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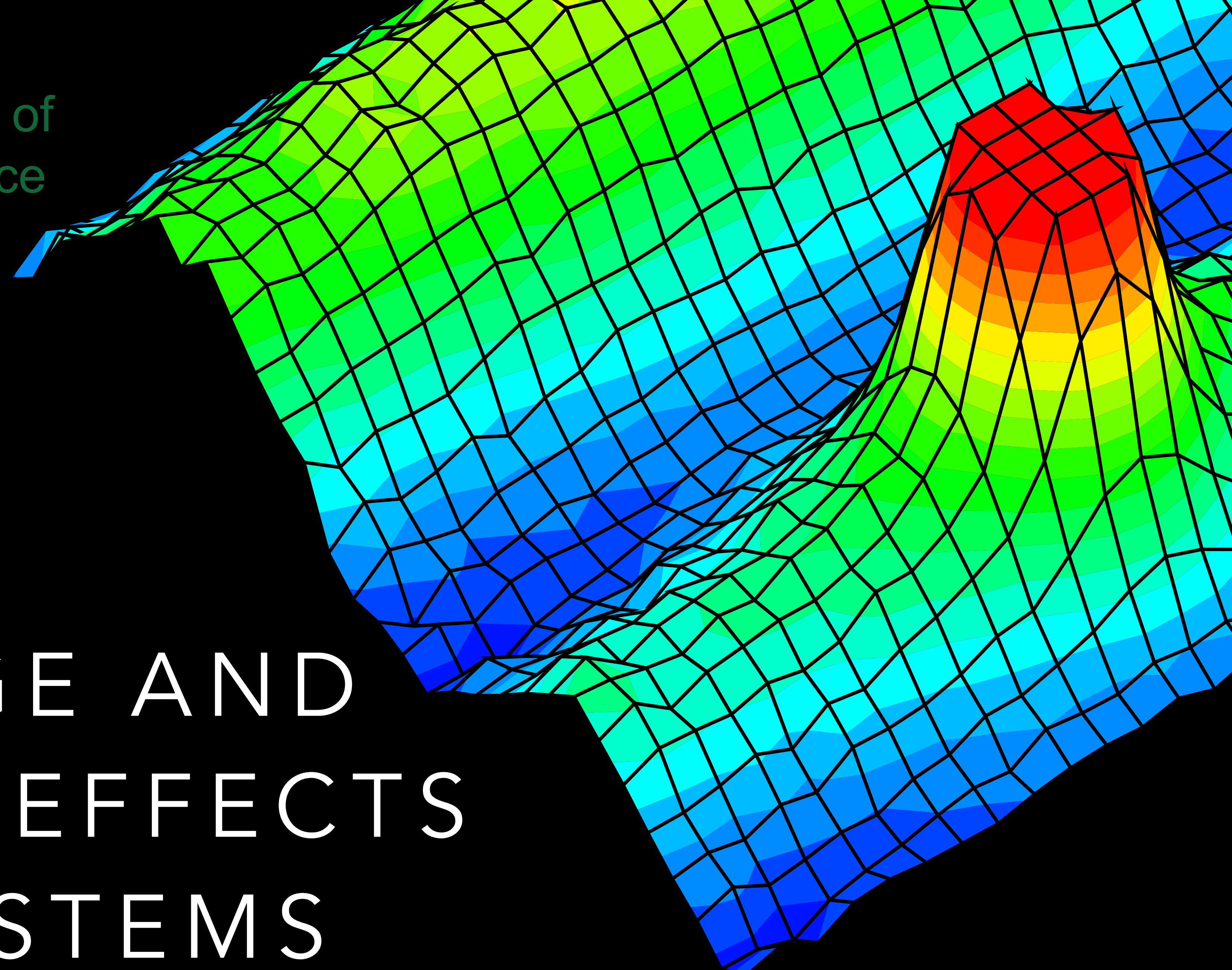


INITIAL STAGE AND COLLECTIVE EFFECTS IN SMALL SYSTEMS

Björn Schenke
Brookhaven National Laboratory

June 6, 2018
LHCP 2018
Bologna, Italy

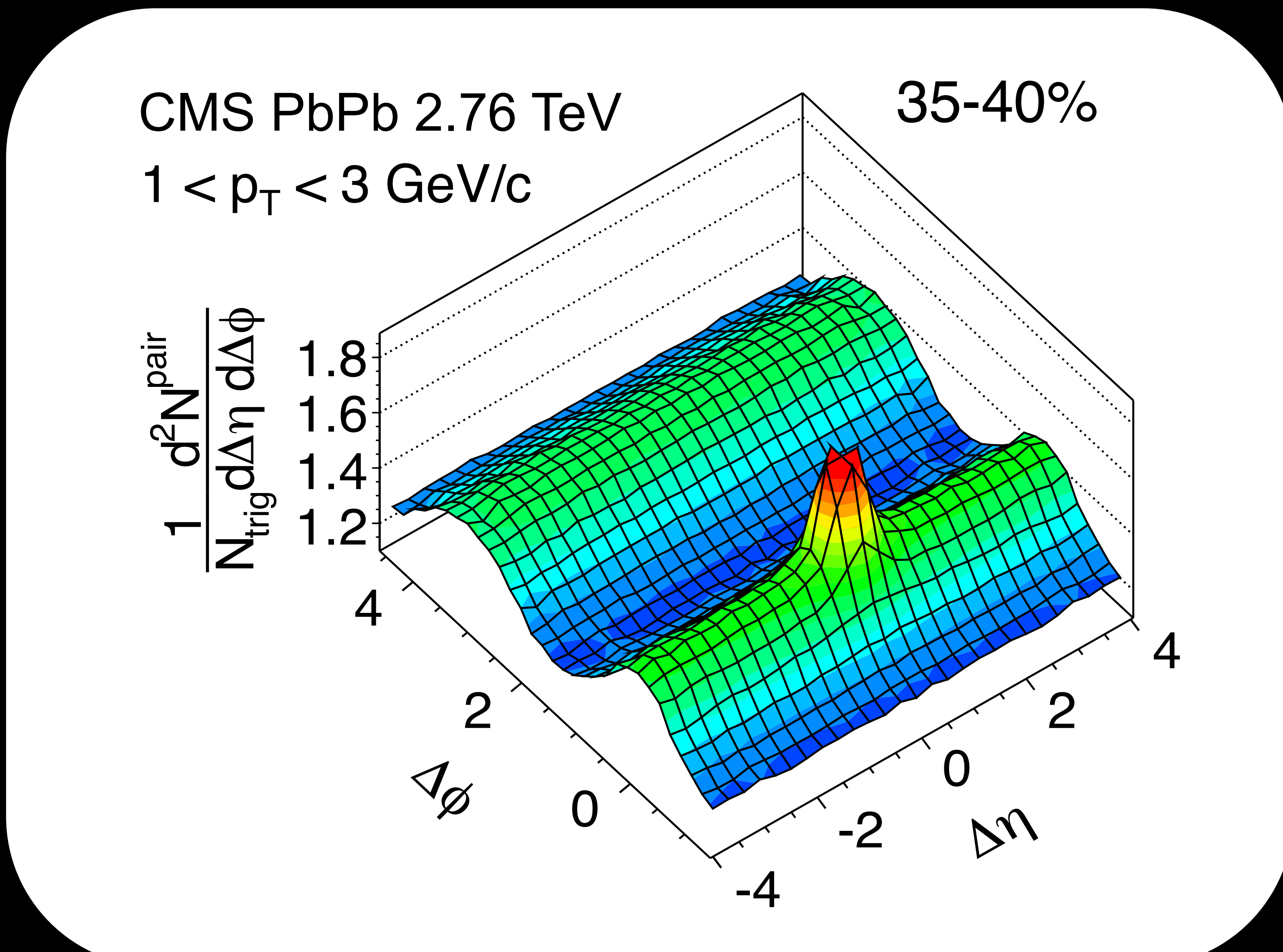
BROOKHAVEN NATIONAL LABORATORY

TWO-PARTICLE CORRELATIONS

2-particle correlation as a function of Δη and Δϕ

ΔΗ: DIFFERENCE IN PSEUDO-RAPIDITY

ΔΦ: DIFFERENCE IN AZIMUTHAL ANGLE



CMS COLLABORATION, EUR. PHYS. J. C72 (2012)

Ridge:
Structure that is long range in Δη and generally shows two bumps in Δϕ "double-ridge"

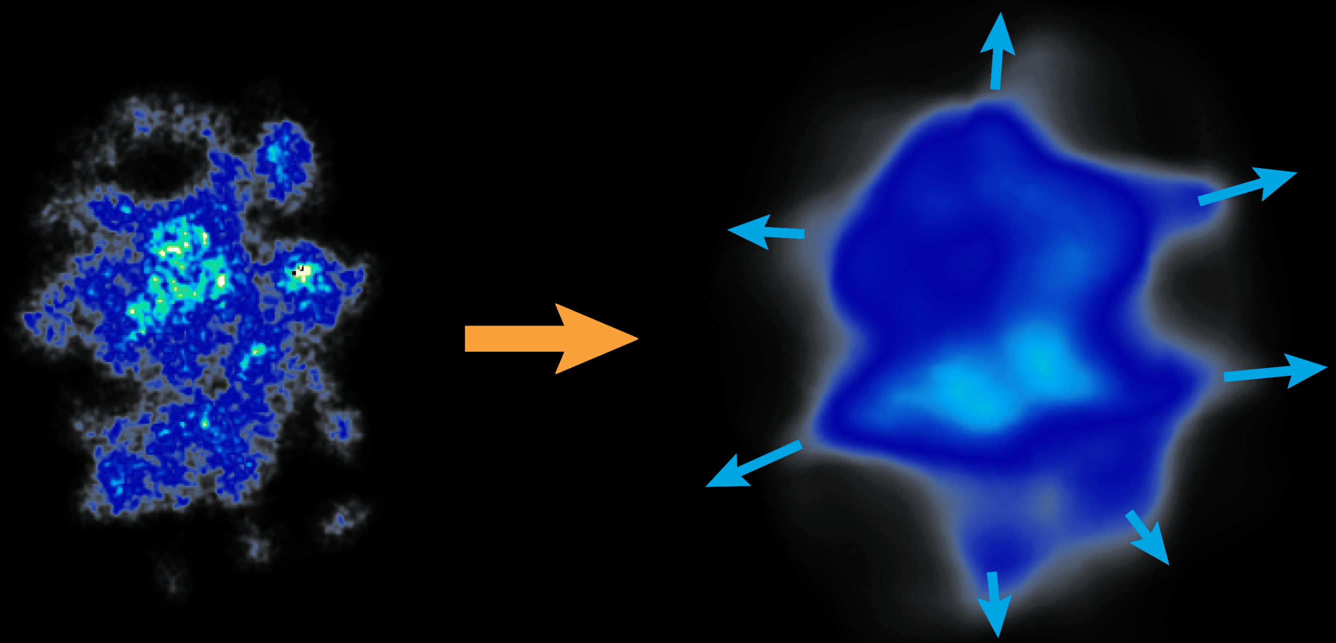
RIDGE IN HEAVY ION COLLISIONS

First seen in heavy ion collisions at RHIC

STAR COLLABORATION, PHYS. REV. C80 (2009) 064912
PHOBOS COLLABORATION, PHYS. REV. LETT. 104 (2010) 062301

Interpretation in heavy ion collision:

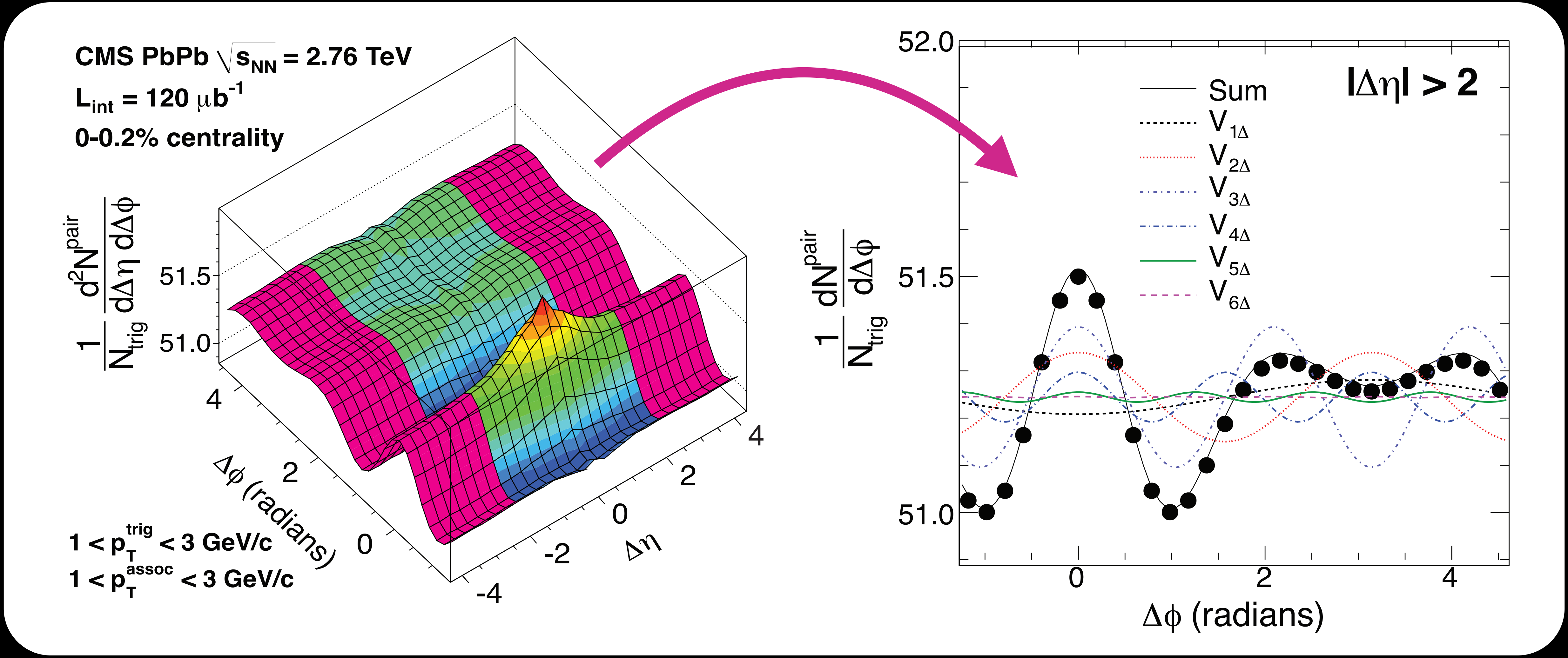
- Long range correlations emerging from early times (causality)
- Azimuthal structure formed by the medium response to the initial transverse geometry (well described by hydrodynamics)



2 ridges come from dominant cos(2ΔΦ) contribution due to the mostly elliptic shape

