# THE INITIAL STATE:

## OMNE INITIUM DIFFICILE EST.


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FSP ALICE
Erforschung von
Universum und Materie

UNIVERSITÄT
BIELEFELD

CRC-TR 211
Strong-interaction matter
under extreme conditions

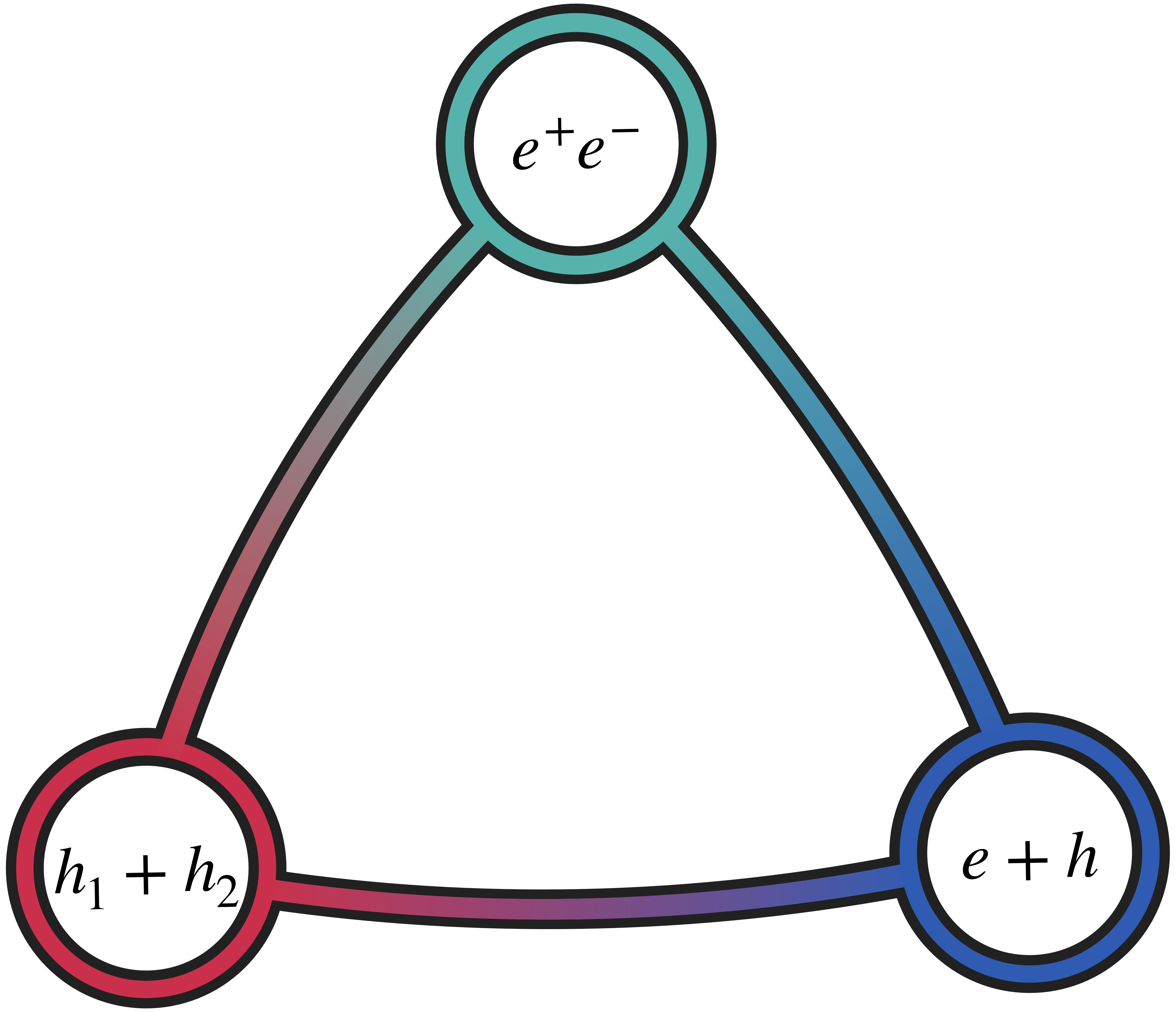
Bundesministerium
für Bildung
und Forschung

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)

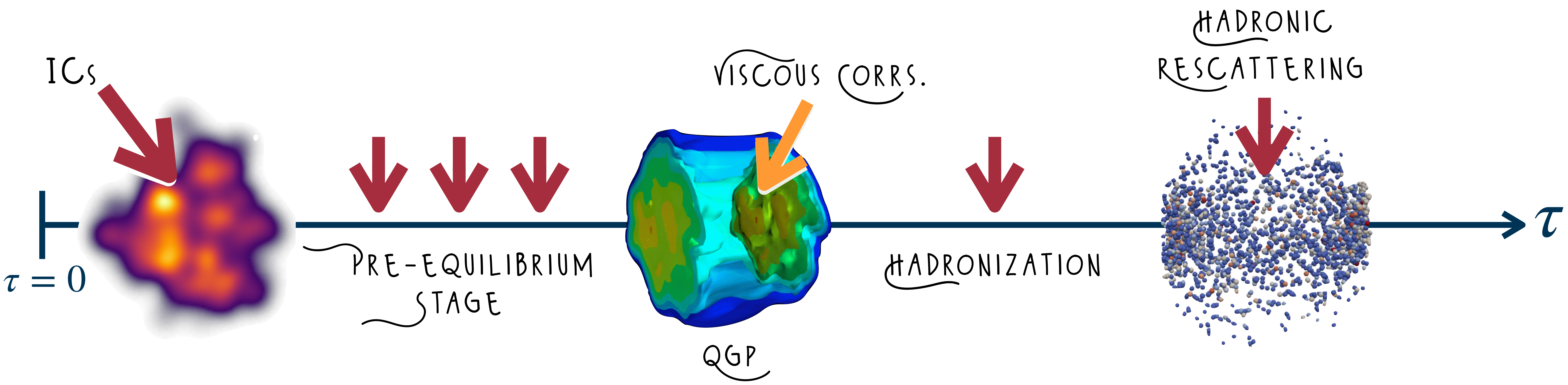
Kinematics complex but some limits are simple

Clear-cut kinematics

Excellent setting to test QCD non-linearities

# THE TENOUSLY THERMAL QGP

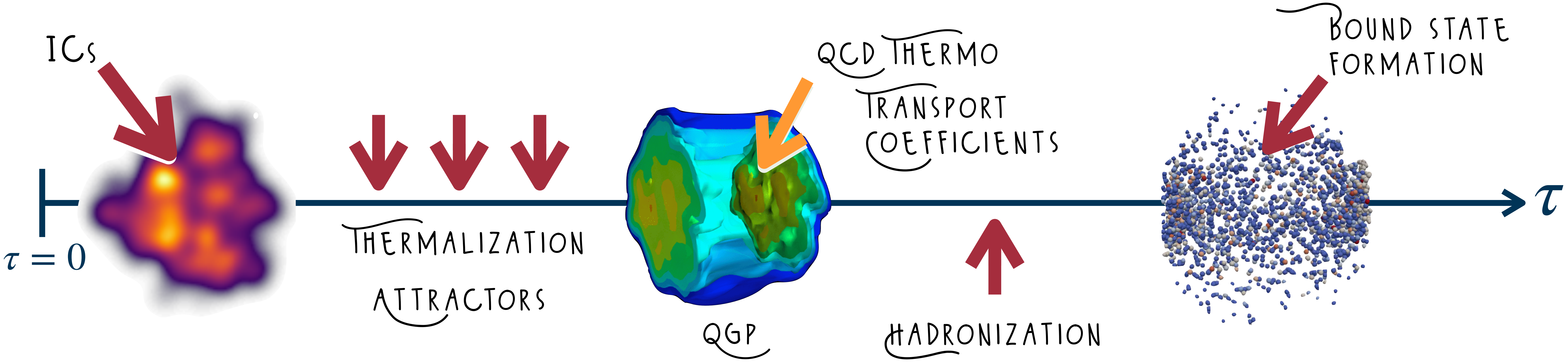
- Heavy-Ion Collisions create a -***very complicated***- Isolated Quantum System which is
  - Initially far away from any equilibrium
  - Self-interacting
  - Expanding against the vacuum
- A system battling to thermalize against all odds.



# WHAT CAN WE LEARN?

## FROM THE TENOUSLY THERMAL QGP

- Thermalisation
  - How can isolated QCD systems thermalize 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

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Seemingly different,
But in reality, intimately related!!

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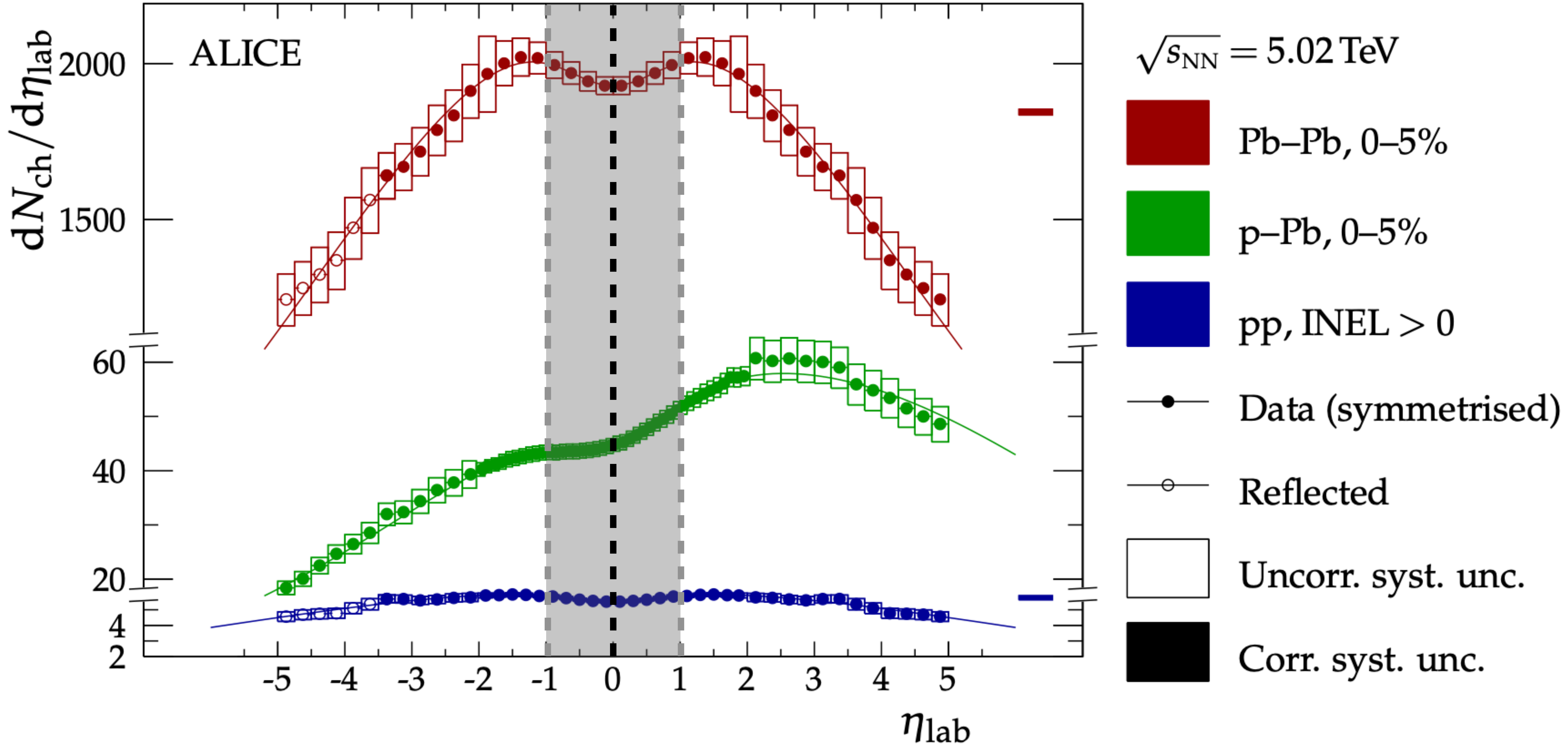
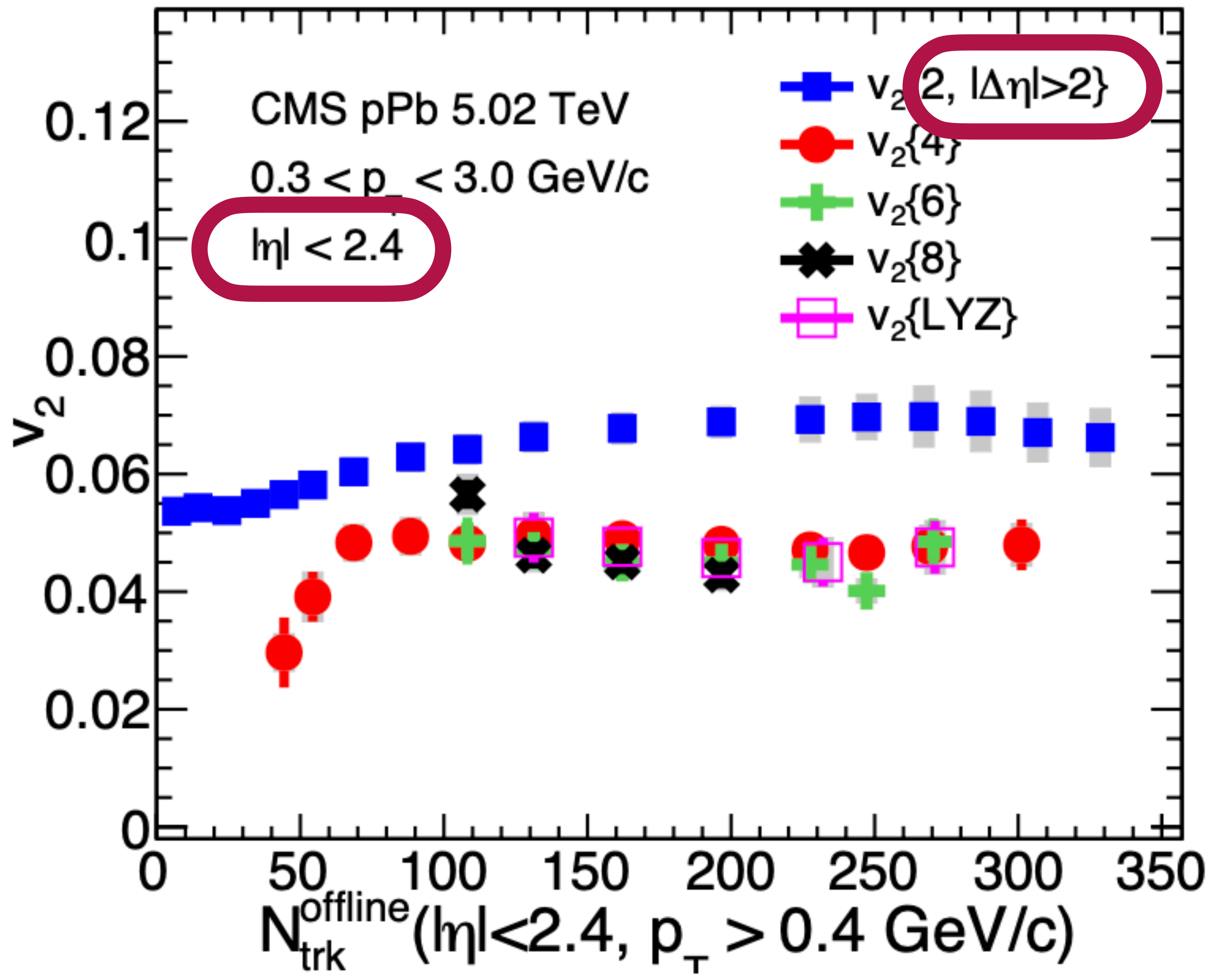
LET'S TAKE A LOOK FIRST AT

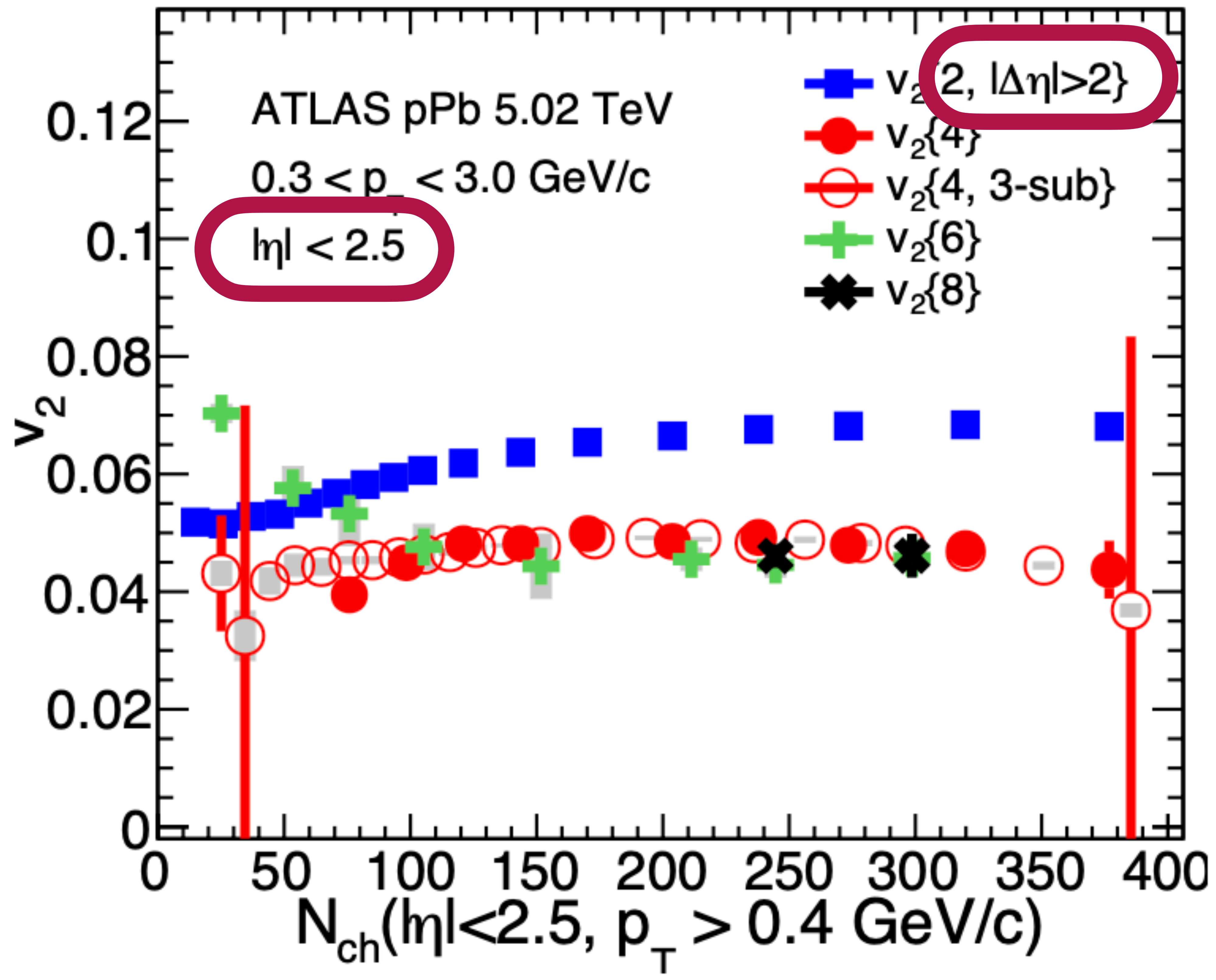
# THE LONGITUDINAL STRUCTURE



## CLOSER LOOK: LONG. STRUCTURE OF

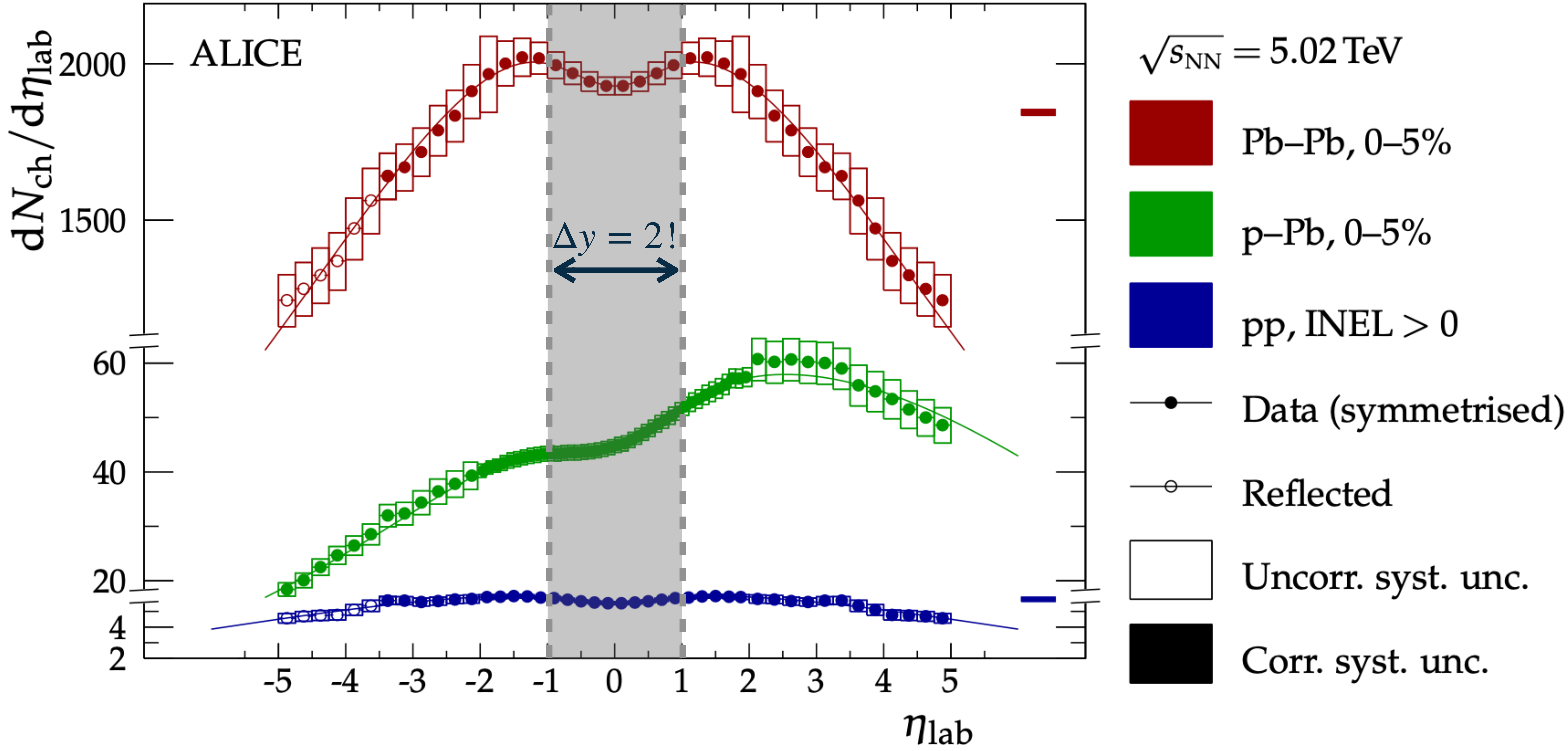
# SMALL SYSTEMS




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

# BOOST INVARIANCE IS...



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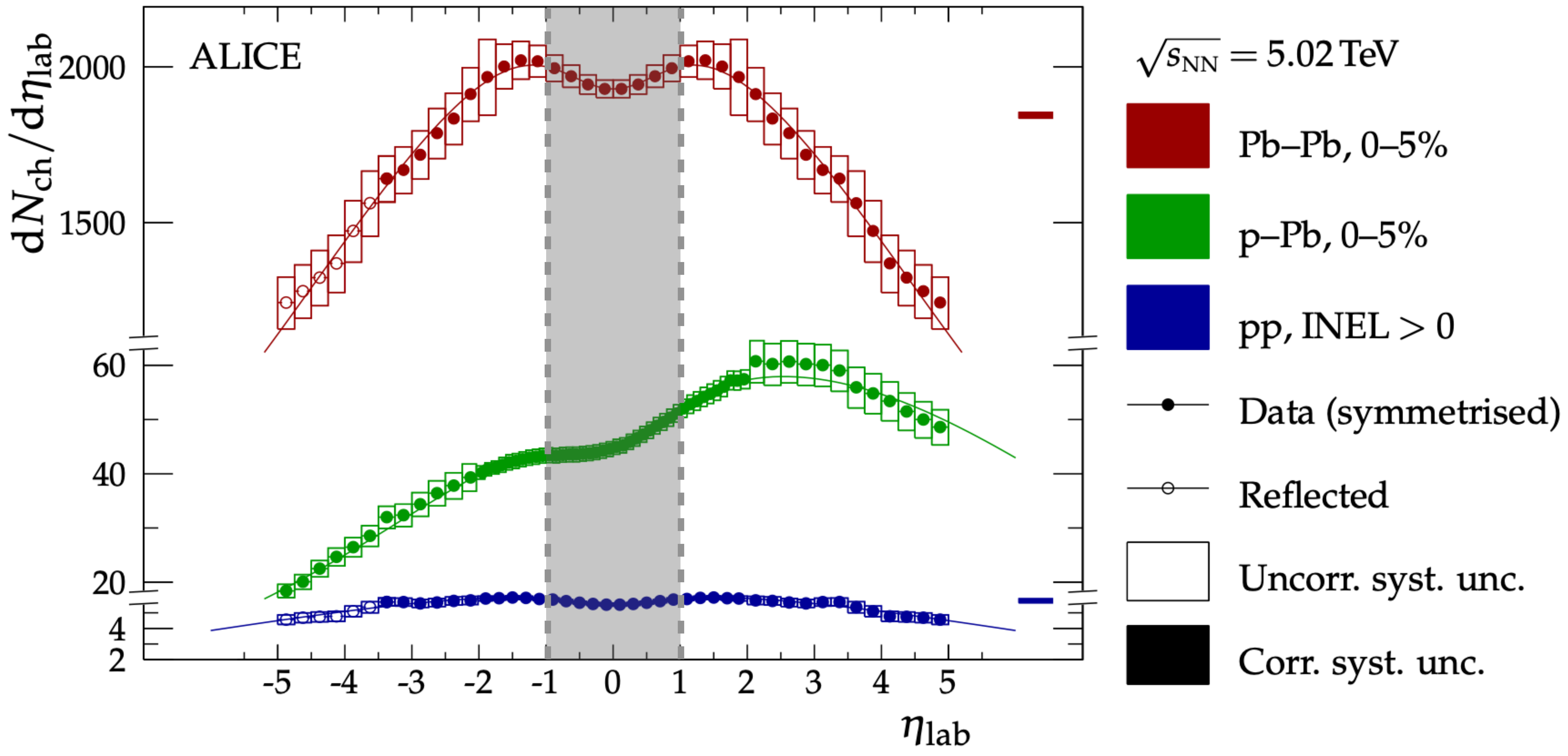
## NOT A GOOD APPROXIMATION*




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

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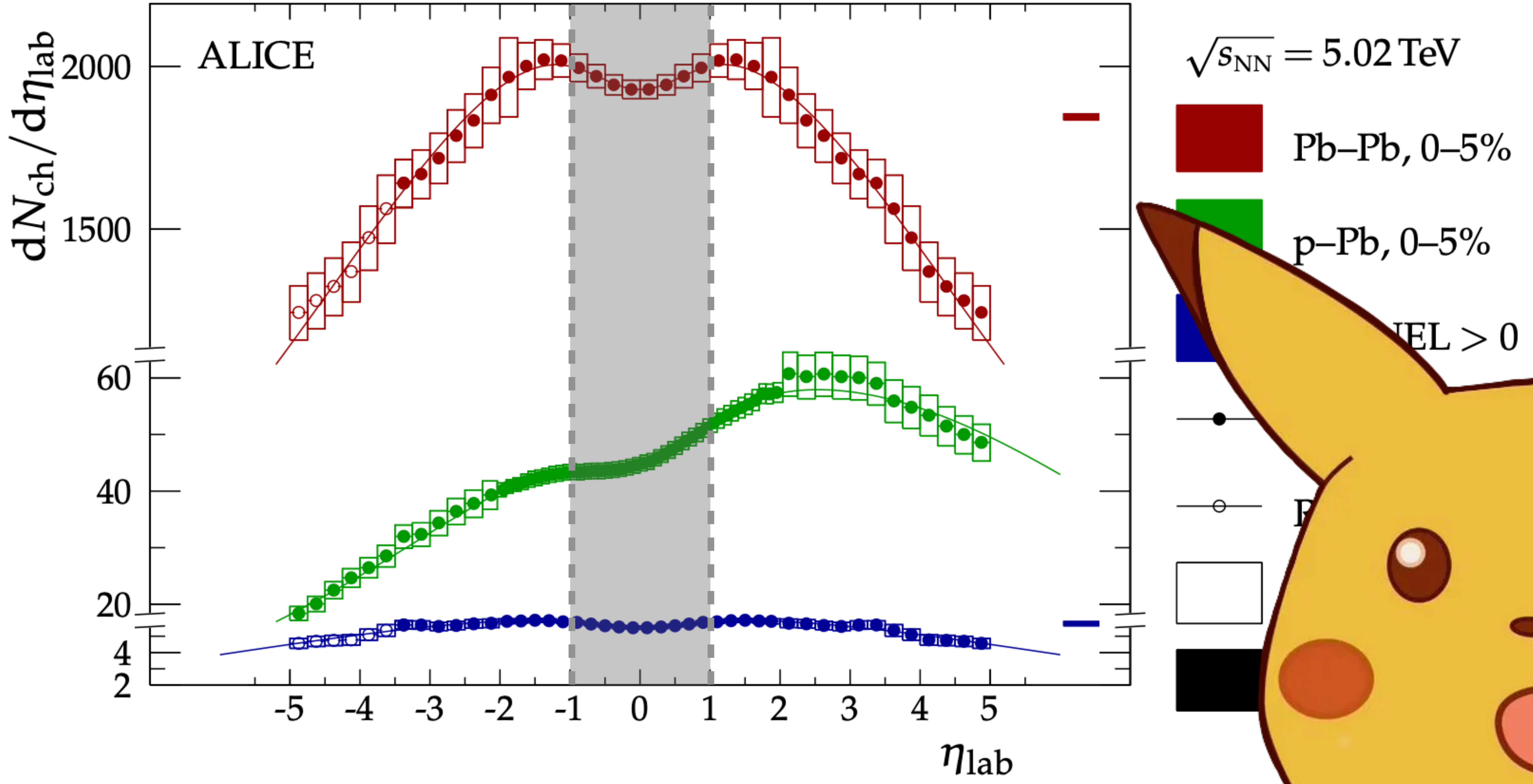


