Future Challenges of Relativistic Heavy Ion Physics

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High Energy QCD Workshop

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Overview

A typical PHENIX planning meeting...

"Now that RHIC has found the Perfect Fluid, what do we meditate on next?"

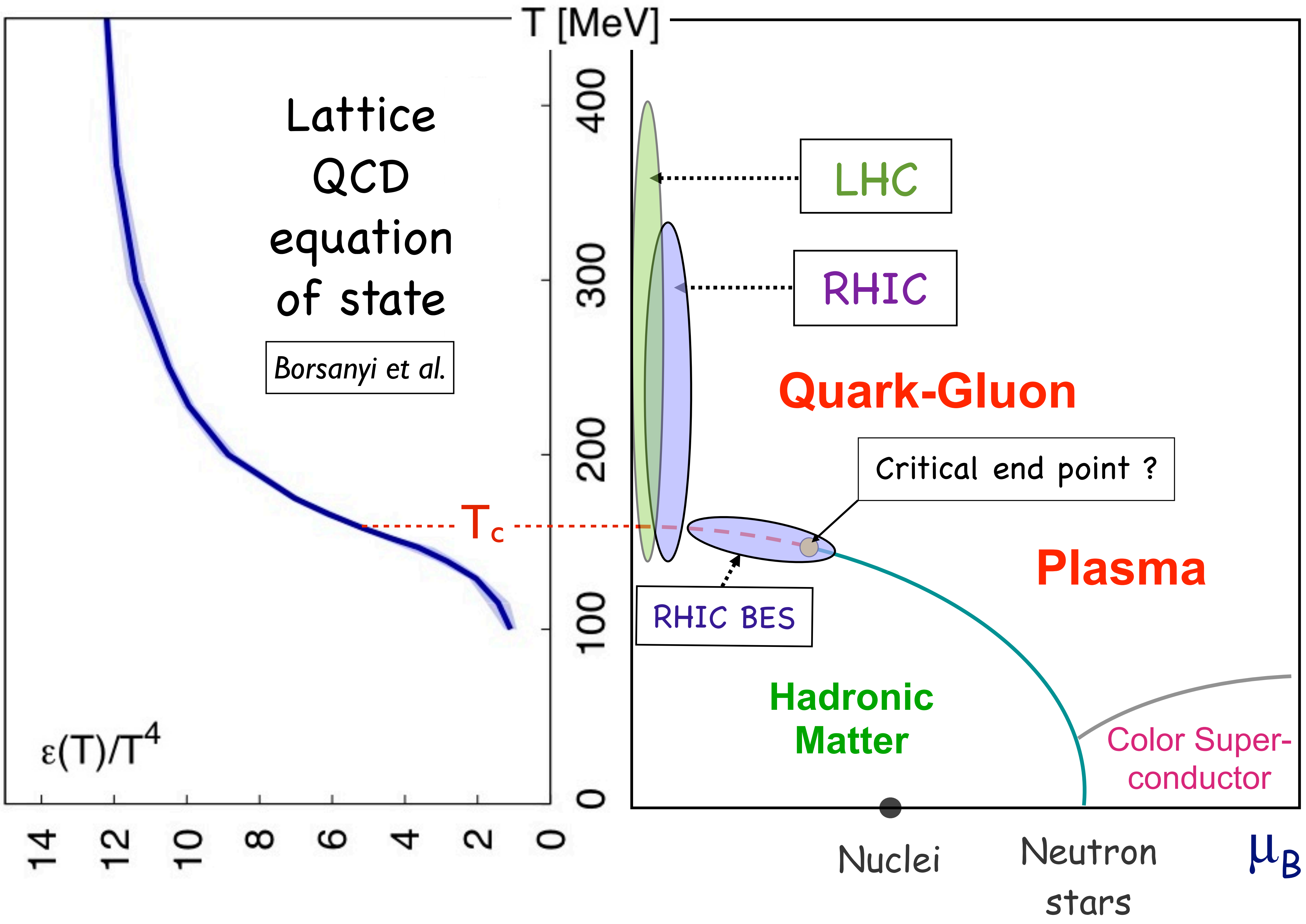
Overview

A typical PHENIX planning meeting…

"Now that RHIC has found the Perfect Fluid, what do we meditate on next?"

- 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

QCD Phase Diagram



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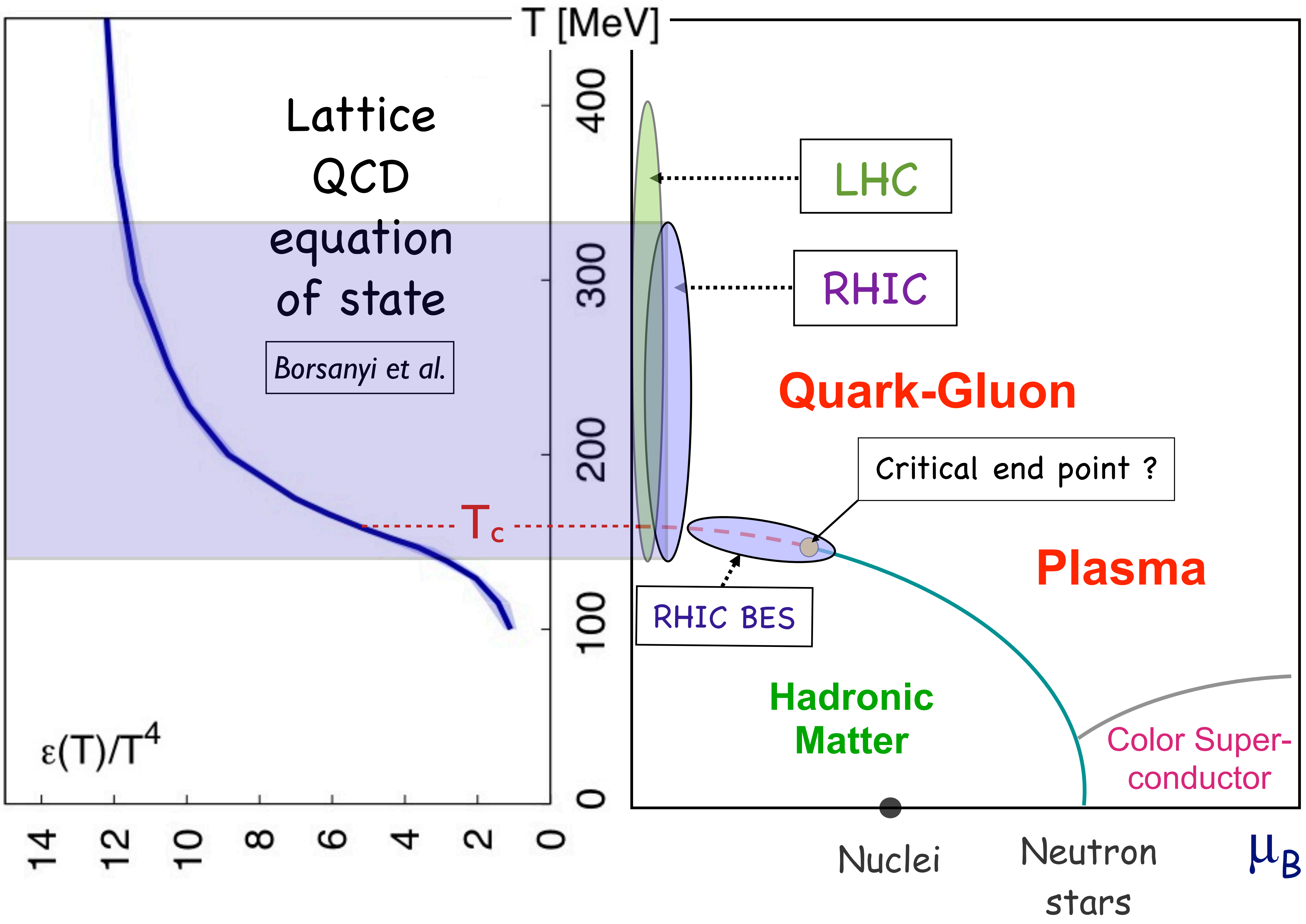

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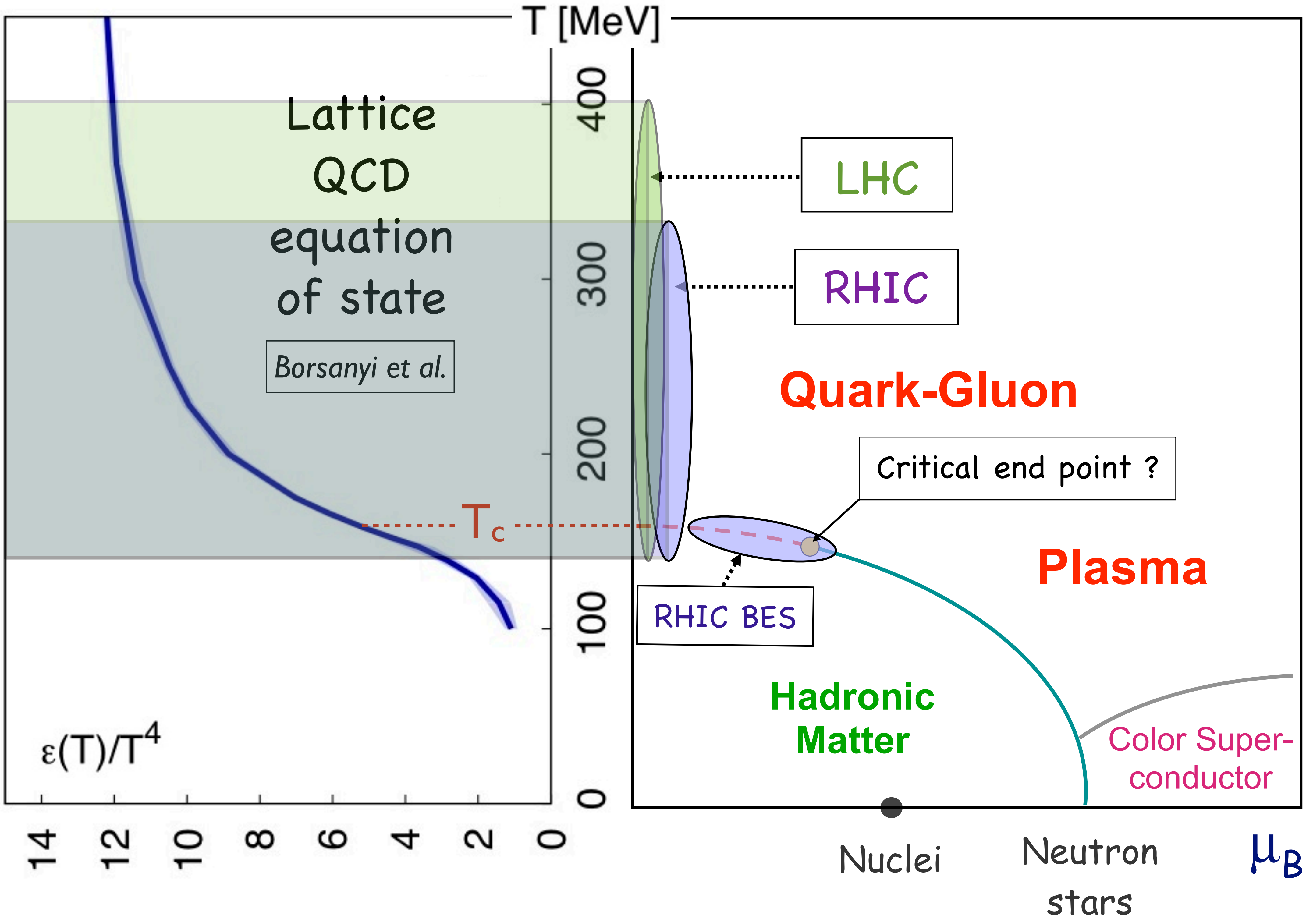
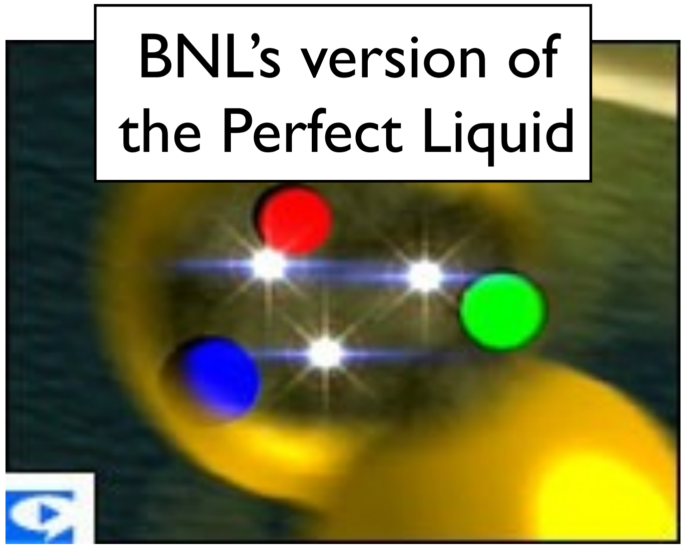


The Big Questions



BNL's version of the Perfect Liquid

Shiseido's version of the Perfect Liquid

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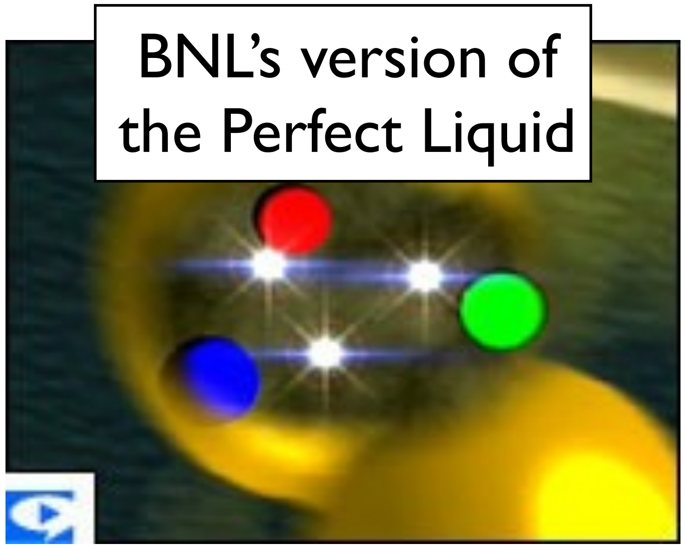

BNL's version of the Perfect Liquid

Shiseido's version of the Perfect Liquid

- **What makes for a Perfect Liquid ?**
- **What makes the sQGP a Perfect Liquid ?**
- **What is the (color) structure of the QGP near T_c ?**
- **At which scale does the transition between weak and strong coupling occur ?**
- **How does the structure of colliding nuclei manifest itself in the QGP ?**

Hot QCD matter properties (I)

Which **properties of hot QCD matter** can we hope to determine ?

$$T_{\mu\nu} \quad \Leftrightarrow \quad \varepsilon, p, s$$

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 \\
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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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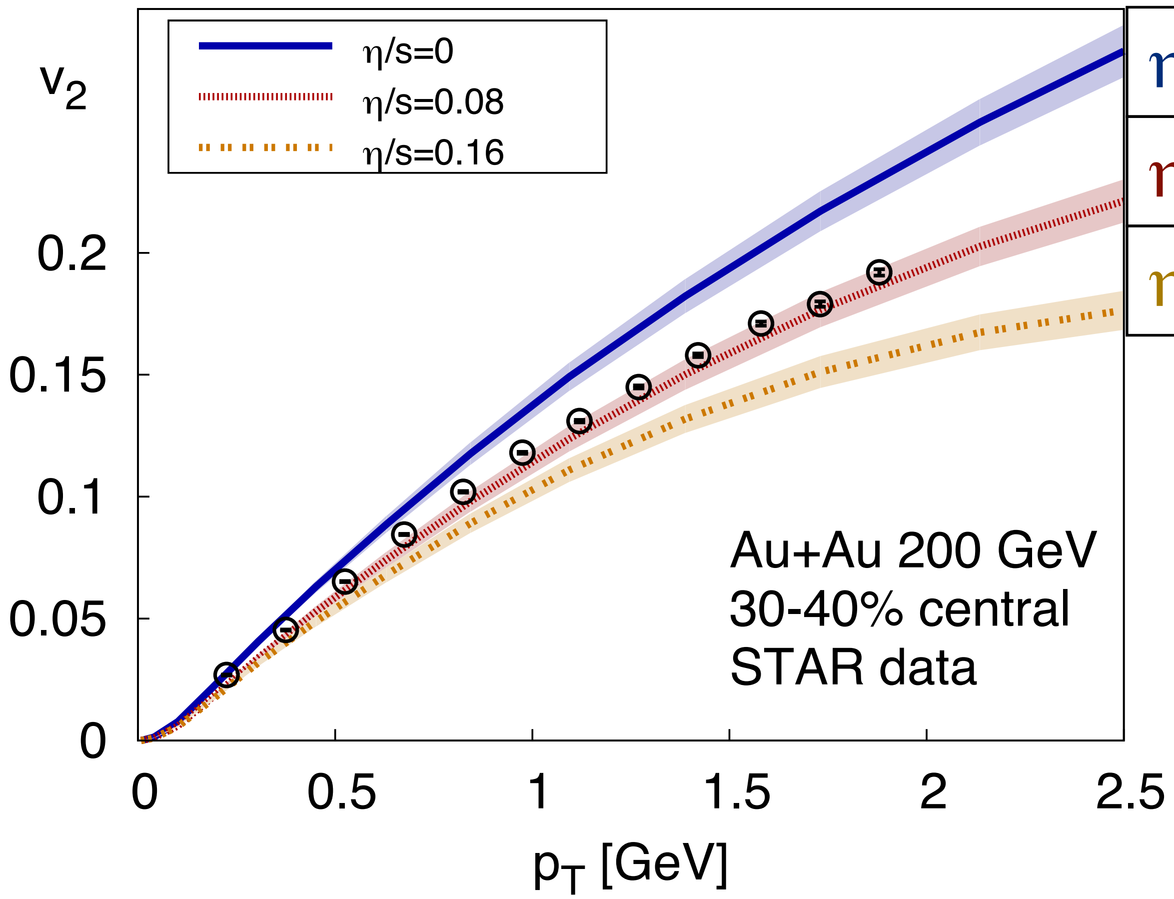
The Liquid QGP

