Energy-Energy Correlators (EEC) in DIS

a novel probe to TMDPDFs

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arXiv:2102.05669 (H. Li, Y. Makris, I. Vitev)

Outline

Introduction to
EEC in ee
TEEC in pp
TEEC in DIS

EEC in DIS (new)

TMD factorization
and universal TMDPDFs

EEC jet function
and hadronization effects

EEC in lepton colliders

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

PRL. 41 (1978) 1585 (C. L. Basham, L. S. Brown, S. D. Ellis, and S.T. Love)

Soft radiation (direct) contribution is suppressed. Recoil from soft radiation needs to be included.

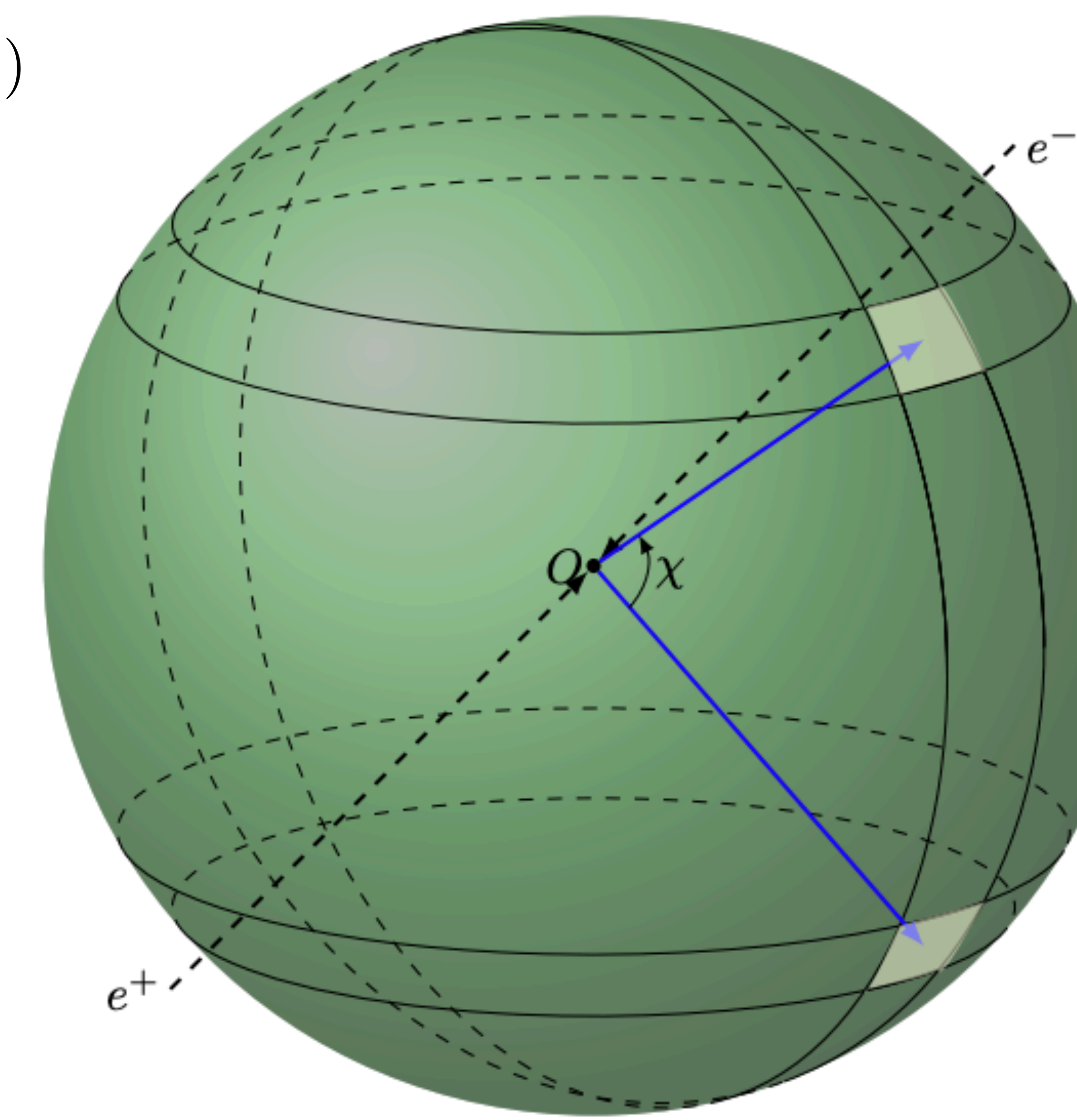

Figure from arXiv:1801.02627 (I. Moult and H.X. Zhu)

EEC in lepton colliders

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<u>EEC measurements/extractions of α_s</u>

PLUTO, Phys. Lett. B 99, 292 (1981)

MARKII, Phys. Rev. Lett. 49, 521 (1982)

MARKJ , Phys. Rev. Lett. 50, 2051 (1983)

CELLO, Phys. Lett. B 138, 311 (1984)

JADE, Z. Phys. C 25, 231 (1984)

MAC, Phys. Rev. D 31, 2724 (1985)

TASSO, Z. Phys. C 36, 349 (1987)

TOPAZ, Phys. Lett. B 227, 495 (1989)

DELPHI, Phys. Lett. B 252, 149 (1990)

OPAL, Phys. Lett. B 252, 159 (1990)

ALEPH, Phys. Lett. B 257, 479 (1991)

L3, Phys. Lett. B 257, 469 (1991)

SLD, Phys. Rev. D 51, 962 (1995)

Transverse-EEC for hadronic colliders

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

Phys. Lett. 141B, 447 (1984) (A. Ali, E. Pietarinen, and W. J. Stirling)

Soft and Beam (direct) contribution is suppressed. Recoil from soft radiation and ISR needs to be included.

