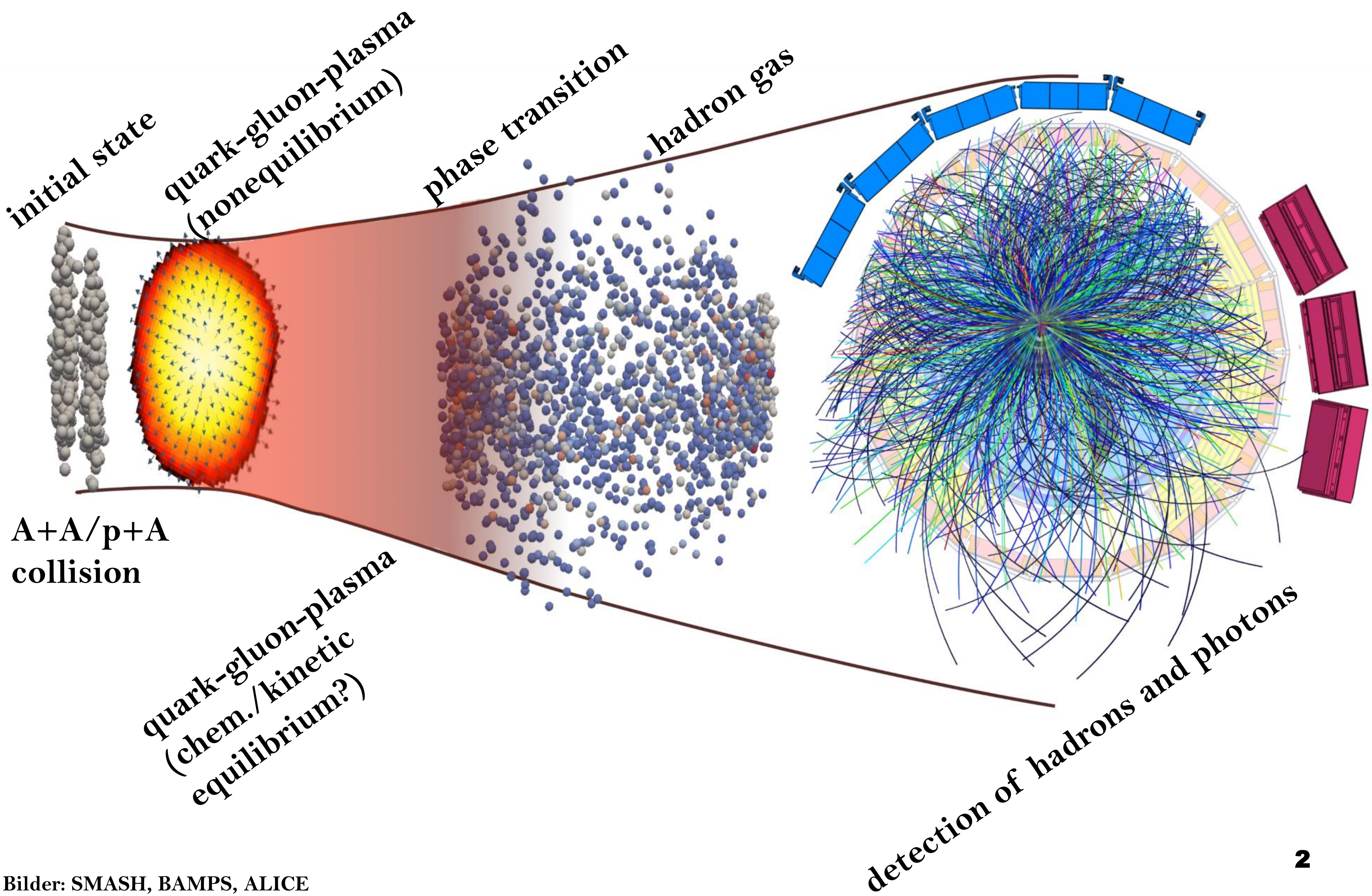
Combined initial + final state + hadronization model

for p+Pb collisions

Moritz Greif
Goethe University
Frankfurt, Germany

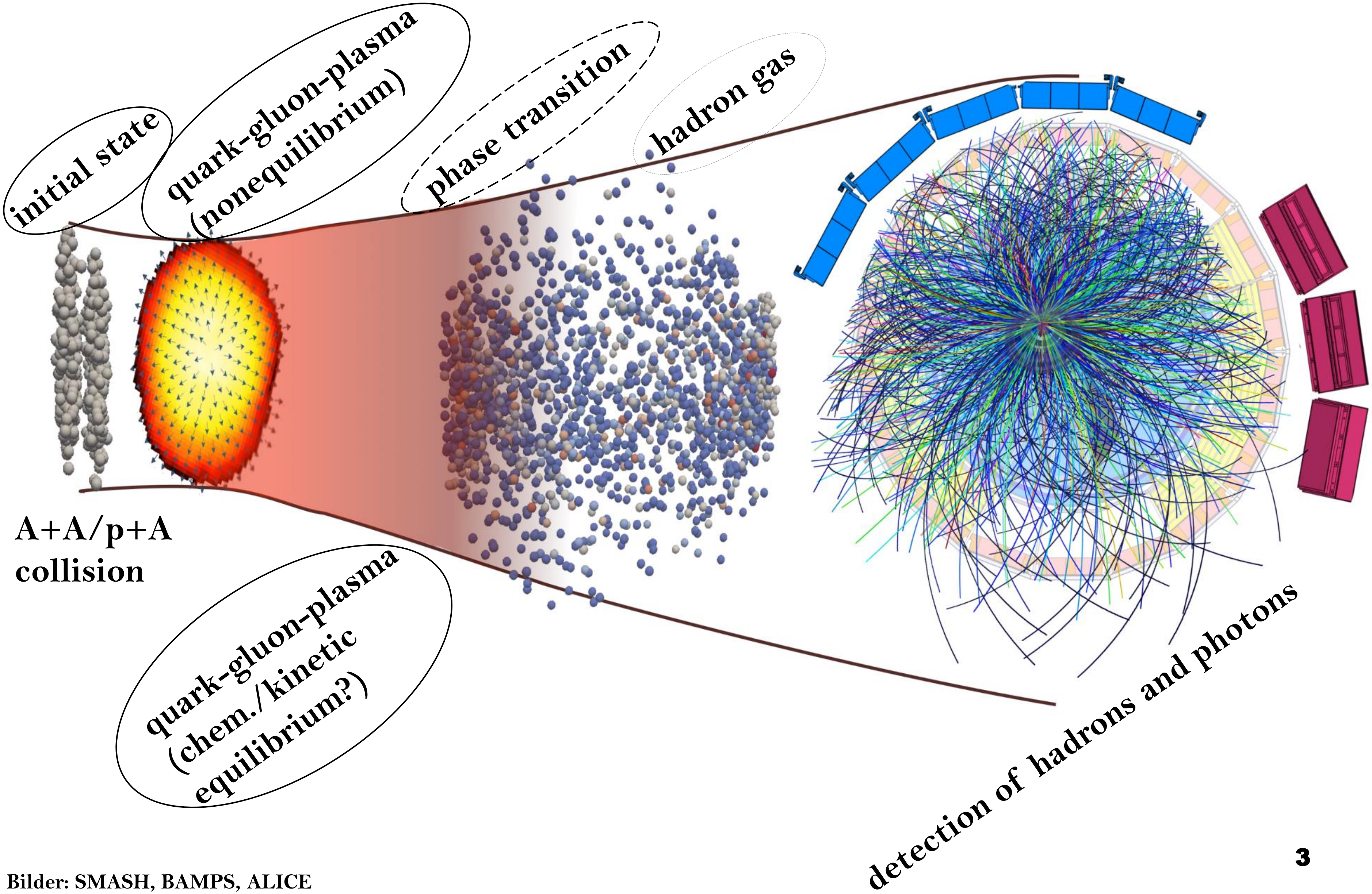
MG, Schlichting, Schenke, Xu, Greiner, PRD 96, 091504, 2017

Collisions of nuclei at high energy



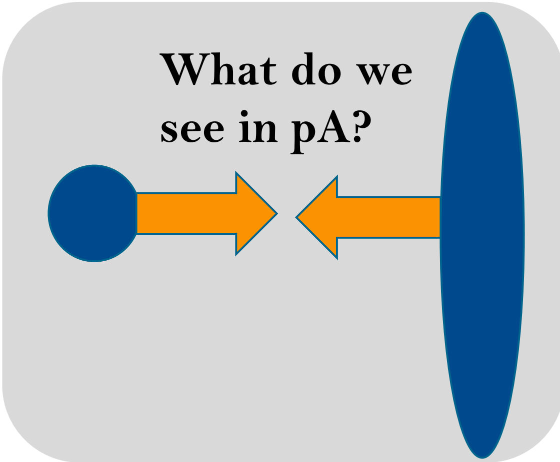
Bilder: SMASH, BAMPS, ALICE

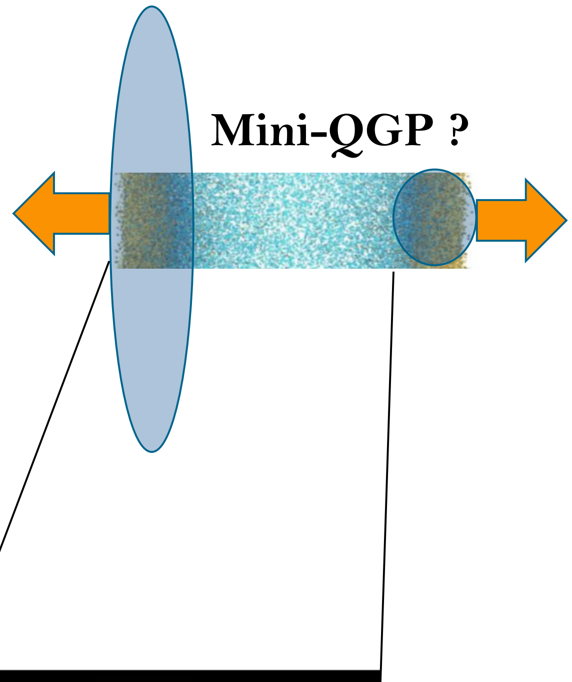
Collisions of nuclei at high energy



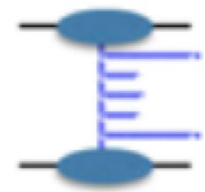
Bilder: SMASH, BAMPS, ALICE

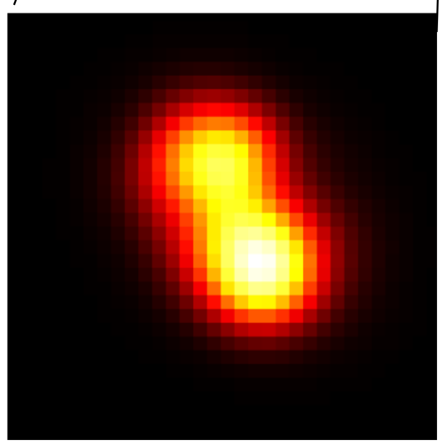
Proton-Heavy-ion (pA) collisions





Or only
„initial state“?

