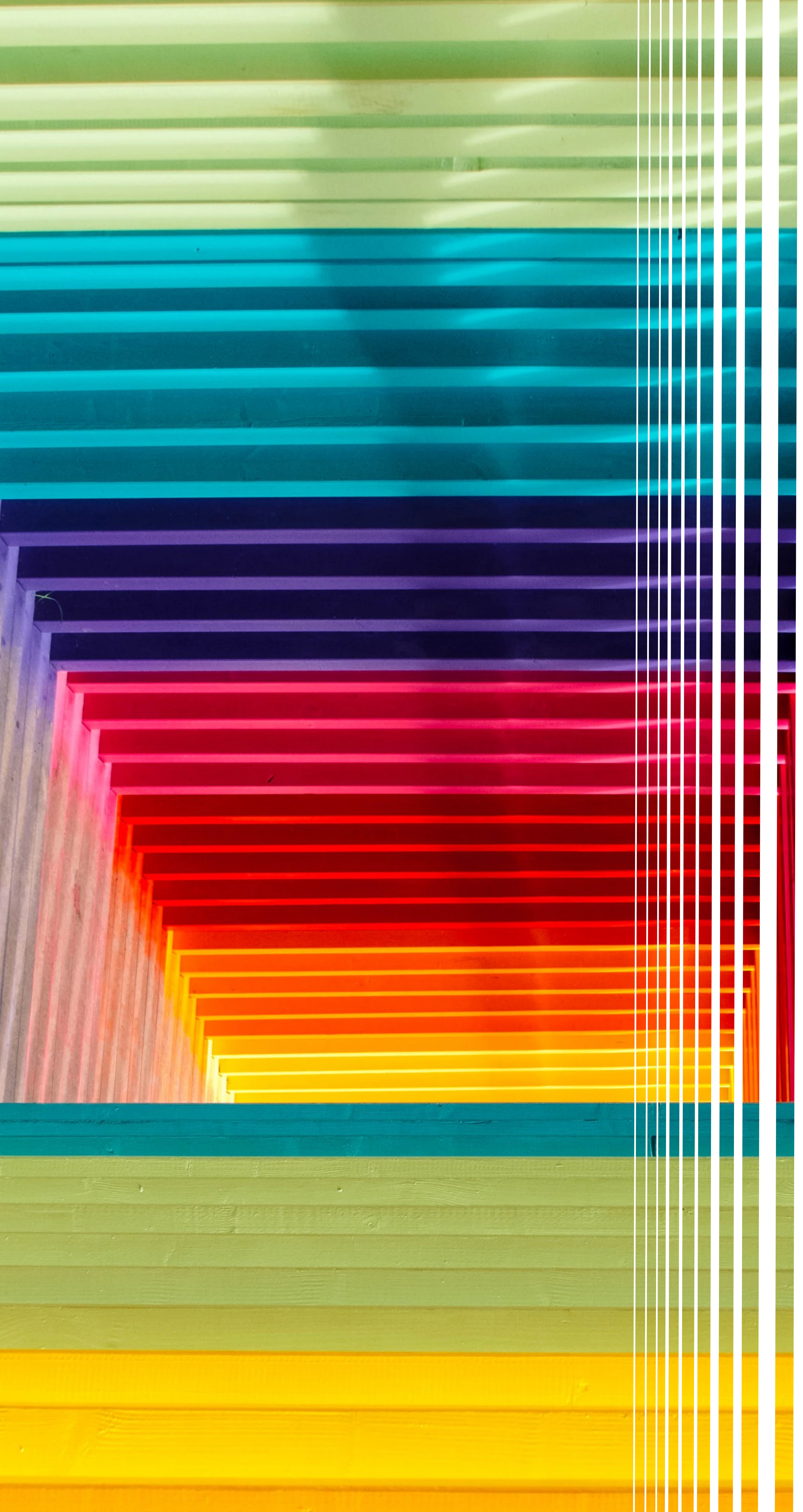

April 2026
Kyoto, Japan

THE INITIAL STATE:

Oscar Garcia-Montero

Instituto Galego de Física de Altas Enerxías
Universidade de Santiago de Compostela

Further questions/comments:

Partially based on
Effective theories for nuclei at high energies
O. G-M, S. Schlichting, *Eur. Phys. J.A* 61 (2025)

ERC

IGFAE

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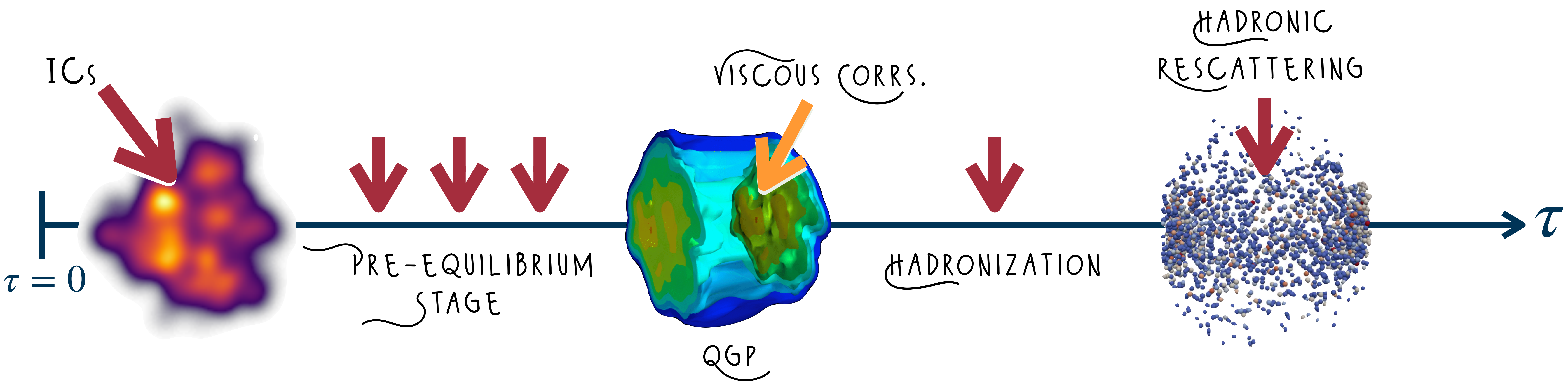
DE COMPOSTELA

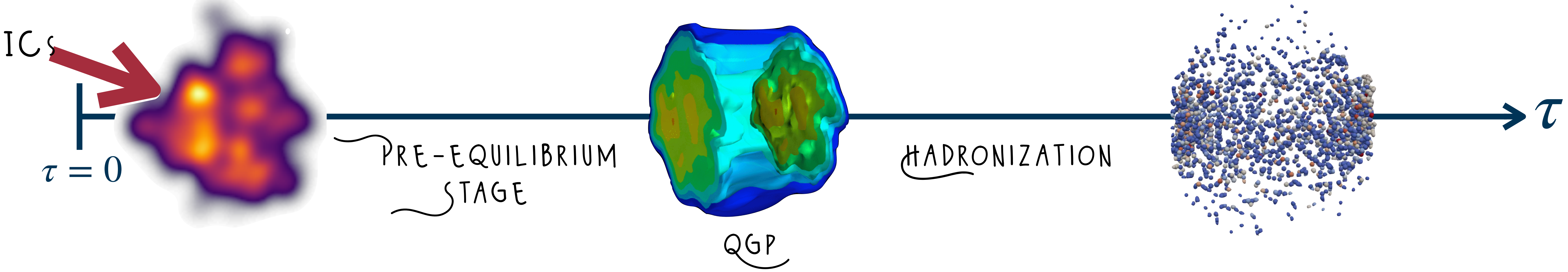
THE TENOUSLY THERMAL QGP

- Heavy-Ion Collisions create a -***very complicated***- Isolated Quantum System which is
  - Initially far away from any equilibrium
  - Self-interacting
  - Expanding against the vacuum
- A system battling to thermalize against all odds.



HEAVY ION COLLISIONS: THE BASIC IDEA

- If we focus for now in the slice at midrapidity, $y = 0$, we can produce some sort of dynamical timeline for the evolution of ultrarelativistic HICs



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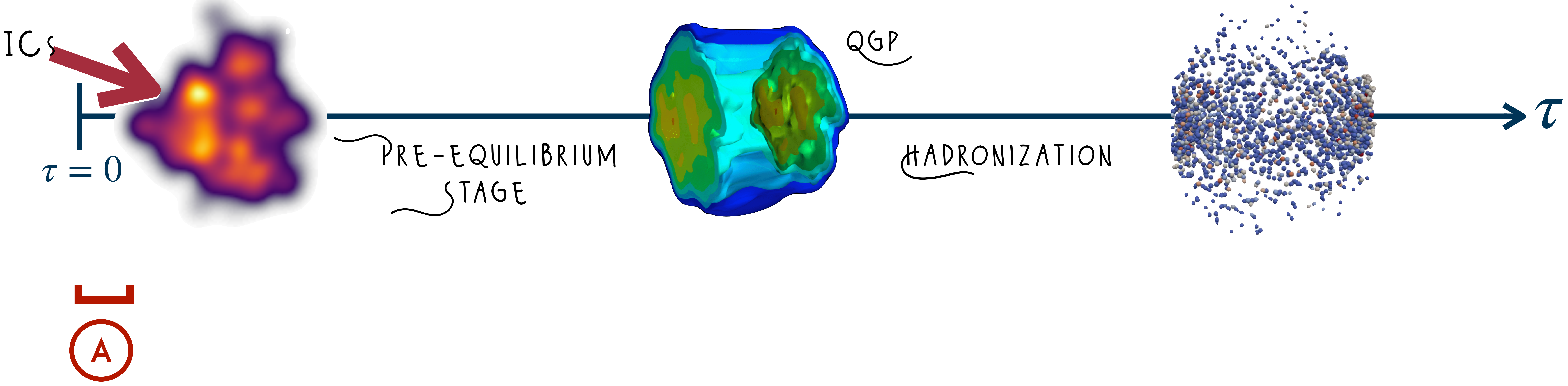

A INITIAL CONDITIONS

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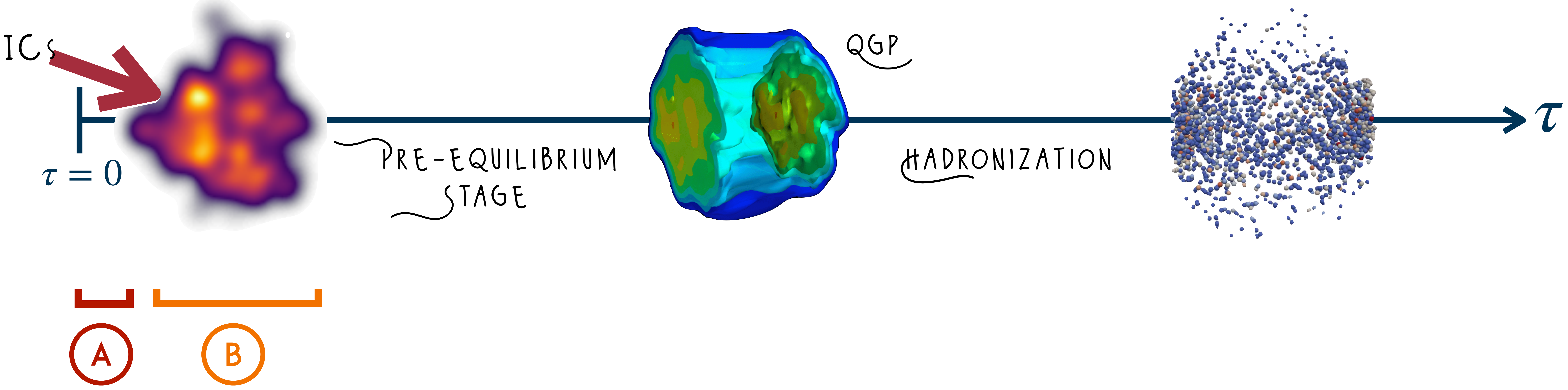

Ⓐ INITIAL CONDITIONS

Ⓑ GLASMA (GLUON PLASMA)

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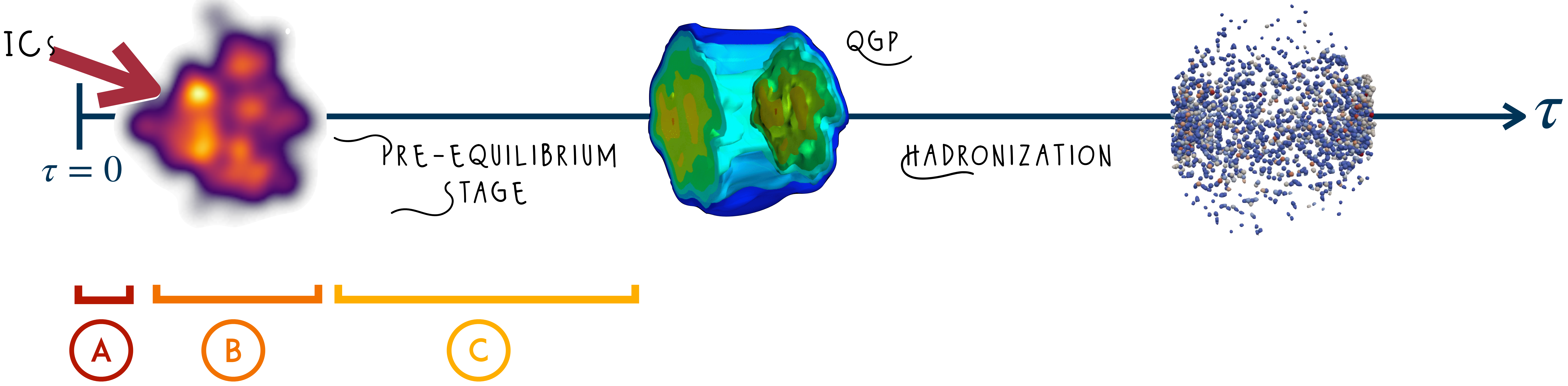

(A) INITIAL CONDITIONS

(B) GLASMA (GLUON PLASMA)

(C) QCD KINETIC STAGE

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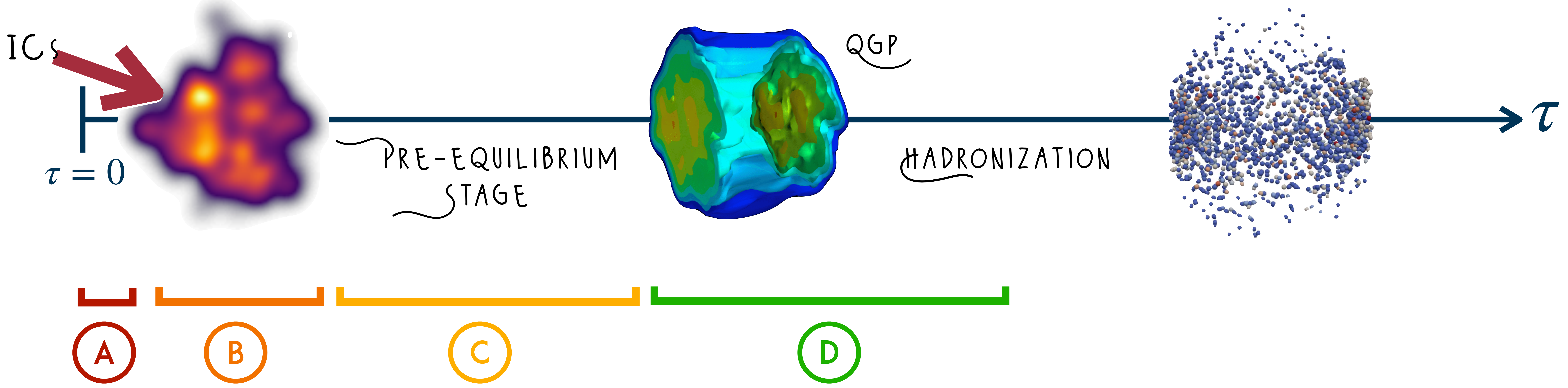

- (A) INITIAL CONDITIONS
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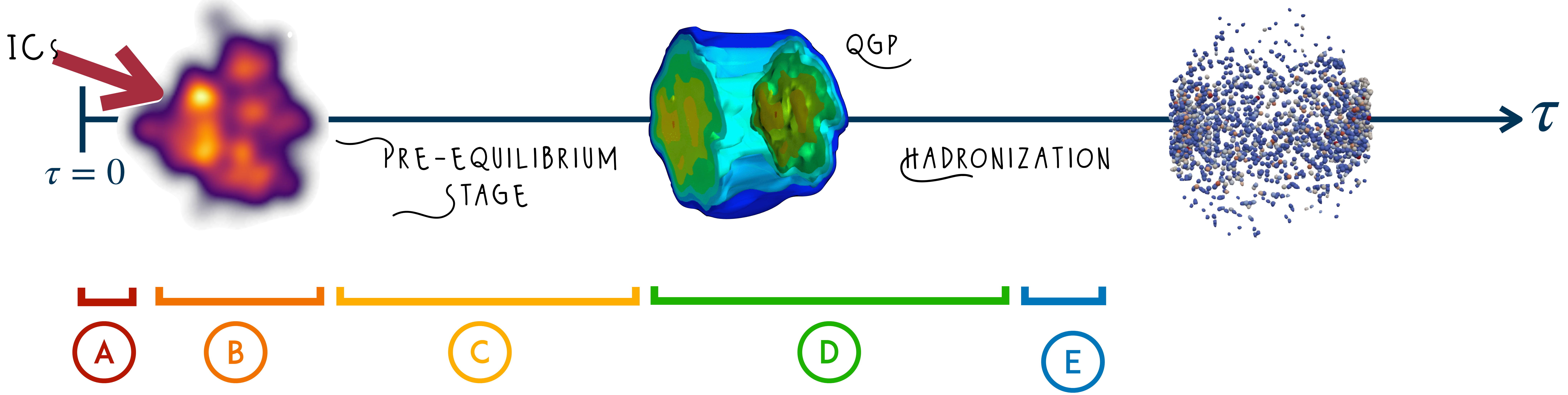

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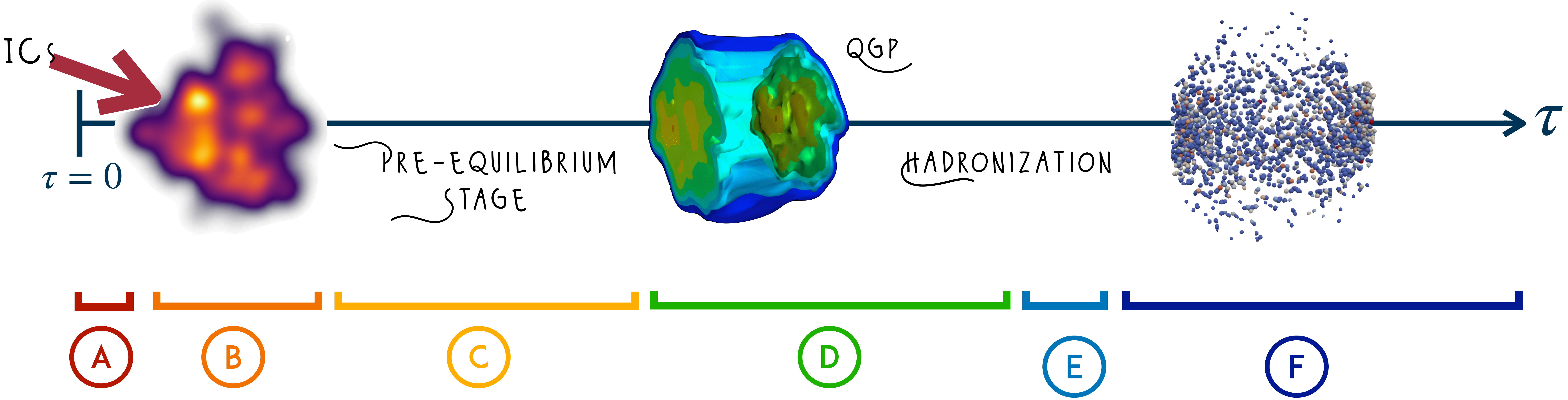

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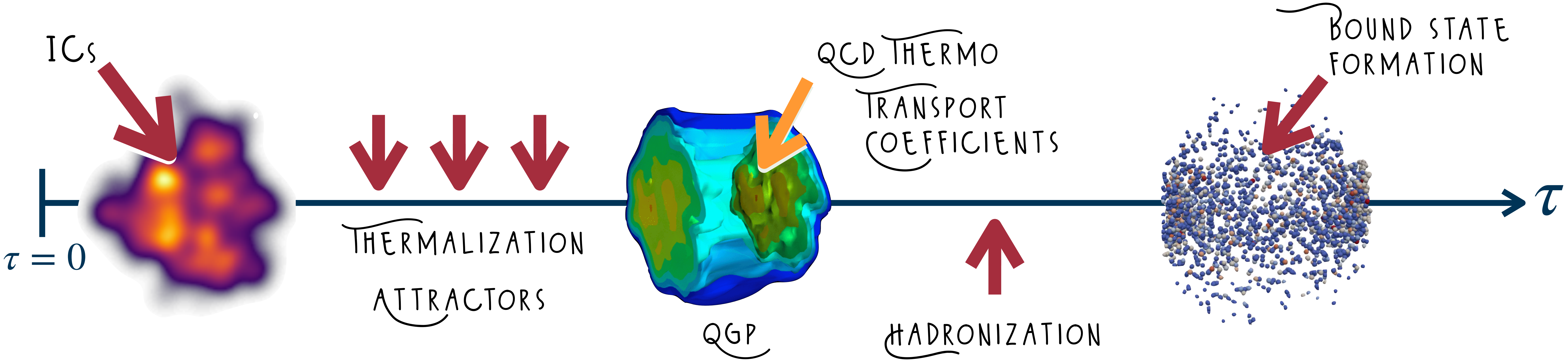
Ⓔ HADRONIZATION

Ⓕ HADRONIC STAGE (ALSO KINETIC)

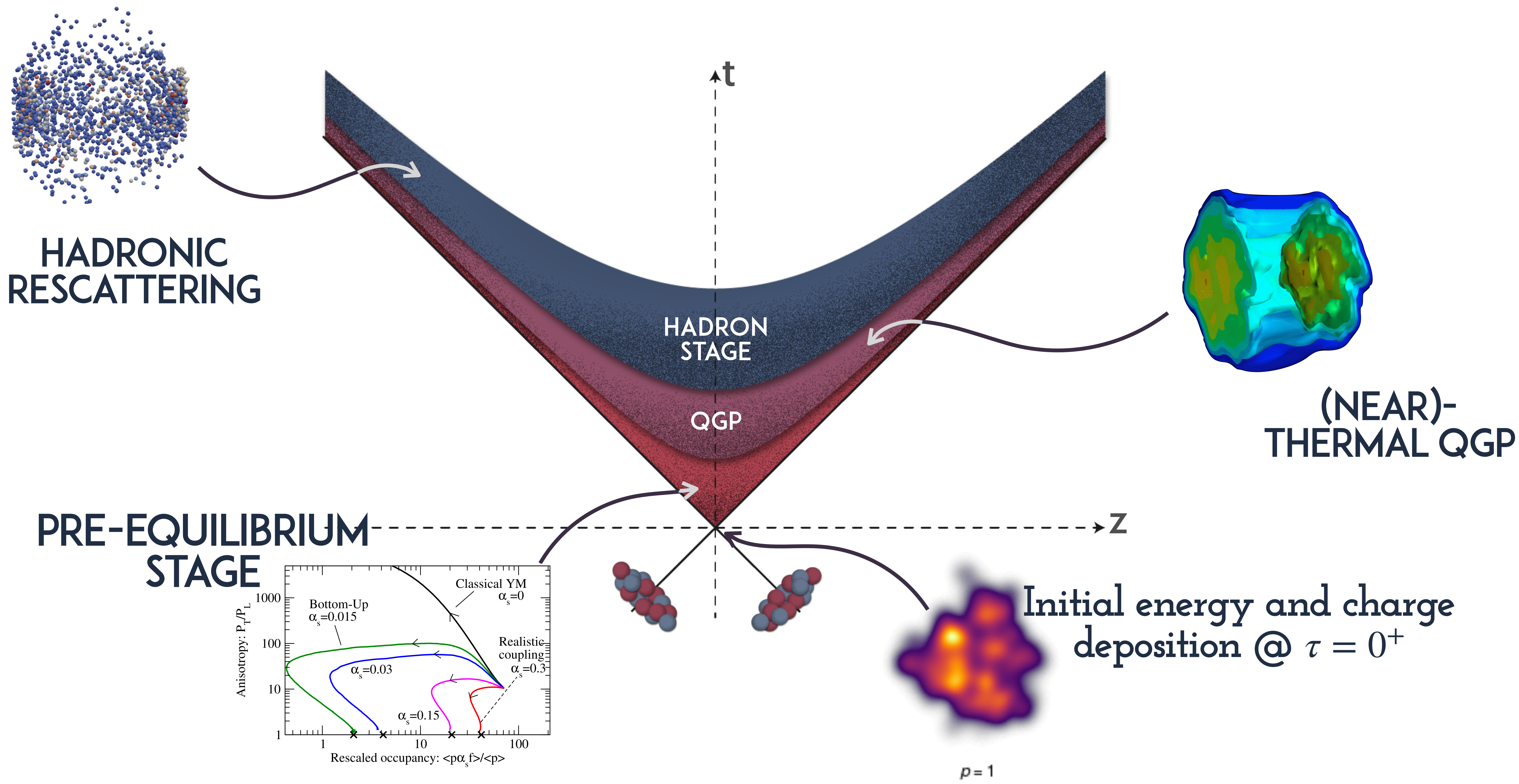
WHAT CAN WE LEARN?

- Thermalisation
  - How can isolated QCD systems thermalize so fast?
  - What drives thermalisation?
- QCD matter
  - Transport coefficients
  - QCD Thermodynamics
- Small Systems: What makes a fluid, a fluid?

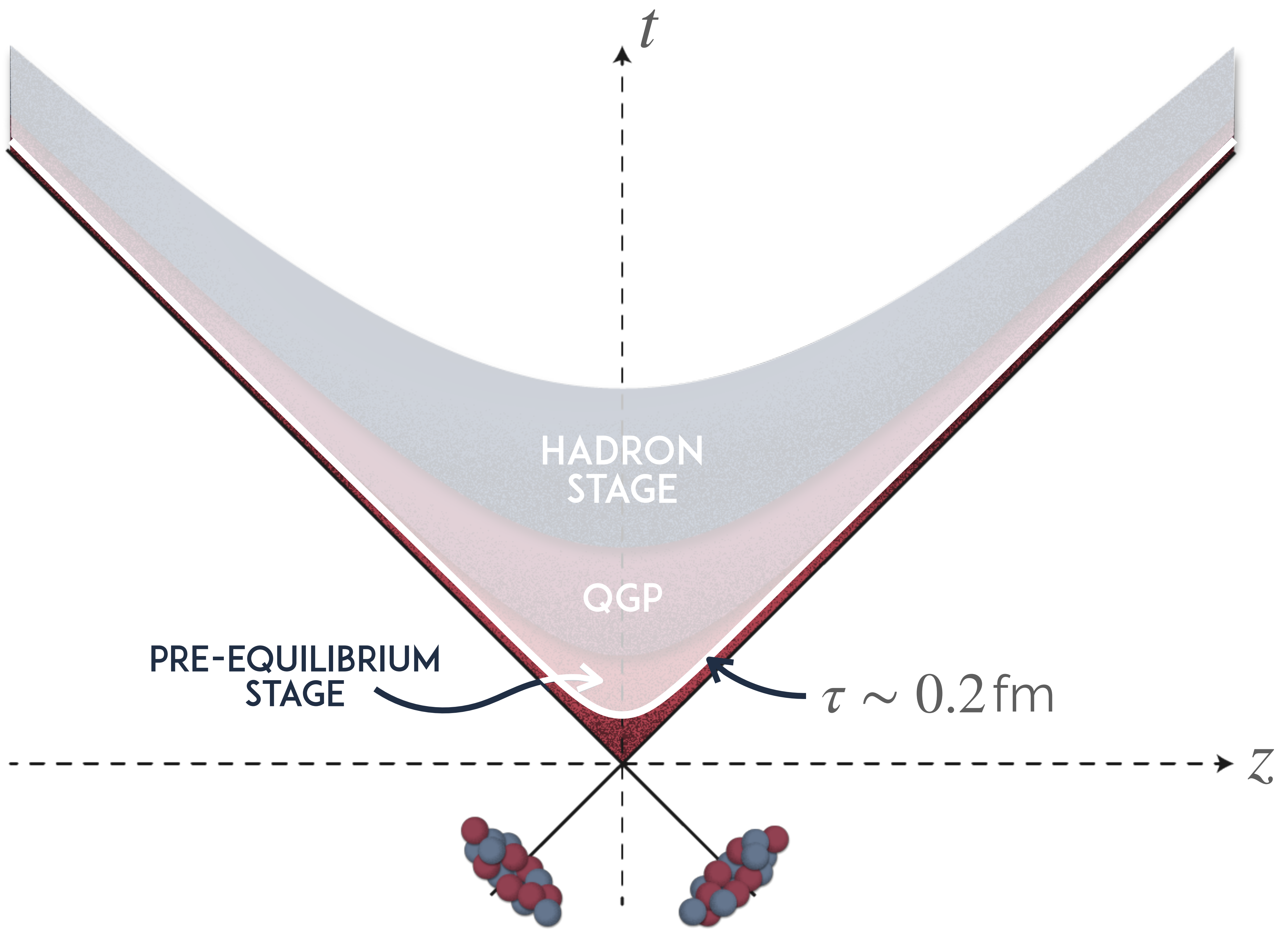


WHAT IS THE INITIAL STATE?

OUR UNDERSTANDING OF A HEAVY ION COLLISION



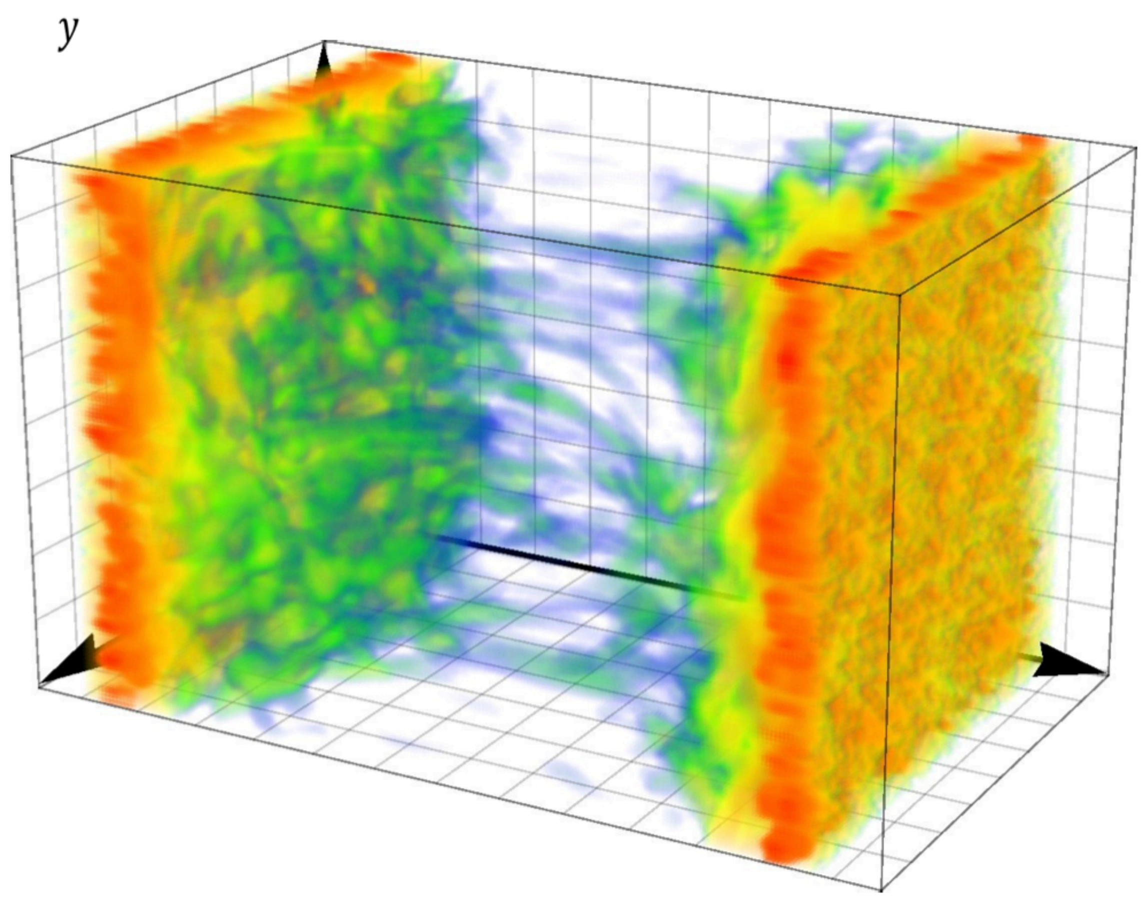
THE INITIAL STAGE OF A HEAVY-ION COLLISION

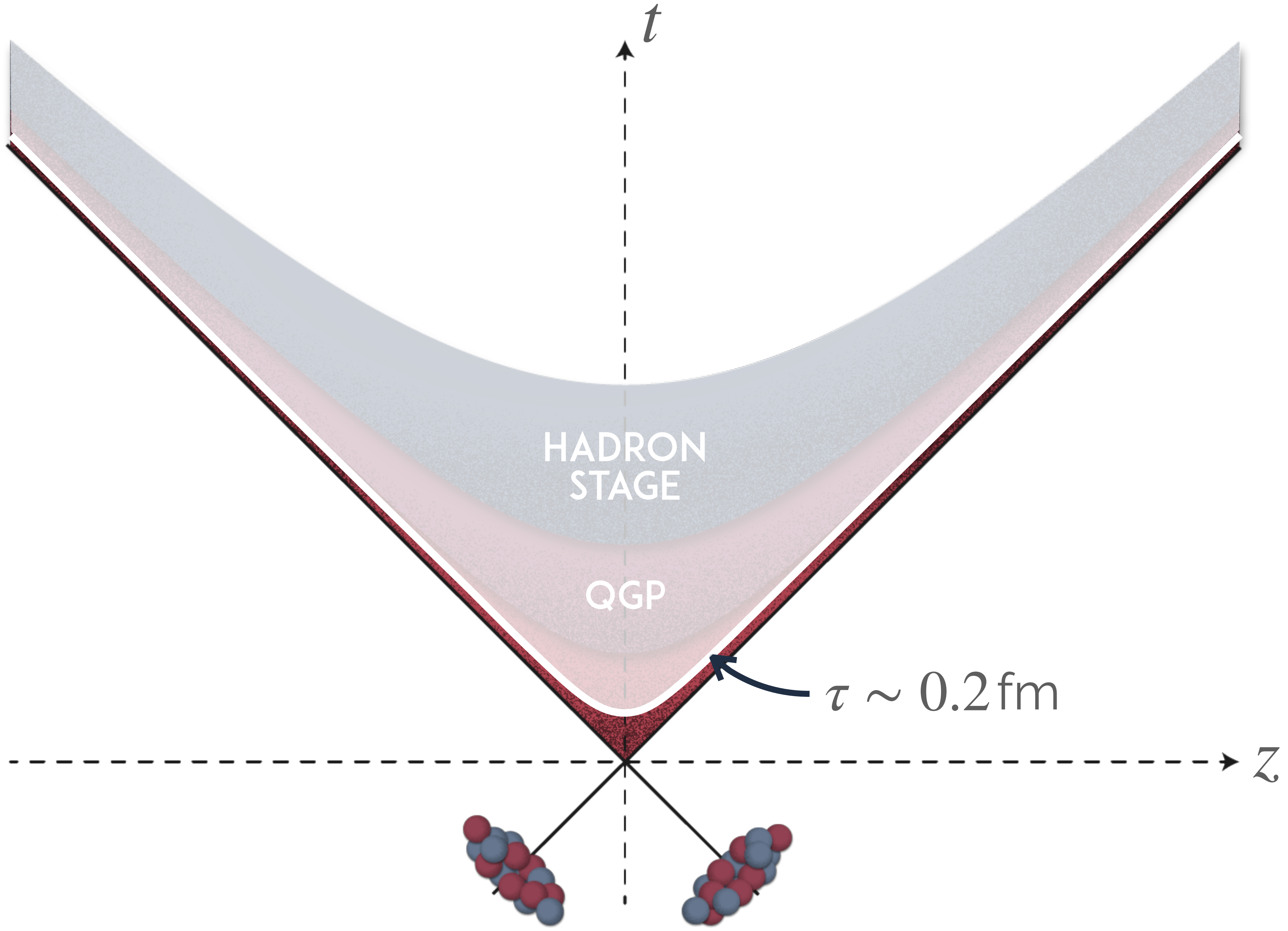


THE INITIAL STAGE OF A HEAVY-ION COLLISION

NOT ONLY

Strong-field dynamics and evolution up to $\tau \sim 0.2\,\mathrm{fm}$





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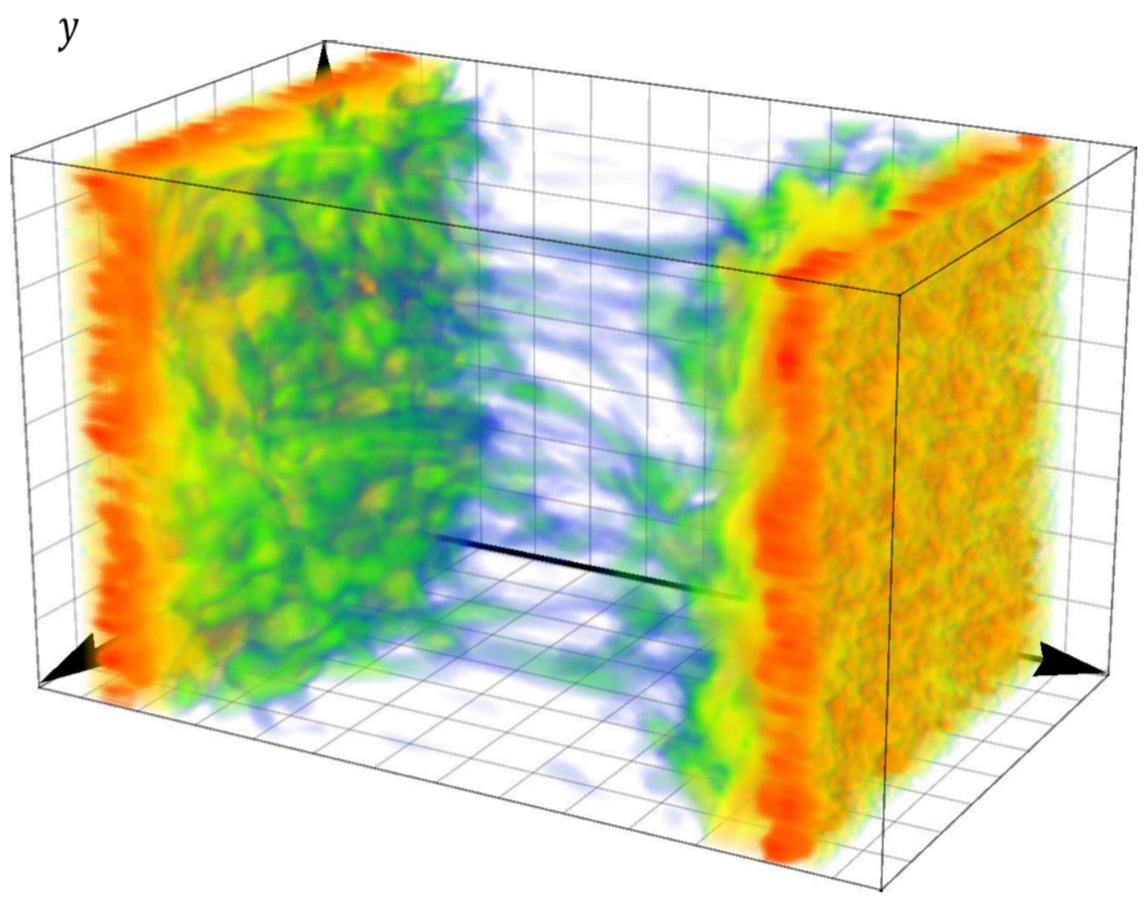
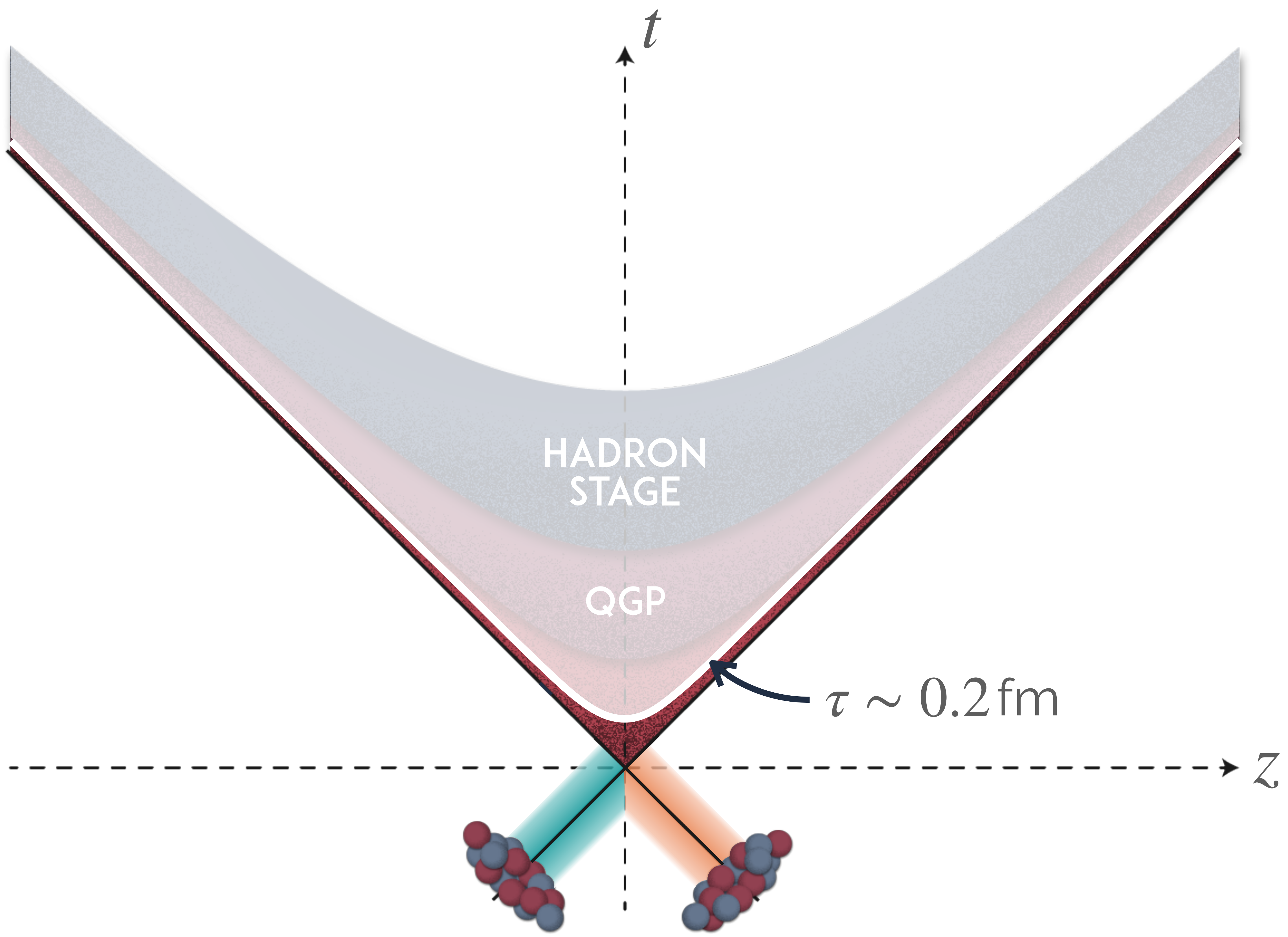
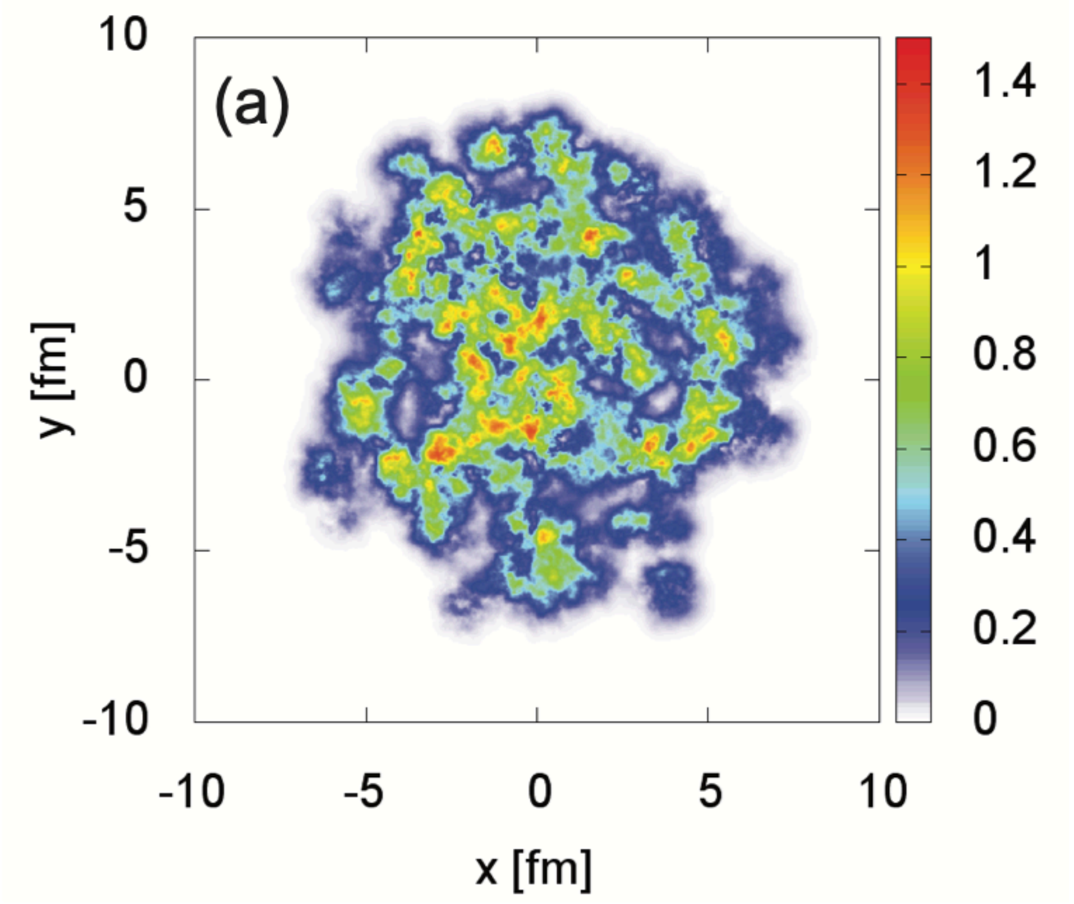




