Initial Conditions in Heavy Ion Collisions

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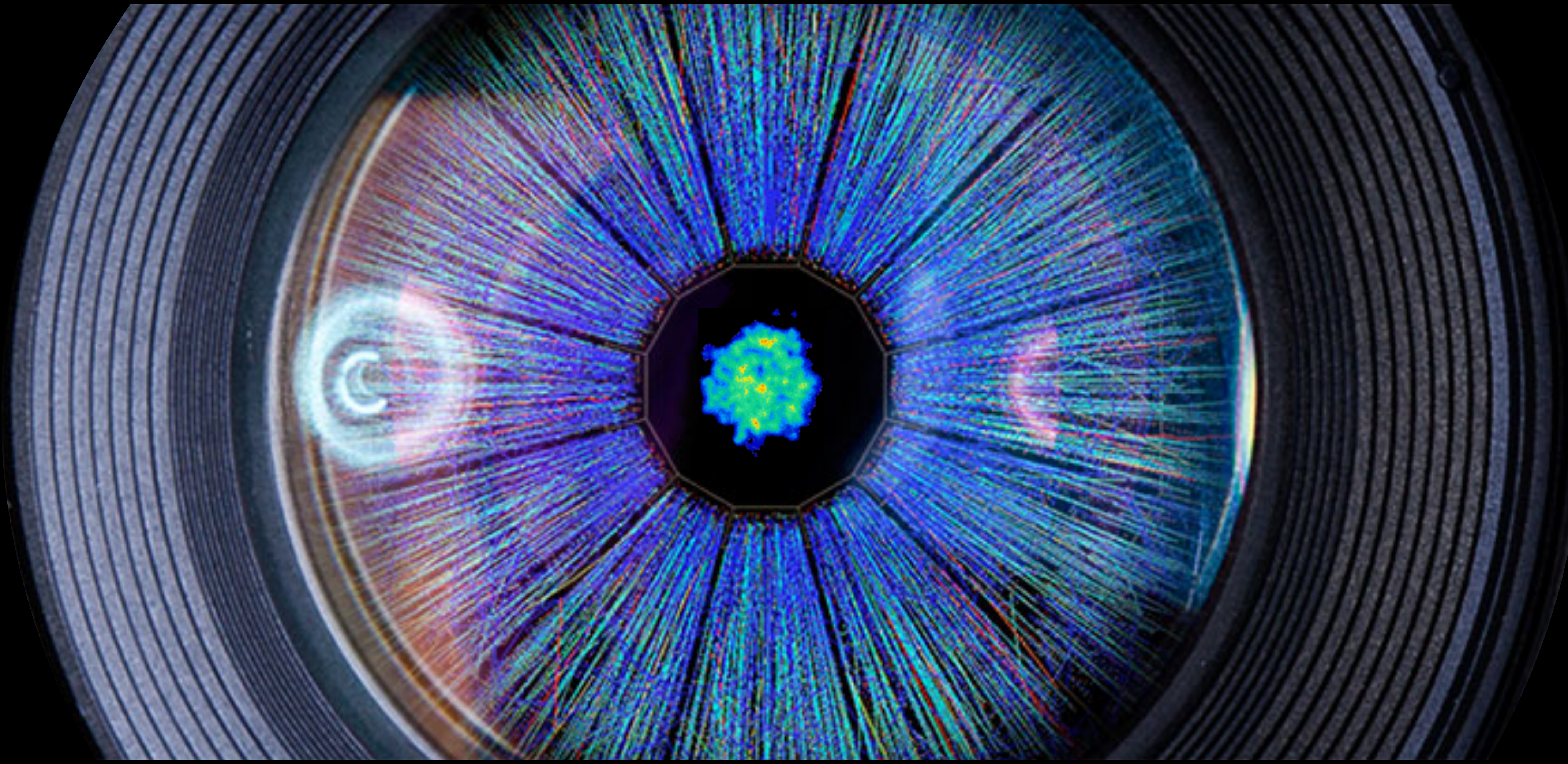

JETSCAPE WINTER SCHOOL 2019

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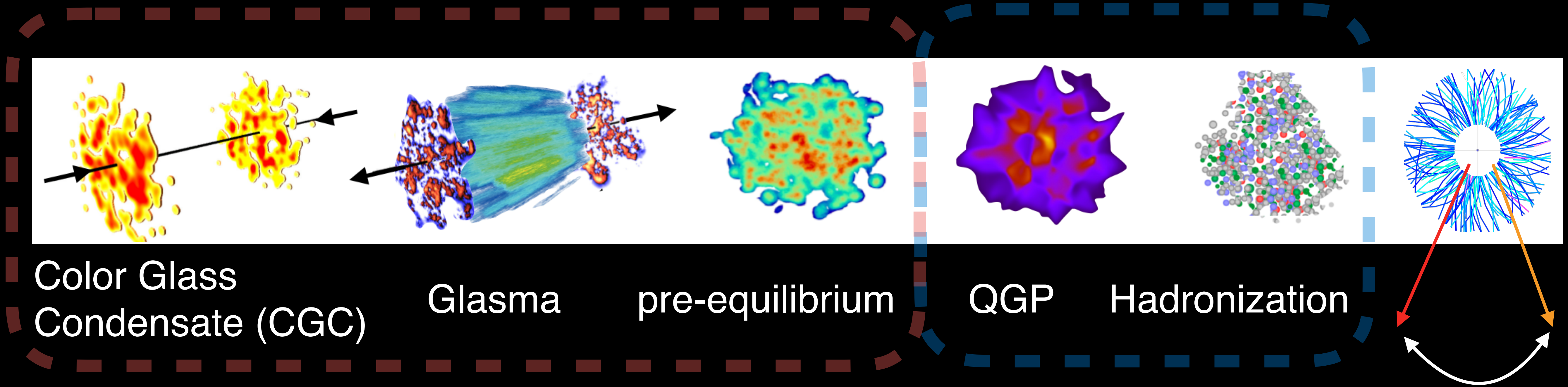
U.S. DEPARTMENT OF ENERGY | Office of Science

What do we mean by initial conditions ?

Different steps in the time evolution are described by solving differential equations that require Initial Conditions



$$\frac{\partial \mathcal{N}}{\partial Y} \approx \kappa \otimes \mathcal{N} - \mathcal{N}^2 \Rightarrow [D_\mu, F^{\mu\nu}] = J^\nu \Rightarrow \partial_\mu T^{\mu\nu} = 0 \Rightarrow p^\mu \partial_\mu f_i = C_i$$

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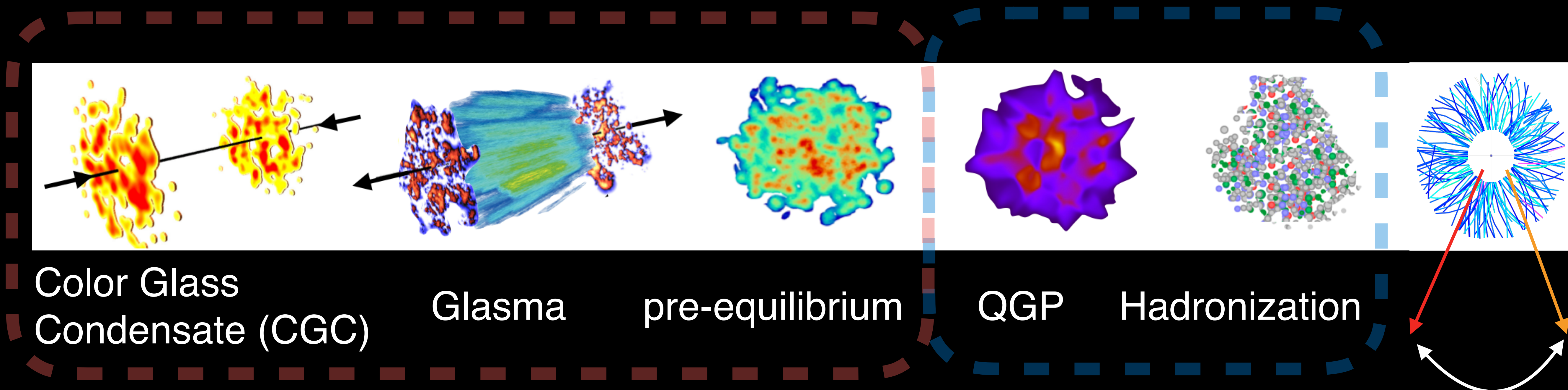
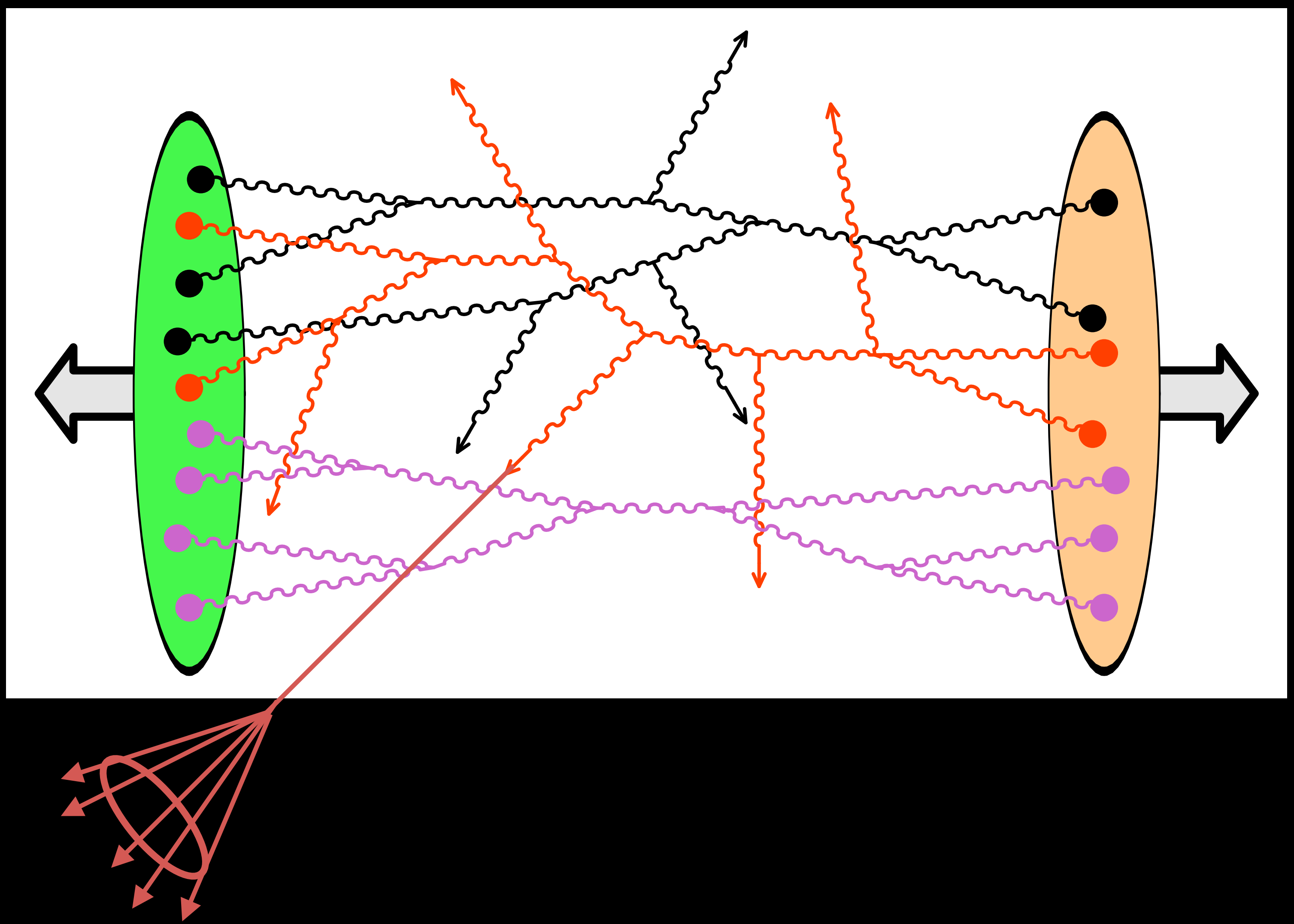


Initial conditions for hydrodynamics ➡ $\partial_\mu T^{\mu\nu} = 0$ ➡ $p^\mu \partial_\mu f_i = C_i$

At some point the system becomes describable by hydrodynamics and we need to compute the initial full $T^{\mu\nu}$

Where are the challenges ?

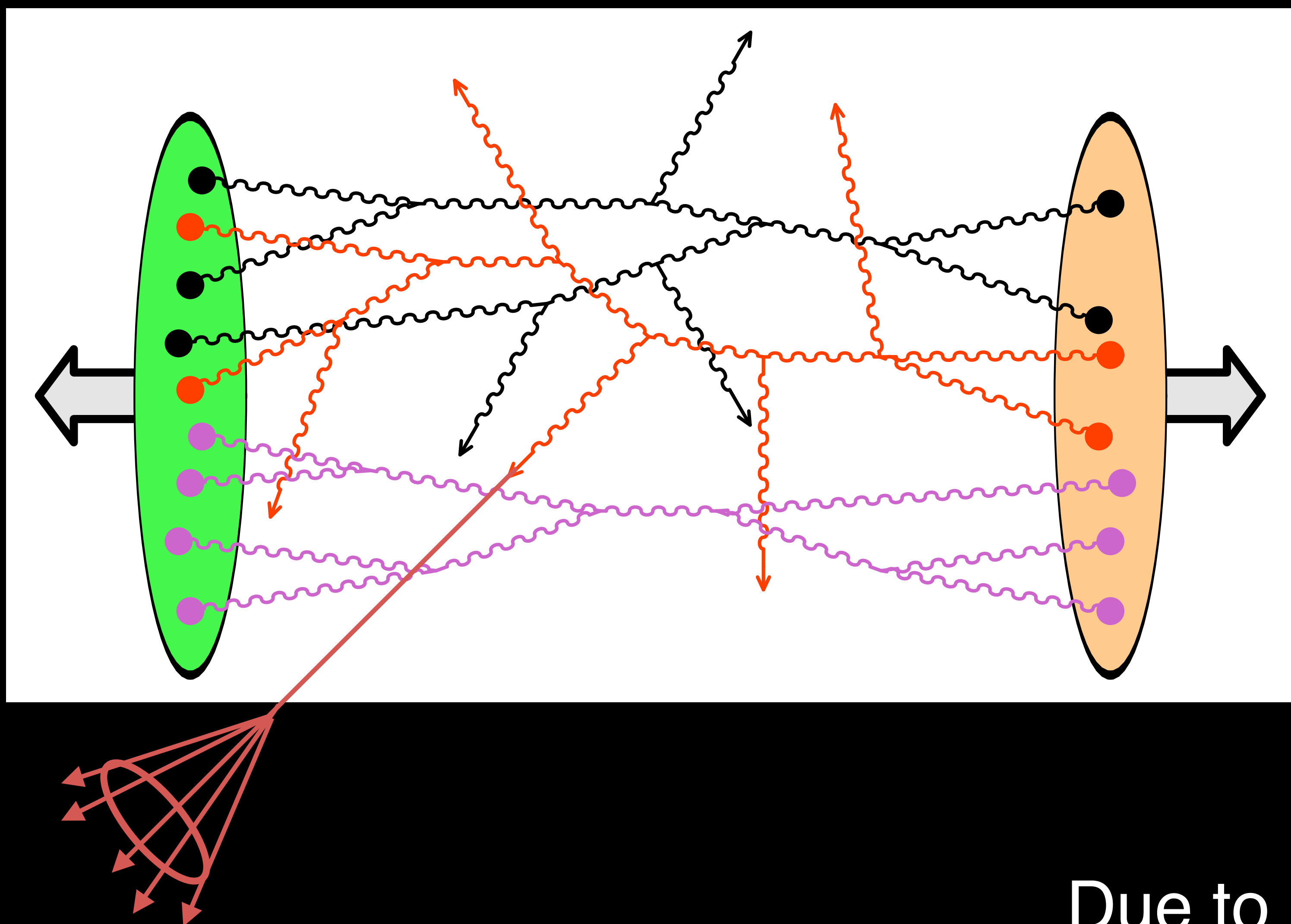
Mostly soft processes



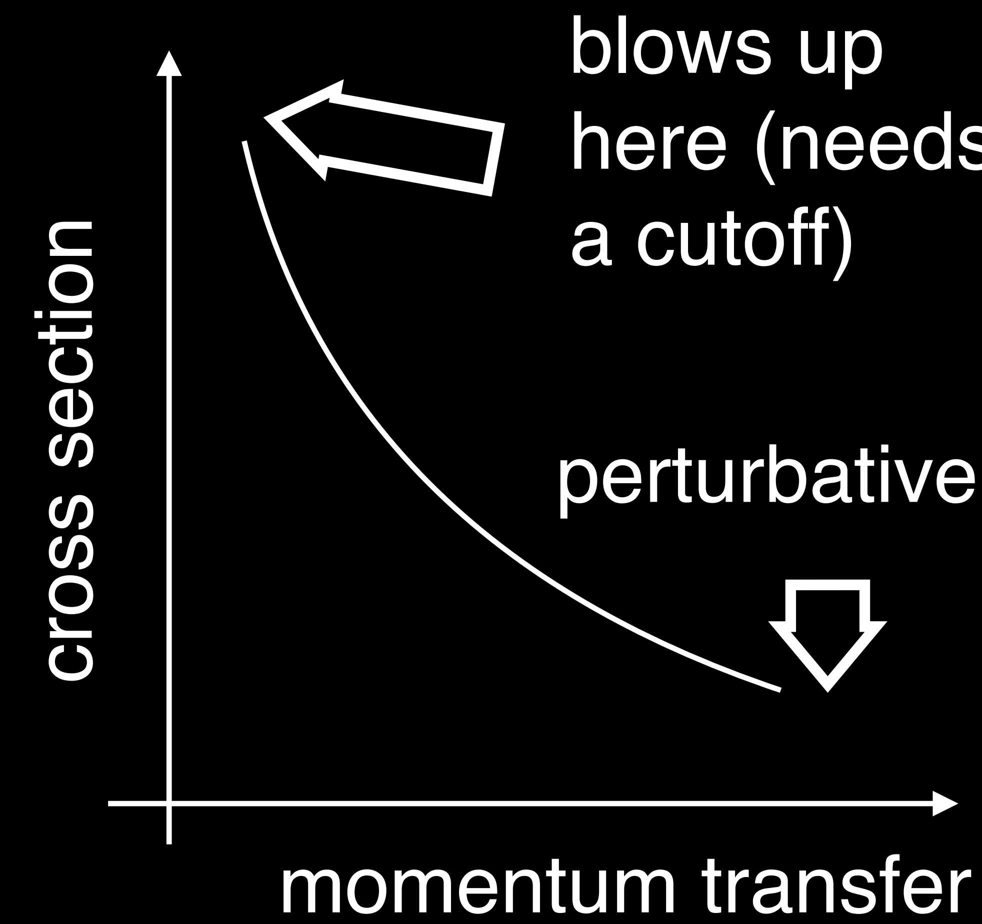
A few hard processes

Where are the challenges ?

Mostly soft processes

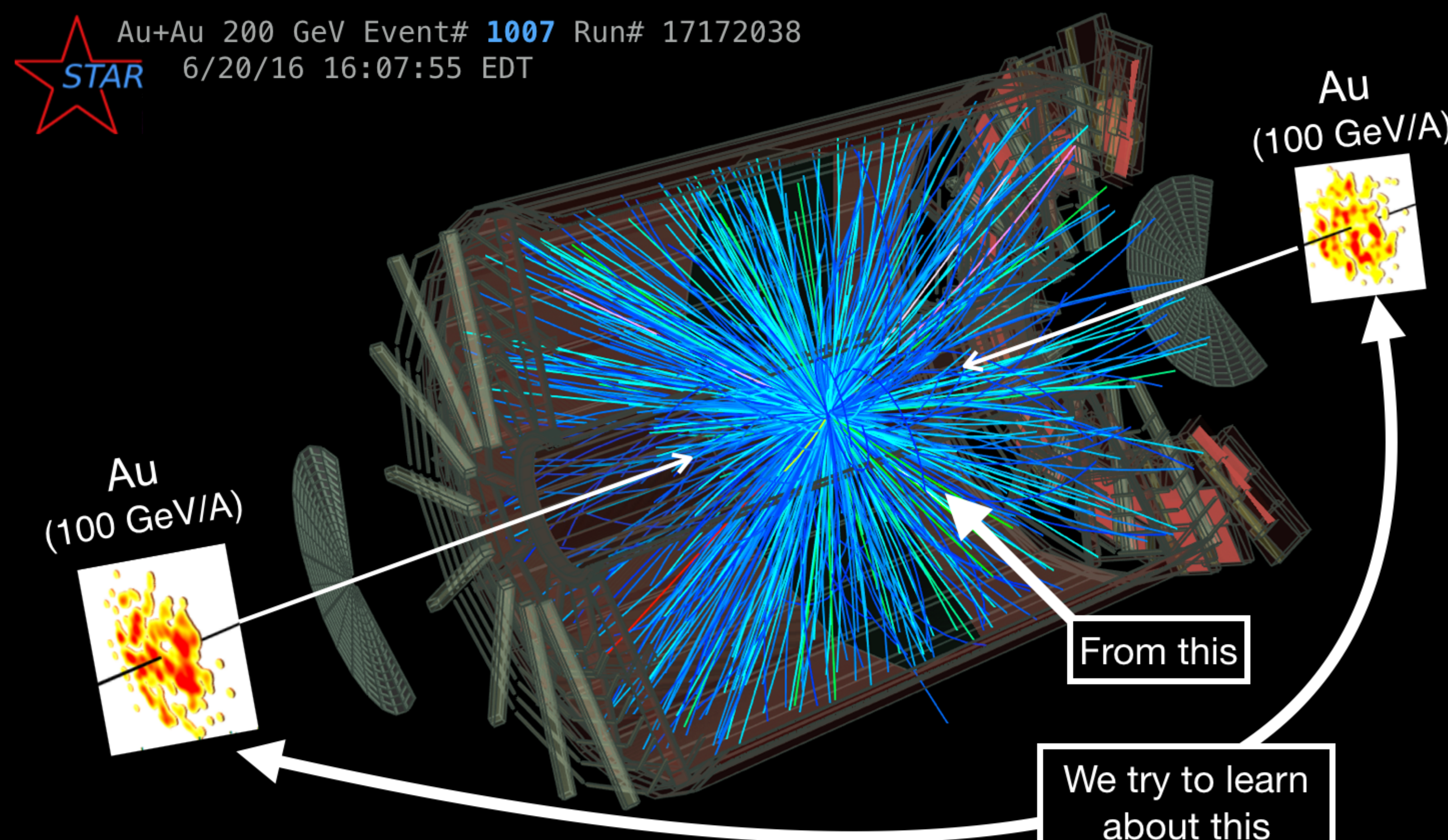


A few hard processes



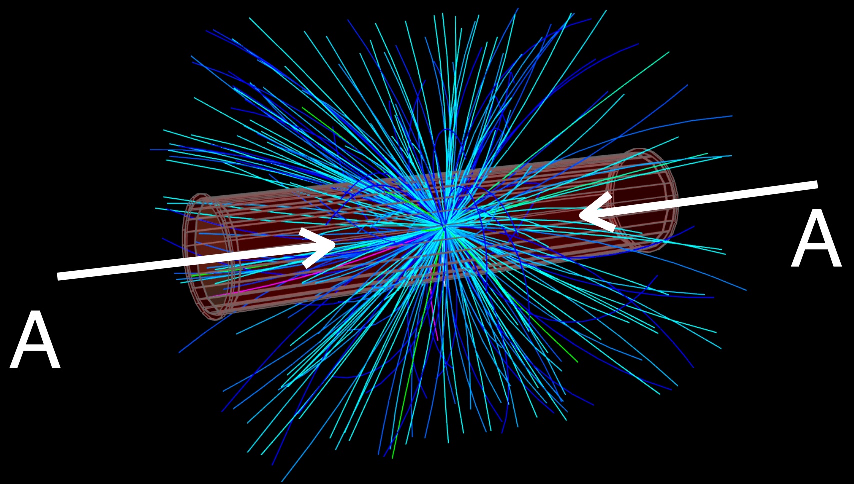
Due to highly non-perturbative nature of the problem, first principle theory calculations are very challenging

Where are the challenges ?

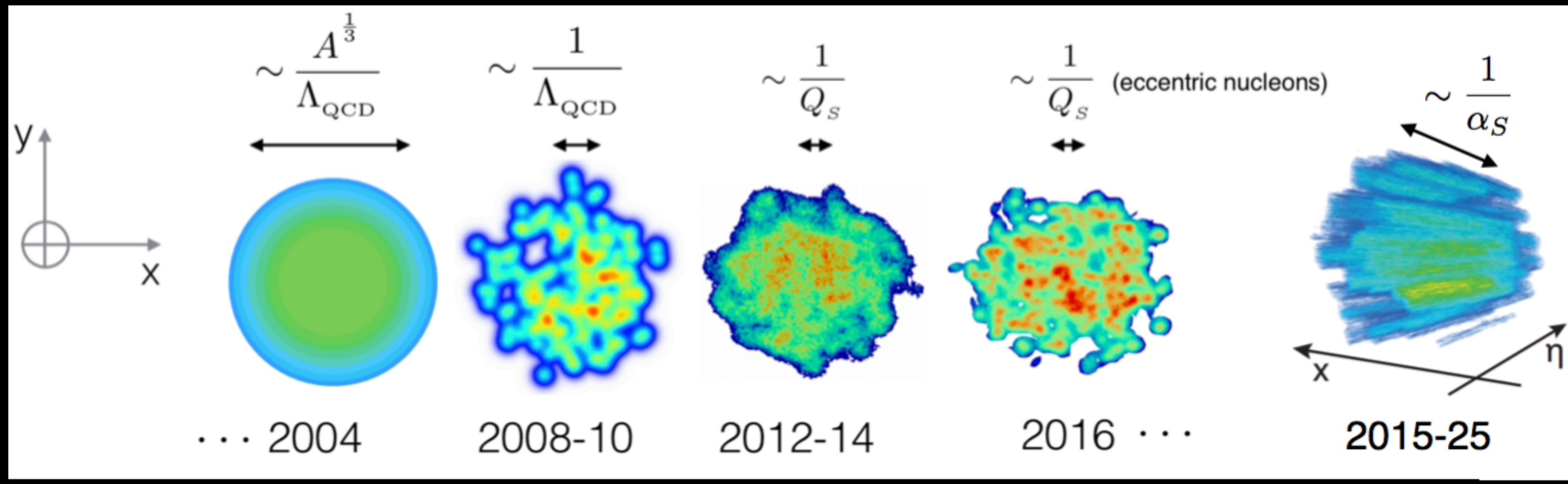


It is not straight forward to come up with measurements that directly constrain initial stages of the collisions

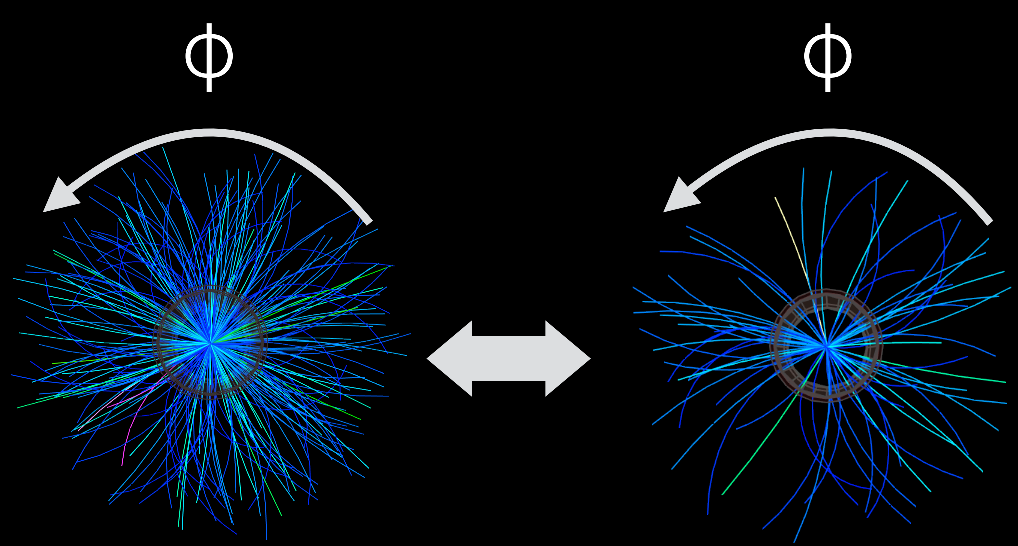
What has happened over the years ?



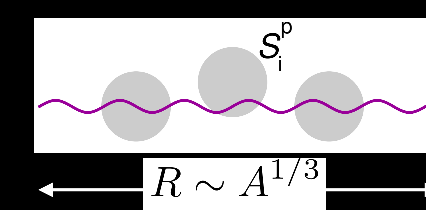
A+A physics ⇒ knowledge of nuclei @ high √s



How did we get there ? Two major steps:



1. New tools to construct nuclei at high energies & simulate A+A collisions

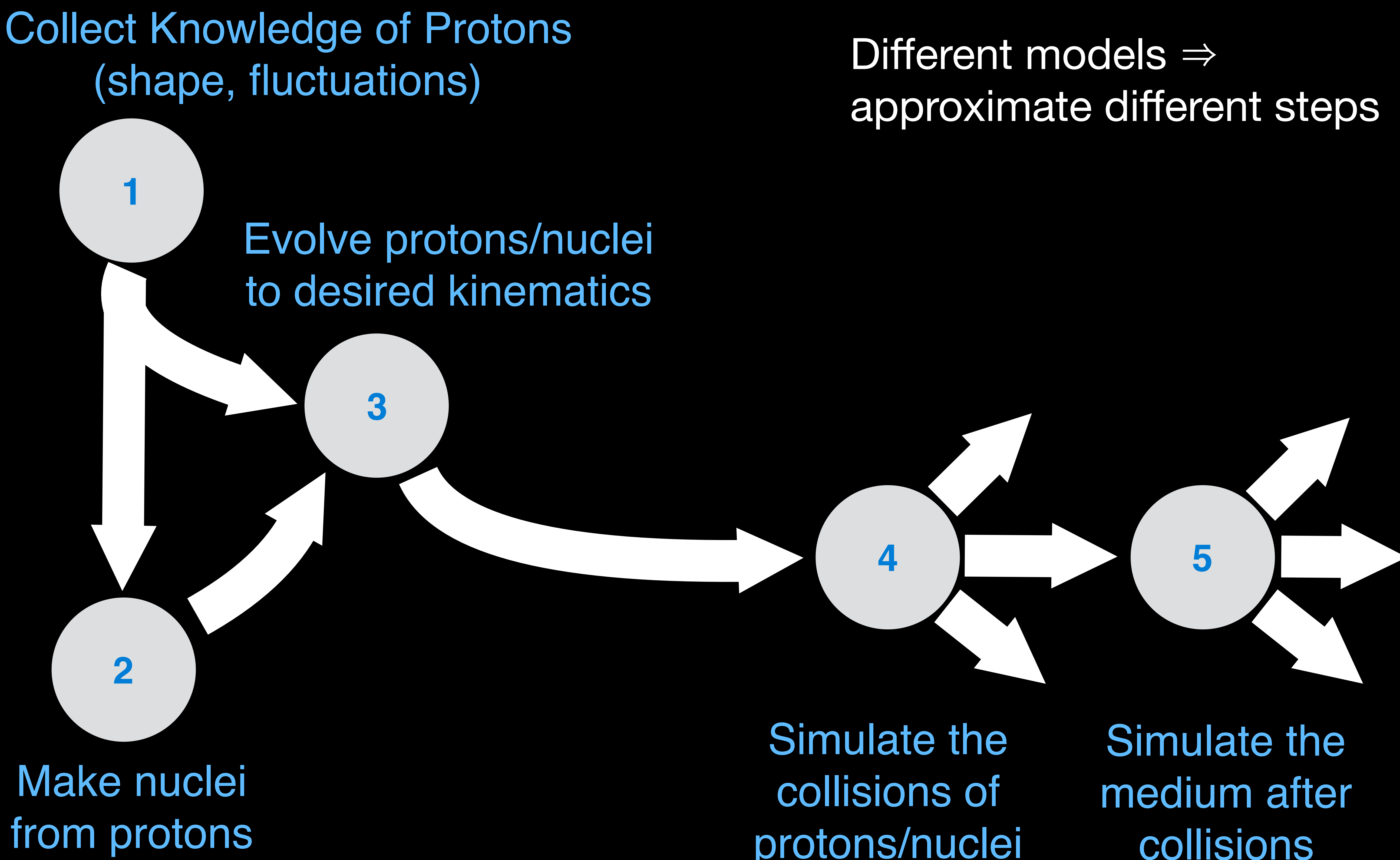


2. Measurements of angular anisotropy & its correlation with multiplicity: $P(v_n \mid N)$

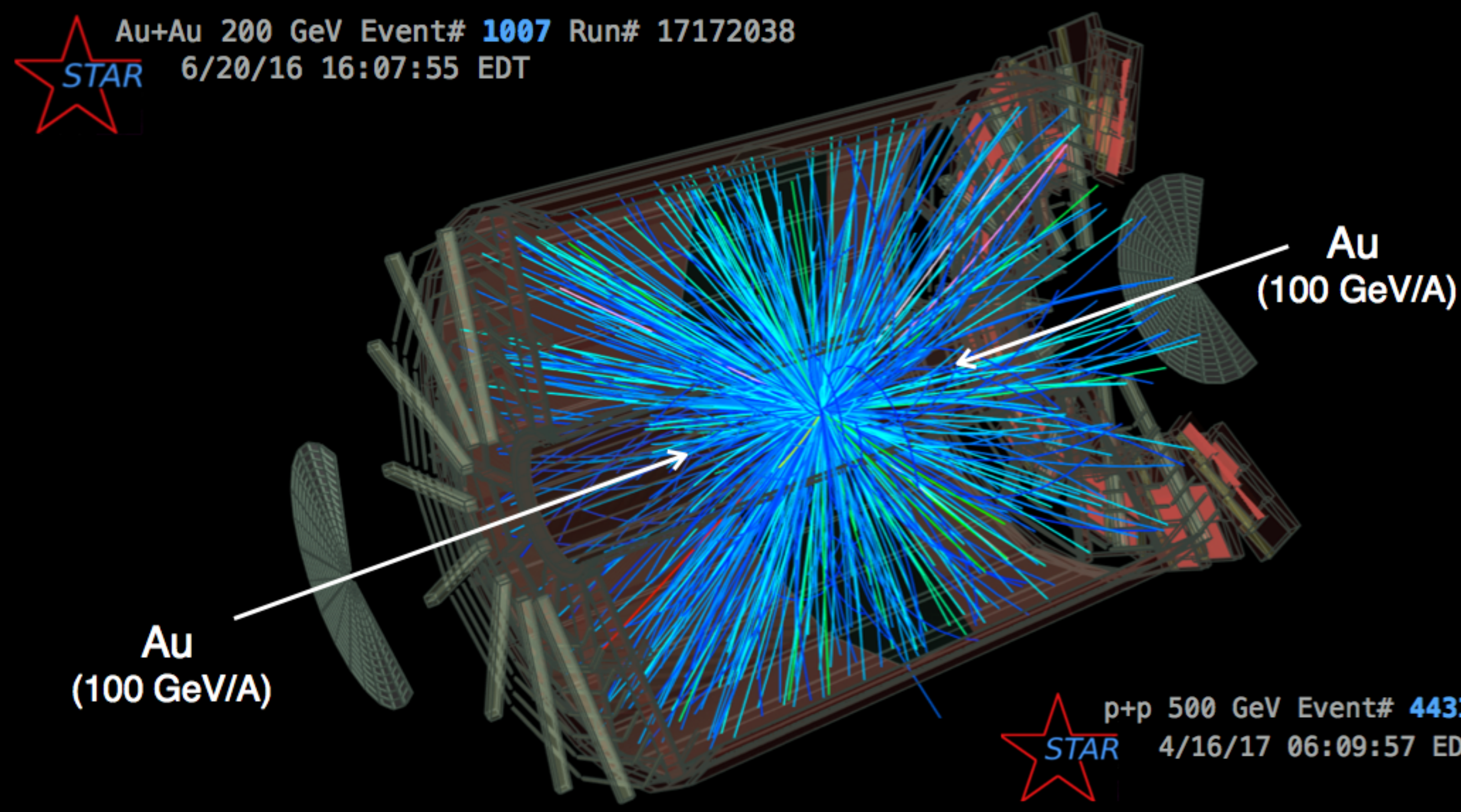
Next decade will improve/verify/falsify our knowledge of nuclei @ high √s

