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ENERGY

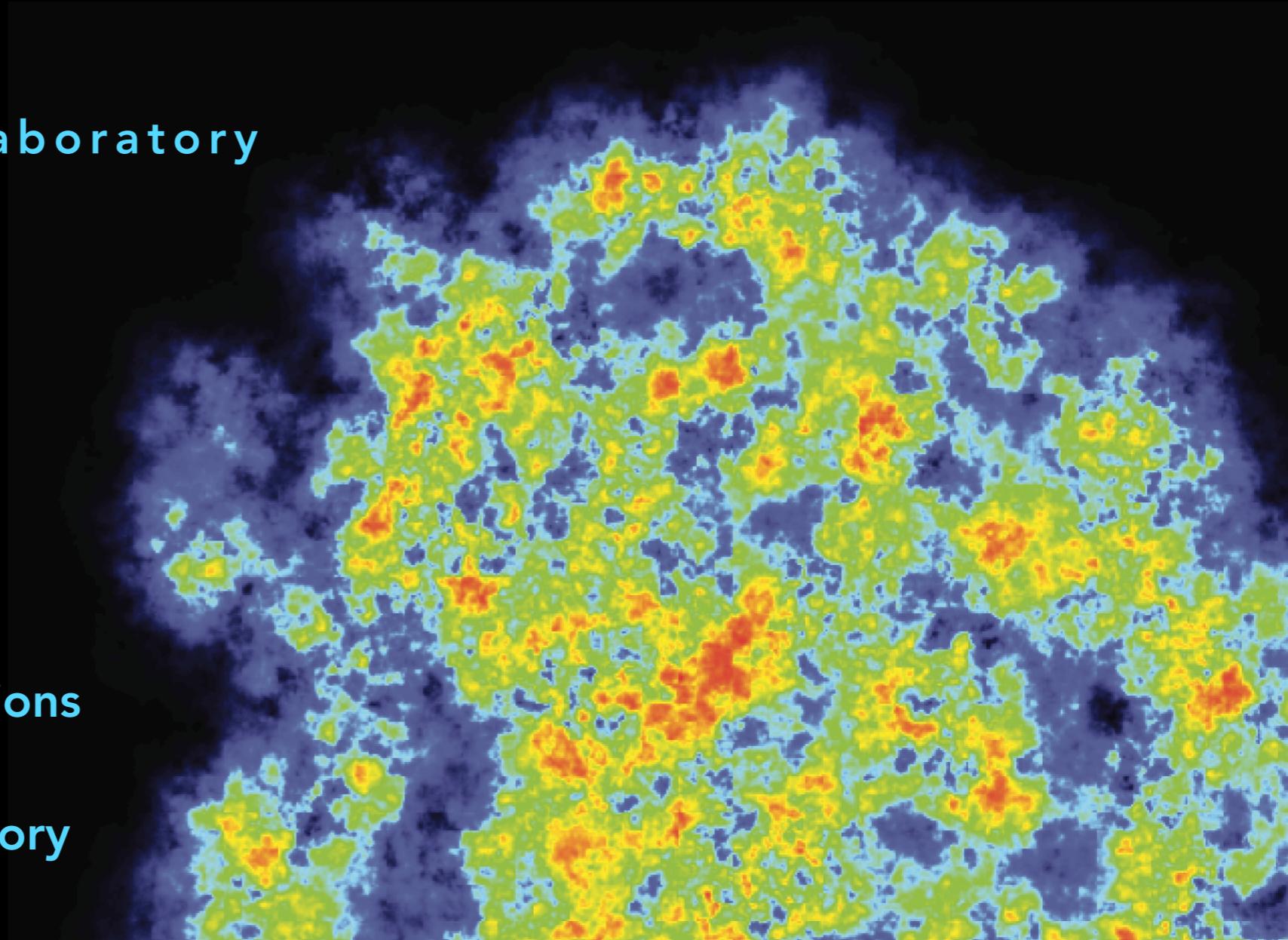
Office of
Science

BROOKHAVEN
NATIONAL LABORATORY

MULTI-PARTICLE CORRELATIONS IN COLLISIONS WITH SMALL NUCLEI

Björn Schenke
Brookhaven National Laboratory

September 4, 2018
Short-range Nuclear Correlations
at an Electron-Ion Collider
Brookhaven National Laboratory

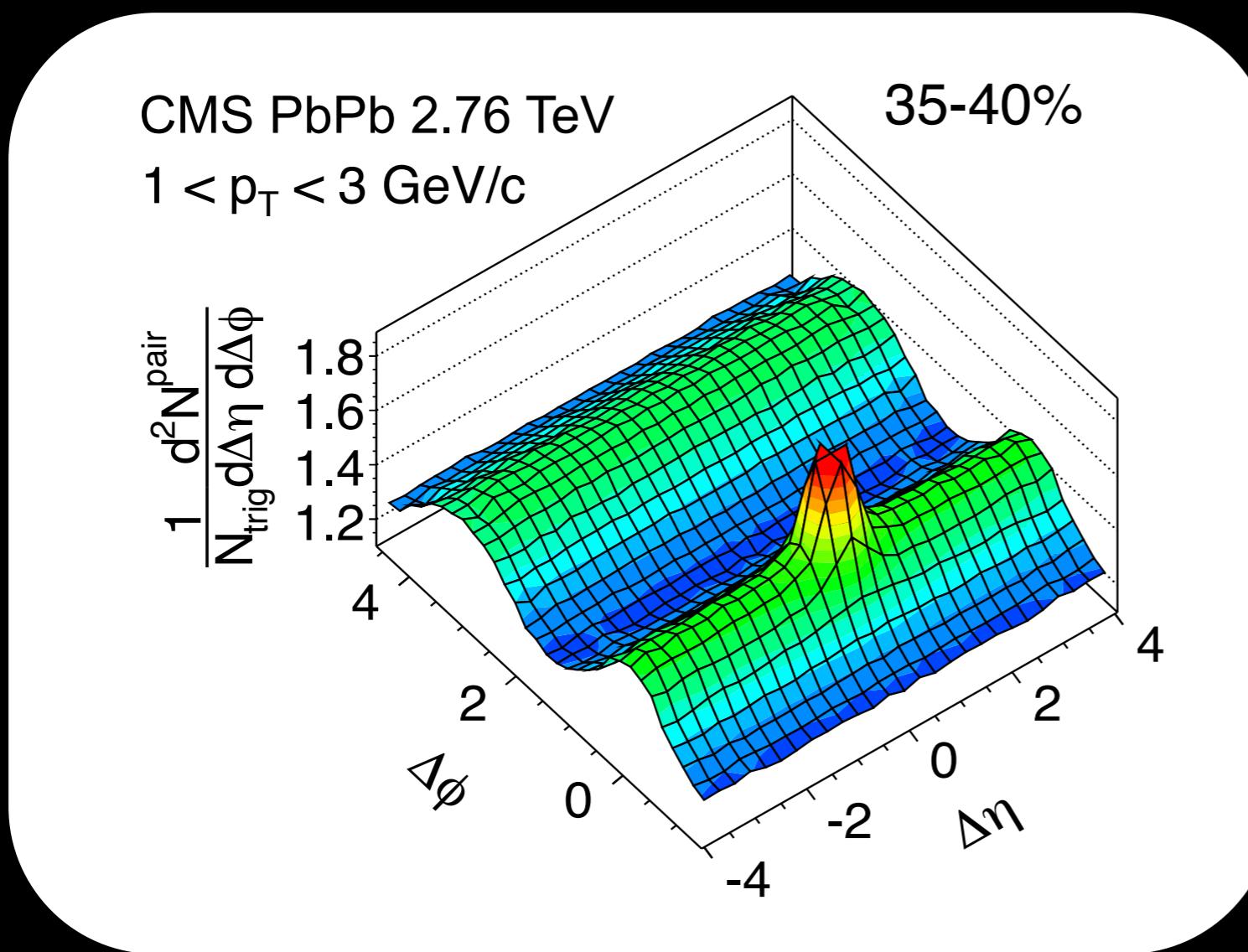


TWO-PARTICLE CORRELATIONS

2-particle correlation as a function of $\Delta\eta$ and $\Delta\phi$

$\Delta\eta$: DIFFERENCE IN PSEUDO-RAPIDITY

$\Delta\phi$: DIFFERENCE IN AZIMUTHAL ANGLE



Ridge:
Structure that is long range in $\Delta\eta$ and generally shows two bumps in $\Delta\phi$
“double-ridge”

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

RIDGE IN HEAVY ION COLLISIONS

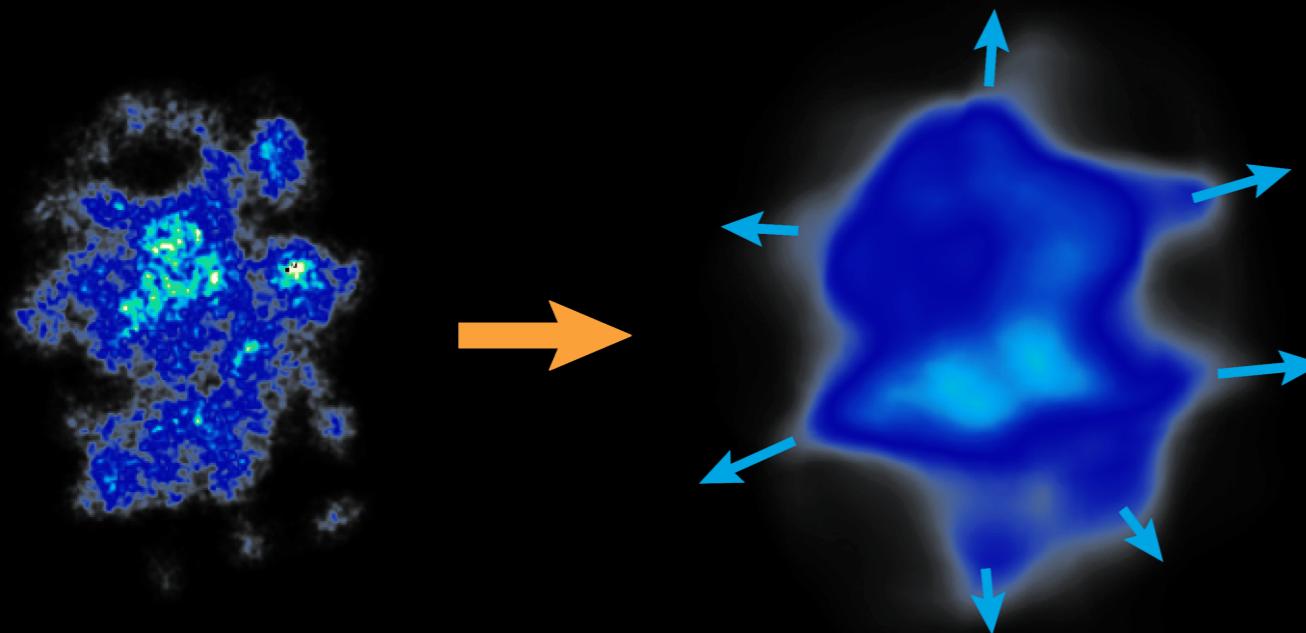
First seen in heavy ion collisions at RHIC

STAR COLLABORATION, PHYS. REV. C80 (2009) 064912

PHOBOS COLLABORATION, PHYS. REV. LETT. 104 (2010) 062301

Interpretation in heavy ion collision:

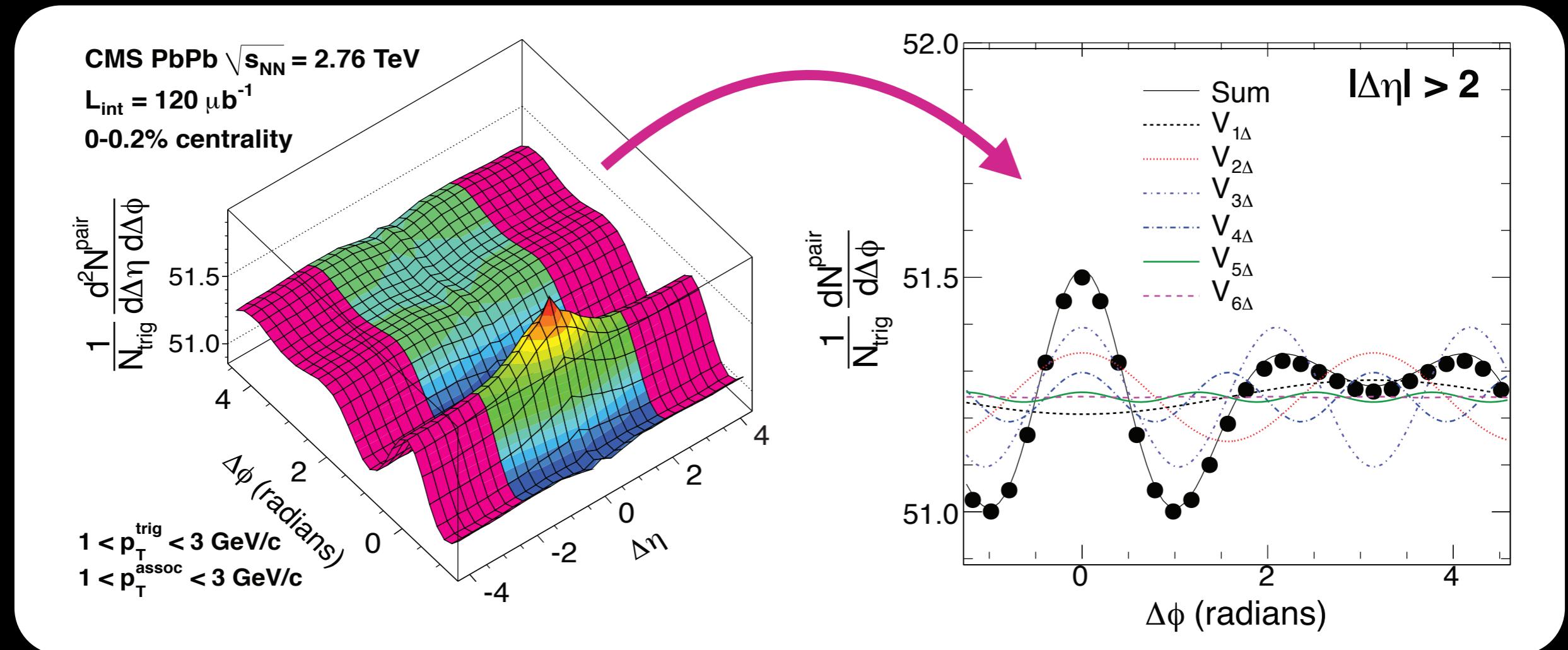
- Long range correlations emerging from early times (causality)
- Azimuthal structure formed by the medium response to the initial transverse geometry (well described by hydrodynamics)



2 ridges come from
dominant $\cos(2\Delta\Phi)$
contribution due to the
mostly elliptic shape

RIDGE IN HEAVY ION COLLISIONS

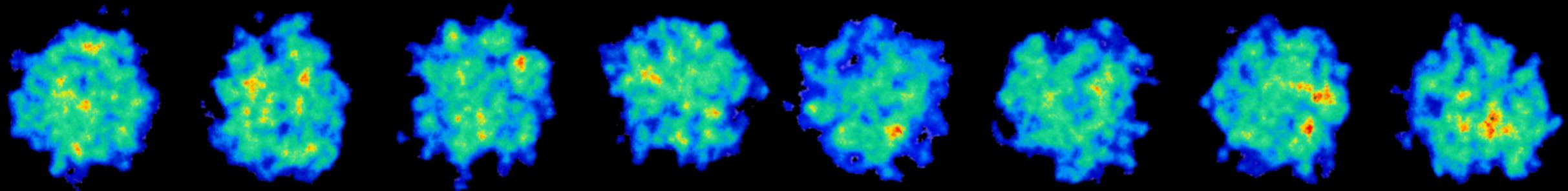
Azimuthal structure quantified using Fourier expansion



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

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

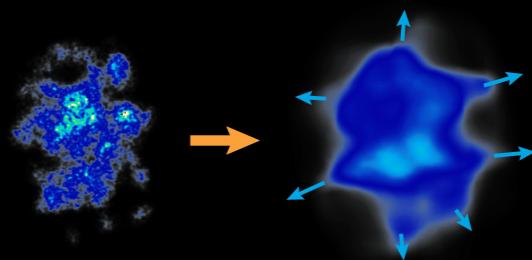
Includes gluon saturation at high densities
(small x and small transverse momentum $p_T \lesssim Q_S$)

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

Pressure gradients drive the evolution

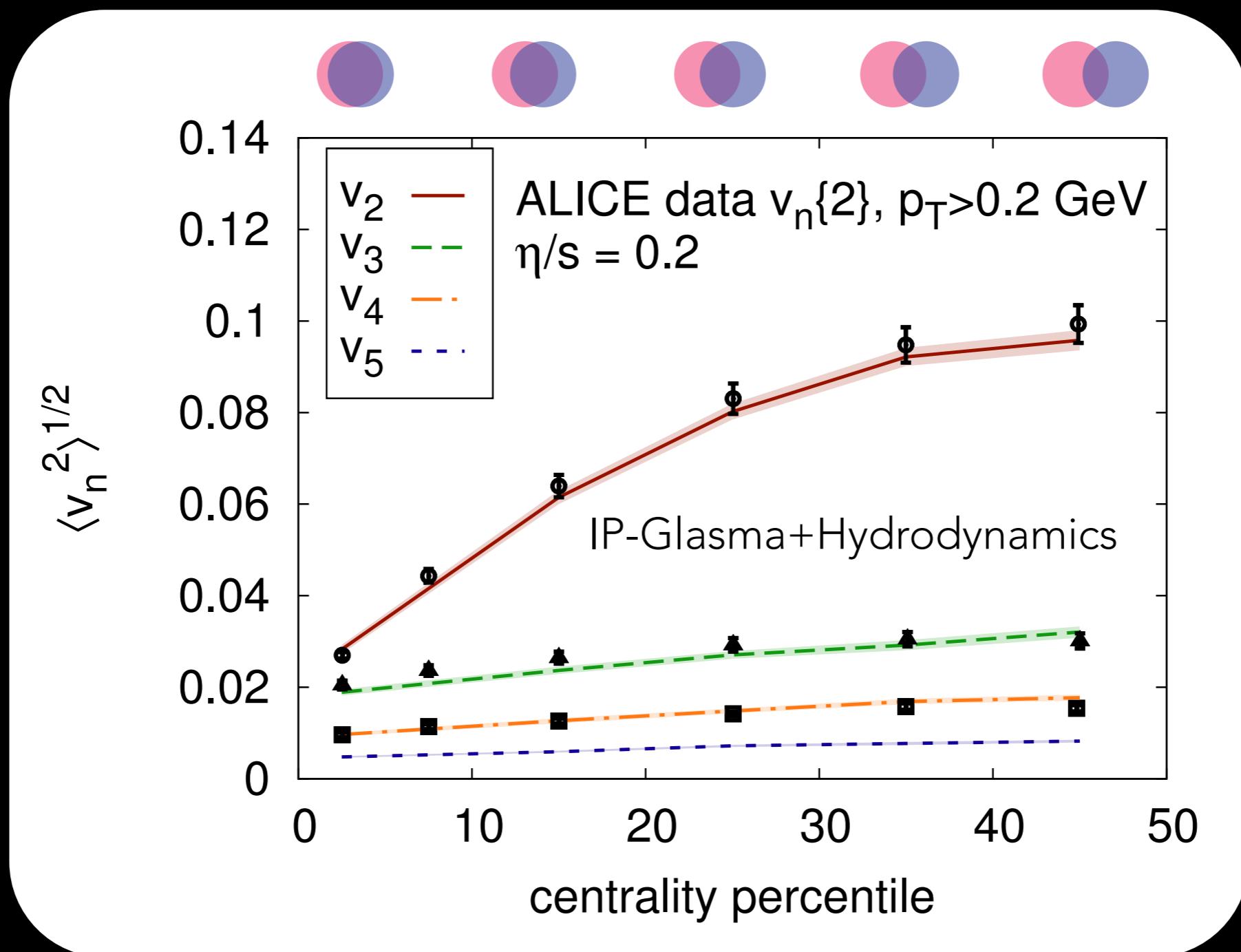
Described by hydrodynamics

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)

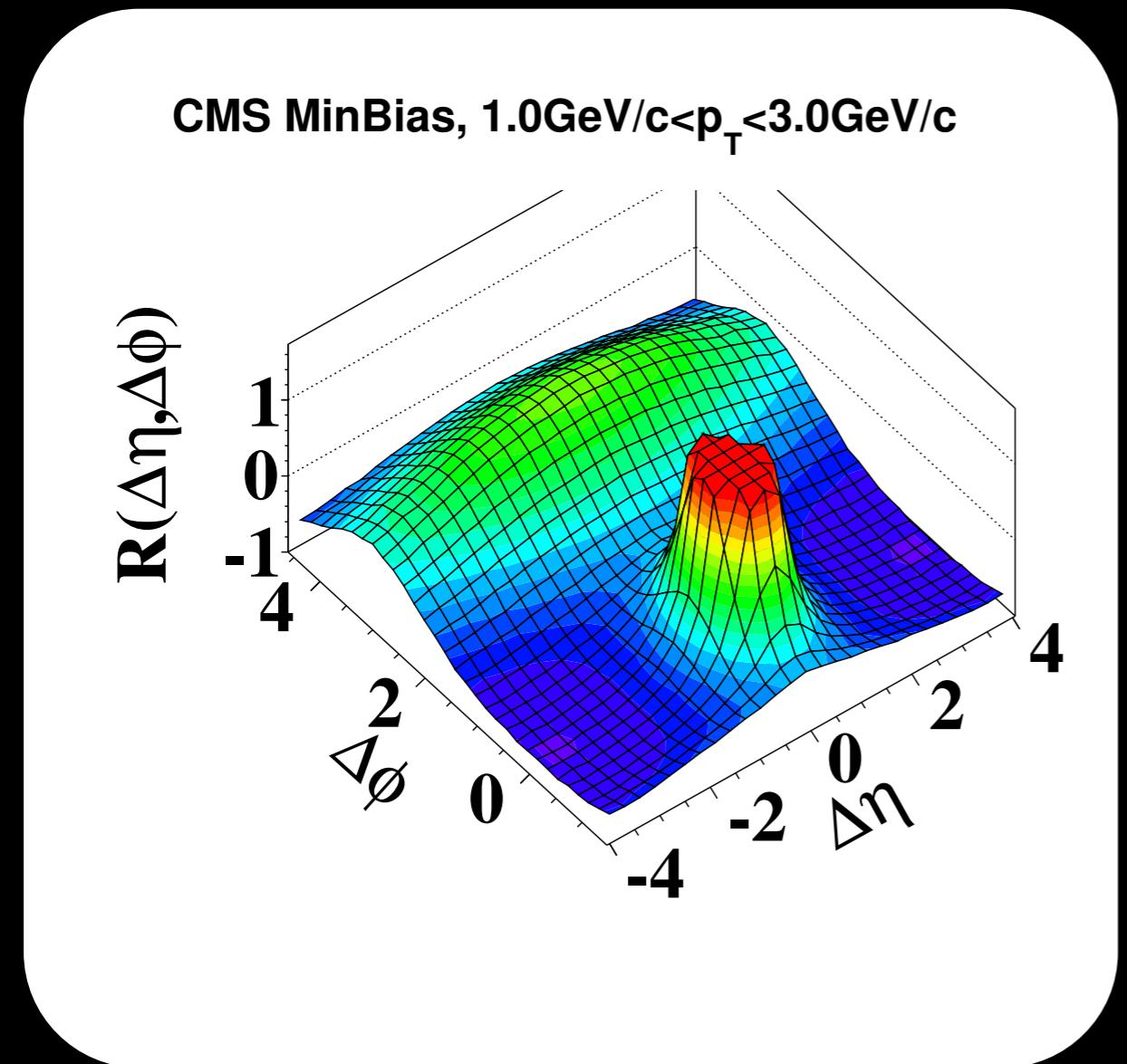


Quantitative description of the experimental data!

