in on perfection...



Closing in on perfection...

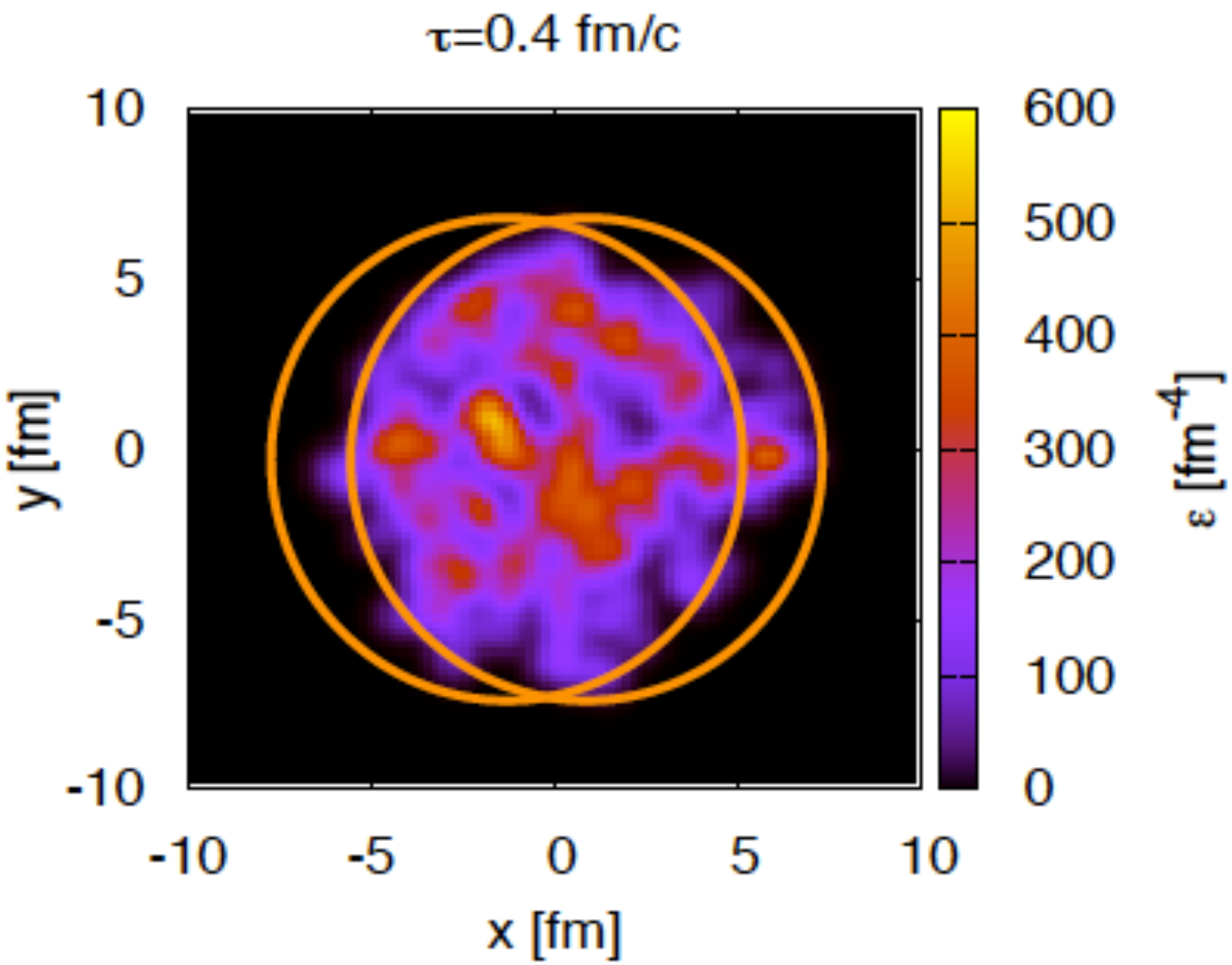
Present limits 2011

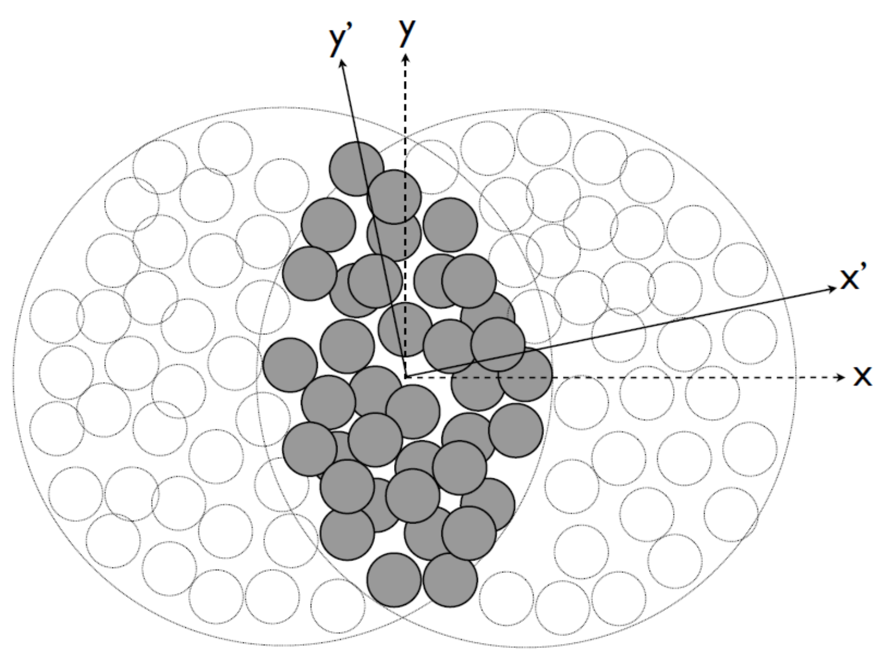


We can reduce the uncertainty by at least a factor 2 or 3

Event by event

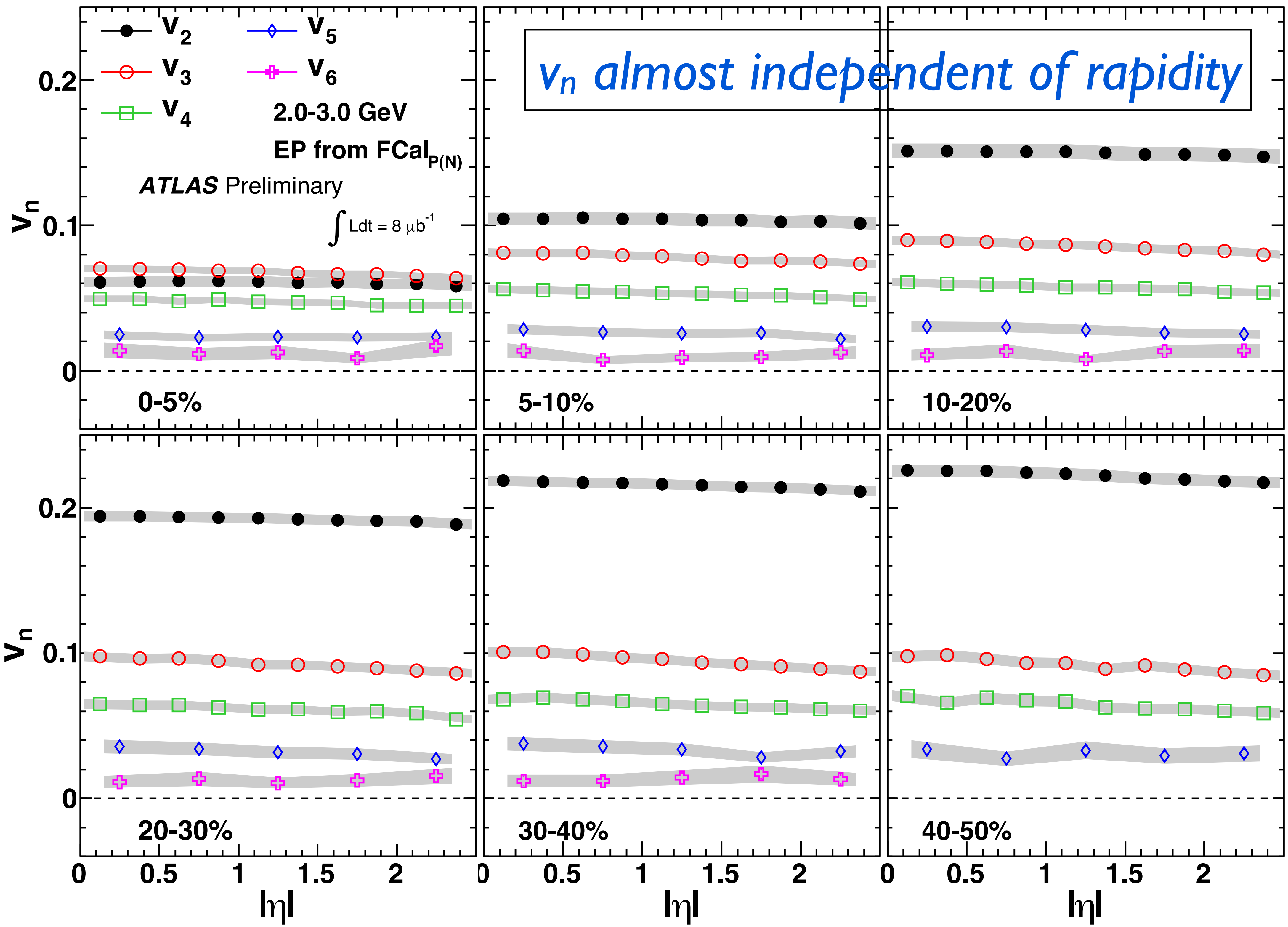
Initial state generated in A+A collision is grainy
event plane ≠ reaction plane
⇒ eccentricities $\varepsilon_1, \varepsilon_2, \varepsilon_3, \varepsilon_4$, etc. $\neq 0$





⇒ flows $v_1, v_2, v_3, v_4, \ldots$

v_n (n = 2,...,6)



v_2
v_3
v_4
v_5
v_6
2.0-3.0 GeV
EP from FCal$_{P(N)}$
ATLAS Preliminary
$\int$ Ldt = 8 μb^{-1}
v_n
0-5%
5-10%
10-20%
20-30%
30-40%
40-50%
|η|
v_n almost independent of rapidity

Future refinements

- Necessary improvements
  - E-by-E (3+1)-dim viscous hydro with cascade freeze-out.
  - Uncertainty check for τ_0, EOS, and ζ.
- Determination of transverse profile
  - Can CGC theory provide a firm prediction?
    - Are there theoretically founded alternatives?
- Check of system independence
  - Cu+Cu, Cu+Au, U+U
    - Very important to demonstrate theoretical control

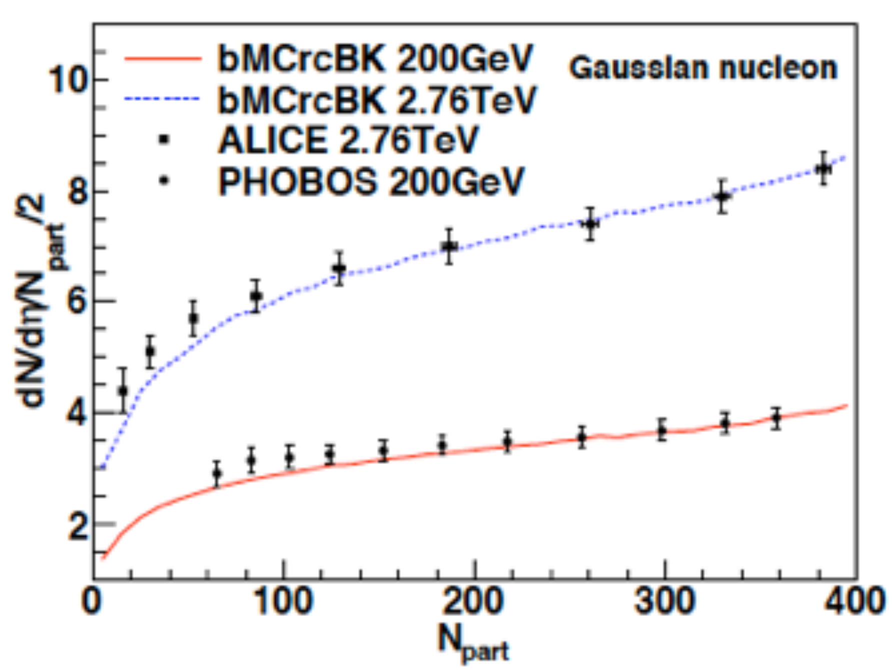
Unravelling $\varepsilon(\tau_0,x)$

What is the correct theory (model) for initial energy density profile ?

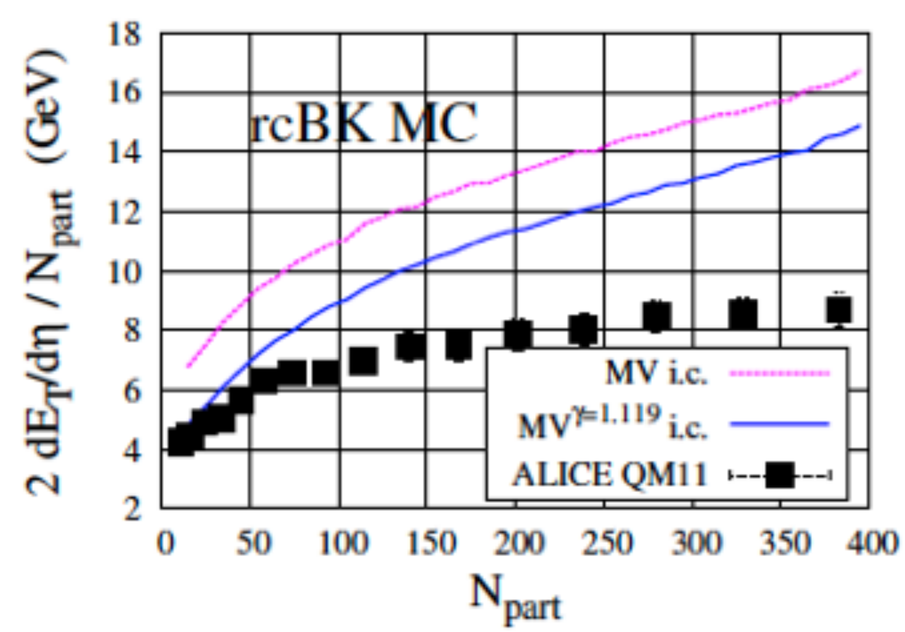
CGC approach needs to be pushed to quantitative predictiveness.

State-of-the-art "explains" final multiplicity, but fails badly on $dE_T/d\eta$. No surprise: hydro expansion reduces E_T, but it (and the hadronic freezeout) also increases the entropy.

Does the approach predict the correct fluctuations of v_n ?



Albacete, Dumitru, Nara, arXiv: 1106.0978



Fluctuation spectrum

Can different distributions of various eccentricities in different collision systems be used to discriminate between energy deposition models / theories?

Can the power spectrum of v_n be used to determine η/s and v_{sound} ? [Mocsy & Sorensen]

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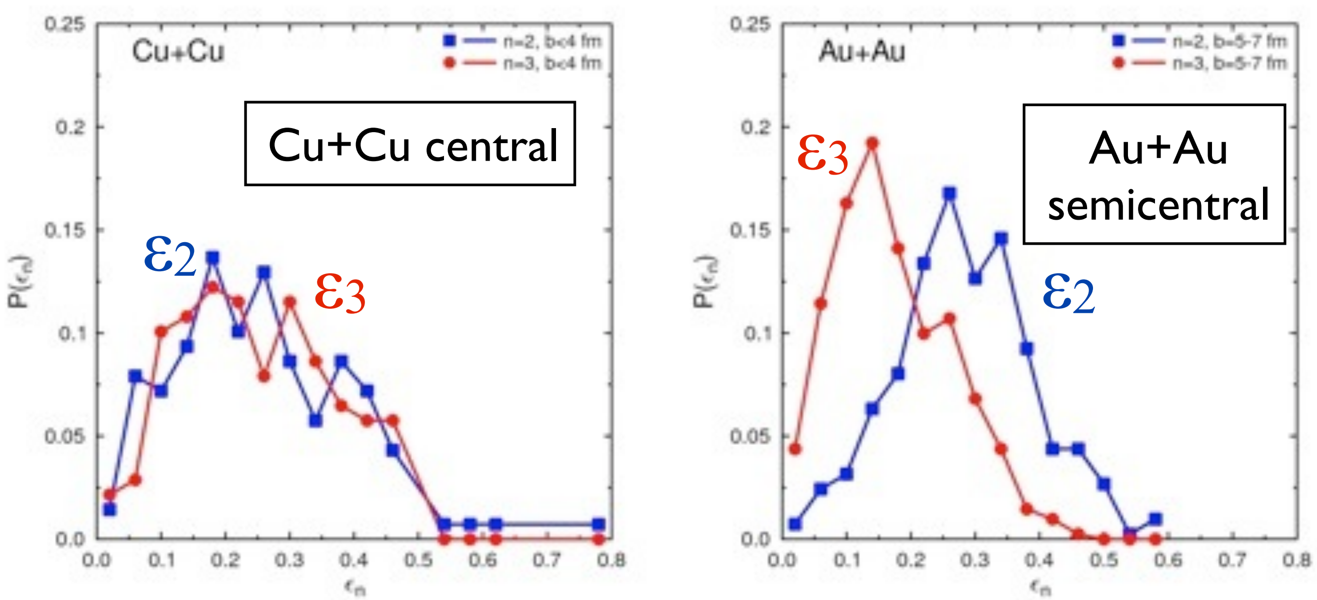

H. Petersen: UrQMD + 3-D hydro + UrQMD

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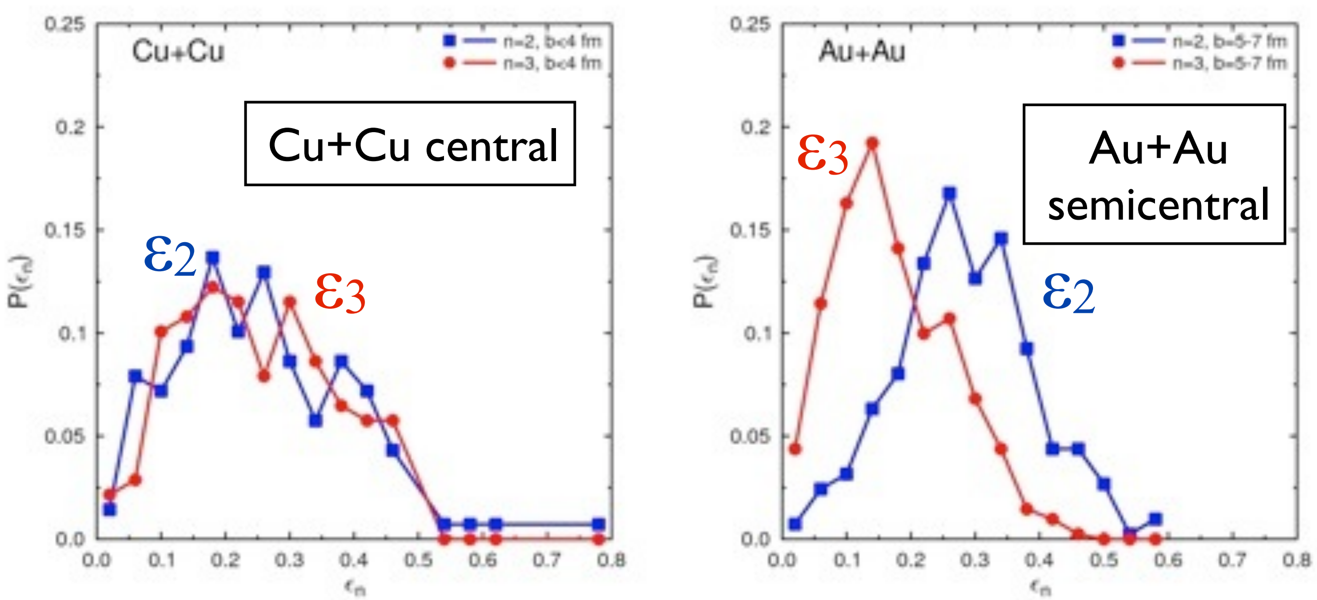