RIDGE IN HEAVY ION COLLISIONS

Azimuthal structure quantified using Fourier expansion



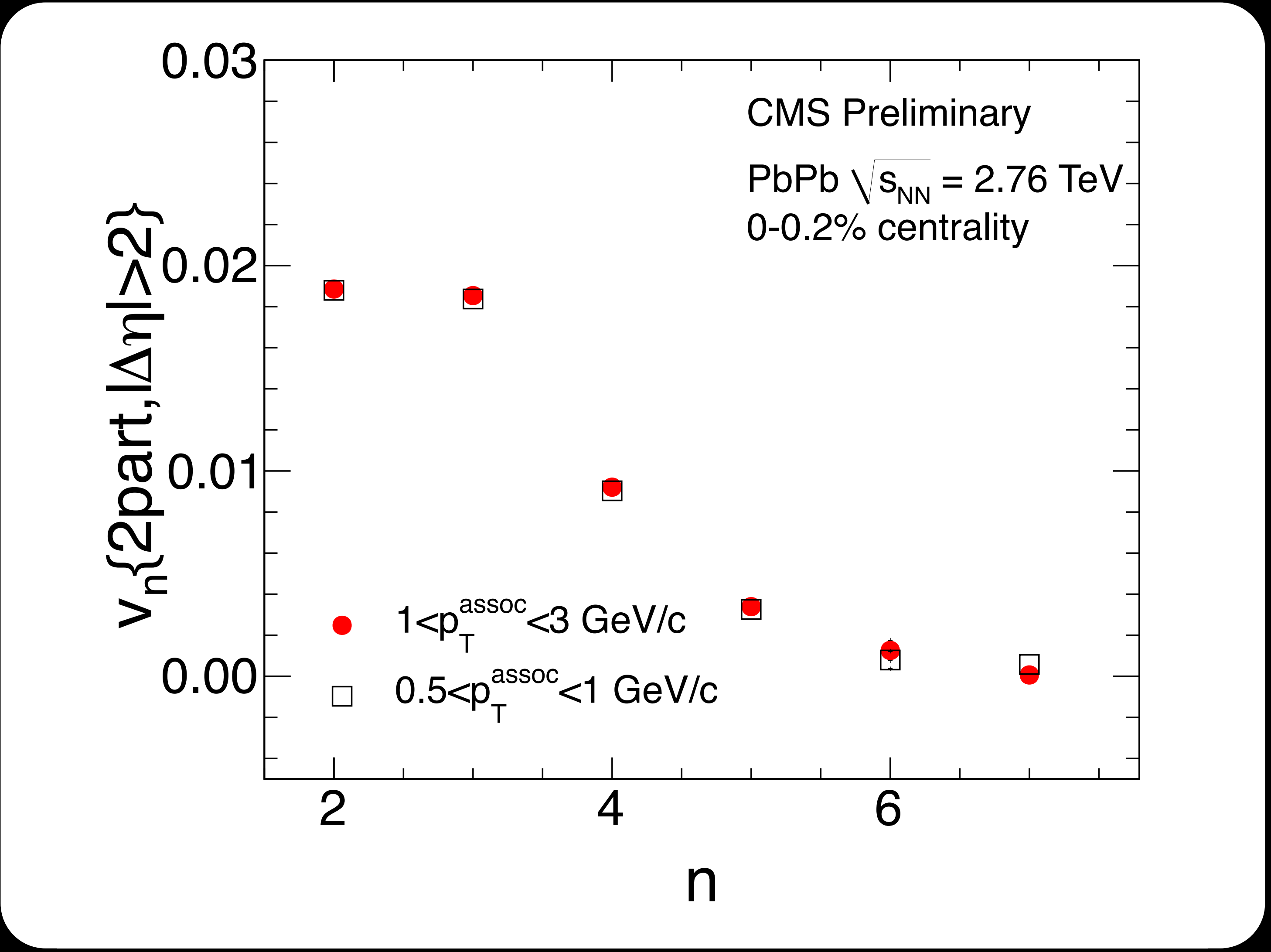
$$\frac{1}{N_{\rm trig}} \frac{dN^{\rm pair}}{d\Delta\phi} \sim 1 + 2 \sum_{n=1}^{n=\infty} V_{n\Delta}(p_T^{\rm trig}, p_T^{\rm assoc}) \cos(n\Delta\phi) \qquad v_n = \sqrt{V_{n\Delta}}$$

CMS COLLABORATION, JHEP 02 (2014) 088

RIDGE IN HEAVY ION COLLISIONS

Azimuthal structure quantified using Fourier expansion

V_n

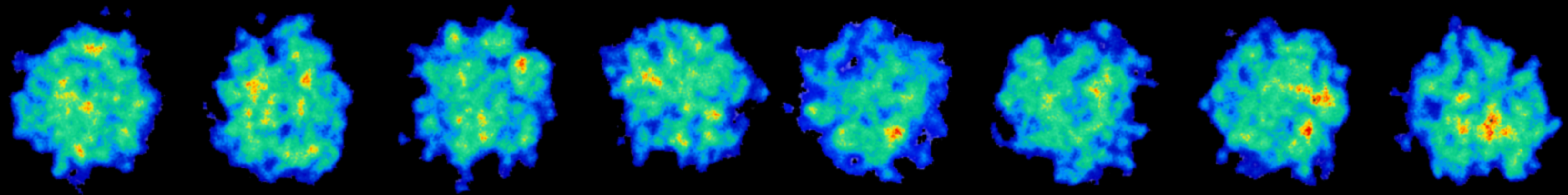


$$\frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}}{d\Delta\phi} \sim 1 + 2\sum_{n=1}^{n=\infty} V_{n\Delta}(p_T^{\rm trig}, p_T^{\rm assoc})\cos(n\Delta\phi) \qquad v_n = \sqrt{V_{n\Delta}}$$

CMS COLLABORATION, JHEP 02 (2014) 088

THEORETICAL DESCRIPTION IN HEAVY IONS

Fluctuating nucleon positions and color charges ➞
Fluctuating deposited energy



High energy: Initial energy density can be computed in the color glass condensate framework (effective theory of QCD)

One realization is the IP-Glasma model

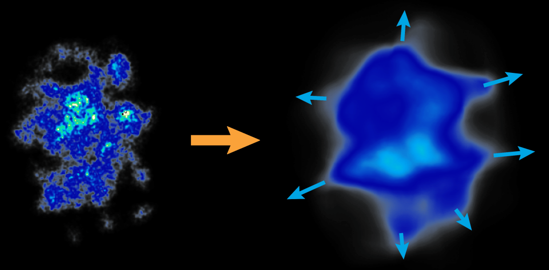
Includes gluon saturation at high densities

(small x and small transverse momentum $p_T \lesssim Q_S$)

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

Pressure gradients drive the evolution

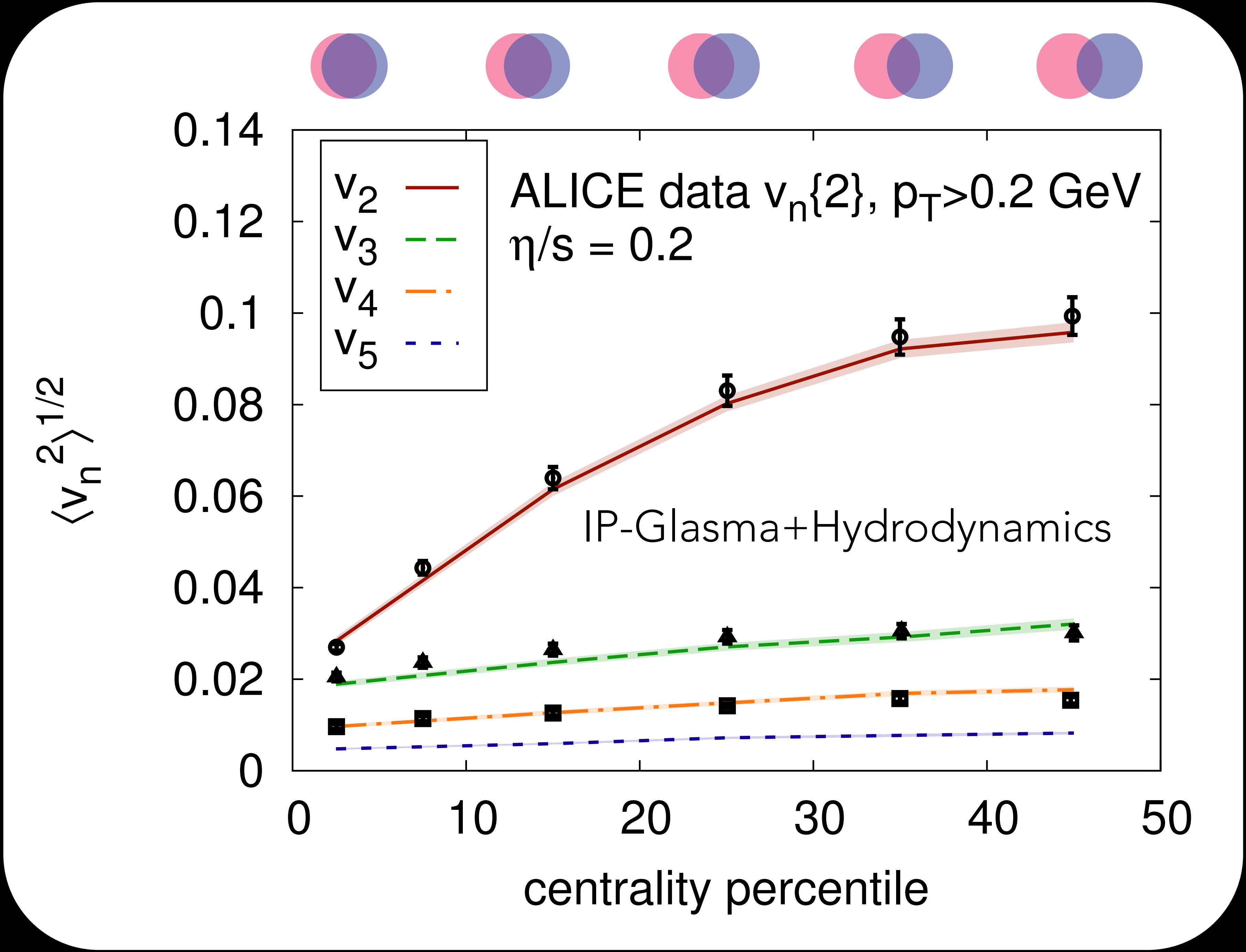
Described by hydrodynamics



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

COMPARISON OF THEORY TO EXPERIMENT

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

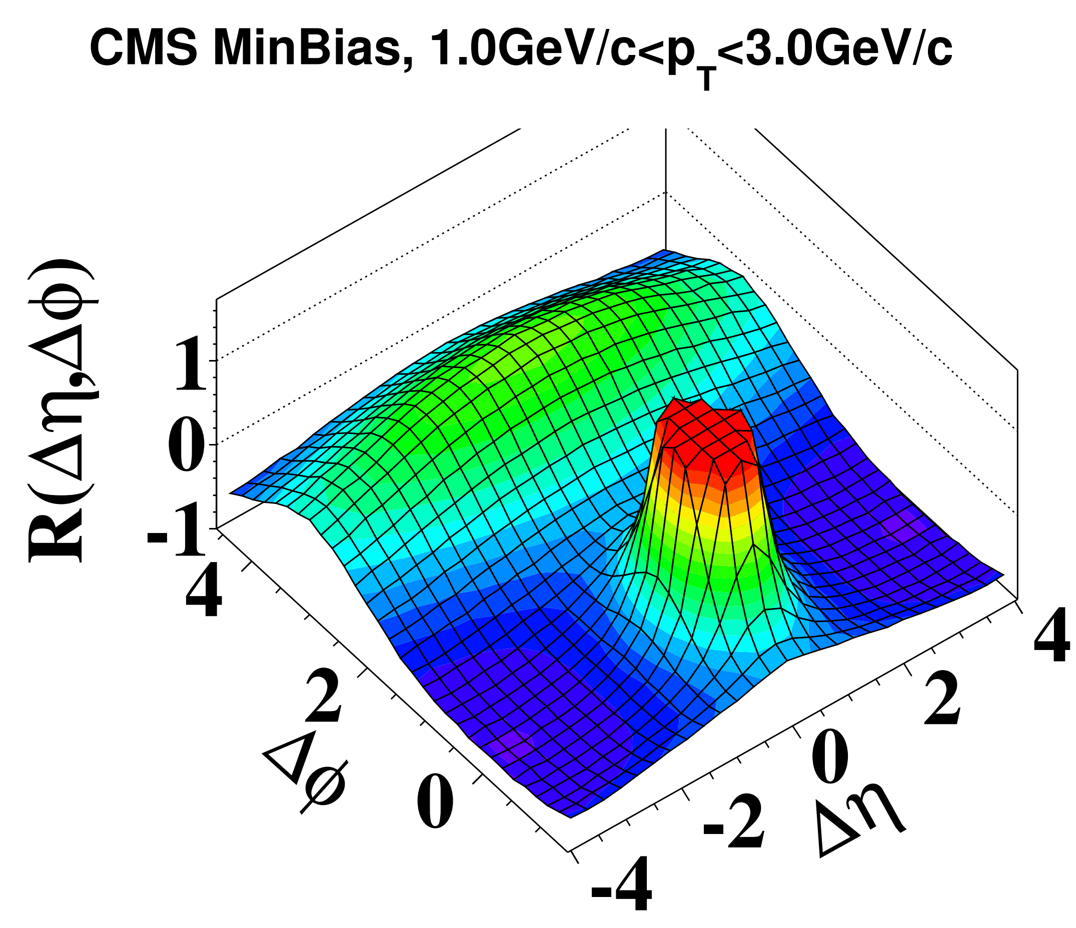


Quantitative description of the experimental data!

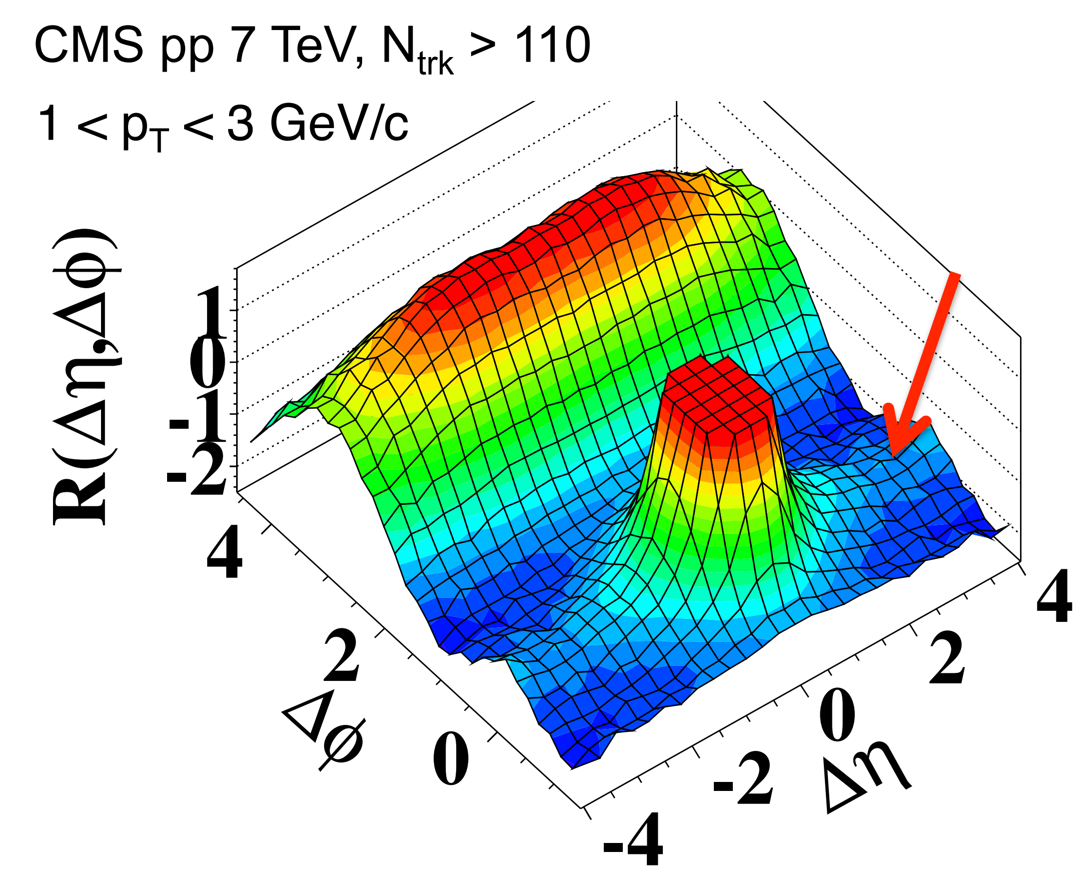
ALICE COLLABORATION, PHYS. REV. LETT. 107, 032301 (2011)

