PARTICLE PRODUCTION AND FINAL STATE EFFECTS IN NUCLEAR COLLISIONS

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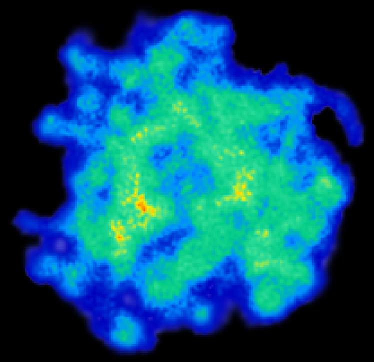
THE 30TH WINTER WORKSHOP ON NUCLEAR DYNAMICS
APRIL 9 2014

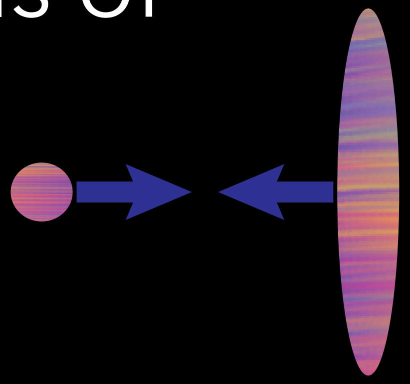
BROOKHAVEN NATIONAL LABORATORY

INTRODUCTION

- Heavy Ion Collisions:
  Initial state fluctuations and collective flow can describe lots of experimental data



- Details of the fluctuations are important
- How to distinguish between different models of multi-particle production



- Are the physics the same in small systems?

COMPUTING THE INITIAL STATE

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Gluon saturation at $p_T \lesssim Q_s(x, \mathbf{b})$
- Strong fields with occupation $\sim 1/\alpha_s$
  Classical description possible
- IP-Sat model parametrizes $Q_s(x, \mathbf{b})$
  (simple way to include impact parameter dependence)
  KOWALSKI, TEANEY, PHYS.REV. D68 (2003) 114005
- Fit parameters to HERA diffractive data

COMPUTING THE INITIAL STATE

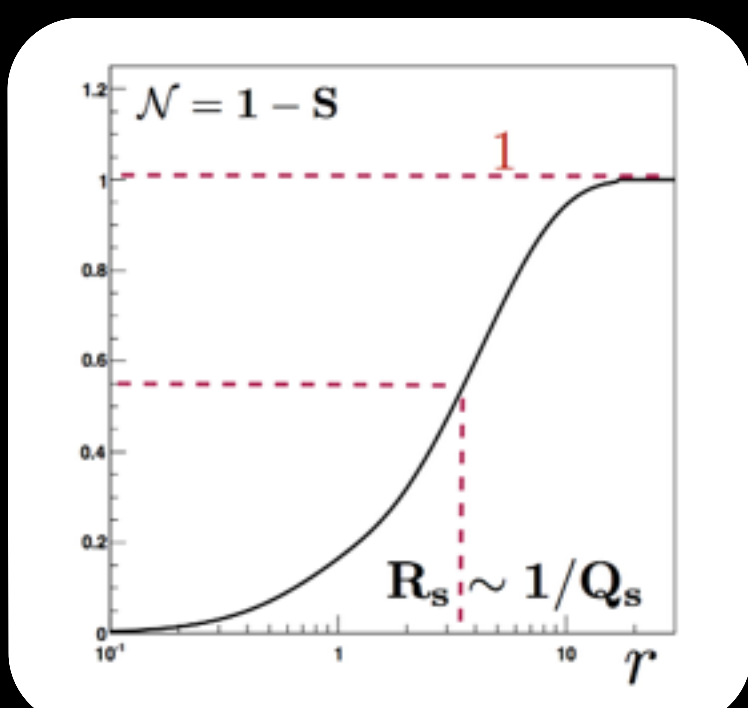
B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

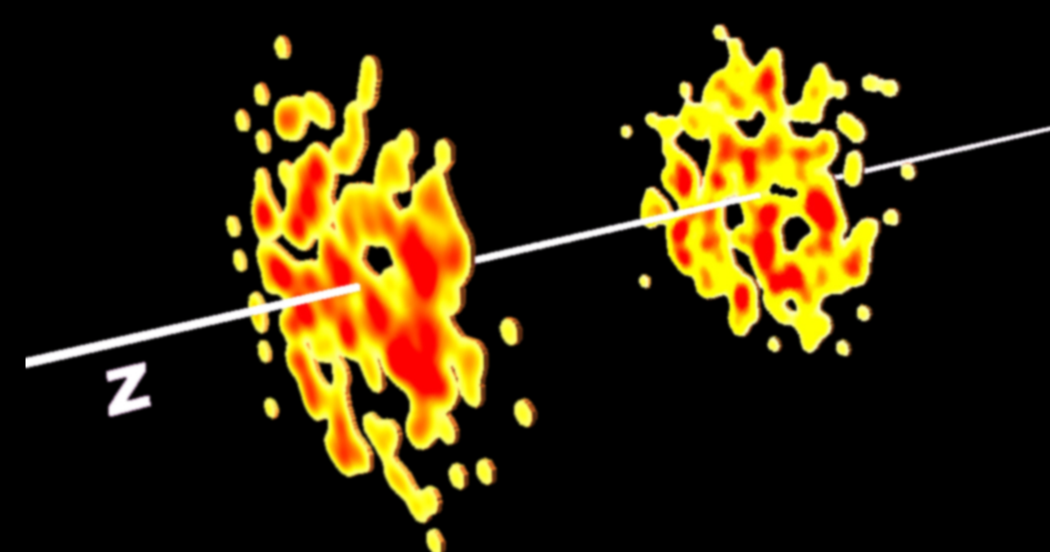
- Sample nucleon positions from Woods-Saxon distribution

- Add all (Gaussian) thickness functions

$$\frac{\mathrm{d}\sigma^{\mathrm{p}}_{\mathrm{dip}}}{\mathrm{d}^2\mathbf{x}_T}(\mathbf{r}_T, x, \mathbf{x}_T) = 2\,\mathcal{N}(\mathbf{r}_T, x, \mathbf{x}_T) = 2\left[1 - \exp\left(-\frac{\pi^2}{2N_c}\mathbf{r}_T^2\alpha_s(Q^2)xg(x,Q^2)\sum_{i=1}^{A} T_p(\mathbf{x}_T - \mathbf{x}_T^i)\right)\right]$$

- Extract $Q_s(x, \mathbf{x}_T)$ and get color charge density distribution





COMPUTING THE INITIAL STATE

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Sample color charge density $\rho^{A/B}(\mathbf{x}_T)$
- For nucleus A and B compute the path-ordered exponential over its longitudinal extend

$$V_{A/B}(\mathbf{x}_T) = \prod_{k=1}^{N_y} \exp\left(-ig\frac{\rho_k^{A/B}(\mathbf{x}_T)}{\nabla_T^2 + m^2}\right)$$

- m is an infrared cutoff of order Λ_{QCD}
- Wilson lines after the collision are then obtained from V_A and V_B via the Yang-Mills equations

COMPUTING THE INITIAL STATE

B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL108, 252301 (2012), PRC86, 034908 (2012)

- Yang-Mills equations determine:
  KRASNITZ, VENUGOPALAN, NUCL.PHYS. B557 (1999) 237
  - Initial gluon fields from color charges
  - Energy density after the collision
  - Early non-equilibrium time evolution

INITIAL STATE AND FLUID DYNAMICS

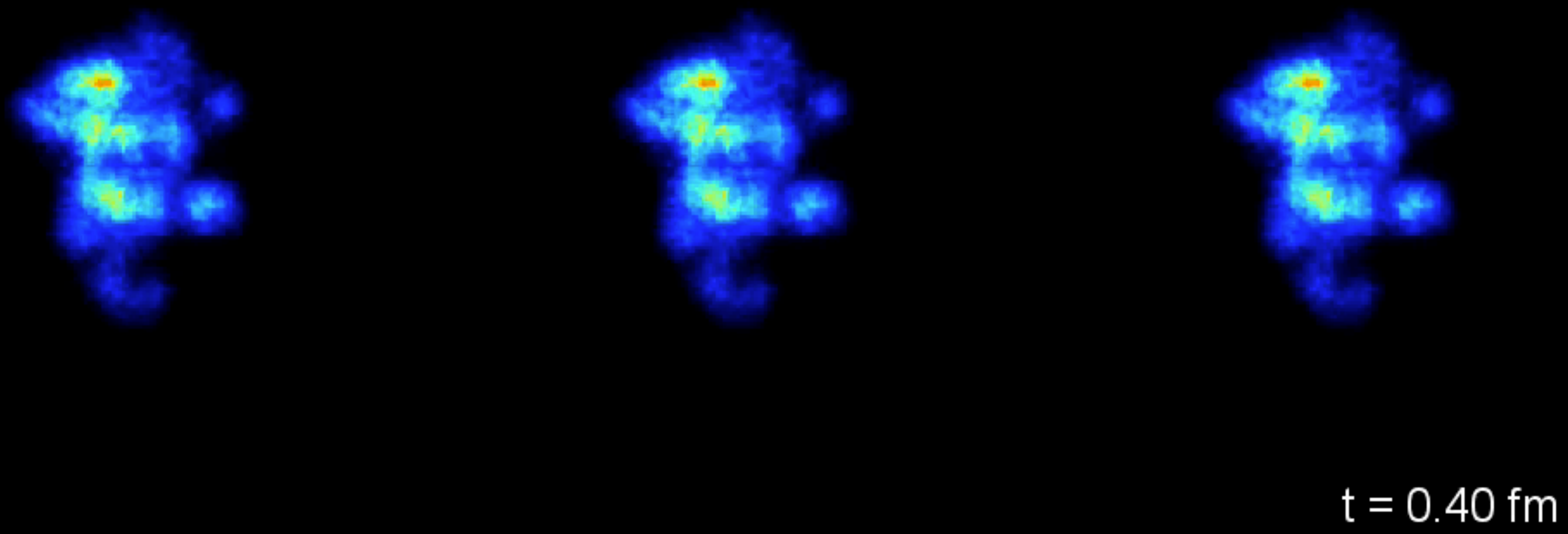
C.GALE, S.JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PHYS.REV.LETT. 110, 012302 (2013)

- Compute energy-momentum tensor $T^{\mu\nu}$ of the classical fields
- Extract energy density and flow vector via $u_\mu T^{\mu\nu} = \varepsilon u^\nu$
- This provides the initial conditions for fluid dynamic simulations
- At the moment set initial $\Pi^{\mu\nu} = 0$

INITIAL STATE AND FLUID DYNAMICS

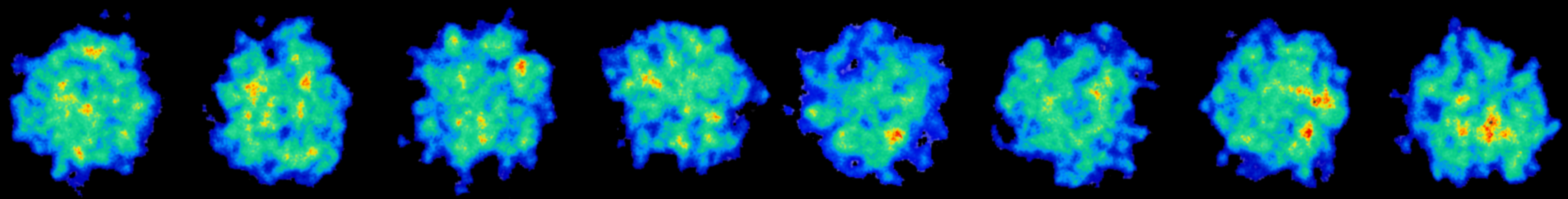
C.GALE, S.JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PHYS.REV.LETT. 110, 012302 (2013)

$\eta/s = 0$ $\eta/s = 0.1$ $\eta/s = 0.2$



EVENT-BY-EVENT FLUID DYNAMICS

C.GALE, S.JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PHYS.REV.LETT. 110, 012302 (2013)

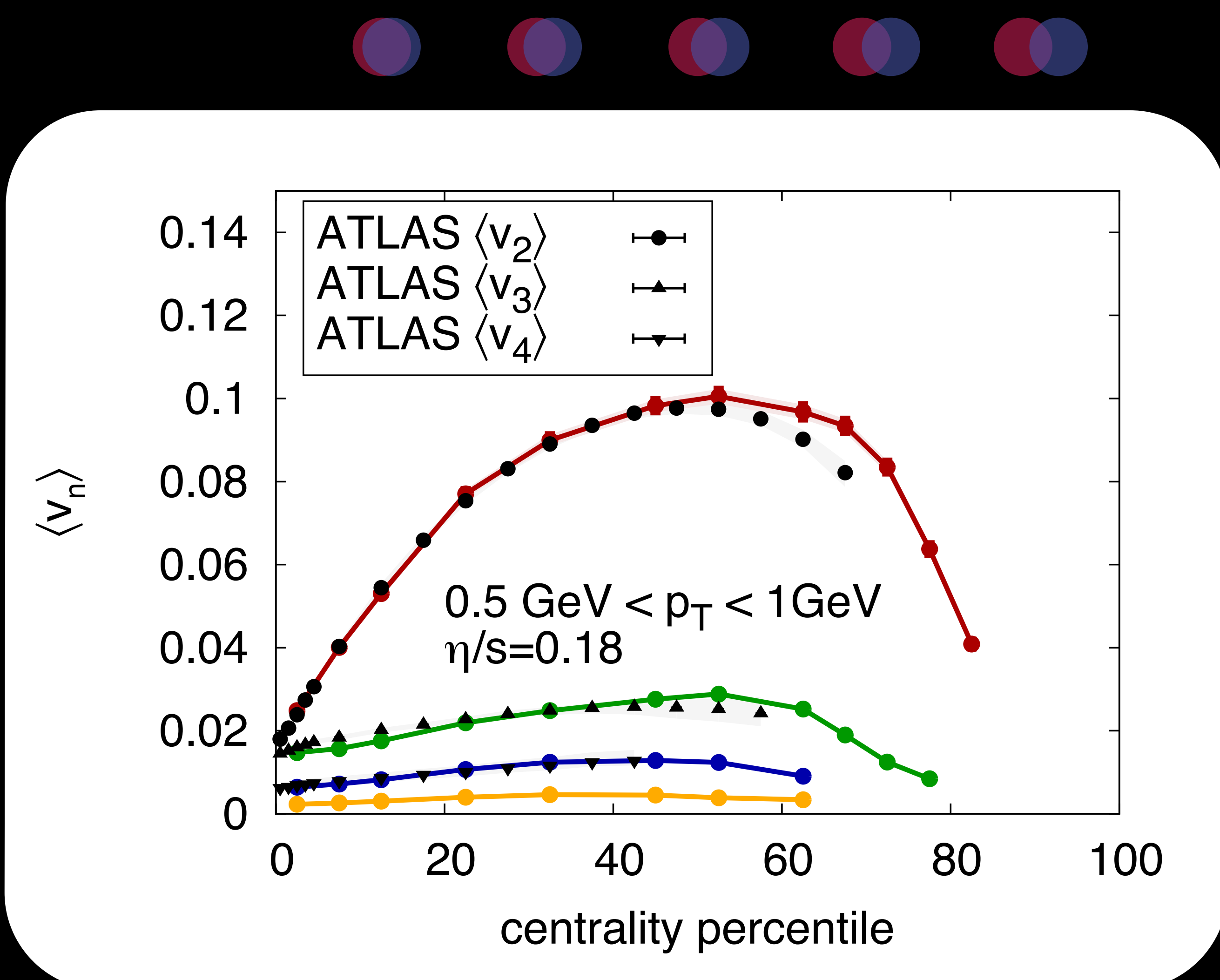


- Evolve many initial shapes using viscous fluid dynamics
- Convert energy density to particles ("freeze-out")
- Determine v_n coefficients of particle distributions
- Average and compare to experimental data

AVERAGE AND RMS v_n

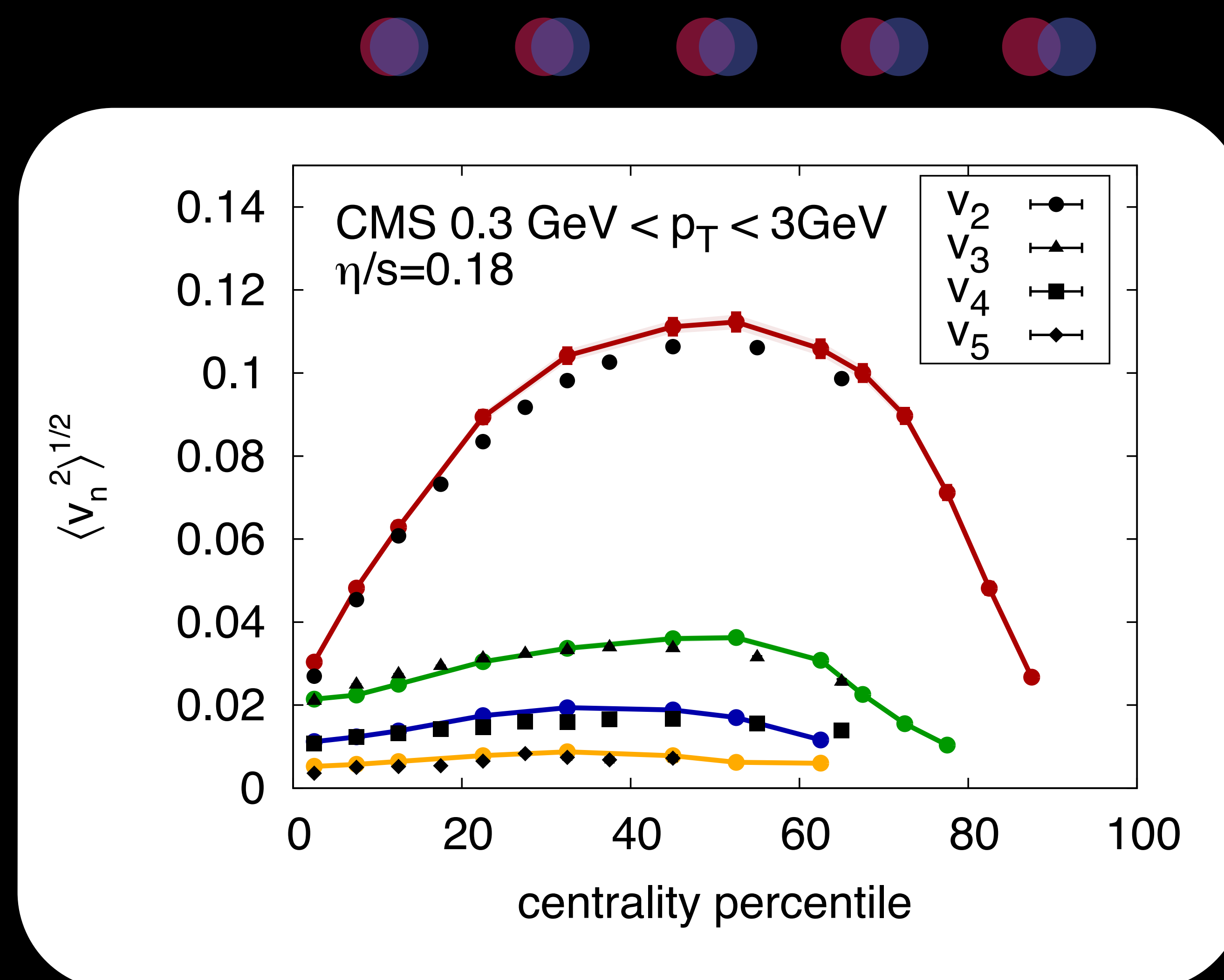
ATLAS COLLABORATION, JHEP 1311 (2013) 183
CMS COLLABORATION, PRC 87(2013) 014902, ARXIV:1310.8651