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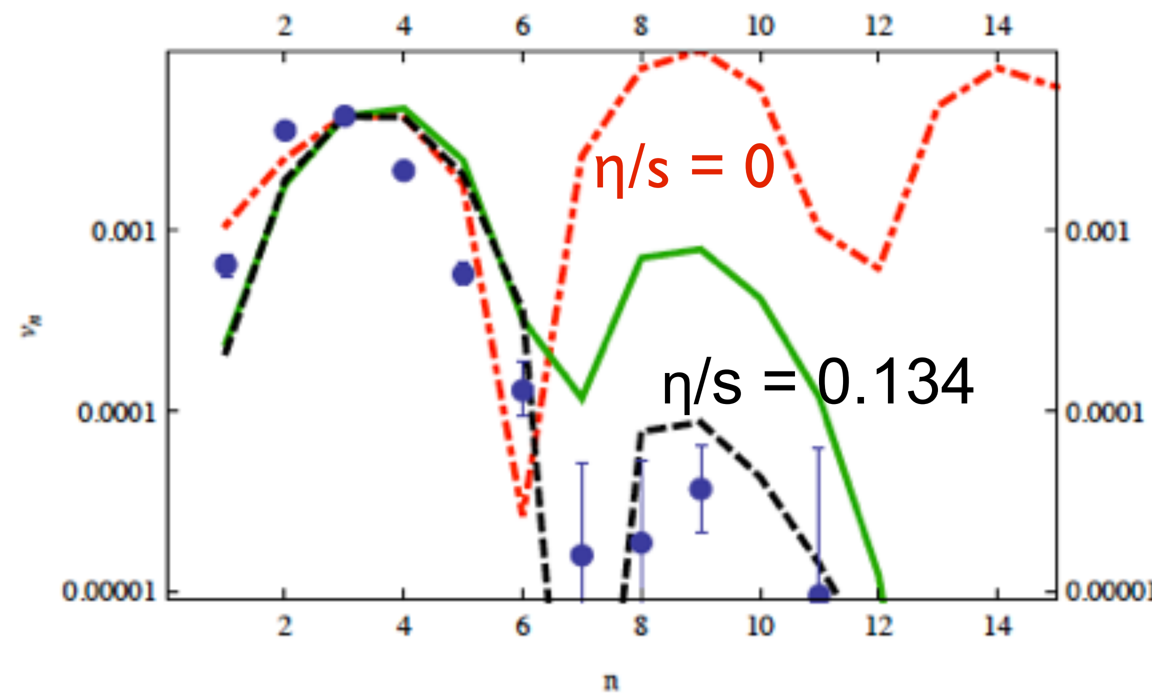
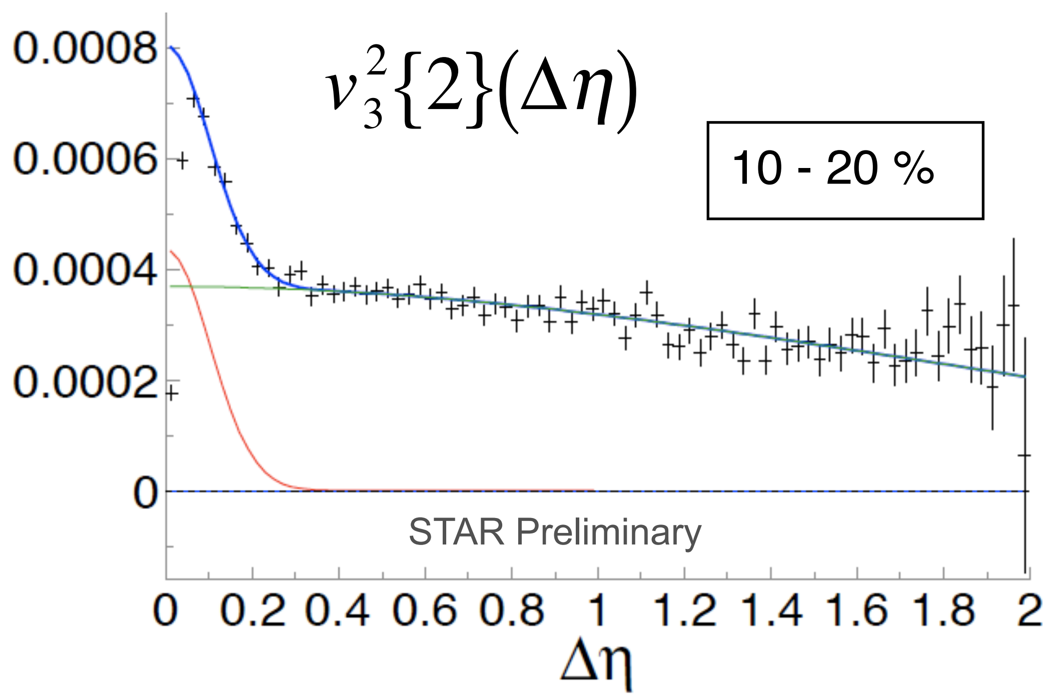
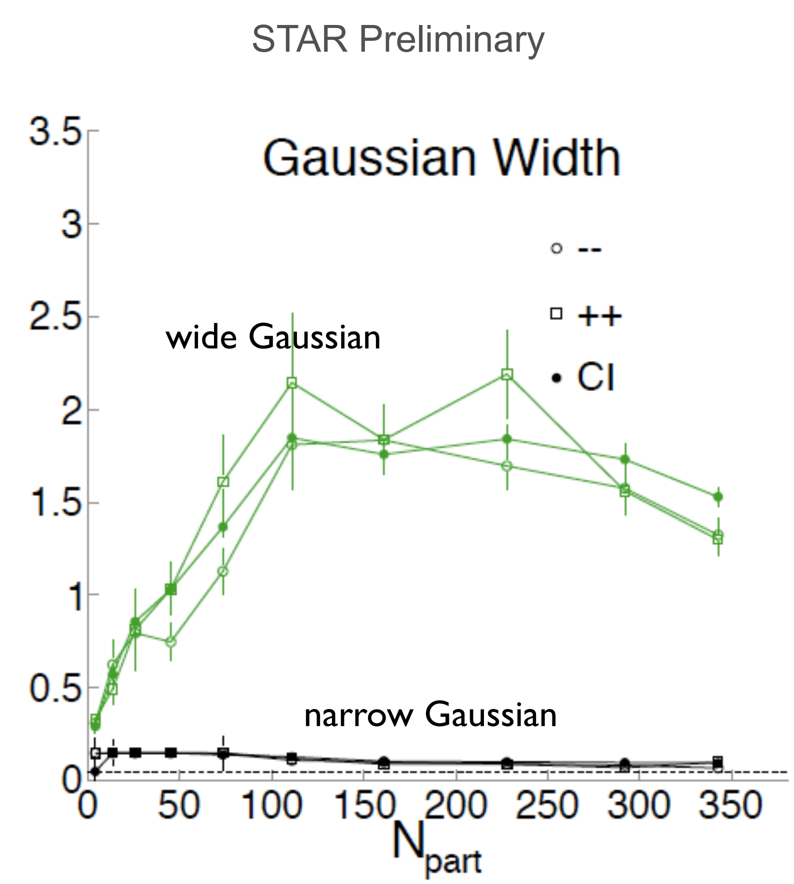
Staig & Shuryak, arXiv:1106.3243



Analysis not yet reliable in detail, but clearly the way to go!

Correlations





Driven by longitudinal correlation of initial-state density fluctuations or by thermal density fluctuations during hydrodynamic phase ? Are the v_3 correlations universal ?

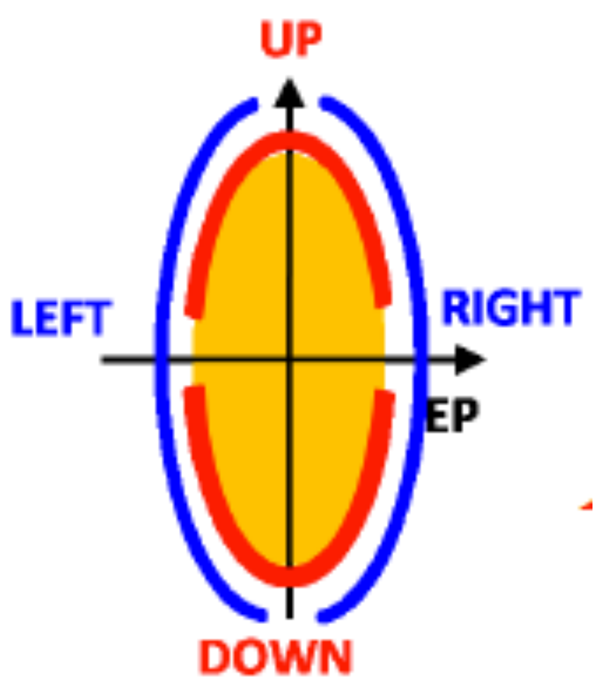
CGC approach: $\sigma_{\Delta\eta} \sim 1/\alpha_s$ [e.g. Dusling et al., NPA 836 (2010) 159]

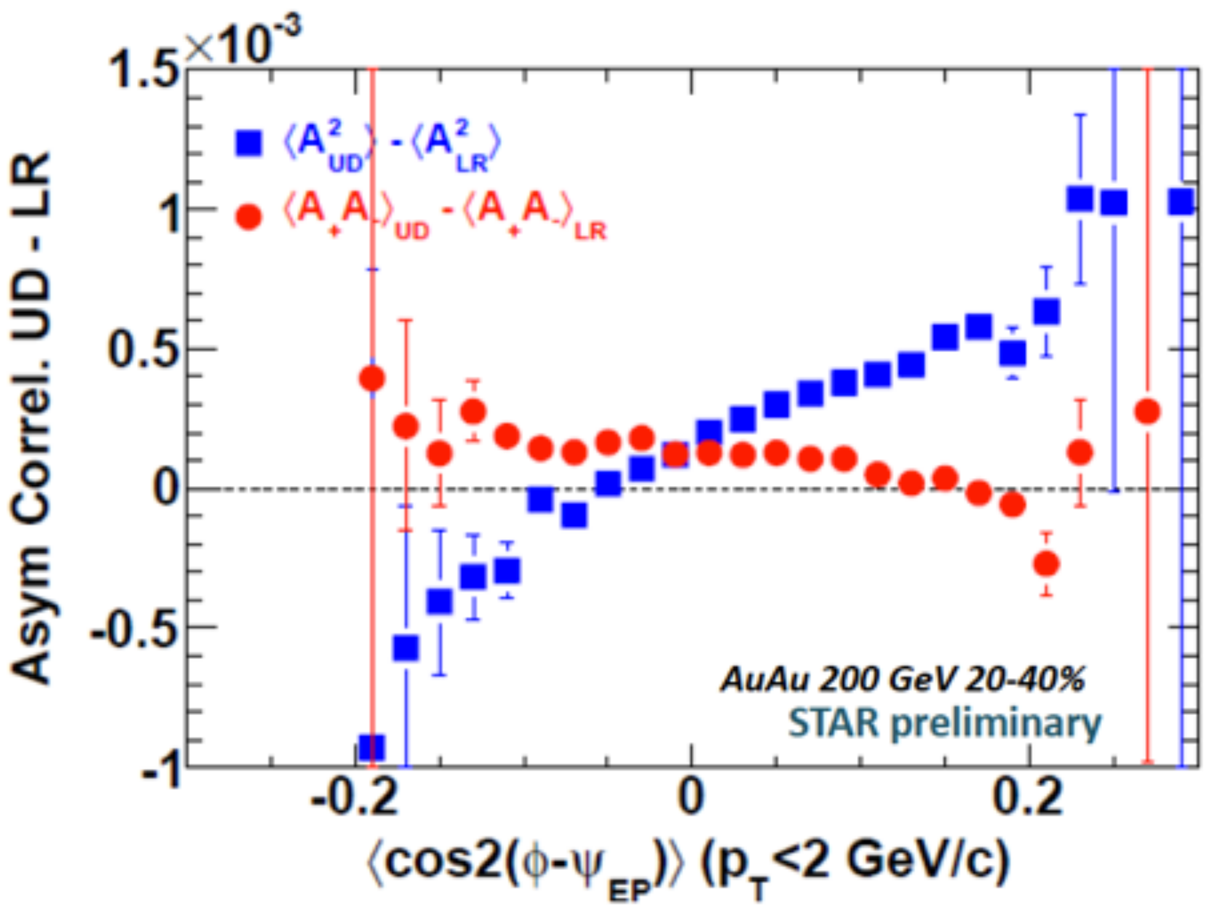
Hydro transport: $\sigma_{\Delta\eta} \sim 2v_s \log(\tau_f/\tau_i)$ [Kapusta, Stephanov, BM, to be published]

Problems are just...

...opportunities in disguise

Eccentricity fluctuations permit selection of events with $b \neq 0$, but $v_2 = 0$. Use to probe origin of charge asymmetry fluctuations.





Qang Wang (STAR)
Poster #583 QM2011

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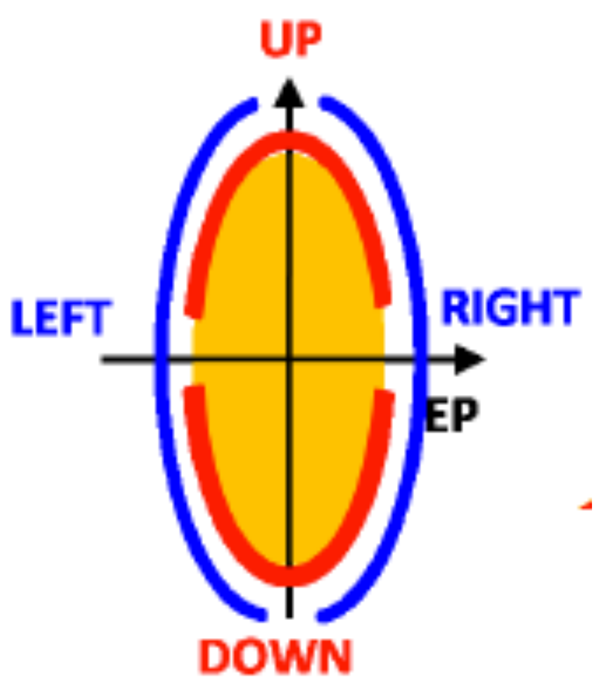

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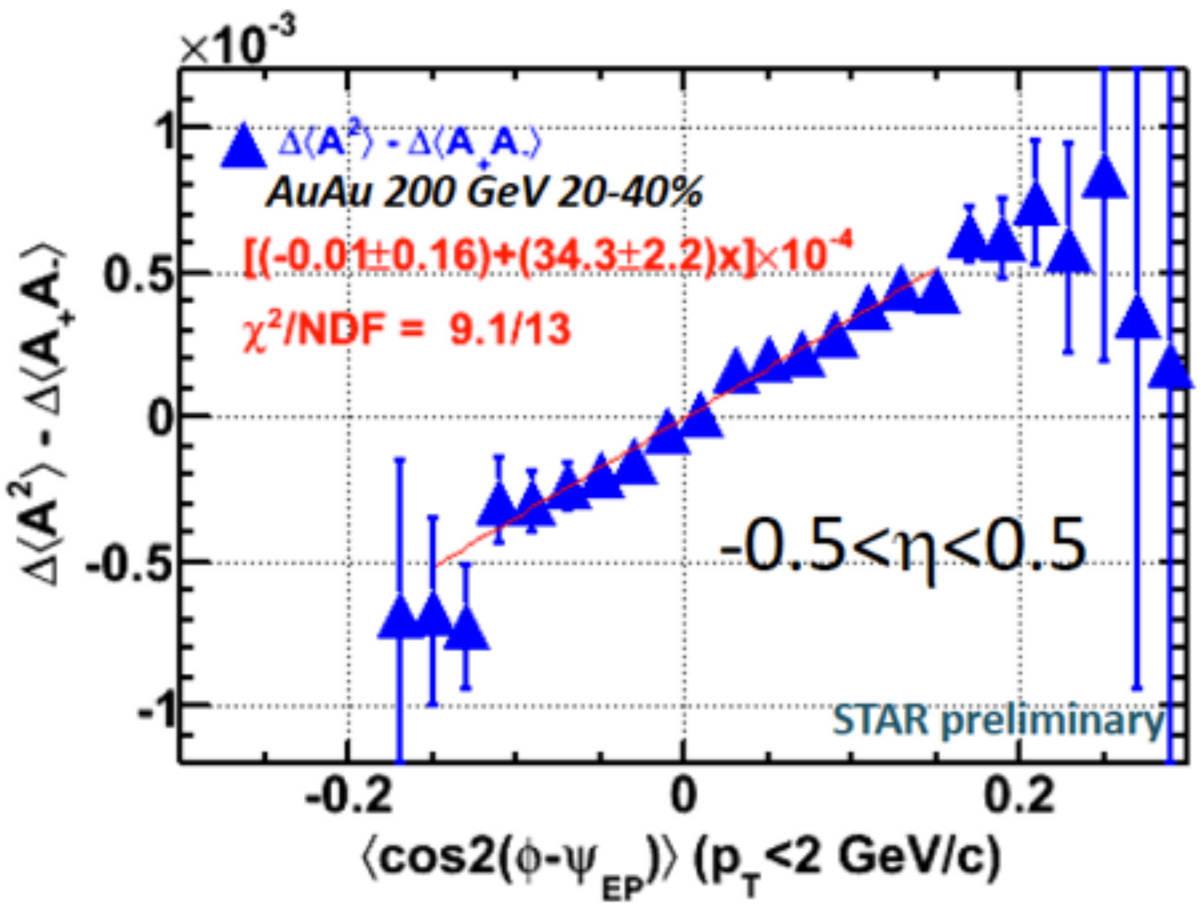
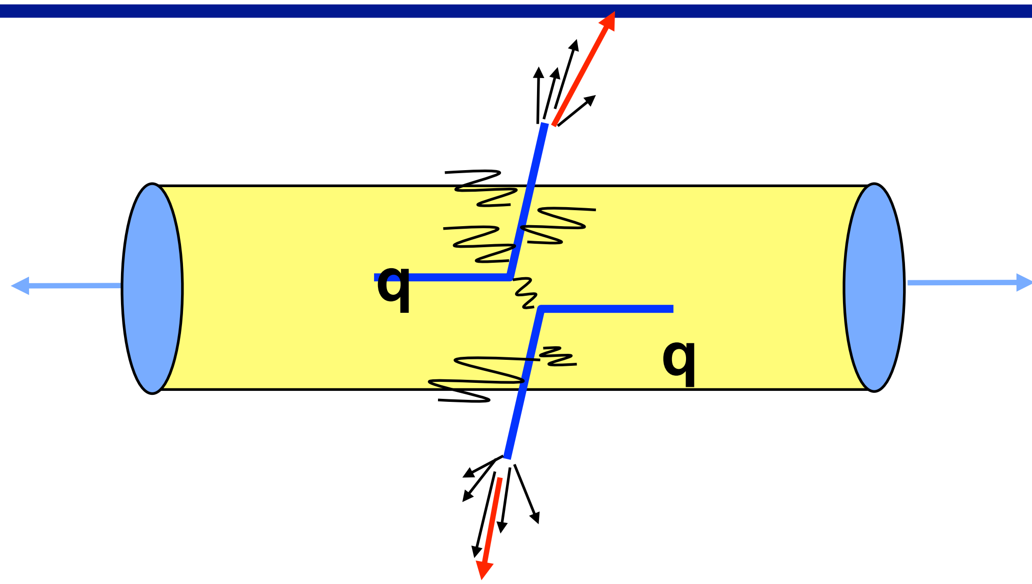


Upper limit of charge separation: **4×10^{-5}** at 98% CL.

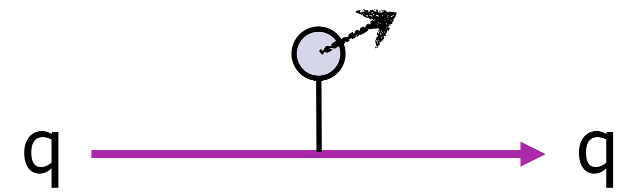
The Opaque QGP

Parton energy loss

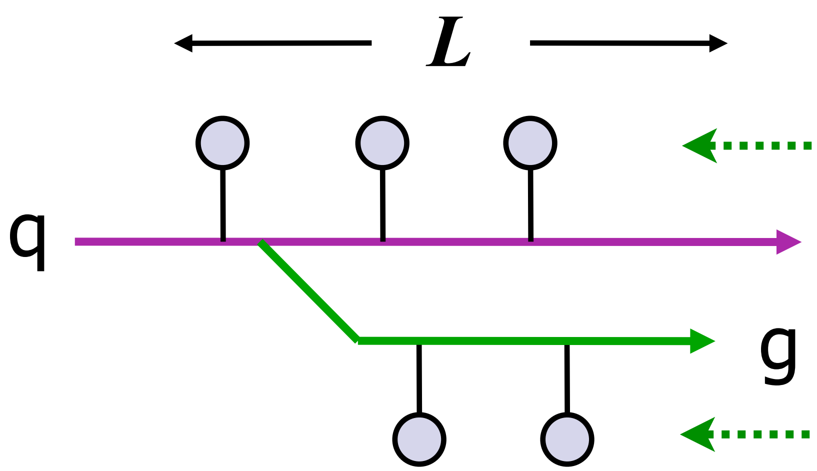


Elastic energy loss:

$$\frac{dE}{dx} = -C_2\,\hat{e}$$



Radiative energy loss:



Scattering centers
$\Leftrightarrow$ color charges

$$\frac{dE}{dx} = -C_2\,\hat{q}\,L$$

$$\hat{q} = \rho \int q^2\, dq^2\, \frac{d\sigma}{dq^2} = \int dx^- \left\langle F_i^{+}(x^-) F^{+i}(0) \right\rangle$$

Goals and questions

- Goals:
  - Determine medium properties ($\hat{q}, \hat{e}$ in NL Twist; ....??)
  - Density tomography of the medium
  - Explore energy flow into, and response by, the QGP
  - Explore scale of transition from weak to strong coupling

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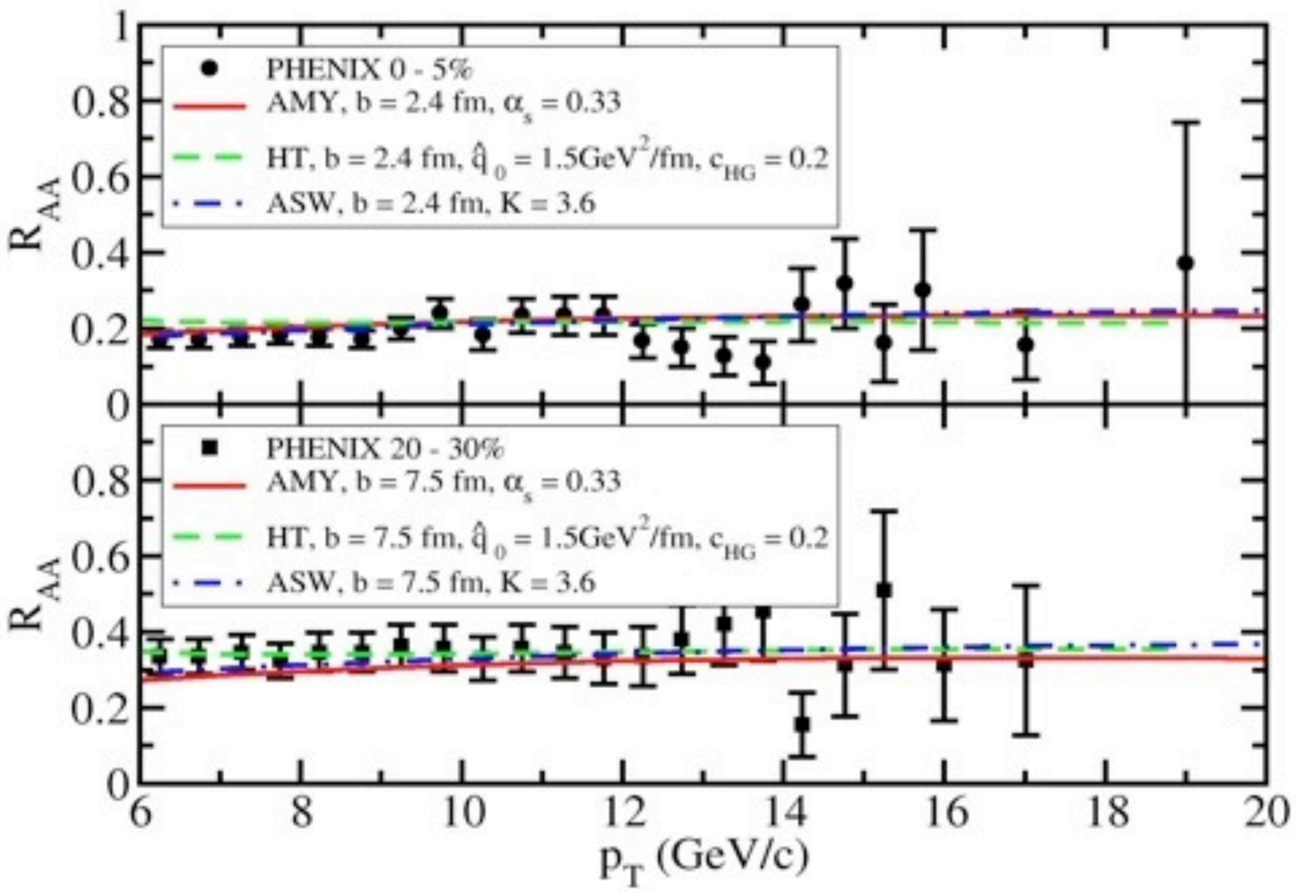
- Questions:
  - Momentum dependence of parton energy loss
  - Density, length dependence of PEL
  - Color/flavor dependence of PEL
  - Redistribution of energy in jet cone (j_T, z) versus ...
  - ... flow of energy out of the jet cone

Identifying the problem

Good fits for light hadrons are possible for all energy loss models with 3-D hydro evolution, ***but...*** their conclusions disagree badly!