RIDGE IN SMALL COLLISION SYSTEMS

minimum bias p+p



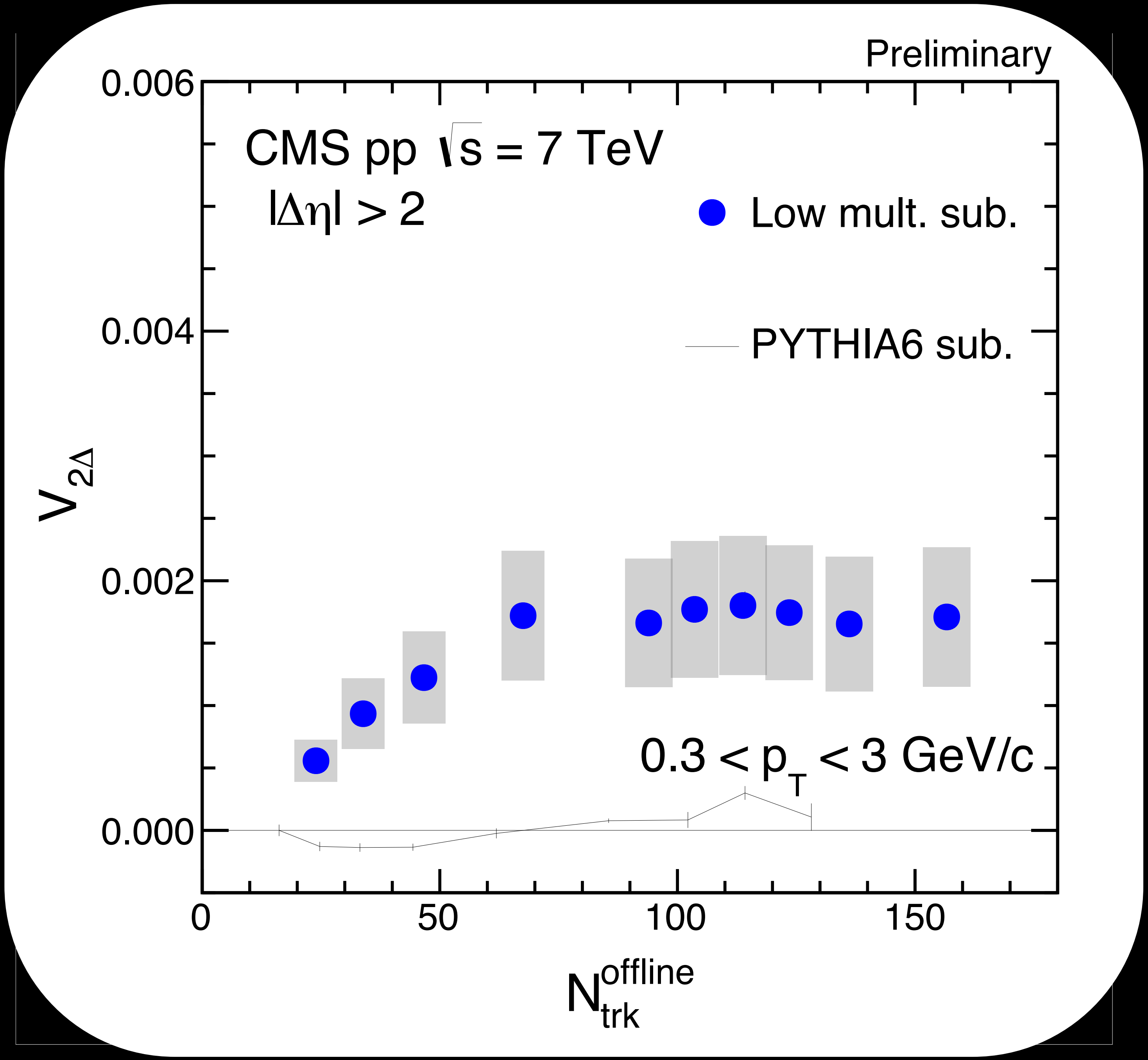
high multiplicity p+p



CMS COLLABORATION, JHEP09 (2010) 091

$v_{2\Delta}$ IN p+p COLLISIONS

Result after correcting for back-to-back jet correlations estimated from low multiplicity events



No ridge in PYTHIA

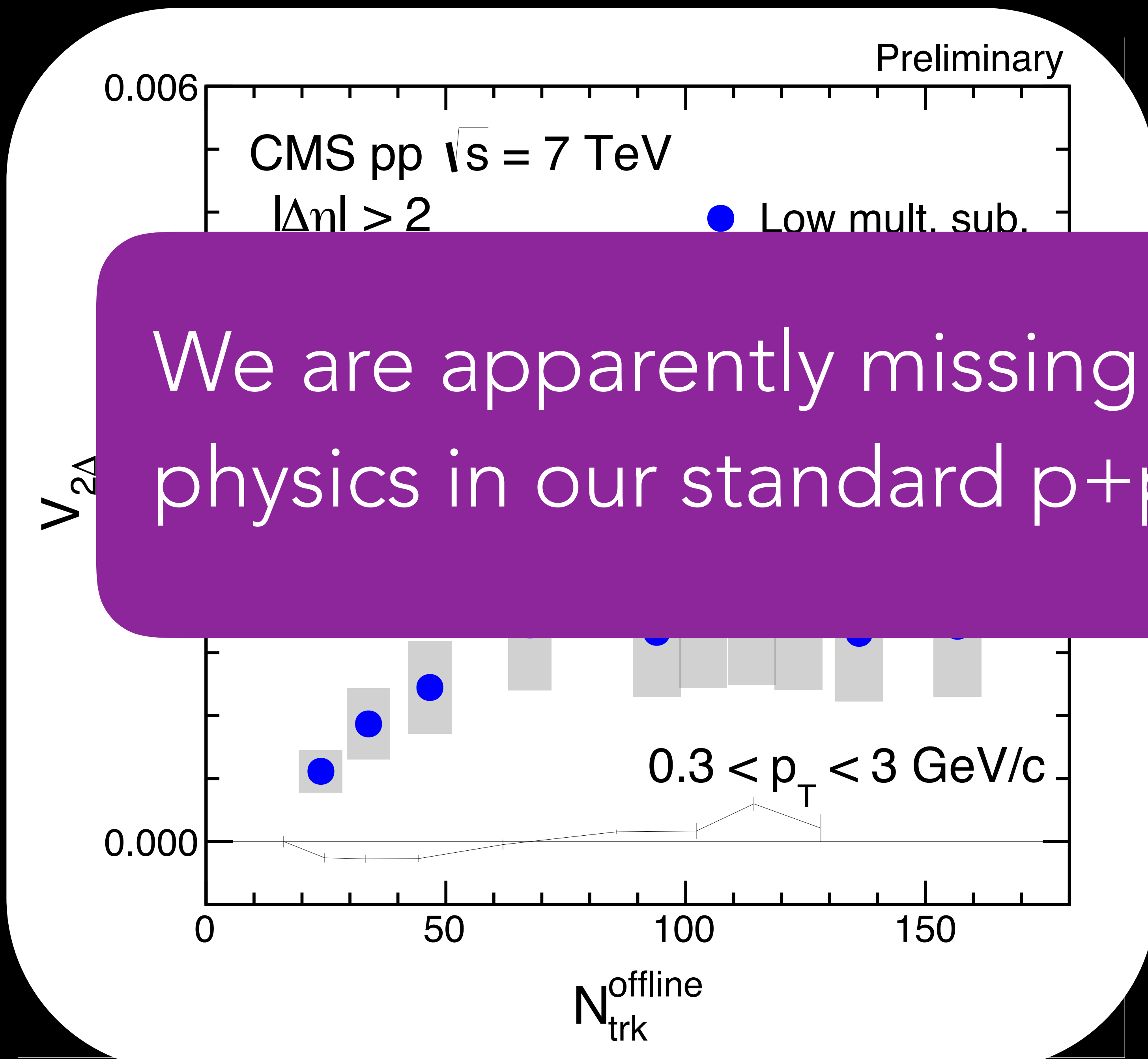
CMS PAS HIN-15-009

But progress including *final* state effects via 'string shoving'

In Pythia8 v.8.235; Bierlich, Gustafson, Lönnblad: PLB779 (2018) 58-63
Bierlich, arXiv:1606.09456 [hep-ph]
Bierlich, Gustafson, Lönnblad, Tarasov JHEP 1503 (2015) 148

$V_{2\Delta}$ IN p+p COLLISIONS

Result after correcting for back-to-back jet correlations estimated from low multiplicity events



No ridge in PYTHIA

ding

ia

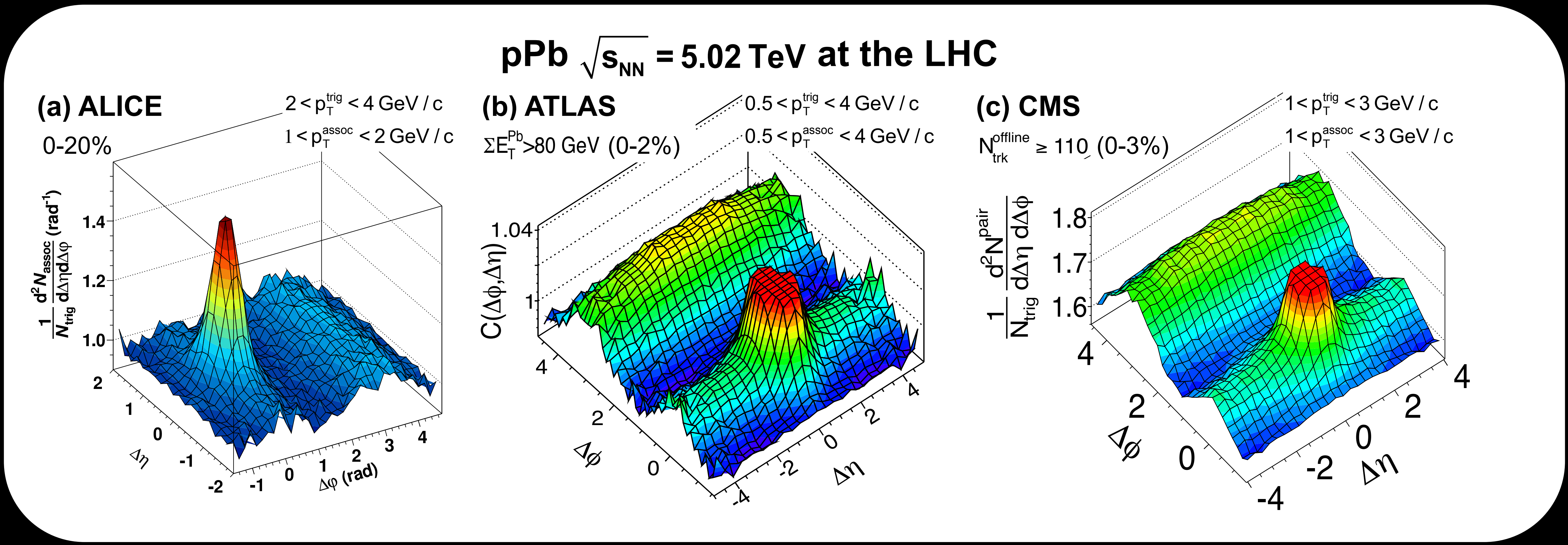
'string shoving'

We are apparently missing important physics in our standard p+p event generators!

In Pythia8 v.8.235; Bierlich, Gustafson, Lönnblad: PLB779 (2018) 58-63
Bierlich, arXiv:1606.09456 [hep-ph]
Bierlich, Gustafson, Lönnblad, Tarasov JHEP 1503 (2015) 148

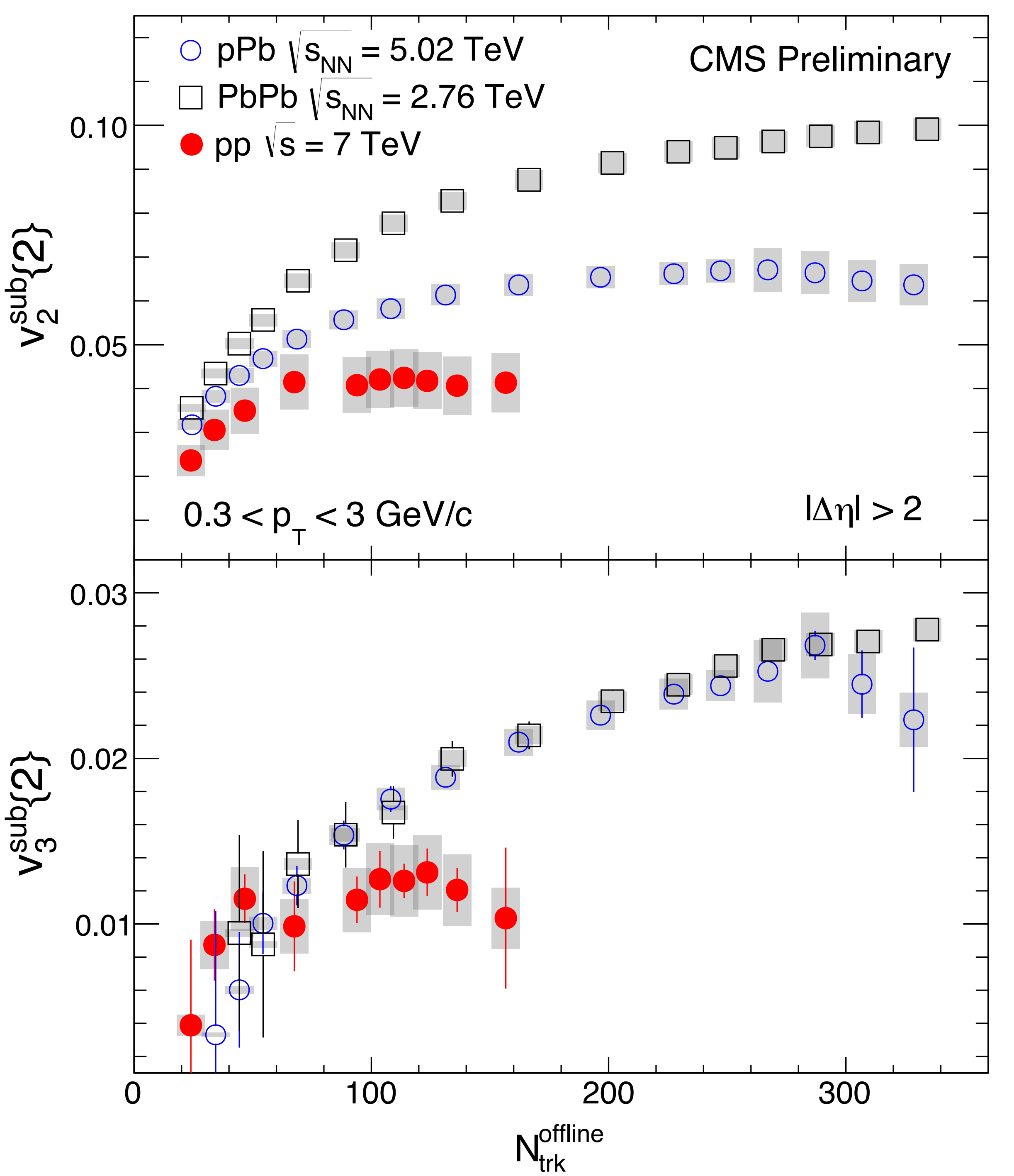
RIDGE IN p+Pb COLLISIONS

high multiplicity p+Pb



ALICE COLLABORATION, PHYS. LETT. B 719 (2013) 29
ATLAS COLLABORATION, PHYS. REV. LETT. 110 (2013) 182302
CMS COLLABORATION, PHYS. LETT. B 718 (2013) 795

v_2 IN p+p, p+Pb, Pb+Pb COLLISIONS



CMS PAS HIN-15-009

SEE ALSO:

ALICE COLLABORATION
PHYS. LETT. B719 (2013) 29-41;
PHYS. REV. C 90, 054901

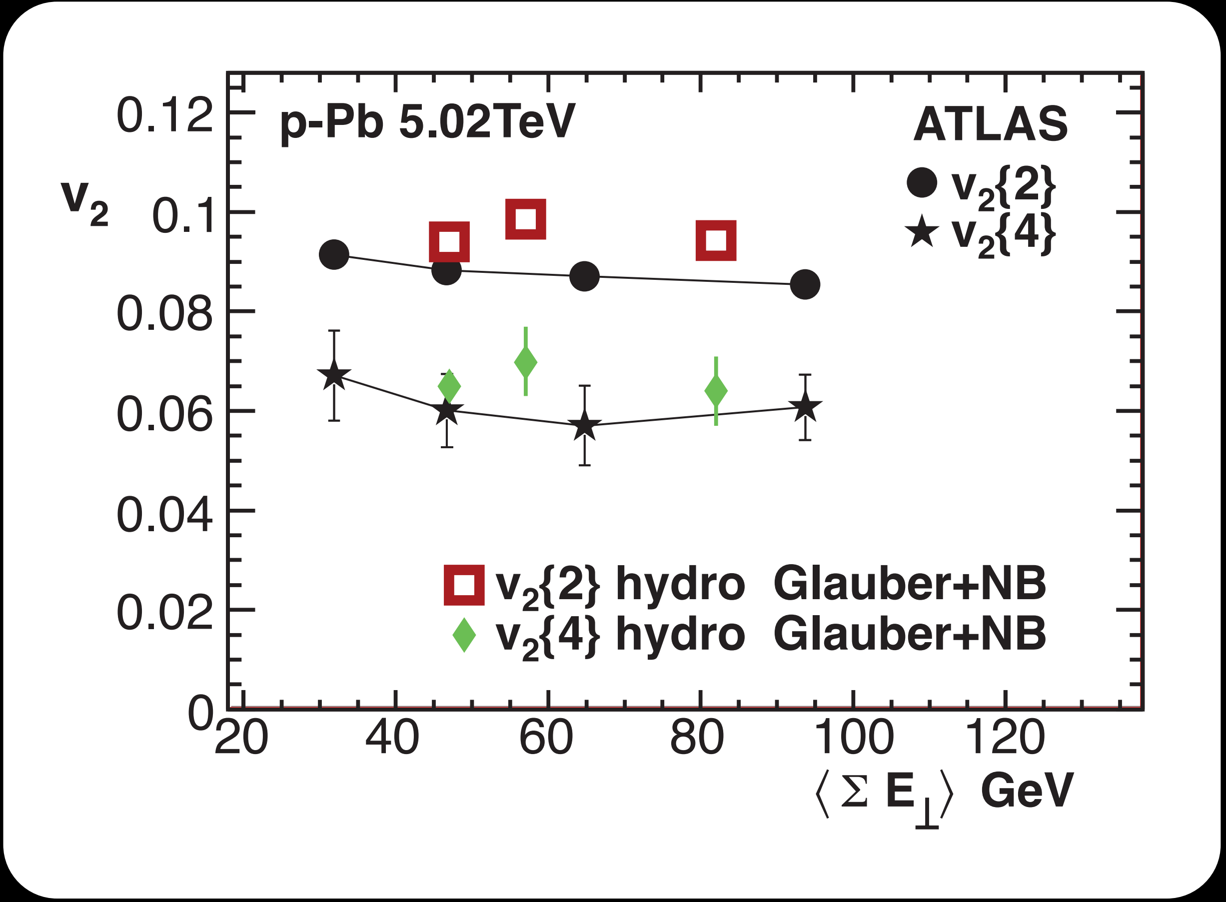
ATLAS COLLABORATION
PHYS. REV. LETT. 110, 182302 (2013); PHYS. REV. C 90.044906 (2014)

CMS COLLABORATION
PHYS.REV.LETT. 115, 012301 (2015)

HYDRO IN SMALL SYSTEMS

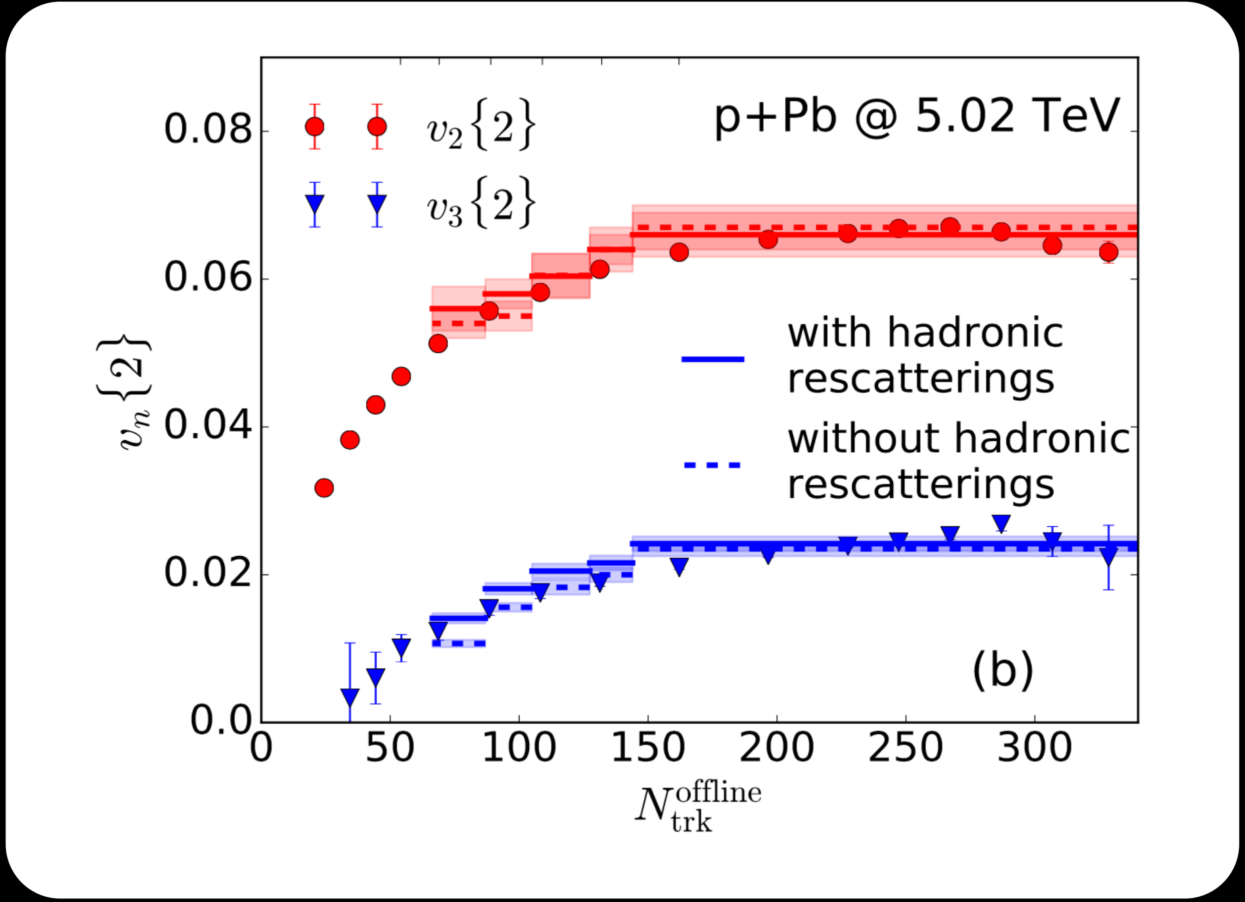
MC-Glauber initial state + viscous hydrodynamics works

ATLAS Coll. PLB725 (2013) 60-78



Bozek, Broniowski, PRC88 (2013) 014903

CMS Coll. PLB724, 213–240 (2013)

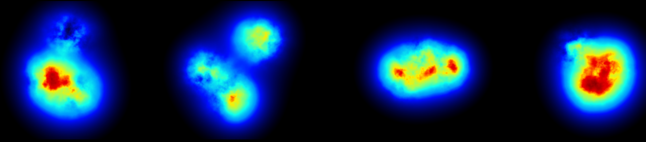


Shen, Paquet, Denicol, Jeon, Gale, PRC95 (2017) 014906

Also see: Kozlov, Luzum, Denicol, Jeon, Gale; Werner, Beicher, Guiot, Karpenko, Pierog; Romatschke; Kalaydzhyan, Shuryak, Zahed; Ghosh, Muhuri, Nayak, Varma; Qin, Mueller; Bozek, Broniowski, Torrieri; Habich, Miller, Romatschke, Xiang; T. Hirano, K. Kawaguchi, K. Murase; …

IP-Glasma + hydro + fluctuating proton geometry

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)

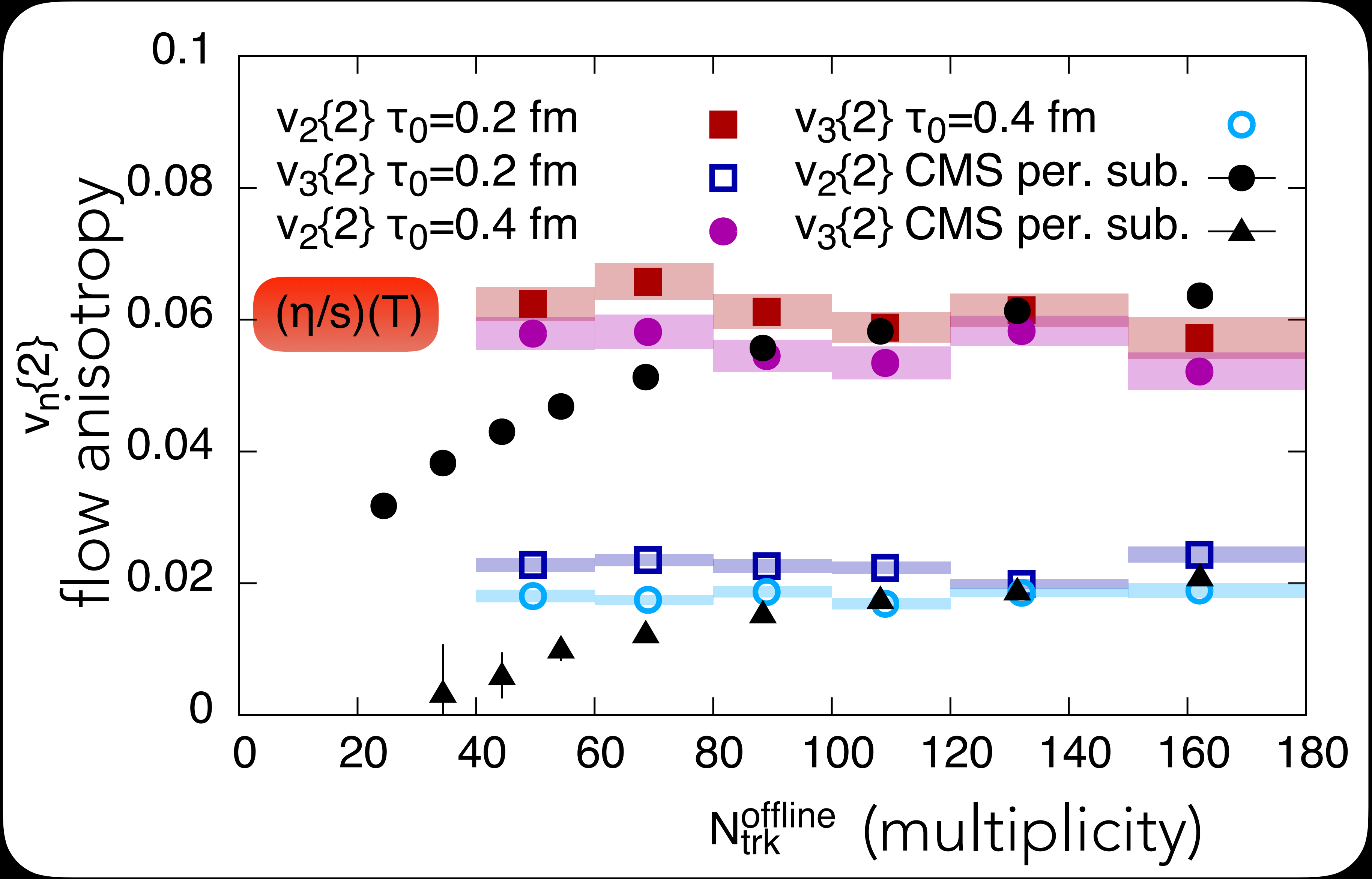


Constrain that fluctuating geometry by HERA diffractive J/Ψ prod.

H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

Round proton would produce much smaller v_n

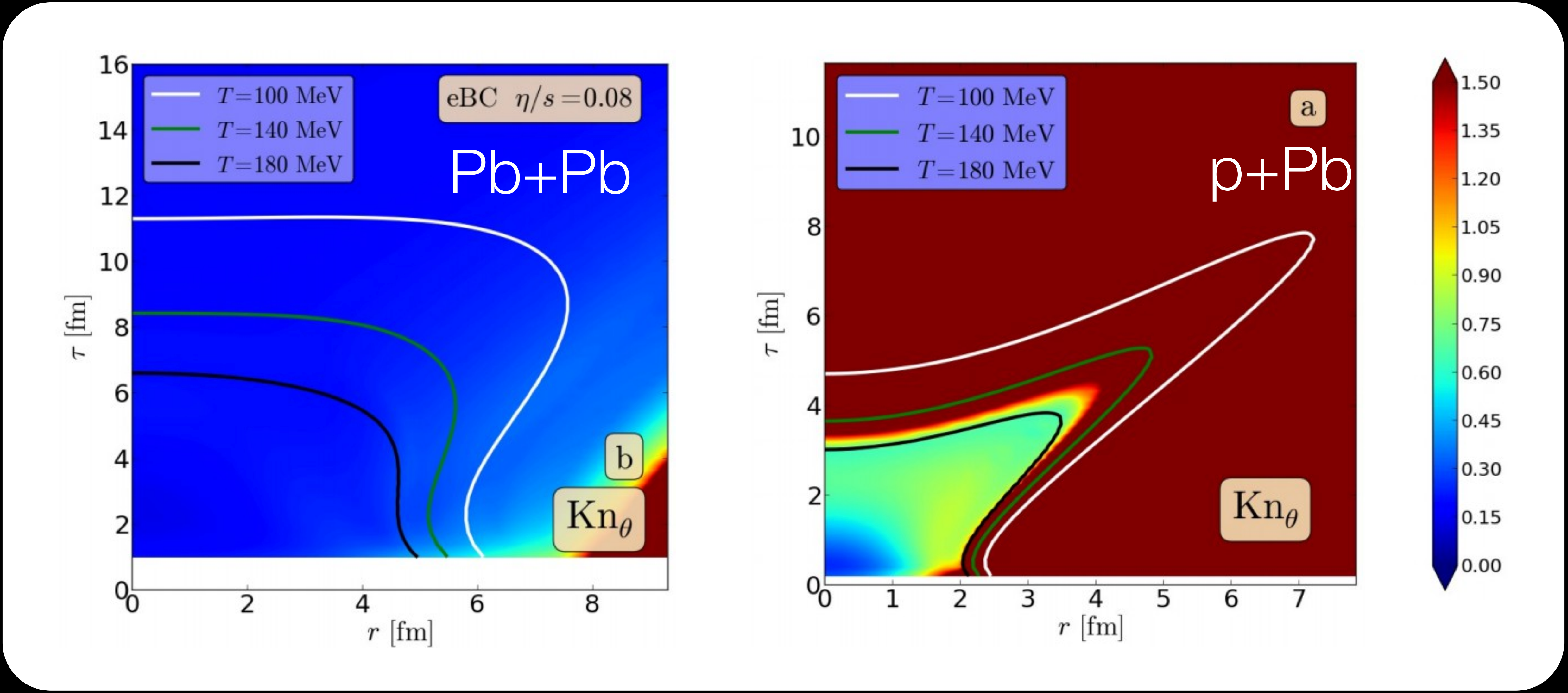
Would not describe the data



CAN WE TRUST HYDRODYNAMICS?