ATLAS



Mean from distributions

CMS



Event-plane method

EVENT-BY-EVENT FLOW

ATLAS COLLABORATION, JHEP 1311 (2013) 183

C. GALE, S. JEON, B.SCHENKE, P.TRIBEDY, R.VENUGOPALAN, PRL110, 012302 (2013)

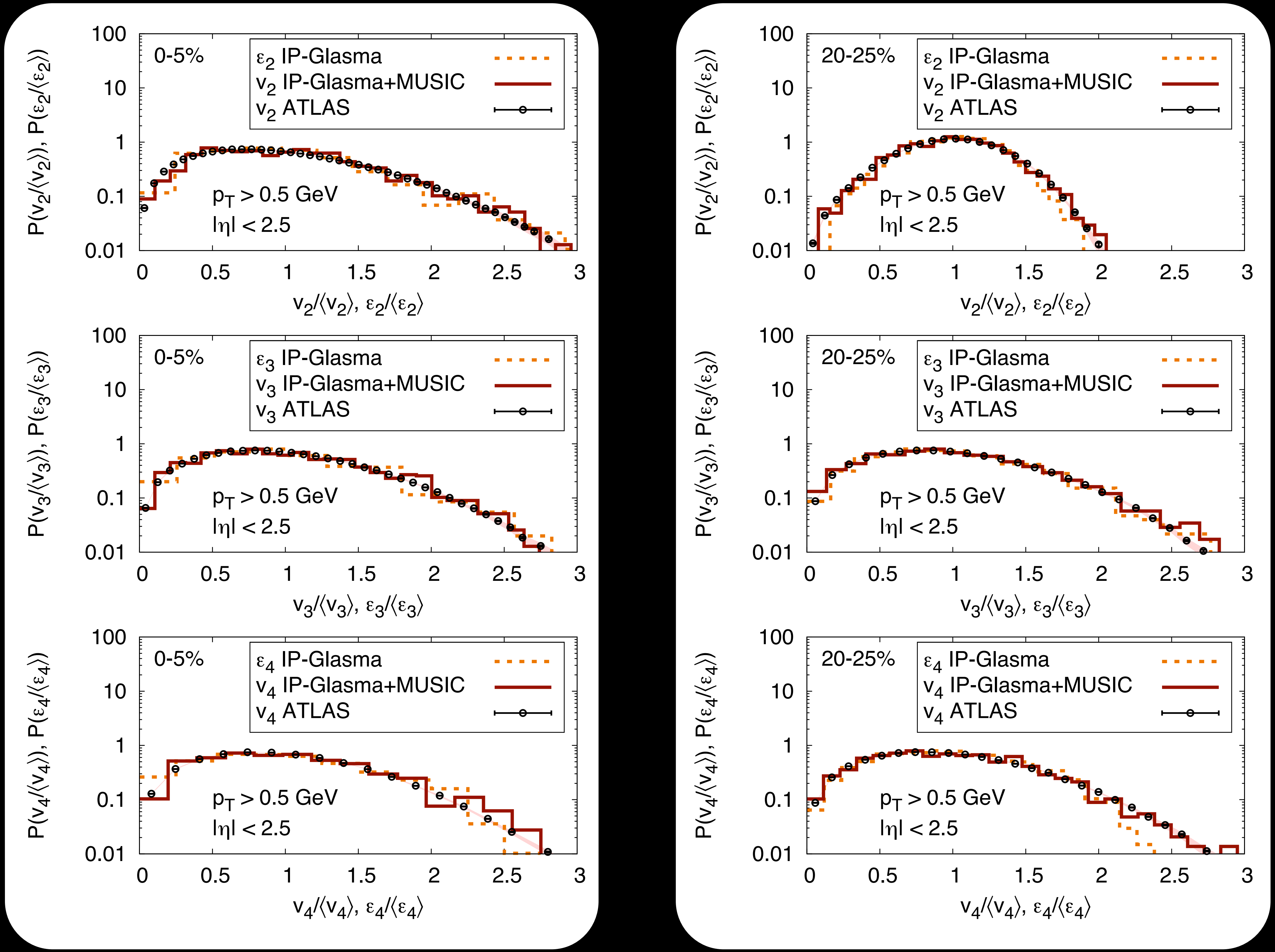
0-5%

20-25%

v_2

v_3

v_4



EVENT-BY-EVENT FLOW

ATLAS COLLABORATION, JHEP 1311 (2013) 183

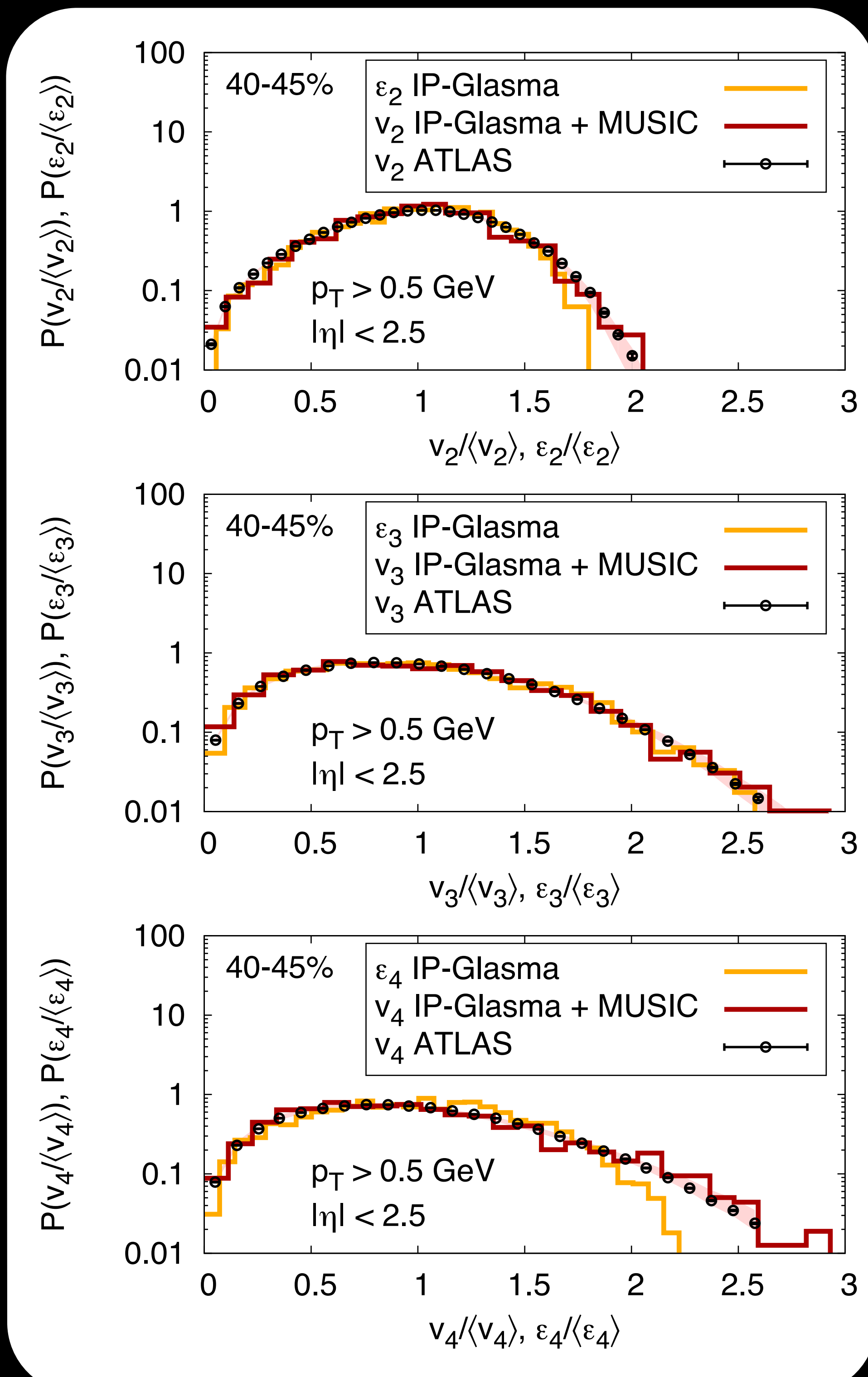
40-45%

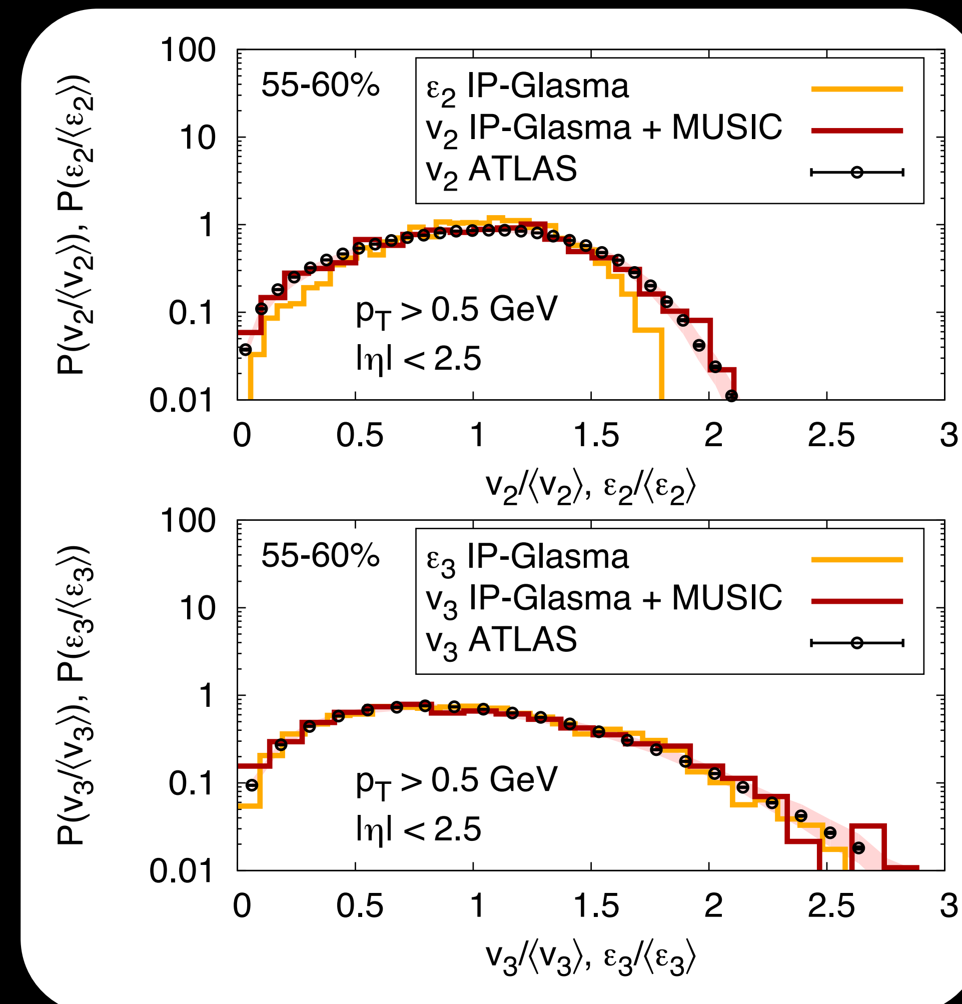
55-60%

v_2

v_3

v_4



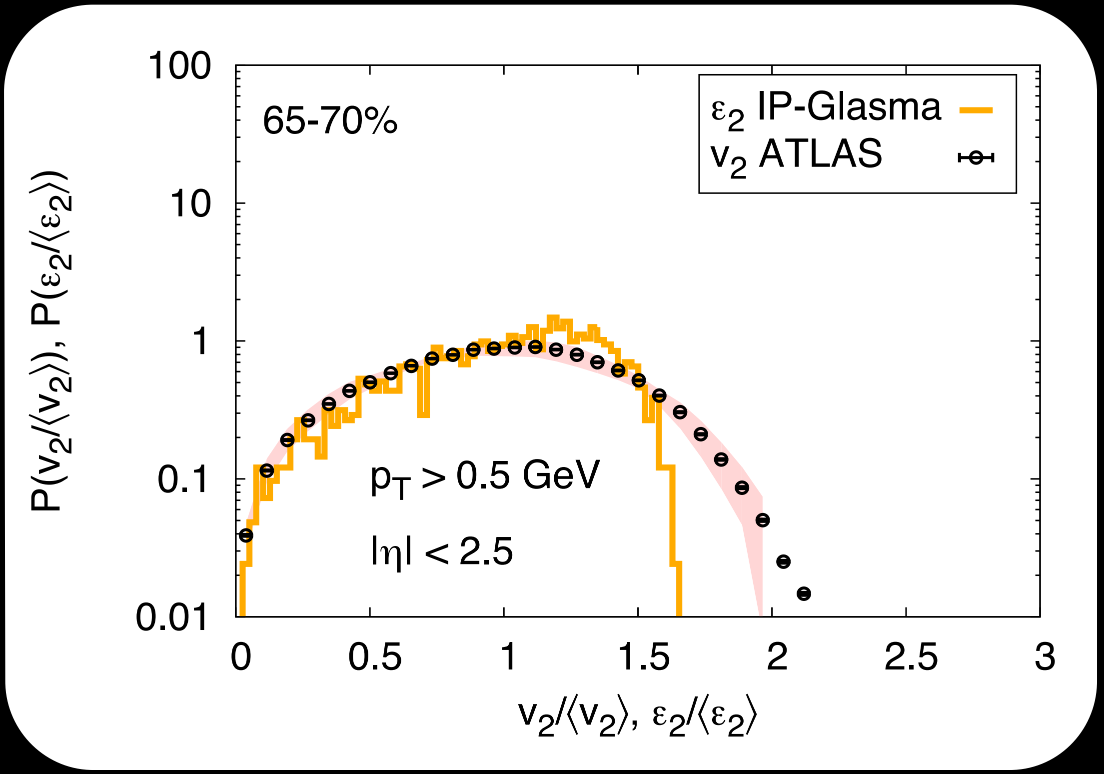


EVENT-BY-EVENT FLOW

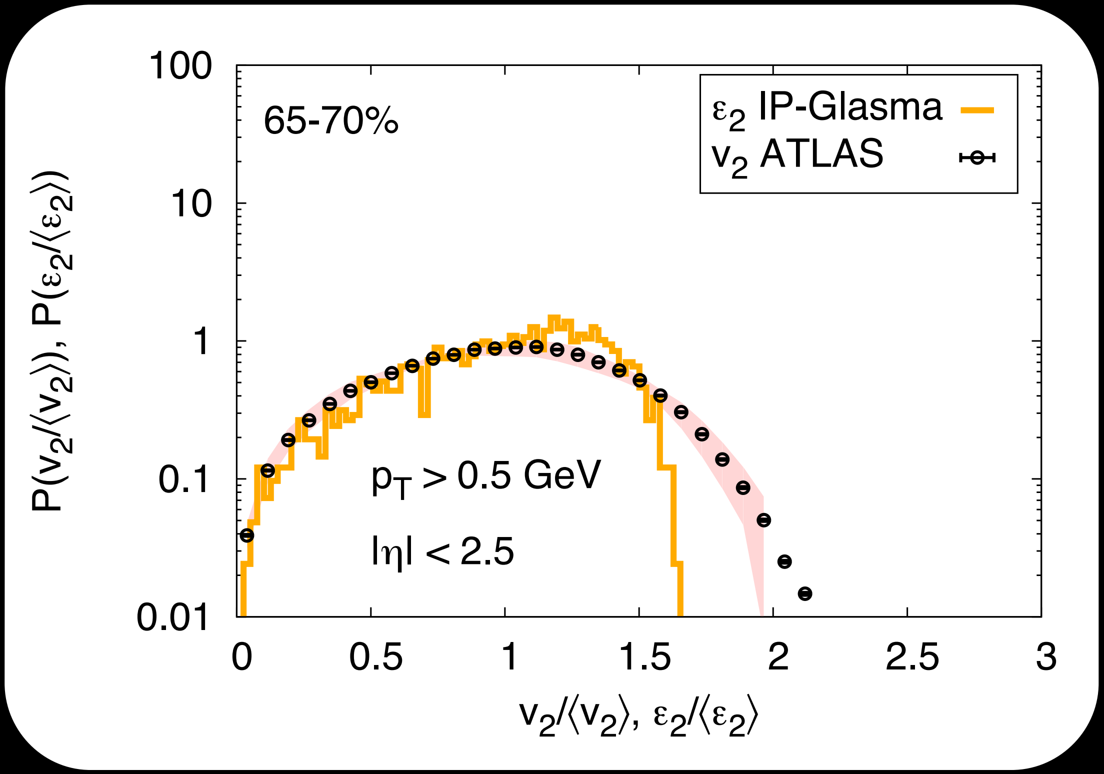
ATLAS COLLABORATION, JHEP 1311 (2013) 183