Elliptic flow “measures” η_{QGP}

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



$\eta/s = 0$

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

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

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

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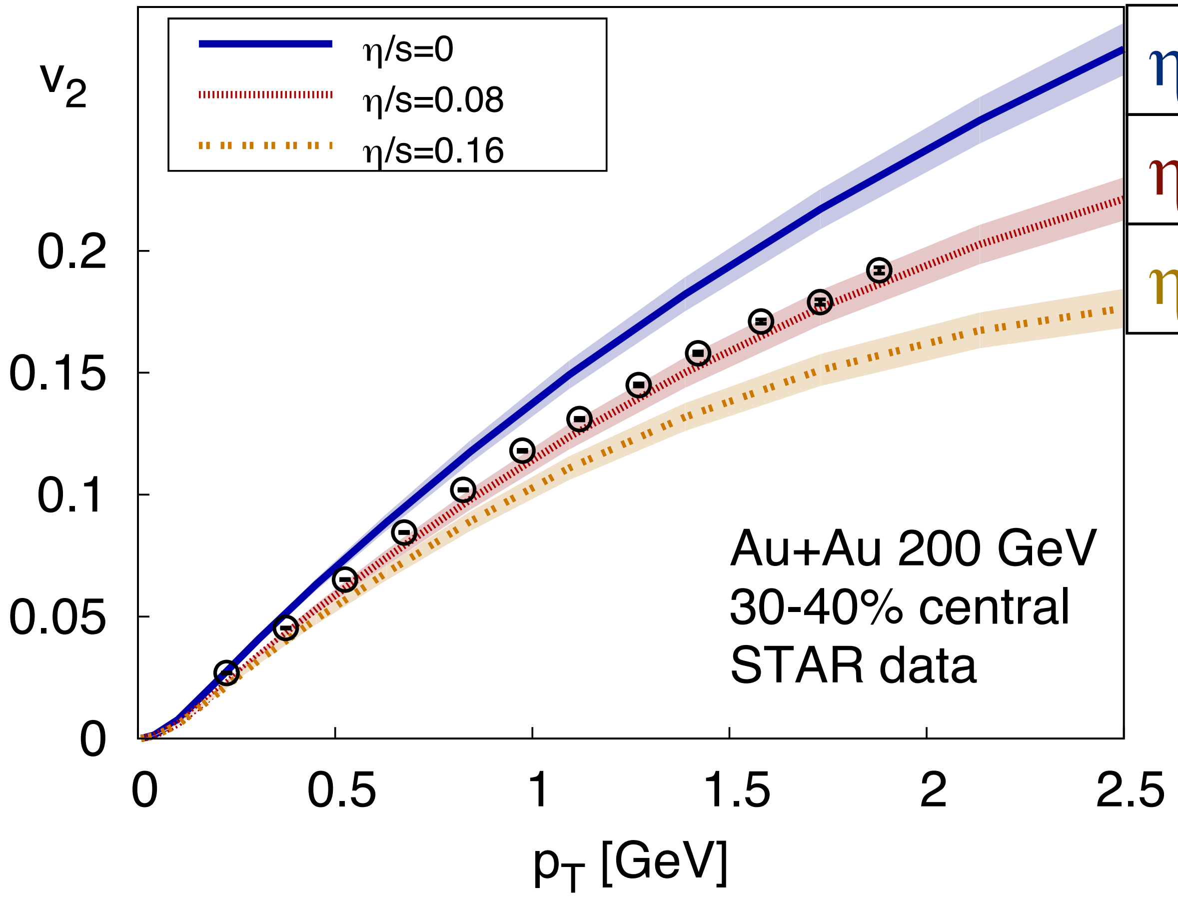

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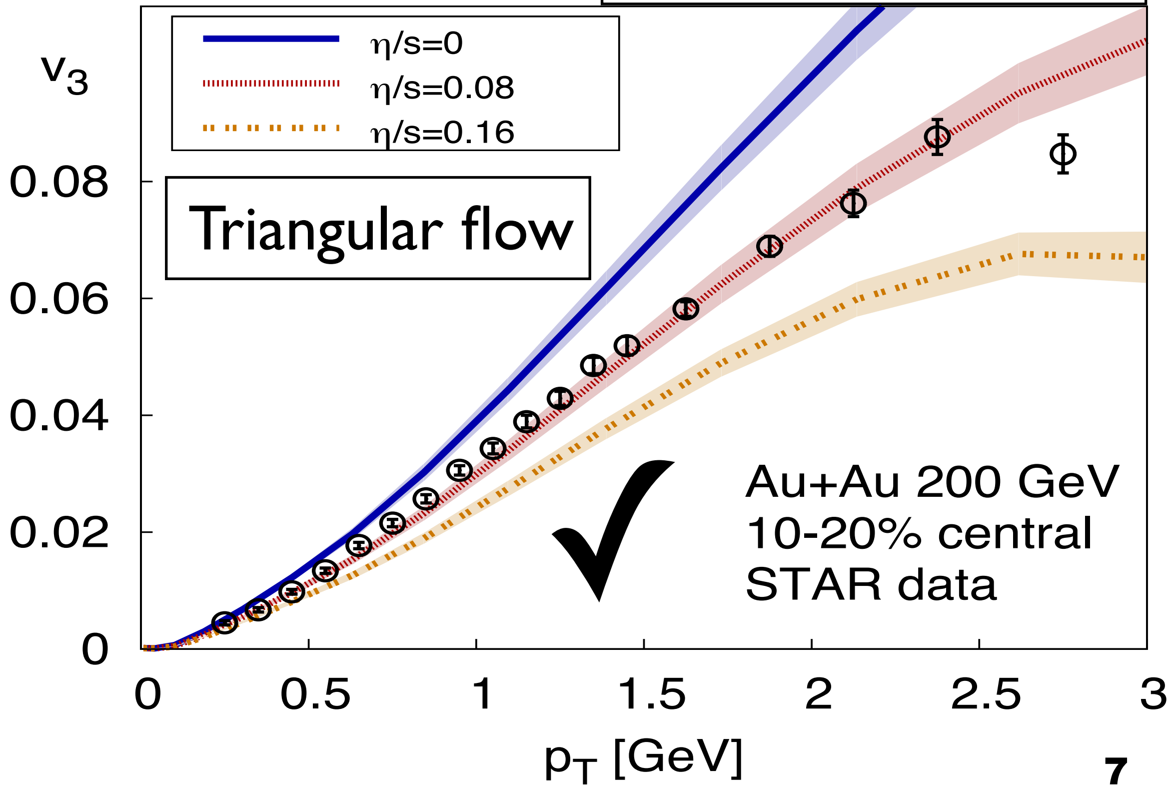
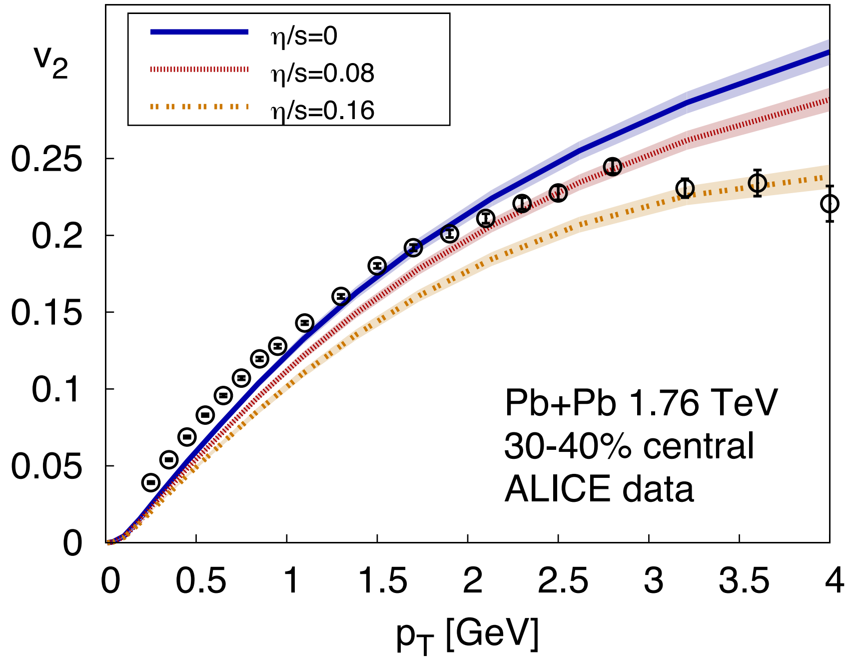
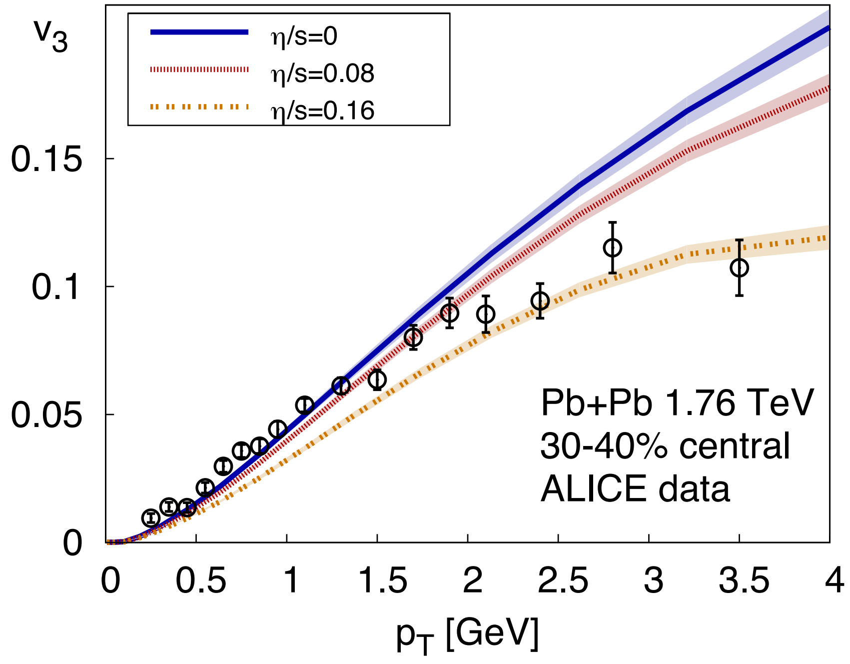
Consistency check:

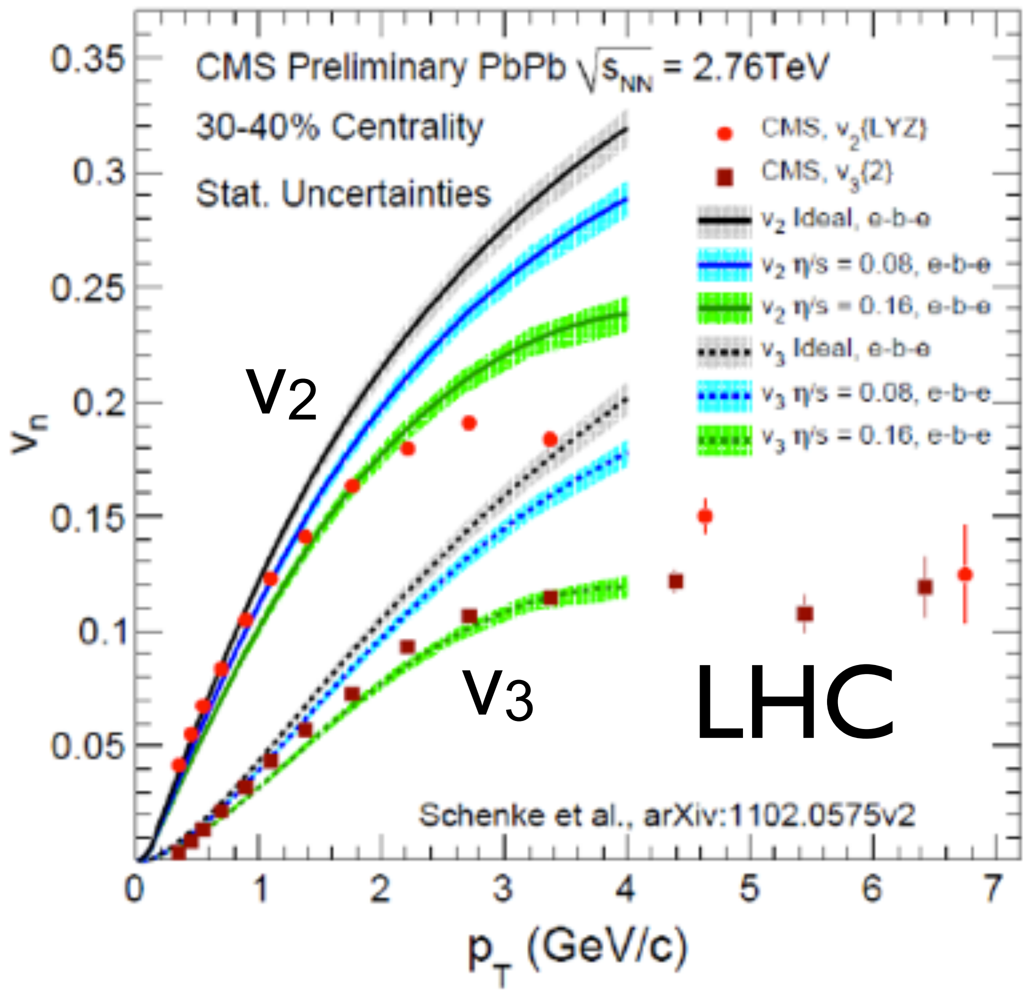


v_2 & v_3 @ LHC

Flow results agree nicely with RHIC



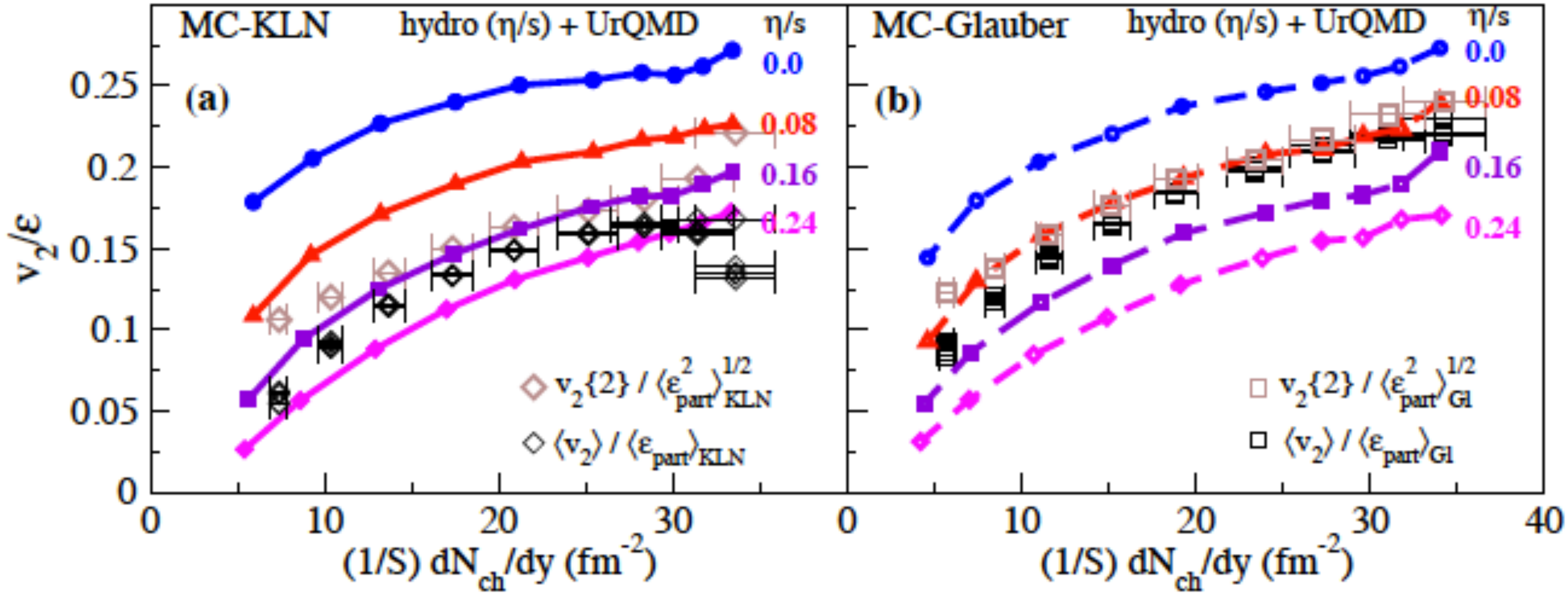




η/s from v_3 might be slightly larger than η/s from v_2. If true, this could indicate a momentum dependence of η, because events with large v_3 are more granular than on average.

Shear viscosity

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



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

Remaining uncertainty mainly due to initial density profile

How far can we reduce the uncertainty ?