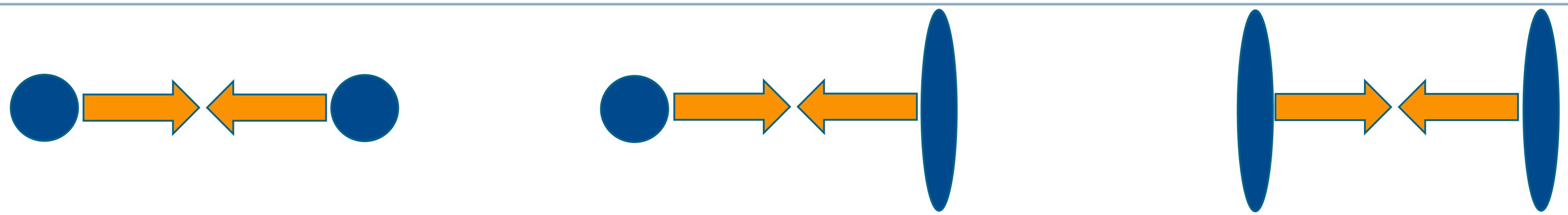




pPb $\sqrt{s_{NN}}$ = 5.02 TeV at the LHC

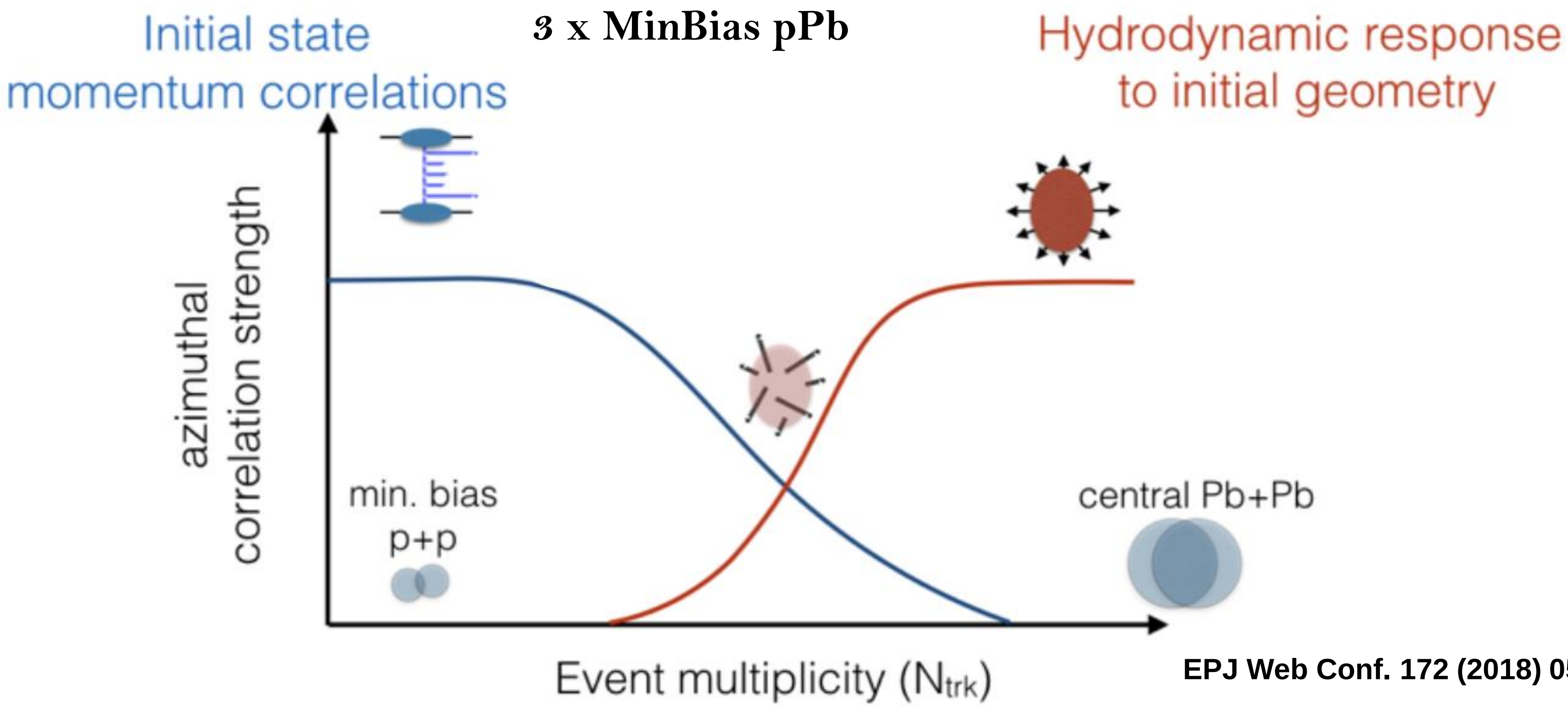
Characterization of
momentum correlations:
„elliptic flow“ v_2

Origin of correlations in small systems



$\mathrm{d}N_{pp}^{\mathrm{min.bias}}/\mathrm{d}y \sim 5$ $\mathrm{d}N_{pPb}^{\mathrm{min.bias}}/\mathrm{d}y \sim 8$ $\mathrm{d}N_{\mathrm{PbPb}}^{0-5\%}/\mathrm{d}y \sim 1500$

70% Centrality PbPb ~ 3 x MinBias pPb



EPJ Web Conf. 172 (2018) 05007

Our Model: Initial + Final state interactions

initial state with correlations

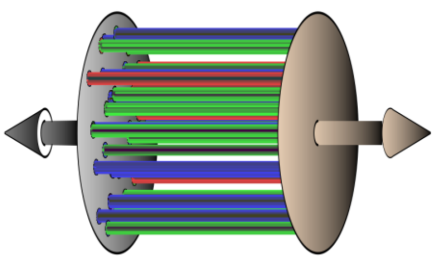
(Glasma: „IP-Glasma“)

\+ **final** state with interactions (QGP)

(parton cascade: „BAMPS“)

\+ **hadronization**

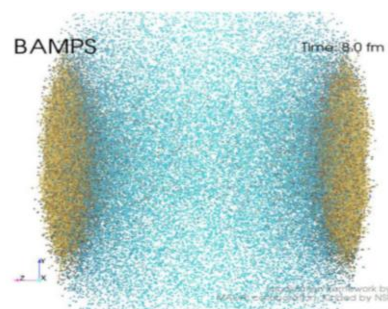
(event generator HERWIG)



Time: 0–0.2 fm/c

Classical Yang Mills

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



0.2 – 2 fm/c

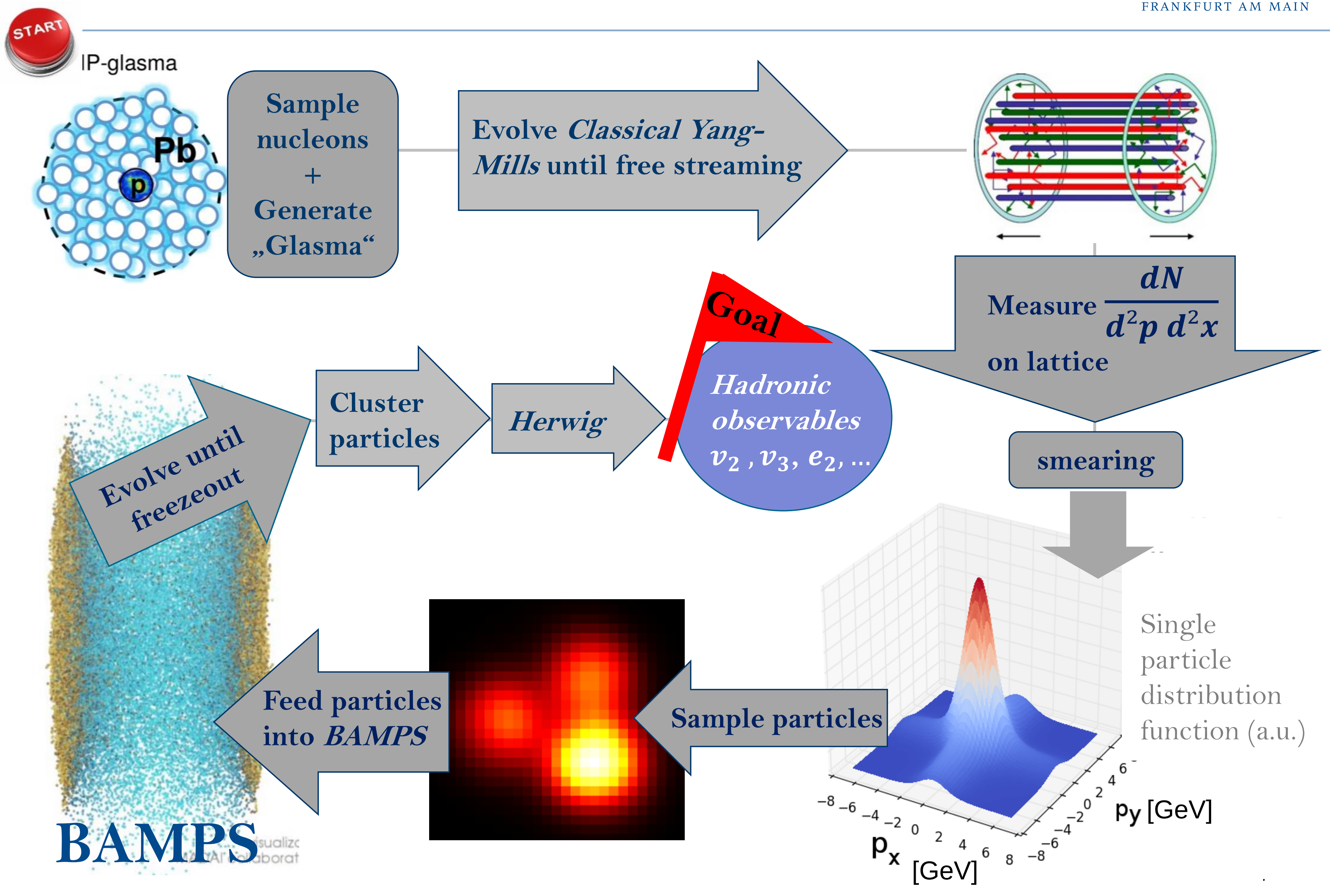
Boltzmann Equation (pQCD interactions)

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

H7

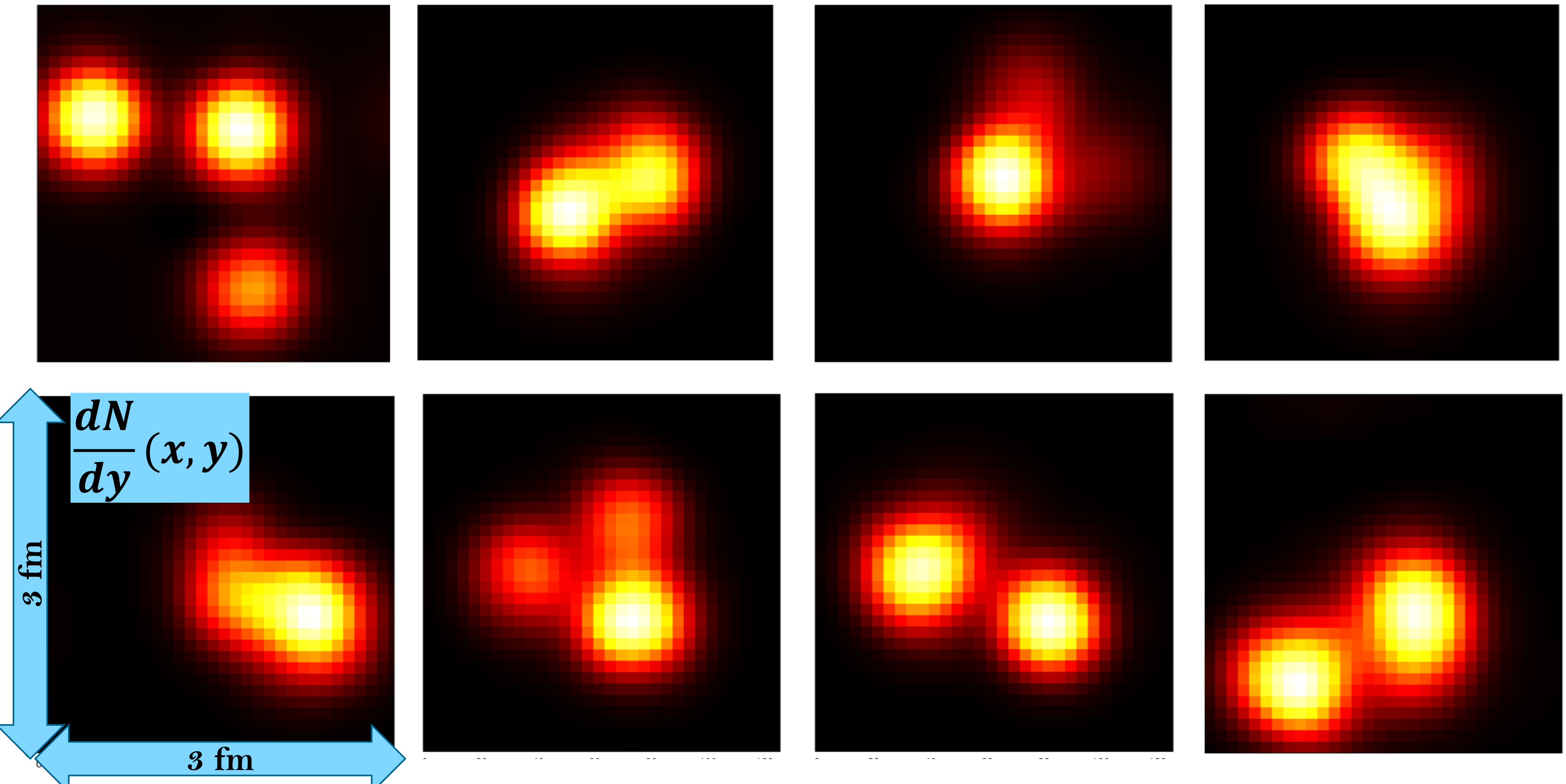
cluster hadronization model

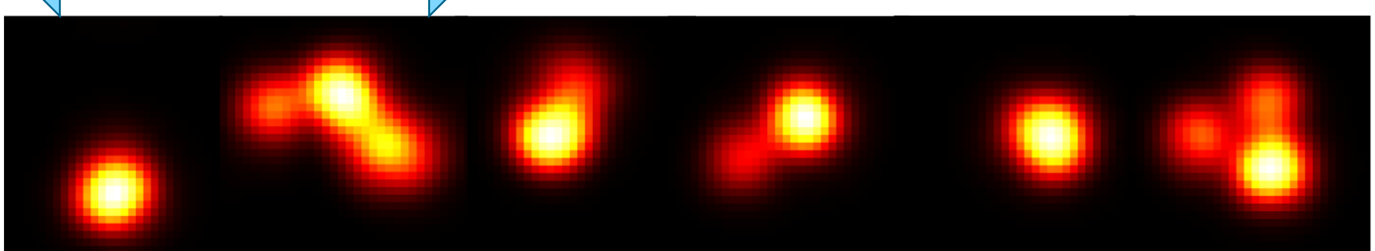
Our Model: Initial + Final state interactions



