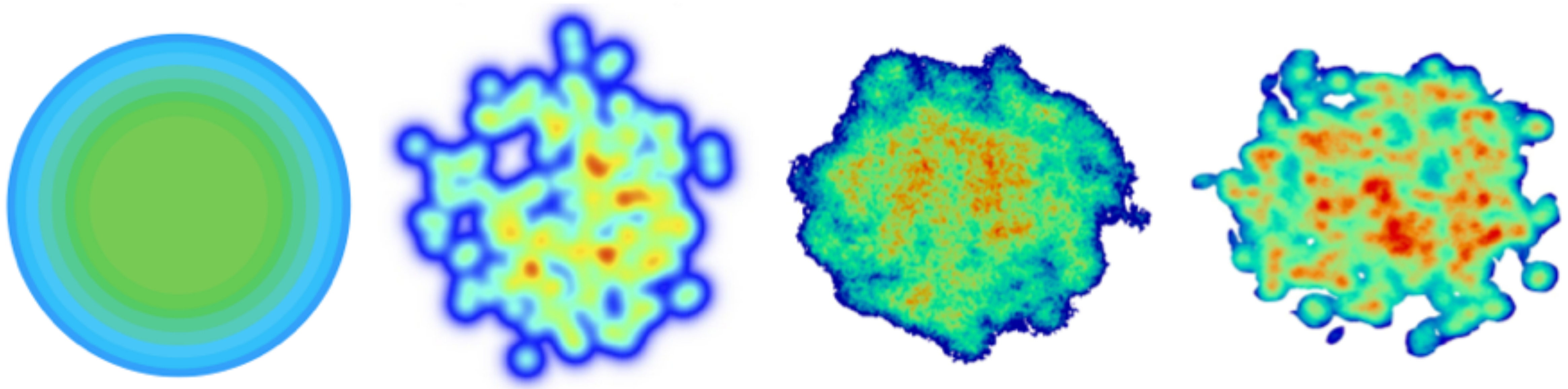
The Initial Stages of Colliding Nuclei and Hadrons

Prithwish Tribedy

BROOKHAVEN NATIONAL LABORATORY

Hot Quarks 2016, workshop for young scientist on the physics of ultra relativistic A-A collisions

September 12-17, 2016, on South Padre Island, TX, USA



HQ'04 HQ'08 HQ'12 HQ'16

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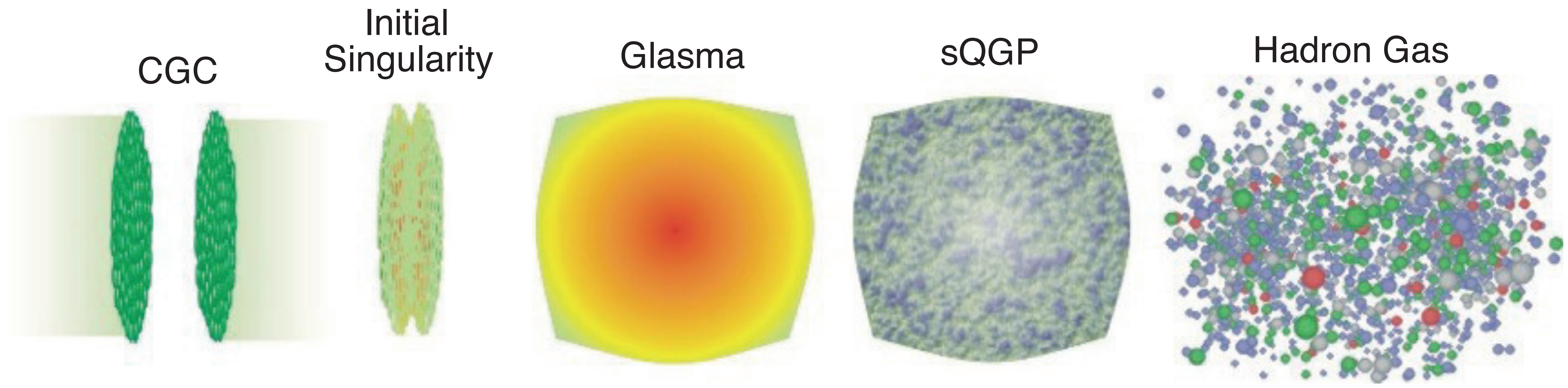
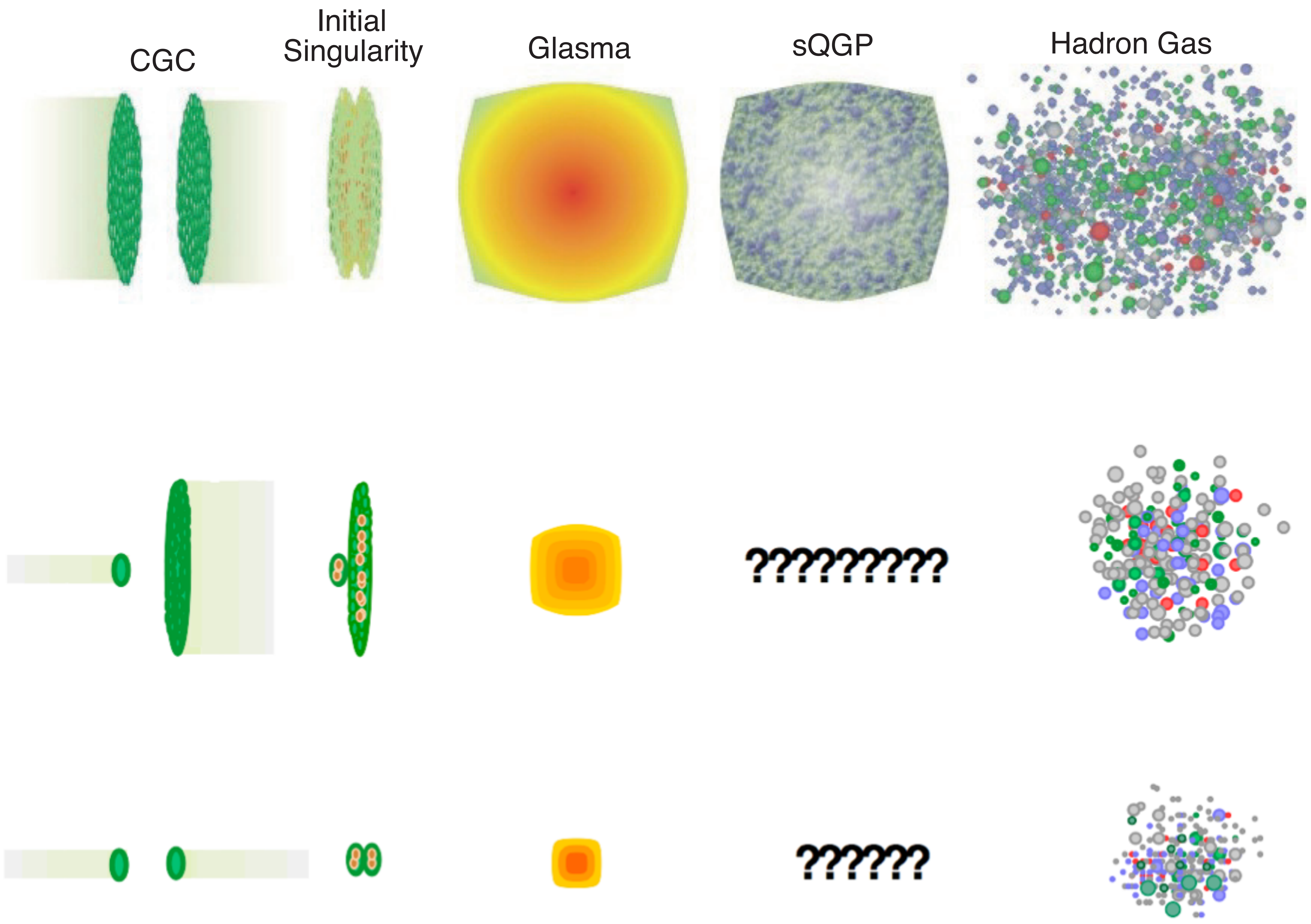
A conventional picture of collisions



You have seen this before
but let me add two more…

A conventional picture of collisions



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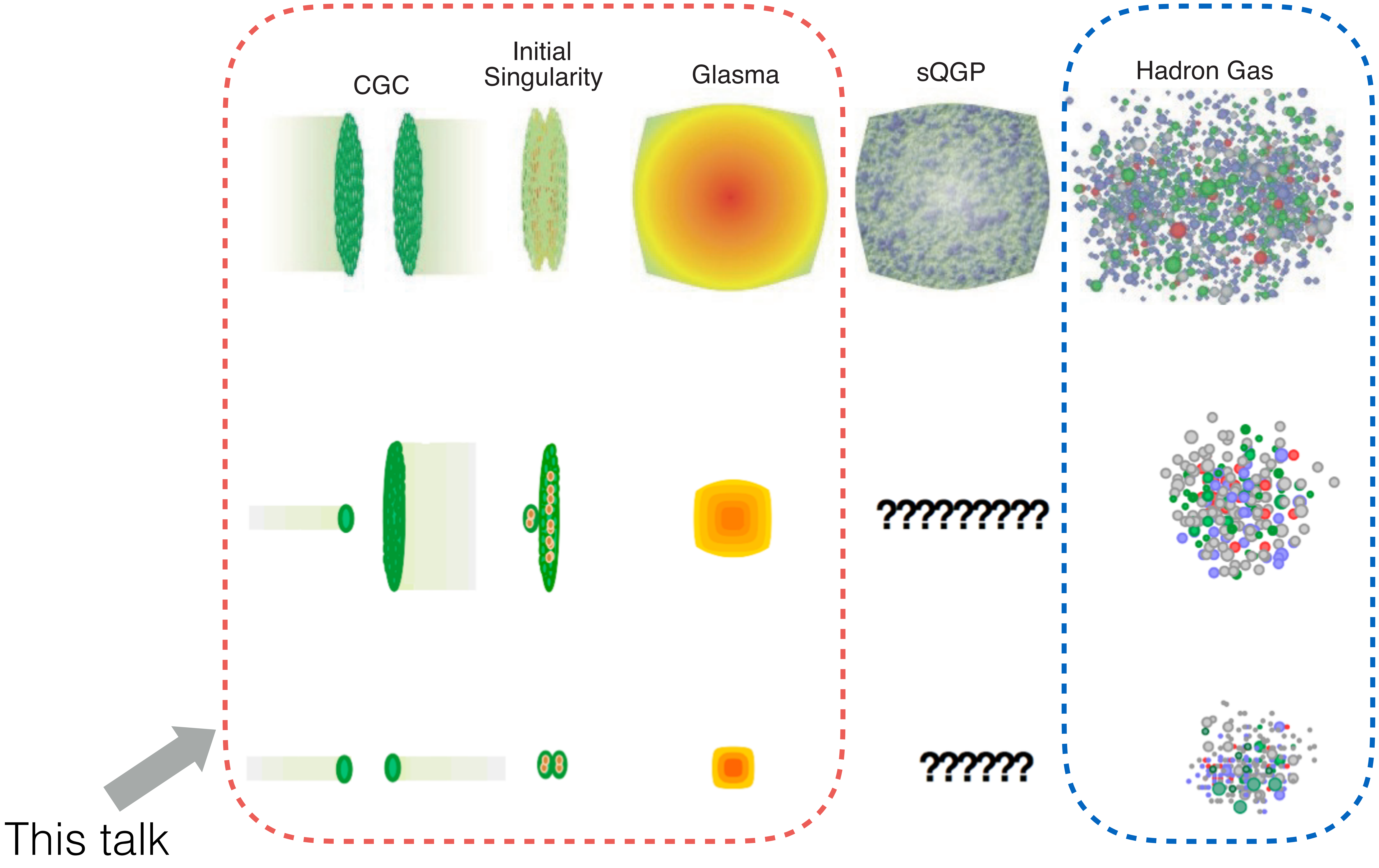

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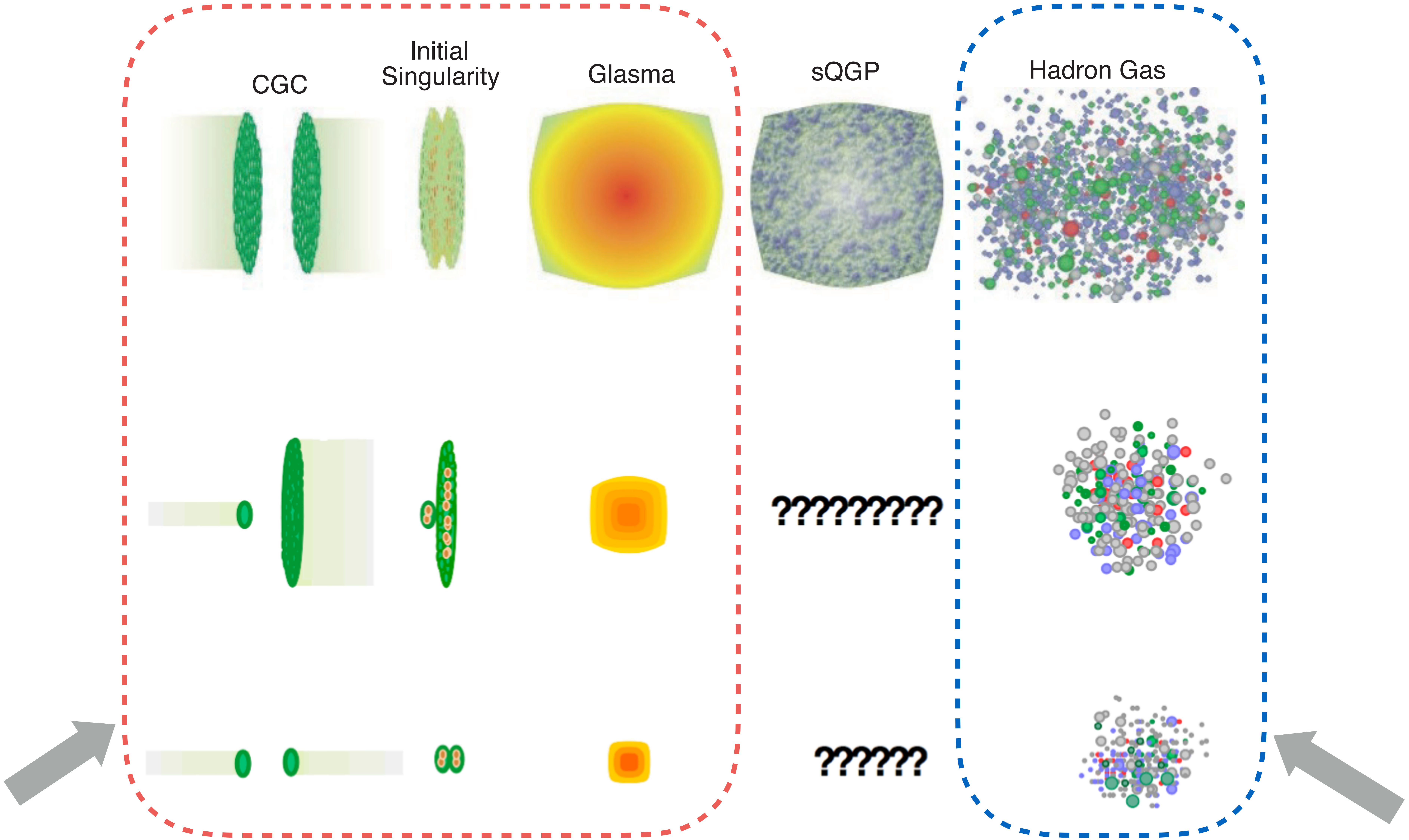


dynamics of initial state

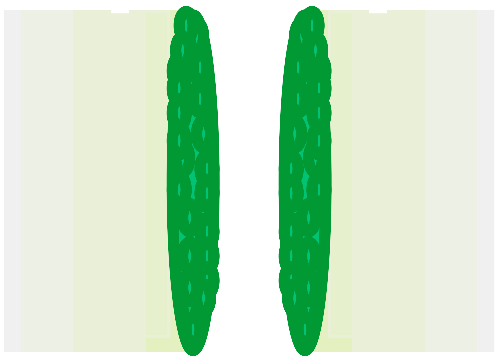
observation in final state

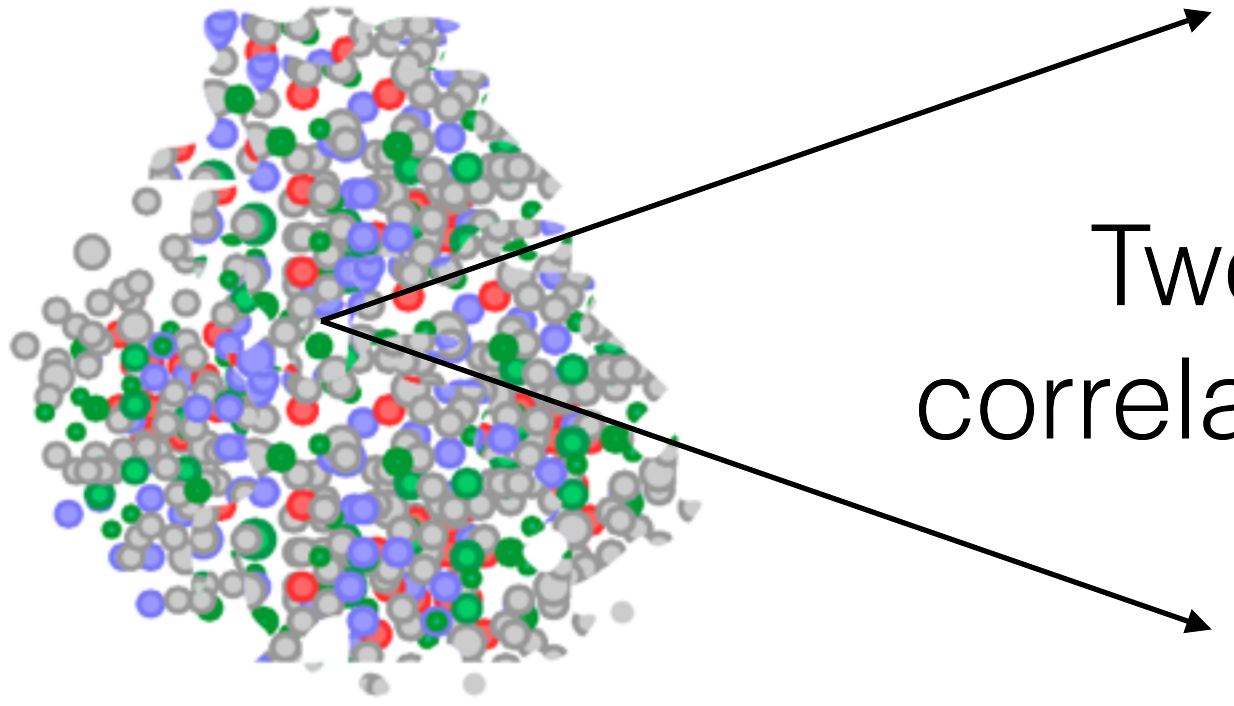
How can we possibly know about initial states ?

How can we possibly know about initial states ?

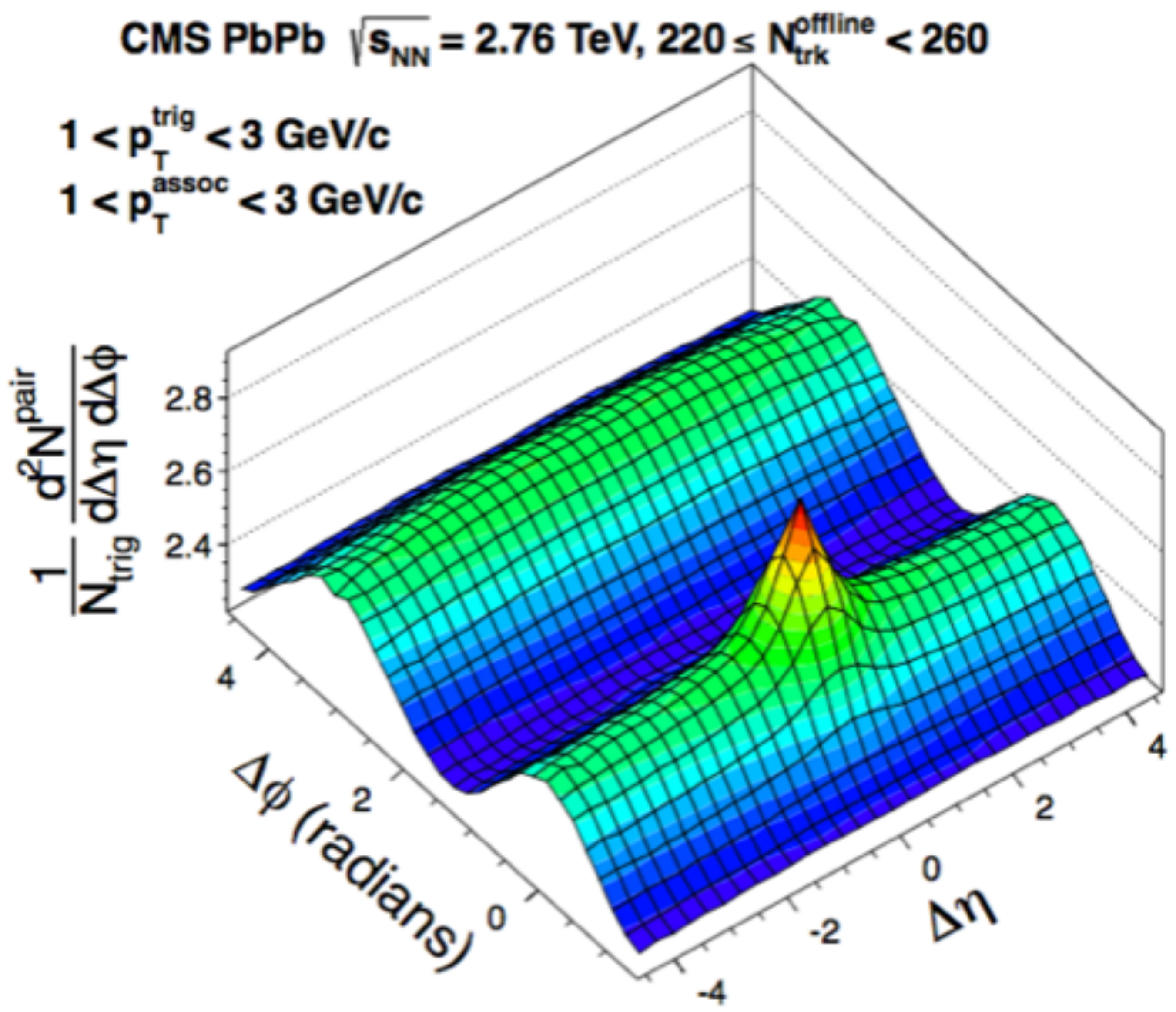
Lets first focus on heavy ion collisions

talk by Soumya





Two particle correlation function



Long range correlations

talk by Soumya

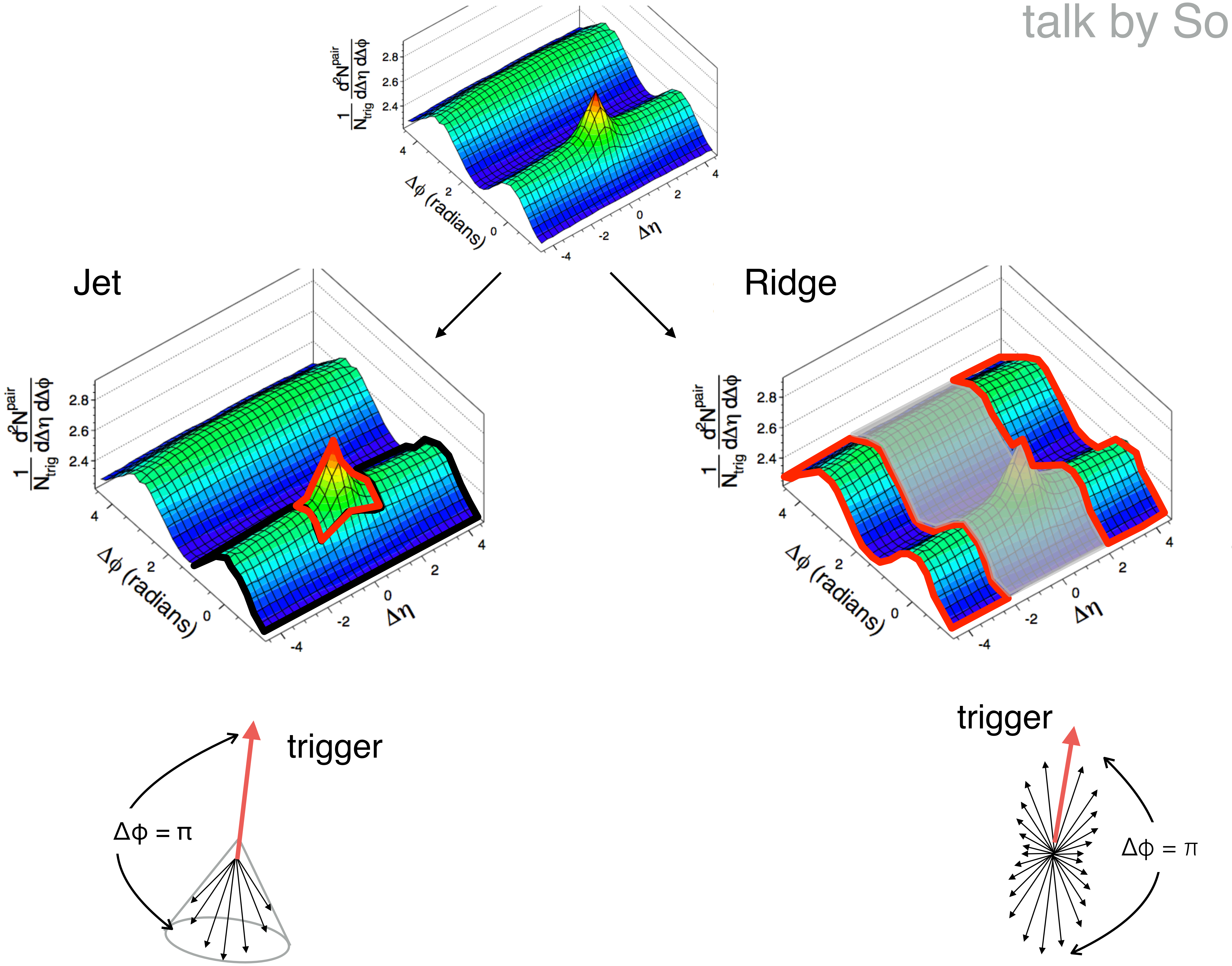
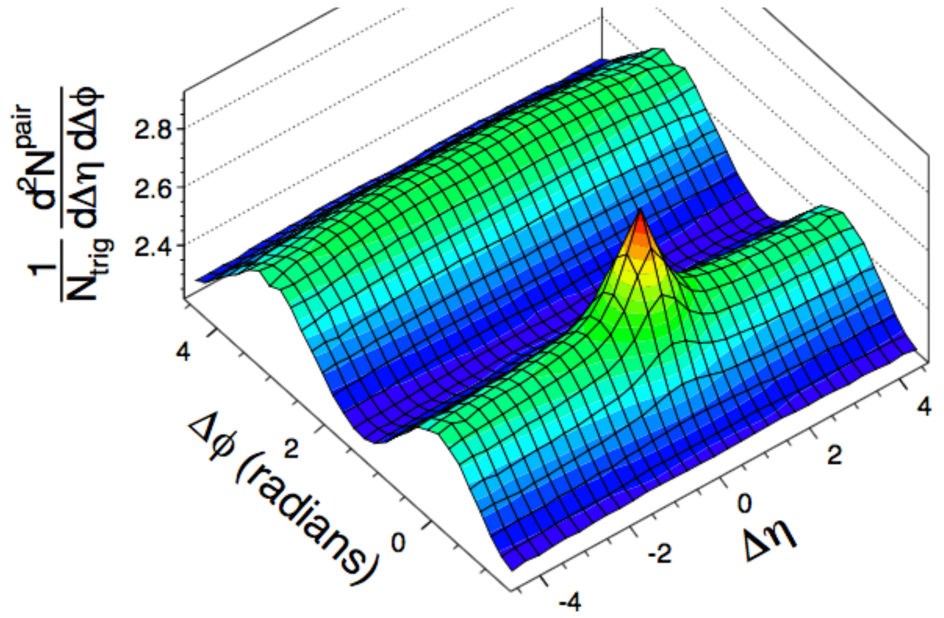
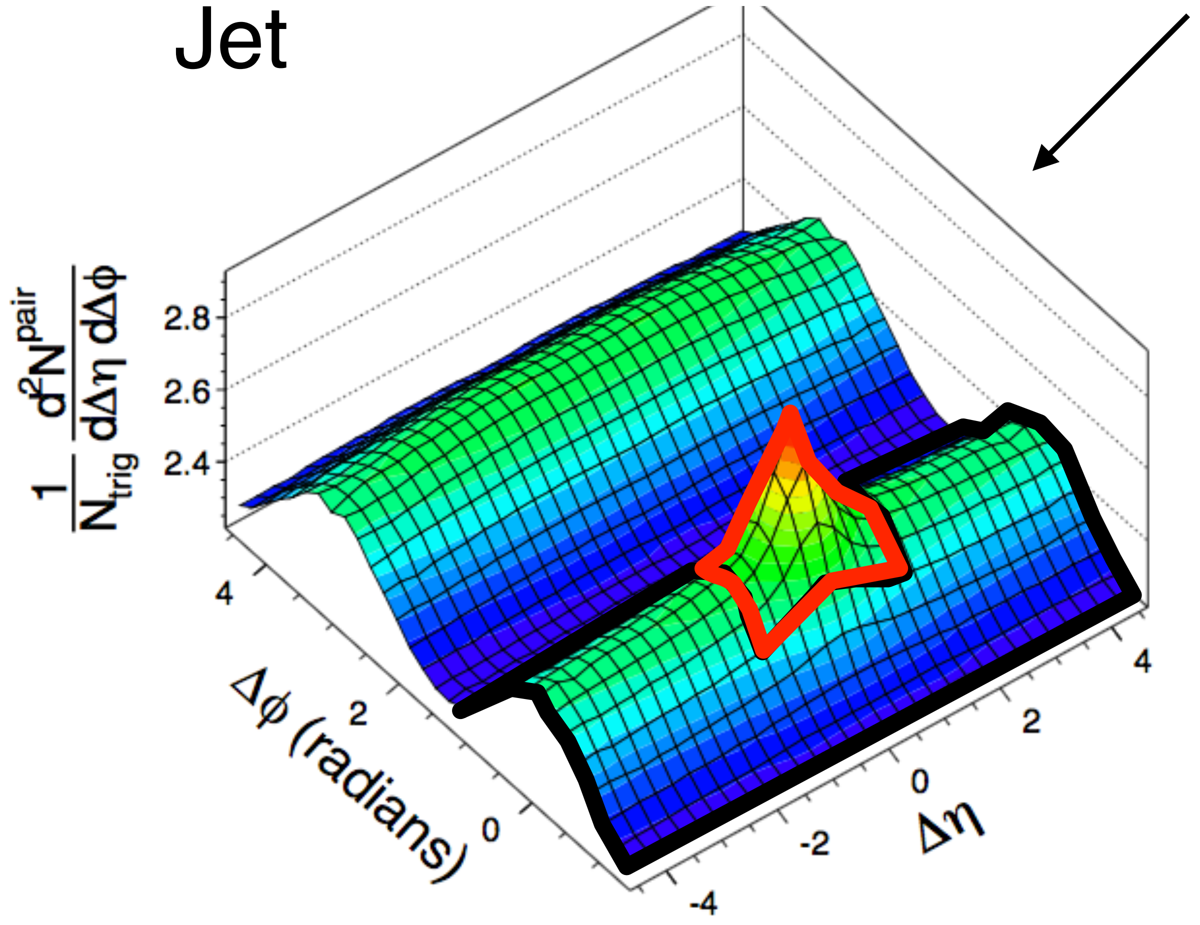


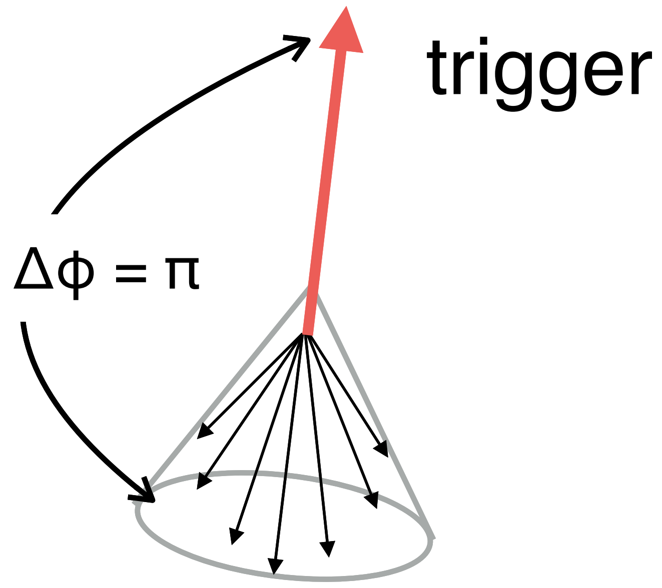
fig : Quan Wang (ISMD'16)

