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H-QM Helmholtz Research School Quark Matter Studies

HGS-HIRe for FAIR Helmholtz Graduate School for Hadron and Ion Research

Initial and final state interactions in proton-lead collisions

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**in collaboration with
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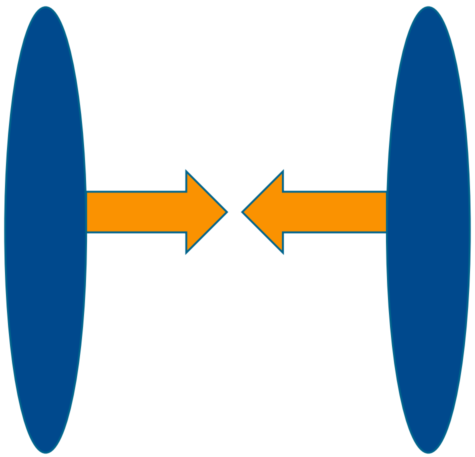
Zhe Xu, Carsten Greiner**

CRC-TR 211 Strong-interaction matter under extreme conditions

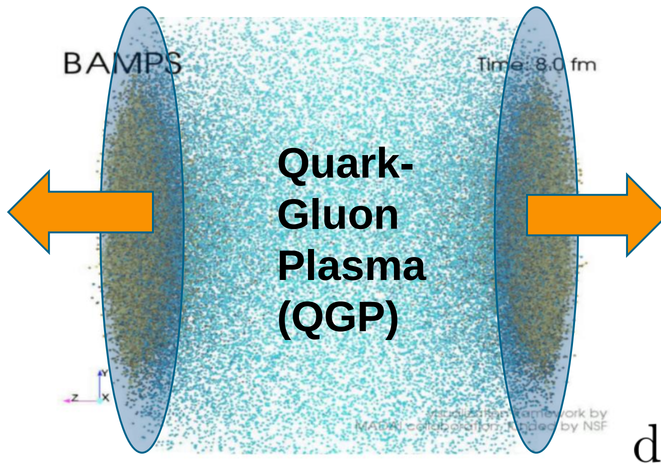
Phys. Rev. D 96, 091504, 2017

Bormio 2018

Heavy-ion collisions



e.g. Pb+Pb @ 5 TeV

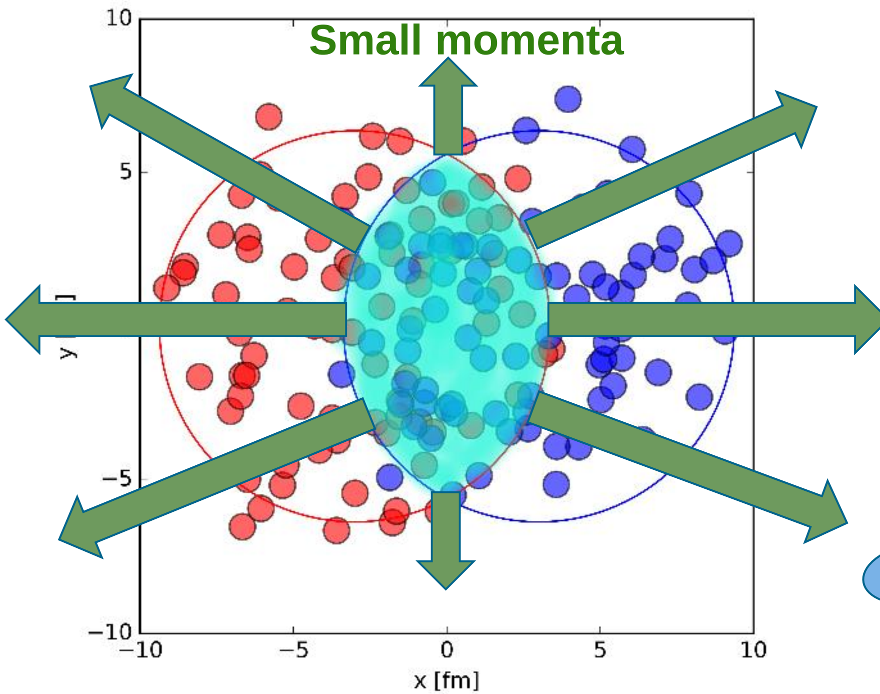


- Very opaque medium
- Strong energyloss
- Azimuthal correlations of low energy particles

$$\mathrm{d}N^{0-5\%}_{\mathrm{PbPb}}/\mathrm{d}y \sim 1500$$

Momentum asymmetry measurable:

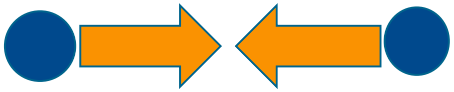
„elliptic flow“ – hydrodynamic response to initial geometry



Large momenta due to large pressure gradient

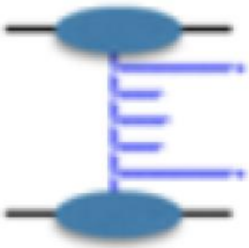
„well understood“ ☺

Different physics in smaller systems (?)

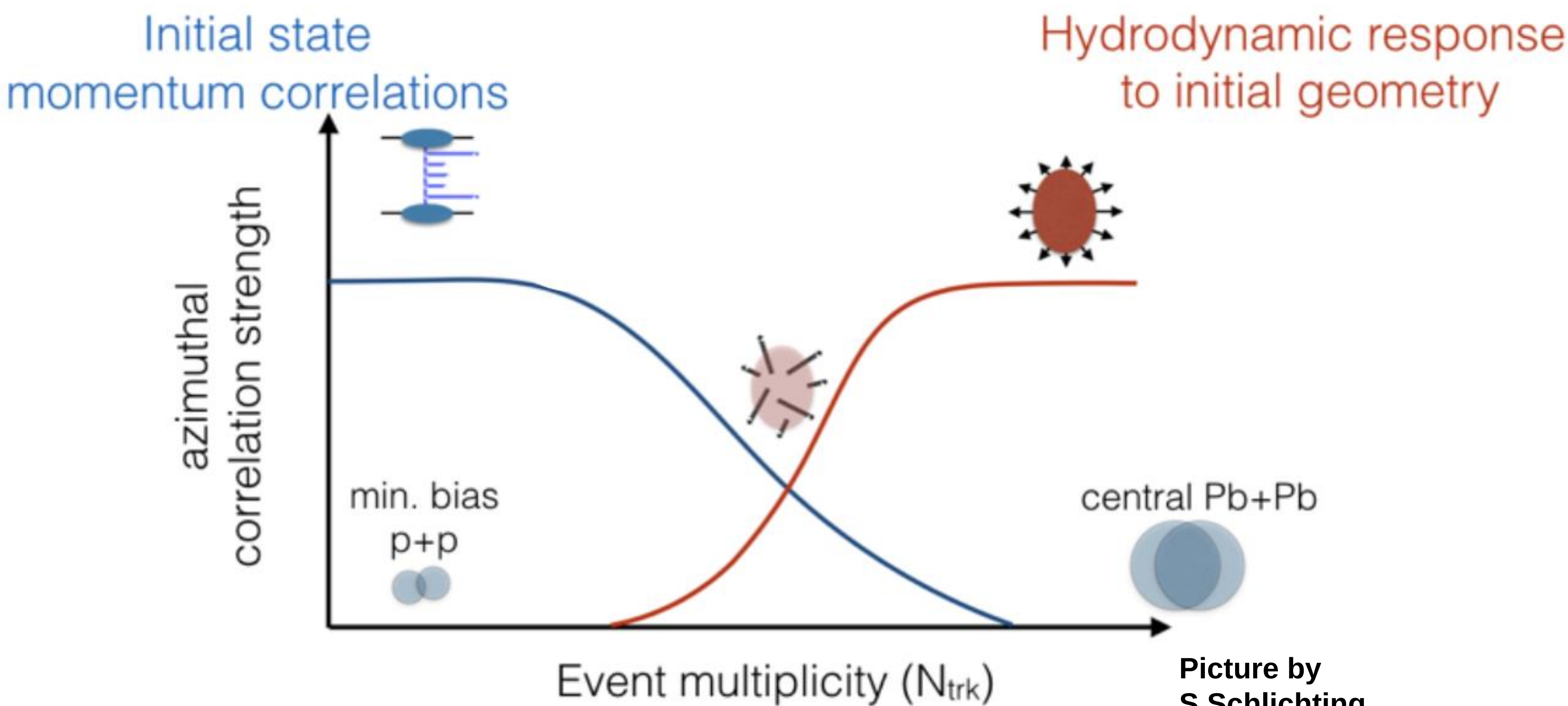


Proton-proton collisions

$$\mathrm{d}N_{pp}^{\mathrm{min.bias}}/\mathrm{d}y \sim 5$$

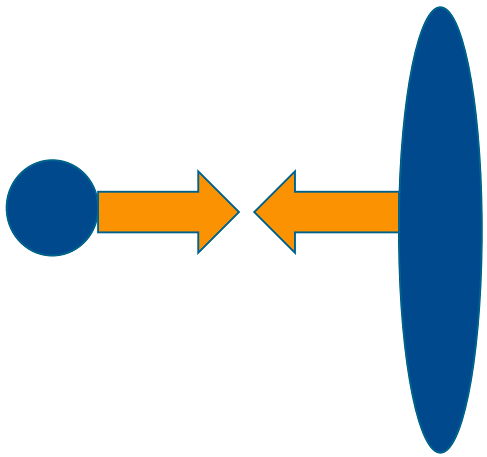


Initial state momentum correlations

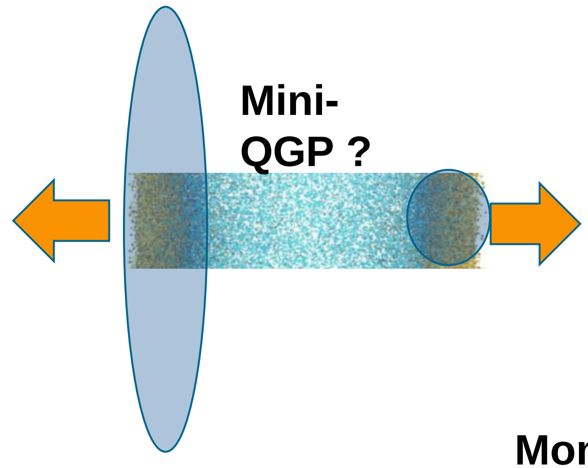


Picture by S.Schlichting

Proton-Heavy-ion (pA) collisions

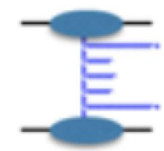


Proton - Lead collision



Mini-
QGP ?

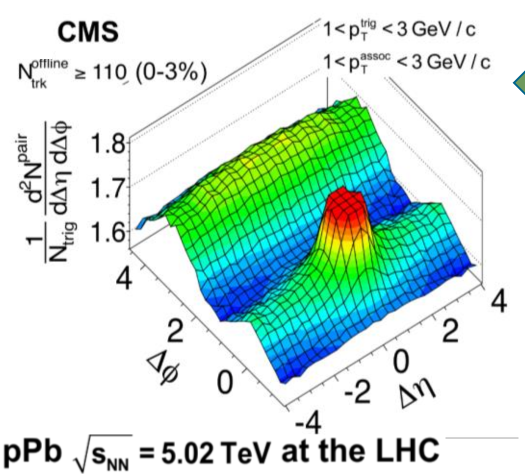
Or only
„initial state“?

