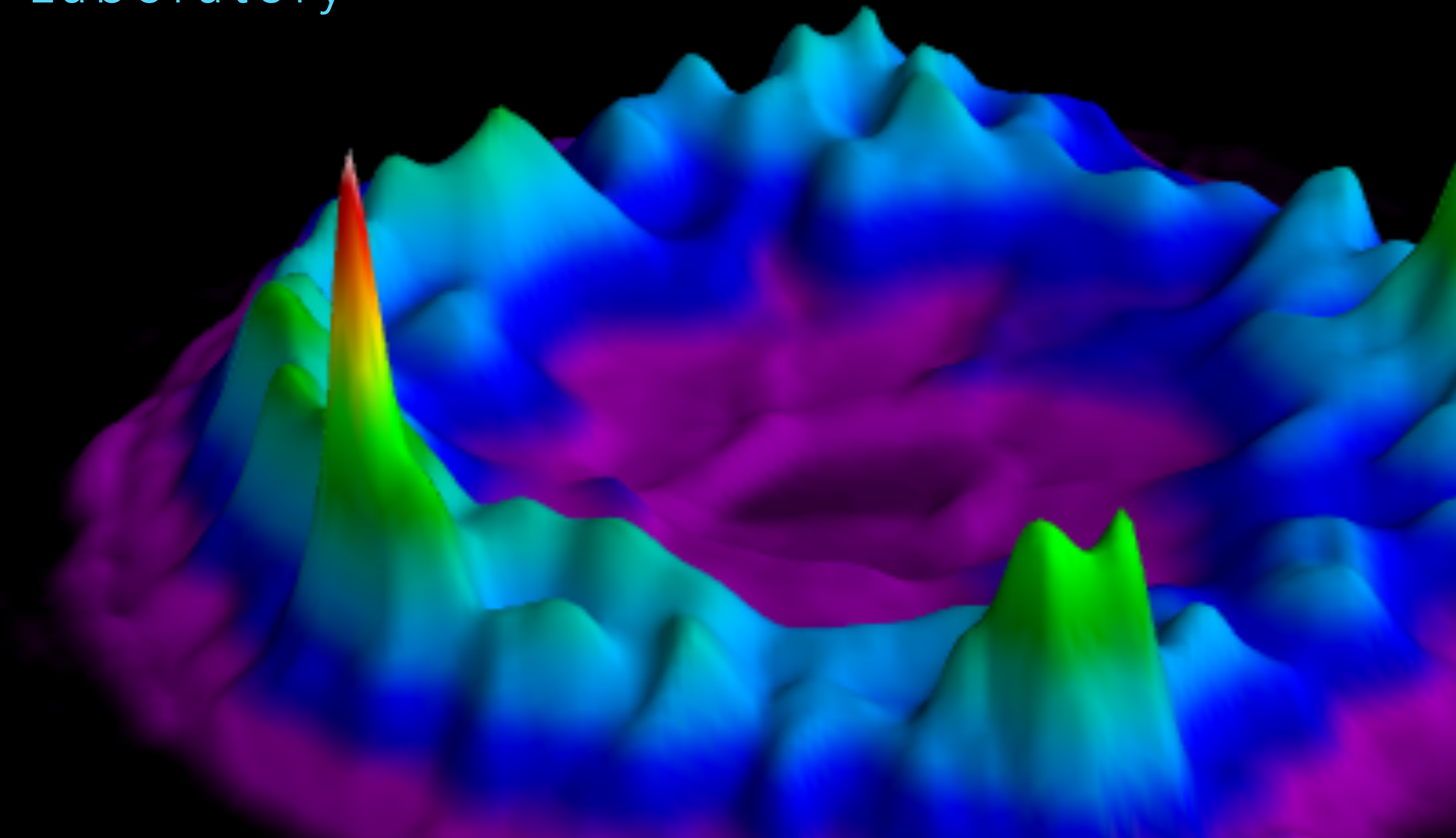
U.S. DEPARTMENT OF ENERGY | Office of Science

BROOKHAVEN NATIONAL LABORATORY

ORIGINS OF AZIMUTHAL CORRELATIONS IN HIGH ENERGY NUCLEAR COLLISIONS

Björn Schenke
Brookhaven National Laboratory



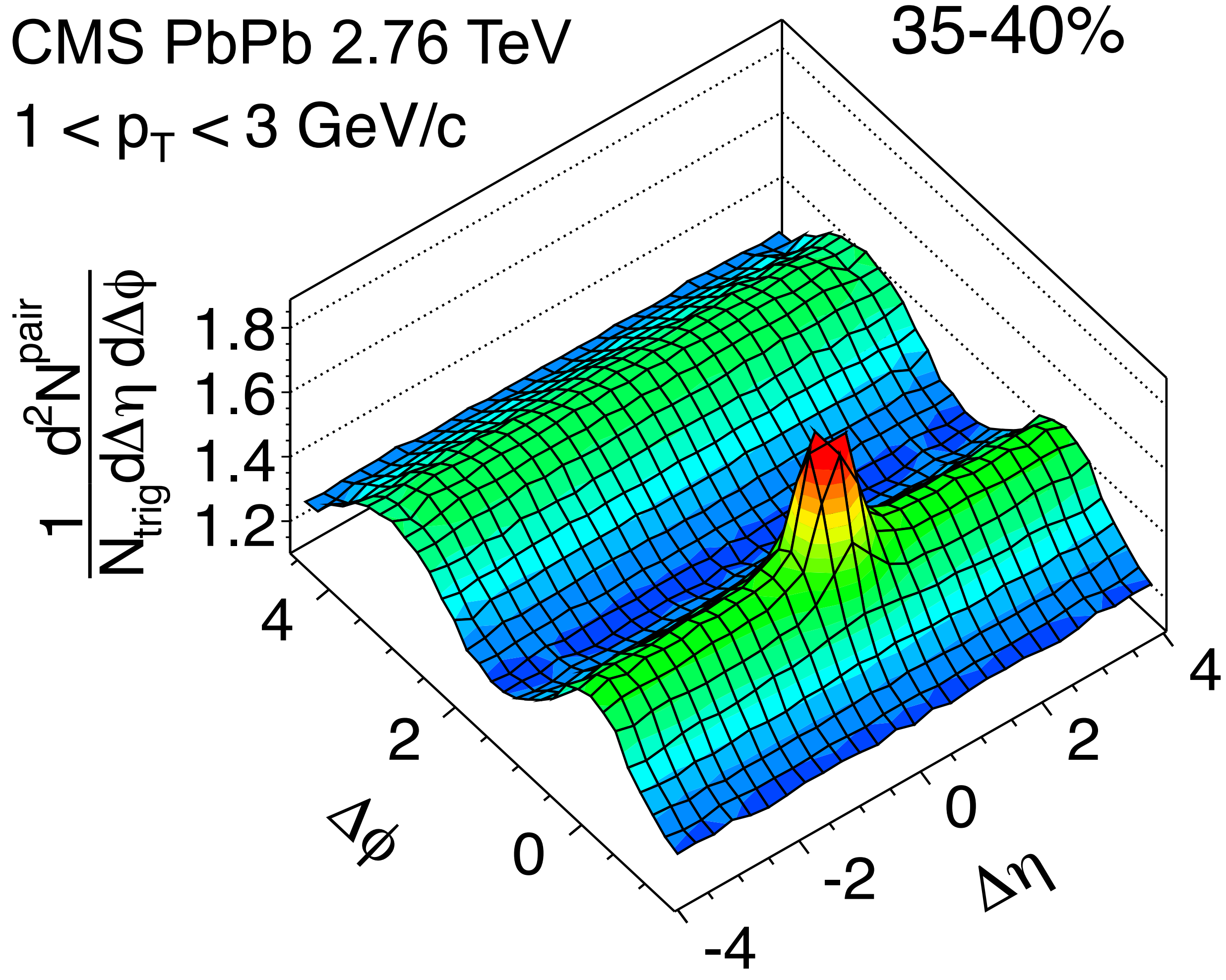
Zimányi School '17
December 4 2017

MULTI-PARTICLE CORRELATIONS

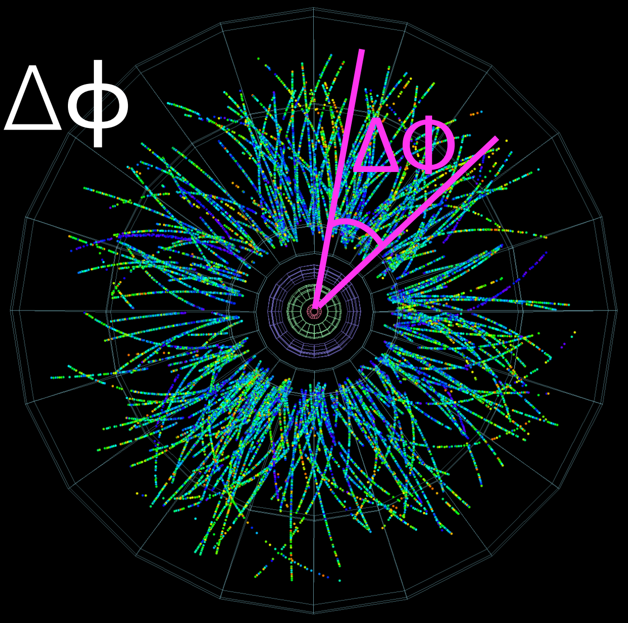
2-particle correlation as a function of $\Delta\eta$ and $\Delta\phi$

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

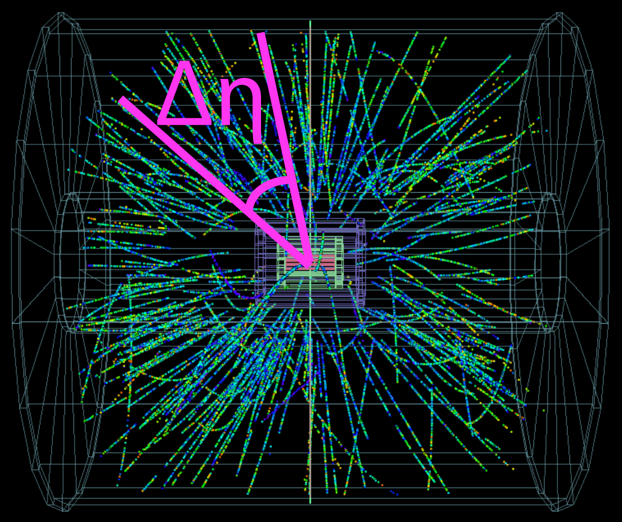
$\Delta\Phi$: DIFFERENCE IN AZIMUTHAL ANGLE



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



$\Delta\Phi$: DIFFERENCE IN AZIMUTHAL ANGLE

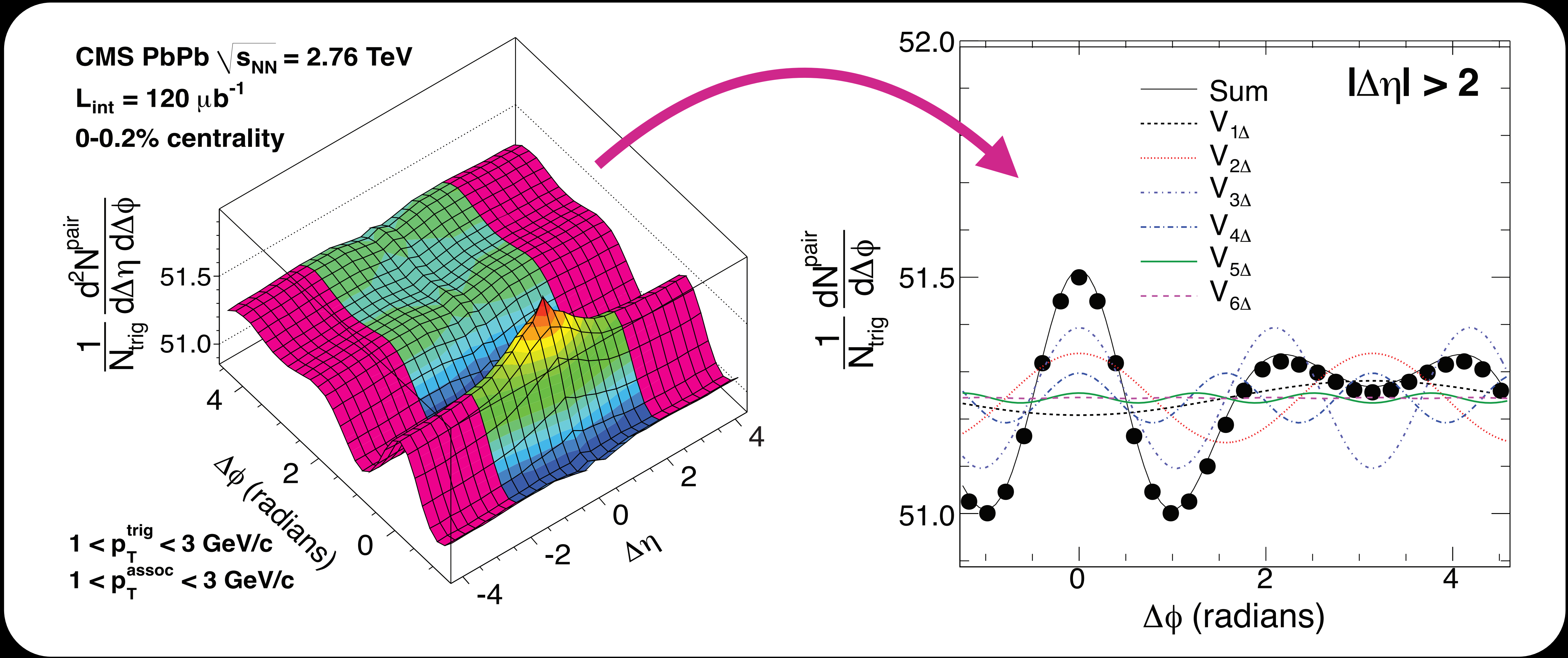


$\Delta\eta$: DIFFERENCE IN PSEUDO-RAPIDITY

Event Displays: © 2012 CERN, ALICE

FOURIER EXPANSION

Azimuthal structure quantified using Fourier expansion



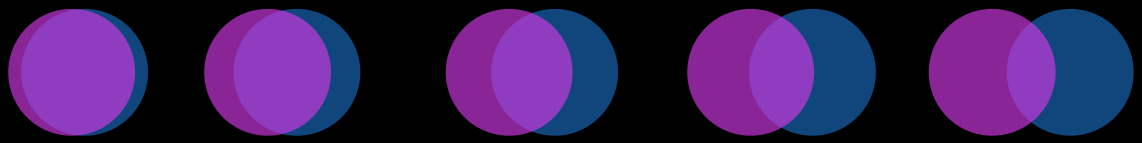
$$\frac{1}{N_{\mathrm{trig}}}\frac{dN^{\mathrm{pair}}}{d\Delta\phi} \sim 1 + 2\sum_{n=1}^{n=\infty} V_{n\Delta}(p_T^{\mathrm{trig}}, p_T^{\mathrm{assoc}})\cos(n\Delta\phi)$$

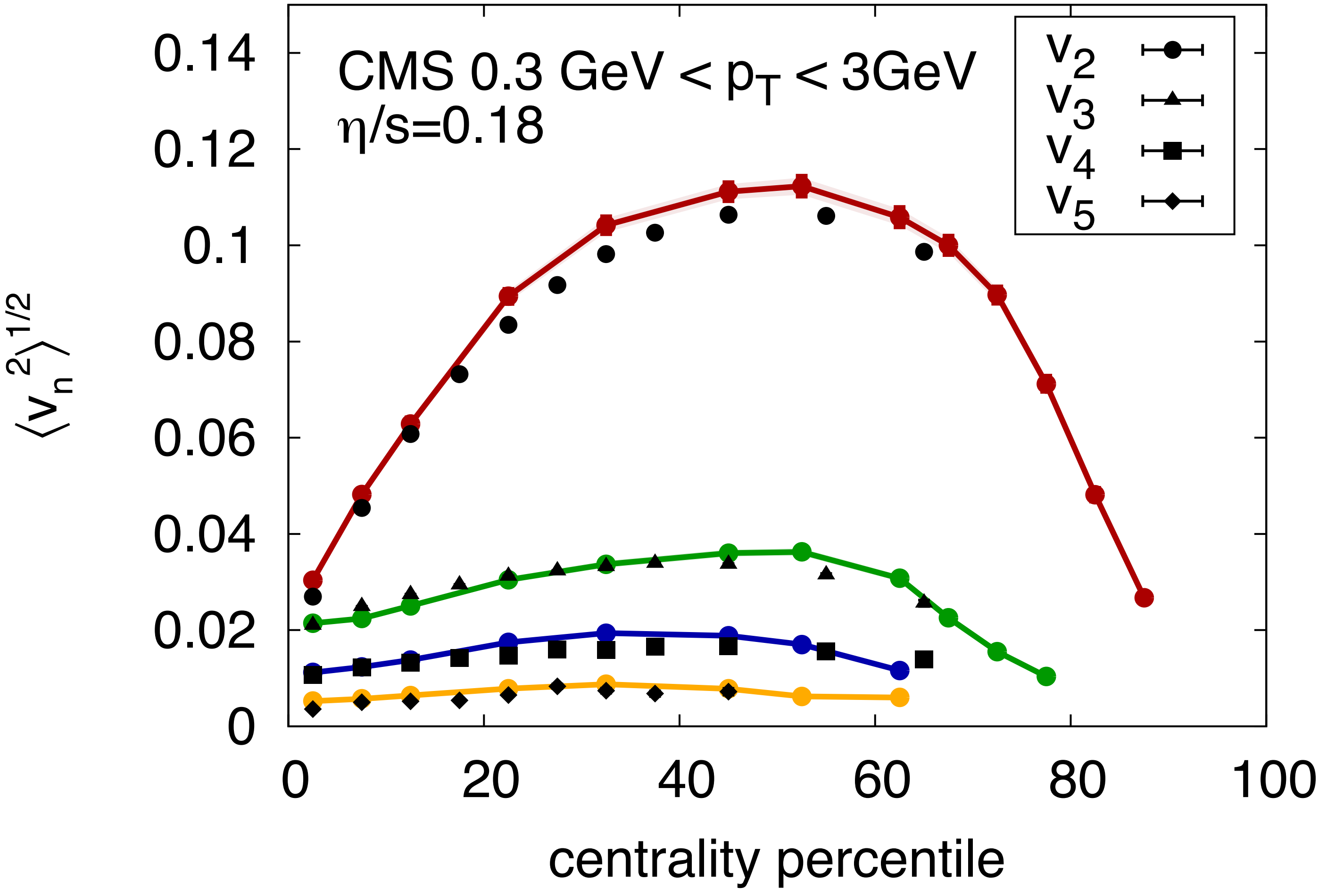
$$v_n = \sqrt{V_{n\Delta}}$$

CMS COLLABORATION, JHEP 02 (2014) 088

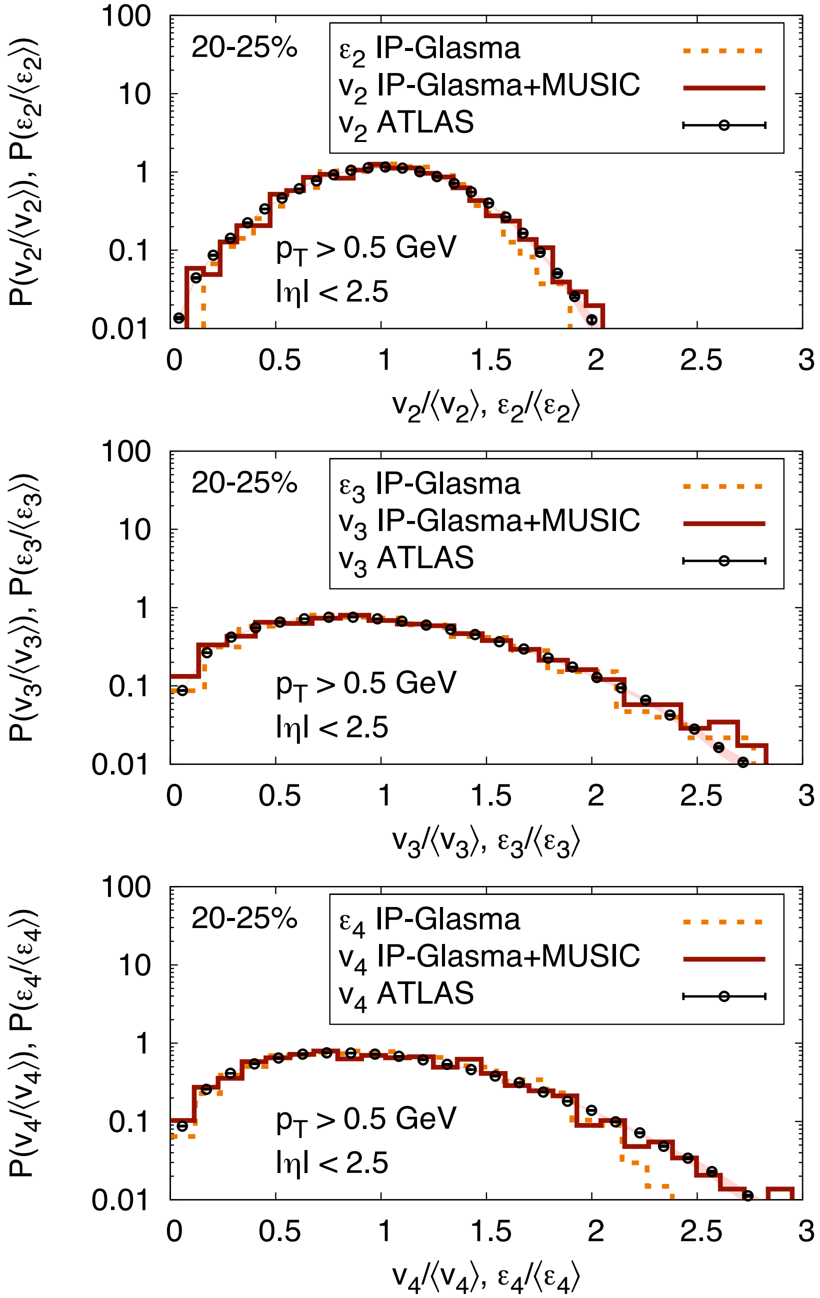
A+A: Initial geometry from IP-Glasma (Yang-Mills) plus hydrodynamics works

C.Gale, S.Jeon, B.Schenke, P.Tribedy, R.Venugopalan, Phys.Rev.Lett. 110, 012302 (2013)
B. Schenke, R. Venugopalan, Phys.Rev.Lett. 113 (2014) 102301





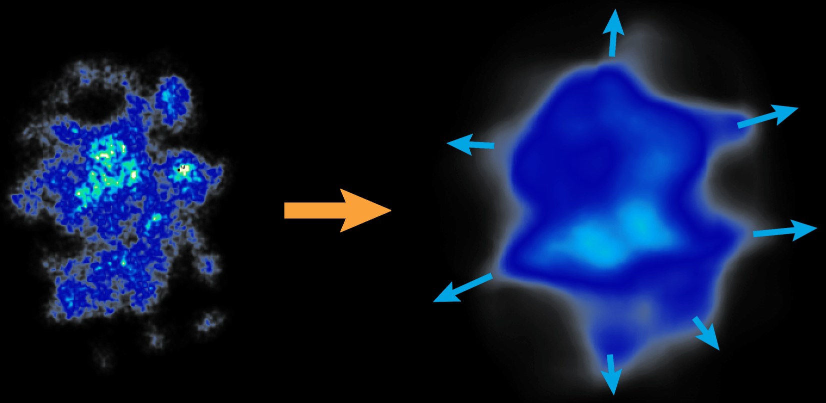
CMS Collaboration, PRC 87(2013) 014902



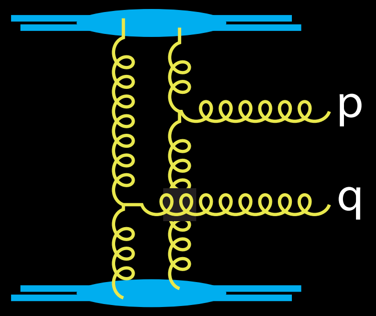
ATLAS Collaboration, JHEP 1311 (2013) 183

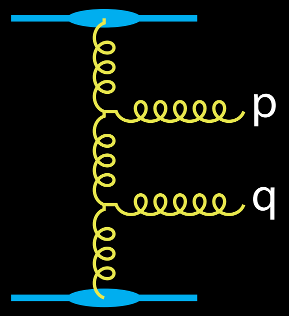
ORIGINS OF COLLECTIVITY IN SMALL SYSTEMS

1. **Final state correlations:**
   Particles acquire momentum space correlations via final state interactions (conversion of spatial structure into momentum correlations e.g. via hydrodynamic flow)



2. **Initial state correlations:**
   Particles are produced with their momentum space correlations





DO WE EXPECT HYDRO TO WORK?

"Local isotropy required for hydrodynamics to apply"

P. B. Arnold, J. Lenaghan, G. D. Moore, and L. G. Yaffe, Phys. Rev. Lett. 94, 072302 (2005)

Expanding system: No theory produces a pressure anisotropy <50% at τ=1fm (weak or strong coupling)

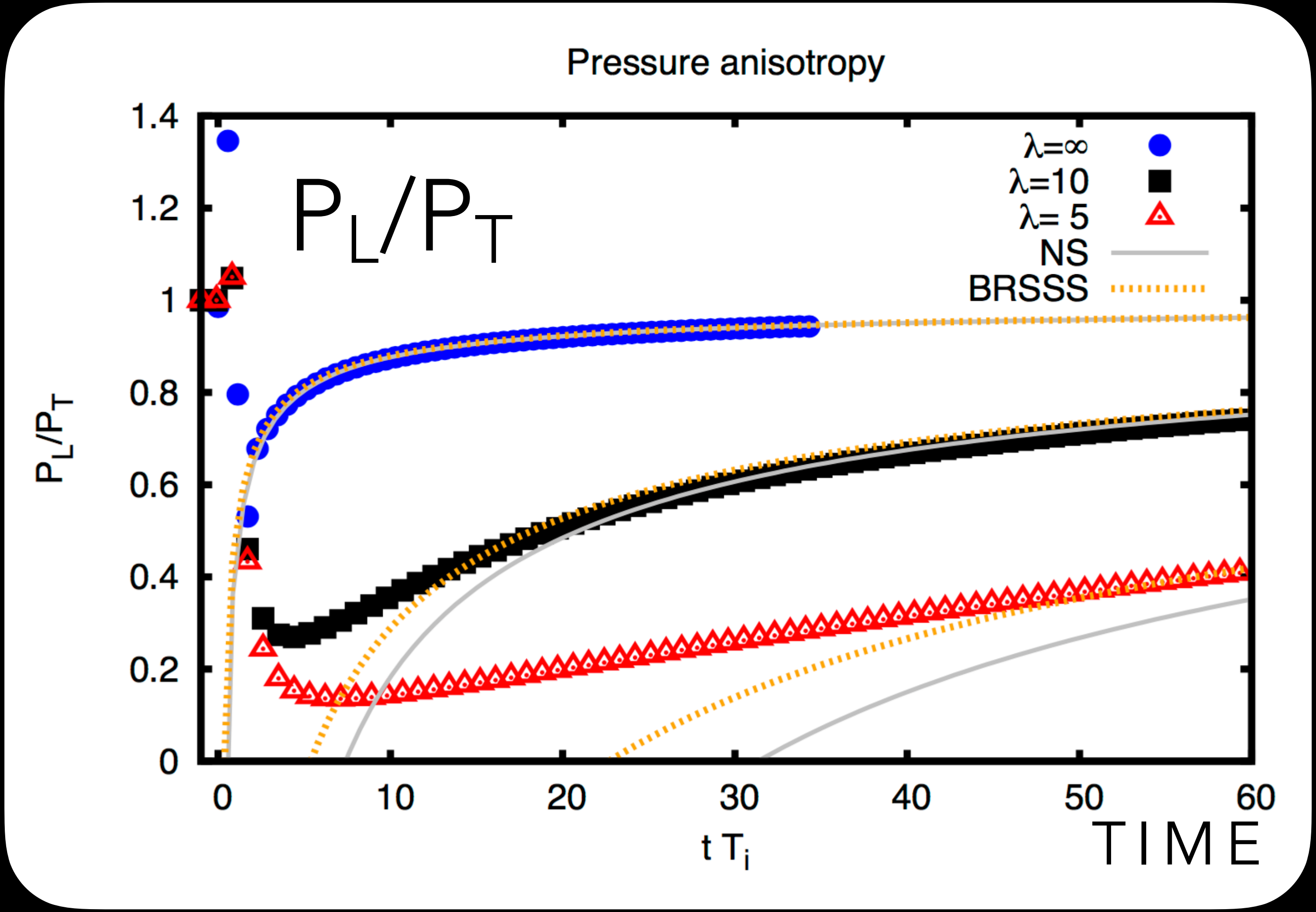
P. Romatschke, Eur.Phys.J. C77 (2017) 21

But hydro works for large anisotropy

L. Keegan, A. Kurkela, P. Romatschke,
W. van der Schee, Y. Zhu, JHEP 04, 031 (2016)

P. Romatschke, Eur.Phys.J. C77 (2017) 21

Kinetic theory (λ = 5,10)
Gauge/gravity duality ($\lambda = \infty$)
Hydro 1st order (NS) and
2nd order gradient exp. (BRSSS)



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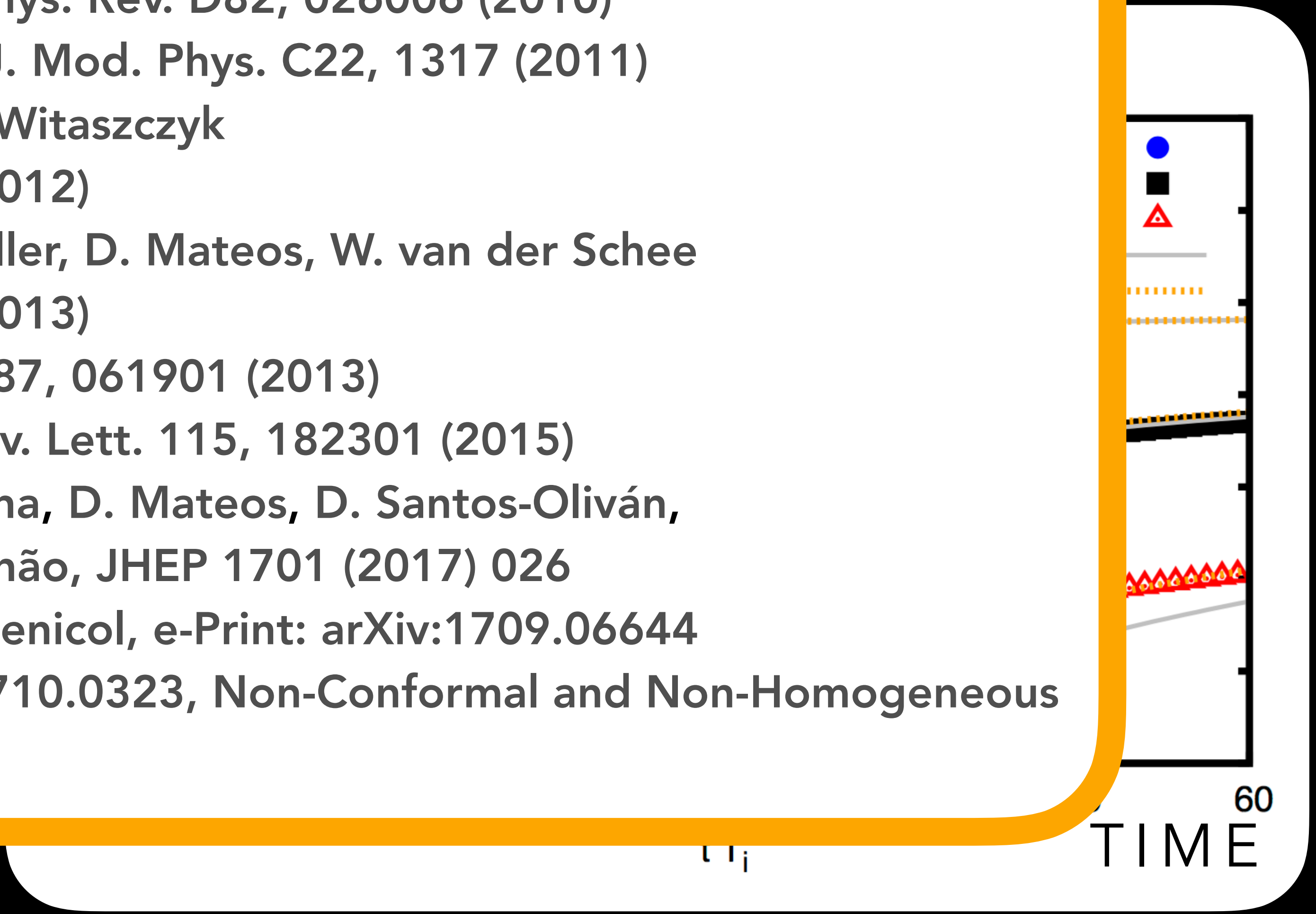
Gauge/g

Hydro 1st

2nd order gradient exp. (BRSSS)



Many studies with similar results:

1) P. M. Chesler and L. G. Yaffe, Phys. Rev. D82, 026006 (2010)
2) B. Wu and P. Romatschke, Int. J. Mod. Phys. C22, 1317 (2011)
3) M. P. Heller, R. A. Janik, and P. Witaszczyk
   Phys. Rev. Lett. 108, 201602 (2012)
4) J. Casalderrey-Solana, M. P. Heller, D. Mateos, W. van der Schee
   Phys. Rev. Lett. 111, 181601 (2013)
5) W. van der Schee, Phys. Rev. D87, 061901 (2013)
6) A. Kurkela and Y. Zhu, Phys. Rev. Lett. 115, 182301 (2015)
7) M. Attems, J. Casalderrey-Solana, D. Mateos, D. Santos-Oliván,
   C.F. Sopuerta, M. Triana, M. Zilhão, JHEP 1701 (2017) 026
8) M. Strickland, J. Noronha, G. Denicol, e-Print: arXiv:1709.06644
9) P. Romatschke, e-Print: arXiv:1710.0323, Non-Conformal and Non-Homogeneous

...

