Initial state/stages and how to differentiate between different models

In what way does the initial state and stages of a collision imprint itself on the final state observables? And how can we distinguish different models of the stages of evolution in nuclear collisions?

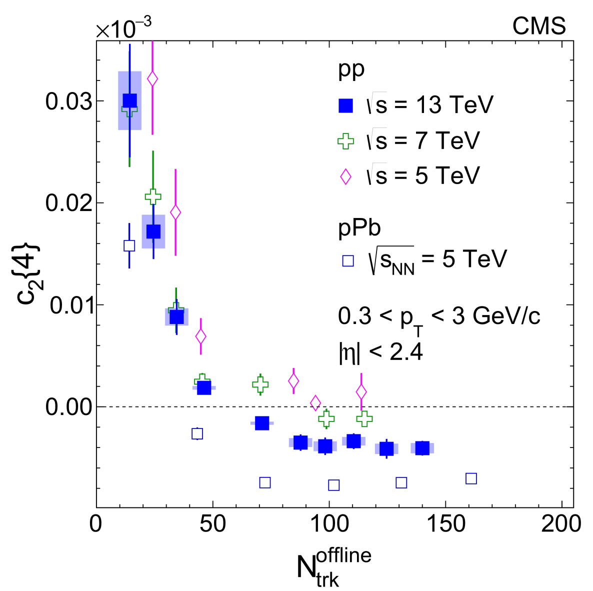
3rd International þing on QCD Challenges from pp to AA

August 23, 2019 — Lund University

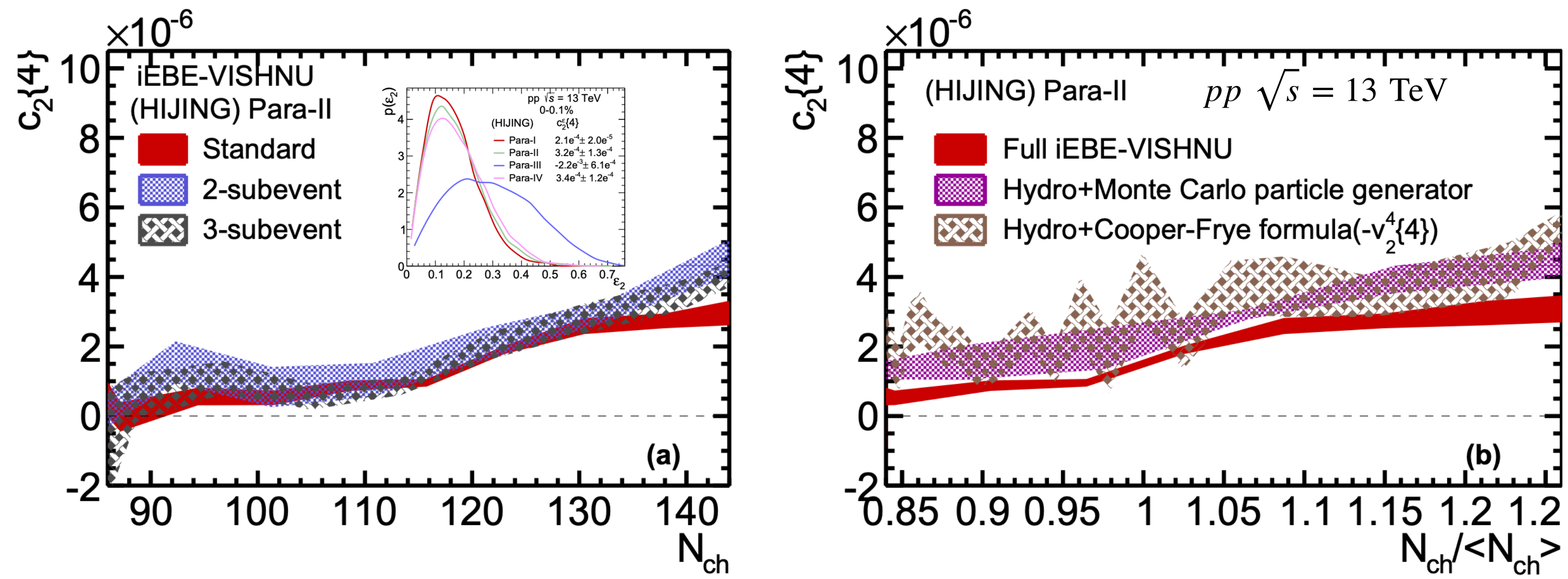
Convenors: Mark Mace, Andreas Morsch
Piotr Bozek, Christian Bierlich, Christopher Plumberg, Christine Rasmussen, Robin Törnkvist

Testing the limits of the hydrodynamic paradigm

Absence of four-particle v_2 in *pp* from hydro



PRL 115 (2015)



Zhao, Zhou, Xu, Deng, Song PLB 780 (2018)

Candidate calculation for hydro/kinetic theory/string shoving/etc:

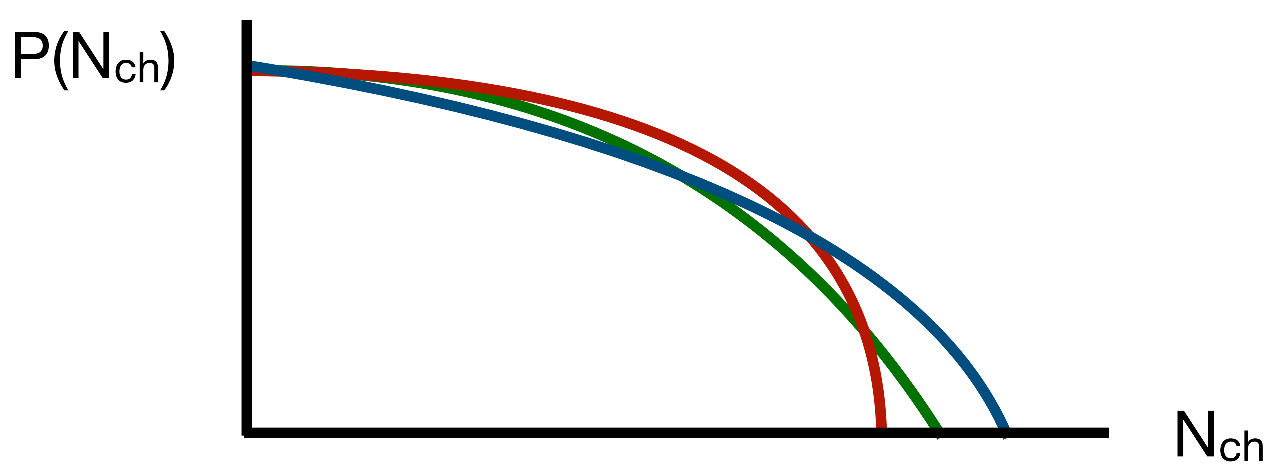
Construct initial condition with $\epsilon_2\{4\} < 0$,

show this can lead to $c_2\{4\} < 0$

What is $c_2\{4\}$ from CGC?

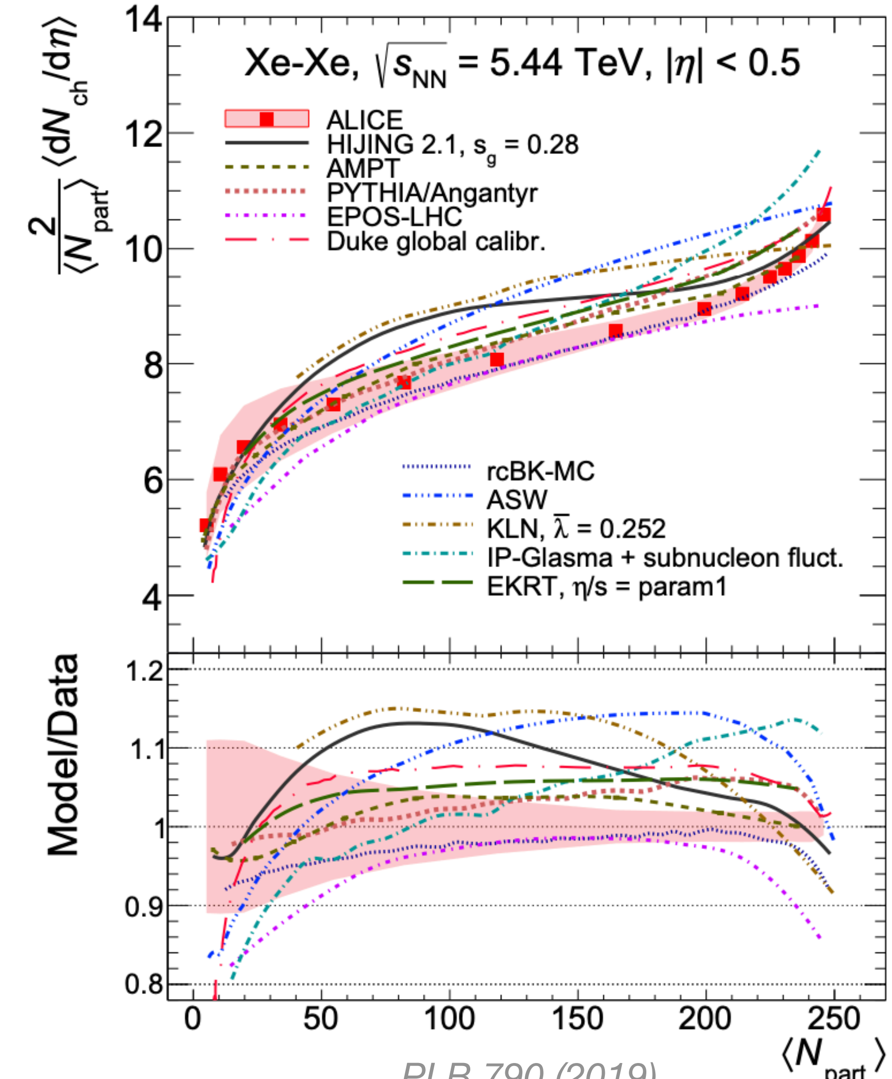
Multiplicity distributions

A request to experimentalists at RHIC and the LHC: Publishing p/^{3}He+Au multiplicity distributions would be very helpful



Slope at 0-5% multiplicity informs about fluctuations about $Q_s, p_{\perp 0}, \dots$

Further study of uptick (1% region) may help disentangle models



PLB 790 (2019)

Multiplicity fluctuations should also be measured/calculated (see poster by A. Morsch)

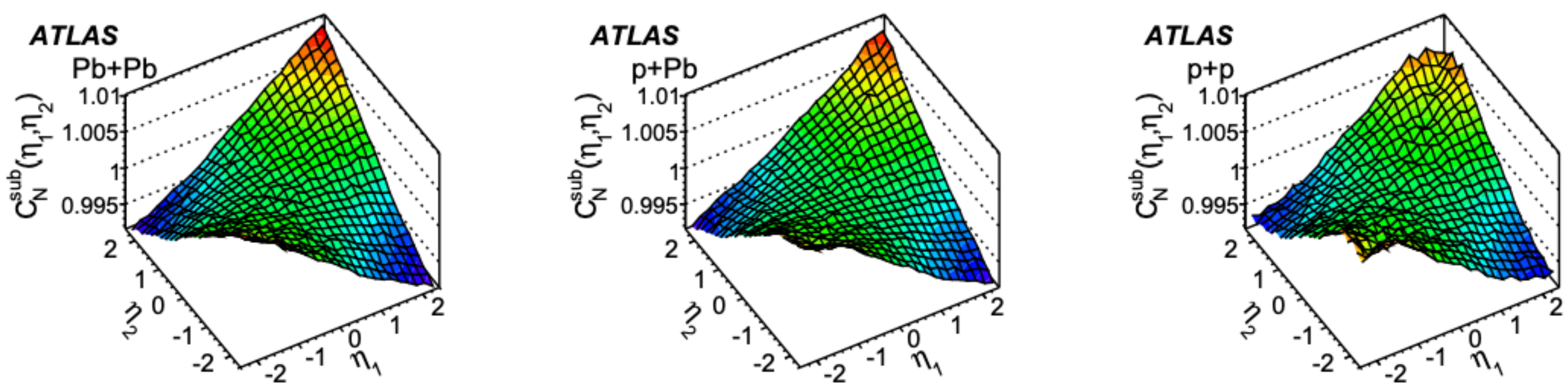
Longitudinal correlations

(Multiplicity/multiplicity, $p_\perp / p_\perp$, …)

Large separation in rapidity is a window into the early time dynamics (by causality)

Necessary to break of boost invariance in initial conditions

E.g.



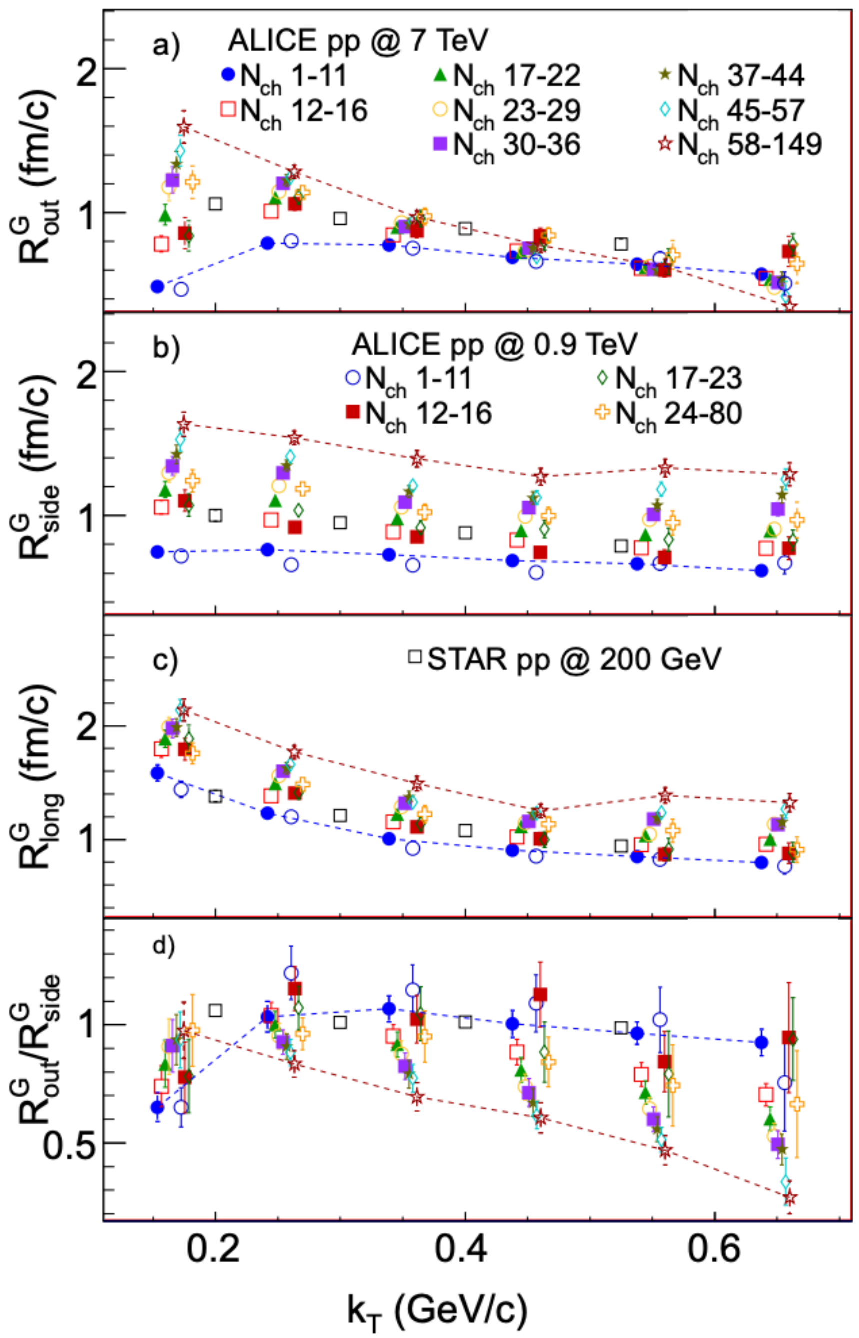
PRC 95 (2017)

Angantyr: get to work

CGC: Further development 3D IP-Glasma needed

Schenke, Schlichting PRC 94 (2016)

HBT radii



ALICE PRD (2011)

k_T-scaling of HBT radii expected from collective hydrodynamic expansion

e.g. Pratt PRL 53 (1984), Heinz, Tomasik, Wiedemann, Wu, Acta Phys. Hung. A 4 249 (1996)

Should also be able to simultaneously reproduce $dN_{ch}/d\eta$

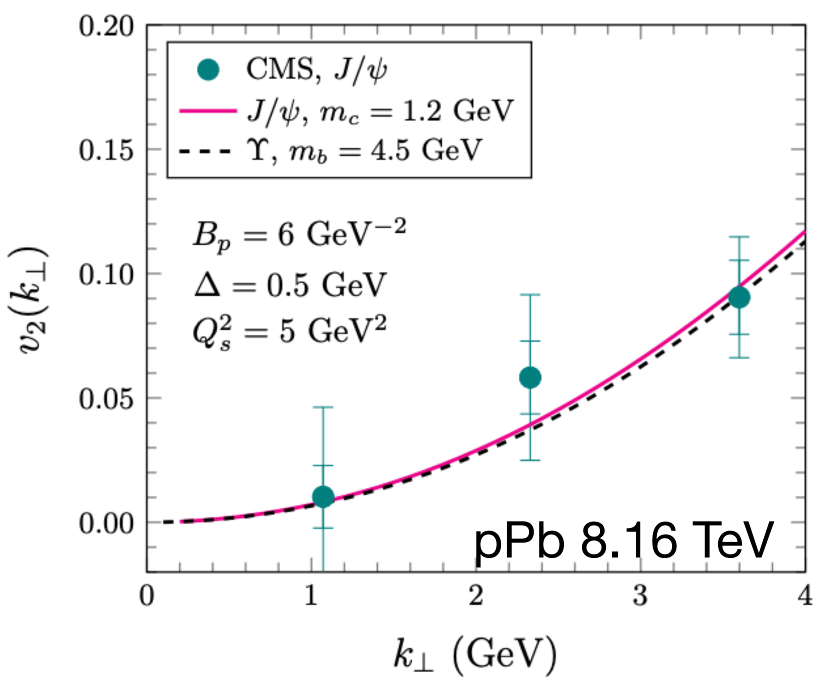
Can k_T scaling of HBT radii observed experimentally be observed in string models?

