Possible α_s extraction in the unexpected post-confinement regime of EEC

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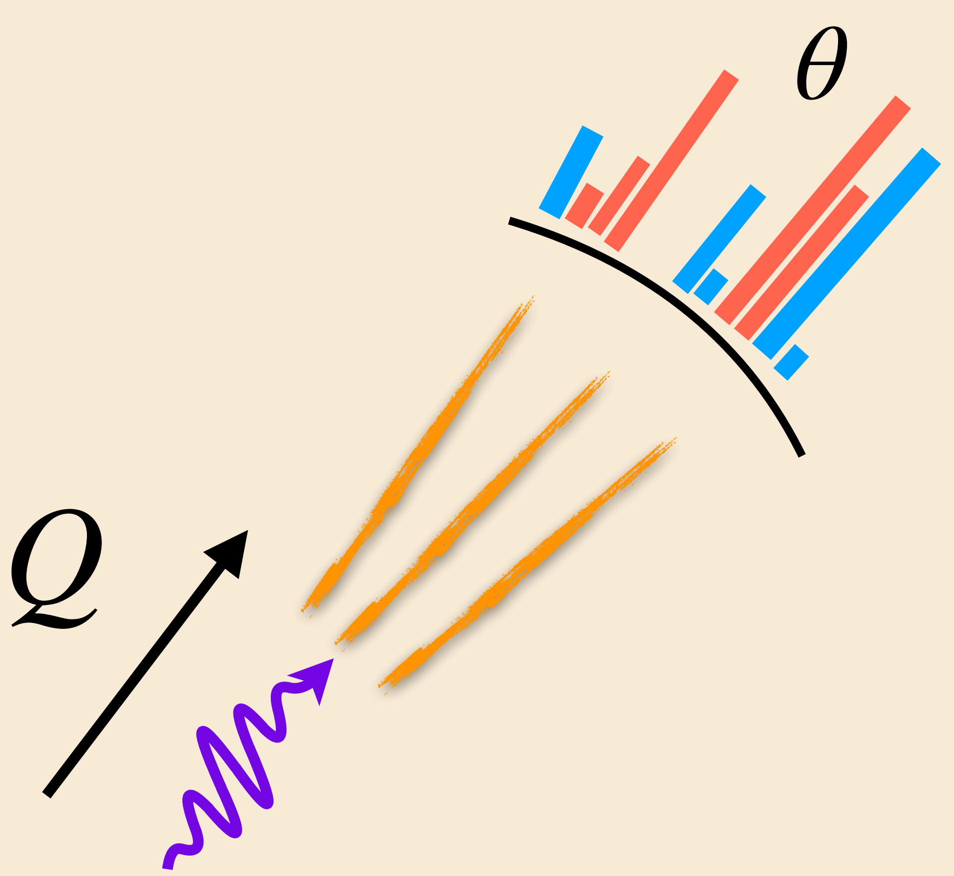
PRL 134 (2025), PRL 136 (2026)

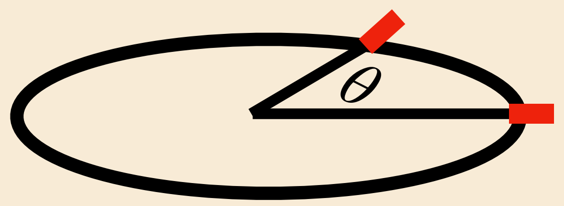
Zhan Wang ,et al. In preparation

Outline

- Scaling behavior of the post-confinement EEC
  - light-ray OPE Analysis
- Phenomenology
  - Comparison with current data
  - α_s extraction
- Conclusion

Energy Energy Correlators



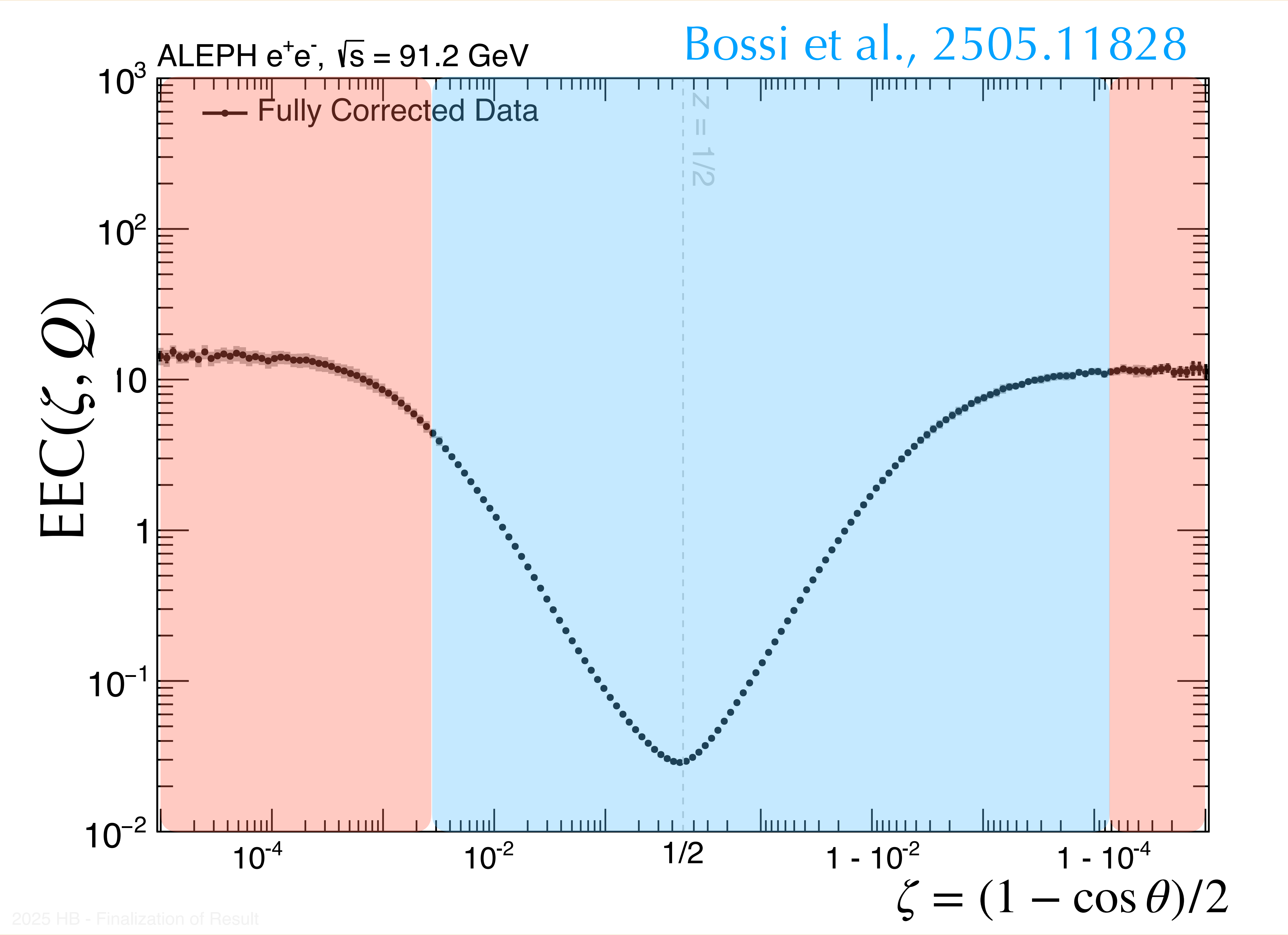


$$\text{EEC} = \frac{1}{\sigma}\int d\sigma \sum_{ij} \frac{E_i E_j}{Q^2}\delta(\theta - \theta_{ij})$$

$$= \frac{\langle \mathcal{E}(n_i)\mathcal{E}(n_j)\rangle}{Q^2} \qquad \mathcal{E}(n) = \lim_{\bar{n}\cdot x\to\infty} (\bar{n}\cdot x)^{4-2}\int dn \cdot x T_{\mu\nu}\bar{n}^\mu \bar{n}^\nu$$

Sterman, 1975, Bashman, et al. 1978

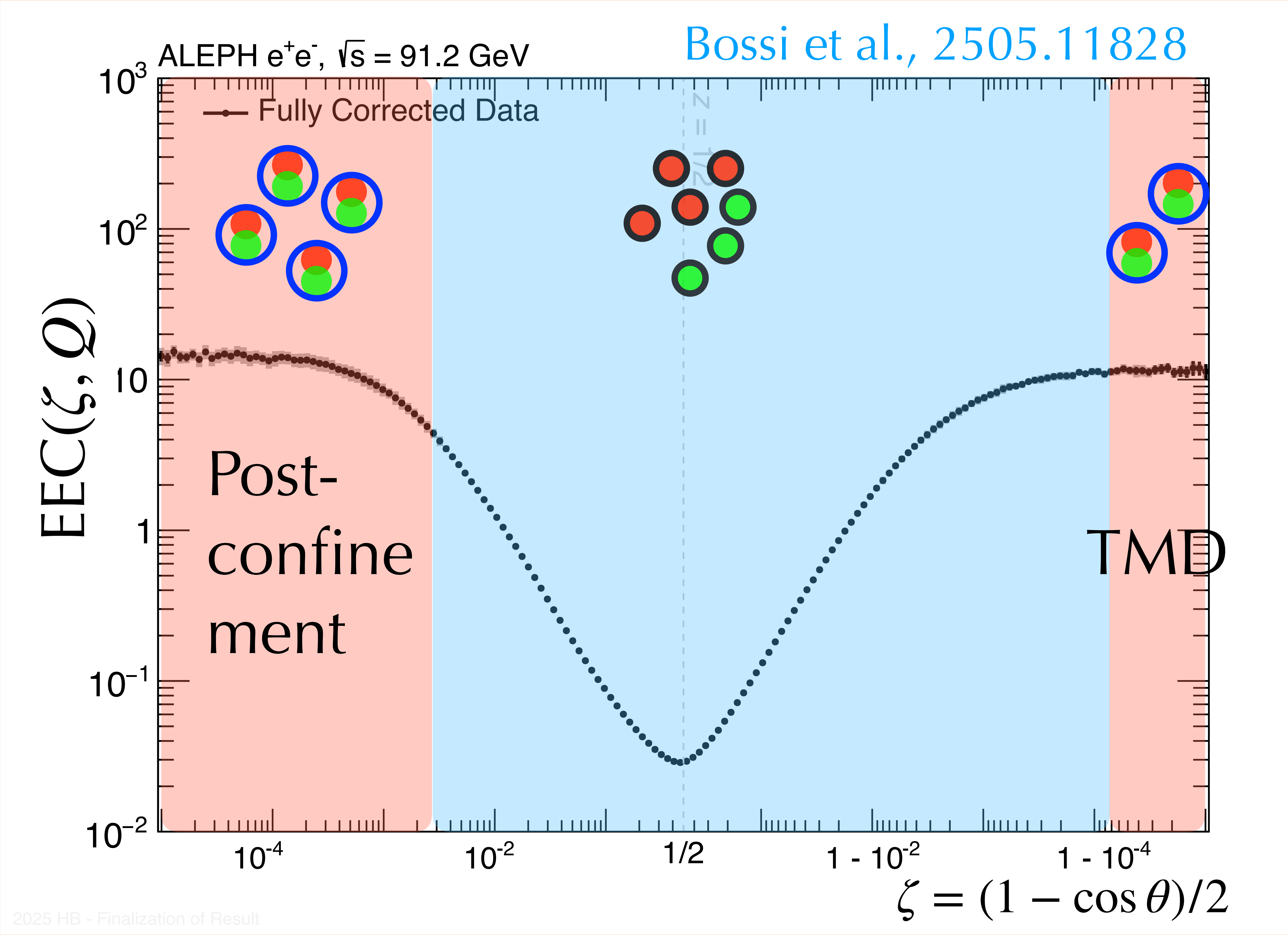
Moult, Zhu, 2506.09119 for reivew

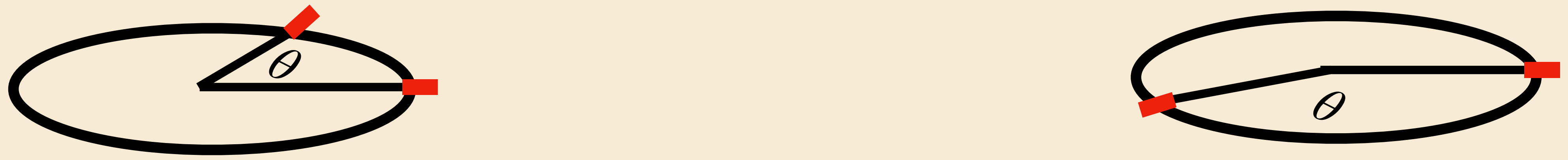


- Jet w/o jet algorithms, a portal to hadrons
- Fundamental object in QFT

Energy Energy Correlators

- Different angles probe physics at different scales $\sim Q\min(\sqrt{\zeta}, \sqrt{1-\zeta})$
- Most regions are well-understood
- The post-confinement region, $\zeta \to 0 \lesssim \Lambda_{QCD}/Q$, remains challenging