Knudsen number: ratio of a microscopic over macroscopic scale

Small Knudsen number means hydrodynamics is valid



H. NIEMI, G.S. DENICOL, E-PRINT: ARXIV:1404.7327

see review W. Florkowski, M. P. Heller, M. Spalinski, Rept.Prog.Phys. 81 (2018) 046001 on recent progress in understanding the validity of relativistic hydrodynamics in systems with large gradients

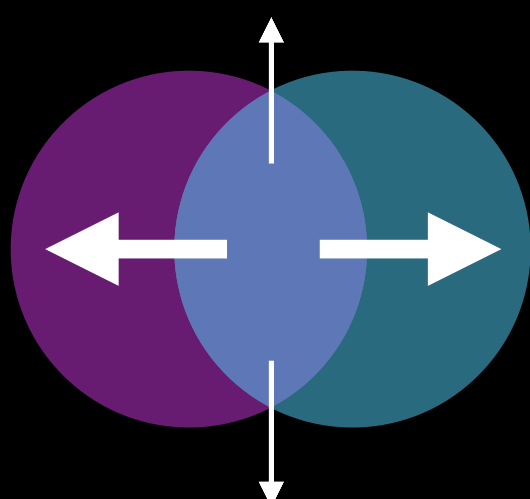
SEE TALK BY S. FLOERCHINGER ON TUESDAY

KINETIC THEORY "ANISOTROPIC ESCAPE"

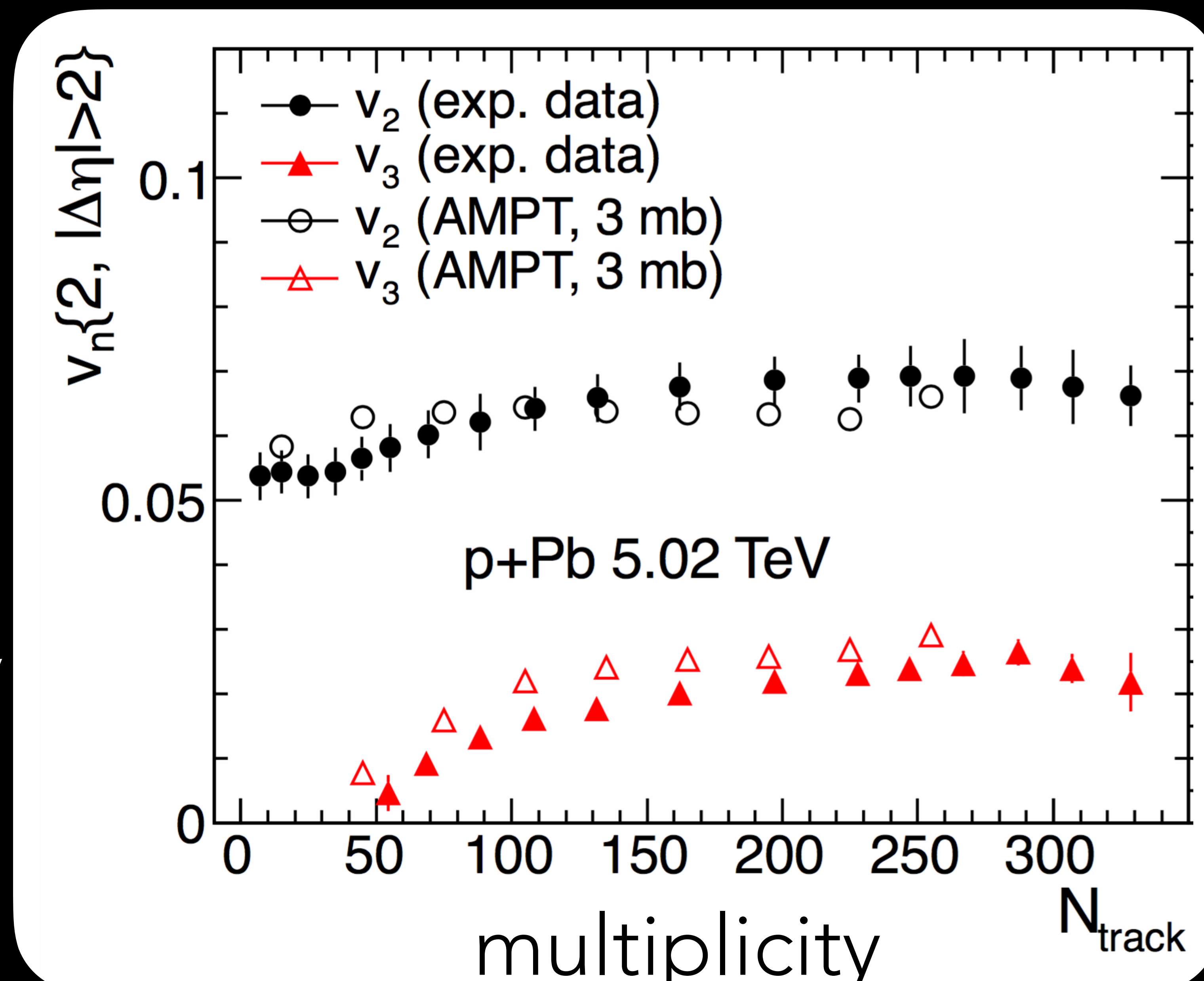
A. Bzdak, G.-L. Ma, PRL113 (2014) 252301; G.-L. Ma, A. Bzdak, PLB739 (2014) 209-213;
J.D. Orjuela Koop, A. Adare, D. McGlinchey, J.L. Nagle, PRC92 (2015) 054903; P. Bozek, A. Bzdak, G.-L. Ma, PLB748 (2015) 301-305; L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, F. Wang, PLB753 (2016)

Final state effect, but weakly interacting (3 mb x-sect.)

Described in AMPT

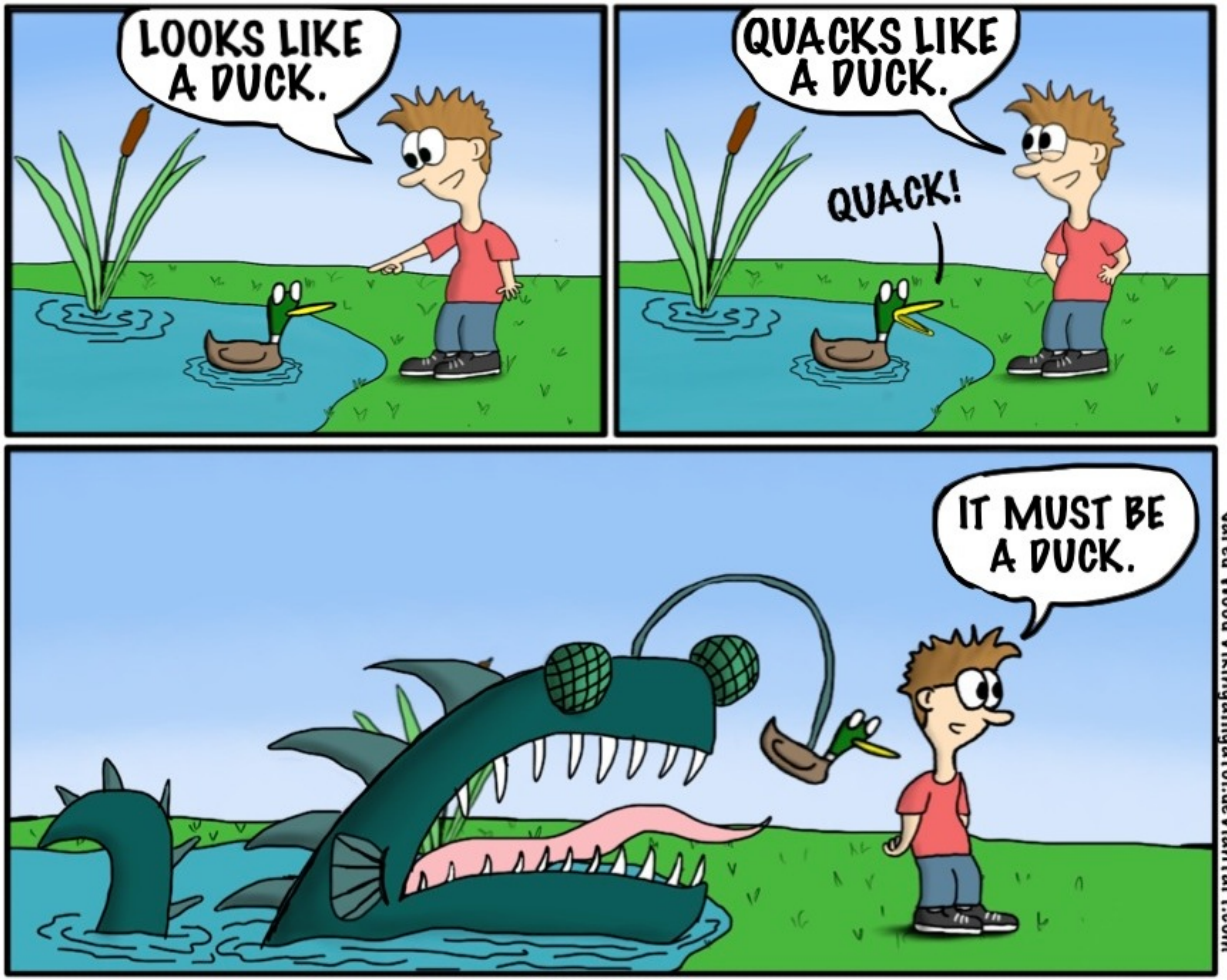


Partons are more likely to escape in the short direction → v_n



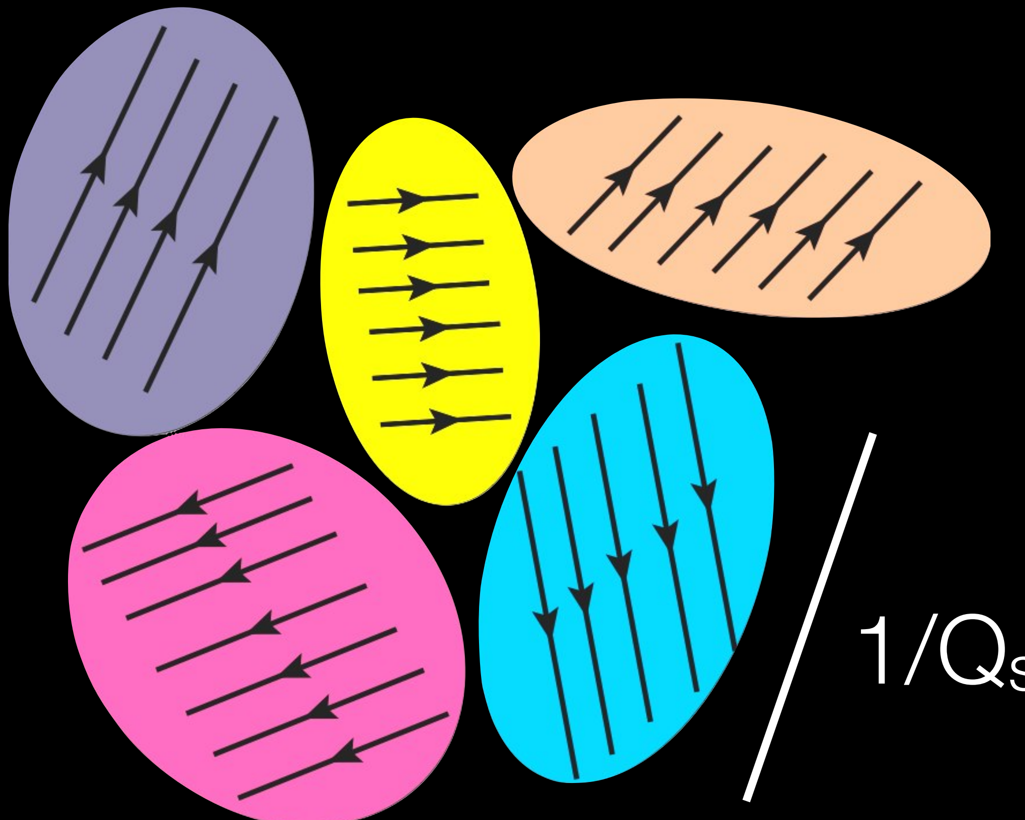
also see Kurkela, Wiedemann, Wu, arXiv:1803.02072

INITIAL STATE MOMENTUM CORRELATIONS



INITIAL STATE PICTURE

Intuitive picture:
Quarks or gluons are produced from color field domains in the Pb or p target



Particles that come from the same domain are correlated

Effect is suppressed by the number of colors and the number of domains (it is small for heavy ions)

FIGURE: T. LAPPI, B. SCHENKE, S. SCHLICHTING, R. VENUGOPALAN JHEP 1601 (2016) 061; SEE ALSO: A. DUMITRU, A.V. GIANNINI, NUCL.PHYS.A933 (2014) 212; A. DUMITRU, V. SKOKOV, PHYS.REV.D91 (2015) 074006; A. DUMITRU L. MCLERRAN, V. SKOKOV, PHYS.LETT.B743 (2015), 134; V. SKOKOV. PHYS.REV.D91 (2015) 054014

INITIAL STATE PICTURE

High-multiplicity events are rare configurations of nuclear wave-function with large number of small-x gluons

Situation described by the **Color Glass Condensate** an effective theory of QCD at high energy.
Particle production is governed by the **Yang Mills equations**

$$[D_\mu, F^{\mu\nu}] = J^\nu$$

J^ν: Combination of incoming target and projectile color currents

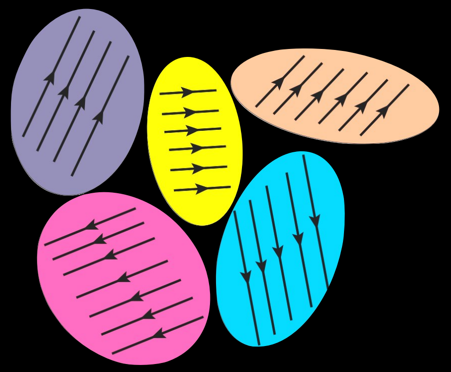
This is it.

Different approximations and assumptions on the market

APPROXIMATIONS

- **Glasma graph approximation:** two gluon exchange (not more) and Gaussian statistics of color charges (MV model)
  Gelis,Lappi Venugopalan PRD 78 054020 (2008), PRD 79 094017 (2009); Dumitru, Gelis, McLerran,Venugopalan NPA810, 91 (2008); Dumitru, Jalilian-Marian PRD 81 094015 (2010); Dusling, Venugopalan PRD 87 (2013), ...
- **Non-linear Gaussian approximation:**
  Resums multi-gluon exchanges - still Gaussian statistics
  McLerran, Venugopalan, PRD 59 (1999) 094002; Dominguez, Marquet, Wu, NPA 823 (2009) 99; Lappi, Schenke, Schlichting, Venugopalan, JHEP 1601 (2016) 061; ...
- **Numerical solution:** Solves the Yang-Mills equations exactly for any initial color source statistics and spatial configuration, includes multiple-gluon exchange, "rescattering"
  Krasnitz, Venugopalan, NPB 557 (1999) 237; Krasnitz, Nara, Venugopalan, NPA 717 (2003) 268; Lappi, PRC 67 (2003) 054903; Schenke, Tribedy, Venugopalan, PRL 108 (2012) 252301; Schenke, Schlichting, Venugopalan, PLB 747, 76-82 (2015), ...
- One can add **JIMWLK** evolution which will introduce leading quantum correction and (some) non-Gaussian correlations
  J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, NPB504, 415 (1997), PRD59, 014014 (1999)
  E. Iancu, A. Leonidov, and L. D. McLerran, NPA692, 583 (2001); A. H. Mueller, PLB523, 243 (2001)
  Lappi, PLB 744 (2015) 315-319, ...