Future refinements

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- Necessary improvements
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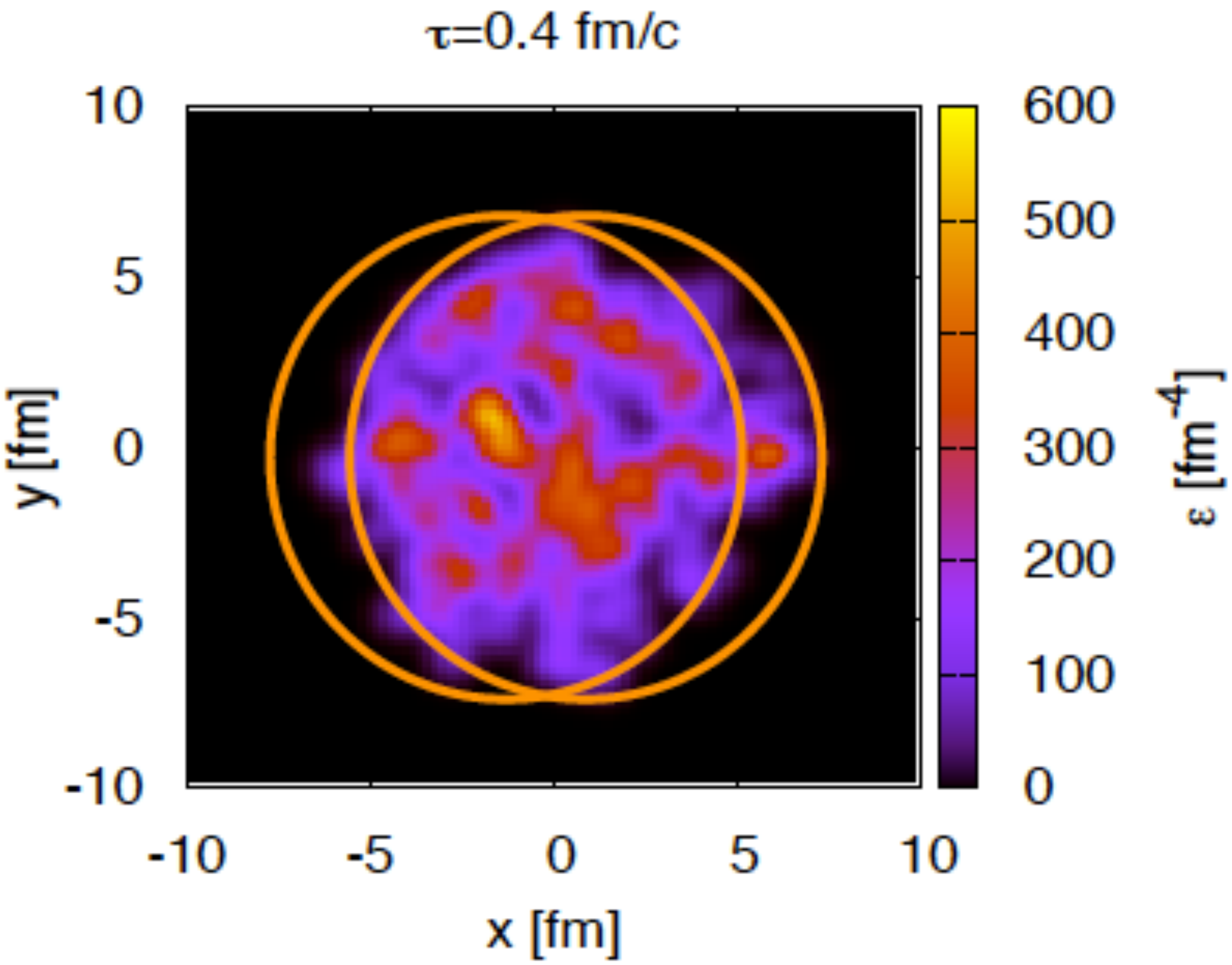
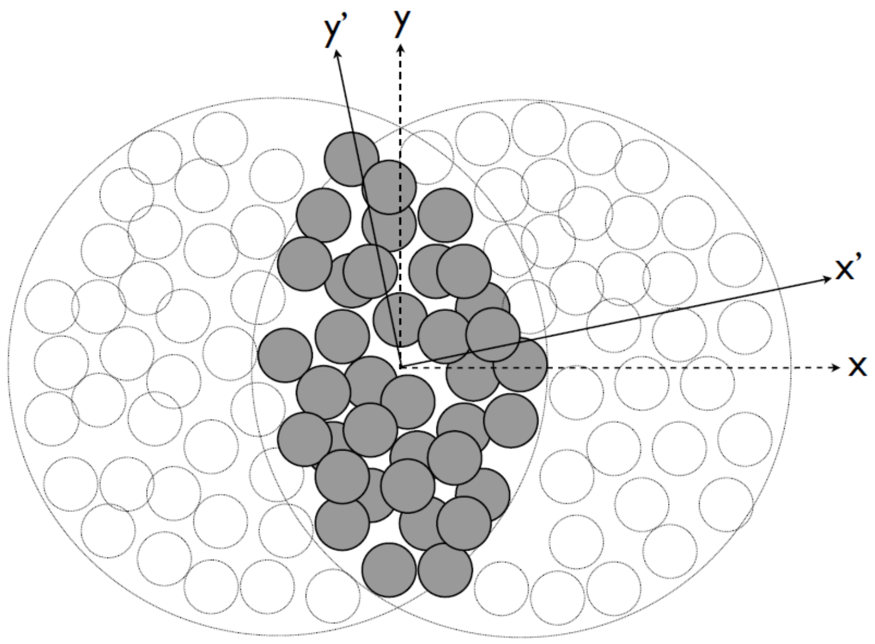
    - Are there theoretically founded alternatives?
- Check of system independence
  - Cu+Cu, Cu+Au, U+U
    - Very important to demonstrate theoretical control

Event by event

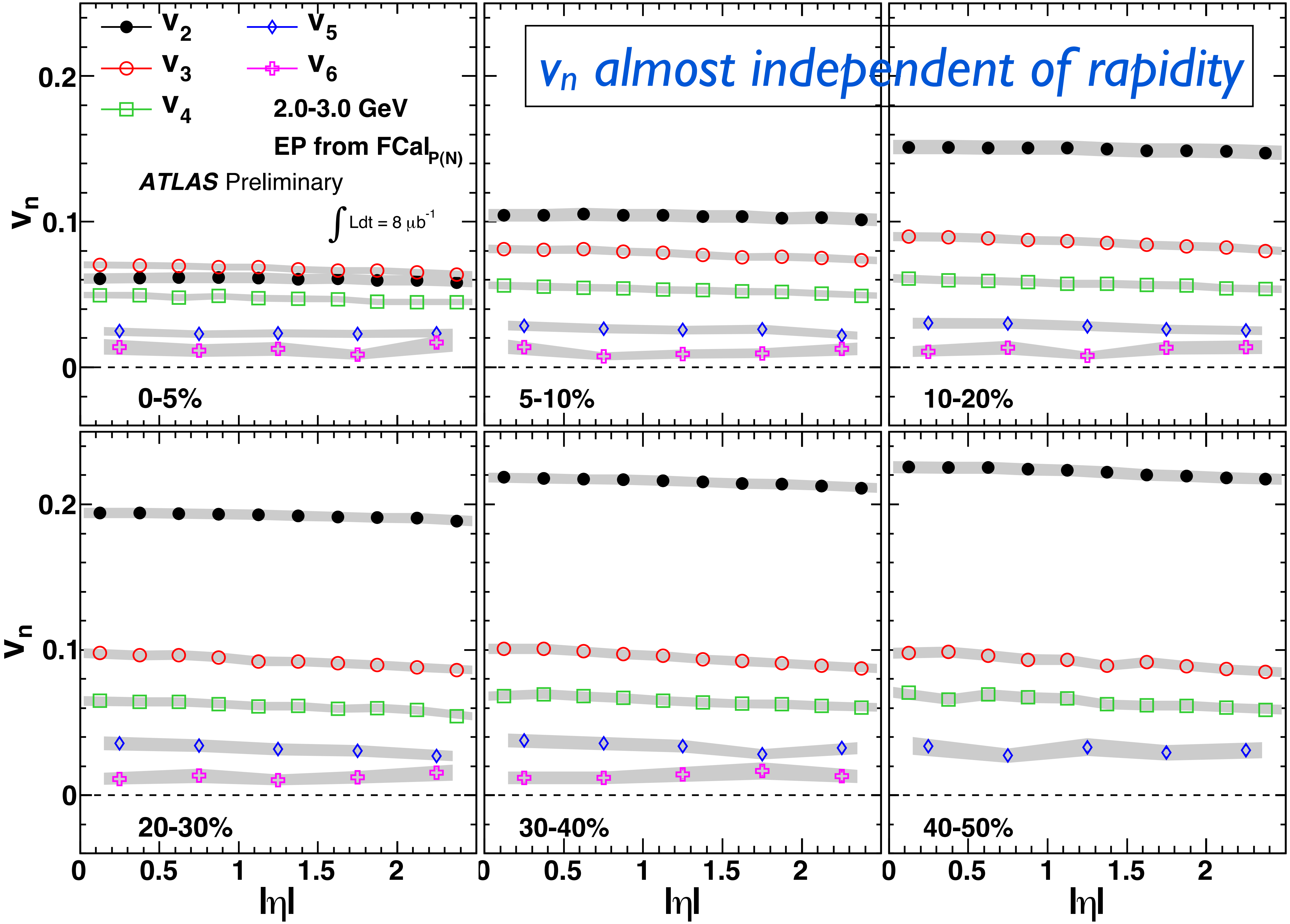
Initial state generated in A+A collision is grainy
event plane ≠ reaction plane
⇒ eccentricities ε_1, ε_2, ε_3, ε_4, etc. ≠ 0





⇒ flows v_1, v_2, v_3, v_4,…

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

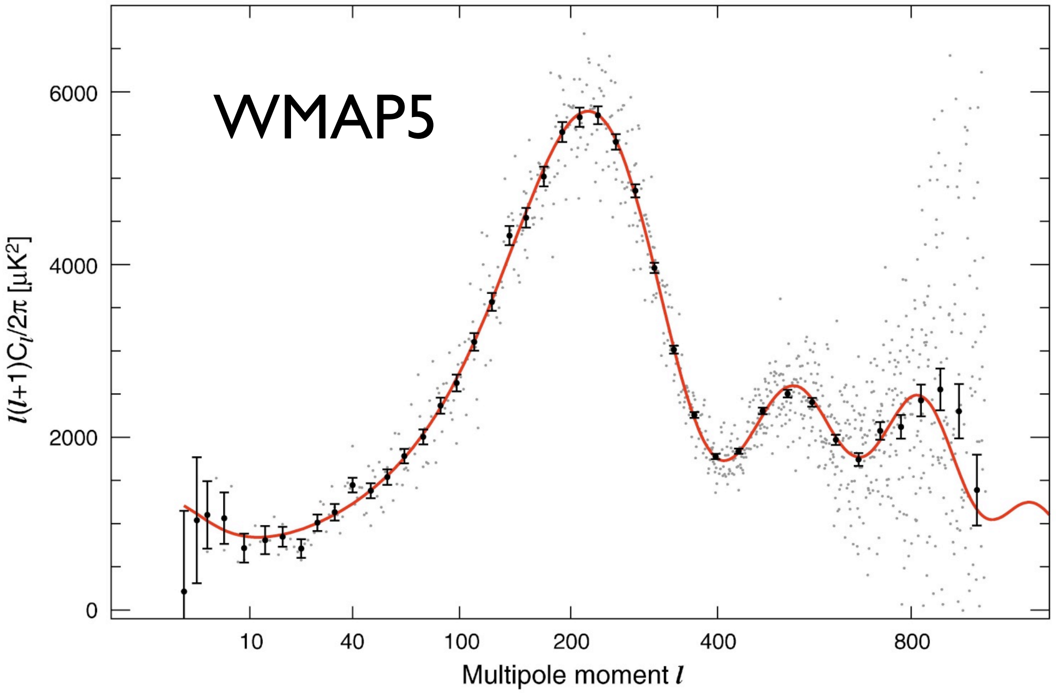


v_n almost independent of rapidity

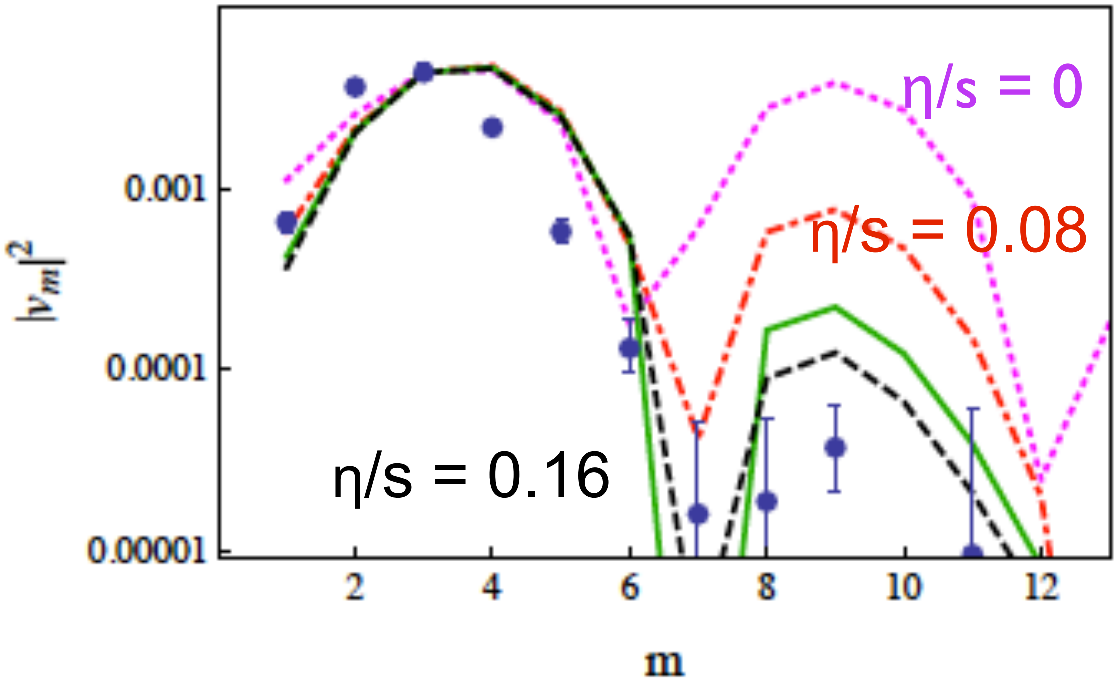
Fluctuation spectrum

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} ?



Staig & Shuryak, arXiv:1106.3243



Analysis not reliable quantitatively ($c_s^2 = 1/3$, schematic hydro) but clearly shows the potential.

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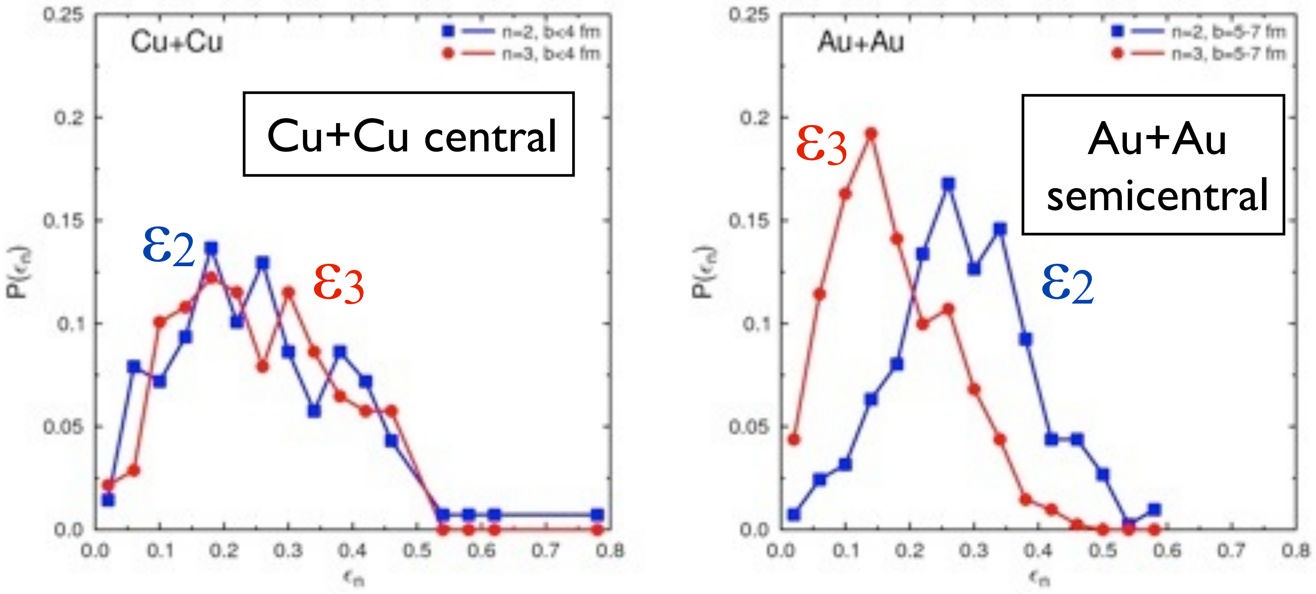

H. Petersen: UrQMD + 3-D hydro + UrQMD

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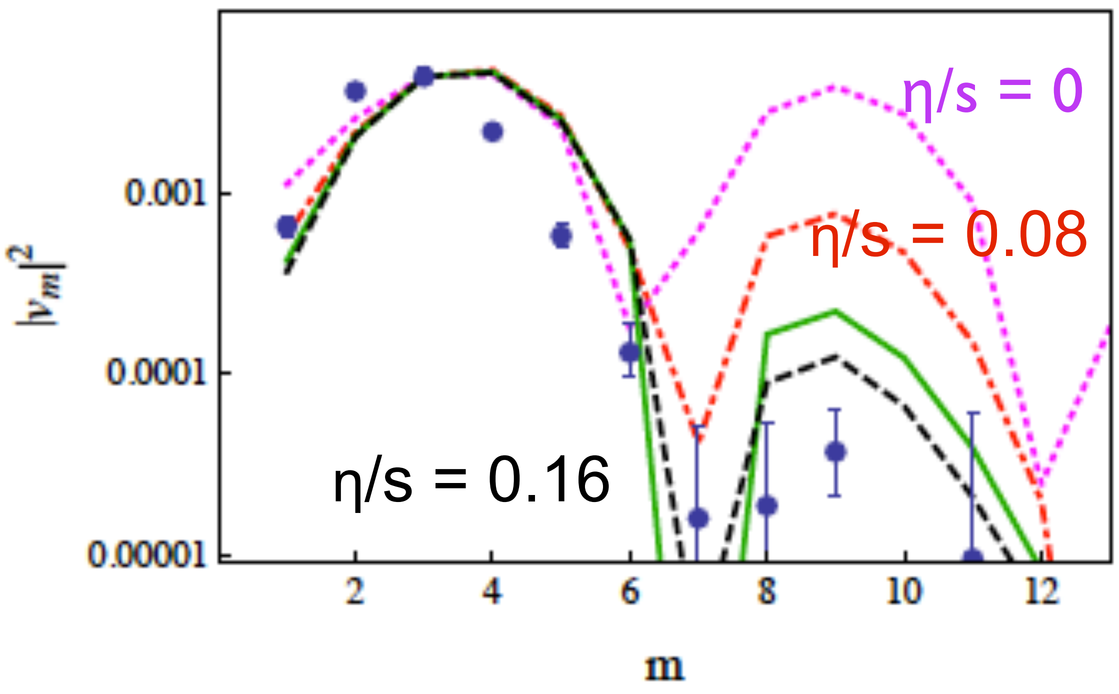

The RHIC advantage:
We have many knobs to turn,not just a single universe to observe.