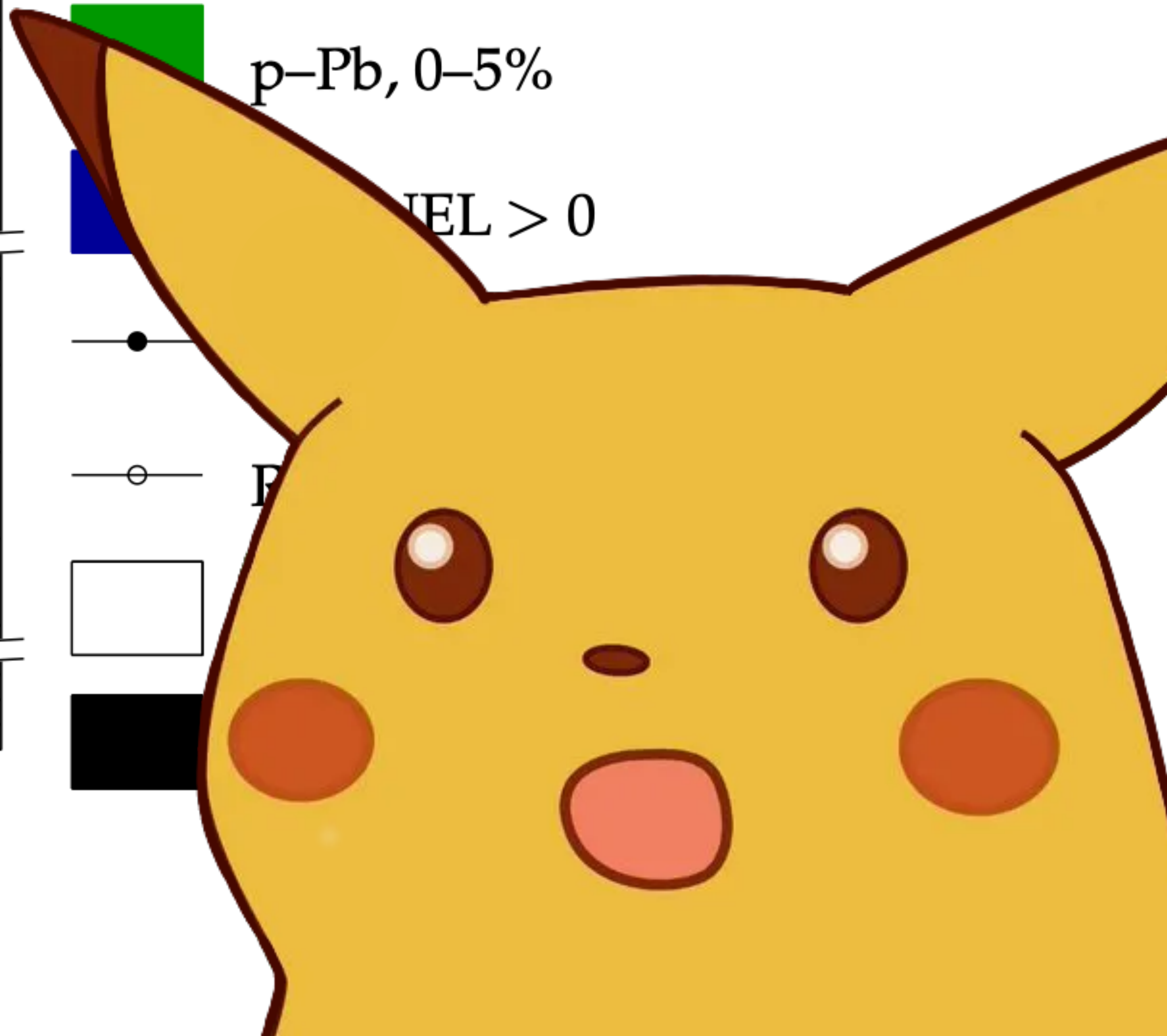

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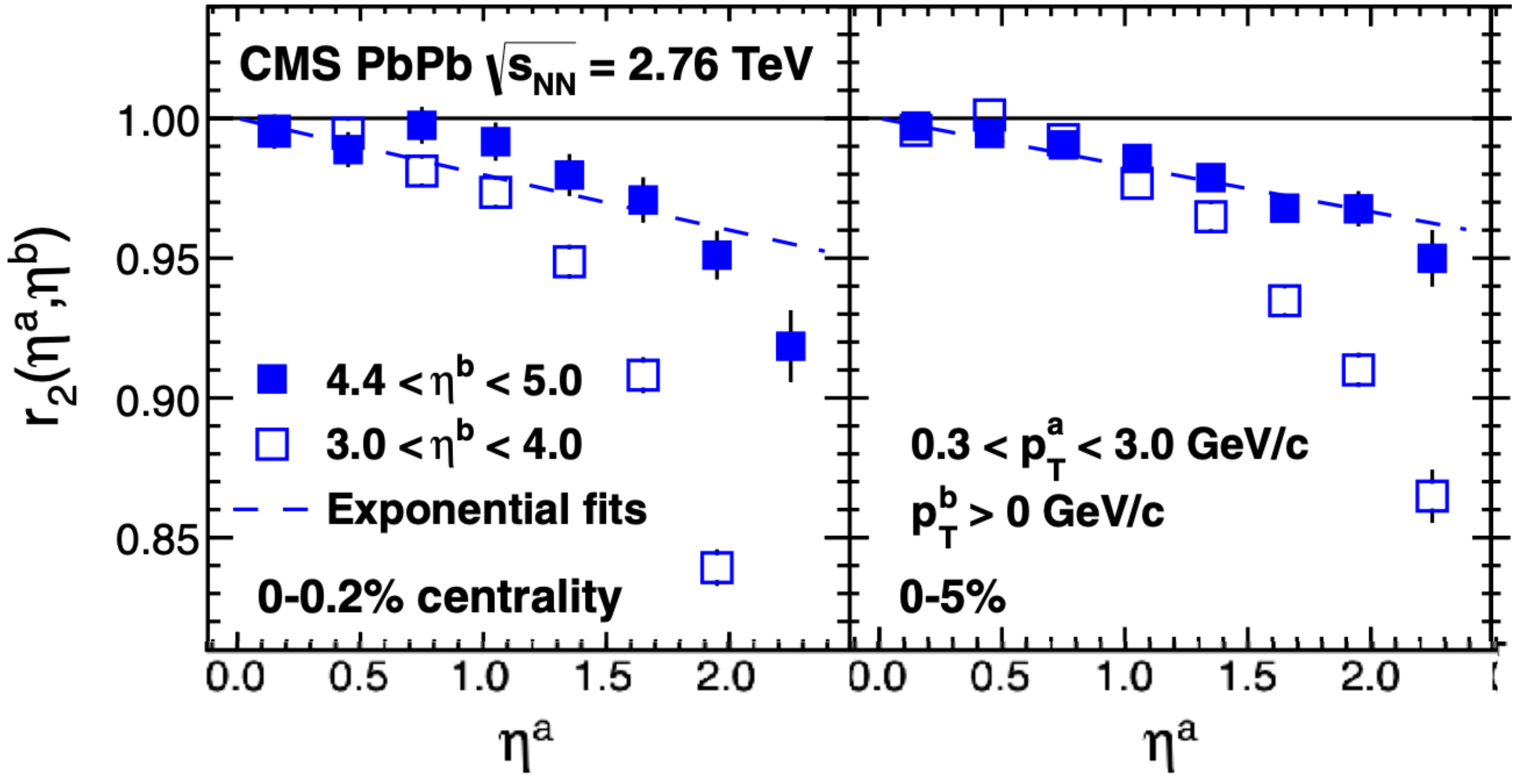
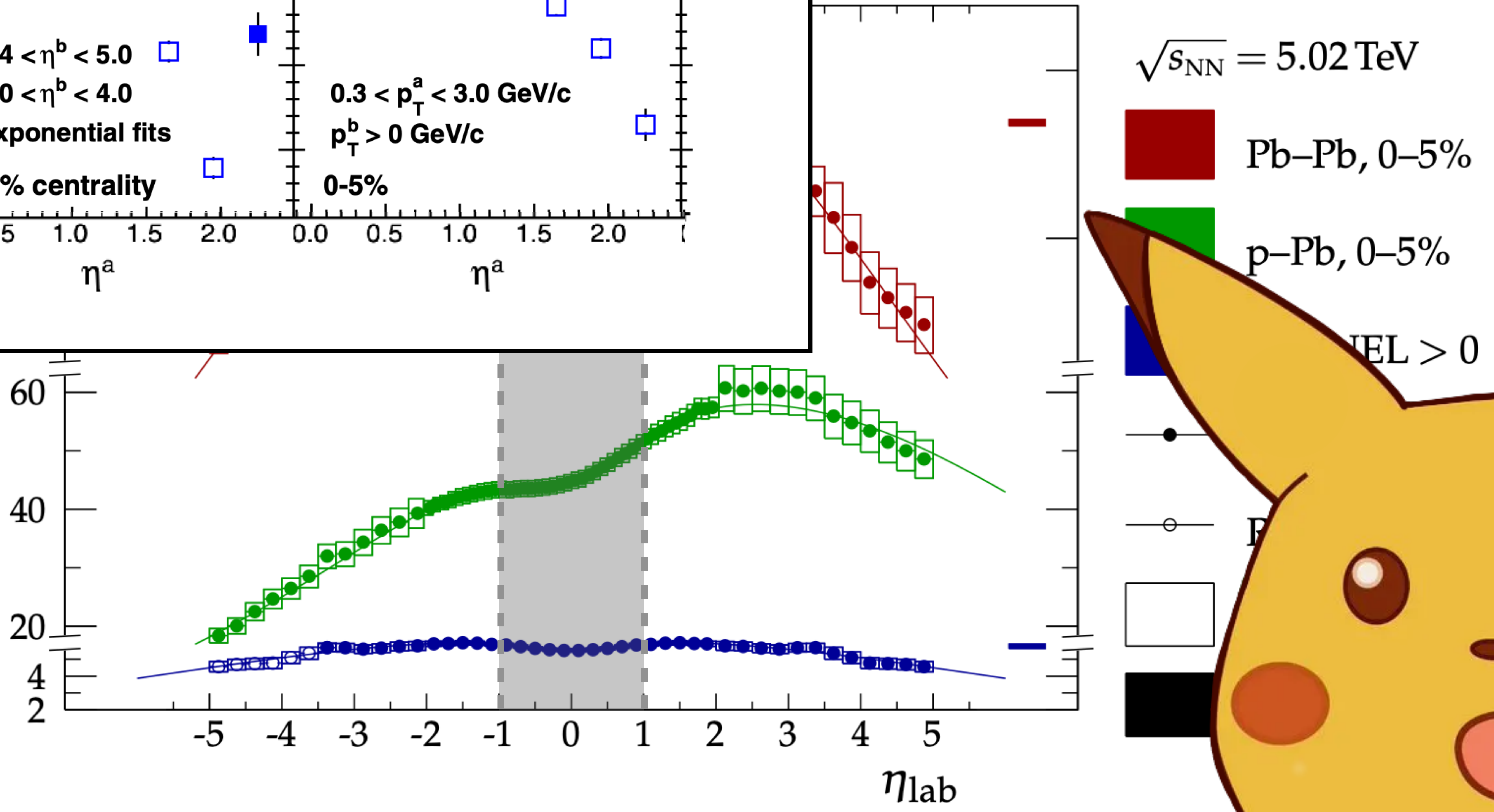
RIANCE IS...

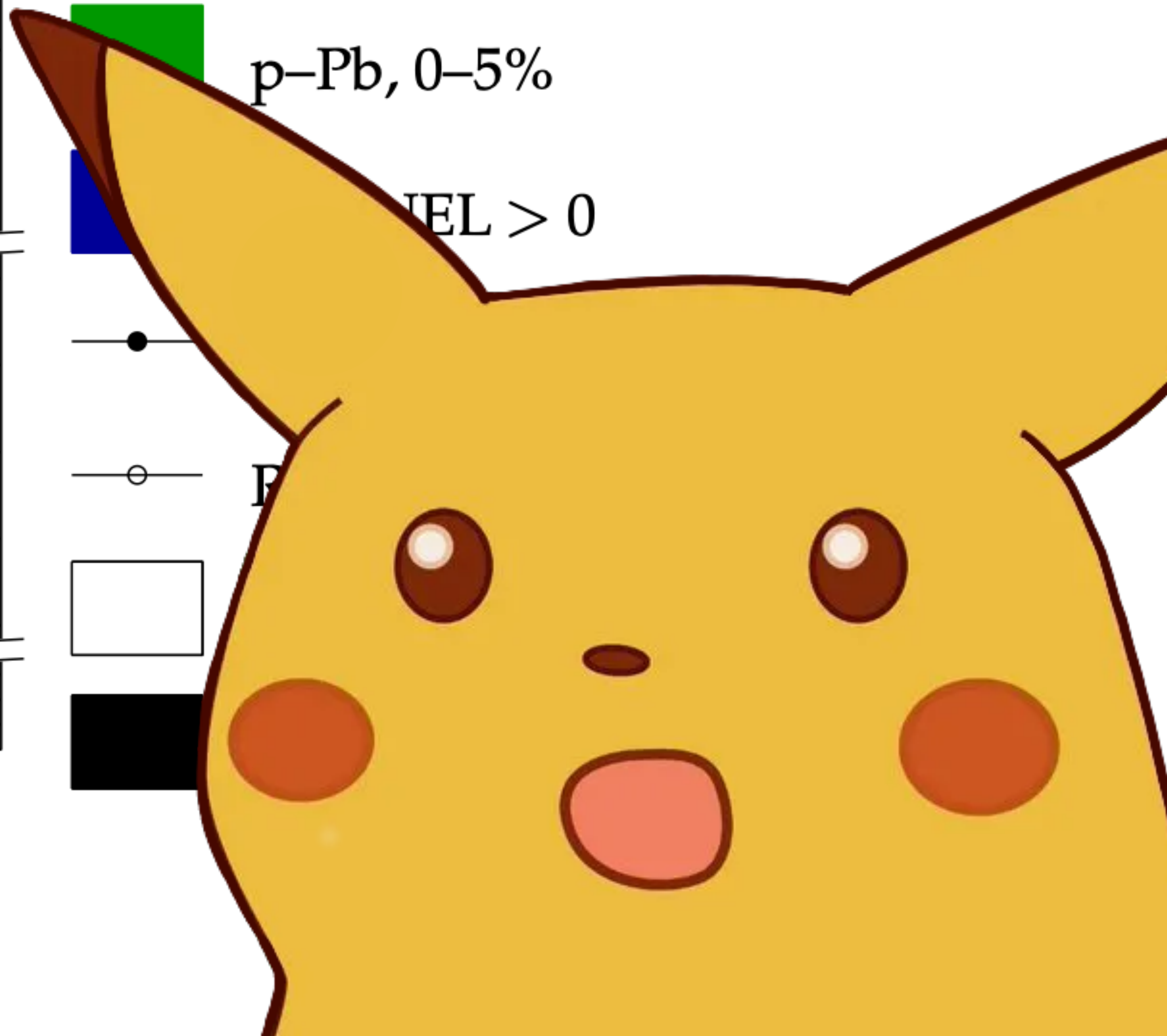
ROXIMATION

# FLOW DECORRELATION

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



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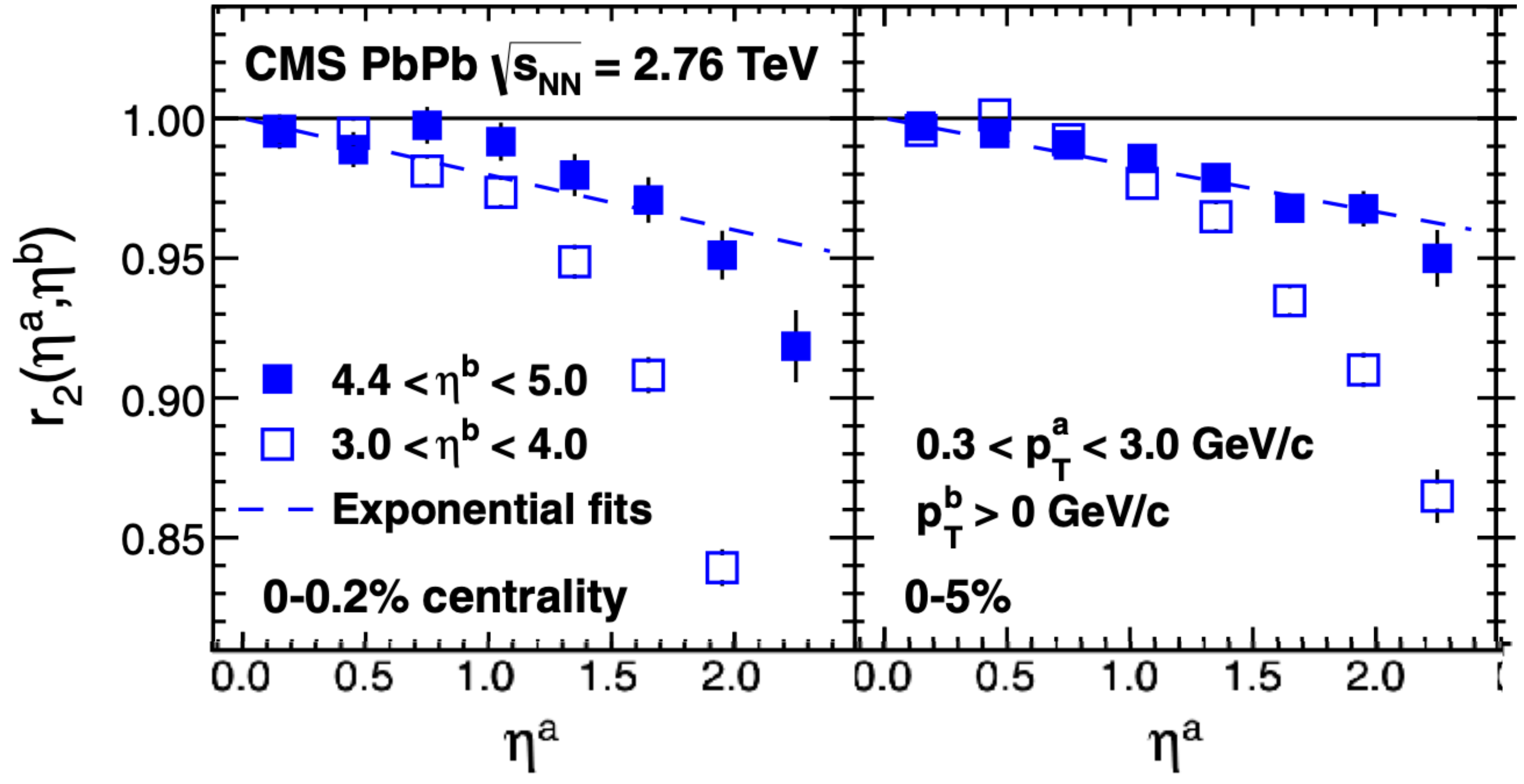
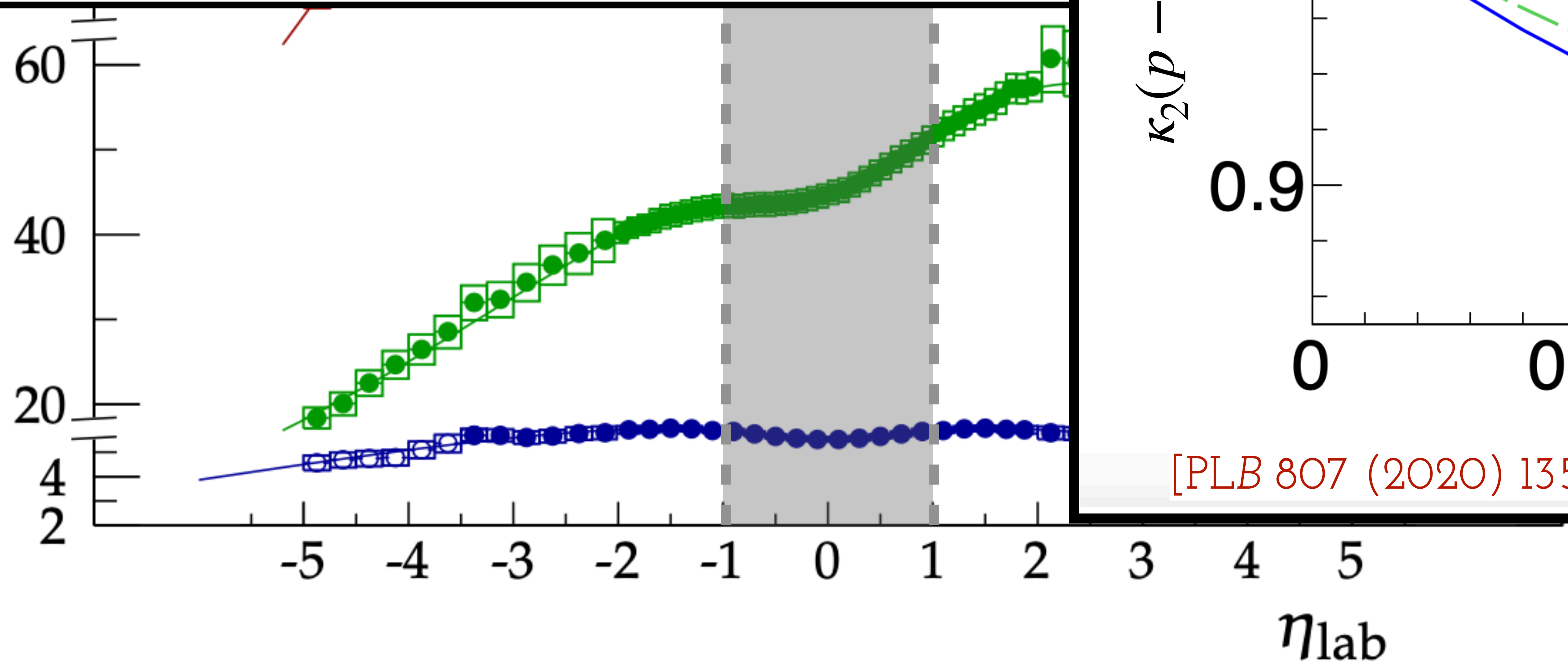
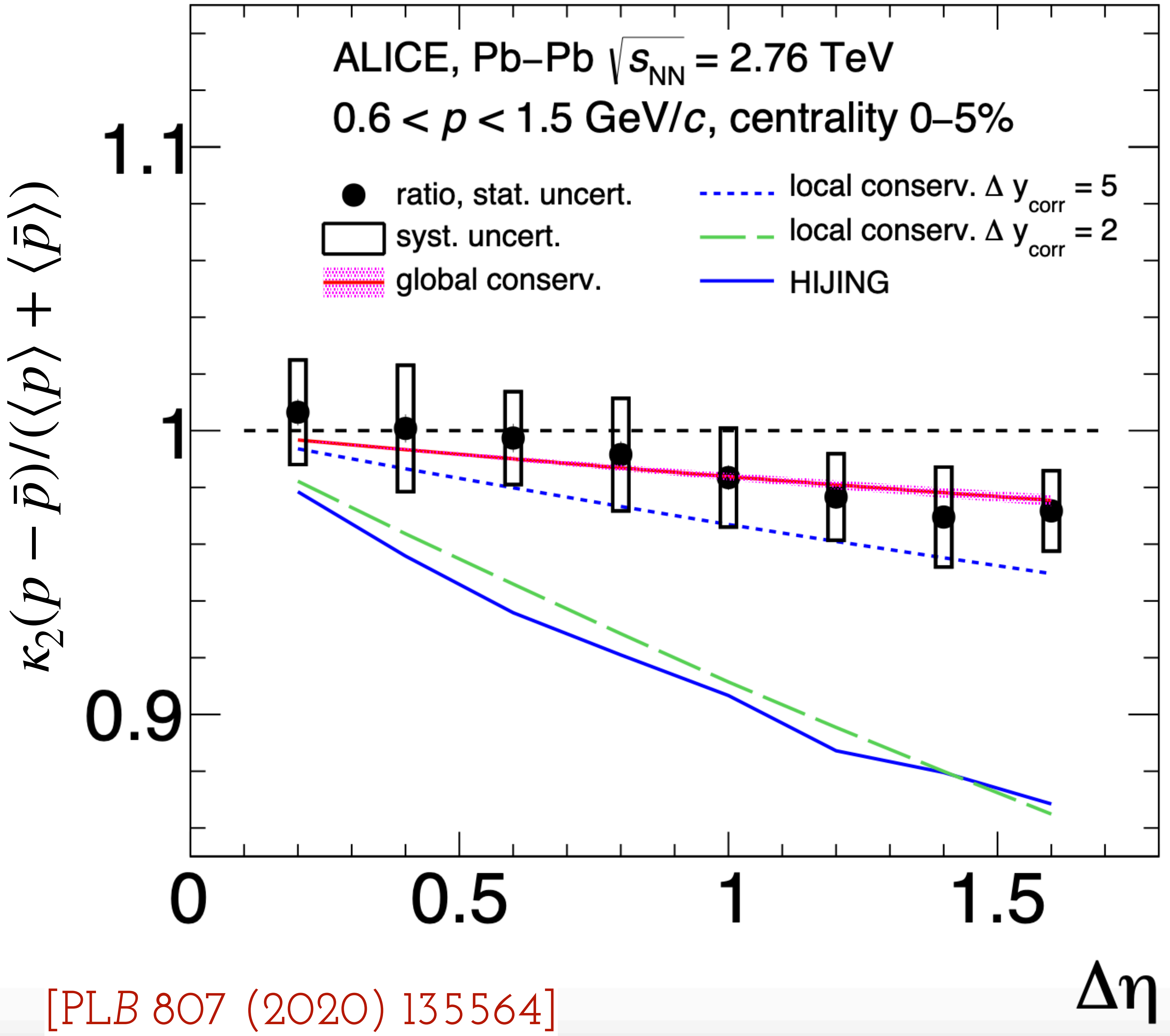
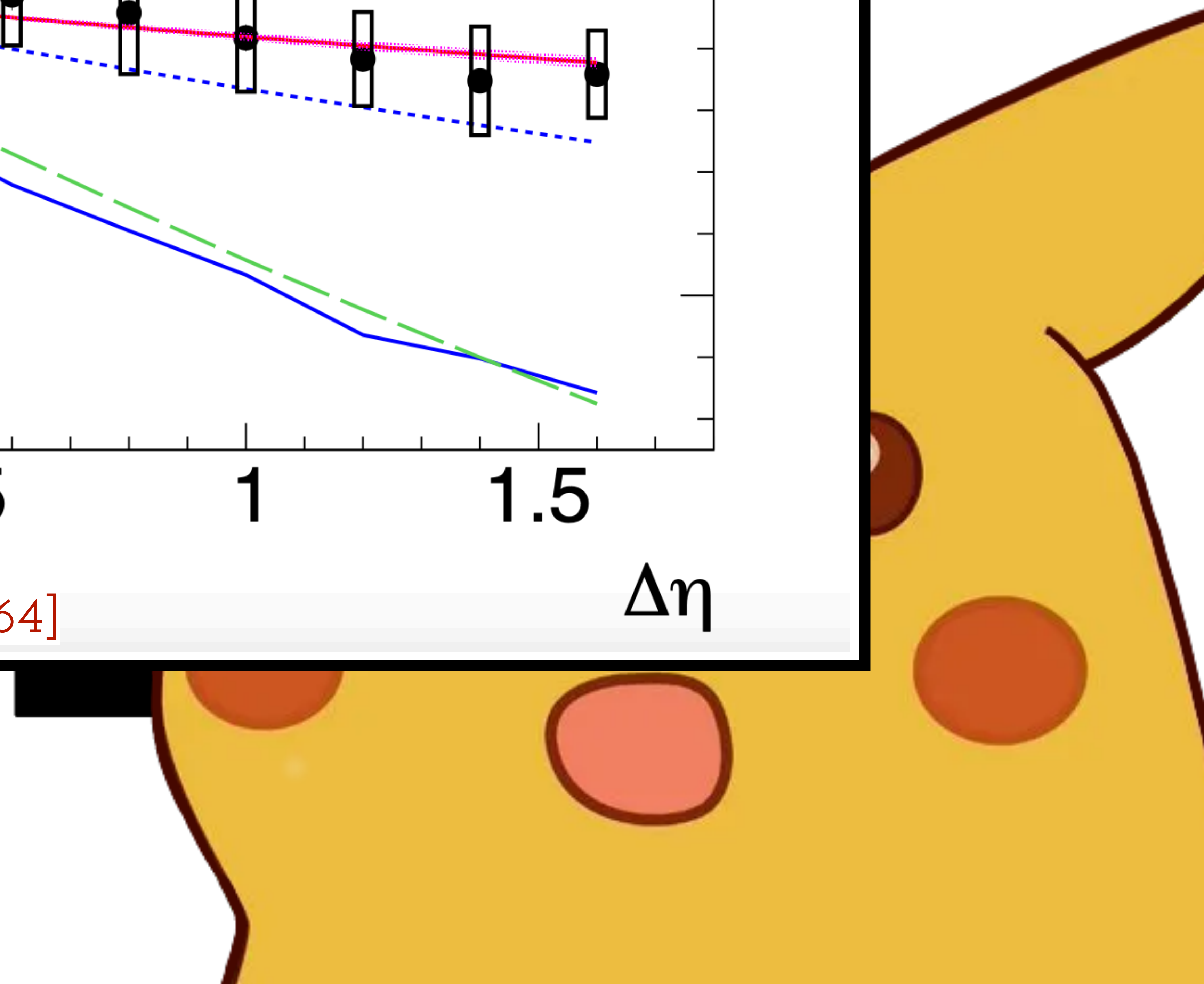



## BARYON LONG. CORRS.




[PLB 807 (2020) 135564]



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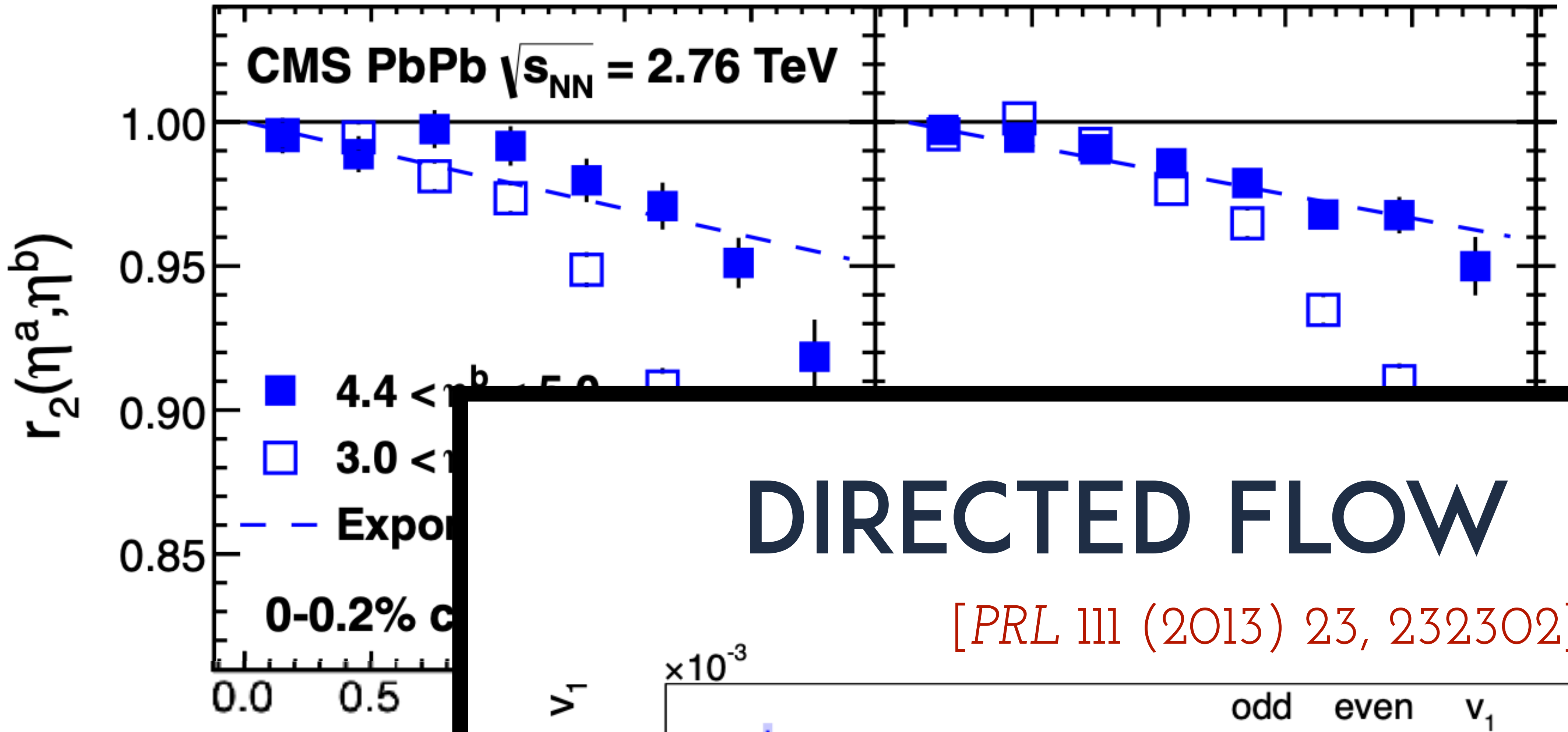
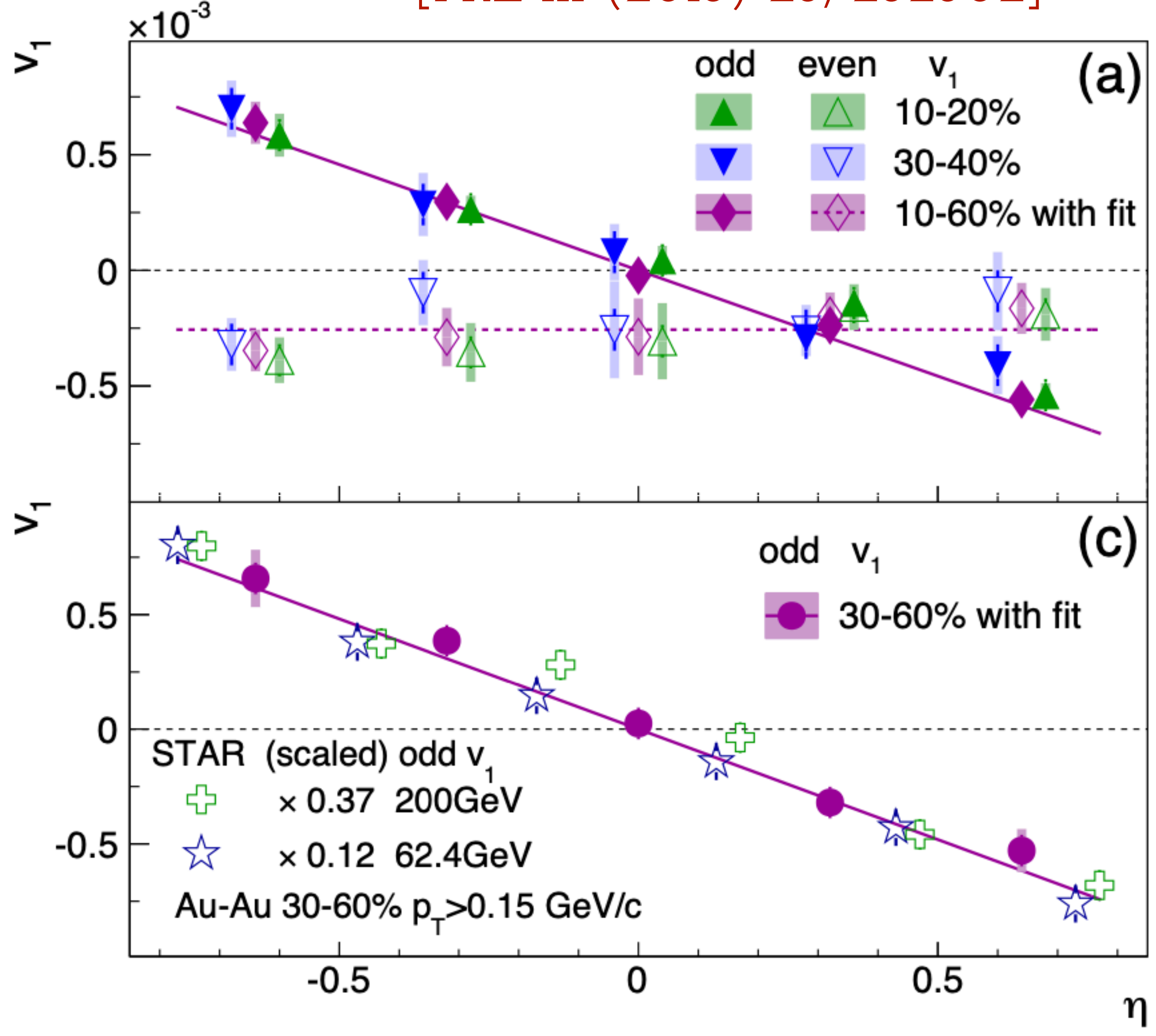



## DIRECTED FLOW

[*PRL* 111 (2013) 23, 232302]

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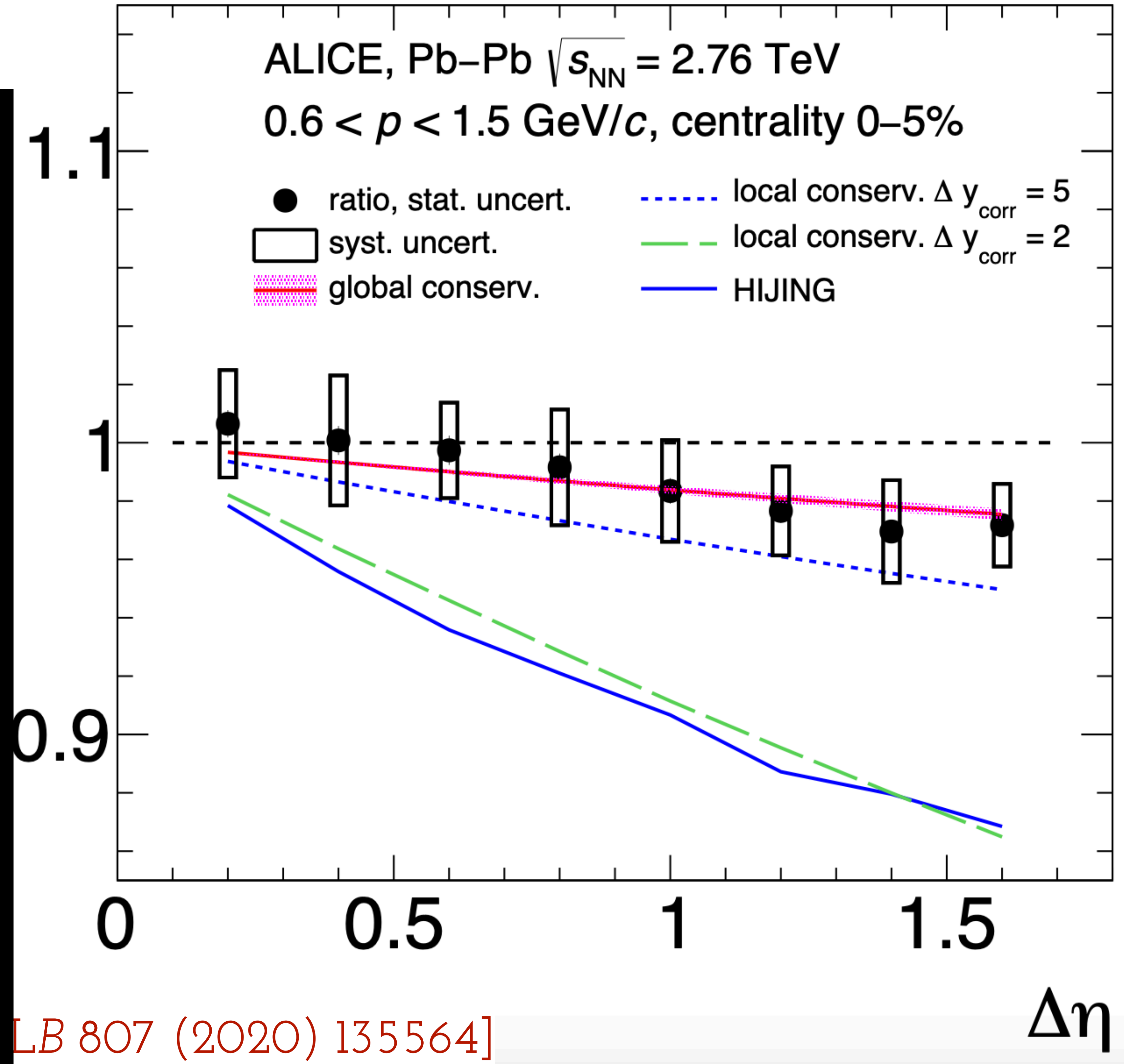