v_2

65-70%



65-70% IDEAL

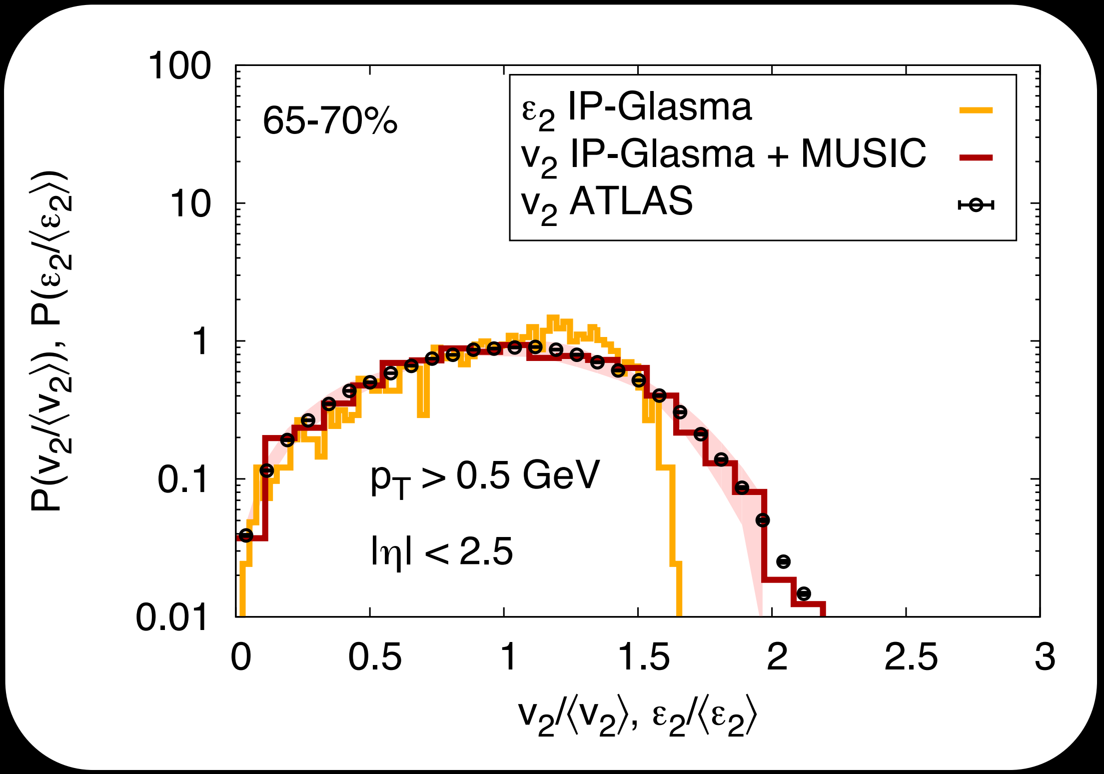


EVENT-BY-EVENT FLOW

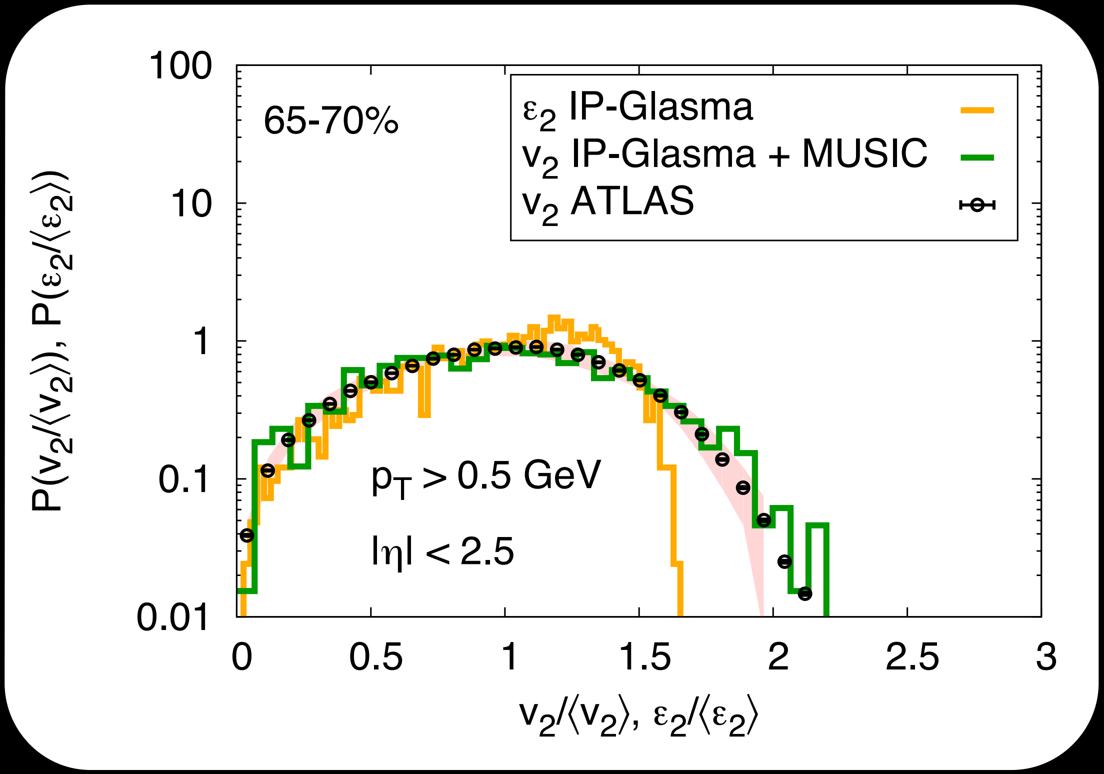
ATLAS COLLABORATION, JHEP 1311 (2013) 183

v_2

65-70%



65-70% IDEAL



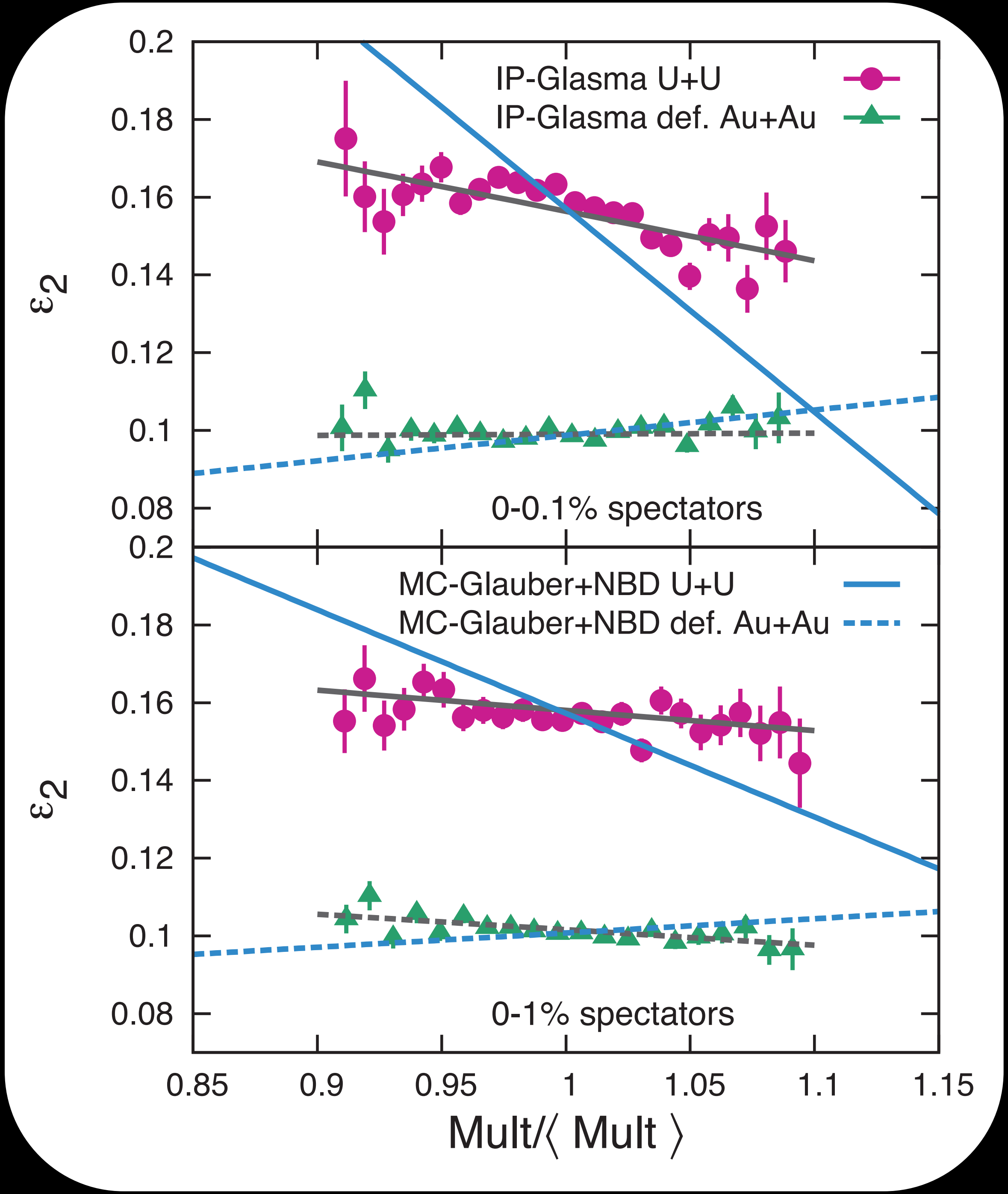
ALSO SEE TALK BY SOUMYA MOHAPATRA ON NON-LINEAR EFFECTS

DEFORMED NUCLEI

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232

- Select ultra-central events based on neutrons in the ZDC
- Study correlation between v_2 and multiplicity
- MC-Glauber gets (anti-)correlation because of $N_{\rm coll}$ in

$$\frac{dN}{d\eta} = n_{\rm pp}\left(xN_{\rm coll} + (1-x)\frac{N_{\rm part}}{2}\right)$$

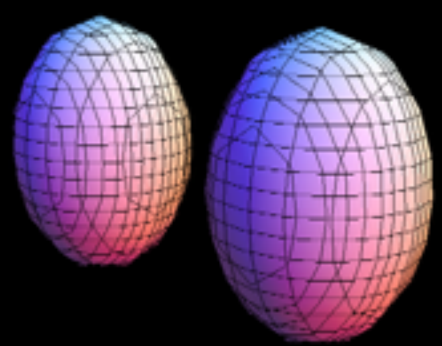


- IP-Glasma finds weaker anti-correlation

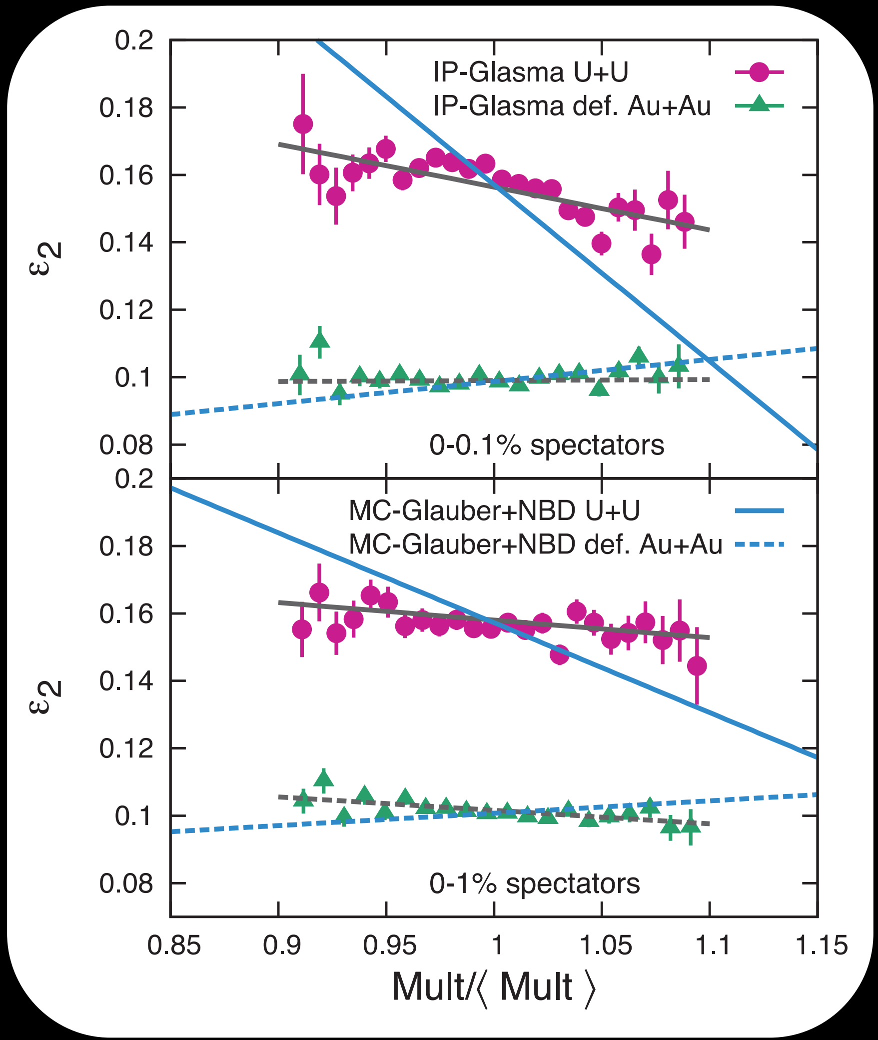
DEFORMED NUCLEI

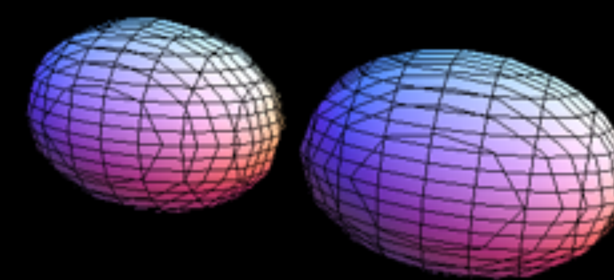
B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, ARXIV:1403.2232

- Uranium: prolate
- Gold: oblate

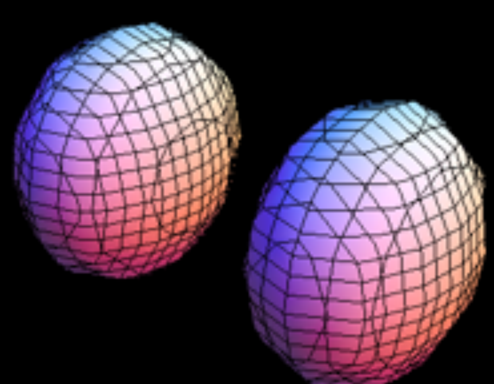


U+U, side-side

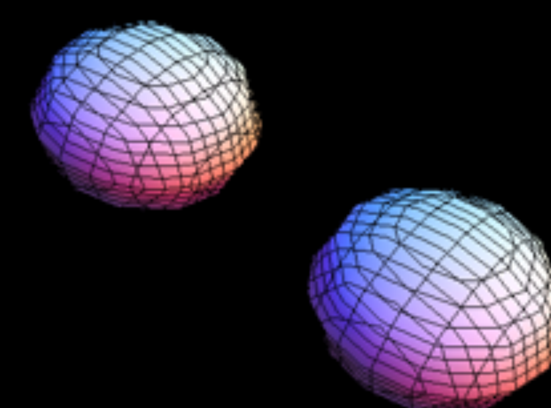




U+U, tip-tip



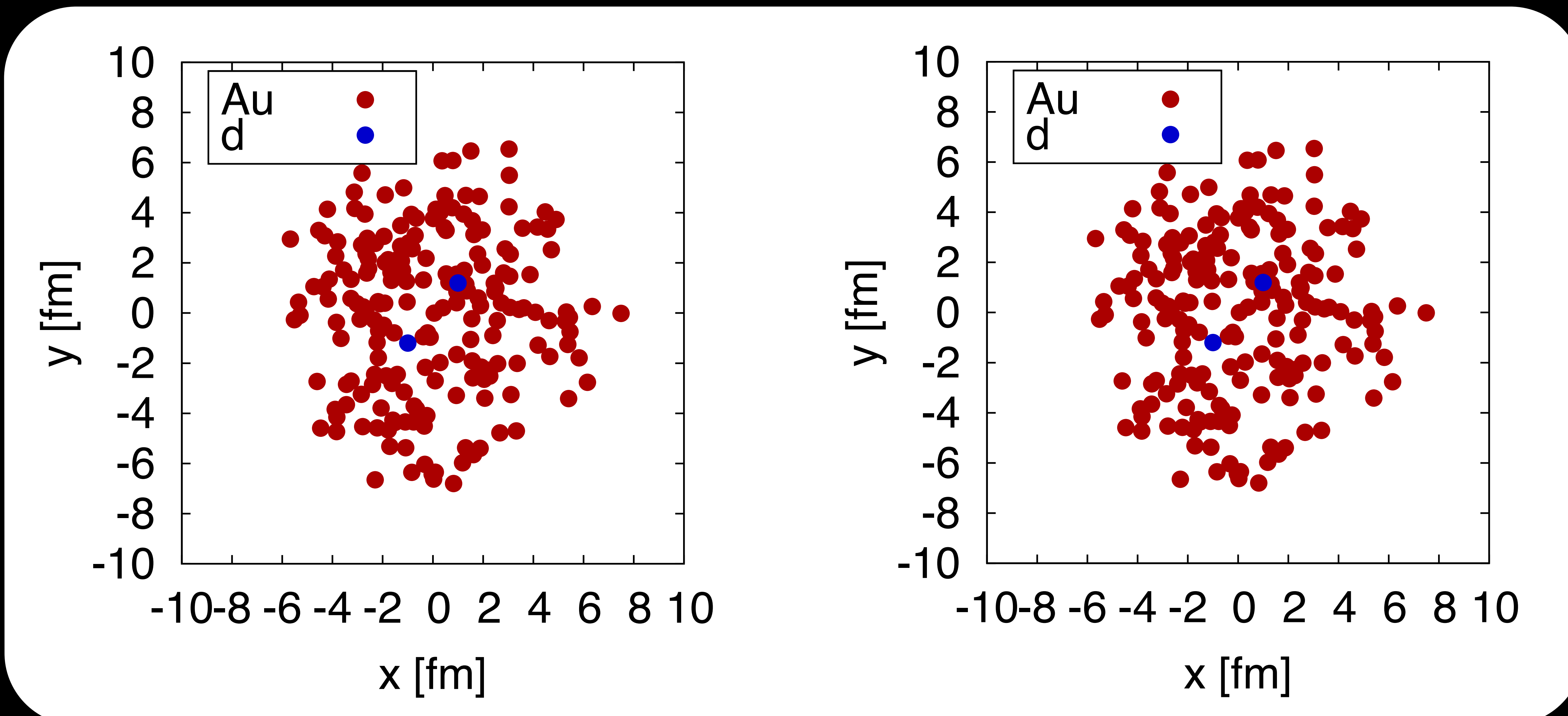
Au+Au, side-side



Au+Au, "tip-tip"

SMALL SYSTEMS

A. BZDAK, B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PRC87, 064906 (2013)



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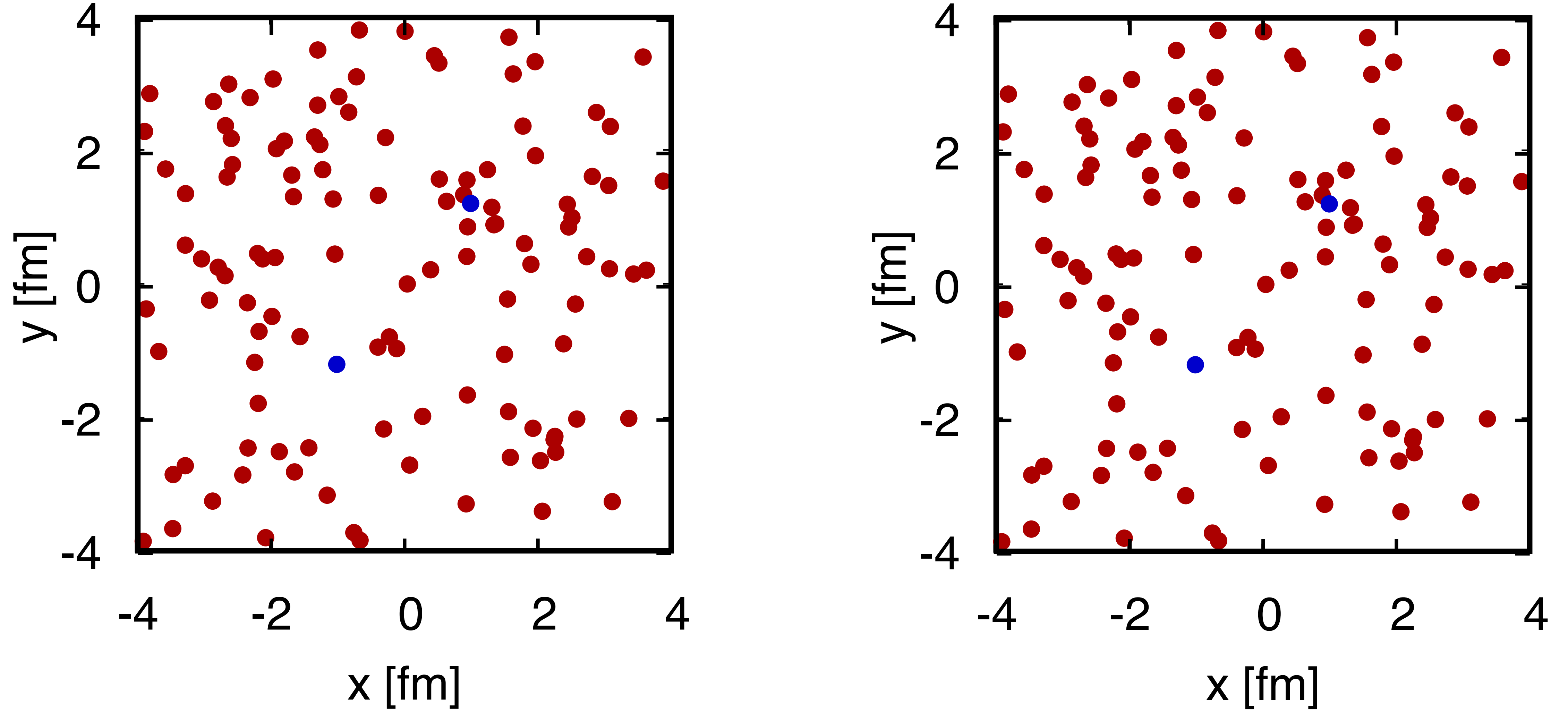