Long range correlations



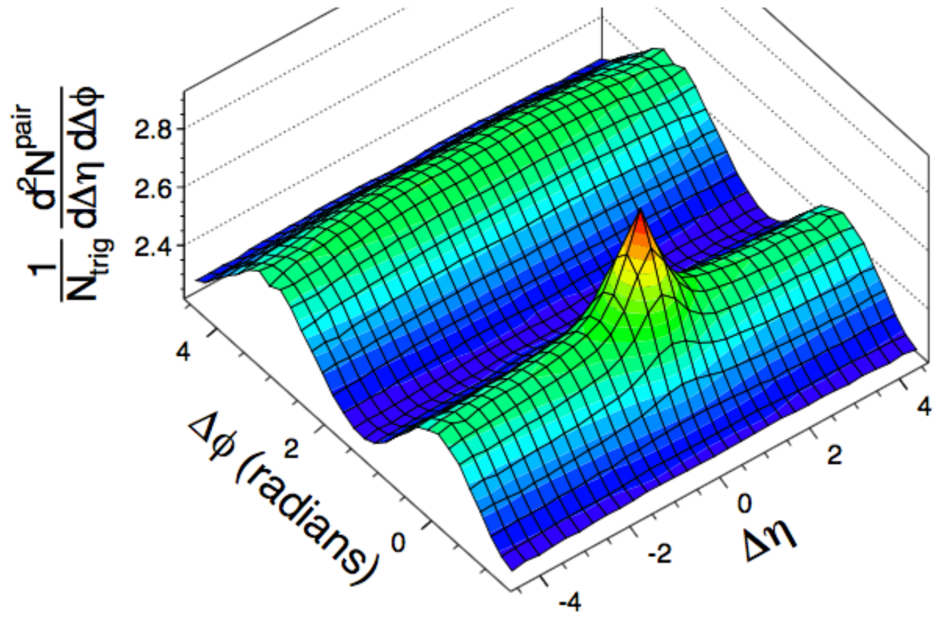
Jet



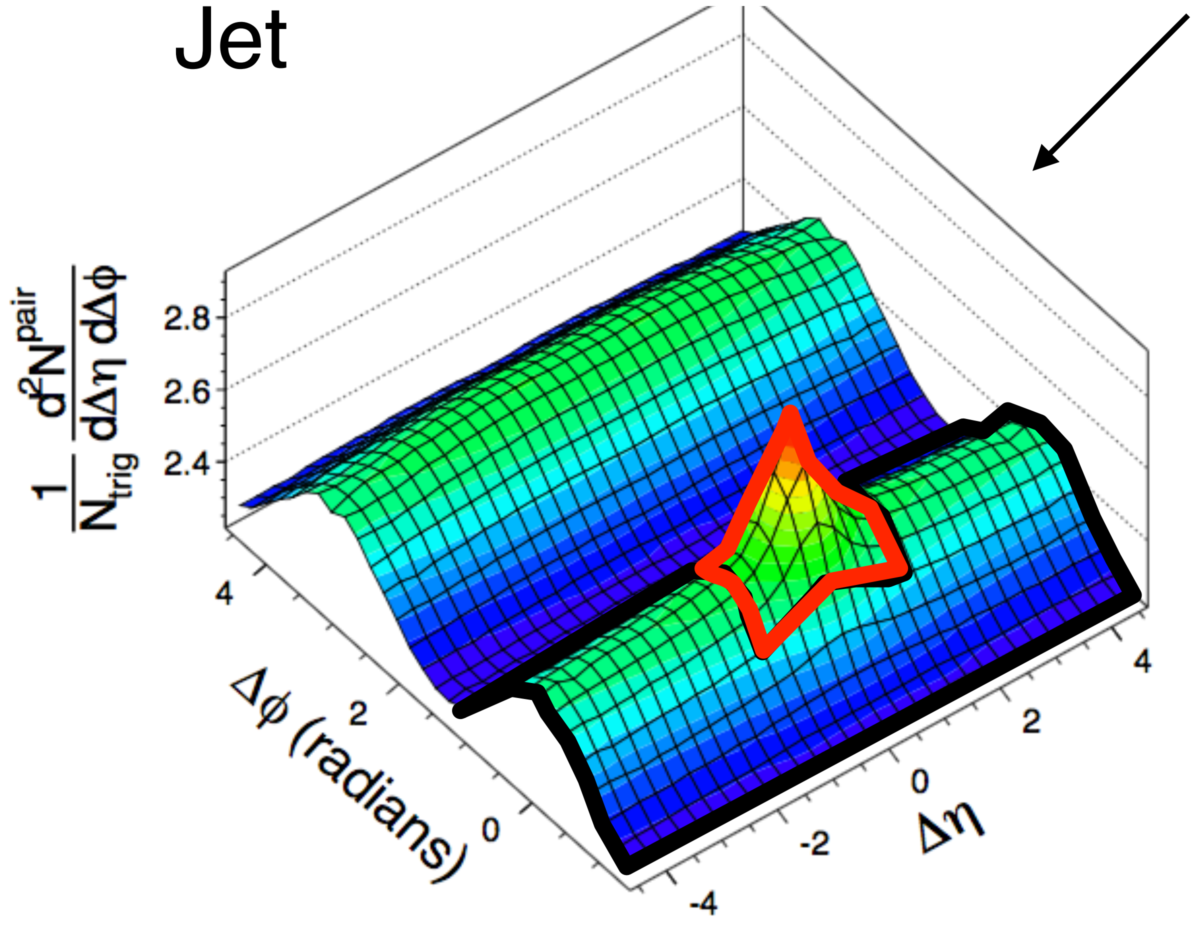


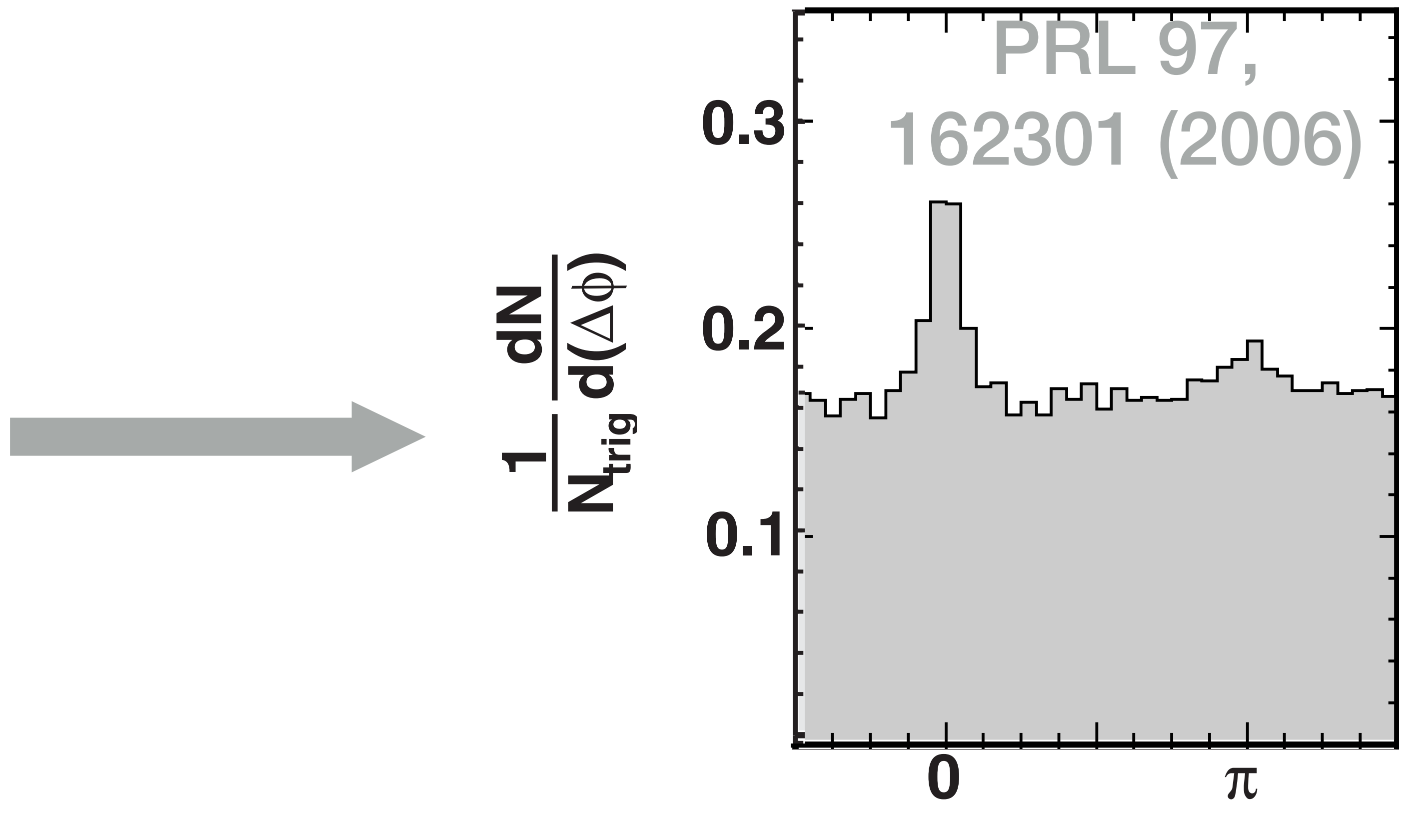
Long range correlations

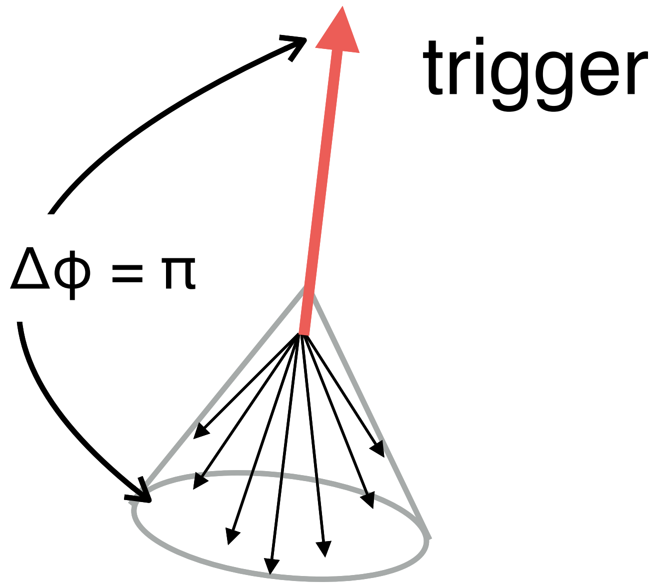
fig: Quan Wang (ISMD'16)



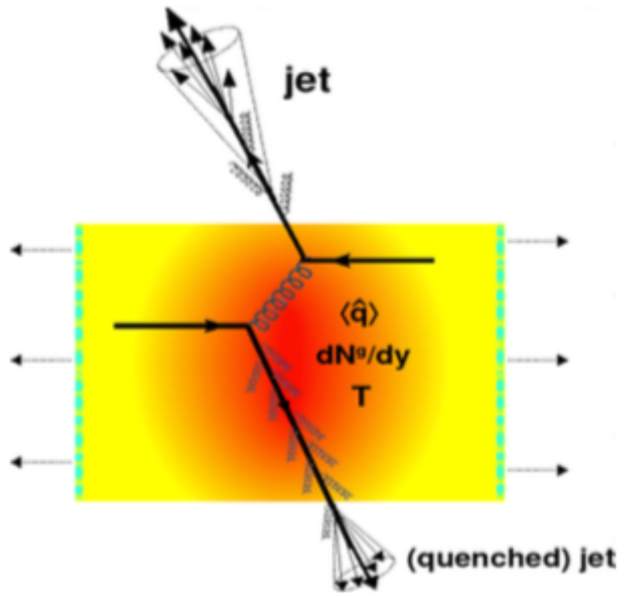
Jet



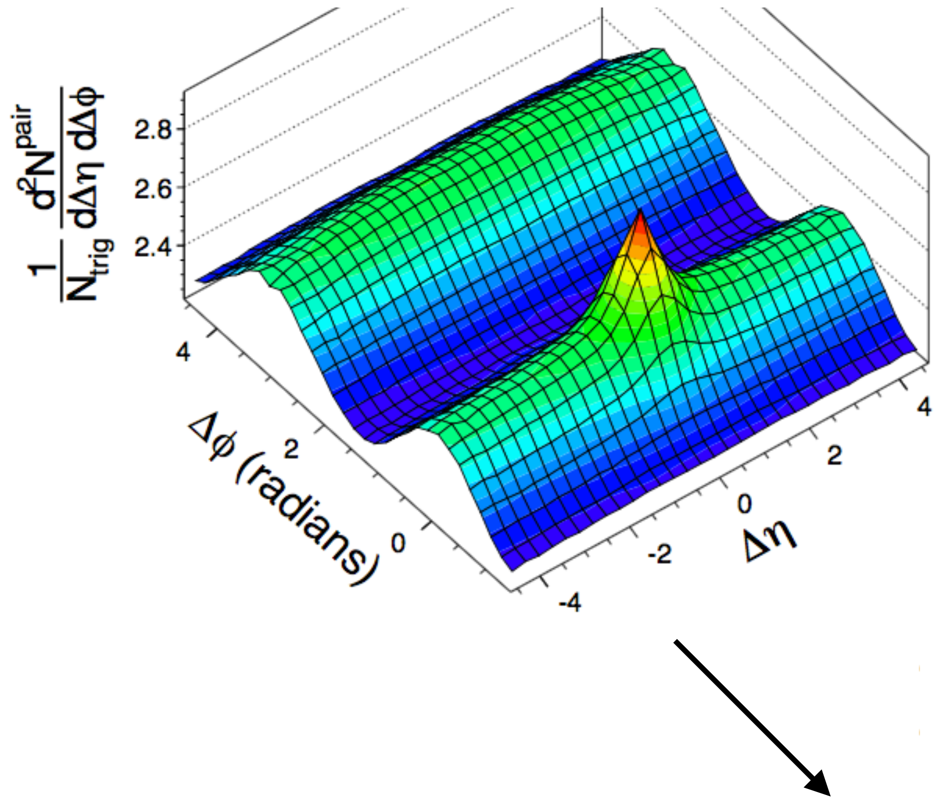




signature of
jet-quenching



Long range correlations



Ridge

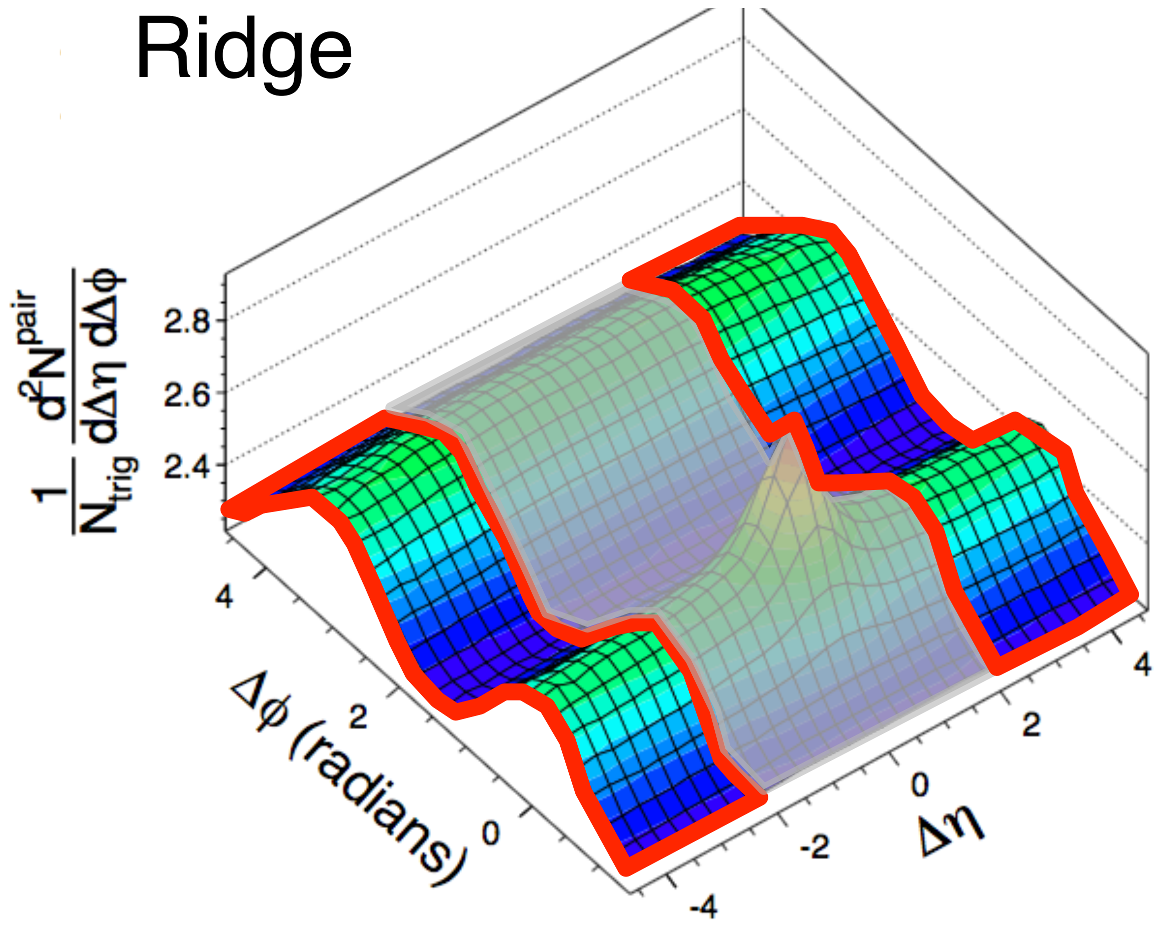
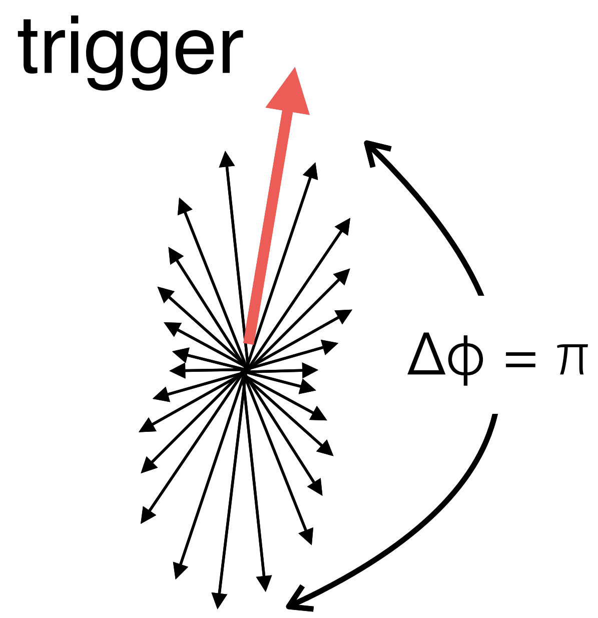
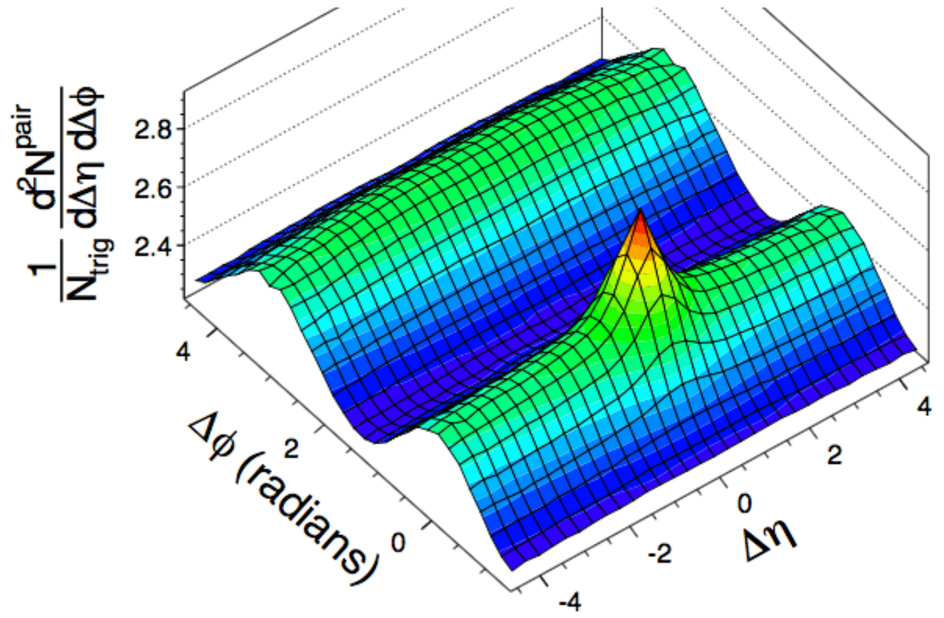
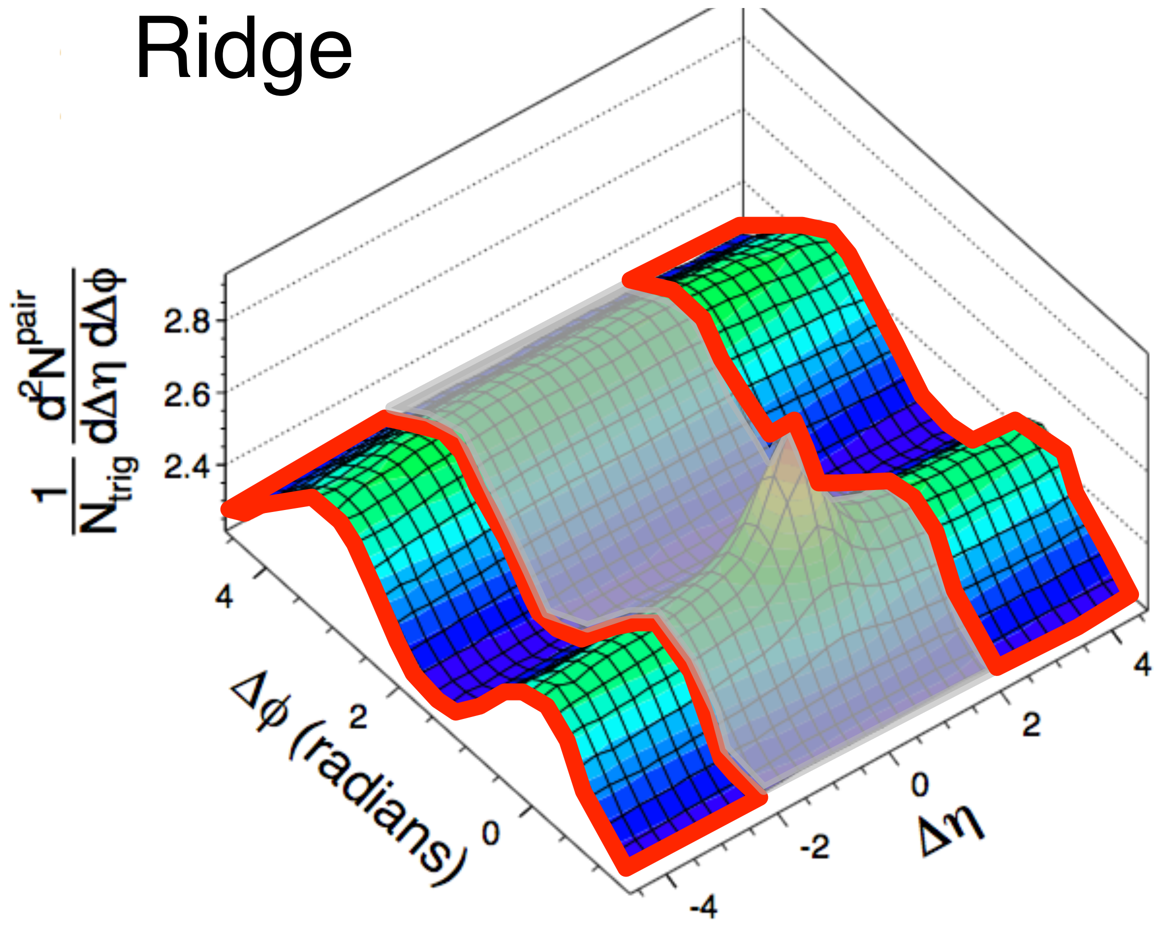


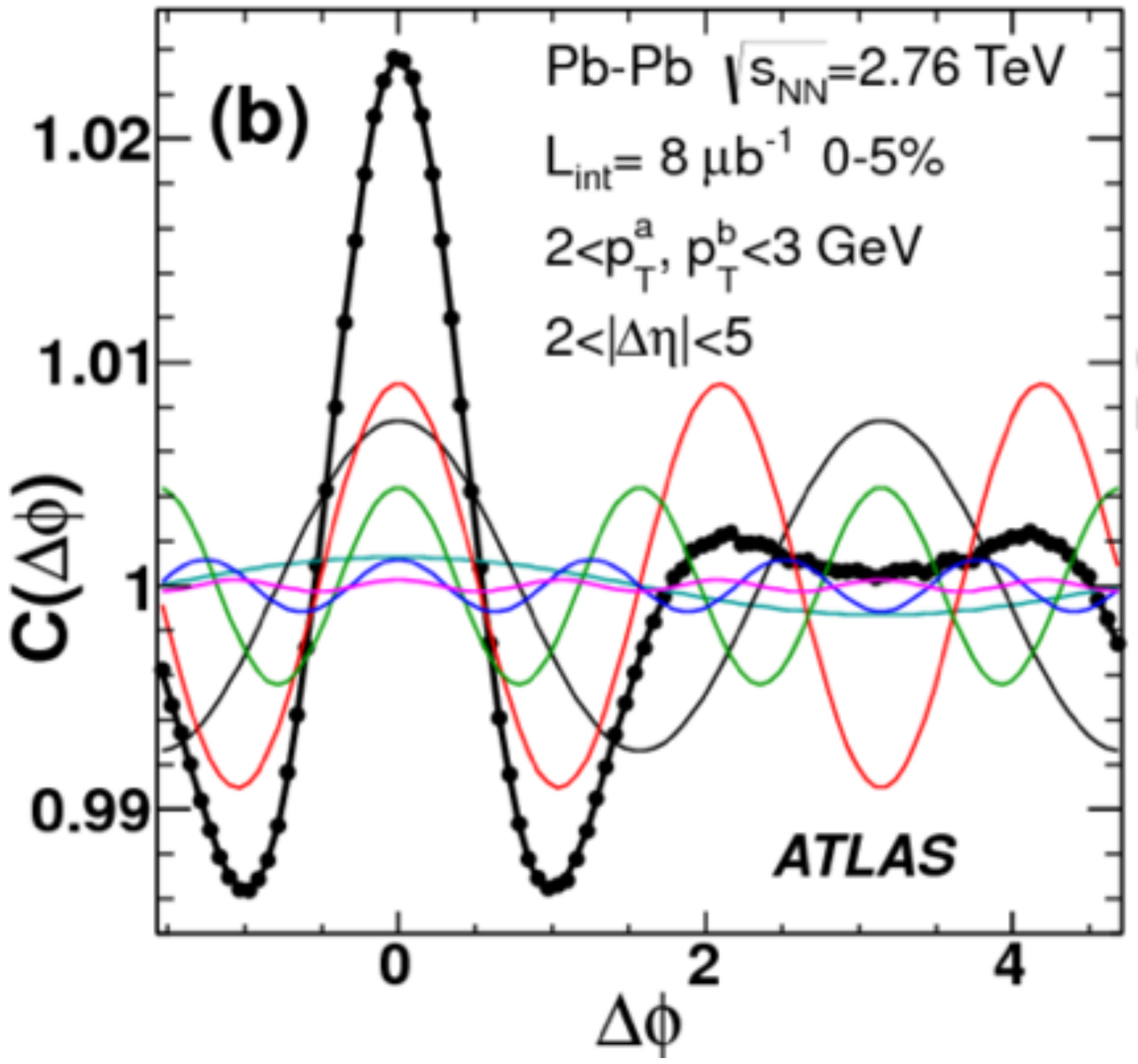
fig: Quan Wang (ISMD'16)



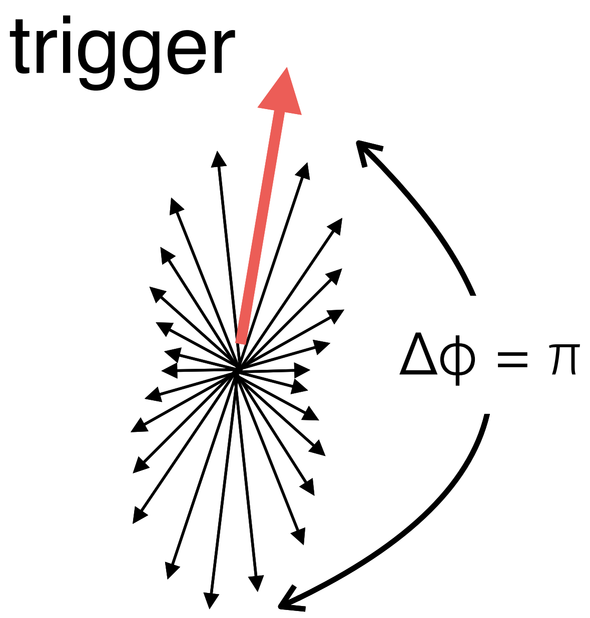
Long range correlations



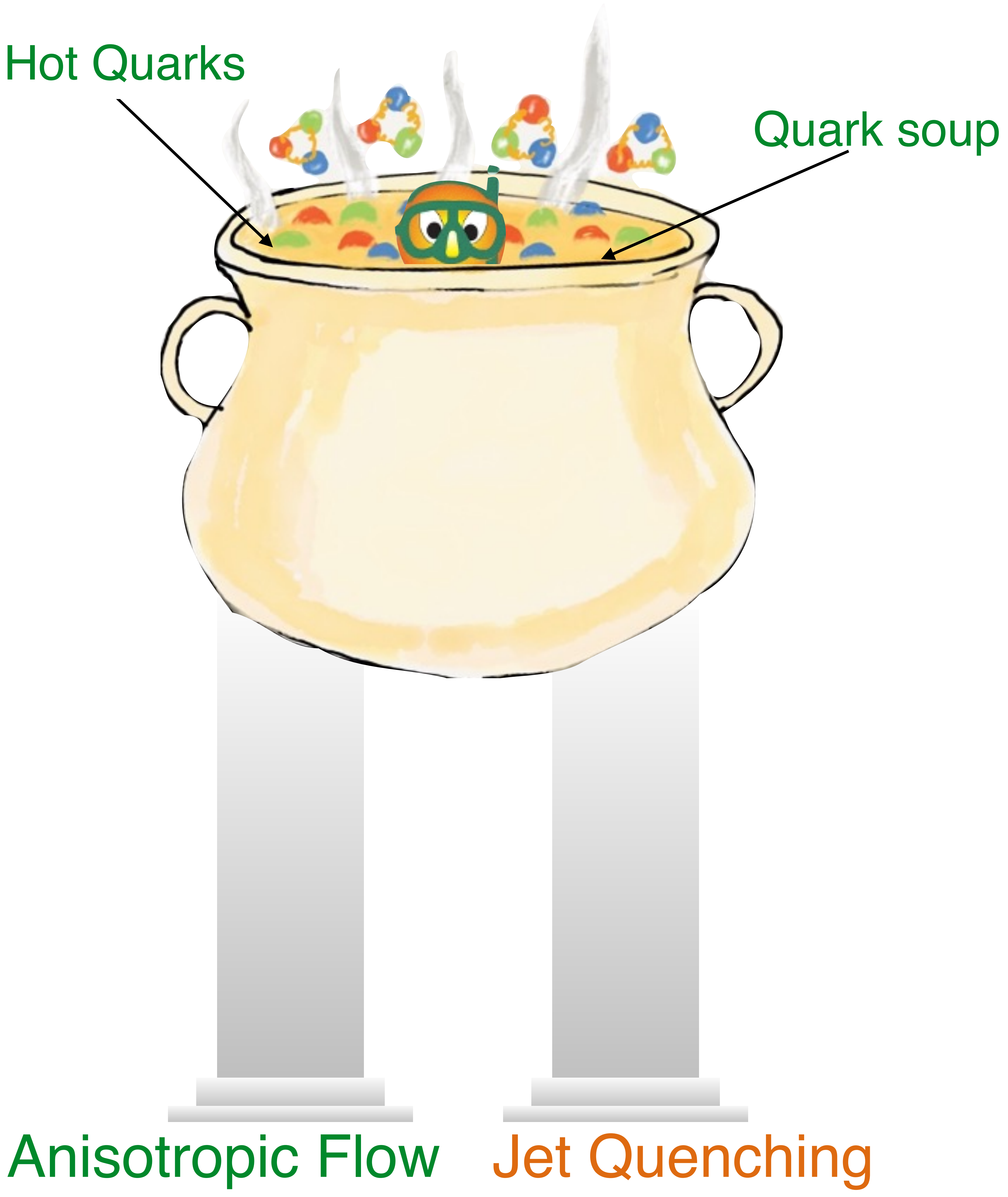




signature of
anisotropic flow



Signature of medium formation



Evidence of medium formation

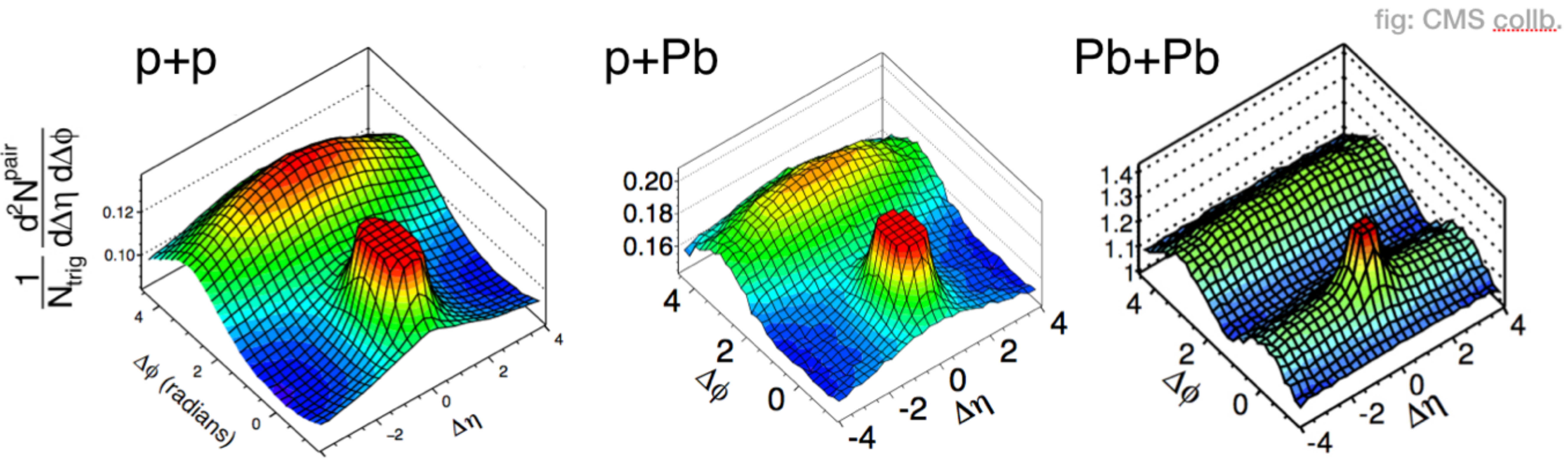
↓

The two major pillars are signature of flow and jet-quanching

↓

Formation of a thermalized medium that shows collectivity in heavy ion collisions

The results that changed everything



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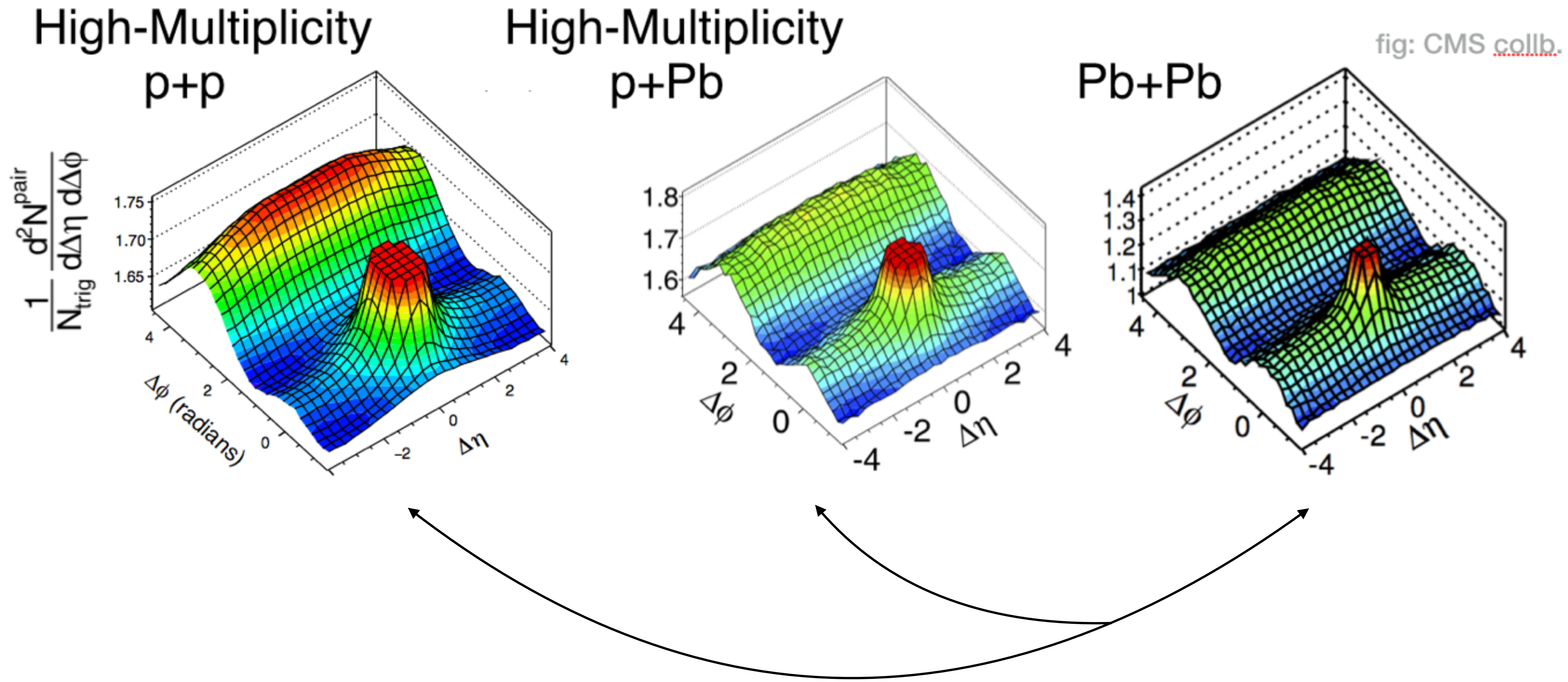
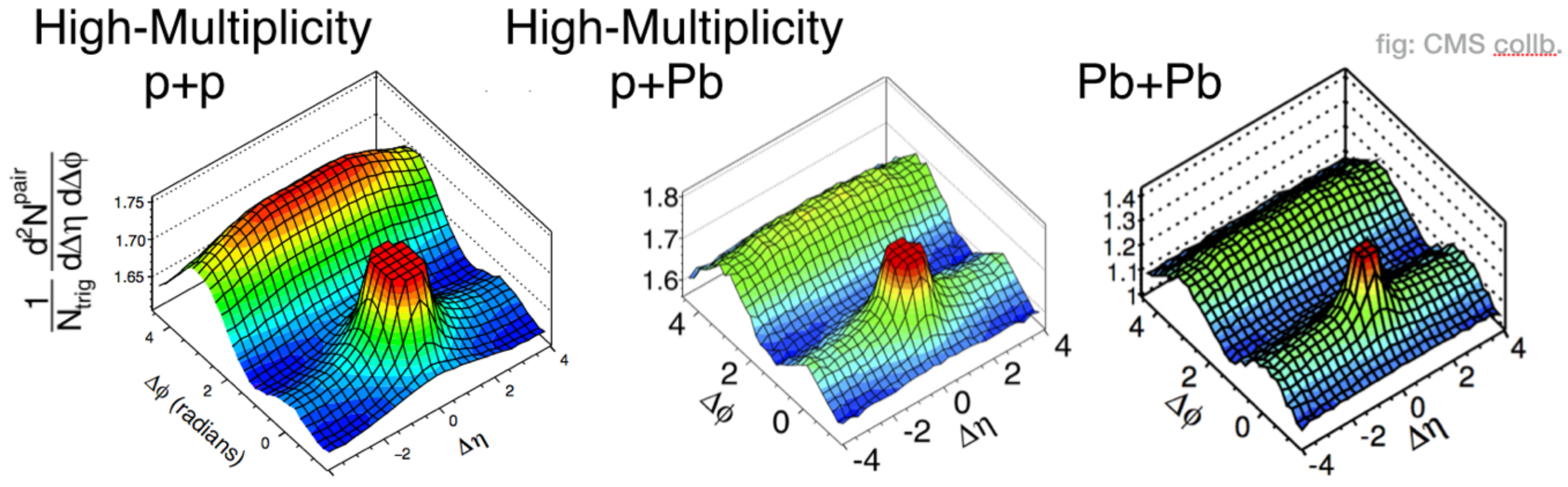


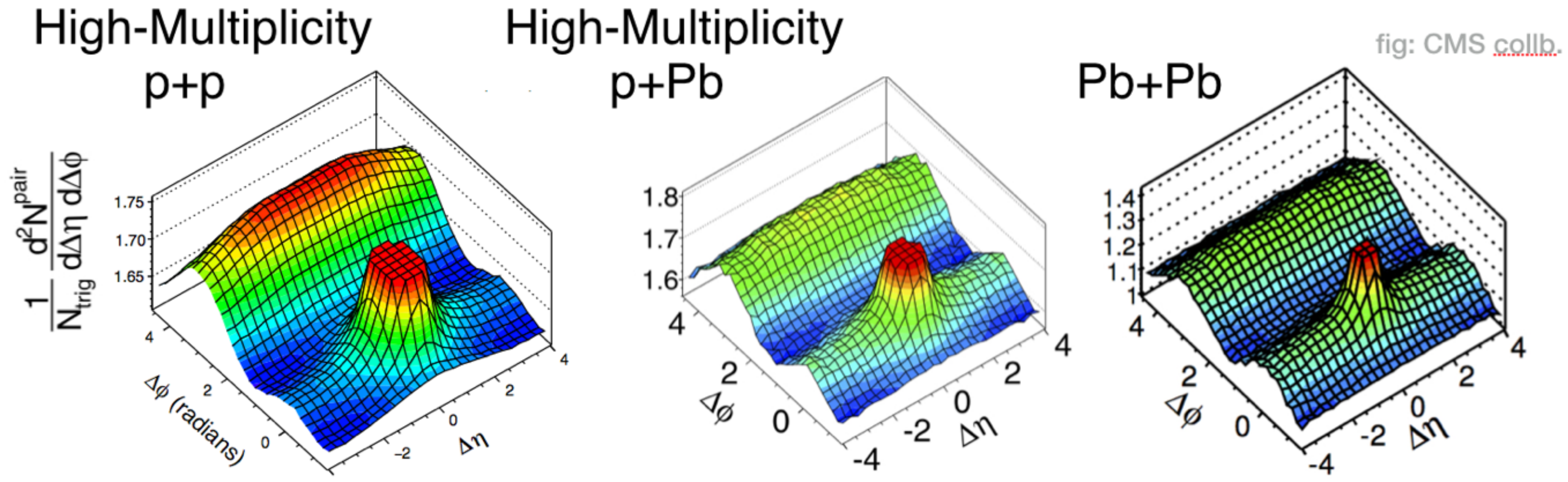
Striking similarity

The results that changed everything



Is this hydro or CGC ?
Is this signature of collectivity ?
Is this signature of QGP ?

