THE INITIAL STATE:

OMNE INITIUM DIFFICILE EST.

Oscar Garcia-Montero

Fakultät für Physik

Universität Bielefeld

GARCIA@PHYSIK.UNI-BIELEFELD.DE

Sept. 2024
Münster

FSP ALICE
Erforschung von
Universum und Materie

UNIVERSITÄT
BIELEFELD

CRC-TR 211
Strong-interaction matter
under extreme conditions

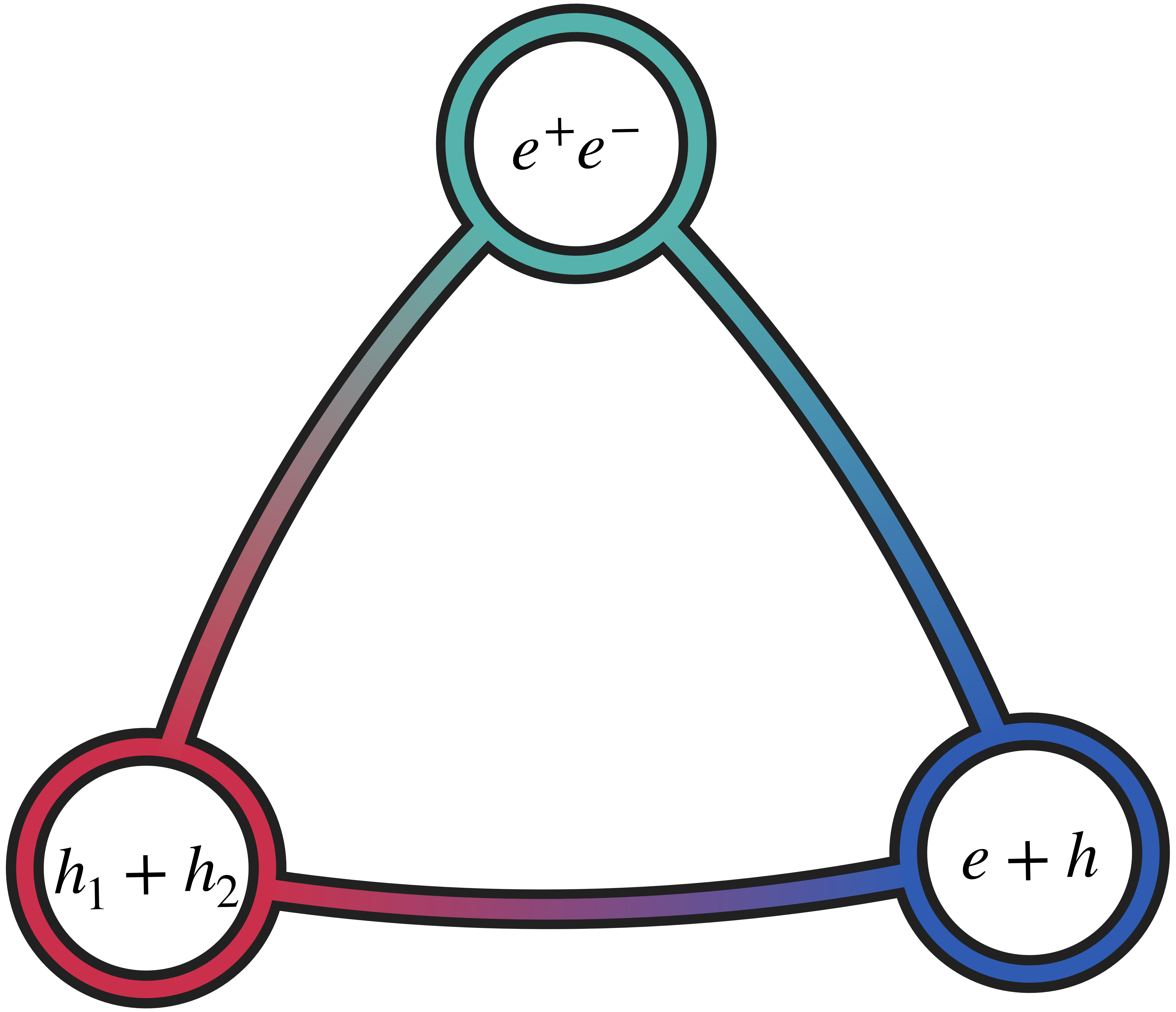
Bundesministerium
für Bildung
und Forschung

UNDERSTANDING QCD:

COMPLEMENTARITY

EW relatively well understood

Fun QCD shenanigans not fully understood in (see *soft photon puzzle*)



Systematic build-up of system size (complexity frontier)

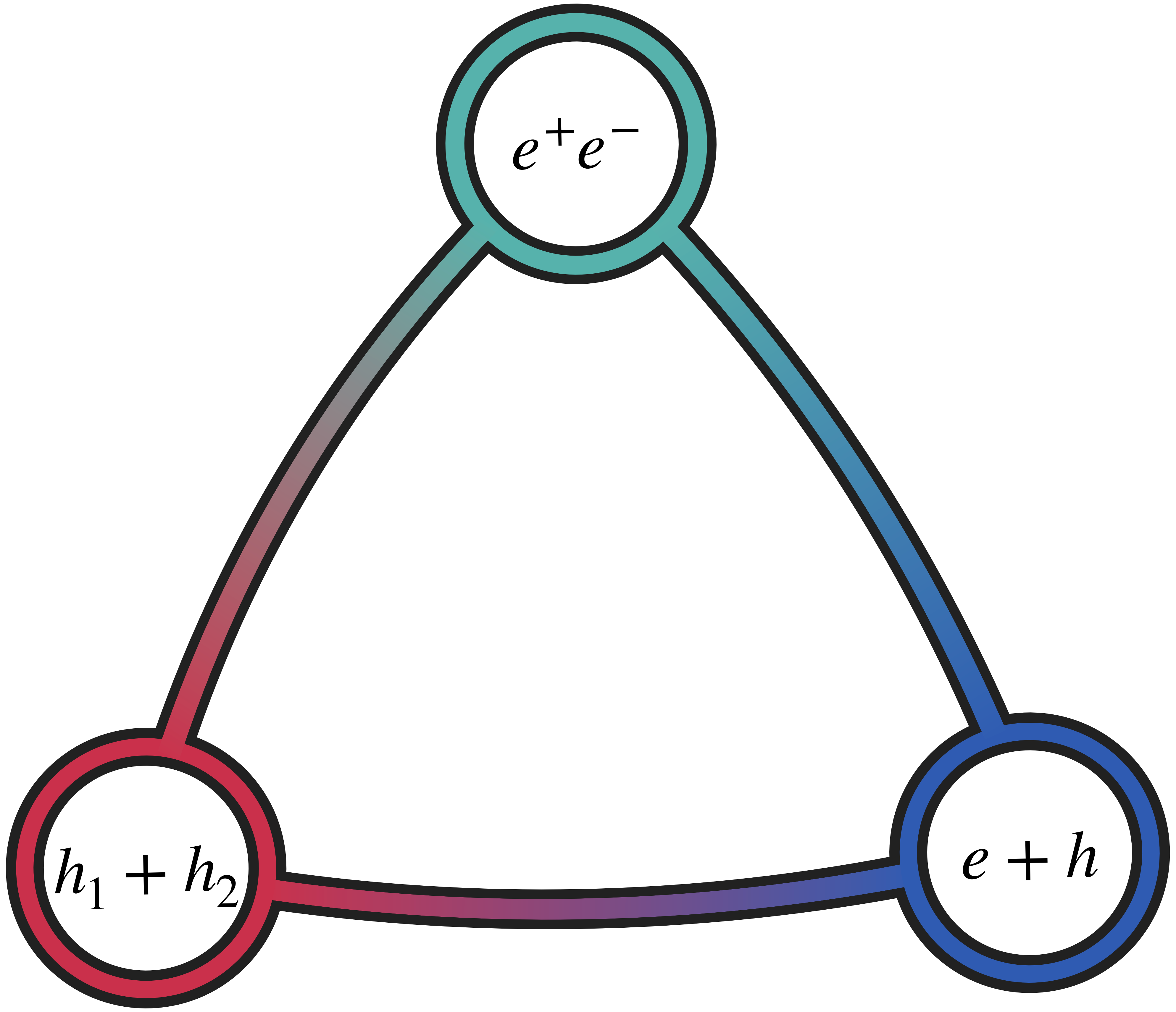
Kinematics complex but some limits are simple

Clear-cut kinematics

Excellent setting to test QCD non-linearities

EW relatively well understood

Fun QCD shenanigans not fully understood in (see *soft photon puzzle*)



PP/PA/AA

Systematic build-up of system size (complexity frontier)

Kinematics complex but some limits are simple

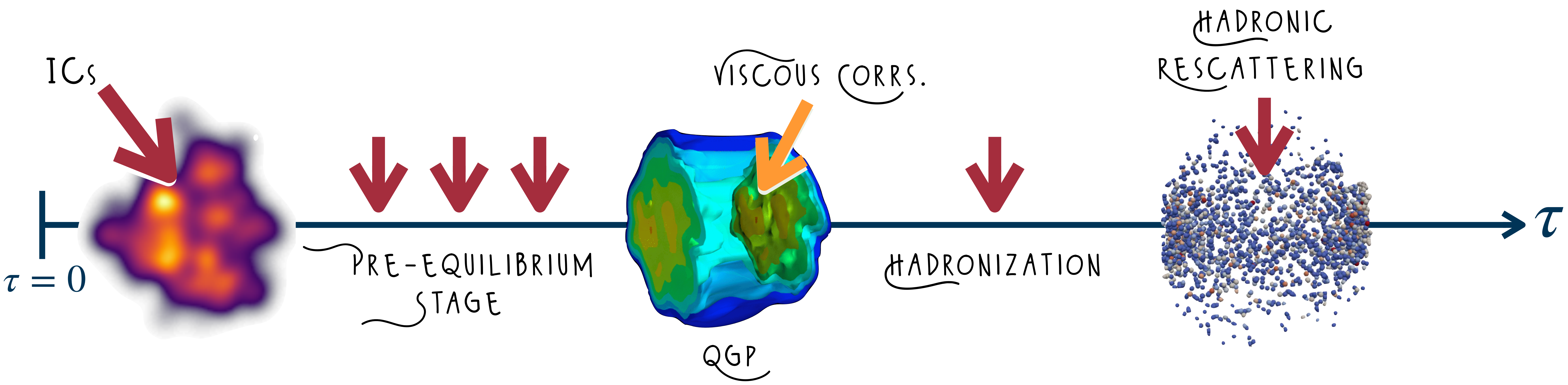
UPCs/EIC

Clear-cut kinematics

Excellent setting to test QCD non-linearities

THE TENOUSLY THERMAL QGP

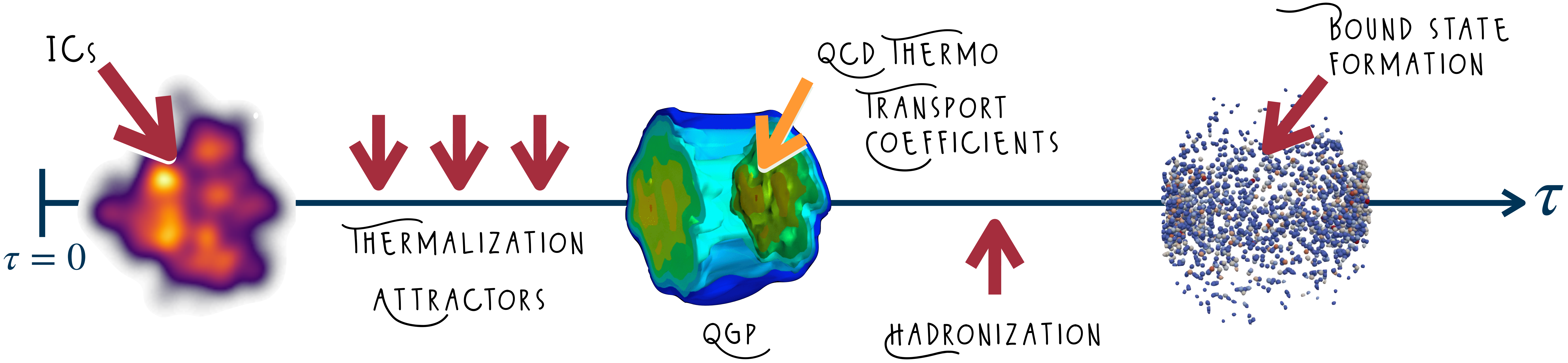
- Heavy-Ion Collisions create a -***very complicated***- Isolated Quantum System
  which is
  - Initially far away from any equilibrium
  - Self-interacting
  - Expanding against the vacuum
- A system battling to thermalize against all odds.



WHAT CAN WE LEARN?

FROM THE TENOUSLY THERMAL QGP

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



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

INITIAL CONDITIONS

As of today, I could compile 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

INITIAL CONDITIONS

As of today, I could compile 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

Seemingly different,
But in reality, intimately related!!

INITIAL CONDITIONS

As of today, I could compile a list of current, pressing avenues on the initial states

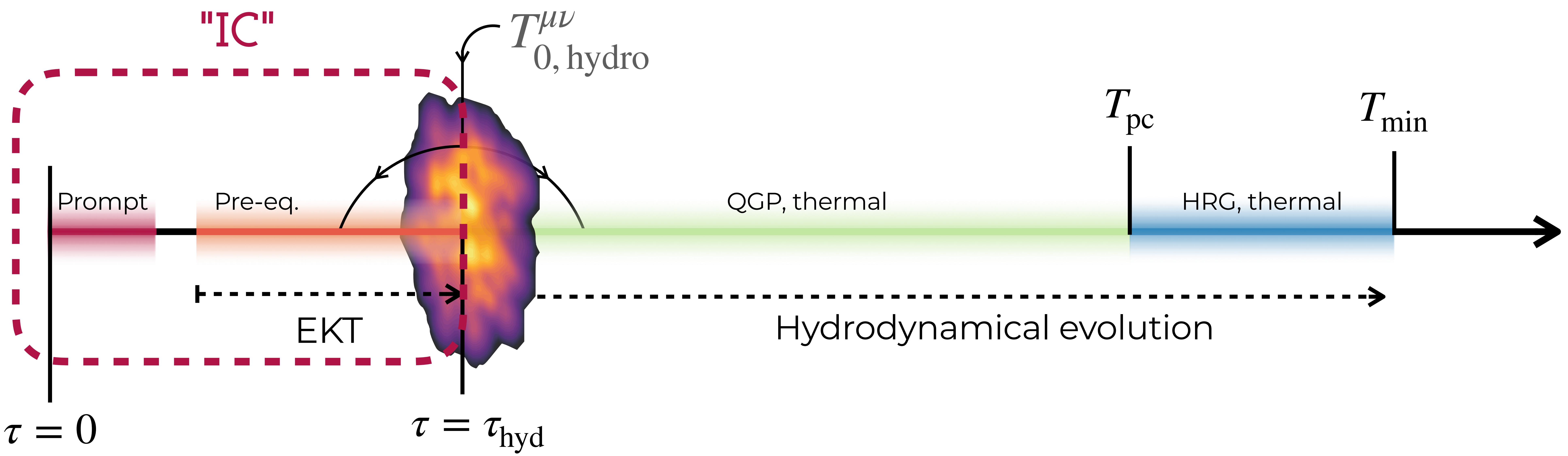
- Initial condition: $\sqrt{s_{NN}}$ dependence and longitudinal structure
- *B,Q,S* Charge deposition and the search for the CP
- From medium to small systems
- Better quantification of ICs for large systems
- Initial condition for hard probes

Seemingly different,
But in reality, intimately related!!

THE INITIAL STATE OF A HIC

What do we need?

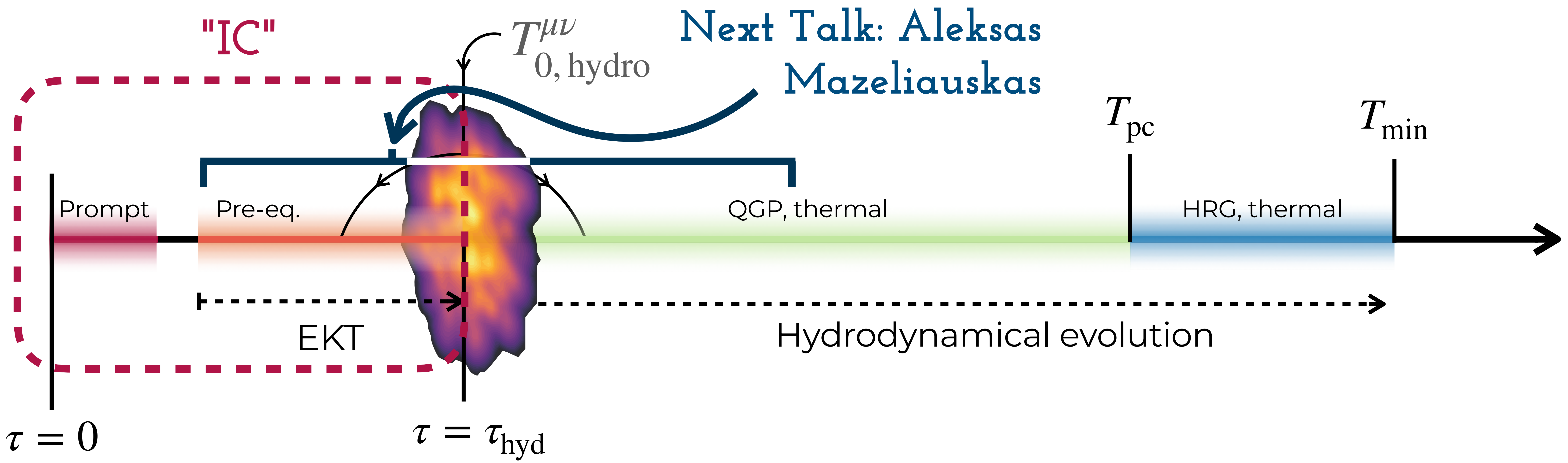
- IC is commonly taken to be up to the beginning of hydro evolution.
- Then, the initial energy stress tensor, $T^{\mu\nu}_{0,\,\mathrm{hydro}}$, is needed.



THE INITIAL STATE OF A HIC

What do we need?

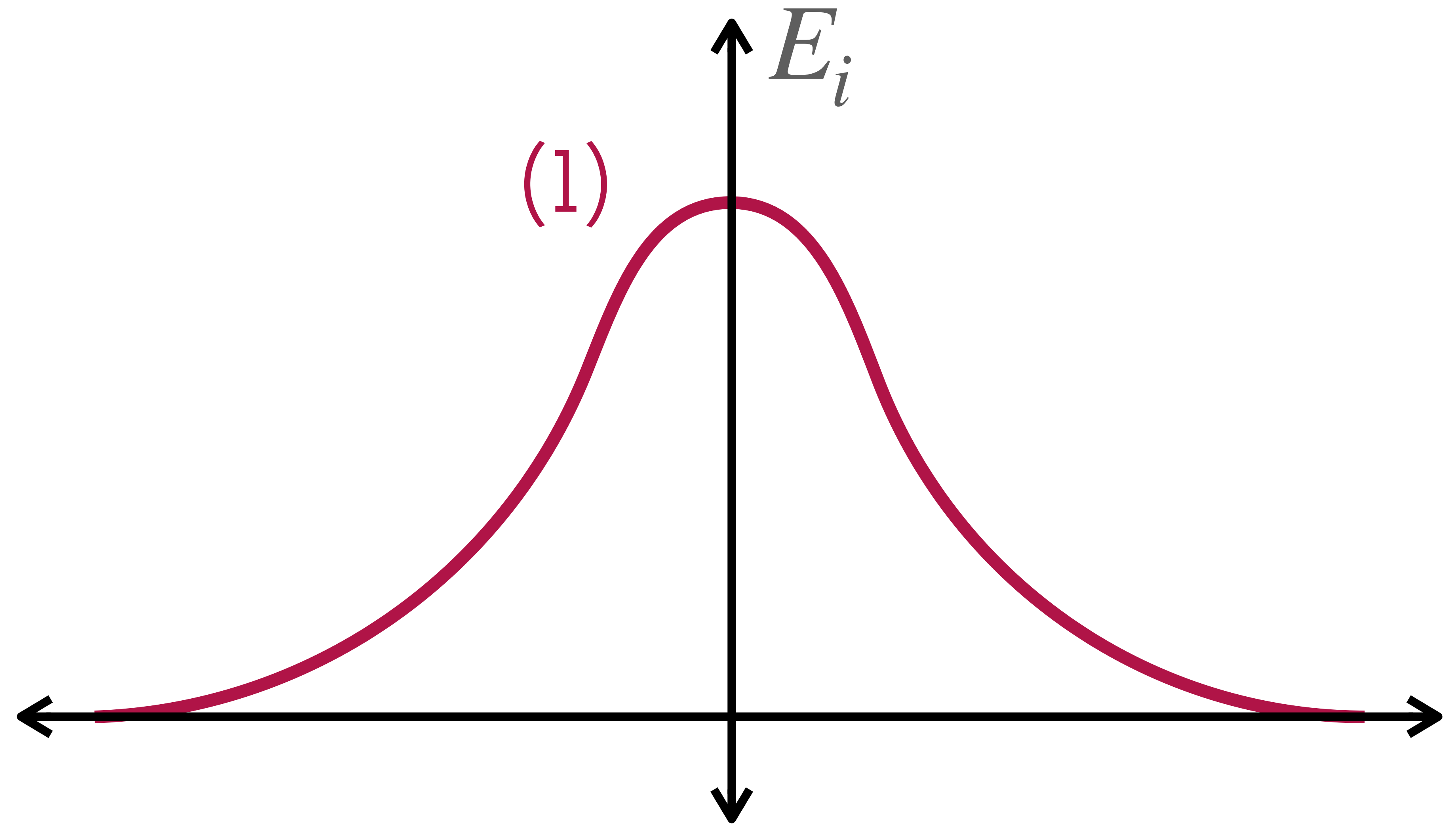
- IC is commonly taken to be up to the beginning of hydro evolution.
- Then, the initial energy stress tensor, $T^{\mu\nu}_{0,\,\mathrm{hydro}}$, is needed.



THE INITIAL STATE OF A HIC … IN 3D.

What do we expect to have?

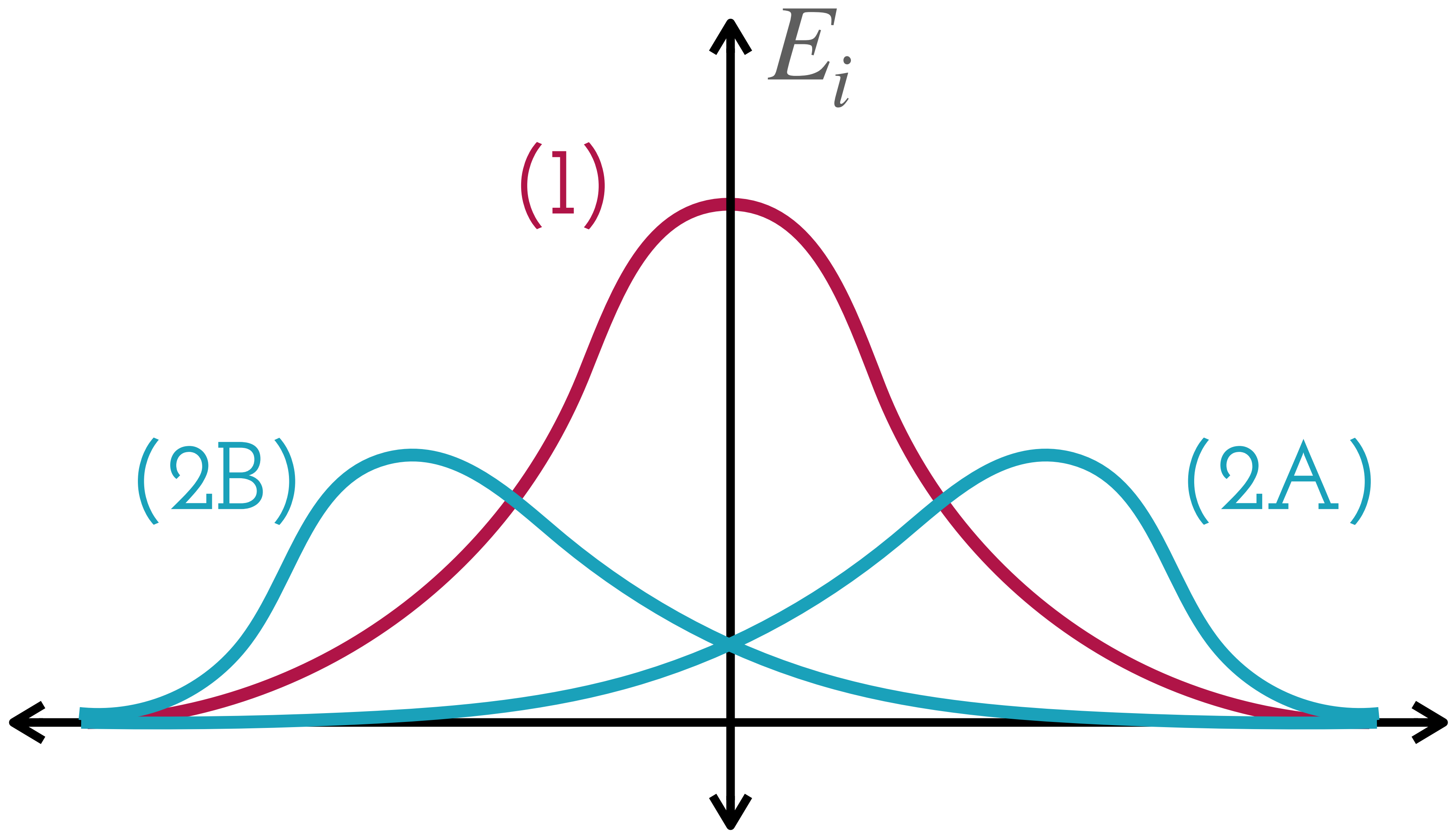
- Nature of DoFs depends model-by-model
- (1) Fireball energy deposition: C.o.M of collision favours midrapidity.
  - High density of gluons, string breaking, etc.



THE INITIAL STATE OF A HIC … IN 3D.

What do we expect to have?

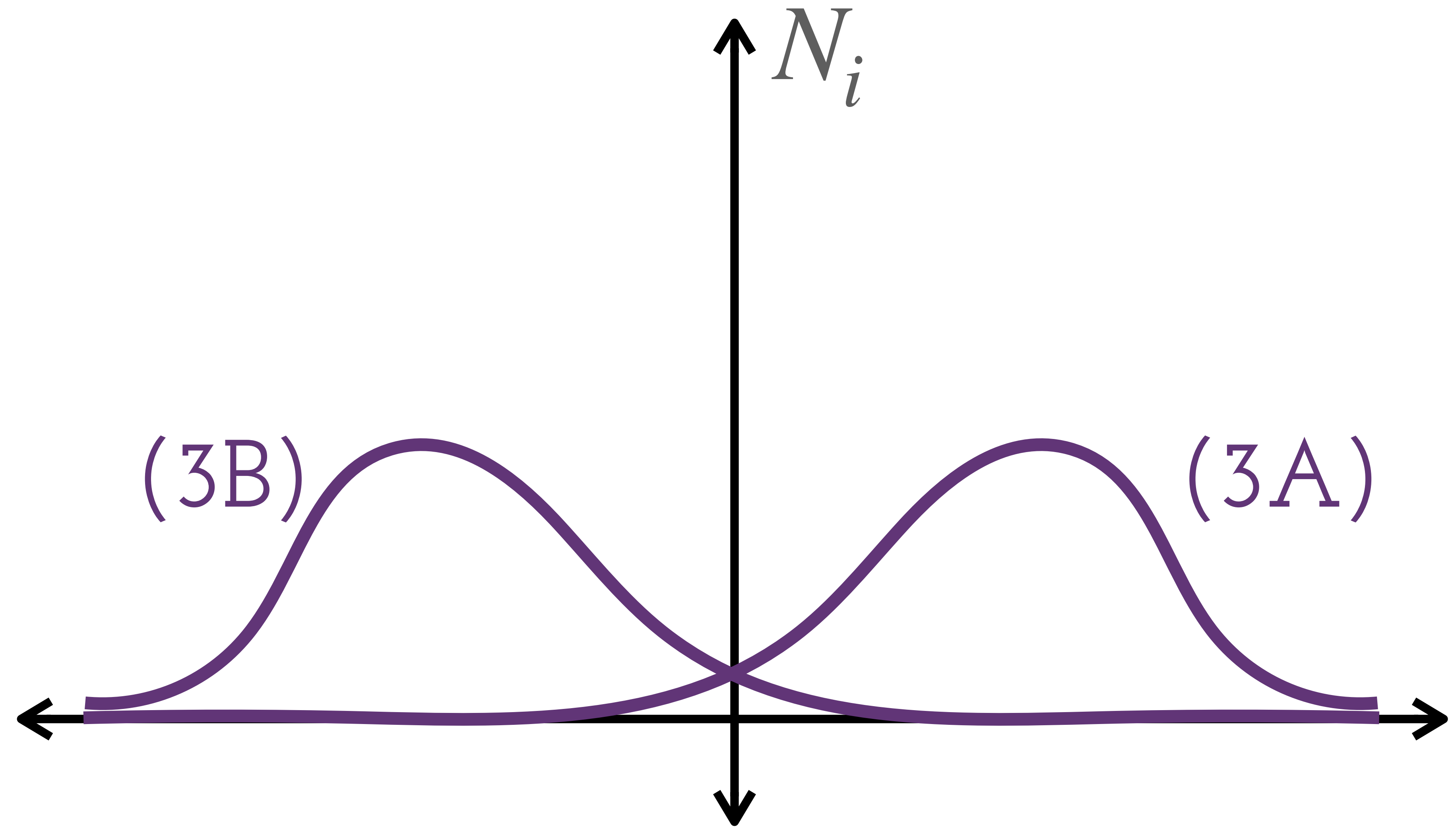
- Nature of DoFs depends model-by-model
- (1) Fireball energy deposition: C.o.M of collision favours midrapidity.
  - High density of gluons, string breaking, etc.
- (2) Fragmentation region energy deposition: C.o.M of collision favours midrapidity.
  - Quark scattering, baryon junction, hadrons?



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.
- (2) Fragmentation region energy deposition: C.o.M of collision favours midrapidity.
  - Quark scattering, baryon junction, hadrons?
- (2) Fragmentation region charge deposition: Q,B and S (in fluctuations)



SO, WHERE ARE WE?
WHAT IS THERE?
AND... WHAT IS MISSING?