$\hat{q}(\vec{r},\tau)$ scales as	ASW $\hat{q}_0$	HT $\hat{q}_0$	AMY $\hat{q}_0$
$T(\vec{r},\tau)$	10 $\mathrm{GeV}^2/\mathrm{fm}$	2.3 $\mathrm{GeV}^2/\mathrm{fm}$	4.1 $\mathrm{GeV}^2/\mathrm{fm}$
$\epsilon^{3/4}(\vec{r},\tau)$	18.5 $\mathrm{GeV}^2/\mathrm{fm}$	4.5 $\mathrm{GeV}^2/\mathrm{fm}$	
$s(\vec{r},\tau)$		4.3 $\mathrm{GeV}^2/\mathrm{fm}$	

Bass, Gale, Majumder, Nonaka, Qin, Renk & Ruppert, PRC 79 (2009) 024901



All schemes are based on the same physics; variation in $\hat{q}$ is caused by different treatment of regions outside the range of validity of the eikonal collinear approximation used in all implementations.

TEC-HQM

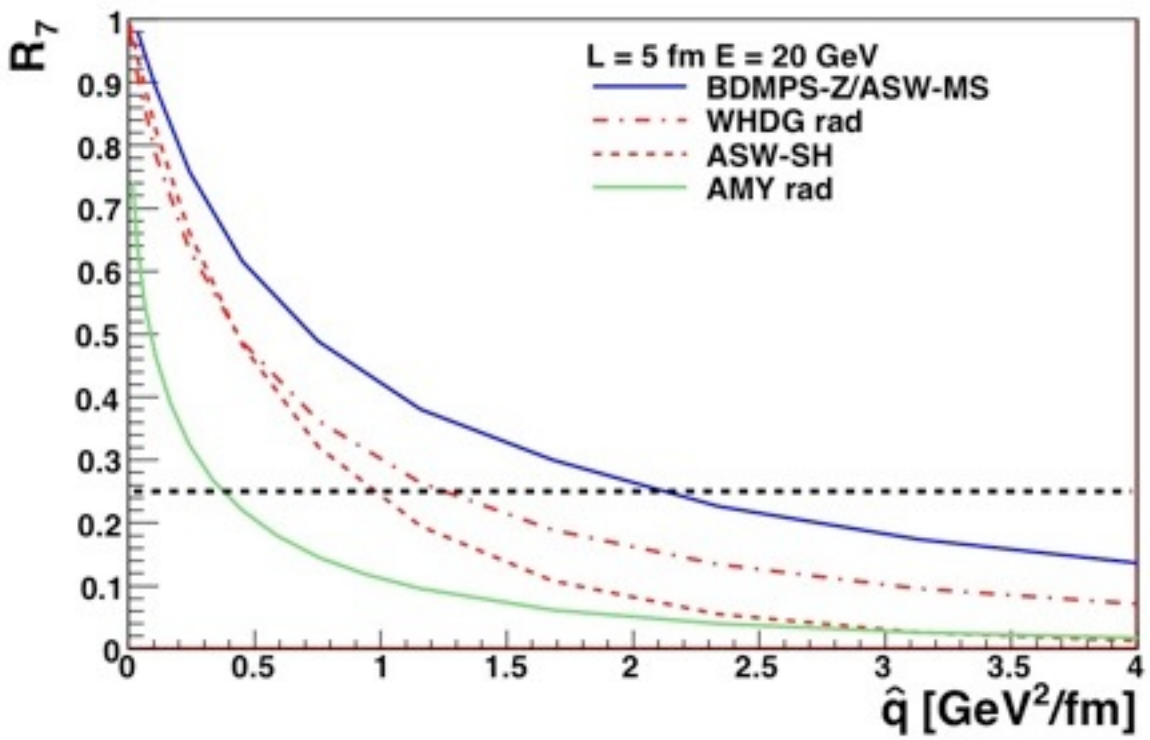
Comparison of Jet Quenching Formalisms for a Quark-Gluon Plasma "Brick"

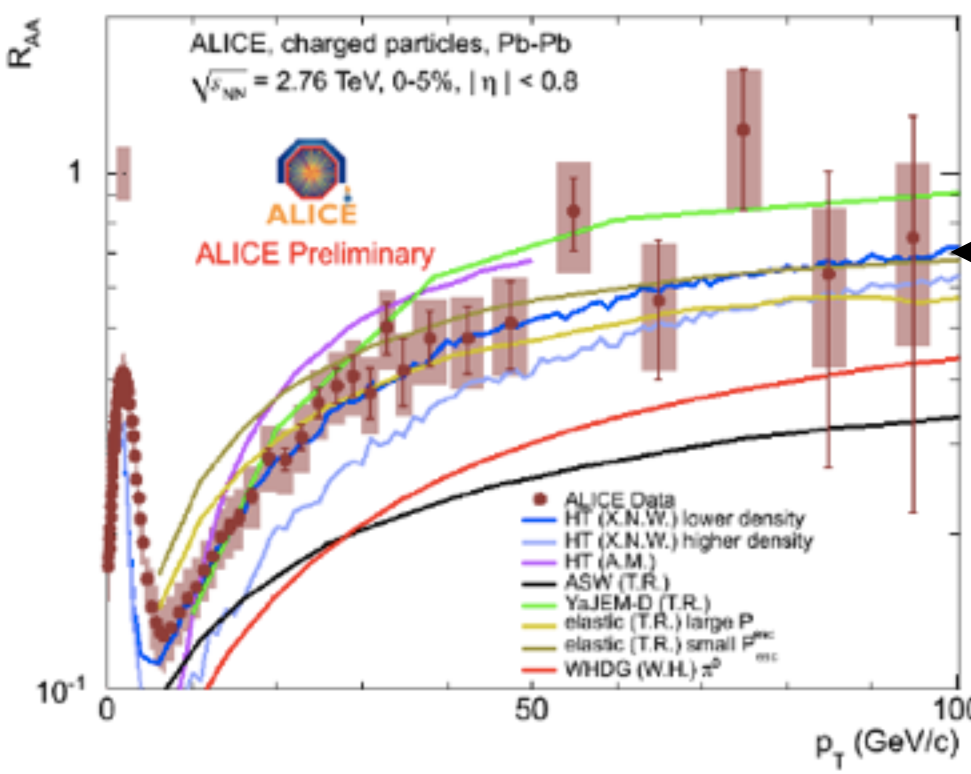
Nestor Armesto,[1] Brian Cole,[2] Charles Gale,[3] Willam A. Horowitz,[4,5] Peter Jacobs,[6] Sangyong Jeon,[3] Marco van Leeuwen,[7] Abhijit Majumder,[4] Berndt Müller,[8] Guang-You Qin,[8] Carlos A. Salgado,[1] Björn Schenke,[3,9] Marta Verweij,[7] Xin-Nian Wang,[10,6] and Urs Achim Wiedemann[11]

arXiv:1106.1106

Wide differences confirmed for standardized "QCD Brick"

MC schemes and NLO treatment of wide-angle radiation required to reduce inherent uncertainties (*in progress*).





pQCD theory of jet quenching is alive and well.

Virtuality matters

Virtuality Q^2 of the parton in the medium controls physics of radiative energy loss:

$$Q^2(L) \approx \max\left(\underbrace{\hat{q}\,L}_{\text{medium}}, \underbrace{\frac{E}{L}}_{\text{vacuum}} \right)$$

RHIC: 30 GeV parton, *L* = 3 fm

$$\hat{q}\,L \approx 4.5\,\mathrm{GeV}^2 \quad \gg \quad \frac{E}{L} \approx 2\,\mathrm{GeV}^2$$

Virtuality of primary parton is medium dominated and small enough to “experience” the strongly coupled medium

LHC: 200 GeV parton, *L* = 3 fm

$$\hat{q}\,L \approx 9\,\mathrm{GeV}^2 \quad < \quad \frac{E}{L} \approx 13\,\mathrm{GeV}^2$$

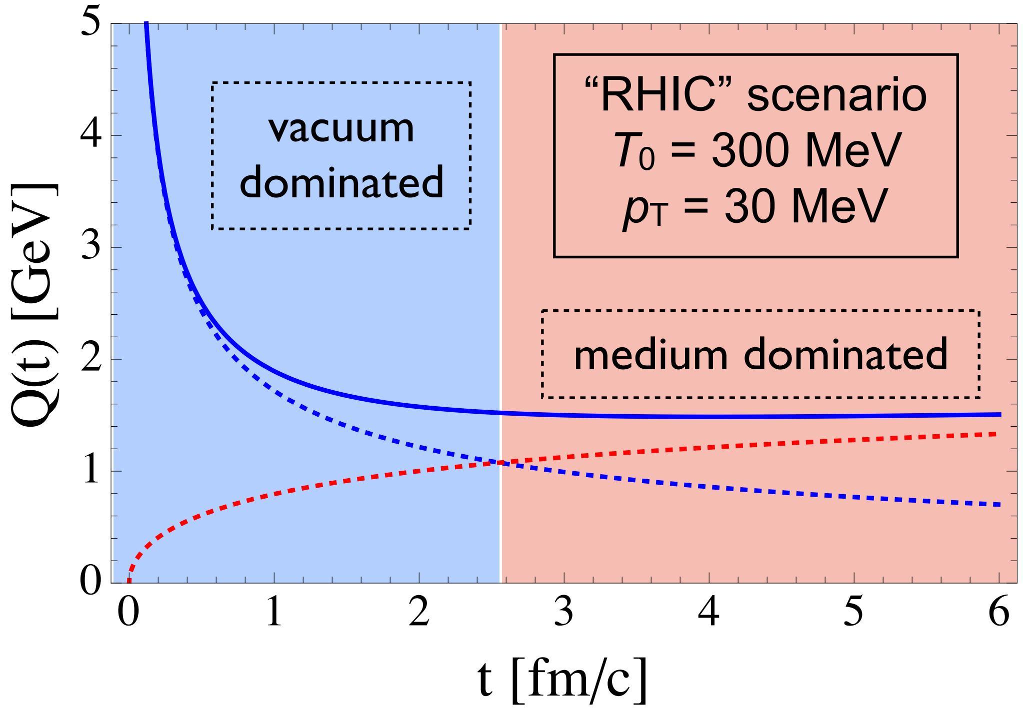
Virtuality of primary parton is vacuum dominated and only its gluon cloud “experiences” the strongly coupled medium

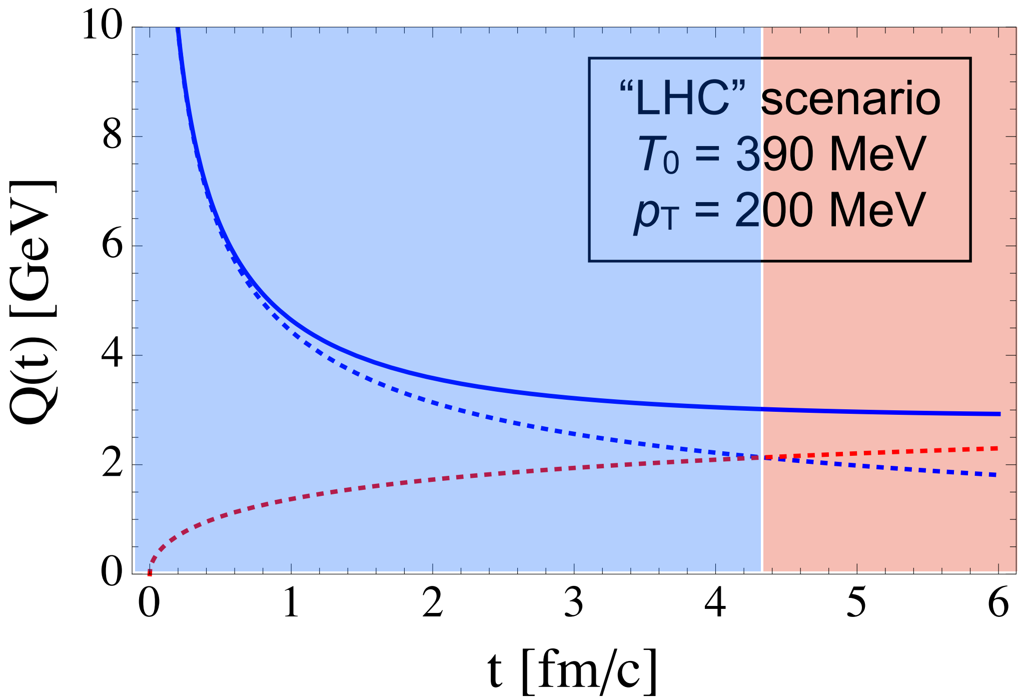
Consequences largely unexplored (but see: T. Renk, arXiv:1010.4116)

Why RHIC ≠ LHC

Virtuality evolution of a hard scattered parton

$$Q^2_{vac}(t) = \frac{E}{2t} \qquad Q^2_{med}(t) = \int \hat{q}(t)\,dt \qquad Q^2(t) = Q^2_{vac}(t) + Q^2_{med}(t)$$





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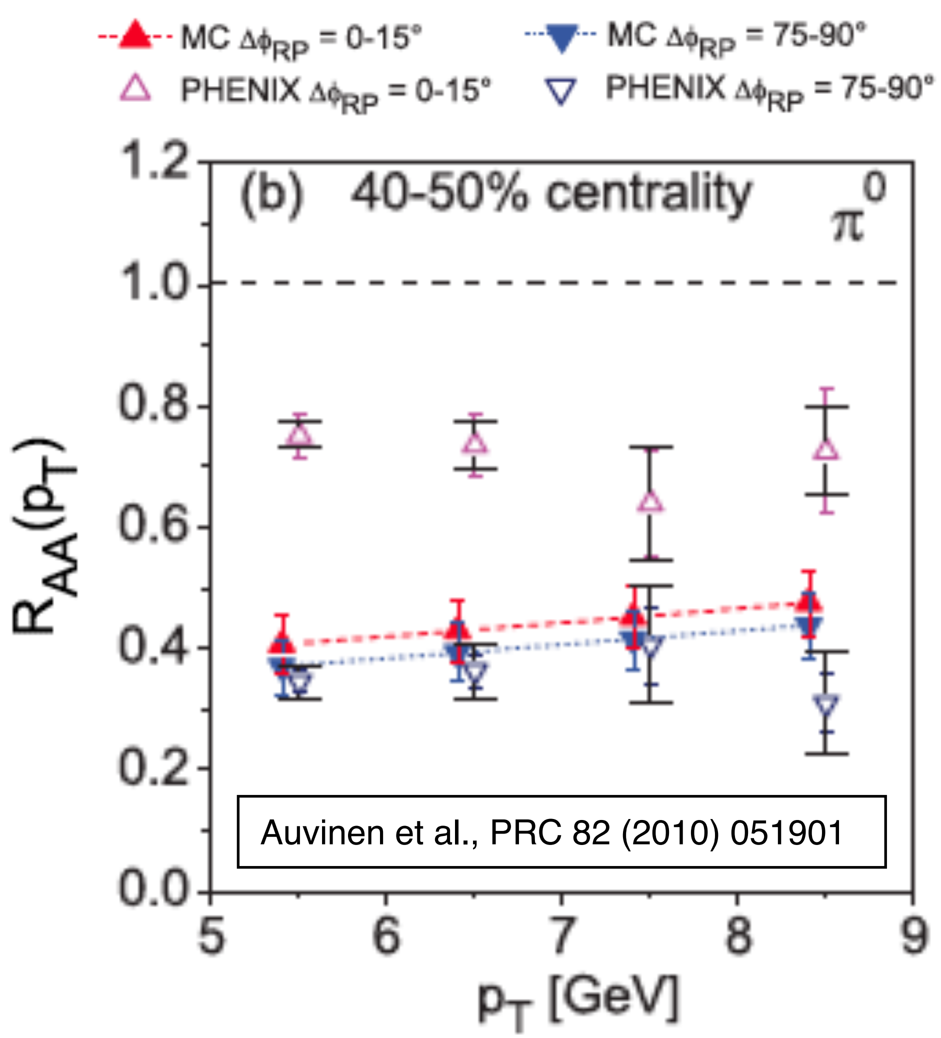
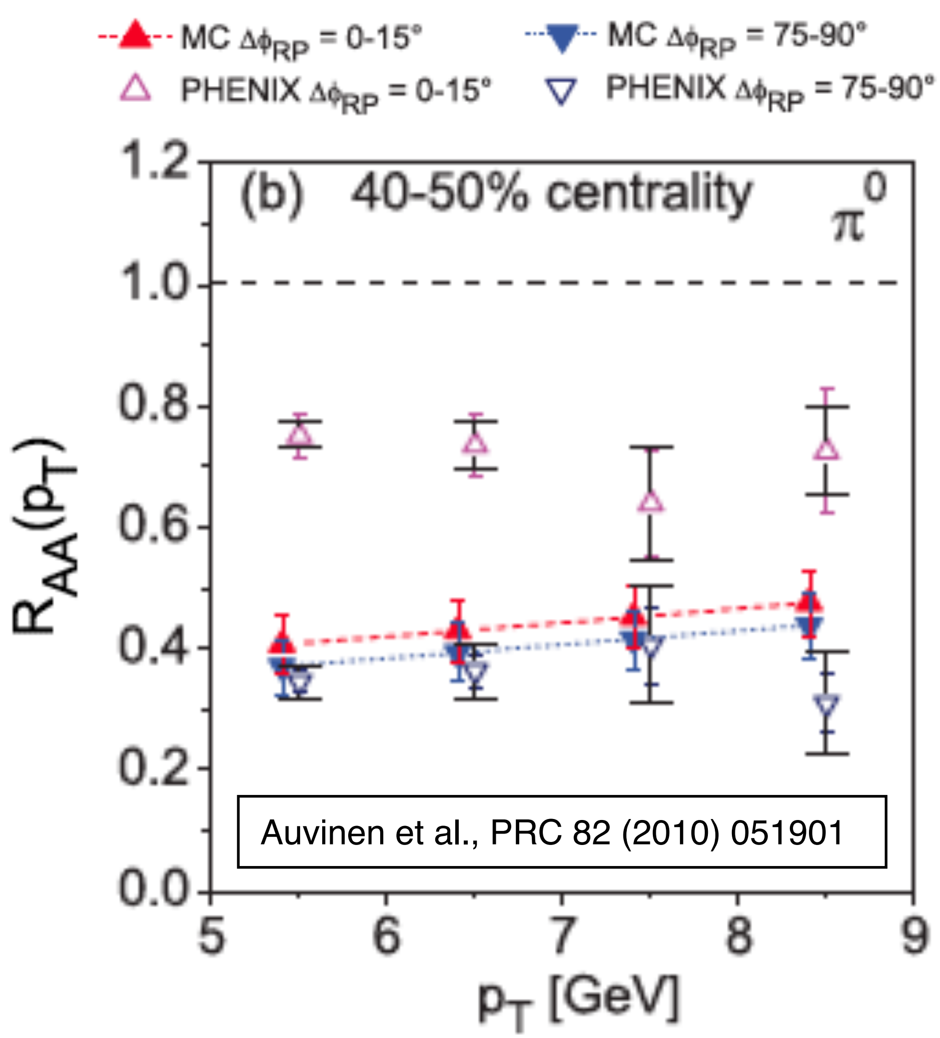
L dependence of energy loss



Elastic energy loss fails badly.