Event-by-Event: Coordinate Space Distributions

After classical Yang-Mills evolution: IP-GLASMA



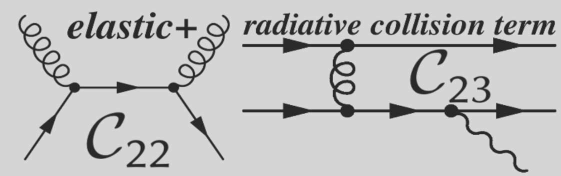


Typically 50-100 events per multiplicity class sufficient here

Final state with interactions: BAMPS

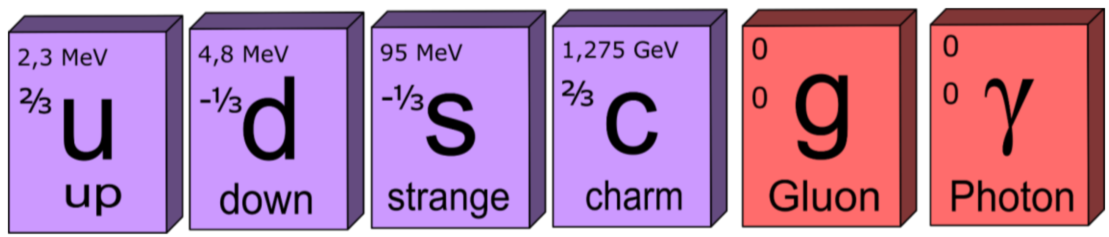
Boltzmann **A**pproach to **M**ulti-**P**arton **S**catterings „**BAMPS**“

$$k_i^{\mu}\partial_{\mu}f_{\mathbf{k}}^{i} + k_{\nu}q_i F^{\mu\nu}\partial_{\mu}f_{\mathbf{k}}^{i} = C_{2\leftrightarrow 2}[f] + C_{2\leftrightarrow 3}[f]$$



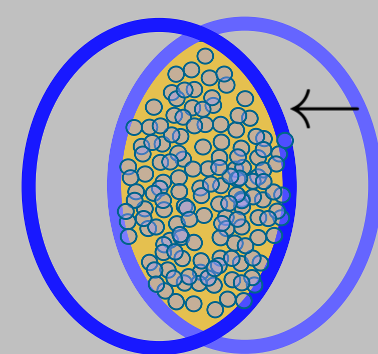
„numerically exact“ solution (Xu & Greiner, PRC 71 (2005) 064901)

Species:



Universal tool for A+A and p+A

- pQCD cross sections
- Binary and radiative scattering
- 3+1d, different possible initial states



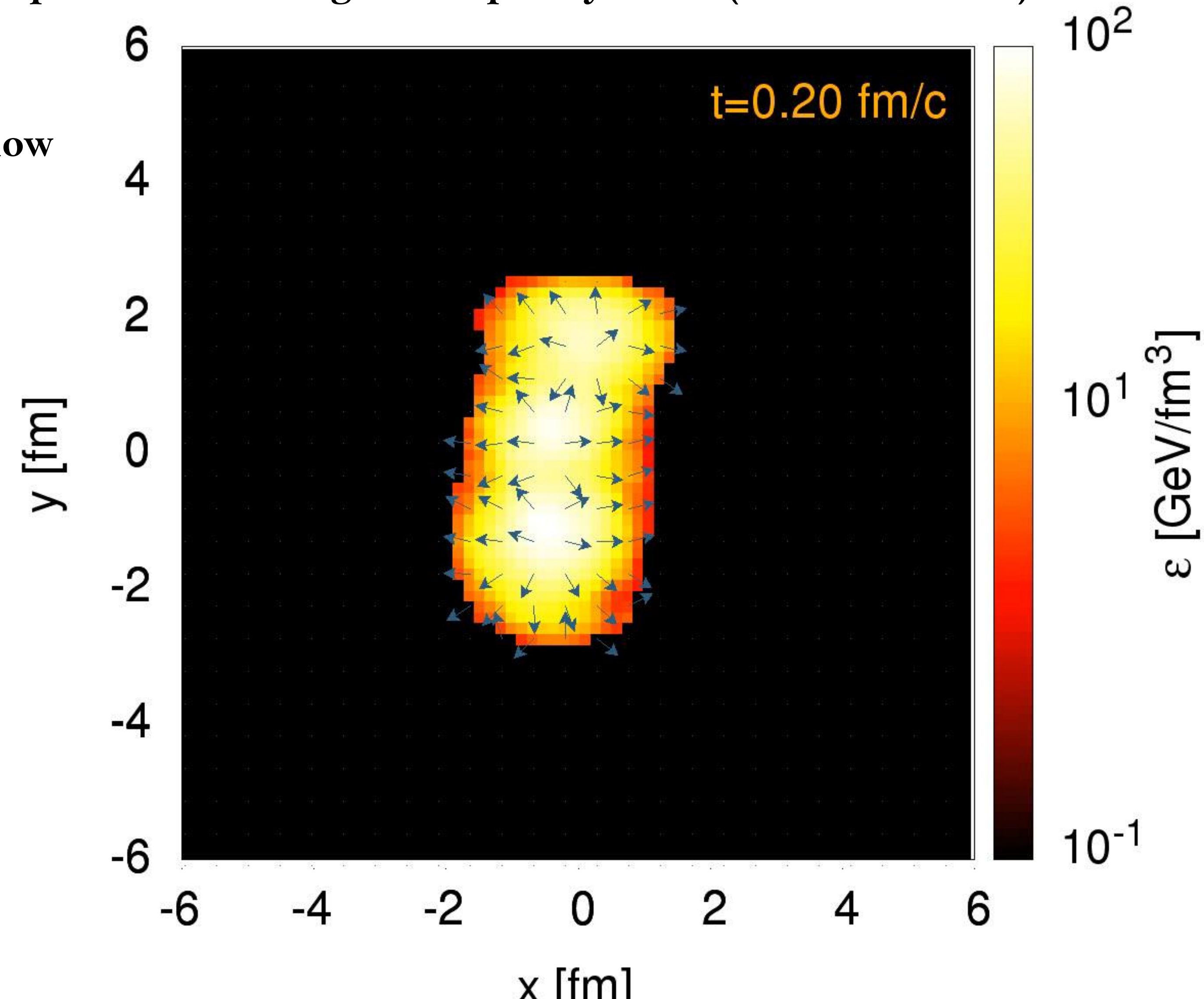
“$f(x,k)$”

Typical Energydensity evolution

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

5.02 TeV pPb collision, high multiplicity event (3.45 x min bias)

Arrows show cell flow direction

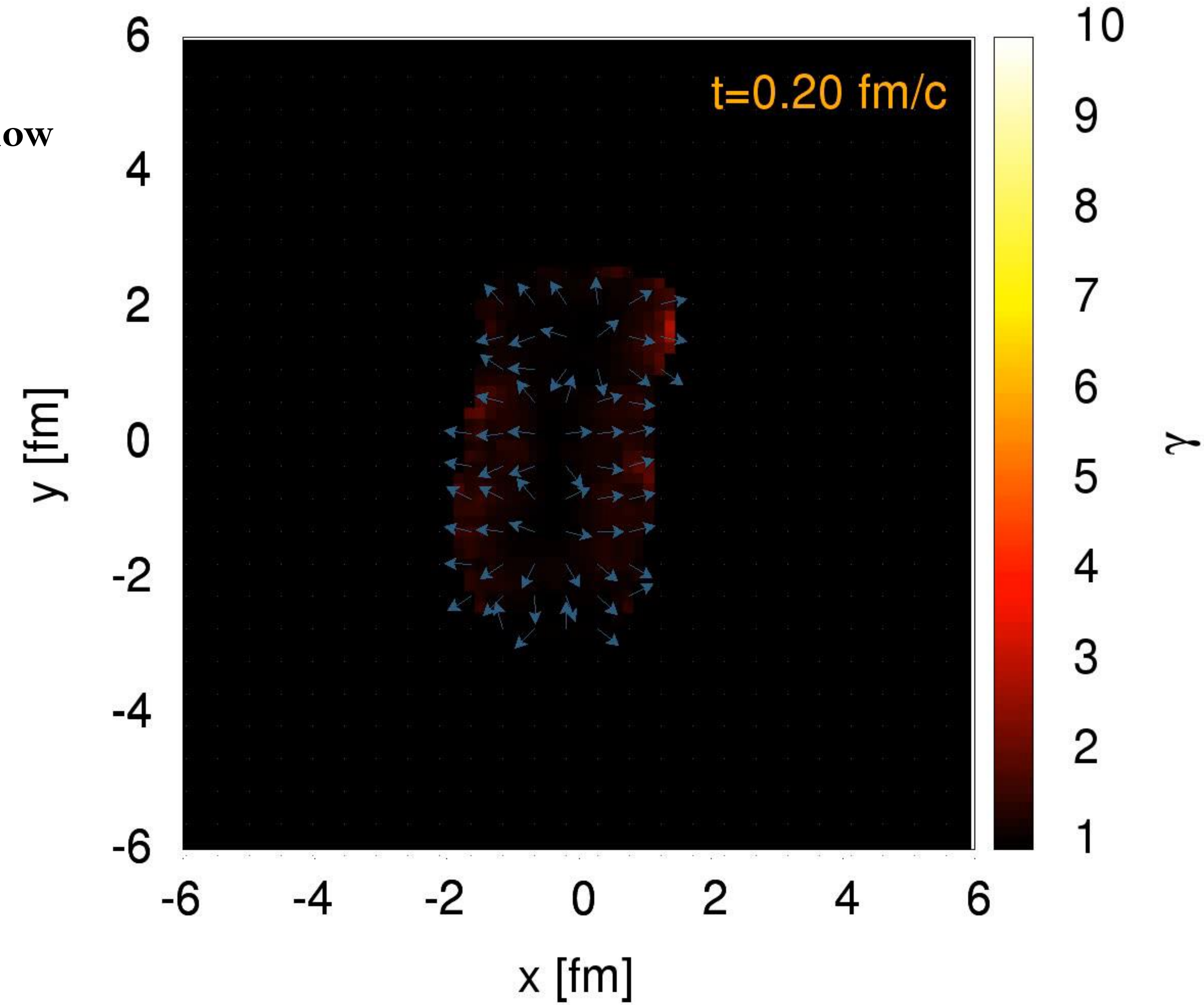


Typical flow evolution

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

5.02 TeV pPb collision, high multiplicity event (3.45 x min bias)

Arrows show cell flow direction



BAMPS evolution of proton-lead collision

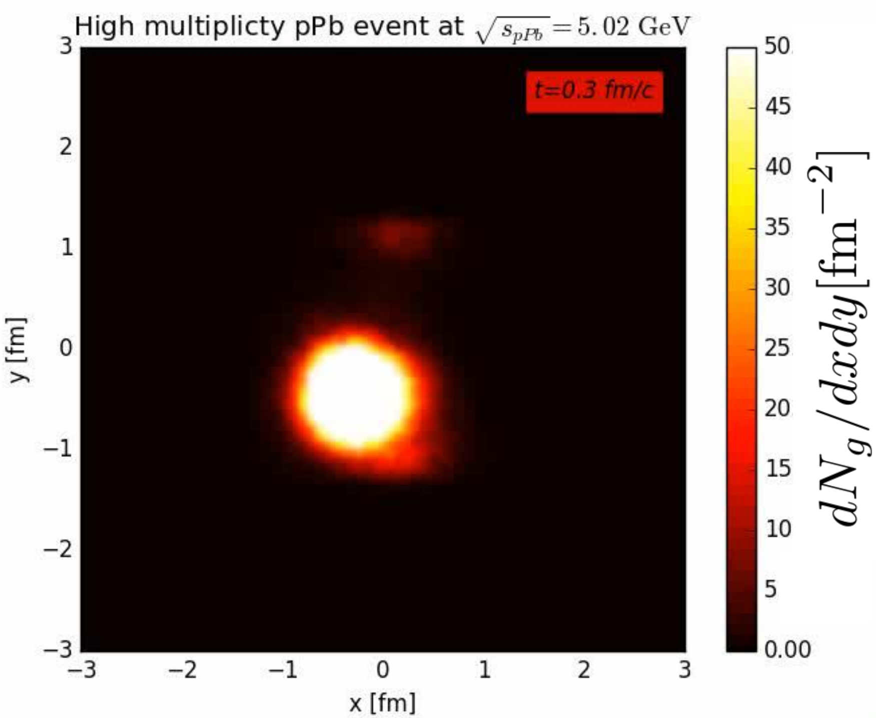
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

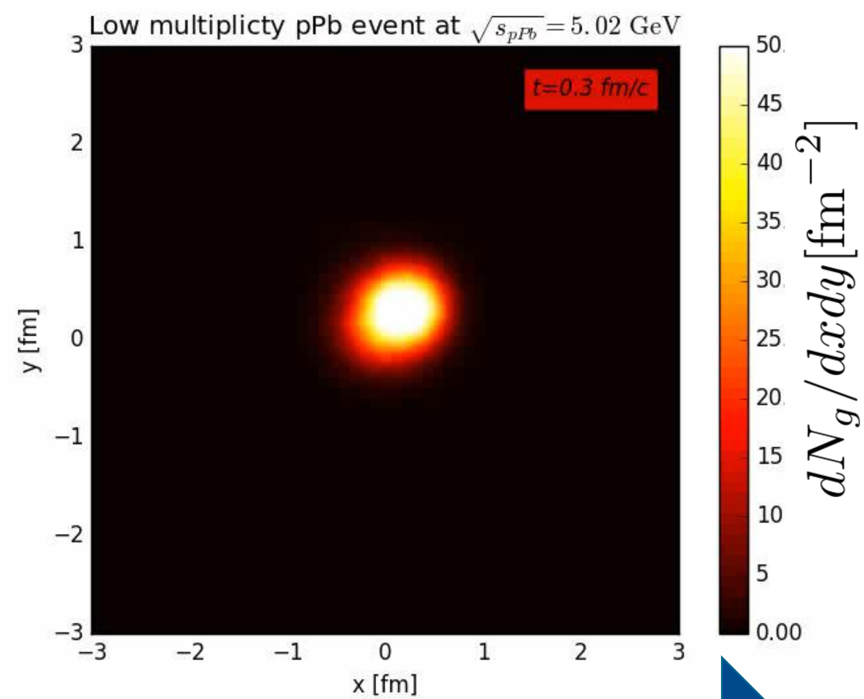
High multiplicity:

Pressure gradients build up flow?