WHY WOULD HYDRO WORK IN SMALL SYSTEMS?

Analysis of gradient expansion in AdS/CFT and kinetic theory:

M. P. Heller, R. A. Janik, and P. Witaszczyk, PRL 110, 211602 (2013); M. P. Heller and M. Spalinski, PRL 115, 072501 (2015); A. Buchel, M. P. Heller, and J. Noronha, arXiv:1603.05344; G. S. Denicol and J. Noronha, arXiv:1608.07869; M. P. Heller, A. Kurkela, and M. Spalinski, arXiv:1609.04803

recent review: W. Florkowski, M. P. Heller, M. Spalinski, e-Print: arXiv:1707.02282

Gradient expansion is a divergent series because of the presence of non-hydrodynamic degrees of freedom

$$T^{\mu\nu} = T^{\mu\nu}_{\mathrm{hydro}} + T^{\mu\nu}_{\mathrm{non-hydro}}$$

Hydro modes: $\omega(k) \to 0$ for $k \to 0$ (slowly dissipating modes)

One way to argue: Hydro works when hydrodynamic modes dominate

P. Romatschke, Eur. Phys. J. C76, 352 (2016)

When hydro modes disappear (for given k): Hydro breaks down

→Numerical estimate of the smallest possible QGP droplet ~0.15 fm

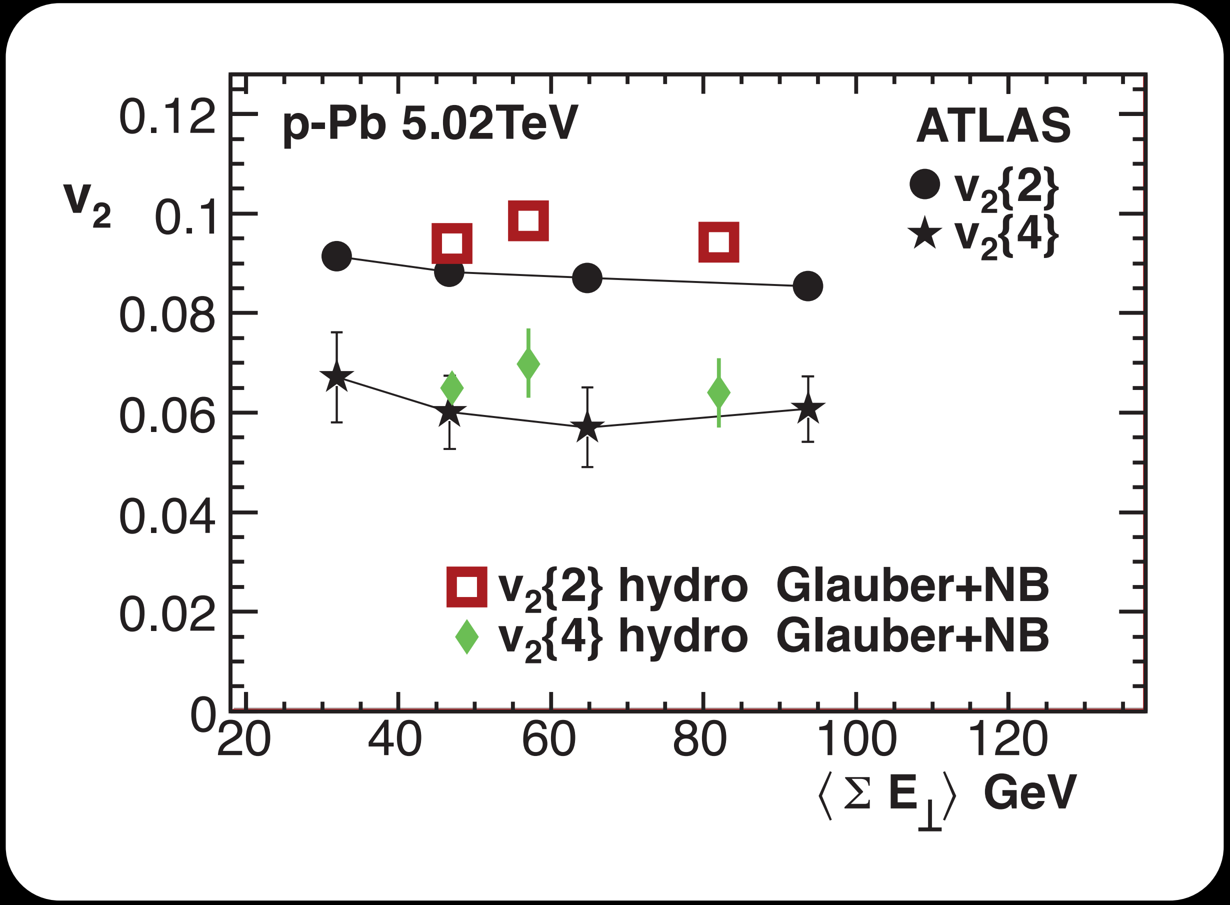
P. Romatschke, Eur.Phys.J. C77 (2017) 21

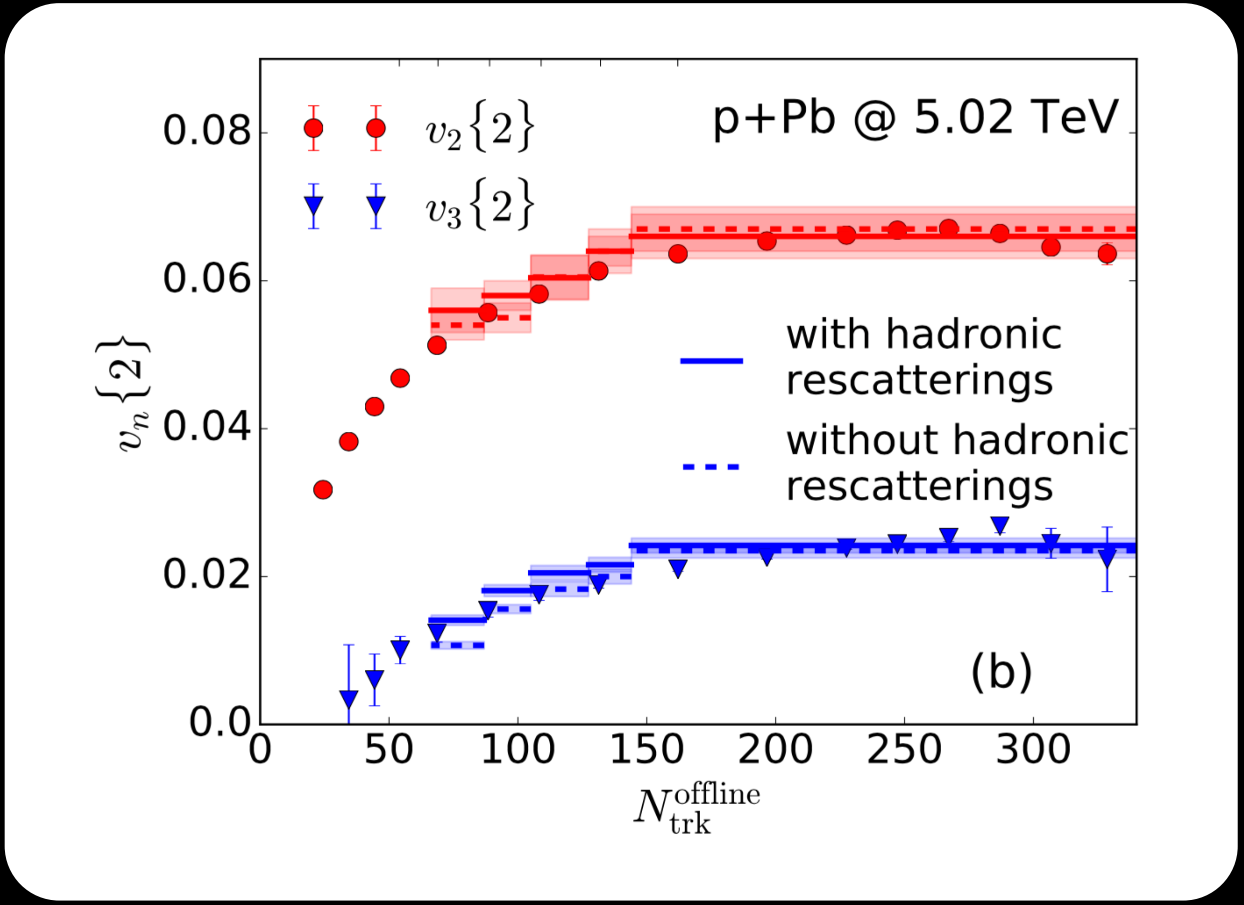
HYDRO IN SMALL SYSTEMS

MC-Glauber initial state + viscous hydrodynamics works

ATLAS Coll. PLB725 (2013) 60-78

CMS Coll. PLB724, 213–240 (2013)





Bozek, Broniowski, PRC88 (2013) 014903

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

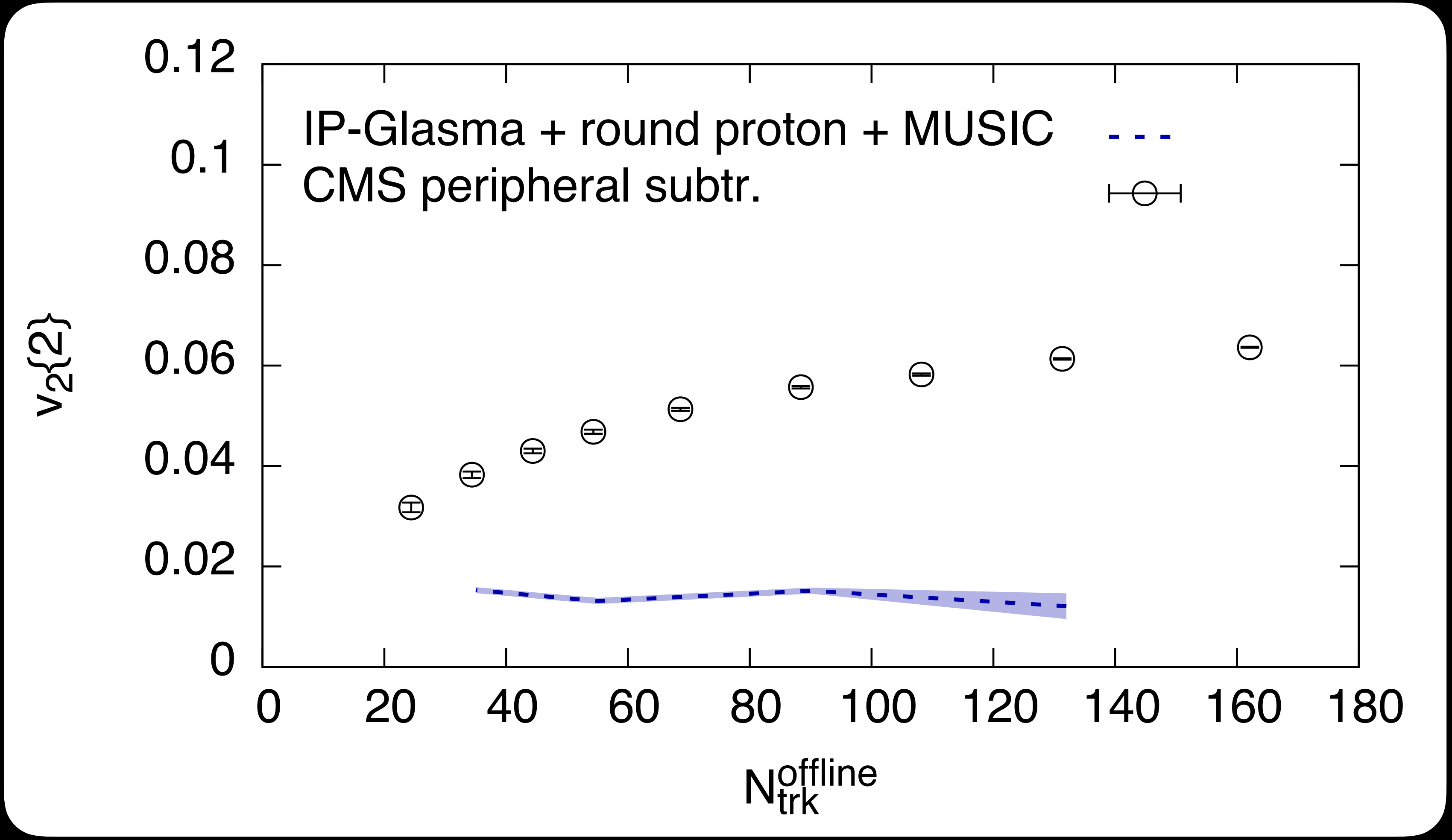
Also see: Kozlov, Luzum, Denicol, Jeon, Gale; Werner, Beicher, Guiot, Karpenko, Pierog; Romatschke; Kalaydzhyan, Shuryak, Zahed; Ghosh, Muhuri, Nayak, Varma; Qin, Mueller; Bozek, Broniowski, Torrieri; Habich, Miller, Romatschke, Xiang; T. Hirano, K. Kawaguchi, K. Murase; …

p+Pb v_2 IP-GLASMA + MUSIC

Did not work.

Not because hydro does not work.

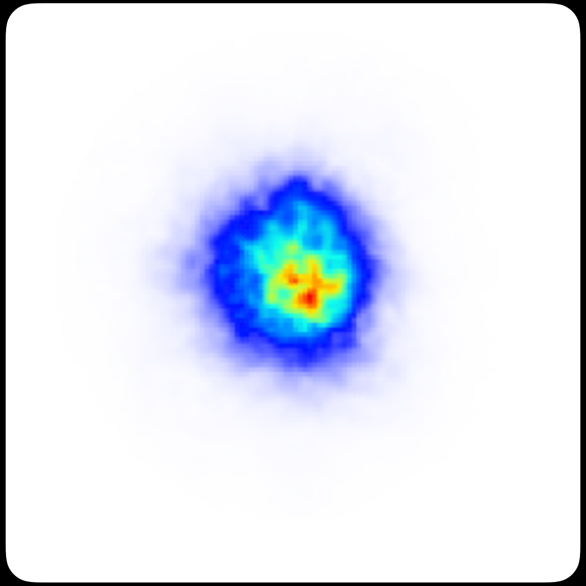
But because initial state was missing physics.



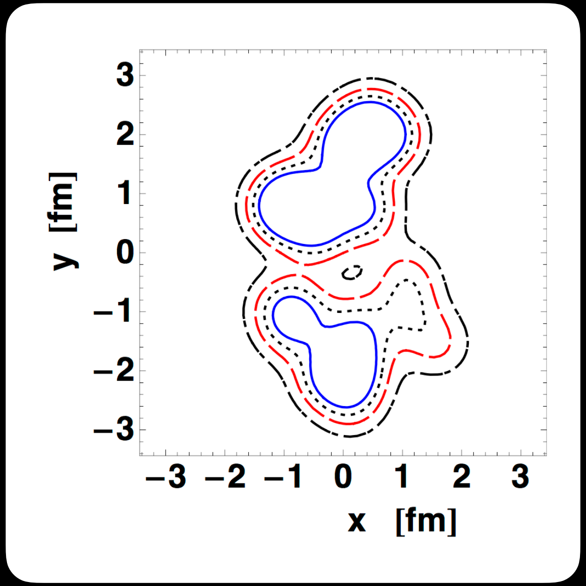
B. Schenke, R. Venugopalan, Phys. Rev. Lett. 113, 102301 (2014)

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

IP-Glasma



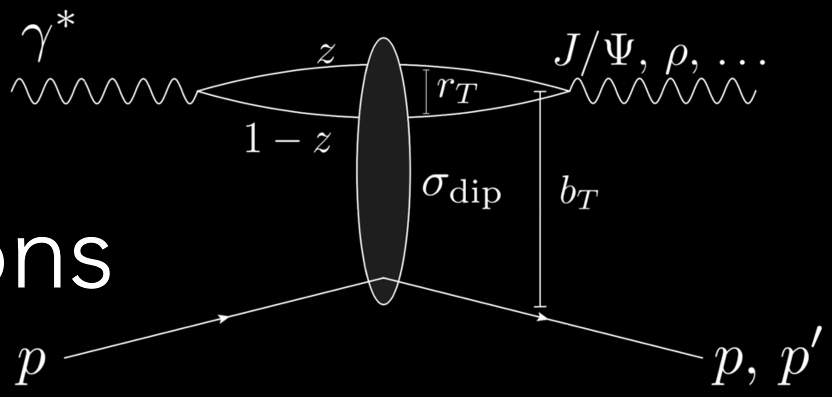
MC-Glauber



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

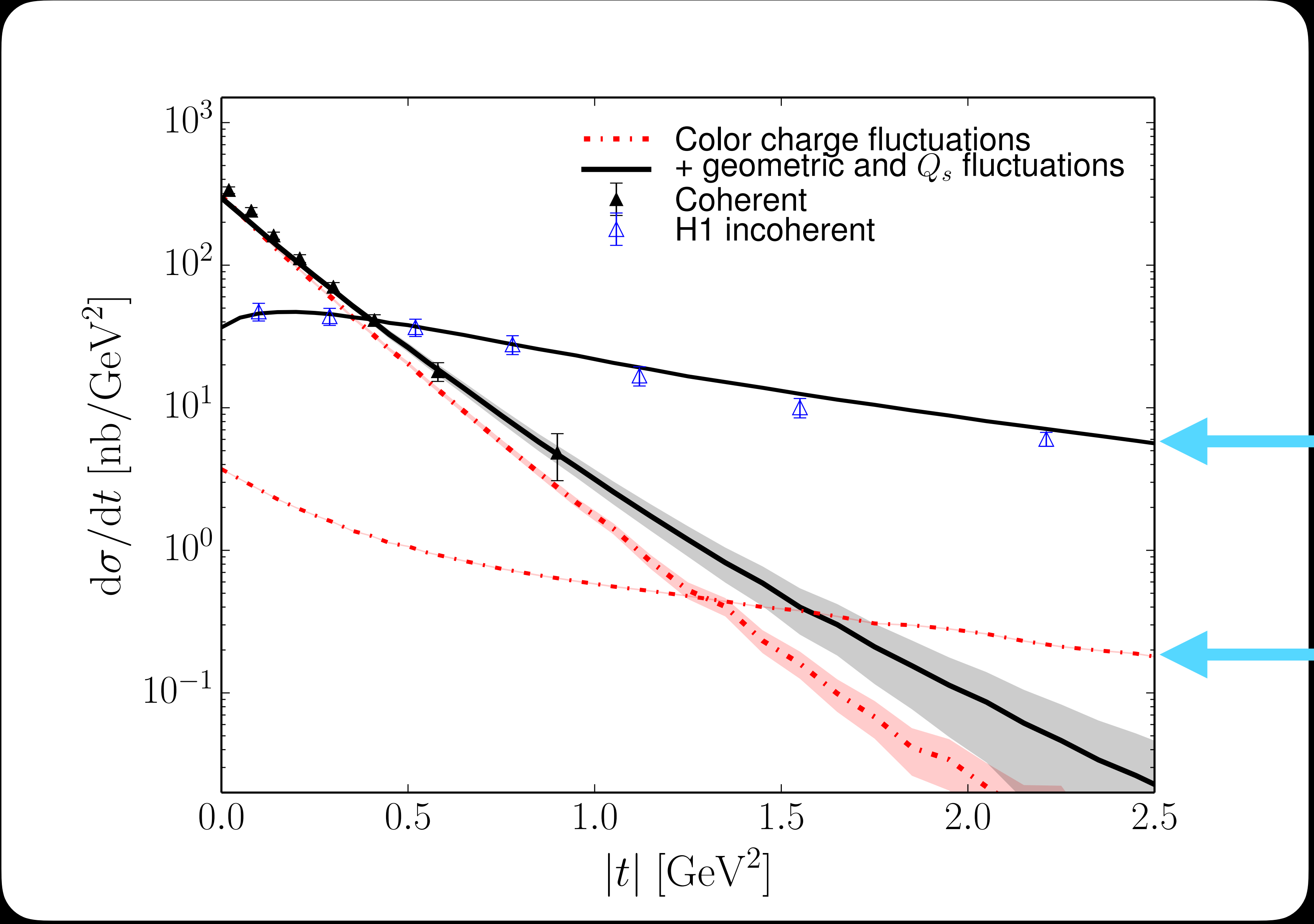
NEED PROTON SHAPE FLUCTUATIONS!

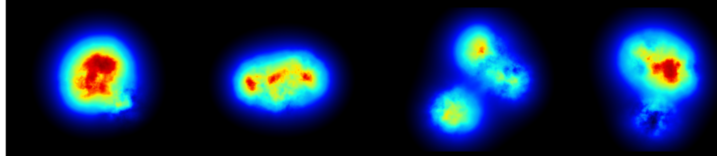
H. Mäntysaari, B. Schenke, Phys. Rev. Lett. 117 (2016) 052301; Phys.Rev. D94 (2016) 034042



Exclusive diffractive J/Ψ production:

Incoherent x-sec sensitive to fluctuations





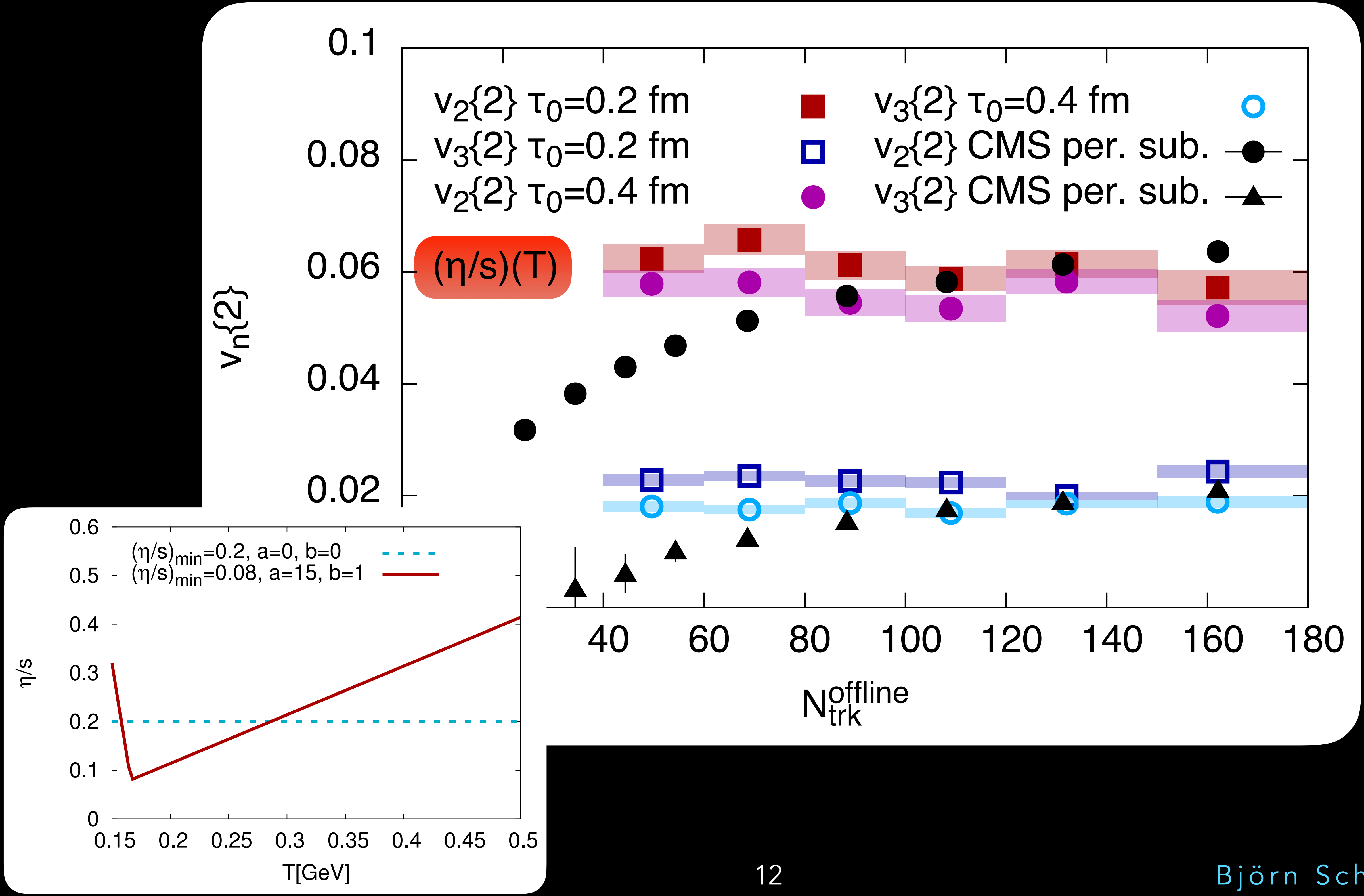
tuned shape fluctuations

round proton

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

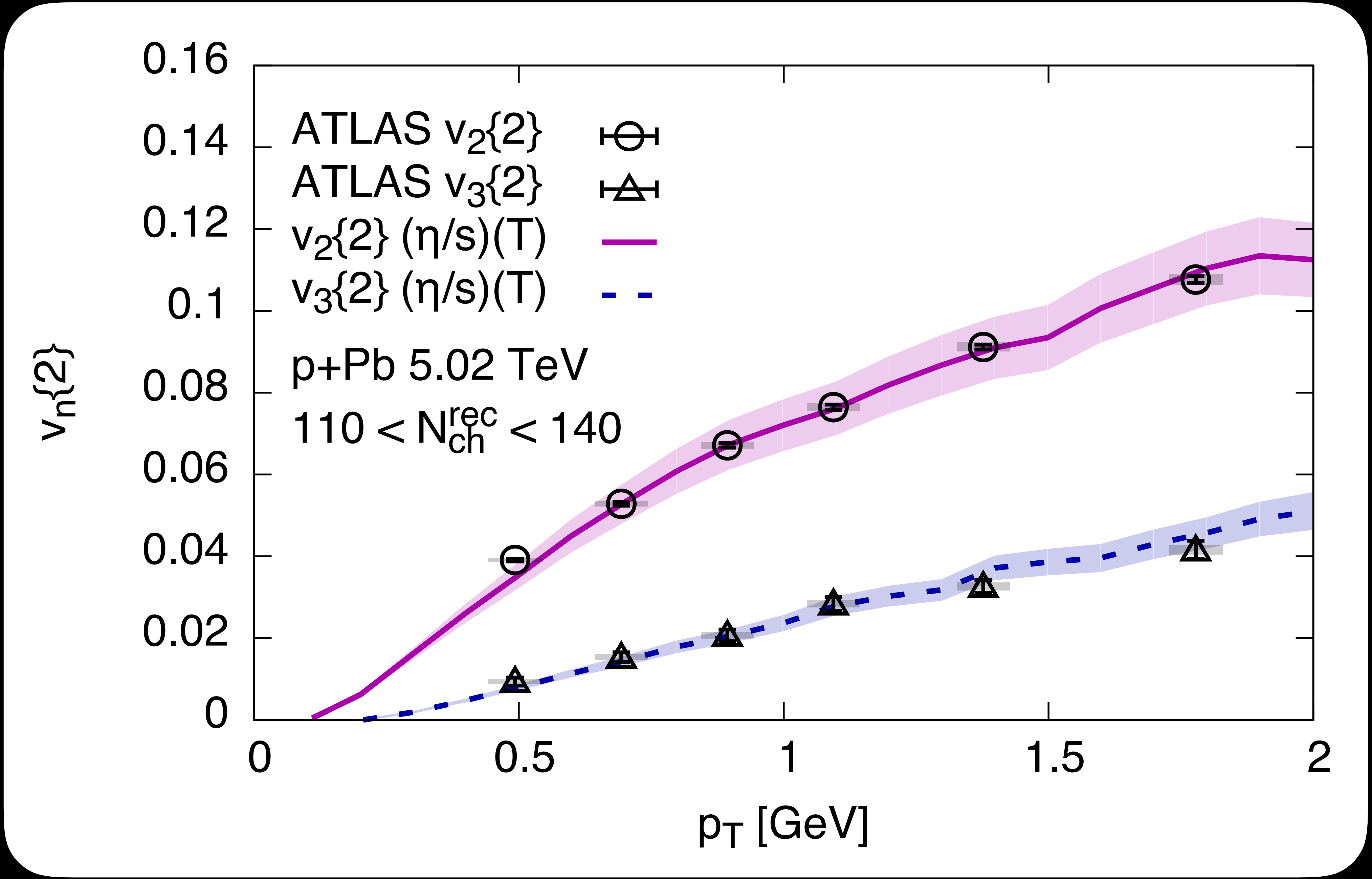
IP-Glasma+subnucleonic fluctuations

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



p_T-differential anisotropic flow

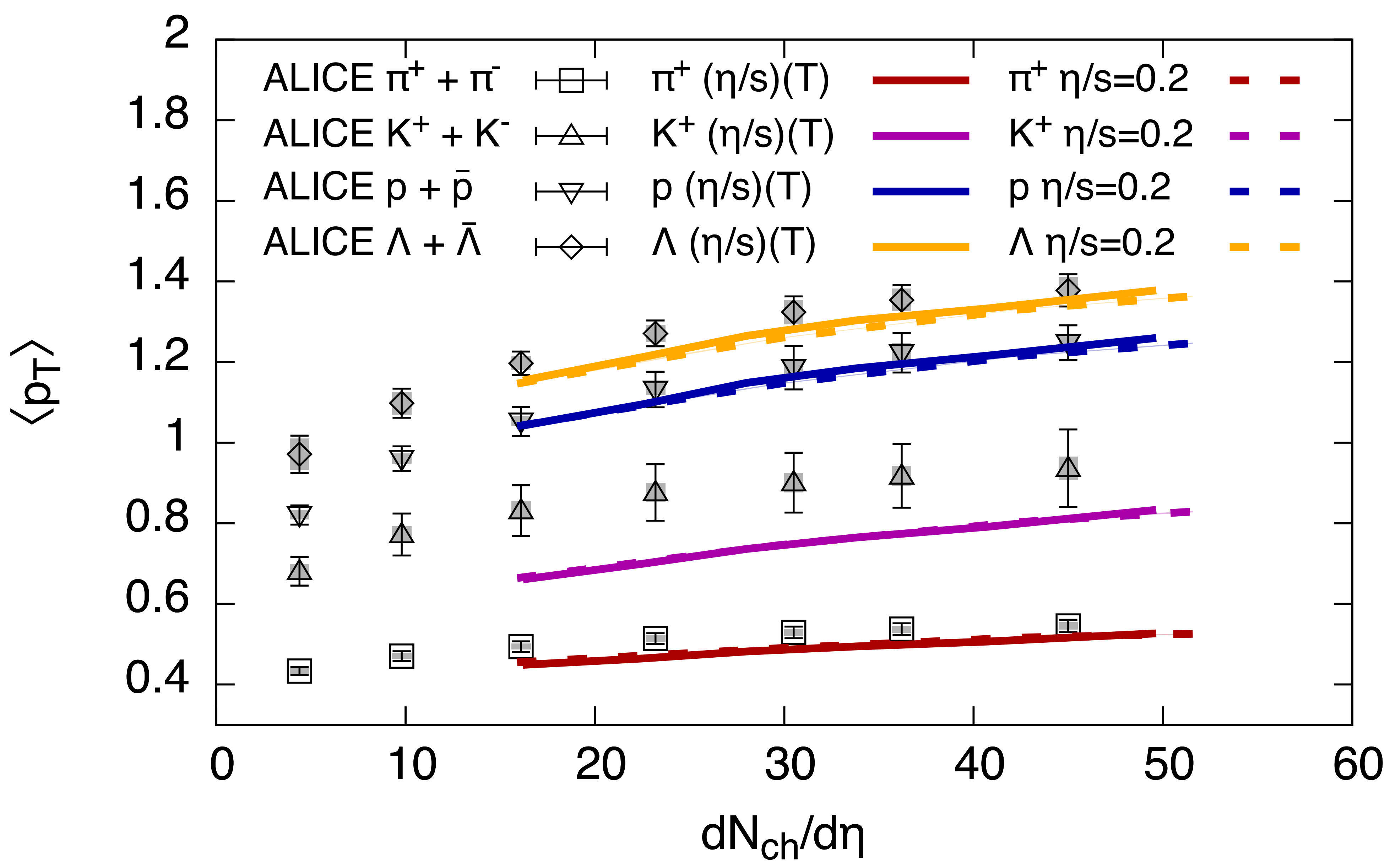
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)



τ_0=0.4 fm

Identified particle mean p_T

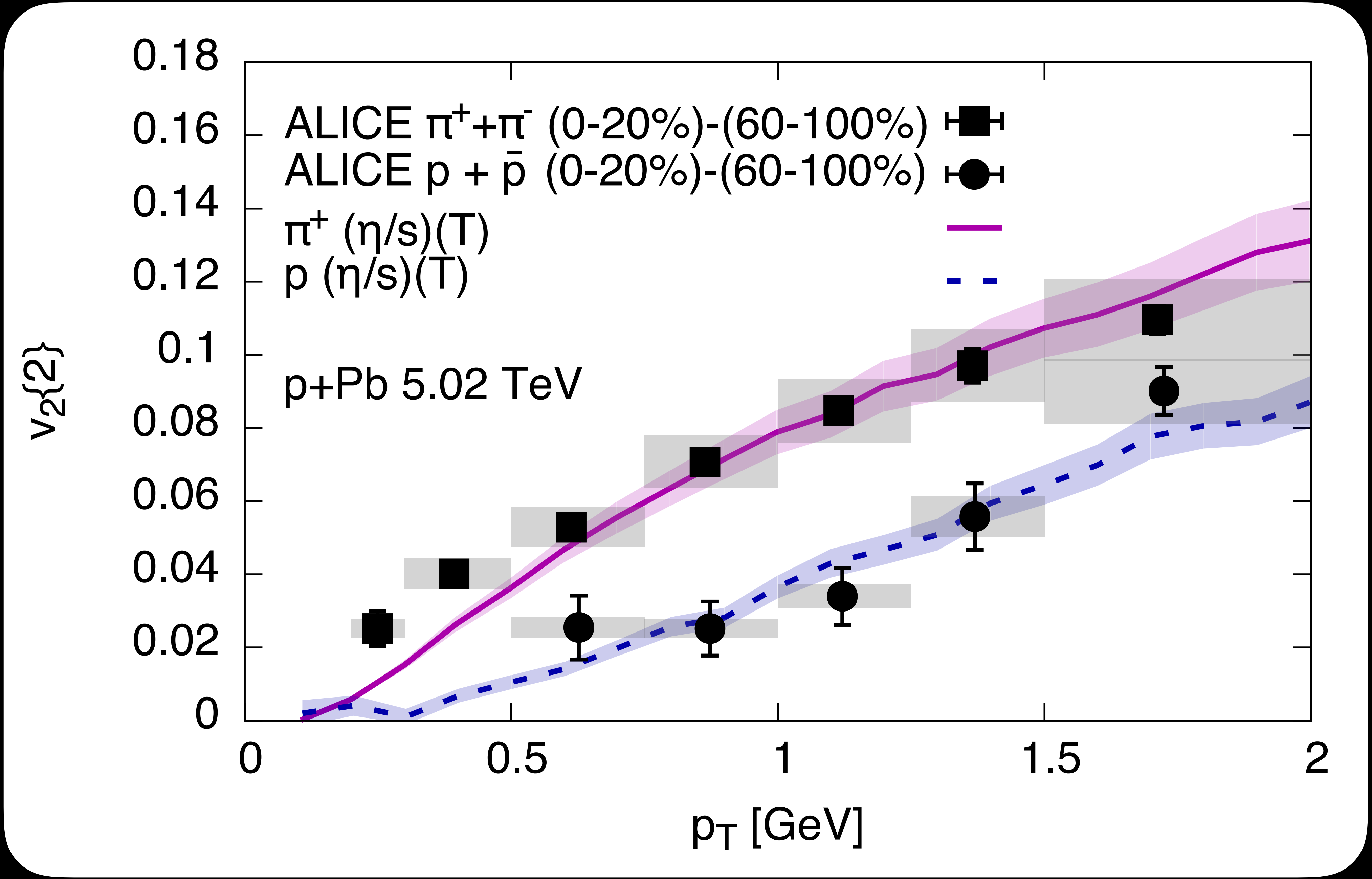
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)



Experimental data: ALICE Collaboration, Phys. Lett. B728, 25 (2014)

Identified particle flow

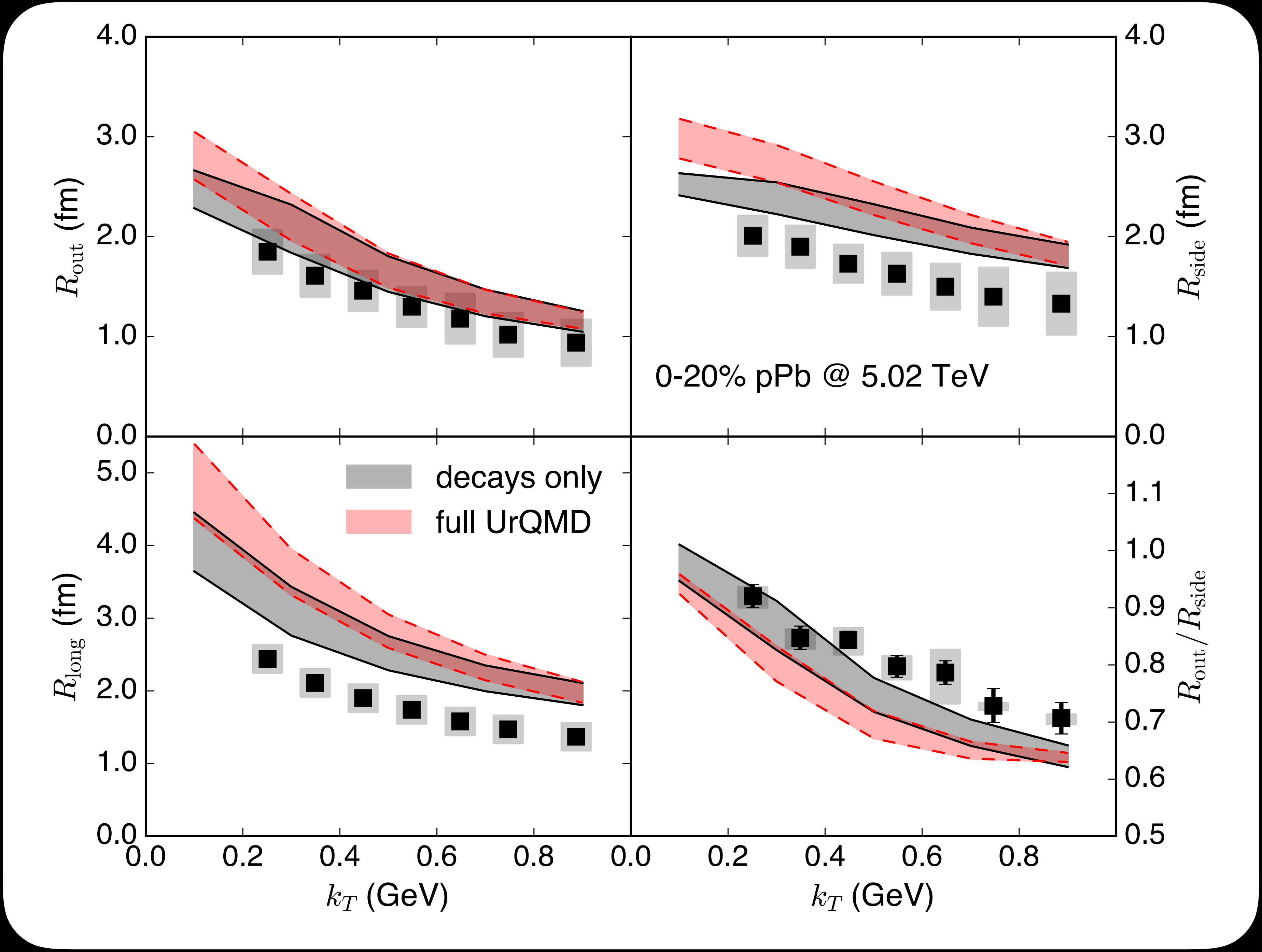
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)



τ_0=0.4 fm

HBT radii

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)
Data: ALICE Collaboration, J. Adam et al. (ALICE), Phys. Rev. C91, 034906 (2015)



τ_0=0.4 fm (η/s)(T)

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
Some include extra contributions, important at lower multiplicity

APPROXIMATIONS

- **Glasma graph approximation:** two gluon exchange (not more) and Gaussian statistics of color charges (MV model)

- **Non-linear Gaussian approximation:**
  Resums multi-gluon exchanges - still Gaussian statistics

- **Numerical solution:** Solves the Yang-Mills equations exactly for any initial color source statistics and spatial configuration, includes multiple-gluon exchange, “rescattering”

- One can add **JIMWLK** evolution which will introduce (some) non-Gaussian correlations

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, …

INITIAL STATE PICTURE ALSO 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

WHICH EFFECT DOMINATES THE EXPERIMENTAL DATA?

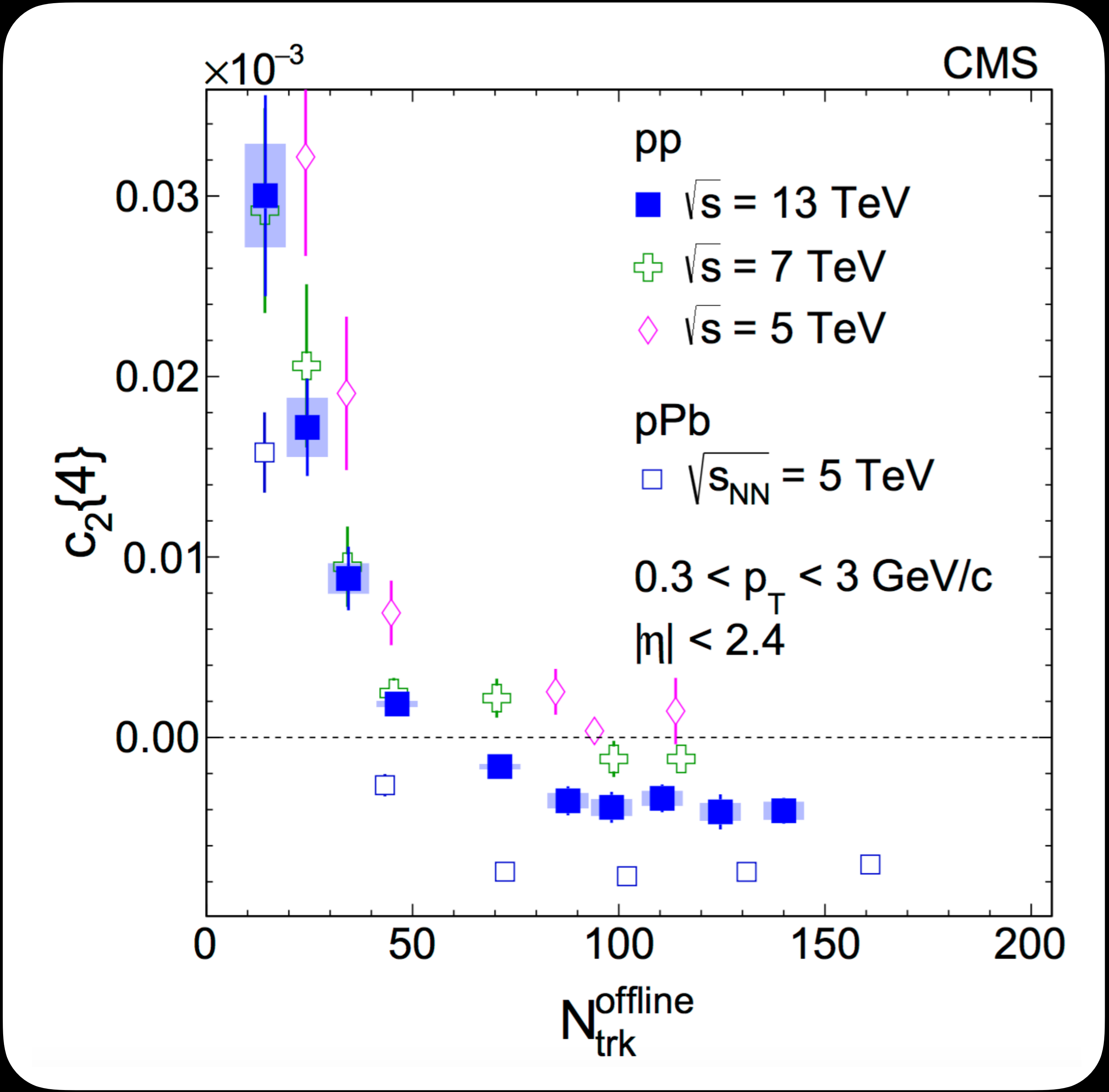
- Sign change of $c_2\{4\}$
- Multi particle (>2) cumulants
- Odd harmonics
- Different collision systems

- Beam energy dependence
- Mass ordering
- Jet quenching
- Electromagnetic probes
- Angular dependent HBT

SIGN CHANGE OF $c_2\{4\}$

$v_2\{4\} = \sqrt[4]{-c_2\{4\}}$ real only for negative $c_2\{4\}$

Data shows a sign change with increasing multiplicity



CMS Collaboration, Phys. Lett. B 765 (2017) 193

SIGN CHANGE OF $c_2\{4\}$

Onset of hydrodynamics?

E. Avsar, C. Flensburg, Y. Hatta, J-Y Ollitrault, T. Ueda, Phys.Lett. B702 (2011) 394-397

$$c_n\{4\} = \langle\cos[n(\phi_1+\phi_2-\phi_3-\phi_4)]\rangle - 2\langle\cos[n(\phi_1-\phi_2)]\rangle^2$$

$$= v_n^4 - 2(v_n^2)^2 + \ldots = -v_n^4 + \ldots \text{ (neglecting fluctuations)}$$

Glasma graphs lead to positive $c_2\{4\}$ for all multiplicities

Additional non-linear and non-Gaussian effects can lead to a negative contribution

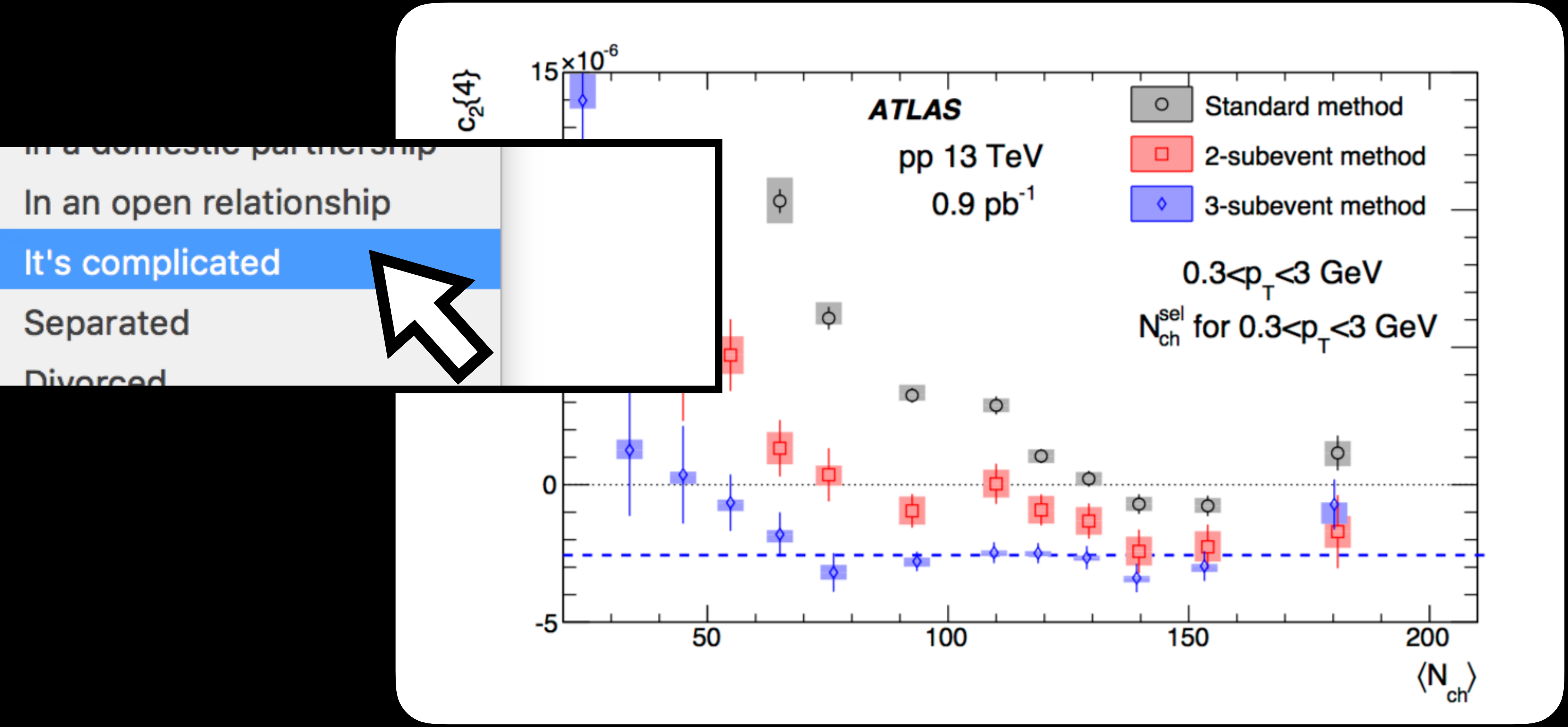
$$c_2\{4\} = \frac{1}{N_D^3}\left[\frac{1}{4(N_c^2-1)^3} - \mathcal{A}^4\right]$$

color domain model

A. Dumitru, L. McLerran, V. Skokov, Phys.Lett. B743 (2015) 134-137

MULTIPLICITY FLUCTUATIONS

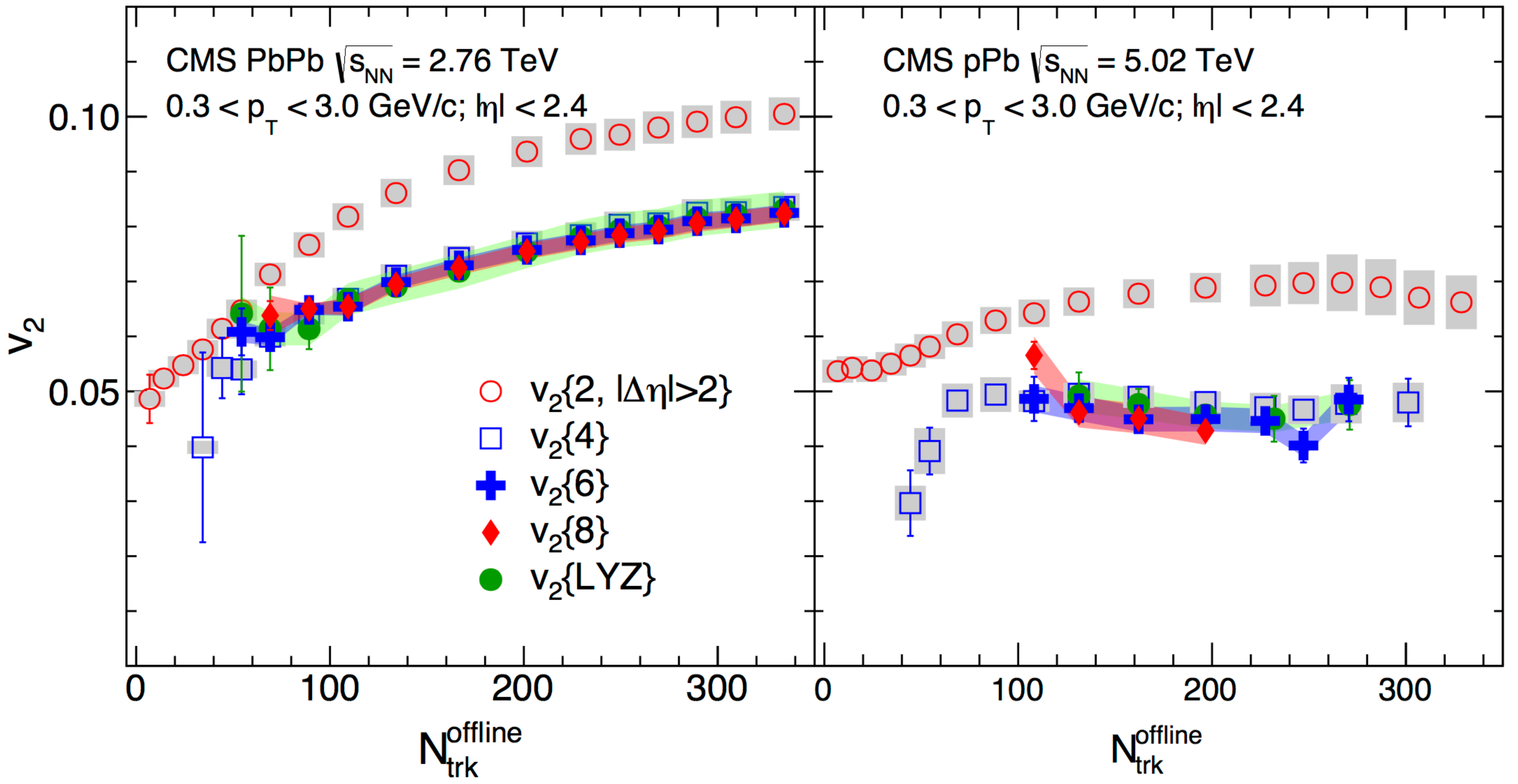
- The sign of $c_n\{4\}$ depends on the detailed definition of centrality, because $P(v_n)$ in each bin depends on it
- Non-flow, mostly eliminated by the three-sub-event method, also affects the sign of $c_n\{4\}$



