EEC with Jets in back to back region

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Based on the work with Zhi-Hong He, Ding Yu Shao in preparation

"New Opportunities in Particle and Nuclear Physics with Energy Correlators”

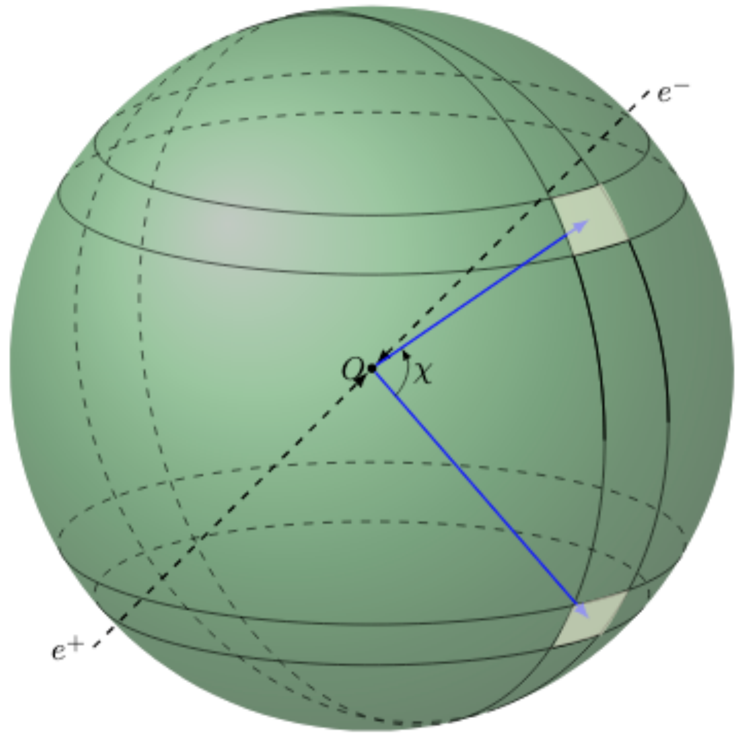
C3N, CCNU, May 6th to May 17th, 2025

Outline

- Introduction (EEC in back to back limit)
- EEC with jets
- EEC with groomed jets
- Summary

Introduction

e^+e^- Collisions



Hadronic initial state

observable

$$\text{EEC} = \sum_{a,b} \int d\sigma_{V\to a+b+X} \frac{2E_a E_b}{Q^2 \sigma_{\text{tot}}} \delta(\cos(\theta_{ab}) - \cos(\chi))$$

$$\text{TEEC} = \sum_{a,b} \int d\sigma_{pp\to a+b+X} \frac{2E_{T,a} E_{T,b}}{|\sum_i E_{T,i}|^2} \delta(\cos\phi_{ab} - \cos\phi)$$

- sum over all the jets for each event
- sum over all the particles for each event

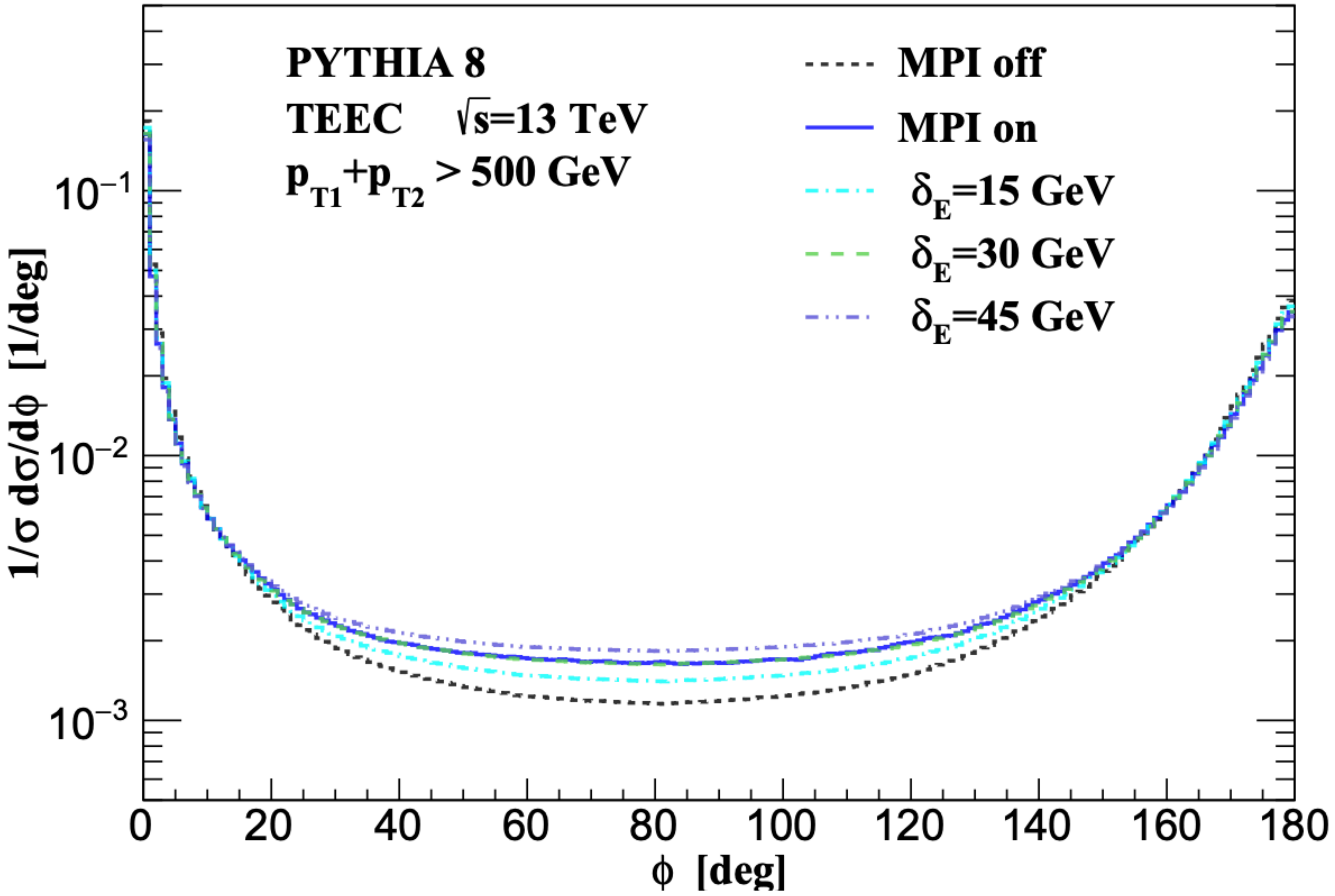
- weighted cross section
- the soft radiation does not contribute directly to the observable at leading power
- soft gluon contributes only via recoil

Basham et al 1978
Moult, Zhu, 2018

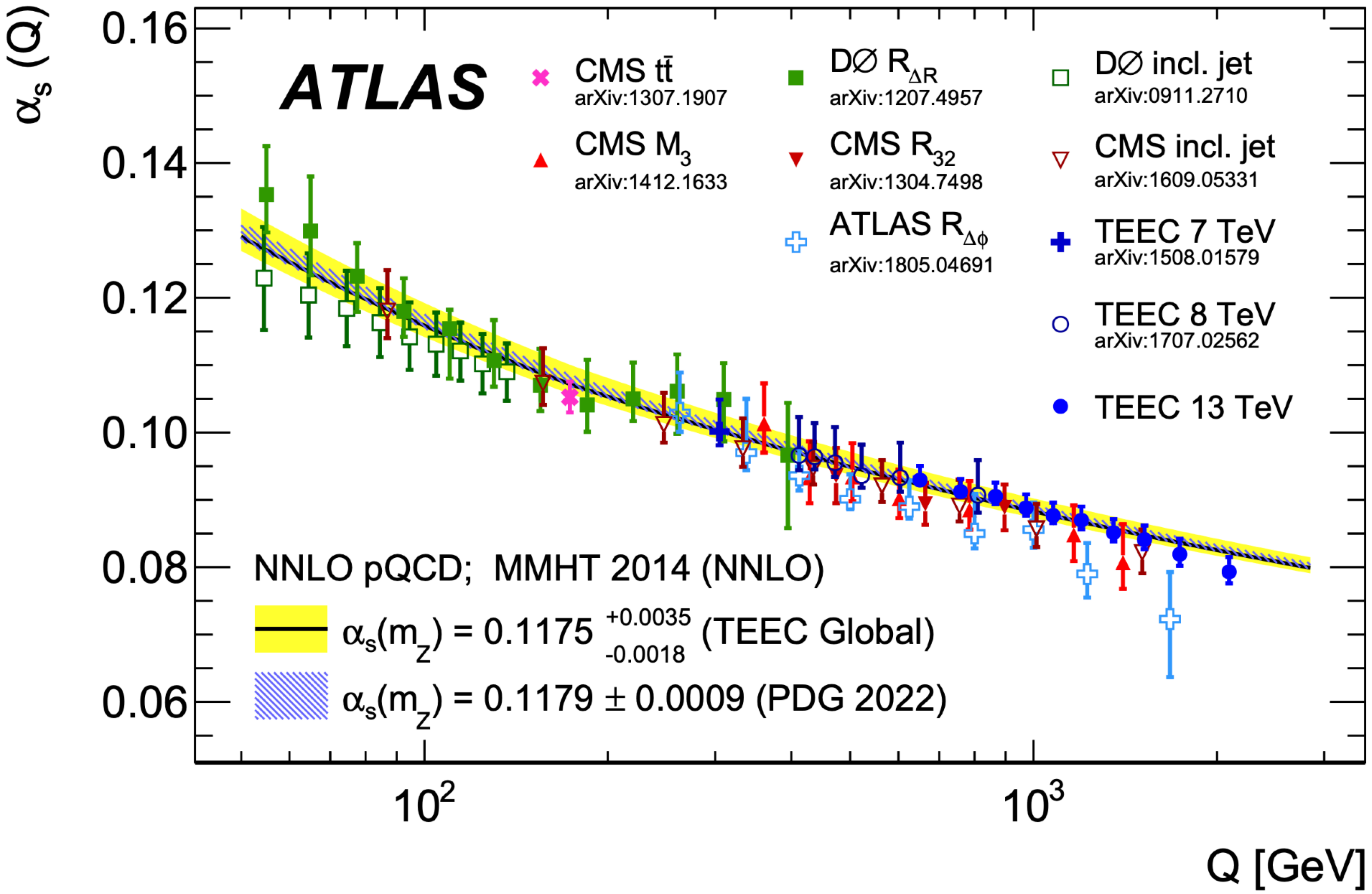
Ali et al 1984
Gao, HTL, Moult, Zhu, PRL, 2019 & JHEP

Introduction

TEEC in pp

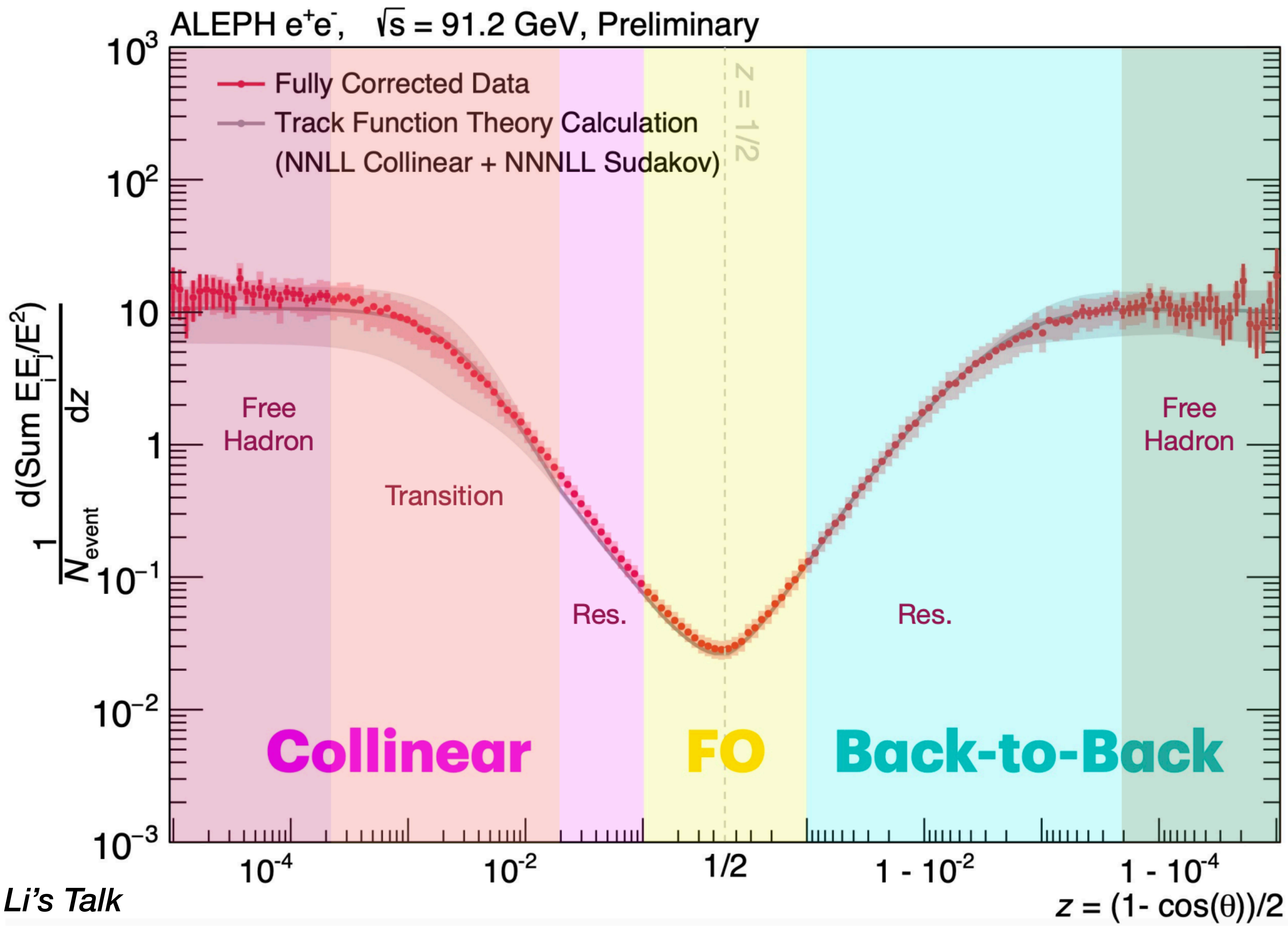


Gao, HTL, Moult, Zhu, PRL, 19 & JHEP 24



ATLAS, 2023

Introduction



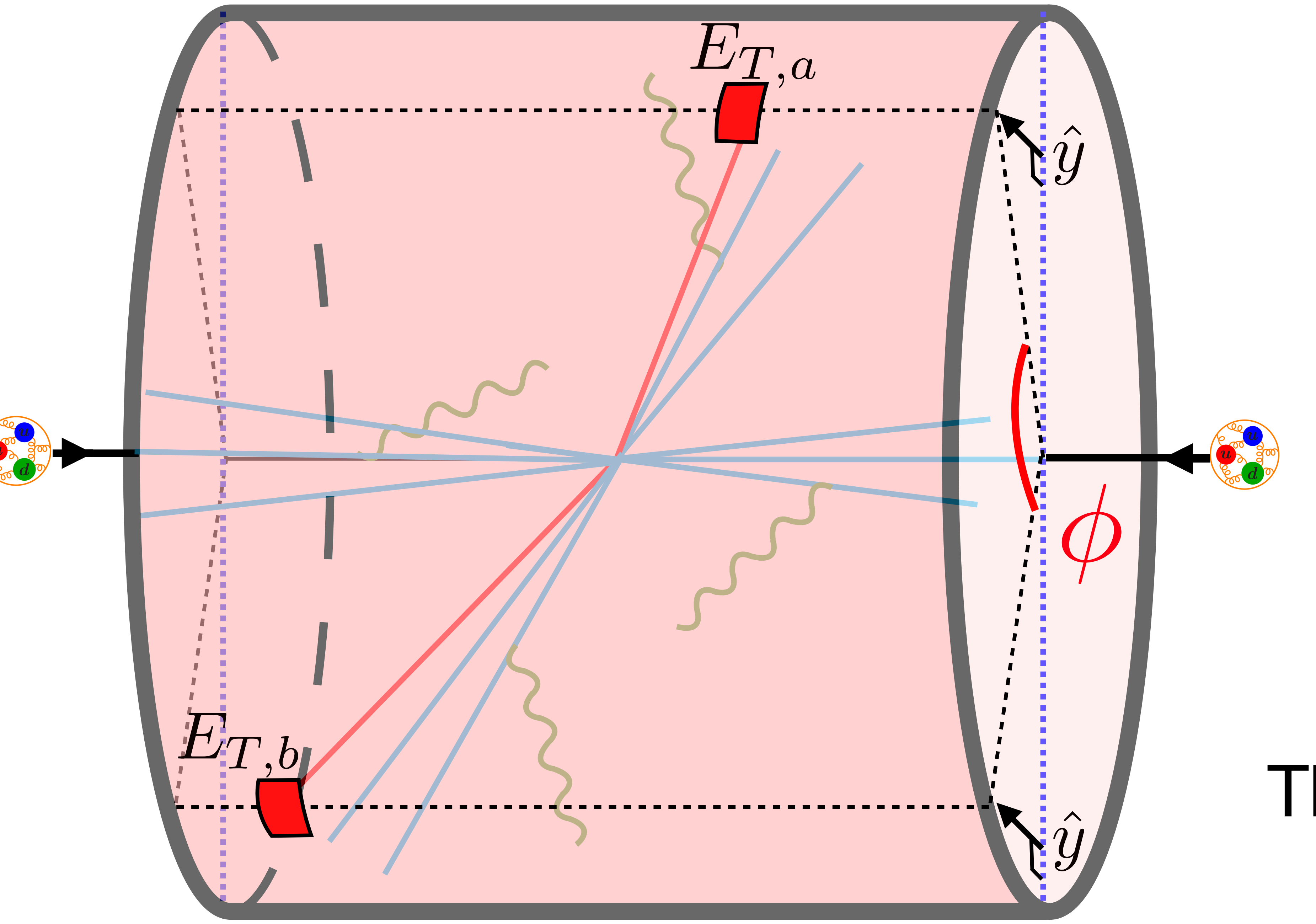
from Yebei Li's Talk

Introduction

In the back to back limit

$$h_1 + h_2 \to J_1 + J_2 + x$$

$$n_1 = (1,0,0,1), n_2 = (1,0,0,-1) \quad n_3 = (1, \sin\theta, 0, \cos\theta), n_4 = (1, -\sin\theta, 0, -\cos\theta)$$



$$\frac{1+\cos\phi}{2} = \frac{\left(\frac{k_{3,y}}{\xi_3} + \frac{k_{4,y}}{\xi_4} + k_{1,y} + k_{2,y} - k_{s,y}\right)^2}{4P_T^2} + \dots$$