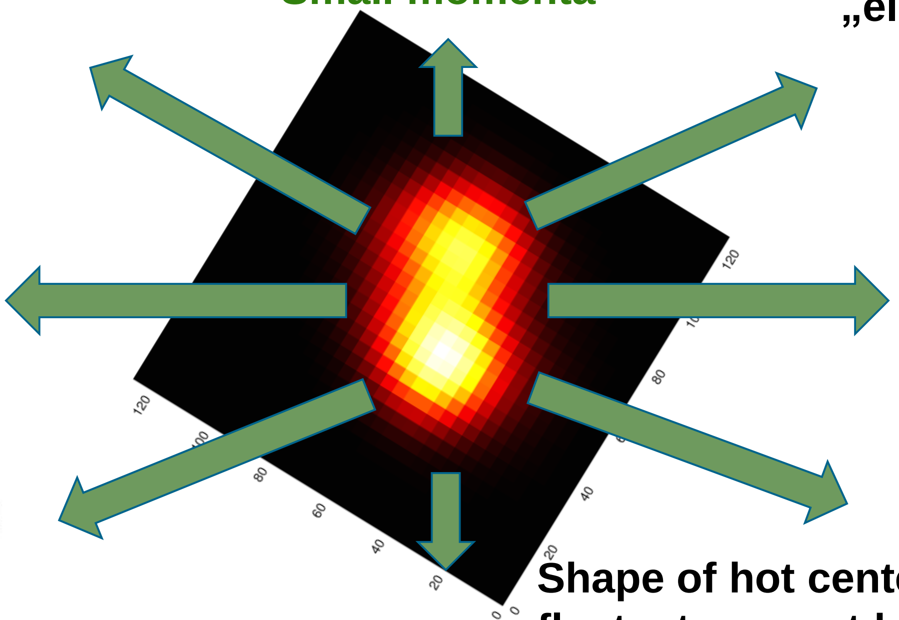


Momentum asymmetry
measurable:
„elliptic flow“ v_2

Small momenta

Also long-range
correlations:





Large momenta due to
- pressure gradient ?
- Initial state momentum configuration ?

Shape of hot center
fluctuates event by event

Our model

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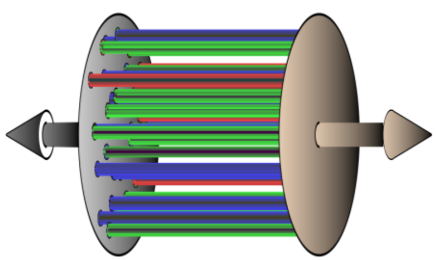
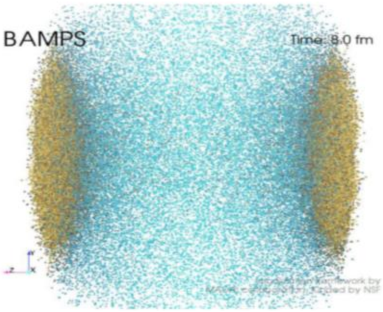
initial state with interactions

(Glasma: „IP-Glasma“)

+ final state with interactions

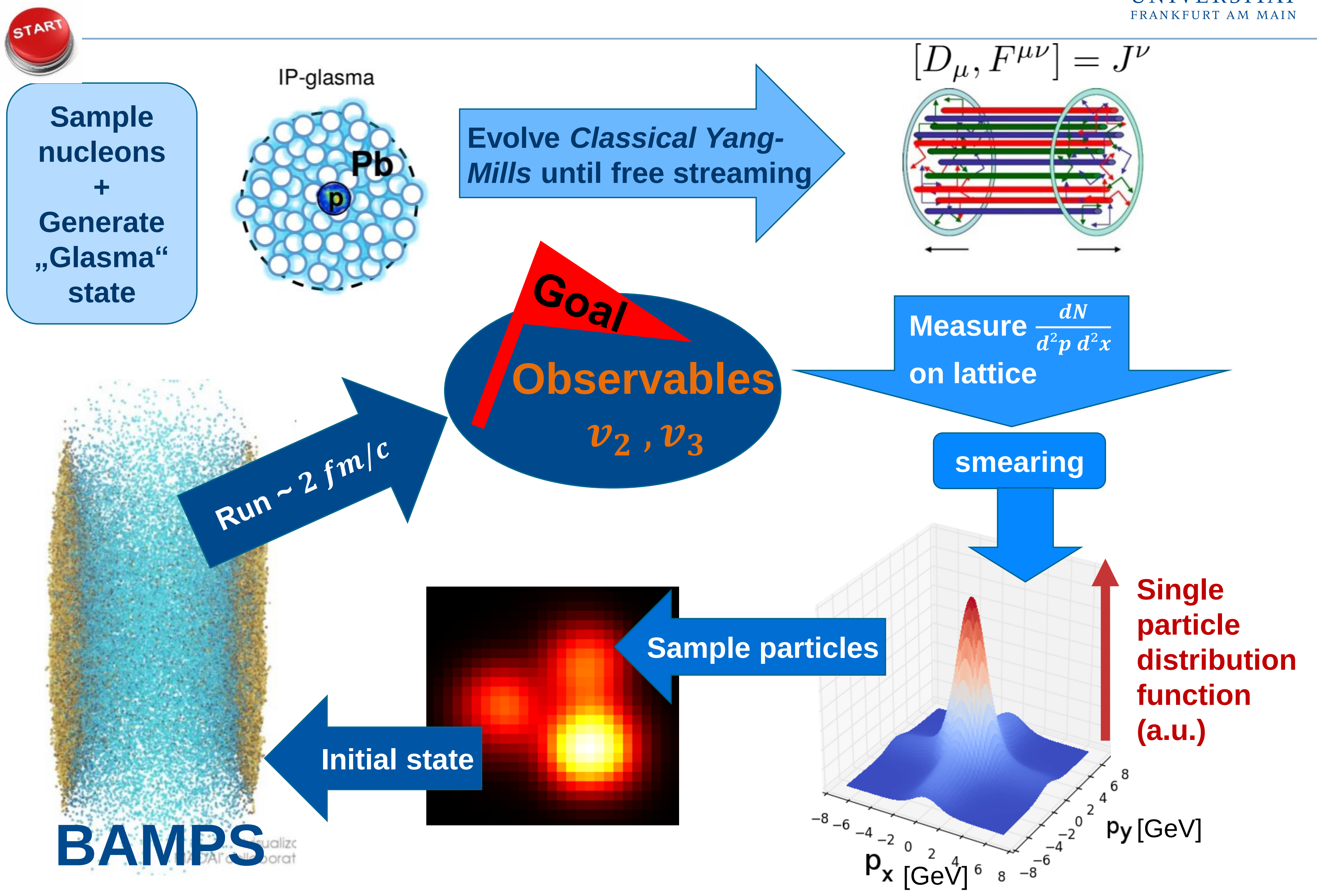
(parton cascade: „BAMPS“)





Time: 0-0.2 fm/c   **0.2 – 2 fm/c**

New Model: Initial + Final state interactions



Initial state: Color Glass Condensate „CGC“

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Color charge sources: $J^{\mu,a} = \delta^{\mu+}\delta(x^-)\rho^a_A(x_\perp)$

Classical Yang-Mills equations: $[D_\mu, F^{\mu\nu}] = J^\nu$

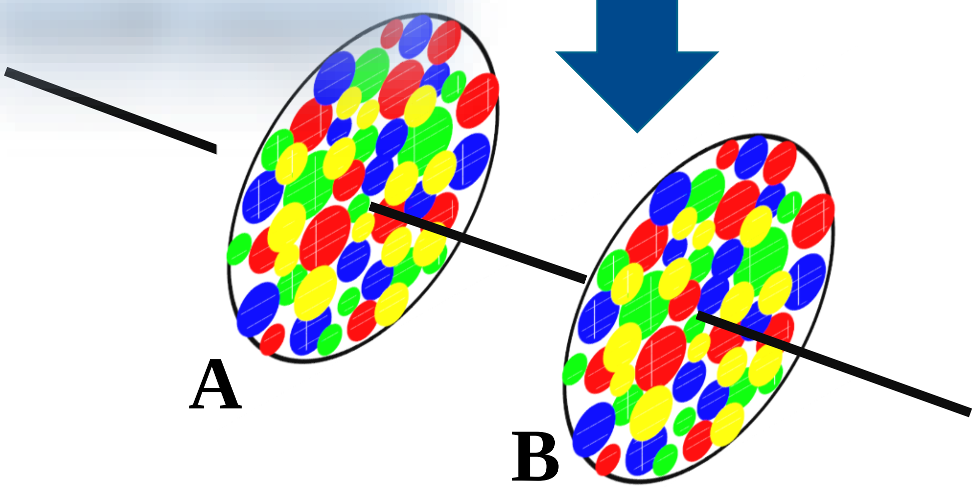
with $D_\mu = \partial_\nu - igA^a_\mu T^a$ and $(T^a)_{bc} = -if_{abc}$

Consider gluons as **classical fields**:
Source: Color current $J^{\mu,a}$
Color charge: $\rho^a_A(x_T, x^-)$

Claim

CGC: Fundamental matter of high energy hadrons

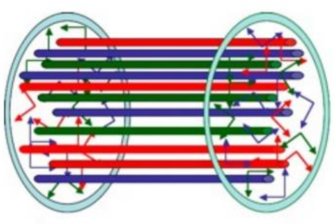
Two sheets of color charge collide: Gluon dominated system



IP-Sat model
(Impact parameter saturation)

- Sample nucleon positions
- Color charge sampled per nucleon
- Proton gluon distributions constrained by HERA e+p DIS data

Kowalski & Teaney, PRD68,114005 (2003)
Schenke et al., PRL 108,252301 (2012)



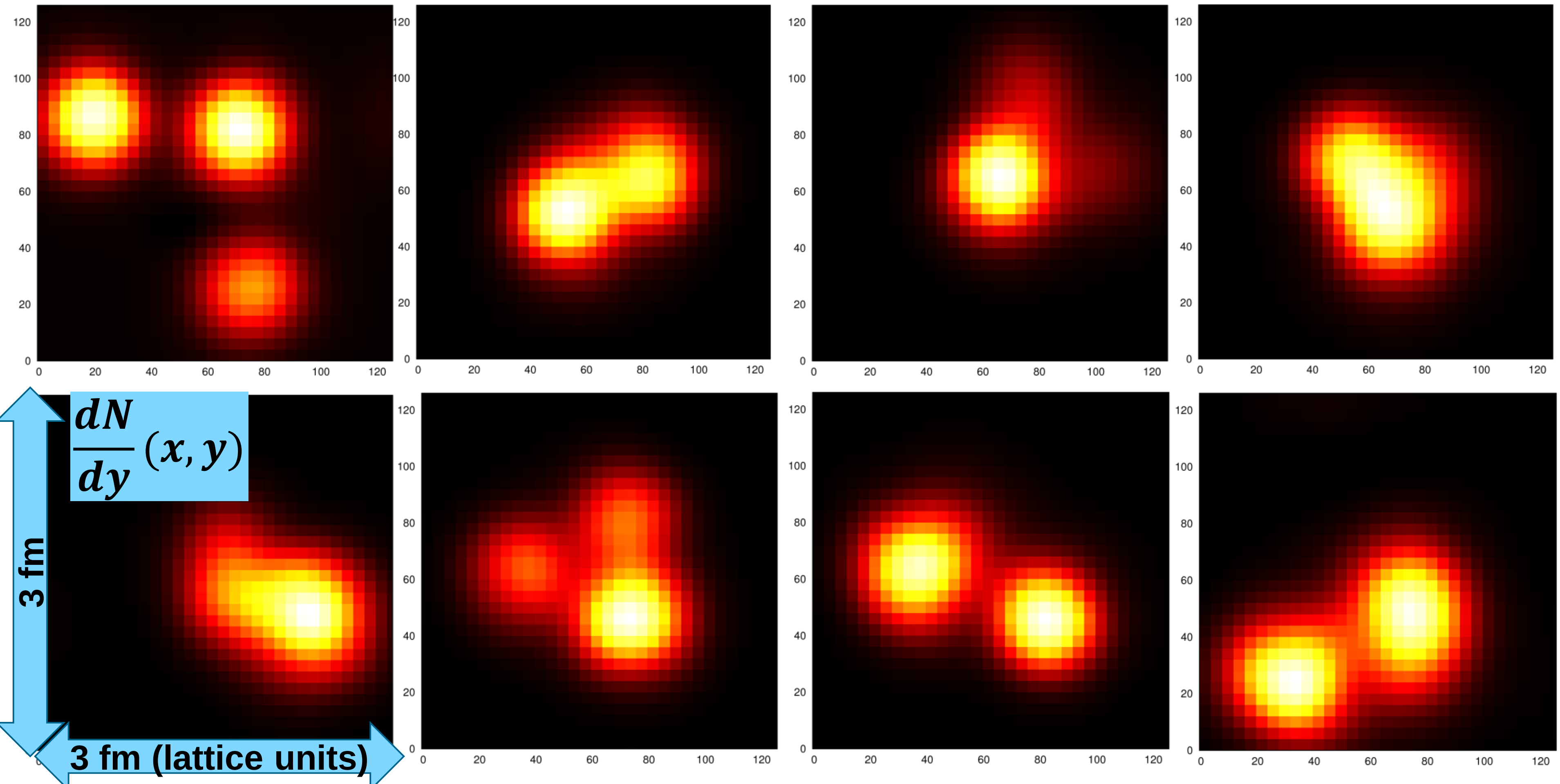
Initially longitudinal *E* and *B* fields