L dependence of energy loss



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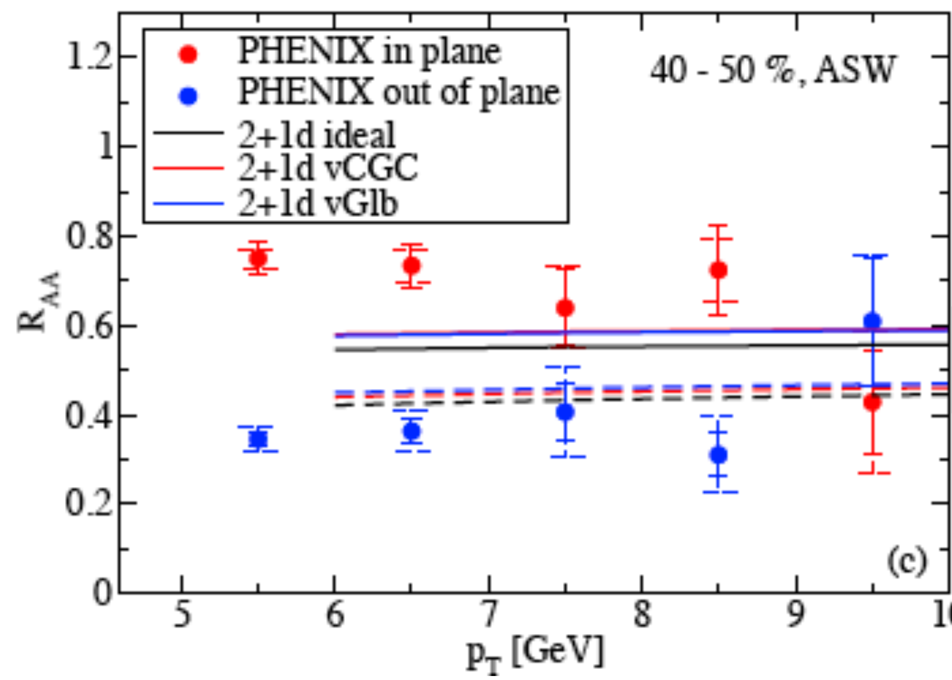
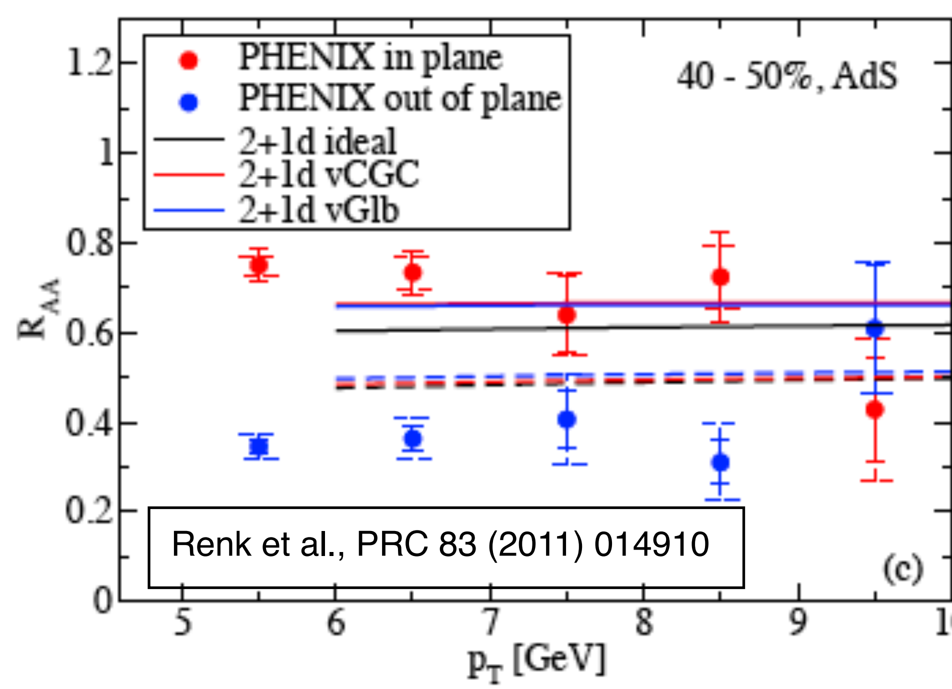
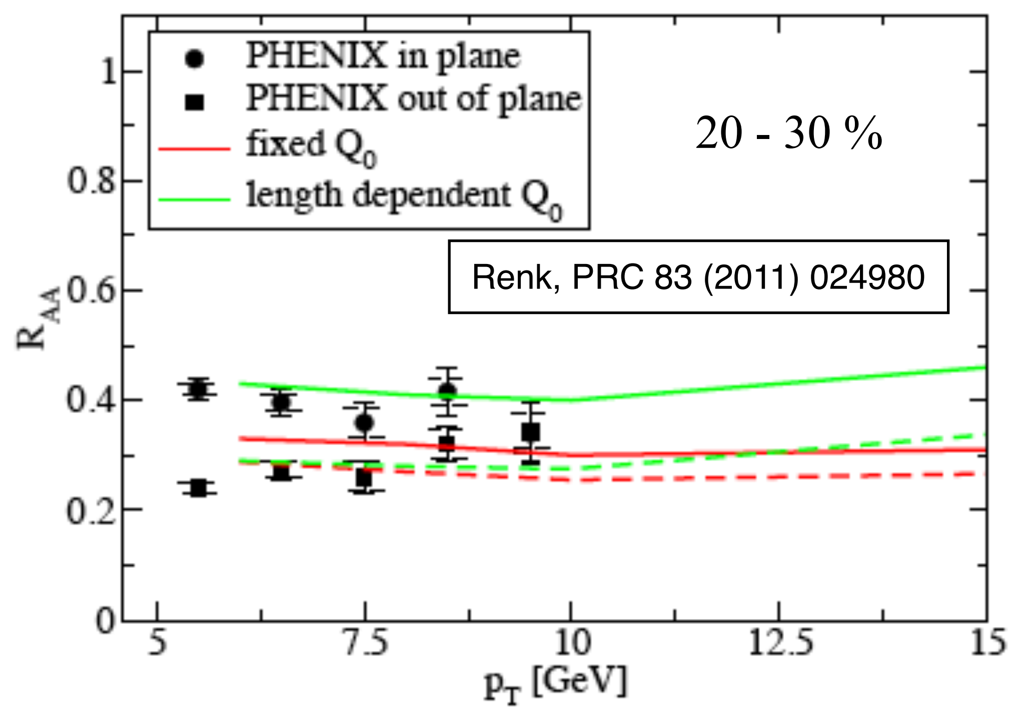


$\Delta E \sim L^2$

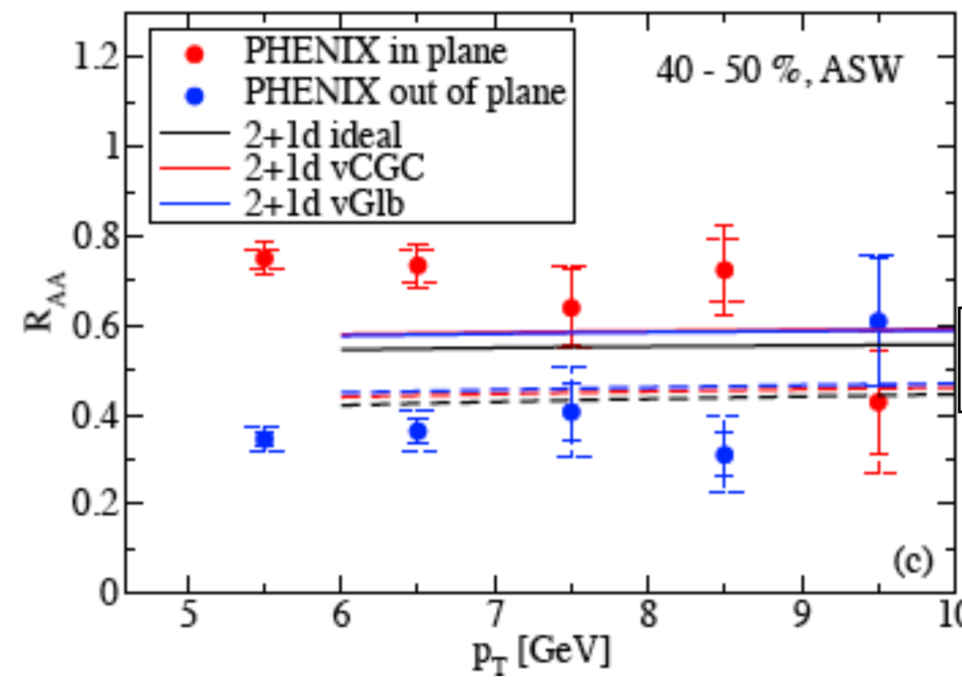


$\Delta E \sim L^3$

L dependence of energy loss



Length dependent virtuality cut-off $Q_0^2 = E/L$ also explains strong ϕ-dependence of R_{AA} fo.



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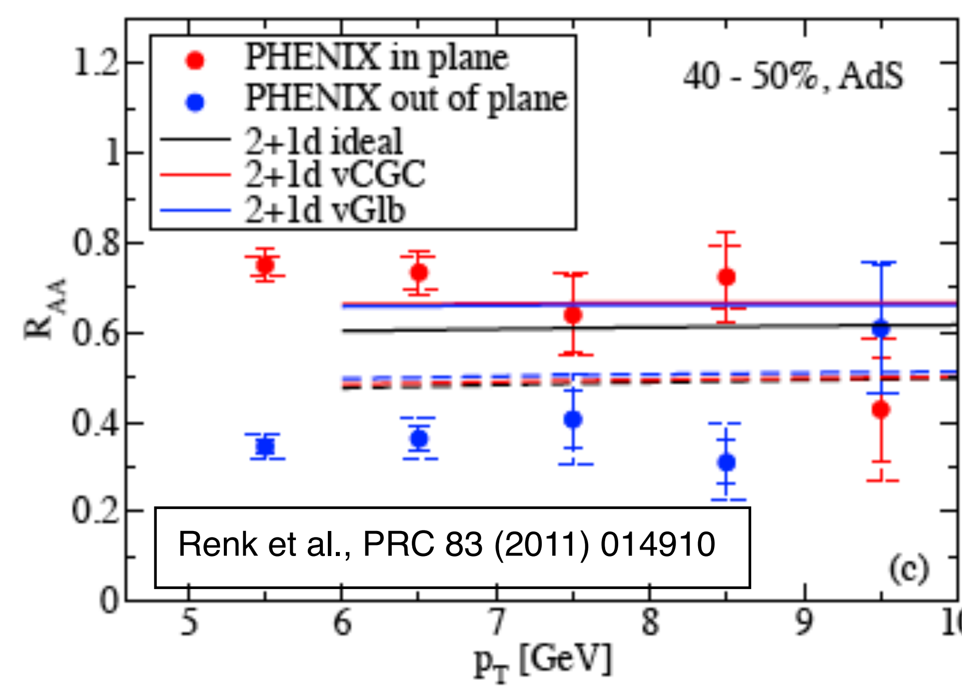
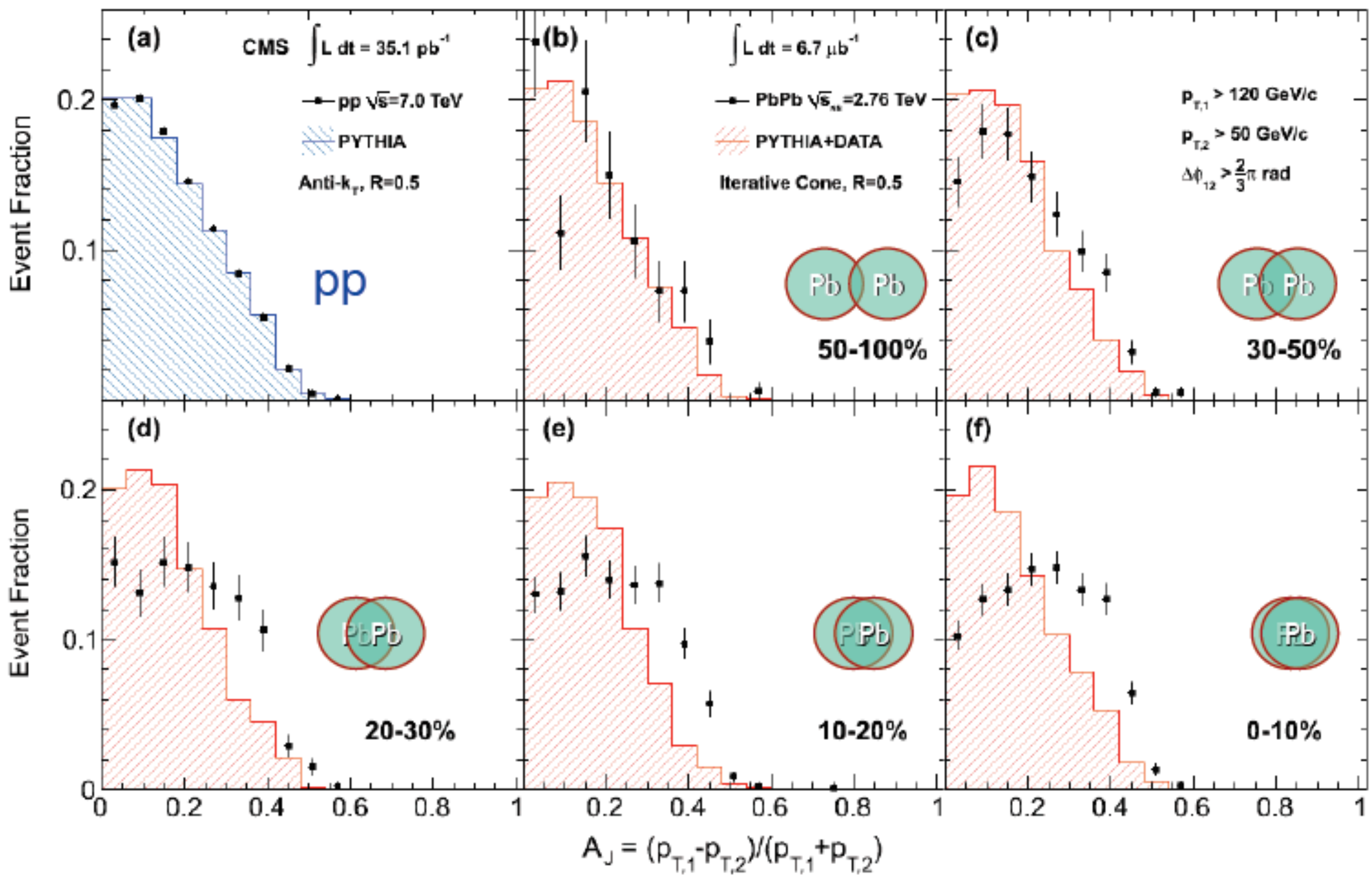


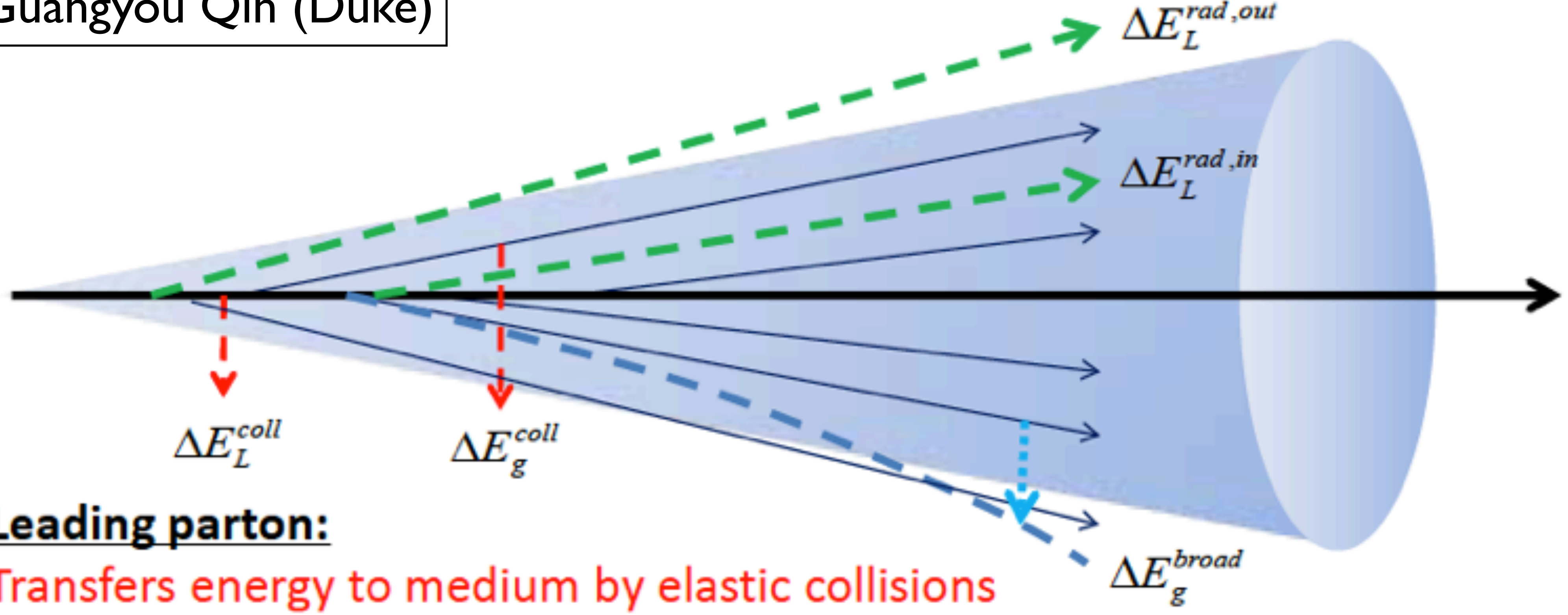
$\Delta E \sim L^3$

Di-jet asymmetry



Parton shower in matter

Guangyou Qin (Duke)



Leading parton:

Transfers energy to medium by elastic collisions

Radiates gluons scattering in the medium (*inside* and *outside* jet cone)

$$E_L(t) = E_L(t_i) - \int \hat{e}_L dt - \int \omega d\omega dk_\perp^2 dt \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

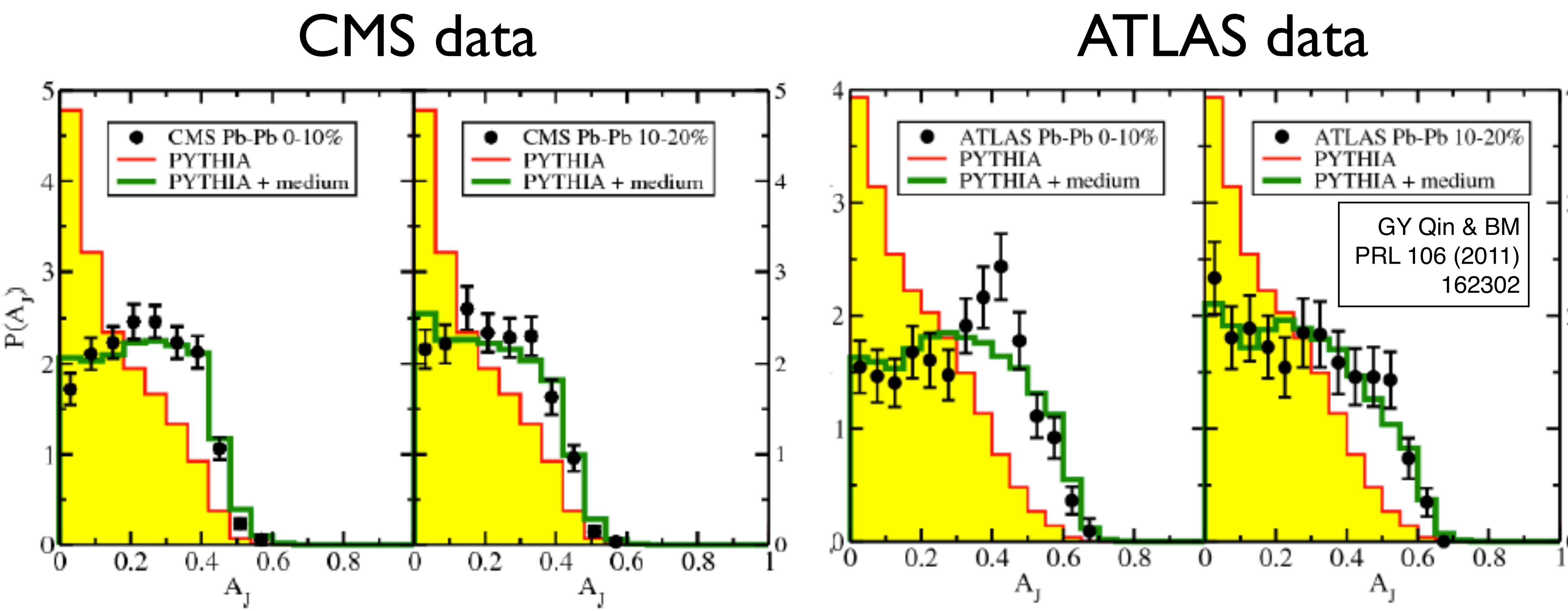
Radiated gluons (*vacuum* & *medium-induced*):