The factorization formula in the back-to-back limit is

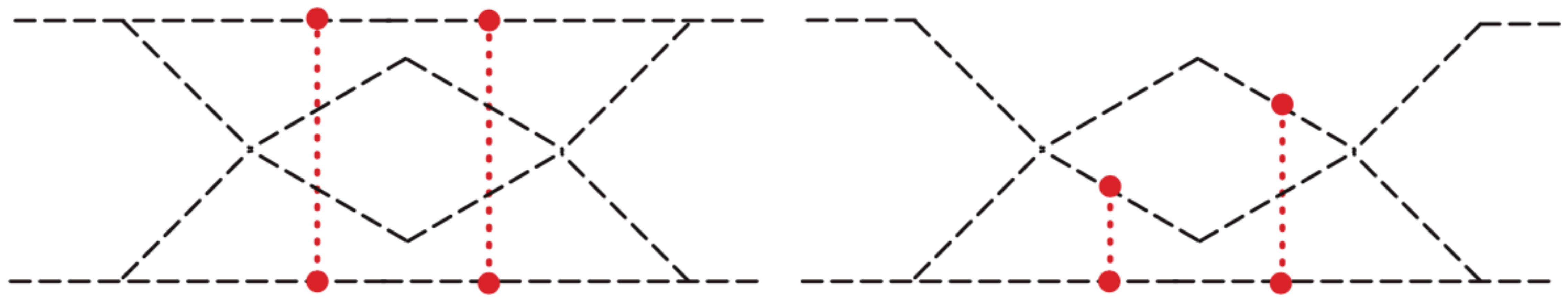
$$\frac{d\sigma^{(0)}}{d\tau} = \frac{p_T}{16\pi s^2(1+\delta_{f_3 f_4})\sqrt{\tau}} \sum_{\text{channels}} \frac{1}{N_{\text{init}}} \int \frac{dy_3 dy_4 dp_T^2}{\xi_1 \xi_2} \int_{-\infty}^{\infty} \frac{db}{2\pi} e^{-2ib\sqrt{\tau}p_T} \text{tr}\big[\mathbf{H}^{f_1 f_2 \to f_3 f_4}(p_T, y^*, \mu)\mathbf{S}(b, y^*, \mu, \nu)$$
$$\cdot B_{f_1/N_1}(b,\, \xi_1,\, \mu,\, \nu)\, B_{f_2/N_2}(b,\, \xi_2,\, \mu,\, \nu) J_{f_3}(b, \mu, \nu)\, J_{f_4}(b, \mu, \nu)\,.$$

The azimuthal angle distribution

$$1 + \cos(\phi) \approx 2\tau$$

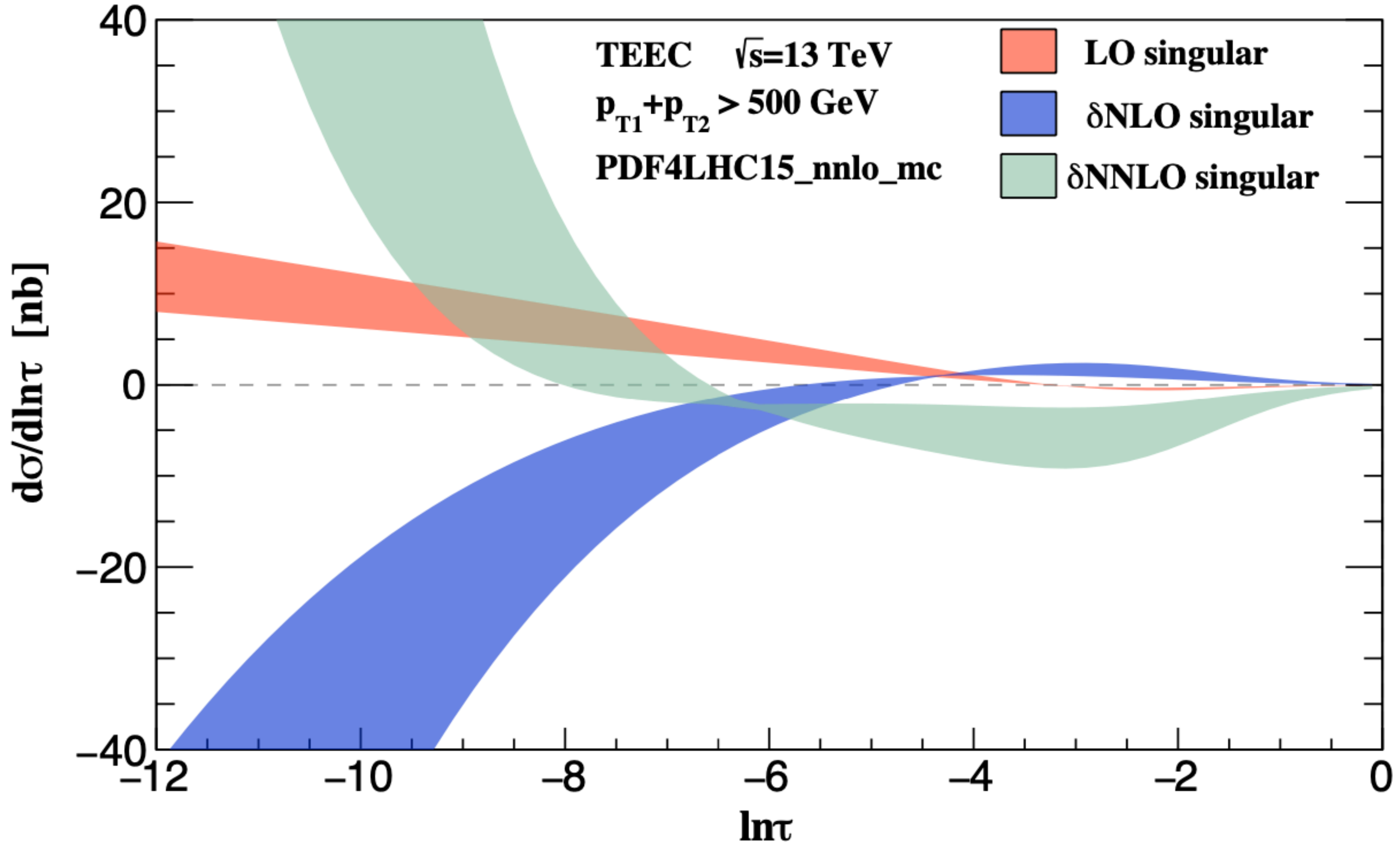
Introduction

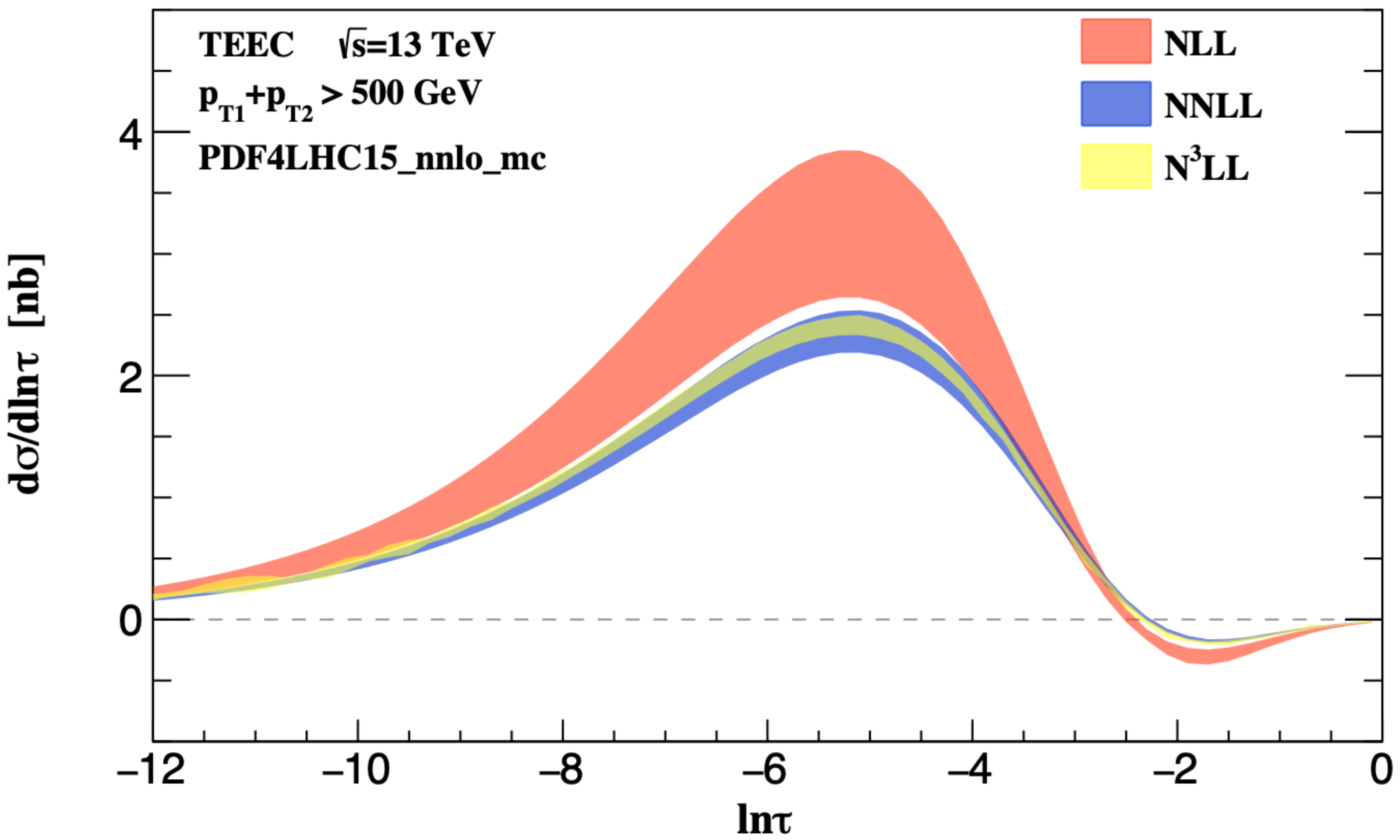
$$\mathscr{L}^{(0)} = \mathscr{L}^{(0)}_{B_1} + \mathscr{L}^{(0)}_{B_2} + \mathscr{L}^{(0)}_{J_1} + \mathscr{L}^{(0)}_{J_2} + \boxed{\mathscr{L}^{(0)}_{G}}$$



in pp collisions

- ❏ Such as violation in collinear factorization
- ❏ Whether rapidity factorization is still valid
- ❏ RG invariance of the cross section



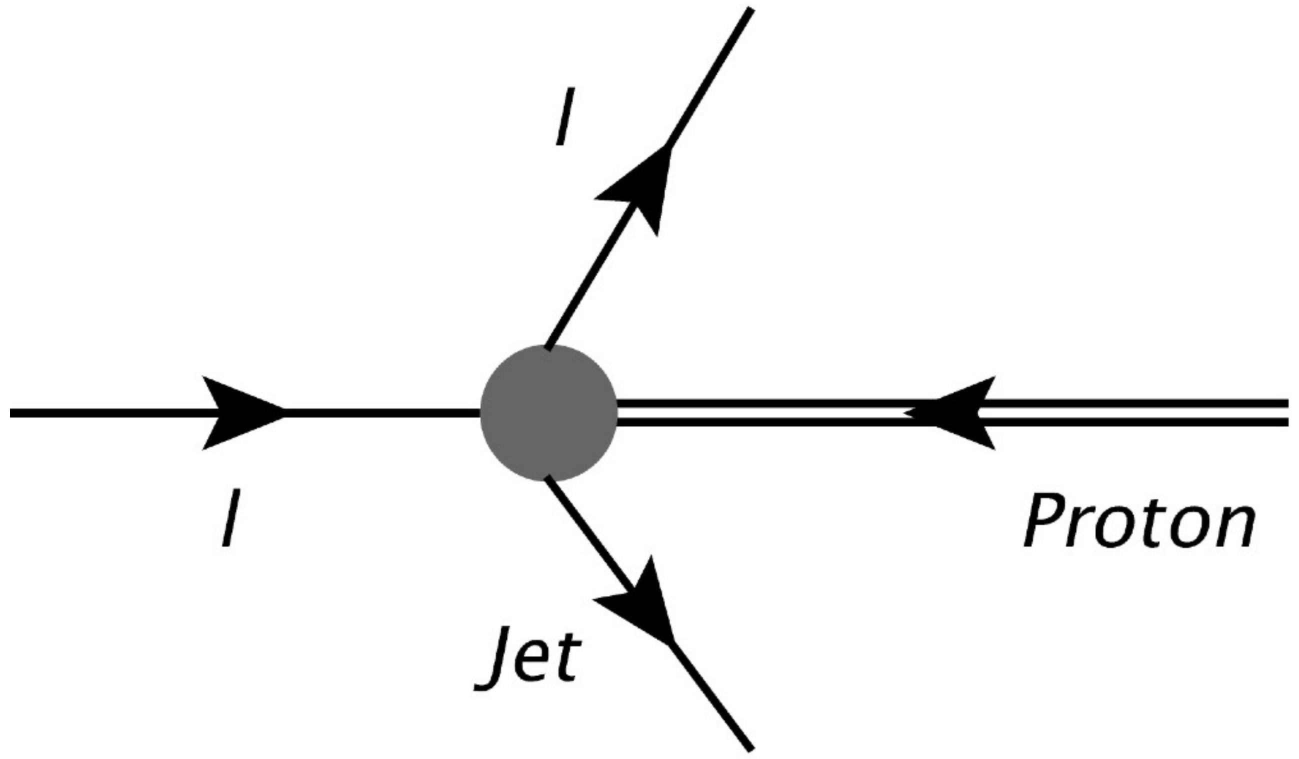


NNNLL accuracy for a hadron collider diet event shape for the first time.

Gao, HTL, Moult, Zhu, PRL, 19 & JHEP 24

Introduction

TEEC in DIS



Definition

$$\text{TEEC} = \sum_{a} \int d\sigma_{lp\to l+a+X} \frac{E_{T,l}E_{T,a}}{E_{T,l}\sum_i E_{T,i}} \delta(\cos\phi_{la} - \cos\phi)$$