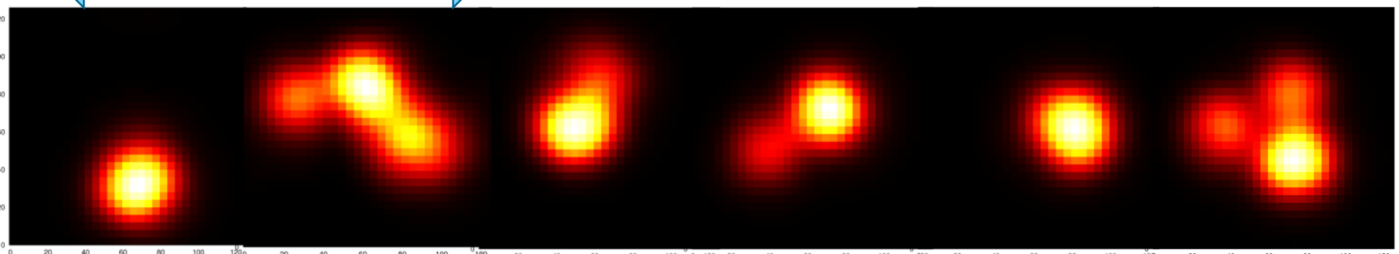
„Glasma“. Solved on the lattice.
(→ S.Schlichting & B.Schenke)

McLerran et al., Phys.Rev. D49 (1994) 2233, 3352 D50 (1994) 2225

Event-by-Event: Coordinate Space Distributions

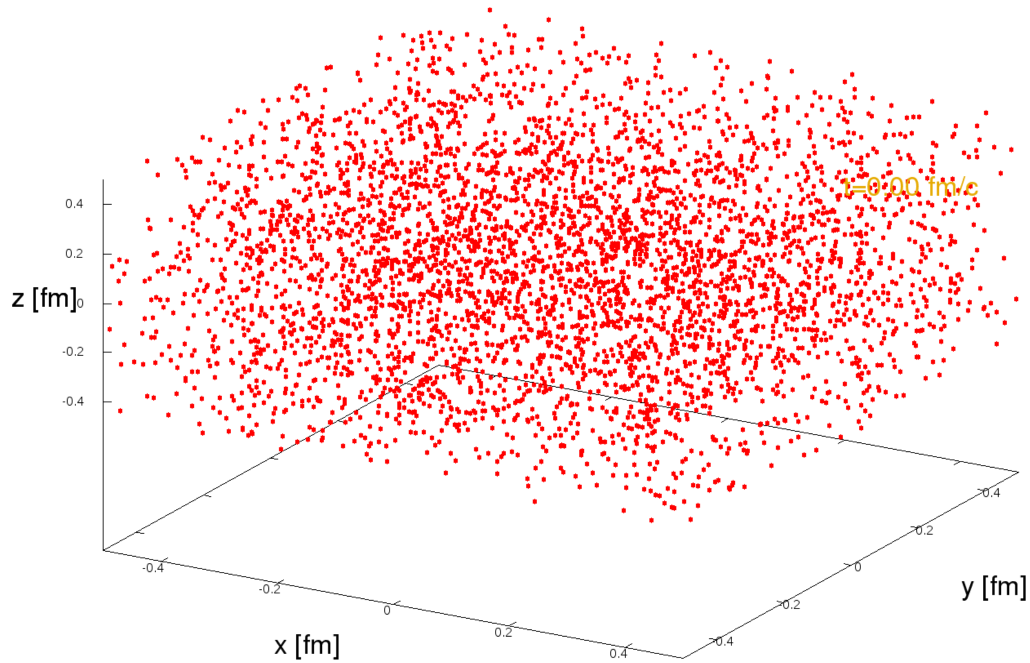
After classical Yang-Mills evolution





Typically 50-100 events per multiplicity class sufficient here

Parton cascade „BAMPS“



Solves the Boltzmann equation
(numerically exact, Monte Carlo)

"$f(x,p)$"

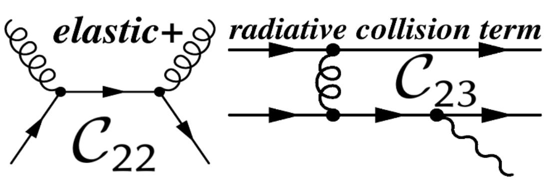
Single particle distribution function (a.u.)

- Quarks + Gluons
- pQCD/QED cross sections
- Elastic + radiative scattering
- Ideal equation of state

Used as model for heavy-ion collision:
Expanding 3+1d geometry

BAMPS: **B**oltzmann **A**pproach to **M**ulti-**P**arton **S**catterings

$$p^\mu \partial_\mu f(x,p) = \mathcal{C}_{22}[f] + \mathcal{C}_{23}[f]$$



cf. Talk of Carsten Greiner

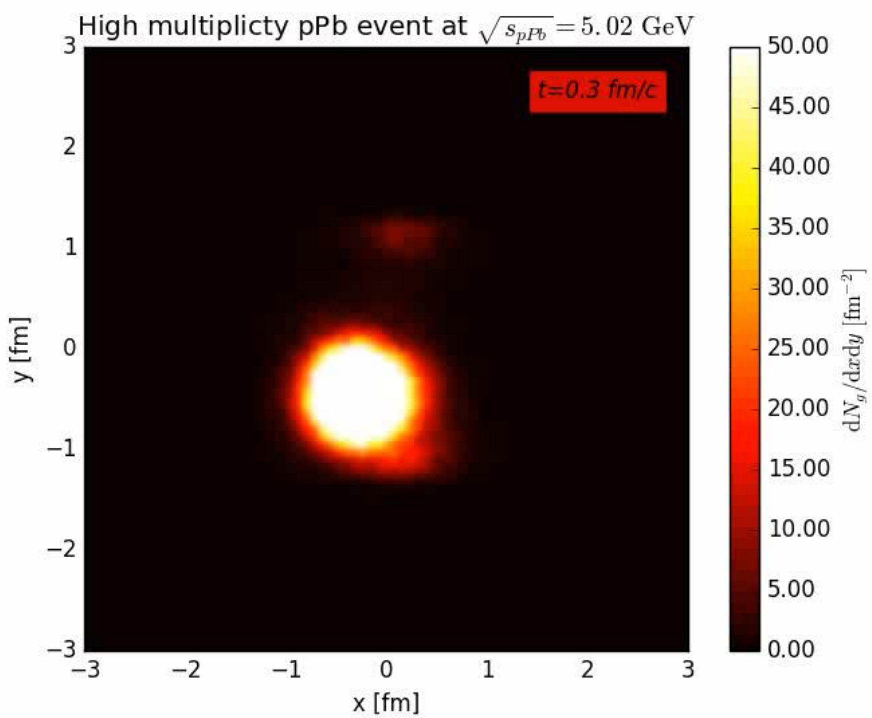
BAMPS evolution of proton-lead collision

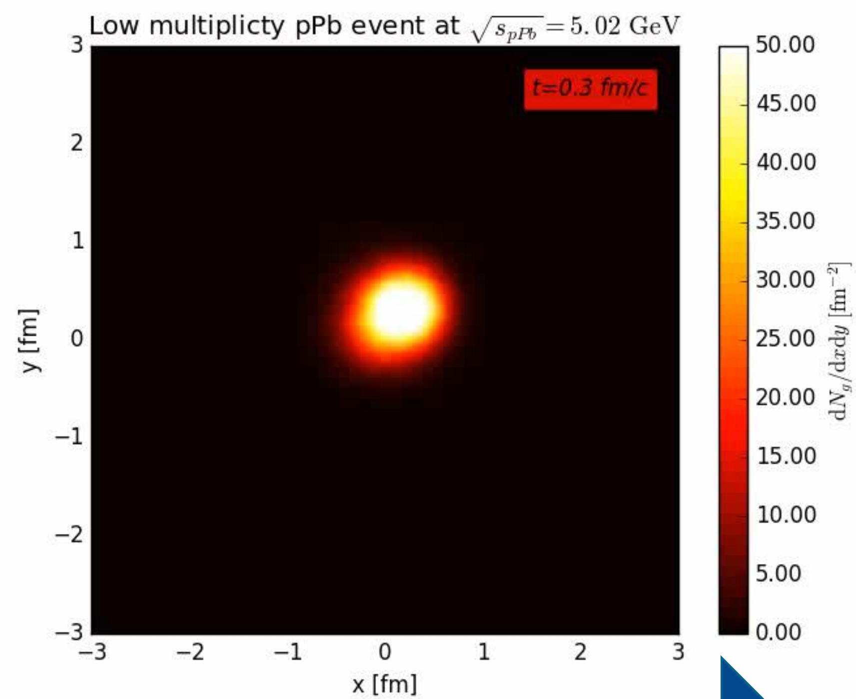
High multiplicity:

Pressure gradients build up flow?

Low multiplicity:

Anisotropy due to initial fluctuation?



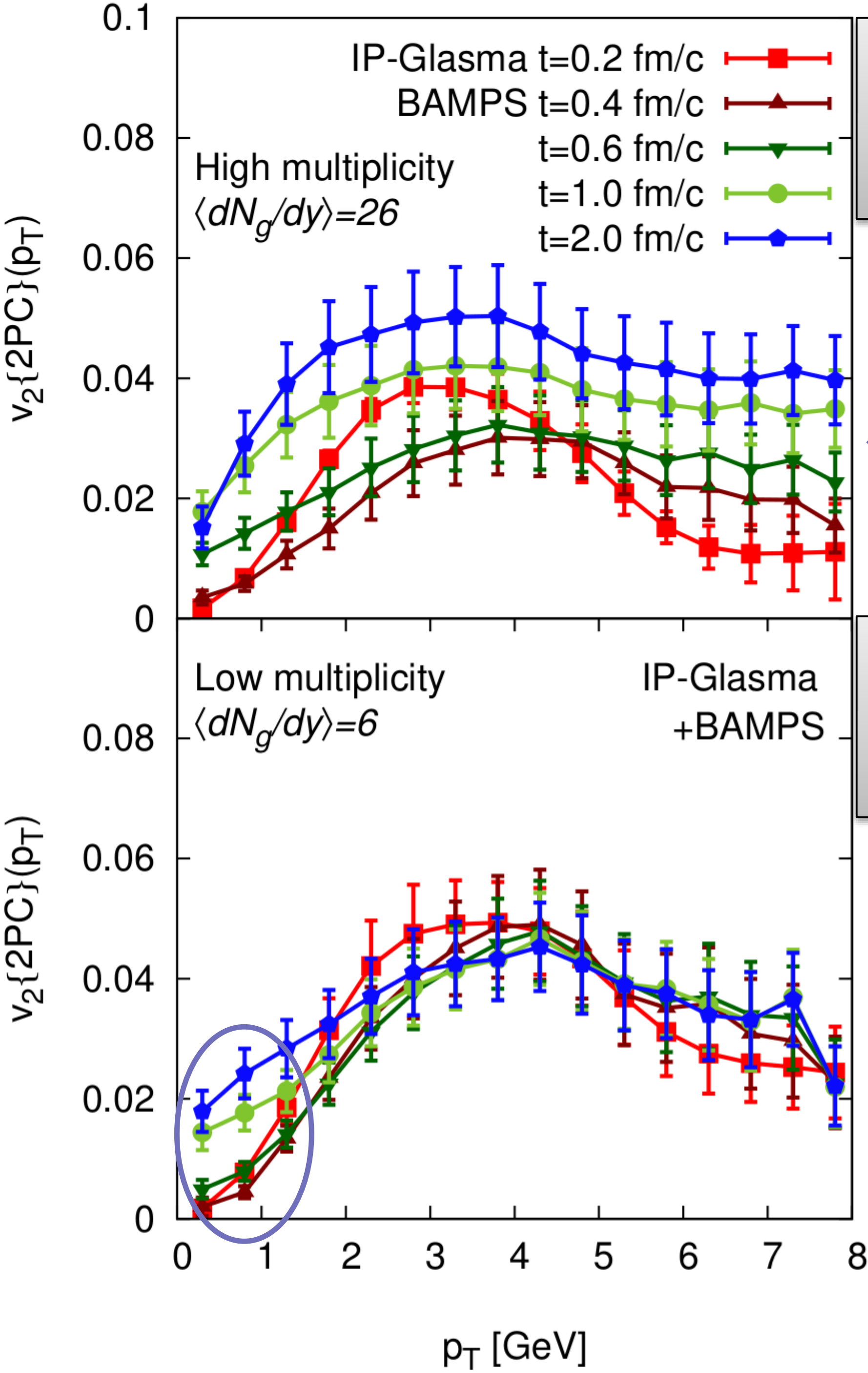


We are working more differential on 6 multiplicity classes

(Color code: particle number / transverse area)
rapidity integrated, only formed particles

