Energy-Energy Correlators at High Energy Frontiers

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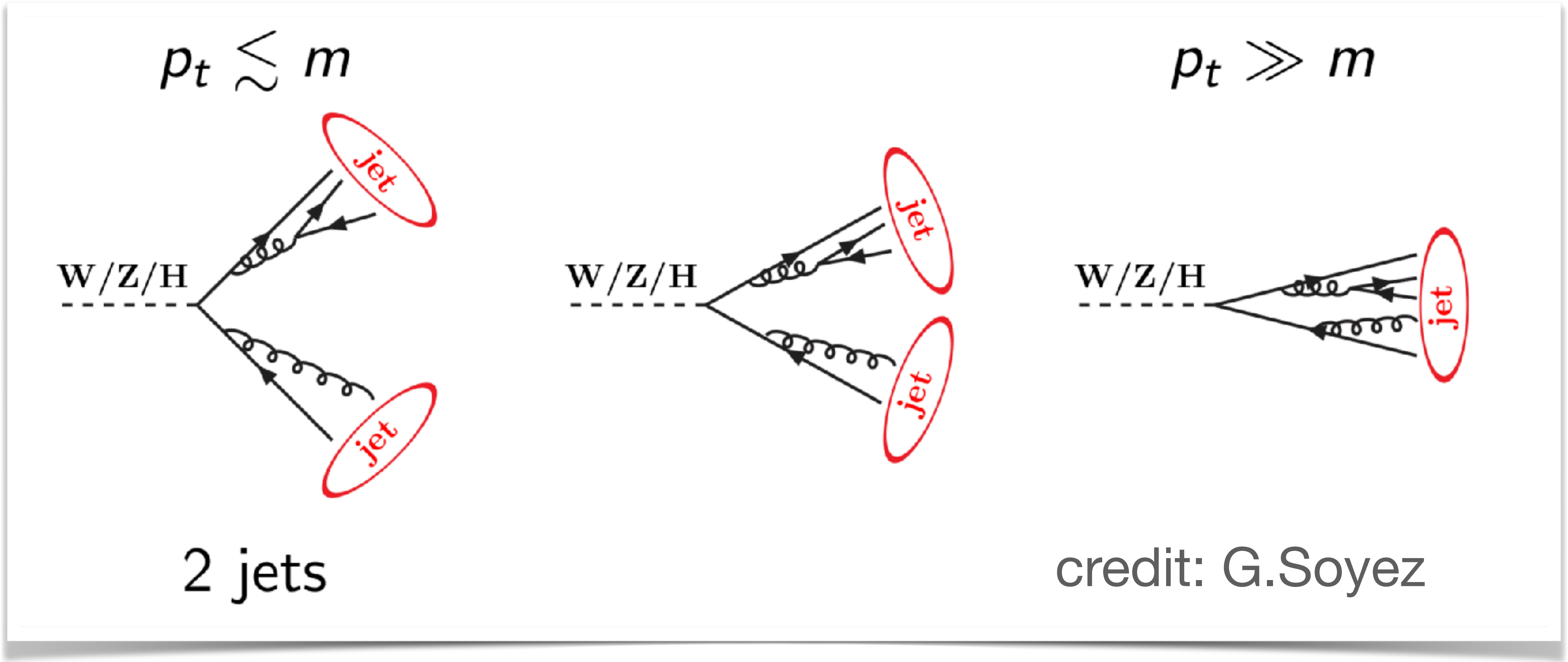
Different views on jet substructure

Traditional motivation: A window to boosted objects

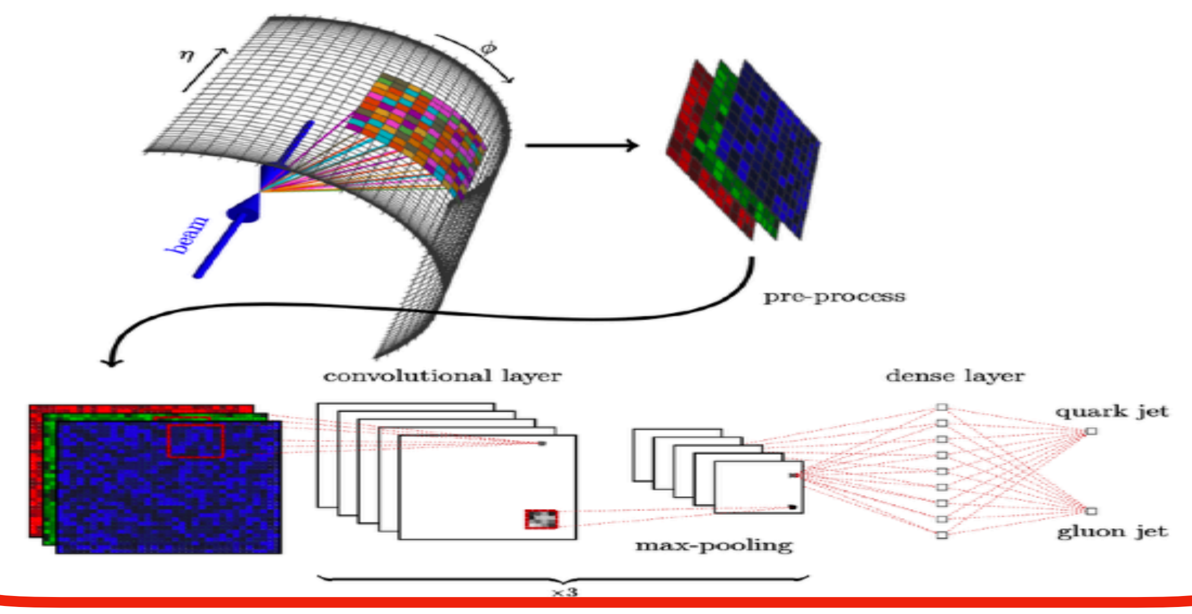
Boost the potential for physics discovery at high energy collider



“Jet shape” crafted with expertise knowledge:

Jet mass, jet broadening, angularities, jet pull, jet charge, EFP, N-subjetiness, …
trimming, pruning, grooming, soft-drop + xxx

Data driven:



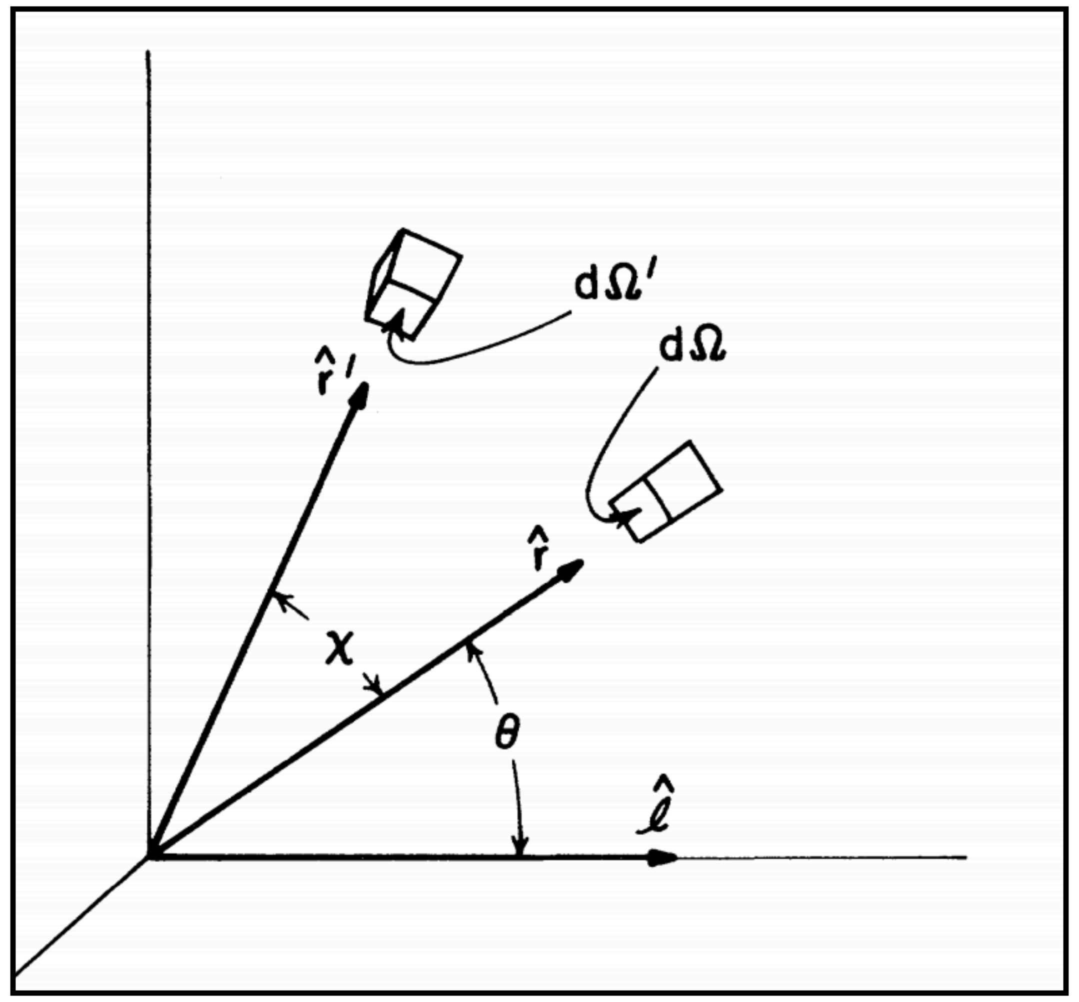
Alternative motivation: probing structure of high energy QCD

also give insight to non-perturbative hadronization and structure

Energy weighted Angular correlation function of particles (within jet)

EEC in e+e-

Basham, Brown, Ellis, Love, 1978



EEC: Correlation of energy deposition between two detector at an angle χ

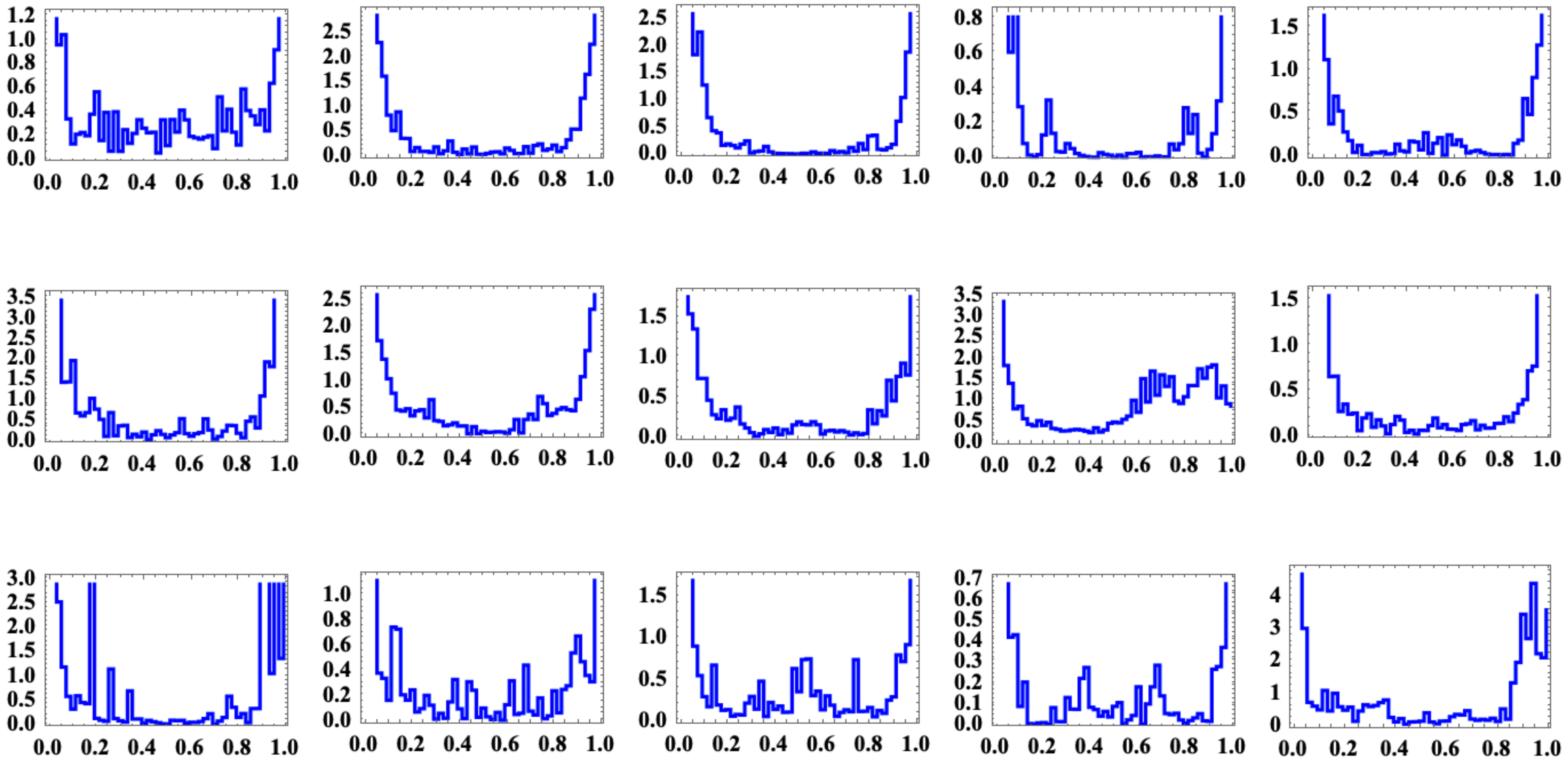
$$\mathrm{EEC}(\chi) = \frac{1}{N}\sum_{\text{events}}^{N}\sum_{i,j}^{N_{\text{particles}}}\frac{E_iE_j}{E_{\text{tot}}^2}\left(\frac{1}{\Delta\chi}\int_{\chi-\Delta\frac{\chi}{2}}^{\chi+\Delta\frac{\chi}{2}}\delta(\chi'-\chi_{ij})d\chi'\right)$$