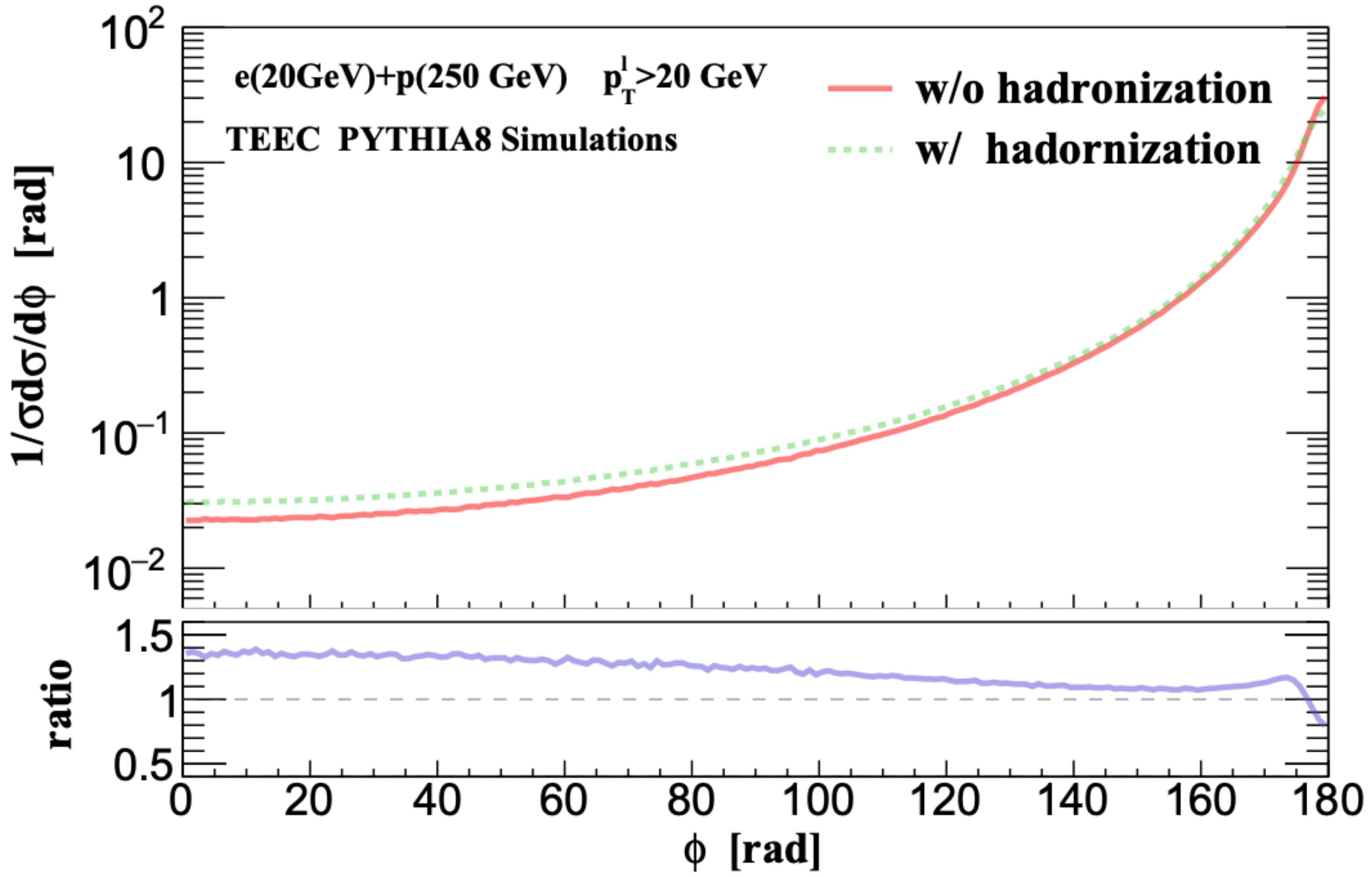
sum over all hadrons

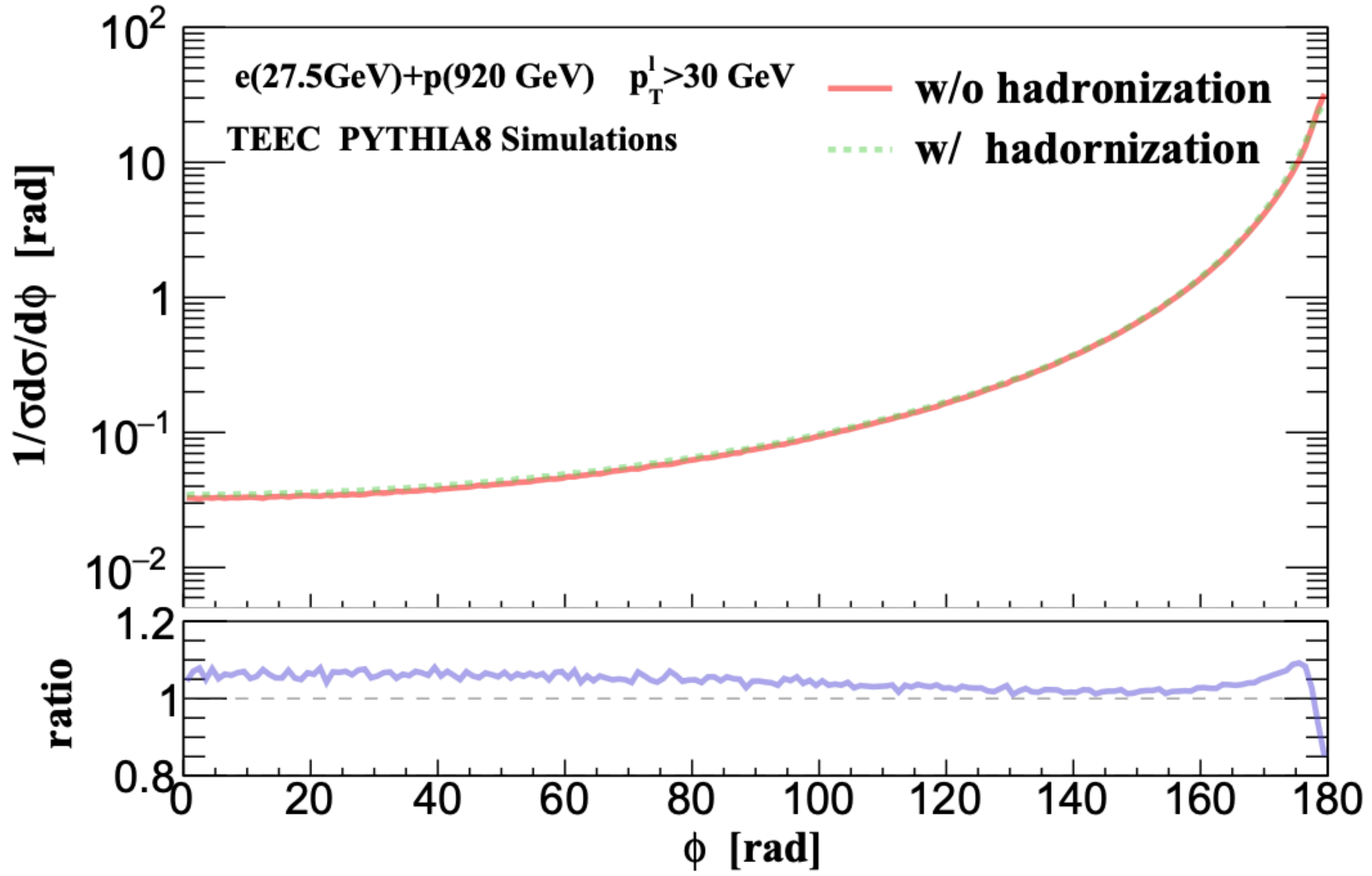
energy weighted

measure azimuthal angle correlations

Simulation by Pythia

HTL, Vitev, Zhu, JHEP, 20



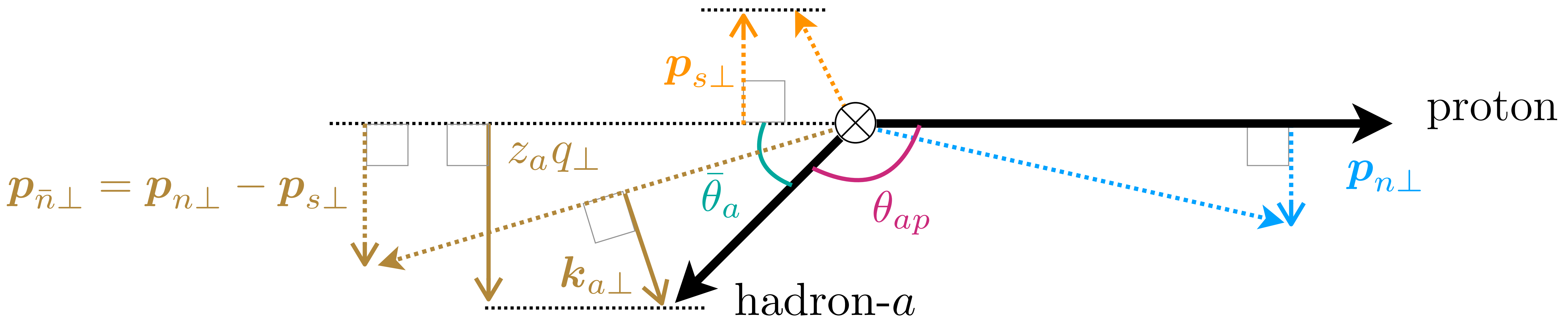


Introduction

EEC in DIS

In Breit Frame.

proton + γ^* → jet/hadron + X



We proposed a new definition of EEC in DIS:
correlation between initial proton and final state hadron

In the back to back limit

$$\mathrm{EEC} = \sum_a \int d\sigma_{lp\to l+a+X} \left(\frac{p\cdot p_a}{\sum_i p\cdot p_i}\right) \delta(\cos\chi - \cos\theta_{ap})$$

$$\frac{d\sigma_h}{d^2p_\perp} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 H(Q,\mu) \int \frac{db}{2\pi} e^{ib_\perp\cdot p_\perp} f_{f/N}(b,\xi,\mu,\nu)\, S\left(b, \frac{n_2\cdot n_4}{2}, \mu, \nu\right) \int dz F_{h/f}(z, b/z, E_4, \mu, \nu)$$

HTL, Makris, Vitev, PRD, 2021

Introduction

EEC in DIS

In Breit Frame.

proton $+ \gamma^* \rightarrow$ jet/hadron $+ X$

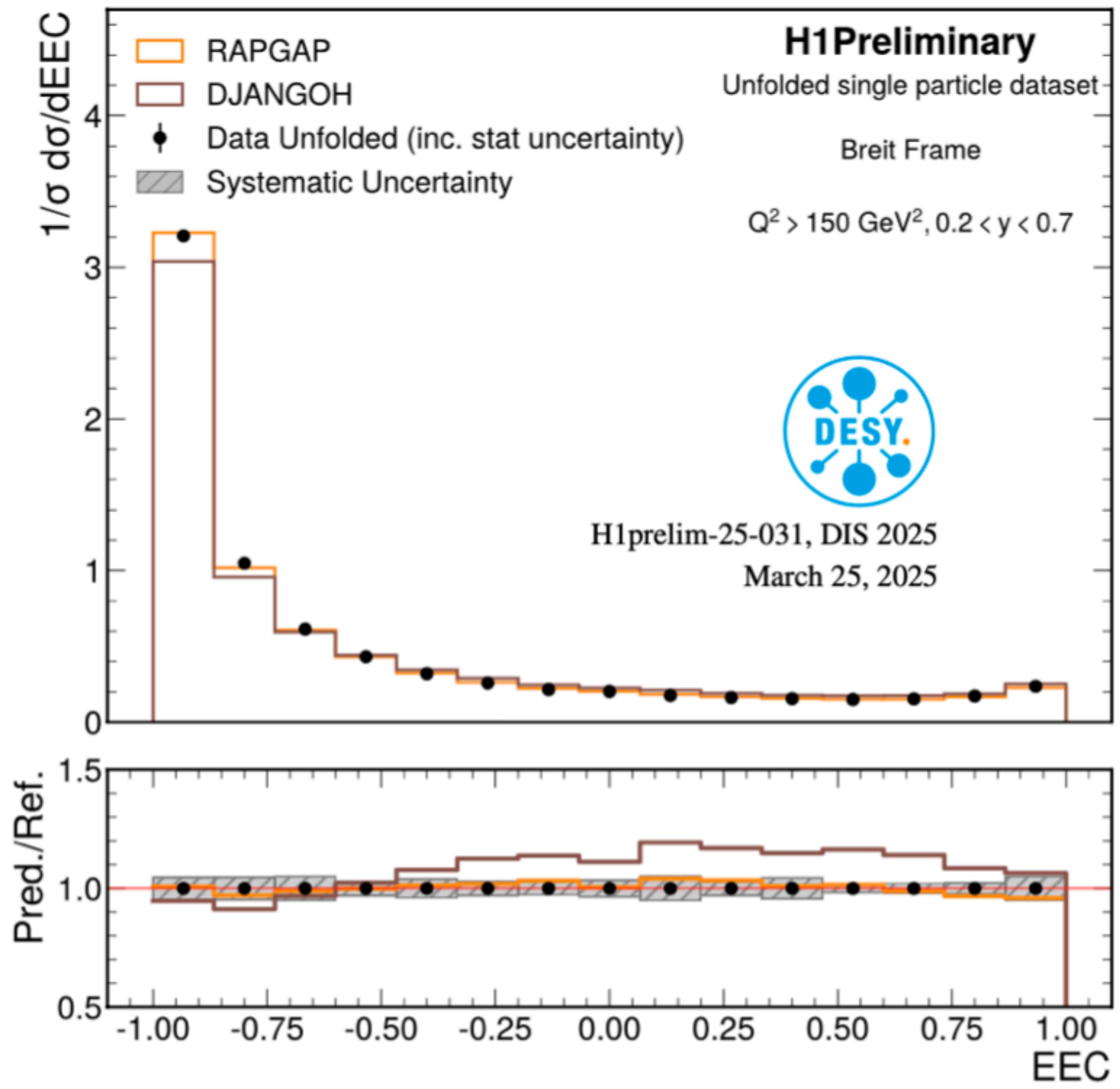
$p_{\bar{n}}$

We proposed a new definition of EEC
correlation b

In the back to back limit $\mathrm{EEC} = \sum_a \int$

$$\frac{d\sigma_h}{d^2 p_\perp} = \sum_f \int \frac{d\xi dQ^2}{\xi Q^2} Q_f^2 H(Q,\mu) \int \frac{db}{2\pi} e^{ib_\perp \cdot p_\perp}$$

HTL, Makris, Vitev, PRD, 2021



proton
$p_{n\perp}$

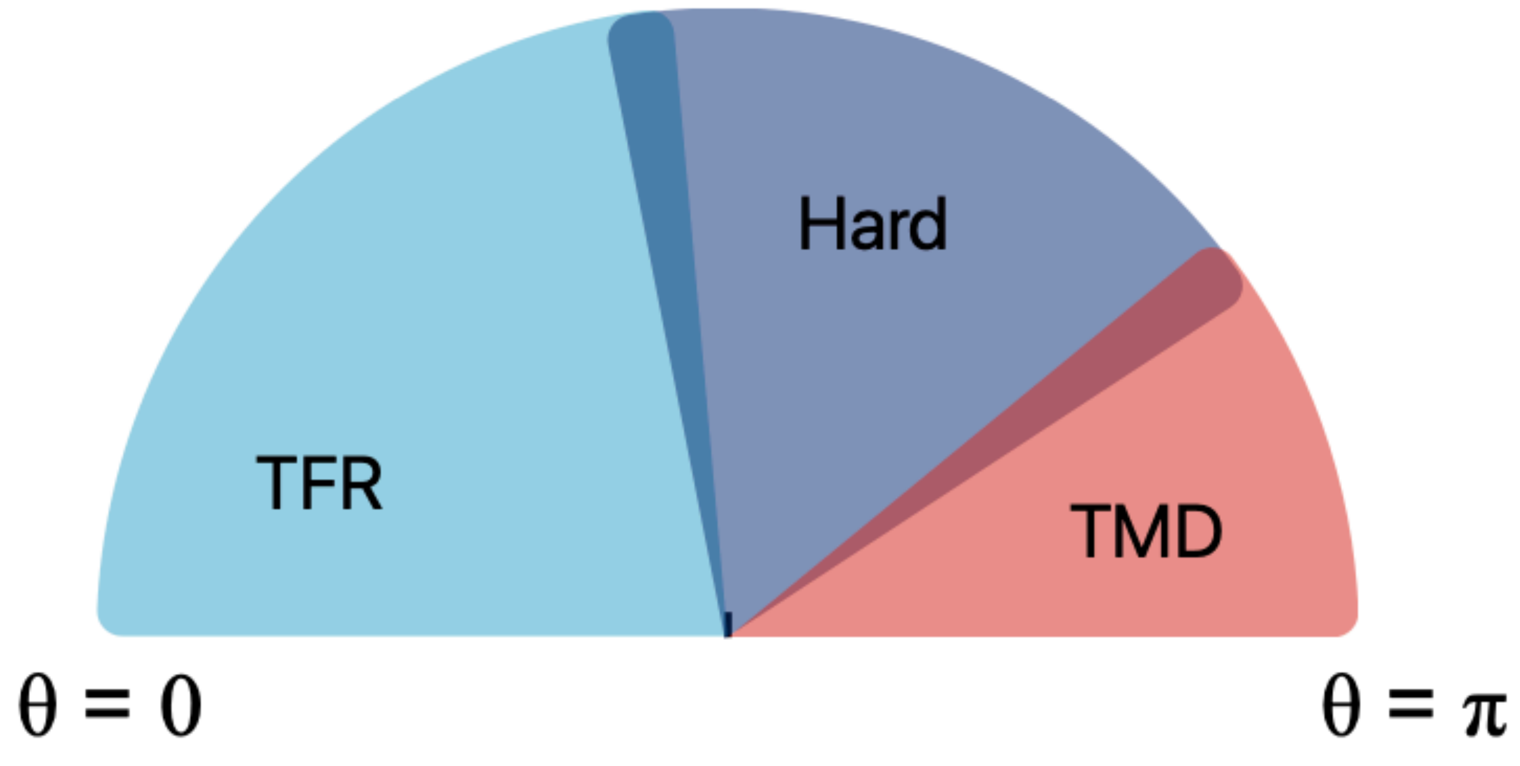
Introduction

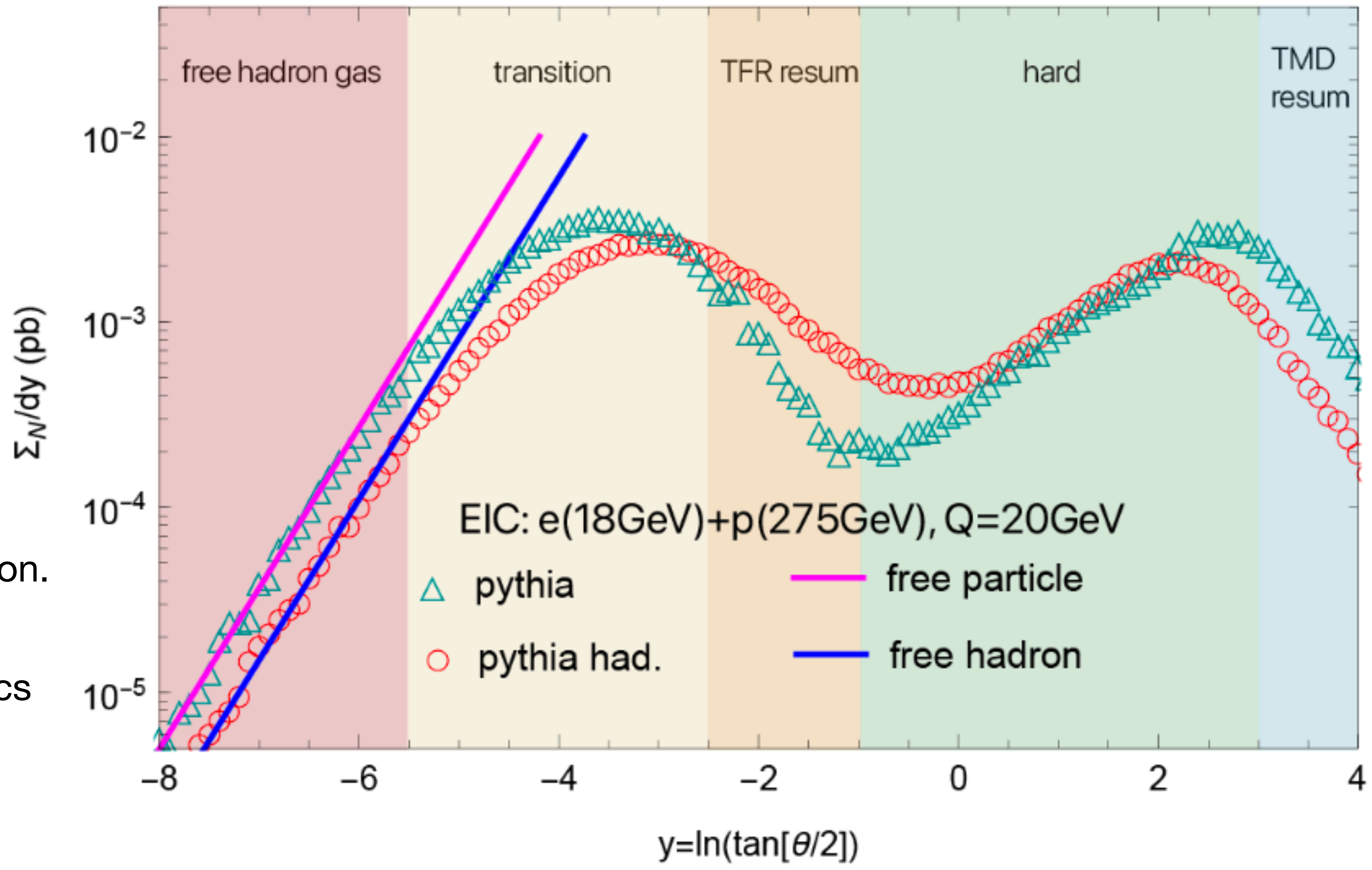
NEEC in DIS

Nucleon Energy Correlators

$$\Sigma_N(Q^2,\theta^2) = \sum_i \int d\sigma(x_B, Q^2, p_i)\, x_B^{N-1} \frac{\bar{n}\cdot p_i}{P}\, \delta(\theta^2 - \theta_i^2)$$