Results

Flow observables for p+Pb



High multiplicity

$$(\mathrm{d}N_g/\mathrm{d}y)\,/\,\langle \mathrm{d}N_g/\mathrm{d}y\rangle > 2.5$$

Time evolution of momentum symmetry non trivial

- Symmetry-axis rotates
- Isotropization
- Pressure driven expansion

Low multiplicity

$$0.5 < (\mathrm{d}N_g/\mathrm{d}y)\,/\,\langle \mathrm{d}N_g/\mathrm{d}y\rangle < 1$$

Only at low p_T pressure driven enhancement

At higher momenta: initial state correlations persists

Test: Randomize momenta

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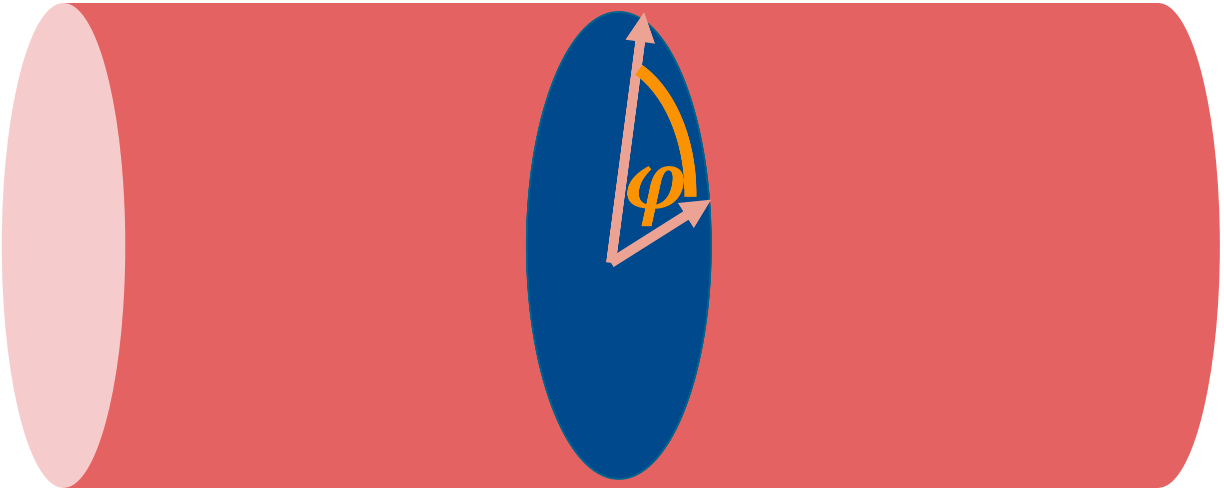
*Which influence comes from **geometry**, which part comes from **initial momentum correlations** ?*

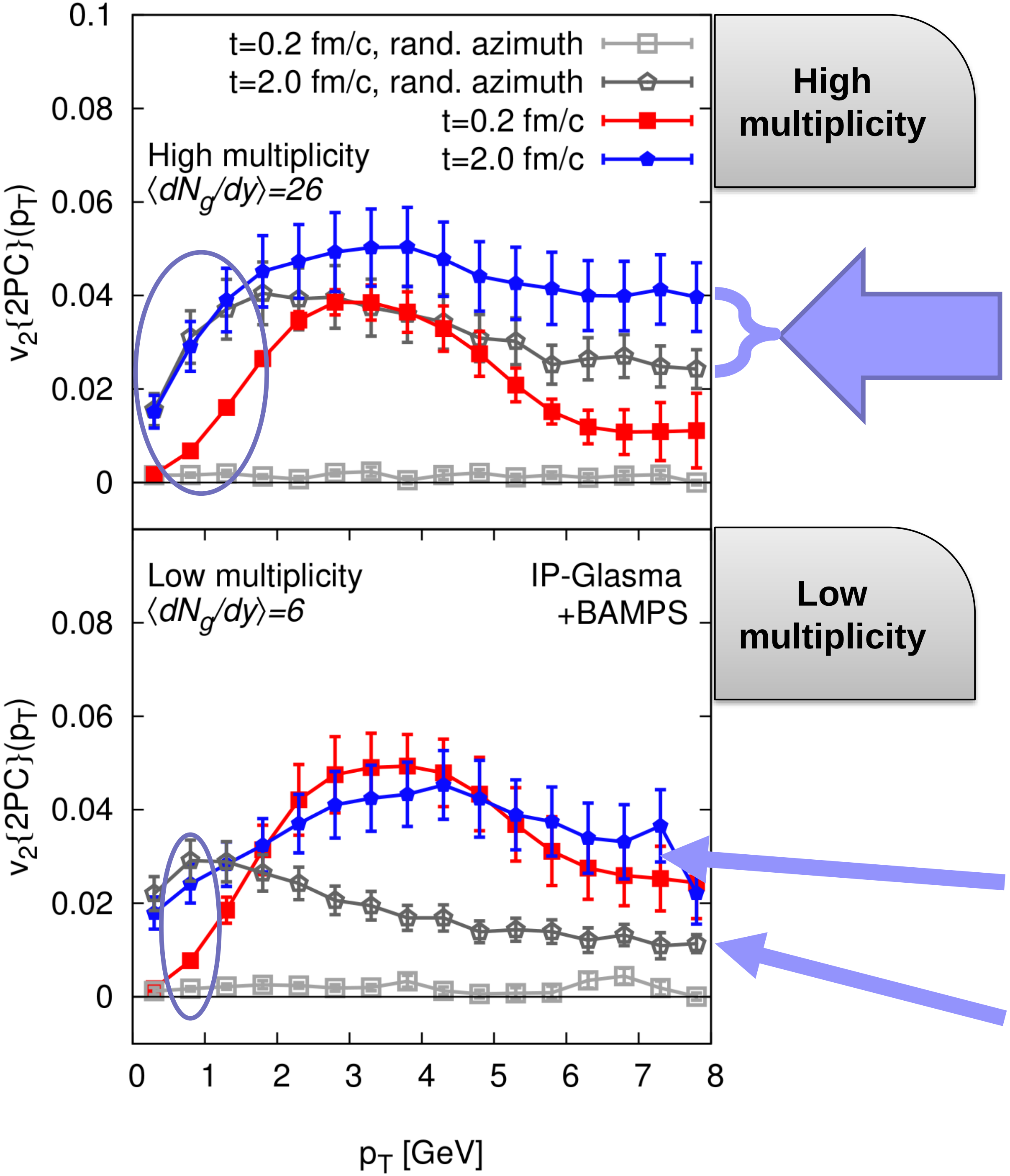
This is what hydro does!



Randomize initial transverse momentum direction

- **Keep $|p_T|, y, \vec{x}$ fix (from usual IP-Glasma)**

Look at $v_2(2PC)$ and $v_2(eccentricity\ plane)$



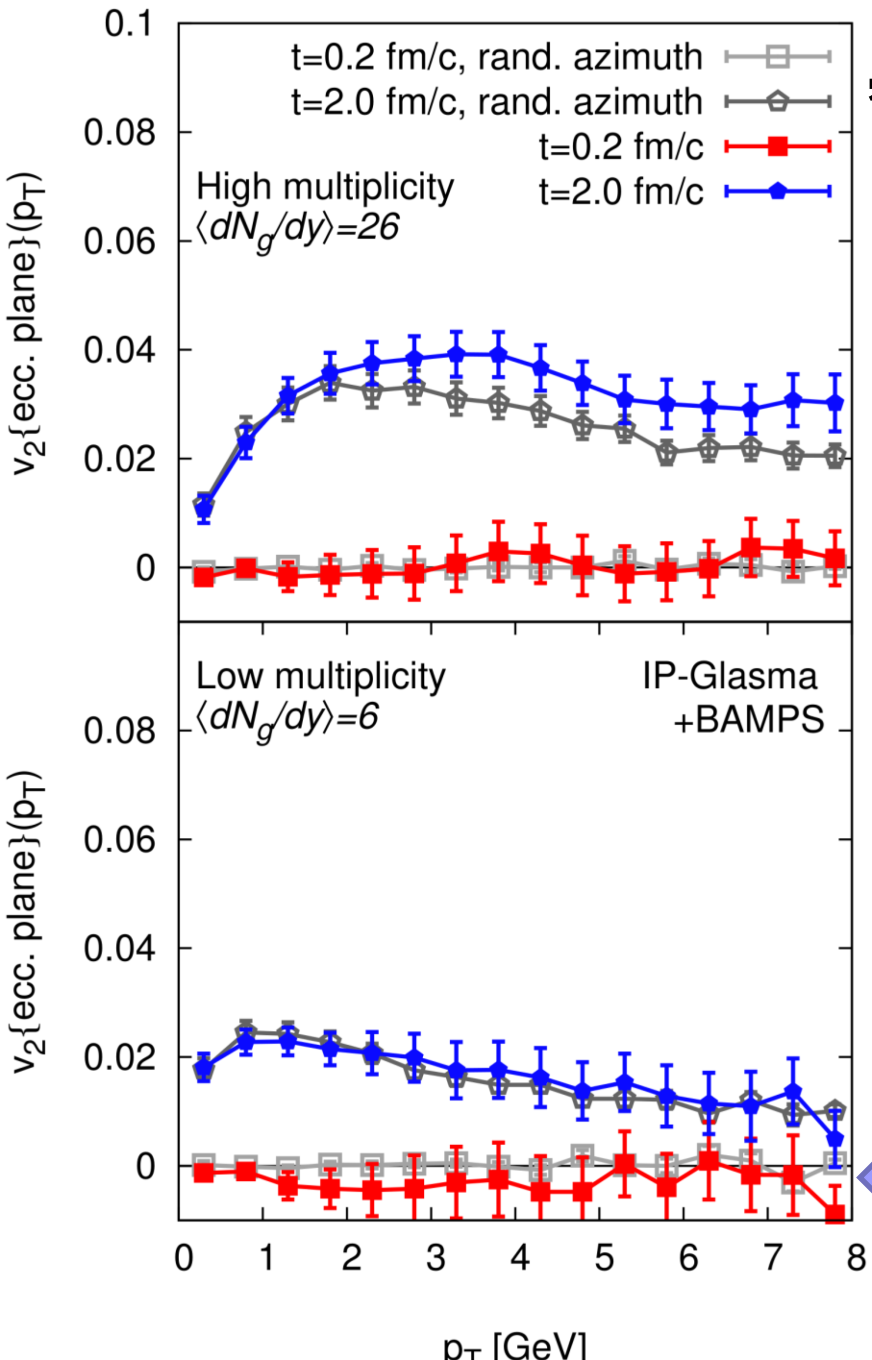
High multiplicity

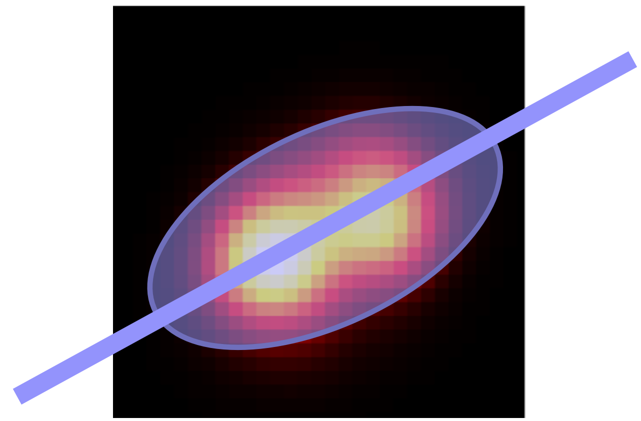
- **Low momenta ($p_T < 2\ GeV$): geometric response pivotal**
- **At higher p_T initial state correlations contribute 50-100%**