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

METHODS: STATE OF THE ART

DoFs/motivation behind the energy and charge deposition

LARGE-X

Collinear fact.
Described by PDFs

AMPT, EKRT

GEOMETRICAL

Effective description
Often parametrical

TRENTO

LOW-X

Overoccupied
Color fields

METHODS: STATE OF THE ART

DoFs/motivation behind the energy and charge deposition

LARGE-X

Collinear fact.
Described by PDFs

GEOMETRICAL

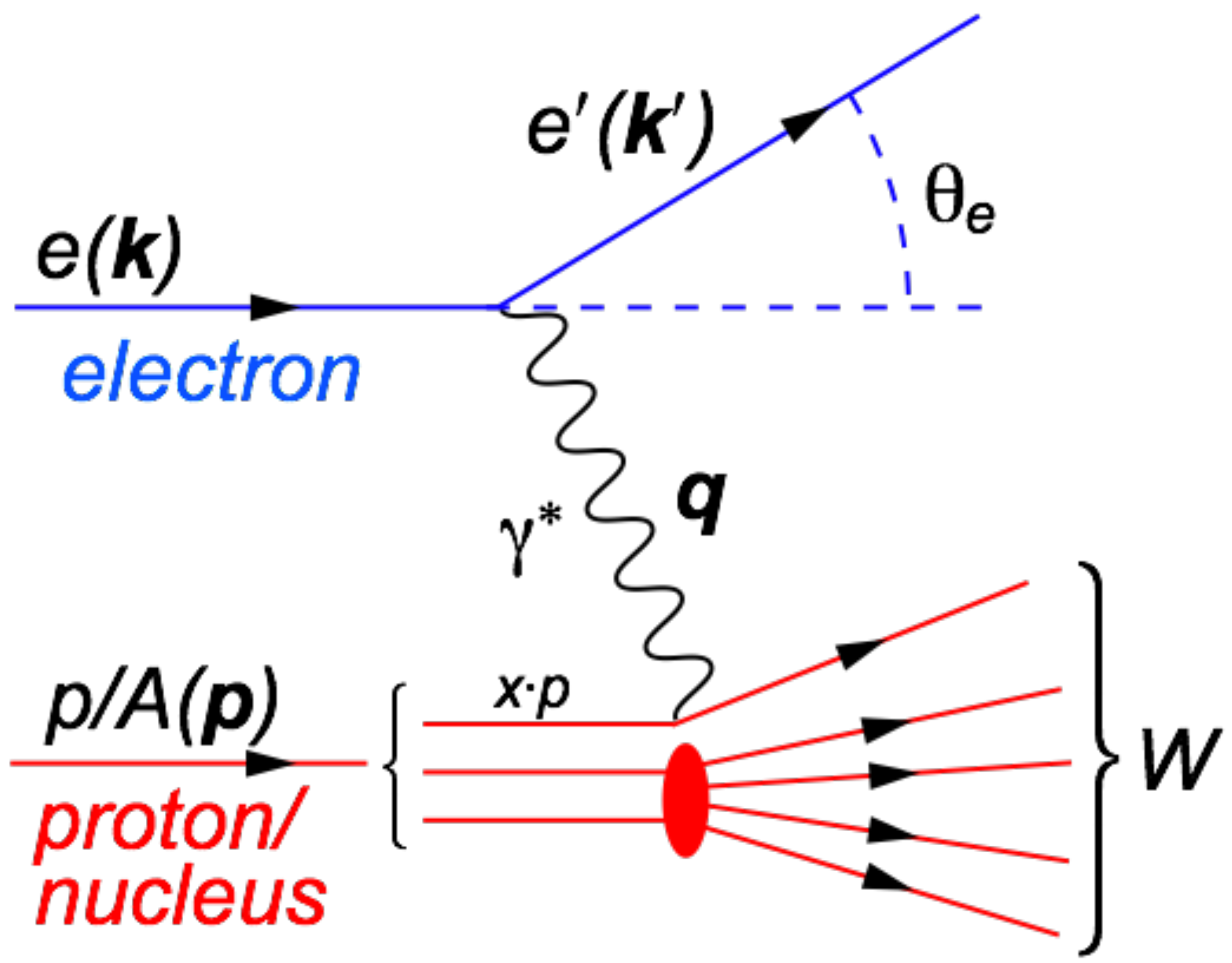
Effective description
Often parametrical

LOW-X

Overoccupied
Color fields

SATURATION MODELS

Deeply Inelastic Scattering (DIS)



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

$Q^2 = -q^2$ → Resolution power

$x = \frac{-q^2}{p \cdot q}$ → Fraction of momentum carried

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

- Using QED probe to test QCD properties
- Great control over kinematics
- Inclusive and exclusive channels (vector meson prod.,DVCS, etc)
- Great control over kinematics

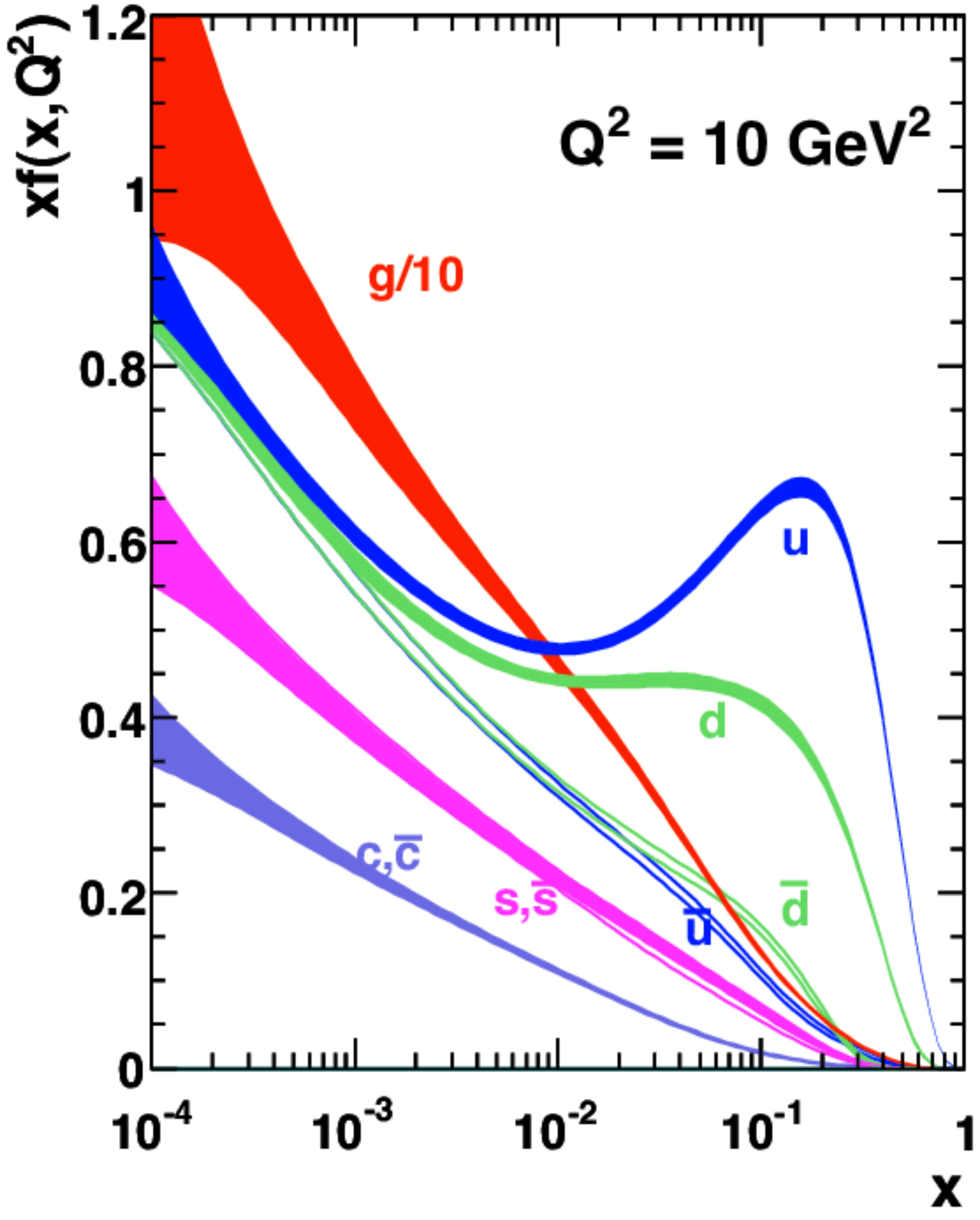
SATURATION MODELS

NUCLEAR STRUCTURE

- PDFs from fit to Experiments (DIS)

  x ~ energy/momentum fraction carried by parton

  Q^2 ~ resolution scale



SATURATION MODELS

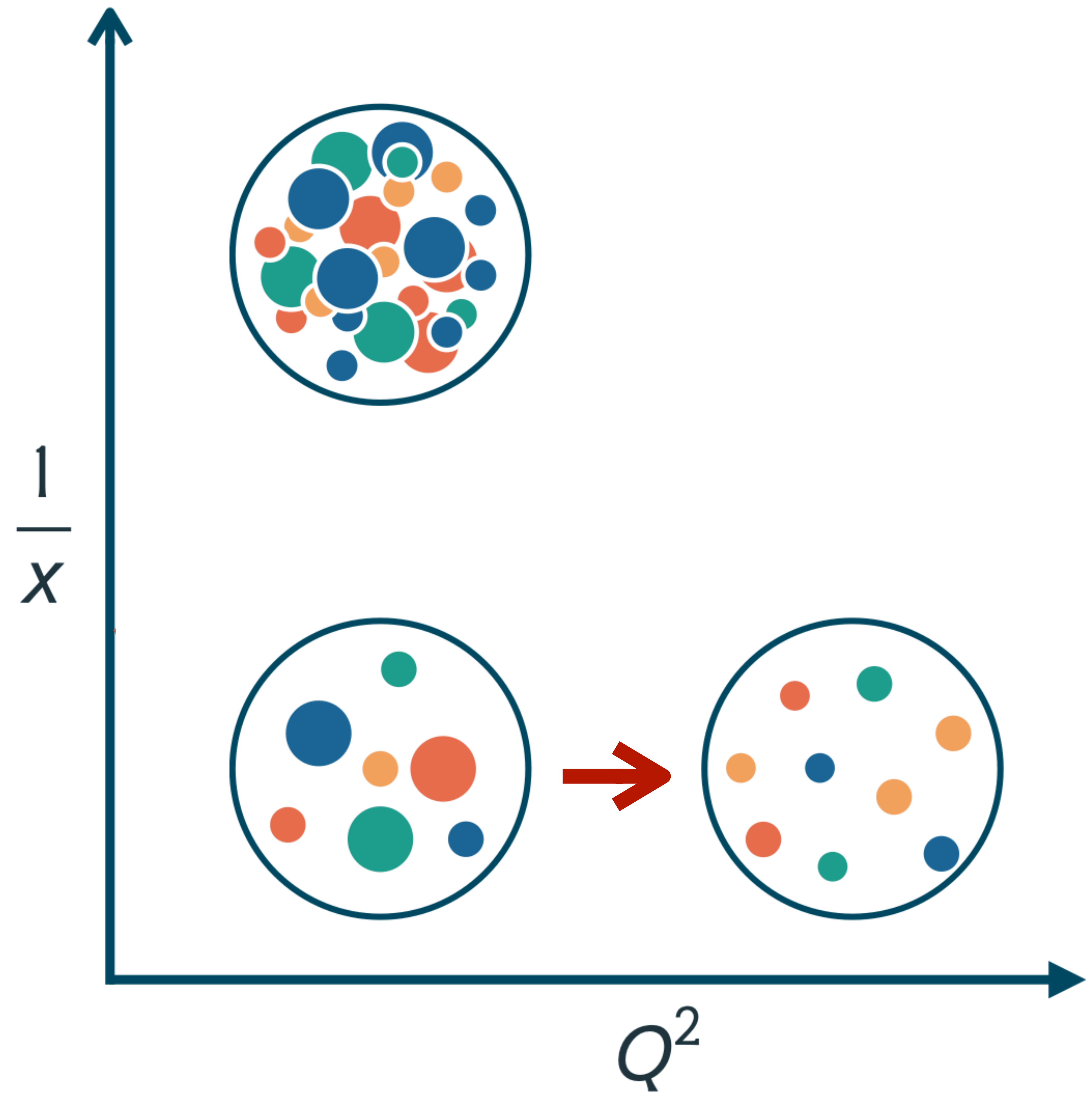
NUCLEAR STRUCTURE

- PDFs from fit to Experiments (DIS)

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

  $Q^2 \sim$ resolution scale

- QCD evolution in Q^2 given by the DGLAP equation



SATURATION MODELS

NUCLEAR STRUCTURE

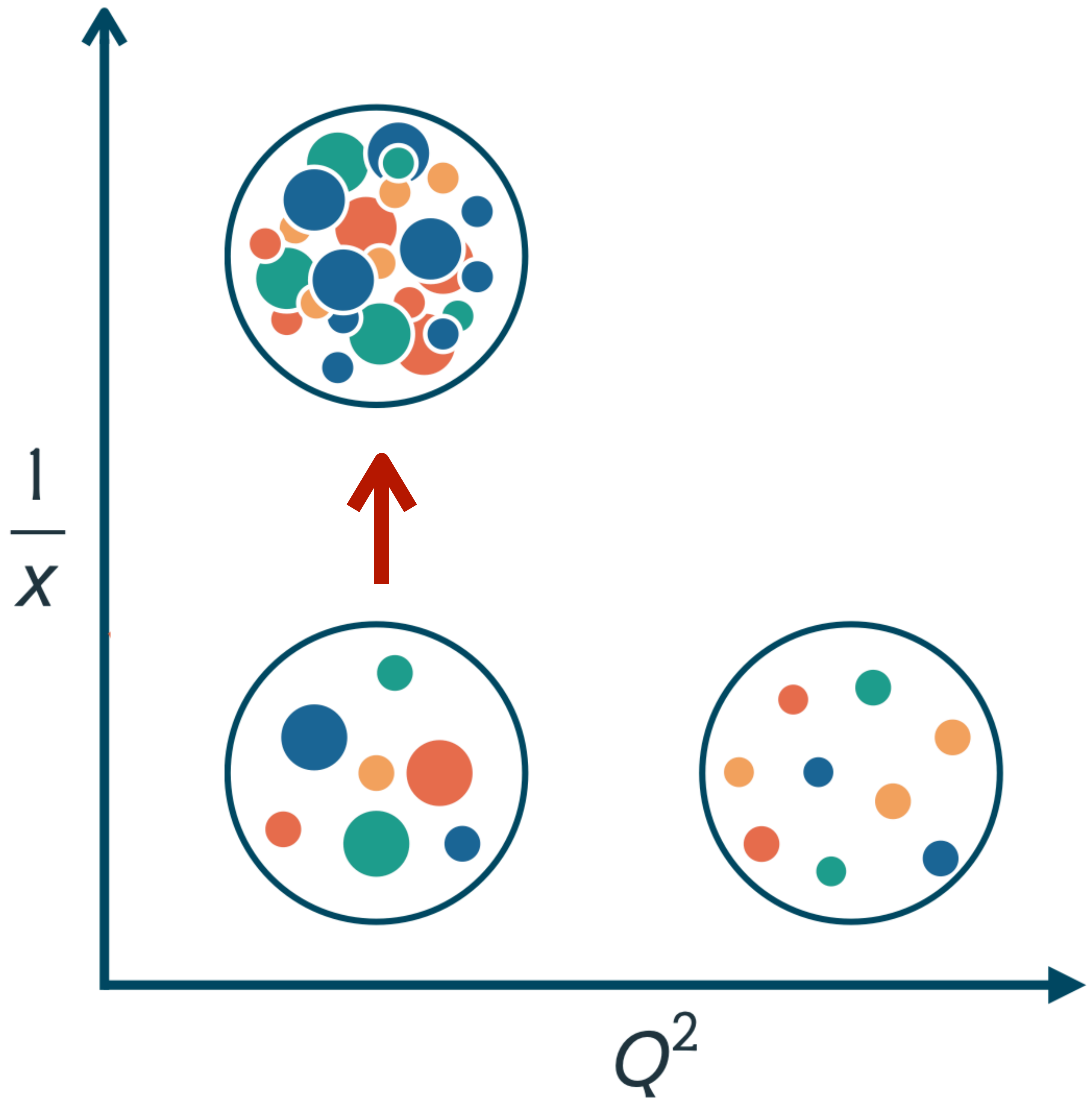
- PDFs from fit to Experiments (DIS)

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

  $Q^2 \sim$ resolution scale

- QCD evolution in Q^2 given by the DGLAP equation

- QCD non-linear evolution in x given by the BK equation



SATURATION MODELS

NUCLEAR STRUCTURE

- PDFs from fit to Experiments (DIS)

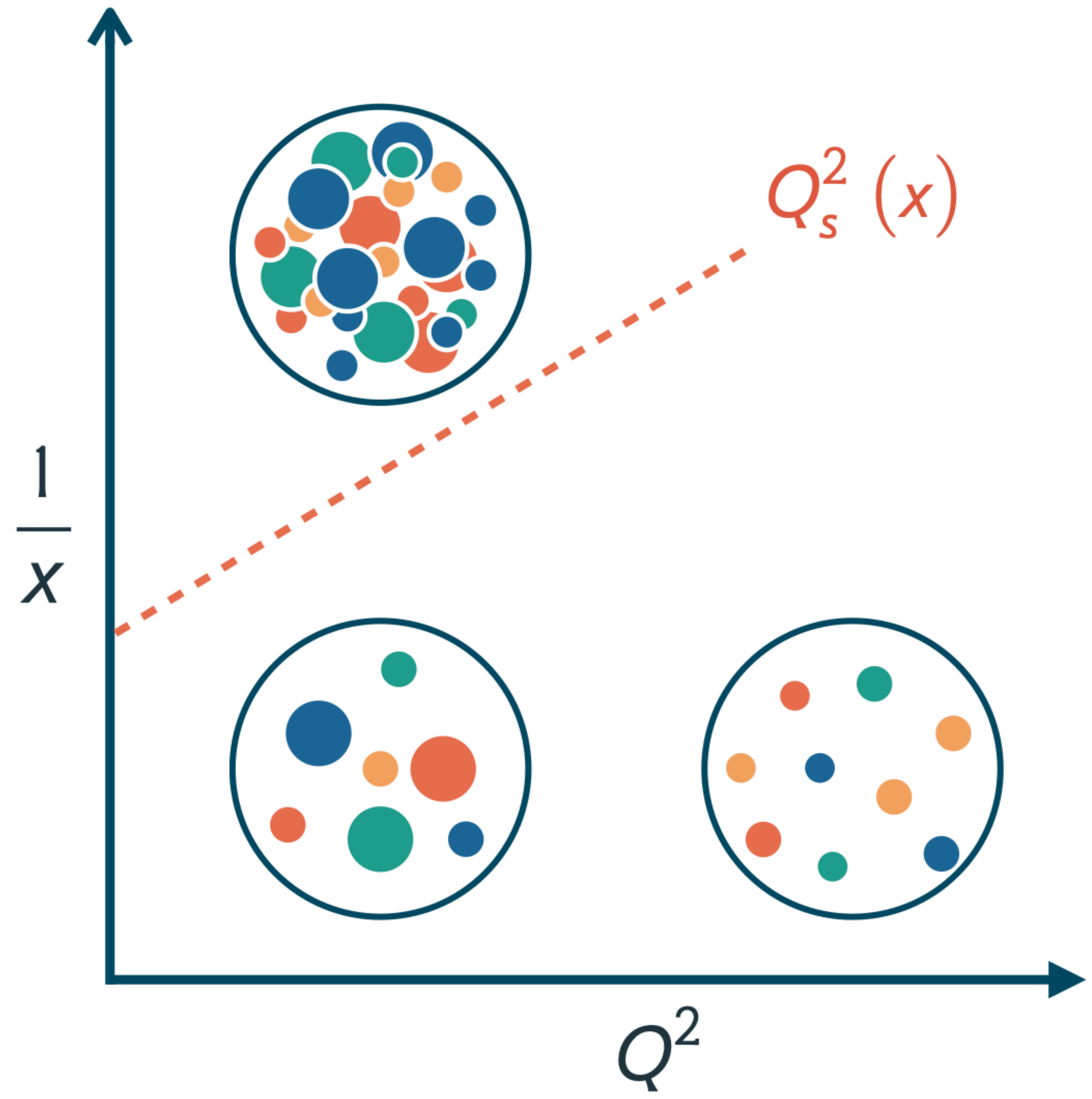
  $x \sim$ energy/momentum fraction carried by parton

  $Q^2 \sim$ resolution scale

- QCD evolution in Q^2 given by the DGLAP equation

- QCD non-linear evolution in x given by the BK equation

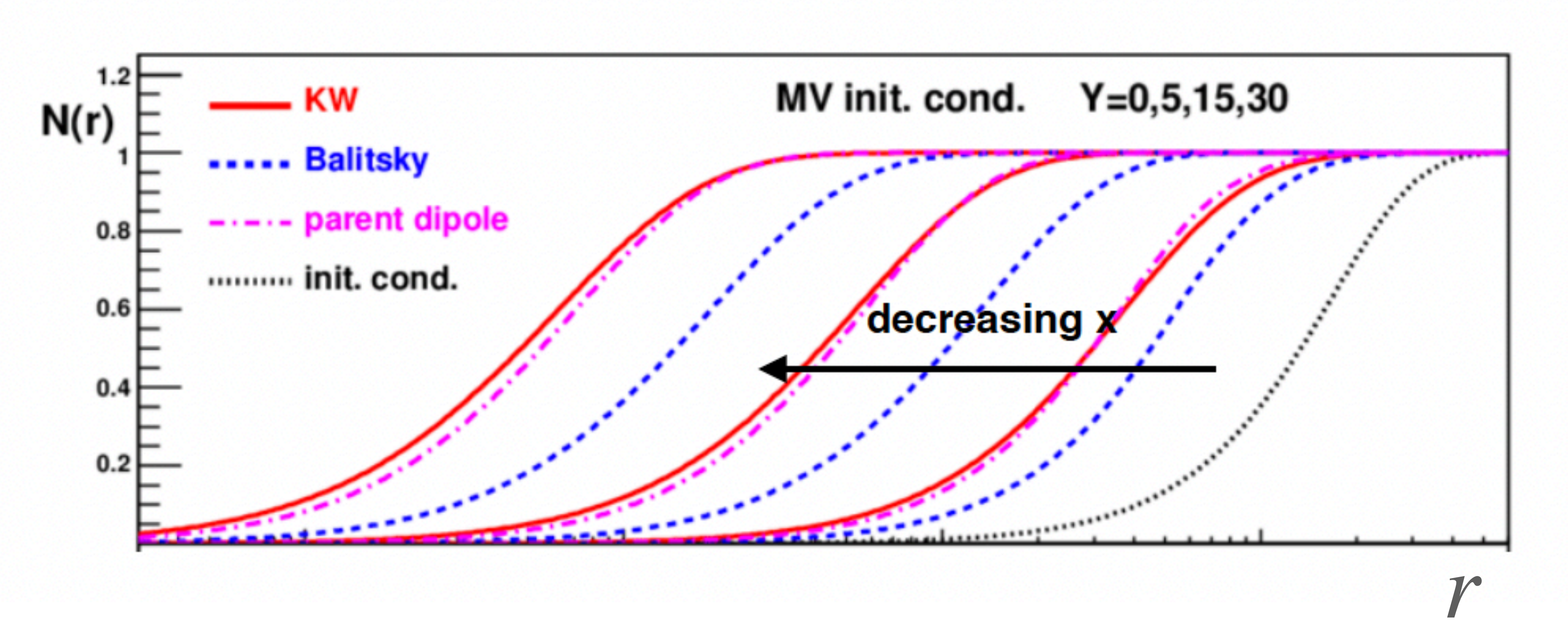
- Balance between gluon emission and recombination leads t saturation of the gluon density (black disk limit $N \sim 1$)



SATURATION MODELS

NUCLEAR STRUCTURE

- Emergence of a ***semi-hard*** saturation scale Q_s is created dynamically

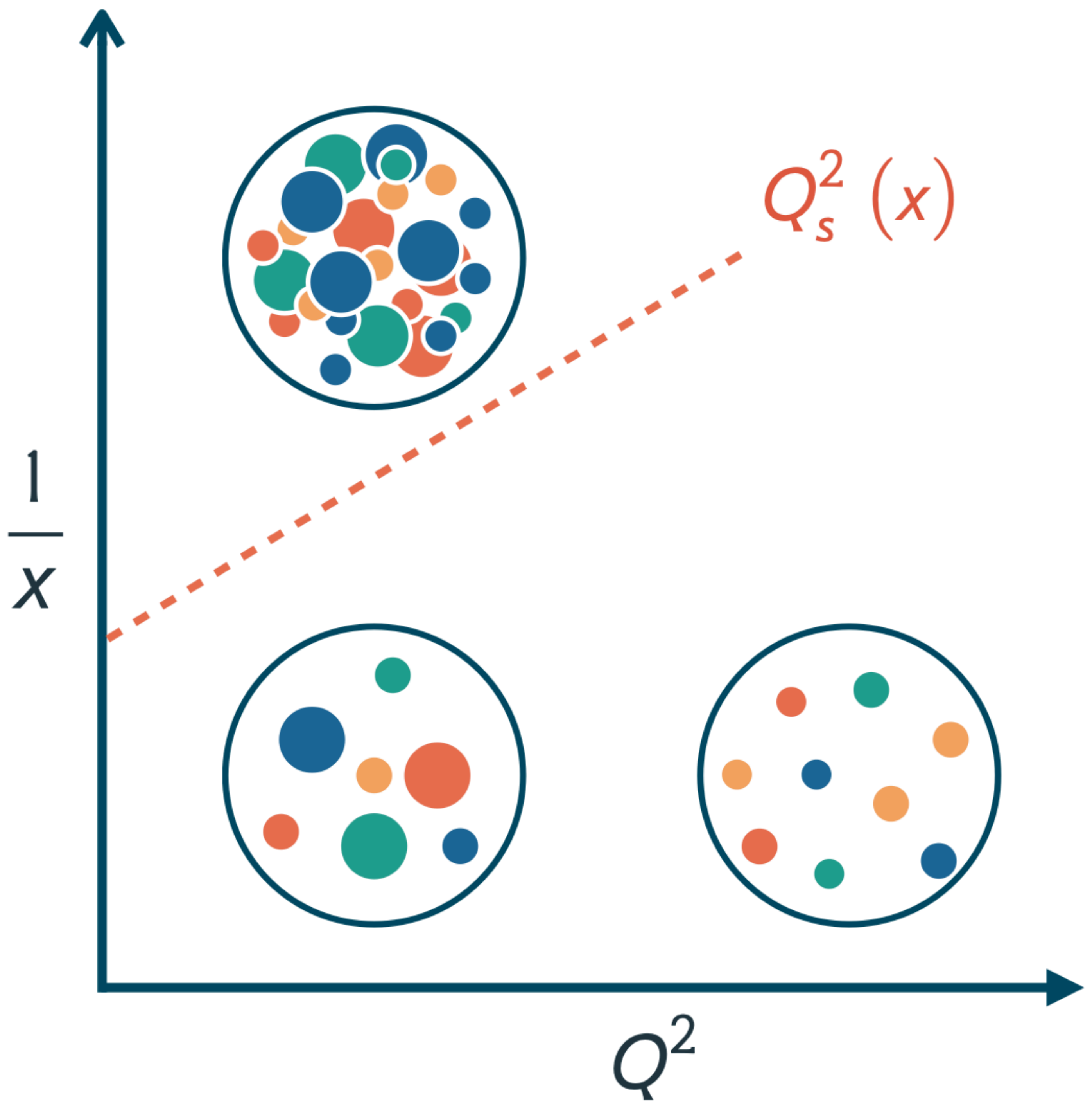


- Gluon distributions saturate with $k_\perp < Q_S$ ($r > Q_S^{-1}$ in pos. space)

- A simplified, parametric form:

  With energy: $Q_S \sim x^{-\lambda}$

  With system size $Q_S \sim A^{1/3}$



THE COLOR GLASS CONDENSATE™

GLUE

Q_s

Soft Partons

Macroscopic Field

$A(x)$

Hard Partons

Static Color Sources

$J^\mu(x) = g\,\delta(x^-)\,\delta^{\mu +}\,\rho(\boldsymbol{x}_\perp)$

THE COLOR GLASS CONDENSATE

GLUE

Q_s

Soft Partons

Macroscopic Field

$$A(x)$$

Hard Partons

Static Color Sources

$$J^{\mu}(x) = g\,\delta(x^-)\,\delta^{\mu +}\,\rho(\boldsymbol{x}_{\perp})$$

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

Yang-Mills Equations

$$A_p^{\mu}(x) = -\,g\,\delta^{\mu +}\,\delta(x^-)\,\frac{1}{\nabla_{\perp}^2}\,\rho(\boldsymbol{x}_{\perp})$$

THE COLOR GLASS CONDENSATE

GLUE

Q_s

Soft Partons

Macroscopic Field

$A(x)$

Hard Partons

Static Color Sources

$J^\mu(x) = g\,\delta(x^-)\,\delta^{\mu +}\,\rho(\boldsymbol{x}_\perp)$

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

Yang-Mills Equations

$$A_p^\mu(x) = -\,g\,\delta^{\mu +}\,\delta(x^-)\,\frac{1}{\nabla_\perp^2}\,\rho(\boldsymbol{x}_\perp)$$

$$\frac{\alpha_s}{Q_S^2(x)}\,\frac{x f_g(x, Q_S^2)}{\pi R^2} \sim 1$$

THE COLOR GLASS CONDENSATE

GLUE

Q_s

Soft Partons

Macroscopic Field

$A(x)$

Hard Partons

Static Color Sources

$J^{\mu}(x) = g\,\delta(x^-)\,\delta^{\mu +}\rho(\boldsymbol{x}_\perp)$

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

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

THE COLOR GLASS CONDENSATE

GLUE

Soft Partons

Macroscopic Field

$A(x)$

Q_s

Hard Partons

Static Color Sources

$J^\mu(x) = g\,\delta(x^-)\,\delta^{\mu +}\,\rho(\boldsymbol{x}_\perp)$

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

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

SPECIAL CASE

McLerran-Venugopalan Model

$$\langle \rho^a(\boldsymbol{x}_\perp)\,\rho^b(\boldsymbol{y}_\perp)\rangle = g^2\,\delta^{ab}\,\mu^2\delta^{(2)}(\boldsymbol{x}_\perp - \boldsymbol{y}_\perp)$$

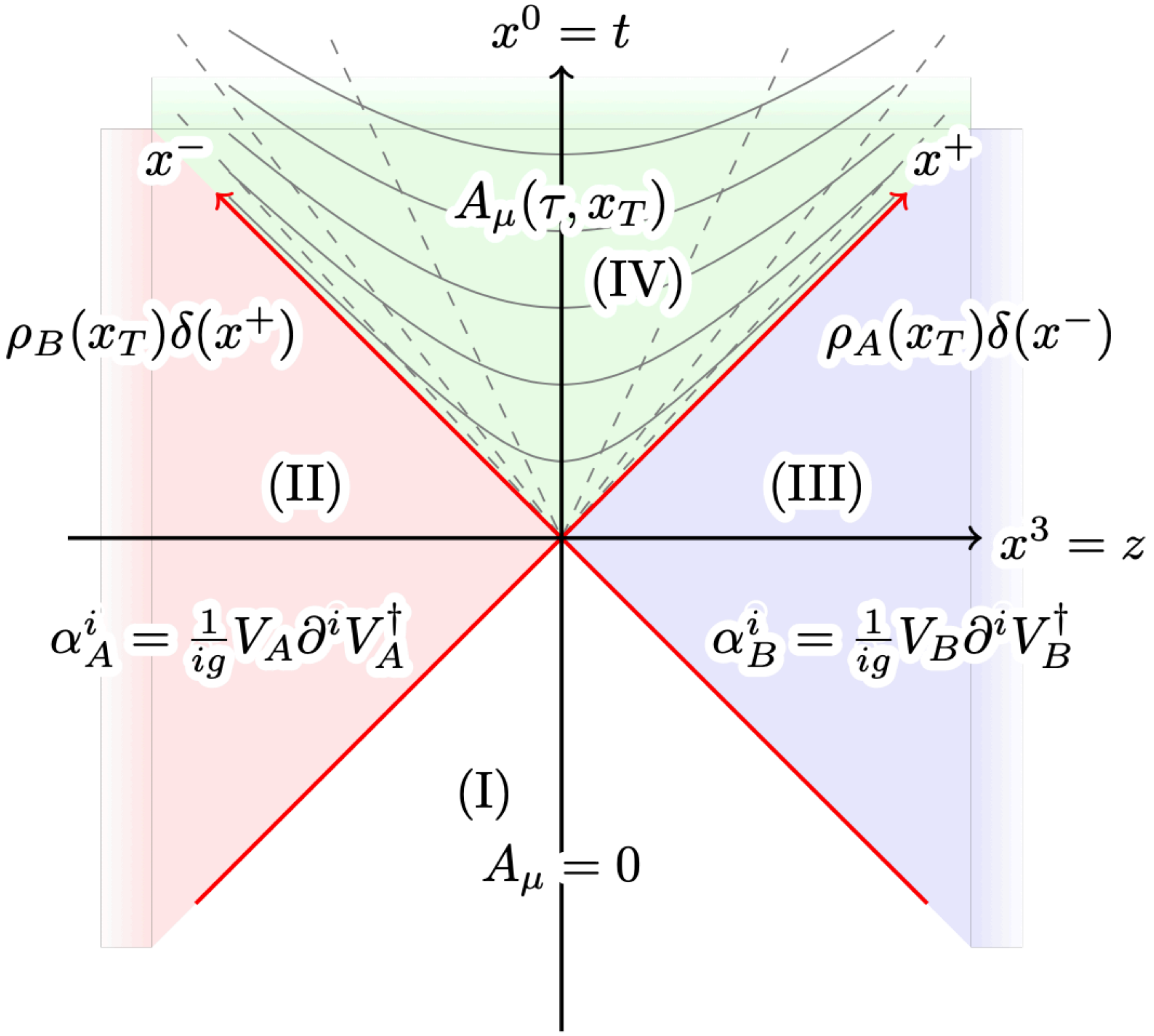
SATURATION: IP-GLASMA

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

IP-GLASMA

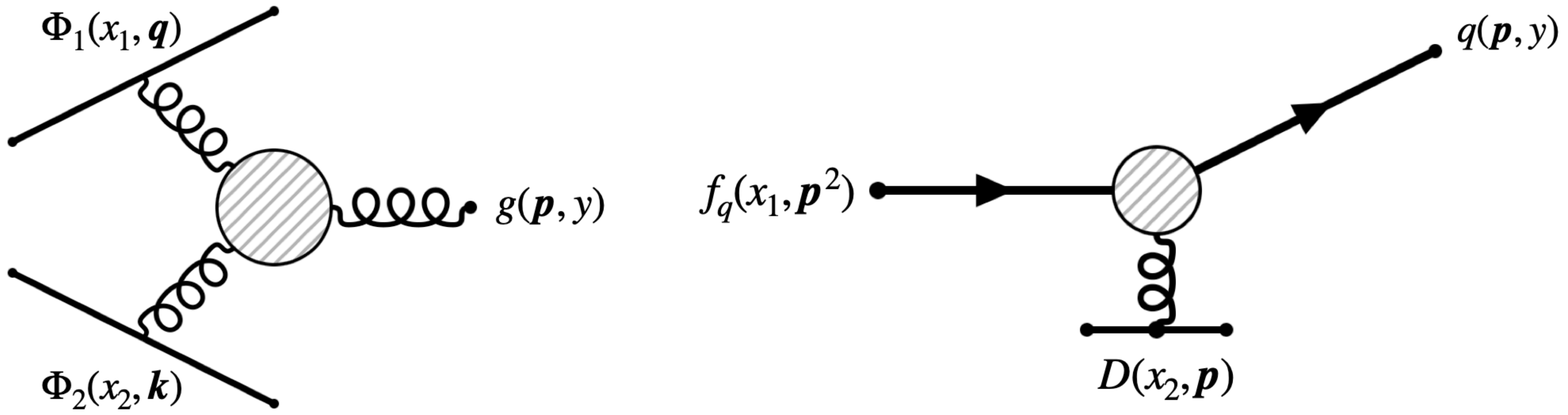
1) Sample nucleon positions (e.g. MC-Glauber)
2) Sample color currents from those nucleons ($J_{A,B}$)
3) Solve Yang-Mills in the presence of both currents and conservation laws for currents.
4) Get energy-stress tensor, $T^{\mu\nu}$

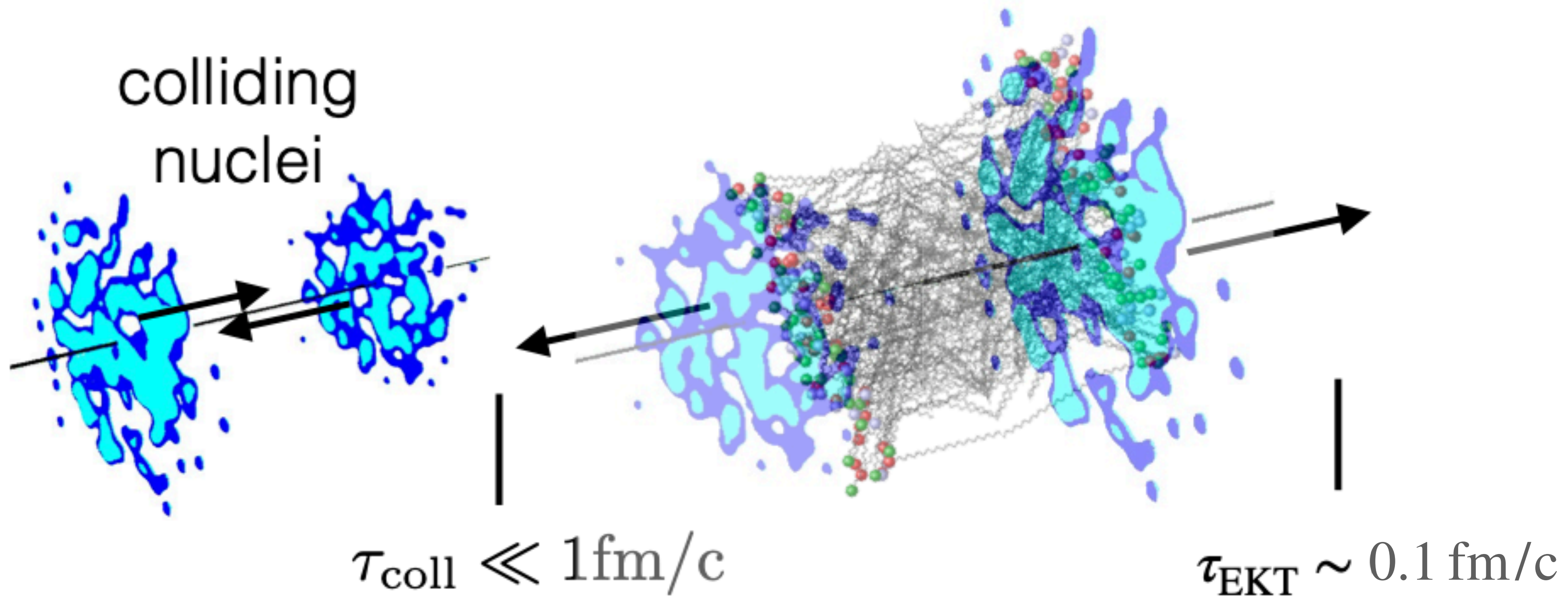
NOTE: EXTENSION TO 3D IS NOT TRIVIAL



RAPIDITY RESOLUTION ↔ LONG. RESOLUTION

LONGITUDINAL STRUCTURE





PERTURBATIVE CASE

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

COMPLETE LO CASE

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

SATURATION: 3D-IP-GLASMA

LO approximation for the CGC evolution of a dense-dense system. [*PRC* 108 (2023) 6, 064910]

IP-GLASMA 3+1D (V1)