Liu, Zhu, arXiv:2209.02080
Cao, Liu, Zhu, arXiv:2303.01530





TFR: the correlation of the energy flows from the initial nucleon.
Hard: measures the perturbative behavior of QCD
TMD: measures perturbative and nonperturbative TMD physics

Cao, HTL, Mi, PRD, 24

Introduction

NEEC in DIS

Nucleon Energy Correlators

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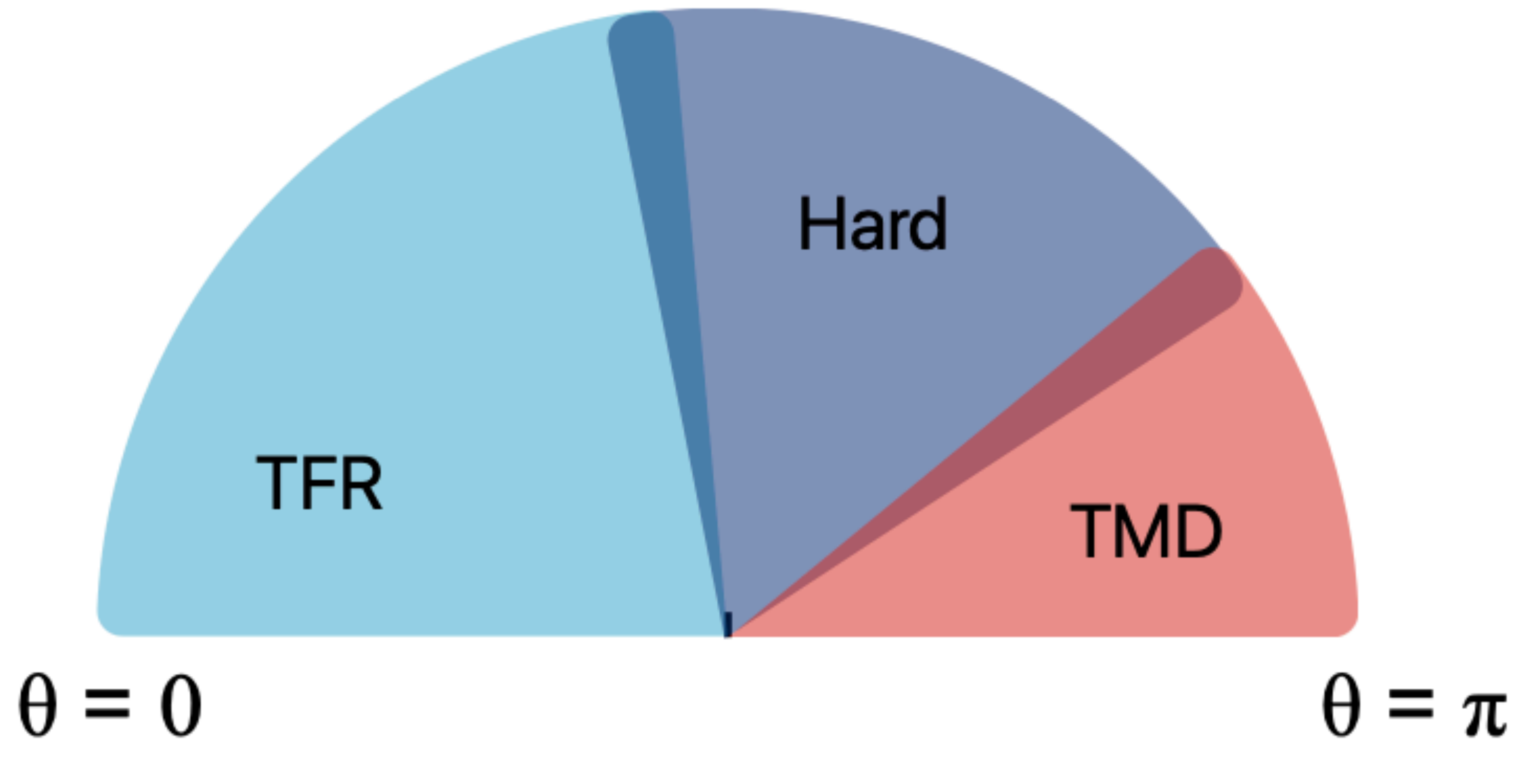

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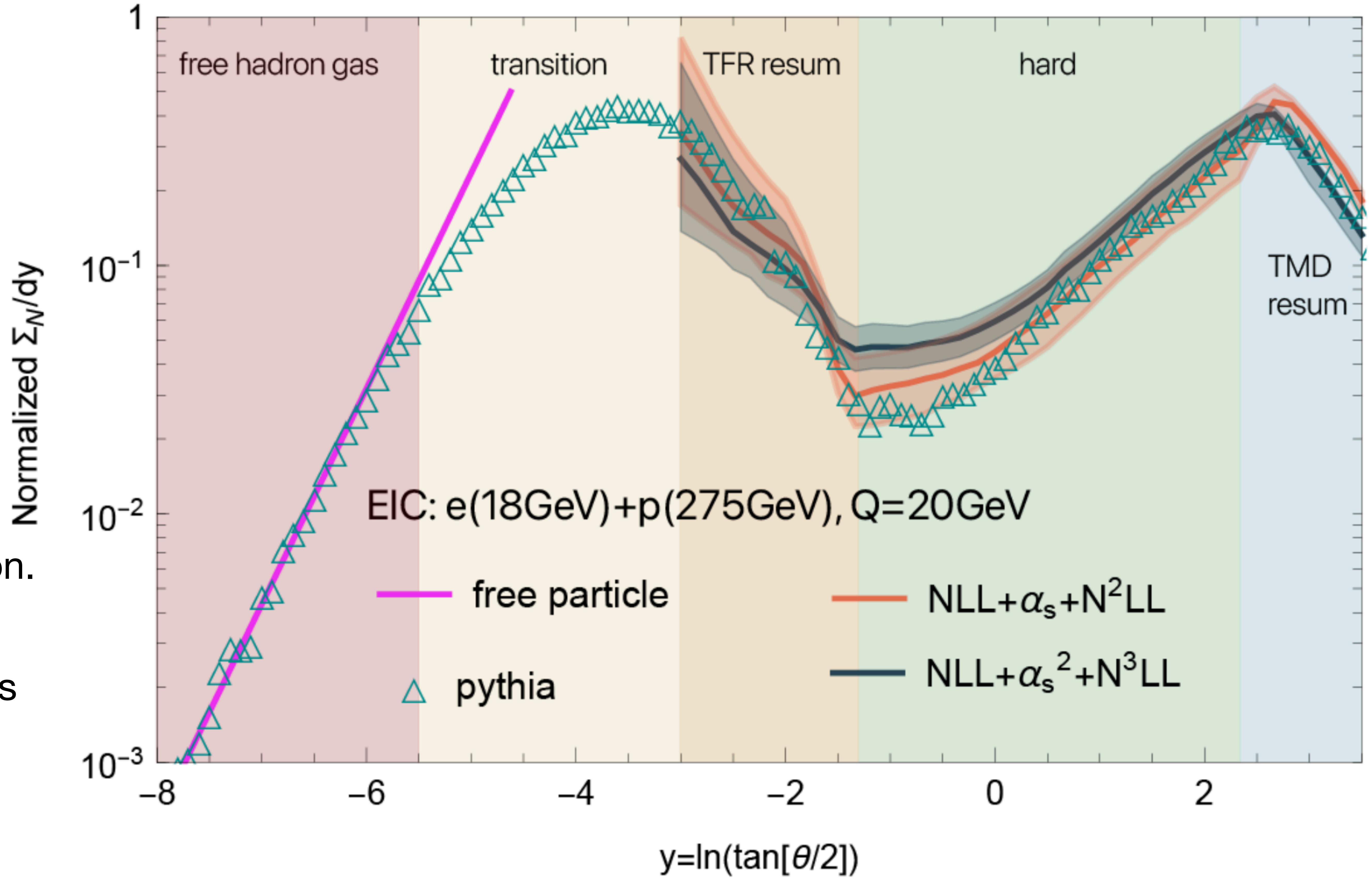

Cao, HTL, Mi, PRD, 24

Introduction

EEC/TEEC is a class of observables which can be studied for various processes

In DIS

$$\text{TEEC} = \sum_a \int d\sigma_{lp\to l+a+X} \frac{E_{T,l}E_{T,a}}{E_{T,l}\sum_i E_{T,i}} \delta(\cos\phi_{la} - \cos\phi)$$

For Dijet

$$\text{TEEC} = \sum_{a,b} \int d\sigma_{pp\to a+b+X} \frac{2E_{T,a}E_{T,b}}{|\sum_i E_{T,i}|^2} \delta(\cos\phi_{ab} - \cos\phi)$$

For Drell-Yan

$$\frac{d\sigma}{d\cos\phi} = \int d\sigma_{pp\to l^+ + l^- + X} \delta\left(\cos\phi_{l^+l^-} - \cos\phi\right)$$

For V+Jets

$$\frac{d\sigma}{d\cos\phi} = \sum_a \int d\sigma_{pp\to V+a+X} \frac{E_V E_{T,a}}{E_V \sum_i E_{T,i}} \delta\left(\cos\phi_{Va} - \cos\phi\right)$$

- From the definition, for TEEC contribution from soft radiations is suppressed by construction
- TEEC is simply defined in comparison with other event shape observables
- It is calculable at high orders

Universality of QCD in the infrared regime

Introduction

$$\text{TEEC} = \sum_{a,b} \int d\sigma_{pp\to a+b+X} \frac{2E_{T,a}E_{T,b}}{|\sum_i E_{T,i}|^2} \delta(\cos\phi_{ab} - \cos\phi)$$

Jets as input

- The jets are usually defined through an angular resolution parameter R and a transverse momentum cutoff
- Less contamination from underlying events
- Introduce new cutoff scale
- Problem of globalness, i.e. non-global logs
- Measurable at LHC and EIC

Particles as input

- Simpler defined observable
- relative larger effects from underlying events
- NO new cutoff scale introduced
- Global event shapes
- Measurable at LHC and EIC

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- **EEC with jets**
- EEC with groomed jets
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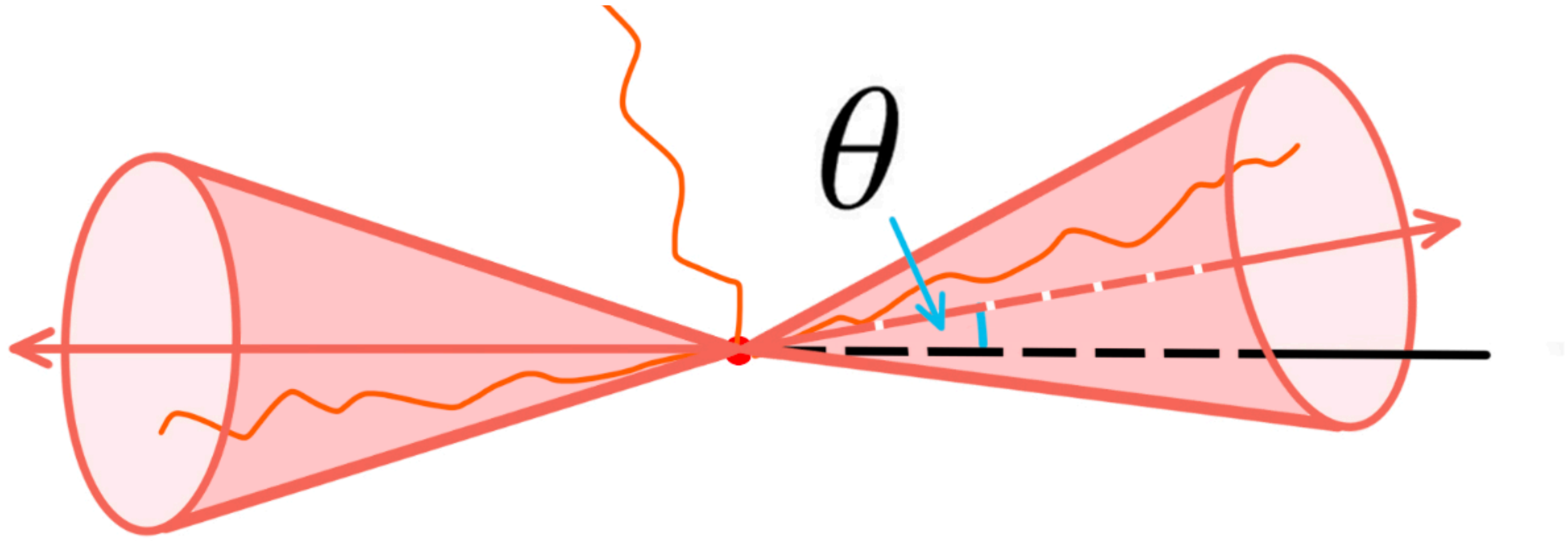
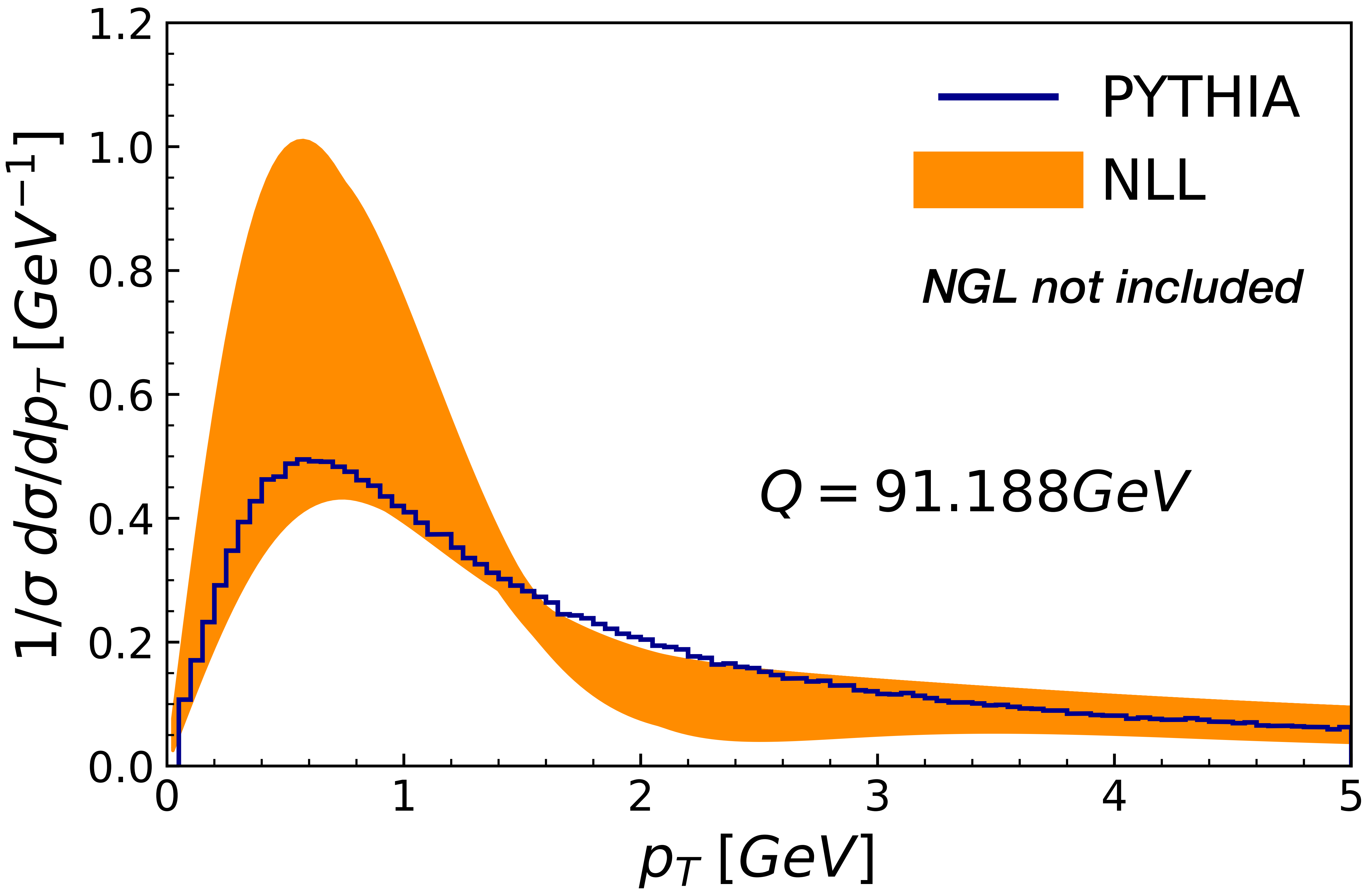
EEC with jets

$$\mathrm{EEC} = \sum_{a,b} \int d\sigma_{V\to a+b+X} \frac{2E_a E_b}{Q^2\sigma_{\mathrm{tot}}} \delta(\cos(\theta_{ab}) - \cos(\chi))$$