ATLAS Collaboration, arXiv:1708.03559

HIGHER ORDER CUMULANTS

Data shows $|v_2\{2m\}| \approx |v_2\{2m'\}|$ for m, m′ ≳ 4



CMS Collaboration, Phys. Rev. Lett. 115 (2015) 012301

MULTI-PARTICLE CUMULANTS

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

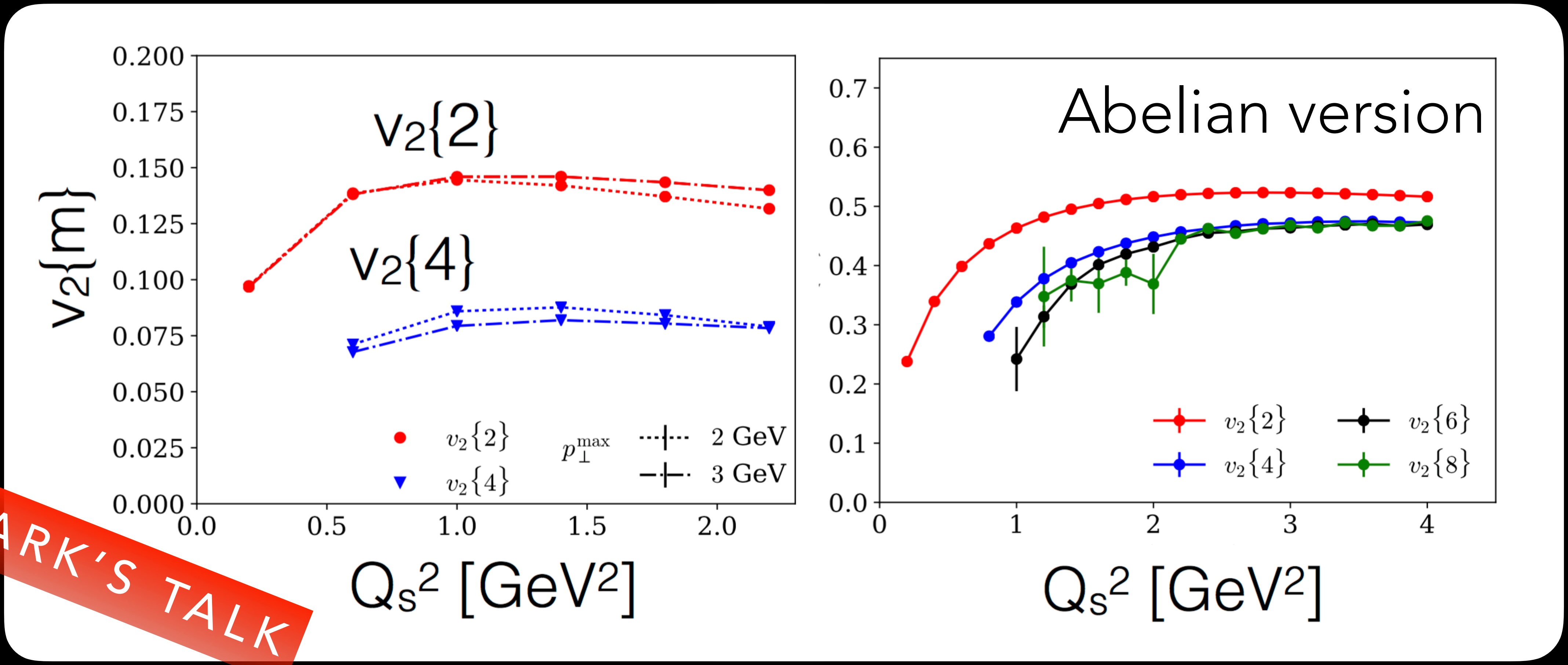
All particles correlated with a common event plane

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

$v_2\{4\}$ imaginary in glasma-graph approximation

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

Including multiple interactions will make it real



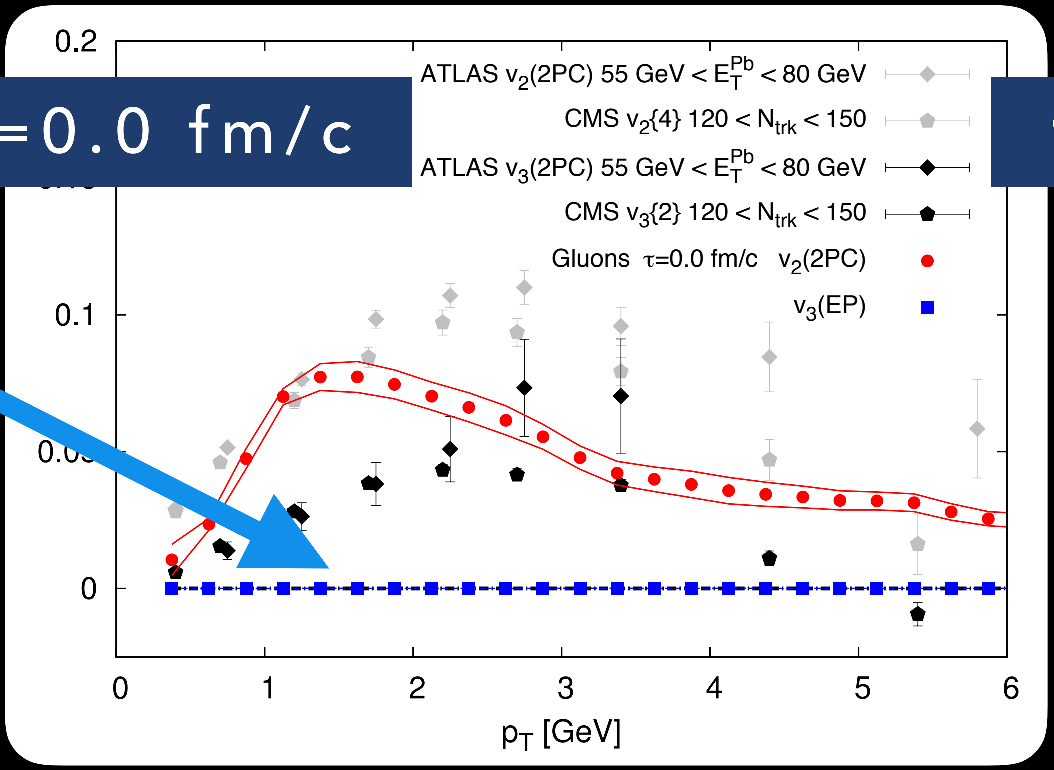
SEE MARK'S TALK

K. Dusling, M. Mace, R. Venugopalan arXiv:1705.00745

ODD HARMONICS

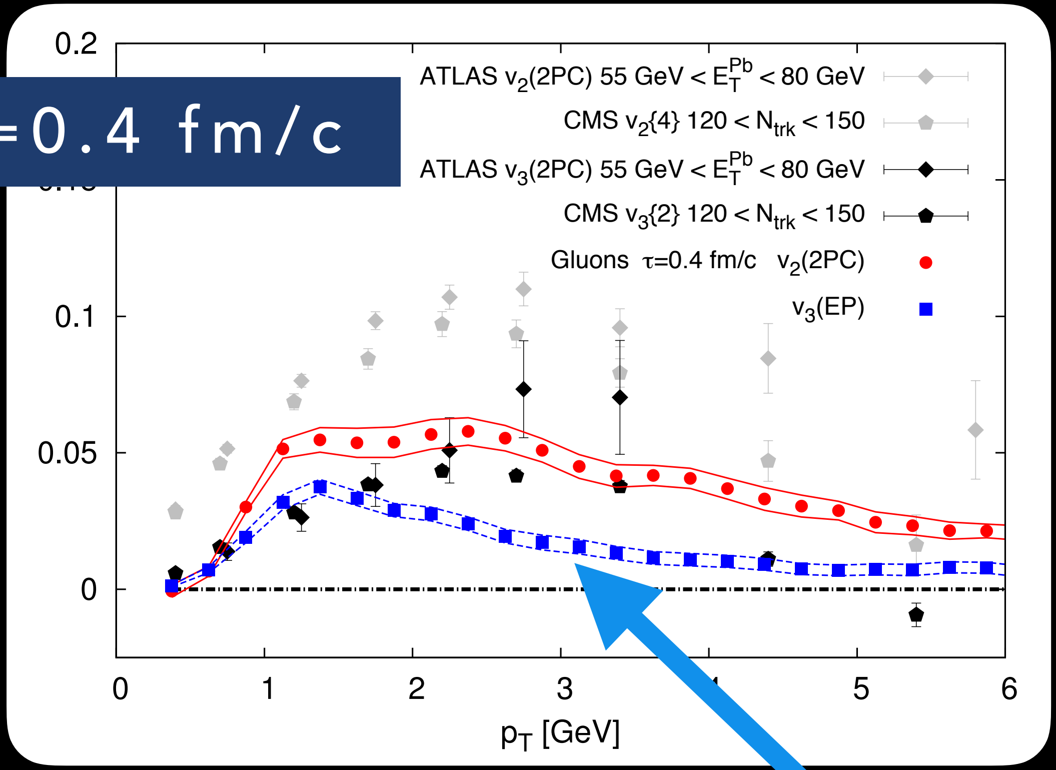
CGC: Final state interactions needed to produce odd harmonics for gluons in classical approximation

B. Schenke, S. Schlichting, R. Venugopalan, Phys. Lett. B747, 76-82 (2015)



τ=0.0 fm/c

V_3



τ=0.4 fm/c

Analytic proof: **L. McLerran, V. Skokov, Nucl.Phys. A959 (2017) 83-101, 1611.09870**

V_3

Odd harmonics without final state interactions

A. Kovner, M. Lublinsky, V. Skokov, arXiv:1612.07790

E. Gotsman, E. Levin, and U. Maor, Eur. Phys. J. C76, 607 (2016) arXiv:1607.00594

E. Gotsman and E. Levin (2016) arXiv:1611.01653

SEE MARK'S TALK

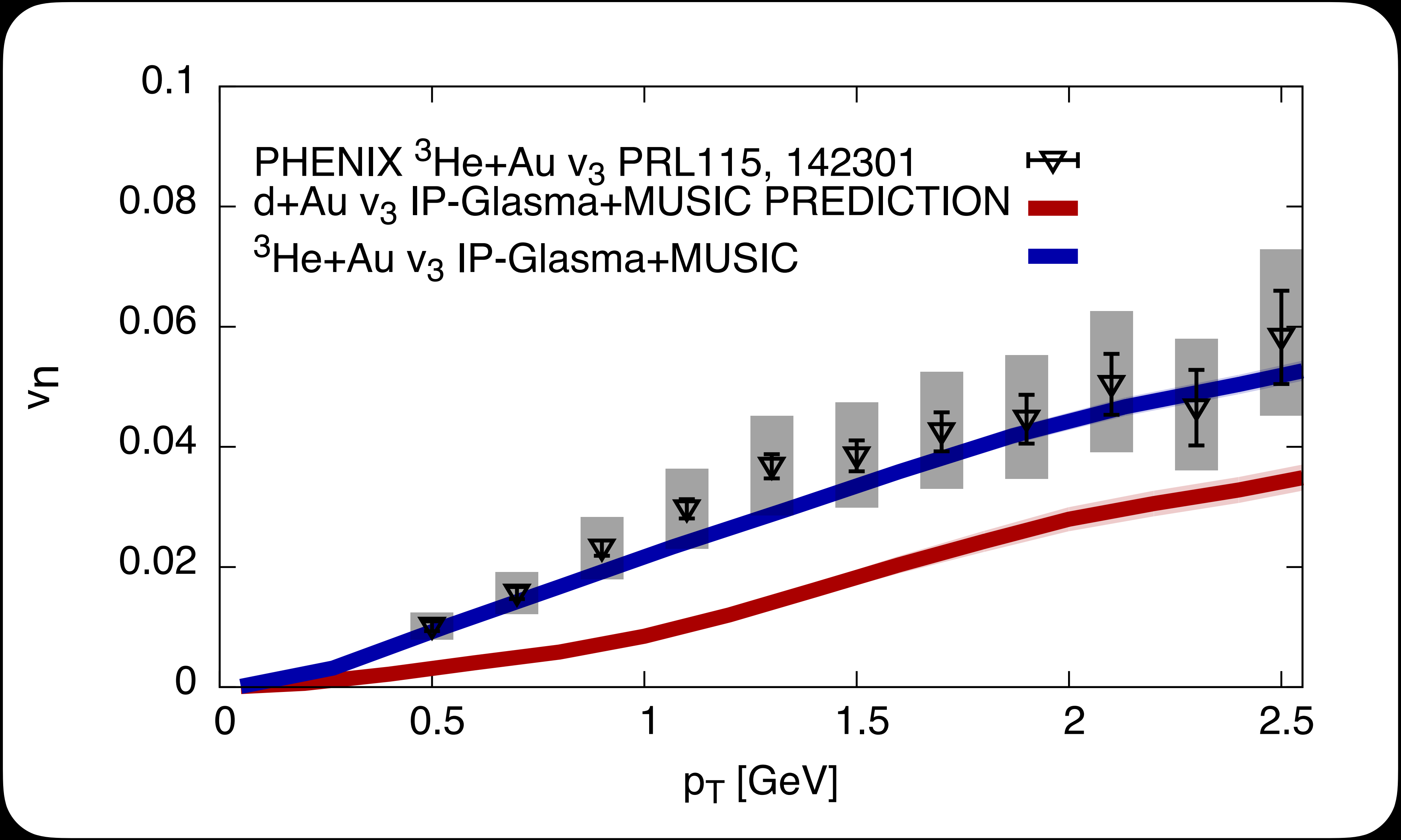
beyond classical
and beyond dilute

DIFFERENT SMALL SYSTEMS

d+Au, ^{3}He+Au HYDRO PREDICTIONS

Calculation with $\eta/s=0.18$

d+Au v_3 is a true prediction **(shown @2015 RHIC&AGS Users' Meeting)**



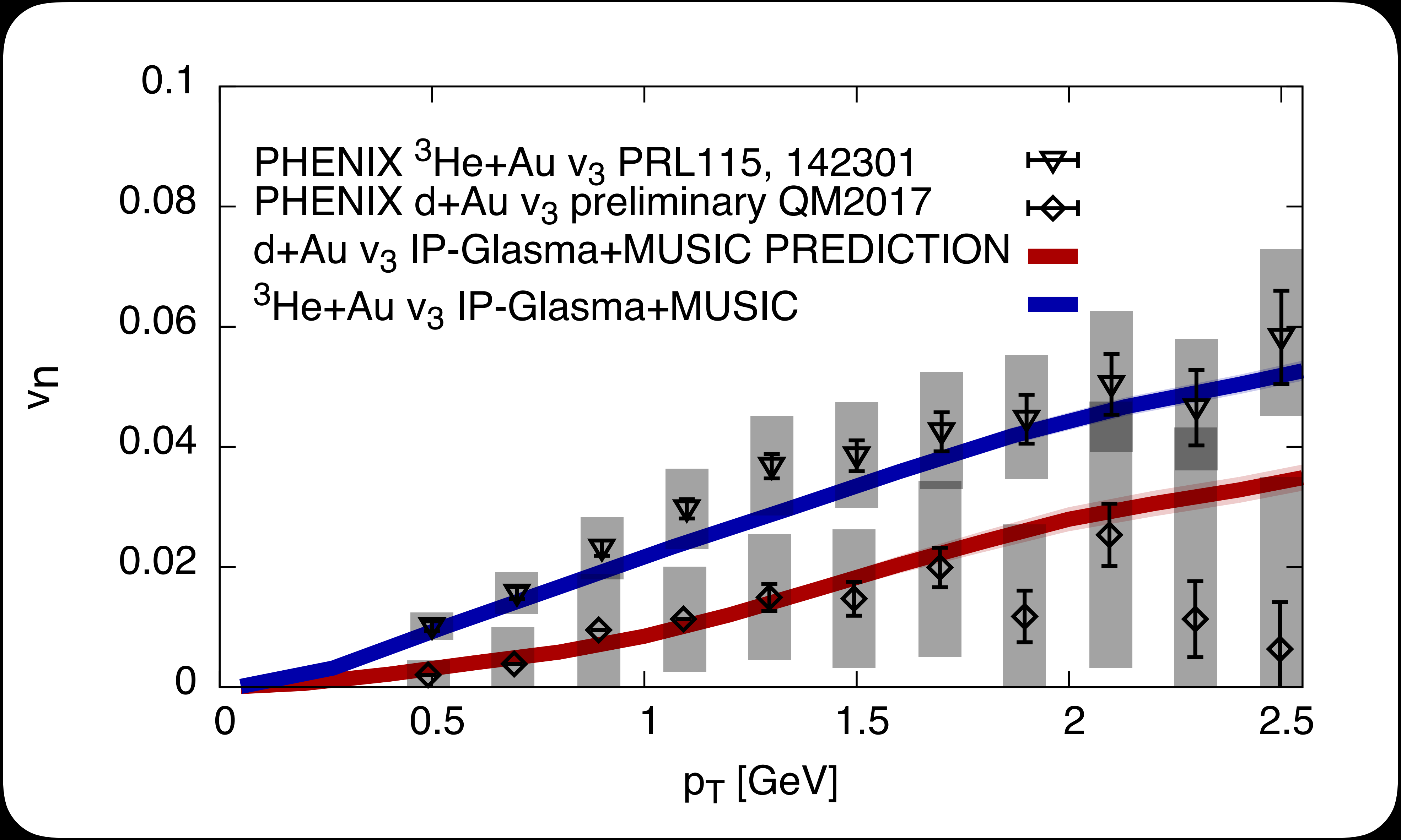
B. Schenke and R. Venugopalan, Nucl. Phys. A 931 (2014) 1039 $\eta/s=0.12$

DIFFERENT SMALL SYSTEMS

d+Au, ^{3}He+Au HYDRO PREDICTIONS

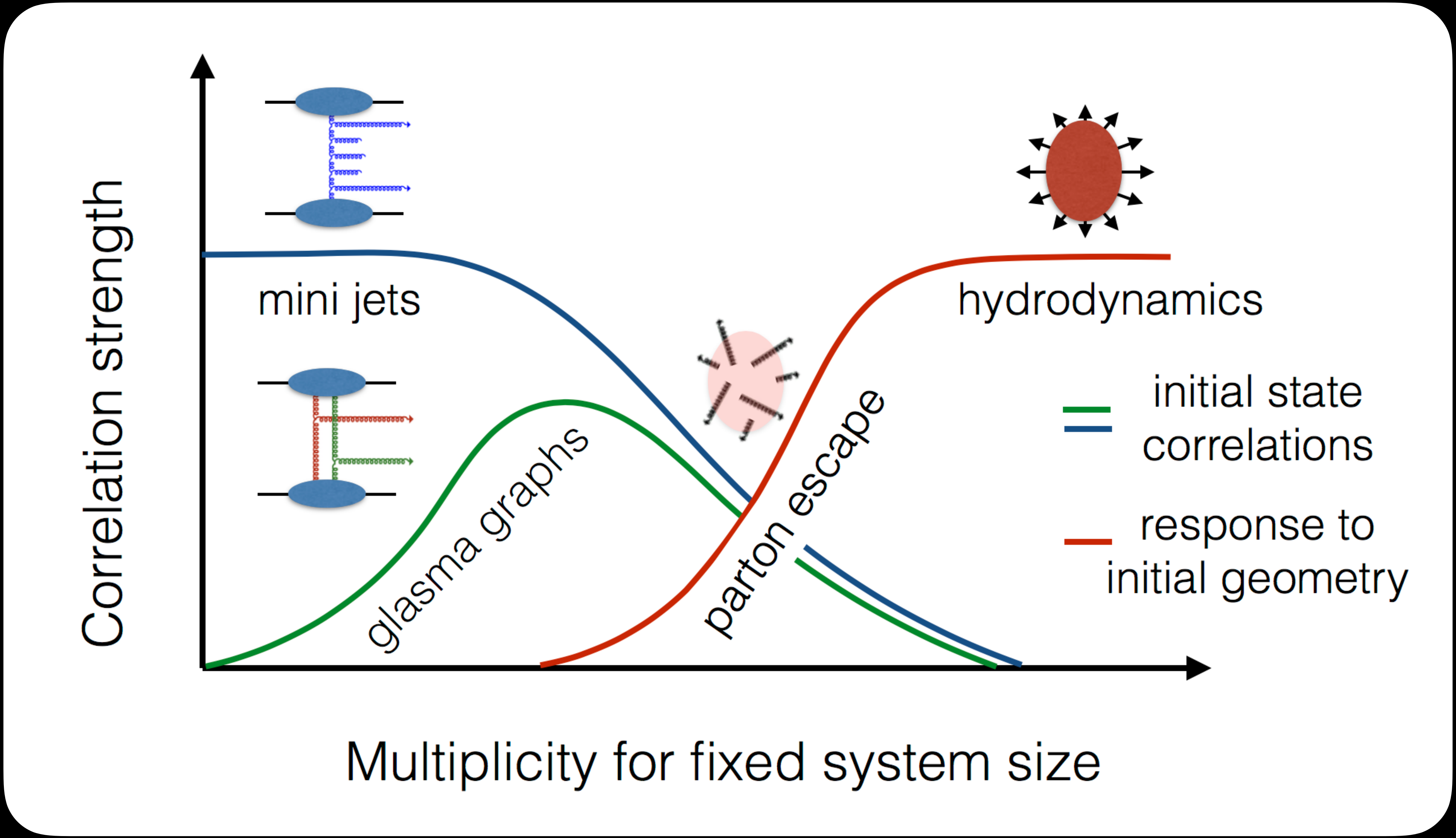
Calculation with **η**/s=0.18

d+Au v_3 is a true prediction **(shown @2015 RHIC&AGS Users' Meeting)**



B. Schenke and R. Venugopalan, Nucl. Phys. A 931 (2014) 1039 **η/s=0.12**

STUDY RELATIVE STRENGTH OF INITIAL AND FINAL STATE CORRELATIONS IN THEORY



S. Schlichting, Quark Matter 2015

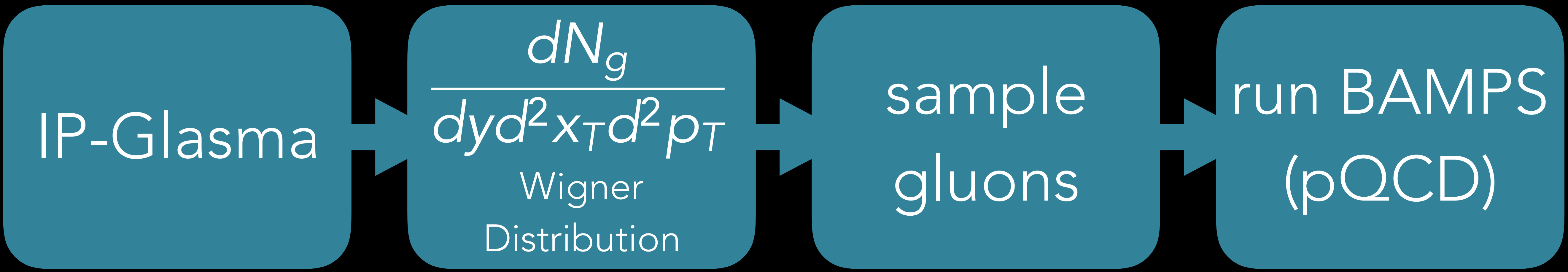
Calculate the relative contribution of "glasma graphs" and final state effects

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

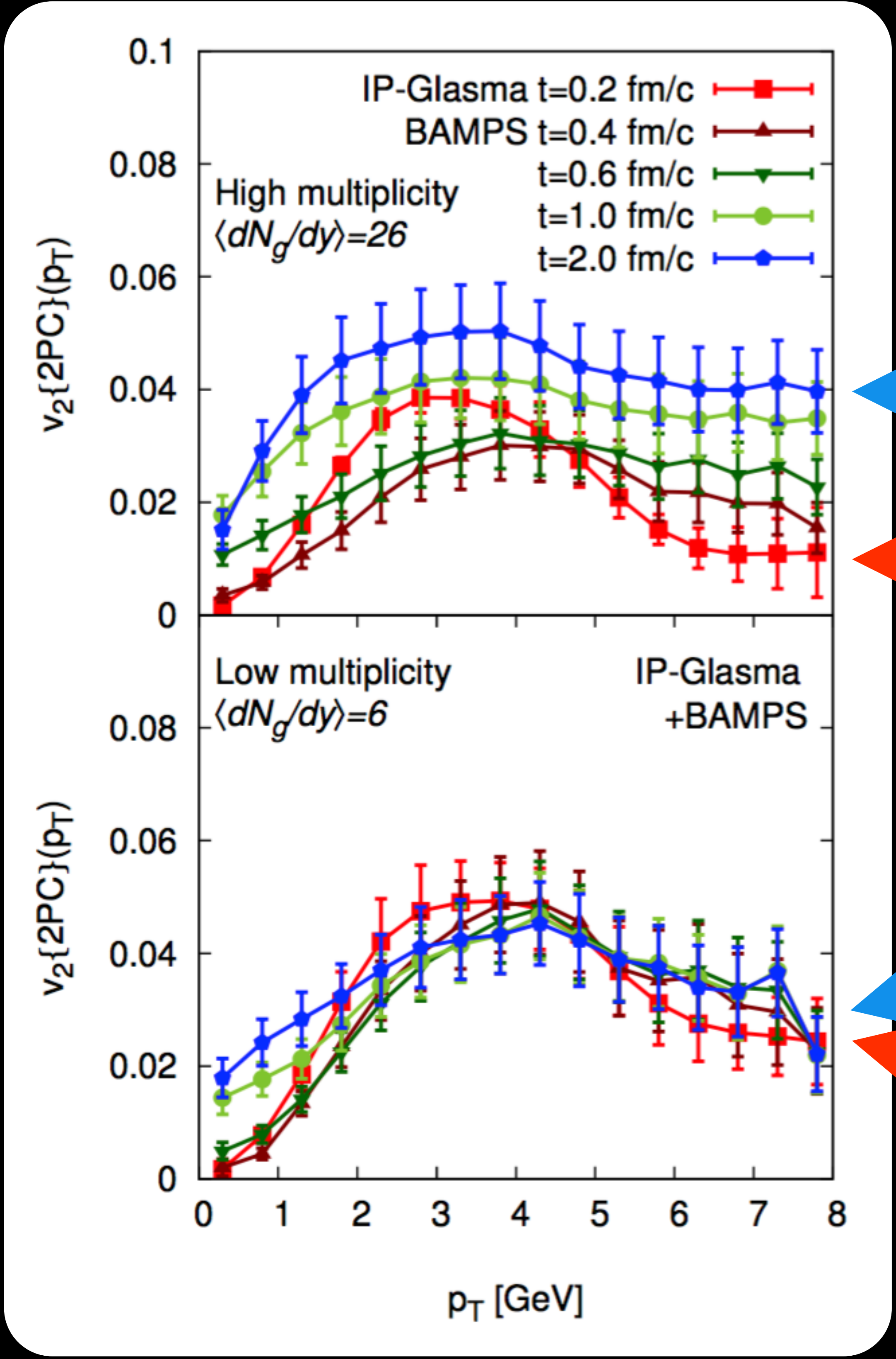
→ study momentum anisotropy as function of time

Time evolution of v_2

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

high multiplicity

low multiplicity



final v_2 (2fm)

initial v_2 (0.2fm)

final v_2 (2fm)

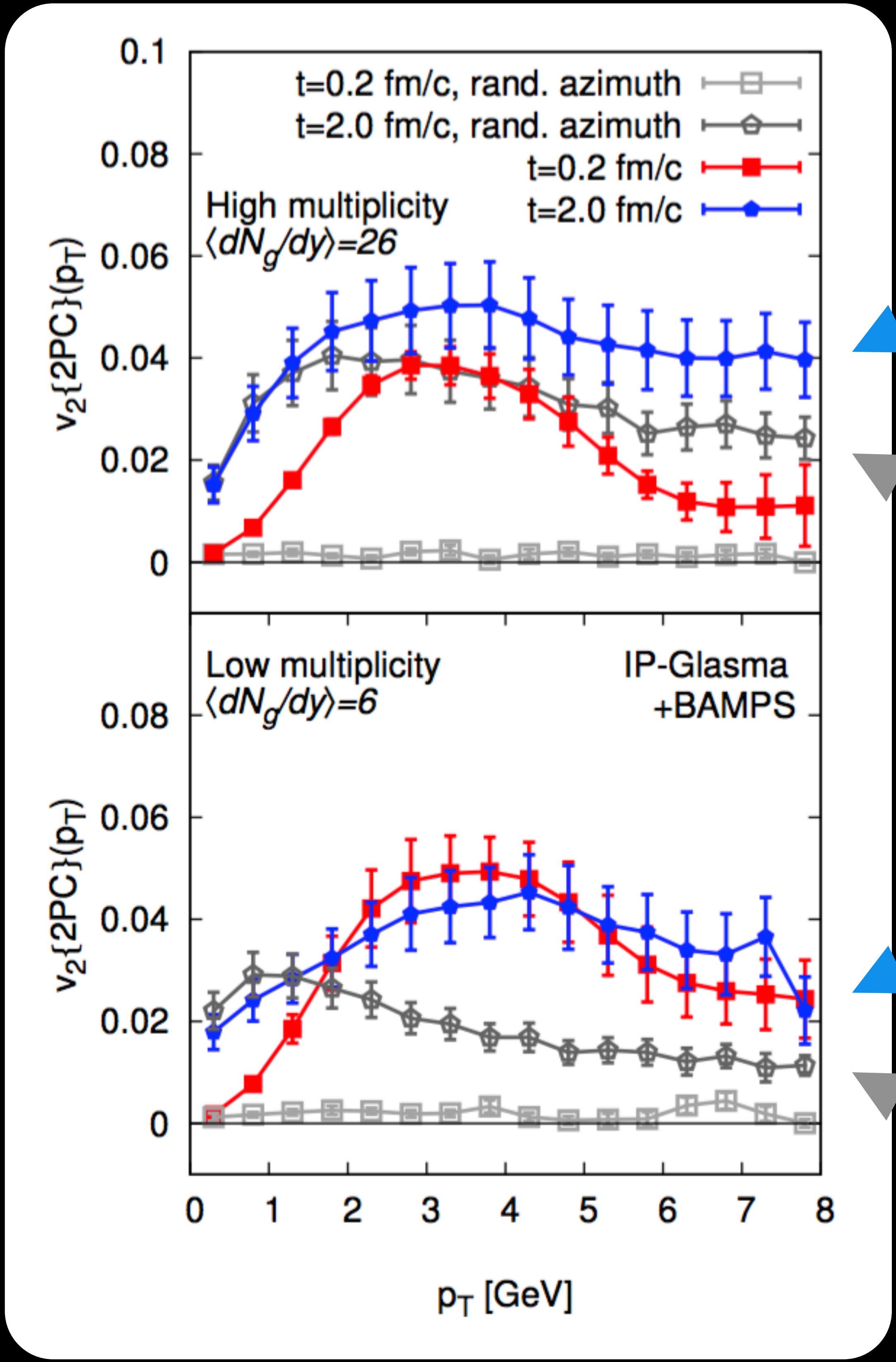
initial v_2 (0.2fm)

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.