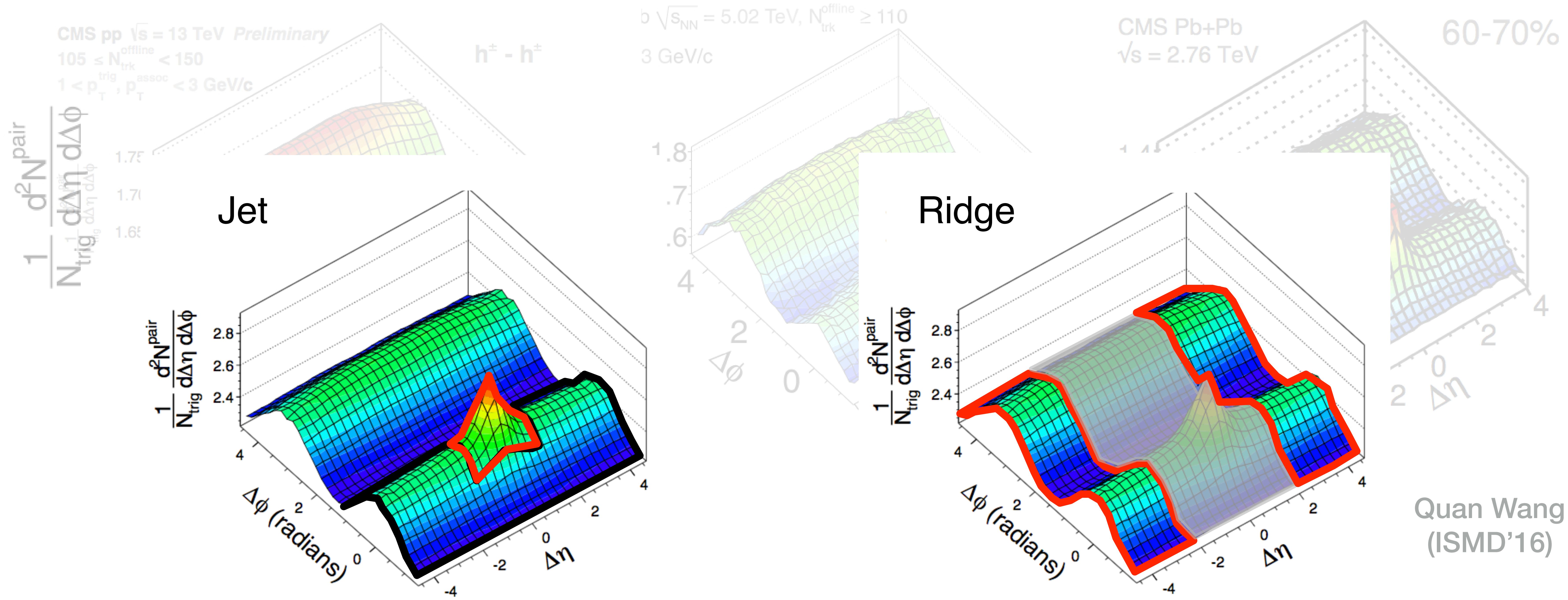
The results that changed everything



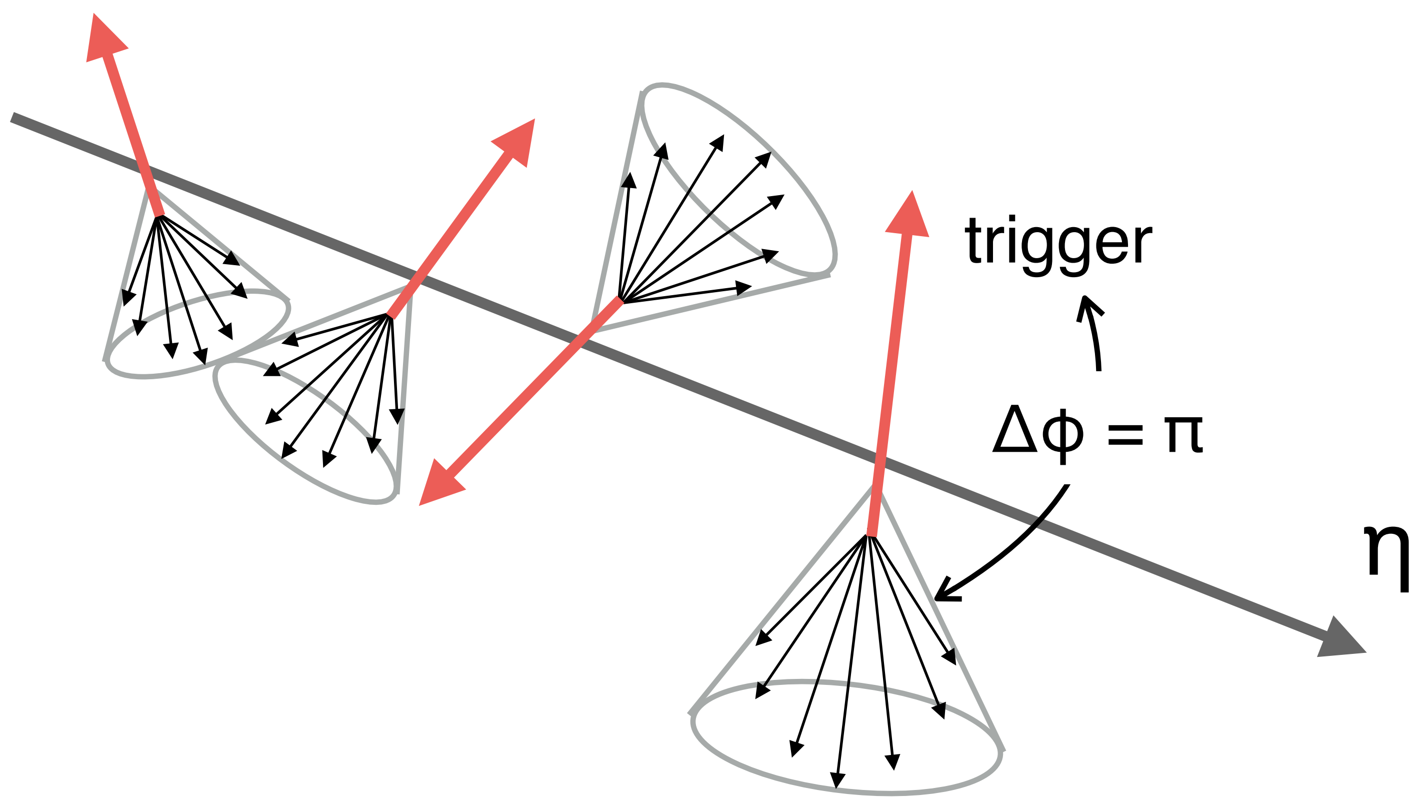
~~Is this hydro or CGC ?~~
~~Is this signature of collectivity ?~~
~~Is this signature of QGP ?~~

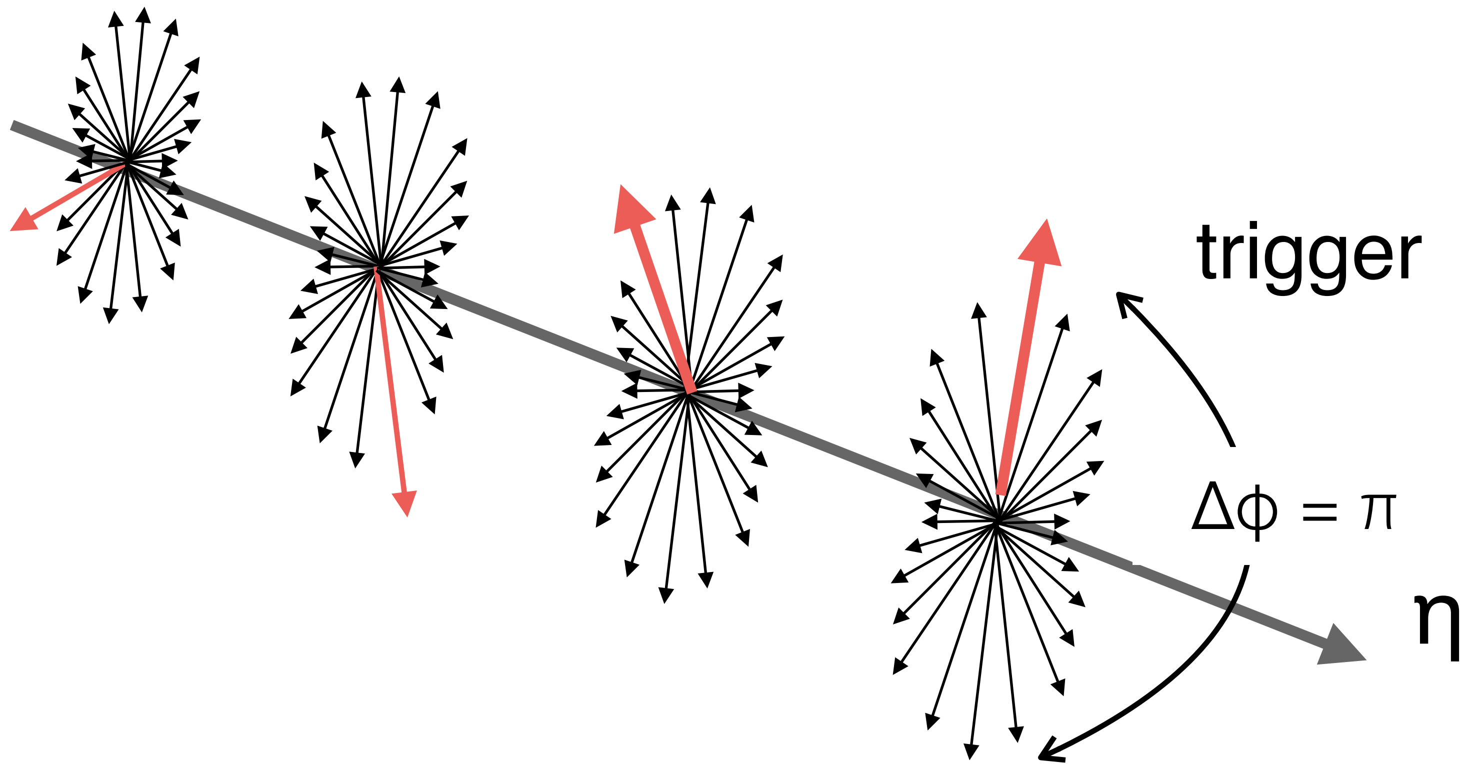
Lets focus on the long range correlations

talk by Soumya

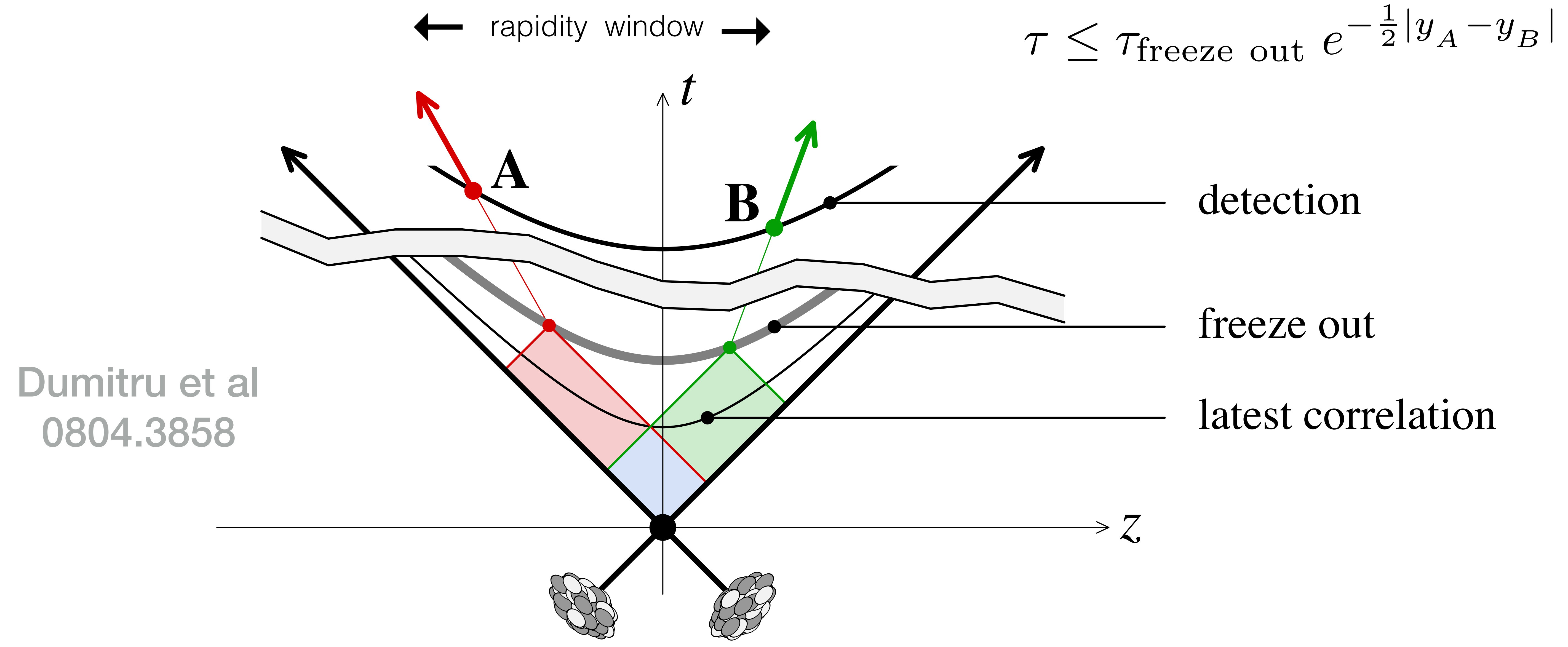


Quan Wang (ISMD'16)



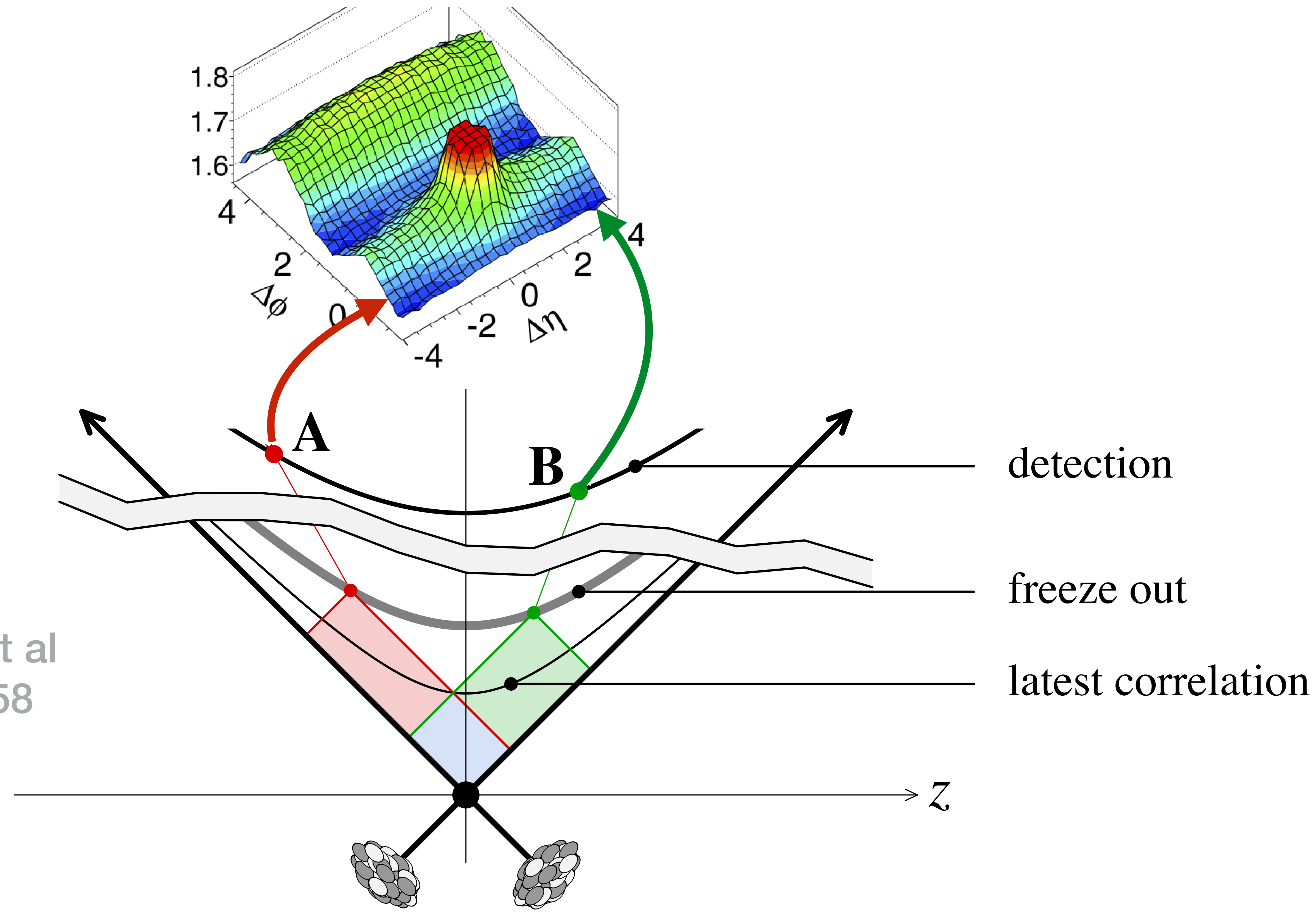


The origin of long range correlations



Causality argument tells it must have origin as very early stages

The origin of long range correlations



Dumitru et al
0804.3858

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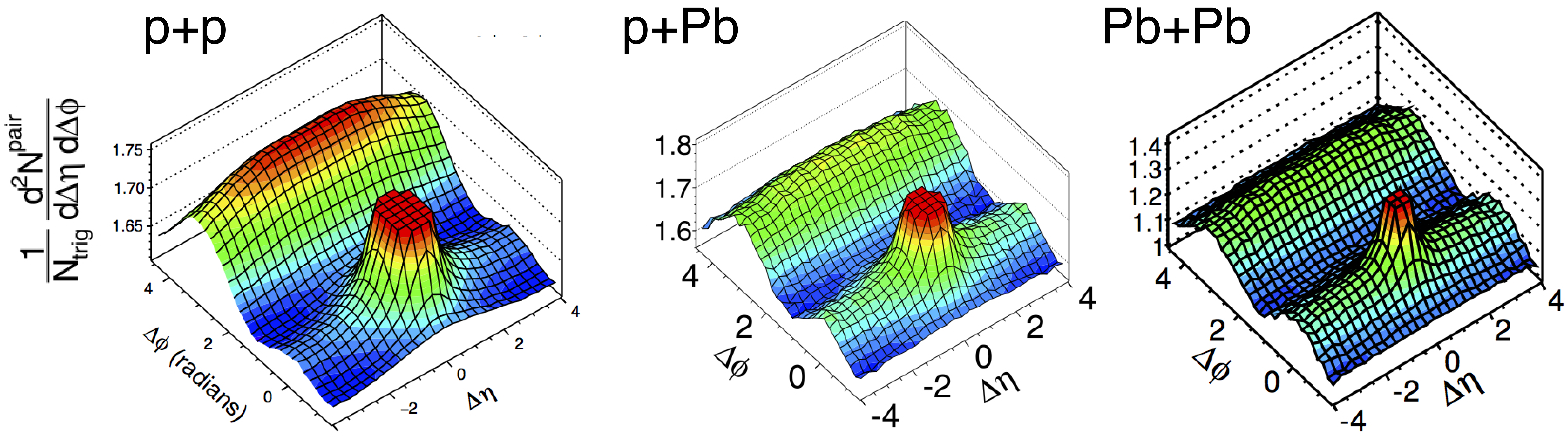
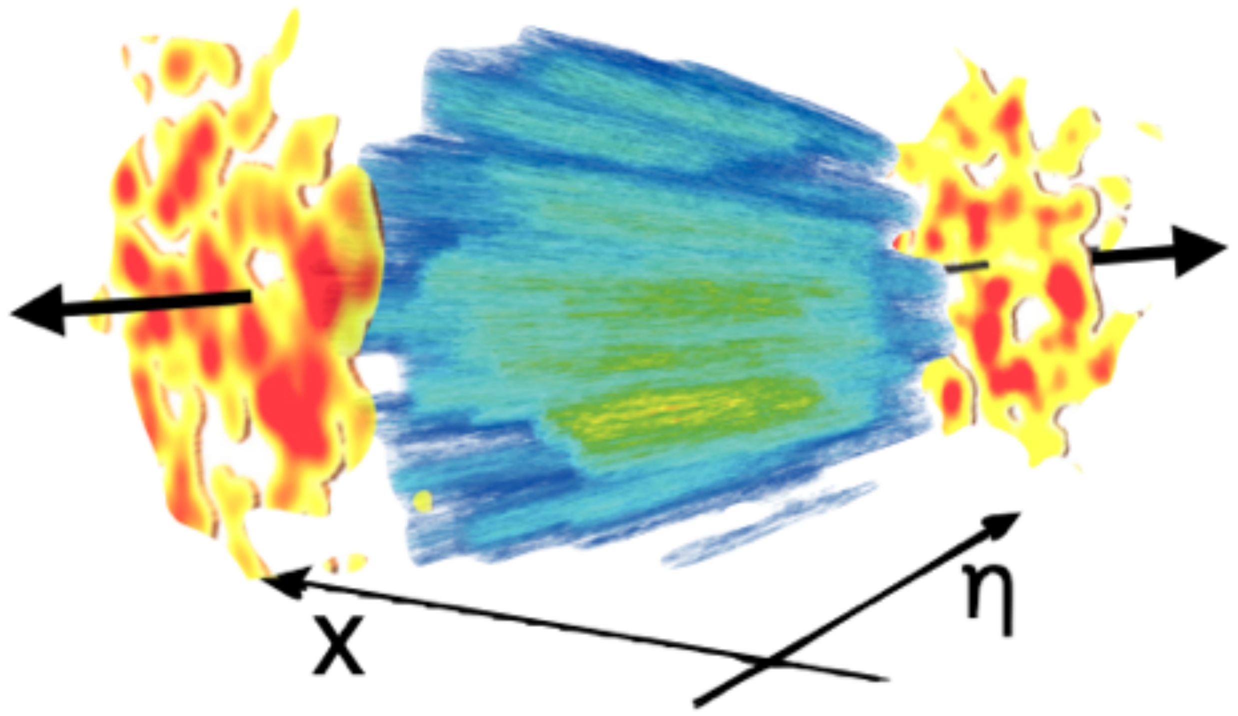
Long range correlations



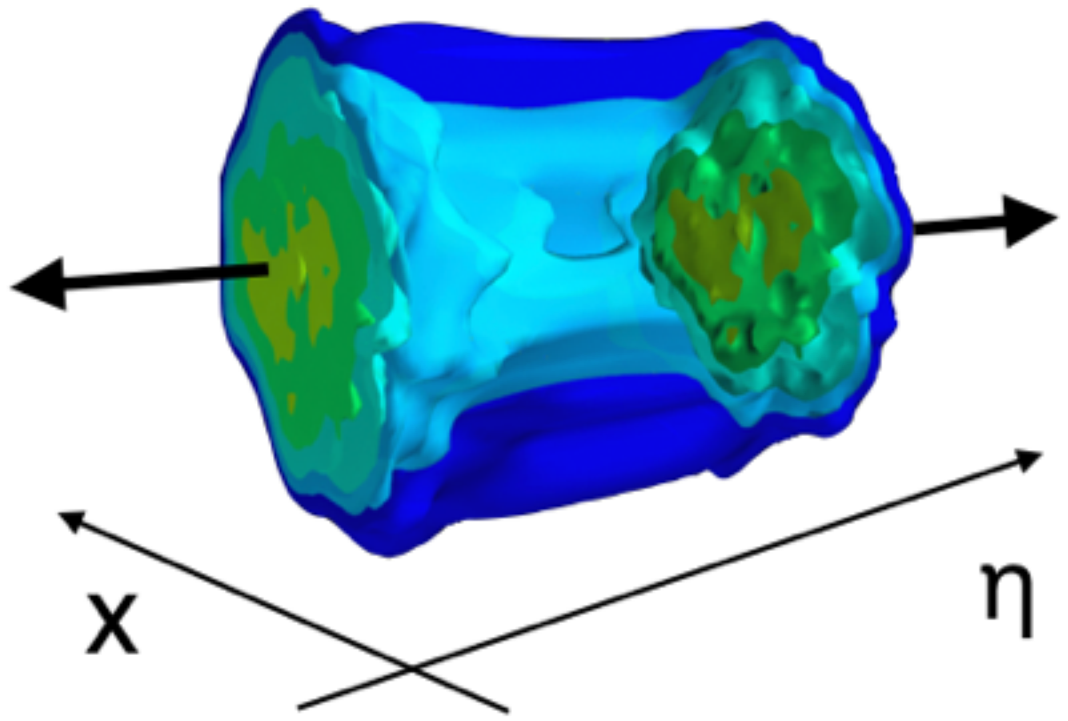
Is this due to **initial state** momentum space correlation
or **initial state** position space correlations ?

For A+A collisions we know the answer

Nearly boost invariant initial state position space correlations
+ collective flow → ridge like structure in A+A



boost invariant initial state

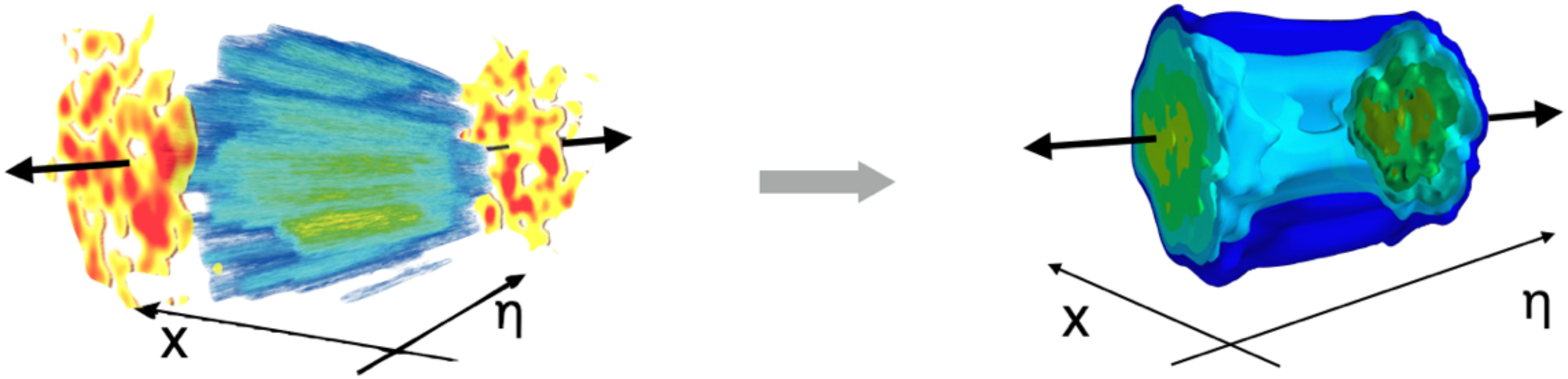


boost invariant hydro evolution

Still initial state drives the phenomenon

Initial state position space correlations

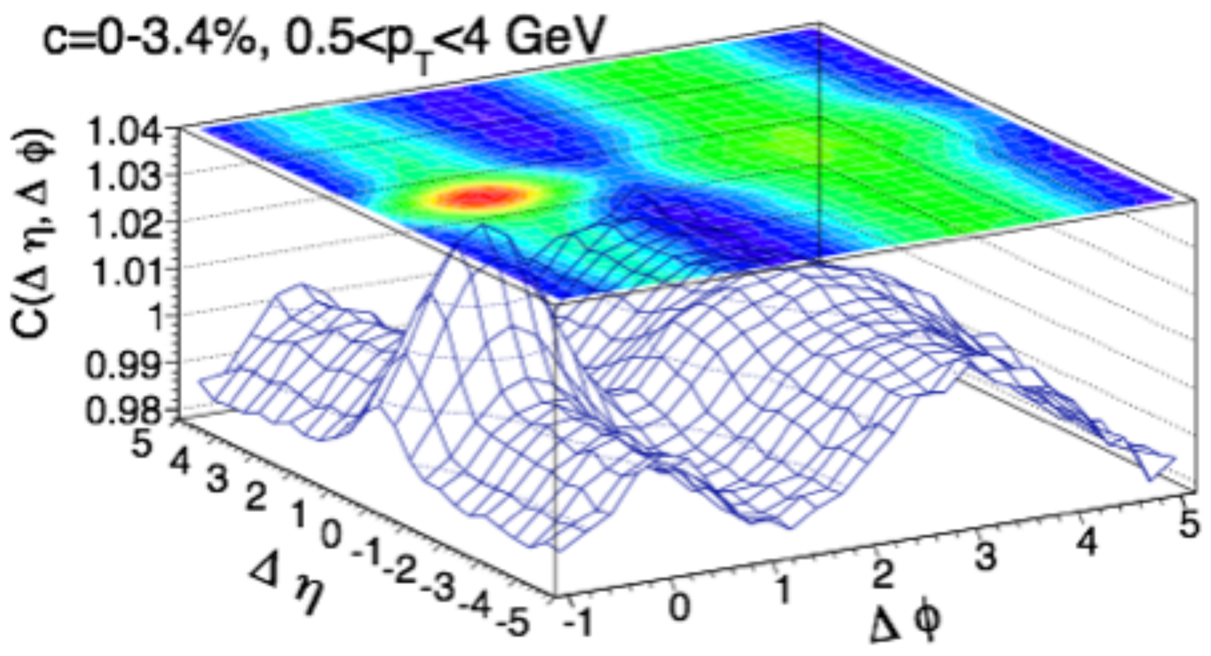
Nearly boost invariant initial state position space correlations
+ collective flow → ridge like structure in A+A

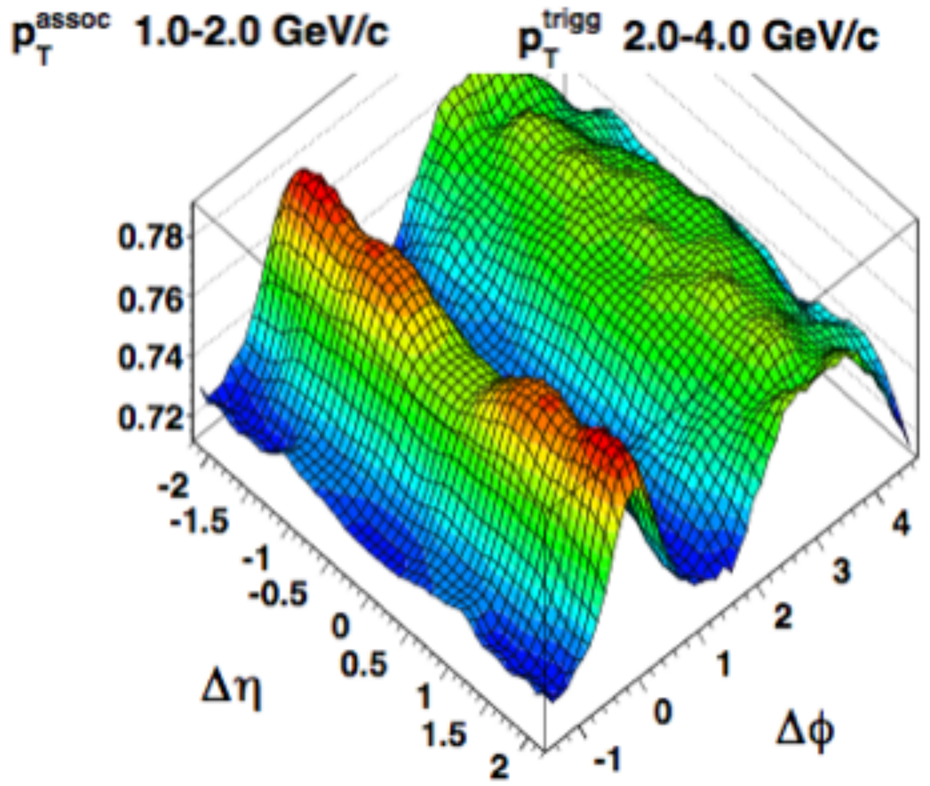


Bozek, Broniowski 1304.3044

K. Werner *et al* 1307.4379

Same story for small systems ?

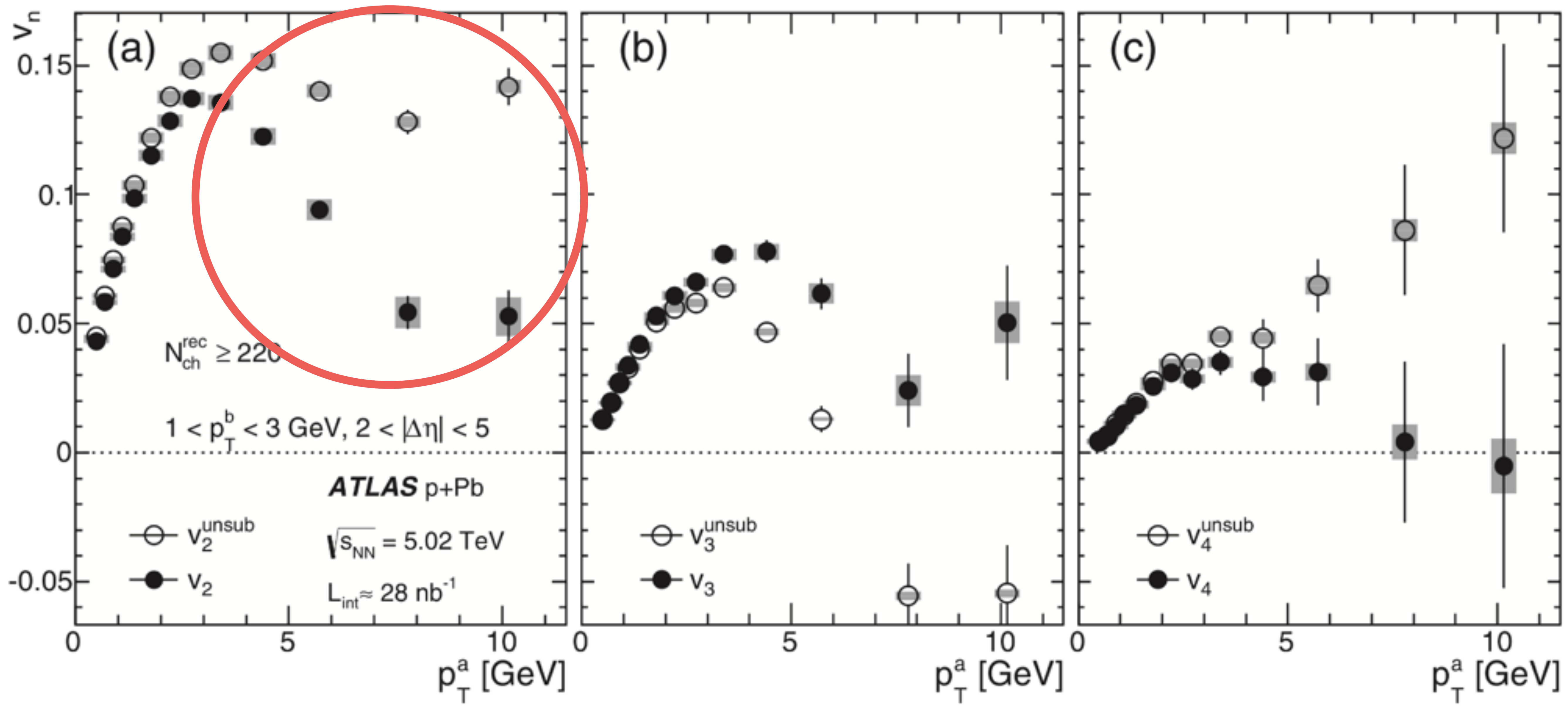




Then we need to estimate the right initial conditions ?