BUT ALSO

The nuclei up to the interaction

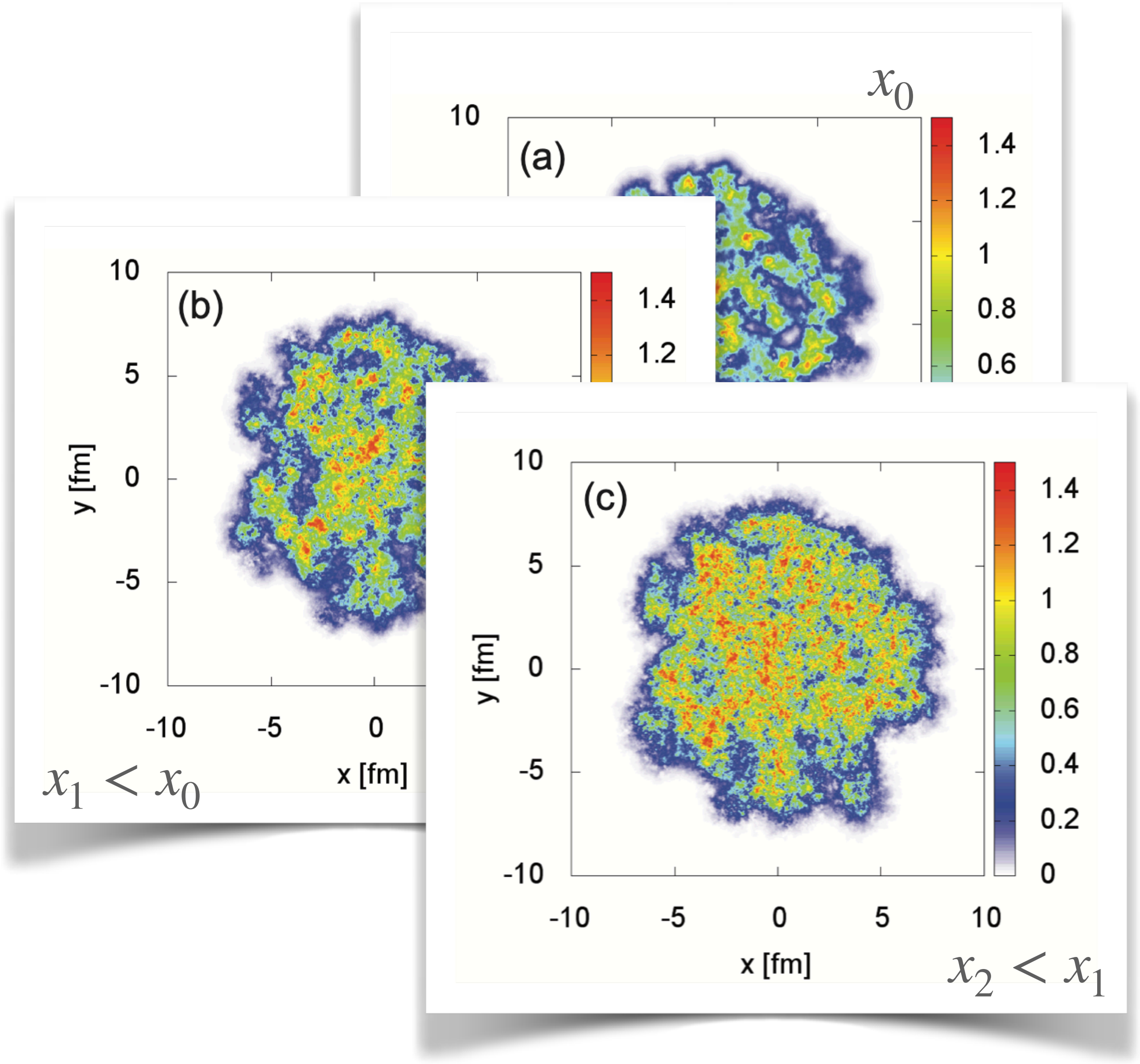
Parton (spatial, momentum) distributions, correlations, etc.



THE TWO MAIN TASKS:

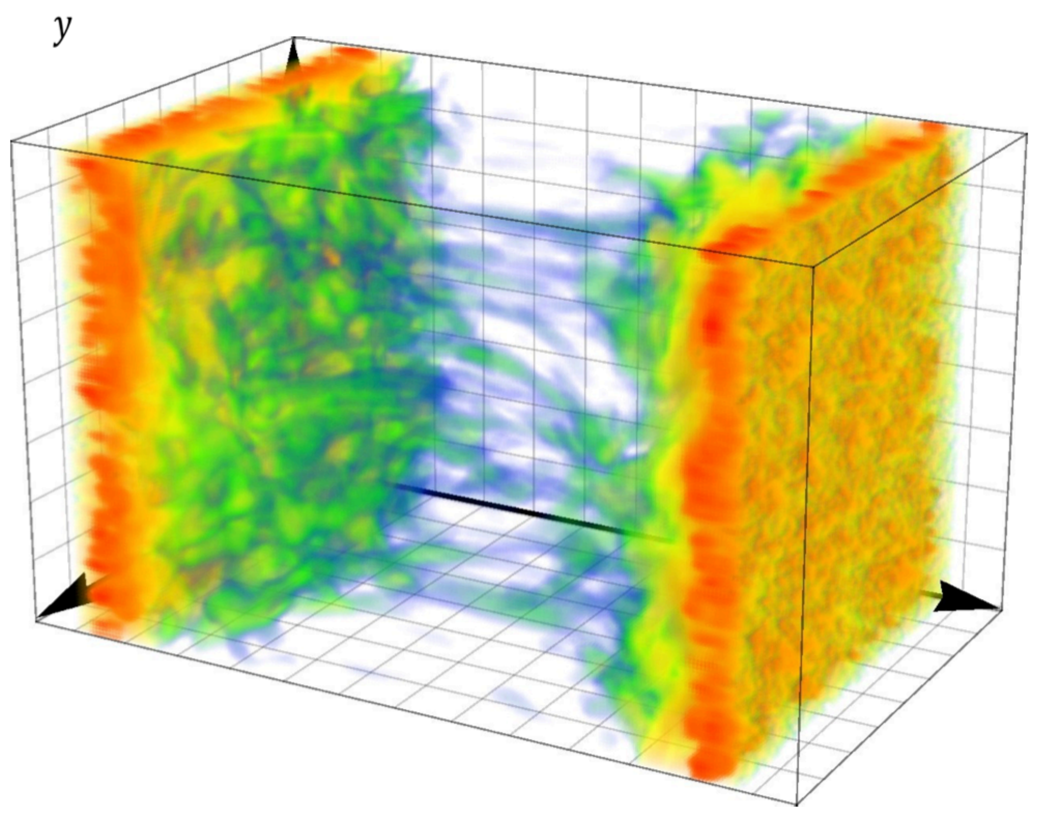
(A) To get a better grasp of the accelerated nucleus for $\tau < 0^-$

Initial correlations, energy dependence, resolution dependence, etc



B) To create a more complete description of the initial dynamics of hadronic collisions $0^+ < \tau < 0.2\text{fm}$

Include quantum corrections, quarks in the early stage, etc.



Every *endeavour* we take on in HICs depends heavily on the initial assumptions of the energy and charge deposition of the models.

BUT

if we are interested in low-E nuclear structure, having a robust Initial State is of maximal importance

INITIAL CONDITIONS

From the Hot QCD White Paper, a list of current, pressing avenues on the initial states

- Initial condition: $\sqrt{s_{NN}}$ dependence and longitudinal structure
- B,Q,S Charge deposition and the search for the CP
- From medium to small systems
- Better quantification of ICs for large systems
- Initial condition for hard probes

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Seemingly different,
But in reality, intimately related!!

QGP LONGITUDINAL STRUCTURE

$\sqrt{s_{NN}}$ dependence

longitudinal structure

INITIAL STATE

small systems

NUCLEAR DENSITY DEPENDENCE + STRUCTURE

WHAT DO WE NEED TO KNOW THE QUARK-GLUON PLASMA

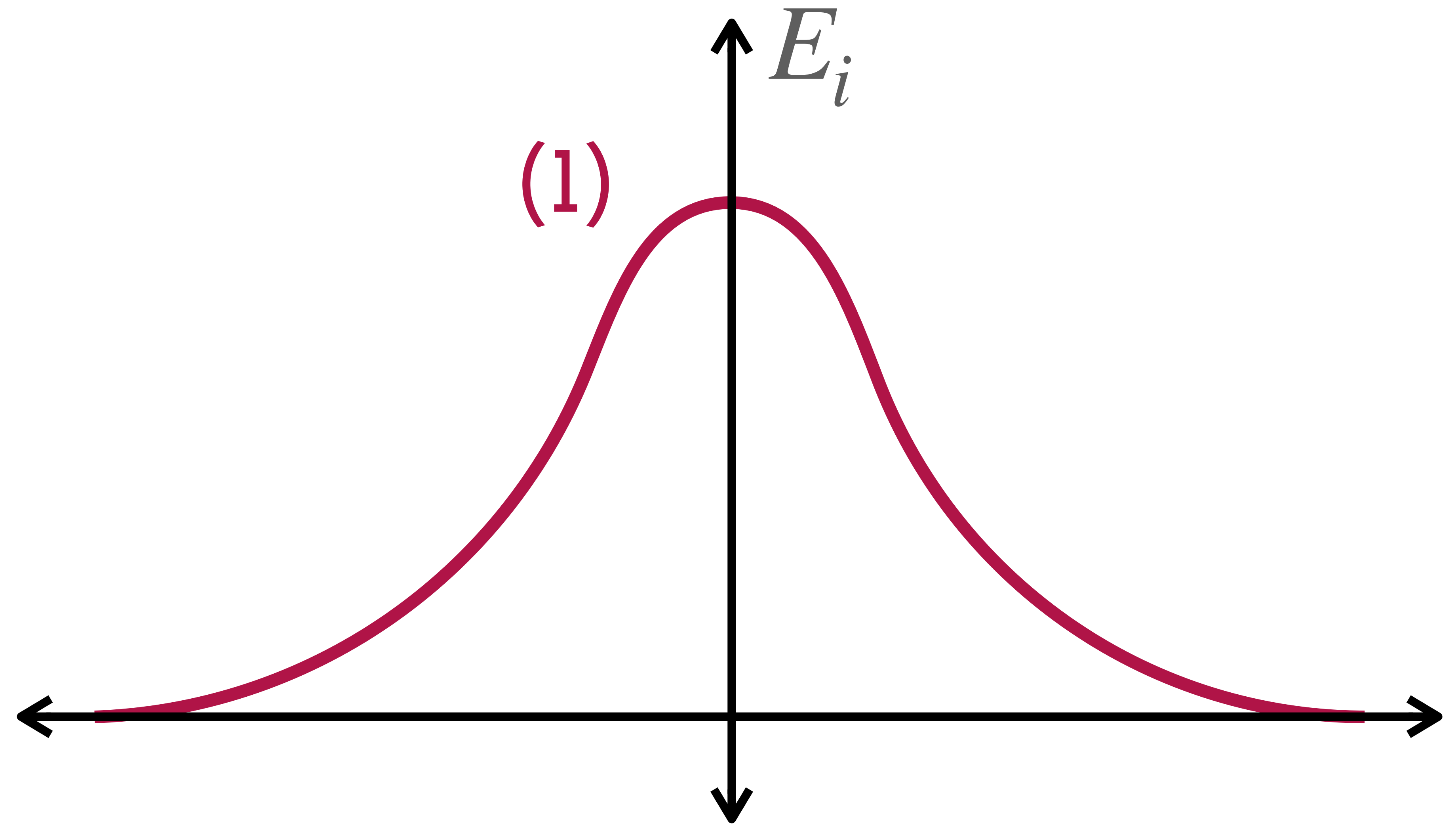
WHAT DO WE NEED TO KNOW THE QUARK-GLUON PLASMA

IN 3-D!

THE INITIAL STATE OF A HIC … IN 3D.

What do we expect to have?

- Nature of DoFs depends model-by-model
- (1) Fireball energy deposition: C.o.M of collision favours midrapidity.
  - High density of gluons, string breaking, etc.



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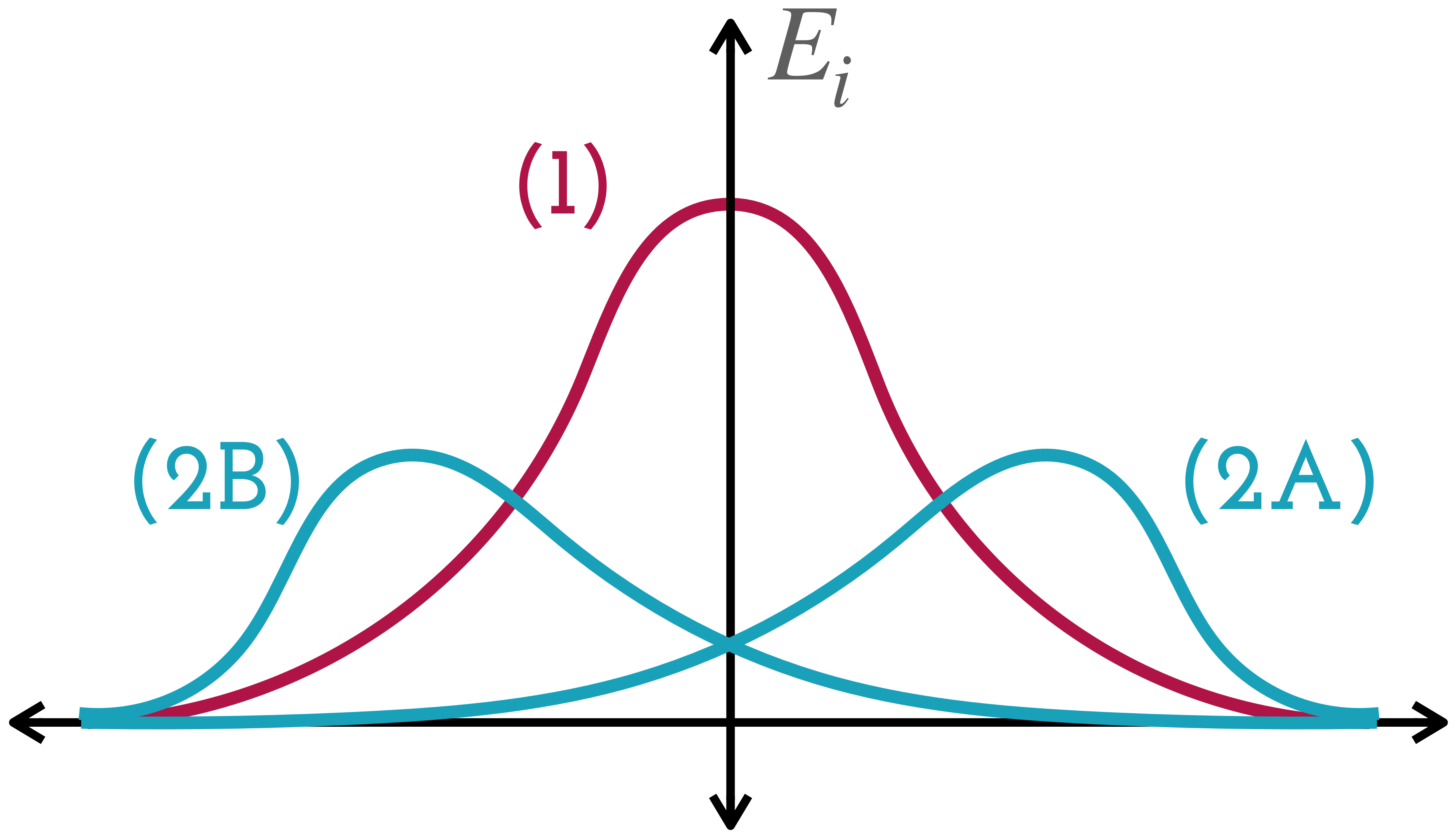
  - Quark scattering, baryon junction, hadrons?



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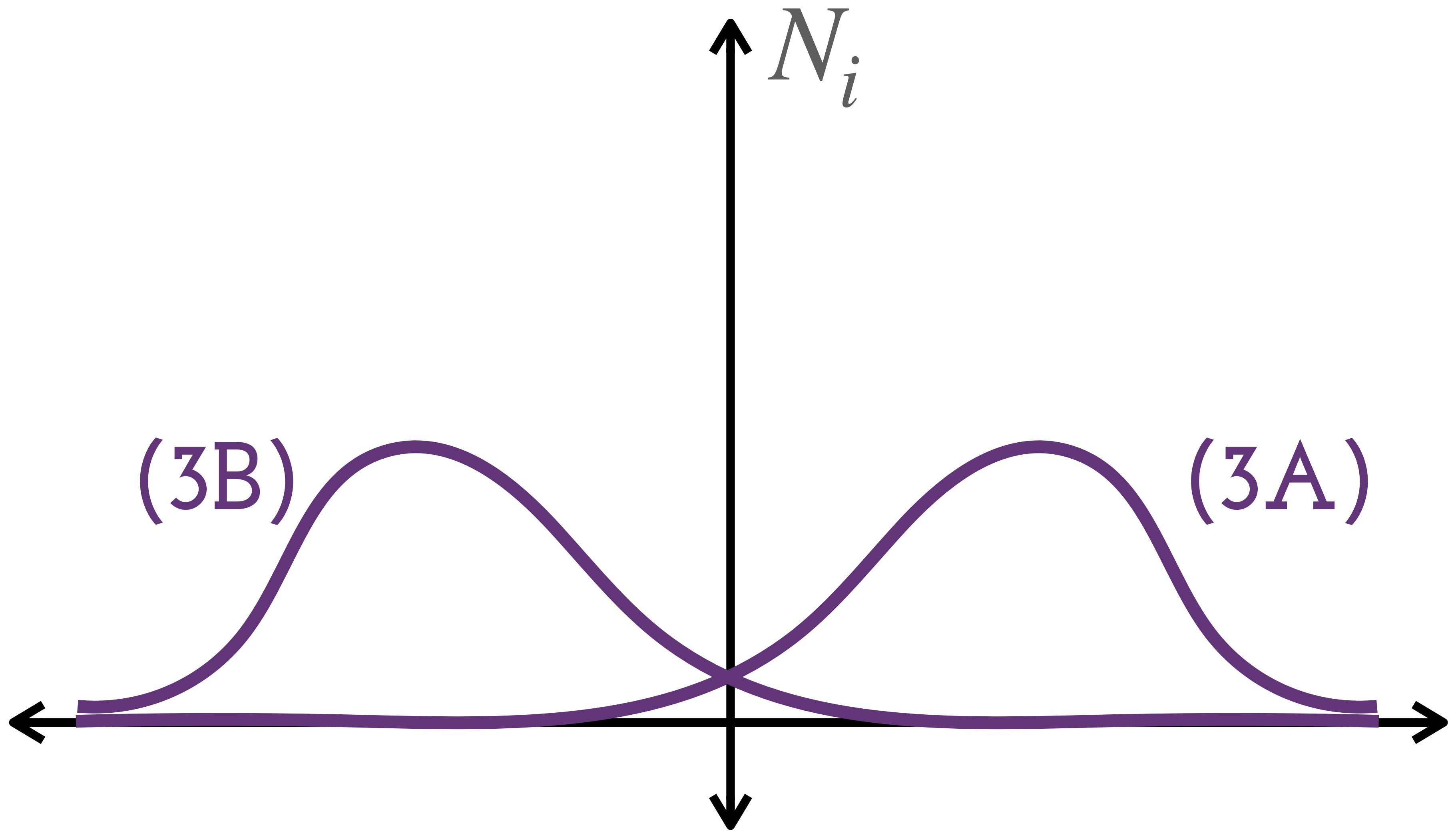

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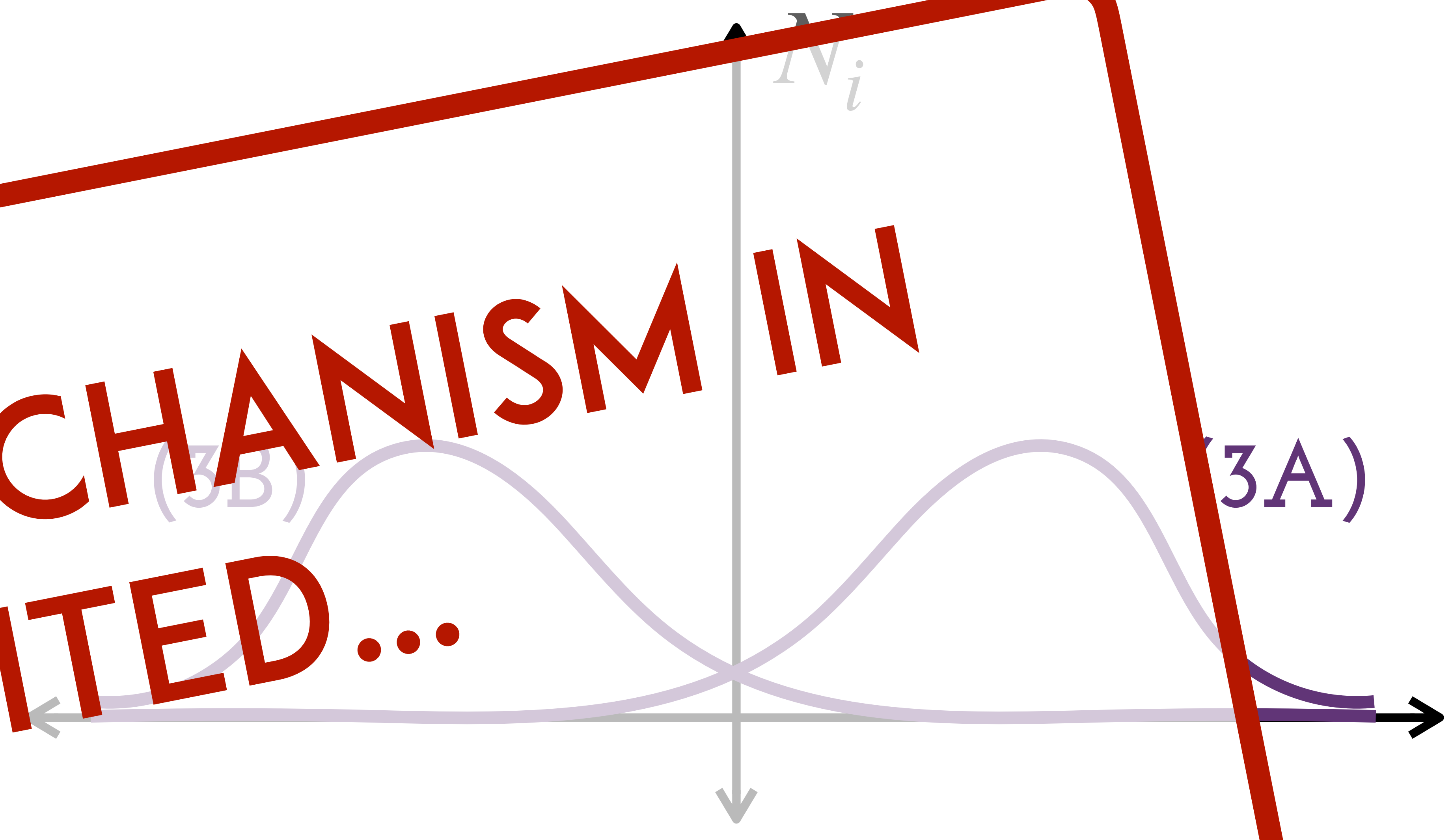


AND NATURALLY, THE MECHANISM IN WHICH THEY ARE DEPOSITED…

BUT WAIT… THERE IS MORE

The initial State: When, what and how?

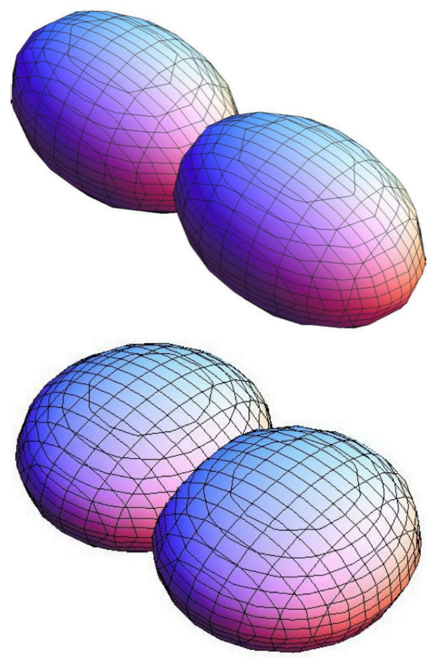
Initial State Modeling: *"Finding the correct number and density of conserved charges, and their **spatial distribution**"*

Initial state fluctuations

Geometric

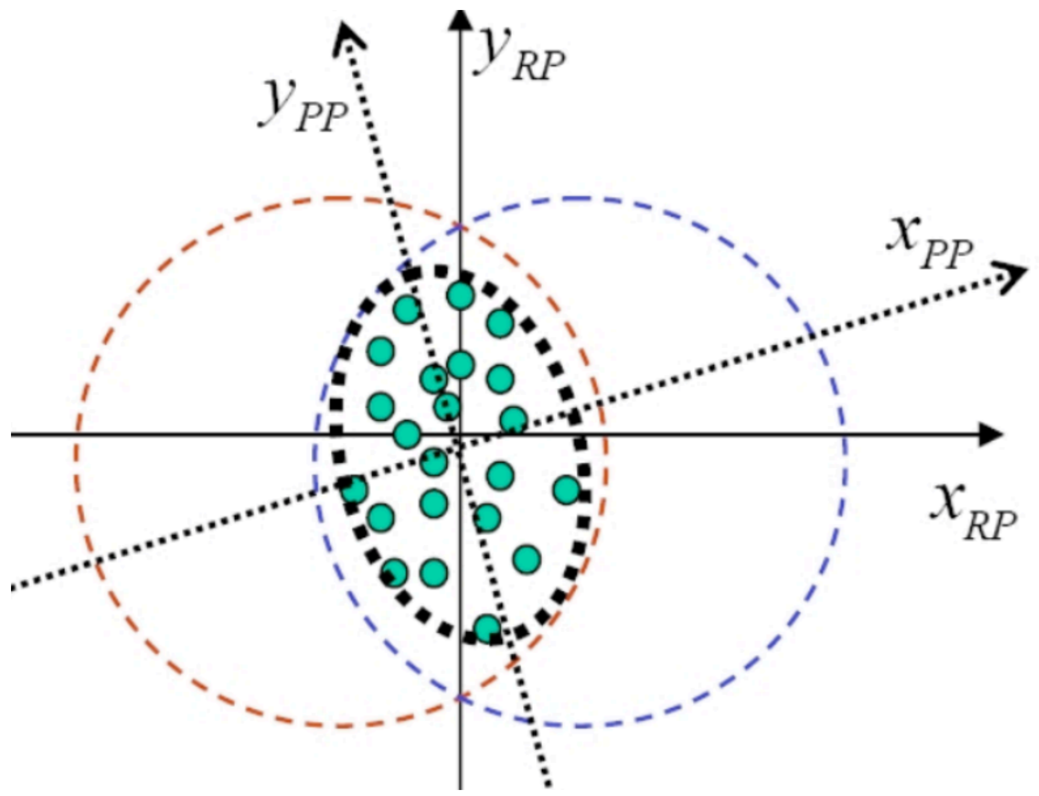
Deformation

Nucleus is not spherical (prolate or oblate)



Collisional

Collisions generate geometrical anisotropies

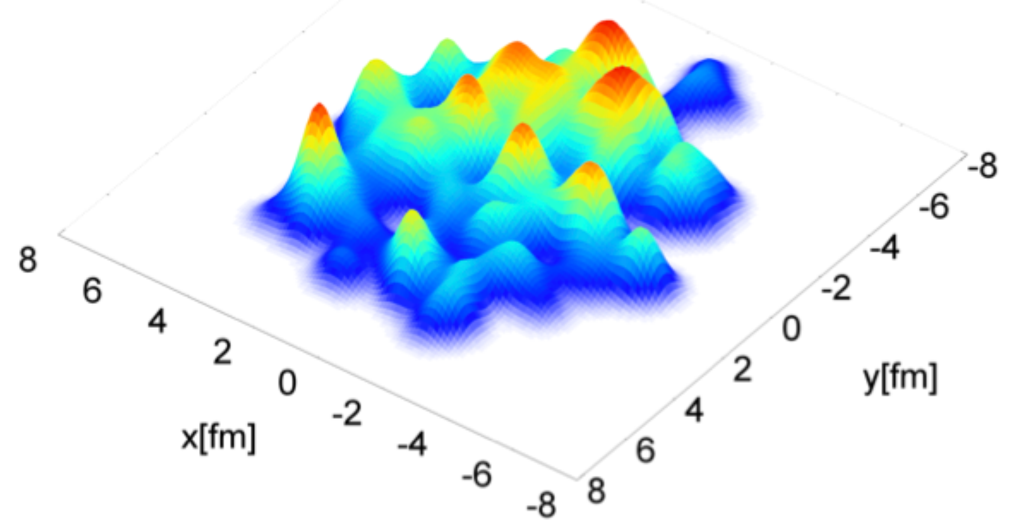


Dynamical

Nucleonic

Energy and charge density fluctuations at the level of nucleons

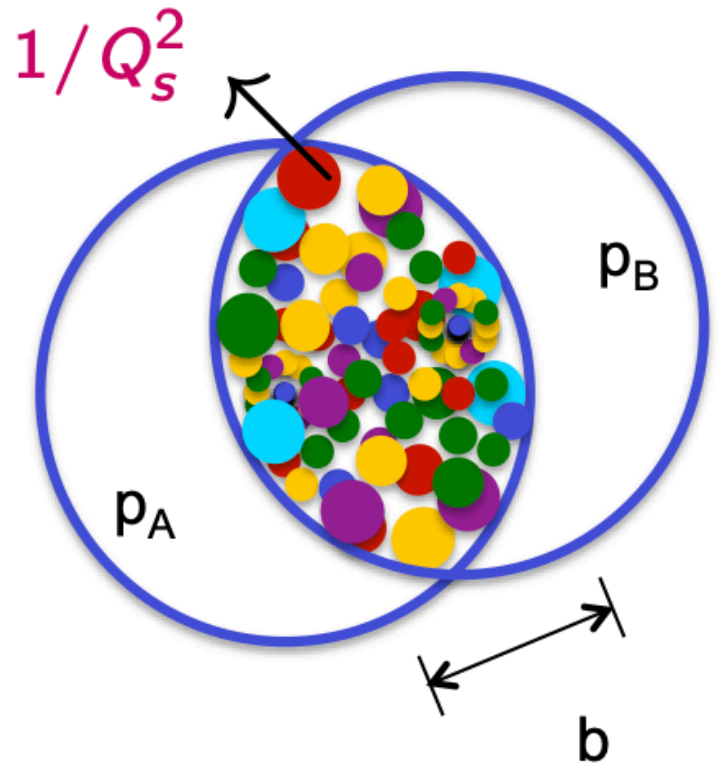
$d \sim R_p$



Sub-nucleonic

Energy and charge density fluctuations at the level of partons

$d \sim 1/Q_S$



METHODS: STATE OF THE ART

DoFs/motivation behind the energy and charge deposition

LARGE-X

Collinear fact.
Described by PDFs

GEOMETRICAL

Effective description
Often parametrical

LOW-X

Overoccupied
Color fields

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CGC

SATURATION*

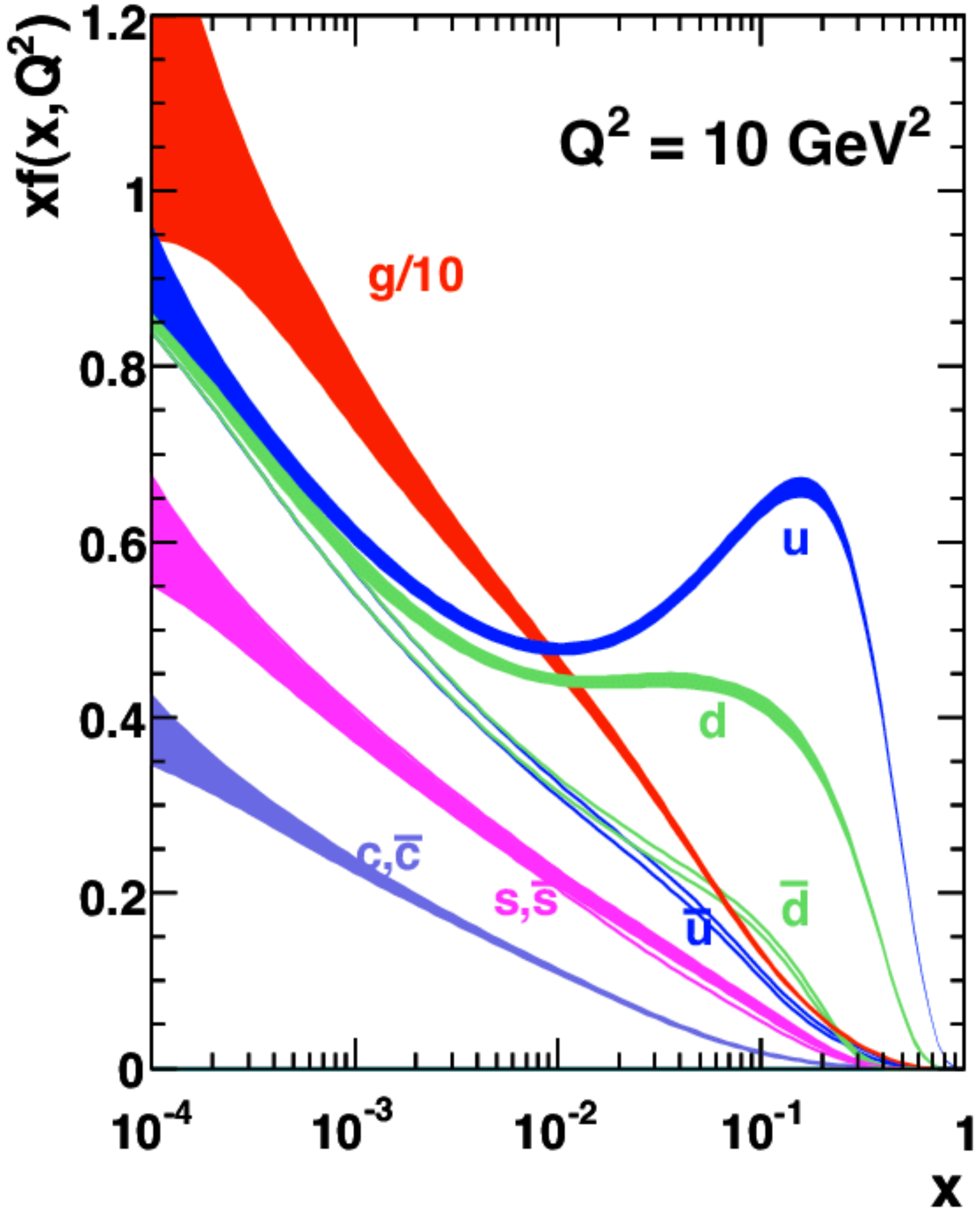
SATURATION MODELS

NUCLEAR STRUCTURE

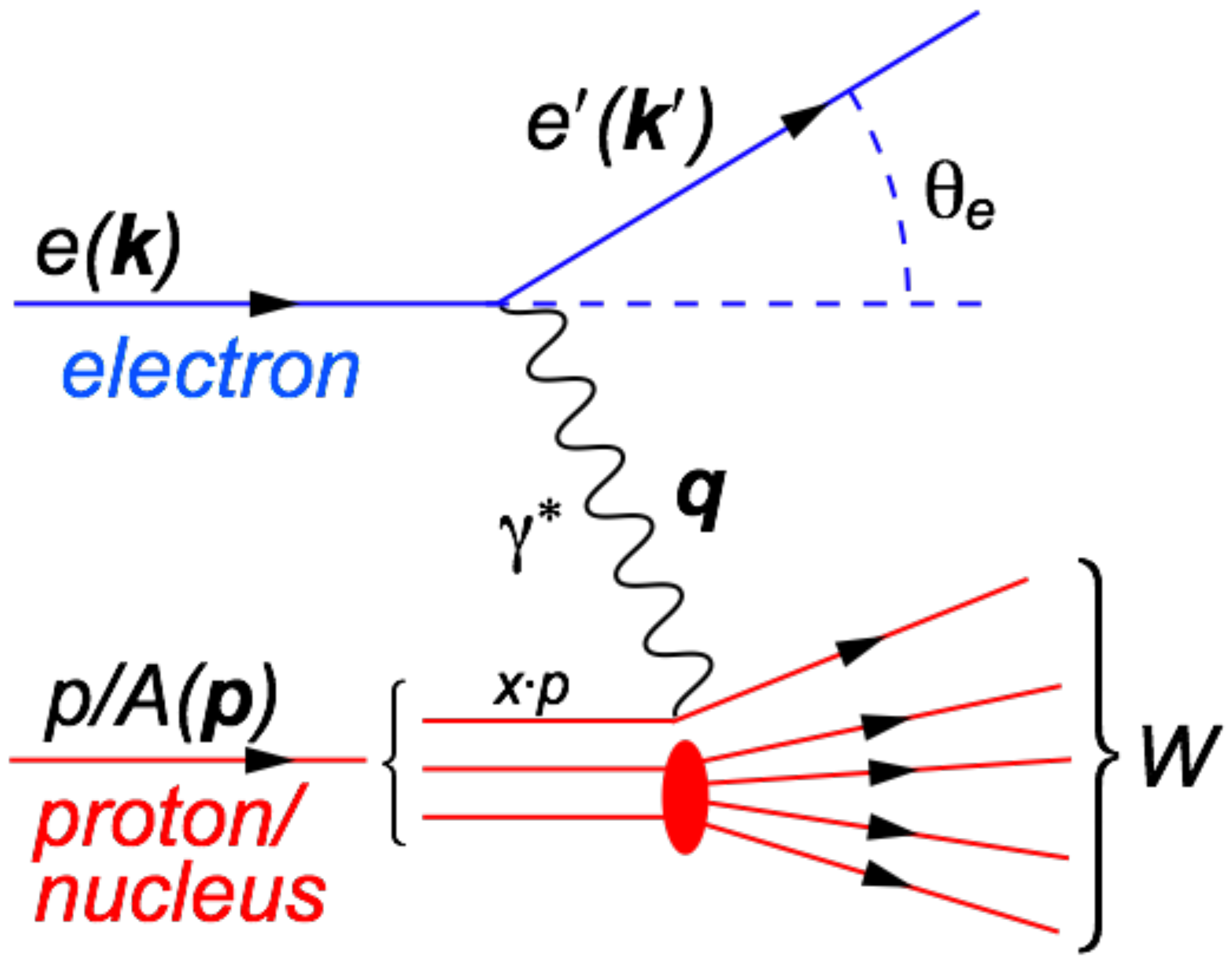
- PDFs from fit to Experiments (DIS)

  $x \sim$ energy/momentum fraction carried by parton

  $Q^2 \sim$ resolution scale



DEEPLY INELASTIC SCATTERING (DIS)



$s = (k+p)^2$ → Center of mass energy (squared)

$Q^2 = -q^2$ → Resolution power

$x = \frac{-q^2}{p \cdot q} \sim 1/\sqrt{s}$ → Fraction of momentum carried

$y = \frac{p \cdot q}{p \cdot k}$ → Inelasticity

- Using QED probe to test QCD properties
- Inclusive and exclusive channels (vector meson prod., deeply virtual Compton scattering, etc)
- PDF $\approx$ #of partons in a hadron
  - at energy $\sim 1/x$
  - at a transverse resolution Q.

