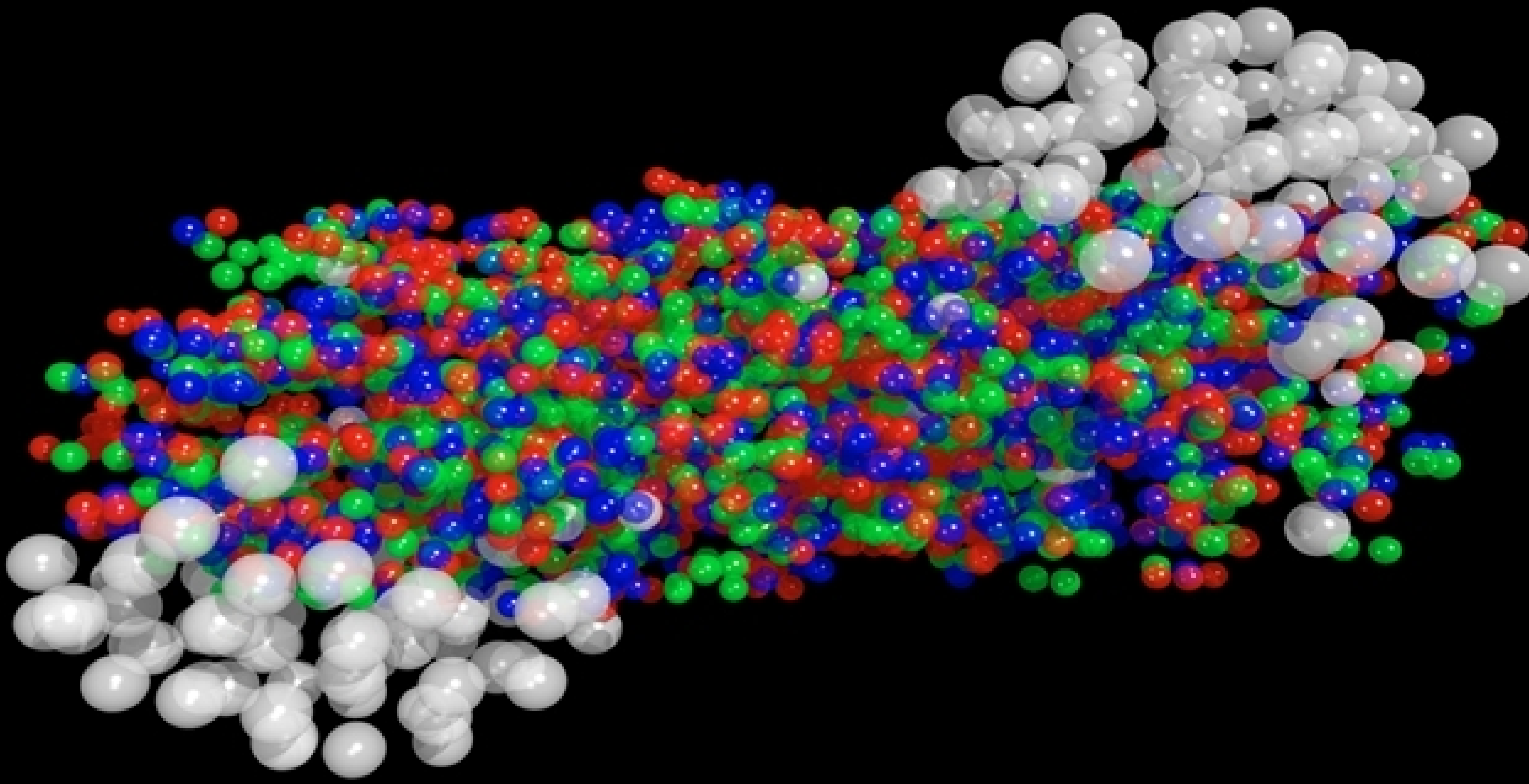
Quark Matter and High Energy Heavy-Ion Collisions

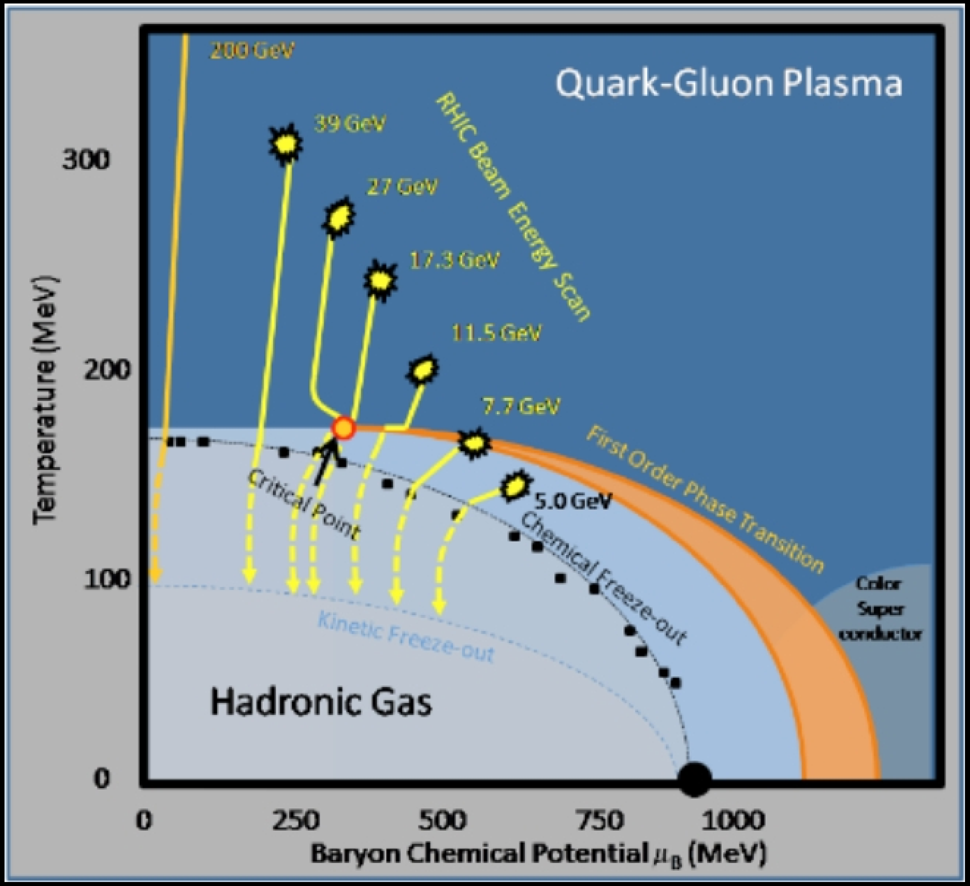


Christine Nattrass
University of Tennessee at Knoxville

Subjects

- Phase diagram of nuclear matter
- Global observables and the initial state
- Hydrodynamical flow
- Partonic energy loss in the medium
- Provocative ideas

The phase diagram of nuclear matter

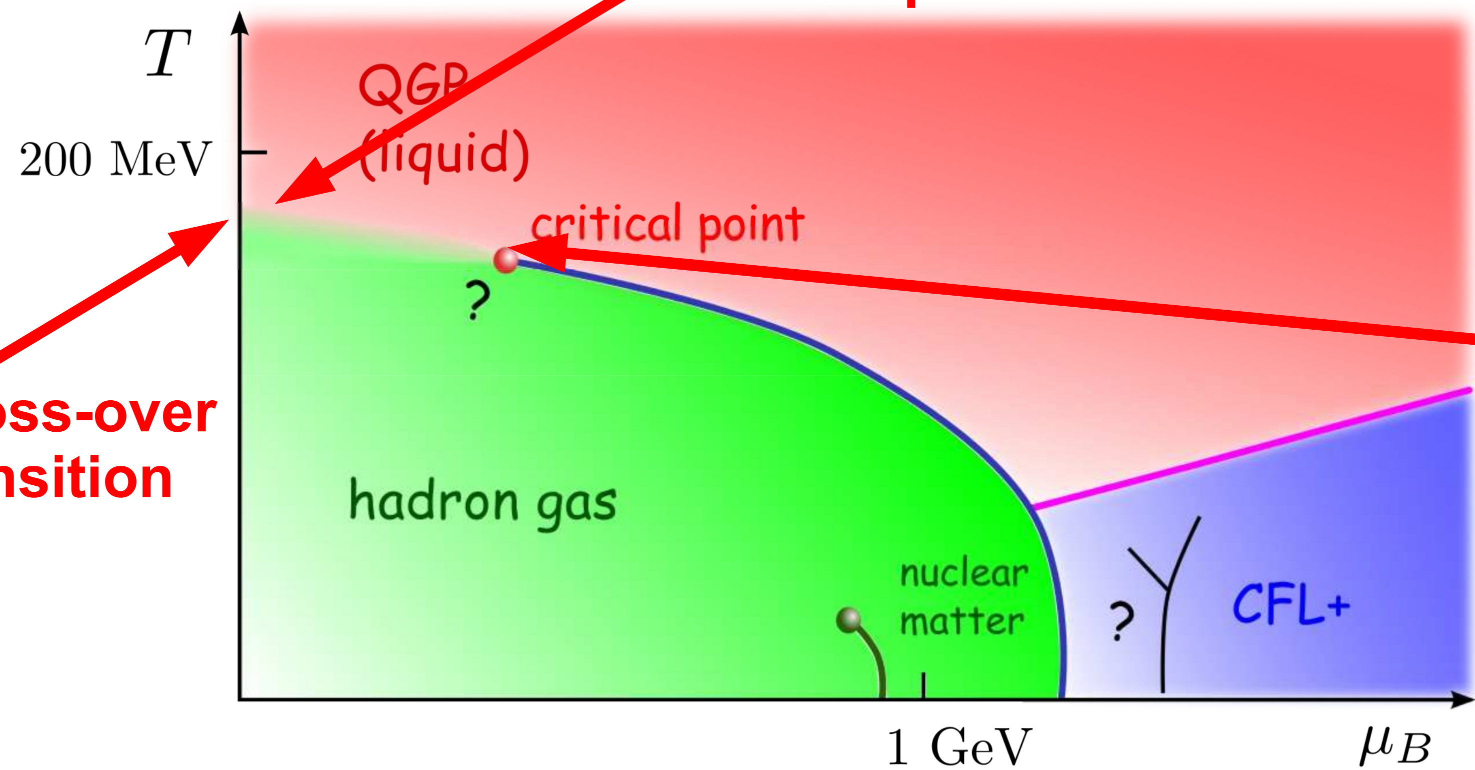


Dan Cebra
Misha Stephanov
Swagato Mukherjee
Rajan Gupta
Grzegorz Stefanek

QCD phase diagram

Lattice groups agree on critical temperature

Cross-over transition

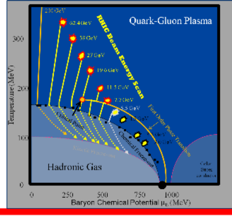


Theoretical searches for the critical point

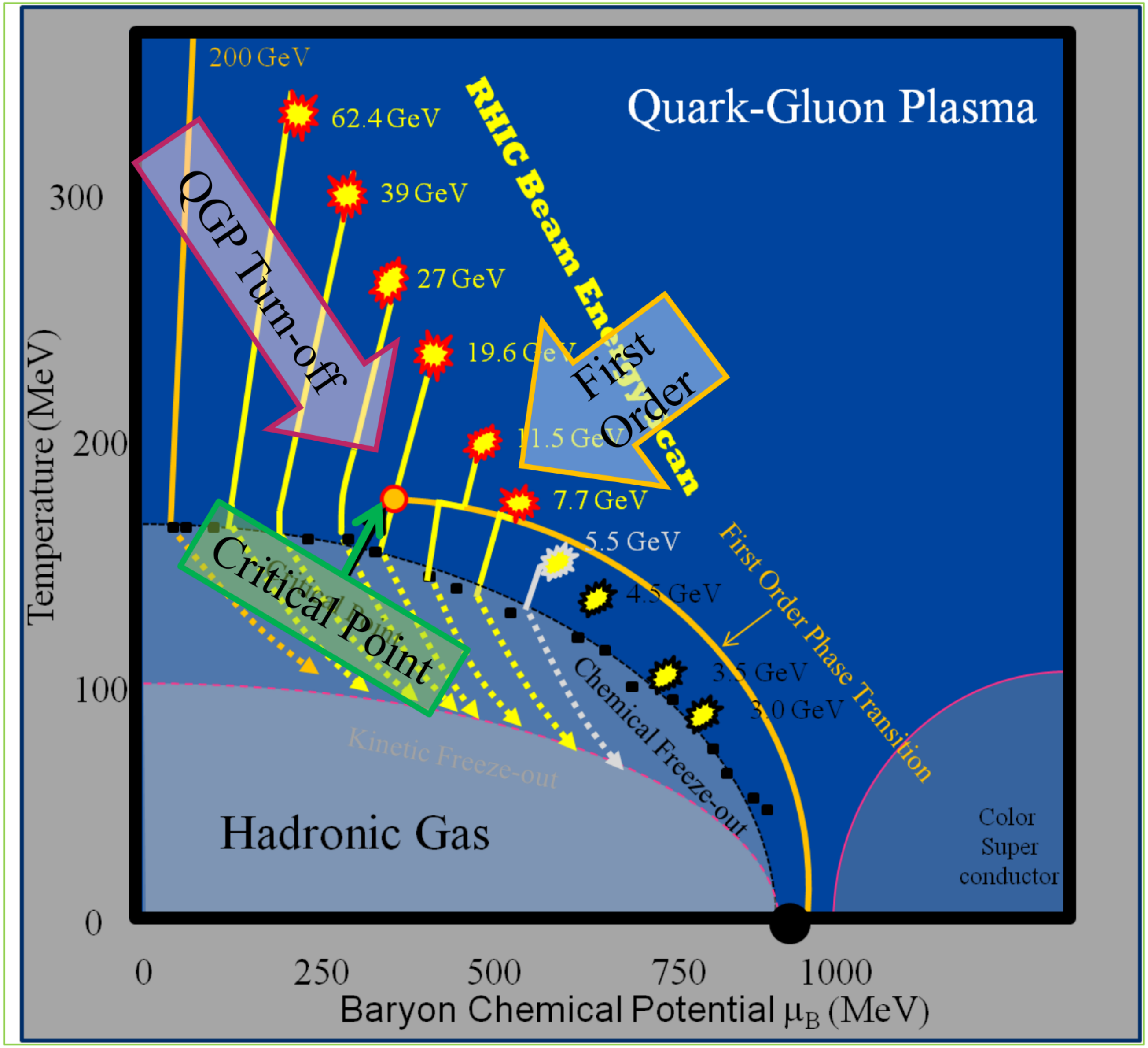
- Lattice: QCD transition at $\mu_B = 0$ a crossover.
  More in talks by S. Mukherjee and R. Gupta.
- Models (and lattice) suggest the transition becomes 1
- Can we observe the critical point in heav

Rajan Gupta
Misha Stephanov
Swagato Mukherjee

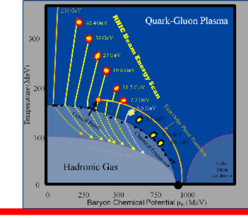
The RHIC Beam Energy Scan



- Since the original design of RHIC (1985), running at lower energies has been envisioned.
- RHIC has studied running lower energies with a series of test runs: 19.6 GeV Au+Au in 2001, 22.4 GeV Cu+Cu in 2005, and 9.2 GeV Au+Au in 2008.
- In 2009 the RHIC PAC approved a series of six energies to search for the **turn-off of QGP signatures**, the **critical point**, and evidence of a **first order phase transition**.
- The scan was completed during the 2010 and 2011 run periods.