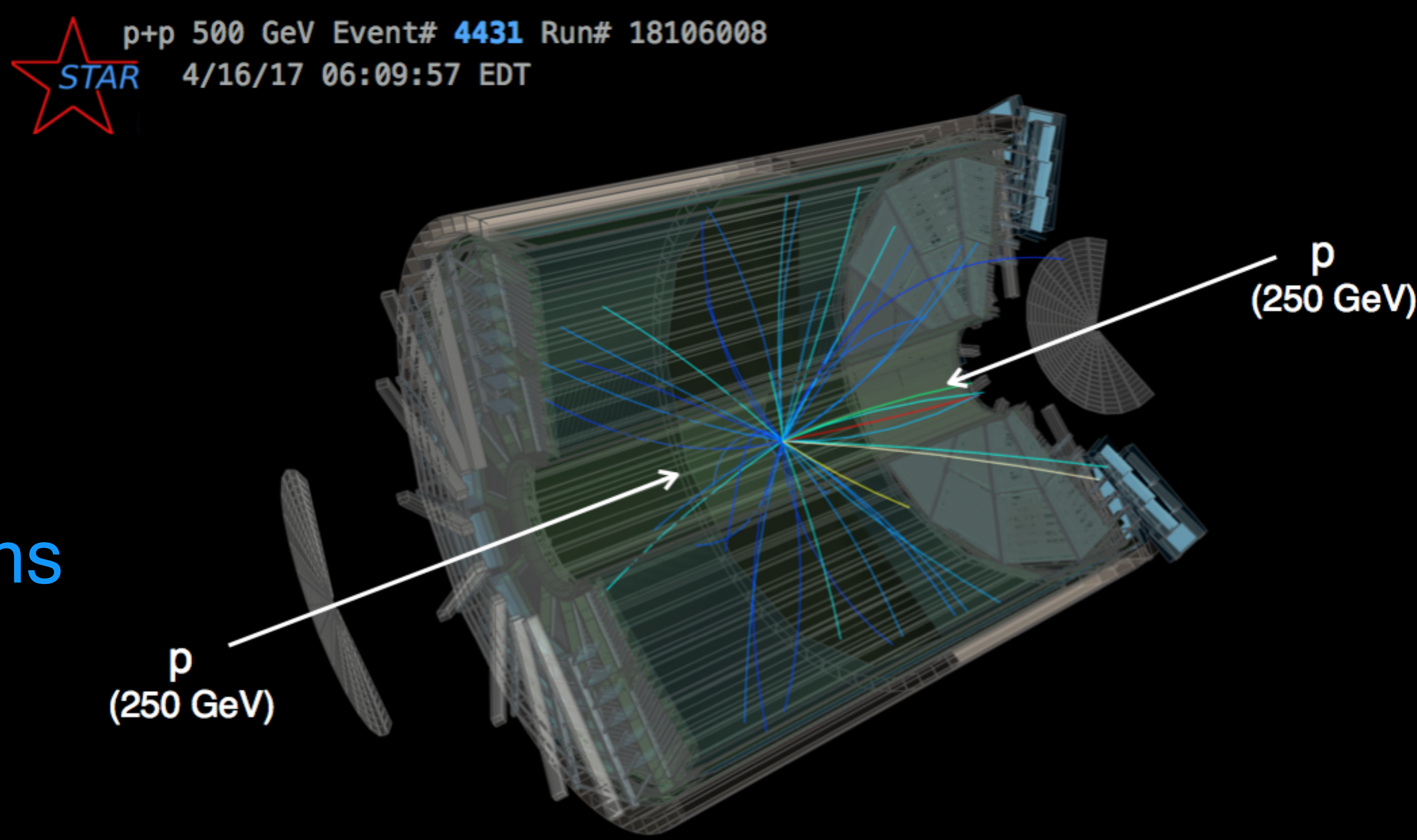
Steps towards computing Initial conditions

Different models ⇒ approximate different steps

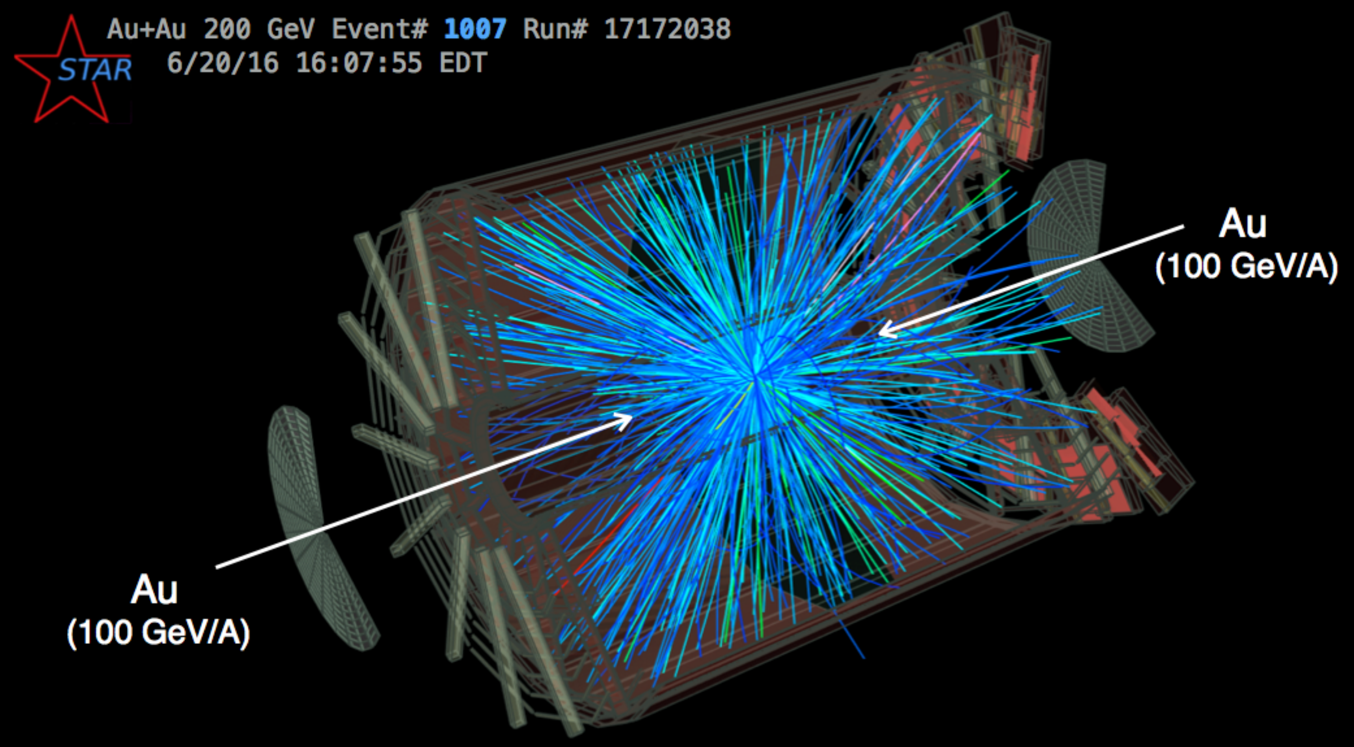


But we need something more than that

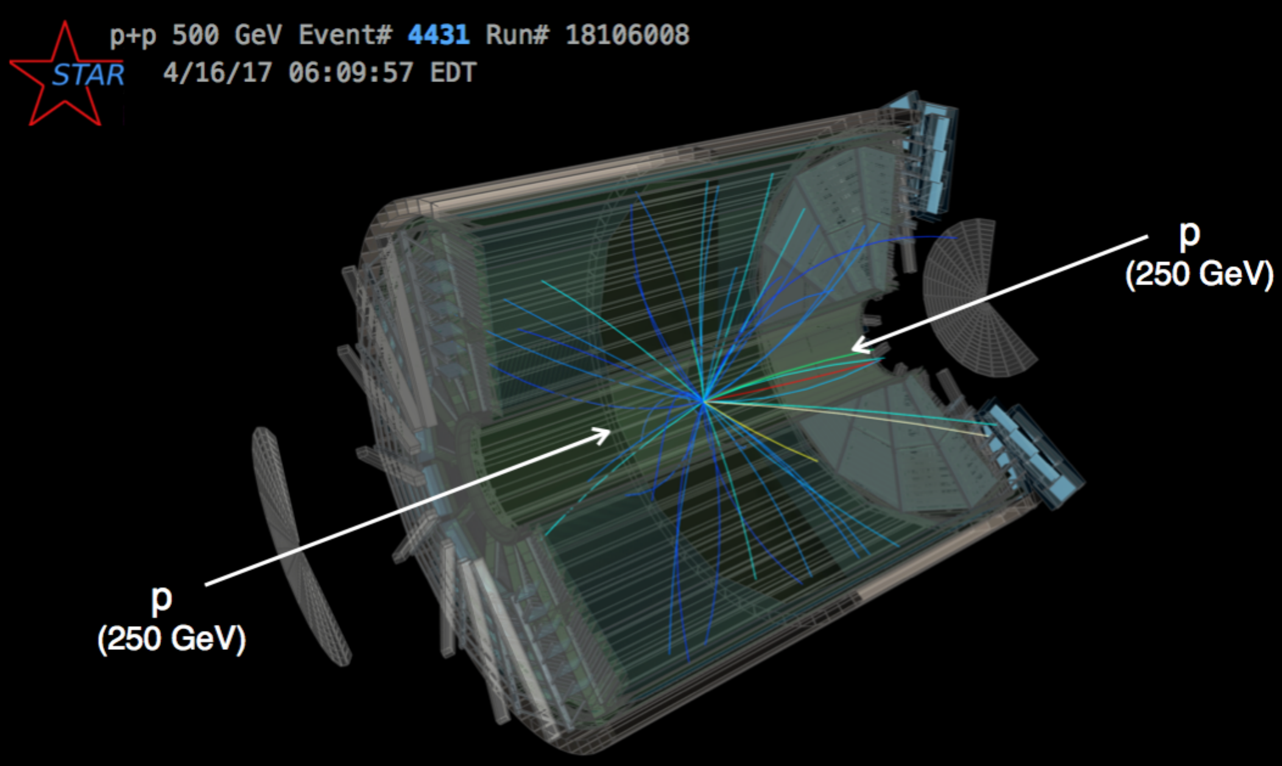




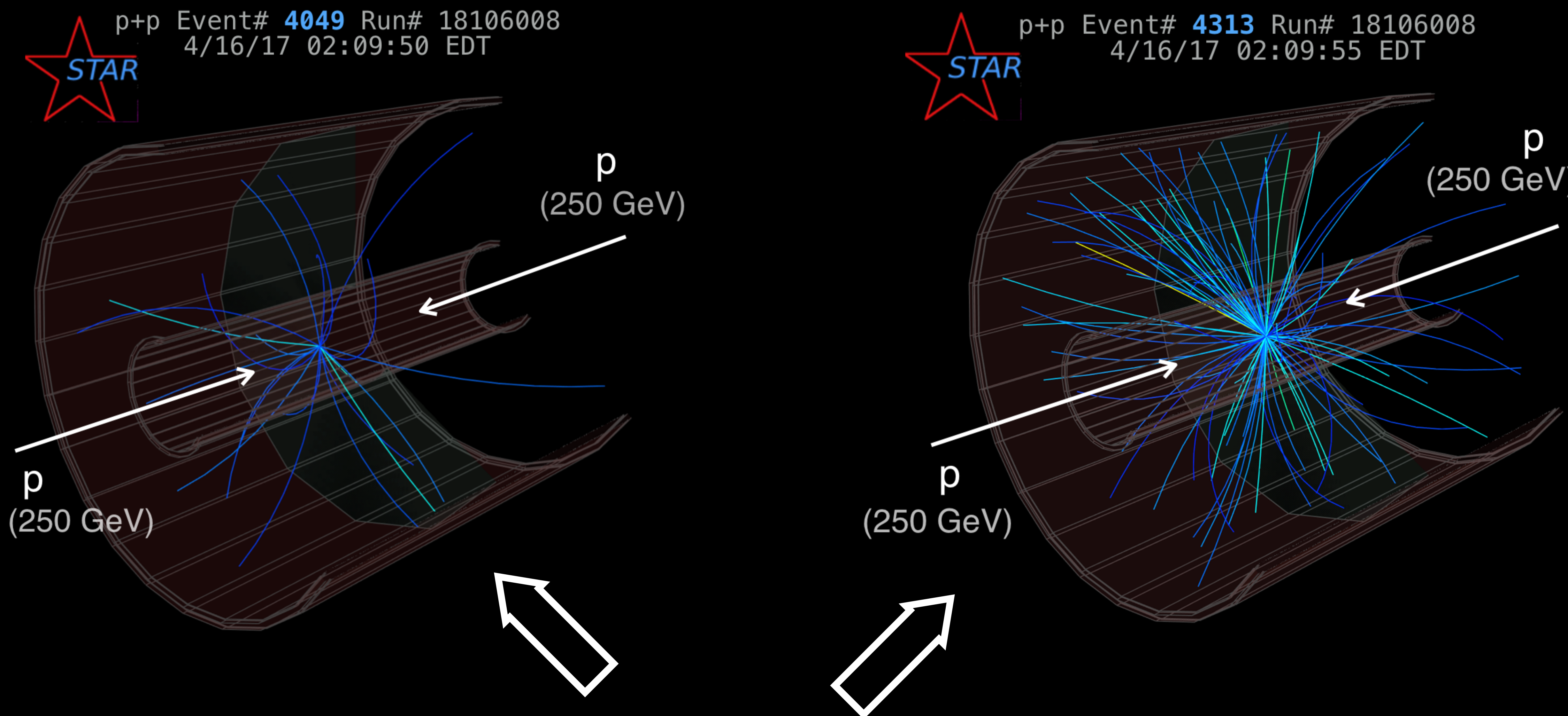
The most essential element
is the event-by-event fluctuations



Role of initial geometry & e-by-e fluctuations



Let's start with p+p collisions

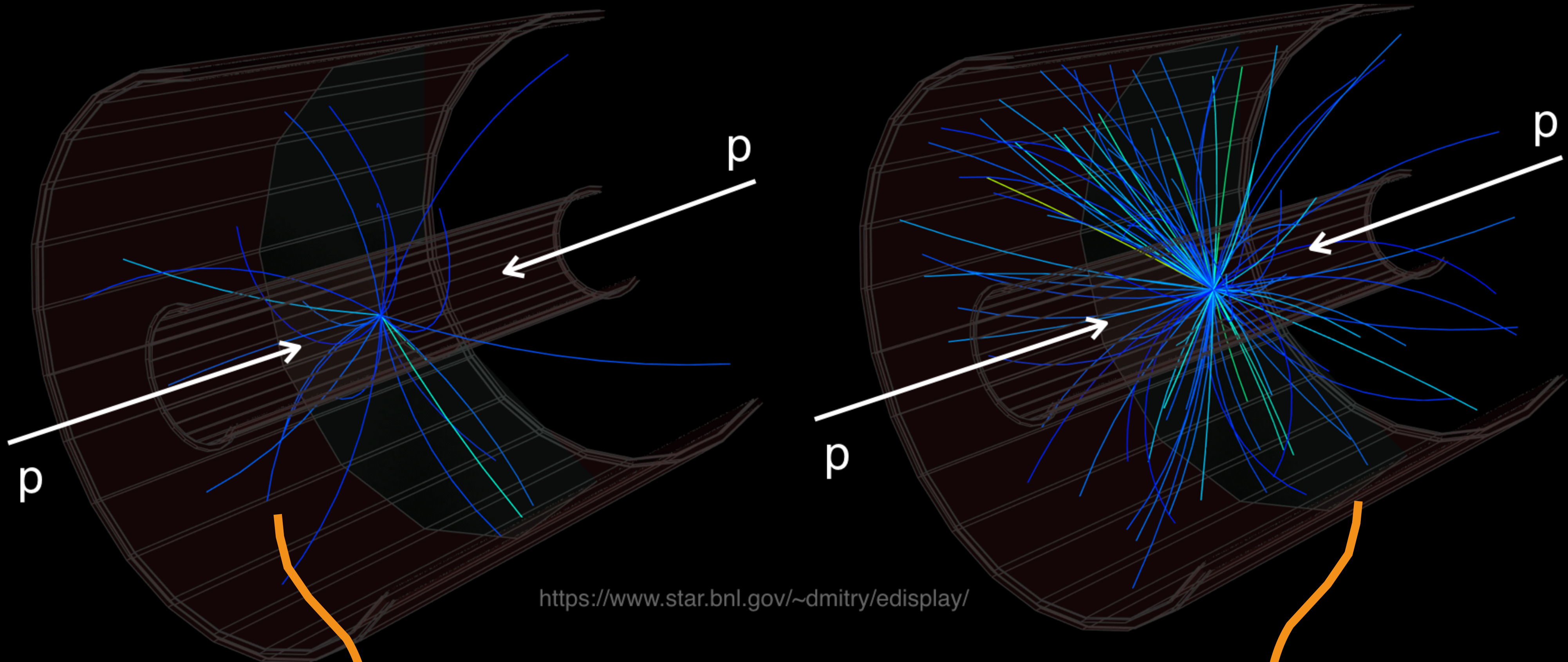


What is the main difference ??

Two different p+p collisions at the same energy are very different

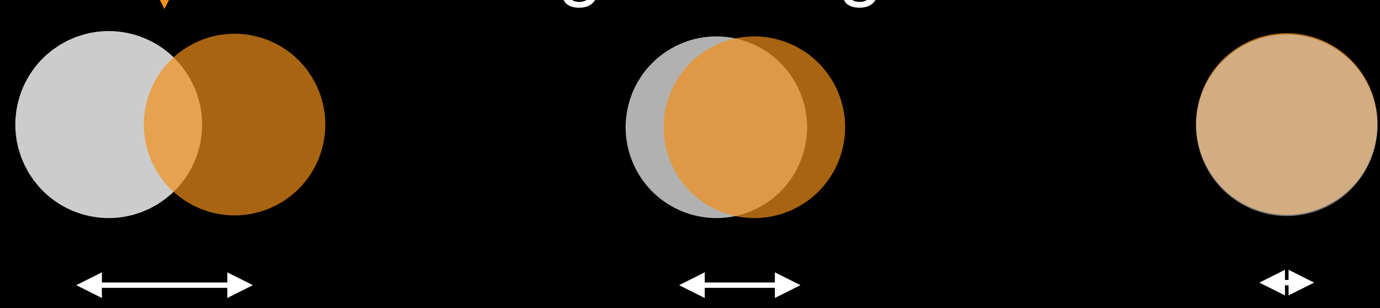
In some rare events many particles are produced, how this happen ?

Let’s start with p+p collisions



Average configuration

Peripheral
(few particles)

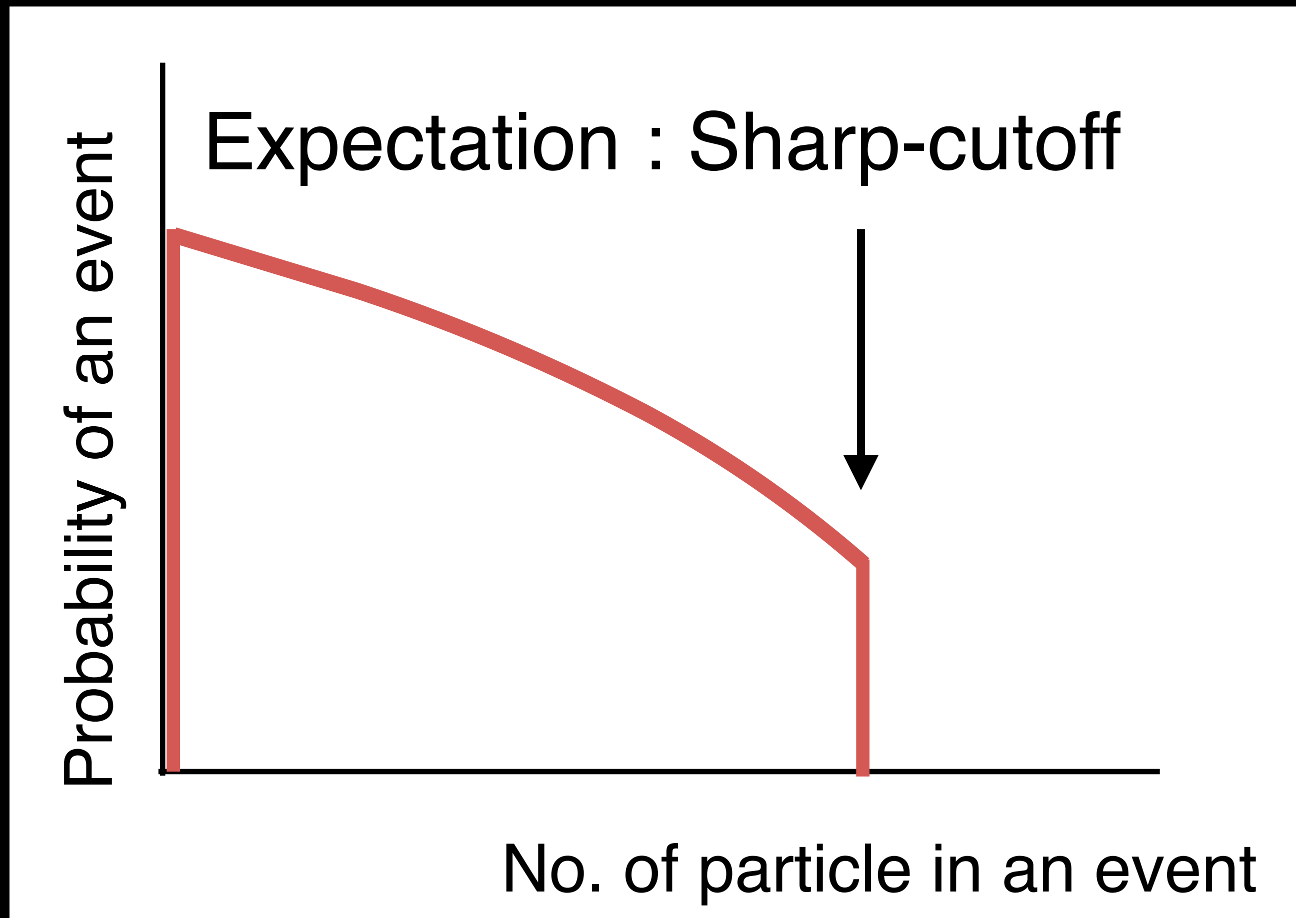


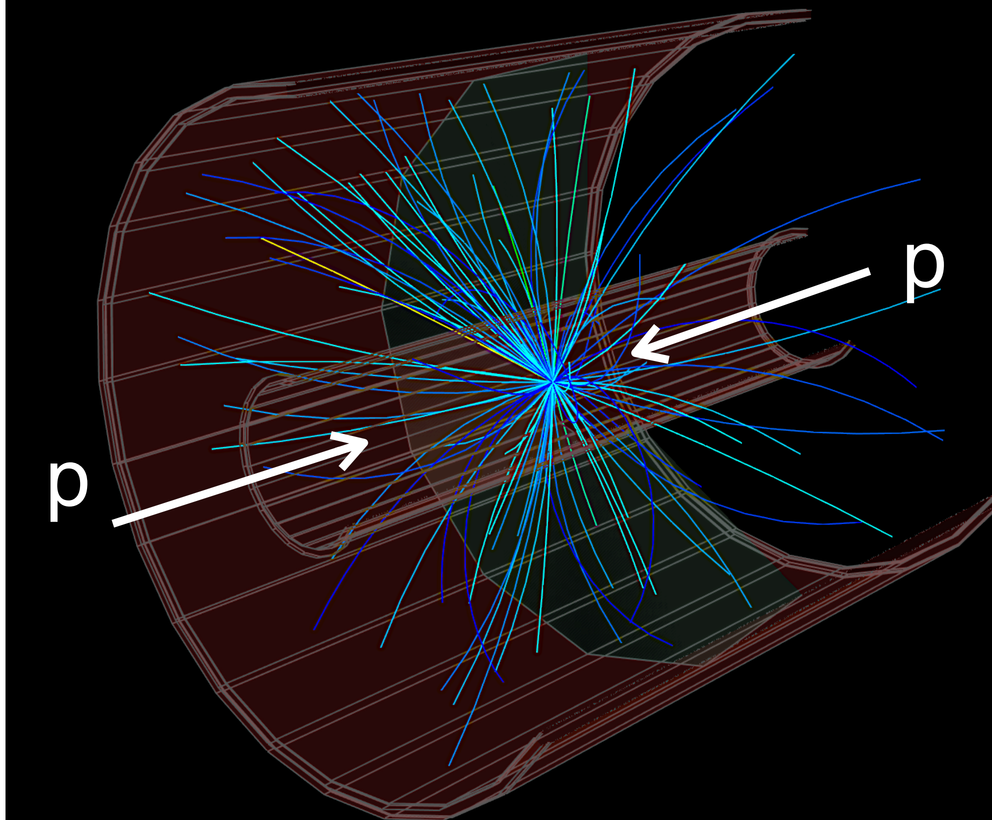
Central
(many particles)

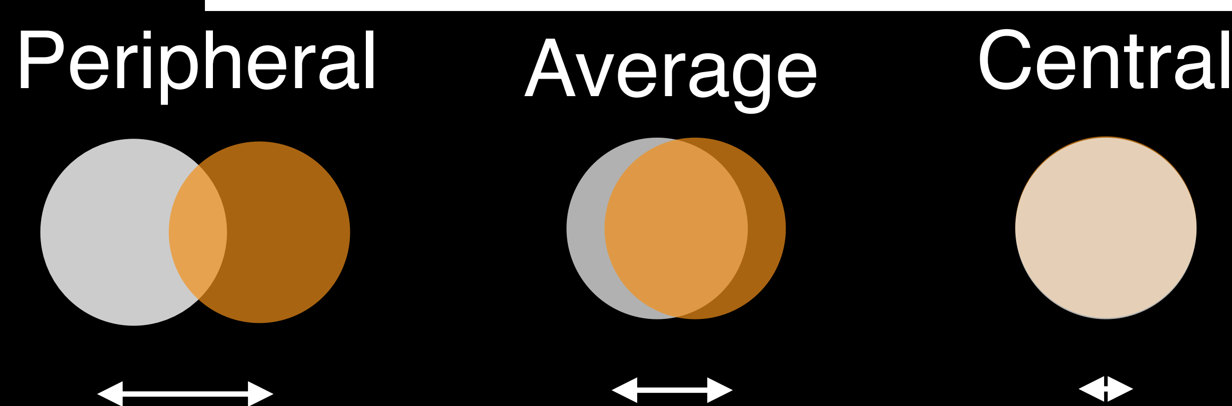
Possibilities:

1. Protons are extended objects & head-on collisions are rare ?

What leads to rare events in p+p collisions?







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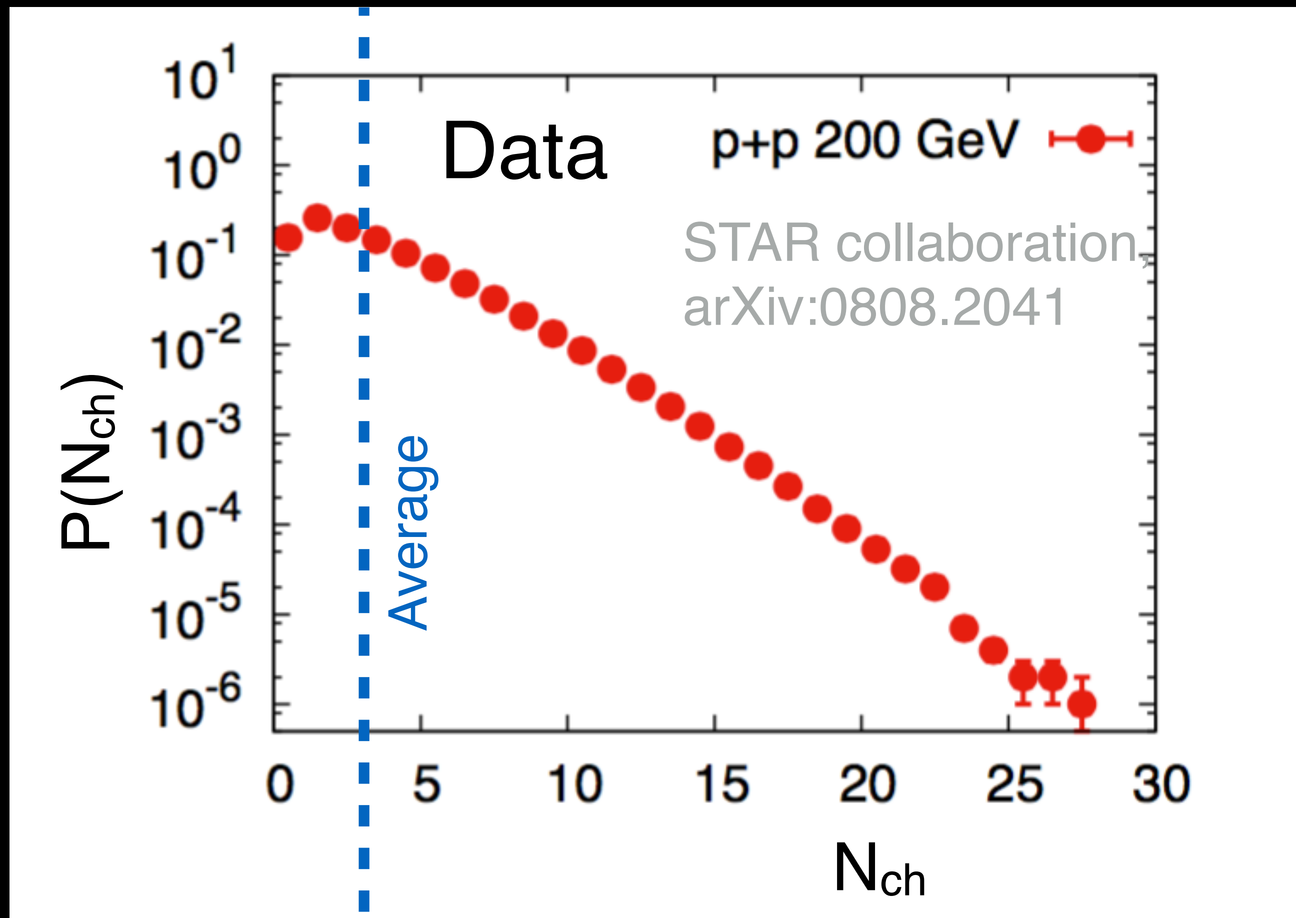