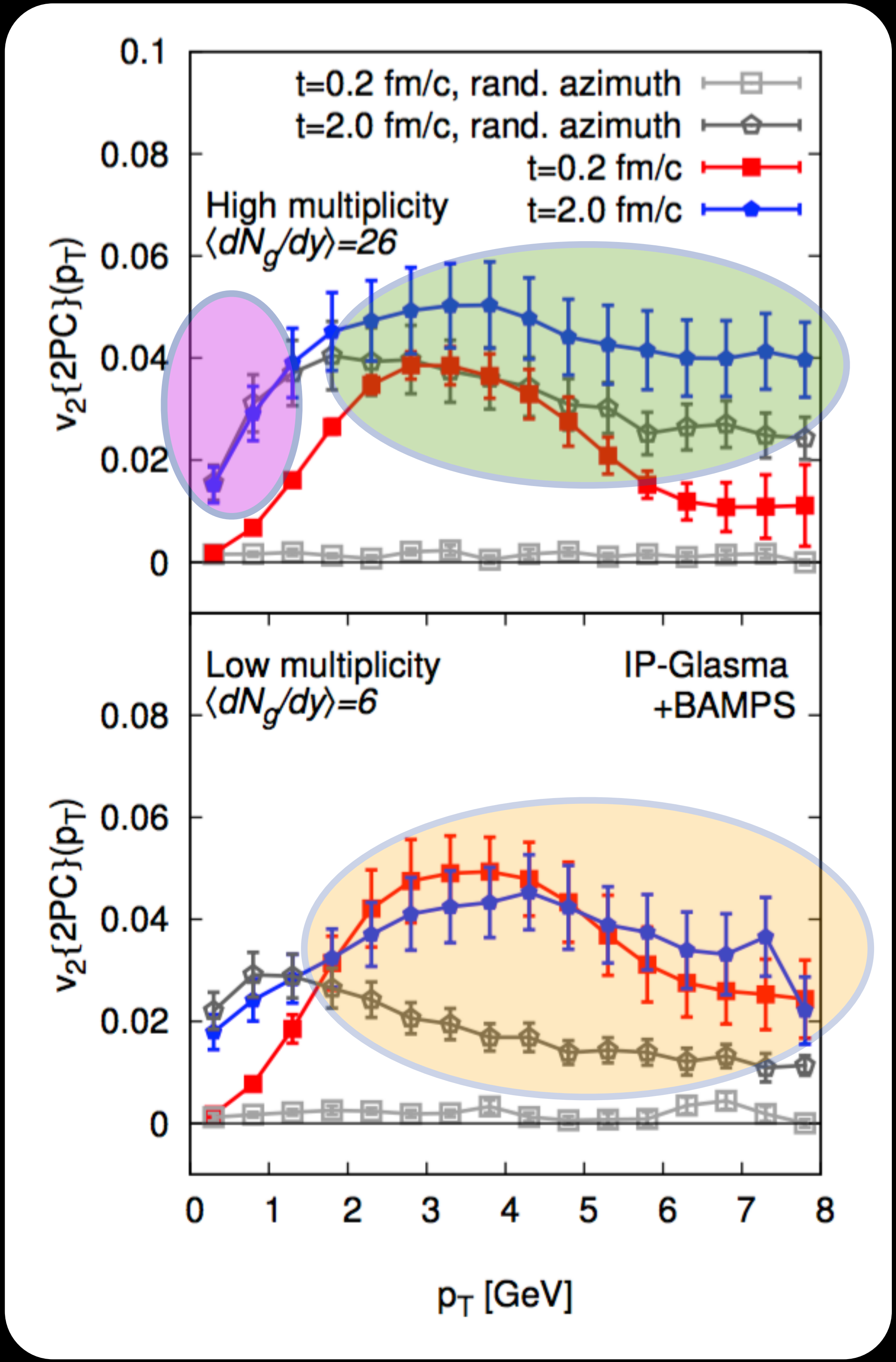
without initial corr.

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



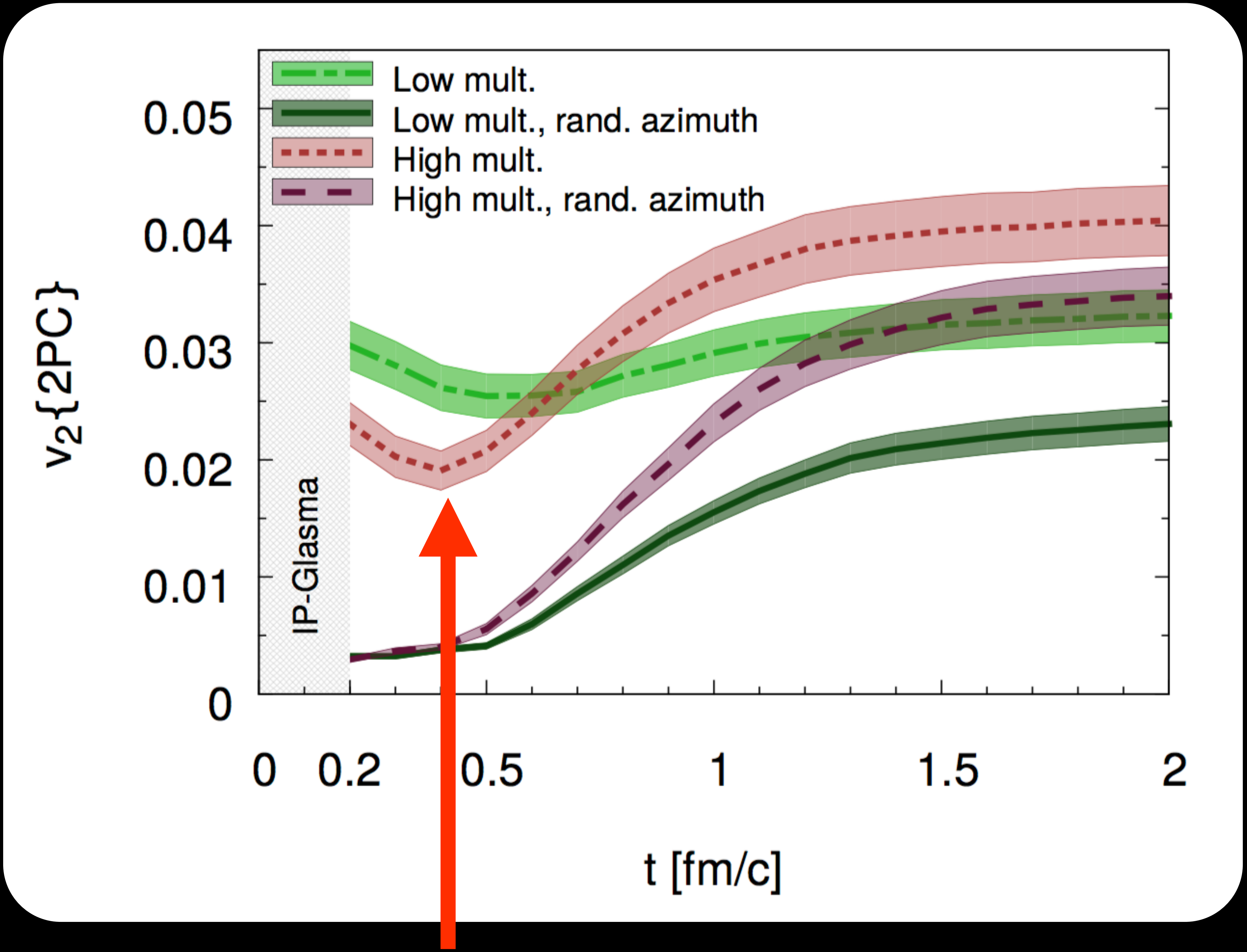
🟣 negligible effect at small p_T and high multiplicity

🟠 significant effect at p_T >2 GeV and low multiplicity

🟢 visible effect at p_T >3 GeV and high multiplicity

Evolution of integrated v_2

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



Both high and low multiplicity integrated v_2 are affected by initial correlations

First, initial correlation is reduced then final state correlation built up

CONCLUSIONS & OUTLOOK

- There is NO question initial state correlations exist
  but do they survive the final state in high multiplicity events?

- In high multiplicity events and at small p_T (<1.5 GeV)
  we likely see a dominant final state effect

- More and more detailed observables becoming available:
  Factorization breaking with p_T and y, correlations between v_n, symmetric cumulants, system dependence, beam energy dependence, (angular dependent) HBT, high-p_T probes, electromagnetic probes, …

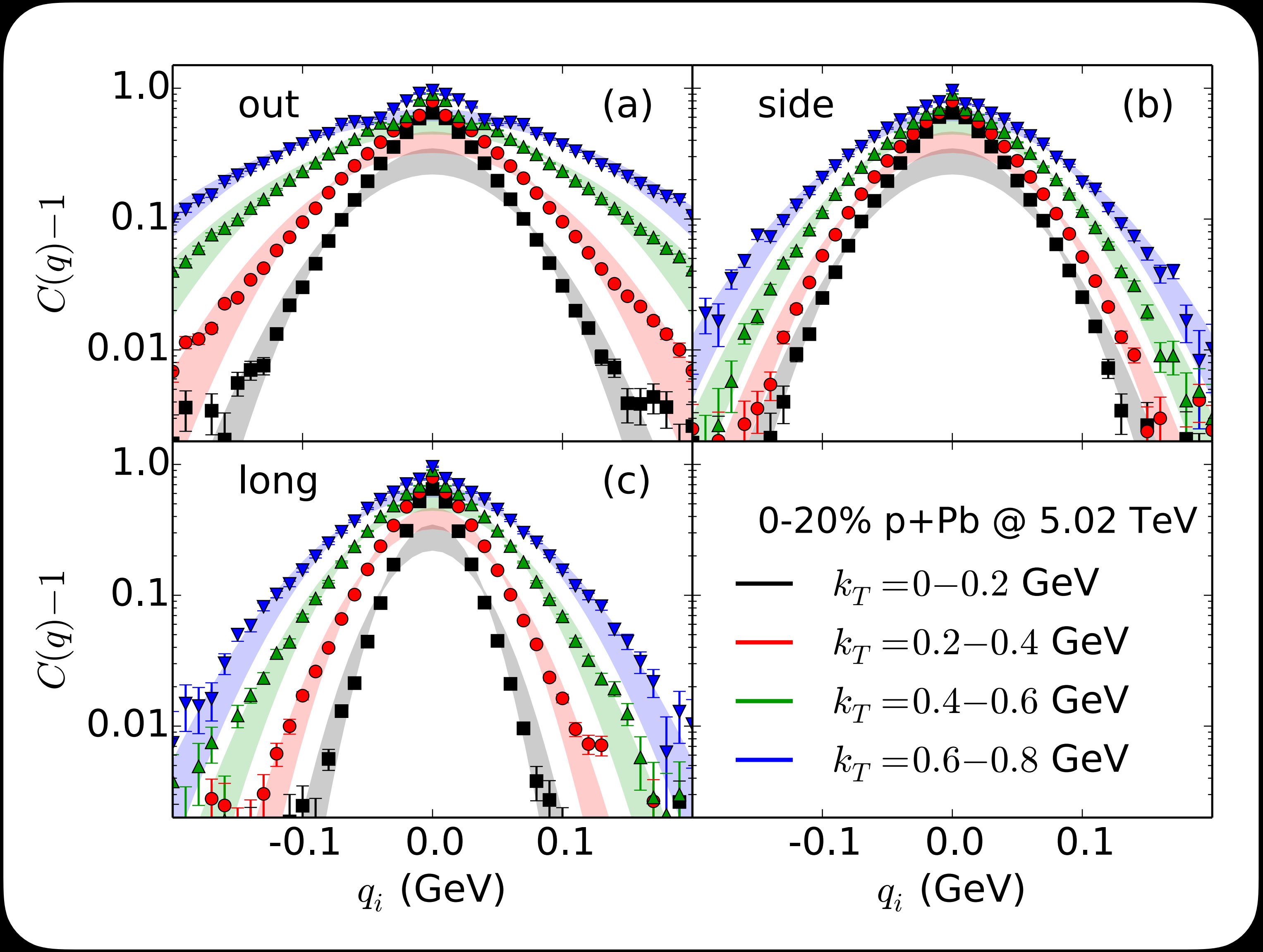
BACKUP

HBT radii

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

$$C(\mathbf{q}) = 1 + \frac{\frac{1}{\langle N_{\rm pair}\rangle}\langle \sum_{ij}\cos(q_{ij}\cdot x_{ij})\rangle}{\frac{1}{\langle N_{\rm mix\,pair}\rangle}\langle N_{\rm mix\,pair}(q)\rangle}$$

M. A. Lisa, S. Pratt, R. Soltz, and U. Wiedemann,
Ann. Rev. Nucl. Part. Sci. 55, 357 (2005)
R. Hanbury Brown and R. Q. Twiss
Nature 178, 1046 (1956)

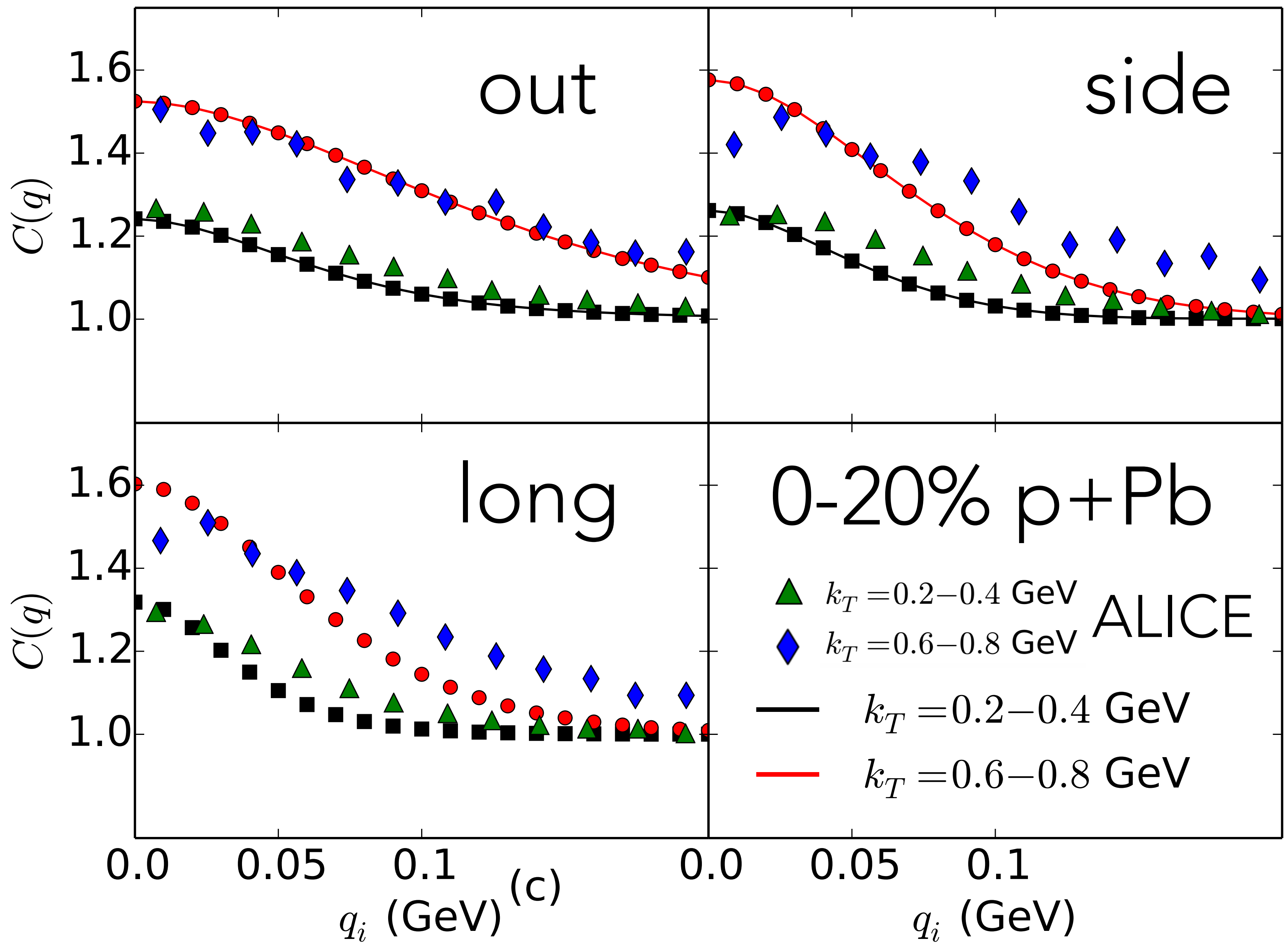


Fit to the Pratt-Bertsch parametrization in the longitudinally co-moving system

S. Pratt, Phys. Rev. D33, 1314 (1986)
G. Bertsch, M. Gong, and M. Tohyama
Phys. Rev. C37, 1896 (1988).

HBT radii: C(q) compared to data

H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, Phys. Lett. B772, 681–686 (2017)
Data: ALICE Collaboration, J. Adam et al. (ALICE), Phys. Rev. C91, 034906 (2015)



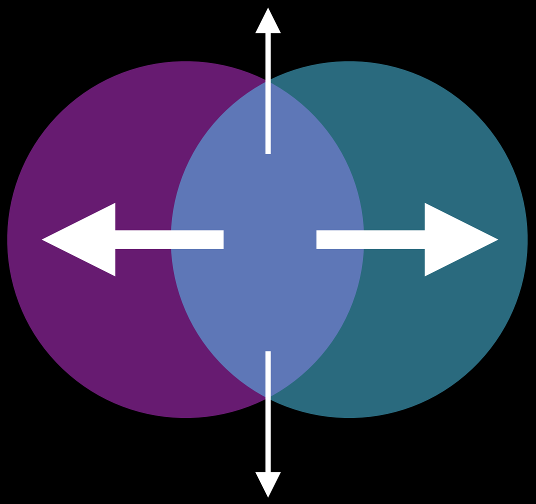
τ_0=0.4 fm (η/s)(T)

KINETIC THEORY "ANISOTROPIC ESCAPE"

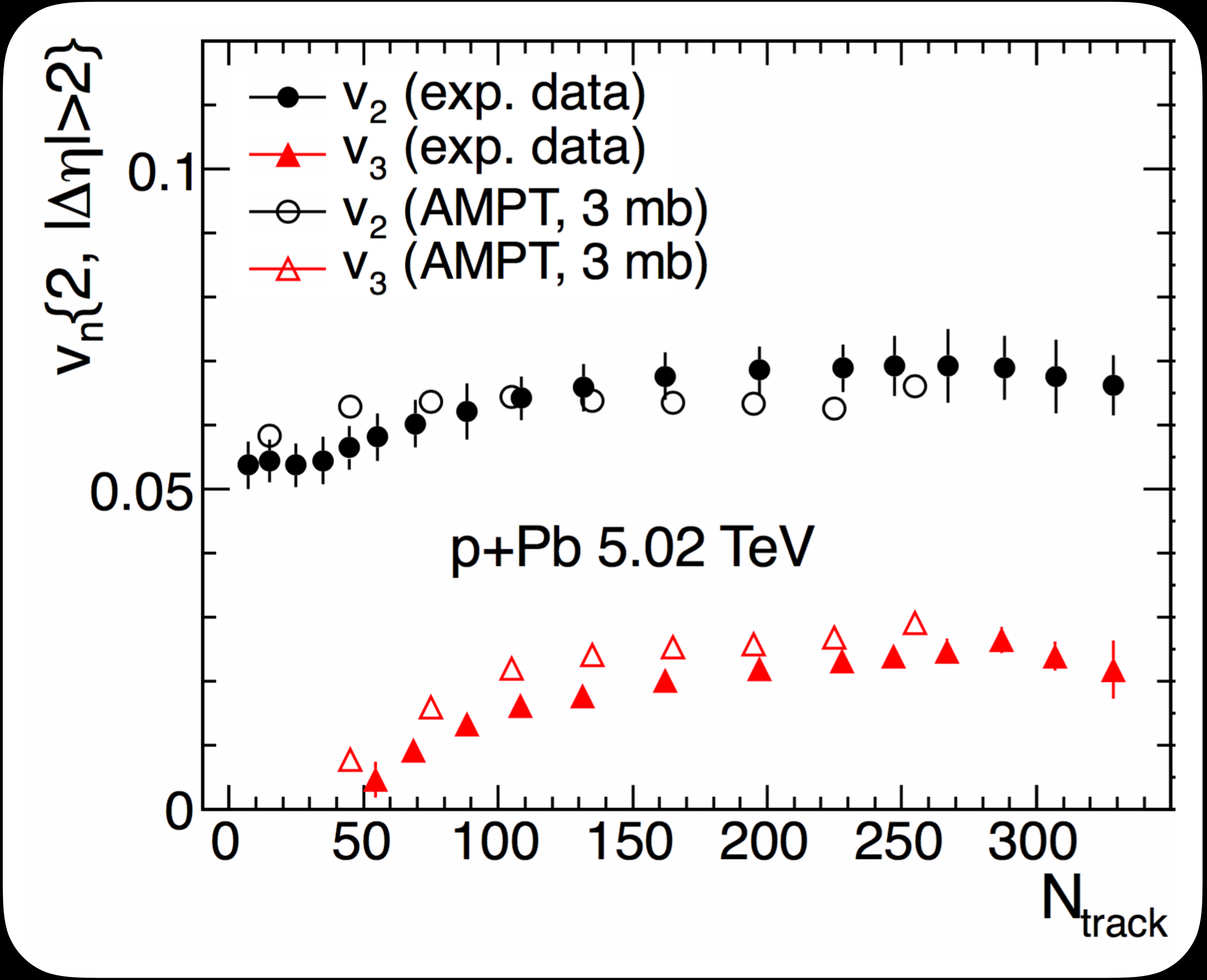
A. Bzdak, G.-L. Ma, PRL113 (2014) 252301; G.-L. Ma, A. Bzdak, PLB739 (2014) 209-213; J.D. Orjuela Koop, A. Adare, D. McGlinchey, J.L. Nagle, PRC92 (2015) 054903; P. Bozek, A. Bzdak, G.-L. Ma, PLB748 (2015) 301-305; L. He, T. Edmonds, Z.-W. Lin, F. Liu, D. Molnar, F. Wang, PLB753 (2016)

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



MASS ORDERING

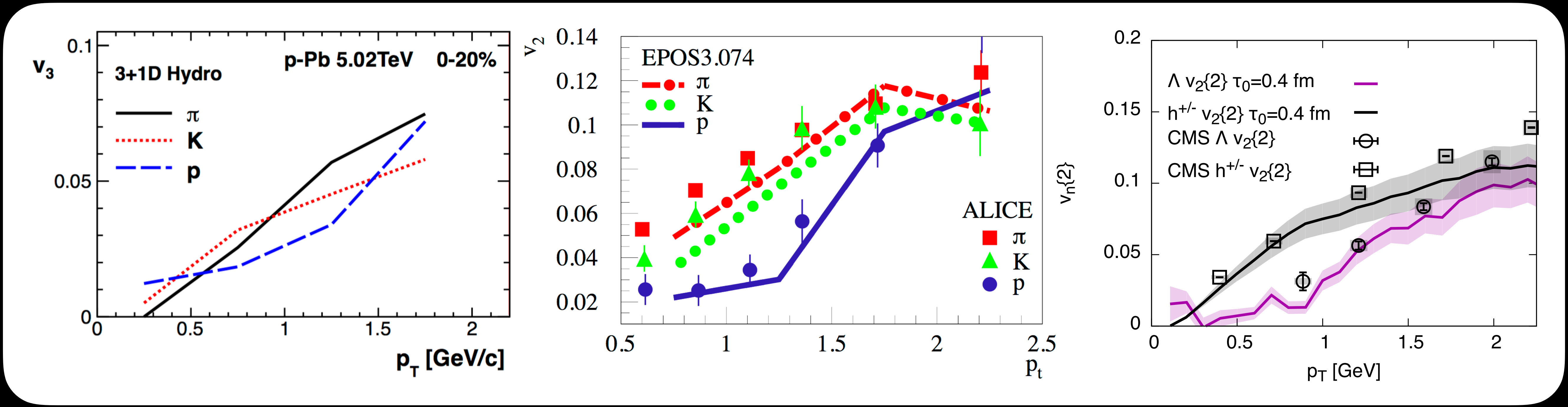
History repeating itself?

Mass splitting of ⟨p_T⟩ in p+$\bar{p}$ collisions explained with and without hydrodynamic QGP phase

P. Levai, B. Mueller, PRL67, 1519 (1991)

X.-N. Wang, M. Gyulassy, PLB282, 466 (1992)

Hydrodynamic flow produces mass ordering of ⟨p_T⟩ and v_n



P. Bozek, W. Broniowski, G. Torrieri, Phys.Rev.Lett. 111 (2013) 172303

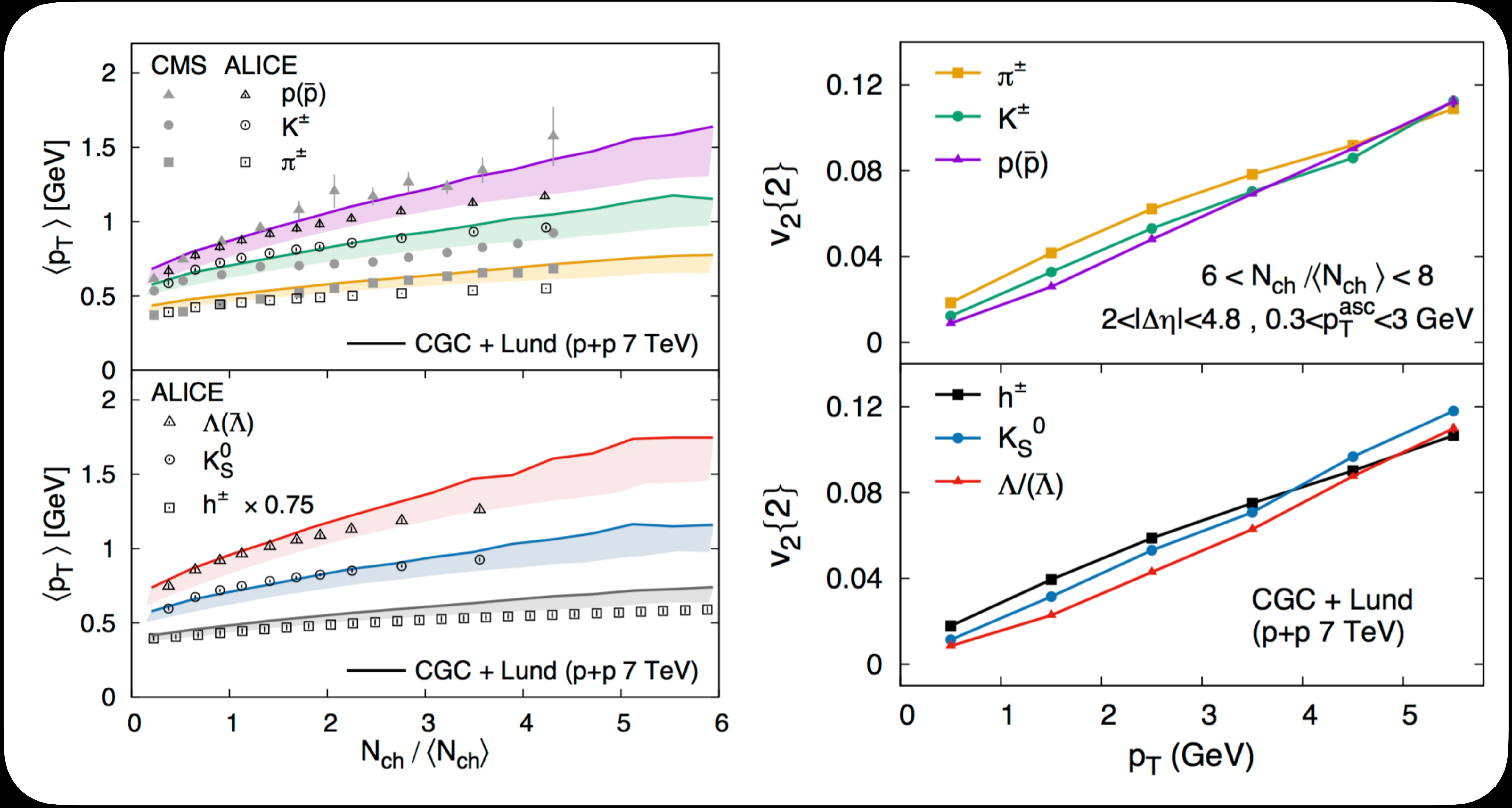
K. Werner, M. Bleicher, B. Guiot, Iu. Karpenko, T. Pierog, Phys.Rev.Lett. 112 (2014) 232301

H. Mäntysaari, P. Tribedy, B. Schenke, C. Shen, in preparation (2017)

MASS ORDERING FROM INITIAL STATE

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

Yang-Mills initial state + Lund fragmentation

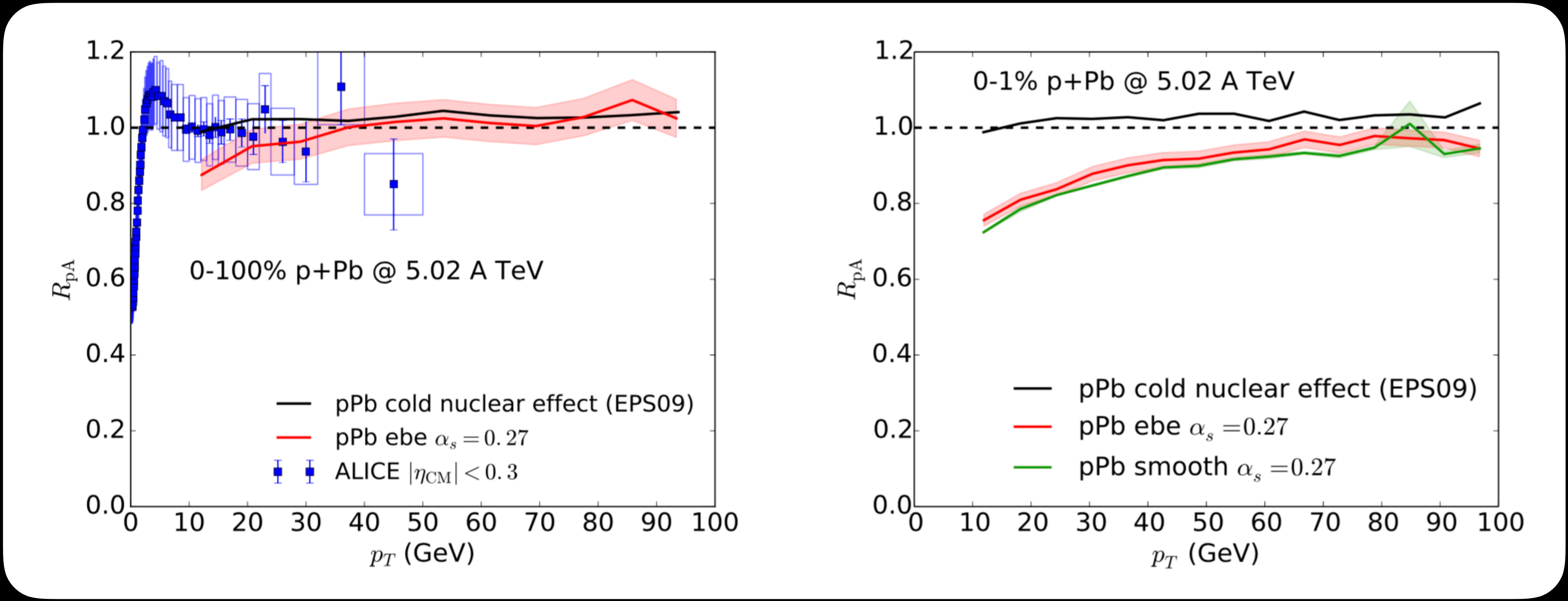


Emission from common boosted source

JET QUENCHING

Not much modification measured in small systems

Could this be compatible with formation of hot (hydro-) fireball?