What about CGC?

Heavy flavor observables

Final state based models seem unable to generate large v_2 for heavy flavor

Quarks/gluon dipole +color evaporation model



Zhang, Marquet, Qin, Shi, Xiao PRL 122 (2019)

Can be seen in CGC-based model

Interesting prediction about Υ, can this be measured?

Would expect that heavy and light flavor v_2 are produced with respect to the same plane — challenge then for CGC to be able to describe light flavor

Thanks for letting us clash!

Posters

Collective flow in collisions with light polarized nuclei

Piotr Bożek[1] and Wojciech Broniowski[1,3]

1) Institute of Nuclear Physics PAN, Krakow, Poland
2) Rzeszow University, Poland
3) Jan Kochanowski University, Kielce, Poland

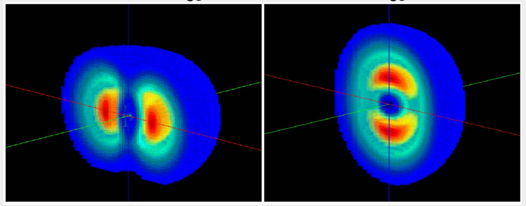
Abstract

We propose to collide light polarized nuclei with a large nucleus. The intrinsic quadrupole deformation of many light nuclei can be controlled using the spin polarization. In such collisions the azimuthal symmetry is broken via polarization of the wave function of the light nucleus, resulting in nonzero one-body elliptic flow coefficient evaluated relative to the polarization axis. Our estimates involve experimentally well known features of light nuclei, such as their quadrupole moment and the charge radius, yielding the one-body elliptic flow coefficient in the range from 1% for the deuteron to 5% for ^{10}B nucleus. Estimates for elliptic flow in collisions of polarized light nuclei with spin $\mathbf{j} \geq \mathbf{1}$ with a heavy nucleus are given.

Quadrupole deformation

Light nuclei with spin $\mathbf{j} \geq \mathbf{1}$ can have a quadrupole deformation. The deuteron in spin states $\mathbf{j_3 = \pm 1}$ or $\mathbf{j_3 = 0}$ has a sizable deformation with respect to the polarization axis (due to the 5% admixture of $^3\mathbf{D_1}$ wave).

$\mathbf{j_3 = 0}$ $\qquad$ $\mathbf{j_3 = \pm 1}$



Deuteron densities in two spin states.
(M. Garcon, J. W. Van Orden, Adv. Nucl. Phys. 26 (2001) 293)

Using the deuteron wave function

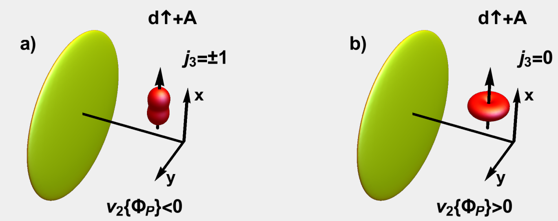
$$
\begin{aligned}
&|\Psi(r;1)\rangle = U(r)|00\rangle|11\rangle \\
&+V(r)\left[\sqrt{\tfrac{3}{5}}|22\rangle|1\ -1\rangle - \sqrt{\tfrac{3}{10}}|21\rangle|10\rangle + \sqrt{\tfrac{1}{10}}|20\rangle|11\rangle\right], \\
&|\Psi(r;0)\rangle = U(r)|00\rangle|10\rangle \\
&+V(r)\left[\sqrt{\tfrac{3}{10}}|21\rangle|1\ -1\rangle - \sqrt{\tfrac{2}{5}}|20\rangle|10\rangle + \sqrt{\tfrac{3}{10}}|2\ -1\rangle|11\rangle\right].
\end{aligned}
$$

The densities are

$$
\begin{aligned}
&|\Psi(r,\theta,\phi;\pm 1)|^2 = \frac{1}{16\pi}\left[4U(r)^2 - \right. \\
&\left. 2\sqrt{2}\left(1-3\cos^2(\theta)\right)U(r)V(r) + \left(5-3\cos^2(\theta)\right)V(r)^2\right], \\
&|\Psi(r,\theta,\phi;0)|^2 = \frac{1}{8\pi}\left[2U(r)^2 + \right. \\
&\left. 2\sqrt{2}\left(1-3\cos^2(\theta)\right)U(r)V(r) + \left(1+3\cos^2(\theta)\right)V(r)^2\right],
\end{aligned}
$$

The mixed term $\mathbf{U(r)V(r)}$ yields a significant deformation of the densities

$$\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} \simeq 0.1 \qquad \epsilon_2^{|\Psi|^2_{j_3=\pm1}}\{\Phi_P\} \simeq -0.05$$



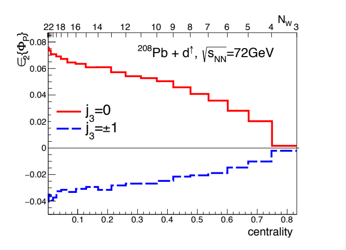
Schematic view of the collision of a polarized deuteron with a large nucleus.

References

[1] P. Bożek, W. Broniowski, Phys. Rev. Lett. 121 (2018) 202301.
[2] W. Broniowski, P. Bożek , arXiv: 1906.09045.

Glauber model and hydrodynamic response

In a collisions with a polarized light nucleus participant nucleons from the large nucleus also contribute to the fireball. The fireball has an elliptic deformation with respect to the polarization axis. The ellipticity is reduced due to the wash-out of the shape (of the order of the average N-N wounding distance).



Ellipticities for LHC experiements on a fixed *polarized* deuteron target

Estimates from the Glauber model give

$$\epsilon_2^{|\Psi|^2_{j_3=0}}\{\Phi_P\} \simeq 0.06 \qquad \epsilon_2^{|\Psi|^2_{j_3=\pm1}}\{\Phi_P\} \simeq -0.03$$

in central collisions. The initial deformation is transformed to the final elliptic flow via the hydrodynamic response $\mathbf{v_2 \simeq k\epsilon_2}$, with $\mathbf{k \simeq 0.2}$. The final observed elliptic flow respect to the polarization axis is $\mathbf{v_2\{\Phi_P\} \simeq k\epsilon_2\{\Phi_P\}P_{zz}}$. For experimentally accessible target polarizations $\mathbf{-1.5 \leq P_{zz} \leq 0.7\%}$ the observed azimuthal asymmetry in the particle emission with respect to the polarization axis is about 1%. This effect is easy to measure as it is a property of the one-particle distribution not a two-particle correlation as in standard collective flow measurements.

Other light nuclei

The same idea can be applied to other small nuclei with quadrupole deformation. The size of the effect can be estimated from nuclear properties (quadrupole deformation $\mathbf{Q_2}$ and charge radius $\langle \mathbf{r^2} \rangle$), without explicit knowledge of the wave function. The estimated ellipticities $\epsilon_2\{\Phi_P\} \simeq -\frac{3Q_2}{4Z\langle r^2\rangle}$ are

	j	j_3	$\langle r^2\rangle^{1/2}_{\rm ch}$ [fm]	Q_2 [fm^2]	$-\frac{3Q_2}{4Z\langle r^2\rangle}$ [%]
d	**1**	$\pm$**1**	2.1421(88)	0.2860(15)	**−5.6**
		0		×**(−2)**	×**(−2)**
^{7}Li	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.444(42)	**−4.03(4)**	**19**
		$\pm\frac{1}{2}$		×**(−1)**	×**(−1)**
^{9}Be	$\frac{3}{2}$	$\pm\frac{3}{2}$	2.519(12)	**5.29(4)**	**−17**
		$\pm\frac{1}{2}$		×**(−1)**	×**(−1)**
^{10}B	$\pm$**3**	$\pm$**3**	2.428(50)	**8.47(6)**	**−25**
		$\pm$**2**		×**0**	0
		$\pm$**1**		×**(−3/5)**	×**(−3/5)**
		0		×**(−4/5)**	×**(−4/5)**

The final estimate for the elliptic flow in differently spin states is

$$v_2\{\Phi_P\} \simeq -k\frac{3Q_2}{4Z(\langle r^2\rangle + \frac{3}{2}\langle b^2\rangle)}\frac{3j_3^2 - j(j+1)}{j(2j-1)}$$

($\mathbf{b}$ is the N-N wounding distance in the Glauber model). The predicted signal is stronger for nuclei with larger quadrupole deformation. The model predicts a specific dependence on the spin state (Wigner-Eckart theorem).

Conclusions

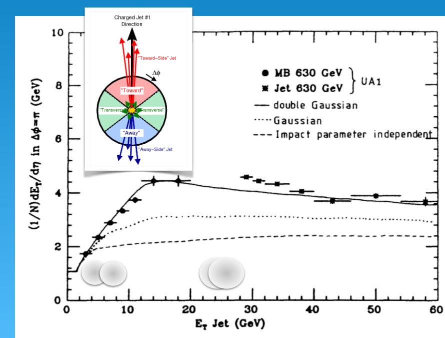
A new experimental signature of collectivity in small systems is proposed. In collisions with light polarized nuclei the deformation of the fireball with respect to a fixed axis can be controlled. In the presence of collective flow particle emission is azimuthally asymmetric. This observable is not sensitive to non-flow correlations. (Project supported by the Polish National Science Centre grant 2018/29/B/ST2/00244)

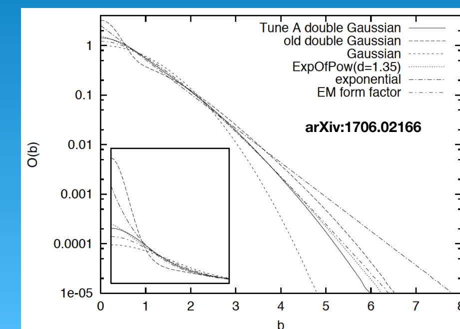
Constraints on Matter Distribution Inside the Proton

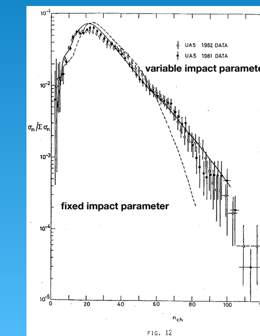
Andreas Morsch, CERN

Proton radial matter profile and pp overlap essential to describe Jet-Pedestal effect …

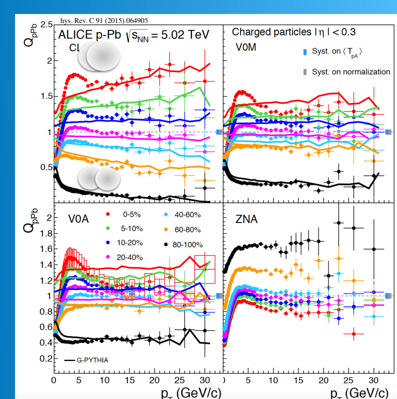
… and multiplicity distributions



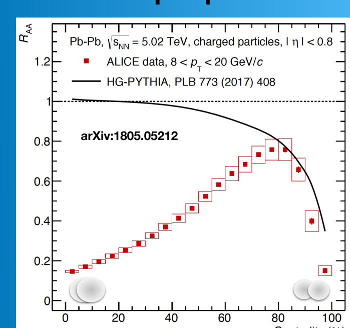




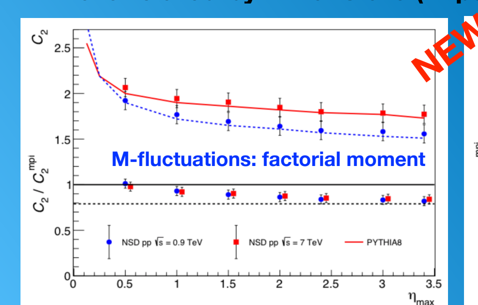
Works surprisingly well also for p-Pb soft-hard correlations …

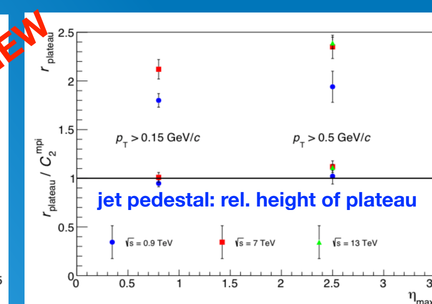


and even for peripheral Pb-Pb …



Multiplicity fluctuations and the height of the jet pedestal are related by initial state (impact parameter) fluctuations





Number of MPI in presence of a trigger particle:

$$\mathcal{P}(N_{\rm mpi}|Y) = \frac{(1-(1-\alpha)^{N_{\rm mpi}})\mathcal{P}_{\rm mpi}(N_{\rm mpi})}{1-\langle(1-\alpha)^{N_{\rm mpi}}\rangle}$$

Height of the jet pedestal:

$$\langle N_{\rm mpi}\rangle_{\rm plateau} = \frac{\langle N^2_{\rm mpi}\rangle}{\langle N_{\rm mpi}\rangle}$$

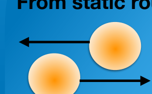
Relative height:

$$r^{\rm mpi}_{\rm plateau} = \frac{\langle N_{\rm mpi}\rangle_{\rm plateau}}{\langle N_{\rm mpi}\rangle} = \frac{\langle N^2_{\rm mpi}\rangle}{\langle N_{\rm mpi}\rangle^2} = C_2^{\rm mpi}$$

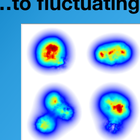
For small α (rare probe):

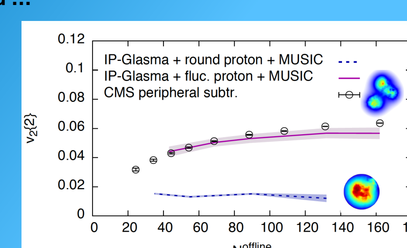
$$\mathcal{P}(N_{\rm mpi}|Y) = \frac{N_{\rm mpi}}{\langle N_{\rm mpi}\rangle}\mathcal{P}_{\rm mpi}(N_{\rm mpi})$$

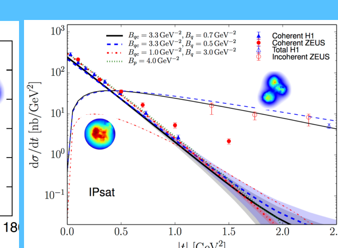
From static round …

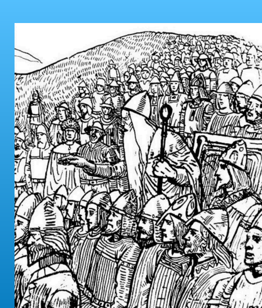


…to fluctuating









- **Are models including spatial fluctuations consistent with measured**
  - **soft hard correlations?**
  - **multiplicity fluctuations?**
- **Can these measurements provide additional constraints?**
- **How would Pythia pp overlap plus spatial fluctuations perform ?**

Dipole evolution and the proton structure

Christian Bierlich[1,2], Christine O. Rasmussen[1]

[1]Lund University, [2]University of Copenhagen. Based on `arXiv:1907.12871 [hep-ph]`

At a glance

Space-time structure of MPIs which:

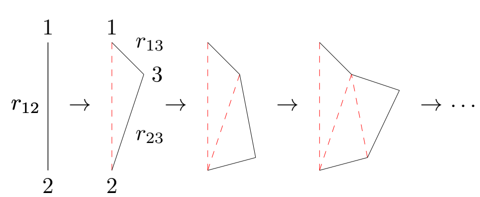
- Predicts eccentricities and normalized symmetric cumulants.
- Is not fitted to flow measurements.
- Is theoretically well motivated.