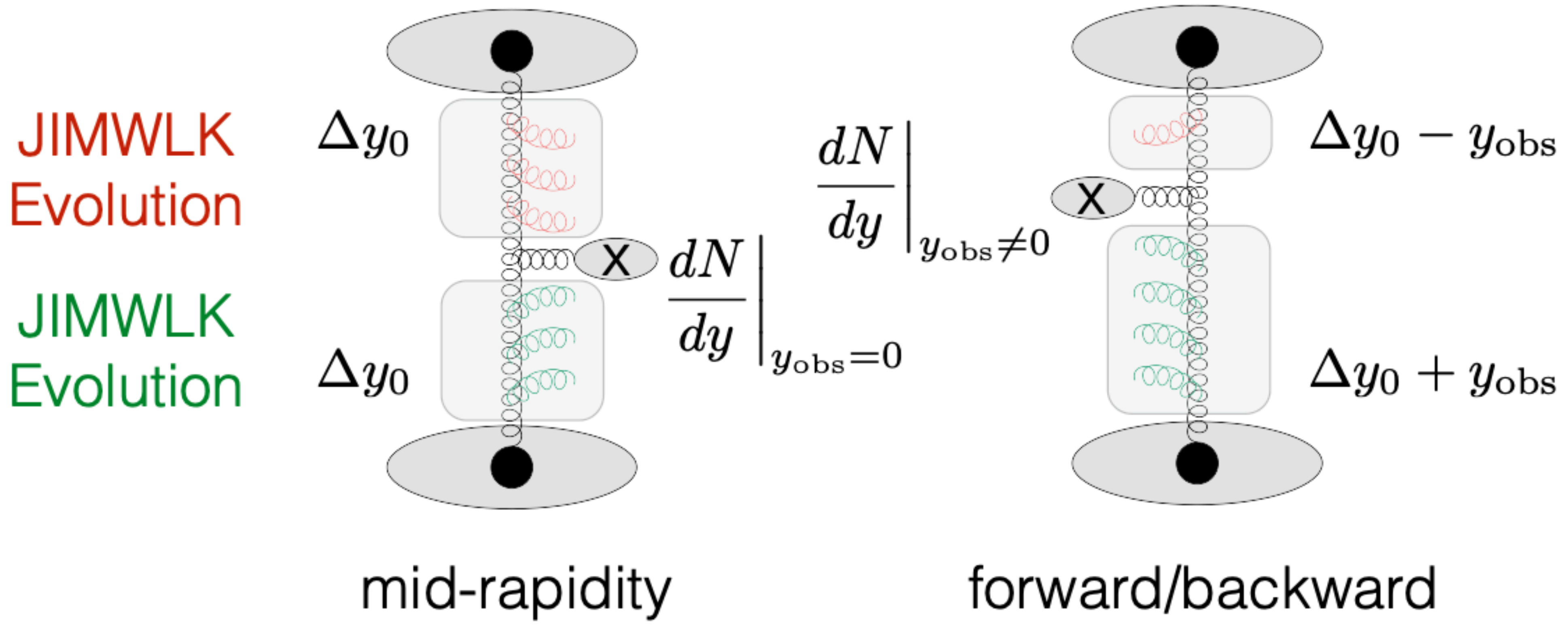
1) Sample nucleon positions (e.g. MC-Glauber)

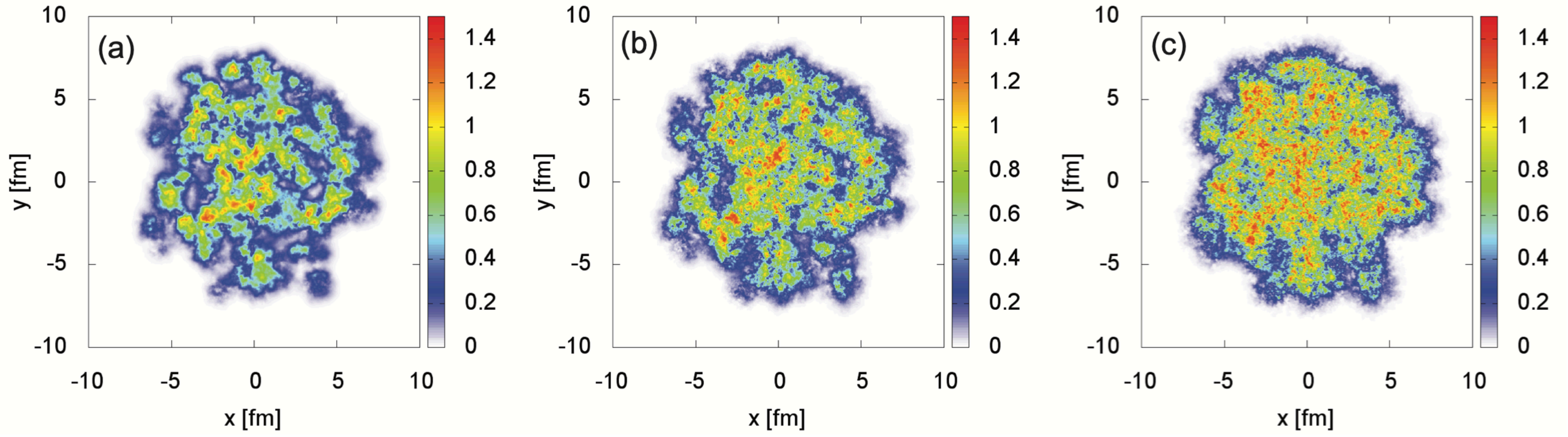
2) Sample color currents from those nucleons ($J_{A,B}$)

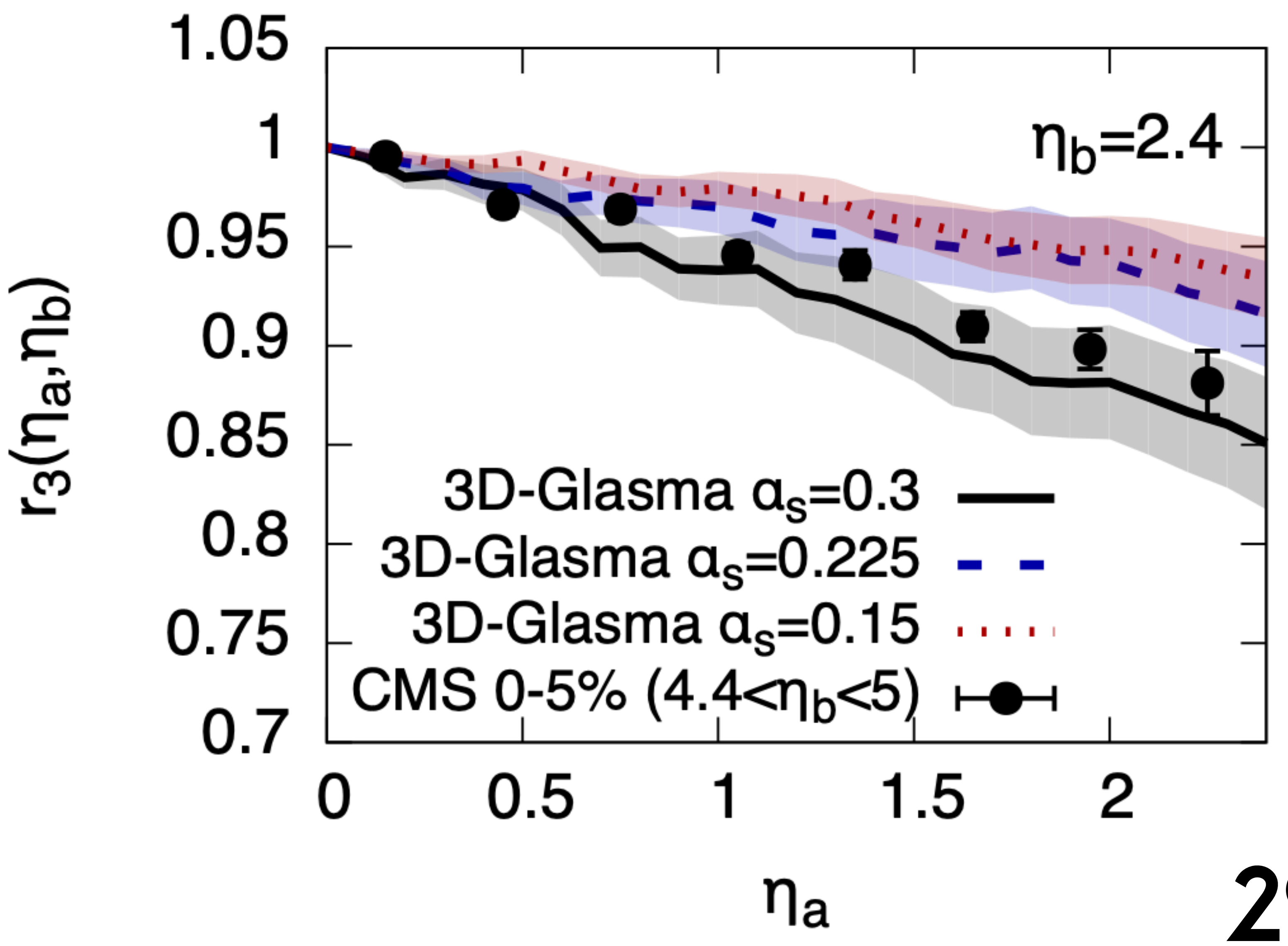
3) Boost your nuclei to the desired forward/backward cone using the JIMWLK equations

4) Solve Yang-Mills

5) Get $T^{\mu\nu}$ and evolution







SATURATION: 3D-IP-GLASMA

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

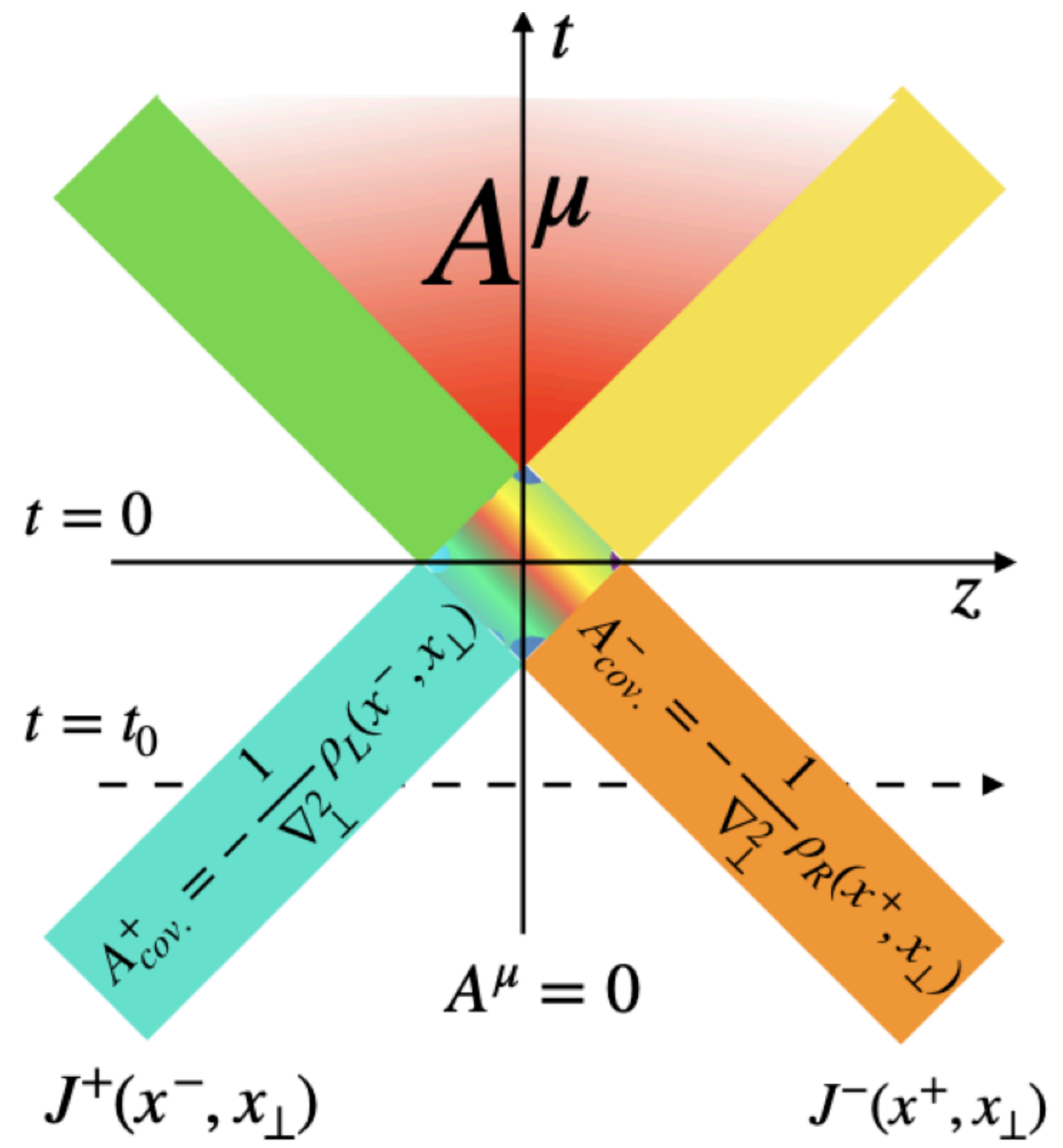
IP-GLASMA 3+1D (V2)

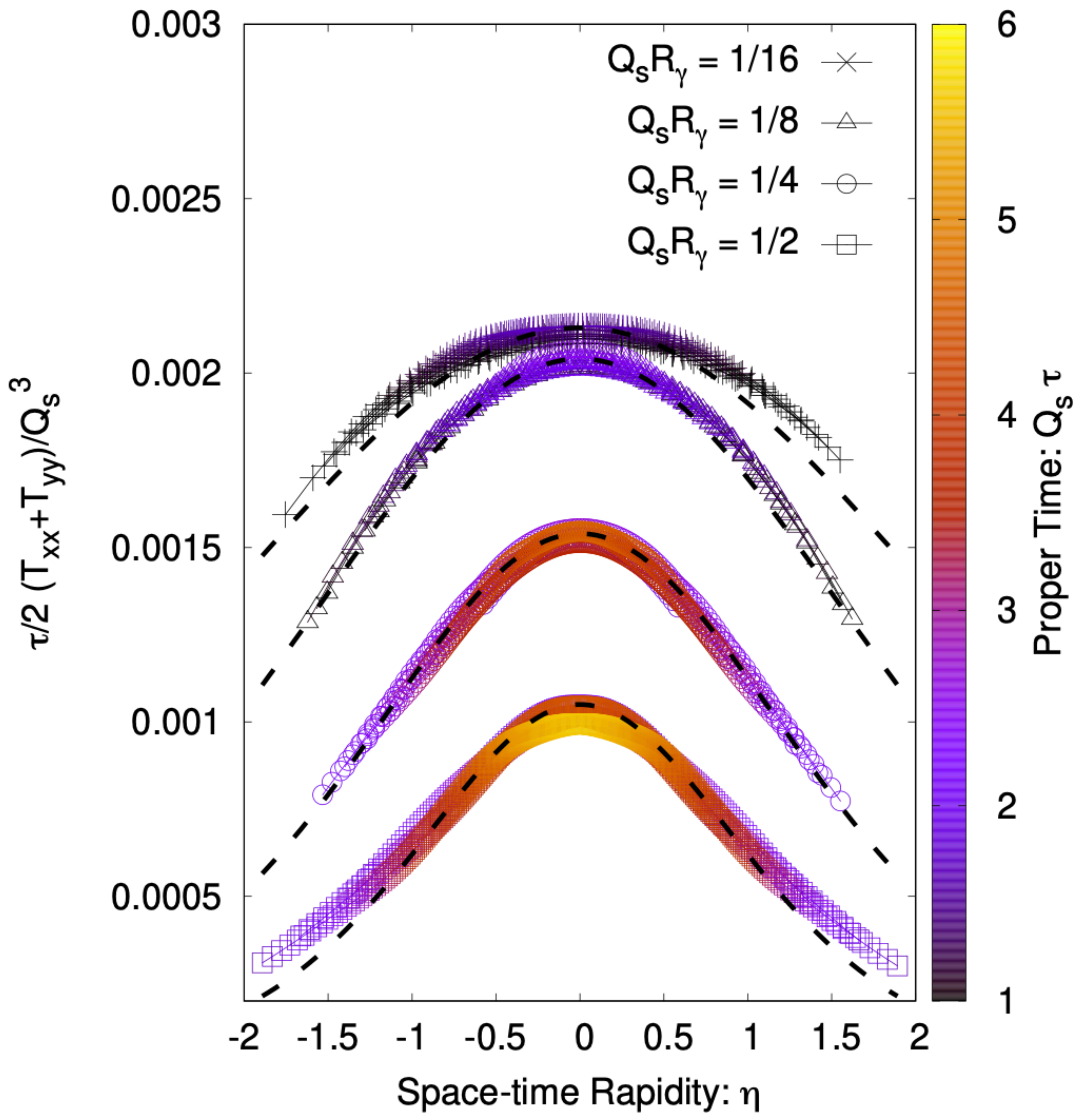
1) Sample nucleon positions (e.g. MC-Glauber)

2) Sample color currents from those nucleons ($J_{A,B}$) but now your nuclei have an extent in z (more accurate in $x^{\pm}$)

4) Solve Yang-Mills in 3+1D

5) Get $T^{\mu\nu}$ and evolution





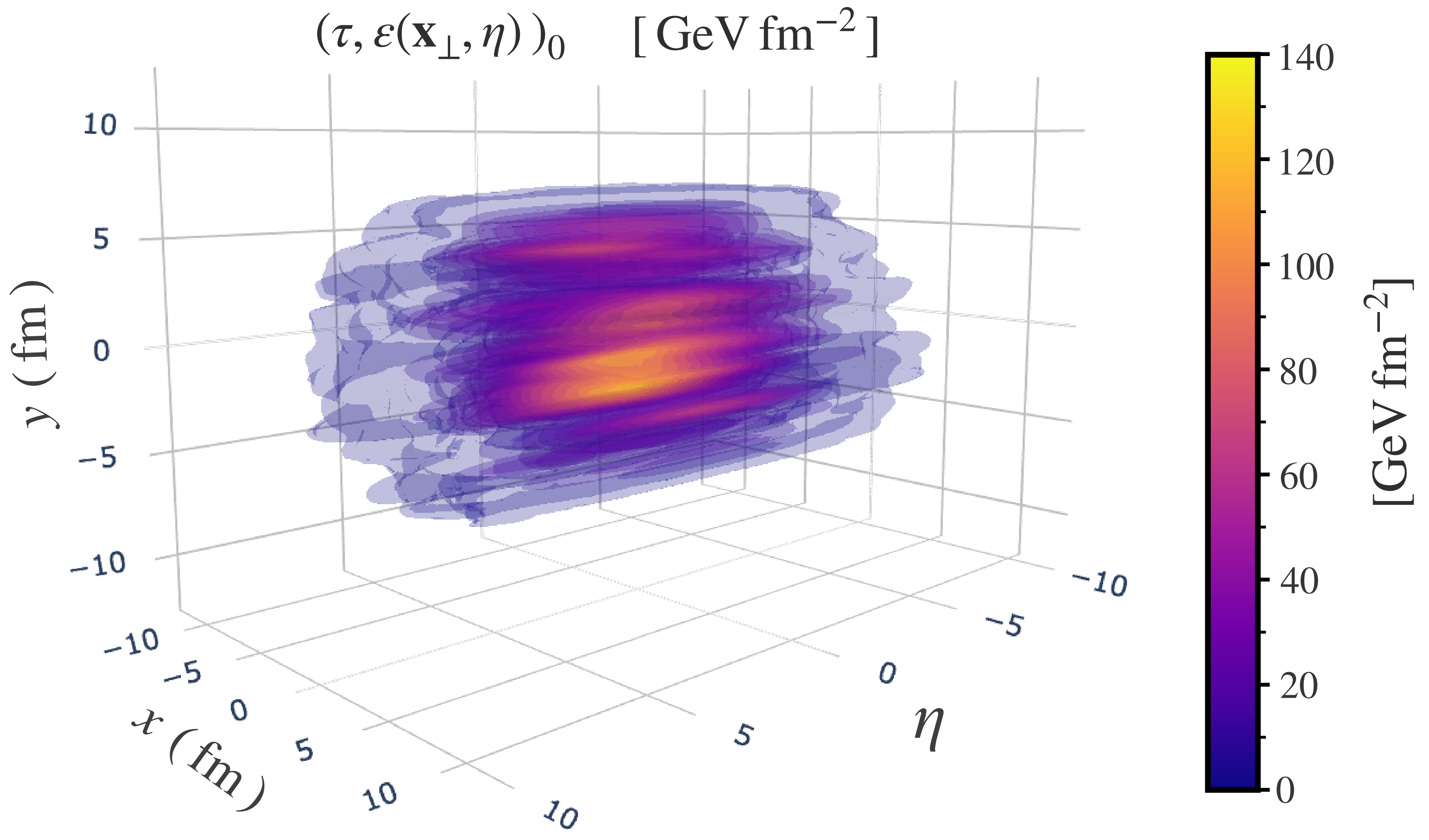
[*Phys.Rev.D* 103 (2021) 1, 014003]

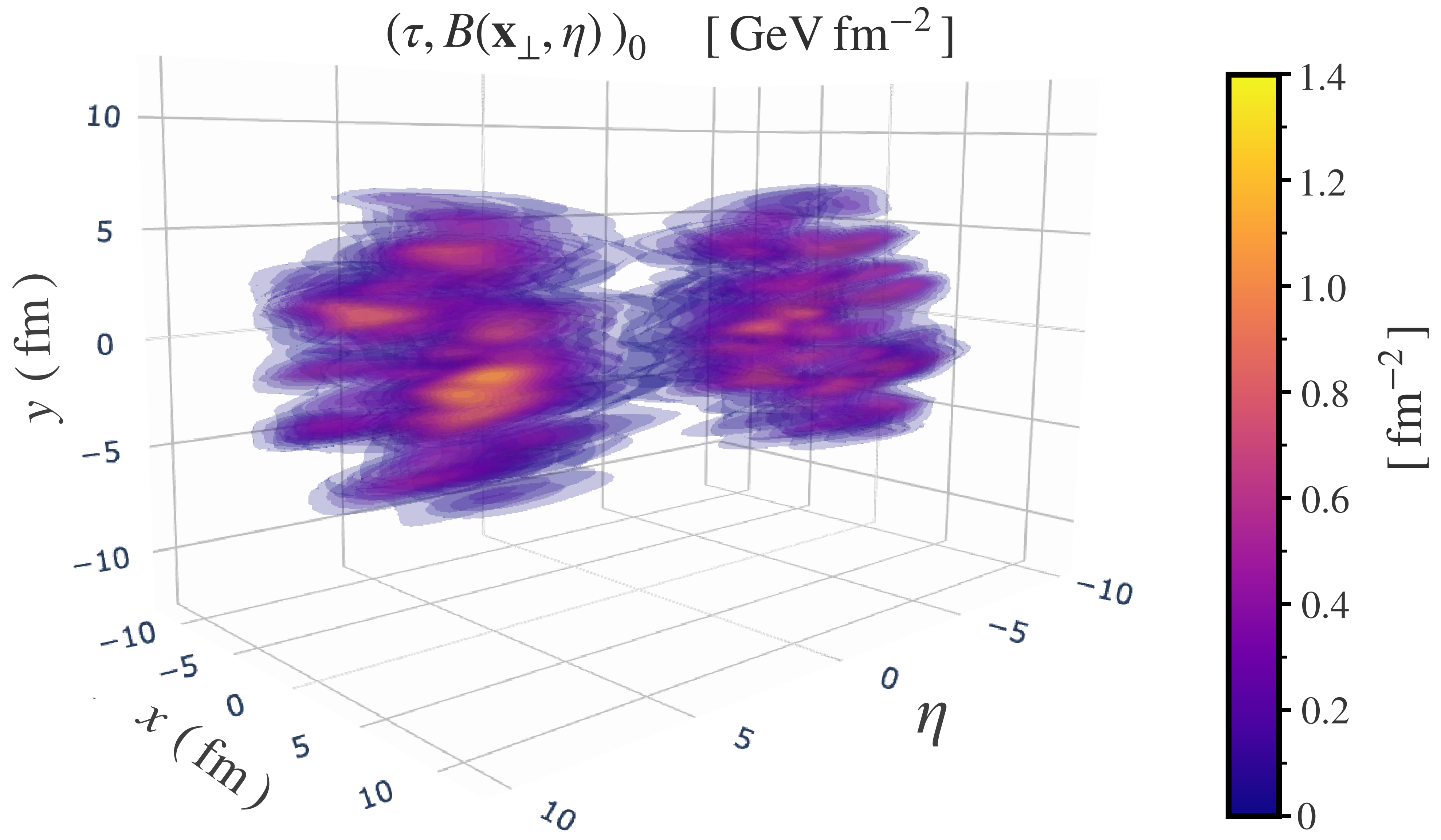
CGC IN 3D: THE McDIPPER

Monte-Carlo Dipole Parallel Event GeneRator

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

Perturbative realisation of the LO glasma graph + Baryon stopping by CGC

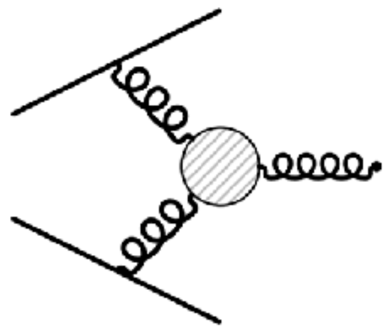




FROM MICRO TO MACRO

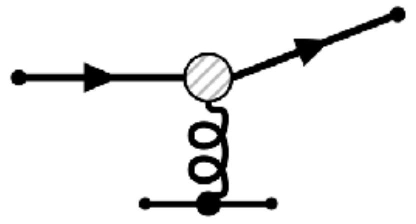
- Low-x gluons dominate the midrapidity region

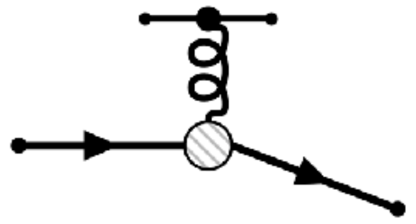
$$\frac{dN_g}{d^2\boldsymbol{x}d^2\boldsymbol{p}dy} = \frac{g^2}{8\pi^5 C_F \boldsymbol{p}^2}\int \frac{d^2\boldsymbol{q}}{(2\pi)^2}\frac{d^2\boldsymbol{k}}{(2\pi)^2}(2\pi)^2\delta(\boldsymbol{p}+\boldsymbol{q}-\boldsymbol{p}) \times \Phi_1(x_1,\boldsymbol{x},\boldsymbol{q})\ \Phi_2(x_2,\boldsymbol{x},\boldsymbol{k})$$



- 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→ $q\bar{q}$ production through gluon fusion

CGC IN 3D: 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 functions: (uGDF) + (collinear) parton distribution functions (PDFs)

Gluon production: $k_\perp$ factorization ~ UGD^2

Quark production hybrid formalism ~ PDF ⊗ UGD

- 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 EbE input.

[GM, Schlichting, Elfner, PRC 109 (2024) 4, 044916]

FROM MICRO TO MACRO

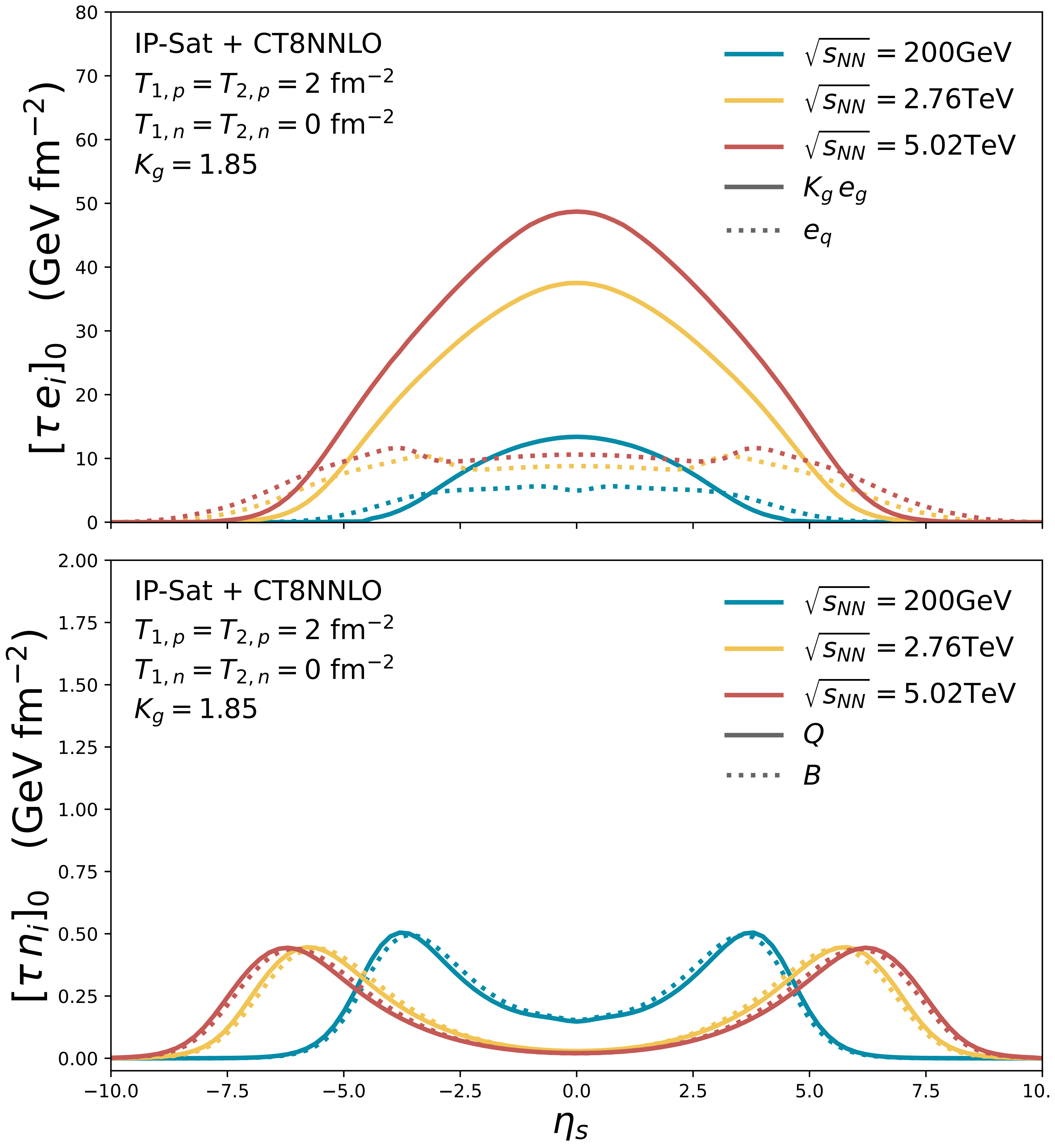
- Macroscopic quantities (energy, charges) are computed as moments of the single particle distributions
  - Total energy deposition

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

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

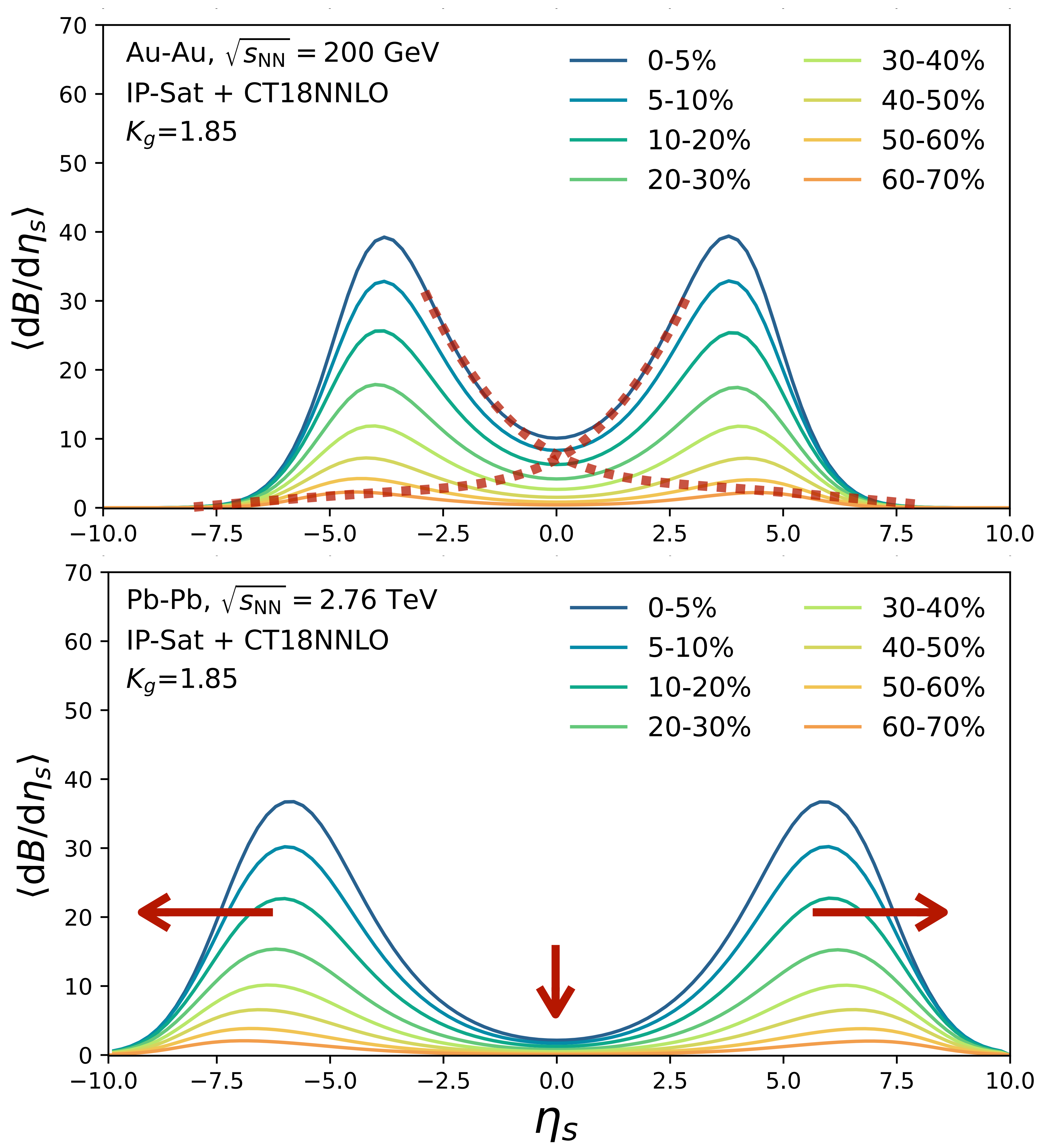
$$(Q\tau)_0 = \sum_f Q_f \int d^2\mathbf{p}\ \left[\frac{dN_f}{d^2\mathbf{x}d^2\mathbf{p}dy} - \frac{dN_{\bar{f}}}{d^2\mathbf{x}d^2\mathbf{p}dy} \right]_{y=\eta_s}$$

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



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!