Sources of fluctuations

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  - “Hot spots” (nuclear density fluctuations, color field fluctuations, etc.)

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  - Mach cones etc. (?)

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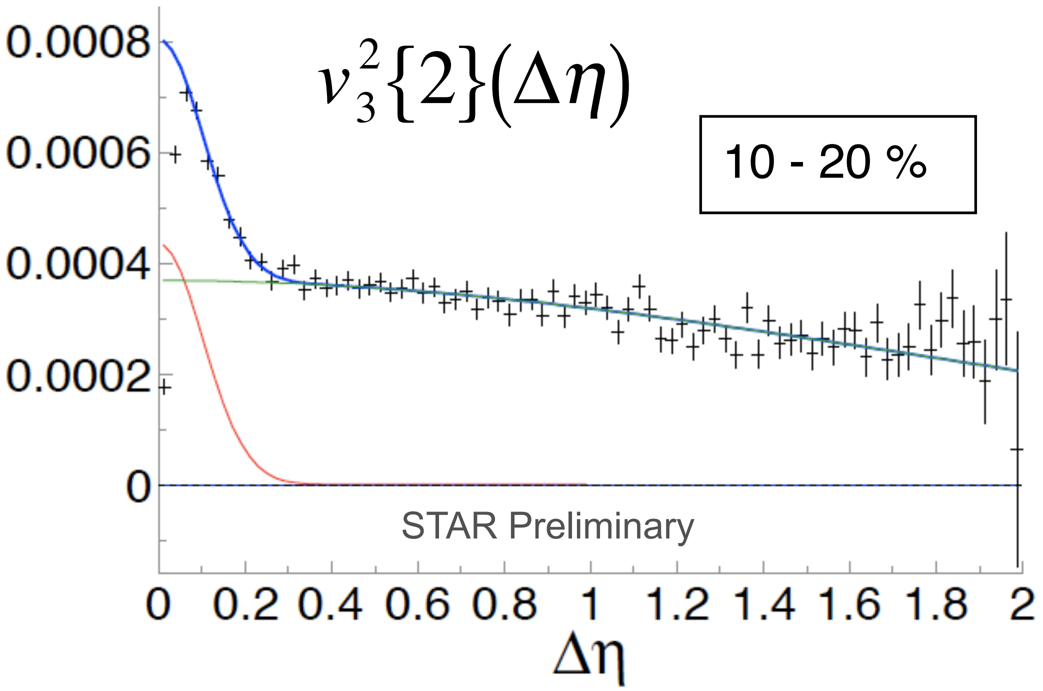
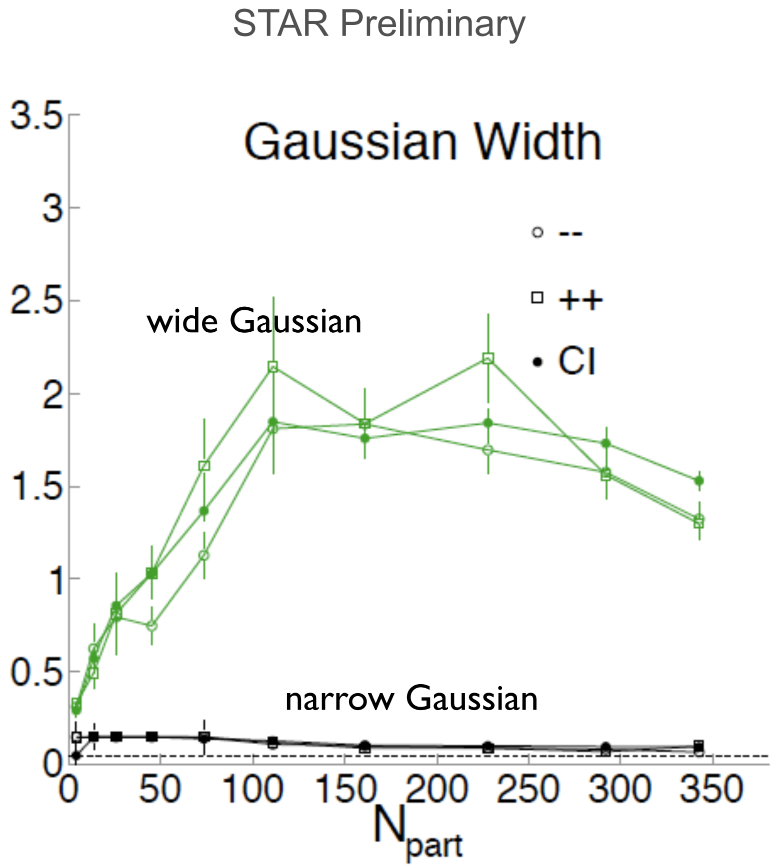
- Freeze-out fluctuations
  - Finite particle number effects, critical fluct’s, spinodal decomposition

Correlations





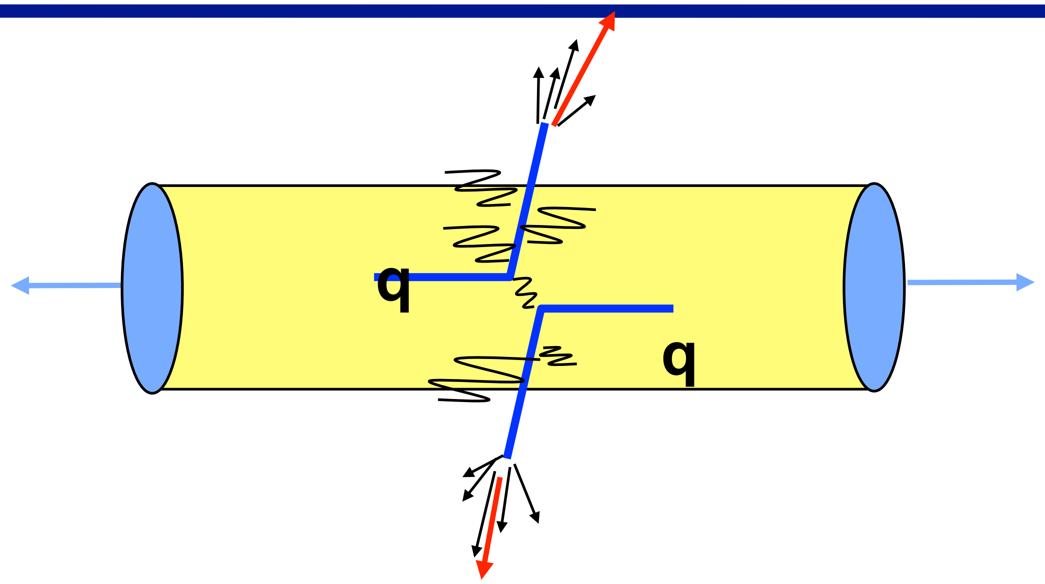
Driven by longitudinal correlation of initial-state density fluctuations or by thermal density fluctuations during hydrodynamic phase ?

Are the v_3 correlations universal ?

Is there any interplay with high-pT phenomena?

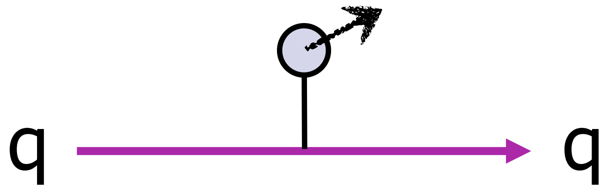
The Opaque QGP

Parton energy loss

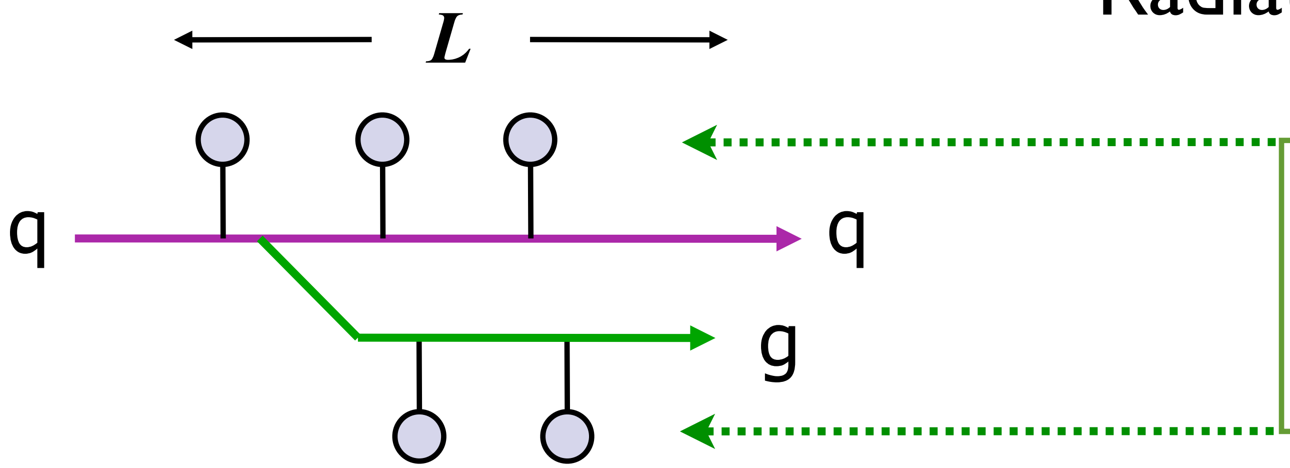


Elastic energy loss:

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



Radiative energy loss:



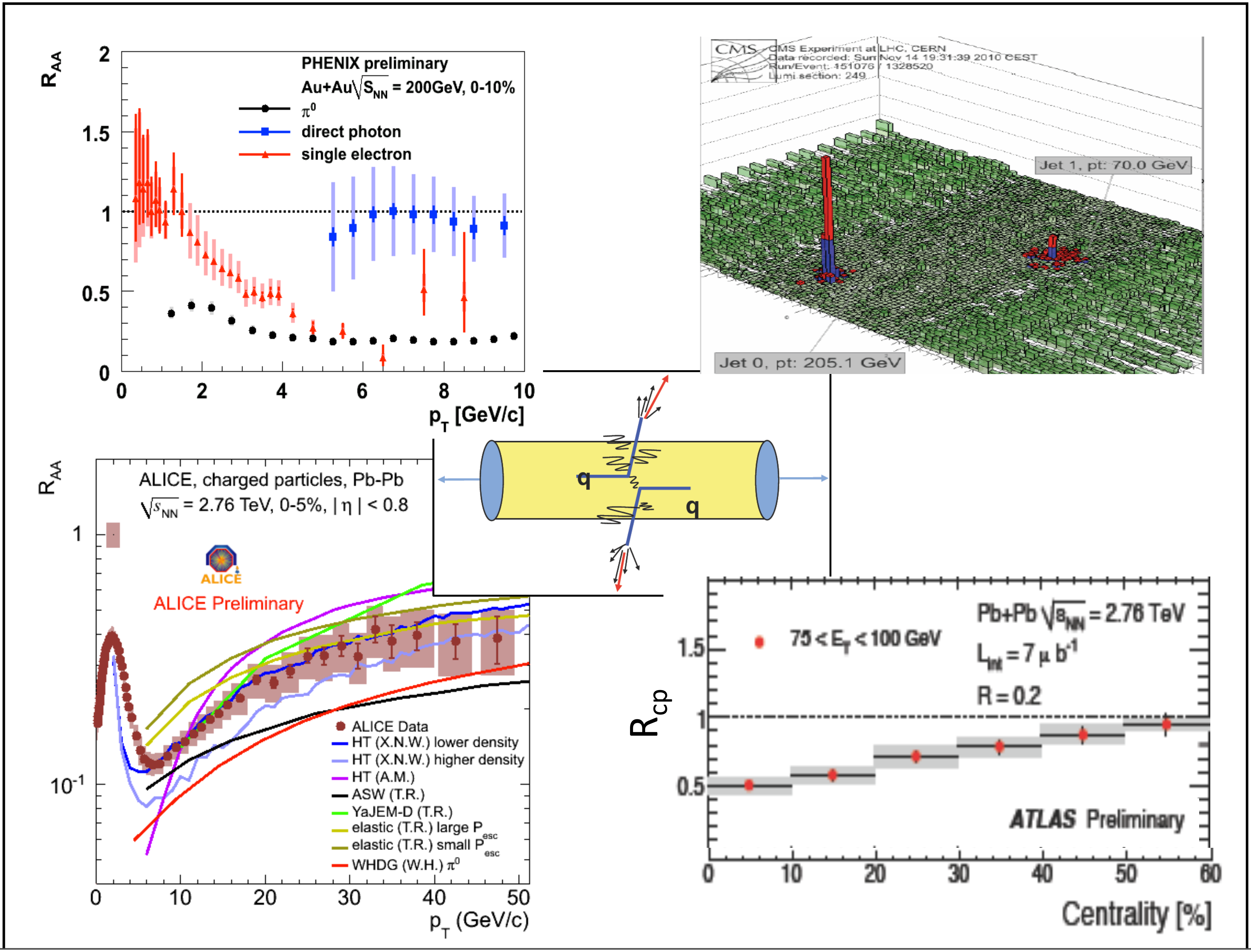
Scattering centers

⇔ color charges

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

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

Observables proliferate



Goals and questions

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  - Determine medium properties ($\hat{q}, \hat{e}$ in NL Twist; ....??)
  - Density tomography of the medium
  - Explore energy flow into, and response by, the QGP
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- Questions:
  - Momentum dependence of parton energy loss (PEL)
  - 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

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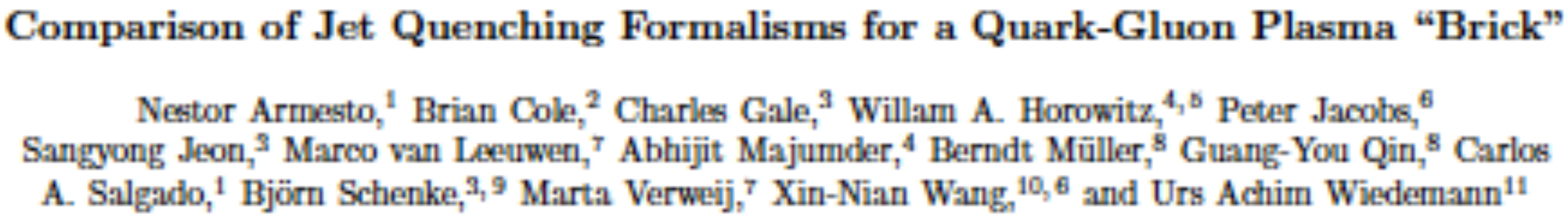
- How do the answers depend on the parton flavor ?