Low multiplicity

- **Low momenta ($p_T < 2\ GeV$): geometric response pivotal**
- **At higher p_T final state unimportant.**
- **Pure geometric response much smaller**

„Eccentricity-plane $v_2(p_T)$“

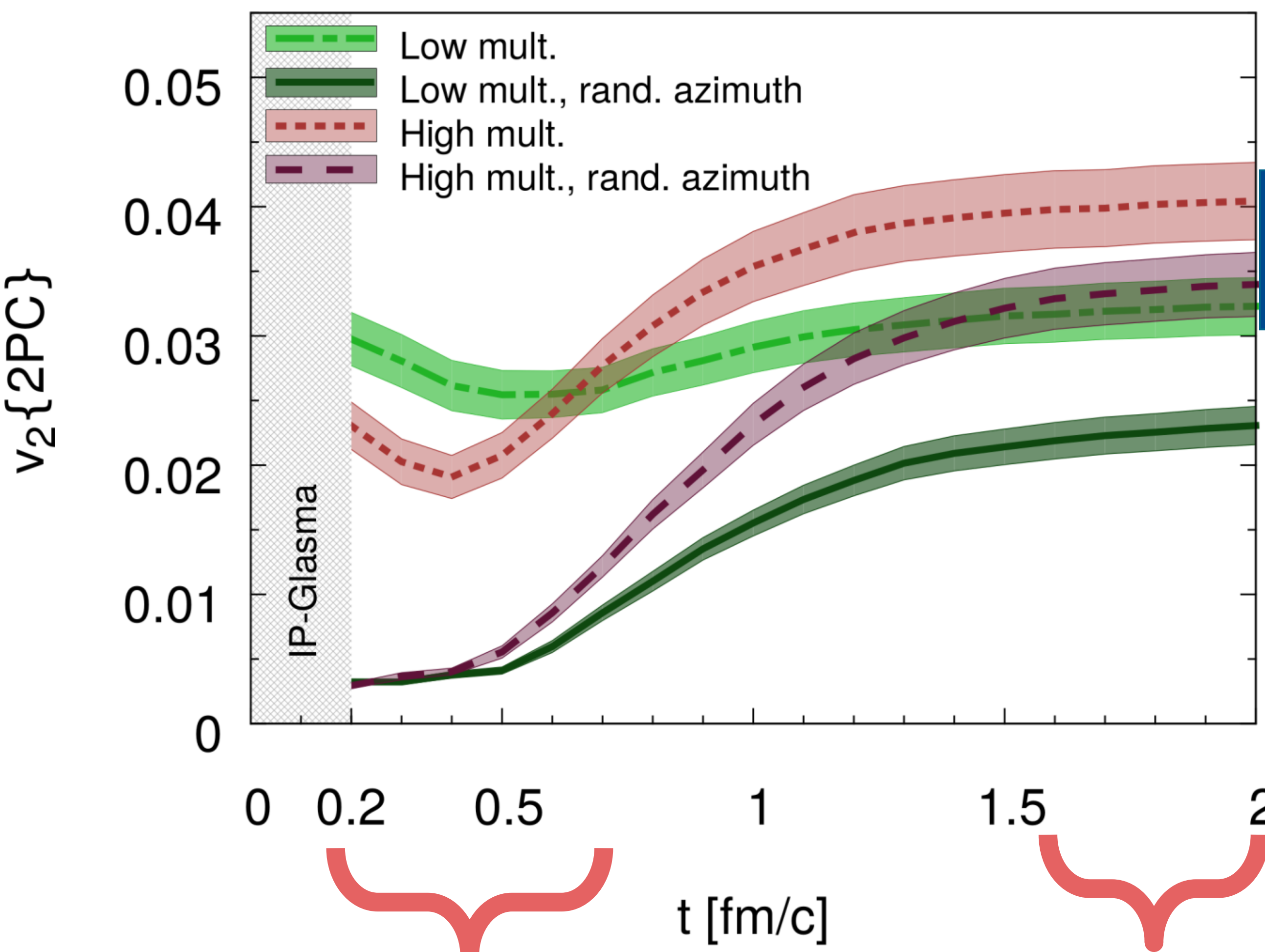


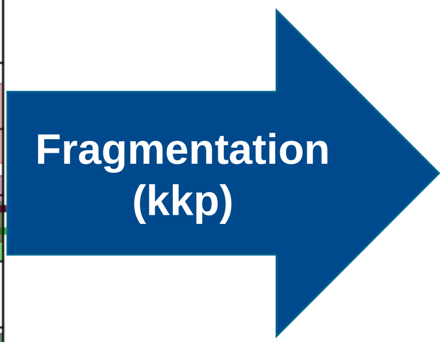


Geometric axis of transverse density distribution

Momenta and geometry not correlated in the beginning (red curve)

Momentum-integrated elliptic flow





Interesting dynamic behavior

Only little change

Conclusions & Outlook

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What ?

- First combined initial and final state calculation for p+Pb collisions
- Initial state: IP-Glasma (Impact parameter saturation, CGC, Glasma)
- Final state: BAMPS (pQCD parton cascade)

Results

- Strong difference for high and low multiplicities
- High Multiplicities: Large final state elliptic flow buildup
- Low Multiplicities: Almost no final state elliptic flow buildup
- Eccentricity plane: weak dependence on initial momenta

Phys. Rev. D 96, 091504, 2017 (rapid communication)

Future possibilities

- Systematic multiplicity scan
- Survival of flow: Hadrons and Photons ?
- 3D-IP-Glasma initial state ?

Similar work done in Frankfurt

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Björn Wagenbach (group of Owe Philipsen):

- solve classical Yang-Mills eq. for McLerran-Venugopalan CGC initial setup on the lattice
- use static box and expanding geometry, both in SU(2) and SU(3)

Goal: study hydrodynamization (e.g. via P_L/P_T) and chromo-Weibel instabilities

Attems, Philipsen, Schäfer, Wagenbach, Zafeiropoulos, ***Acta Phys.Polon.Supp. 9 (2016) 603***

Kai Gallmeister and Harri Niemi:

Comparison of dissipative Hydro and BAMPS for small (p+p, p+A) and large systems (A+A) in a Bjorken picture (academic study)

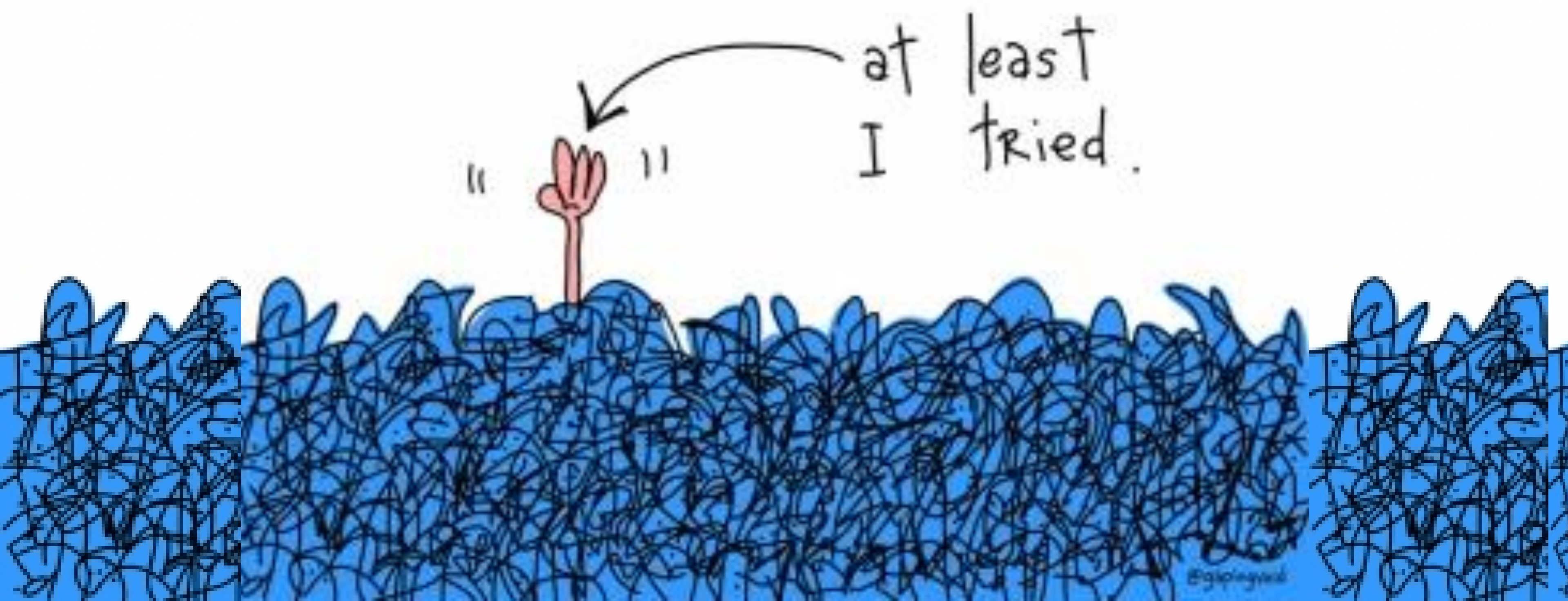
good agreement, even for large Knudsen numbers:

- densities, temperatures, fugacities, ...
- minor deviations in components of shear stress tensor
- no difference between large and small systems

dependence on freeze-out:

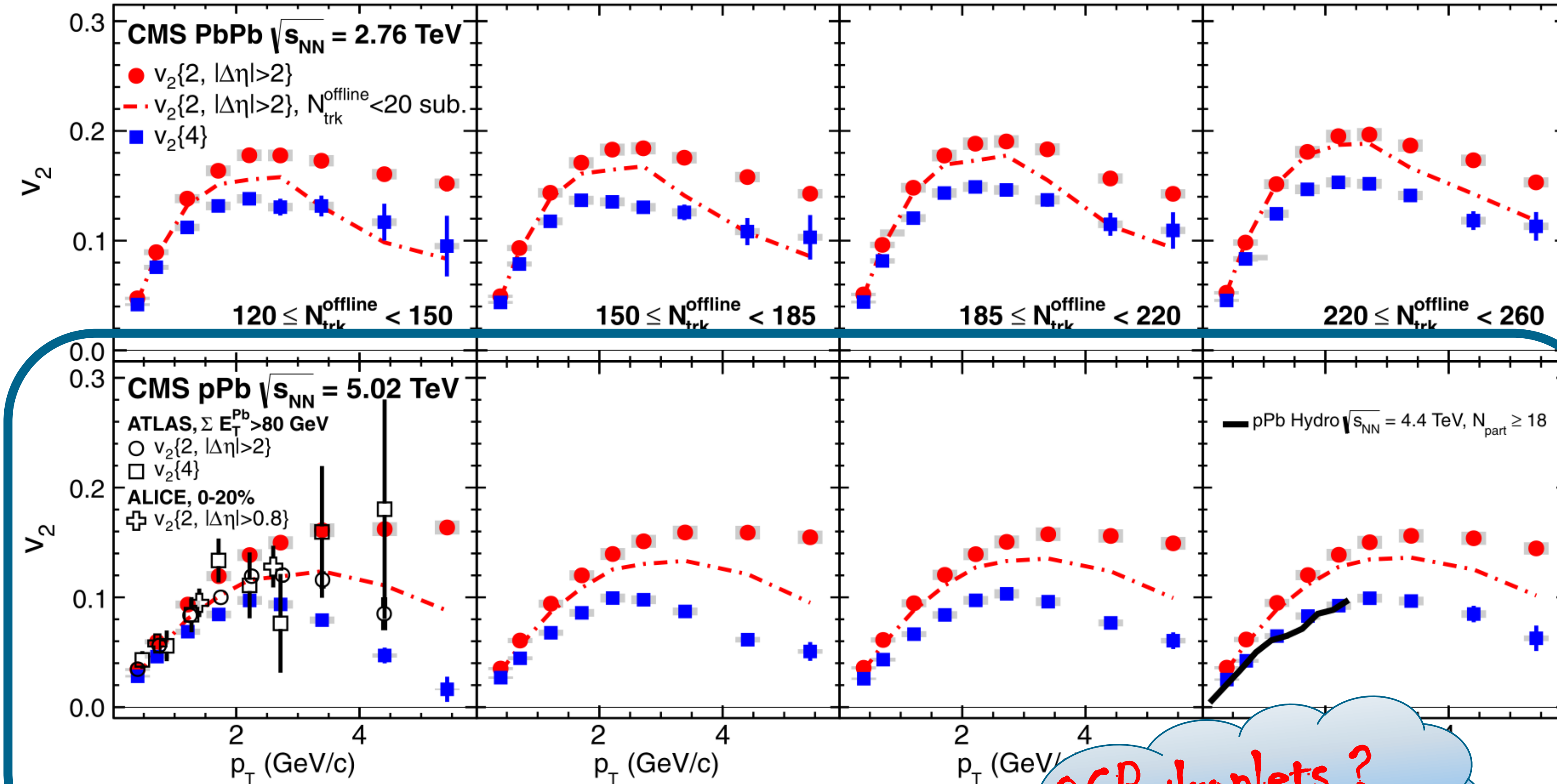
- ε_P & v_2

Correlations and Flow in small systems



Evidence of collectivity in small systems

CMS Collaboration / Physics Letters B 724 (2013) 213–240

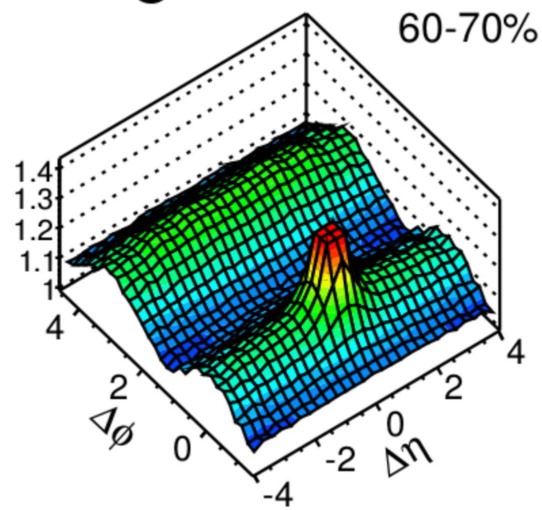


Proton – Lead collisions

QGP droplets ?
Local equilibration?

Correlations in small systems

PbPb @ 2.76 TeV



CMS, Eur.Phys.J. C72 (2012) 2012

Long-range correlations ($\Delta\eta$):

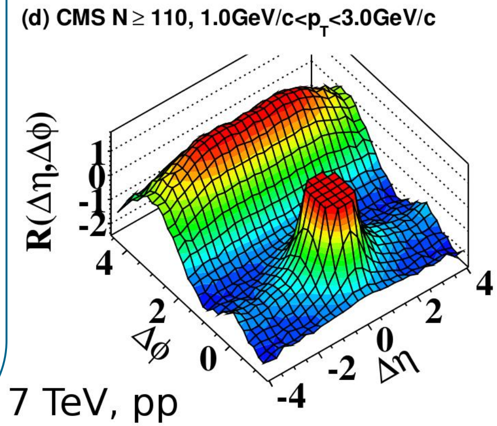
- Initial state correlation (CGC)

- or -

- Triangular flow effect (initial state fluctuations) ?

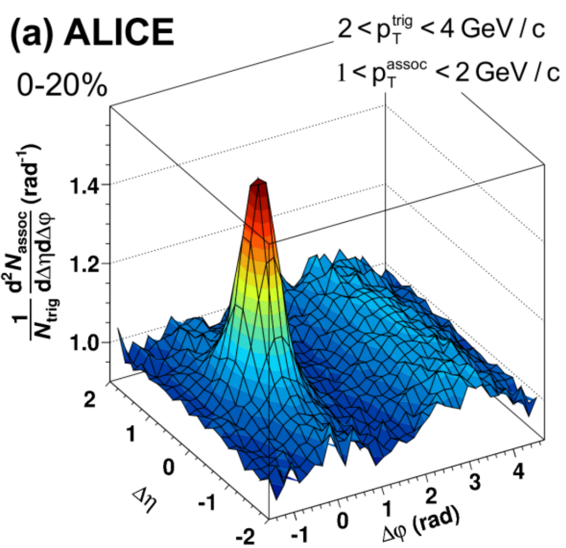
Common origin of ridge ?

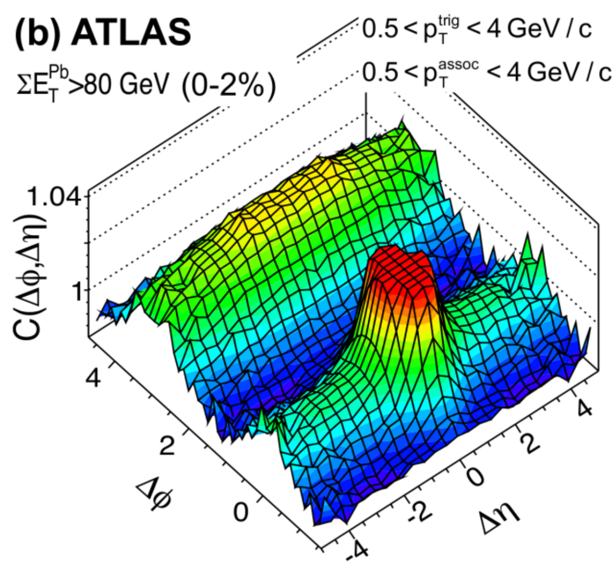
CMS coll., JHEP 1009 (2010) 091

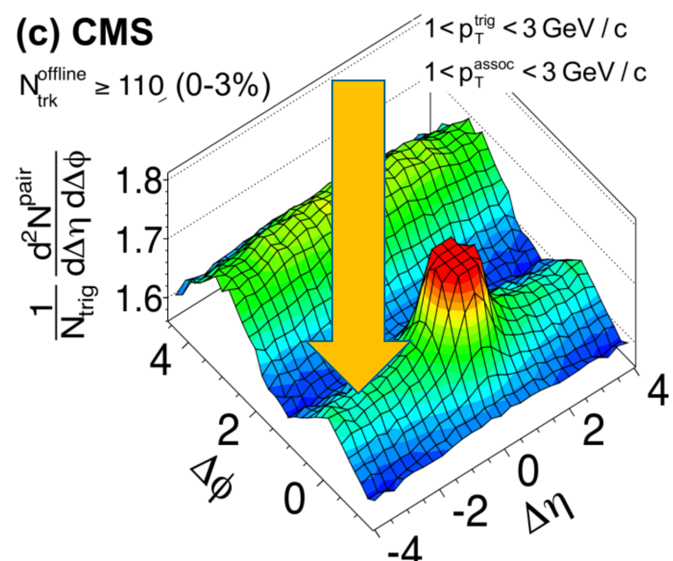


7 TeV, pp

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

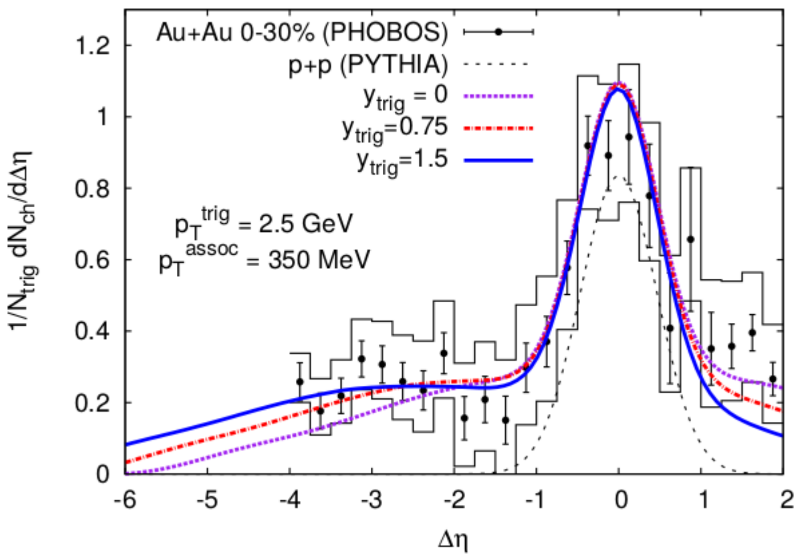




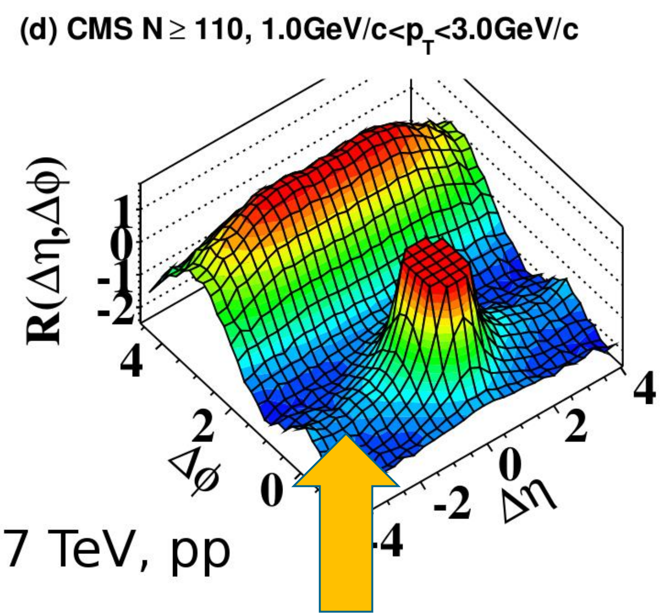


Pictures cf. B. Schenke

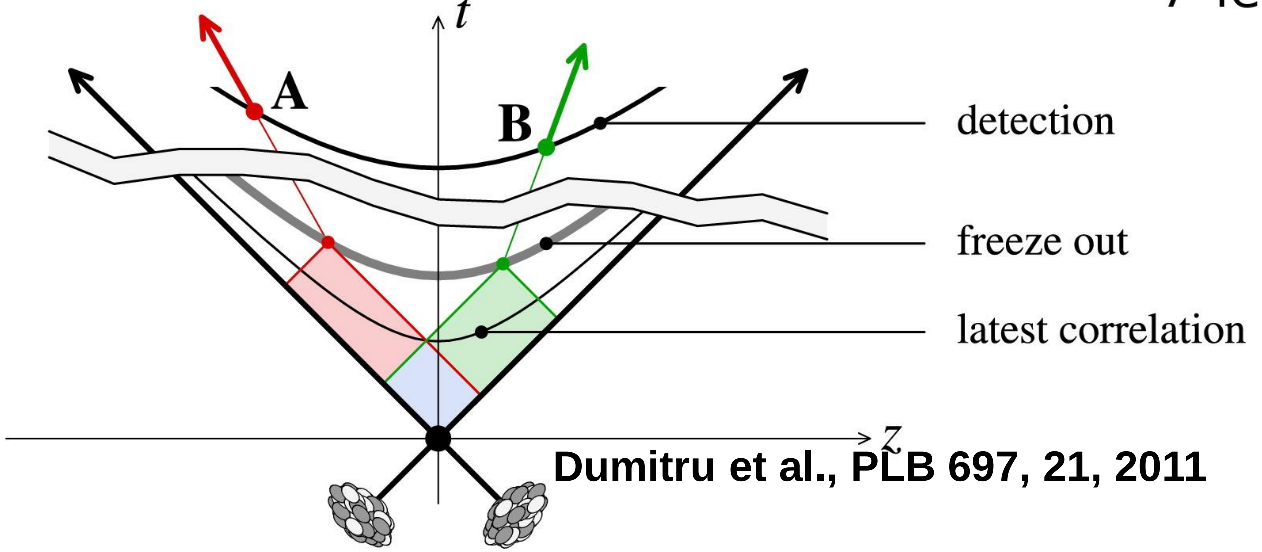
Correlations from CGC?