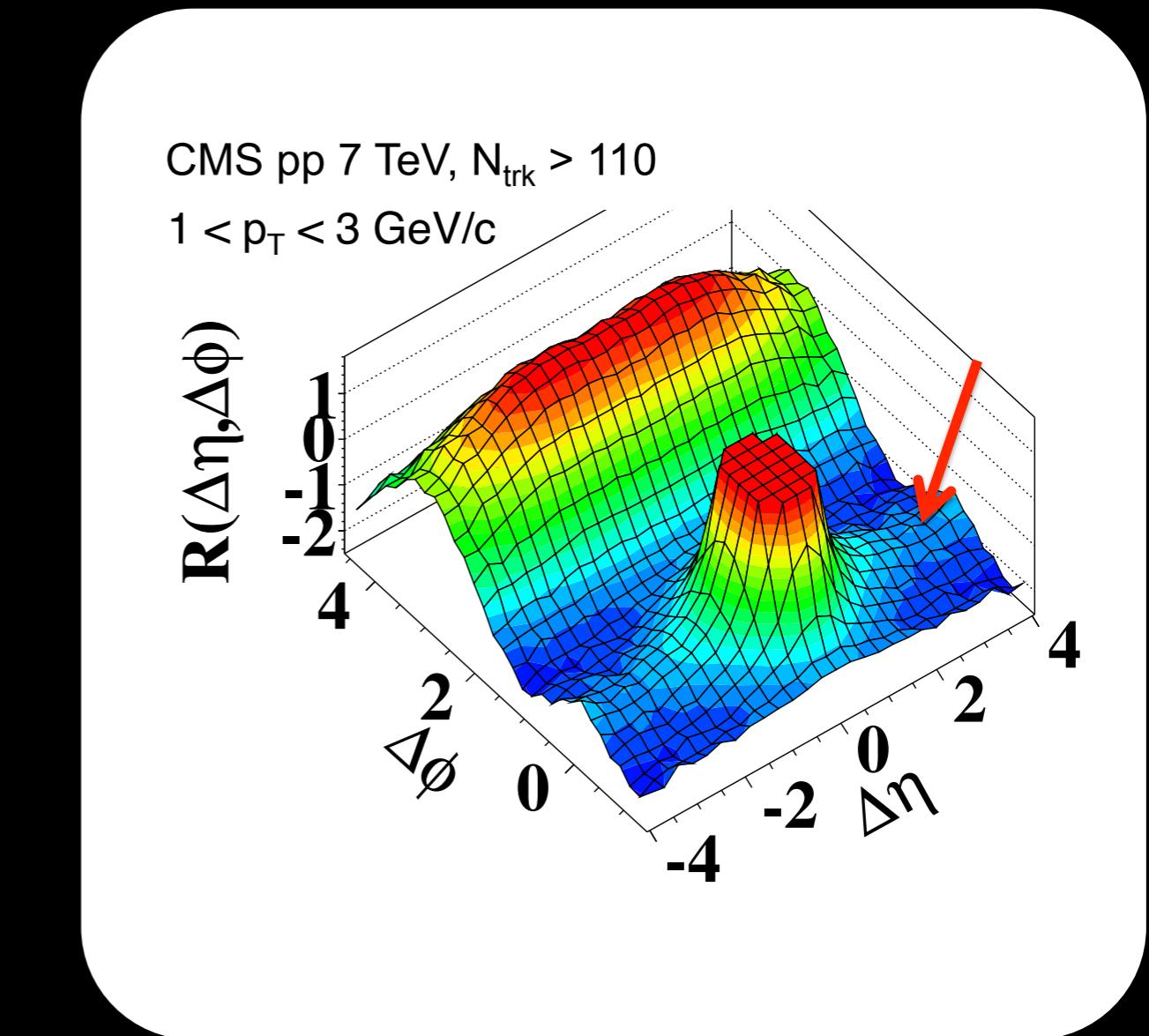
ALICE COLLABORATION, PHYS. REV. LETT. 107, 032301 (2011)

RIDGE IN SMALL COLLISION SYSTEMS

minimum bias p+p

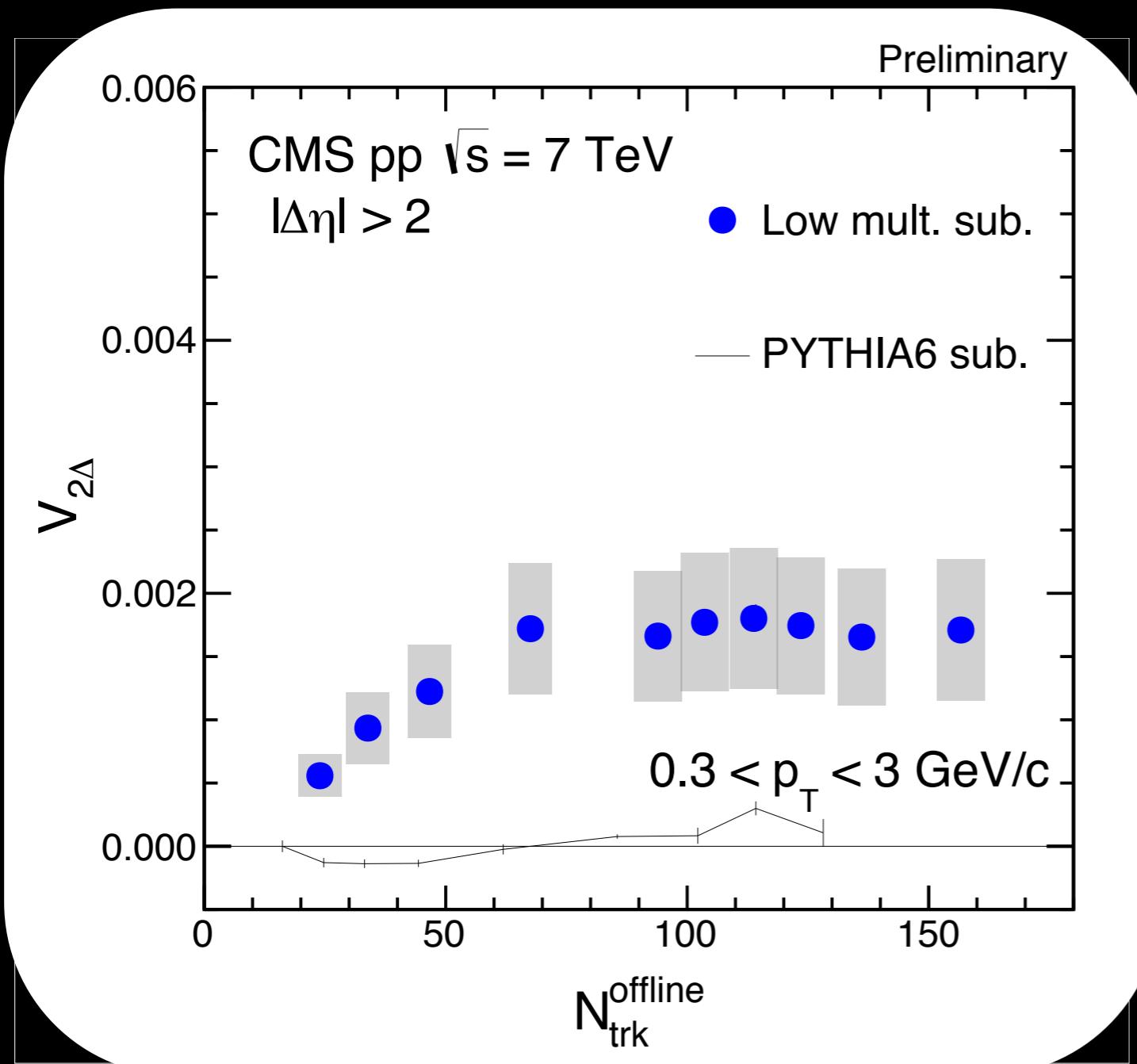


high multiplicity p+p



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

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



No ridge in PYTHIA

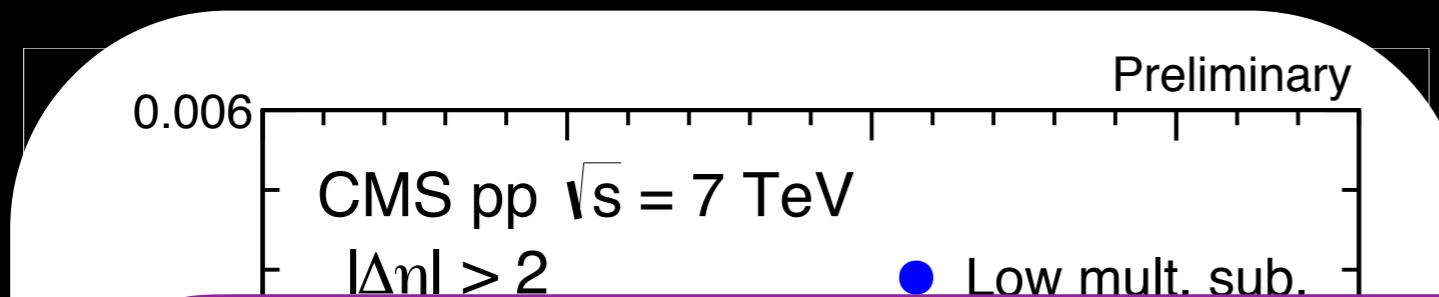
CMS PAS HIN-15-009

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

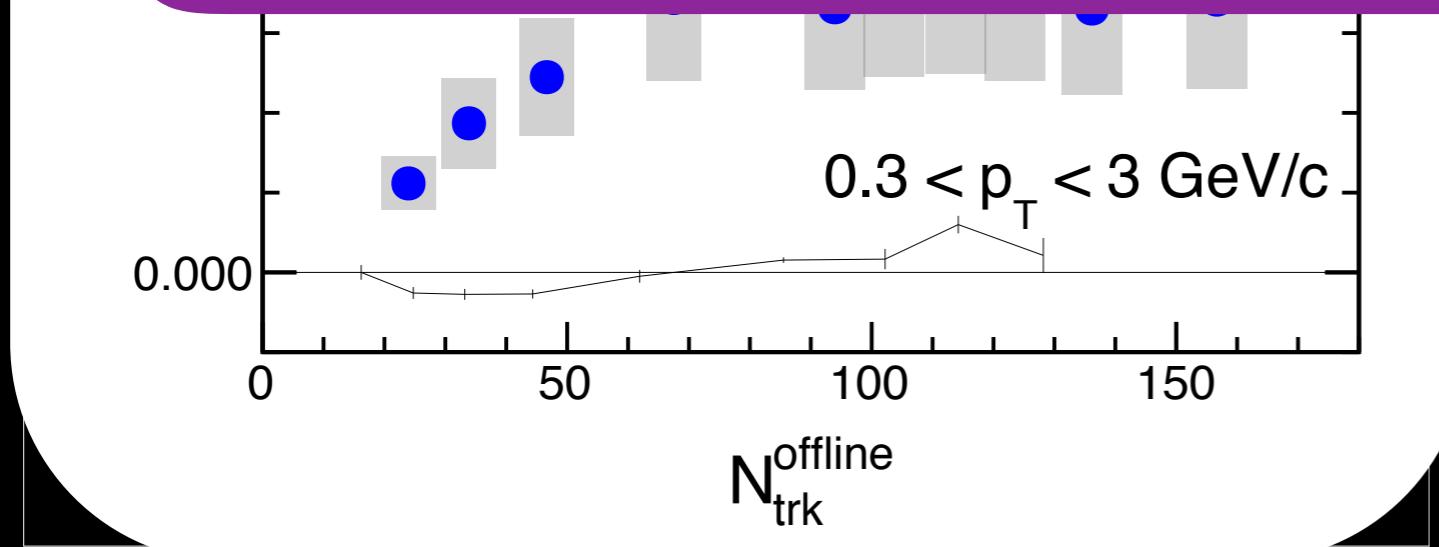
$V_{2\Delta}$ IN p+p COLLISIONS

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



No ridge in PYTHIA

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



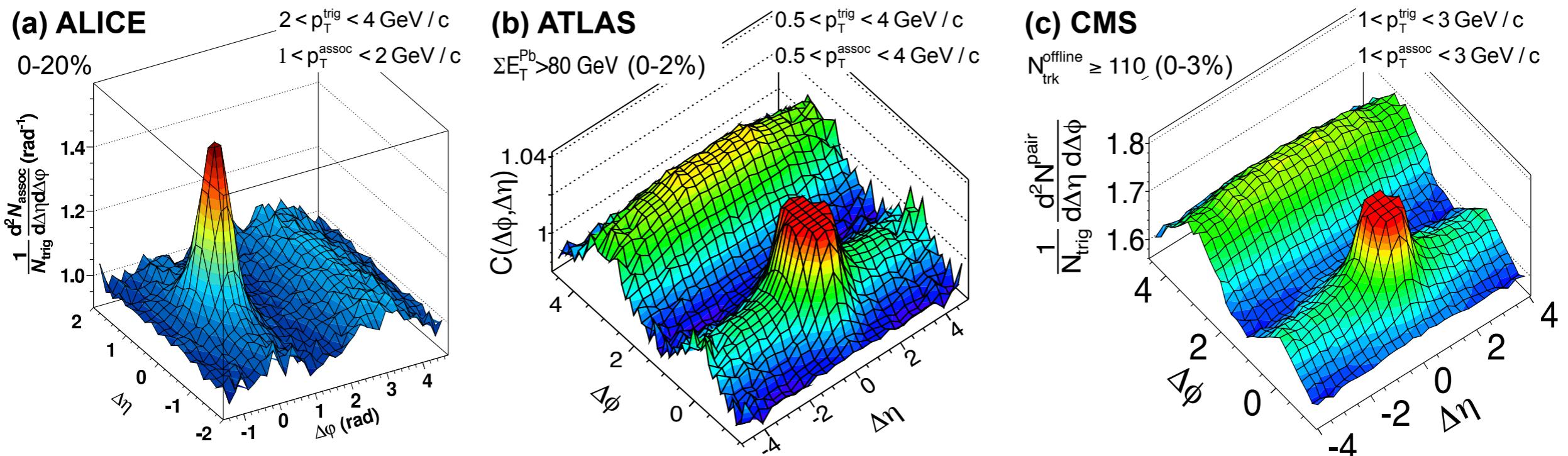
'string shoving'

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

RIDGE IN p+Pb COLLISIONS

high multiplicity p+Pb

pPb $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ at the LHC

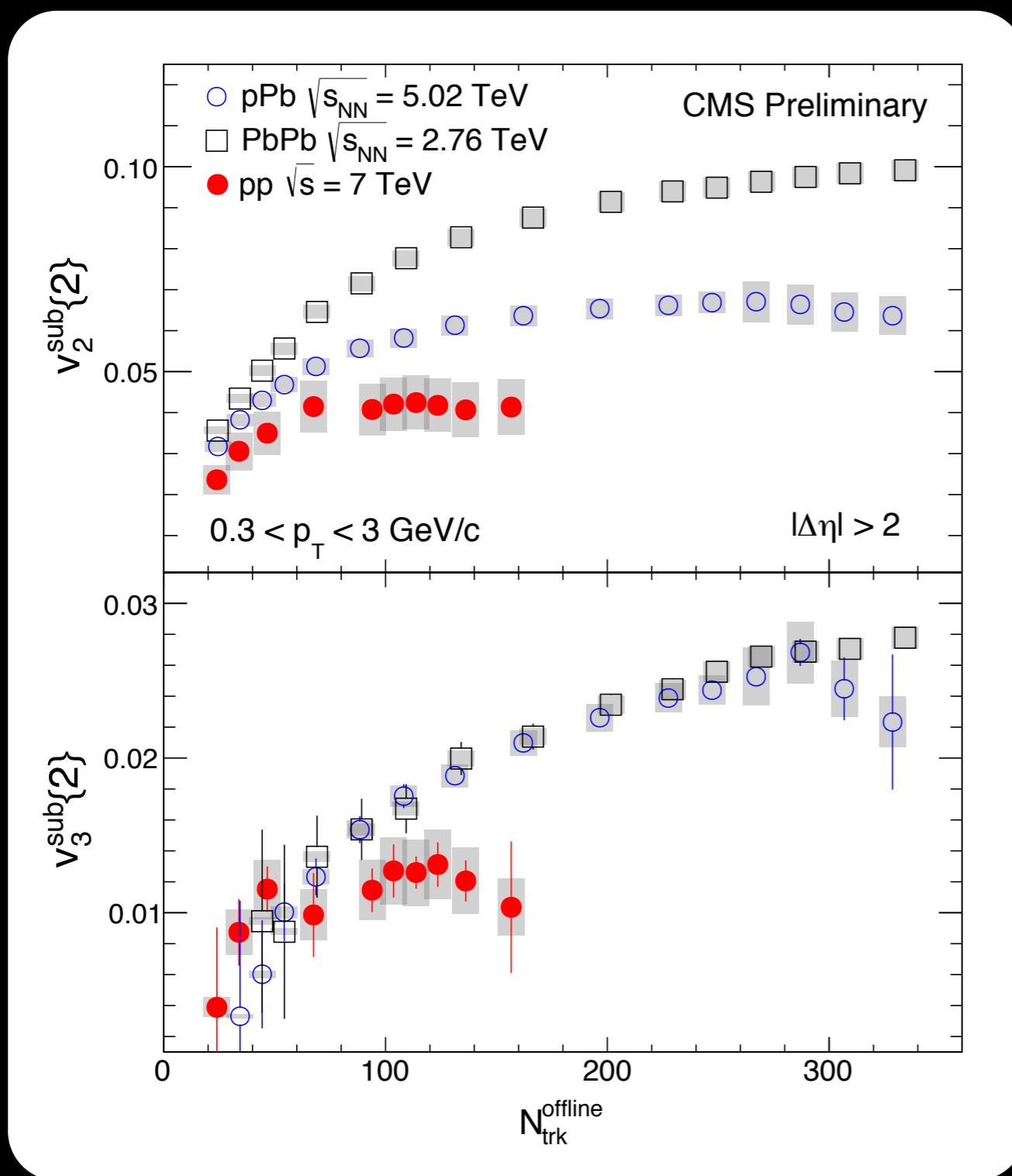


ALICE COLLABORATION, PHYS. LETT. B 719 (2013) 29

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



SEE ALSO:

ALICE COLLABORATION

PHYS. LETT. B719 (2013) 29-41;

PHYS. REV. C 90, 054901

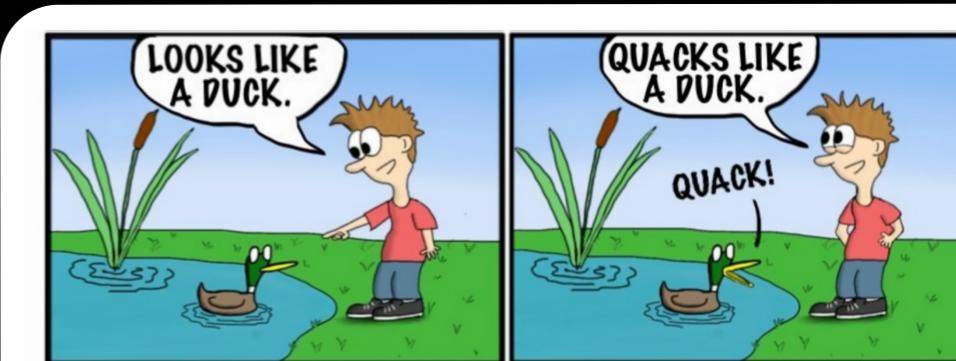
ATLAS COLLABORATION

PHYS. REV. LETT. 110, 182302

(2013); PHYS. REV. C 90.044906
(2014)