In jet, soft and/or collinear radiations do not change the opening angle of the jets

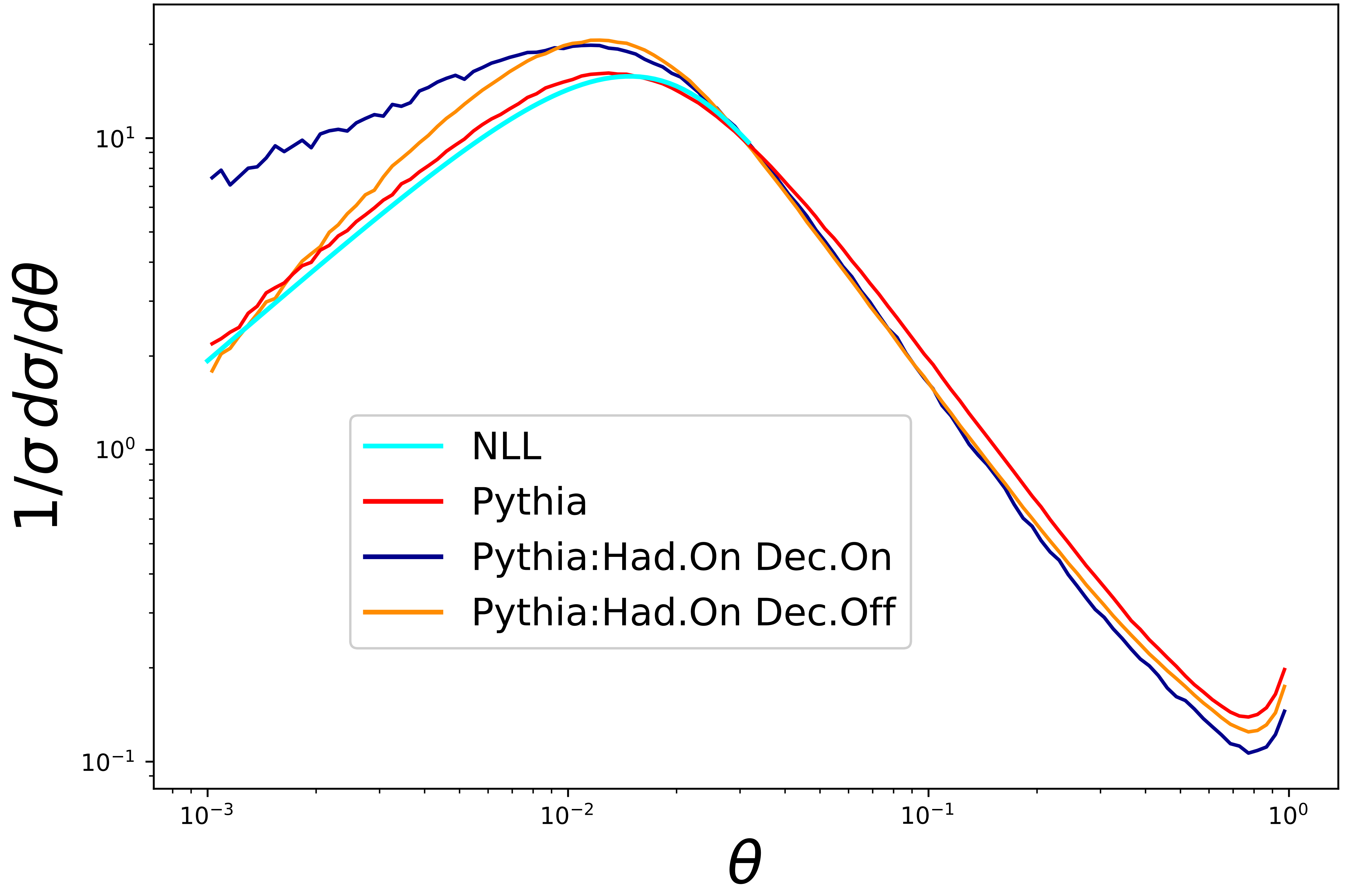
Outside of jet, soft radiation would shift the angle away from back to back region

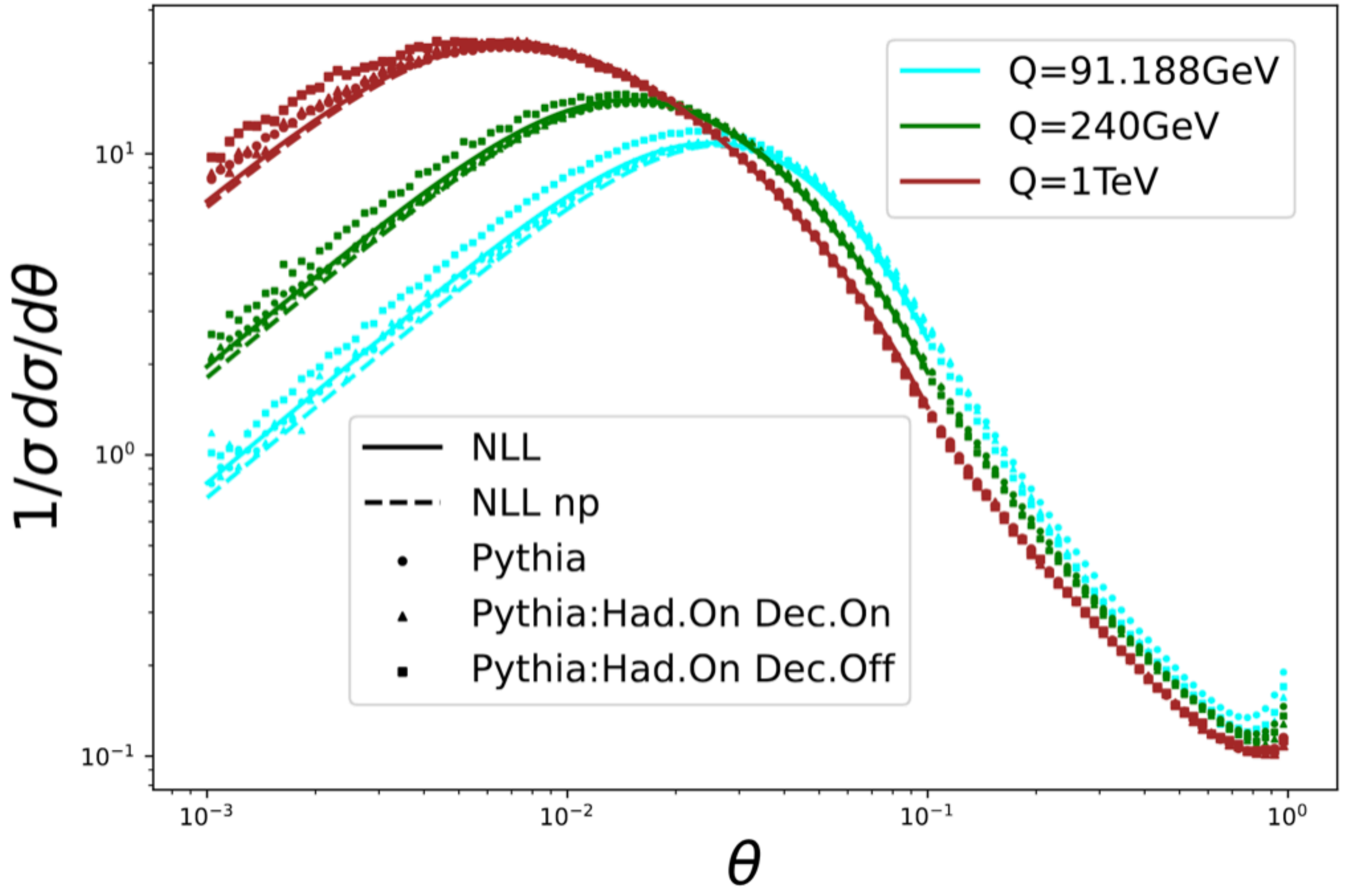
$$\frac{1}{\sigma_0}\frac{d\sigma}{d^2\mathbf{p}_\perp} = H\left(Q^2,\mu\right) J_c\left(Q^2,\delta,\mu\right) J_{\bar{c}}\left(Q^2,\delta,\mu\right) \times \int \frac{d\vec{b}}{(2\pi)^2} e^{i\vec{b}\cdot\vec{p}_\perp} S\left(Q^2,\vec{b},\mu,\nu\right) S_{sc}\left(\delta Q^2,\vec{b},\mu,\nu\right) S_{s\bar{c}}\left(\delta Q^2,\vec{b},\mu,\nu\right)$$

EEC with jets

EEC in the back to back region has a similar factorization formula

$\theta \to 0$ is the back to back limit





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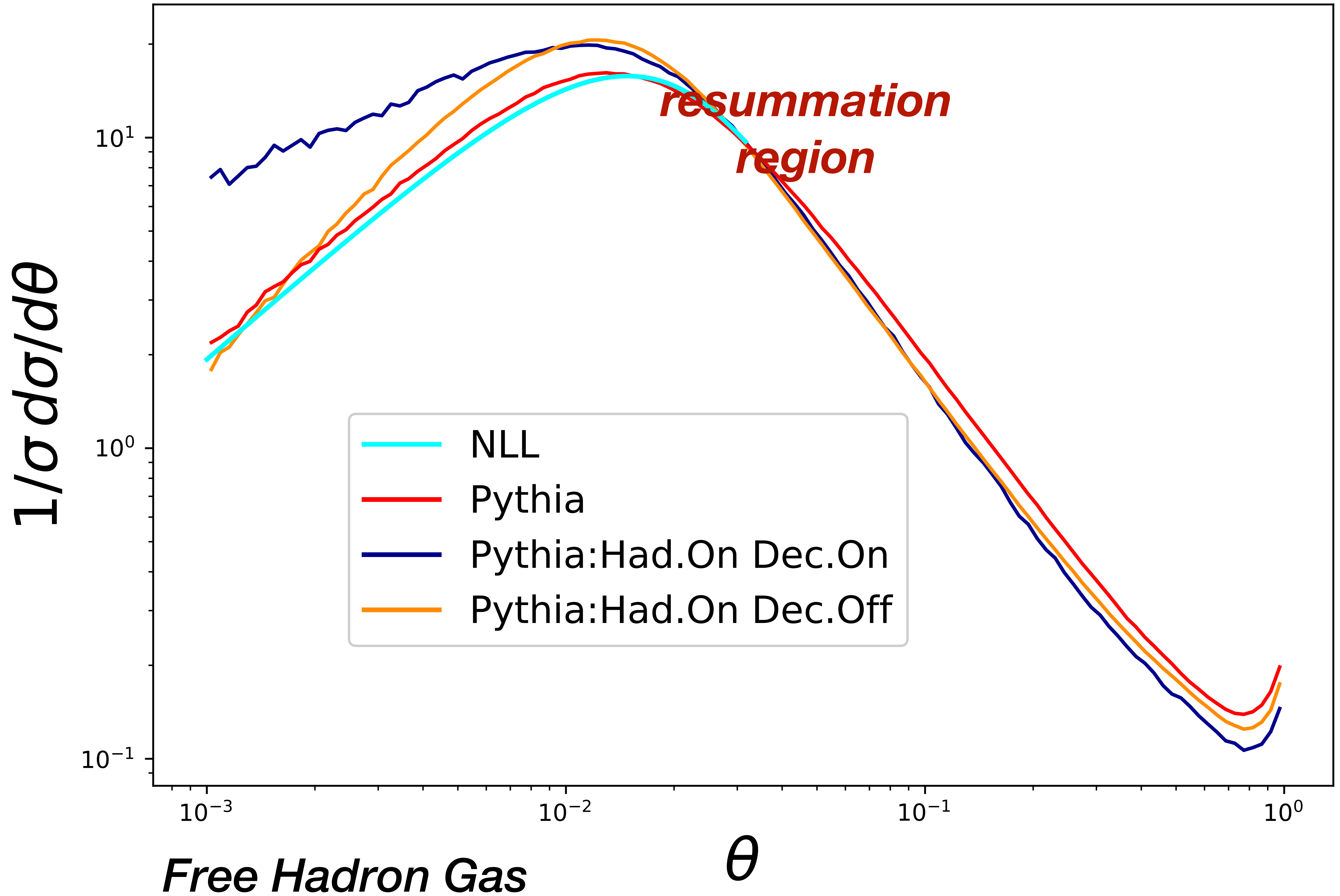
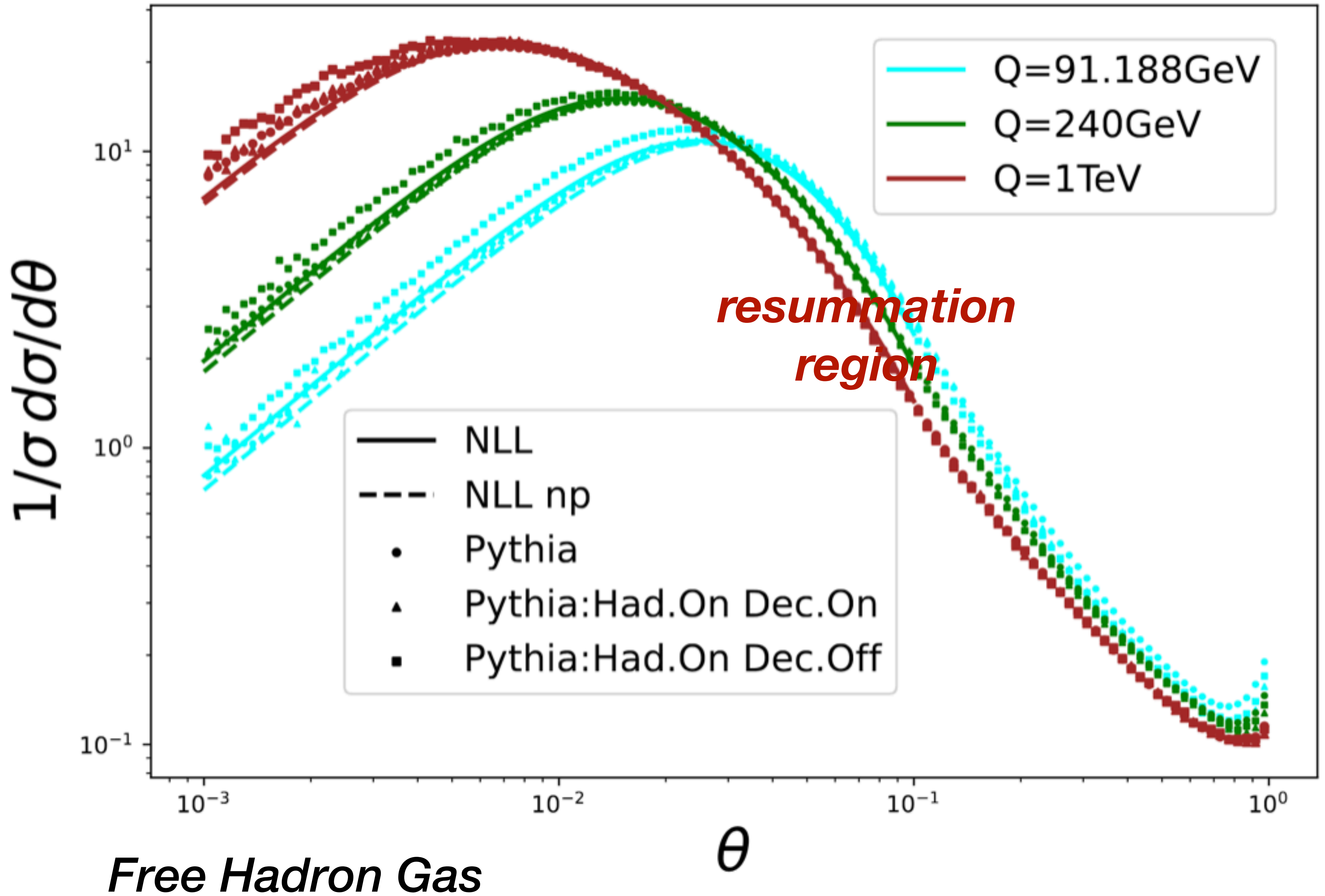