Monte-Carlo event generator MARTINI in hydro background

C. Shen, C. Park, J.-F. Paquet, G.S. Denicol, S. Jeon, C. Gale, Nucl.Phys. A956 (2016) 741-744

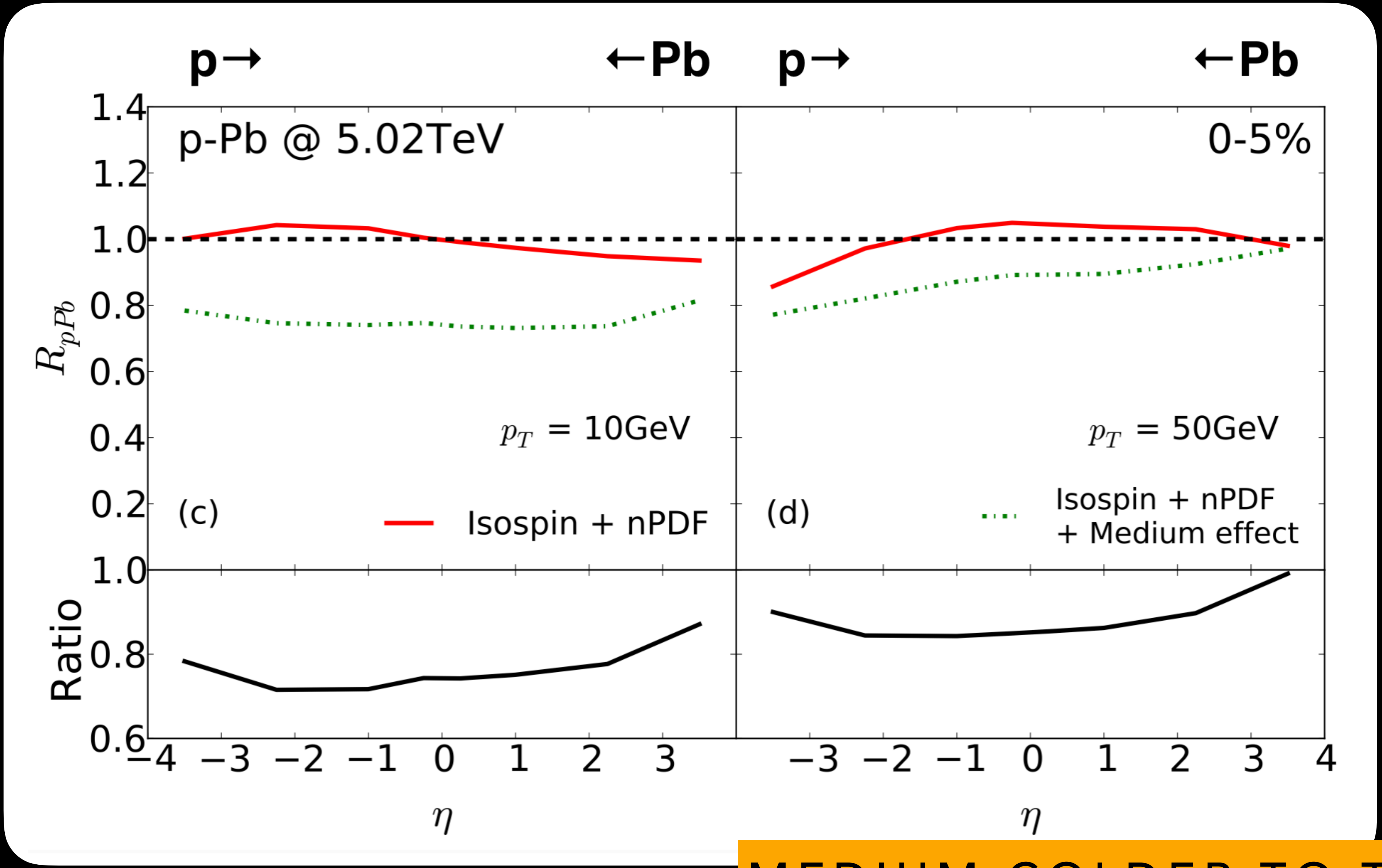
ALICE Collaboration, Phys. Rev. Lett. 110 (8) (2013) 082302

Also see calculations of energy loss in cold QCD matter

Z.-B. Kang, I. Vitev, H. Xing, Phys. Rev. C92 (2015) 054911

JET QUENCHING

Prediction of the rapidity dependent nuclear modification factor

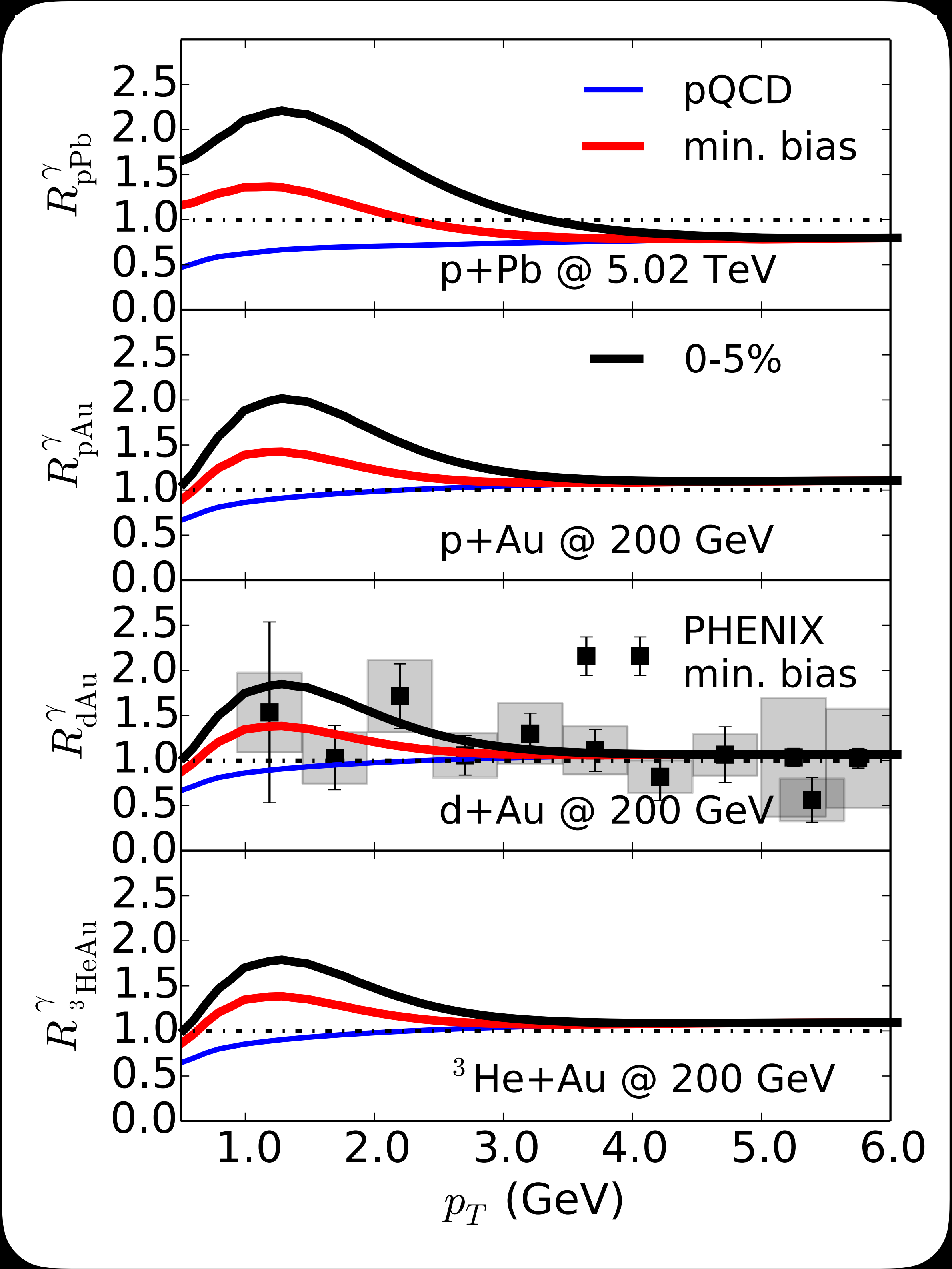


MEDIUM COLDER TO THE RIGHT

Monte-Carlo event generator MARTINI in 3+1D hydro background

C. Shen, C. Park, J.-F. Paquet, G.S. Denicol, S. Jeon, C. Gale, Nucl.Phys. A956 (2016) 741-744

ELECTROMAGNETIC PROBES



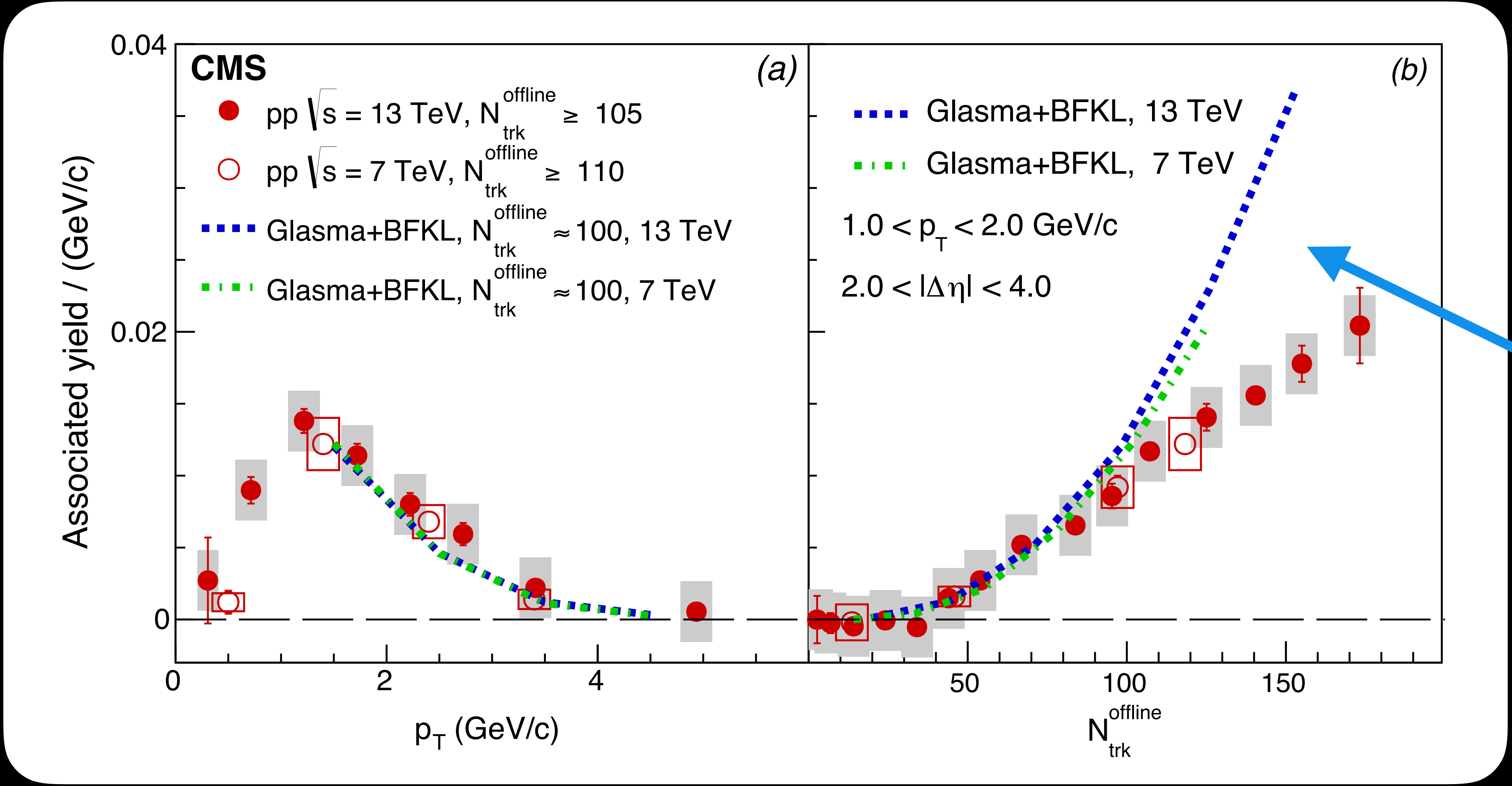
Direct photon enhancement (factor 2 for central collisions) predicted if hot and dense thermal system is created

Provides independent test of the hydrodynamic picture

C. Shen, J.-F. Paquet, G.S. Denicol, S. Jeon, C. Gale
Phys.Rev. C95 (2017) 014906
PHENIX Collaboration, Phys. Rev. C87, 054907 (2013)

COLLISION ENERGY DEPENDENCE

CGC predicts energy independent associated yield in p+p:
One single saturation scale →
Same multiplicity means same associated yield

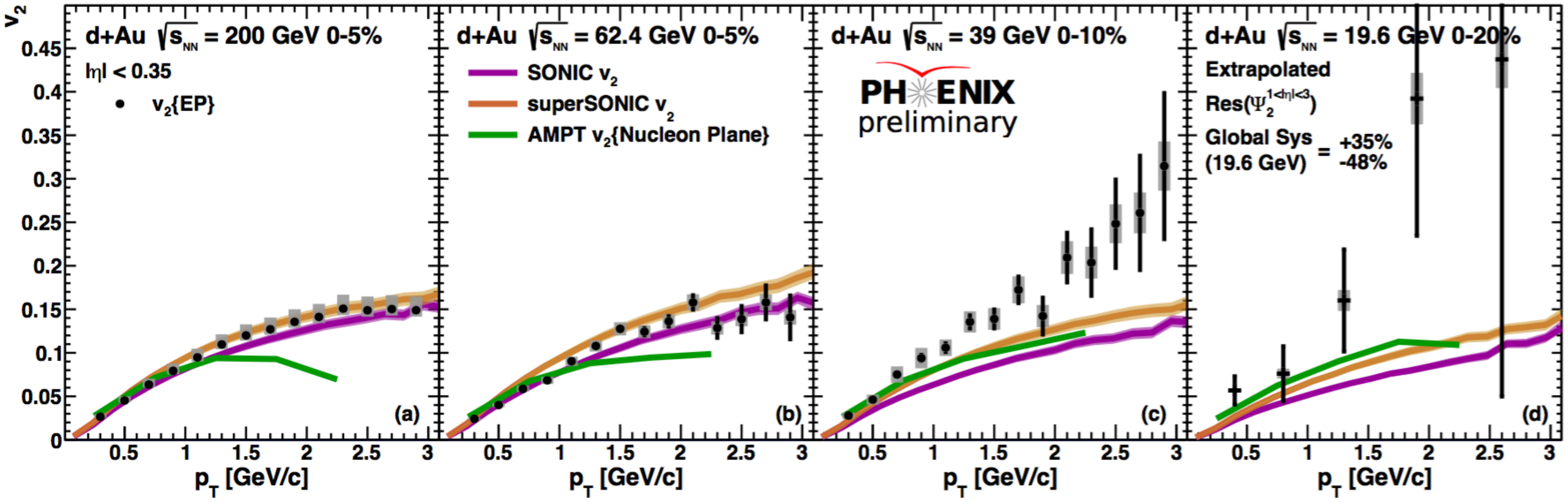


Dilute limit
fails at high
multiplicity
Full CYM calculation
could improve this

CMS Collaboration, Phys.Rev.Lett. 116 (2016) 172302
K. Dusling, P. Tribedy, R. Venugopalan,Phys.Rev. D93 (2016) 014034

d+Au BEAM ENERGY SCAN

New at QM2017

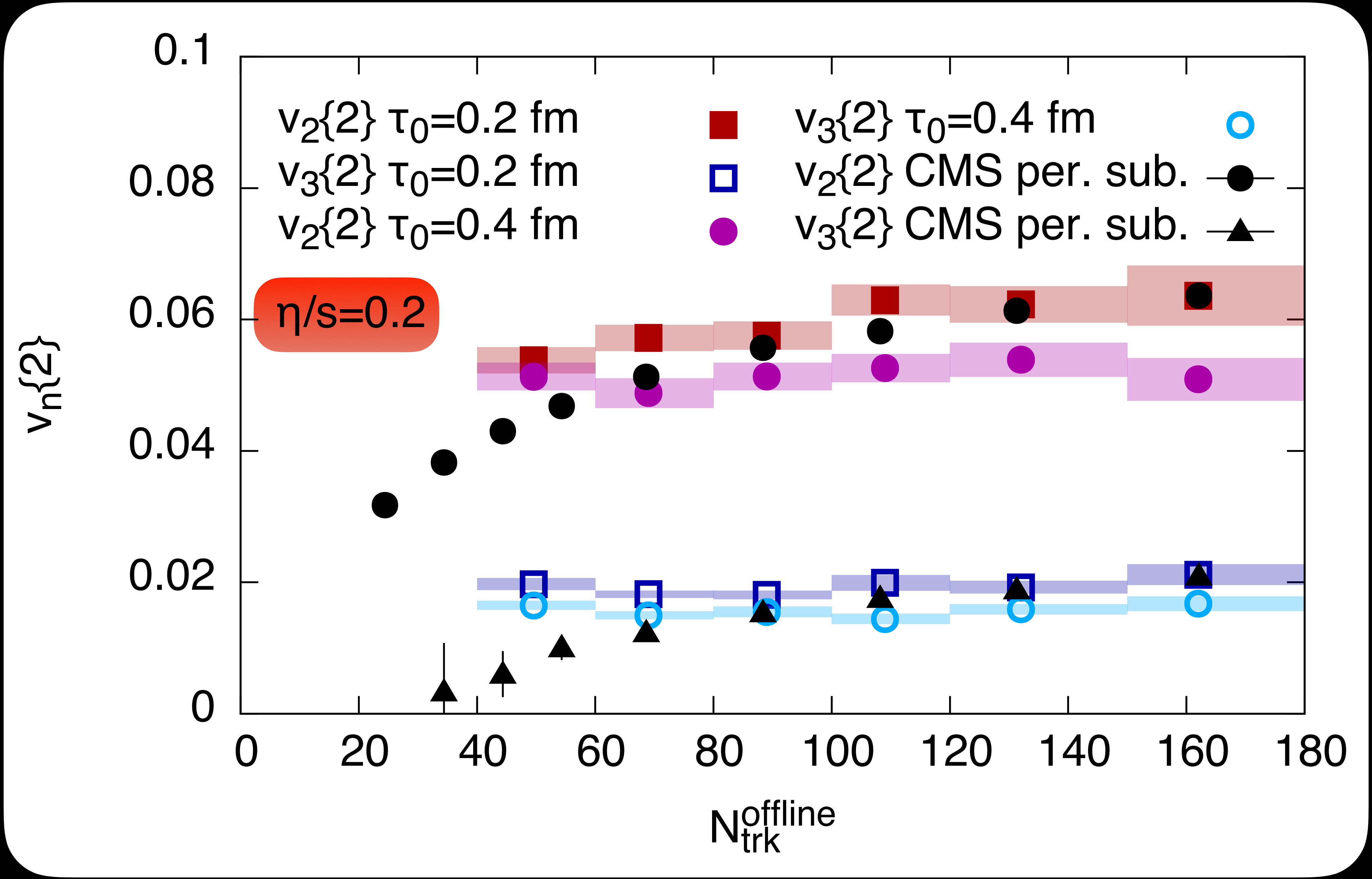


Experimental data: PHENIX Collaboration preliminary

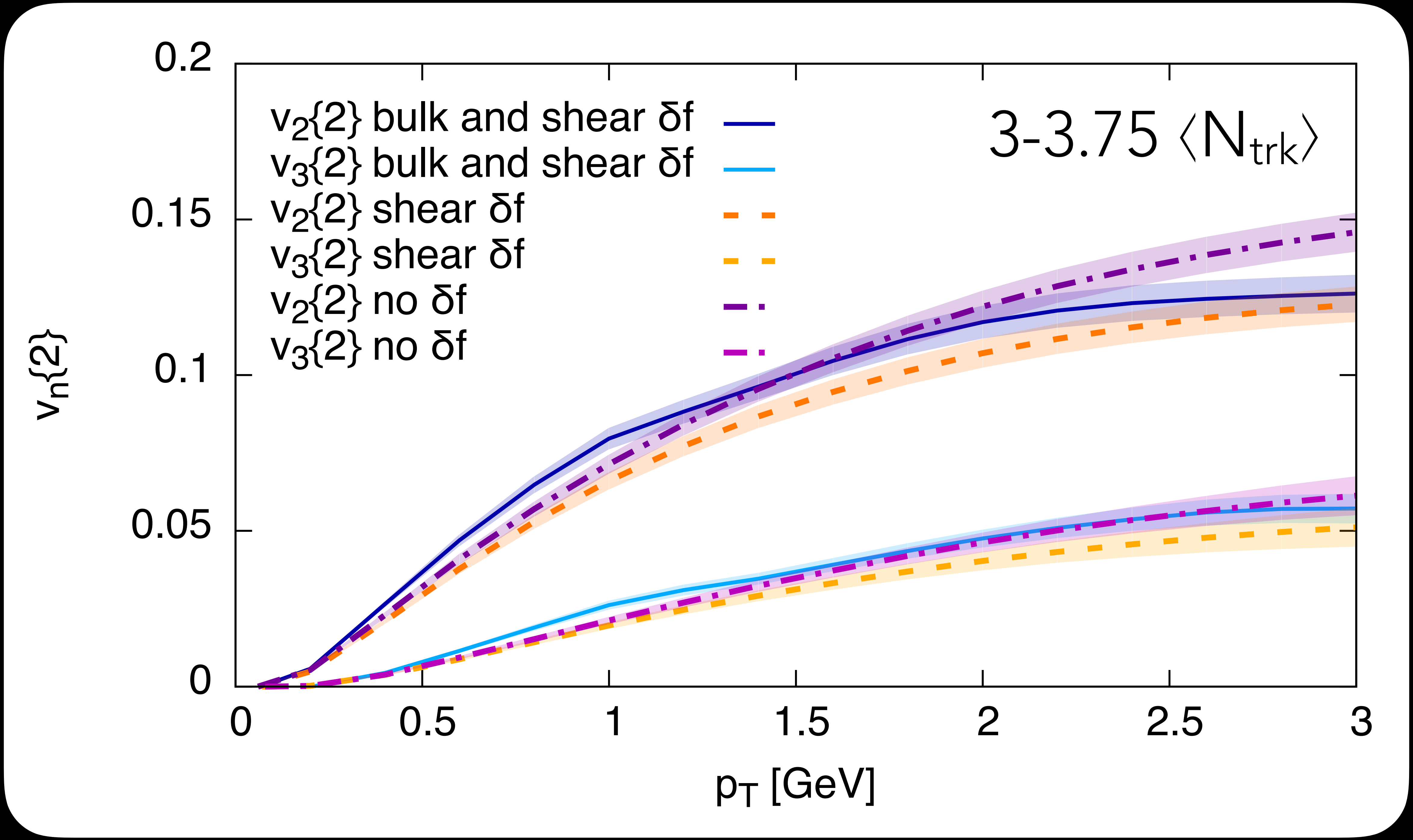
Calculations: J.D. Orjuela Koop, R. Belmont, P. Yin, J.L. Nagle, Phys.Rev. C93 (2016) 044910