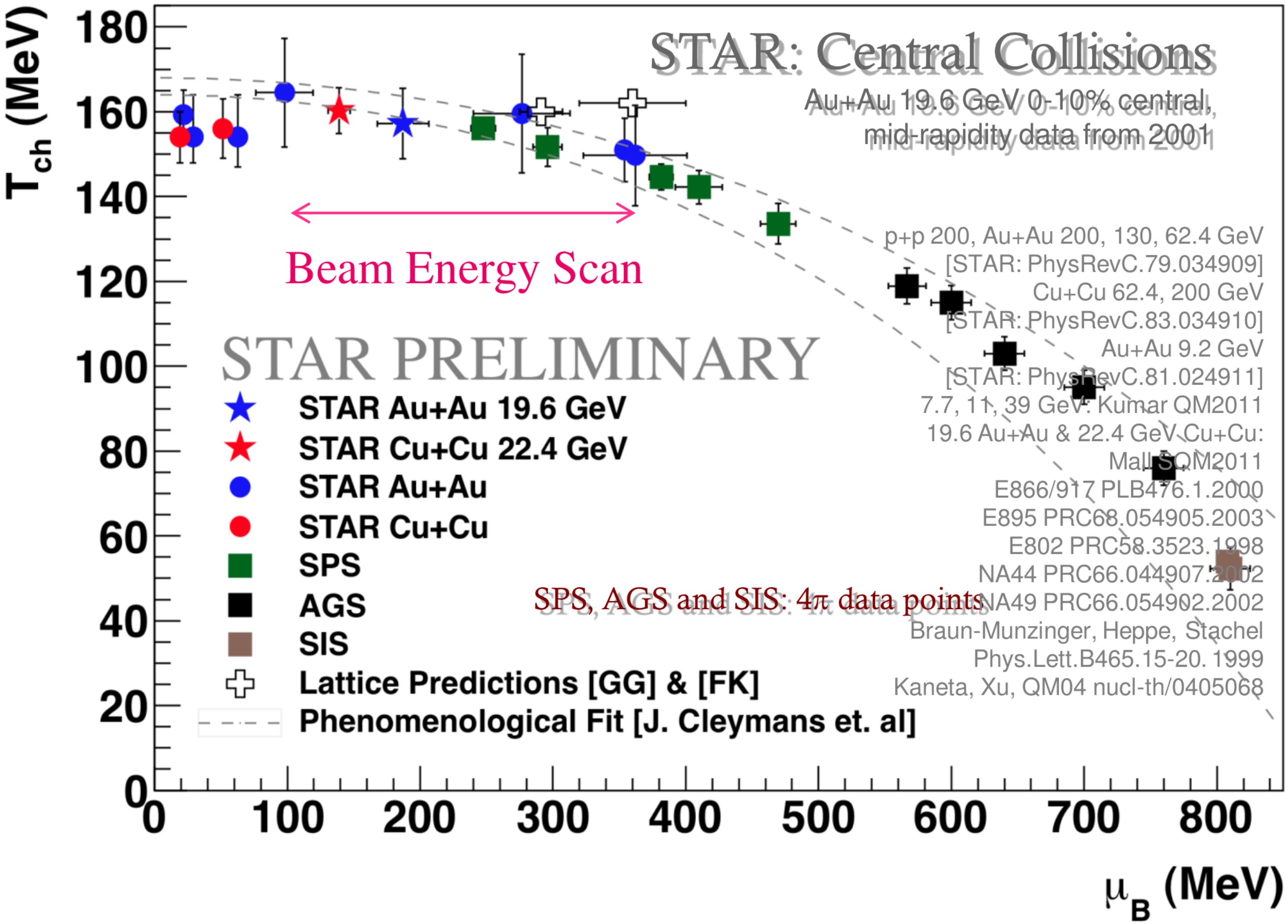


Where are We on the Phase Diagram



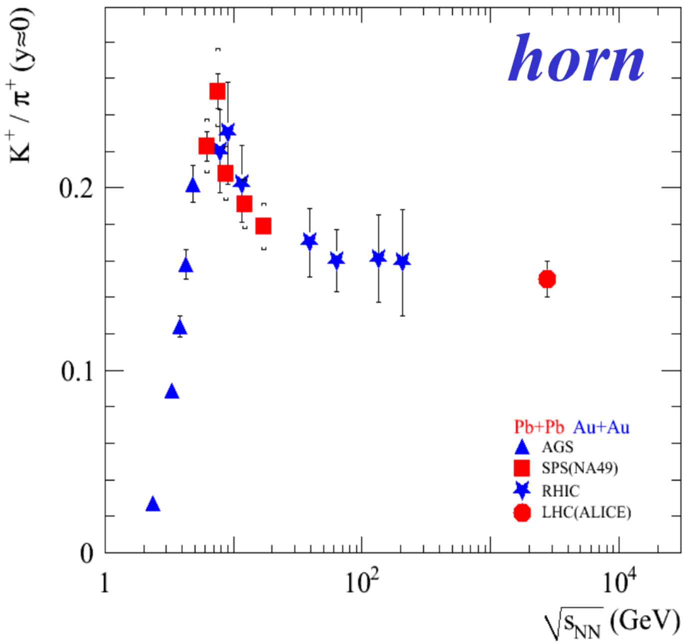
$$\frac{d^6N}{dx^3dp^3} = g \ln\left(\frac{1}{e^{\frac{E-\mu}{T}} \pm 1}\right)$$

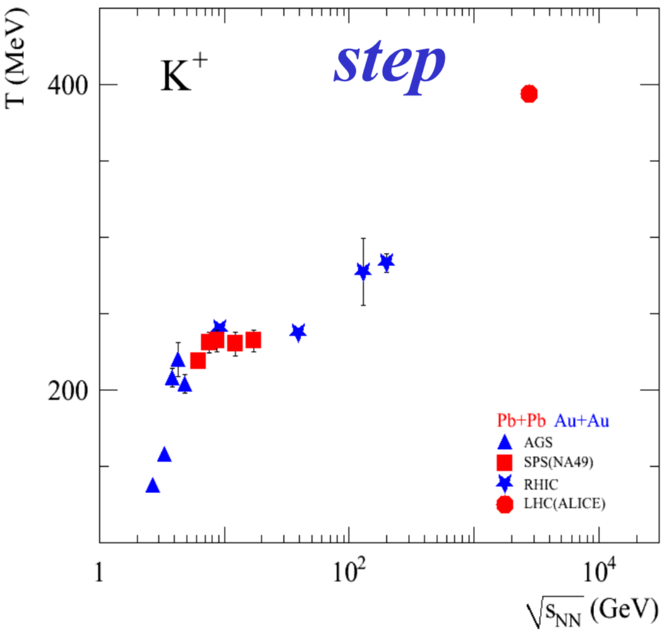
Using the particle ratios from the π, K, and p and a thermal model, we can determine our location on the phase diagram

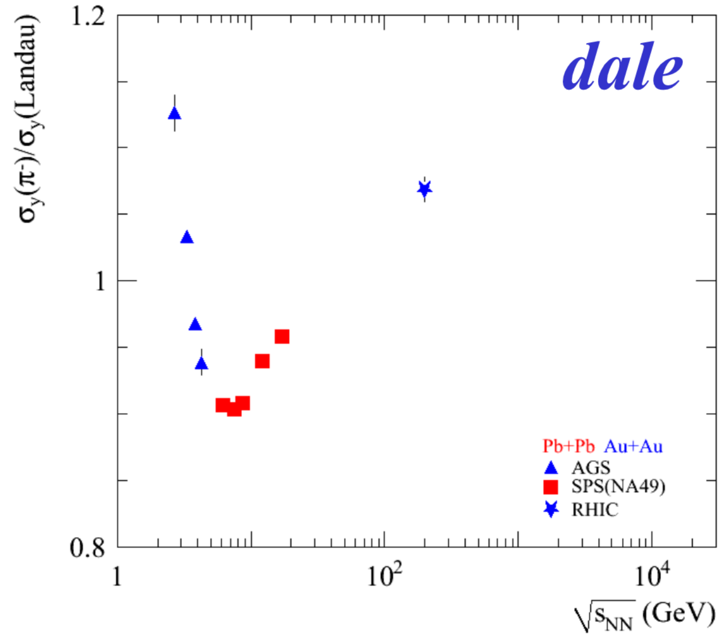


S. Brovko DNP2011

Evidence for the onset of deconfinement







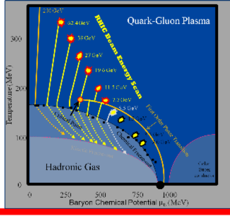
- **rapid changes in energy dependence of hadron production properties provide evidence for the phase transition**
- **the LHC and RHIC BES points confirm NA49 measurements and trends**

Data:
NA49: C.Alt et al., PRC 77, 024903 (2008)
STAR: L.Kumar, arXiv:1106:6071 (2011), B.Mohanty,QM2011
ALICE: J.Schukraft QM2011, M.Floris QM2011, A.Toia QM2011
and
A.Rustamov, arXiv:1201.4520

Theoretical predictions:
M.Gazdzicki, M.Gorenstein, APP B30, 2705 (99)

Evidence for the onset of deconfinement in Pb+Pb collisions at $\sqrt{s_{NN}} \approx 8$ GeV

Grzegorz Stefanek



Conclusions

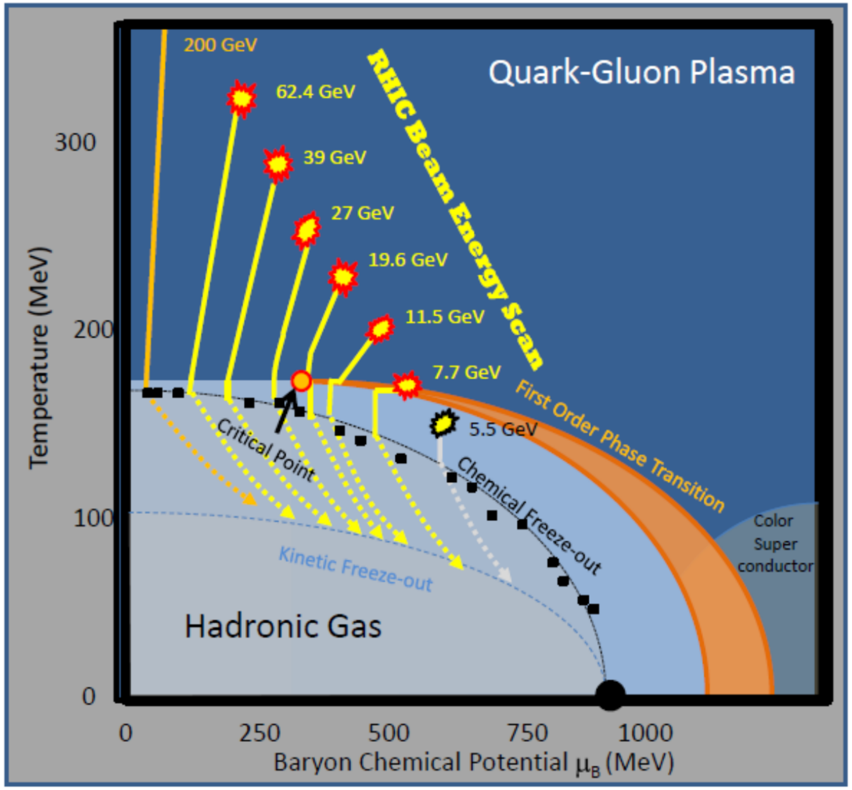
- The RHIC facility has successfully completed a *phase I* beam energy scan.

- Charged particle spectra allow determination of a location on the phase diagram.

- Clear evidence of turn-off of QGP signatures
  - Constituent quark scaling of flow
  - High p_T suppression
  - Chiral magnetic effect anisotropies

- Some evidence for first order phase transition
  - The magnitude of the elliptic flow
  - The directed flow
  - The azimuthal HBT

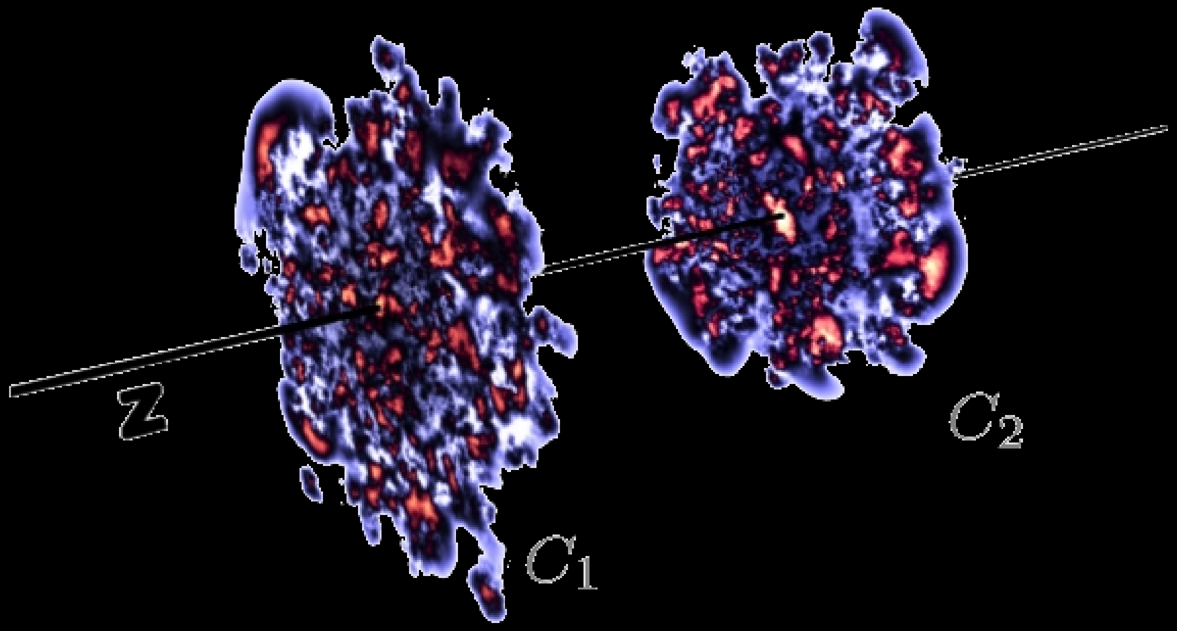
- Searches for critical point signatures
  - Particle ratio fluctuations (K/π etc.)
  - Skew and Kurtosis of conserved quantities



Take home messages

- Theory:
  - Agreement on critical temperature from Lattice
  - Searches for critical point
- Experiment:
  - Unprecedented wealth of data
  - Some evidence for the critical point... but not yet conclusive
  - RHIC & SPS data agree

Global observables and the initial condition



Bjoern Schenke
David Silvermyr
Magdelena Malek
Sooraj Radhakrishnan

IP-Glasma: Initial energy density

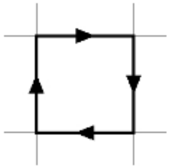
Initial energy density at $\tau = 0$:

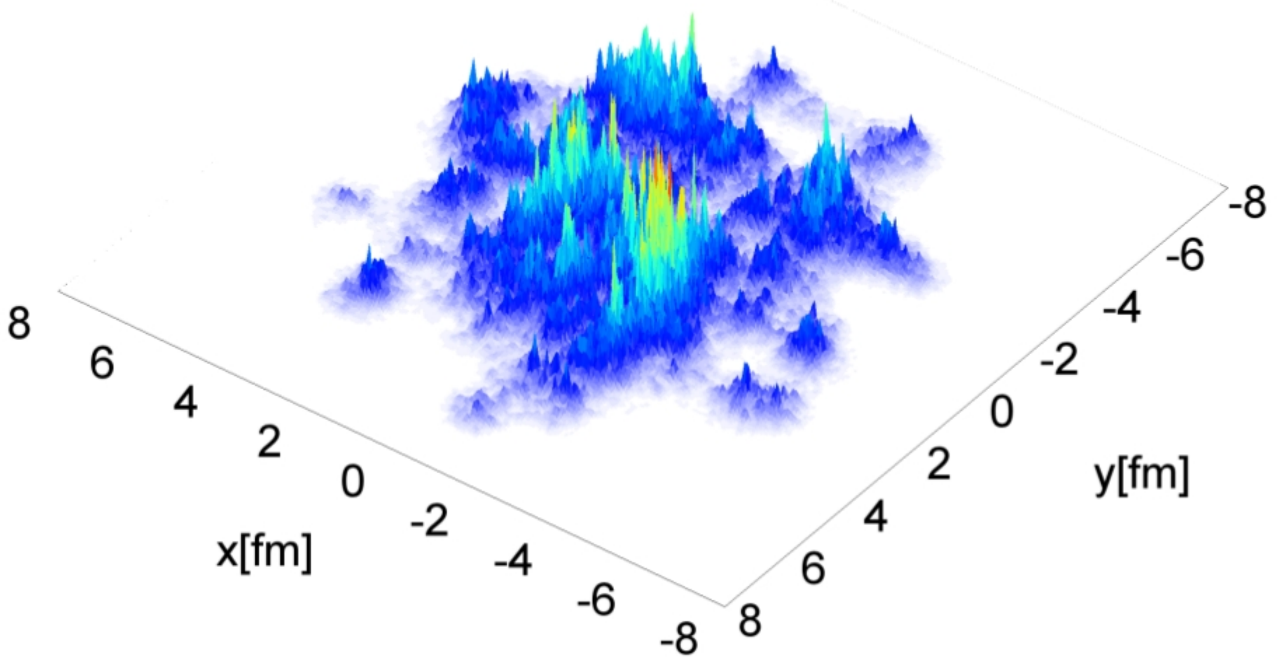
$$\varepsilon(\tau = 0) = \frac{2}{g^2 a^4}(N_c - \mathrm{Re}\,\mathrm{tr}\,U_\square) + \frac{1}{a^4}\mathrm{tr}\,E_\eta^2$$

with the longitudinal magnetic and electric energy density.