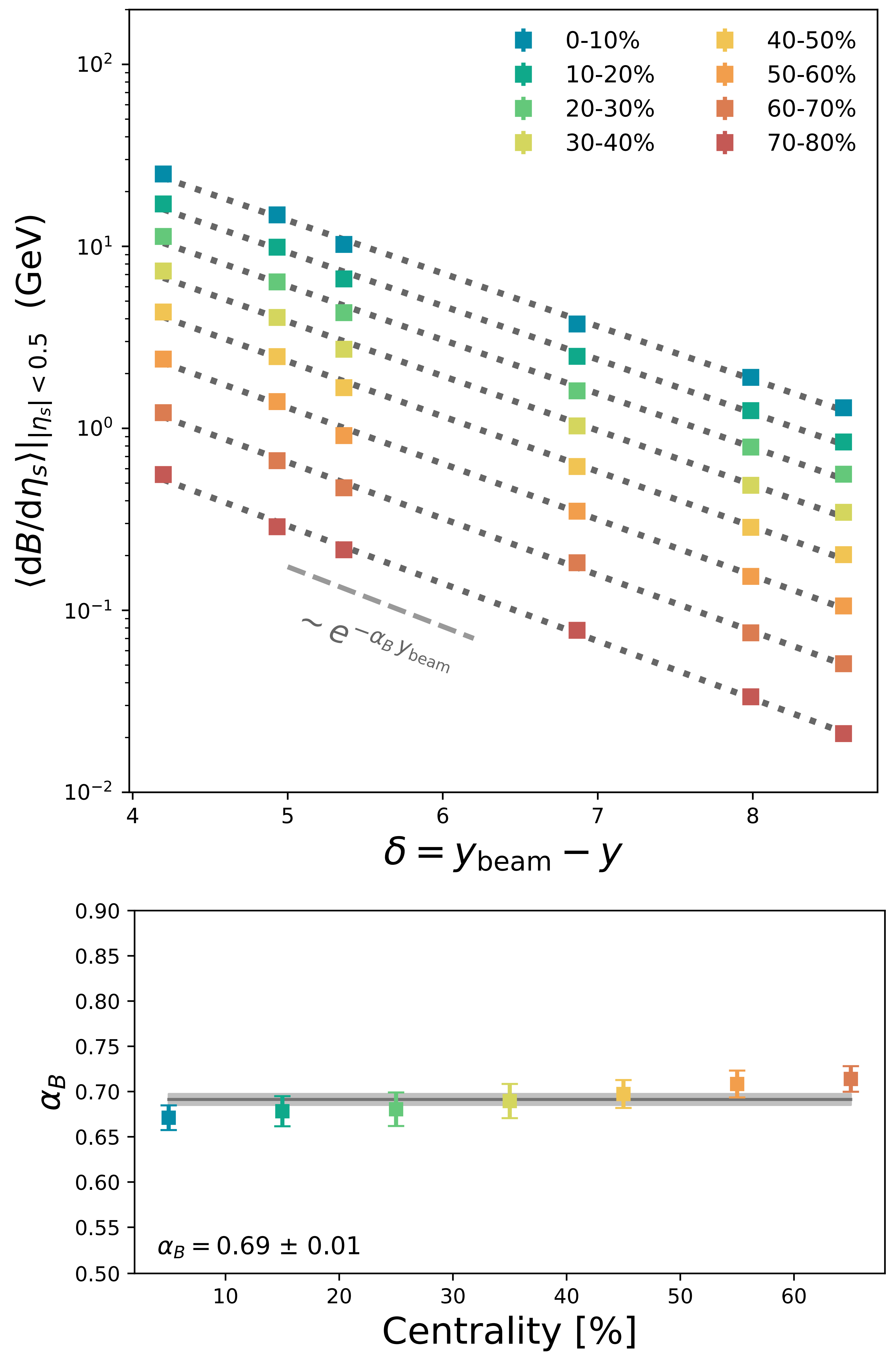


(see *PRC* 108 (2023) 4, 4)

CHARGE DEPOSITION

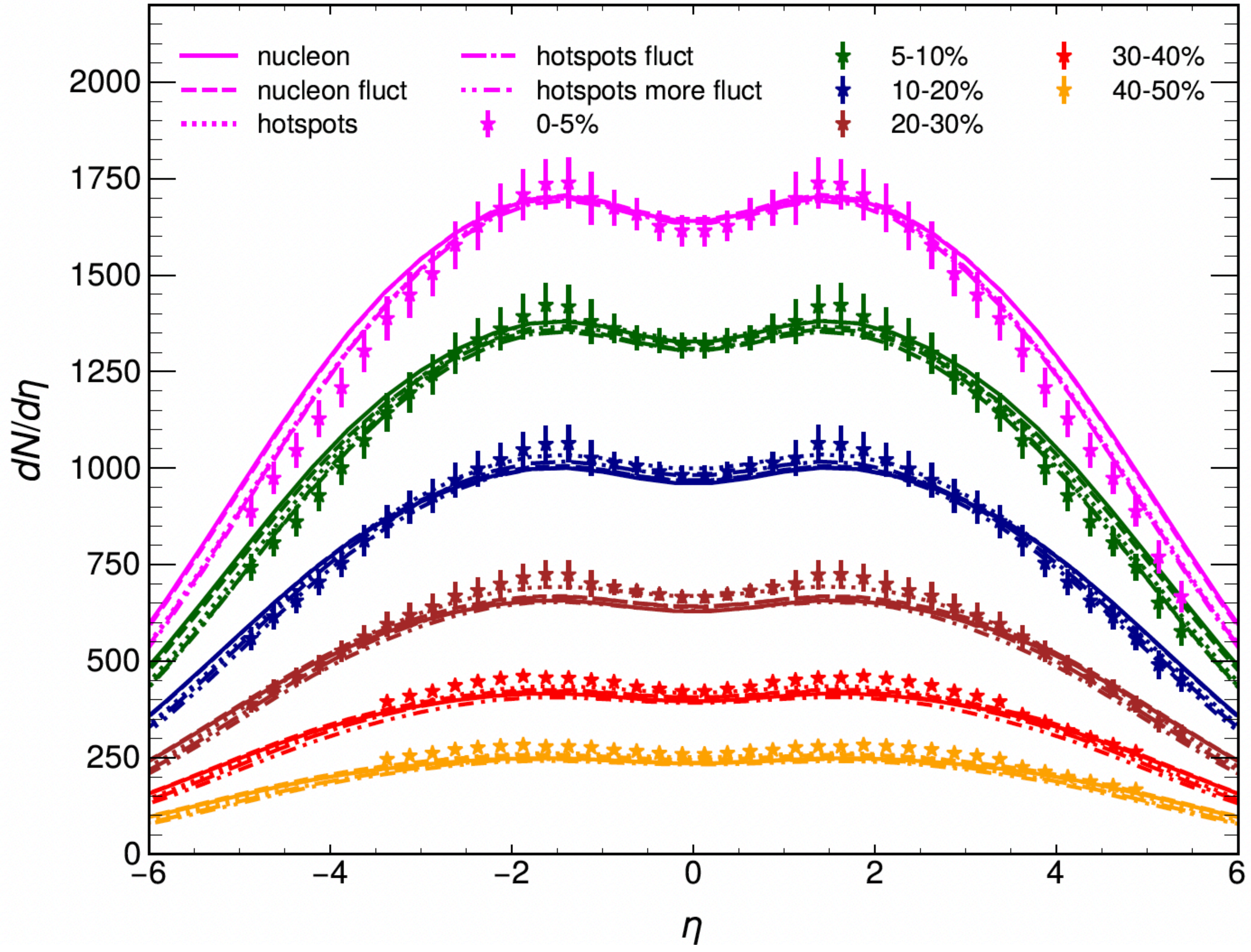
- Non-trivial interaction between x-dependence of gluon uGDs and quark PDFs gives tails in the charge deposition
- Even at higher rapidities, non-zero baryon stopping is found!
- Midrapidity baryon charge deposition follows an exponential shift in the rapidity shift

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

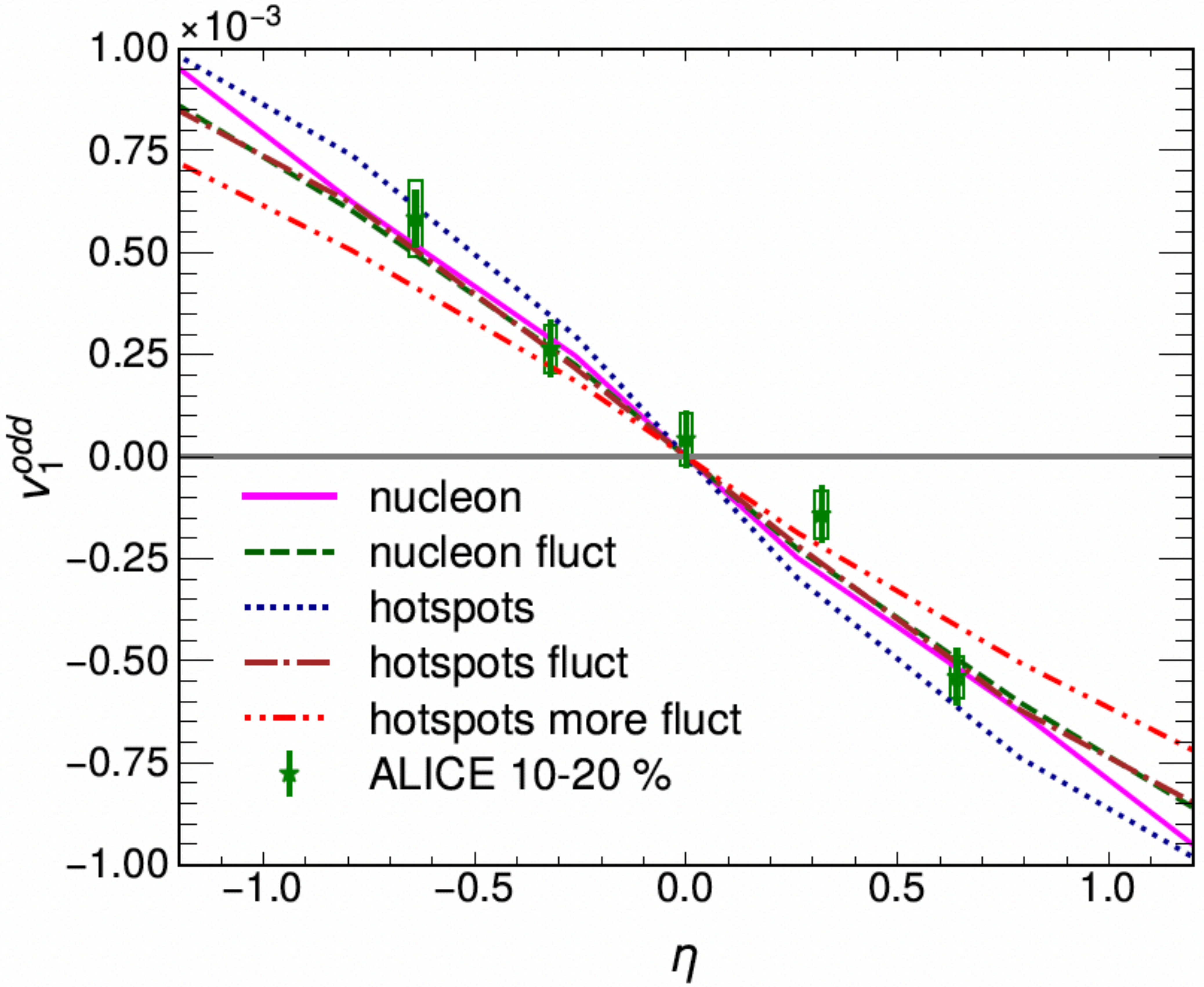


THE McDIPPER+CLVISC

SOME INTERESTING RESULTS (...TO ME)



Minimal IC tuning.

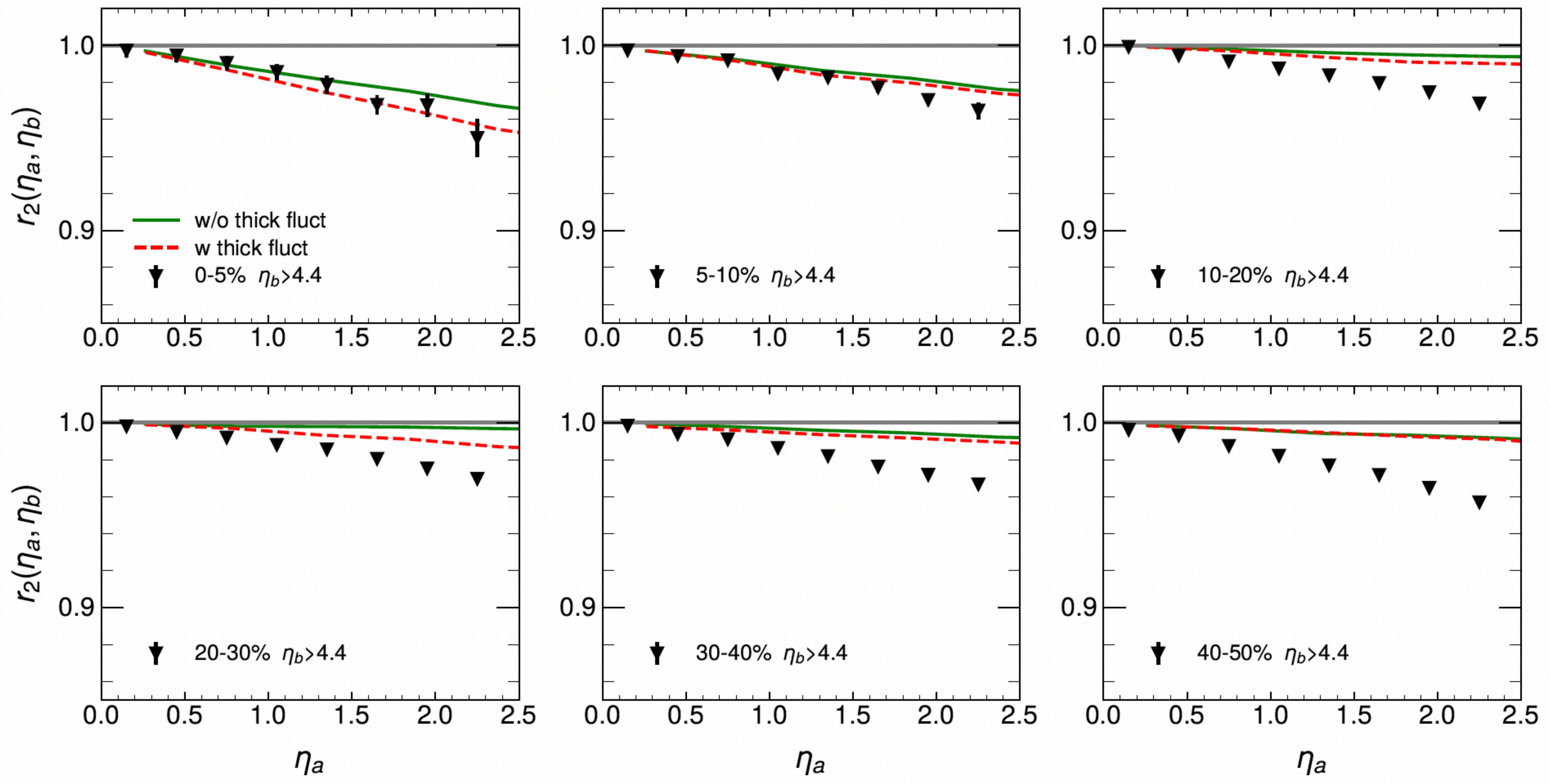


Added hotspot fluctuations

[GM, Schlichting, Zhu, *in preparation*]

THE McDIPPER+CLVISC

SOME INTERESTING RESULTS (...TO ME)



Decorrelation due to non-trivial x-dependence of uGHs and PDFs

Additional fluctuations needed to explain flow decorrelation. WIP: charge fluctuations in the valence sector (PDF sampling of valence charges)

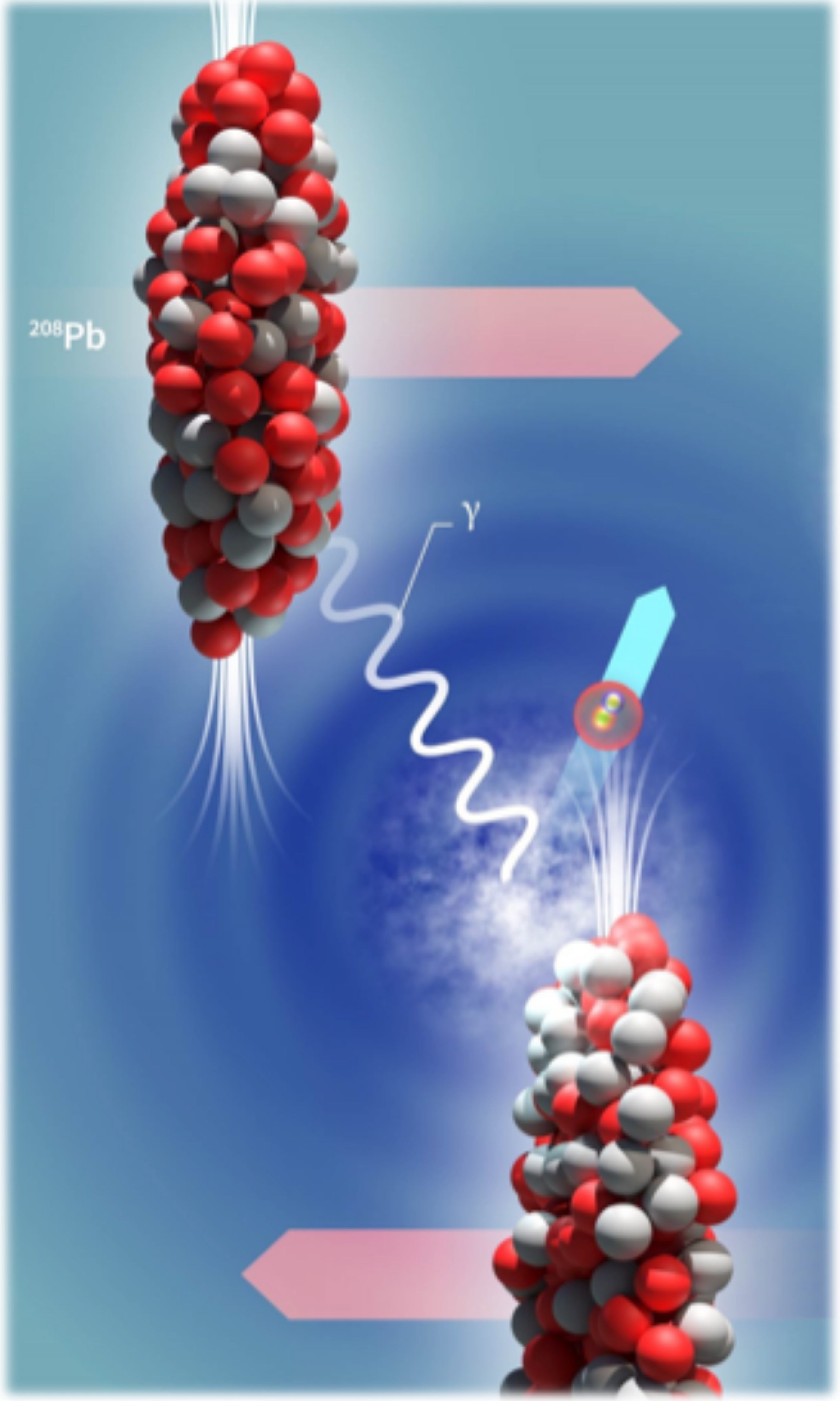
[GM, Schlichting, Zhu, *in preparation*]

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.

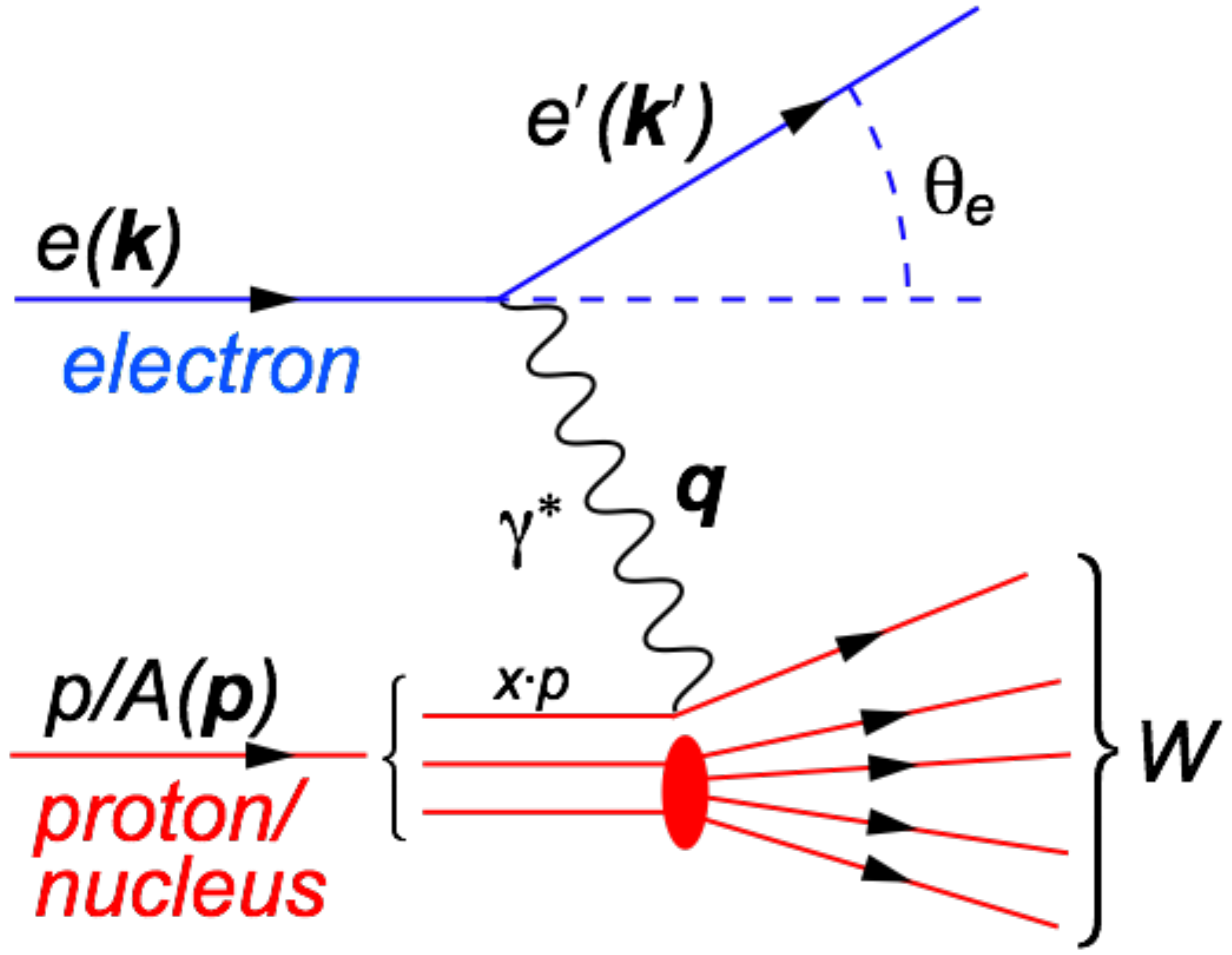
ULTRA PERIPHERAL COLLISIONS

AS A WAY TO TEST THE INITIAL STATE



UPC PHYSICS ~ DIS PHYSICS

(WITH EXTRA STEPS)



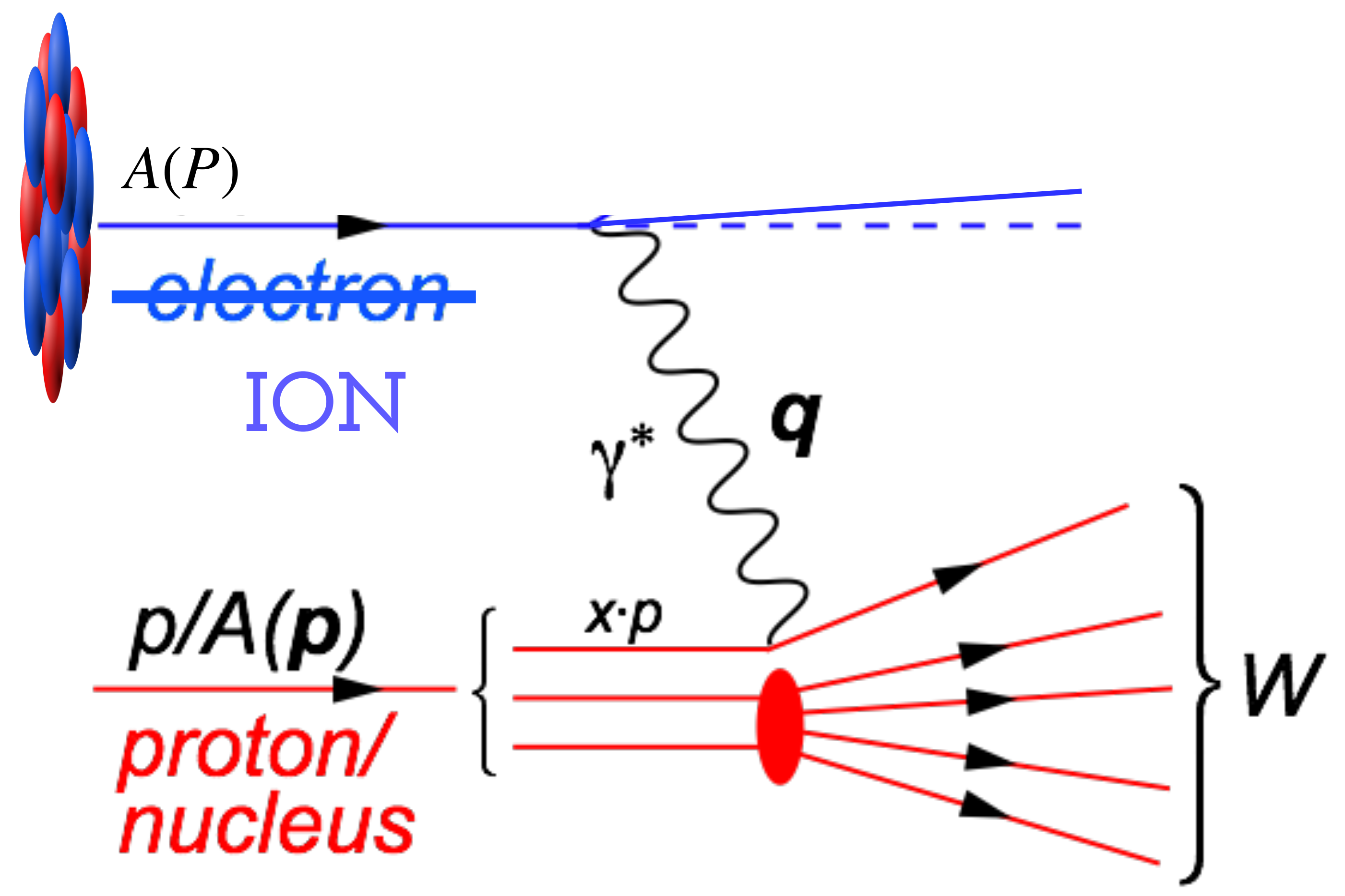
$s = (k + p)^2$ → Center of mass energy (squared)

$Q^2 = -q^2$ → Resolution power

$x = \frac{-q^2}{p \cdot q}$ → Fraction of momentum carried by interacting parton

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

UPC PHYSICS ~ DIS PHYSICS
(WITH EXTRA STEPS)



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

$Q^2 = -q^2$ → Resolution power

$x = \frac{-q^2}{p \cdot q}$ → Fraction of momentum carried by interacting parton

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

WITH CAVEATS

- Produced photon is quasi-real, low virtuality
- XS of any process is a convolution of the rate of production with the photonuclear nXS

$$\sigma_x = \int \mathrm{d}k \, \frac{\mathrm{d}N_\gamma}{\mathrm{d}k} \sigma_x^\gamma(k)$$

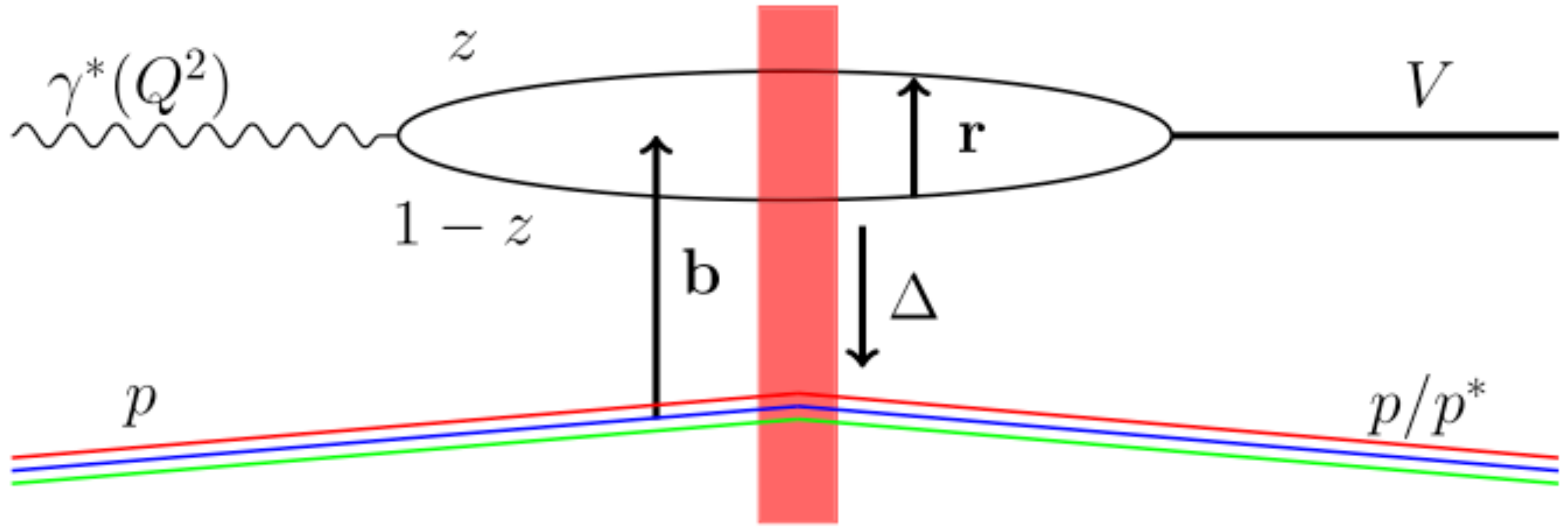
- Both incoming hadrons can be the photon source

$$\frac{d\sigma_{\mathrm{PbPb}}(y)}{dy} = N_{\gamma/\mathrm{Pb}}(y, M)\sigma_{\gamma\mathrm{Pb}}(y) + N_{\gamma/\mathrm{Pb}}(-y, M)\sigma_{\gamma\mathrm{Pb}}(-y)$$

- Possible quantum interference effects!

ACCESSING NUCLEAR SPATIAL INFORMATION:

VECTOR MESON PRODUCTION



Coherent:
Fully diffractive

$$e + A \rightarrow e + A + J/\psi$$

Incoherent:
Breaks up the nucleus.

$$e + A \rightarrow e + (A' + X) + J/\psi$$

ACCESSING NUCLEAR SPATIAL INFORMATION:

VECTOR MESON PRODUCTION

- **Coherent:** Fully diffractive

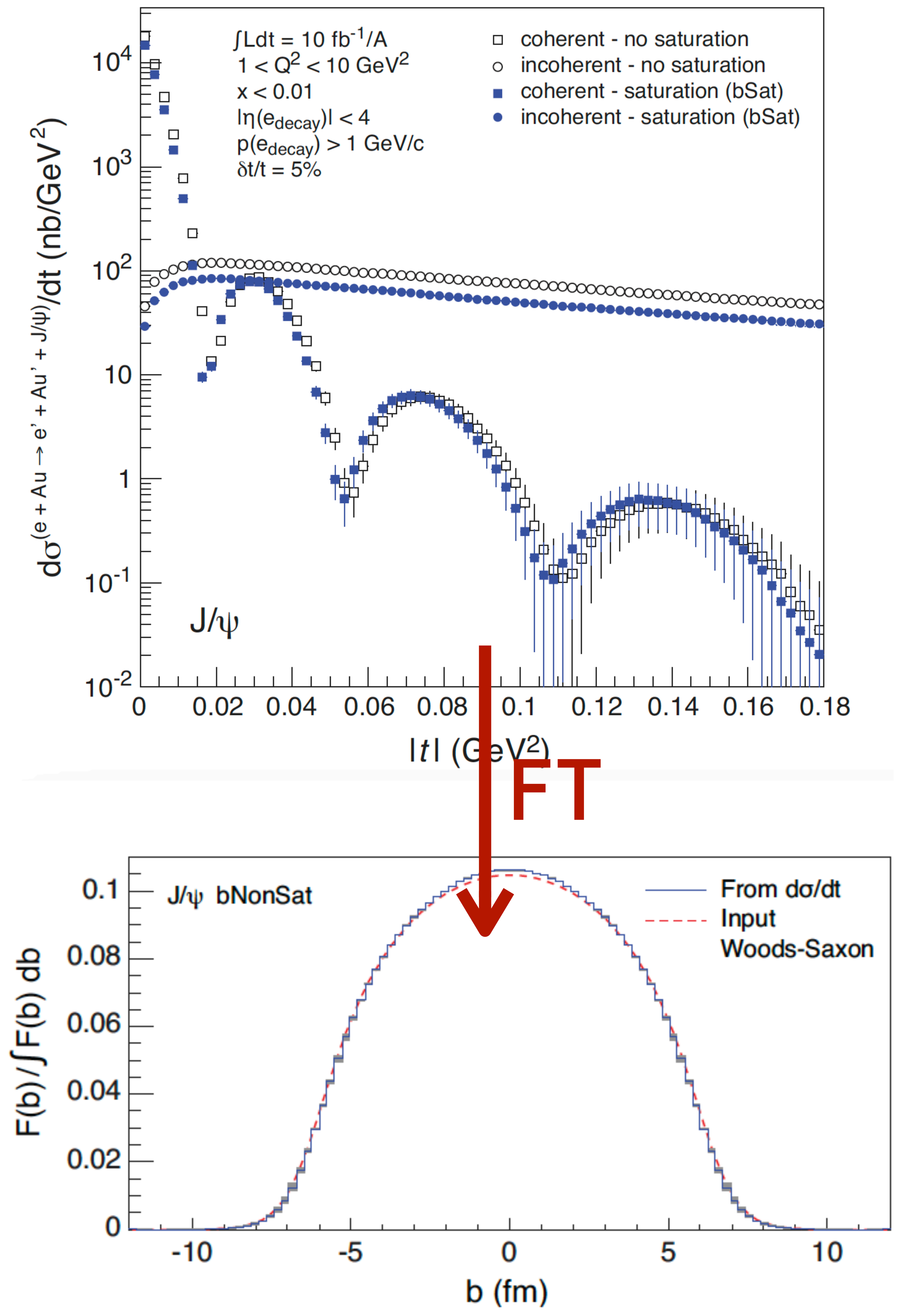
  $e + A \rightarrow e + A + J/\psi$

  Incoherent: Breaks up the nucleus.