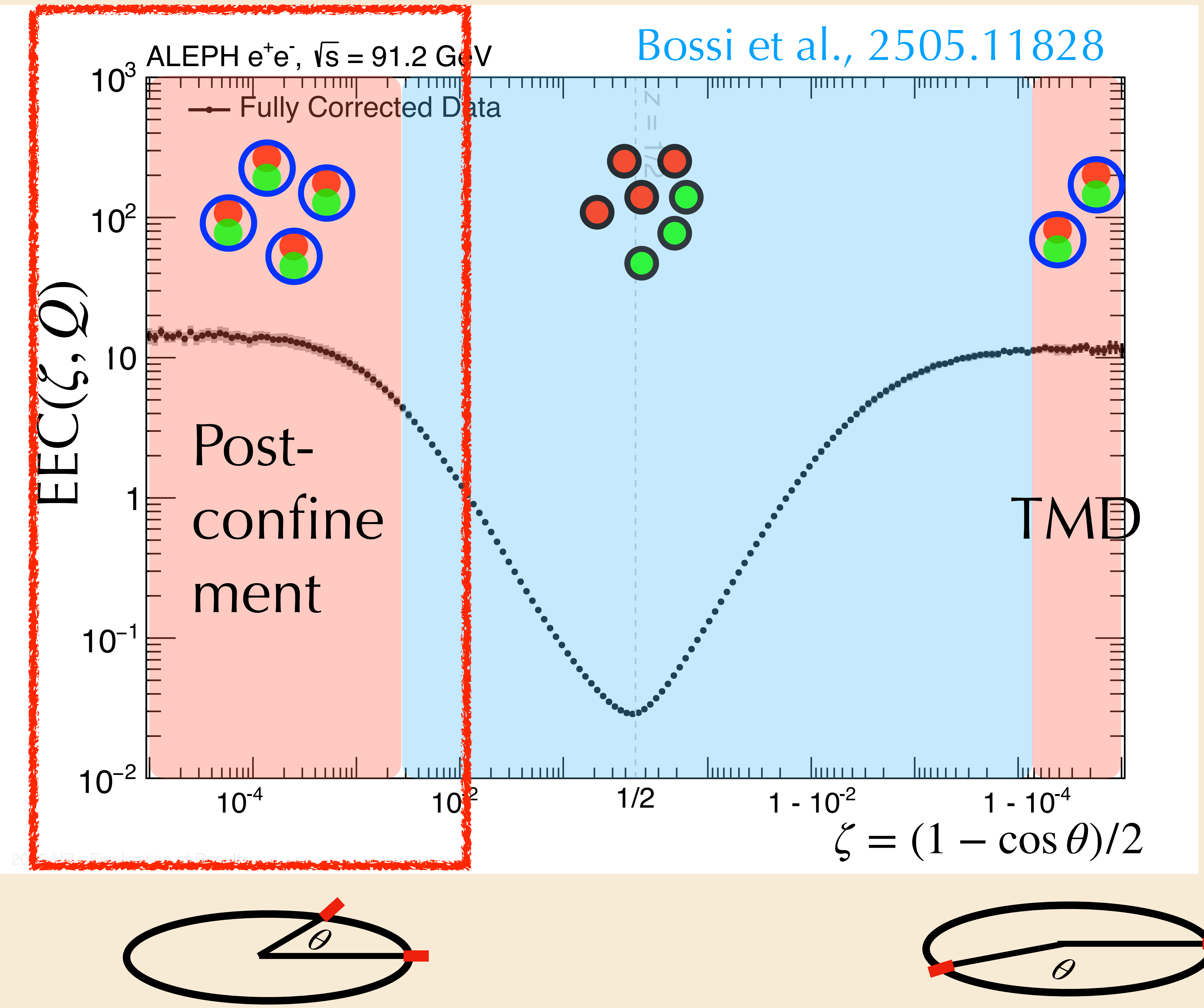
Energy Energy Correlators

- The post-confinement region, $\zeta \to 0 \lesssim \Lambda_{QCD}/Q$

AdS/CFT: Hofman, Maldacena, 2008

$$\mathrm{EEC}(\zeta) \sim 1 + \frac{6\pi^2}{\lambda}\left(\frac{2}{3} - 4\zeta(1-\zeta)\right) + \ldots$$

- Height of the plateau $\propto Q^0$
- The shape is only a function of ζ or θ



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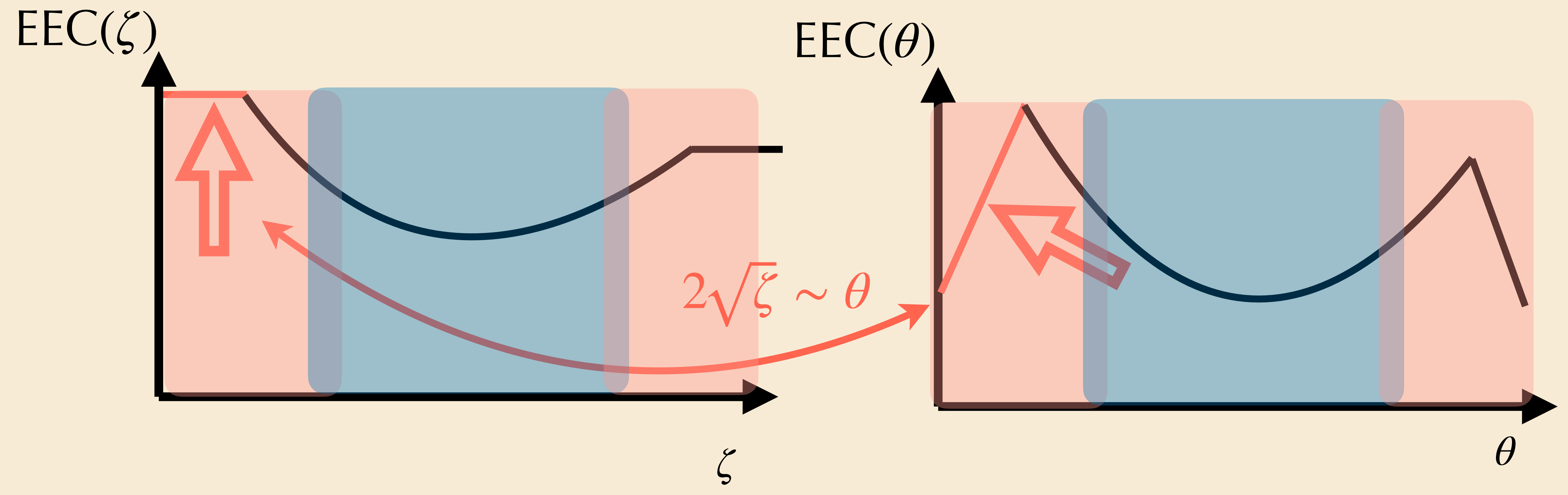
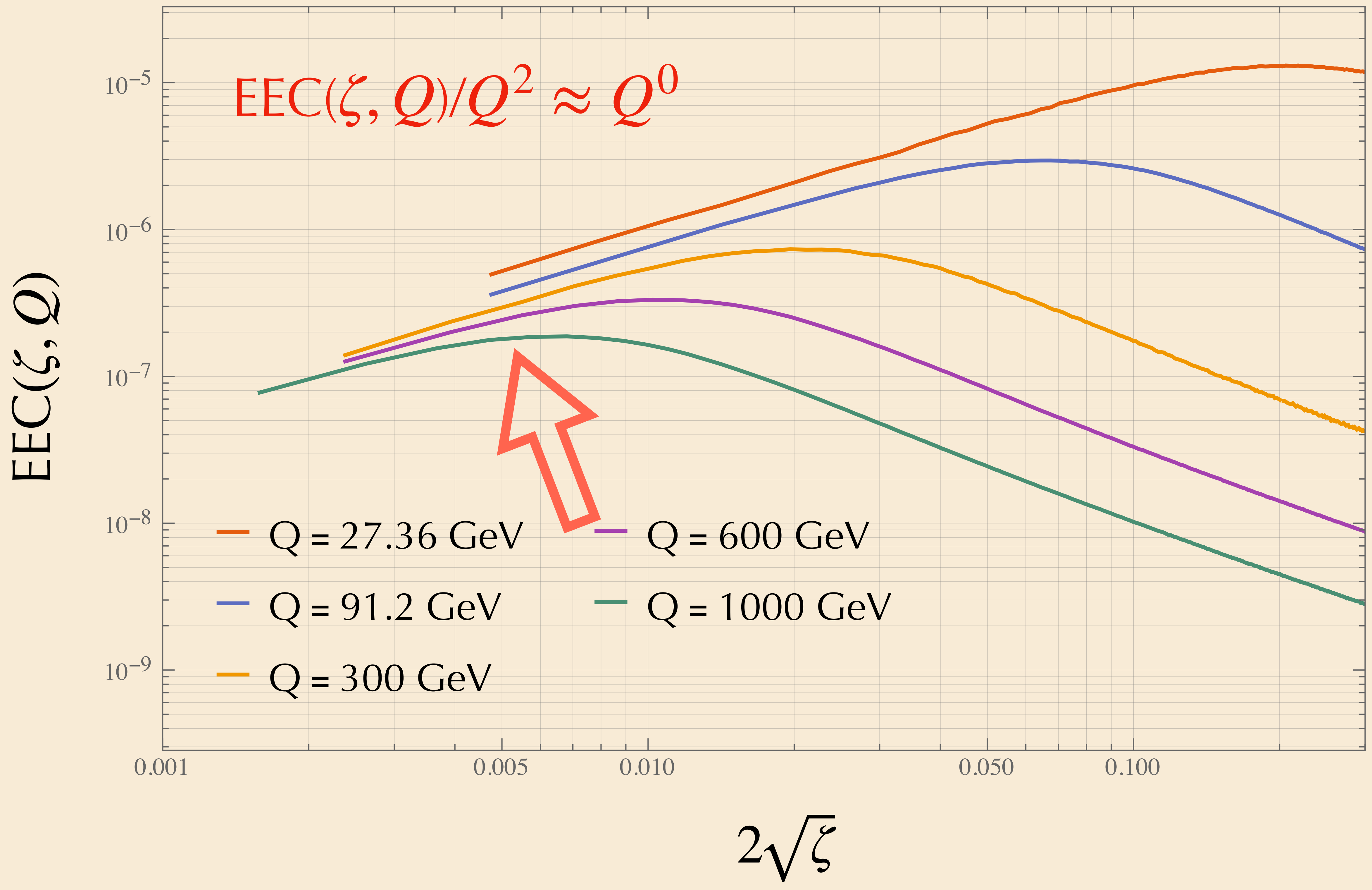


