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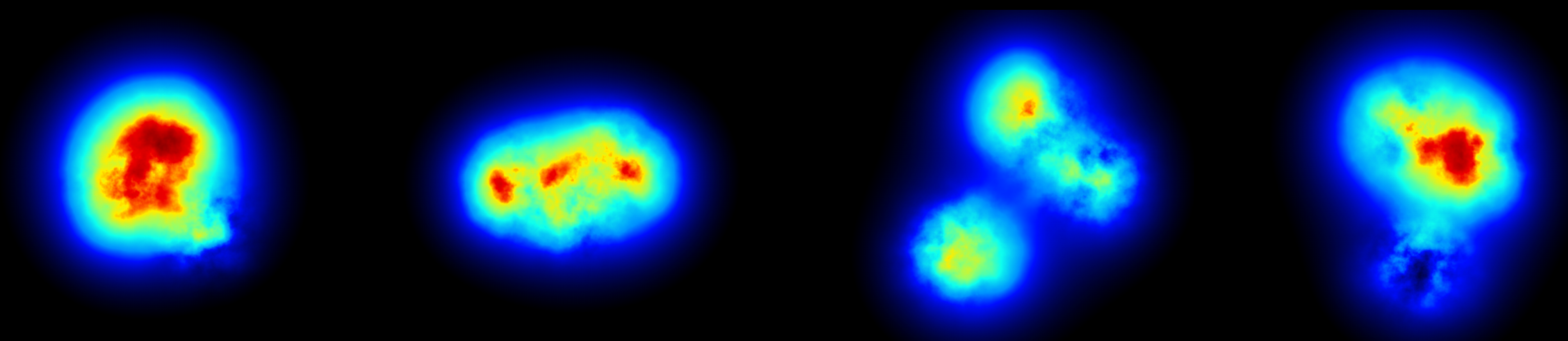
BROOKHAVEN NATIONAL LABORATORY

COLLECTIVITY IN SMALL SYSTEMS: INITIAL CORRELATIONS OR FINAL STATE FLOW?

Björn Schenke
Brookhaven National Laboratory



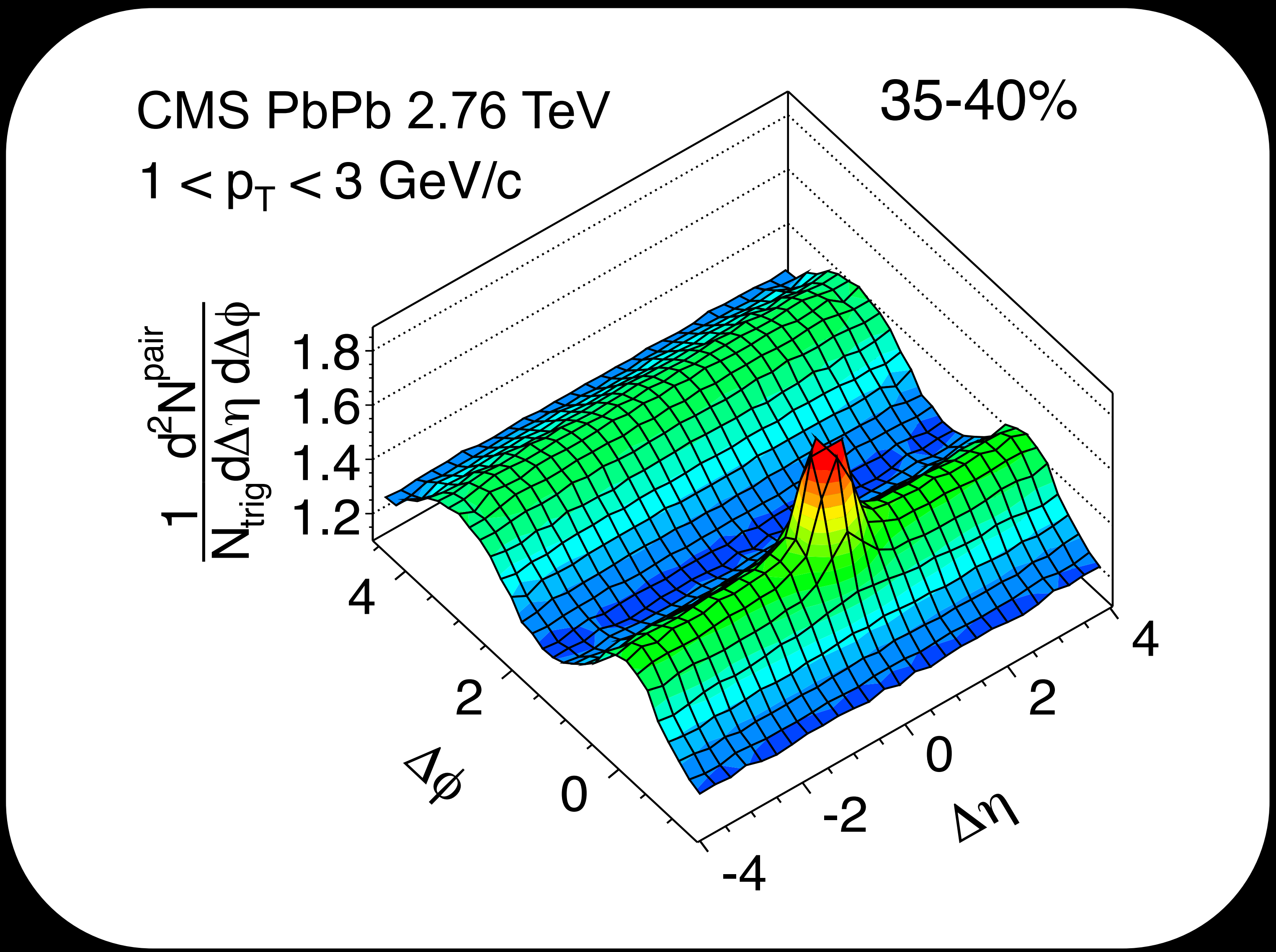
June 28, 2016
Strangeness in Quark Matter
UC Berkeley

TWO PARTICLE CORRELATIONS

2-particle correlation as a function of Δη and Δϕ

Δη: DIFFERENCE IN PSEUDO-RAPIDITY

Δϕ: DIFFERENCE IN AZIMUTHAL ANGLE



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

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

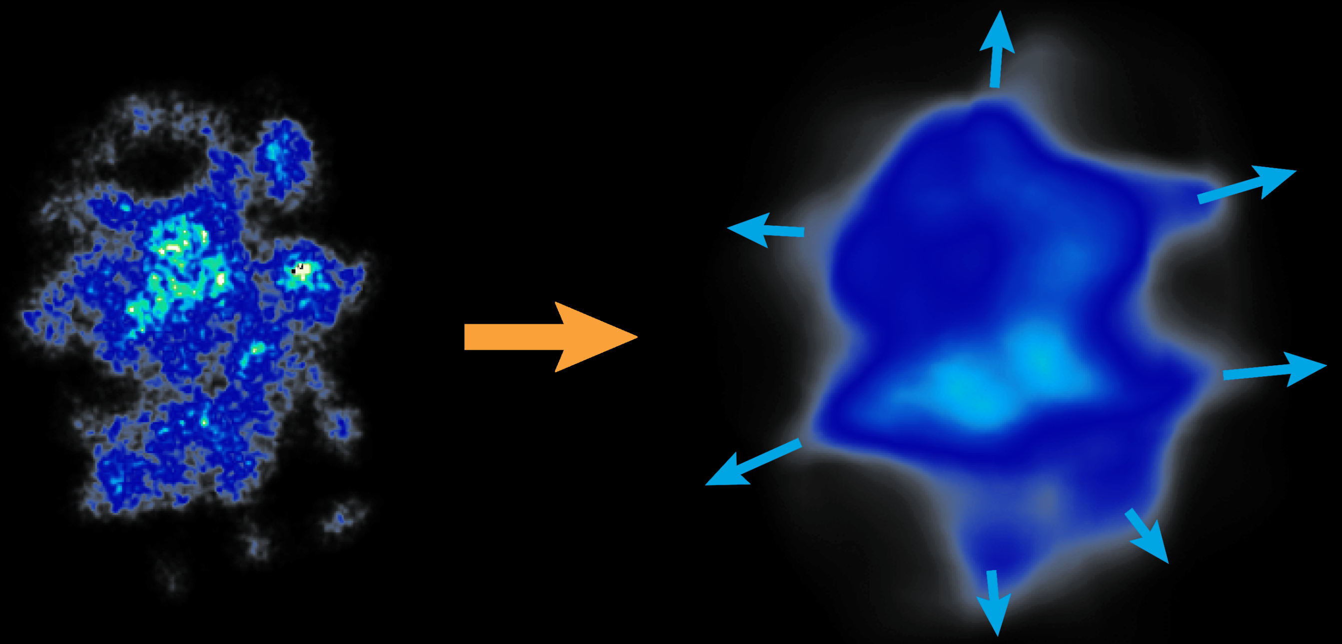
RIDGE IN HEAVY ION COLLISIONS

First seen in heavy ion collisions at RHIC

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

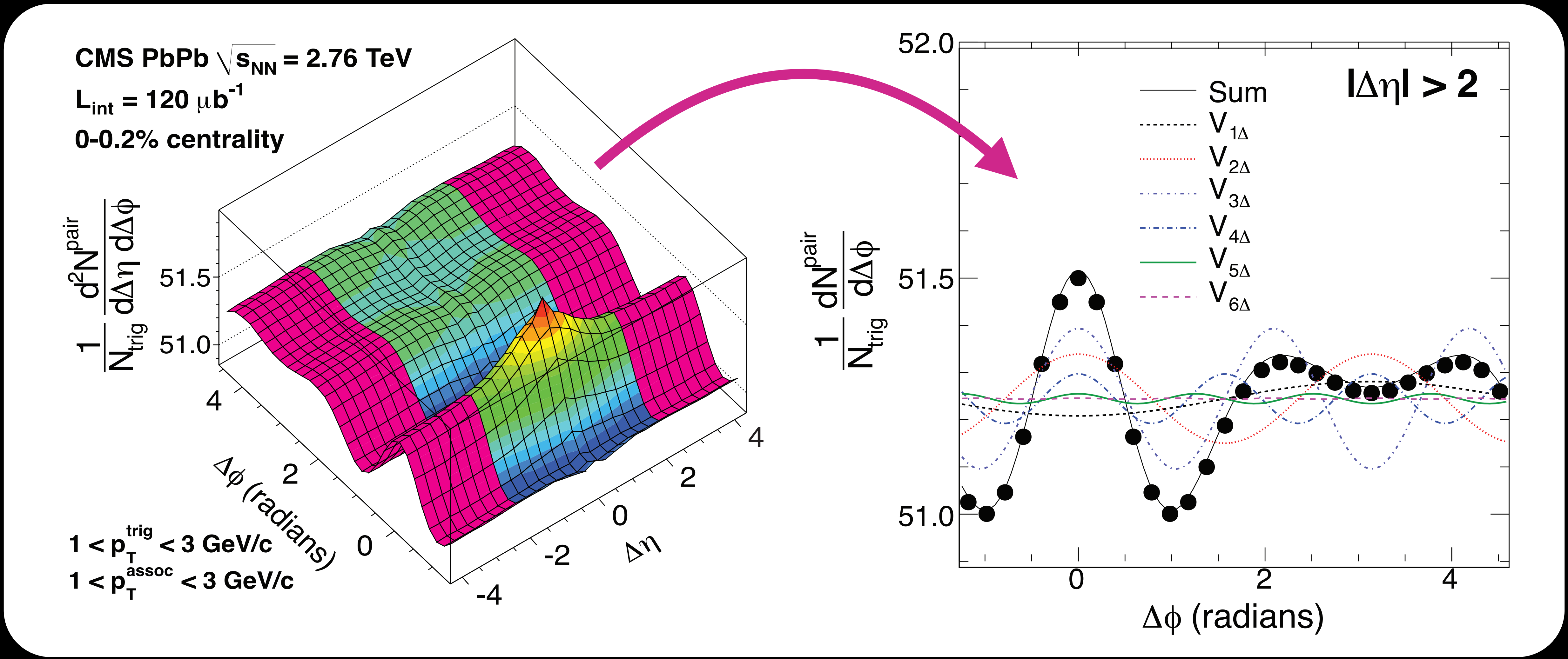
Interpretation in heavy ion collision:

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



RIDGE IN HEAVY ION COLLISIONS

Azimuthal structure quantified using Fourier expansion



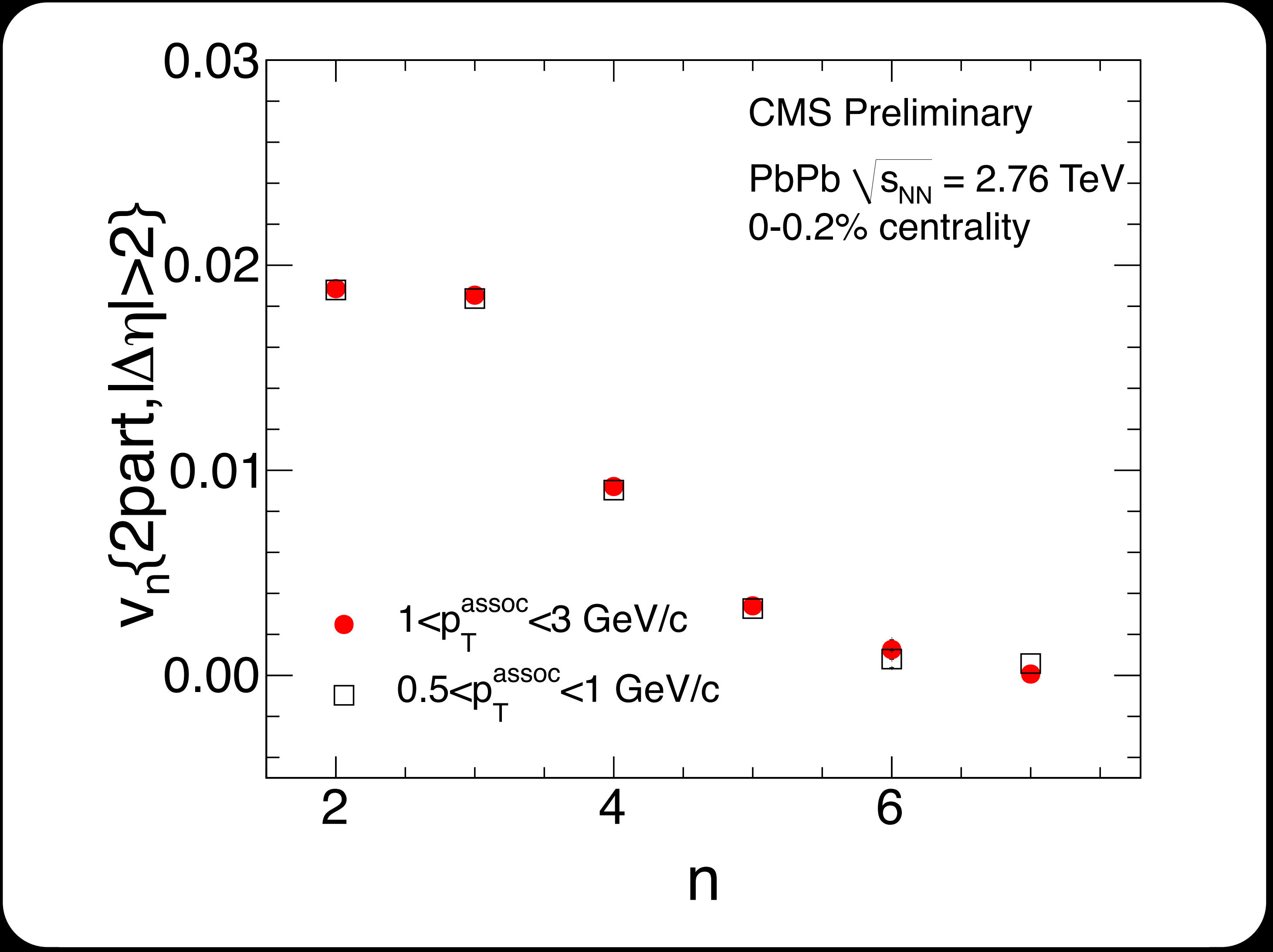
$$\frac{1}{N_{\text{trig}}} \frac{dN^{\text{pair}}}{d\Delta\phi} \sim 1 + 2 \sum_{n=1}^{n=\infty} V_{n\Delta}(p_T^{\text{trig}}, p_T^{\text{assoc}}) \cos(n\Delta\phi) \qquad v_n = \sqrt{V_{n\Delta}}$$

CMS COLLABORATION, JHEP 02 (2014) 088

RIDGE IN HEAVY ION COLLISIONS

Azimuthal structure quantified using Fourier expansion

V_n

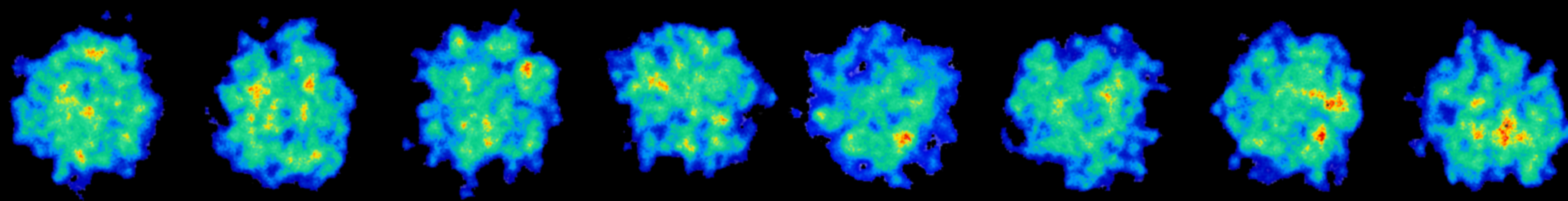


$$\frac{1}{N_{\rm trig}}\frac{dN^{\rm pair}}{d\Delta\phi} \sim 1 + 2\sum_{n=1}^{n=\infty} V_{n\Delta}(p_T^{\rm trig}, p_T^{\rm assoc})\cos(n\Delta\phi) \qquad v_n = \sqrt{V_{n\Delta}}$$

CMS COLLABORATION, JHEP 02 (2014) 088

THEORETICAL DESCRIPTION IN HEAVY IONS

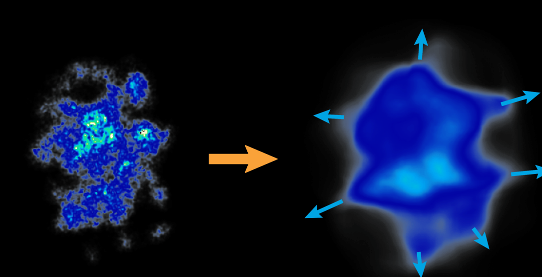
Fluctuating nucleon positions and color charges ➞
Fluctuating deposited energy