CMS COLLABORATION

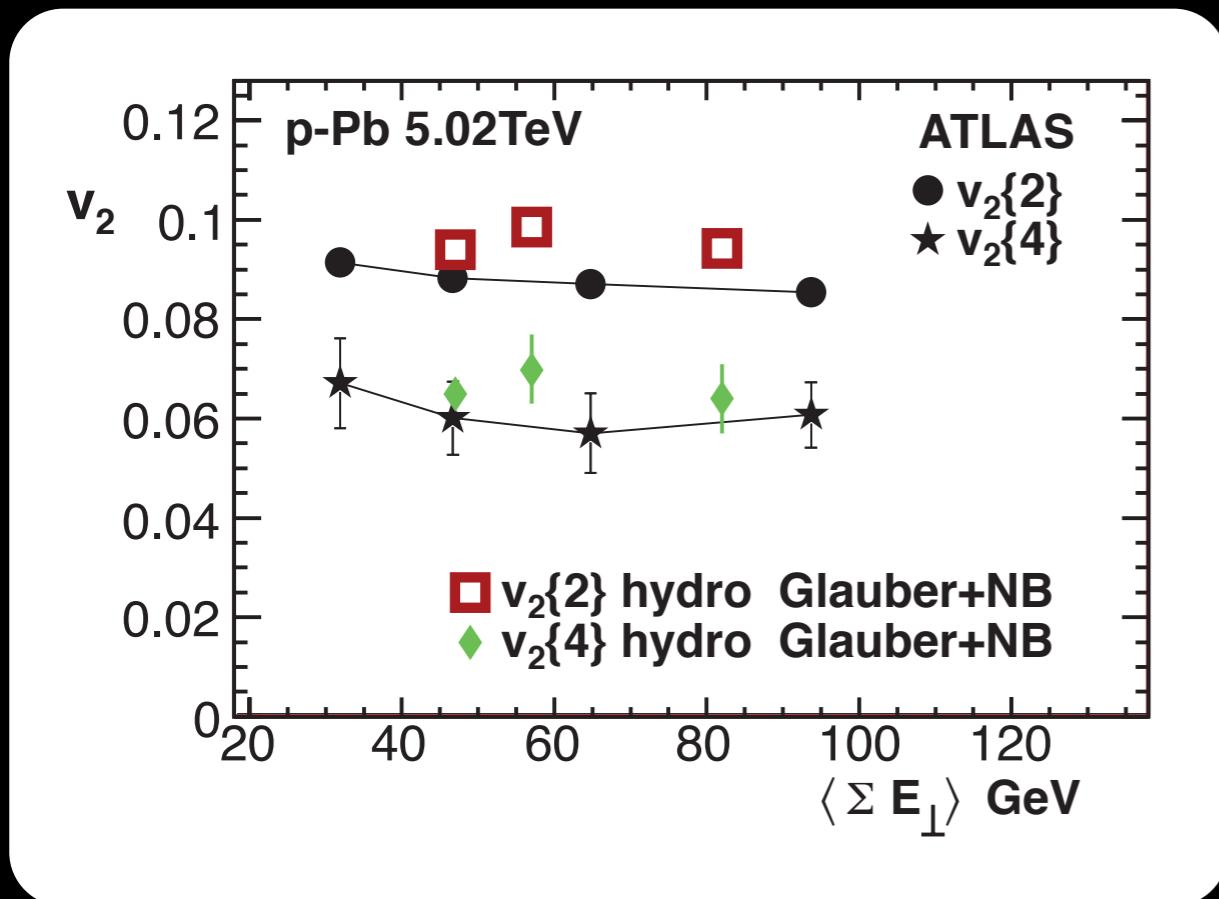
PHYS.REV.LETT. 115, 012301 (2015)



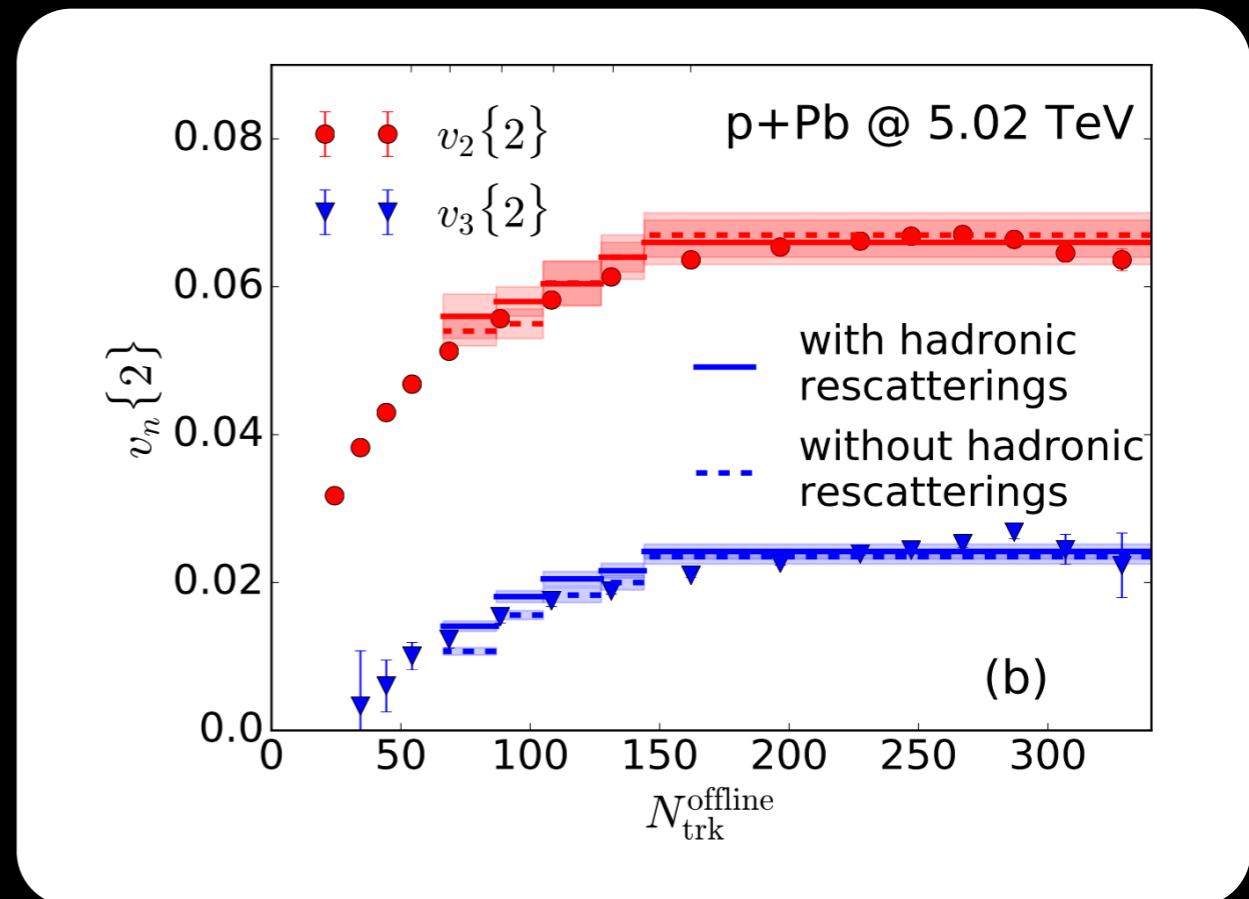
HYDRO IN SMALL SYSTEMS

MC-Glauber initial state + viscous hydrodynamics works

ATLAS Coll. PLB725 (2013) 60-78



CMS Coll. PLB724, 213–240 (2013)

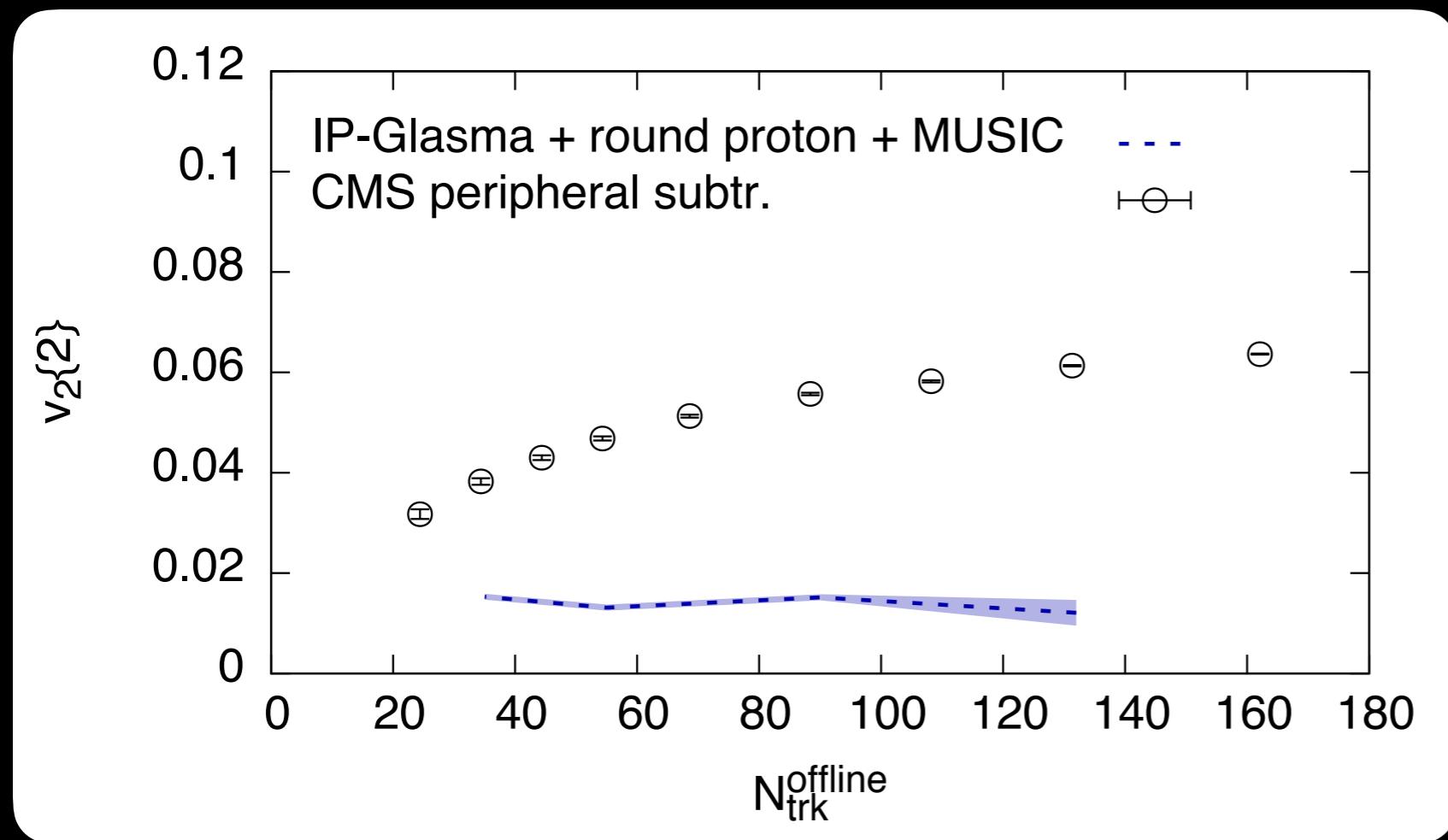


Bozek, Broniowski, PRC88 (2013) 014903

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; ...

p + Pb v_2 from IP-GLASMA + Hydro

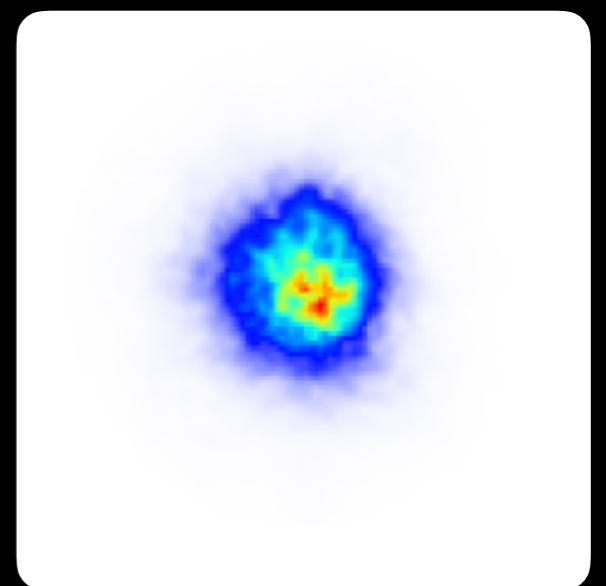
Model worked well in A+A. In p+A it did not.
Not because hydro does not work.
But because initial state was missing physics.



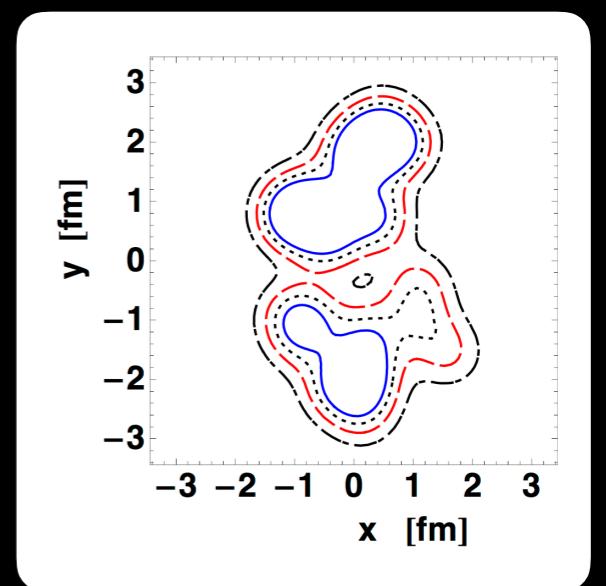
B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)

Experimental data: CMS Collaboration, Phys.Lett. B724, 213 (2013)

IP-Glasma



MC-Glauber

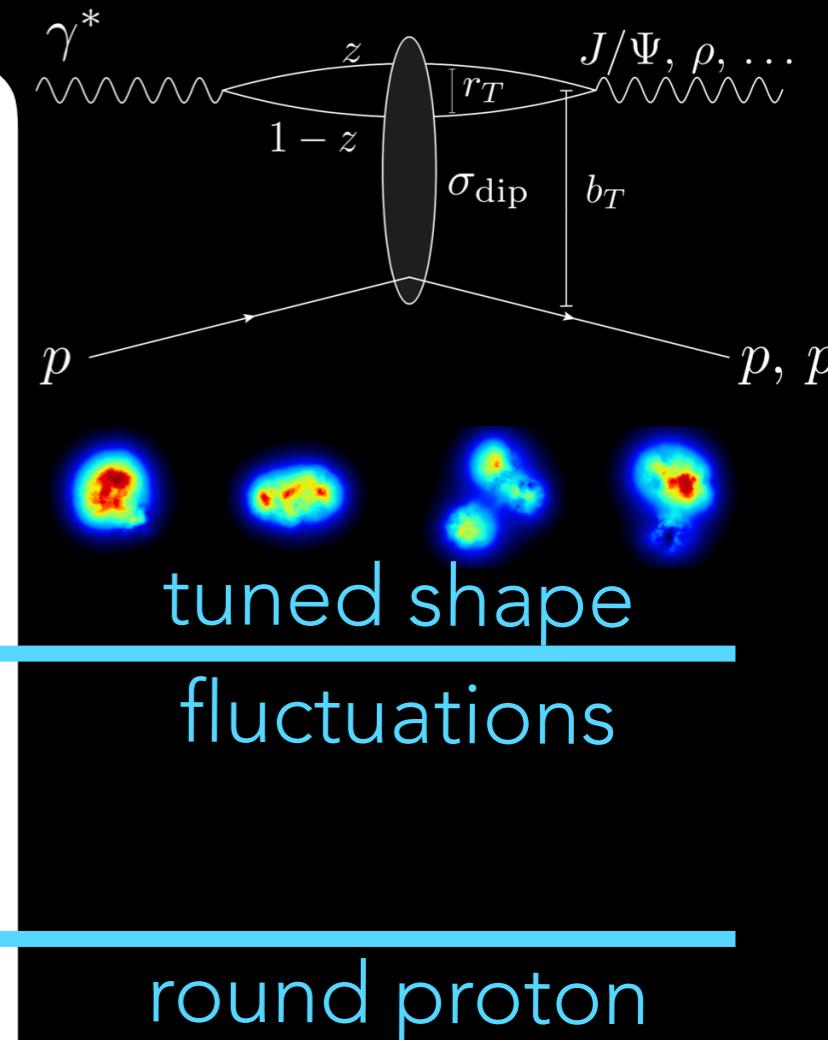
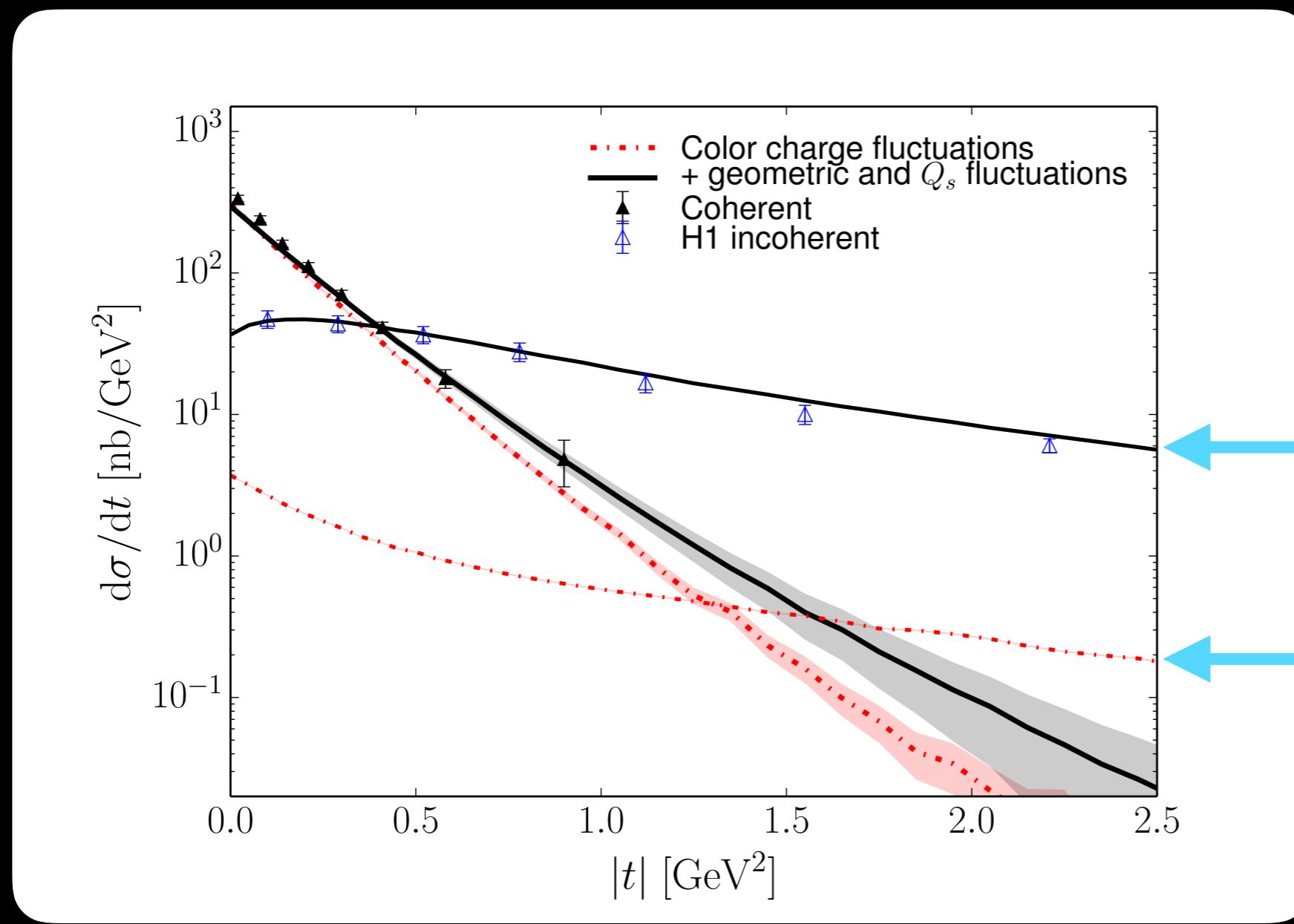


P. Bozek, Phys.Rev. C85 (2012) 014911

NEED PROTON SHAPE FLUCTUATIONS!