Low multiplicity:

Anisotropy due to initial fluctuation?

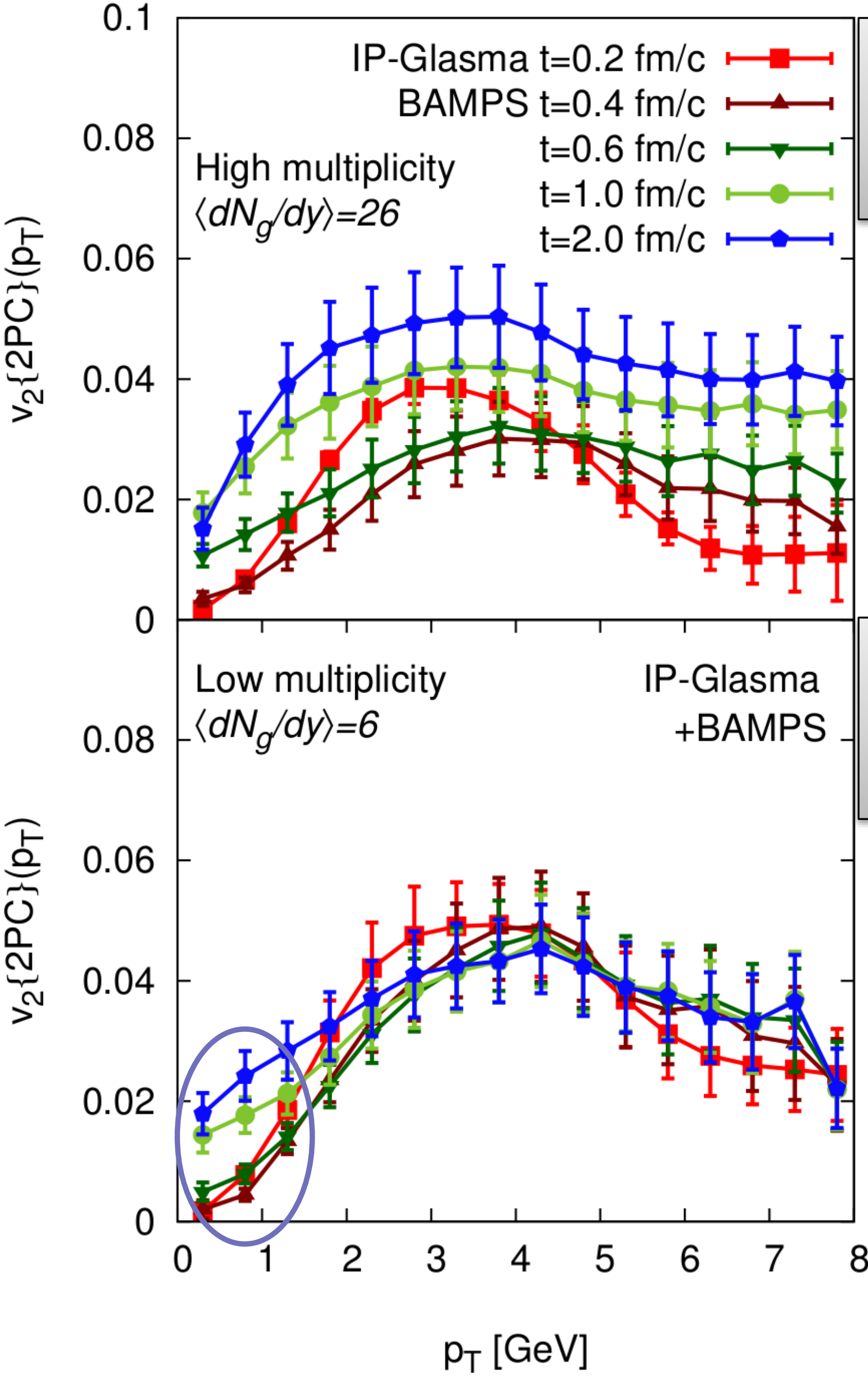




Goal: more differential on 6 multiplicity classes

Initial condition for BAMPS: IP-GLASMA, Schenke et al., Phys.Rev.Lett. 108 (2012) 252301

Flow observables for p+Pb



High multiplicity

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

Evolution of momentum asymmetry non trivial:

- Symmetry-axis rotates
- Isotropization
- **Geometric response to eccentricity**

Low multiplicity

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

Geometric response only at low p_T

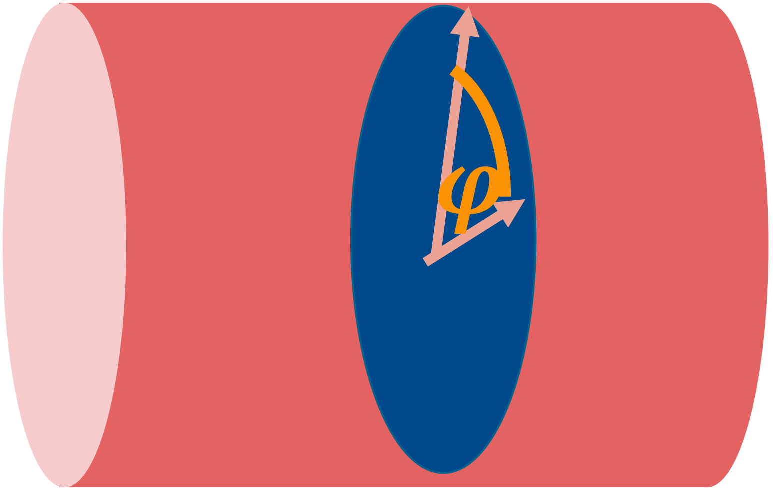
At higher momenta: initial state correlations persists

Disentangle the role of geometry

Number of
- small angle scatterings:
- large angle scatterings:

	Low Multiplicity	High Multiplicity
small angle scatterings	4.5 ± 1.1	5.6 ± 1.1
large angle scatterings	0.53 ± 0.14	1 ± 0.18

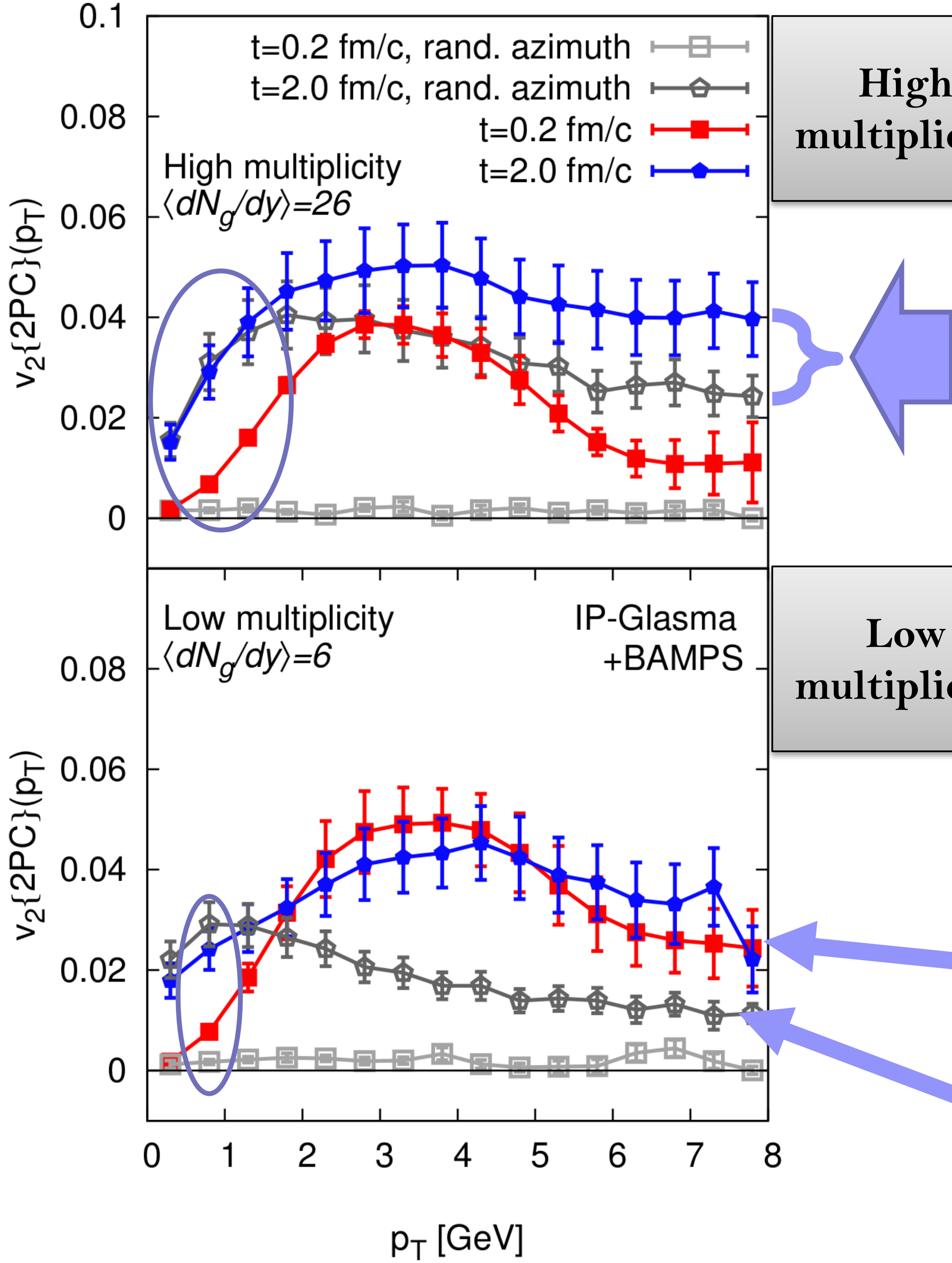
*Which influence comes from **geometry**, which part comes from **initial momentum correlations** ?*



Test: **Randomize initial transverse momentum direction: Eliminate initial correlations**