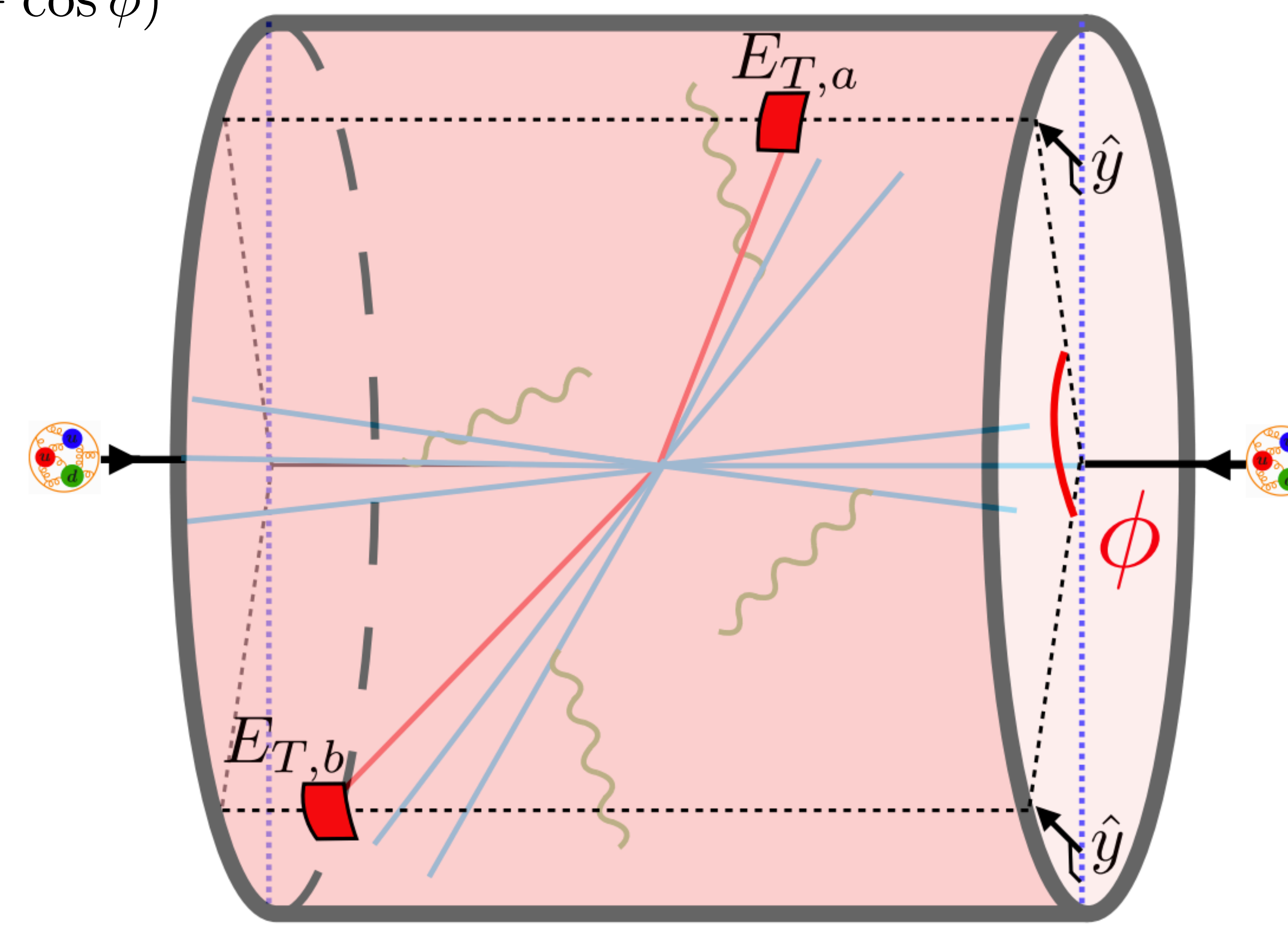


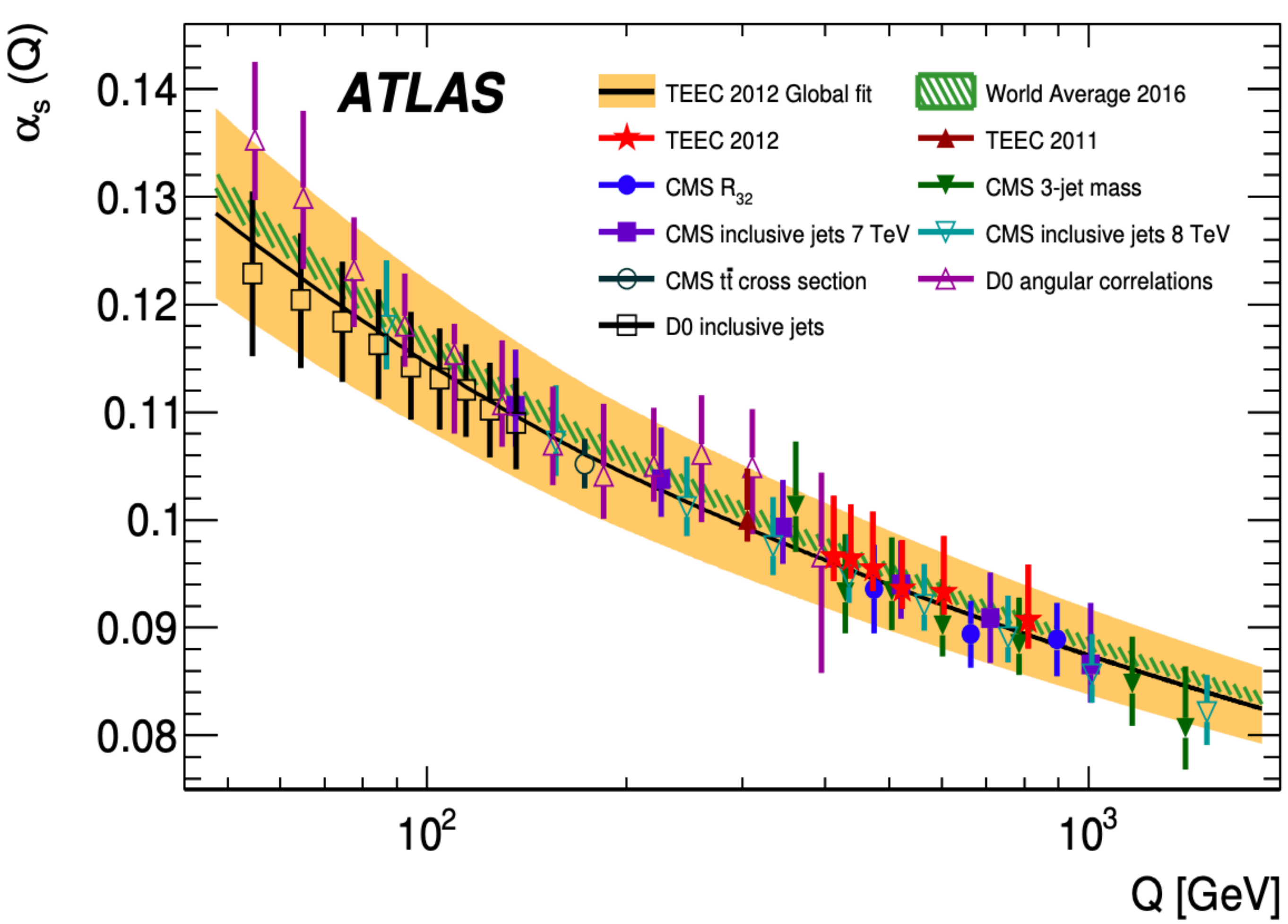
Figure from arXiv:1901.04497 (A. Gao, H.T. Li, I. Moult, and H.X. Zhu)