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

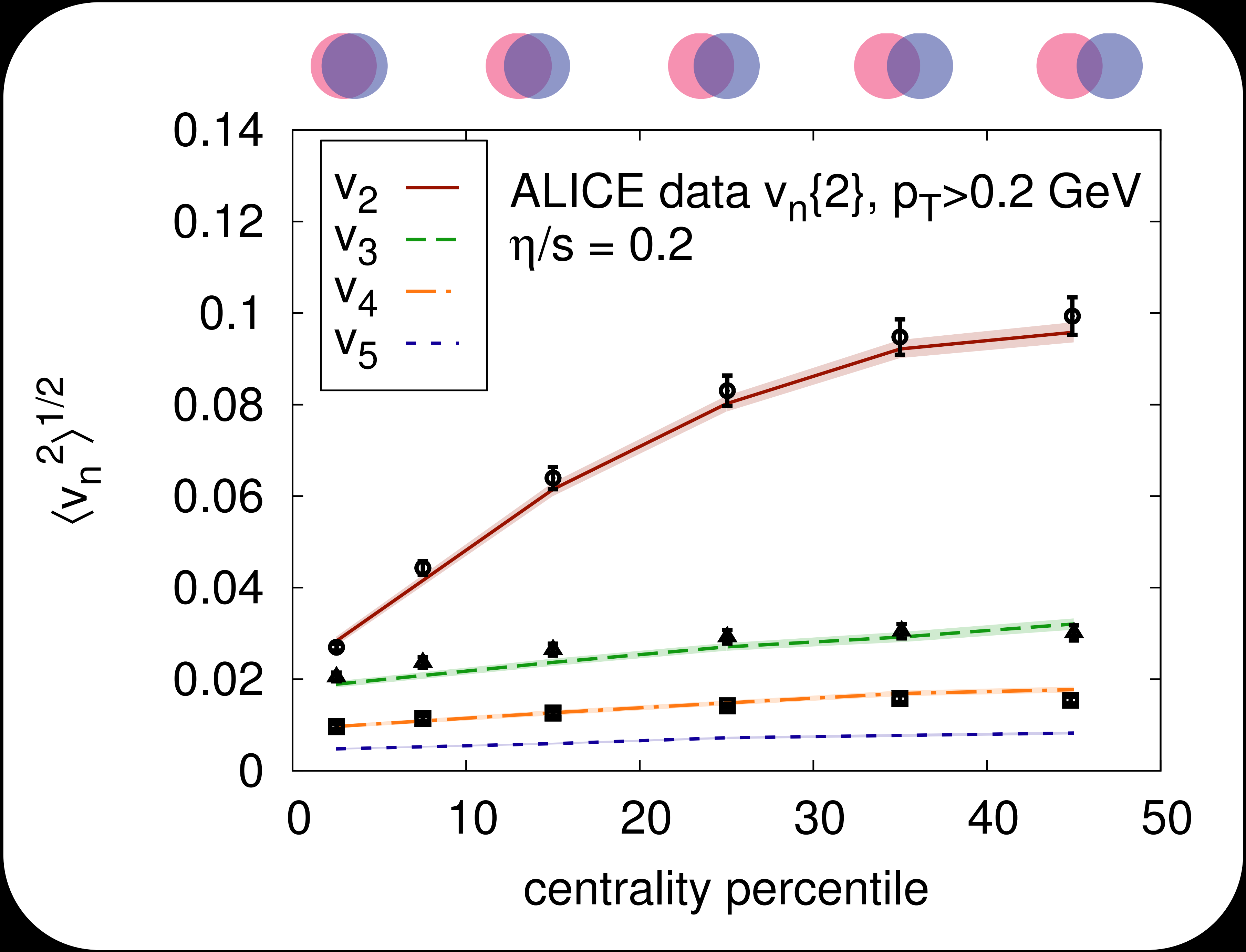
Pressure gradients drive the evolution
Described by hydrodynamics



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)

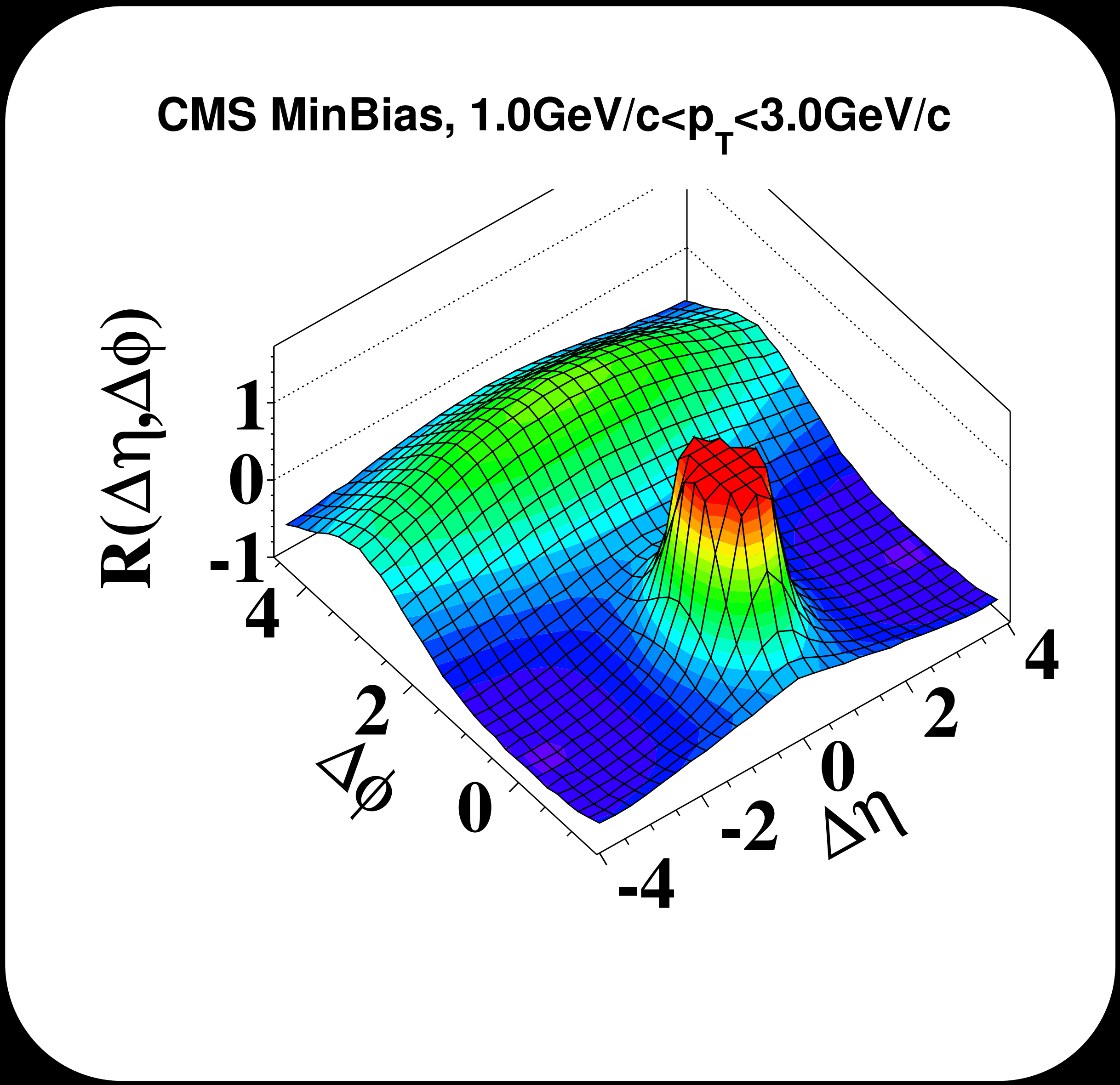


Quantitative description of the experimental data!

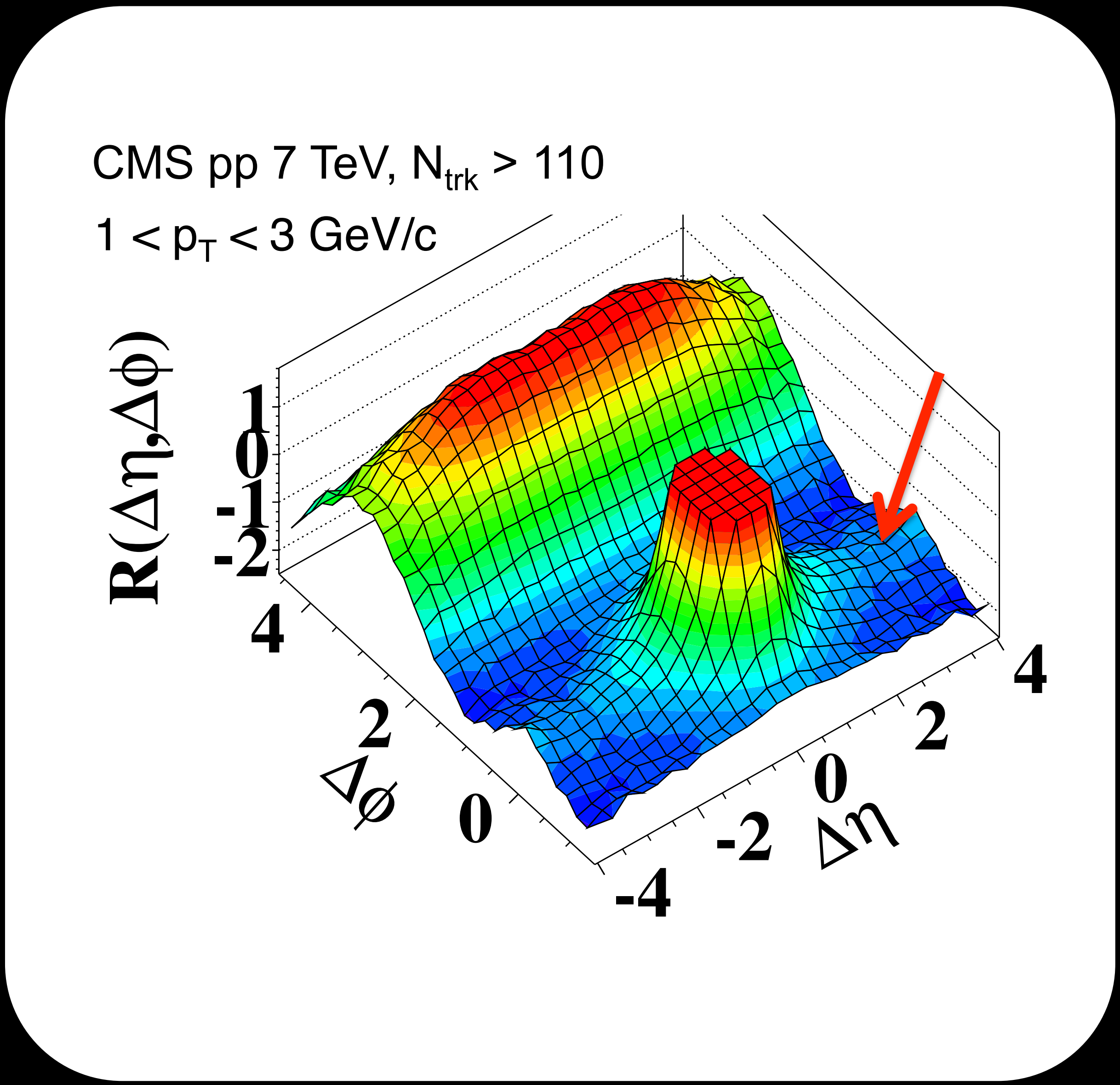
ALICE COLLABORATION, PHYS. REV. LETT. 107, 032301 (2011)