Free Hadron Gas

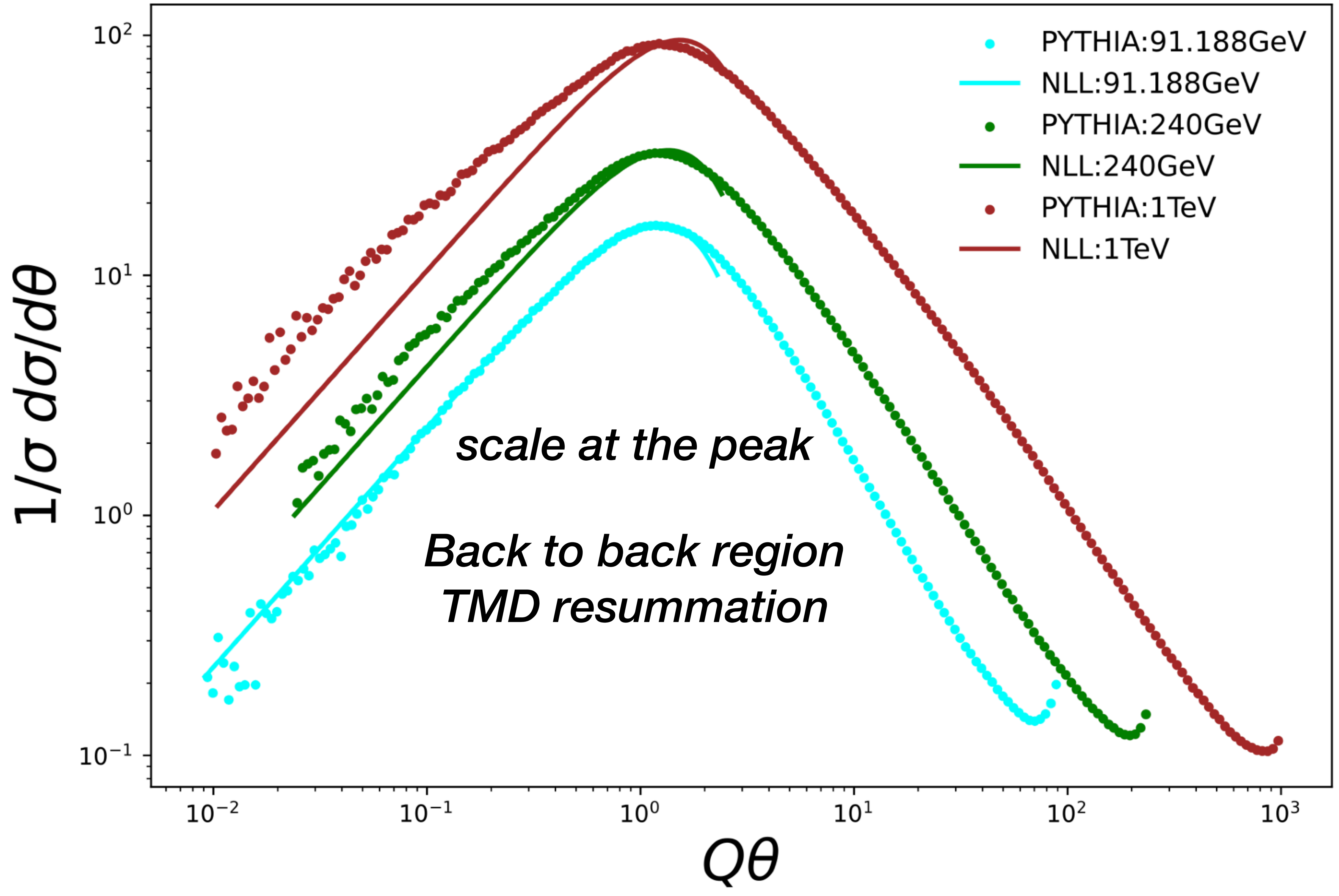
Obtained by perturbative calculations



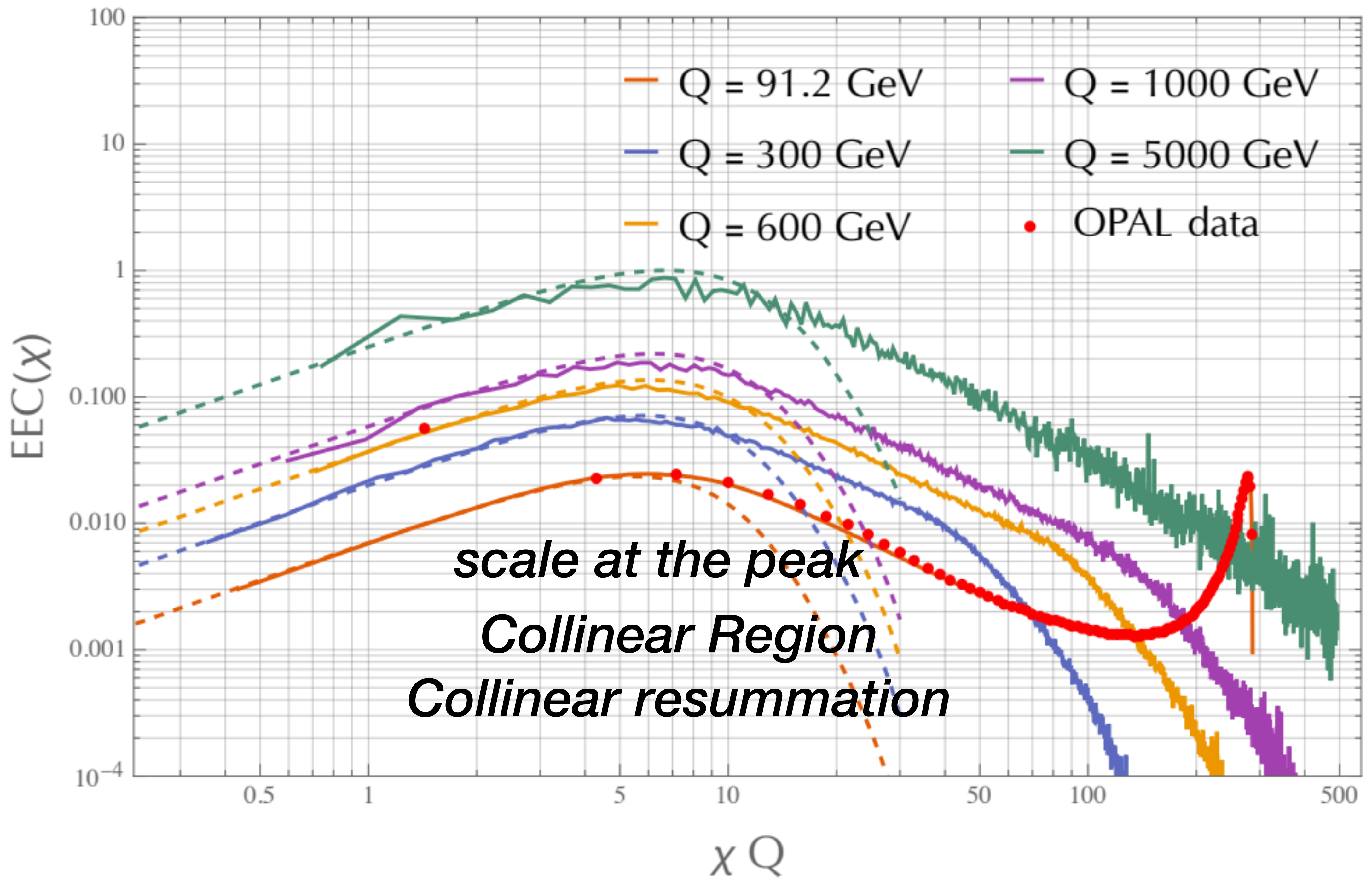
Free Hadron Gas

Obtained by perturbative calculations

EEC with jets



He, HTL, Shao, in preparation



$$c^3 N E_J^2 \chi \int dbbJ_0\left(cE_J\chi b\right) e^{-\frac{g_1}{c^2}b^2} \times e^{-\frac{g_2}{2}\ln\left(\frac{b}{b_*}\right)\ln\frac{cE_J}{\mu_0}}$$

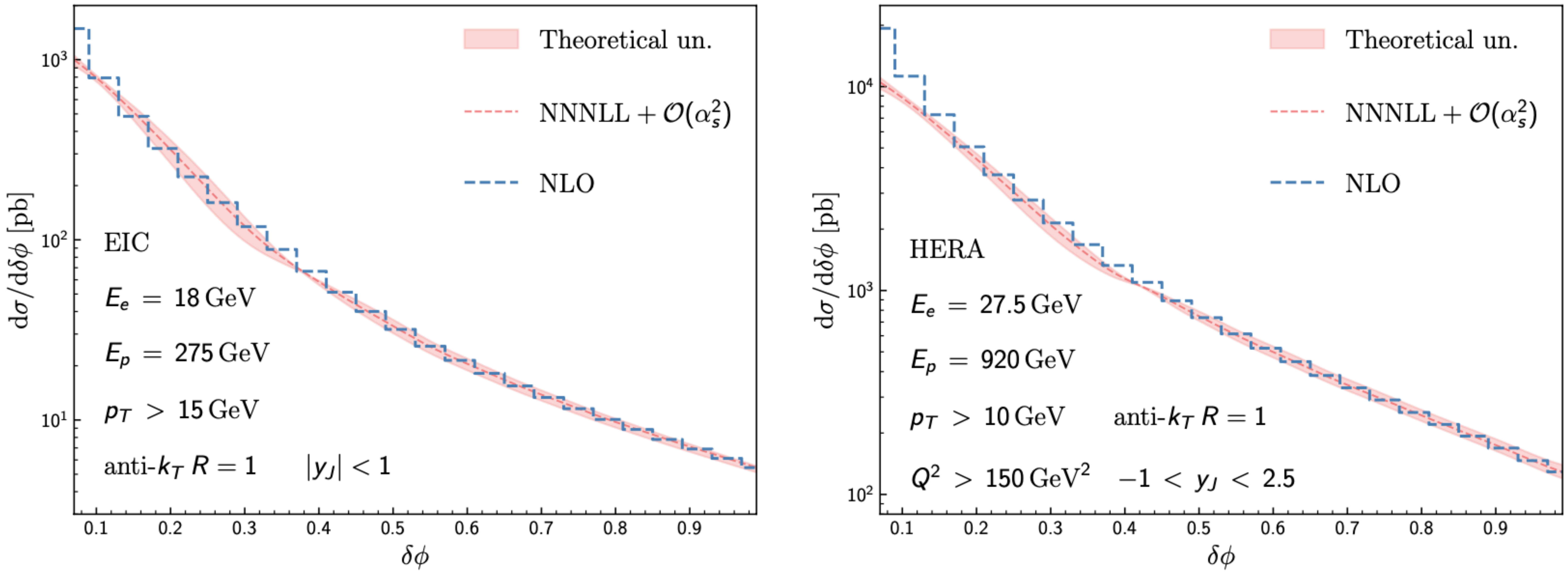
Liu, Yuan, Zhu, PRL 2025

EEC with jets

WTA jet axis in ee and DIS

Jets are defined by the anti-kTclustering algorithm and the winner-take-all recombination scheme.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}^2 p_T\,\mathrm{d}y_J\,\mathrm{d}\lambda_x} = \sigma_0\,H(Q,\mu)\int_{-\infty}^{+\infty}\frac{\mathrm{d}b_x}{2\pi}e^{ib_x\lambda_x}\sum_q e_q^2\,\mathcal{B}_{q/p}\left(x_{\mathtt{bj}},b_x,\mu,\zeta_B/\nu^2\right)$$
$$\times\,\mathcal{J}_q\left(b_x,\mu,\zeta_{\mathcal{J}}/\nu^2\right)\,\mathcal{S}\left(b_x,n\cdot n_J,\mu,\nu\right),$$



Feng, Gao, HTL, Shao, JHEP 25

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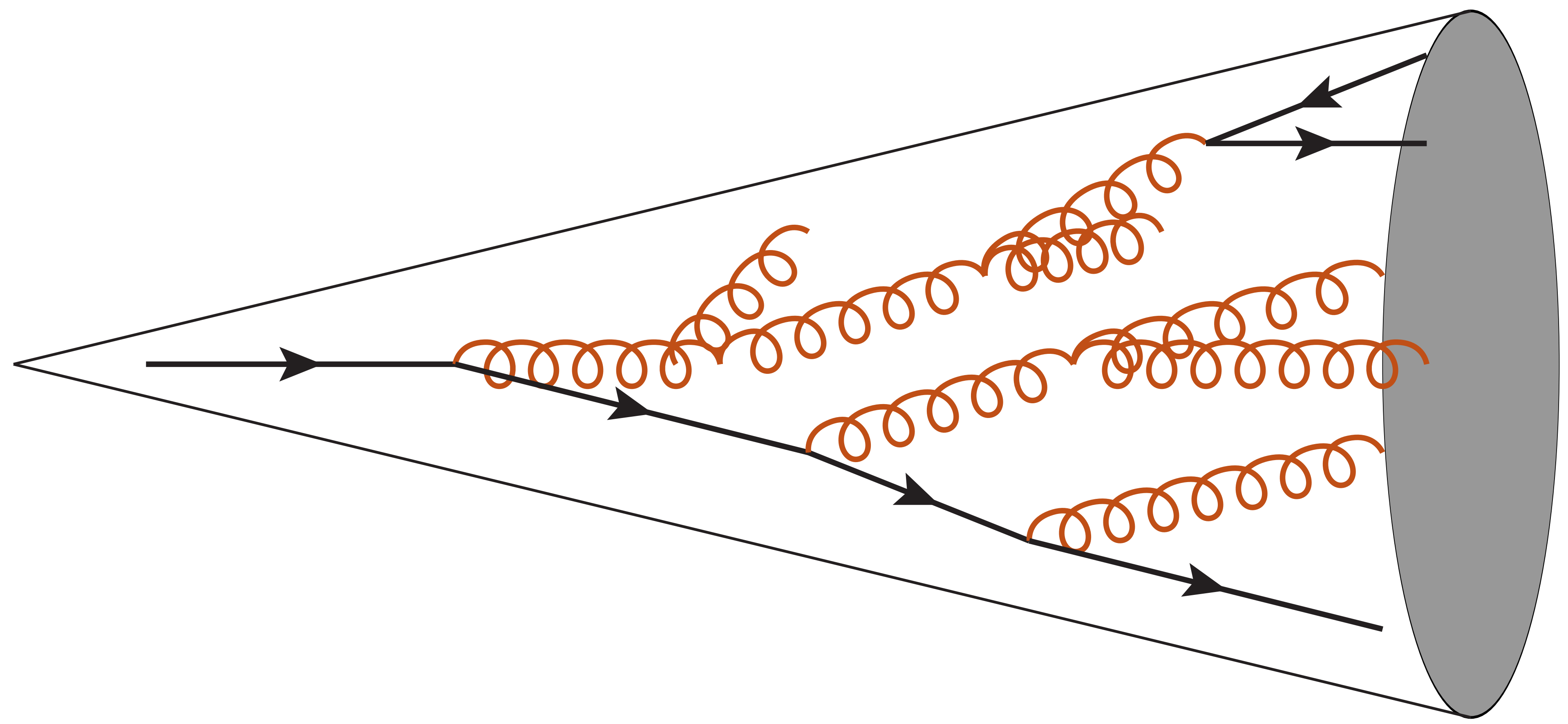
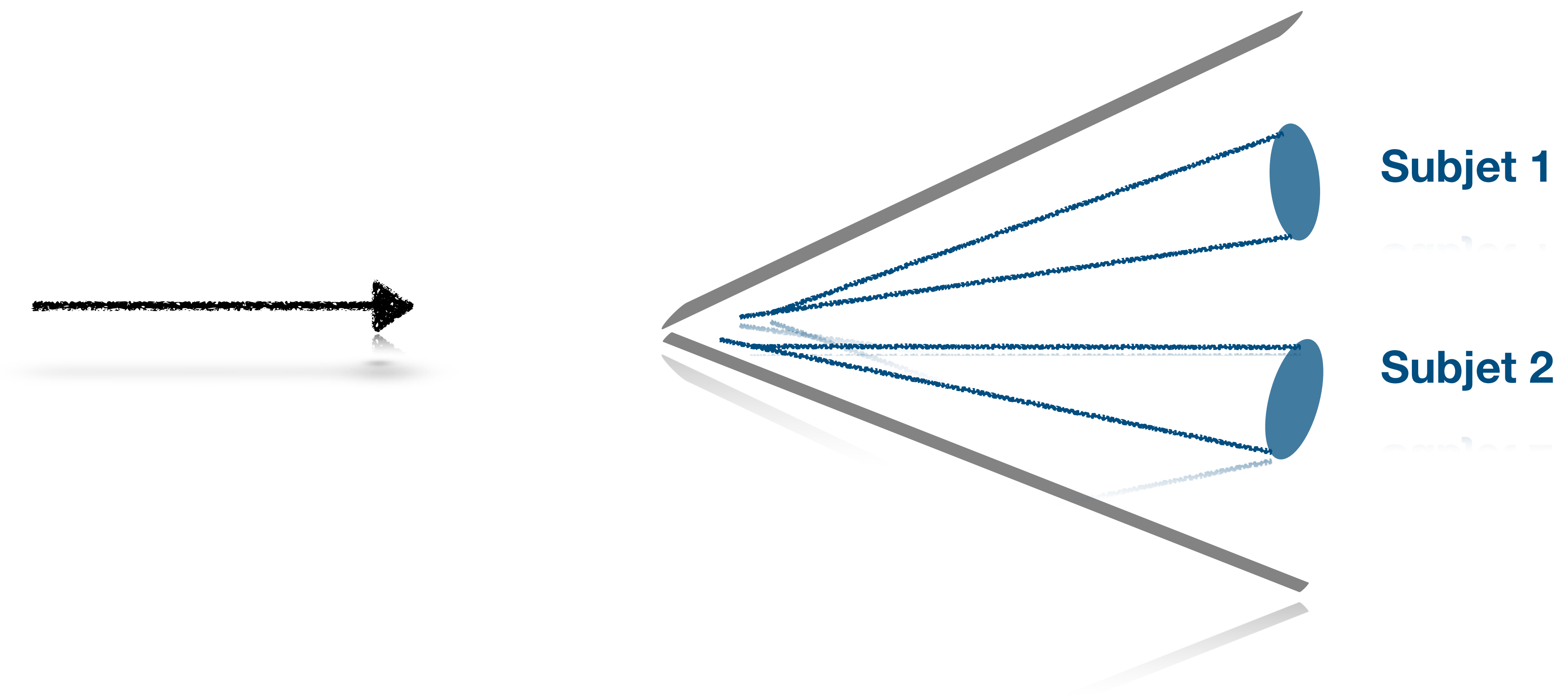
EEC with Groomed Jets