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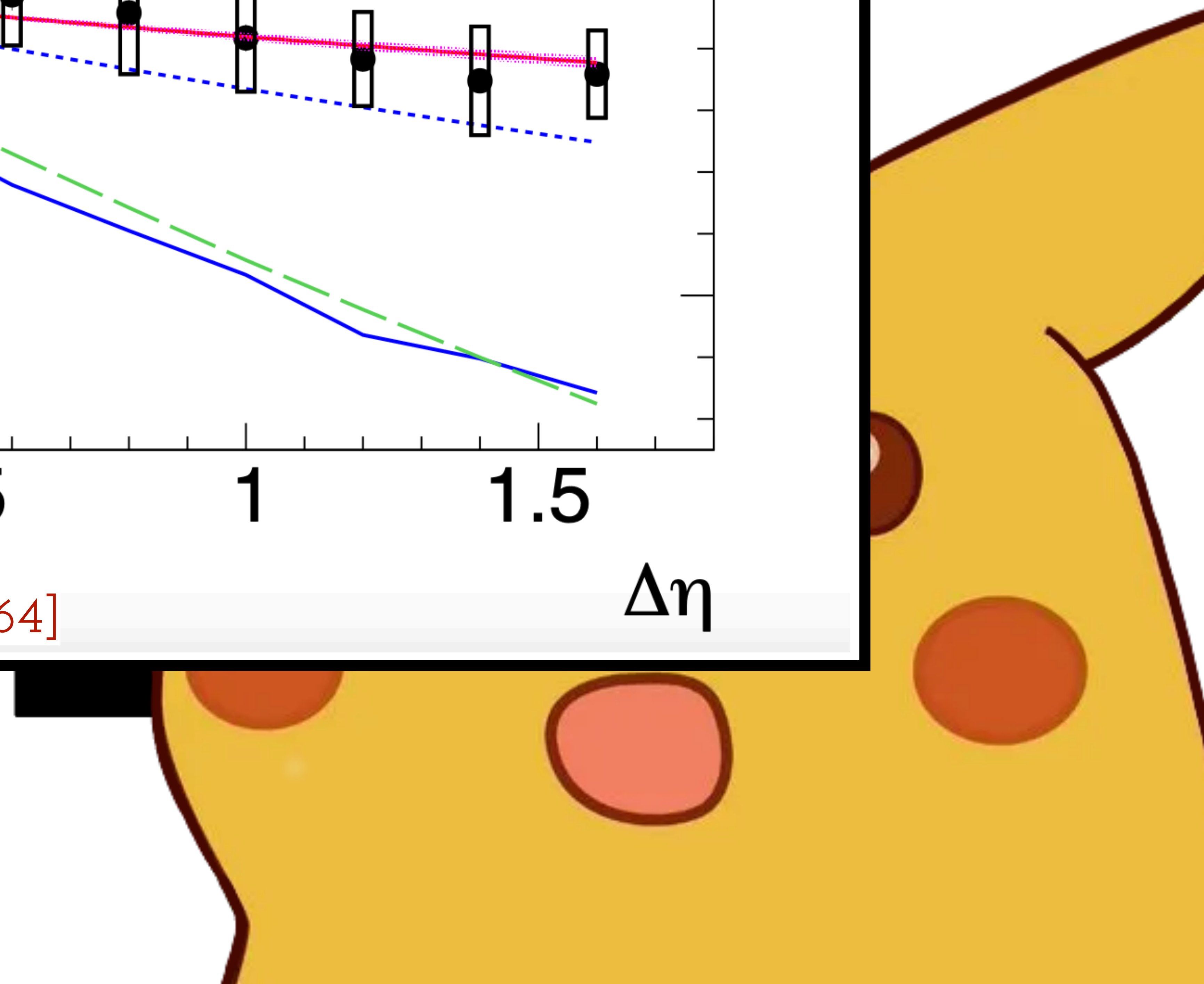

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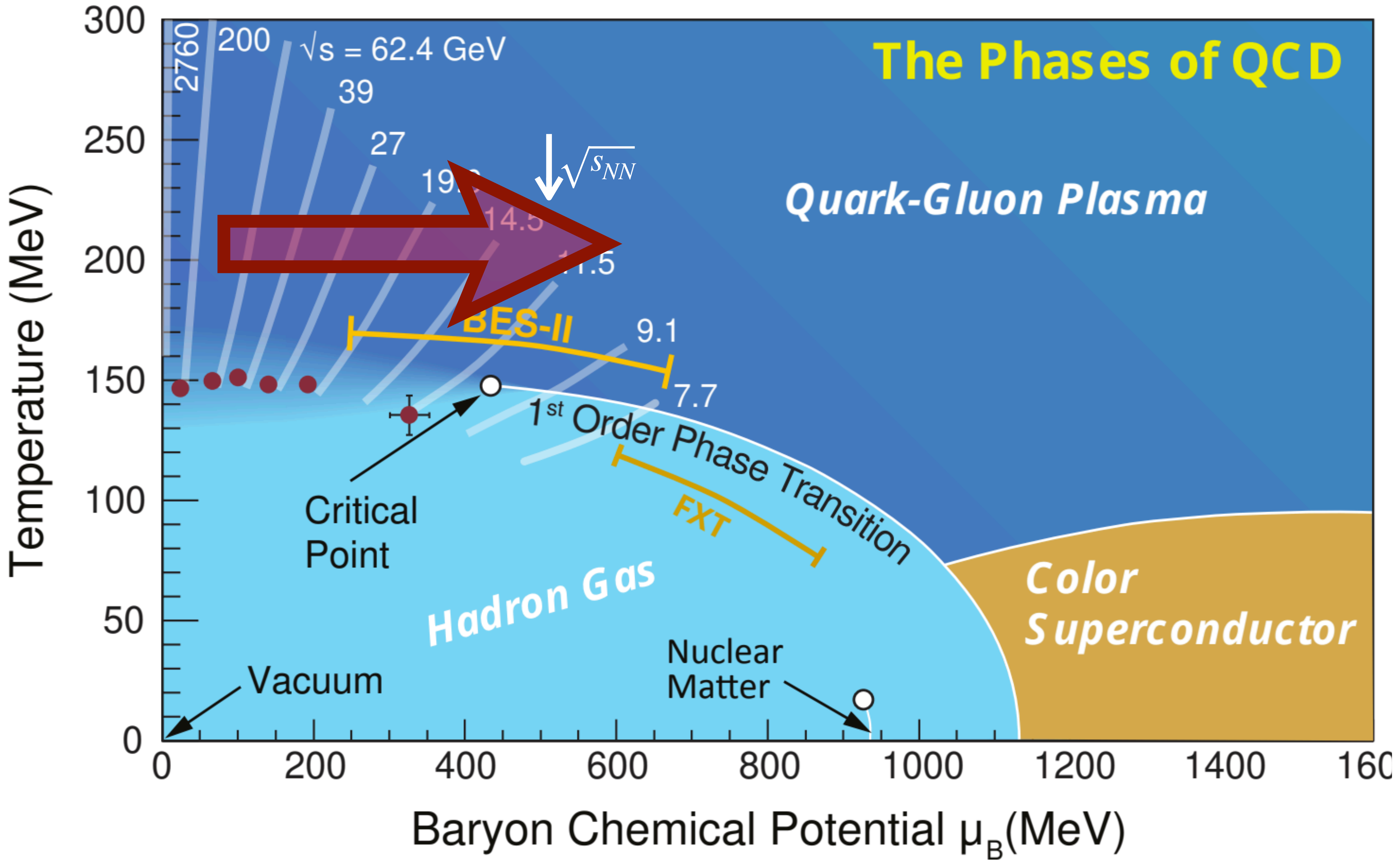
# RAPIDITY RESOLUTION

## 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

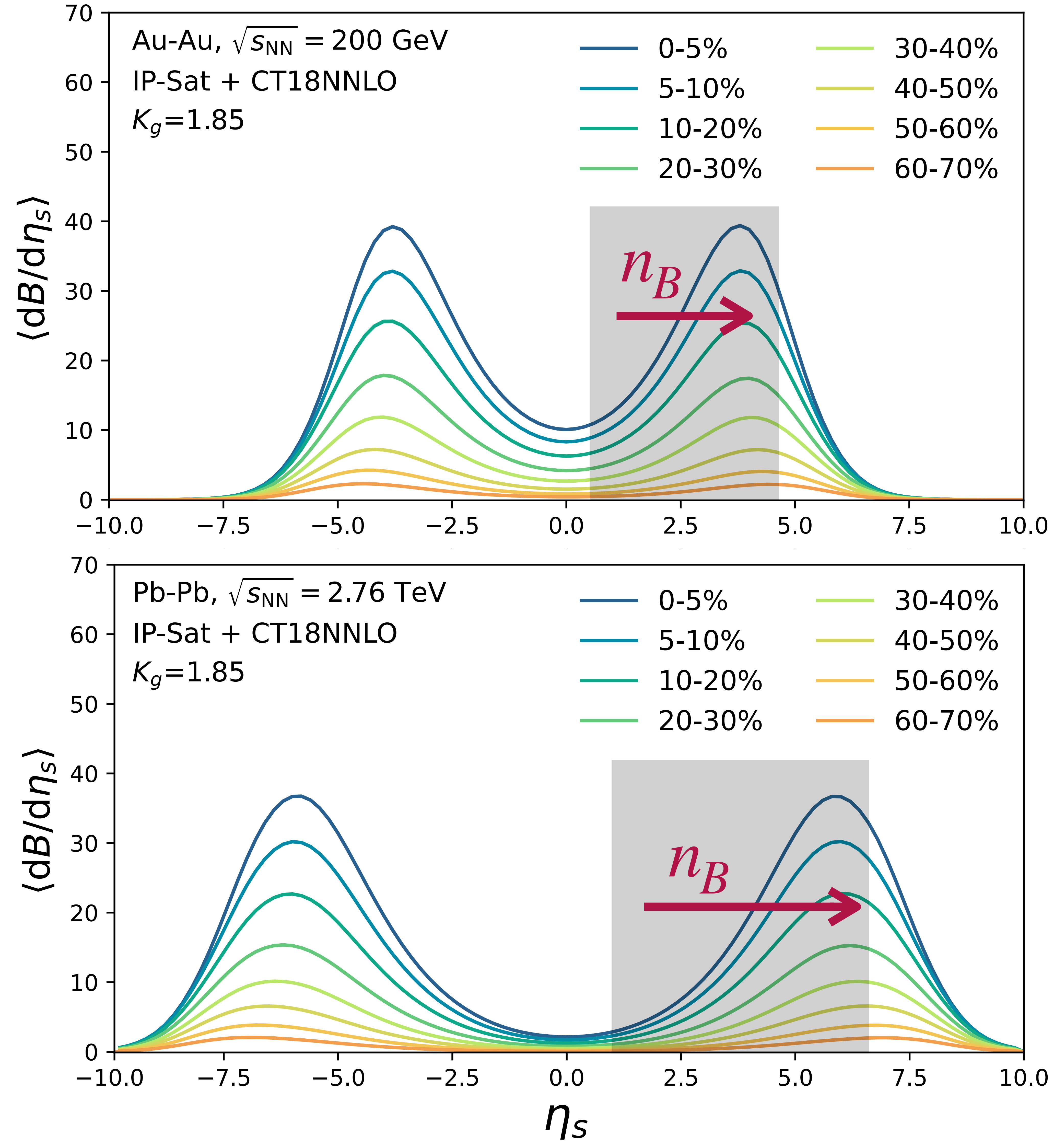
Baryon stopping is also seen at larger energies, leading to zones of of high $n_B$

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-$\mu_B$ observables.



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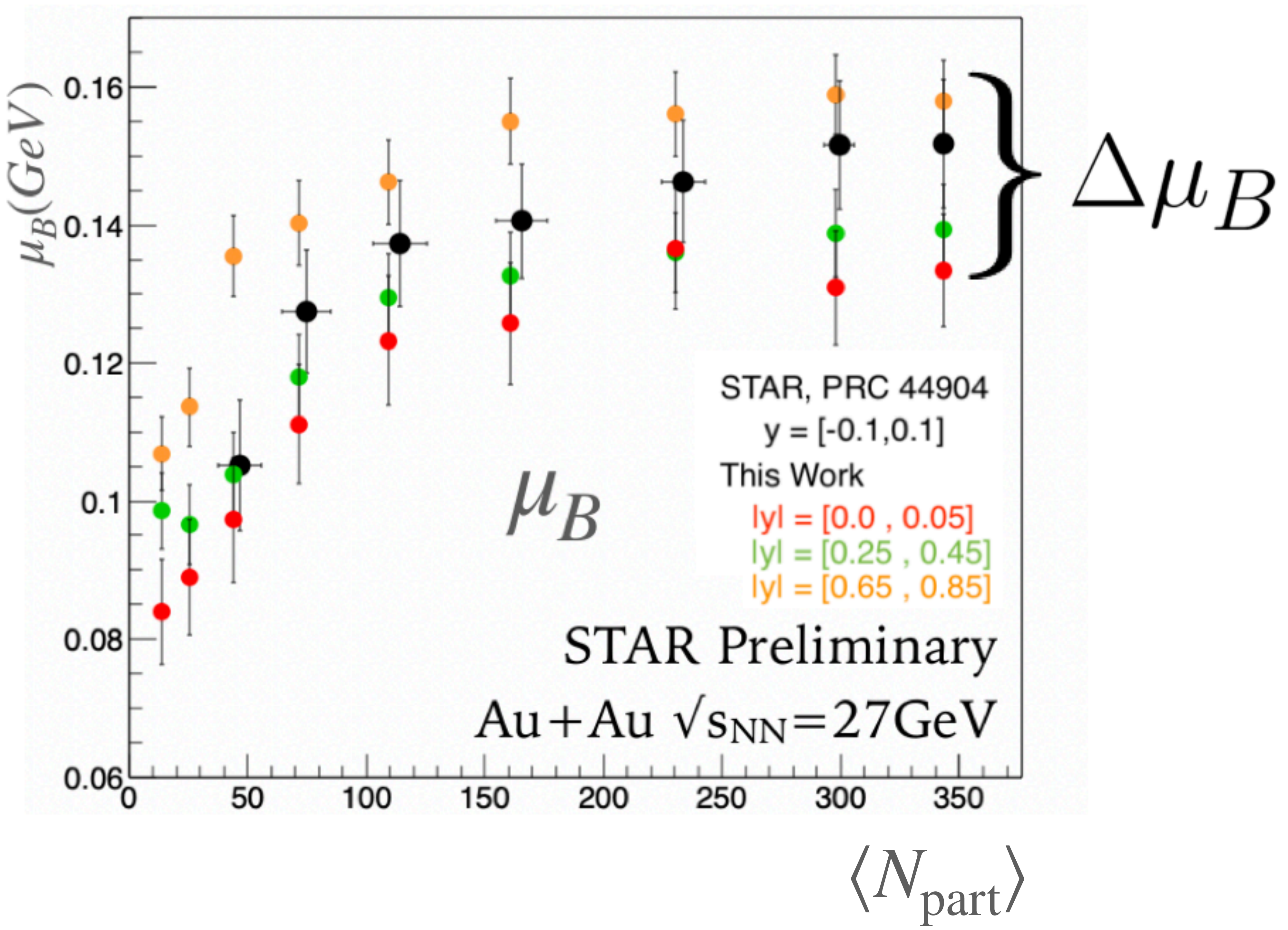
PROOF OF CONCEPT

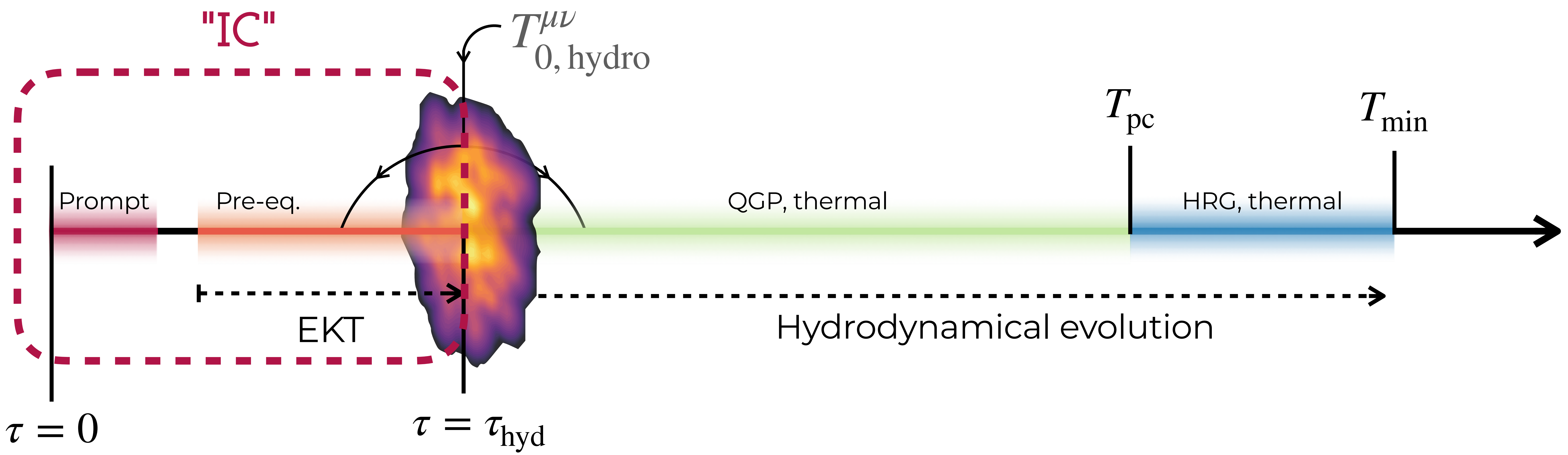


We need a well controlled 3D initial energy, and charge (BQS) deposition to initialise -precision physics era- EbE simulations

# THE INITIAL STATE OF A HIC

What do we need?

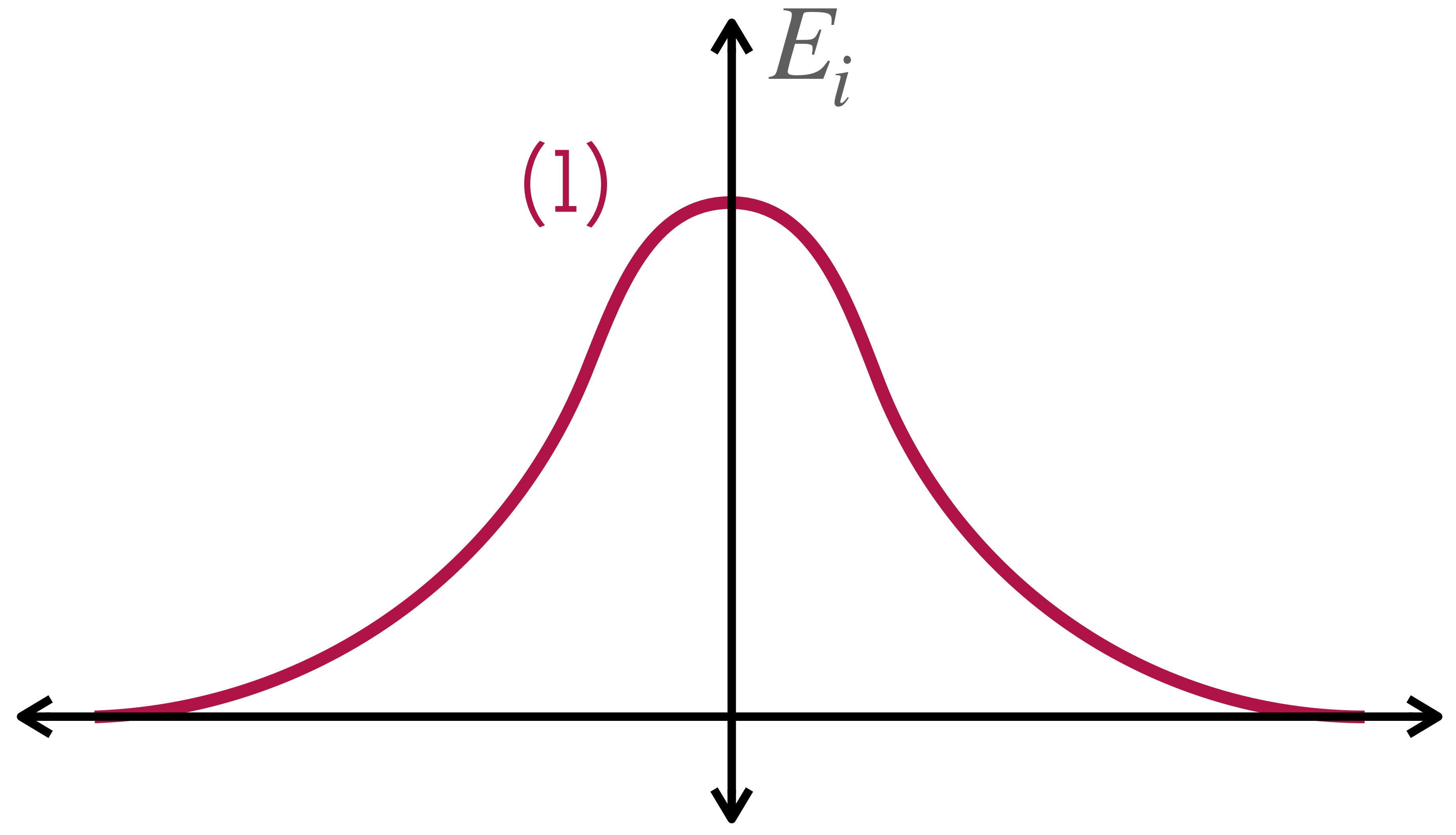
- IC is commonly taken to be up to the beginning of hydro evolution.
- Then, the initial energy stress tensor, $T^{\mu\nu}_{0,\,\mathrm{hydro}}$ , is needed.



# 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.



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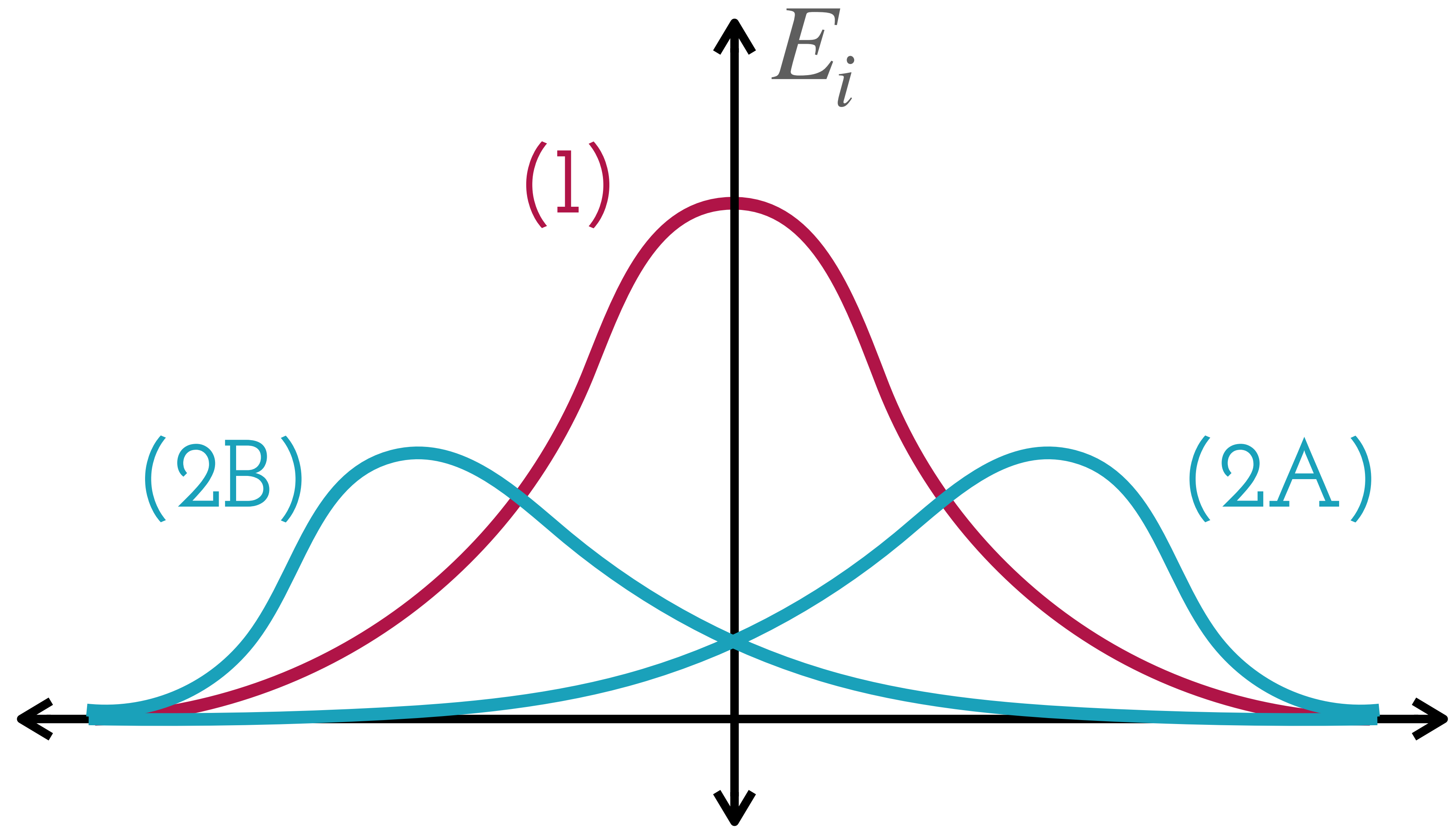
  - Quark scattering, baryon junction, hadrons?



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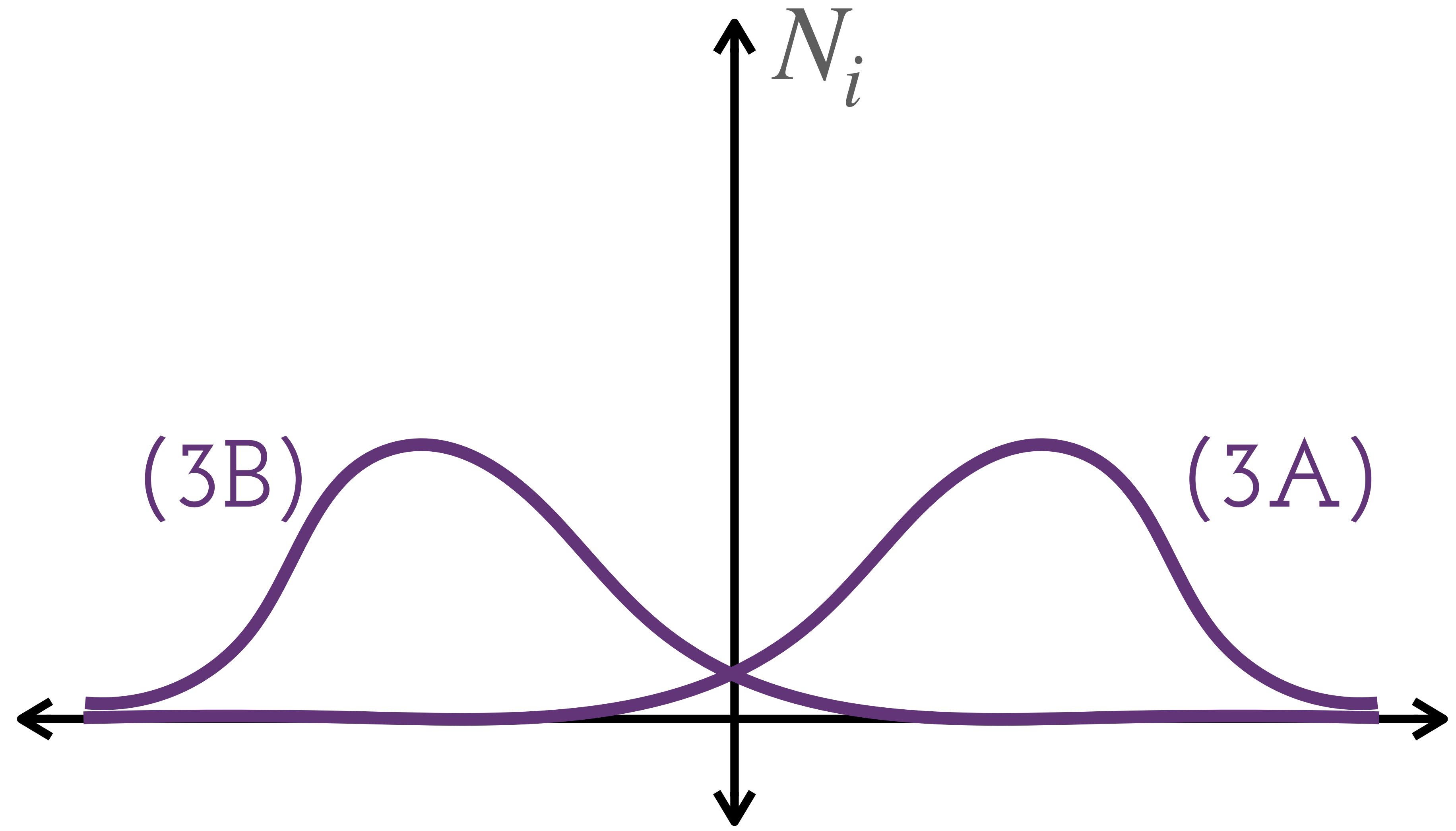
- (2) Fragmentation region charge deposition: Q,B and S (in fluctuations)



# 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

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AMPT, EKRT
(Next Talk!)