RIDGE IN SMALL COLLISION SYSTEMS

minimum bias p+p



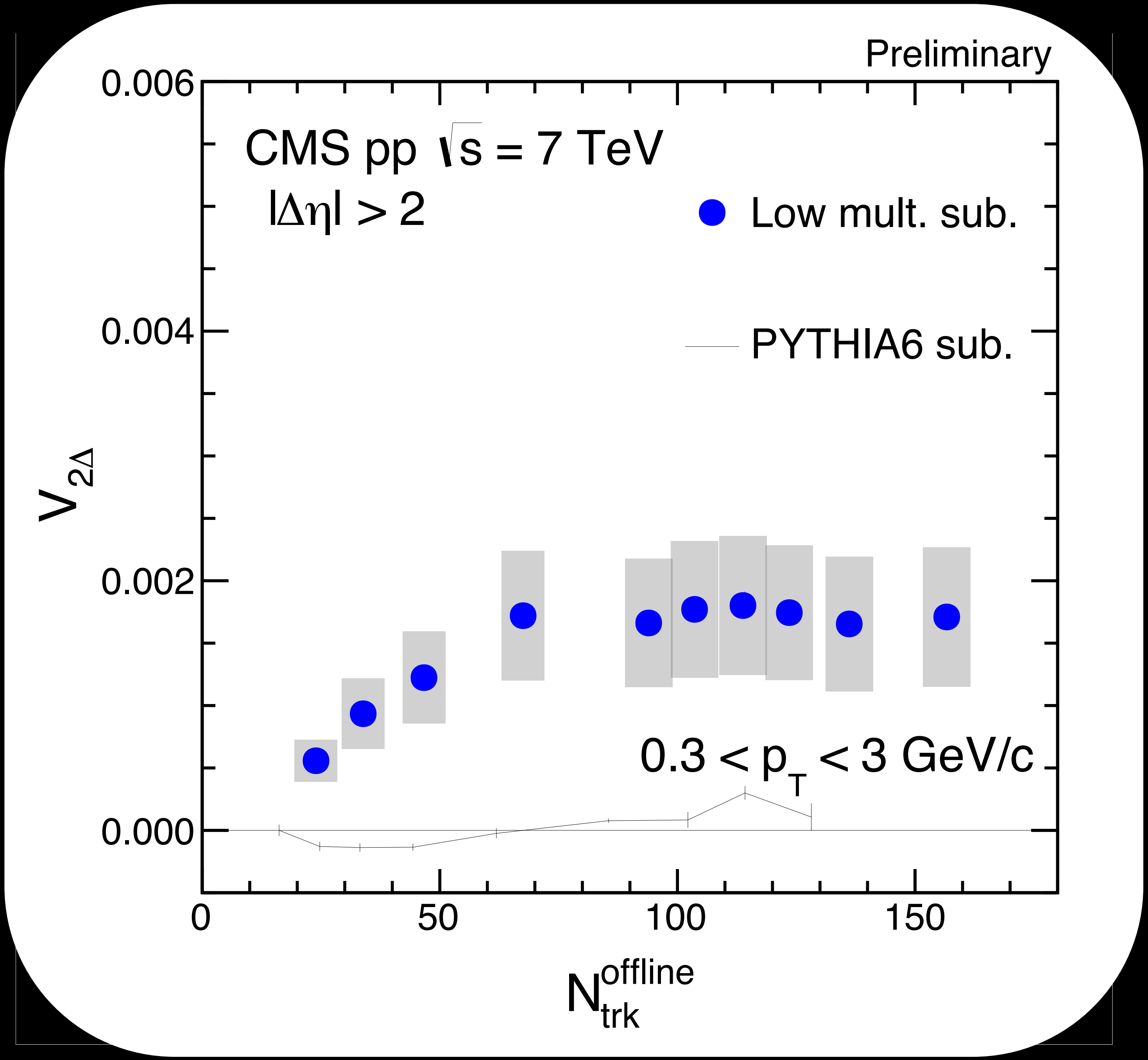
high multiplicity p+p



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

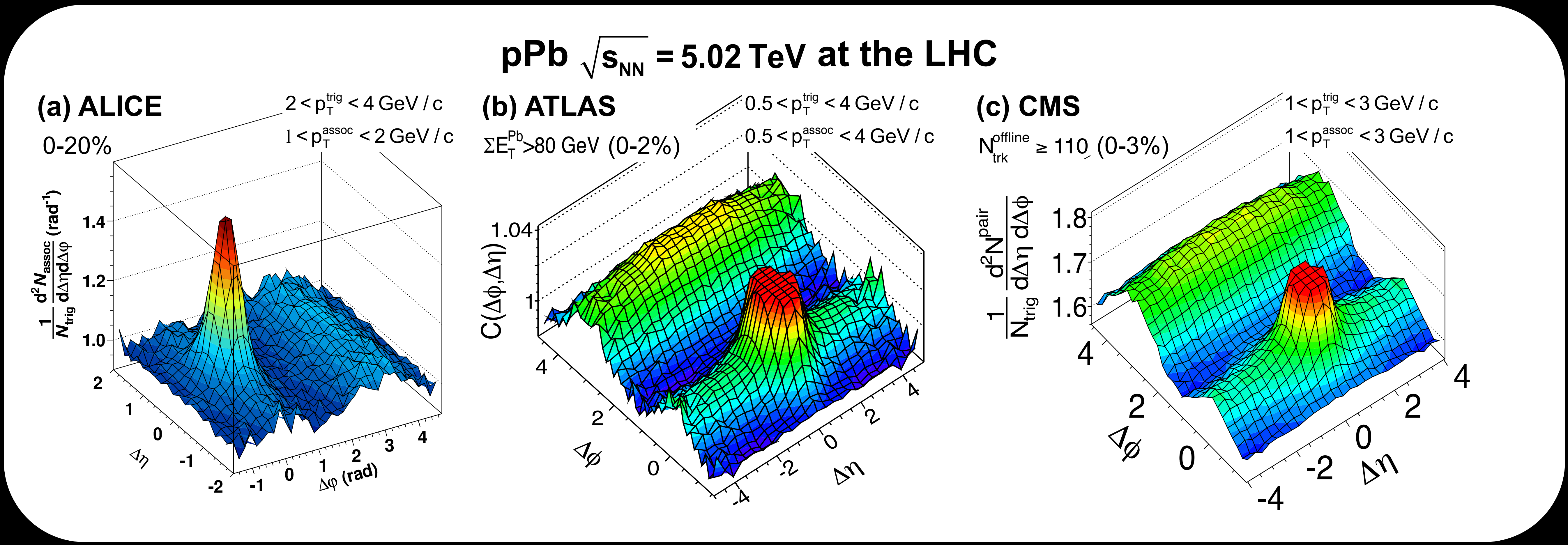


No ridge in PYTHIA

CMS PAS HIN-15-009

RIDGE IN p+Pb COLLISIONS

high multiplicity p+Pb

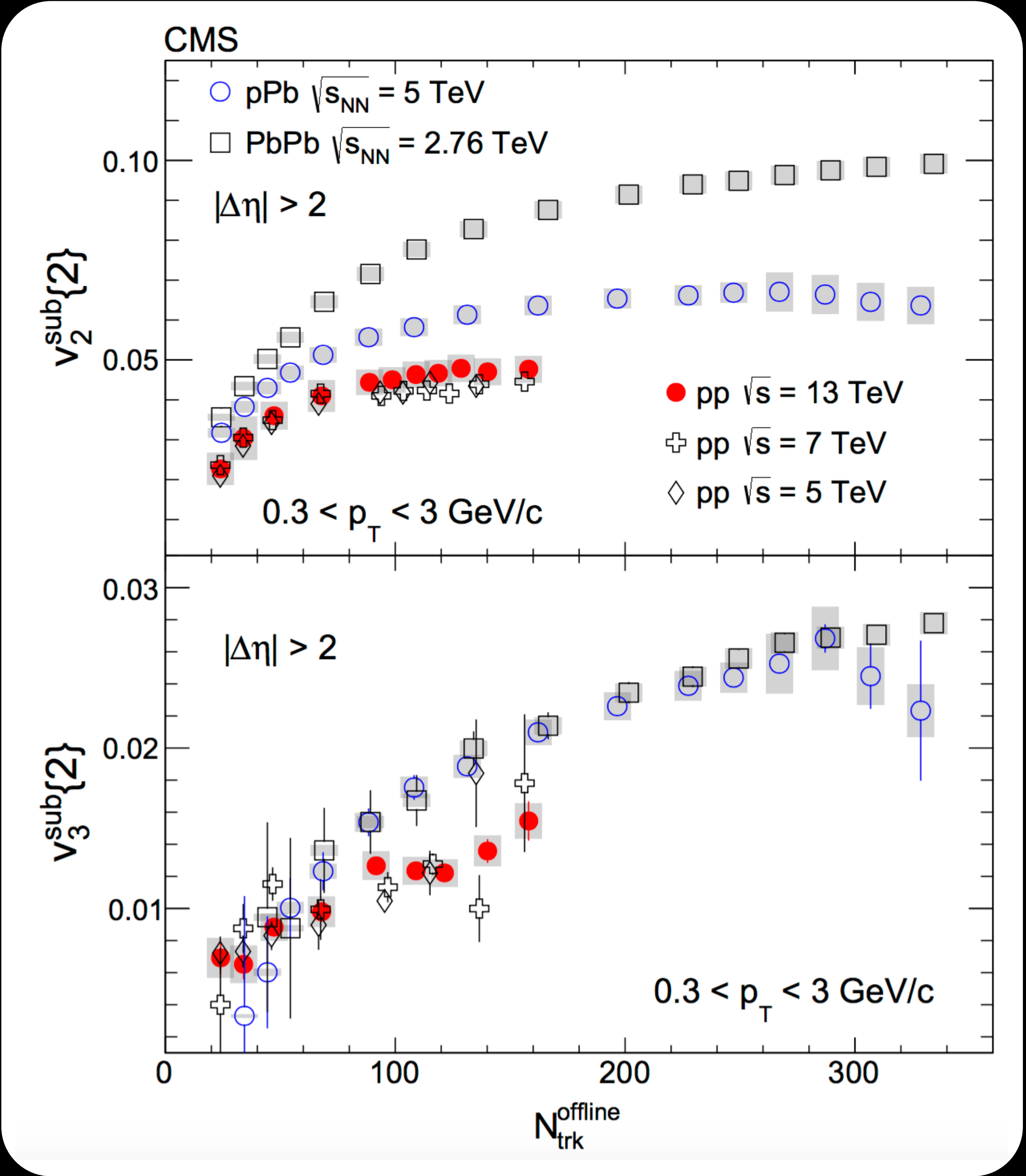


ALICE COLLABORATION, PHYS. LETT. B 719 (2013) 29

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



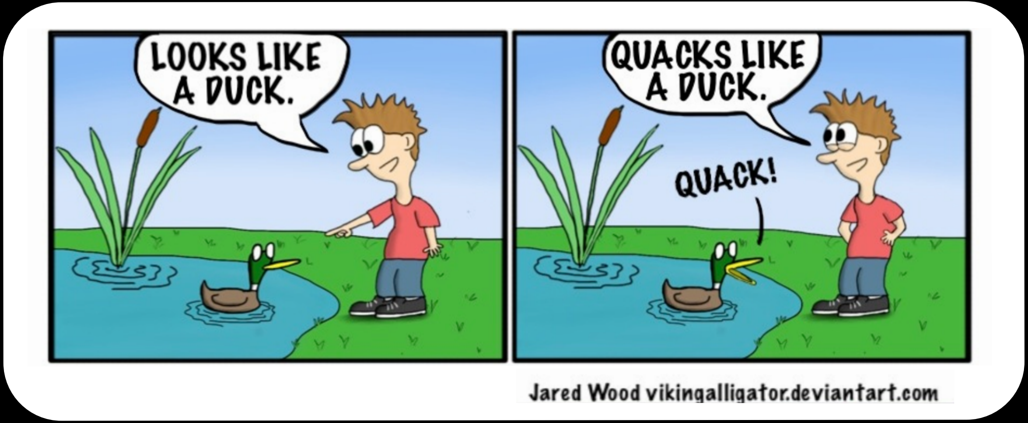
CMS COLLABORATION, ARXIV:1606.06198

SEE ALSO:

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

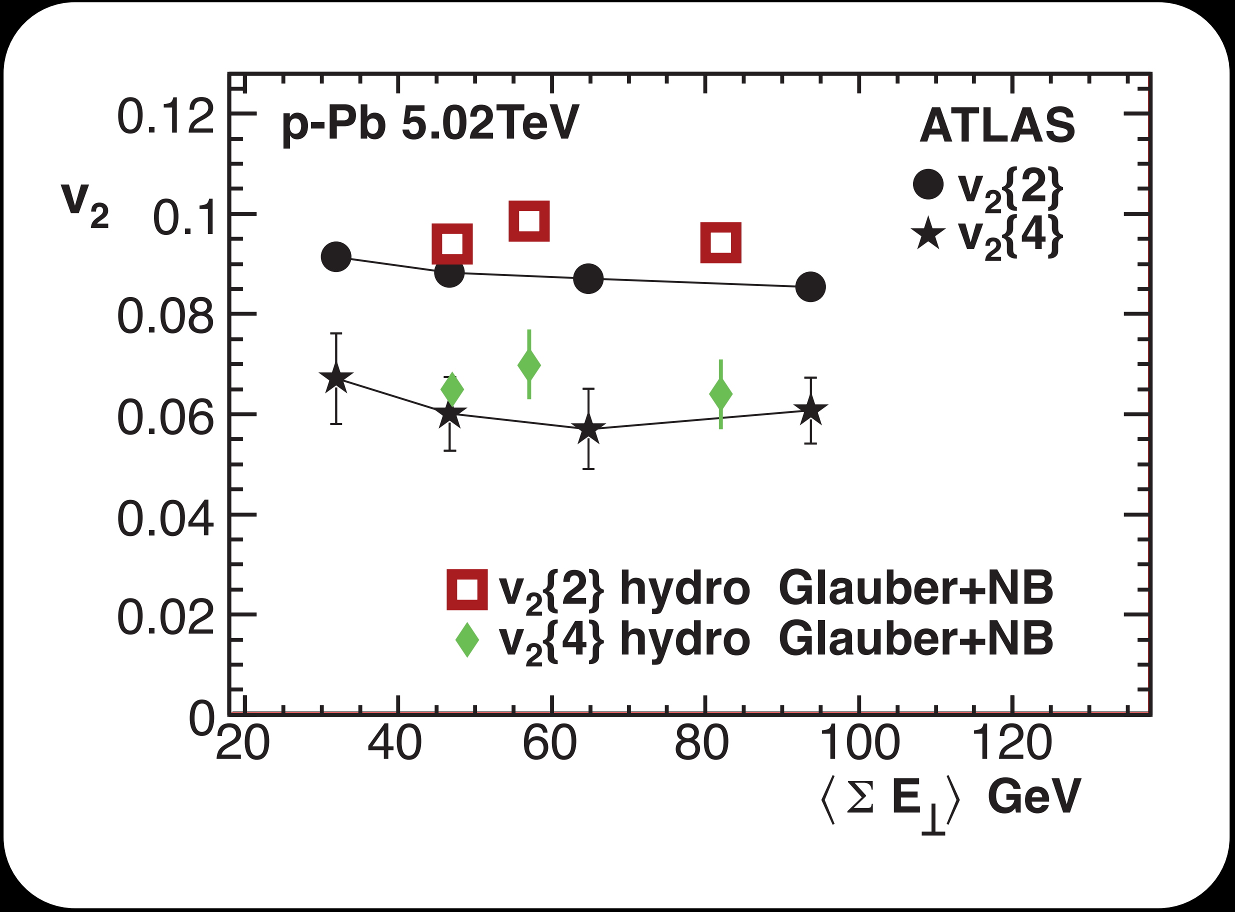
ATLAS COLLABORATION
PHYS. REV. LETT. 110, 182302 (2013); PHYS. REV. C 90.044906 (2014)

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



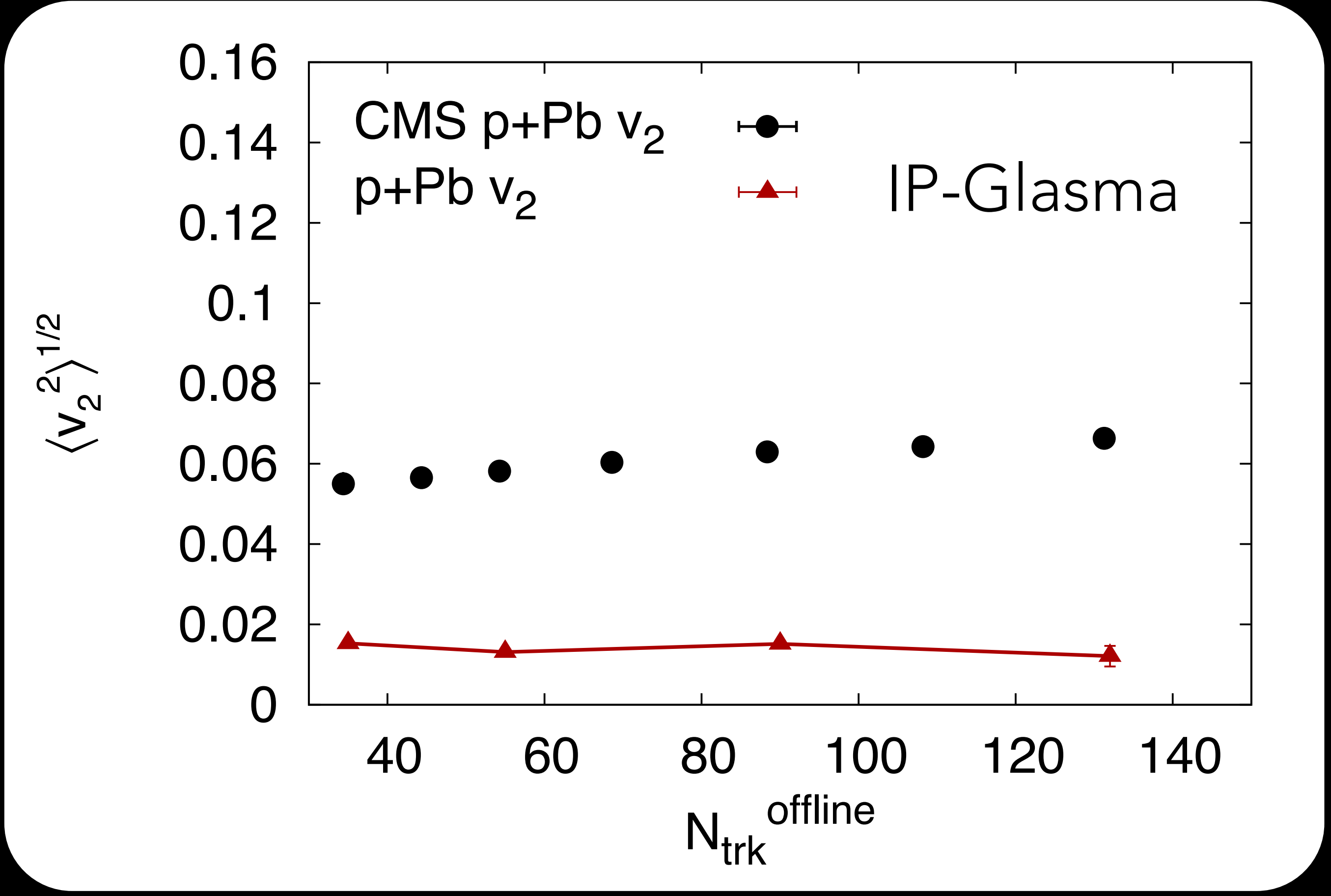
STRONG FINAL STATE EFFECTS IN SMALL SYSTEMS? EVEN HYDRODYNAMICS?

Simple initial state + hydro works



BOZEK, BRONIOWSKI
PRC88 (2013) 014903

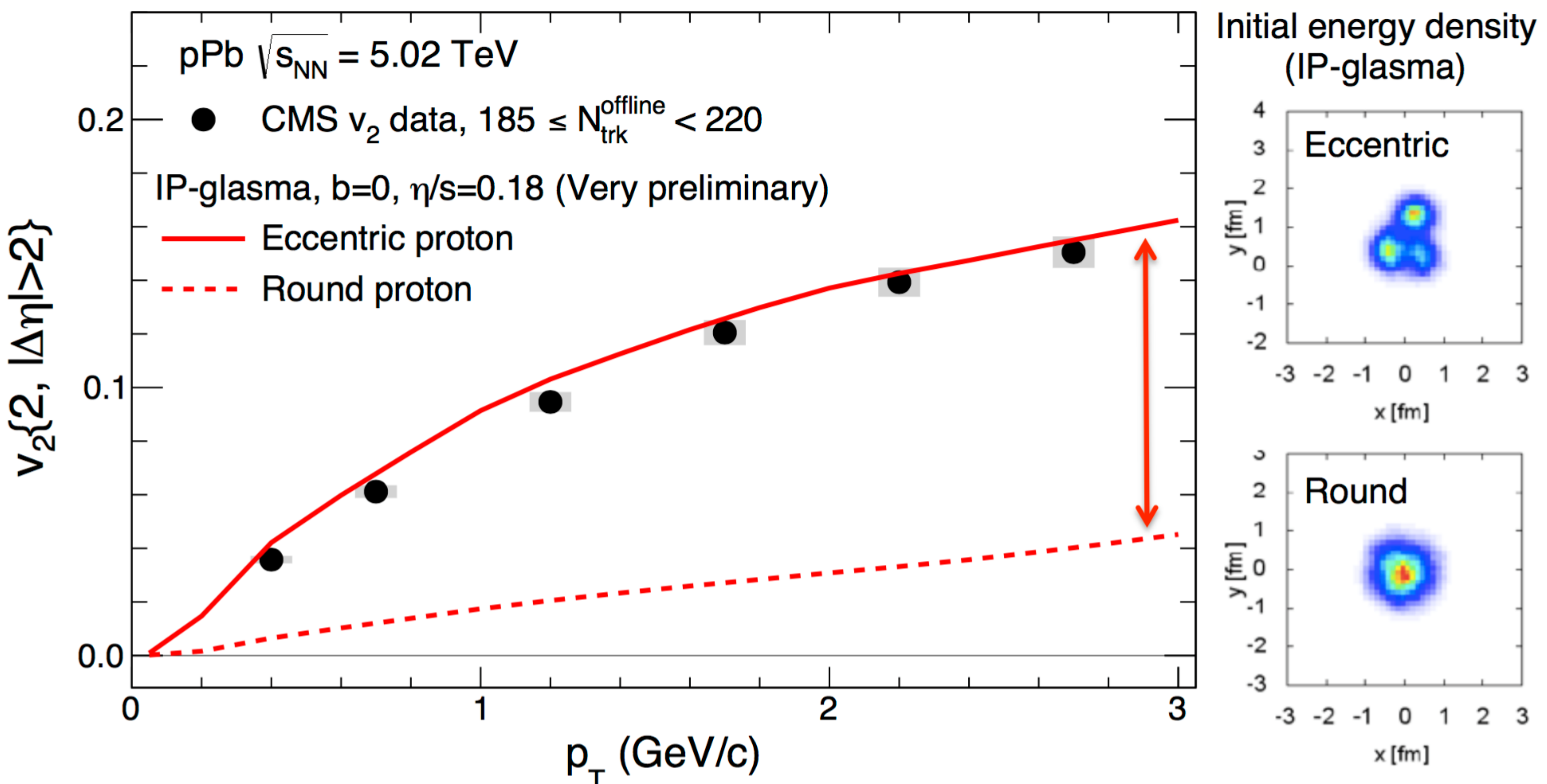
Calculation I showed before does not work in p+Pb



SCHENKE, VENUGOPALAN
PRL113 (2014) 102301

OTHER CALCULATIONS: KOZLOV, LUZUM, DENICOL, JEON, GALE; WERNER, GUIOT, KARPENKO, PIEROG; ROMATSCHKE, ...