Transfer energy to medium by elastic collisions

Be kicked out of the jet cone by multiple scatterings after emission

$$\frac{df_g(\omega, k_\perp^2, t)}{dt} = \hat{e}\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_g + \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

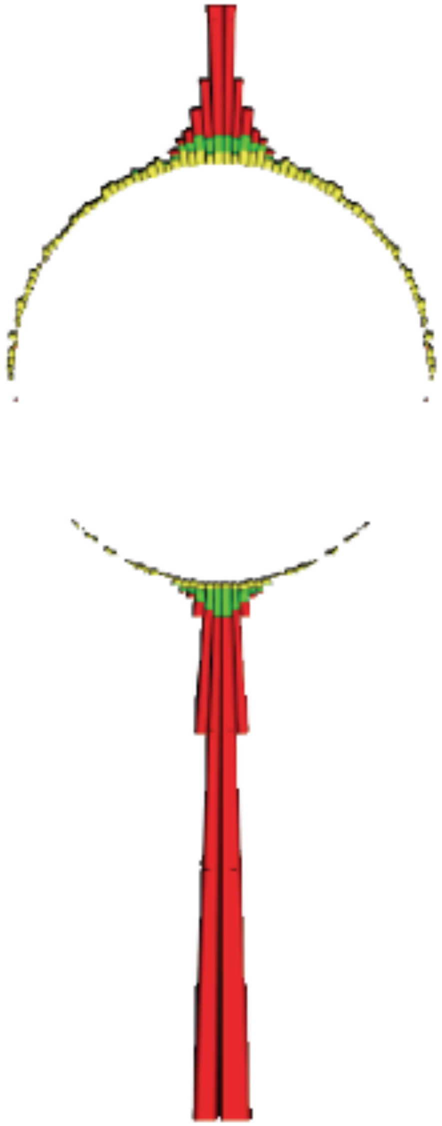
Di-jet asymmetry

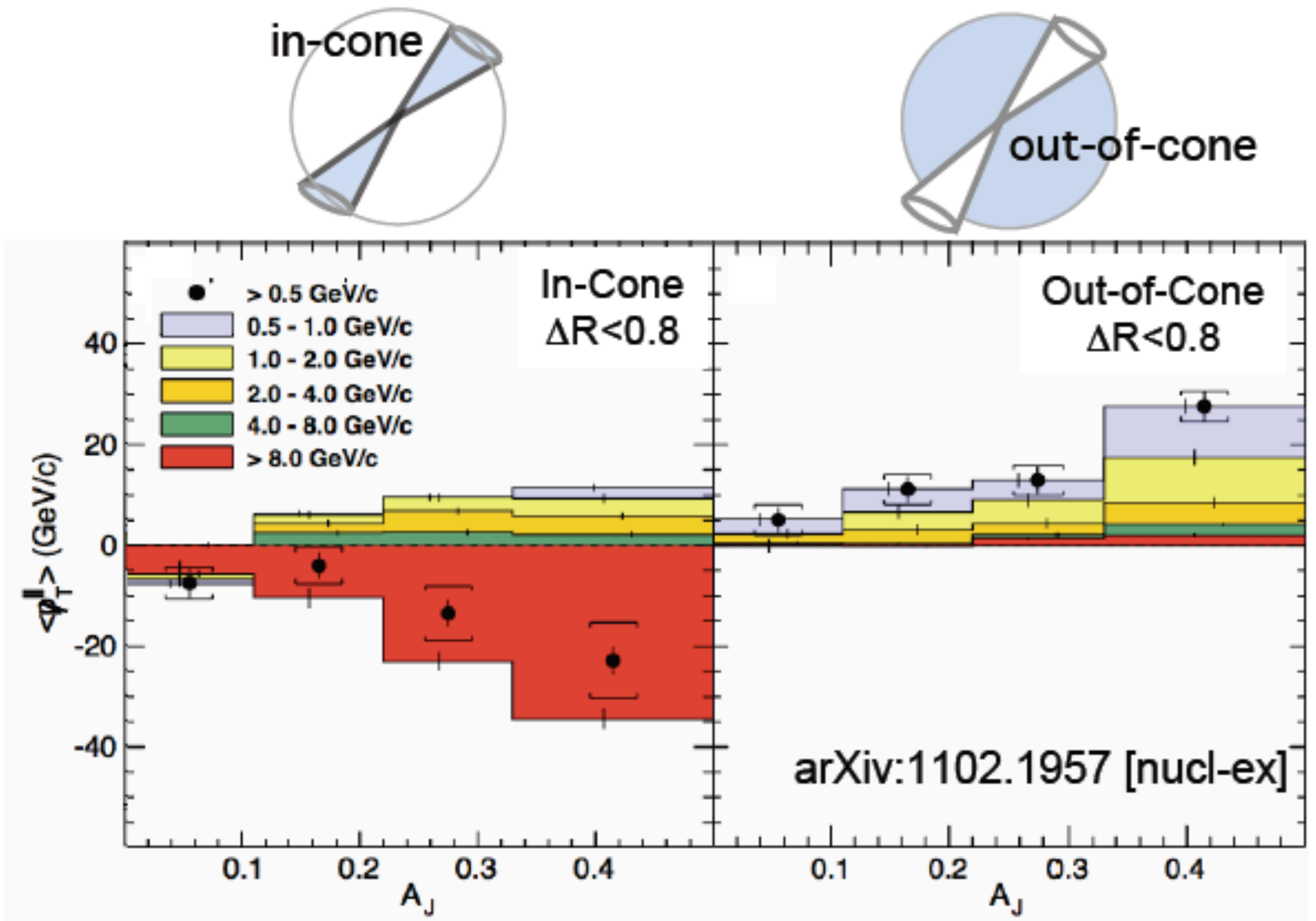


ATLAS and CMS data differ in cuts on jet energy, cone angle, etc; results depend somewhat on precise cuts and background corrections.
Fits of CMS and ATLAS data require ~20% different parameters.
Several other calculations using pQCD physics input also fit the data.

General conclusion: *pQCD jet quenching can explain these data.*

p_T balance



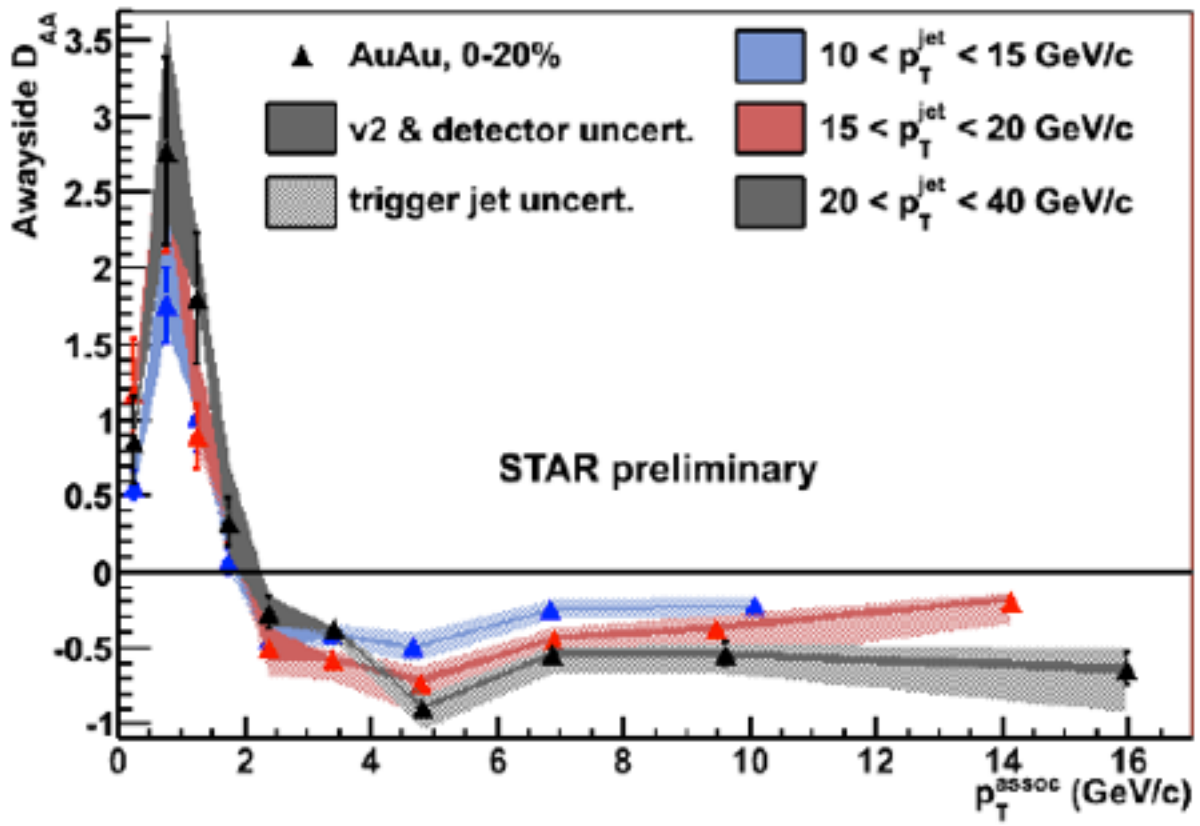


Di-jet momentum difference is balanced by low-p_T particles outside a wide cone.

"Di-jets" at RHIC

Reconstructed jet - hadron correlations instead of full di-jet measurements

$$\Delta B = \int dp_T^{assoc} D_{AA}(p_T^{assoc})$$



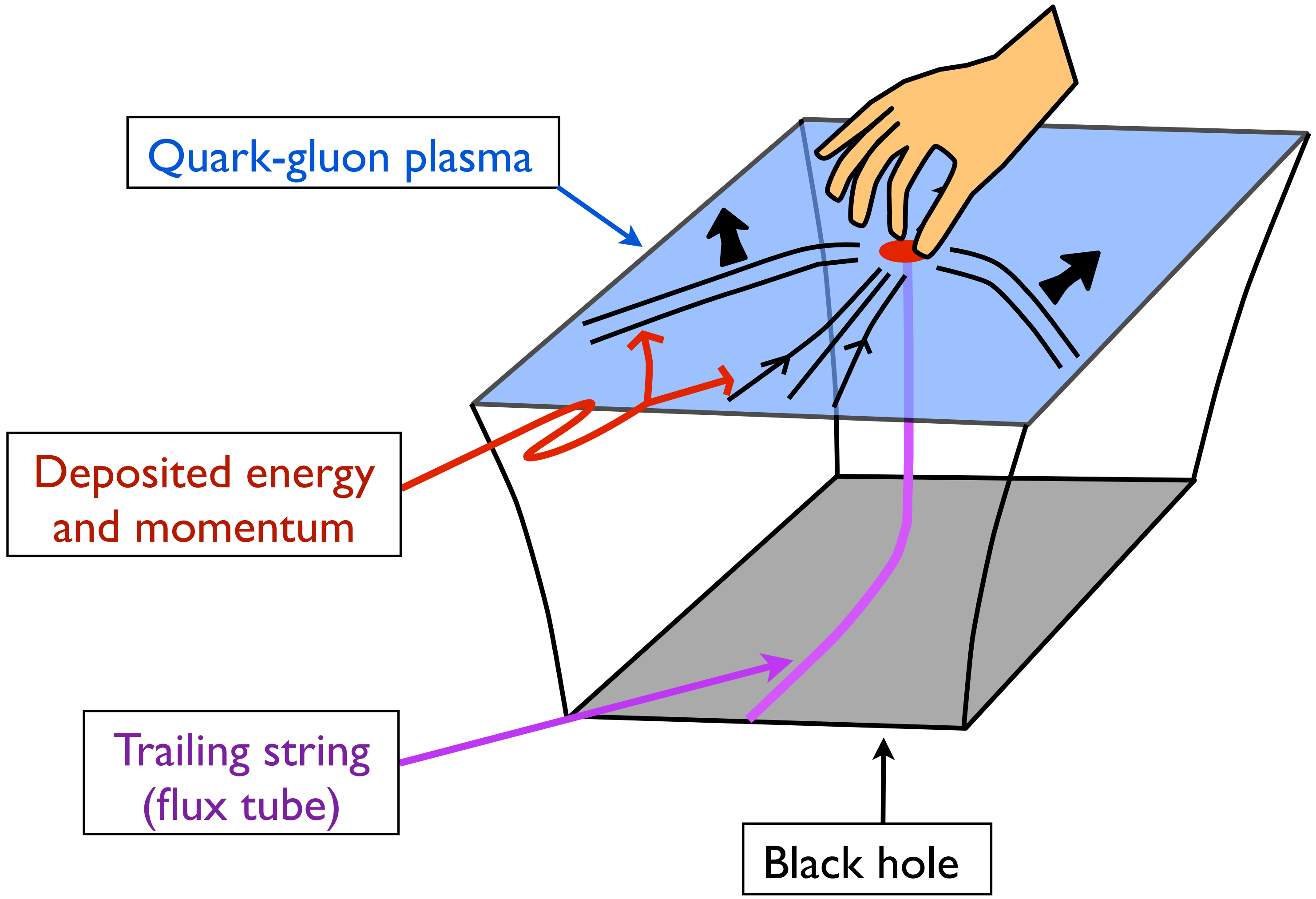
p_T^{jet} (GeV/c)	AS ΔB (GeV/c)
10-15	$1.6^{+1.5+0.5}_{-0.3-0.5}$
15-20	$2.3^{+1.8+0.5}_{-0.5-1.3}$
20-40	$2.5^{+2.0+0.5}_{-0.8-0.8}$

Energy lost at high p_T approximately recovered at low p_T and high R

Jet modification seems to be consistent with radiative energy loss picture; black + white models are disfavoured.

Is this difference real ? If so, what causes it ?

AdS/CFT energy loss



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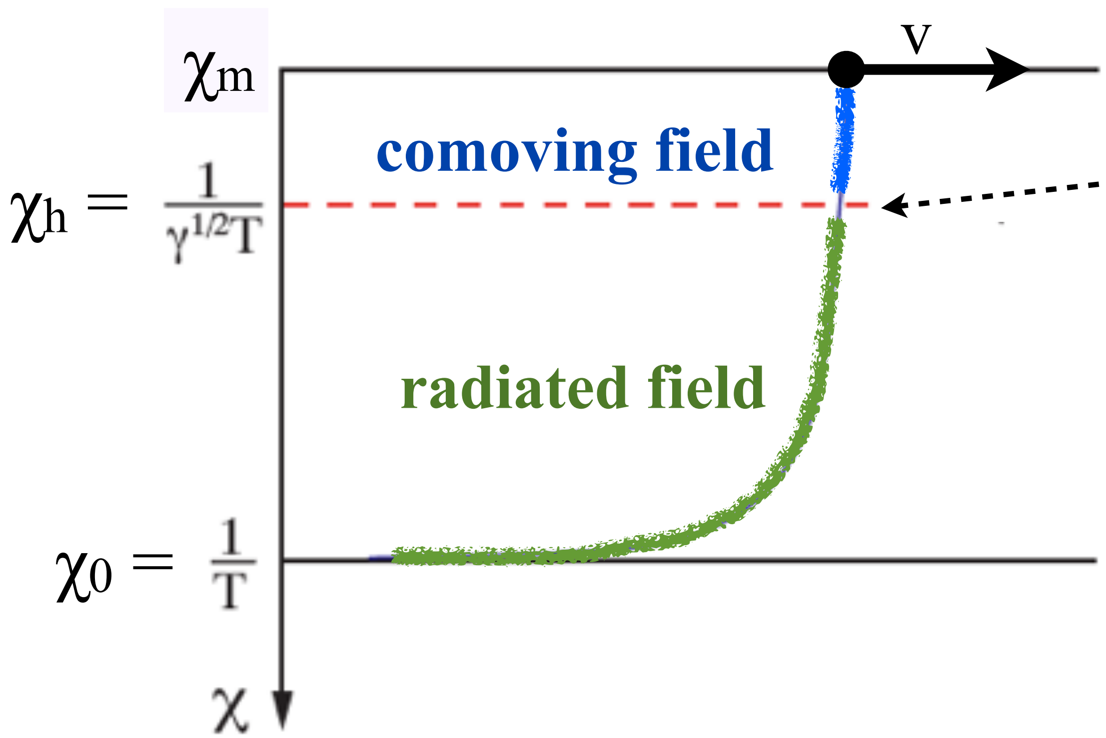
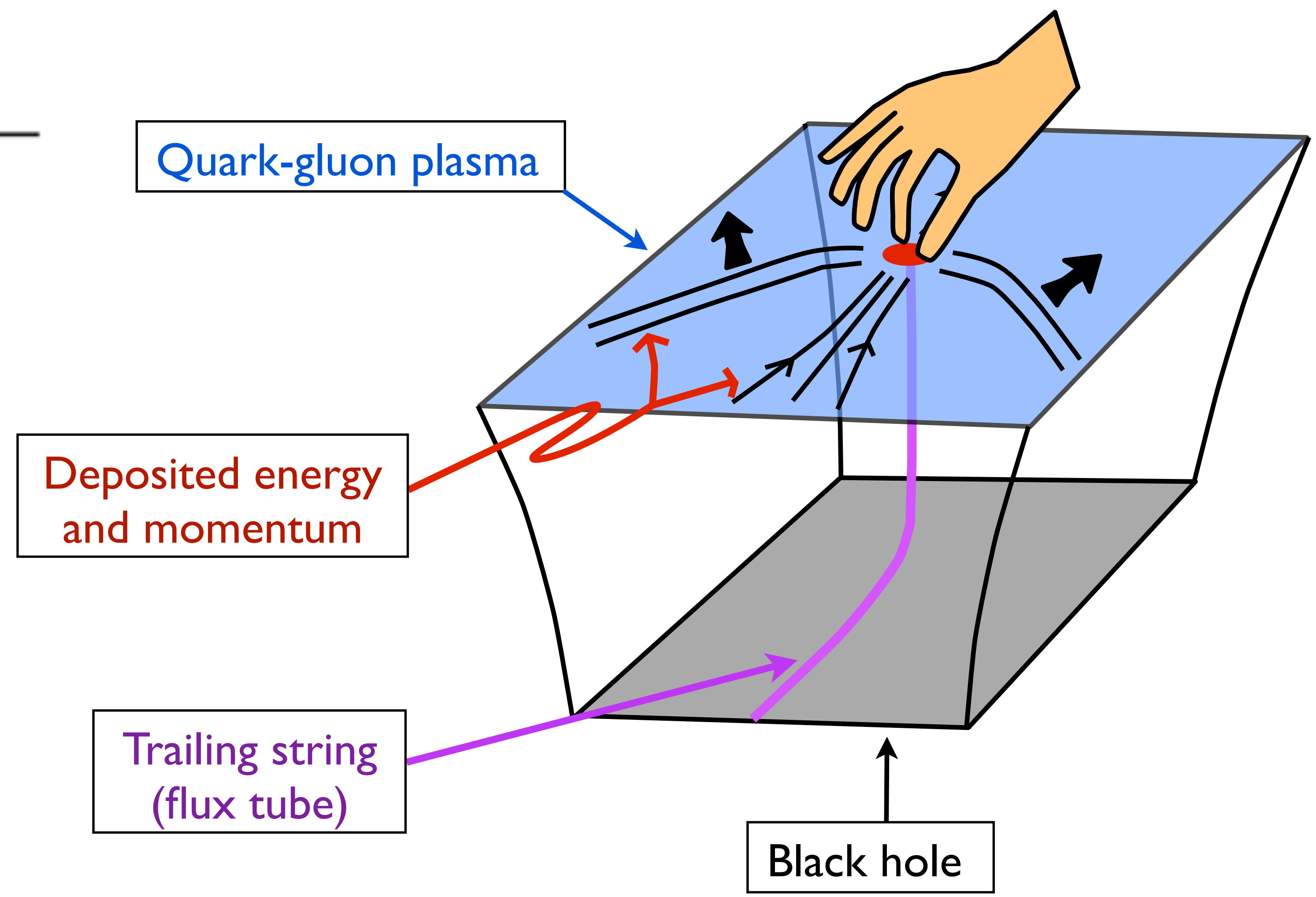


$$\chi_h = \frac{\chi_0}{\sqrt{\gamma}} = \frac{1}{\pi T \sqrt{\gamma}}$$

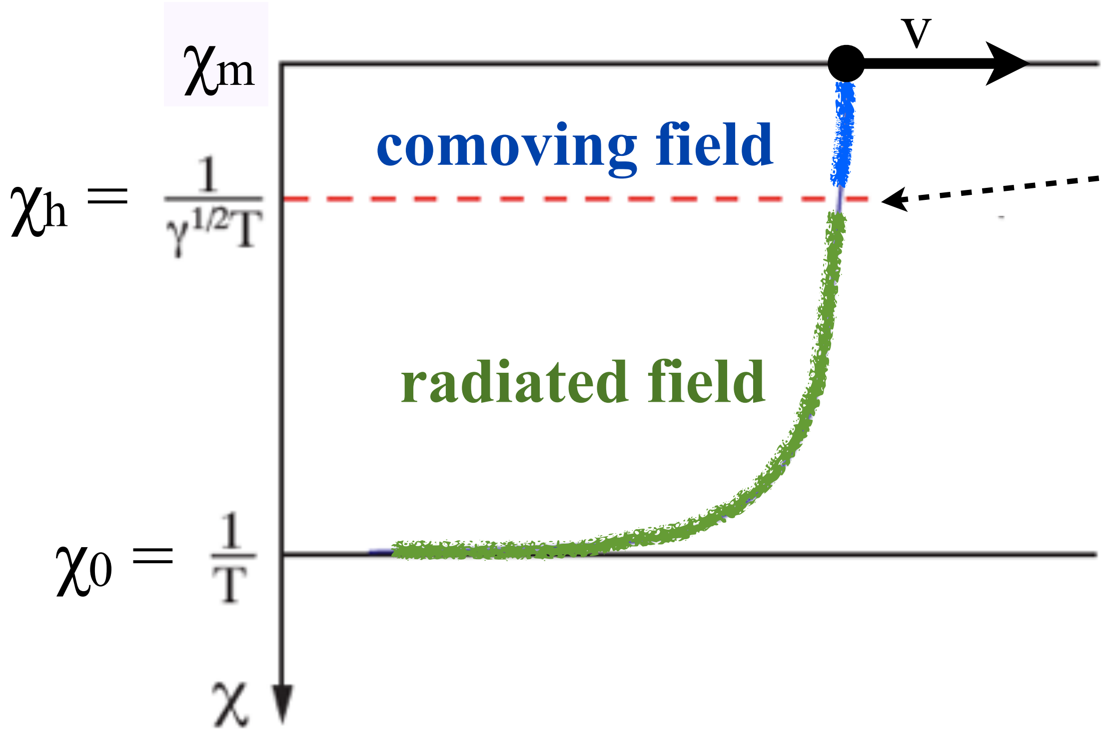
Upper and lower parts of the training string are causally disconnected



If quark is sufficiently massive or off-shell after scattering, it travels above the string horizon.