The plaquette is given by

$$U_\square^j = U_j^x\, U_{j+\hat{x}}^y\, U_{j+\hat{y}}^{x\dagger}\, U_j^{y\dagger} =$$

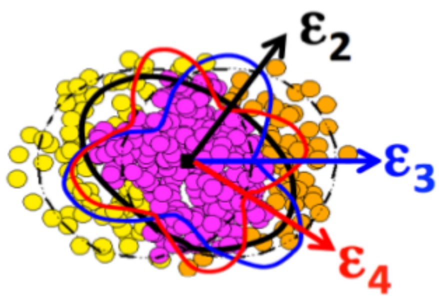




arbitrary units

Björn Schenke

Flow and initial density fluctuations



$$\Rightarrow \frac{dN}{d\phi} \propto 1 + 2\sum_{n=1}^{\infty} v_n cos(n(\phi - \Psi_n))$$

$$v_n = \langle cos(n(\phi - \Psi_n))\rangle$$

$$\epsilon_n = \frac{\sqrt{\langle r^n cos(n\phi)\rangle^2 + \langle r^n sin(n\phi)\rangle^2}}{\langle r^n\rangle}$$

- Collective pressure driven expansion. Initial spatial assymetry $\rightarrow$ final momenutum space anisotrpy
- The flow signal is sensitive to initial geomtry and dynamics of the medium $\rightarrow$ equation of state, transport coeffiecents: shear viscosity

Event Plane Analysis

- EP direction:

  $$tan(n\Psi_n) = \frac{\sum_i w_i cos(n\phi_i)}{\sum_i w_i sin(n\phi_i)}$$

- Correlate EP with tracks

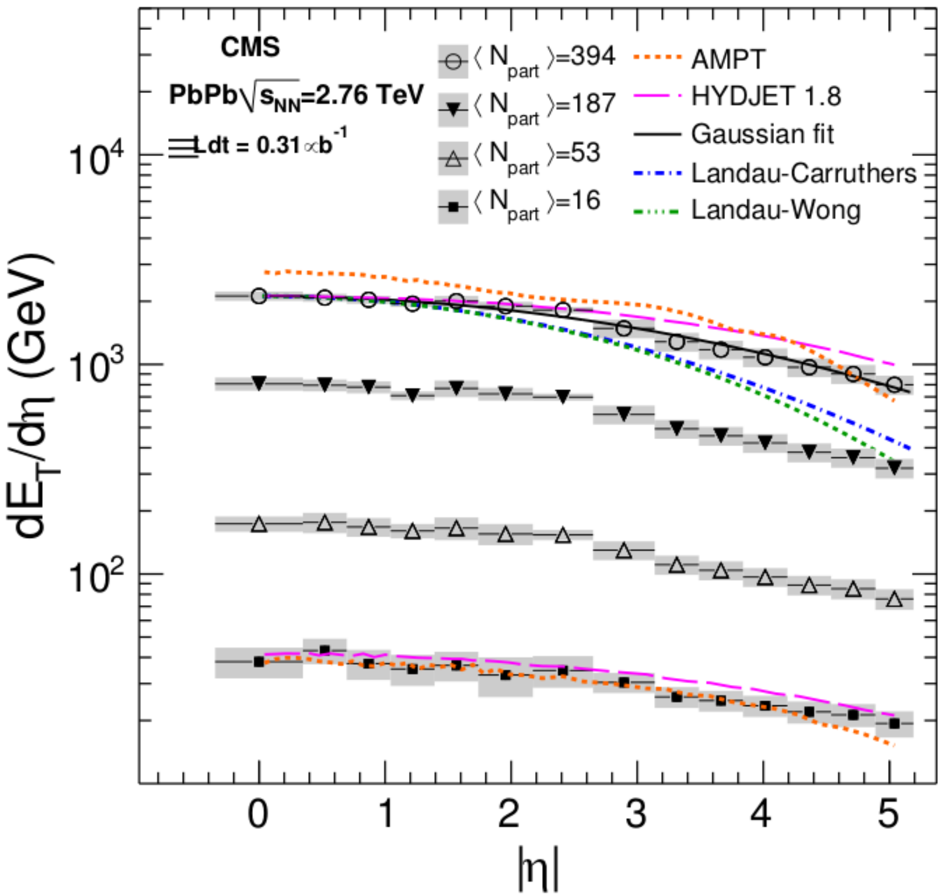
  $$v_n = \langle cos(n(\phi - \Psi_n))\rangle$$

- Resolution correction $v_n^{actual} = v_n/R$;

  $$R \approx \langle\sqrt{2cos(\Psi_a - \Psi_b)}\rangle$$

- Ensure rapidity gap to reduce jet correlations

Pb+Pb | Energy density: η dependence

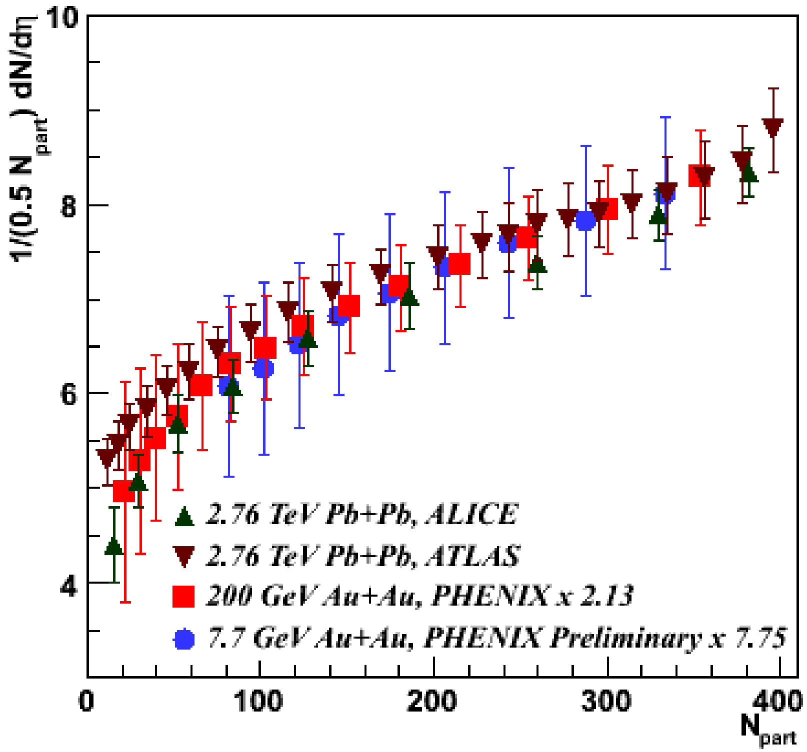


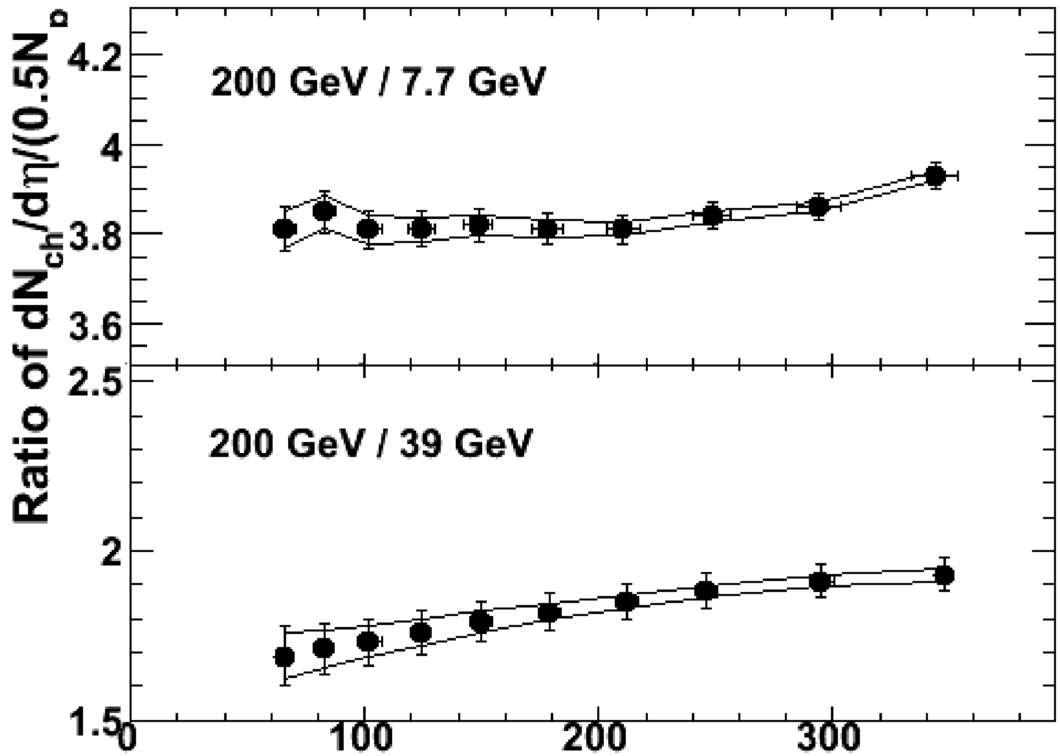
- $\sim$ 2.1 TeV at $\eta = 0$; at least 3 times larger than at RHIC
- BRAHMS data described by Landau hydro; Gaussian with $\sigma = \sqrt{\ln \gamma}$
- for $|\eta| < 5.2$ and centrality 0-2.5%: $dE_T/d\eta$ consistent with a Gaussian with $\sigma_\eta = 3.6 \pm 0.1$
- for $\tau_0 = 1$ fm/c and $R = 7.1$ fm: energy density of ≈ 15 GeV/fm^3
- for central events total transverse energy per pair of participating nucleons is 92$\pm$ 6 GeV

arXiv:1205.2488v1 [nucl-ex]

Magdelena Malek

dNch/dη

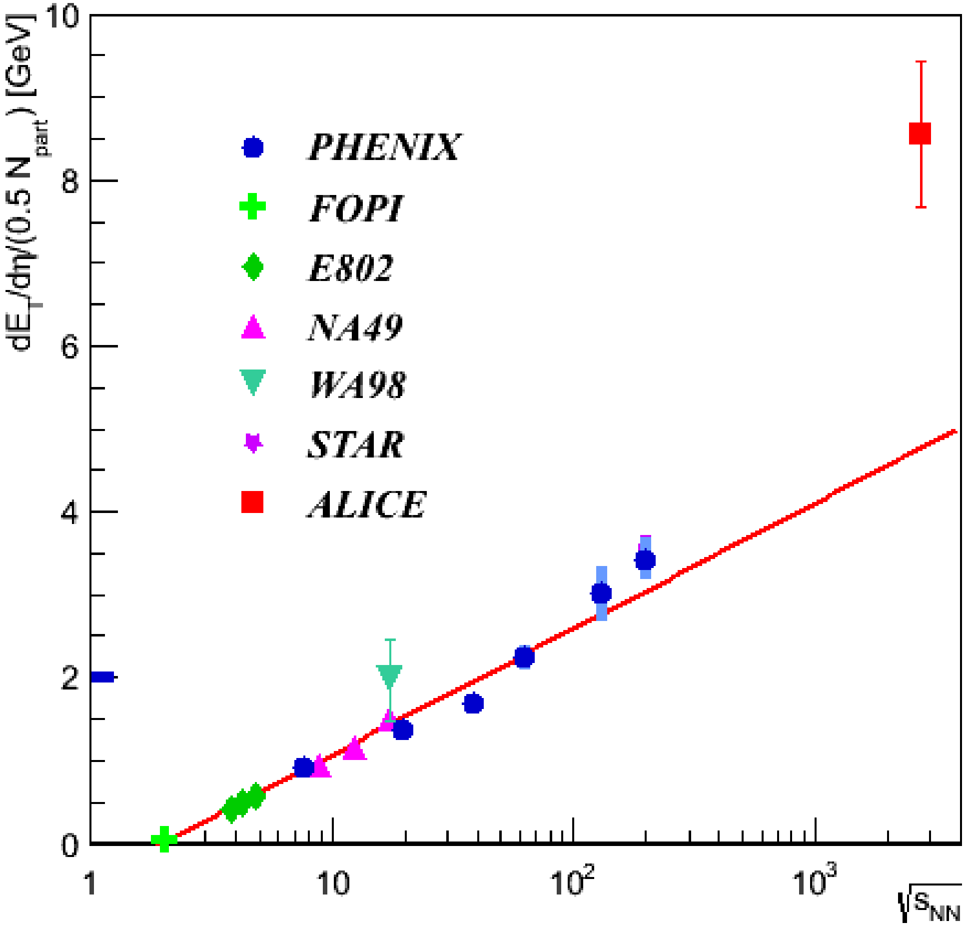


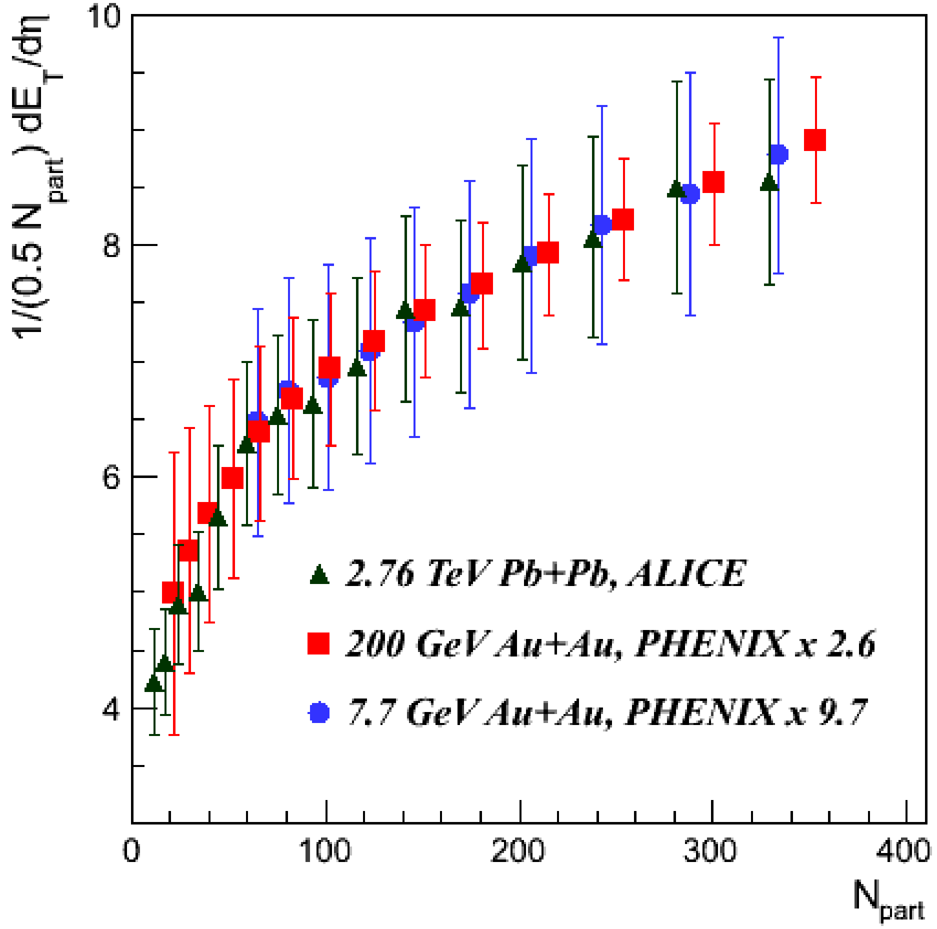


N.B.: Approx. same centrality dependence at 7.7 GeV as at 2.76 TeV!
[note: no RHIC average here, just PHENIX..]