Another piece of puzzle

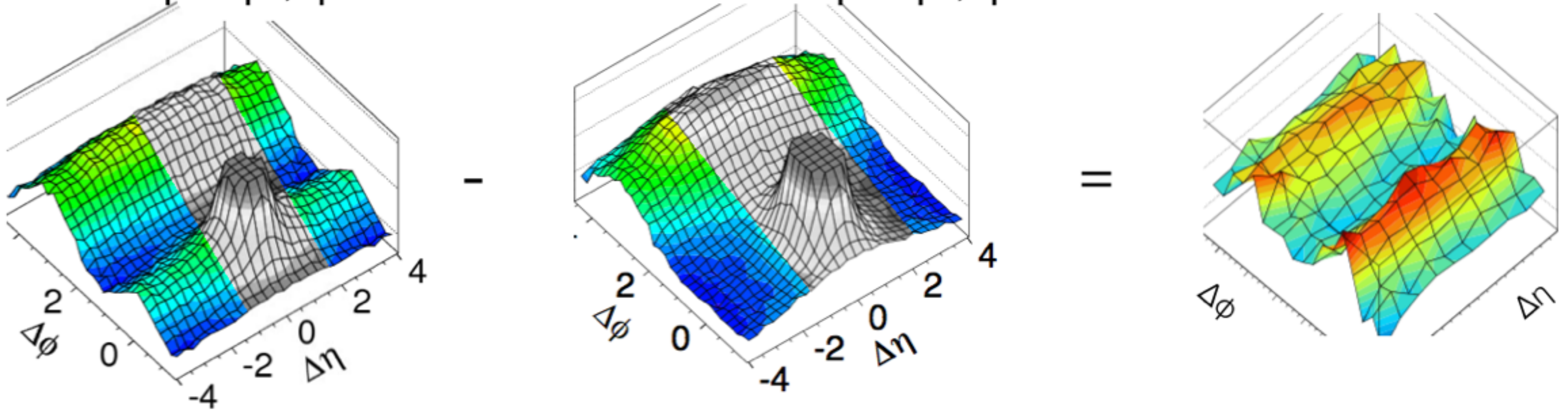
p+Pb



However it persist up to very large $p_\perp$ = 10 GeV
some semi-hard (short distance) QCD dynamics playing a role ?

Flow like patten but how about jet-quenching ?

high mult p+p, p+Pb   low mult p+p, p+Pb



No convincing evidence for mini-jet quenching seen in data

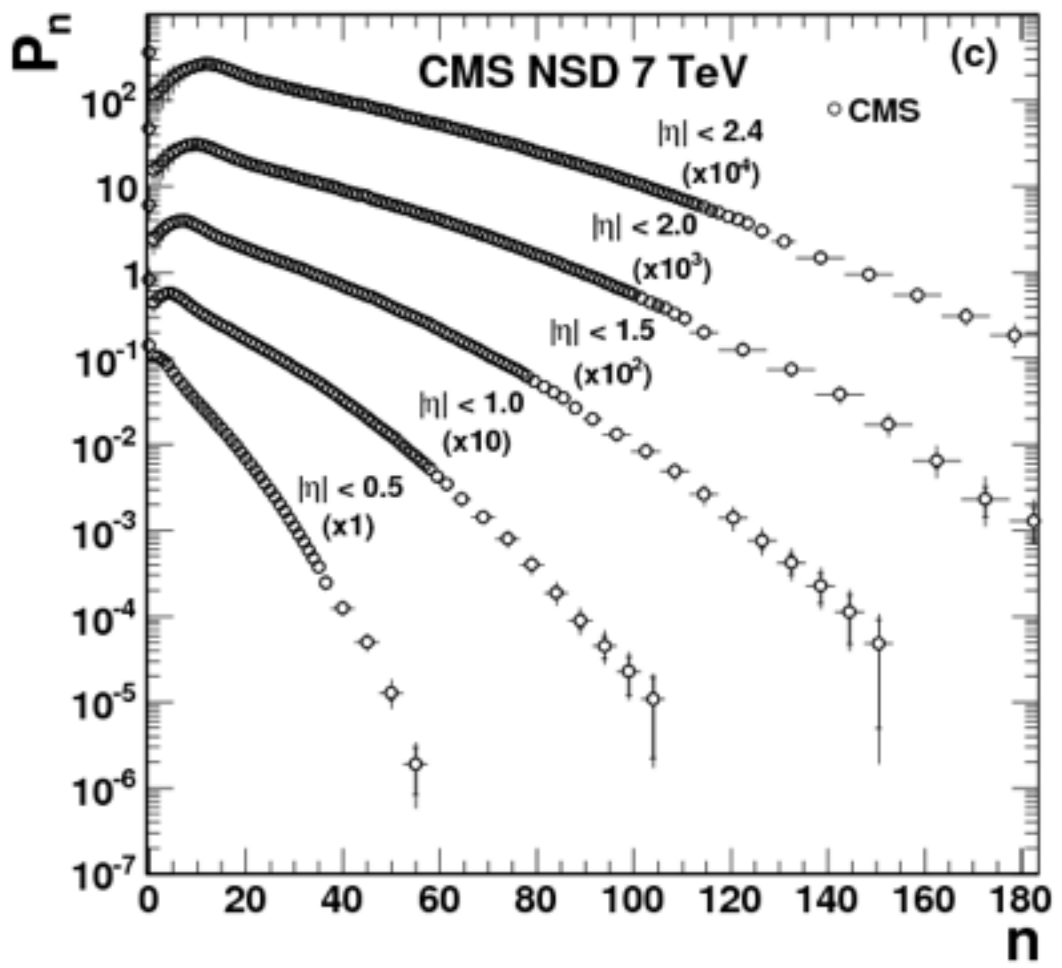
The away side is almost un-modified, even used for subtraction

approach towards thermalization → mini-jets must be fully quenched

One more thing we shouldn't forget

Ridge appears only in high multiplicity events in small systems

arXiv: 1011.5531



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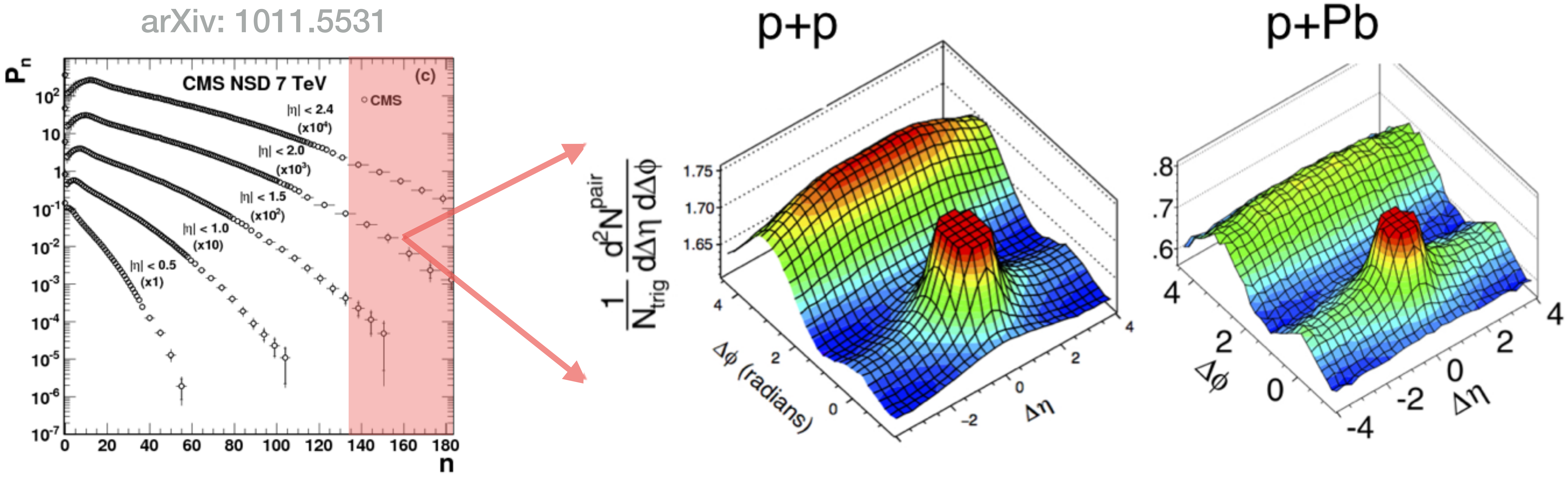
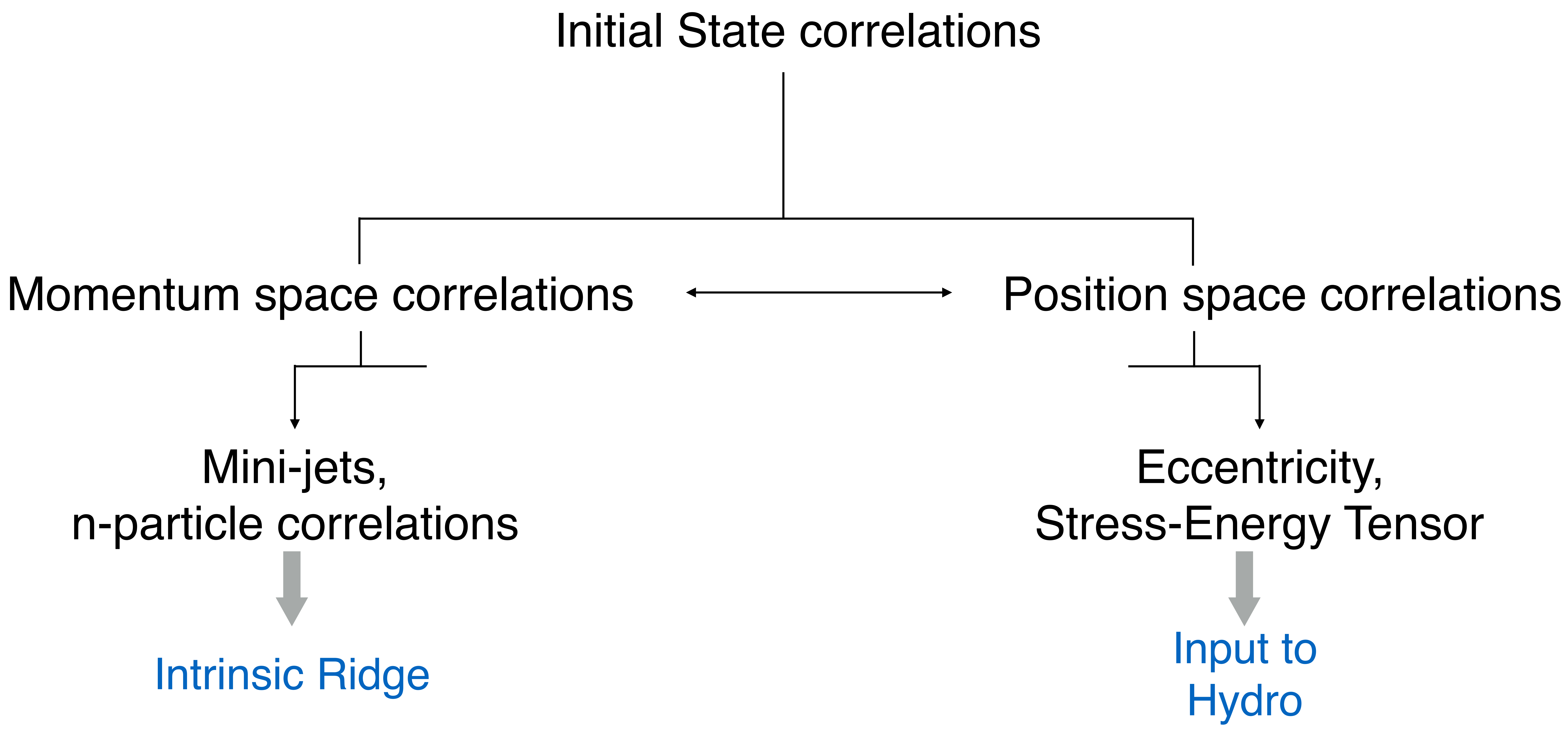


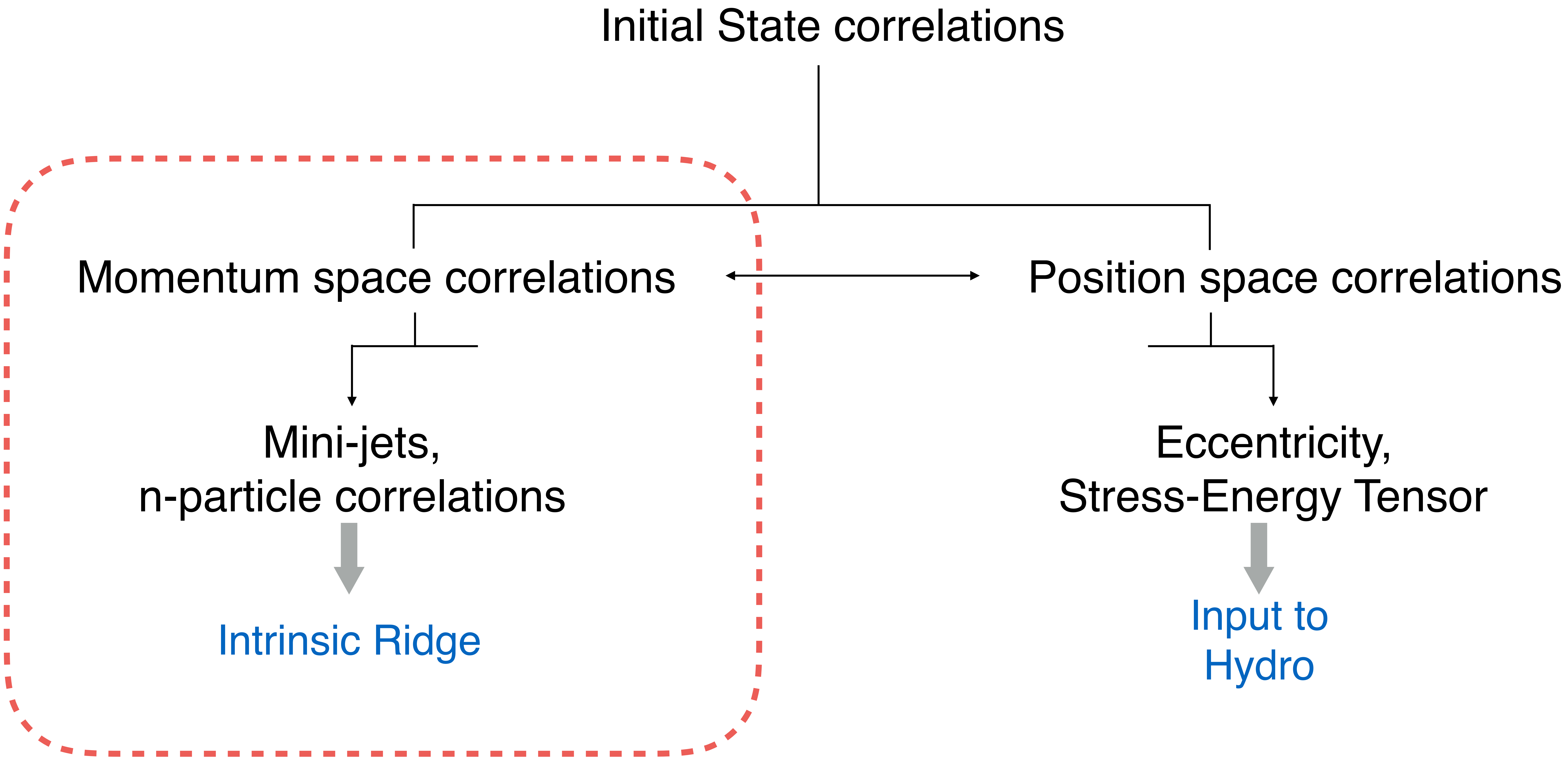
Origin of high multiplicity events ⟷ Systematics of Δη-Δϕ correlations

Similar underlying dynamics must drive these phenomenon

Initial state correlations



Initial state correlations

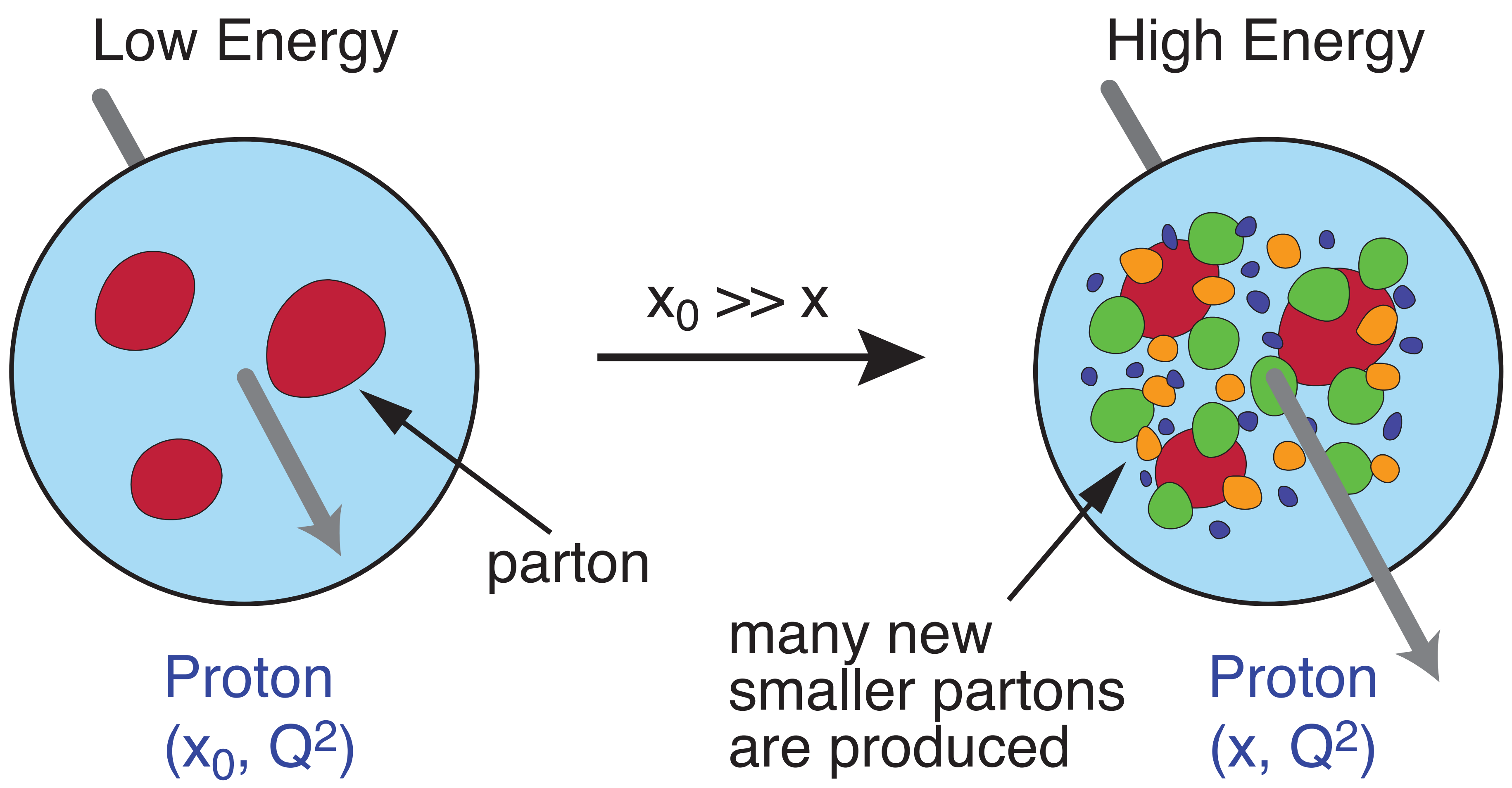


Initial stages of colliding hadrons/nuclei

At high energies in **Regge Gribov limit** $\sqrt{s} \to \infty, x \to 0$: gluon saturation

- Non-linear processes stop growth of gluons, emergence of a scale $Q_S(x) > \Lambda_{QCD}$

arXiv: 1212.1701



"Color Glass Condensate"

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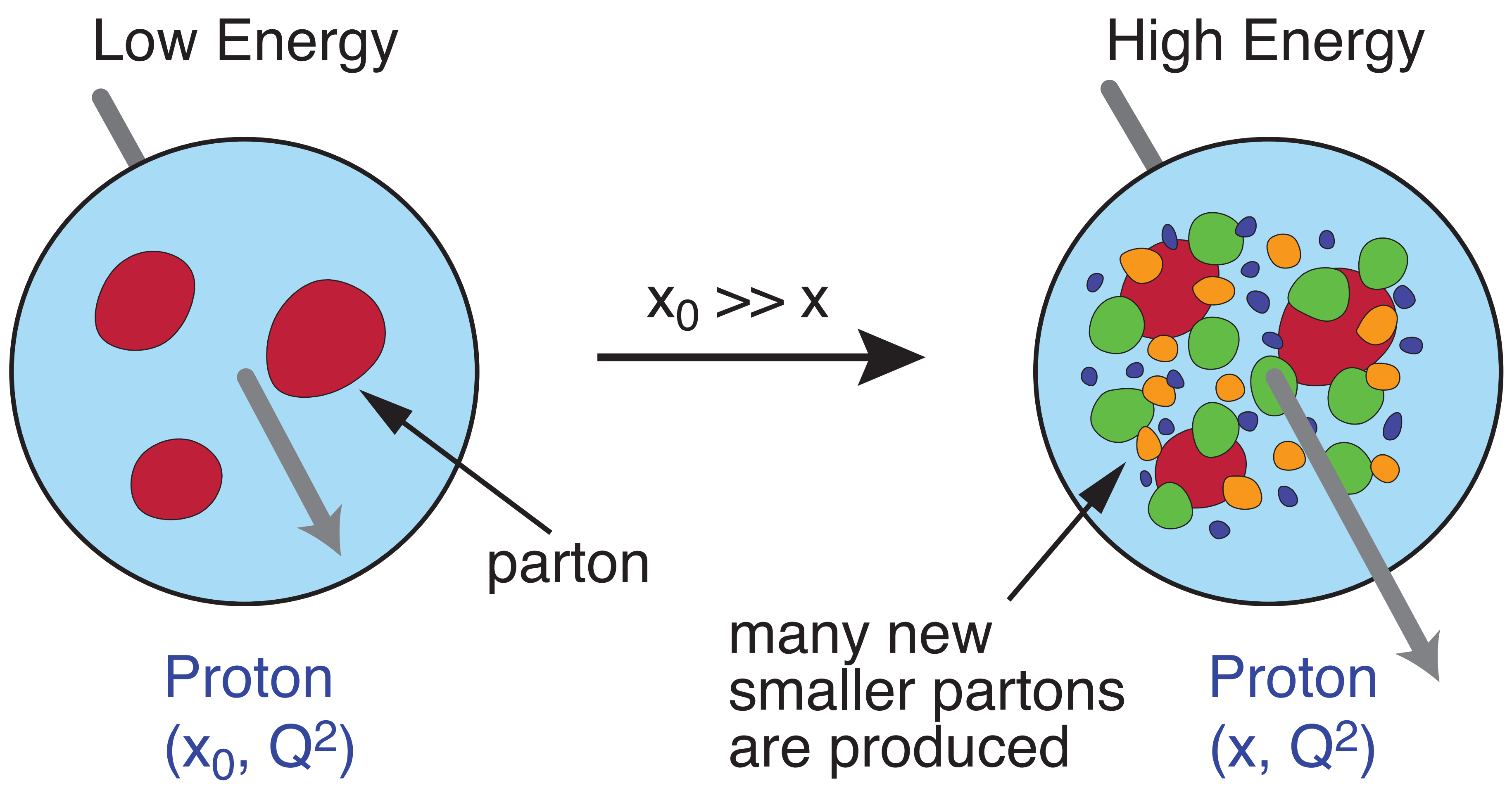
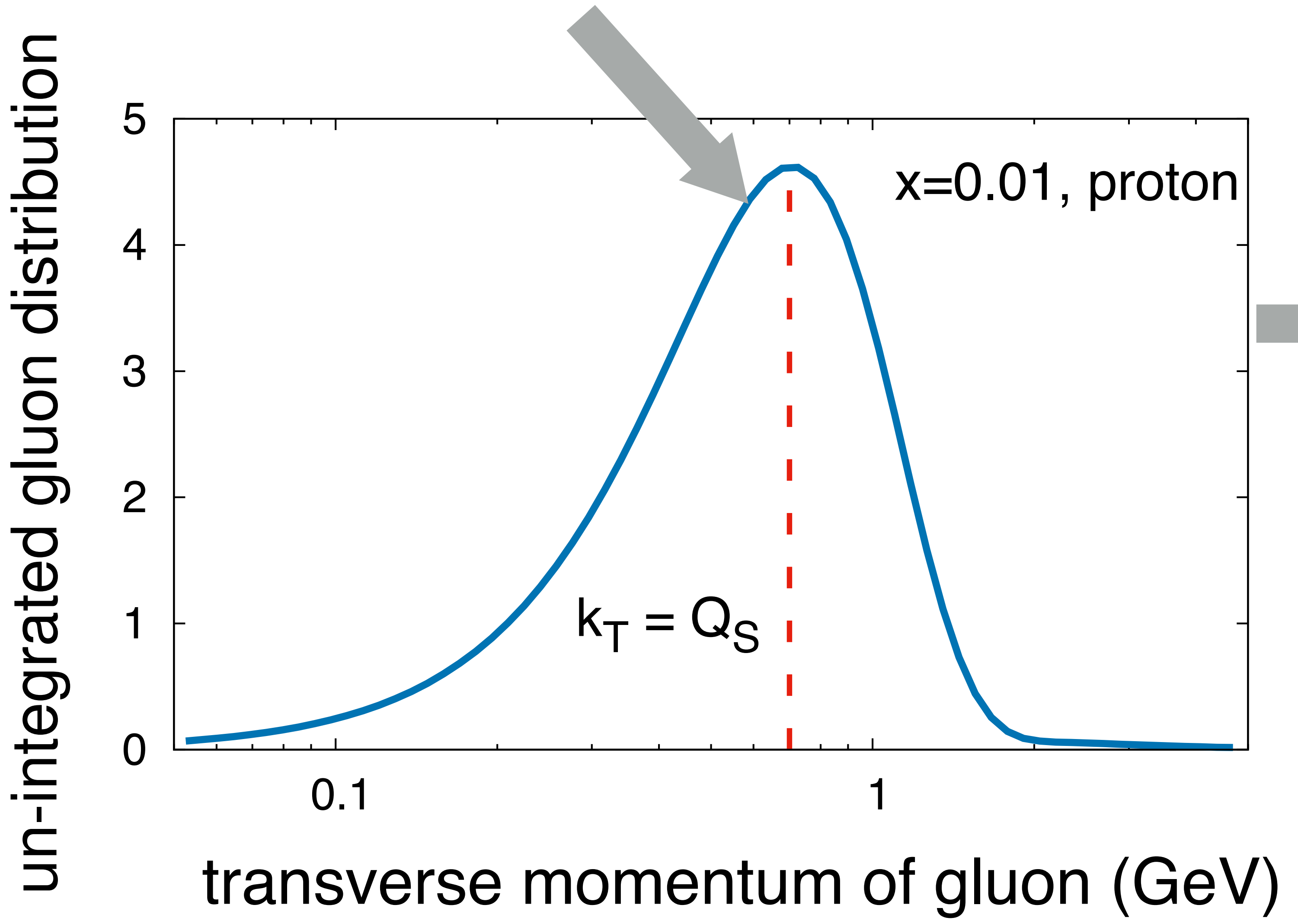
- Non-linear processes stop growth of gluons, emergence of a scale $Q_S(x) > \Lambda_{QCD}$
- **Gluon dominated wave function**, high occupancy $\sim \frac{1}{\alpha_S}$ peaked at $Q_S(x)$

arXiv: 1212.1701



"Color Glass Condensate"

most gluons are here

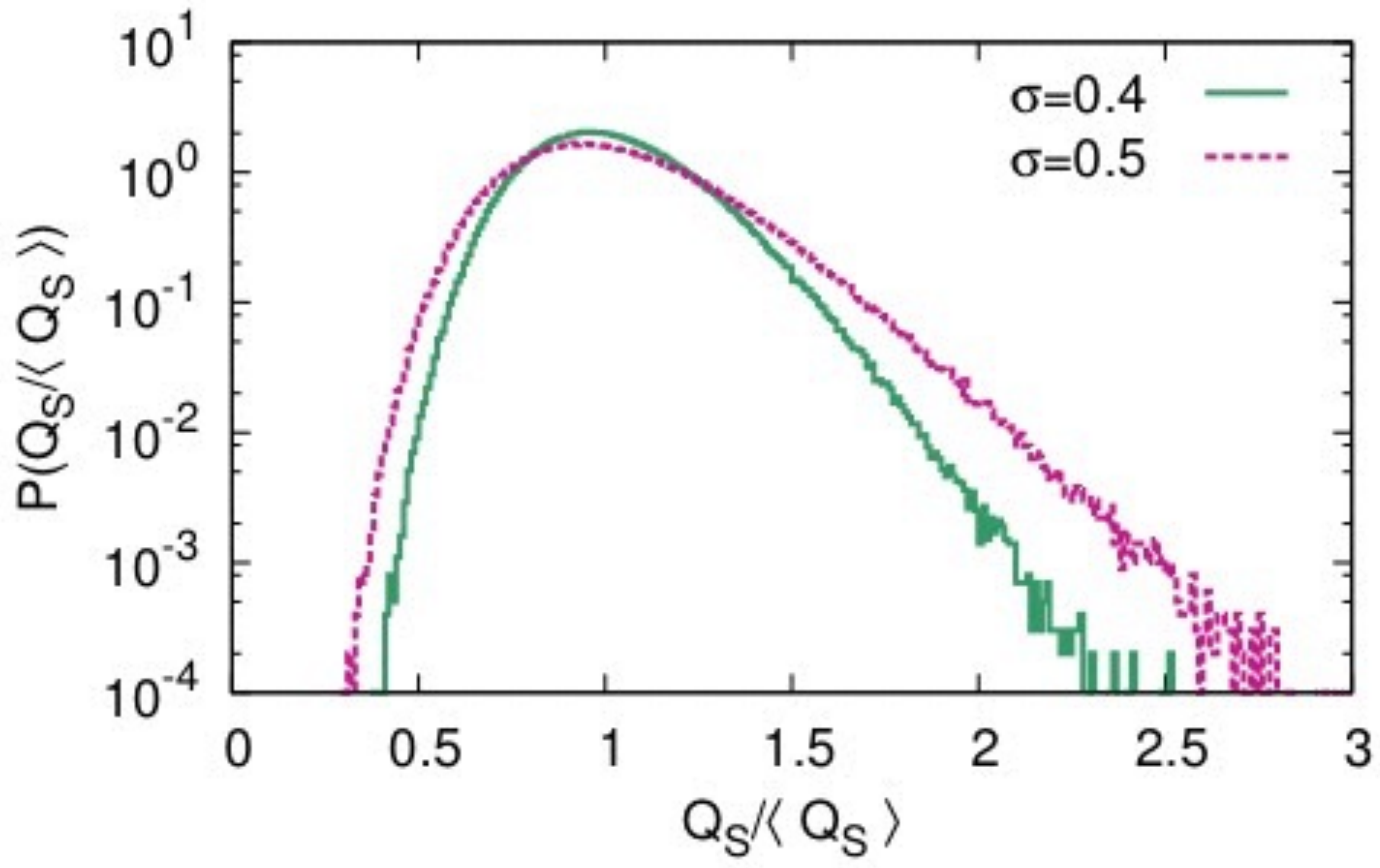


obtained from HERA DIS data

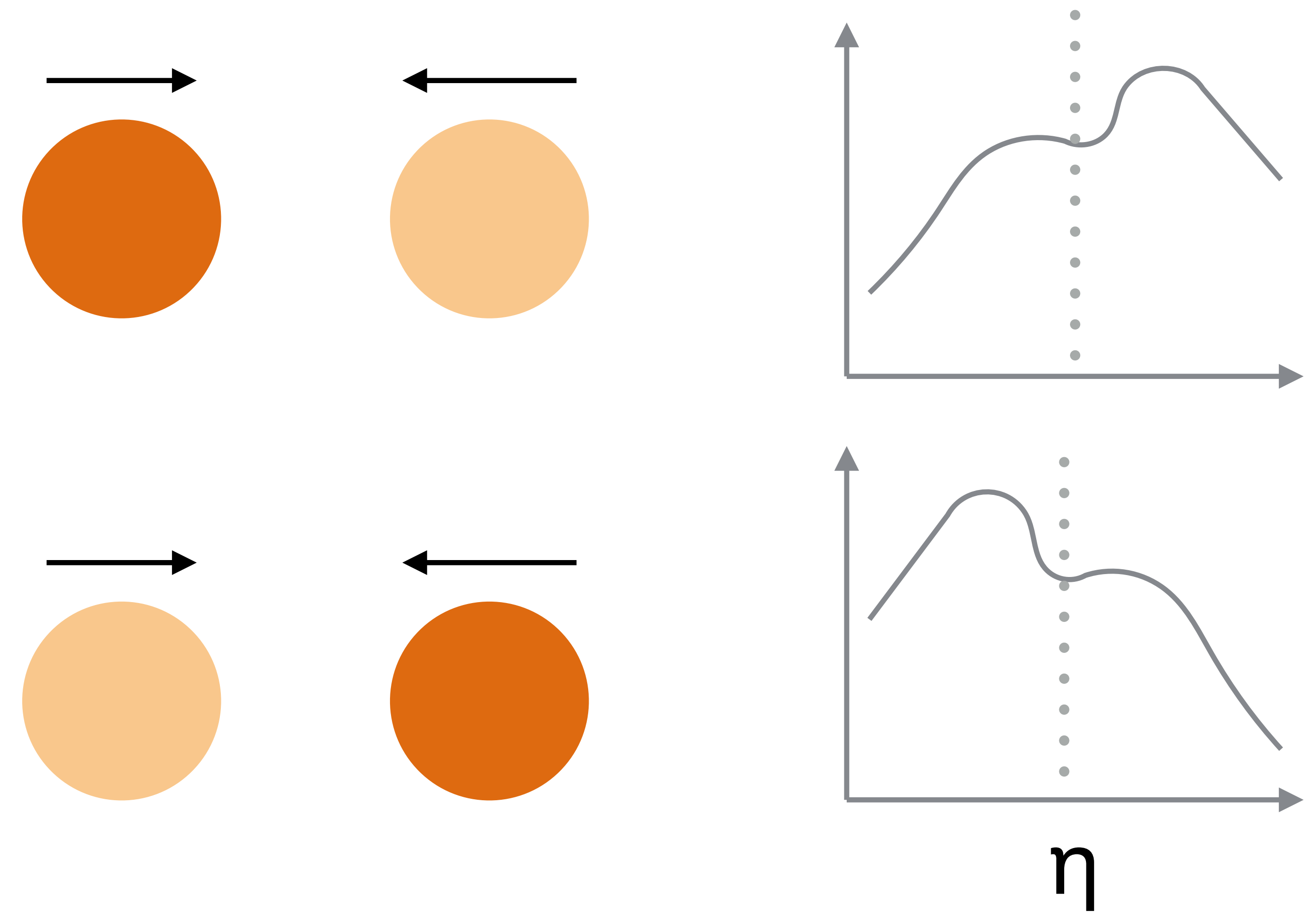
Proton fluctuation : Saturation momentum

The wave function of a hadron $|H\rangle = |qqq\rangle + |qqqg\rangle + \cdots + |qqqgg\ldots gg\rangle$