Integrated anisotropic flow

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

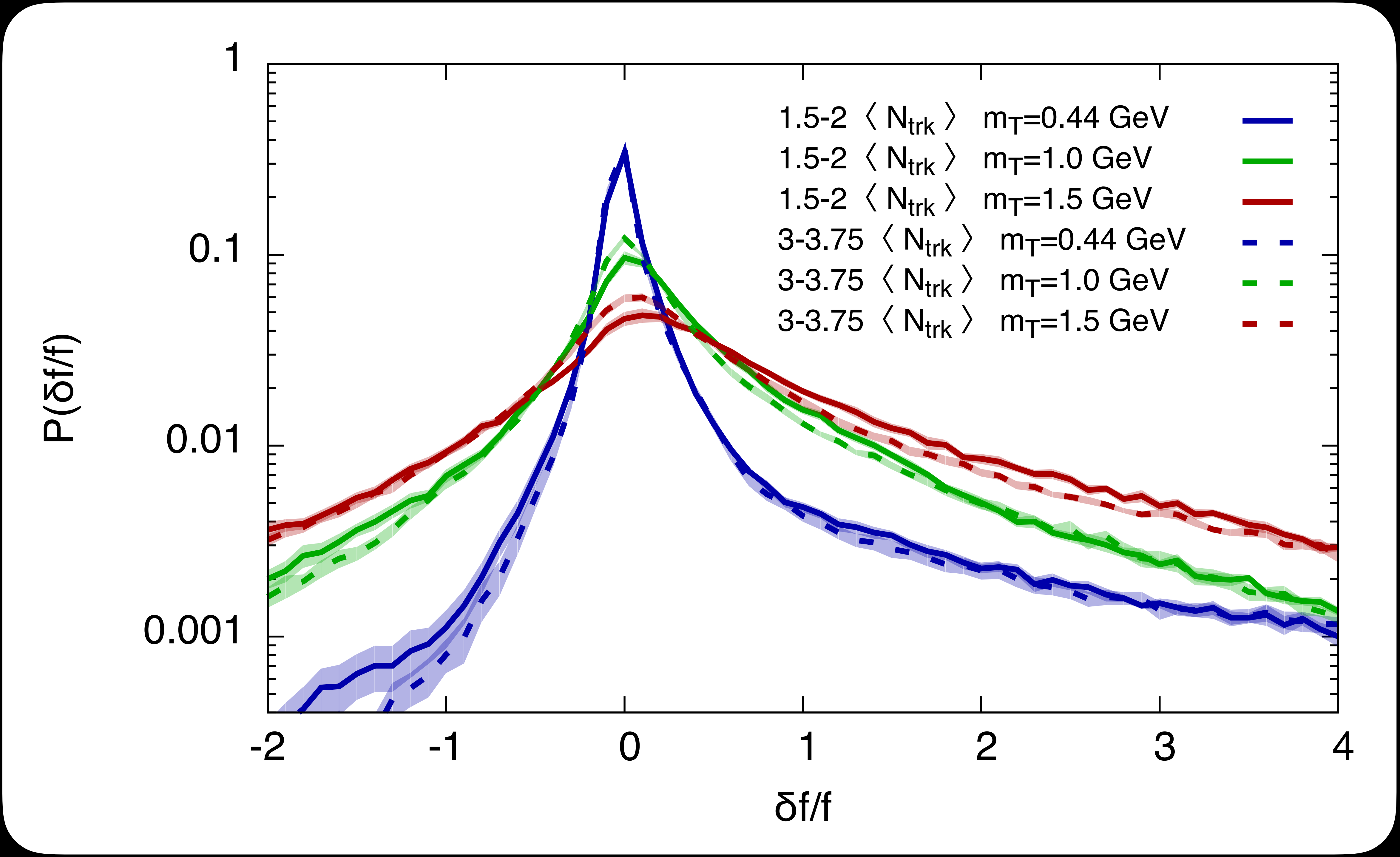


δf effect in p+Pb



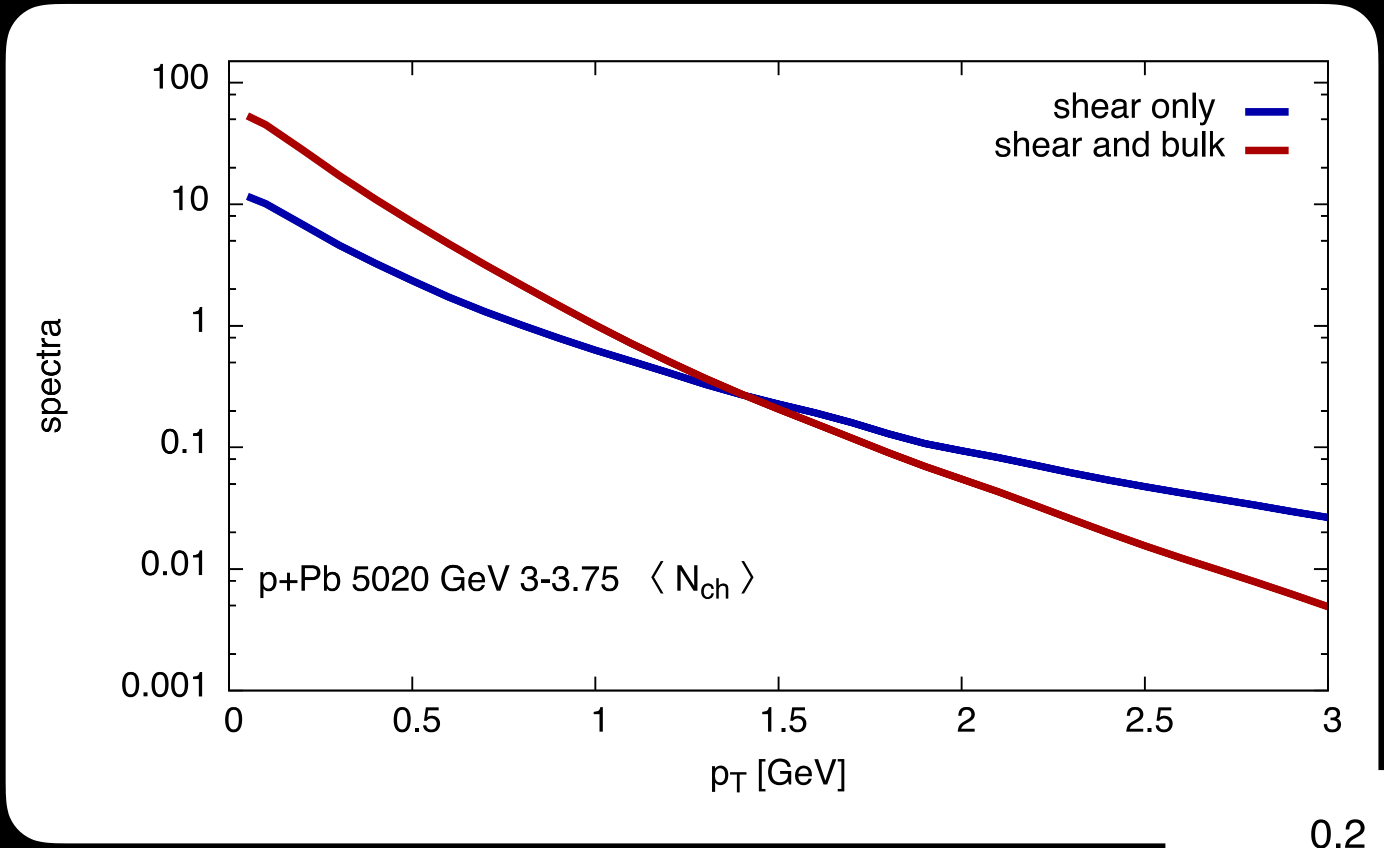
$\eta/s=0.2$

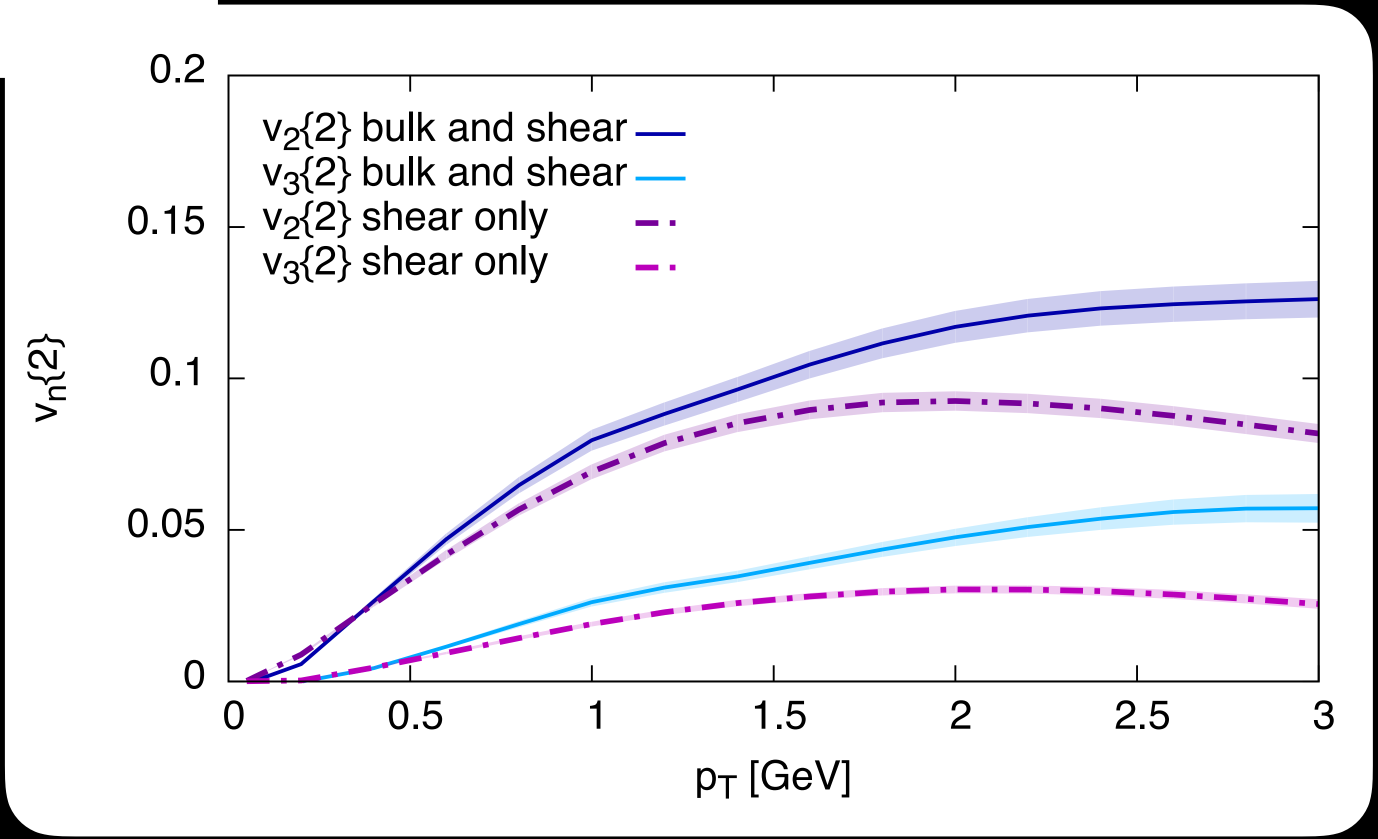
δf effect in p+Pb



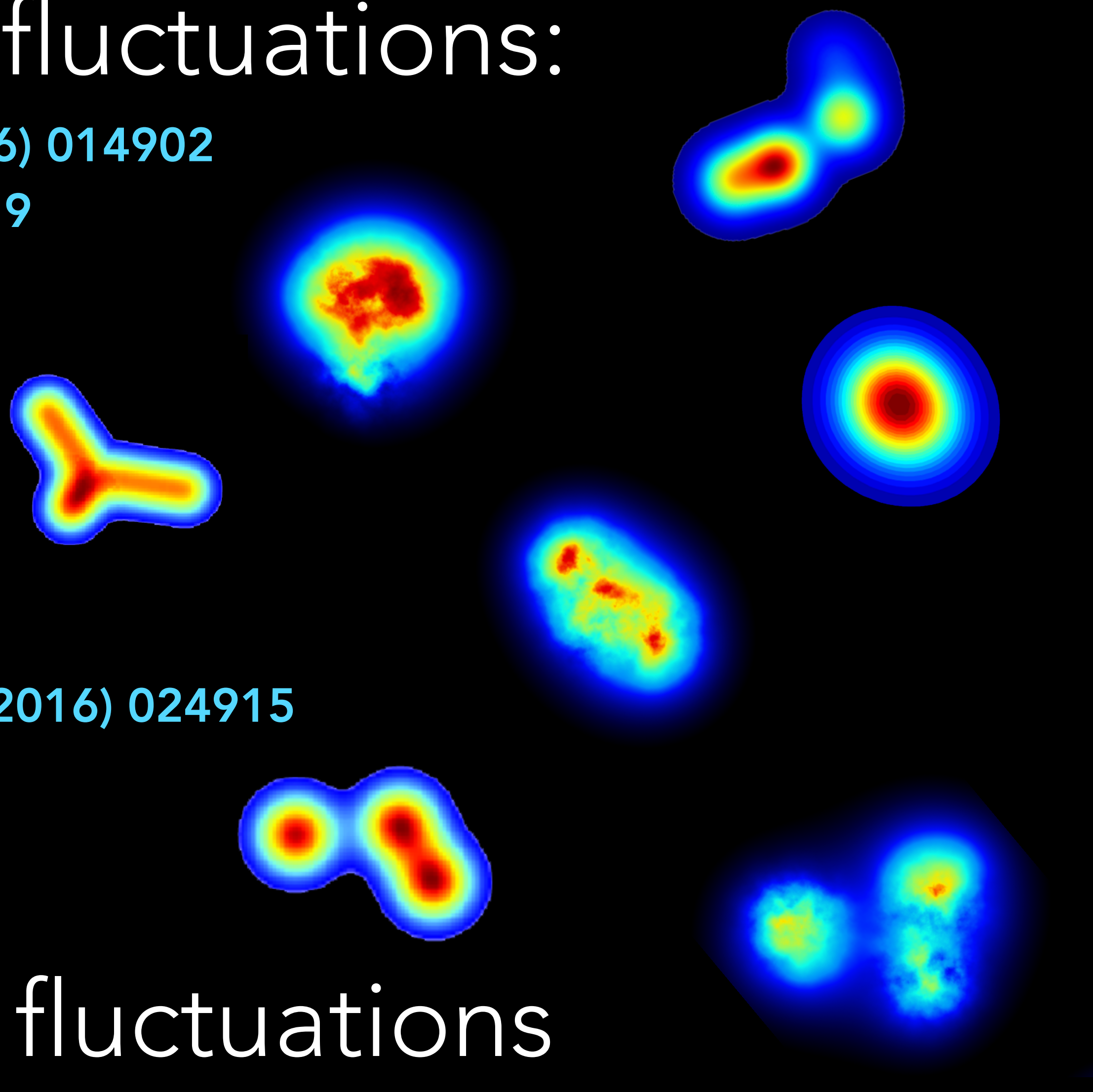
$\eta/s=0.2$

Effect of bulk viscosity





INCREASED INTEREST IN FLUCTUATING PROTON SHAPE AND SIZE



1. Wounded quarks and shape fluctuations:

   P. Bożek, W. Broniowski, M. Rybczyński, Phys. Rev. C94 (2016) 014902
   K. Welsh, J. Singer, U.W. Heinz, Phys. Rev. C94 (2016) 024919
   R. D. Weller and P. Romatschke arXiv:1701.07145
   P. Bozek, W. Broniowski, arXiv:1701.09105
   …

2. Size fluctuations

   D. McGlinchey, J.L. Nagle, D.V. Perepelitsa, Phys. Rev. C94 (2016) 024915
   …

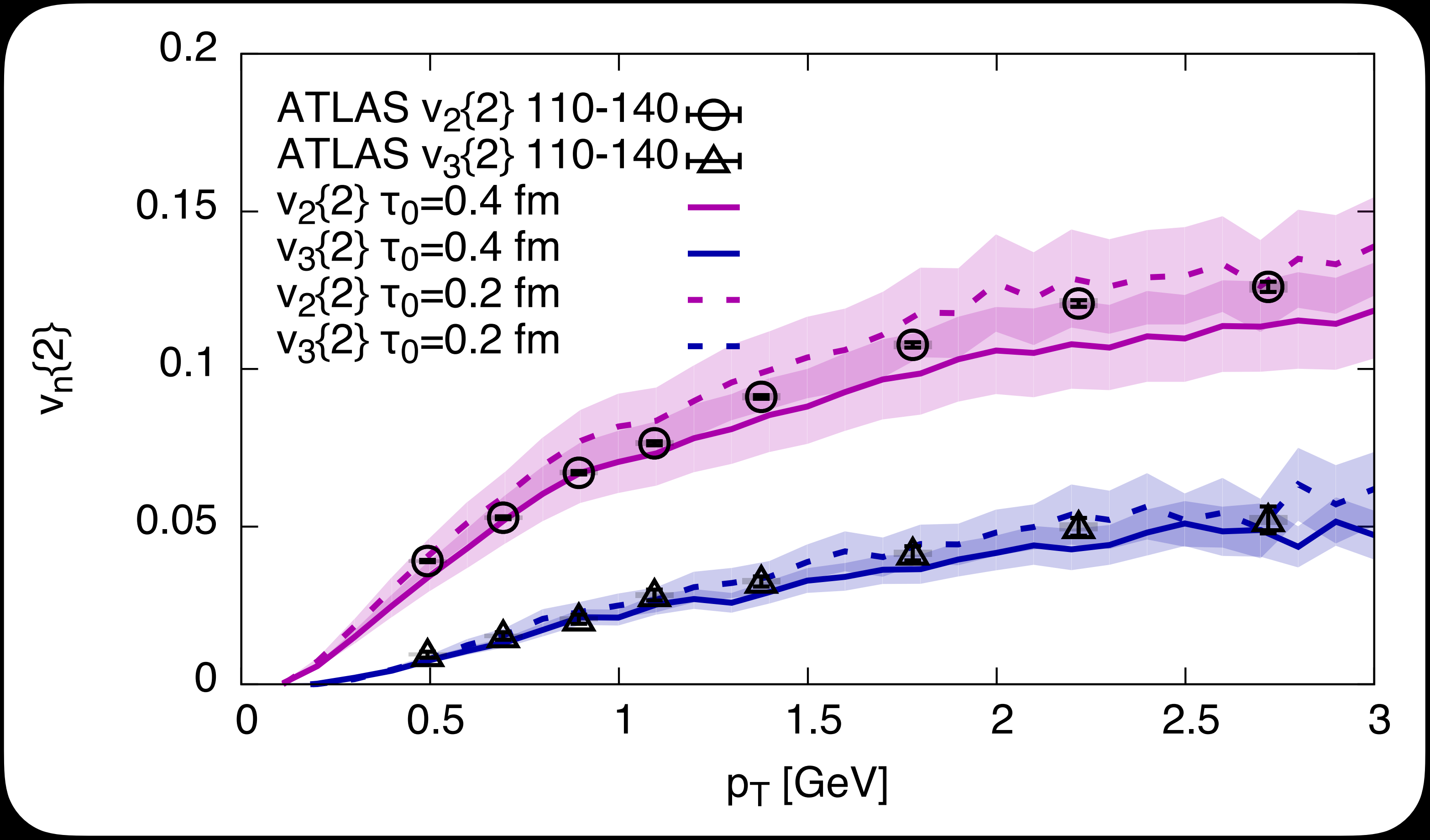
3. Shape fluctuations from spin fluctuations

   M. Habich, G.A. Miller, P. Romatschke, W. Xiang, Eur.Phys.J. C76 (2016) 408
   …

Proton substructure also important for particle production:
PHENIX Collaboration, Phys.Rev. C89 (2014) 044905

IP-Glasma+MUSIC+UrQMD

H. Mäntysaari, P. Tribedy, B. Schenke, C. Shen, in preparation (2017)



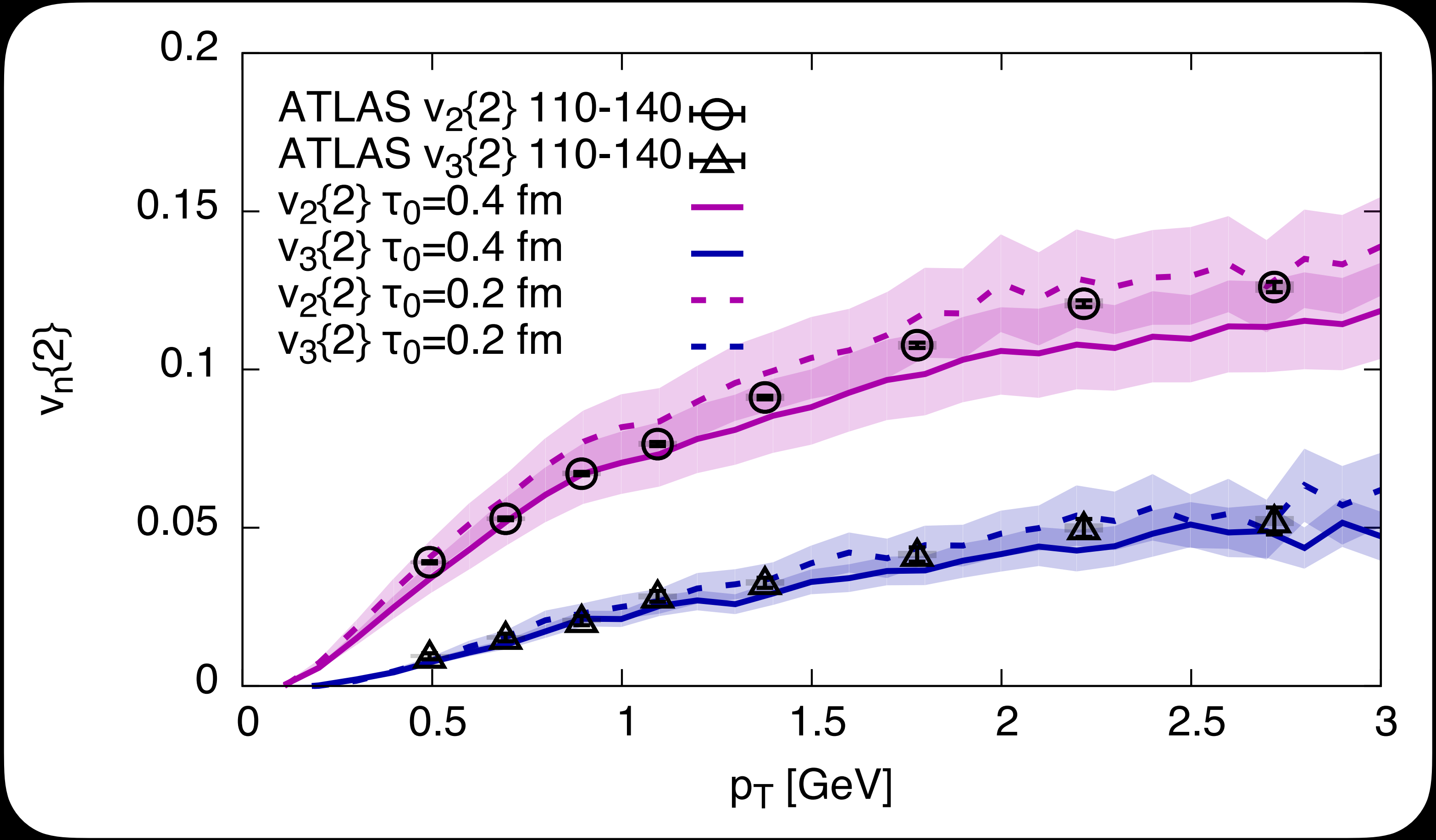
ATLAS Collaboration, Phys.Rev. C90 (2014) 044906

$\eta/s=0.2$

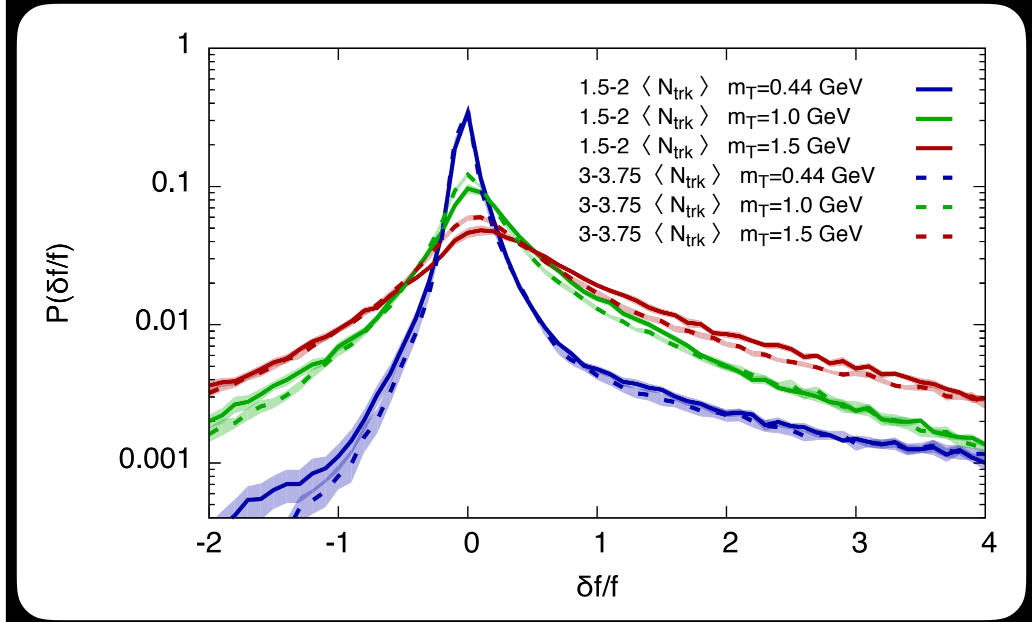
Fair warning: Strong dependence on whether initial shear stress tensor is included and the relaxation time.

IP-Glasma+MUSIC p+Pb

H. Mäntysaari, P. Tribedy, B. Schenke, C. Shen, in preparation (2017)



ATLAS Collaboration, Phys.Rev. C90 (2014) 044906



$\eta/s=0.2$

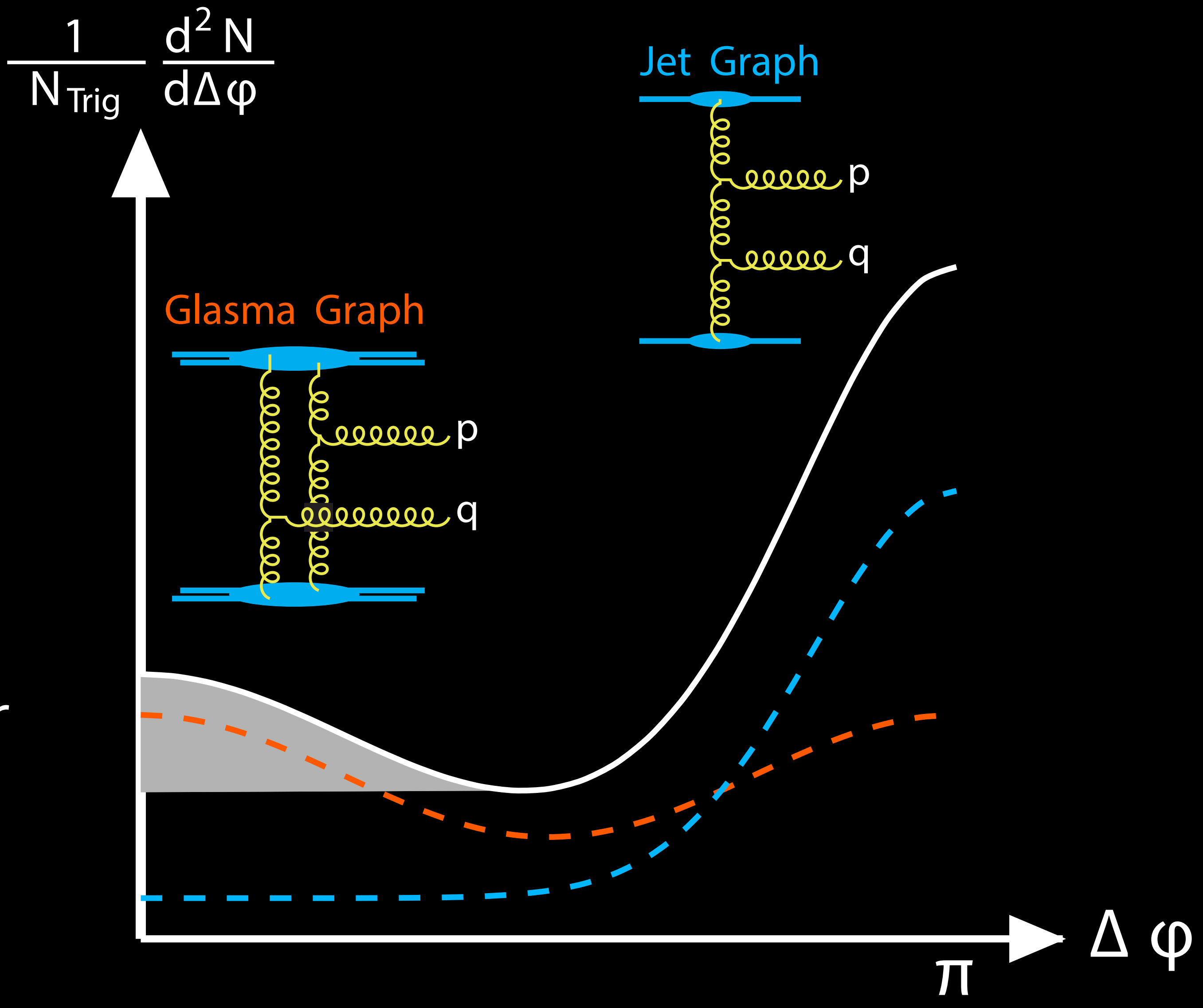
Fair warning: Strong dependence on whether initial shear stress tensor is included and the relaxation time. δf can be ≫ f in many freeze-out surface cells

GLASMA GRAPH APPROXIMATION

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

"Glasma graphs" dominate
over "Jet graphs"
at high multiplicity

- Two gluon exchange only
- Gaussian statistics
- Using k_T factorization, valid for momenta $> Q_S$
- Jet-piece is beyond CYM