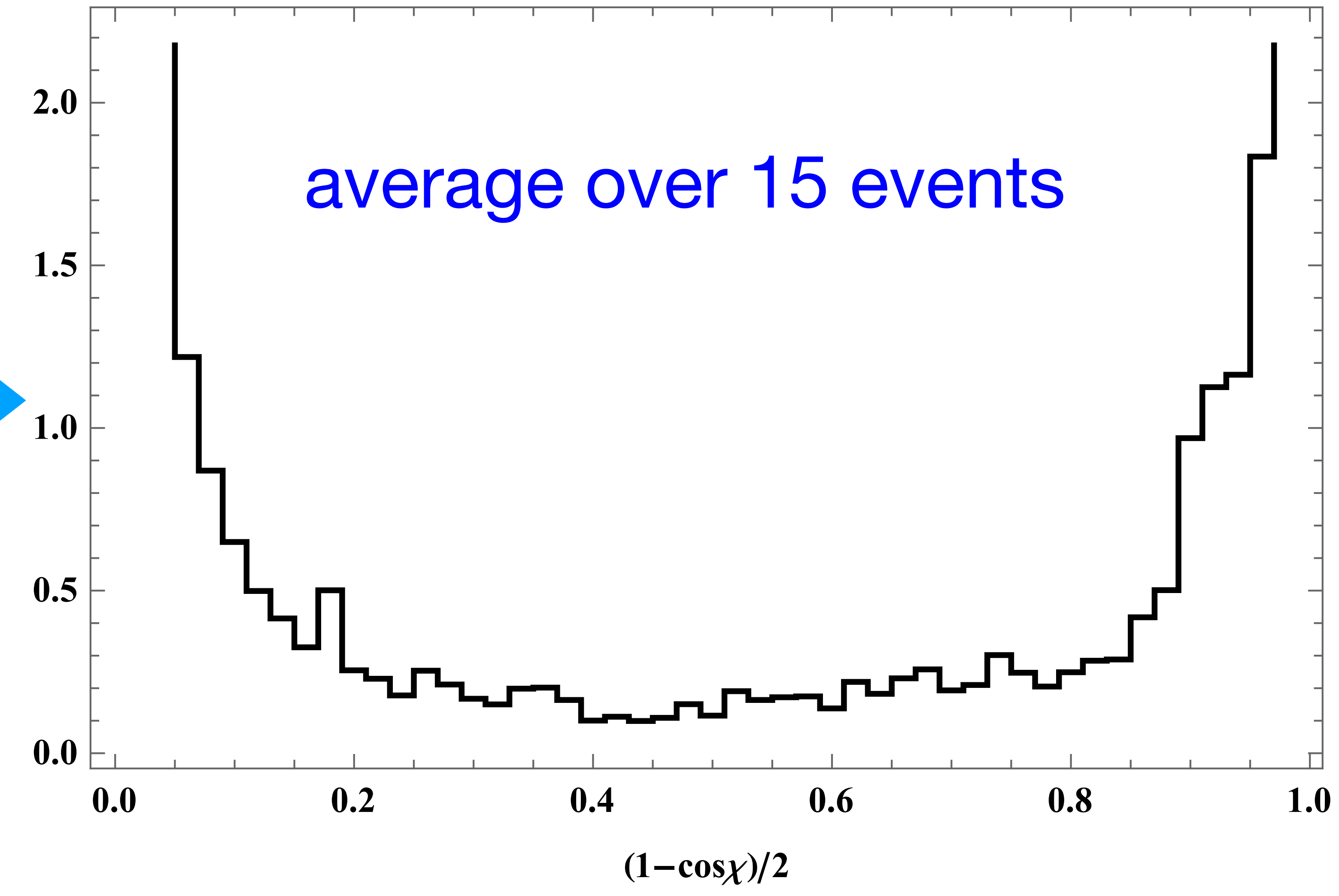
Experiment defintion

$$\mathrm{EEC}(\chi) = \frac{1}{\sigma_{\text{tot}}}\sum_{i,j}\int d\sigma_{e^+e^-\to i,j+X}\frac{E_iE_j}{E_{\text{tot}}^2}\delta(\chi-\chi_{ij})$$

Theory definition #1

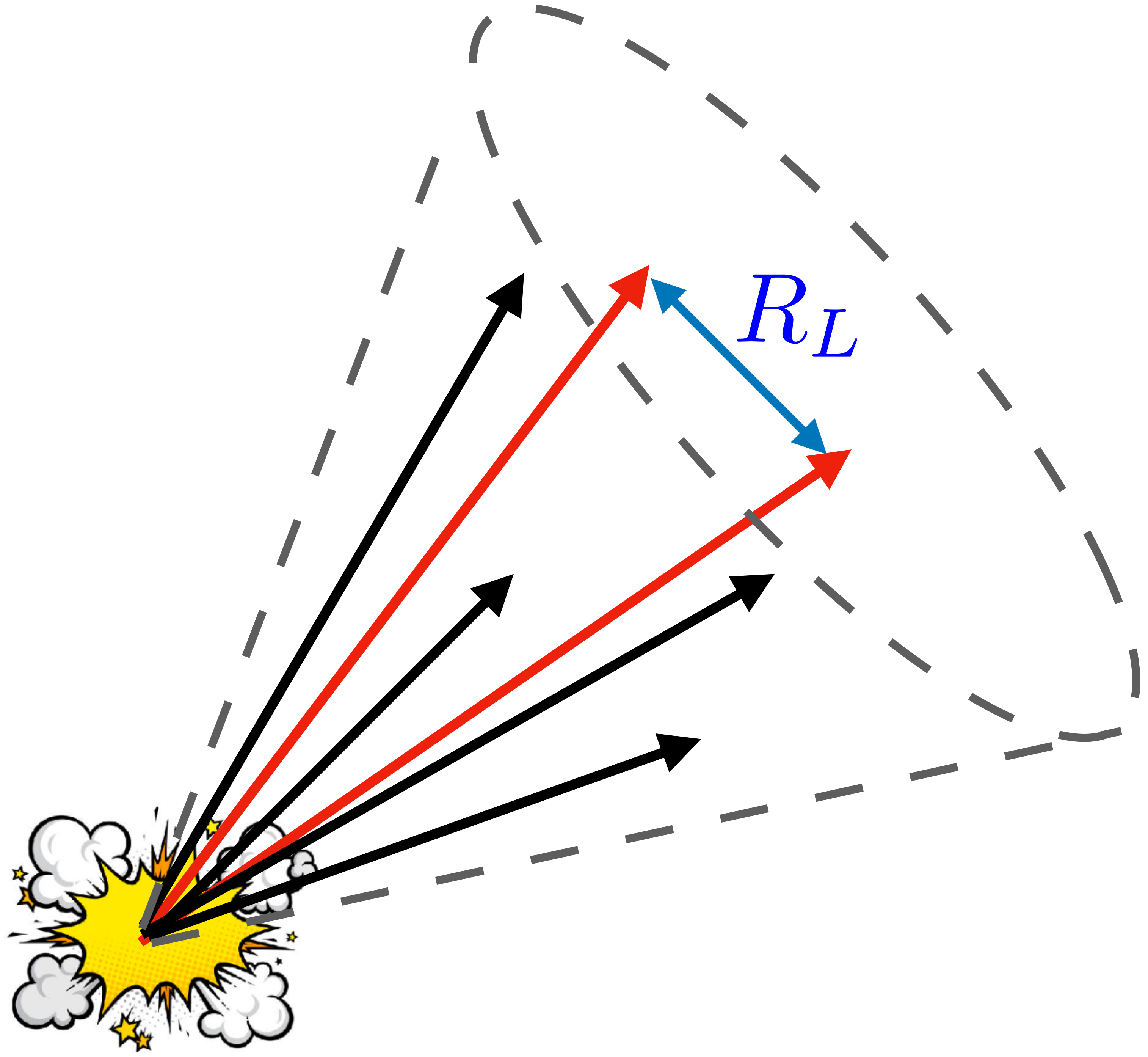
Measurement on a single event gives a function





collinear log **Sudakov log**

EEC within high energy jet



Sample over

different pair of particles

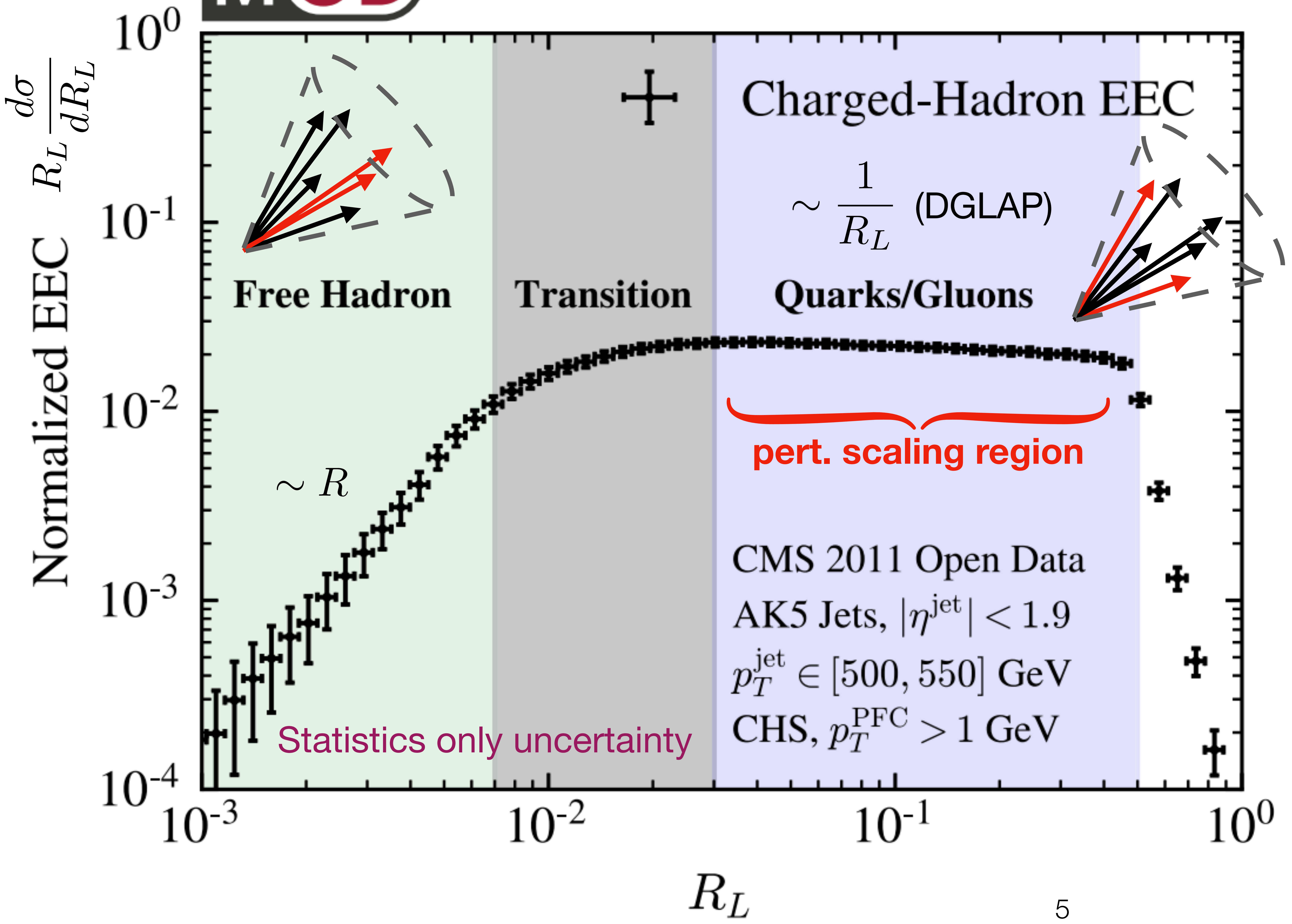
an ensemble of jet

What new thing can we learn form this utterly simple measurement?

1. LHC provides numerous large pT jet unimaginable from LEP
2. Advancement in experimental analysis allows unprecedented small angle correlation
3. Measurement of energy flow angular correlation strongly motivated by conformal field theory

Visualizing hadronization through EEC

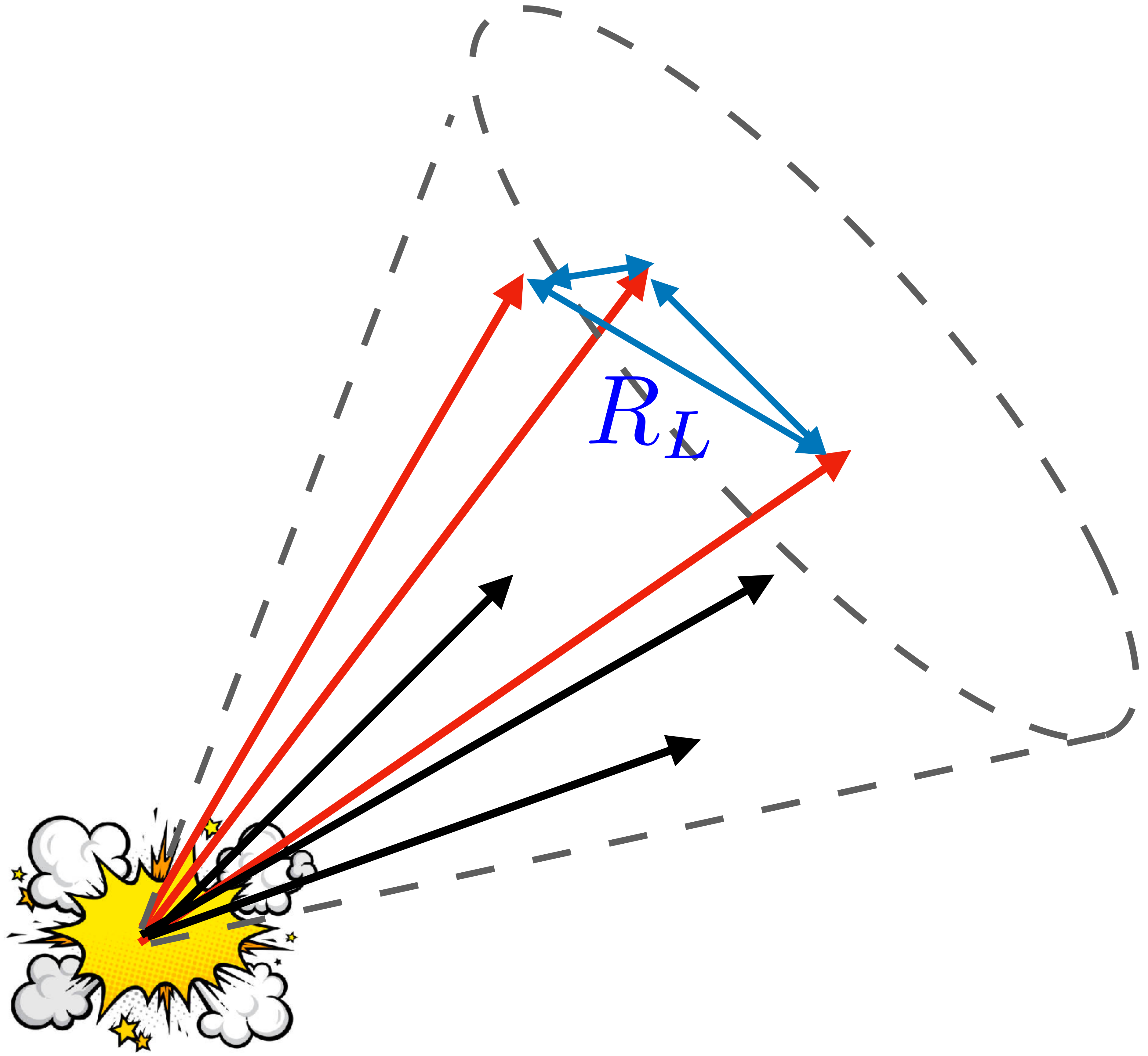
P. Komiske, I. Moult, J. Thaler, HXZ, PRL130, 051901 (2023)