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TRENTO

## LOW-X

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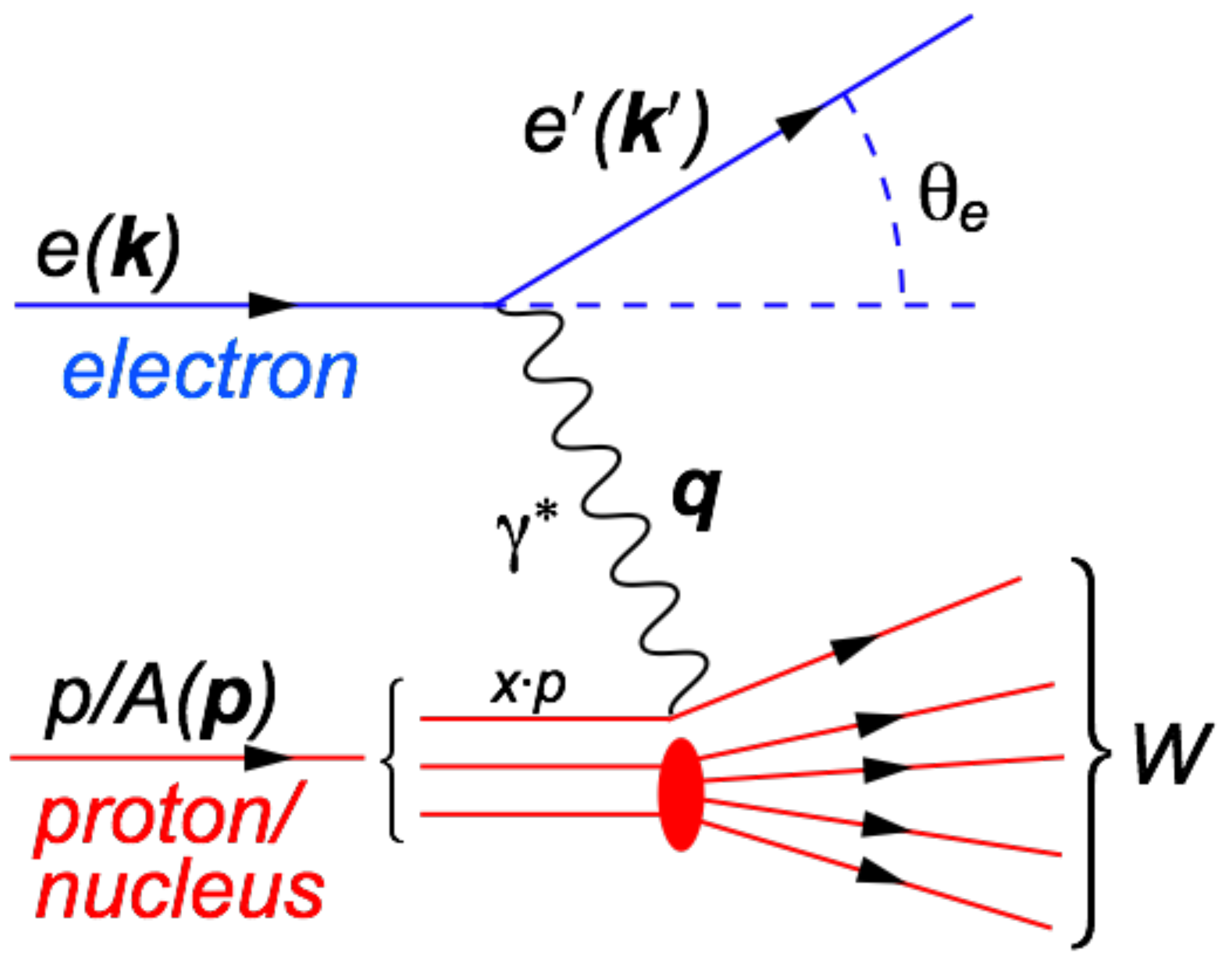
# SATURATION MODELS

# 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

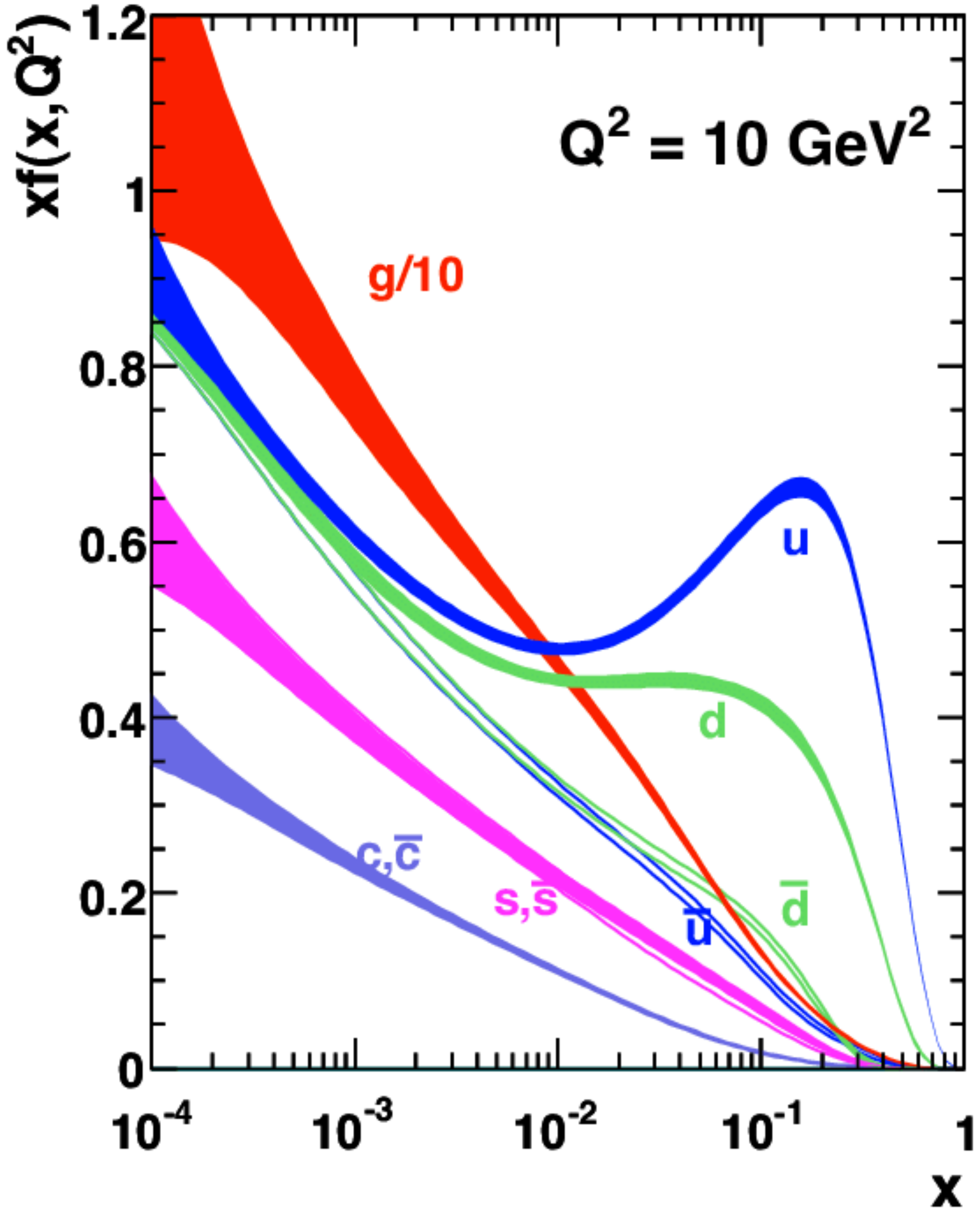
# SATURATION MODELS

## NUCLEAR STRUCTURE

- PDFs from fit to Experiments (DIS)

  $x$ ~ energy/momentum fraction carried by parton

  $Q^2$ ~ resolution scale



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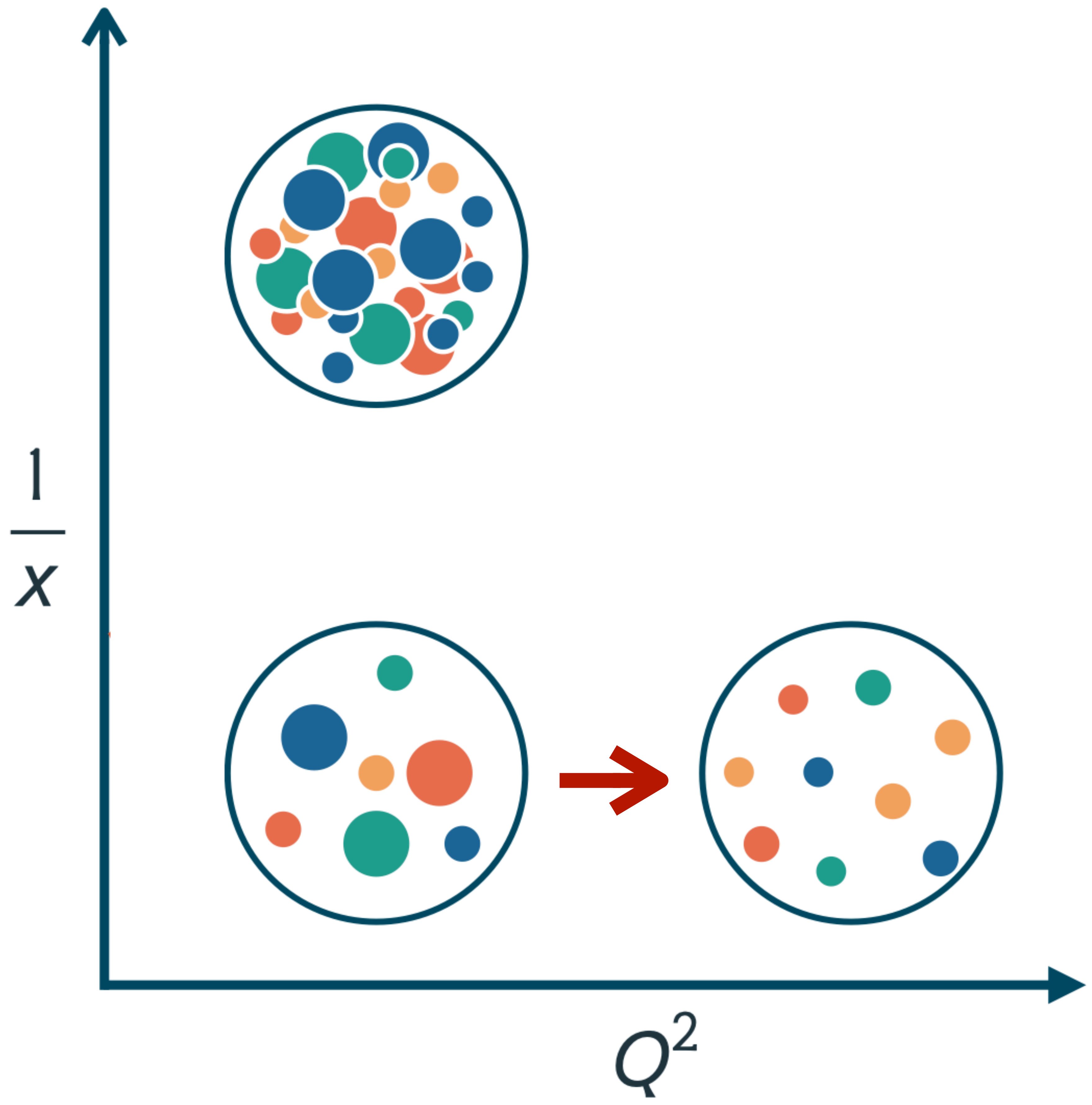

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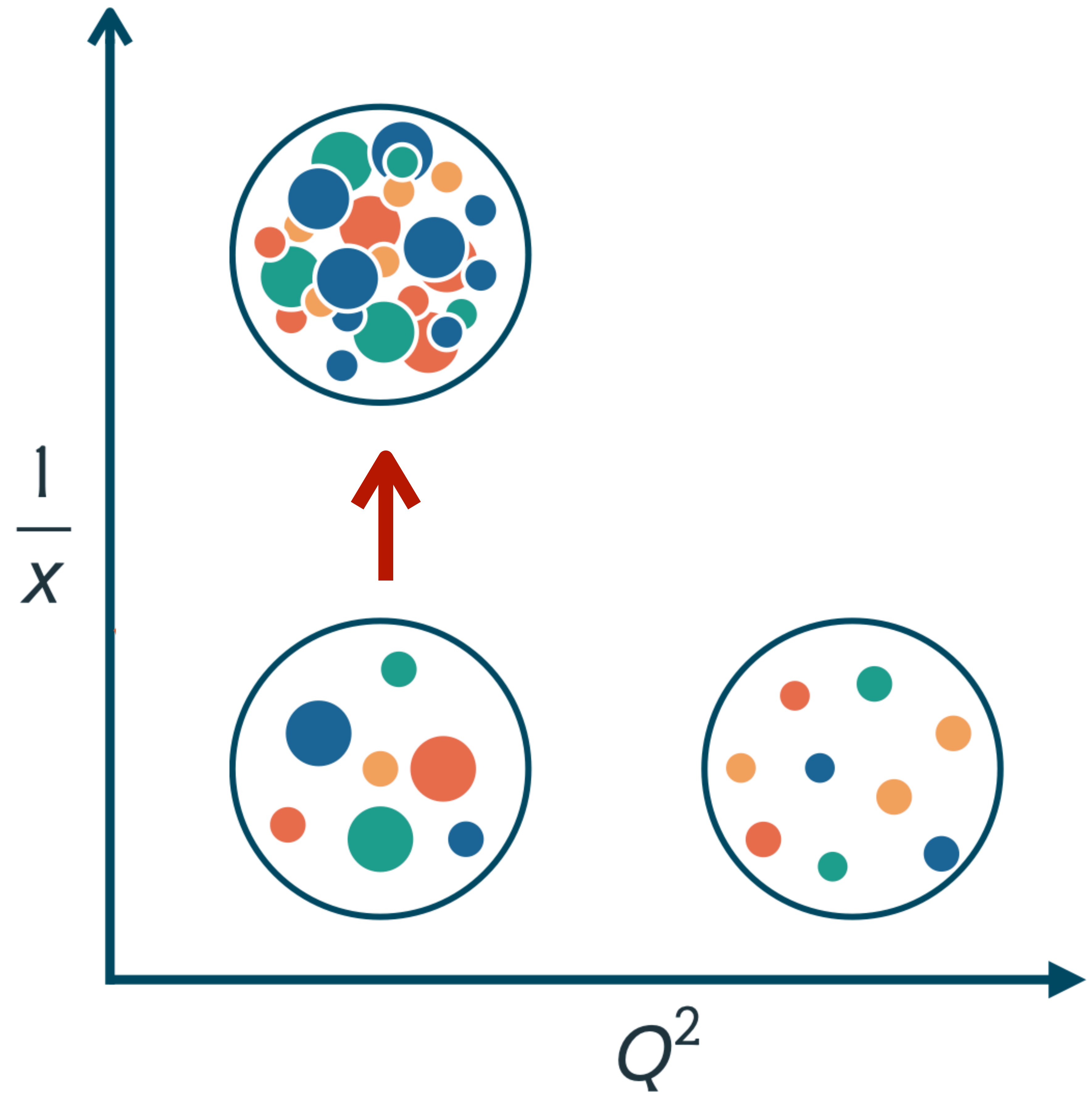

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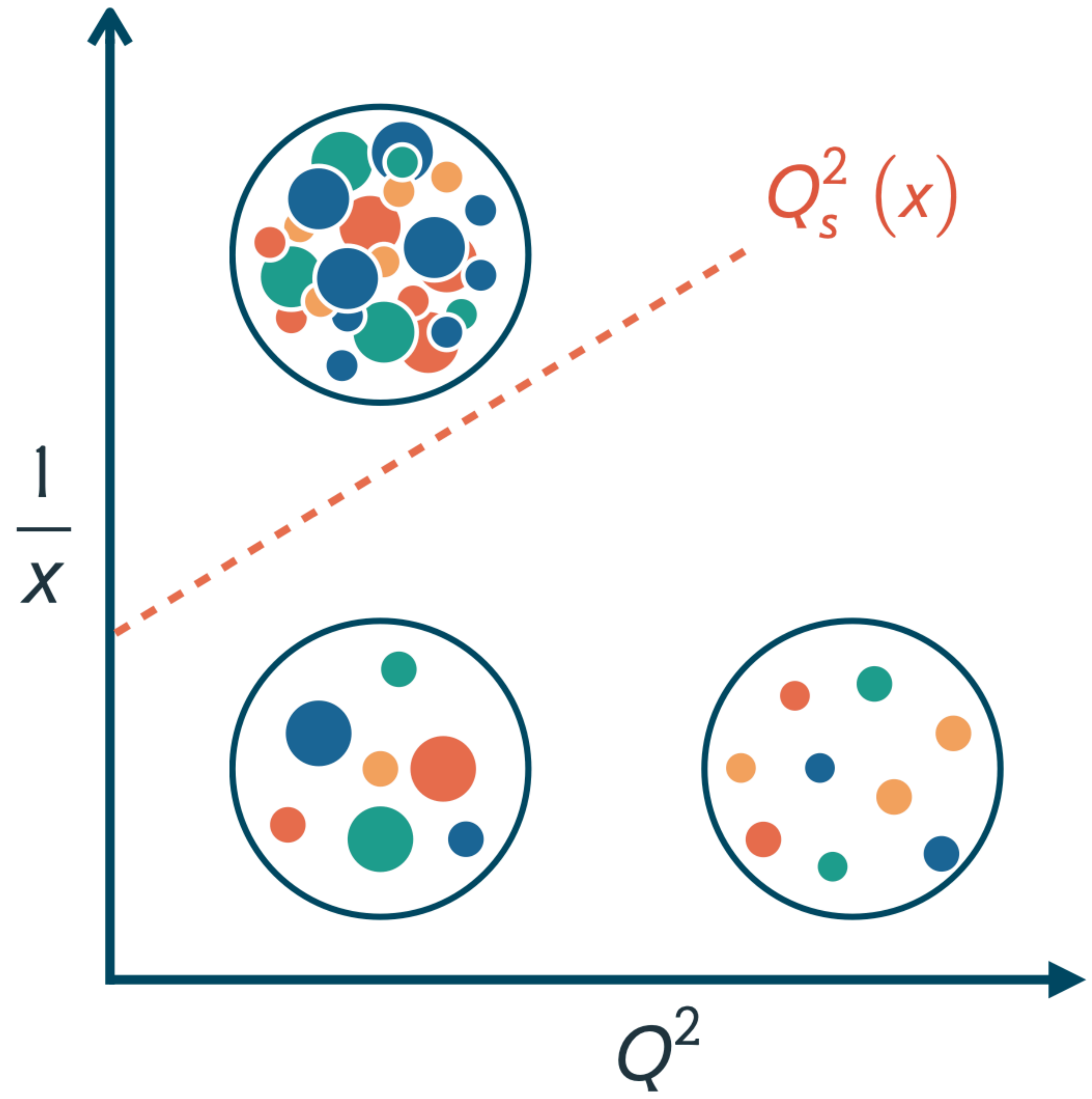
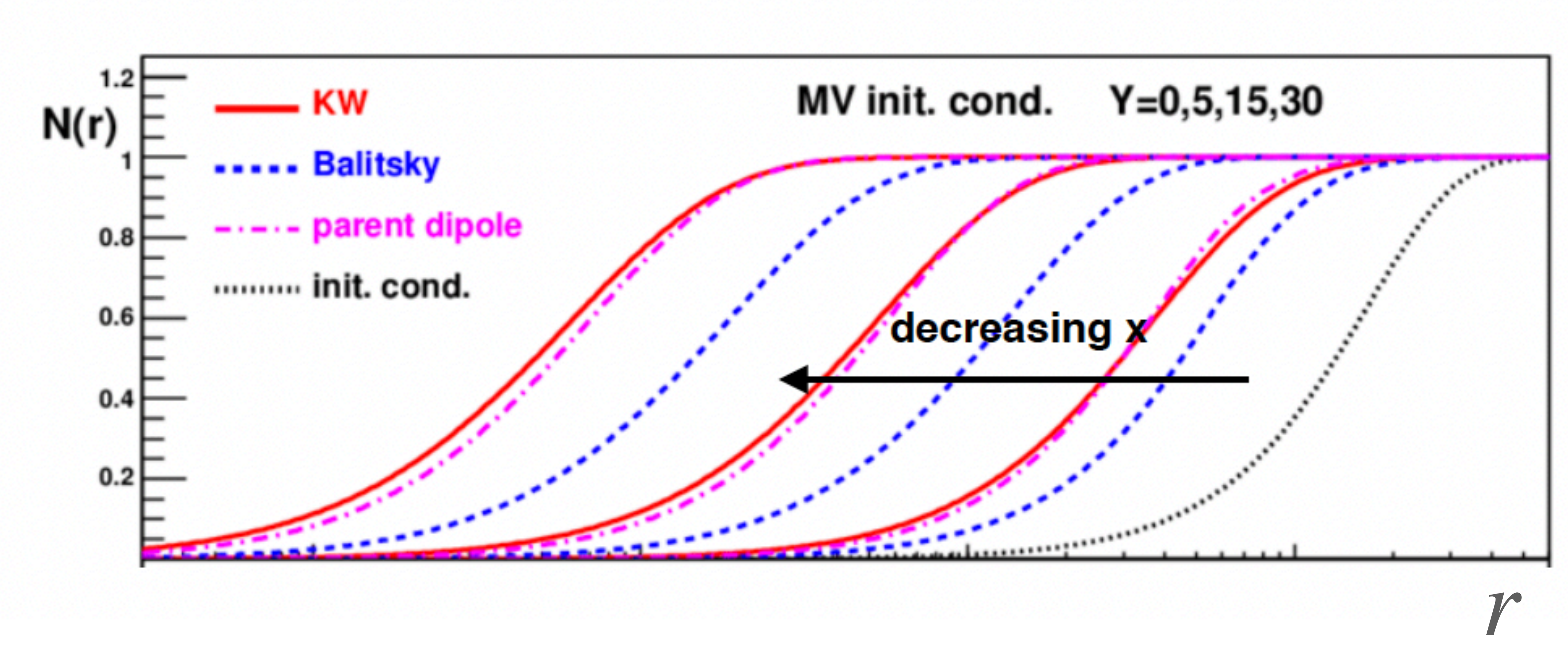
- Balance between gluon emission and recombination leads t saturation of the gluon density (black disk limit $N \sim 1$)



# SATURATION MODELS

## NUCLEAR STRUCTURE

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

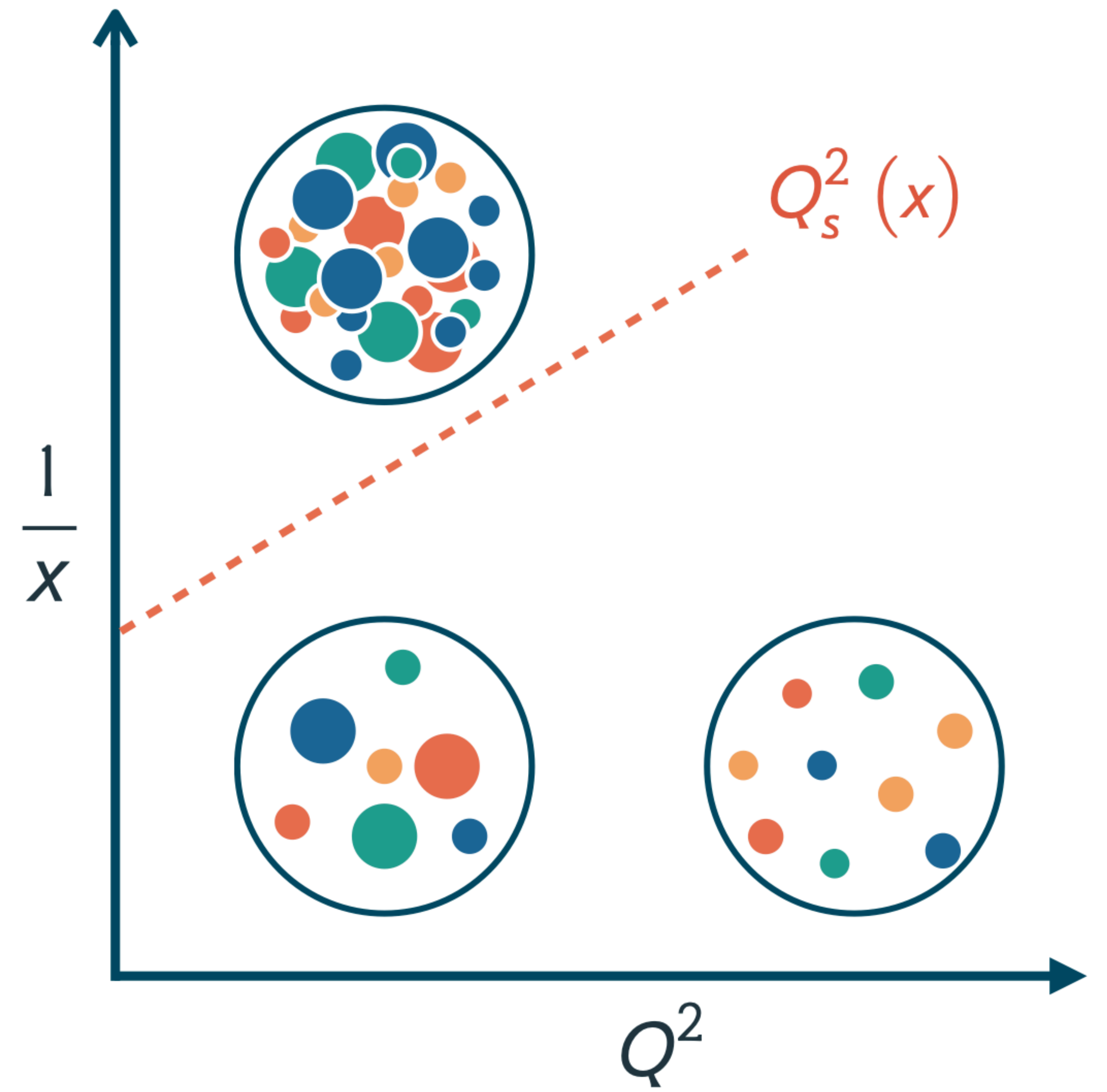



- Gluon distributions saturate with $k_\perp < Q_S$ ($r > Q_S^{-1}$ in pos. space)

- Parametrically, an simple 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

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

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

**Yang-Mills Equations**

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

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

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

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

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$W[x;\rho]$ : 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

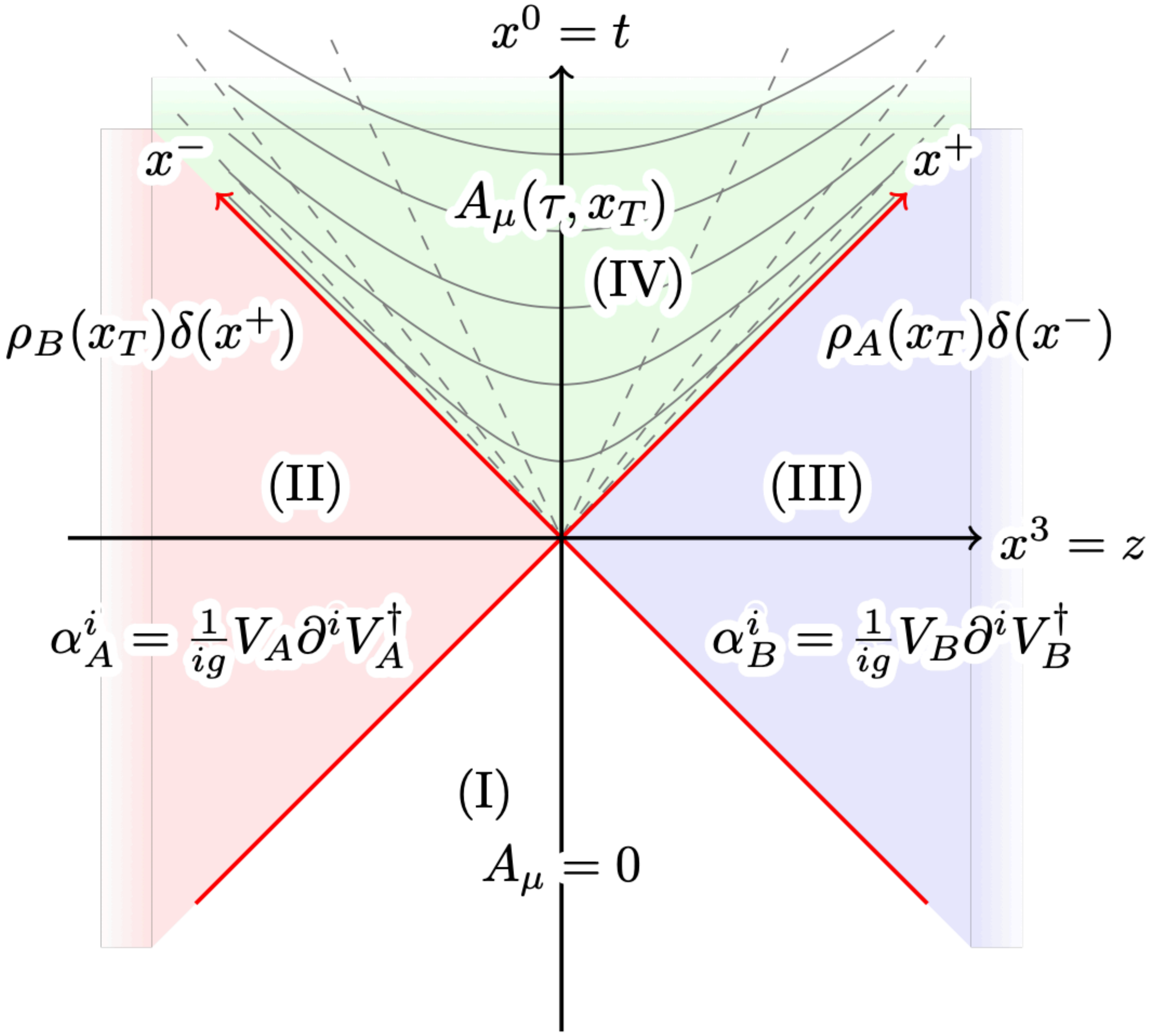


LO approximation for the CGC evolution of a dense-dense system.

## IP-GLASMA

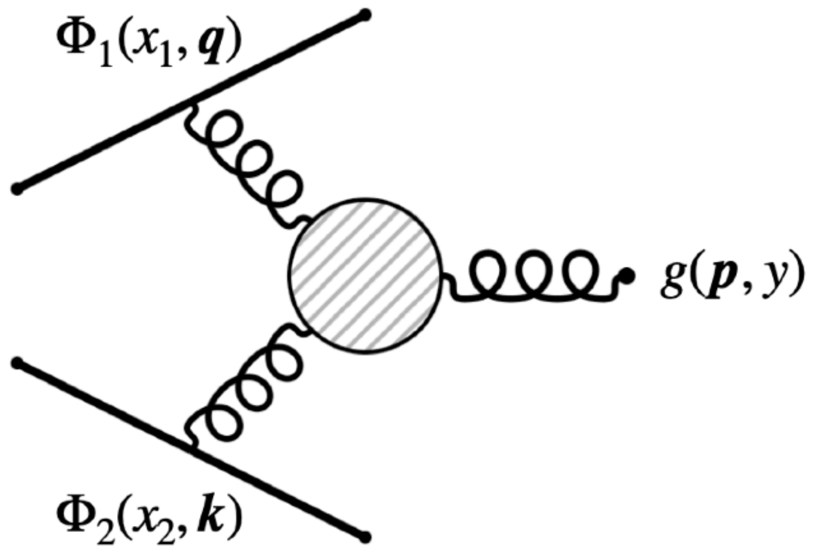
1) Sample nucleon positions (e.g. MC-Glauber)
2) Sample color currents from those nucleons ($J_{A,B}$)
3) Solve Yang-Mills in the presence of both currents and conservation laws for currents.
4) Get energy-stress tensor, $T^{\mu\nu}$

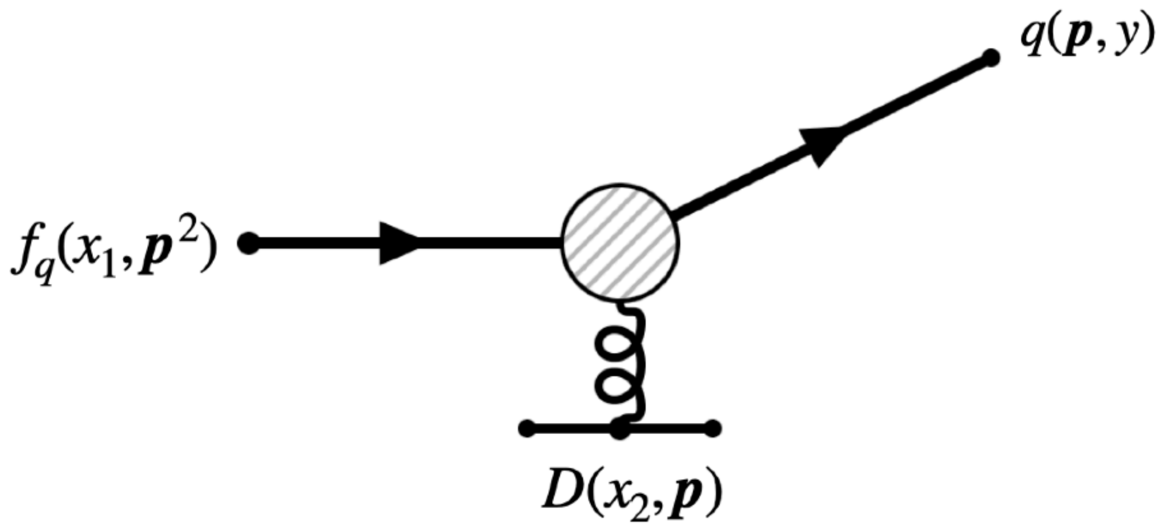
**NOTE: EXTENSION TO 3D IS NOT TRIVIAL**



# RAPIDITY RESOLUTION $\leftrightarrow$ LONG. RESOLUTION

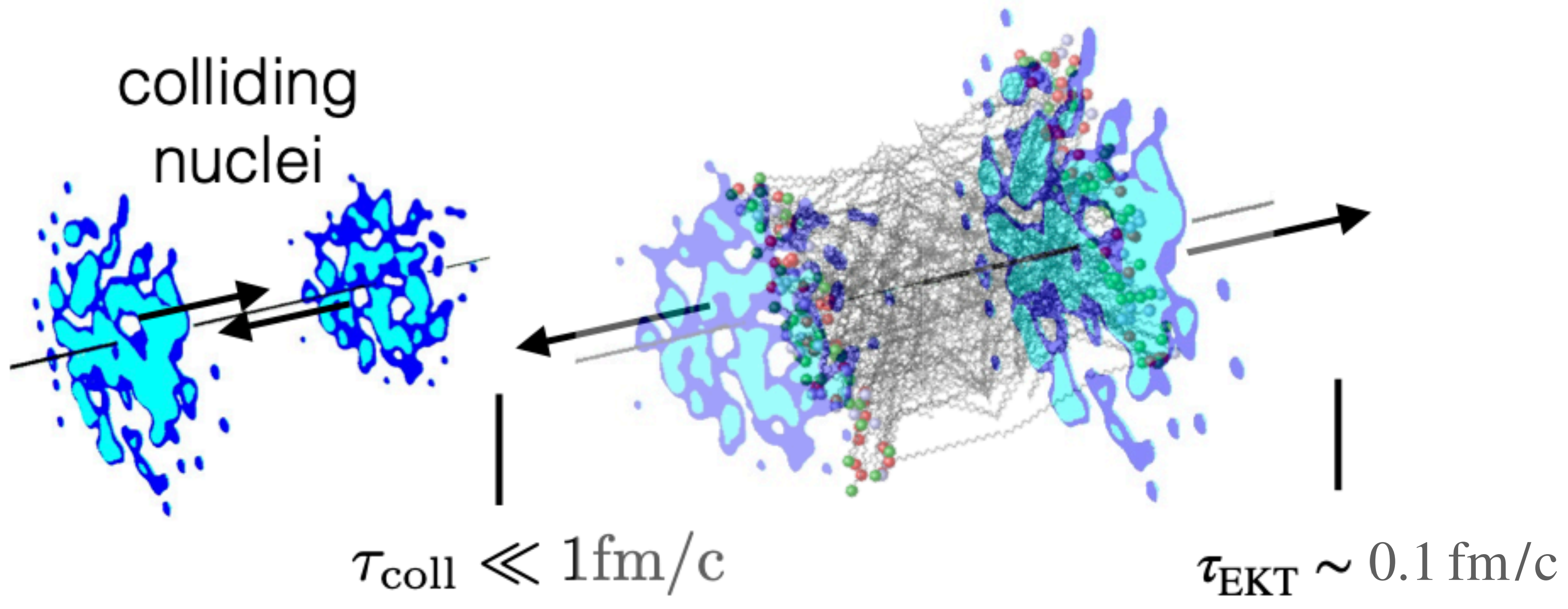
## LONGITUDINAL STRUCTURE




### 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

LOW-X

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

## IP-GLASMA 3+1D (V1)

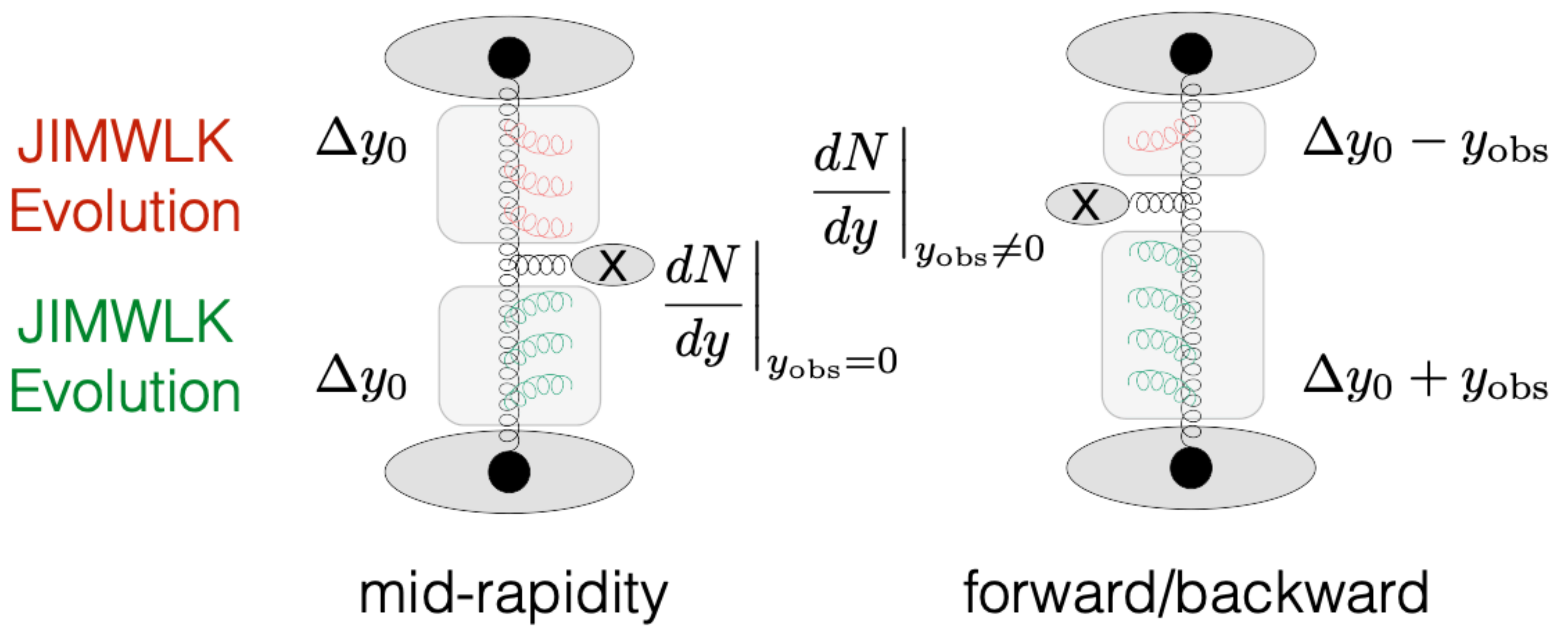
1) Sample nucleon positions (e.g. MC-Glauber)