Great control over kinematics

SATURATION MODELS

NUCLEAR STRUCTURE

- PDFs ≈ #of partons in a hadron @
  $1/x \sim$ energy/momentum fraction
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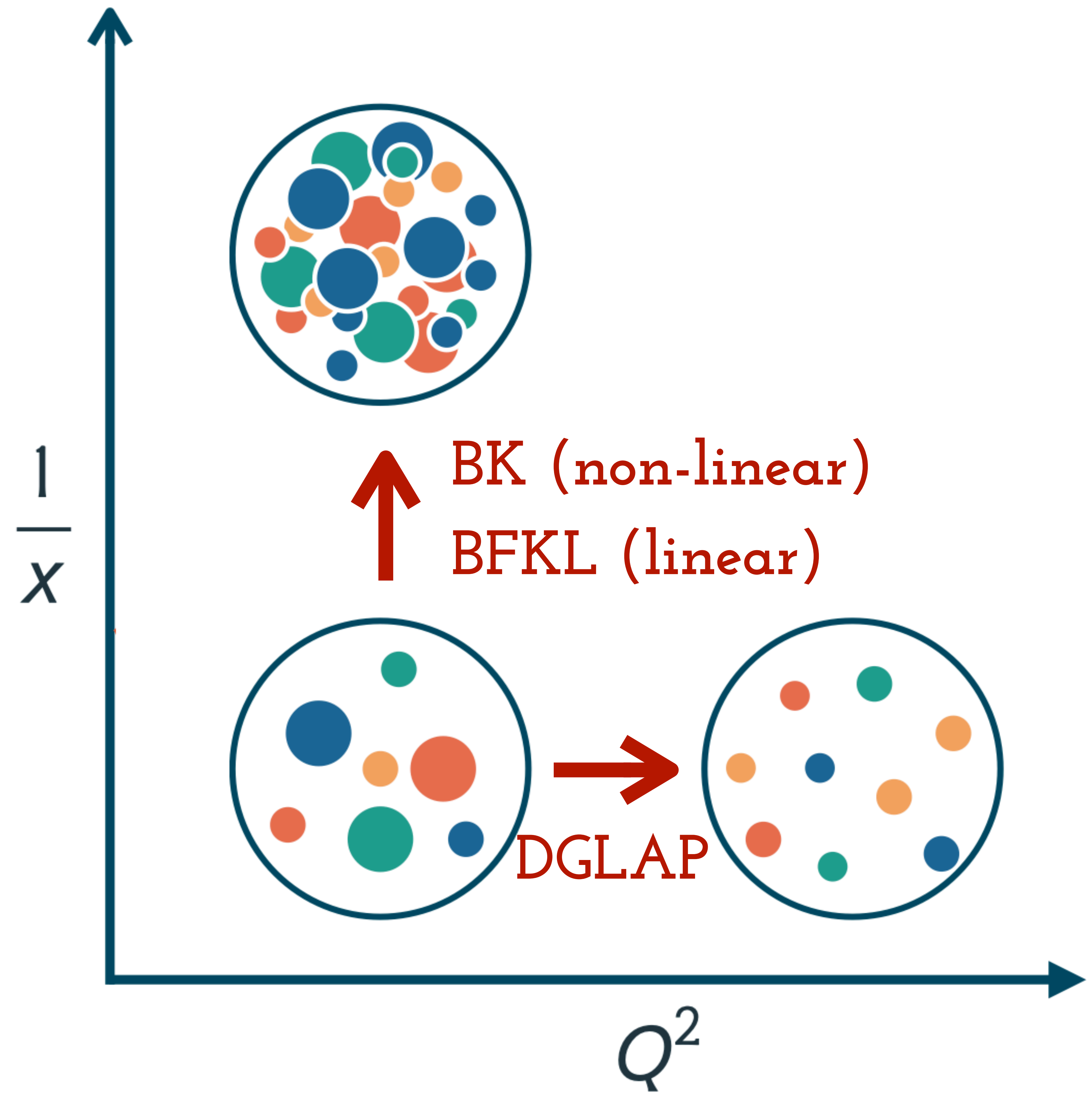
- Non-perturbative objects, but evolvable due to renormalization equations

  Given a PDF at a specific scale $f_i(x, Q^2)$
  - Evolution along x → **BFKL/BK** equation
  - Evolution along Q → **DGLAP** equation.



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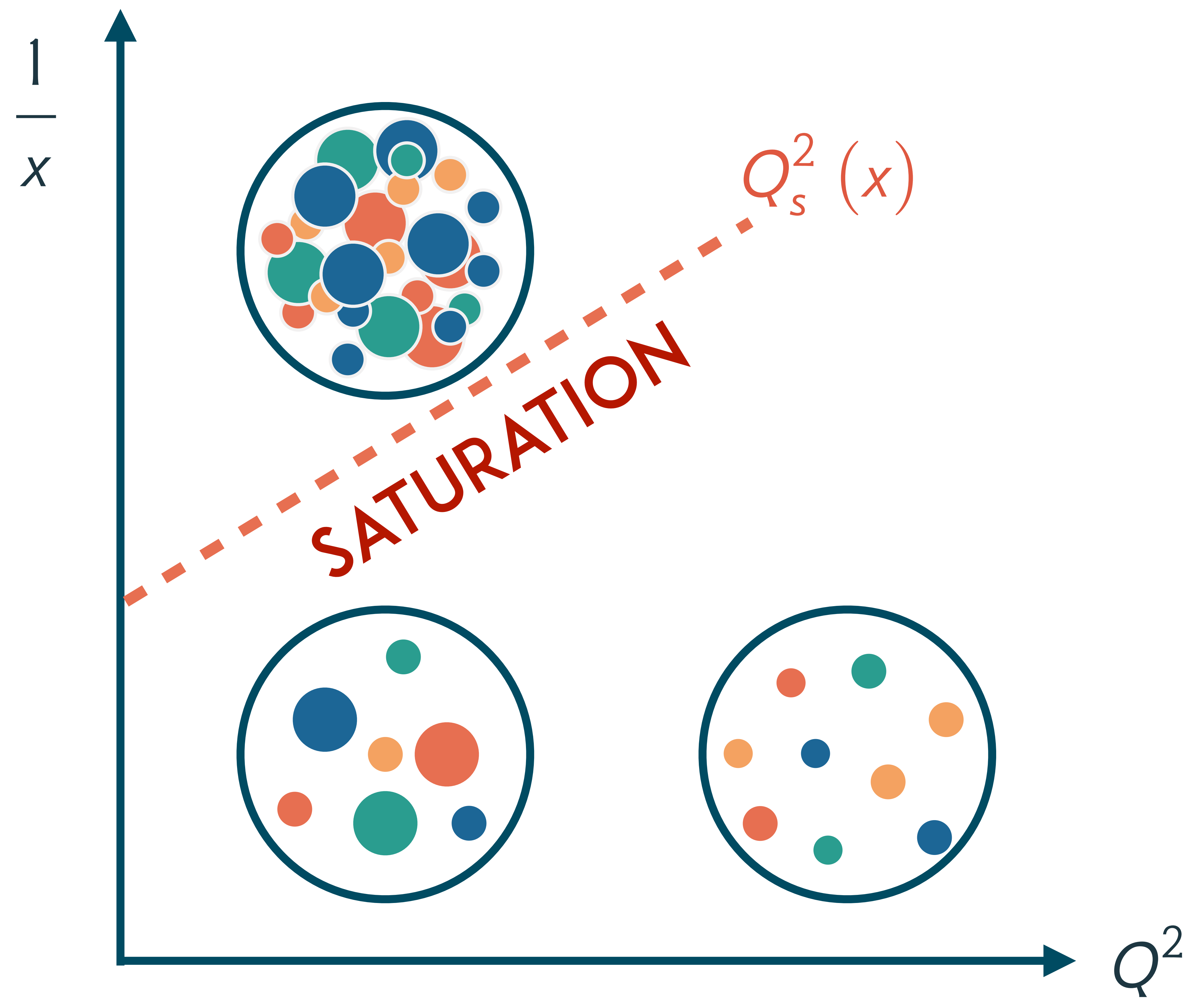
- Non-linearities in BK: Emergence of a ***semi-hard*** saturation scale Q_s

$$\frac{dN(x,\mathbf{r})}{d\ln(1/x)} = \frac{\alpha_s N_c}{\pi^2}\int d^2\mathbf{b}\, K(\mathbf{r},\mathbf{b})\,\left[N(x,\mathbf{b}) + N_x(\mathbf{r}-\mathbf{b}) - N_x(\mathbf{r}) - N_x(\mathbf{b})\,N_x(\mathbf{r}-\mathbf{b})\right]$$



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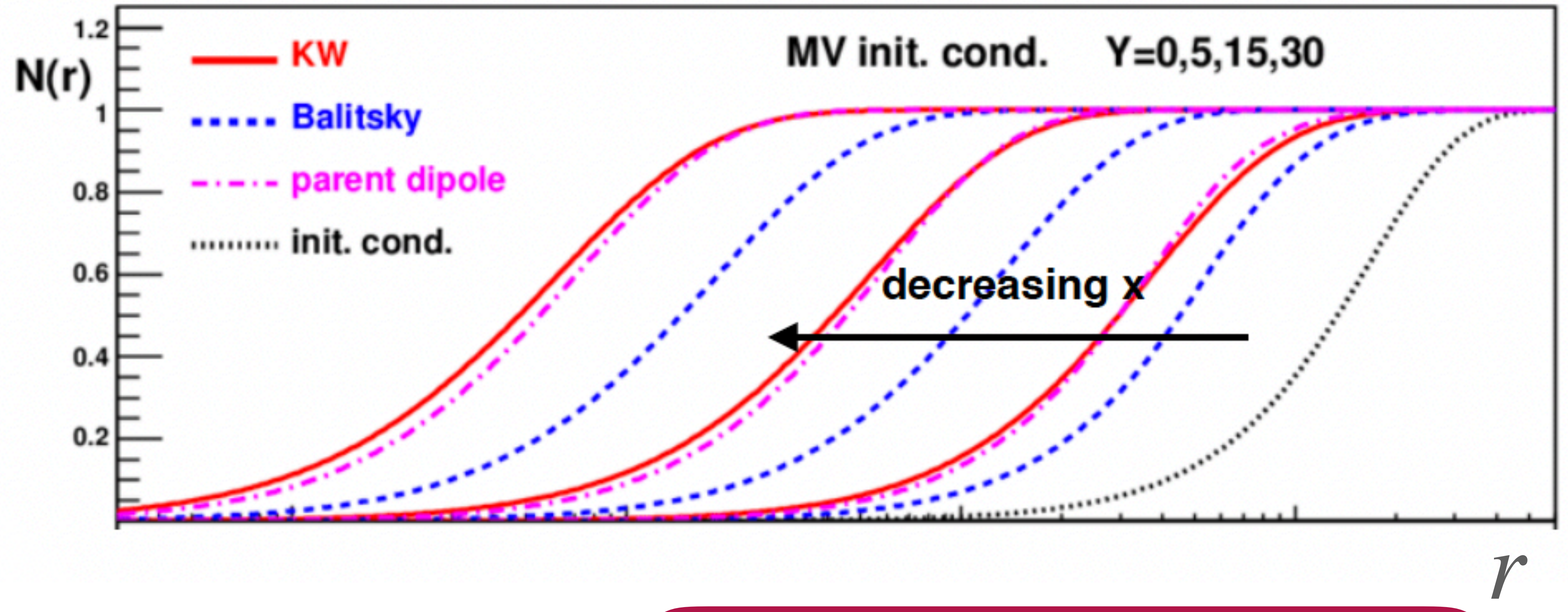
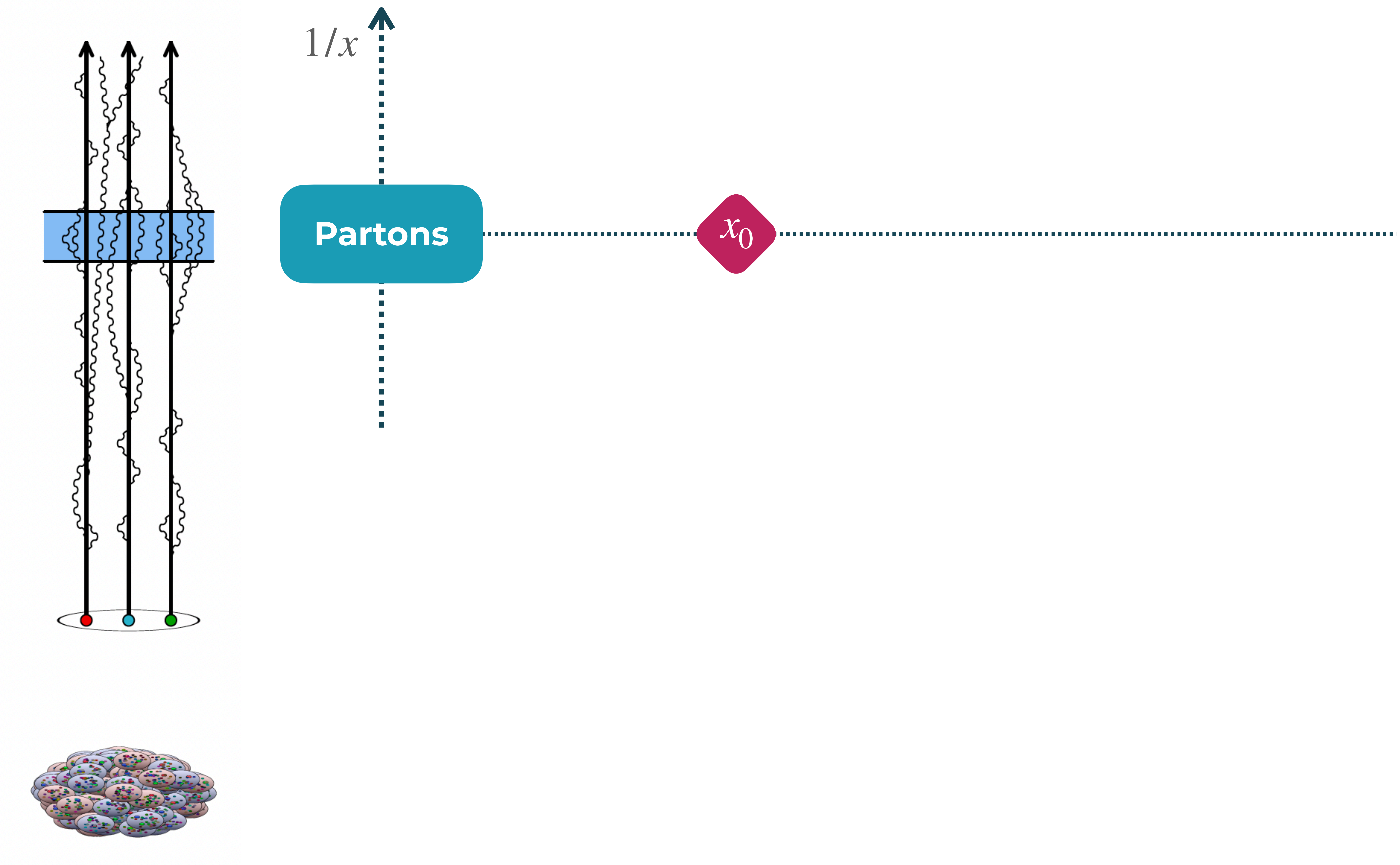
- Gluon distributions saturate with $k_\perp < Q_S$ ($r > Q_S^{-1}$ in pos. space)



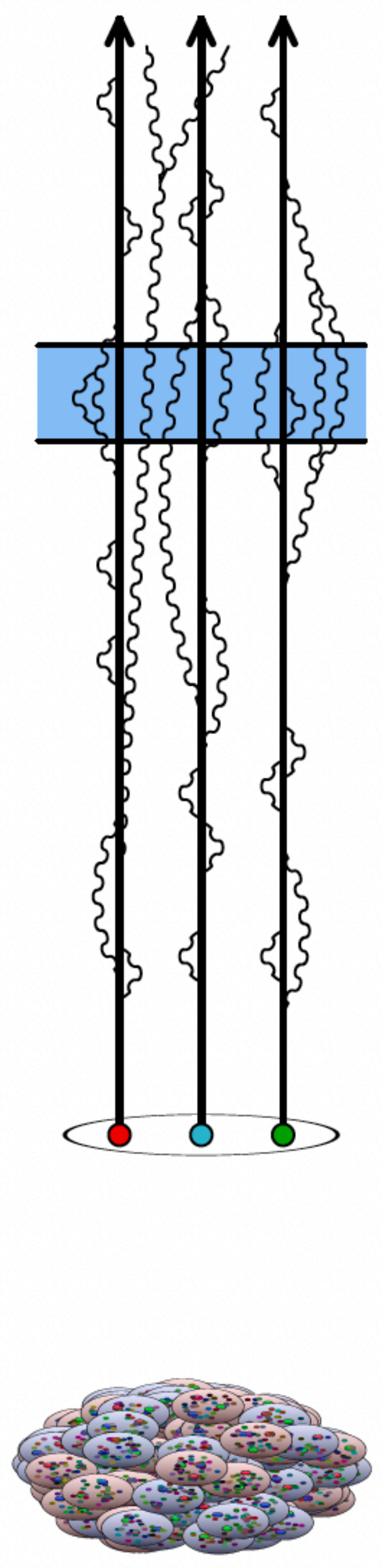
$$Q_S^2(x) \sim x^{-\lambda} A^{1/3} \sim s^{\lambda/2} A^{1/3}$$

THE COLOUR GLASS CONDENSATE™

THE COLOR GLASS CONDENSATE



THE COLOR GLASS CONDENSATE



$1/x$

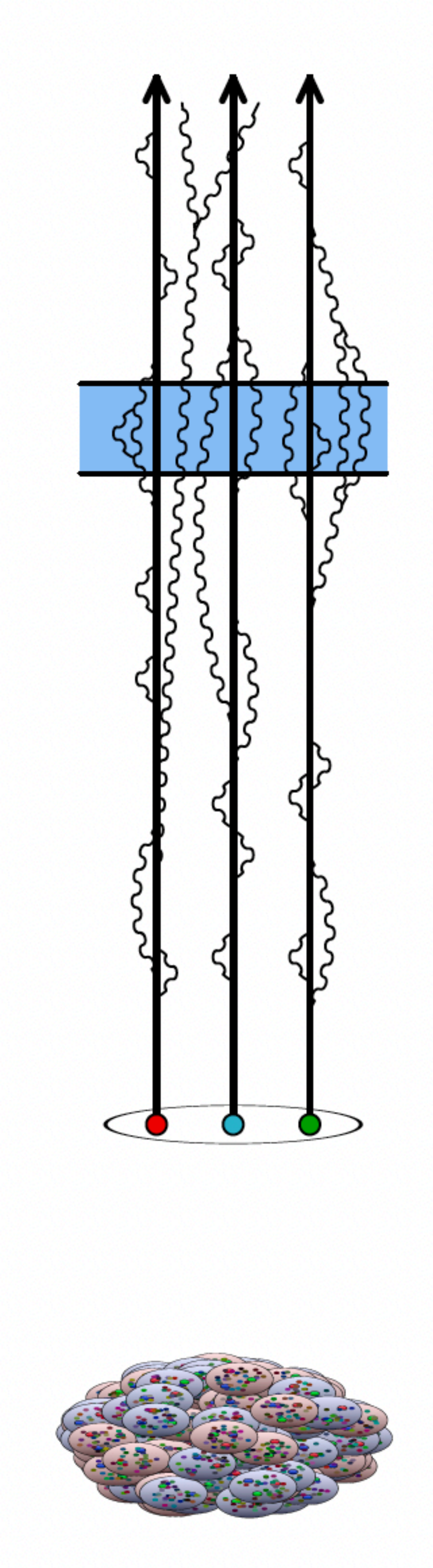
Partons

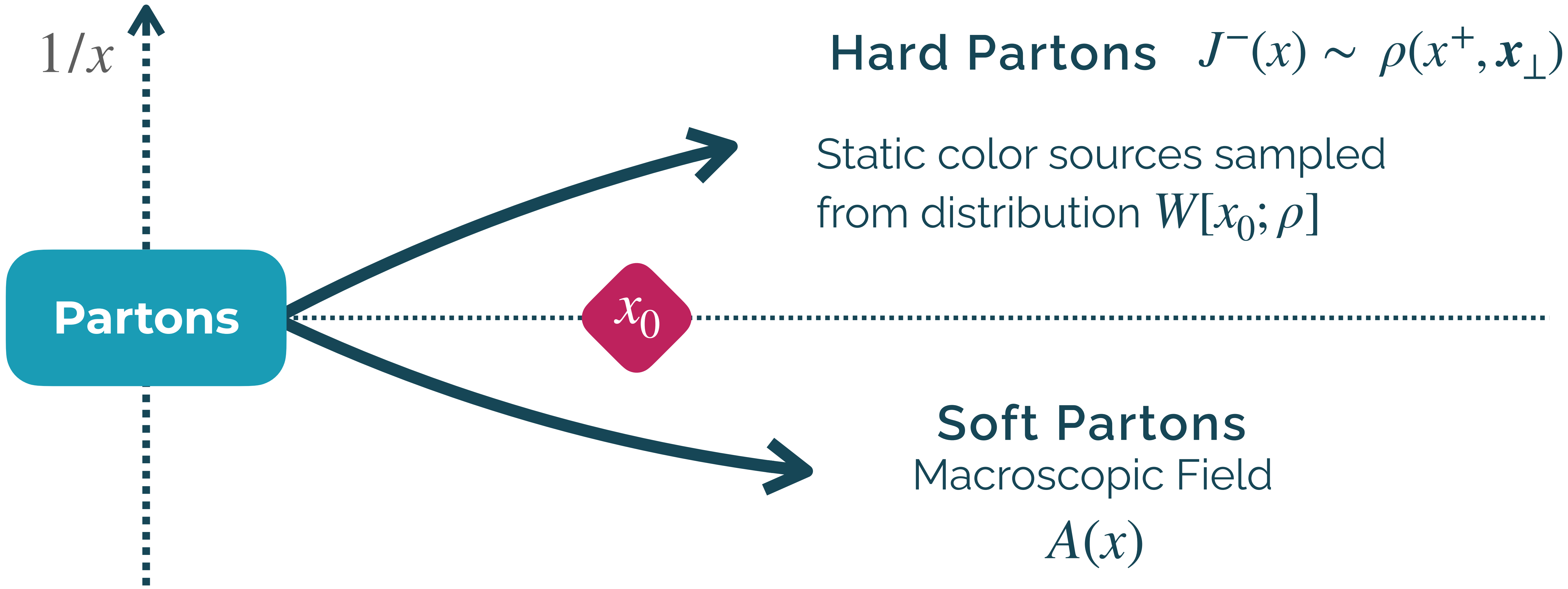
x_0

Hard Partons $J^{-}(x) \sim \rho(x^{+}, \boldsymbol{x}_{\perp})$

Static color sources sampled from distribution $W[x_0; \rho]$

THE COLOR GLASS CONDENSATE





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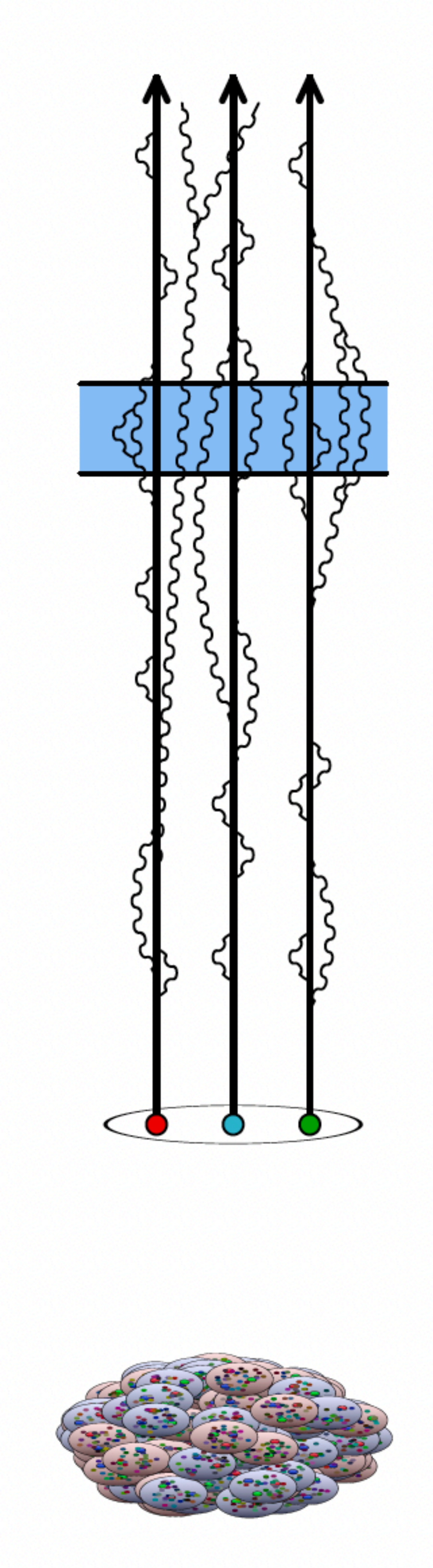

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Soft Partons

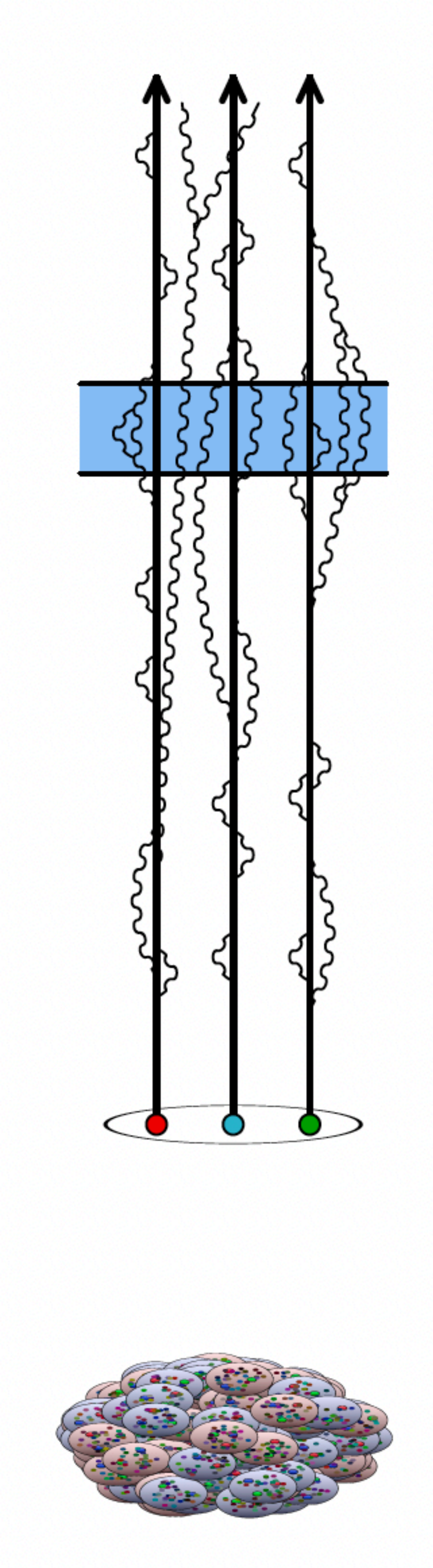
Macroscopic Field

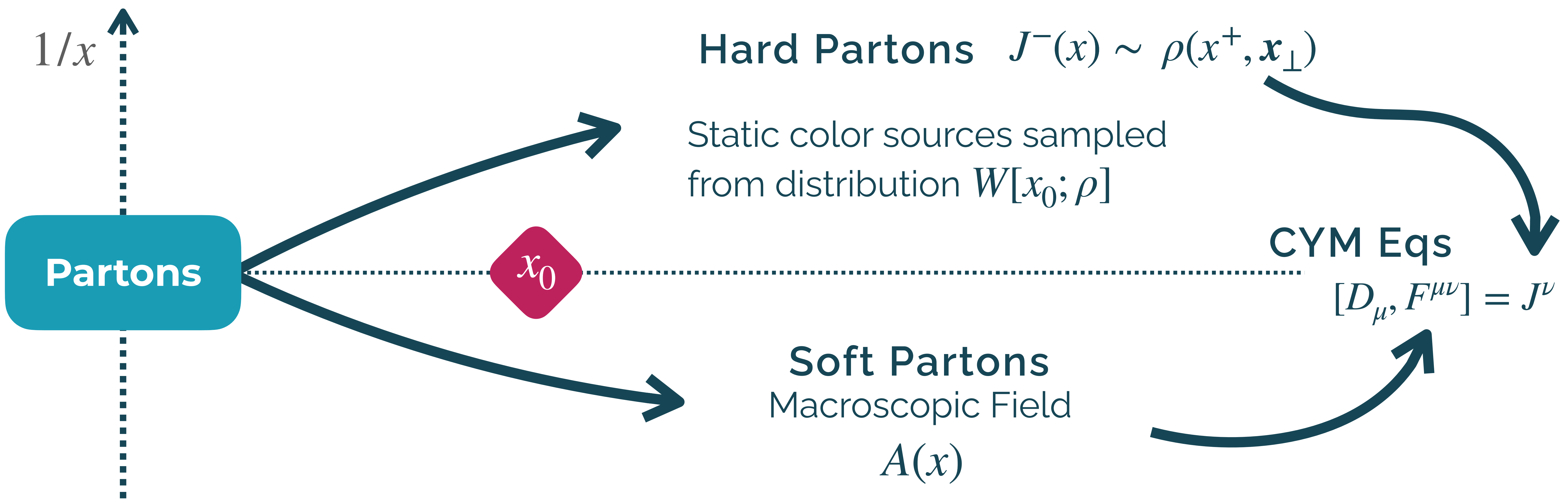
$A(x)$

CYM Eqs

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

THE COLOR GLASS CONDENSATE





$$\langle \mathcal{O}[\rho] \rangle = \int \mathcal{D}\rho \, W[x; \rho] \mathcal{O}[\rho]$$

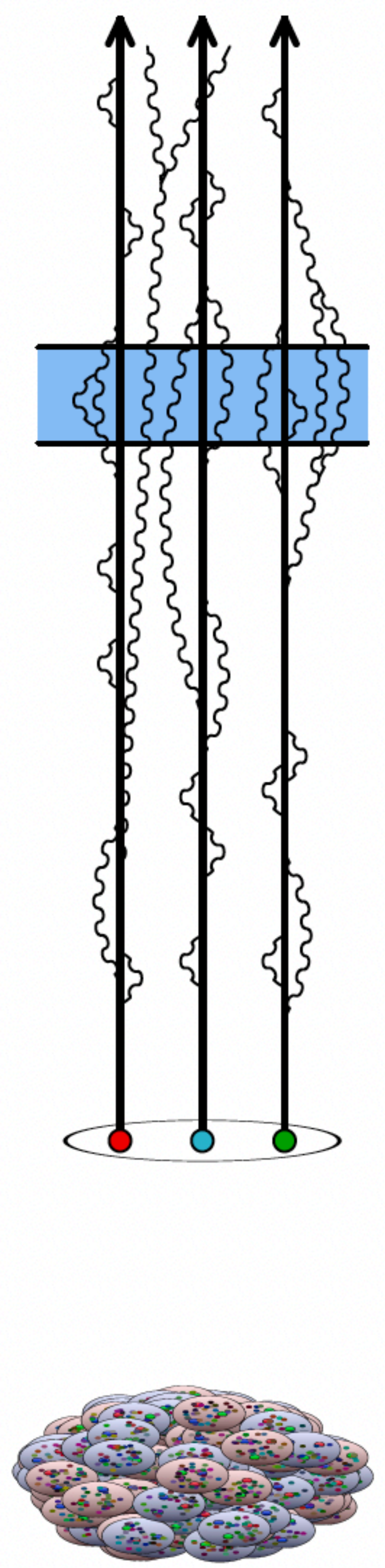
$W[x; \rho]$: gauge invariant probability distribution

SPECIAL CASE: GAUSSIAN ICS

McLerran-Venugopalan model

$$W[x_0; \rho] \approx e^{-\rho^2}$$

THE COLOR GLASS CONDENSATE



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Soft Partons

Macroscopic Field

$A(x)$

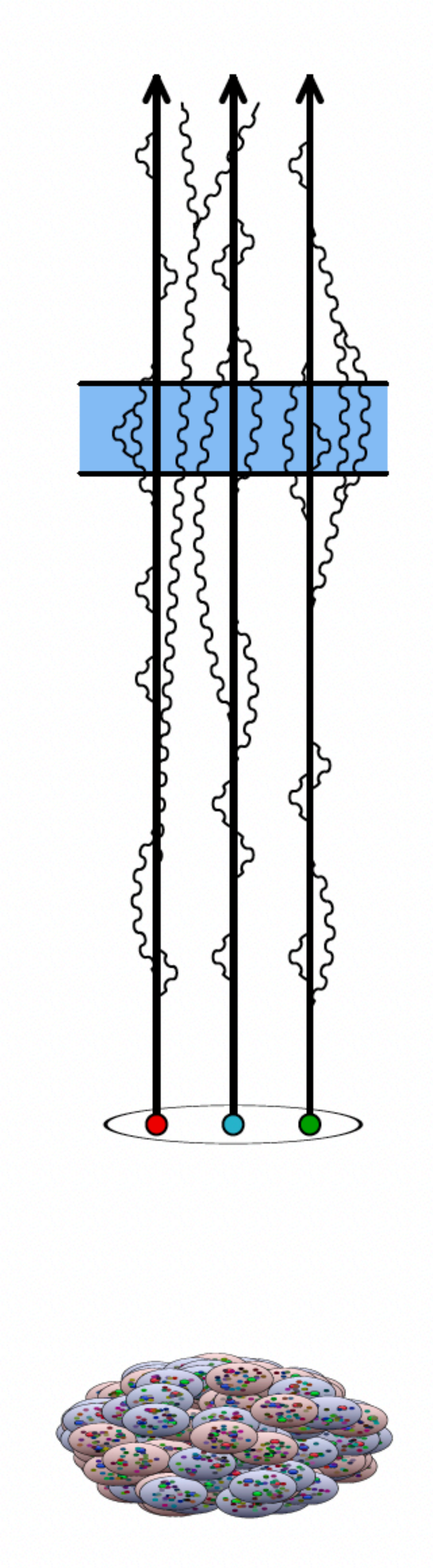
SPECIAL CASE: GAUSSIAN ICS

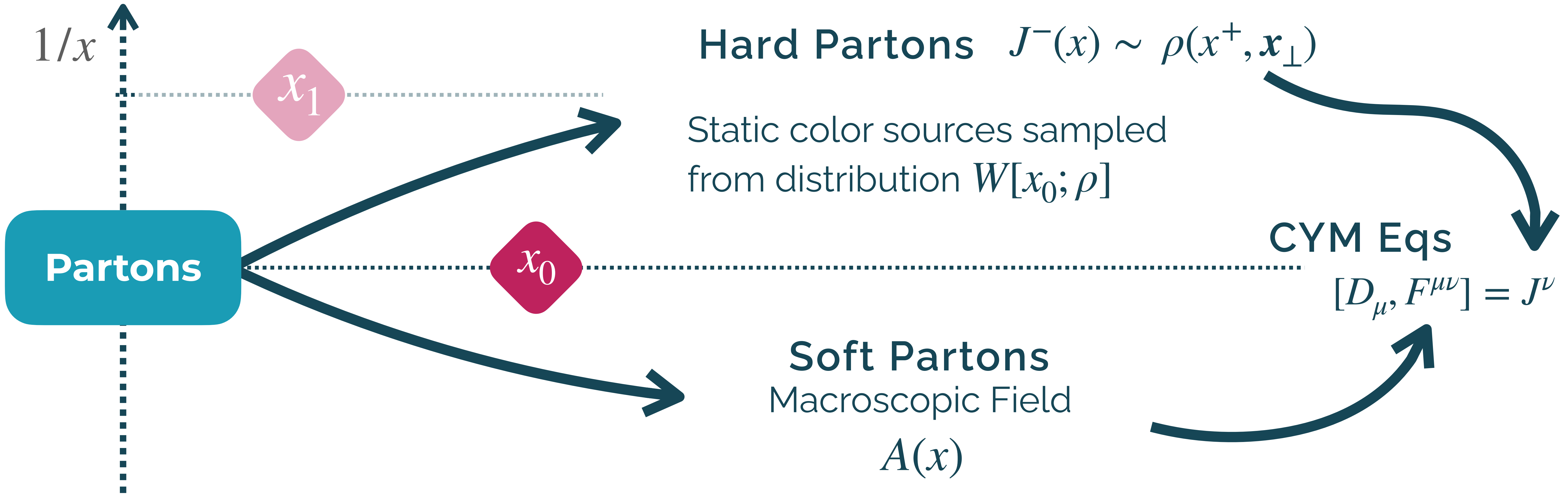
$$\langle \rho_a(\mathbf{x}_{\perp})\, \rho_b(\mathbf{y}_{\perp}) \rangle = \mu^2(\mathbf{x}_{\perp})\ \delta^{(2)}(\mathbf{x}_{\perp} - \mathbf{y}_{\perp})$$

where

$\mu^2(\mathbf{x}_{\perp}) \sim T(x_{\perp})$ Colour charge density in the nucleus

THE COLOR GLASS CONDENSATE





WHAT IF WE WANT TO CHANGE x_0?

Cutoff change
changes the effective action

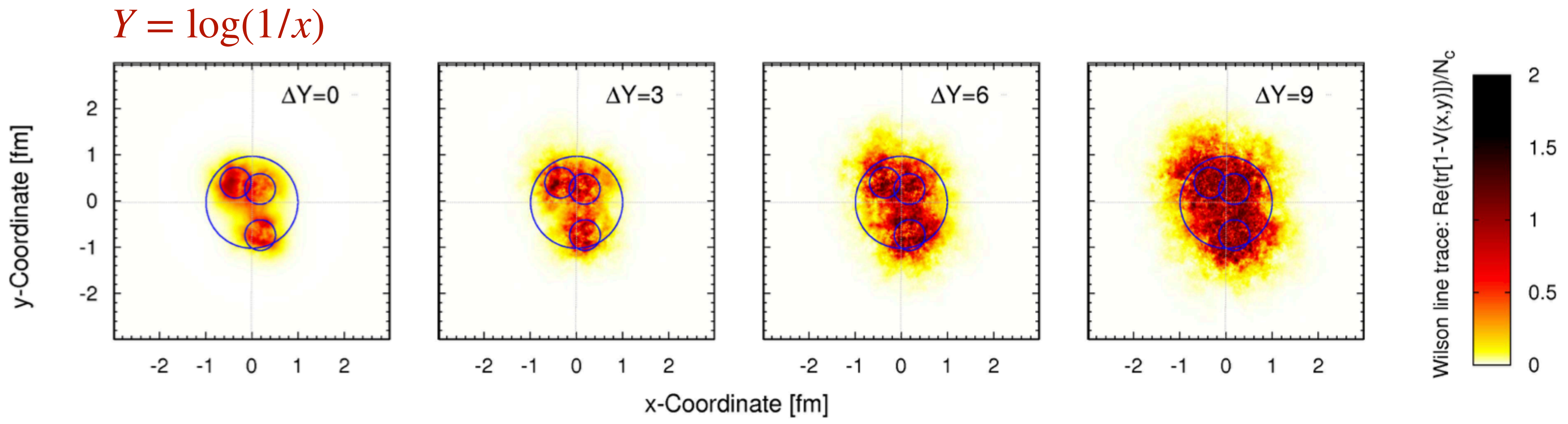
$W[x_0; \rho] \rightarrow W[x_1; \rho]$

RG-FLOW IN THE CGC!