Real World:

XL, Vogelsang, Yuan, Zhu, PRL 134 (2025)



- Height of the plateau $\propto Q^2$ + corrections
- The shape also depends on Q
- EEC $\sim Q^2/\Lambda^2_{QCD}$

Scaling behavior by light-ray OPE

Chang, Chen, **XL**, Simmons-Duffin, Yuan, Zhu, PRL 136 (2026) 8, 081903

Approach using dihadron picture see: Lee, Stewart, PRL 2026

Kang, et al., PRL 2026

Guo, et al., PRL 2026

Scaling behavior by ~~light-ray OPE~~

primary school math

Chang, Chen, XL, Simmons-Duffin, Yuan, Zhu, PRL 136 (2026) 8, 081903

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Scaling behavior by light-ray OPE

Scaling under
$n \to \rho n, \bar{n} \to \rho^{-1}\bar{n}$
$\mathbb{O}(\rho n) = \rho^{J_L}\mathbb{O}(n)$

Dimension,
classic scaling

$$\mathbb{O}^{-\Delta_L, J_L} \sim \lim_{\bar{n}\cdot x \to \infty} (\bar{n}\cdot x)^{\Delta - J} \int dn \cdot x \, \mathcal{O}^{\Delta, J}_{\mu_1 \ldots \mu_J}(x)\bar{n}^{\mu_1}\ldots\bar{n}^{\mu_J}$$

Spin

e.g. $T_{\mu\nu}$

$\bar{\psi}\gamma_{\mu_1} iD_{\mu_2}\ldots iD_{\mu_J}\psi$

1905.01311

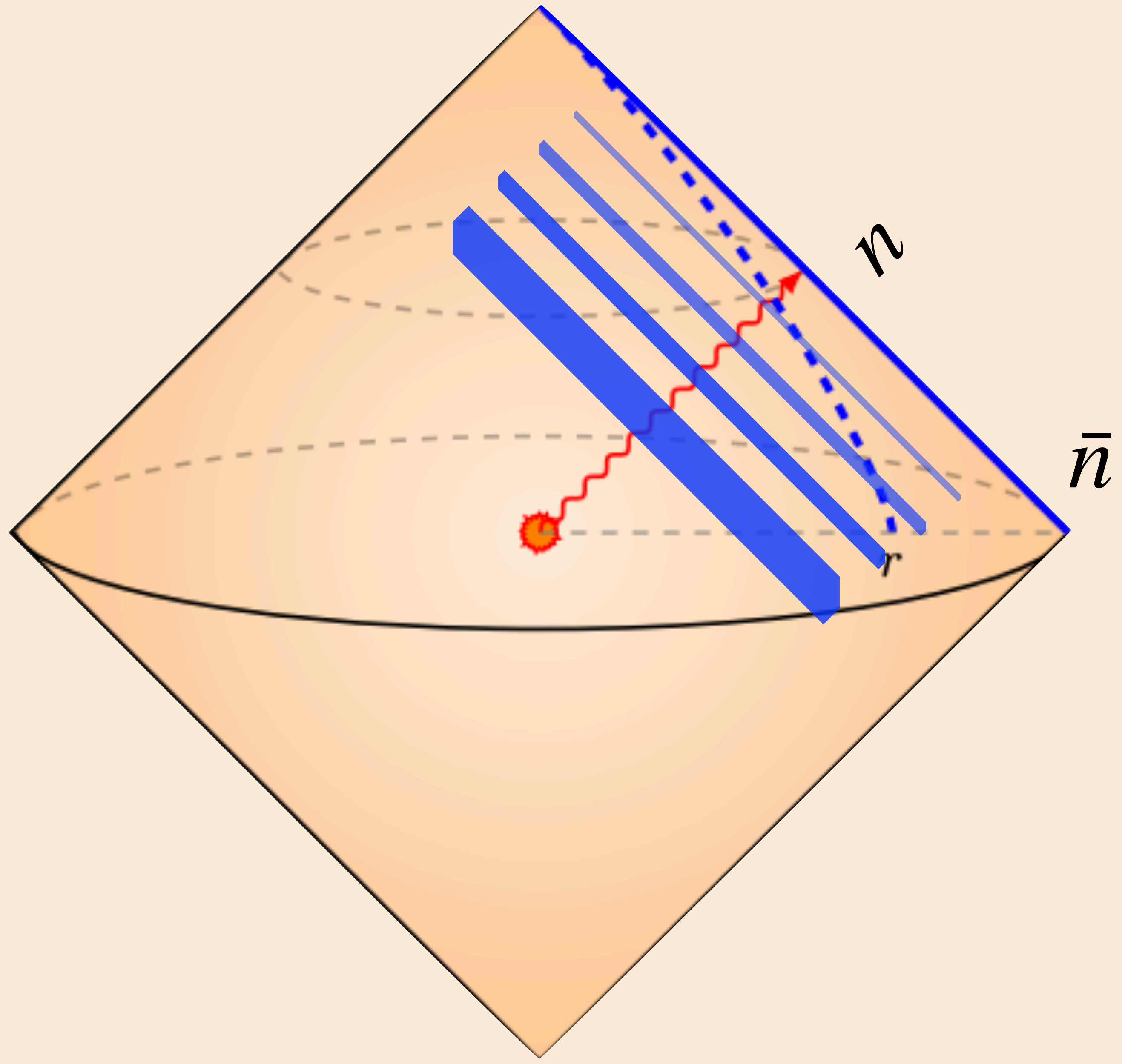
Light-ray operator

Light transform

Local operator

$$-\Delta_L = \Delta - 1 - \Delta + J = J - 1 \quad J_L = -\Delta + J + 1 - J = -\Delta + 1$$

$$\Delta_L - J_L = \Delta - J = \tau$$ Conserves twist



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$n \to \rho n, \bar{n} \to \rho^{-1}\bar{n}$
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1905.01311

$$\mathbb{O}^{-\Delta_L, J_L} \sim \lim_{\bar{n}\cdot x \to \infty} (\bar{n}\cdot x)^{\Delta - J} \int dn \cdot x \, \mathcal{O}^{\Delta, J}_{\mu_1 \ldots \mu_J}(x) \bar{n}^{\mu_1} \ldots \bar{n}^{\mu_J}$$

Light-ray operator

Light transform

Local operator

Dimension, classic scaling

Spin

$\mathcal{E}$: $-\Delta_L = 2 - 1 = 1\,, \quad J_L = -4 + 1 = -3$ $\quad T_{\mu\nu}$

$\sqrt{\zeta}$: $-\Delta_L = 0\,, \quad J_L = 1$ $(p_\perp \sim \bar{n}\cdot P\sqrt{\zeta}$ unchanged under boost)

$\mathcal{D}_{\text{DGLAP}}$, Light-ray transformation of the local twist-2 operators: $\tau = 2 = \Delta - J = \Delta_L - J_L$ $\quad \bar{\psi}\gamma_{\mu_1} iD_{\mu_2}\ldots iD_{\mu_J}\psi$

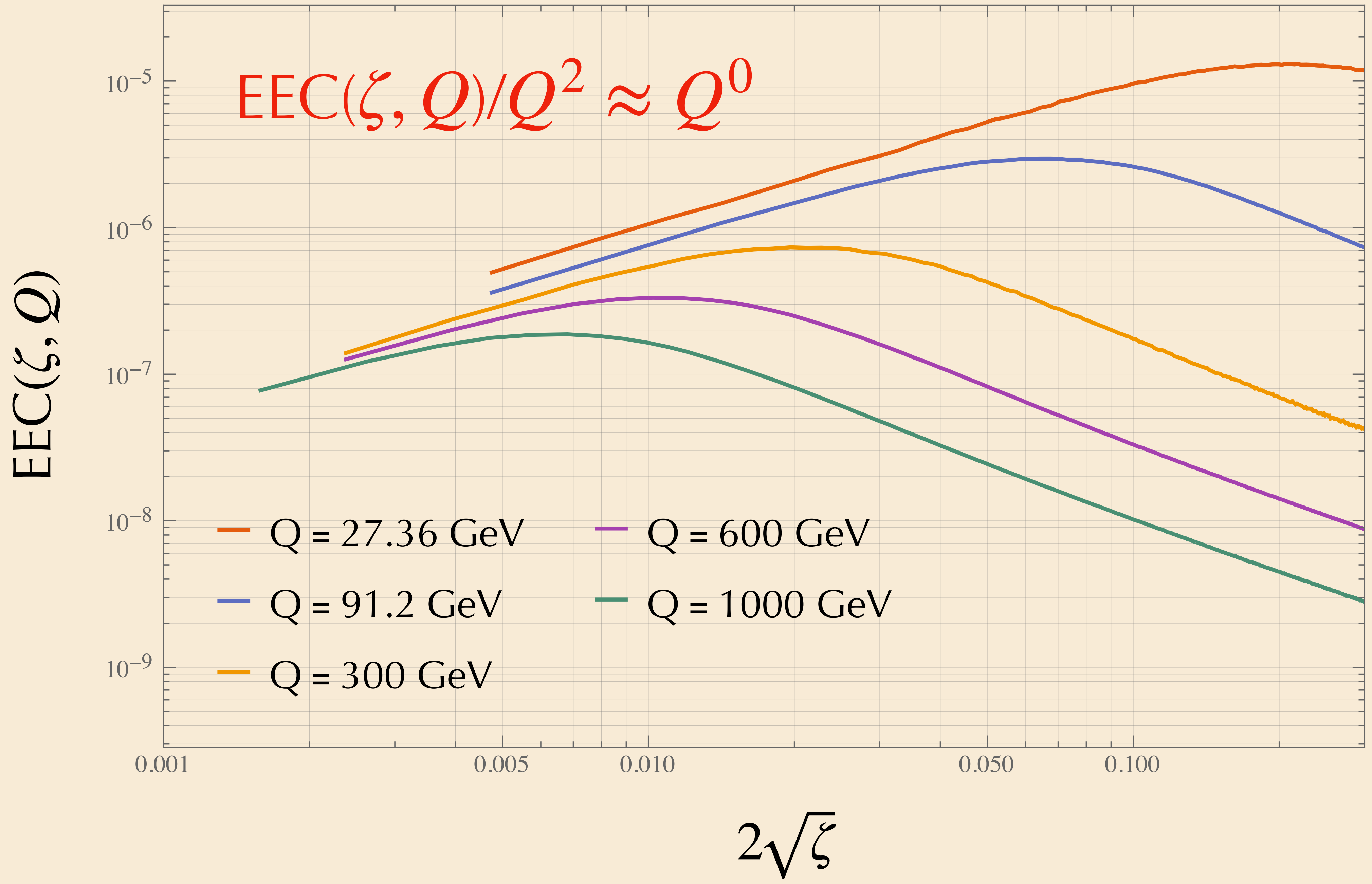
$$\frac{d\mathcal{D}_{\text{DGLAP}}}{d\ln\mu^2} = \hat{\gamma}(J)\mathcal{D}_{\text{DGLAP}}$$

Scaling behavior by light-ray OPE

$$\lim_{n_1 \to n_2} \mathcal{E}(n_1)\mathcal{E}(n_2) \approx z^0 \frac{1}{\Lambda_{\rm QCD}^2} \mathcal{F}(\mu^2) \times \mathcal{D}_{\rm DGLAP}^{-\Delta_L = -(2-6)=4, J_L=-6}(\mu^2) + \mathcal{O}(z, \Lambda_{\rm QCD}^{-1})$$