McLerran, PT 1508.03292



p+p collisions are asymmetric

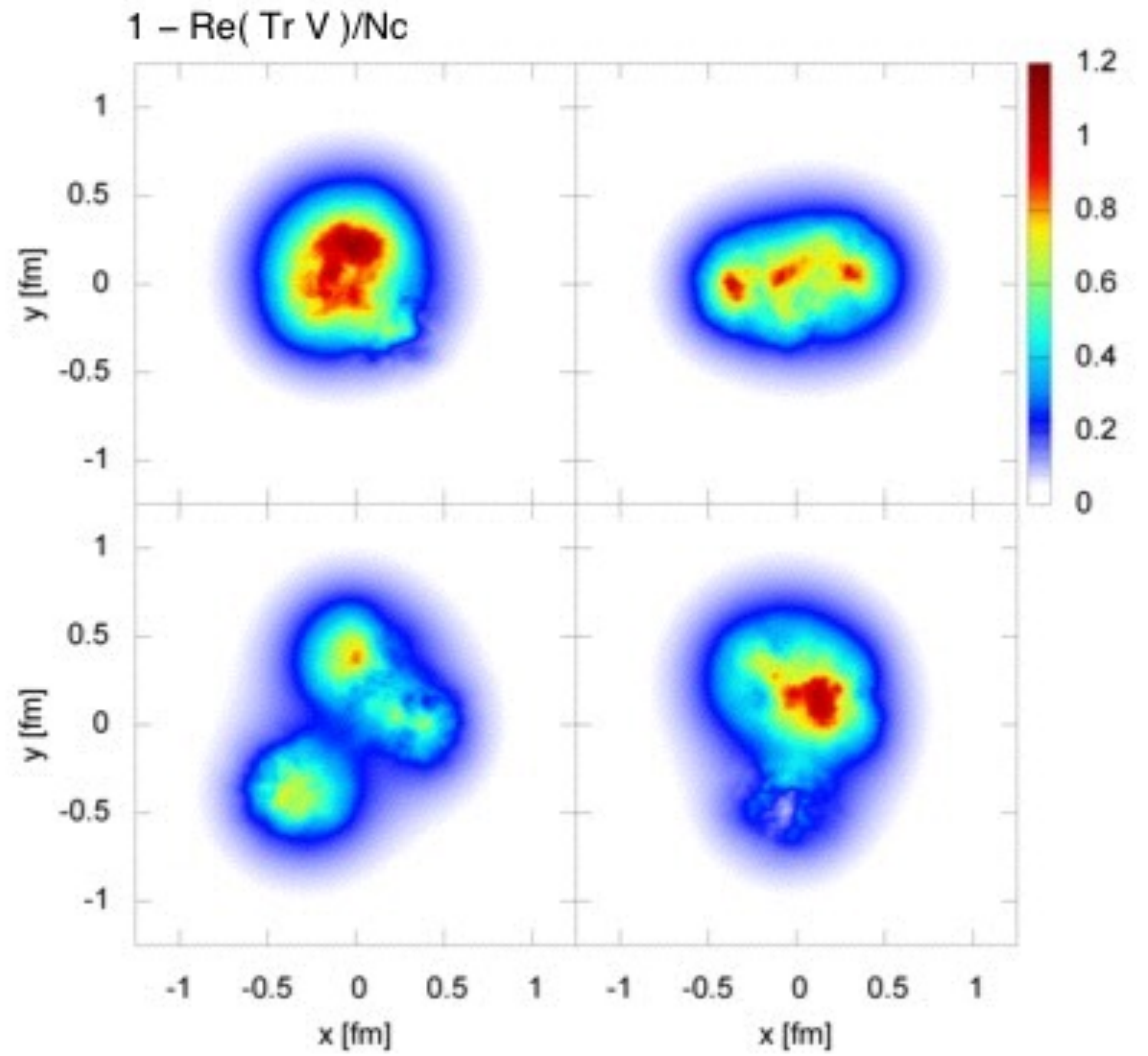


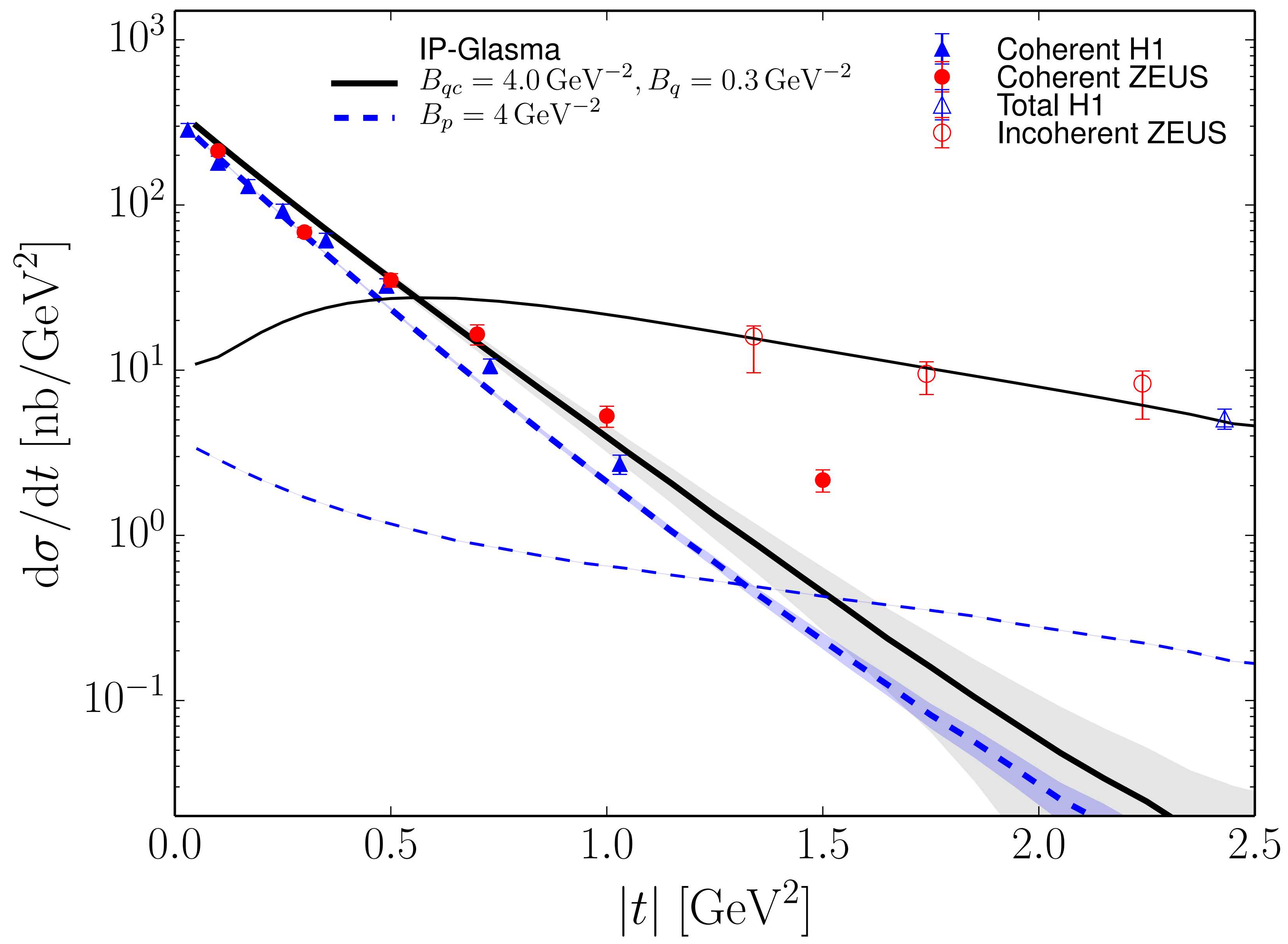
Distribution of Partons are driven by stochastic process

Proton fluctuation : Intrinsic shape

Quark structure Essential for description of Incoherent DIS data

Schenke, Mantysaari 1603.04349

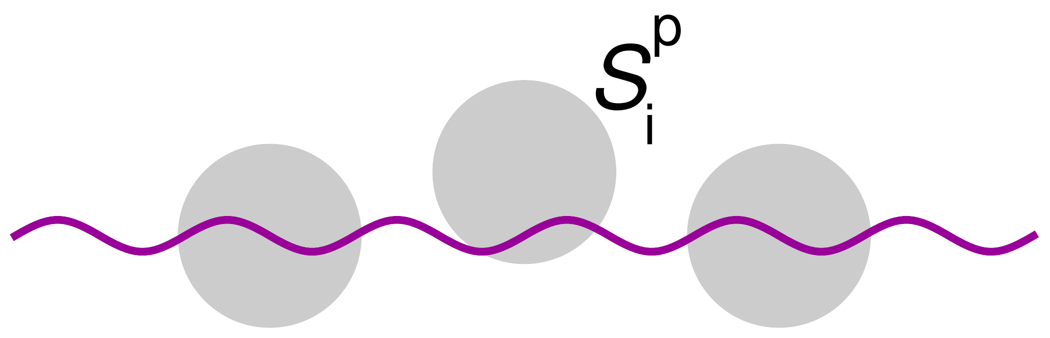




p+p collisions are eccentric

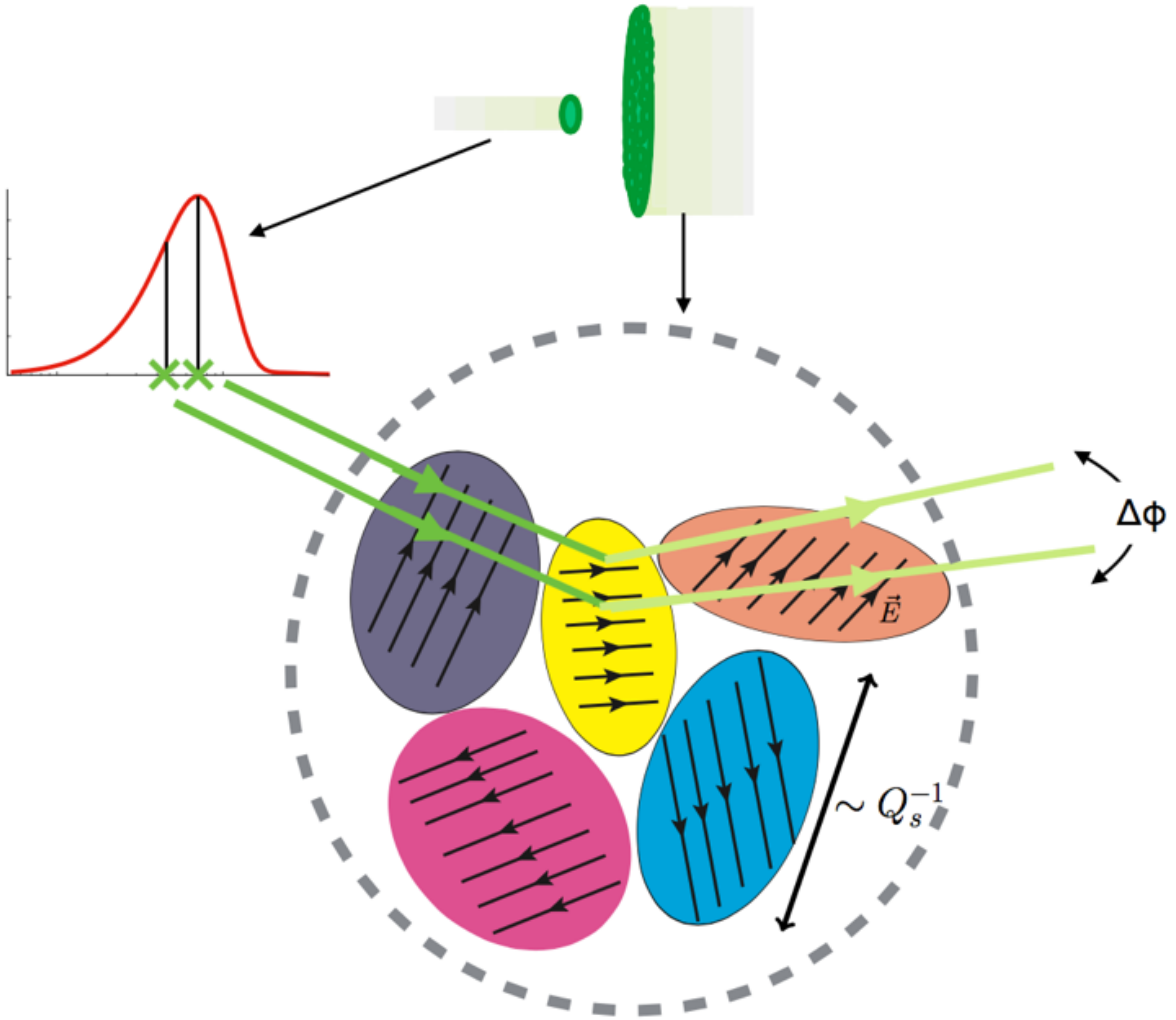
Nucleus multiple proton target

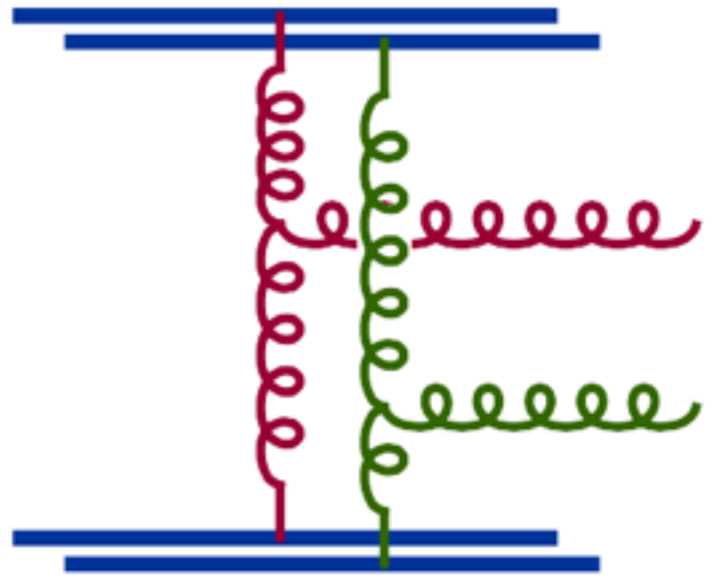
$$S^A_{\mathrm{dip}}(\mathbf{r}_\perp, x, \mathbf{b}_\perp) = \prod_{i=0}^{A} S^p_{\mathrm{dip}}(\mathbf{r}_\perp, x, \mathbf{b}_\perp)$$



Initial state momentum correlation

Intrinsic momentum space correlations collimated emission of particles

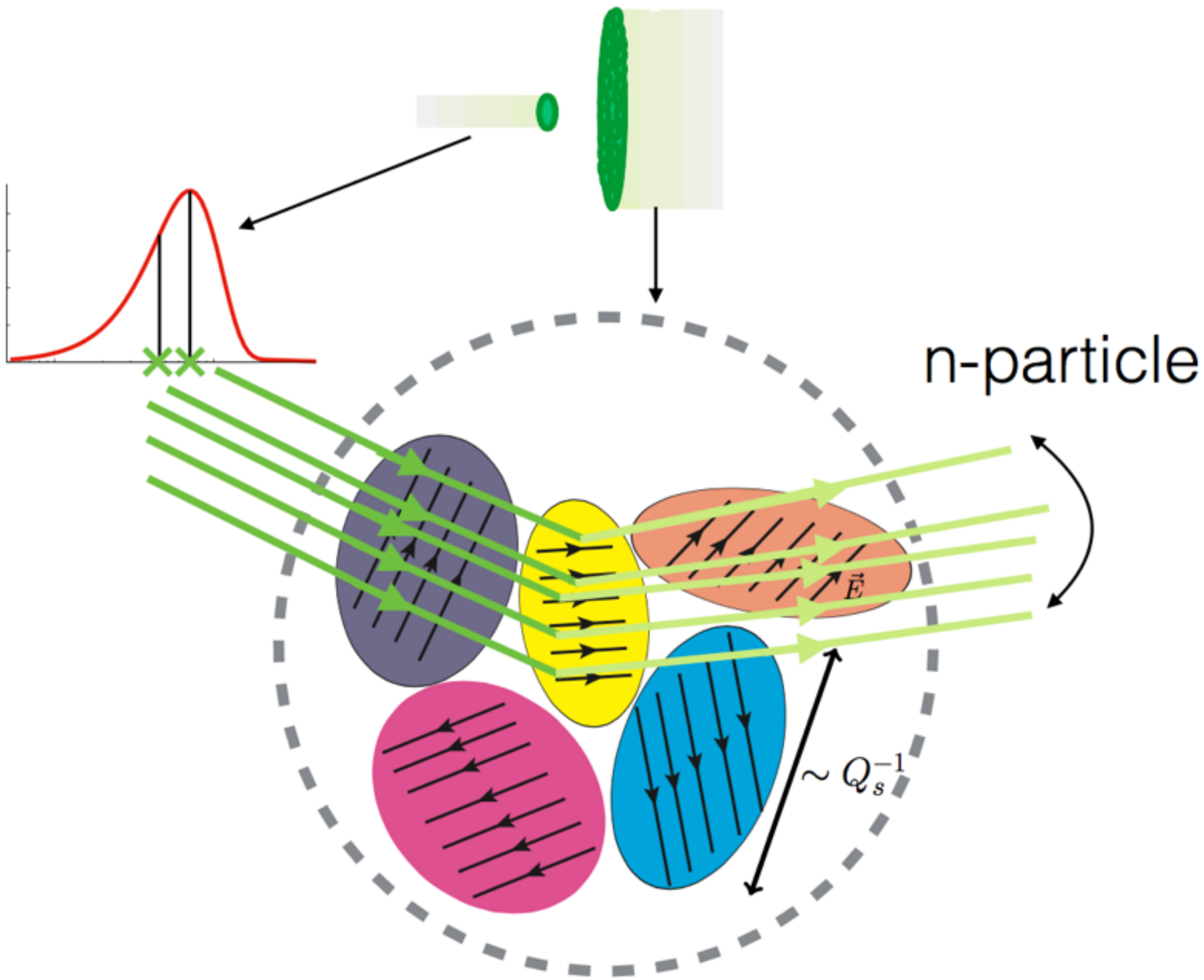


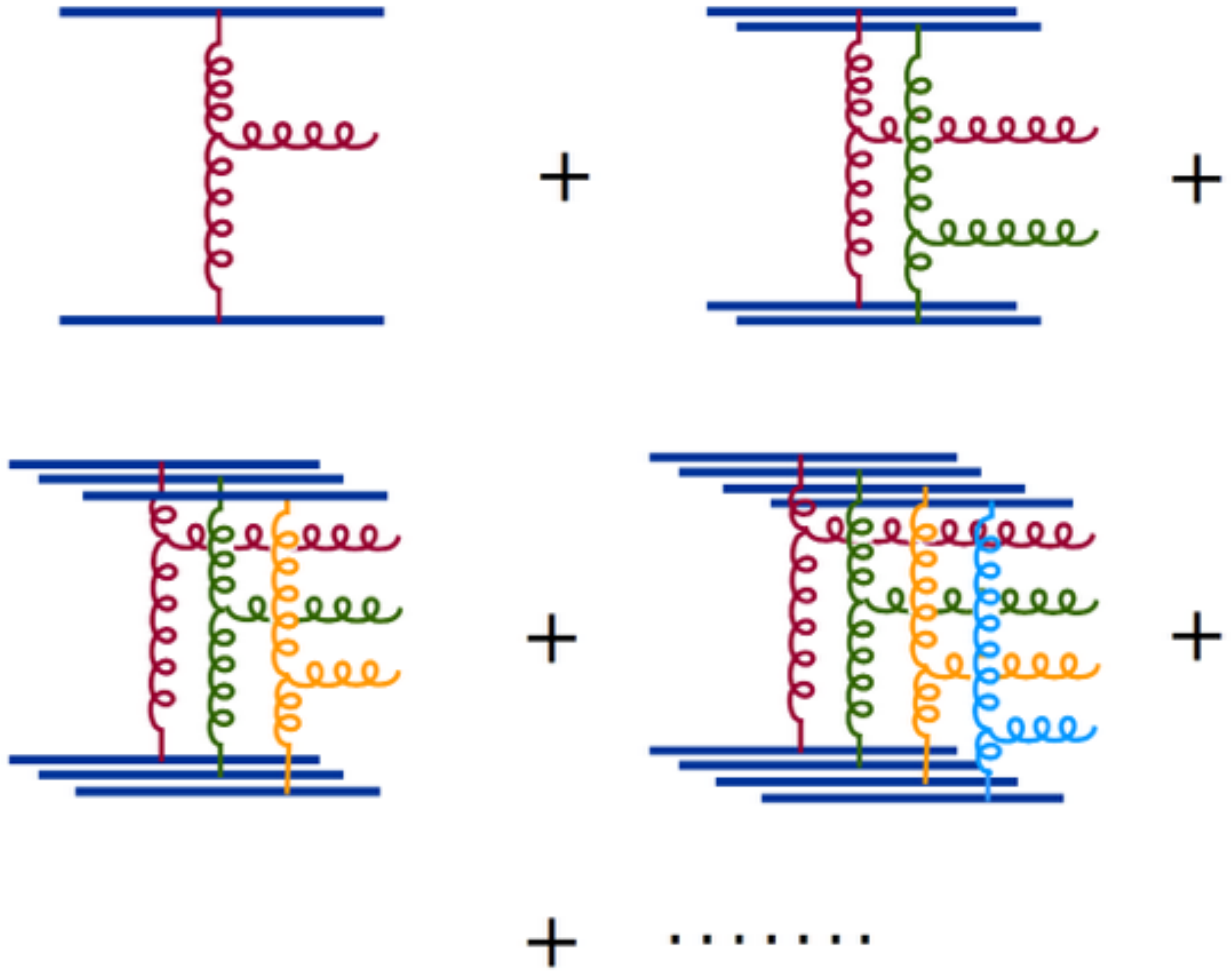


$$\langle n^2 \rangle - \langle n \rangle^2 \sim \frac{1}{Q_S^2 S_\perp}$$

Correlations already present among partons in projectile wave function survive after scattering off the color fields of target

Initial state momentum correlation





n-particle correlations → negative binomial distributions (NBD)
NBD + Qs-fluctuations + collision geometry → multiplicity distributions

Classical Yang-Mills : Numerical solutions

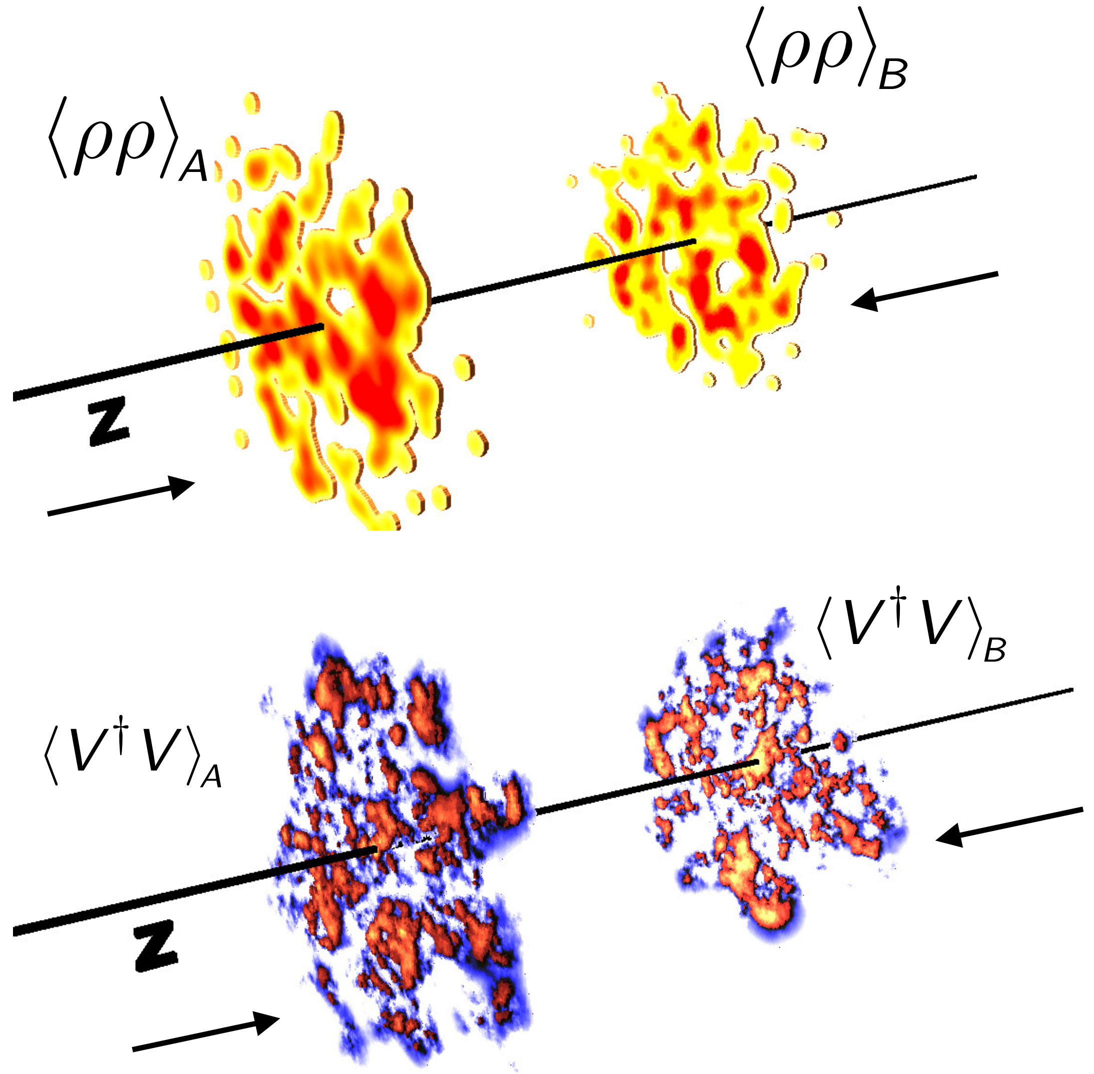
IP-Glasma model in a nutshell

Schenke, PT, Venugopalan 1202.6646

Colliding nuclei

→ classical color charge $\rho(x_\perp)$

→ classical color field solving $[D_\mu, F_{\mu\nu}] = J_\nu$



Talk by Steven

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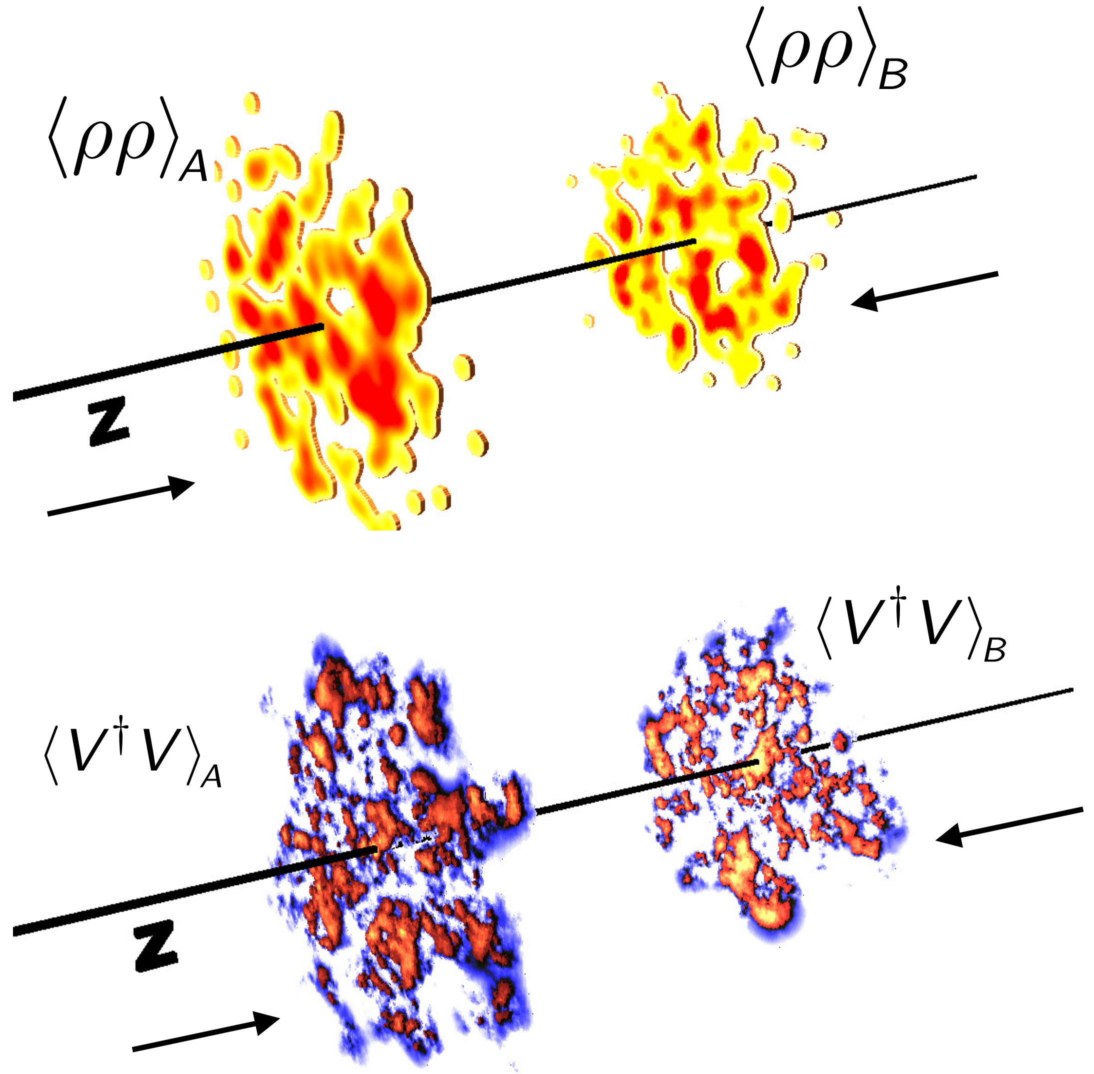

Colliding nuclei

→ classical color charge $\rho(x_\perp)$

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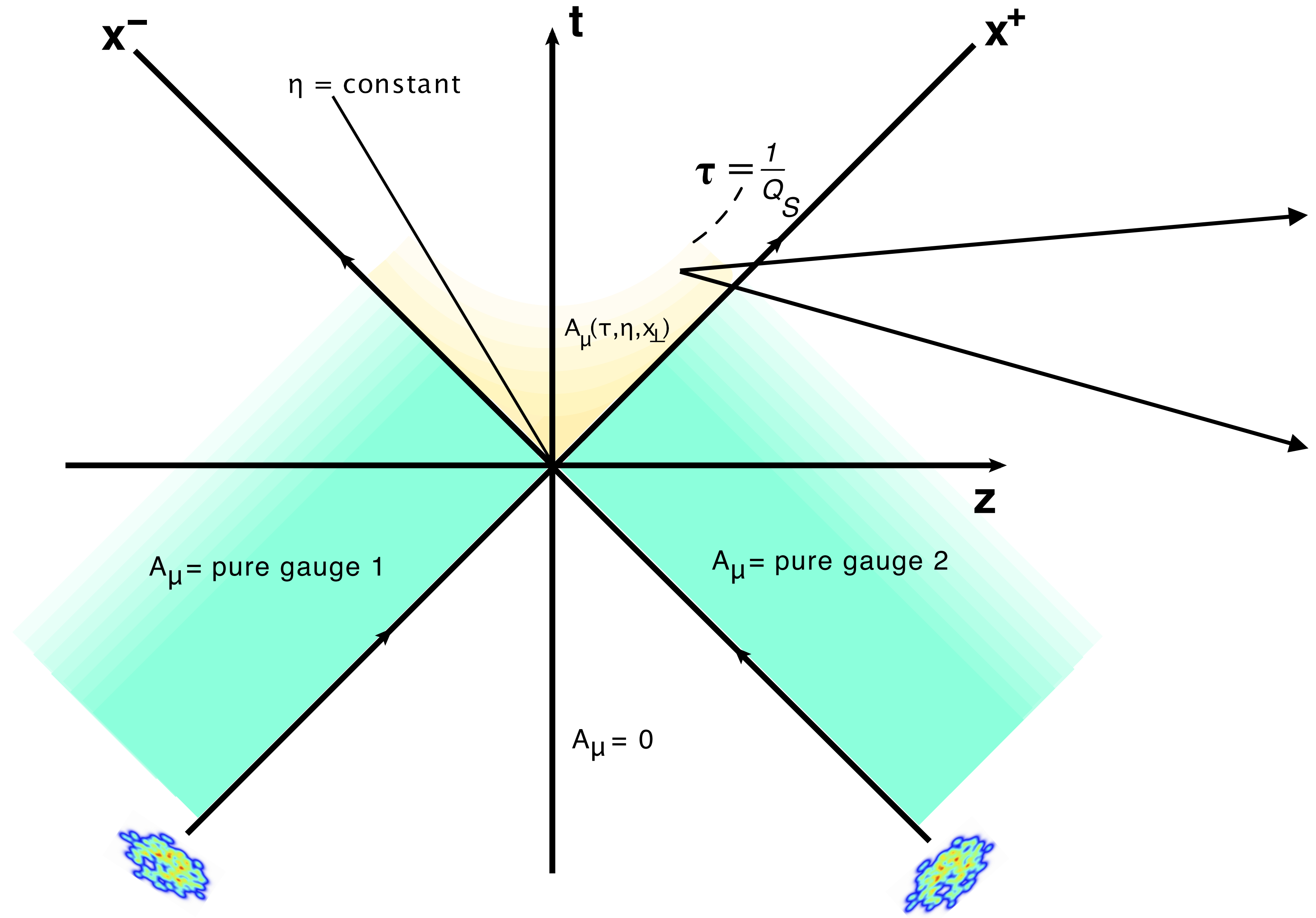
Field after collisions → combination of colliding fields



$$T_{\mu,\nu}(\tau, x_\perp, \eta)$$

$$\frac{dN}{d\mathbf{p}_{T1}dy_1 \ldots d\mathbf{p}_{Tn}dy_n}$$

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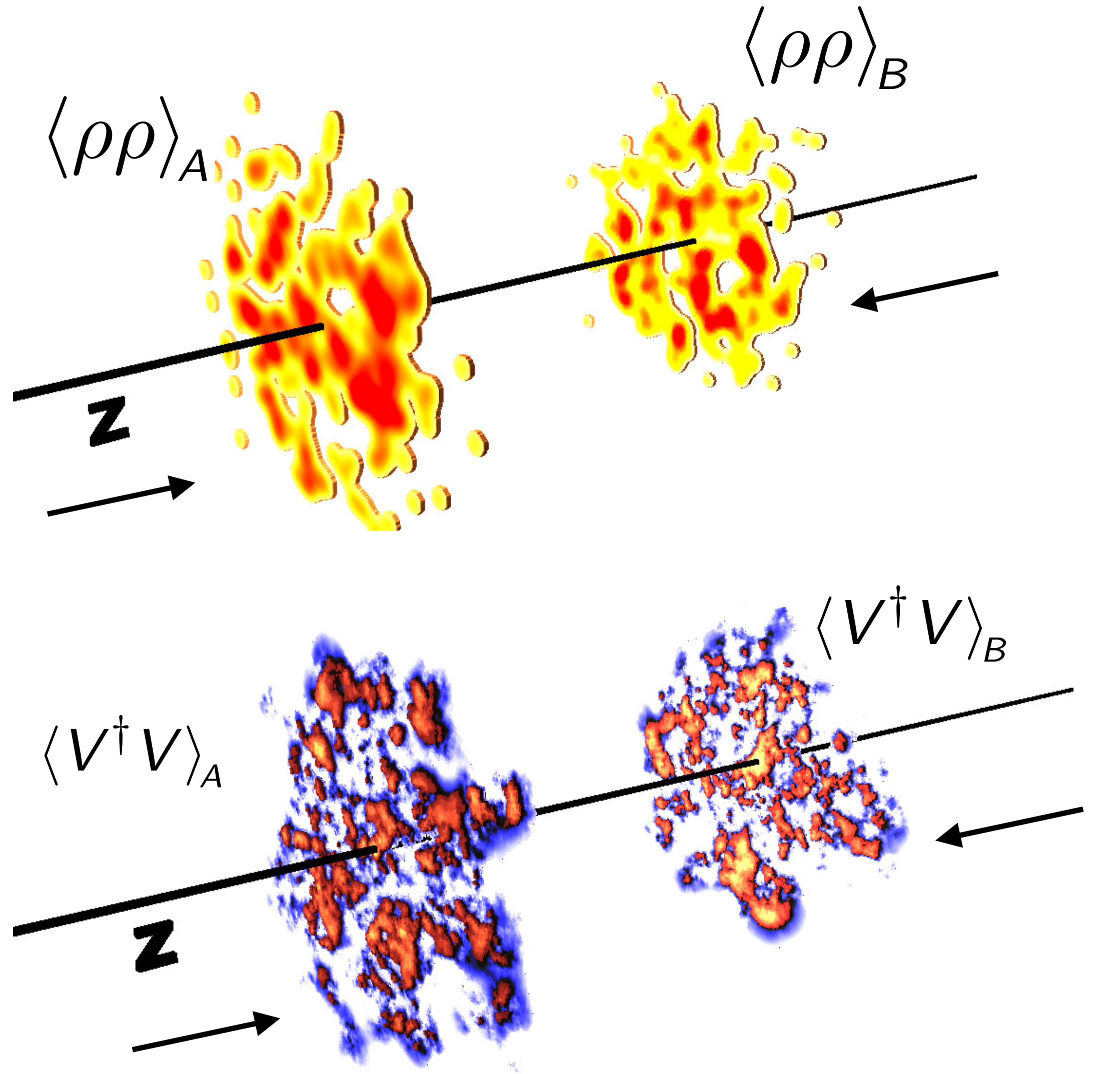
IP-Glasma model in a nutshell