RG Eqs: JIMWLK

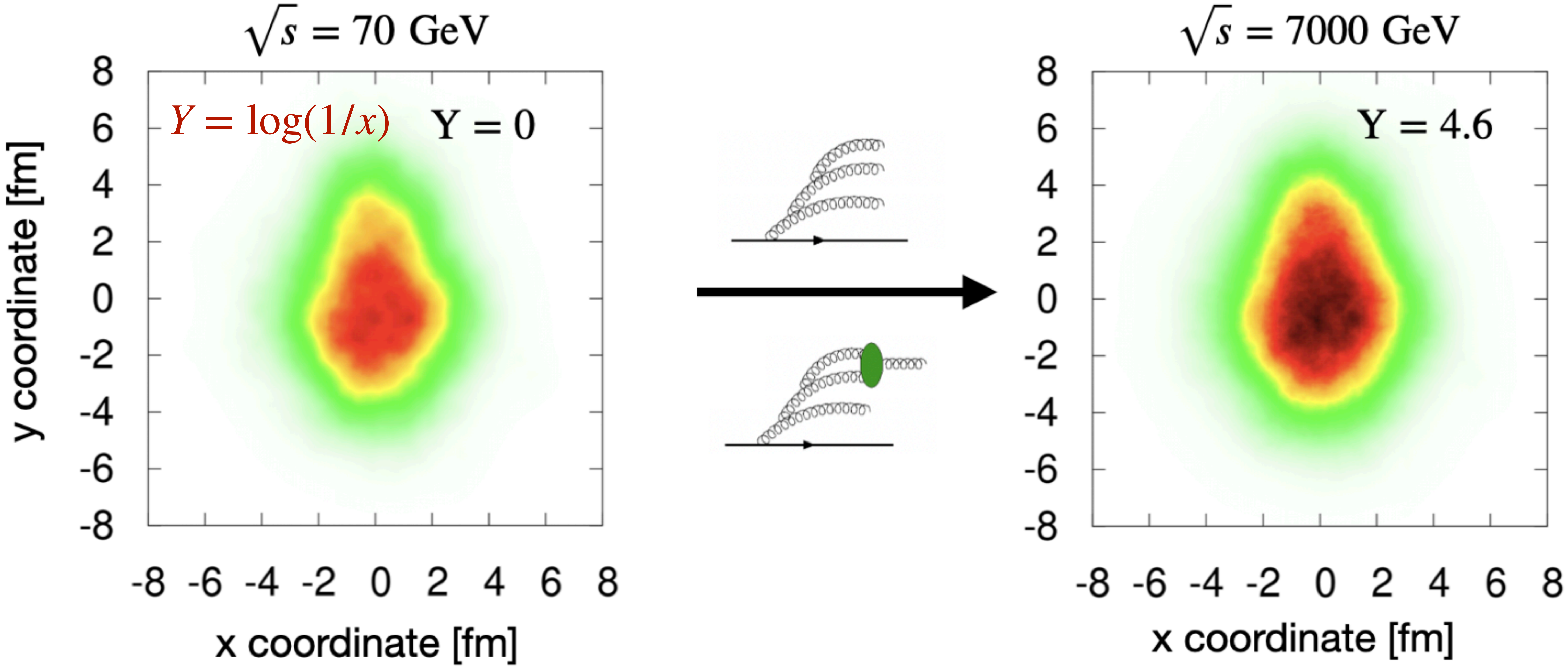
$$\frac{dW_x[\rho]}{d\log(1/x)} = \hat{H}_{eff} W_x[\rho]$$

THE EFFECT OF EVOLUTION



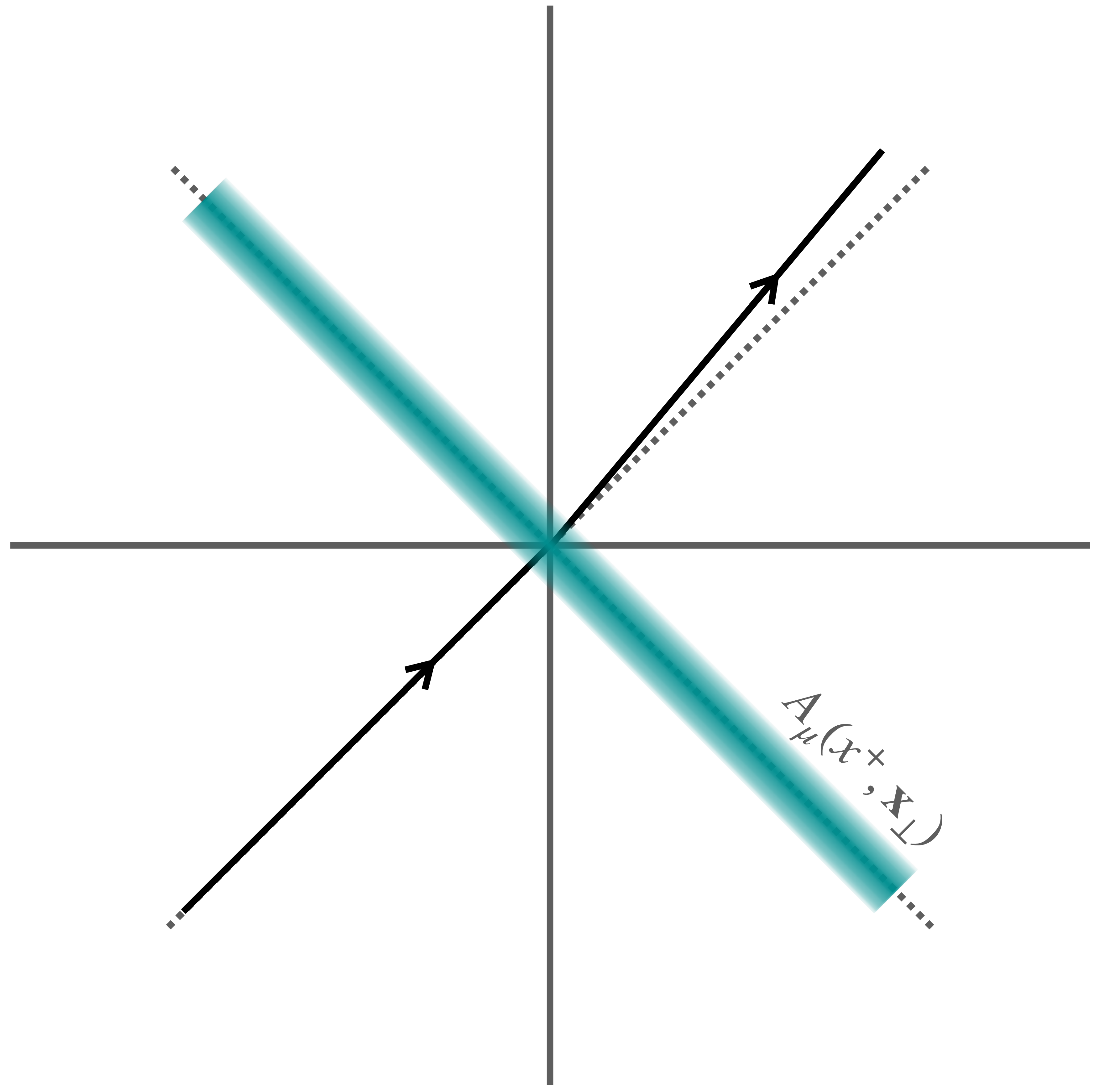
PROTON

NEON

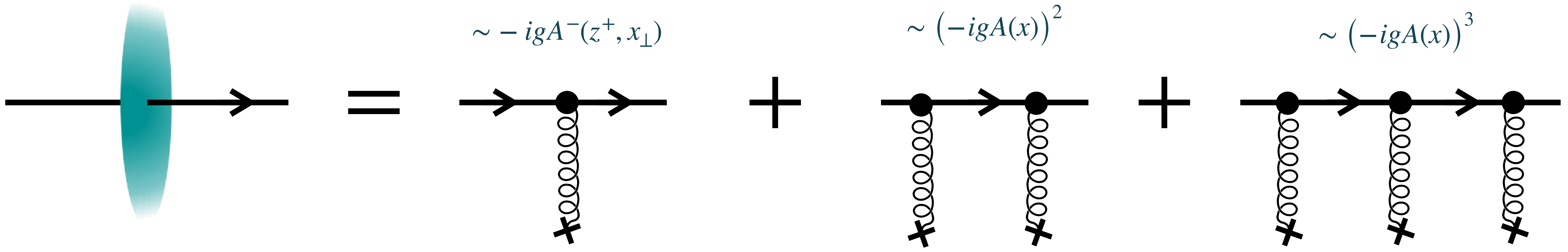


[From *EPJ Web Conf.* 296 (2024) 10005]

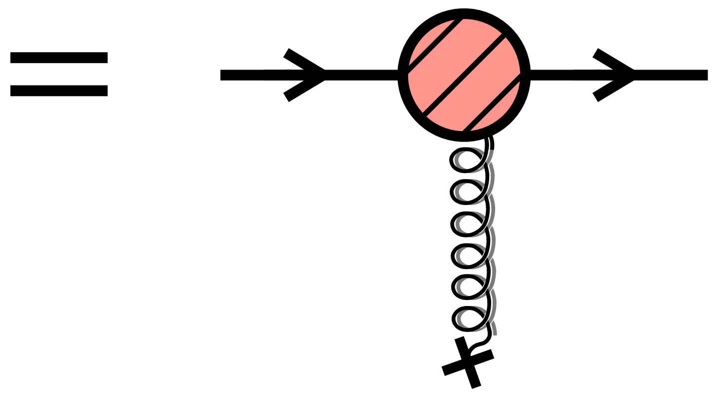
THE COLOR GLASS CONDENSATE



Simplest setting: Single charge meeting a wall of gluons



+ symmetrization



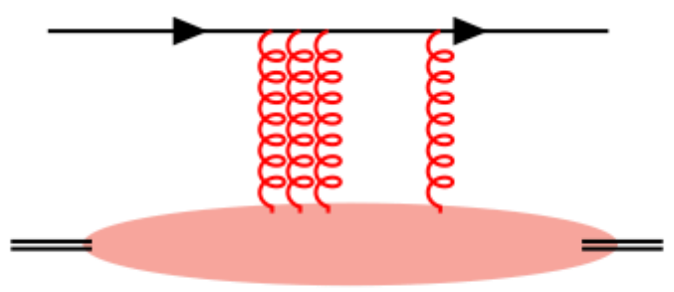
"Reggeized gluon"

$$V_{x_\perp} = e^{-ig\int dz^+ A^-(z^+, x_\perp)}$$

a.k.a. Wilson Line

All possible "kicks" by the gluons within the target

Test particle's transverse momentum (initially 0) is broadened dynamically (with mean around $Q_s(x)$!)



CGC → Strong classical fields:
Multiple scattering, broadening

→ A theory of Wilson lines $V_{x_\perp} = e^{-ig\int dz^+ A^-(z^+, x_\perp)}$, re-sums $\alpha_s \log 1/x$ terms

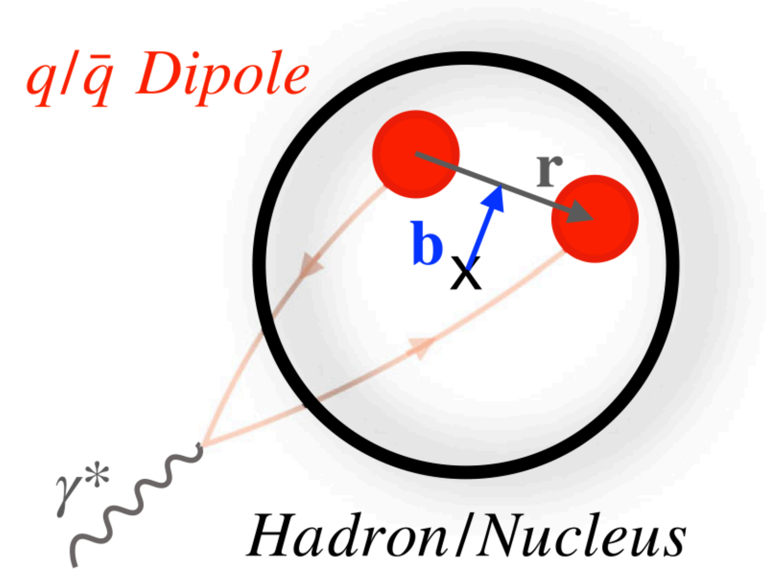
→ Observables are a combination of hard-factors and colour averaged source functionals

Dynamics of obs.

$$\langle \hat{O} \rangle_x = \int_{\{k_i\}} \Theta(\{k_i\}) \otimes \langle F[\{\rho_i\}] \rangle_x$$

Parton distributions + Low-x evolution

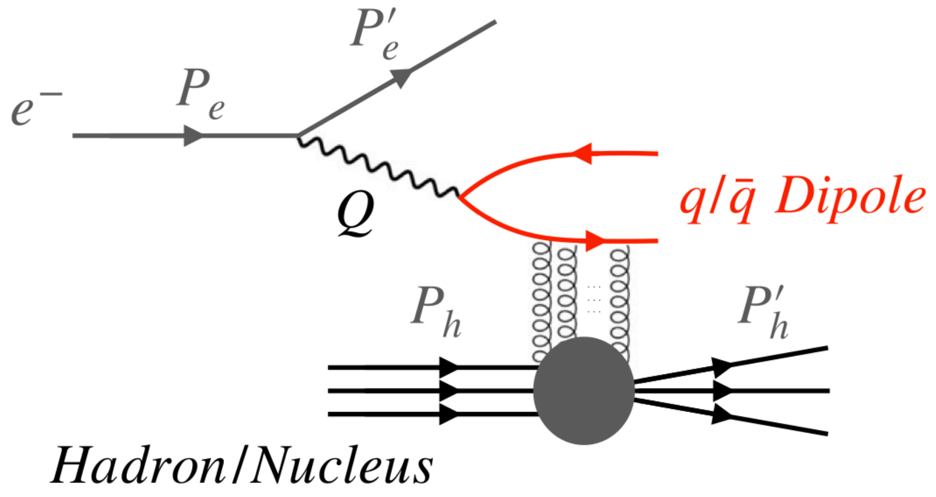
$$\langle F[\rho] \rangle_x = \int \mathscr{D}\rho \, W[x;\rho] F[\rho]$$



→ Classic example: dipole cross section at LO in α_S

$$\sigma^{\gamma^* p}_{L,T} = 2 \sum_f \int_{\mathbf{b}_\perp, \mathbf{r}_\perp} \int_z \left| \psi^{\gamma^* \to q\bar{q}}_{L,T}(r, z, Q^2) \right|^2 D(x, b, r)$$

where $D(x,b,r) = \frac{1}{N_c} \mathrm{Tr_c} \left\langle 1 - V\left(r + \frac{b}{2}\right) V^\dagger \left(r - \frac{b}{2}\right) \right\rangle_x$



HOW TO CONSTRAIN THE INITIAL CONDITIONS?

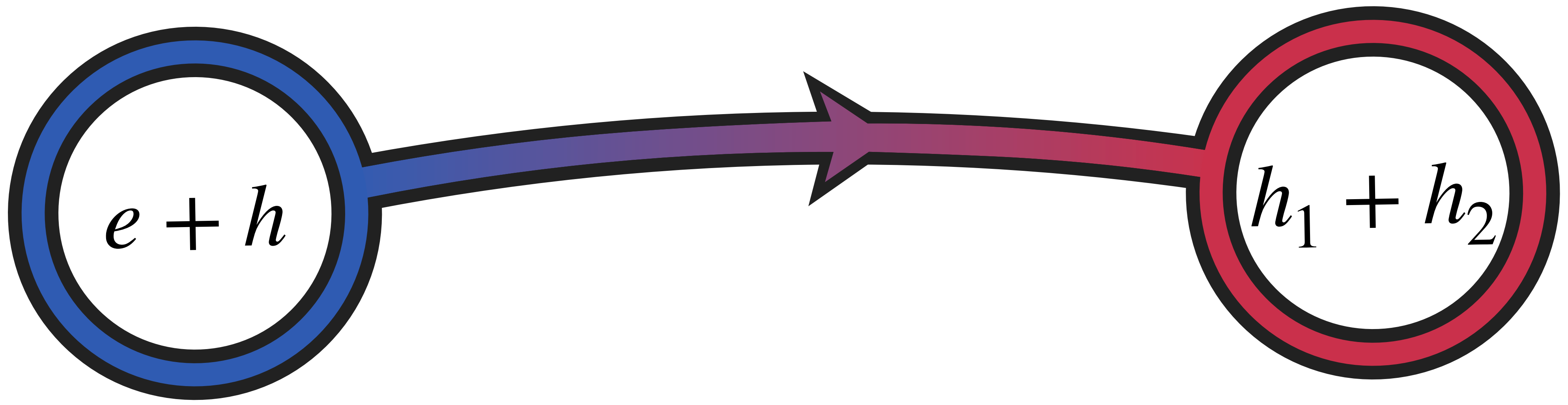
EXTRACT INFORMATION,
GO TO HIGHER ORDERS,
RINSE, REPEAT

HOW TO EXTRACT INFORMATION?

Photo-nuclear reactions
HERA/EIC

Clear-cut kinematics

Direct probe of gluon distributions in the nucleus



Hadronic Collisions
PP/PA/AA

Systematic build-up of complexity (both from kinematics and system size)

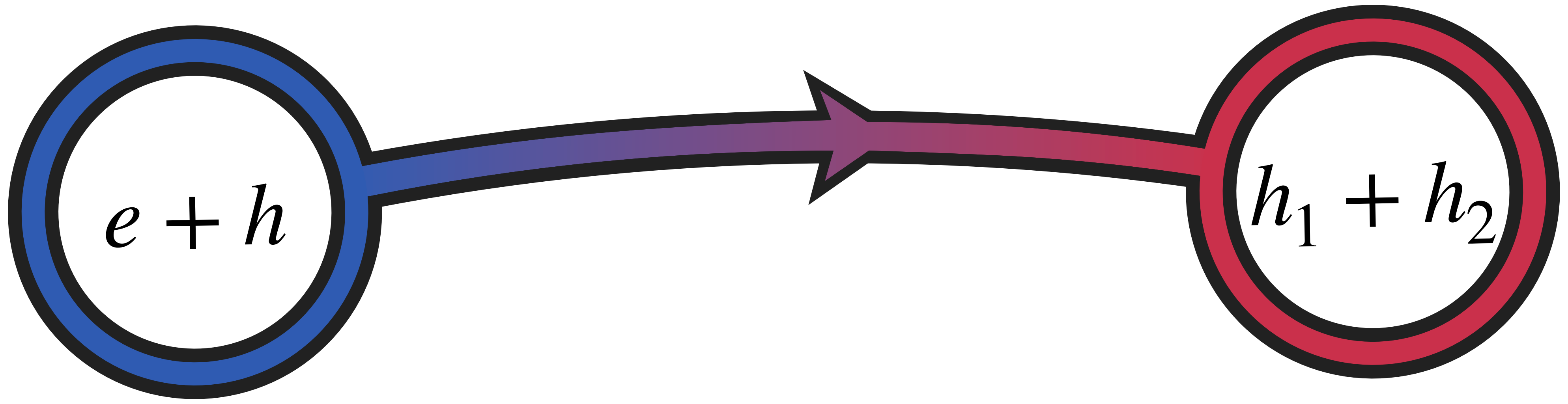
Kinematics generally complex and computations prohibitive.

HOW TO EXTRACT INFORMATION?

Photo-nuclear reactions
HERA/EIC

Clear-cut kinematics

Direct probe of gluon distributions in the nucleus



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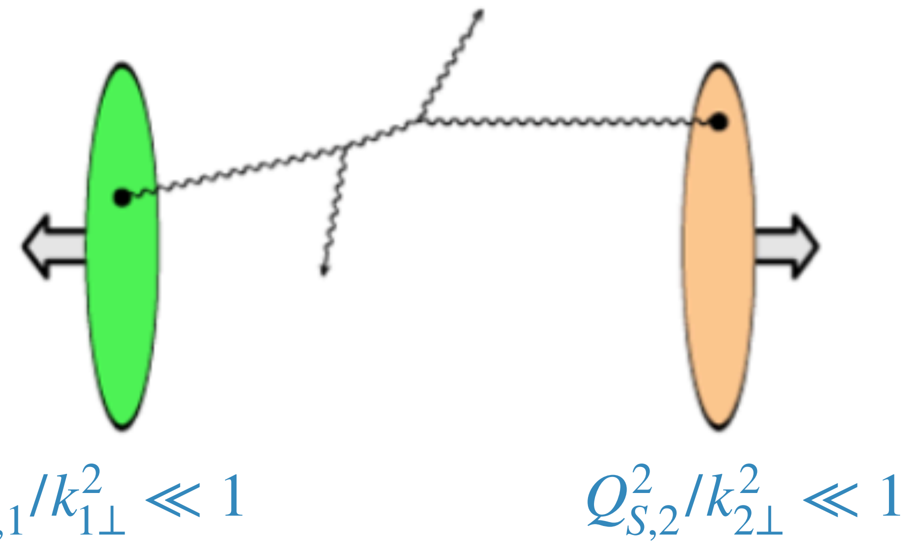
DILUTE-DILUTE



p+p

$$Q_S^2(x) \sim x^{-\lambda} A^{1/3} \sim s^{\lambda/2} A^{1/3}$$

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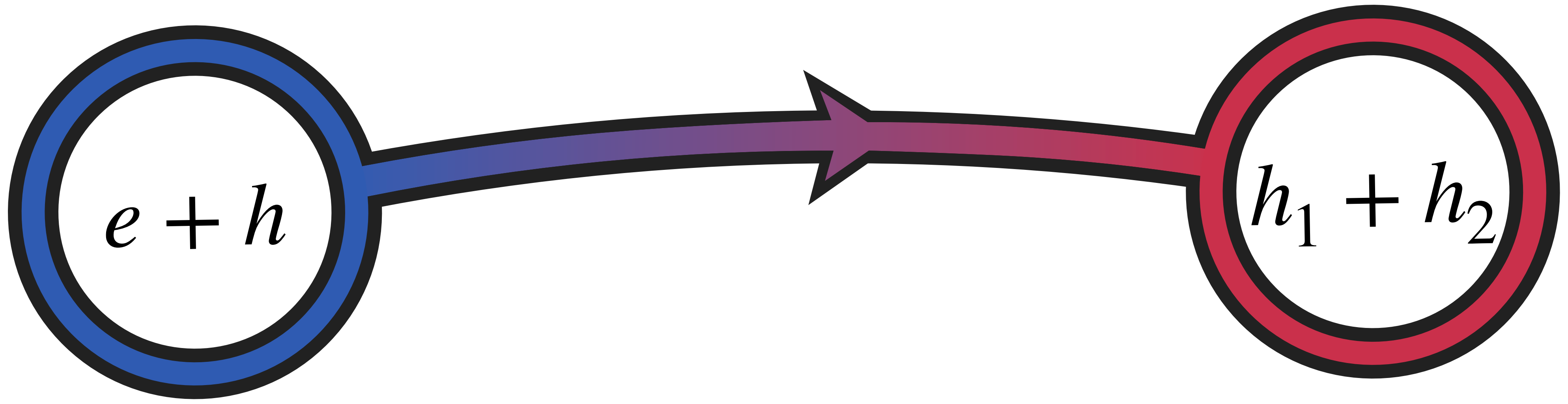

Hadronic Collisions
PP/PA/AA

Systematic build-up of complexity (both from kinematics and system size)

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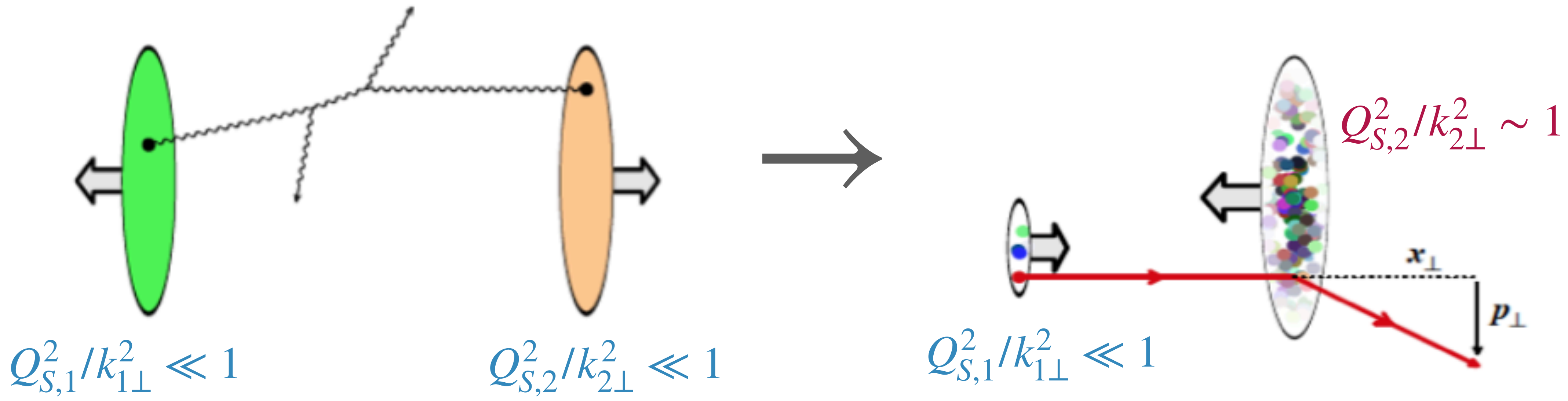
DILUTE-DILUTE → DILUTE-DENSE



p+p

p+A

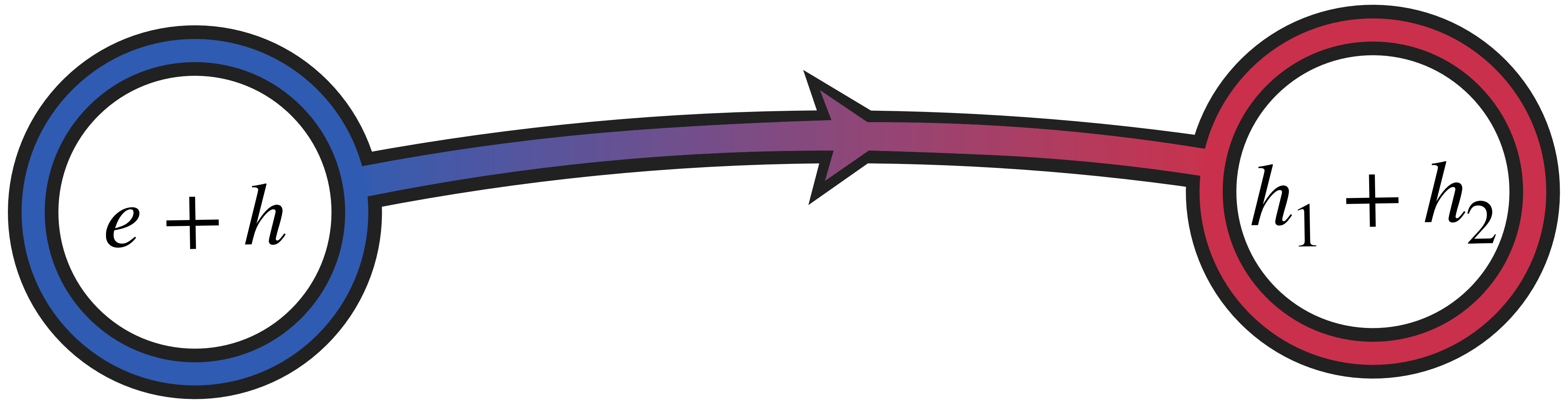
$$Q_S^2(x) \sim x^{-\lambda} A^{1/3} \sim s^{\lambda/2} A^{1/3}$$

HOW TO EXTRACT INFORMATION?

Photo-nuclear reactions
HERA/EIC

Clear-cut kinematics

Direct probe of gluon distributions in the nucleus



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PP/PA/AA

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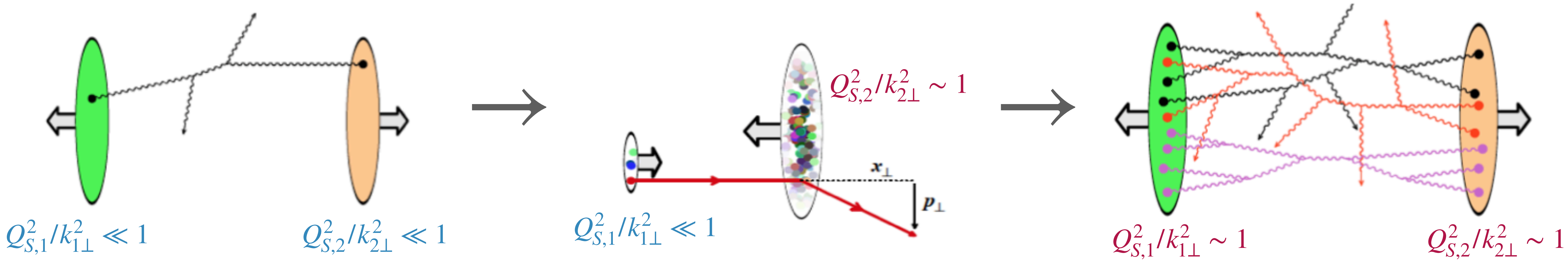
$$Q_S^2(x) \sim x^{-\lambda} A^{1/3} \sim s^{\lambda/2} A^{1/3}$$

DILUTE-DILUTE → DILUTE-DENSE → DENSE-DENSE



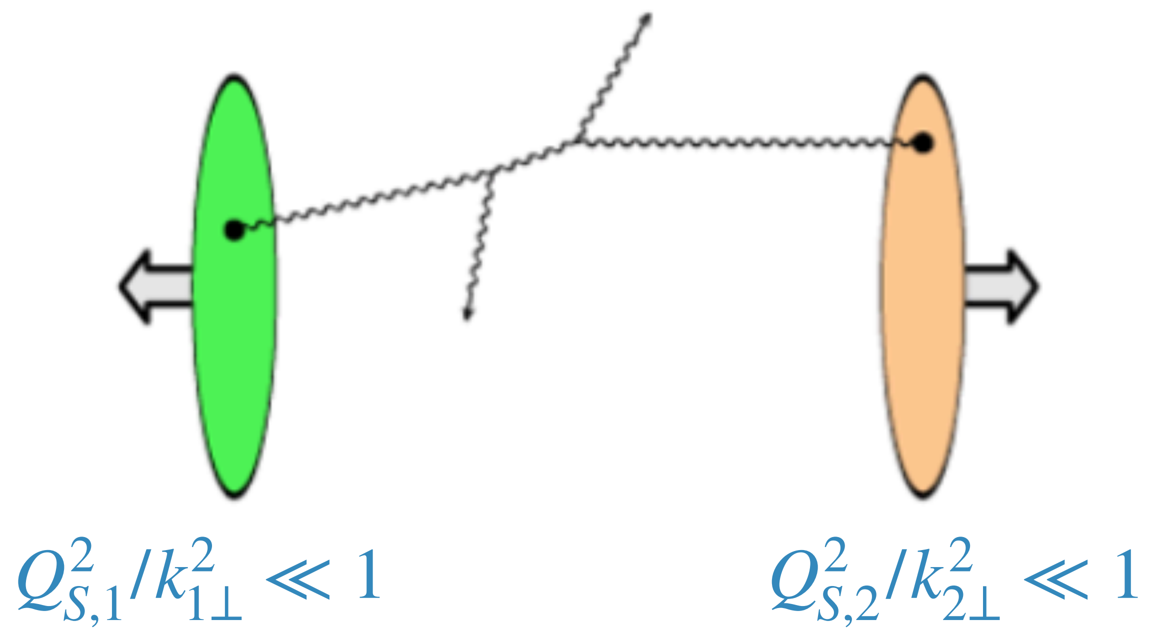
p+p p+A A+A

POWER-COUNTING IN THE CGC

WHICH APPROXIMATION?

Depends on $\sqrt{s}$, A_1/A_2, centrality, rapidity range, and k_T of particles

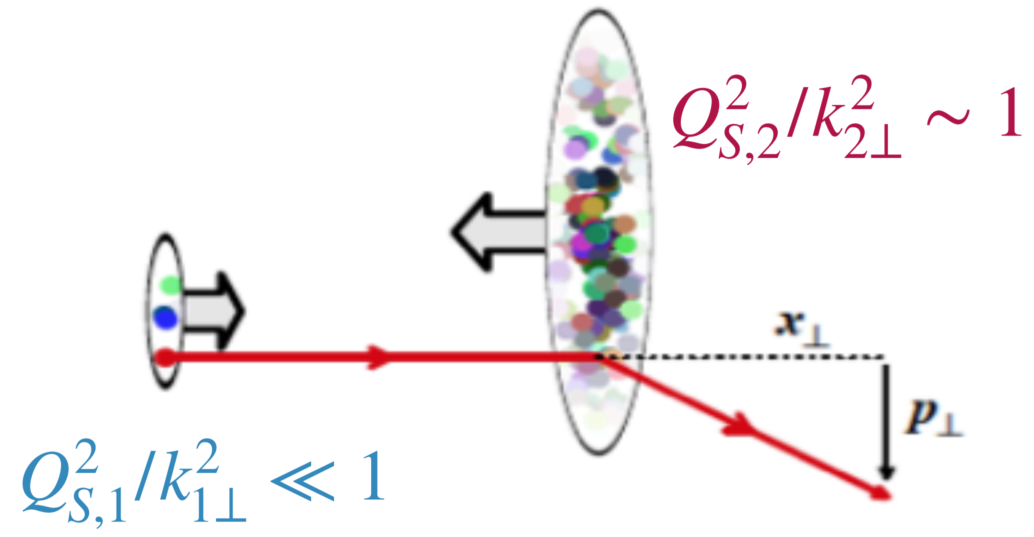
DILUTE-DILUTE



$gA_{1,2} \ll 1$, so that LO:
$\langle \hat{O} \rangle_x \sim \mathcal{O}(\rho_1 \rho_2)$

Match pQCD computations in the collinear limit ($k_\perp/Q_S^2 \gg 1$)

DILUTE-DENSE



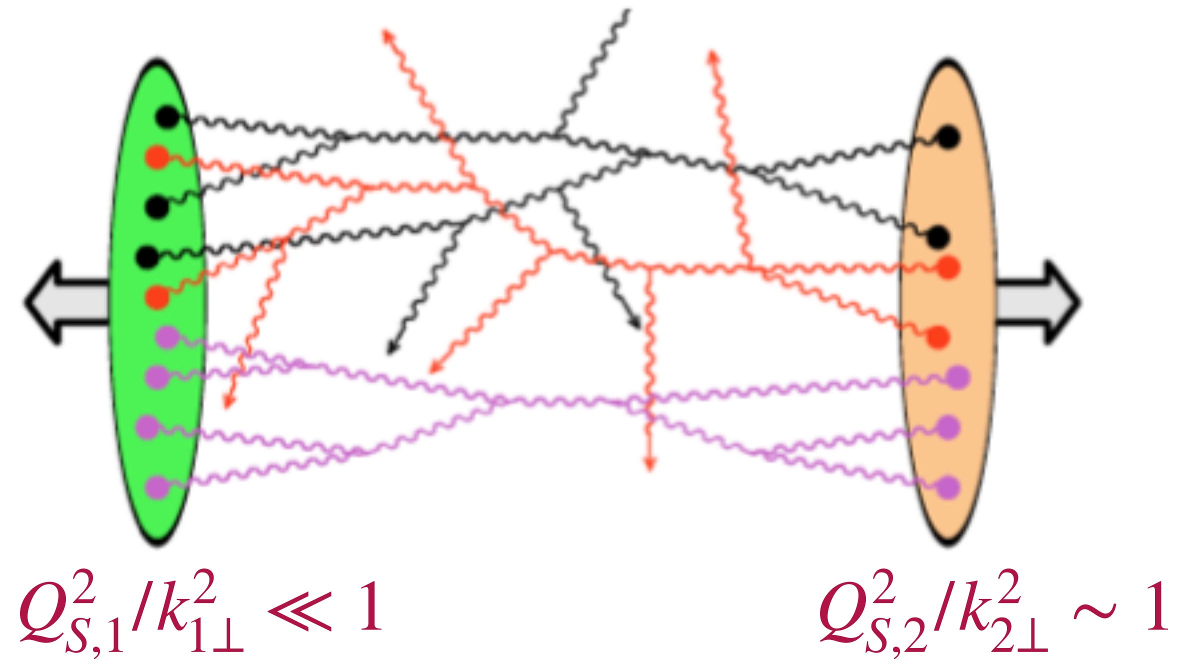
$\langle \hat{O} \rangle_x \sim \mathcal{O}(\rho_1)$ all orders in ρ_2

Forward limit: hybrid factorization.
pQCD projectile PDFs + CGC target unintegrated gluon distribution.

⇓

Search for saturation: Probing a nuclear target with ind. partons!

DENSE-DENSE



$gA_{1,2} > 1 \implies \langle \hat{O} \rangle_x$
all orders in ρ_1 and ρ_2

Analytically intractable:
CYM equations in 3+1 (2+1) D, numerically solved

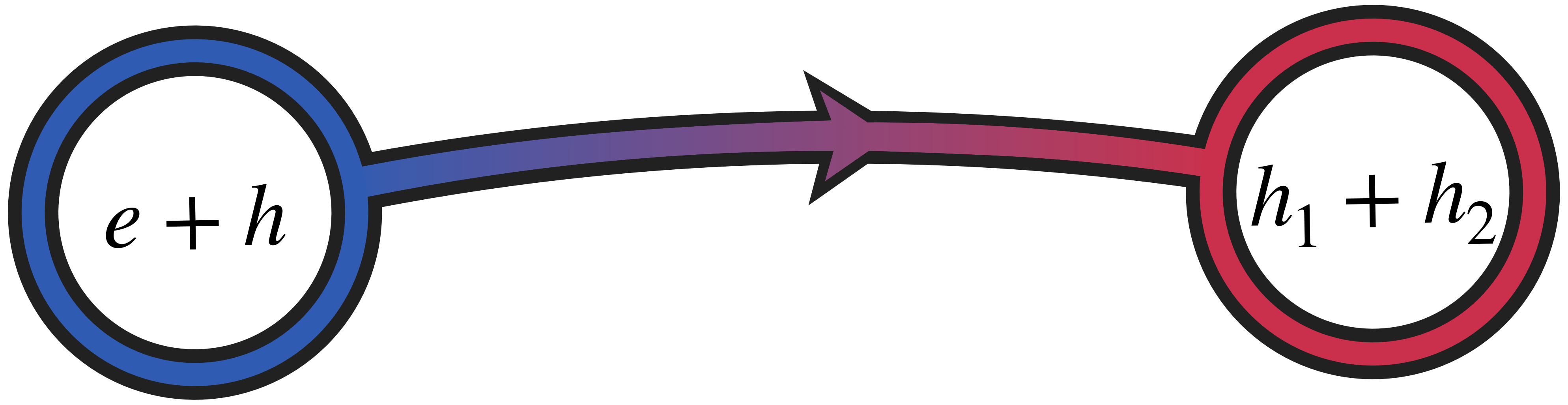
HOW TO EXTRACT INFORMATION?

Photo-nuclear reactions
HERA/EIC

Clear-cut kinematics

Direct probe of gluon distributions in the nucleus

Excellent setting to test QCD non-linearities since target can be both DILUTE or DENSE



Hadronic Collisions
PP/PA/AA

Systematic build-up of complexity (both from kinematics and system size)

Kinematics generally complex and computations prohibitive.

Kinematics is also a useful knob, e.g.

$A_1 \ll A_2$ provides a system where the projectile is DILUTE and target dense DENSE

OR

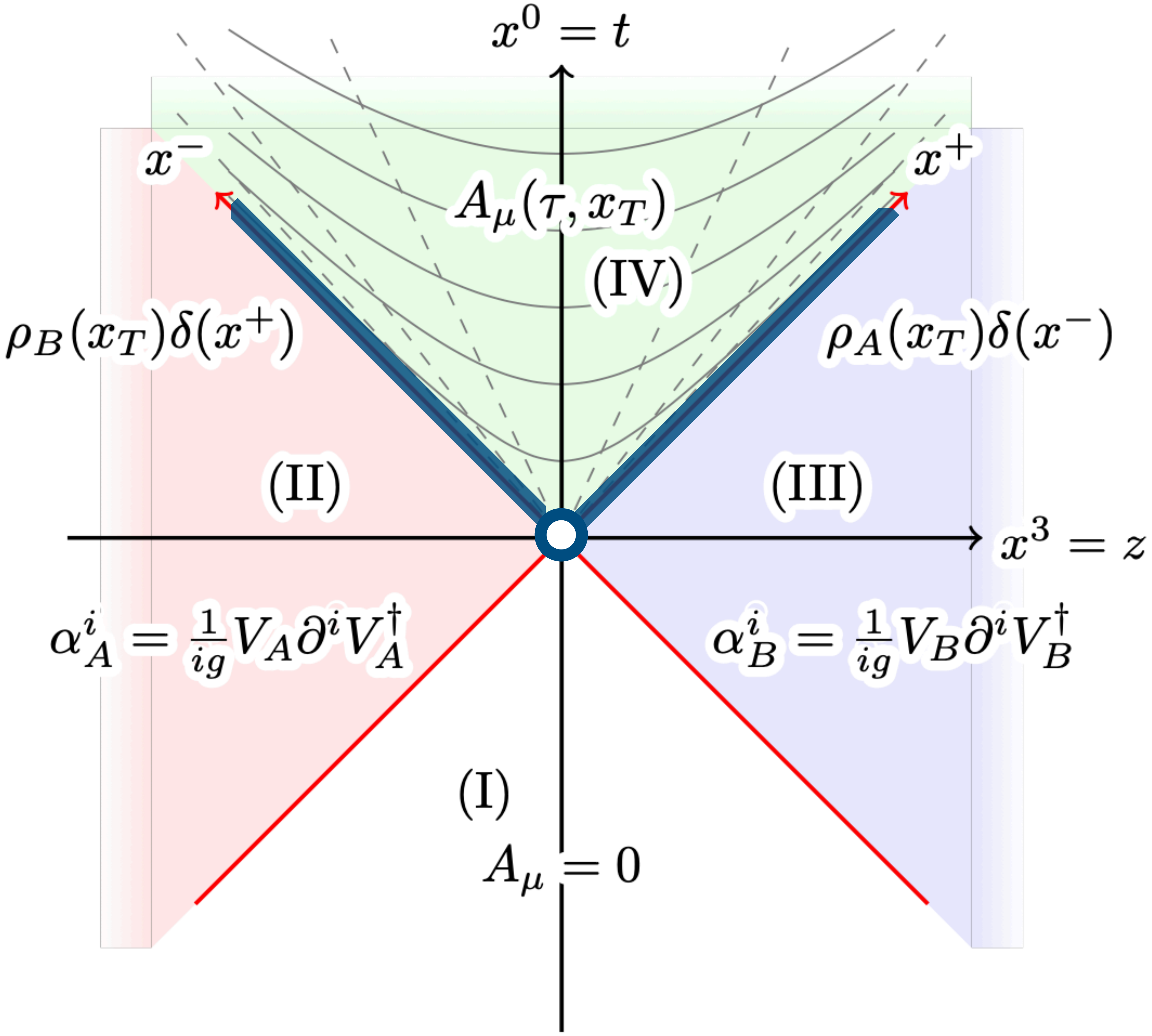
Forward/backward rapidity: the projectile is large-x (DILUTE) while target is low-x (DENSE)

DENSE-DENSE: IP-GLASMA

LO approximation for the CGC evolution of a dense-dense system.