Dipole evolution

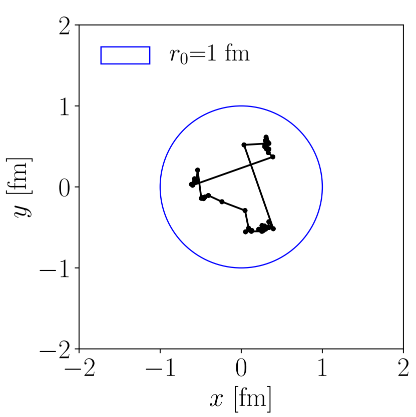
The proton sub-structure is calculated using the Mueller dipole model for QCD. A proton is approximated by three dipoles, evolved in rapidity according to:

$$\frac{\mathrm{d}\mathcal{P}}{\mathrm{d}y\ \mathrm{d}^2\vec{r}_3} = \frac{N_c \alpha_s}{2\pi^2} \frac{r_{12}^2}{r_{13}^2 r_{23}^2} \Delta(y_{\min}, y),$$

where r_{ij} denotes transverse sizes as in the sketch, and Δ is a Sudakov form factor.

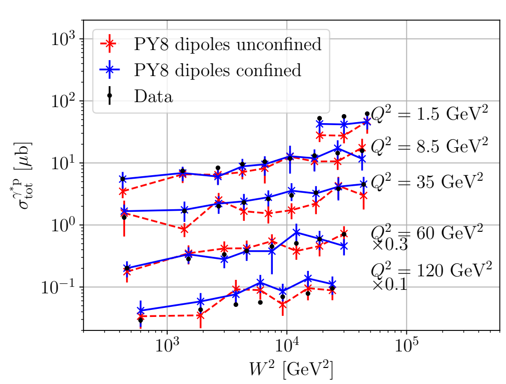


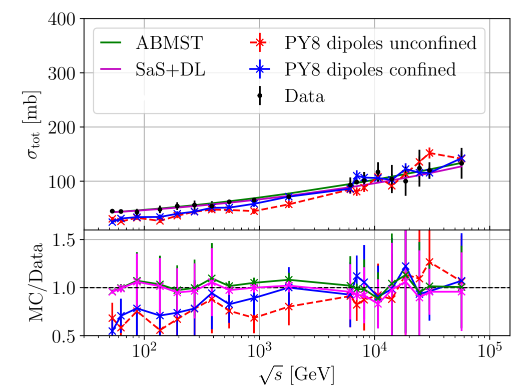
The result is a proton Fock state.



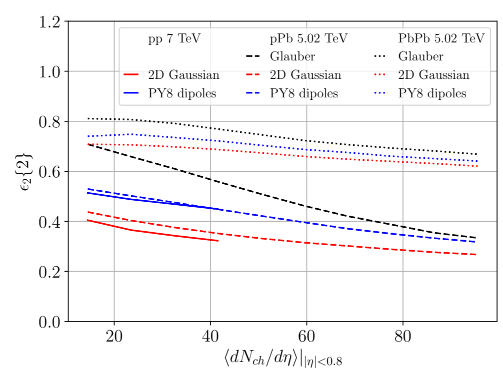
Results

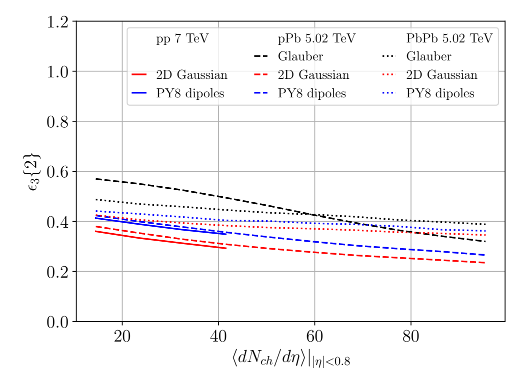
All model parameters are tuned to e**p and pp cross sections**.



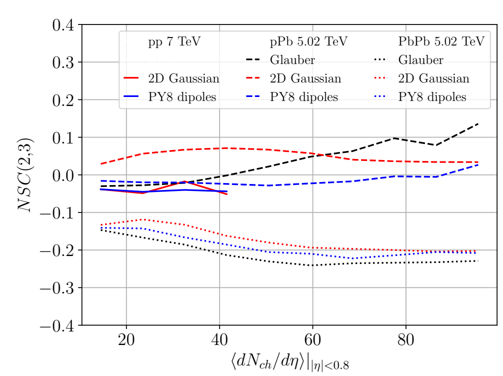


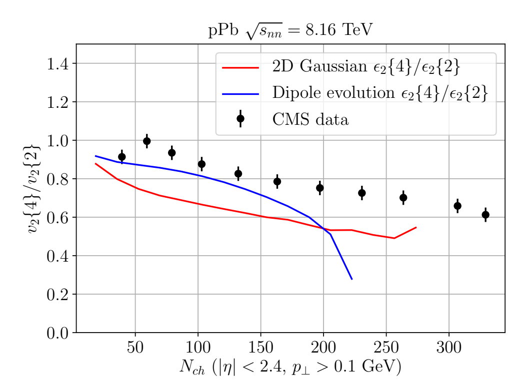
Flow coefficients $v_{2,3} \propto \epsilon_{2,3}$ (eccentricities) in a fluid scenario. Peripheral/small systems differentiates between models. Dipole model predicts $\epsilon_{2,3}$ equal for pp and pPb.





Normalized symmetric cumulants and **flow fluctuations** can inform directly about geometry. Best discriminative power in pPb collisions.



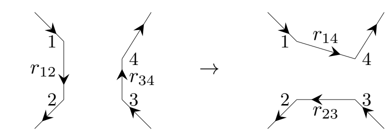


Matching to MPIs

Pythia MPIs are given a vertex position in transverse space. Either randomly from a 2D-Gaussian, inspired by the proton mass distribution, or according to the dipole evolution. The interaction probability of projectile-target dipole pairs is given at LO by:

$$f_{ij} = \frac{\alpha_s^2}{2} \log^2 \left| \frac{r_{13} r_{24}}{r_{14} r_{24}} \right|.$$

where r_{ij} are distances between dipole ends.



MPIs are placed on dipole interaction vertices with the hardest MPI linked to the most probable interaction.

Contact

`christian.bierlich@thep.lu.se`
`christine.rasmussen@thep.lu.se`

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Particle Interferometry from pp to AA

Christopher Plumberg

Dept. of Theoretical Physics and Astronomy, Lund University

Lund University

Overview and Motivation

A central goal of the heavy-ion program is to create and study the quark-gluon plasma (QGP). The QGP should behave like a strongly coupled fluid of deconfined color charges, so it is normally identified by looking for fluid-like signatures. Such signatures include collective motion (defined by strong correlations between position-space and momentum-space) and jet-quenching (implying directional suppression high-p_T partons).

Intriguingly, some (but not all) of these same signatures have been observed in small collision systems (e.g., p+p vs. Pb+Pb) which were traditionally thought to be too small to permit the formation of QGP. A wide variety of models, including "initial-state models" (e.g., color-glass condensate [CGC] physics [1]), event generators (e.g., Pythia/Angantyr [2]), and "final-state models" (e.g., hydrodynamics [3]) have been proposed to explain these features. The challenge is to understand how one can discriminate experimentally between different competing models.

The proposal of this work is that particle interferometry — also known as Hanbury Brown-Twiss (HBT) interferometry — is ideally suited to this task. Moreover, I argue that hydrodynamics, in addition to explaining more conventional QGP-signatures such as anisotropic flow $v_n(p_T)$, also models correctly the space-time evolution of nuclear collisions, such as is probed by interferometric observables. This implies that HBT interferometry could provide information which is useful in distinguishing between the different approaches to modeling nuclear collisions.

Building Blocks of Interferometry

Particle production in nuclear collisions can be characterized by an emission density $S(x,K)$, which gives the probability to emit a particle from a point x^μ with four-momentum K^μ. In terms of $S(x,K)$, the HBT radii may be computed by

$$R^2_{ij}(\vec{K}) \equiv \left\langle (\tilde{x}_i - \beta_i \tilde{t})(\tilde{x}_j - \beta_j \tilde{t}) \right\rangle_S$$

where the "source average" is

$$\langle f(x) \rangle_S \equiv \frac{\int d^4x\, f(x) S(x,K)}{\int d^4x\, S(x,K)}$$

and

$$\tilde{x}_i \equiv x_i - \langle x_i \rangle_S \,,\; \tilde{t} \equiv t - \langle t \rangle_S \,,\; \vec{\beta} \equiv \vec{K}/K^0$$

In this way, HBT radii probe spatio-temporal properties of the particle production process in nuclear collisions.

From pp to AA in hydrodynamics

Consider three separate collision systems — Pb+Pb, p+Pb, and p+p — at fixed $\sqrt{s_{NN}} = 5.02$ TeV and $dN^{\mathrm{ch}}/d\eta = 100$, as modeled by hydrodynamics [3]. What does the space-time evolution look like in these cases?

We find:

✓ Similar freeze-out volumes $\Longrightarrow$ similar multiplicities

✓ Strong time-position correlations in smaller systems $\Longrightarrow$ stronger collective flow!

✓ Very different space-time volumes

These effects should be visible in the HBT radii.

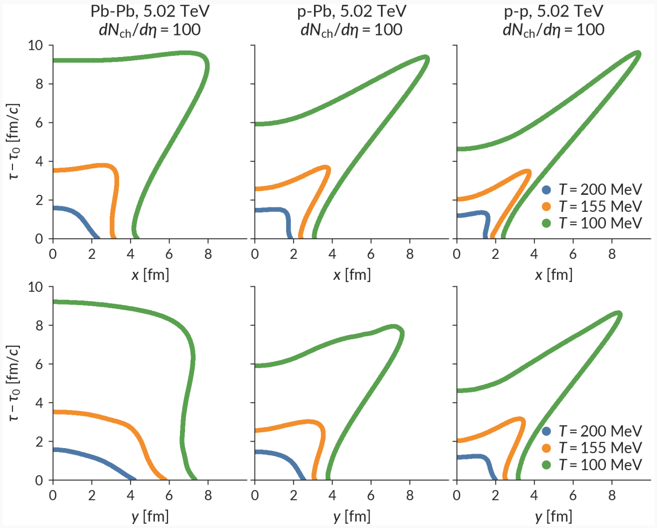


Fig. 1: Isotherms in Pb+Pb, p+Pb, and p+p collisions at fixed $dN^{\mathrm{ch}}/d\eta = 100$. Taken from Ref. [4] with permission.

Interferometry and Model Studies

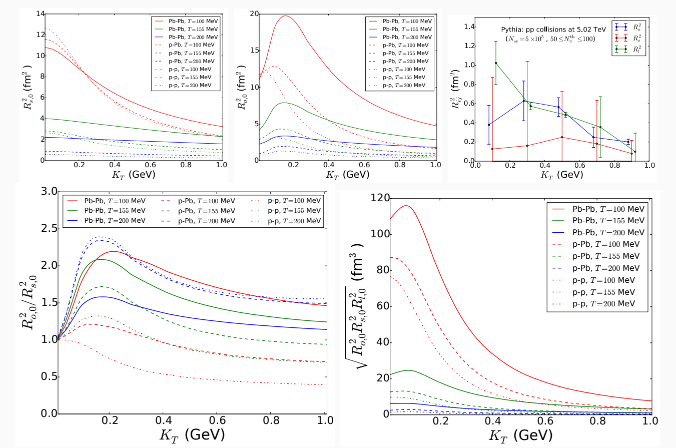


Fig. 2: The top row shows K_T-dependence of side (left) and out (center) radii in p+p, p+Pb, and Pb+Pb collisions, on the isotherms contained in Fig. 1.
The righthand plot in the top row shows for comparison the three radii R^2_o, R^2_s, and R^2_l obtained using the new space-time picture of hadronization available in Pythia [2], without any collective effects [5]. Although the latter shows large uncertainties (especially in R^2_s), we find that pp collisions tend to have $R^2_o/R^2_s < 1$ and $R^2_s \sim$ const., both of which are consistent with an absence of collective motion. This is likely to change once collective effects are included.
The bottom row shows the corresponding ratio R^2_o/R^2_s (left) and the volume of the freeze-out surface (right) from hydrodynamics. Only thermal pions have been used. The effects of strong collective flow (K_T-scaling of transverse $R^2_{ij} \sim K_T^{-1}$ and $R^2_o/R^2_s < 1$) and very different freeze-out volumes (factors of 2-3 between p+p and Pb+Pb) are apparent.

Discussion

This discussion allows us to formulate some focused questions for better constraining the various modeling approaches of nuclear collisions using HBT.

- How well do CGC-based models and event generators exhibit K_T-scaling in the transverse HBT radii?
- Which models best describe the $dN^{\mathrm{ch}}/d\eta$-dependence of the HBT radii and volume? In particular, how should we understand the weaker dependence in p+p as compared with A+A (cf. [6])?
- Which model yields a space-time picture which allows to understand the non-observation of jet quenching in small collision systems [7]?

A comprehensive description of nuclear collisions requires the ability to model both the dynamical (momentum-space) and kinematical (coordinate-space) evolution of these systems. Correctly describing both aspects simultaneously is clearly a difficult task. The interferometric observables discussed here should therefore allow for much-needed, non-trivial tests of the various approaches to modeling collision systems.

References

[1] A. Bzdak, B. Schenke, P. Tribedy and R. Venugopalan, Phys. Rev. C **87**, 064906 (2013)

[2] S. Ferreres-Solé and T. Sjöstrand, Eur. Phys. J. C **78**, 983 (2018)

[3] H. Song and U. W. Heinz, Phys. Rev. C **77**, 064901 (2008)

[4] U. W. Heinz and J. S. Moreland, J. Phys. Conf. Ser. **1271**, 012018 (2019)

[5] C. Bierlich, G. Gustafson and L. Lönnblad, arXiv:1612.05132 [hep-ph].