  $e + A \rightarrow e + (A' + X) + J/\psi$

- **Coherent:** Sensitive to average geometry

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

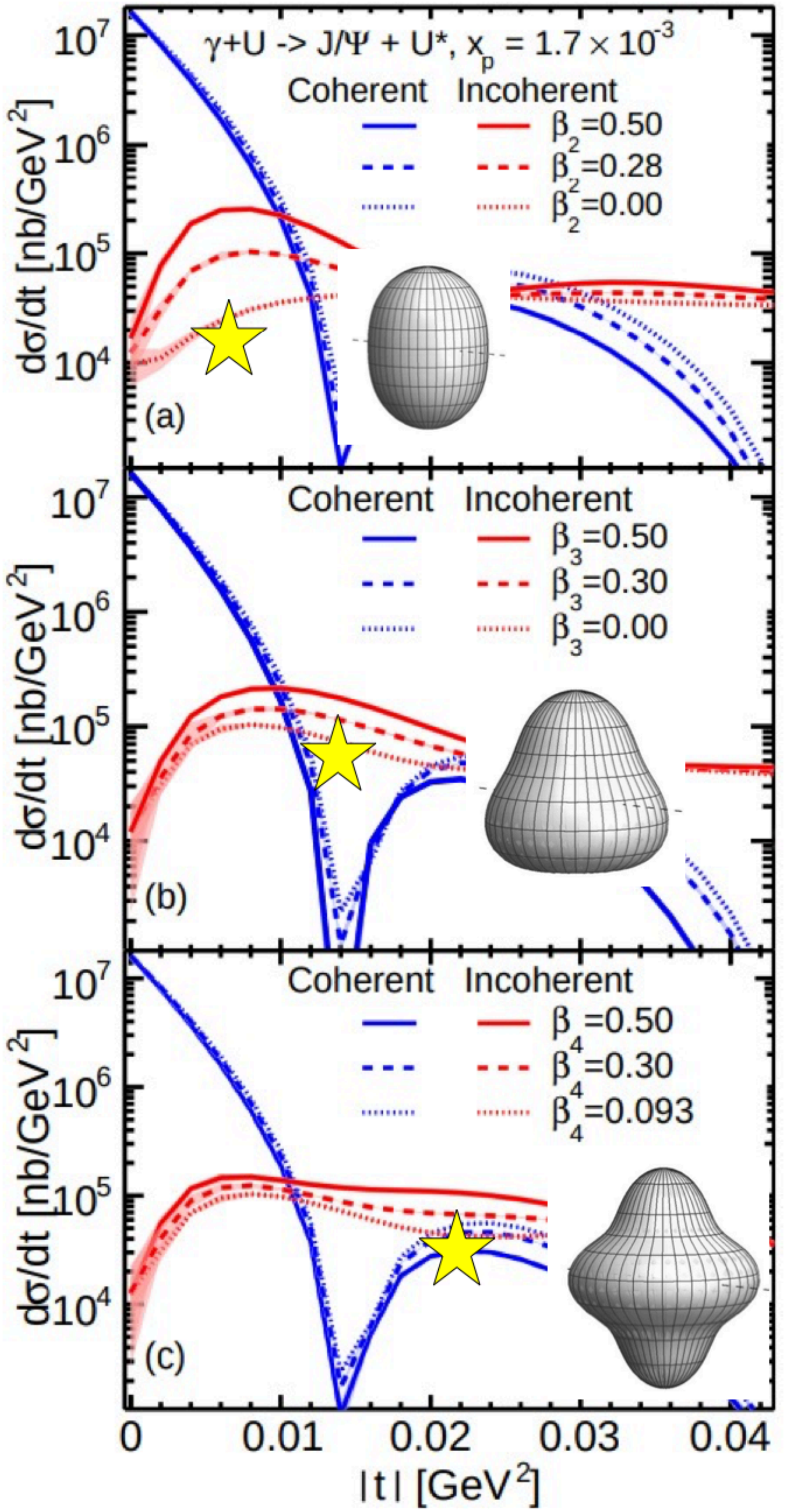


VECTOR MESON PRODUCTION

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

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

- Incoherent: Sensitive to EbE fluctuations
  Sensitive to nuclear structure



ACCESSING NUCLEAR SPATIAL INFORMATION:

VECTOR MESON PRODUCTION

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

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

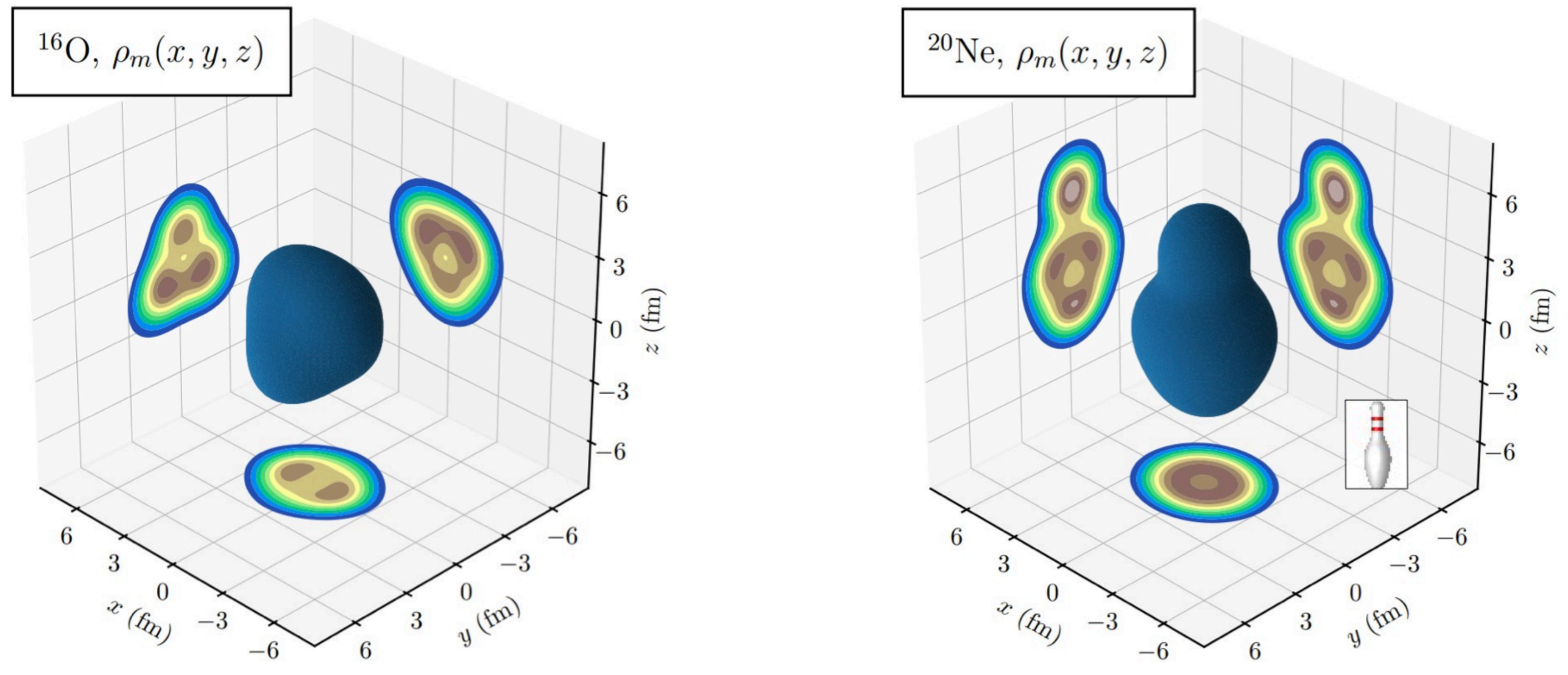
- Coherent: Sensitive to average geometry

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

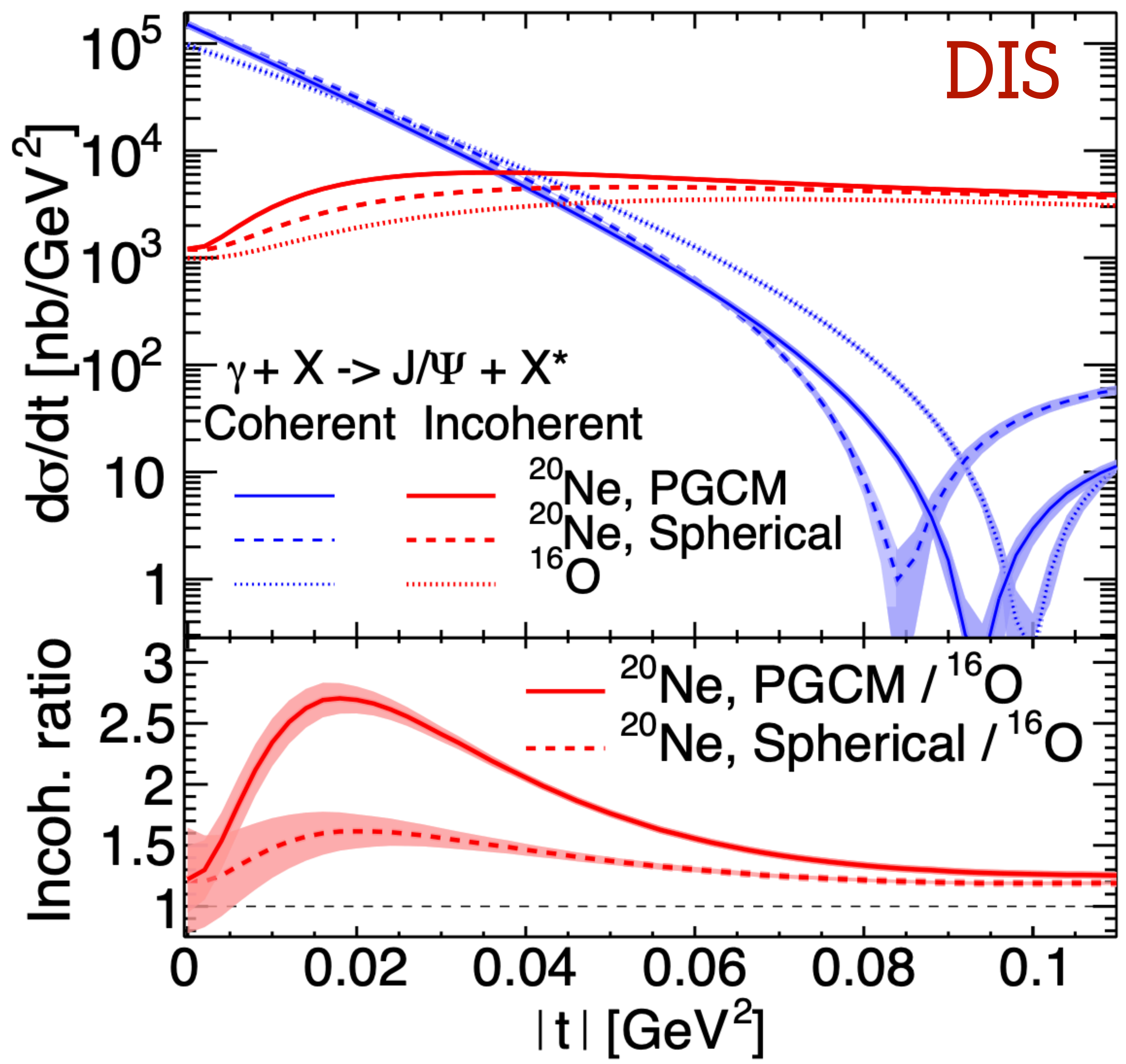
- Incoherent: Sensitive to EbE fluctuations

  Sensitive to nuclear structure

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]

ACCESSING NUCLEAR SPATIAL INFORMATION:

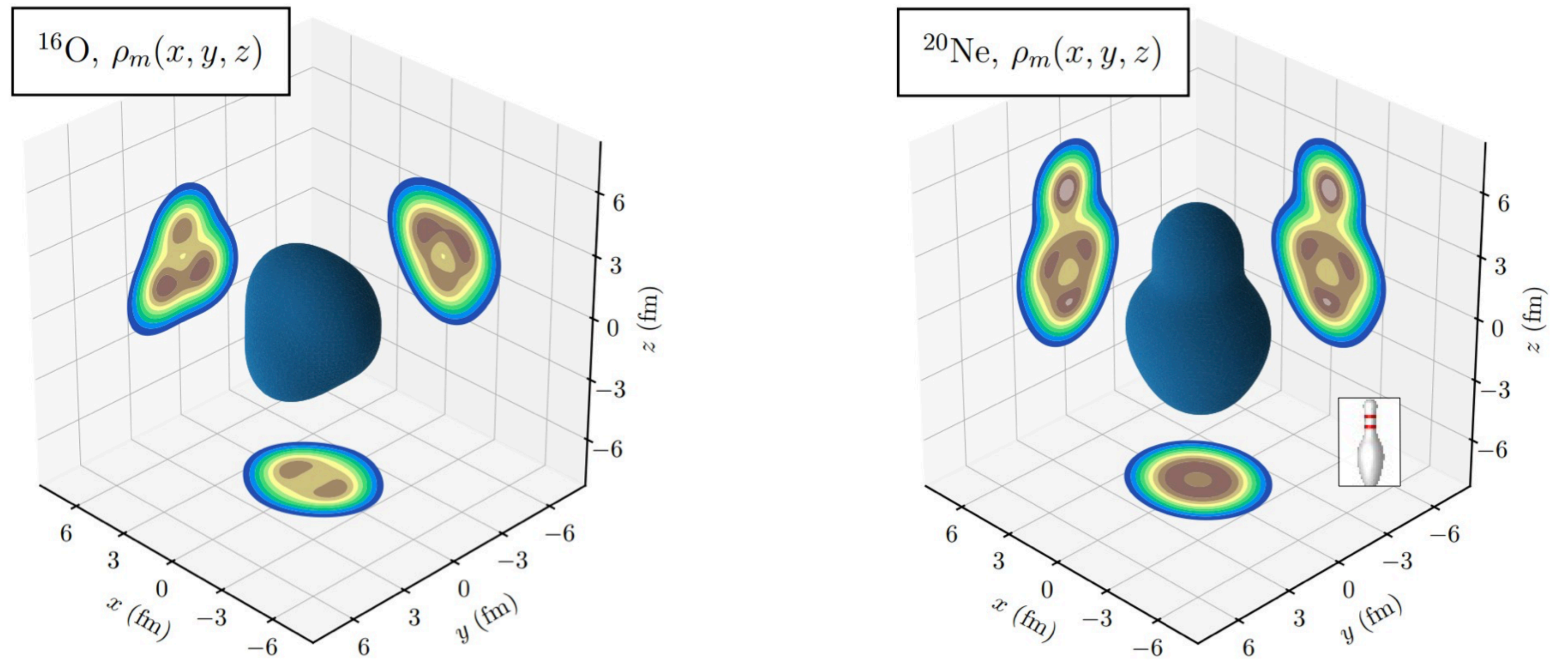
VECTOR MESON PRODUCTION

Coherent: Fully diffractive

$$e + A \to e + A + J/\psi$$

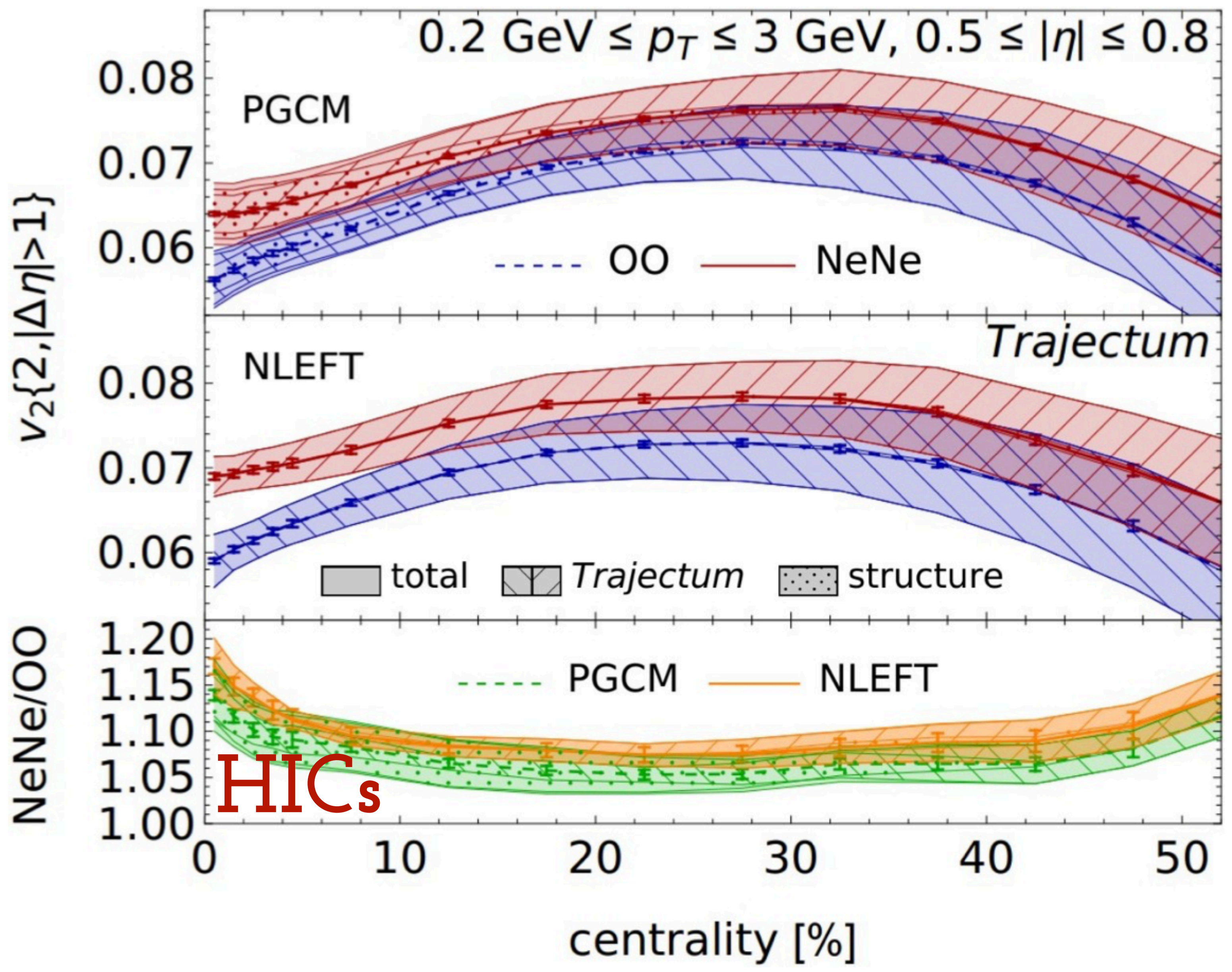
Incoherent: Breaks up the nucleus.

$$e + A \to e + (A' + X) + J/\psi$$



- **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



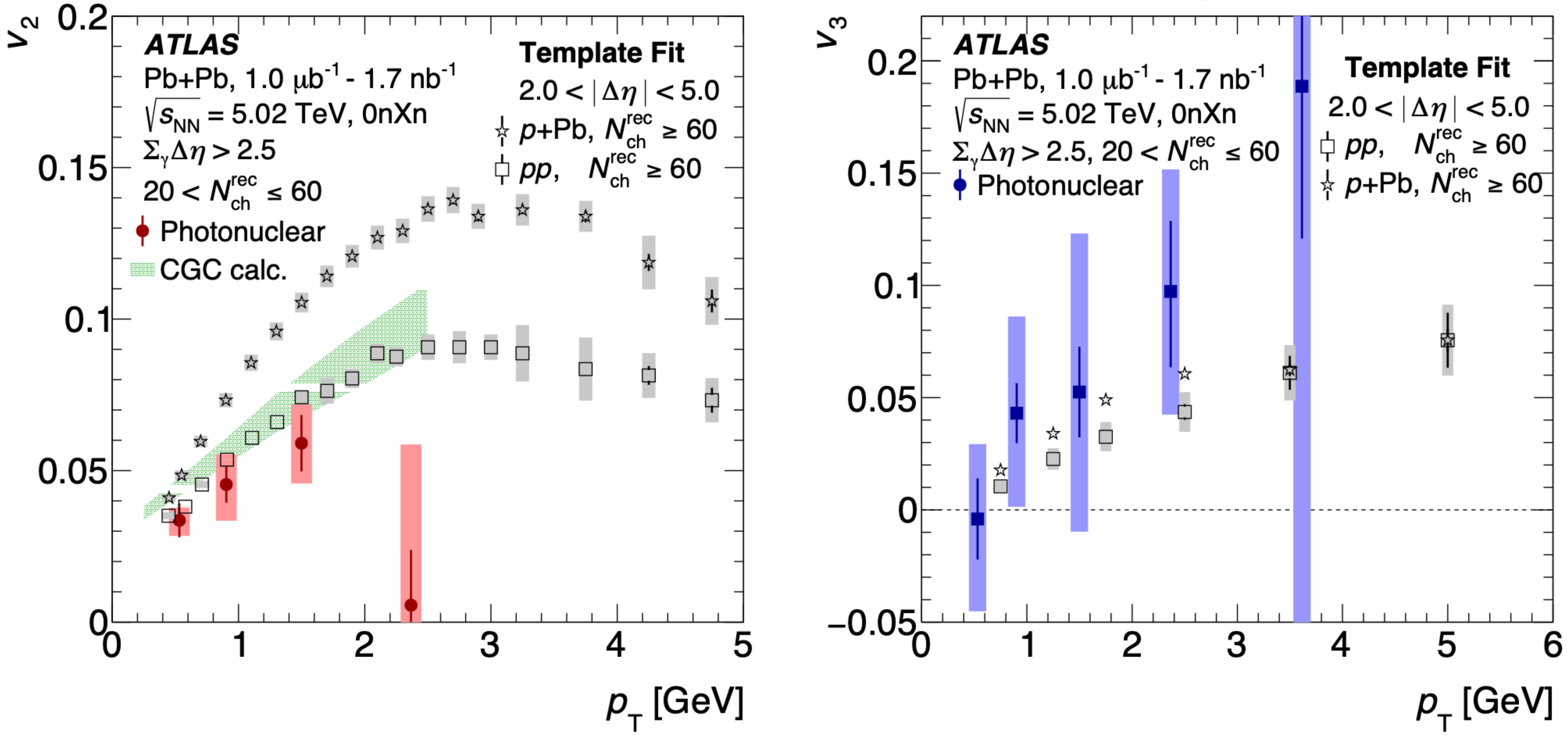
Ab initio computations of nuclear densities can help include ***nucleonic n-point*** correlations into initial geometry

Flanking from both LHC and EIC?

ANISOTROPY IN UPCS

[*PRC*, vol. 104, no. 1, p. 014903, 2021]

- Non vanishing 2-particle correlations after non-flow subtraction in Pb+Pb collisions at 5.02 TeV



- Correlations seem to be described well by CGC via dipole-dipole correlations (Corr. of four Wilson Lines)

- More realistic of the computation centered on 2-gluon production formula, [JHEP, 2022, 77 (2022).]

- Alternative explanation lies in the creation of a small droplet of QGP taking the cuasivirtual photon as a ρ-meson

CORE IDEAS OF THE EIC

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

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

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

QUESTIONS FOR UPCS

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

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

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

SYNERGIES HICS-UPCS

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

QUESTIONS FOR UPCS

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

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

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

SYNERGIES HICS-UPCS

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

QUESTIONS FOR UPCS

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

B How do **color charges**, (and colorless 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**?

SYNERGIES HICS-UPCS

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

QUESTIONS FOR UPCS

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

B. How do **color charges**, (and colorless 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**?

SYNERGIES HICS-UPCS

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

QUESTIONS FOR UPCS

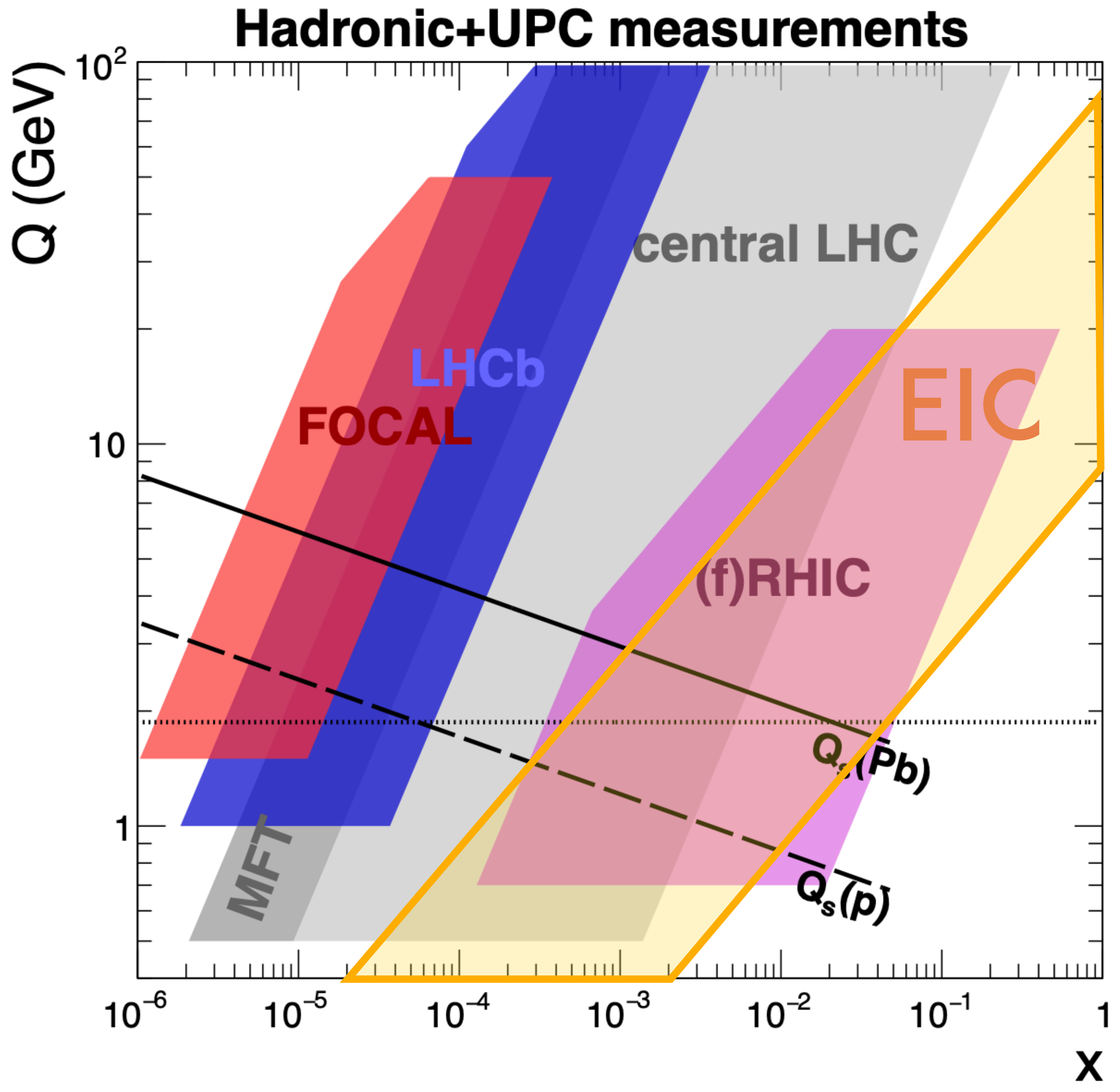
A How are quarks and gluons, and their spins, **distributed in space and momentum** inside the nucleon?

B How do **color charges**, (and colorless 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**?

STILL A LOT TO TALK ABOUT

- Hadron correlations and Quantum Effects.
- 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]
- DIS in the EIC era
  - More control on virtual photon energy
  - In general larger-x, large Q^2 sweep



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.

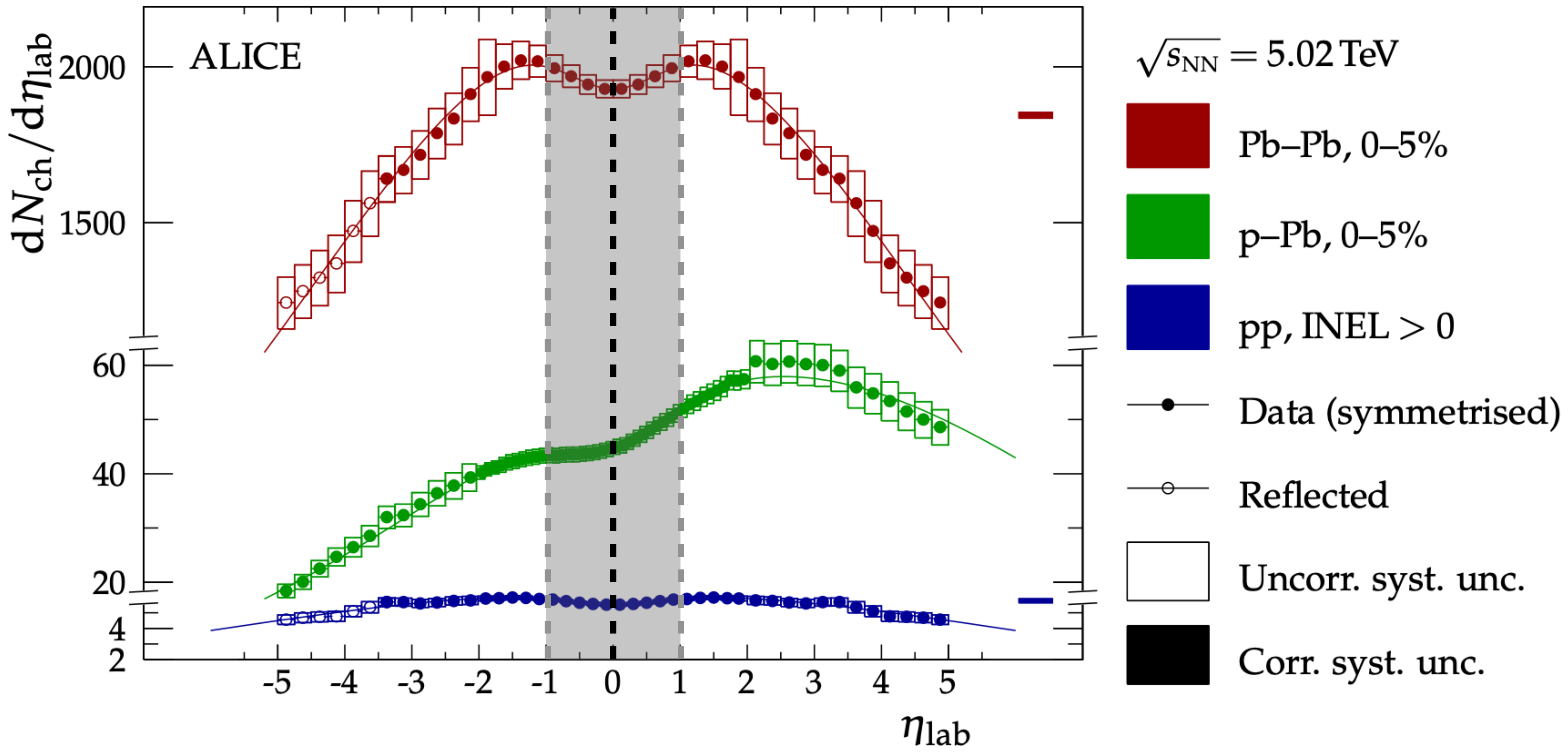
Necessary: Models should establish themselves *conceptually* (if not computationally) consistent throughout wide range of energies and systems.

Exciting Future: The EIC and UPCs pose as excellent complements to the HICs program. The ICs can be refined using its measurements.