CMS coll., JHEP 1009 (2010) 091



$$\tau_{\rm init} = \tau_{f.o.} \exp\left(-\tfrac{1}{2}\Delta y\right)$$

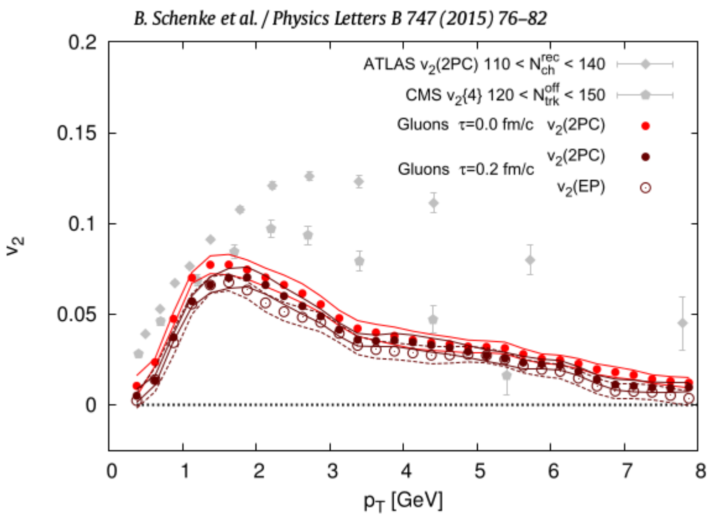


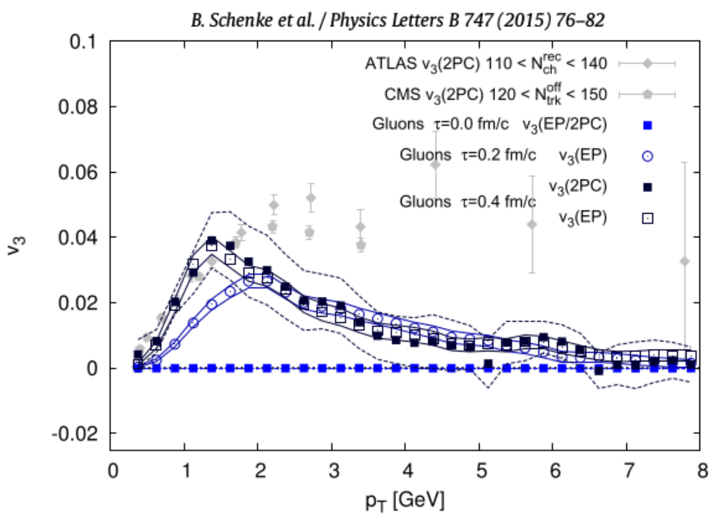
Dumitru et al., PLB 697, 21, 2011

See also Dusling & Venugopalan, PRD 87, 094034 (2013): compare CGC to pp & pA dihadron data → quantum interference between rapidity separated gluons

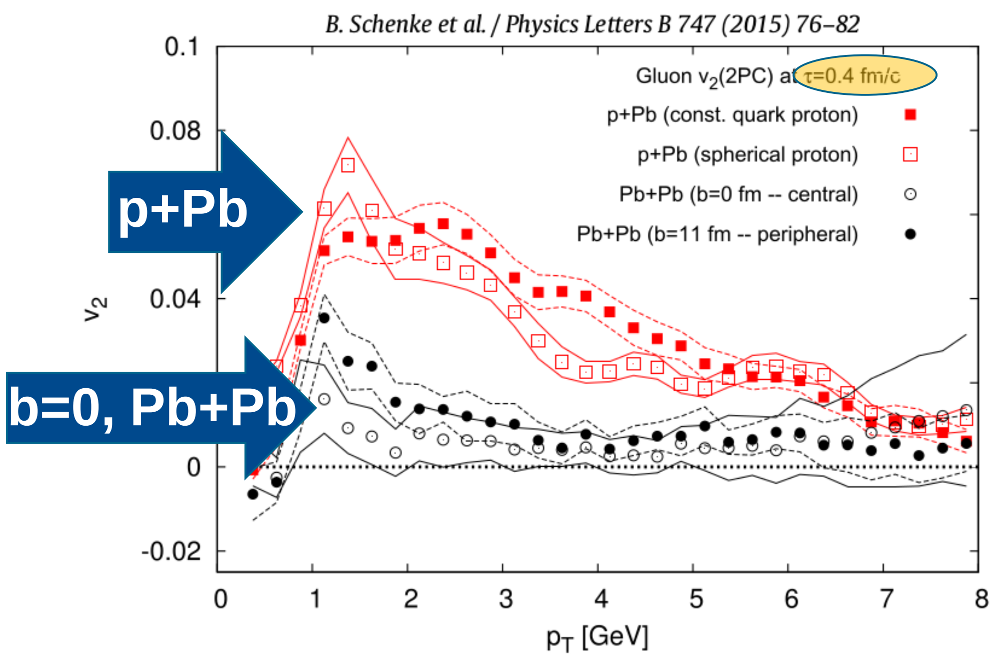
Correlations from CGC?

Schenke, Schlichting
& Venugopalan PLB 747, 76 (2015)





- Initial anisotropy v_2 from **IP-Glasma**
- Pre-equilibrium dynamics (Classical Yang Mills) generates **odd** harmonics
- Pb+Pb needs collective flow (hydro-like). Too many uncorrelated color-field domains



Correlations in small systems from Hydro?

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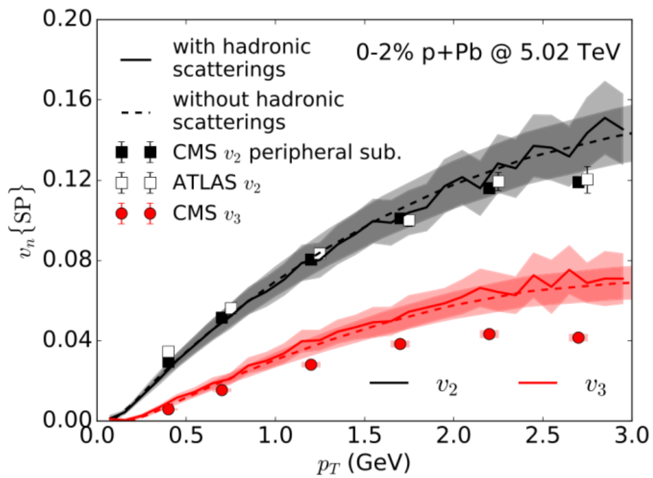
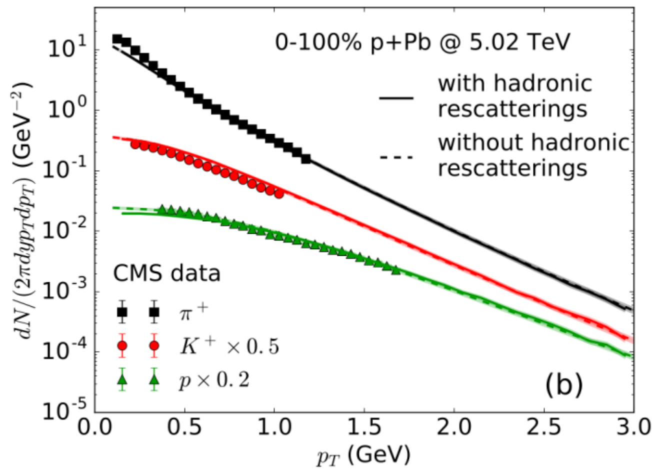
Hydro models challenged – but work well:





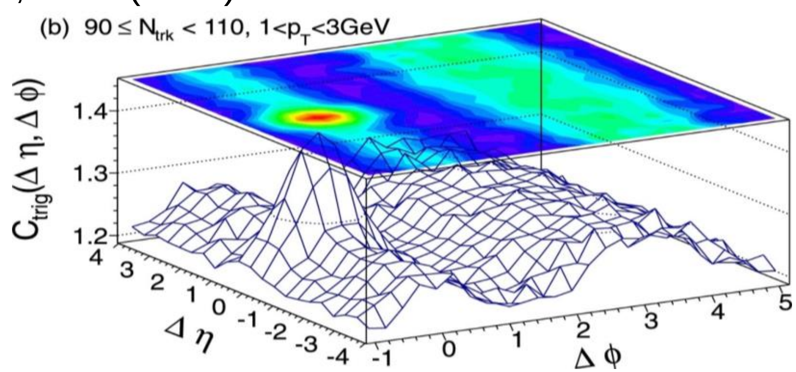
Here:

- MC-Glauber initial state
- (3+1)d viscous hydro + UrQMD

Shen et al., PRC95, 014906 (2017)

Hydro claims to explain ridge in pPb:

Bożek & Broniowski, PLB 718, 1557 (2013)

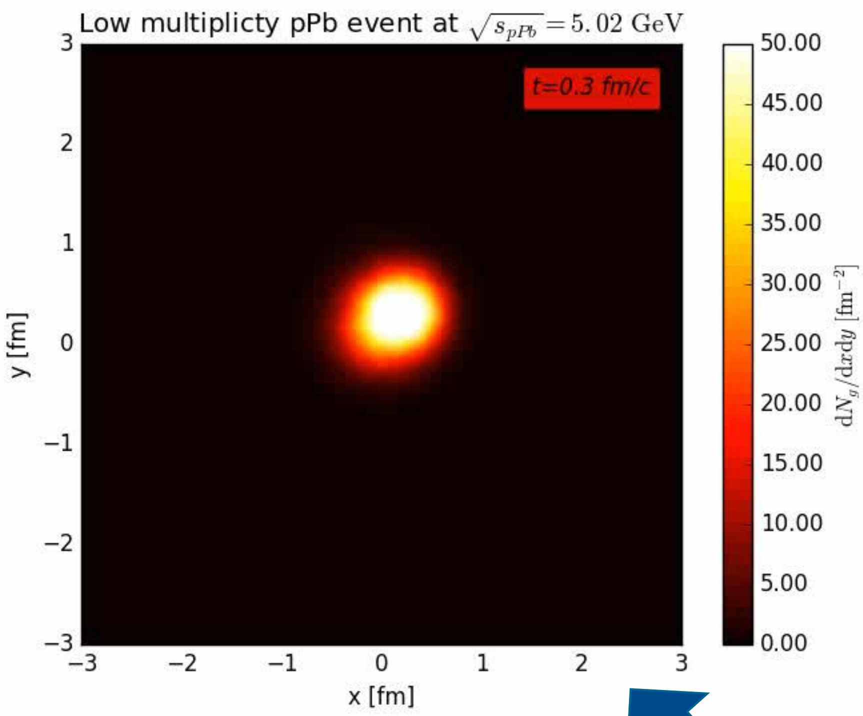


See also Luzum, PLB 696, 499 (2011): ridge data consistent with only collective flow

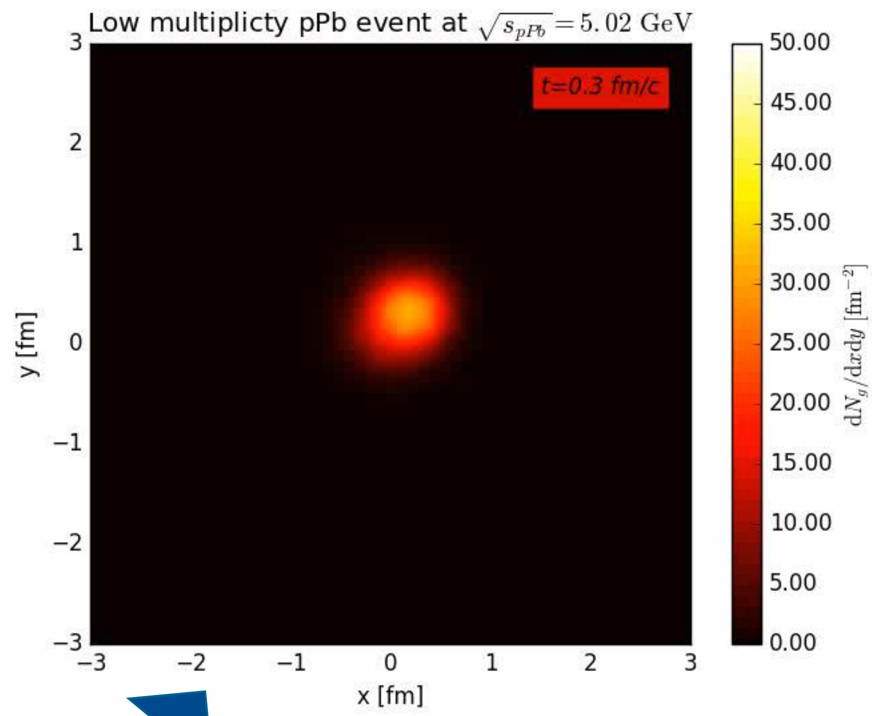
IP-Glasma + MUSIC explains v_n for p+Pb. In prep., Mäntisaari et al, 2017