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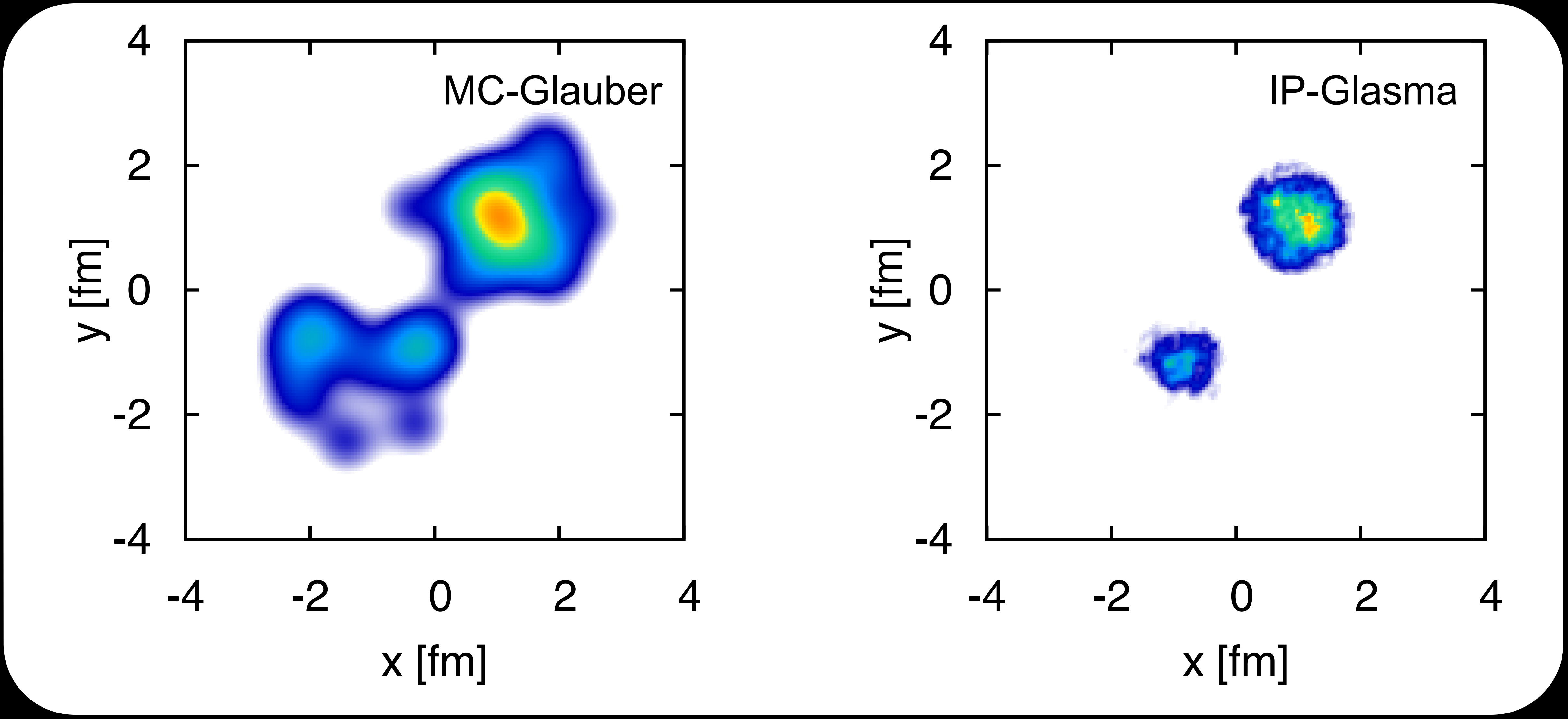

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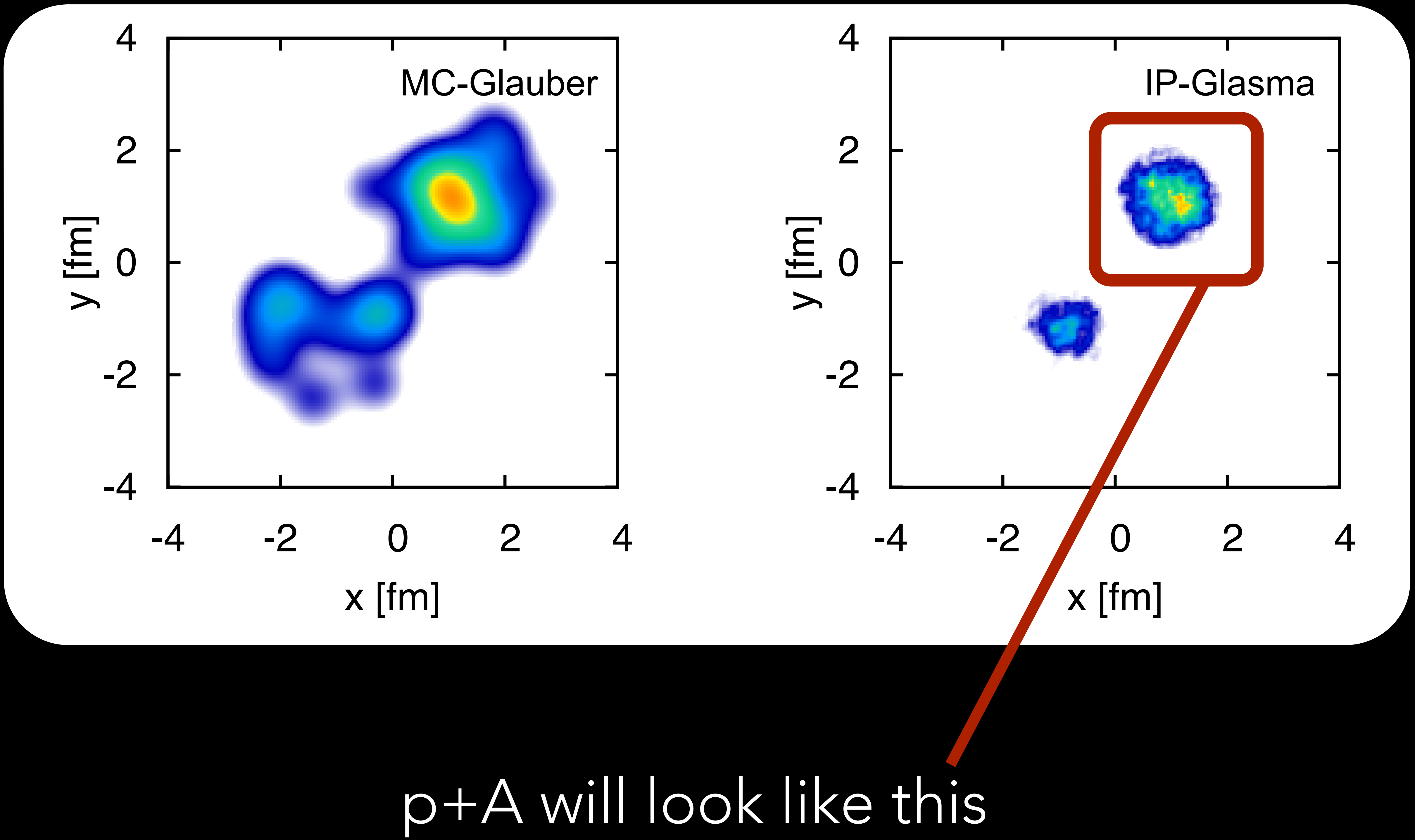

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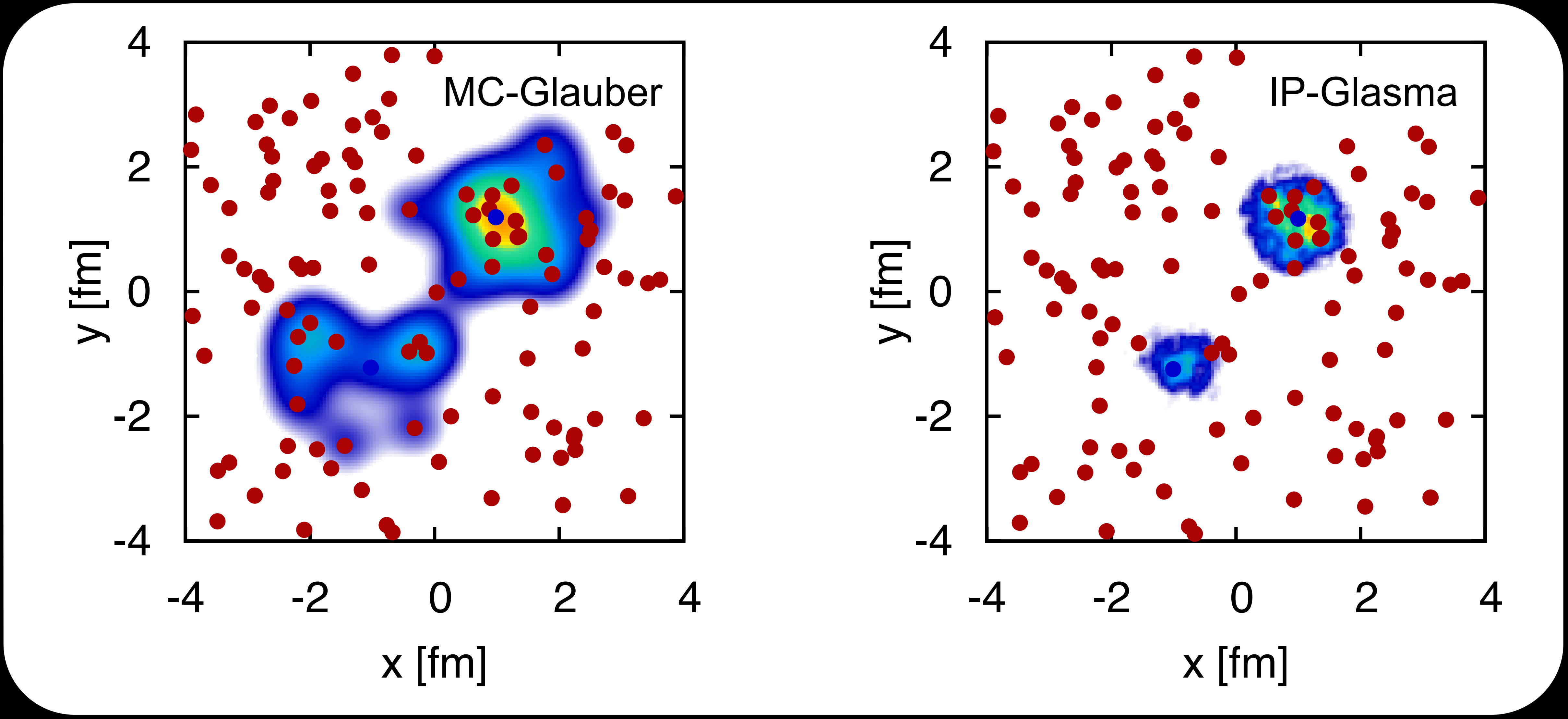
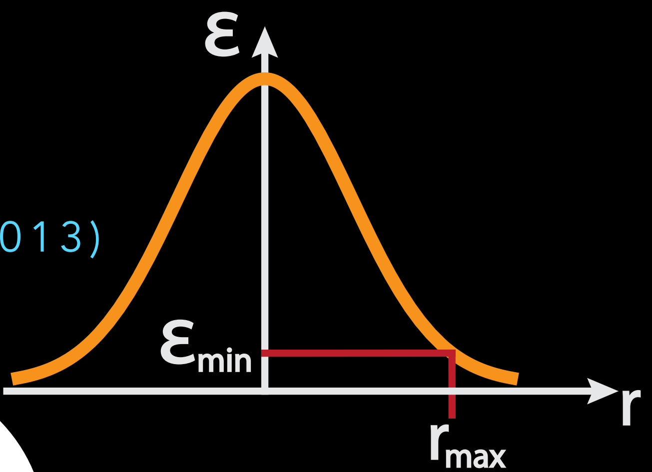
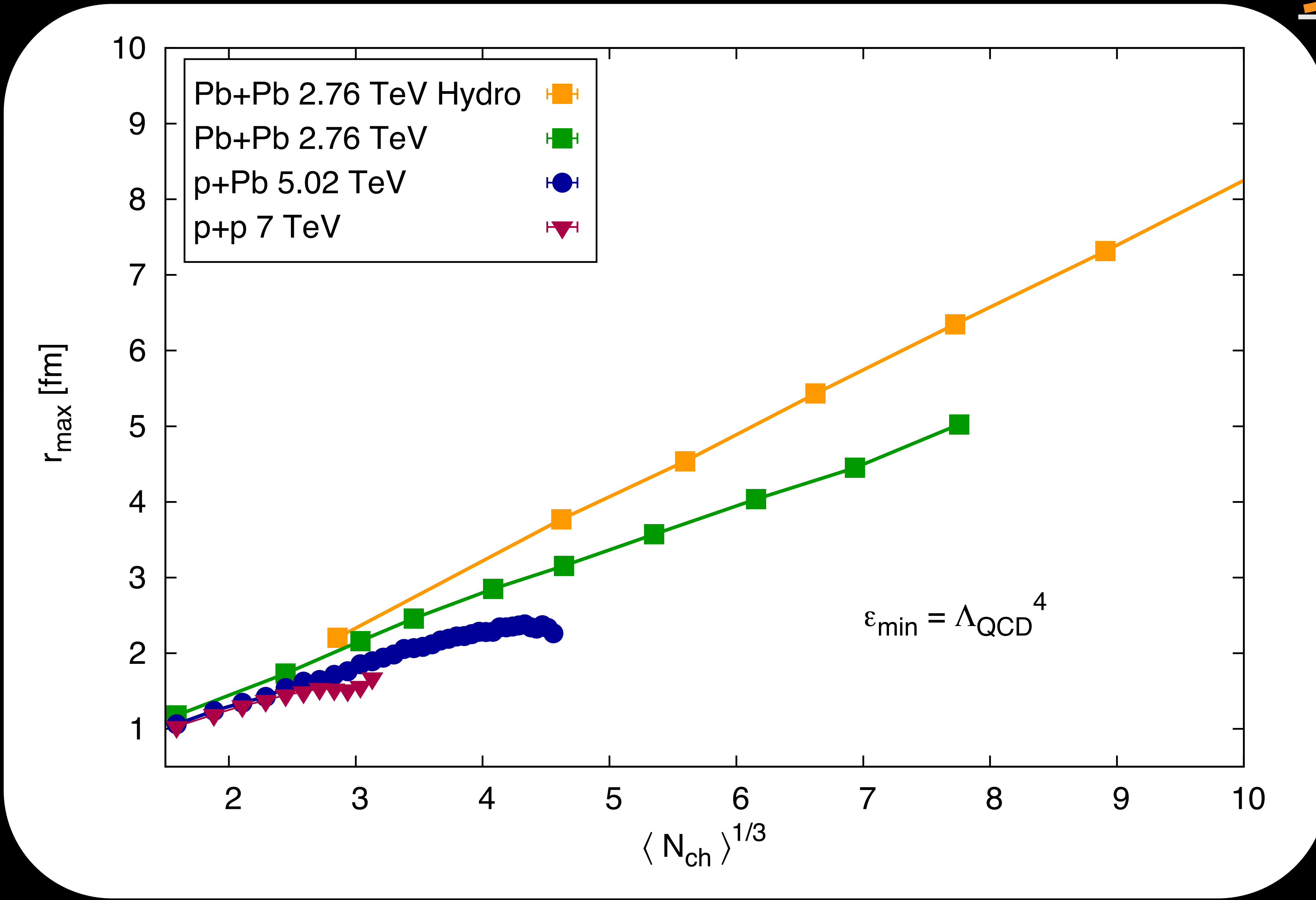


SYSTEM SIZE

A. BZDAK, B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PRC87, 064906 (2013)



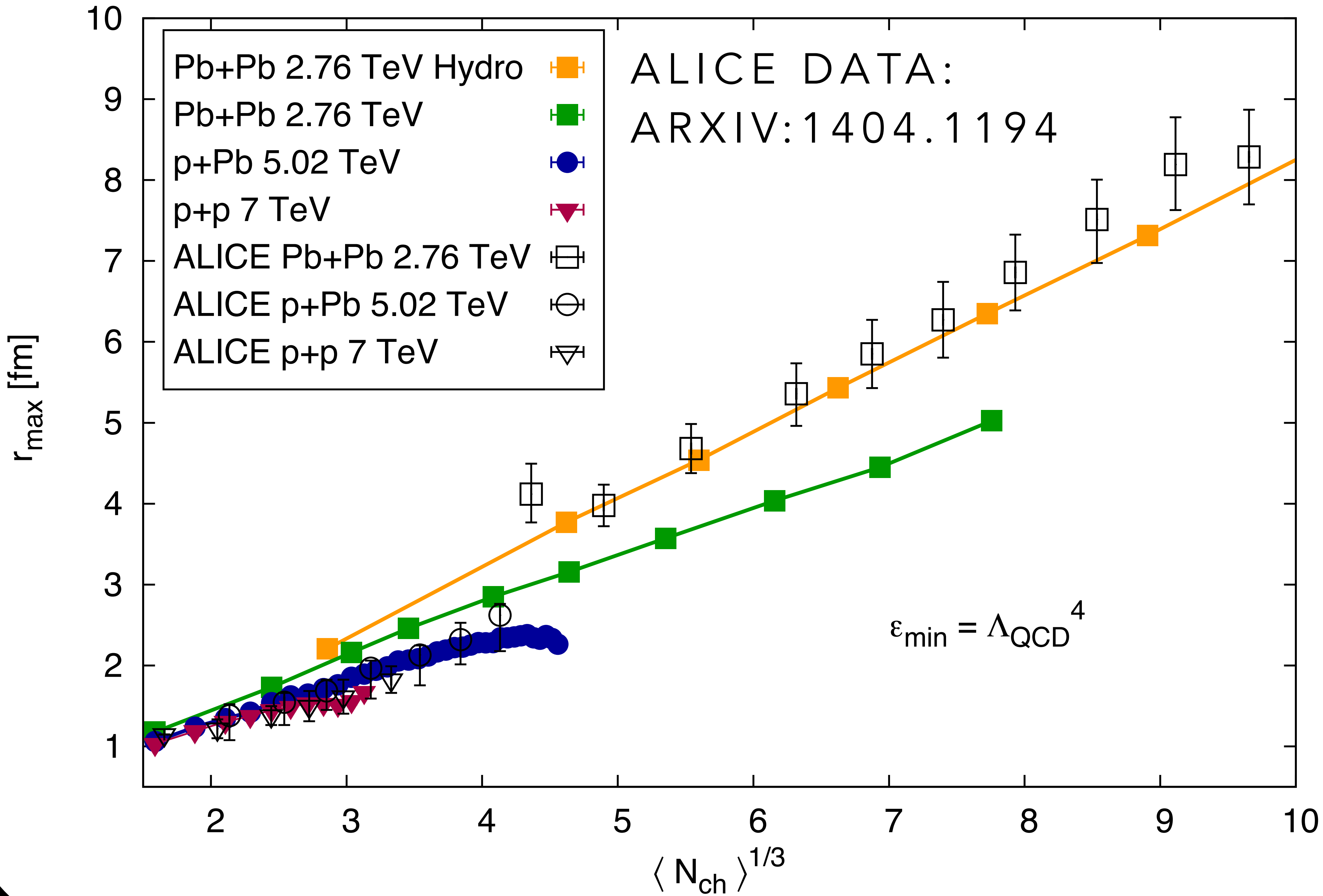


$$N_{ch} = \frac{2}{3} N_g$$

SEE TALK BY DHEVAN RAJA GANGADHARAN (ALICE)