David Silvermyr

dET/dη





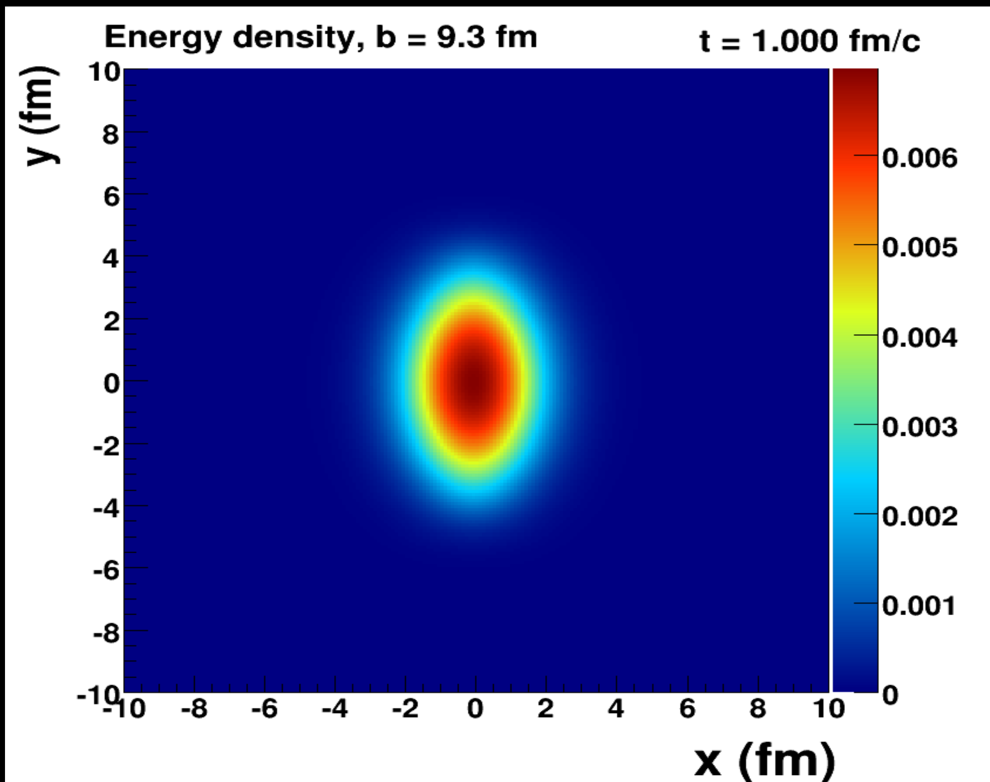
Also for transverse energy:
Approx. same centrality dependence at 7.7 GeV as at 2.76 TeV!

David Silvermyr

Take home messages

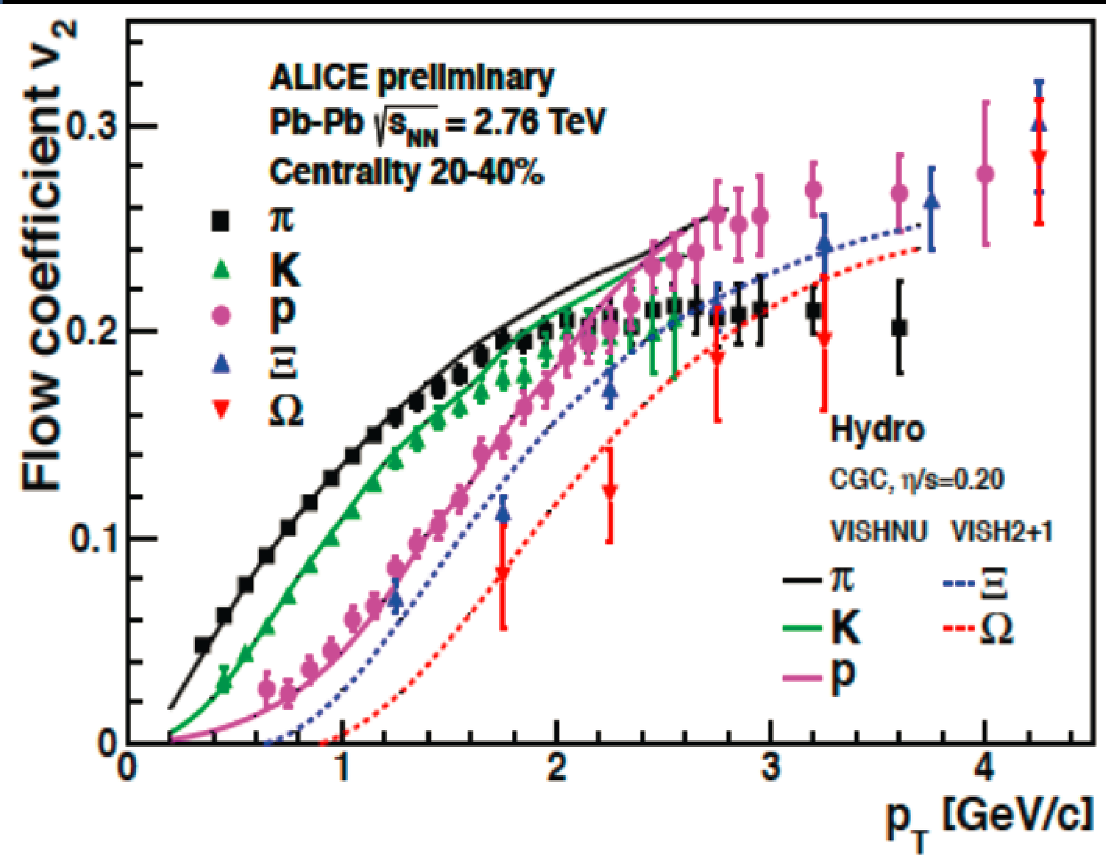
- Theory:
  - Fluctuations in initial state energy density are very important
- Experiment:
  - Energy densities reached at the LHC several times the critical energy density
  - Same dependence of particle multiplicity, transverse energy produced on system size independent of collision energy
- Outlook
  - Advances in calculations will allow us to distinguish between different proposed initial states

Flow

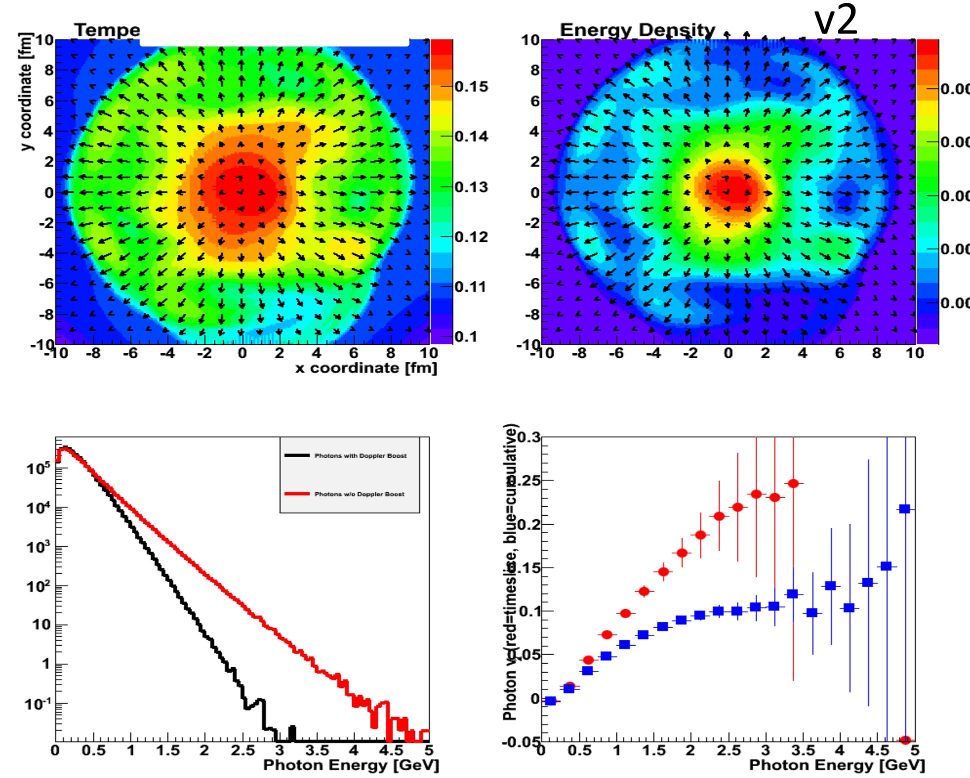


Huichao Song
Michael Strickland
ShinIchi Esumi
Monika Sharma
Ramiro Debbe

Perfect Fluid and Hydrodynamics



Temperature Profile + Velocity Vectors

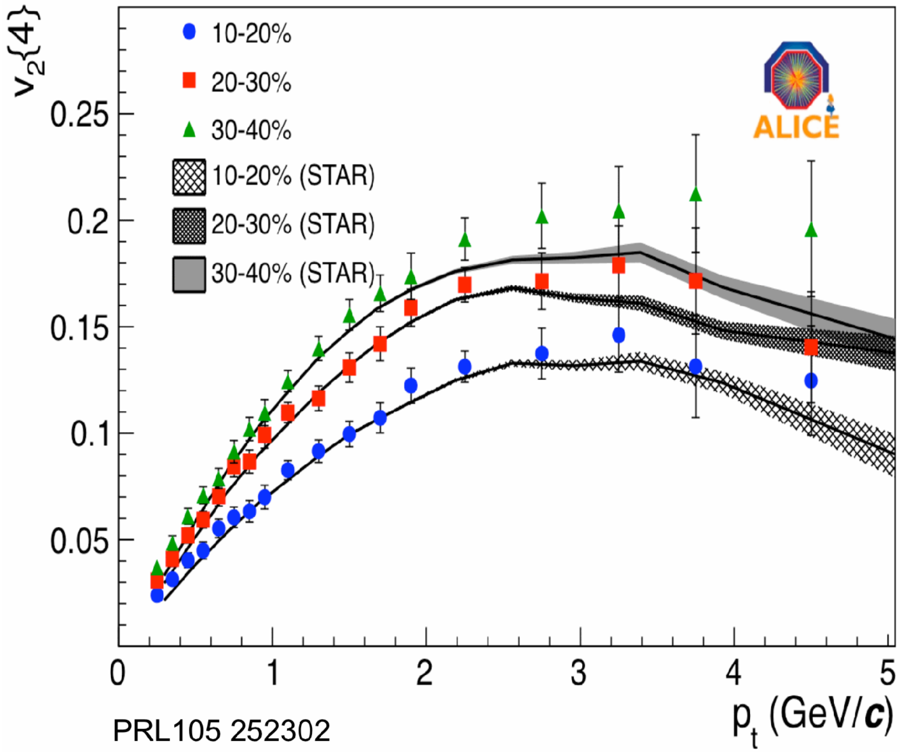


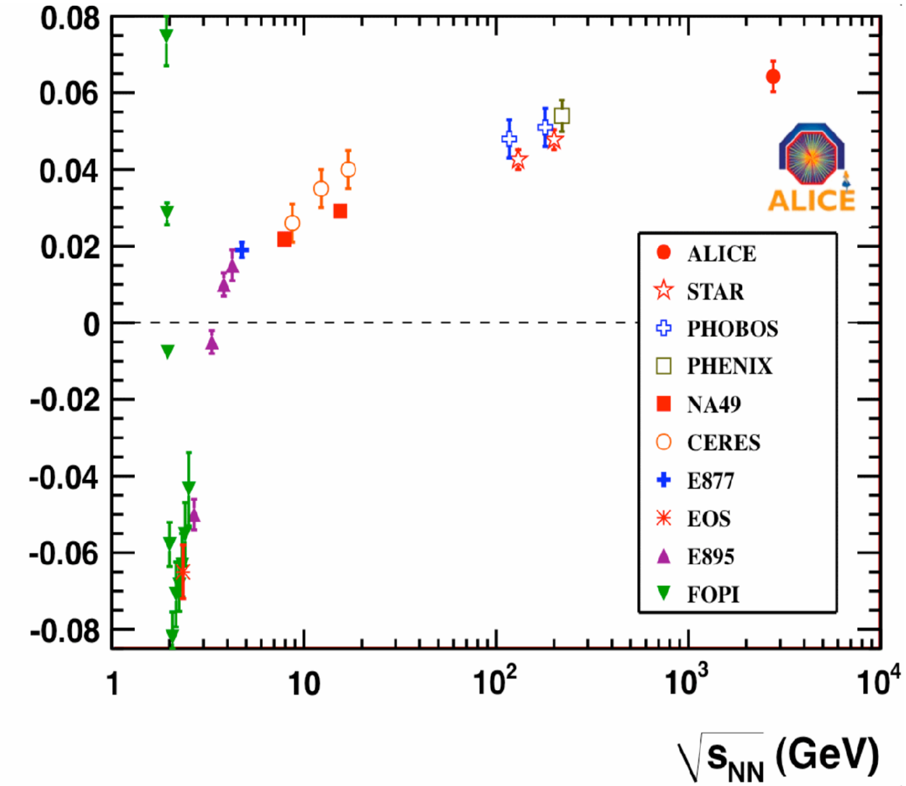
2005 – RHIC Discovery of QGP as nearly perfect fluid