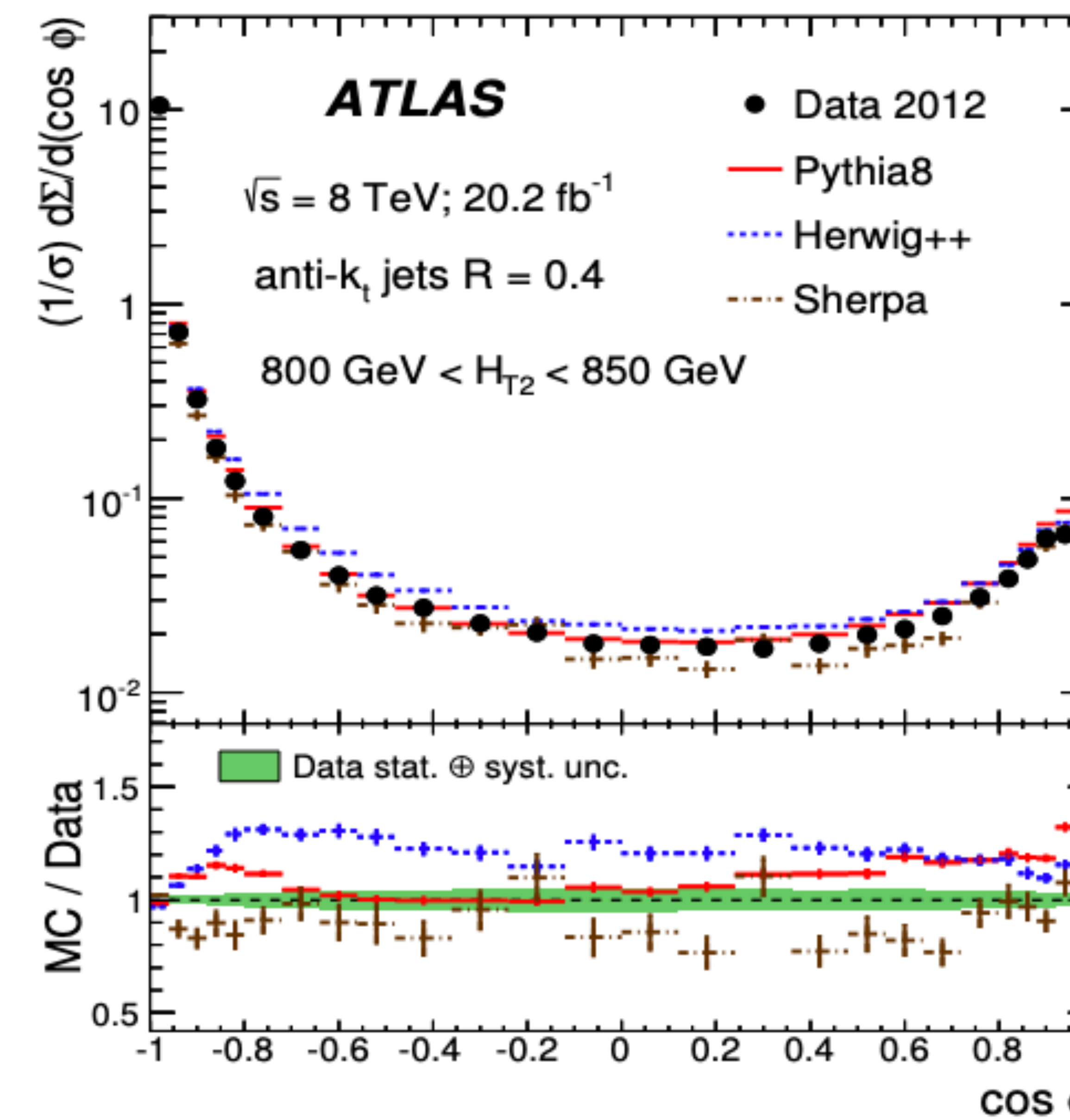
Transverse-EEC for hadronic colliders

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

arXiv: 1508.01579 (**ATLAS**)

arXiv: 1707.02562 (**ATLAS**)

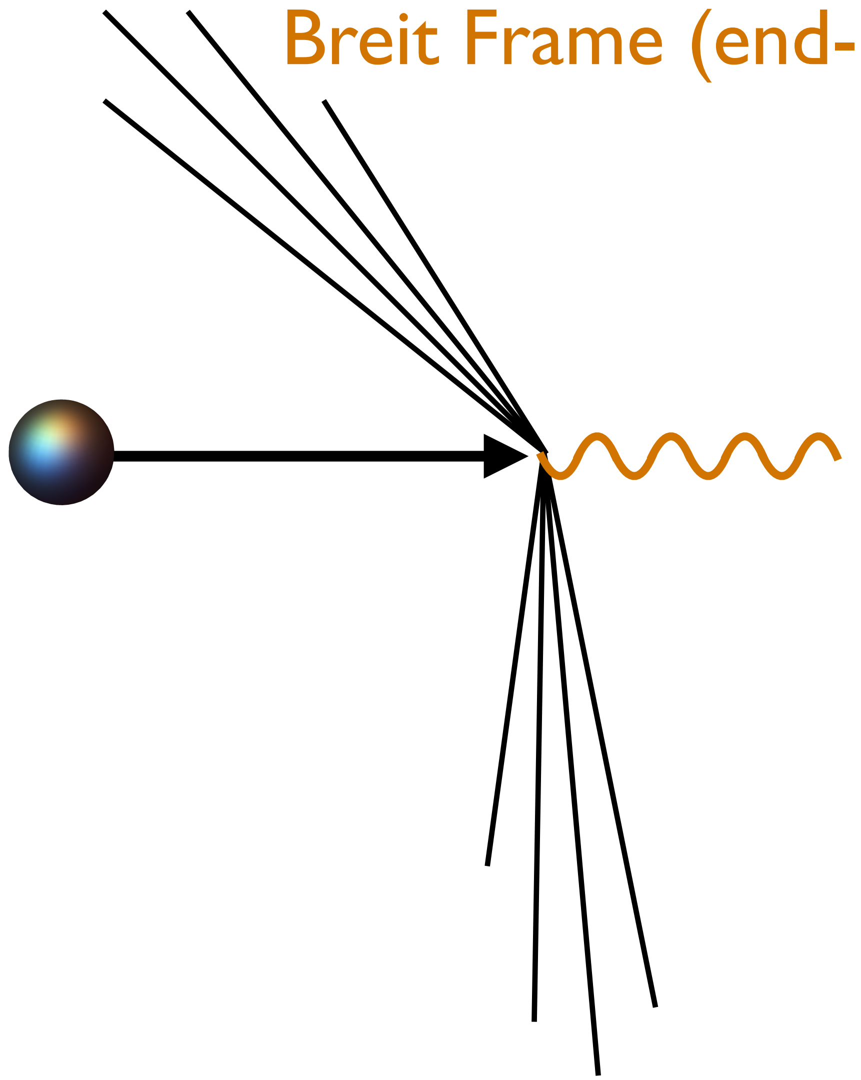




Adaptations of TEEC in DIS

arXiv: 2008.00271 (A. Ali, G. Li, W. Wang, Z-P. Xing)

Breit Frame (end-point: dijets)

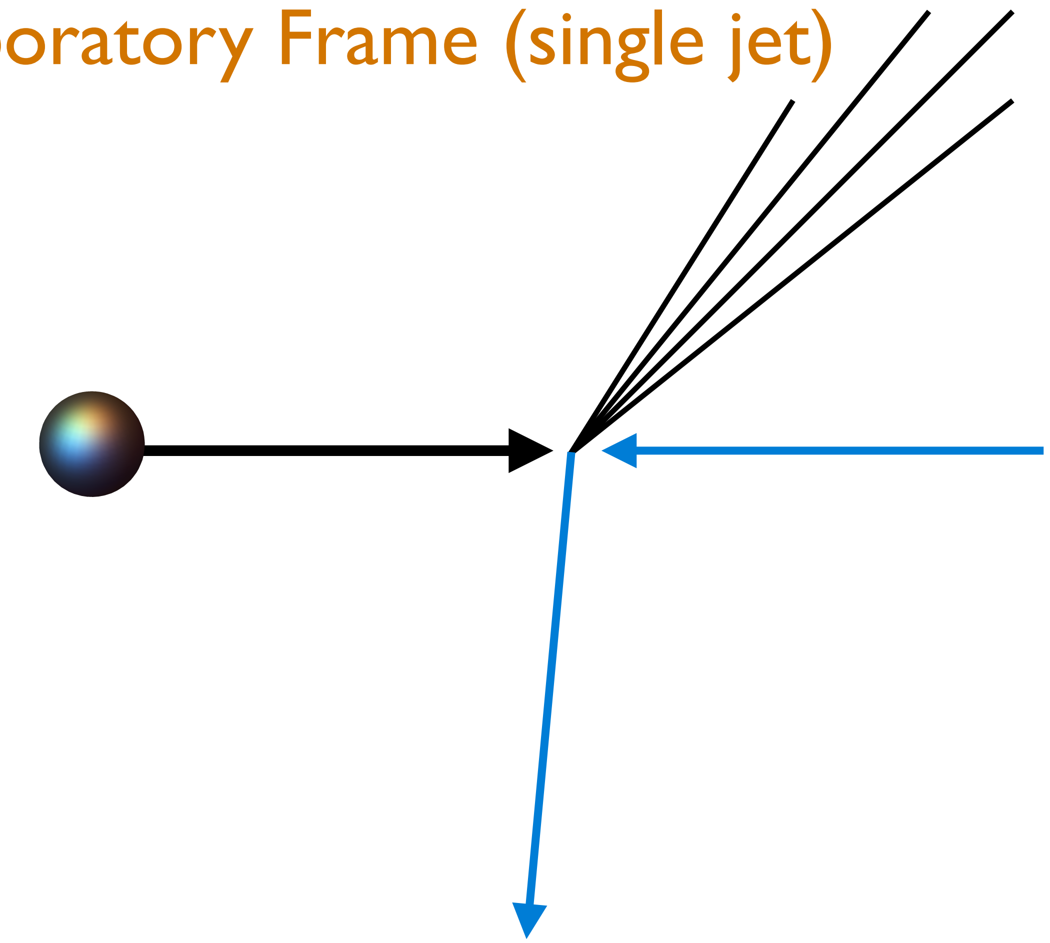


The definition is the same as before:

$$\mathrm{TEEC} = \sum_{a,b} \int \frac{d\sigma(ep \to a+b+X)}{\sigma} \frac{2E_{T,a}E_{T,b}}{(E_T^{\mathrm{total}})^2} \delta(\cos\phi_{ab} - \cos\phi)$$

arXiv: 2006.02437 (H. T. Li, I. Vitev, Y. J. Zhu)

Laboratory Frame (single jet)



Defined as lepton-hadron correlation:

$$\mathrm{TEEC}_{\mathrm{Lab.}} = \sum_{a} \int \frac{d\sigma(ep \to e+a+X)}{\sigma} \frac{2E_{T,l}E_{T,a}}{E_{T,l}E_T^{\mathrm{hadr.}}} \delta(\cos\phi_{ab} - \cos\phi)$$

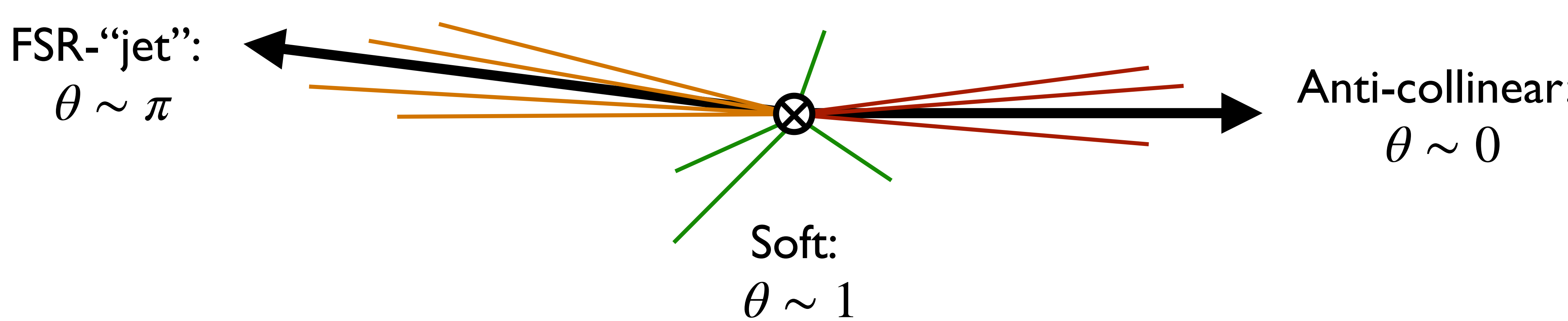
An EEC definition for DIS

$$z_a \equiv \frac{P\cdot p_a}{P\cdot q}\Big|_{\text{B.F.}} \simeq \frac{p_a^+}{Q}$$

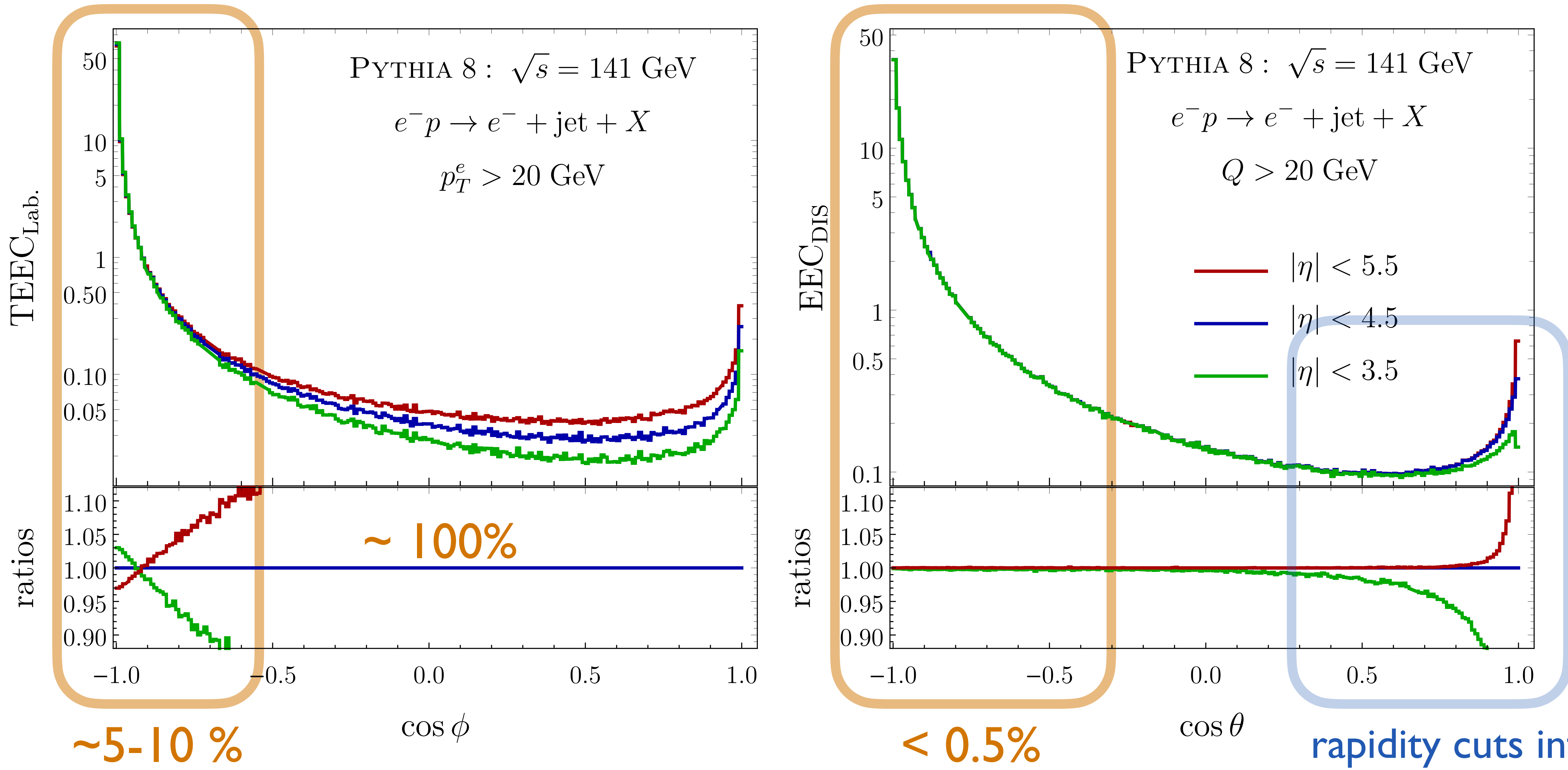
Soft and anti-collinear radiation is suppressed (also true in $\text{TEEC}_{\text{Lab.}}$)

$$\text{EEC}_{\text{DIS}} = \sum_a \int \frac{d\sigma_{ep\to e+a+X}}{\sigma}\, z_a\, \delta(\cos\theta_{ap} - \cos\theta)$$