BAMPS evolution for different multiplicities

Low multiplicity, **g=2:**



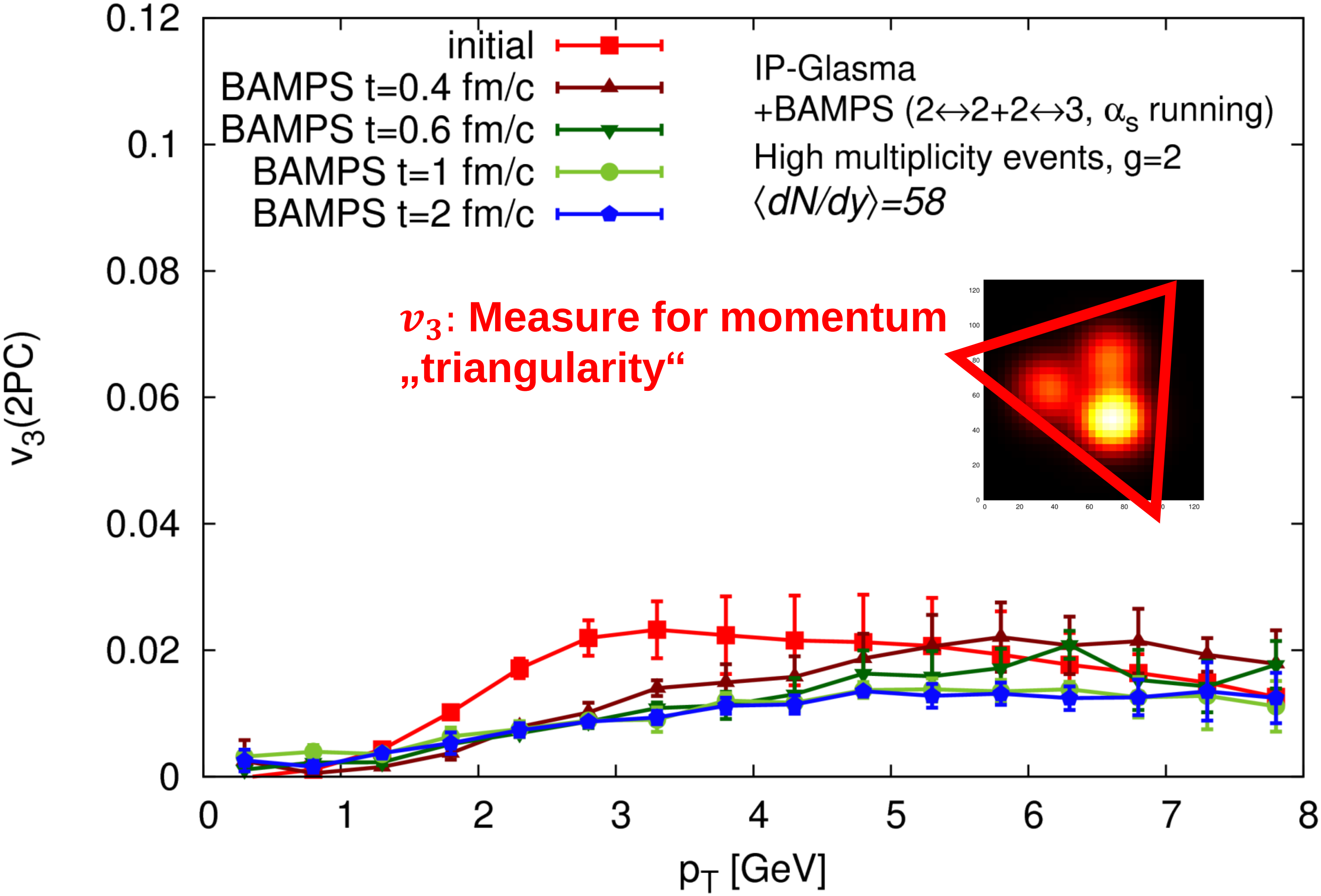
Low multiplicity, **g=3:**



Same initial Glasma state

Color code: particle number / transverse area
Rapidity integrated, only formed particles

High multiplicity 2-particle corr. v_3



Low multiplicity 2-particle corr. v_3

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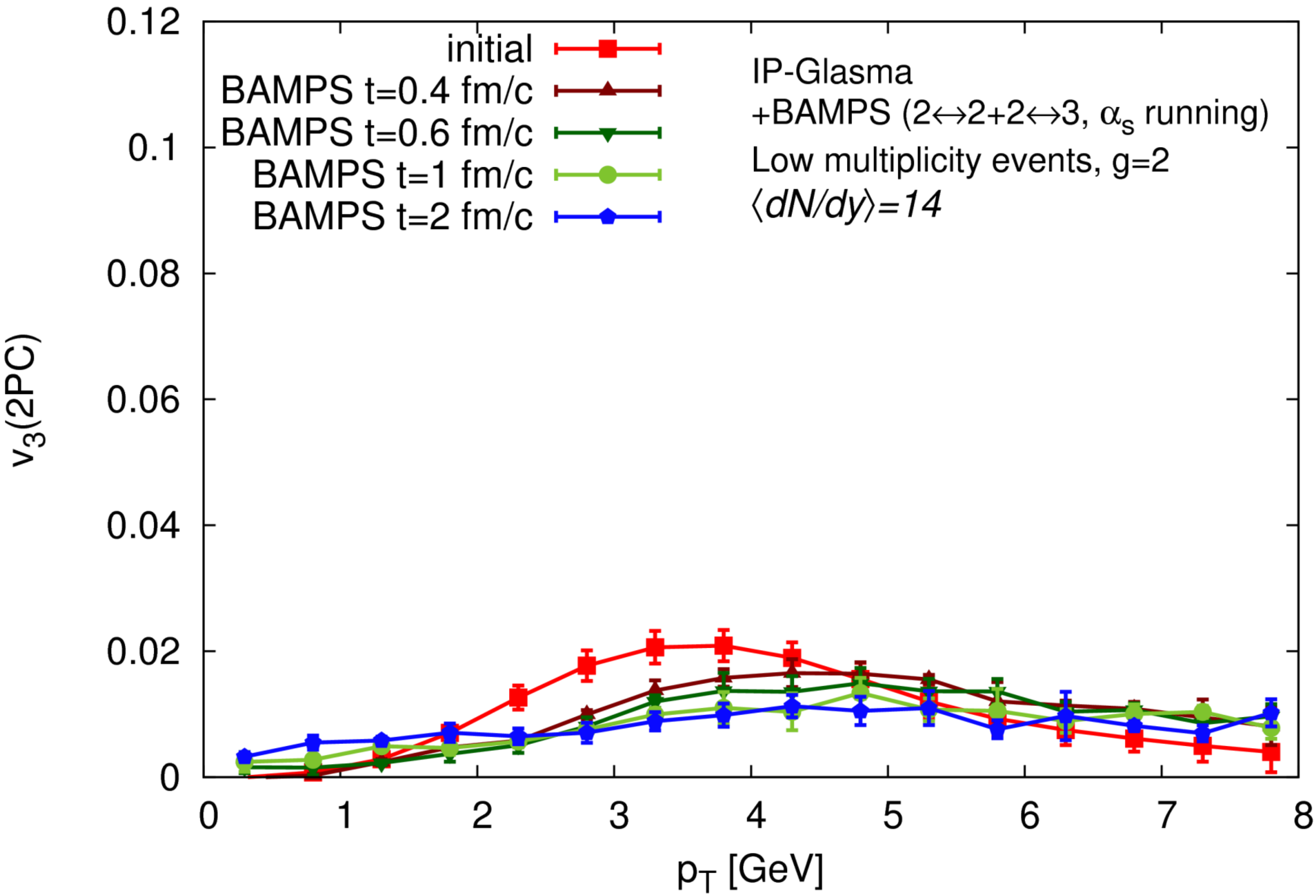
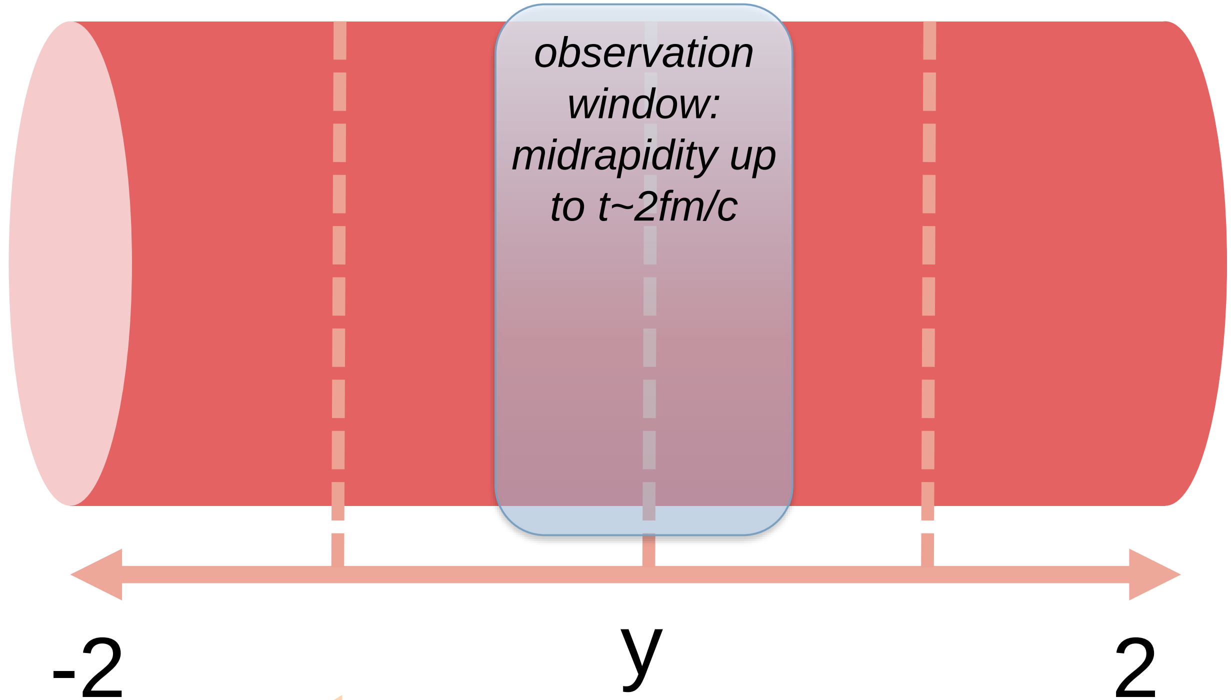
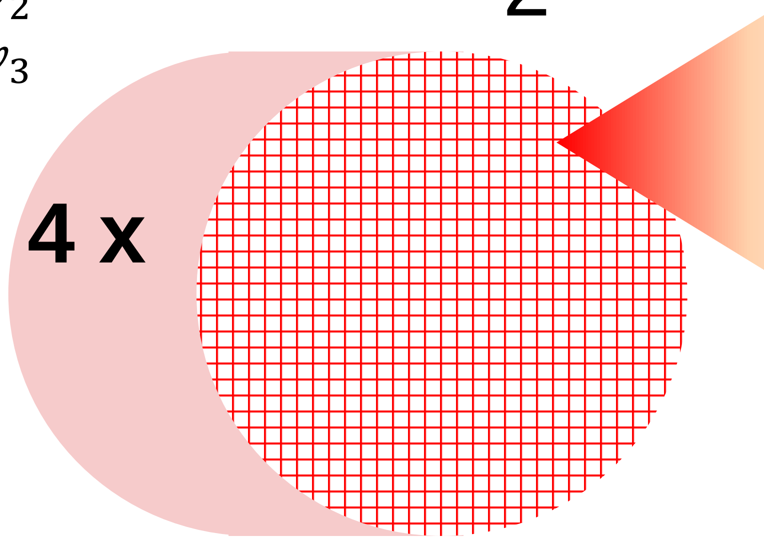


Generate boost invariant initial state from discrete IP-Glasma $dN/(dy d^2\vec{x} d^2\vec{p})$

- Sample $\frac{dN}{dy} \cdot N_{test}$ for 4 rap.units
- momenta: (64x64: p_x p_y) for (32x32: x y) lattice
- Check carefully (with original distribution):
  - ✓ Energy density
  - ✓ v_2
  - ✓ v_3





Fill cells with $dN/d^2p_T(\vec{x})$ from CYM, $p_z = p_T \sinh y$

Input:
- 50 High Multiplicity p+Pb events @ 5 TeV
- 50 Low Multiplicity p+Pb events @ 5 TeV