2011 – LHC energy density increase more than **x2.6**
perfect fluidity persists

Jamie Nagle

$v_2(p_T)$, $\langle v_2 \rangle$ comparison between RHIC and LHC





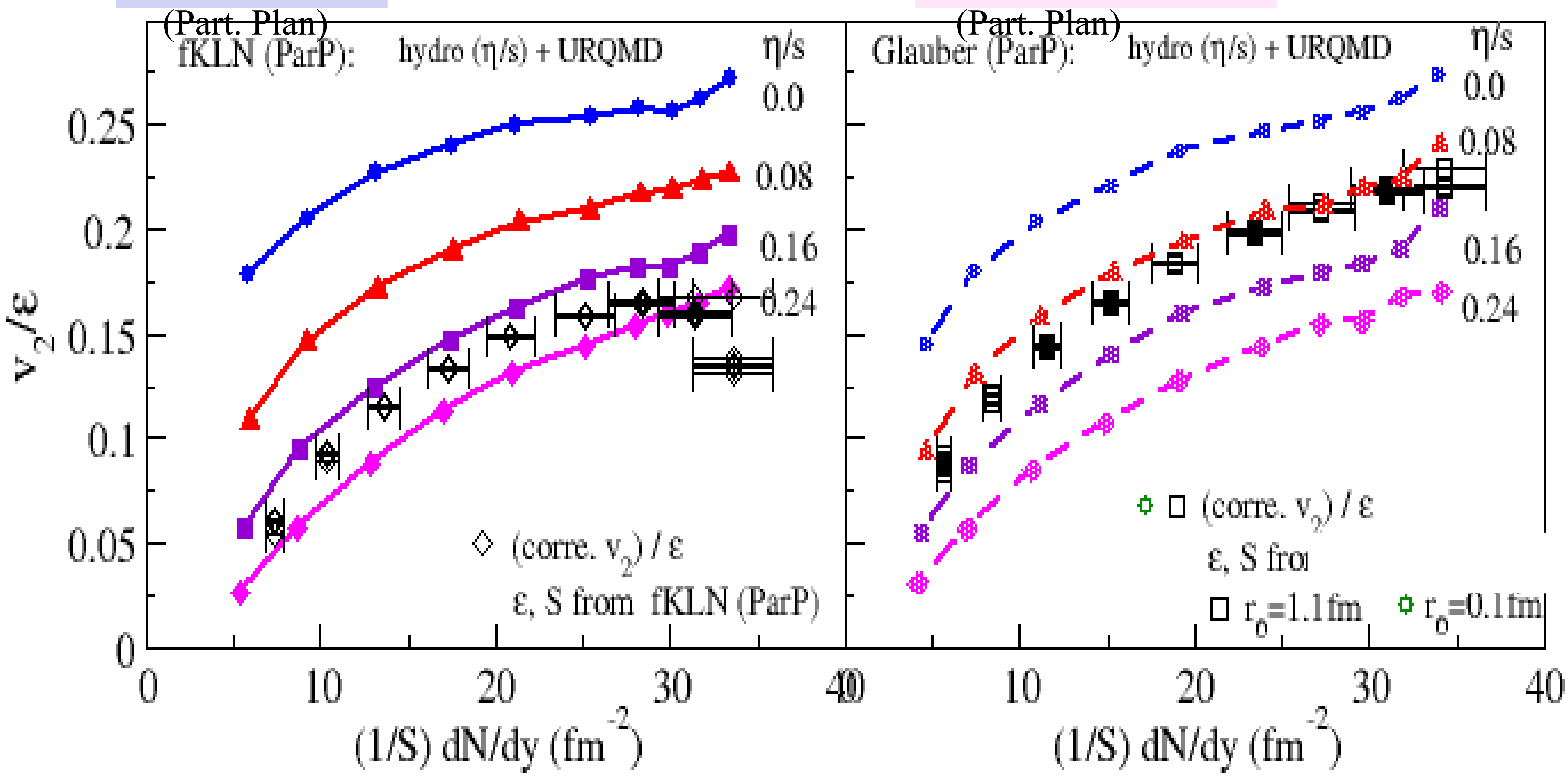
similar hydro properties

$\langle v_2 \rangle$ still increases with $\langle p_T \rangle$

ShinIchi Esumi

QGP viscosity from $v_2/\varepsilon - (1/S)dN/dy$

MC-**KLN** MC-**Glauber**



$$1\times(1/4\pi) \le \eta/s \le 3\times(1/4\pi)$$

$\eta/s = 0.16 - 0.24$ for MC-**KLN** initial conditions

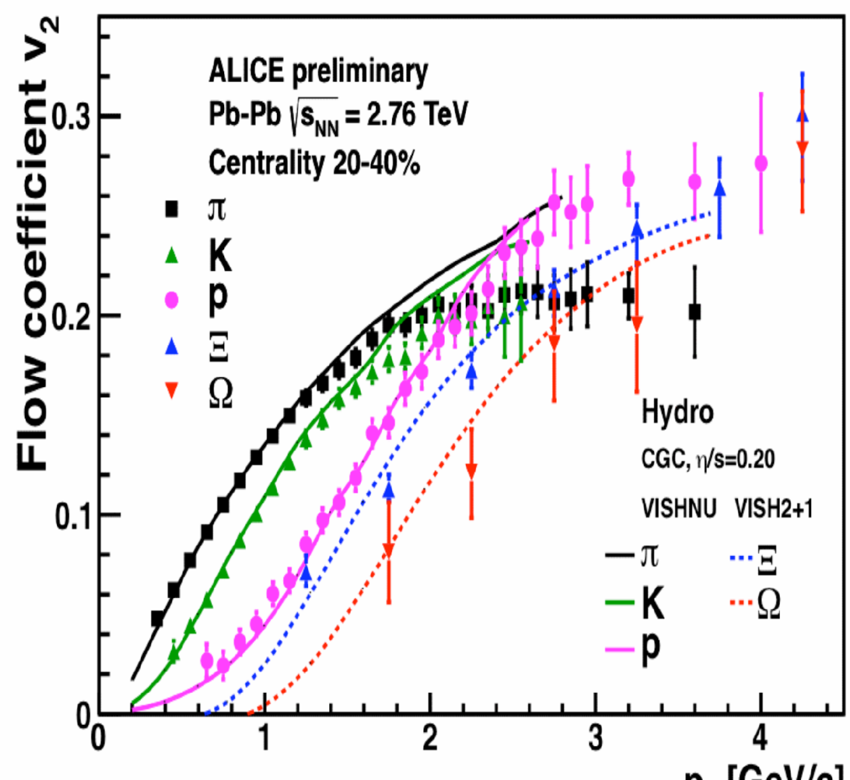
$\eta/s = 0.08 - 0.16$ for MC-**Glauber** initial conditions

H. Song, S. Bass, U. Heinz, T. Hirano, and C. Shen,

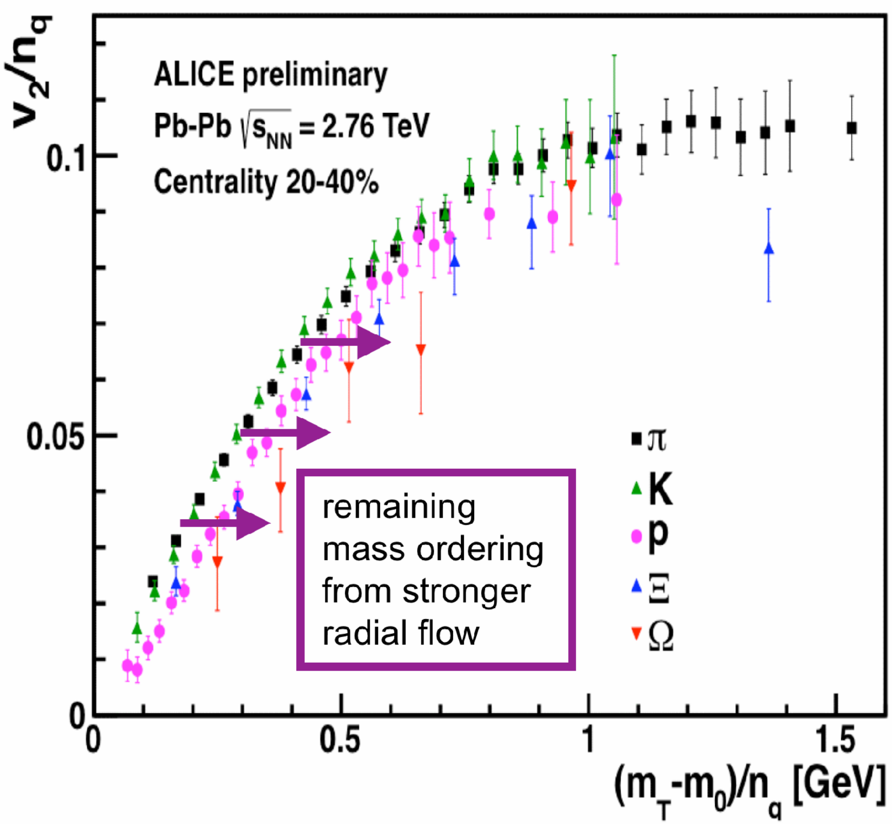
Huichao Song

Identified particle v_2 and $(m_T-m_0)/n_{quark}$ scaling

--- including strangeness/heavy baryons ---



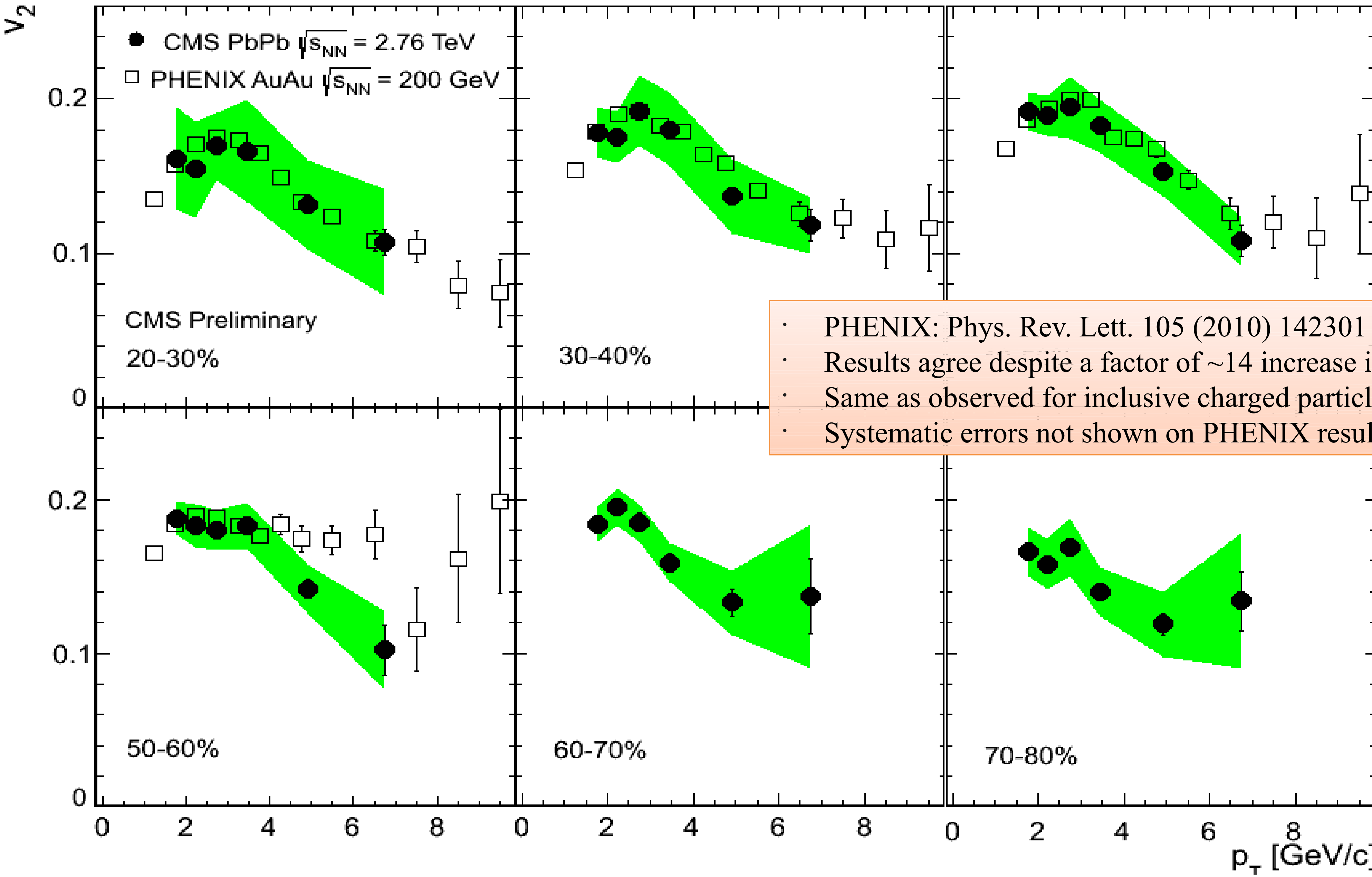
R. Snellings, QNP12



Scaling does not work
as good as at RHIC

ShinIchi Esumi

CMS π0 v2 results compared to PHENIX π0 v2

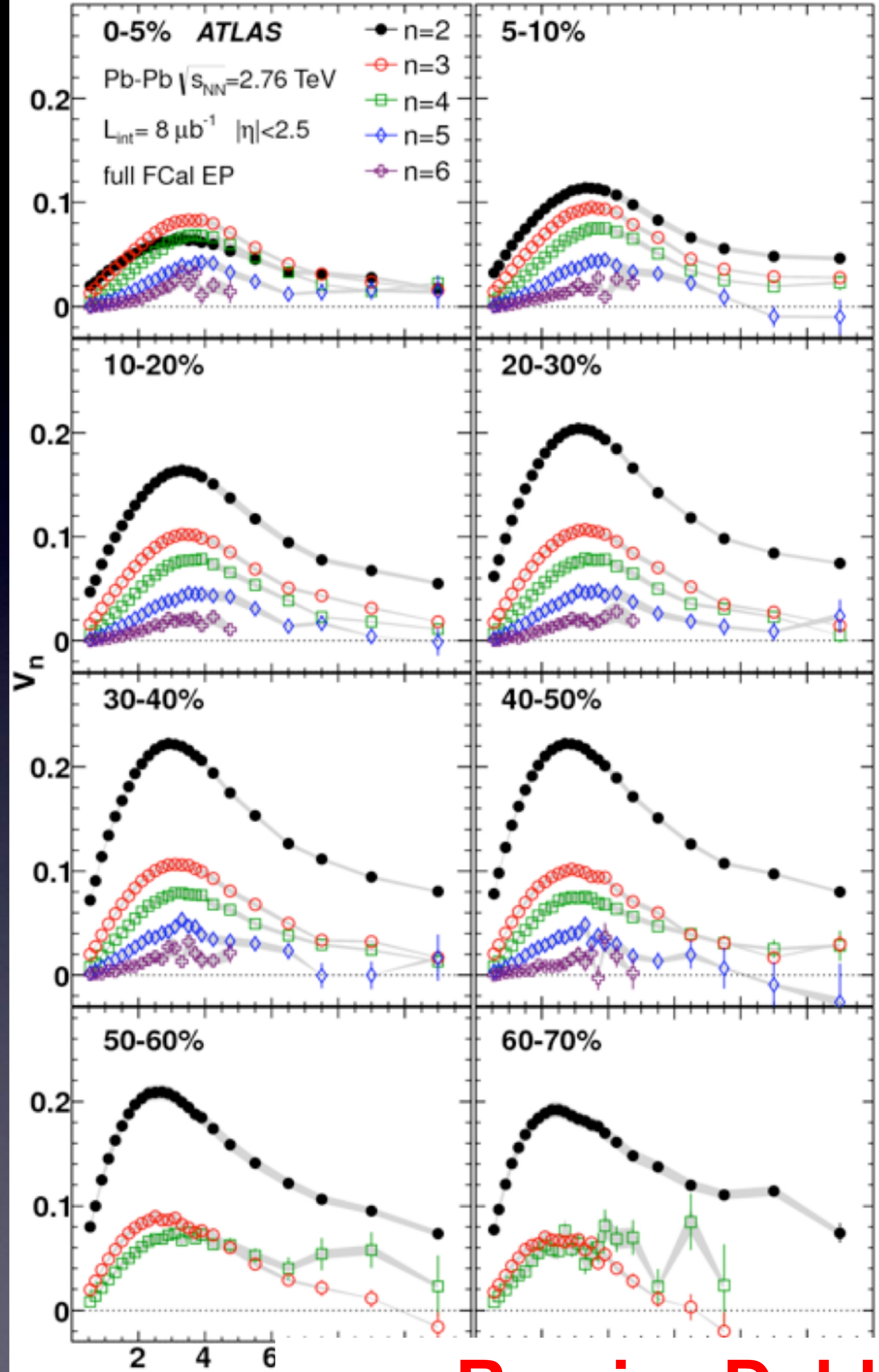


- PHENIX: Phys. Rev. Lett. 105 (2010) 142301
- Results agree despite a factor of ~14 increase in √s
- Same as observed for inclusive charged particles
- Systematic errors not shown on PHENIX results

Monika Sharma

All harmonics show the same behavior as when extracted from different bins of transverse momentum; They all increase in value to a maximum at ~3-4 GeV/c and then drop into a long tail at high p_T.

The ordering of the harmonics by magnitude is the same at all centralities except at the very central events.