TEC-HQM



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

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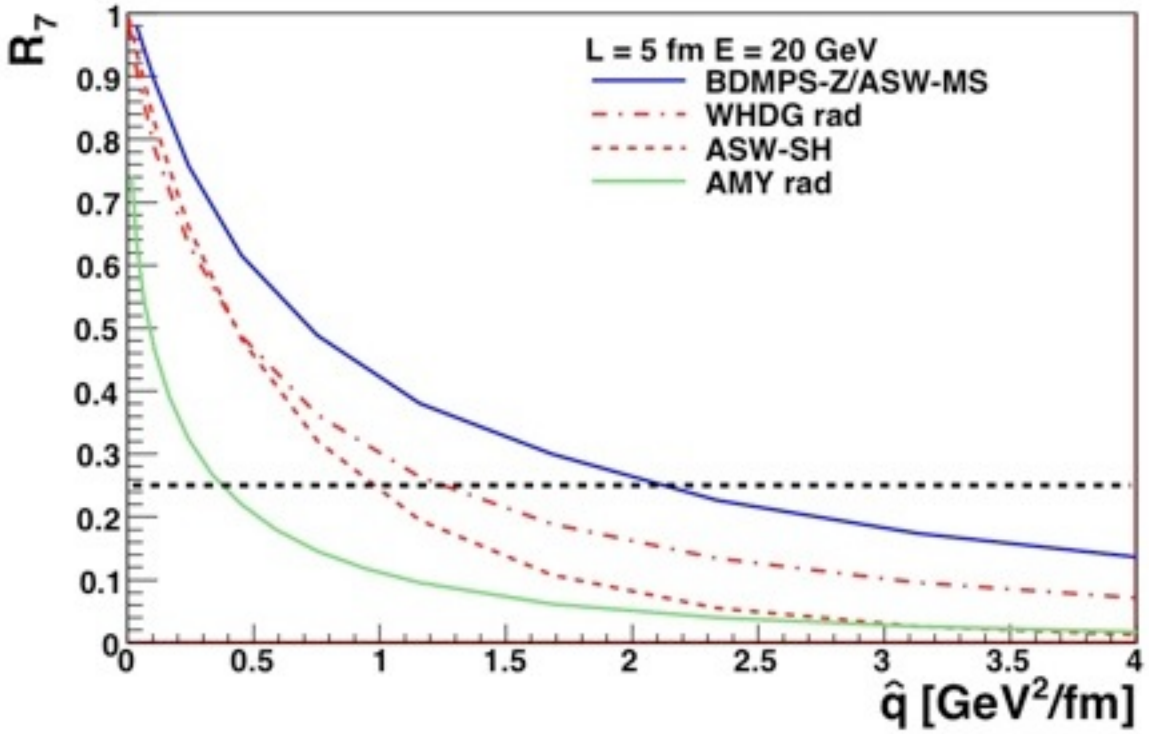
arXiv:1106.1106

Wide differences confirmed for standardized "QCD Brick" →

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



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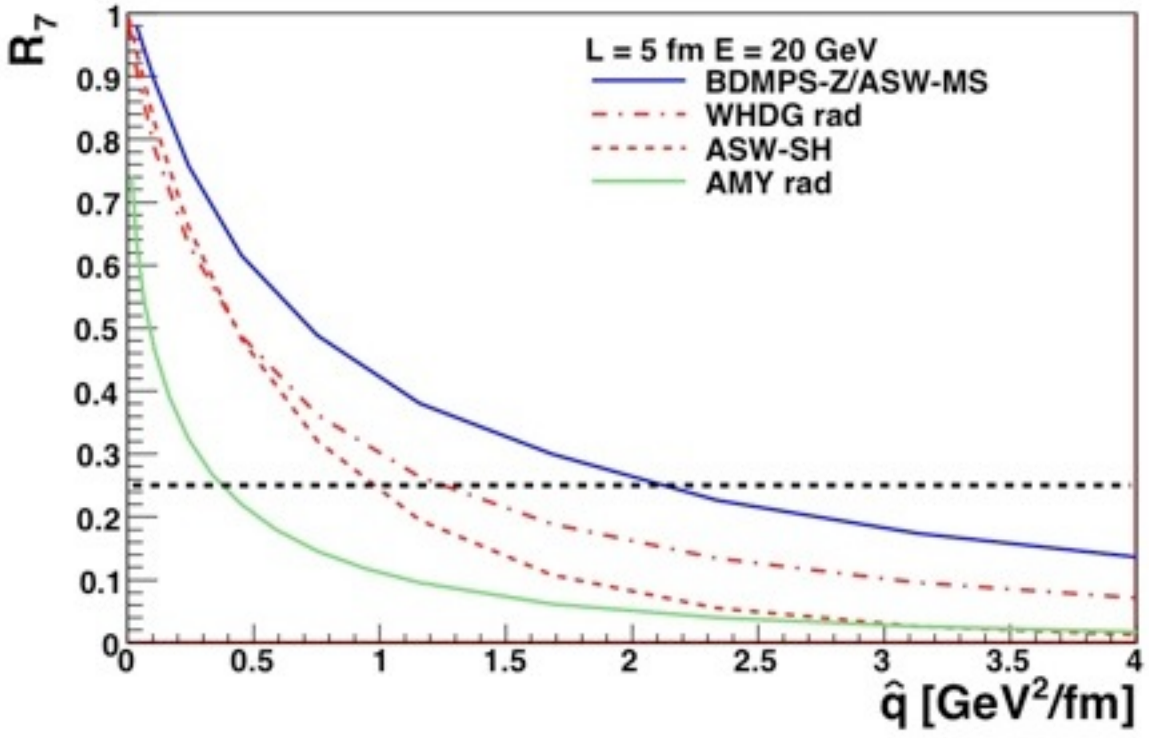

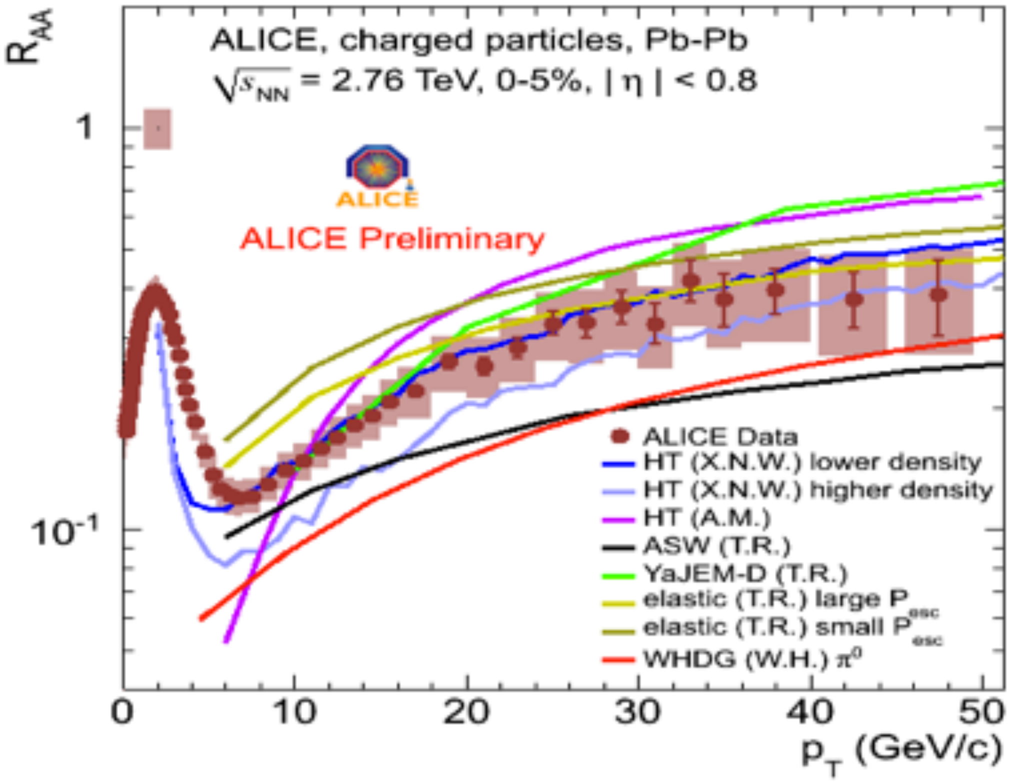

LHC:
pQCD
theory of
jet
quenching
is alive but
needs
refinement

Virtuality matters

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

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

Weak coupling scenario

RHIC: 20 GeV parton, *L* = 3 fm

$$\hat{q}\, L \approx 4.5\,\mathrm{GeV}^2 \quad \gg \quad \frac{E}{L} \approx 1.5\,\mathrm{GeV}^2$$

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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

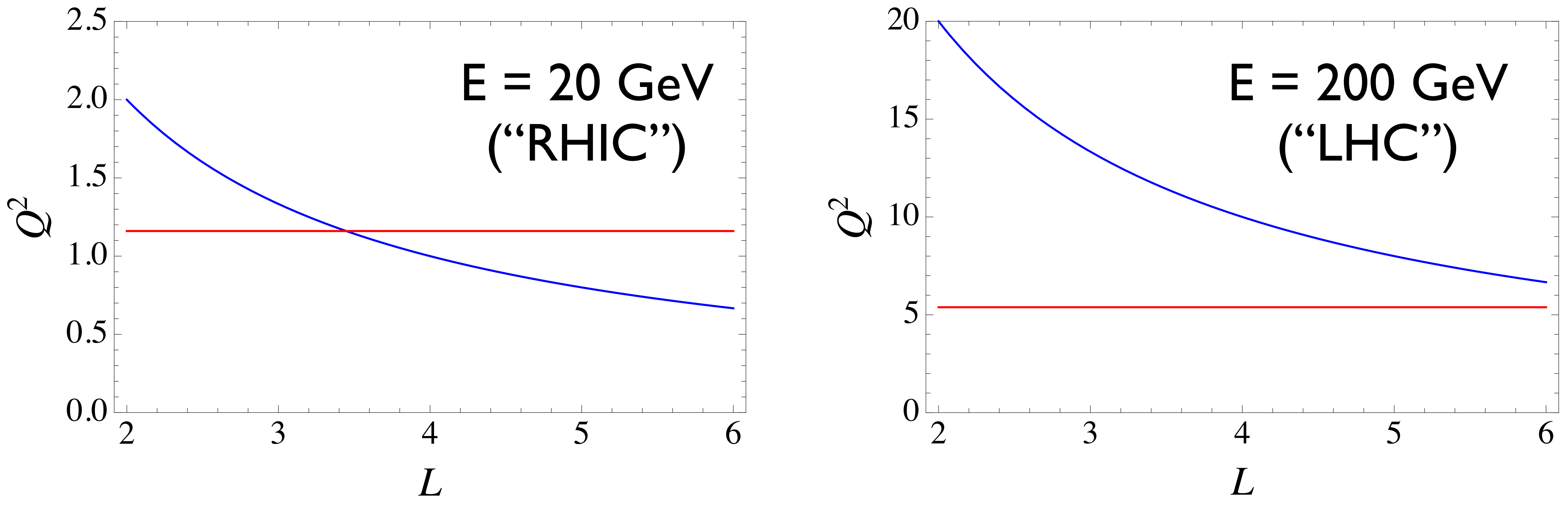
Virtuality evolution II

Strong coupling:

Virtuality is controlled by:

Time after scattering: $Q^2 \sim E/L$

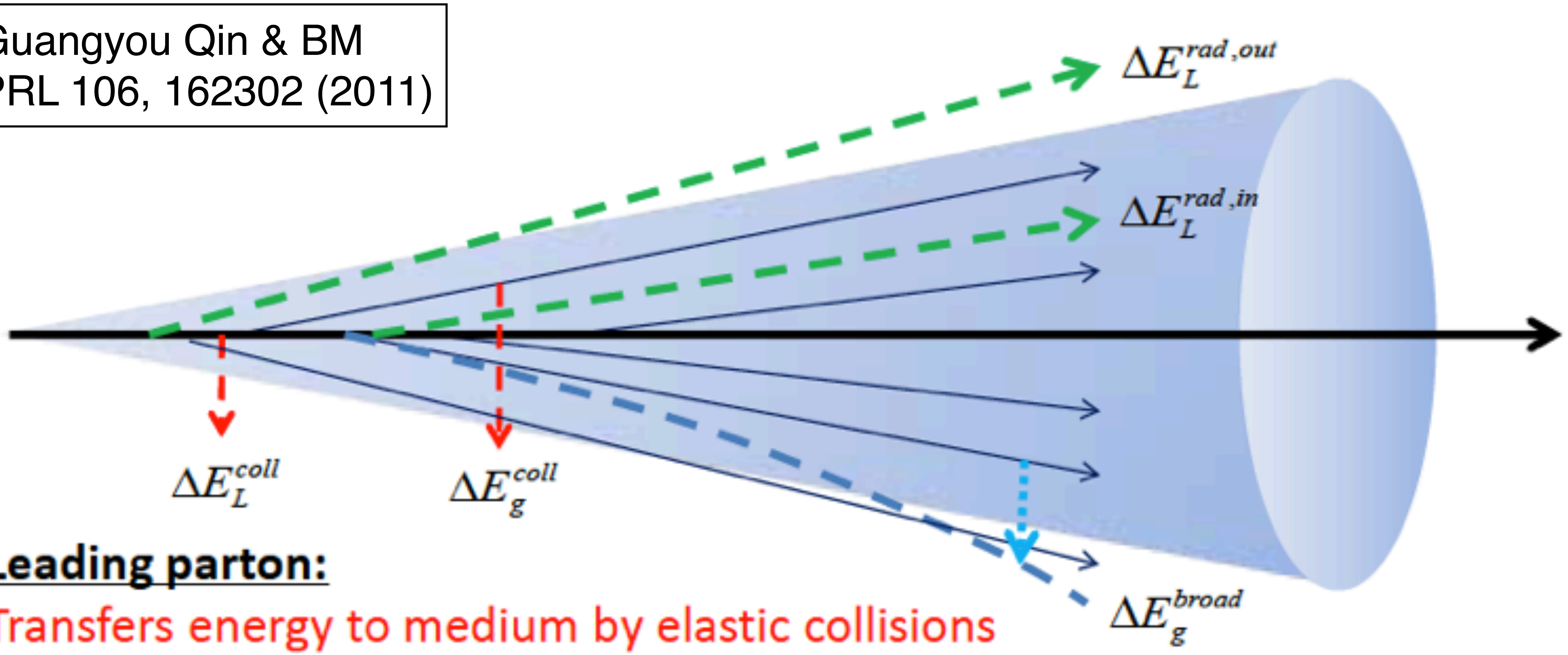
Scattering in medium: $Q \sim \sqrt{\gamma}\, T$



Final vacuum fragmentation: $D(z,Q^2(L))$

Parton shower in matter

Guangyou Qin & BM
PRL 106, 162302 (2011)



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*):

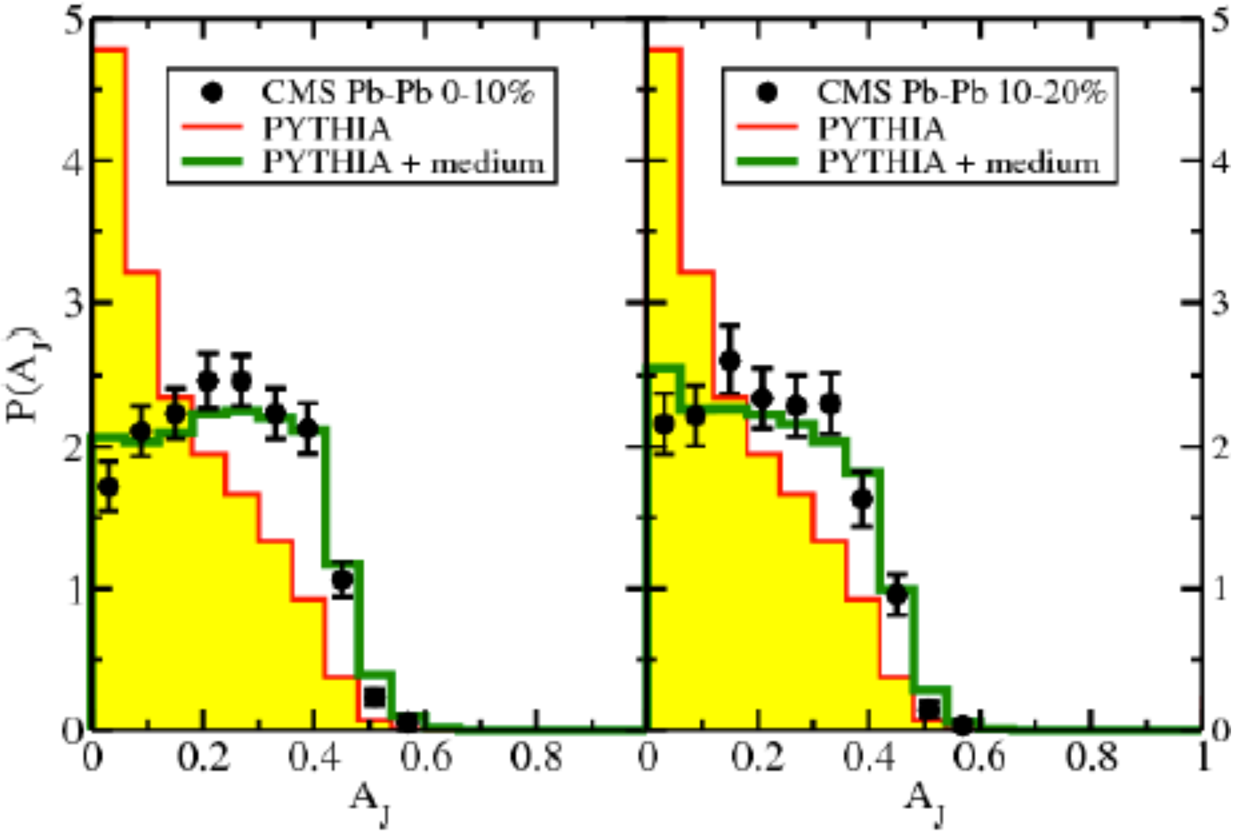
Transfer energy to medium by elastic collisions

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

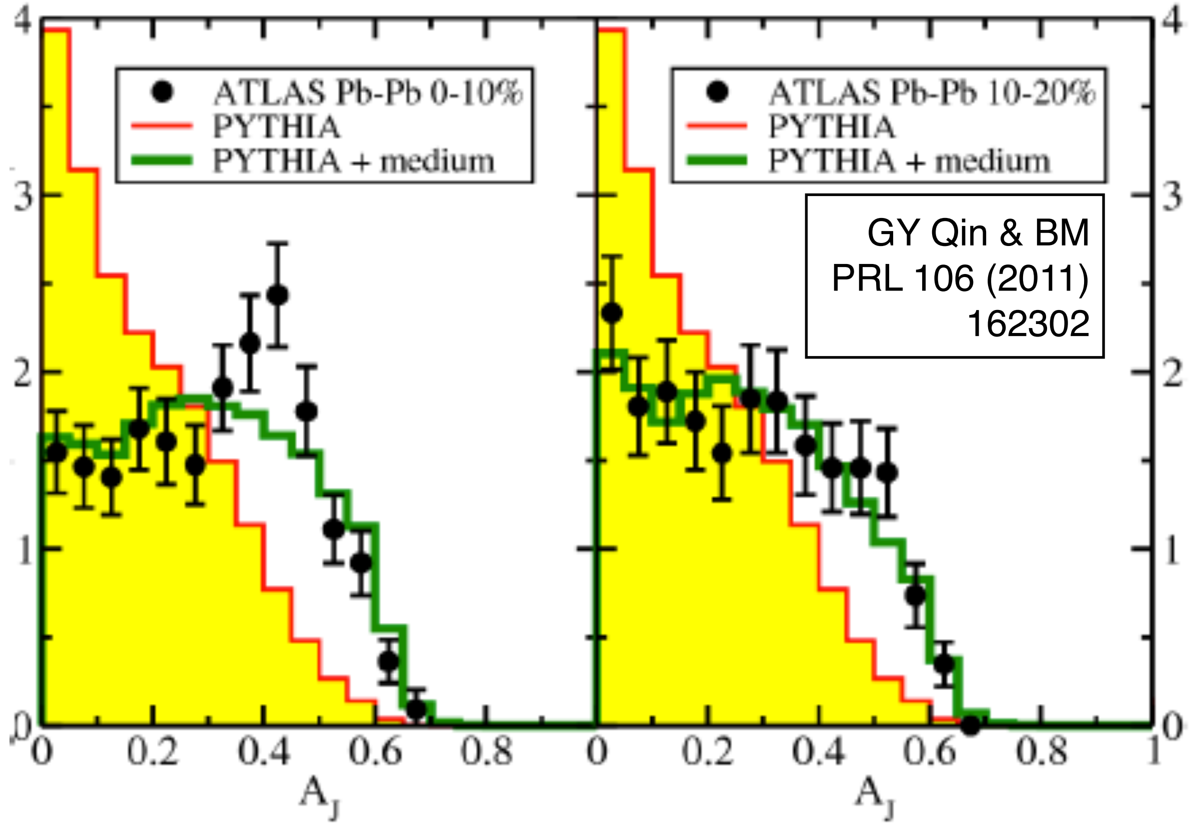
$$\frac{df_g(\omega, k_\perp^2, t)}{dt} = \hat{e}\frac{\partial f_g}{\partial \omega} + \frac{1}{4}\hat{q}\nabla_{k_\perp}^2 f_g + \frac{dN_g^{med}}{d\omega dk_\perp^2 dt}$$