BACK-UP

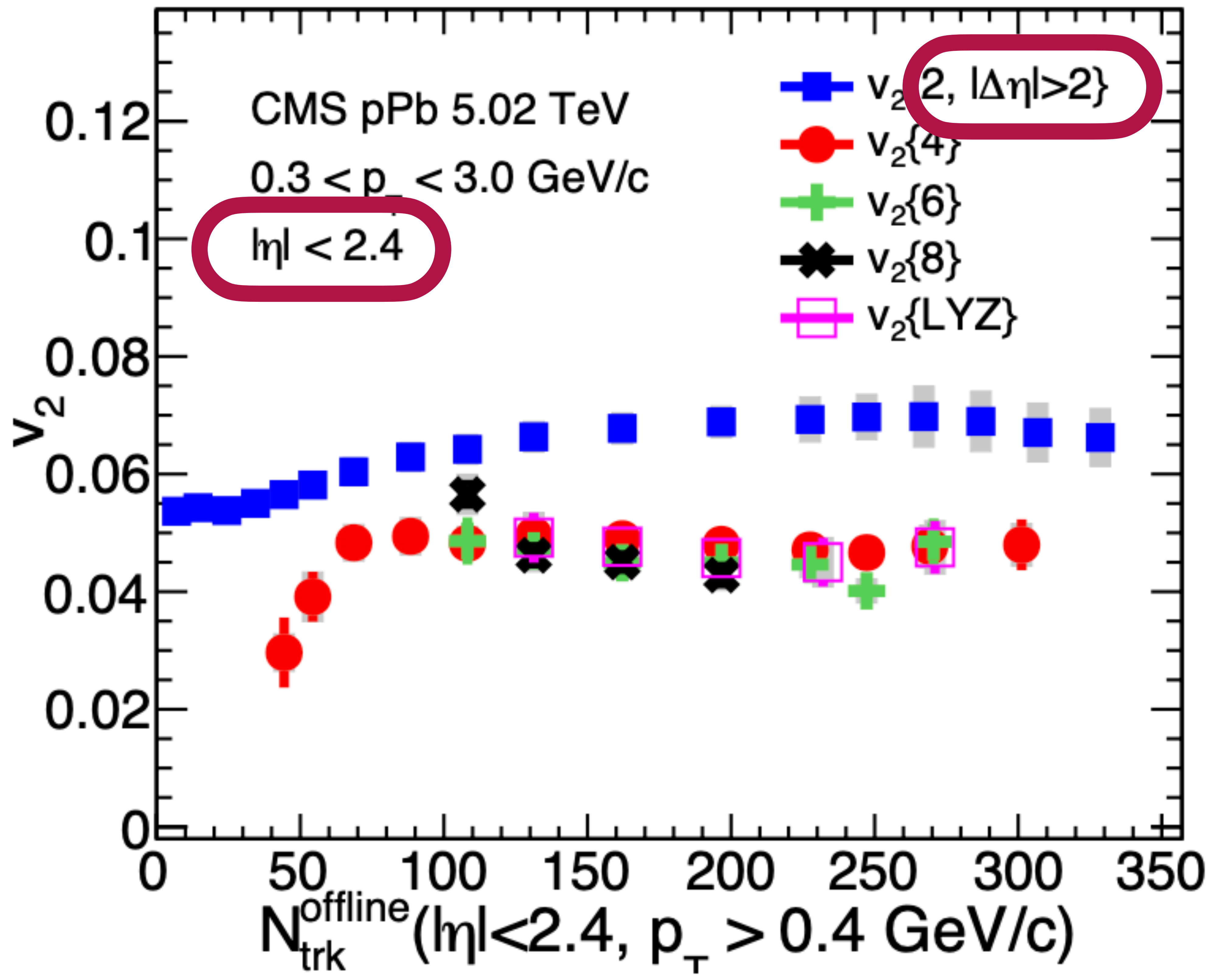
LET'S TAKE A LOOK FIRST AT

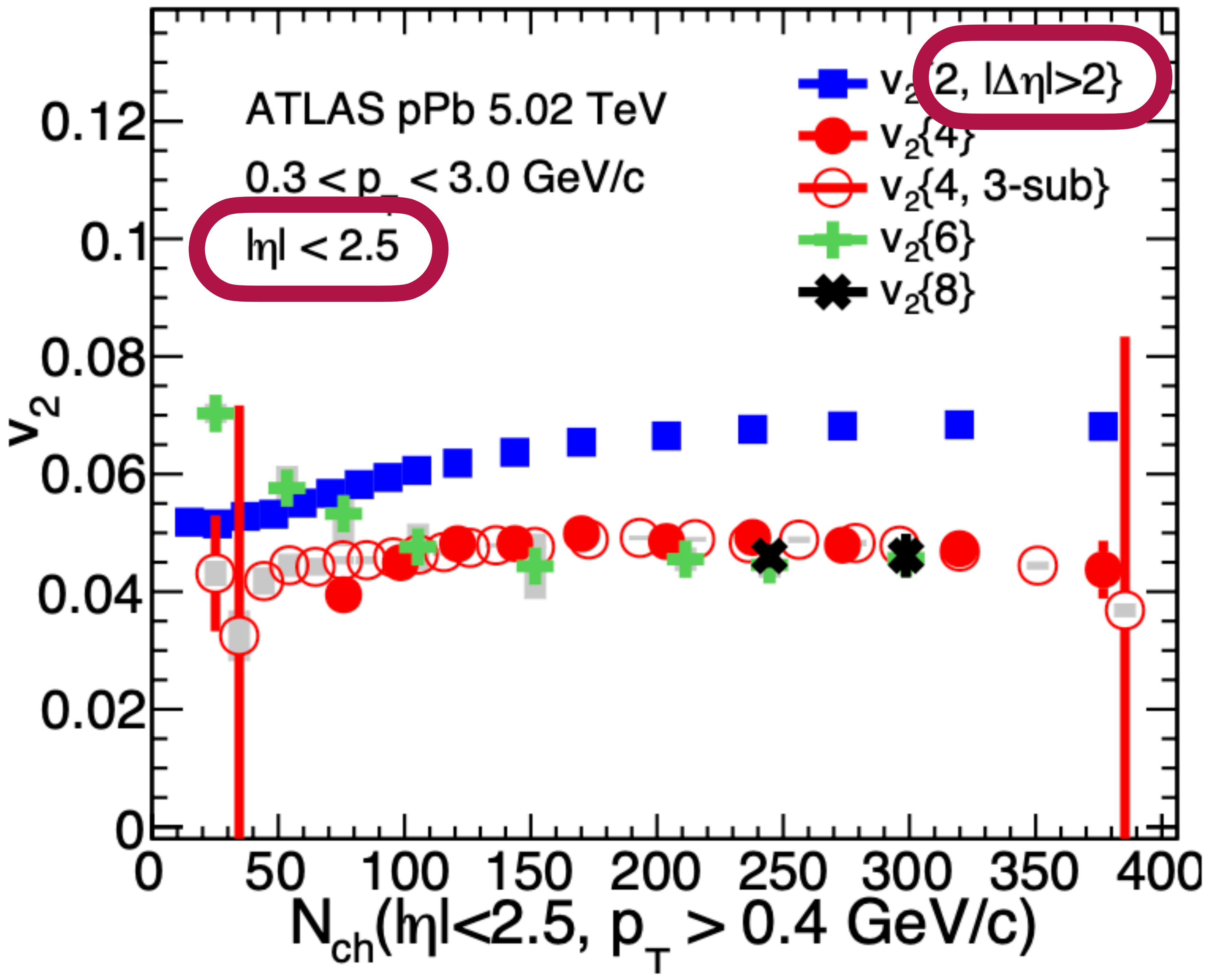
THE LONGITUDINAL STRUCTURE



CLOSER LOOK: LONG. STRUCTURE OF

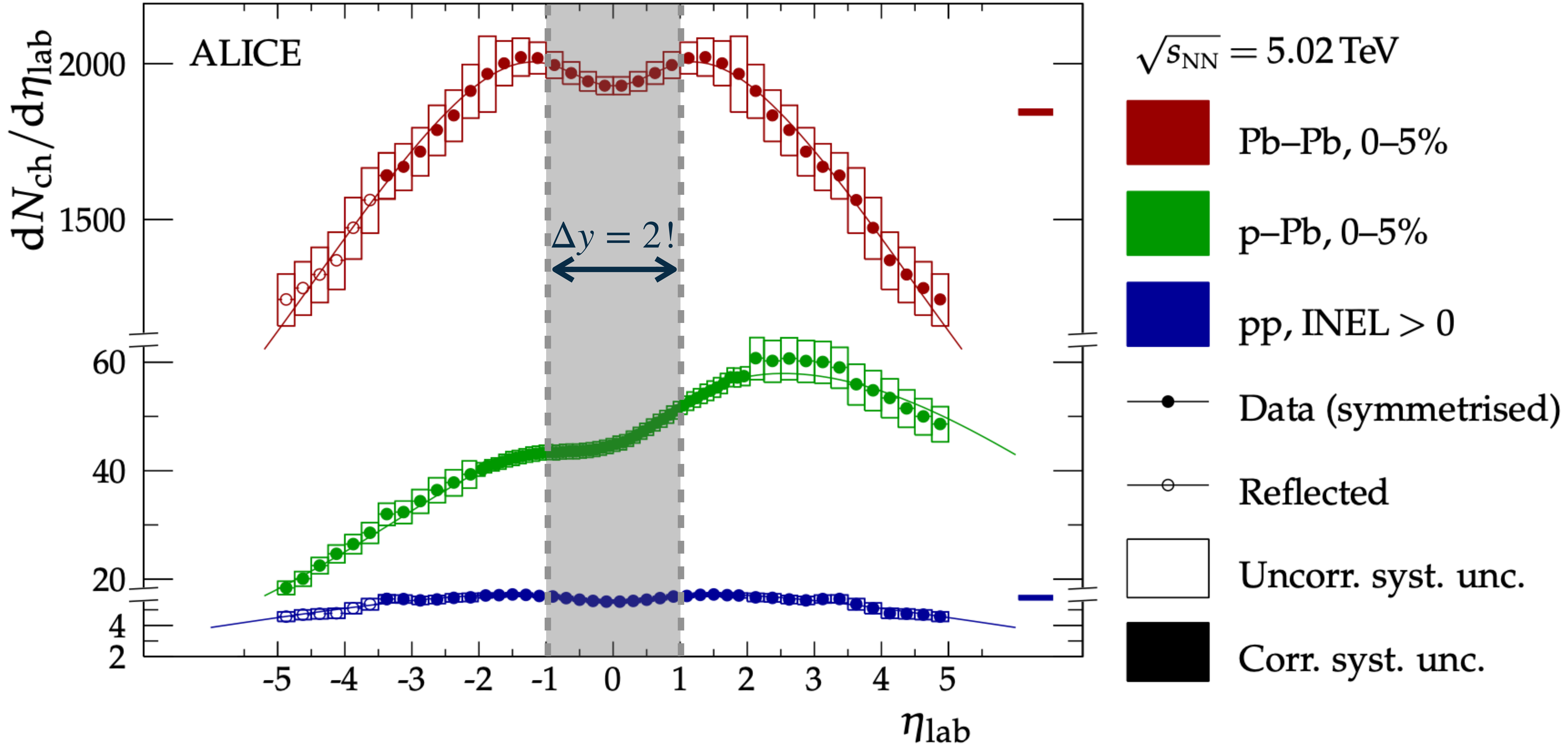
SMALL SYSTEMS





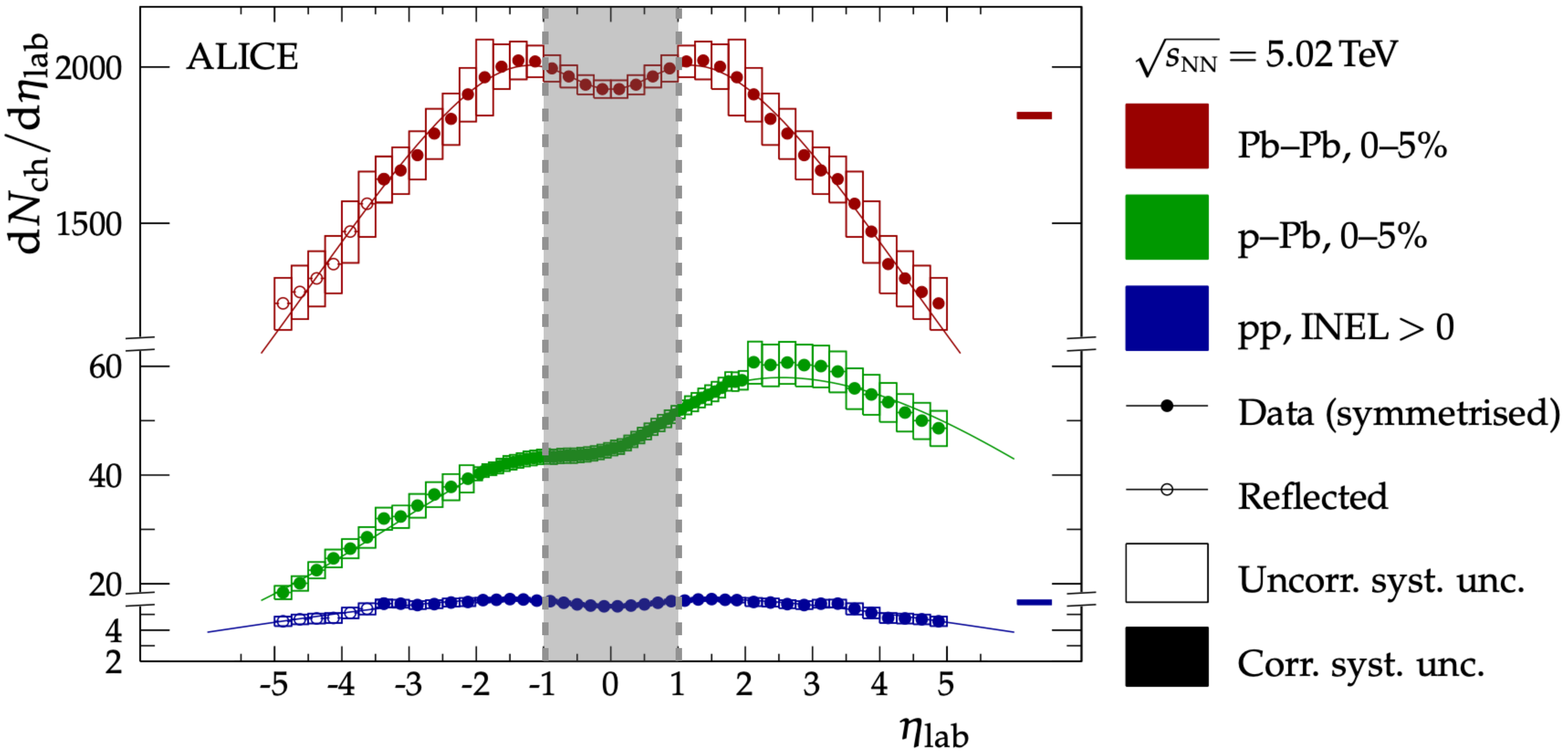
The theoretical assumptions measured small system flow coeffincients are not consistent with

BOOST INVARIANCE IS...



BOOST INVARIANCE IS...

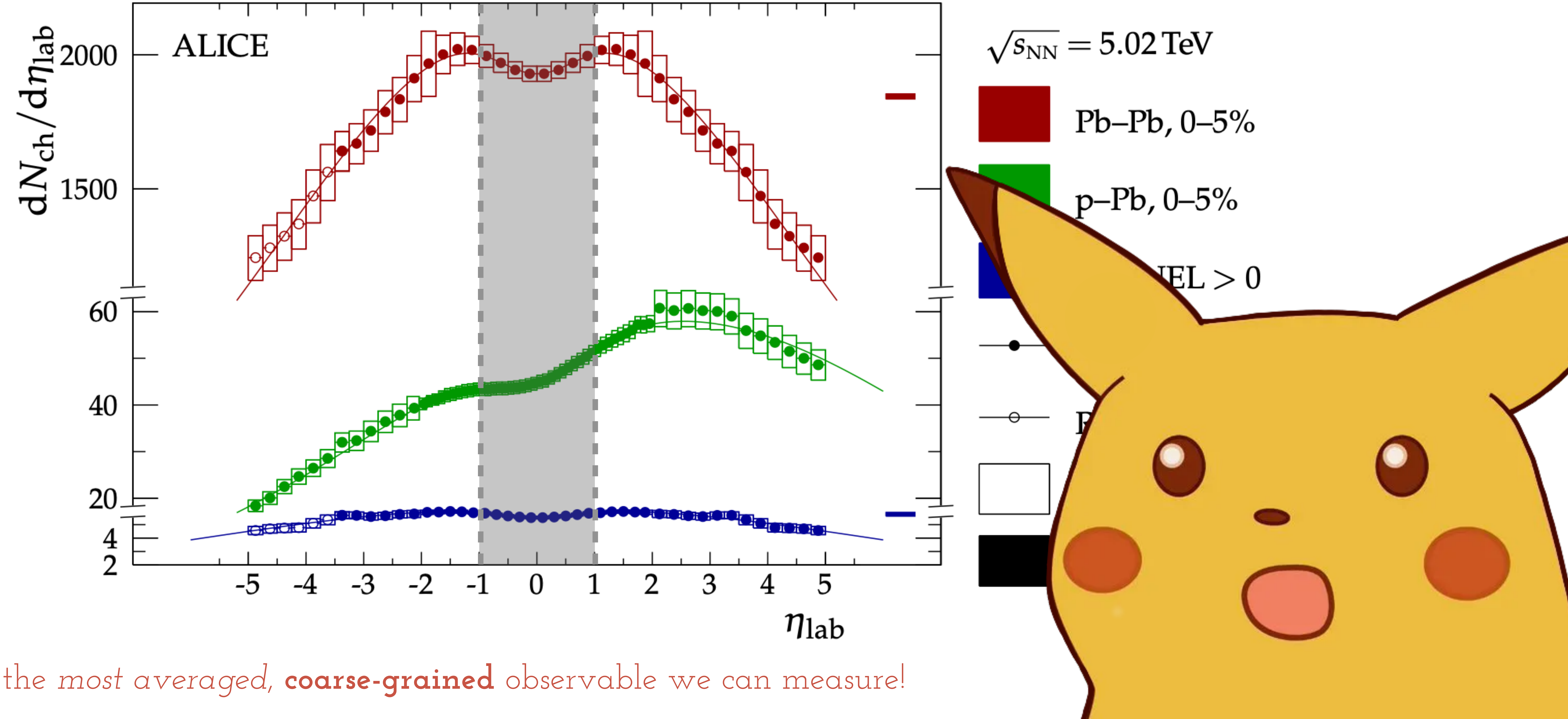
NOT A GOOD APPROXIMATION*



*And this is the *most averaged*, **coarse-grained** observable we can measure!

BOOST INVARIANCE IS...

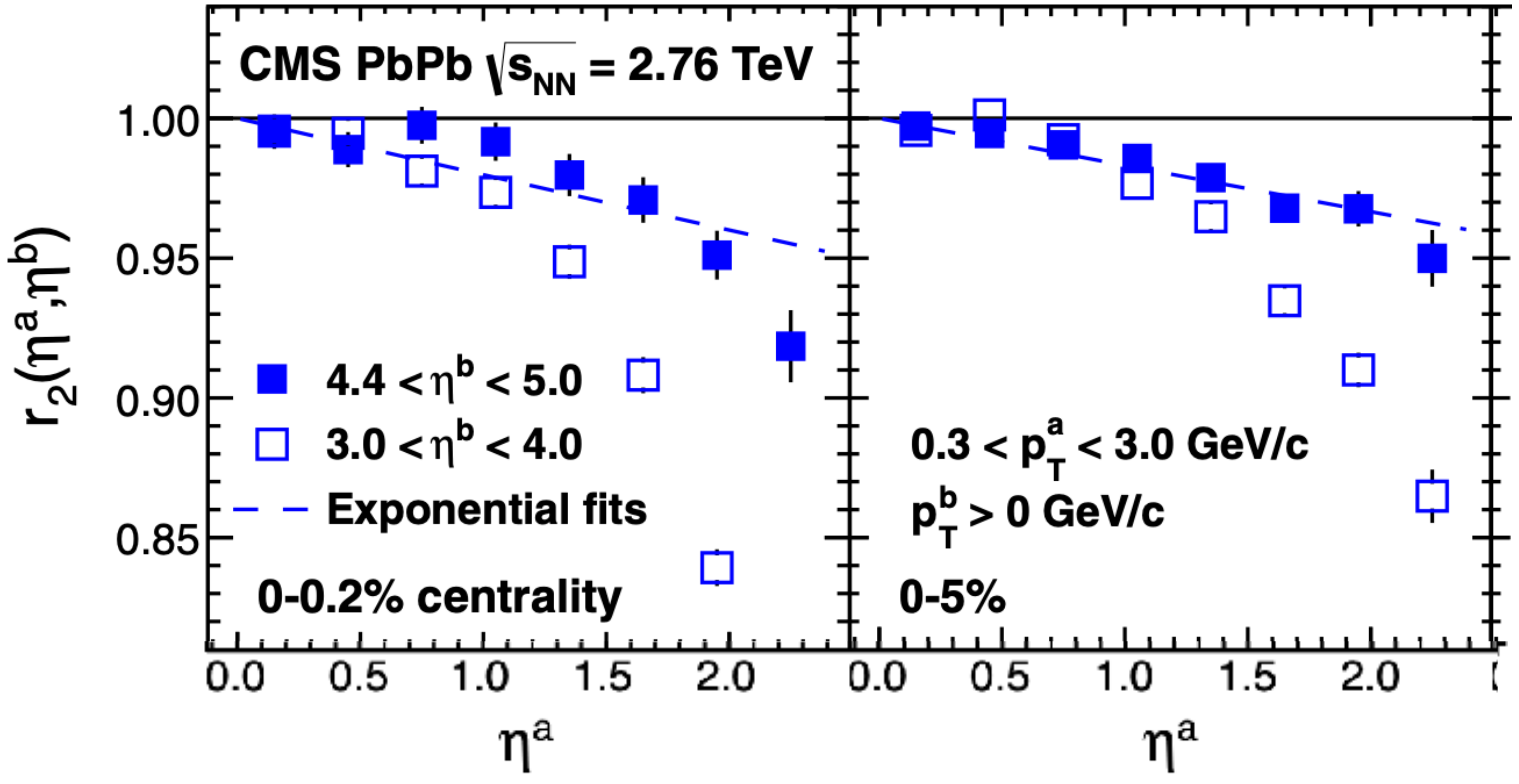
NOT A GOOD APPROXIMATION



*And this is the *most averaged*, **coarse-grained** observable we can measure!

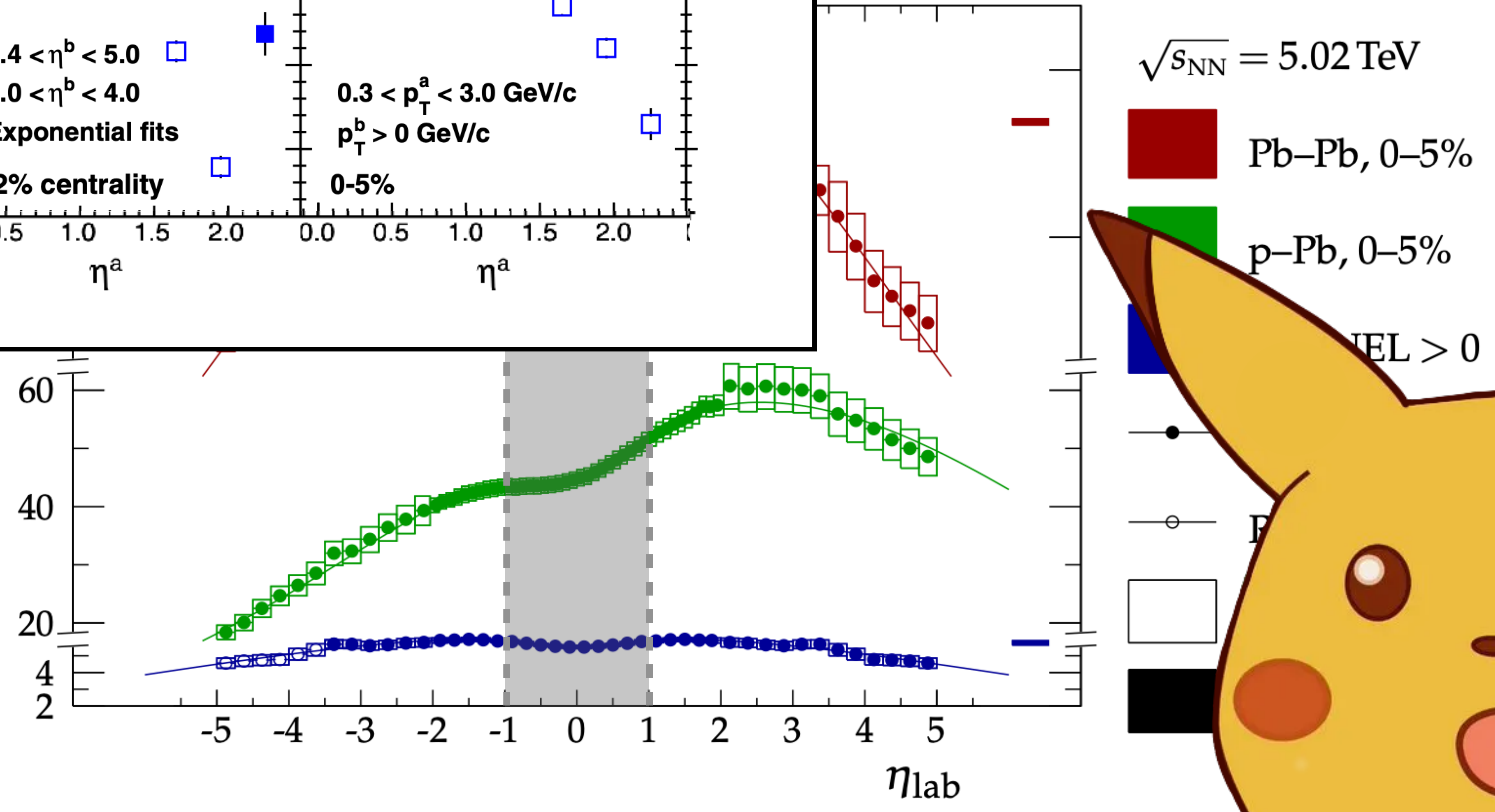
FLOW DECORRELATION

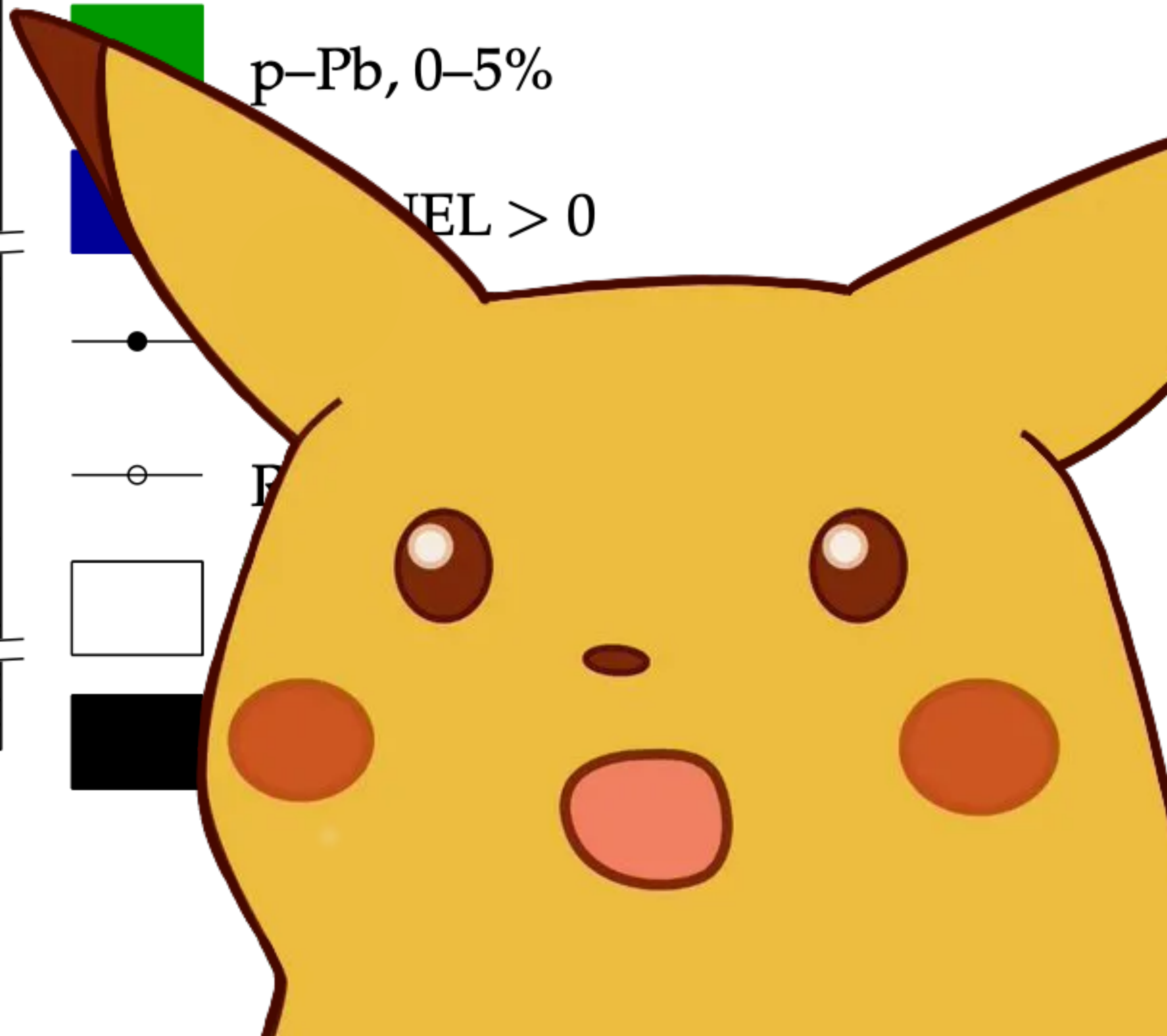
[*Phys.Rev.C* 92 (2015) 3, 034911]



RIANCE IS…

PROXIMATION





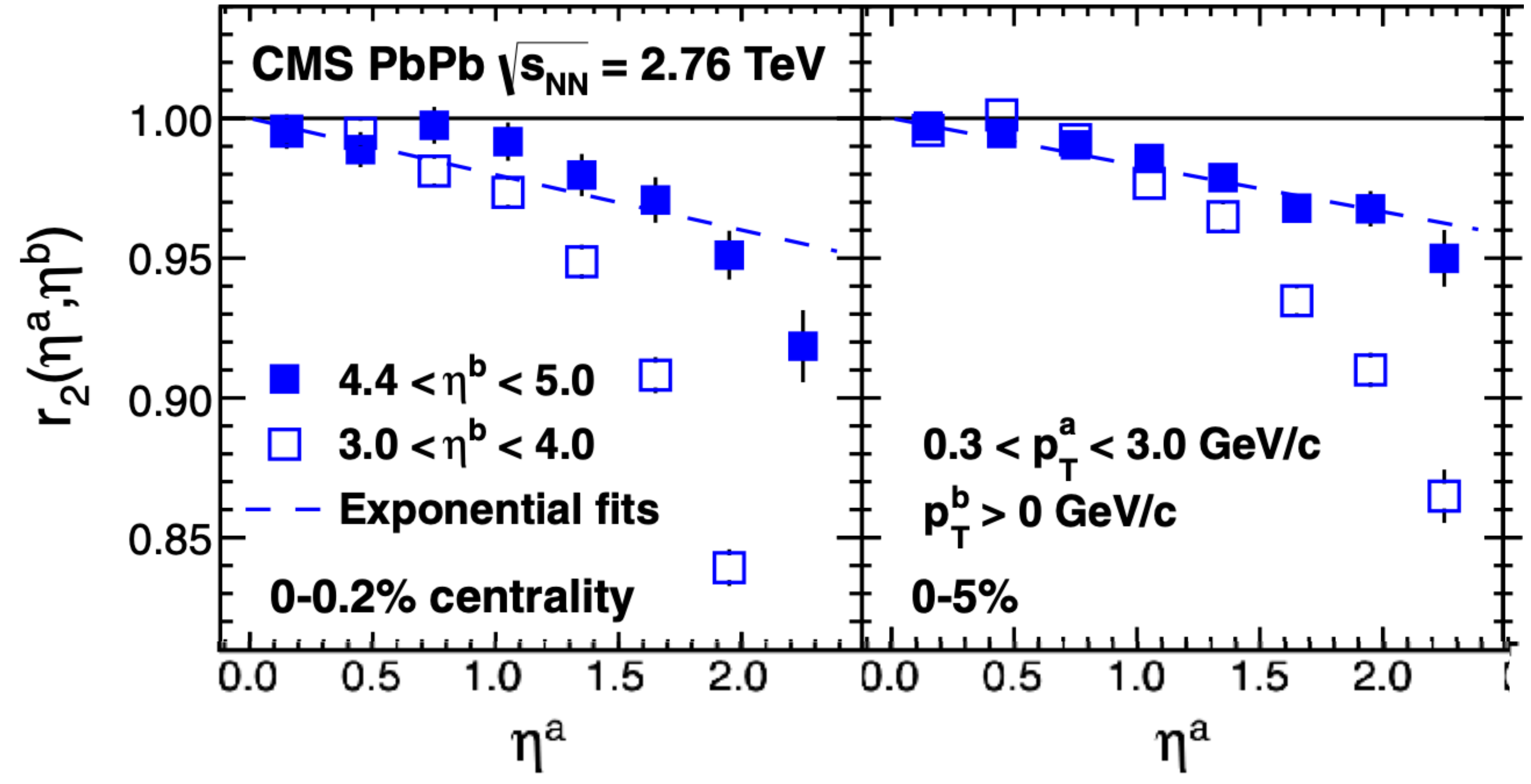
*And this is the *most averaged*, **coarse-grained** observable we can measure!

RIANCE IS…

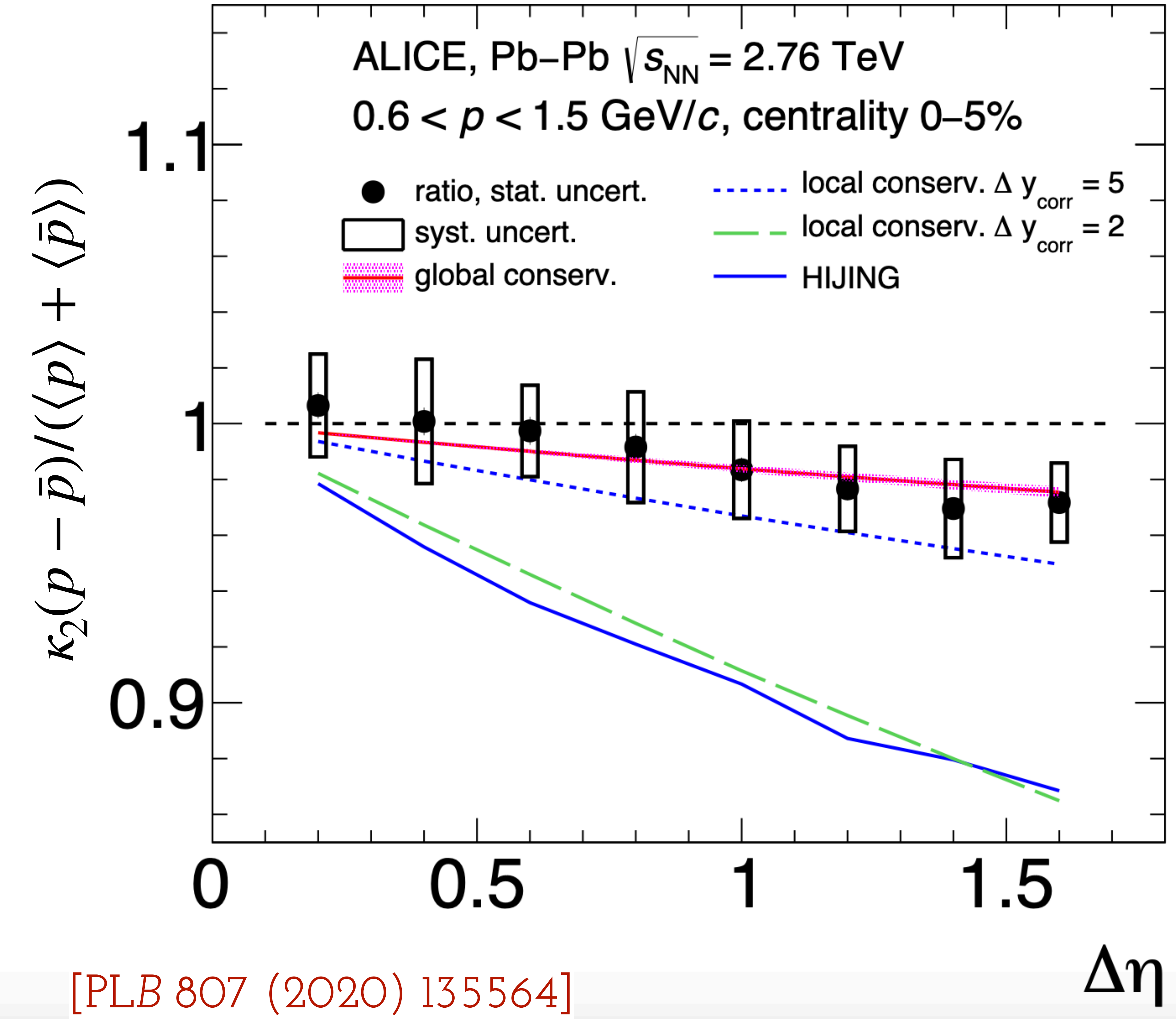
ROXIMATION

FLOW DECORRELATION

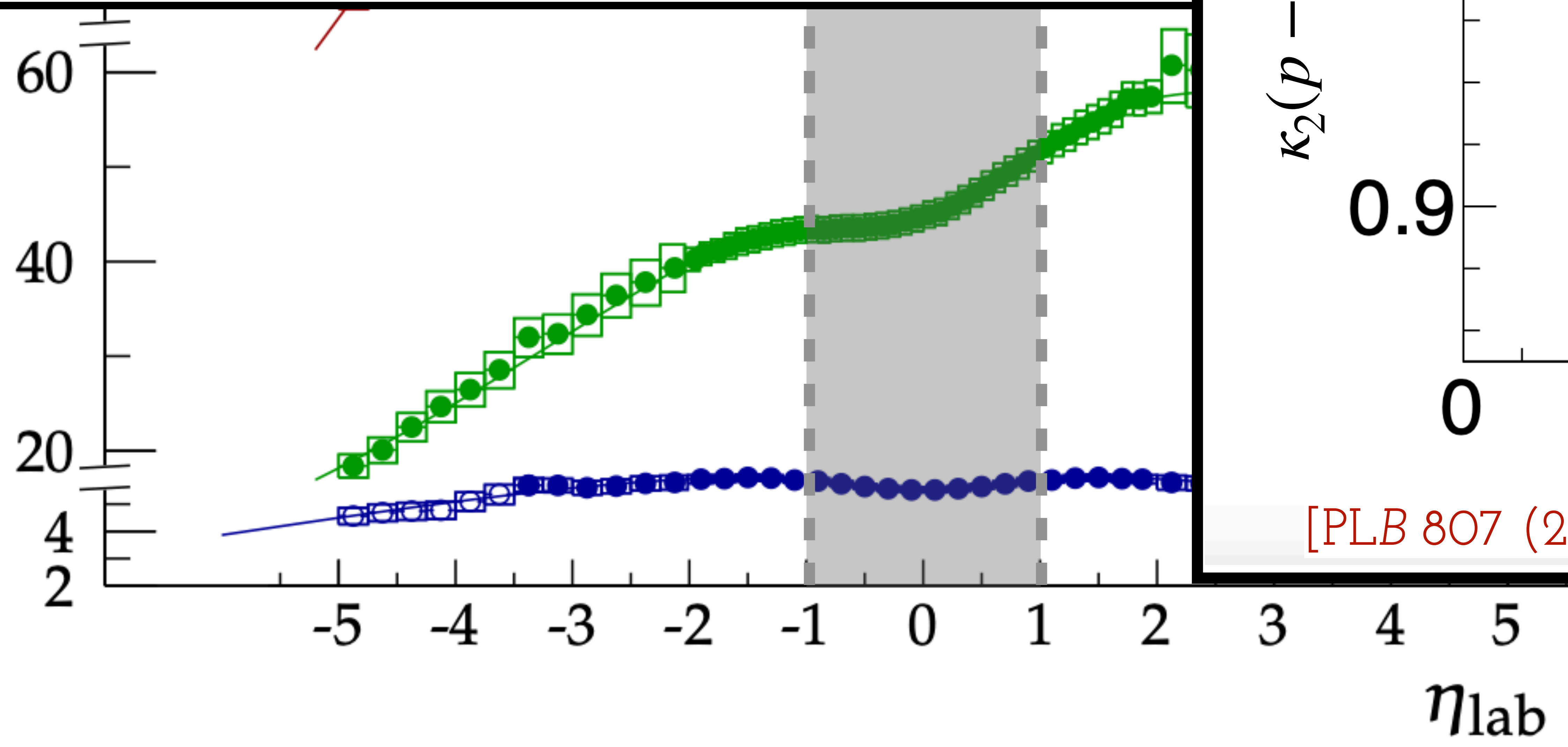
[*Phys.Rev.C* 92 (2015) 3, 034911]

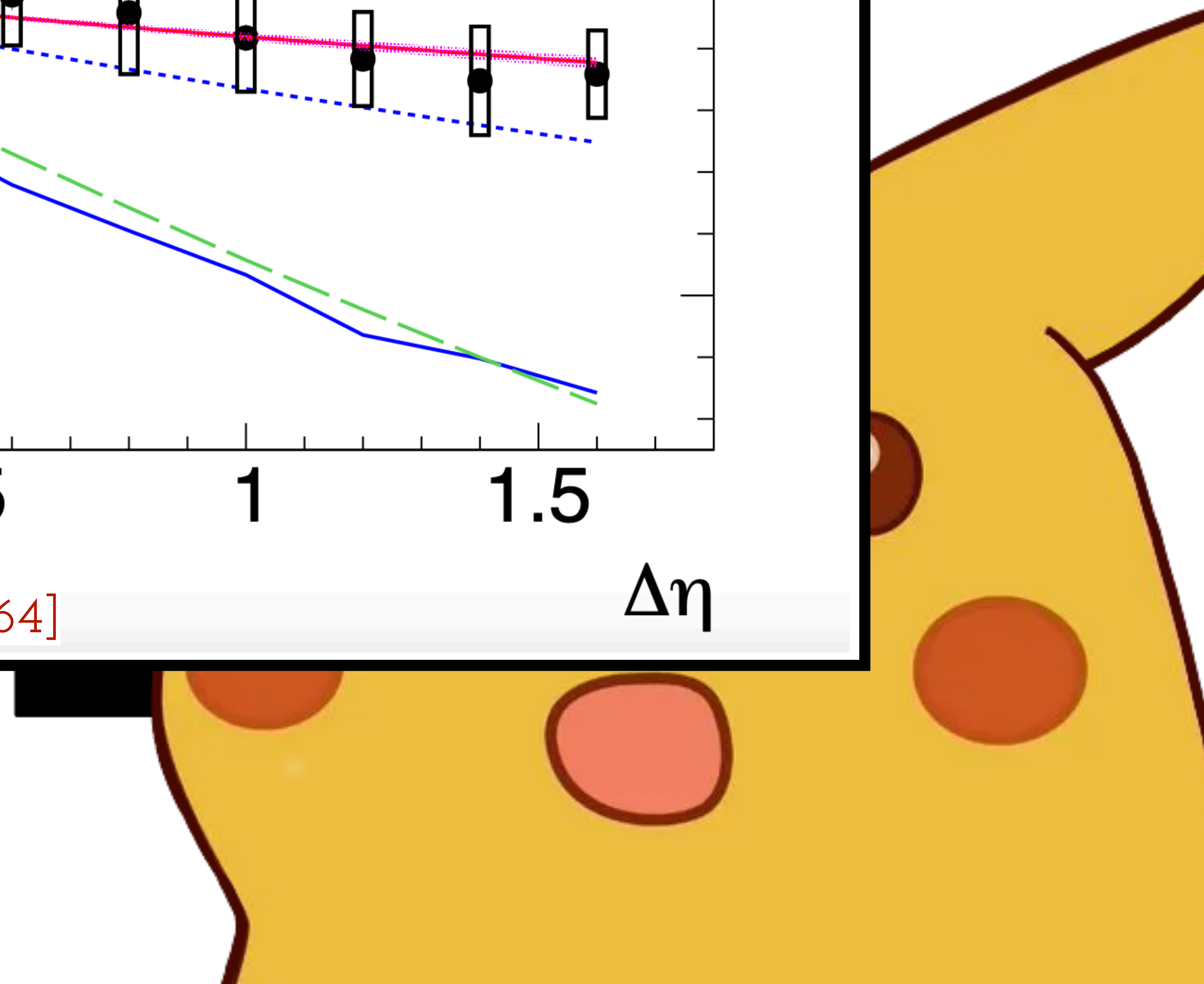


BARYON LONG. CORRS.