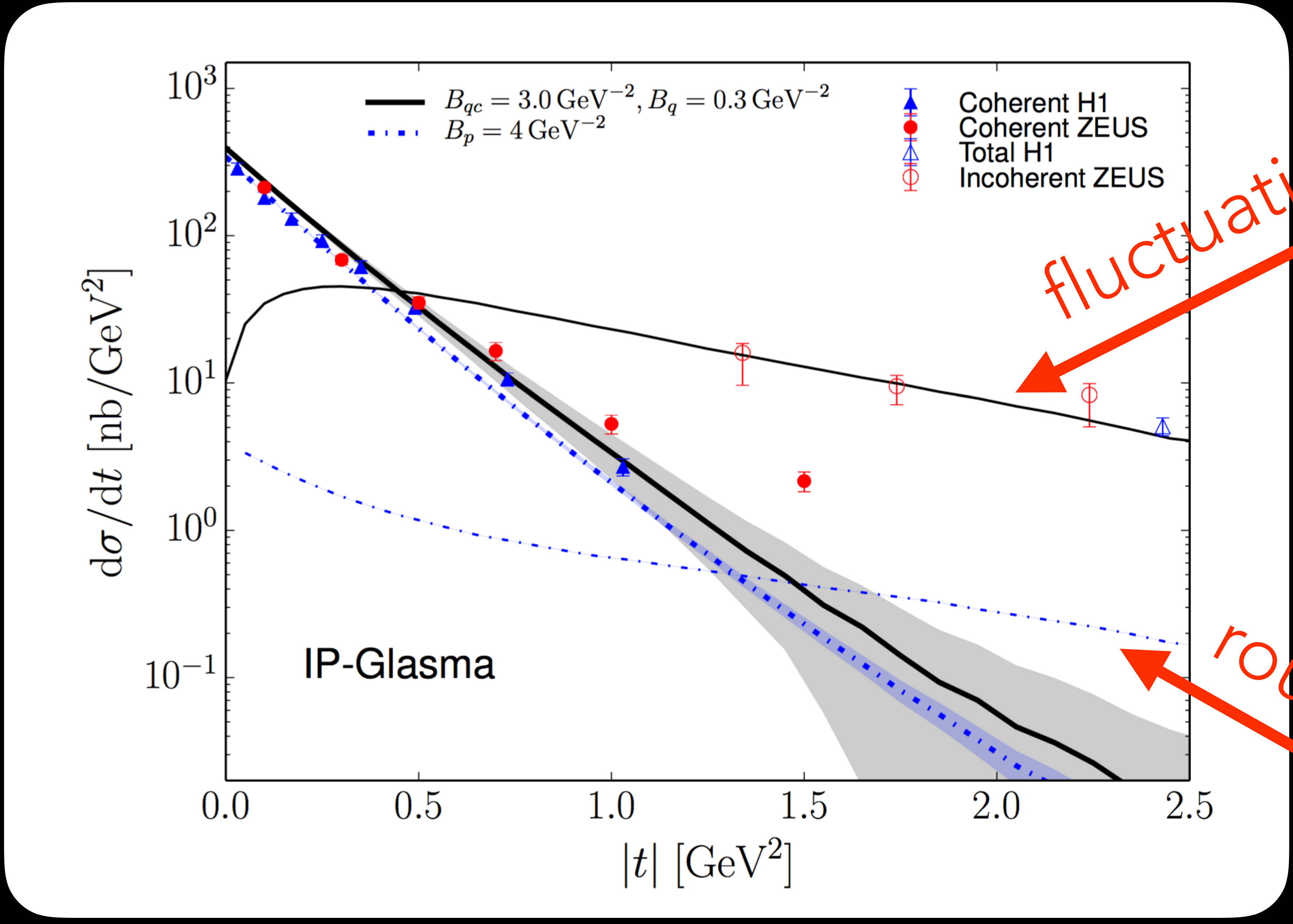
WITH FLUCTUATING PROTON IP-GLASMA DOES DESCRIBE p+Pb v_2

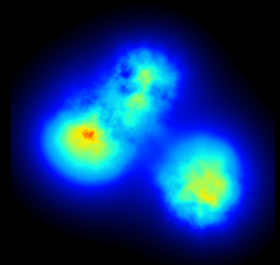


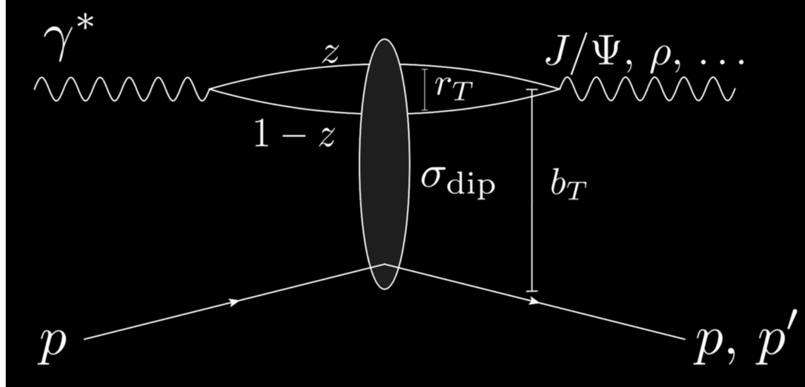
MORE EVIDENCE FOR PROTON SHAPE FLUCTUATIONS

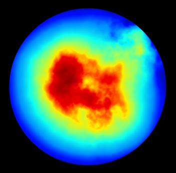
H. MÄNTYSAARI, B. SCHENKE, ARXIV:1603.04349, PRL IN PRINT

Exclusive diffractive J/Ψ production



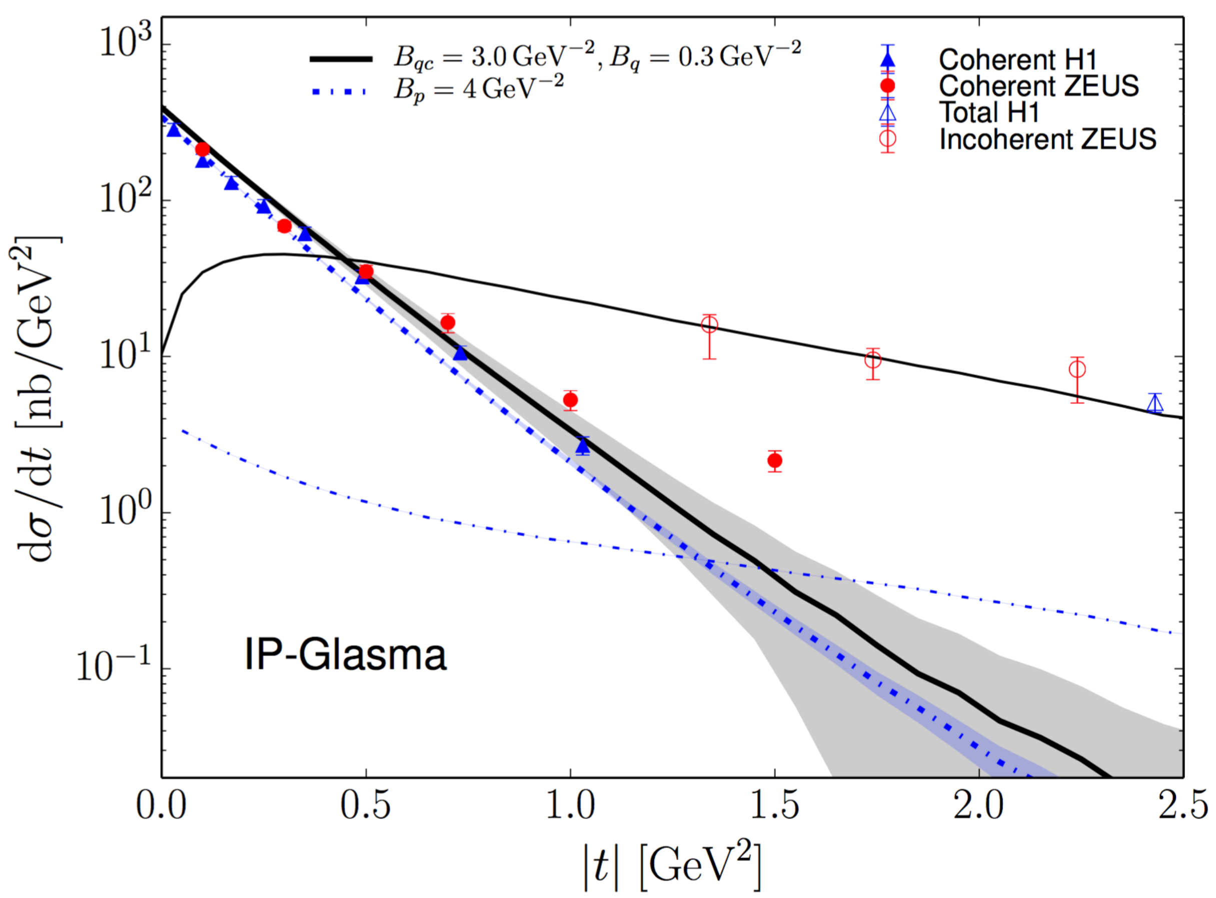




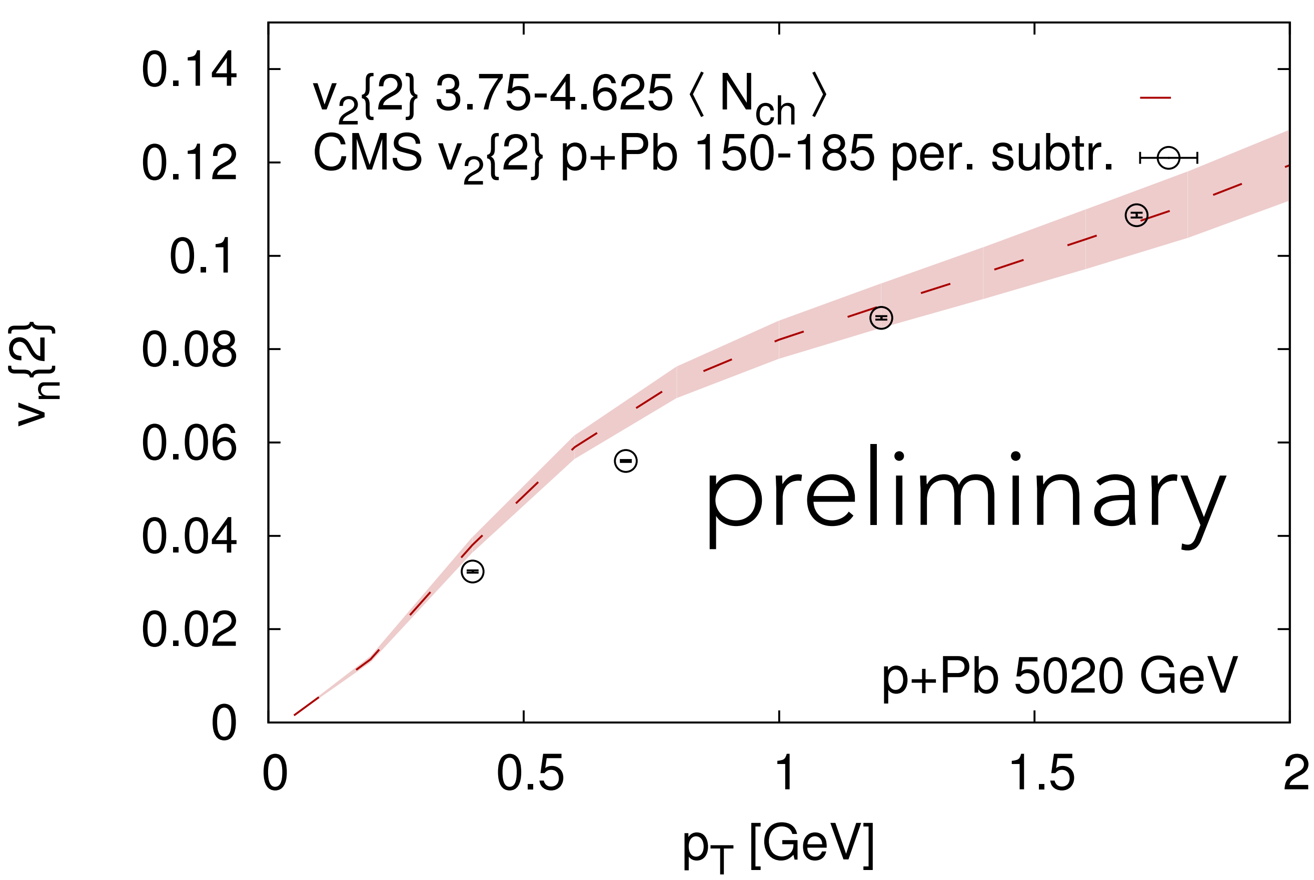


STRATEGY: CONSTRAIN PROTON FLUCTUATIONS WITH J/Ψ PRODUCTION AND PREDICT FLOW IN p+Pb COLLISIONS

H. MÄNTYSAARI, P. TRIBEDY, B. SCHENKE, IN PREPARATION



Use constrained proton to predict v_2 in p+Pb collisions

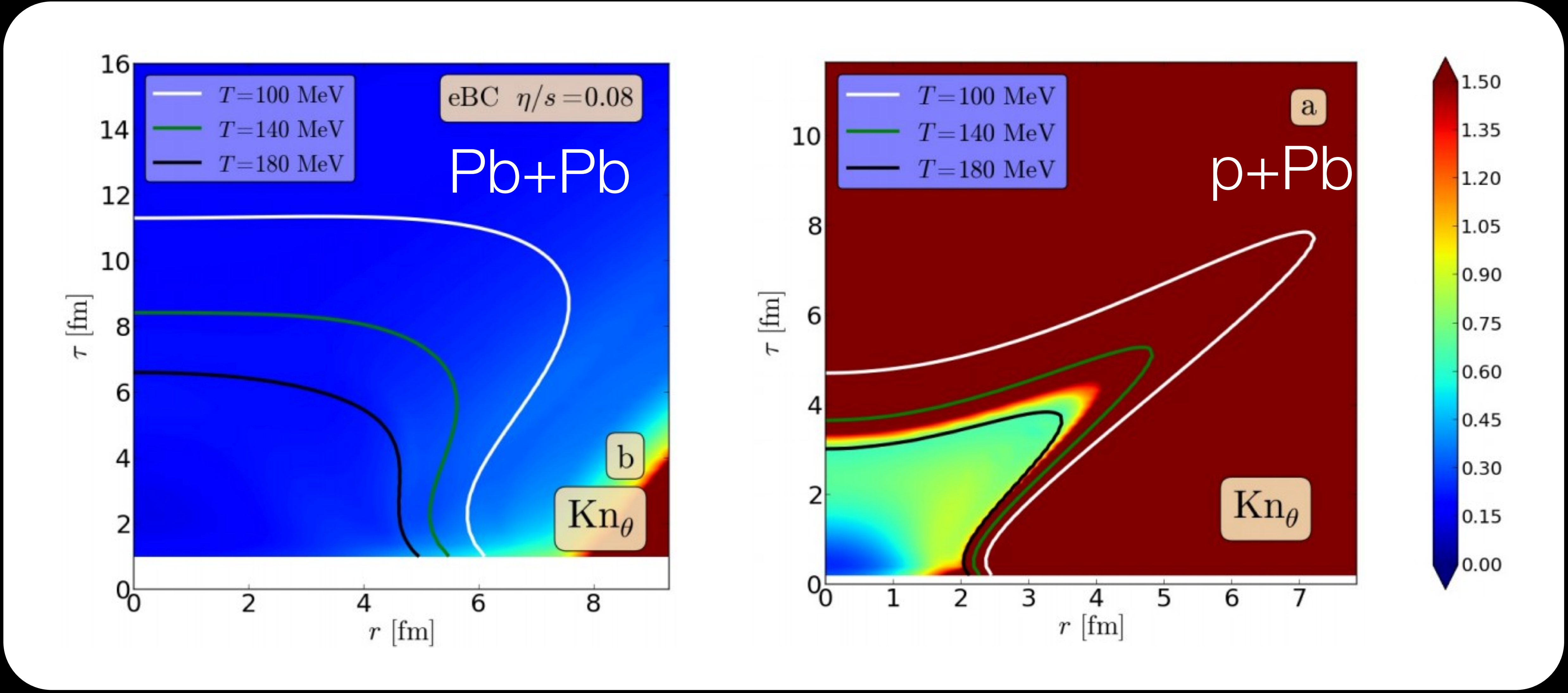


Temperature dependent η/s constrained in A+A collisions

G. DENICOL, A. MONNAI, B. SCHENKE
PHYS.REV.LETT. 116 (2016) NO.21, 212301

PROBLEM WITH HYDRODYNAMICS

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

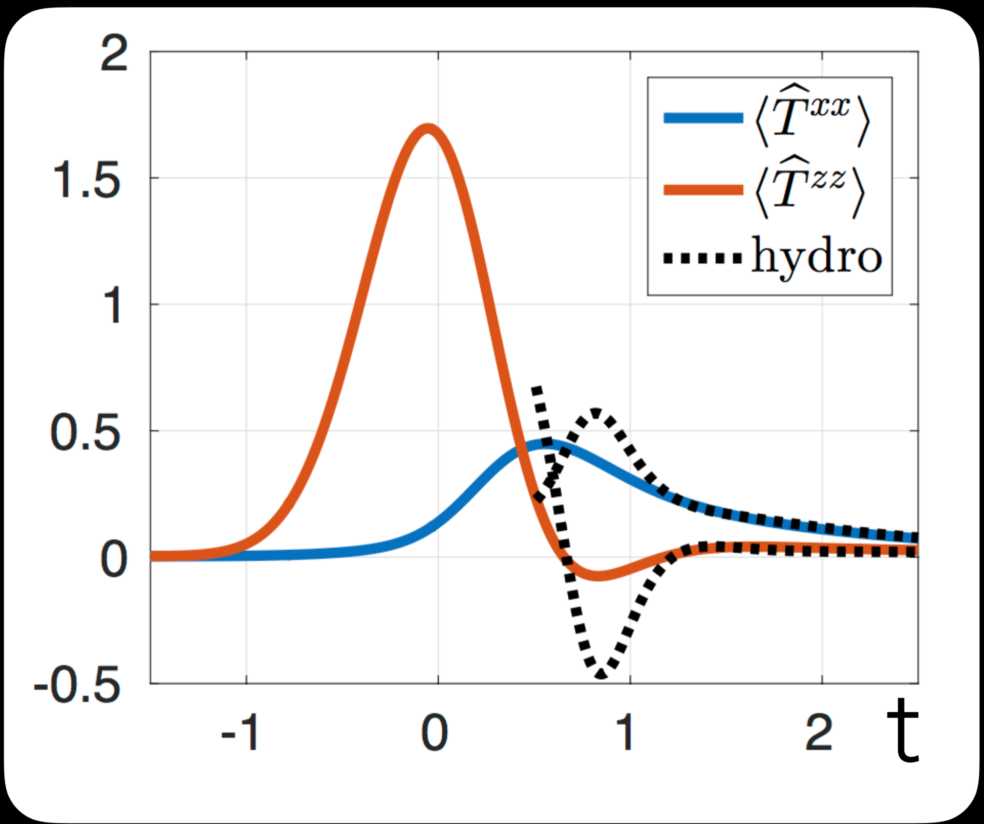


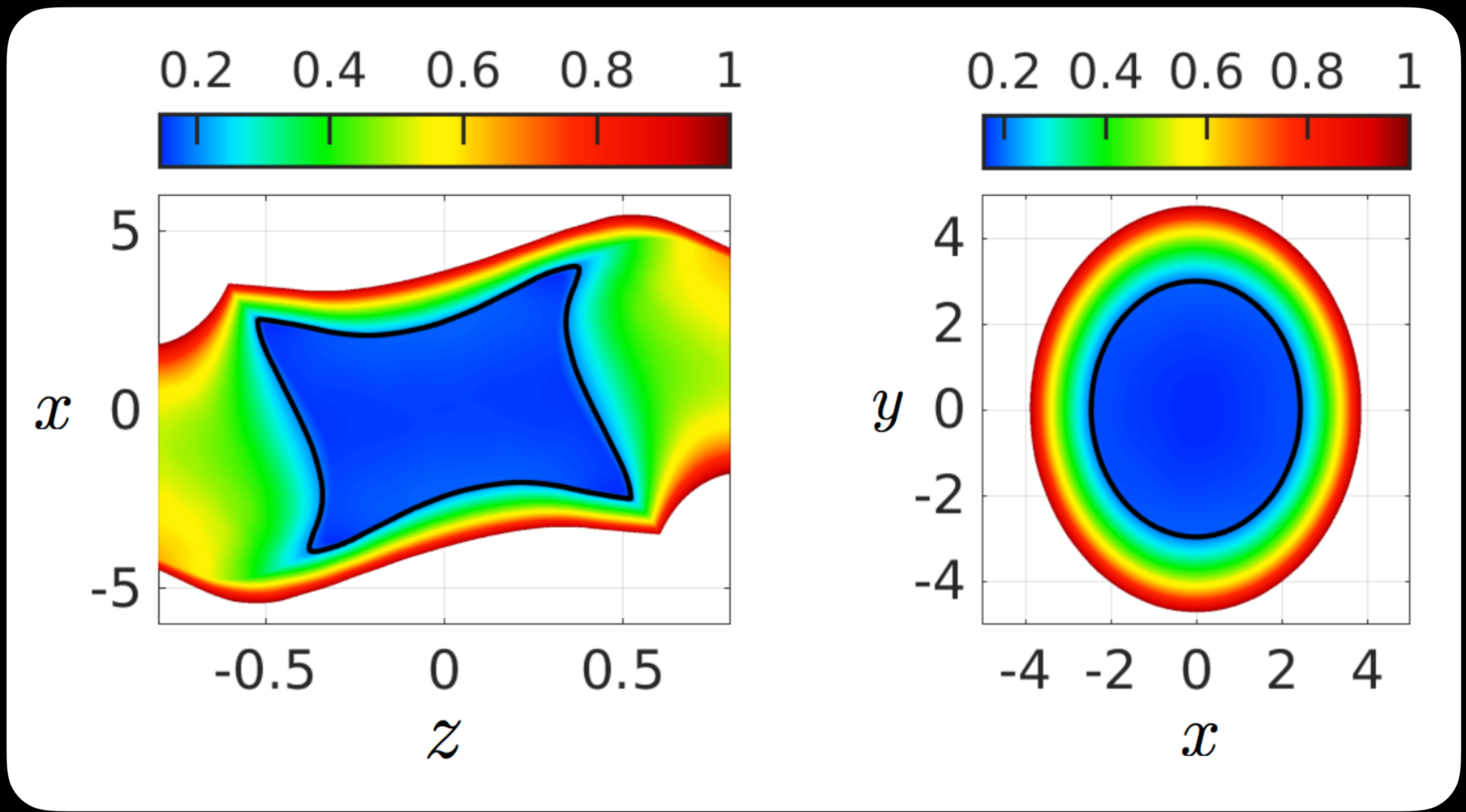
H. NIEMI, G.S. DENICOL, E-PRINT: ARXIV:1404.7327