Original jet with radius

Undo last stage of C/A clustering

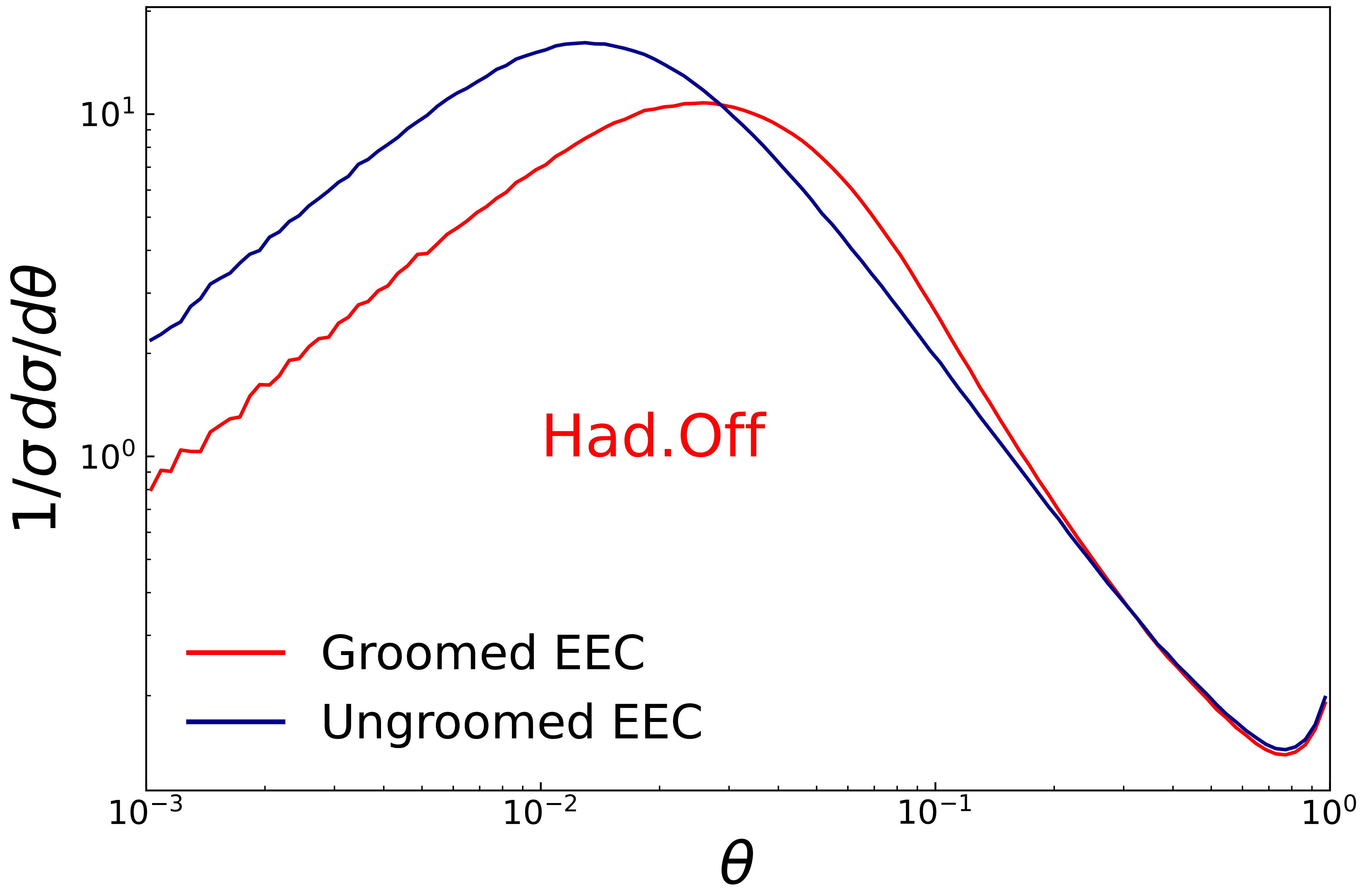
Define $$z_g = \frac{\min\left(p_{T1}, p_{T2}\right)}{p_{TG1} + p_{T2}}$$

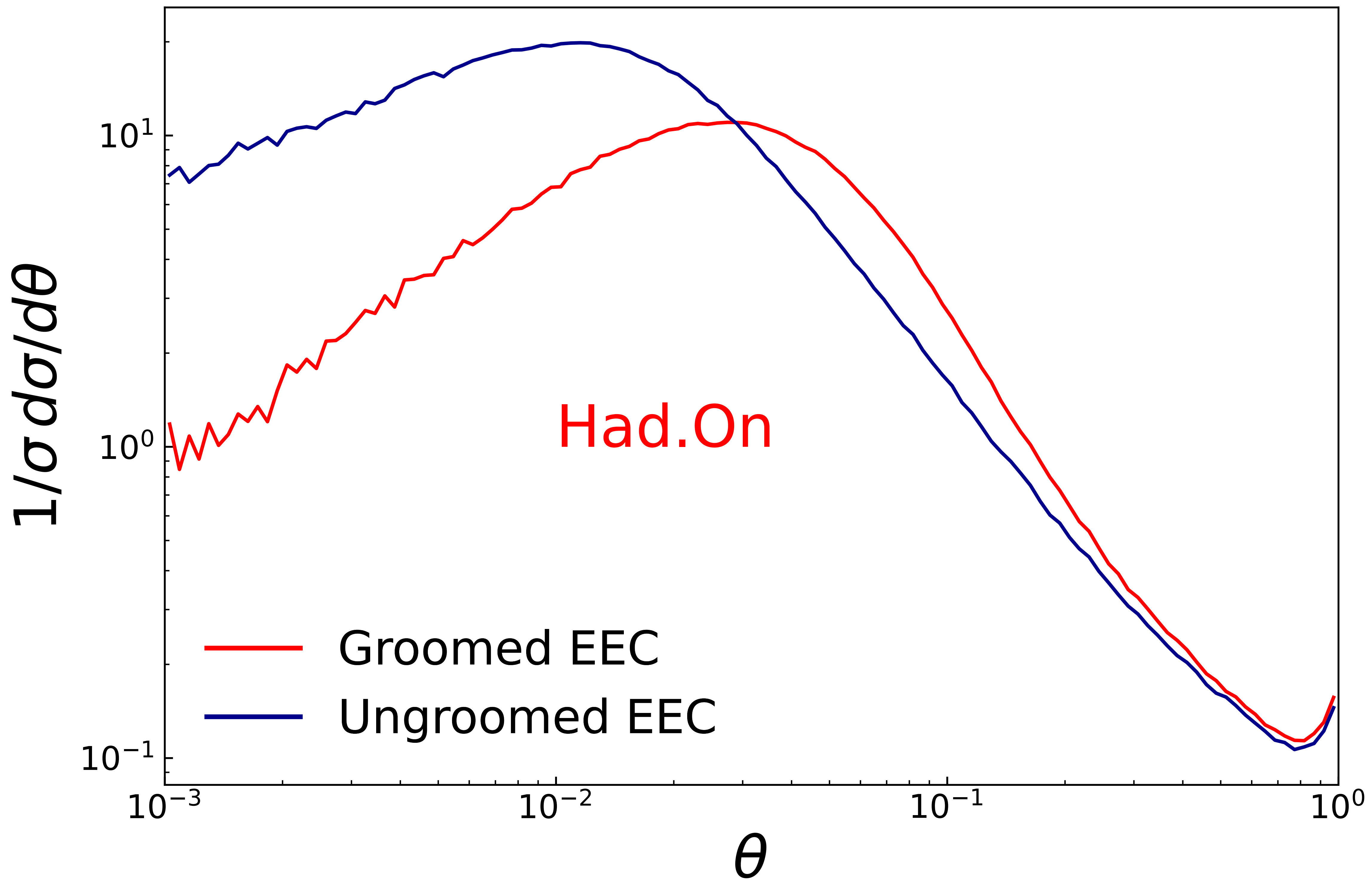
If $z_g < z_{\text{cut}} \left(\frac{\Delta R_{12}}{R_0}\right)^{\beta}$ redefine j to be the harder one,

else we have the two-prong subjets

EEC with Groomed Jets

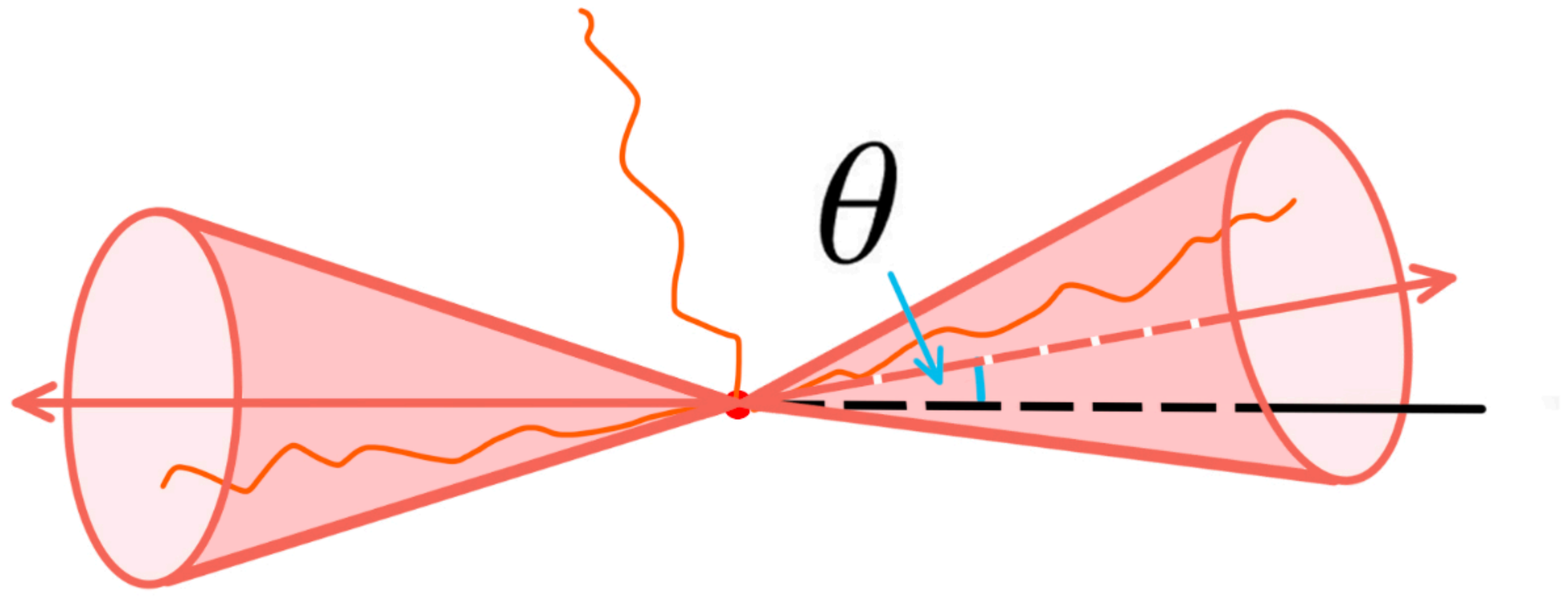
Pythia simulation in back to back region





EEC with Groomed Jets

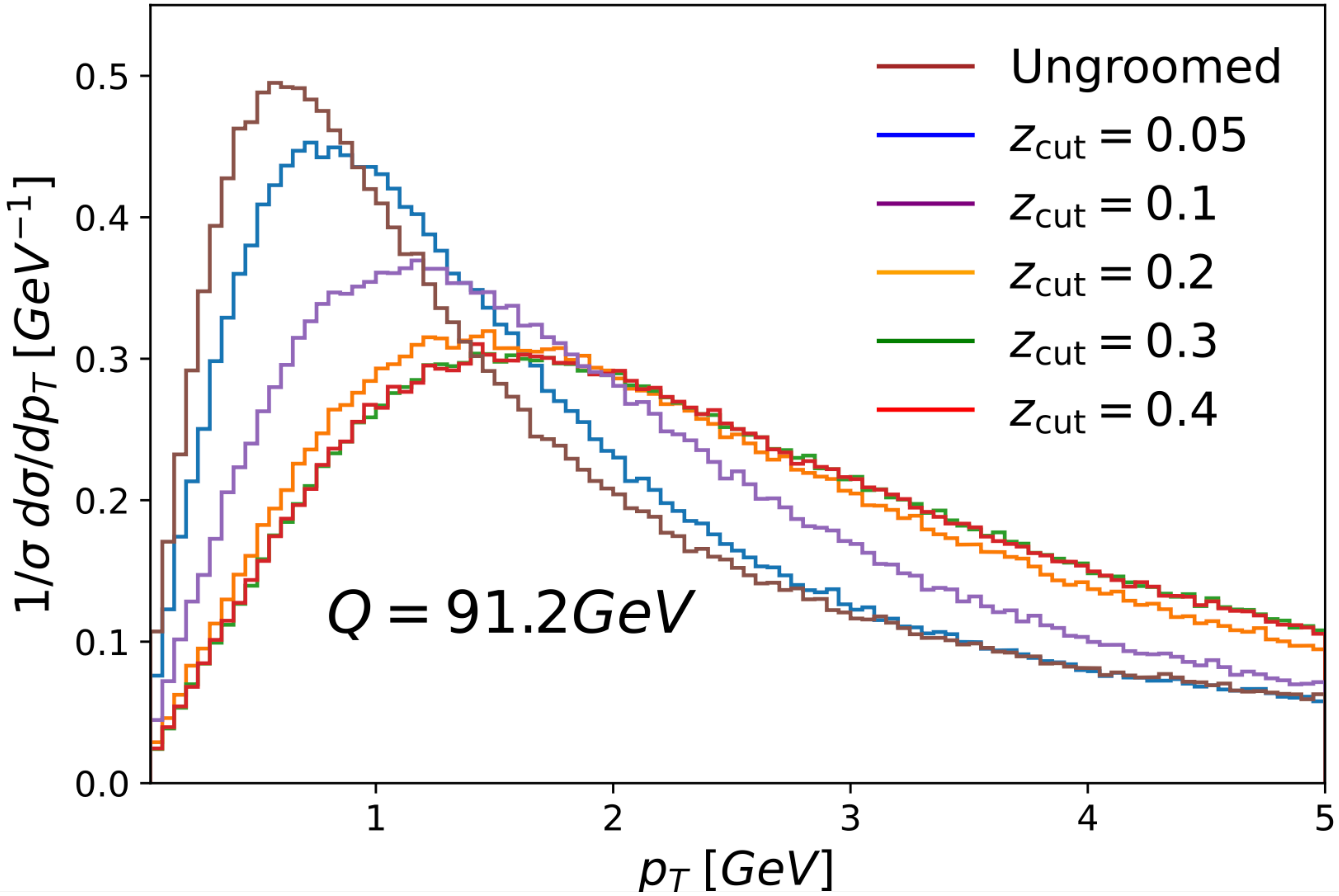
Groomed Jet



In jet, soft and collinear radiations with small energy will change the opening angle of the jets

Outside of jet, soft radiation would shift the angle away from back to back region