Schenke, PT, Venugopalan 1202.6646

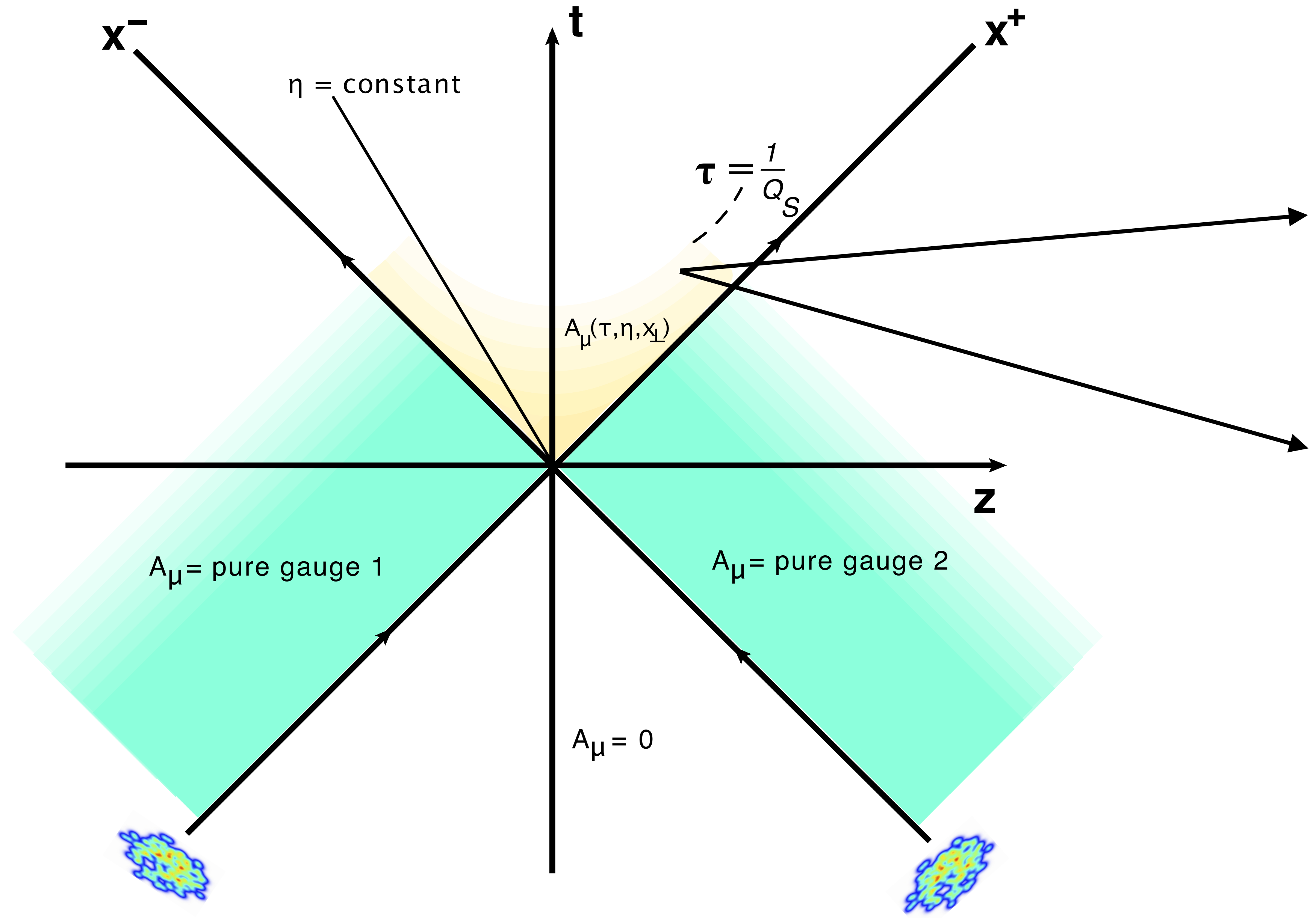


Colliding nuclei

→ classical color charge $\rho(x_\perp)$

→ classical color field solving $[D_\mu, F_{\mu\nu}] = J_\nu$

Field after collisions → combination of colliding fields



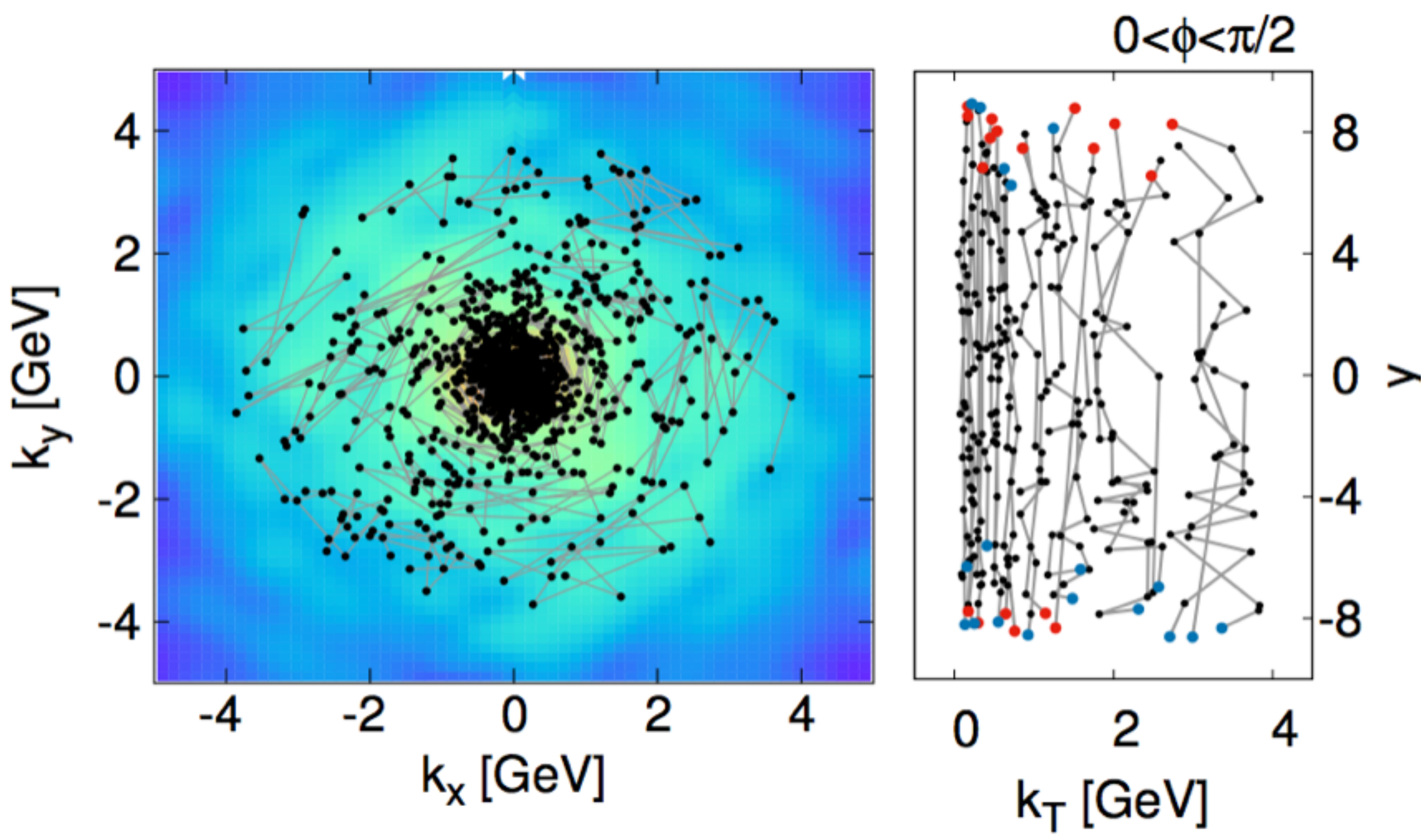
$$T_{\mu,\nu}(\tau, x_\perp, \eta)$$

$$\frac{dN}{d\mathbf{p}_{T1} dy_1 \ldots d\mathbf{p}_{Tn} dy_n}$$

Talk by Steven

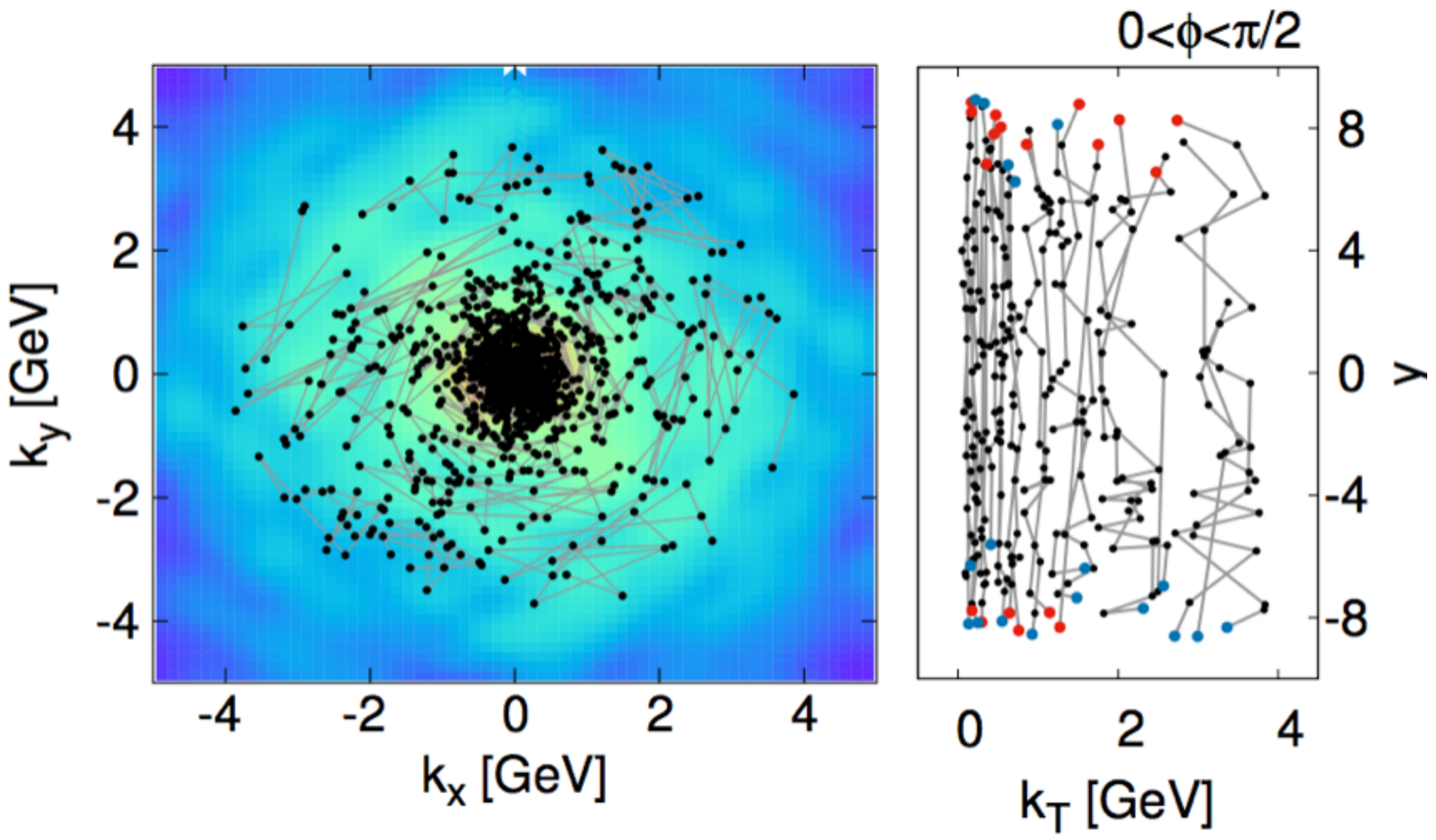
CGC (IP-Glasma) + PYTHIA (Fragmentation)

Schenke, Schlichting, PT and Venugopalan, 1607.02496 (to appear in PRL)

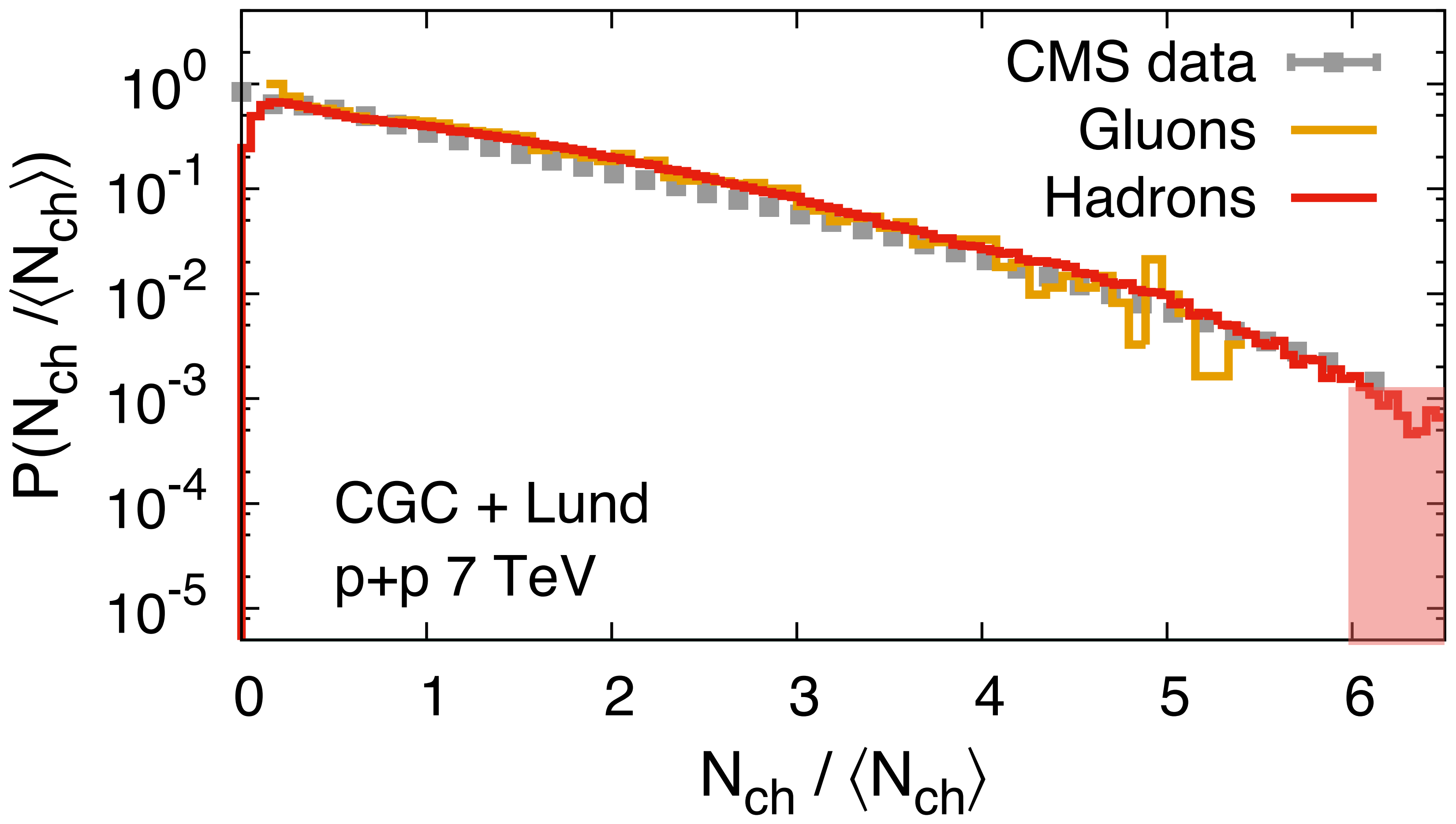


$$\frac{dN}{d\mathbf{p}_{T1}dy_1 \dots d\mathbf{p}_{Tn}dy_n}$$

CGC (IP-Glasma) + PYTHIA (Fragmentation)

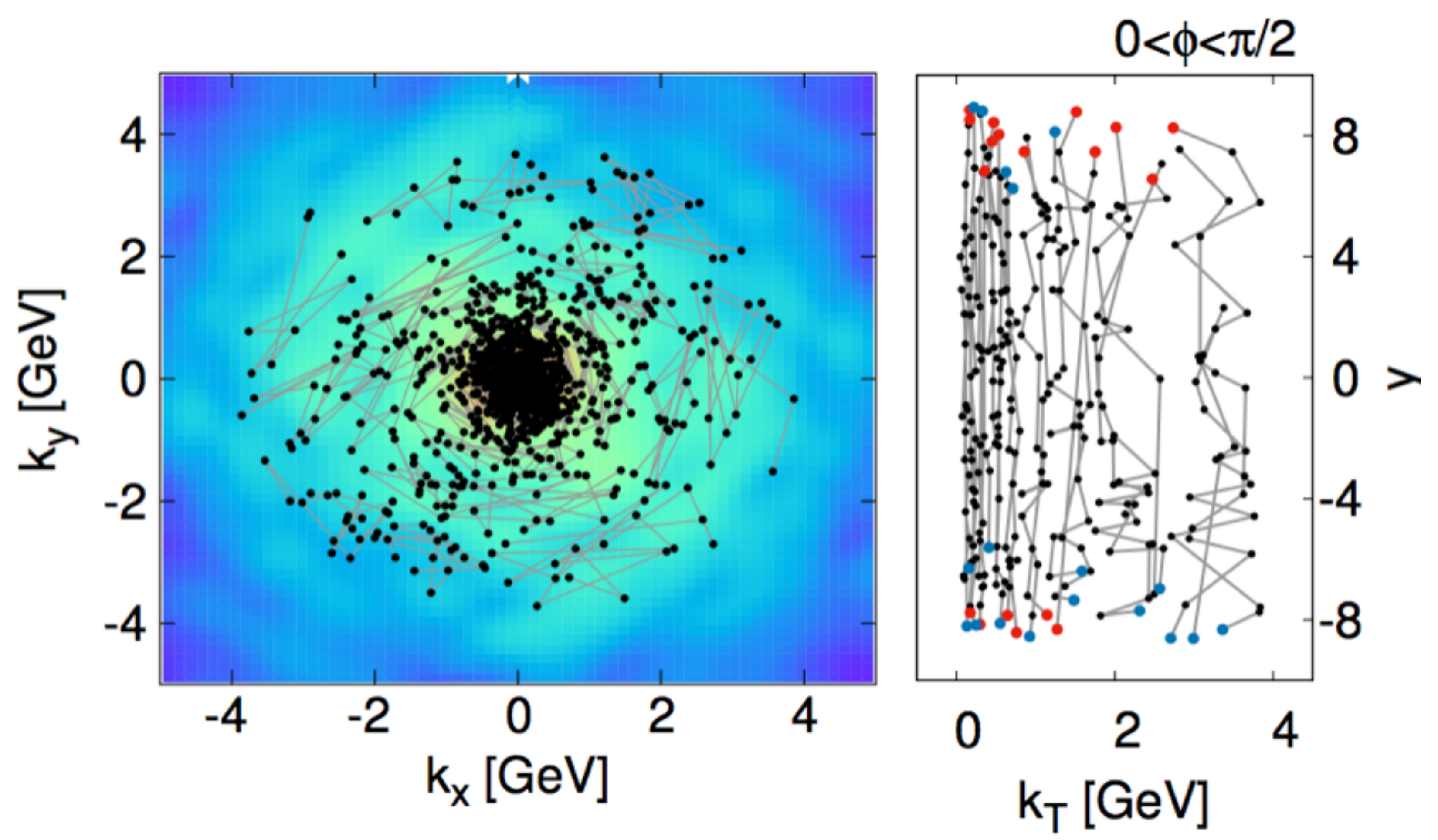


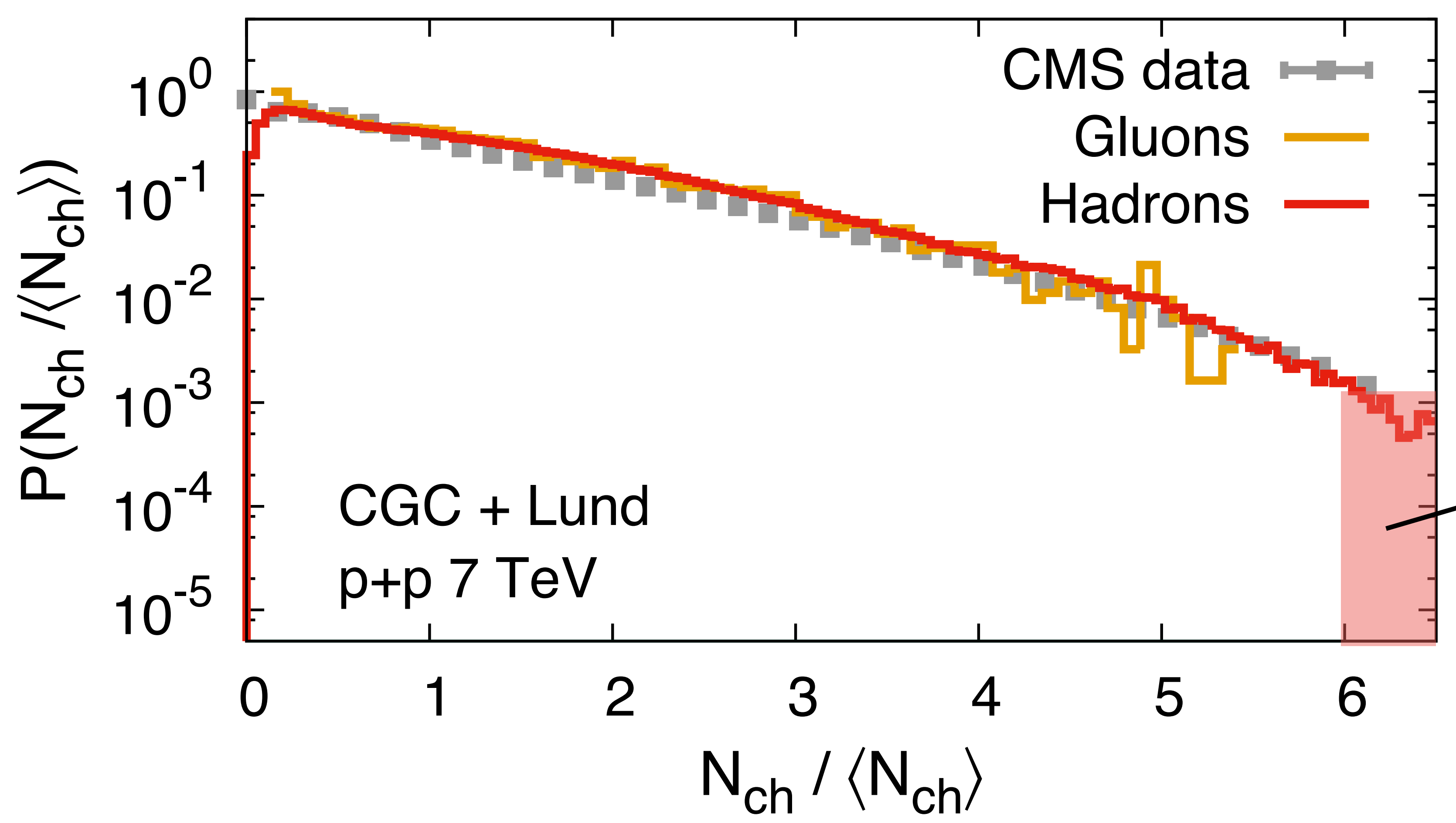
Schenke, Schlichting, PT and Venugopalan, 1607.02496 (to appear in PRL)

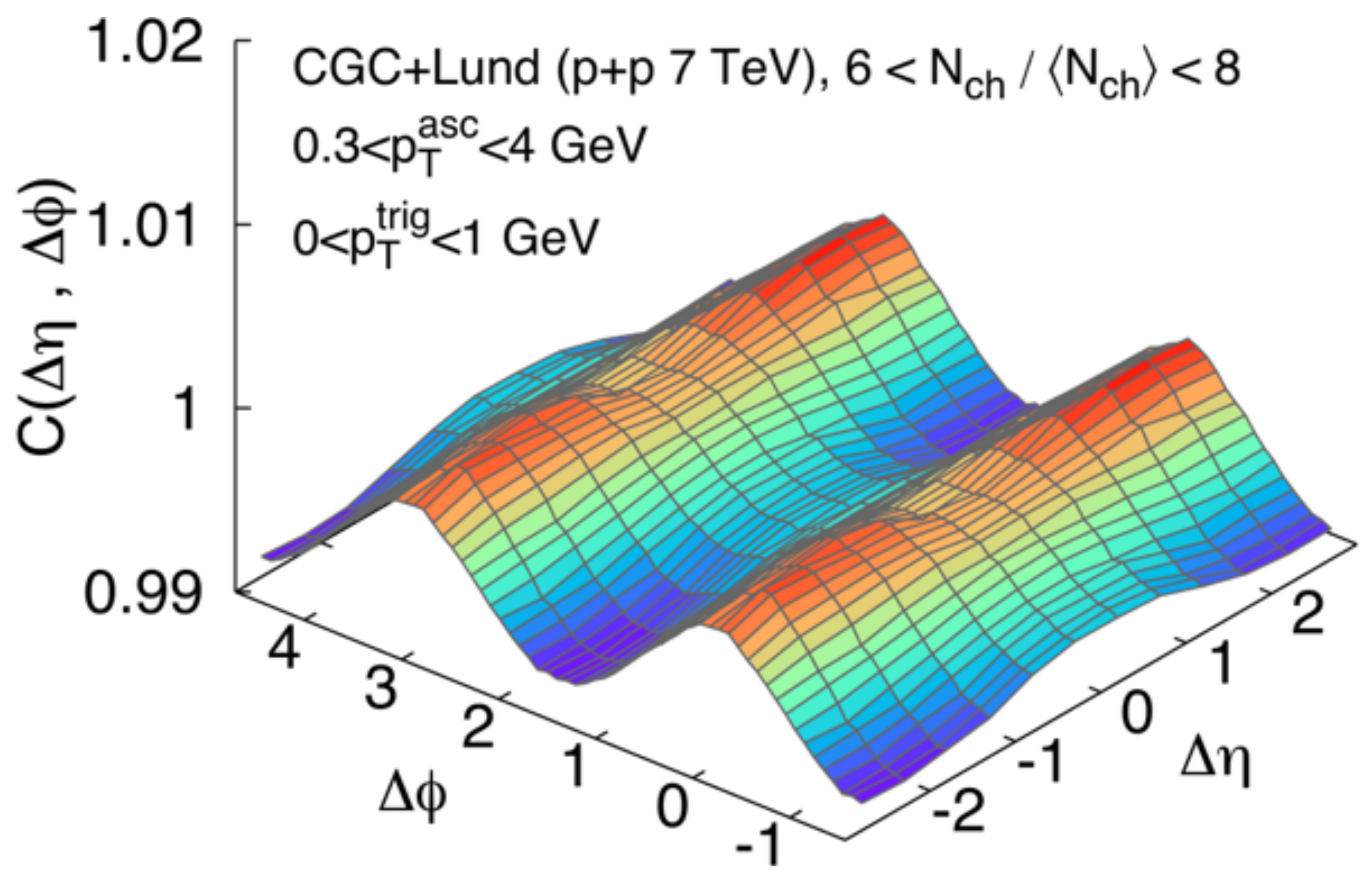


CGC (IP-Glasma) + PYTHIA (Fragmentation)

Schenke, Schlichting, PT and Venugopalan, 1607.02496 (to appear in PRL)



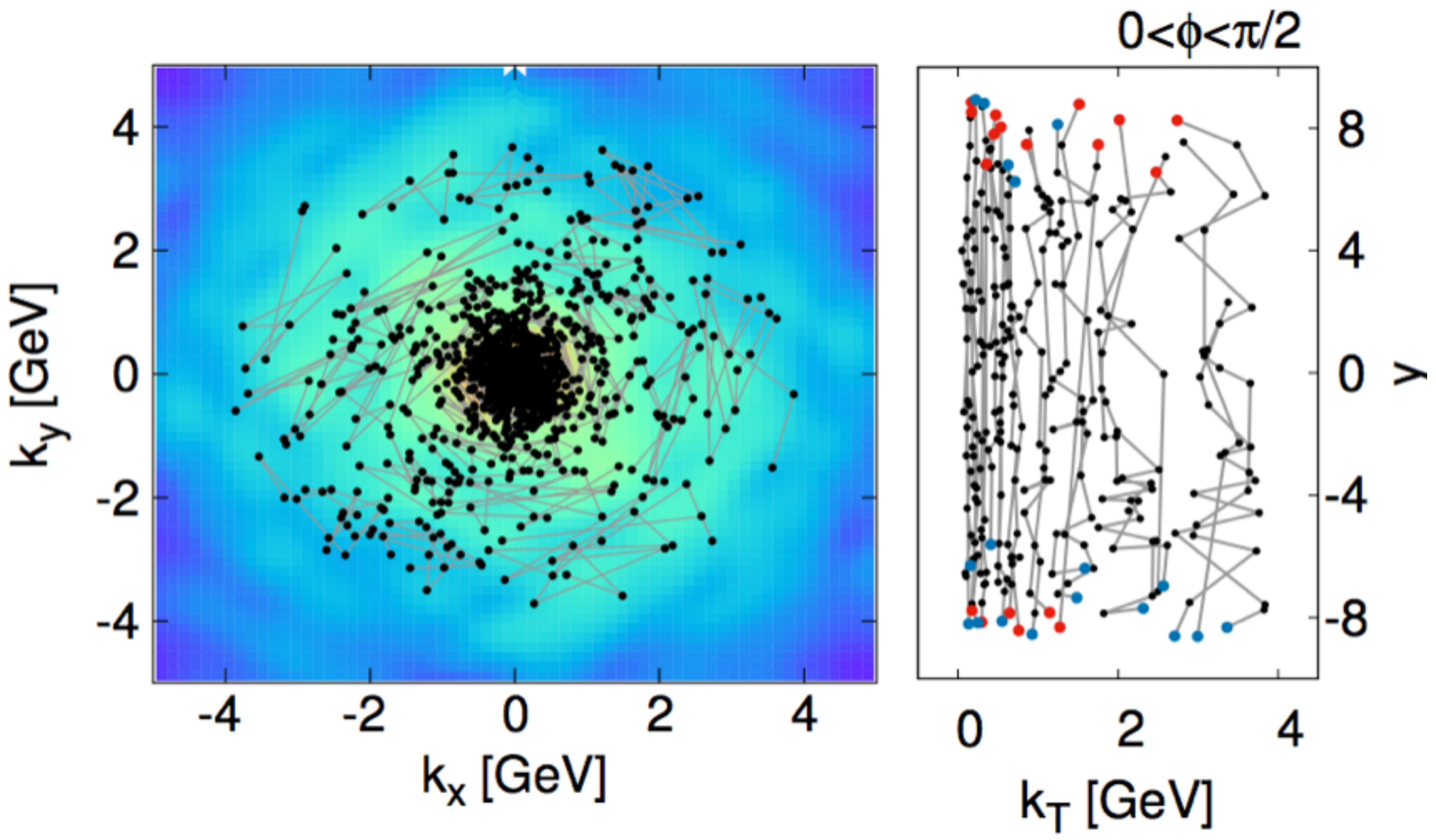


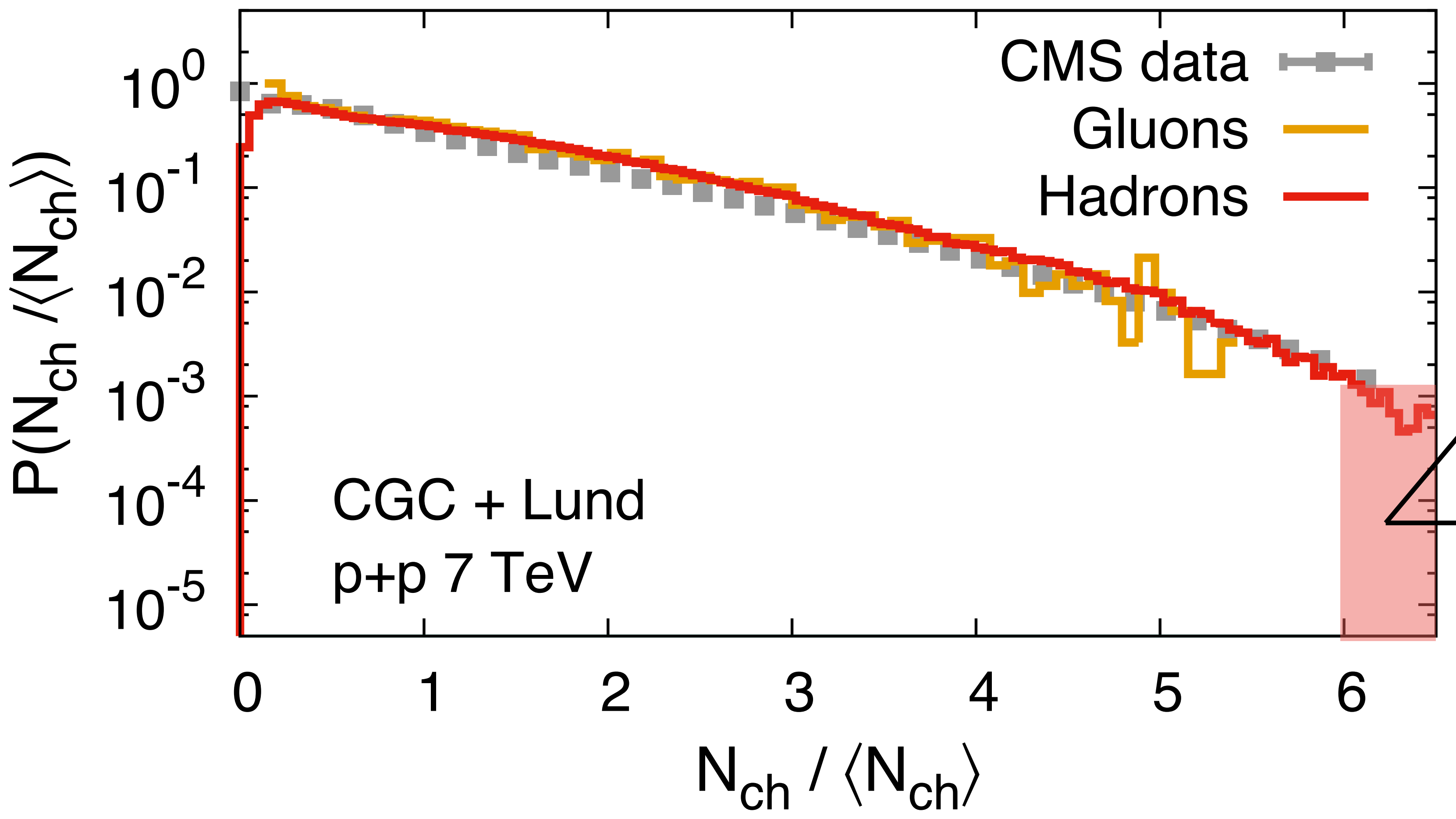


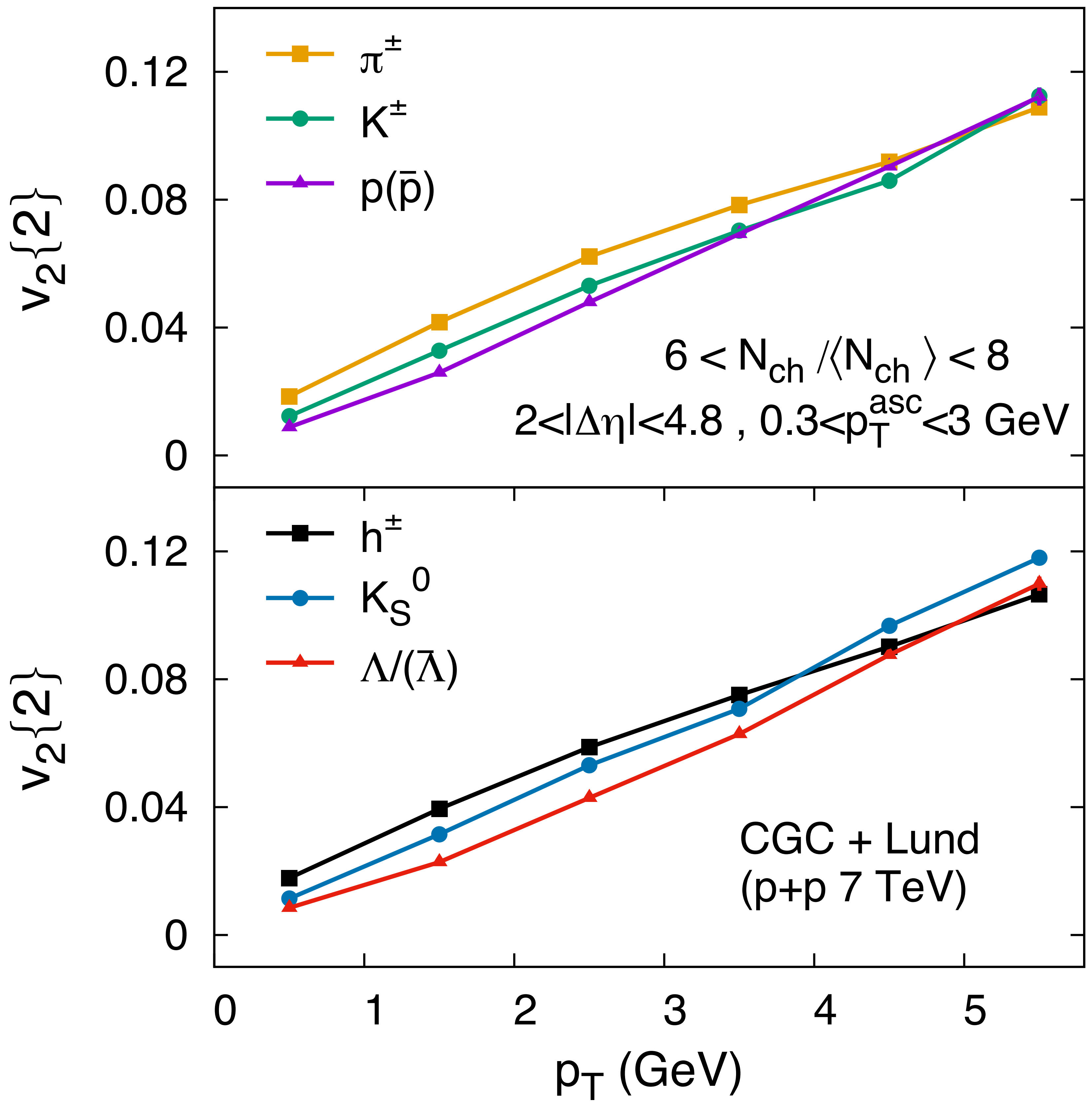
Purely momentum space correlations of gluons produce ridge after fragmentation

CGC (IP-Glasma) + PYTHIA (Fragmentation)

Schenke, Schlichting, PT and Venugopalan, 1607.02496 (to appear in PRL)