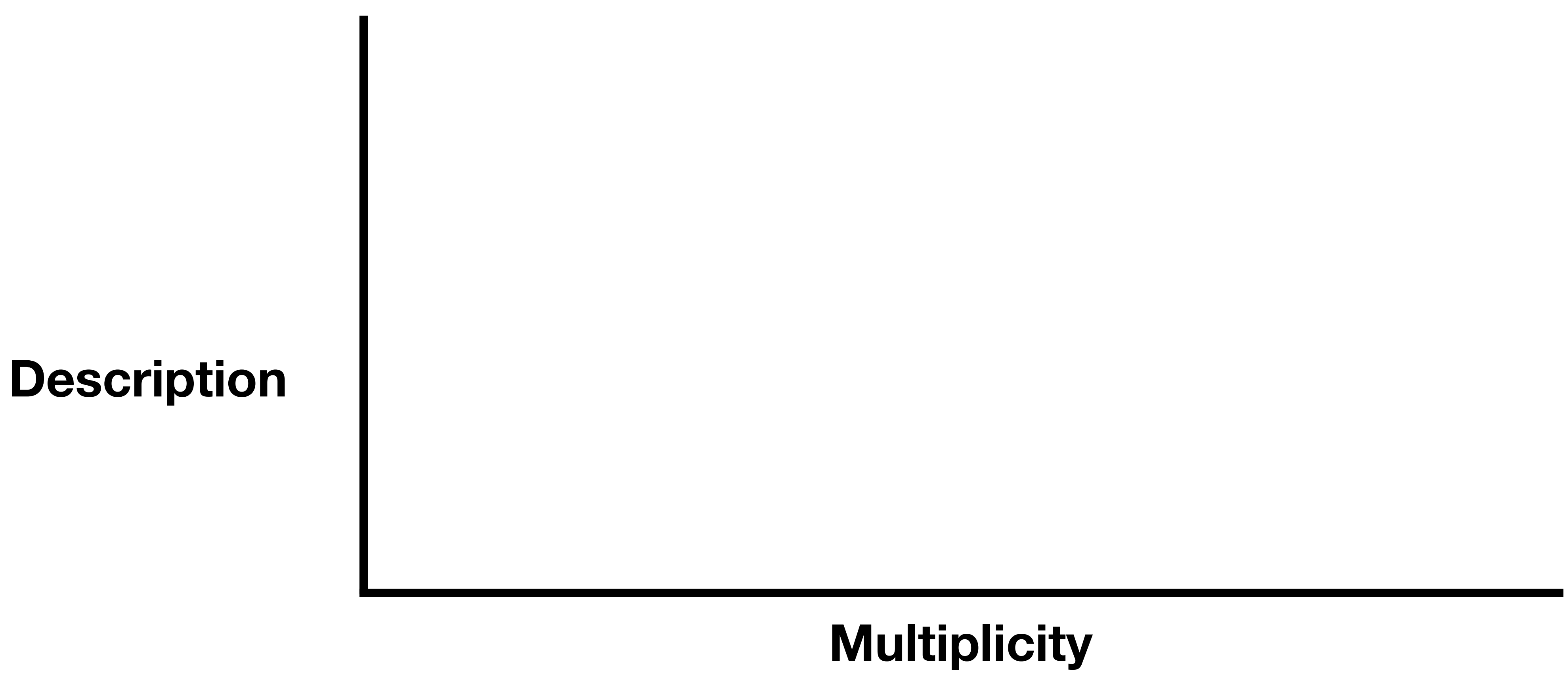
[6] K. Aamodt *et al.* [ALICE Collaboration], Phys. Rev. D **84**, 112004 (2011)

[7] J. L. Nagle and W. A. Zajc, Ann. Rev. Nucl. Part. Sci. **68**, 211 (2018)