BUT ADS/CFT SAYS IT'S OK

P. CHESLER, JHEP 1603 (2016) 146

Degree of "hydrodynamization" $\Delta(t,\boldsymbol{x}) \equiv \max_{t'\geq t}\left[\frac{||\langle T^{\mu\nu}(t',\boldsymbol{x})\rangle - T^{\mu\nu}_{\rm hydro}(t',\boldsymbol{x})||}{p(t',\boldsymbol{x})}\right]$





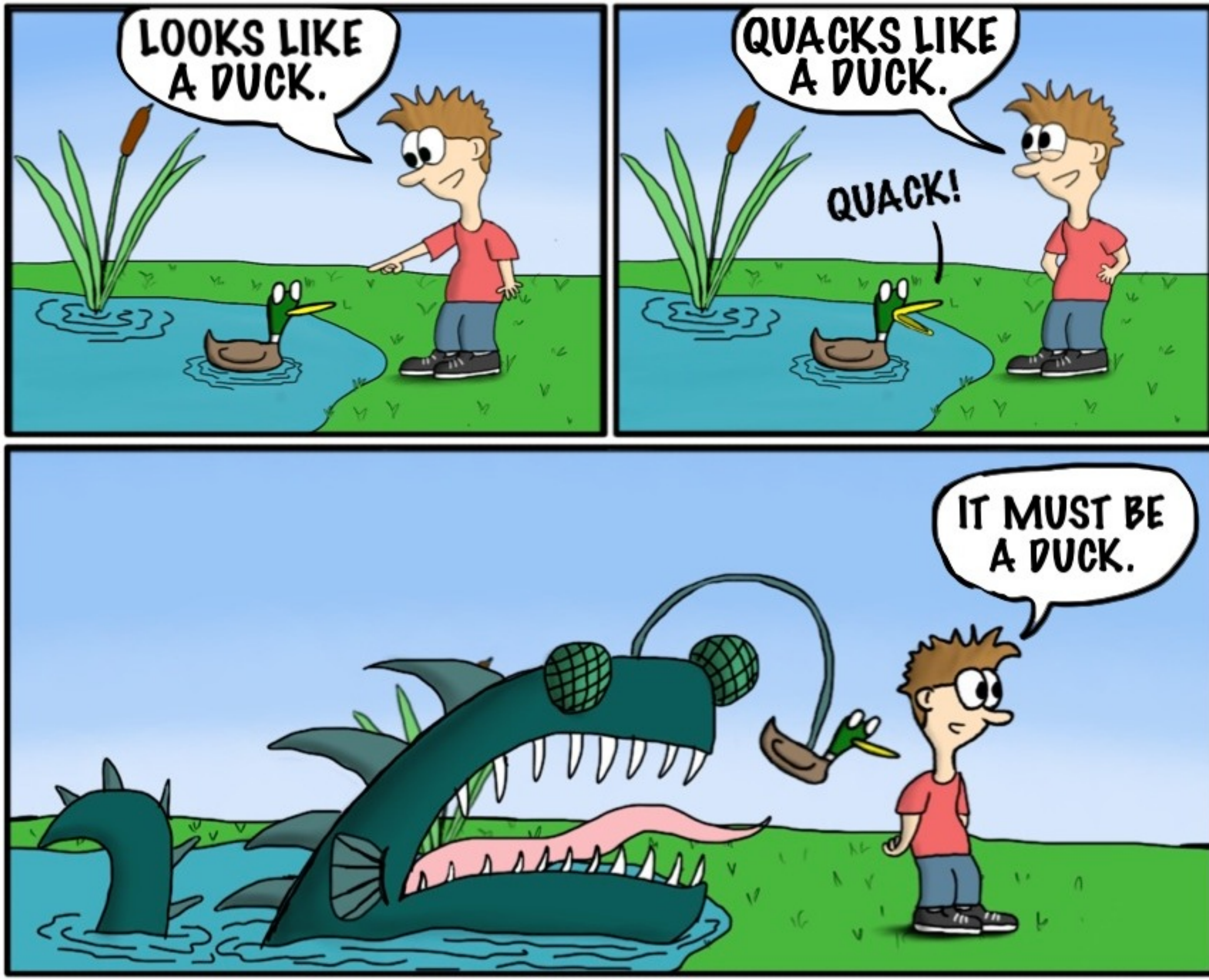
x=y=z=0

t =1.5 ≈ 0.375 fm

Δ≲0.2 hydrodynamic

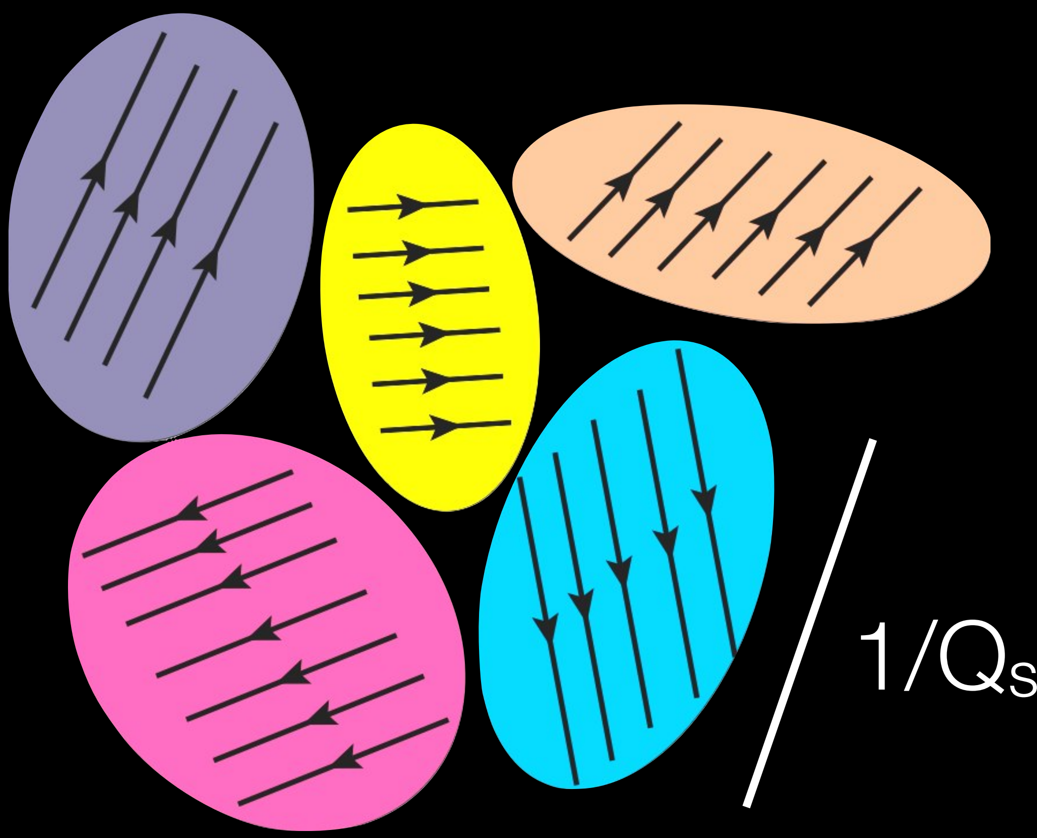
Δ≳0.8 really not hydrodynamic

OTHER EXPLANATIONS



OTHER EXPLANATIONS: INITIAL STATE

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

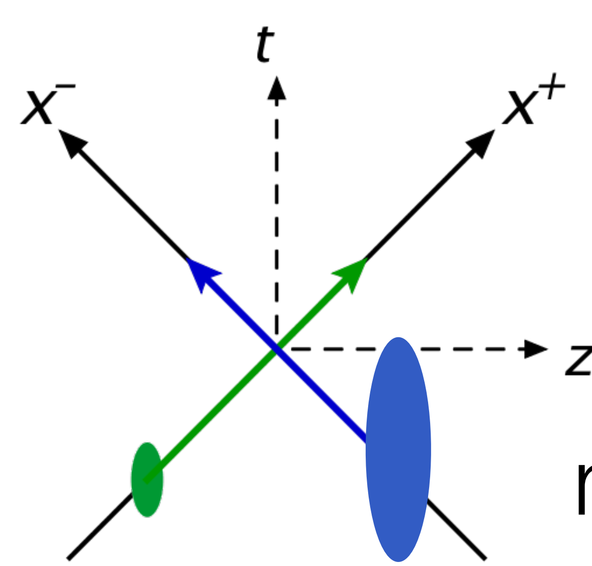
CORRELATIONS FROM THE INITIAL STATE

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

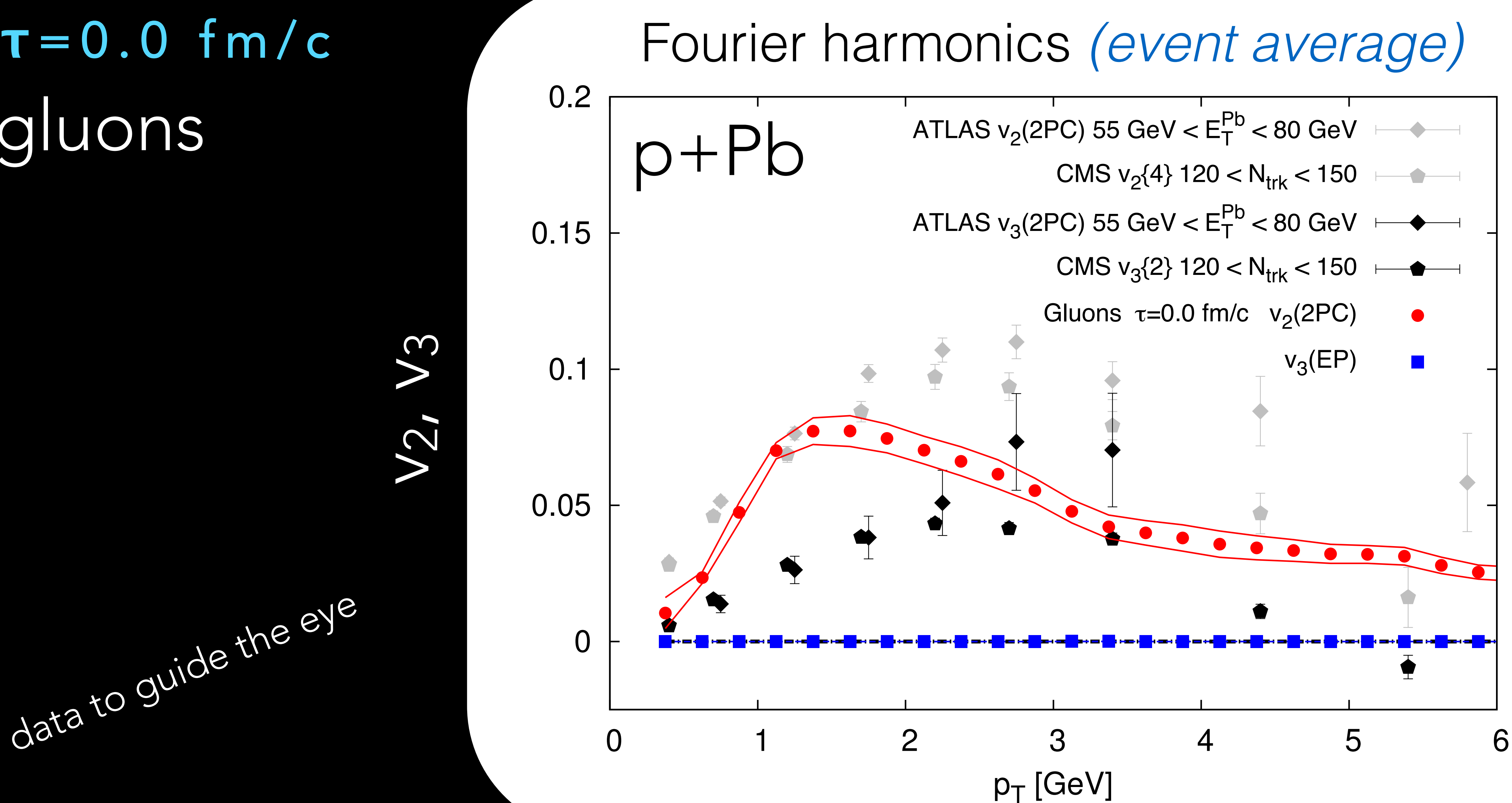
Compute the gluon momentum distribution from the initial fields after the collision - Then analyze its anisotropy