Geometrical separation of: collinear, soft, and anti-collinear



Insensitive to (pseudo)rapidity constraints



rapidity cuts influence only the beam region

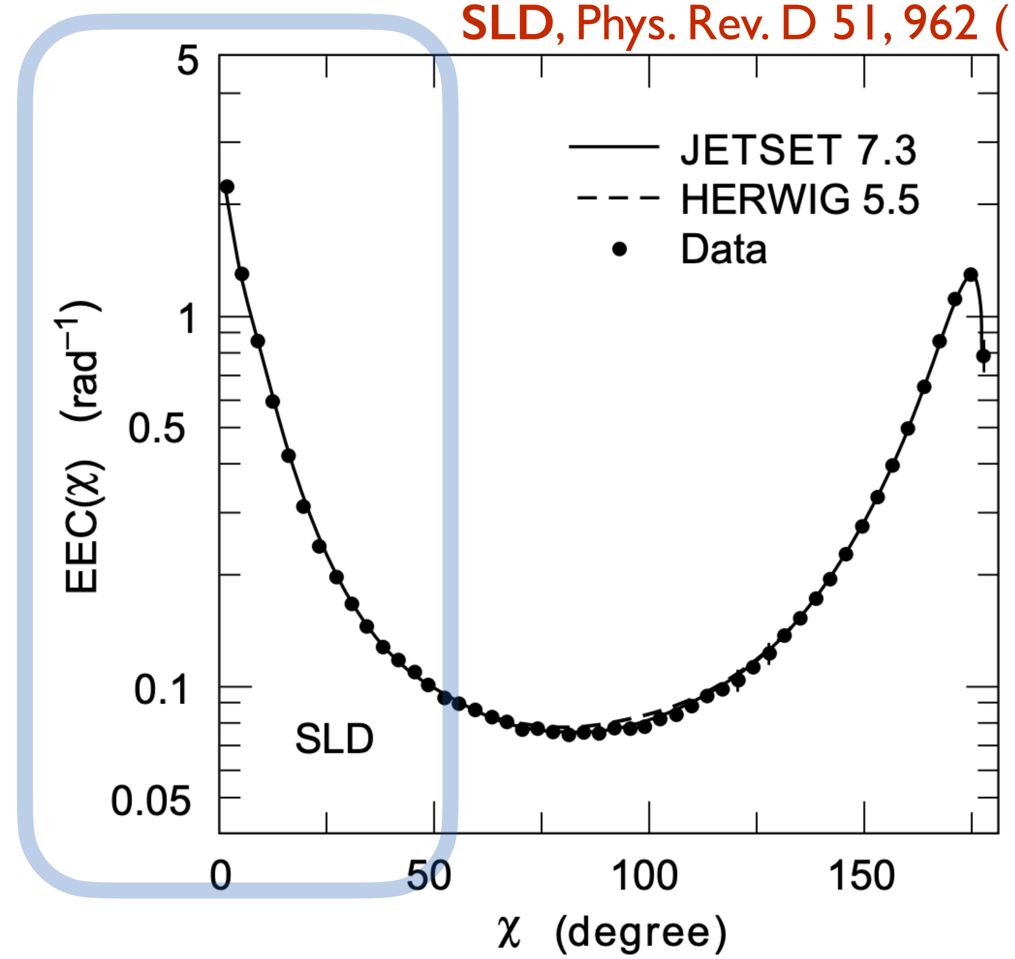
EEC as a probe to TMDs

$$\mathrm{EEC} = \sum_{a,b} \int \frac{d\sigma(e^+e^- \to a+b+X)}{\sigma} \frac{2E_aE_b}{s} \delta(\cos\theta_{ab} - \cos(\chi))$$

back-to-back limit:
TMD observable

EEC(back-to-back)
~
weighted TMD factorization

SLD, Phys. Rev. D 51, 962 (1995)



$$\mathrm{EEC}_{\mathrm{DIS}} = \sum_{a} \int \frac{d\sigma_{ep\to e+a+X}}{\sigma} z_a\, \delta(\cos\theta_{ap} - \cos\theta)$$

Connection to universal TMDs (unpolarized case)

$\cos\theta \sim -1$

$$\mathrm{EEC}_{\mathrm{DIS}} = \sigma_0(Q,x,y) H_{ij}(Q,x,\mu) \int d\boldsymbol{q}_T\, \delta\Big(\cos\theta - \frac{2|\boldsymbol{q}_T|^2}{Q^2} + 1\Big) \int \frac{d\boldsymbol{b}}{(2\pi)^2} \exp(-i\boldsymbol{b}\cdot\boldsymbol{q}_T)\, f_{1,\,j\leftarrow P}(x,b,\mu,\nu)\, J_i(b,\mu,\nu)$$

* universal = back-to-back four Wilson-line soft function incorporated into the definition.

TEEC case: **Not** back-to-back

Does not involve the variable z_h included TMD studies in SIDIS

TMD PDF

The **universal*** TMD parton distribution function, unpolarized in this case.
For Trans. pol. beam modification: replace with Sivers.

EEC Jet function

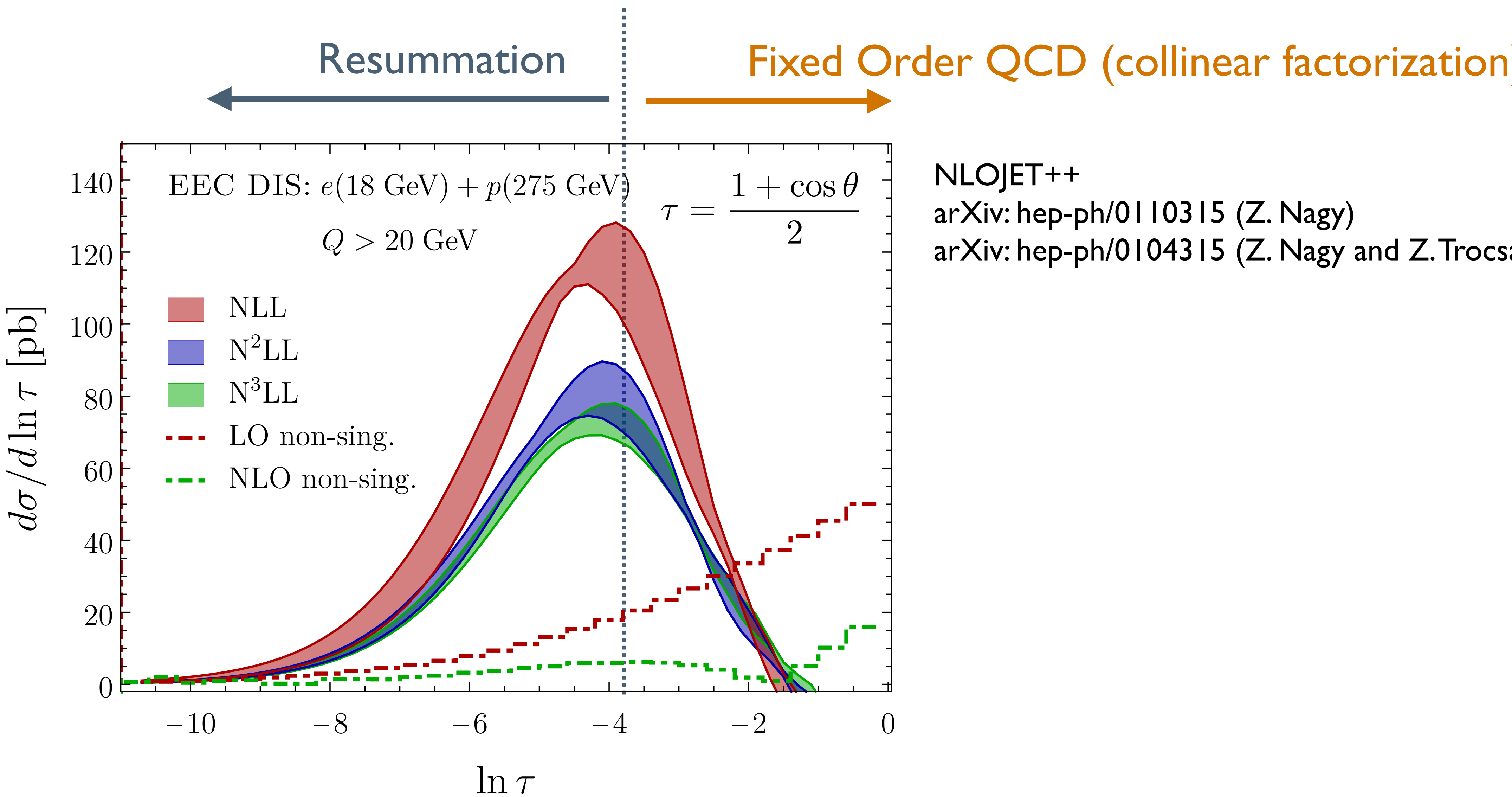
The same jet function that appears in the original EEC observable. Can be written as the weighed integral of the **universal*** TMD fragmentation functions.