Knut and Alice Wallenberg Foundation

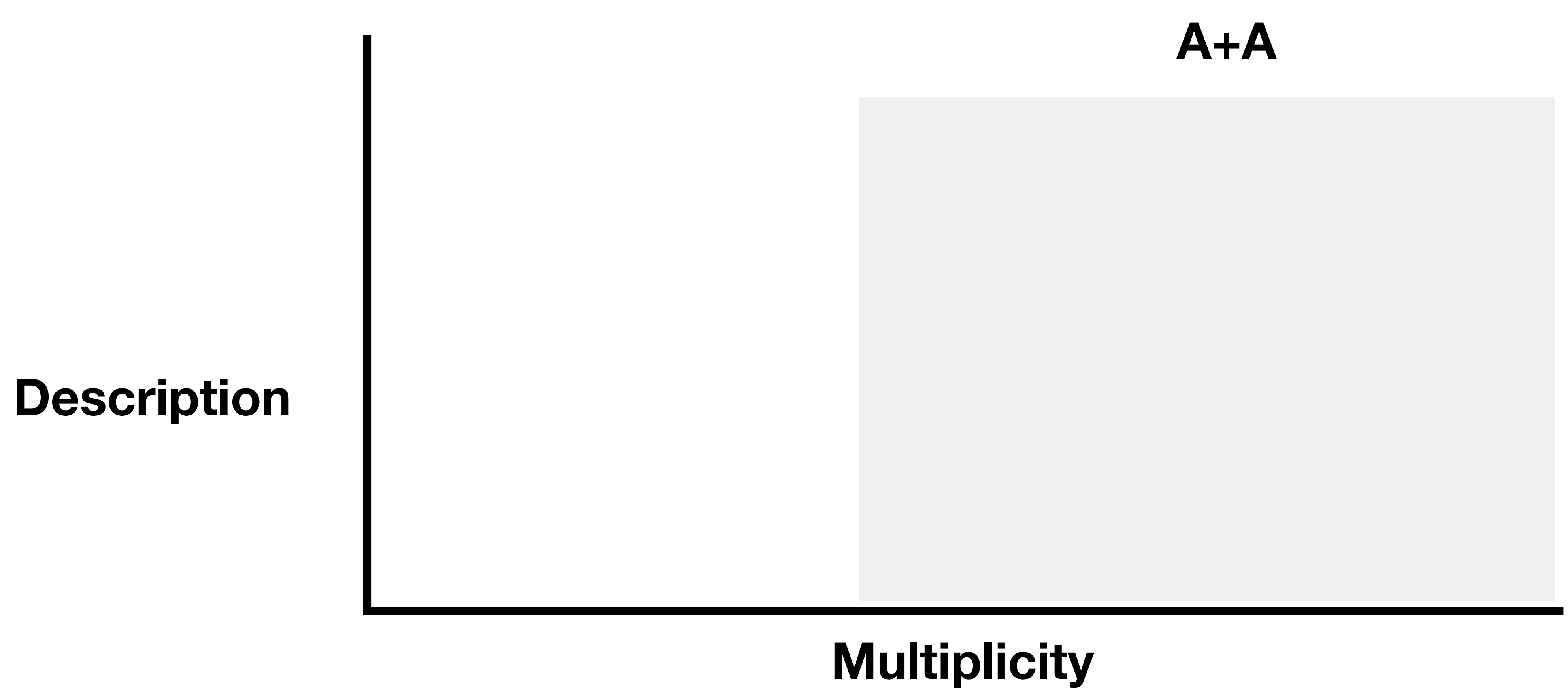
The landscape of calculations

How to understand particle production in high energy collisions



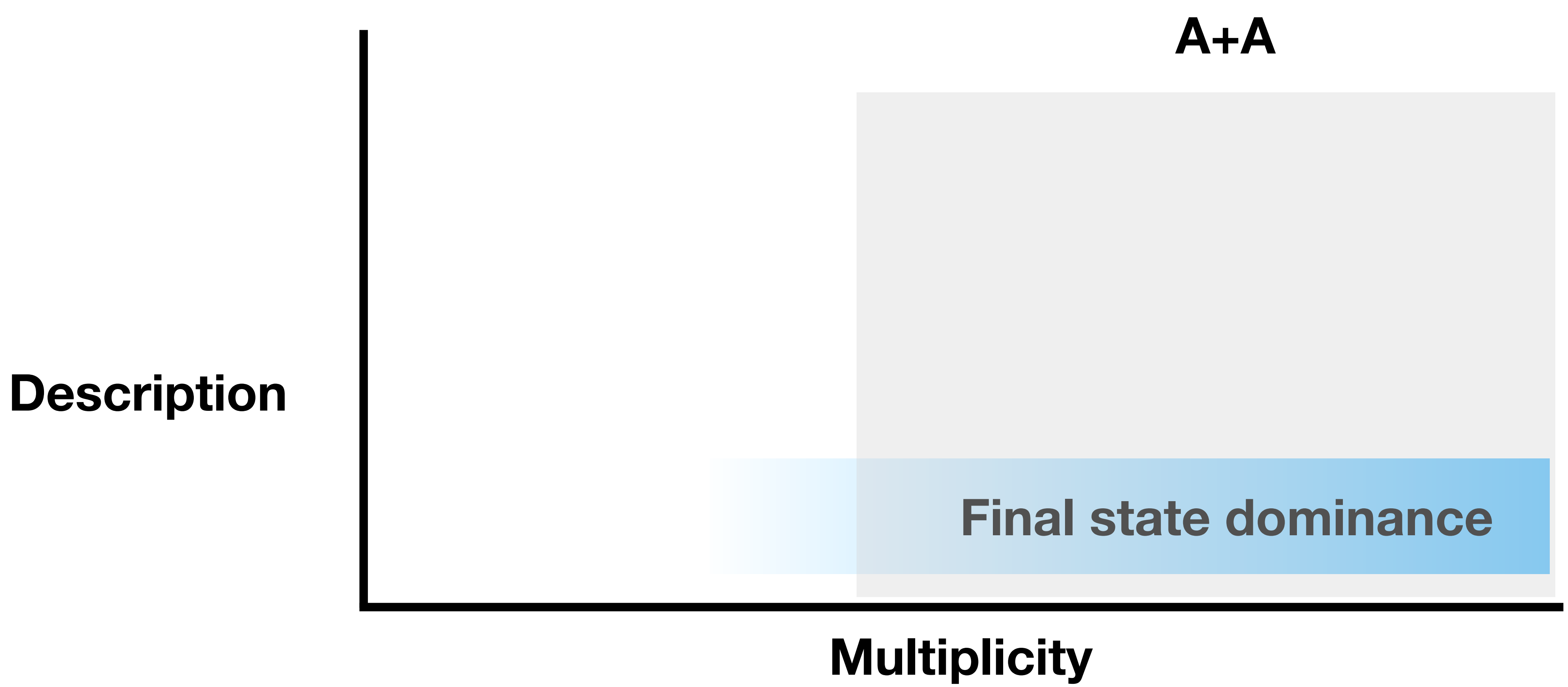
The landscape of calculations

How to understand particle production in high energy collisions



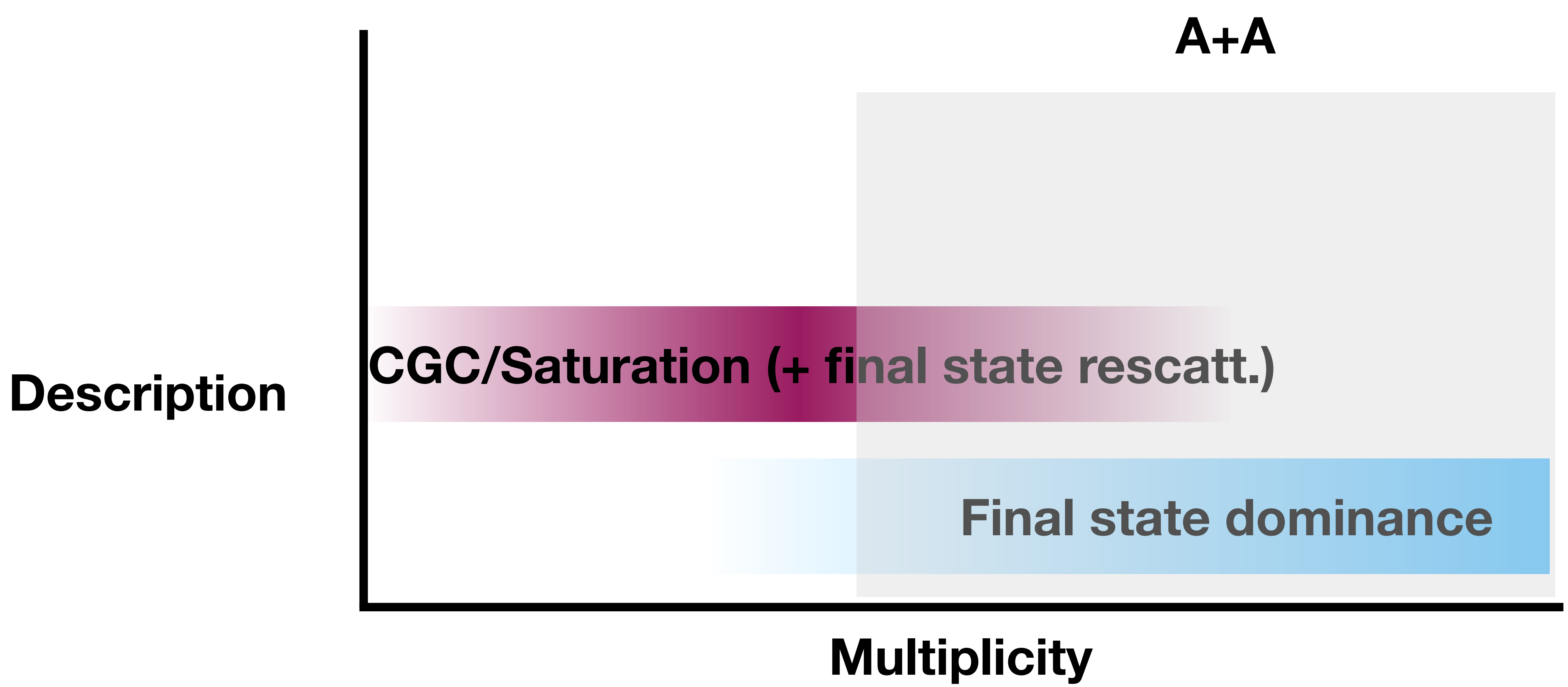
The landscape of calculations

How to understand particle production in high energy collisions



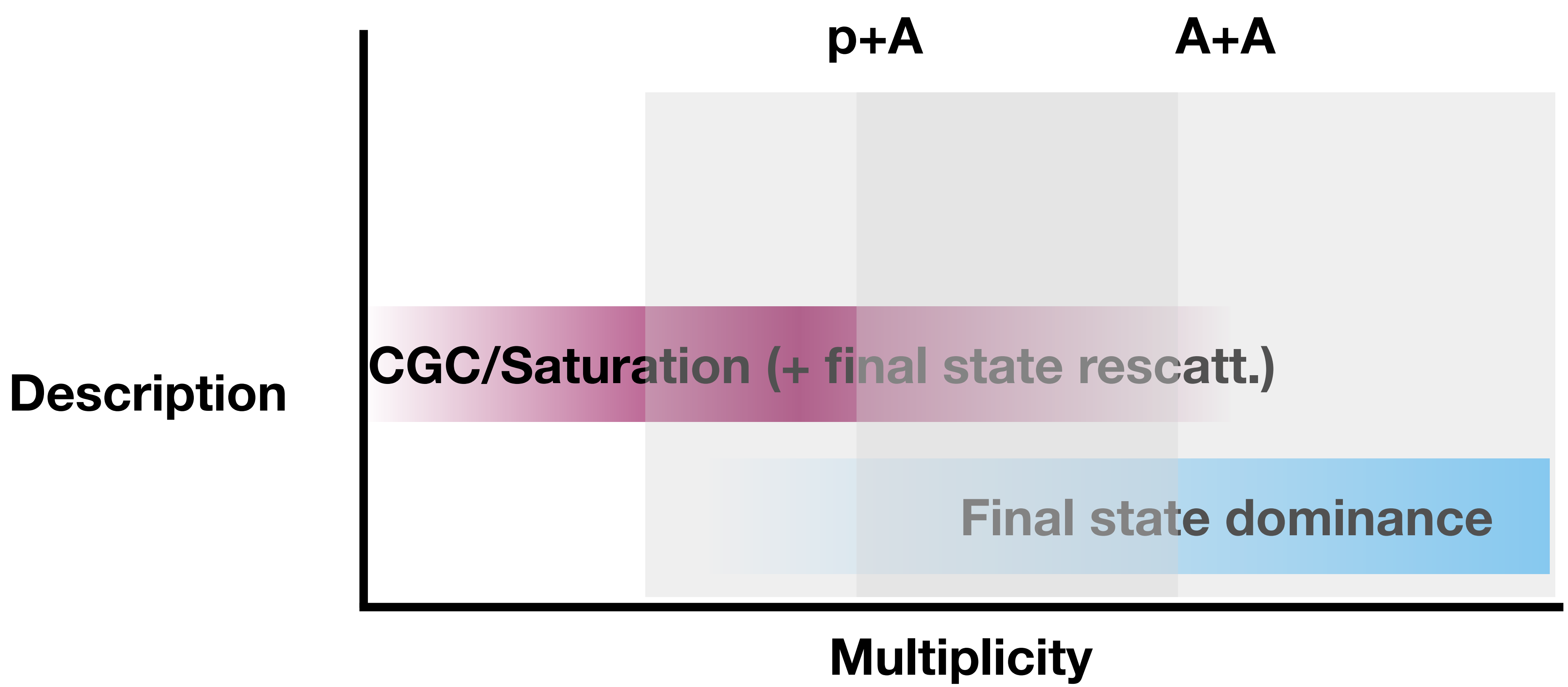
The landscape of calculations

How to understand particle production in high energy collisions



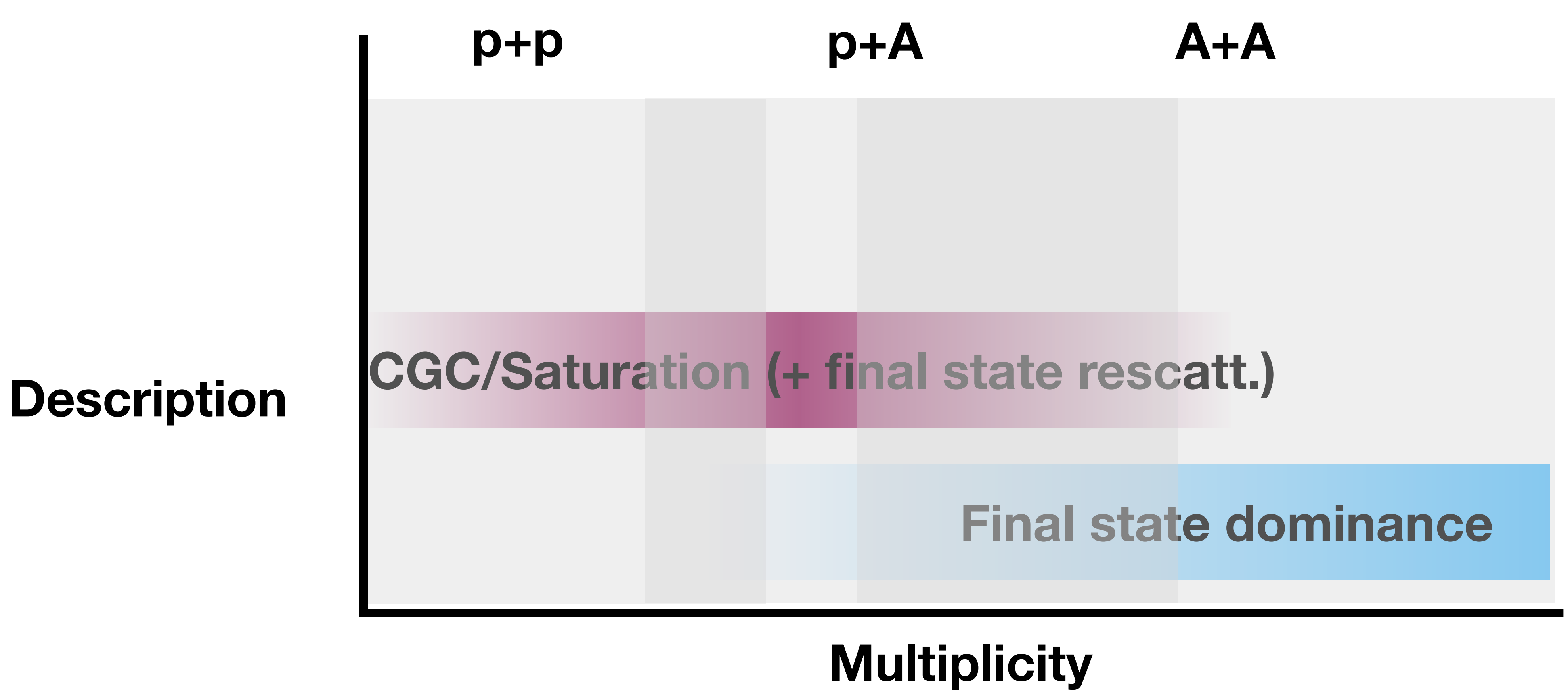
The landscape of calculations

How to understand particle production in high energy collisions



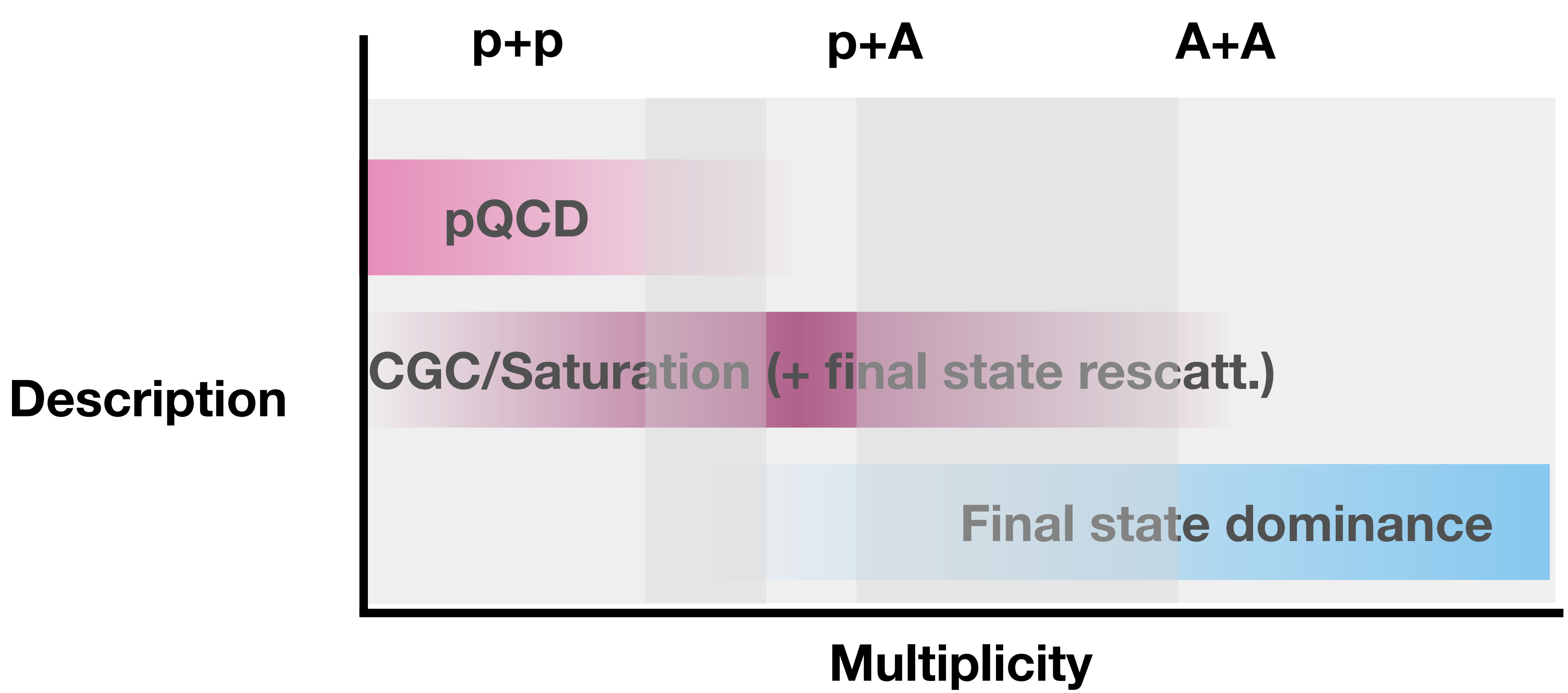
The landscape of calculations

How to understand particle production in high energy collisions



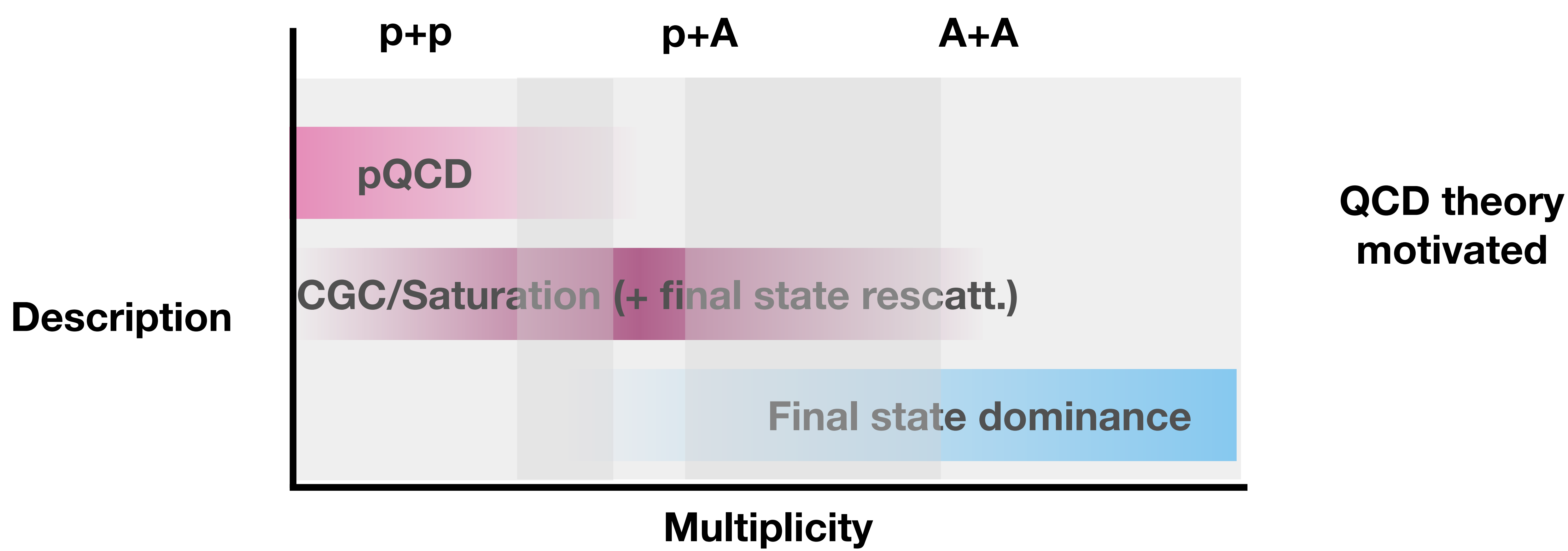
The landscape of calculations

How to understand particle production in high energy collisions



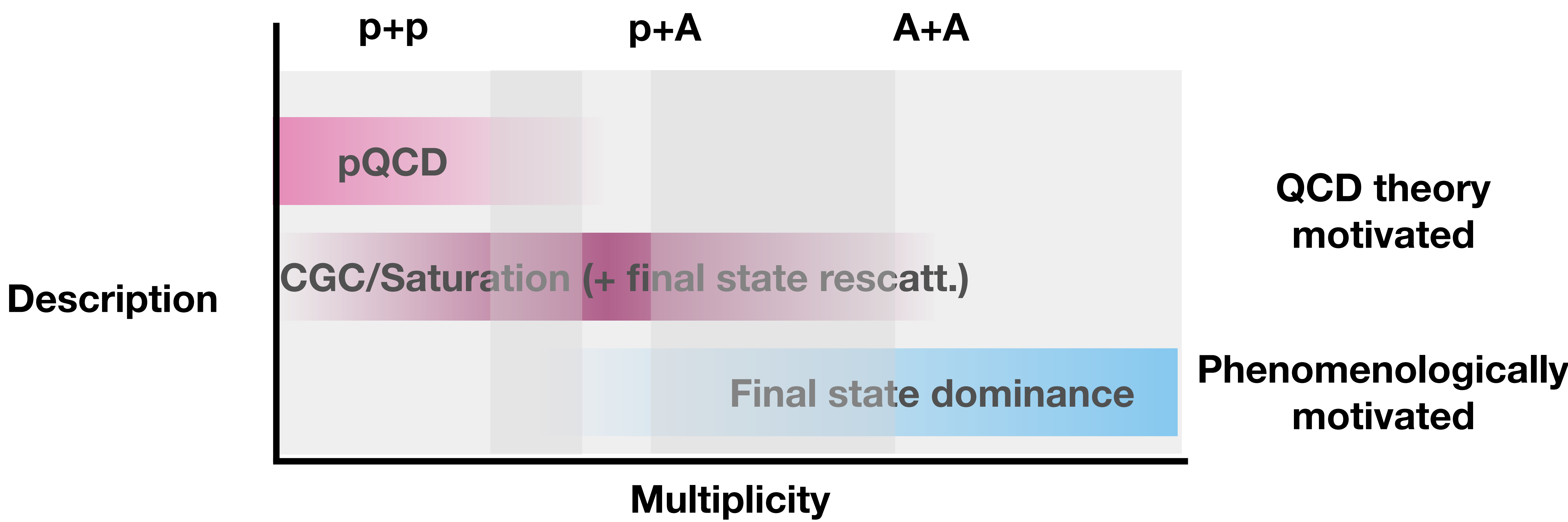
The landscape of calculations

How to understand particle production in high energy collisions



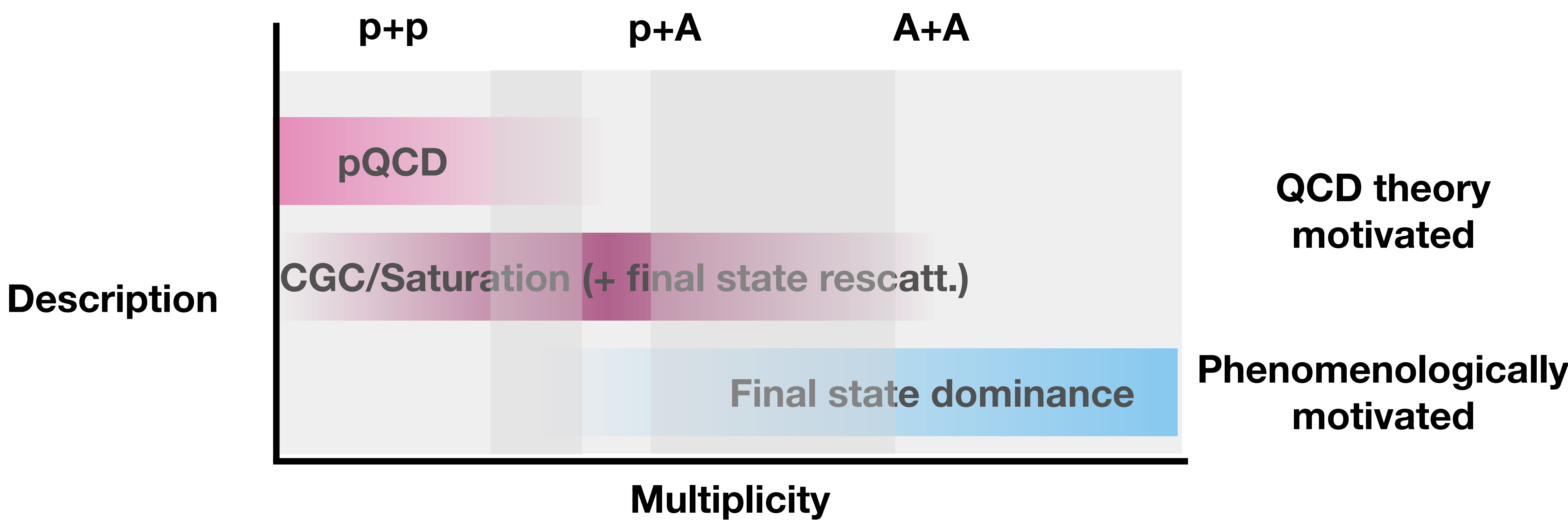
The landscape of calculations

How to understand particle production in high energy collisions



The landscape of calculations

How to understand particle production in high energy collisions



How to bridge the gap between QCD and phenomenological models?