Ramiro Debbe

A short summary

- v_2 is sensitive to η / s

Extraction η / s from elliptic flow data using viscous hydro + UrQMD indicates:

$$1\times(1/4\pi) \le \eta / s \le 3\times(1/4\pi)$$

Similar averaged QGP viscosity at RHIC and LHC energies

-Relatively larger uncertainties are from initial geometry

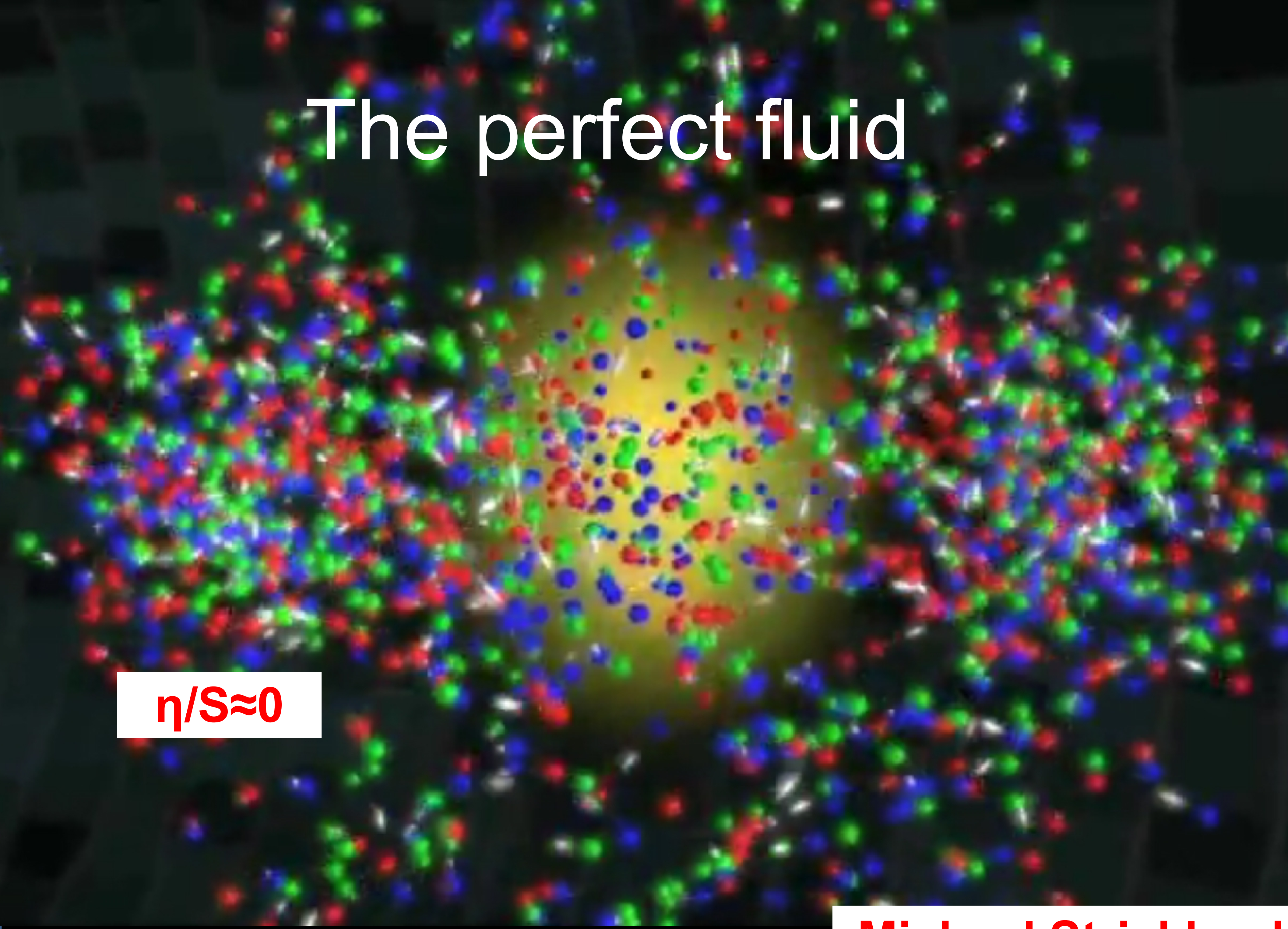
MC-Glauber: $\eta / s = (1-2)\times(1/4\pi)$ **MC-KLN:** $\eta / s = (2-3)\times(1/4\pi)$

-Relatively smaller uncertainties are from

initial flow, bulk viscosity, single short hydro vs. e-by-e simulations …

Huichao Song

The perfect fluid



The not-so-perfect fluid

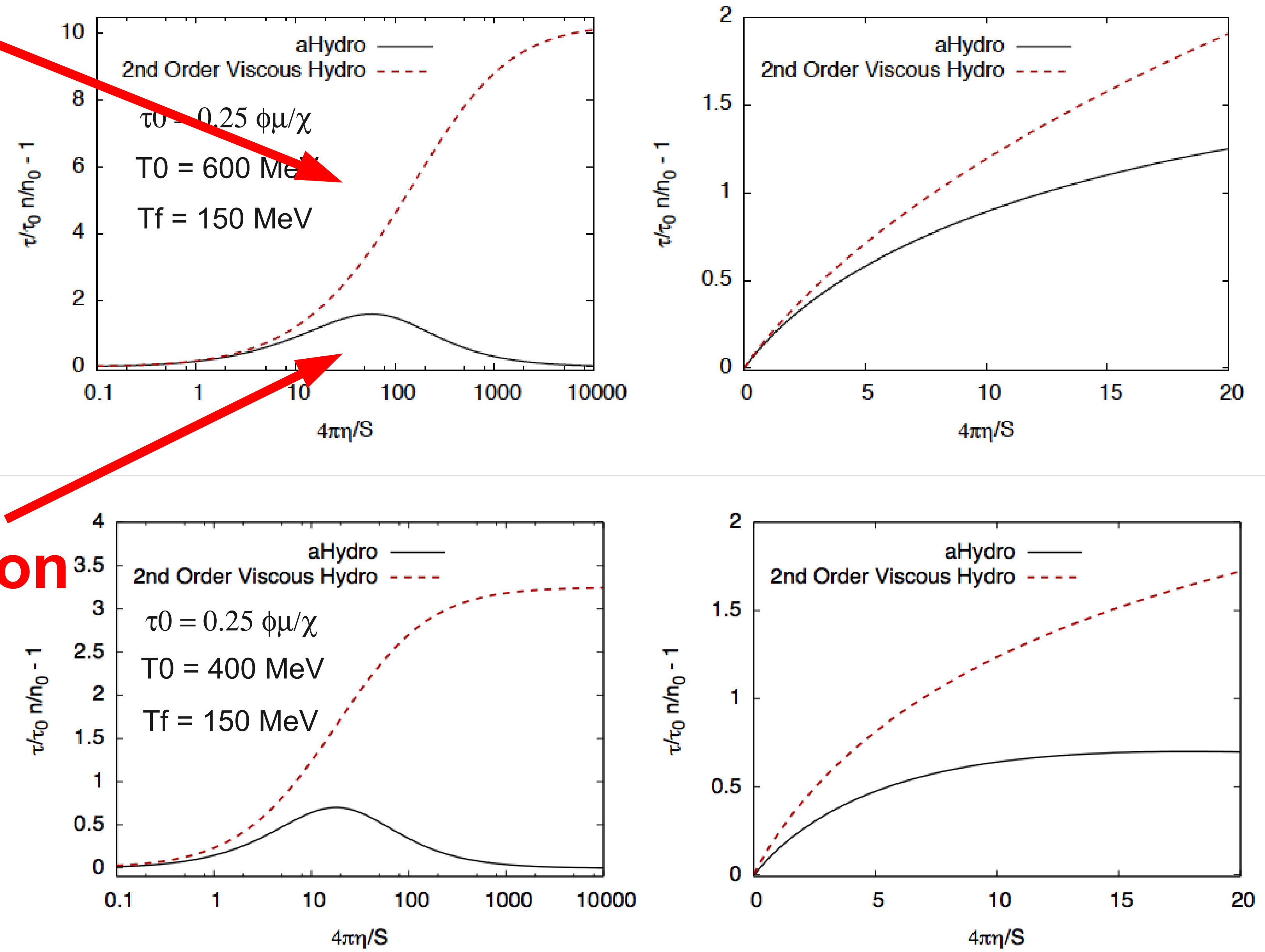
$\eta/S>>0$

Michael Strickland

Entropy Production

2nd order approximation

Exact solution

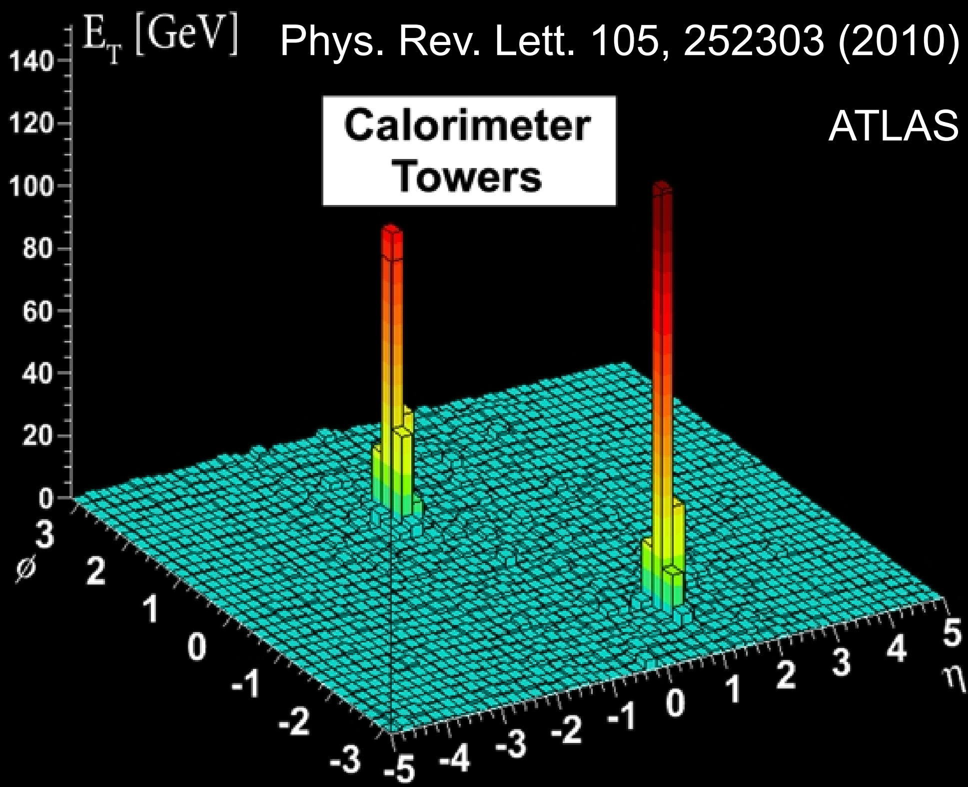


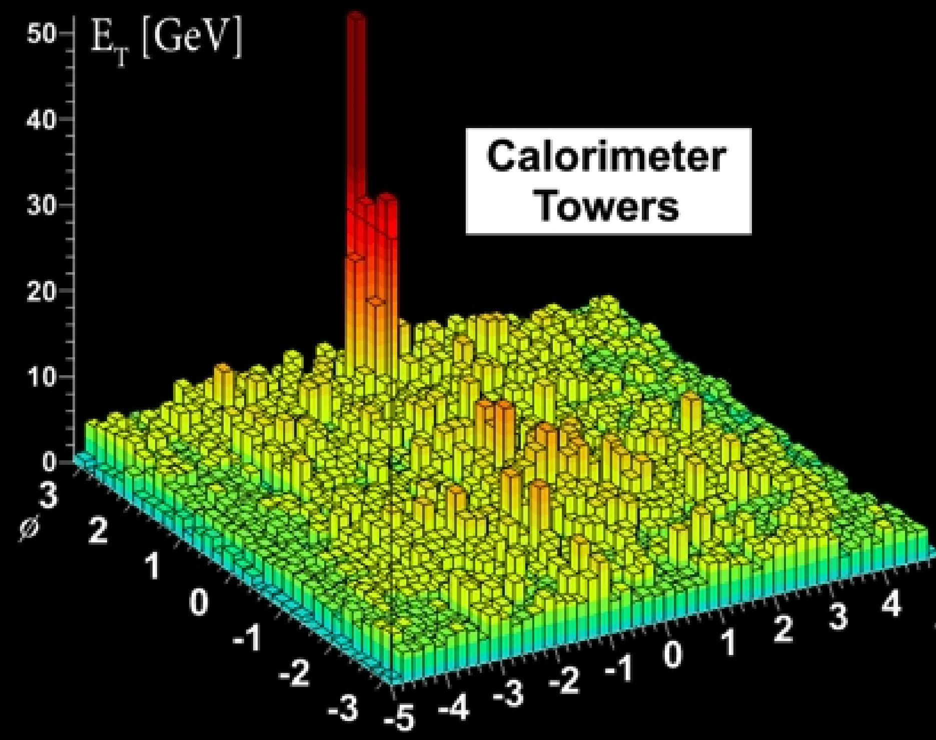
Michael Strickland

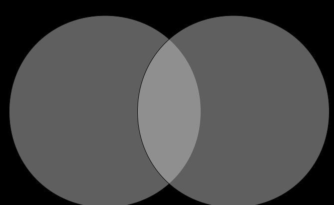
Take home messages

- Theory:
    - Hydrodynamical flow is a powerful tool to understand the properties of the medium (ie, η/S, T)...
    - ...provided we take all relevant effects into account
- Experiment:
    - Extensive experimental data over a wide range of momenta, particle type
- Outlook
    - Upcoming U+U, Cu+Au results from RHIC valuable for distinguishing models

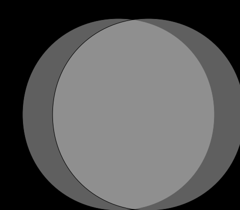
Jets and energy loss





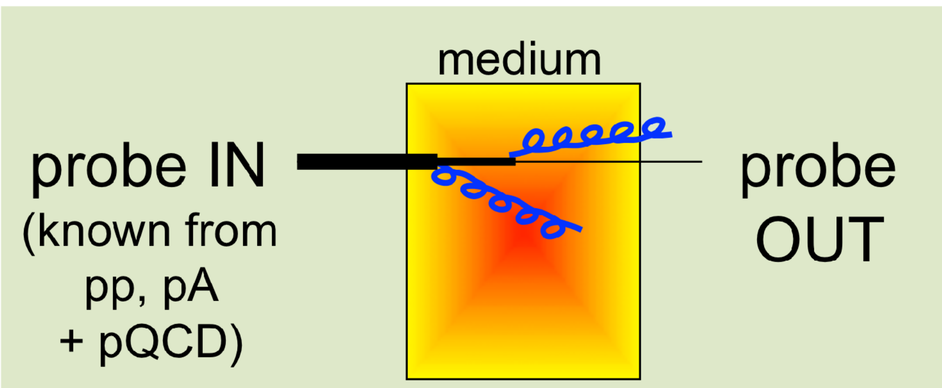


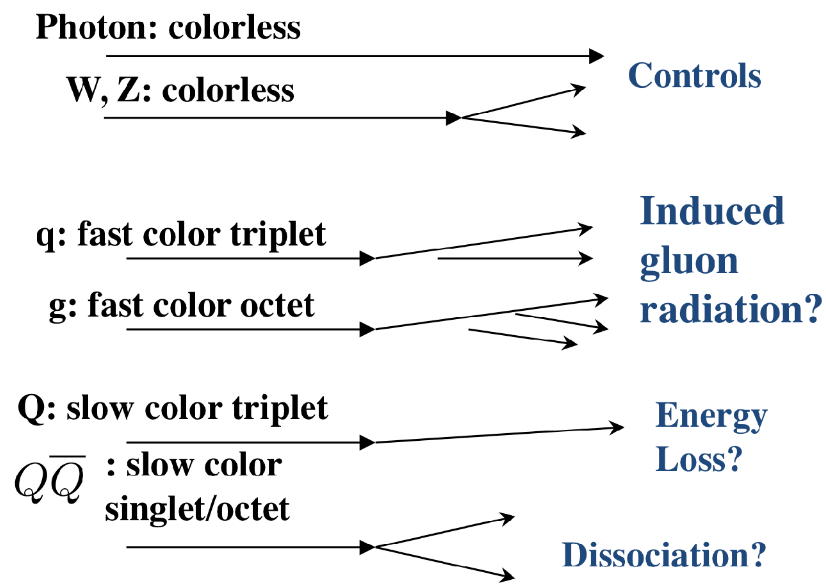
Guang-you Qin
Sevil Salur
Jinfeng Liao
Di-lun Yang
Ramiro Debbe



Ramiro Debbe

Tomographic probes





Diagnosing QCD medium: (simplified idea)
pass a QCD-sensitive probe through it, then look for any modifications due to the medium.