Soft field is continuously stripped off; quark emerges from matter in a highly virtual state with a truncated color field.

AdS/CFT energy loss



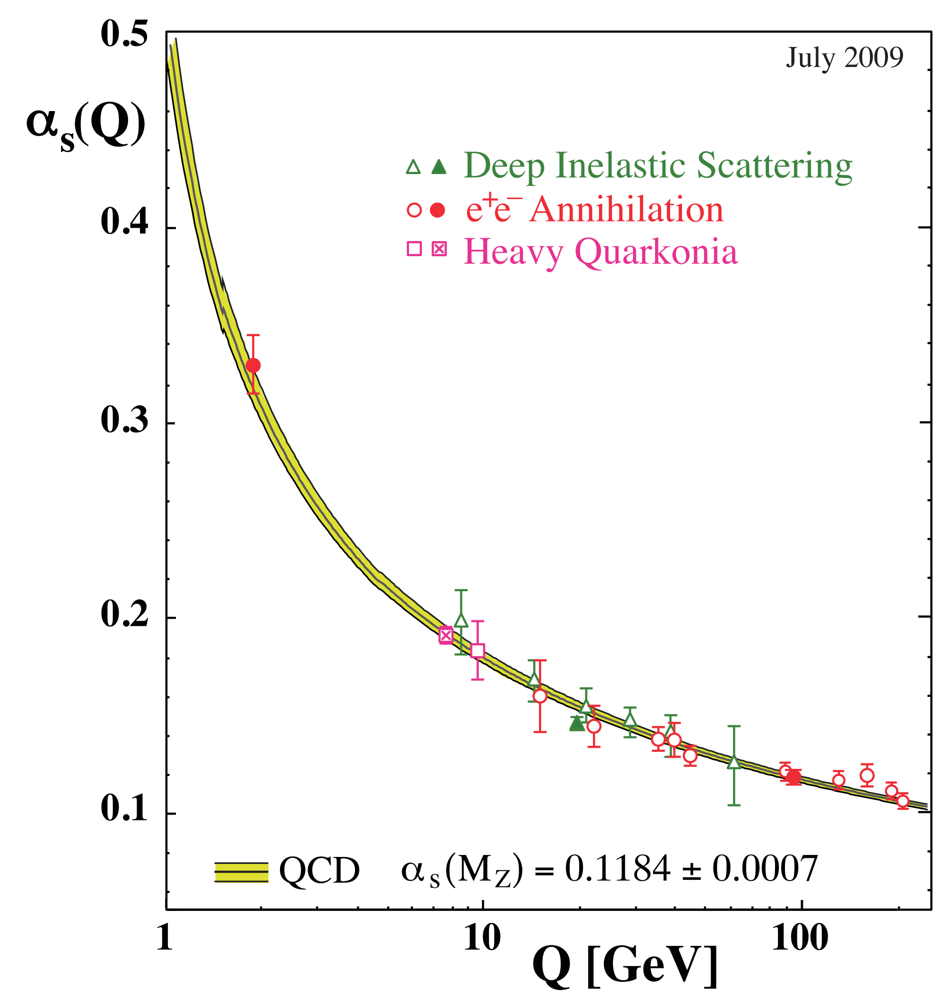
$$\chi_h = \frac{\chi_0}{\sqrt{\gamma}} = \frac{1}{\pi T \sqrt{\gamma}}$$

Upper and lower parts of the training string are causally disconnected

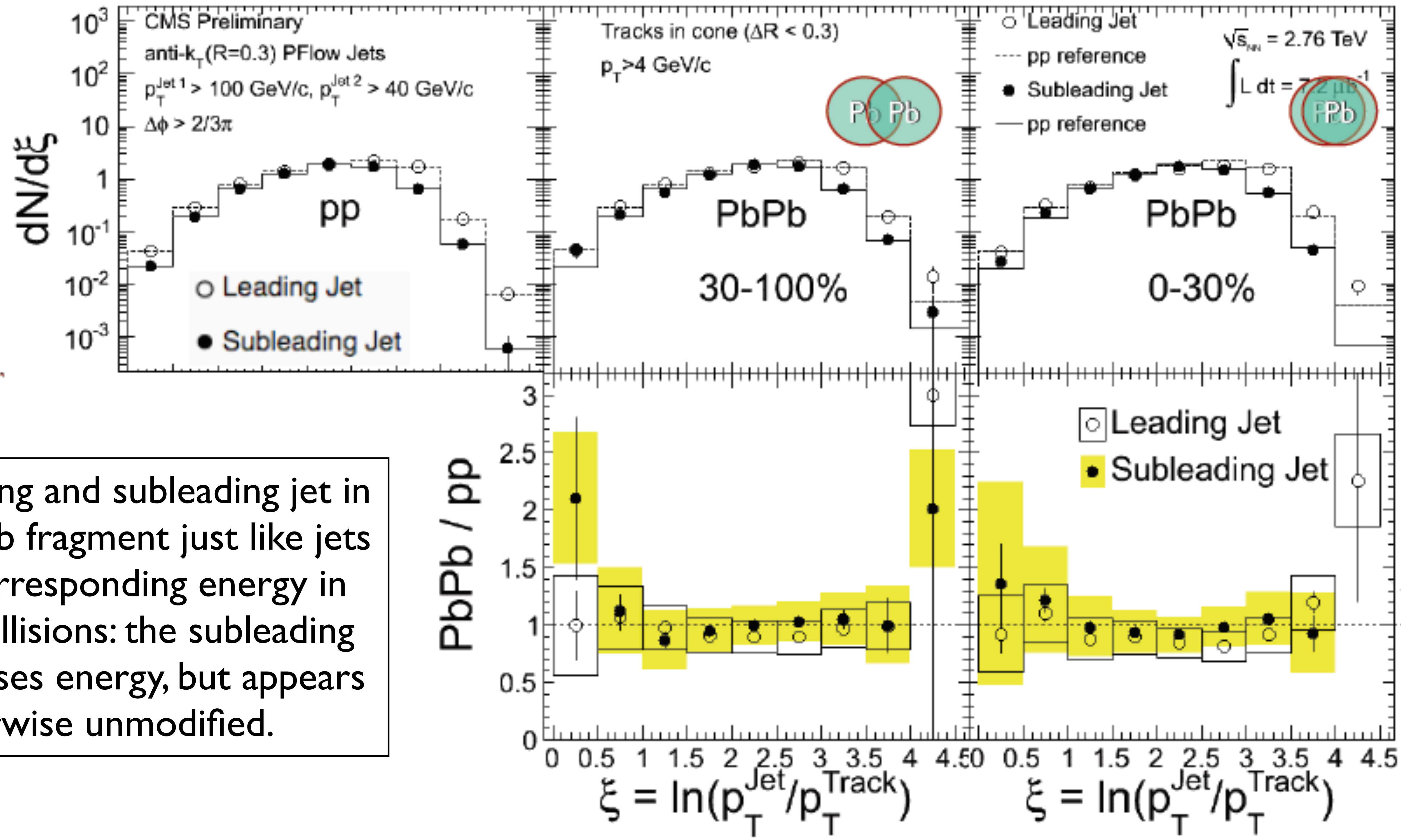
QCD coupling is strong only below a certain virtuality Q_{crit} .

Whether $T\sqrt{\gamma} > Q_{crit}$ or $< Q_{crit}$ depends on T and $\gamma = E/Q$.

This may explain the different behavior at LHC and RHIC ?



Fragmentation



Leading and subleading jet in Pb+Pb fragment just like jets of corresponding energy in *pp* collisions: the subleading jet loses energy, but appears otherwise unmodified.

A fallacy

First thought: “This just shows that the fragmentation of reduced energy jet shower happens outside the medium.”

But wait: The fragmentation function depends on the virtuality Q^2 of the fragmenting parton, which should be $O(p_T^2) \sim 10^4$ GeV^2 in *pp,* and in PbPb the virtuality of the degraded parton after it exists the medium:

$$Q^2 \sim \max(\, \hat{q}L\ ,\ E/L\,) \sim 5\text{–}10\ \mathrm{GeV}^2.$$

So, why do the two fragmentation patterns look alike?

Future opportunities

Jet tomography: Study the structure of the matter using jet quenching.

This means selecting event samples with similar spatial structure, e.g.

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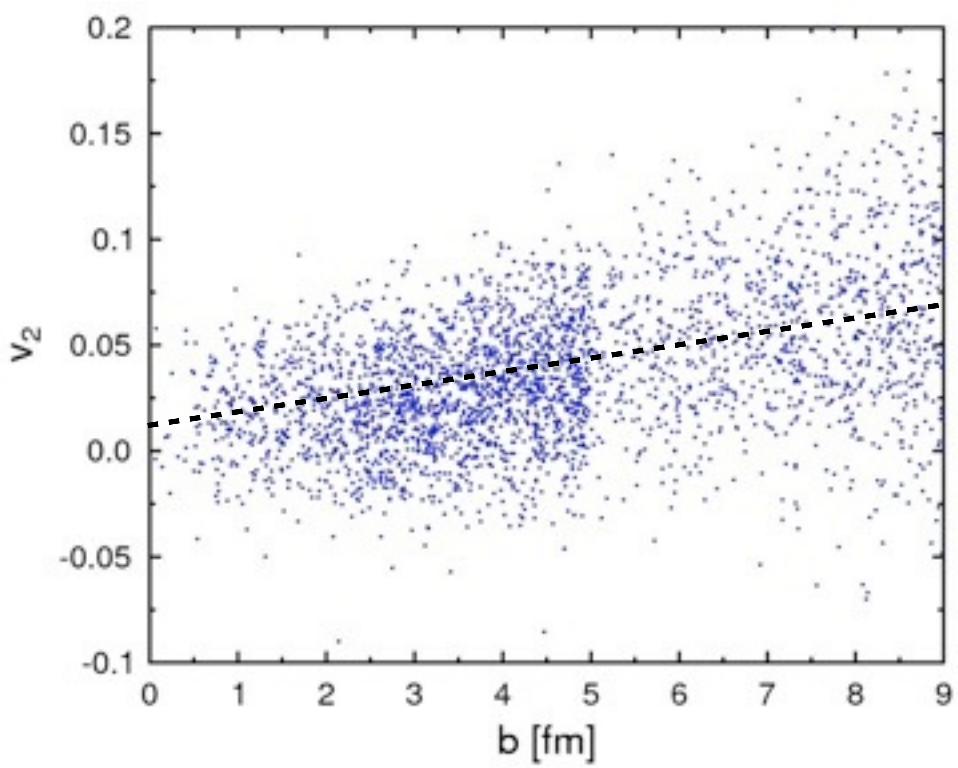

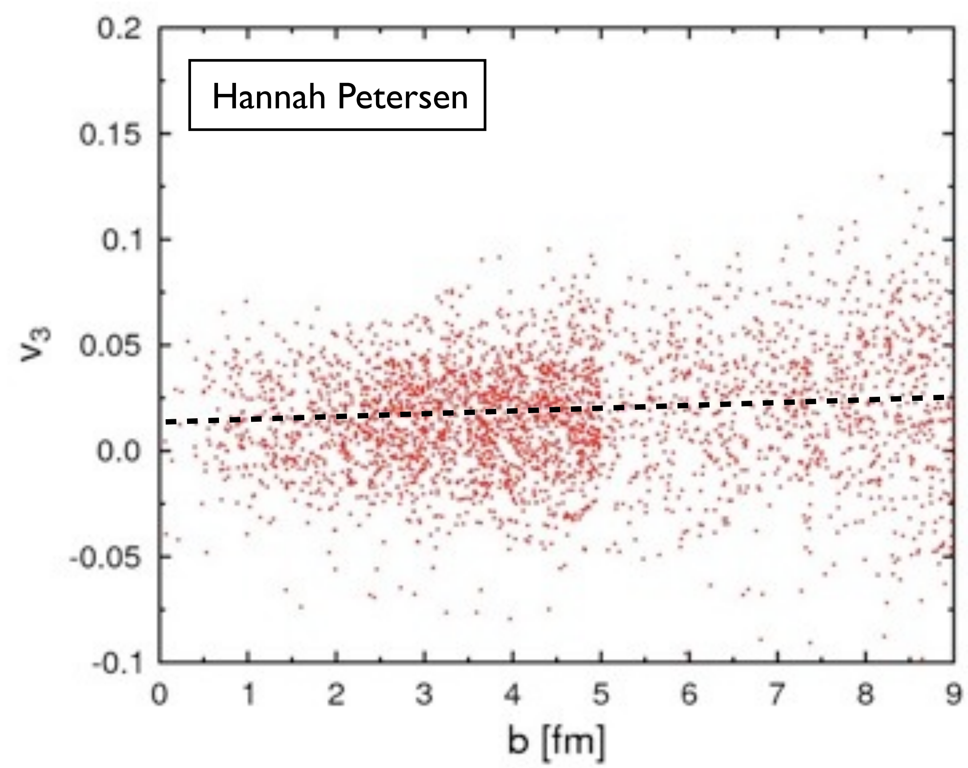

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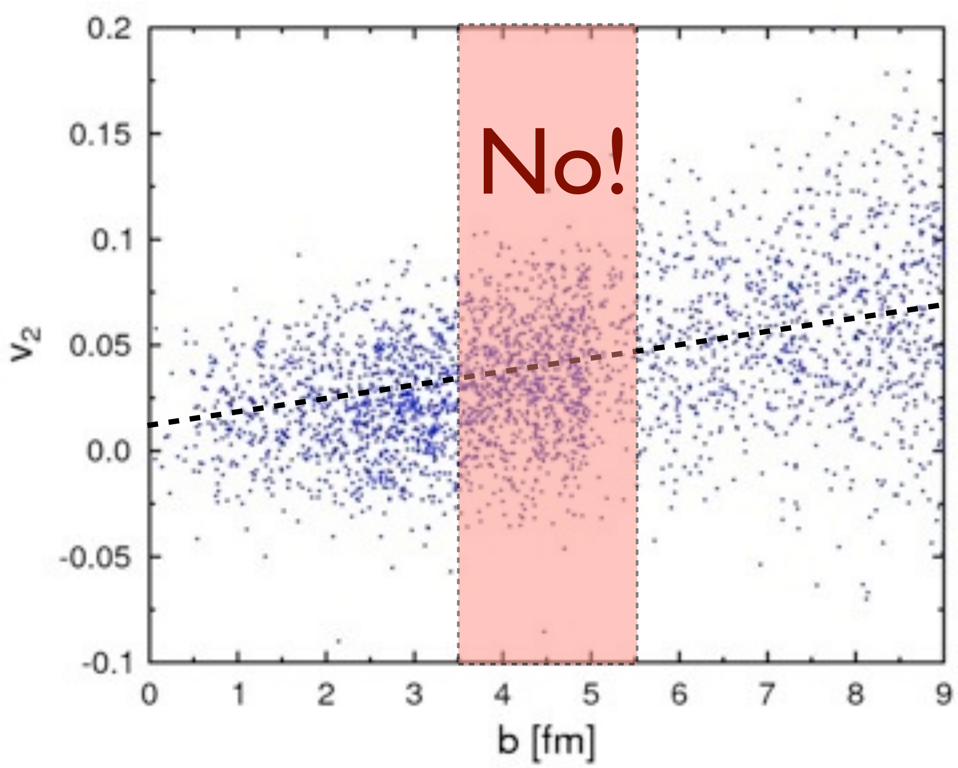

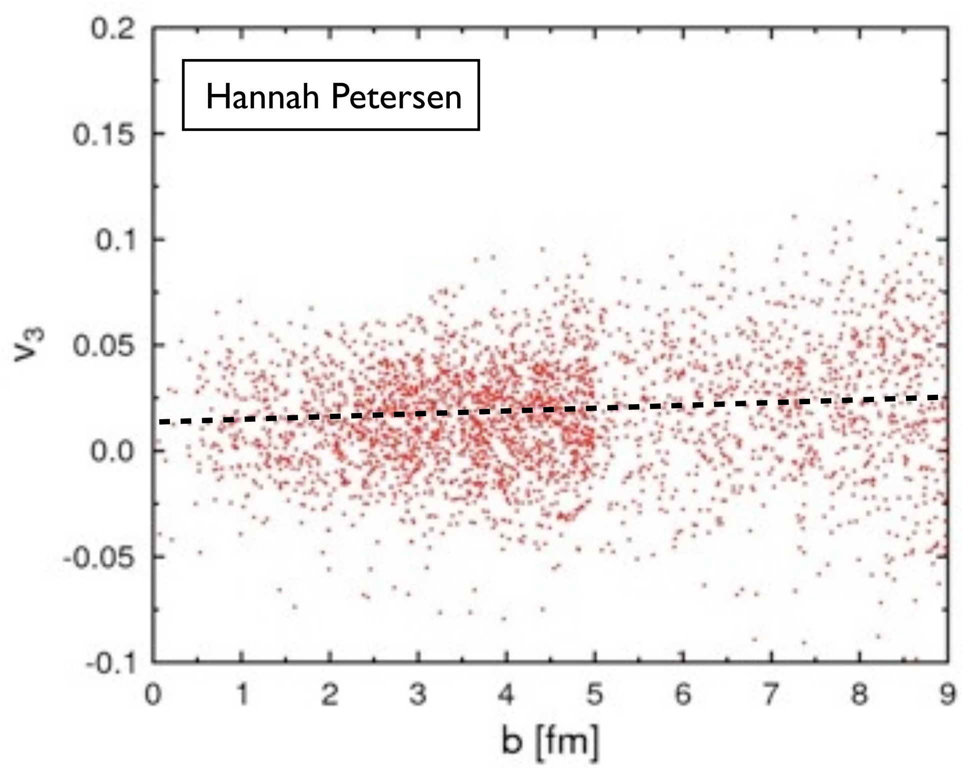

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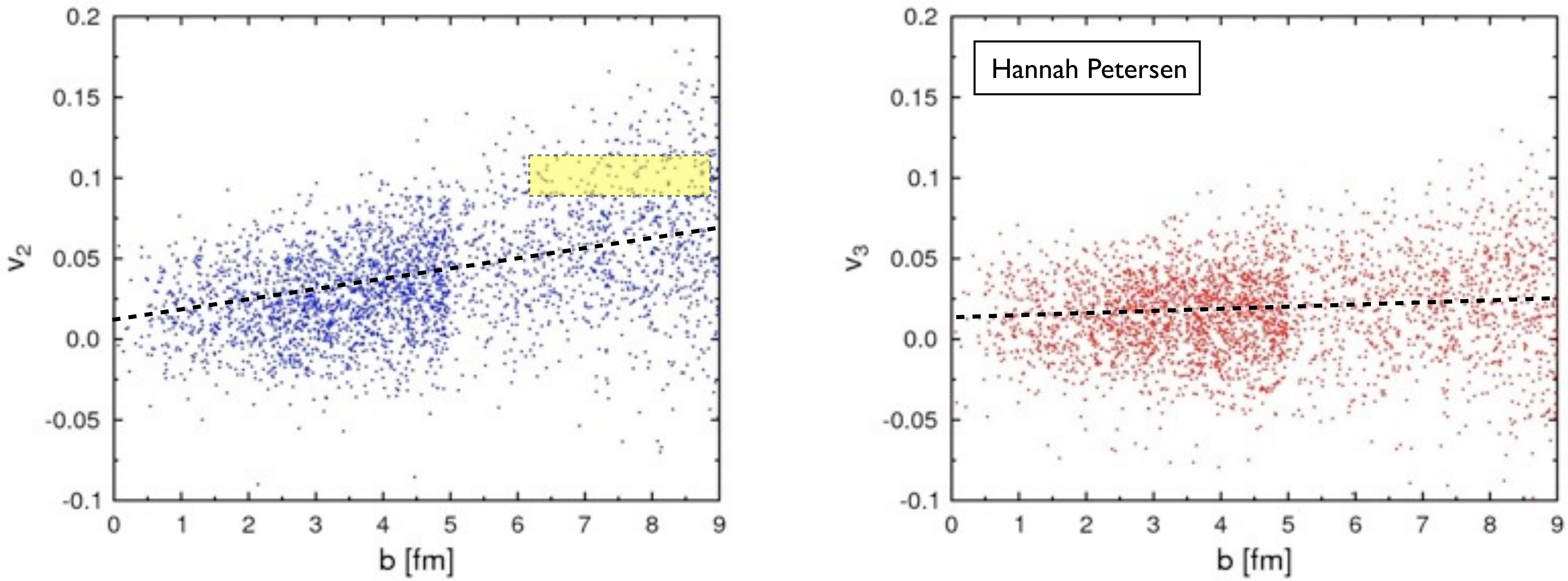