IP-GLASMA

1) Sample nucleon positions (e.g. MC-Glauber)
2) Sample color currents from those nucleons ($J_{A,B}$)
3) Solve Yang-Mills*,** in the presence of both currents, and $D_\mu J^\mu = 0$.
    - * Boundary conditions and state at $\tau = 0^+$ well known analytically
    - ** Assume boost invariance and solve numerically in τ and $\boldsymbol{x}_\perp$
4) Get energy-stress tensor, $T^{\mu\nu}$



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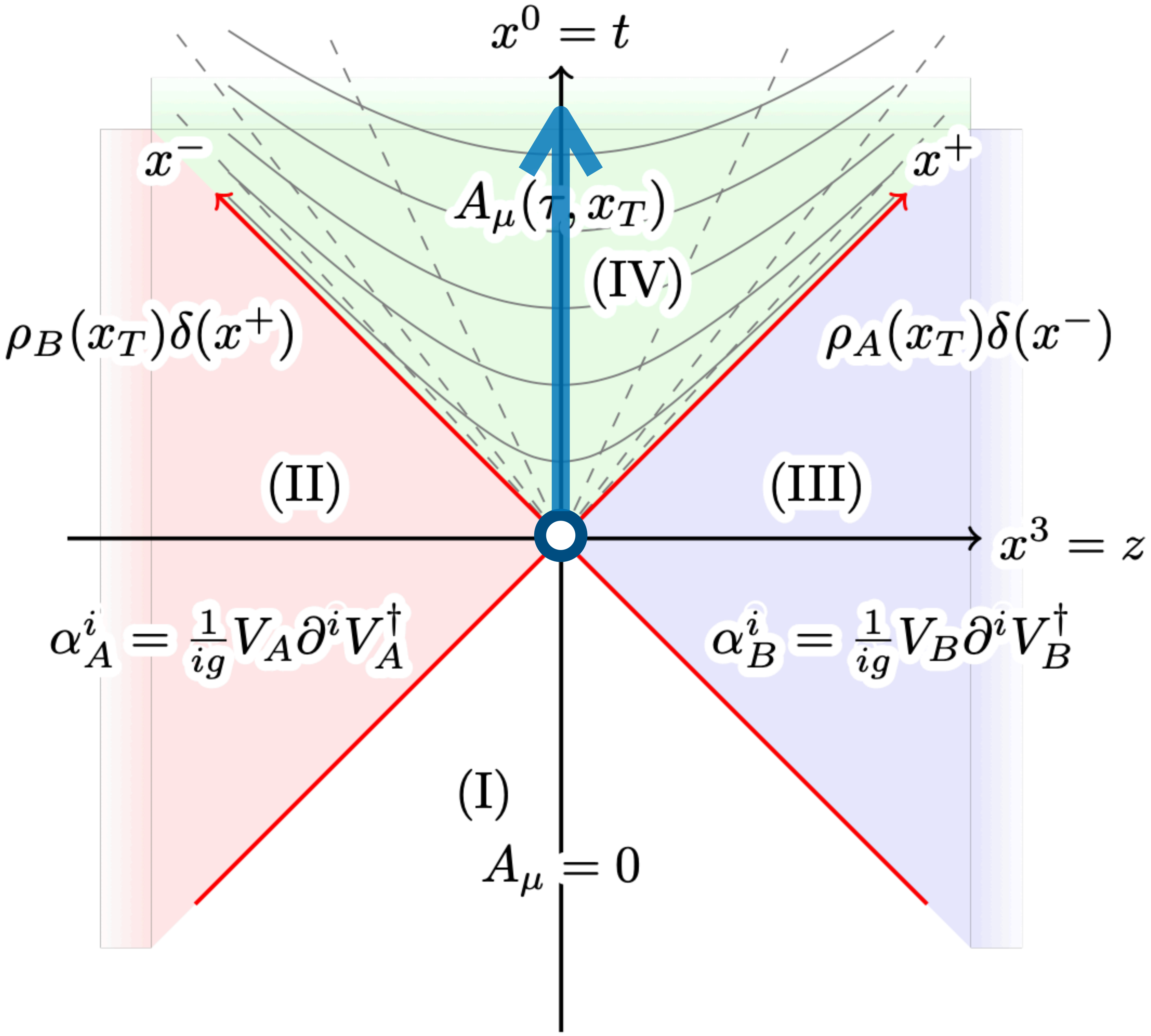

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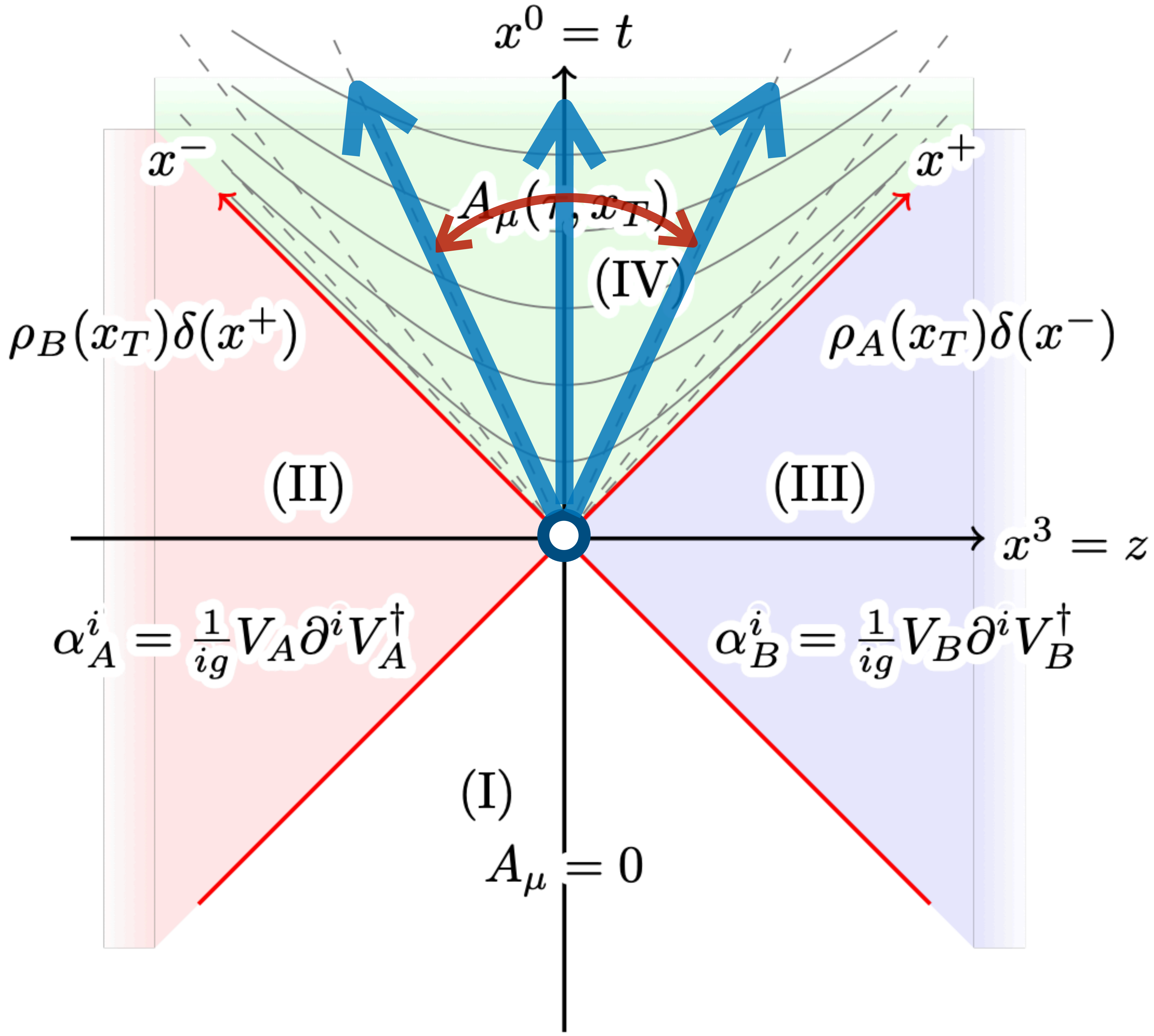
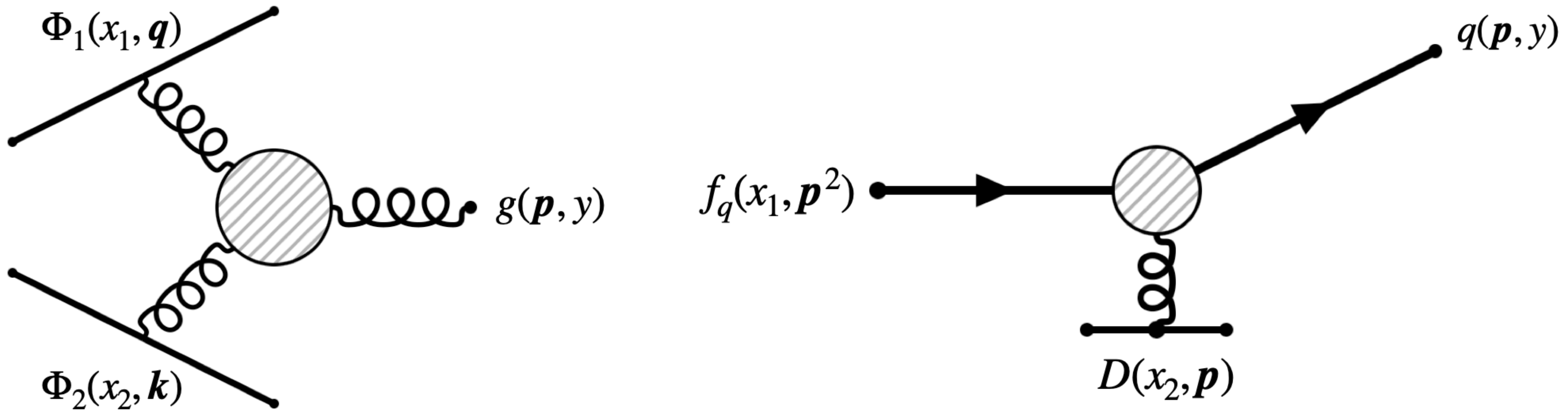
4) Get energy-stress tensor, $T^{\mu\nu}$

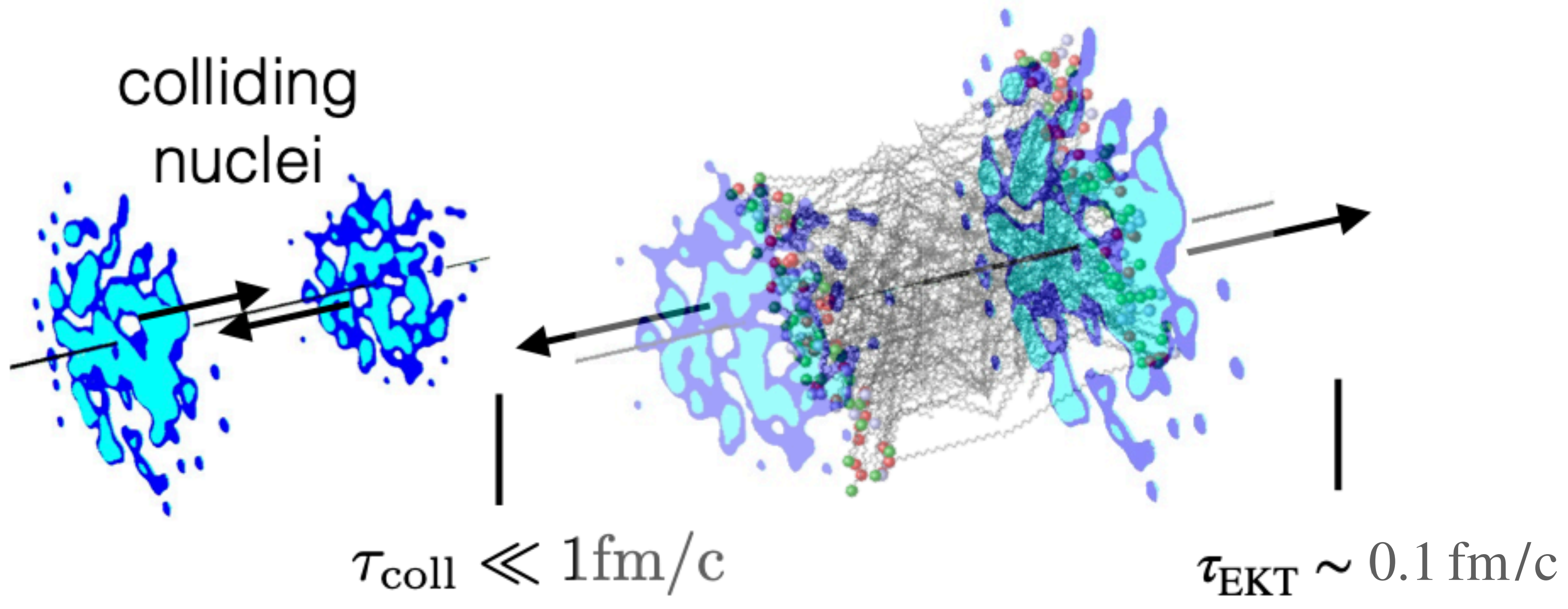
NOTE: EXTENSION TO 3D IS NOT TRIVIAL



RAPIDITY RESOLUTION ↔ LONG. RESOLUTION

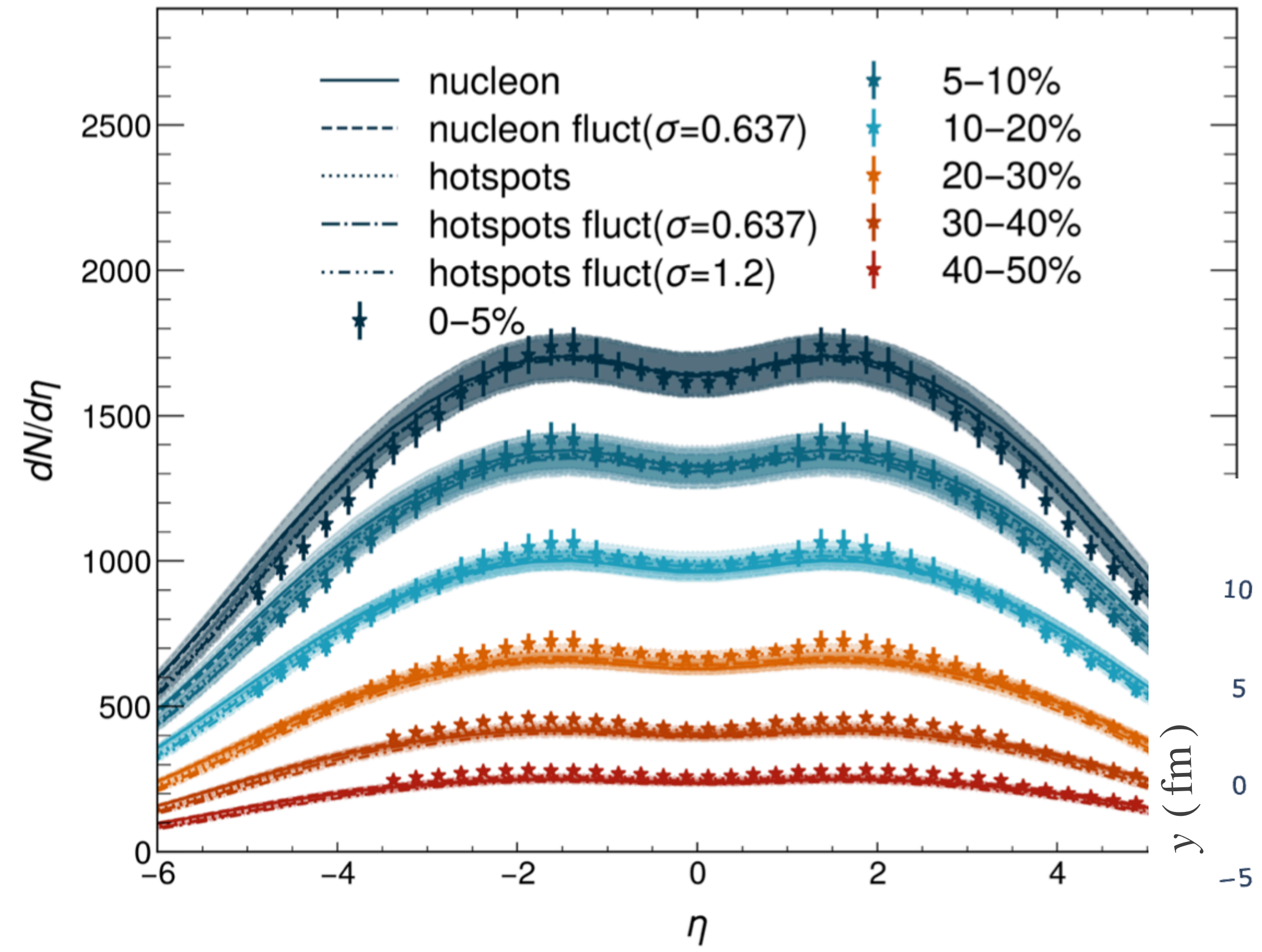


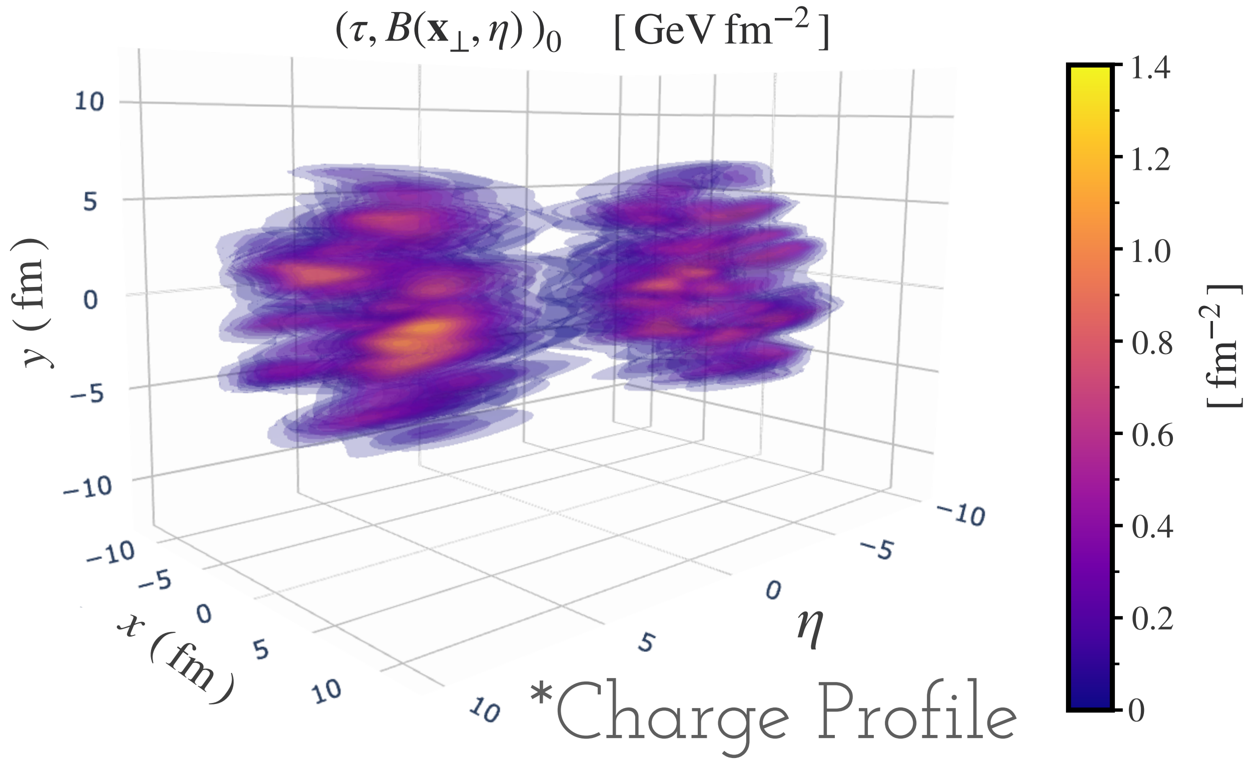
Perturbative expansion on the sources allows simple kinematics, connection $x \leftrightarrow y$ straightforward



Every contribution of sources taken on account, solvable numerically, but connection $x \leftrightarrow y$ is very complex

ONE SOLUTION:
THE DILUTE GLASMA



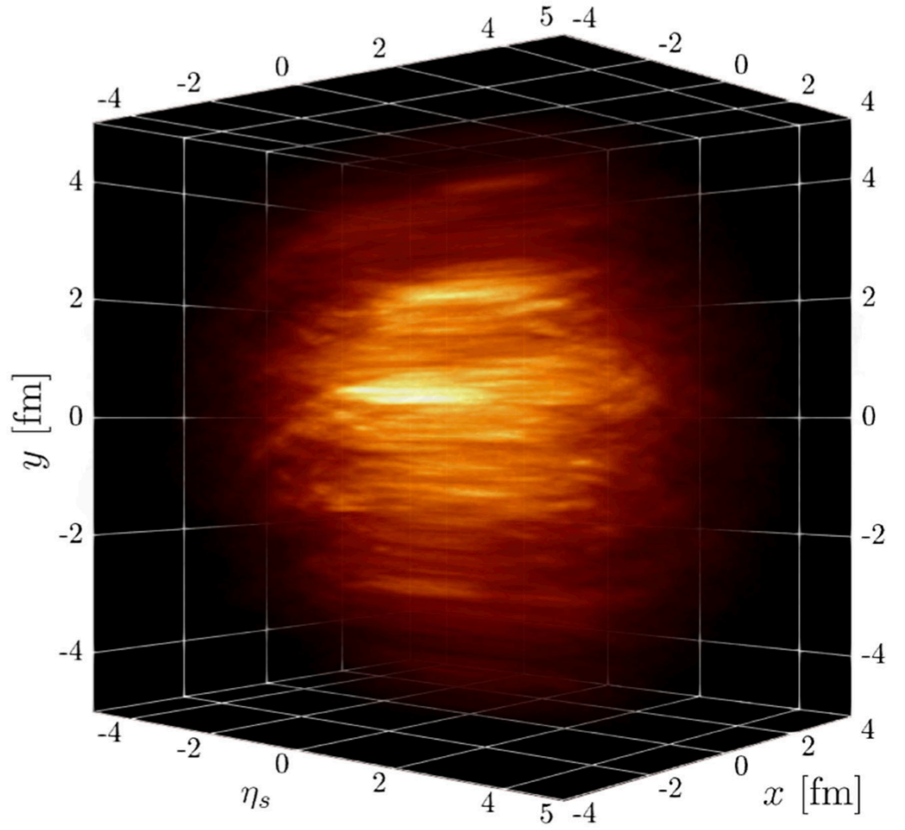


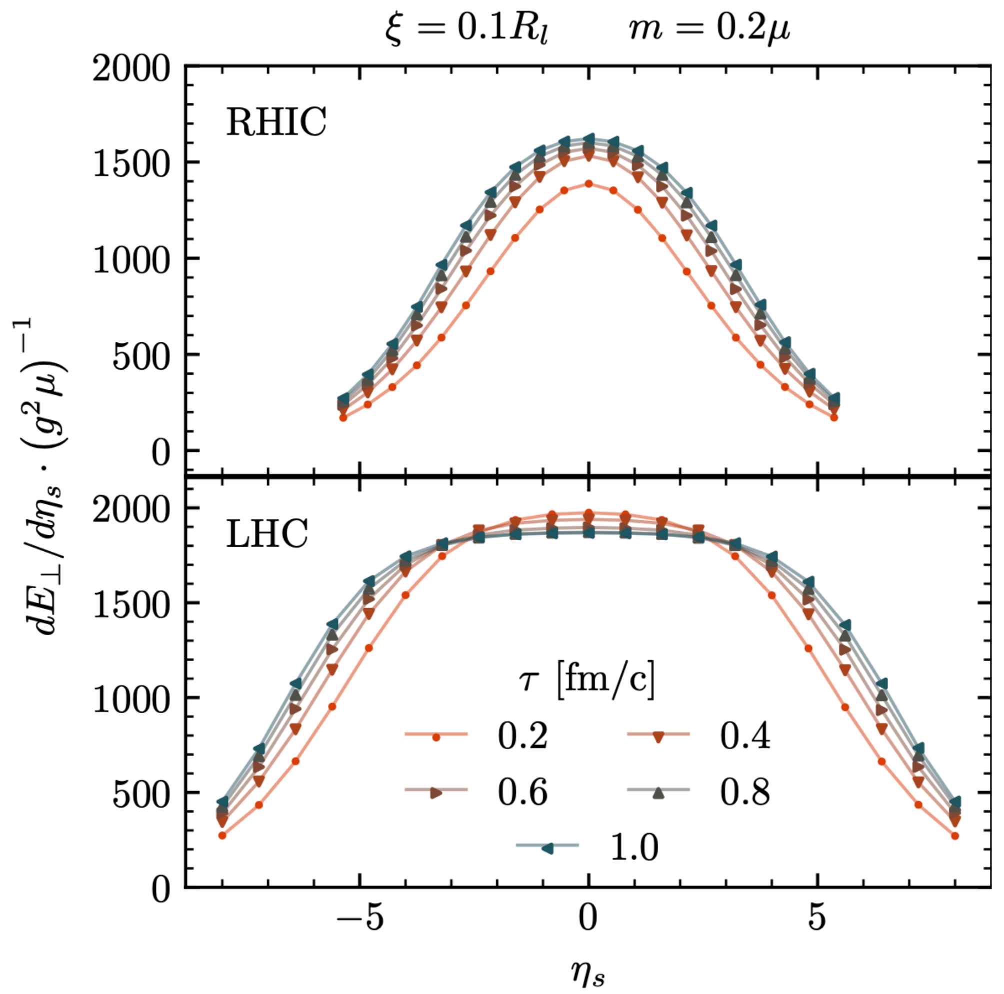
*Charge Profile

Initial Energy and charge deposition via UGDs (low-x) and PDF (large-x)

Natural incorporation of charge deposition via quark deflection

[O.G-M., Schlichting, Zhu, *Phys.Rev.D* 111 (2025) 7, 076029 ; *O.G-M., Schlichting, Phys.Rev.C* 111 (2025) 2, 024912, O.G-M., Elfner, Schlichting *Phys.Rev.C* 109 (2024) 4, 044916]





In position space, space-time evolution of the $T^{\mu\nu}$ of the initial state.

Association of $x \leftrightarrow \eta$ is less simple in this case, however identification with mom. space has been done.

[Ipp *et al*, *Phys.Rev.D 109 (2024) 9, 094040; Phys.Rev.D 104 (2021) 11, 114040*]

THE McDIPPER

Monte-Carlo Dipole Parallel Event GeneRator

Framework for comparison of saturation model predictions and creation of IC for HE Heavy-Ion Collisions

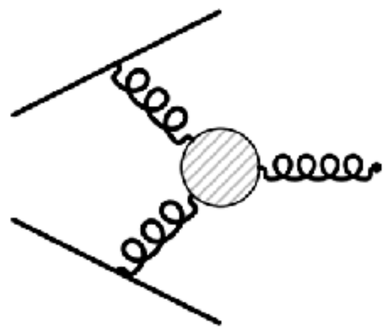
HOW DOES IT WORK?

- Model input: gluon unintegrated distribution function (uGDF) + (collinear) parton distribution functions (PDFs)
- Compute energy and charges using single particle production formulas and tabulate (η, T_1, T_2)
- Use Glauber sampling to produce events -*fast*- using (η, T_1, T_2) as an event-by-event input.

FROM MICRO TO MACRO

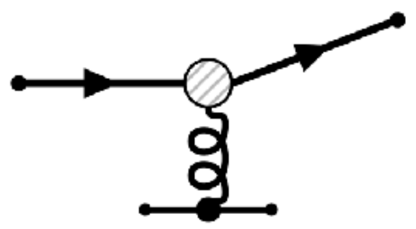
- Low-x gluons dominate the midrapidity region

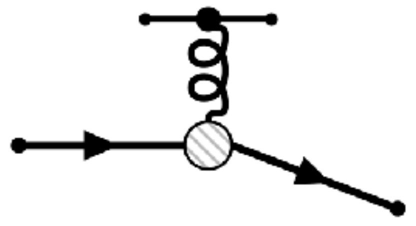
$$\frac{dN_g}{d^2\mathbf{x}d^2\boldsymbol{p}dy} = \frac{g^2}{8\pi^5\, C_F\, \boldsymbol{p}^2}\int \frac{d^2\boldsymbol{q}}{(2\pi)^2}\frac{d^2\boldsymbol{k}}{(2\pi)^2}(2\pi)^2\delta(\boldsymbol{p}+\boldsymbol{q}-\boldsymbol{p}) \times \Phi_1(x_1,\boldsymbol{x},\boldsymbol{q})\ \Phi_2(x_2,\boldsymbol{x},\boldsymbol{k})$$



- At forward/backward rapidities, particle production dominated by baryon stopping

$$\frac{dN_{q_f}}{d^2\mathbf{x}d^2\mathbf{p}dy} = \frac{x_1 q_f^A(x_1,\mathbf{p}^2,\mathbf{x})\ D_{\mathrm{fun}}(x_2,\mathbf{x},\mathbf{p})}{(2\pi)^2} + \frac{x_2 q_f^A(x_2,\mathbf{p}^2,\mathbf{x})\ D_{\mathrm{fun}}(x_1,\mathbf{x},\mathbf{p})}{(2\pi)^2}\,.$$





THE INPUT

Low-x gluons

uGDFs $\rightarrow$ $\Phi_i(x,\boldsymbol{r},\boldsymbol{q}) \sim \boldsymbol{q}^2 D_{\mathrm{adj}}(x,\boldsymbol{r},\boldsymbol{q})$

Dipoles $\rightarrow$ $D_{\mathrm{adj}}(x,\boldsymbol{r},\boldsymbol{q})$, $D_{\mathrm{fun}}(x,\boldsymbol{r},\boldsymbol{q})$

- GBW, IP-Sat, MV...

High-x partons

PDFs $\rightarrow$ $x_i\, q_f(x_i,\mathbf{p}^2)$

Different PDF sets*.

*Accessible in the McDIPPER through the LHAPDF library

Systematically Improvable e.g. by including NLO gg$\rightarrow$ $q\bar{q}$ production through gluon fusion

FROM MICRO TO MACRO

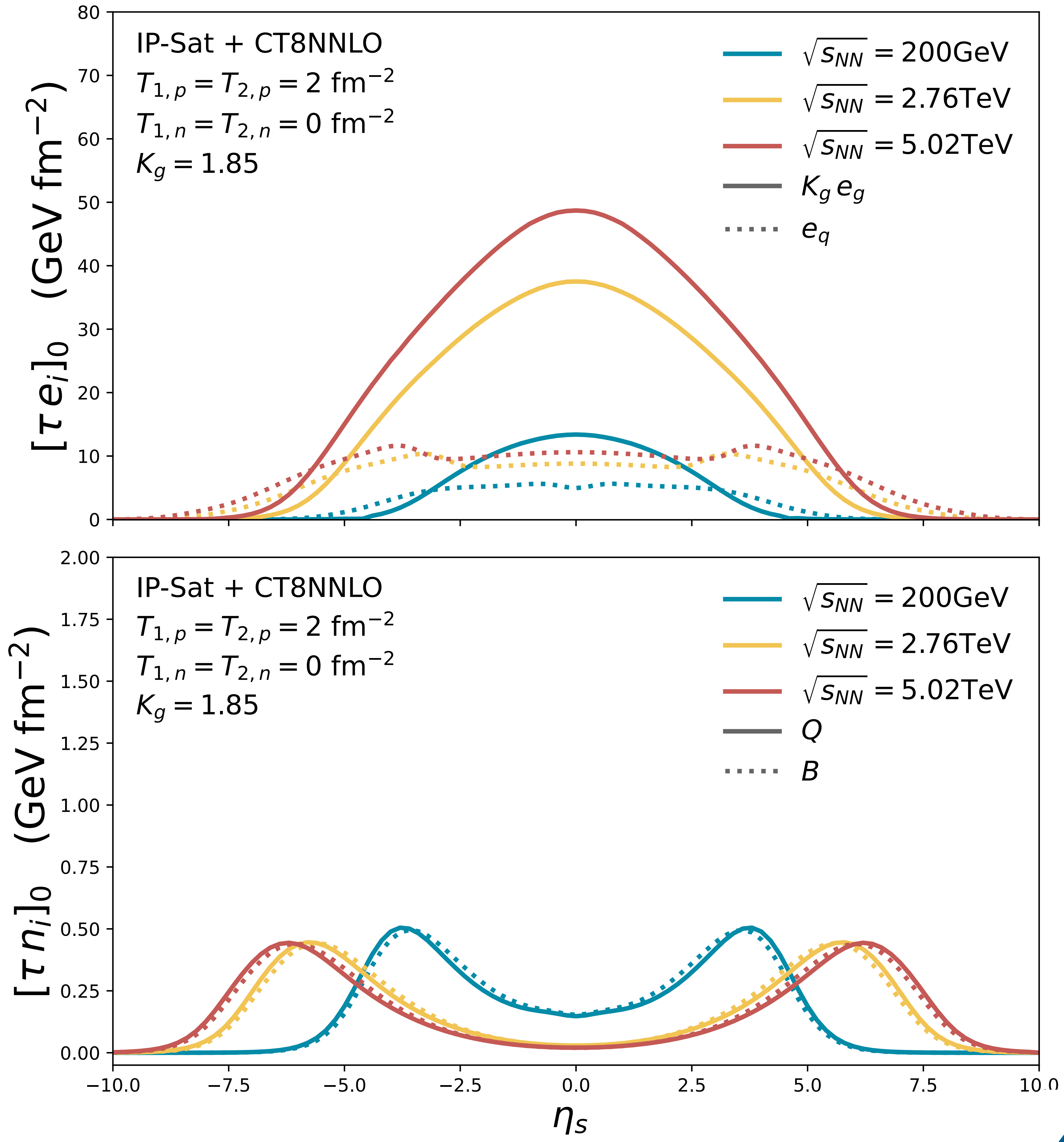
- Macroscopic quantities (energy, charges) are computed as moments of the single particle distributions
  - Total energy deposition

$$(e\tau)_0 = \int d^2\mathbf{p}\ |\mathbf{p}|\ \left[K_g \frac{dN_g}{d^2\mathbf{x}d^2\mathbf{p}dy} + \sum_{f,\bar{f}} \frac{dN_{q_f}}{d^2\mathbf{x}d^2\mathbf{p}dy}\right]_{y=\eta_s}$$

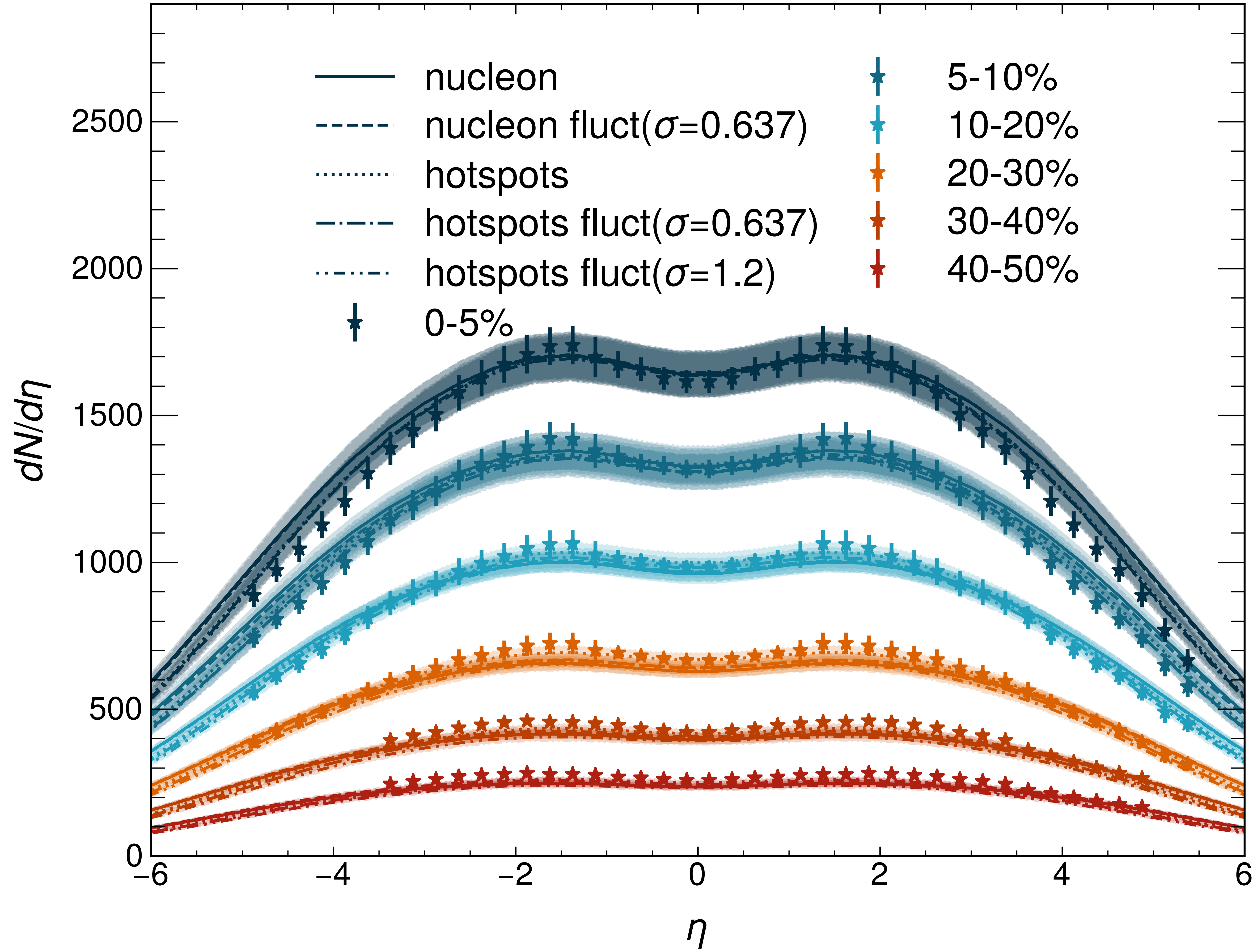
  - Charges (u,d,s) deposited can be used to compute conserved charges such as, i.e. electric charge,

$$(Q\tau)_0 = \sum_f Q_f \int d^2\mathbf{p}\ \left[\frac{dN_f}{d^2\mathbf{x}d^2\mathbf{p}dy} - \frac{dN_{\bar{f}}}{d^2\mathbf{x}d^2\mathbf{p}dy}\right]_{y=\eta_s}$$

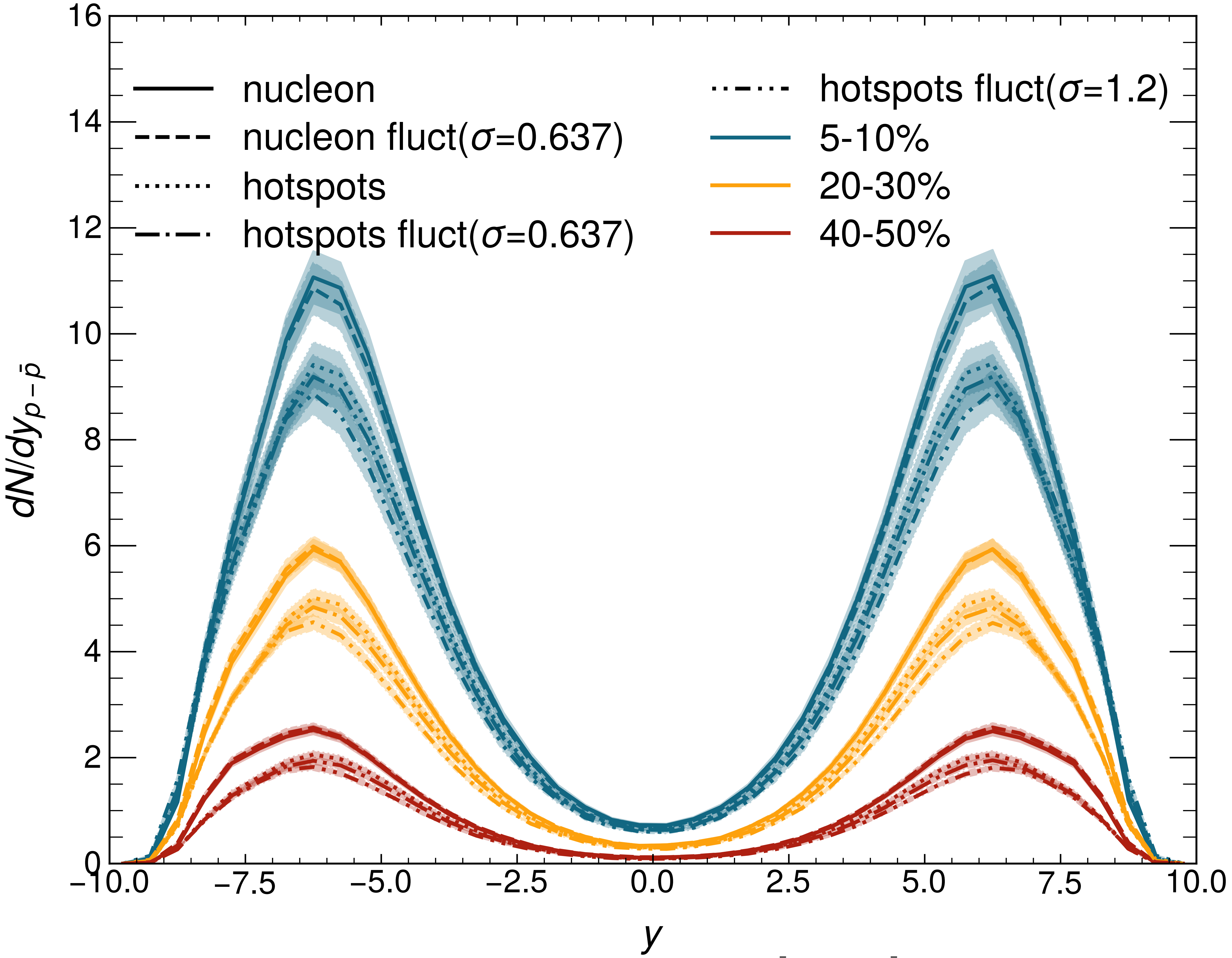
$$(B\tau)_0 = \sum_f B_f \int d^2\mathbf{p}\ \left[\frac{dN_f}{d^2\mathbf{x}d^2\mathbf{p}dy} - \frac{dN_{\bar{f}}}{d^2\mathbf{x}d^2\mathbf{p}dy}\right]_{y=\eta_s}$$



FLUCTUATIONS IN LARGE SYSTEMS



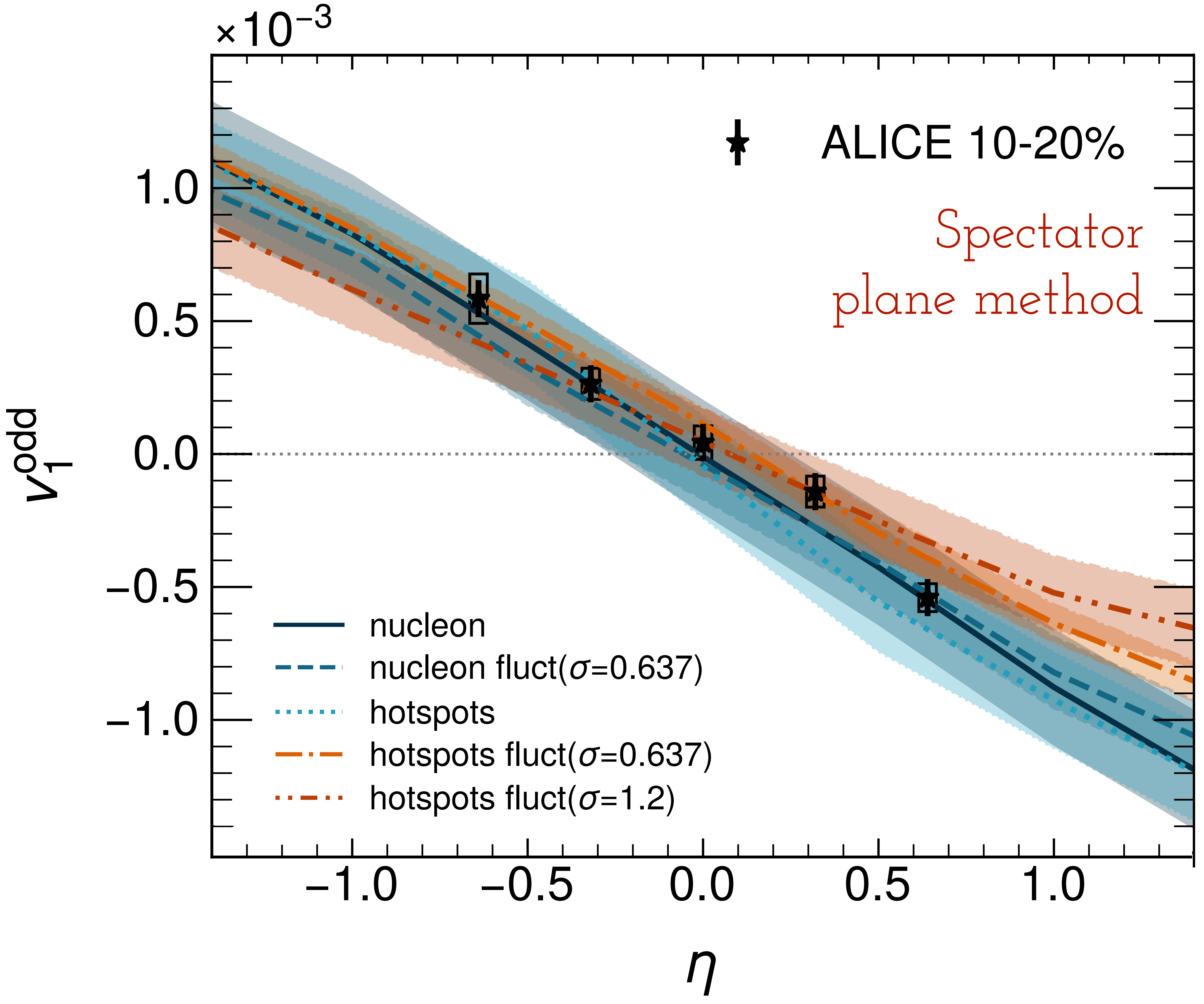
Minimal IC tuning. Shape of $\mathrm{d}N_{ch}/\mathrm{d}\eta$ given by IP-Sat



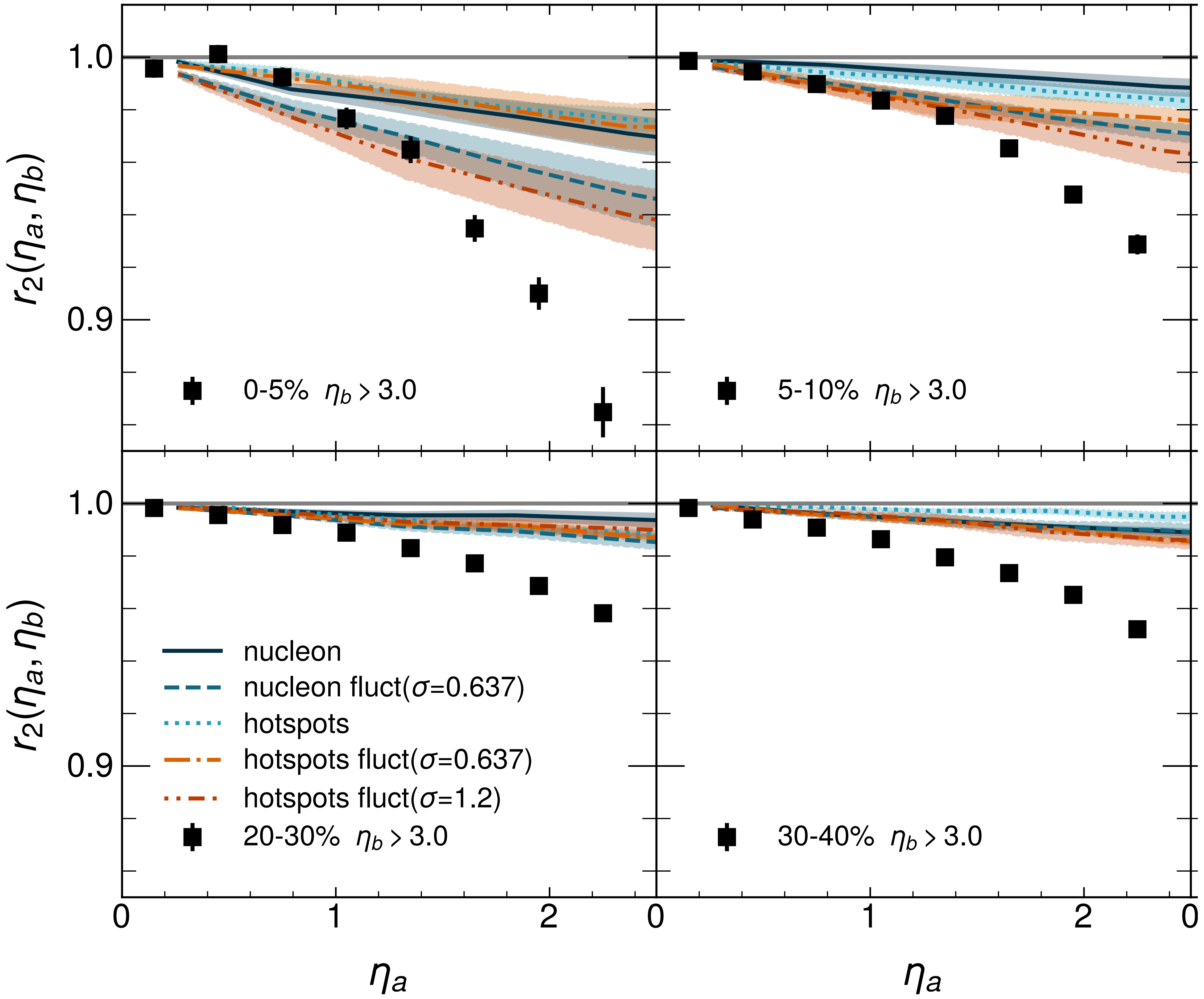
Baryon stopping and evolution (including baryon diffusion)