Di-jet asymmetry

CMS data



ATLAS data

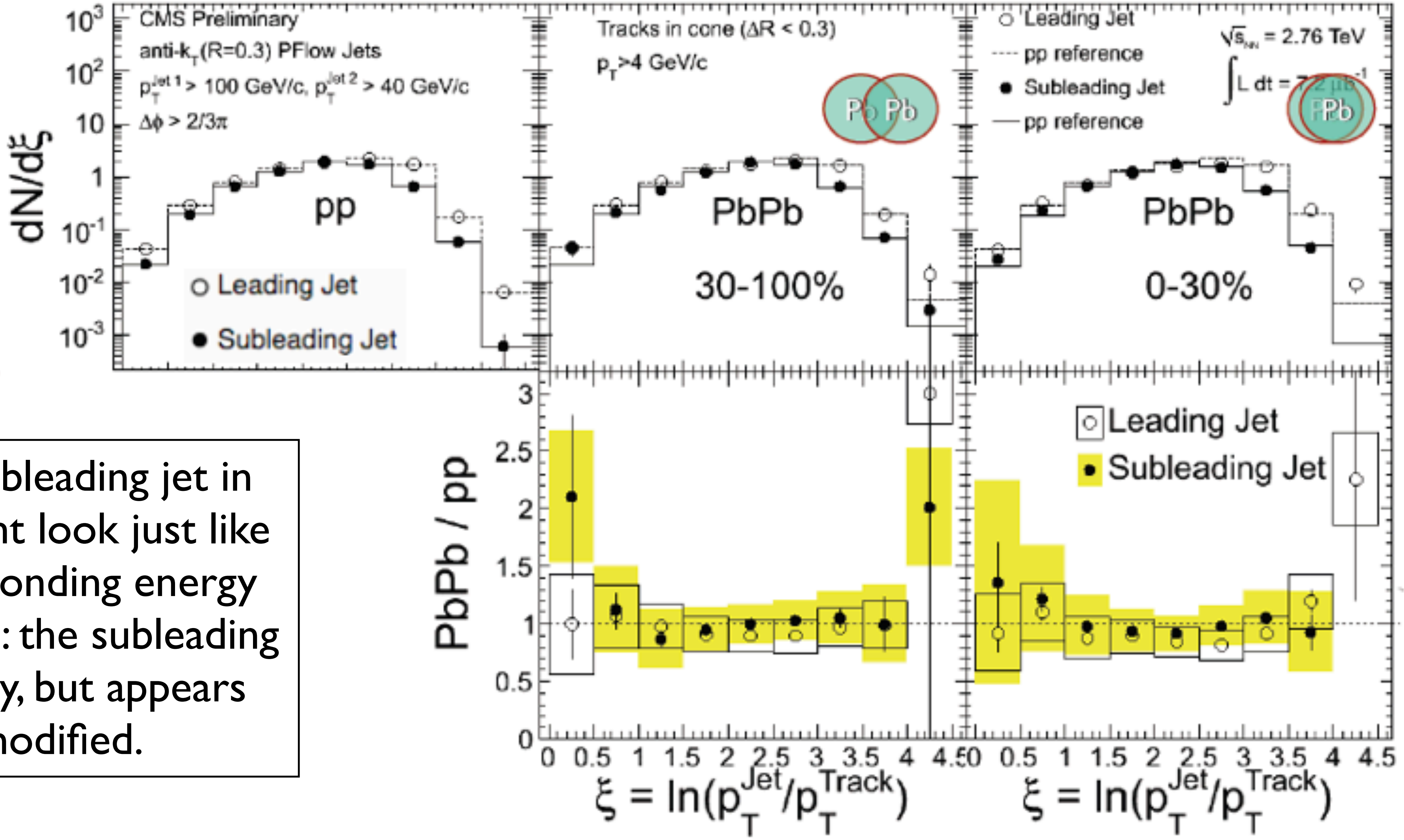


GY Qin & BM
PRL 106 (2011)
162302

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.*

Fragmentation



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

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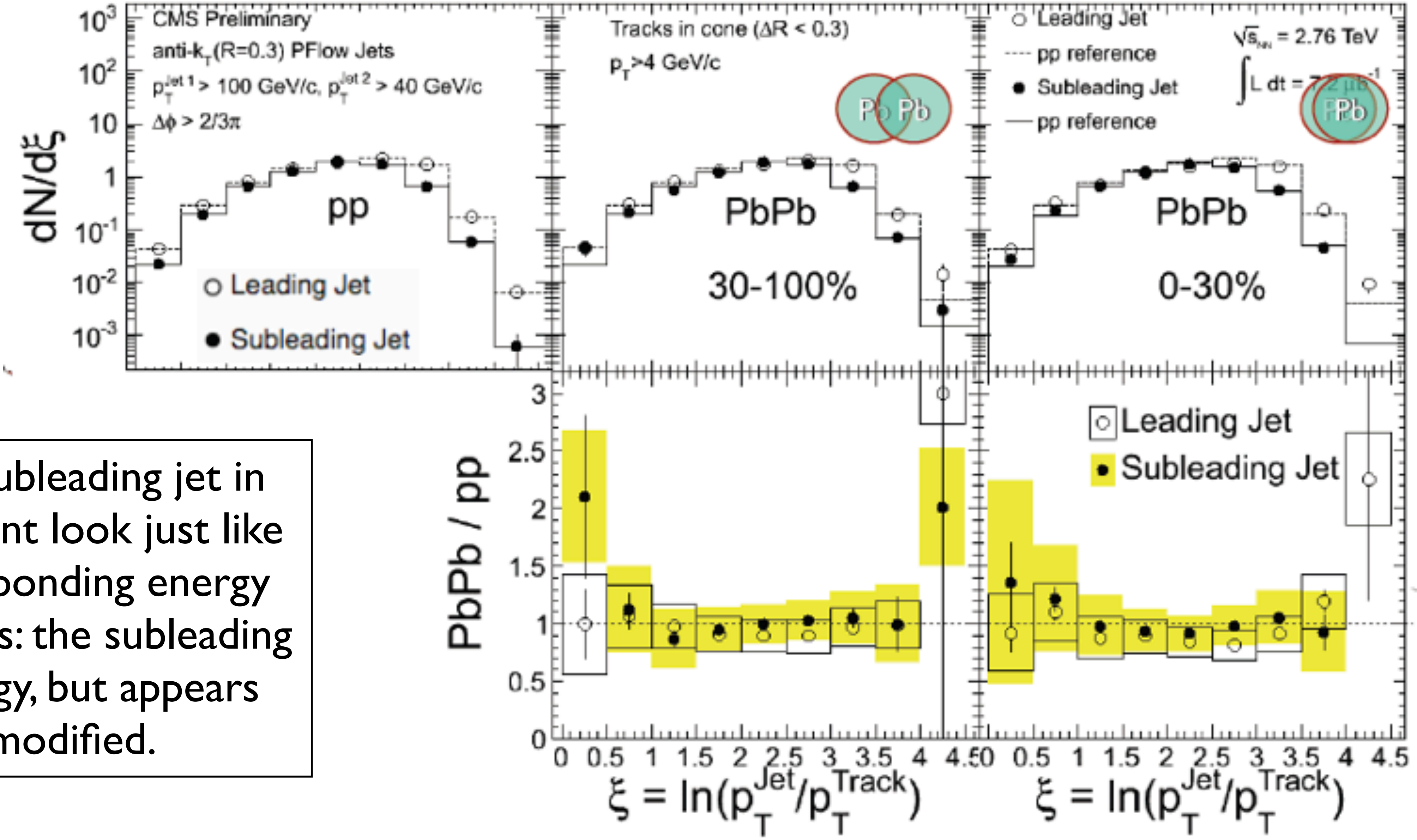


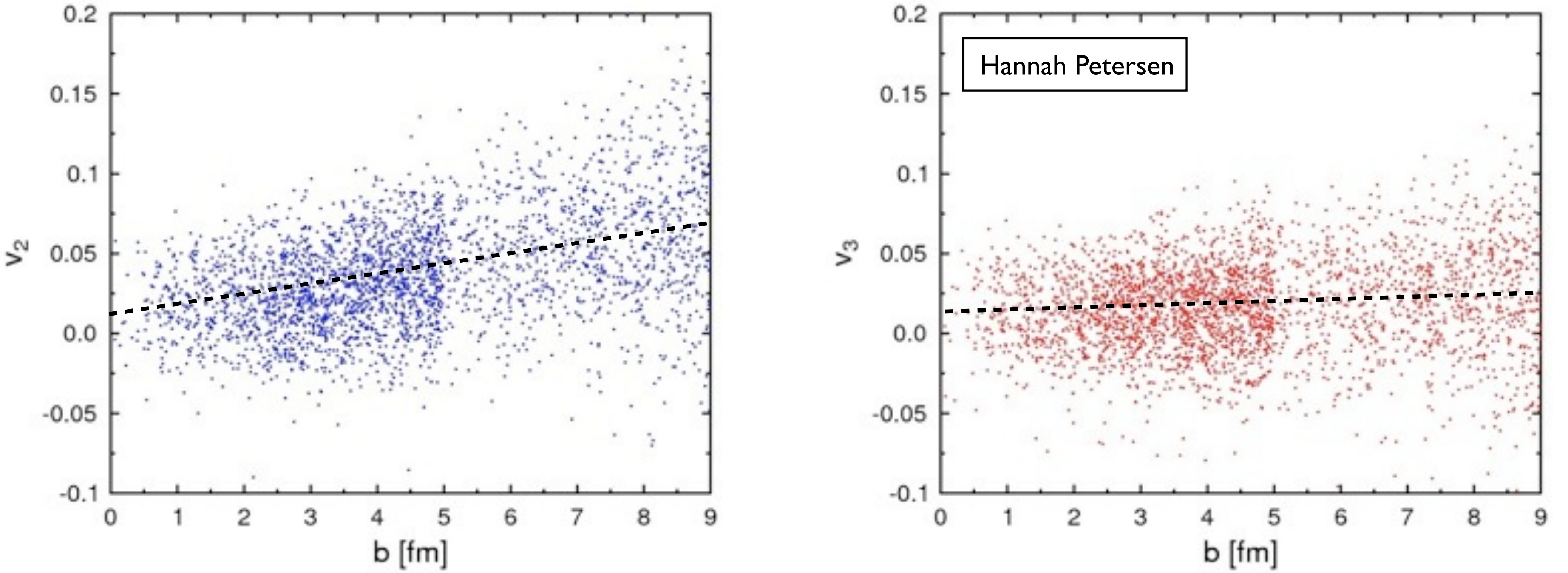
Leading and subleading jet in Pb+Pb fragment look just like jets of corresponding energy in *pp* collisions: the subleading jet loses energy, but appears otherwise unmodified.

Nontrivial, because the fragmentation function depends on the maximal virtuality Q^2 of the fragmenting parton, which is $O(p_T^2)$ in *pp,* but in PbPb the virtuality of the degraded parton **after** it exits the medium Q^2 ~ max(q^L , E/L) ~ 5–10 GeV^2

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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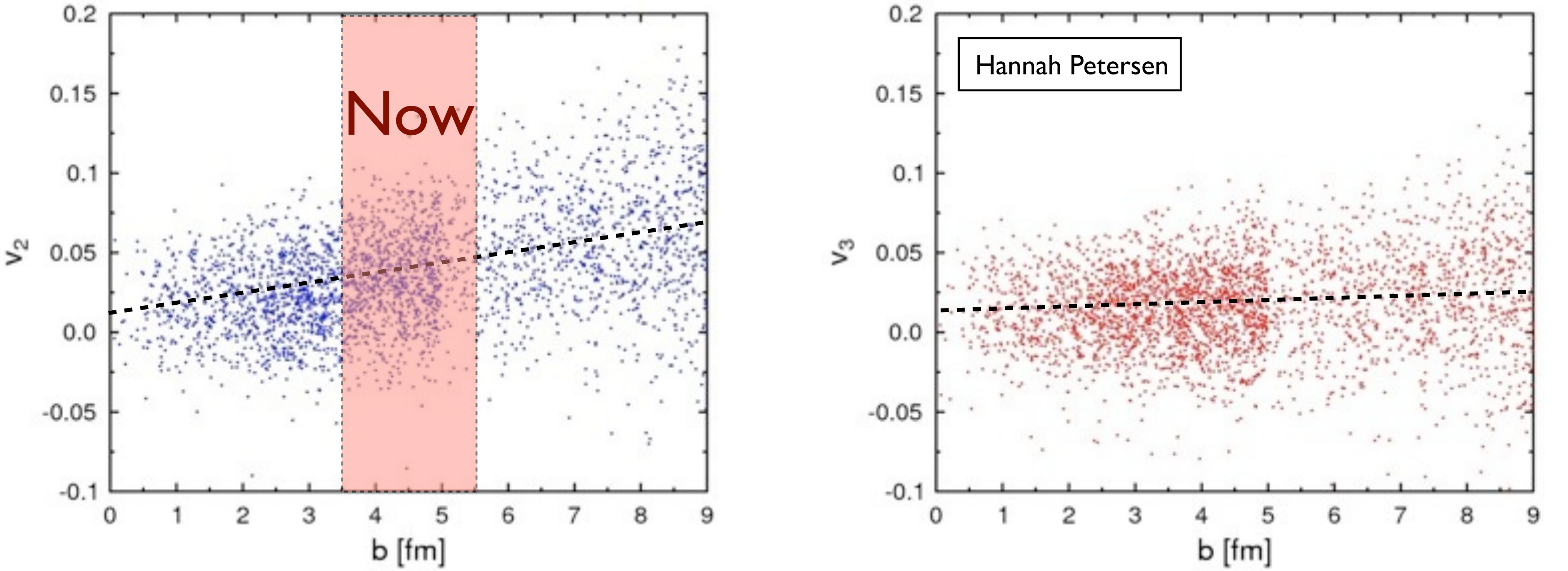

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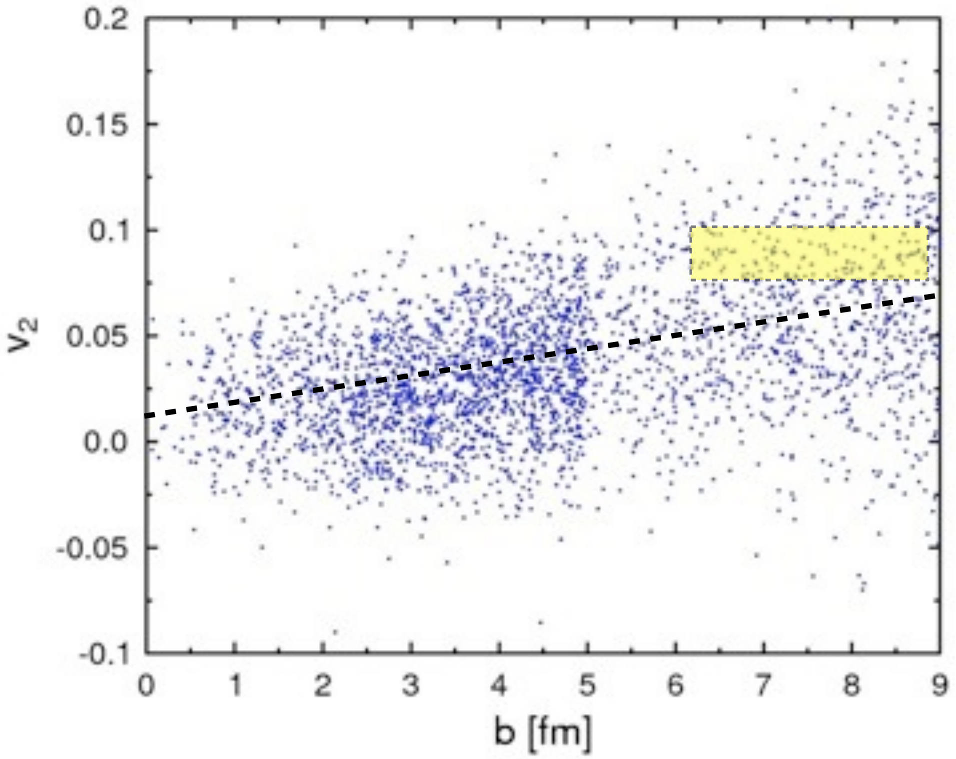