[PL*B* 807 (2020) 135564]





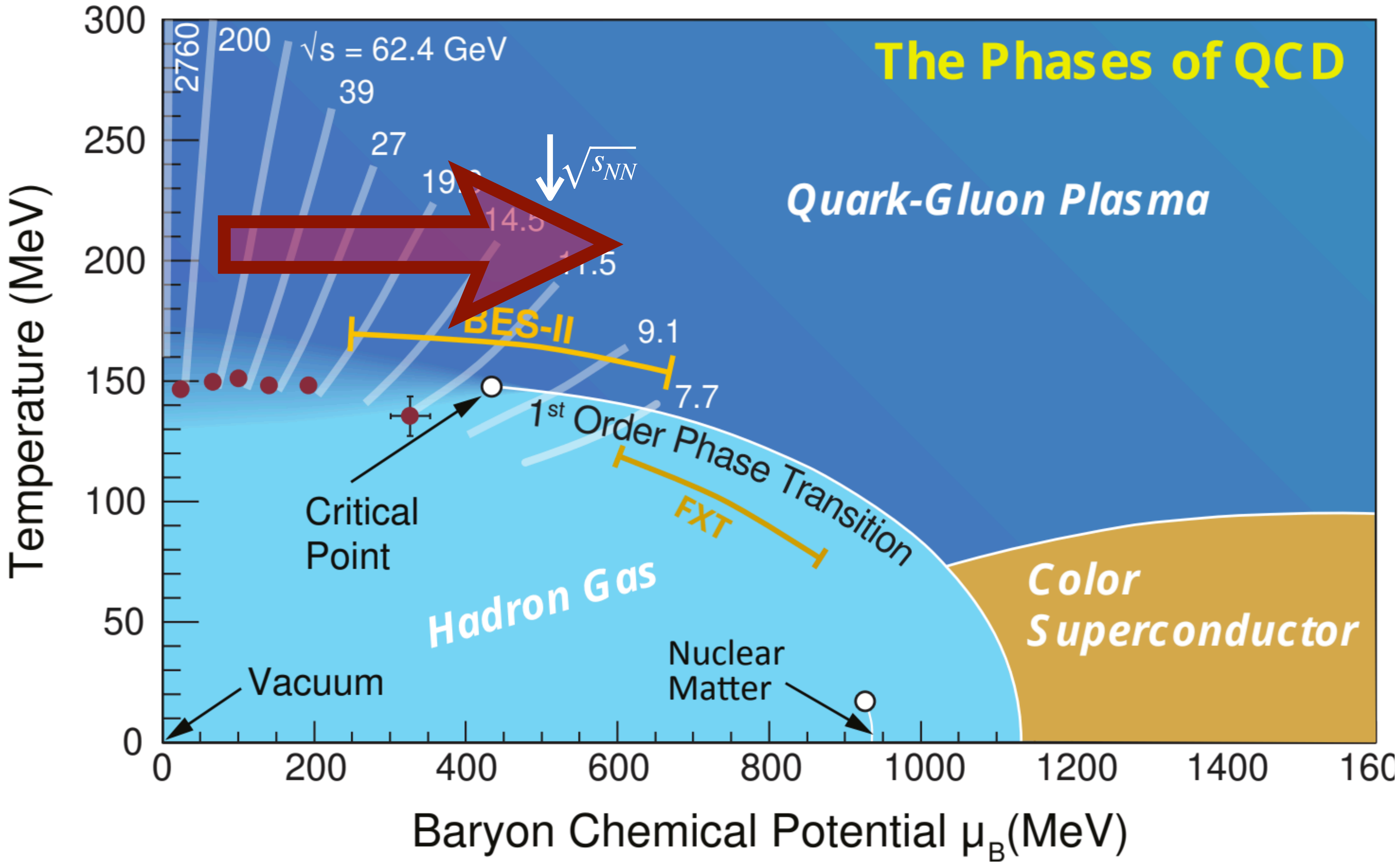
*And this is the *most averaged*, **coarse-grained** observable we can measure!


RIANCE IS…
PROXIMATION
FLOW DECORRELATION
[Phys.Rev.C 92 (2015) 3, 034911]
CMS PbPb √sNN = 2.76 TeV
r2(ηa,ηb)
0-0.2% c
BARYON LONG. CORRS.
ALICE, Pb–Pb √sNN = 2.76 TeV
0.6 < p < 1.5 GeV/c, centrality 0–5%
ratio, stat. uncert.
syst. uncert.
global conserv.
local conserv. Δ ycorr = 5
local conserv. Δ ycorr = 2
HIJING
Δη
LB 807 (2020) 135564]
DIRECTED FLOW
[PRL 111 (2013) 23, 232302]
odd even v1
10-20%
30-40%
10-60% with fit
(a)
(c)
odd v1
30-60% with fit
STAR (scaled) odd v1
× 0.37 200GeV
× 0.12 62.4GeV
Au-Au 30-60% pT>0.15 GeV/c
η
ηlab
*And this is the most averaged, coarse grained observable we can measure!

RAPIDITY RESOLUTION

LARGE BARYON DENSITIES

ANOTHER PERSPECTIVE



HOWEVER,

ICs not well theoretically constrained around the intermediate energies

It is not fully understood which are the right initial degrees of freedom for these collisions

For this, models are not available along this change in $\sqrt{s_{NN}}$

RAPIDITY RESOLUTION

LARGE BARYON DENSITIES

From the McDIPPER

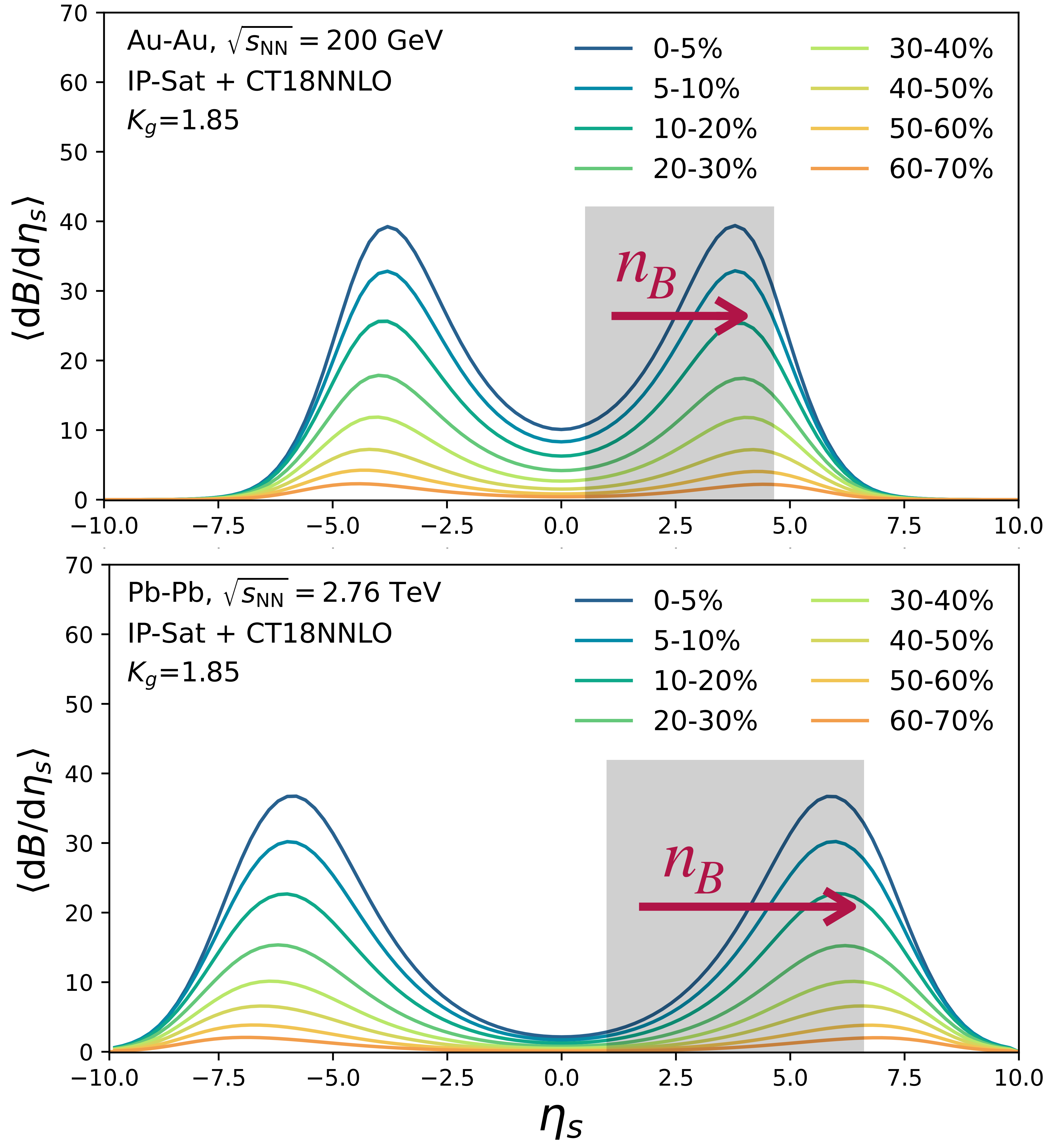
Baryon stopping is also seen at larger energies, leading to zones of of high n_B

Rapidity is a finer-resolution probe of the critical regime than $\sqrt{s_{NN}}$ for the LHC Run3 upgrade

[Brewer *et. al.*, PRC 98, 061901 (2018)]

At higher energies (LHC) the -**midrapidity**- ICs are much better constrained

A robust extension to 3D may result in a smaller uncertainty in large-μ_B observables.



RAPIDITY RESOLUTION

LARGE BARYON DENSITIES

Baryon stopping is also seen at larger energies, leading to zones of of high n_B

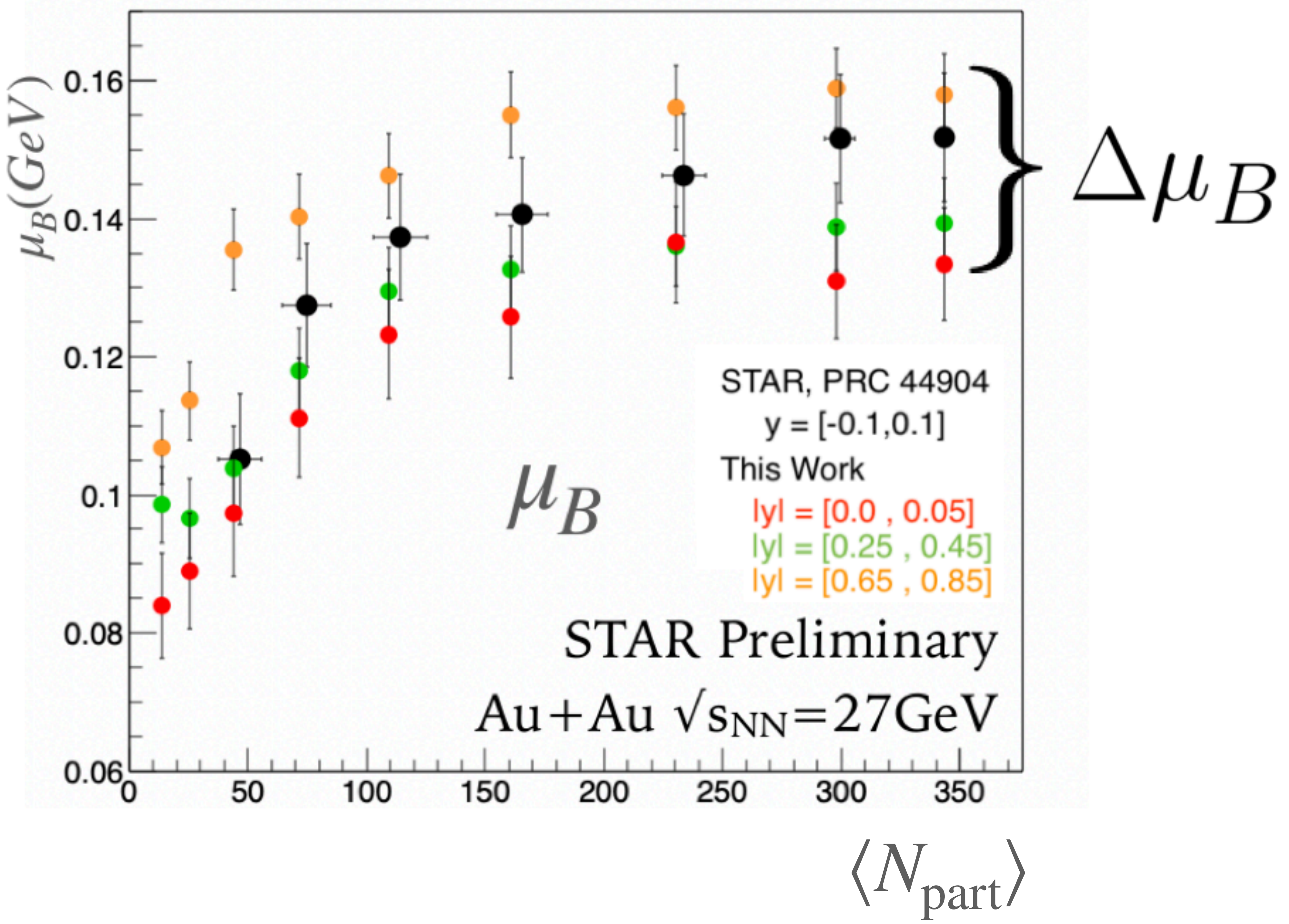
Rapidity is a finer-resolution probe of the critical regime than $\sqrt{s_{NN}}$ for the LHC Run3 upgrade

[Brewer *et. al.*, PRC 98, 061901 (2018)]

At higher energies (LHC) the -**midrapidity**- ICs are much better constrained

A robust extension to 3D may result in a smaller uncertainty in large-μ_B observables.

PROOF OF CONCEPT

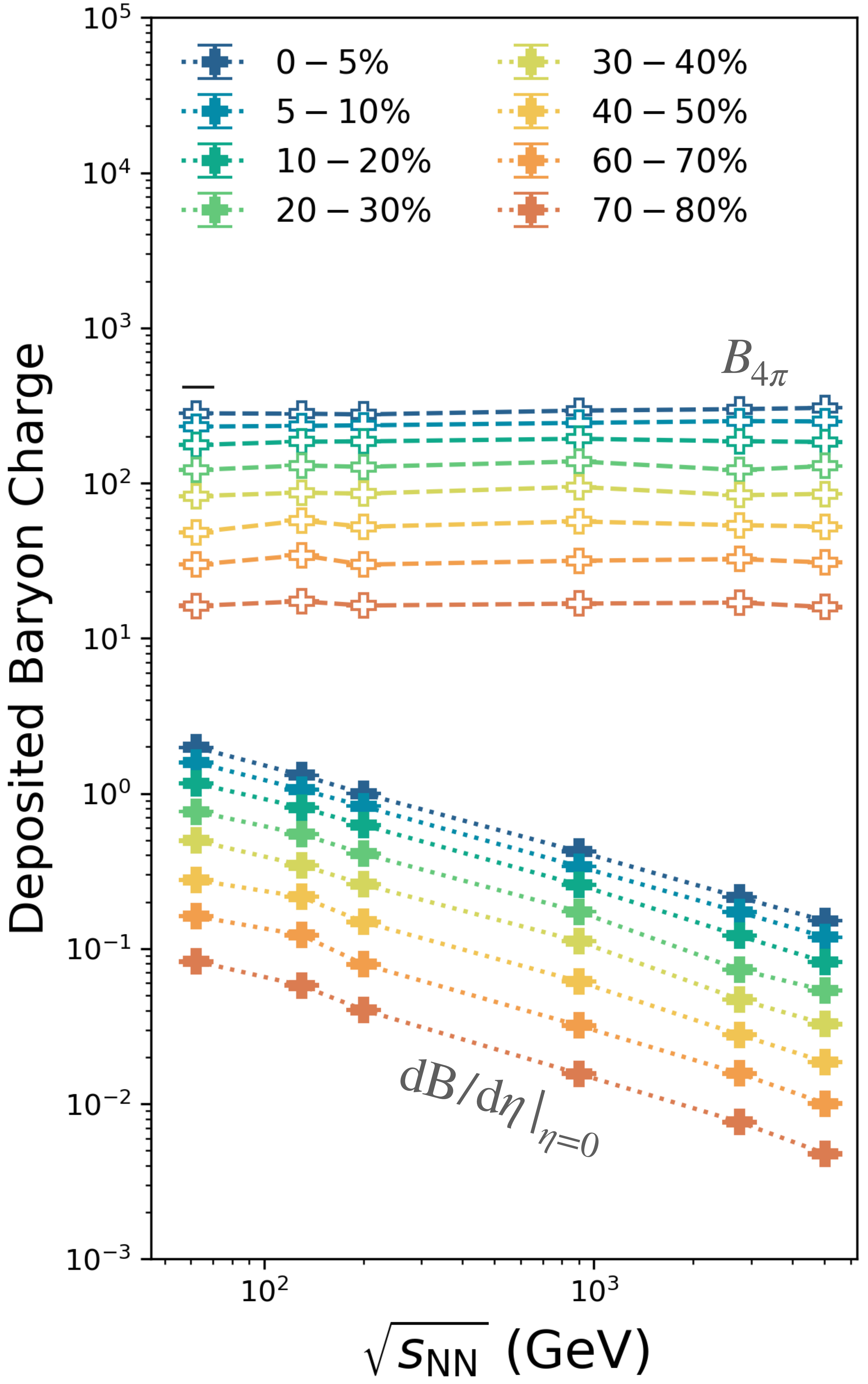


We need a well controlled 3D initial energy, and charge (BQS) deposition to initialise -precision physics era- EbE simulations

CHARGE DEPOSITION

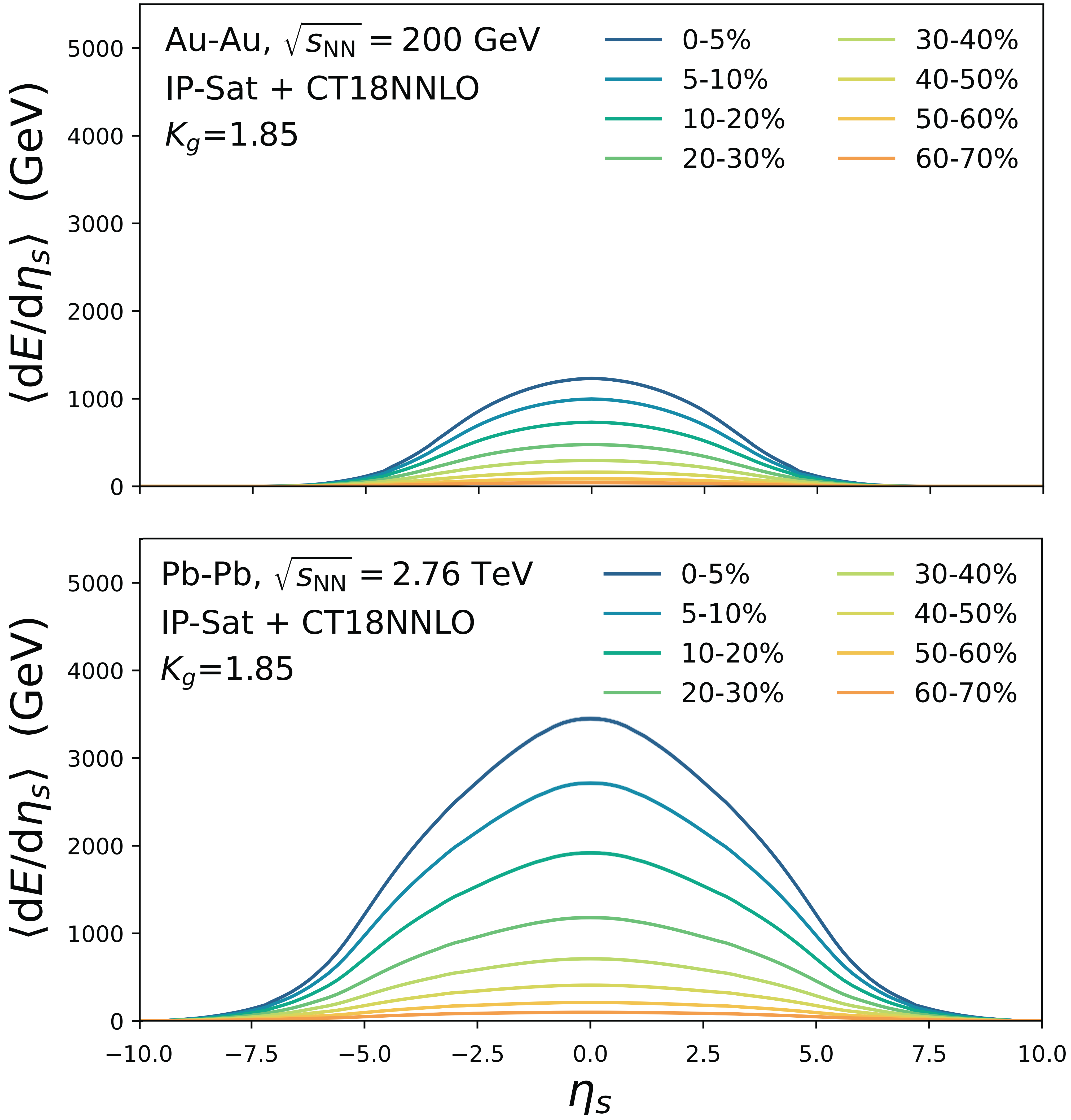
- Non-trivial interaction between x-dependence of gluon uGDs and quark PDFs gives tails in the charge deposition
- Even at higher rapidities, non-zero baryon stopping is found!
- Midrapidity baryon charge deposition follows a power-law trend

$$\left.\frac{\mathrm{dB}}{\mathrm{d}\eta}\right|_{\eta=0} \sim \left(\sqrt{s_{NN}}\right)^{\alpha}$$



CHARGE DEPOSITION

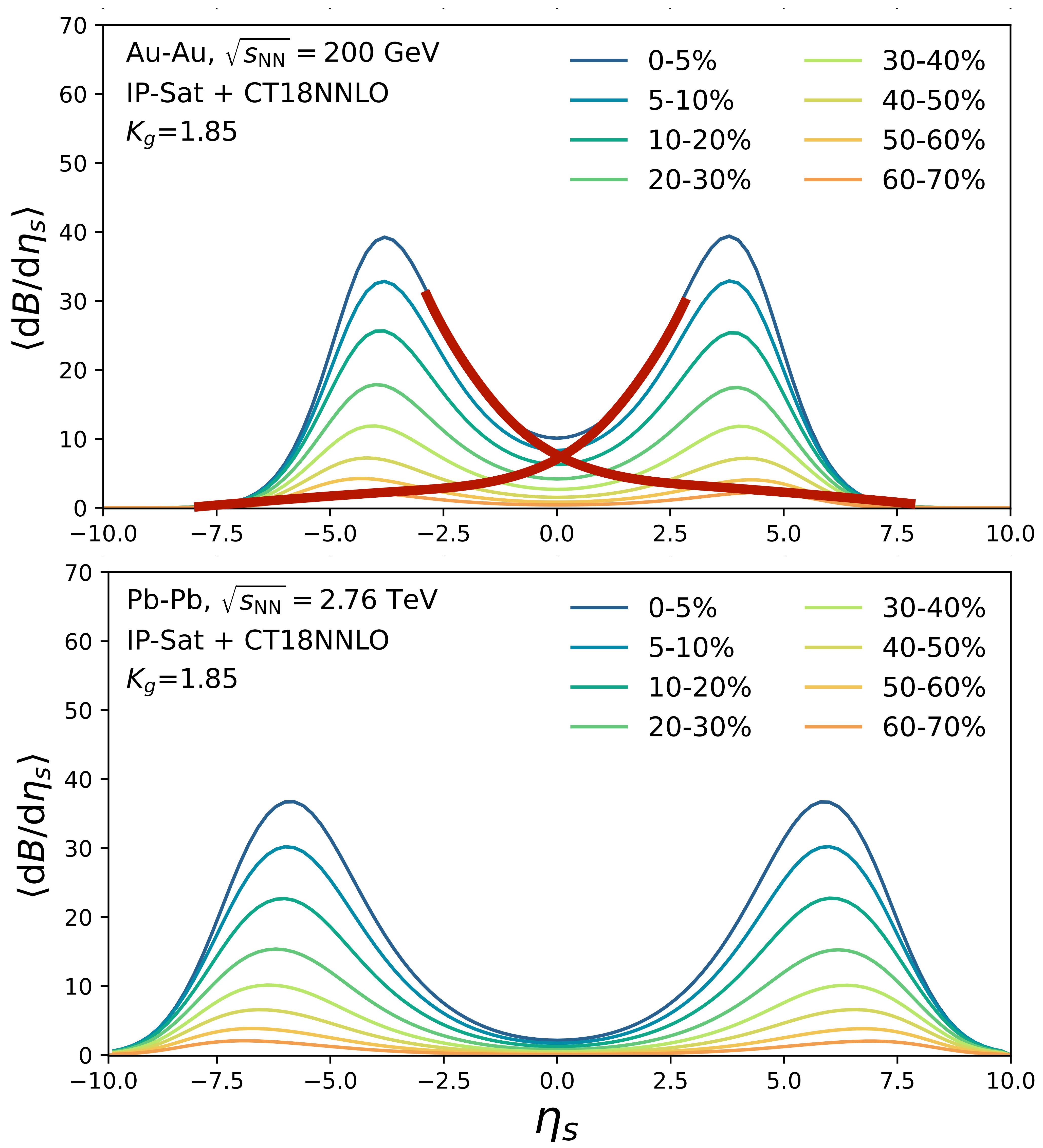
- Non-trivial interaction between x-dependence of gluon uGDs gives tails in the **energy** deposition



[GM, Schlichting, Elfner, PRC 109 (2024) 4, 044916]

CHARGE DEPOSITION

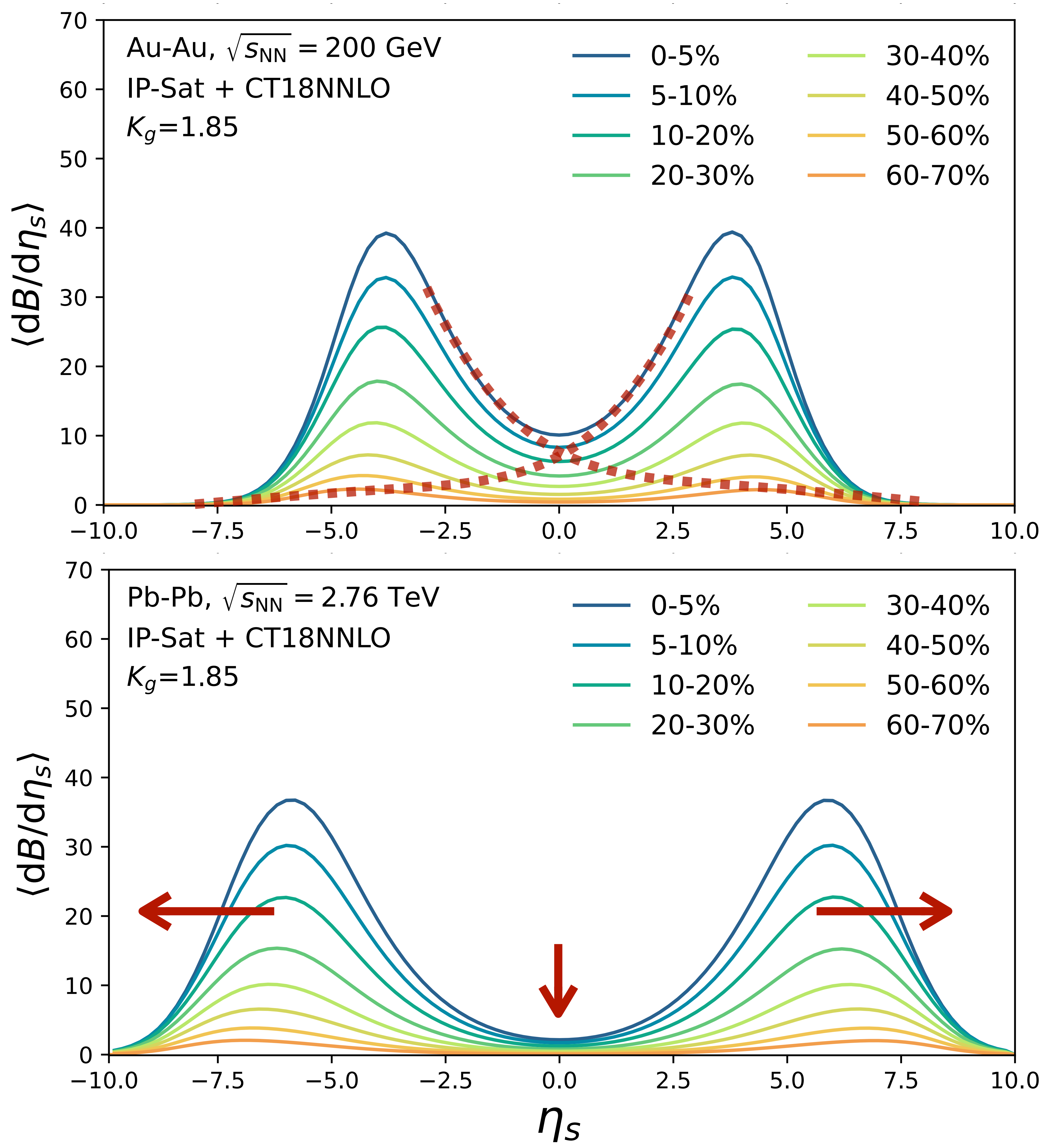
- Non-trivial interaction between x-dependence of gluon uGDs and quark PDFs gives tails in the charge deposition
- Even at higher rapidities, non-zero baryon stopping is found!



[GM, Schlichting, Elfner, PRC 109 (2024) 4, 044916]

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!