Unknown Medium

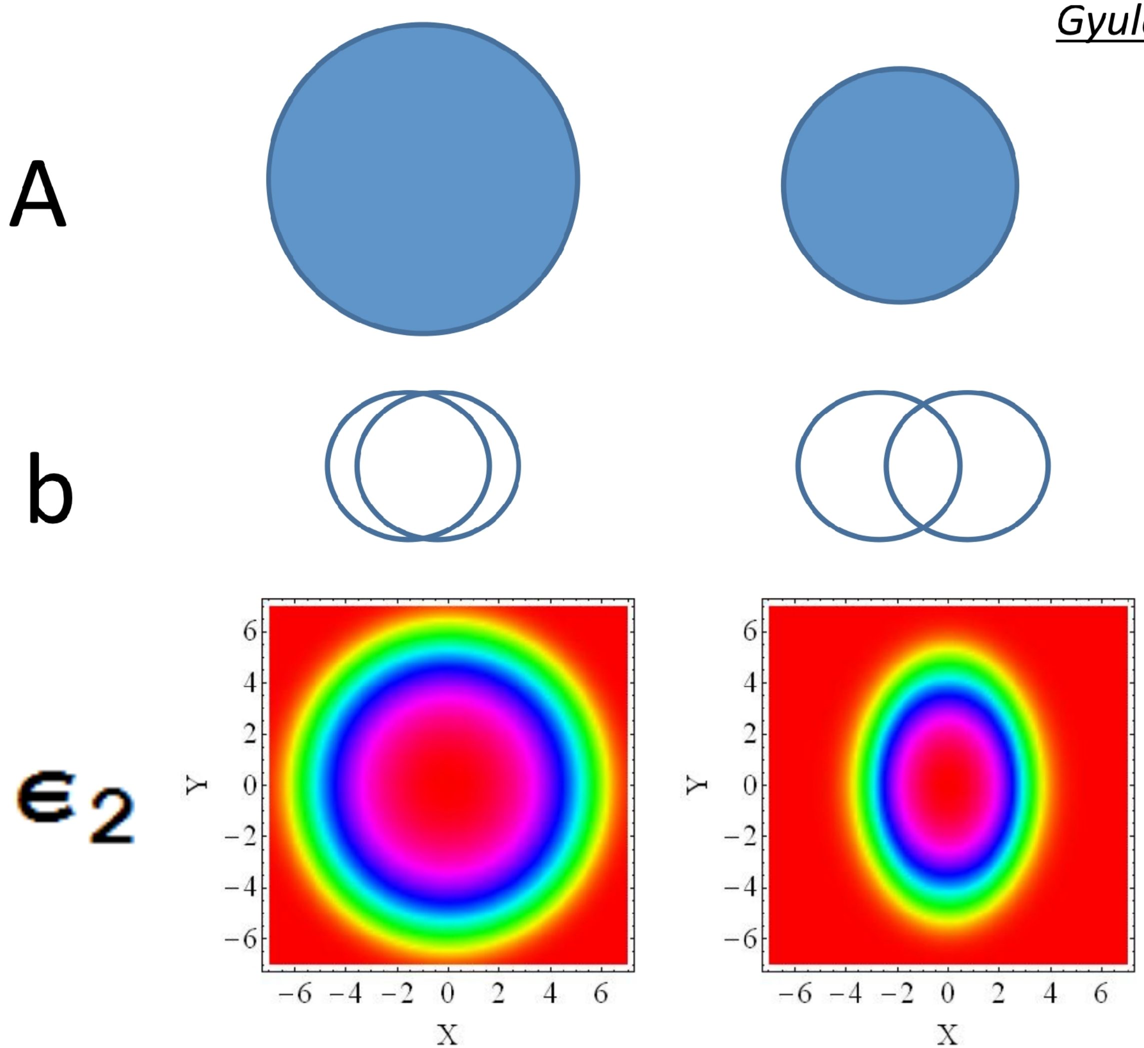
Hard Probes of QGP: Jets, W, Z , photons ...

Sevil Salur

Geometric Tomography

Geometry of nuclei and geometry of collisions play essential roles in jet quenching.

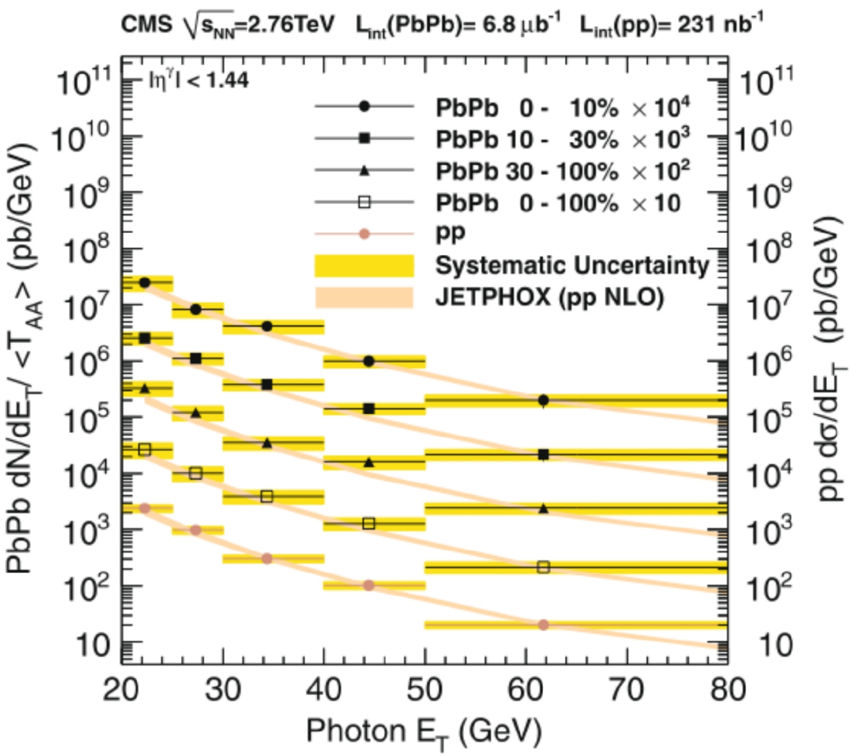
Gyulassy, Vitev, Wang; ……

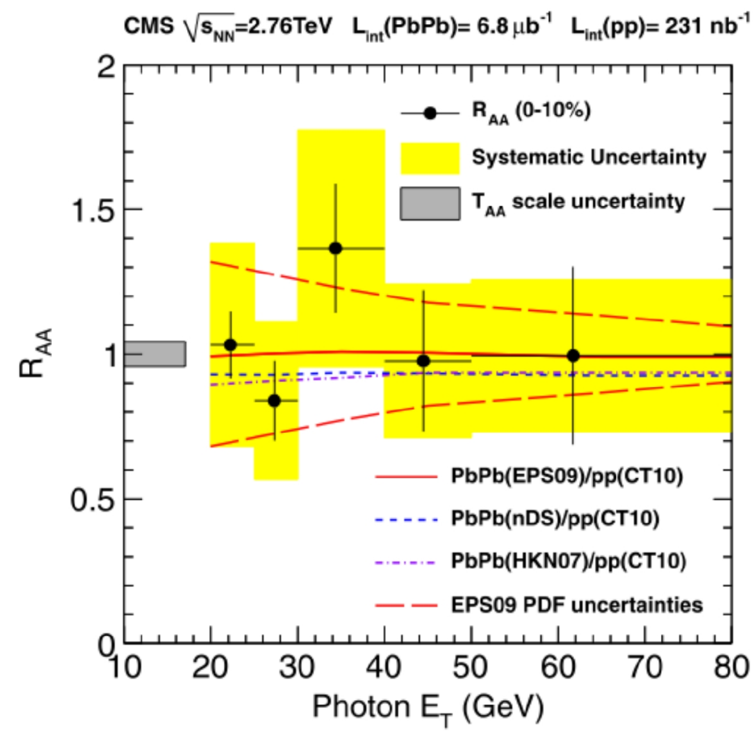


Same dynamics, different geometry → predictable change in exp. outcome with geometry!

Jinfeng Liao

Photons





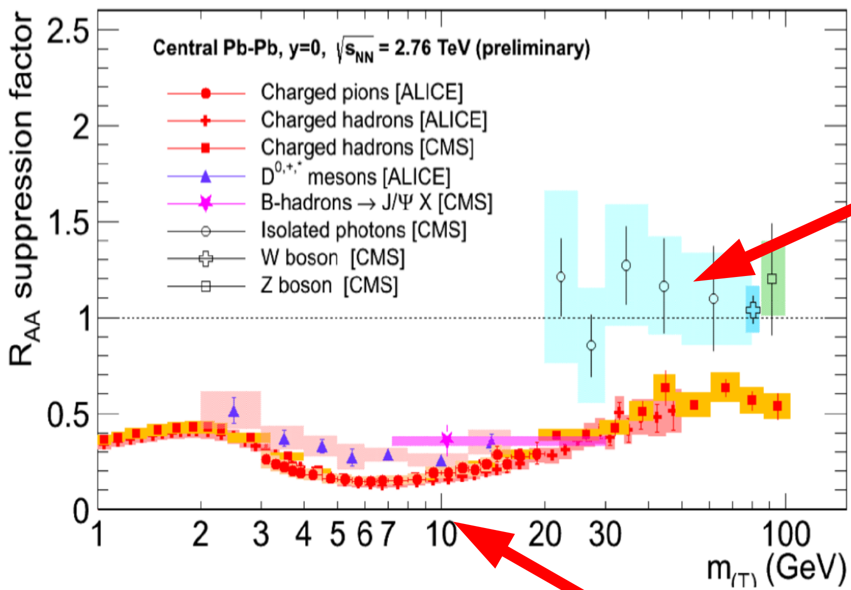
CMS, PLB 710 (2012) 256

Good agreement data – NLO for both pp & PbPb systems.

No modification of initial state:

Hard scattering processes scale with <Ncoll> calculated by Glauber model

Suppression in A+A



No suppression

- Pions are suppressed
- Electroweak probes (γ,W,Z) are unsuppressed
- B-mesons (secondary J/Ψ) are suppressed
- D-mesons (D0,±,*) are suppressed

Number of particles in A+A

Number of nucleon-nucleon collisions * Number of particles in p+p

CMS, EPJC 72 (2012) 1945
ALICE, PLB 696 (2011) 30
ATLAS-CONF-2011-079

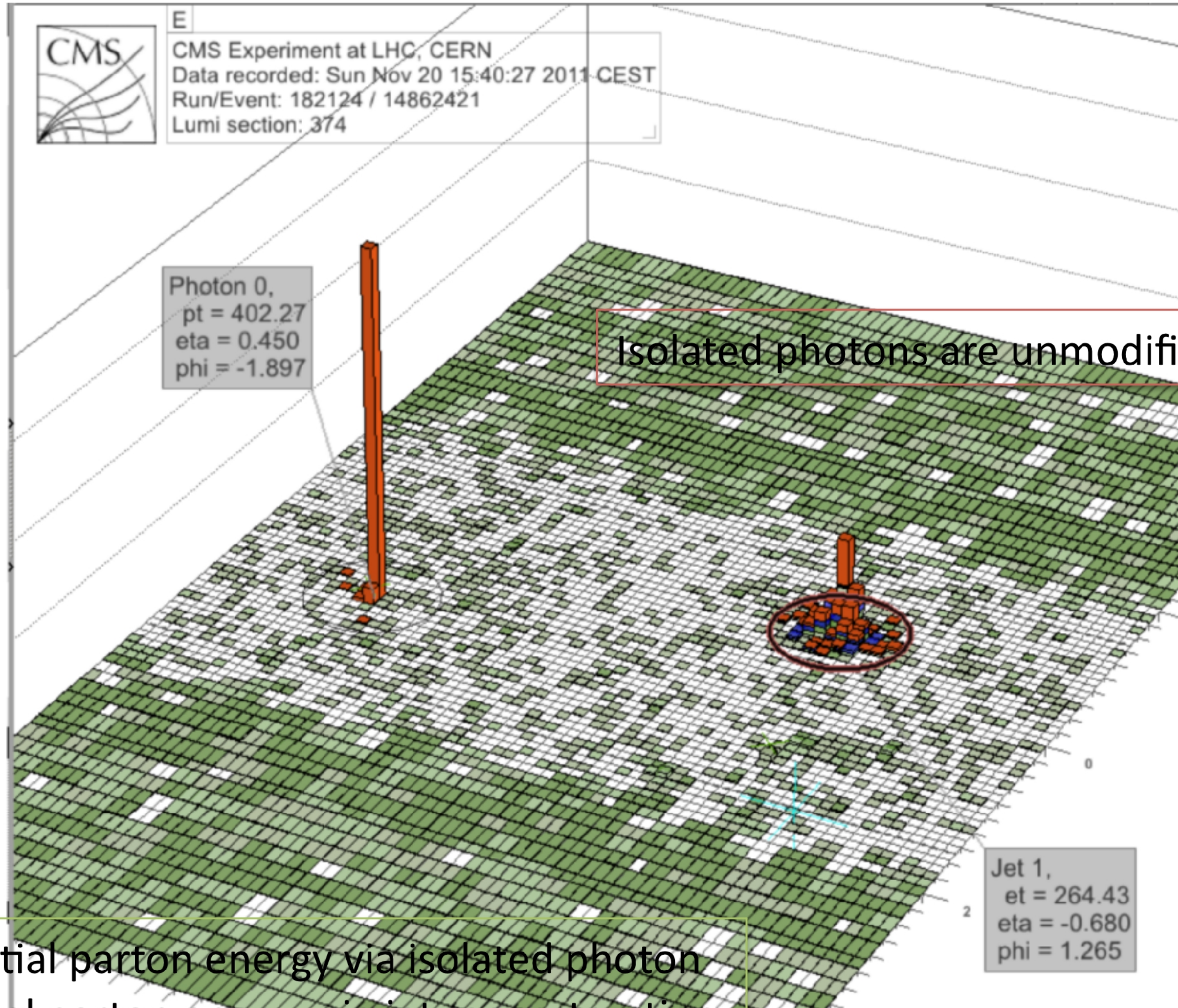
arXiv:1202.2554
Phys.Rev.Lett.106:212301,20
arXiv:1201.3093
arXiv:1201.5069

Suppression

LHC hadrons suppressed by up to factor of ~6 at pT~7 GeV.
Slow rise and plateau at RAA~ 0.5 in pT~40 – 100 GeV

Sevil Salur

Photon+Jet



Isolated photons are unmodified

Access to the initial parton energy via isolated photon
Access to the final parton energy via jet reconstruction

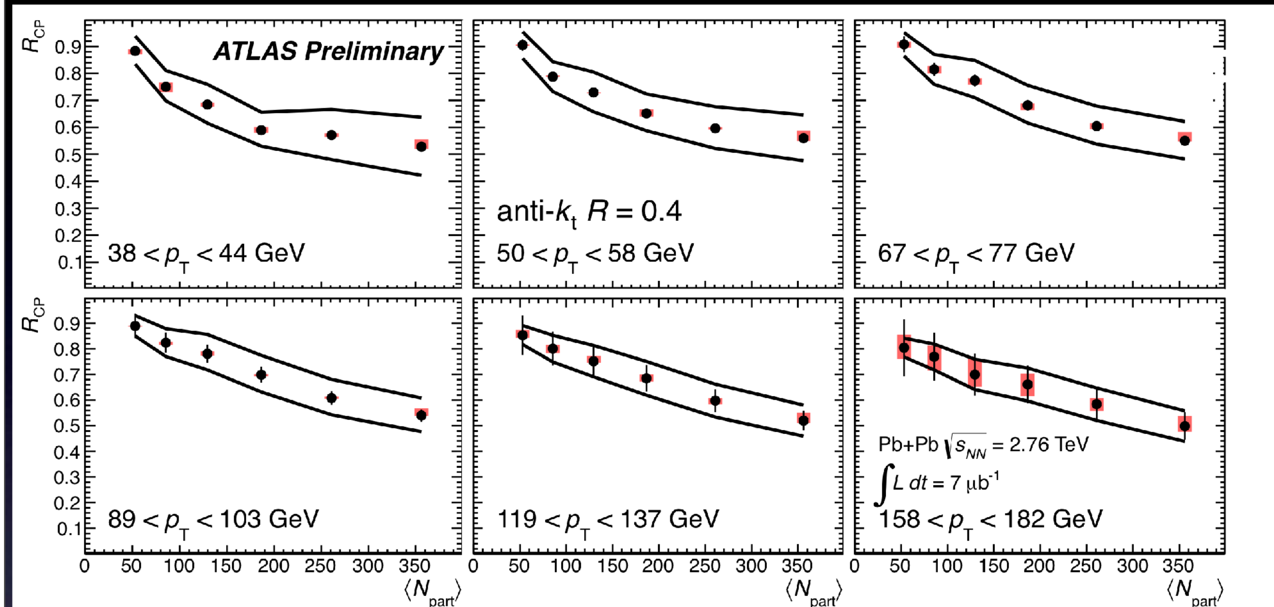
P. Stankus, Ann. Rev. Nucl. Part. Sci. 55, 517 (2005)
X. Wang, Z. Huang, Phys.Rev.C55:3047-3061 (1997)