- R_L is the angle distance of the correlated pair, dimensionless
- $P_T{}^*R_L$ is the transverse momentum exchanged between the correlated pair
- Observation of three strikingly different regions
- D.O.F. in perturbative scaling region are quark and gluons
- Transition region represents quark/ gluon hadronization phase transition
- At very small angle hadrons are uncorrelated due to confinement
- First time that we can visualize from experiment the evolution of d.o.f from quark/gluon to hadrons

Generalization to N-point correlation

H. Chen, I. Moult, X.Y. Zhang, HXZ, Phys.Rev.D 102 (2020) 5, 054012



Three-point energy correlator

- Correlation between more than two particles (weighted by energy)
- Multidimensional observable, can be projected to the longest side
- A plethora of observable for arbitrary N (including even fractional value)
- Obey similar power law as EEC
- Exponent of power law determine by anomalous dimension of twist-2 operator

$$(R_L)^{\gamma_{N+1}} \qquad \bar{\psi}(D^+)^N\gamma^+\psi$$

note: for even N appropriate analytic continuation is required

Ratios of N-point energy correlators as precision observable

H. Chen, I. Moult, X.Y. Zhang, HXZ, Phys.Rev.D 102 (2020) 5, 054012

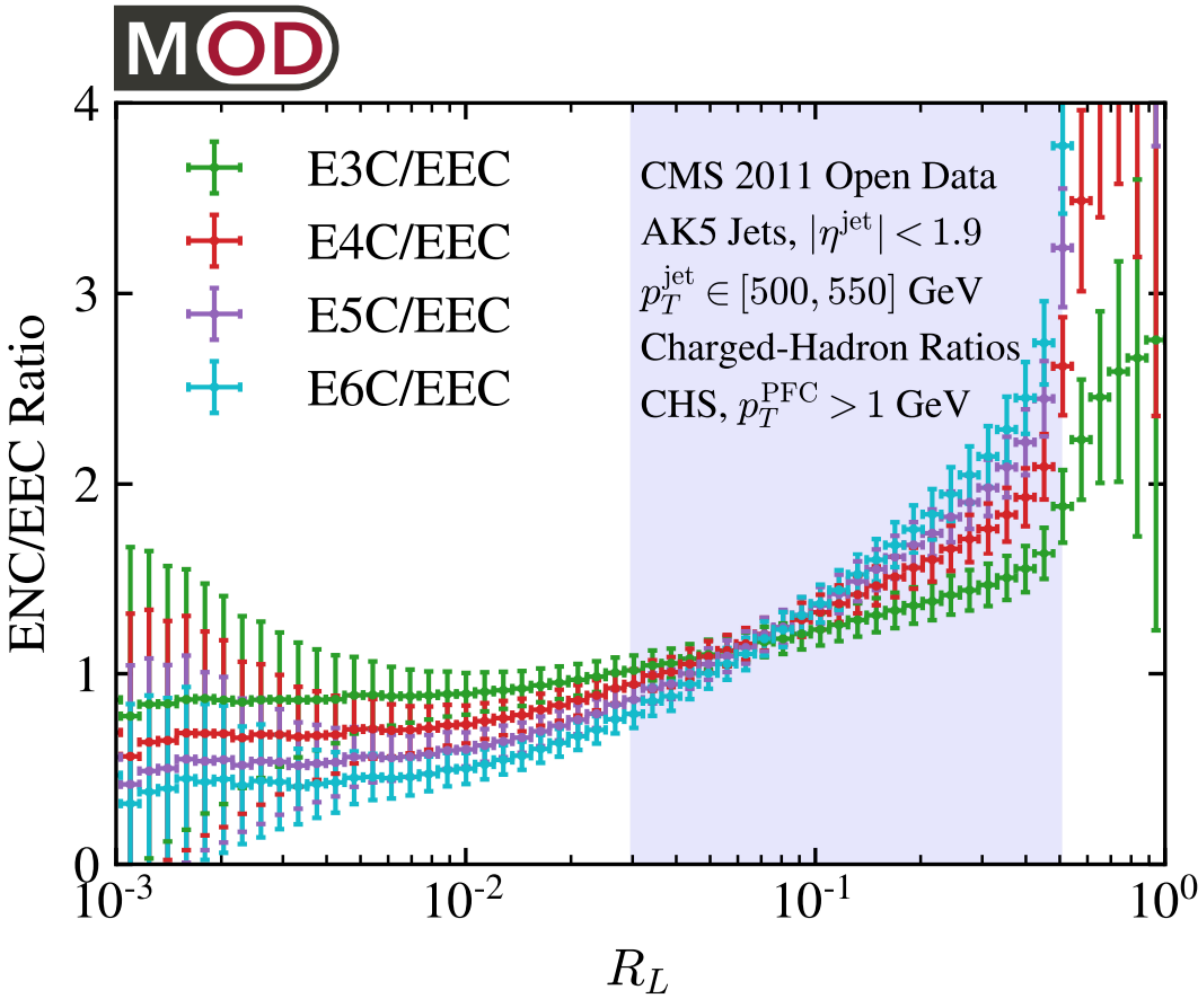
Ratio of projected N-point correlation and EEC

$$\text{Ratio}(R_L, N) = \frac{\text{ENC}(R_L)}{\text{EEC}(R_L)}$$

- Many theory and systematic uncertainties are cancelled in the ratio: scale uncertainties, hadronization corrections, PDFs, experimental systematics
- Leading to better theory control, ideal for precision measurement, e.g. α_s

Power law for ratio: $(R_L)^{\gamma_{N+1}-\gamma_3}$

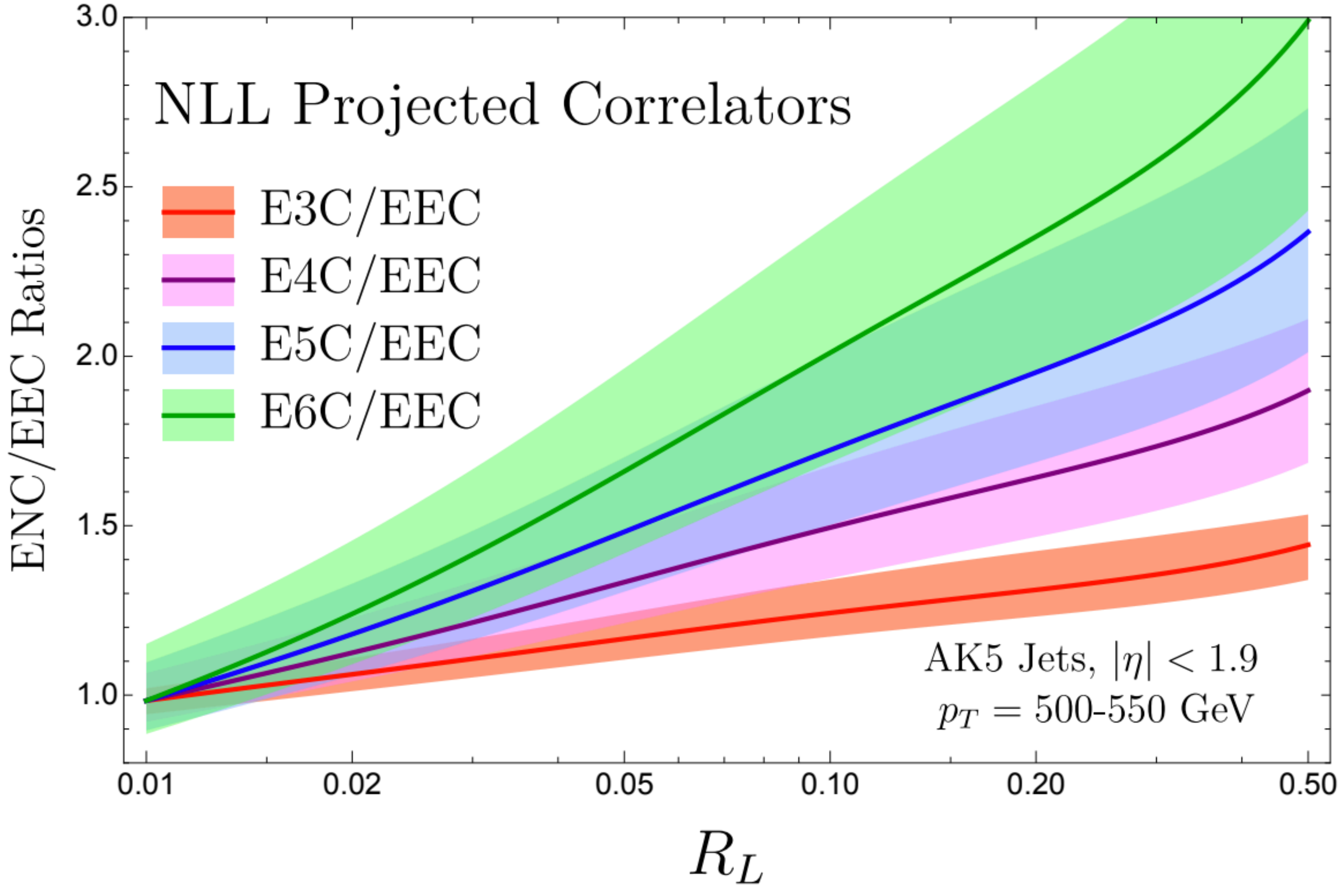
P. Komiske, I. Moult, J. Thaler, HXZ, PRL130, 051901 (2023)



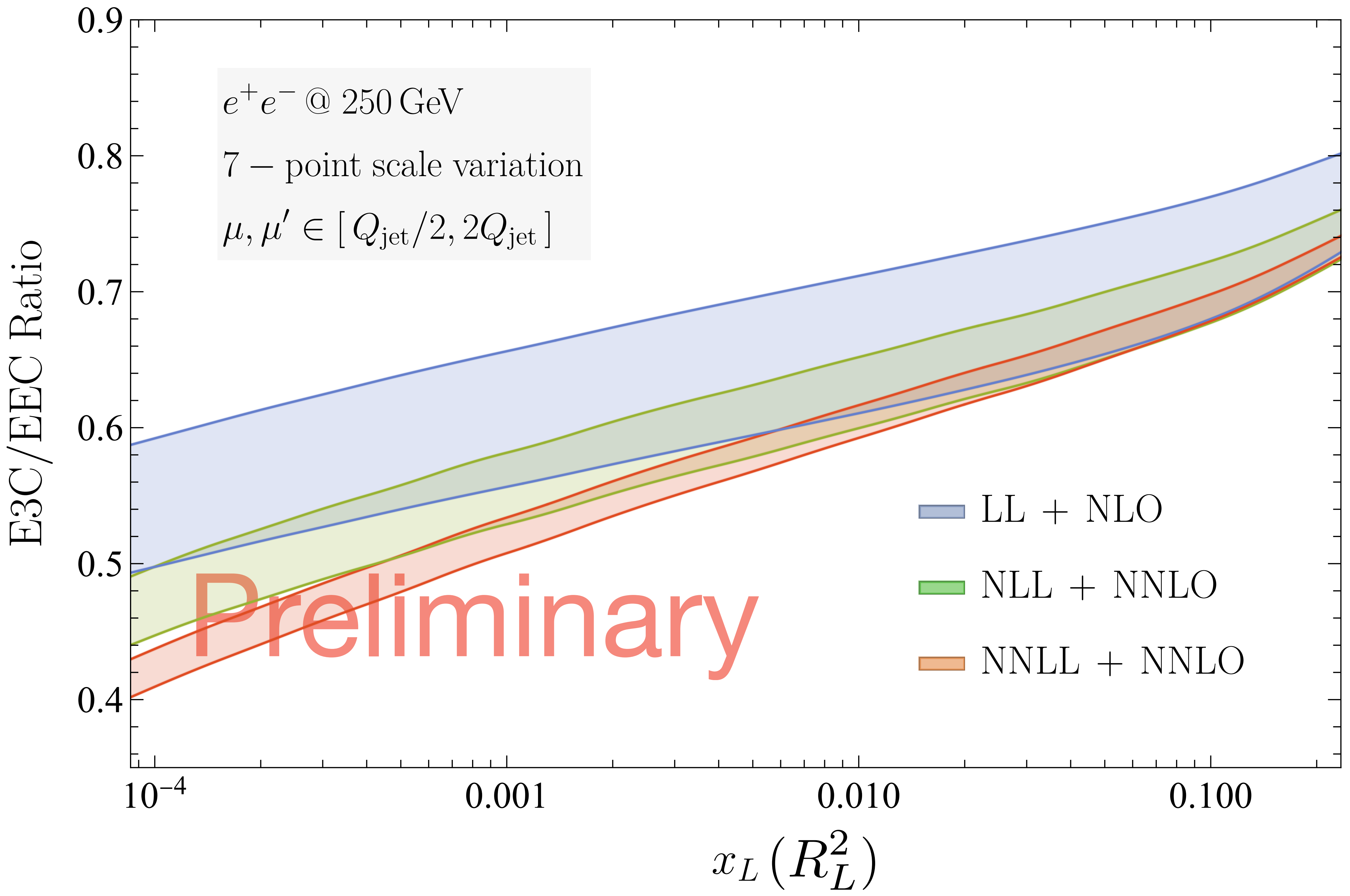
The increase in slop is a consequence of monotonicity of anomalous dimension