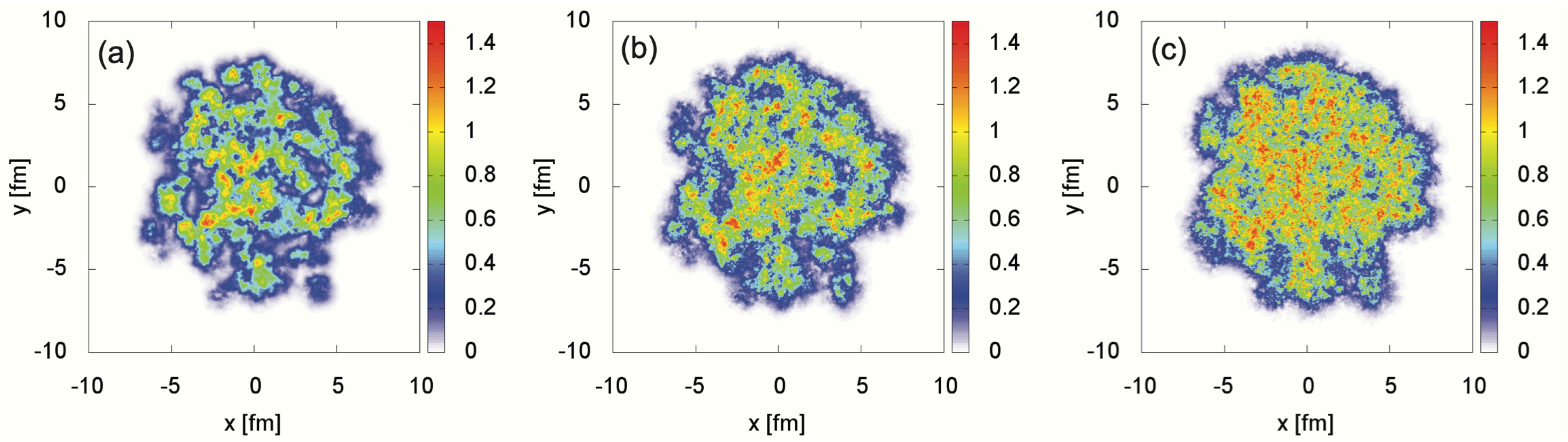
2) Sample color currents from those nucleons ($J_{A,B}$)

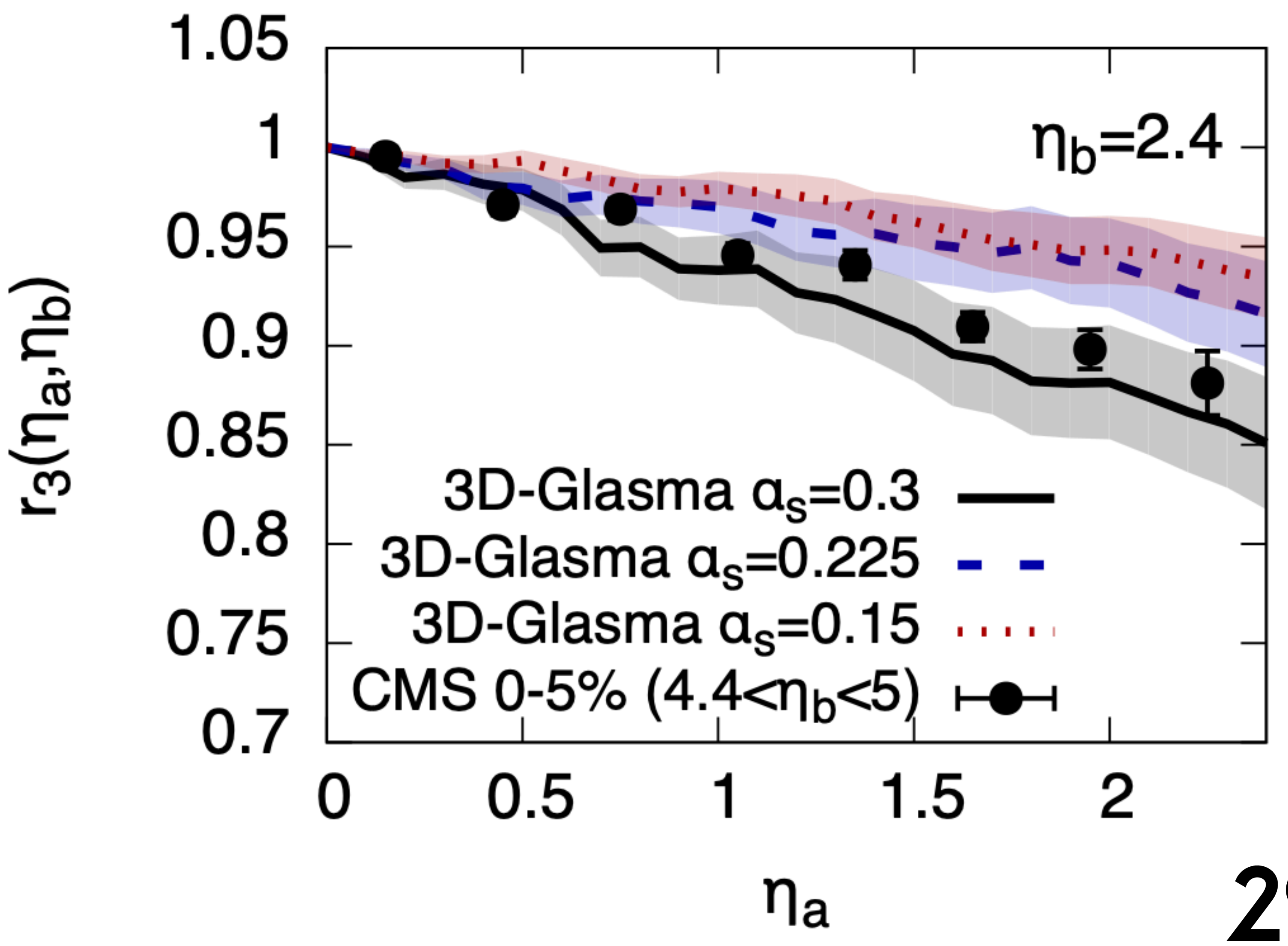
3) Boost your nuclei to the desired forward/backward cone using the JIMWLK equations

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.

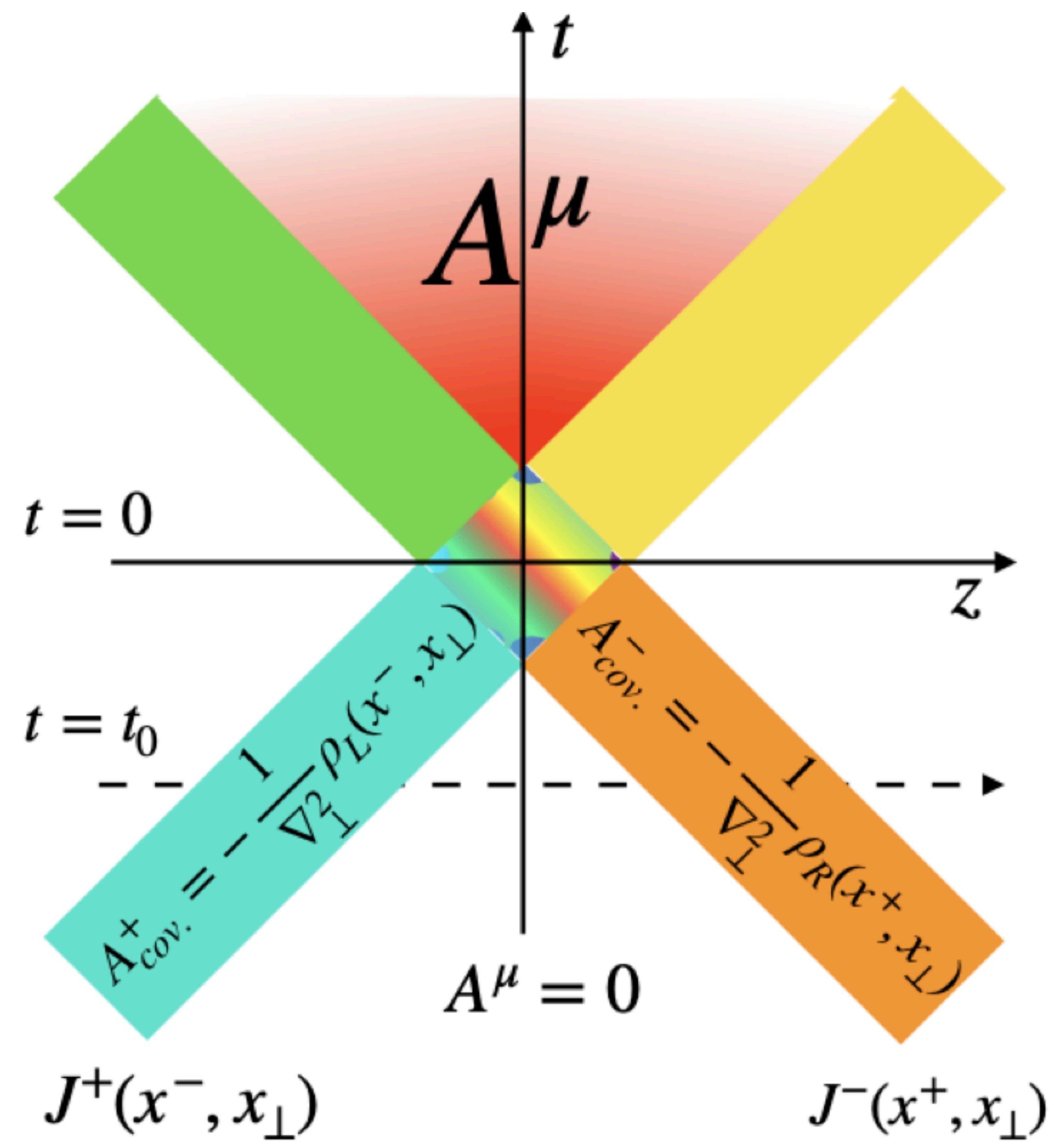
## IP-GLASMA 3+1D (V2)

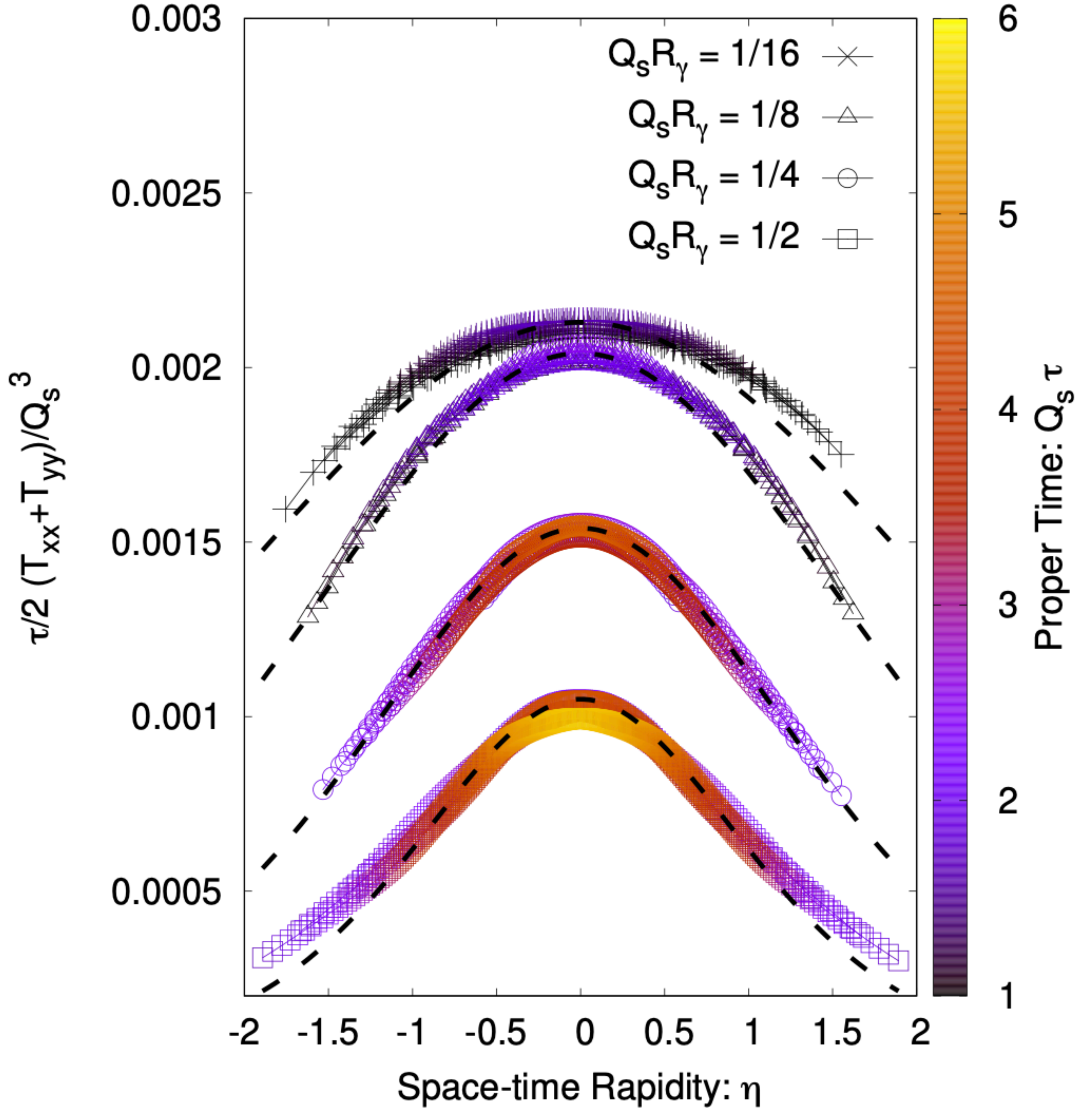
1) Sample nucleon positions (e.g. MC-Glauber)

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



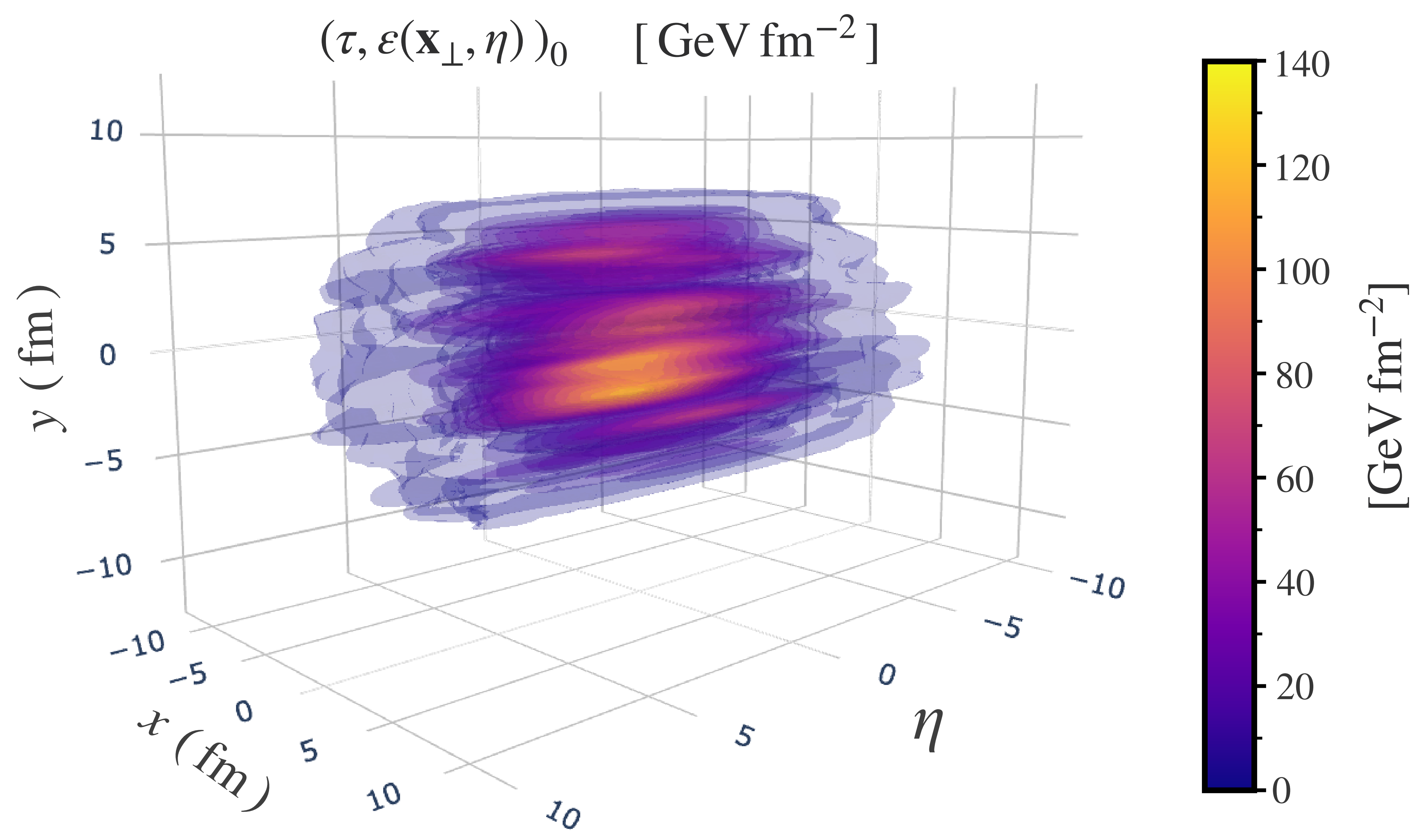

[*Phys.Rev.D* 103 (2021) 1, 014003]

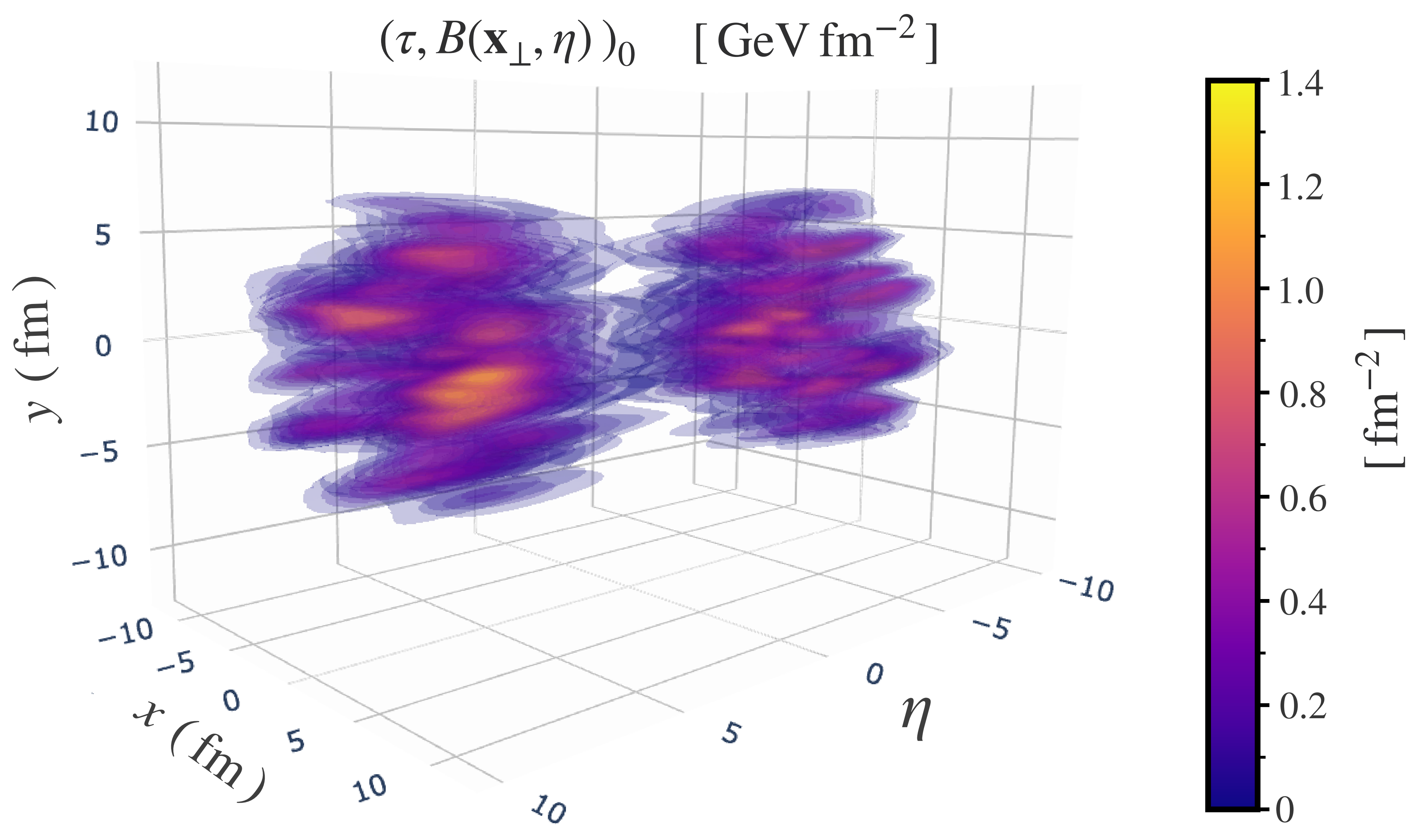
# CGC IN 3D: THE McDIPPER

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**



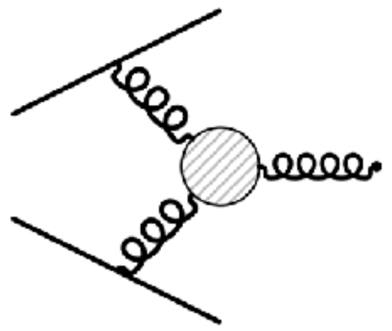



# FROM MICRO TO MACRO



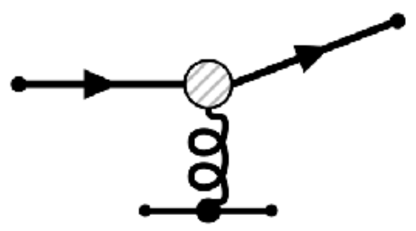
- Low-$x$ gluons dominate the midrapidity region

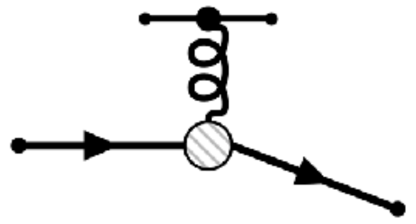
$$\frac{dN_g}{d^2\mathbf{x}d^2\boldsymbol{p}dy} = \frac{g^2}{8\pi^5 C_F\, \boldsymbol{p}^2}\int \frac{d^2\boldsymbol{q}}{(2\pi)^2}\frac{d^2\boldsymbol{k}}{(2\pi)^2}(2\pi)^2\delta(\boldsymbol{p}+\boldsymbol{q}-\boldsymbol{p}) \times \Phi_1(x_1,\boldsymbol{x},\boldsymbol{q})\ \Phi_2(x_2,\boldsymbol{x},\boldsymbol{k})$$



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

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





## THE INPUT

**Low-$x$ gluons**

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

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

- 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 $(\eta, T_1, T_2)$

- Use Glauber sampling to produce events -fast- using $(\eta, T_1, T_2)$ as an EbE input.

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

# FROM MICRO TO MACRO



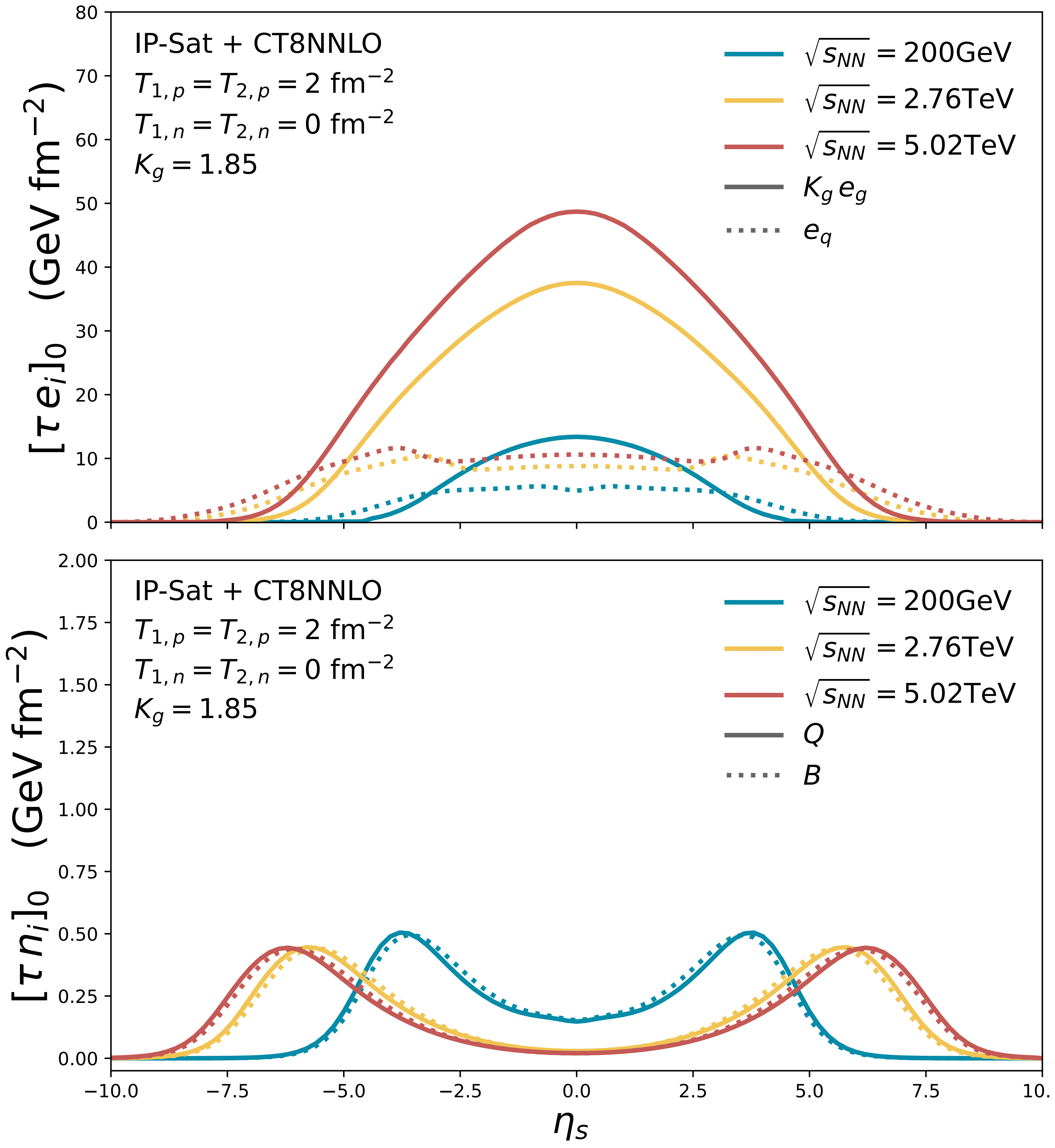
- Macroscopic quantities (energy, charges) are computed as moments of the single particle distributions
  - Total energy deposition

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

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

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

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



# TUNING

## FIXING THE K-FACTOR

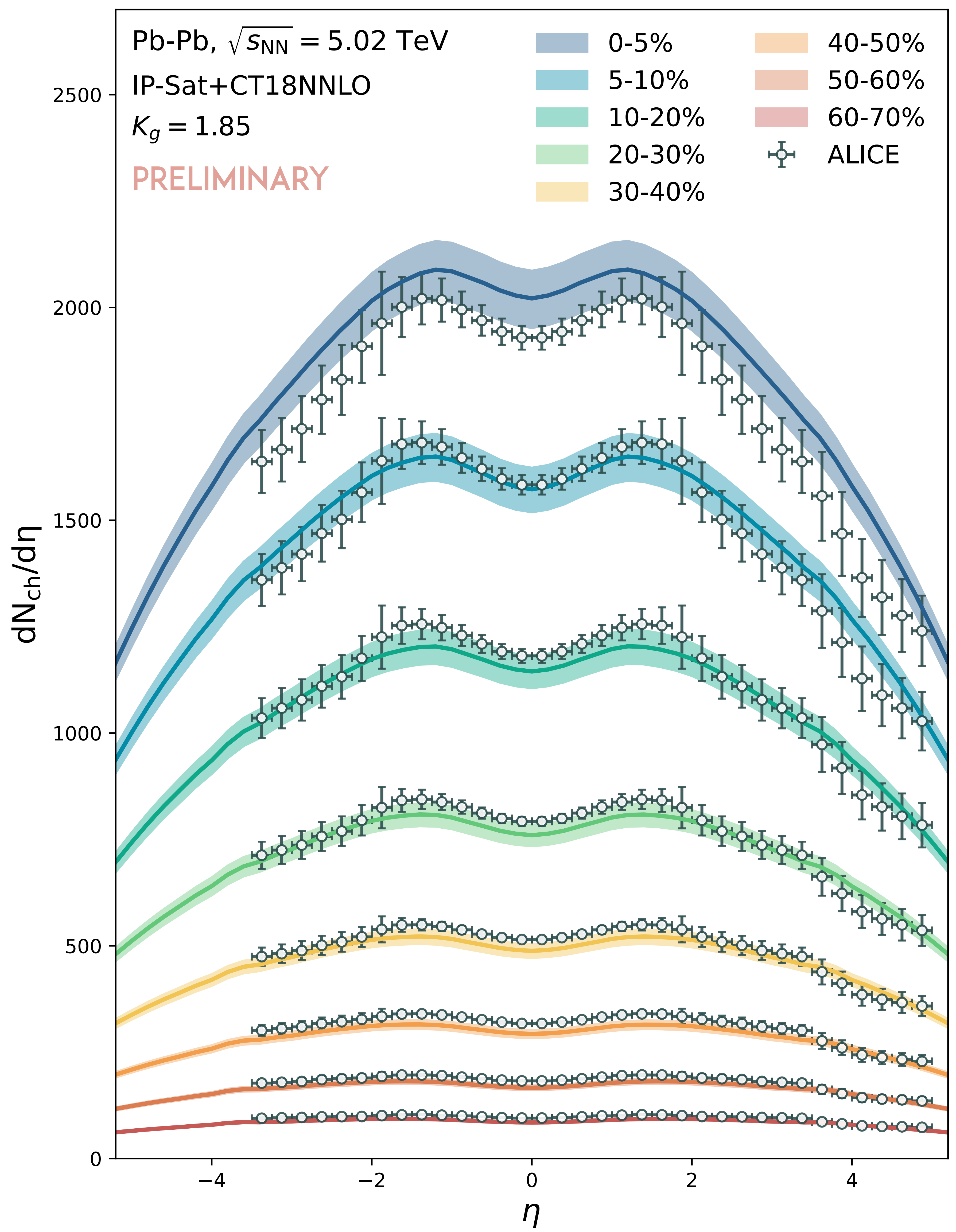
- Input model parameters can be **fixed by other experiments** e.g. DIS (e+p, e+A,...)
- Overall normalisation of $(e_g\tau)_0$ treated as a free parameter, $K_g$ , to account for perturbative corrections
- Tune $K_g$ using $E_\perp$ in $pp$ min. bias collisions at $\sqrt{s_{NN}} = 5.02\,\mathrm{TeV}$

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

- Multiplicity can be then estimated using

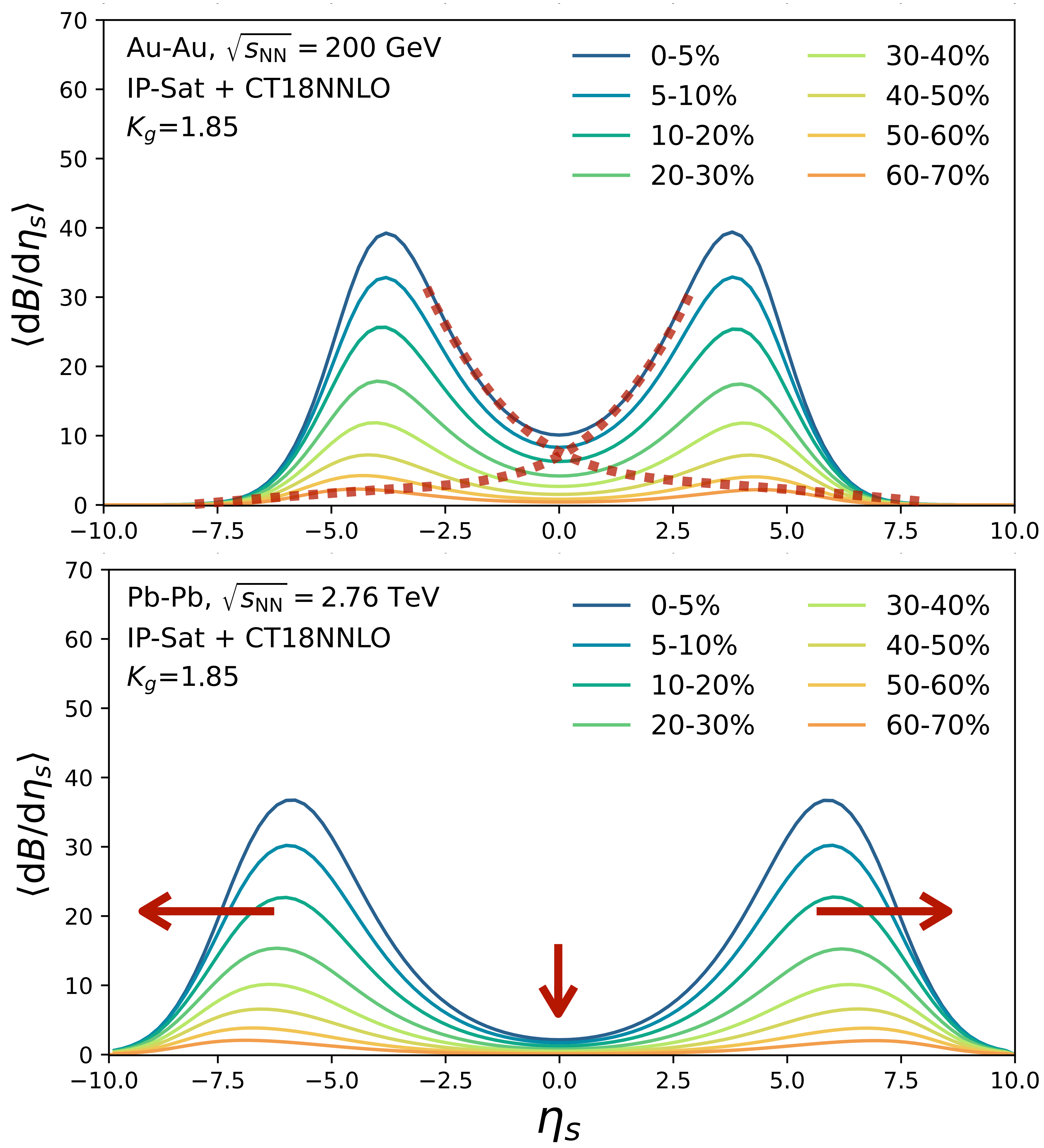
$$\left\langle \frac{dN_{ch}}{dy} \right\rangle = \frac{4}{3}\frac{N_{ch}}{S} C_\infty^{3/4} \left(4\pi \frac{\eta}{s}\right)^{1/3} \left(\frac{\pi^2}{30}\nu_{\text{eff}}\right)^{1/3} \int d^2\mathbf{x} \left[\tau e(y,\mathbf{x})\right]_0^{2/3}$$