$$J_i(b,\mu,\nu) = \sum_a \int_0^1 dz\; z\; D_{i\to a}(z,b,\mu,\nu)$$

$\mathrm{N}^3\mathrm{LL} + \mathcal{O}(\alpha_s^2)$ predictions

$\cos\theta \sim -1$

$$\mathrm{EEC}_{\mathrm{DIS}} = \sigma_0(Q,x,y) H_{ij}(Q,x,\mu) \int d\boldsymbol{q}_T\, \delta\Big(\cos\theta - \frac{2|\boldsymbol{q}_T|^2}{Q^2} + 1\Big) \int \frac{d\boldsymbol{b}}{(2\pi)^2} \exp(-i\boldsymbol{b}\cdot\boldsymbol{q}_T)\, f_{1,\,j\leftarrow P}(x,b,\mu,\nu)\, J_i(b,\mu,\nu)$$



NLOJET++
arXiv: hep-ph/0110315 (Z. Nagy)
arXiv: hep-ph/0104315 (Z. Nagy and Z. Trocsanyi)

EEC jet function: hadronization effects

$$J_i(b,\mu,\nu) = \sum_a \int_0^1 dz\; z\; D_{i\to a}(z,b,\mu,\nu)$$

$$J_i^{\mathrm{OPE}}(b,\mu,\nu) = \sum_j \int_0^1 dz\; z\; \mathcal{I}_{ij}(b,z,\mu,\nu)$$

perturbative matching onto collinear-FFs

Sum rules for FF

$$D_{i\to a}(z,b,\mu,\nu) = \sum_j \int_z^1 \frac{du}{u} \mathcal{I}_{ij}\Big(b,\frac{z}{u},\mu,\nu\Big) d_{j\to a}(u,\mu) + \mathcal{O}\Big(\Lambda_{\mathrm{QCD}}^2 b^2, \frac{\Lambda_{\mathrm{QCD}}^2}{Q^2}\Big)$$

Ansatz used in extractions of TMD-FF

$$\sqrt{S} D_{i/a}(z,b;\mu_0,\nu_0) = \sqrt{S^{\mathrm{pert.}}} D_{i/a}^{\mathrm{OPE}}(z,b;\mu_0,\nu_0) D_{i/a}^{\mathrm{NP}}(z,b)$$

$$\sqrt{S} J_i(b,\mu_0,\nu_0) = \sqrt{S^{\mathrm{pert.}}} J_i^{\mathrm{OPE}}(b,\mu_0,\nu_0)\, j_i(b)$$

Chalenges

Prone to experimental uncertainties due to the inclusion of neutral particles

Handle over flavor separation

$$j_i(b) = \Big[J_i^{\mathrm{OPE}}(b,\mu_0,\nu_0)\Big]^{-1} \sum_a \int_0^1 dudy\,(uy)\; \mathcal{I}_{ij}\Big(\frac{b}{u},u;\mu_0,\nu_0\Big)\; d_{i/a}(y,\mu_0)\; D_{i/a}^{\mathrm{NP}}(uy,b)$$

EEC jet function: hadronization effects

$$j_i(b) = \Big[J_i^{\rm OPE}(b,\mu_0,\nu_0)\Big]^{-1} \sum_a \int_0^1 du dy\,(uy)\ \mathcal{I}_{ij}\Big(\frac{b}{u}, u; \mu_0, \nu_0\Big)\ d_{i/a}(y,\mu_0)\ D_{i/a}^{\rm NP}(uy, b)$$

arXiv:0707.1506 (D. de Florian, R. Sassot, M. Stratmann)
arXiv:hep-ph/0703242 (D. de Florian, R. Sassot, M. Stratmann)

$$D_{i/a}^{\rm NP}(y,b) = \exp\Big(-0.042\frac{b^2}{y^2}\Big)$$

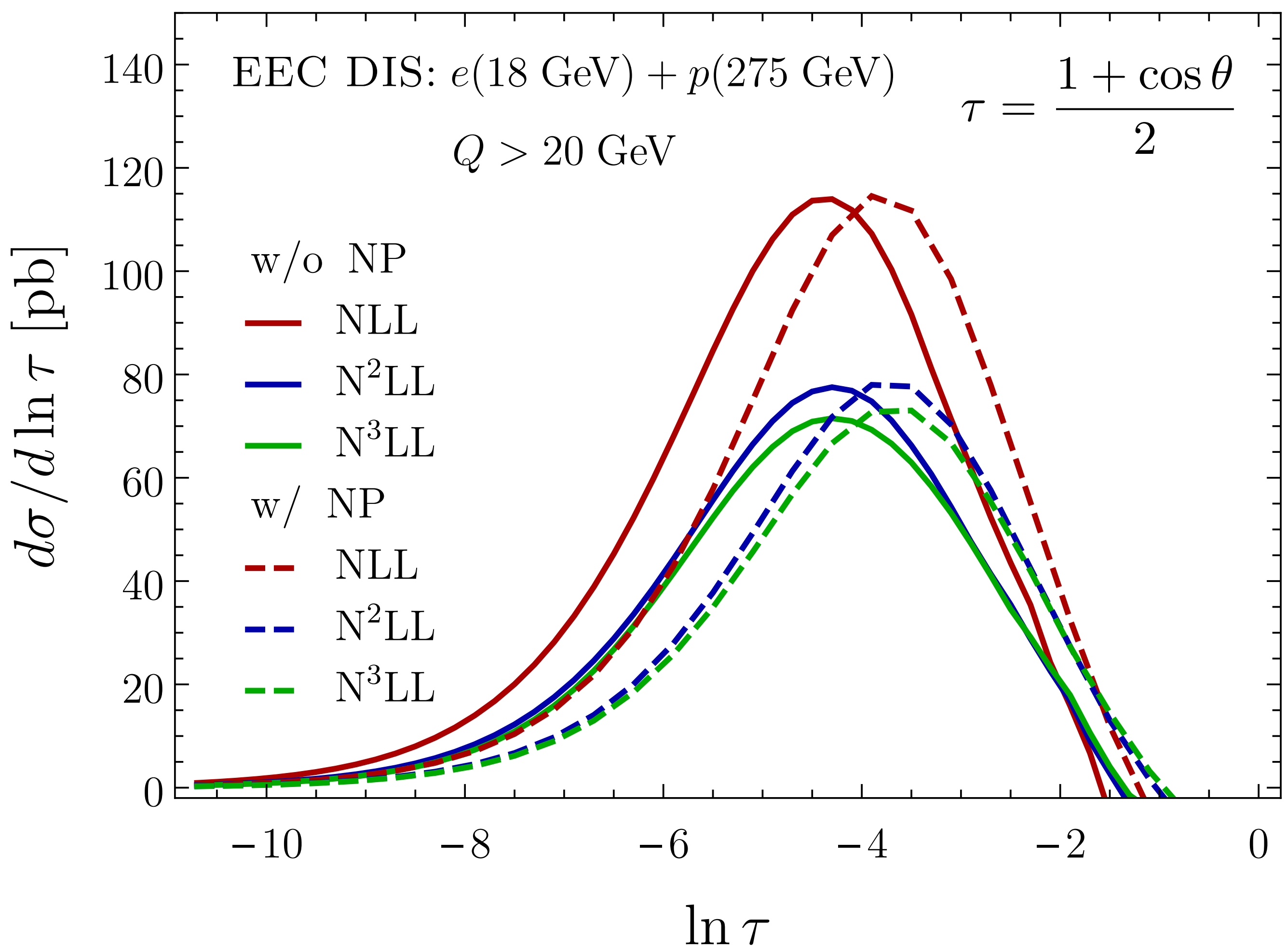
arXiv:1406.3073 (P. Sun, J. Isaacson, C.-P. Yuan, F. Yuan)
arXiv:1505.05588 (A. Prokudin, P. Sun, F. Yuan