Precision calculation for the ratios

NLL: two-loop anomalous dimension; NNLL: three-loop anomalous dimension



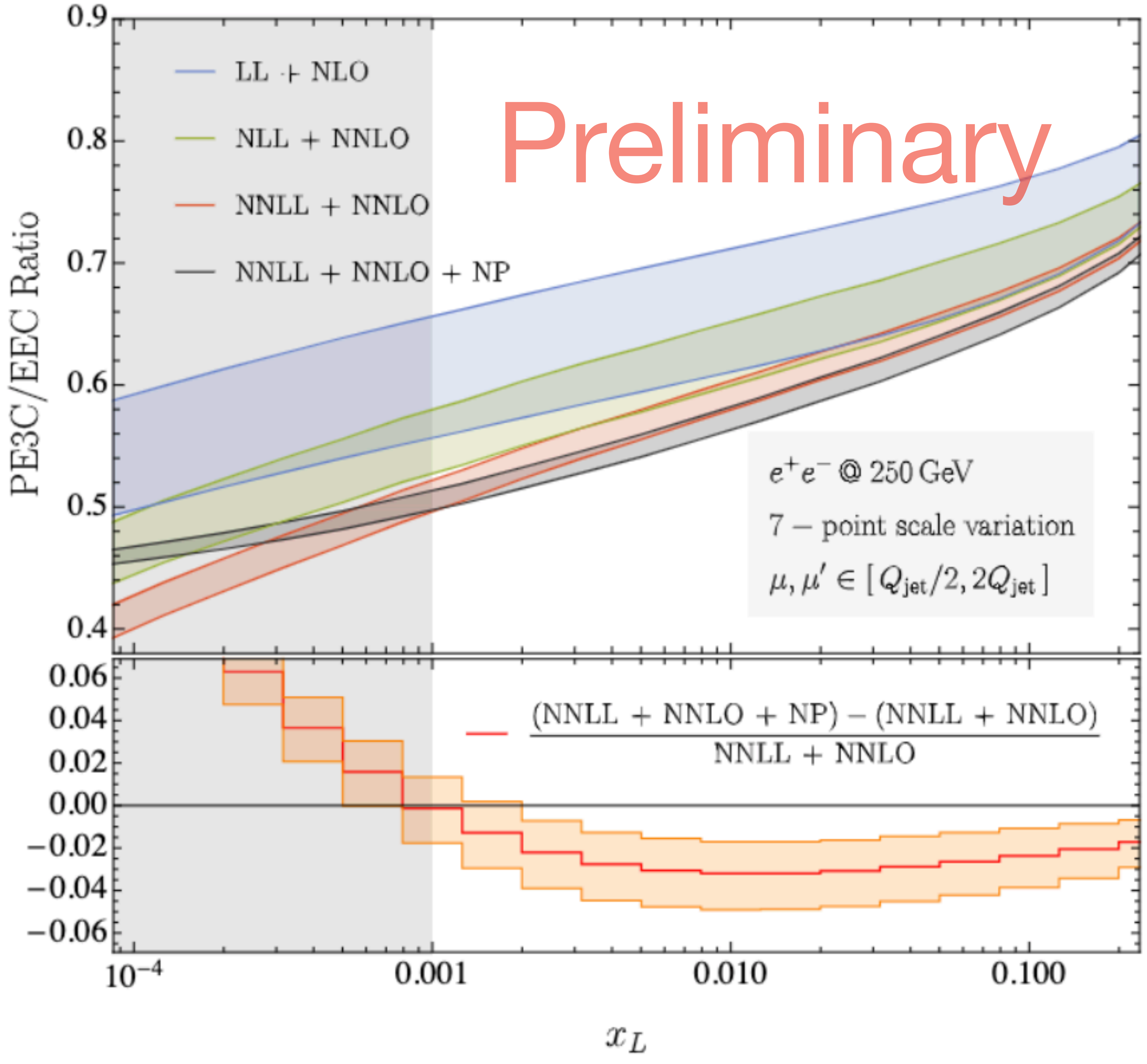
K. Lee, B. Mecaj, I. Moult, 2205.03414



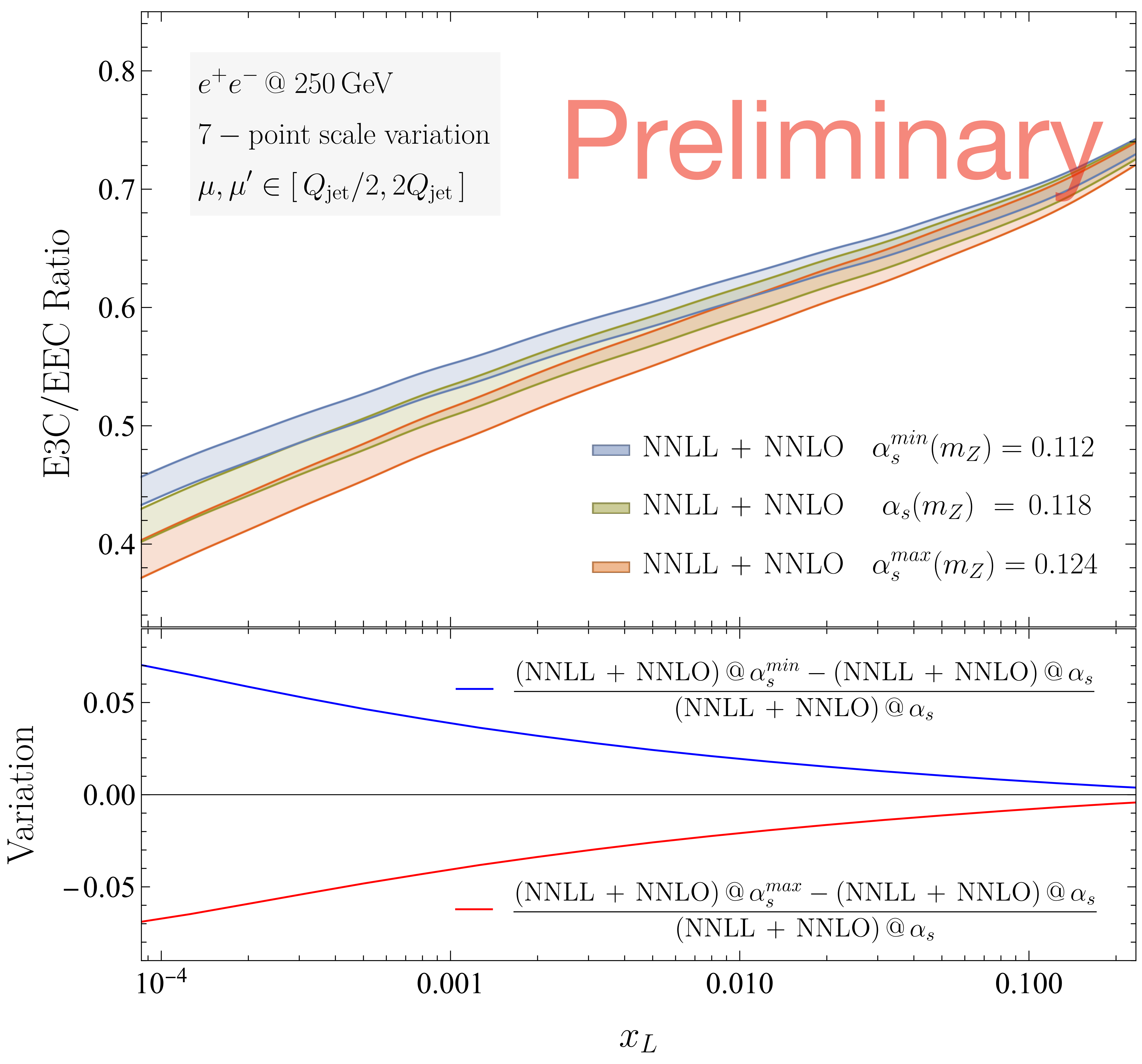
W. Chen, J. Gao, Y.B. Li, Z. Xu, X.Y. Zhang, HXZ, in progress

Sensitivities to strong coupling constant

W. Chen, J. Gao, Y.B. Li, Z. Xu, X.Y. Zhang, HXZ, in progress

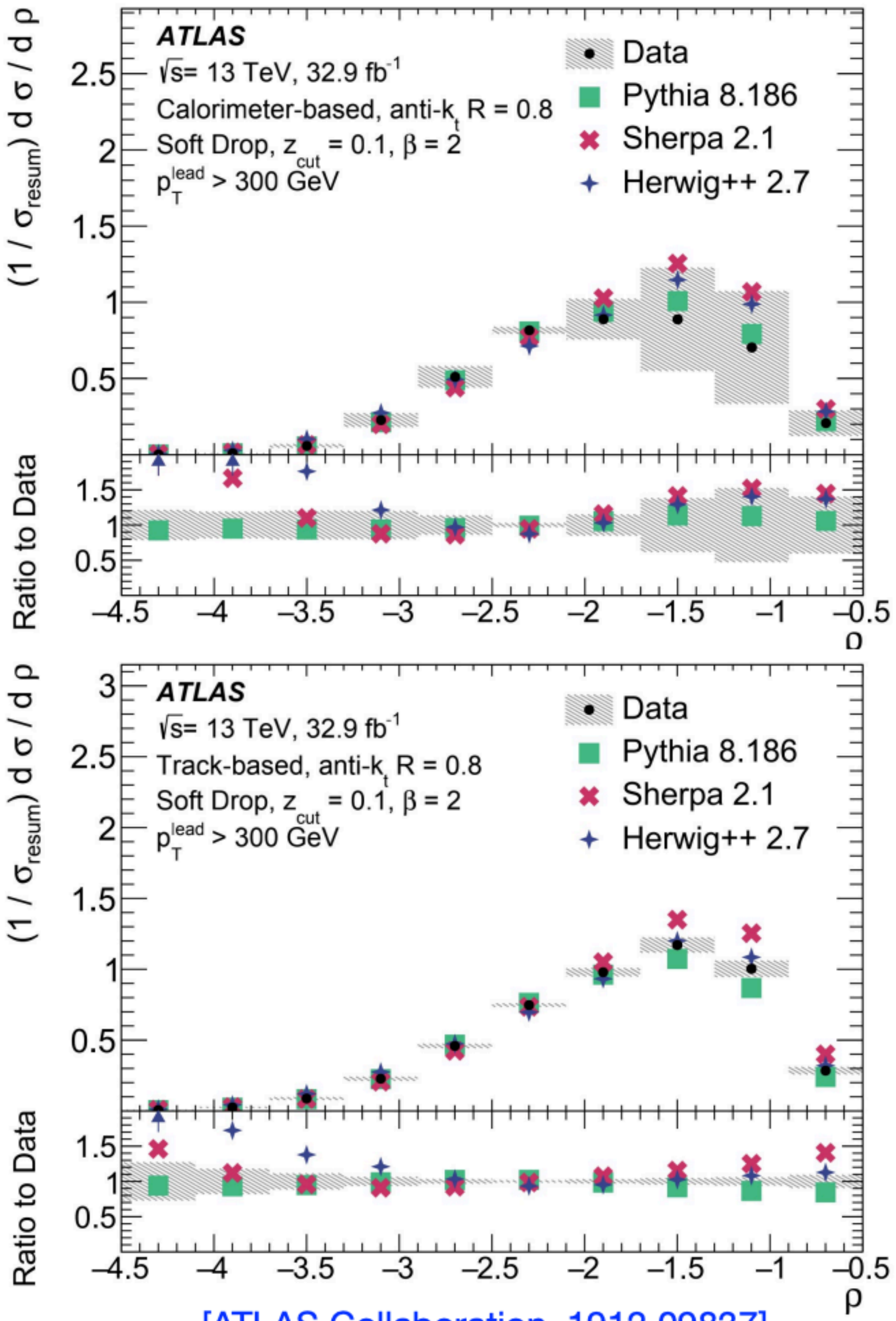


Hadronziation corrections from Pythia



Dependence on strong coupling constant

Extending to (energy-weighted) charge particle correlation



[ATLAS Collaboration, 1912.09837]

- So far we have been talking about energy correlation between all constituents in jet
- Experimentally it's more favorable to measure correlation between constituents with electric charge
- Strong motivation to develop first principle techniques for calculation of charge particle correlations

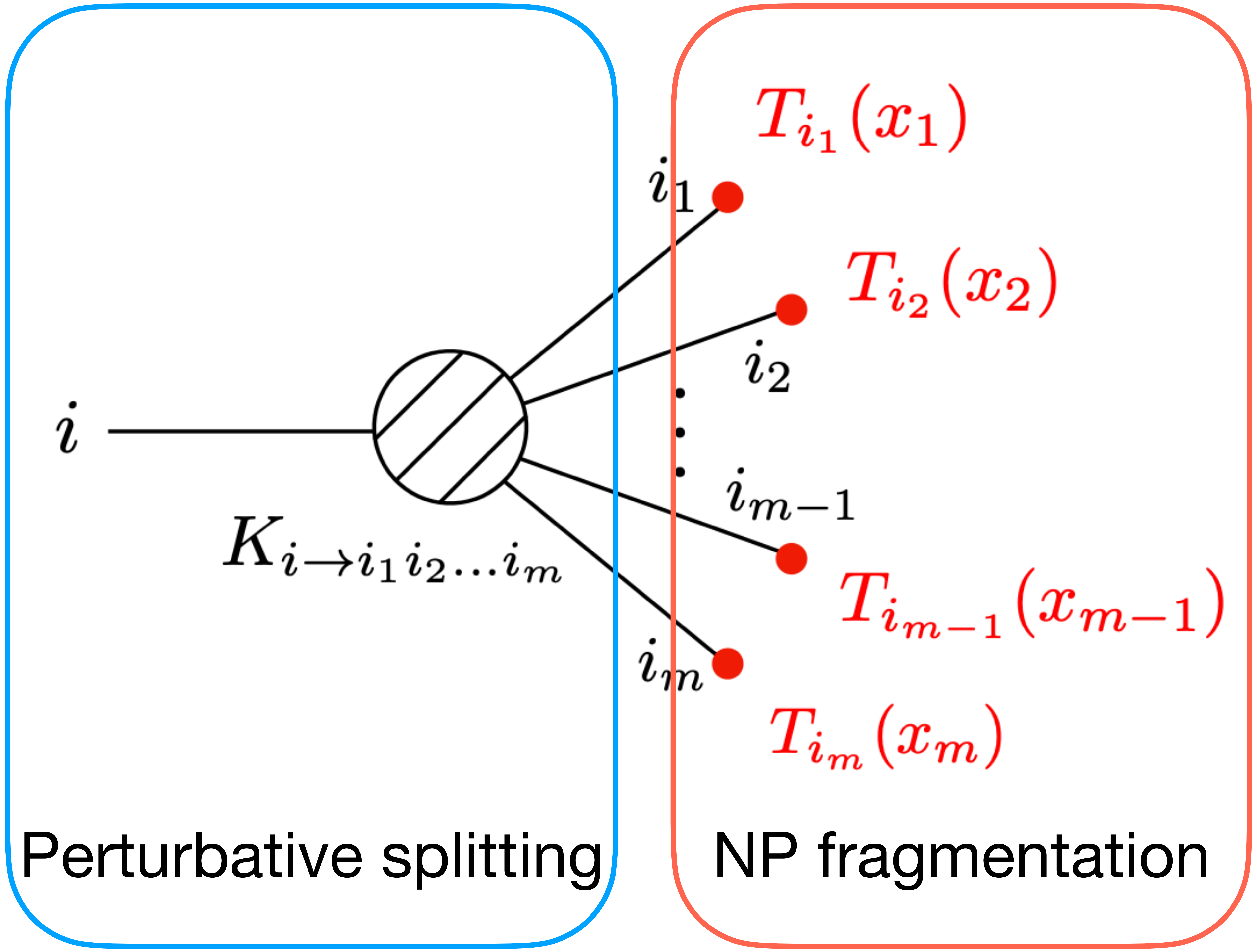
> These studies also enable a comparison of the sizes of the uncertainties for calorimeter-based and track-based observables. For all of these observables, the uncertainties for the track-based observables are significantly smaller than those for the calorimeter-based observables, particularly for higher values of β, where more soft radiation is included within the jet. However, since no track-based calculations exist at the present time, calorimeter-based measurements are still useful for precision QCD studies.