INITIAL STATE PICTURE GENERATES ANISOTROPY



Gelis,Lappi Venugopalan PRD 78 054020 (2008), PRD 79 094017 (2009)
Dumitru, Gelis, McLerran,Venugopalan NPA810, 91 (2008); Dumitru, Jalilian-Marian PRD 81 094015 (2010);
A. Dumitru, K. Dusling, F. Gelis, J. Jalilian-Marian, T. Lappi, R. Venugopalan, PLB697 (2011) 21-25
Dusling, Venugopalan PRD 87 (2013) 5, 051502; PRD 87 (2013) 5, 054014; PRD 87 (2013) 9, 094034

CAN WE DISTINGUISH INITIAL FROM FINAL STATE EFFECTS?

Many possibilities. Different observables.

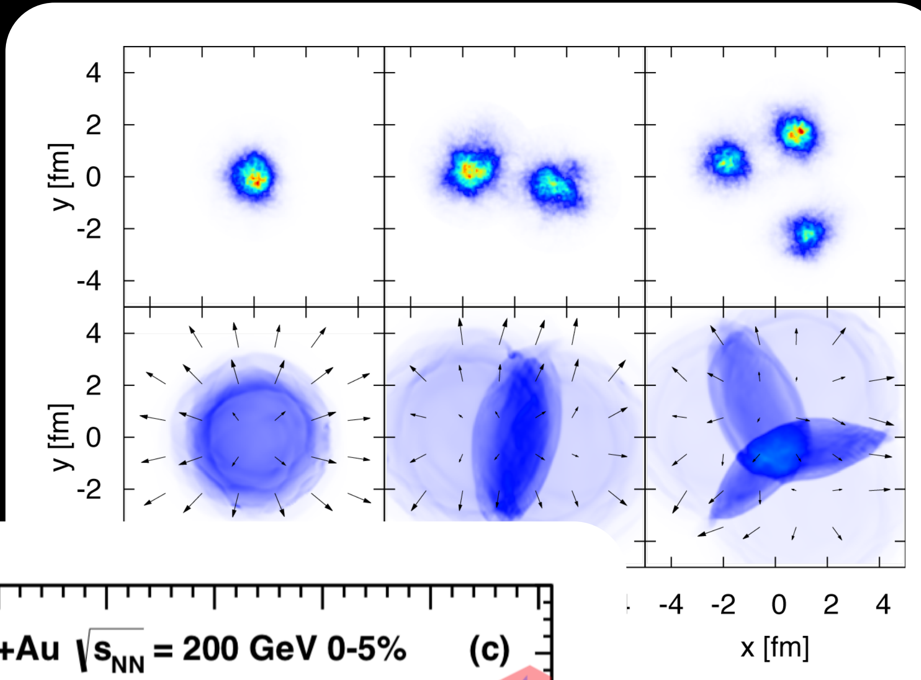
I will focus on studying

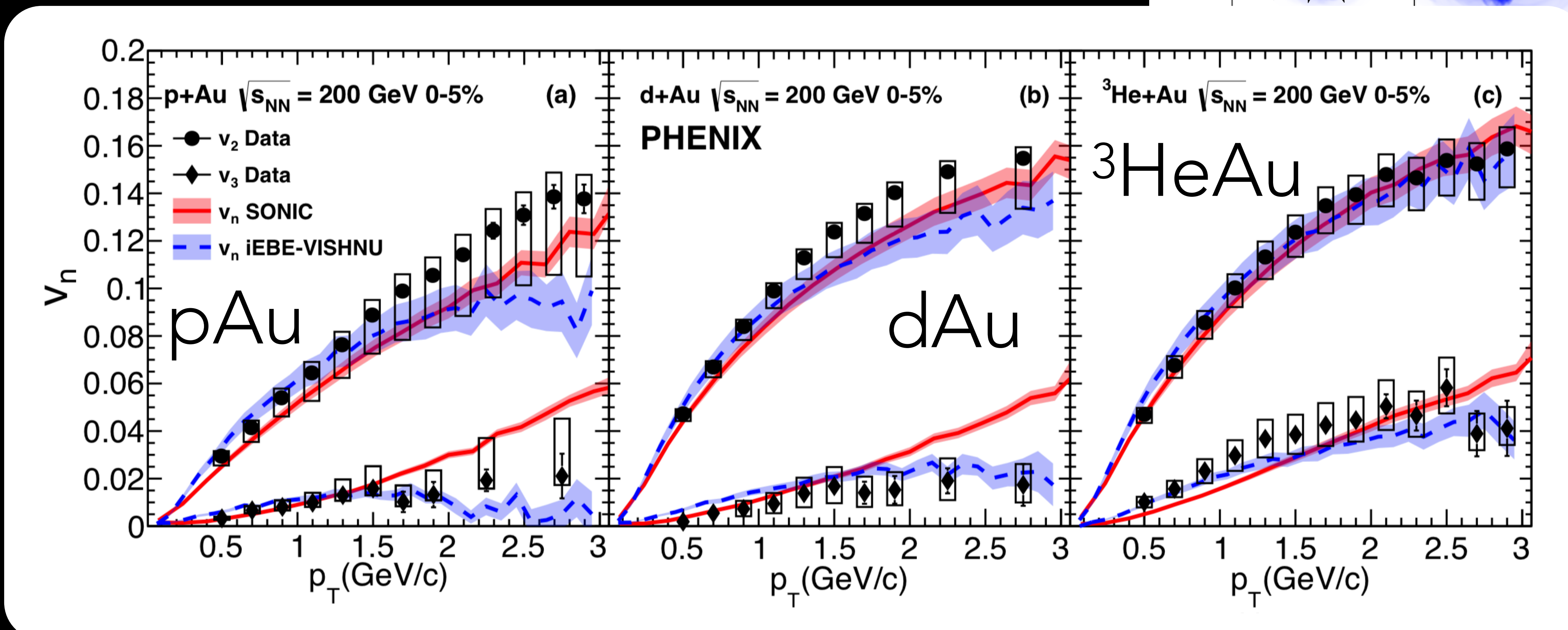
Different collision systems: Allow to control initial geometry

They are (were?) the most promising tool

SYSTEM DEPENDENCE OF ANISOTROPIES

Hydrodynamics converts initial shape to momentum anisotropy.
At RHIC different systems with different average shapes were studied.





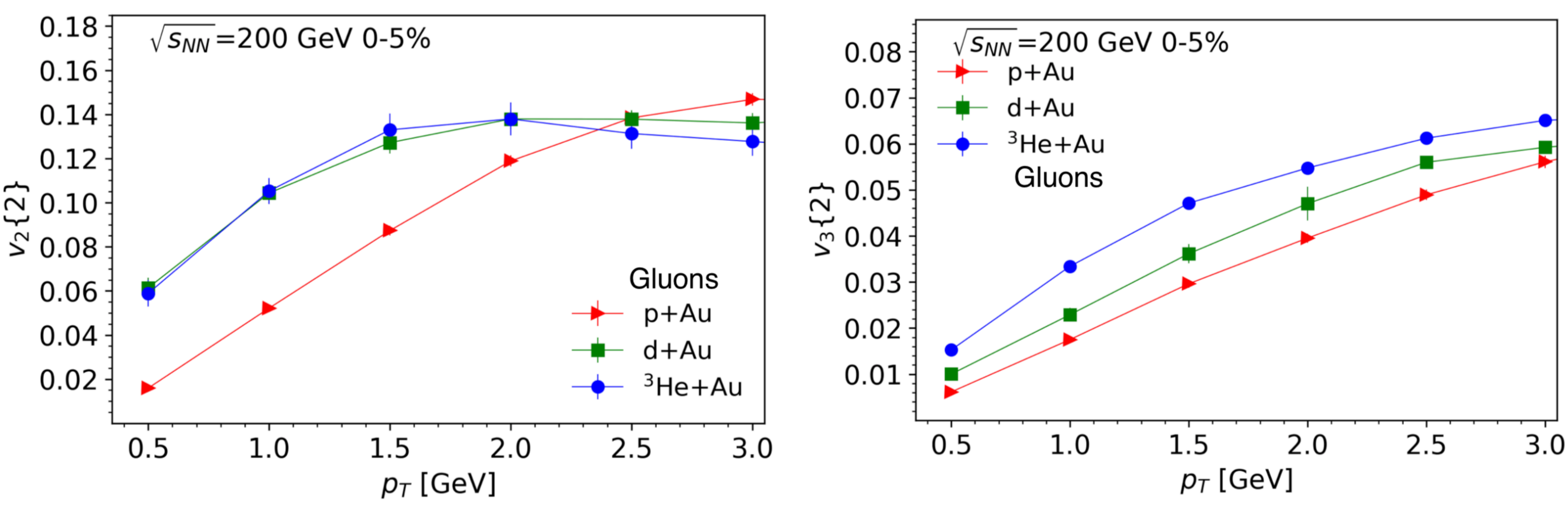
PHENIX, arXiv:1805.02973

Hydrodynamics correctly describes anisotropies in different systems

OTHER *CALCULATIONS:* BOZEK, BRONIOWSKI, PLB739 (2014) 308; NAGLE ET AL, PRL113 (2014); BOZEK, BRONIOWSKI, PLB747 (2015) 135; SCHENKE, VENUGOPALAN, NPA931 (2014) 1039; ROMATSCHKE, EUR. PHYS. J. C75 (2015) 305

SYSTEM DEPENDENCE OF ANISOTROPIES

Recent results from initial state momentum correlations:



Mark Mace, Vladimir V. Skokov, Prithwish Tribedy, Raju Venugopalan, arXiv:1805.09342

System dependence present when selecting 0-5% central events (which have different multiplicities in different systems)

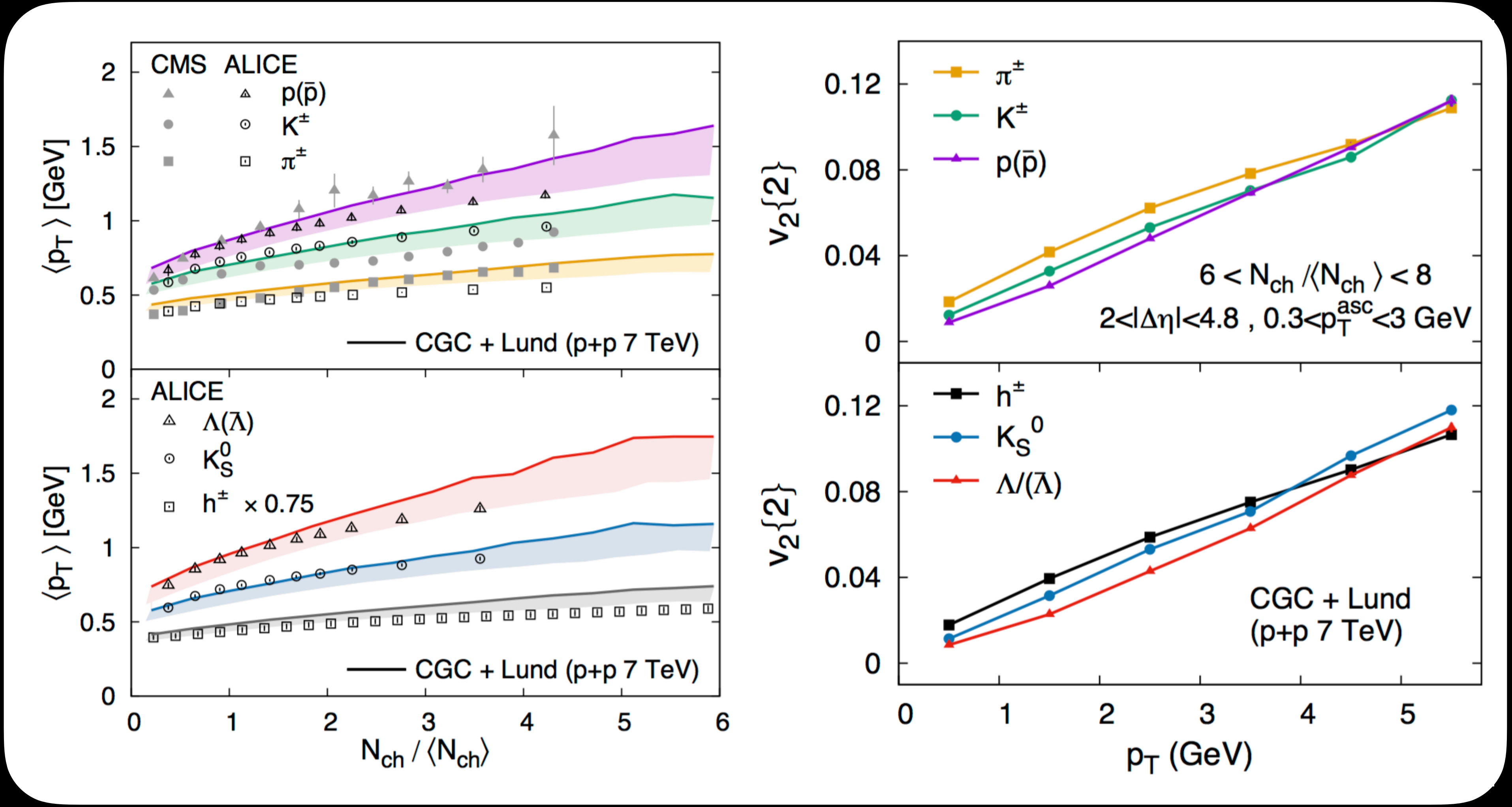
IP-GLASMA ~~+ HYDRO~~ + LUND

B. Schenke, S. Schlichting, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. 117, 162301 (2016)

First step towards an event generator with dense initial gluon fields and Lund fragmentation

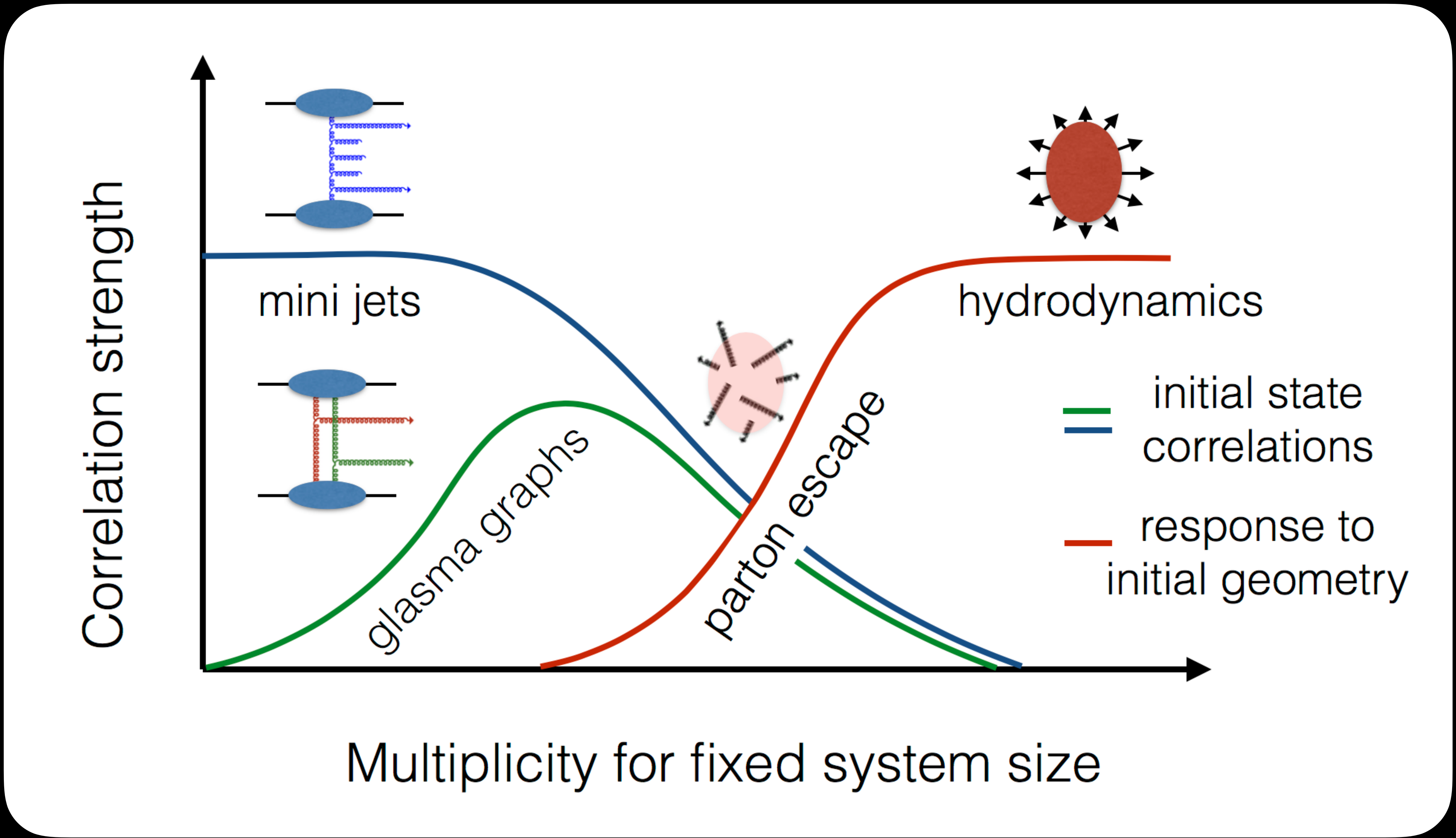
Sample gluons and connect with Lund strings