[PRL. 123, 262301]



# 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)

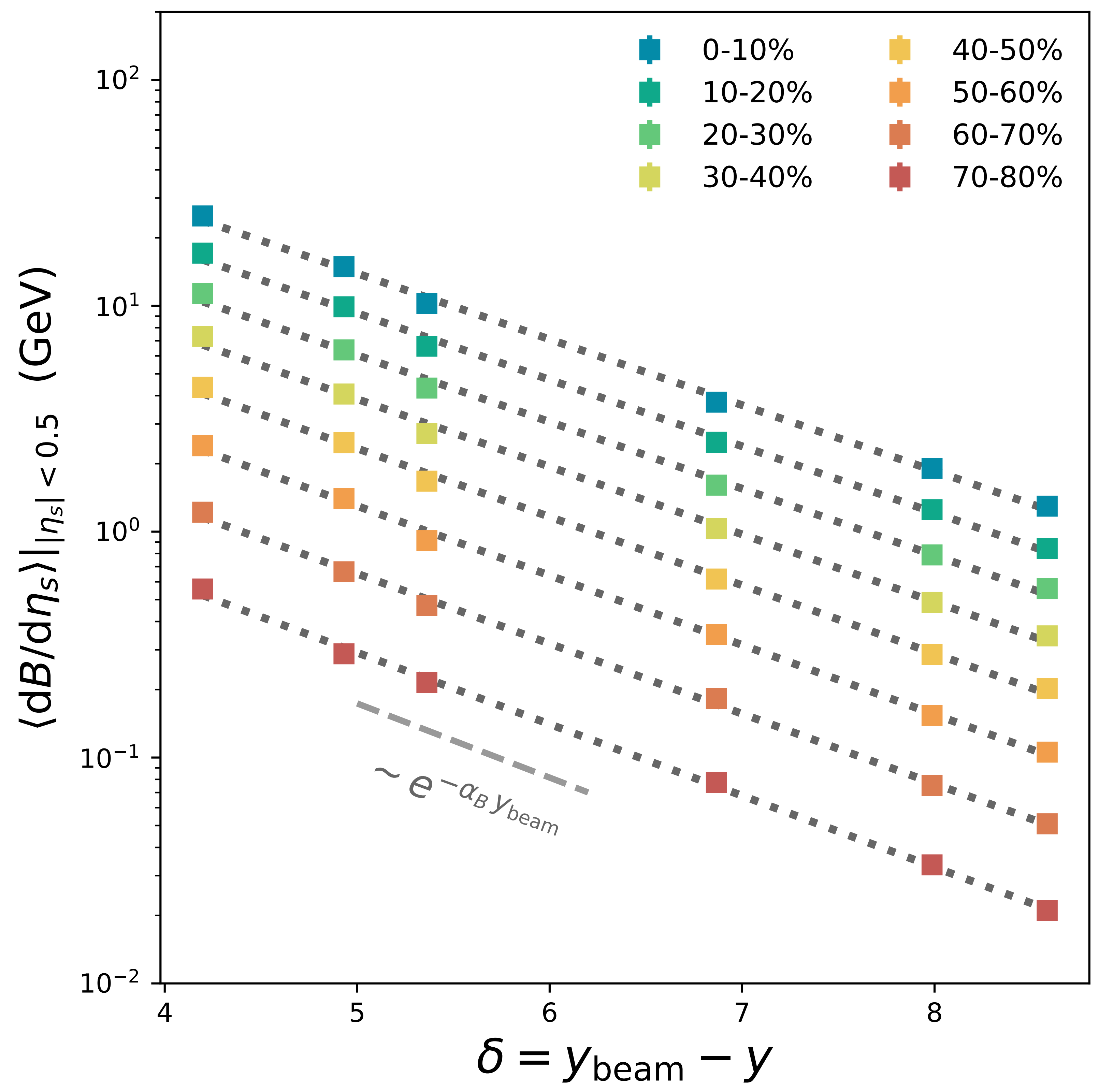
# CHARGE DEPOSITION

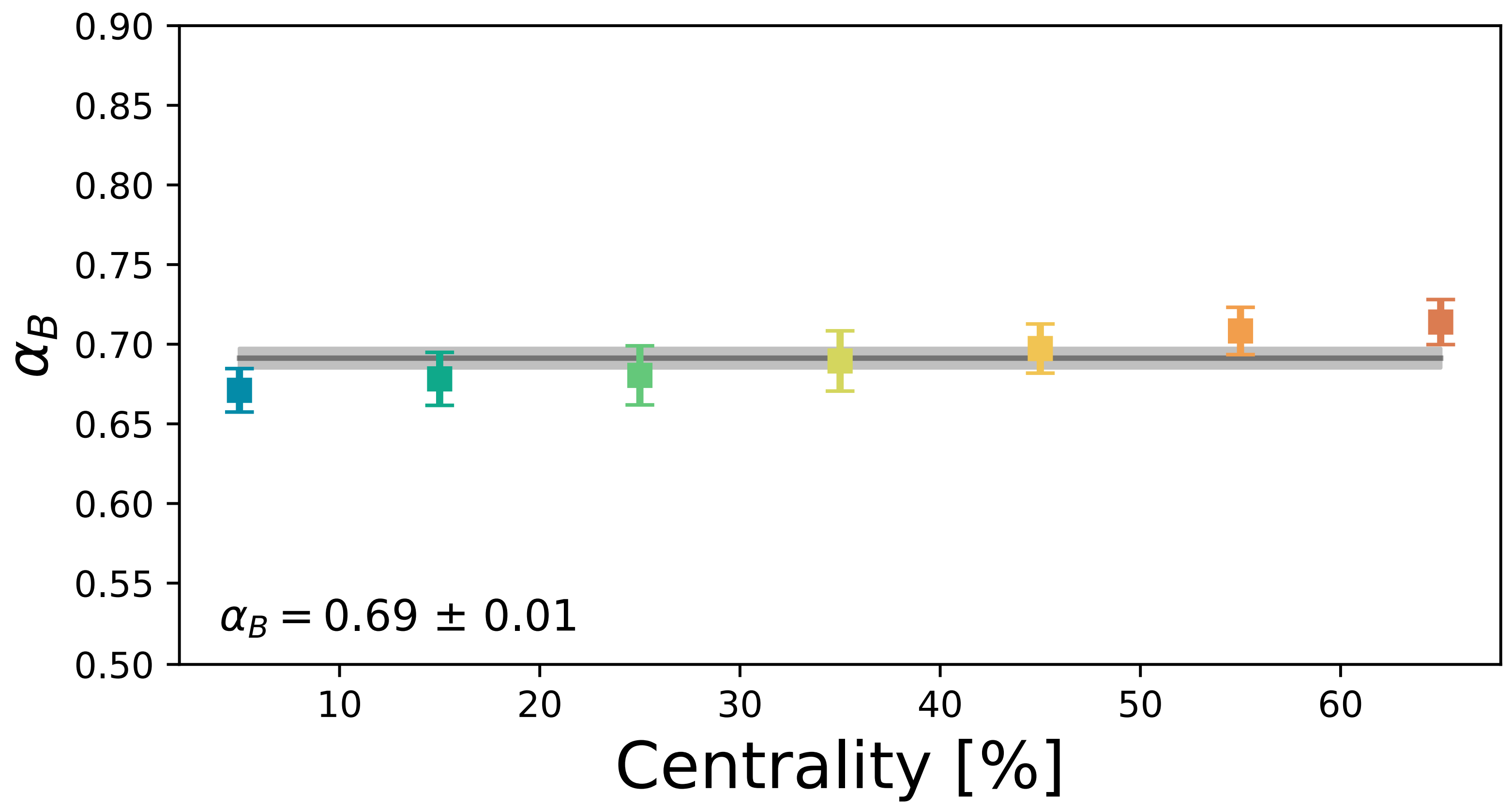
- Non-trivial interaction between x-dependence of gluon uGDs and quark PDFs gives tails in the charge deposition

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

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

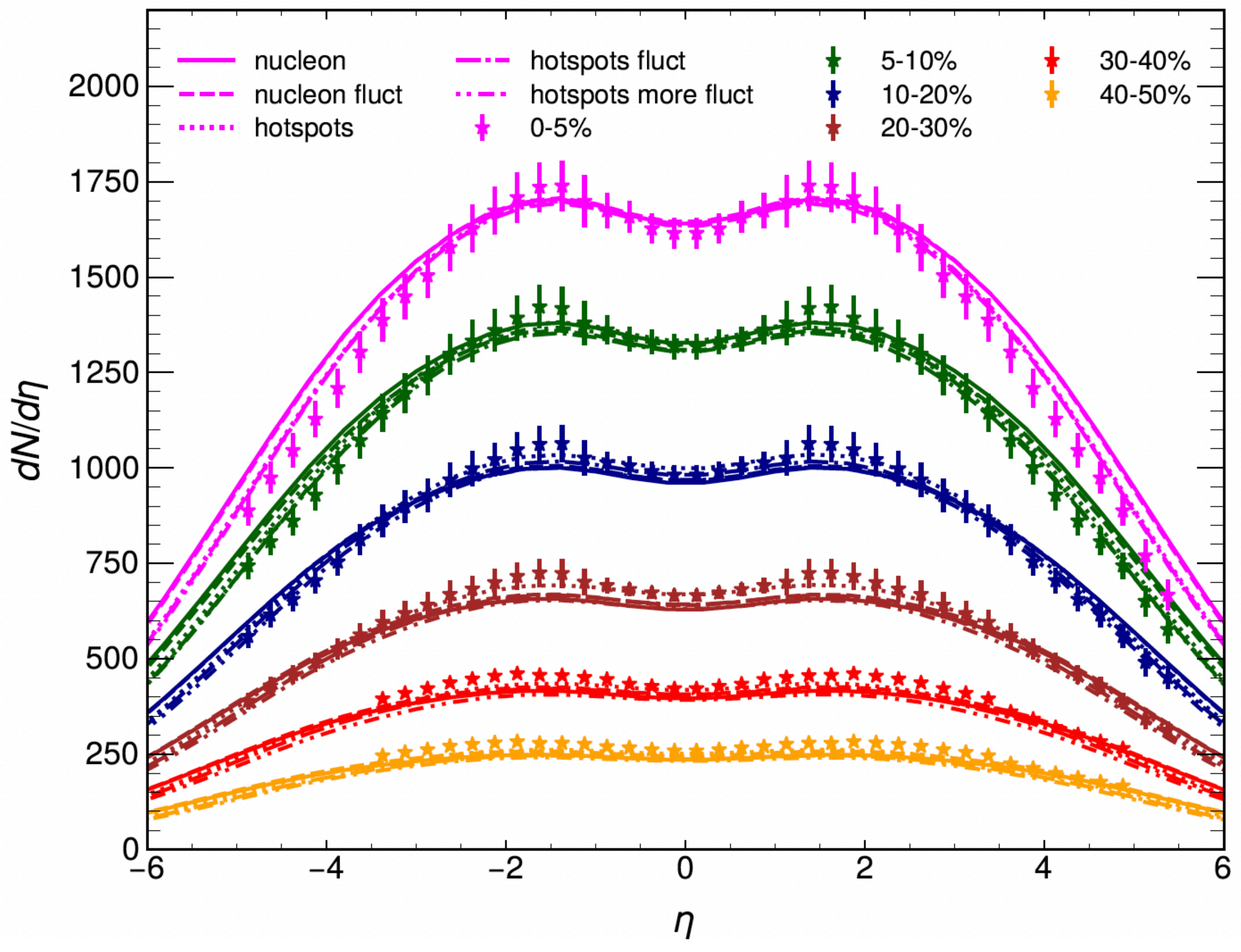
$$\left.\frac{\mathrm{dB}}{\mathrm{d}\eta}\right|_{\eta=0} \sim e^{-\alpha_B y_{\mathrm{beam}}} \quad \text{with} \quad y_{\mathrm{beam}} \approx \frac{1}{2}\log\left[\frac{\sqrt{s_{\mathrm{NN}}}}{m_N}\right]$$



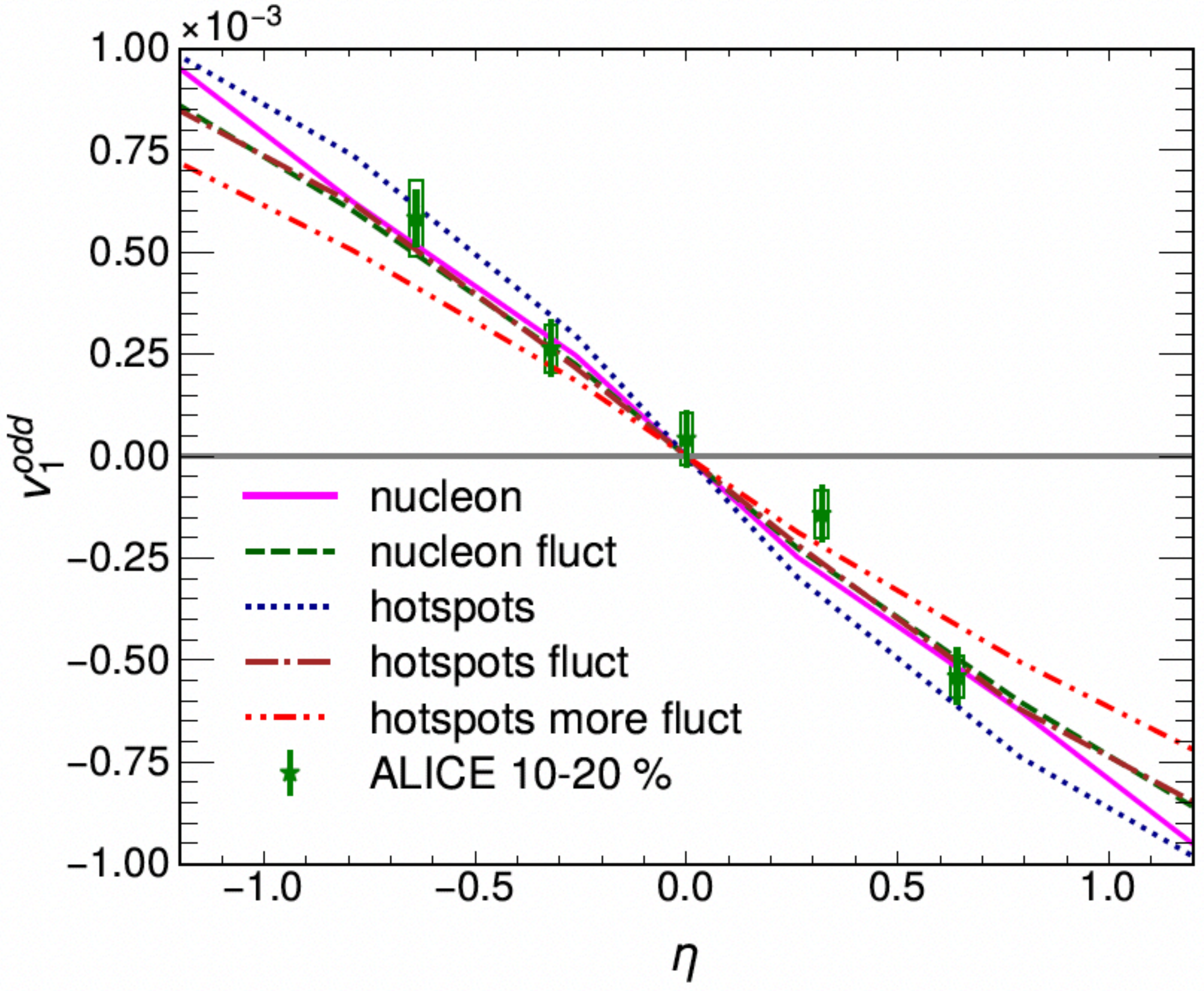



# THE McDIPPER+CLVISC

## SOME INTERESTING RESULTS (...TO ME)




Minimal IC tuning.




Added hotspot fluctuations

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

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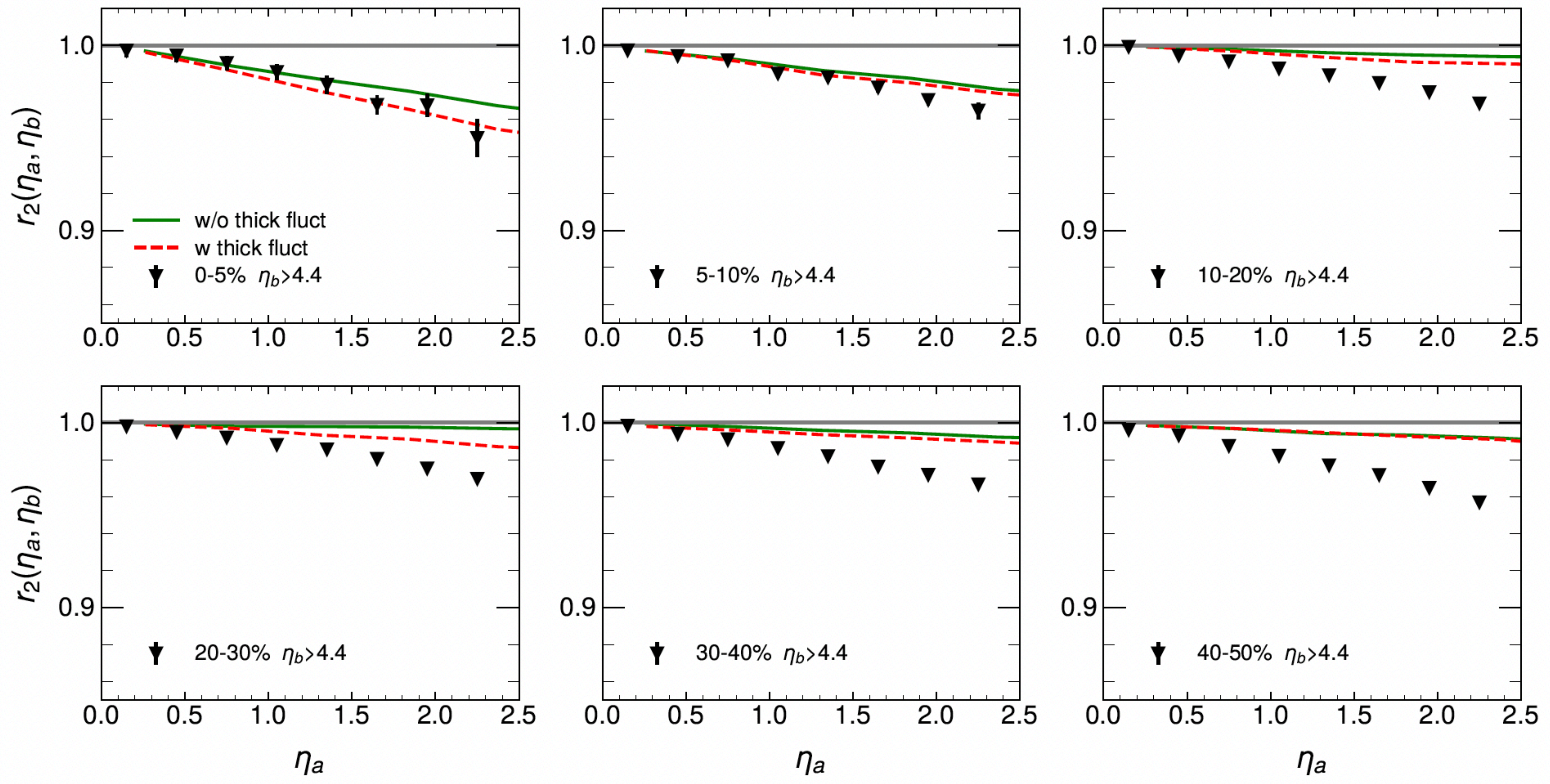



Decorrelation due to non-trivial $x$-dependence of uGHs and PDFs

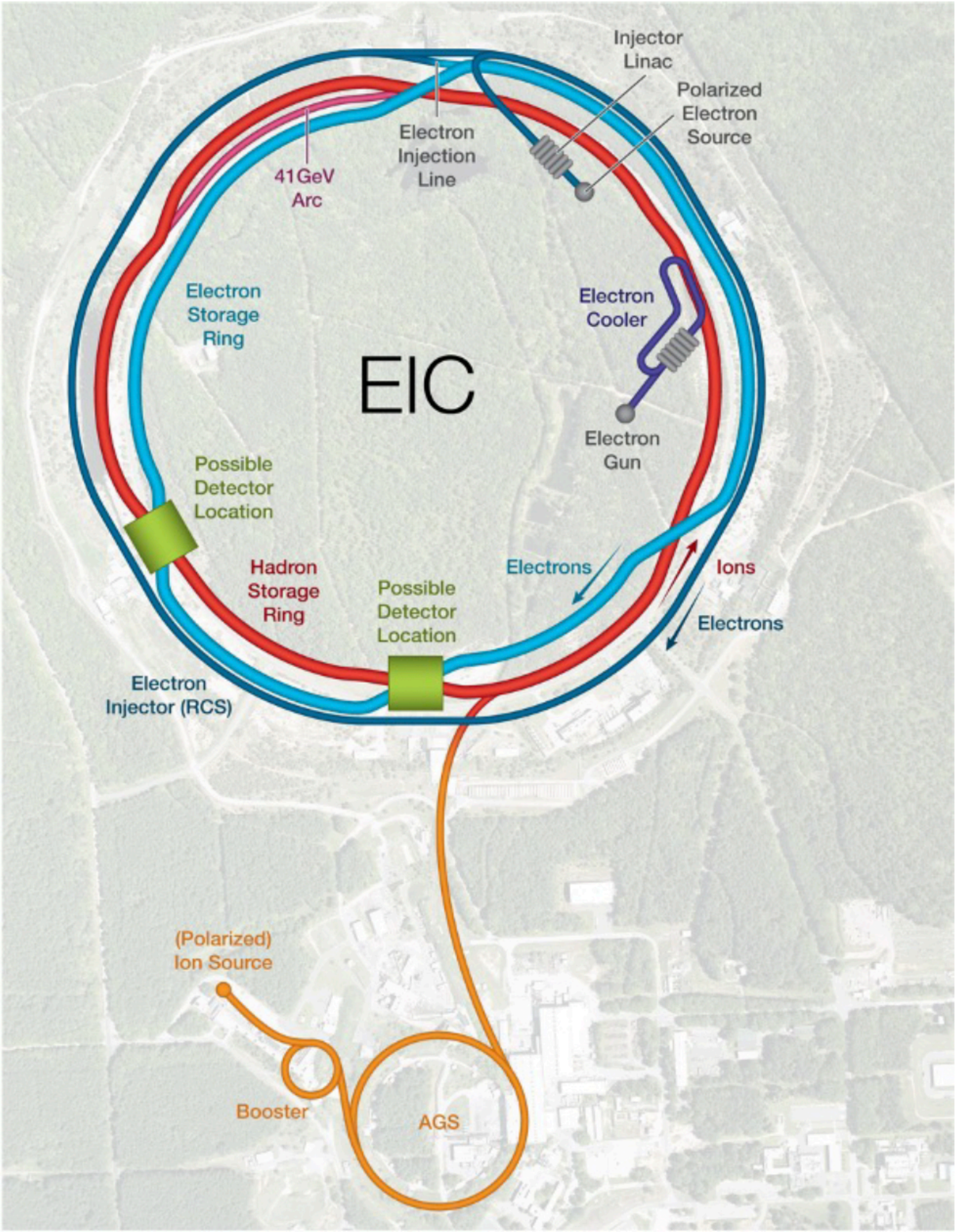
Additional fluctuations needed to explain flow decorrelation. WIP: charge fluctuations in the valence sector (PDF sampling of valence charges)

[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.

# THE ELECTRON-ION COLLIDER



# CORE IDEAS OF THE EIC

**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 LHC-EIC

## 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

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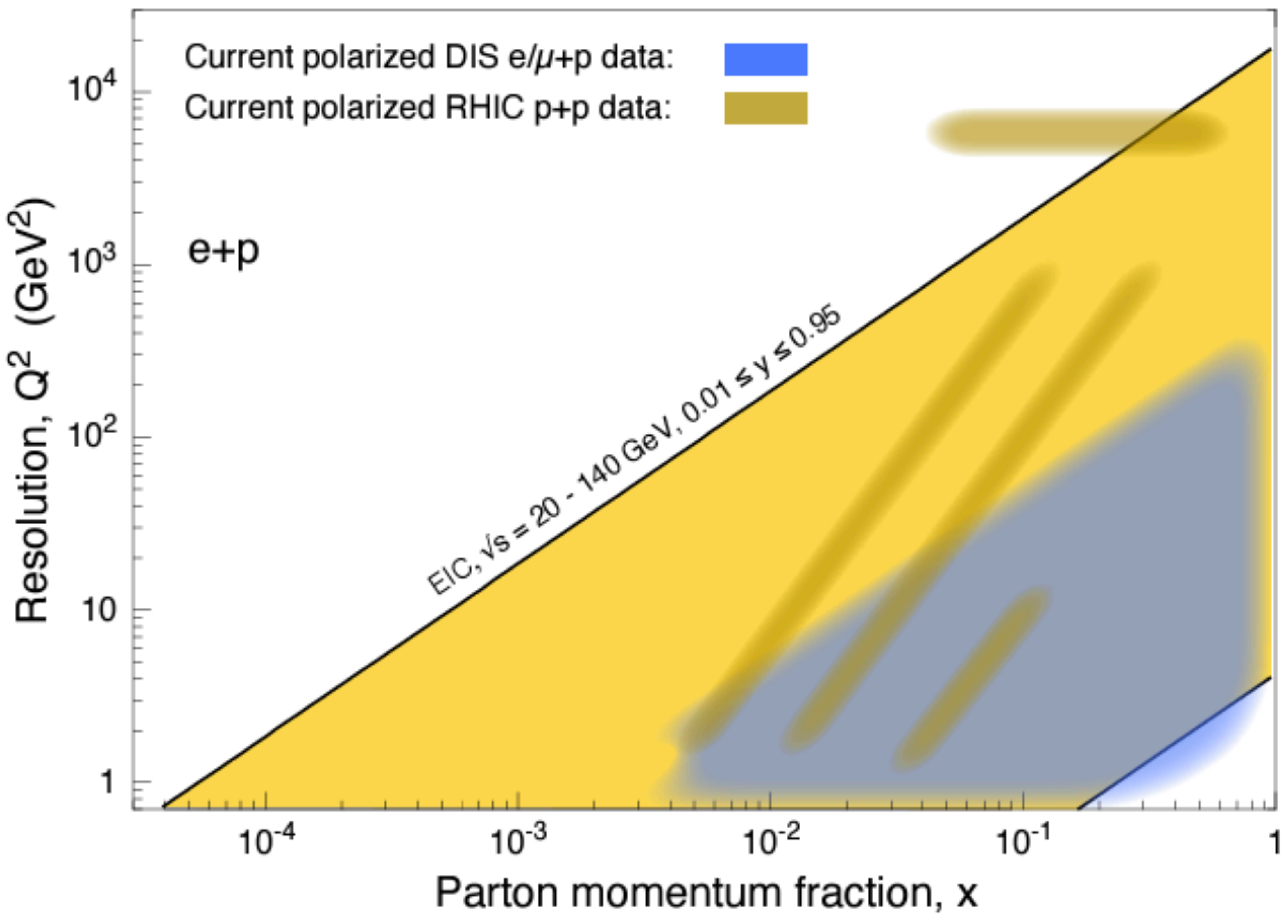
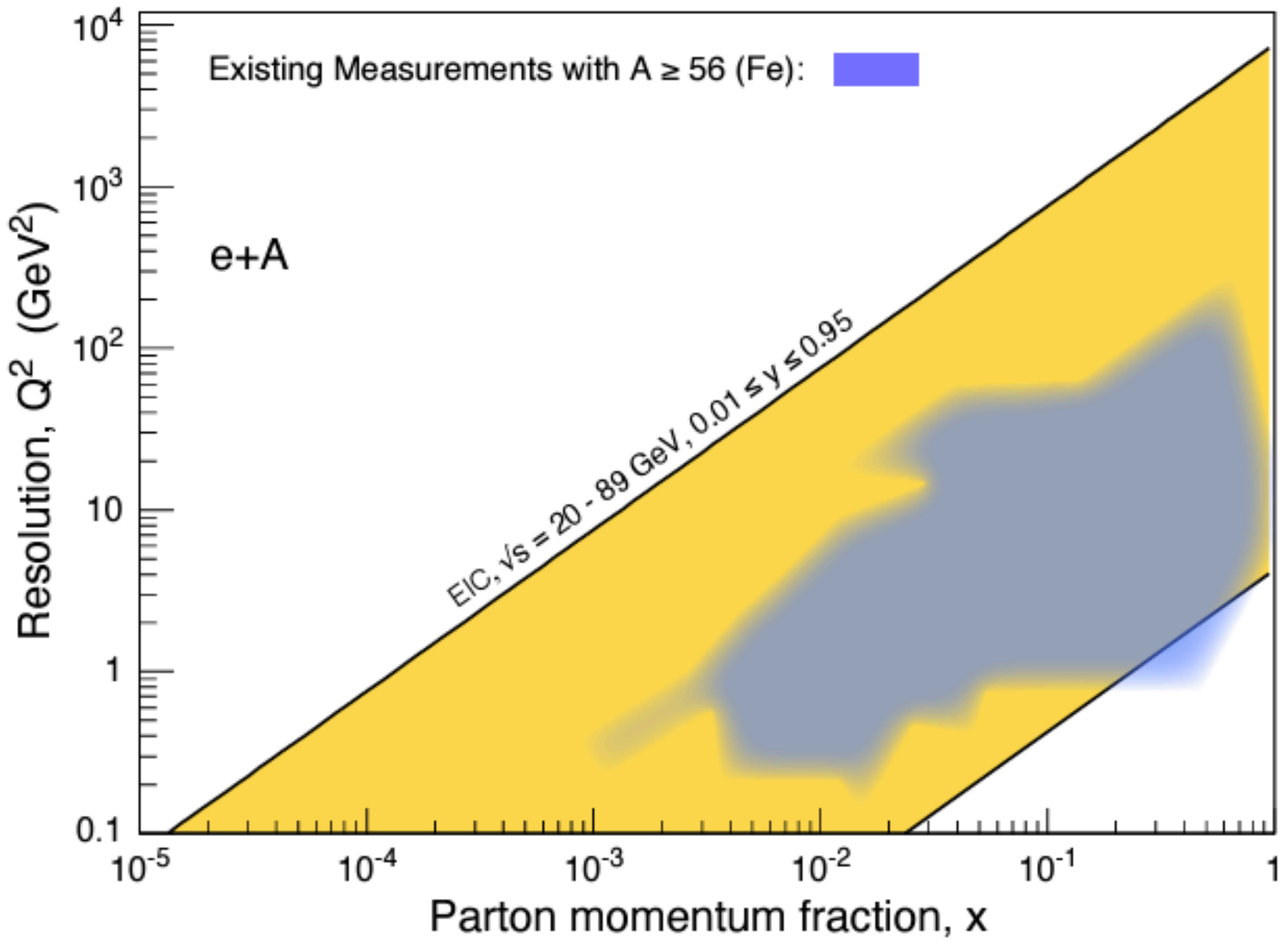
# TESTING SATURATION MODELS



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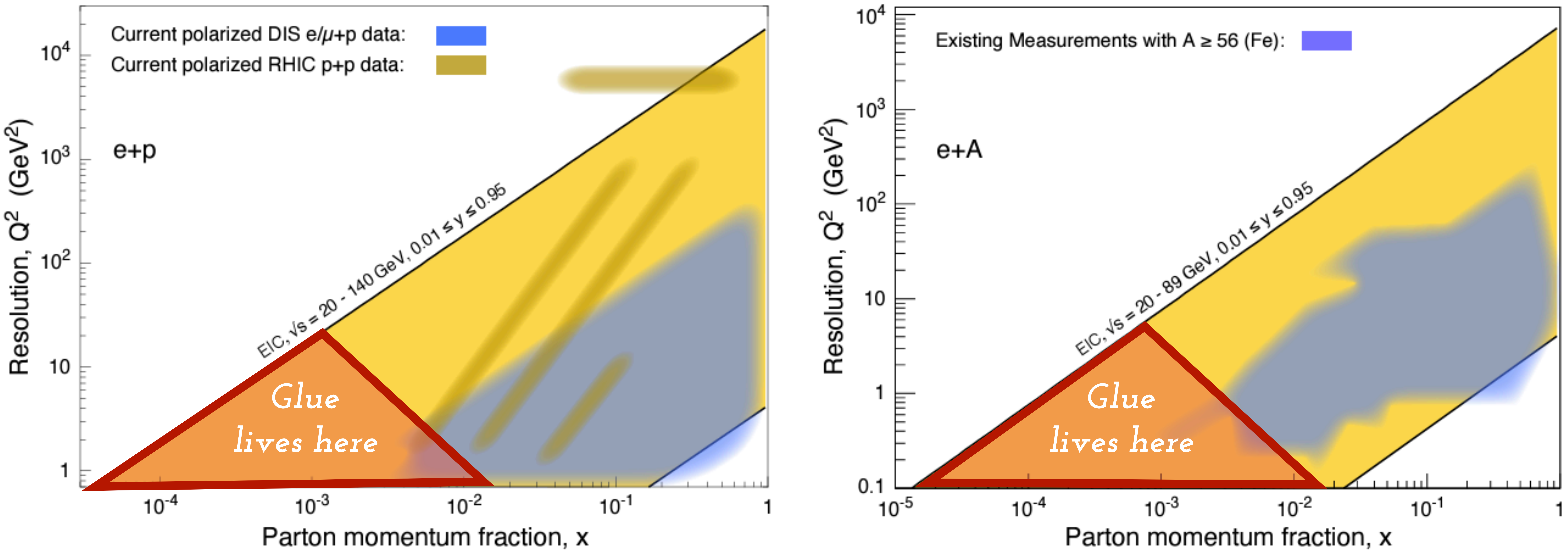