ATLAS, 1912.09837

> 0.4 and 0.8. For each quantity, we define a variant where the observables is calculated using only the charged constituents in anti-k_T algorithm ("charged"). While observables computed with both charged and neutral constituents can be described more easily from first-principle calculations, the charged variants can be measured with a better resolution as a result of the high efficiency and precision of the tracking detector.

CMS, 2109.03340

All-hadron v.s. charged hadron



- Energy correlation for all hadrons is IRC safe

- Correlation of particles with specific global charge requires NP fragmentation

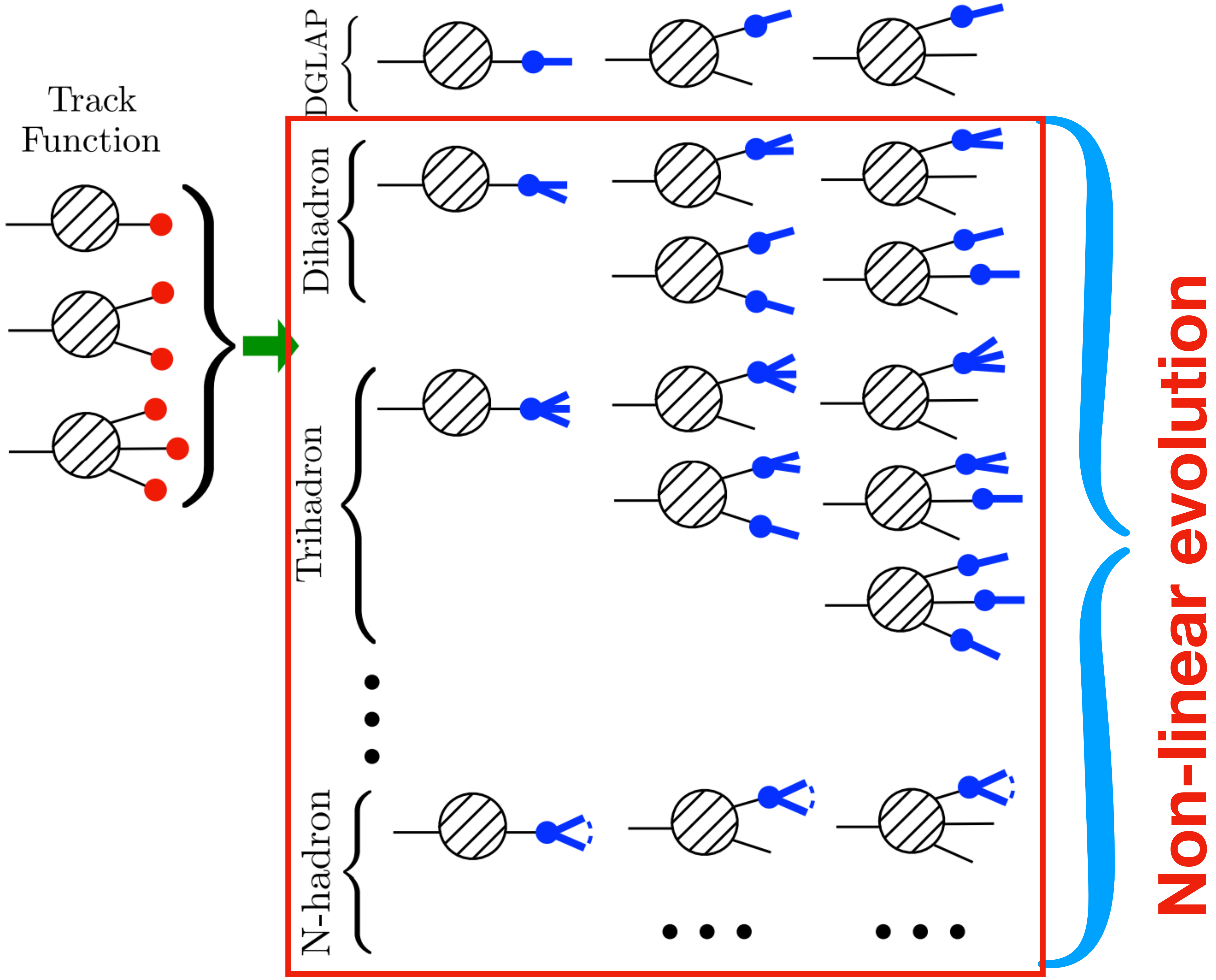
  Example: track function $T_i(x)$ describes parton fragmentation to charge particles with momentum frack x

  H.M. Chang, M. Procura, J. Thaler, W. Waalewijn, PRL111, 102002(2013)

- The NP fragmentation modifies of collinear evolution from the linear DGLAP to non-linear one

- Main missing ingredient for first principle precision calculation

Multi-collinear evolution kernel



H. Chen, et. al., 2210.10061, 2210.10058

Generic multi-collinear evolution equation

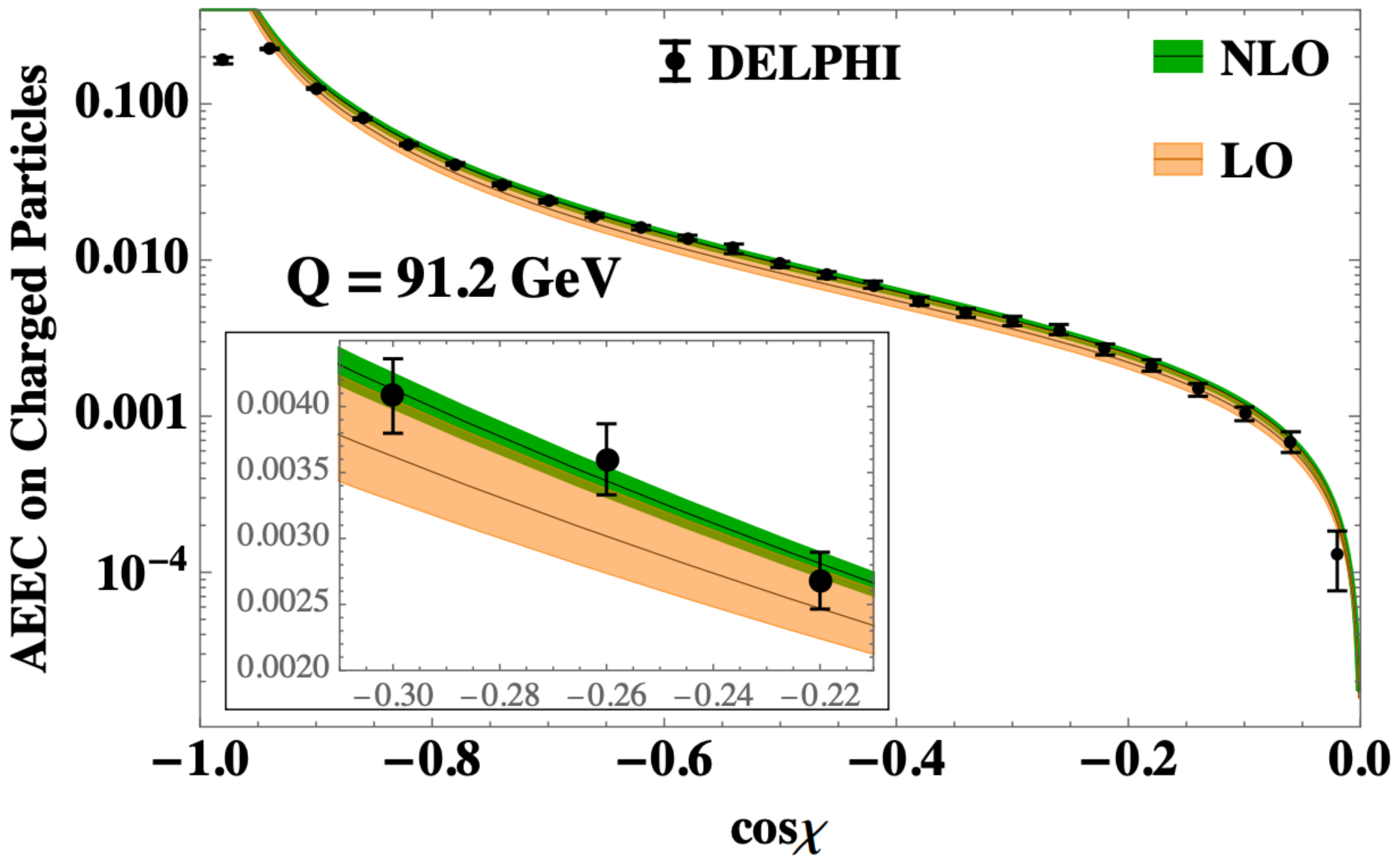
$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu^2}T_i(x) = a_s\Big[K^{(0)}_{i\to i}T_i(x) + K^{(0)}_{i\to i_1 i_2}\otimes T_{i_1}T_{i_2}(x)\Big] + a_s^2\Big[K^{(1)}_{i\to i}T_i(x) + K^{(1)}_{i\to i_1 i_2}\otimes T_{i_1}T_{i_2}(x) + K^{(1)}_{i\to i_1 i_2 i_3}\otimes T_{i_1}T_{i_2}T_{i_3}(x)\Big] + \mathcal{O}(a_s^3)\,,$$

Dihadron fragmentation evolution at NLO

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}\ln\mu^2}D_{i\to h_1 h_2}(y_1,y_2) = &\Big\{K_{i\to i}D_{i\to h_1 h_2}(y_1,y_2) + \sum_{\{i_f\}}K_{i\to i_1 i_2}\otimes[D_{i_1\to h_1 h_2} + D_{i_2\to h_1 h_2}] \\ &+ \sum_{\{i_f\}}K_{i\to i_1 i_2 i_3}\otimes[D_{i_1\to h_1 h_2} + D_{i_2\to h_1 h_2} + D_{i_3\to h_1 h_2}]\Big\} \\ &+ \Big\{\sum_{\{i_f\}}K_{i\to i_1 i_2}\otimes[D_{i_1\to h_1}D_{i_2\to h_2} + D_{i_1\to h_2}D_{i_2\to h_1}] \\ &+ \sum_{\{i_f\}}K_{i\to i_1 i_2 i_3}\otimes[D_{i_1\to h_1}D_{i_2\to h_2} + D_{i_1\to h_2}D_{i_2\to h_1} + D_{i_1\to h_1}D_{i_3\to h_2} \\ &+ D_{i_1\to h_2}D_{i_3\to h_1} + D_{i_2\to h_1}D_{i_3\to h_2} + D_{i_2\to h_2}D_{i_3\to h_1}]\Big\}.\end{aligned}$$