[GM, Schlichting, Zhu, 2501.14872]

FLUCTUATIONS IN LARGE SYSTEMS



IC-information tunes the sensitive longitudinal structures, and describes data quantitatively



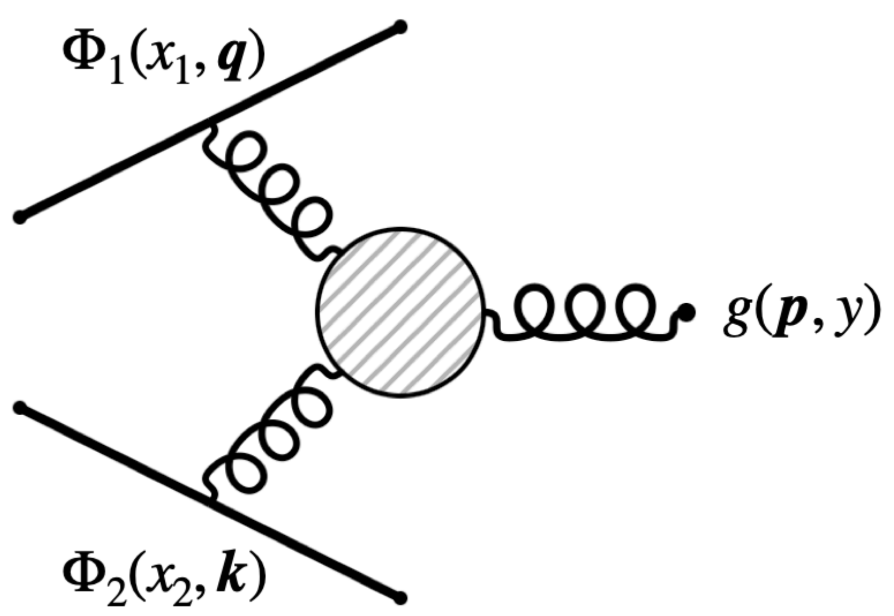
Decorrelation sensitive to fluctuations. Less agreement where quark sector is relevant (more peripheral collisions and higher η's)

[GM, Schlichting, Zhu, 2501.14872]

A SIMPLE CASE

- GBW model (gaussian gluon distributions) $D(x, \mathbf{k}_\perp, \mathbf{x}_\perp) \sim \exp\left(-\frac{\mathbf{k}_\perp^2}{Q_A^2(x, \mathbf{x}_\perp)}\right)$ $Q_A^2(x, \mathbf{x}_\perp) \sim x^{-\lambda} T(\mathbf{x}_\perp)$

- Simple kinematics
  Fixed by "measured" gluon $x_1 = \frac{p_\perp e^y}{\sqrt{s_{NN}}}$ $x_2 = \frac{p_\perp e^{-y}}{\sqrt{s_{NN}}}$



- Gluon distribution dominated by saturation scale $x_{1,2} = \frac{Q_{1,2}^2(x, T)\, e^{\pm y}}{\sqrt{s_{NN}}}$

- Analytical solution to energy $e\tau_0 \sim \frac{Q_A^2 Q_B^2}{(Q_A^2 + Q_B^2)^{5/2}}(2Q_A^4 + 2Q_B^4 + 7Q_A^2 Q_B^2)$ Complex function $e\tau_0[T_1, T_2]$

- Something like TRENTO

$$e\tau_0 \sim \left[\frac{T_A^p + T_B^p}{2}\right]^{1/p}$$

A SIMPLE CASE

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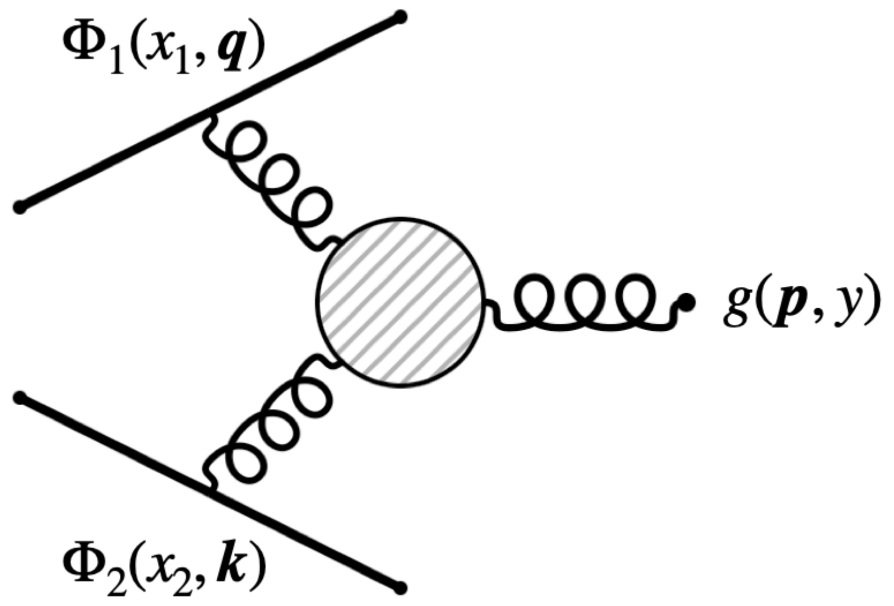
- Simple kinematics
  Fixed by "measured" gluon $x_1 = \frac{p_\perp e^y}{\sqrt{s_{NN}}}$ $x_2 = \frac{p_\perp e^{-y}}{\sqrt{s_{NN}}}$



- Gluon distribution dominated by saturation scale $x_{1,2} = \frac{Q_{1,2}^2(x, T)\, e^{\pm y}}{\sqrt{s_{NN}}}$

- Analytical solution to energy $e\tau_0 \sim \frac{Q_A^2 Q_B^2}{(Q_A^2 + Q_B^2)^{5/2}}(2Q_A^4 + 2Q_B^4 + 7Q_A^2 Q_B^2)$ Complex function $e\tau_0[T_1, T_2]$

- Something like TRENTO

$$e\tau_0 \sim \left[\frac{T_A^p + T_B^p}{2}\right]^{1/p}$$

WHY IS THIS IMPORTANT?

Particle correlations take $\langle \cdot \rangle$ of powers of thermo. quantities.
Even when subleading, extra-powers may induce error.

INITIAL CONDITIONS

From the Hot QCD White Paper, a list of current, pressing avenues on the initial states

- Initial condition: $\sqrt{s_{NN}}$ dependence and longitudinal structure
- B,Q,S Charge deposition and the search for the CP
- From medium to small systems
- Better quantification of ICs for large systems
- Initial condition for hard probes

Relevant momentum fraction x

T Characteristic nuclear density

Seemingly different,
But in reality, intimately related!!

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Relevant momentum fraction x

QCD evolution: Low E↔High E Interplay

T Characteristic nuclear density

Seemingly different, But in reality, intimately related!!


BUT WAIT
SATURATION!
INCLUDING:
IP-GLASMA
McDIPPER
THERE'S MORE!
imgflip.com

NON-GAUSSIANITIES IN THE EFFECTIVE ACTION

MV-MODEL: Gaussian distribution $\log W_{x_0}[\rho] \sim -\int_z \frac{1}{2\mu_z^2}\rho_z \cdot \rho_z$

- Simplest corrections: cubic (odderon) and quartic operator

  Jeon, Venugopalan, *PRD* 71 (2005) 125003, *PRD* 70 (2004) 105012

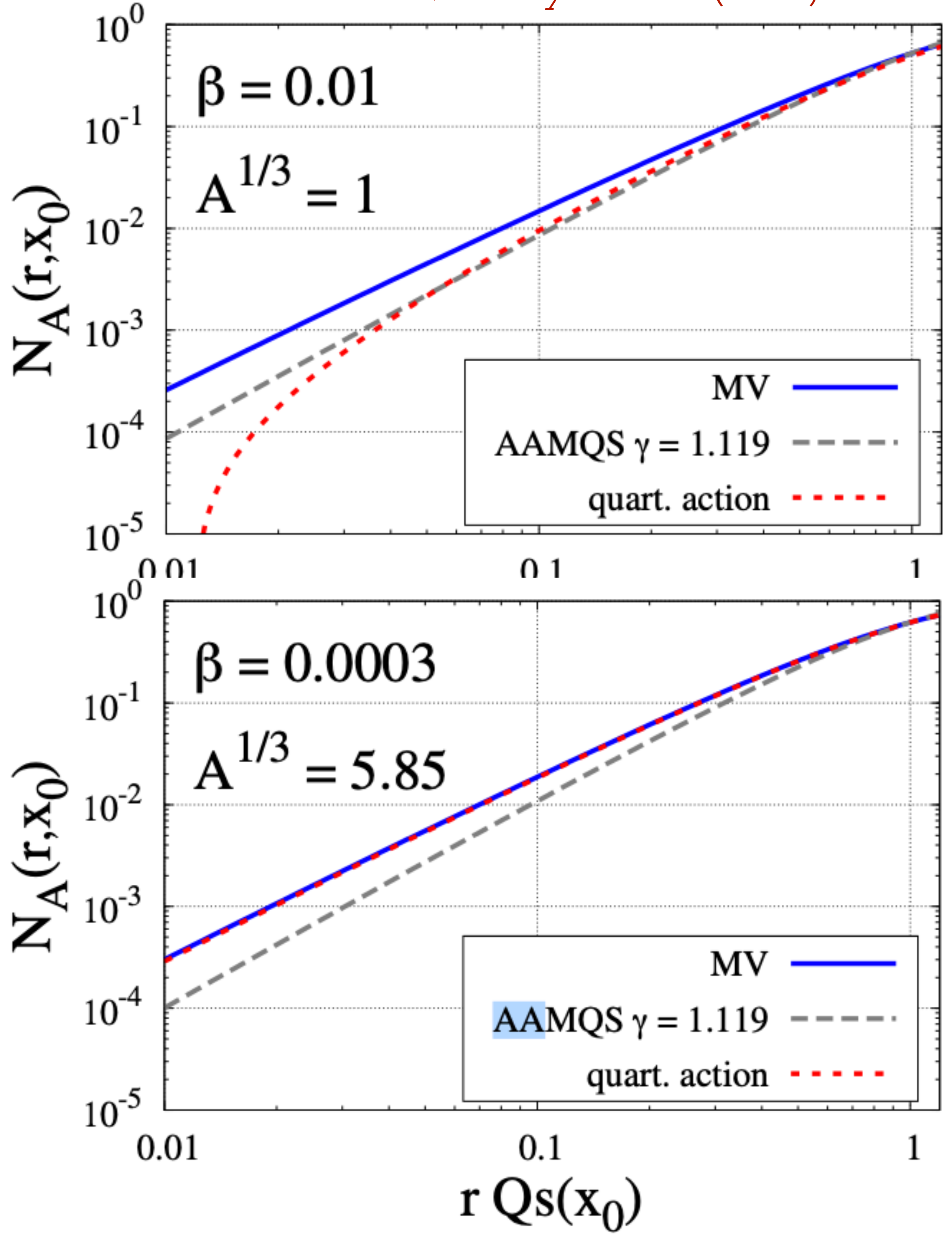
$$\delta \log W_x[\rho] \sim \int_z \frac{d_{abc}}{2\kappa_3}\rho_z^a \rho_z^b \rho_z^c - \int_z \frac{1}{\kappa_4}(\rho_z \cdot \rho_z)^2$$

- Operators are system size dependent

$$\mu^2 = \frac{g^2}{2}\frac{A}{\pi R_A^2} \sim A^{1/3}, \quad \kappa_3 = 3g^3\left(\frac{A}{\pi R_A^2}\right)^2 \sim A^{2/3} \quad \text{and} \quad \kappa_4 = 6g^4\left(\frac{A}{\pi R_A^2}\right)^3 \sim A^1$$

$\Longrightarrow$ **Quite relevant** for small systems!

From Dumitru, Petreska, *Nucl.Phys.A* 879 (2012) 59-76



NON-GAUSSIANITIES IN THE EFFECTIVE ACTION

RECENT (AND LESS SO) WORK

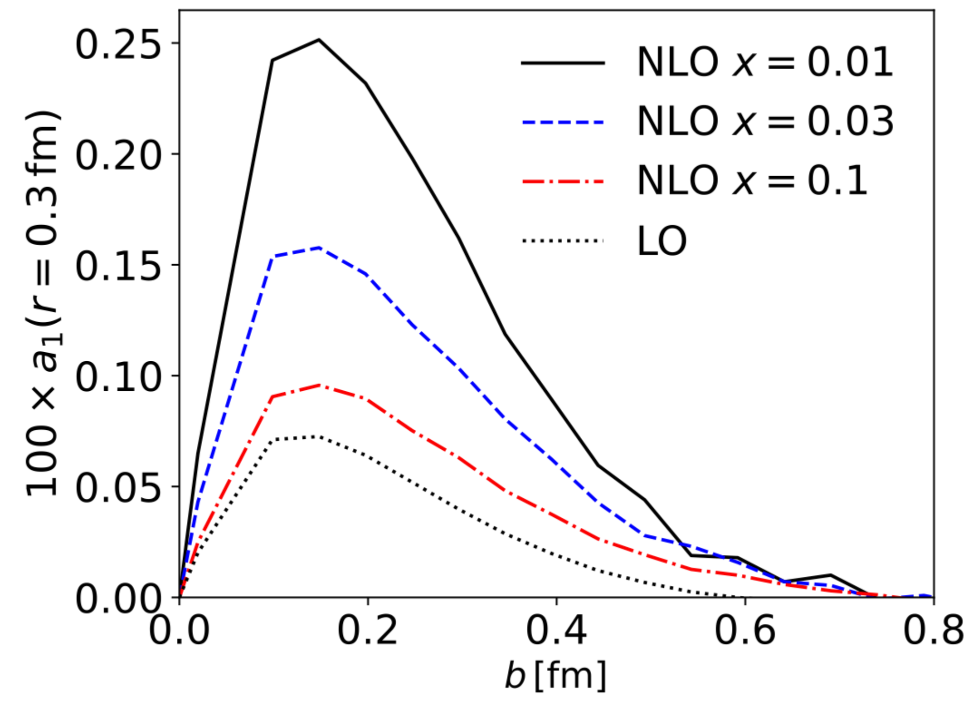
- Perturbative computation of effects of quartic action

  Dumitru, Petreska, *Phys.Rev.D* 84 (2011) 014018

  Giannini, Nara, *Eur.Phys.J.C* 82 (2022) 2, 109

  Dumitru, Petreska, *Nucl.Phys.A* 879 (2012) 59-76

From *PRD* 107, L011501 (2023)



- The Odderon and its effects on collisional systems **Review:** Hatta *et al*, *NPA* 760 (2005) 172-207

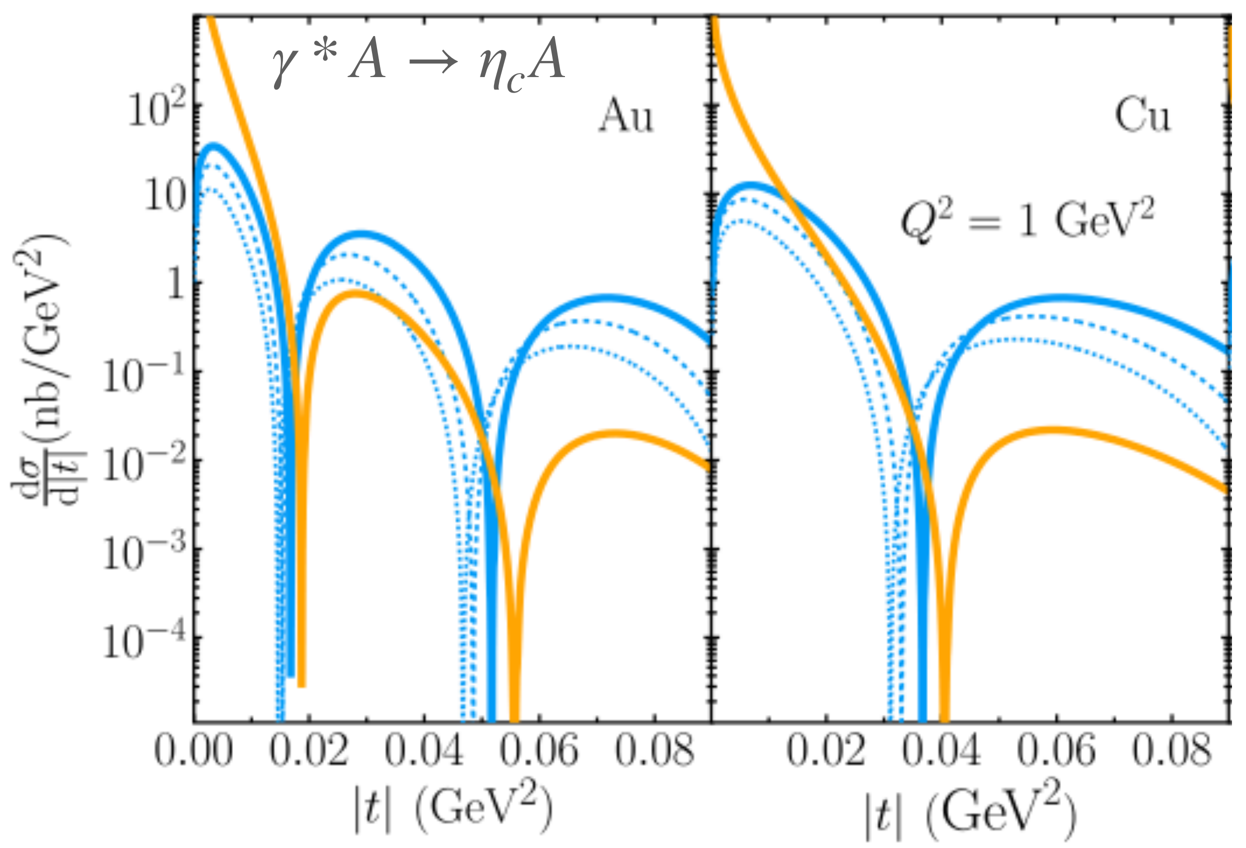
  Dumitru et al, *PRD* 107, L011501 (2023)

  Benic et al. *PRD* 106 (2022) 11, 114025; Benic, Vivoda, *PRD* 110 (2024); Benic *et al*, *PRD* 111 (2025) 9, 094027

  Dumitru, Mäntysaari, Paatelainen, *PRD* 107 (2023) 1, L011501

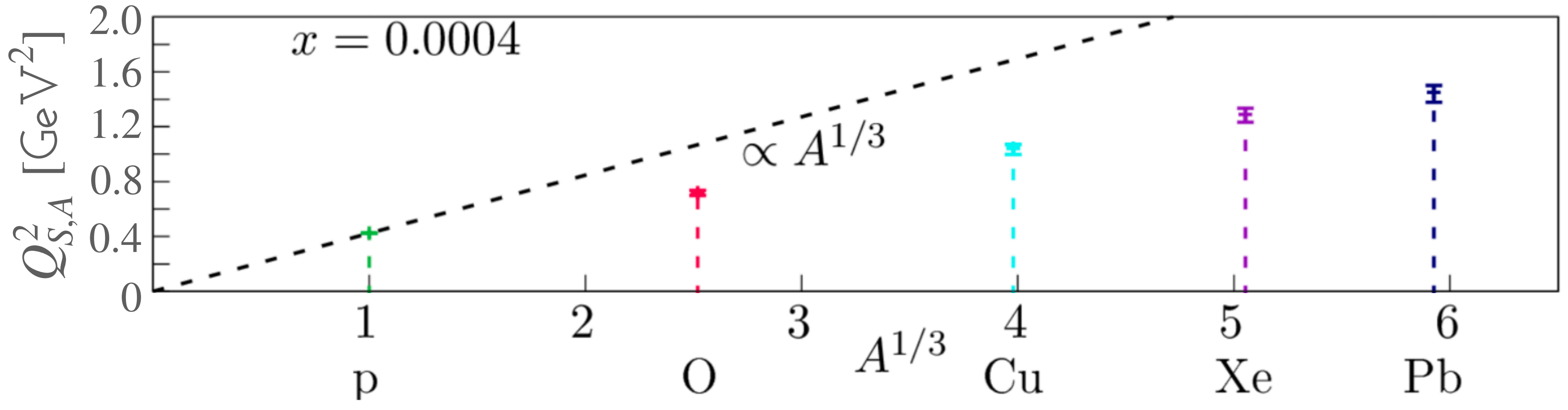
  O.G-M. *Effects of CGC non-gaussianities on baryon stopping*: 2510.XXXX

From *PRD* 106 (2022) 11, 114025



- New method to compute correlations of arbitrary distributions Penttala, 2507.18711

- **Sampling effects?** Deganutti *et al.* *JHEP* 01 (2024) 159



Sampling changes the effective behaviour (A-dependence)

Consequences for μ^2/κ_3, μ^2/κ_4, ... !

WHY SHOULD WE CARE ABOUT THIS?

Energy density set by gluon dist. in the targets.

$$e\tau_0 \sim \frac{Q_A^2 Q_B^2}{(Q_A^2 + Q_B^2)^{5/2}}(2Q_A^4 + 2Q_B^4 + 7Q_A^2 Q_B^2) \qquad \text{with} \qquad Q_A^2 \sim T_A^{2/(2+\lambda)} e^{-2\eta_s/2+\lambda} s^{-\lambda/(2+\lambda)}$$

Energy density set by gluon dist. in the targets.

$$e\tau_0 \sim \frac{Q_A^2 Q_B^2}{(Q_A^2 + Q_B^2)^{5/2}}(2Q_A^4 + 2Q_B^4 + 7Q_A^2 Q_B^2) + \sum_{ij} O((Q_B^2)^{-\alpha_i}(Q_B^2)^{-\beta_j})$$

This becomes important for smaller systems, but also for forward/backward rapidities!

Will be important to understand 3D dynamics and for the proposal of Light**er** ions

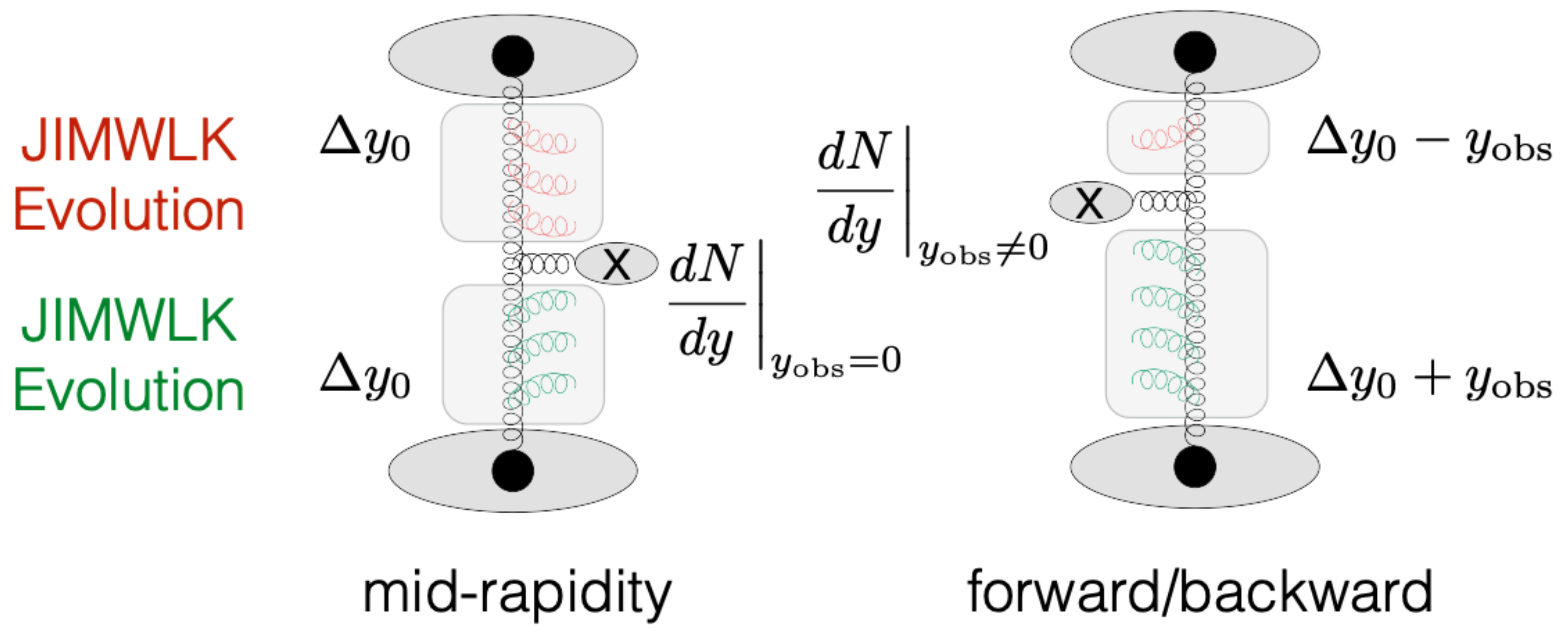
IP-GLASMA IN 3D

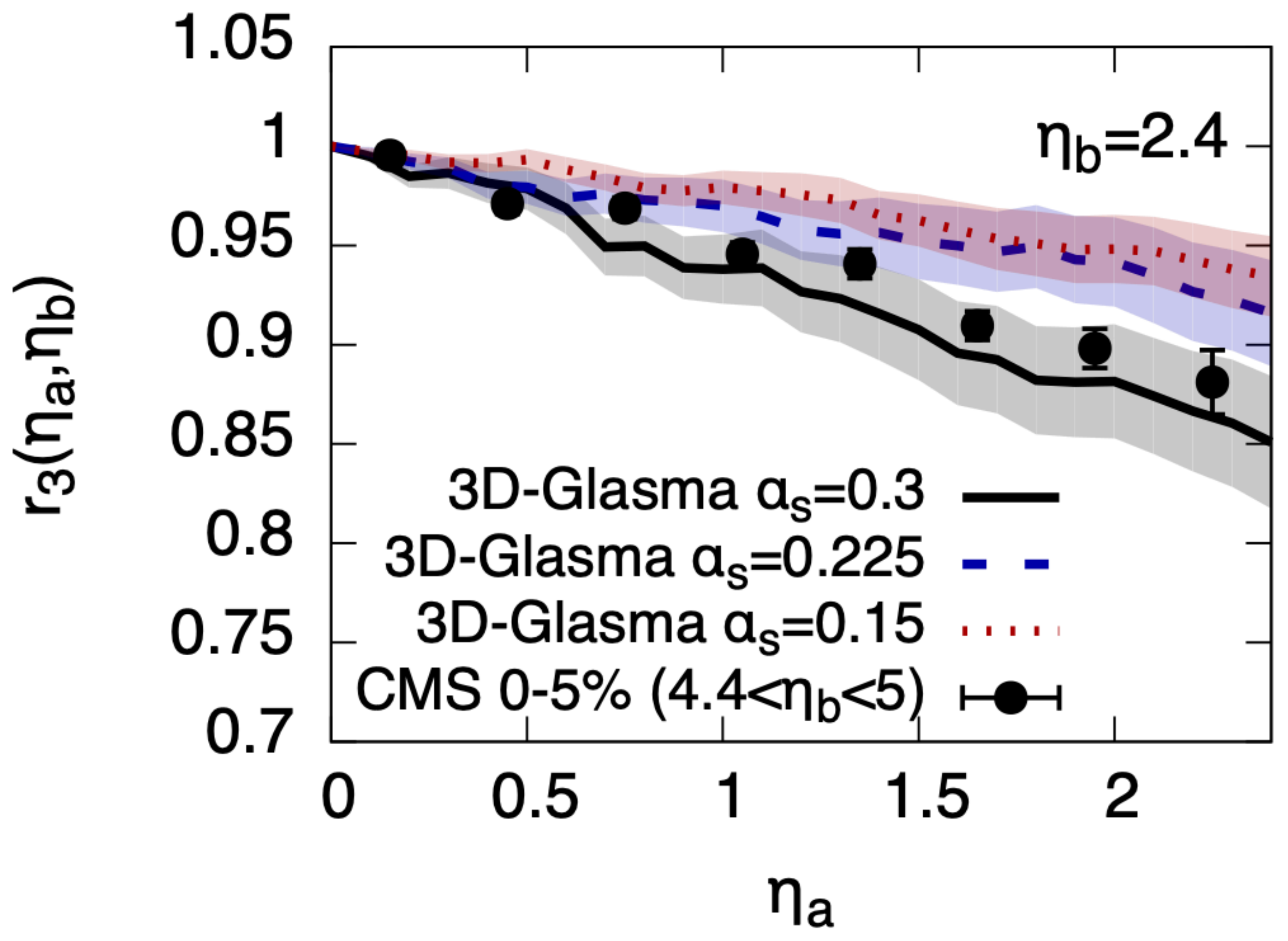
- ✔ Boost of the incoming nuclei, sheets of (JIMWLK) evolved Schenke, Schlichting *PRC* 94 (2016) 4, 044907

  JIMWLK evo. of targets contains quantum corrections for particles emitted at $\Delta y \ll \alpha_S^{-1}$
  Gelis et al, *Phys.Rev.D* 78 (2008) 054019

  A new HICS global analysis based on this method:
  Mäntysaari *et al*, 2508.20432

Add 3D-CYM evolution
[McDonald, Jeon, Gale *PRC* 108 (2023) 6, 064910]





SUMMARY AND CONCLUSIONS

3D is now. Understanding the longitudinal structure of the initial energy deposition is **a *necessity for the studies on small systems***

Many models. We need also a way to discriminate models of the initial stages.

Hydro evolution in Small Systems has to be taken cautiously. Non-equilibrium effects may be more important that we think!

Desirable: Models should establish themselves *conceptually* (if not computationally) consistent throughout wide range of energies and systems.

Further work: refine ICs using other experiments at hand (DIS, forward p+A collisions)

CUT FOR TIME

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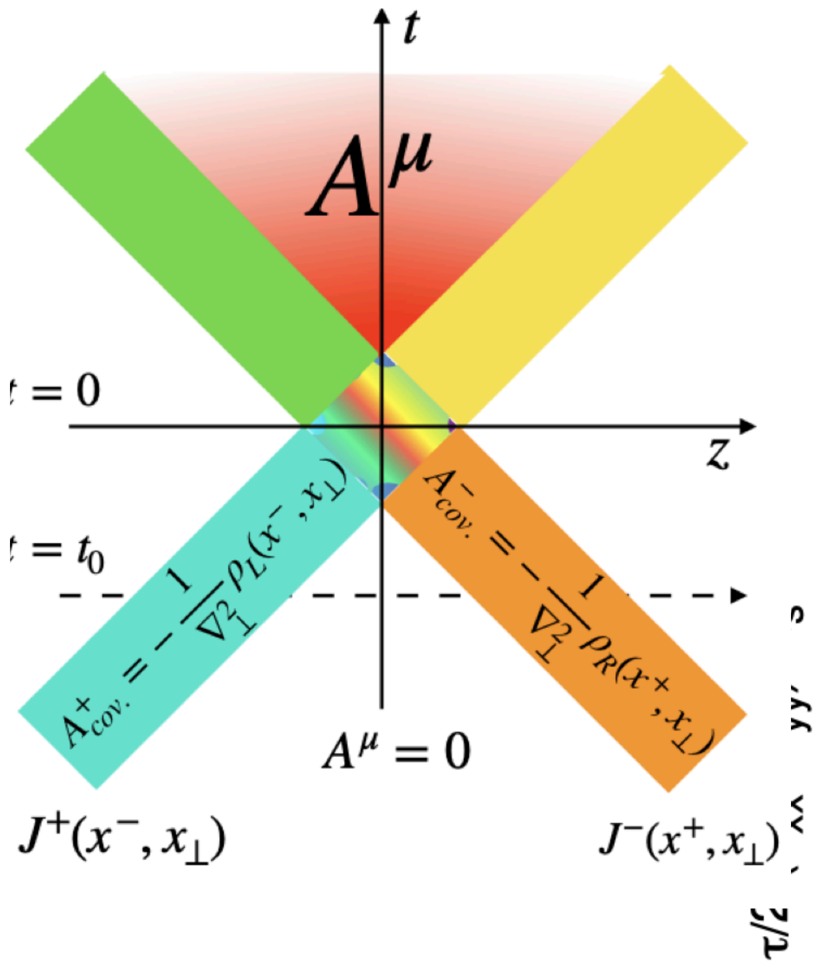
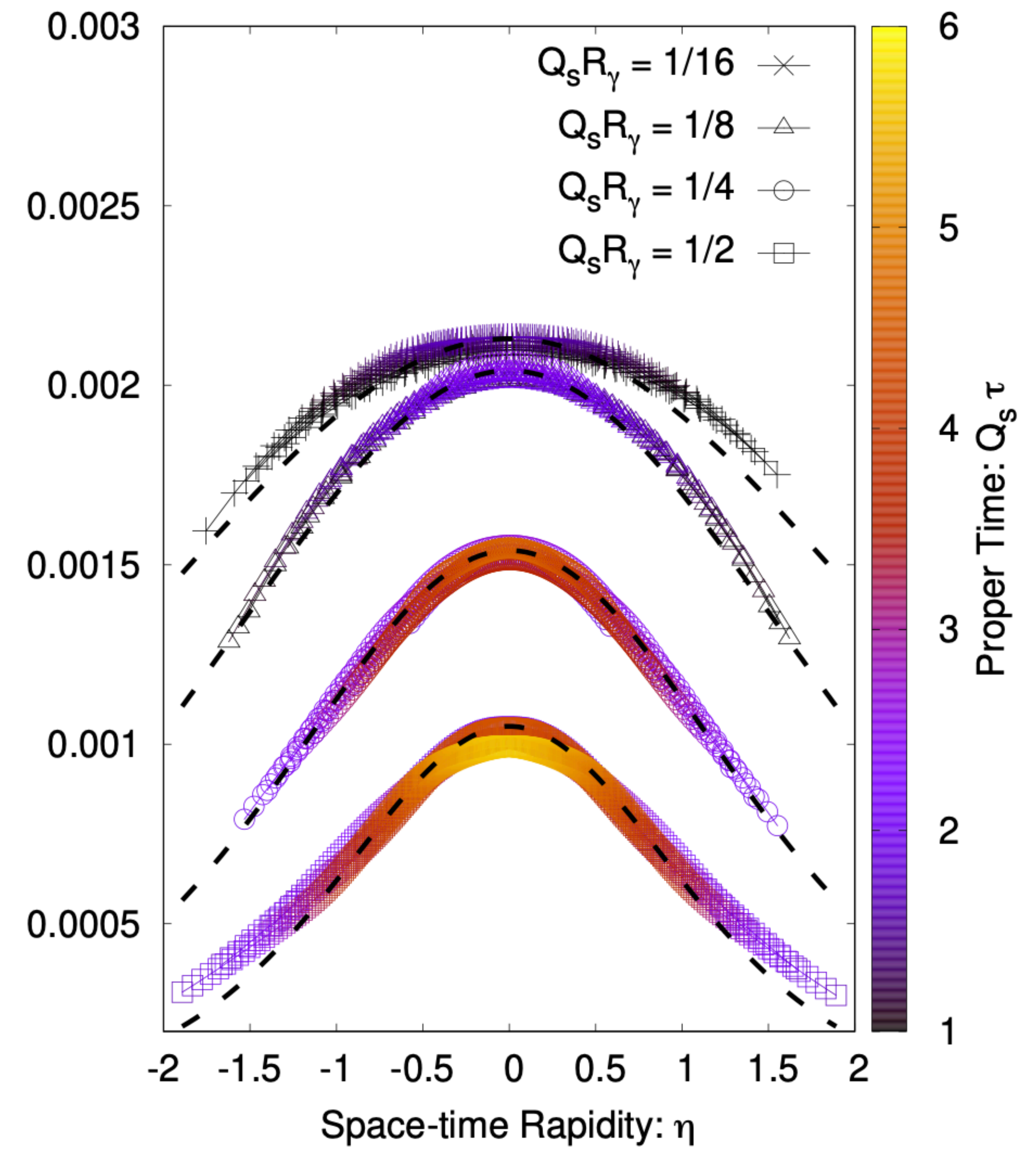




- Take on account the longitudinal extension of the incoming ions.

  [Schlichting, Singh PRD 103 (2021) 1, 014003] *[Schenke, Schlichting, Singh PRD 105 (2022) 9, 094023]*

- **Challenges: [We are still at LO!]** Next quantum corrections (eg. quarks), boost invariance breaking via sub-eikonal corrections, etc.

  $\Longrightarrow$ Still a lot to work on!