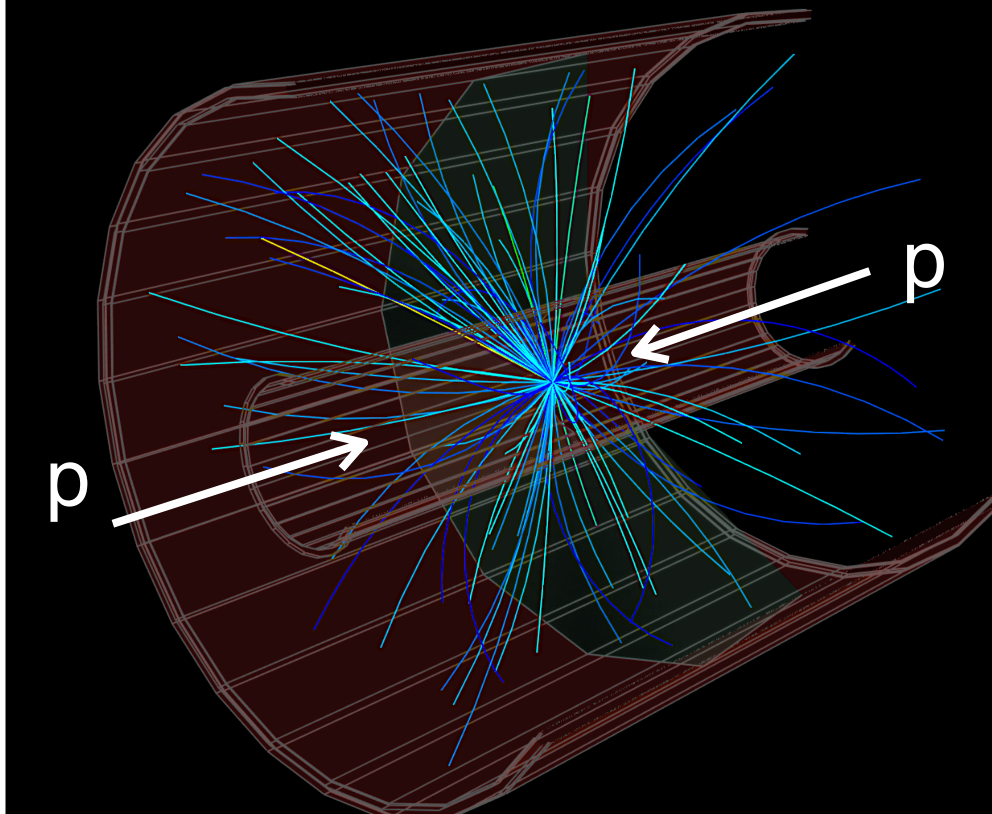

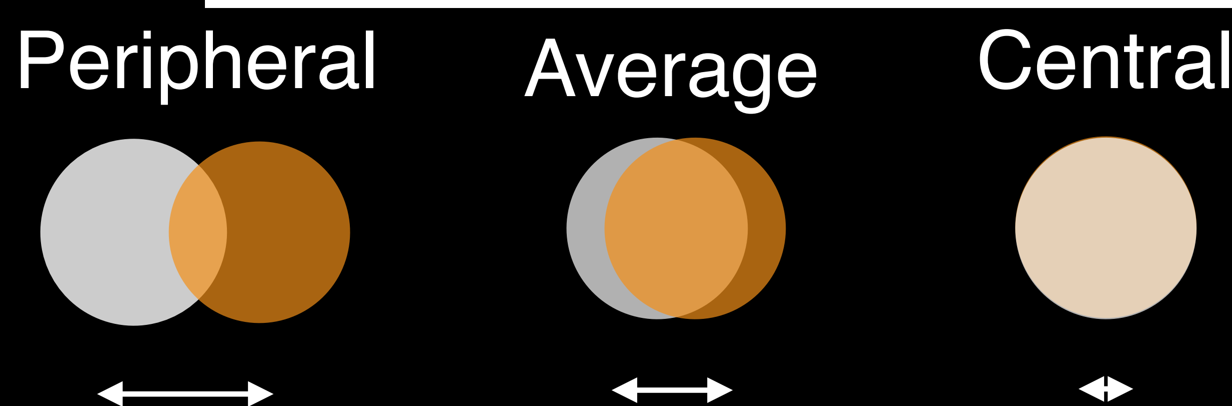

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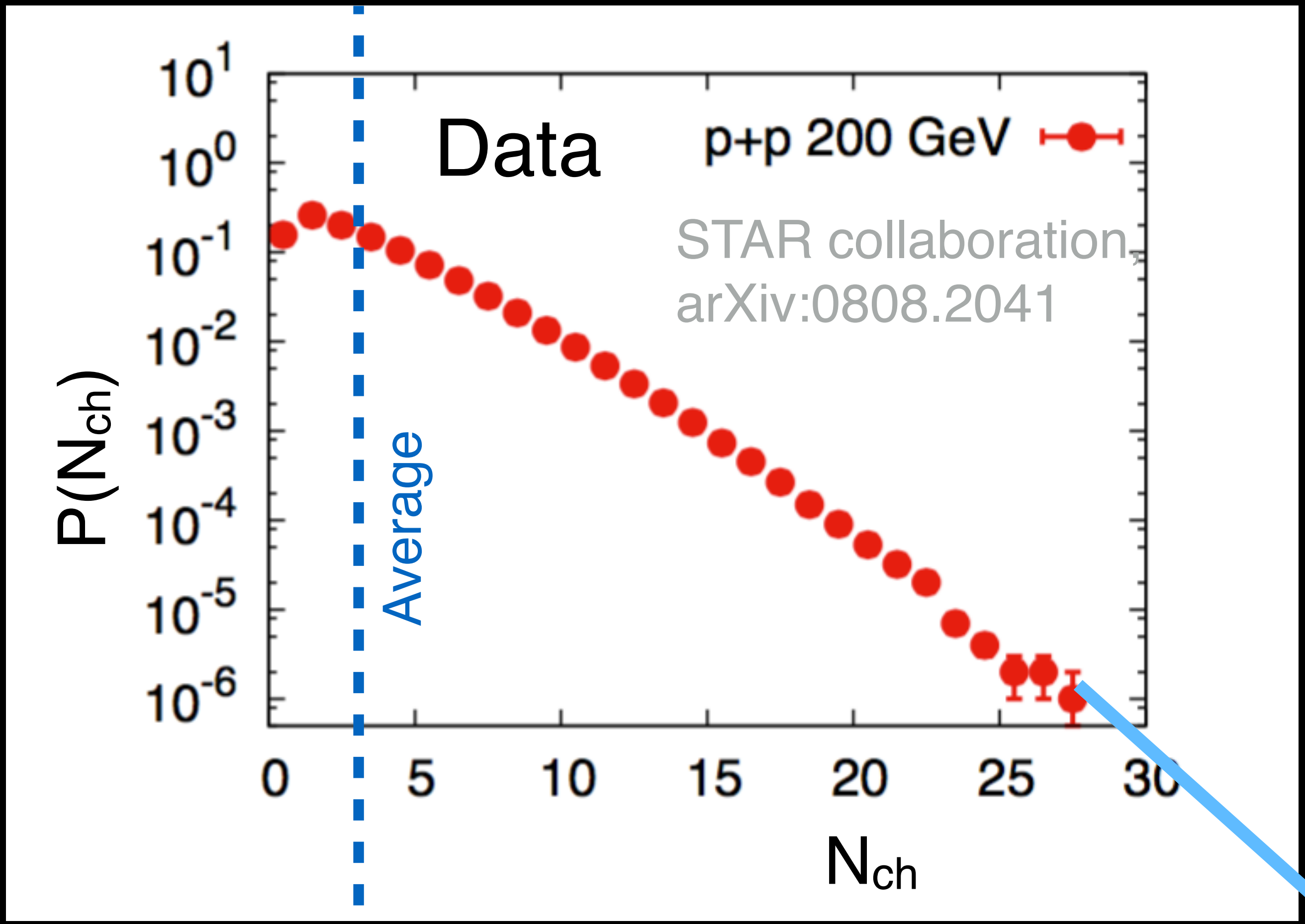
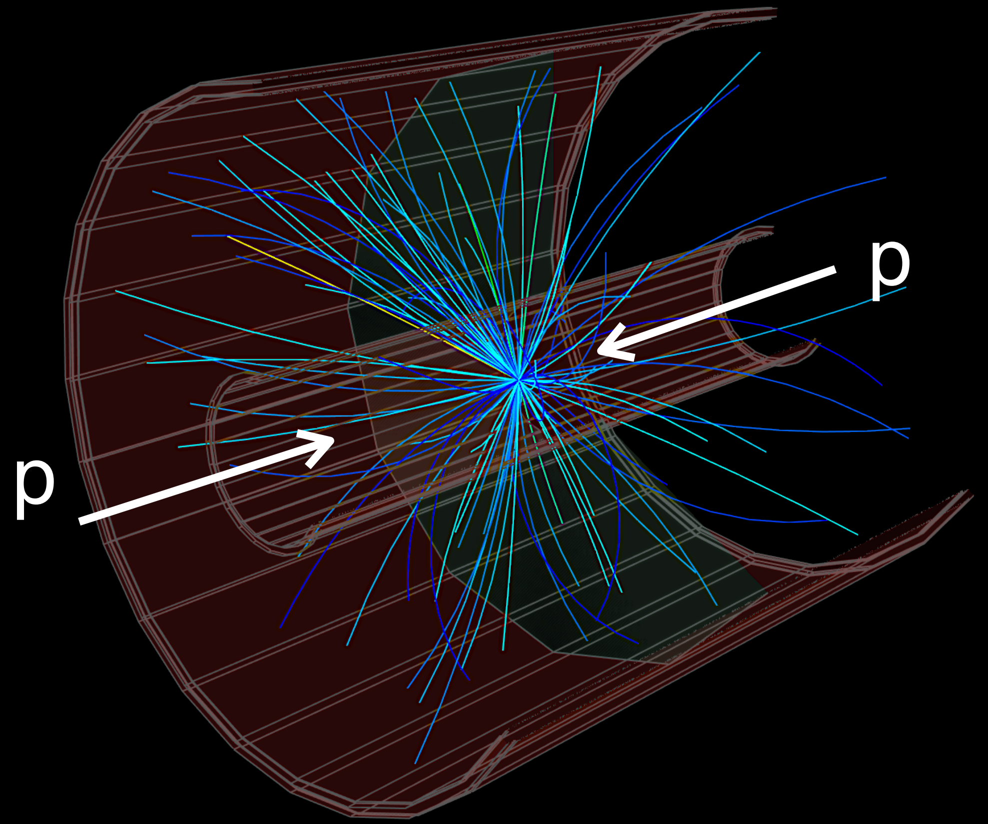
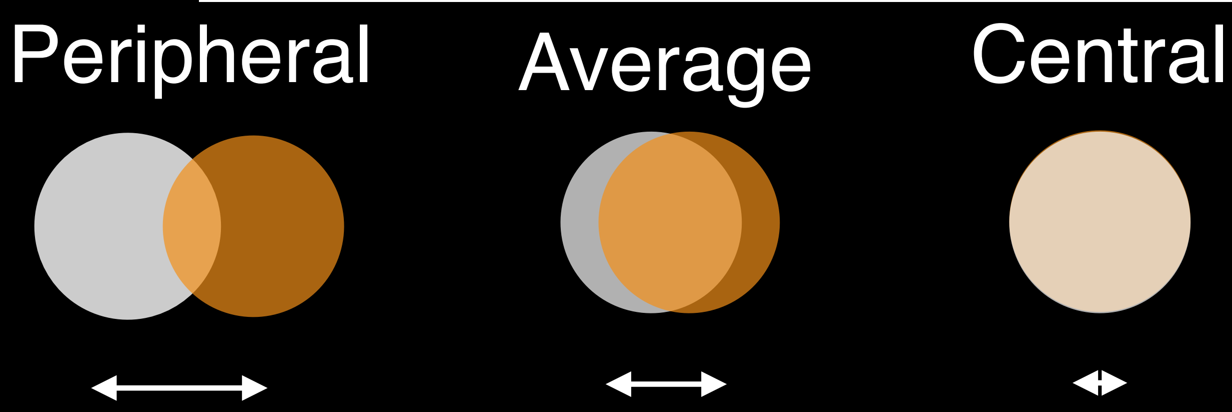




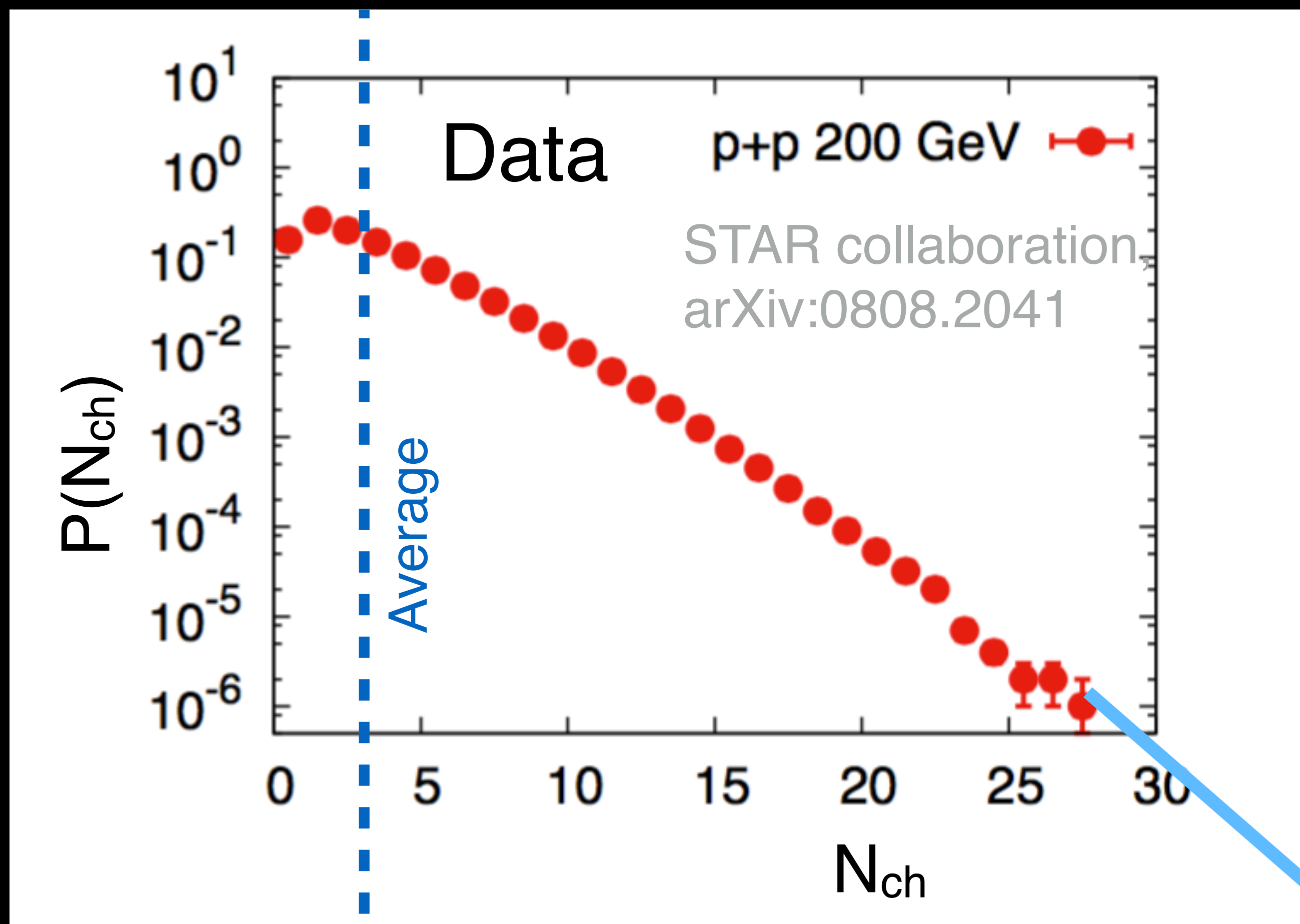


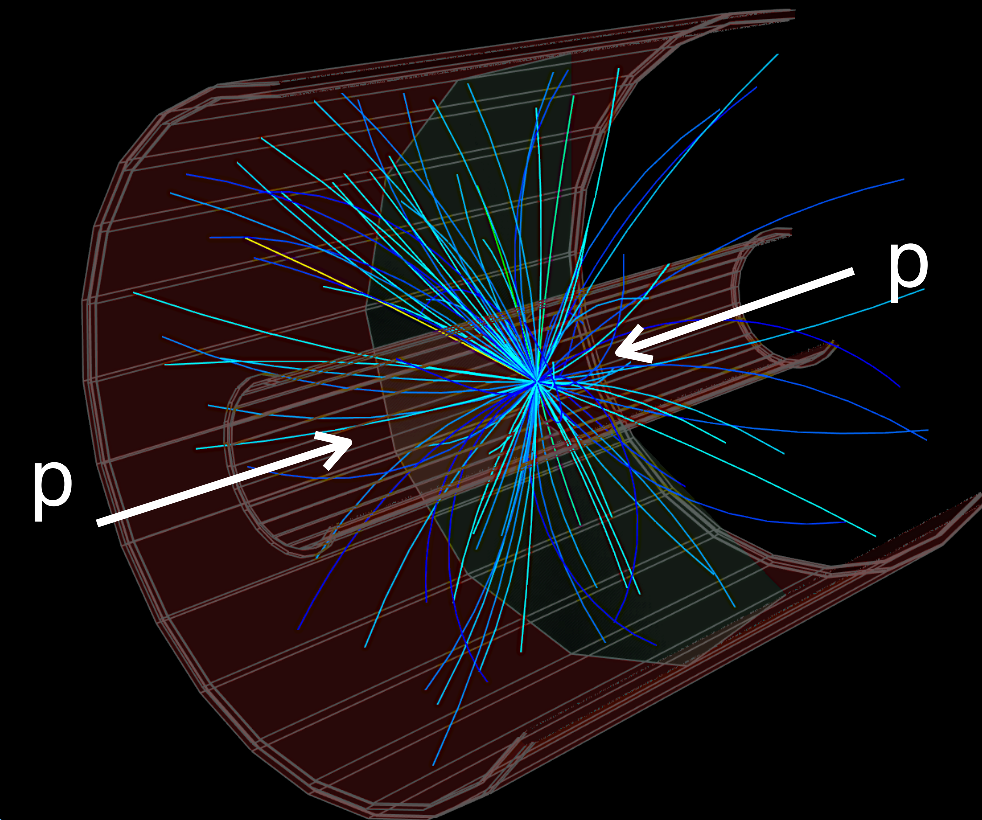
? ? ? ? ? ?
No sharp cutoff !!

Possibilities:

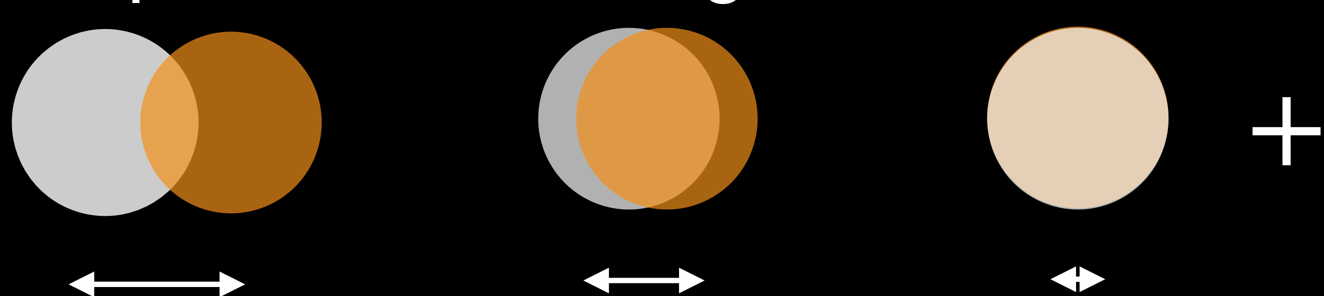
1. Protons are extended objects & head-on collisions are rare ?
2. There are other fluctuations inside the protons ?

What leads to rare events in p+p collisions?





Peripheral Average Central



Sub-nucleonic fluctuations

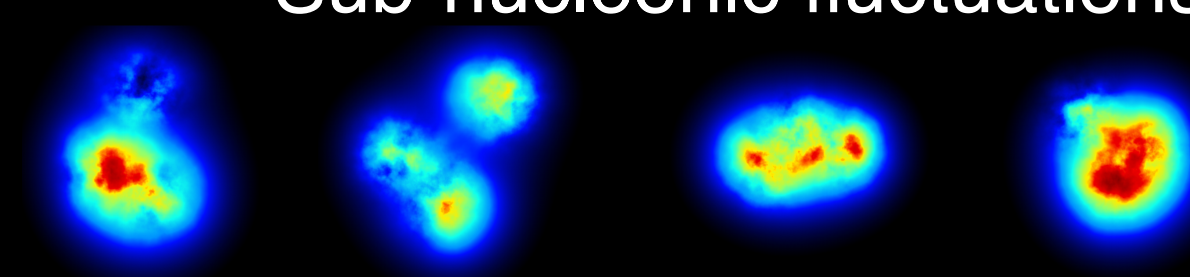


fig: arXiv:1603.04349

A combination of proton geometry & fluctuations can explain p+p data

This essential feature of the data must be incorporated in modeling of I.C.

Steps towards computing Initial conditions

Collect Knowledge of Protons
(shape, fluctuations)

1

Understanding the shape of a proton

A closer look at the proton shape

Deep inelastic scattering of electron with proton (e+p)

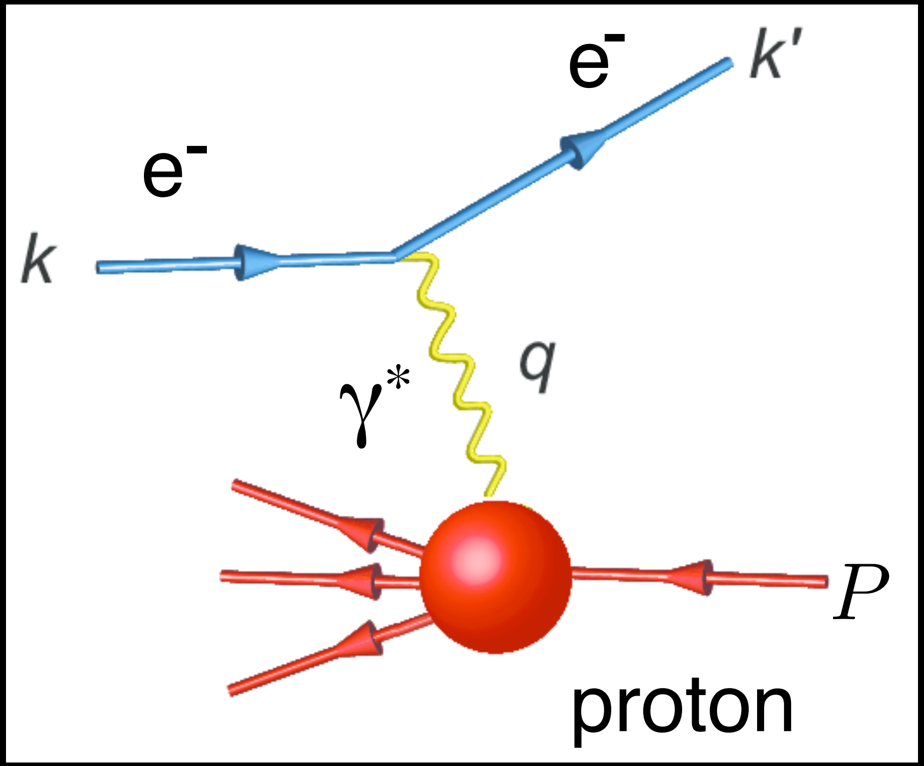


fig: Accardi *et al* arXiv:1212.1701

Hadron-**E**lectron **R**ing **A**ccelerator (HERA) at DESY, Hamburg (1992-2007)

Growth of gluons in electron-proton collisions

Deep inelastic scattering of electron with proton (e+p)

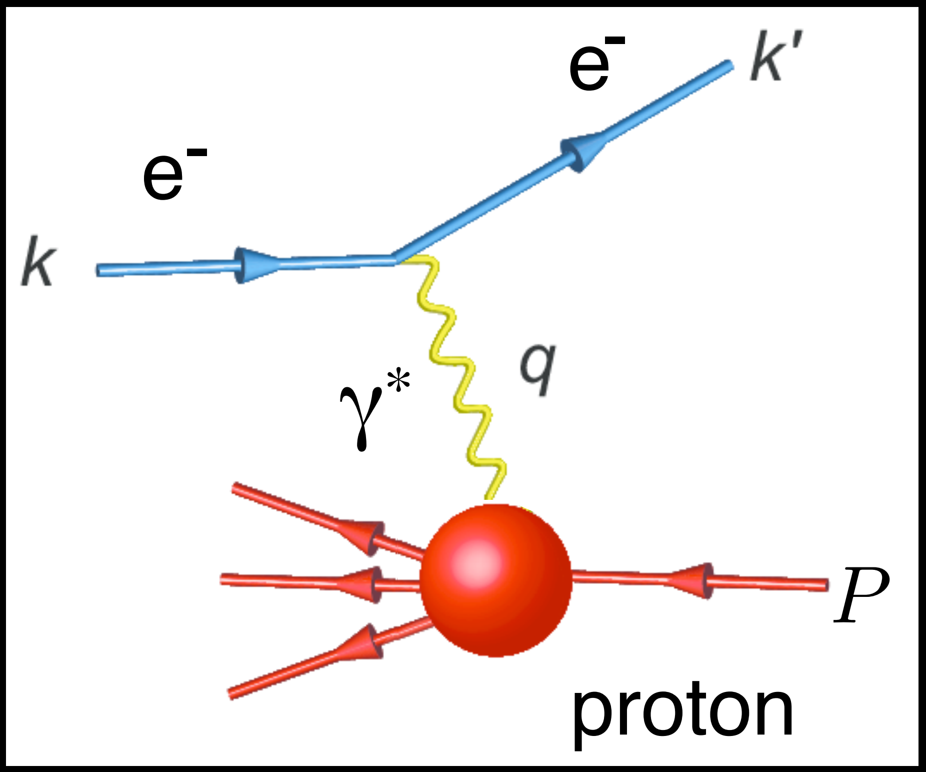
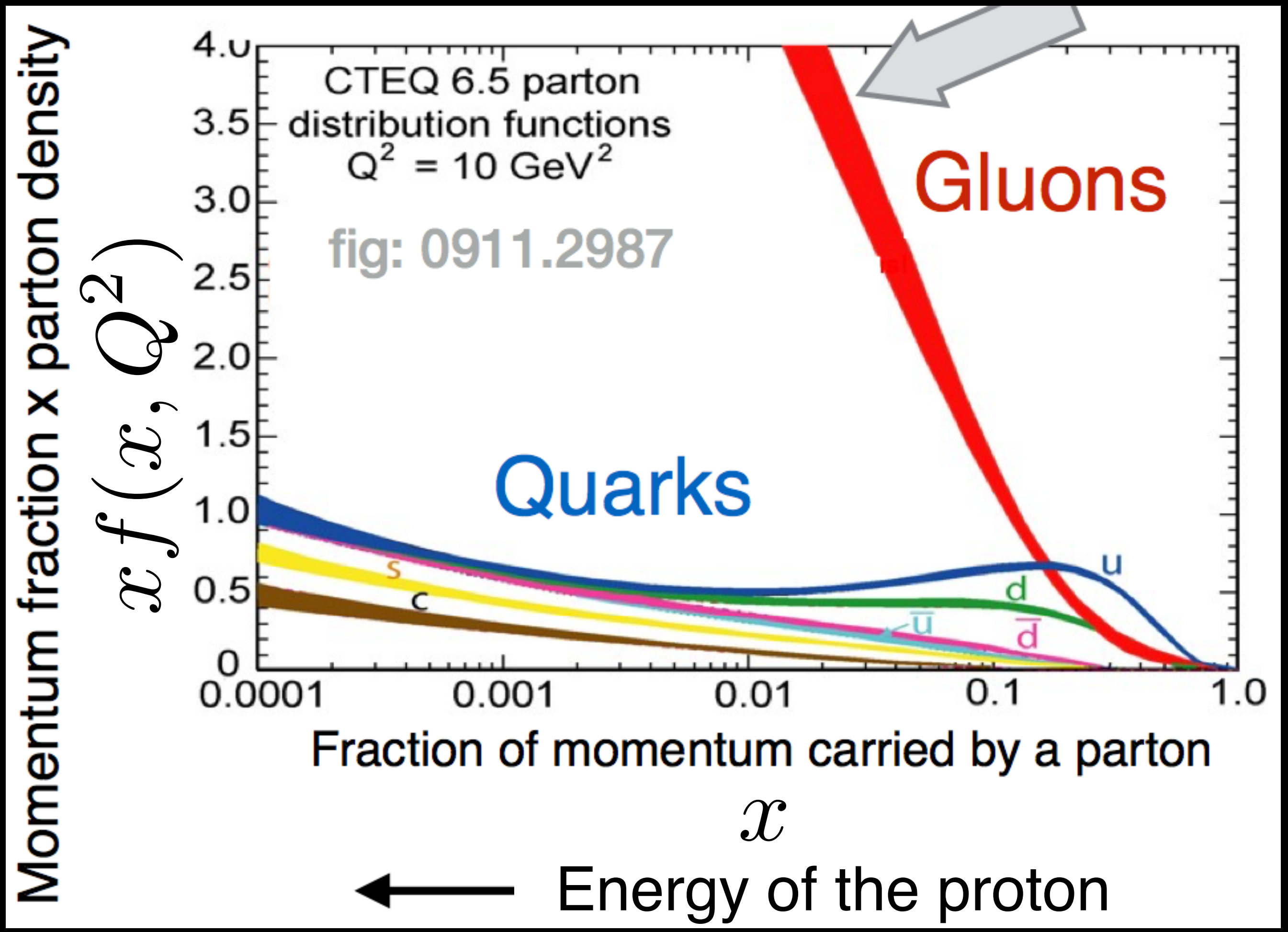


fig: Accardi *et al* arXiv:1212.1701

Rapid growth of gluon density



Faster moving proton becomes more dressed with gluons

Growth of gluons in electron-proton collisions

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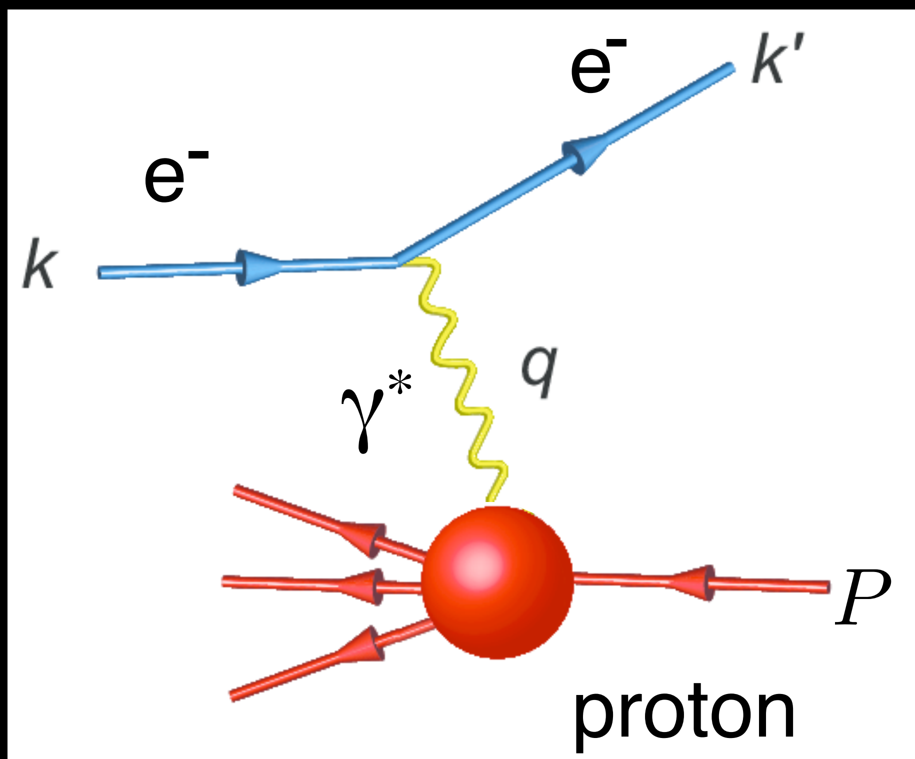

fig: Accardi

Faster moving proton becomes more dressed with gluons

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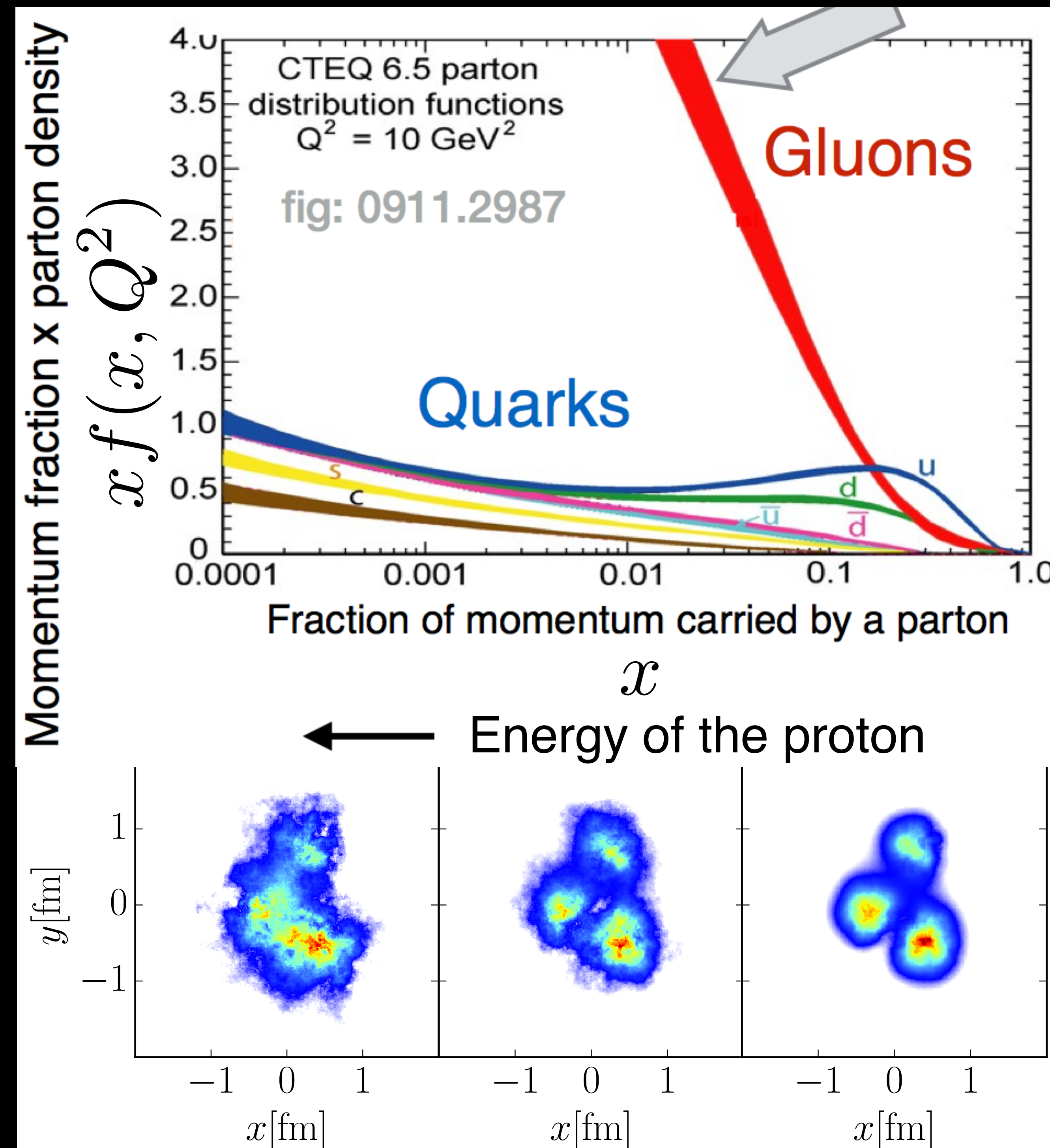
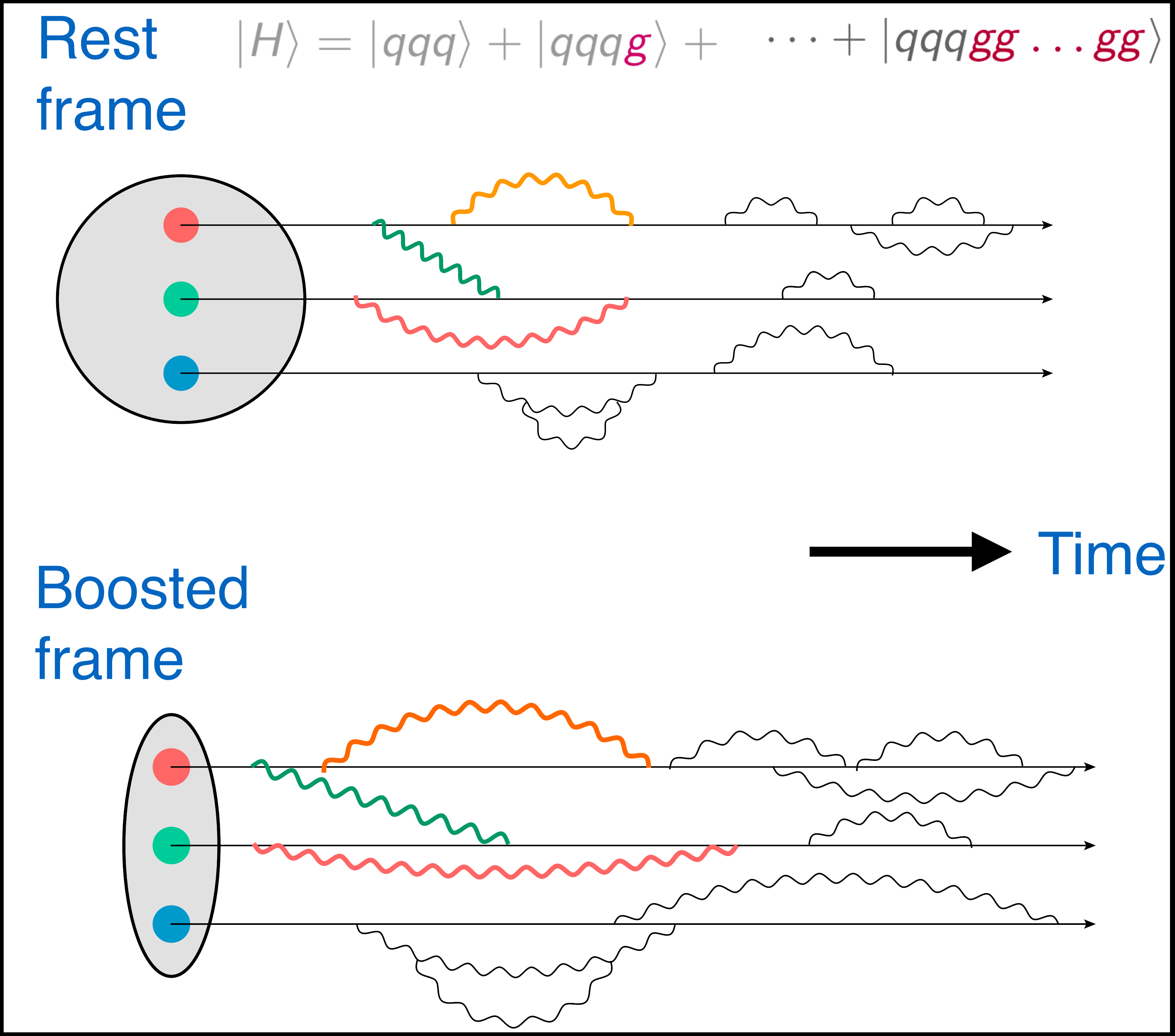