Correlation production mechanisms

two extremes

Initial state (e.g. CGC)

Produced by initial momentum correlations which pre-exist in nuclei before collisions and/or develop at quickly after collision

Contains classical correlations (domains, as well as density gradients)

Contains quantum effects: Bose enhancement in incoming wavefunction, as well as gluon HBT

Final state/hydrodynamics

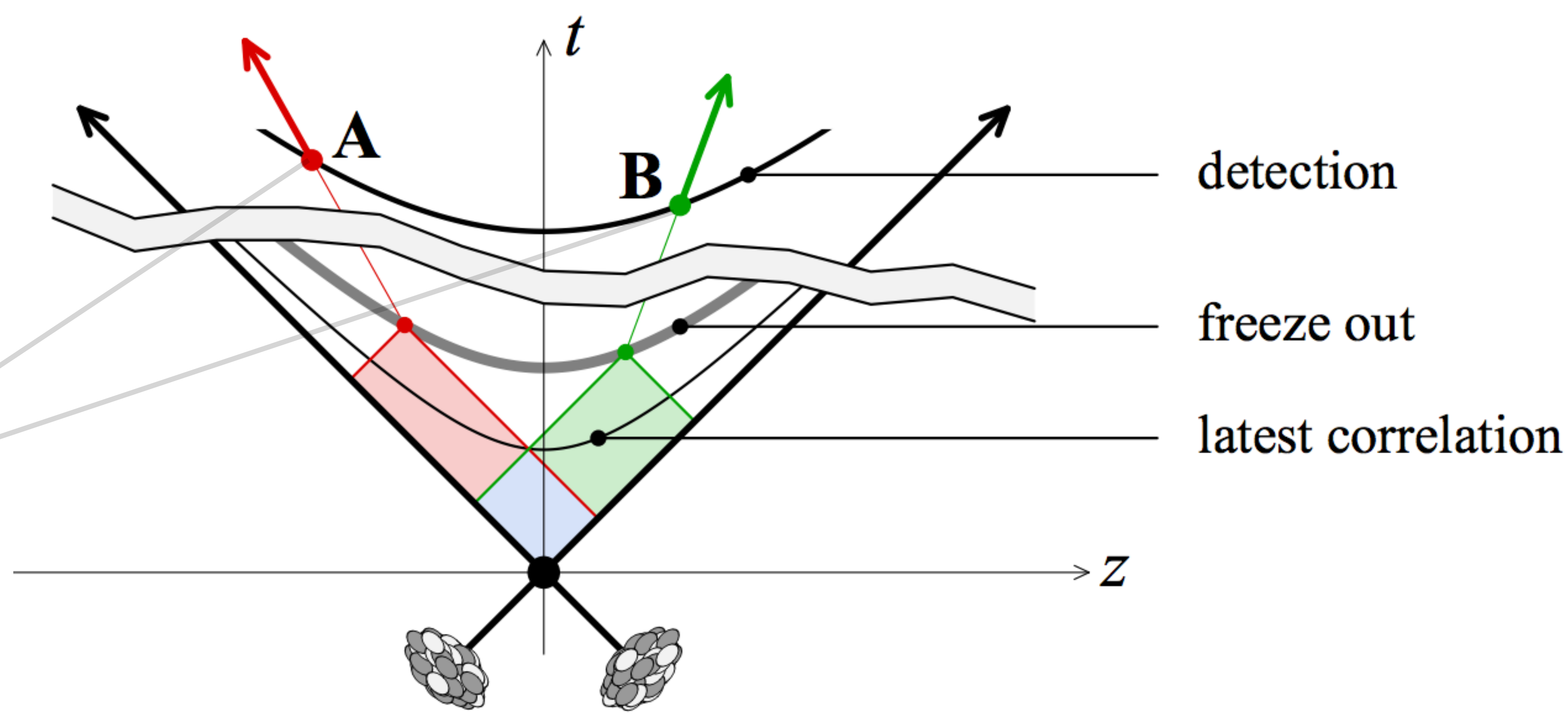
Produced by conversion of initial spatial (geometry) correlations are converted to final momentum correlations

Develops throughout evolution of the system

Well motivated from A+A, theory questions linger for smaller systems

Long range rapidity correlations as a chronometer

Consider pair of particles correlated rapidity Δy

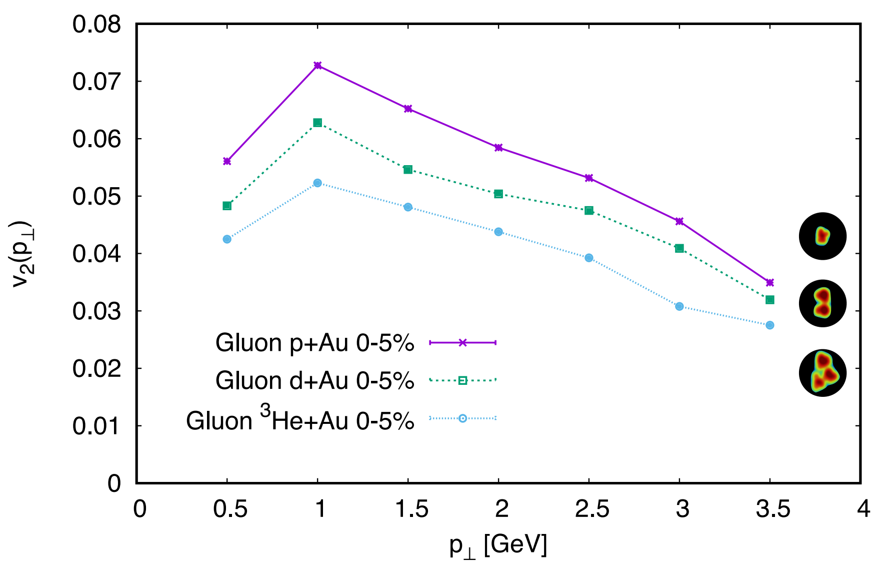


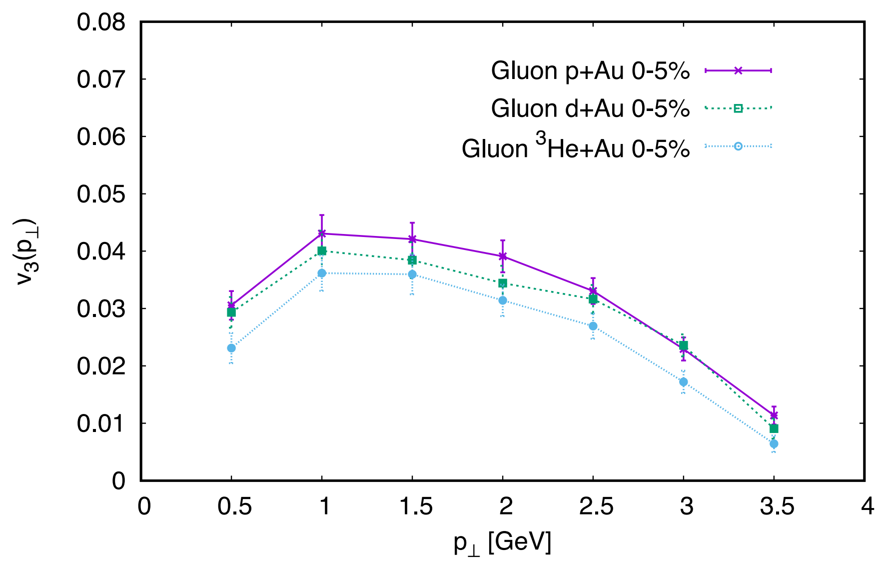
Dumitru, Gelis, McLerran, Venugopalan
NPA 810 (2008) 91-108

By causality, long-range rapidity correlations sensitive to early time dynamics, $\tau < \tau_{f.o.} e^{-\Delta y/2}$,in collision

CGC gluons

Purely initial state correlations from CGC gets opposite hierarchy of *p*/*d*/³He+Au seen by PHENIX



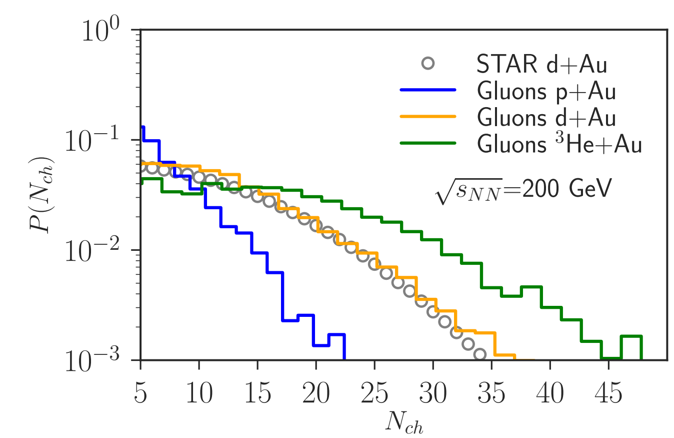


MM, Skokov, Tribedy, Venugopalan, PRL+Erratum

Qualitatively similar results from IP-Glasma (dense-dense) calculations

Other observables where initial state may be more transparent e.g. photons, DIS, UPCs,…

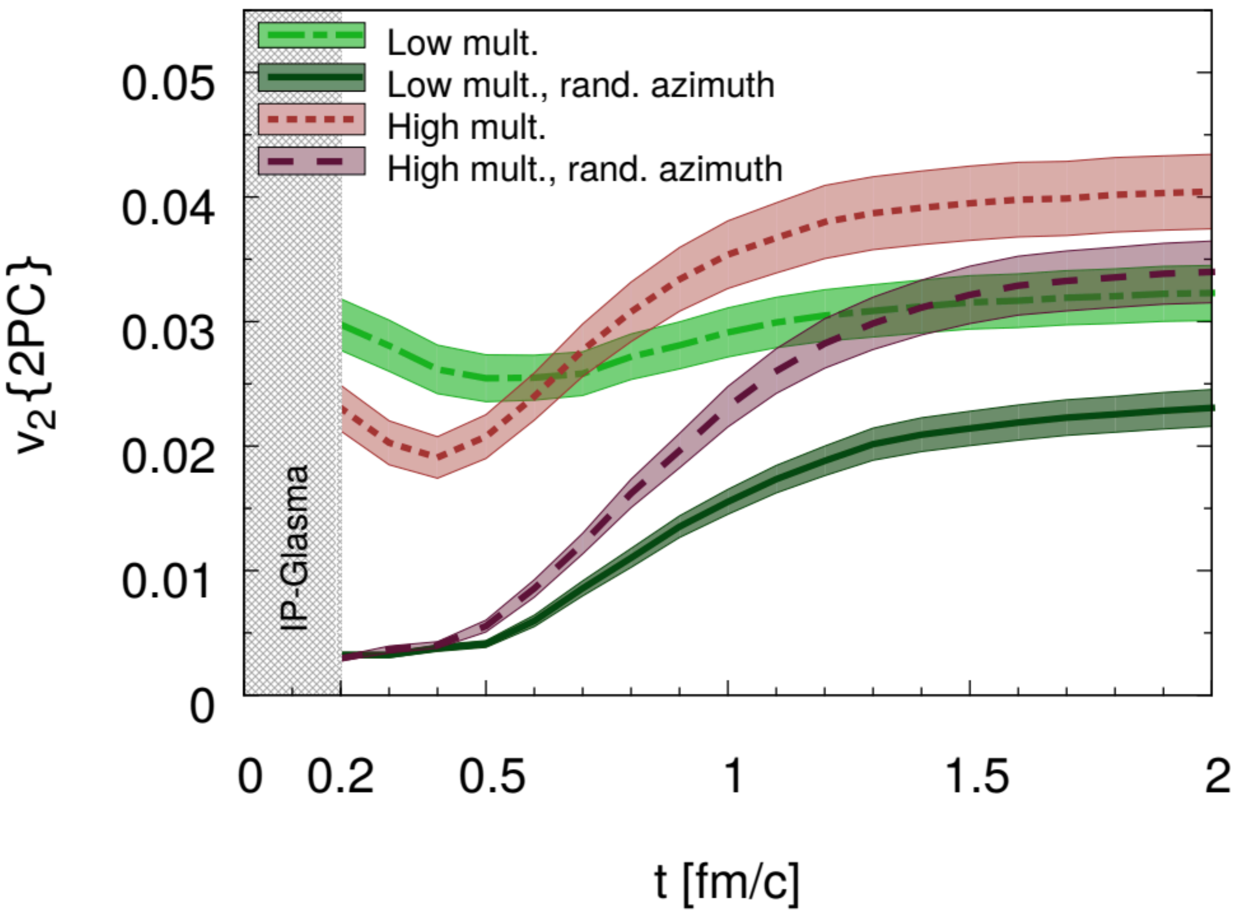
Multiplicity and v_2 anti-correlated in pure CGC calculations

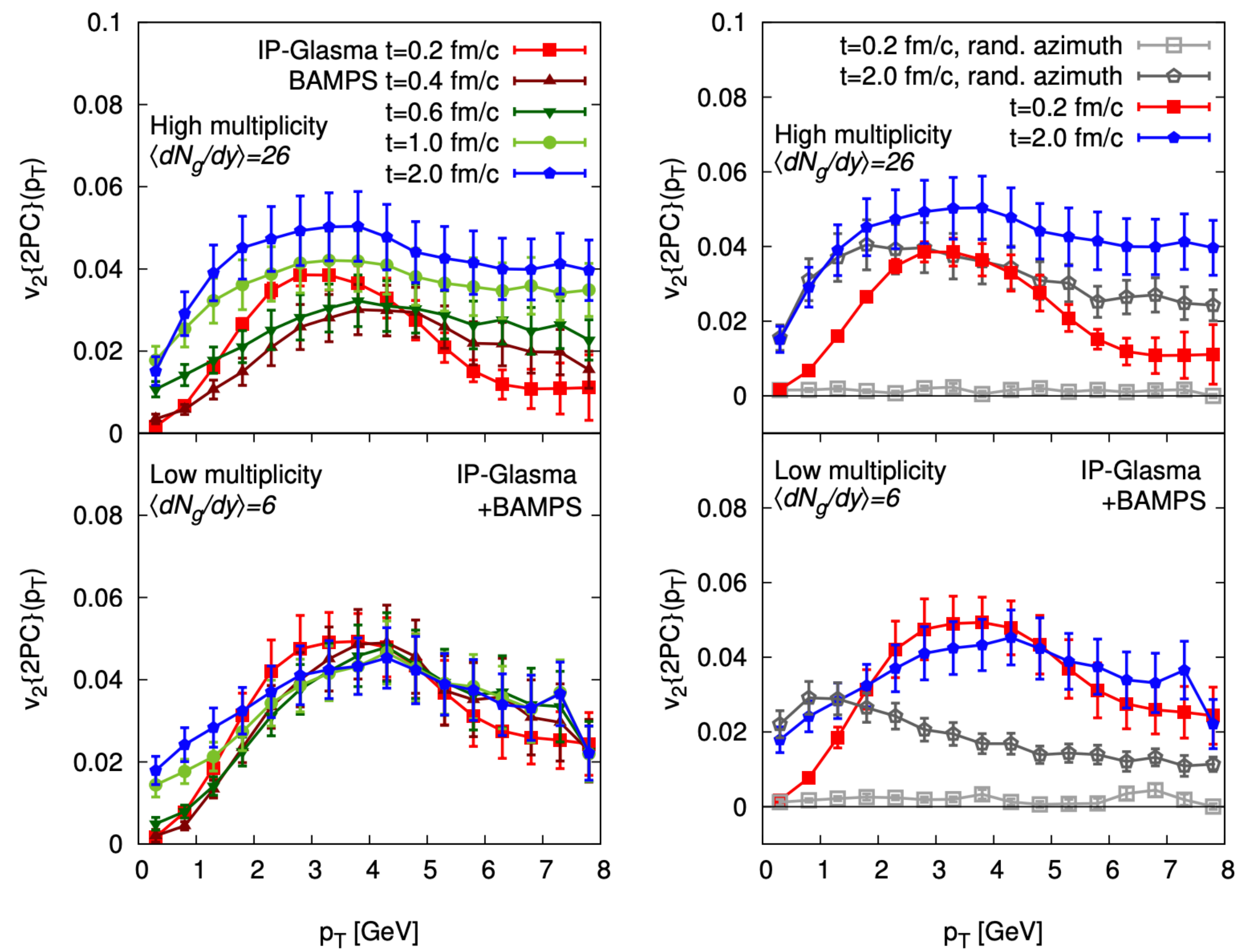


Purely initial state CGC approach seems unlikely to be able to describe the hadronic v_n *alone*

A few more kicks

IP-Glasma+BAMPS(kinetic theory)



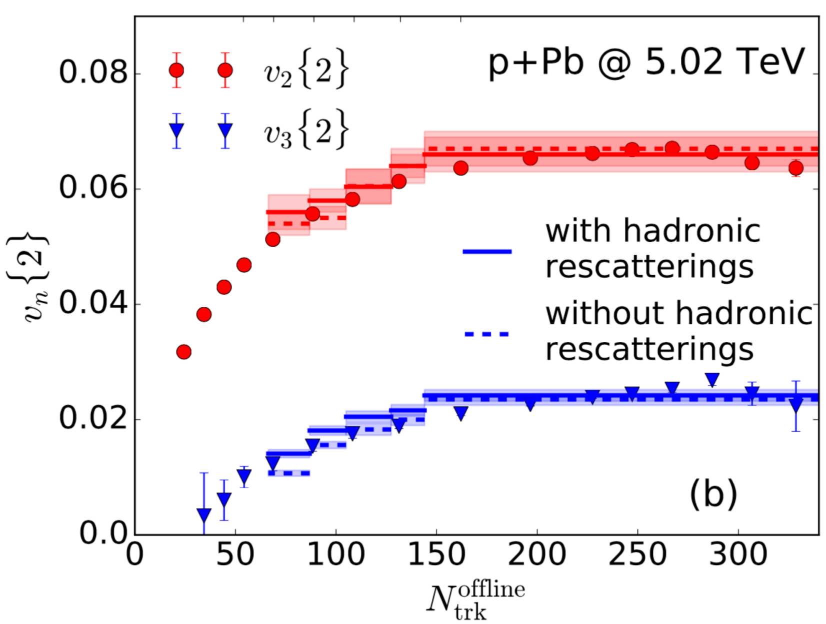


Initial CGC gives smaller v_2 for larger multiplicity system, but quickly reverse by kinetic theory

Greif, Greiner, Schenke, Schlichting, Xu PRD 96 (2017)

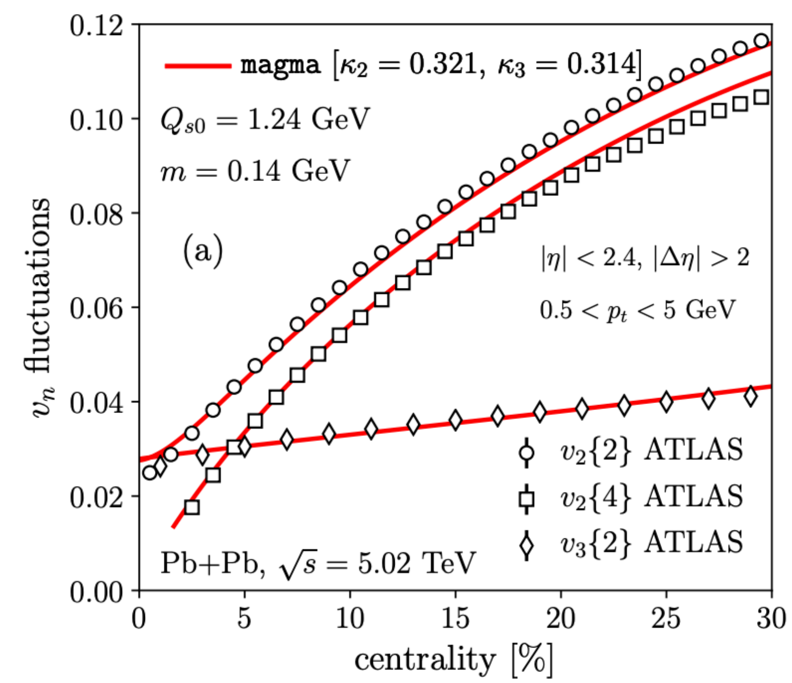
CGC+hydrodynamics

IP-Glasma (Glauber+IP-Sat)
+ MUSIC + UrQMD



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

CGC energy-momentum correlations
+ linear response



Gelis, Giacalone, Guerrero-Rodríguez, Marquet, Ollitrault arXiv:1907.10948

Is there an over-counting of fluctuations in models like MSTV (and IP-Glasma) by also including Glauber modeling?