In back to back limit

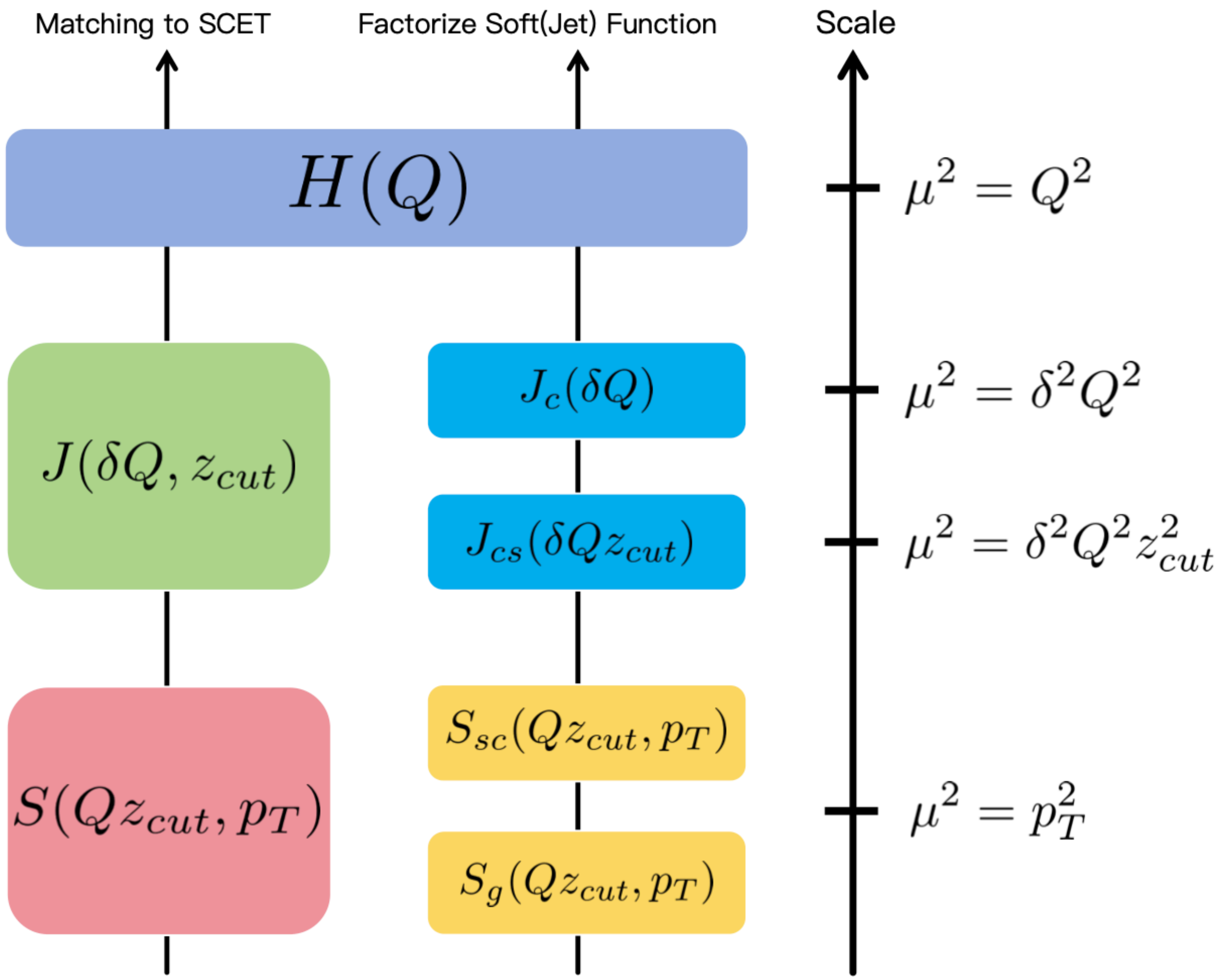


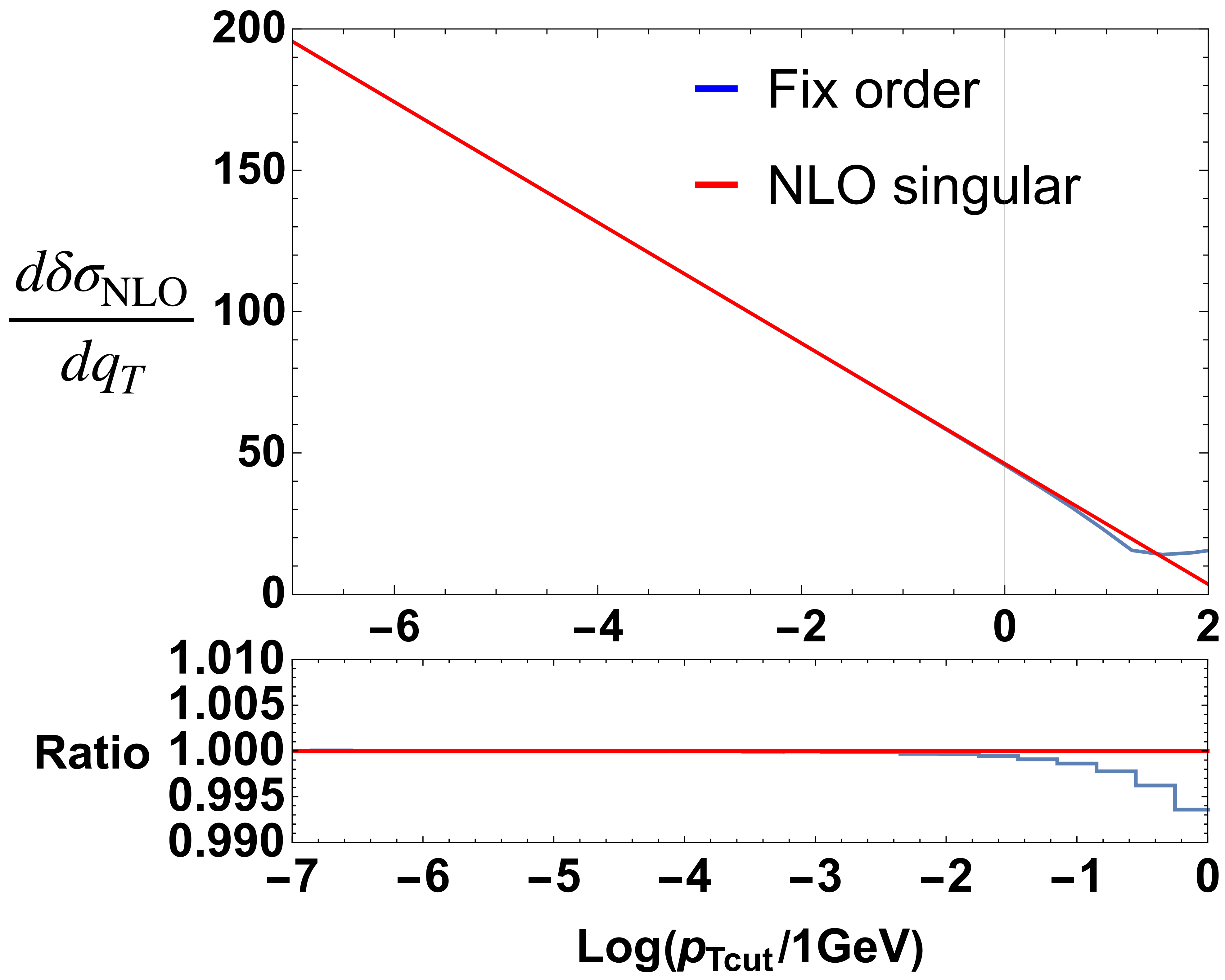
EEC with Groomed Jets

Groomed jets in back to back limits

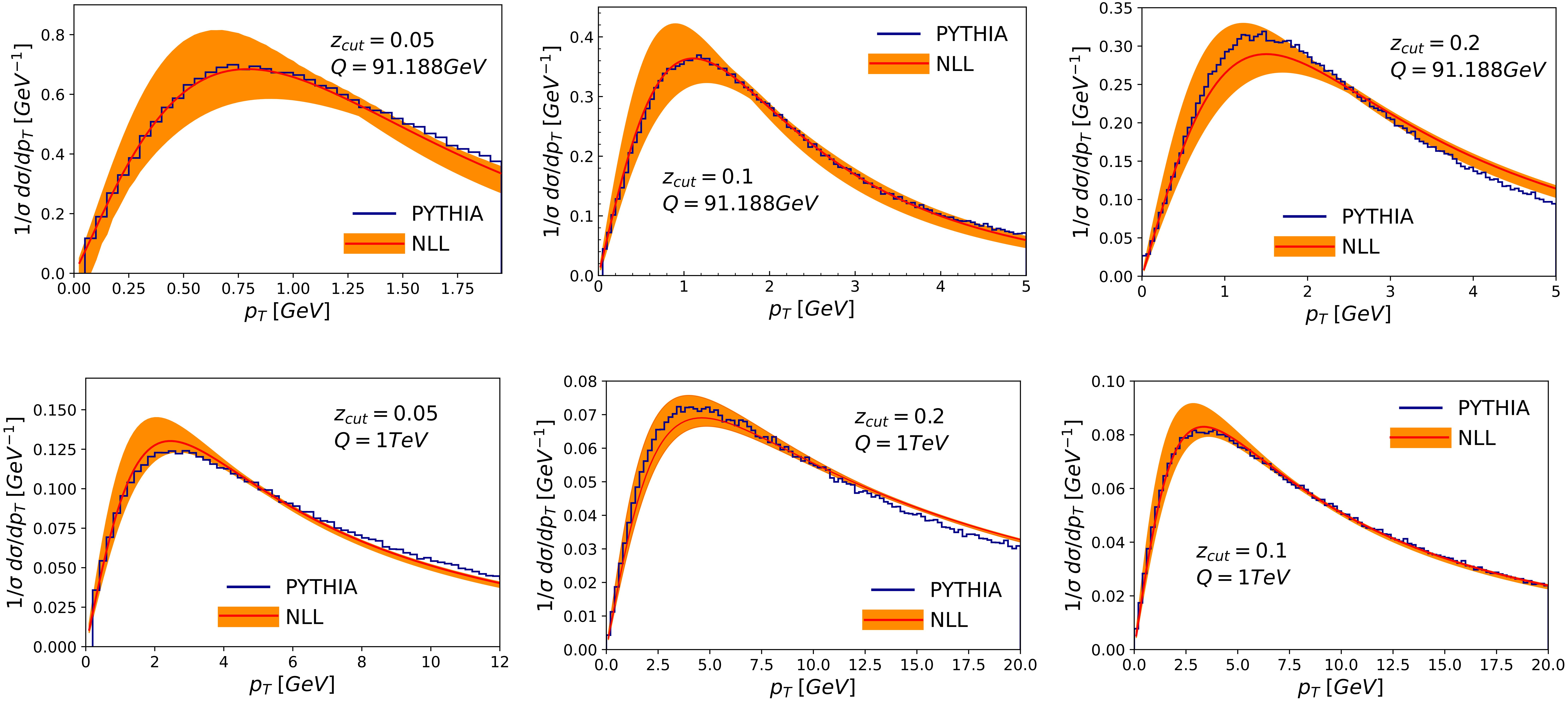
$$\frac{1}{\sigma_0}\frac{d\sigma}{d^2\mathbf{p}_\perp} = H\left(Q^2,\mu\right) J_c\left(Q^2,\delta,\mu\right) J_{\bar{c}}\left(Q^2,\delta,\mu\right) J_{cs}\left(Q^2,\delta,z_{\rm cut},\mu\right) J_{\bar{c}s}\left(Q^2,\delta,z_{\rm cut},\mu\right)$$

$$\times \int \frac{d\vec{b}}{(2\pi)^2} e^{i\vec{b}\cdot\vec{p}_\perp} S\left(Q^2,\vec{b},\mu,\nu\right) S_{sc}\left(Q^2,\vec{b},z_{\rm cut},\mu,\nu\right) S_{s\bar{c}}\left(Q^2,\vec{b},z_{\rm cut},\mu,\nu\right)$$



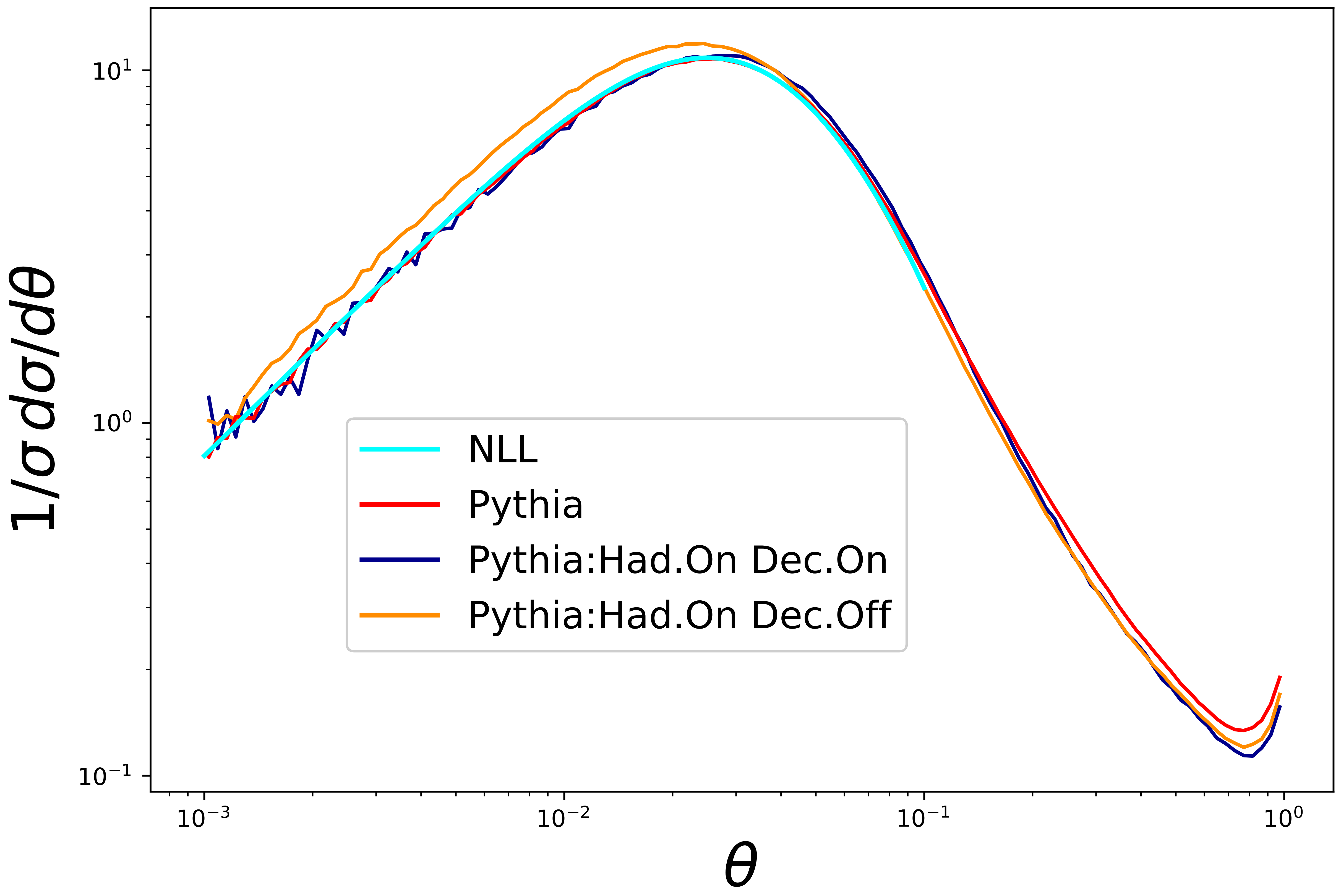


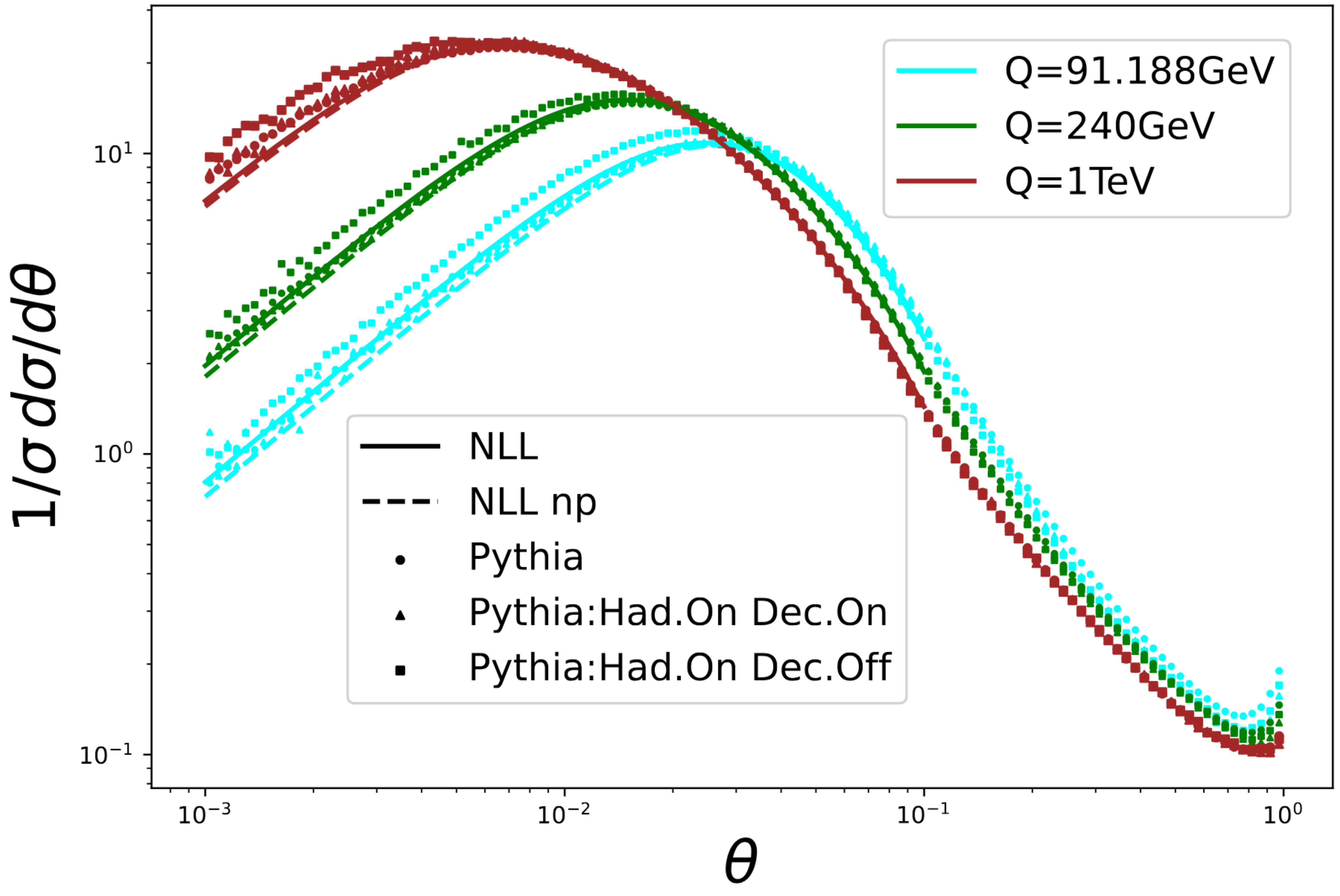
EEC with Groomed Jets



EEC with Groomed Jets

EEC with groomed jet





Summary

- EEC/TEEC in the back to back limits as TMD probe
- Particle level EEC/TEEC has been discussed
- EEC with jets and groomed jets shows interesting perturbative and non perturbative properties
- It is promising to apply EEC with jets to heavy ion collisions

Thank You！