CORRELATIONS FROM THE INITIAL STATE

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

τ=0.0 fm/c

gluons



Significant v_2 at time 0

No odd harmonics for gluons without final state interactions

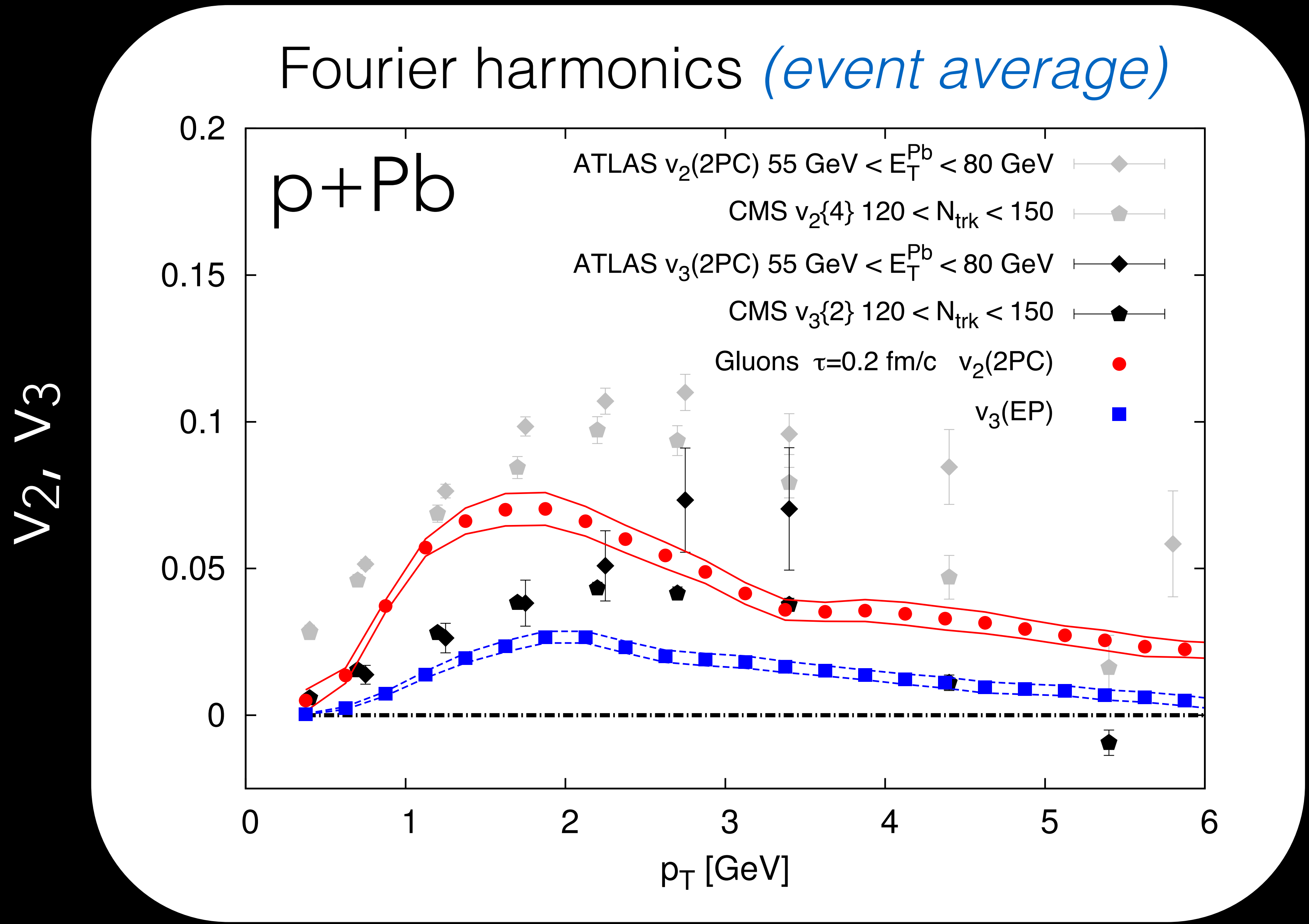
CORRELATIONS FROM THE INITIAL STATE

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

τ=0.2 fm/c

gluons

data to guide the eye



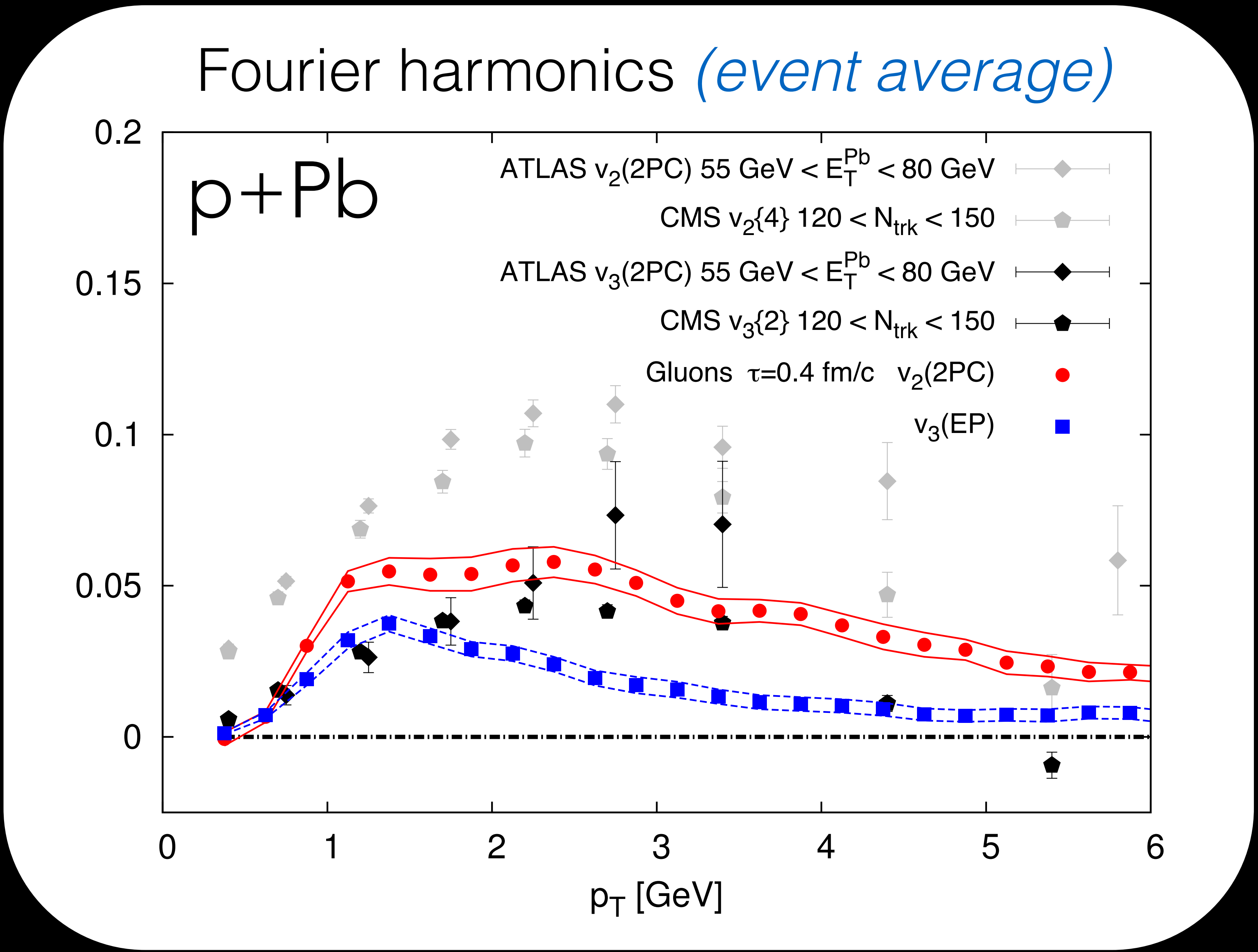
CORRELATIONS FROM THE INITIAL STATE

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

τ=0.4 fm/c

gluons

data to guide the eye



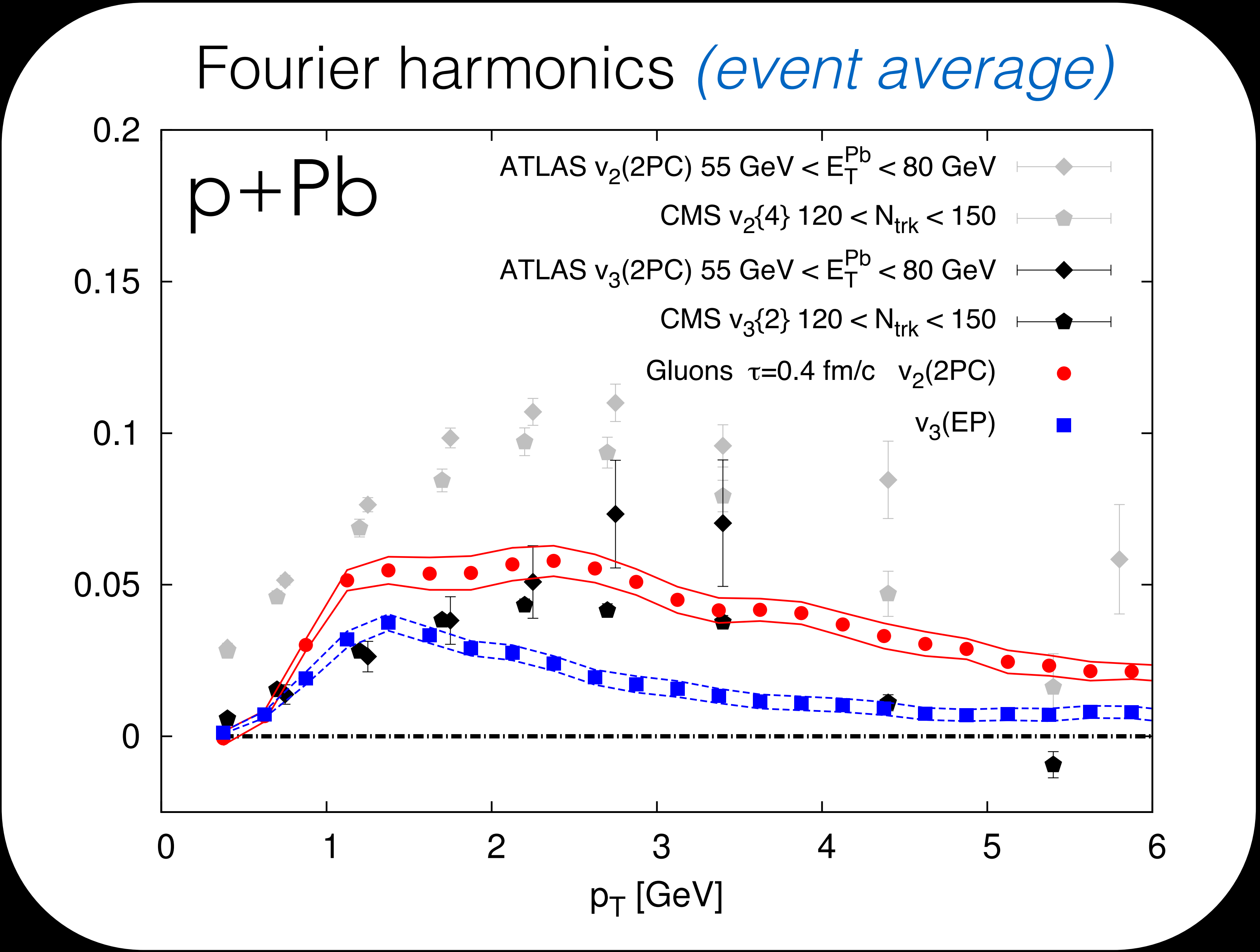
Odd harmonics generated by pre-equilibrium dynamics

CORRELATIONS FROM THE INITIAL STATE

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

τ=0.4 fm/c

gluons

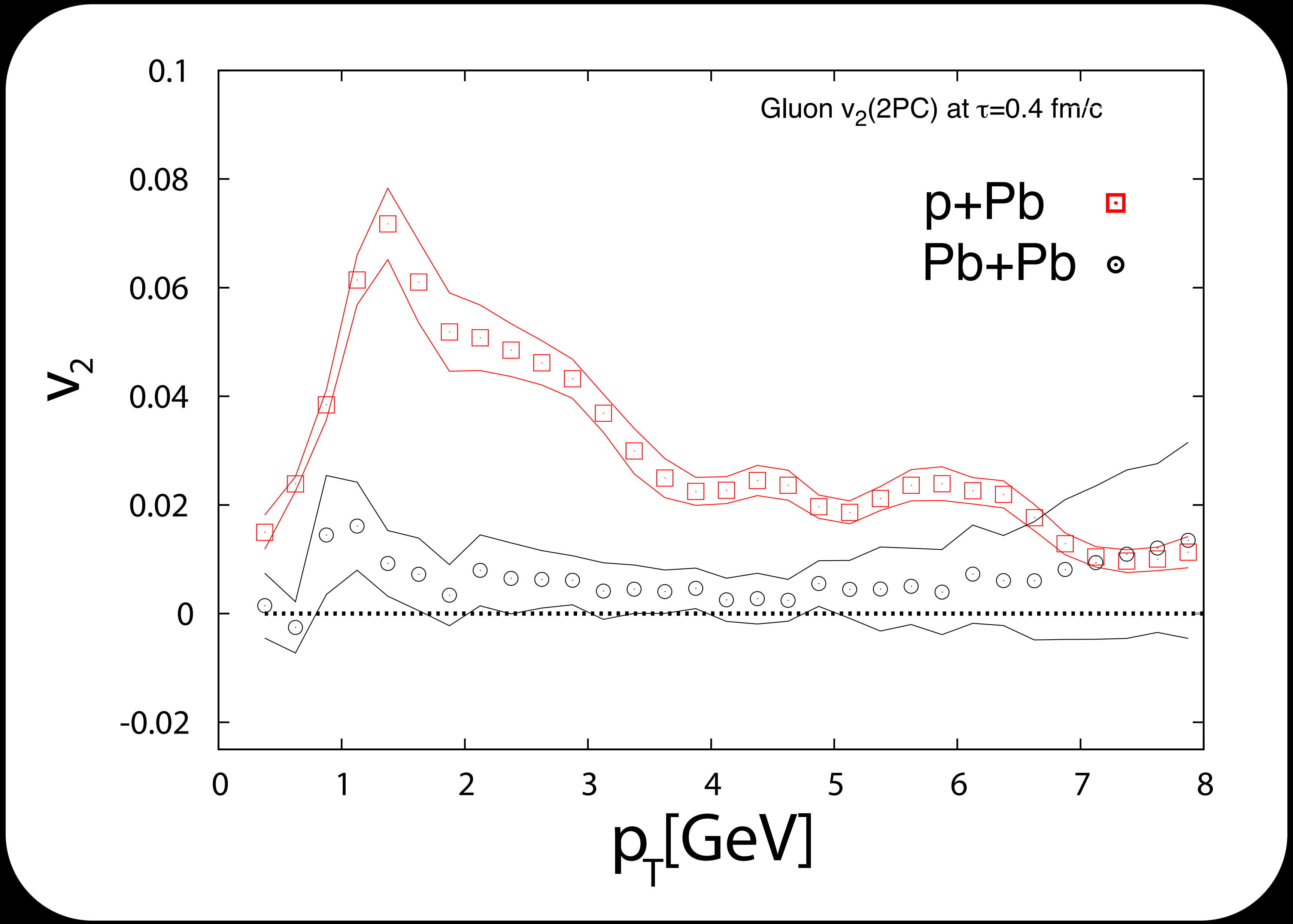


data to guide the eye

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

FRAGMENTATION OF THE CYM RESULT

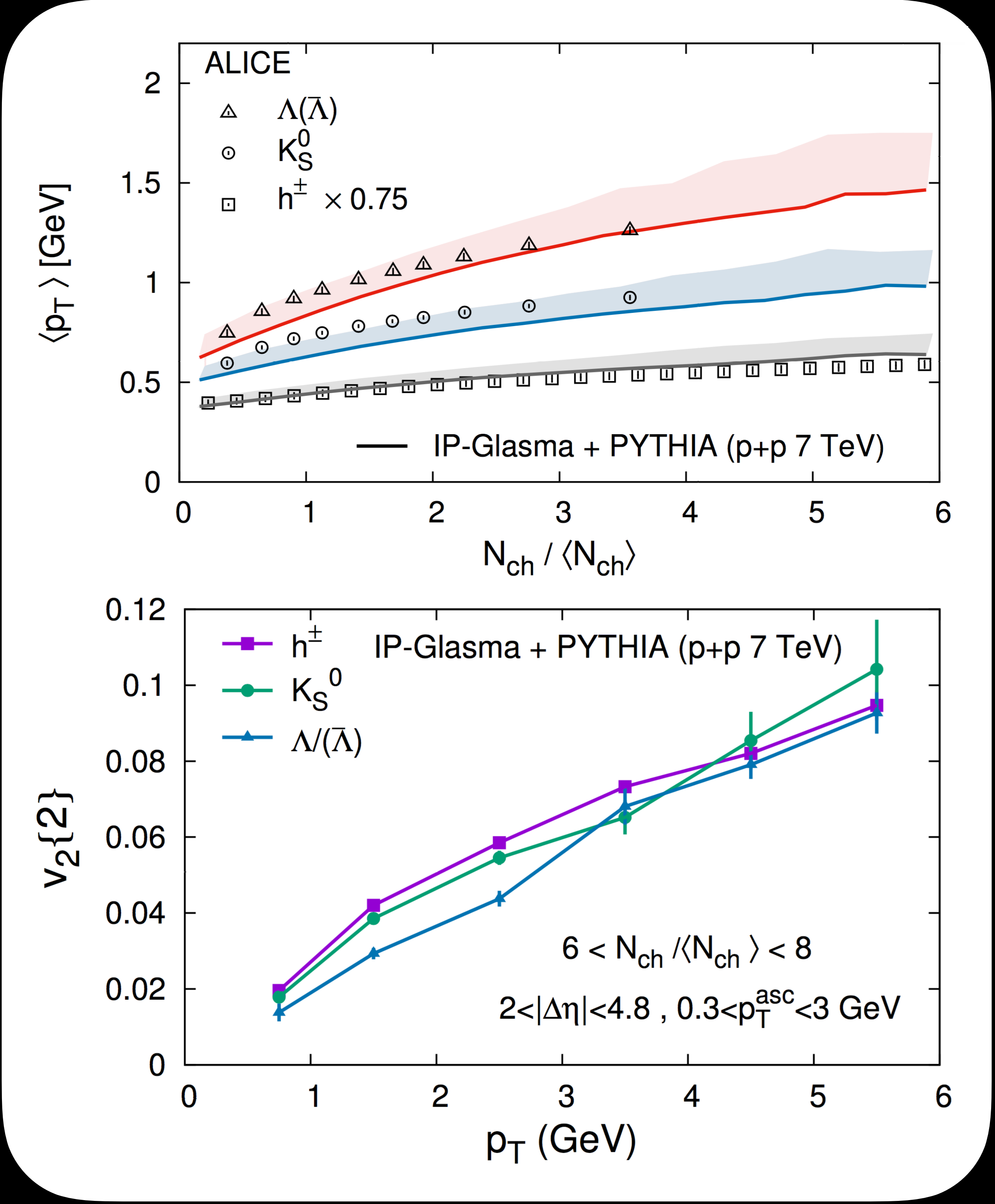
SCHENKE, SCHLICHTING, TRIBEDY, VENUGOPALAN, IN PREPARATION

Do we see mass splitting without hydro?

Classical Yang-Mills coupled to PYTHIA's Lund fragmentation

Gluon v_2 is translated to hadron v_2

Mass splitting in $\langle p_T \rangle$ and v_2!