METHODS: STATE OF THE ART

DoFs/motivation behind the energy and charge deposition

LARGE-X

Collinear fact.
Described by PDFs

GEOMETRICAL

Effective description
Often parametrical

LOW-X

Overoccupied
Color fields

3D-TRENTO

GEOMETRICAL

[PRC 102 (2020)]

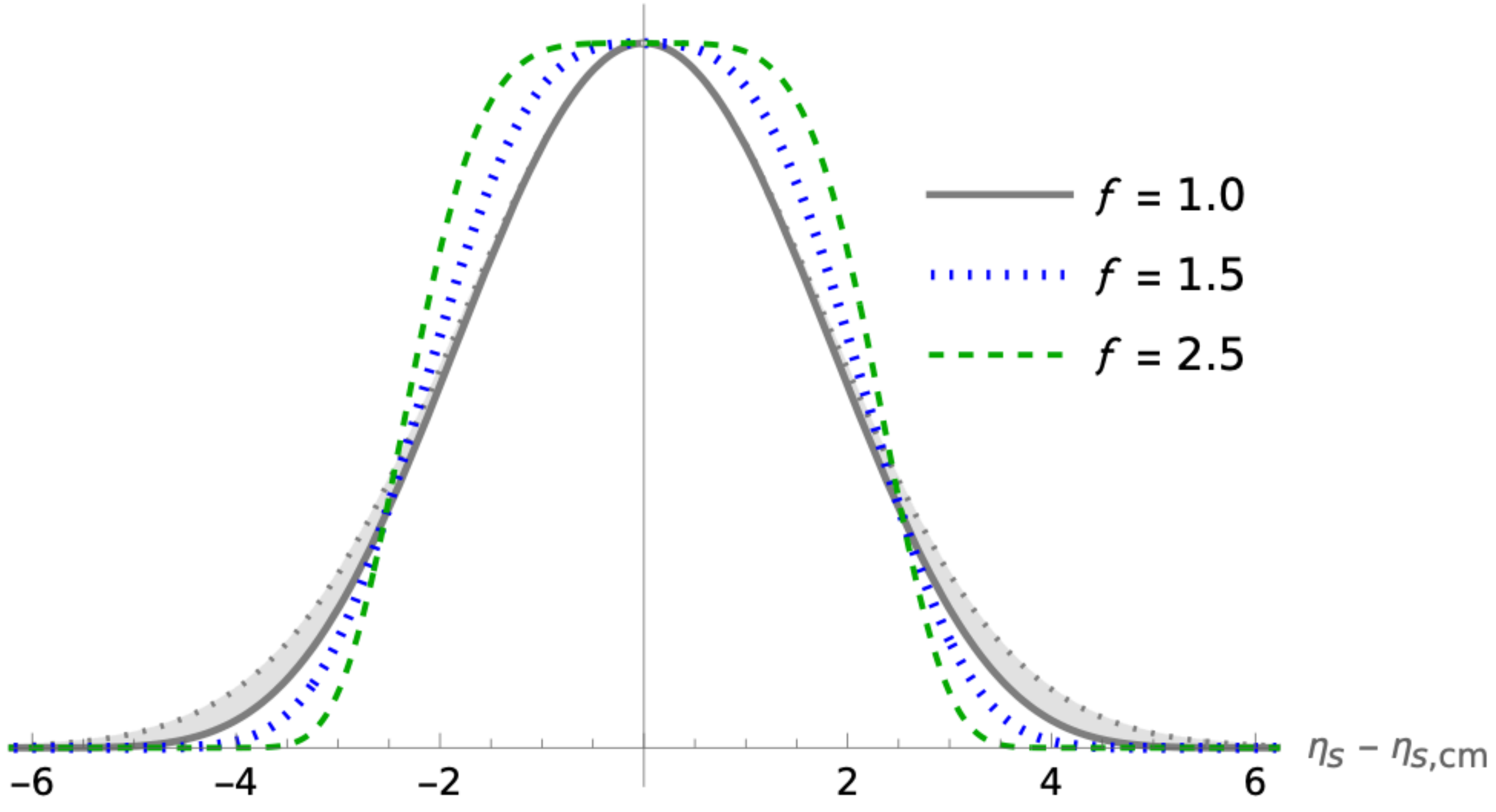
- Parametrical model of energy deposition of the HIC
- Extension to 3D, TRENTo includes a central fireball and forward and backward fragmentation regions.

$$\epsilon(\boldsymbol{x}, \eta) = \epsilon_{\text{fb}}(\boldsymbol{x}, \eta) + \epsilon_{\text{frag},+}(\boldsymbol{x}, \eta) + \epsilon_{\text{frag},-}(\boldsymbol{x}, \eta)$$

- Central fireball is parametrized in rapidity

$$\varepsilon_{\text{fb}}(\vec{x}_\perp, \eta_s) = N_{\text{fb}} \sqrt{T_A(\vec{x}_\perp)\, T_B(\vec{x}_\perp)}\; f_{\text{fb}}(\eta_s - \eta_{s,\text{cm}}(x_\perp)),$$

Plateau-fitting of the fireball



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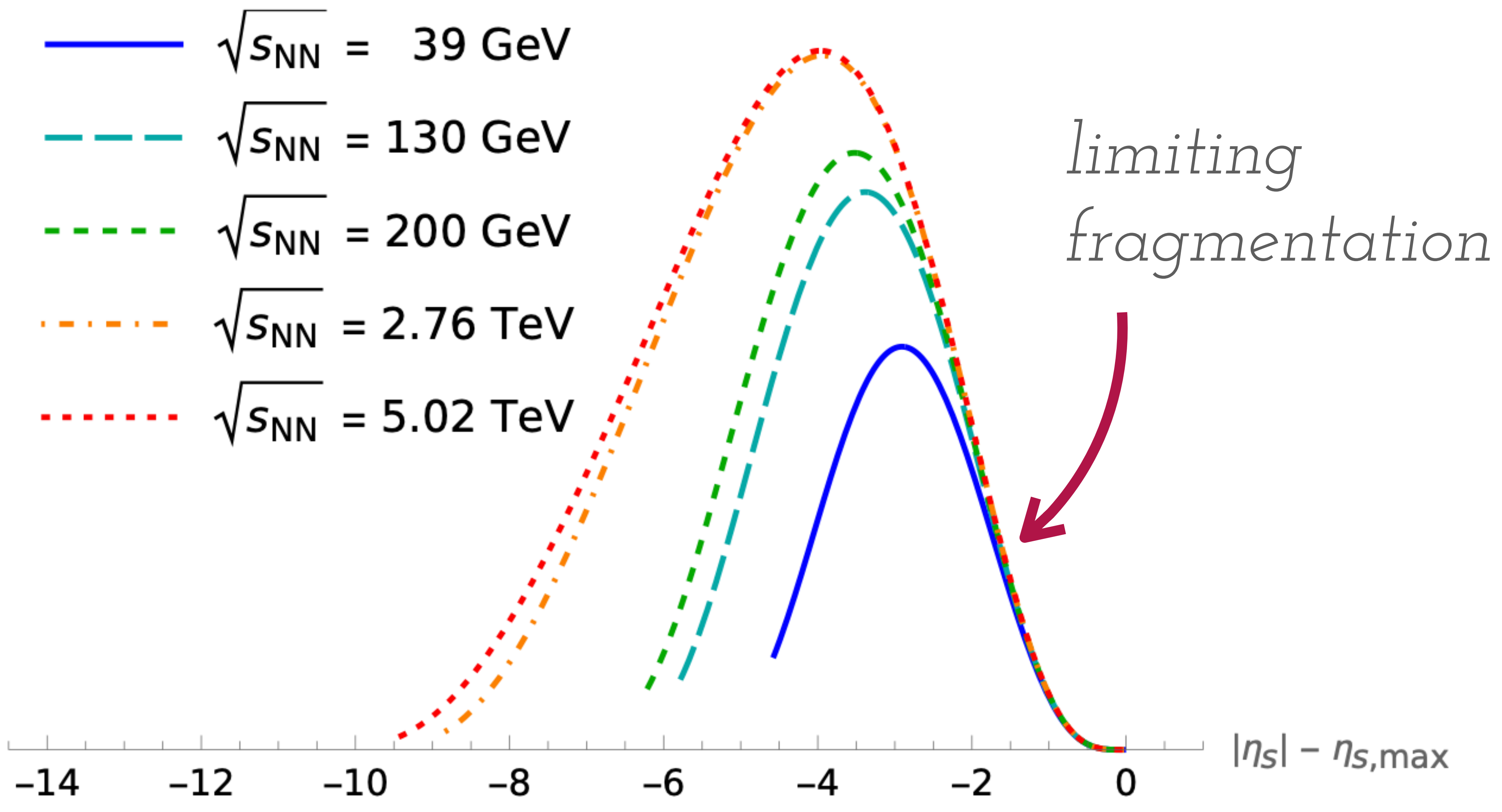
- Fragmentation deposition is constrained by *limiting fragmentation*

$$\varepsilon_{\text{frag},X}(\vec{x}_\perp,\eta_s) = \frac{k_{\text{T,min}}}{N_{\text{frag}}}\,F_X(\vec{x}_\perp)\;f_{\text{frag}}(e^{-\eta_{s,\max}\pm\eta_s}),$$



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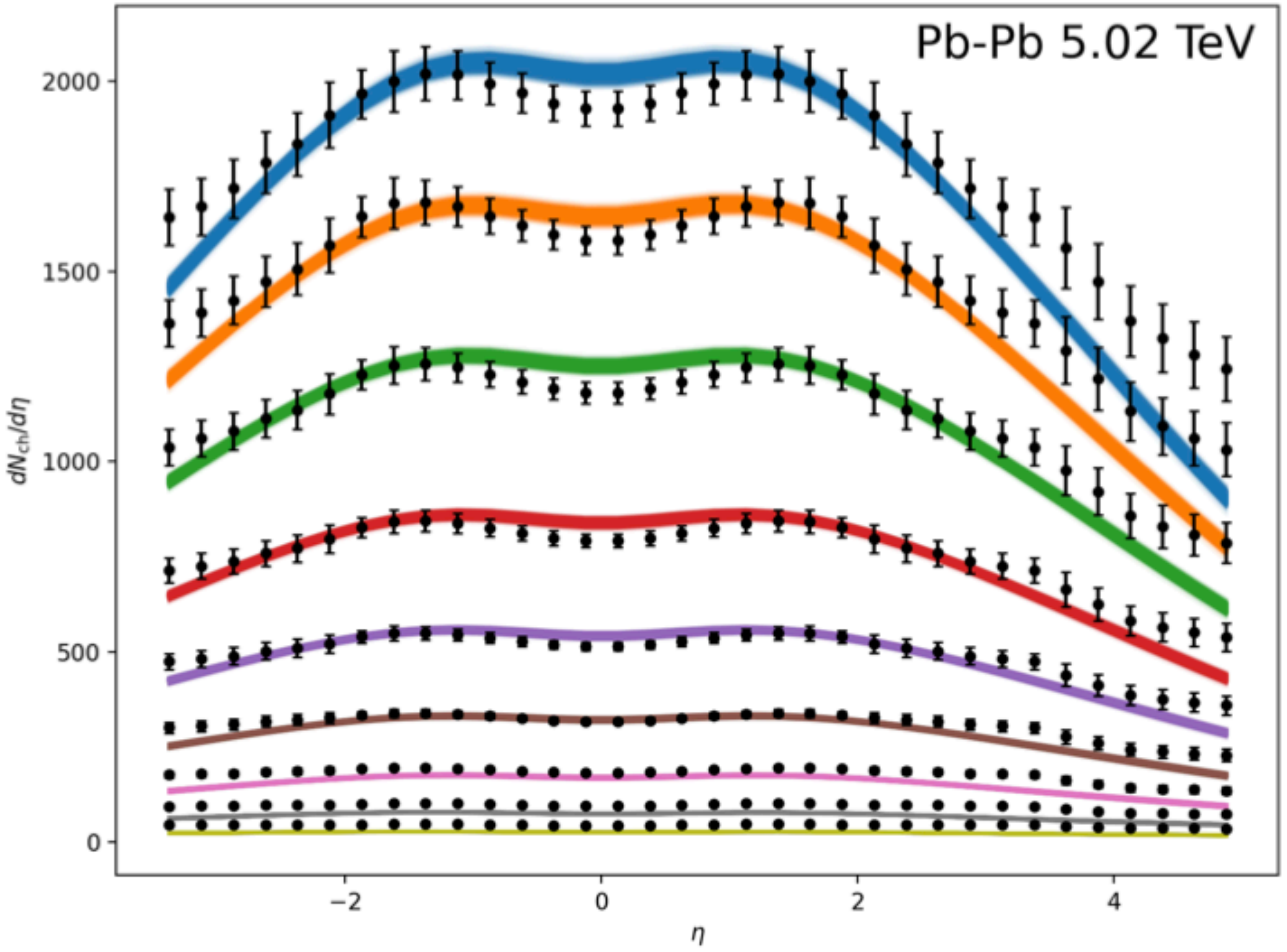


No charge deposition.
Useful for bayesian analysis

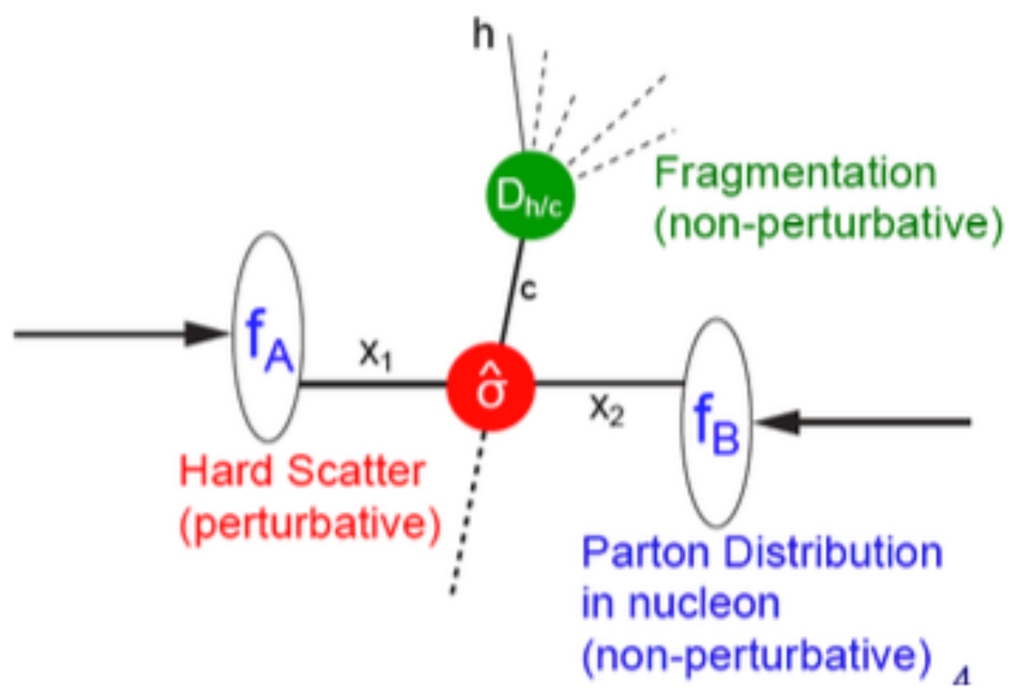
EKRT

LARGE-X

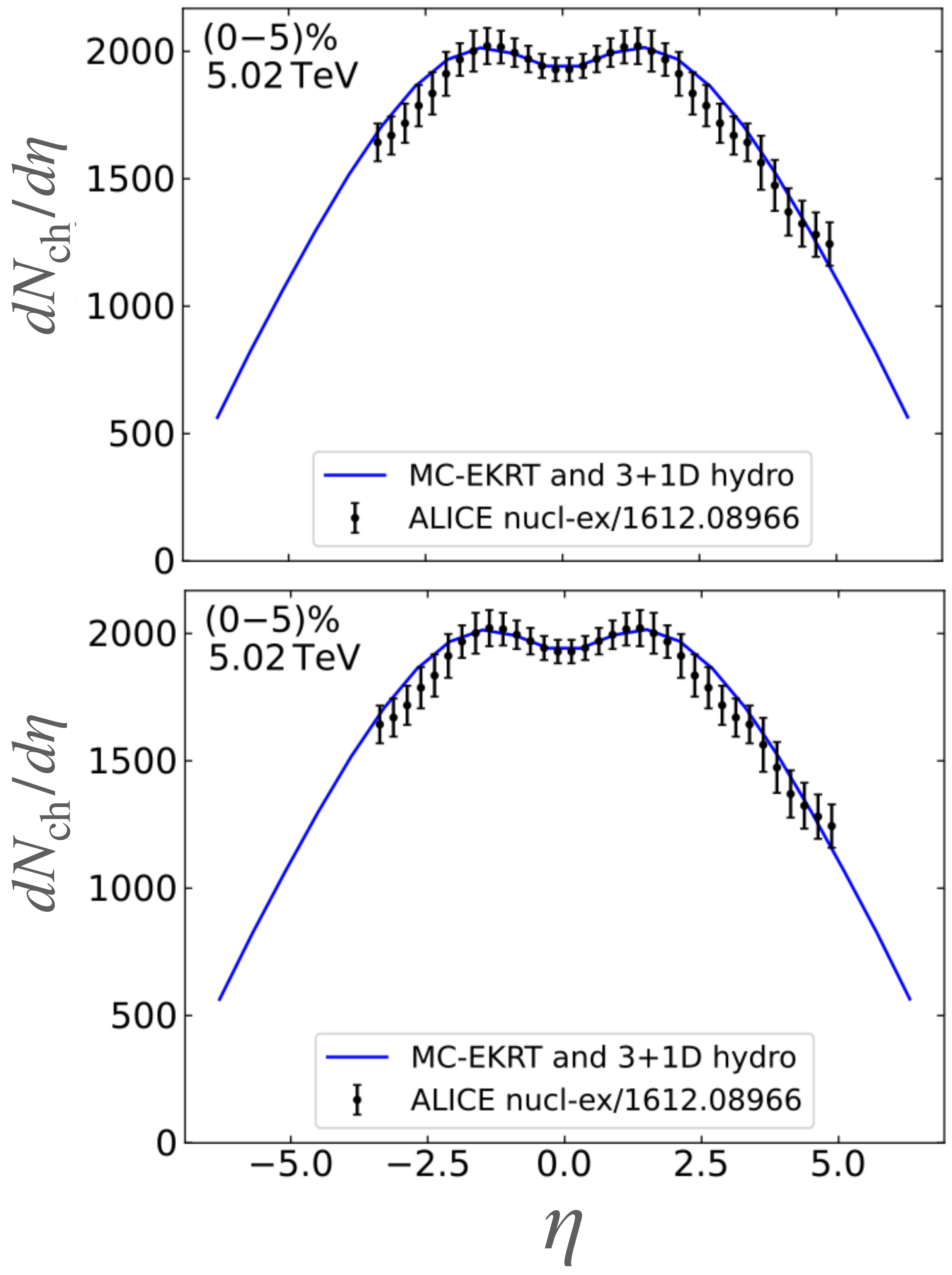
DoFs: collinearly factorized partons

Method of deposition: pQCD minijet production

Low $p_\perp$ control: saturation conjecture: 2-3 processes are equivalent to 2-2 processes at production.



[M. Kuha *et al*, QM, Houston 2023]



INPUT Spatially dependent nPDF

OUTPUT $T^{\mu\nu}$ for hydrodynamical evolution*

METHOD

1) Sample nucleon coordinates for the nuclei A and B.
2) Produce minijets ($p_\perp > p_{\perp,0} = 1$ GeV) with pQCD and collinear factorization from the nucleon-nucleon pair
3) Mini-jets are filtered: mom. Conservation and "saturation"
4) Feed the remaining minijets to hydro at proper time $\tau_0 = 1/p_{\perp,0}$ with Gaussian smearing in the transverse coordi- nates and spacetime rapidity.

[Paatelainen *et al*, Phys. Lett. B 731, 126 (2014)] [Eskola *et al* Eur. Phys. J. C 82, 413 (2022)]

WHY DOES ALL OF THIS MATTER FOR THE PHENOMENOLOGY?

CHALLENGES IN ICs-HICS

- Initial condition: $\sqrt{s_{NN}}$ dependence and longitudinal structure
- B,Q,S Charge deposition and the search for the CP
- From medium to small systems
- Better quantification of ICs for large systems
- Initial condition for hard probes

CORE QUESTIONS IN γA REACTIONS*

A How are quarks and gluons, and their spins, **distributed in space and momentum** inside the nucleon?

B How do **color charges**, (and jets) interact with a **nuclear medium**?

C Does gluon density **saturate at high energies in nuclei**? Is this a universal property in all nuclei, even the **proton**?

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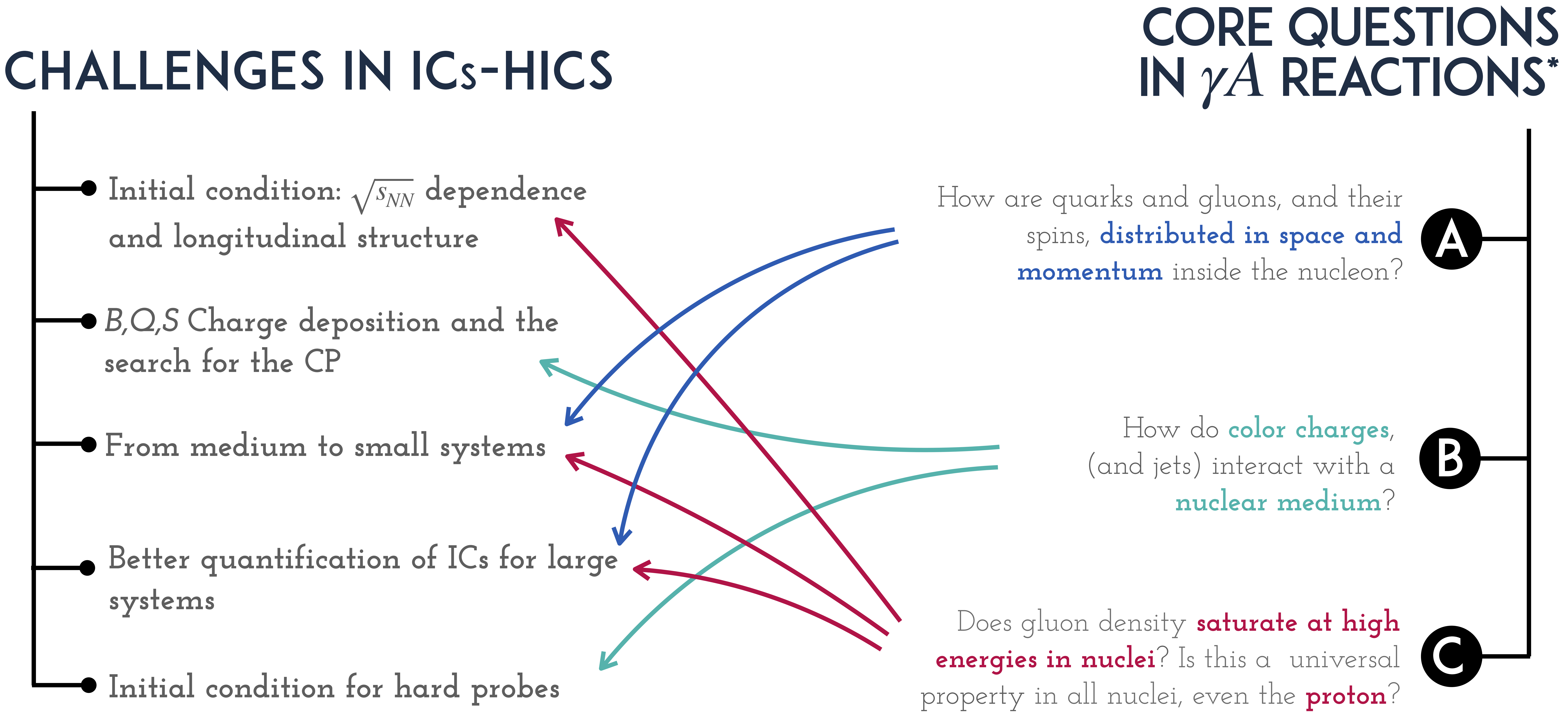
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C

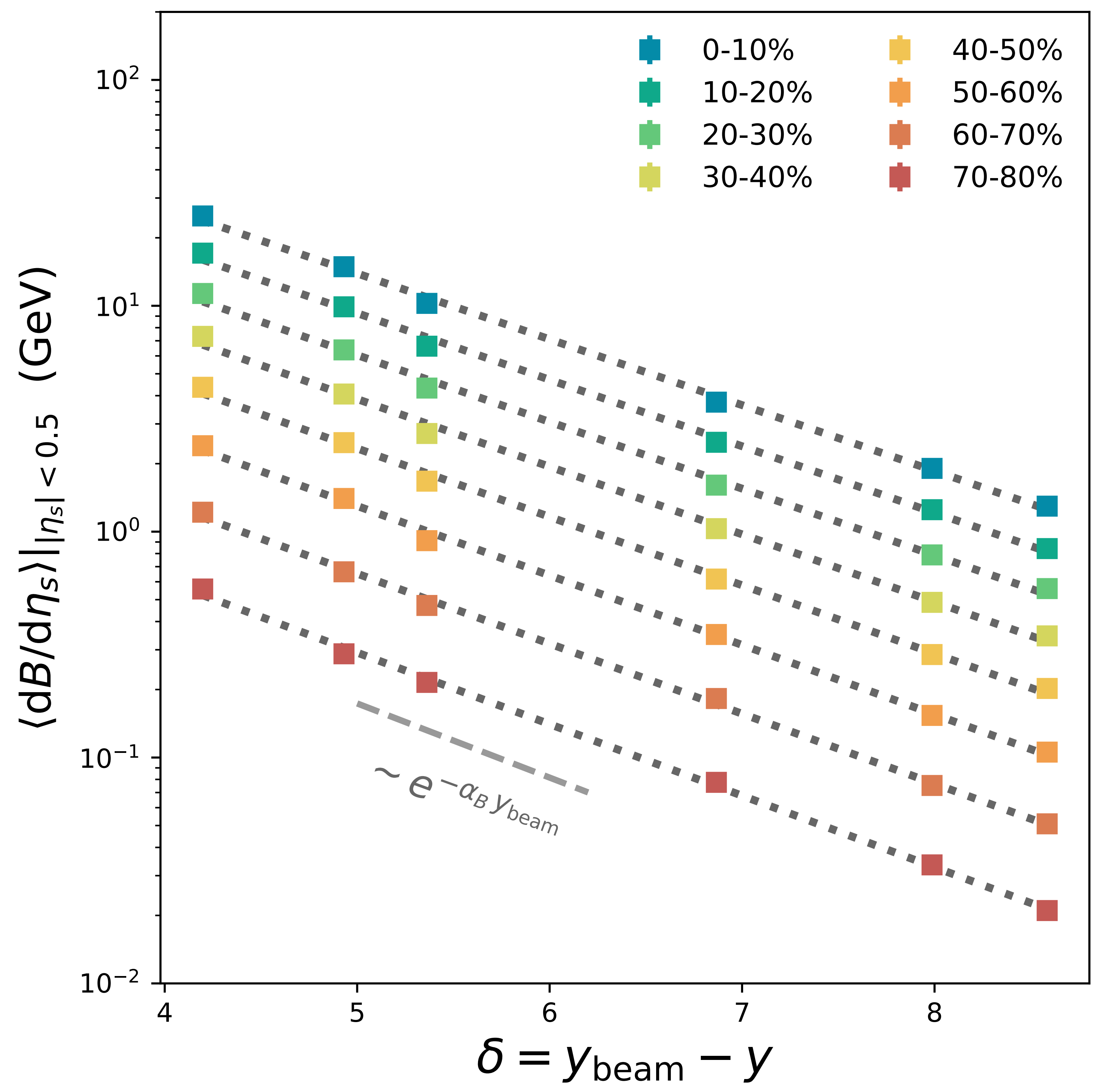
CHARGE DEPOSITION

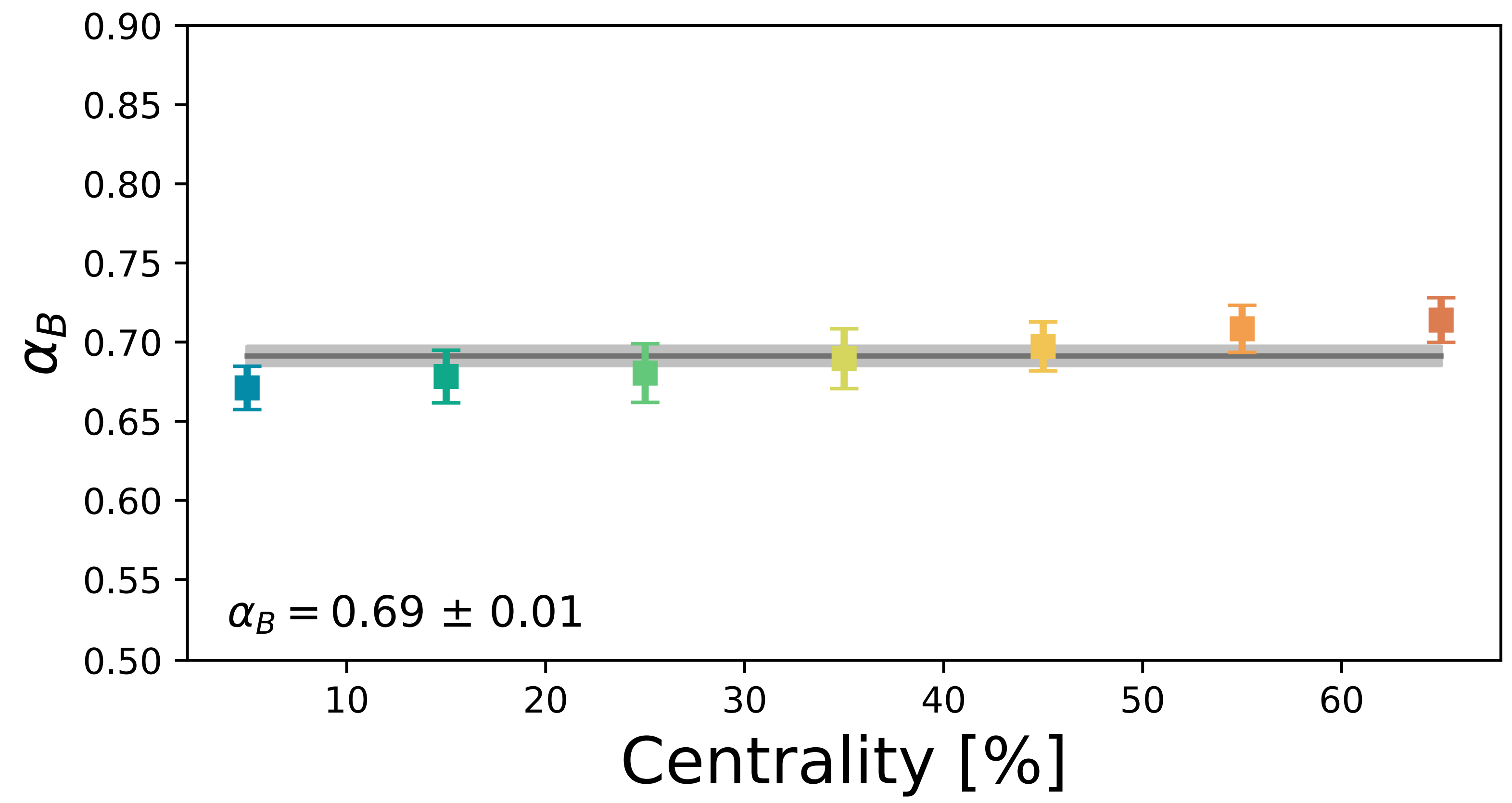
- Non-trivial interaction between x-dependence of gluon uGDs and quark PDFs gives tails in the charge deposition

- Even at higher rapidities, non-zero baryon stopping is found!

- Midrapidity baryon charge deposition follows an exponential shift in the rapidity shift

$$\left.\frac{\mathrm{dB}}{\mathrm{d}\eta}\right|_{\eta=0} \sim e^{-\alpha_B y_{\mathrm{beam}}} \quad \text{with} \quad y_{\mathrm{beam}} \approx \frac{1}{2}\log\left[\frac{\sqrt{s_{\mathrm{NN}}}}{m_N}\right]$$

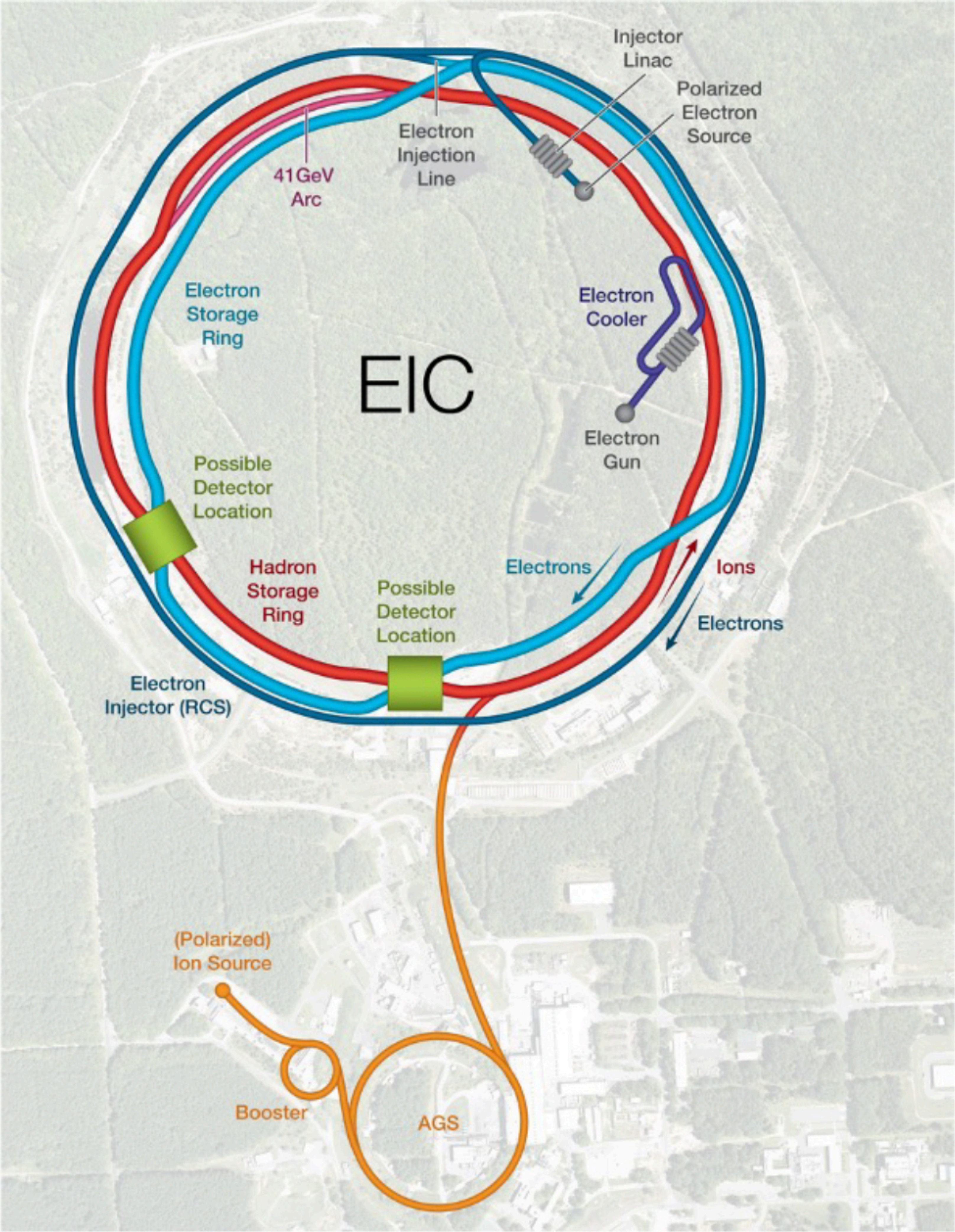




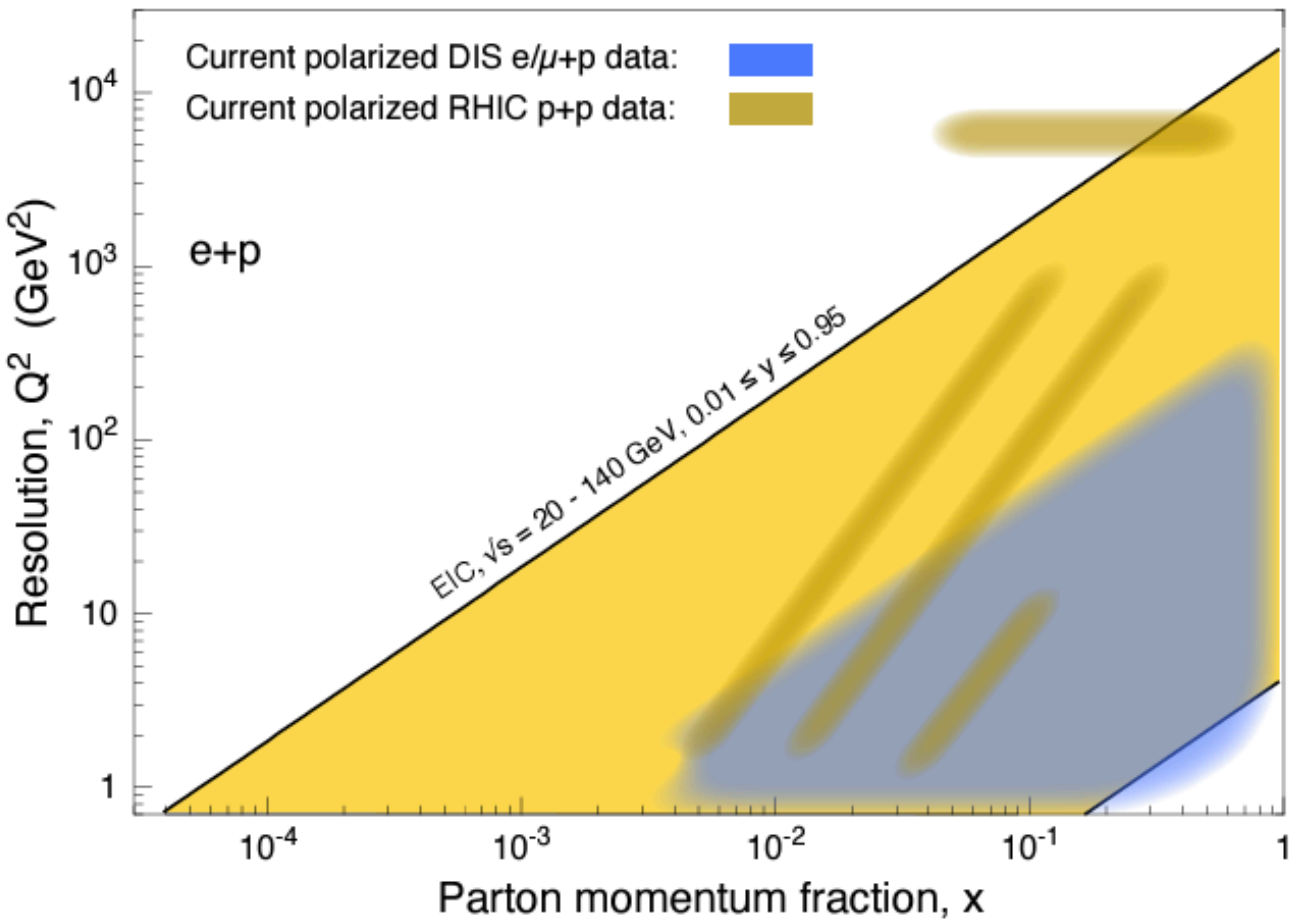
We should strive to use IC models in HICs that can model and describe simultaneously collisions for smaller systems (e+A, p+A).

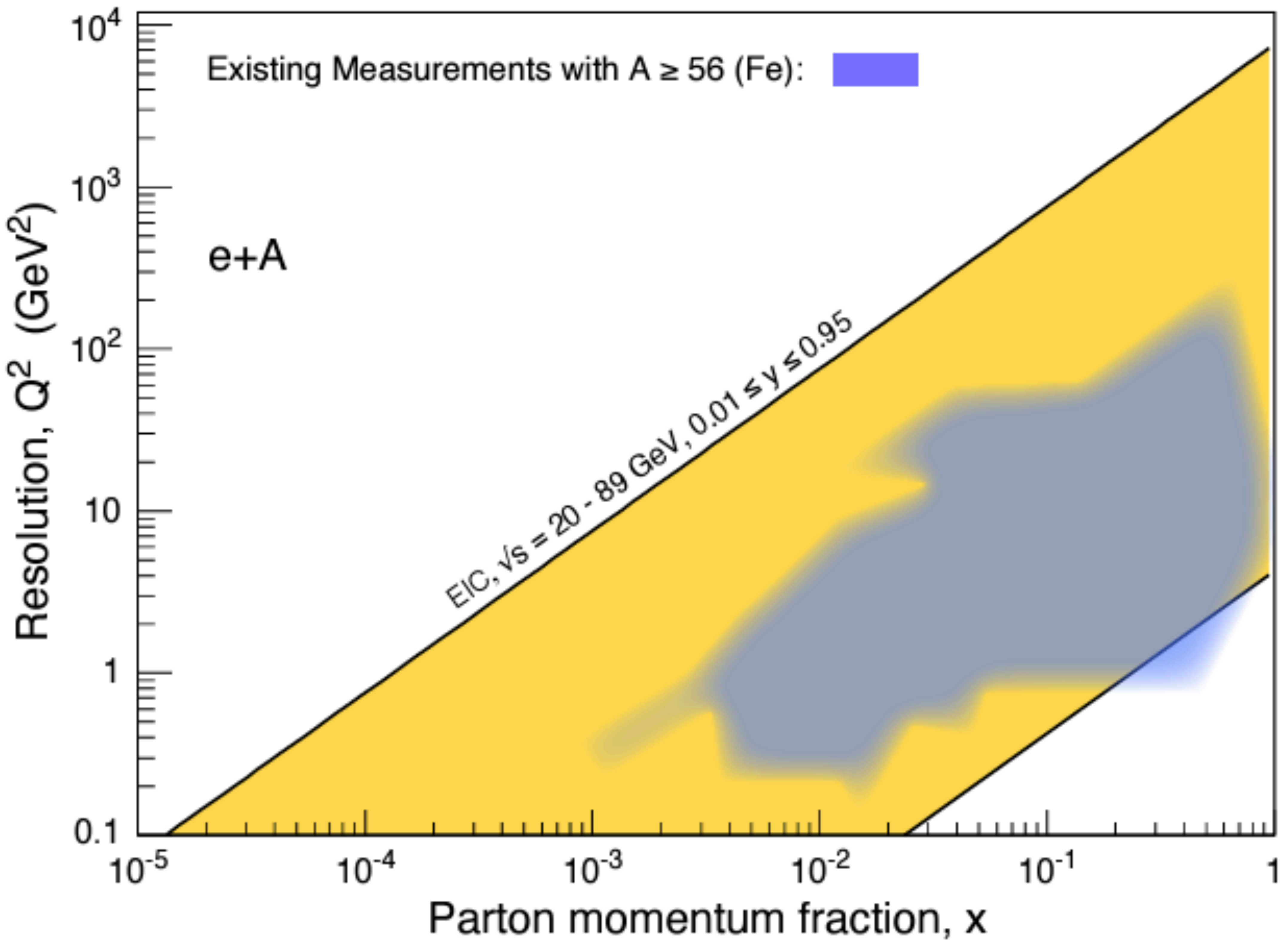
Consistency is key.