fig: Mantysaari, Schenke arXiv:1806.06783

Proton at rest vs fast moving proton



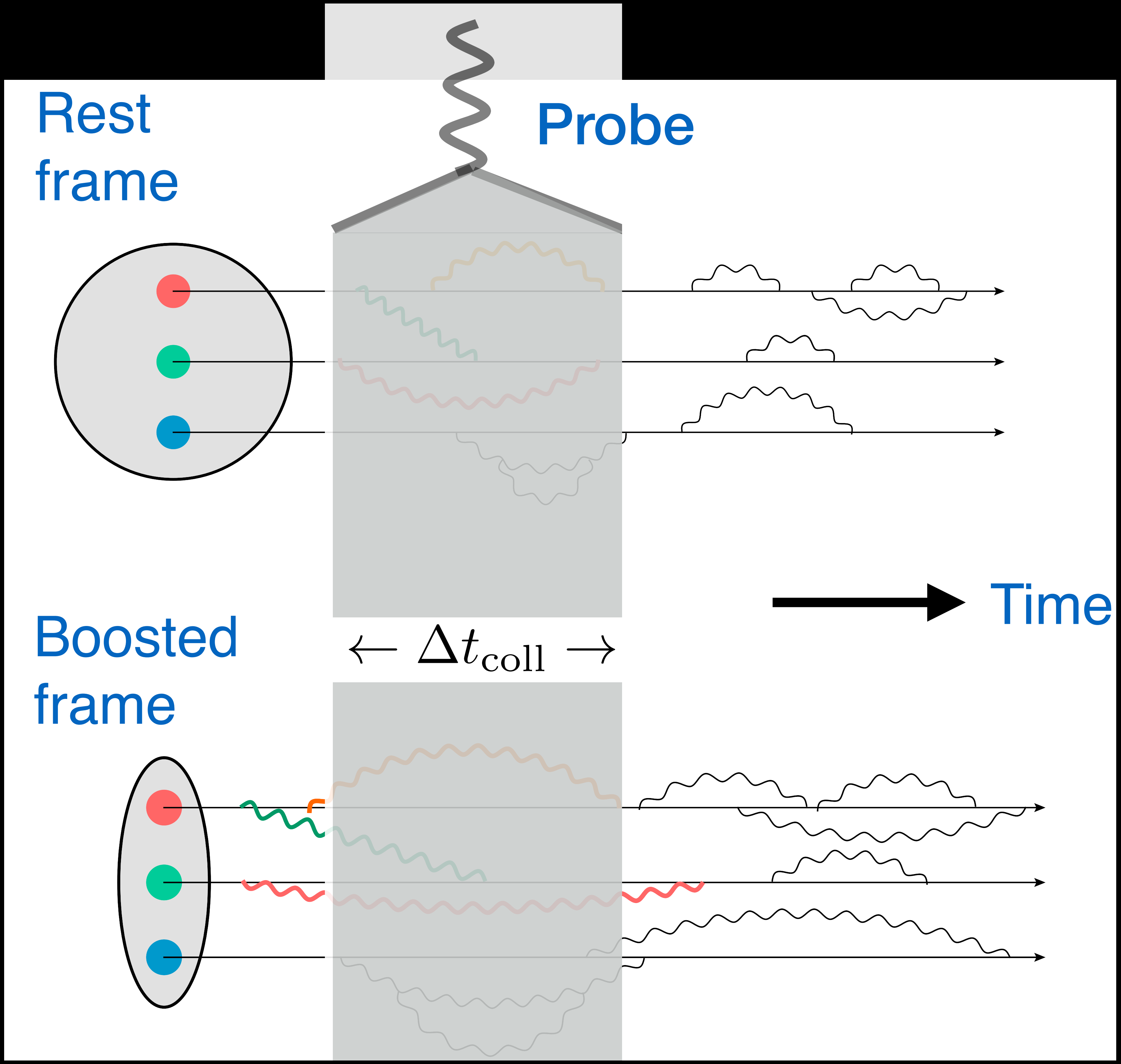
Quantum fluctuations

$$\Delta t_{\text{fluc}} = \Delta t_{\text{RF}}$$

Long-lived Quantum fluctuations

$$\Delta t_{\text{fluc}} = \gamma \Delta t_{\text{RF}}$$

Proton at rest vs fast moving proton



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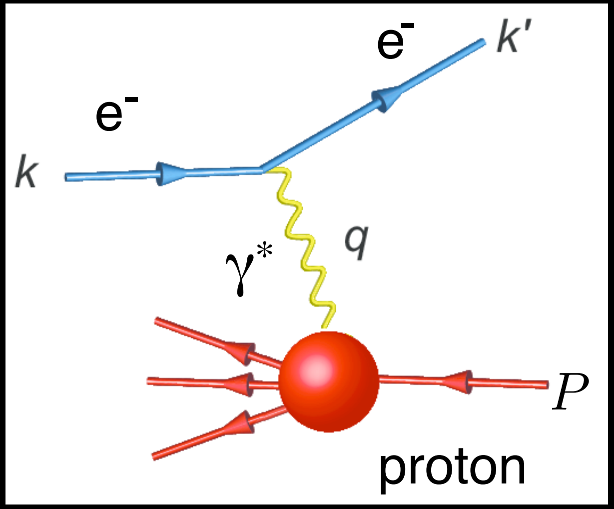
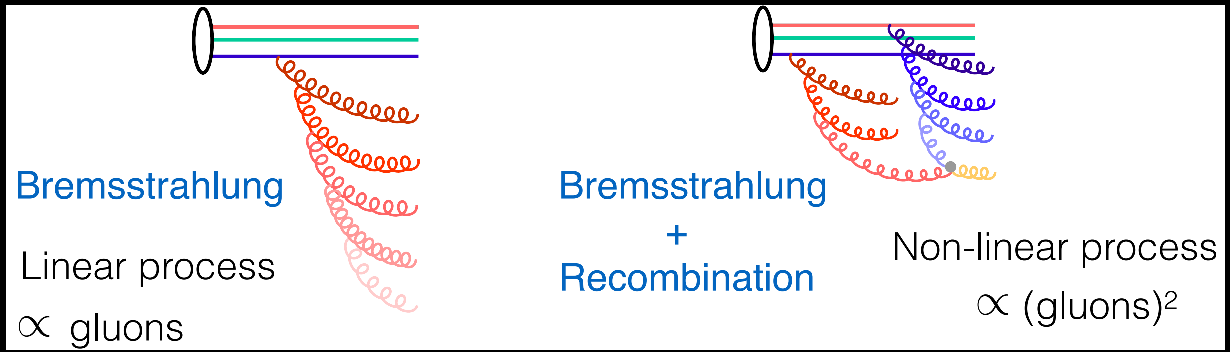


fig: Accardi

Gribov, Levin Ryskin 1983



The competition between two processes leads to gluon saturation

Rapid growth of gluon density

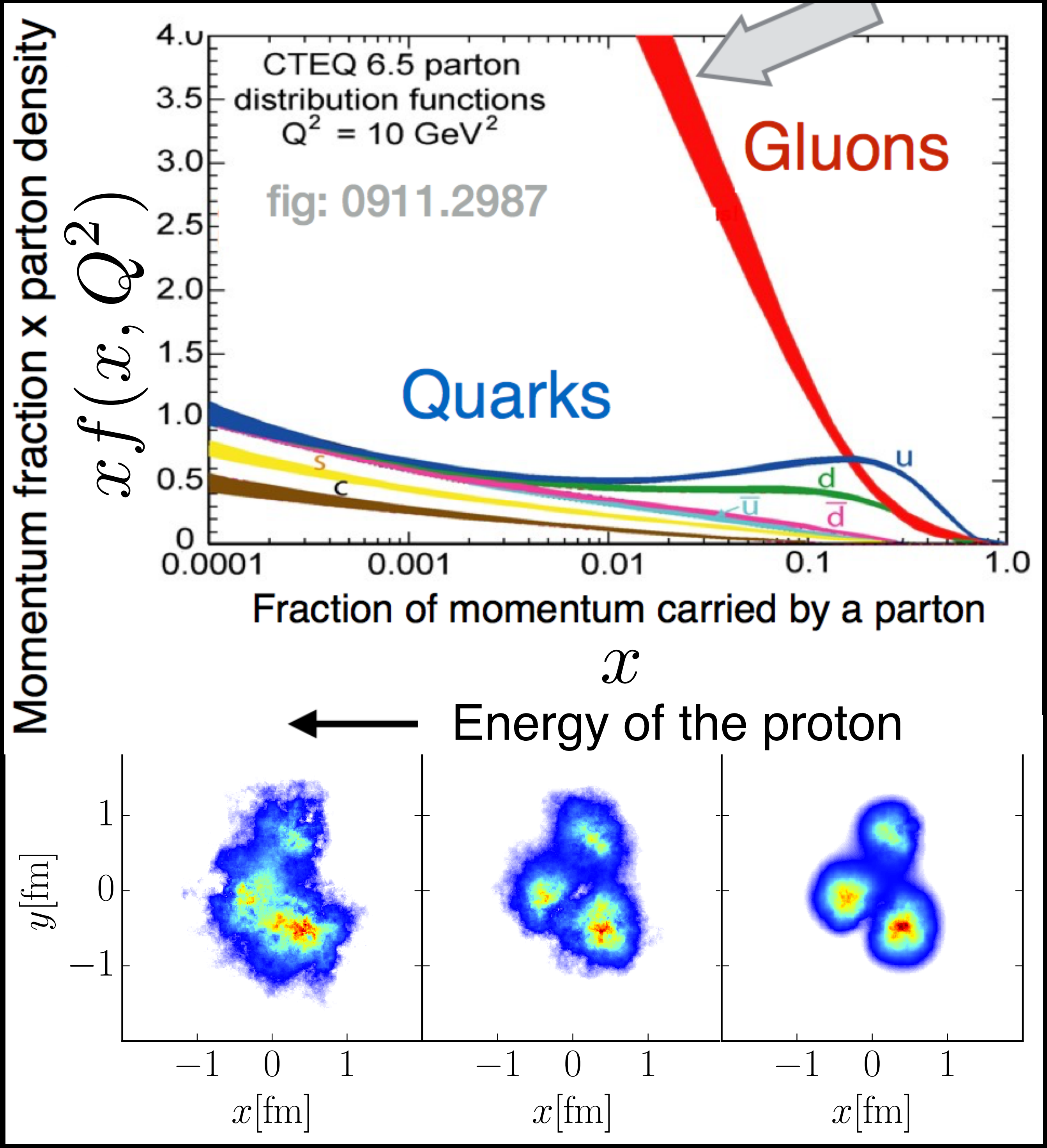


fig: Mantysaari, Schenke arXiv:1806.06783

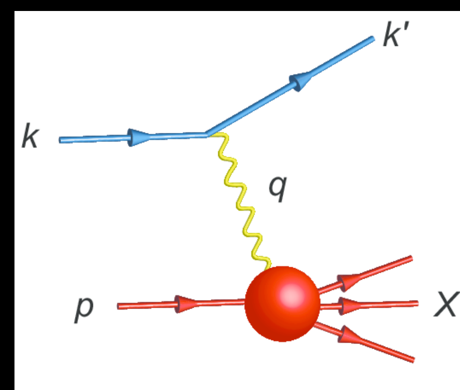
How do we know the shape of a proton?

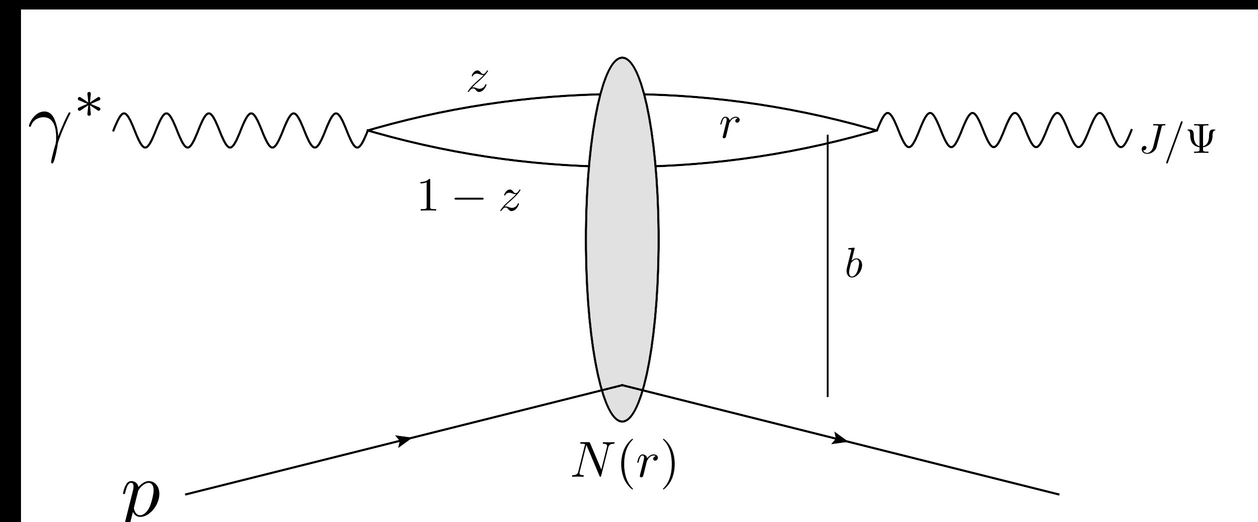
We study exclusive diffractive vector meson production in DIS e+p :

γ^*+p → J/ψ+p, no color exchange between the proton & the probe

Kowalski, Teaney hep-ph/0304189v3

Mantysaari, Schenke, Phys. Rev. Lett. 117, 052301 (2016), Phys.Rev. D94 (2016) 034042





Coherent diffraction :

Proton remains intact, probes to average gluon distribution ⇒

$$\frac{\mathrm{d}\sigma^{\gamma^* p \to J/\Psi p}}{\mathrm{d}t} = \frac{1}{16\pi} \left| \langle A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \rangle \right|^2$$

Incoherent diffraction :

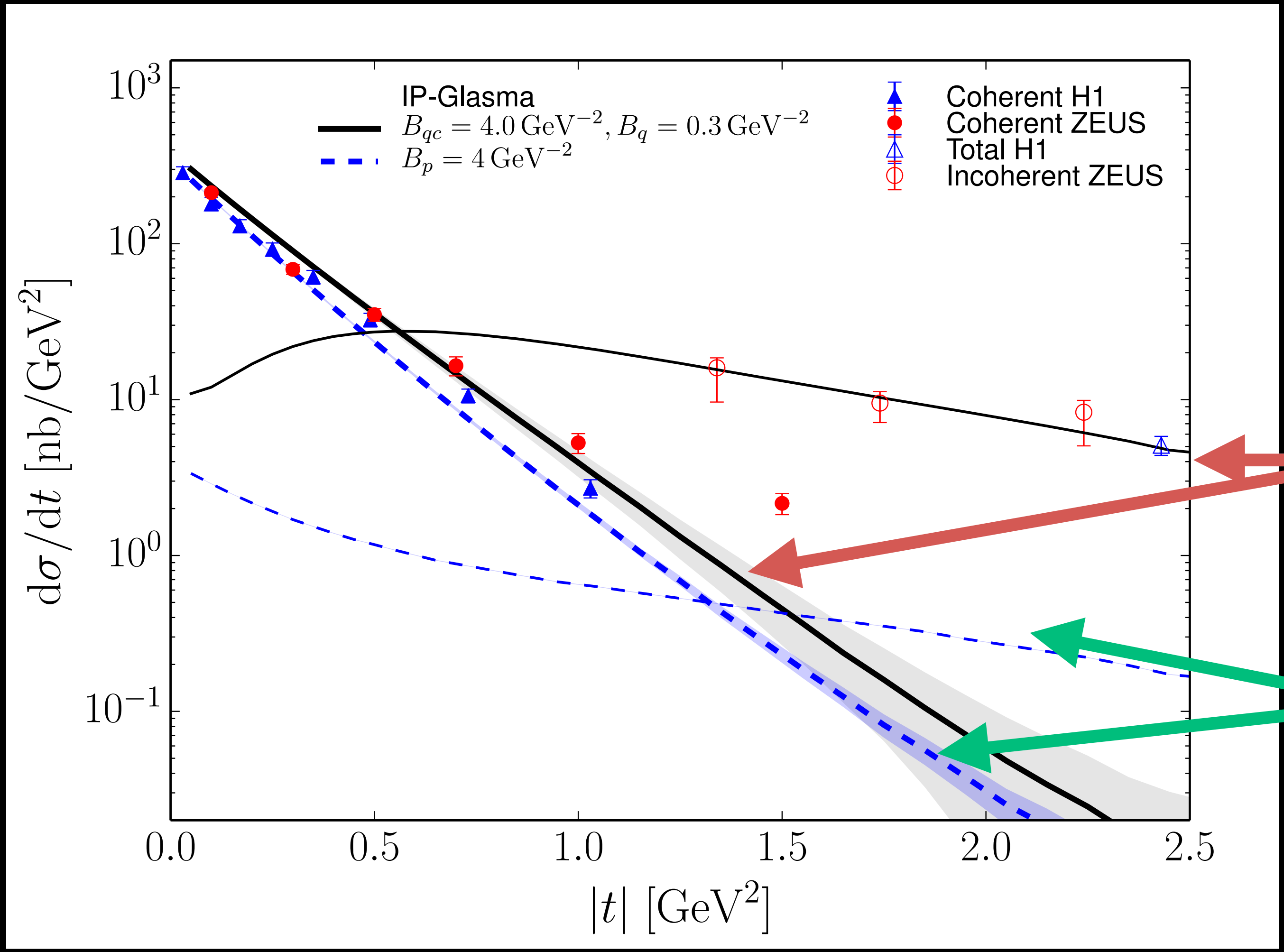
Proton breaks up, probes the shape fluctuations of the proton ⇒

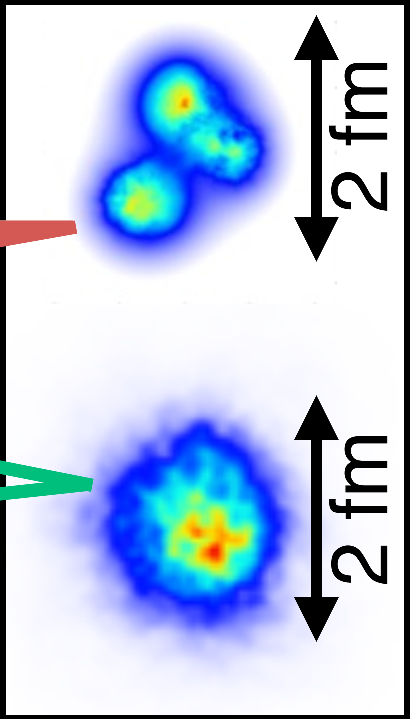
$$\frac{\mathrm{d}\sigma^{\gamma^* N \to J/\Psi N^*}}{\mathrm{d}t} = \frac{1}{16\pi} \left(\left\langle \left| A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \right|^2 \right\rangle - \left| \langle A(x_{\mathbb{P}}, Q^2, \mathbf{\Delta}) \rangle \right|^2 \right)$$

The shape & fluctuations inside a proton

Mantysaari, Schenke, Phys. Rev. Lett. 117, 052301 (2016), Phys.Rev. D94 (2016) 034042

Differential e-p DIS cross section :





Gluon saturation +
Eccentric proton
(fits coherent &
incoherent data)

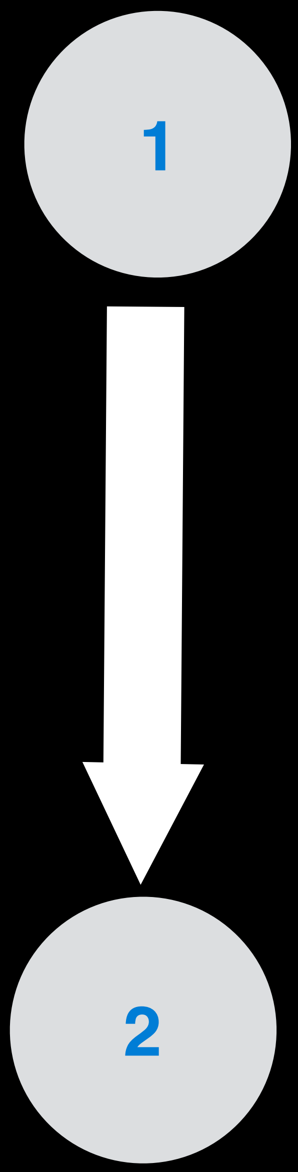
Gluon saturation +
Round proton
(fits coherent data)

Quark structure (hotspots) → successful ansatz to describe DIS data

Bottom line : DIS e+p data → crucial input on proton shape & fluctuations

Steps towards computing Initial conditions

Collect Knowledge of Protons (shape, pdf)



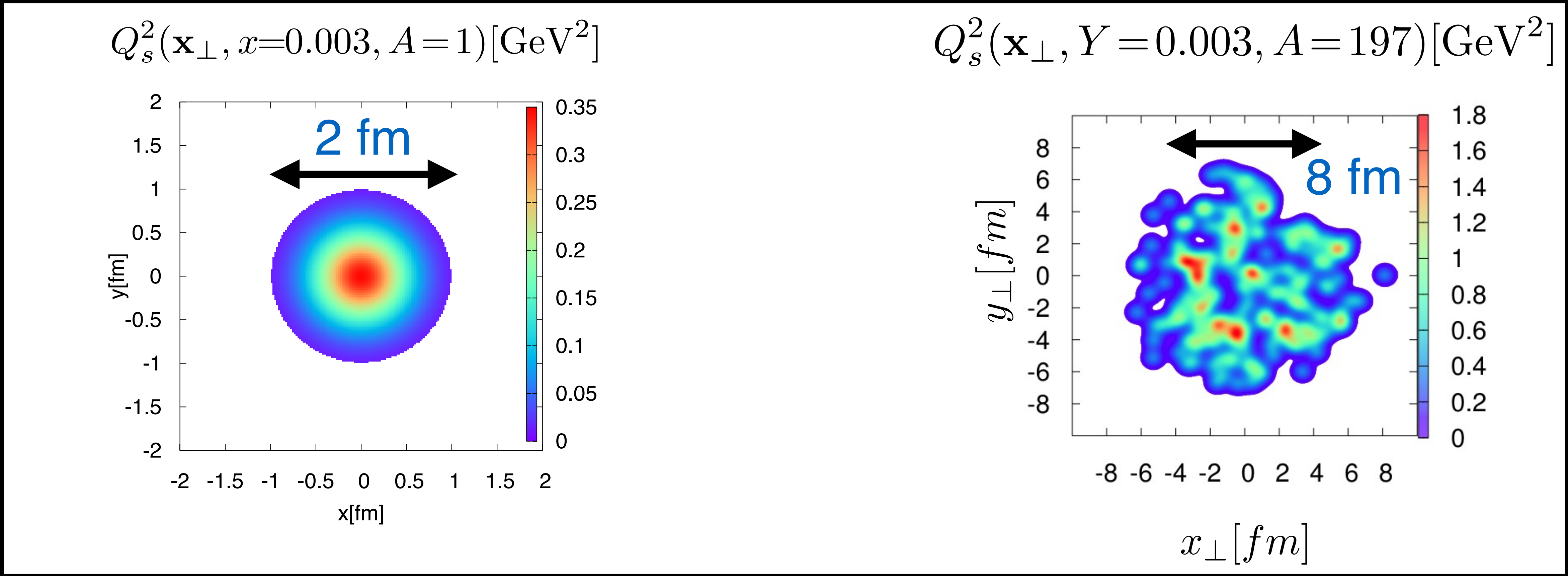
Make nuclei from protons

Constructing a nuclei from a proton

IP-Sat : saturation models of DIS

Kowalski, Teaney hep-ph/0304189v3

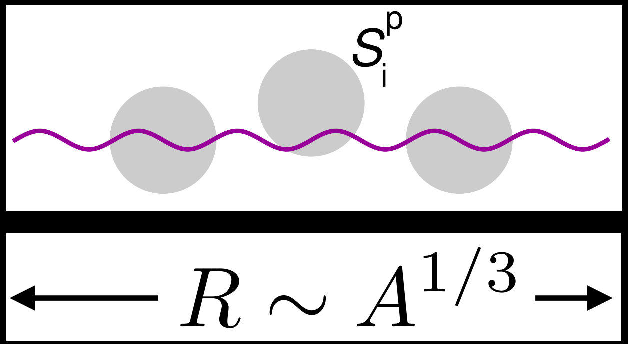
Round proton | Lumpy Nucleus (single conf.)



Less boost is needed to saturate a nucleus, larger A → larger Q_S

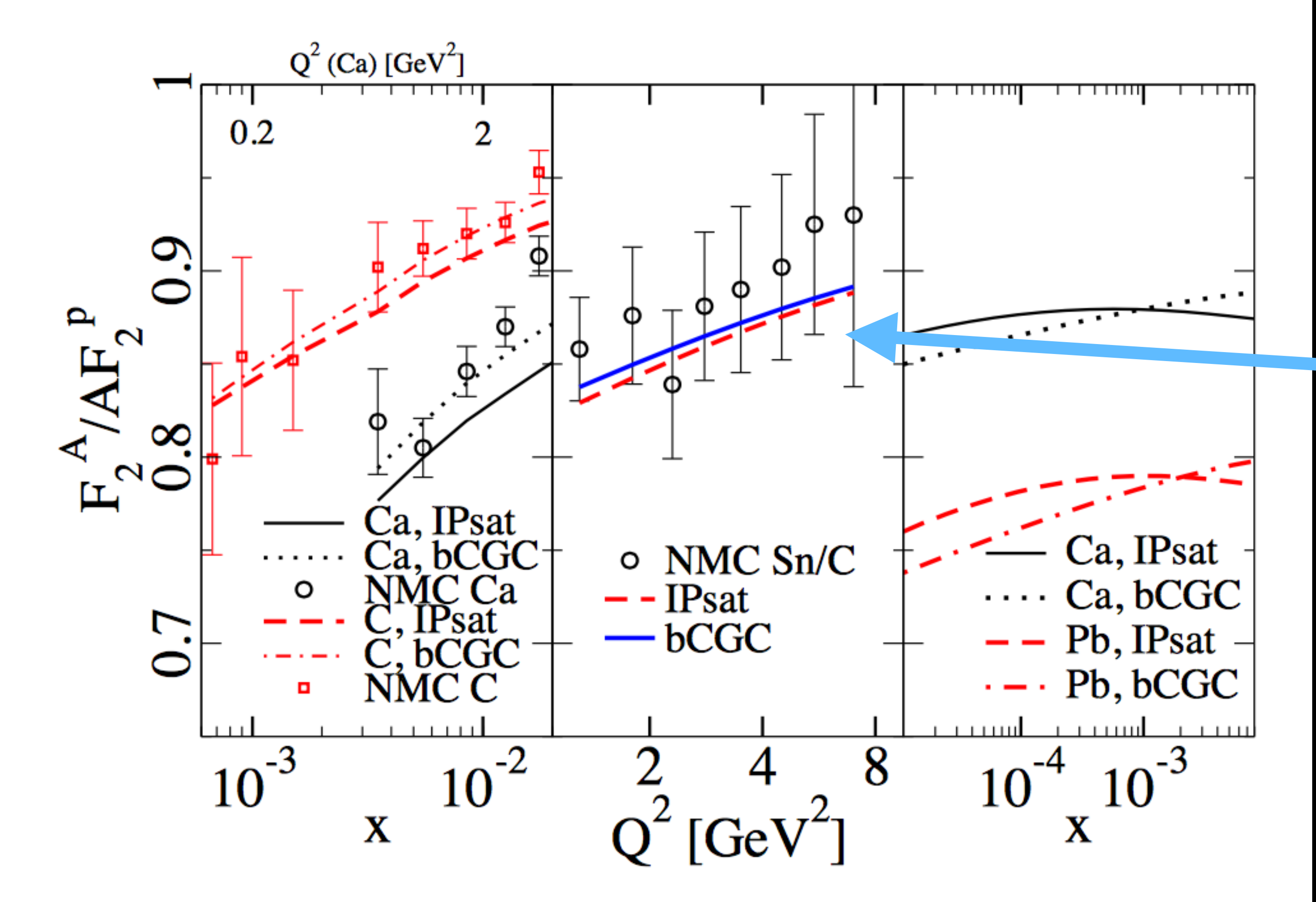
Nucleus → multiple scattering centers :

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



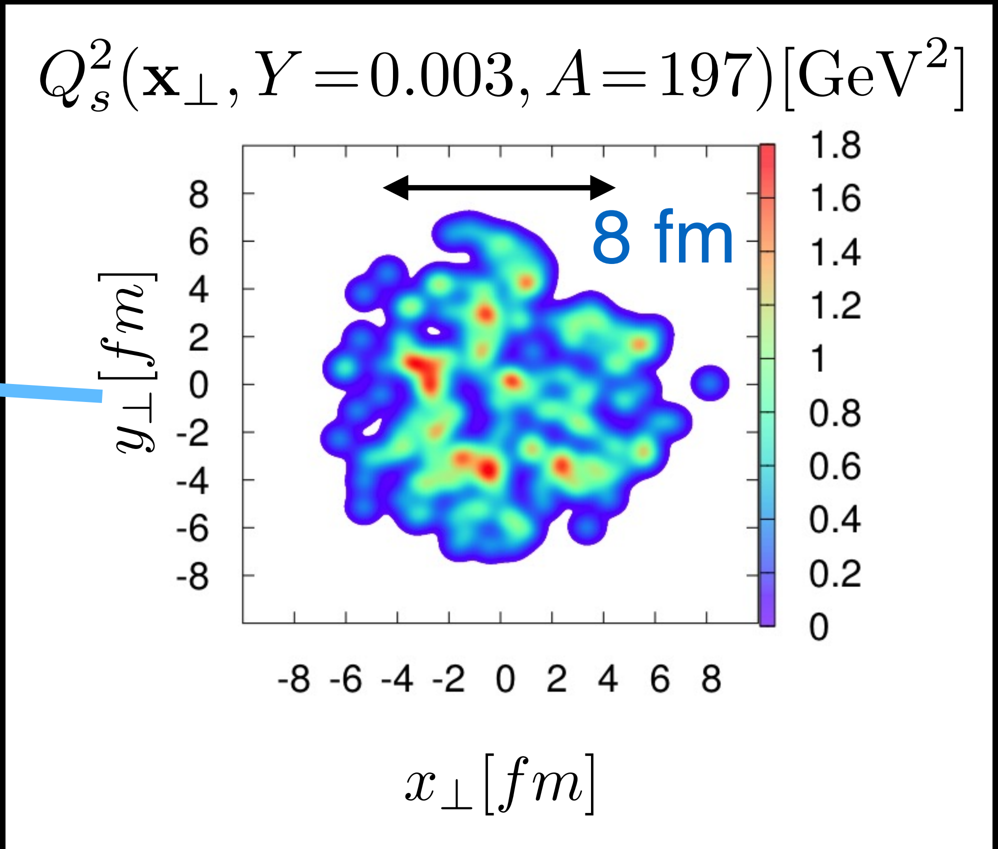
How do we know our nuclei are correct ?

NMC collab. hep-ph/9503291
Kowalski, Lappi, Venugopalan

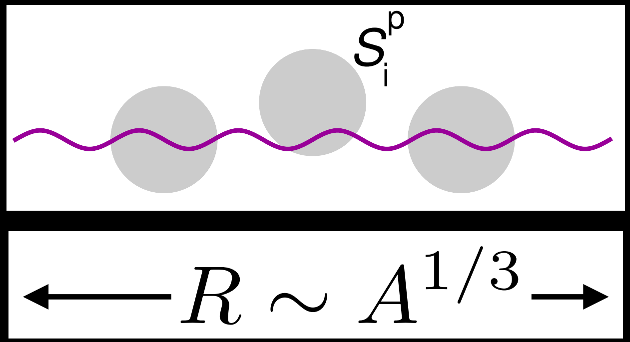


Kowalski, Teaney hep-ph/0304189v3

Lumpy Nucleus (single conf.)