MANY CALCULATIONS OF RIDGE EFFECT FROM INITIAL STATE

Many different calculations using different approximations exist Dumitru, Dusling, Fernandez-Fraile, Gavin, Gelis, Jalilian-Marian, Kovchegov, Lappi, McLerran, Dominguez, Marquet, McLerran, Moschelli, Schenke, Schlichting, Skokov, Venugopalan, Wu, …

They all find a ridge without any hydrodynamics

Some are compared in

T. LAPPI, B. SCHENKE, S. SCHLICHTING, R. VENUGOPALAN, JHEP 1601 (2016) 061

See the review article

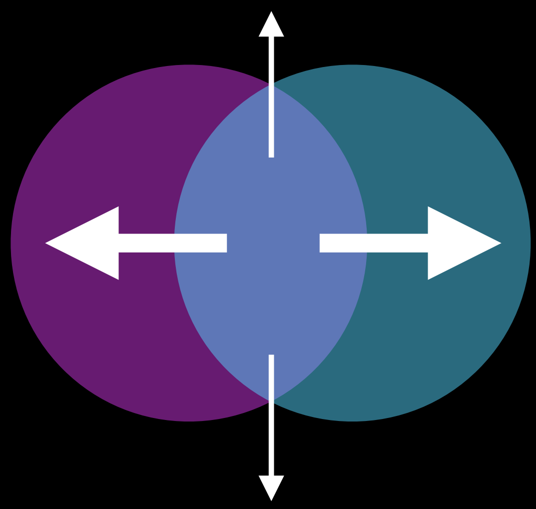
K. DUSLING, W. LI, B. SCHENKE, INT. J. MOD. PHYS. E25, 1630002 (2016)

KINETIC THEORY "ANISOTROPIC ESCAPE"

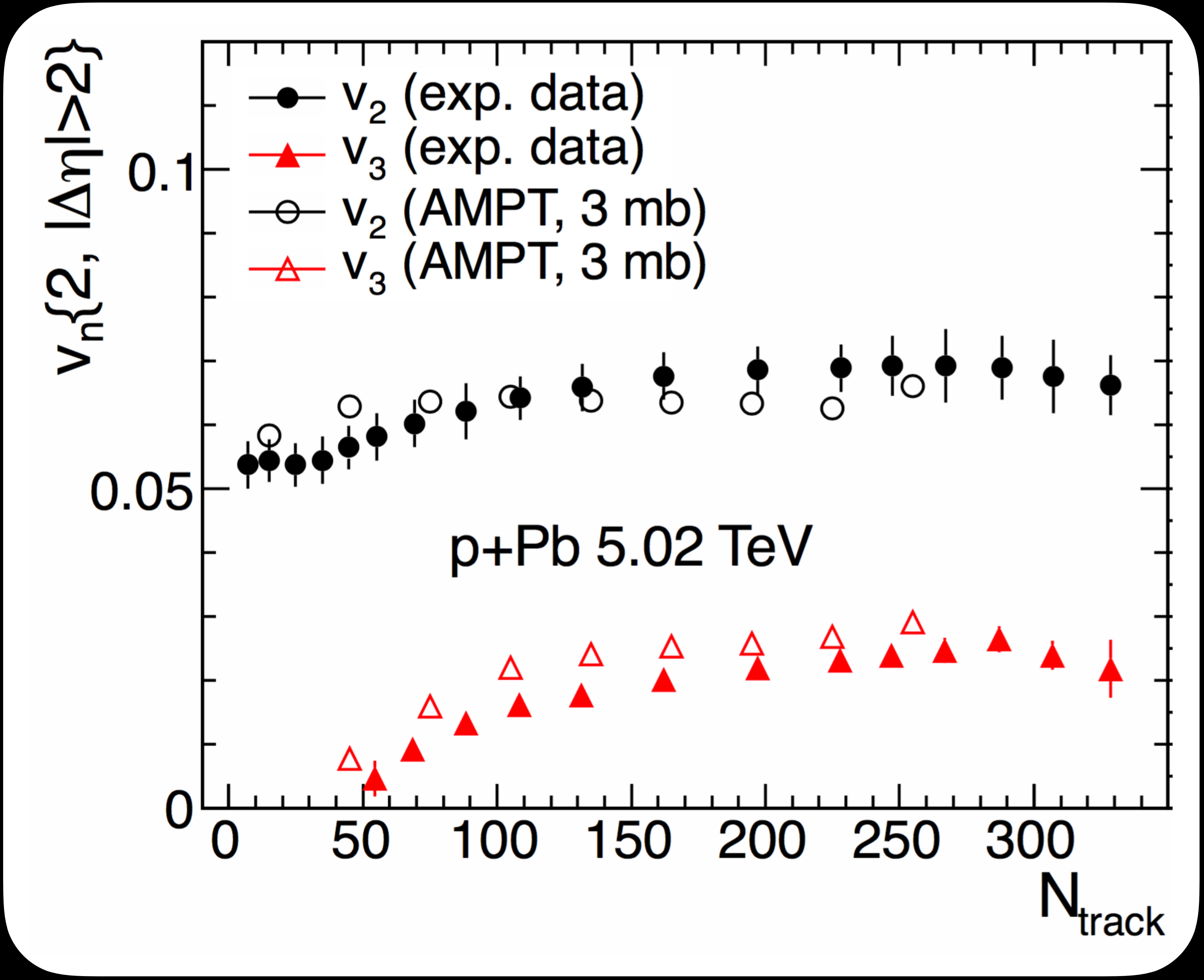
A. BZDAK, G.-L. MA, PRL 113 (2014)
L. HE, T. EDMONDS, Z.-W. LIN, F. LIU, D. MOLNAR, F. WANG, PLB753 (2016)

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

Described in AMPT

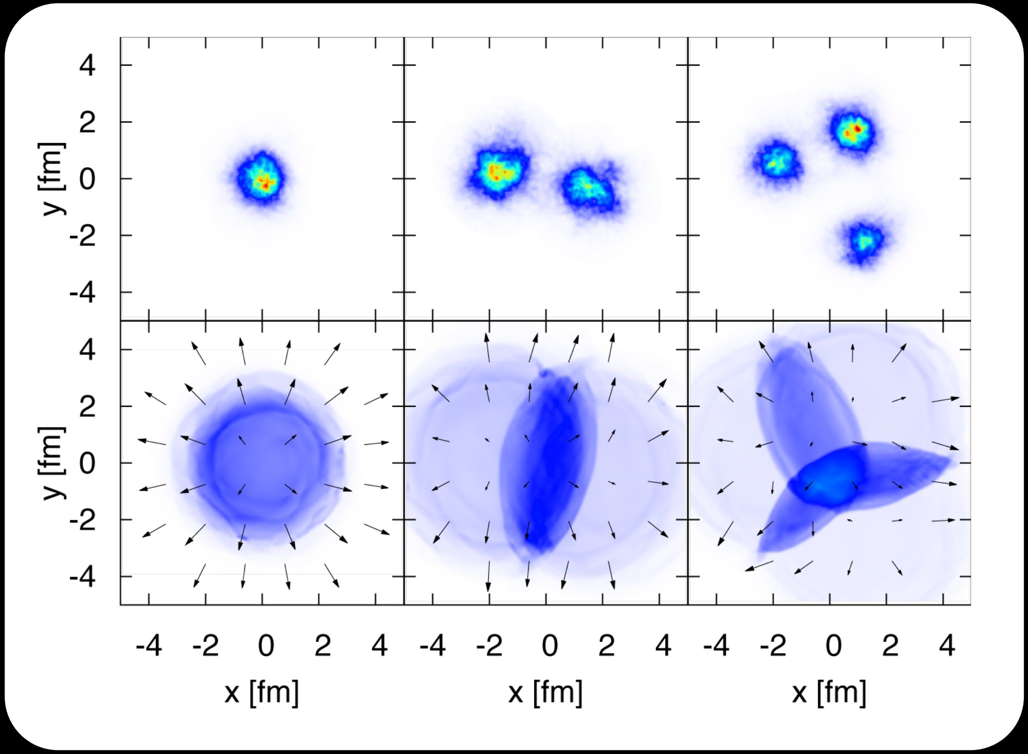


Partons are more likely to escape in the short direction → v_n



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

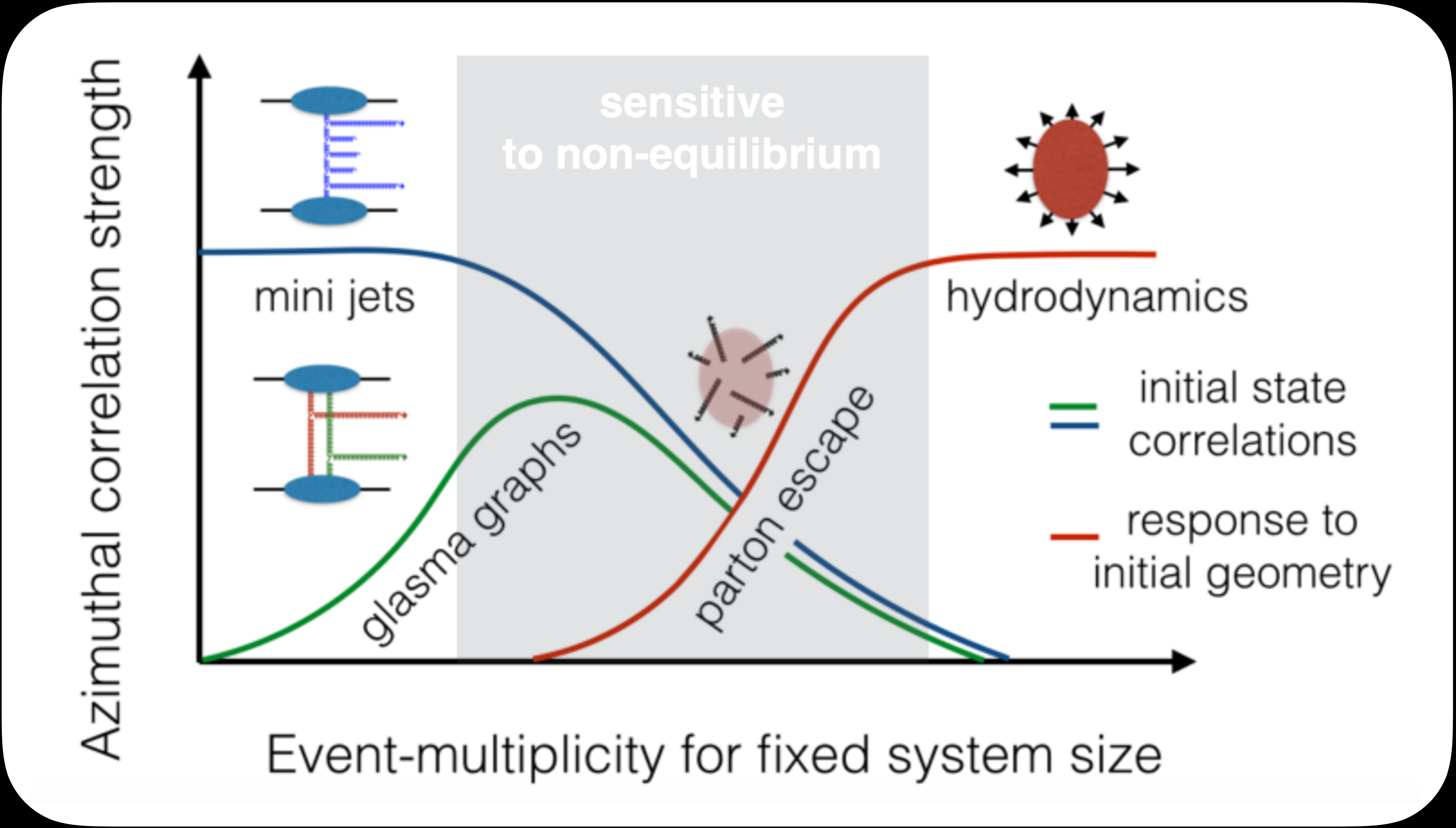
HOW TO DISTINGUISH "FLOW" FROM AN "INITIAL STATE" SCENARIO

- **Mass splitting of mean p_T and v_n:** (probably not good)
  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

COMPLETE PICTURE



S. SCHLICHTING, QUARK MATTER PROCEEDINGS, ARXIV:1601.01177

SUMMARY

U.S. DEPARTMENT OF ENERGY | Office of Science

- Azimuthal anisotropies in A+A collisions well understood
- Results in p+p and p+A look very similar
- Final state effect or initial state correlations?
- Probably we have a mixture of both - need to determine what effect dominates in which system/multiplicity

In any case: Exciting opportunity to learn about fluctuating proton shape and/or correlated multi-gluon distributions in nuclei!

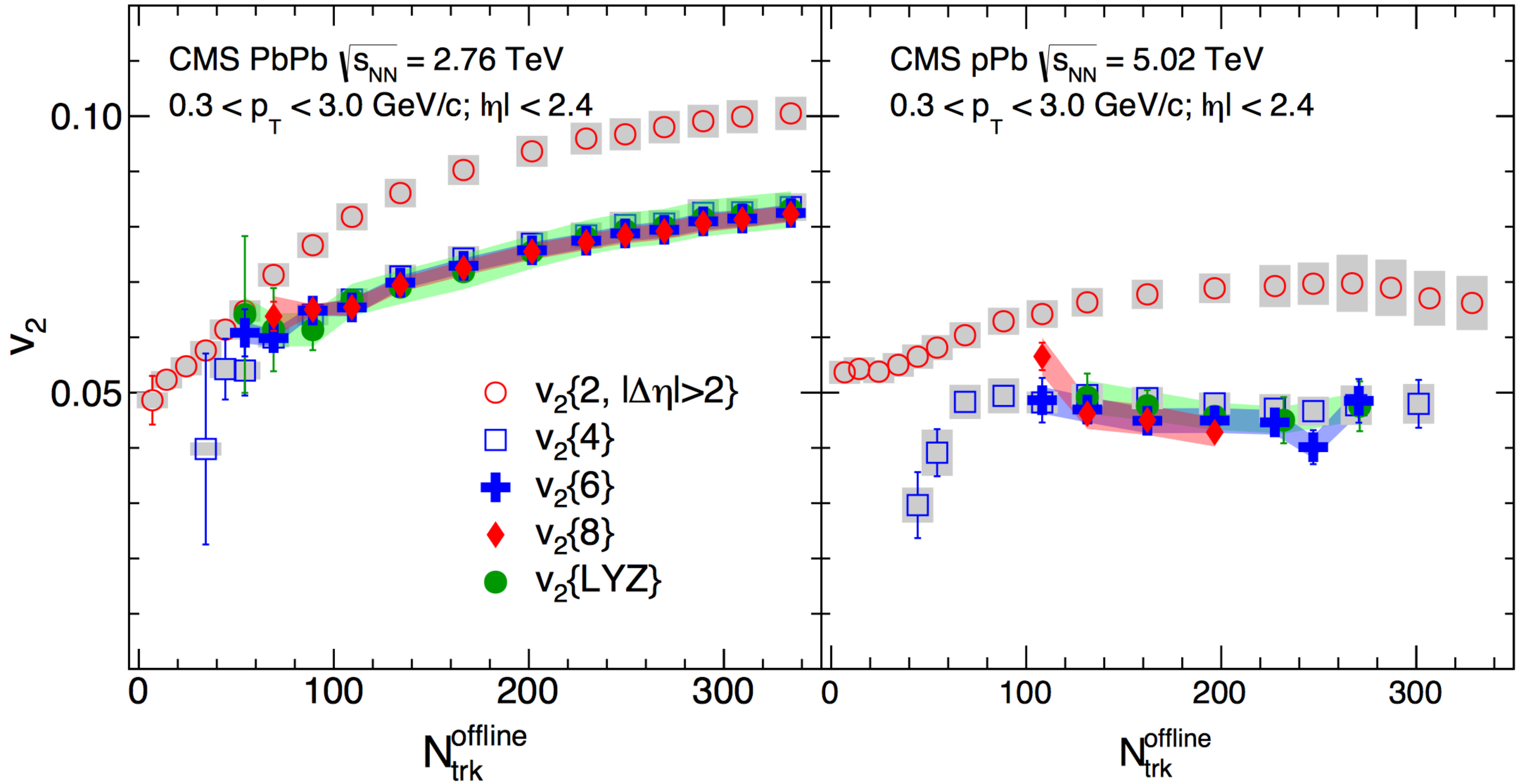
BACKUP

MANY CALCULATIONS OF RIDGE EFFECT FROM INITIAL STATE

T. LAPPI, B. SCHENKE, S. SCHLICHTING, R. VENUGOPALAN, JHEP 1601 (2016) 061

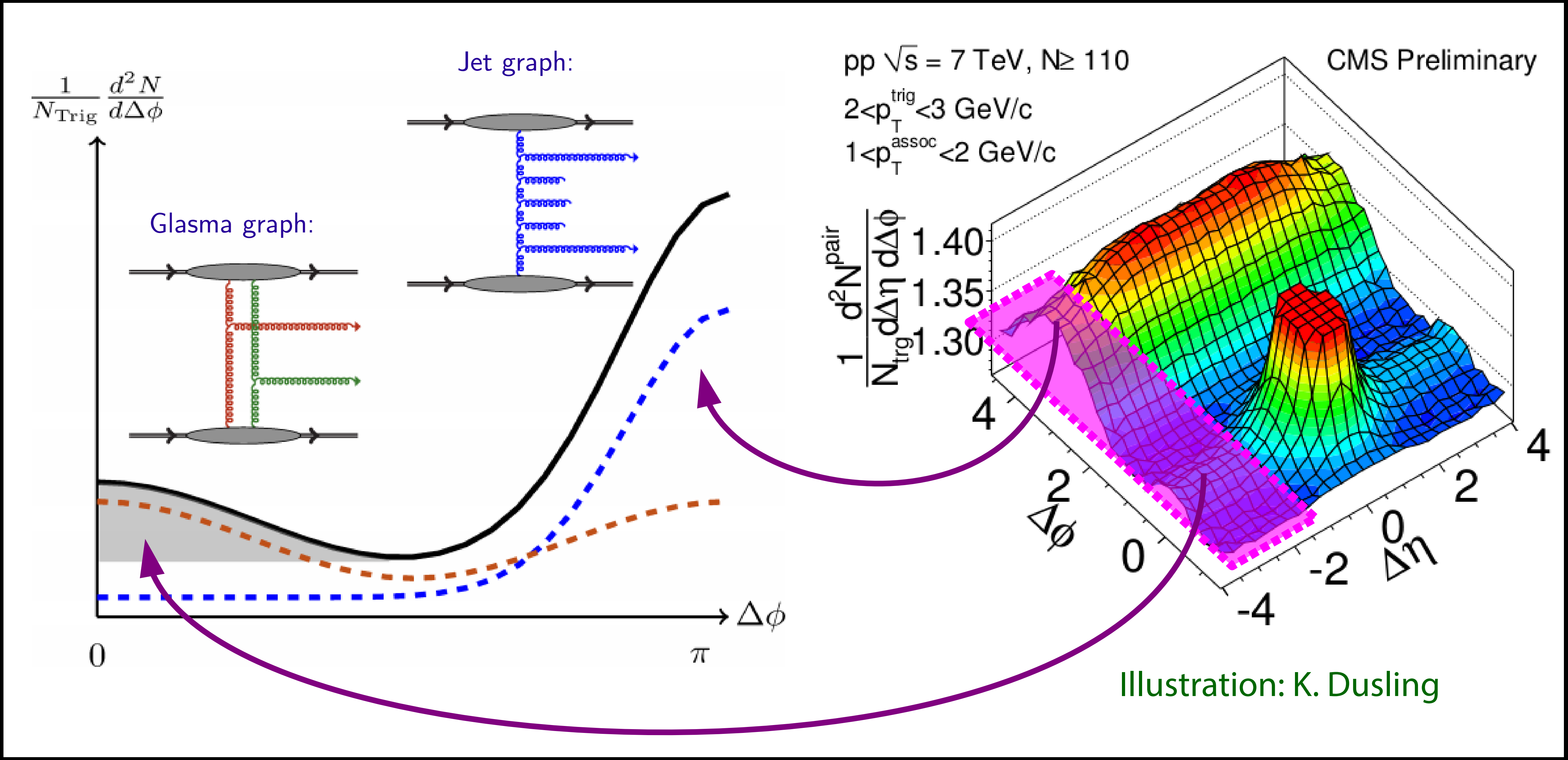
1. Dilute-dense limit:
    - **Glasma graph approximation** Dumitru, Dusling, Fernandez-Fraile, Gavin, Gelis, Kovchegov, Jalilian-Marian, Lappi, McLerran, Moschelli, Venugopalan, …
      two gluon exchange (not more) and Gaussian statistics of color charges (MV model) - closer to dilute-dilute limit
    - **Nonlinear Gaussian approximation** Dominguez, Marquet, Wu; Lappi, Schenke, Schlichting, Venugopalan
      resums multiple gluon exchanges, neglects non-Gaussianities
    - **JIMWLK evolution** Lappi, Phys.Lett. B744 (2015) 315-319
      introduces non-Gaussianities via evolution
      Color Domain Model A. Dumitru, A.V. Giannini, L. McLerran, V. Skokov
      introduces additional non-Gaussian correlations (like the ones introduced by JIMWLK evolution (small) or intrinsic four point correlations of significant magnitude)
2. Dense-dense limit:
    - **Classical Yang-Mills calculation** Schenke, Schlichting, Venugopalan
      includes multiple-gluon exchange, “rescattering”