$-\Delta_{L,\mathcal{E}\mathcal{E}} = 2 \quad J_{L,\mathcal{E}\mathcal{E}} = -6$

- Light-ray OPE conserves quantum numbers
- $\langle \mathcal{D}_{\rm DGLAP}^{-\Delta_L=4, J_L=-6}(\mu^2)\rangle \sim \langle \mathbb{L}[\bar{\psi}\gamma^+(iD_+)^{J-1=5-1=4}\psi]\rangle \sim Q^4$, twist-3 $\sim Q^3$
- $\mathrm{EEC}\,|_{z\to 0} = \lim_{n_1 \to n_2} \langle \mathcal{E}(n_1)\mathcal{E}(n_2)\rangle / Q^2 \sim Q^2$, produces the classic scaling



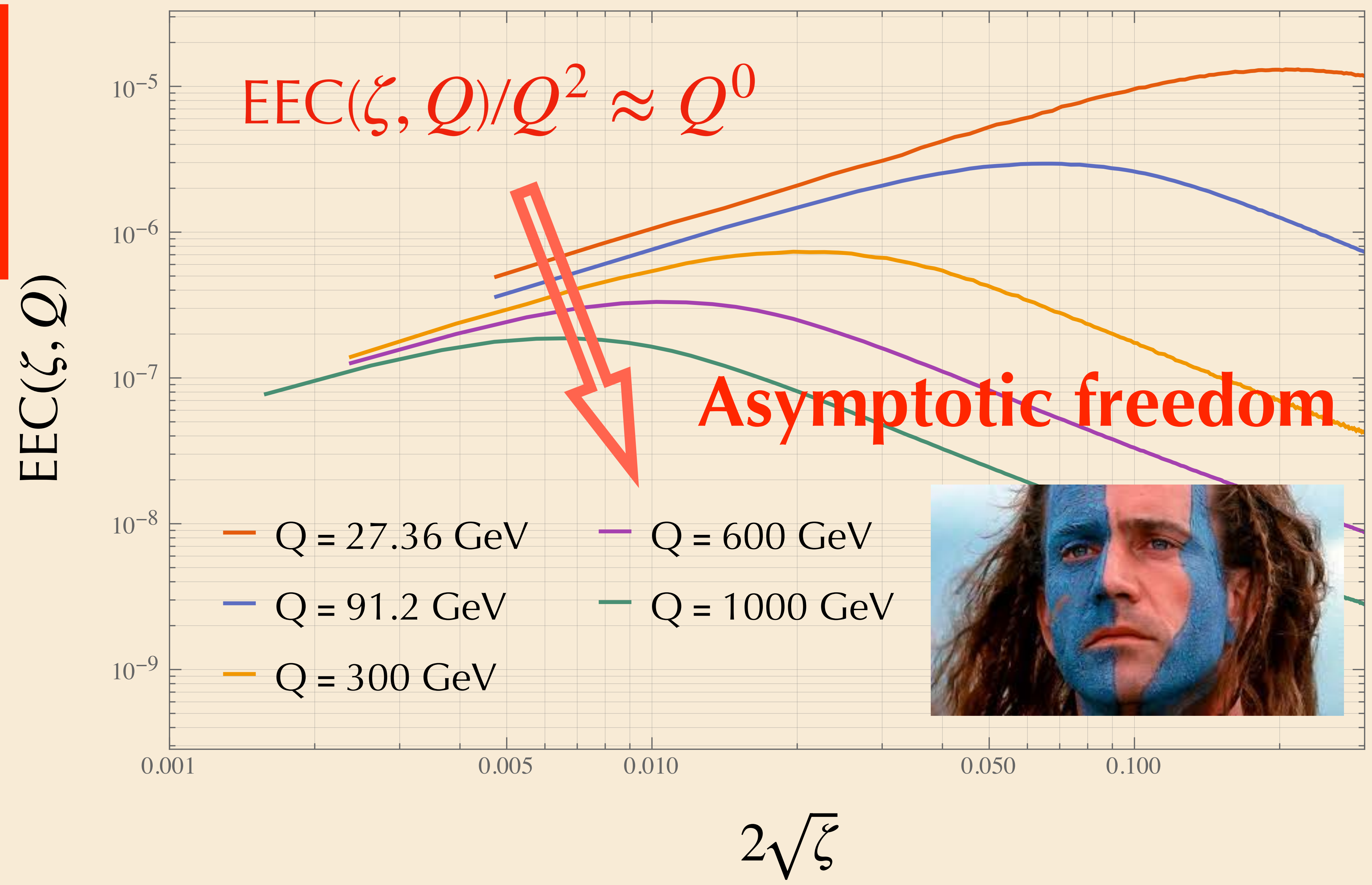
Scaling behavior by light-ray OPE

$$H(Q) \equiv \lim_{n_1 \to n_2} \langle \mathscr{E}(n_1)\mathscr{E}(n_2)\rangle / Q^4 = \frac{1}{\Lambda_{\mathrm{QCD}}^2} \mathscr{F}(\mu^2) \langle \mathscr{D}^{4,-6}_{\mathrm{DGLAP}}(\mu^2)\rangle / Q^4 + \ldots$$

$$\frac{d}{d\ln\mu} \mathscr{D}^{-\Delta_L=4, J_L=-6}_{\mathrm{DGLAP}} = \gamma(J=5)\mathscr{D}^{-\Delta_L=4, J_L=-6}_{\mathrm{DGLAP}}$$

μ cancellation between $\mathscr{F}$ and $\langle \mathscr{D}_{\mathrm{DGLAP}} \rangle$ ⇒

$$\frac{H(Q_2)}{H(Q_1)} \sim \left[\frac{\alpha_s(Q_2)}{\alpha_s(Q_1)}\right]^{\gamma(J=5)/\beta_0}$$



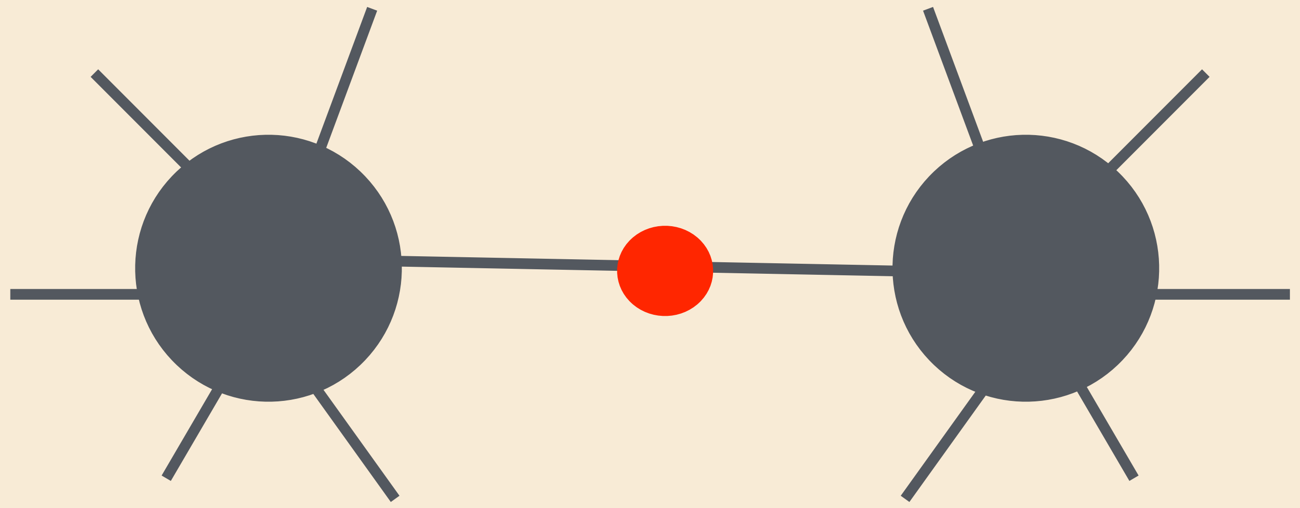
The height difference governed by α_s

Possible for α_s extraction with limited NP inputs

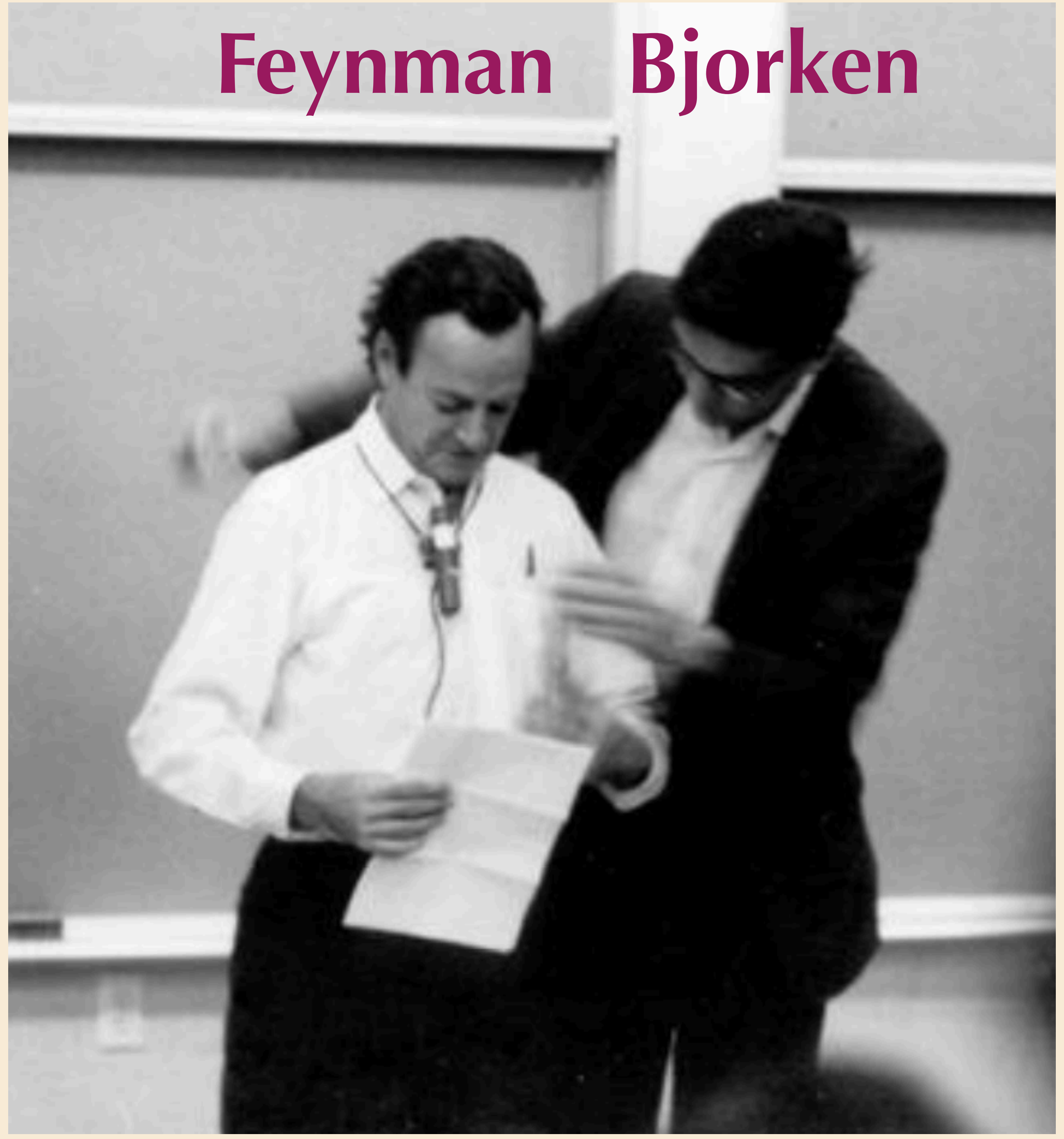
Scaling behavior by light-ray OPE

$$H(Q) \equiv \lim_{n_1 \to n_2} \langle \mathcal{E}(n_1)\mathcal{E}(n_2)\rangle / Q^4 = \frac{1}{\Lambda^2_{\text{QCD}}} \mathcal{F}(\mu^2) \langle \mathcal{D}^{4,-6}_{\text{DGLAP}}(\mu^2)\rangle / Q^4 + \dots$$