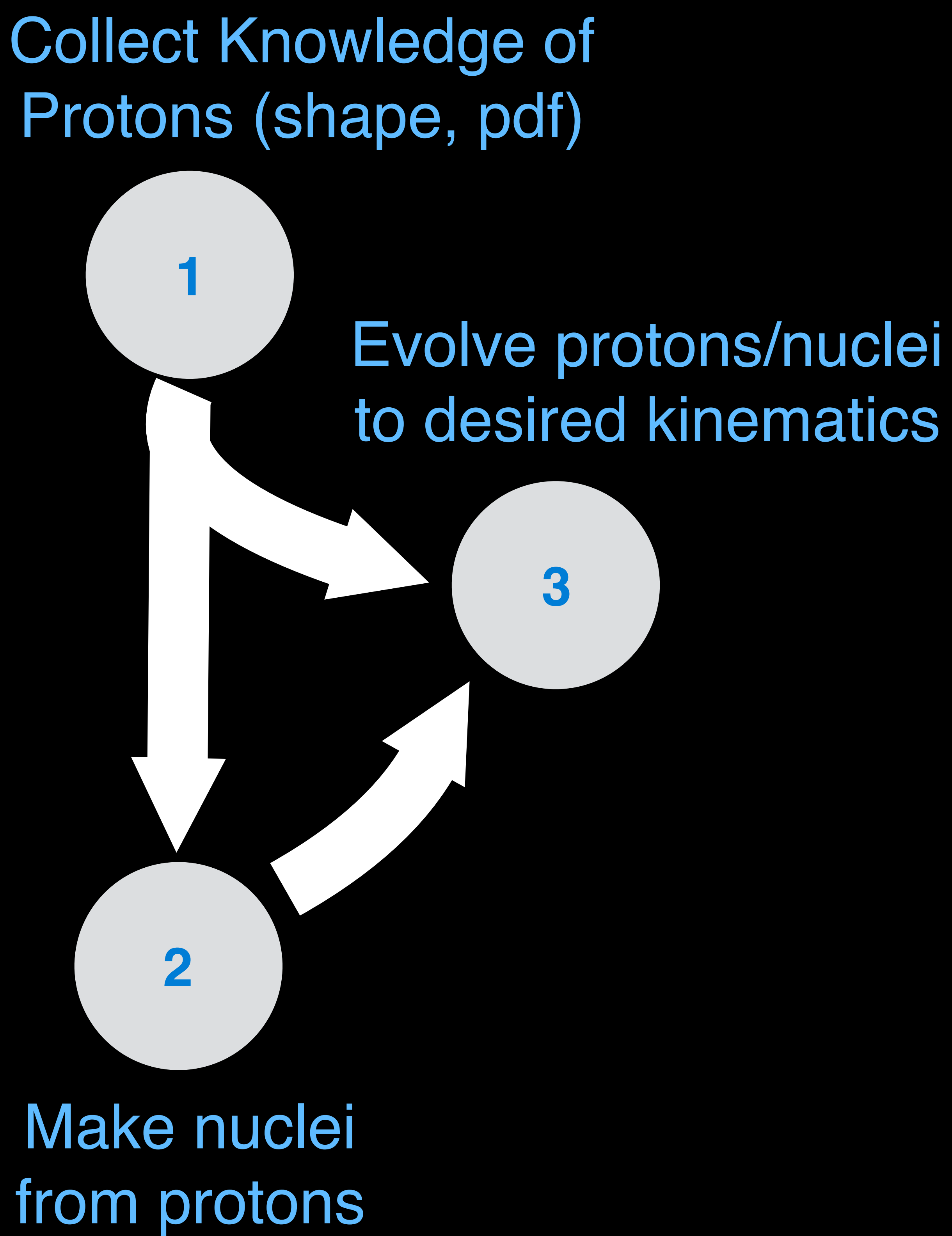


F$_2$ data from DIS μ+A provide some constraints, but measurements @EIC will be the best (my talk at the workshop)



Bottom line : We need an EIC

Steps towards computing Initial conditions

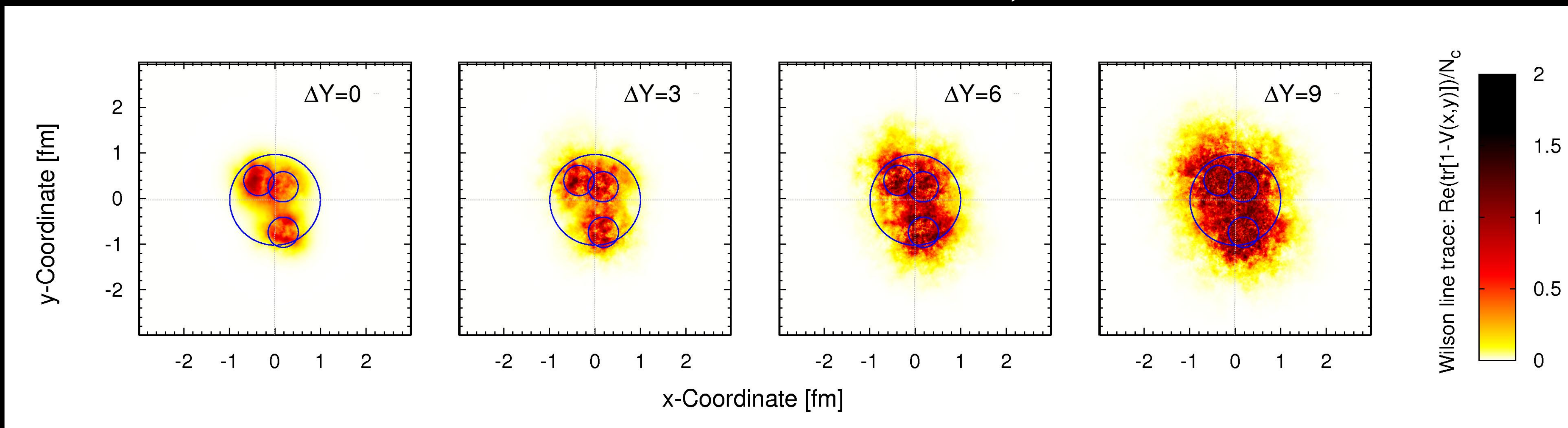


Modeling the rapidity or energy dependence

Proton

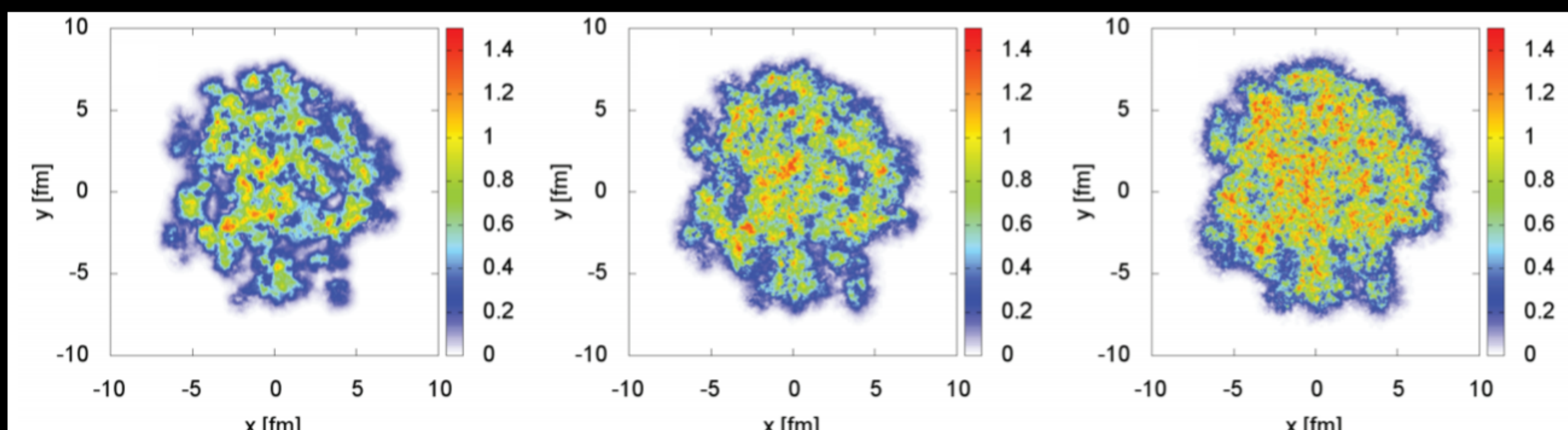
Small x, higher energy →

Schenke, Schlichting 1407.8458
Mantysaari, Schenke arXiv:1806.06783



Nucleus

fig : Schenke, Schlichting 1605.07158

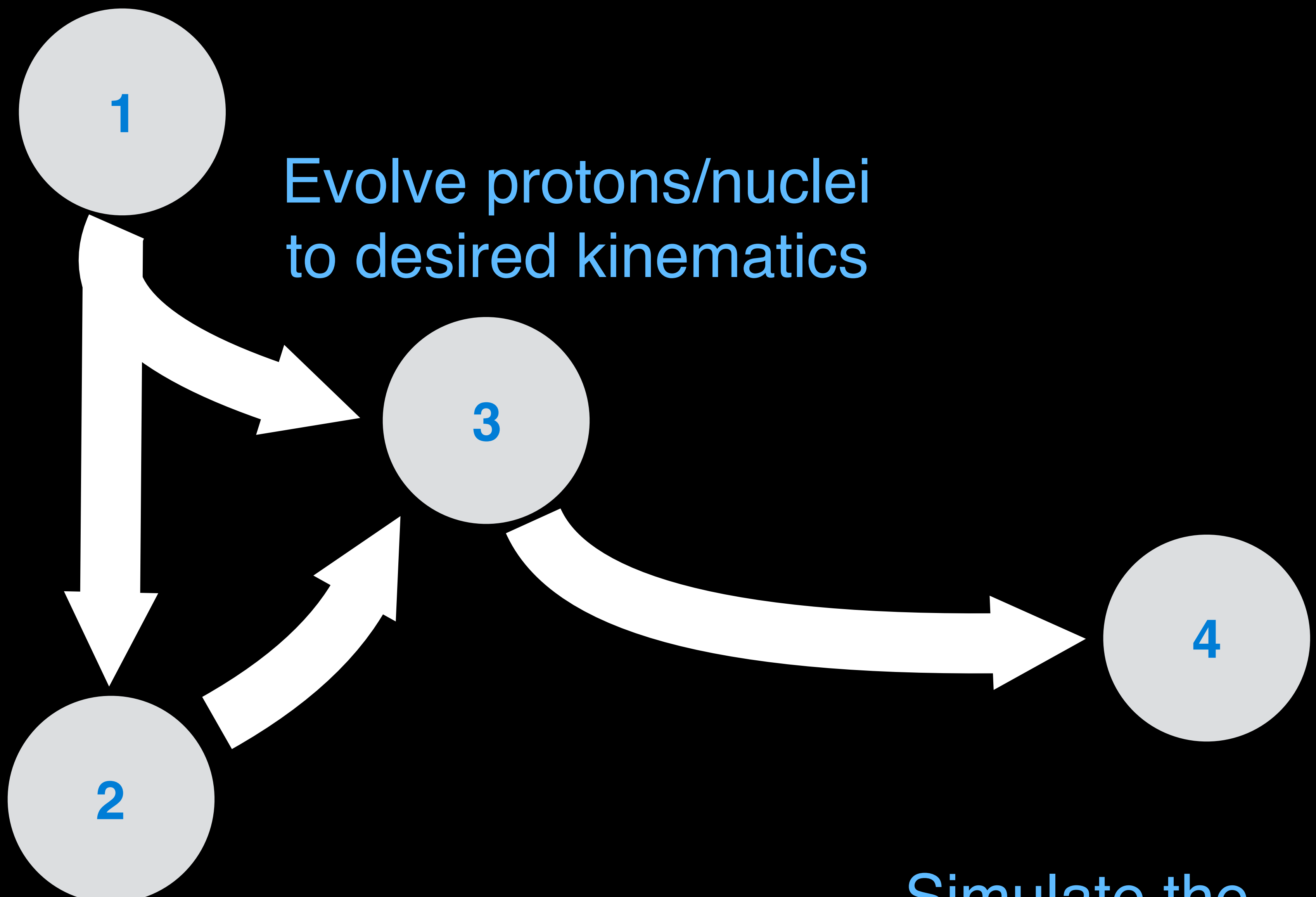


RG evolution eqs. (BK-JIMWLK) describe such growth@high $\sqrt{s}$

Steps towards computing Initial conditions

Collect Knowledge of Protons (shape, pdf)

Evolve protons/nuclei to desired kinematics

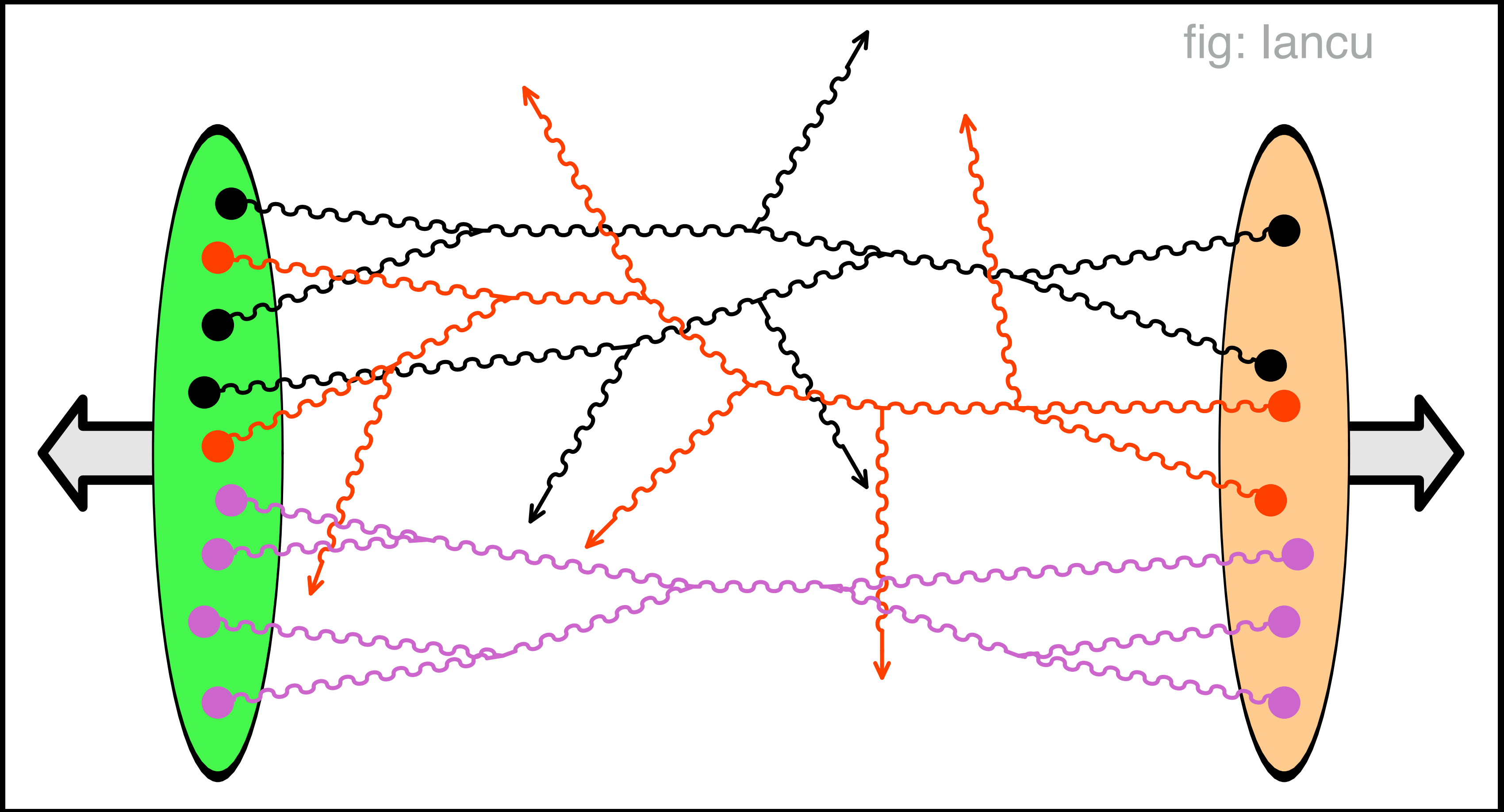


Make nuclei from protons

Simulate the collisions of protons/nuclei

Simulating the collisions: Why challenging ?

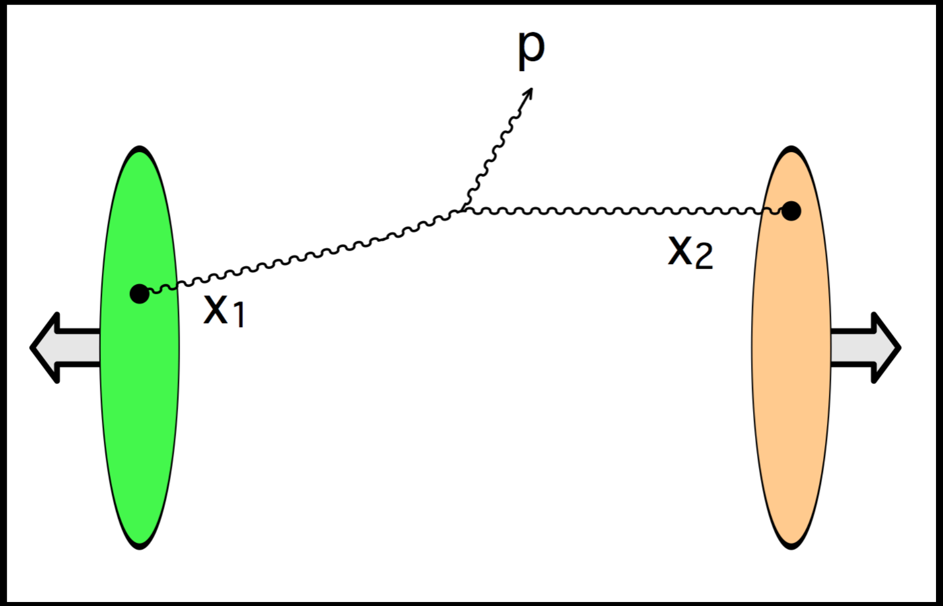
Even if we can learn a great deal about the colliding object, the biggest challenge is how to simulate the collision

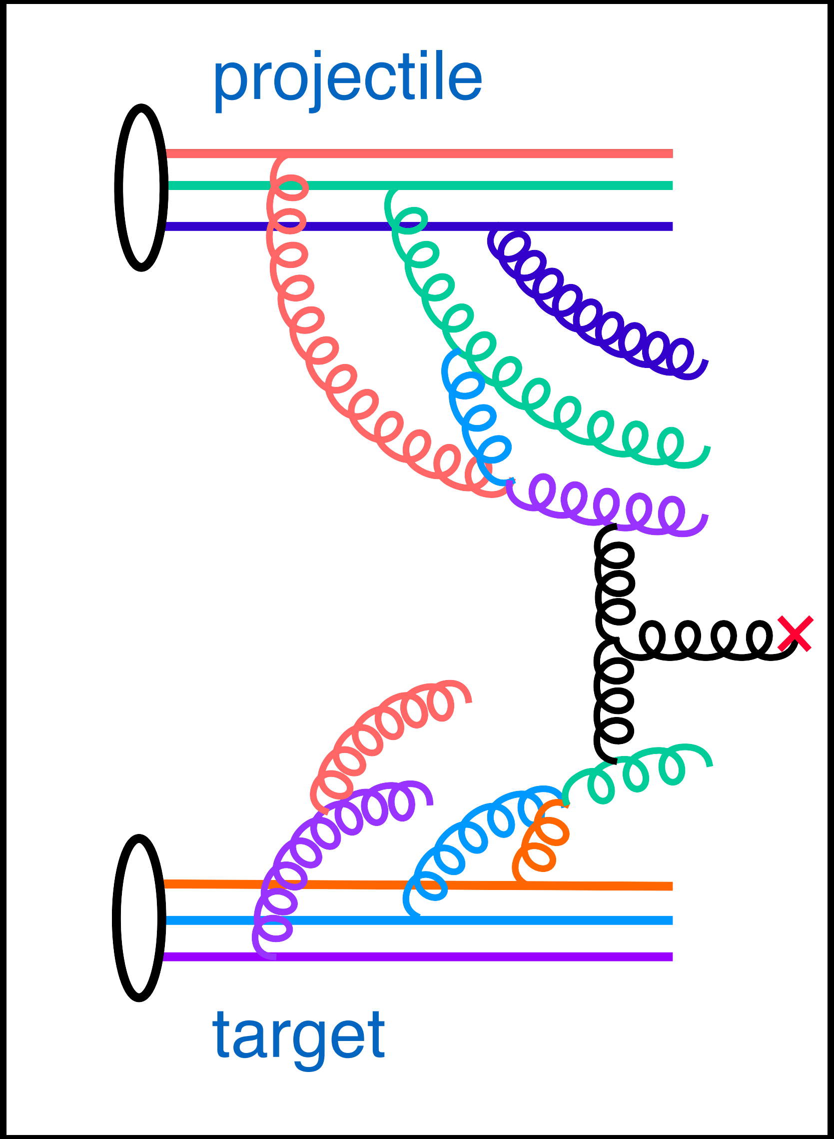


1. Mostly t-channel processes
2. Only a fraction of the processes are perturbative (large p like jets)
3. Multiple scattering & soft processes dominate → highly non-perturbative

A closer look

A single process could be quite complex





This is an intrinsically complicated problem that is highly non-perturbative

How to handle this & compute the essential elements of an I.C. ?

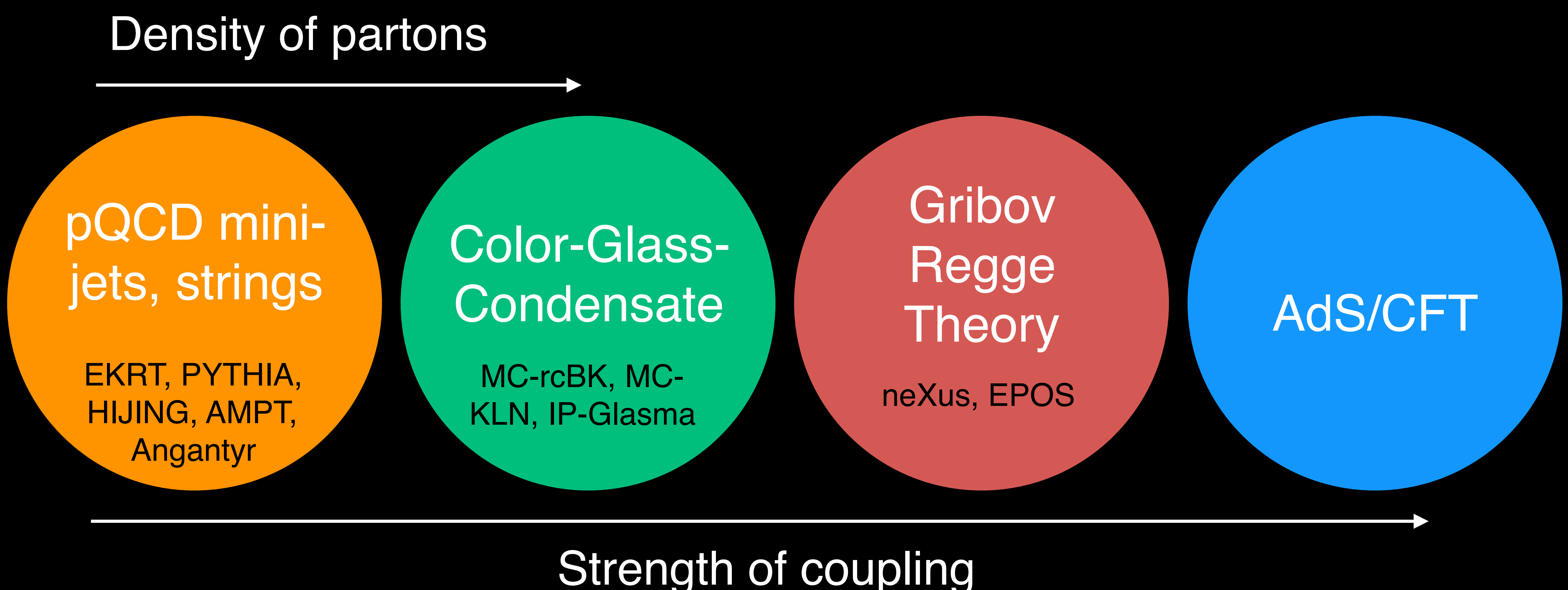
1. Dynamical modeling with effective theories
2. Geometry based Density prescriptions

Many approaches to the problem

Dynamical models

Dynamical model of initial stages

- Implement approaches based on first principles
- Constrained from independent analyses
- Focus on broad aspects, can be multipurpose
- Numerically intense

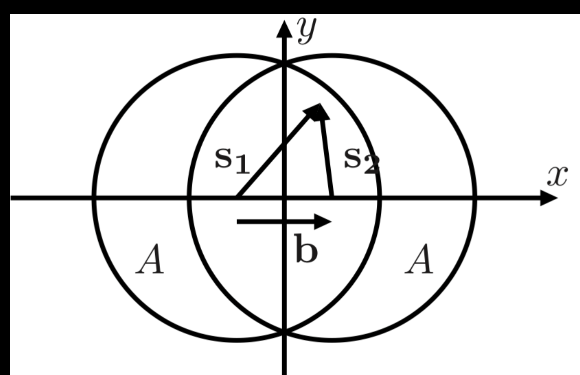


EKRT : pQCD (shadowing) + saturation

Niemi, Eskola, Paatelainen 1505.02677

Computes NLO pQCD cross section of mini-jets :

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



Geometry

pQCD + nPDF

Implementation of saturation when : $\frac{dE_T}{d^2r dy}(2 \to 2) \sim \frac{dE_T}{d^2r dy}(3 \to 2)$

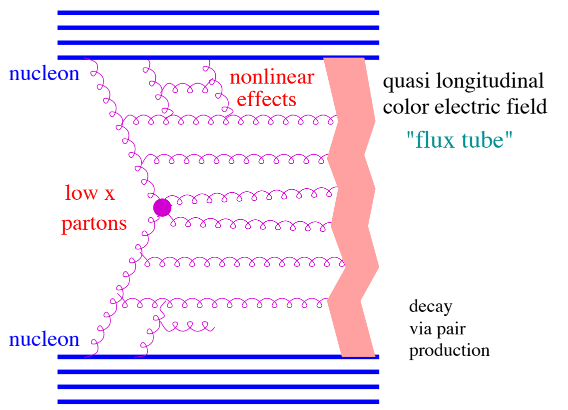
Time evolution → Bjorken like expansion

Conventional pQCD Monte-Carlo: PYTHIA, HIJING, AMPT, Angantyr

Modeling the collisions : effective theories

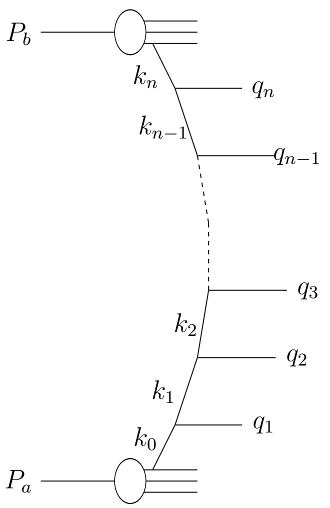
neXus, EPOS : Parton-Based Gribov Regge Theory

Drescher, Hladik, Ostapchenko, Pierog, Werner, hep- ph/0007198.
Werner, Liu, and Pierog, hep-ph/0506232
Pierog, Karpenko, Katzy, Yatsenko, Werner, 1306.0121



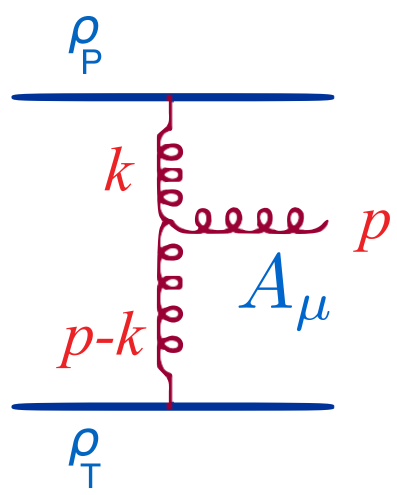
DIPSY : saturation + BFKL cascade

Flensburg Gustafson Lönnblad 1103.4321
Flensburg 1108.4862



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

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



Modeling the collisions : effective theories

neXus, EPOS :

Regge Theory

Drescher, Hladik, Ostapchenko, Pierog, Werner,

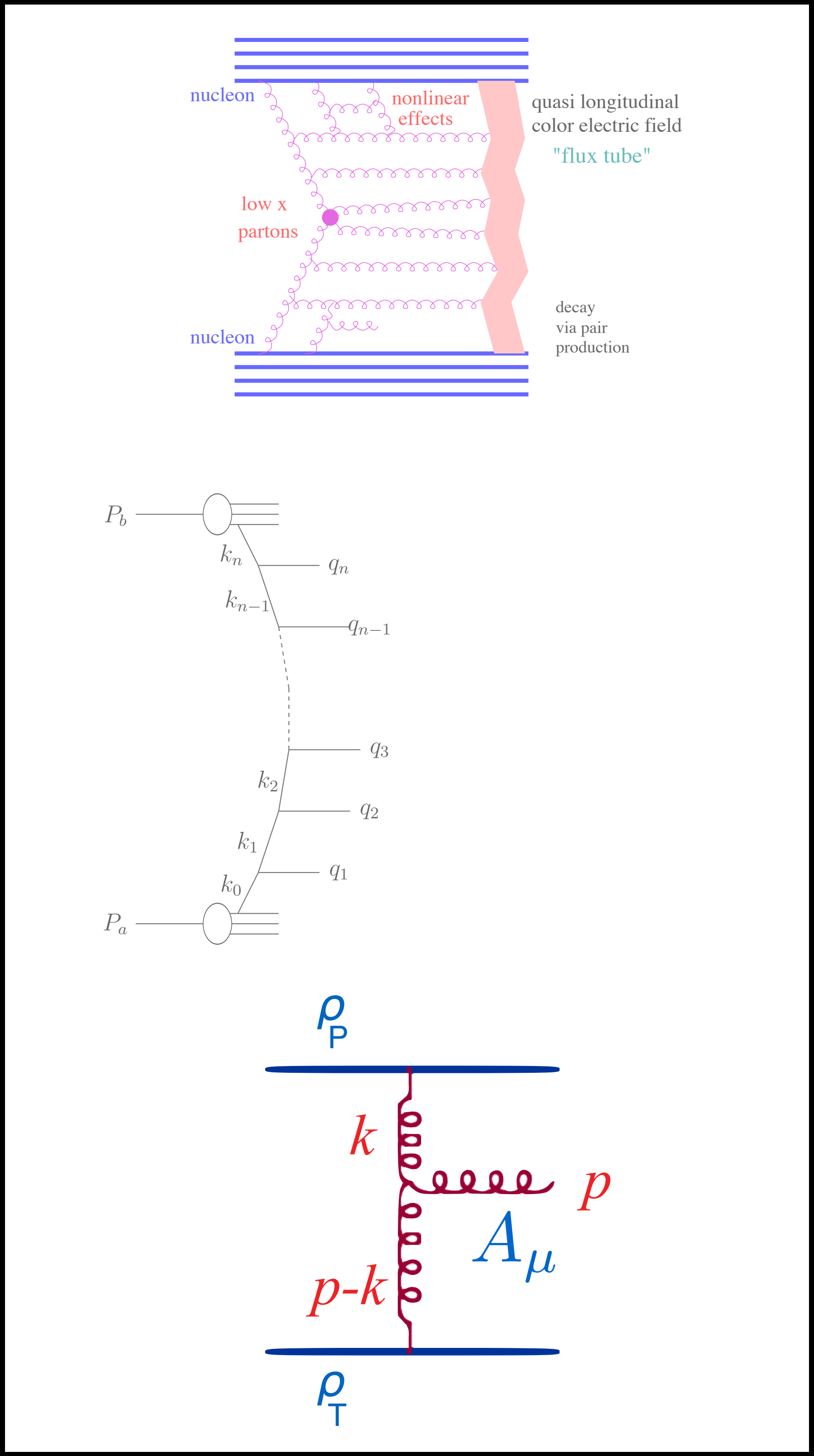
Werner, Liu, and Pierog, hep-ph/0506232
Pierog, Karpenko, Katzy, Yatsenko, Werner,

DIPSY : saturation

Flensburg
Flensburg

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

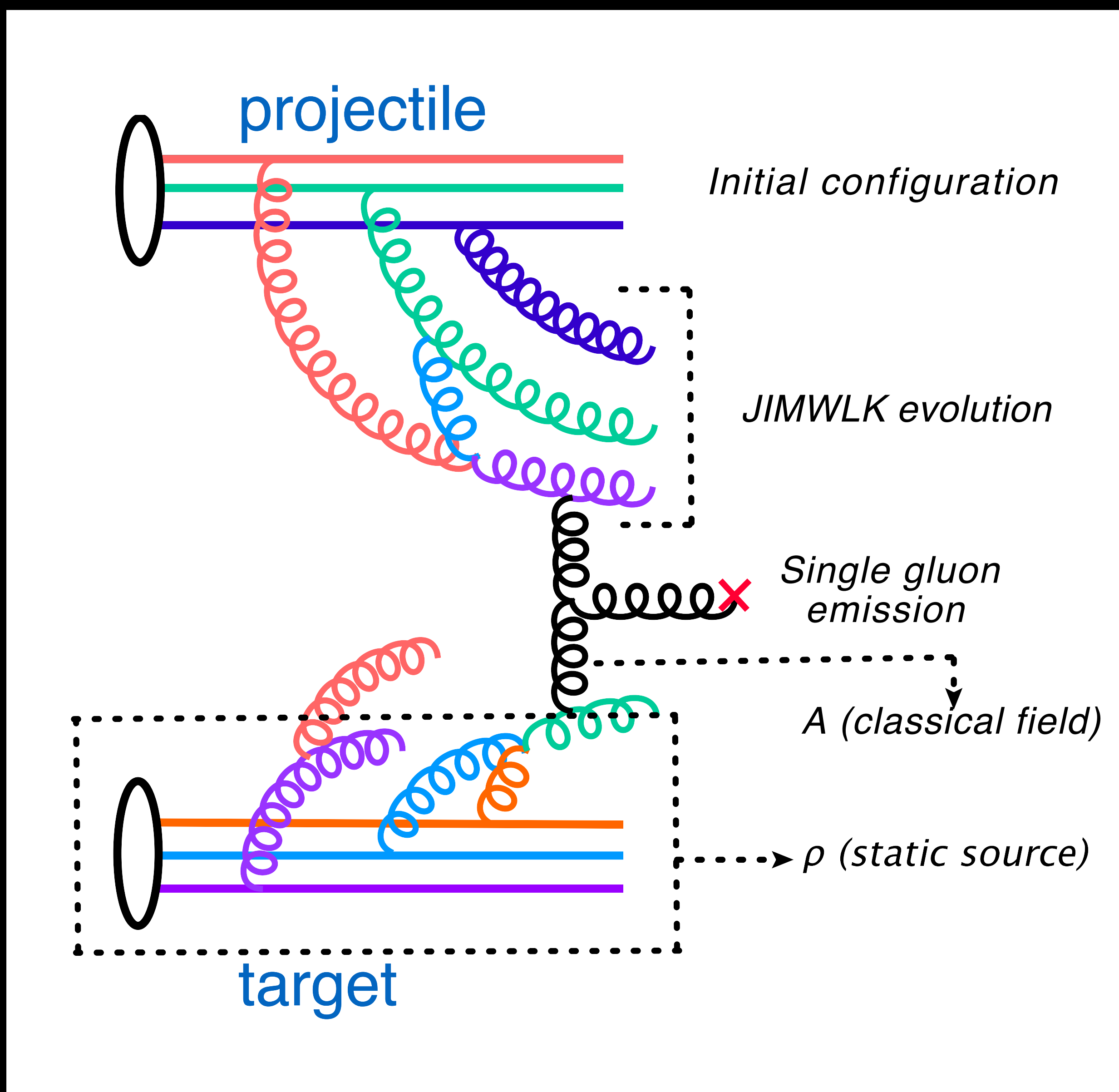
Kharzeev, Levin, Nardi, hep-ph/0111315, Drescher, Nara 0707.0249, Albacete, Dumitru 1011.5161