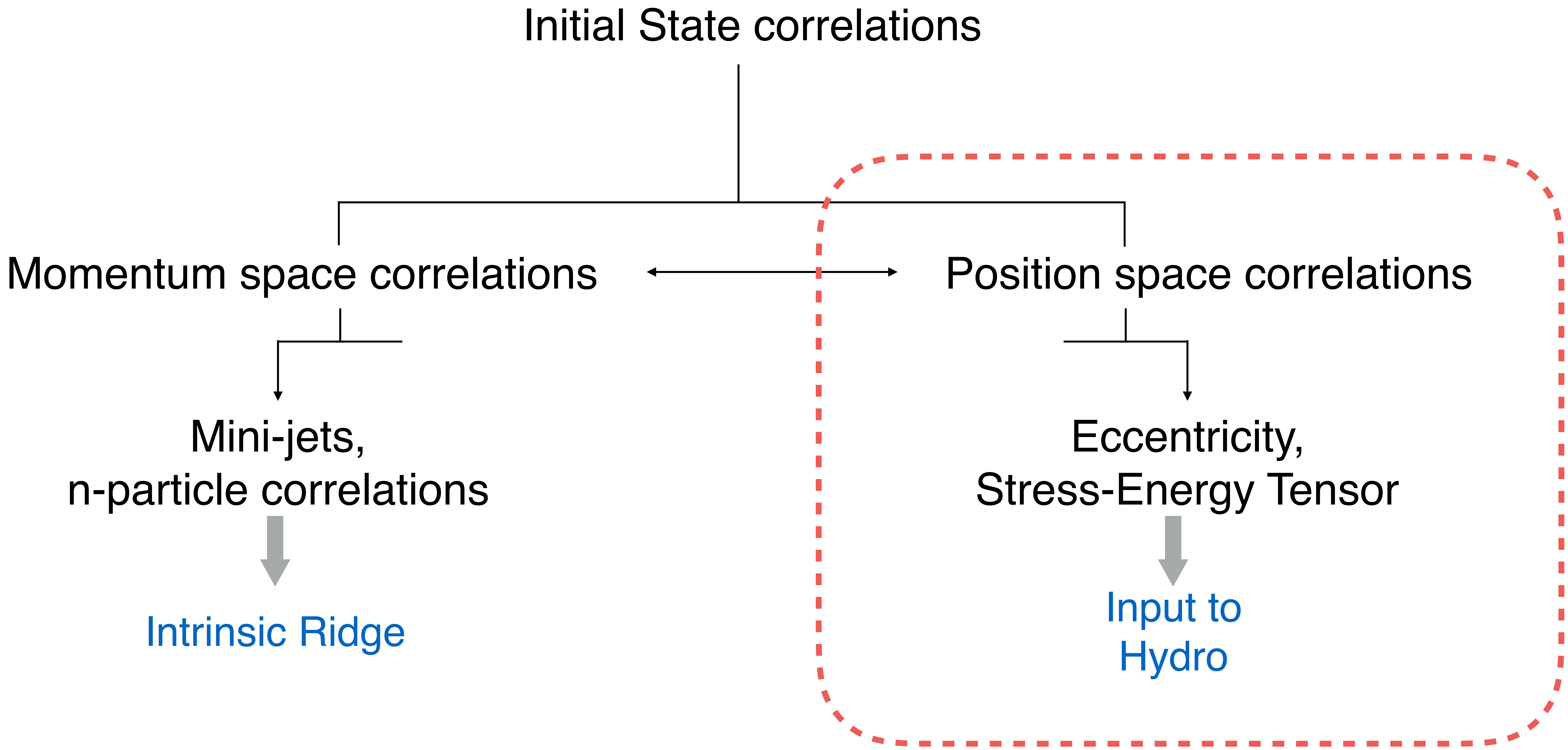






Mass ordering can come from initial state correlations + fragmentations

Initial state correlations



Common Initial conditions

Collision geometry + 2-comp model

CGC perturbative

CGC non-perturbative

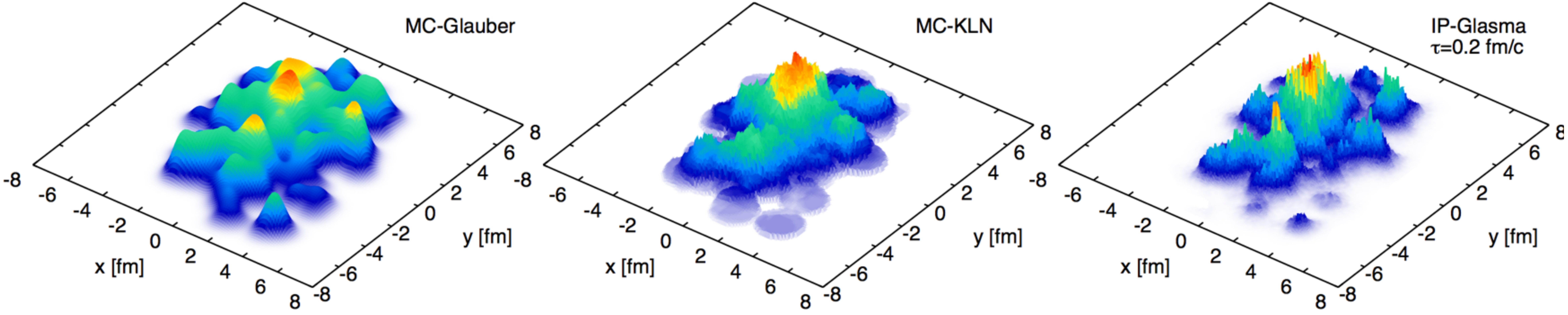


fig: Gale, Jeon, Schenke, Int.J.Mod.Phys. A28 (2013) 1340011

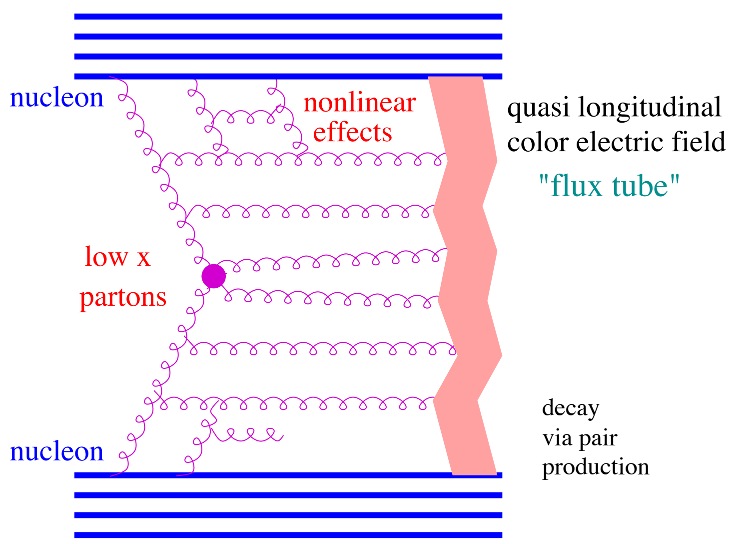
Energy densities from these models are input to hydrodynamic simulations

A few other models of initial conditions

neXus, EPOS : Parton-Based Gribov Regge Theory

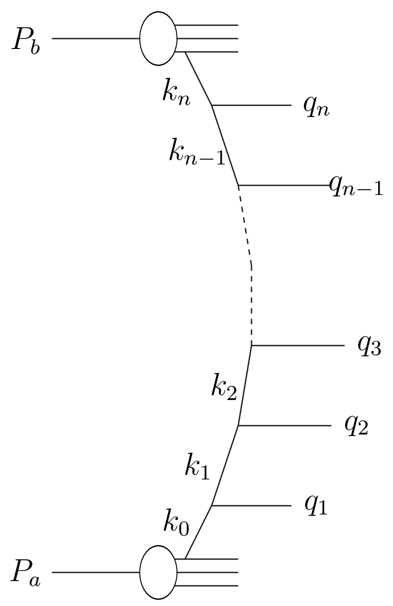
Drescher, Hladik, Ostapchenko, Pierog, Werner, hep- ph/0007198.

Werner, Liu, and Pierog, hep-ph/0506232
Pierog, Karpenko, Katzy, Yatsenko, Werner, 1306.0121



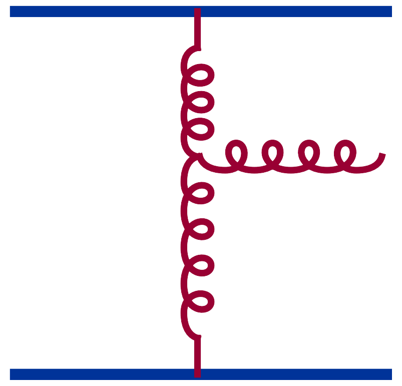
DIPSY : saturation + BFKL cascade

Flensburg,Gustafson, Lönnblad 1103.4321
Flensburg 1108.4862



Kharzeev, Levin, Nardi, hep-ph/0111315, Drescher, Nara 0707.0249, Albacete, Dumitru 1011.5161

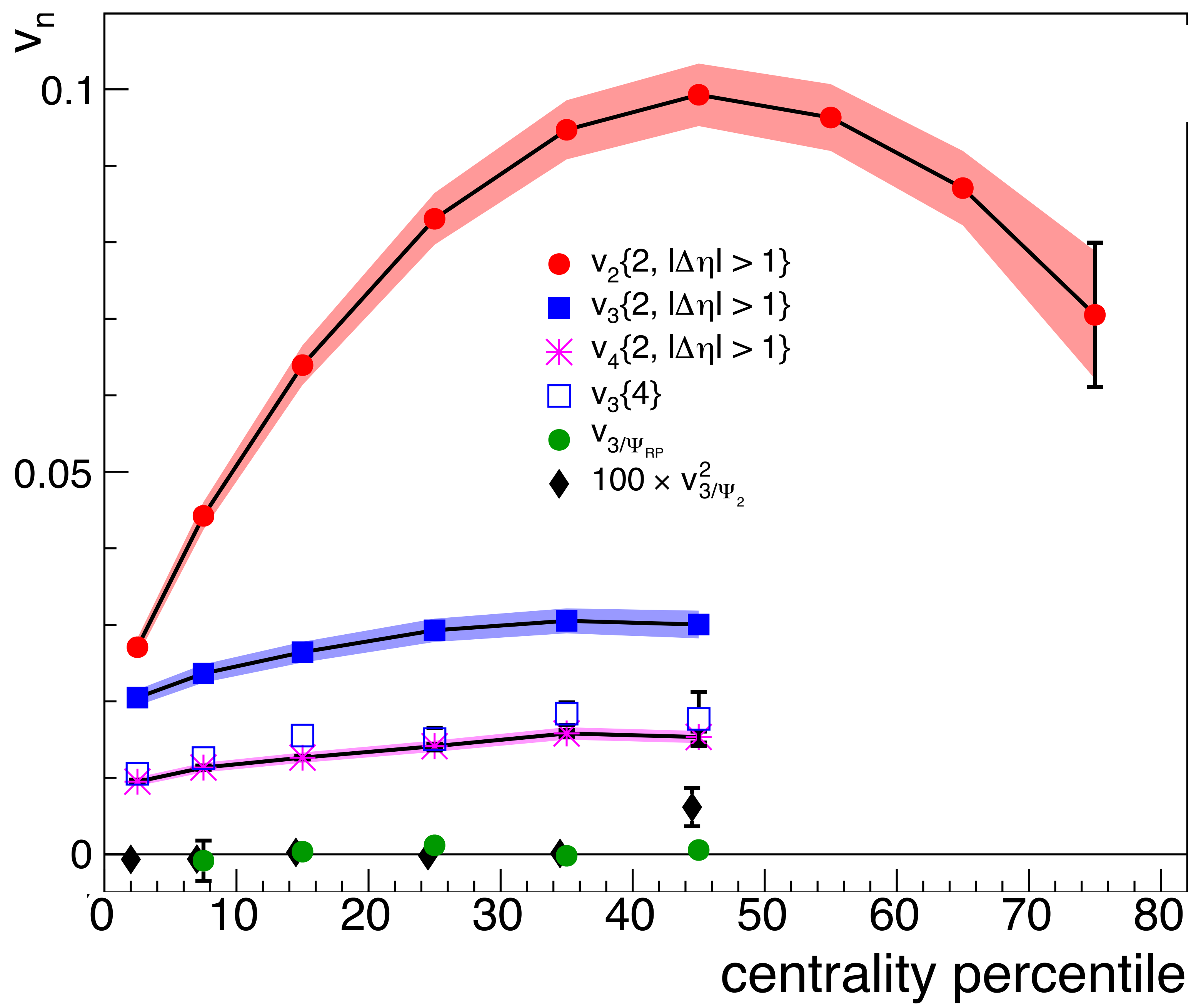
CGC factorization : KLN model, f-KLN, MC-KLN, MC-rcBK

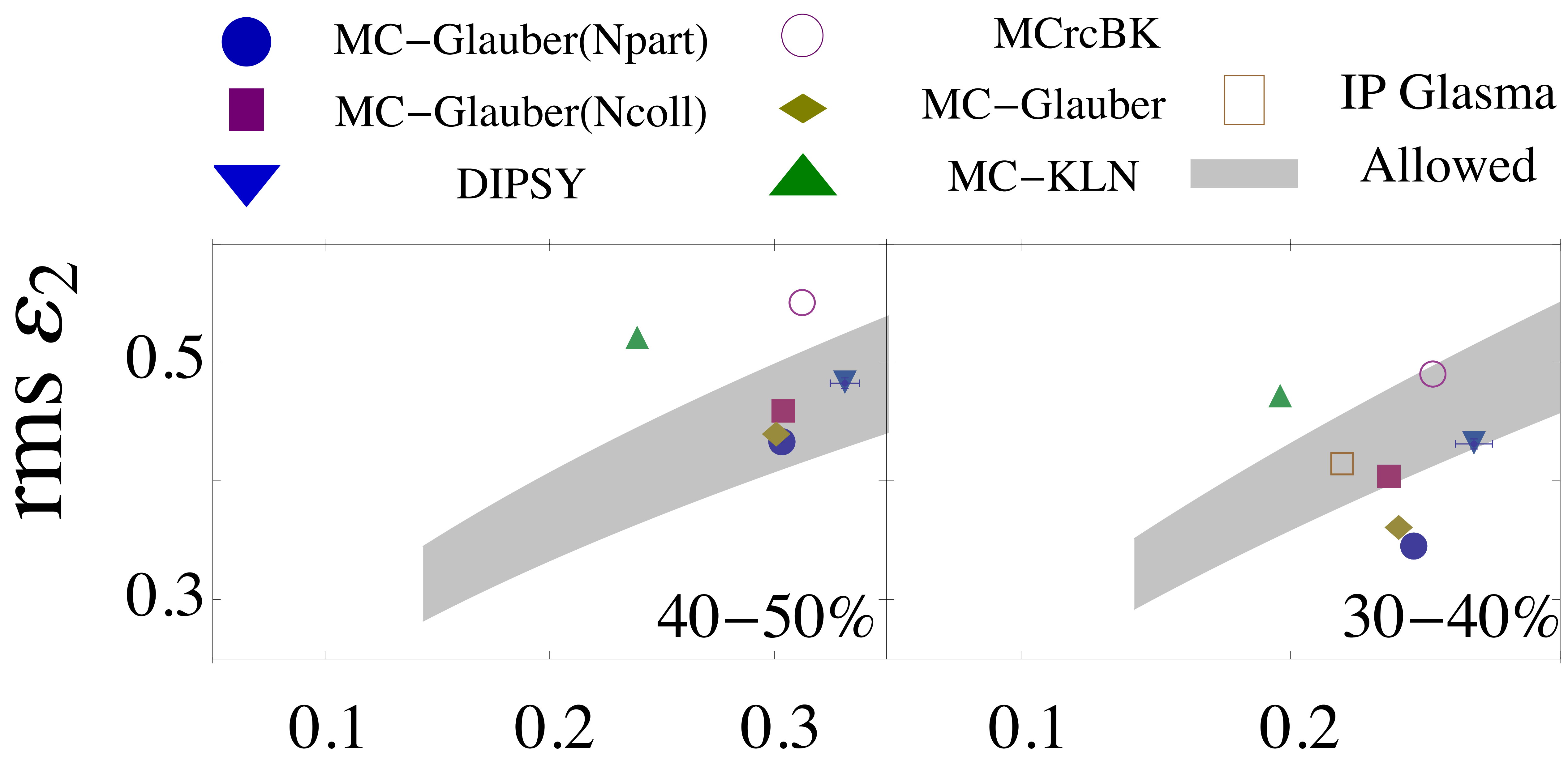


Data that nailed it down

Retinskaya, Luzum, Ollitrault 1311.5339

v_n @ RHIC/LHC : $\varepsilon_3/\varepsilon_2$

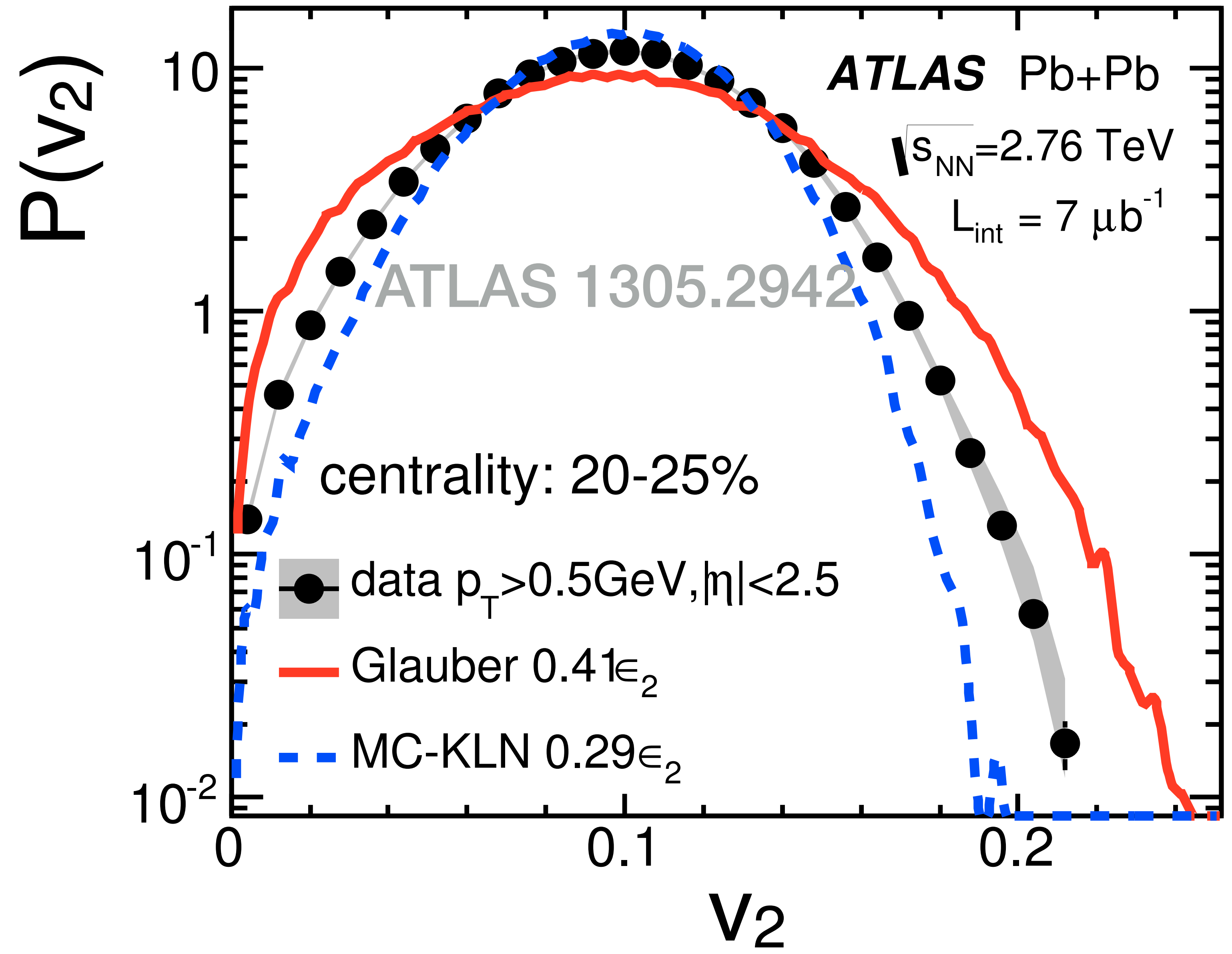




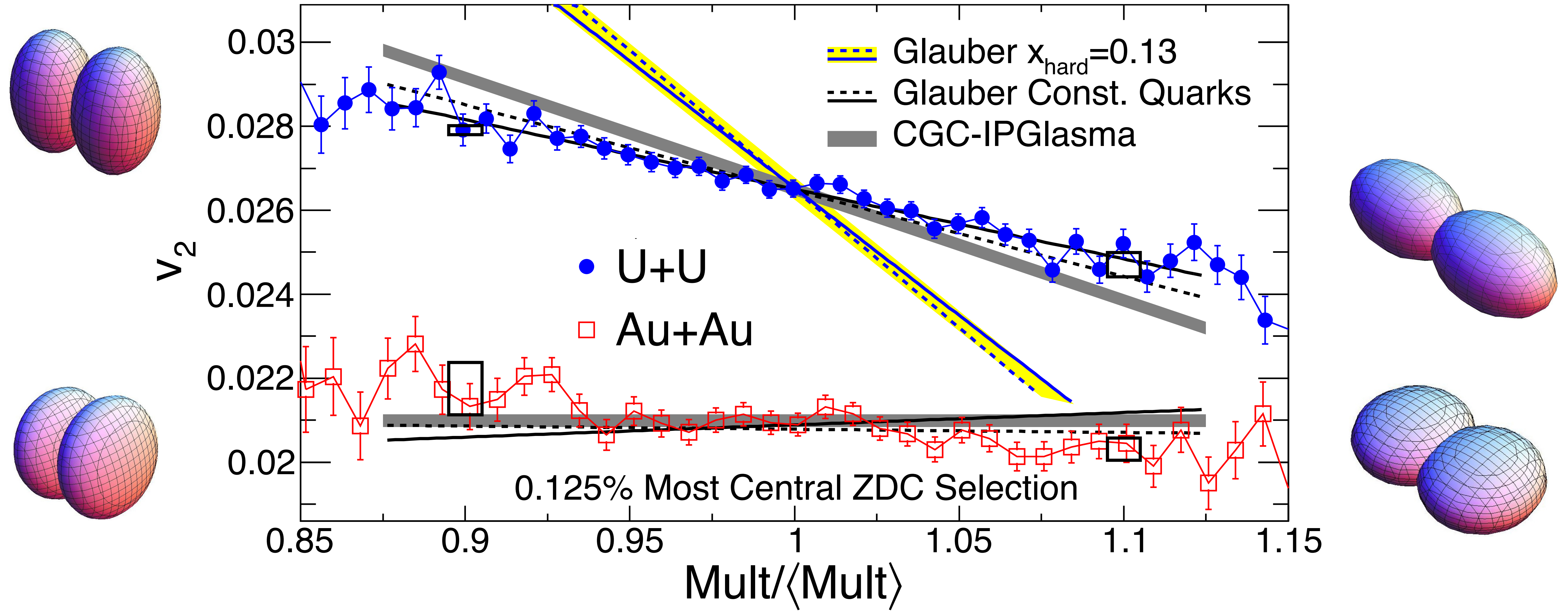
RHIC and LHC v_n data highly constrains initial state models

Data that nailed it down

P(v2) @ LHC



v2 vs multiplicity in ultracentral events @ RHIC



These data constrained many models of initial conditions like MC-KLN & MC-Glauber (correlation between shape and multiplicity)

Improved Glauber Models

Modification of Glauber : additional coherence to be introduced

TRENTO

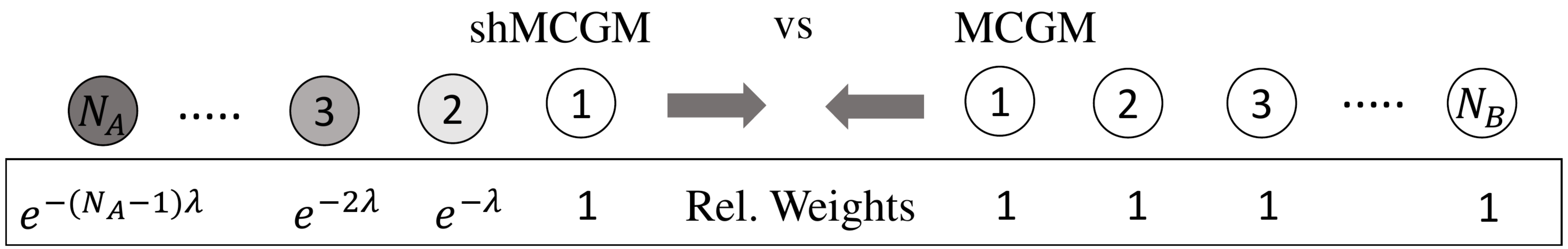
Moreland, Bernhard, Bass 1412.4708

Quark-Glauber

Eremin, Voloshin nucl-th/0302071, PHENIX 1509.06727

Shadowed Glauber

Chatterjee et al 1510.01311, 1601.03971



Shadowed Glauber

Normal Glauber

EKRT : pQCD (shadowing) + saturation

NLO pQCD cross section of mini-jets with nPDF

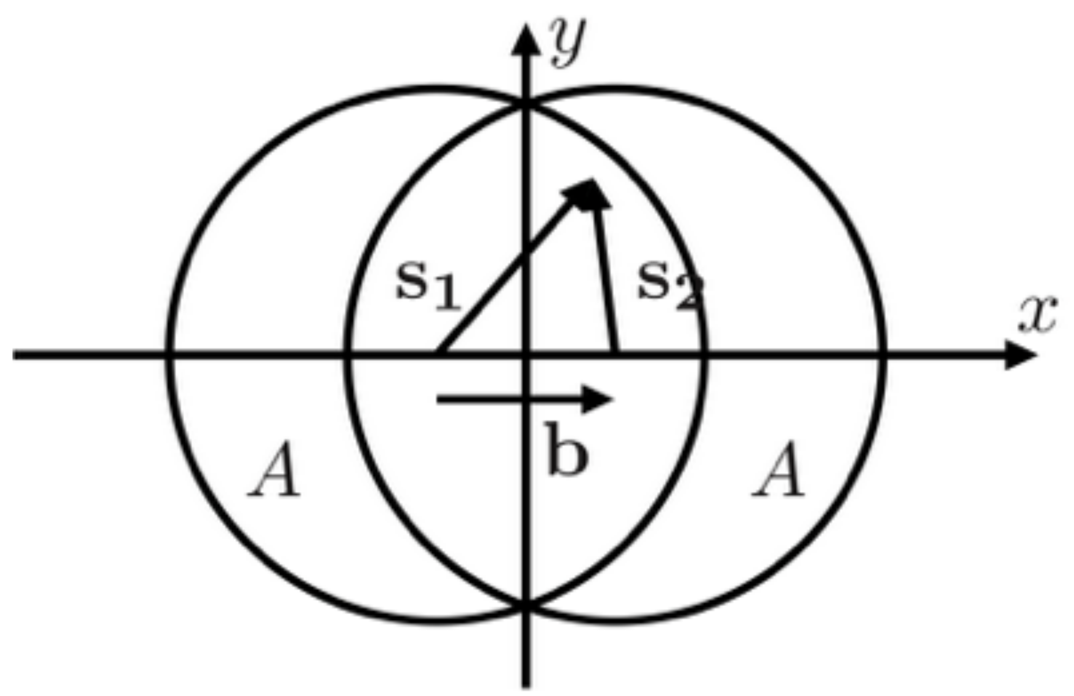
Niemi, Eskola, Paatelainen 1505.02677

$$\frac{dE_T(p_0, \sqrt{s}, \Delta y, \mathbf{s}, \mathbf{b})}{d^2 s} = T_A(\mathbf{s} + \mathbf{b}/2) T_A(\mathbf{s} - \mathbf{b}/2) \sigma \langle E_T \rangle_{p_0, \Delta y}$$

Geometry

pQCD +nPDF

saturation



Implementation of saturation when 2 → 2 ~ 2 →3

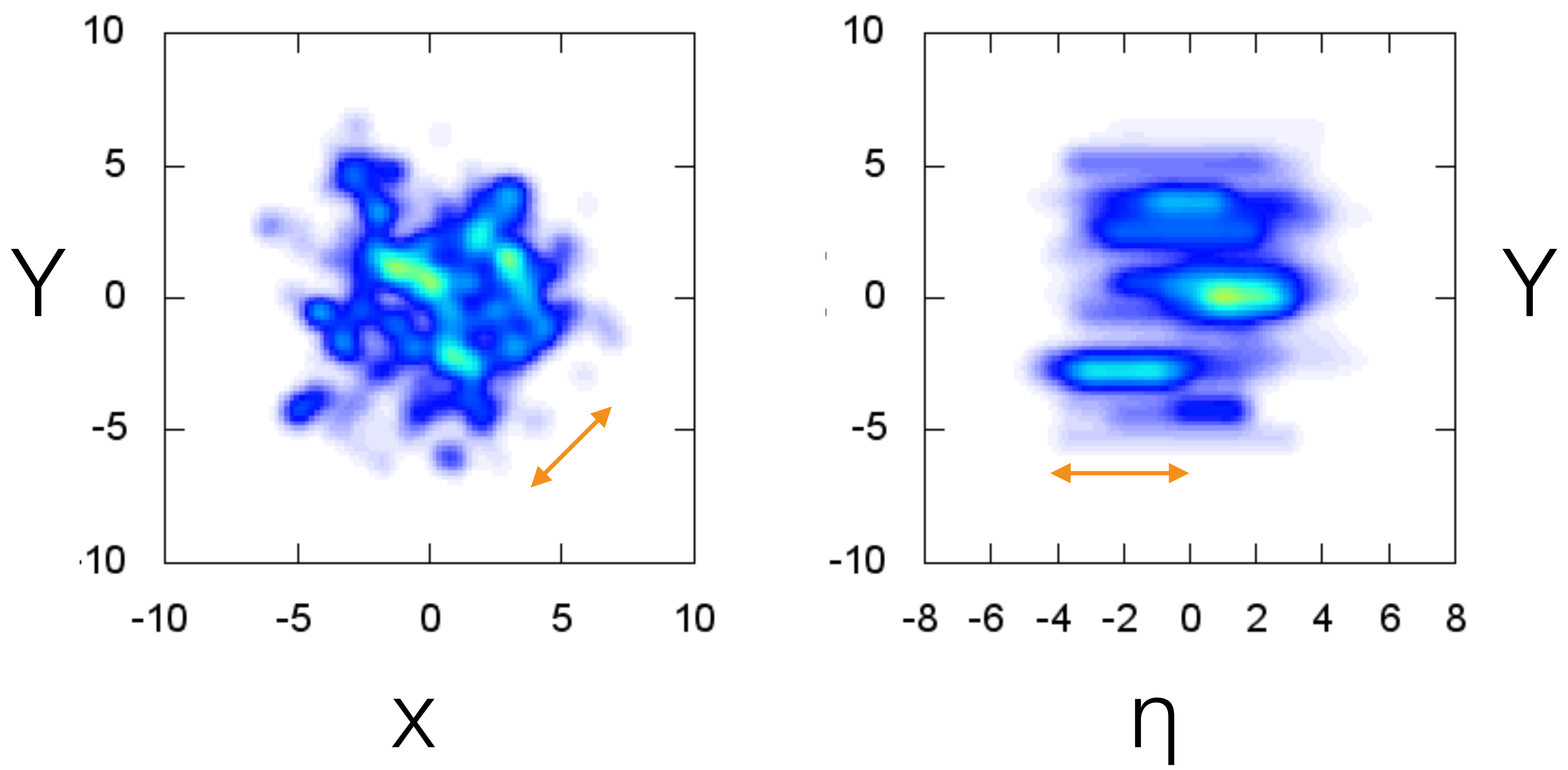
Time evolution → Bjorken like expansion

Very successful phenomenology at RHIC and LHC

3D initial conditions

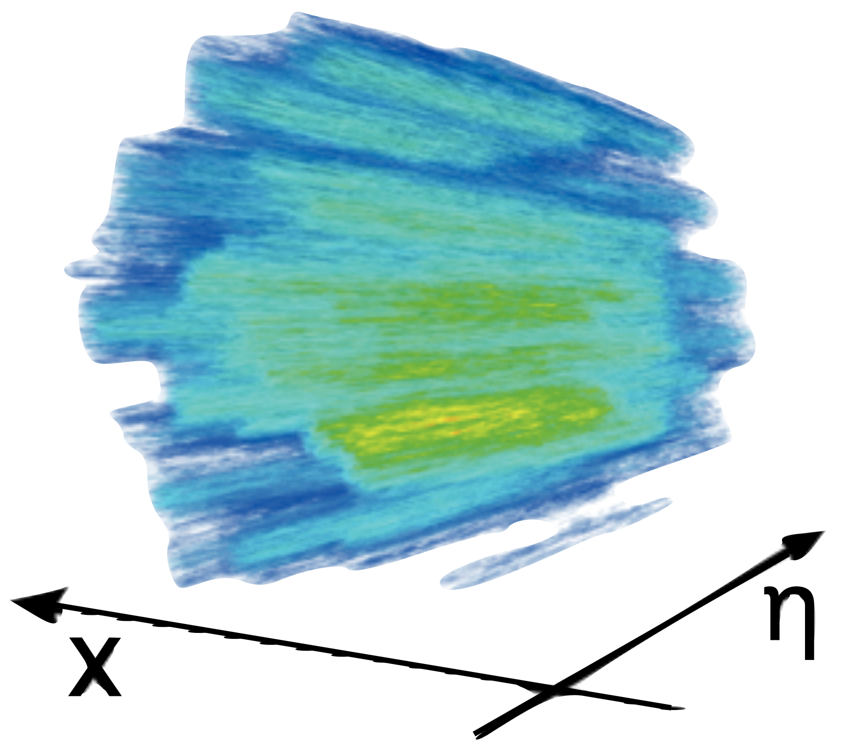
3D-Glauber (LeXUS + Glauber)

Schenke, Monnai 1509.04103



3D-Glasma (JIMWLK + IP-Glasma)

Schenke, Schlichting 1605.07158



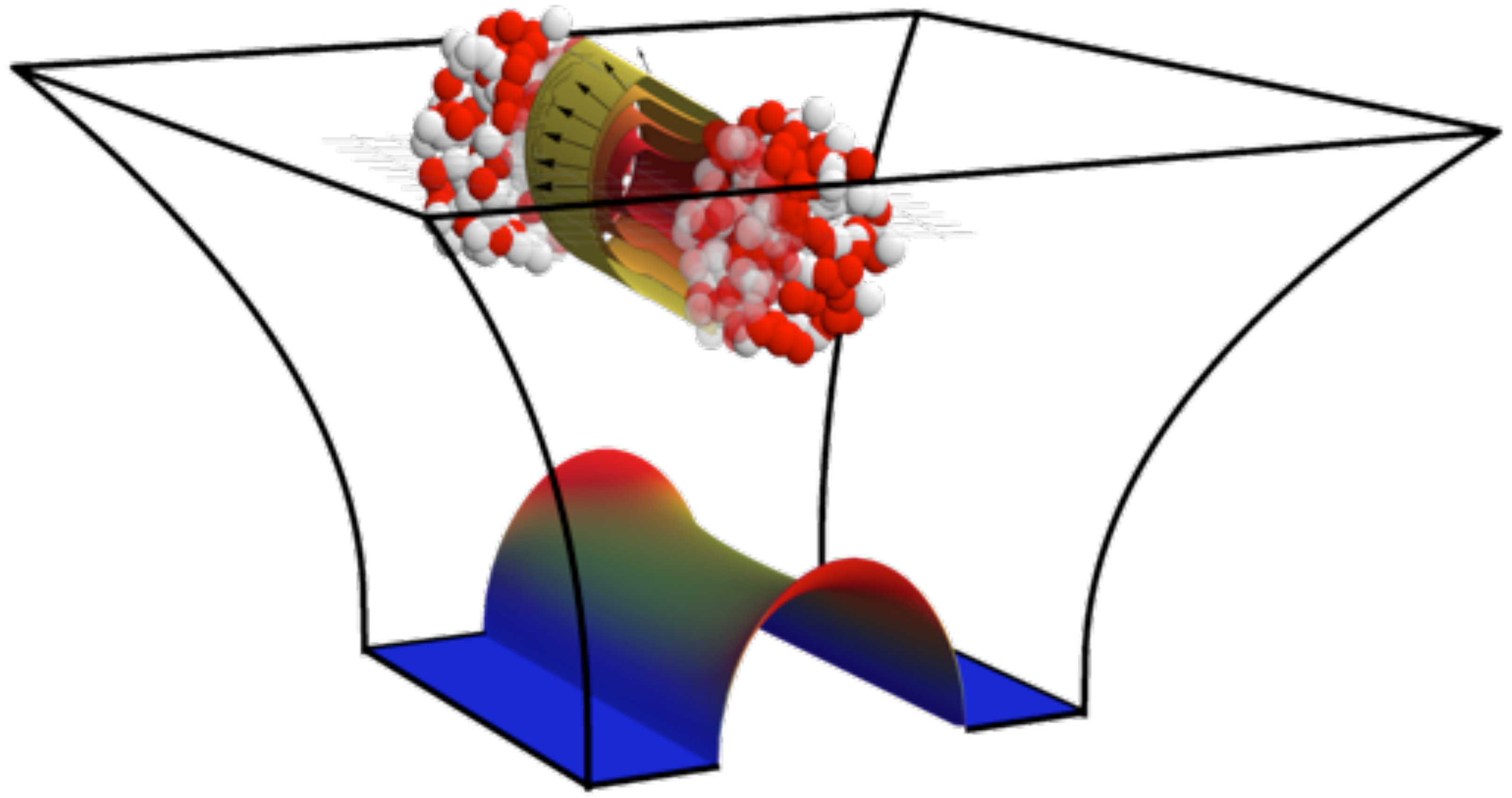
Breaking of **boost-invariance** ➝ due to longitudinal fluctuations
➝ **twist**, **torque**, event-plane **de-correlation**

3D initial state ➝ More important at lower energies

Holographic initial conditions

fig: W. Van der Schee QM'15

Chesler, Kilbertus, Van der Schee 1507.02548,
Van der Schee, Schenke 1507.08195,
Van der Schee, Romatschke, Pratt 1307.2539