- $\mathcal{F} = (\mathcal{F}_q, \mathcal{F}_g)$ Non-pert. Numbers (diFF moments)
- $\langle \mathcal{D}_{\text{DGLAP}} \rangle \sim \langle \mathbb{L}[\bar{\psi}\gamma^+(iD_+)^{J-1}\psi]\rangle$ calculable in pQCD, the 5-th moment of single parton inclusive production cross section



$$\frac{(iD_+)^{J-1}}{Q^{J-1}} = z^{J-1}$$



Phenomenology

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Phenomenology

Precision budget:

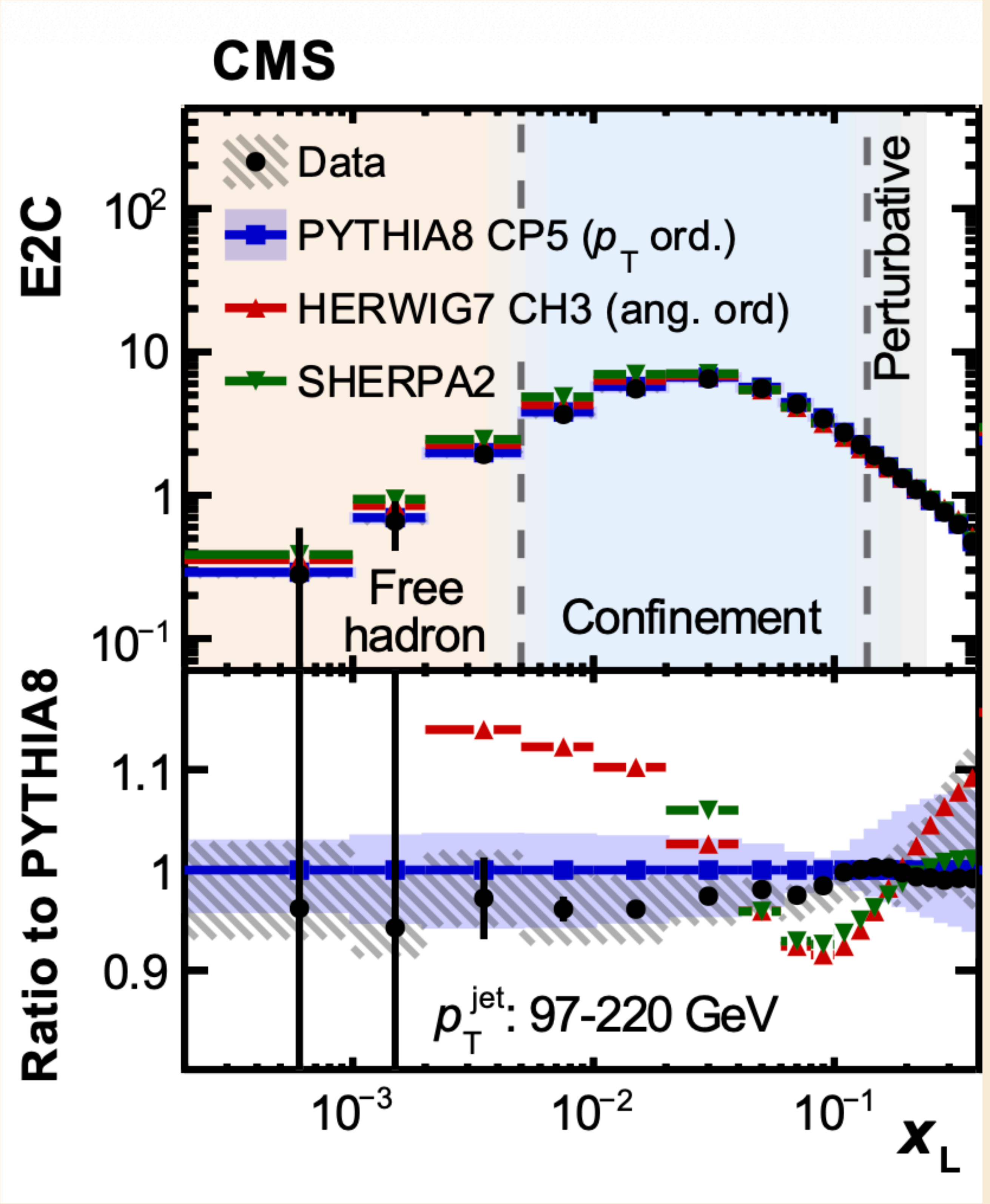
- N3LO + NNLL for e^+e^-, N3LO adapted from hadron leptonic production He, Xing, Yang, Zhu PRL 2025
- NLO + NNLL for pp, NLO by hacking FMNLO C. Liu, X. Shen, B. Zhou, and J. Gao, JHEP 2023
- NNLO + NNLL for pp in principle achievable Czakon, et al., 2025; NNLOJET group, 2025
- N3LO + NNLL for ep in pinrcipleu achievable Dong, Fang, Gao, Li, Shao,Zhu,Zhu, 2603.29673
- N3LL needs 4-loop splitting function, now known for space-like non-singlet

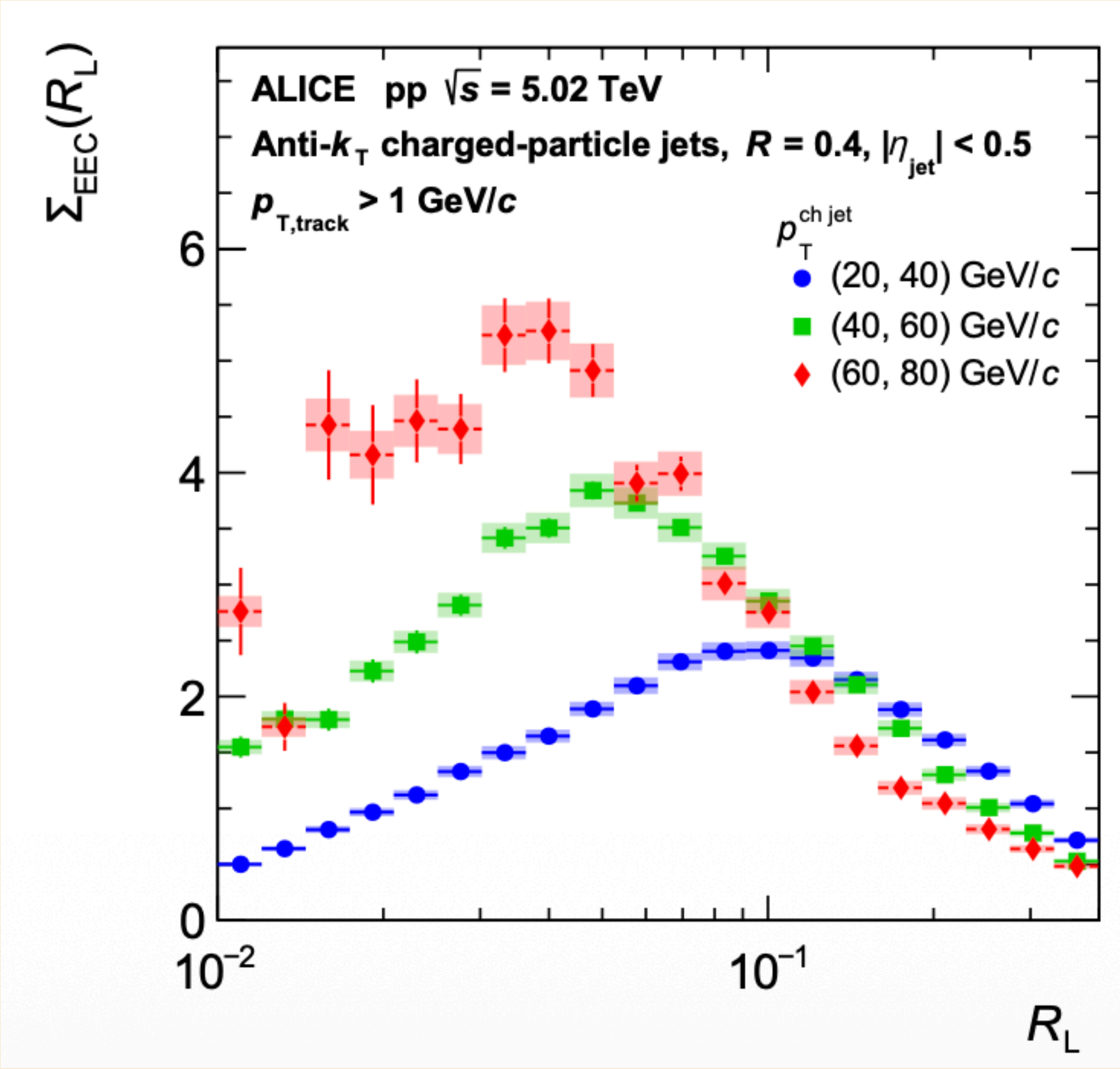
  Gehrmann, Manteuffel, Sotnikov, Yang, 2604.09534

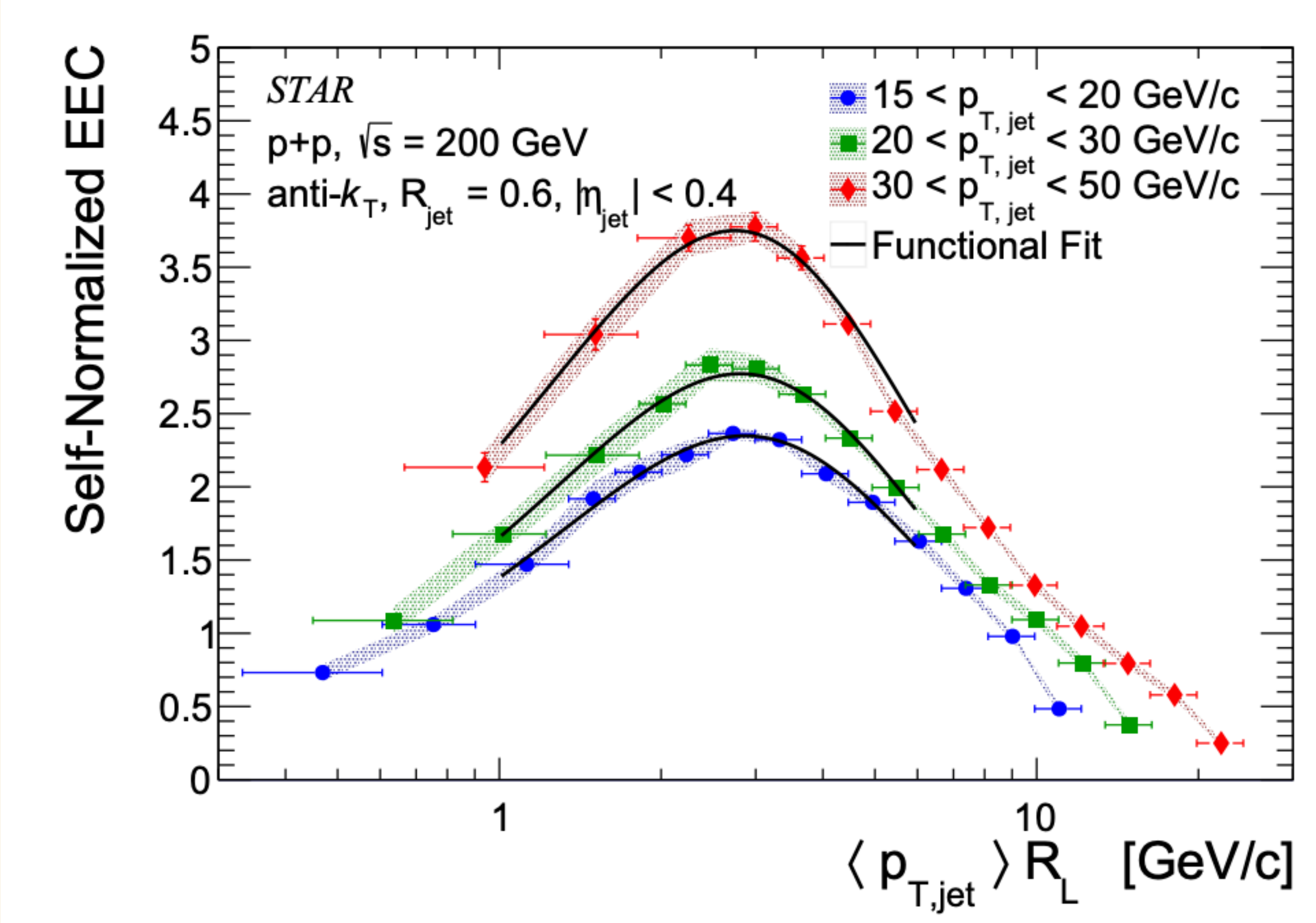
Phenomenology

Experiment status:

- CMS, ALICE, STAR







- All measure EEC and the data cover the post-confinement region
- Not directly the height of the EEC/Q^2, less sensitive to quantum scaling currently
- Linear fit

Phenomenology

CMS, ALICE, STAR

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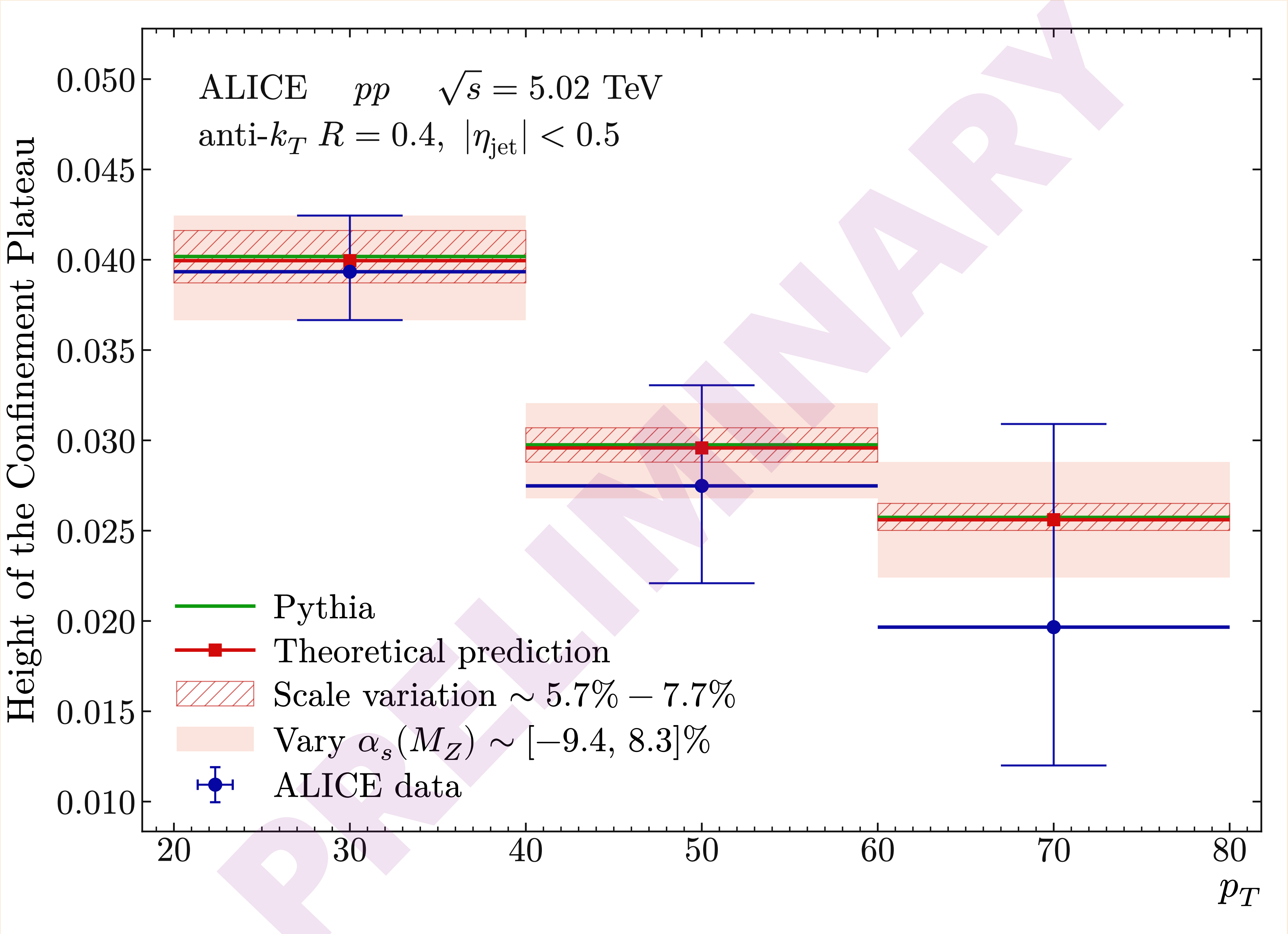
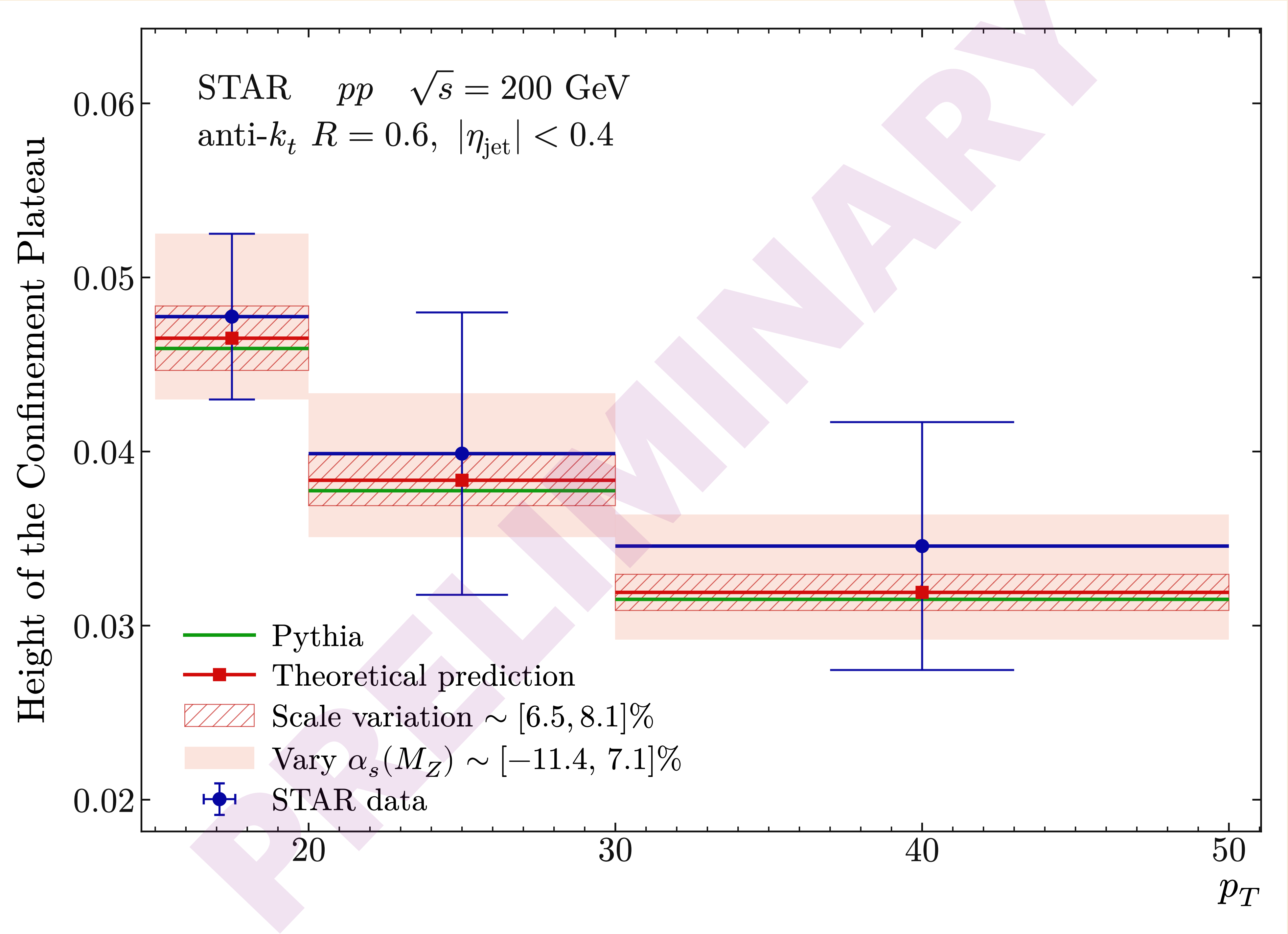


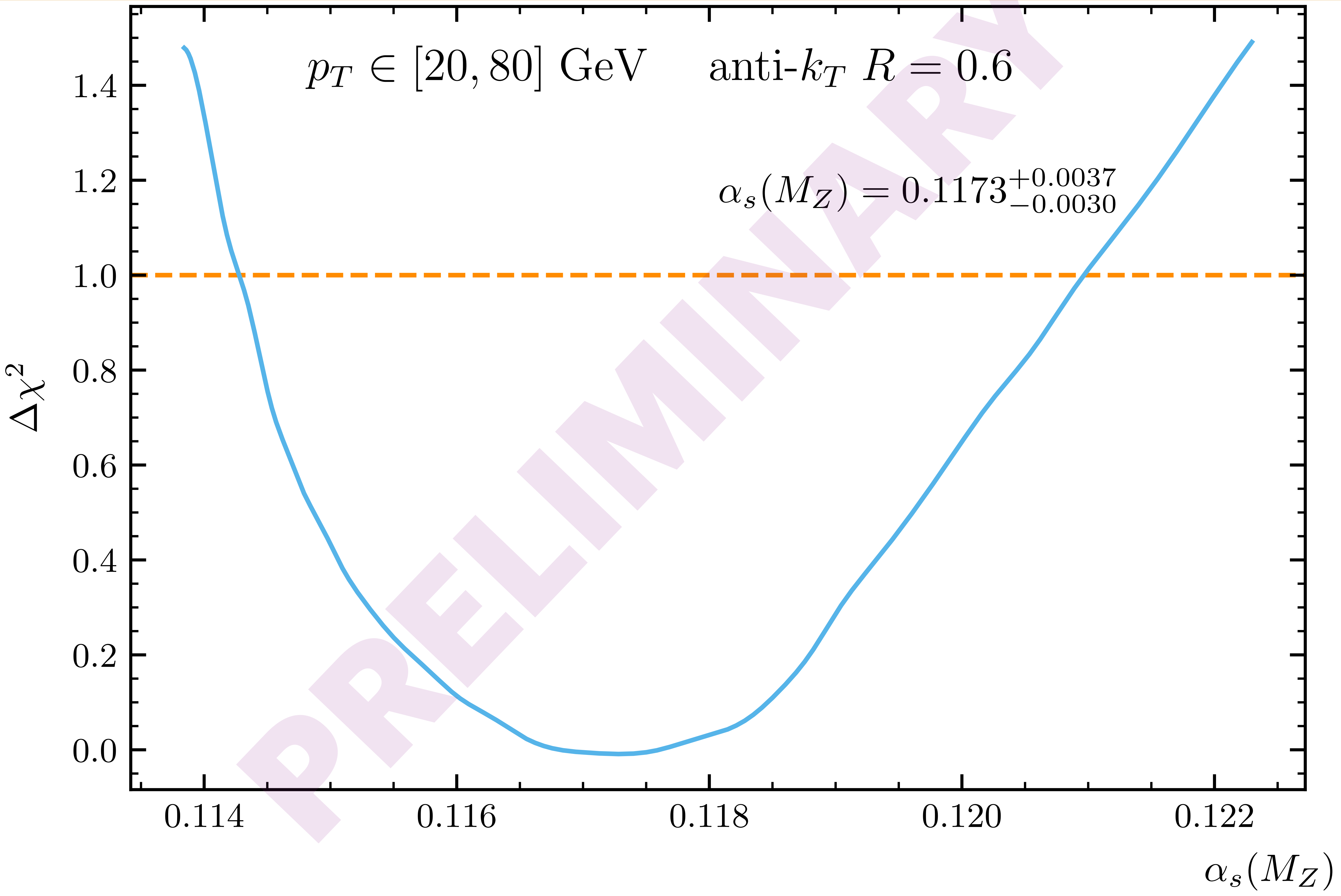


- Overall good agreement with NLO + NNLL @ LHC

Phenomenology

CMS, ALICE, STAR

- α_s extraction study using Pythia pseudo-data
  - Vary α_s while fitting the NP parameters (height)
  - $\sim \pm 5\,\%$ precision in α_s extraction, better than other jet-substructure approaches