+
LO perturbative
components

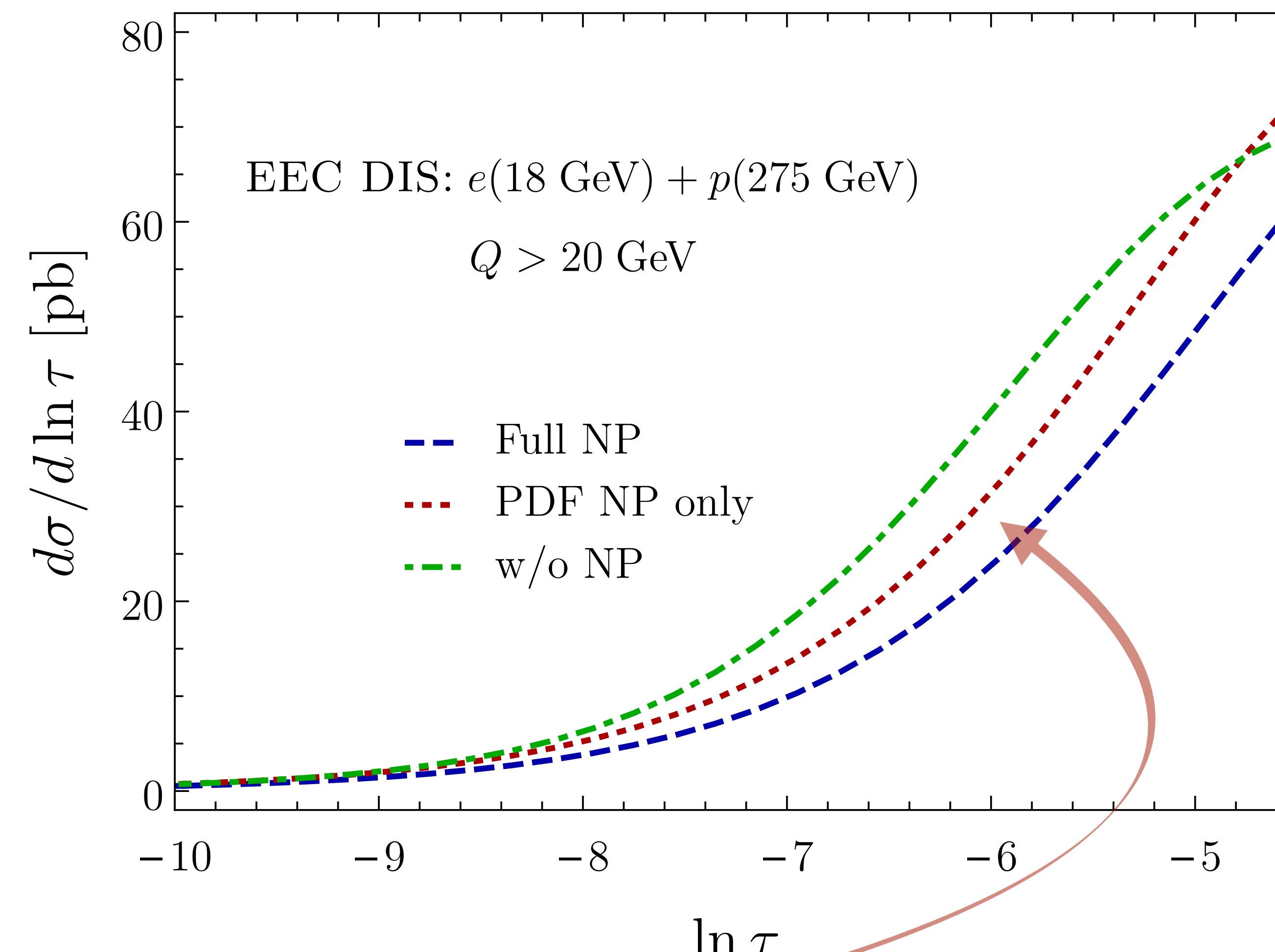
$$j_i(b) = \exp\Big(-0.59b - 0.03b^2\Big)$$

EEC jet function: hadronization effects

Effect of total NP
(TMDPDF + EECjet + Rapidity AD)



Decomposition of NP elements



$$j_i(b) = \exp\Big(-0.59b - 0.03b^2\Big)$$

Summary and Outlook

Introduce definition of EEC in DIS

Provide a factorized cross-section in terms of TMD elements

Provide $\mathrm{N^3LL} + \mathcal{O}(\alpha_s^2)$ predictions

Evaluate NP component of EEC jet function from past TMDFF extractions

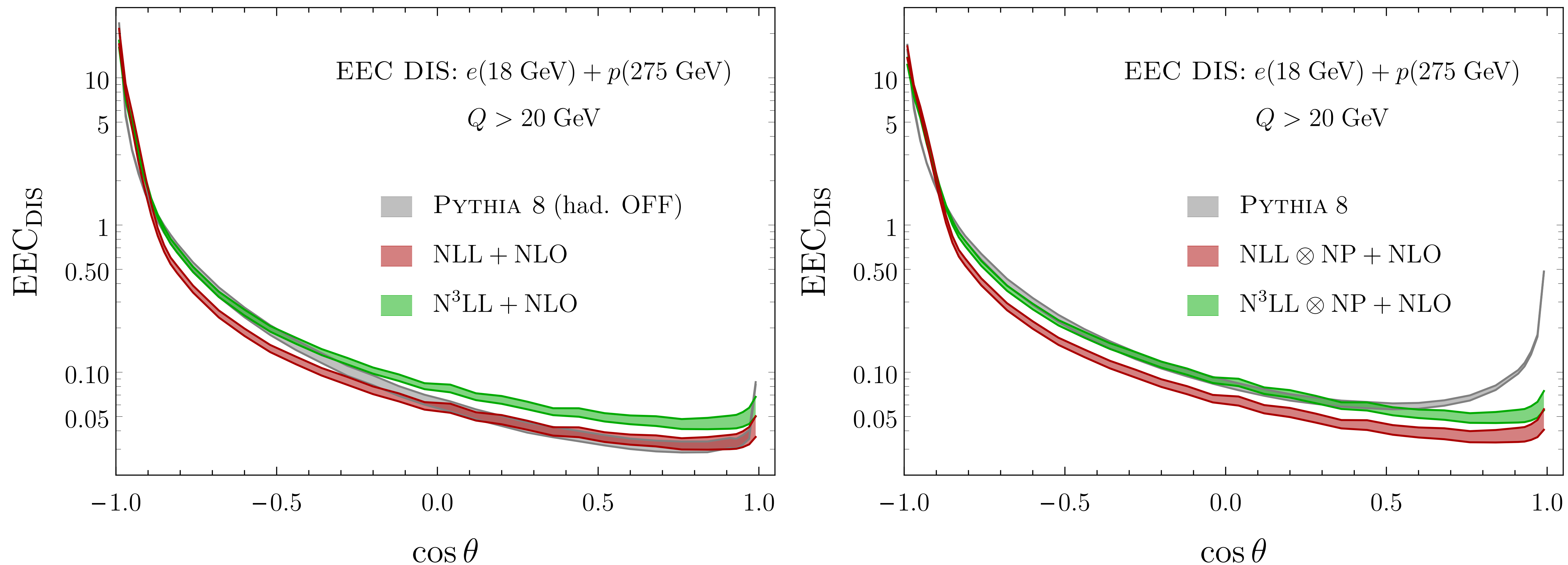
Expand the definition to charge particles only!