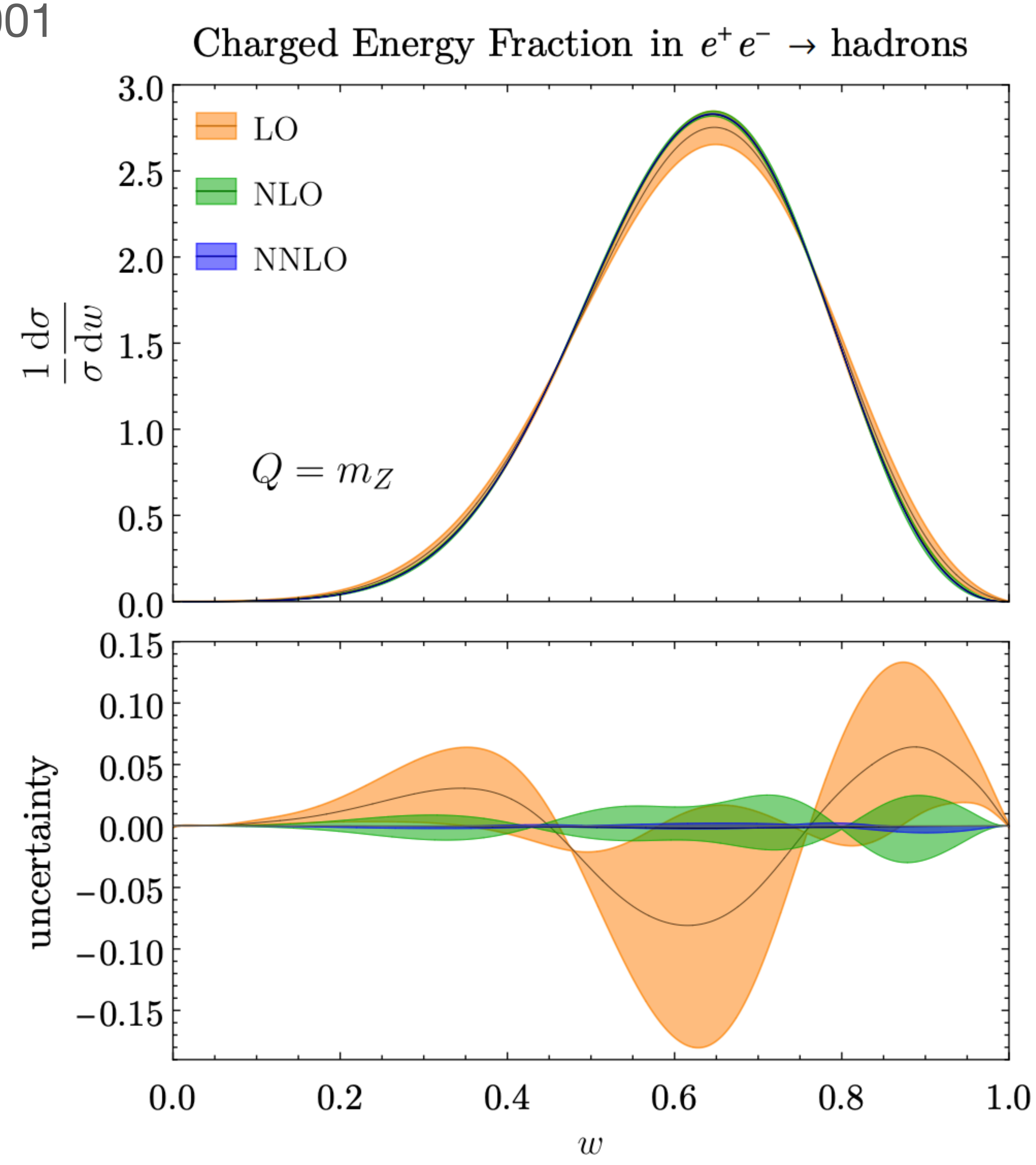
Prediction for track observables

Y.B. Li, I. Moult, van Velzen, W. Waalewijn, HXZ, PRL128 (2022) 18, 182001



Asymmetric EEC $\mathrm{EEC}(\chi) - \mathrm{EEC}(\pi - \chi)$

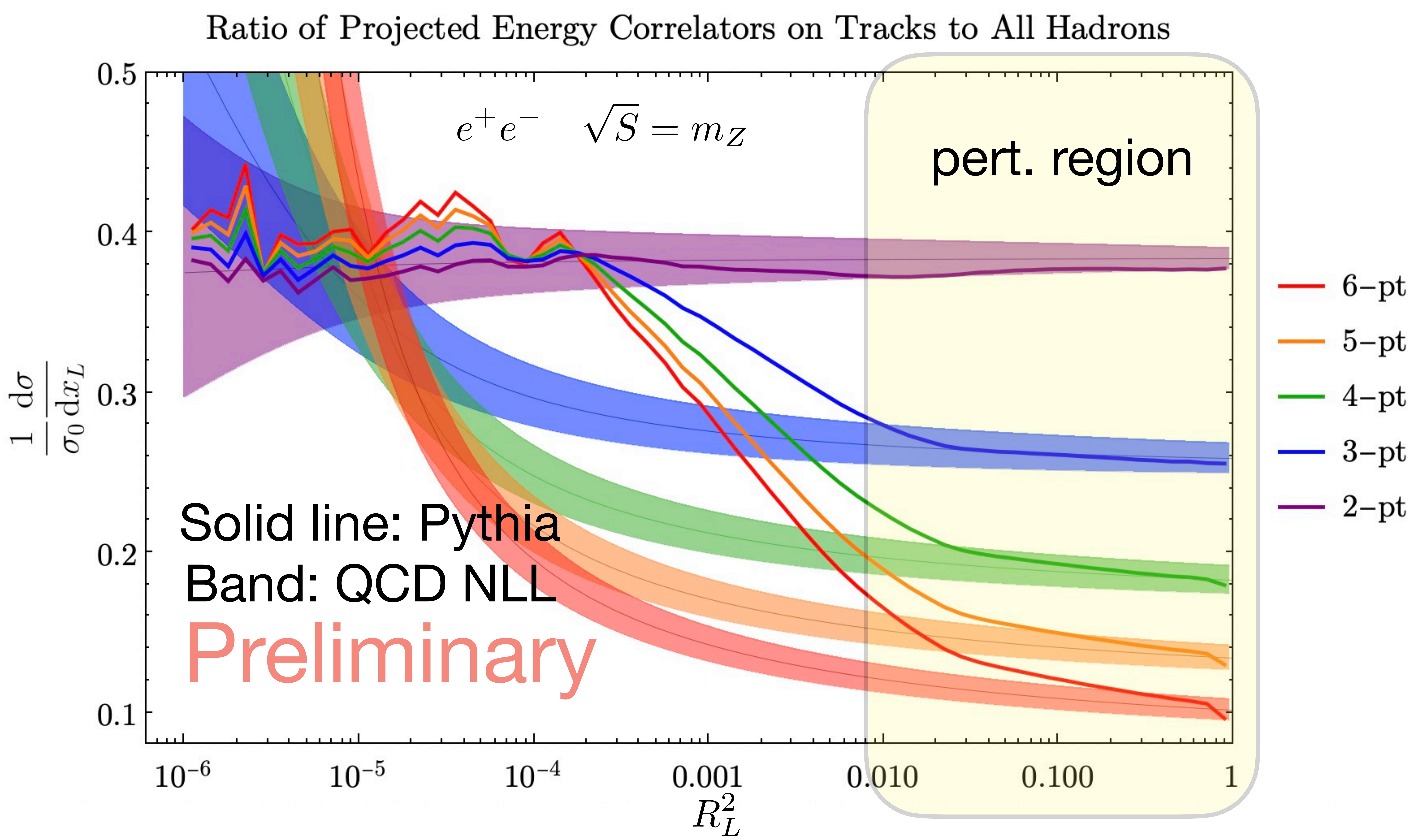
First NLO calculation for charged correlation observable!



H. Chen, et. al., 2210.10061

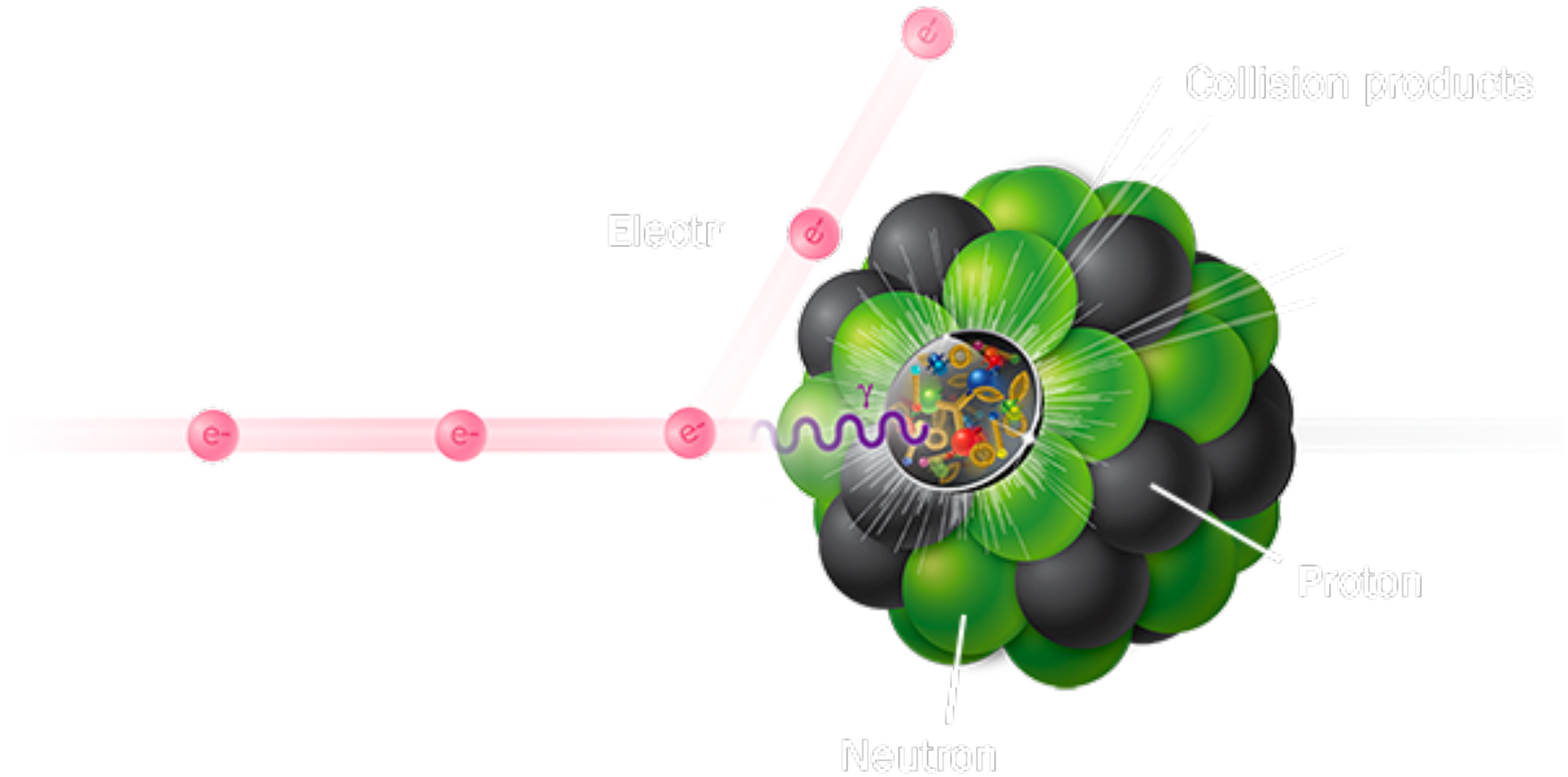
Precision test of the non-linear evolution

- Ratios of projected N point *track* EEC and EEC
- Ideal for probing the non-linearity of track evolution
- Non-linearity increase as N increase
- Good agreement with Pythia for small N, but visible disagreement at large N
- Signal of non-linear evolution? Stay tune!



M. Jaarsma, Y.B. Li, I. Moult, W. Waalewijn, HXZ, in progress

EIC and far forward physics



Detector	Acceptance	Notes
Zero-Degree Calorimeter (ZDC)	$\boldsymbol{\theta} < 5.5$ mrad ($\eta > 6$)	About 4.0 mrad at $\varphi \sim \pi$
Roman Pots (2 stations)	0.0* < $\boldsymbol{\theta}$ < 5.0 mrad ($\eta > 6$)	$0.65 < \frac{p_{z,nucleon}}{p_{z,beam}} < 1.0$ ***10σ cut/beam optics change lower cutoff**
Off-Momentum Detectors (OMD)	$0.0 < \boldsymbol{\theta} < 5.0$ mrad ($\eta > 6$)	Roughly $0.3 < \frac{p_{z,nucleon}}{p_{z,beam}} < 0.6$
B0 Sensors (4 layers, evenly spaced)	$5.5 < \boldsymbol{\theta} < 20.0$ mrad ($4.6 < \eta < 5.9$)	In flux: depends on pipe and electron quad.

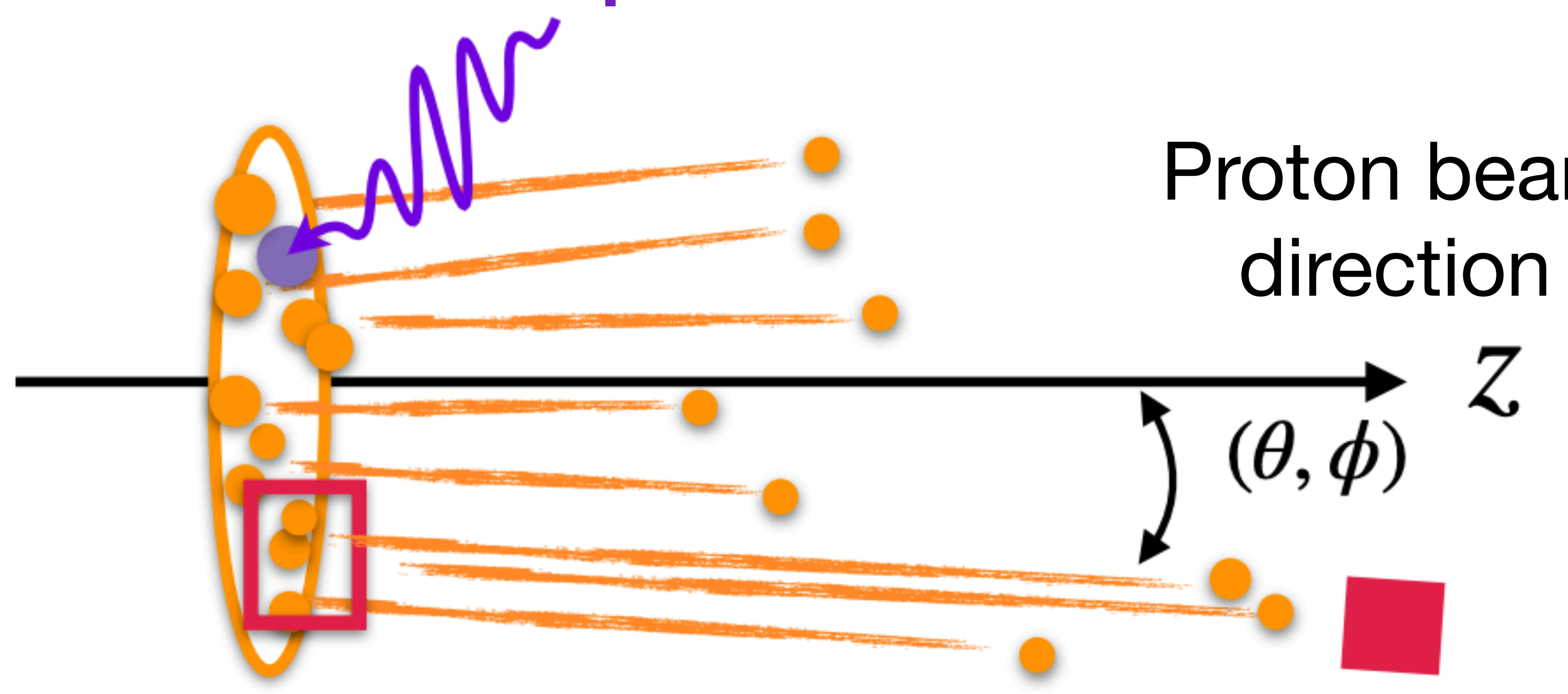
Alex Jentsch, EIC workshop 2021

- High luminosity: 10^{34} cm^{-2}/s
- Large range of energy: 29-140 GeV
- Polarized electron and light ion
- Large range of hadrons
- Large detector acceptance

- Forward detectors cover a lot of interesting QCD physics
  - Proton tagged Deep-Virtual-Compton-Scattering
  - Diffraction
  - Saturation
  - Required clean observable to probe these physics