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

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



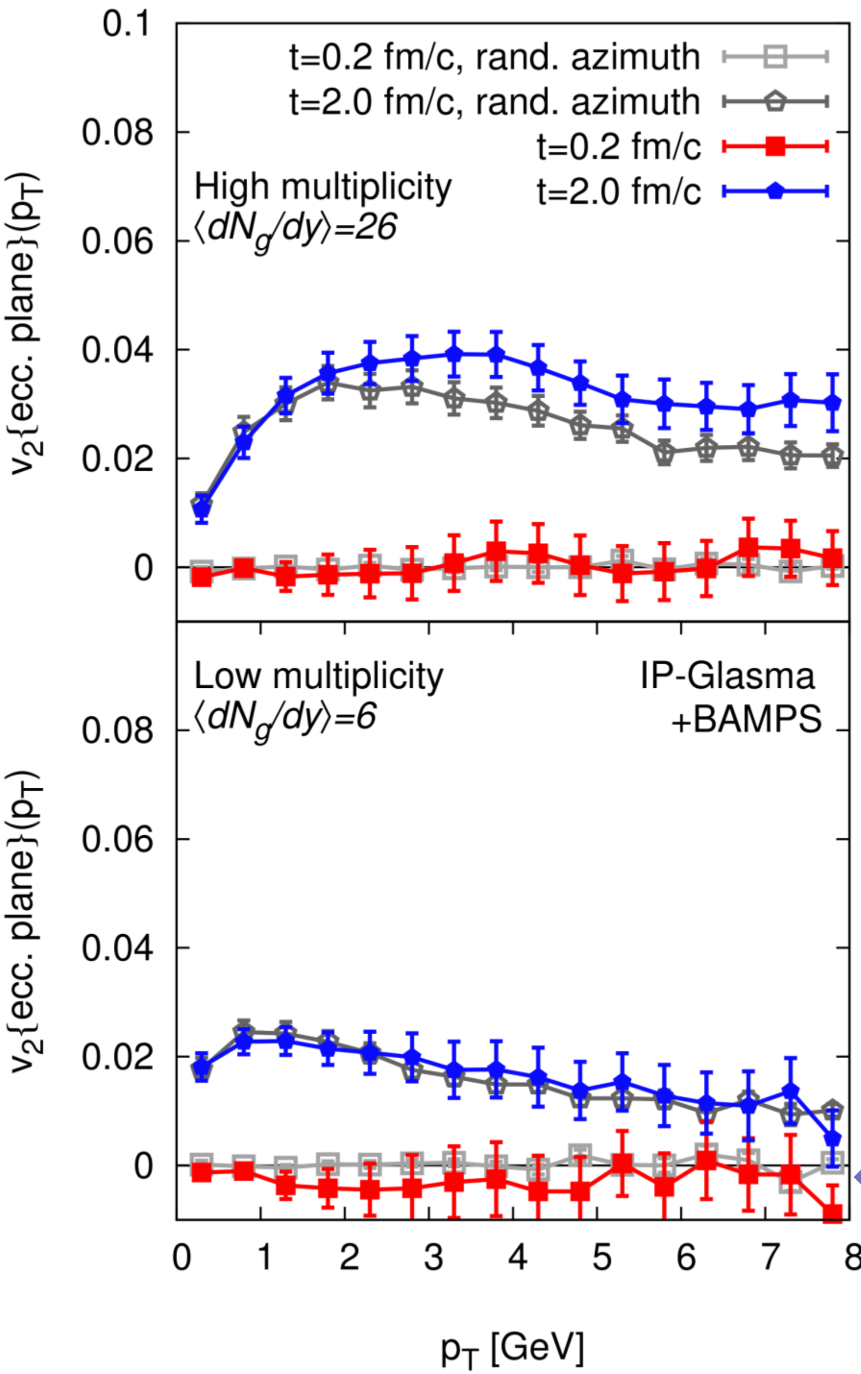
- Low momenta ($p_T < 2\ GeV$): geometric response pivotal
- At higher p_T initial state correlations contribute 50-100%

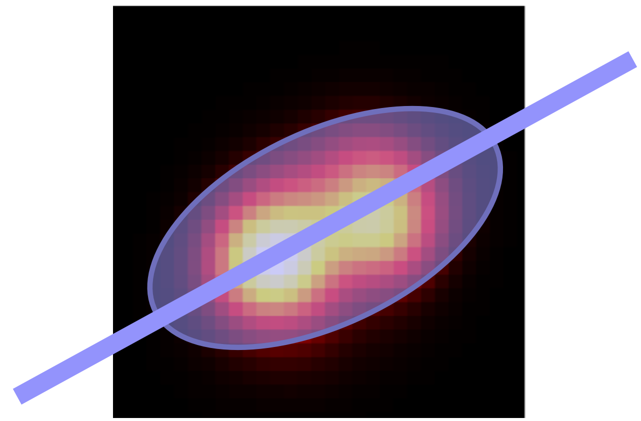
Low momenta ($p_T < 2\ GeV$): geometric response pivotal

At higher p_T final state unimportant.

Pure geometric response much smaller

„Eccentricity-plane $v_2(p_T)$“

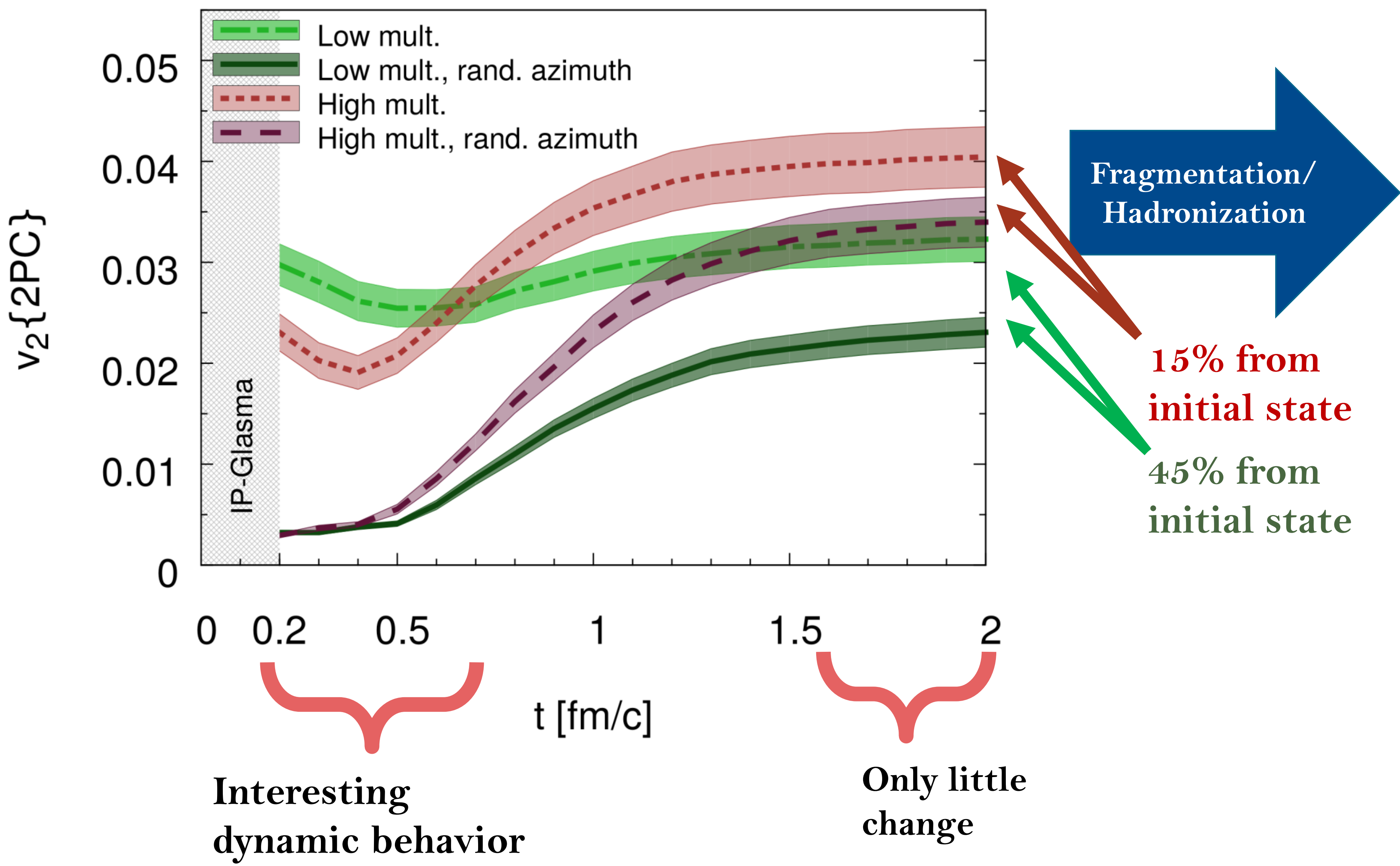




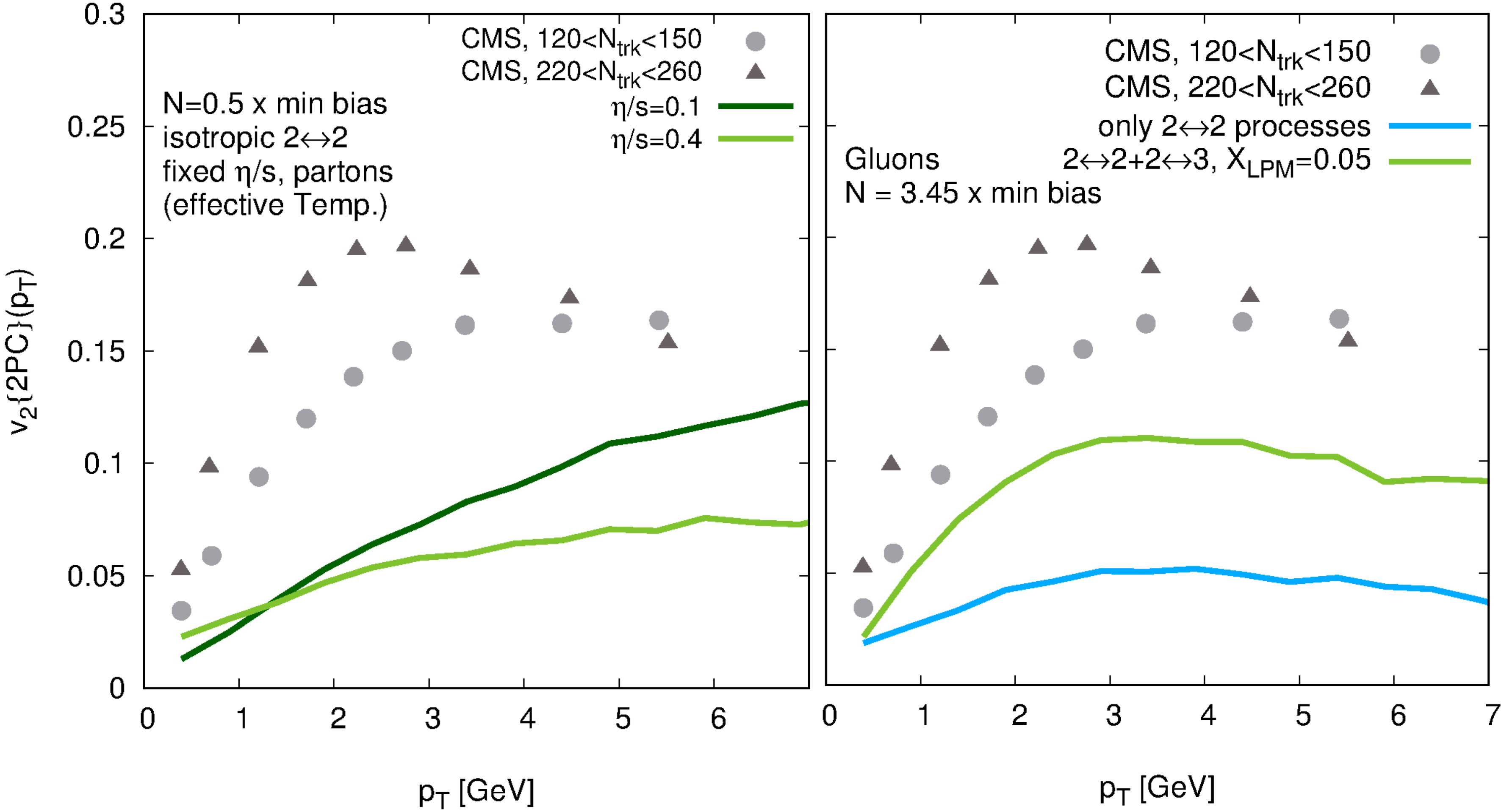
Geometric axis of transverse density distribution