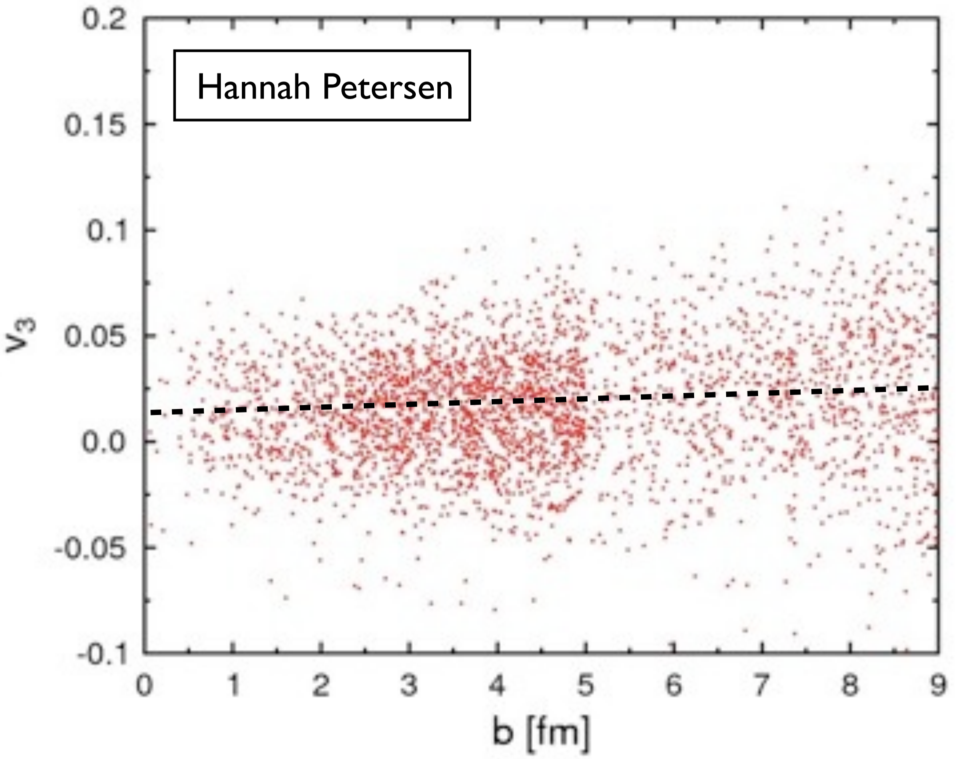

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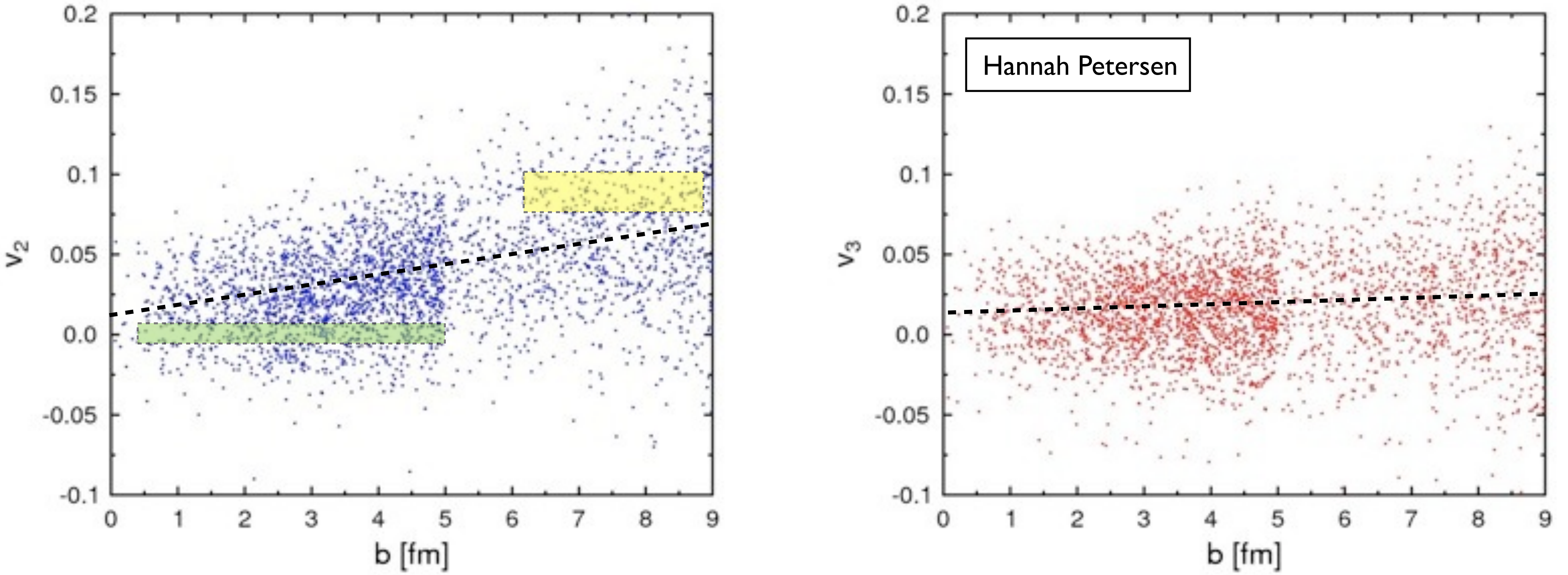

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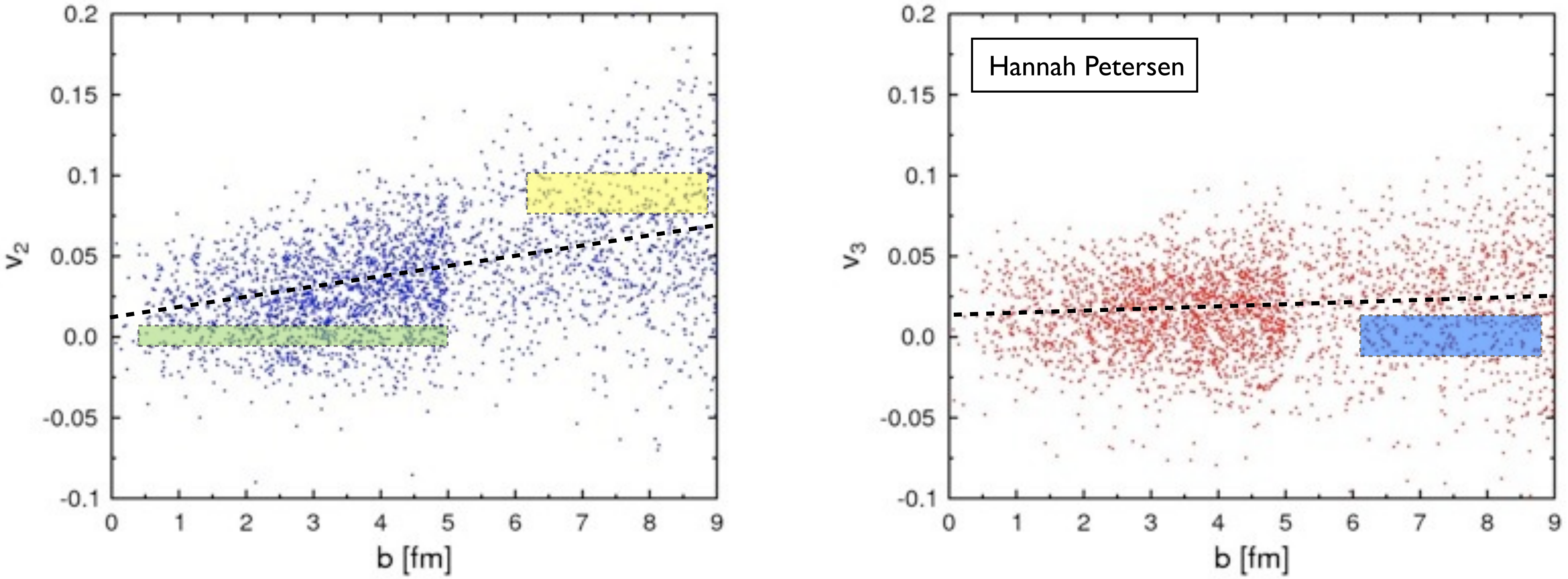

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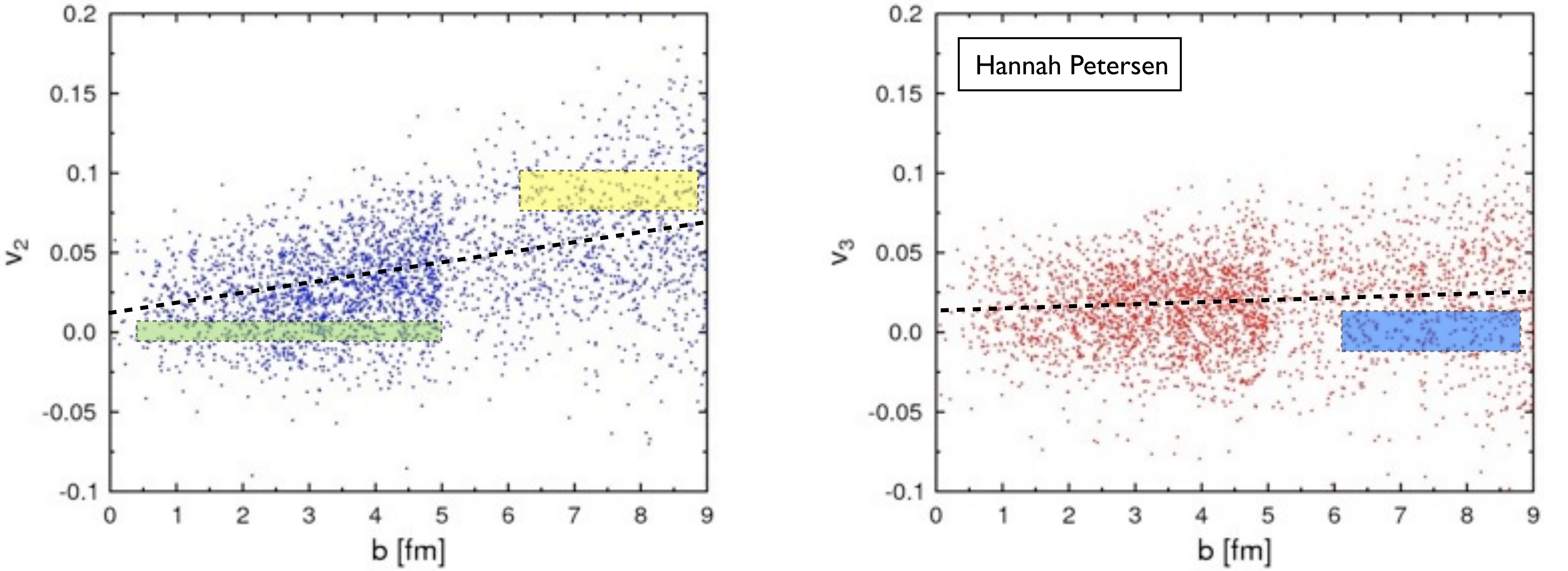

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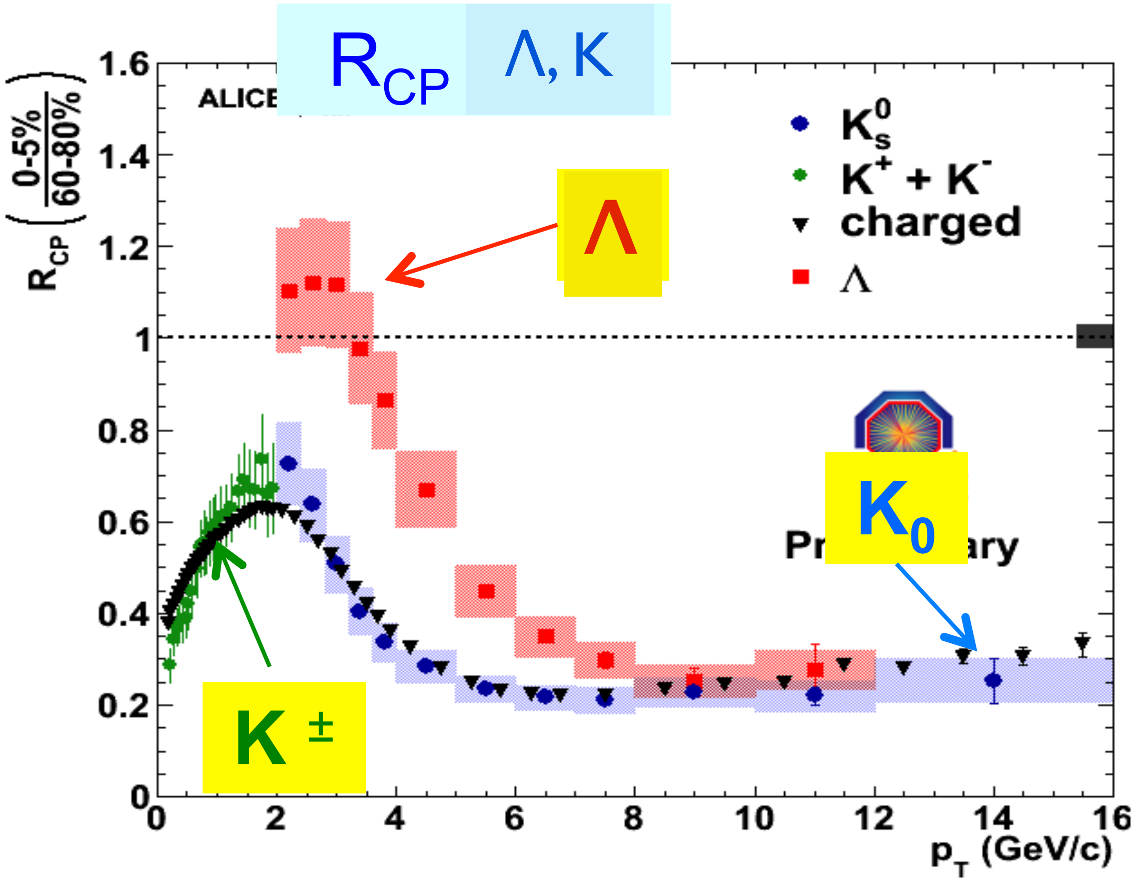
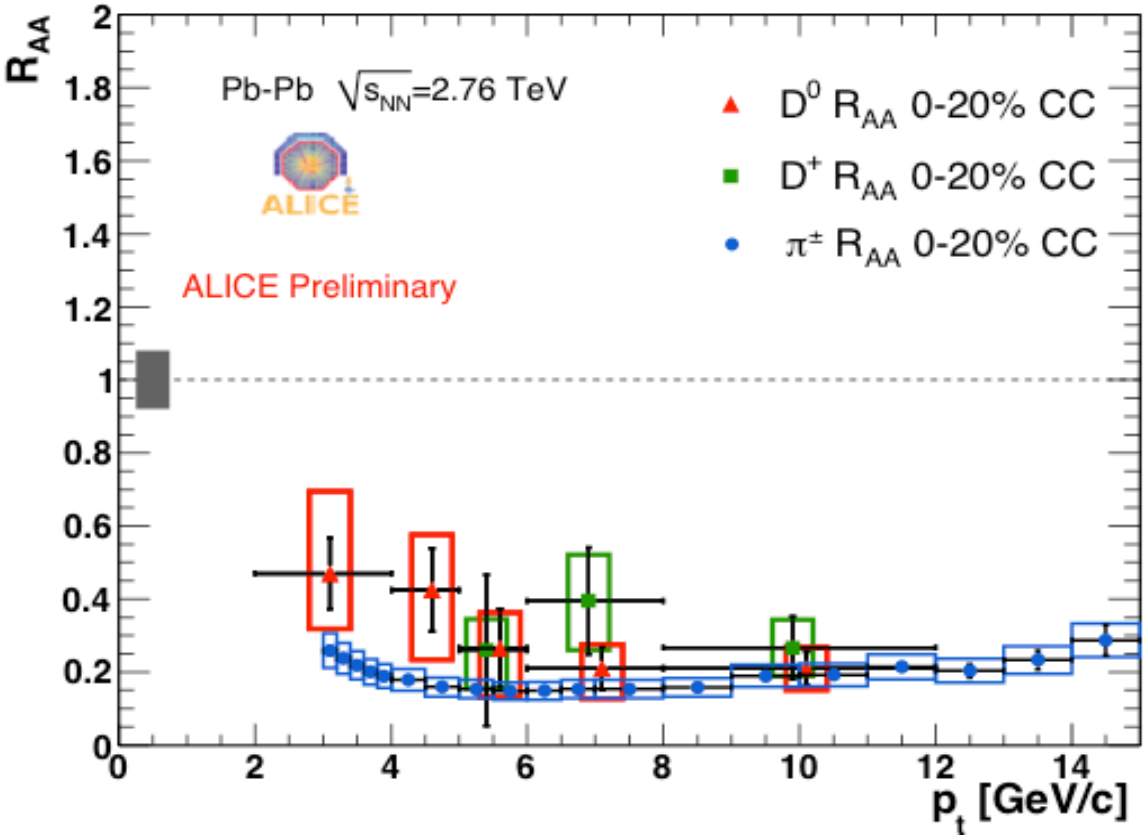
When we have the data to do this, can we really talk about performing ***jet tomography*** !