The Nucleon EEC

X.H. Liu, HXZ, 2209.02080, PRL to appear



Energy weighted angular correlation of ISR with beam

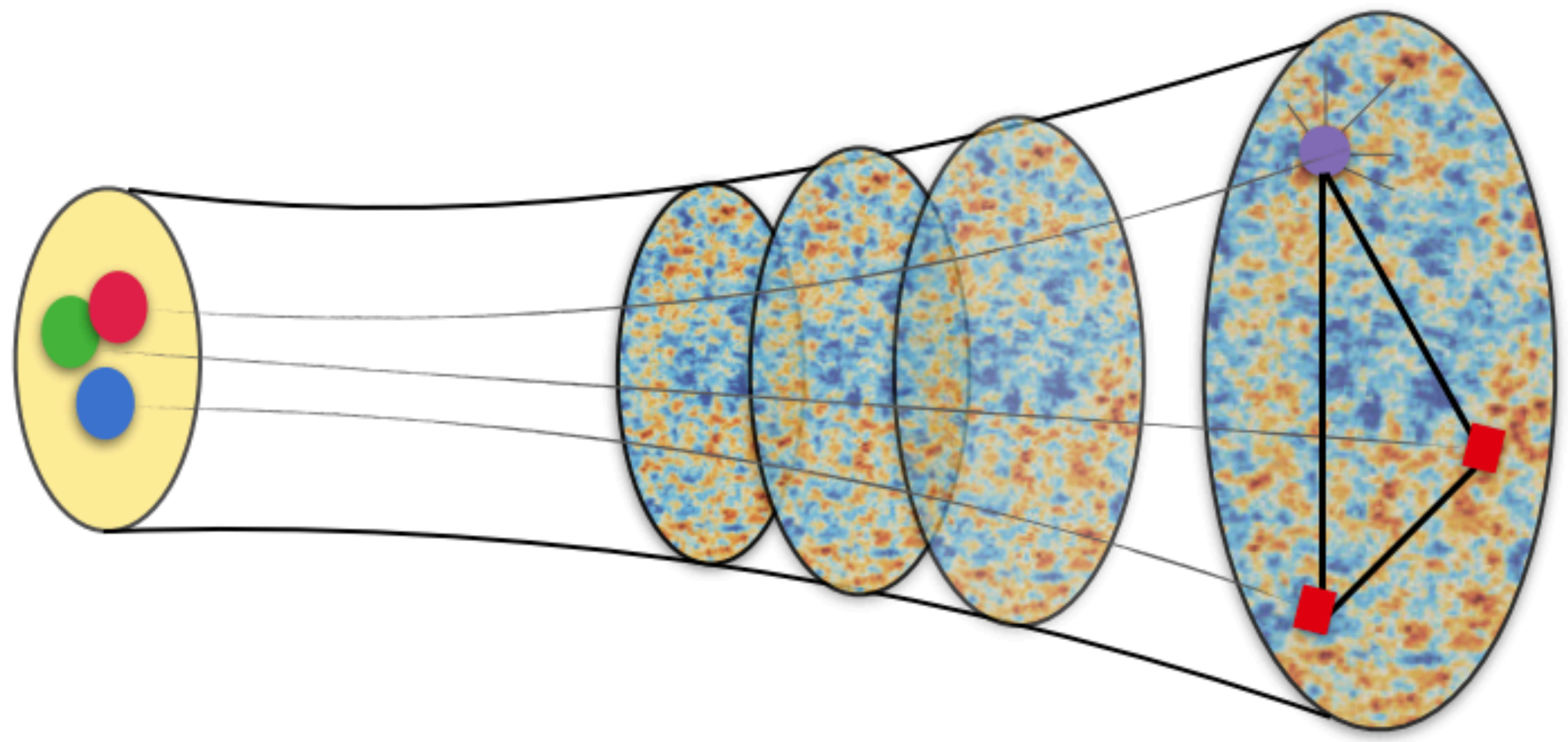
$$f_{q,\mathrm{EEC}}(N,\theta,\phi) = \int_0^1 z^{N-1} \int \frac{dy^-}{2\pi} e^{-izP^+y^-} \left\langle P \left| \bar{\chi}_n(y^-) \frac{\gamma^+}{2} \frac{2\mathcal{E}(\theta,\phi)}{P^+} \chi_n(0) \right| P \right\rangle ,$$
$$f_{g,\mathrm{EEC}}(N,\theta,\phi) = -\int_0^1 z^{N-1} \int \frac{dy^-}{2\pi z P^+} e^{-izP^+y^-} \left\langle P \left| \bar{n}\cdot\mathcal{G}_\perp(y^-) \frac{2\mathcal{E}(\theta,\phi)}{P^+} \bar{n}\cdot\mathcal{G}_\perp(0) \right| P \right\rangle ,$$

Factorization onto collinear PDFs

$$f^i_{EEC}(N,\theta^2,\mu) = I_{ij}(N,\theta^2,\mu) f_{j/P}(N+1,\mu)$$

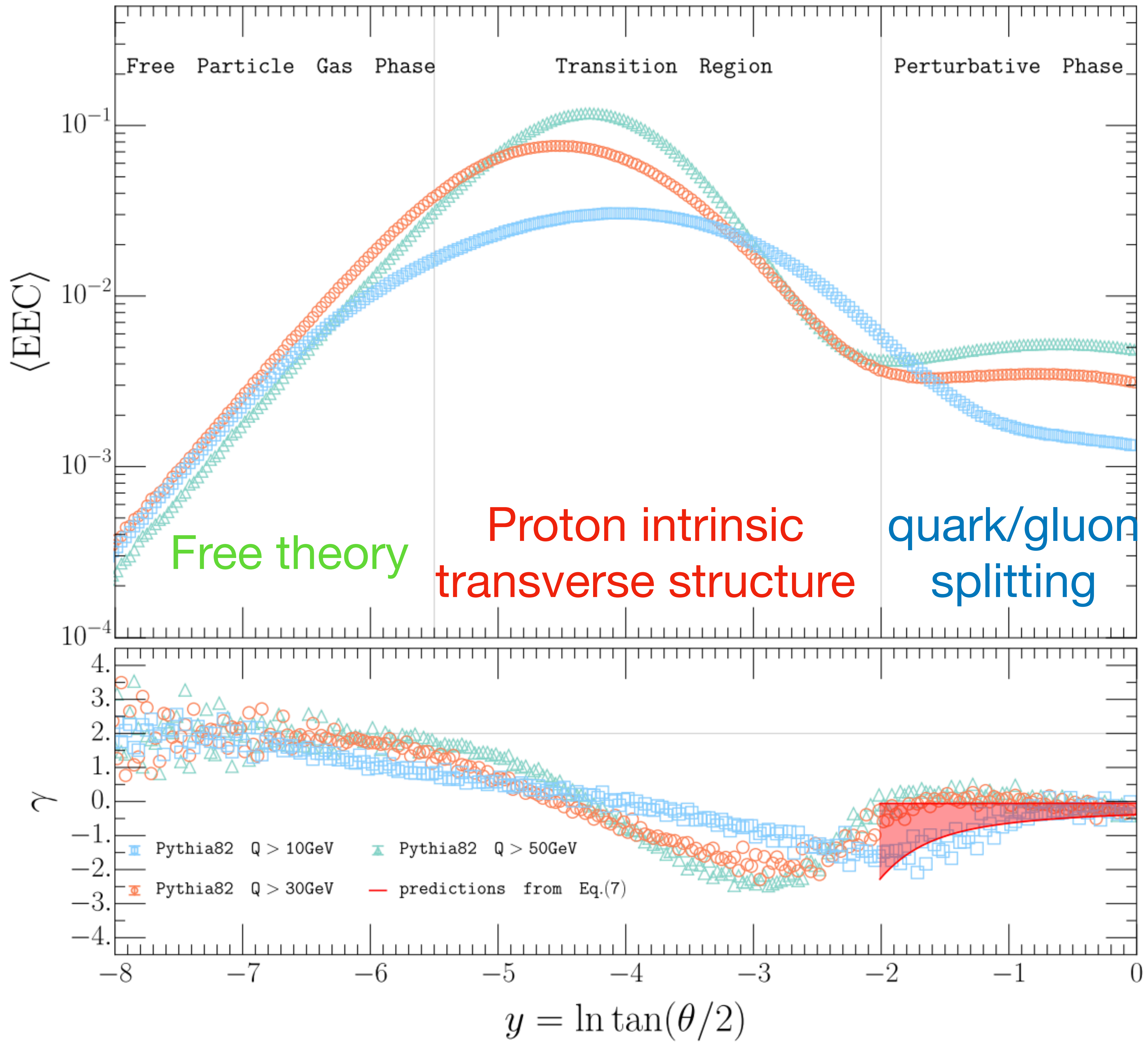
DGLAP type evolution equation for the matching coefficient

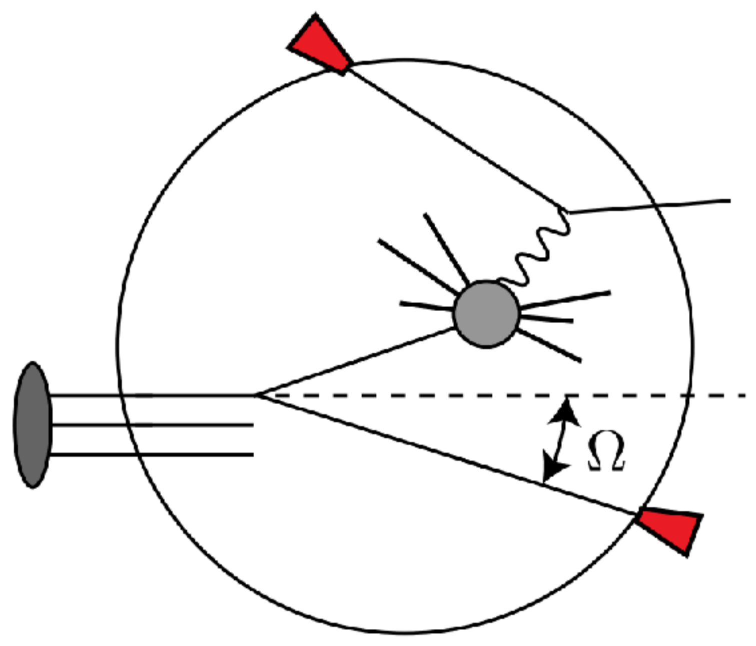
$$\frac{dI_{ij}(N,\theta^2,\mu)}{d\ln\mu^2} = \gamma^N_{ik} I_{kj} - I_{ik}\gamma^{N+1}_{kj}$$