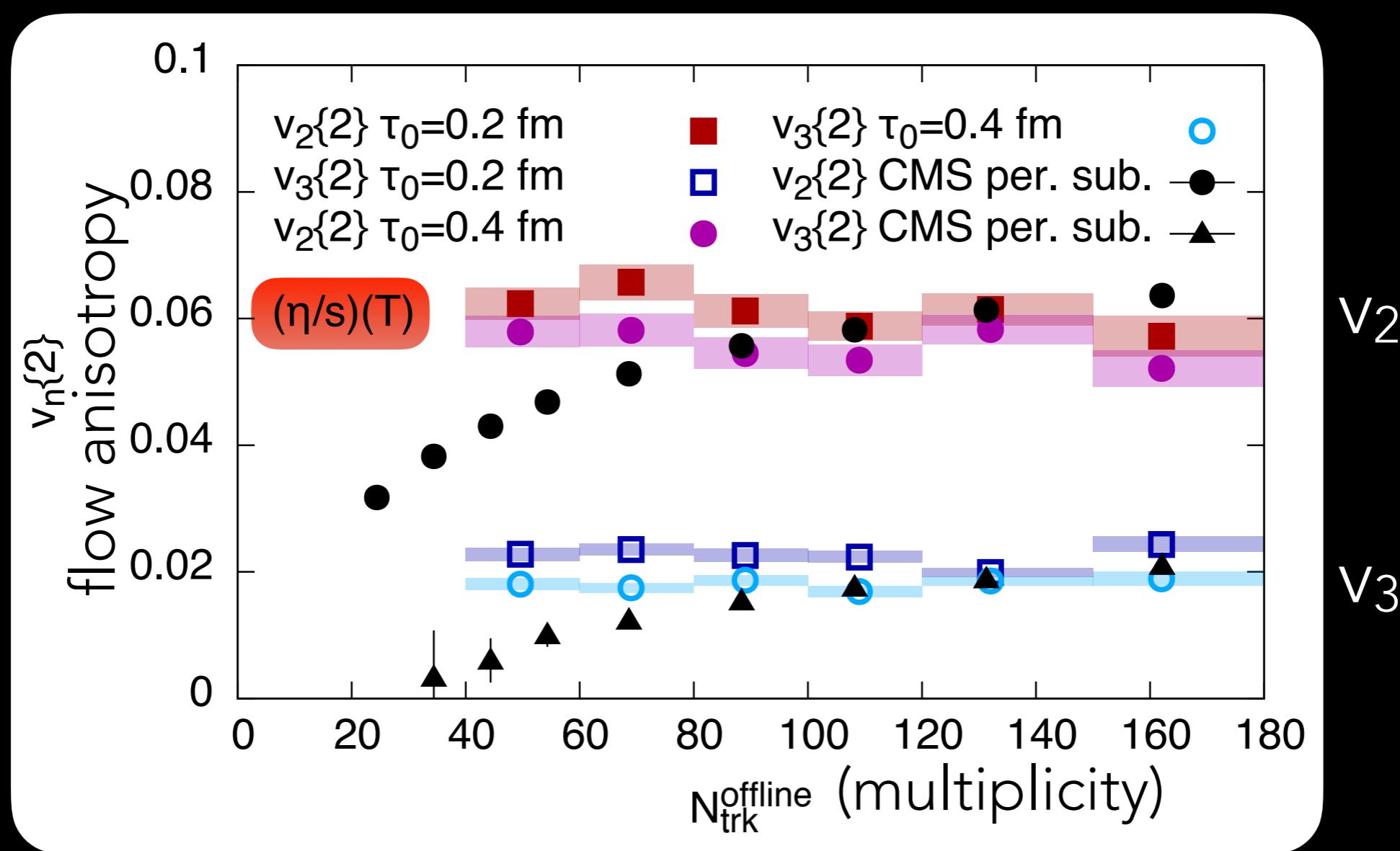
H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys. Rev. D94 (2016) 034042

e+p (HERA) Exclusive diffractive J/ Ψ production:
Incoherent x-sec sensitive to fluctuations



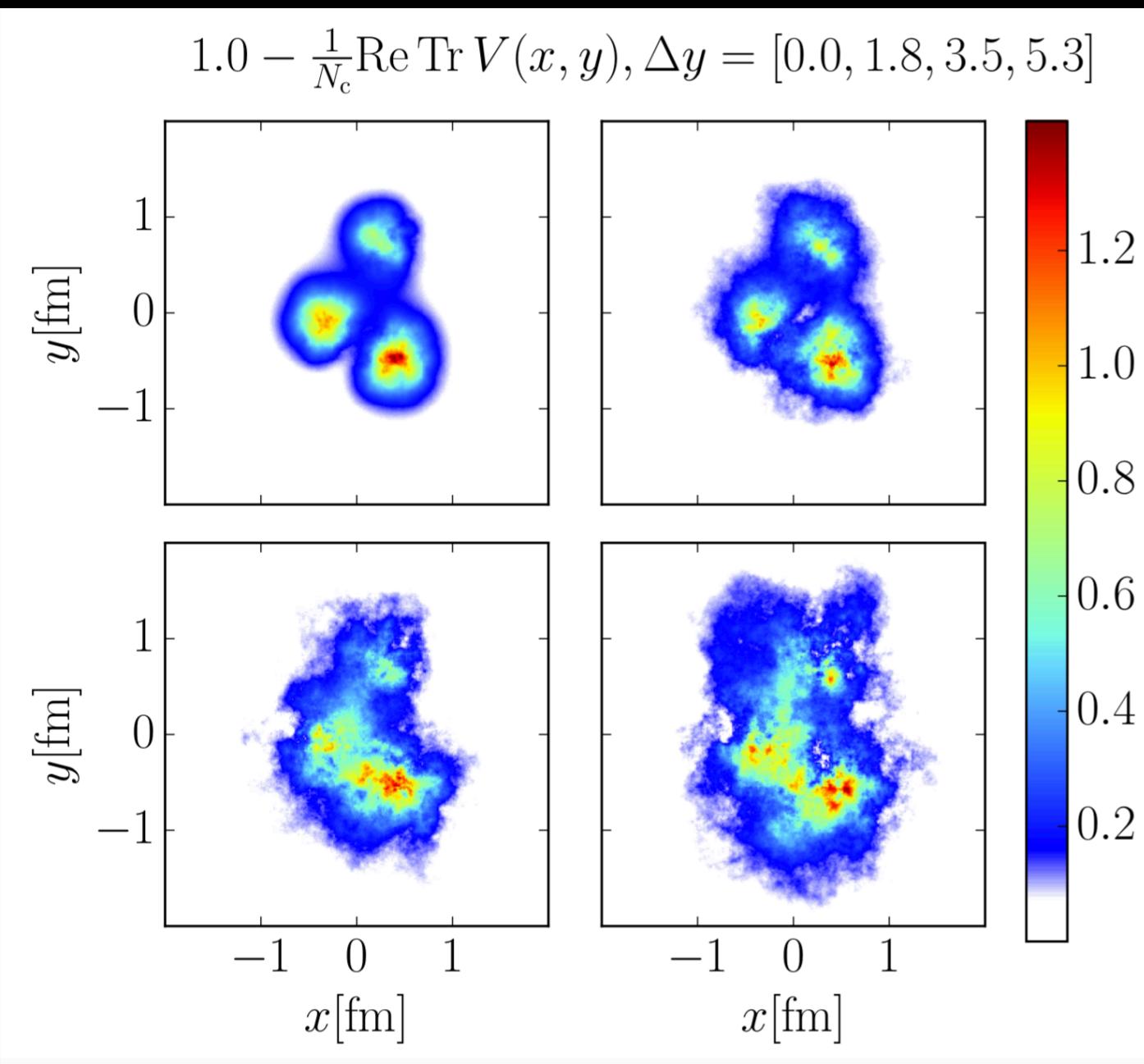
IP-Glasma + hydro + fluctuating proton geometry

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



x -evolution of fluctuating protons

H. Mäntysaari, B. Schenke, Phys. Rev. D98 (2018) 034013; S. Schlichting, B. Schenke, Phys. Lett. B739 (2014) 313



JIMWLK evolution
of gluon structure

Proton size vs. energy

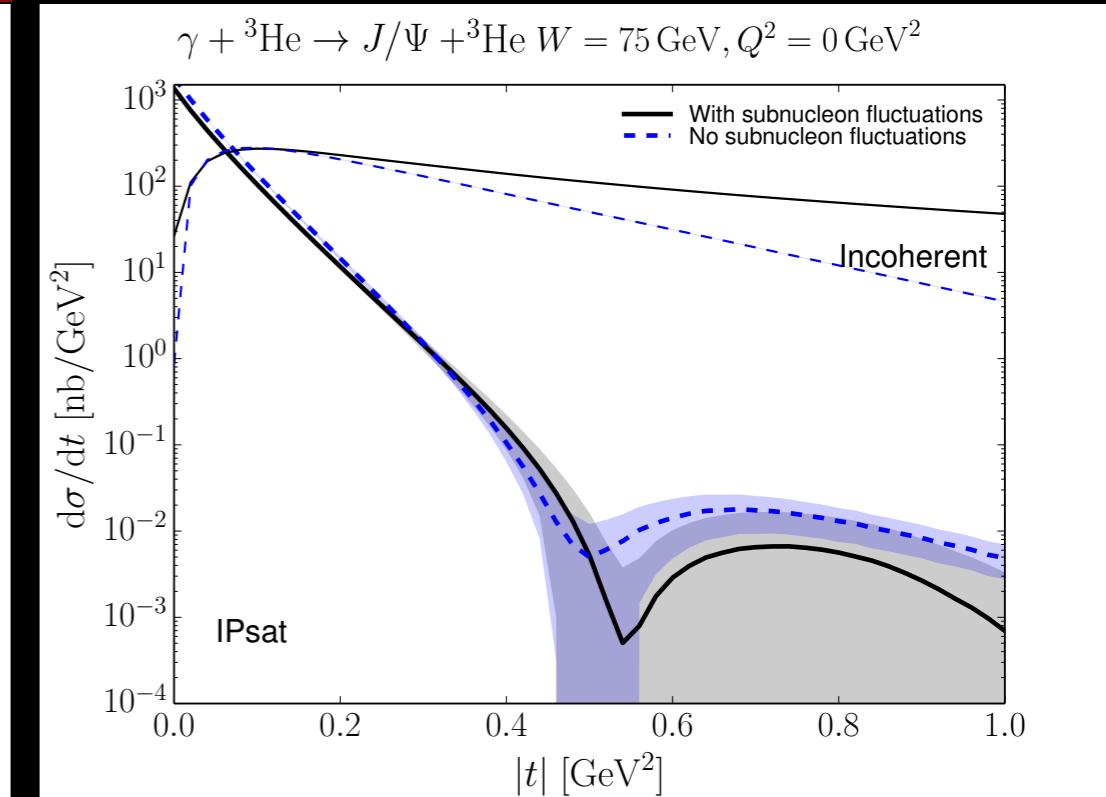
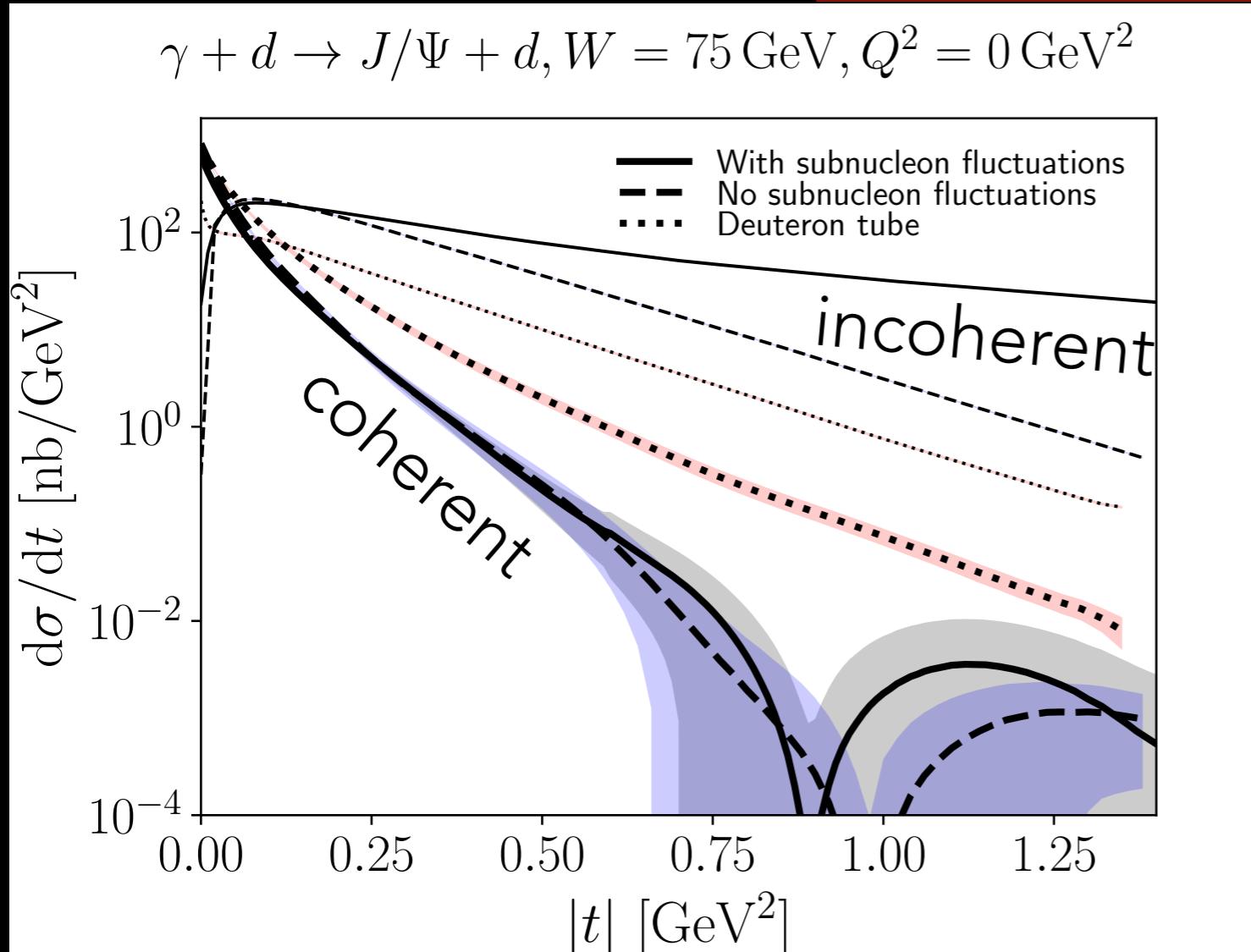
$$\frac{d\sigma^{\gamma p \rightarrow J/\Psi p}}{dt} \sim e^{-B_G|t|}$$

Björn Schenke, BNL

Where are small x gluons in small nuclei?

H. Mäntysaari, B. Schenke, in preparation

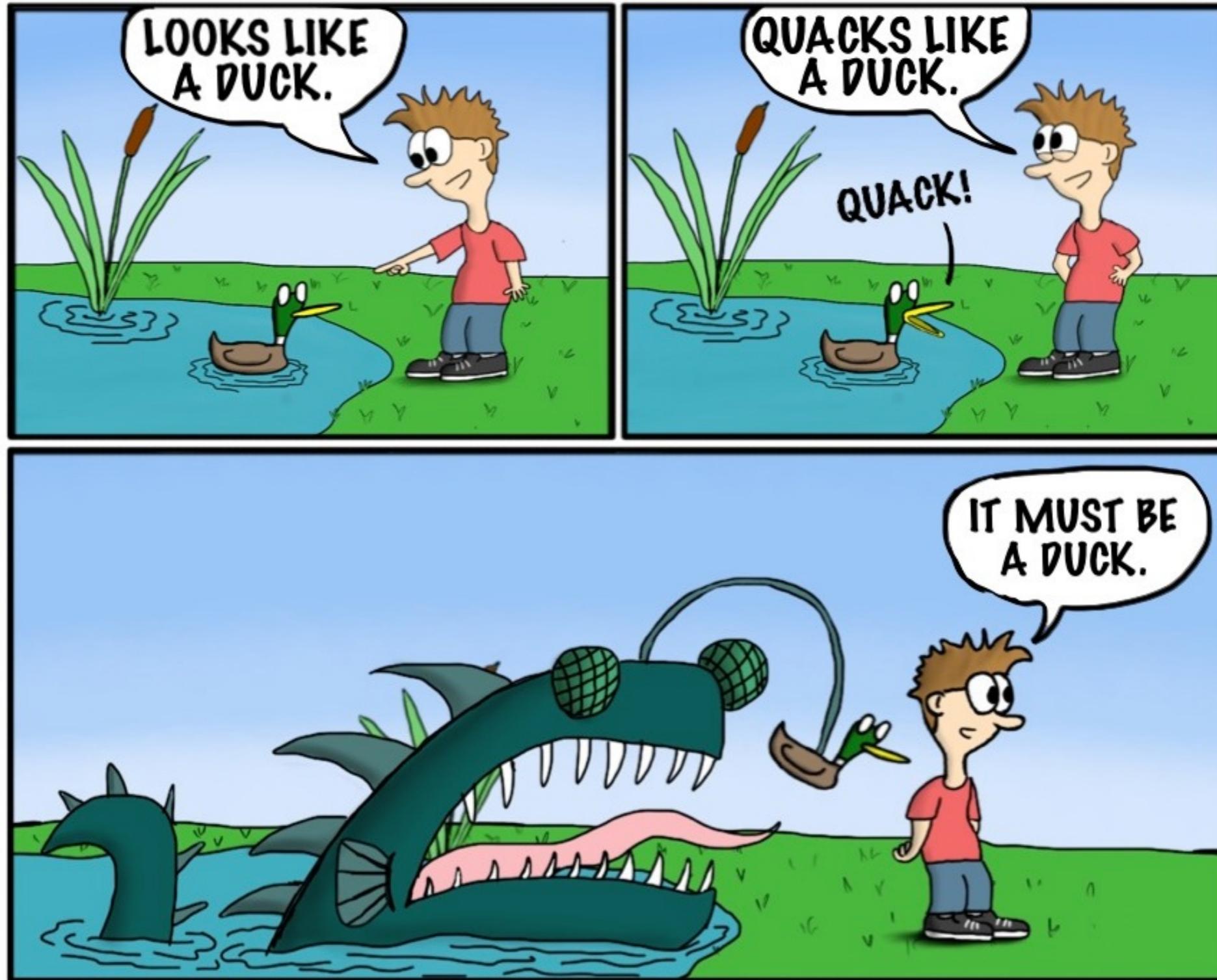
PRELIMINARY



Same for ${}^3\text{He}$

Deuteron with gluons located at nucleon positions
with (solid) and w/o (dashed) subnucleon structure
and gluons in "tube" between nucleons (dotted, red)

INITIAL STATE MOMENTUM CORRELATIONS



INITIAL MOMENTUM CORRELATIONS

SEE MARK MACE'S TALK ON FRIDAY

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)

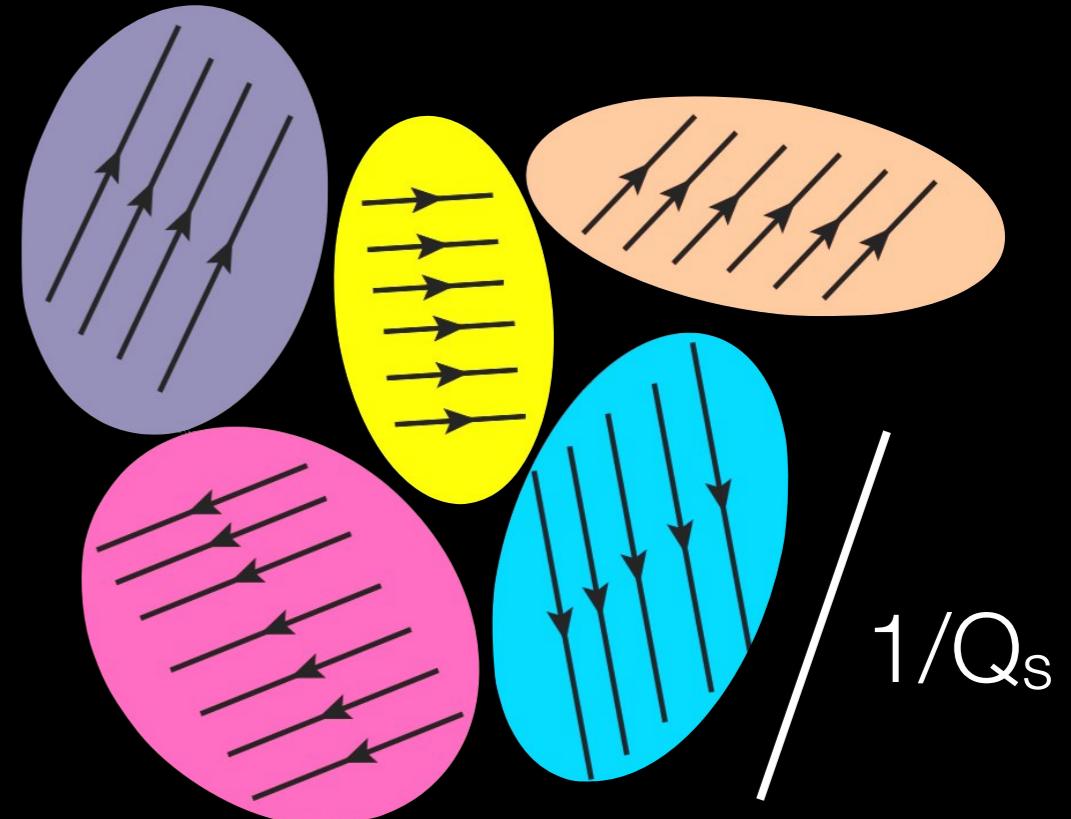
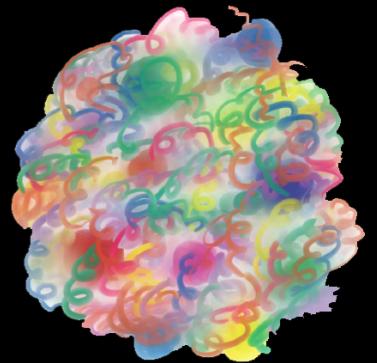


FIGURE: T. LAPPI, B. SCHENKE, S. SCHLICHTING, R. VENUGOPALAN
JHEP 1601 (2016) 061; SEE ALSO: A. DUMITRU, A.V. GIANNINI, NUCL.PHYS.A933 (2014)
212; A. DUMITRU, V. SKOKOV, PHYS.REV.D91 (2015) 074006; A. DUMITRU
L. MCLERRAN, V. SKOKOV, PHYS.LETT.B743 (2015), 134;
V. SKOKOV. PHYS.REV.D91 (2015) 054014

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

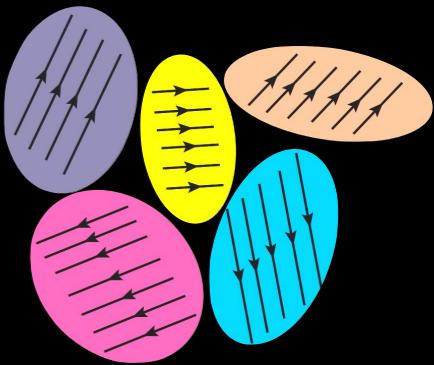
This is it.