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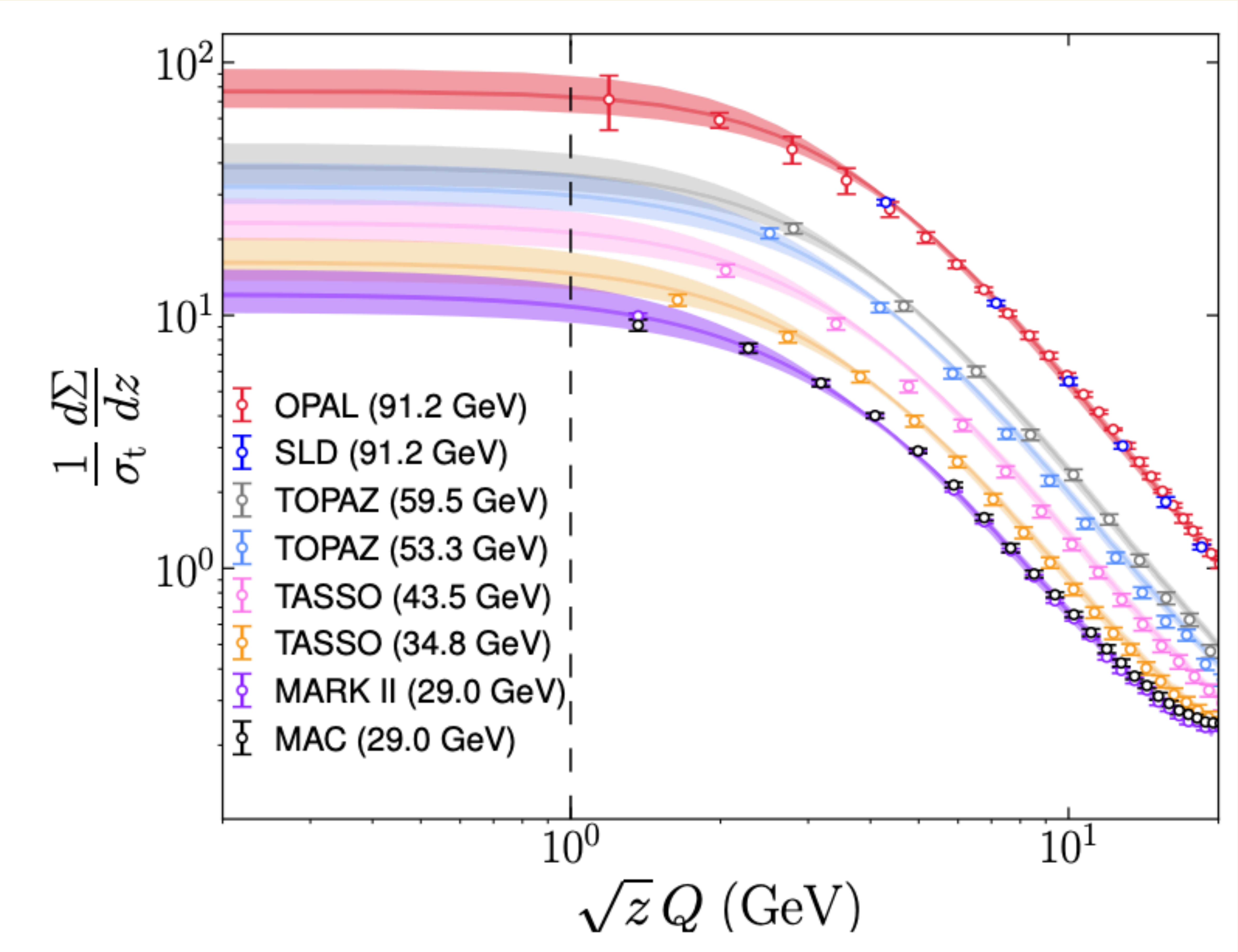
Phenomenology

Experiment status:

- e^+e^-

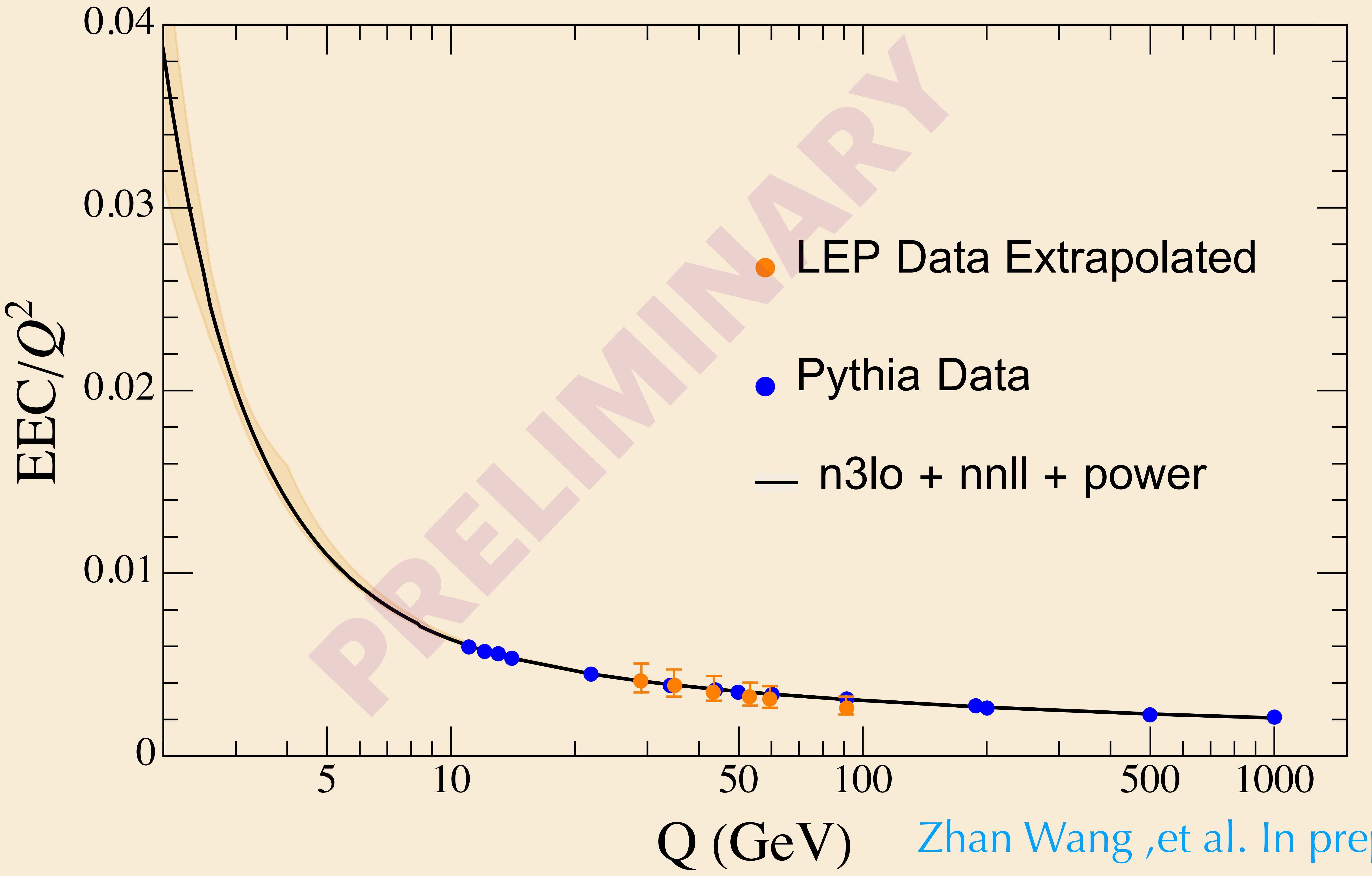


- Mainly old data, do not cover the post-confinement region
- Extrapolation

Herrmann et al., 2507.17704

Phenomenology

e^+e^-



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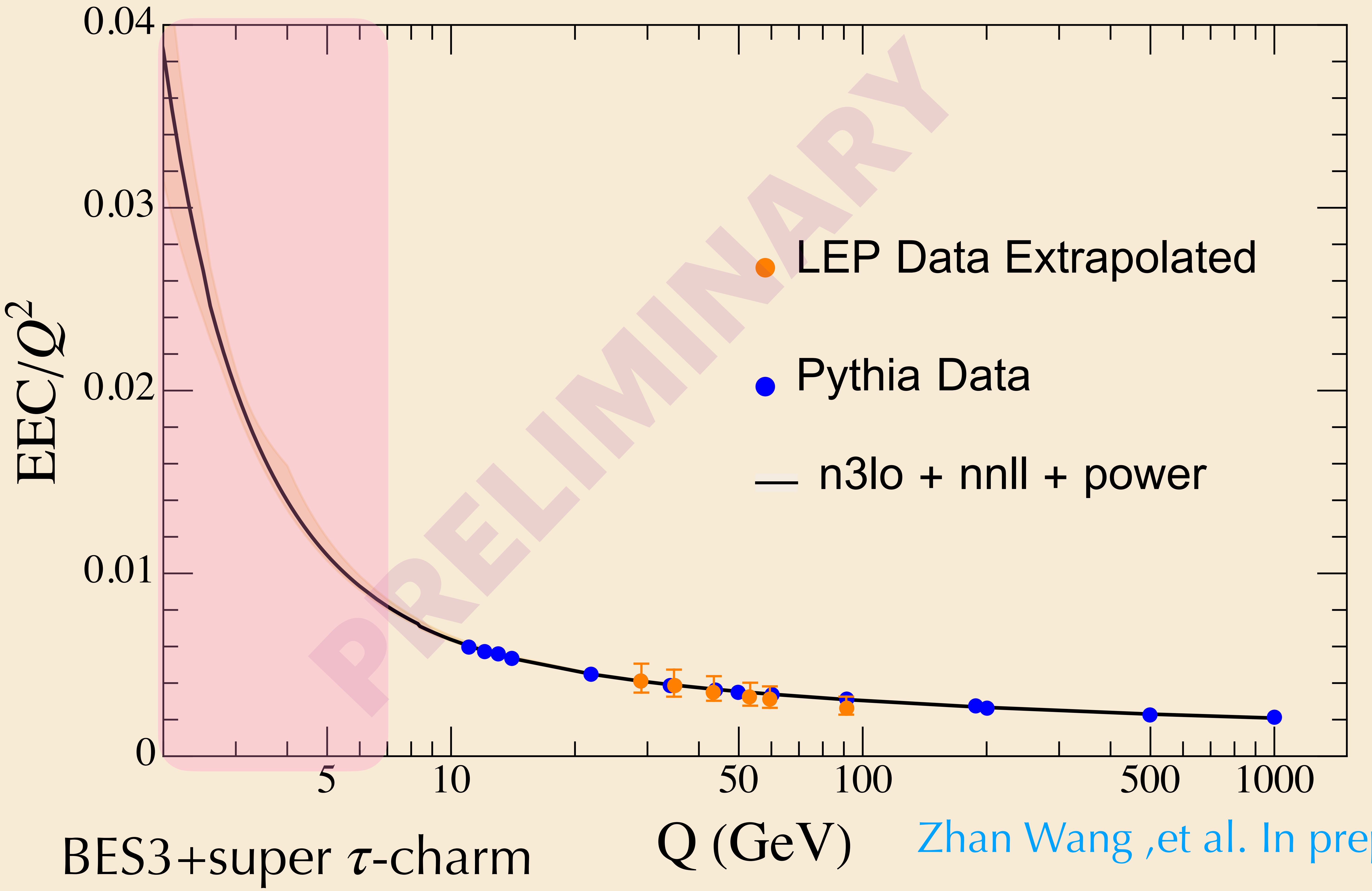
- Overall good agreement with N3LO + NNLL @ LEP kinematics