(see *PRC* 108 (2023) 4, 4)

TUNING

FIXING THE K-FACTOR

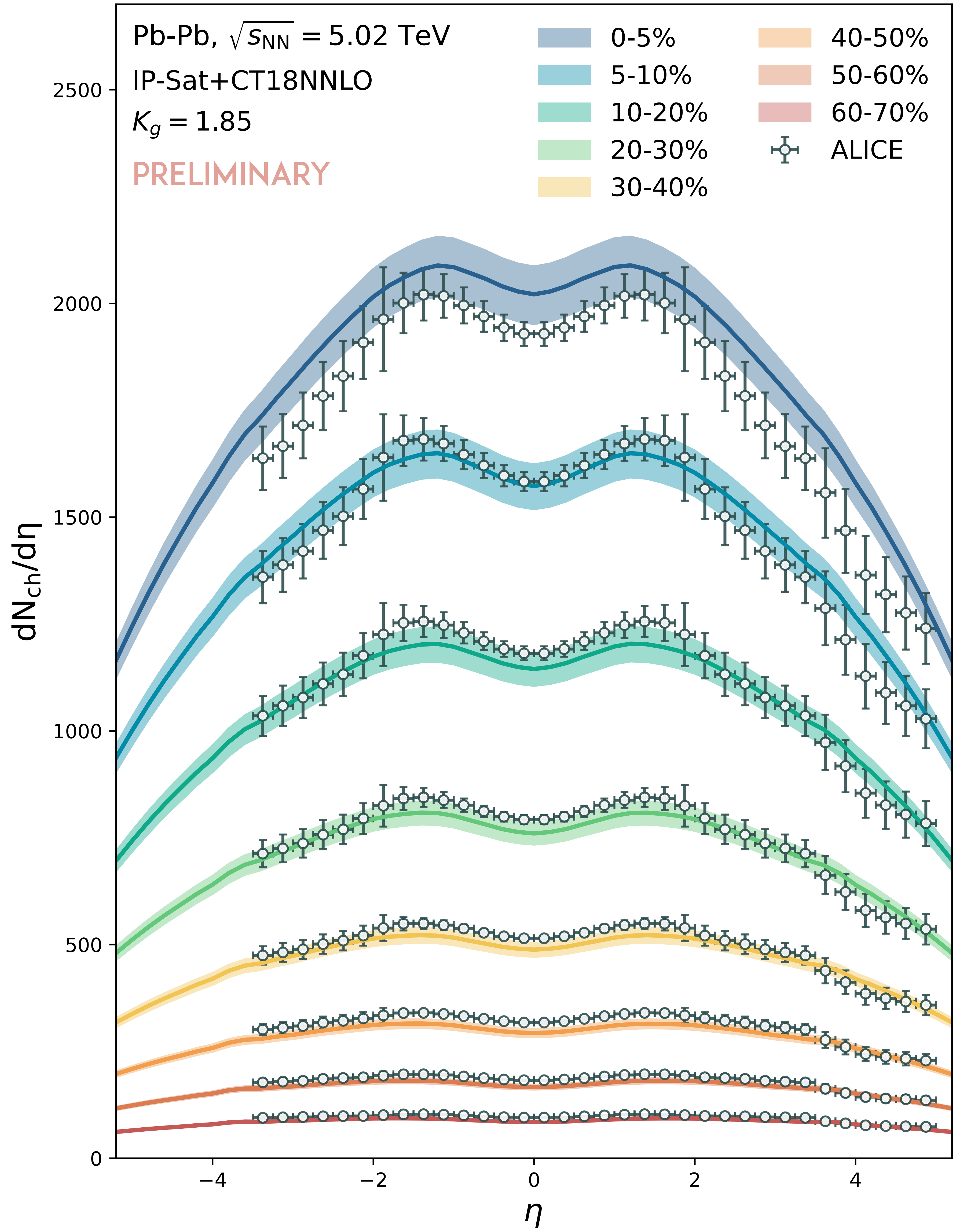
- Input model parameters can be **fixed by other experiments** e.g. **DIS (e+p, e+A,...)**
- Overall normalisation of $(e_g\tau)_0$ treated as a free parameter, K_g, to account for perturbative corrections
- Tune K_g using $E_\perp$ in pp min. bias collisions at $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$

$K_g = 1.25$ {GBW} $K_g = 1.85$ {IP-Sat}

- Multiplicity can be then estimated using

$$\left\langle \frac{dN_{ch}}{dy} \right\rangle = \frac{4}{3}\frac{N_{ch}}{S} C_\infty^{3/4} \left(4\pi\frac{\eta}{s}\right)^{1/3} \left(\frac{\pi^2}{30}\nu_{\mathrm{eff}}\right)^{1/3} \int d^2\mathbf{x}\, \left[\tau e(y,\mathbf{x})\right]_0^{2/3}$$

[PRL. 123, 262301]



3D-TRENTO

GEOMETRICAL

[PRC 102 (2020)]

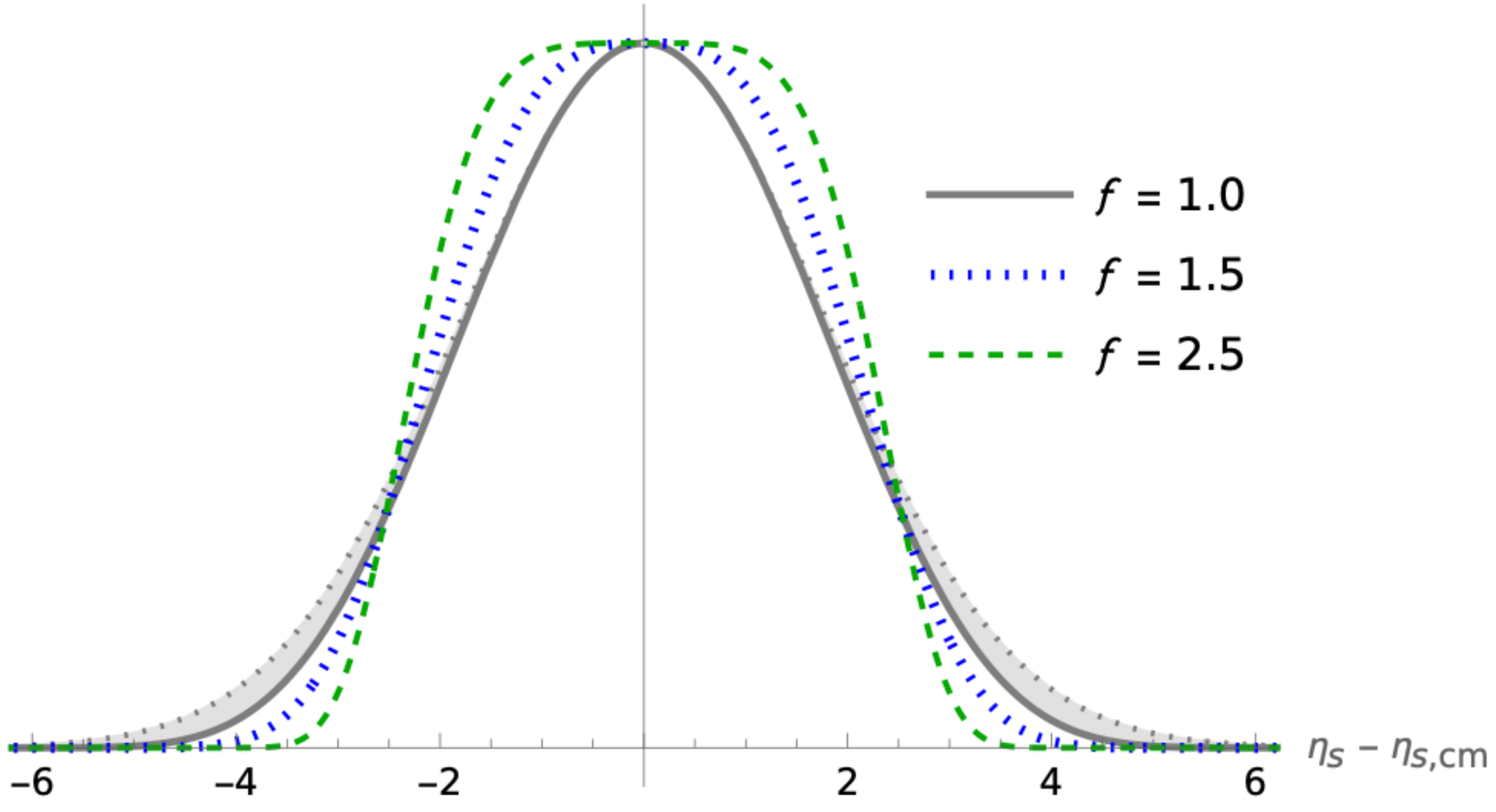
- Parametrical model of energy deposition of the HIC
- Extension to 3D, TRENTo includes a central fireball and forward and backward fragmentation regions.

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

- 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



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.

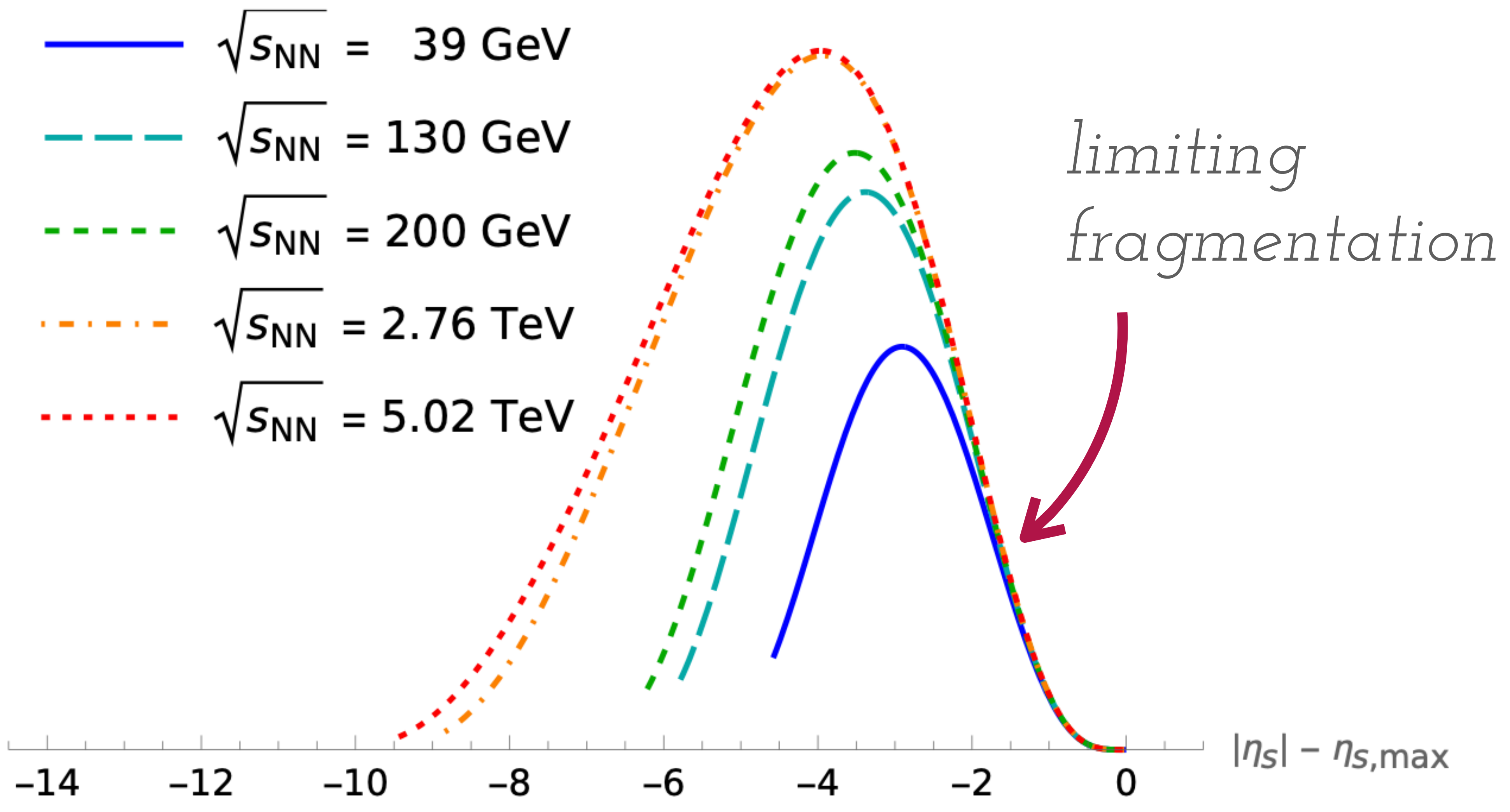
$$\epsilon(\boldsymbol{x},\eta) = \epsilon_{\text{fb}}(\boldsymbol{x},\eta) + \epsilon_{\text{frag},+}(\boldsymbol{x},\eta) + \epsilon_{\text{frag},-}(\boldsymbol{x},\eta)$$

- Central fireball is parametrized in rapidity

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

- Fragmentation deposition is constrained by *limiting fragmentation*

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



3D-TRENTO

GEOMETRICAL

[PRC 102 (2020)]

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

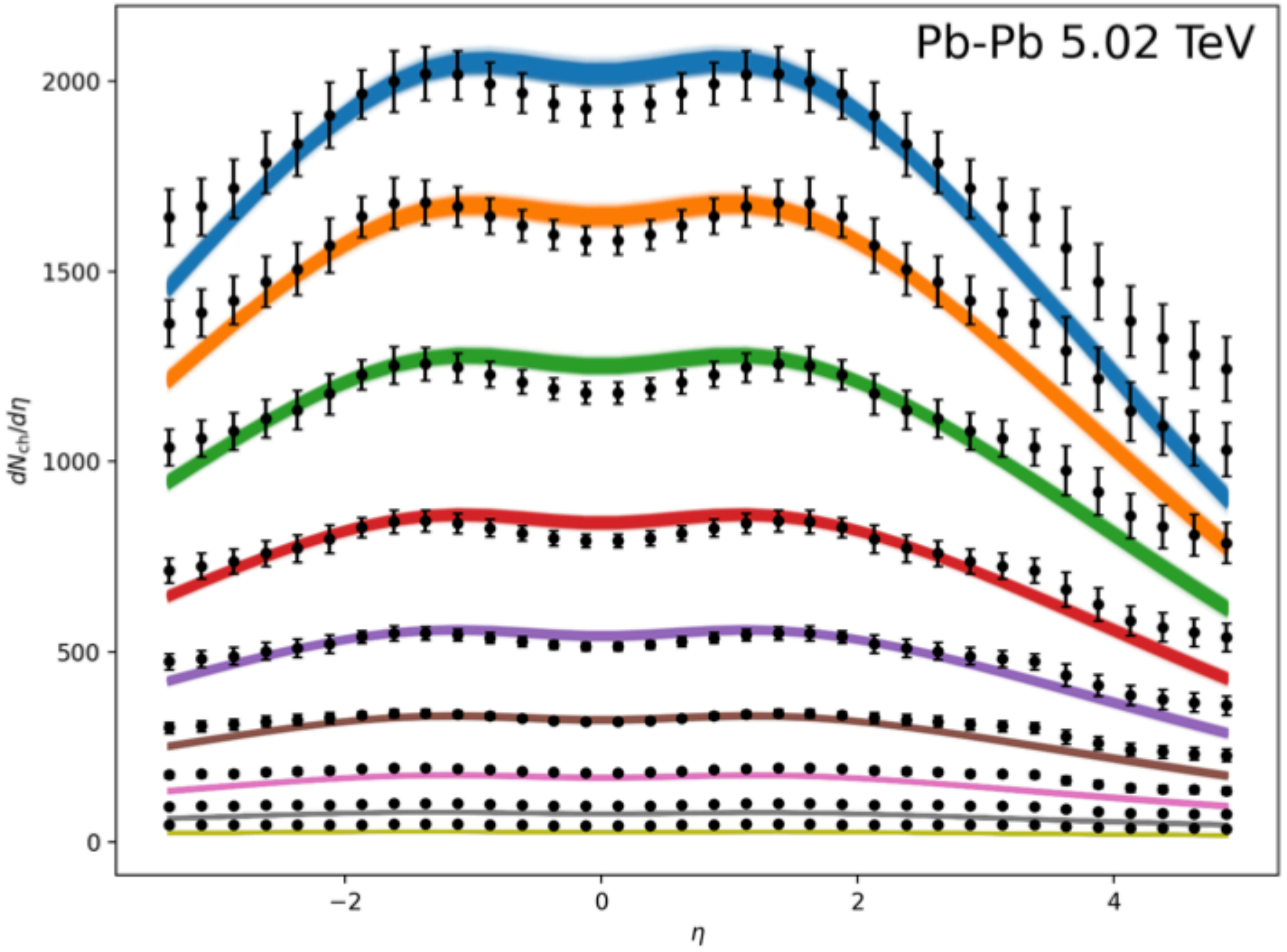
$$\epsilon(\boldsymbol{x},\eta) = \epsilon_{\text{fb}}(\boldsymbol{x},\eta) + \epsilon_{\text{frag},+}(\boldsymbol{x},\eta) + \epsilon_{\text{frag},-}(\boldsymbol{x},\eta)$$

- Central fireball is parametrized in rapidity

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

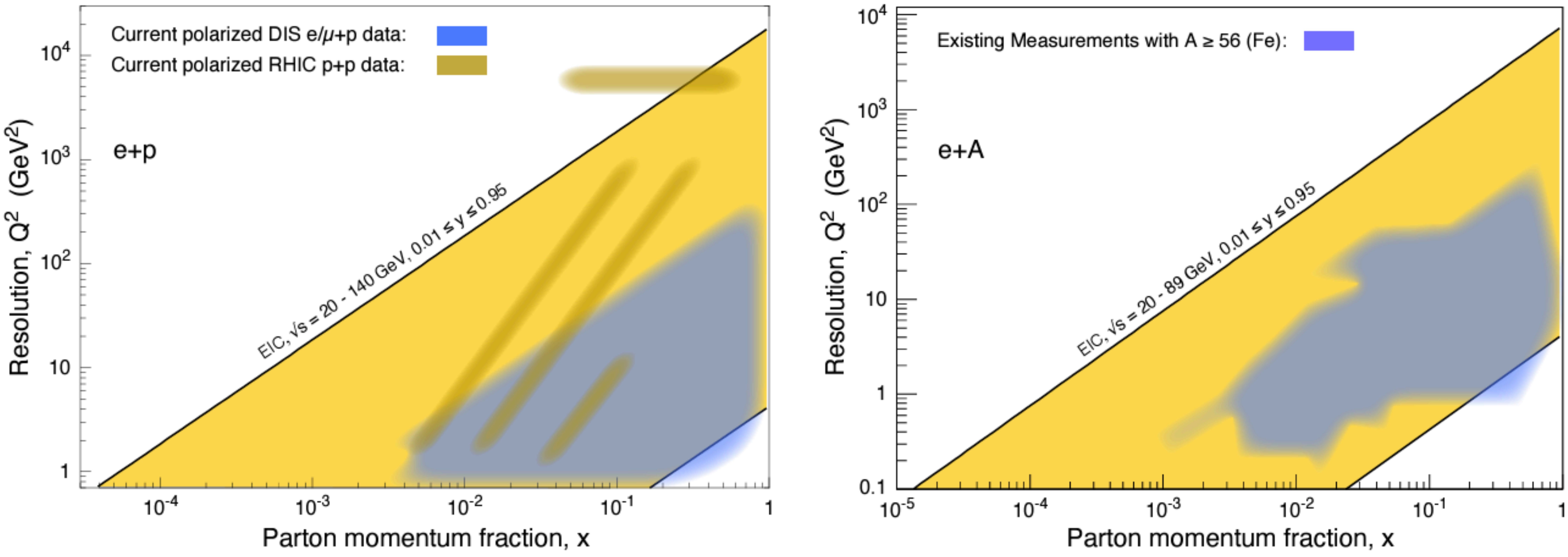
- Fragmentation deposition is constrained by *limiting fragmentation*

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

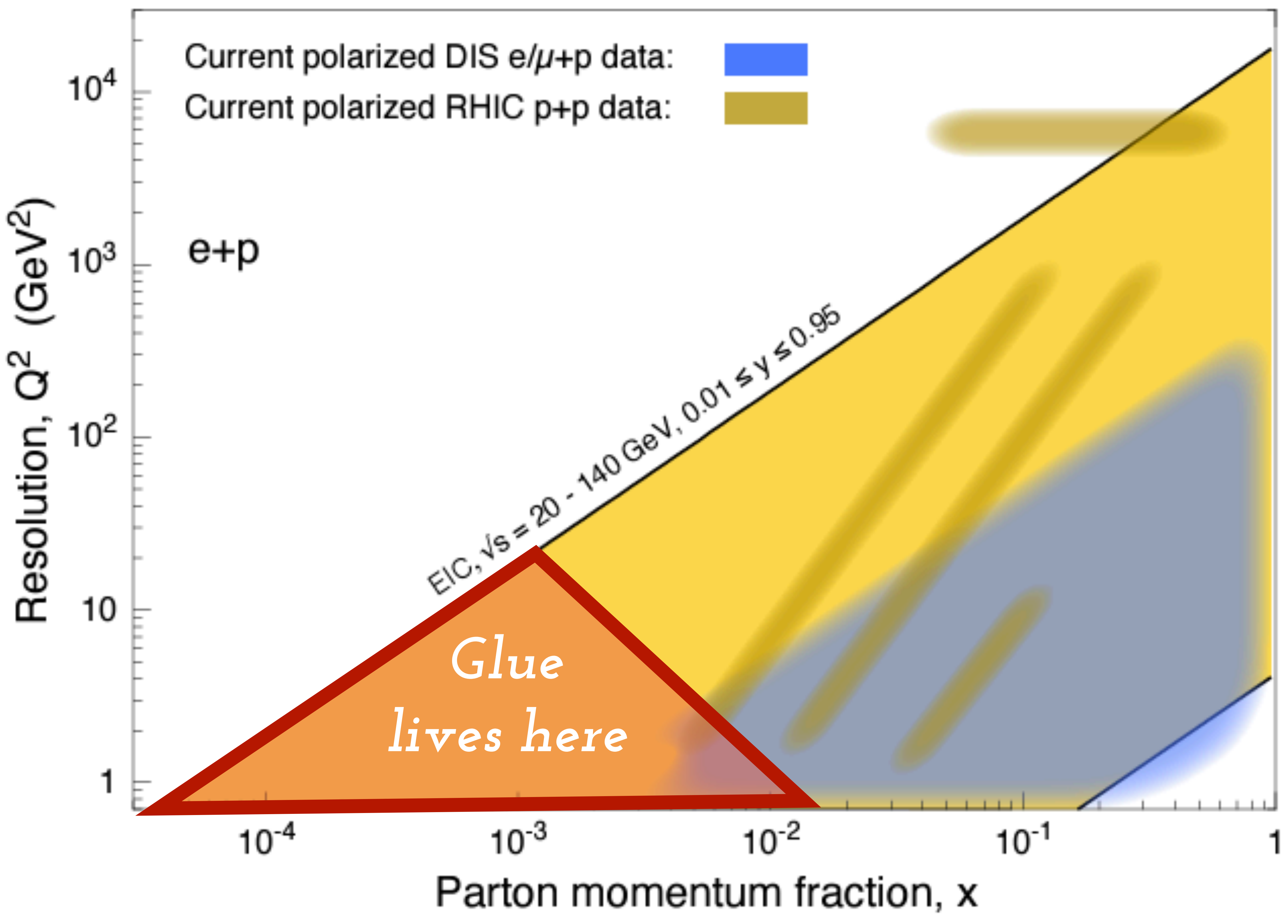


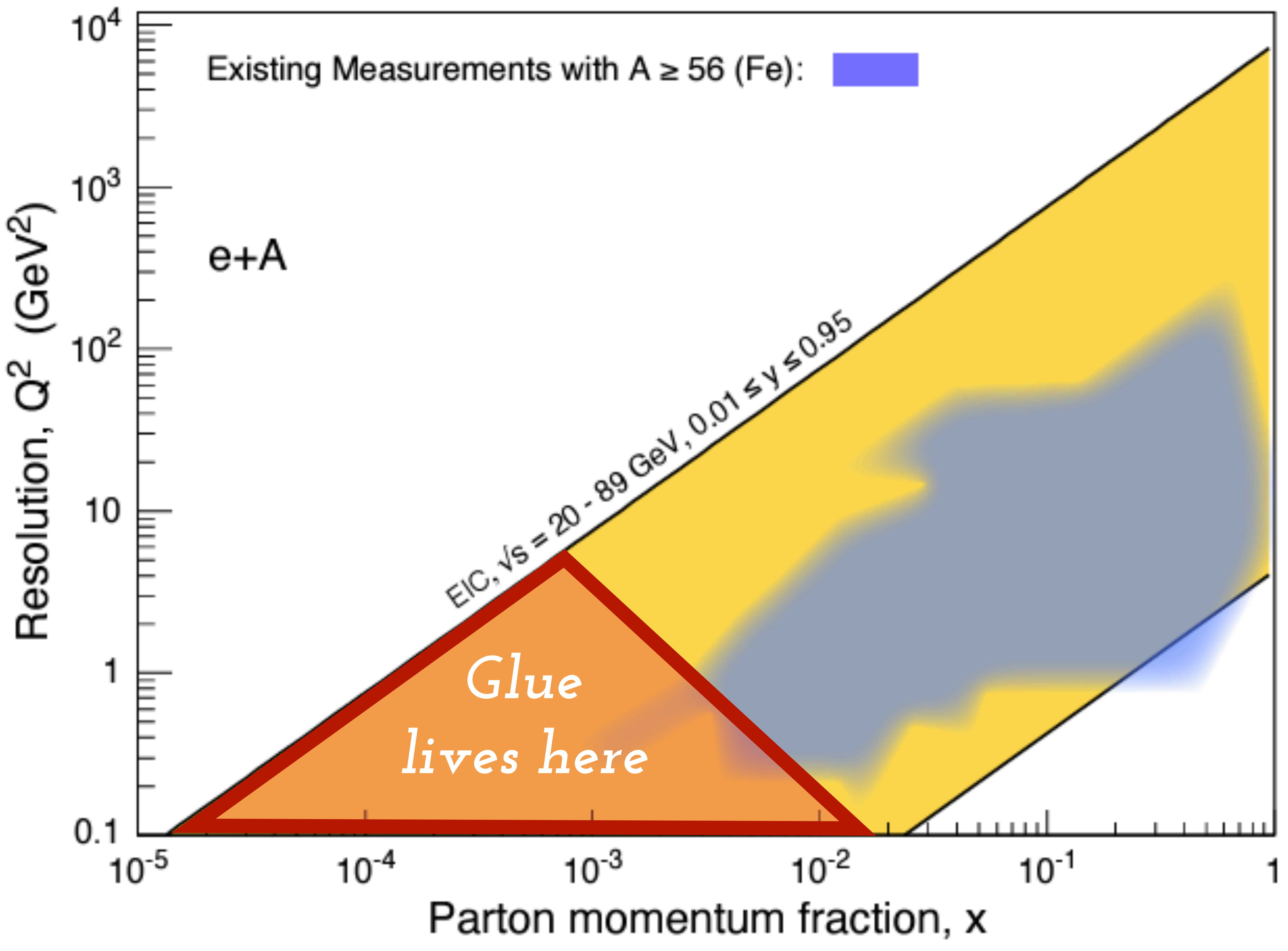
No charge deposition.
Useful for bayesian analysis

TESTING SATURATION MODELS

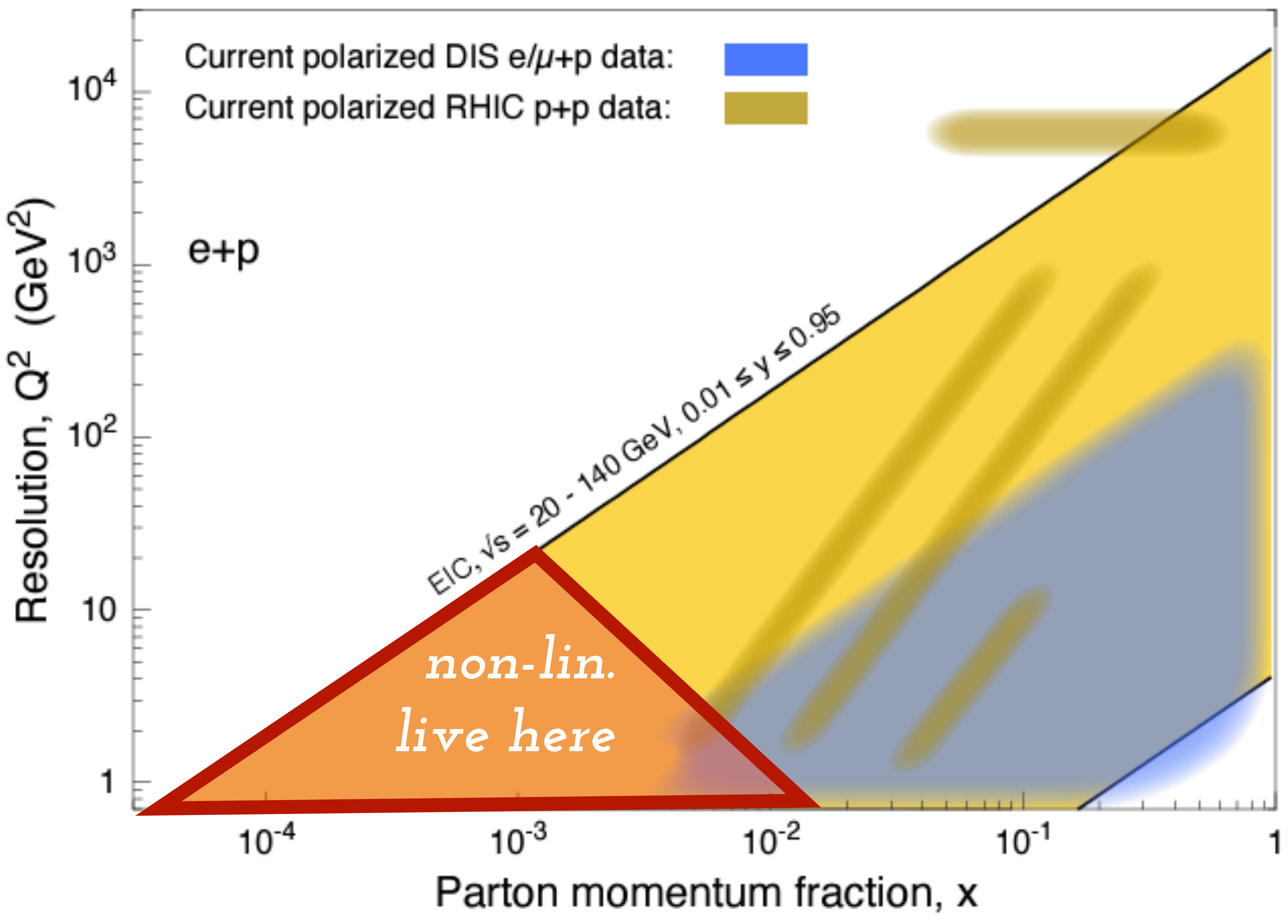


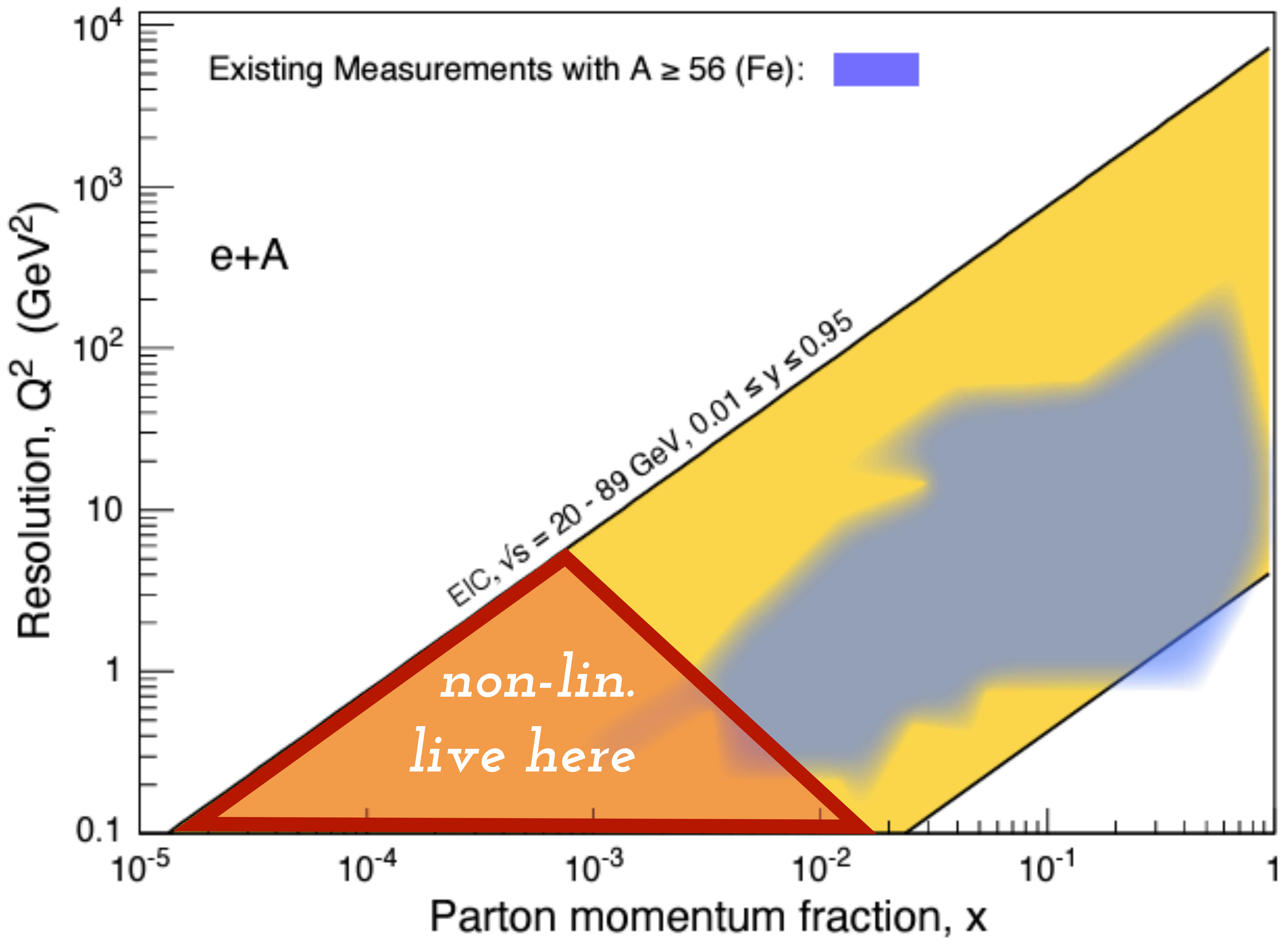
TESTING SATURATION MODELS





TESTING SATURATION MODELS





TESTING SATURATION MODELS

A DIPOLE STORY

- Inclusive DIS cross-section:

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

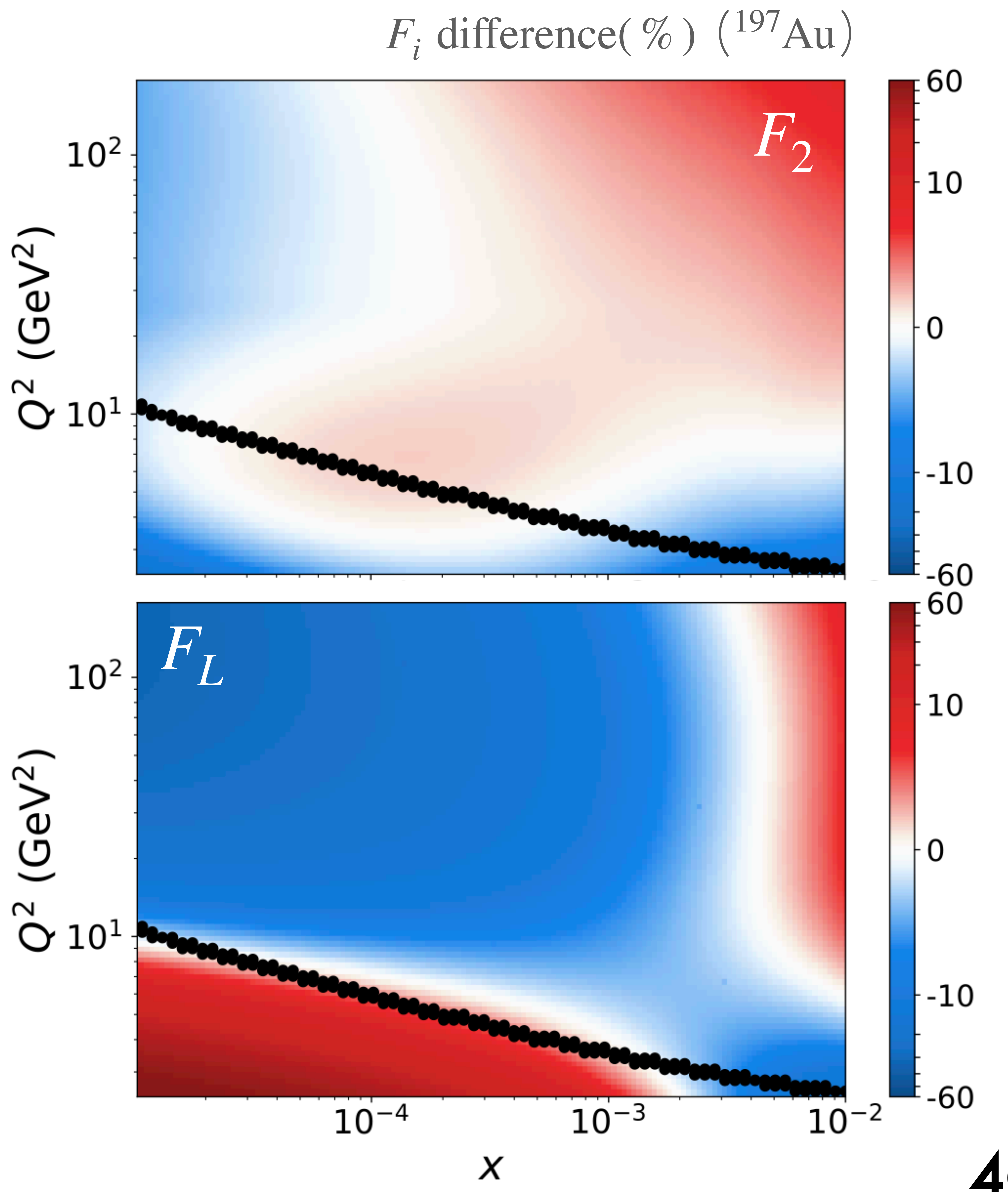
- Can be expressed as a function of structure functions, e.g.

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

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

- 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]