Flavor dependence

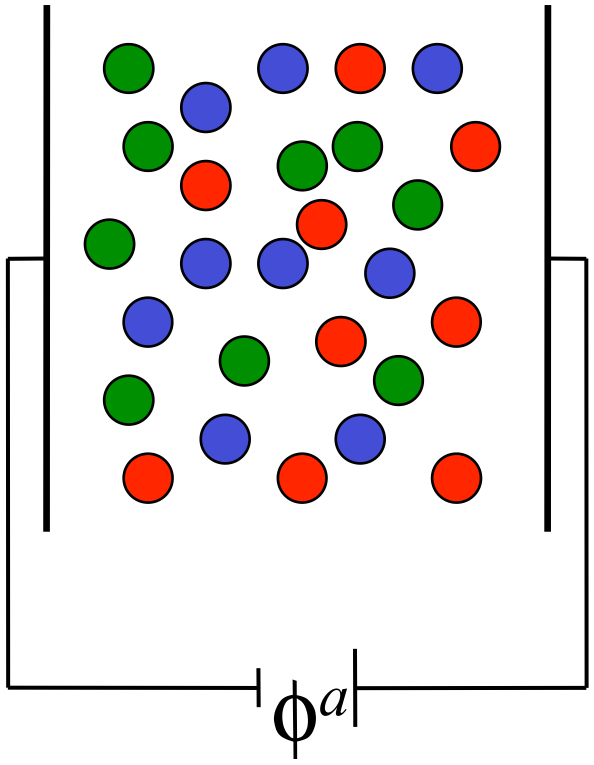
R_{AA} of all hadrons (including D-mesons) appear to converge at $p_T > 10$ GeV.



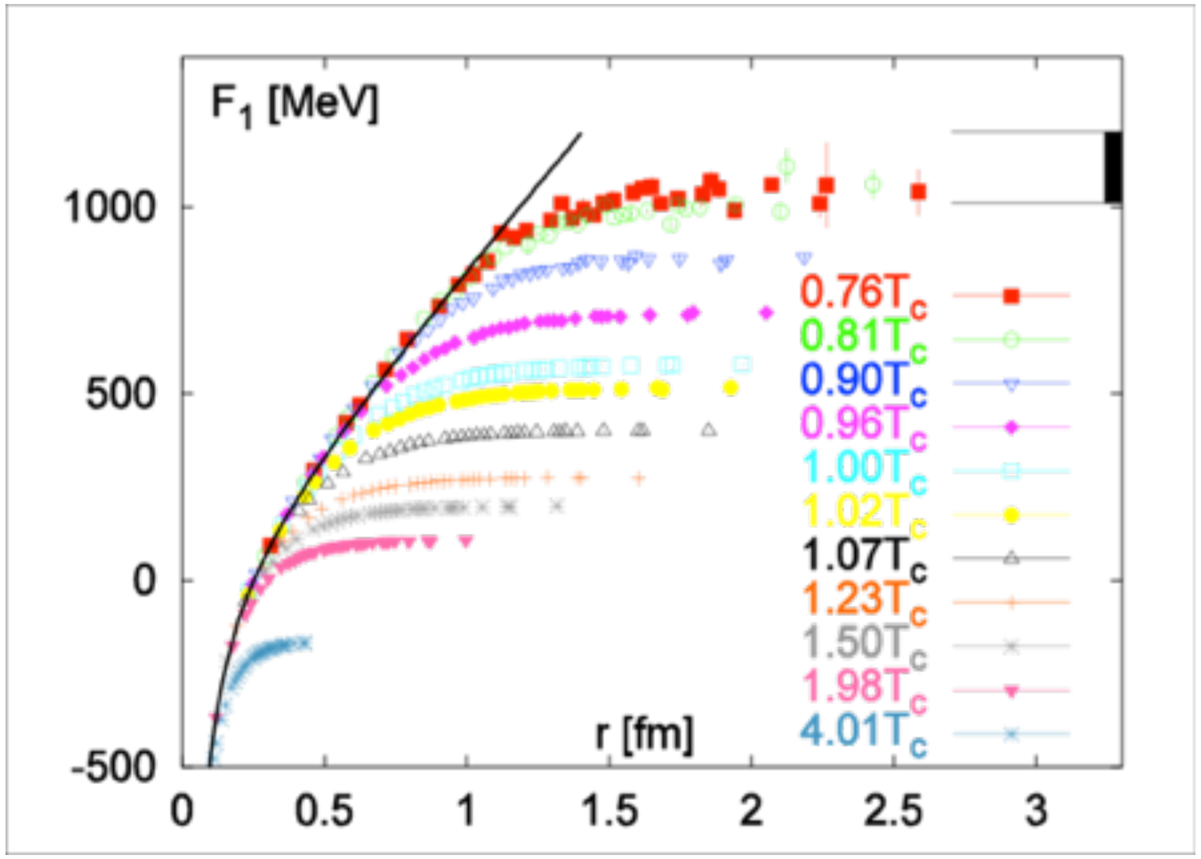


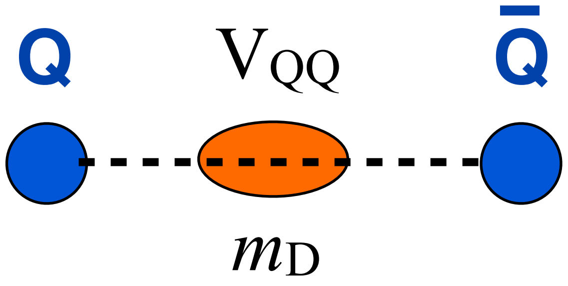
Will this continue to be true for b-quarks ???

Color screening



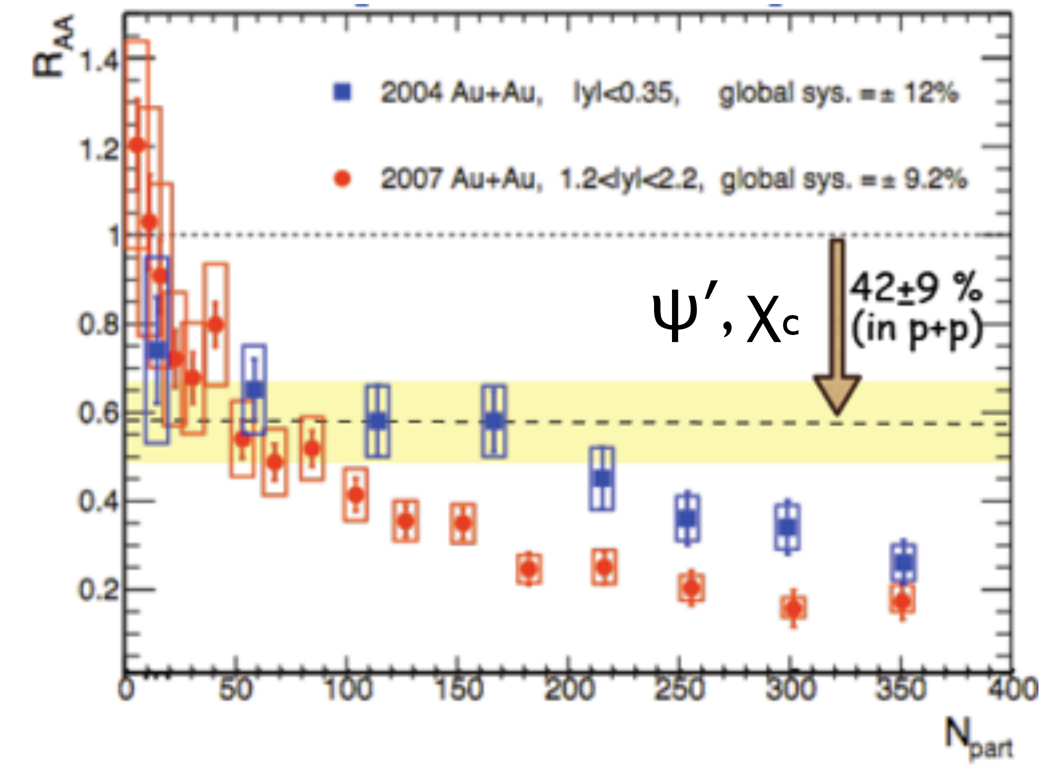
Lattice QCD

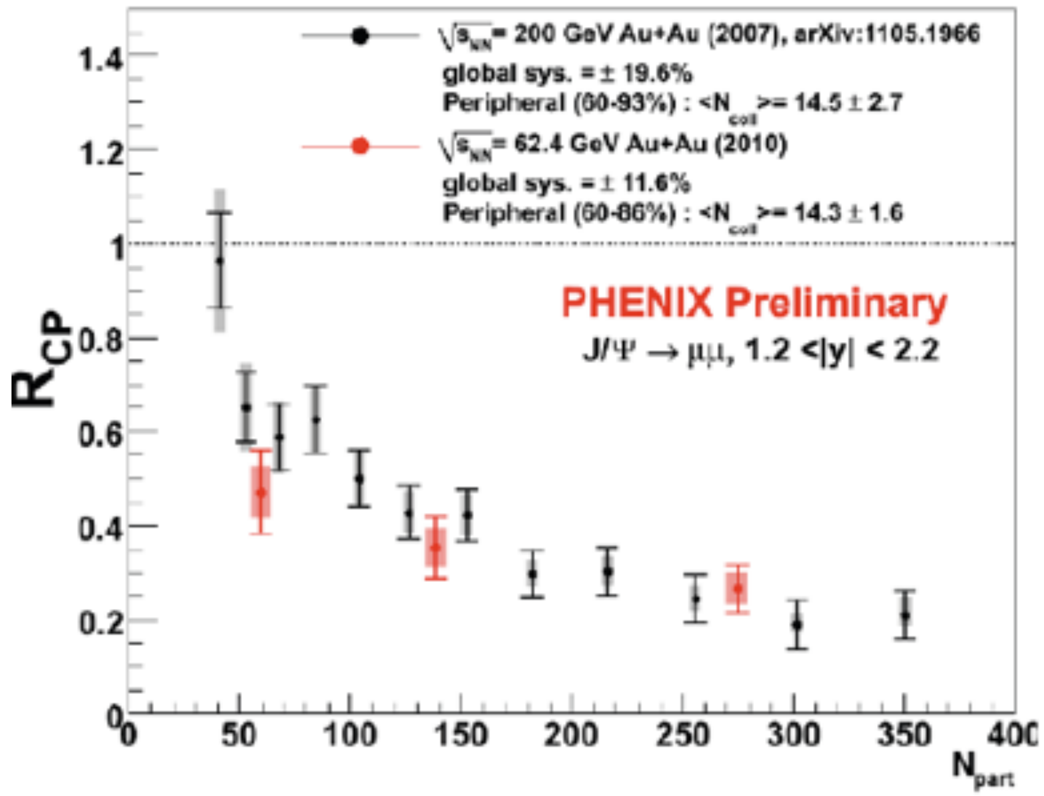




$m_D \sim gT$

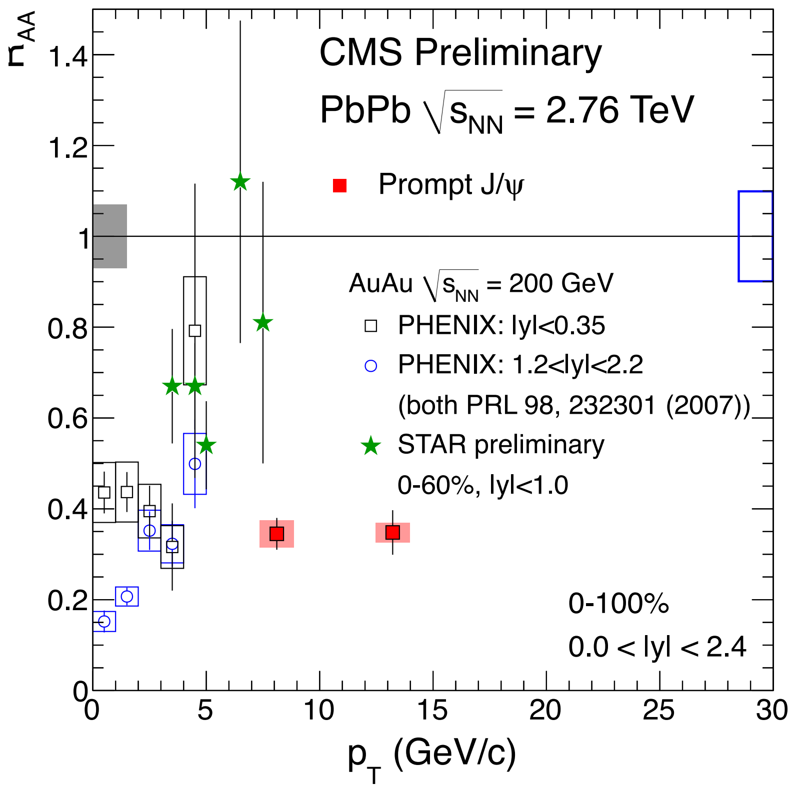
J/ψ suppression is ubiquitous

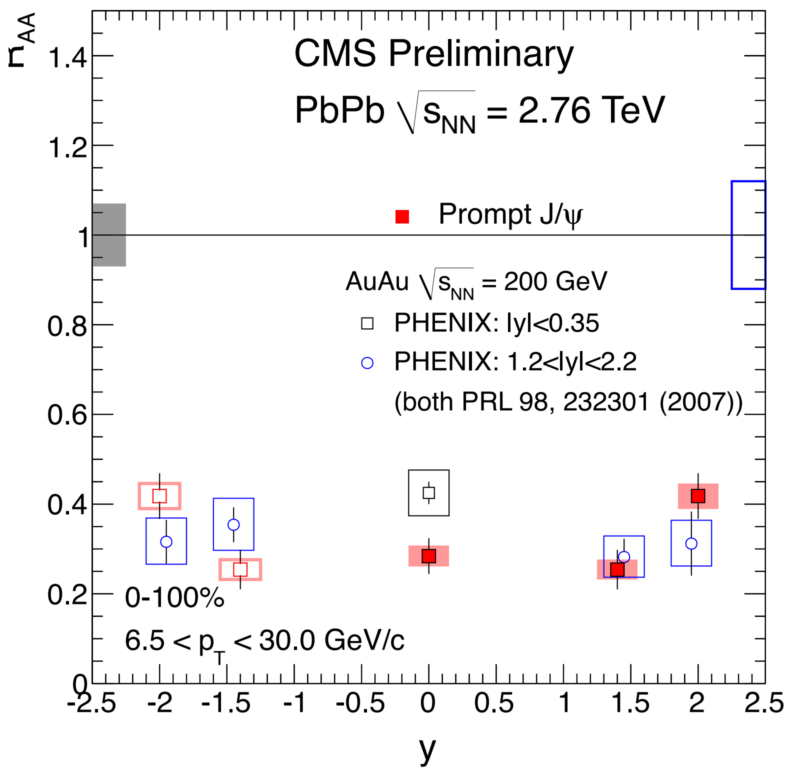




RHIC

LHC

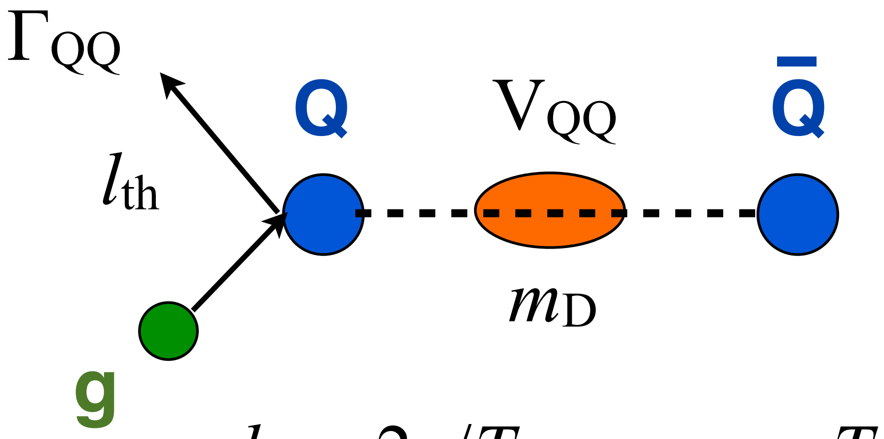




The real story...

...is more complicated that just m_D.

Q-Qbar bound state interacts with medium elastically and inelastically!



$l_{th} \sim 2\pi/T, \quad m_D \sim gT$

$$i\hbar \frac{\partial}{\partial t}\Psi_{Q\bar{Q}} = \left[\frac{p_Q^2 + p_{\bar{Q}}^2}{2M} + V_{Q\bar{Q}} - \frac{i}{2}\Gamma_{Q\bar{Q}} + \eta\right]\Psi_{Q\bar{Q}}$$

Akamatsu & Rothkopf, arXiv:1110.1203

➠ heavy-Q energy loss and Q-Qbar suppression cannot be separated

➢ need to understand contribution of endogynous recombination
can D-Dbar correlations be measured in Au+Au vs. p+p ?

➻ data on cold nuclear matter effects are important

Challenges I

- 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*
- Develop complete theory of fluctuations
- Extend measurement / analysis of fluctuations
  - *Correlations between observables*
  - *Interplay between bulk fluctuations and jets (tomography!)....*
    - *...in both directions!*

Challenges II

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- The theory of jet quenching is becoming quantitative
  - *Development of pQCD based jet MC's & NLO theory*
  - *Kinematic span RHIC − LHC is critical to model discrimination; RHIC provides better medium-vacuum virtuality match*
  - *But: High-p_T data from RHIC of similar quality will be needed*
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- Heavy Quarkonia:
  - *Quantitative theory of elastic and inelastic interactions with the medium is emerging*
  - *High statistics measurements in d+A, A+A over wider kinematic (esp. lower E_{CM}) are important to probe medium dependence*

Challenges III

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- The RHIC program needs detectors that combine
  - *High data taking rate*
  - *Sophisticated (level-3) triggers*
  - *Large acceptance (➠ 4π)*
  - *Energy flow measurement capability (calorimetry)*

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- The RHIC facility’s unique strengths include
  - *High integrated luminosity*
  - *Collision system flexibility*

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- Develop tools for massive data - complex model comparison
    - Needs precision data for hard (and rare) probes
    - Needs realistic models for hard probes in QCD matter

Phases of exploration

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Pre-RHIC

Smoking Gun
Phase

Discovery Phase

RHIC
2000-10

2011-20

Precision
Measurement
Phase

Dream ahead...

.... to 2016

"You know what I hate about this place? The heavy quarks in the liquid I serve."