(a) Pick events with large v_2

Future opportunities

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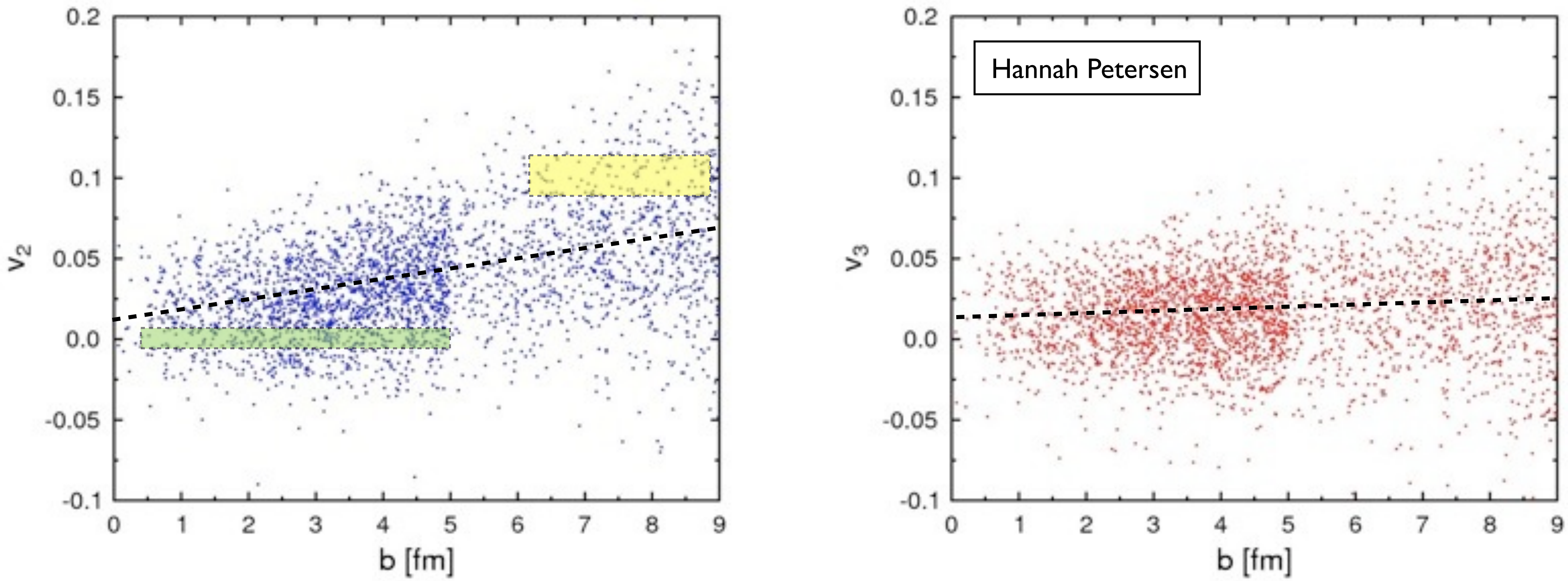

(a) Pick events with large v_2

(b) Pick events with $v_2 \sim 0$

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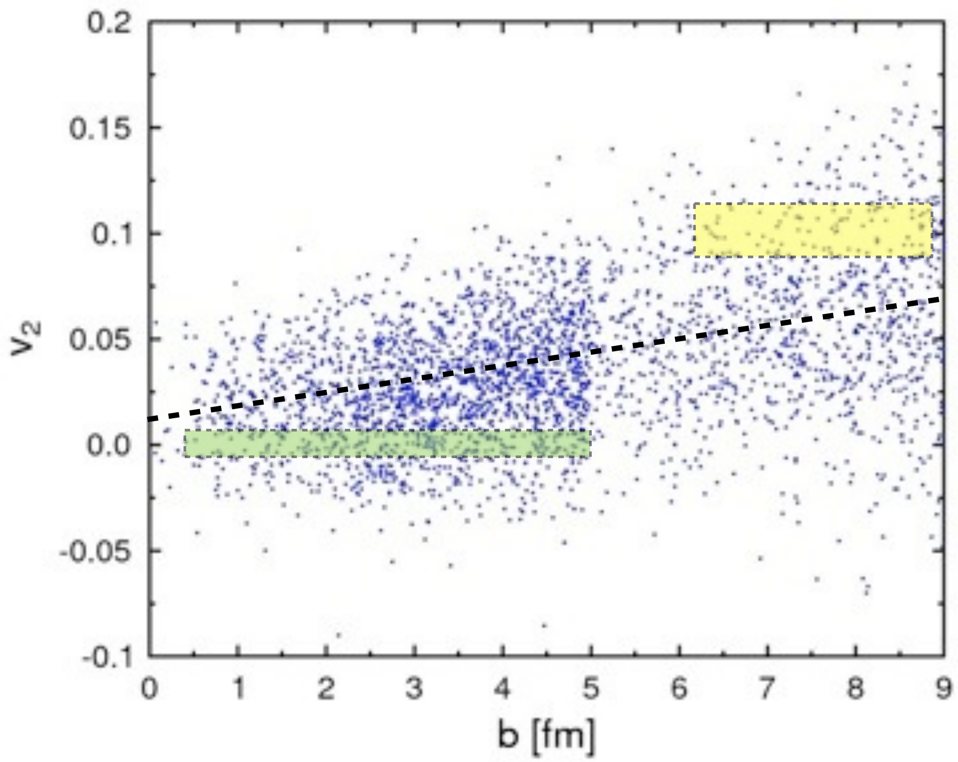

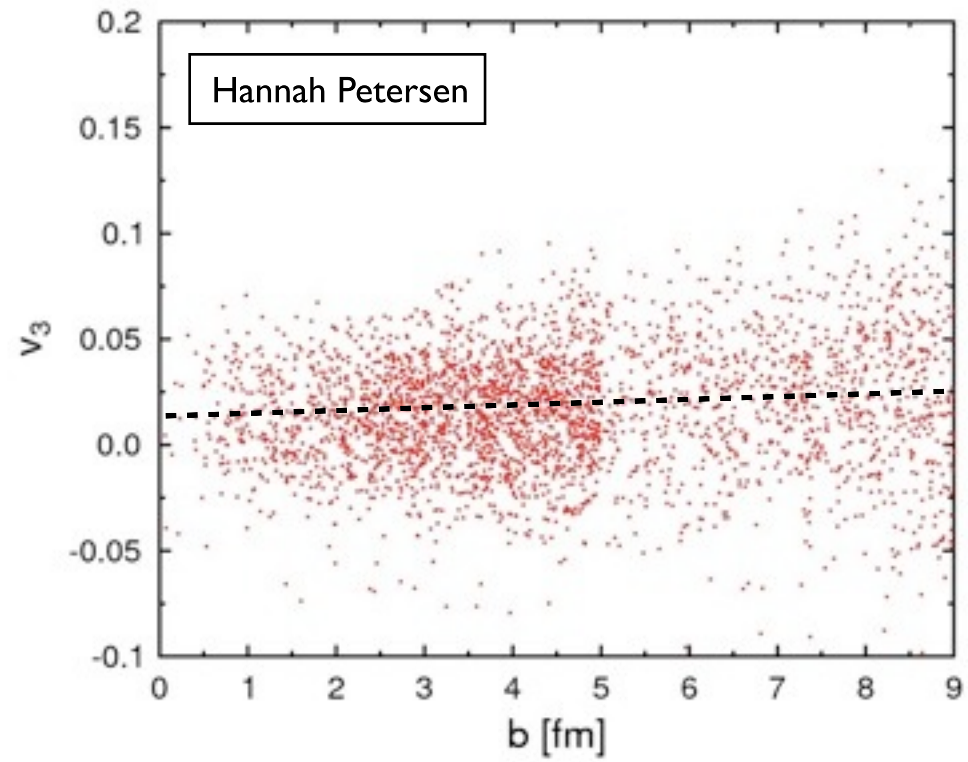

(a) Pick events with large v_2

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(c) Pick events with large v_2 and $v_3 \sim 0$

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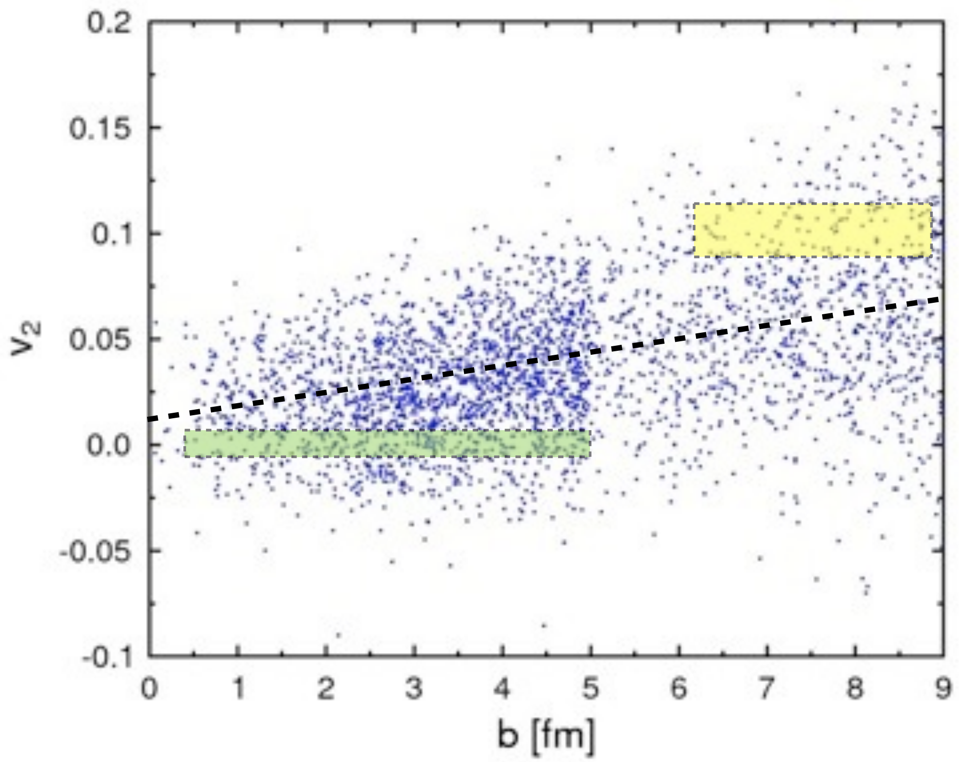

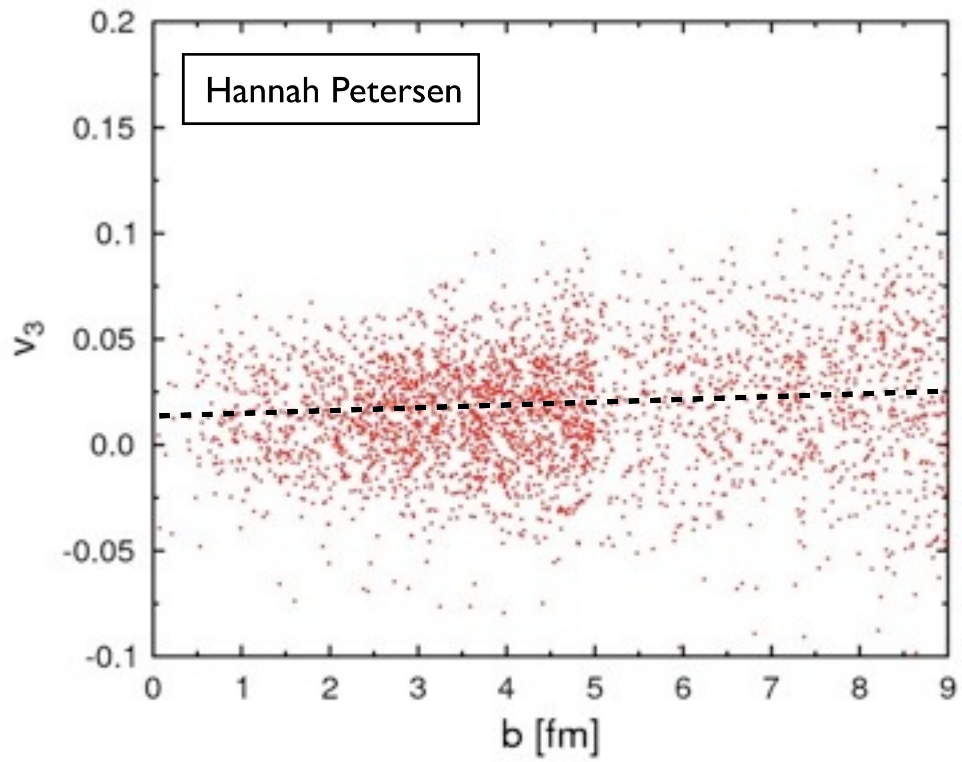

(a) Pick events with large v_2

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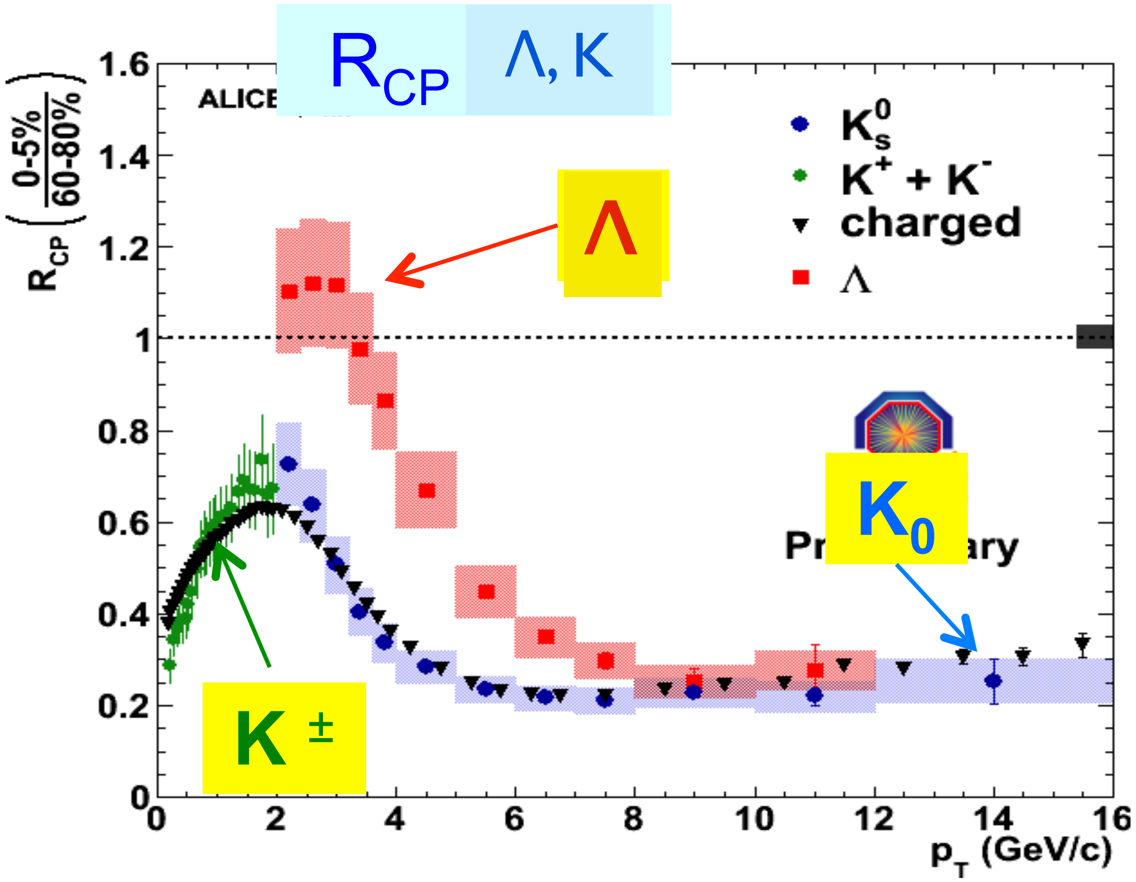
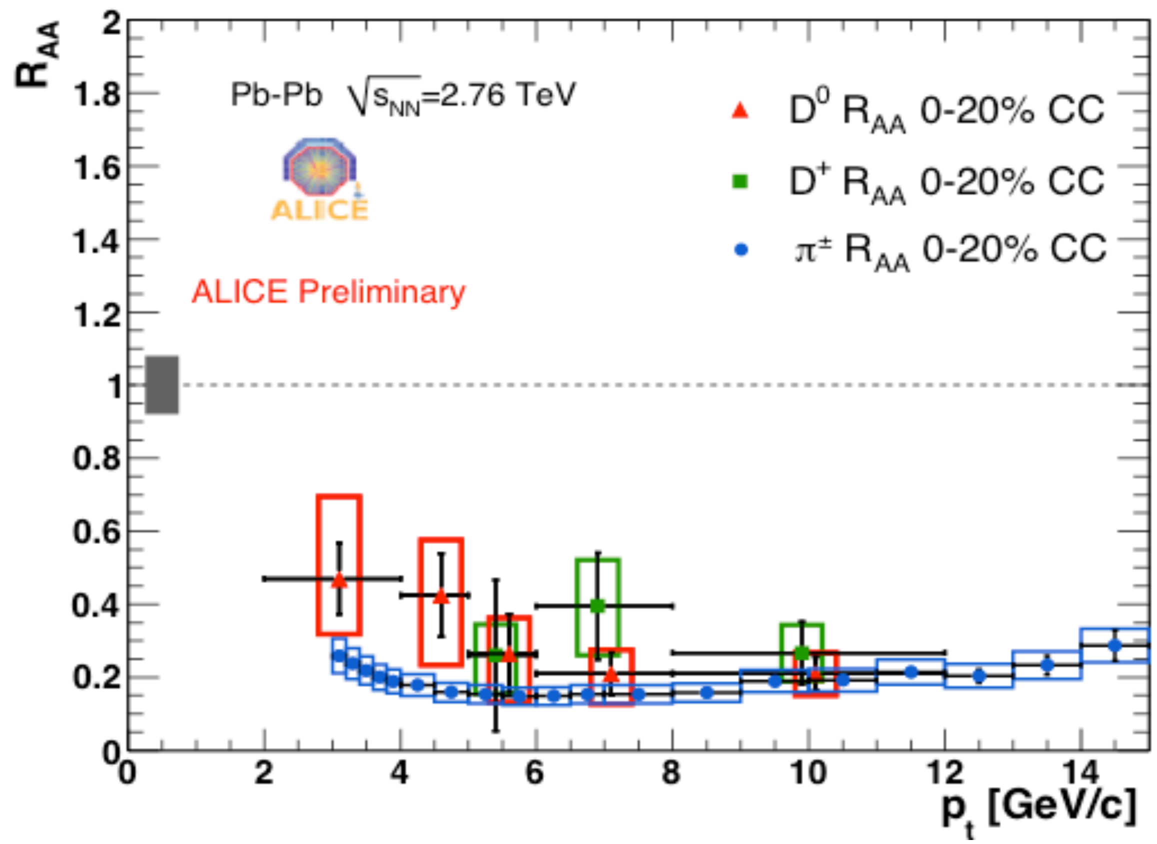
(c) Pick events with large v_2 and $v_3 \sim 0$

Only when we can do this, can we talk about performing ***jet tomography*** !

Flavor dependence

R_{AA} of all hadrons (including D-mesons) appear to converge at p_T > 10 GeV.





Can pQCD energy loss theory explain this? The jury is still out.