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

Momentum-integrated elliptic flow



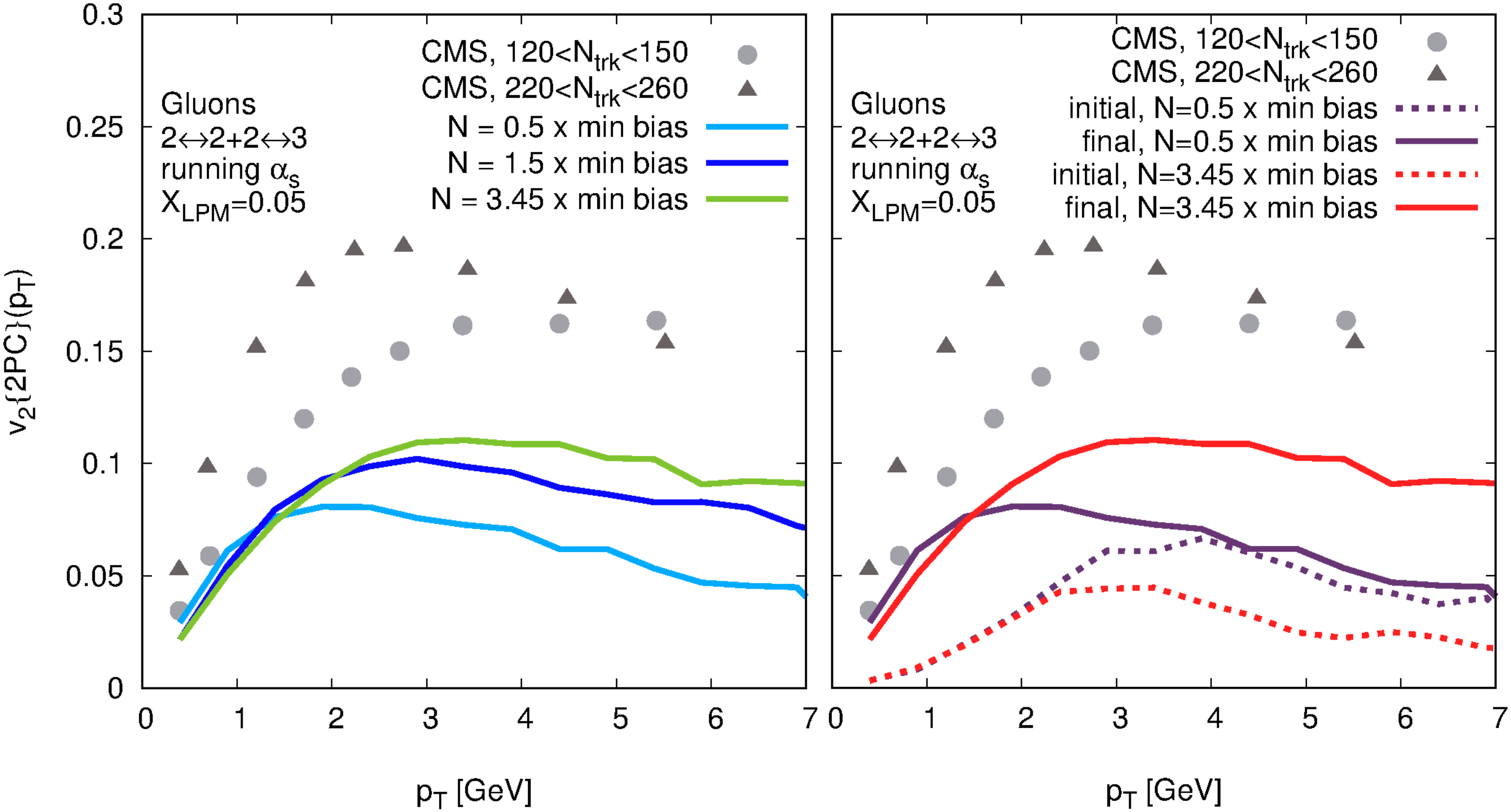
Parton interactions



- **Const η/s unsuitable for non-equilibrium approach**
- **Inelastic processes crucial, but free parameters**

Multiplicity scan

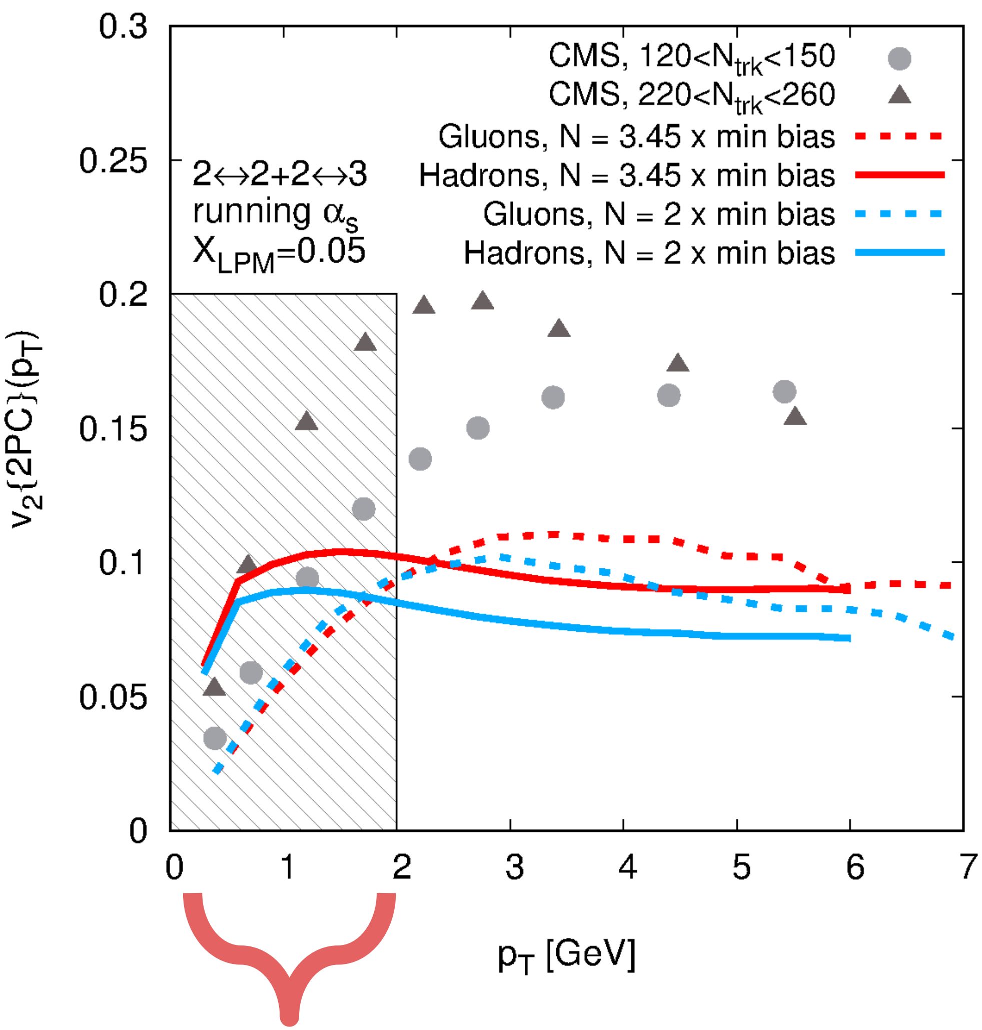
GOETHE UNIVERSITÄT FRANKFURT AM MAIN



- High p_T flow sensitive to multiplicity
- Low p_T flow develops insensitively to multiplicity

Fragmentation

GOETHE UNIVERSITÄT FRANKFURT AM MAIN



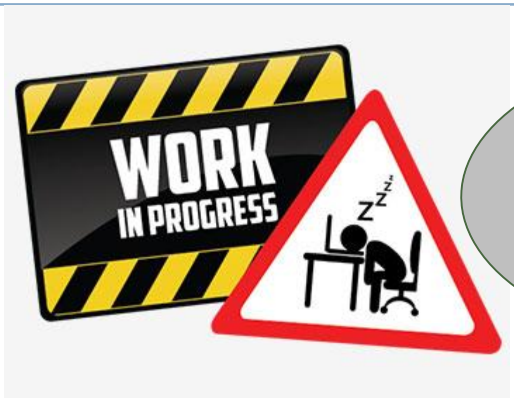
- Shift from high to low p_T
- Should be supplemented with ***microscopic hadronisation*** at low momenta

Fragmentation not reliable
– need microscopic hadronization

Fragmentation functions e.g. KKP (Kniehl, Kramer and Pötter)

Microscopic hadronization

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

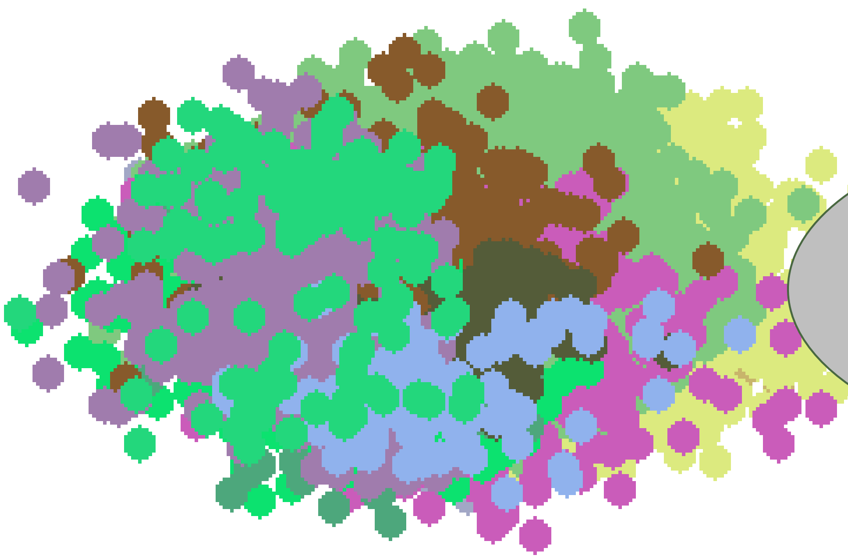


Local freeze-out criterion (energydensity)

Connect partons via colors

Hadron observ ables

Initial state → Parton cascade → „our“ Cluster-Algorithm → Event generator



Distance-of-Closest Approach (last possible interaction)

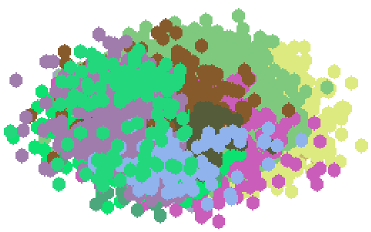
- Cluster independence
- Color connections
- Freeze-out criterion dependence

See e.g., Bahr et al., HERWIG++, Eur.Phys.J. C58 (2008) 639-707
Courtesy to Simon Plätzer from Herwig 7.

Preparating clustering algorithm

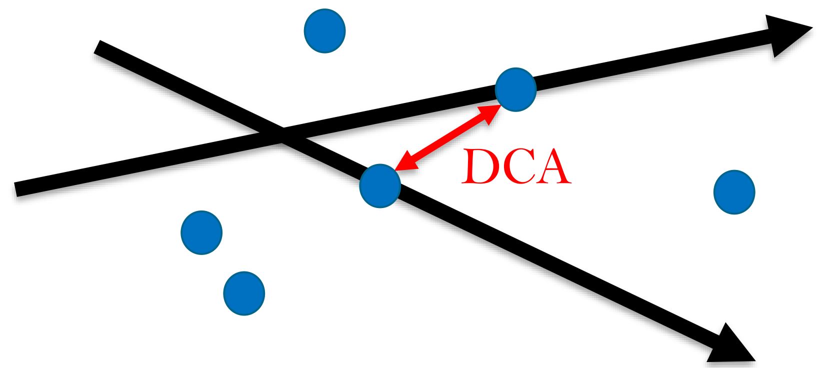
GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Cluster-Algorithm



Problem 1

- Define a freeze-out surface: time
  - Local energydensity
  - Local effective temperature
  - …
- Compute all Distances-of-Closest-Approach (**DCA**)



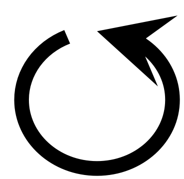
- Compute an „Action“: $$S = \sum_{\text{cluster } i} S_i$$

$$S_i = \left[\langle \text{DCA}^2 \rangle - X^2\right]^2$$

- then „random walk“:

$$P_{\text{split/merge}} \sim e^{-\beta \Delta S}$$

Merge cluster



Split cluster

Preparating clustering algorithm

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Cluster-Algorithm

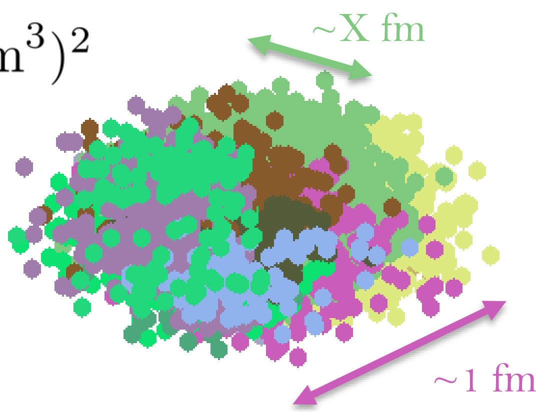
- Action S: $$S = \sum_{\text{cluster } i} S_i$$

$$S_i = \left[\langle \text{DCA}^2 \rangle - X^2\right]^2$$

Problem 2

Or other possibilities…

$$S_i = (\text{DCA}^3 - 1\ \text{fm}^3)^2$$



- Find stable Minimum of S

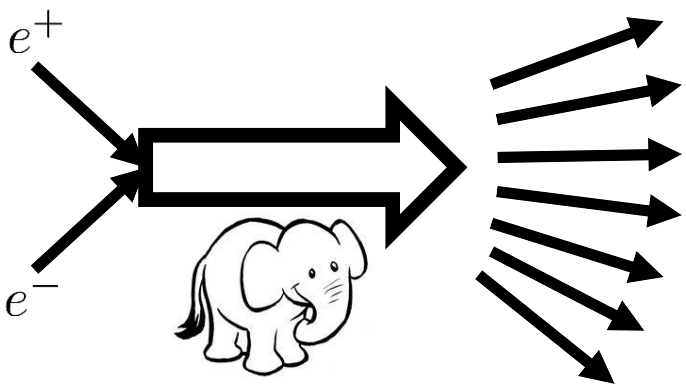
- Invent color connections for all quarks and gluons within Cluster