SYSTEM SIZE

A. BZDAK, B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PRC87, 064906 (2013)



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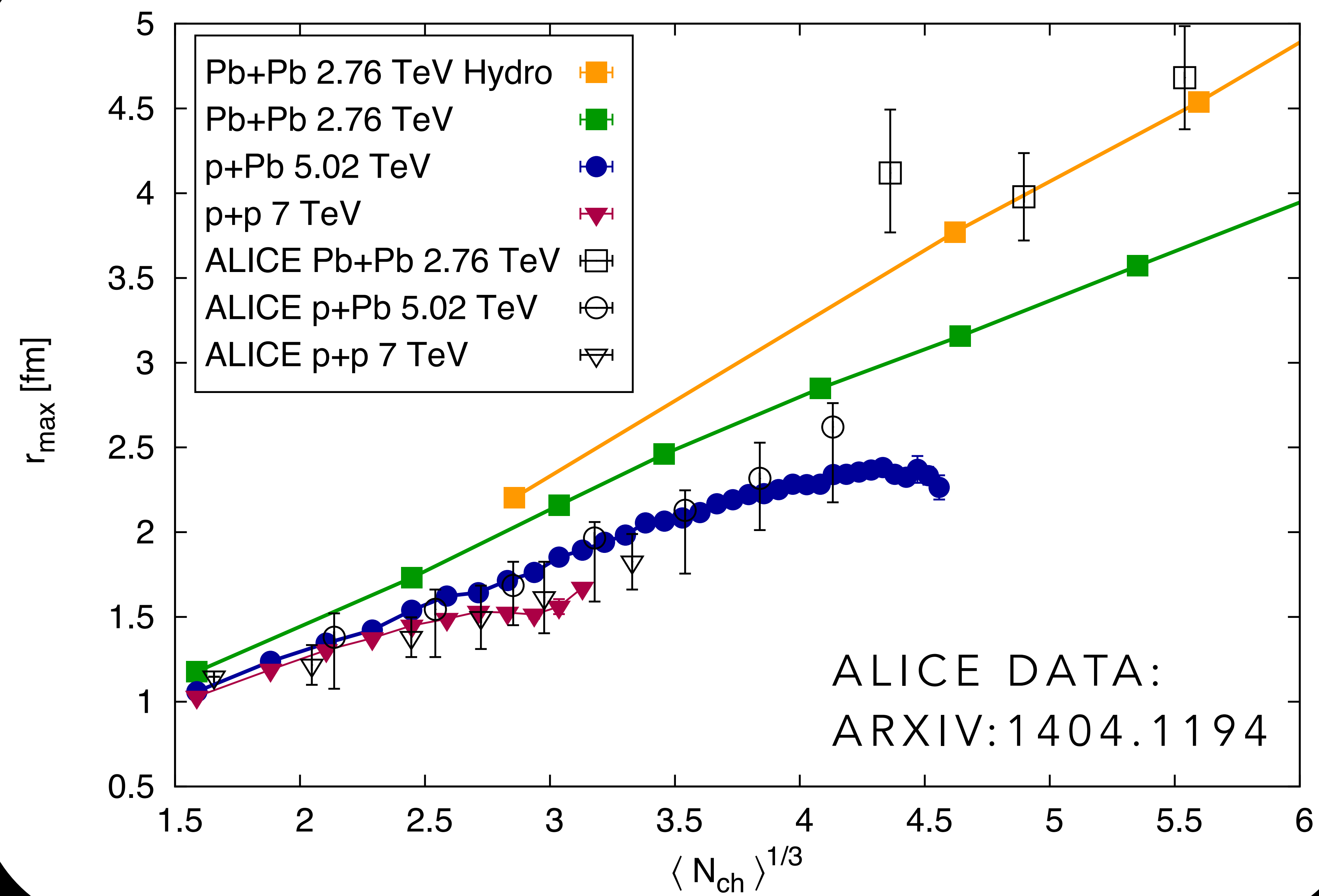
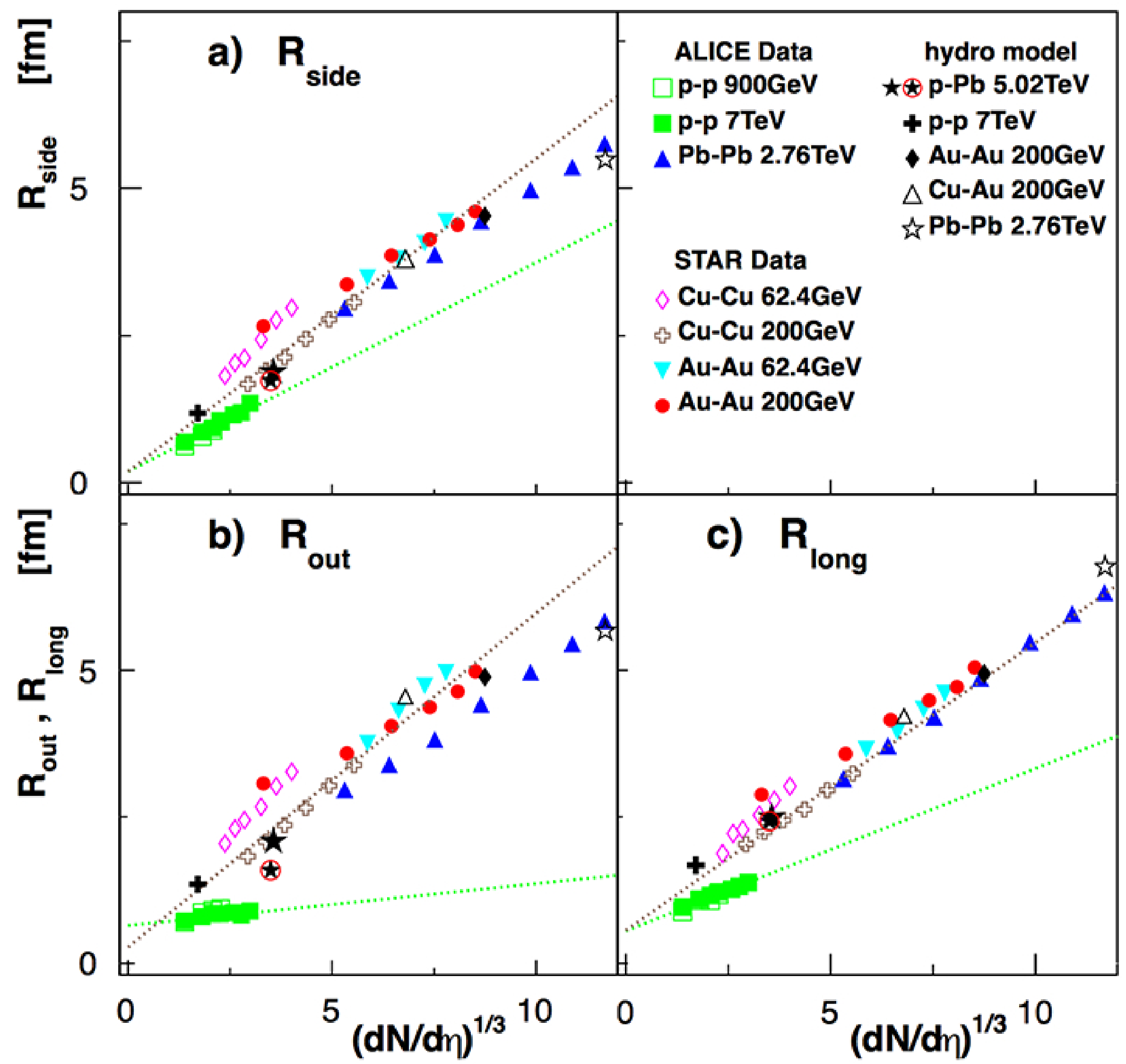


SEE TALK BY DHEVAN RAJA GANGADHARAN (ALICE)

SYSTEM SIZE WITH MC-GLAUBER INITIAL CONDITIONS

P. BOZEK, W. BRONIOWSKI, PHYS.LETT. B720 (2013) 250-253

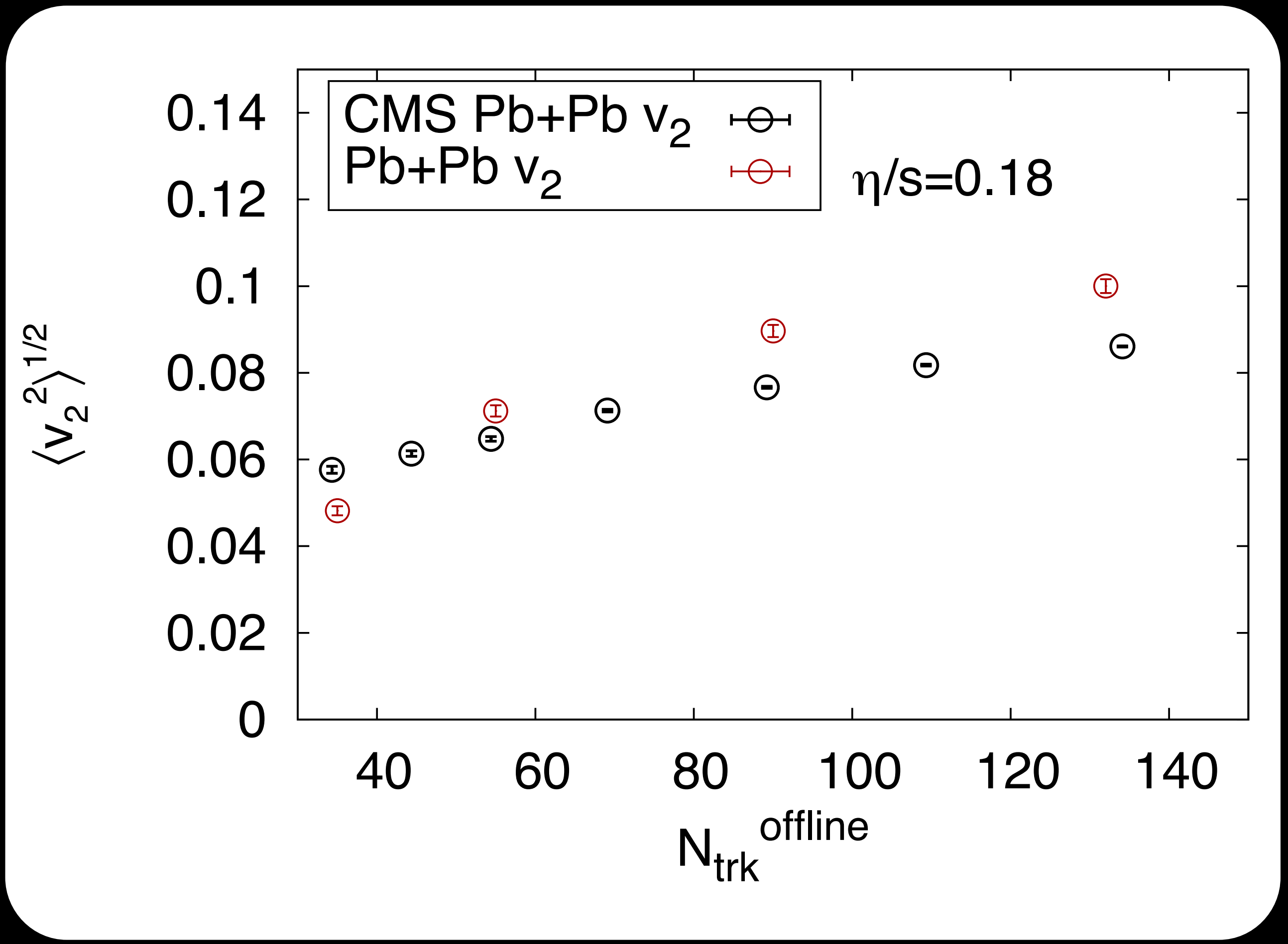


MC-Glauber model + hydro gets size in p+Pb ~ size in Pb+Pb

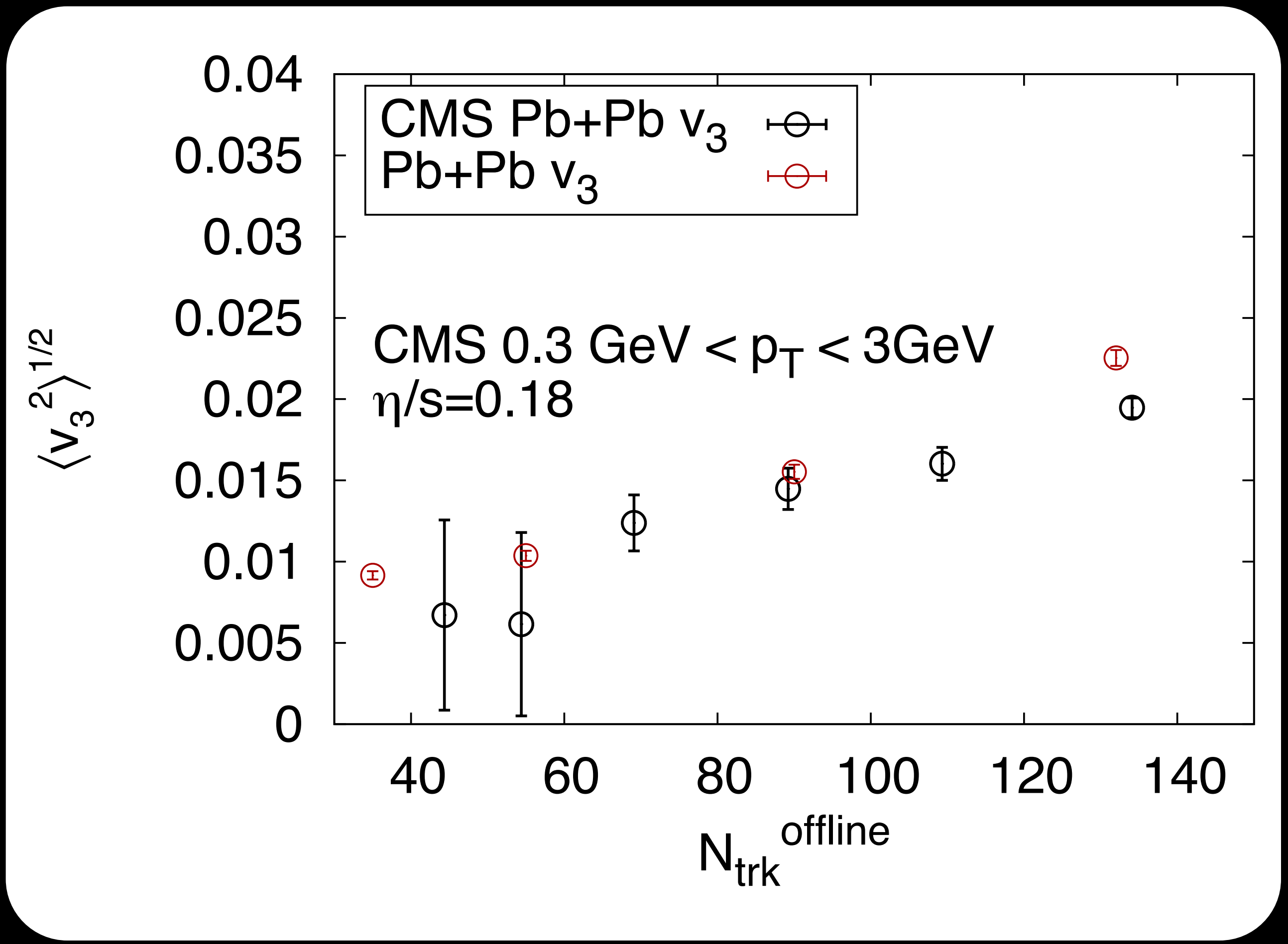
FOURIER HARMONICS IN p+Pb

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240

v_2



v_3



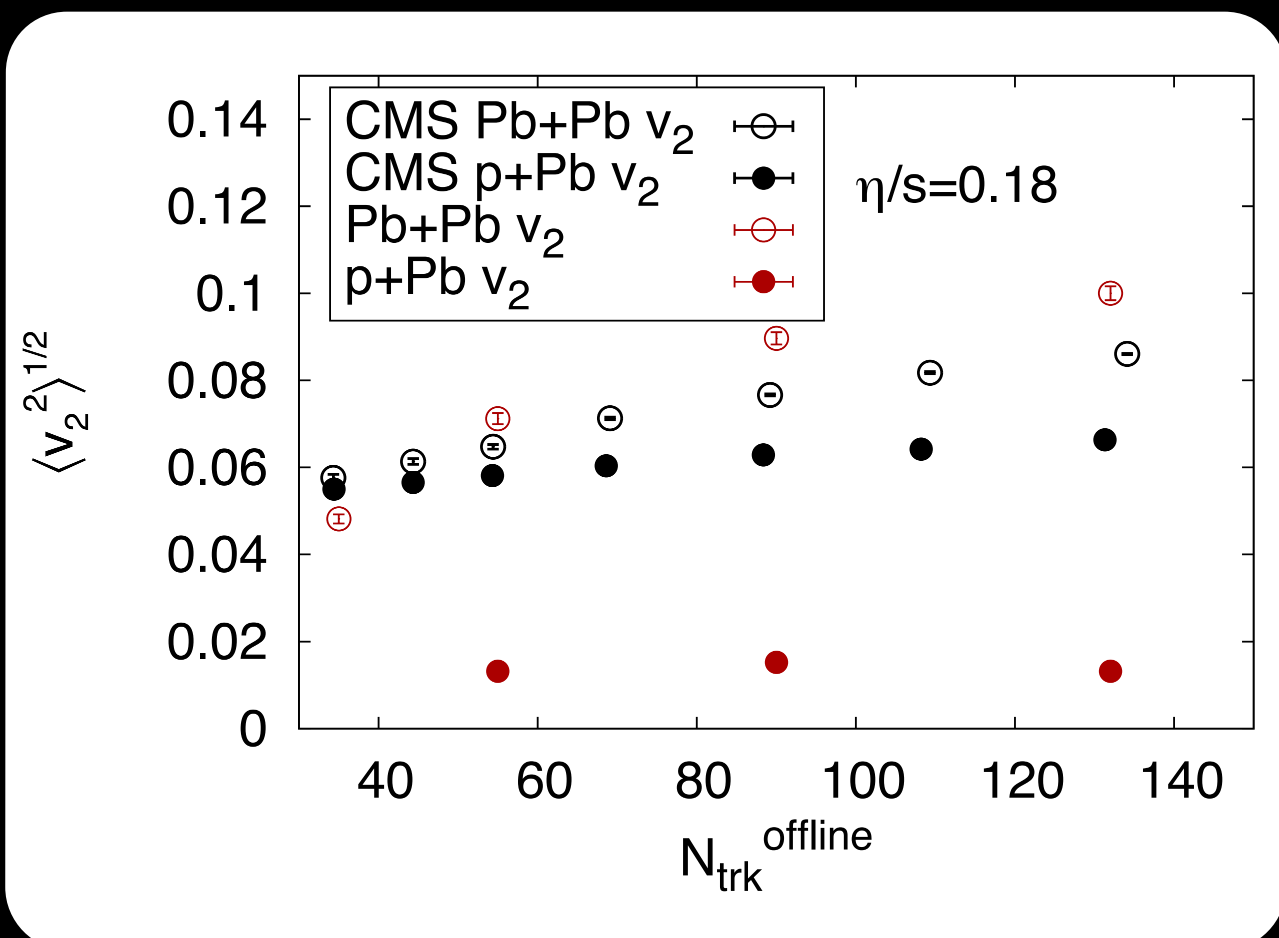
Open symbols: Pb+Pb
Filled symbols: p+Pb