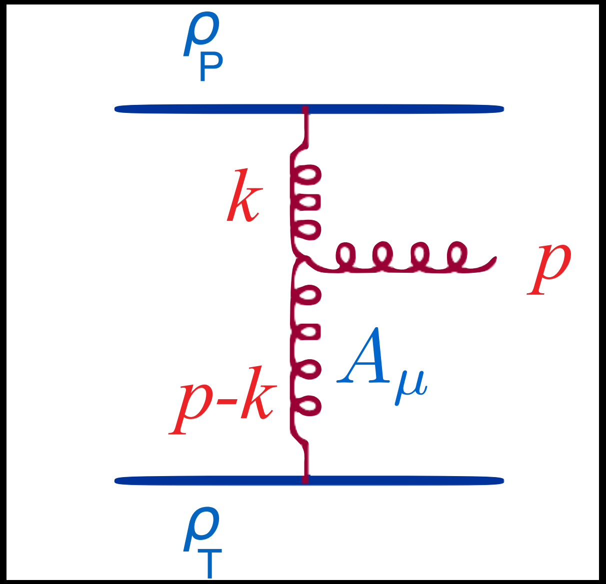


Modeling the collisions : CGC

McLerran & Venugopalan hep-ph/9309289, 9311205

The actual problem of a collision



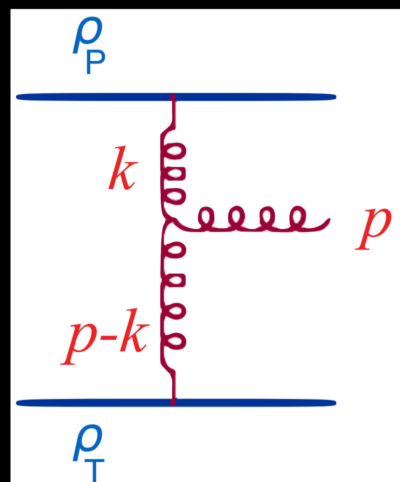


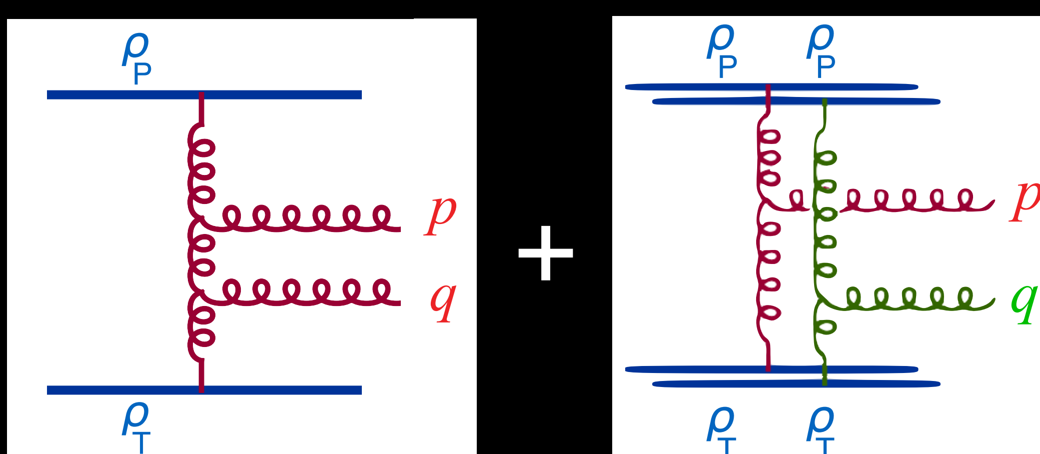
In CGC effective theory

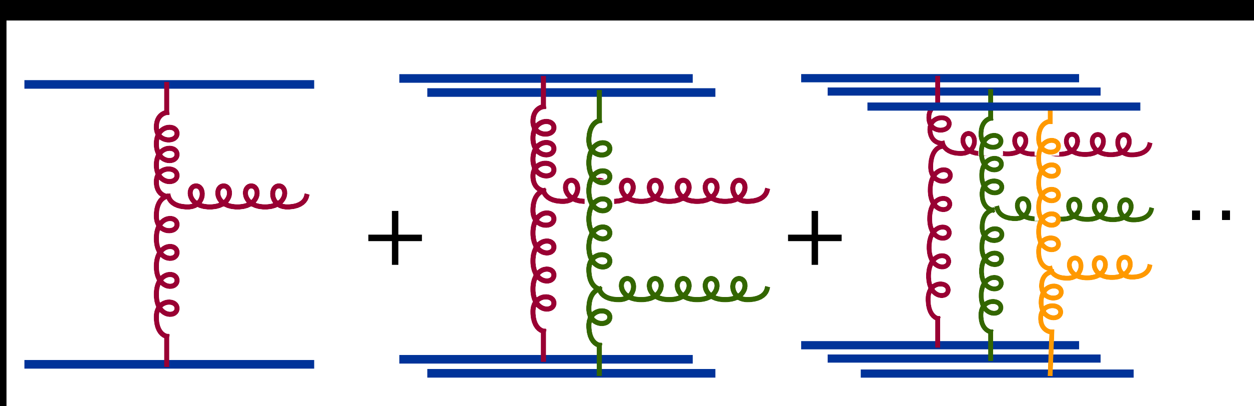
Color Glass Condensate (CGC) effective theory makes the life easier

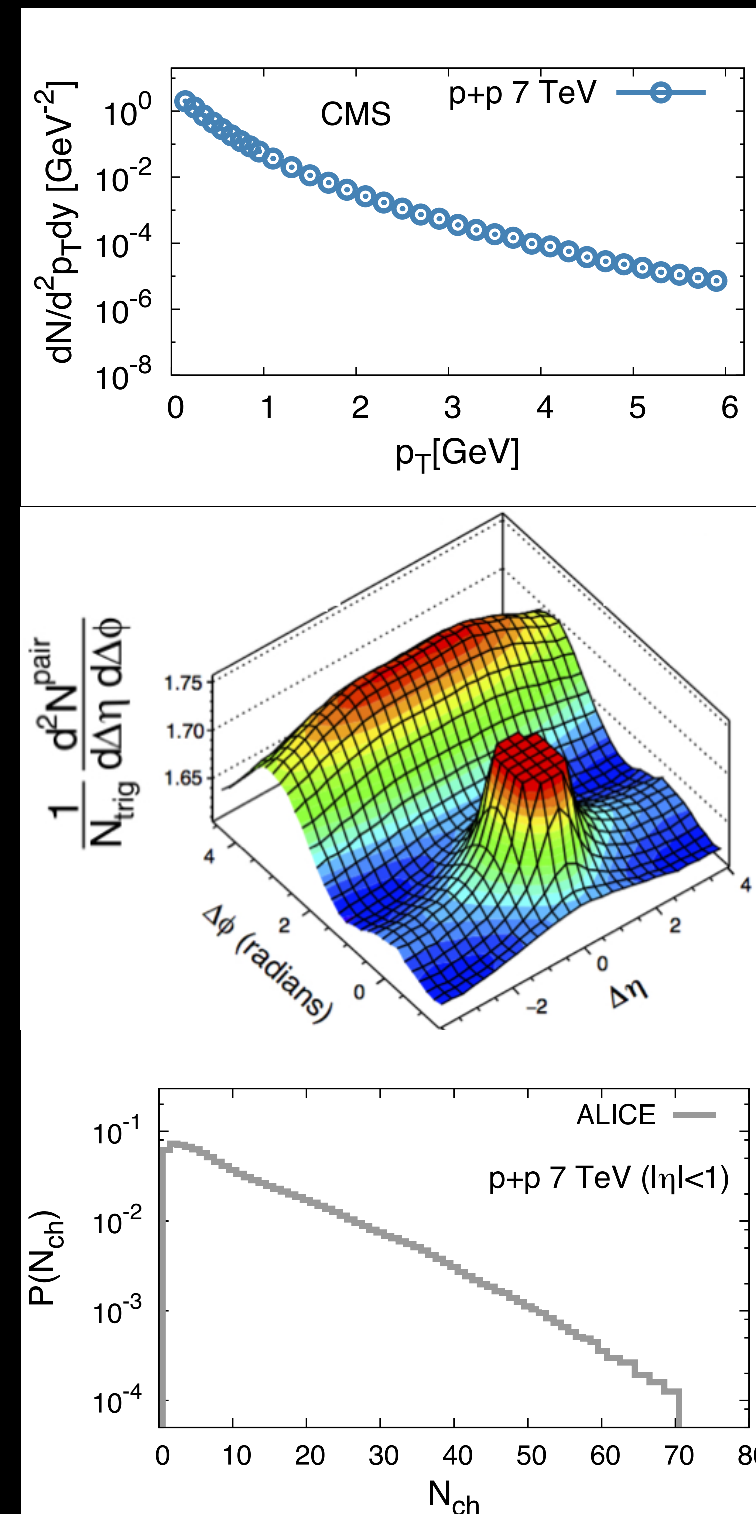
Modeling the collisions: CGC perturbative

Ab initio approach of n-gluon production but cumbersome & approximate









Single-particle production

Two-particle production (Di-jet+ridge)

Multi-particle production

Beyond factorization/perturbative: IP-Glasma

IP-Glasma model in a nutshell

Schenke, PT, Venugopalan Phys. Rev. Lett. 108 (2012) 252301

Colliding nuclei:

→ Classical color charge distribution

$$\langle \rho^a(\mathbf{x}_\perp)\rho^b(\mathbf{y}_\perp)\rangle \propto \delta^{ab}\delta^2(\mathbf{x}_\perp - \mathbf{y}_\perp)Q_s^2(\mathbf{x}_\perp)$$

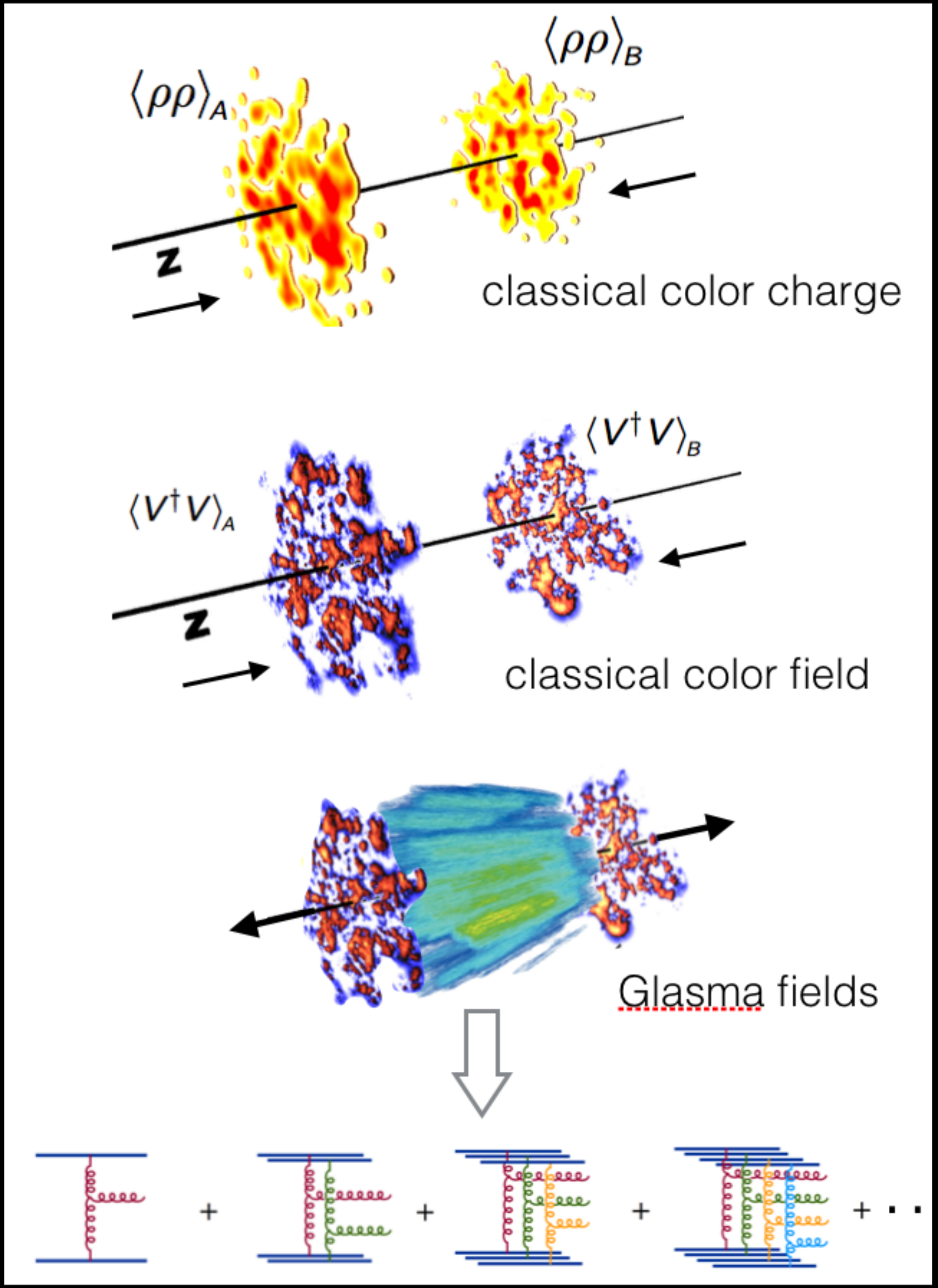
→ Classical color fields that follows

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

After collisions:

→ Glasma gluon fields

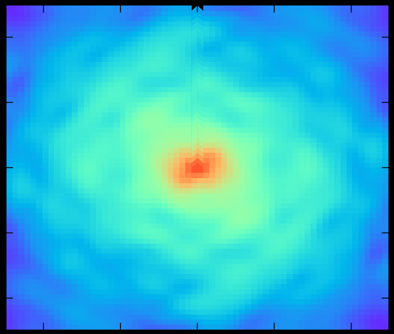
$$A^i = A^i_{(A)} + A^i_{(B)} \qquad A^\eta = \frac{ig}{2}\left[A^i_{(A)}, A^i_{(B)}\right]$$



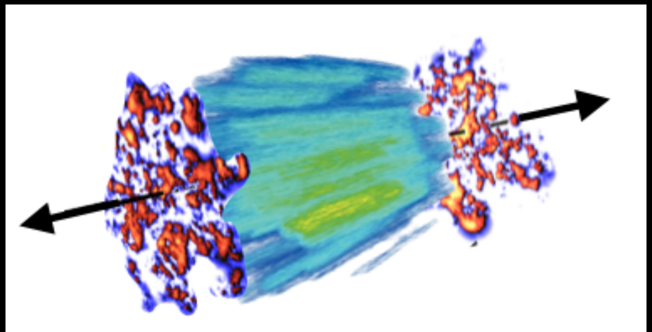
IP-Glasma: what are the unique features

Momentum space correlations : n-gluon distribution

$$\frac{dN_g}{dy} = \frac{2}{N^2}\int \frac{d^2k_T}{\tilde{k}_T}\left[\frac{g^2}{\tau}\mathrm{tr}\left(E_i(\mathbf{k}_\perp)E_i(-\mathbf{k}_\perp)\right)+\tau\,\mathrm{tr}\left(\pi(\mathbf{k}_\perp)\pi(-\mathbf{k}_\perp)\right)\right]$$



Input to PYTHIA, p+p/A collisions

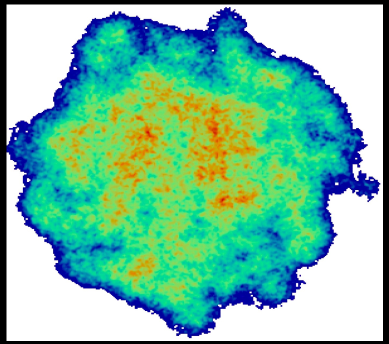


Light-cone gauge-fields

$$U(\mathbf{x}_T) = \mathbb{P}\exp\left\{ig\int dx^- A^+(x^-,\mathbf{x}_T)\right\}$$

Position space correlations : Stress-Energy Tensor

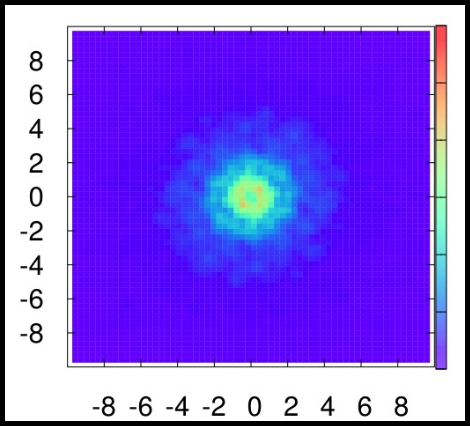
$$T^{\mu\nu} = -g^{\gamma\delta}F^{\mu}_{\ \gamma}F^{\nu}_{\ \delta} + \frac{1}{4}g^{\mu\nu}F^{\gamma}_{\ \delta}F_{\gamma}^{\ \delta}$$



Input to hydro, transport, p+A, A+A collisions

Wave functions: Dipole-gluon & WWs TMDs

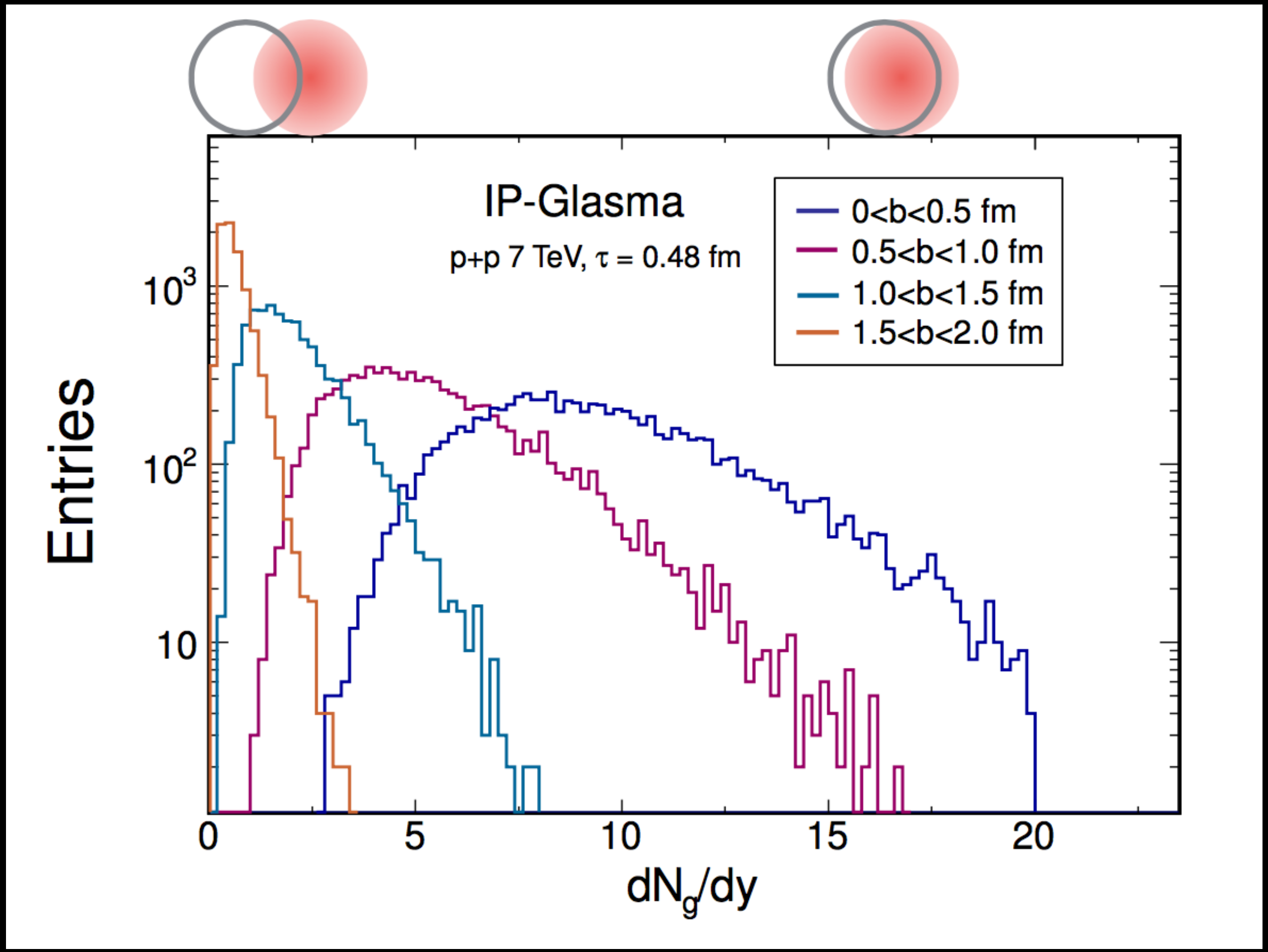
$$xG^{ij}_{\mathrm{WW}}(x,\vec{k}) = \frac{8\pi}{L^2}\int\frac{d^2\mathbf{x}_T}{(2\pi)^2}\frac{d^2\mathbf{y}_T}{(2\pi)^2}e^{-i\mathbf{k}_T\cdot(\mathbf{x}_T-\mathbf{y}_T)}\times\left\langle A^i_a(\mathbf{x}_T)A^j_a(\mathbf{y}_T)\right\rangle$$



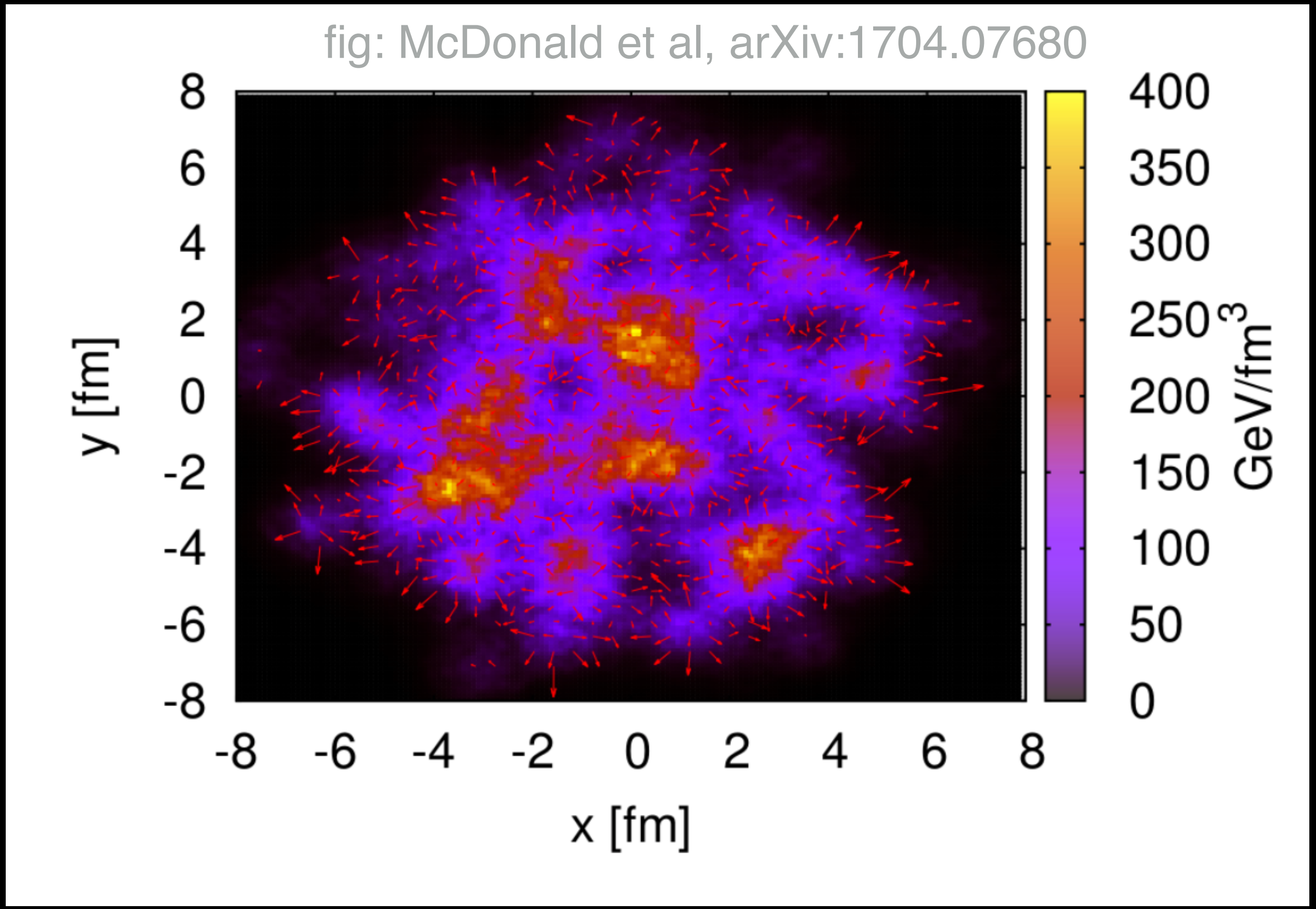
Input for EIC observables e+p/A collisions

Two unique features of IP-Glasma

These features of IP-Glasma are not put by hand but appears naturally



Negative Binomial fluctuations

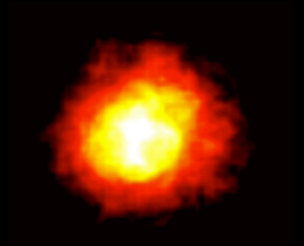


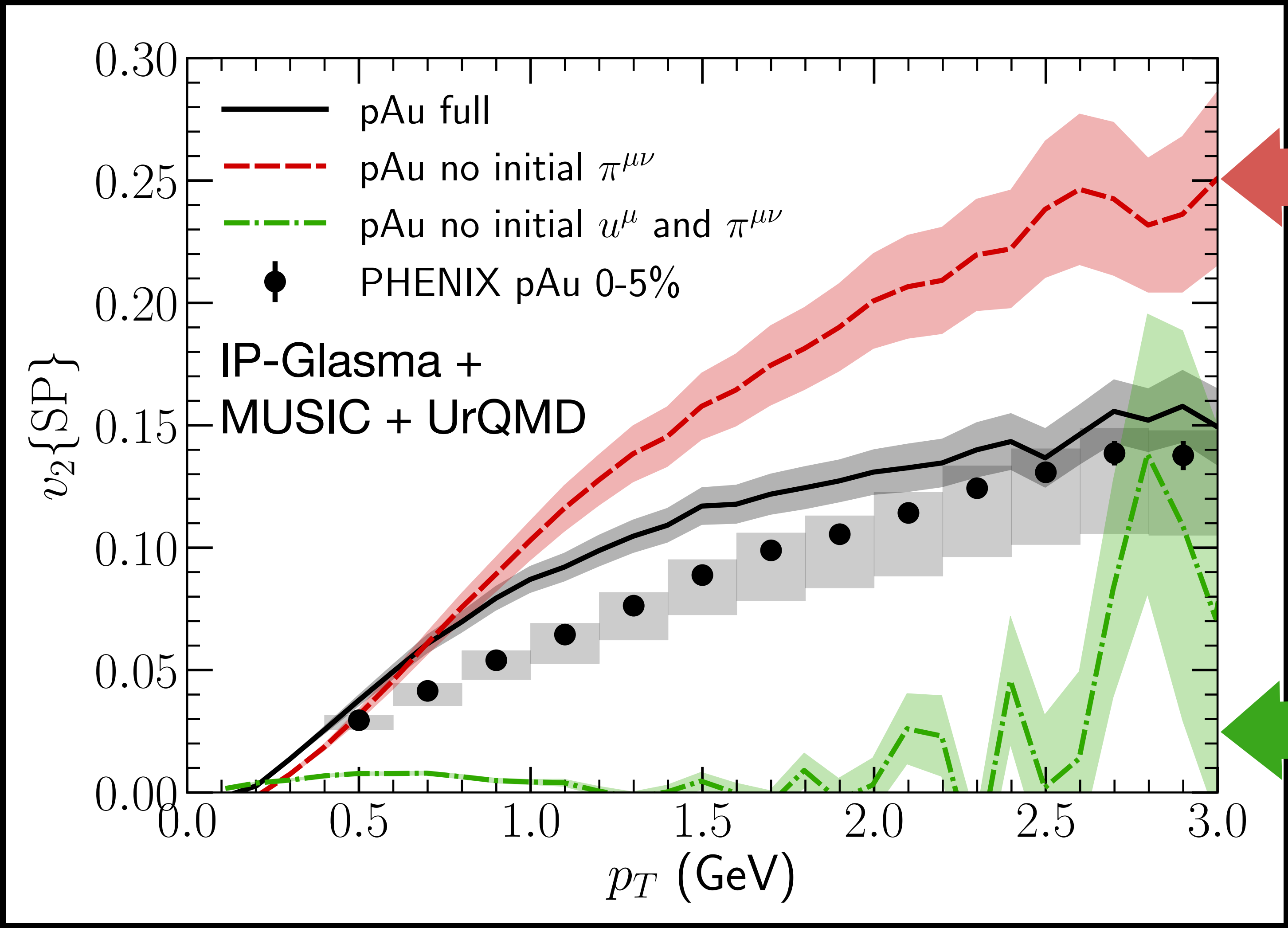
Full stress-energy tensor/ initial flow

Features that are important for small systems

Flow in d+A using a hybrid framework constrained by A+A data at RHIC

B. Schenke, C. Shen, P. Tribedy, in preparation





Too large without full $T^{\mu\nu}$

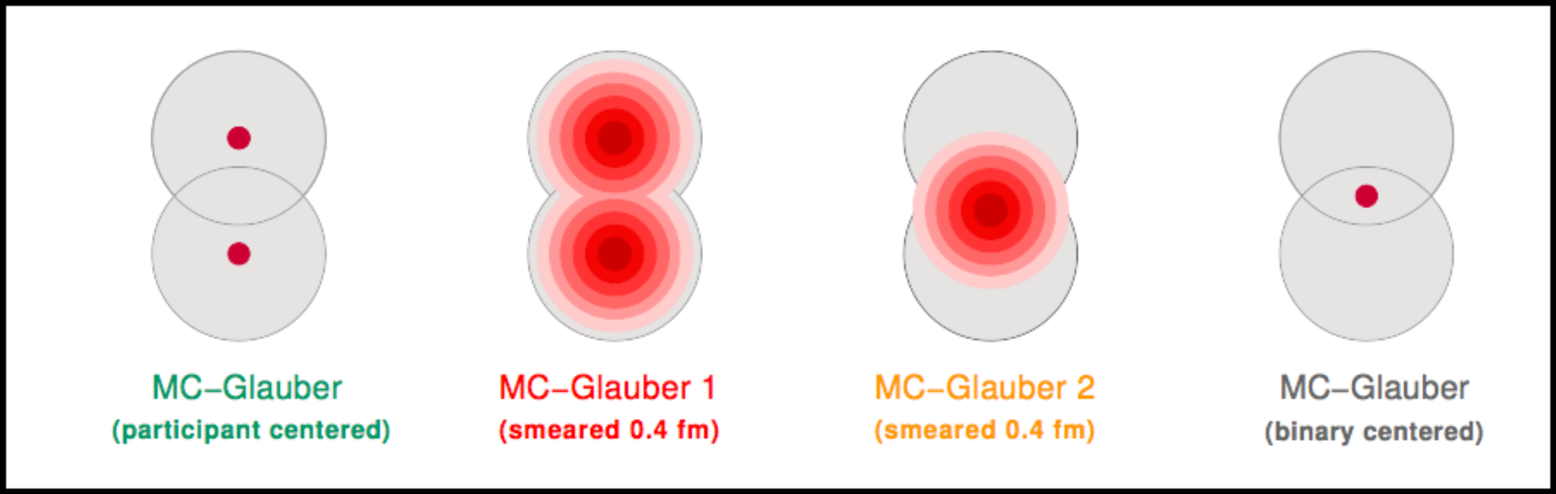
Too little if no initial flow

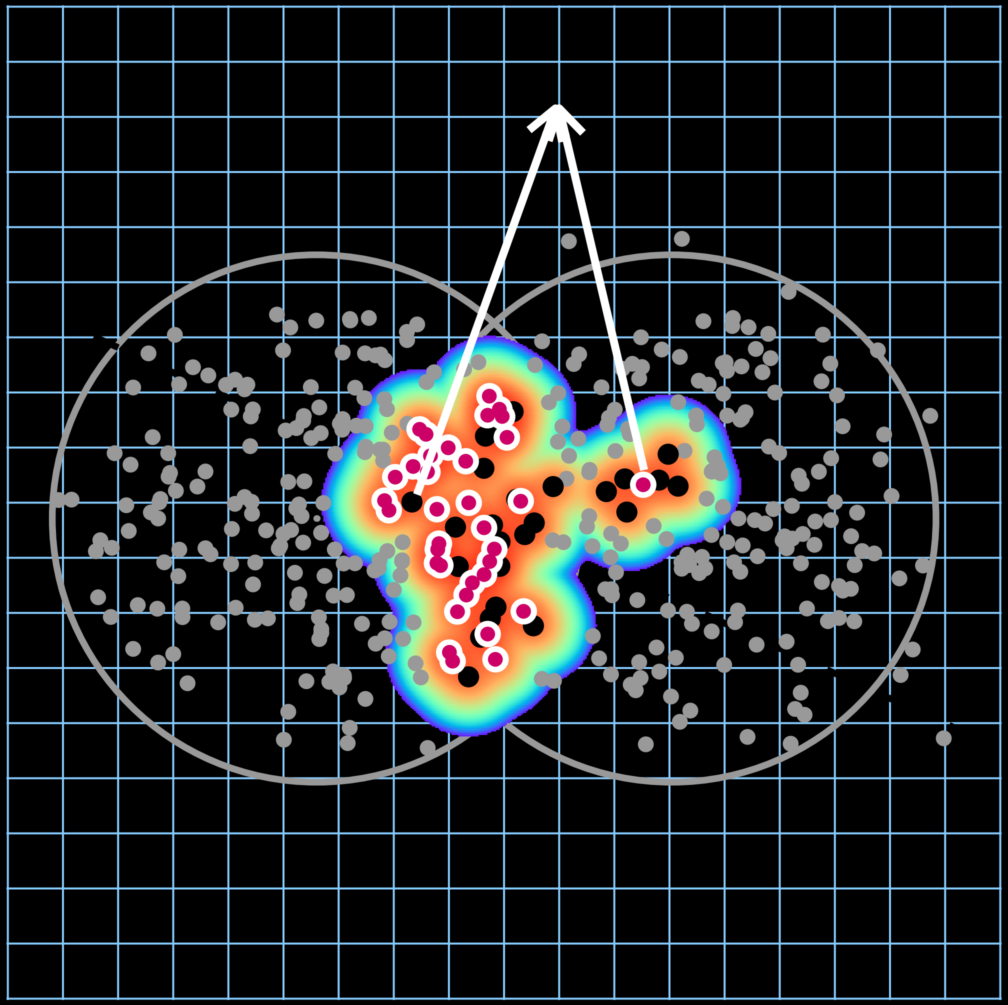
Density prescriptions

Geometry based Density prescriptions

- Tuned to capture many features of the dynamical models but not all.
- Most widely used framework
- Requires an ansatz to compute densities
- Less numerically intense.