v_2 IN p+Pb COLLISIONS
MULTI-PARTICLE CORRELATIONS



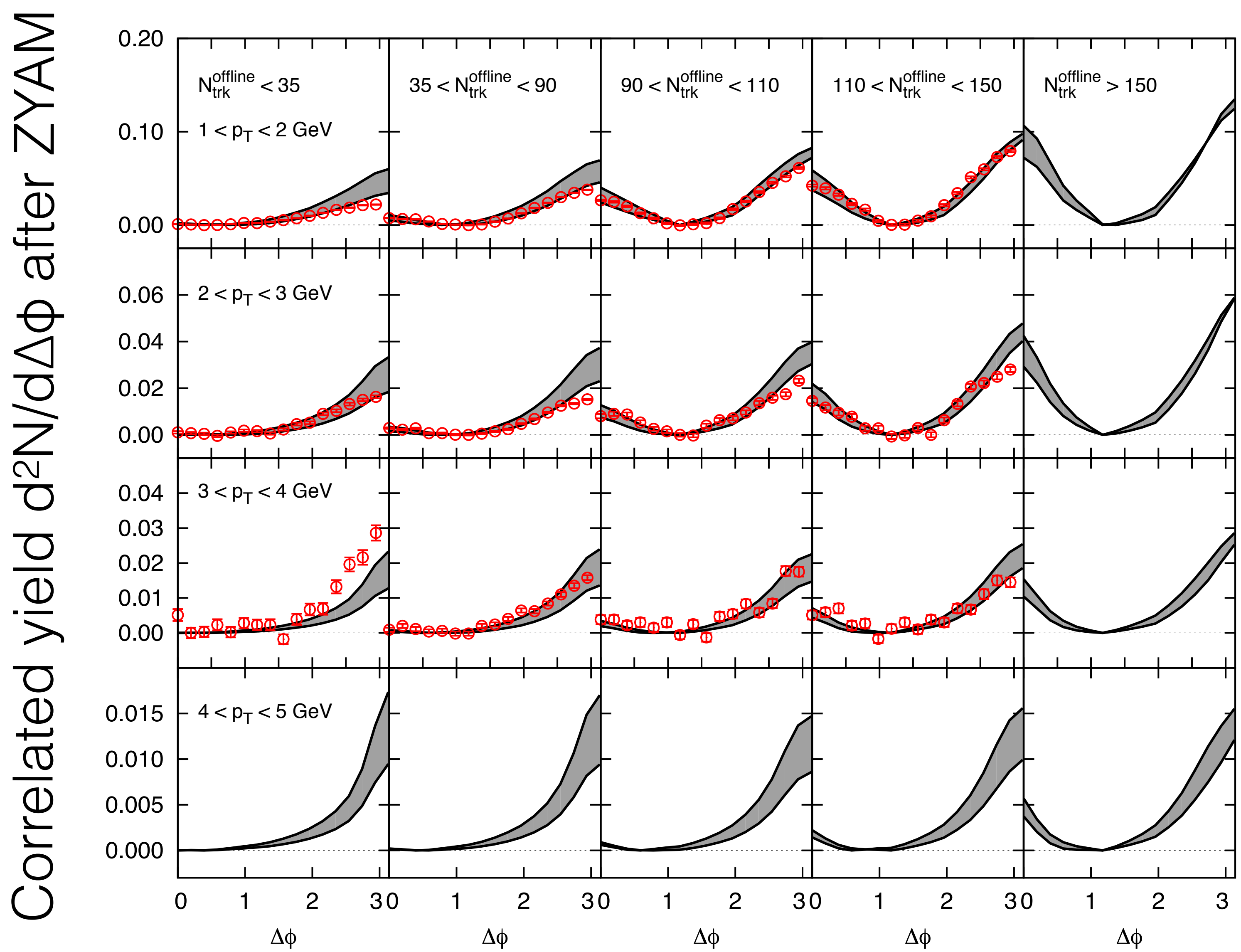
GLASMA GRAPH APPROXIMATION

Dusling, Venugopalan, Phys.Rev. D87 054014 (2013)



Correlated yield vs. angular difference

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



Systematics well described

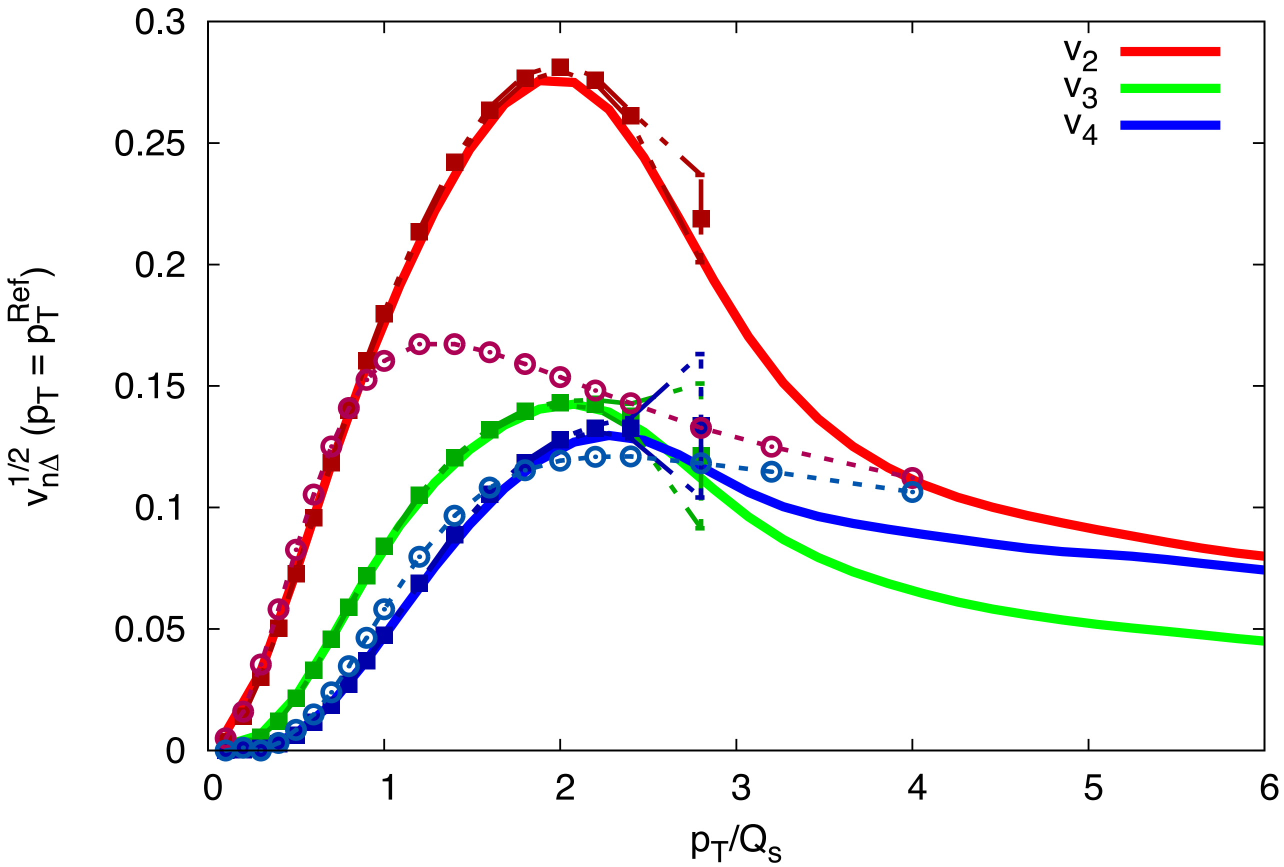
Ridge larger in p+A than in p+p because of larger saturation scale

Dilute-dense limit: approximation schemes

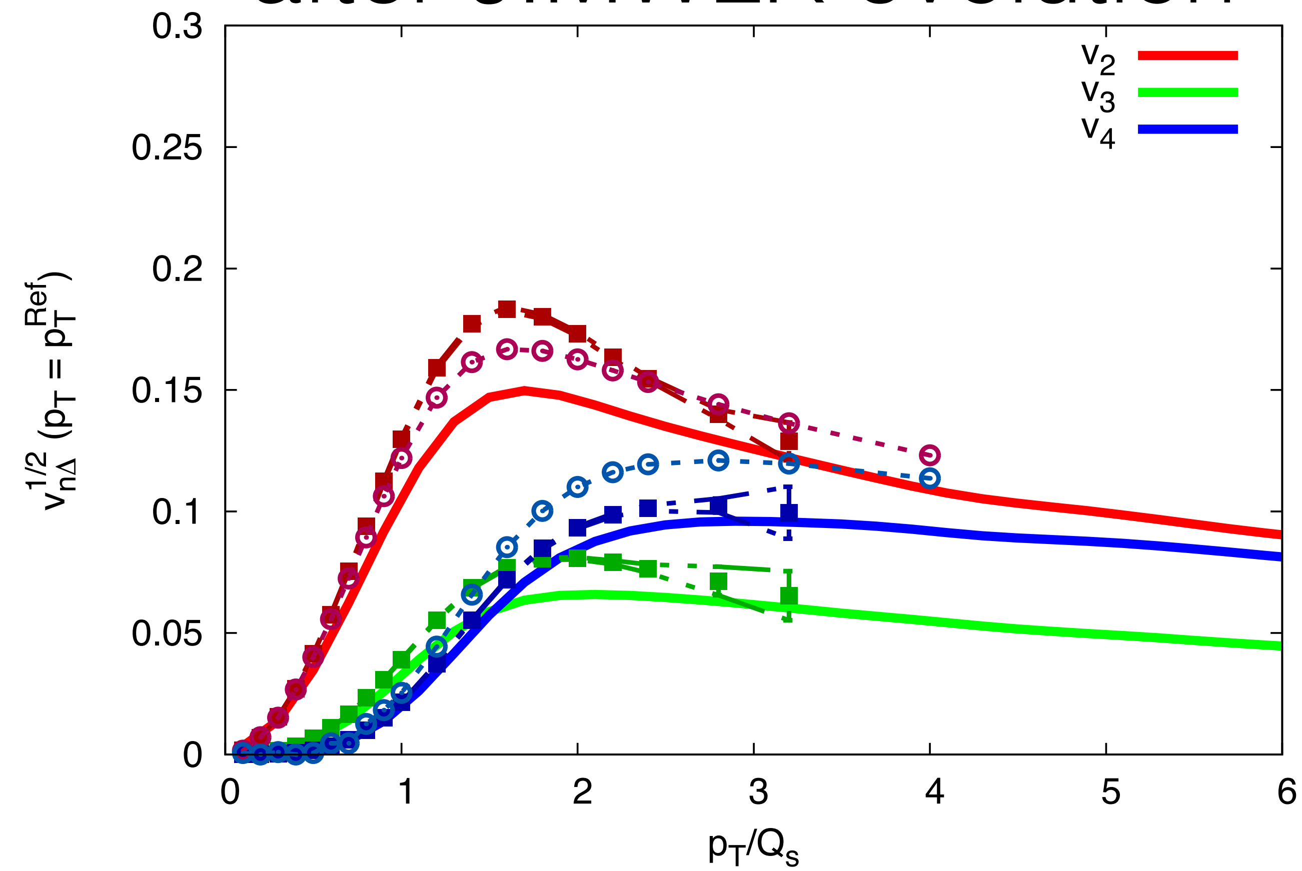
T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 (2016) 061

Scattering of two independent quarks off a large nucleus

MV model



after JIMWLK evolution



solid:numerical JIMWLK
dash-dotted (squares): non-linear Gaussian
dotted (circles): glasma graph

The two approximate schemes use the dipole operator extracted from the numerical JIMWLK evolution

Dilute-dense limit: approximation schemes

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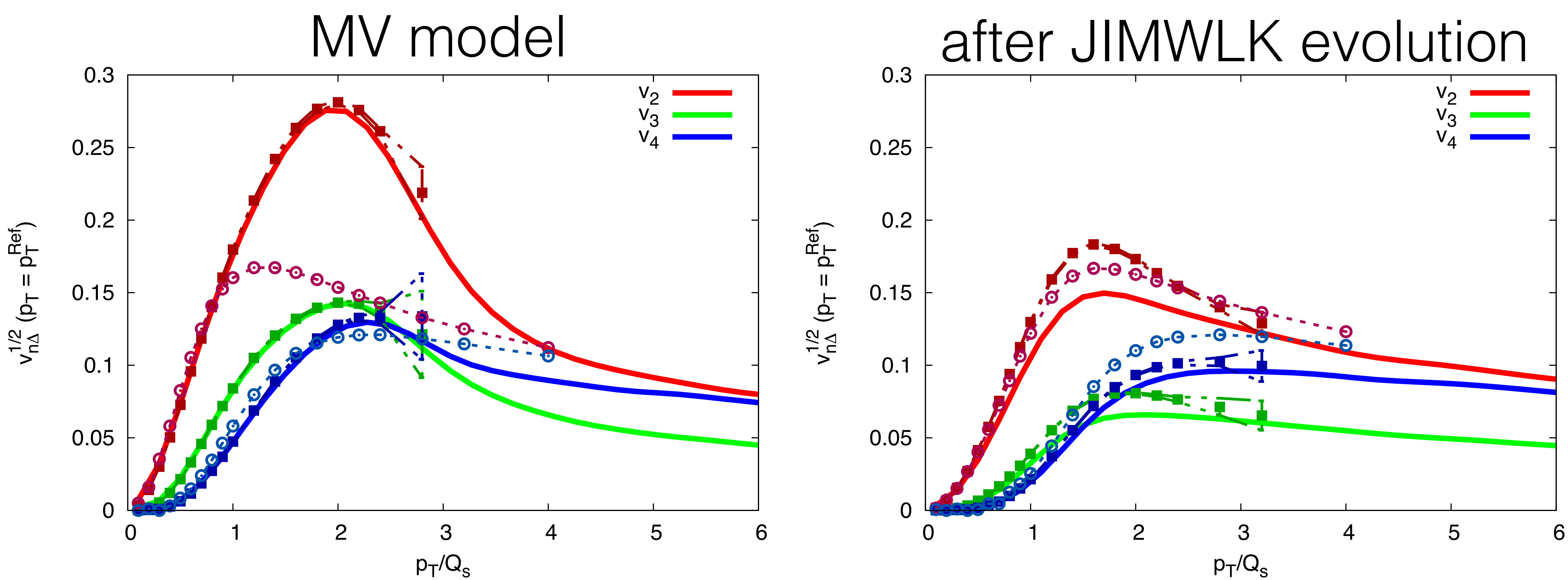

- No odd v_n in glasma graph approximation by symmetry
- Perfect agreement between non-linear Gaussian approximation and numerical result in MV (must be)

Correlations are suppressed by the number of colors

T. Lappi, B. Schenke, S. Schlichting, R. Venugopalan, JHEP 1601 (2016) 061

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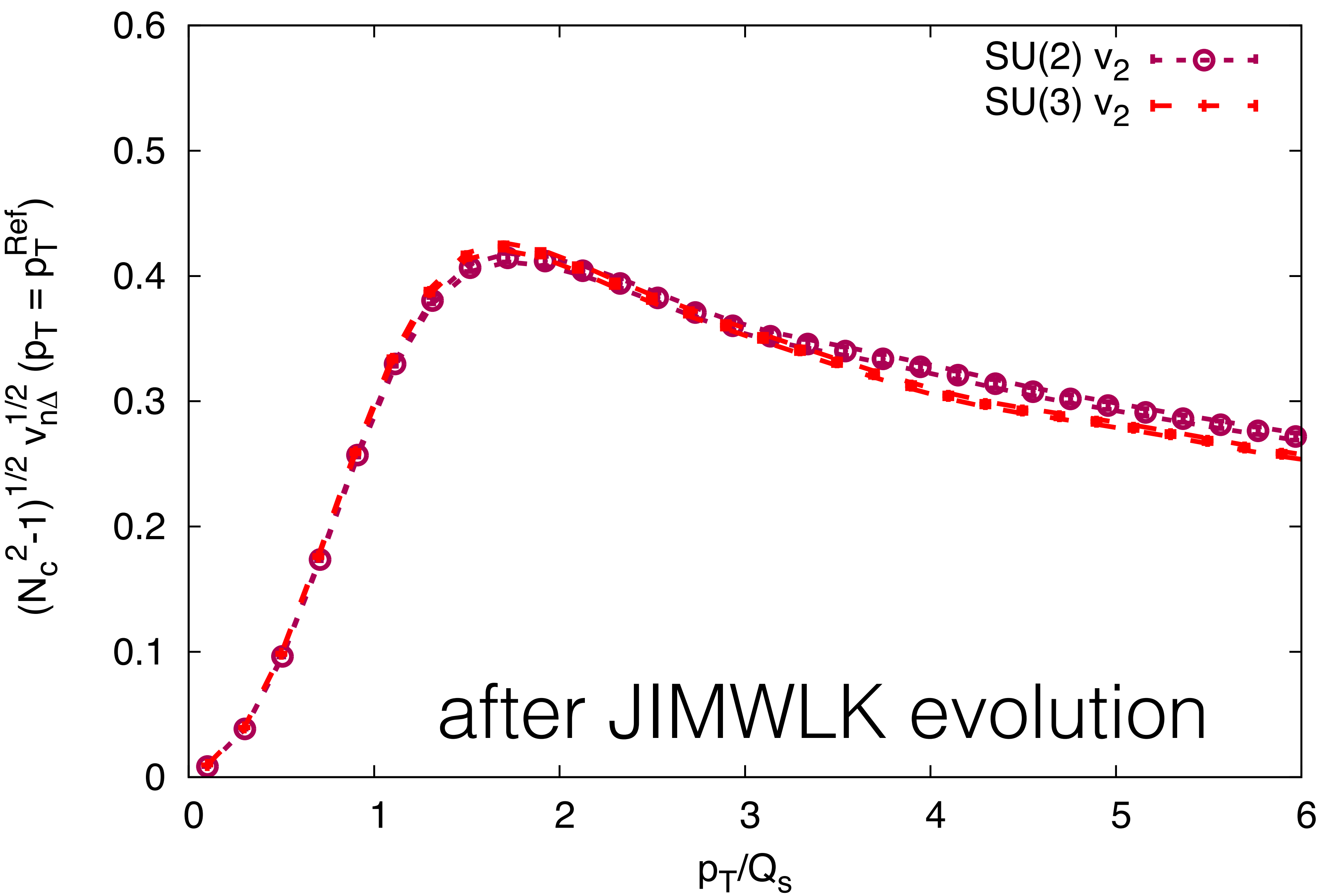

v_n scales as $(N_c^2 - 1)^{-\frac{1}{2}}$

azimuthal correlations in the double inclusive spectrum $\sim (N_c^2 - 1)^{-1}$