Arrange similar to what color reconnection would do



Emission from common boosted source: mass splitting

STUDY RELATIVE STRENGTH OF INITIAL AND FINAL STATE CORRELATIONS IN THEORY



S. Schlichting, Quark Matter 2015

Calculate the relative contribution of "glasma graphs" and final state effects

IP-Glasma + parton cascade

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076, Phys. Rev. D96, 091509(R)

To study how final state interactions affect the initial state correlations, we use a microscopic final state model, the parton cascade BAMPS

Z.Xu, C. Greiner, PRC71, 064901 (2005)

IP-Glasma → $\frac{dN_g}{dy d^2x_T d^2p_T}$ Wigner Distribution → sample gluons → run BAMPS (pQCD)

smear → Husimi Distribution

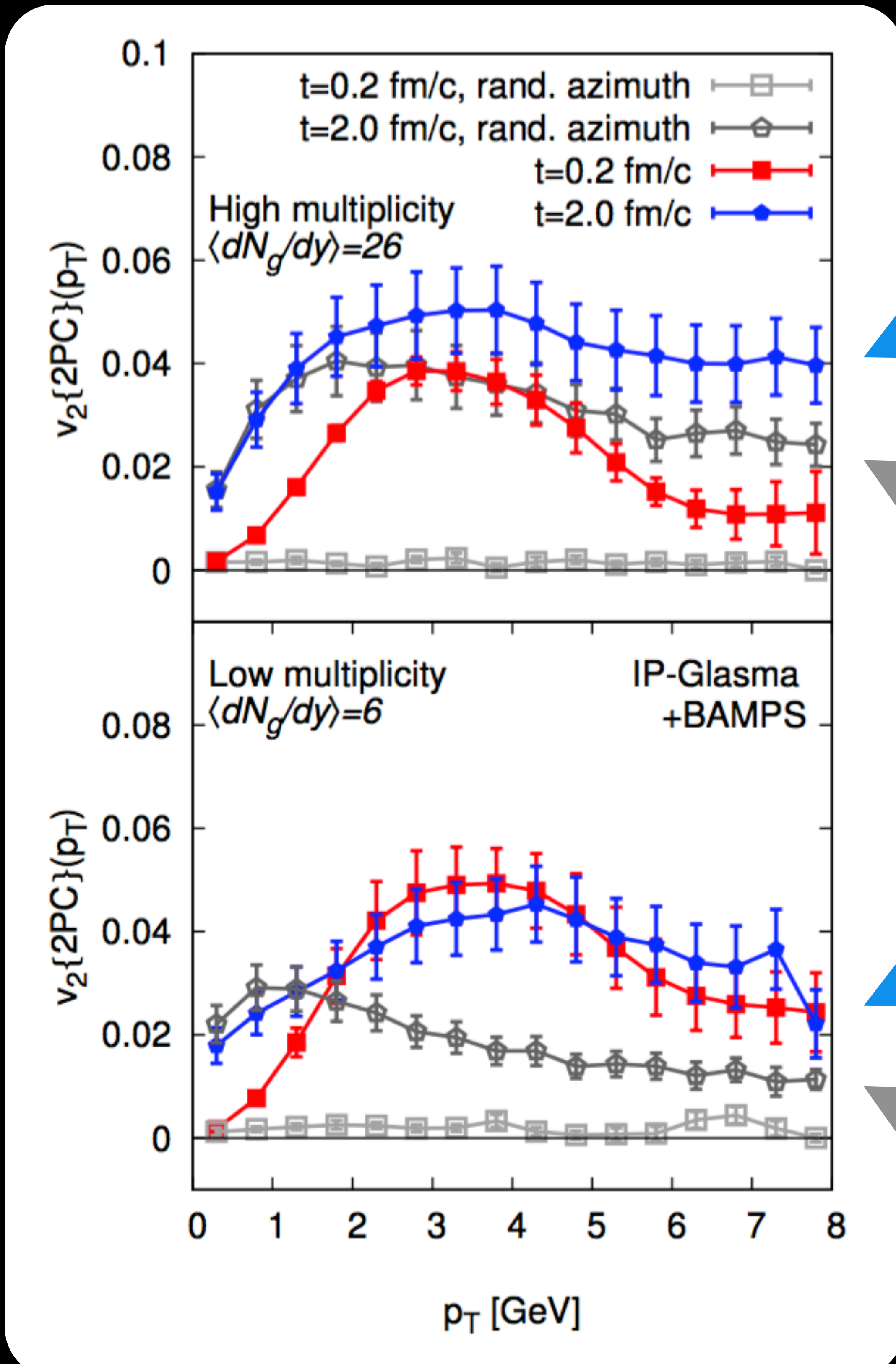
→ study momentum anisotropy as function of time

Effect of initial correlations on final v_2

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076, Phys. Rev. D96, 091509(R)

high multiplicity

low multiplicity



with initial corr.

without initial corr.

with initial corr.

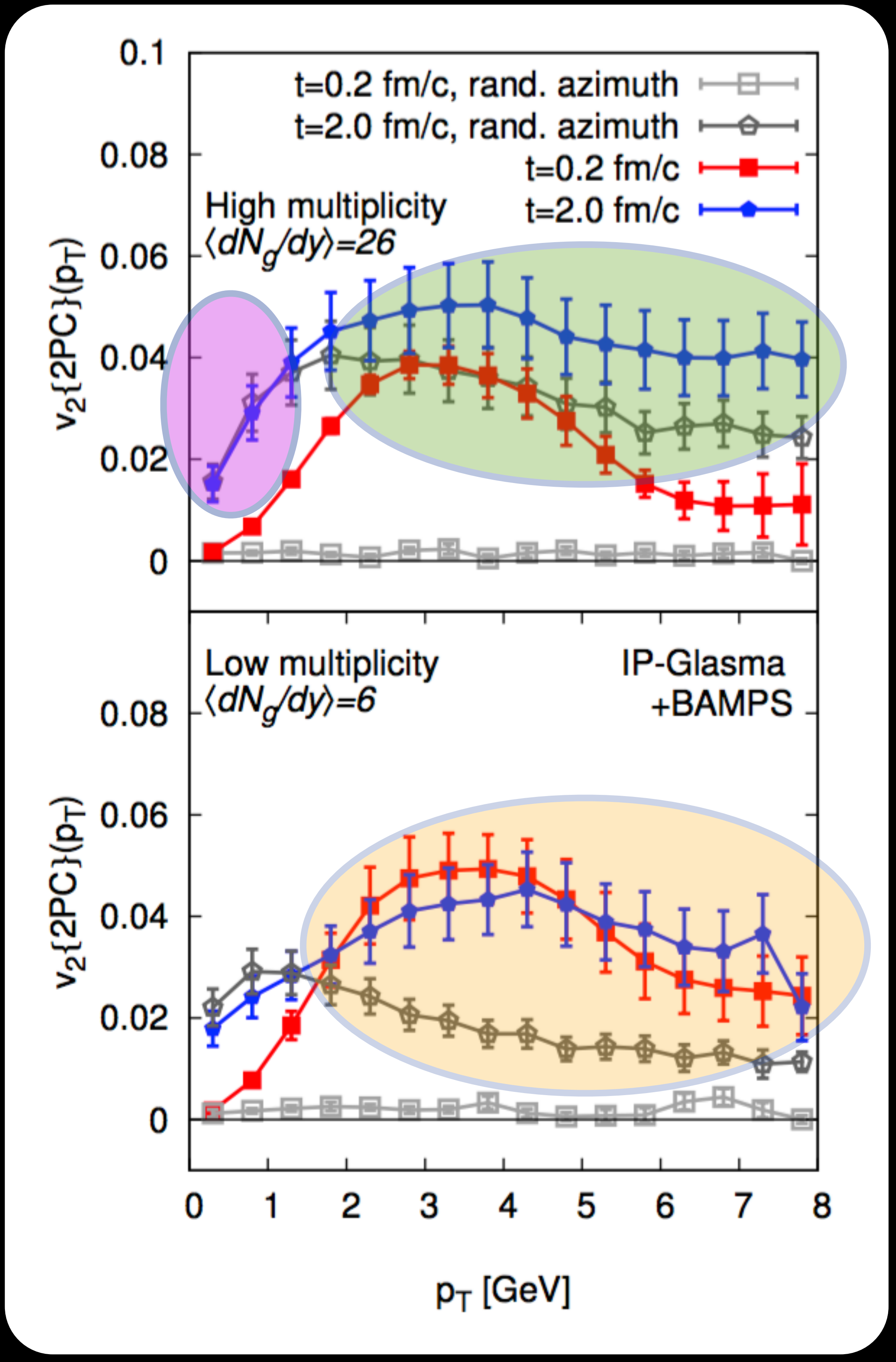
without initial corr.

Effect of initial correlations on final v_2

M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076, Phys. Rev. D96, 091509(R)

high multiplicity

low multiplicity



negligible effect at small p_T and high multiplicity

significant effect at $p_T > 2$ GeV and low multiplicity

visible effect at $p_T > 3$ GeV and high multiplicity

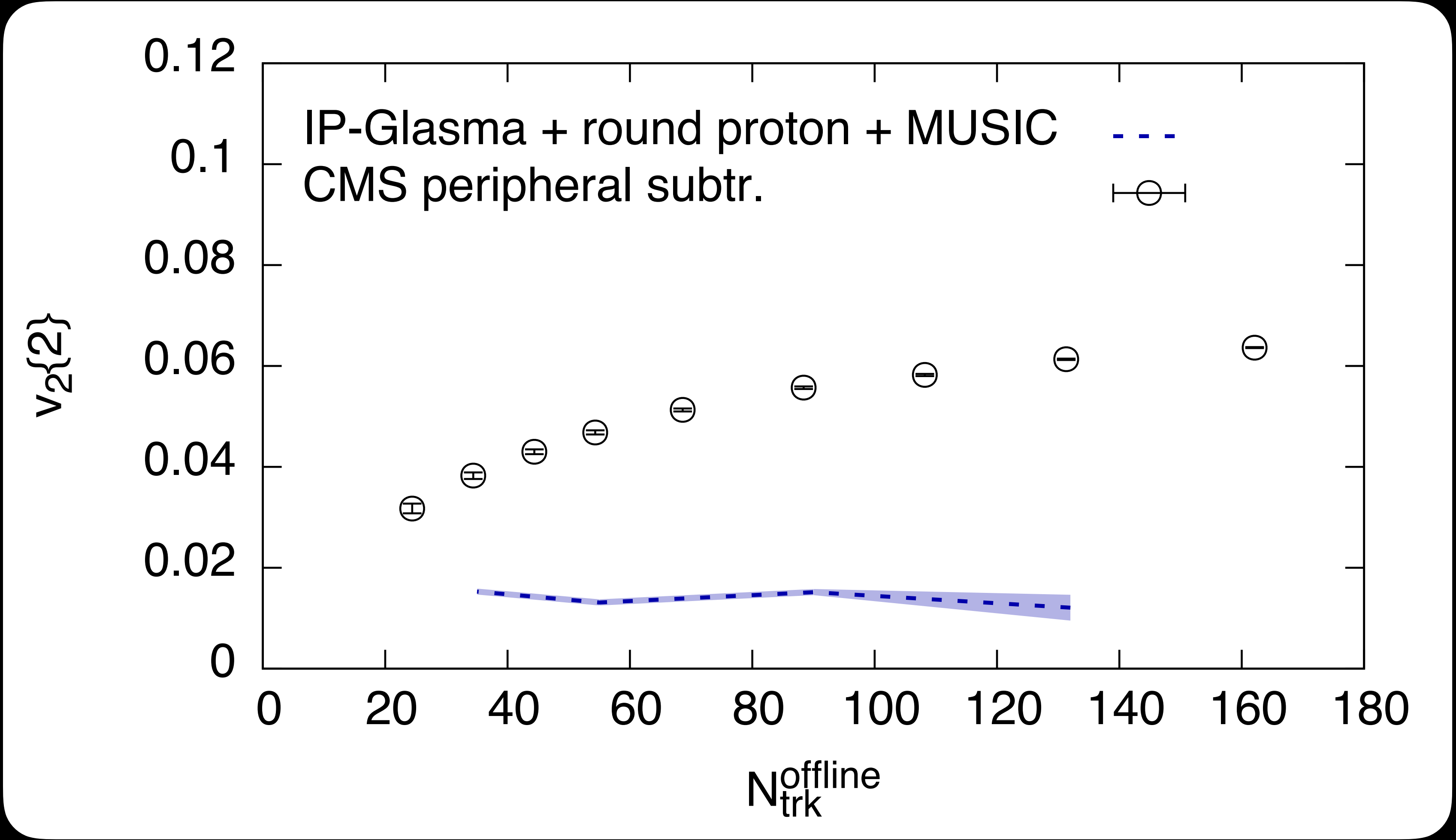
CONCLUSIONS & OUTLOOK

- Multi-particle correlation measurements in small systems (p+p, p/d/He+A) have revealed interesting structures
- There are contributions from initial momentum anisotropies in the QCD particle production
- With increasing multiplicity, final state effects become important: similar to A+A collisions - QGP in p+p?
- Our standard event generators apparently miss this important physics. Work in progress for PYTHIA final state effects. What about the production process in high multiplicity events?

BACKUP

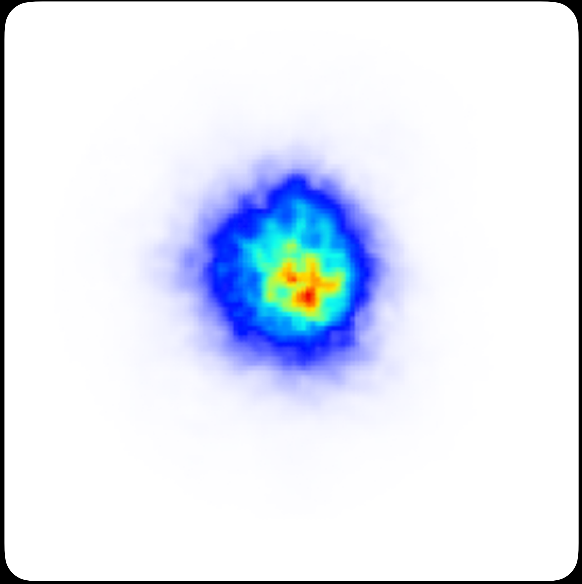
p+Pb v_2 from IP-GLASMA + Hydro

Model worked well in A+A. In p+A it did not.
Not because hydro does not work.
But because initial state was missing physics.