Red points: IP-Glasma + MUSIC

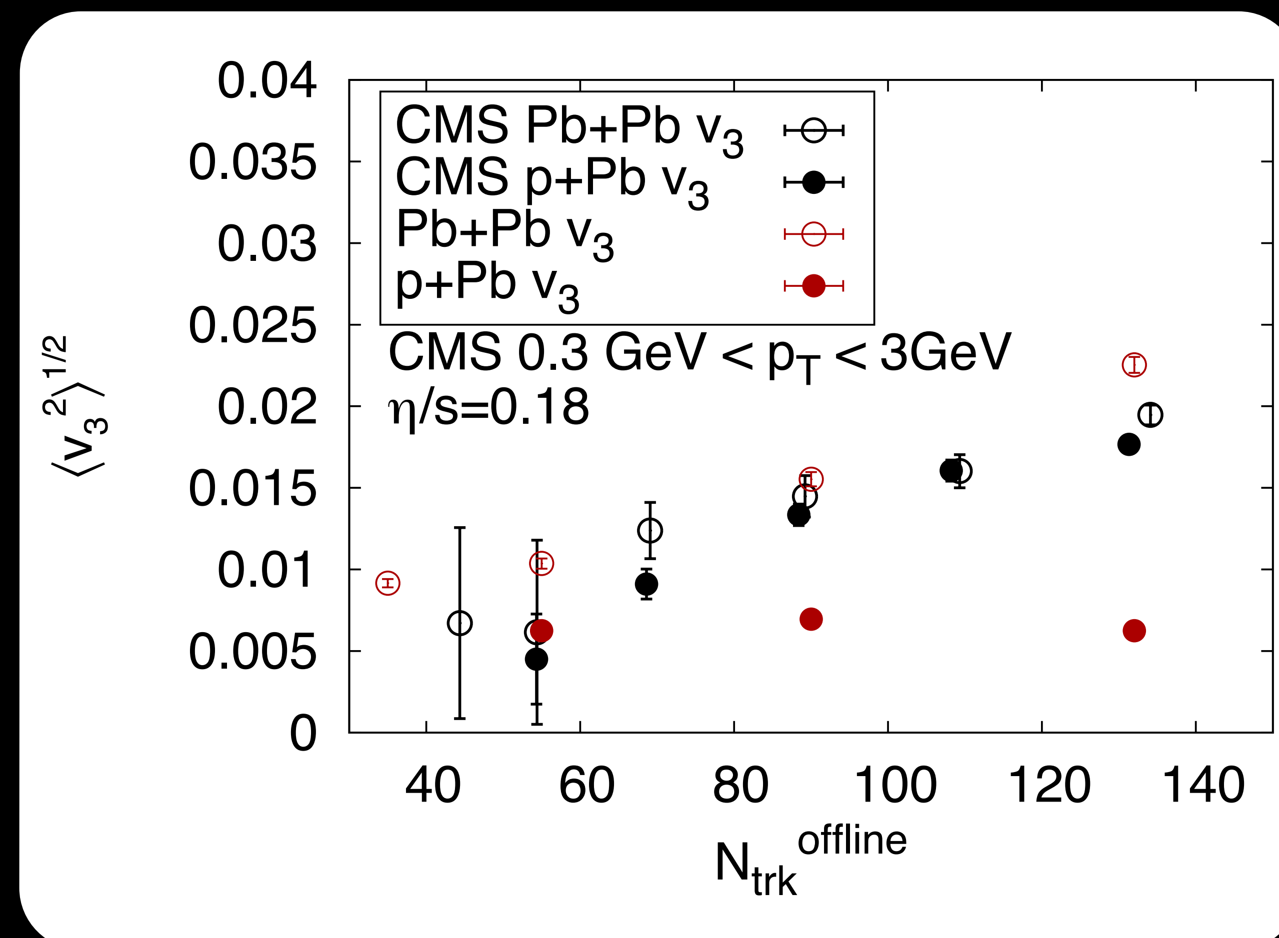
FOURIER HARMONICS IN p+Pb

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240

v_2



v_3



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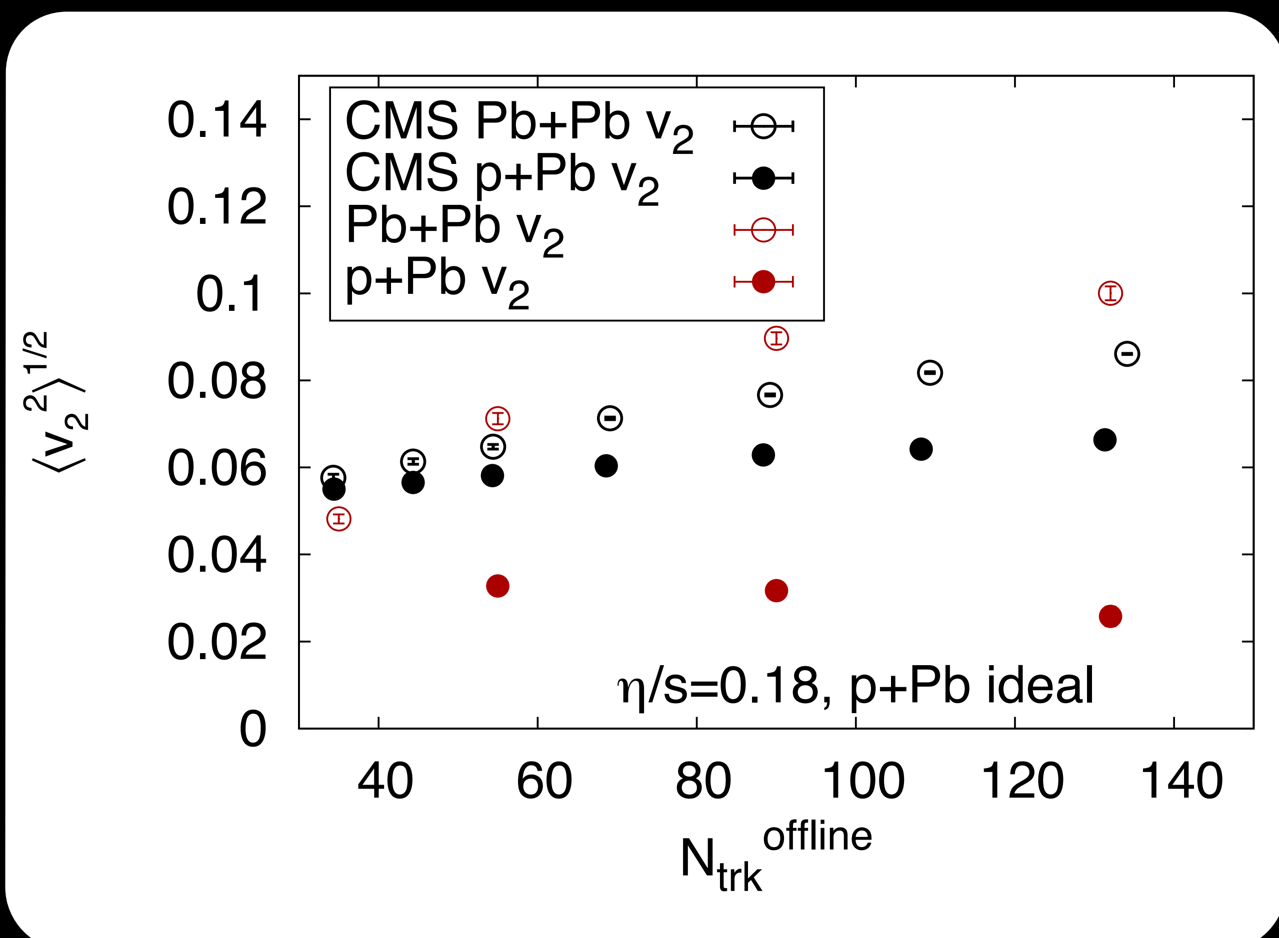
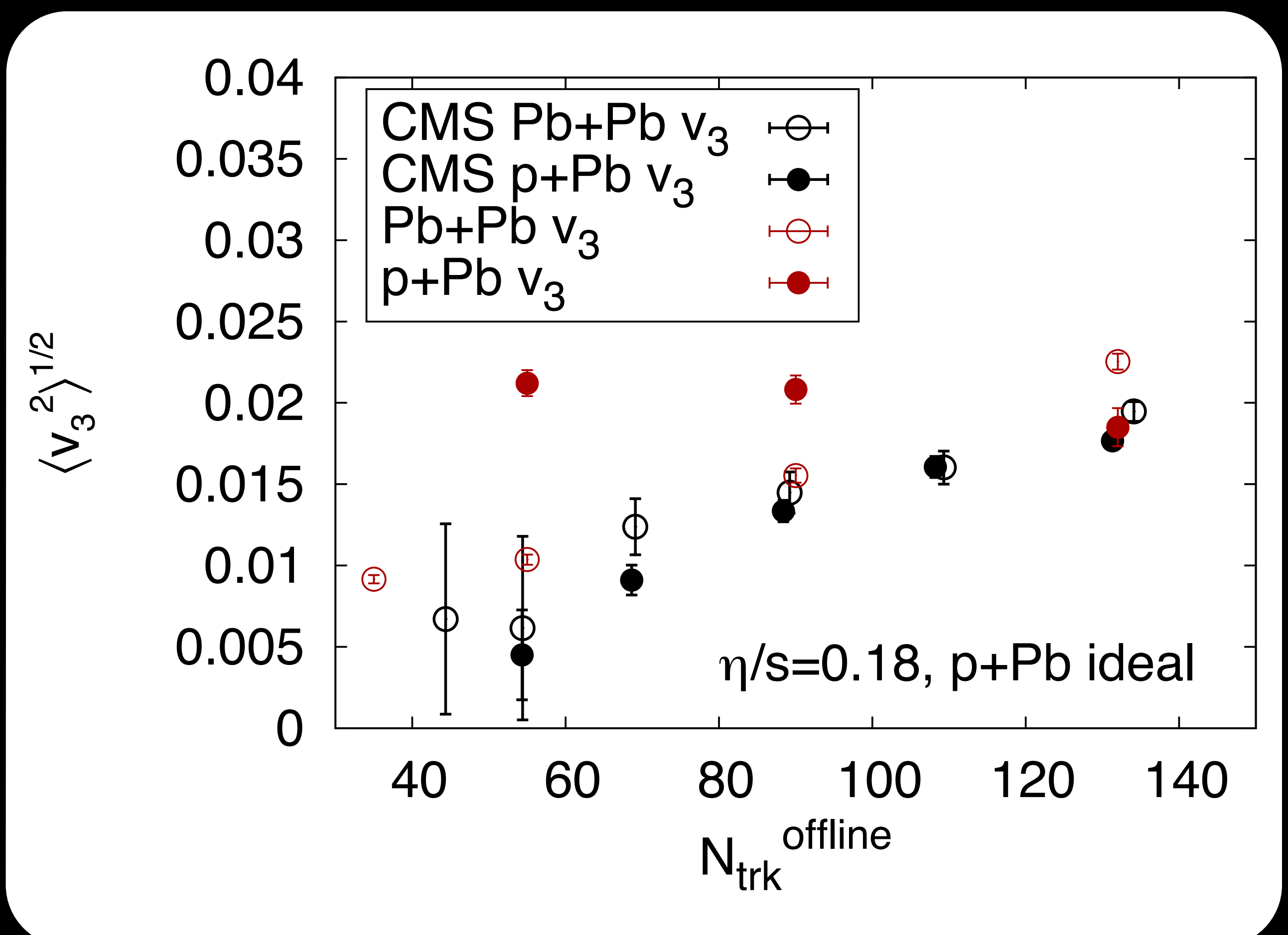
FOURIER HARMONICS IN p+Pb

CMS COLLABORATION, PHYS.LETT. B724 (2013) 213-240

v_2



v_3



Open symbols: Pb+Pb

Filled symbols: p+Pb

Red points: IP-Glasma + MUSIC

FOURIER HARMONICS IN p+Pb

Why doesn't it work?

Two possibilities:

a) We neglected correlations from the initial state

K. DUSLING, R. VENUGOPALAN, PHYS.REV. D87 054014 (2013)

They are there in IP-Glasma - just need to keep them

b) The proton is not spherical and its shape fluctuates

Will this give the right centrality dependence?

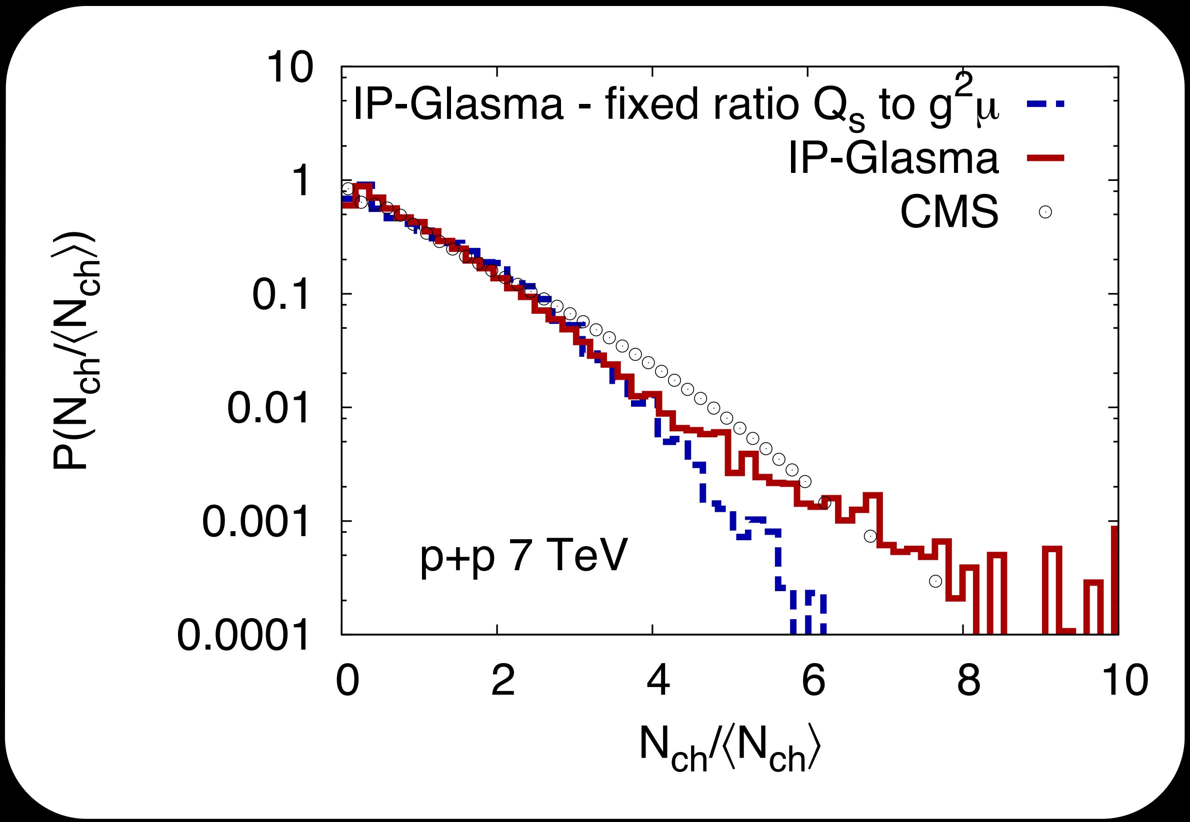
SUMMARY

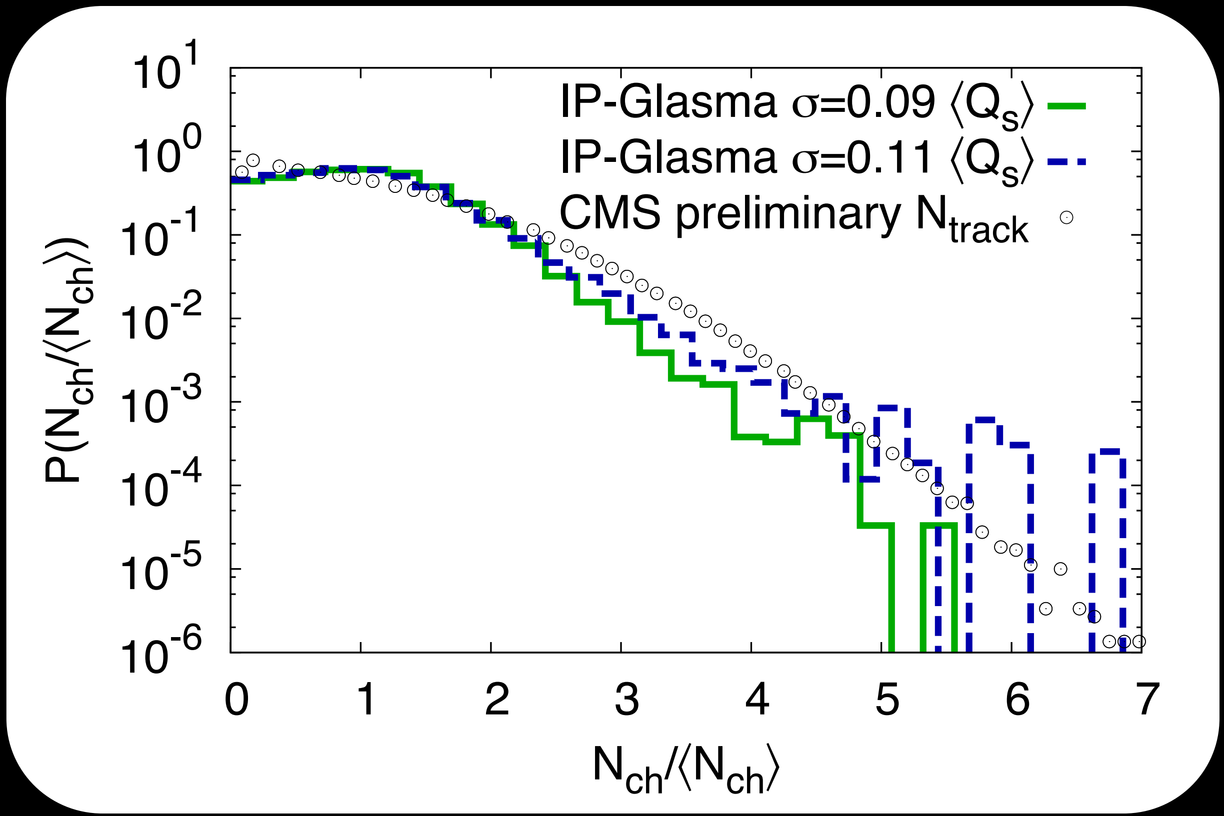
- IP-Glasma + fluid dynamics does very good job in describing experimental data in A+A collisions
- v_n distributions in peripheral events are well described when nonlinear effects from the evolution are included
- Ultra-central collisions of deformed nuclei can give information on particle production mechanism
- Similar size in p+p and p+Pb agrees with ALICE HBT
- Within IP-Glasma+MUSIC model and ignoring initial state correlations, v_n in p+Pb are not well described

BACKUP

MULTIPLICITY DISTRIBUTIONS

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PHYS. REV. C89, 024901 (2014)
CMS COLLABORATION, JHEP 1101, 079 (2011)