THE ELECTRON-ION COLLIDER



TESTING SATURATION MODELS





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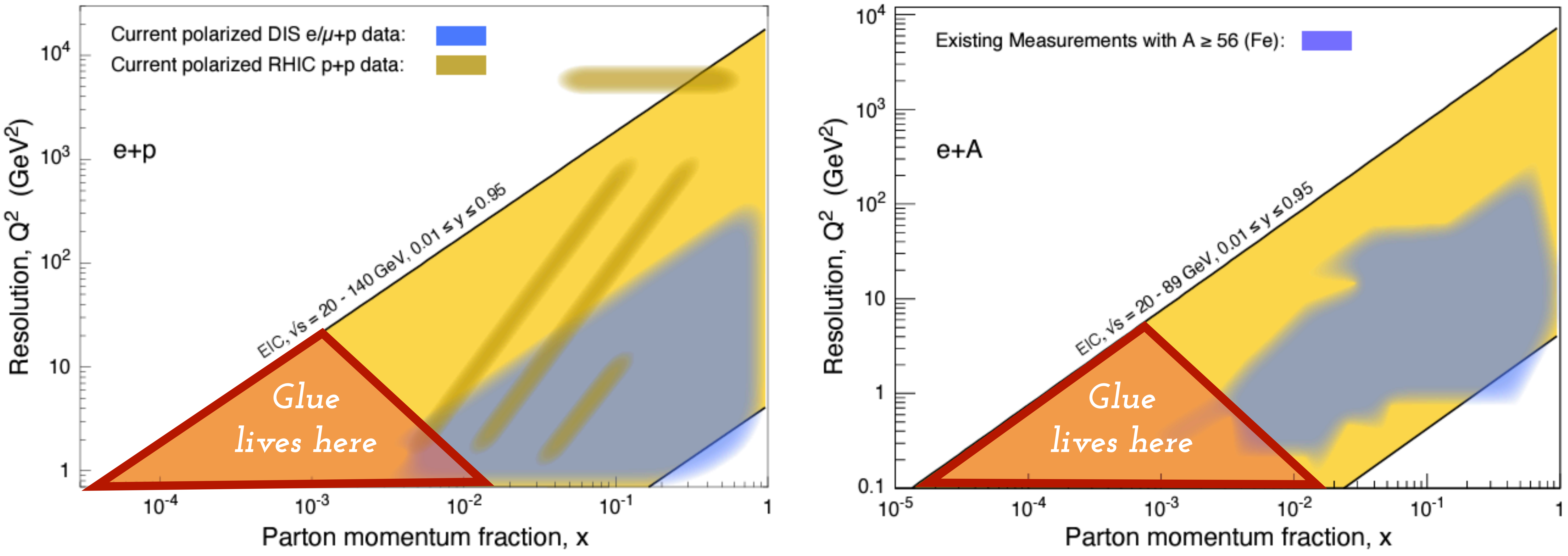

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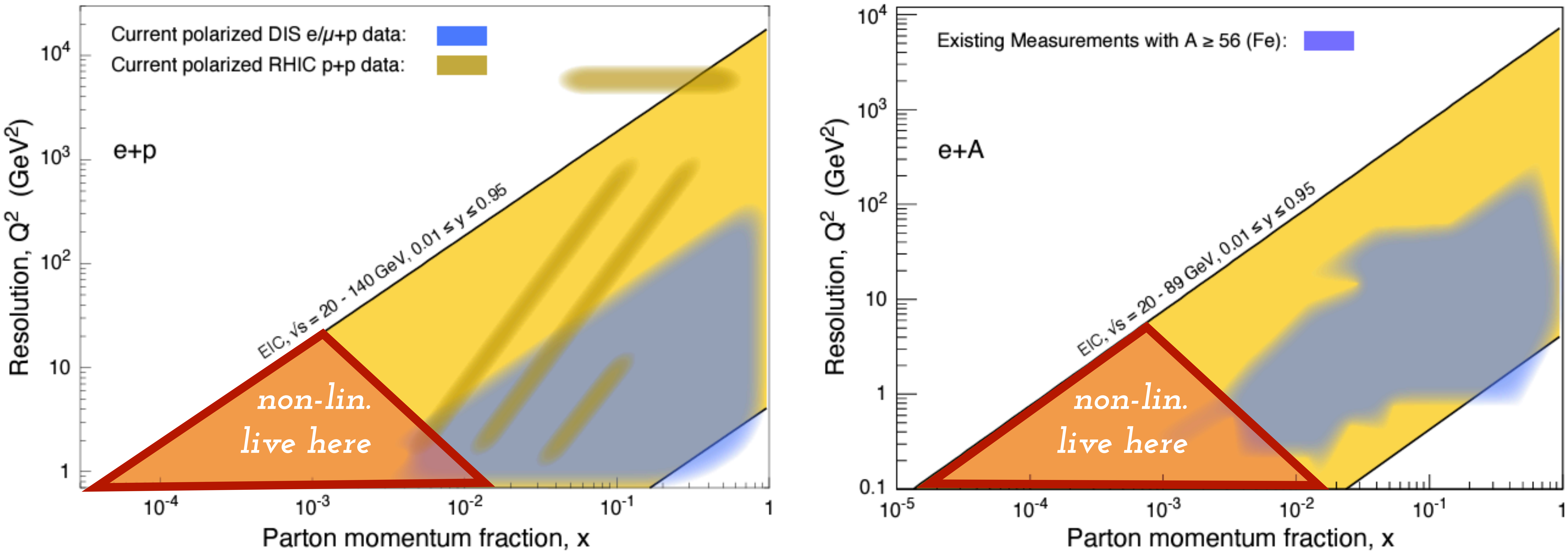


TESTING SATURATION MODELS

A DIPOLE STORY

- Inclusive DIS cross-section:

$$\sigma_{T,L}^{\gamma^* A} = \sum_f \int \mathrm{d}^2\mathbf{b}\mathrm{d}^2\mathbf{r}\mathrm{d}z \left|\psi_{T,L}^{\gamma^*\to q\bar{q}}(\mathbf{r}, z, Q^2)\right|^2 N(\mathbf{b}, \mathbf{r}, x)$$

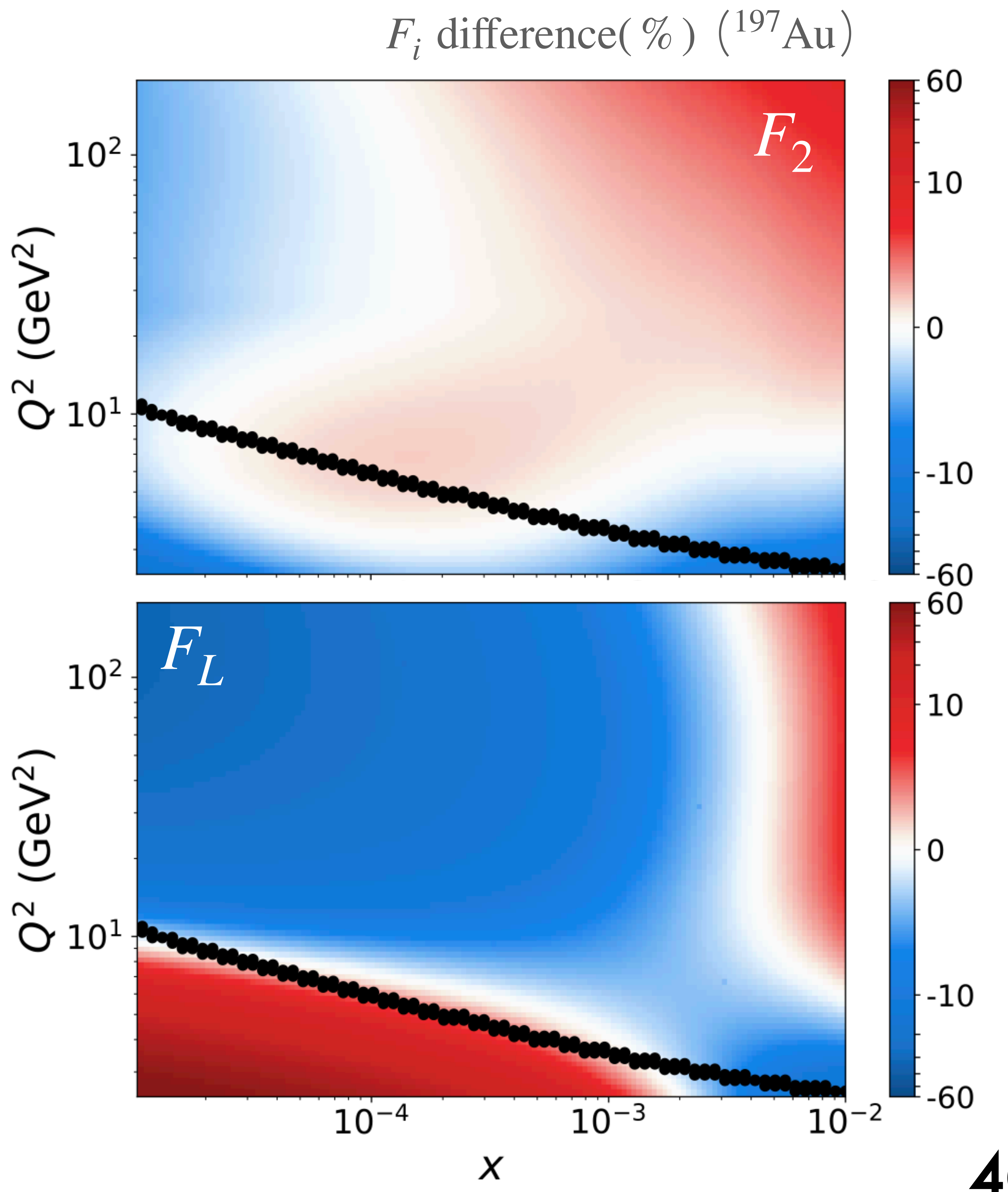
- Can be expressed as a function of structure functions, e.g.

$$e^2 F_2(x, Q) = Q^2 \left(\sigma_T^{\gamma^* A} + \sigma_L^{\gamma^* A}\right)$$

$$e^2 F_L(x, Q) = Q^2 \sigma_L^{\gamma^* A}$$

- Compare linear DGLAP and non-linear BK effects in $F_{2,L}$

How? Expanding $N(\mathbf{b}, \mathbf{r}, x)$ and matching



[Phys.Rev.D 105 (2022) 11, 114017]

HADRON CORRELATIONS

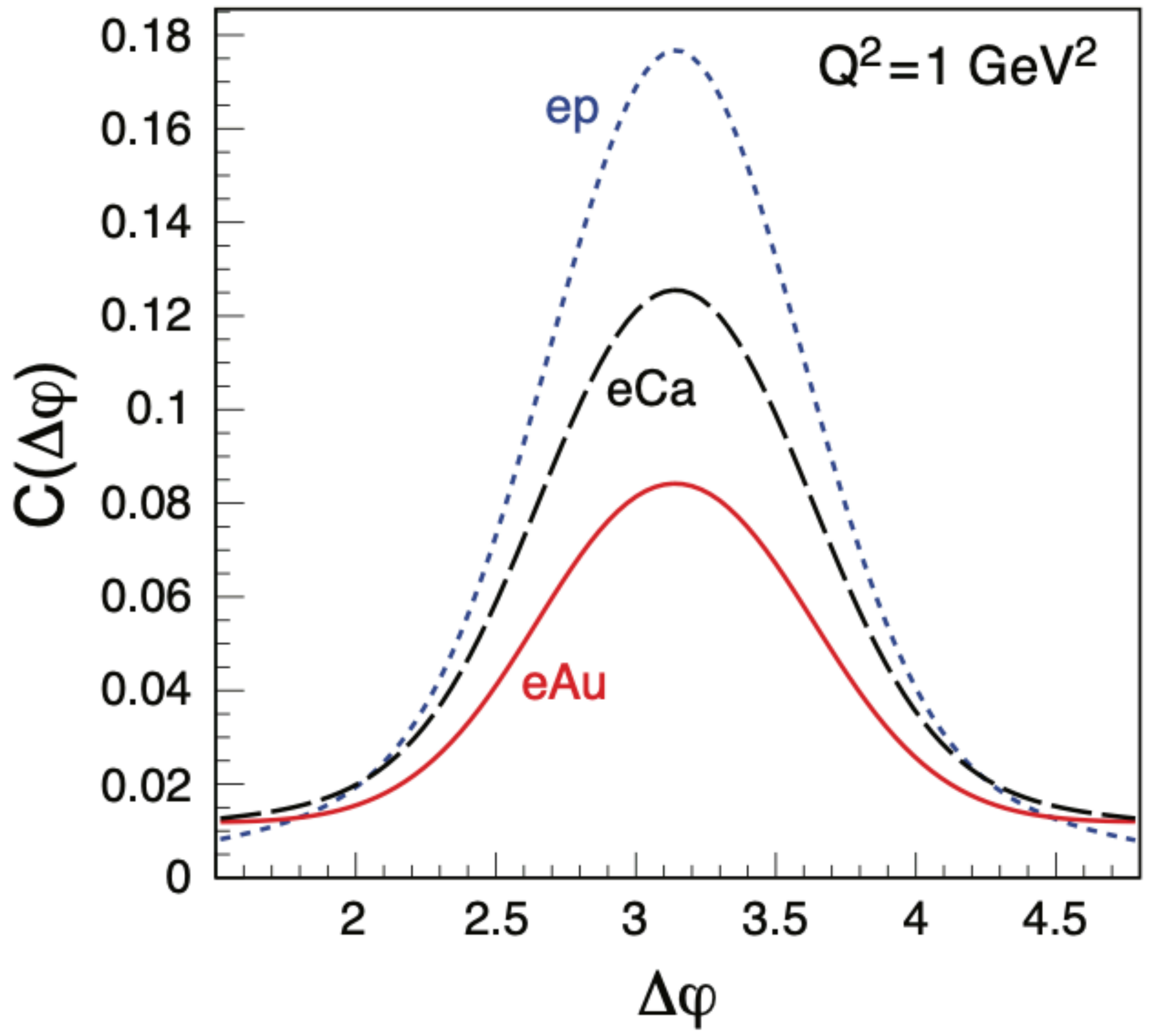
- The semi-inclusive channel $e + A \to h_1 + h_2 + e' + X$ is quite sensitive

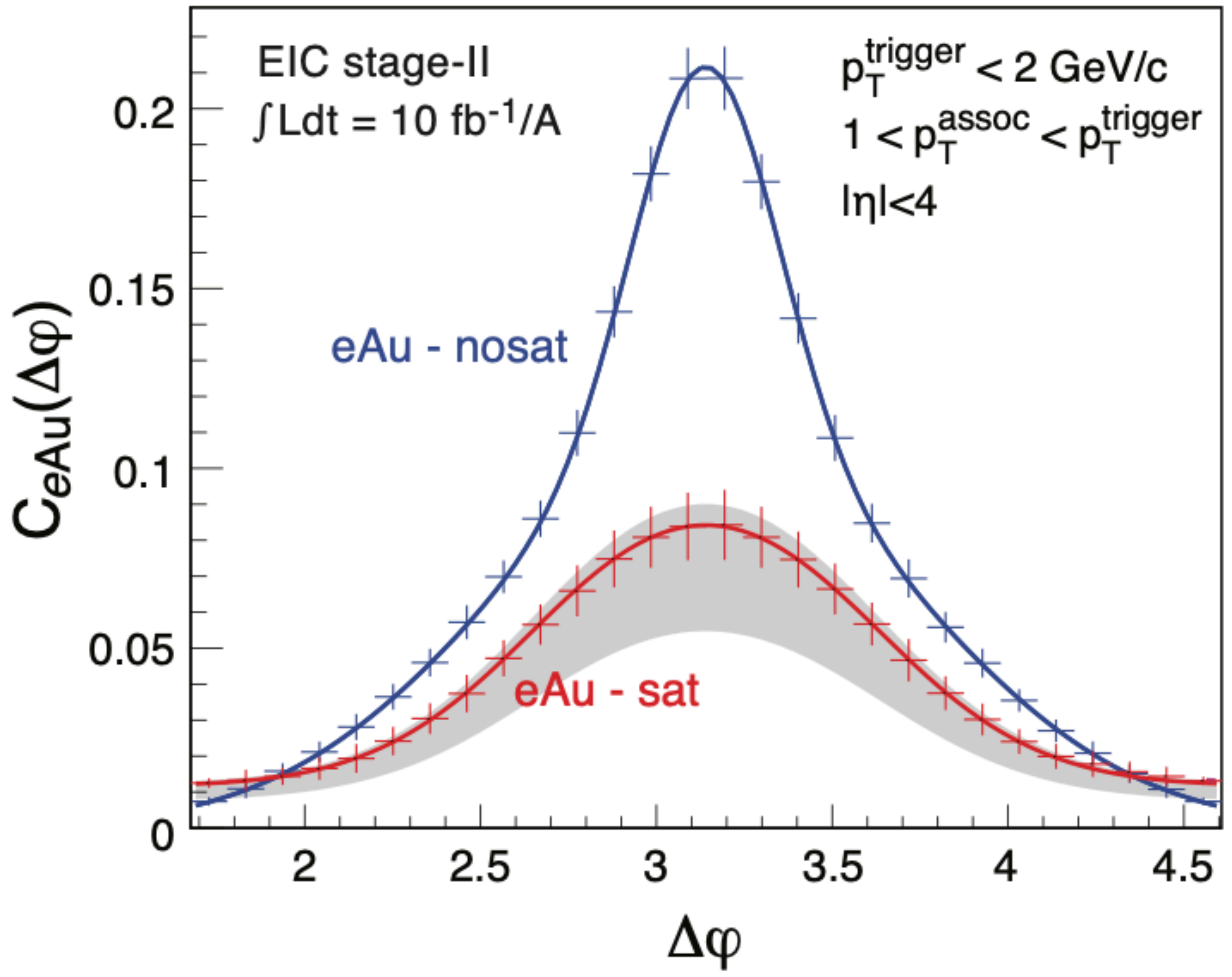
- Multiple scatterings with the soft gluons within the target serve to broaden the back-to-back peak for outgoing particles
  - ↳ When the relative momentum $q_\perp \sim Q_s$, interacting $q\bar{q}$ feels maximally the saturated glue.

- Also, photon-hadron/photon jet should be sensitive to **saturation effects**.

- Progress towards NLO: [Caucal et al, arXiv:2405.19404]

[Phys.Lett.B 682 (2009) 207-211]

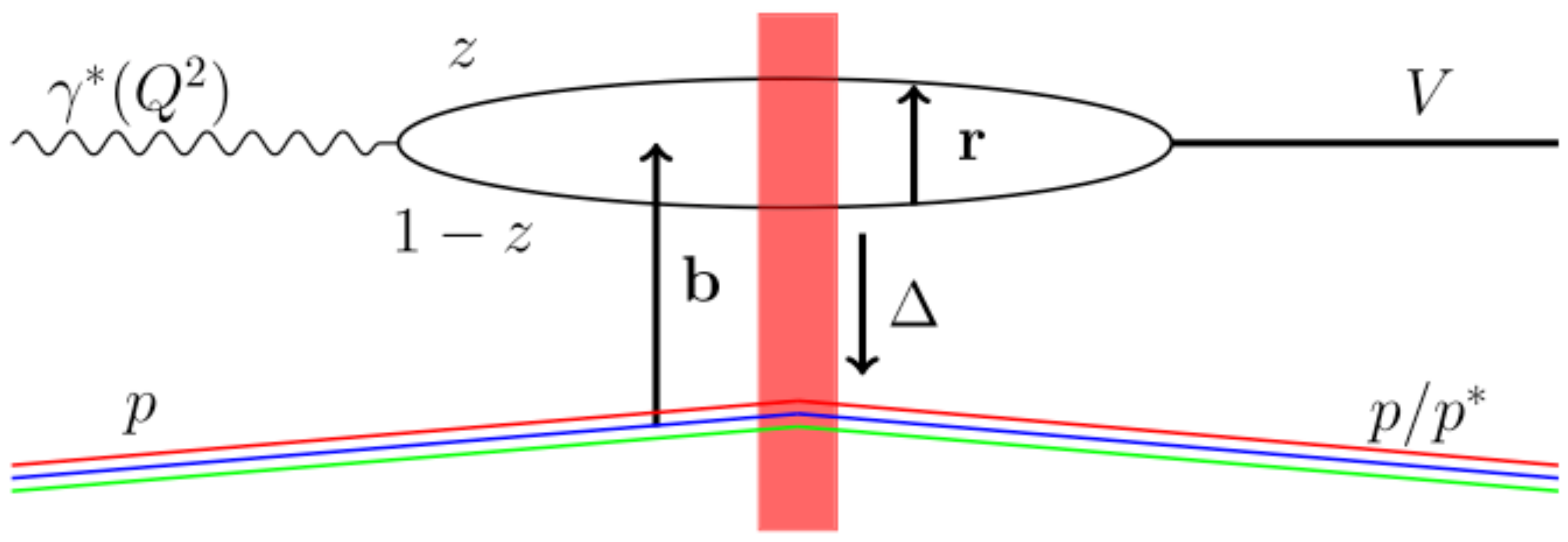




VECTOR MESON PRODUCTION

Coherent:
Fully diffractive
$e + A \rightarrow e + A + J/\psi$

Incoherent:
Breaks up the nucleus.
$e + A \rightarrow e + (A' + X) + J/\psi$



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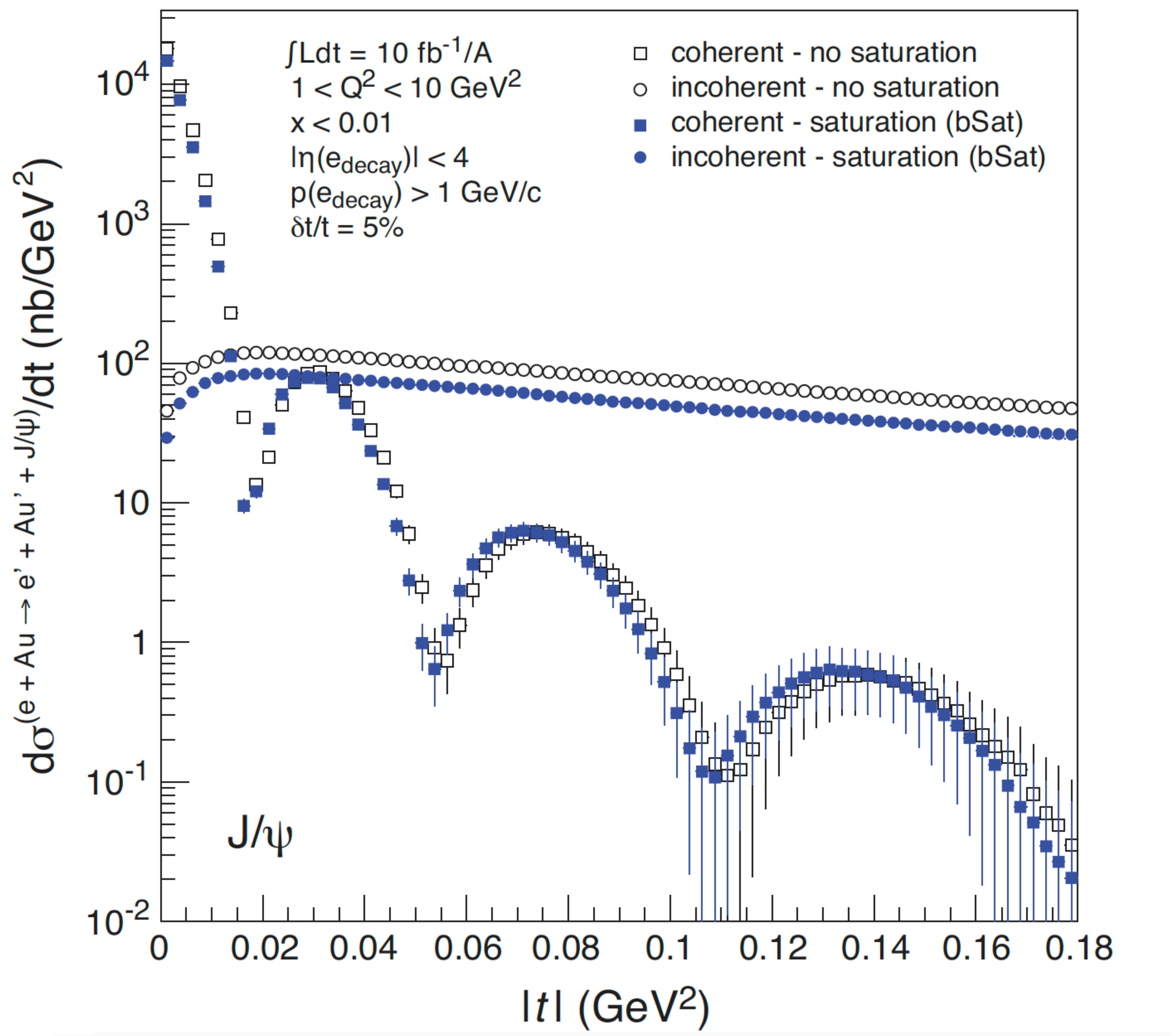
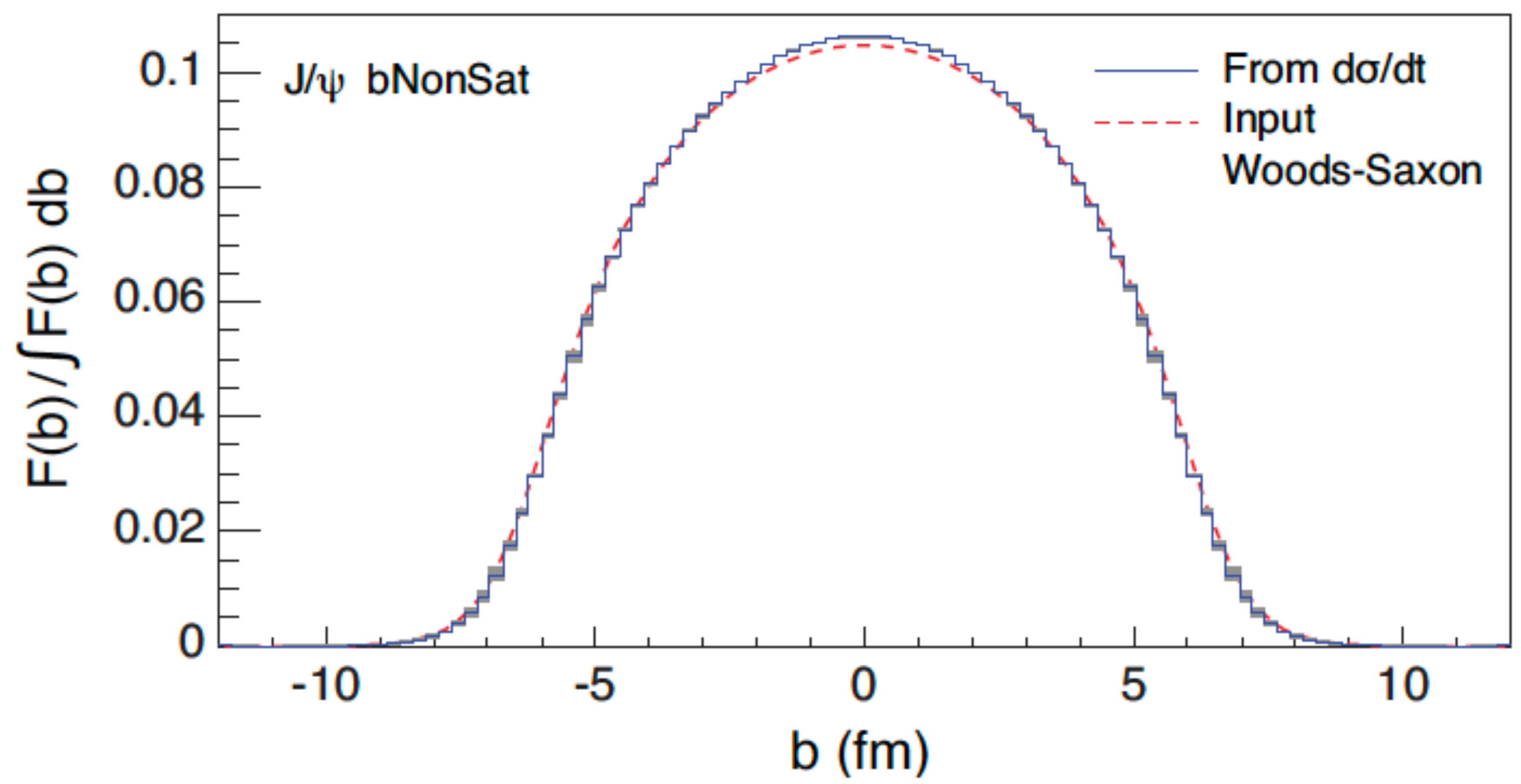
Coherent: Sensitive to average geometry

Diffractive peaks → details of target, non-linearities, etc.





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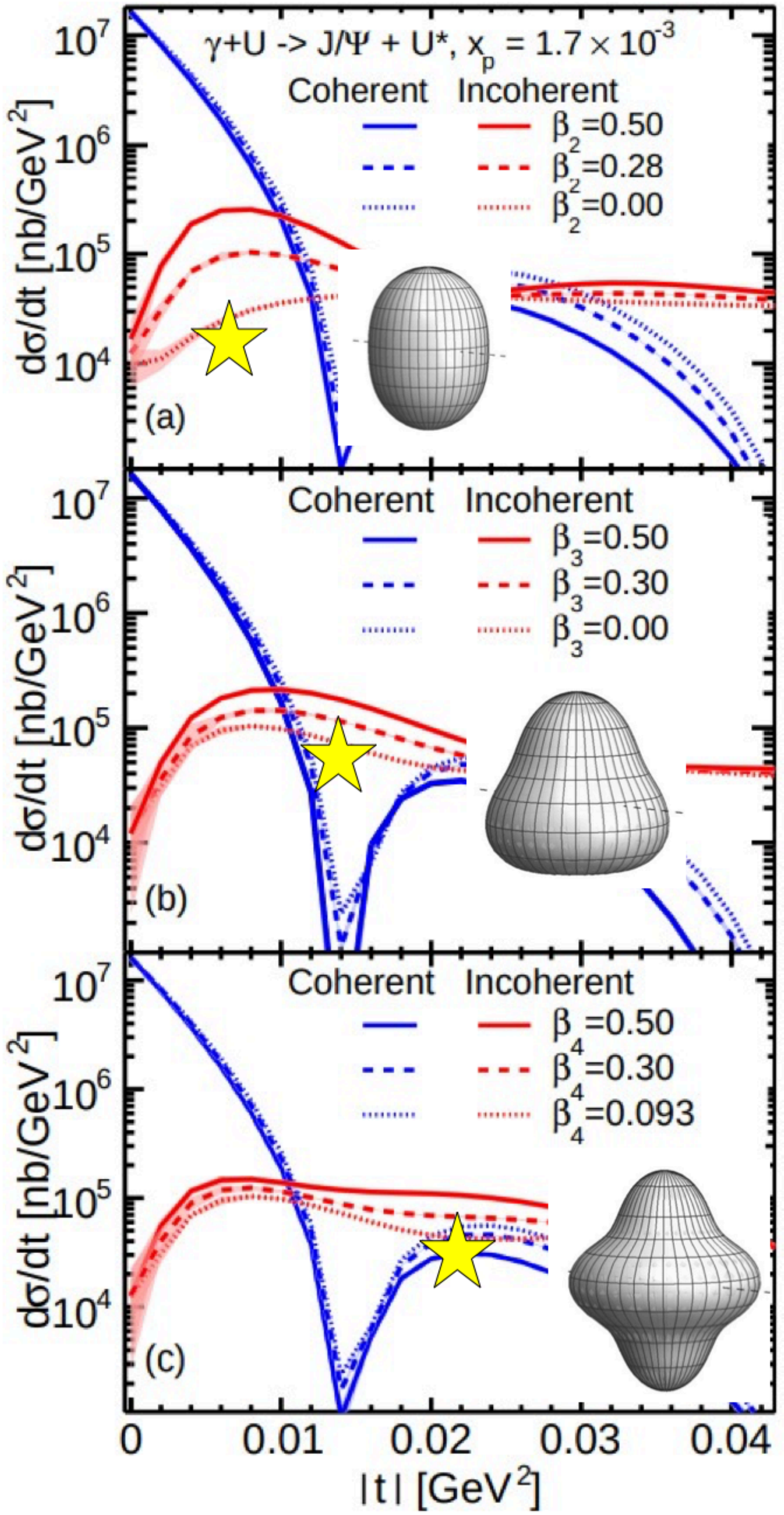
- **Coherent:** Sensitive to average geometry
  - Diffractive peaks → details of target, non-linearities, etc.
- **Incoherent:** Sensitive to EbE fluctuations
  - Sensitive to nuclear structure



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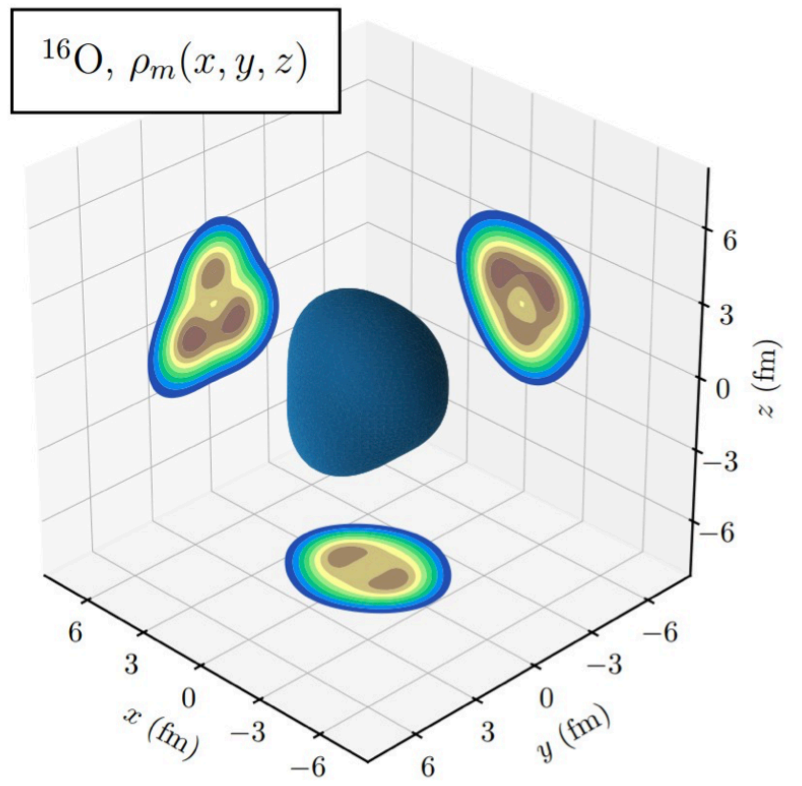
Coherent:
Fully diffractive
$e + A \rightarrow e + A + J/\psi$

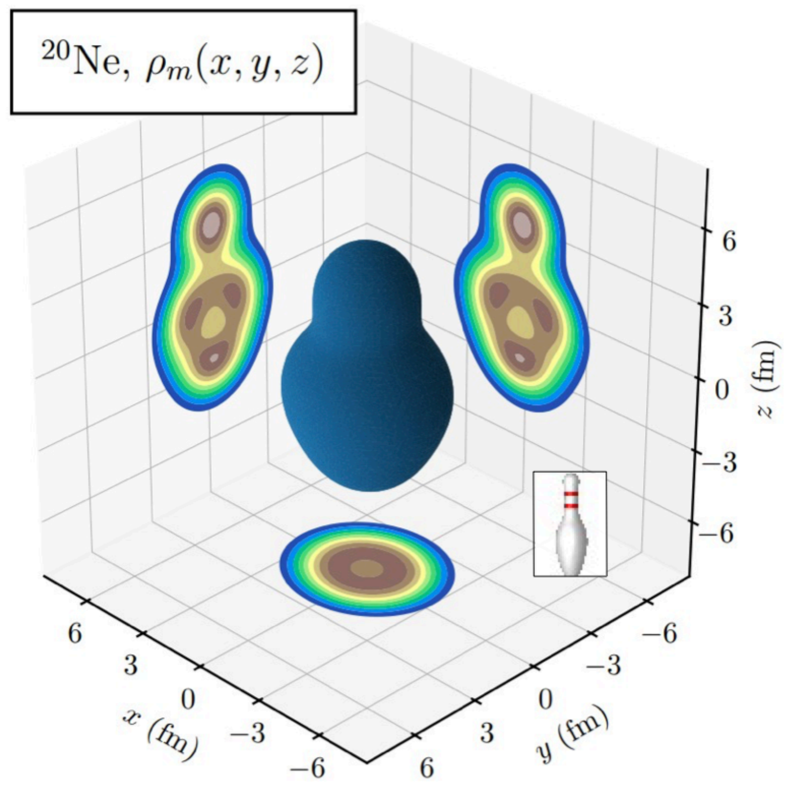
Incoherent:
Breaks up the nucleus.
$e + A \rightarrow e + (A' + X) + J/\psi$

Coherent: Sensitive to average geometry
Diffractive peaks → details of target, non-linearities, etc.

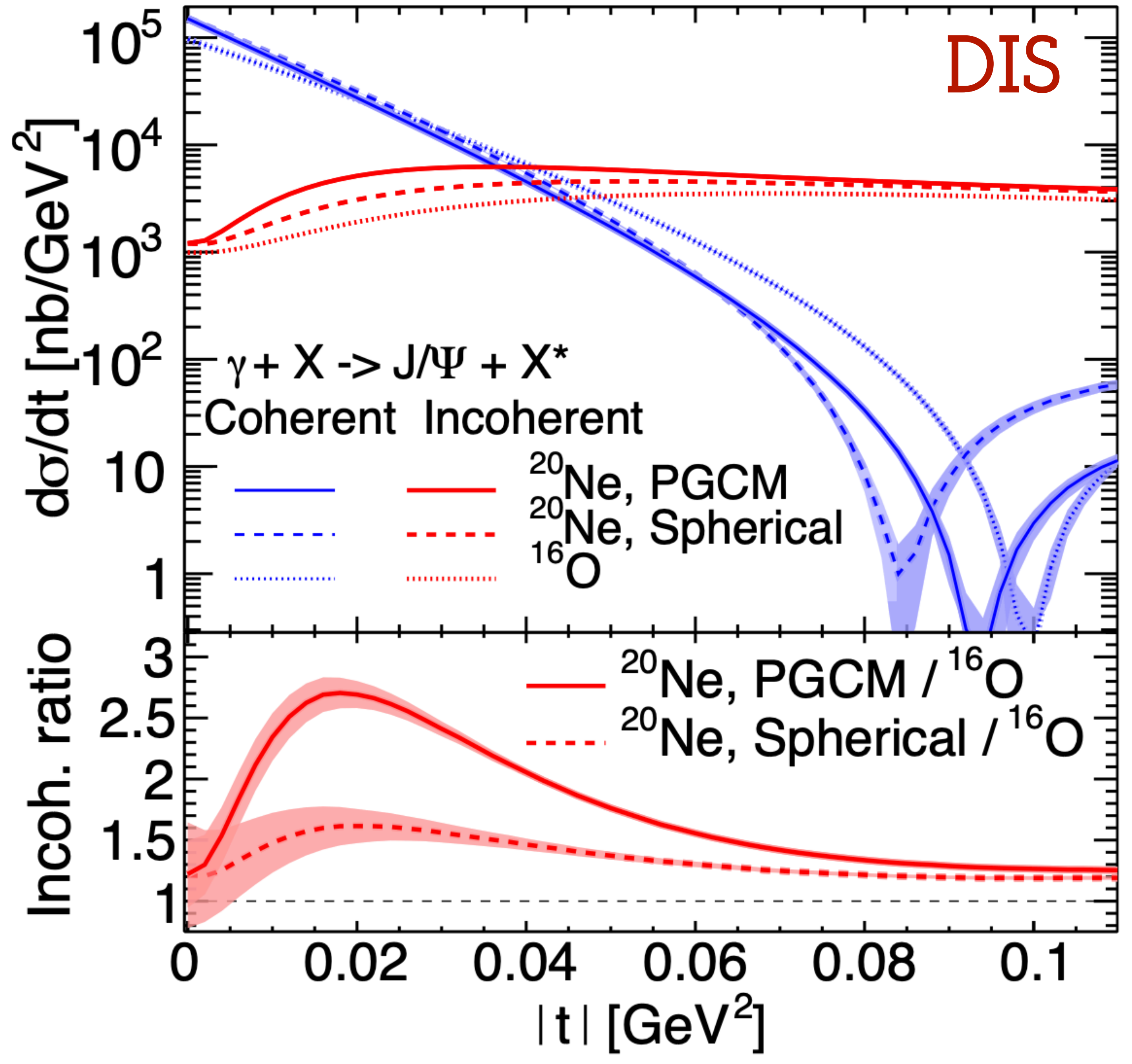
Incoherent: Sensitive to EbE fluctuations
Sensitive to nuclear structure

Ab initio computations of nuclear densities
can help include **nucleonic *n-point*** correlations
into initial geometry





Nuclear structure and DIS

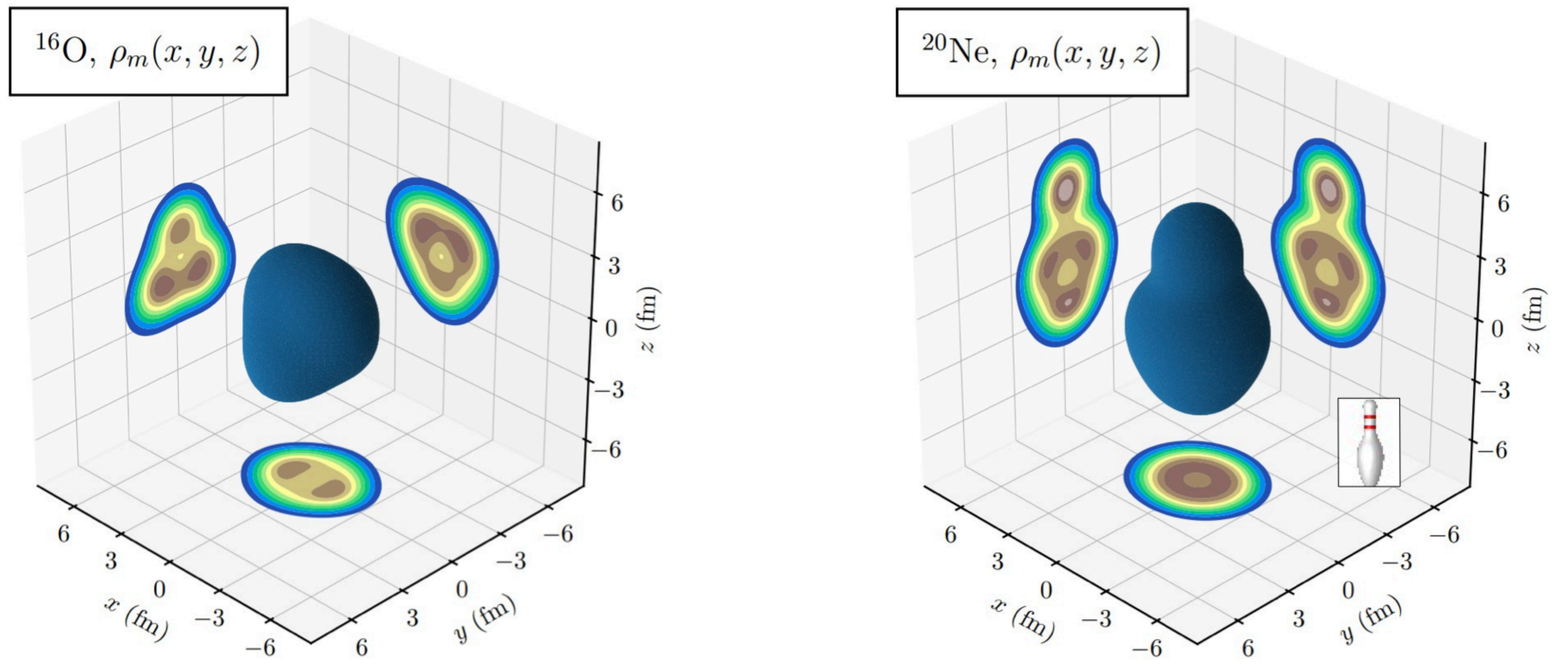


[PRL 131 (2023) 6, 062301]

VECTOR MESON PRODUCTION

Coherent:
Fully diffractive
$e + A \to e + A + J/\psi$

Incoherent:
Breaks up the nucleus.
$e + A \to e + (A' + X) + J/\psi$



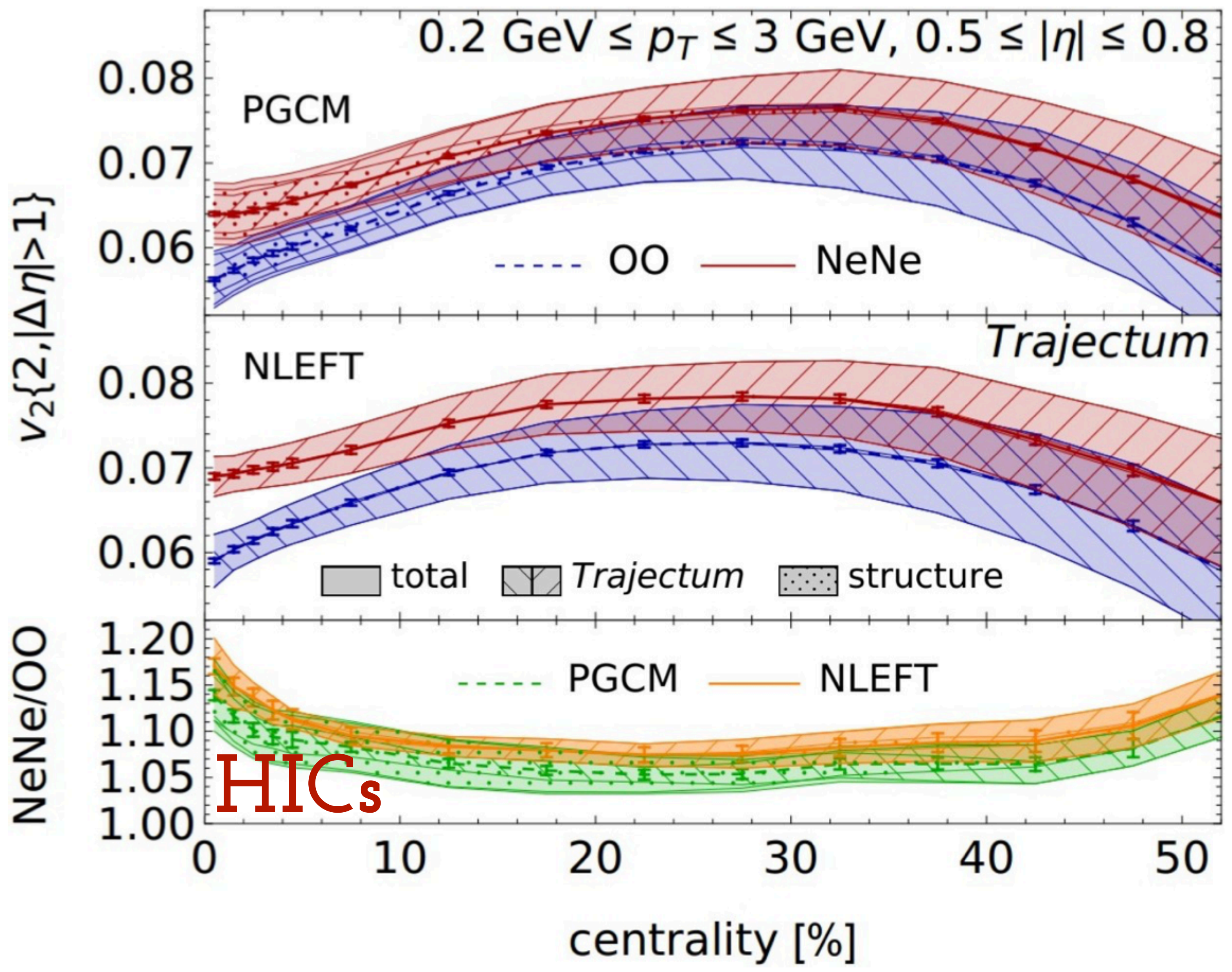
Coherent: Sensitive to average geometry

Diffractive peaks → details of target, non-linearities, etc.

Incoherent: Sensitive to EbE fluctuations

Sensitive to nuclear structure

Nuclear structure and flow



Ab initio computations of nuclear densities can help include **nucleonic *n-point*** correlations into initial geometry

Flanking from both LHC and EIC?

STILL A LOT TO TALK ABOUT

- Ultra-peripheral collisions (DIS-like)
  - Less control on virtual photon energy
  - Smaller-x but at higher Q^2
  - Upcoming ALICE's Forward Calorimeter ***(FoCal)*** offers a complimentary kinematic range
- Forward hadronic (dilute dense collisions)
  - Hadronic + EM measurements + correlations give access to gluon distributions
  - Progress has been done in the previous years, NLO hadron production available now [see *PRD* 109 (2024)3, 034018]