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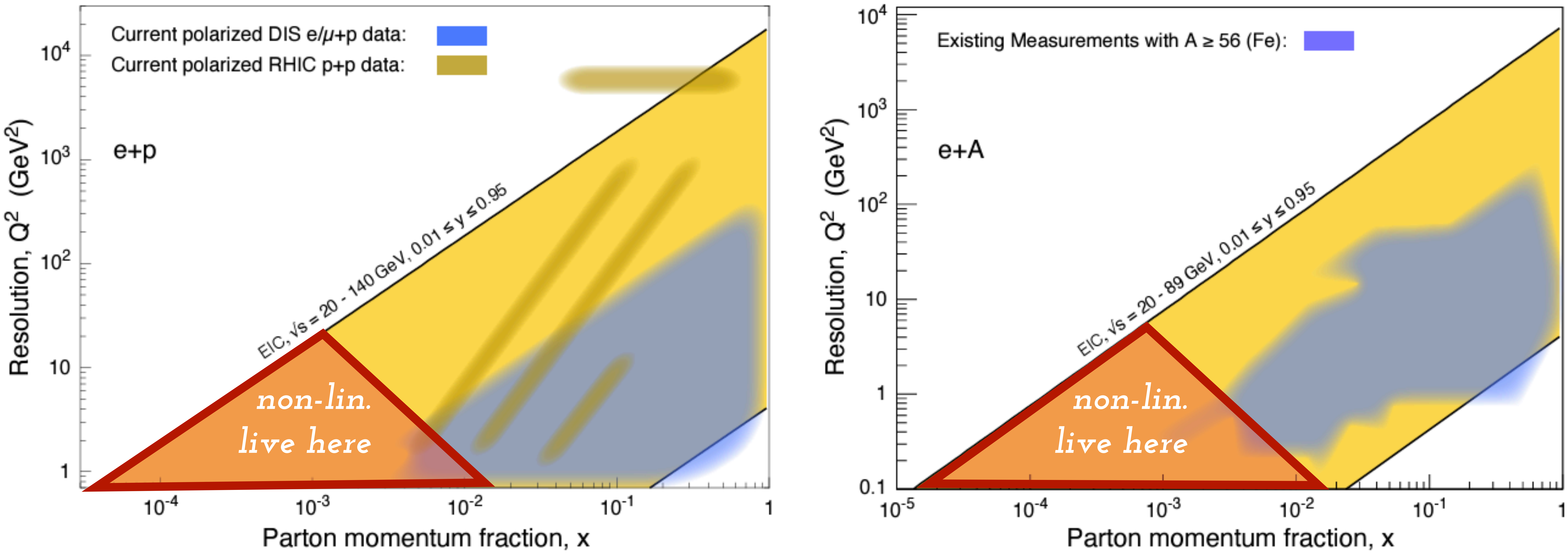


# TESTING SATURATION MODELS

## A DIPOLE STORY

- Inclusive DIS cross-section:

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

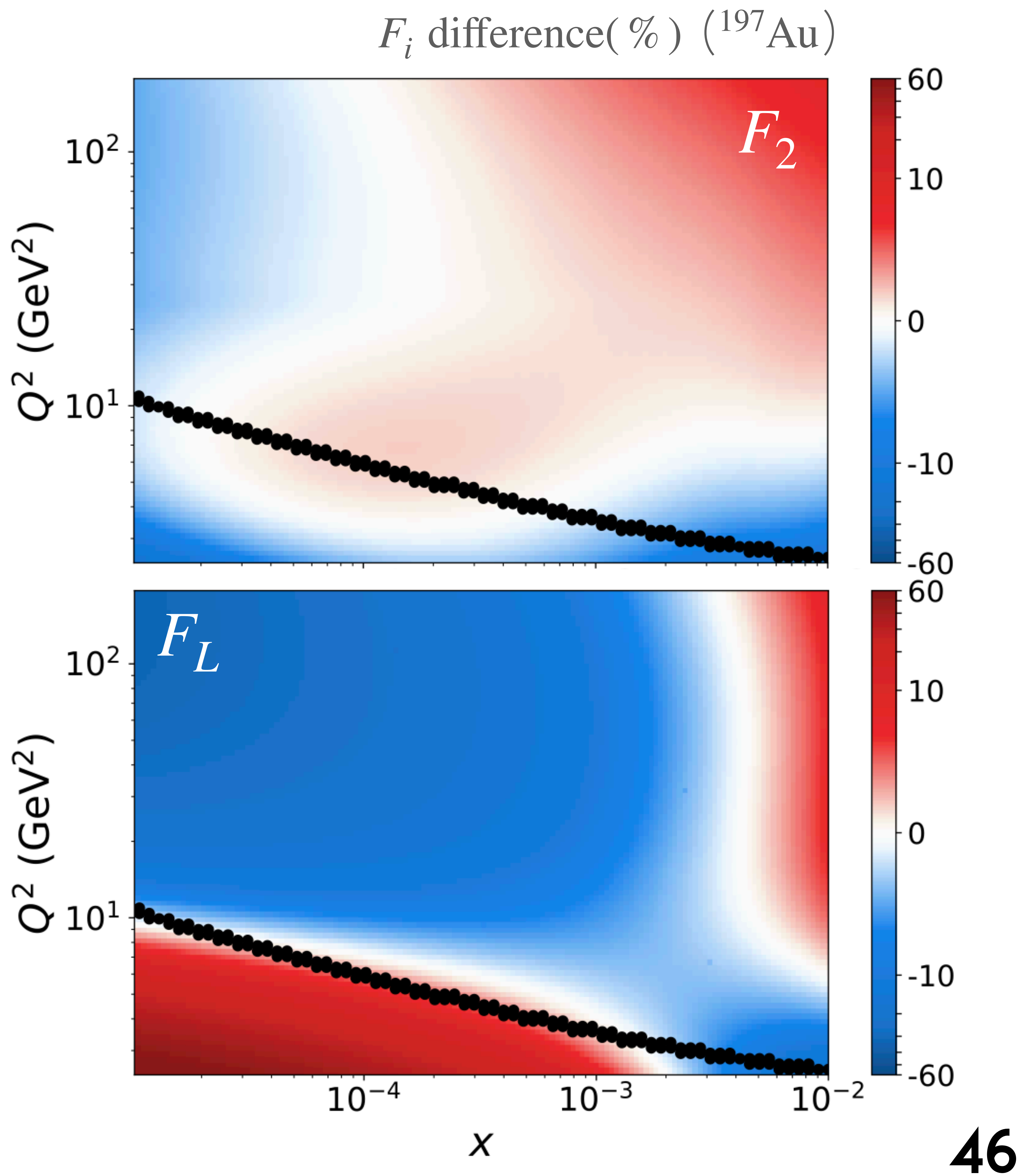
- Can be expressed as a function of structure functions, e.g.

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

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

- 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

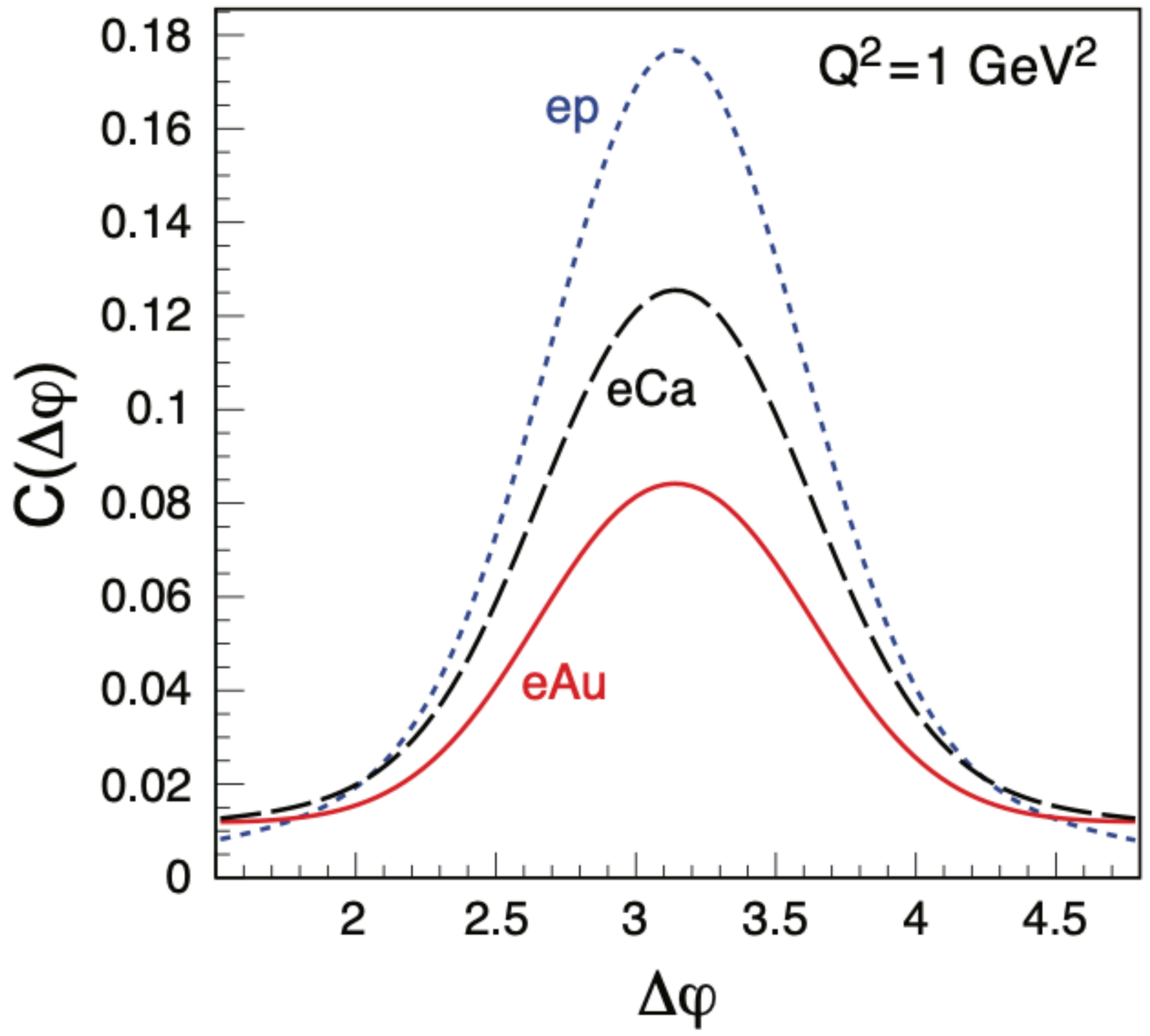
- The semi-inclusive channel $e + A \to h_1 + h_2 + e' + X$ is quite sensitive

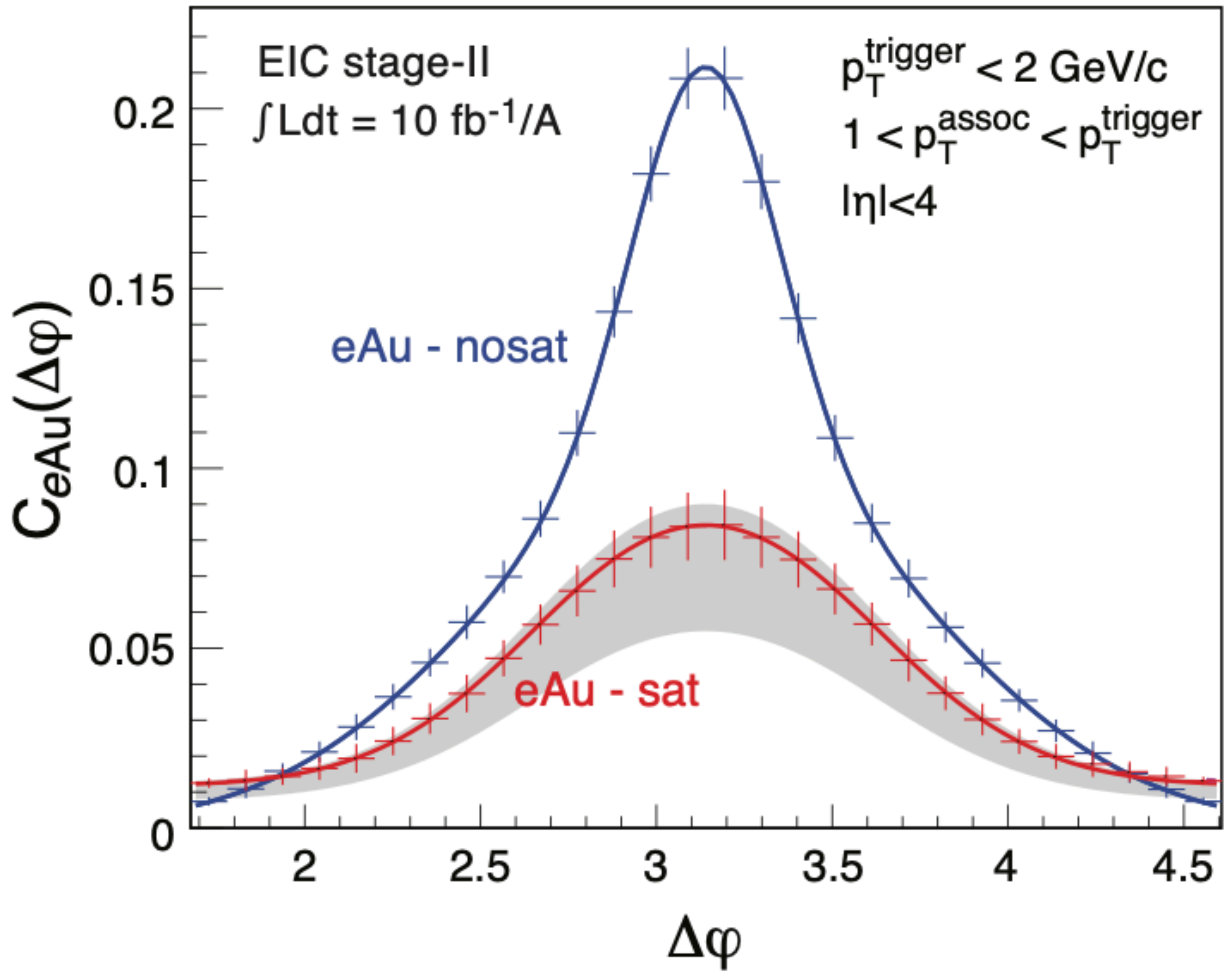
- Multiple scatterings with the soft gluons within the target serve to broaden the back-to-back peak for outgoing particles
  - When the relative momentum $q_\perp \sim Q_s$, interacting $q\bar{q}$ feels maximally the saturated glue.

- 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]

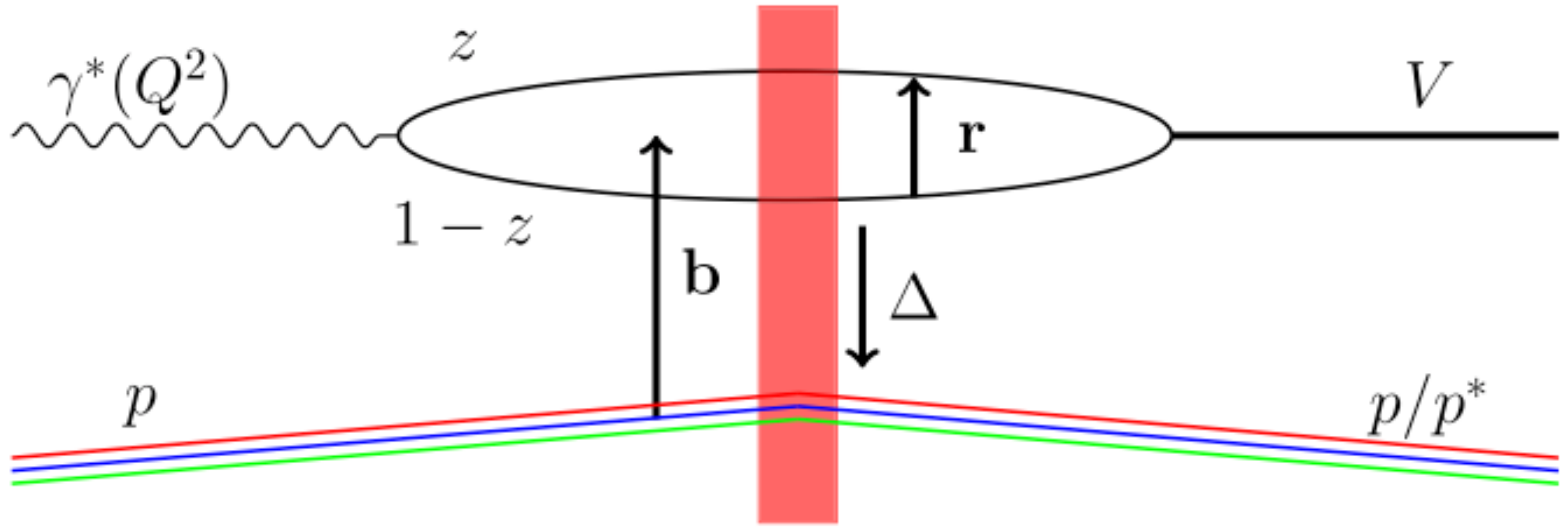


# VECTOR MESON PRODUCTION

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

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



## ACCESSING NUCLEAR SPATIAL INFORMATION:

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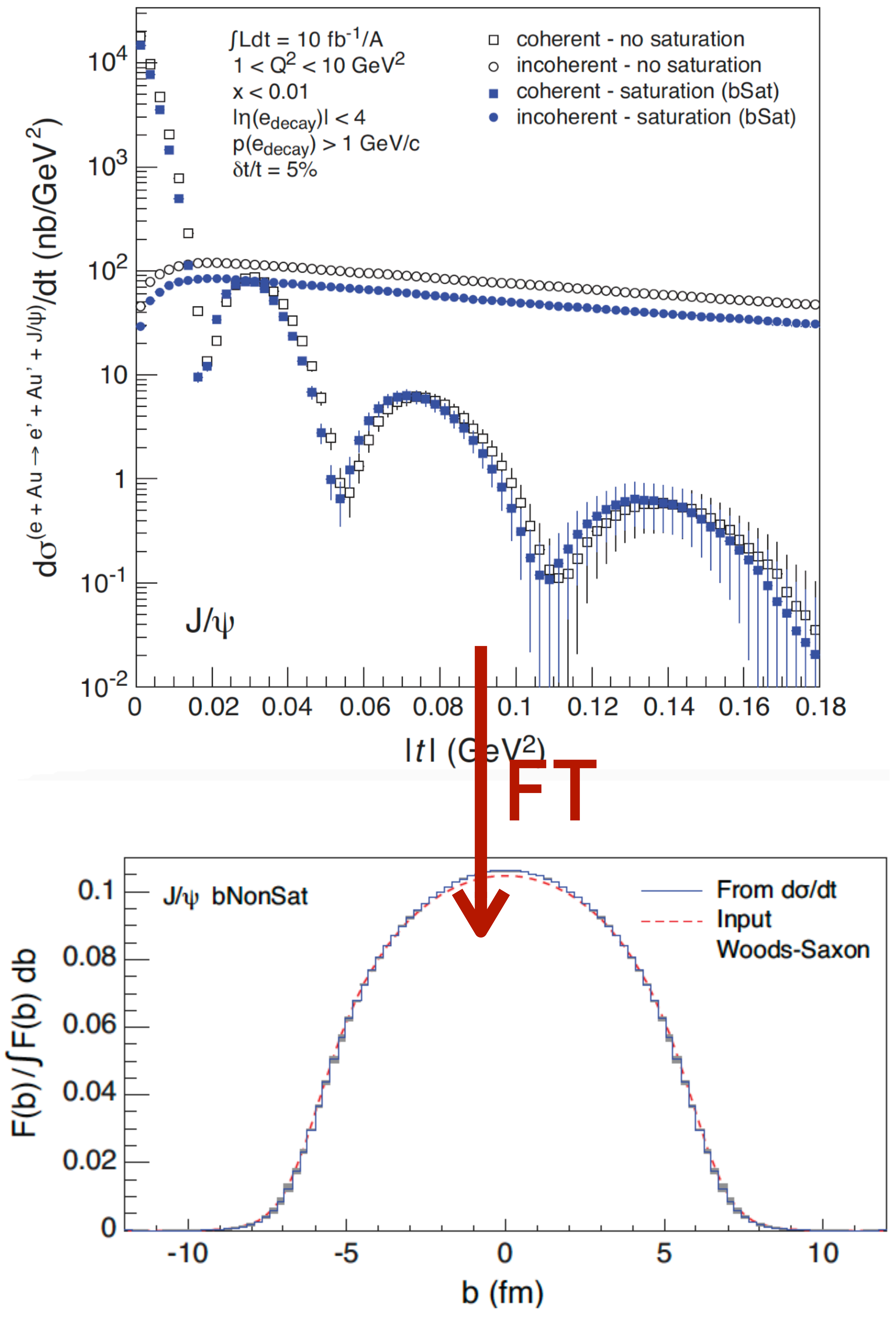
  $e + A \rightarrow e + (A' + X) + J/\psi$

- **Coherent:** Sensitive to average geometry

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



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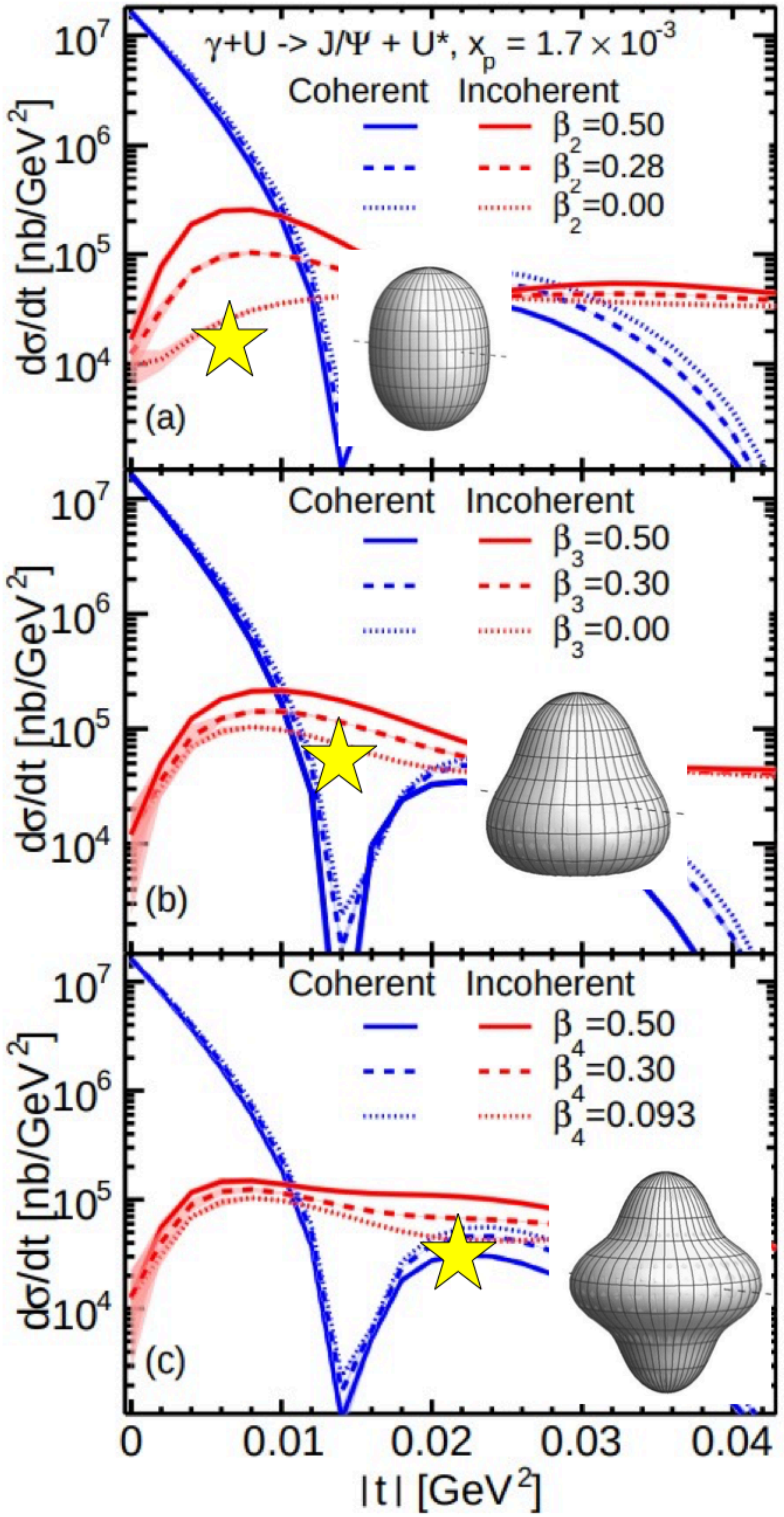
  - Sensitive to nuclear structure



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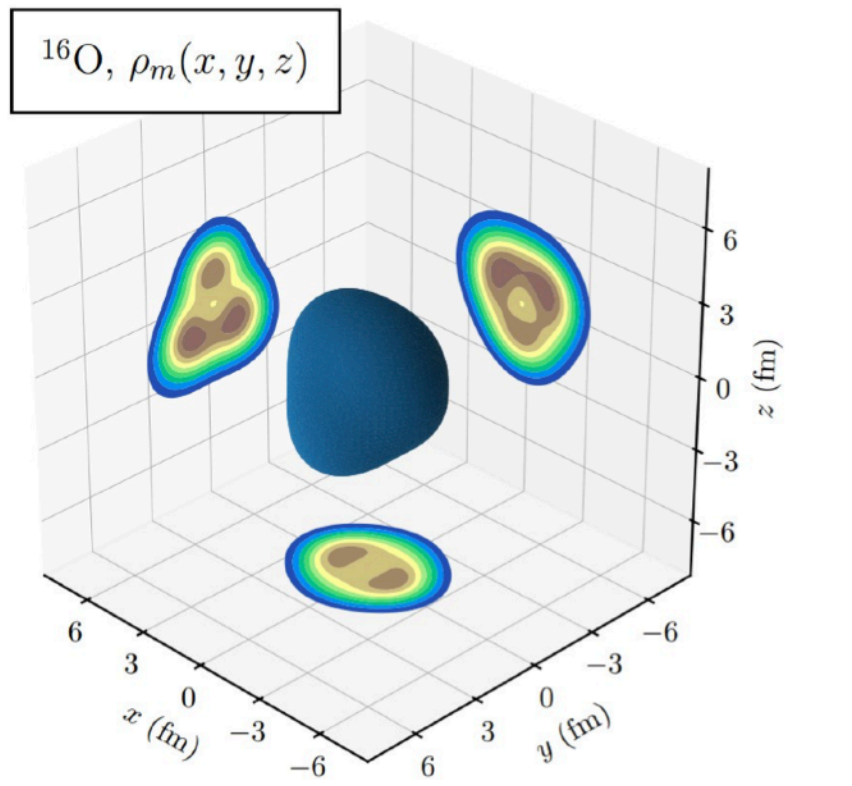


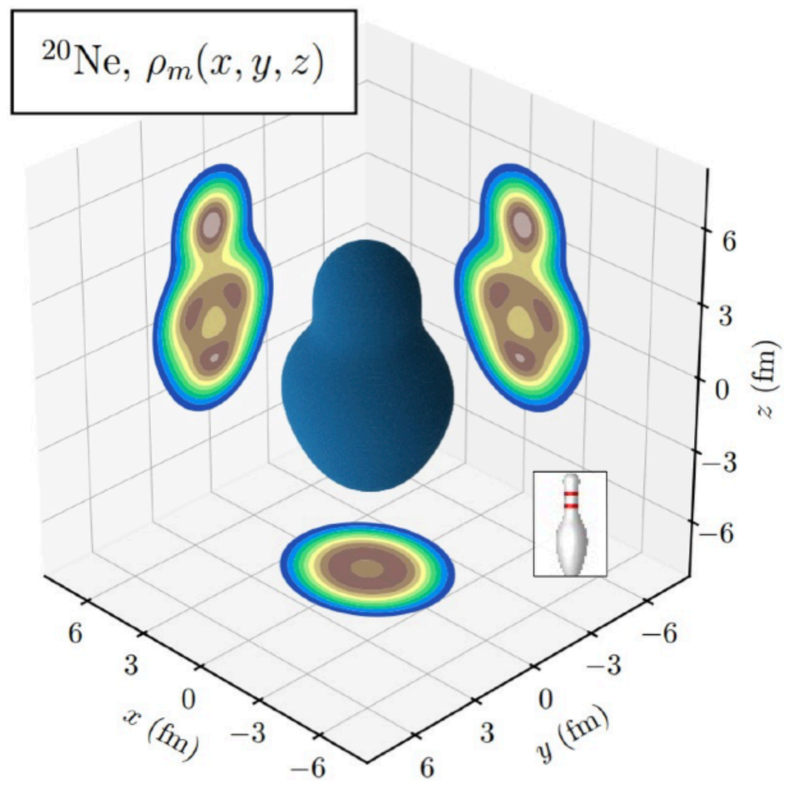


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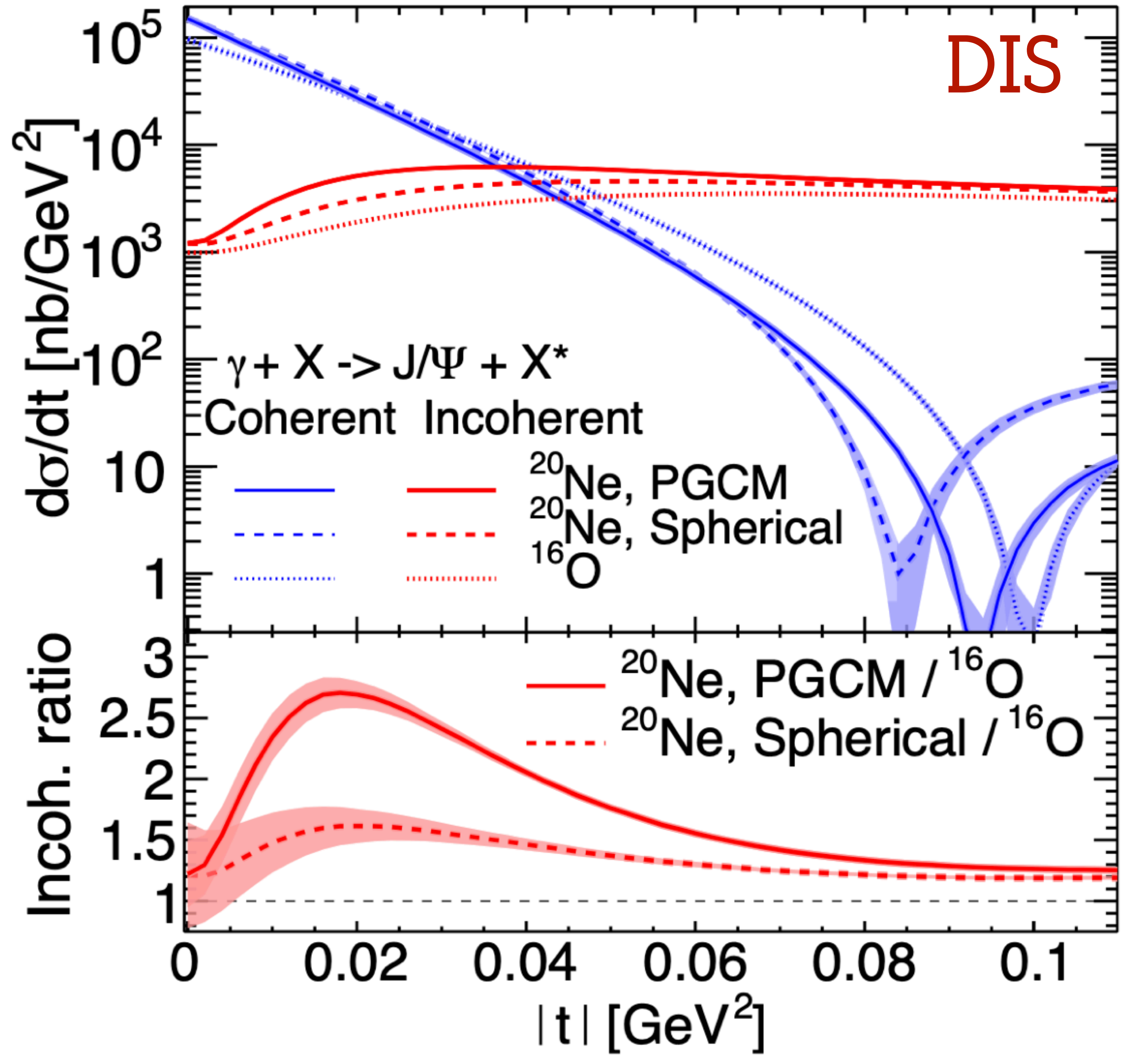
*Ab initio* computations of nuclear densities can help include **nucleonic *n*-point** correlations into initial geometry

## *Nuclear structure and DIS*




[ PRL 131 (2023) 6, 062301 ]

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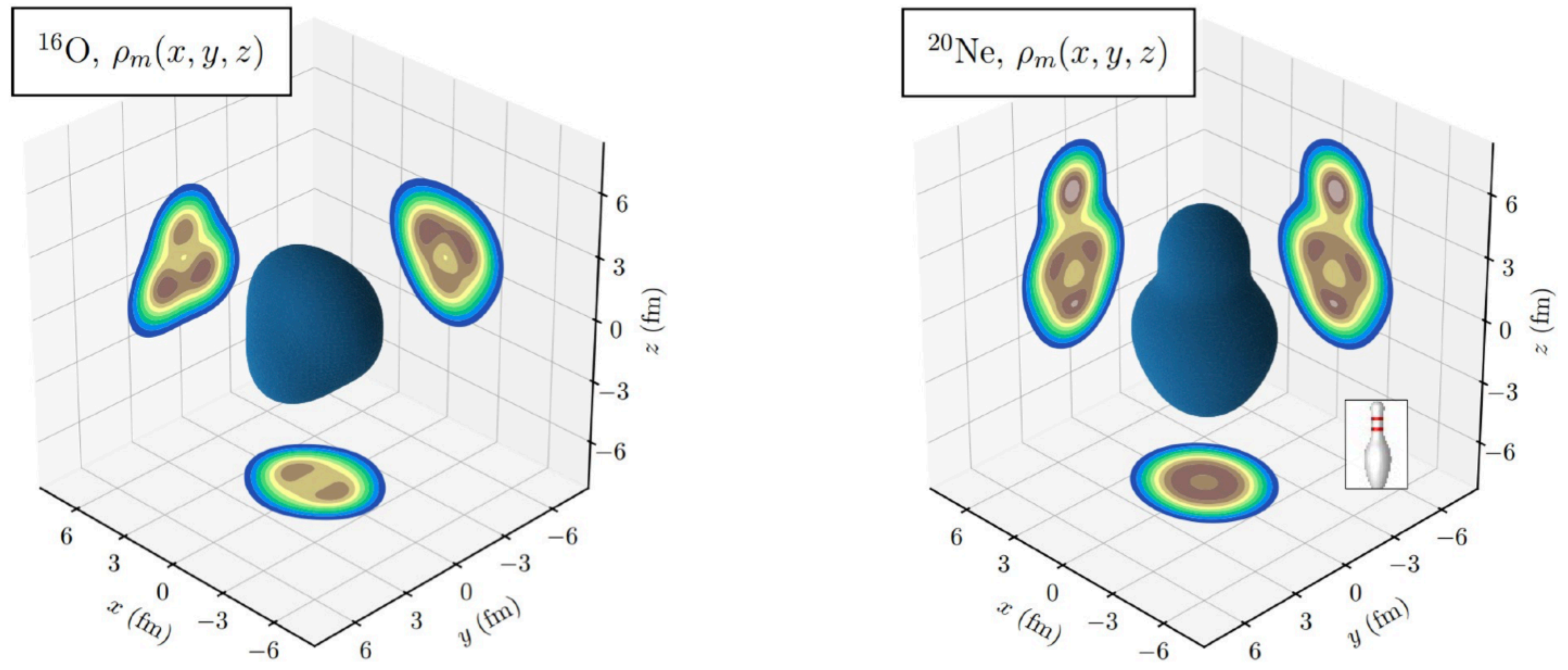