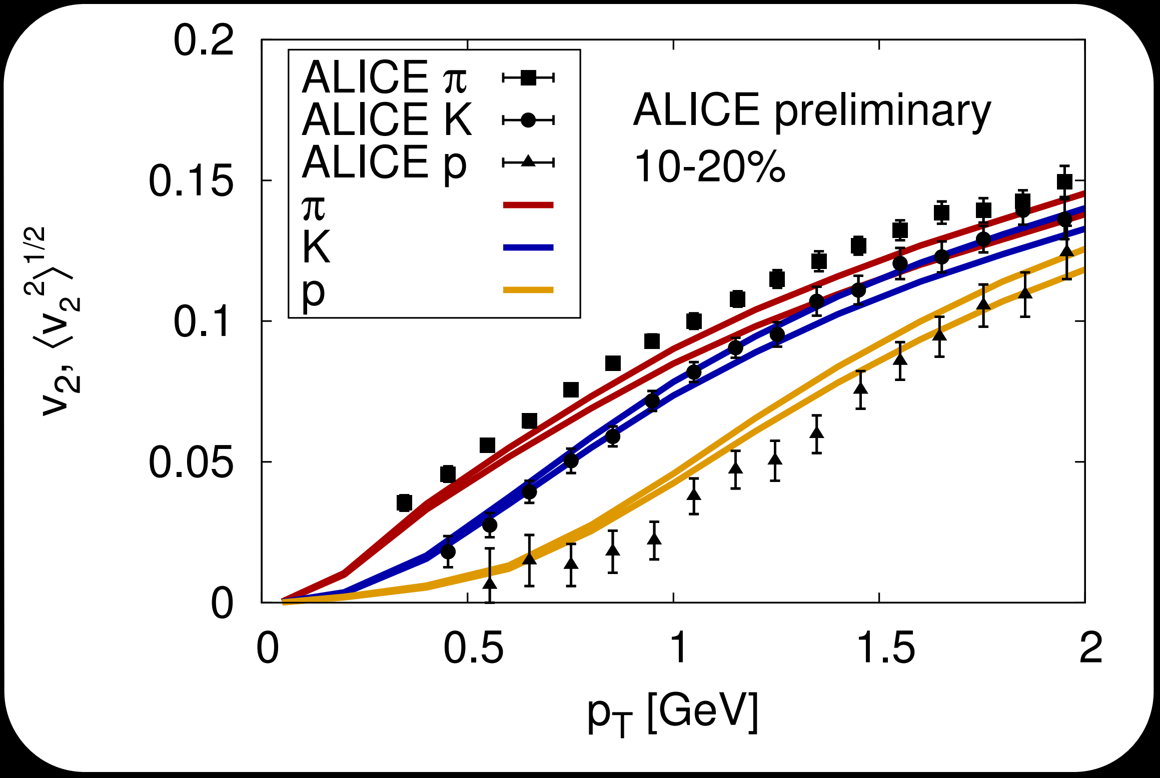
Multiplicity distributions in p+p and p+Pb collisions are not as wide as the experimental data

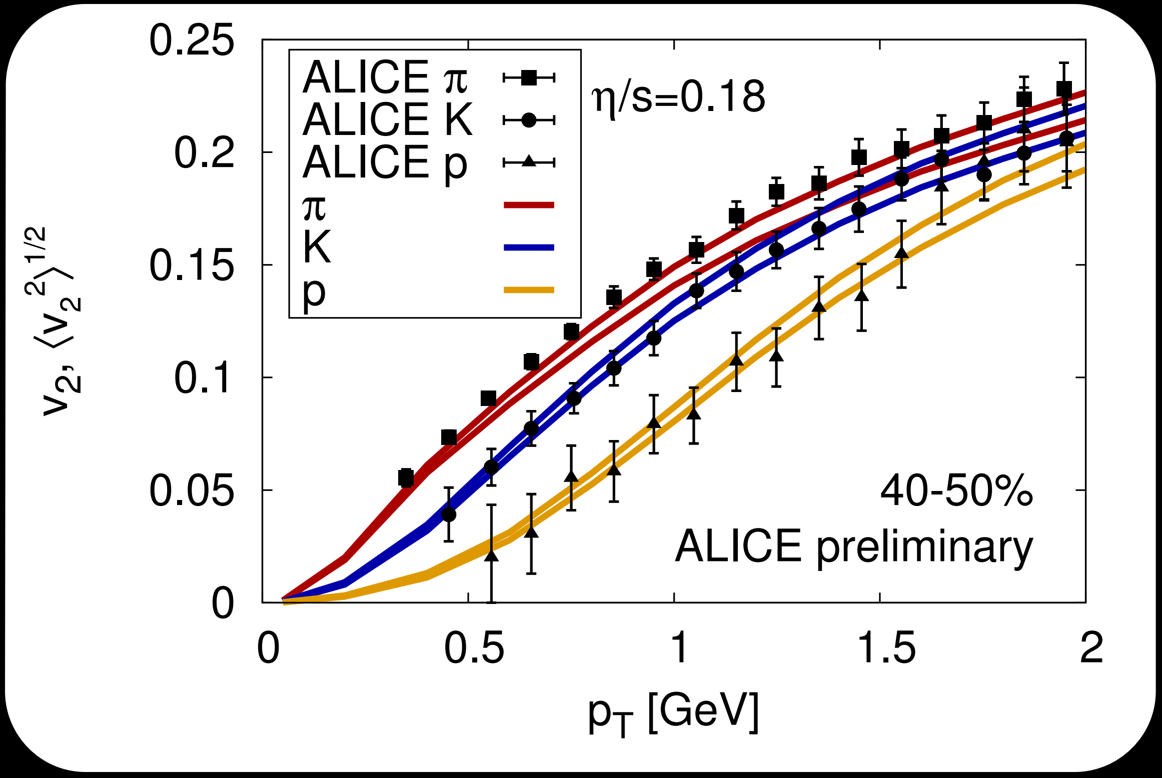
Introduce fluctuation of color charge density

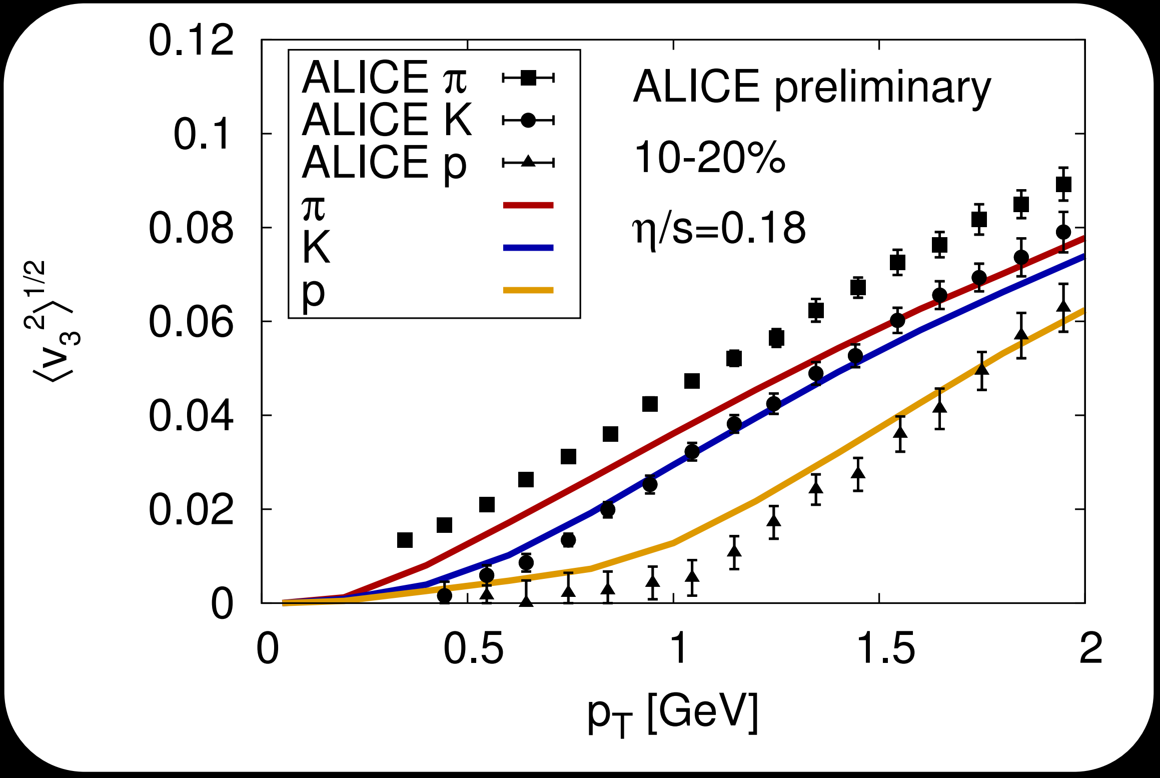
Hadronization can also widen the distribution

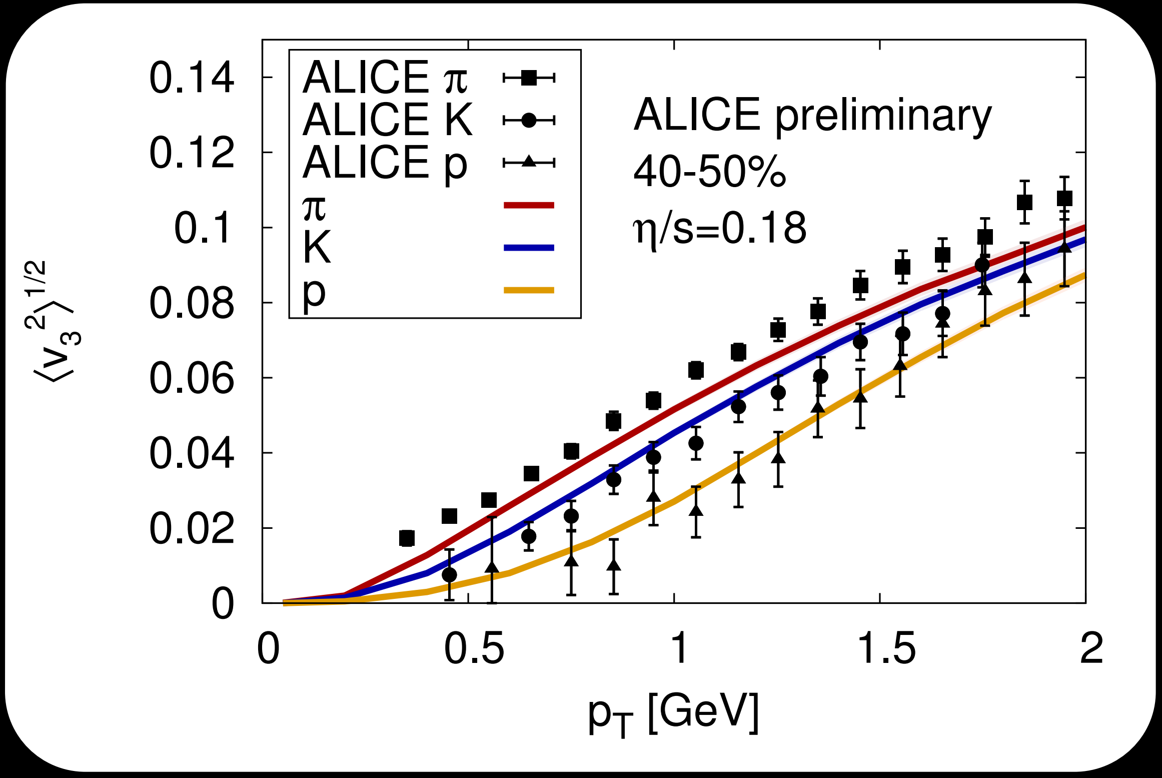
IDENTIFIED PARTICLE FLOW

ALICE COLLABORATION, J.PHYS. G38 (2011) 124047

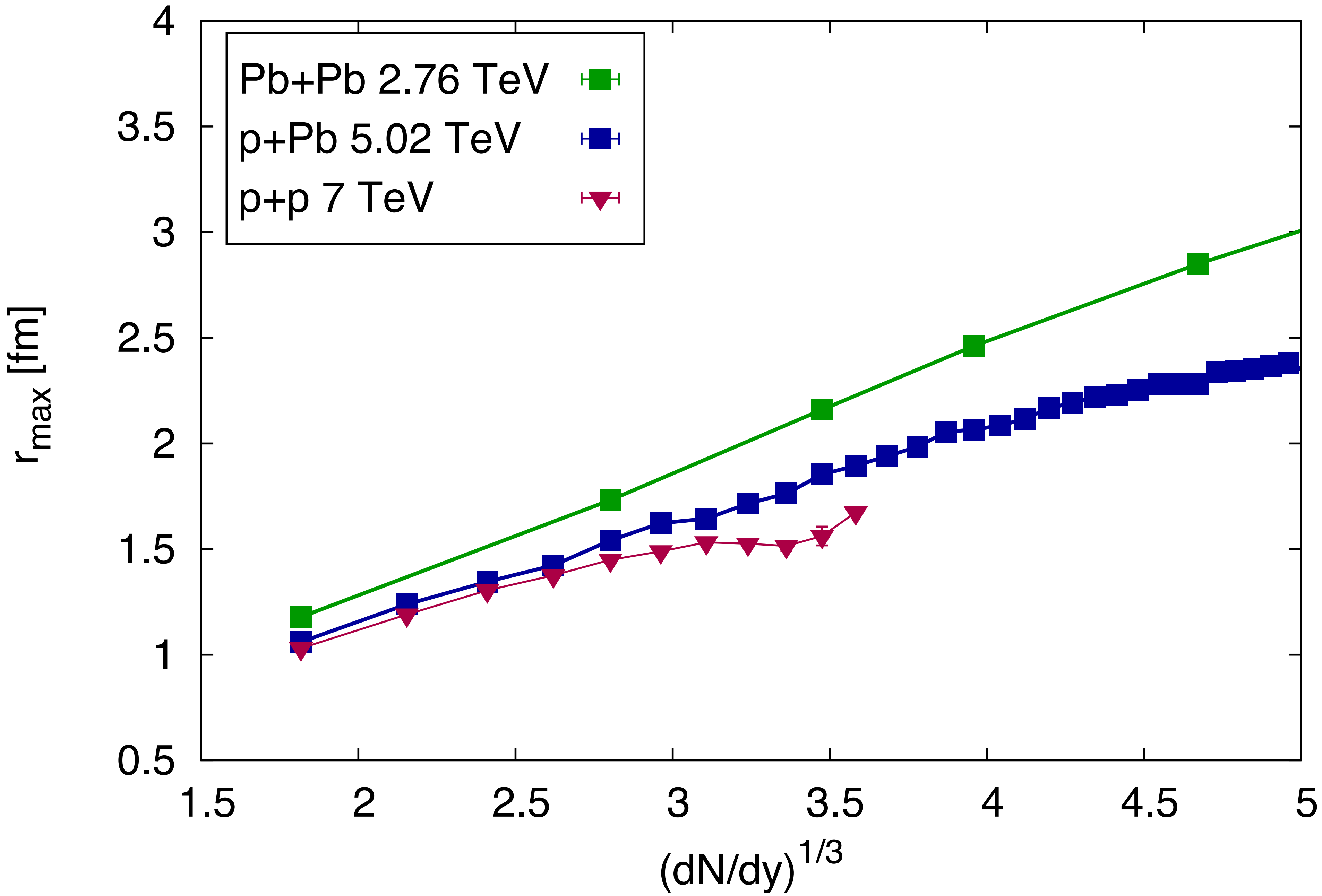








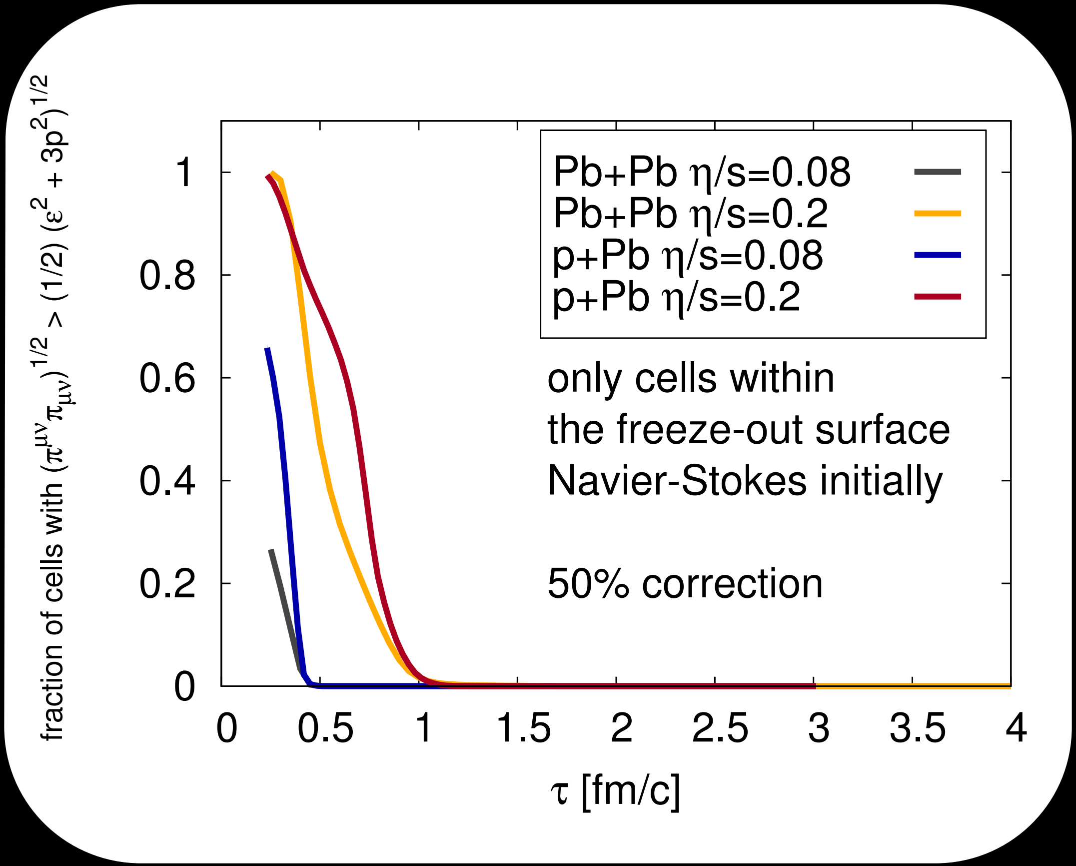
SYSTEM SIZE

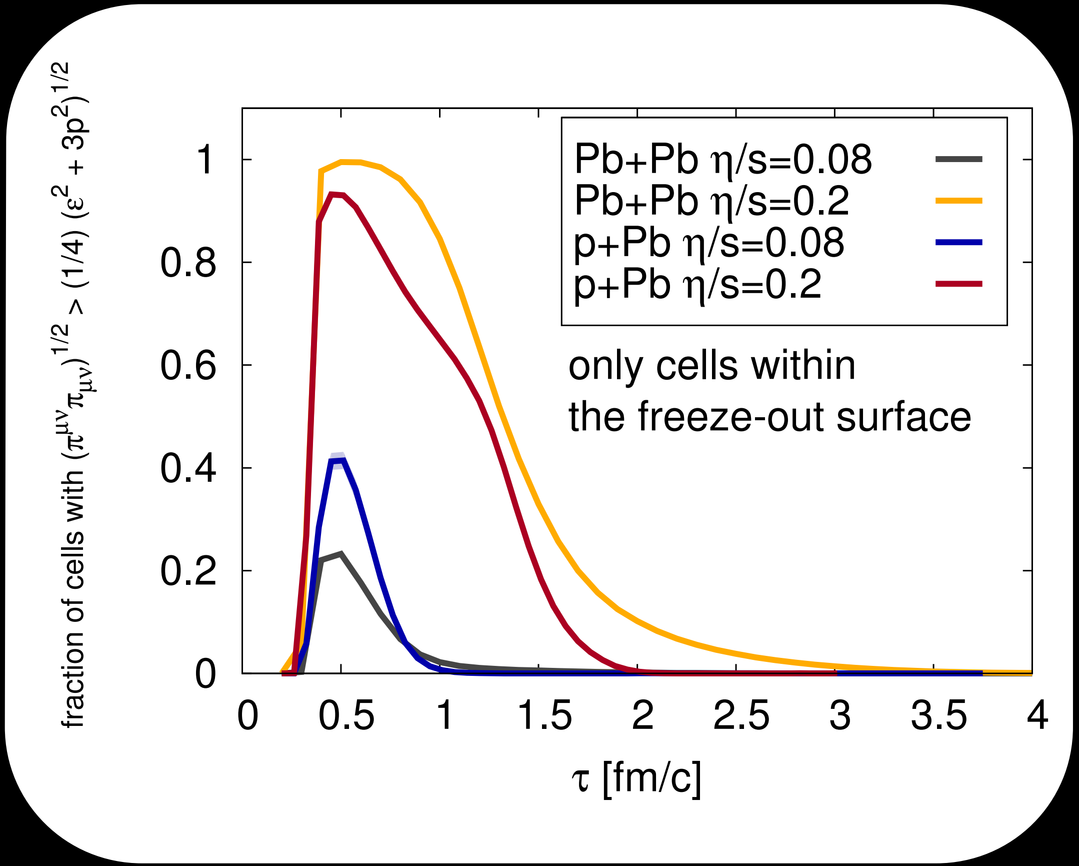


Pb+Pb 2.76 TeV
p+Pb 5.02 TeV
p+p 7 TeV
r_max [fm]
(dN/dy)^1/3
0.5
1
1.5
2
2.5
3
3.5
4
1.5
2
2.5
3
3.5
4
4.5
5