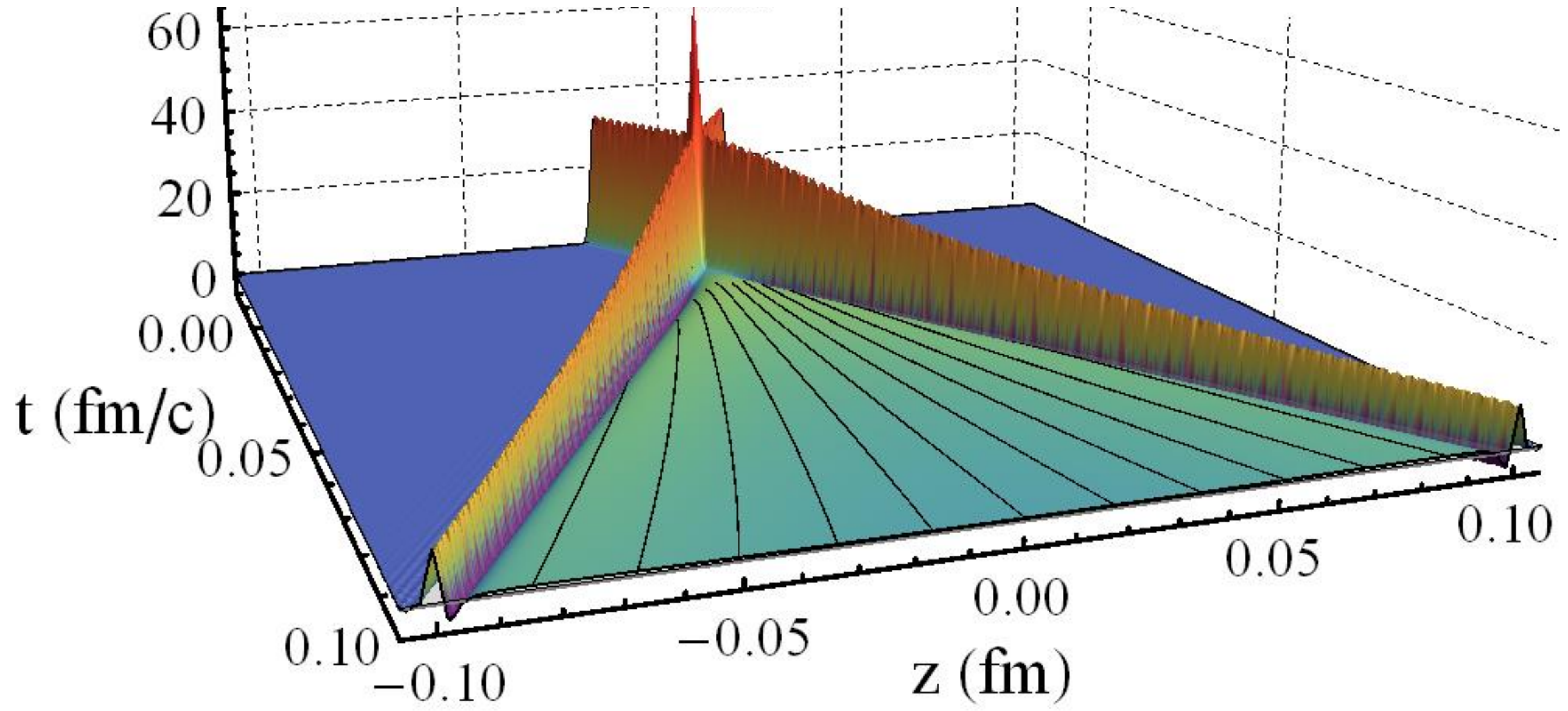


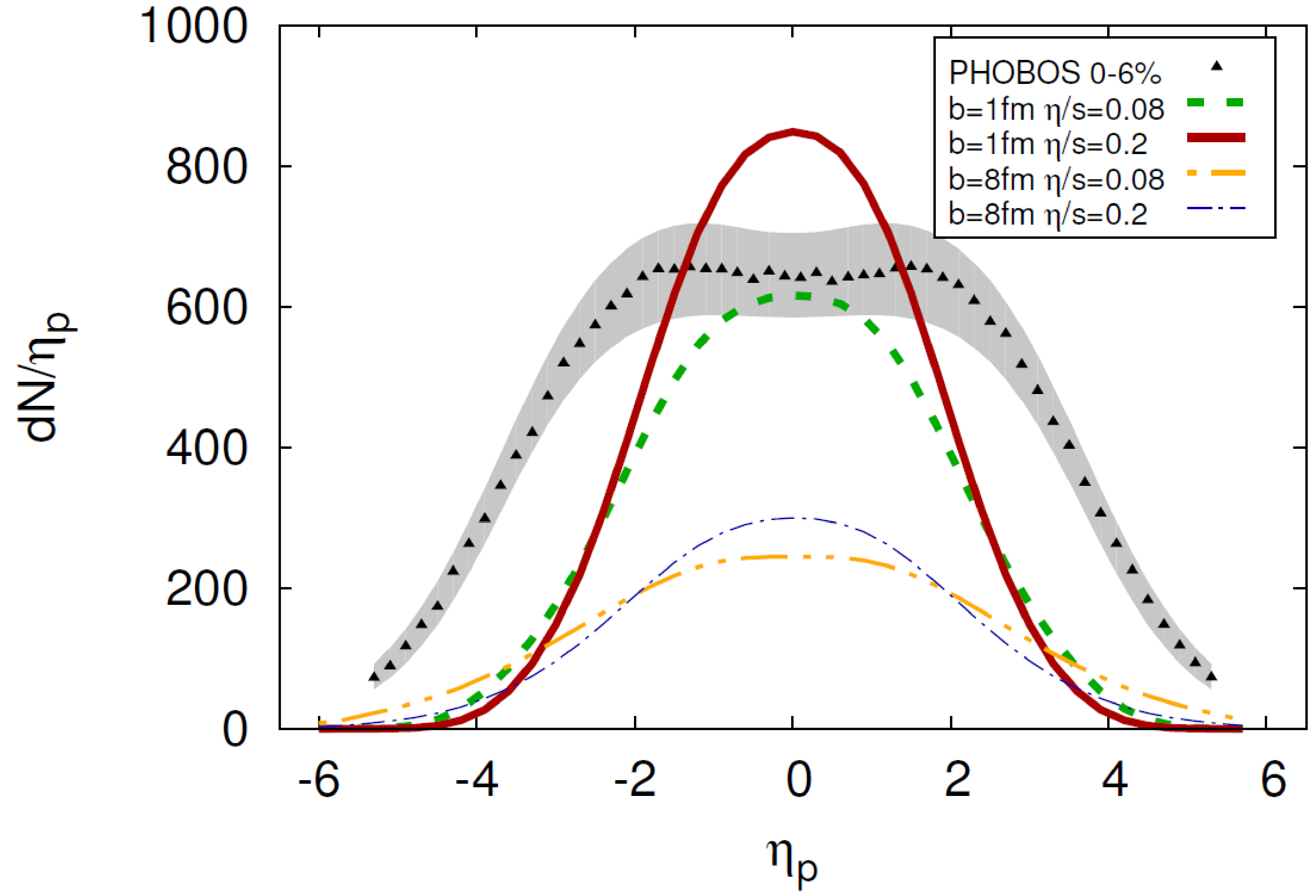
Use AdS/CFT correspondence & matching longitudinal profile of energy density

$$\mathcal{E}(t) = \frac{N_c^2 \Lambda^4}{2\pi^2}\left[\frac{1}{(\Lambda t)^{4/3}} - \frac{2\eta_0}{(\Lambda t)^2}\right]$$

Heller and Janik, hep-th/0703243

collisions of two shocks





Generalized to lower energy, transverse structure introduced separately

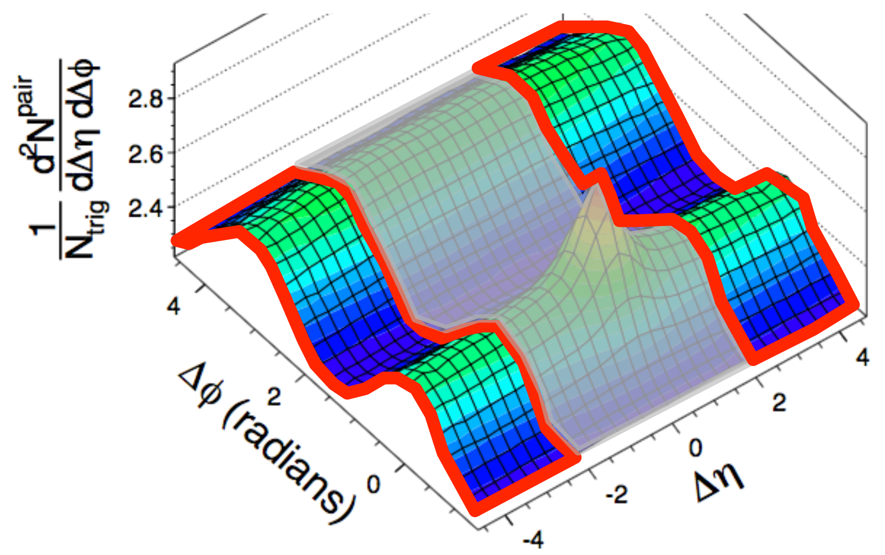
Initial state correlations

Initial State correlations

Momentum space correlations ⟷ Position space correlations

Mini-jets,
n-particle correlations

Intrinsic Ridge →



← Input to Hydro

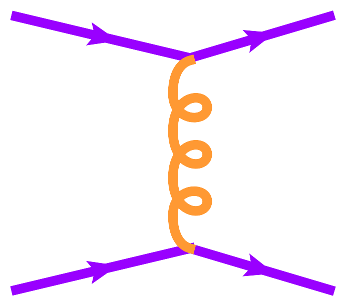
Eccentricity,
Stress-Energy Tensor

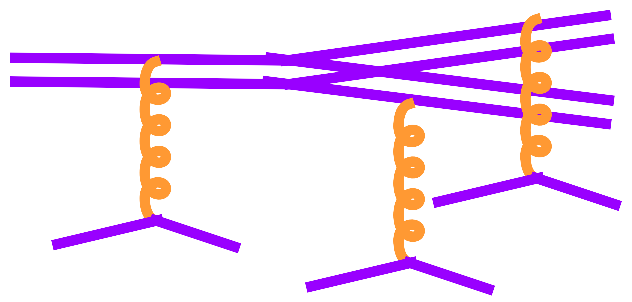
Approach to Isotropization /Thermalization

Pre-equilibrium dynamics - Classical Yang-Mills can not lead to isotropization or thermalization

Effective Kinetic Theory → ab initio approach

$$(\partial_t + \hat{\boldsymbol{p}} \cdot \boldsymbol{\nabla}_{\boldsymbol{x}})\, f_s(\boldsymbol{x}, \boldsymbol{p}, t) = -C_s^{2\leftrightarrow 2}[f] - C_s^{\text{“}1\leftrightarrow 2\text{”}}[f]$$

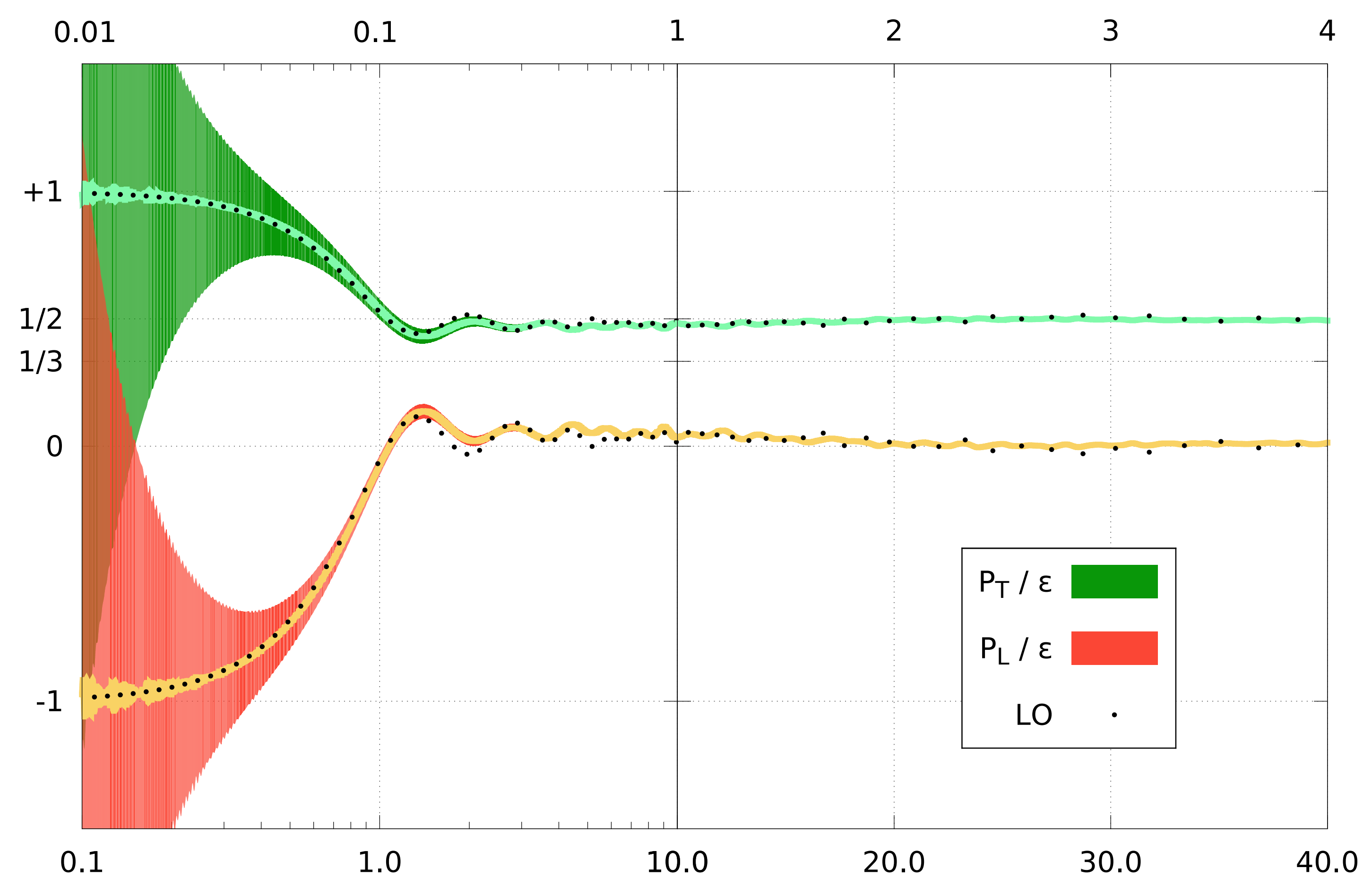




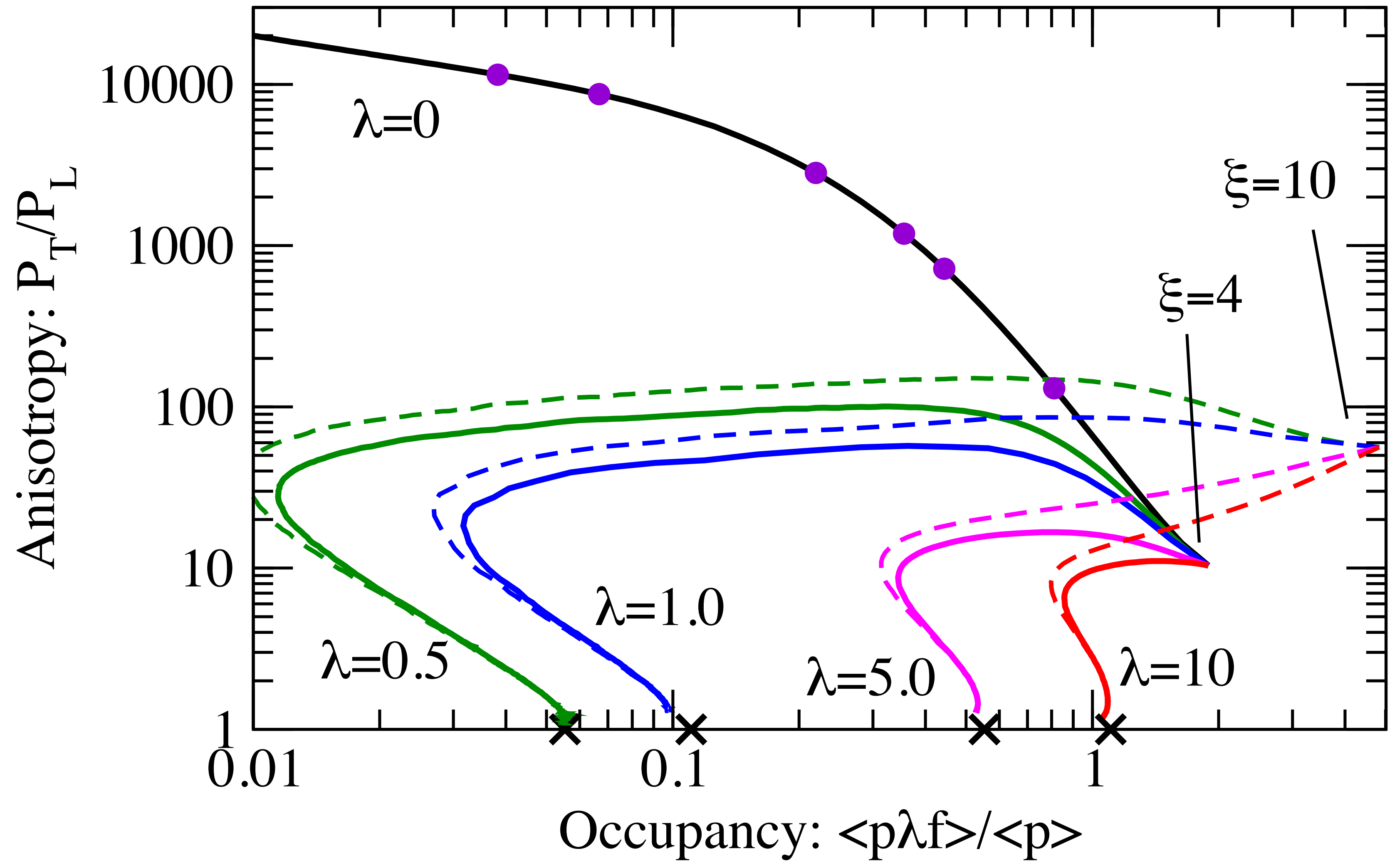
Quasiparticle picture → Isotropization in weak coupling

talk by Aleksas

Epelbaum, Gelis 1307.2214

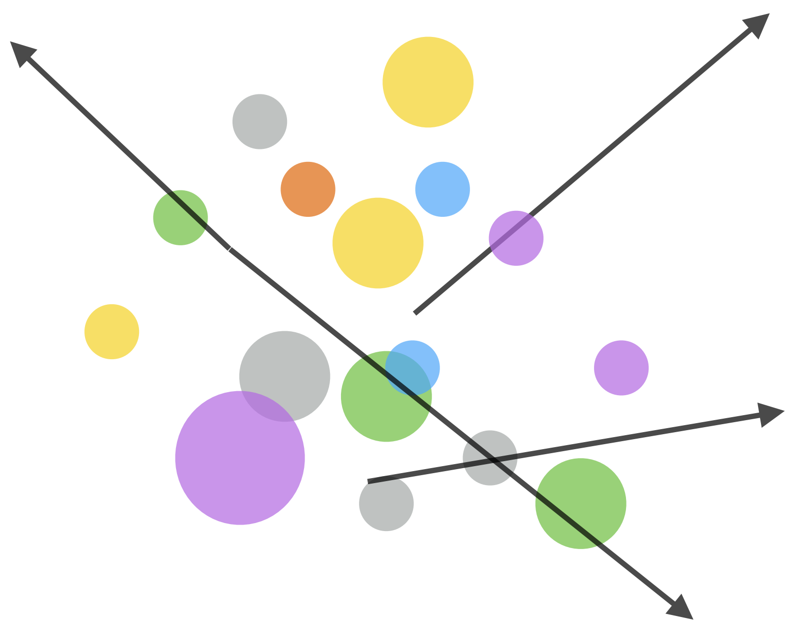


Arnold, Moore, Yaffe hep-ph/0209353
Kurkela, Zhu 1506.06647



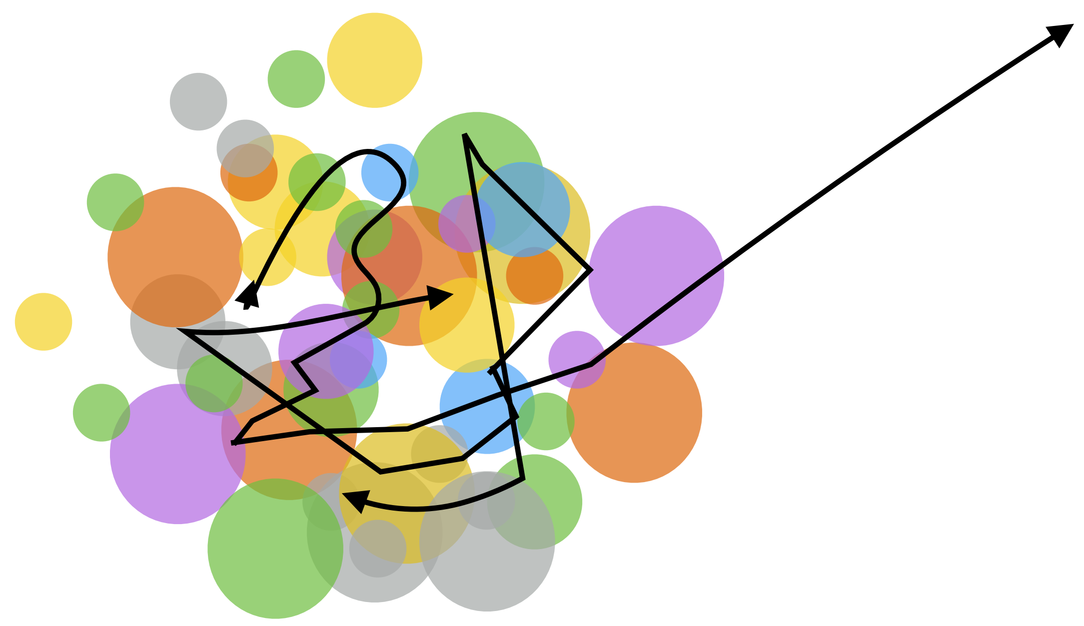
Qualitative Picture : Small systems

low multiplicity events



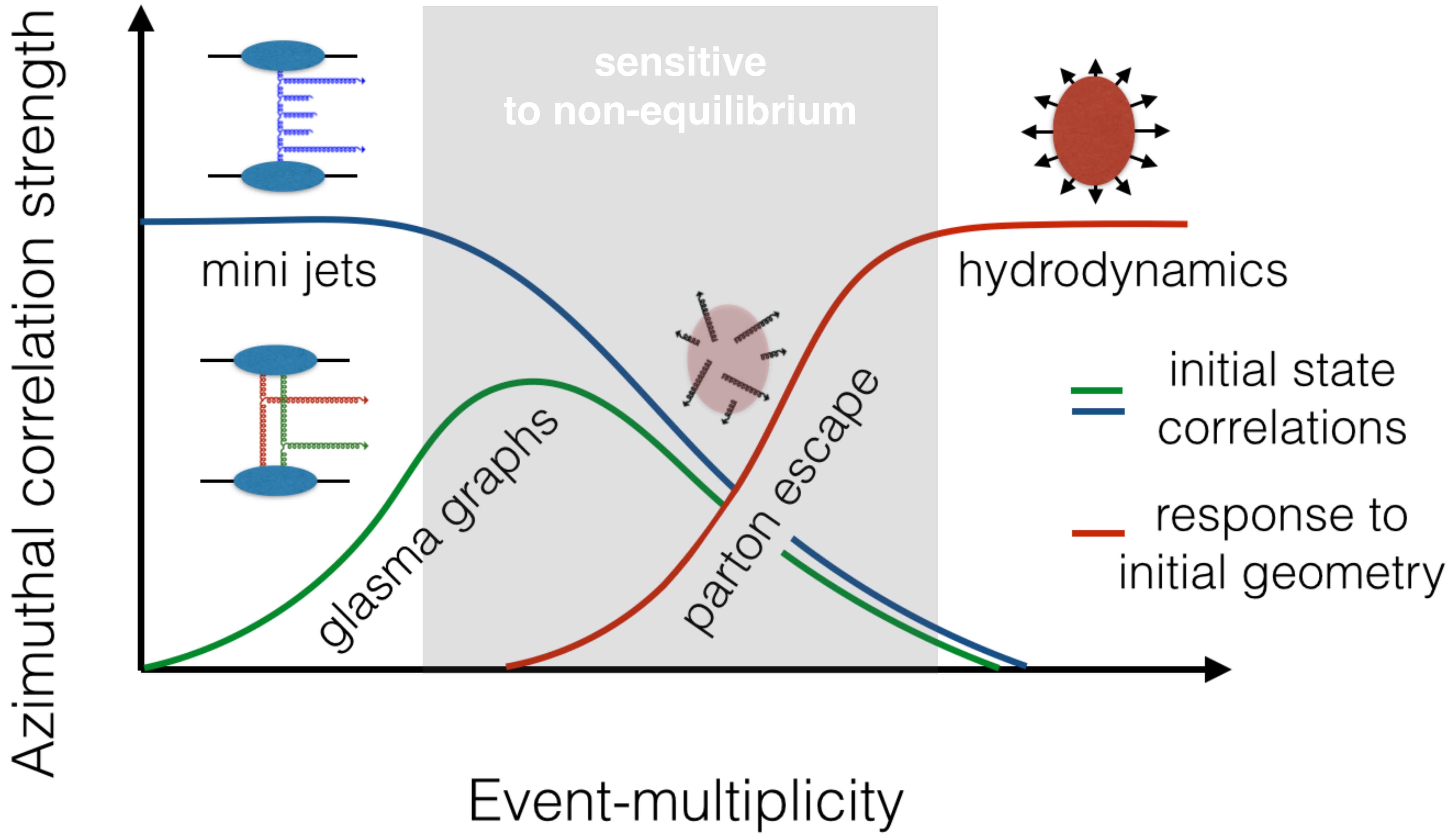
mini-jets escape

high multiplicity events



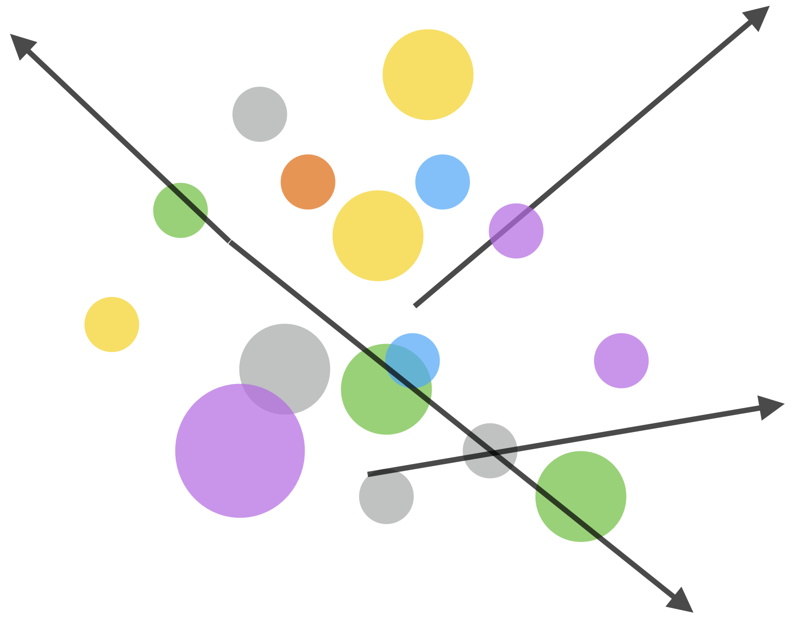
mini-jets quenched

Schlichting's Phase Diagram of Correlation



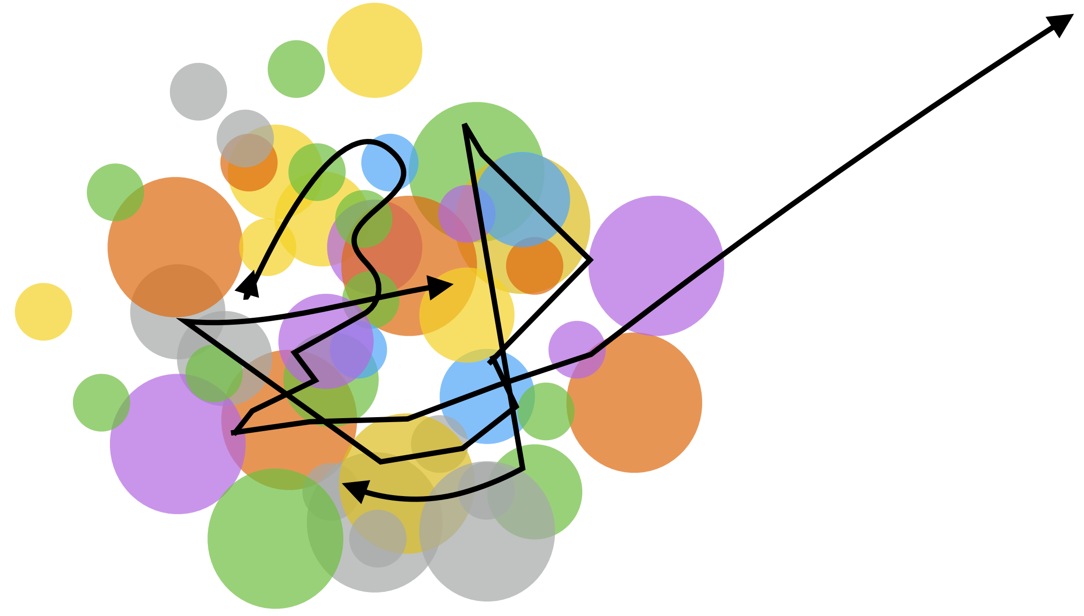
When does the final state take over ?

low multiplicity events



mini-jets escape

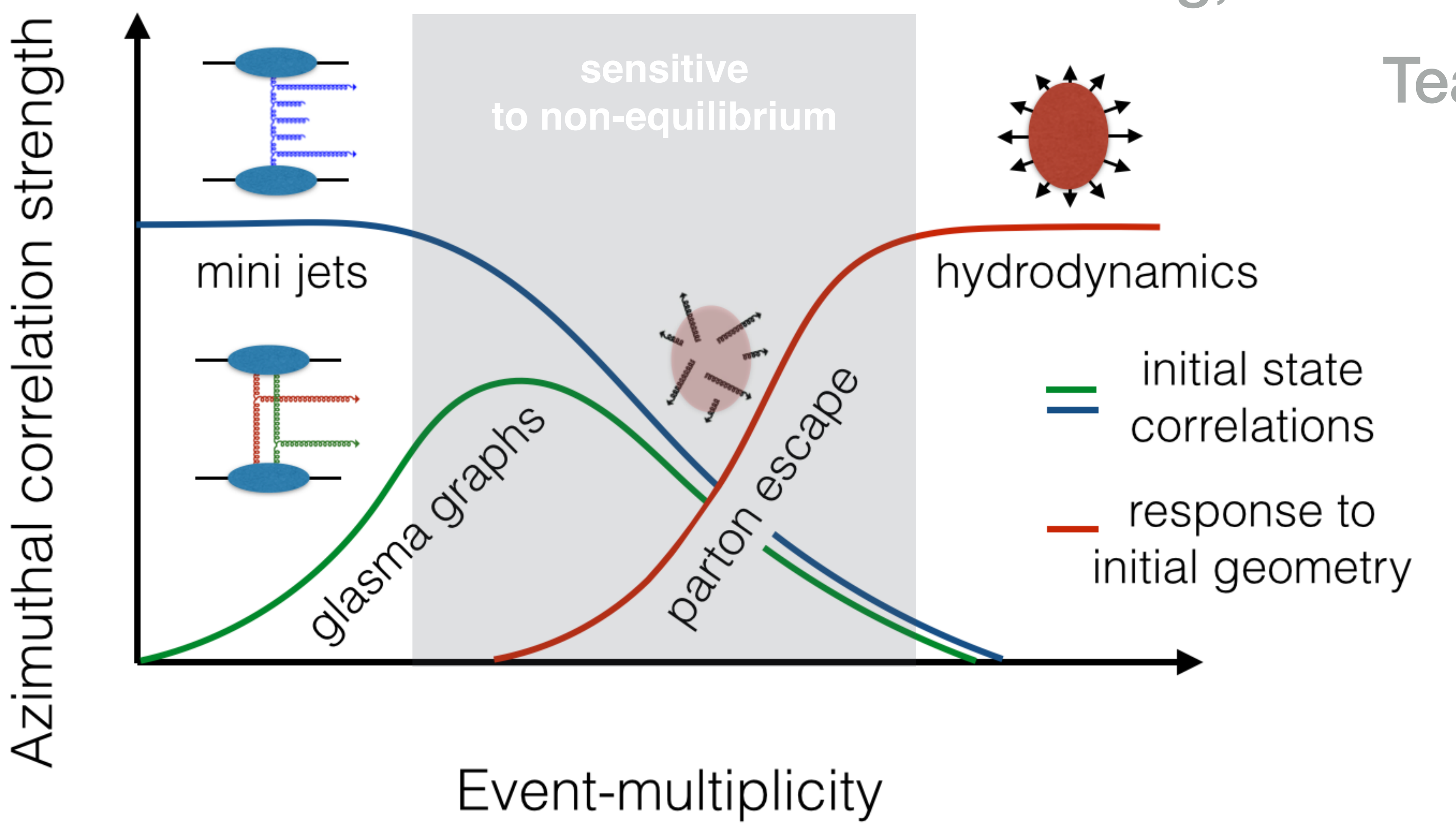
high multiplicity events



mini-jets quenched

Schlichting, PT under preparation

Teaney IS'2016



Kurkela, Zhu 1506.06647

$$Q_s\tau_{eq} \simeq 10(\eta/s)^{4/3}_{T_{eq}}(g^2N_c)^{1/3} \simeq 10$$

Number density $dN/dy \;\simeq\; \xi Q_s^2 \pi R^2$

$$\frac{\tau_{eq}}{R} \simeq \sqrt{\frac{100}{dN/dy}}$$

dN/dy~ 100

Equilibration time ~ system size

Summary

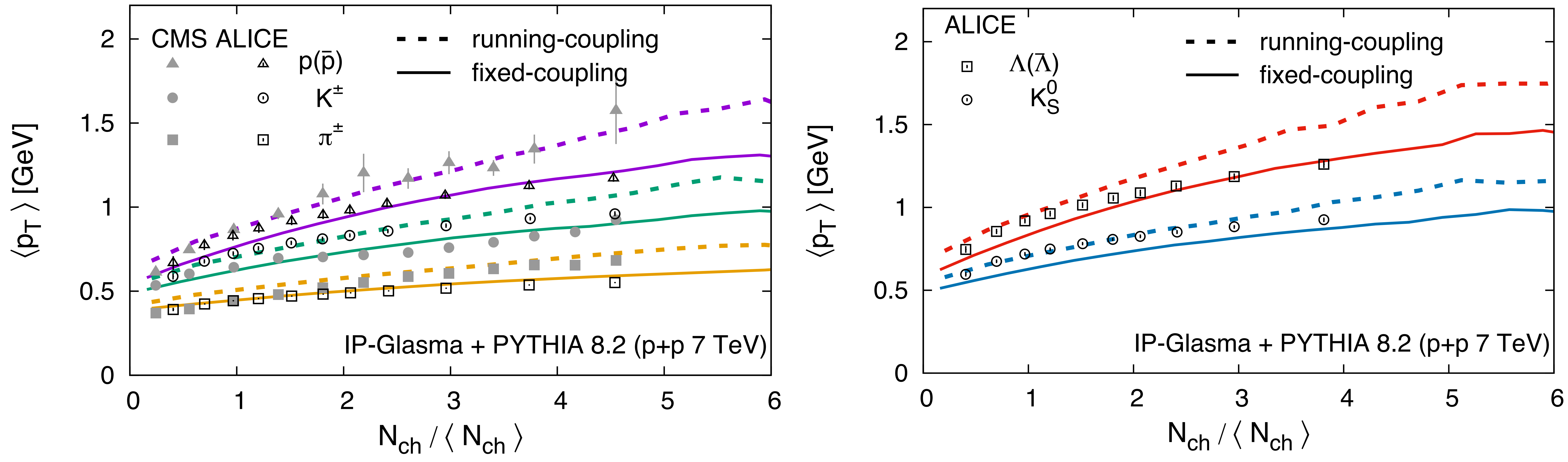
Understanding Initial state from a first principle approach is essential

Data in small systems provide unique opportunities and challenges

Understanding of isotropization will improve complete modeling of HICs

Backup

Mass ordering of average transverse momentum



Effect of running coupling —> increase in $\langle p_T \rangle$

A list of models of initial conditions

Kharzeev, Levin, Nardi, hep-ph/0111315, Drescher, Nara 0707.0249

KLN model, f-KLN, MC-KLN:

$k_\perp$-factorization (dilute-dense approximation) with UGDs dependent on N_{part} $\quad Q_S^2(x_\perp) \propto N_{part}(x_\perp)$

Albacete, Dumitru 1011.5161

MC-rcBK: Monte-Carlo implementation of $k_\perp$-factorization with rc-BK UGDs constrained by HERA-data.

Schenke, PT, Venugopalan 1202.6646

IP-Glasma : IP-Sat initial condition (constrained by HERA data) and solutions of Classical Yang-Mill equations.