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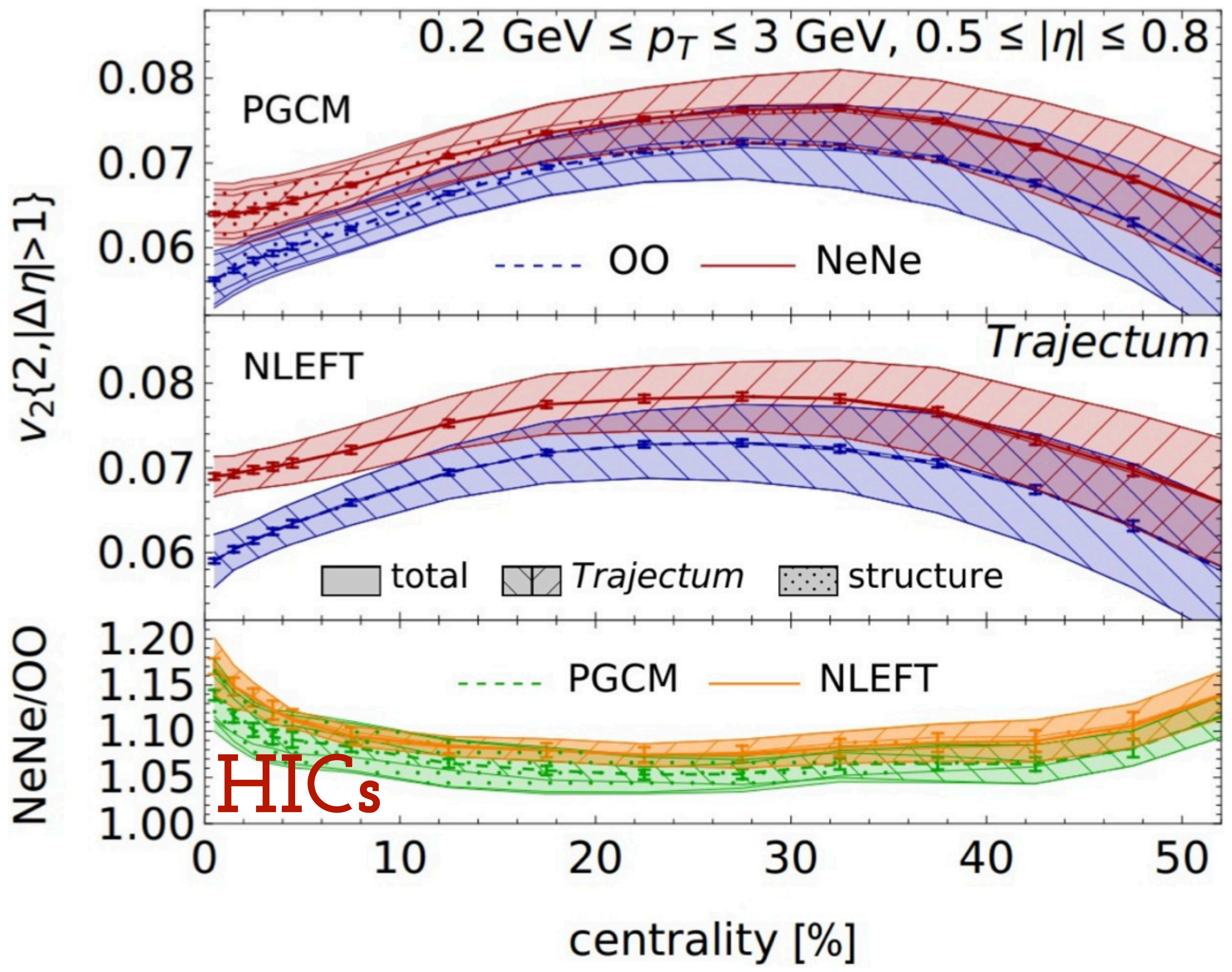
*Nuclear structure and flow*

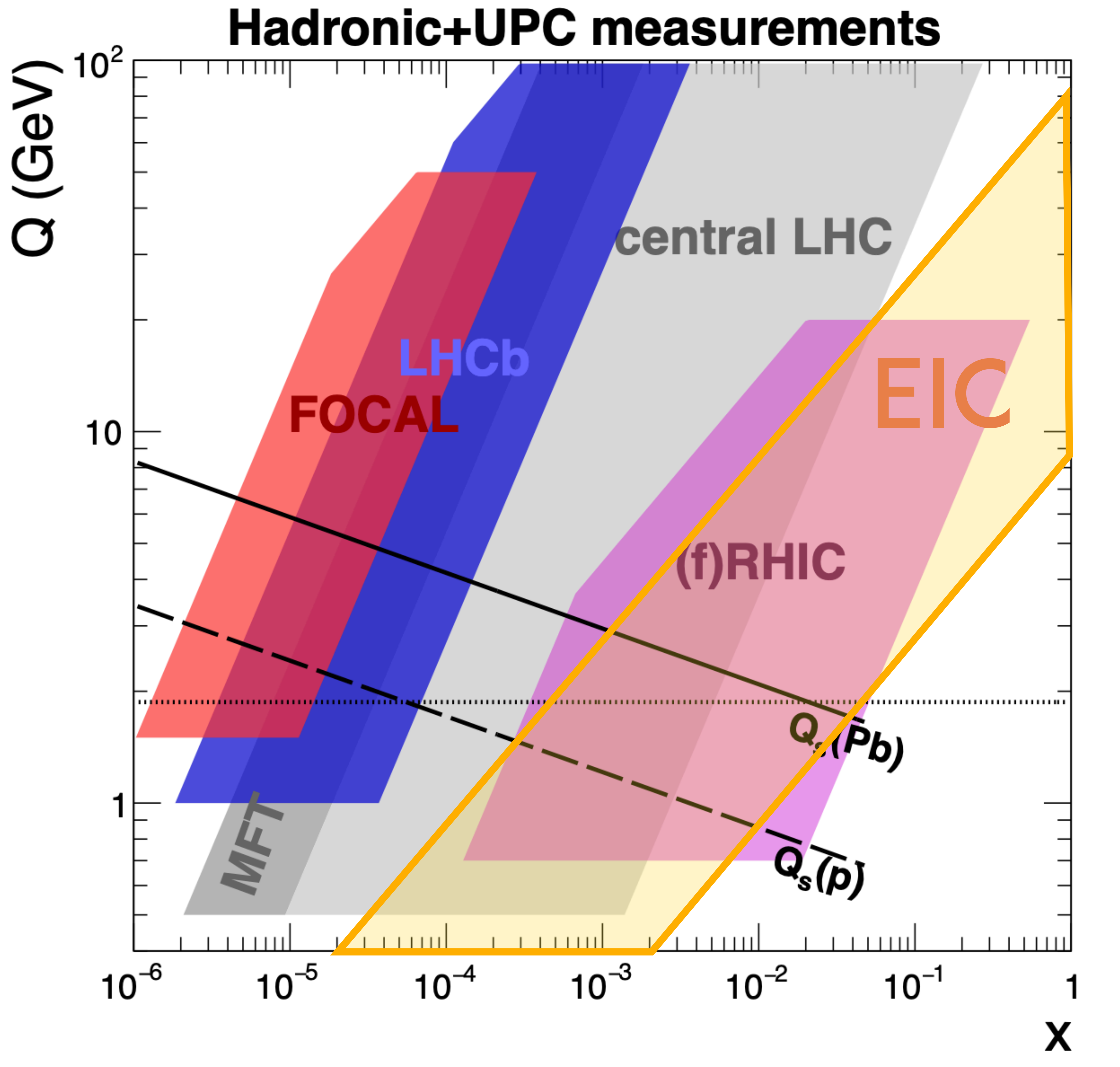



***Ab initio*** computations of nuclear densities can help include **nucleonic *n*-point** correlations into initial geometry

***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]



# 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.

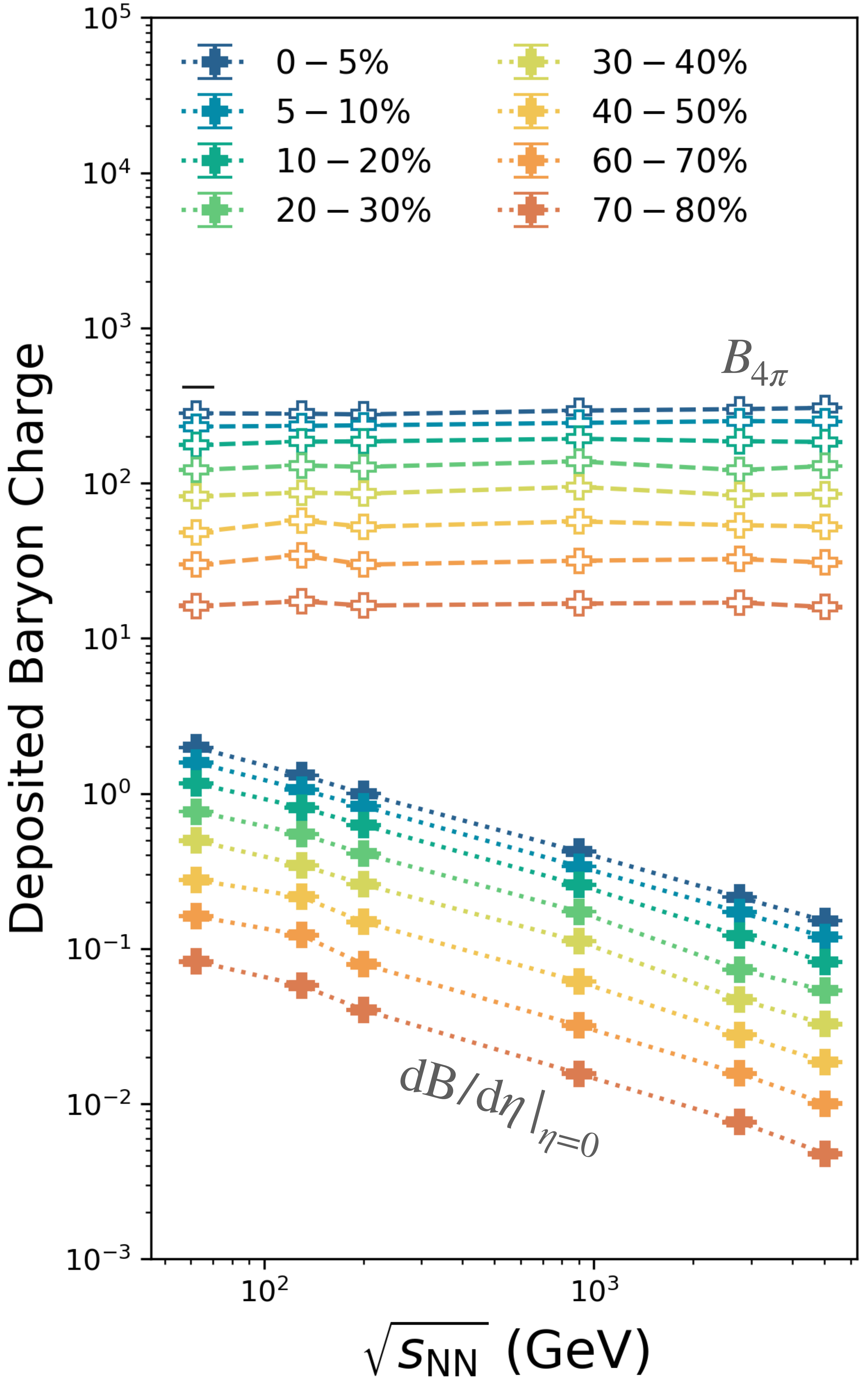
***Exciting Future:*** The EIC poses as an excellent complement to the HICs program. The ICs can be refined using its measurements.

# BACK-UP

# CHARGE DEPOSITION

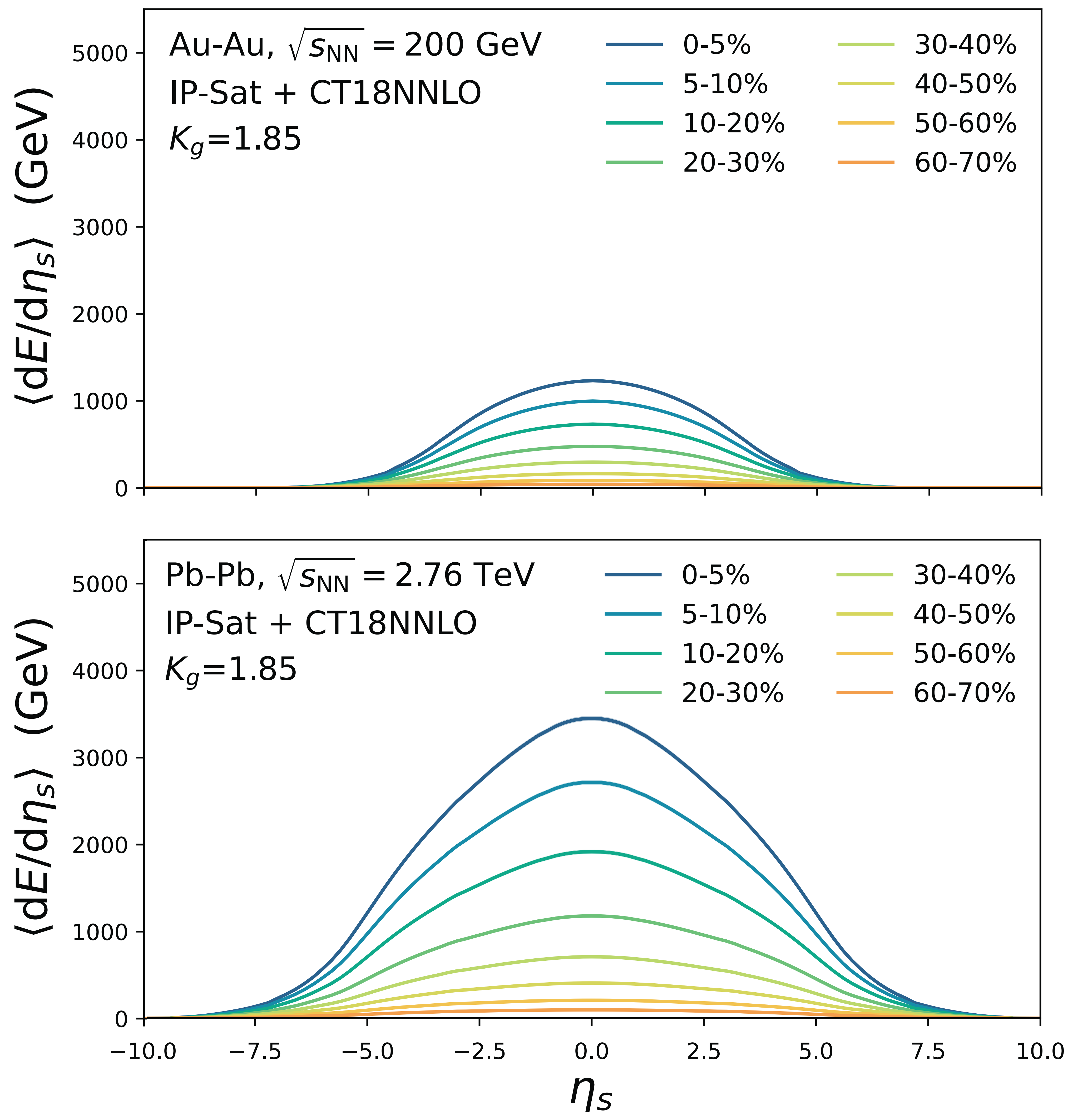
- Non-trivial interaction between x-dependence of gluon uGDs and quark PDFs gives tails in the charge deposition
- Even at higher rapidities, non-zero baryon stopping is found!
- Midrapidity baryon charge deposition follows a power-law trend

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



# 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]

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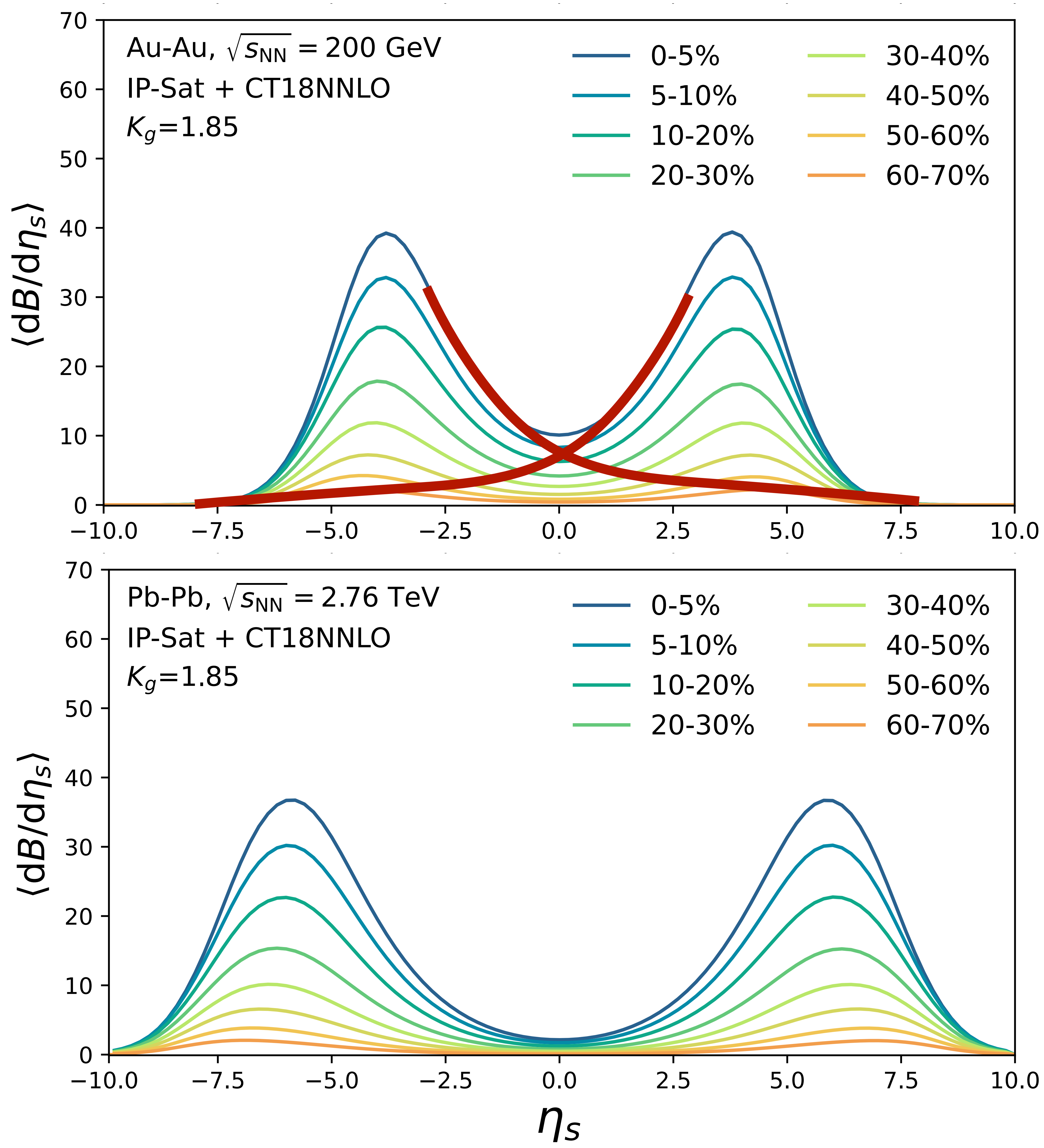
- Even at higher rapidities, non-zero baryon stopping is found!

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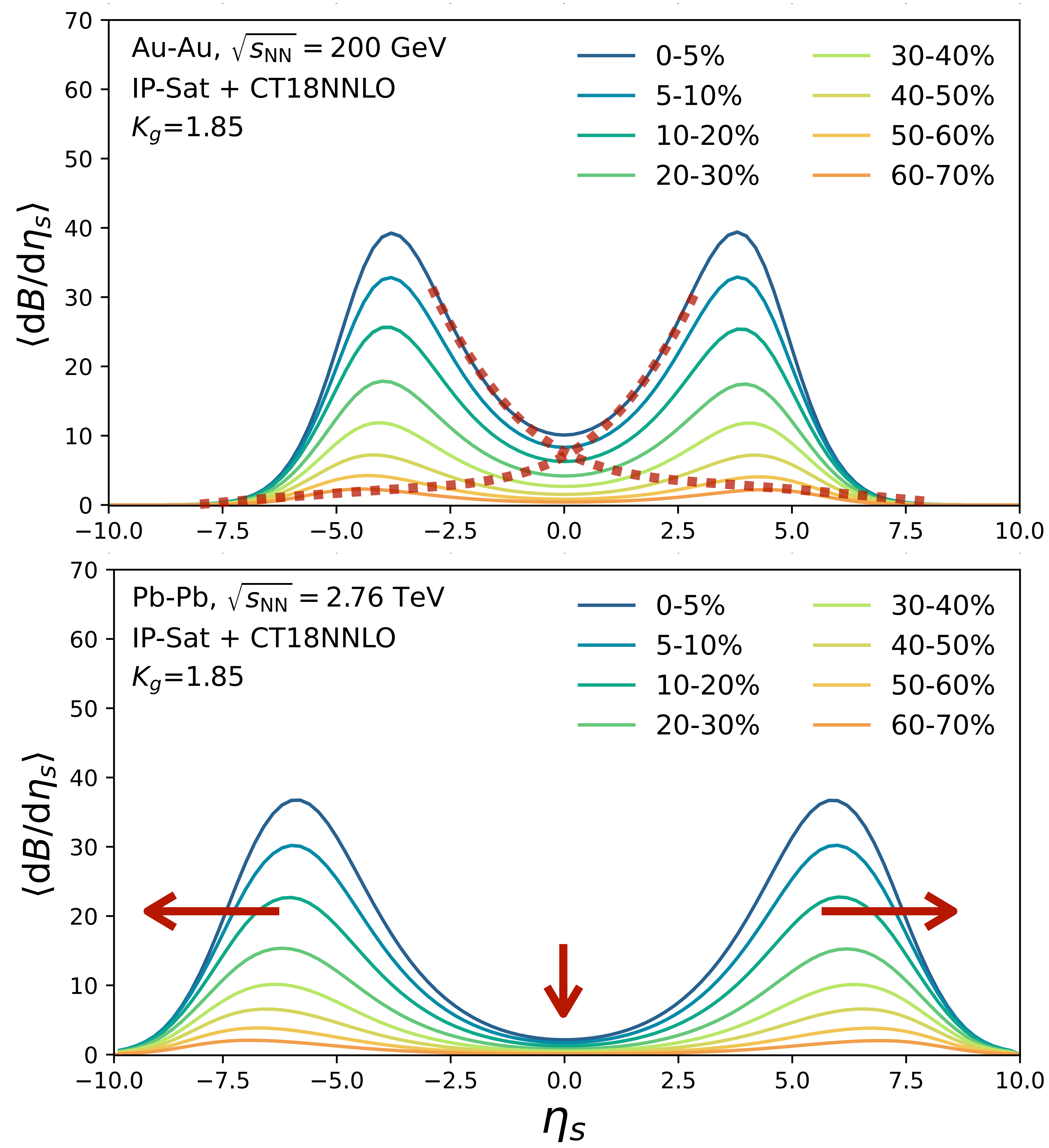


(see *PRC* 108 (2023) 4, 4)

# 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

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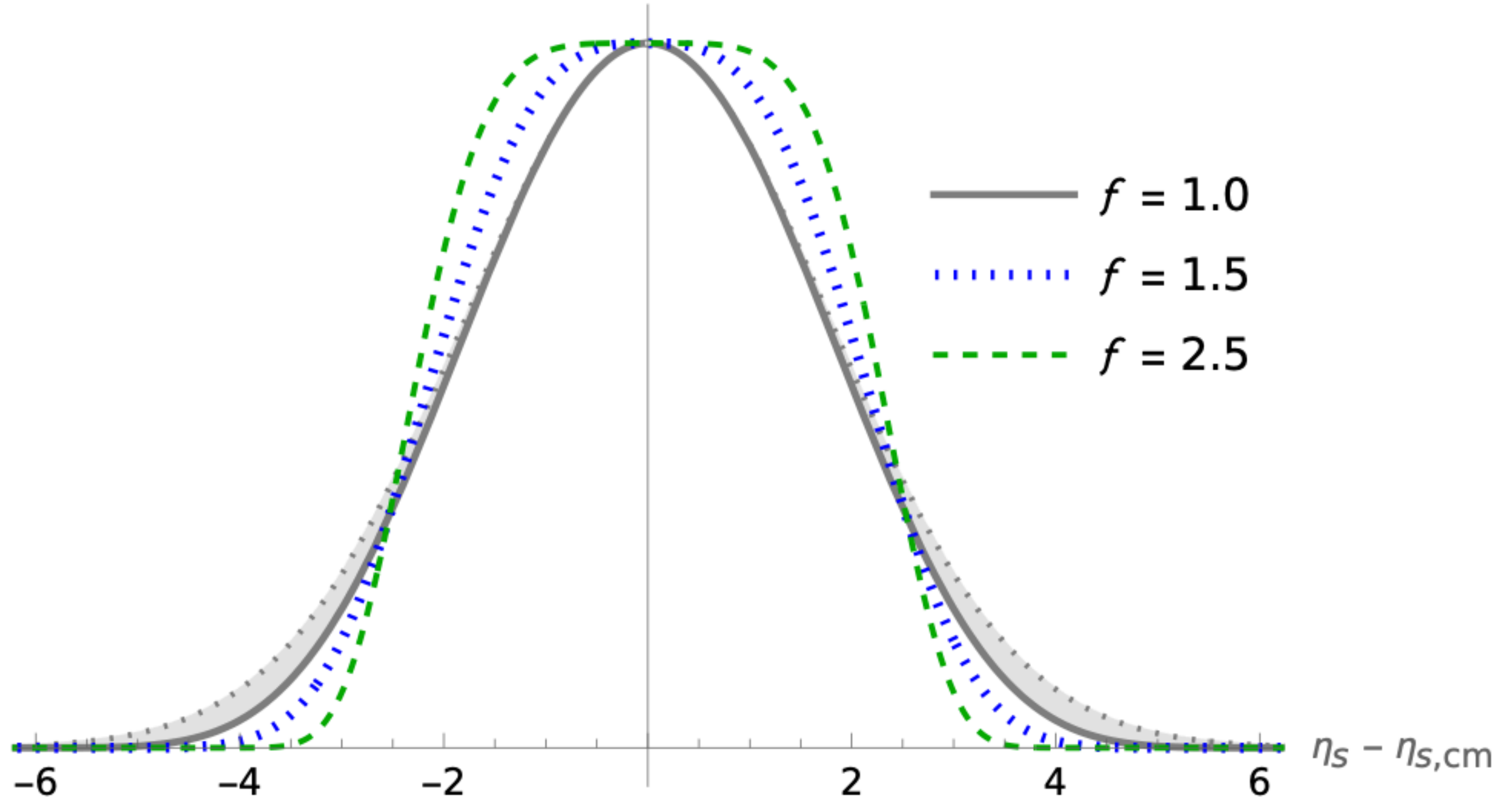
*Plateau*-fitting of the fireball



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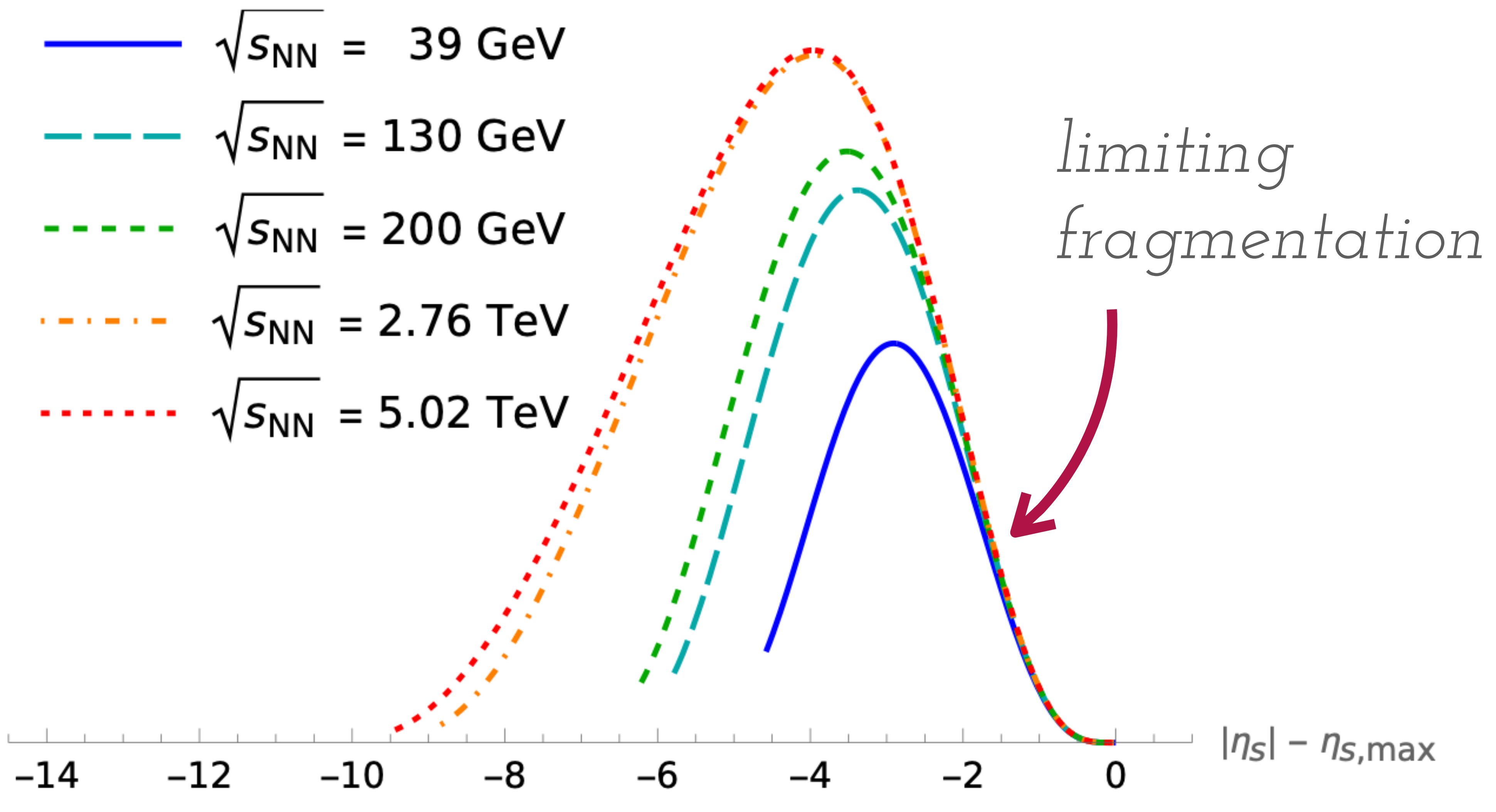

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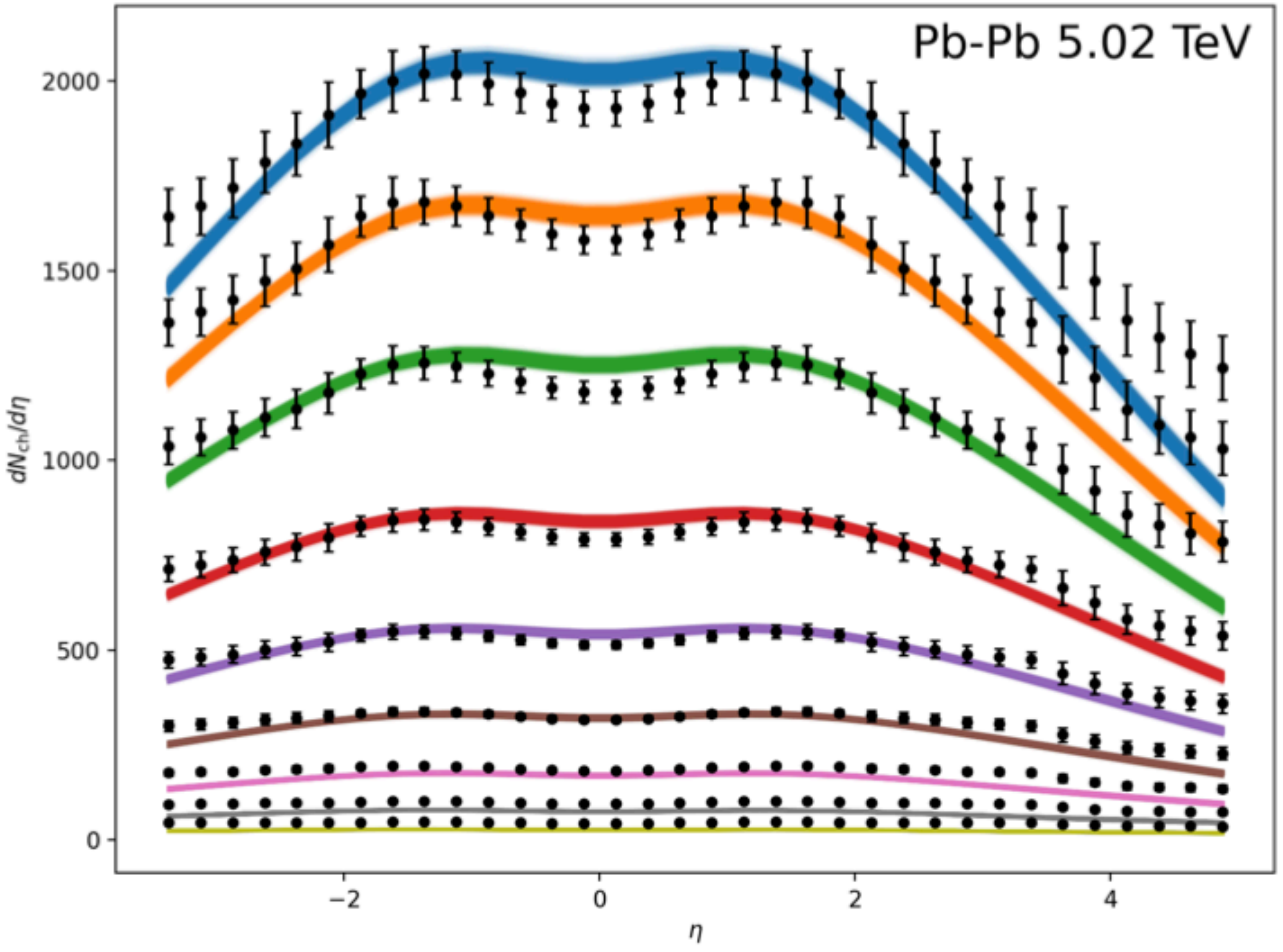


No charge deposition.
Useful for bayesian analysis