Need to disentangle theory (QCD-based) and modeling (not)

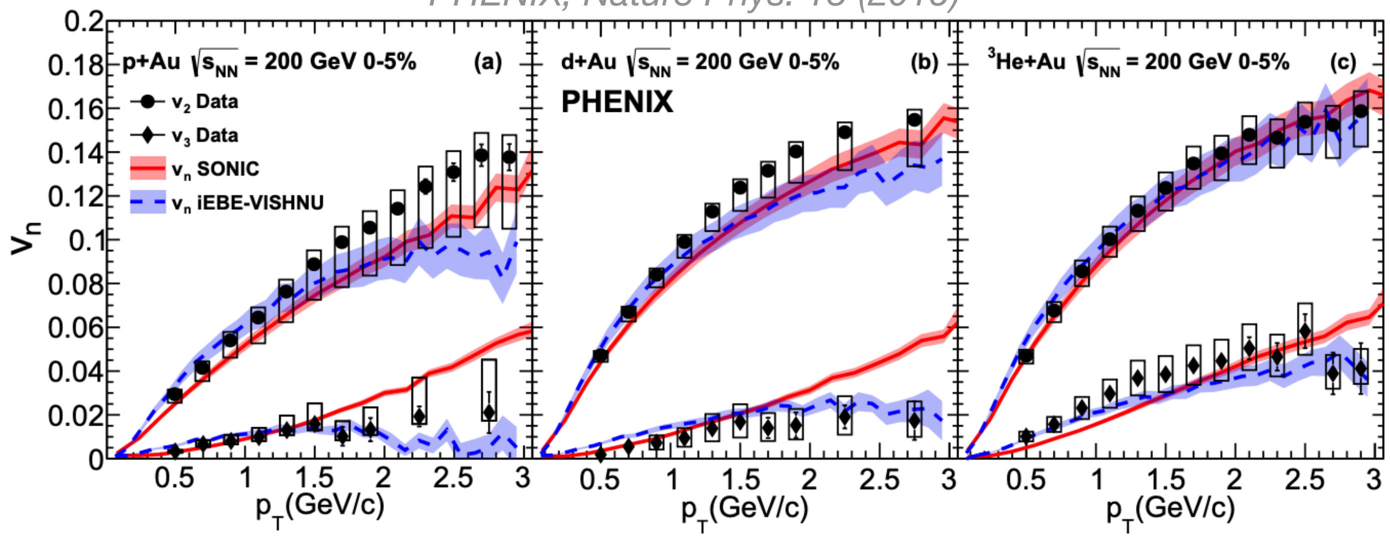
So now what?

Three (somewhat) different initial states coupled to hydro

PHENIX, Nature Phys. 15 (2019)

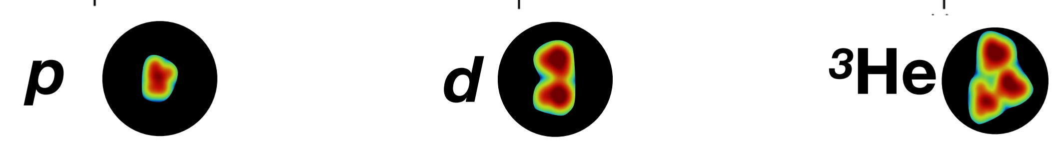
MC-Glauber
+ VISH2+1
+ UrQMD

Shen, Paquet, Denicol, Jeon, Gale PRC 95 (2017)



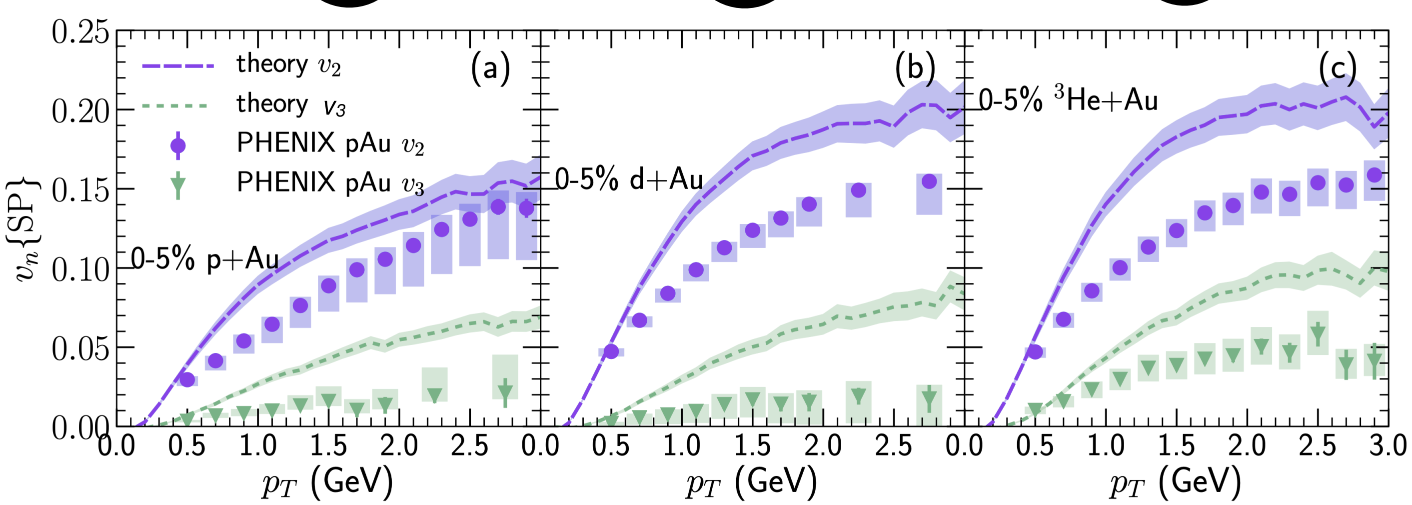
MC-Glauber+AdS
+UVH2+1
+B3D

Habich, Nagle, Romatschke EPJC 75 (2015)



IP-Glasma
+ MUSIC
+ UrQMD

PRELIMINARY
Schenke, Shen, Tribedy, in preparation

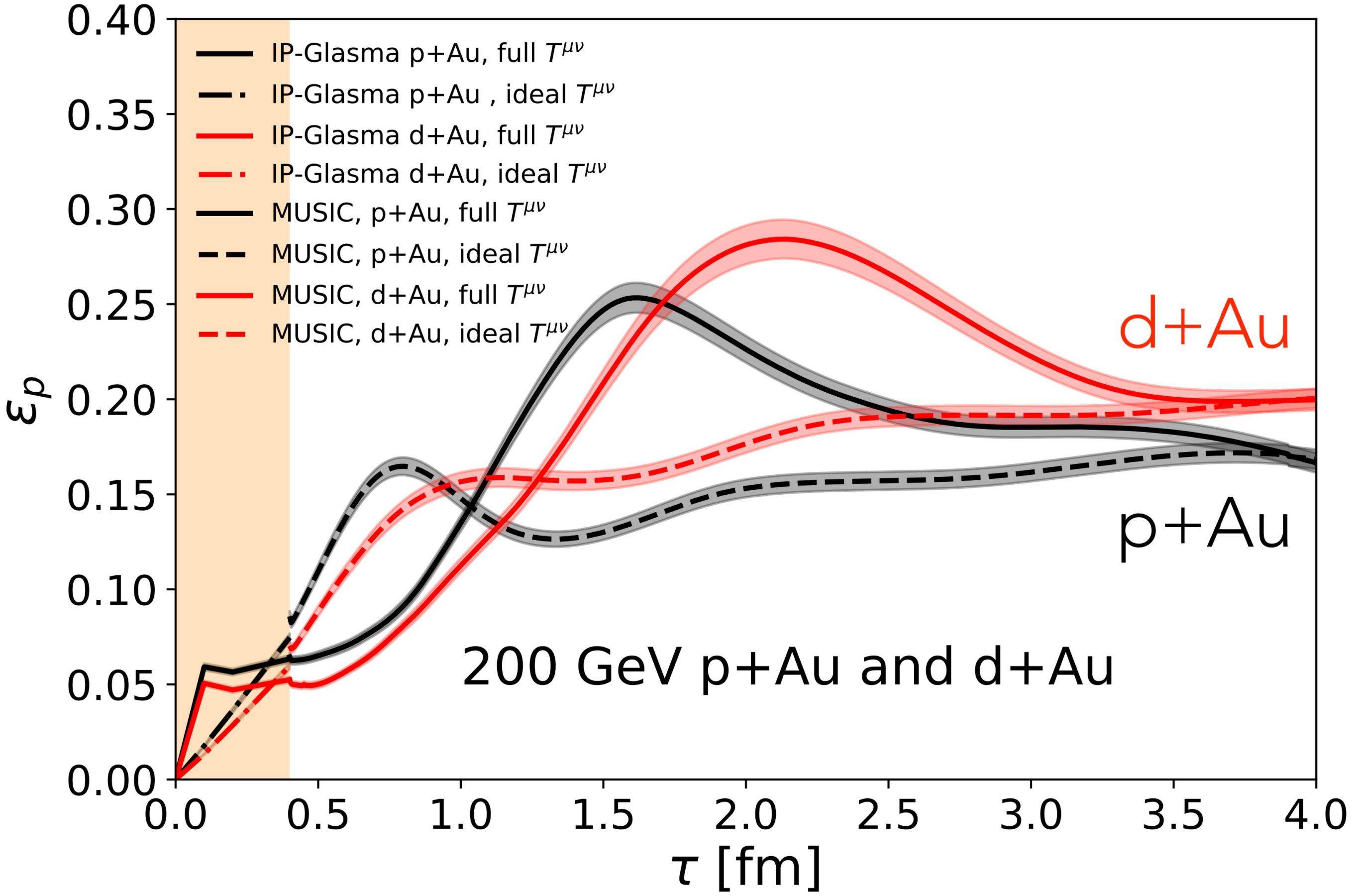


B. Schenke, RHIC-AGS Users Meeting June 4,2019

Important differences — need to begin dissecting initial state

Anisotropy evolution

IP-Glasma+MUSIC+UrQMD



Measure momentum anisotropy

$$\epsilon_p = \sqrt{\frac{\langle T^{xx} - T^{yy}\rangle^2 + \langle 2T^{xy}\rangle^2}{\langle T^{xx} + T^{yy}\rangle^2}}$$

Not a Fourier harmonic

Dashed: ideal part of $T^{\mu\nu}$ only

Solid: full $T^{\mu\nu}$

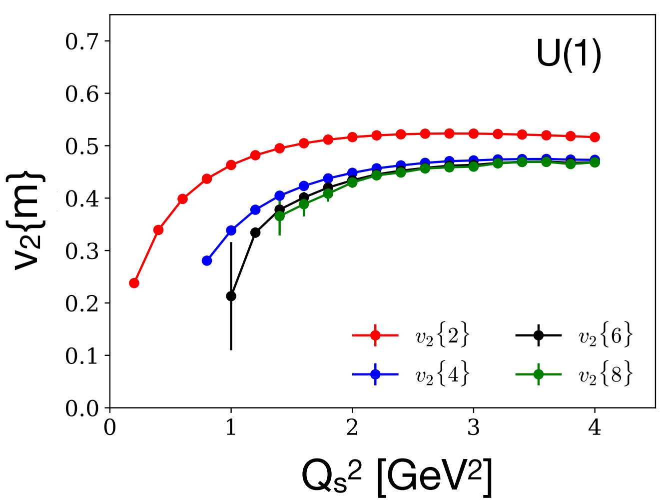
PRELMINARY Schenke, Shen, Tribedy, in preparation

B. Schenke, RHIC-AGS Users Meeting June 4,2019

Collectivity

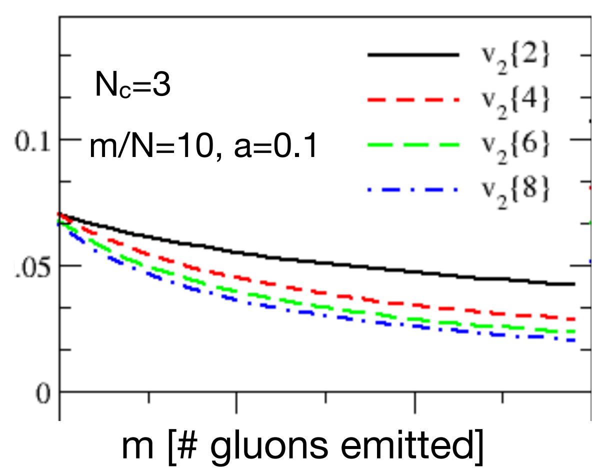
Roughly defined by $v_2\{2\} \gtrsim v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\}$

Parton-CGC model



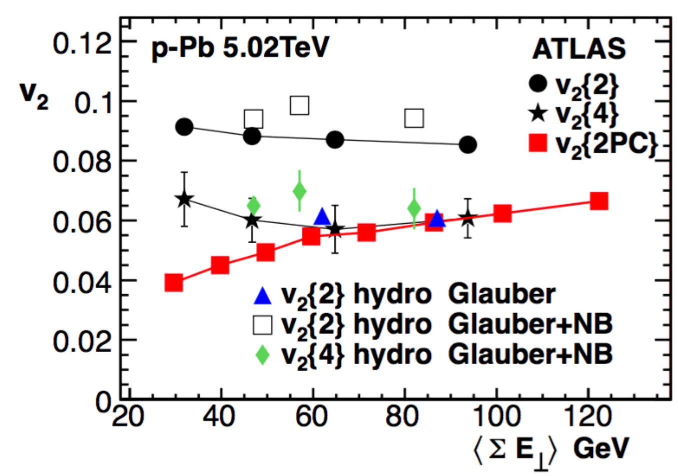
Dusling, MM, Venugopalan PRL 120 (2018)