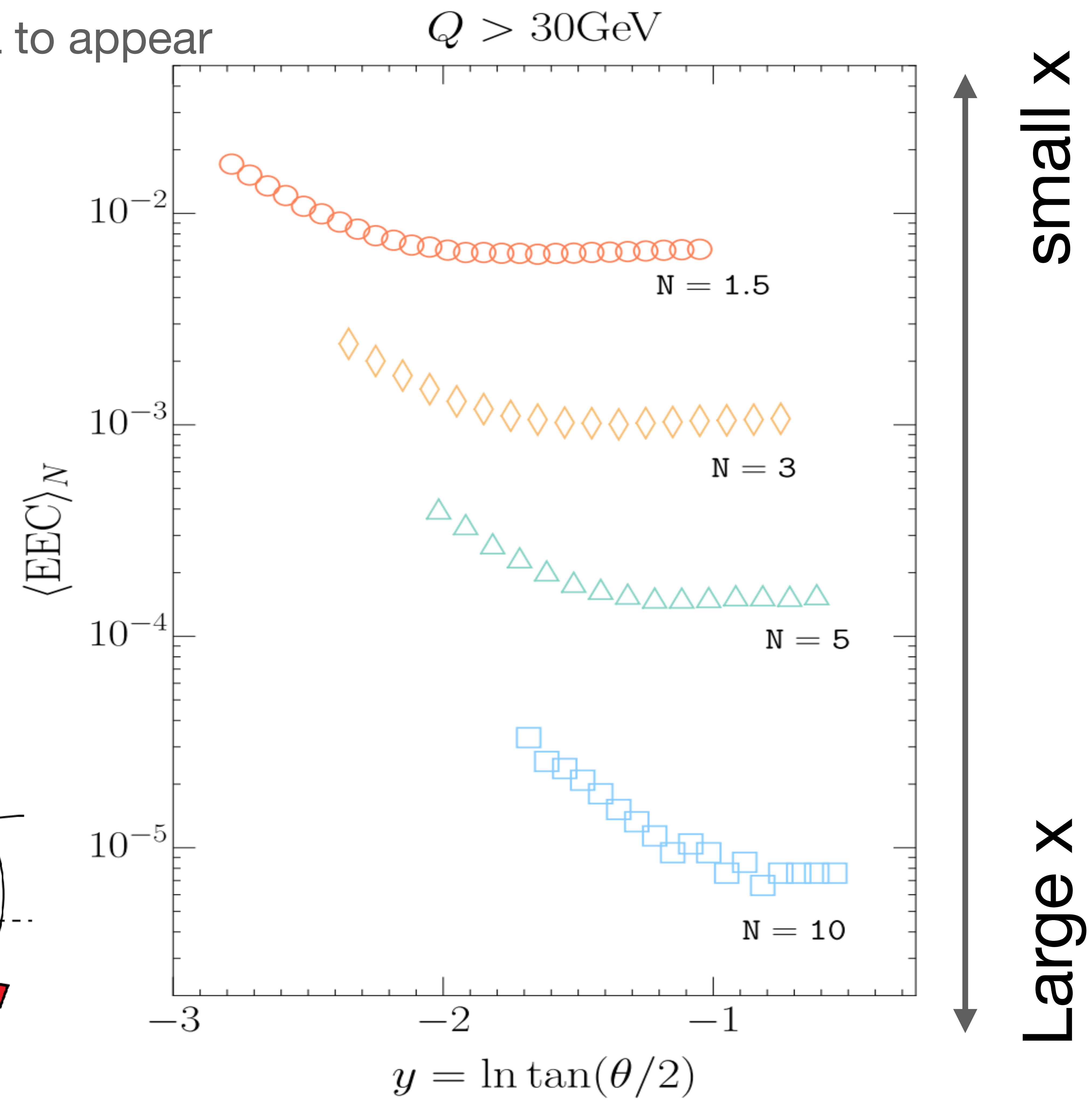


A new window to proton structure

X.H. Liu, HXZ, 2209.02080, PRL to appear







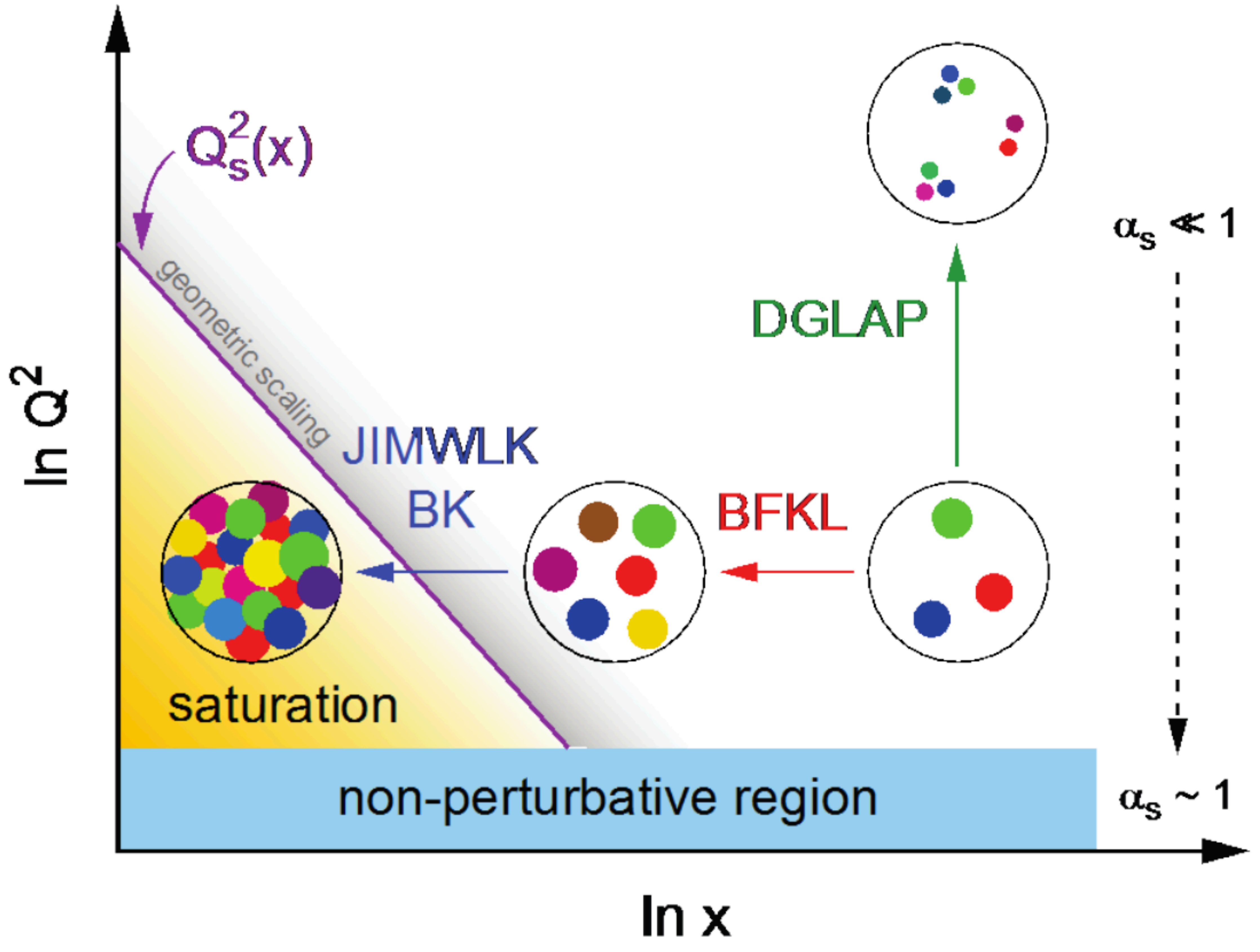
Clean separation of regions!

N is the mellin moment of Bjorken x

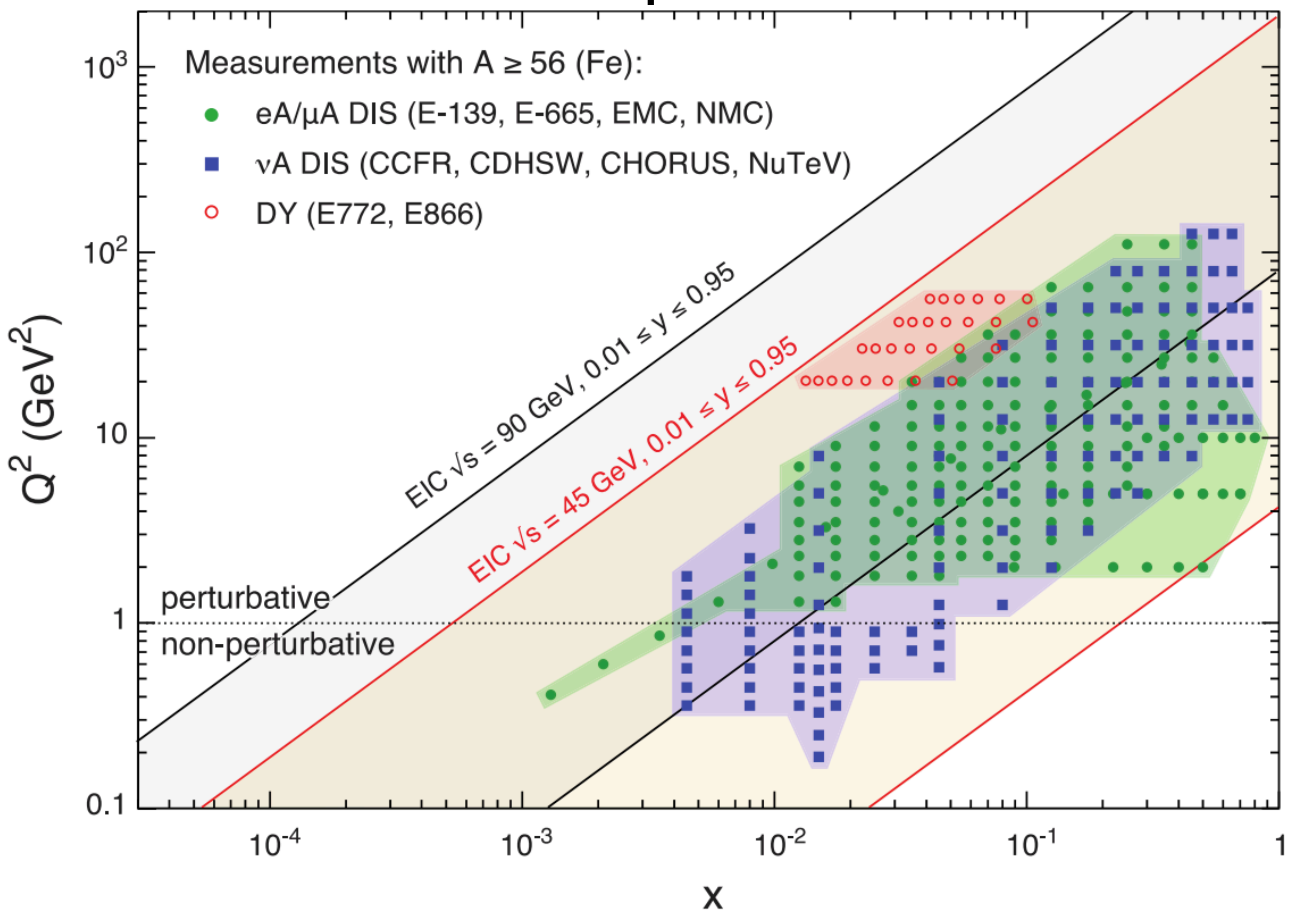
Large phase space at small x

Picture of QCD evolution

EIC yellow book, 1212.1701



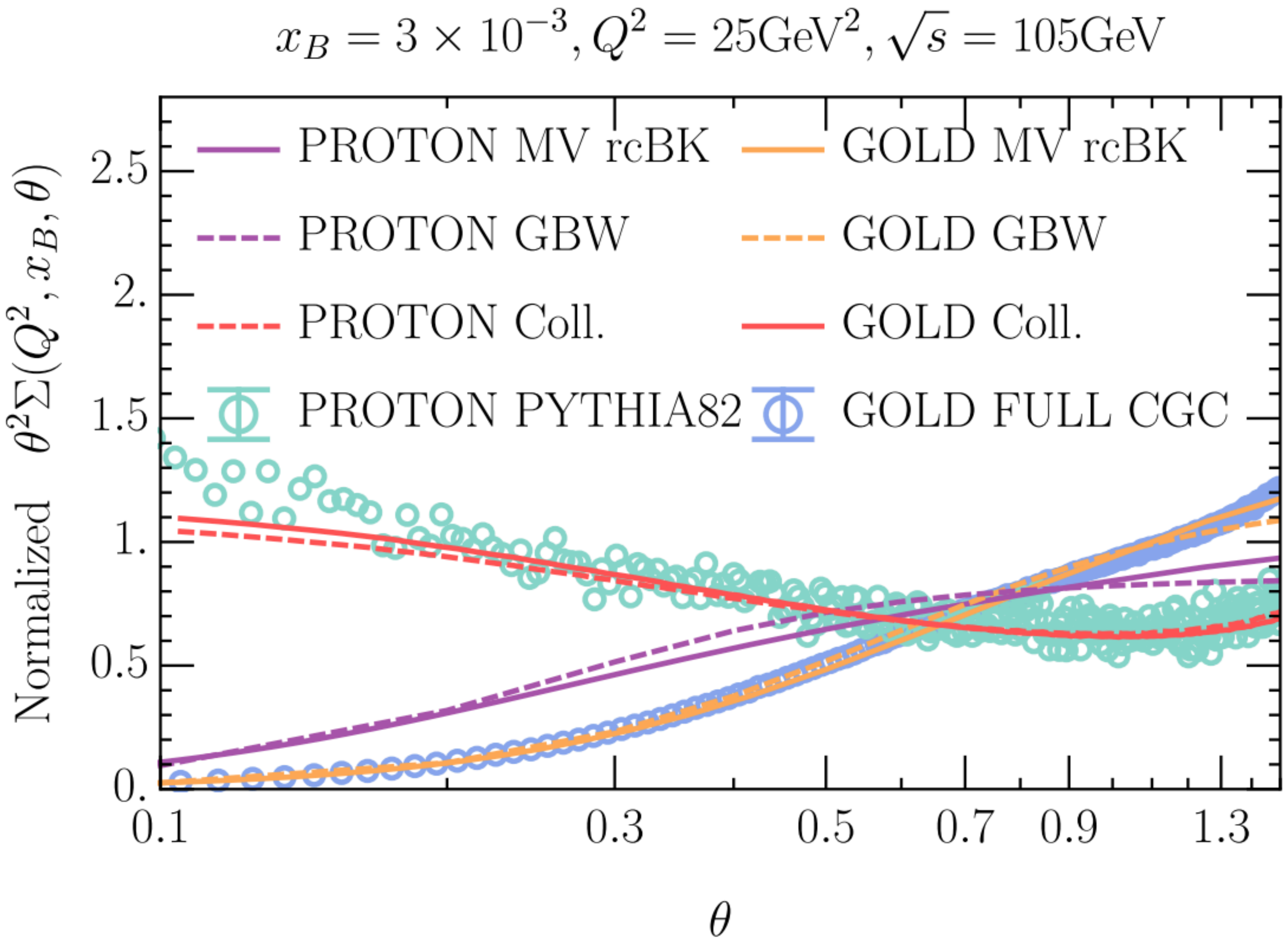
EIC potential



Discovering gluon saturation effects is one of the main goal at EIC

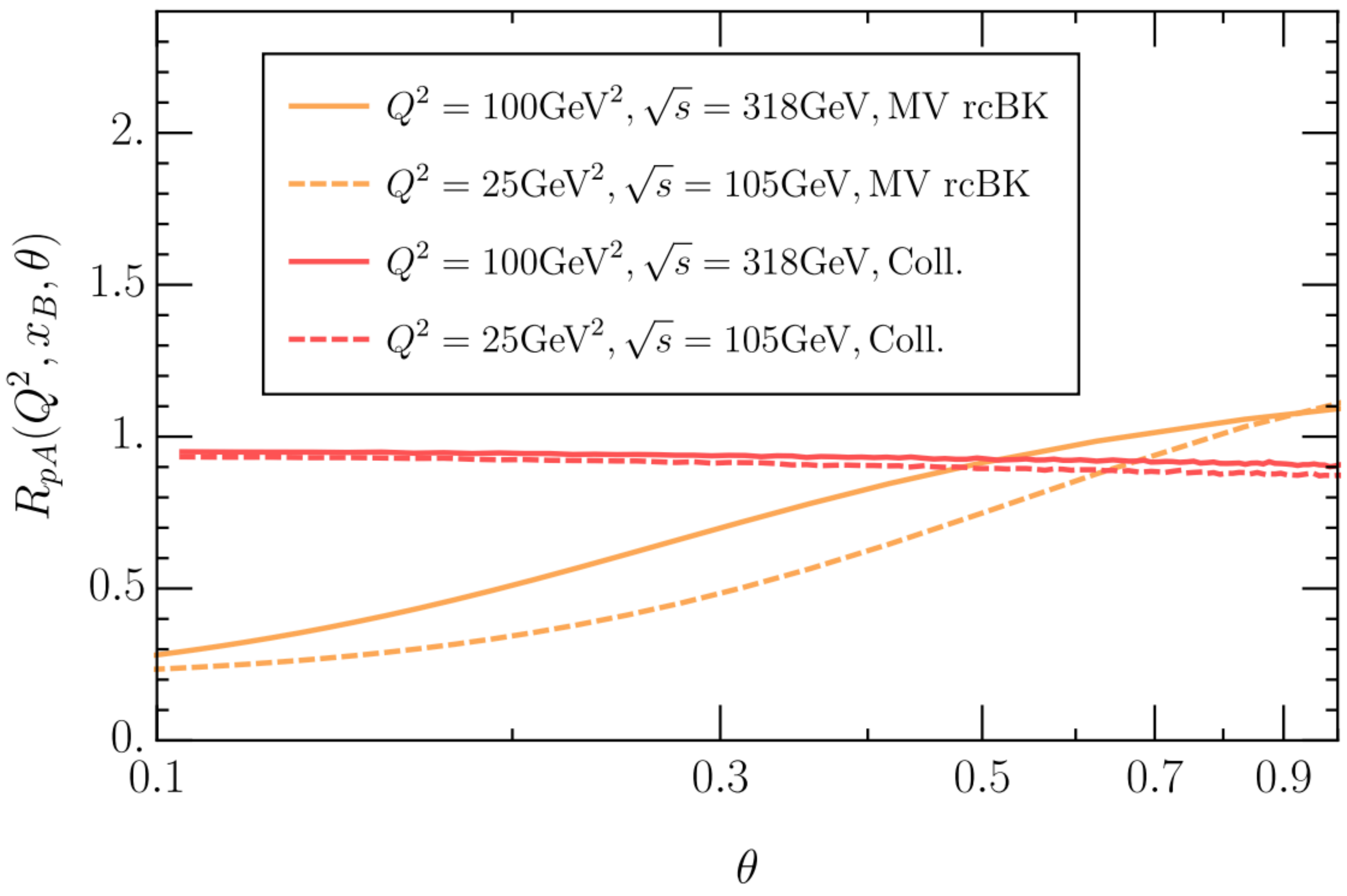
Small-x and saturation

H.Y. Liu, X.H. Liu, P.J. Chen, F. Yuan, HXZ, 2301.01788



Gluon saturation leads to modification of θ scaling. Easy to distinguish from DGLAP scaling

Ration of nucleon EEC between (nuclei and proton)



Saturation scale increase with large nuclei. Modification factor (nuclei/proton) give clean probe of the onset of saturation

Summary

- Multi-point energy correlators open a new window to probe QCD dynamics at high energy
  - Visualizing the phase transtion quark/gluon to hadrons
  - Precision calculation and α_s extraction
  - Incorporating tracks
  - Probing nuclear structure and gluon saturation
- Not covered: gluon spin interference in jet, top quark mass, dead cone effect, probing QGP, …
- Exciting to compare with upcoming experiments