MC-Glauber (2-component)



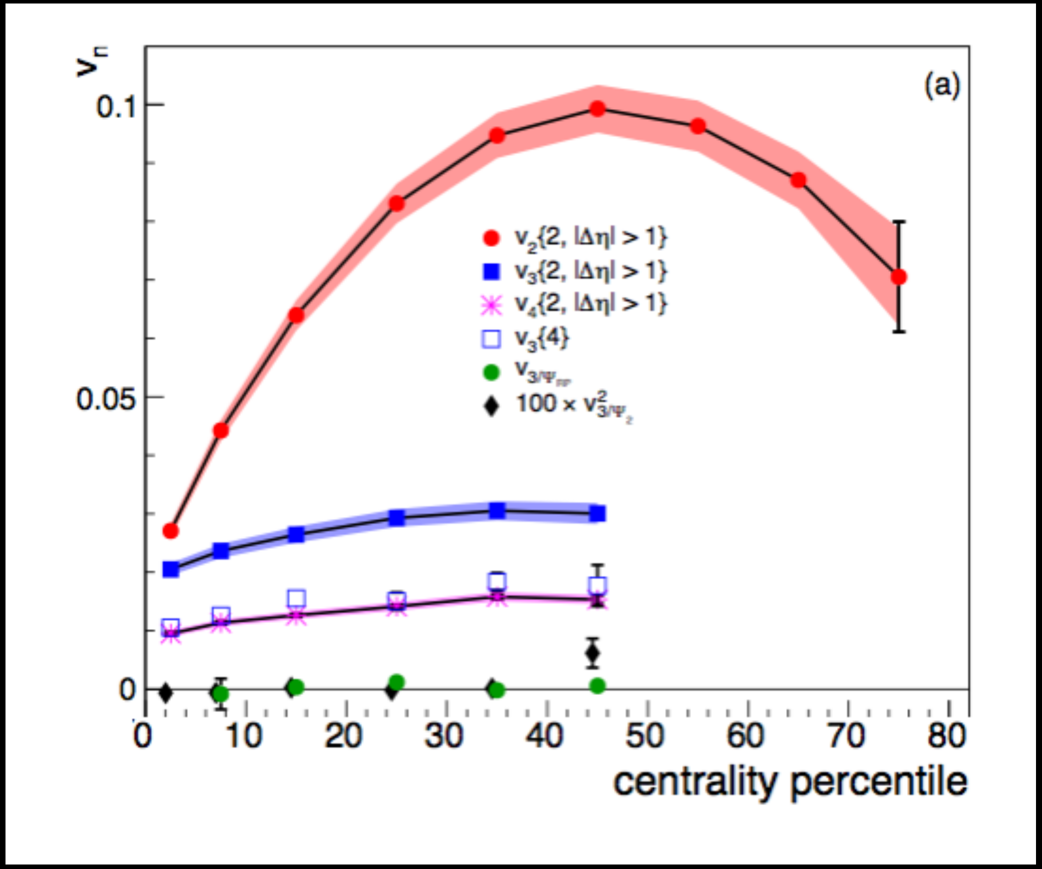


Which one is the right prescription ?

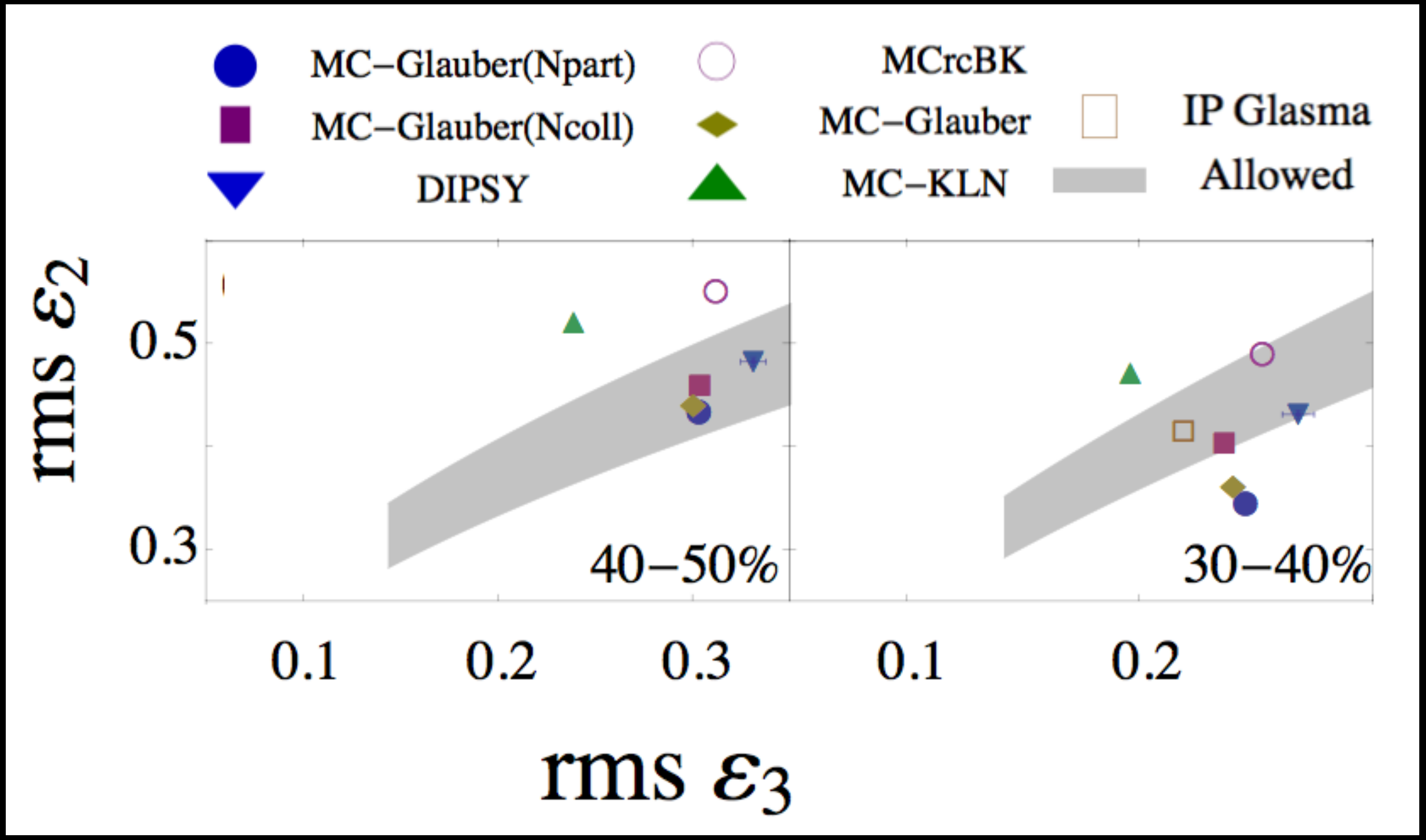
1. Data that nailed it down: v_n @ RHIC/LHC

Retinskaya, Luzum, Ollitrault 1311.5339

v_n @ RHIC/LHC



Constraints @ RHIC/LHC



RHIC and LHC v_n data rules out several initial state models
Rules out Mc-Glauber (N_{part}) but not Mc-Glauber (N_{coll})

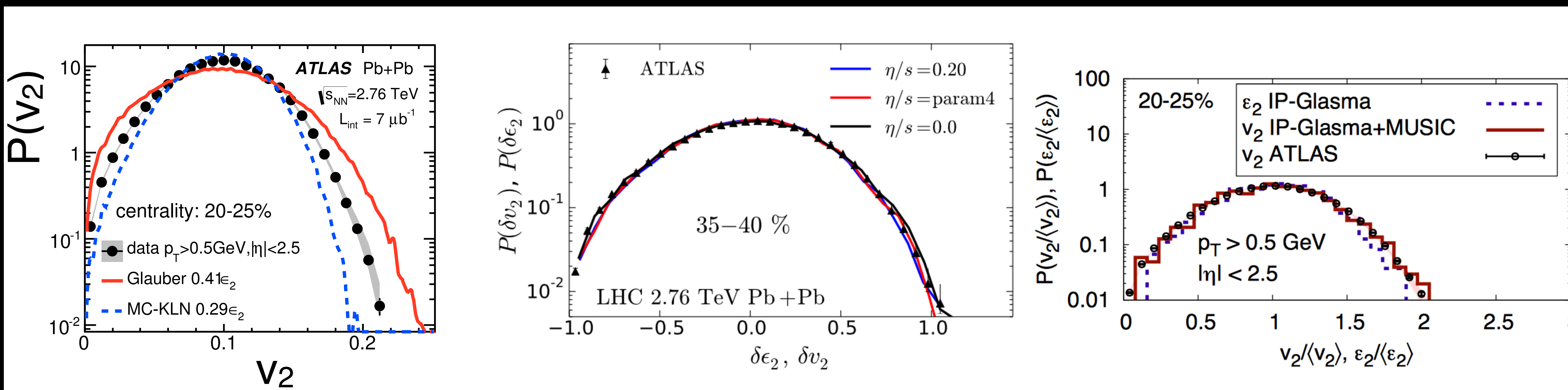
2. Data that nailed it down: $P(v_n)$

ATLAS Collaboration, 1305.2942

Glauber, KLN

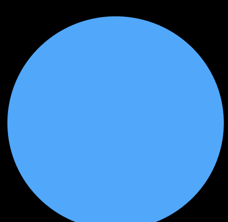
EKRT

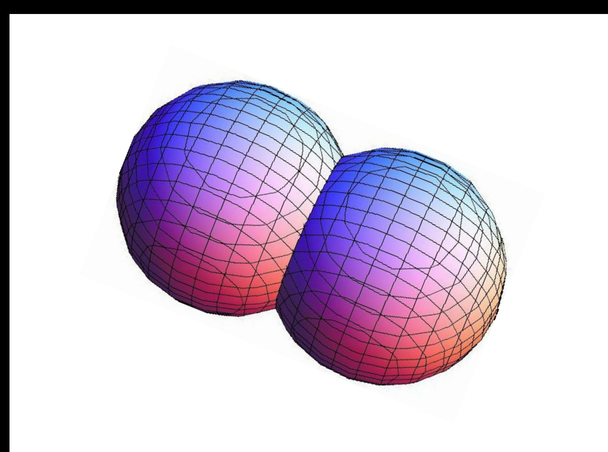
IP-Glasma

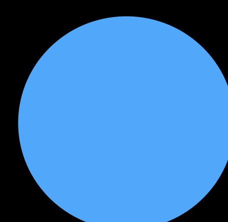


3. Data that nailed it down: ultra-central U+U

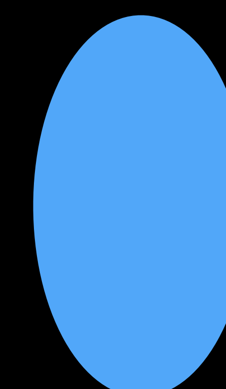
Gold nucleus
(little deformation)



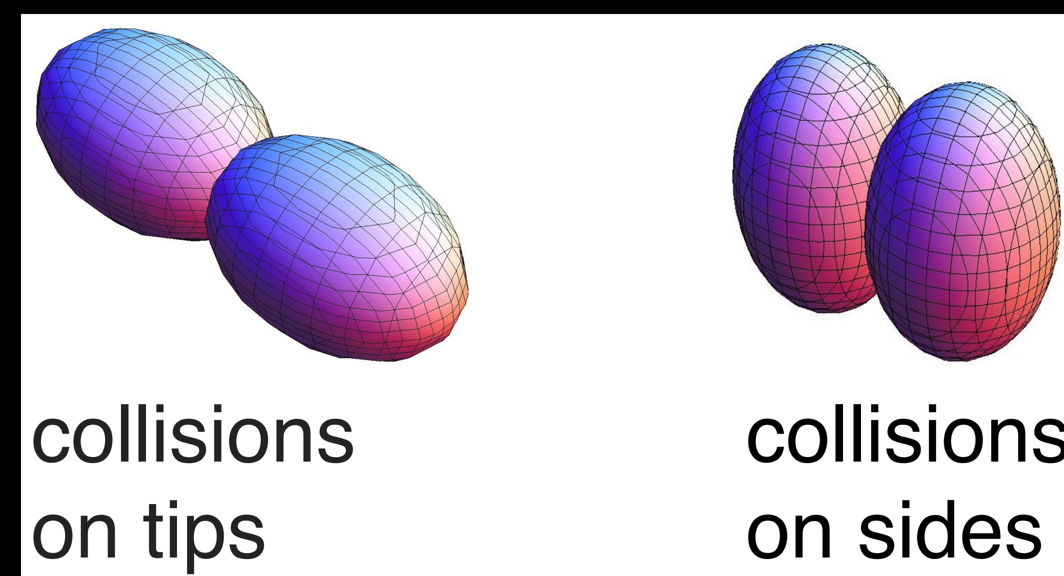




Transverse overlap is different

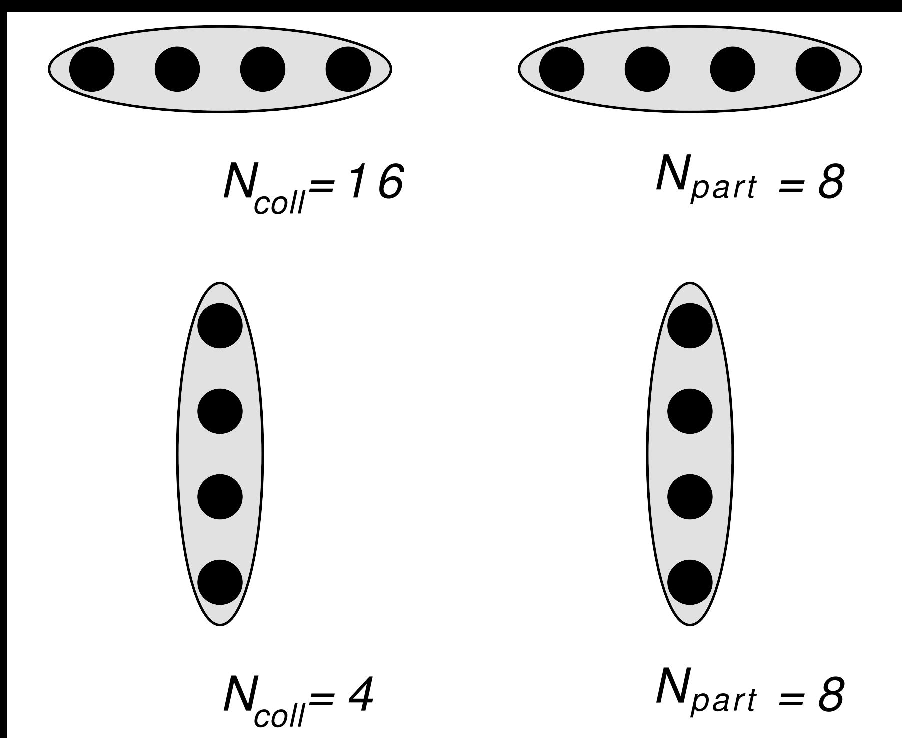


Uranium nucleus
(large prolate deformation)



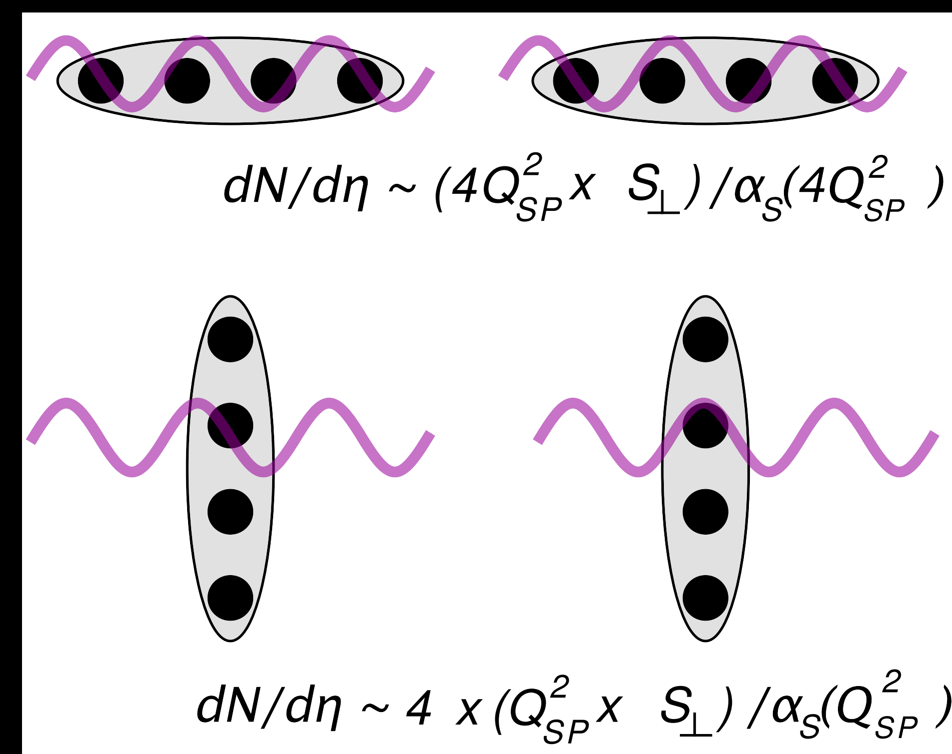
3. Data that nailed it down: ultra-central U+U

Density prescription : Glauber



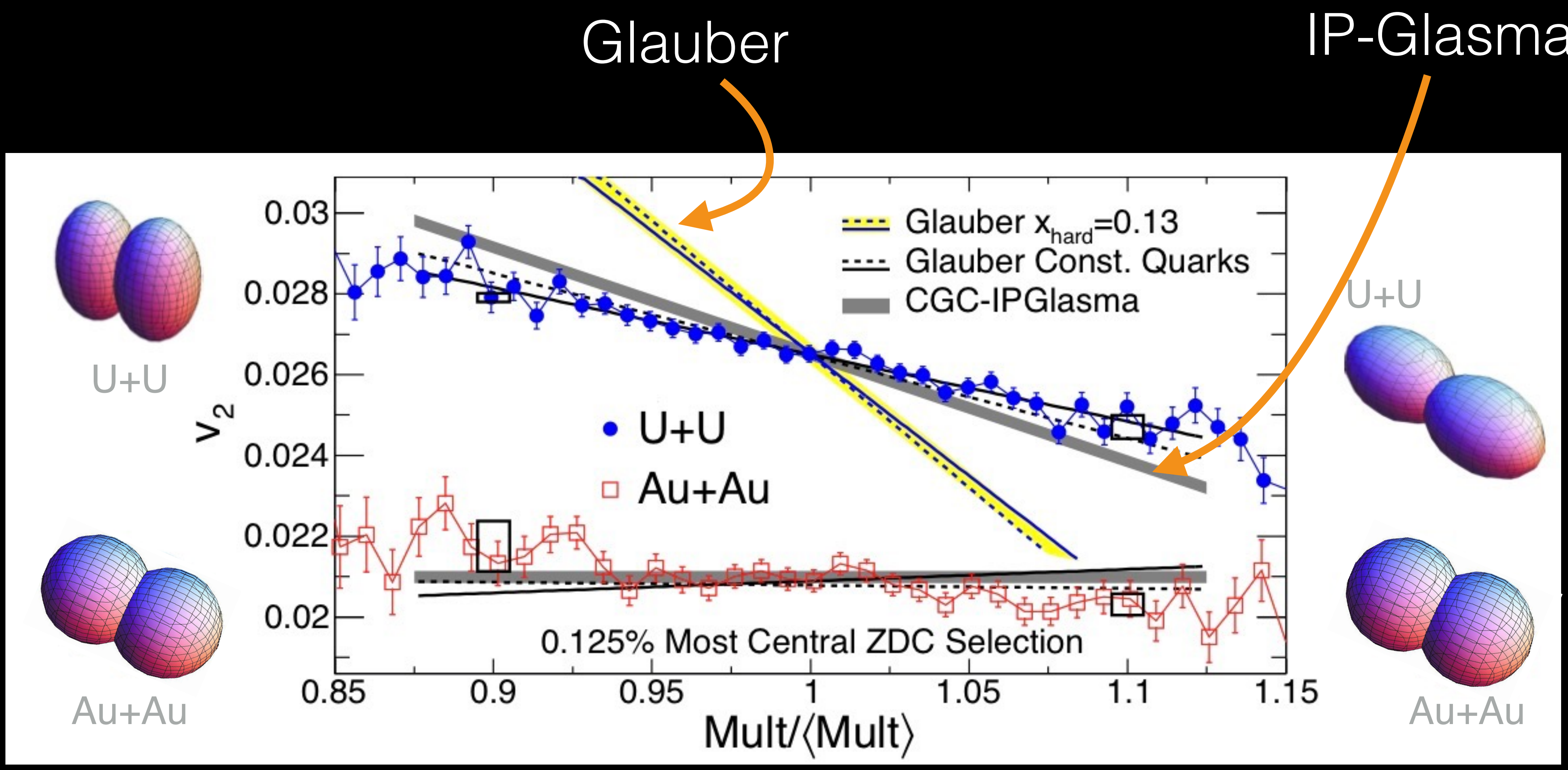
Orientation strongly change how many particles will be produced

Dynamical model : CGC



Orientation weakly change the no. of produced particles

3. Data that nailed it down: ultra-central U+U



Data: STAR collaboration, arXiv: 1505.07812

Correlation of shape (elliptic anisotropy) vs. no. of produced particles indicate 2-component Glauber model cannot explain data

“Improved” density prescriptions

Geometry based Density prescriptions

Failure to describe v_n distribution and ultra-central U+U data
—> Improved MC-Glauber prescriptions :

TRENTO

Moreland, Bernhard, Bass 1412.4708

$$dS/dy \propto f(T_A, T_B)$$

Quark-Glauber

Eremin, Voloshin nucl-th/0302071, PHENIX 1509.06727, Welsh, Singer, Heinz, 1605.09418

$$dE_T/d\eta, dN/d\eta \propto N_{qp}$$

Shadowed Glauber

Chatterjee et al 1510.01311, 1601.03971

$$\epsilon \propto \sum_{n}^{N_{part}} e^{-n\lambda}$$

A recent development, inspired by dilute-dense saturation model :

IP-Jazma $\epsilon \propto g^2 Q_s^2(x,y)_{proj} Q_s^2(x,y)_{targ}$

Nagle, Zajc 1808.01276

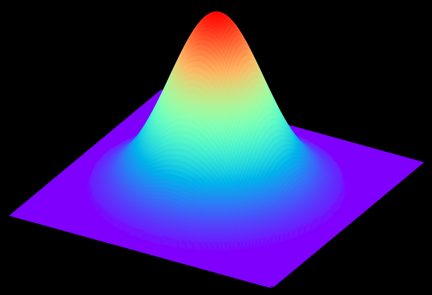
IP-Jazma ⇒large N_c limit of IP-Glasma, p=0 TRENTO

TRENTO: improved MC-Glauber prescription

Moreland, Bernhard, Bass 1412.4708

1. A Gaussian density profile for each colliding nucleons

$$T_{A,B} = w_{A,B} \frac{1}{2\pi B} \exp\left(-\frac{(x-x_{A,B})^2 + (y-y_{A,B})^2}{2B}\right)$$

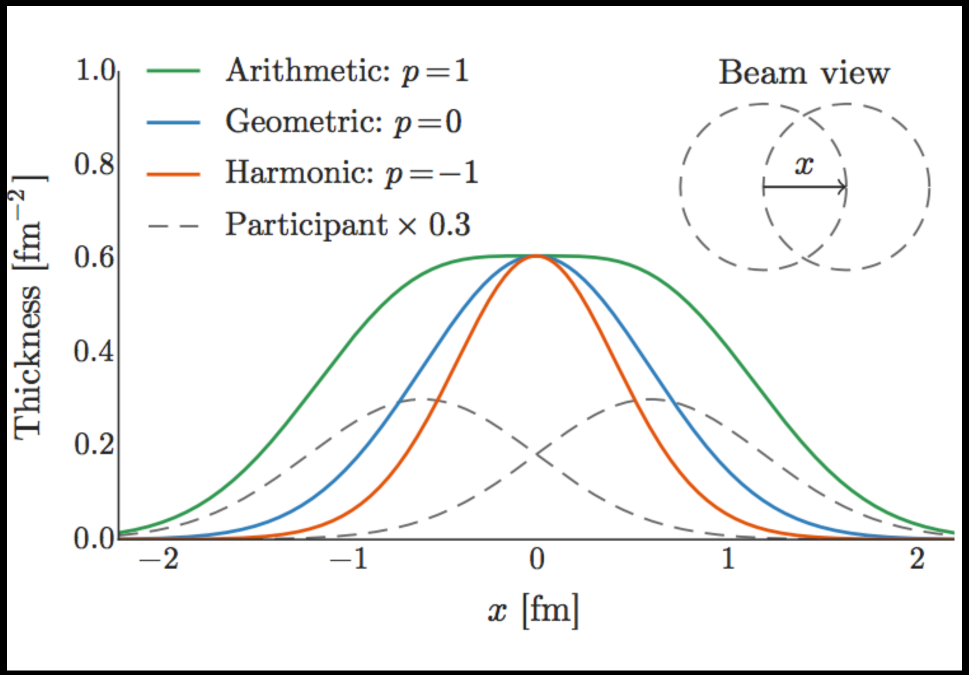


2. Fluctuating weight to incorporates sub-nucleonic fluctuations

$$P_k(w_{A,B}) = \frac{k^k}{\Gamma(k)} w_{A,B}^{k-1} \exp\left(-k w_{A,B}\right)$$

3. Generalized scheme for density after collision

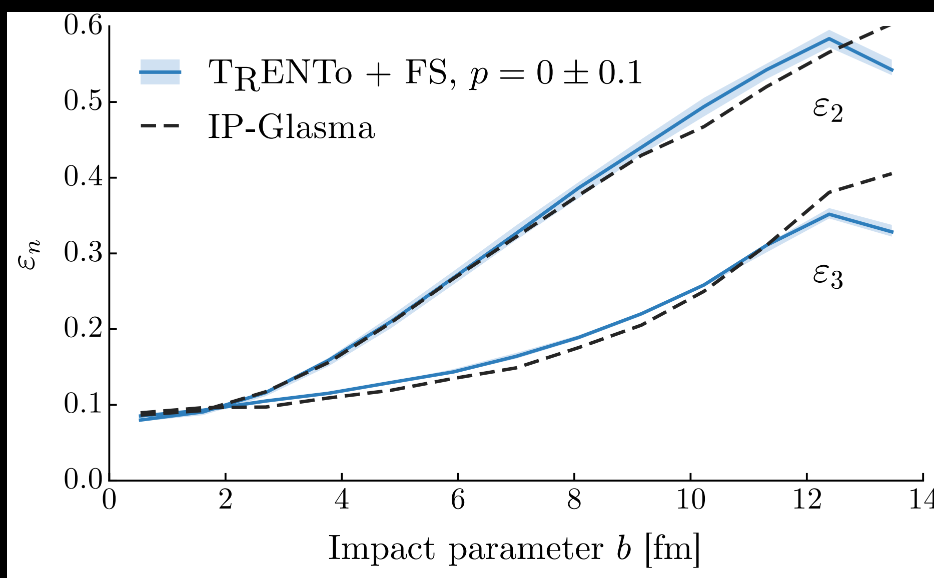
$$f = T_R(p; T_A, T_B) \equiv \left(\frac{T_A^p + T_B^p}{2}\right)^{1/p}$$



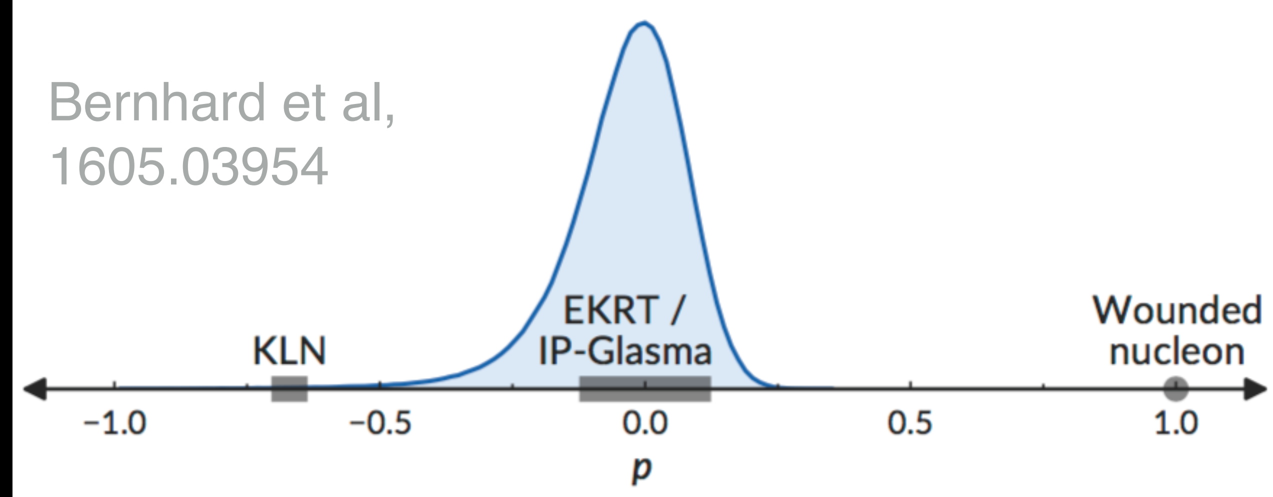
TRENTO provides event-by-event distributions of $(dN/dy) \,|\, (dS/dy) \,|\, \epsilon(x,y) \propto f(T_A, T_B)$

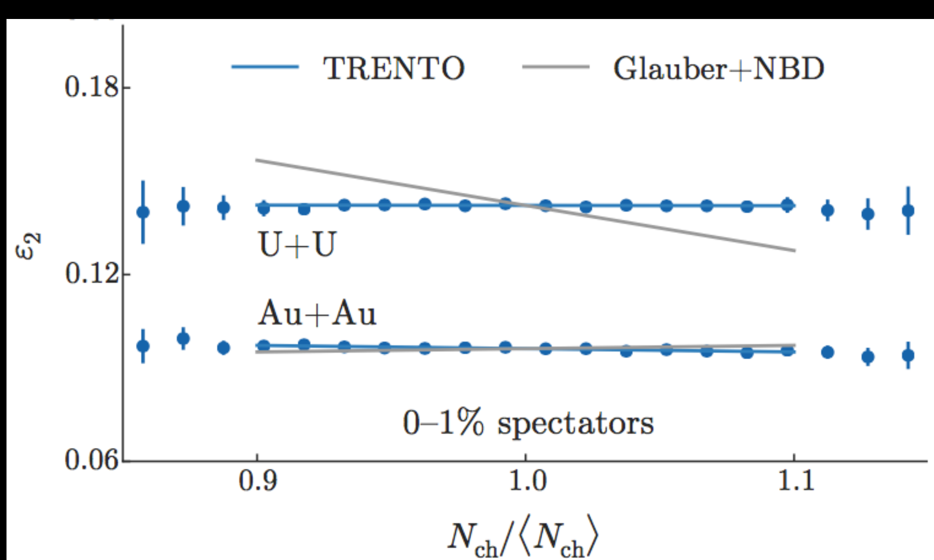
TRENTO: Reproducing existing models

The energy deposition scheme in TRENTO can be tuned to reproduce features of many different initial conditions



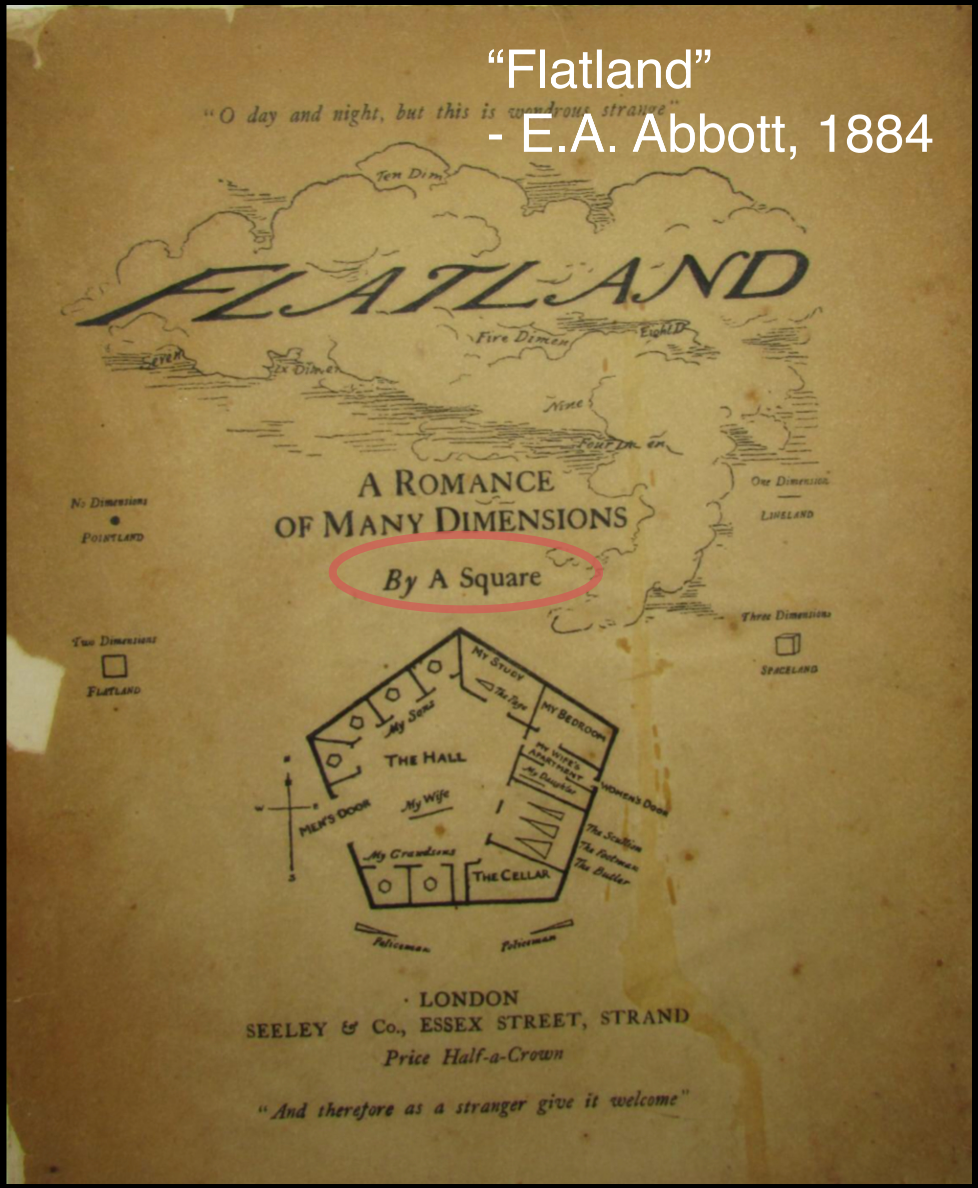
$$T_R = \begin{cases} \max(T_A, T_B) & p \to +\infty, \\ (T_A + T_B)/2 & p = +1, \ \text{(arithmetic)} \\ \sqrt{T_A T_B} & p = 0, \quad \text{(geometric)} \\ 2\,T_A T_B/(T_A + T_B) & p = -1, \quad \text{(harmonic)} \\ \min(T_A, T_B) & p \to -\infty. \end{cases}$$