Break flavor degeneracy with FSR particle selection

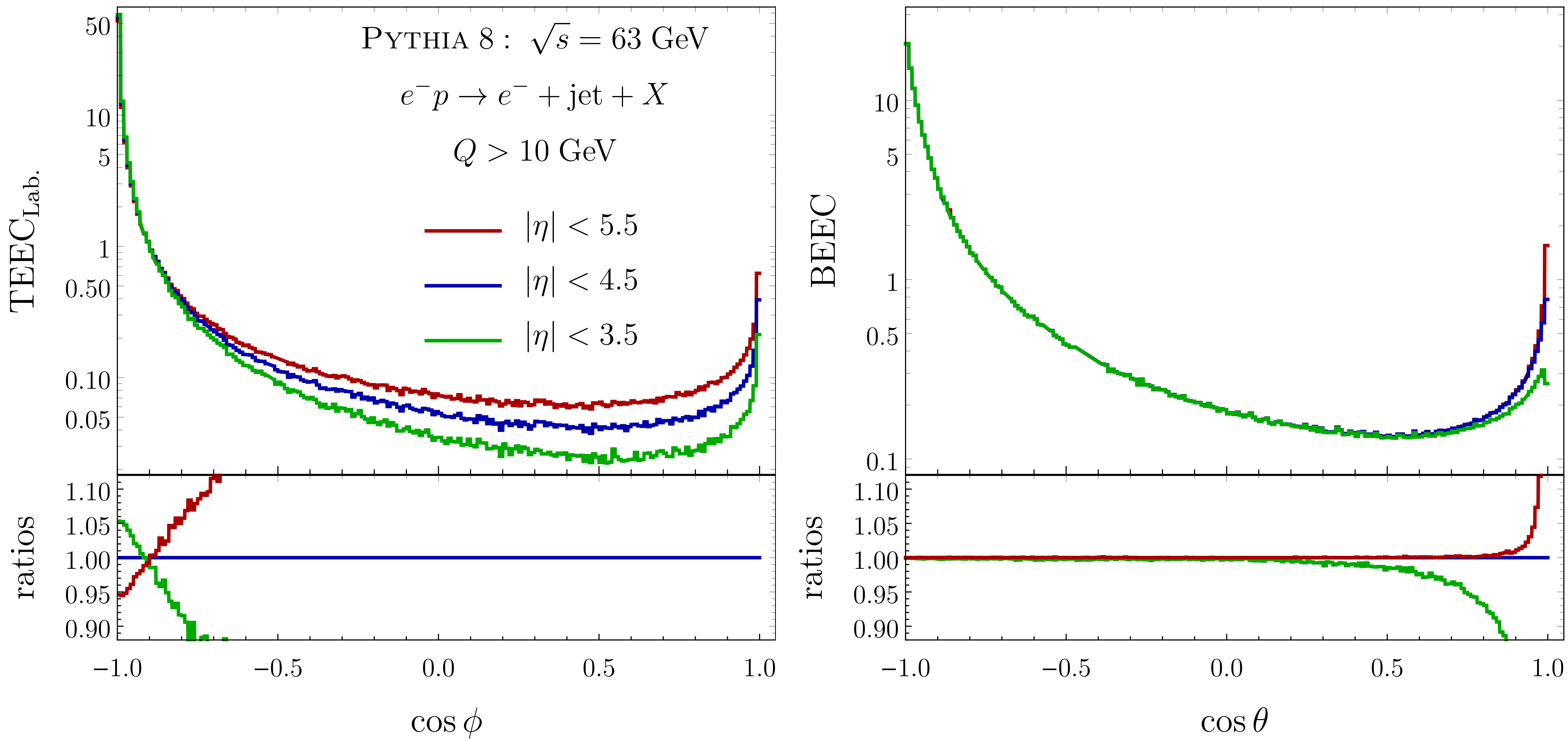
Plethora of EEC data in e^+e^- could be utilized for sim. extraction of rapidity AD EEC jet function and strong coupling

Spin effects: Sivers!

$\mathrm{N^3LL} + \mathcal{O}(\alpha_s^2)$ predictions



EIC kinematics 2



Charged particles and flavor separation: $\sum_a \to \sum_{a\in\mathbb{S}}$

$$J_i(b,\mu,\nu) \to \mathcal{G}_{i\to\mathbb{S}}(b,\mu,\nu) = \sum_{a\in\mathbb{S}} \int_0^1 dz\, z D_{i/a}(z,\boldsymbol{b};\mu,\nu)$$

perturbative matching
onto collinear-FFs

$$\mathcal{G}^{\mathrm{OPE}}_{i\to\mathbb{S}}(b,\mu,\nu) = \sum_j \mathcal{P}_{j\to\mathbb{S}} \int_0^1 dz\; z\; \mathcal{I}_{ij}(b,z,\mu,\nu)$$

~~Sum rules for FF~~

$$D_{i\to a}(z,b,\mu,\nu) = \sum_j \int_z^1 \frac{du}{u} \mathcal{I}_{ij}\Big(b,\frac{z}{u},\mu,\nu\Big) d_{j\to a}(u,\mu) + \mathcal{O}\Big(\Lambda^2_{\mathrm{QCD}} b^2, \frac{\Lambda^2_{\mathrm{QCD}}}{Q^2}\Big)$$

Ansatz used in extractions of TMD-FF

$$\sqrt{S}\mathcal{G}_{i\to\mathbb{S}}(\boldsymbol{b},\mu,\nu) = \sqrt{S^{\mathrm{pert}}} R(\boldsymbol{b},\mu,\nu)\, \mathcal{G}^{\mathrm{OPE}}_{i\to\mathbb{S}}(\boldsymbol{b},\mu_0,\nu_0)\, g_{i\to\mathbb{S}}(\boldsymbol{b})$$

$$\mathcal{G}^{\mathrm{OPE}}_{i\to\mathbb{S}}(\boldsymbol{b},\mu,\nu) = \sum_j \mathcal{F}_{j\to\mathbb{S}}(\mu) \int_0^1 dw\; w\; \mathcal{I}_{ij}\Big(\frac{\boldsymbol{b}}{w}, w;\mu,\nu\Big)$$

Interesting cases

$\mathbb{S} =$ all charge hadrons

$\mathbb{S} = h$

$$g_{i\to\mathbb{S}}(\boldsymbol{b}) = \Big[\mathcal{G}^{\mathrm{OPE}}_{i\to\mathbb{S}}(\boldsymbol{b},\mu_0,\nu_0)\Big]^{-1} \sum_{a\in\mathbb{S}} \int_0^1 dz\, z D_{i/a}(z,\boldsymbol{b};\mu_0,\nu_0)$$