QCD interference diagrams

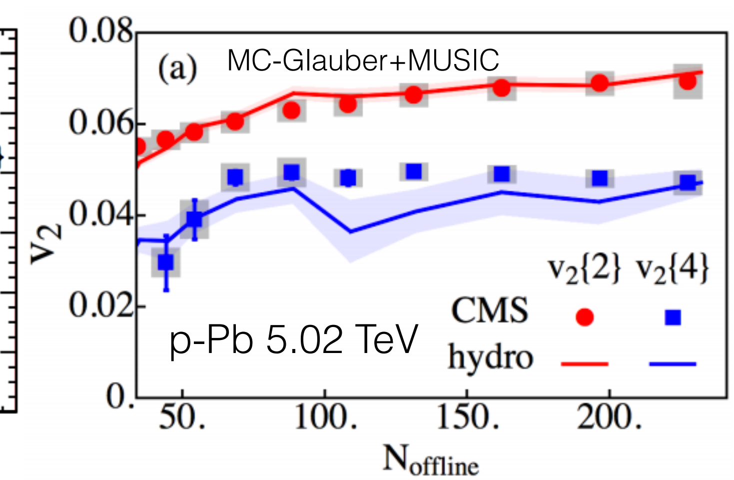


Blok, Wiedemann arXiv:1812.04113

Hydrodynamical models

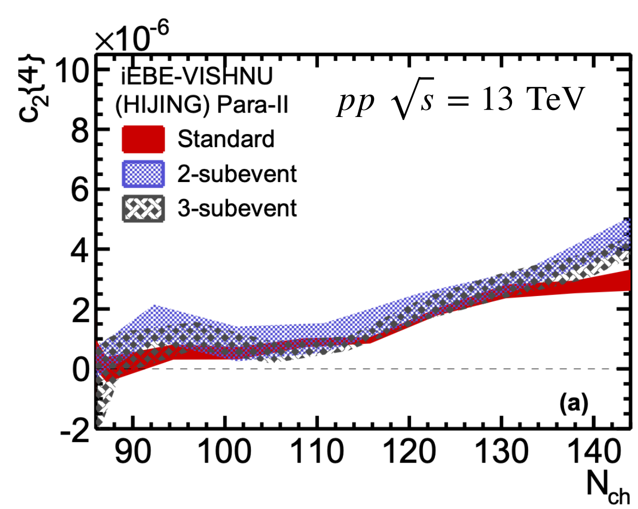


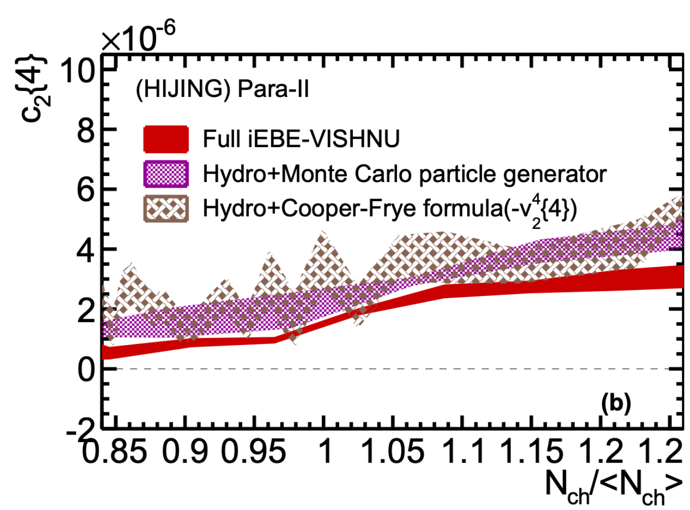
Bozek, Broniowski, PRC88 (2013)



Kozlov, Denicol, Luzum, Jeon, Gale NPA 931 (2014)

Absence of four-particle v_2 from hydro in *pp*





$c_2\{4\} > 0 \rightarrow v_2\{4\} \in \mathbb{C}$

Zhao, Zhou, Xu, Deng, Song PLB 780 (2018)

Outstanding challenges

(as I see them)

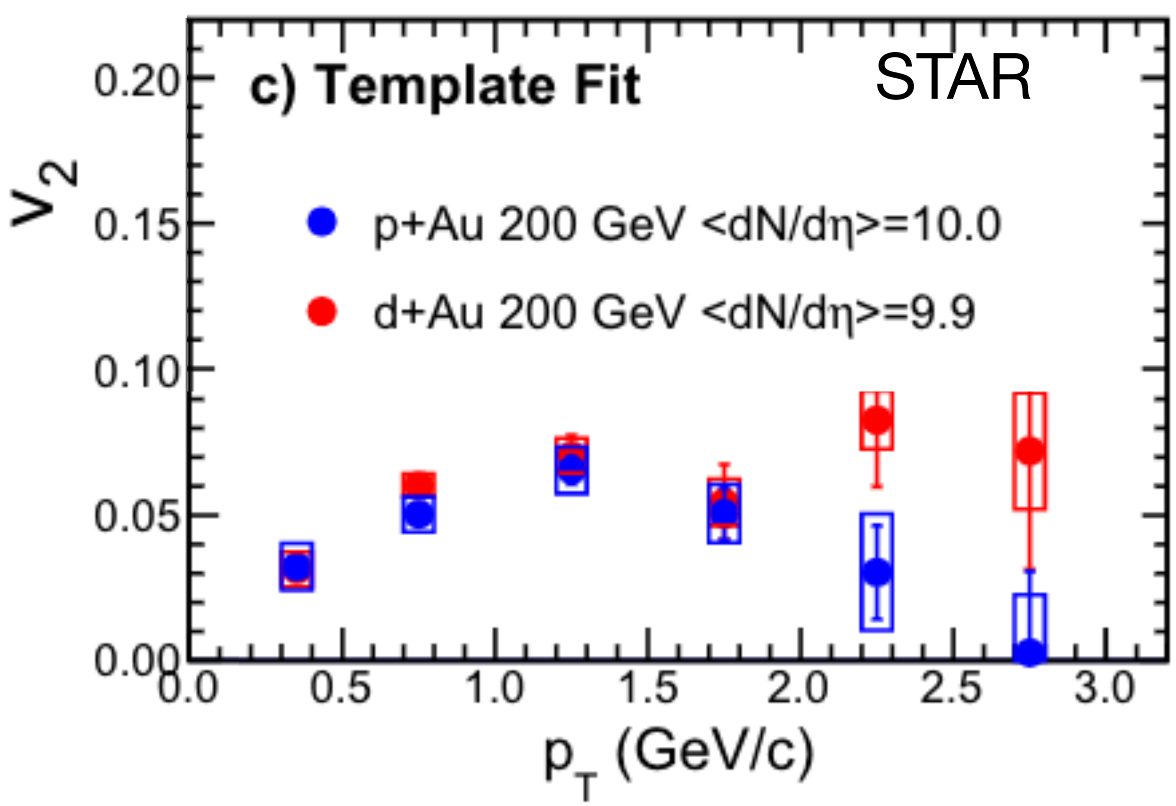
- Would like to know how a nuclei transforms into a fluid using QCD (and back!)
- Bottom-up: Starting from pQCD, when do we need more? (could be gluon saturation, kinetics, fluid)
  - Focus on observables like UPCs, DIS, EIC to directly constrain initial state?
  - Look at non-flow?
- Top-down: use final-state-dominant models to constrain models
  - Greater understanding coming by looking into initial conditions *as a function of time*
  - Further tests, such as larger particle number flow, very important
  - Understand what we are comparing to e.g. how does flow/non-flow subtraction effect results?
    - Particularly important for $c_2\{4,6,\ldots\}$ in small systems, etc

Backup

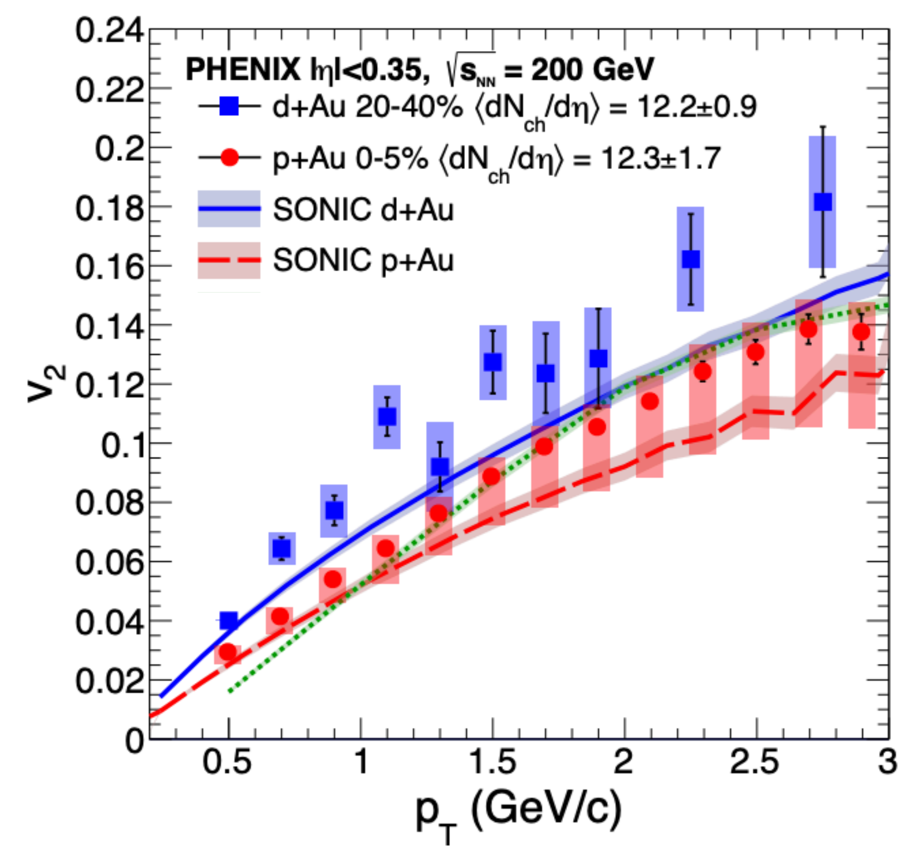
Same multiplicity p/d+Au

Dilute-dense CGC conjecture: same multiplicity ~ similar correlations

MM, Skokov, Tribedy, Venugopalan, PRL 121 (2018)



STAR NPA 982 (2019)

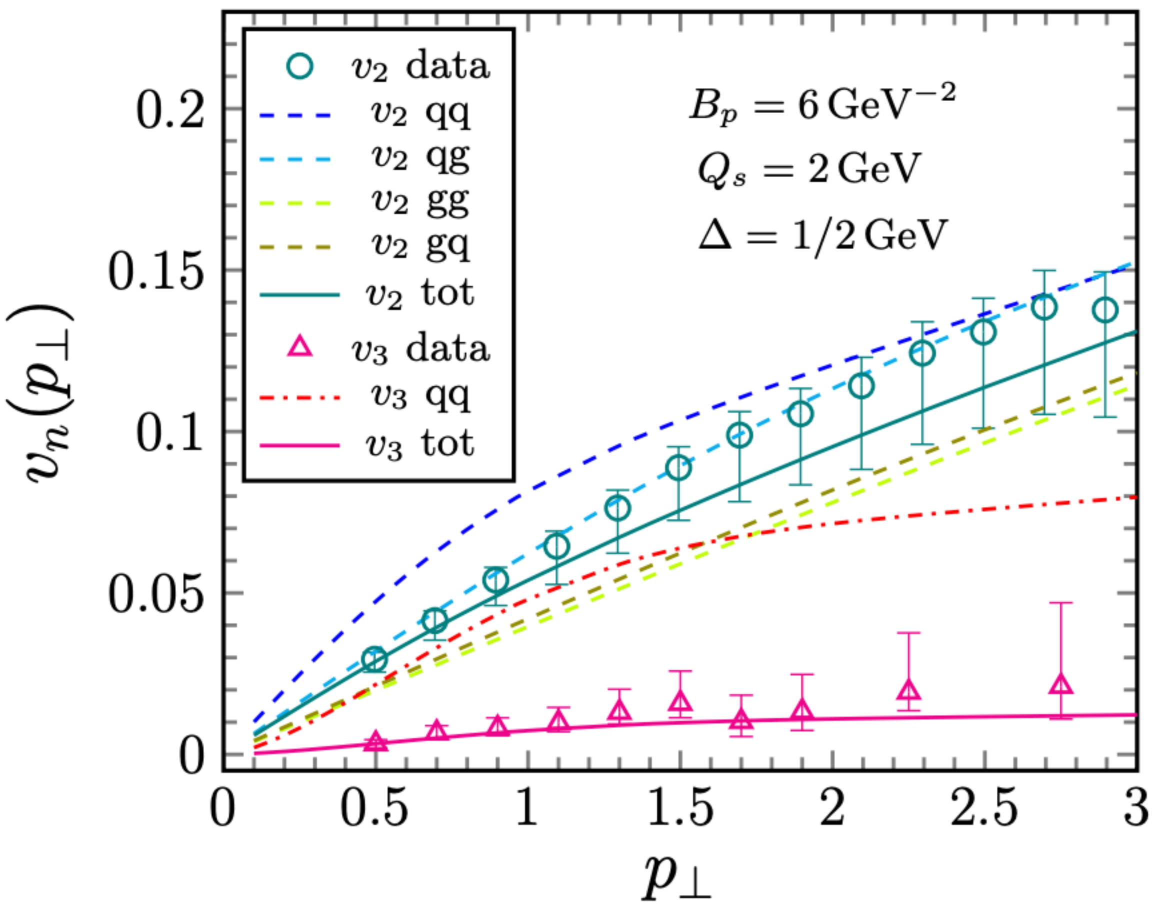


PHENIX Nature Phys. 15 (2019)

Note that color coding is opposite

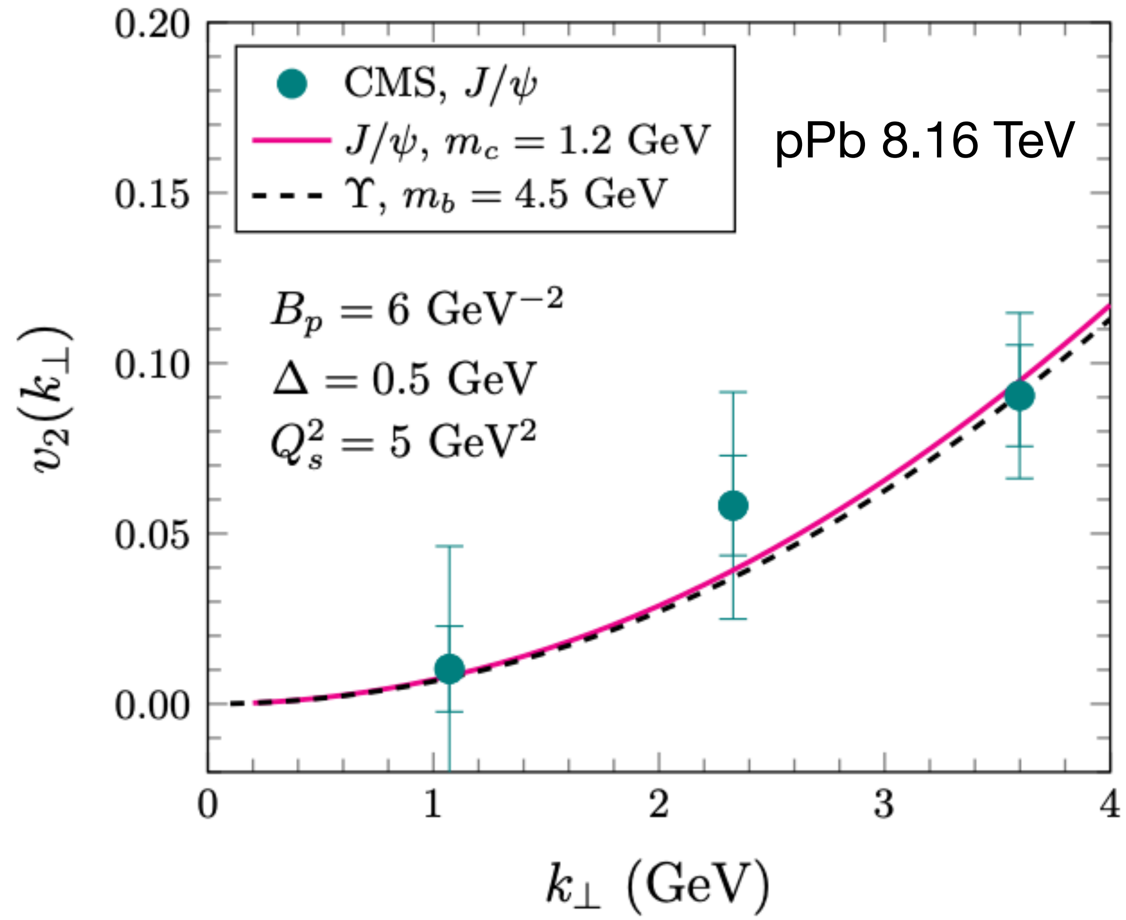
Quark+gluon correlations

Mixture of quark and gluons



Davy, Marquet, Shi, Xiao, Zhang NPA 983 (2019)

Mixture of quarks/gluons +color evaporation model



Zhang, Marquet, Qin, Shi, Xiao PRL 122 (2019)

Compatible with PHENIX p+Au

PHENIX, Nature Phys. 15 (2019)

How to model larger projectiles?

Prediction for Υ