Most compatible “p~0” parameter in TRENTO —> Bayesian analysis

TRENTO consistent to ultra-central U+U data

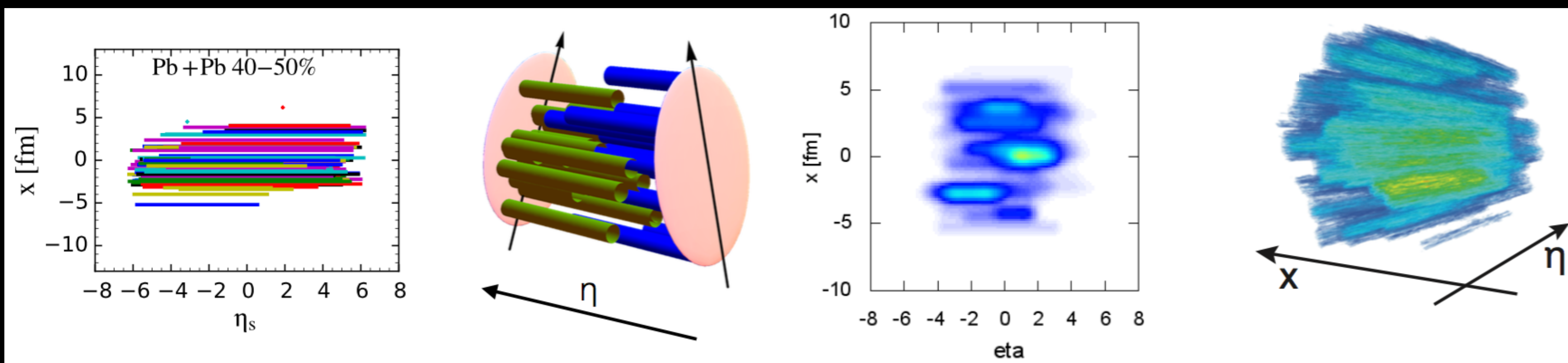


"Flatland"
- E.A. Abbott, 1884

Going to 3D

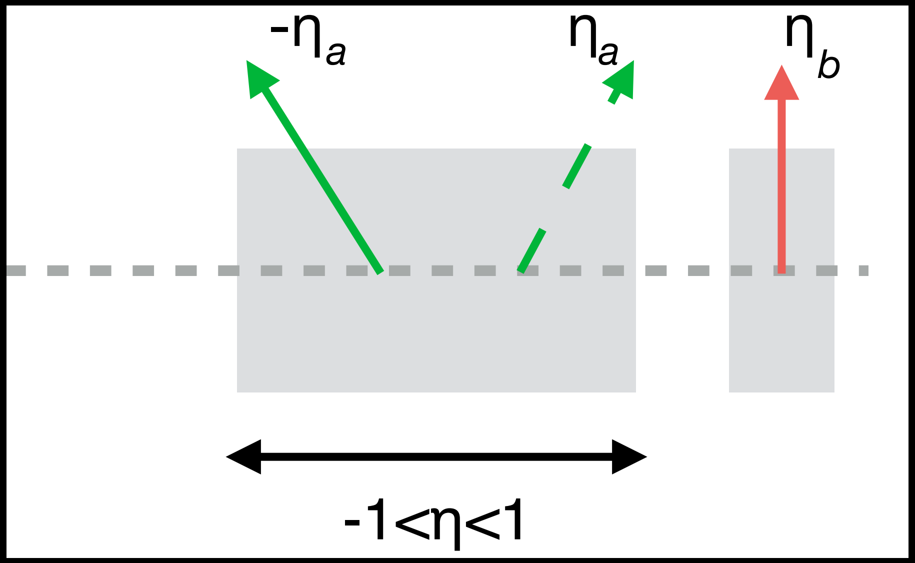
A glimpse of 3D-initial states

Longitudinal strings	Torqued-fireball	3D-Glauber	3D-Glasma
arXiv: 1511.04131	arXiv: 1506.02817	arXiv: 1509.04103	arXiv: 1605.07158

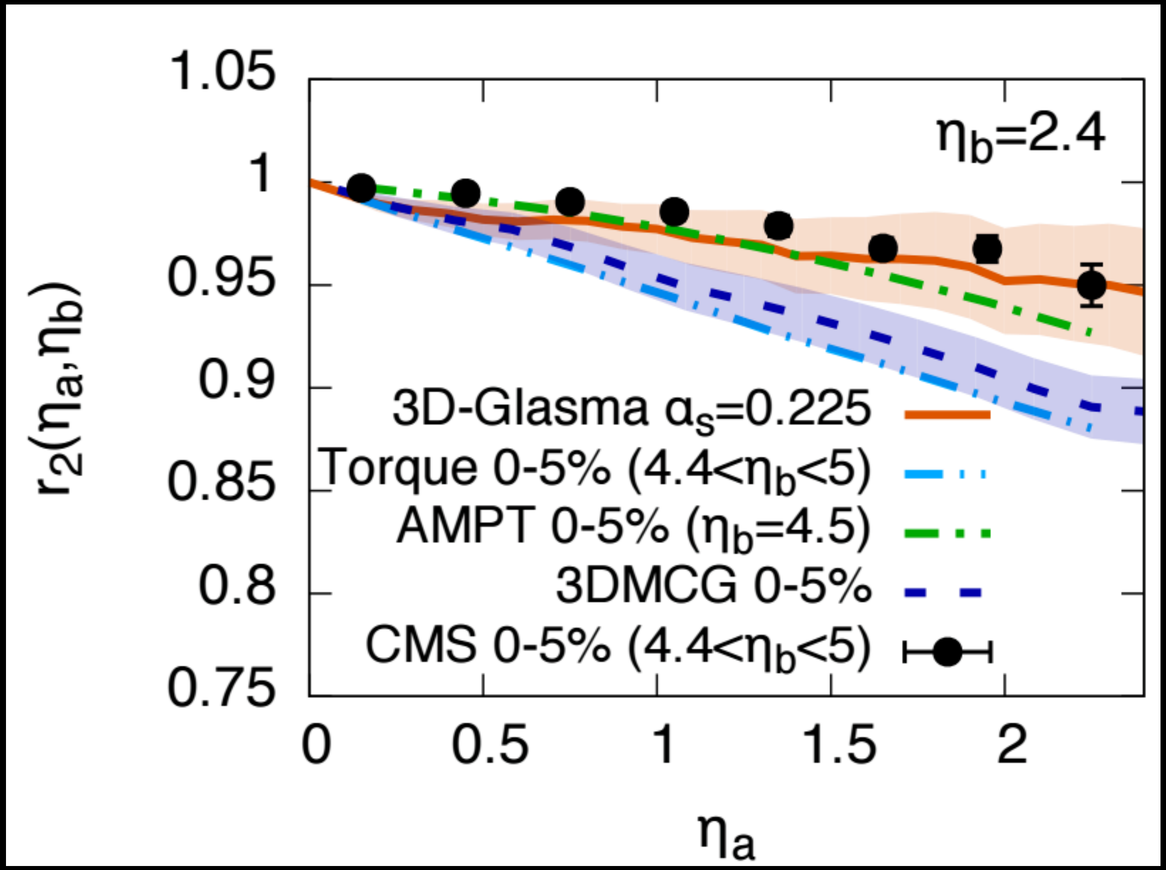


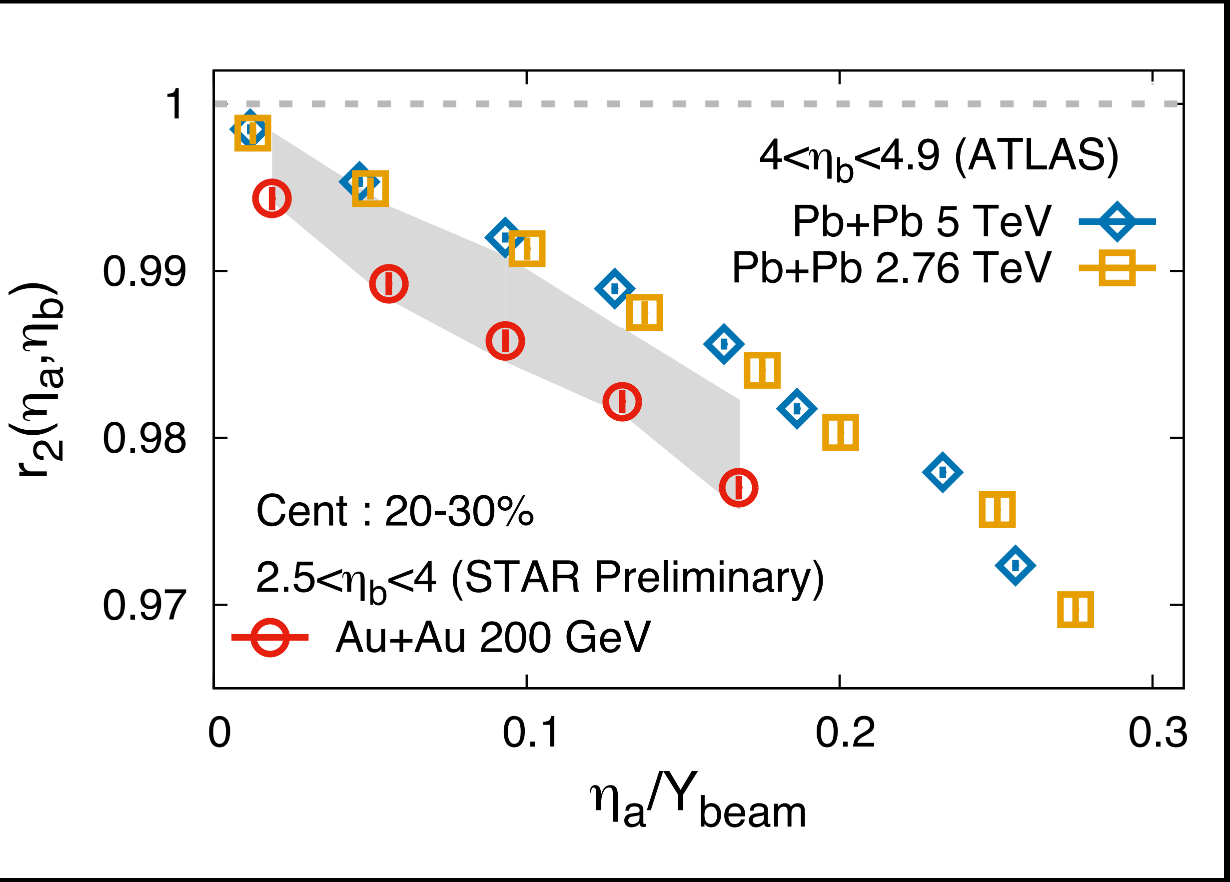
Main question is at what scale does the boost invariance break

How to constrain 3D-initial states ?



$$r_n(\eta^a,\eta^b) \equiv \frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)}$$





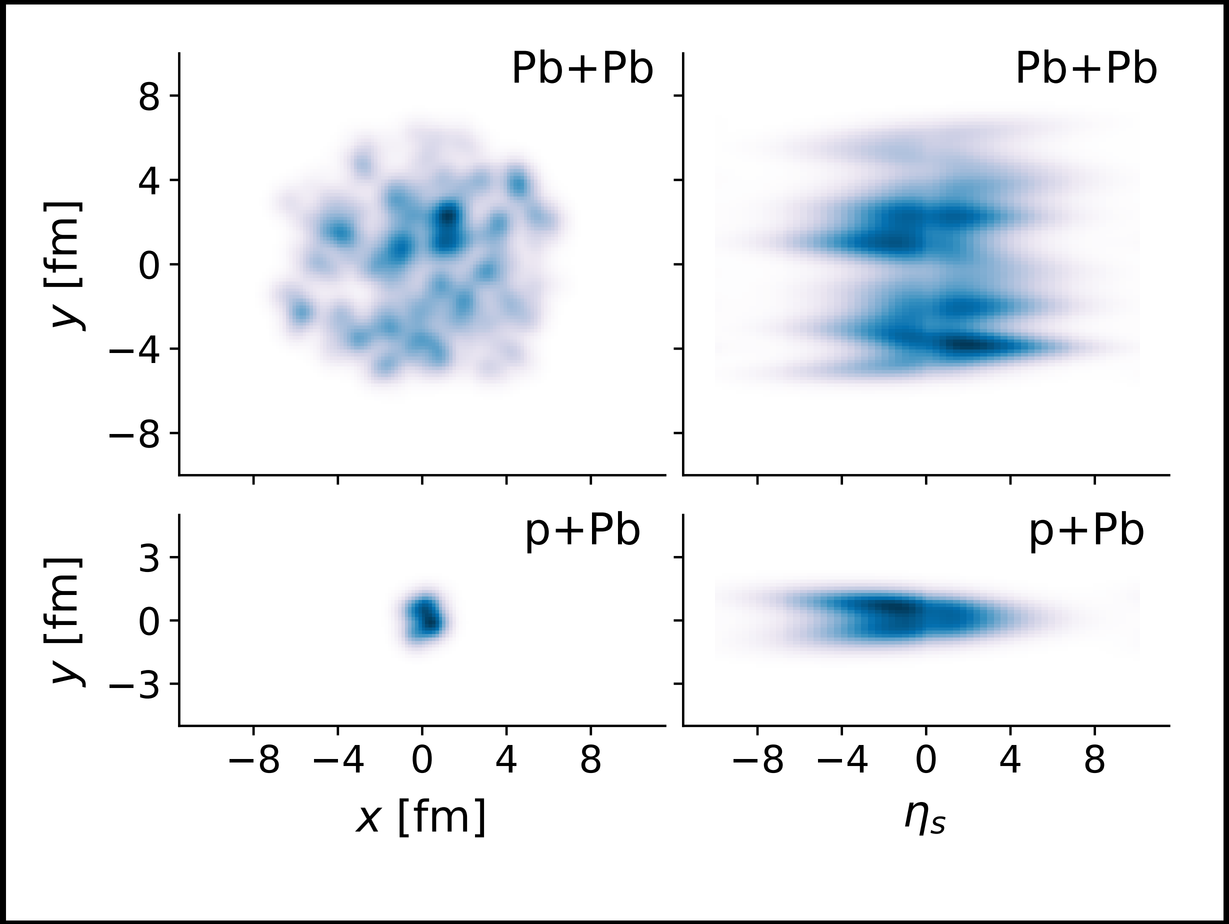
Longitudinal de-correlation show interesting energy dependence

Recent developments

Ke, Moreland, Bernhard, Bass, arXiv:1610.08490

Schenke, Shen arXiv:1710.00881

3D-Trento

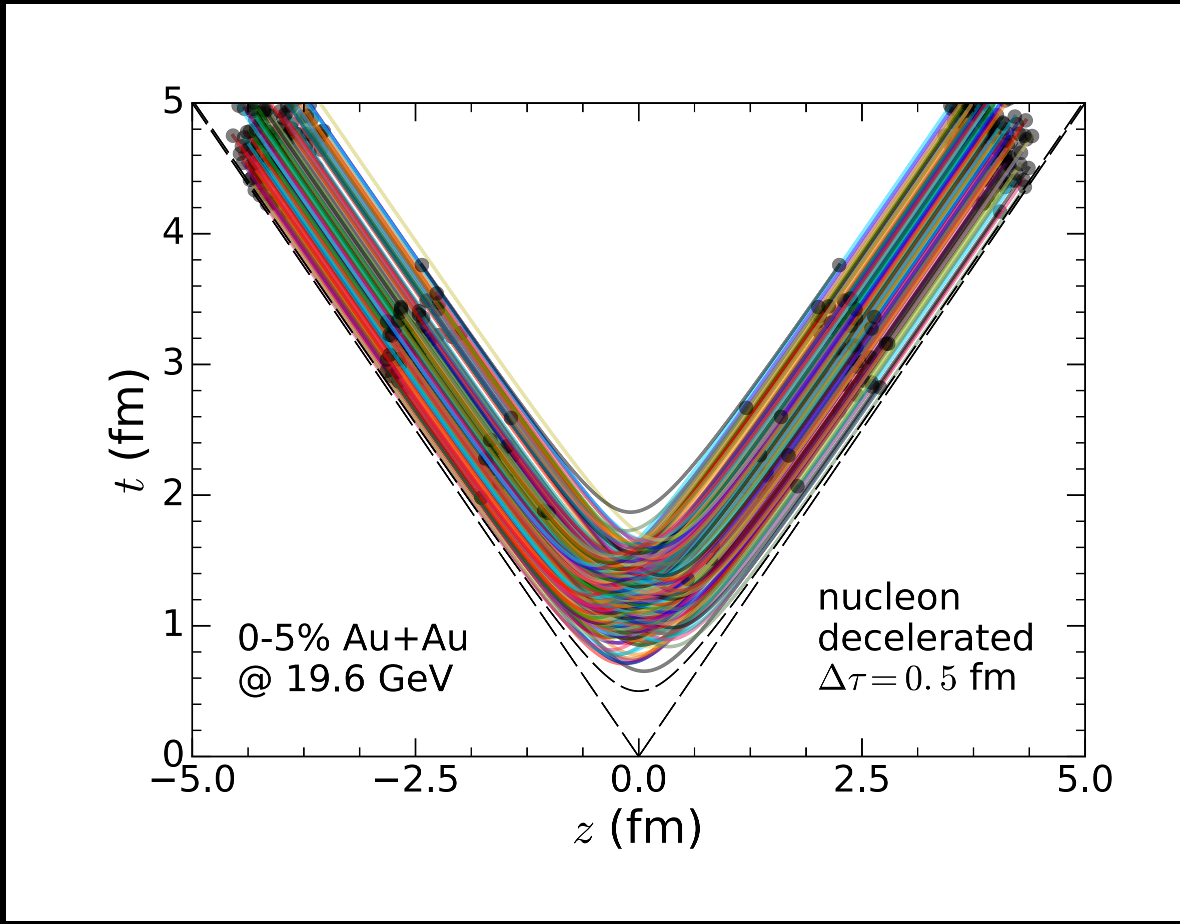


Modeling rapidity dependence:

$$g(\mathbf{x}, y) = \mathcal{F}^{-1}\{\tilde{g}(\mathbf{x}, k)\},$$

$$\log \tilde{g} = i\mu k - \frac{1}{2}\sigma^2 k^2 - \frac{1}{6} i\gamma\sigma^3 k^3 + \cdots$$

3D-LeXus

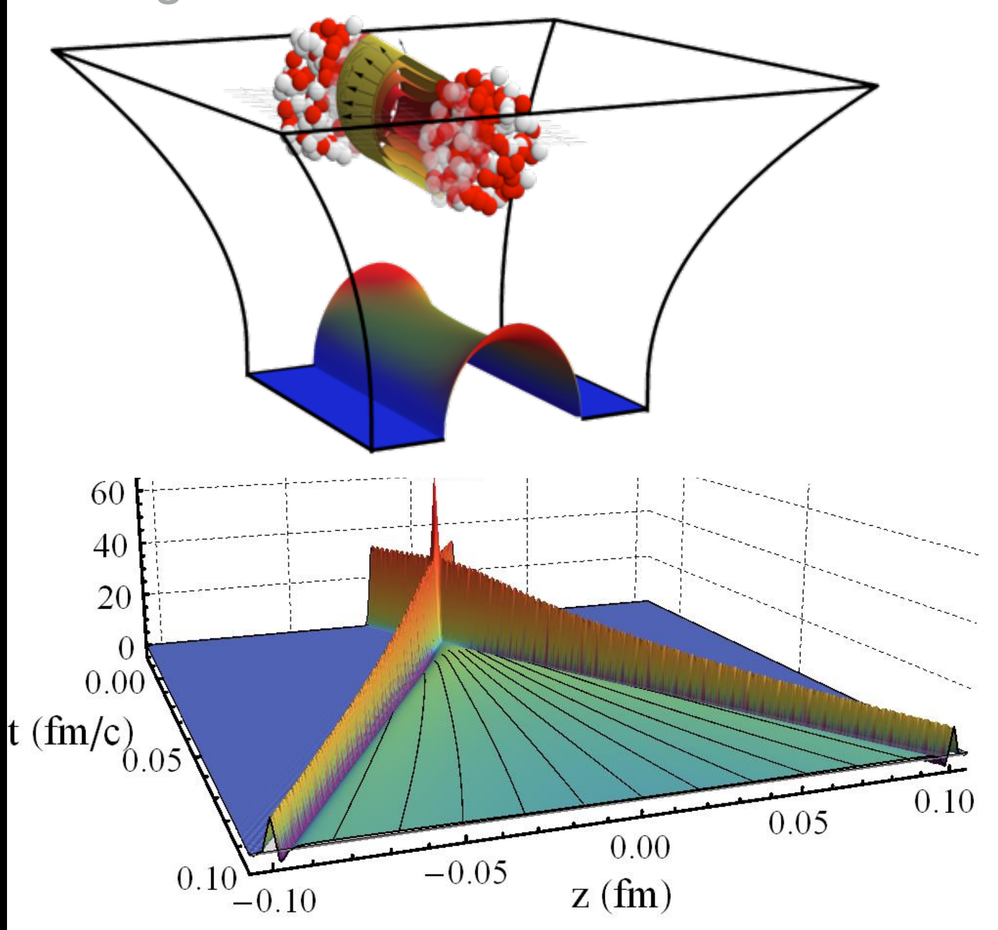


Construct strings between quarks in rapidity from LeXus model & evolve in time

Will be mostly important for beam energy scan (BES) program at RHIC

Holographic initial conditions

fig: W. Van der Schee QM'15



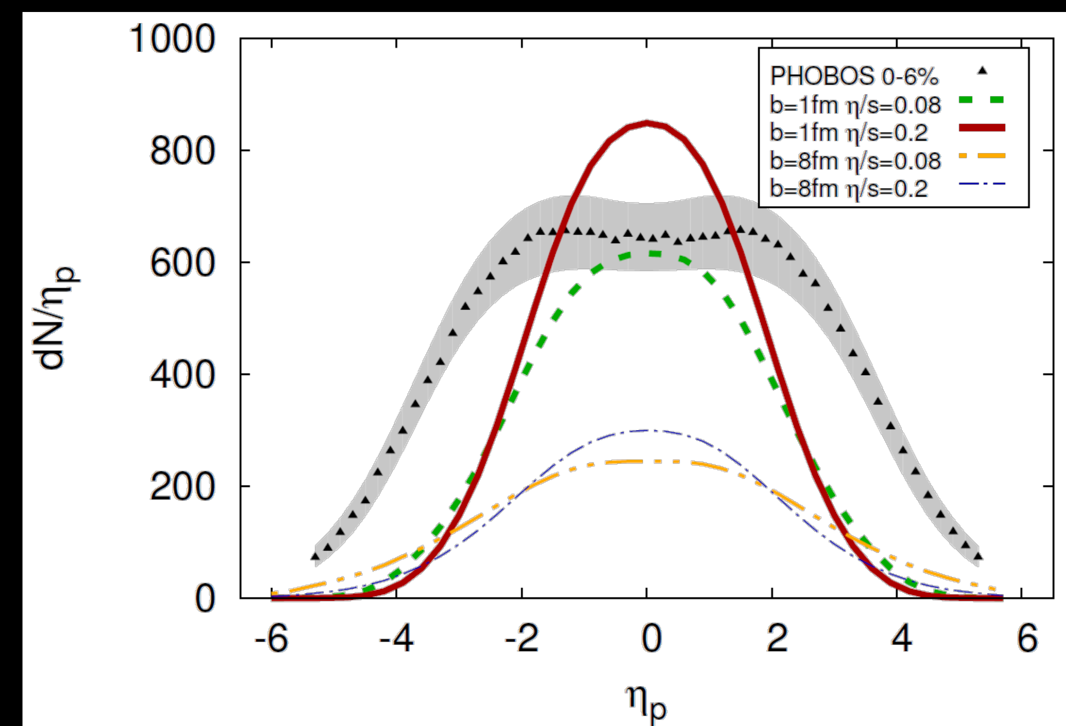
$$\mathcal{E}(t) = \frac{N_c^2\Lambda^4}{2\pi^2}\left[\frac{1}{(\Lambda t)^{4/3}} - \frac{2\eta_0}{(\Lambda t)^2}\right]$$

$$v_i = -0.33\,\tau\,(\partial_i e)/e$$

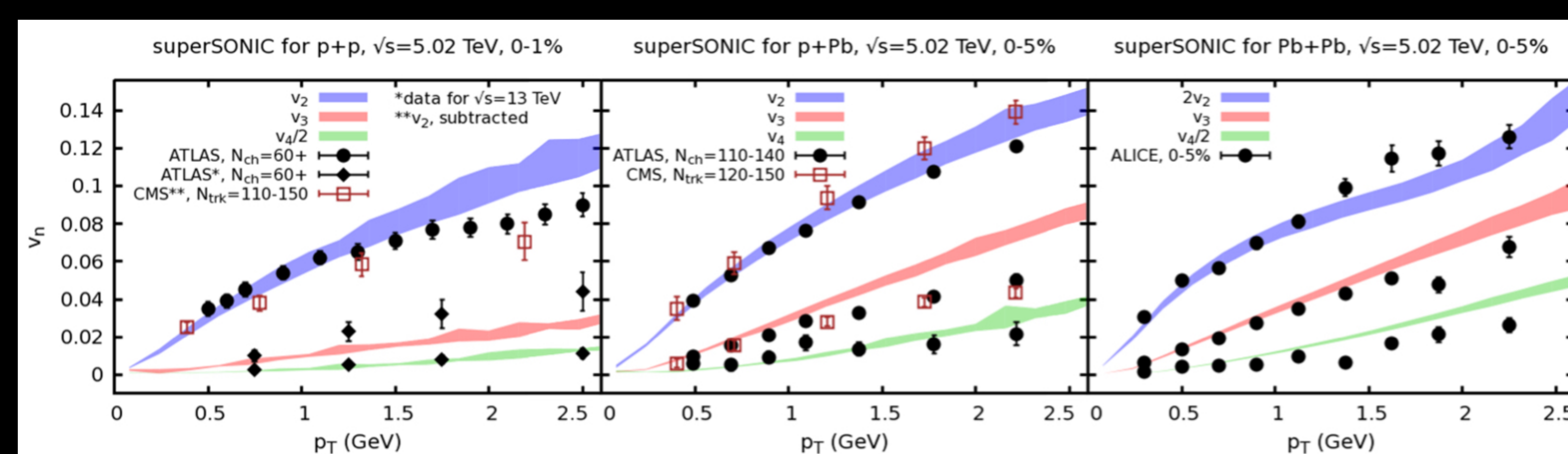
Chesler, Kilbertus, Van der Schee 1507.02548, Van der Schee, Romatschke, Pratt 1307.2539, Heller and Janik, hep-th/0703243

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

Van der Schee, Schenke 1507.08195



Weller, Romatschke 1701.07145



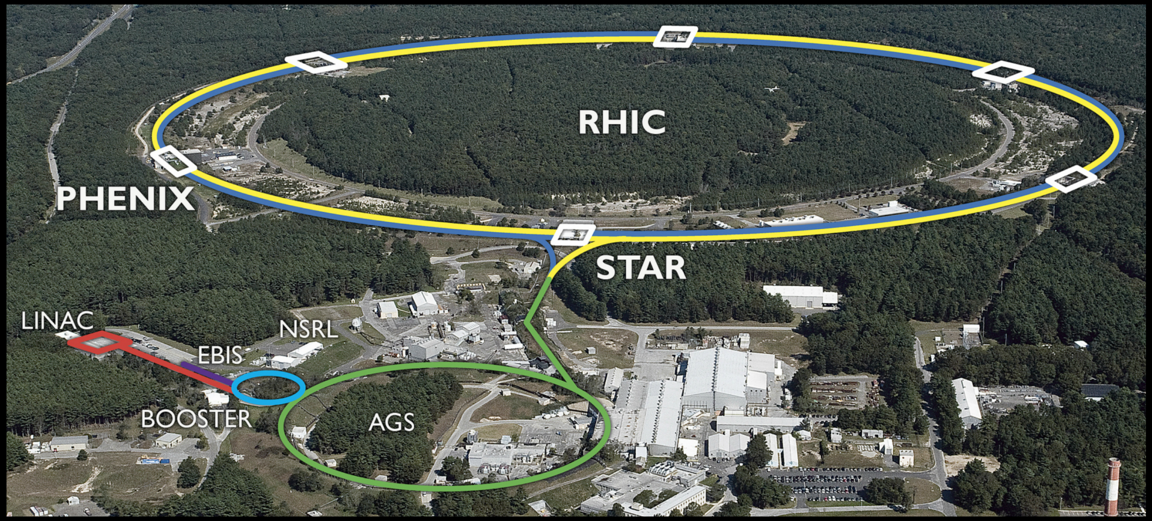
superSONIC:
Glauber + AdS motivated flow

Beyond Heavy Ion Collisions

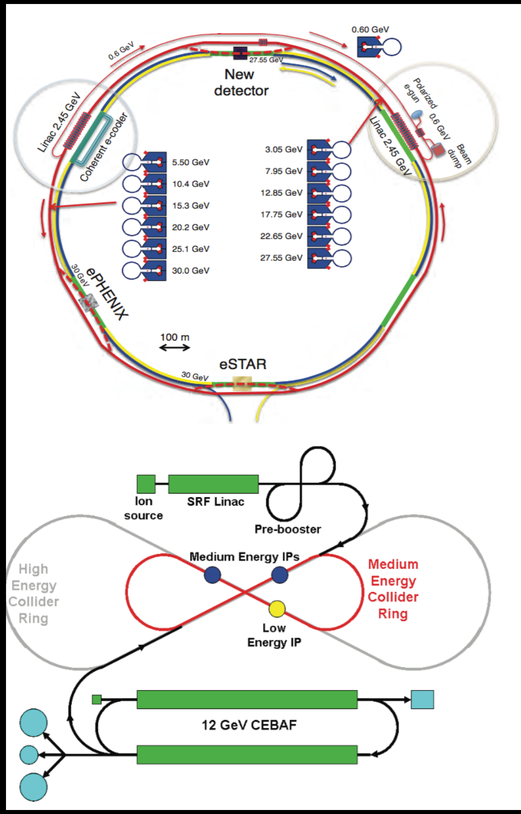
Transition to an EIC era

We are in the middle of a transition

RHIC-era



EIC-era



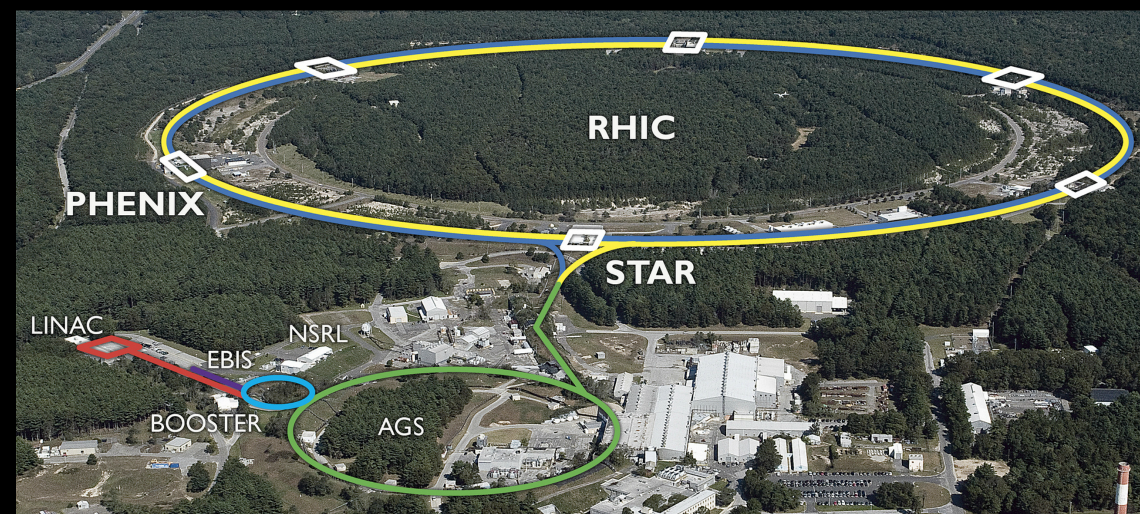
What insight do we heavy ion physicists bring in ?

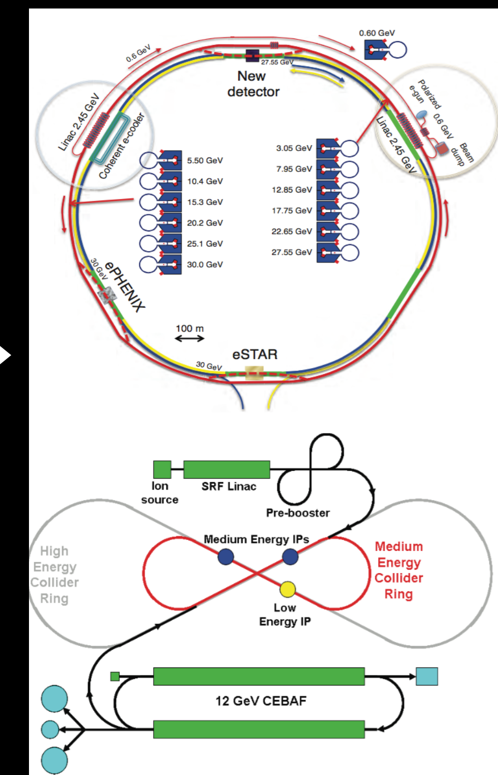
Transition to an EIC era

HERA

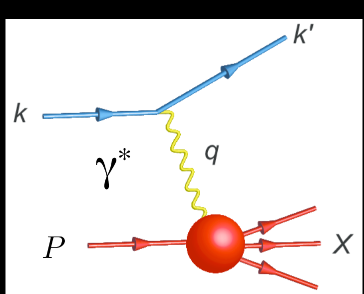
RHIC/LHC

EIC





RHIC era changed our view of nuclei at high energies



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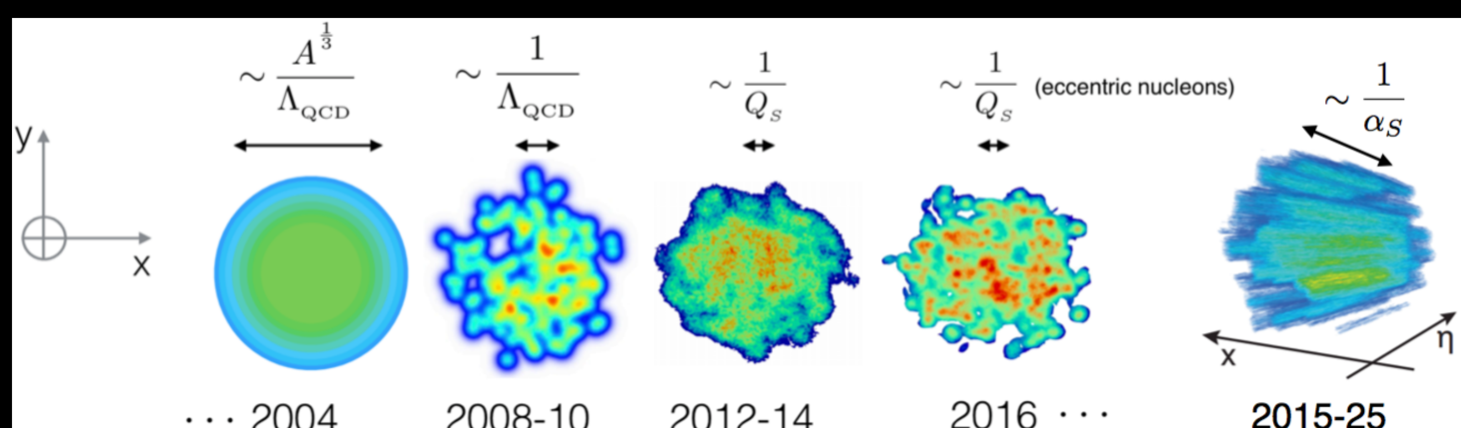

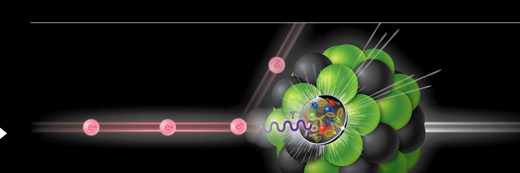

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Can our knowledge of colliding nuclei make a difference to EIC physics?

Summary

- Computing the initial conditions of heavy ion collisions is a challenging due to non-perturbative nature of the problem
- Successful effective first principles approaches have been developed over the years, such as IP-Glasma, EKRT
- Improved density scheme can reproduce features of dynamical models, satisfy requirements to initialize hydro
- Apart from Bayesian analyses independent constraints on initial conditions from HERA and future EIC are most desired

A few recent developments that I couldn't cover in this talk: Approach to thermalization, Initial conditions at low energy collisions, Small systems and ridge

Thanks