[See, e.g., Buzzatti & Gyulassy, arXiv:1106.3061]

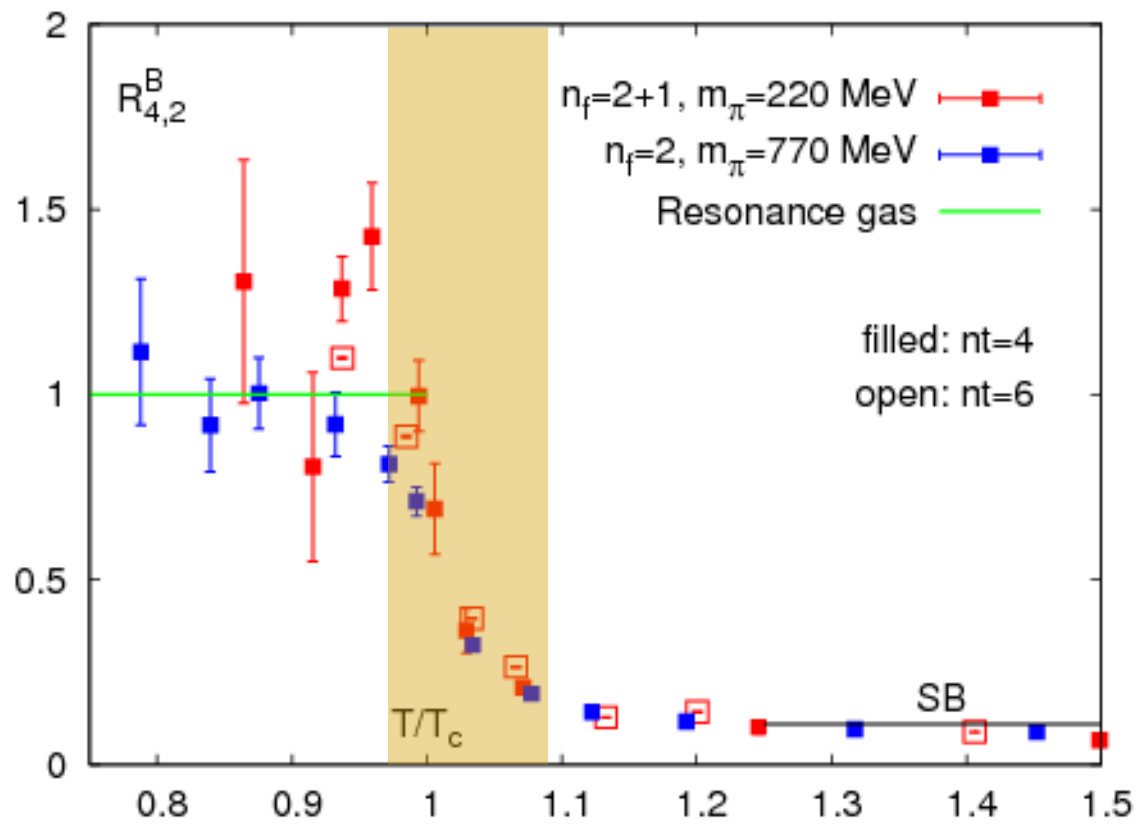
The Flavored QGP

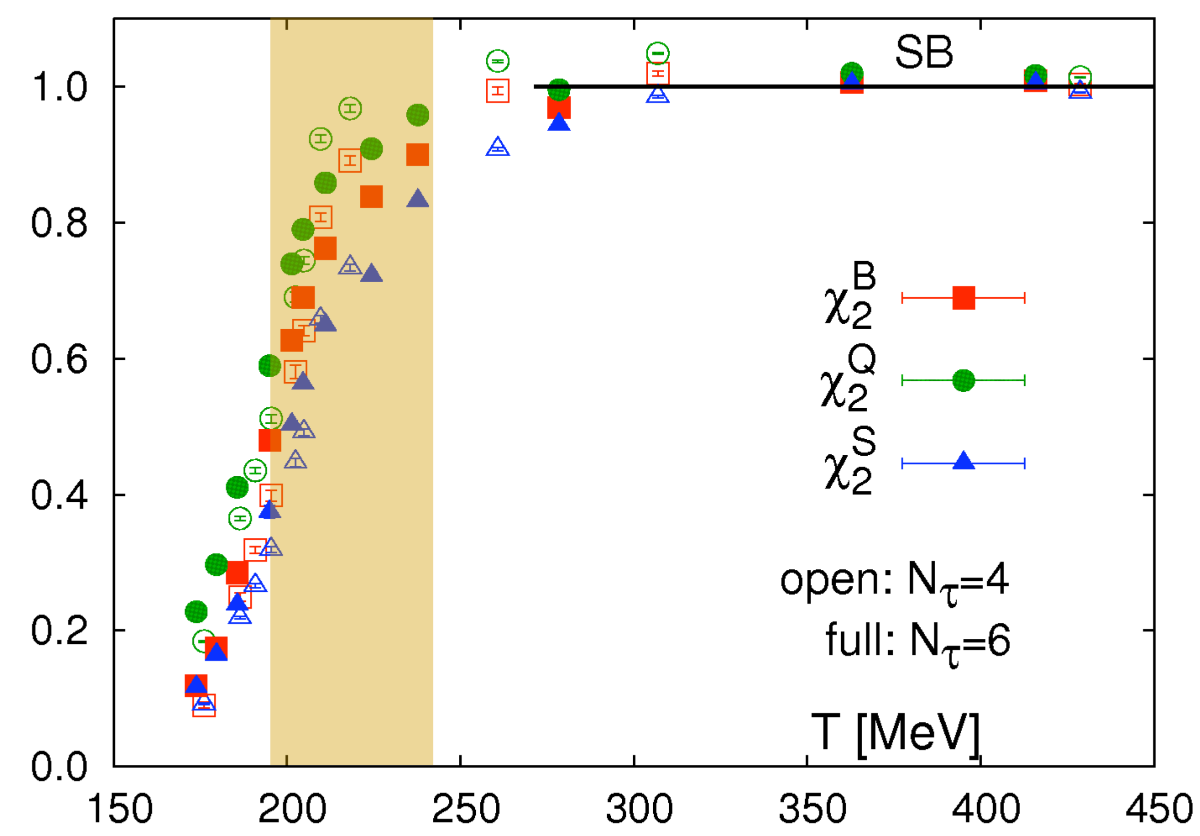
A puzzle

Fluctuations of conserved quantum numbers of quarks above T_c behave "as if" quarks were free:

B = baryon number
Q = electric charge
S = strangeness

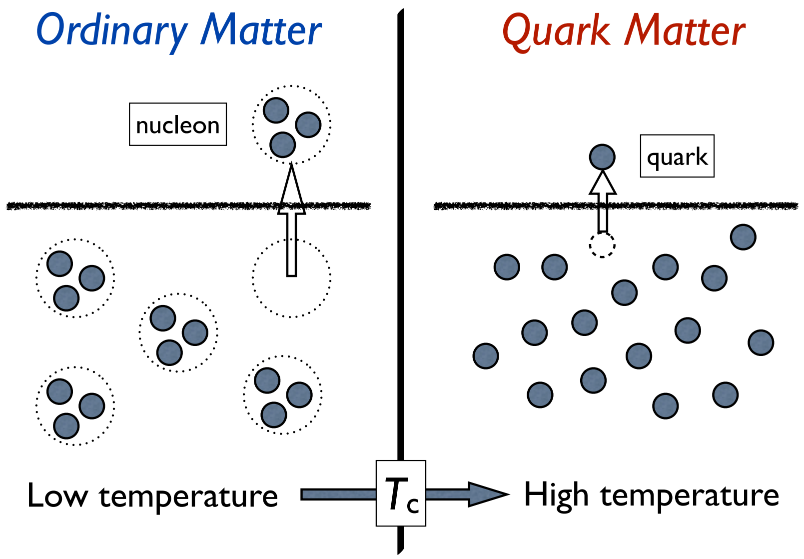
Baryon number kurtosis





How is this behavior compatible with strong coupling and absence of quasi-particle excitations ?

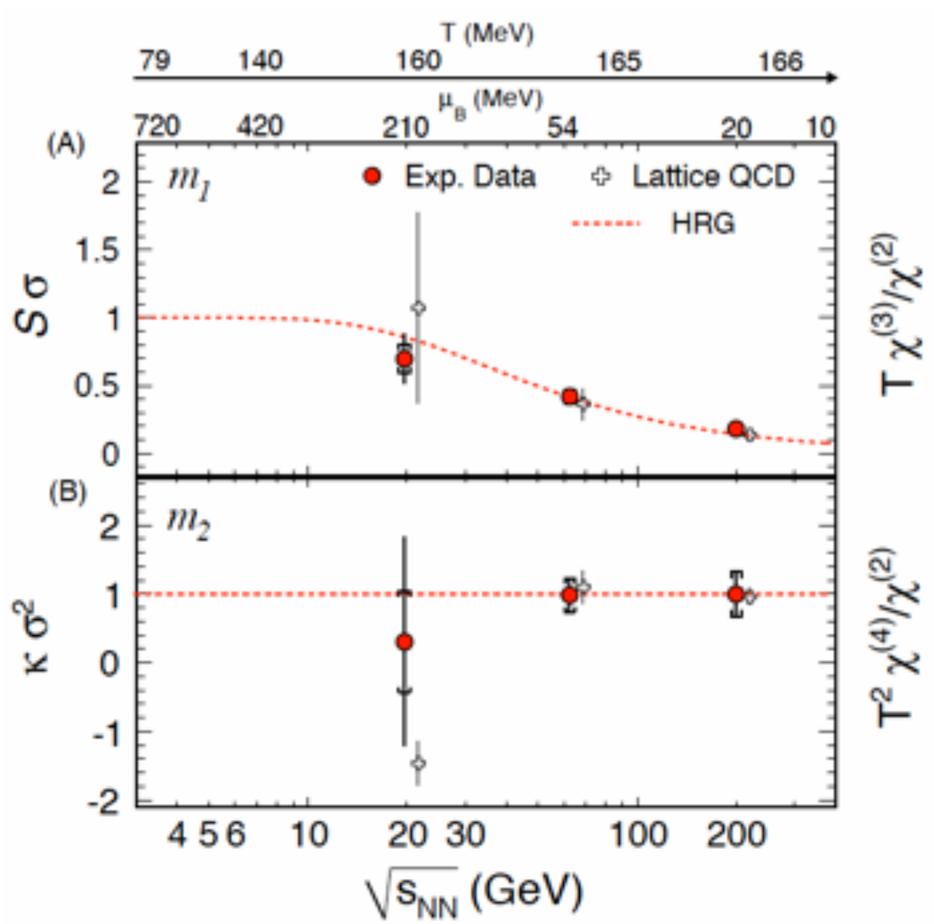
Setting the QCD scale

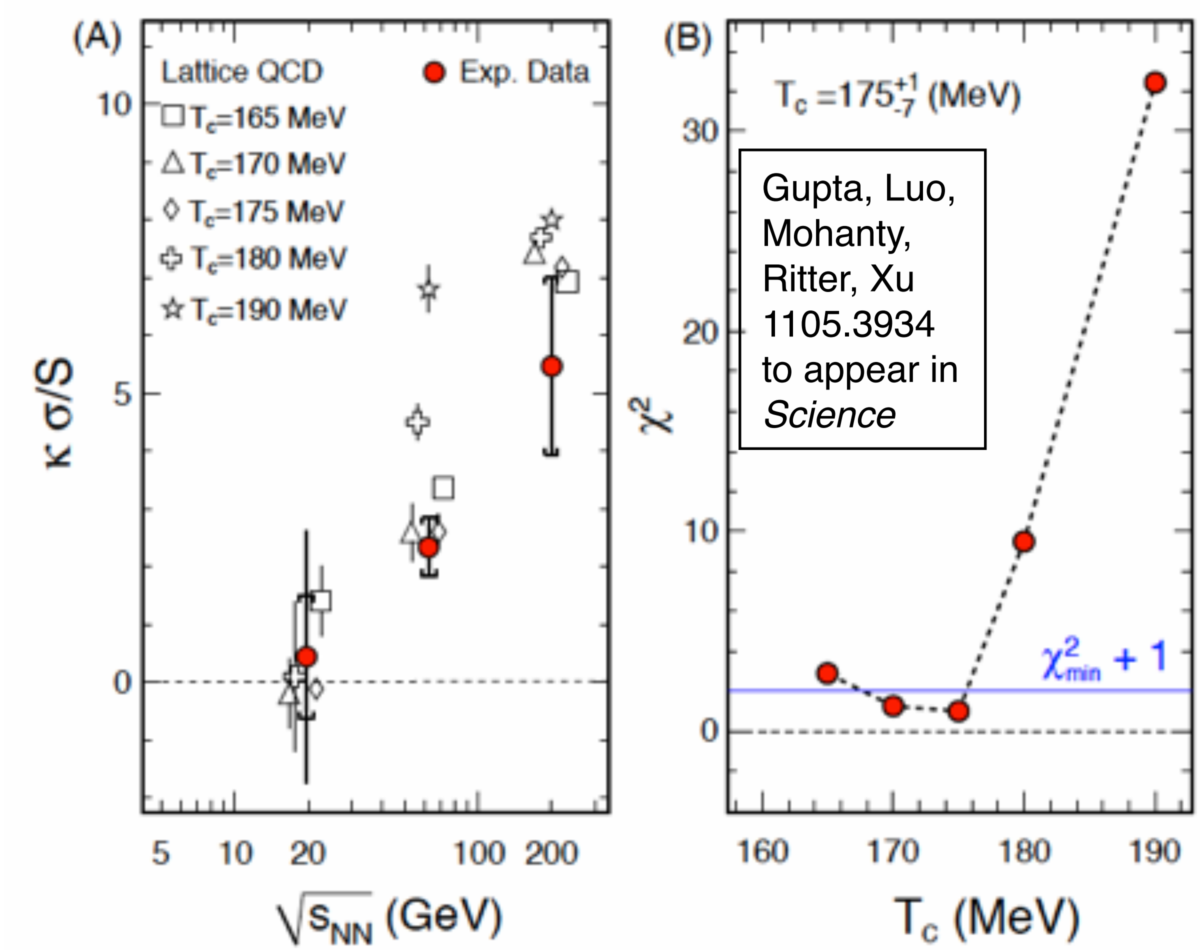


Use data from beam energy scan to fix T, μ_B

Measure net proton distribution to obtain width σ, skewness S, and kurtosis κ

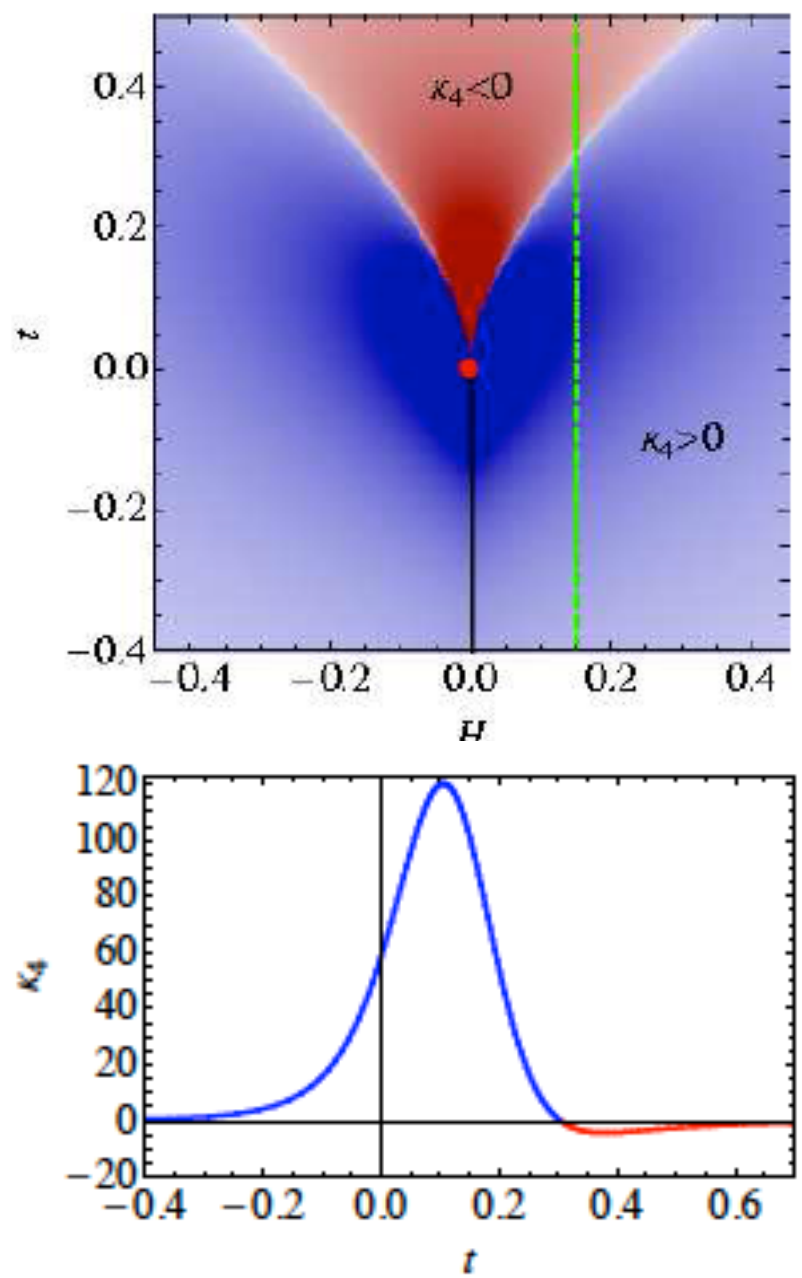
Adjust lattice scale to fit the data.



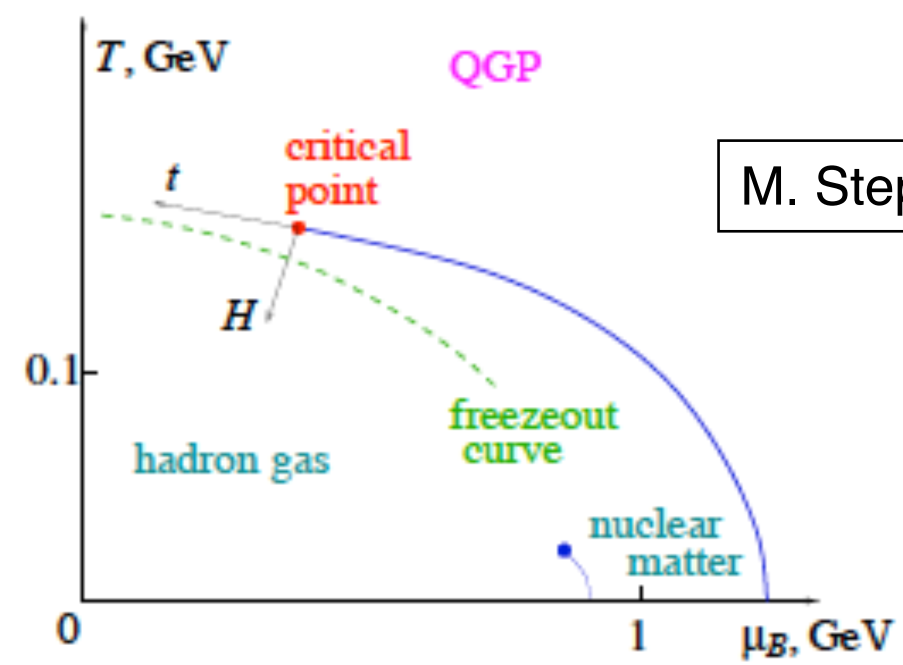


QCD critical point

Lots more to say, but probably no time... One example:



Fluctuations of the chiral order parameter can be related to fluctuations of identified particle multiplicities. Negative kurtosis is characteristic of the region leading to the critical point.



M. Stephanov, arXiv:1104.1627

Conclusions I

- The study of hot QCD matter has undergone its "COBE" revolution: Initial conditions differ massively event by event and can provide bountiful physics opportunities.
- The E-by-E fluctuations can be utilized to
  - *Probe properties of hot QCD matter via fluctuations*
  - *Select events with common properties in a controlled manner*
- Develop theory of fluctuations
- Extend measurement / analysis of fluctuations
  - *Correlations between observables*
  - *Interplay between bulk fluctuations and jets....*
    - *...in both directions!*

Conclusions II

- The theory of jet quenching is becoming quantitative
  - *The uncertainty in determination of q^ is narrowing*
  - *Development of pQCD based jet MC's*
  - *Development of NLO theory of jet modification*
  - *The kinematic span between RHIC and LHC is critical to model discrimination; neither the LHC nor RHIC alone are sufficient*
  - *Jets and E-by-E hydrodynamics*

- Most urgent theoretical challenge:
  - *Quantitative theory (-ies?) of initial conditions for FD, including E-by-E fluctuations*

Conclusions III

- AdS/CFT theory of strongly coupled gauge field plasmas is most predictive for observables involving $T_{\mu\nu}$ ➠ focus on
  - *Collective flow observables*
  - *Energy-momentum related fluctuations and correlations*
  - *Energy flow from jet into medium*
- The RHIC program needs detectors that combine
  - *High data taking rate*
  - *Sophisticated (level-3) triggers*
  - *Large acceptance (➠ 4π)*
  - *Energy flow measurement capability (calorimetry)*
- The RHIC facility's unique strengths include
  - *High integrated luminosity*
  - *Collision system flexibility*

Summary

Which **properties of hot QCD matter** can we hope to determine from relativistic heavy ion data ?

$T_{\mu\nu} \quad \Leftrightarrow \quad \varepsilon, p, s$ **Equation of state**: spectra, collective flow

$c_s^2 = \partial p / \partial \varepsilon$ **Speed of sound**: correlations

$\eta = \frac{1}{T}\int d^4x \left\langle T_{xy}(x) T_{xy}(0) \right\rangle$ **Shear viscosity**: anisotropic collective flow

$$\left.\begin{aligned}
\hat{q} &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1}\int dy^- \left\langle F^{a+i}(y^-) F_i^{a+}(0) \right\rangle \\
\hat{e} &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1}\int dy^- \left\langle i\partial^- A^{a+}(y^-) A^{a+}(0) \right\rangle \\
\hat{e}_2 &= \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1}\int dy^- \left\langle F^{a+-}(y^-) F^{a+-}(0) \right\rangle
\end{aligned}\right\}$$

Momentum/energy diffusion:
parton energy loss
modified jet fragmentation

Color screening: Quarkonium states

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Major theory & detector develop-ments needed; RHiC + LHC !

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Momentum/energy diffusion:
parton energy loss
modified jet fragmentation

$$m_D = -\lim_{|x| \to \infty} \frac{1}{|x|} \ln \left\langle E^a(x) E^a(0) \right\rangle$$

Color screening: Quarkonium states