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

SEE MARK MACE'S TALK ON FRIDAY

CAN WE DISTINGUISH INITIAL FROM FINAL STATE EFFECTS?

Many possibilities. Different observables.

I will focus on studying

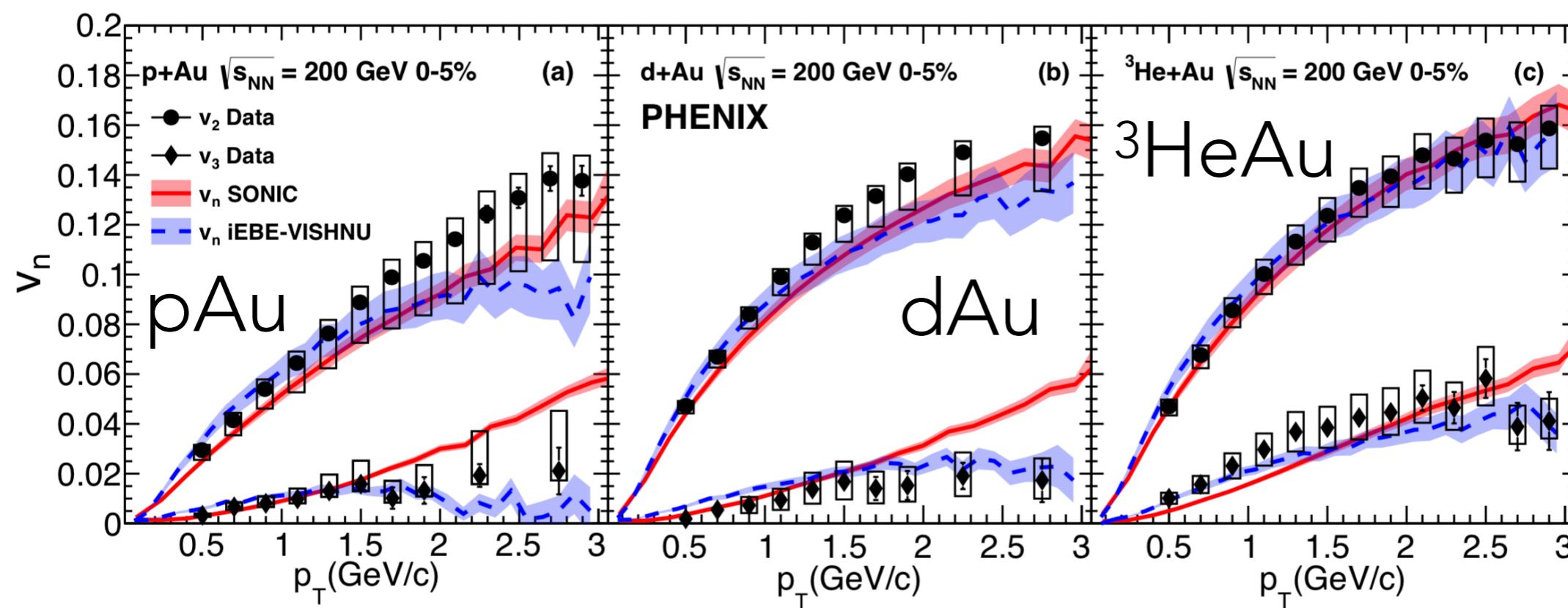
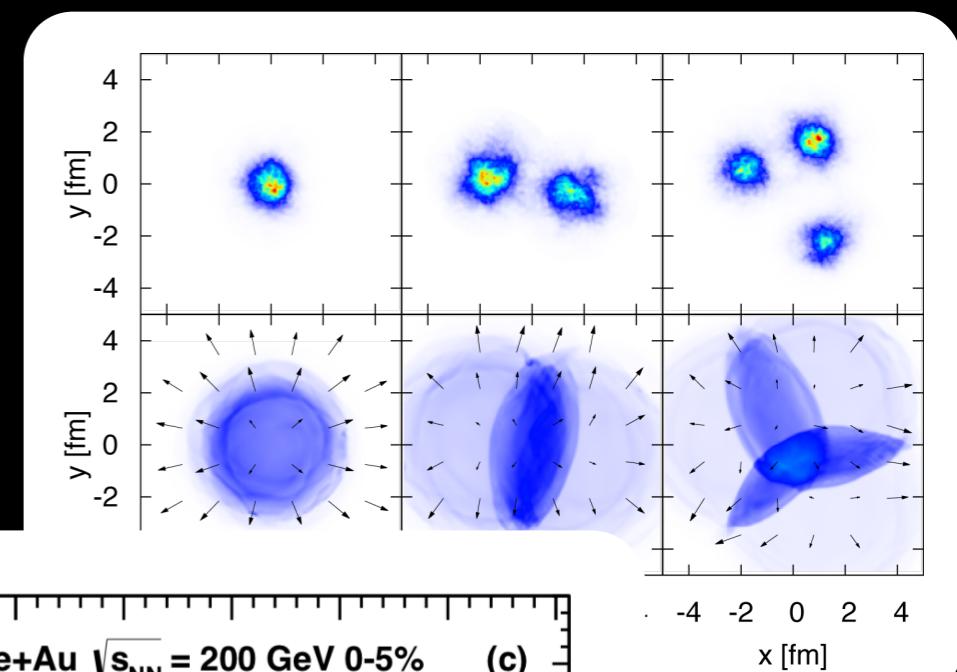
Different collision systems: Allow to control initial geometry

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.



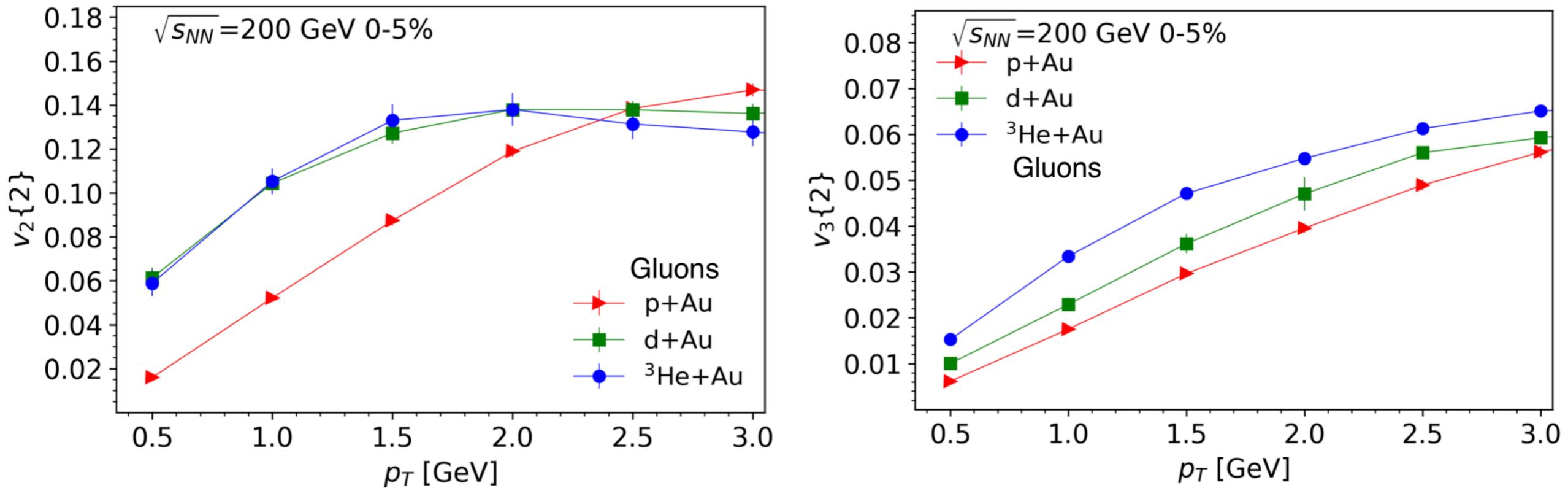
PHENIX, arXiv:1805.02973

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

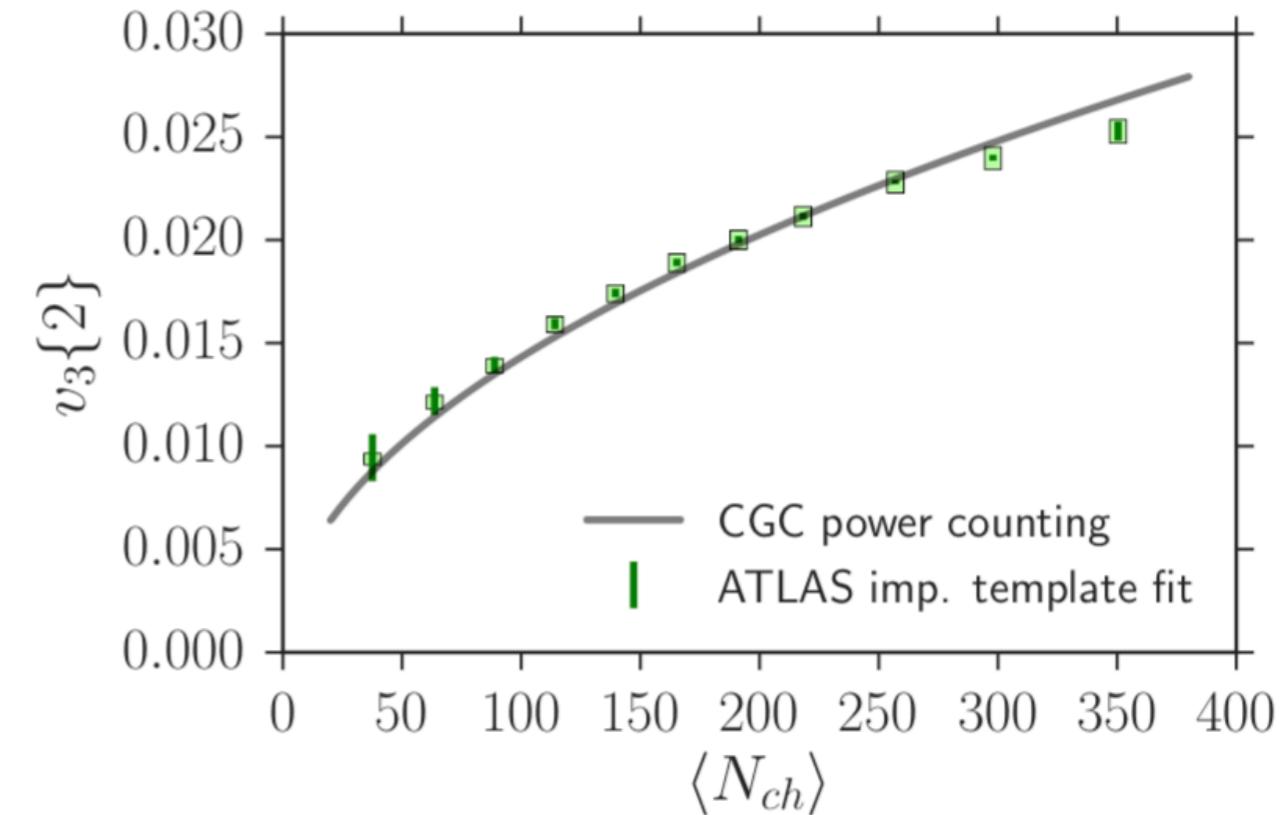
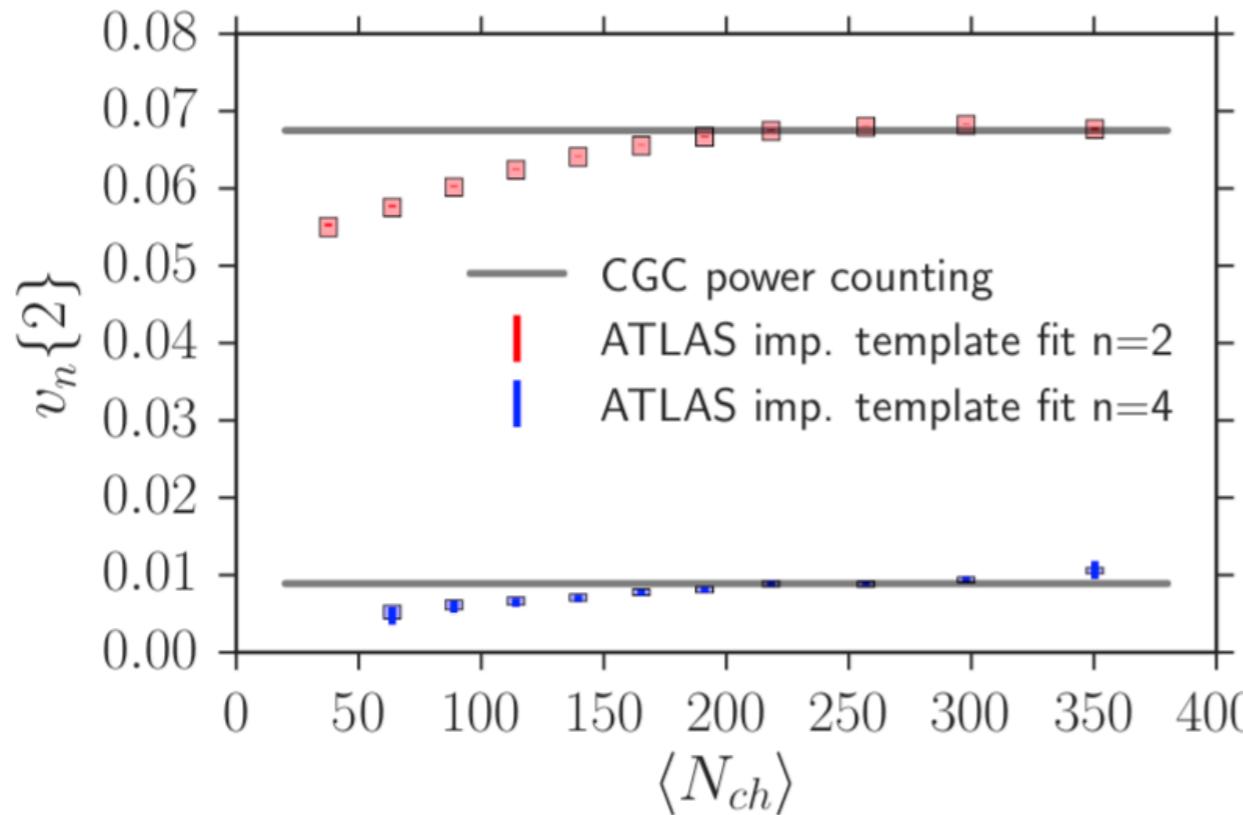
Recent results from initial state momentum correlations:



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)

SYSTEMATICS WITH N_{ch}



Mark Mace, Vladimir V. Skokov, Prithwish Tribedy, Raju Venugopalan, e-Print: arXiv:1807.00825

Rescaling proton color charge density $\rho_p \rightarrow c\rho_p$

$$\frac{dN}{dy}[\rho_p, \rho_t] \rightarrow c^2 \frac{dN}{dy}[\rho_p, \rho_t] + \mathcal{O}(c^3)$$

BECAUSE HIGHER ORDER EFFECT

$$Q_{2n} \rightarrow Q_{2n} \text{ and } Q_{2n+1} \rightarrow cQ_{2n+1} \sim \sqrt{dN/dy}$$

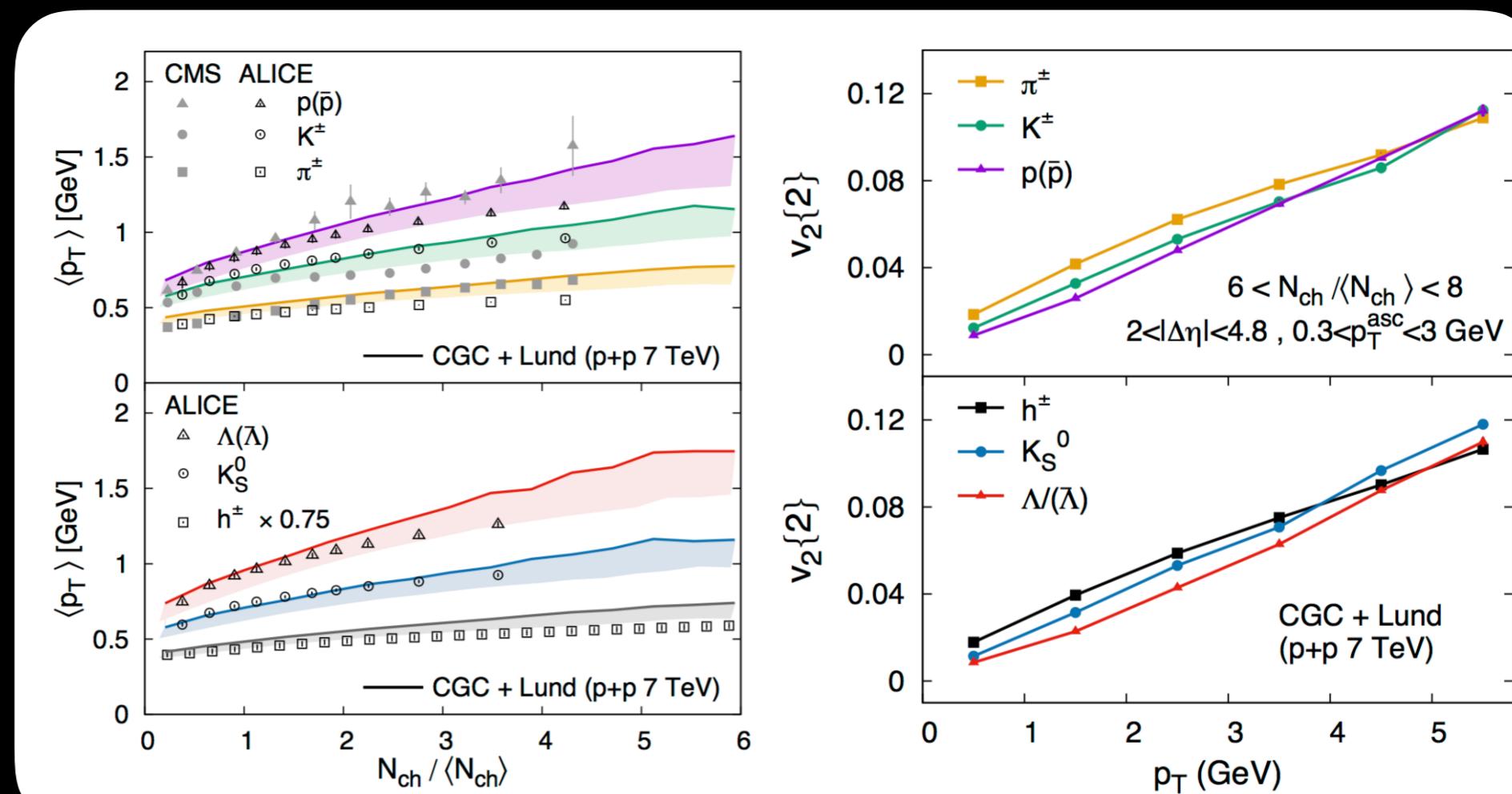
IP-GLASMA + HYDRO + LUND

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

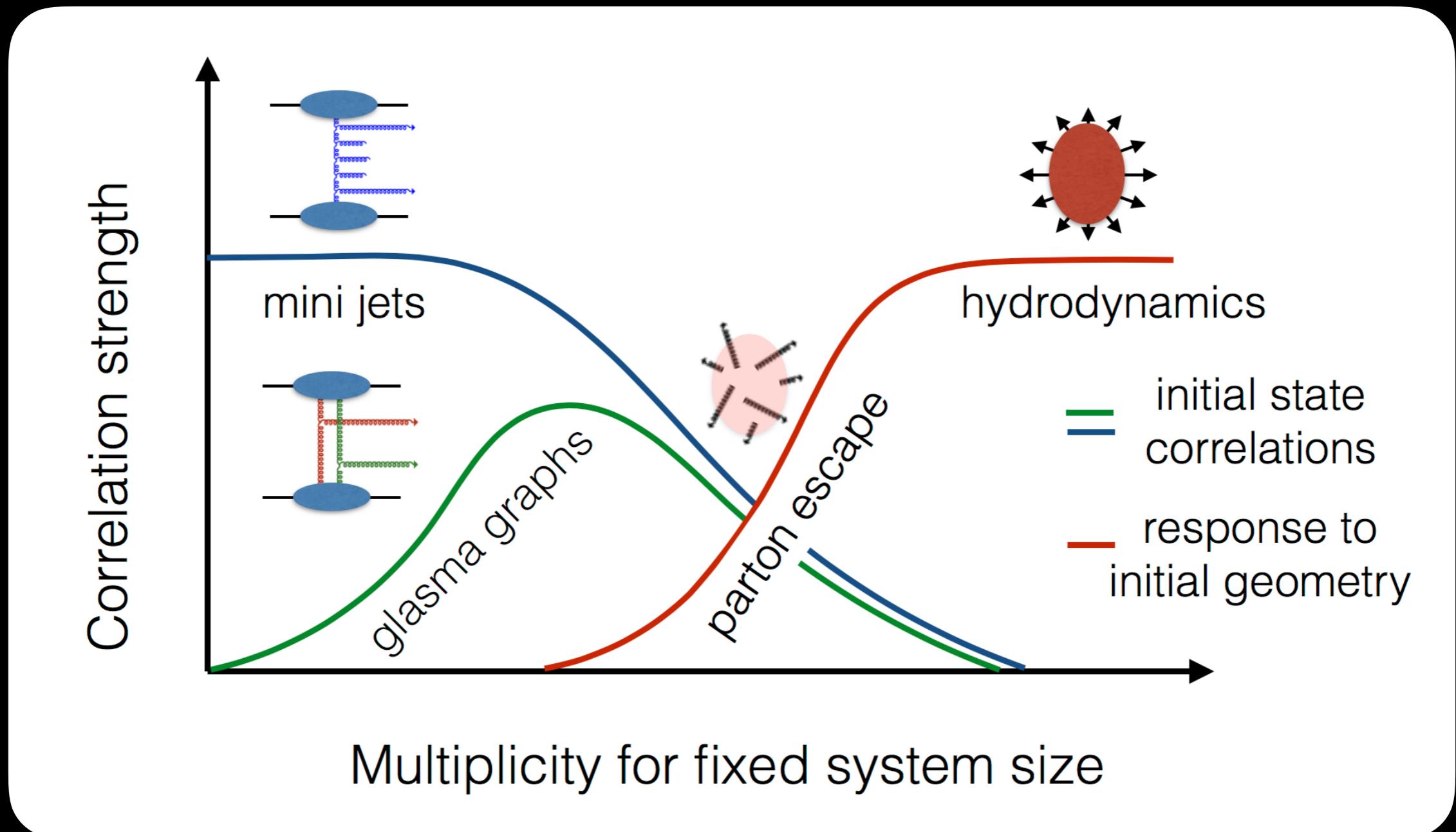
Sample gluons
and connect with
Lund strings