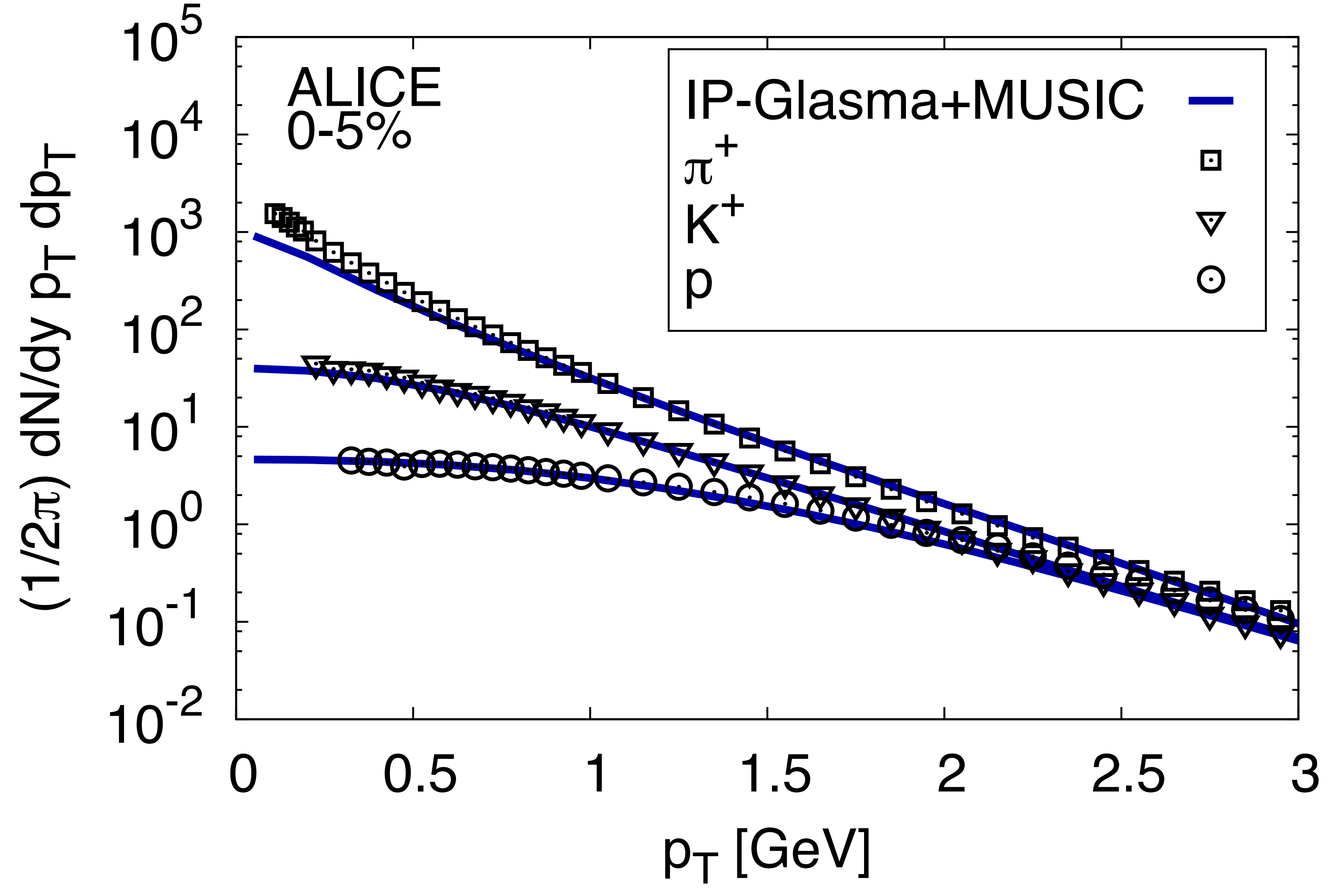
VISCOUS CORRECTION

Fraction of cells with viscous correction larger than 25% (50%) of the ideal term



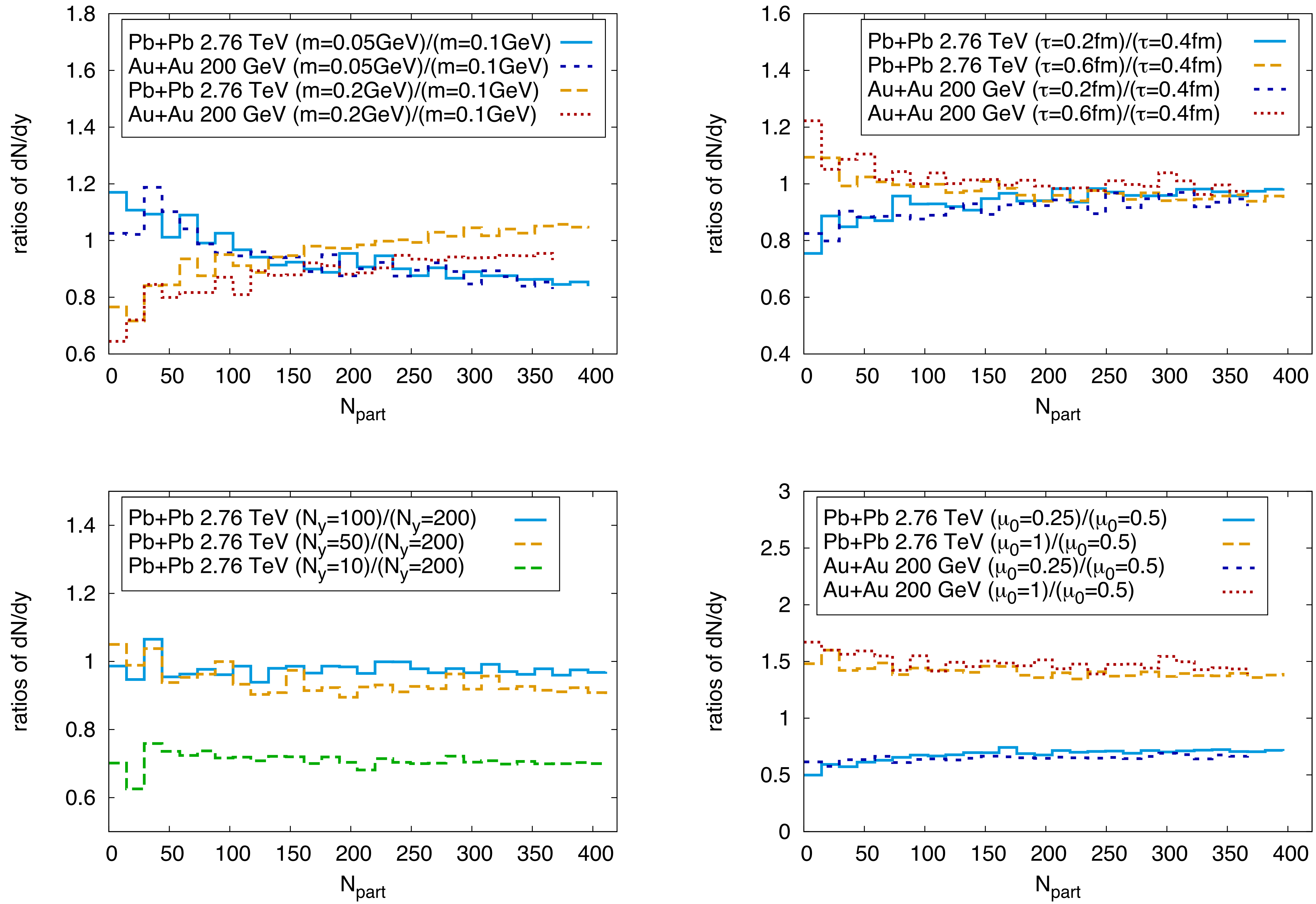


IDENTIFIED PARTICLE SPECTRA



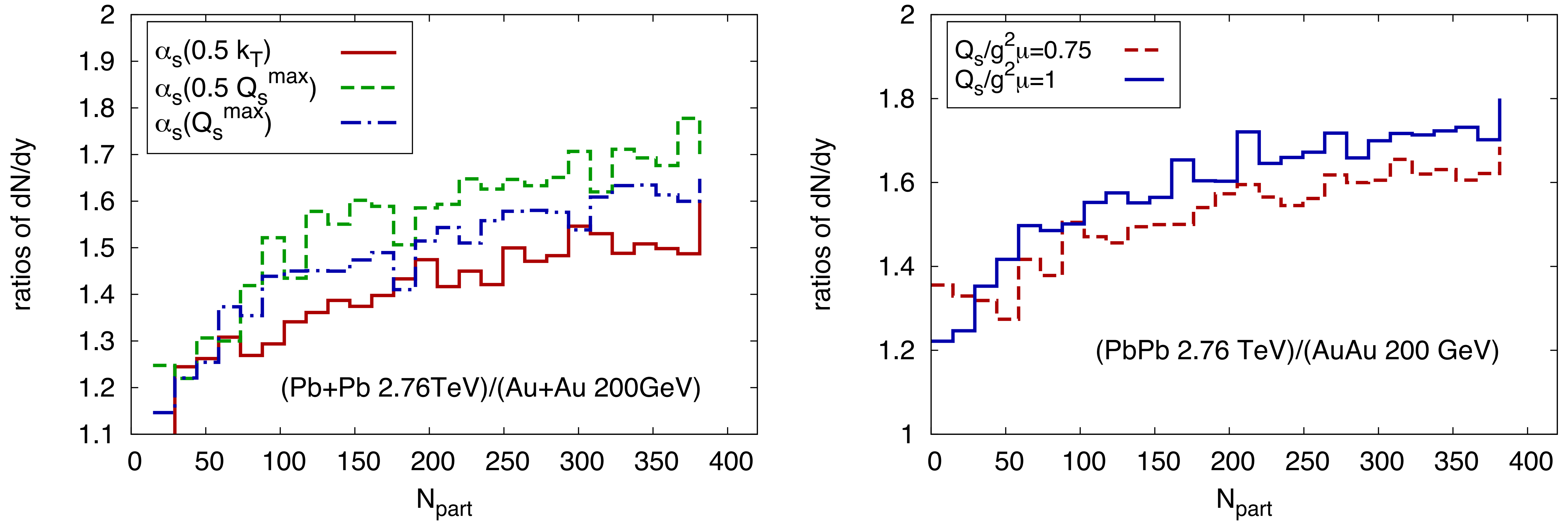
PARAMETER DEPENDENCIES

B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PHYS. REV. C89, 024901 (2014)



PARAMETER DEPENDENCIES

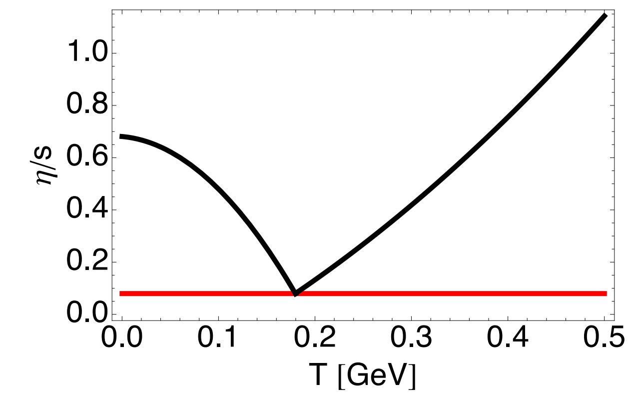
B. SCHENKE, P. TRIBEDY, R. VENUGOPALAN, PHYS. REV. C89, 024901 (2014)



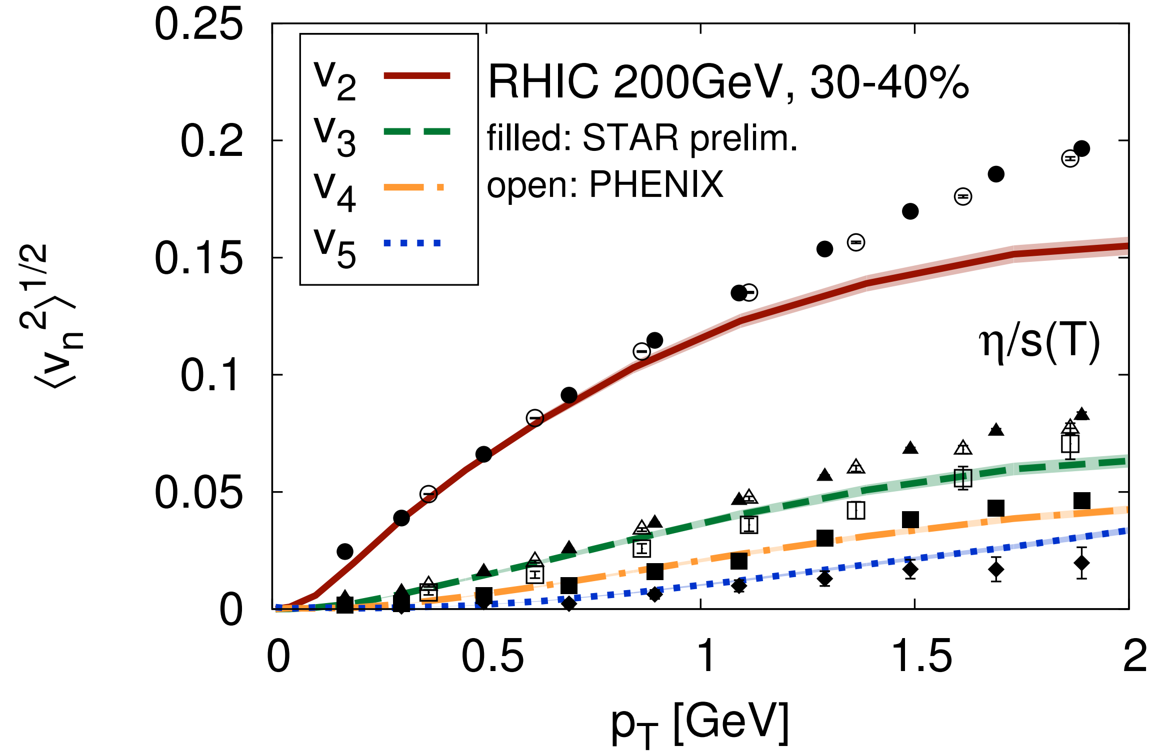
TEMPERATURE DEPENDENT η/s

Use $\eta/s(T)$ as in Niemi et al., Phys.Rev.Lett. 106 (2011) 212302

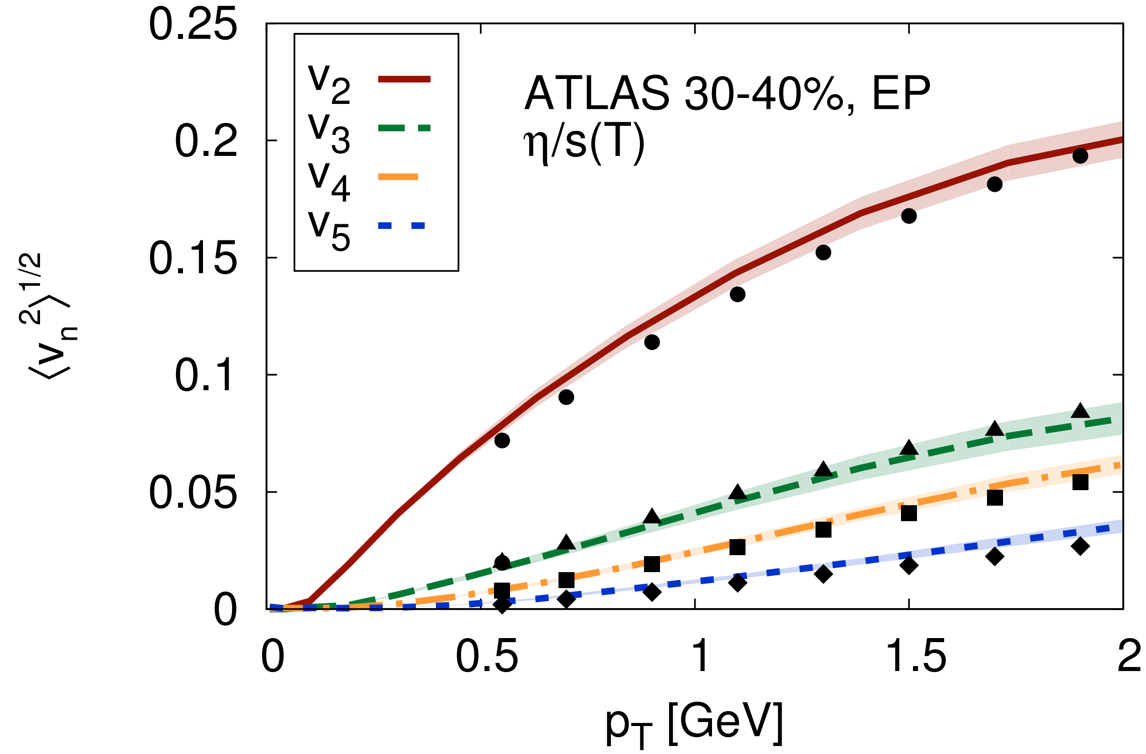
Experimental data: A. Adare et al. (PHENIX), Phys.Rev.Lett. 107, 252301 (2011)
Y. Pandit (STAR), Quark Matter 2012, (2012)
ATLAS collaboration, Phys. Rev. C 86, 014907 (2012)



RHIC



LHC



One $(\eta/s)(T)$ will be able to describe both RHIC and LHC data

Used parametrization not yet perfect: no surprise

More detailed study needed - include different RHIC energies and LHC