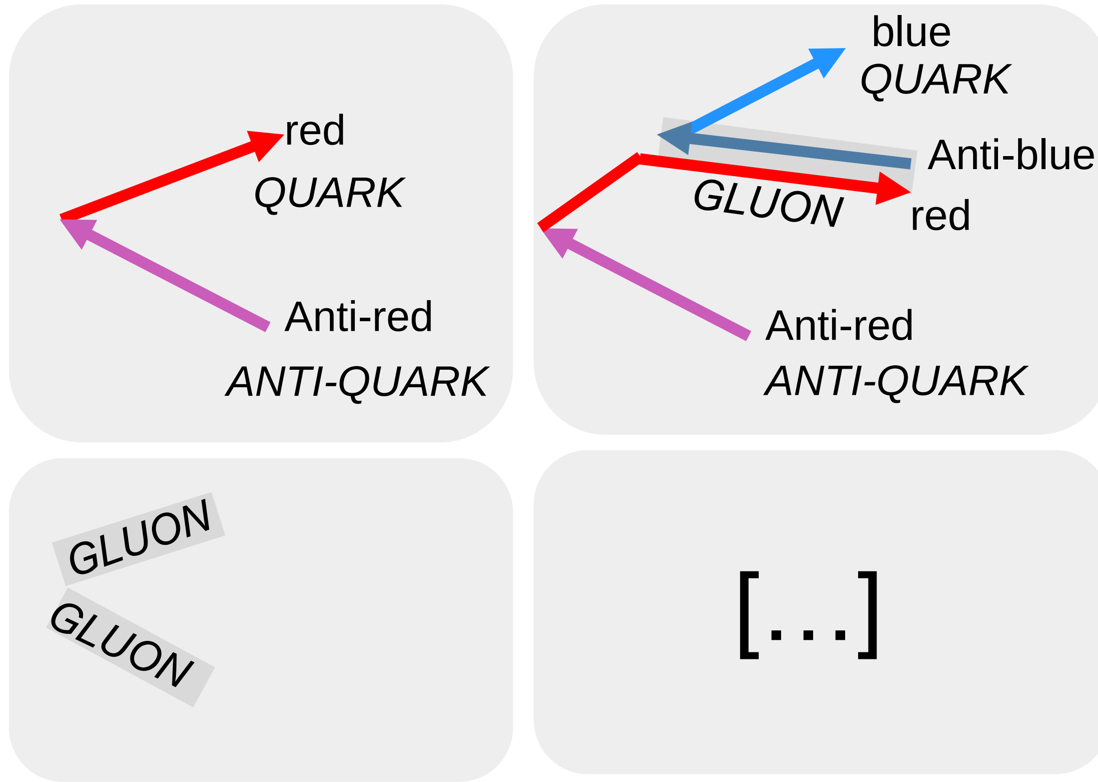
Problem 3

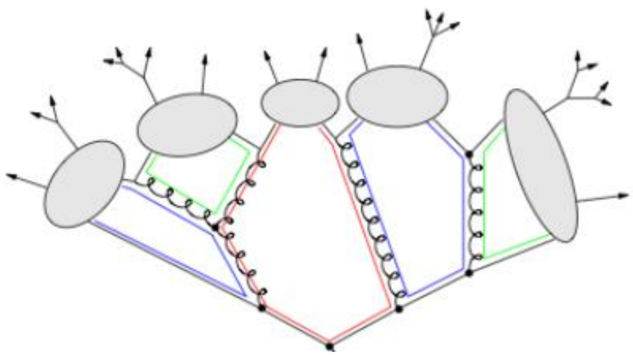
„preconfinement“: Input for Herwig

- Color connections for „fake“ process:

$$e^+ + e^- \longrightarrow \text{white elephant} \longrightarrow \text{all partons}$$



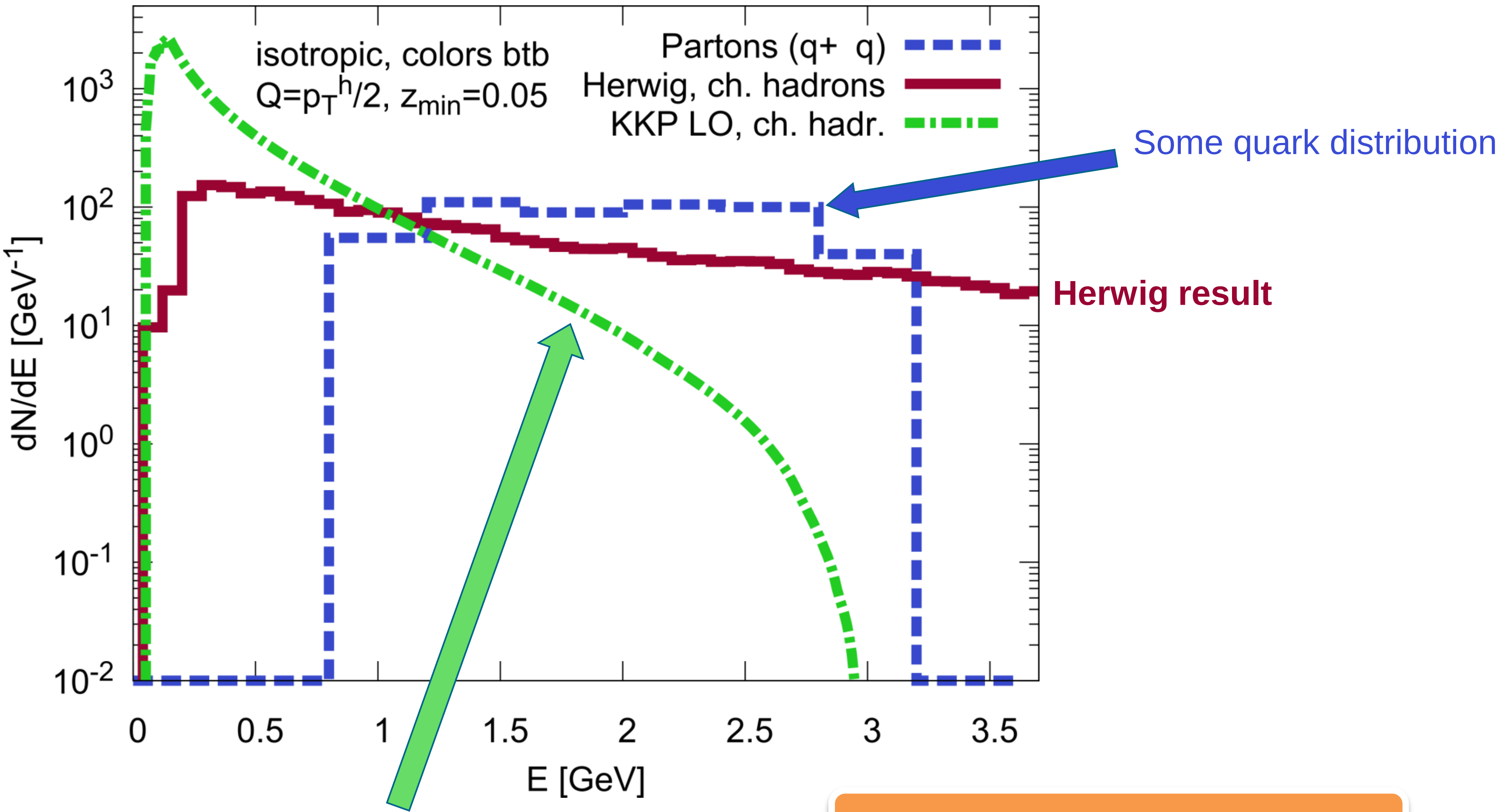




- Make lists of partons (momenta, color, species) for all Clusters
- Feed cluster-lists as input into Herwig 7
- Run cluster hadronization and decay from Herwig 7

Microsc. hadronization vs. fragmentation

GOETHE UNIVERSITÄT FRANKFURT AM MAIN



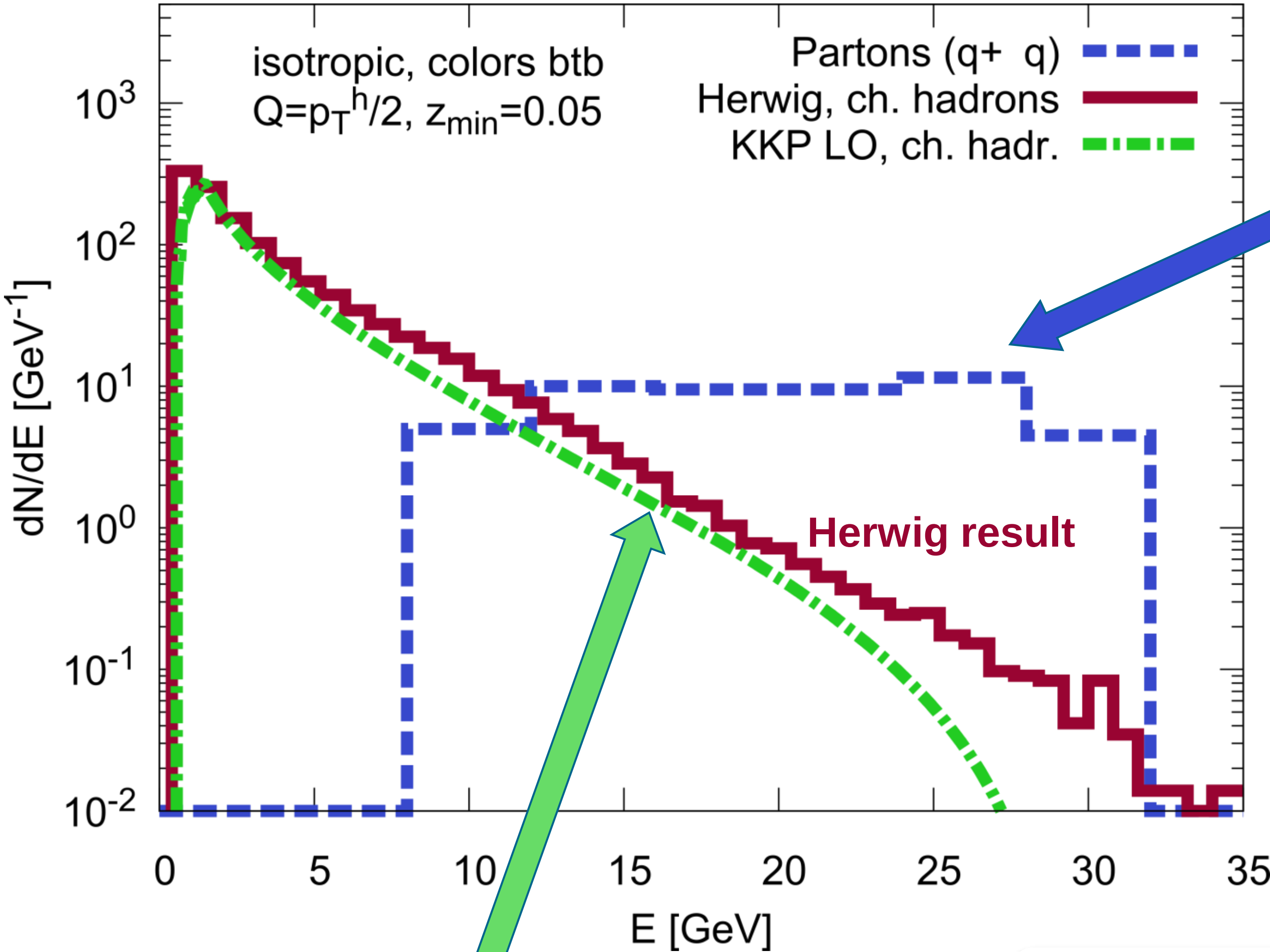
Fragmentation functions modify spectrum

(not applicable @ 2 GeV)