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



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

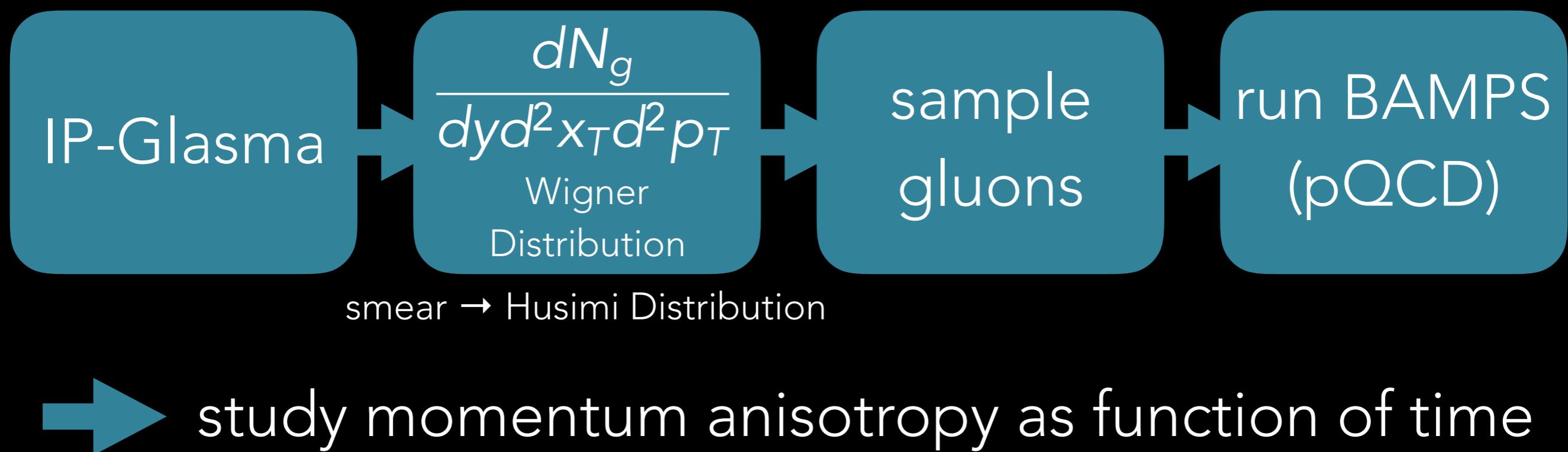
S. Schlichting, Quark Matter 2015

IP-Glasma + parton cascade

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

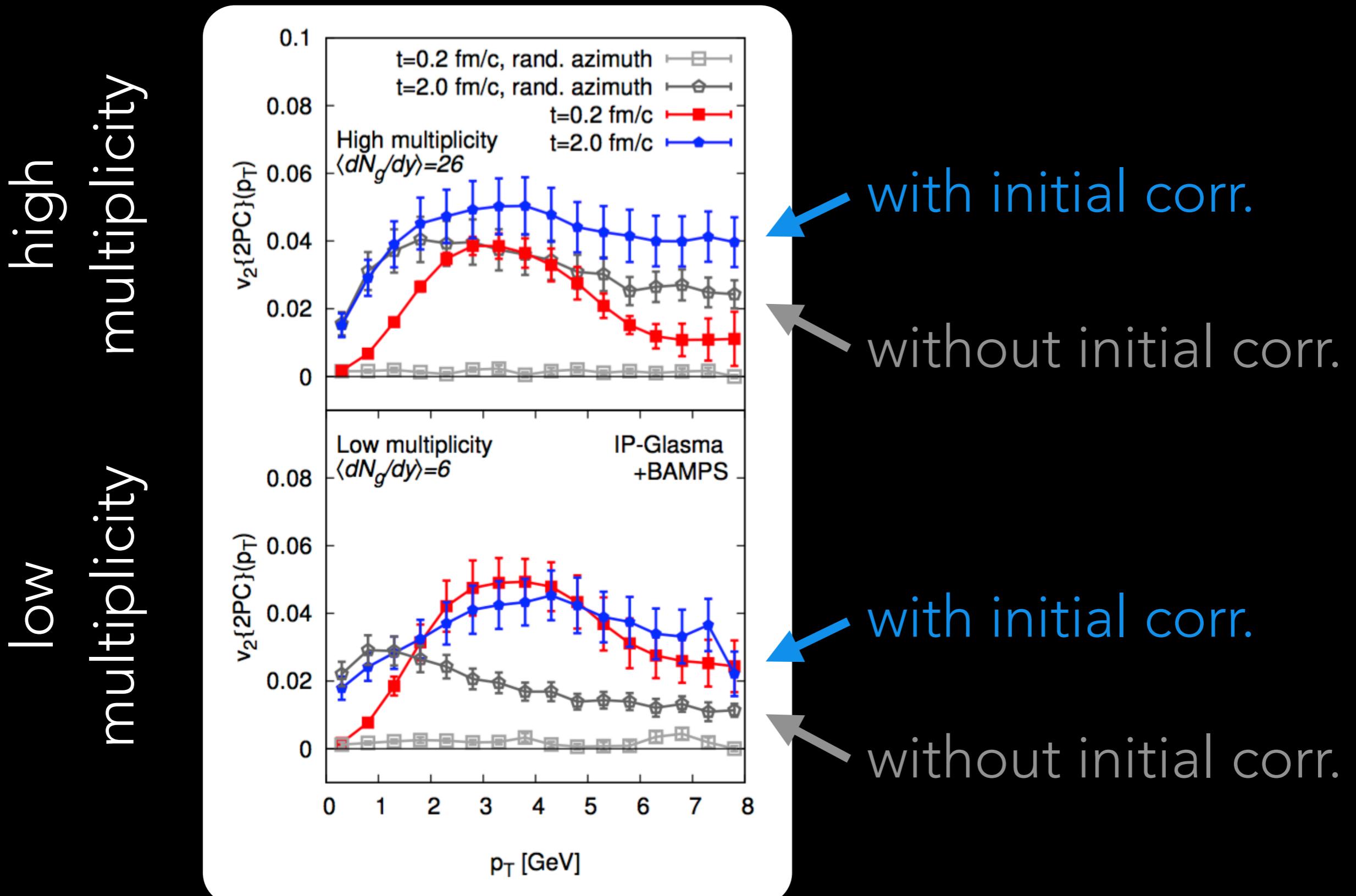
To study how final state interactions affect the initial state correlations, we use a microscopic final state model, the parton cascade BAMPS

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



Effect of initial correlations on final v_2

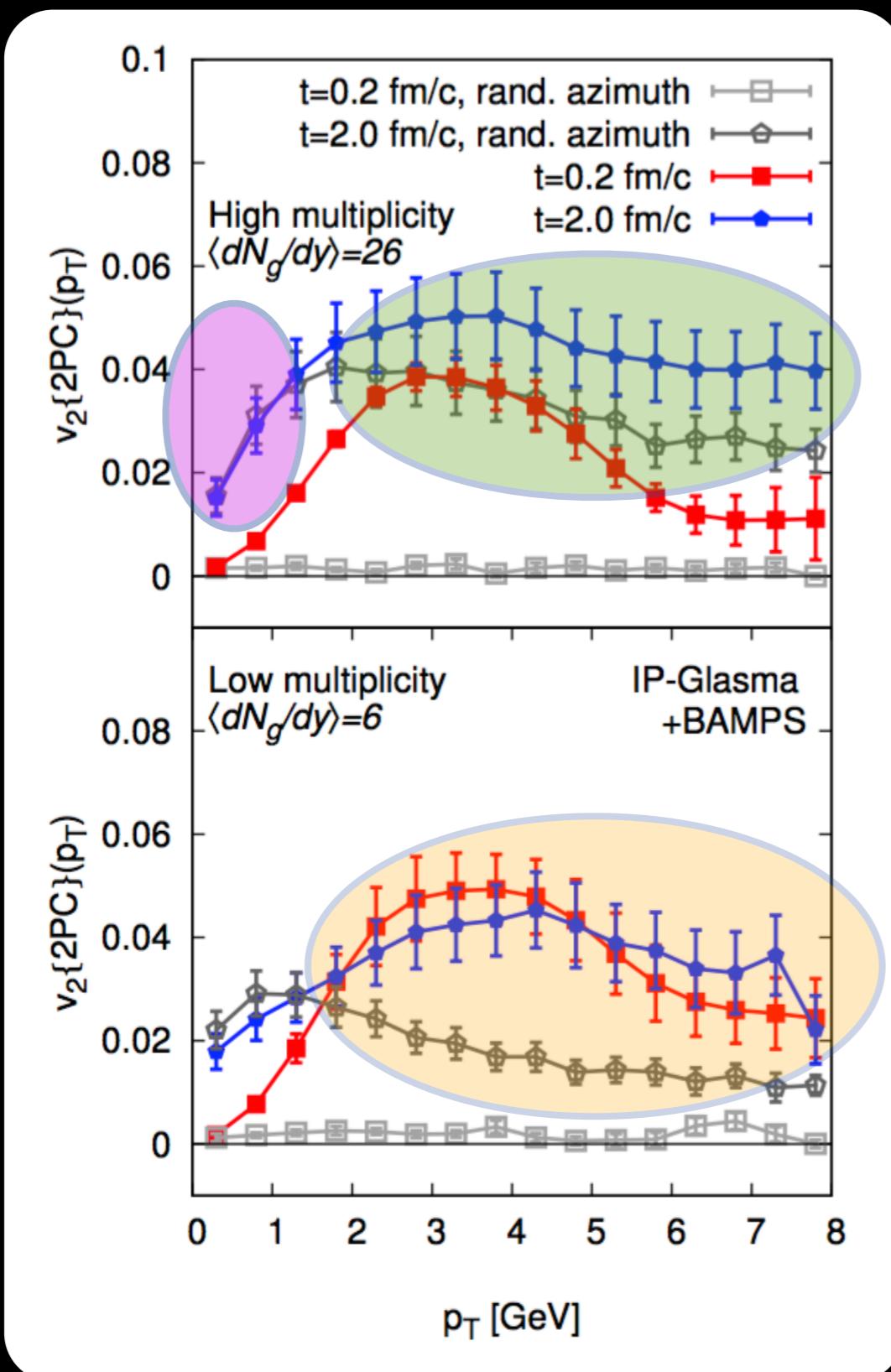
M. Greif, C. Greiner, B. Schenke, S. Schlichting, Z. Xu, arXiv:1708.02076, Phys. Rev. D96, 091509(R)



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

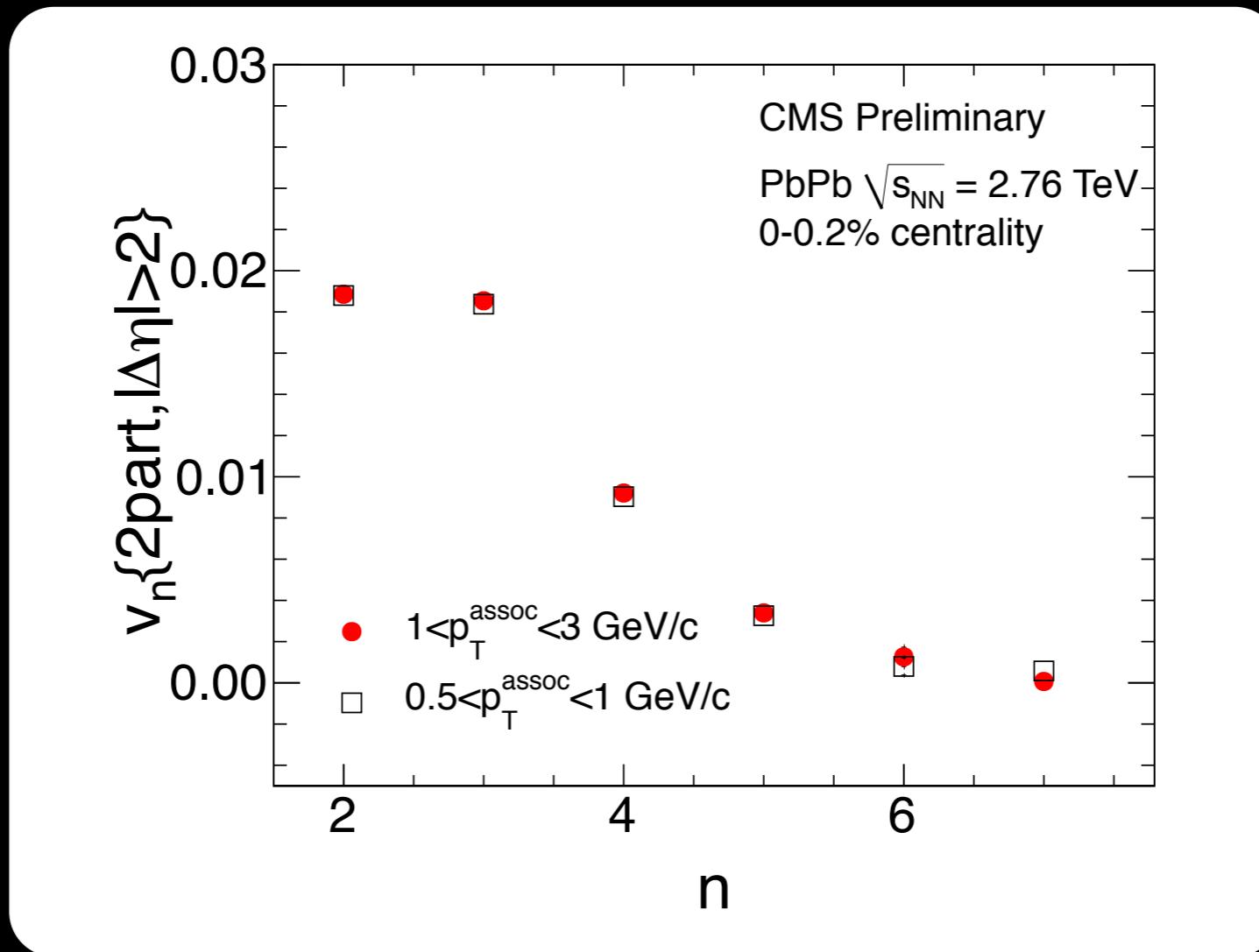
- Multi-particle correlation measurements in small systems ($p+p$, $p/d/He+A$) have revealed interesting structures
- There are contributions from initial momentum anisotropies in the QCD particle production
- With increasing multiplicity, final state effects become important: sensitive to spatial structure
- An EIC can give important information on the gluonic structure of nuclei that is highly relevant for the initial state in collisions involving small nuclei

BACKUP

RIDGE IN HEAVY ION COLLISIONS

Azimuthal structure quantified using Fourier expansion

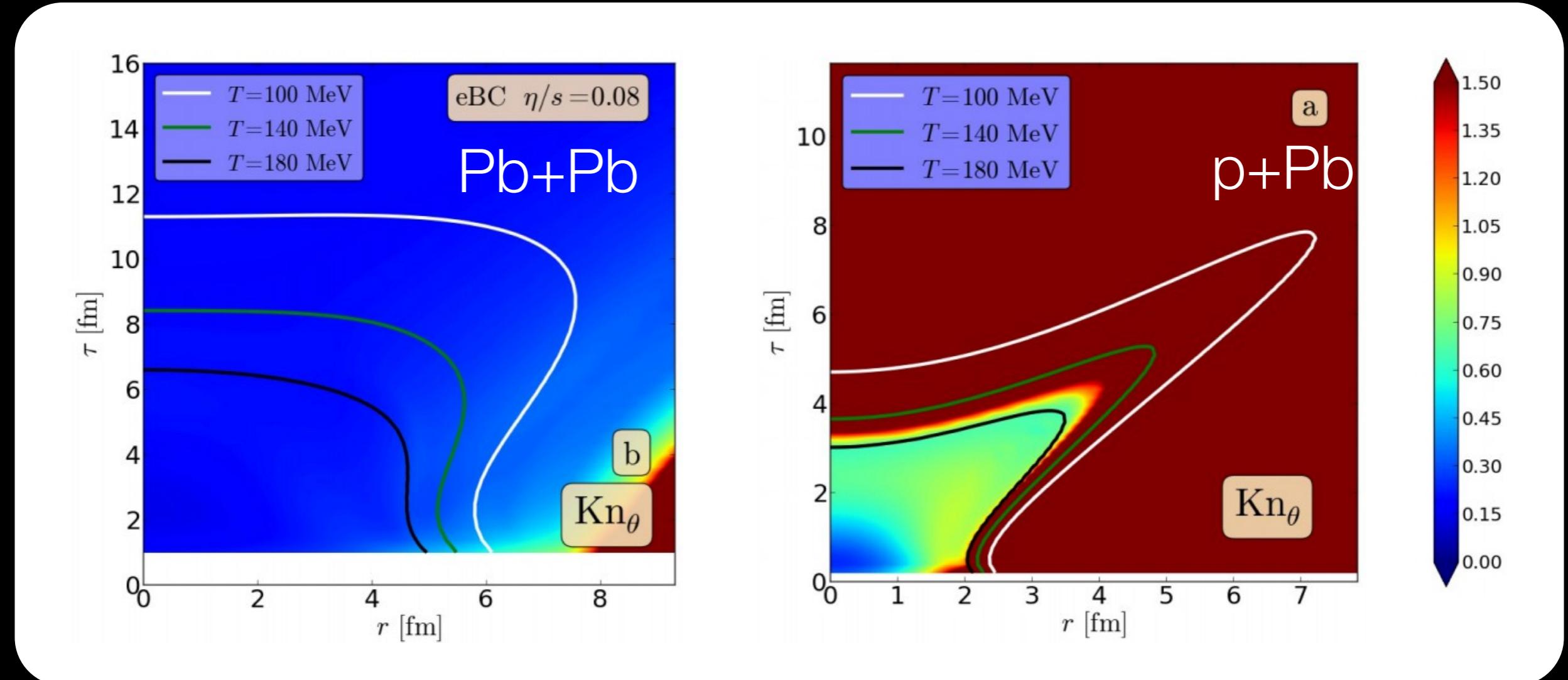
V_n



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

CAN WE TRUST HYDRODYNAMICS?