Photons pass through the medium without interacting so their energy “tags” the original energy of the jet: **Direct measurement of the parton energy loss!**

Sevil Salur

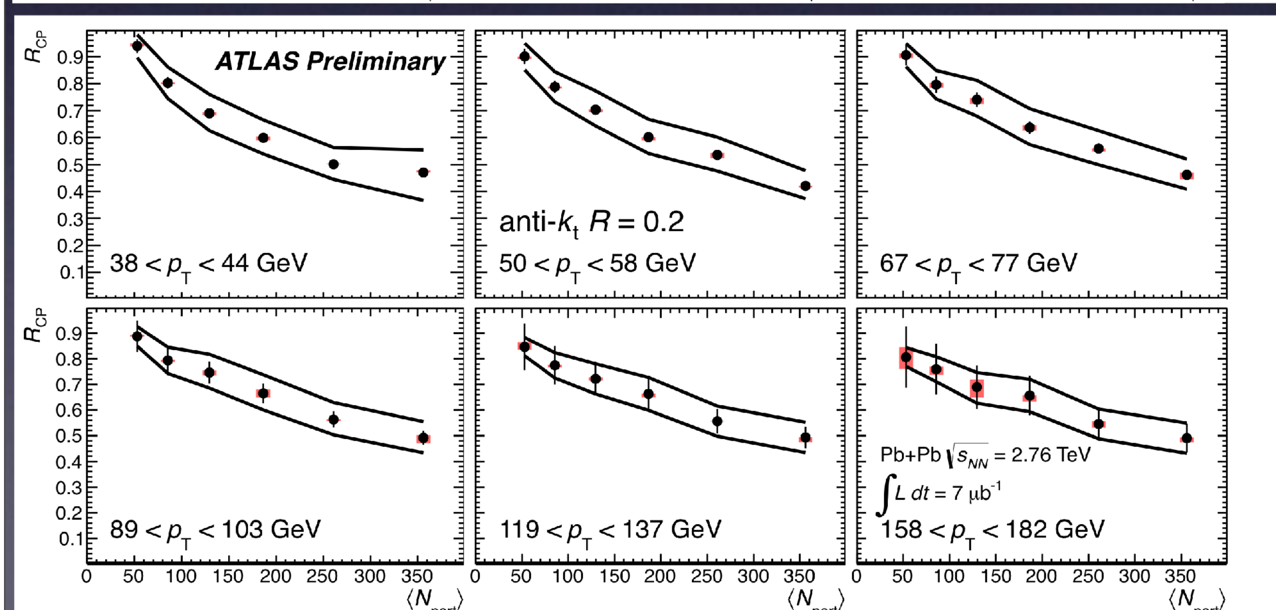
Jet yields from different centrality events are compared using the ratio:

$$R_{CP} = \frac{1/N_{coll}^{cent}}{1/N_{coll}^{periph}} \frac{1/N_{evnt}^{cent}\, dN/dE_T}{1/N_{evnt}^{periph}\, dN/dE_T}$$



=0.4

A factor of 2 suppression is found between central and peripheral events. No cone size R dependence.



Systematic Error:
Bands: Correlated JES, effic., shape, R_{coll}
Red Boxes: part. correl. unfolding regularization, JER.
Error bars: sqrt of diagonal of covariant matrix.
Horizontal width, N_{part} uncertainty

R=0.2

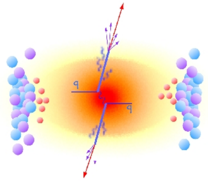
Ramiro Debbe

Take home messages

- Theory:
  - Electromagnetic probes described by pQCD. Strong probes require energy loss.
- Experiment:
  - Data in the LHC era allow quantitative determination of energy loss in the medium
- Outlook
  - Many more detailed measurements of jets

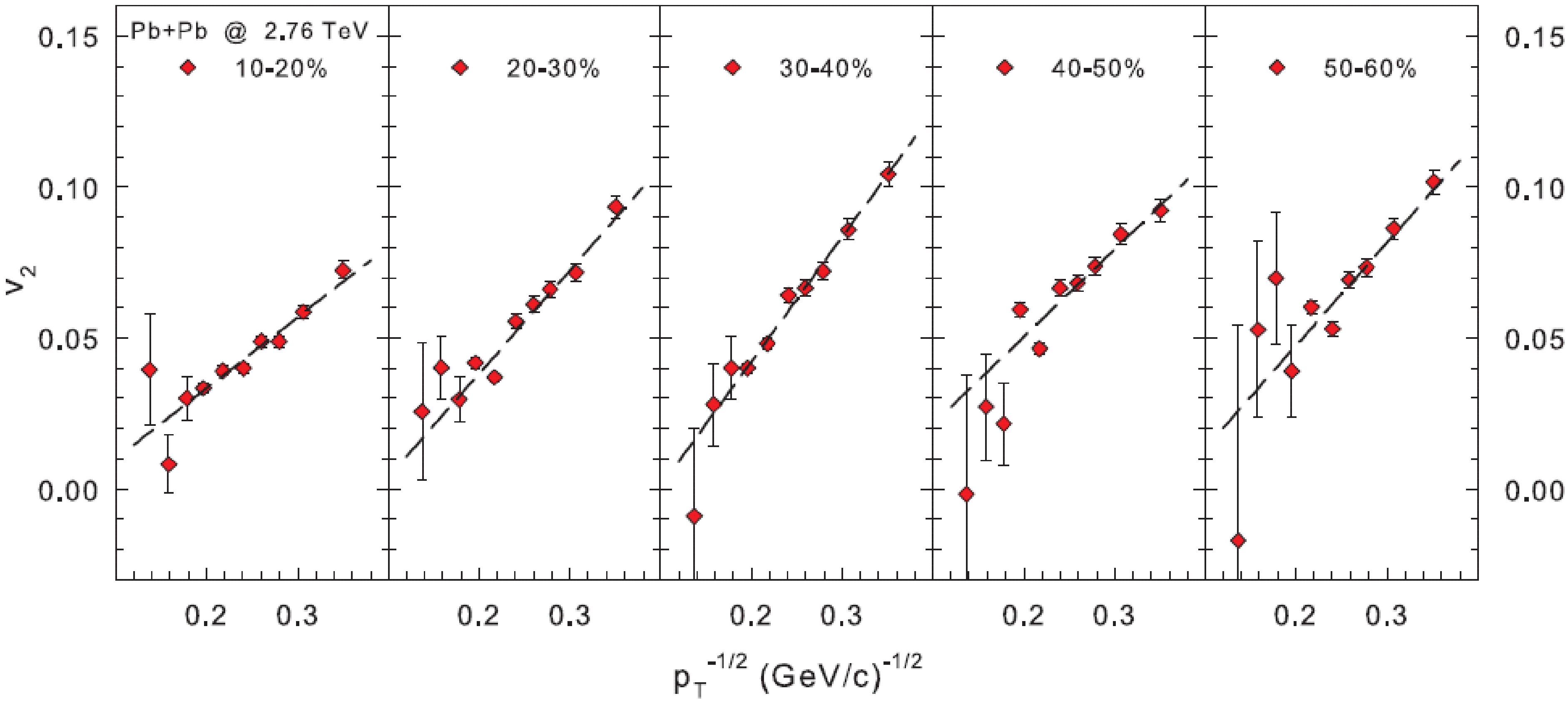
Provocative ideas

Scaling of high-pT v2



$$R^{l}_{\mathrm{AA}}(p_T, L) \simeq \exp\left[-\frac{2\alpha_s C_F}{\sqrt{\pi}}\, L \sqrt{\hat{q}\frac{\mathcal{L}_l}{p_T}}\right]$$

arXiv:1203.3605

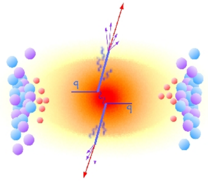


v2 follows the pT dependence observed for jet quenching

Note the expected inversion of the 1/√pT dependence

Roy Lacey

Scaling of high-pT v2



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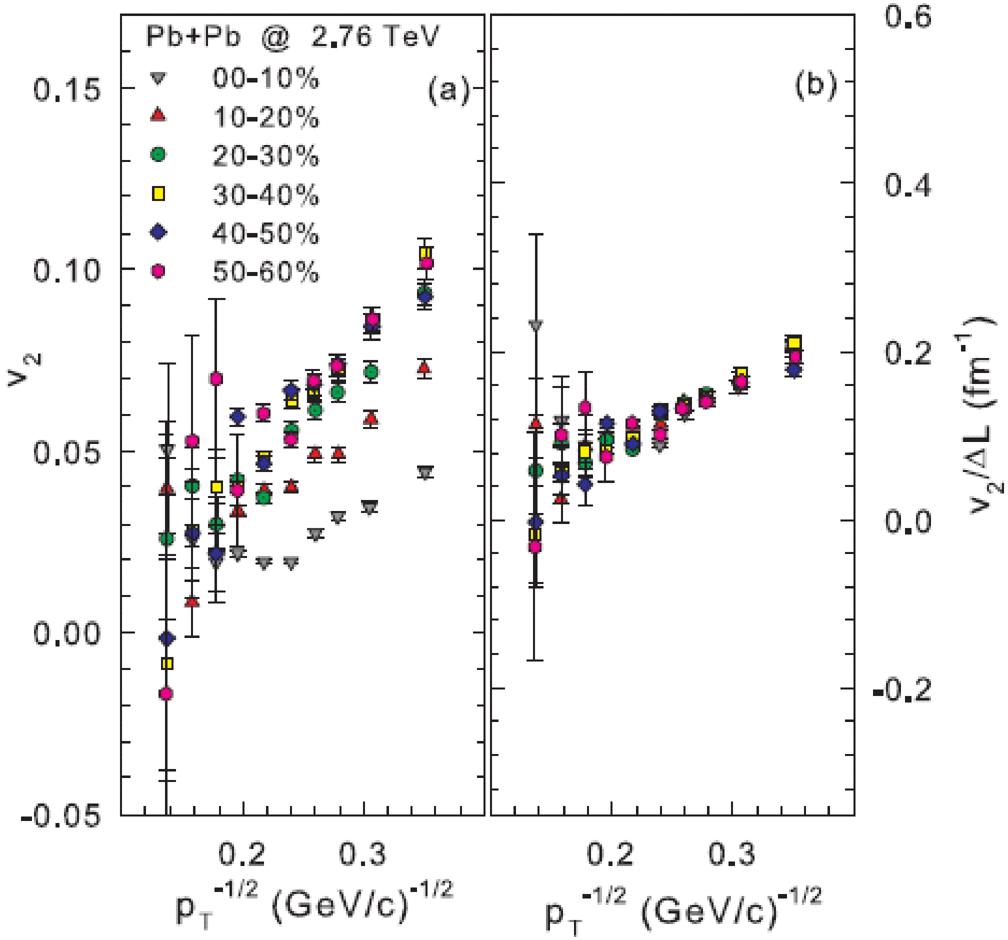
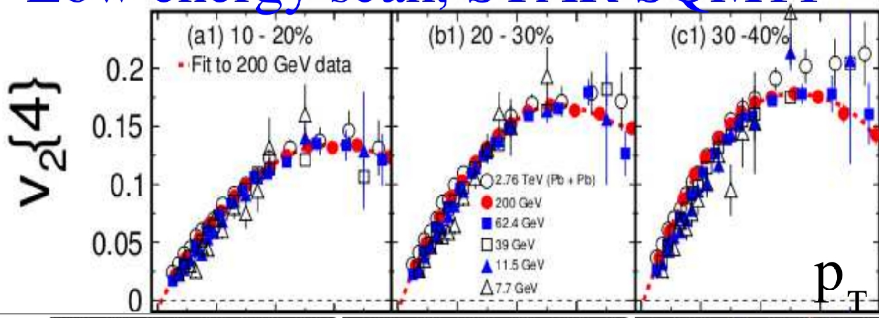
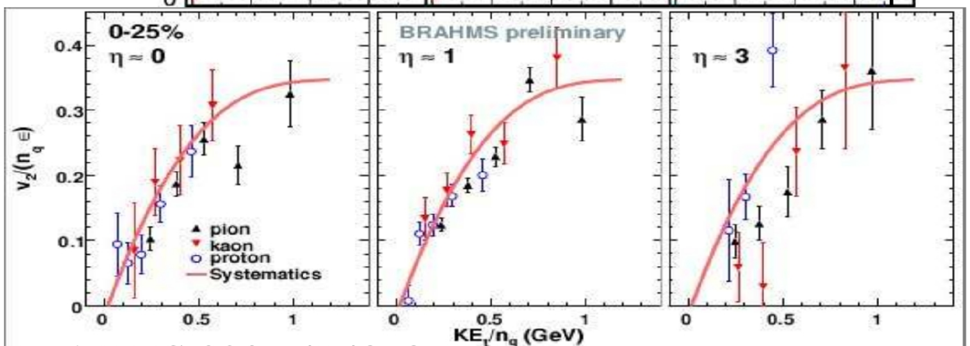


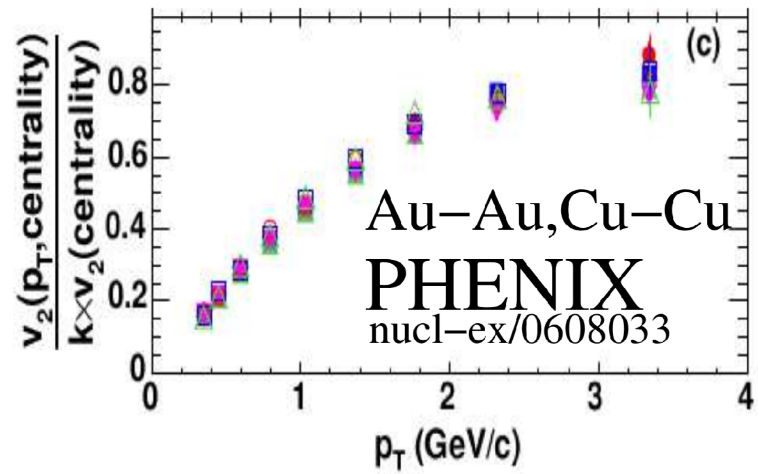
Combined ΔL and 1/√pT scaling single universal curve for v2

Low energy scan, STAR SQM11





BRAHMS,0907.4742v2



Puzzle2: Why is $v_2(p_T)$ constant?

NB: this means $v_2(p_T)/\langle v_2\rangle$ independent of $N_{part}, y, \sqrt{s}$

Giorgio Torrieri

Take home questions

- What causes these empirical scalings?
- Are we measuring the right things?

Summary

- Quantifying the properties of the QGP
- Better understanding of the initial state
- Unprecedented amount of data from RHIC & the LHC to constrain theories
- More to come from data at RHIC & the LHC

Thank you!

Co-convener: Will Horowitz
Plenary speaker: Jamie Nagle
Parallel speakers:

Dan Cebra
Misha Stephanov
Swagato Mukherjee
Rajan Gupta
Grzegorz Stefanek
Bjoern Schenke
David Silvermyr
Magdelena Malek
Sooraj Radhakrishnan
Huichao Song
Michael Strickland
ShinIchi Esumi
Monika Sharma
Ramiro Debbe
Guang-you Qin
Sevil Salur
Jinfeng Liao
Di-lun Yang
Ramiro Debbe
Roy Lacey
Scott Pratt
Paul Stankus
Giorgio Torrieri