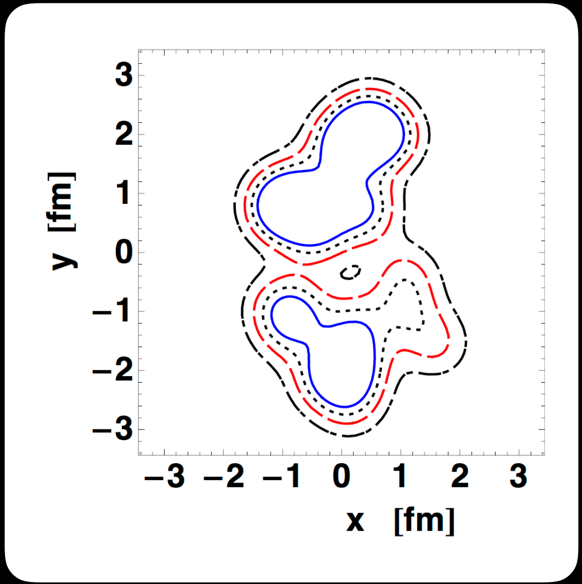


B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)
Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)

IP-Glasma



MC-Glauber



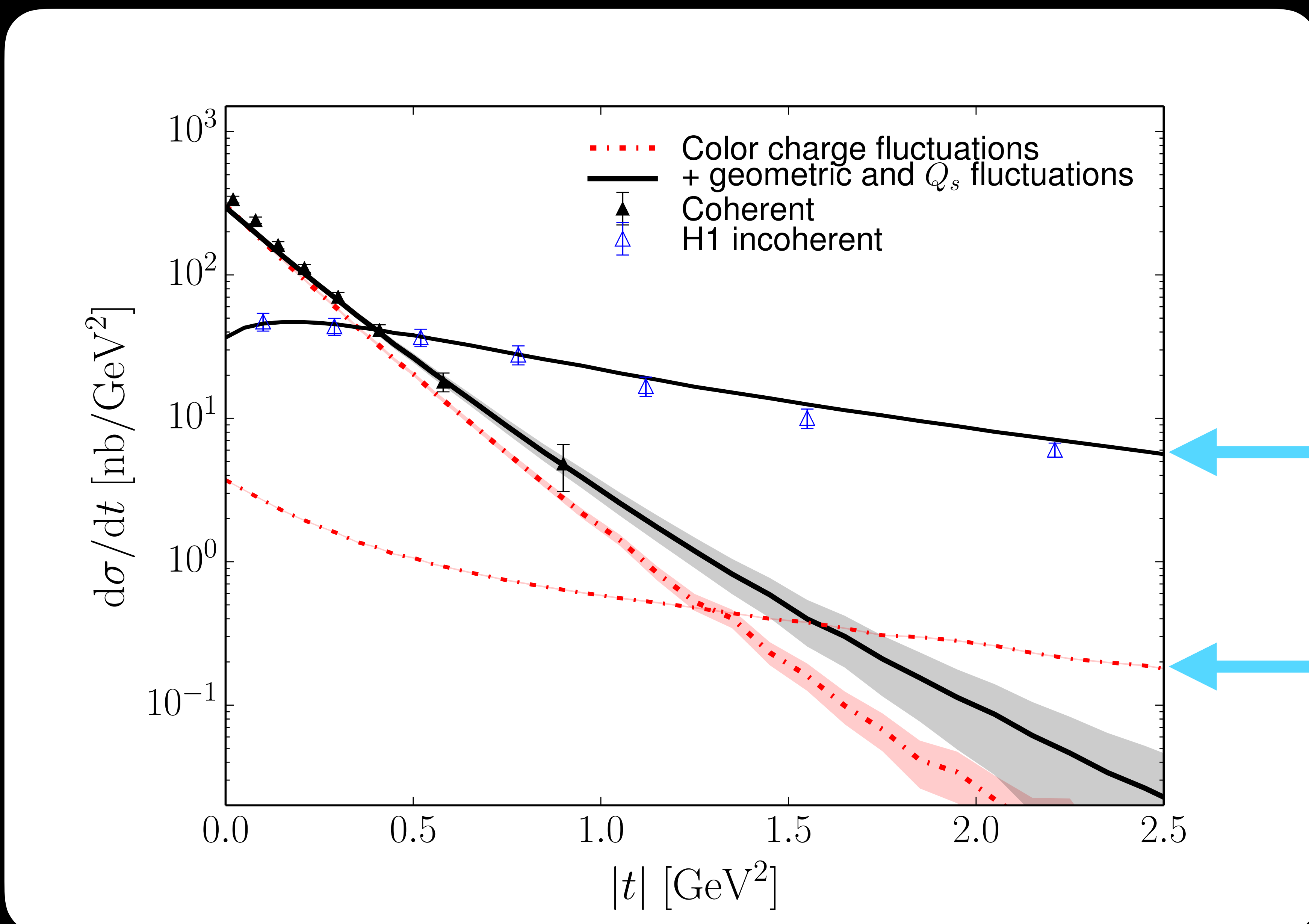
P. Bozek, Phys.Rev. C85 (2012) 014911

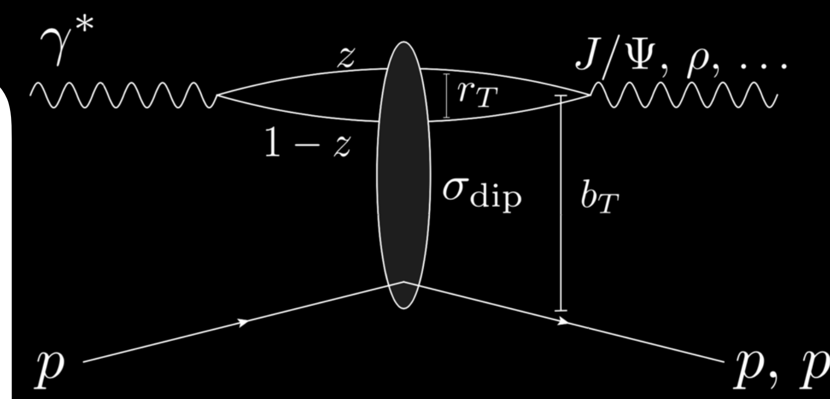
NEED PROTON SHAPE FLUCTUATIONS!

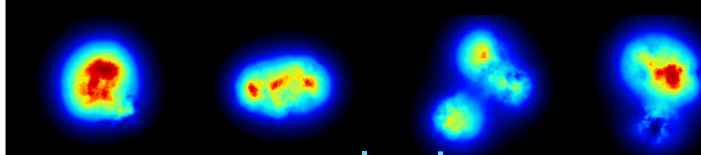
H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042

e+p (HERA) Exclusive diffractive J/Ψ production:

Incoherent x-sec sensitive to fluctuations







tuned shape fluctuations

round proton

H1 Collaboration, Eur. Phys. J. C73 (2013) no. 6 2466

MULTI-PARTICLE CUMULANTS

Hydrodynamics produces ~equal $v_2\{2m\}$ for all m≳4

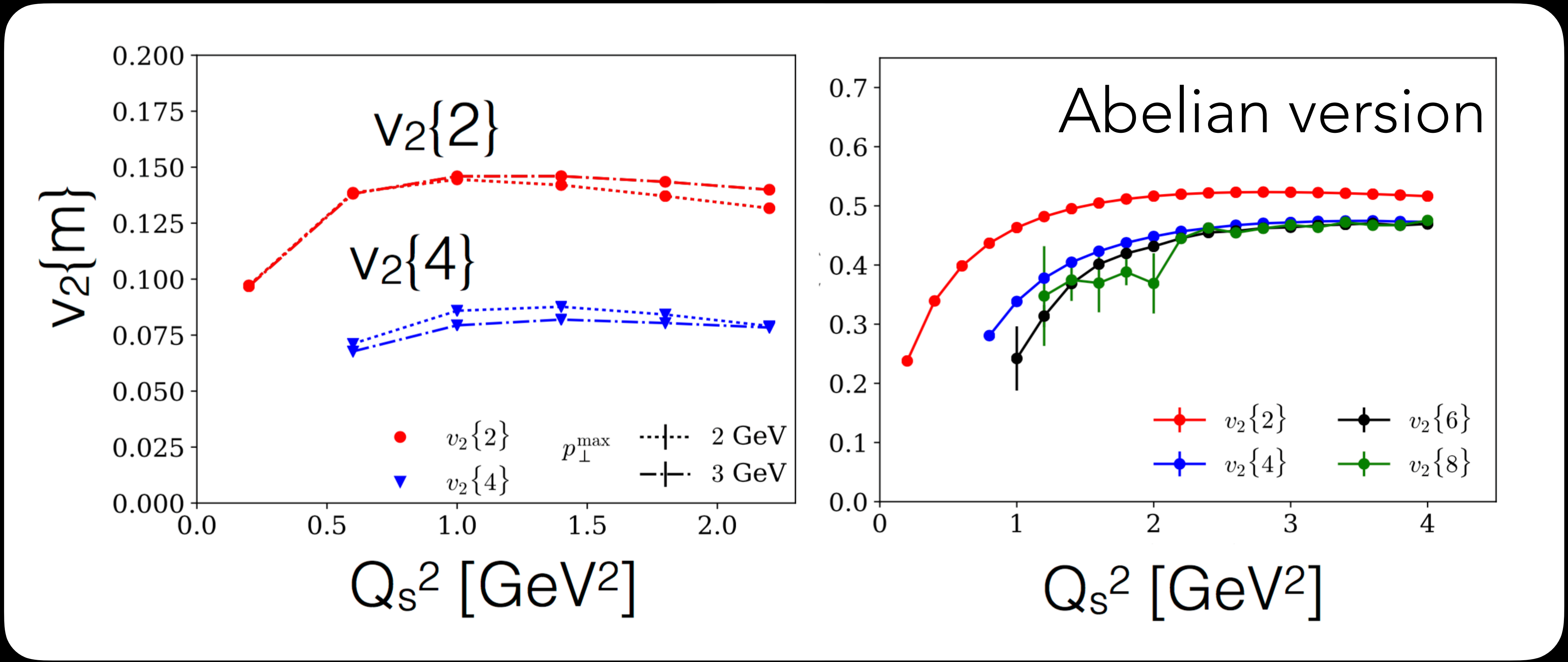
All particles correlated with a common event plane

see e.g. L. Yan, J.-Y. Ollitrault, Phys. Rev. Lett. 112, 082301 (2014)

$v_2\{4\}$ imaginary in 2-gluon exchange approximation

V. Skokov, Phys.Rev. D91 (2015) 054014

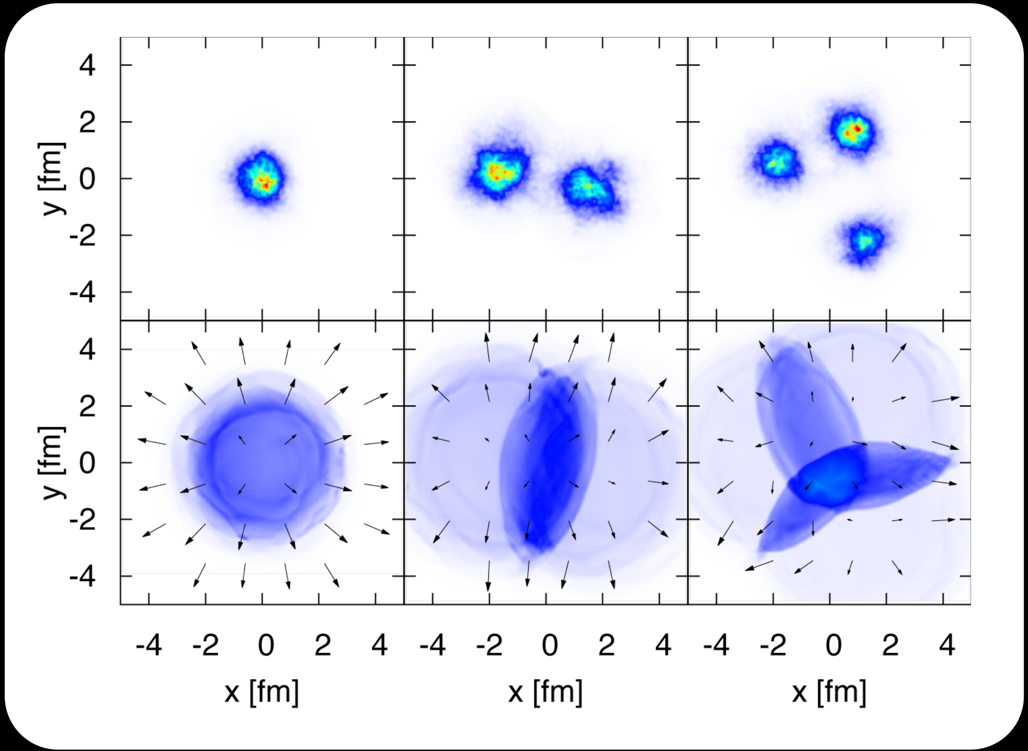
Including multiple interactions will make it real



K. Dusling, M. Mace, R. Venugopalan, Phys.Rev.Lett. 120 (2018) 042002

HOW TO DISTINGUISH "FLOW" FROM AN "INITIAL STATE" SCENARIO

- **^{3}He+Au, d+Au:** Systematics of flow in different systems Explained by hydrodynamics. Initial state: no calculation



MEASUREMENT:
PHENIX COLLABORATION, PRL115,

CALCULATIONS:
BOZEK, BRONIOWSKI, PLB739 (2014) 308
NAGLE ET AL, PRL113 (2014)
BOZEK, BRONIOWSKI, PLB747 (2015) 135
SCHENKE, VENUGOPALAN, NPA931 (2014) 1039
ROMATSCHKE, EUR. PHYS. J. C75 (2015) 305

- Higher order cumulants: Data shows that **$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ ...**
Natural in hydrodynamics but not a unique feature

HOW TO DISTINGUISH "FLOW" FROM AN "INITIAL STATE" SCENARIO

- **Mass splitting of mean p_T and v_n**:
Natural in any situation where particles are produced from a common boosted source: e.g. fluid cell, strings

- **$c_2\{4\}$ turning positive** as multiplicity increases
could mean collectivity sets in but also alternative explanations
DUMITRU, MCLERRAN, SKOKOV, PHYS.LETT. B743 (2015) 134-137

- **HBT**: Relative radii in p+p, p+Pb and Pb+Pb: Data favors description that yields similar radii in p+p and p+Pb
ALICE COLLABORATRION, PHYS. LETT. B 739 (2014) 139-151

APPROXIMATIONS

- **Glasma graph approximation:** two gluon exchange (not more) and Gaussian statistics of color charges (MV model)
  Gelis,Lappi Venugopalan PRD 78 054020 (2008), PRD 79 094017 (2009); Dumitru, Gelis, McLerran,Venugopalan NPA810, 91 (2008); Dumitru, Jalilian-Marian PRD 81 094015 (2010); Dusling, Venugopalan PRD 87 (2013), ...
- **Non-linear Gaussian approximation:**
  Resums multi-gluon exchanges - still Gaussian statistics
  McLerran, Venugopalan, PRD 59 (1999) 094002; Dominguez, Marquet, Wu, NPA 823 (2009) 99; Lappi, Schenke, Schlichting, Venugopalan, JHEP 1601 (2016) 061; ...
- **Numerical solution:** Solves the Yang-Mills equations exactly for any initial color source statistics and spatial configuration, includes multiple-gluon exchange, "rescattering"
  Krasnitz, Venugopalan, NPB 557 (1999) 237; Krasnitz, Nara, Venugopalan, NPA 717 (2003) 268; Lappi, PRC 67 (2003) 054903; Schenke, Tribedy, Venugopalan, PRL 108 (2012) 252301; Schenke, Schlichting, Venugopalan, PLB 747, 76-82 (2015), ...
- One can add **JIMWLK** evolution which will introduce (some) non-Gaussian correlations
  J. Jalilian-Marian, A. Kovner, A. Leonidov, and H. Weigert, NPB504, 415 (1997), PRD59, 014014 (1999)
  E. Iancu, A. Leonidov, and L. D. McLerran, NPA692, 583 (2001); A. H. Mueller, PLB523, 243 (2001)
  Lappi, PLB 744 (2015) 315-319, ...