Quantitative description of many observables in p+p and p+A

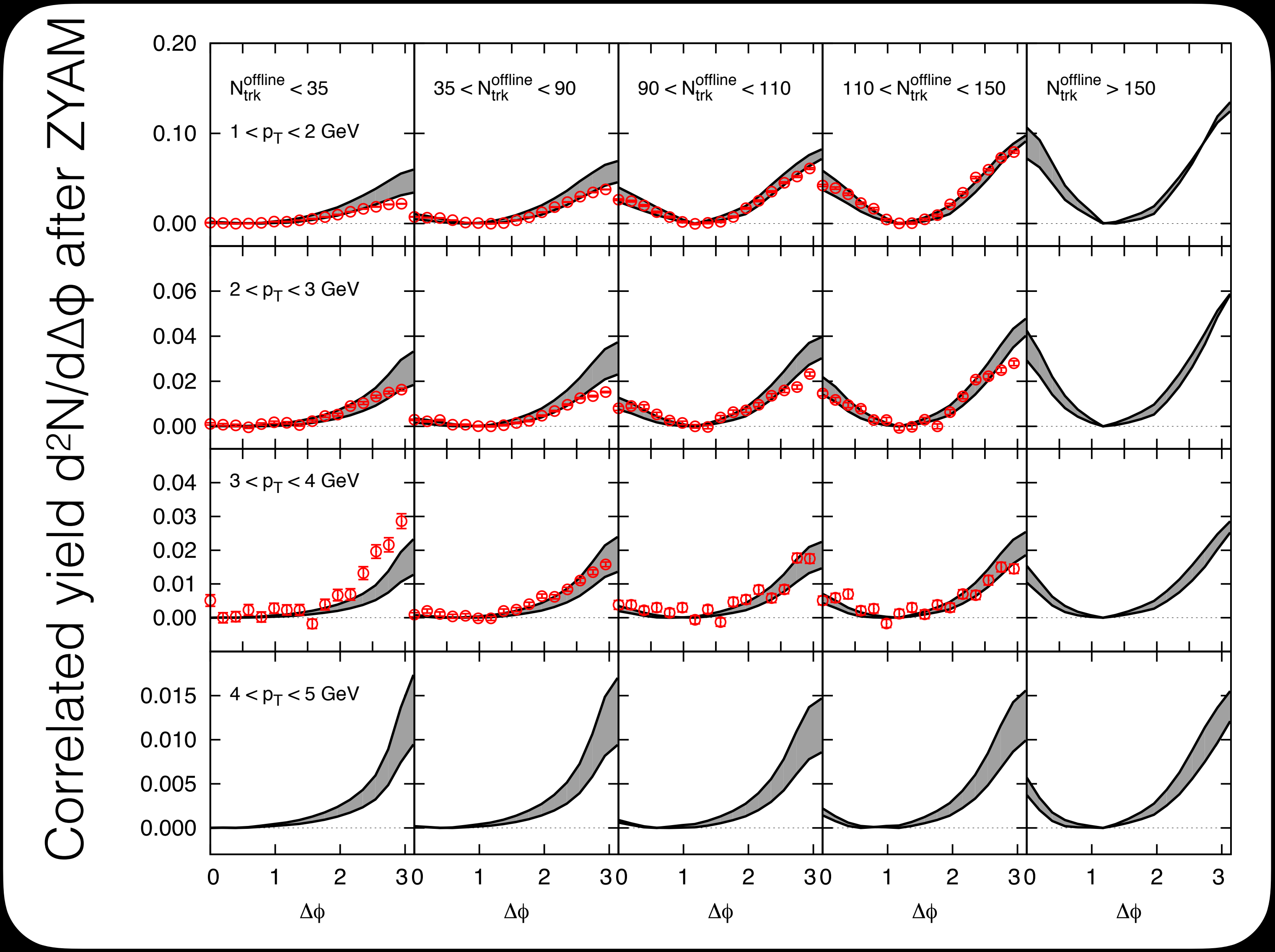
GLASMA GRAPH APPROXIMATION

K. Dusling, R. Venugopalan, Phys.Rev. D87 054014 (2013)
CMS collaboration, Phys. Lett. B 718 795 (2013)

Correlated yield vs. angular difference in p+Pb

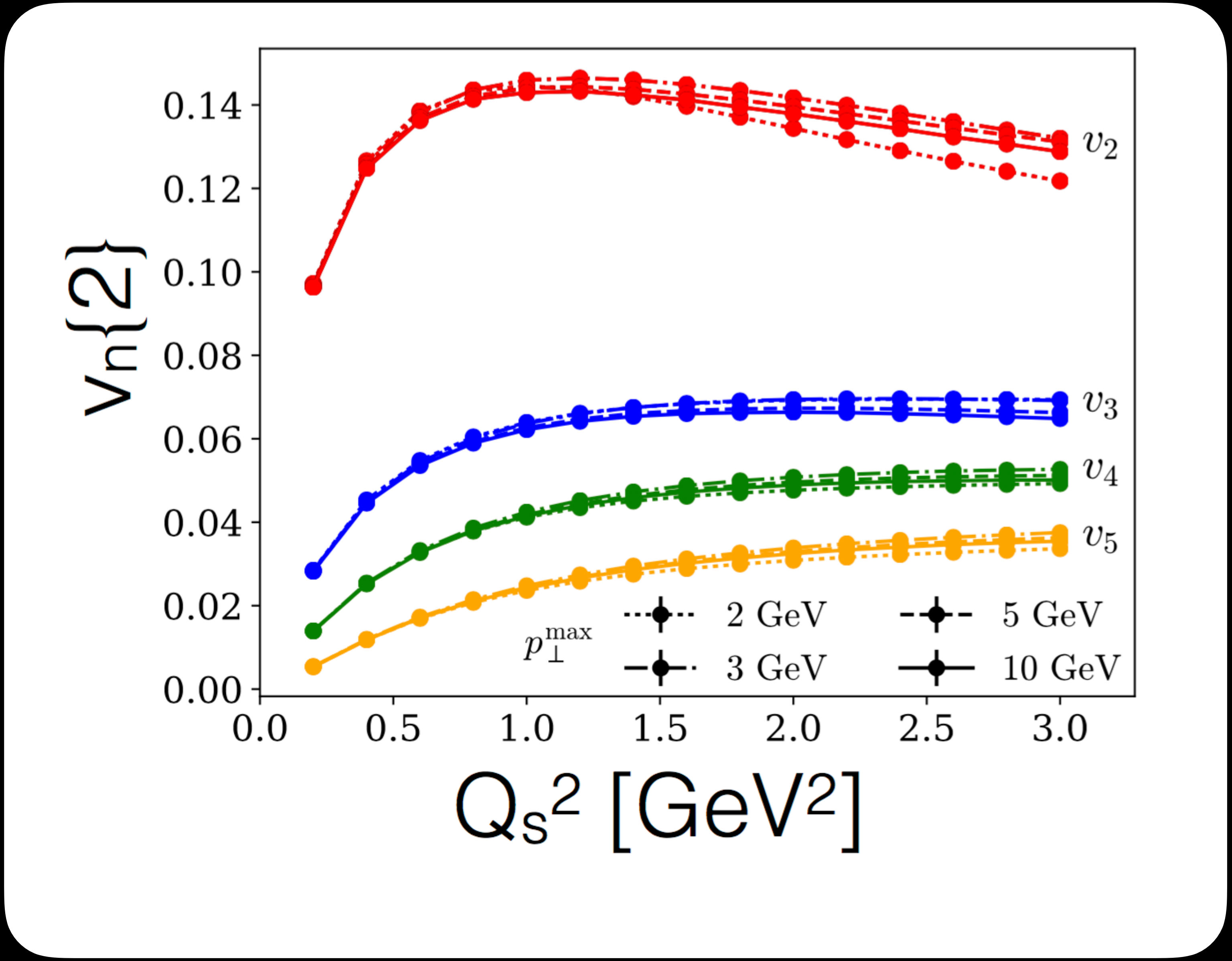
Multiplicity →

Transverse momentum ↓



ODD HARMONICS

Non-linear Gaussian model for quarks shows similar ordering in harmonics to data



SEE MARK'S TALK

For gluons there would be no odd harmonics

K. Dusling, M. Mace, R. Venugopalan arXiv:1705.00745

CORRELATIONS FROM THE INITIAL STATE

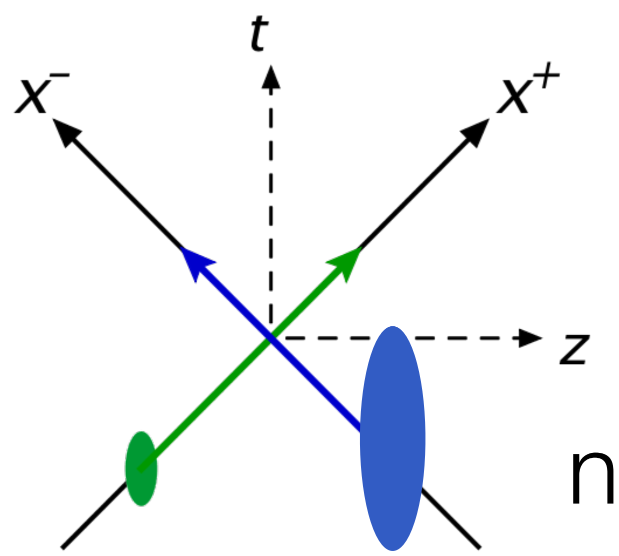
SCHENKE, SCHLICHTING, VENUGOPALAN, PHYS. LETT. B747, 76-82 (2015)

p+A collisions in the Color Glass Condensate:

High multiplicity events: Target and projectile are dense objects
→ Classical Yang-Mills framework

$$J_1^{\mu} = \delta^{\mu +}\rho_1(x^-, \mathbf{x}_T)$$

$$[D_\mu, F^{\mu\nu}] = J_1^{\nu}$$



$$J_2^{\mu} = \delta^{\mu -}\rho_2(x^+, \mathbf{x}_T)$$

$$[D_\mu, F^{\mu\nu}] = J_2^{\nu}$$

KRASNITZ, VENUGOPALAN, NUCL.PHYS. B557 (1999) 237

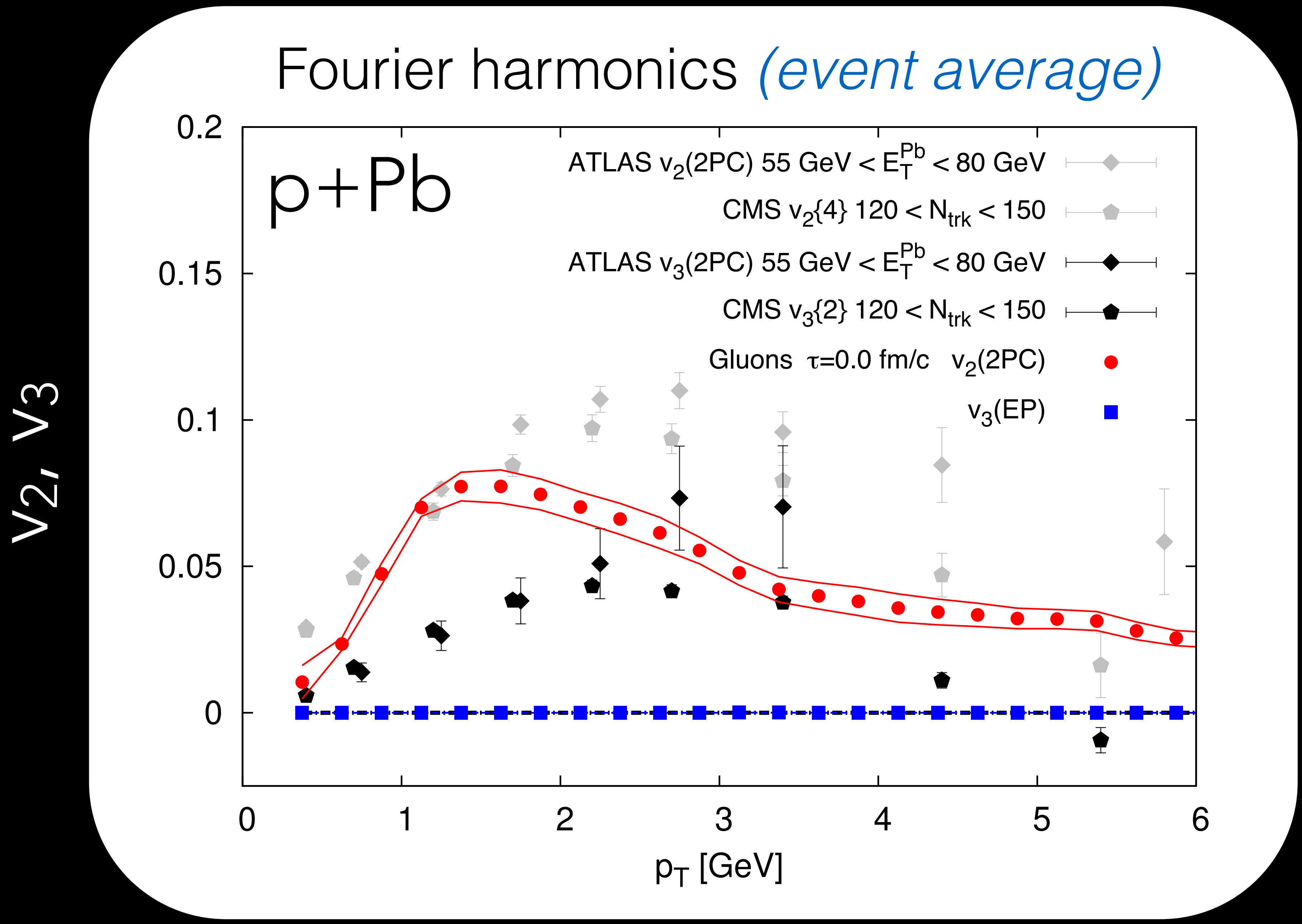
Compute the gluon momentum distribution from the initial fields after the collision - Then analyze its anisotropy

CORRELATIONS FROM THE INITIAL STATE

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

$\tau = 0.0$ fm/c

gluons



data to guide the eye

Significant v_2 at time 0

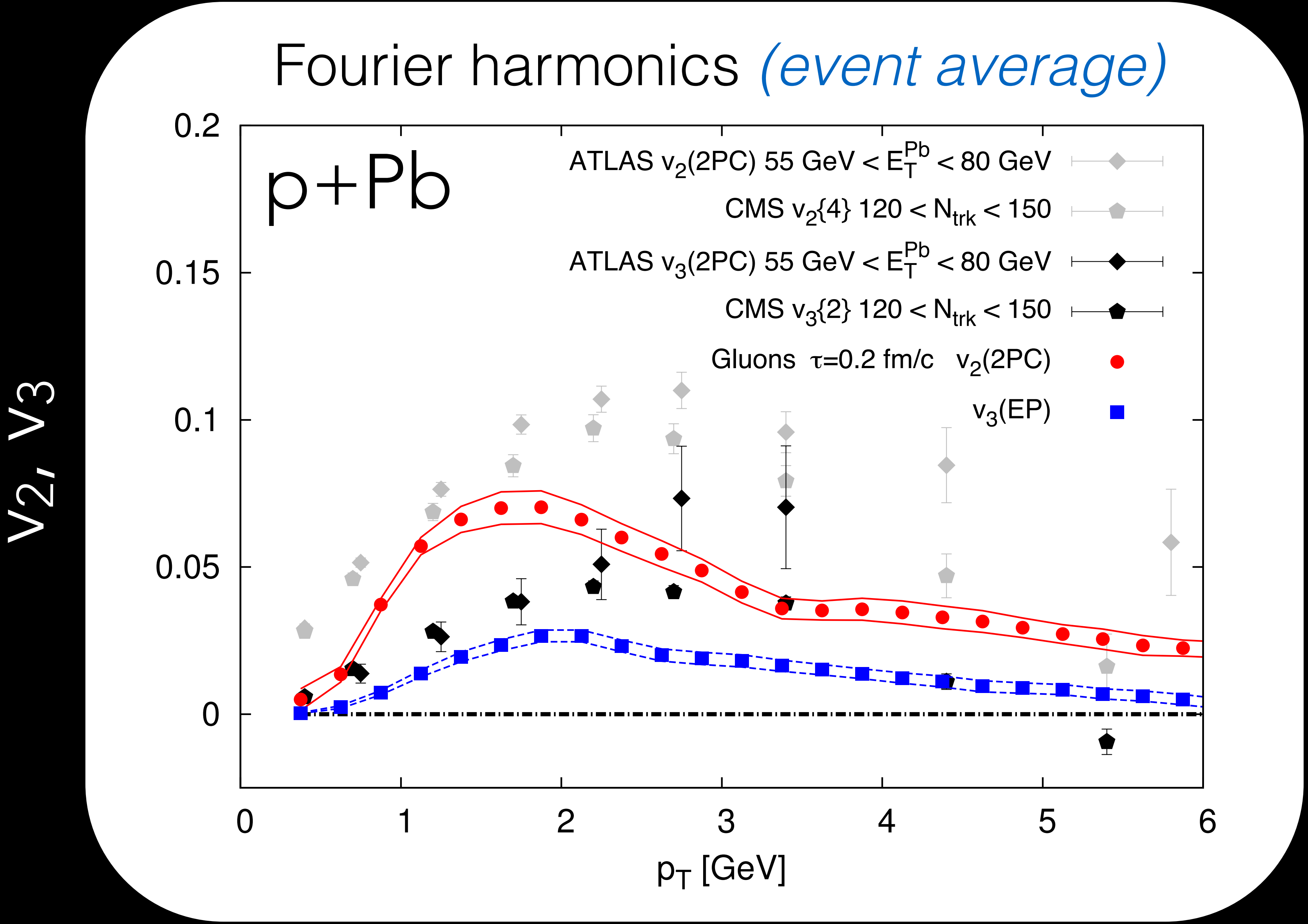
No odd harmonics for gluons without final state interactions

CORRELATIONS FROM THE INITIAL STATE

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

$\tau = 0.2$ fm/c

gluons



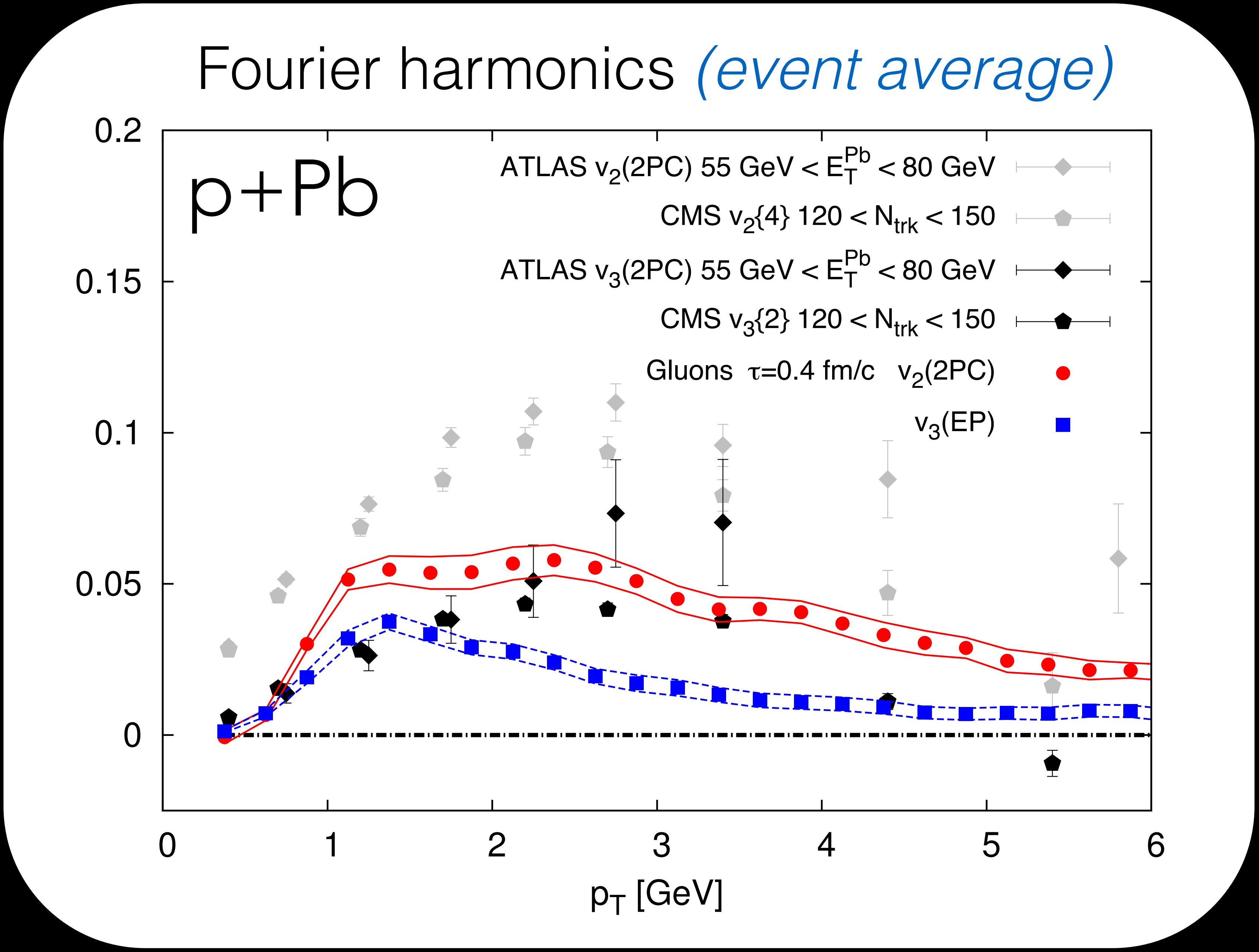
data to guide the eye

CORRELATIONS FROM THE INITIAL STATE

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

$\tau = 0.4$ fm/c

gluons



data to guide the eye

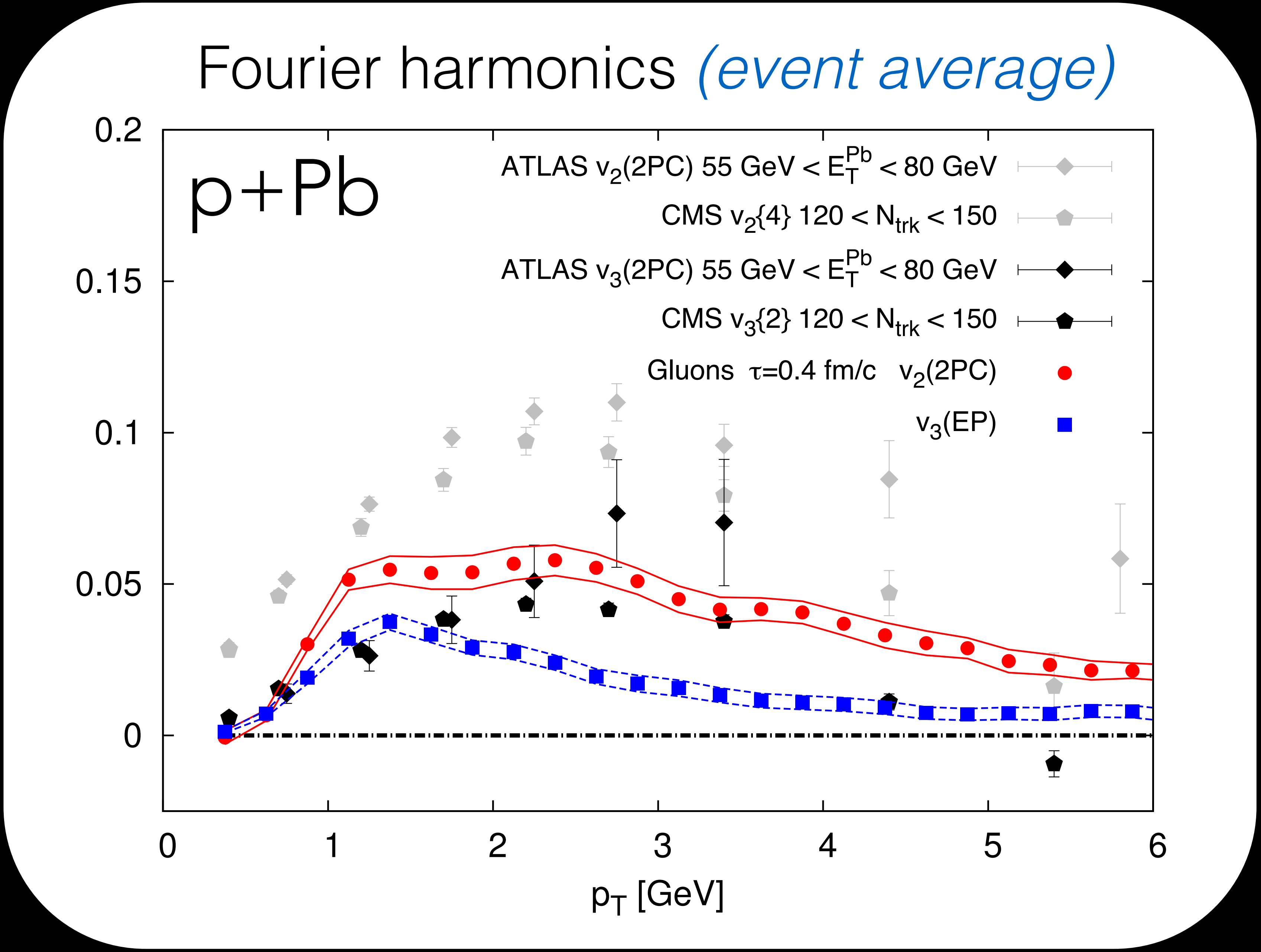
Odd harmonics generated by pre-equilibrium dynamics

CORRELATIONS FROM THE INITIAL STATE

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

$\tau = 0.4$ fm/c

gluons



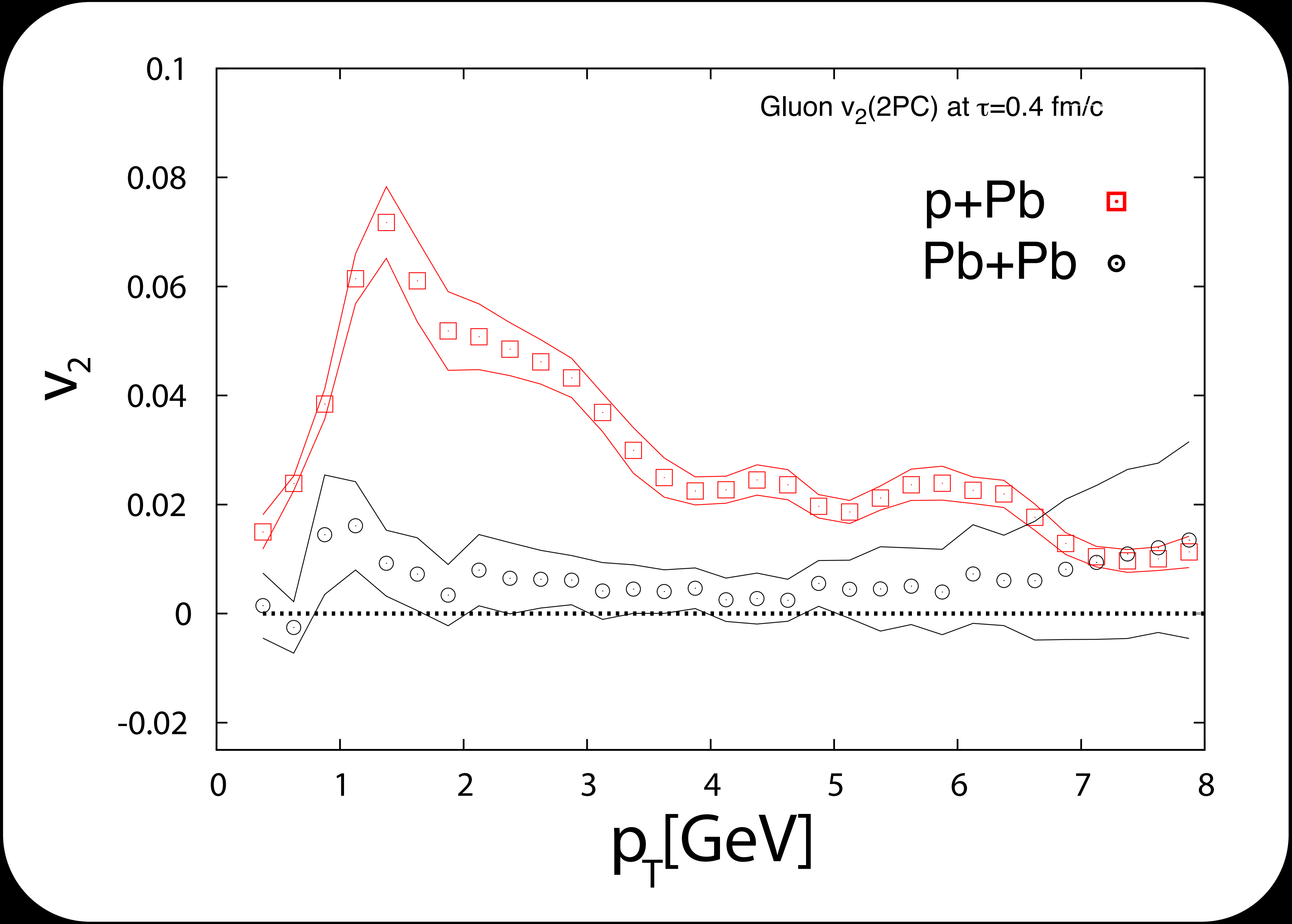
v_2, v_3

data to guide the eye

No correlation with global geometry (ε_2, ε_3) !

SENSITIVITY TO SYSTEM SIZE

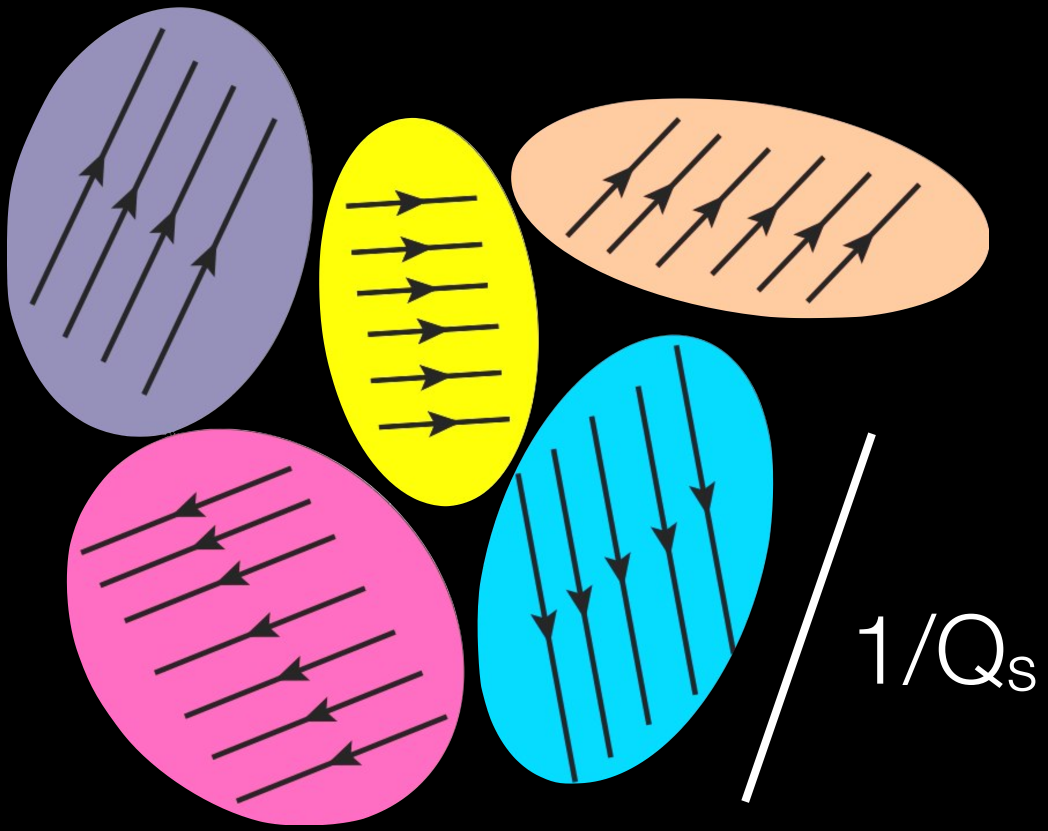
SCHENKE, SCHLICHTING, VENUGOPALAN, PHYS. LETT. B747, 76-82 (2015)



Pb+Pb not described in initial state picture. Reason: Gluons produced from many uncorrelated color field domains

COLOR DOMAIN MODEL

A. Kovner, M. Lublinsky, Phys.Rev. D83 (2011) 034017
A. Kovner, M. Lublinsky, Phys.Rev. D84 (2011) 094011
A. Dumitru, A.V. Giannini, Nucl.Phys. A933 (2014) 212
A. Dumitru, L. McLerran, V. Skokov PLB743 (2015) 134-137



Introduce anisotropic domains
of the color electric field $\vec{E}$
in the target

Model introduces additional **non-linear/non-Gaussian** contributions possibly coming from T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 (2016) 061

- Going beyond the glasma graph approx. where $E^a \propto \rho^a$
- JIMWLK evolution of a Gaussian initial condition
- Intrinsic correlations in the initial condition at large x (e.g. finite number of sources) L. McLerran, V. Skokov, NPA947 (2016) 142-154

See also E. Levin and A. H. Rezaeian, Phys. Rev. D 84 (2011) 034031

OTHER SOURCES OF ANISOTROPIES

- Multiple interaction pQCD bremsstrahlung: v_n moments generated from radiating clusters that have accumulated a net transverse momentum kick on an event-by-event basis
- So far not included in event generators like HIJING

M. Gyulassy, P. Levai, I. Vitev, T.S. Biro, Phys. Rev. D90 (2014) 054025

- Qualitatively predicts weak beam energy dependence of azimuthal anisotropies