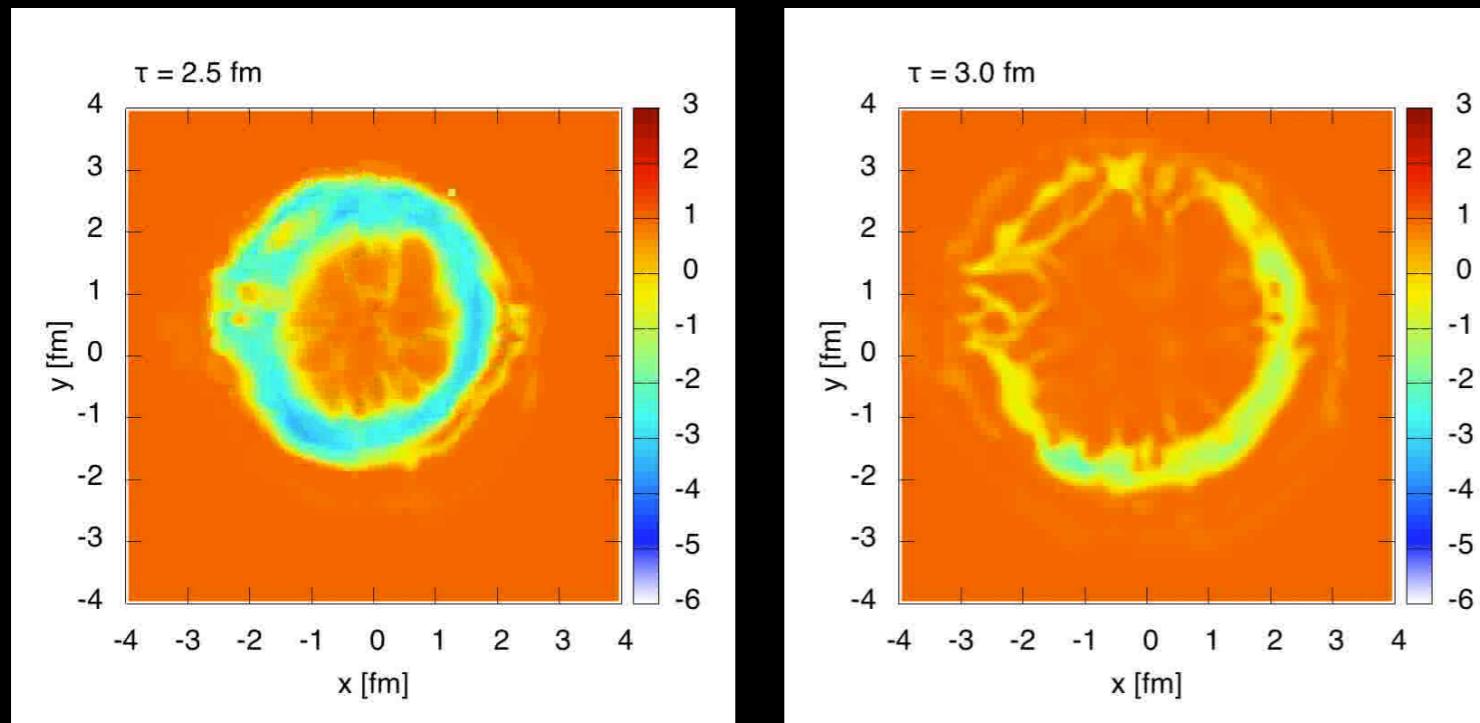
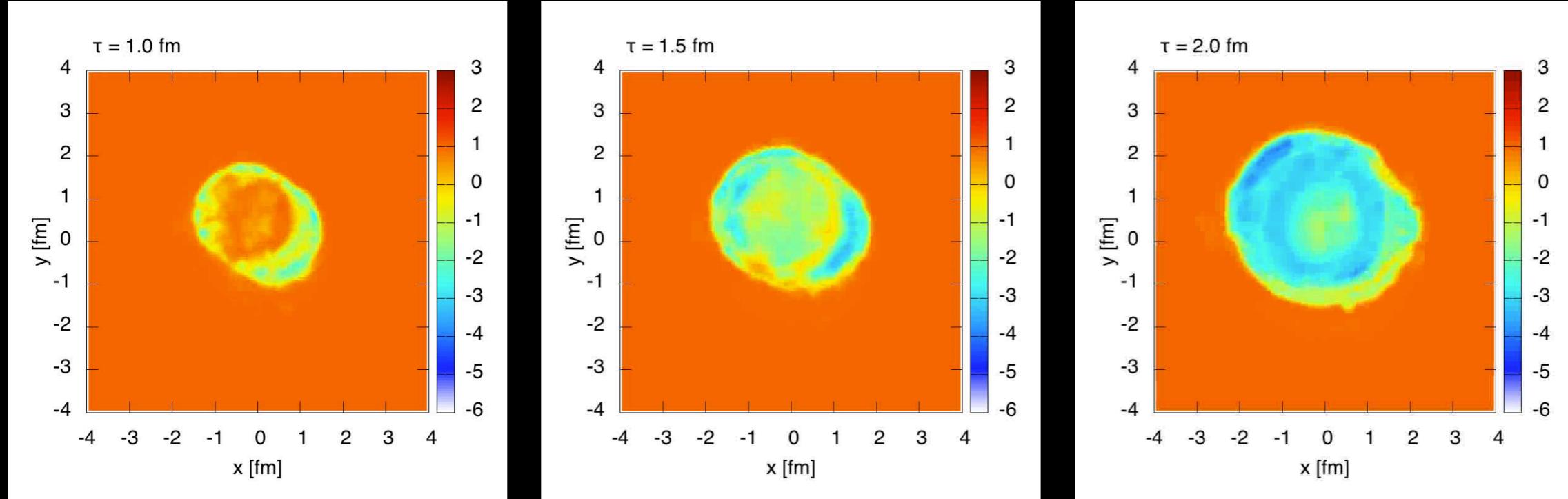
Knudsen number: ratio of a microscopic over macroscopic scale
Small Knudsen number means hydrodynamics is valid



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

NEGATIVE PRESSURE WITH BULK VISCOSITY



$1+\Pi/P$
in a p+Pb collision

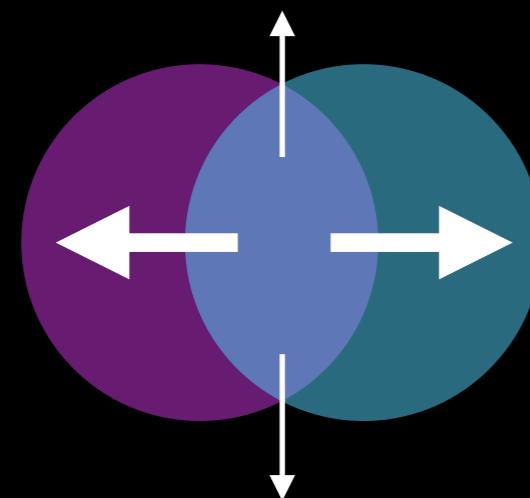
KINETIC THEORY "ANISOTROPIC ESCAPE"

A. Bzdak, G.-L. Ma, PRL113 (2014) 252301; G.-L. Ma, A. Bzdak, PLB739 (2014) 209-213;

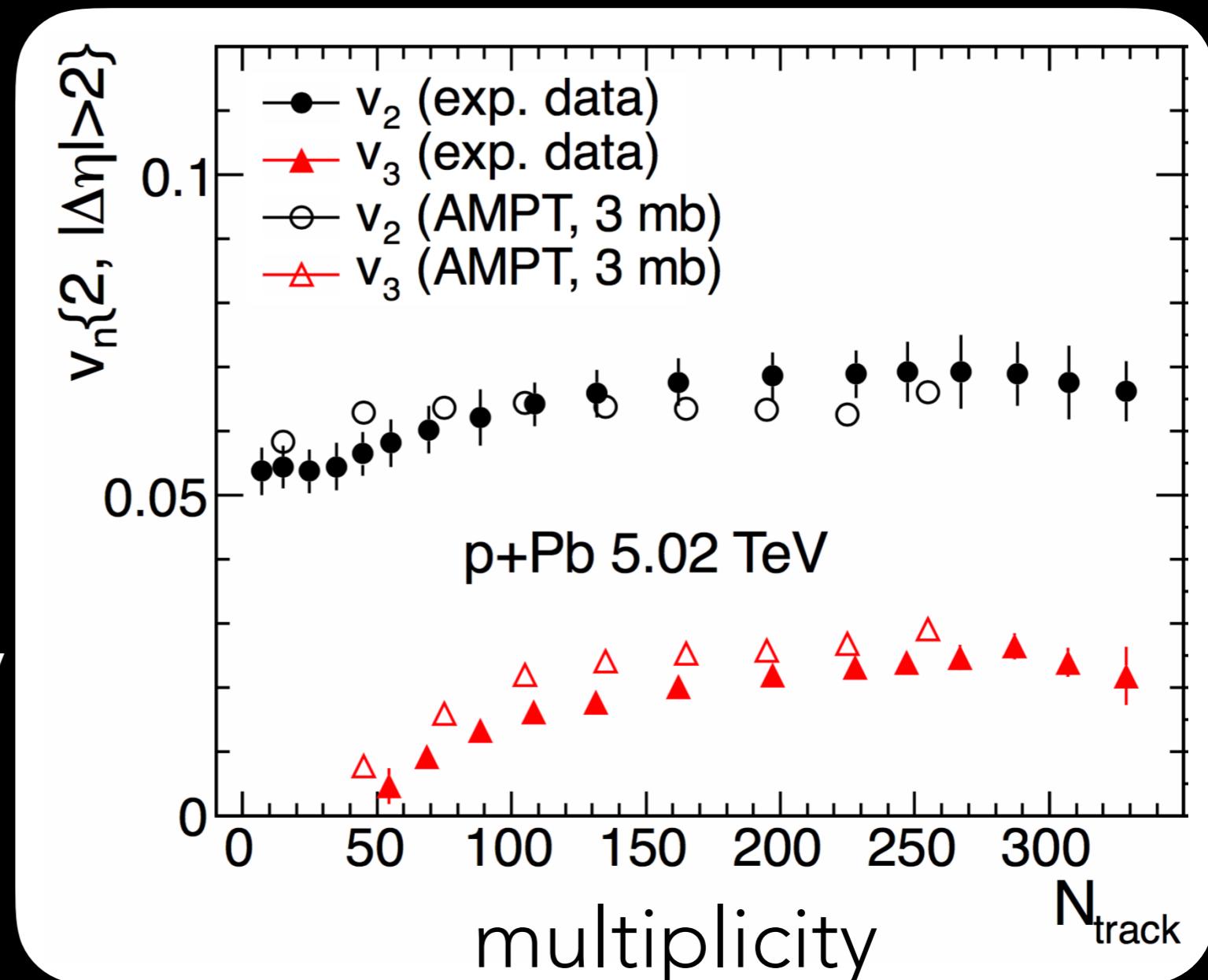
J.D. Orjuela Koop, A. Adare, D. McGlinchey, J.L. Nagle, PRC92 (2015) 054903; P. Bozek, A. Bzdak, G.-L. Ma, PLB748 (2015) 301-305; L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, F. Wang, PLB753 (2016)

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

Described in AMPT



Partons are more likely
to escape in the short
direction $\rightarrow v_n$



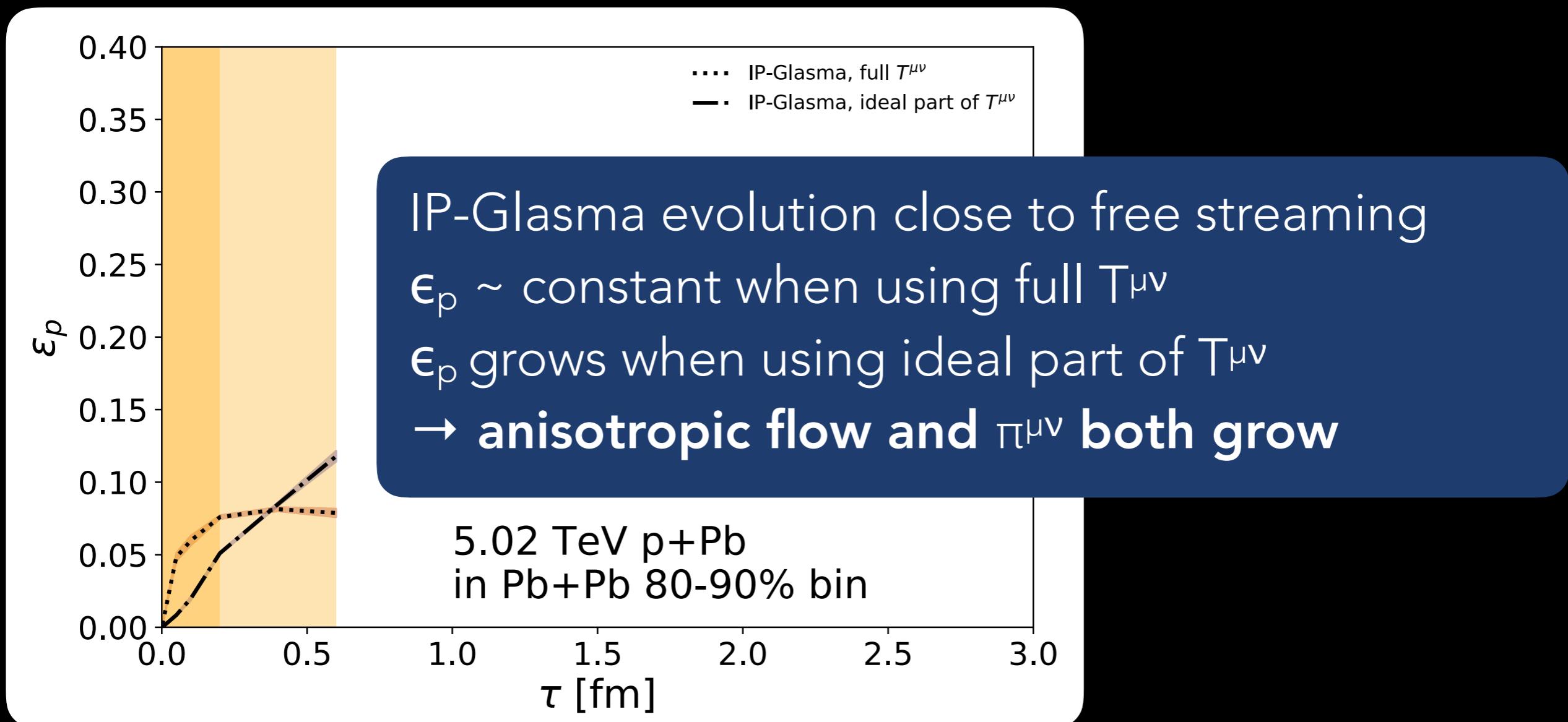
also see Kurkela, Wiedemann, Wu, arXiv:1803.02072

IP-Glasma + hydrodynamics

p+Pb events in 80-90% Pb+Pb class

$$\epsilon_p = \sqrt{\frac{\langle T_{xx} - T_{yy} \rangle^2 + \langle 2T_{xy} \rangle^2}{\langle T_{xx} + T_{yy} \rangle^2}}$$

IP-Glasma

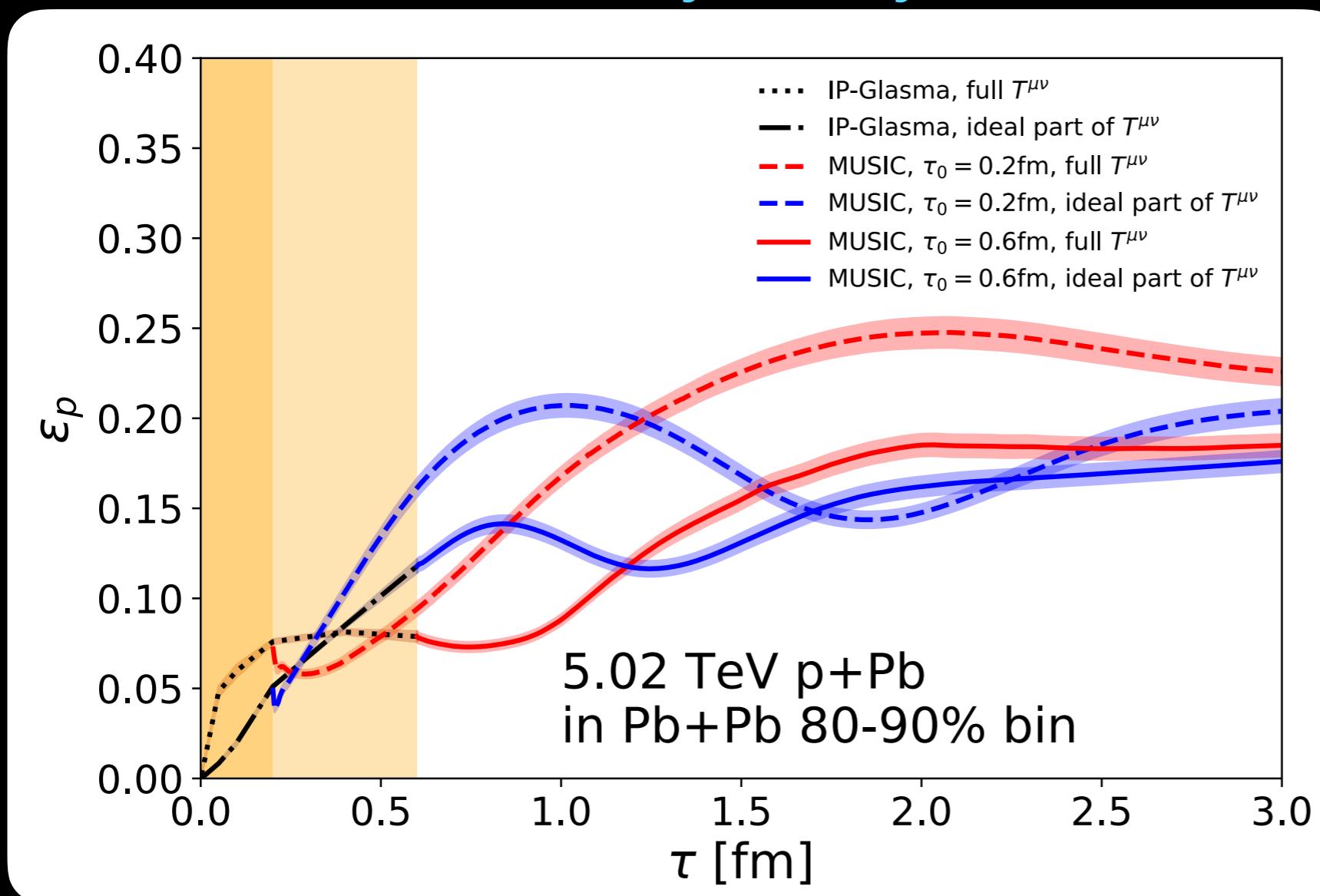


IP-Glasma + hydrodynamics

p+Pb events in 80-90% Pb+Pb class

$$\epsilon_p = \sqrt{\frac{\langle T_{xx} - T_{yy} \rangle^2 + \langle 2T_{xy} \rangle^2}{\langle T_{xx} + T_{yy} \rangle^2}}$$

IP-Glasma Hydrodynamics



Switching at $\tau=0.6$ fm:
(full lines)

ϵ_p with full $T^{\mu\nu}$ ~45%
from initial flow

Switching at $\tau=0.2$ fm:
(dashed lines)

ϵ_p with full $T^{\mu\nu}$ ~35%
from initial flow

MULTI-PARTICLE CUMULANTS

Hydrodynamics produces \sim equal $v_2\{2m\}$ for all $m \geq 4$

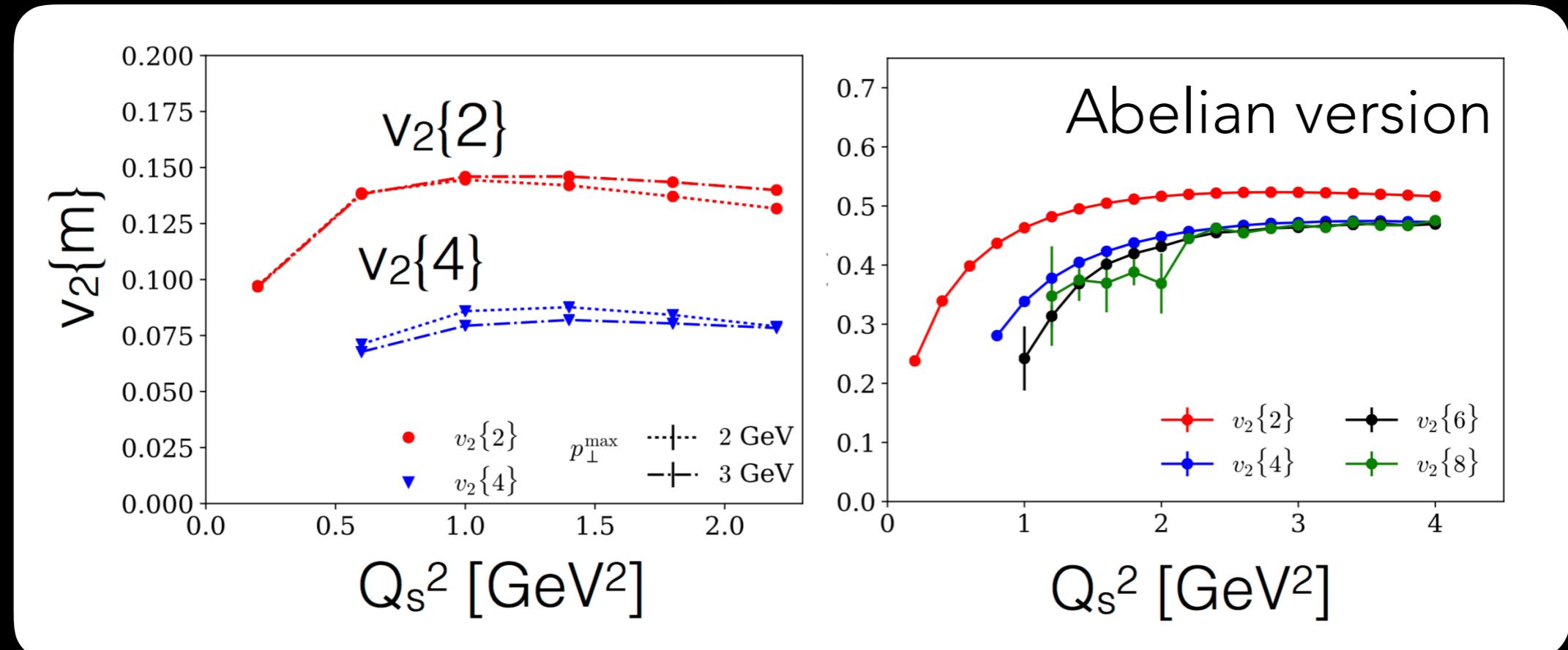
All particles correlated with a common event plane

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



DIFFRACTIVE J/Ψ PRODUCTION

H. MÄNTYSAARI, B. SCHENKE, ARXIV:1603.04349, ARXIV:1607.01711

No exchange of color charge

Large rapidity gap

Coherent diffraction:

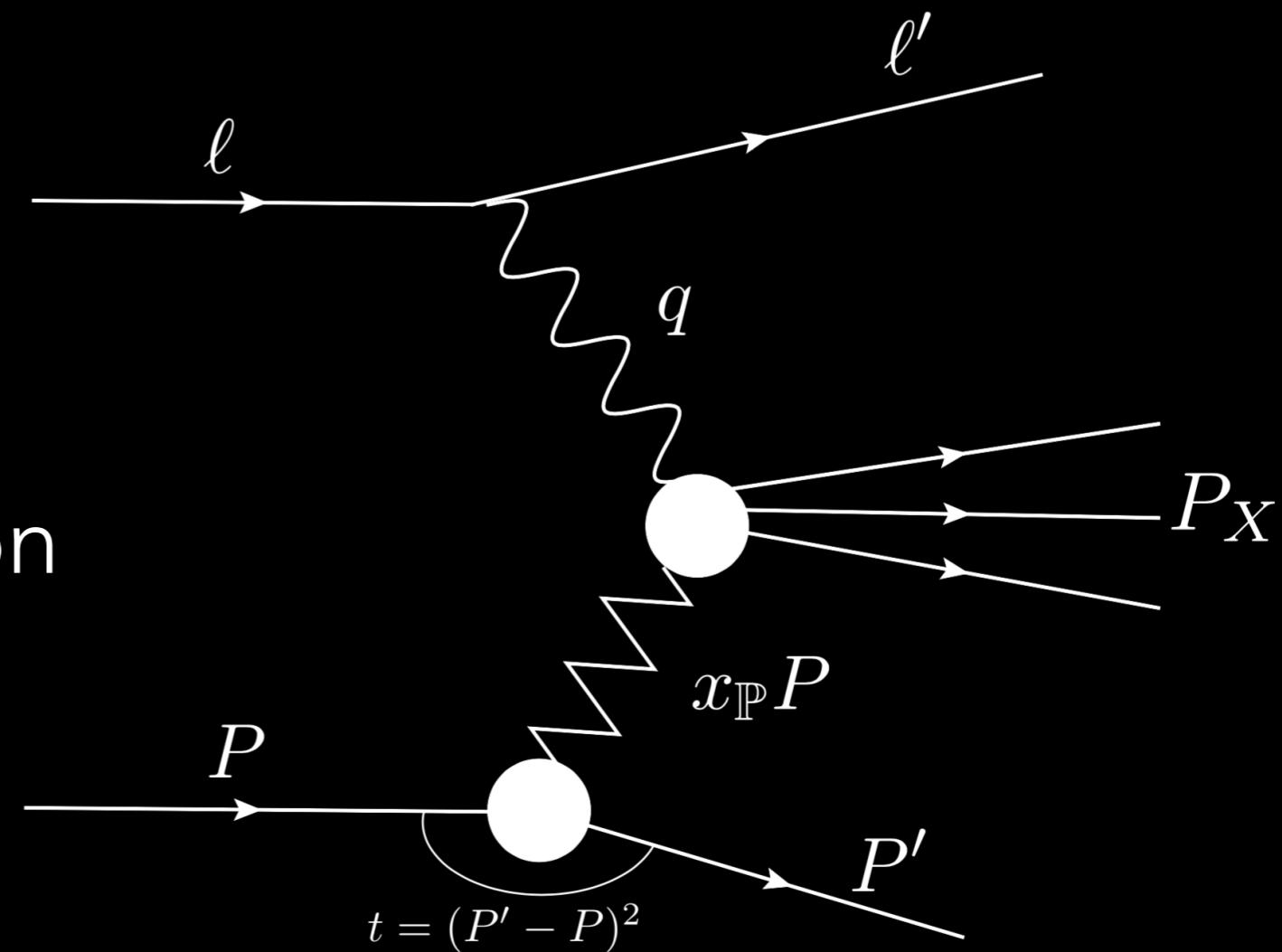
Proton remains intact

Sensitive to average gluon
distribution in the proton

Incoherent diffraction:

Proton breaks up

Sensitive to shape fluctuations



CGC FRAMEWORK J/Ψ PRODUCTION

H. MÄNTYSAARI, B. SCHENKE, ARXIV:1603.04349, ARXIV:1607.01711

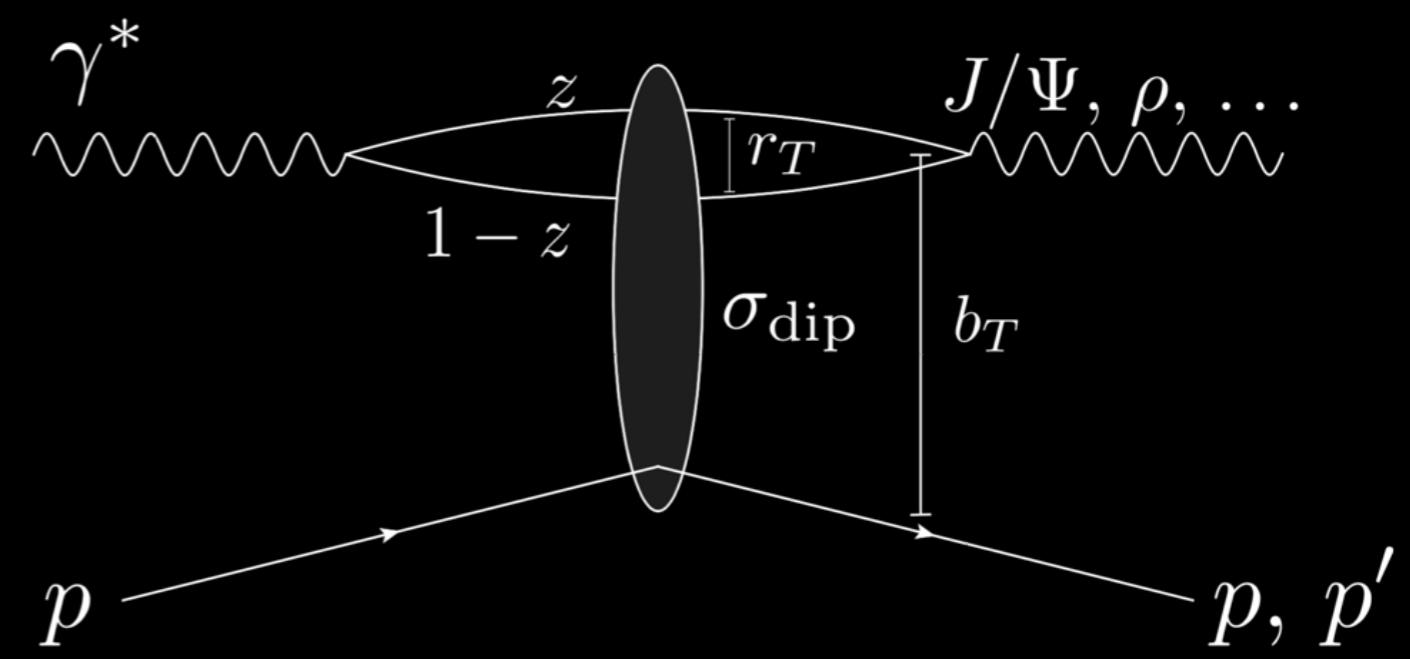
Diffractive eigenstates are color dipoles

at fixed r_T and b_T

SEE

M. L. GOOD AND W. D. WALKER
PHYS. REV. 120 (1960) 1857.

Scattering amplitude



$$\mathcal{A} \sim \int d^2 b dz d^2 r \Psi^* \Psi^V(r, z, Q^2) e^{-ib \cdot \Delta} \textcolor{blue}{N}(r, x, b)$$

$$\sigma_{\text{dip}}(x, r, \Delta) = 2 \int d^2 b e^{ib \cdot \Delta} \textcolor{blue}{N}(r, x, b)$$

AVERAGING OVER THE TARGET

H. MÄNTYSAARI, B. SCHENKE, ARXIV:1603.04349; ARXIV:1607.01711

COHERENT DIFFRACTION:
TARGET STAYS INTACT

$$\frac{d\sigma^{\gamma^* p \rightarrow Vp}}{dt} = \frac{1}{16\pi} \left| \langle \mathcal{A}^{\gamma^* p \rightarrow Vp}(x_{\mathbb{P}}, Q^2, \Delta) \rangle \right|^2$$

INCOHERENT DIFFRACTION:
TARGET BREAKS UP

$$\frac{d\sigma^{\gamma^* p \rightarrow Vp^*}}{dt} = \frac{1}{16\pi} \left(\left\langle \left| \mathcal{A}^{\gamma^* p \rightarrow Vp}(x_{\mathbb{P}}, Q^2, \Delta) \right|^2 \right\rangle - \left| \langle \mathcal{A}^{\gamma^* p \rightarrow Vp}(x_{\mathbb{P}}, Q^2, \Delta) \rangle \right|^2 \right)$$

SENSITIVE TO FLUCTUATIONS!

SEE

H. I. MIETTINEN
AND J. PUMPLIN
PHYS. REV. D18 (1978) 1696

Y. V. KOVCHEGOV
AND L. D. MCLERRAN
PHYS. REV. D60 (1999) 054025

A. KOVNER AND
U. A. WIEDEMANN
PHYS. REV. D64 (2001) 114002

CORRELATIONS FROM THE INITIAL STATE

SCHENKE, SCHLICHTING, VENUGOPALAN, PHYS. LETT. B747, 76-82 (2015)

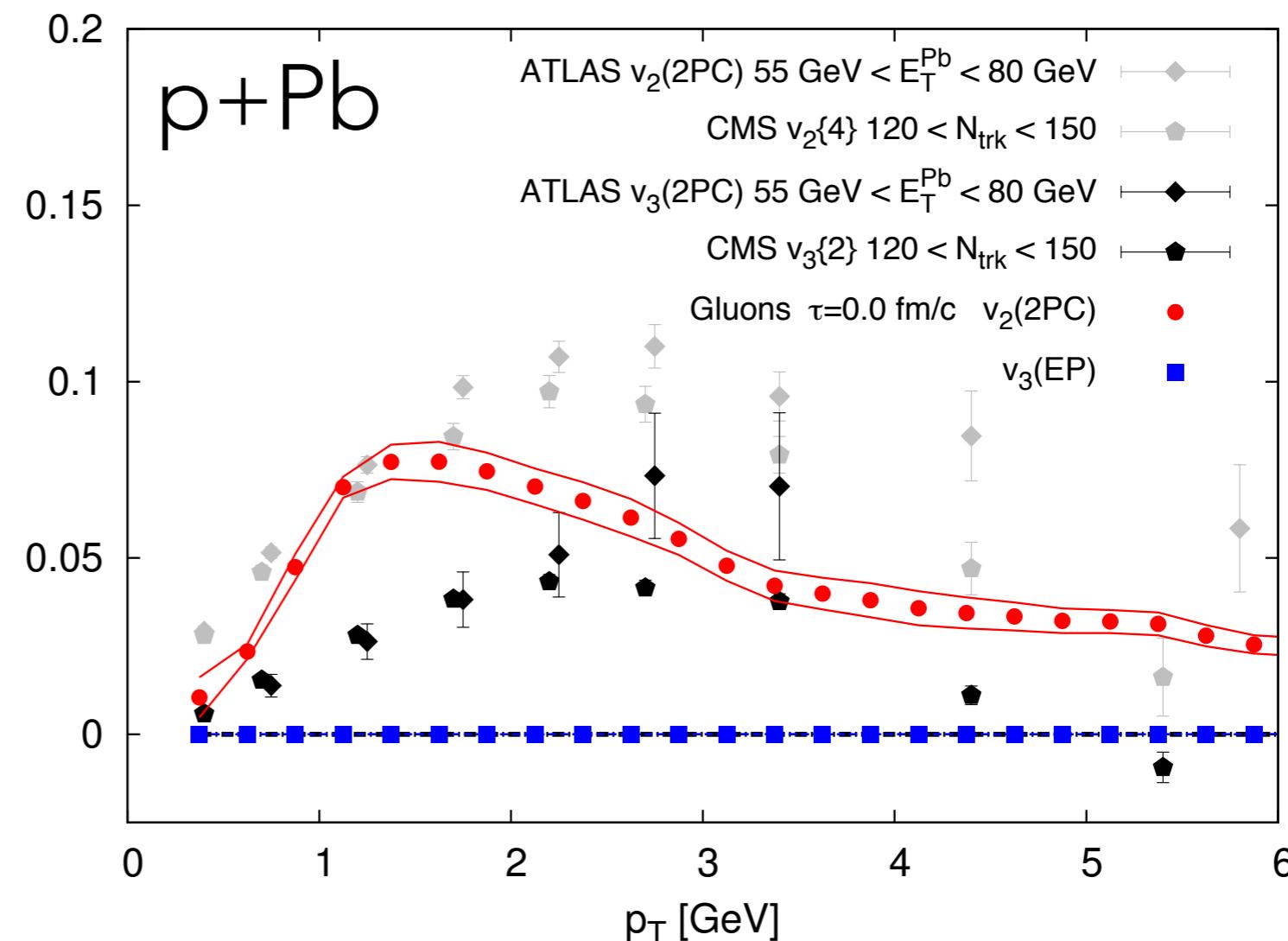
$\tau = 0.0 \text{ fm/c}$

gluons

data to guide the eye

v_2, v_3

Fourier harmonics (*event average*)



Significant v_2 at time 0

No odd harmonics for gluons without final state interactions

CORRELATIONS FROM THE INITIAL STATE

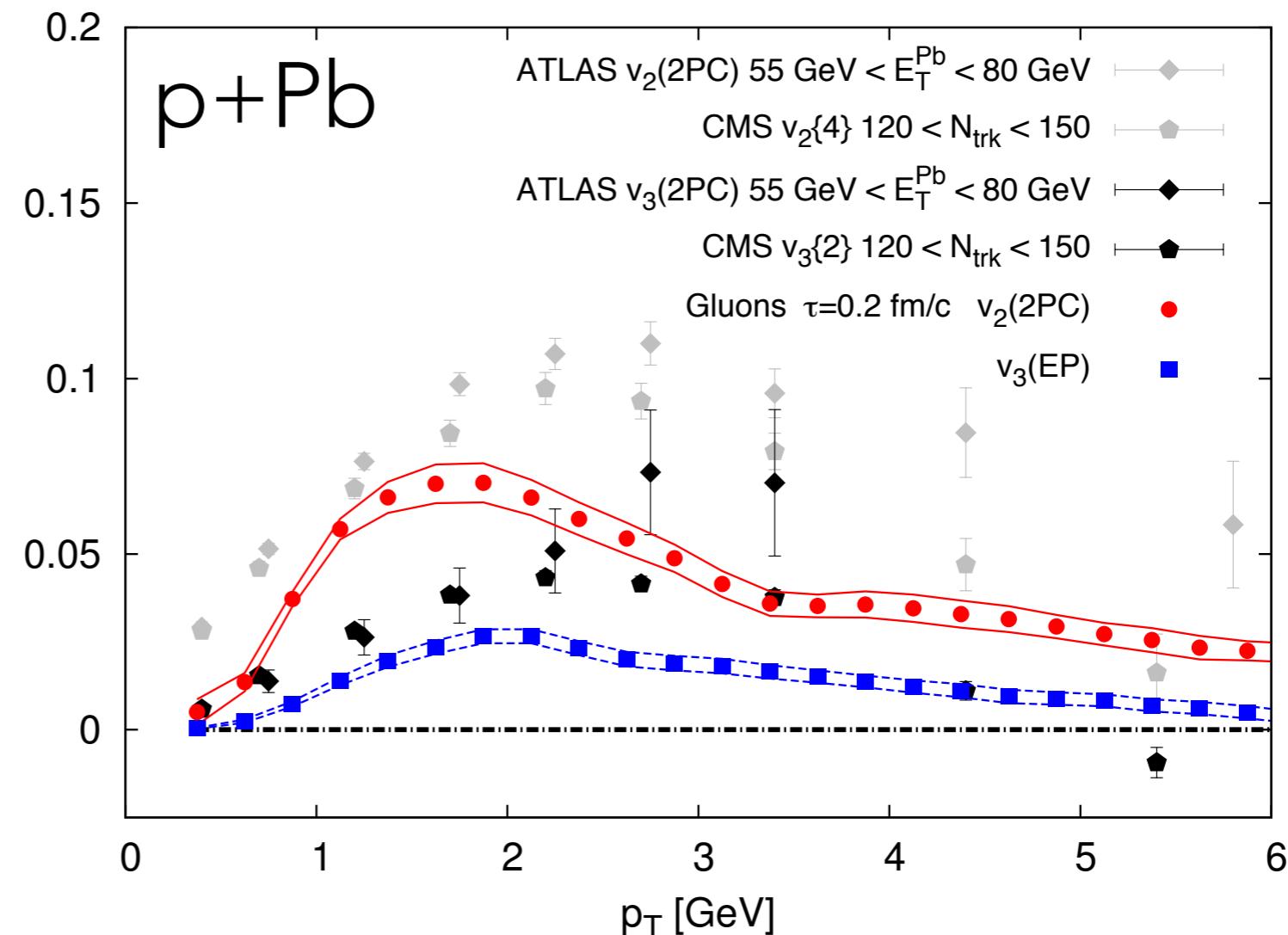
SCHENKE, SCHLICHTING, VENUGOPALAN, PHYS. LETT. B747, 76-82 (2015)

$\tau = 0.2 \text{ fm/c}$
gluons

data to guide the eye

v_2, v_3

Fourier harmonics (*event average*)



CORRELATIONS FROM THE INITIAL STATE

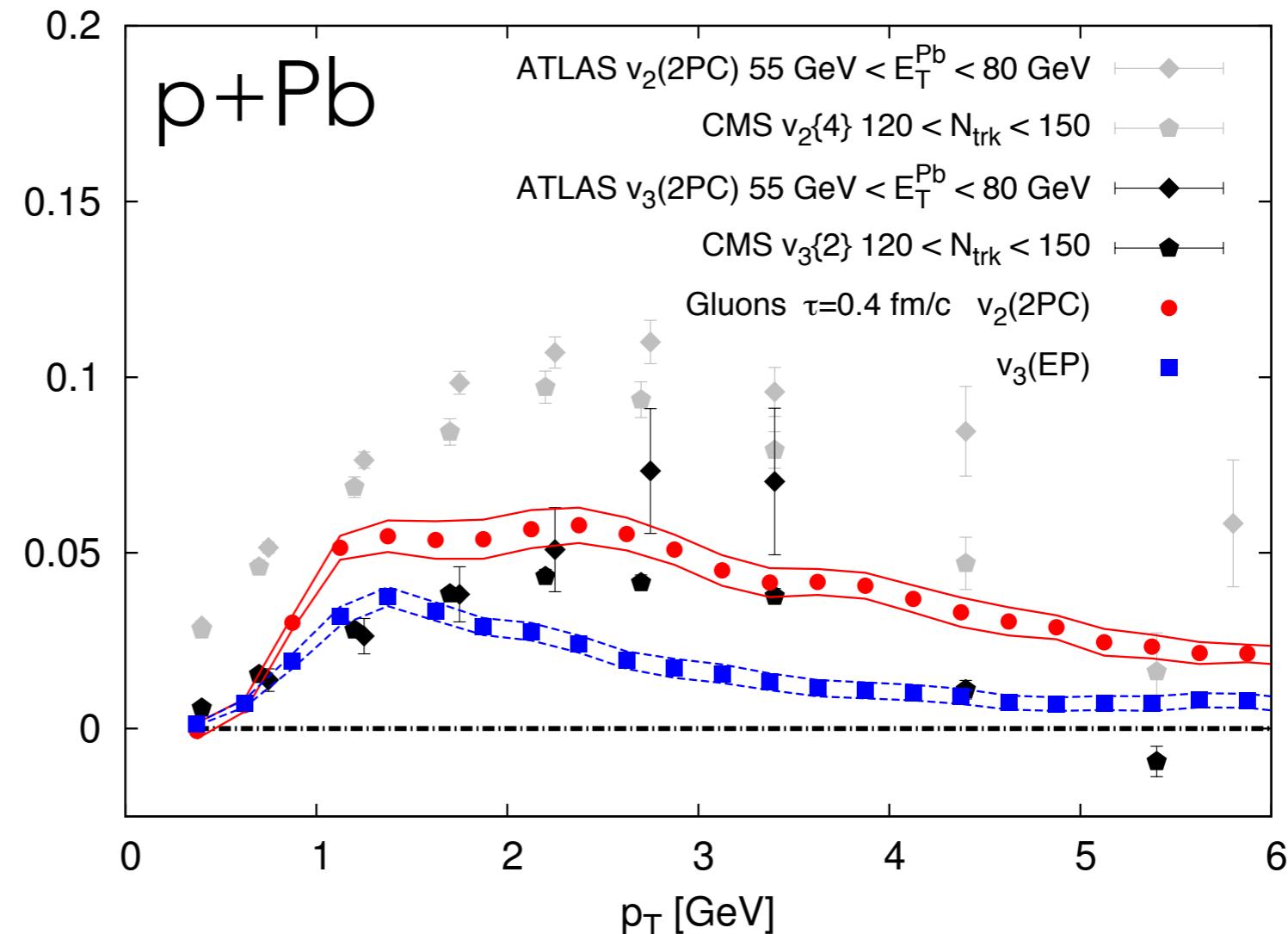
SCHENKE, SCHLICHTING, VENUGOPALAN, PHYS. LETT. B747, 76-82 (2015)

$\tau = 0.4 \text{ fm}/c$
gluons

data to guide the eye

v_2, v_3

Fourier harmonics (*event average*)



Odd harmonics generated by pre-equilibrium dynamics