at typical momenta ~ 2 GeV

Microsc. hadronization vs. fragmentation

GOETHE UNIVERSITÄT FRANKFURT AM MAIN



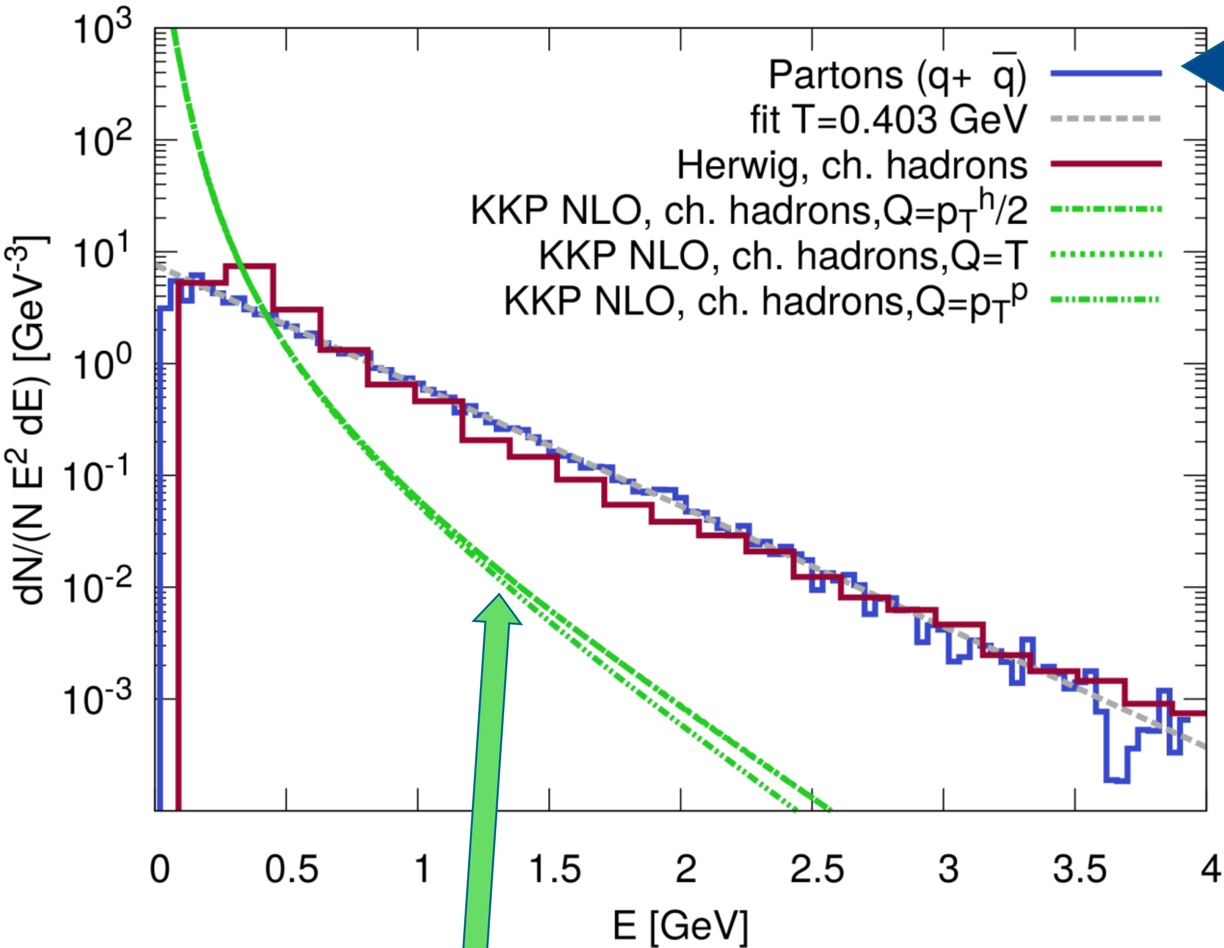
Some quark distribution

Fragmentation function result

at typical momenta ~ 20 GeV

Microsc. hadronization vs. fragmentation

GOETHE UNIVERSITÄT FRANKFURT AM MAIN



Thermal QGP, T=400 MeV

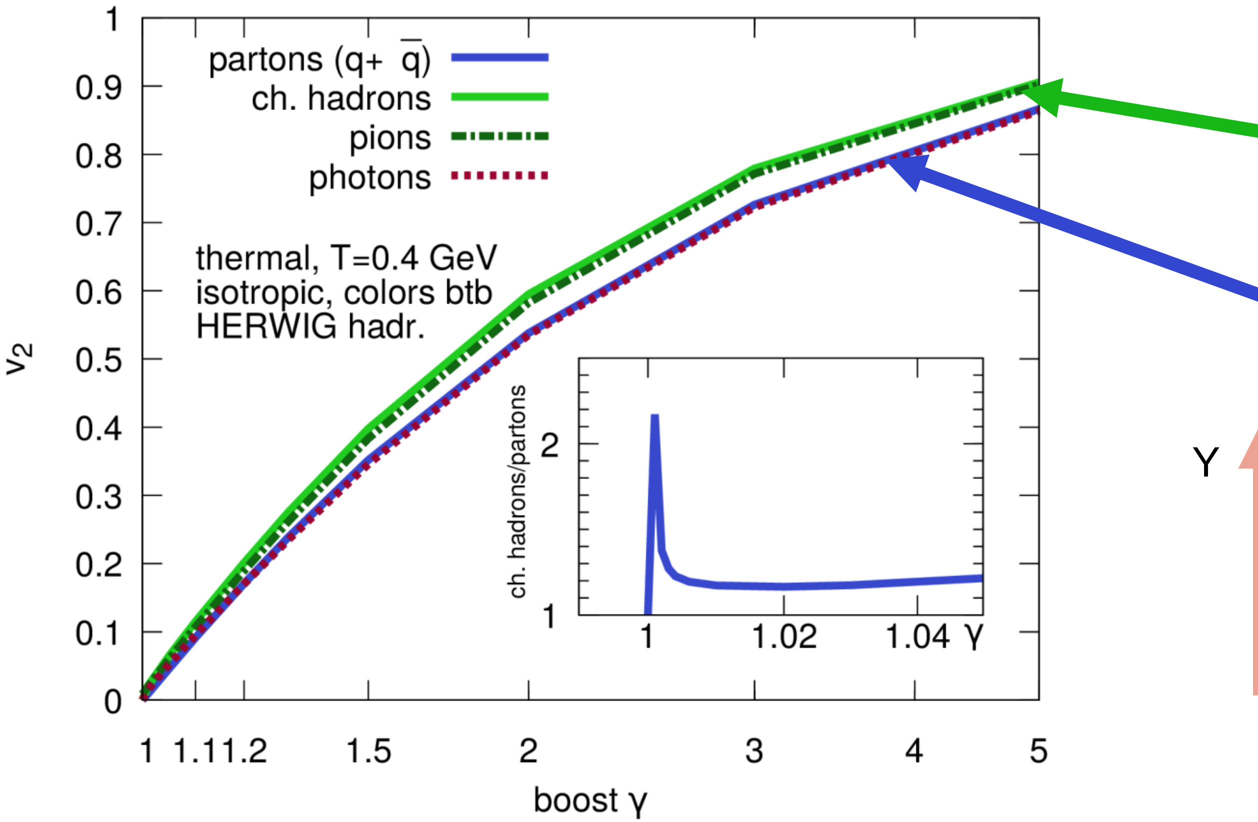
HERWIG seems to *not* change much

Fragmentation functions modify spectrum

(scale actually too low)

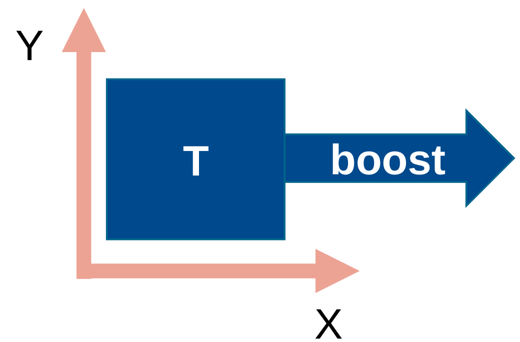
at typical thermal momenta

Hadronization, what can we expect



Hadrons, from HERWIG

Partons, thermal (boosted)



$$\text{“}v_2\text{”} = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$$

Conclusions & Outlook

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Our model

- Combined initial and final state calculation for p+Pb collisions
- Initial state:
- Final state: BAMPS
- Work in Progress: Hadronization (via Herwig 7)

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

Outlook

- Finish, check & test hadronization
- StAndalone-HAdronizeR for pArton lists
- Recompute all hadronic observables
- Systematic multiplicity scan

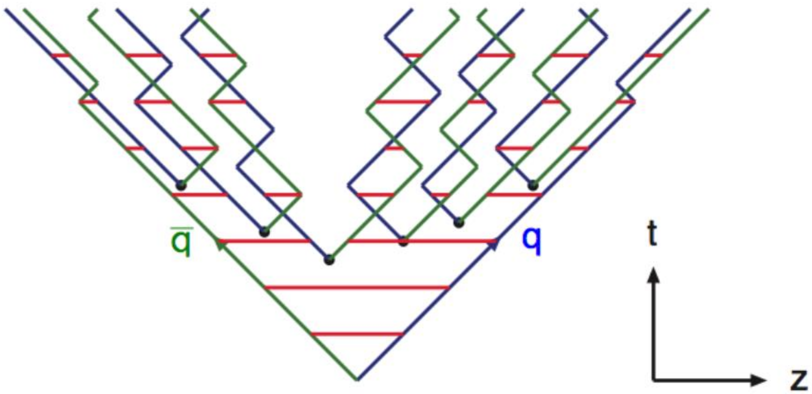
Hadronization schemes

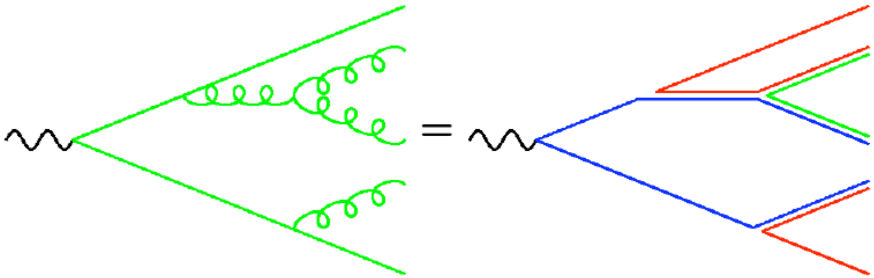
1. **Independent fragmentation**
2. **String model**
3. **Cluster hadronization**
4. **Local Parton-Hadron duality**
5. **Thermal/Statistical models**

Independent fragmentation model:
„Field-Feynman“
MC implementation of „Tube“ model

String Models:
Precurser „Artru-Mennessier“ model
Lund string model - PYTHIA
Expanding successive string breaking
Or „popcorn model“
„Gluons kink string“
Good fits to data
Messy and complicated
Baryons=q+Diquark

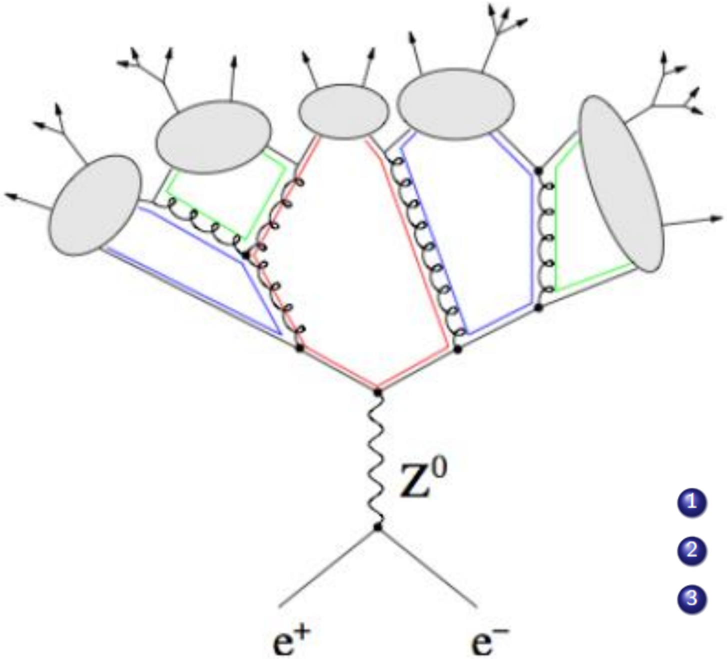
Cluster hadronization:
Herwig++
„Preconfinement“
Follow colors
Color singlet pairs (=„clusters“) projected onto high-mass resonances
+ longitudinal cluster fission





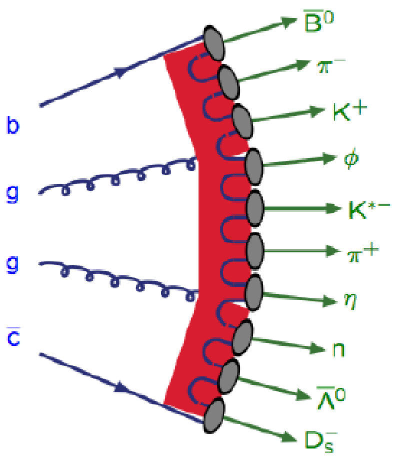
Pictures from T.Sjöstrand et al.

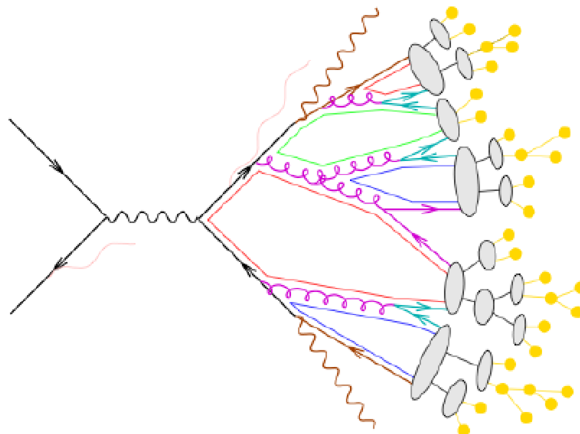
Herwig Cluster Hadronization scheme



1. Introduce forced $g \to q\bar{q}$ branchings
2. Form colour singlet clusters
3. Clusters decay isotropically to 2 hadrons according to phase space weight $\sim (2s_1 + 1)(2s_2 + 1)(2p^*/m)$

Herwig Cluster Hadronization scheme





program	PYTHIA	HERWIG
model	string	cluster
energy–momentum picture	powerful	simple
	predictive	unpredictive
parameters	few	many
flavour composition	messy	simple
	unpredictive	in-between
parameters	many	few

Slide from T. Sjöstrand