Phenomenology

e^+e^-



BES3+super τ-charm

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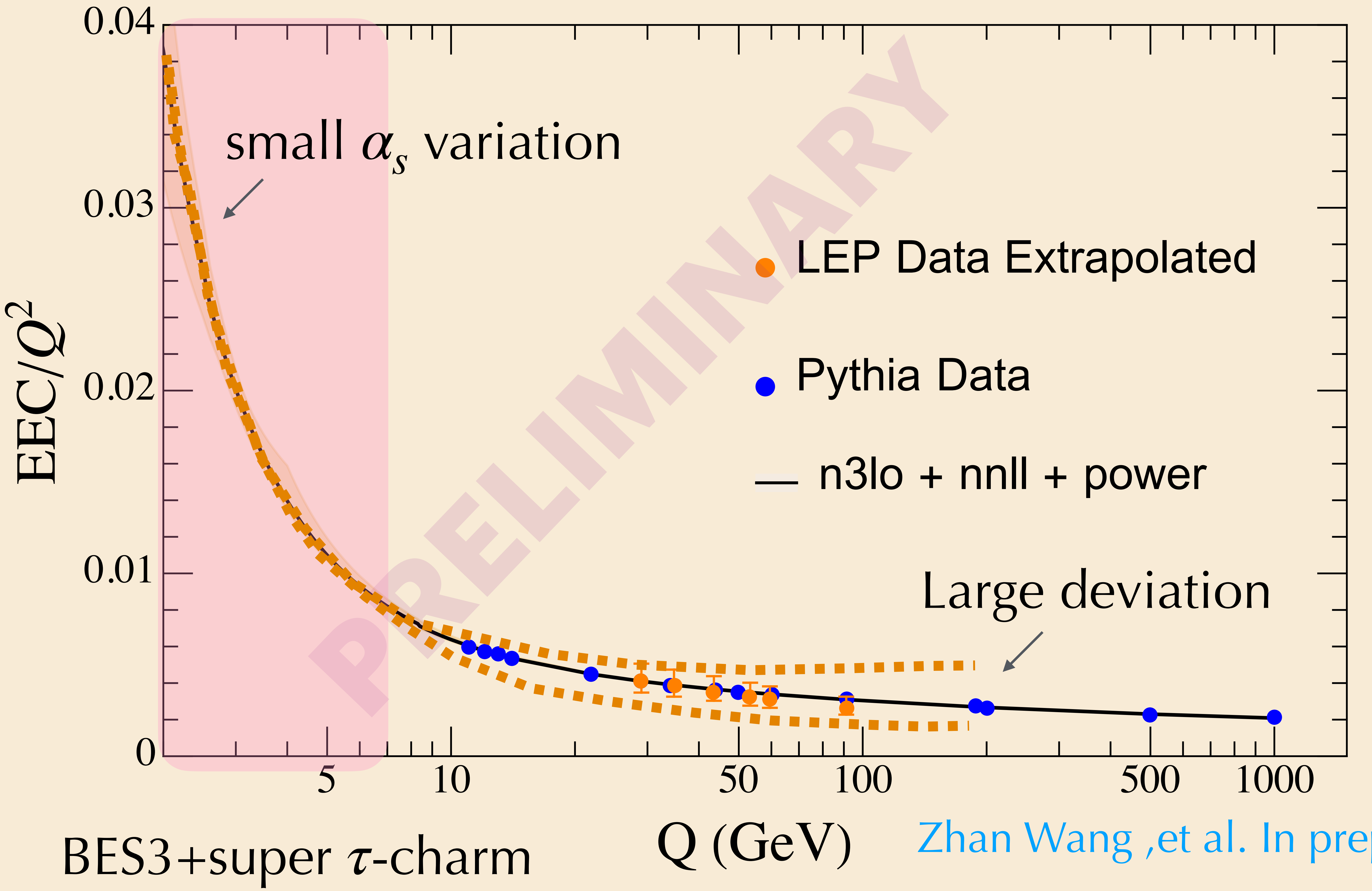
- Overall good agreement with N3LO + NNLL @ LEP kinematics
- Important future check (NP power corrections) within the BES3+super τ -charm region

Phenomenology

e^+e^-



BES3+super τ-charm

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- Possible precision α_s extraction with BES3/super τ-charm + LEP

Conclusion

- Quantum scaling behavior of the post-confinement EEC governed by DGLAP $J = 5$
- Realizing N3LO+NNLL for $e^+e^-$and NLO+NNLL for pp, finding good agreement with current data and Pythia
- Similar Idea applicable to EIC, (EEC or NEEC)
- Further pushing the theory precision and possible α_s extraction in the future

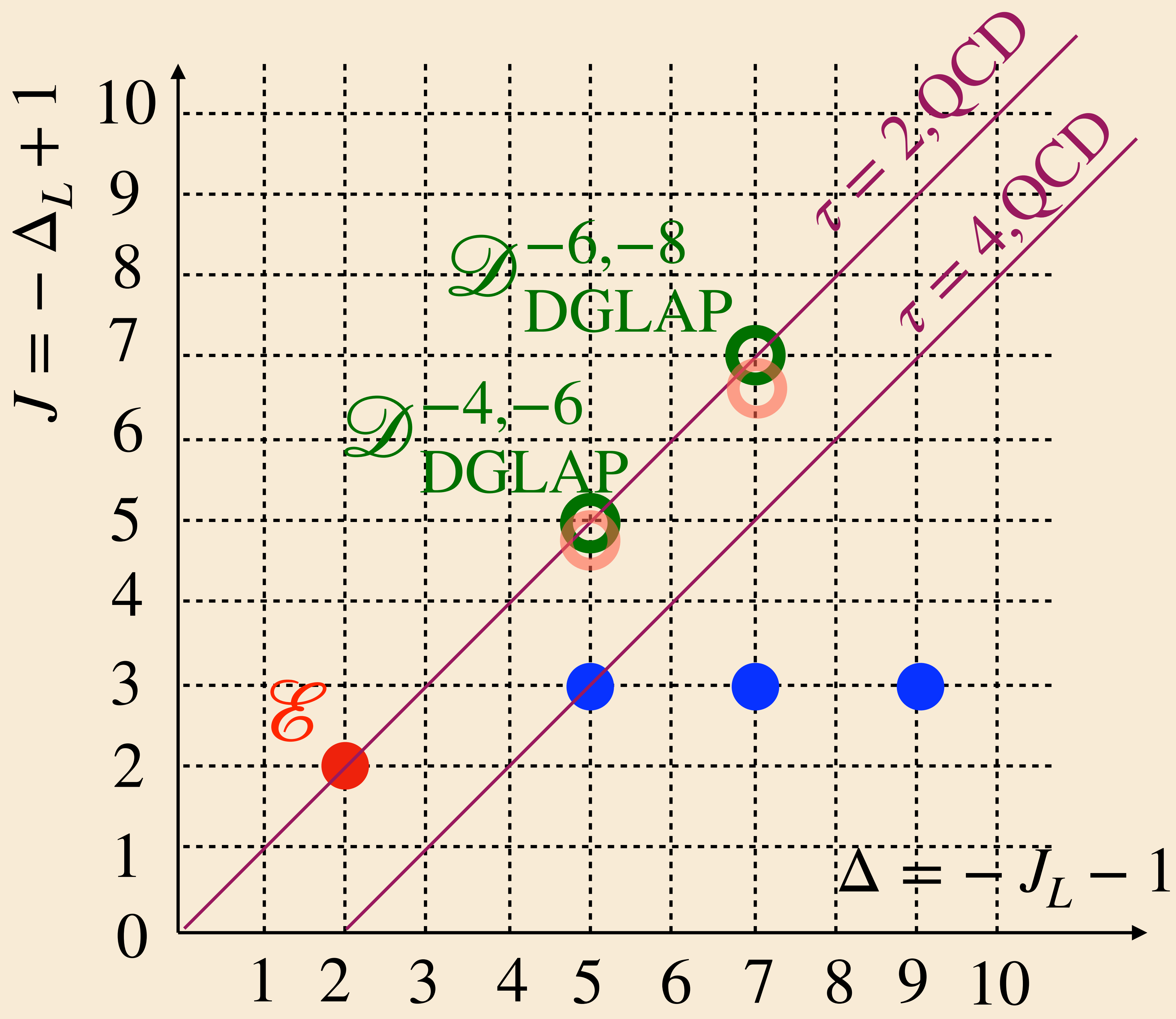
Thanks

Backup: Two Step Matching-1. onto hadronic operators

$$-\Delta_{L,\mathscr{E}\mathscr{E}} = 2 \qquad J_{L,\mathscr{E}\mathscr{E}} = -6$$

$$\mathscr{E}(n_1)\mathscr{E}(n_2) = \sum_{J_L} A_{J_L} \sqrt{\zeta}^{-6-J_L} \mathbb{O}_H^{-2,J_L}(n_2) = A_0 \zeta^0 \mathbb{O}_H^{-2,-6} + \ldots \qquad -\Delta_L = 2, \quad -J_L = 6$$

- Light-ray OPE in the small ζ limit with a hadron EFT ((boost)-Chiral?), in the free hadron regime, assume zero hadron mass
- Equate the Lorentz dimension and Lorentz spin on both sides of the expansion. Keep the dimension unchanged, All $\mathbb{O}_H^{\Delta_L,J_L}$ have the same $\Delta_L = -2$
- Both A_{J_L} and $\mathbb{O}_H$ can be calculated within the hadron EFT



Backup: Two Step Matching-2. onto partonic operators

$$\mathscr{E}(n_1)\mathscr{E}(n_2) = \sum_{J_L} A_{J_L} \sqrt{\zeta}^{-6-J_L} \mathbb{O}_H^{-2,J_L}(n_2) = A_0\, \zeta^0\, \mathbb{O}_H^{-2,-6} + \ldots$$

$-\Delta_{L,\mathscr{E}\mathscr{E}} = 2$, $J_{L,\mathscr{E}\mathscr{E}} = -6$; $-\Delta_L = 2$, $-J_L = 6$

- Match onto quark/gluon operators

$$\mathbb{O}_H^{-2,-6} = \frac{B_{-4}}{\Lambda_{\mathrm{QCD}}^2} \mathscr{D}_{\mathrm{DGLAP}}^{-4,-6}(\mu^2) + \text{higher twist}$$

J_L keeps fixed while Δ_L could change due to Λ_{QCD}