Universality in the Near-Side EEC

Xiaohui Liu

Heavy Flavor and QCD @ Nan Jing, Apr 20, 2025

XL, Vogelsang, Yuan, Zhu, PRL 2025

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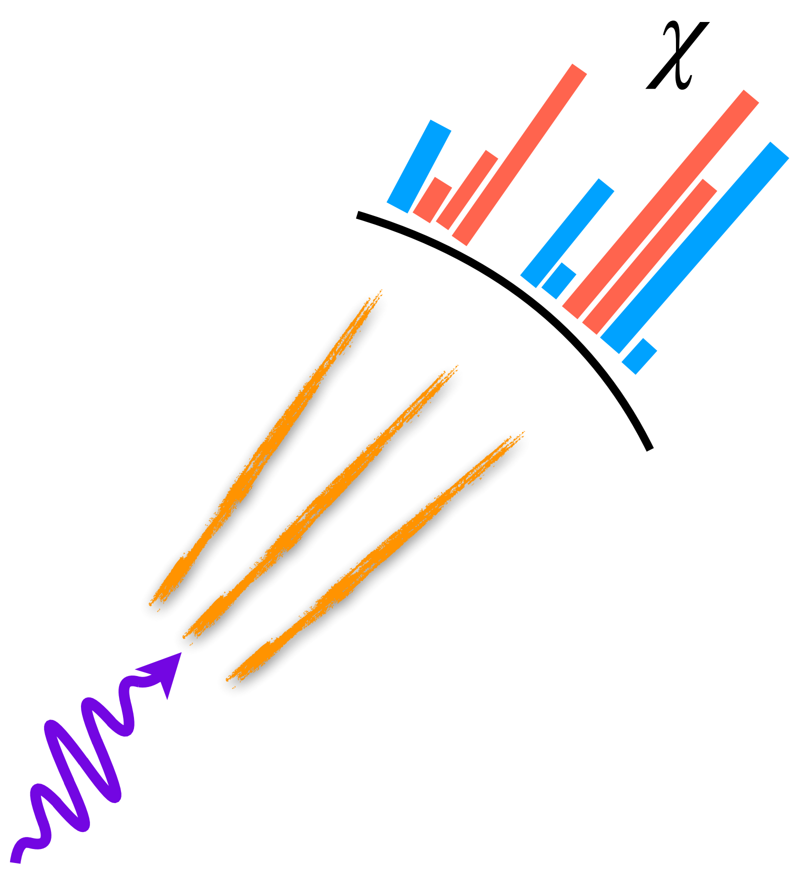
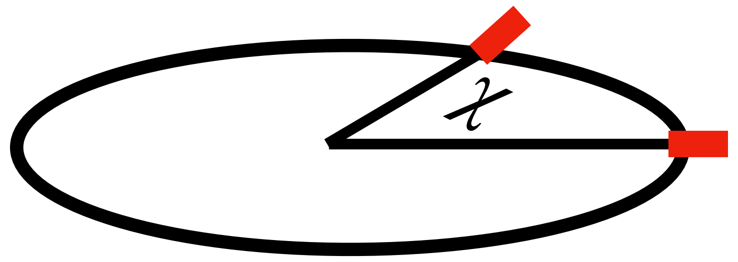
Outline

- Energy Correlator cracks Non-Pert. physics
- A model to understand the near-side EEC
- Conclusion

Energy Correlators

Energy-Energy-Correlator (EEC)





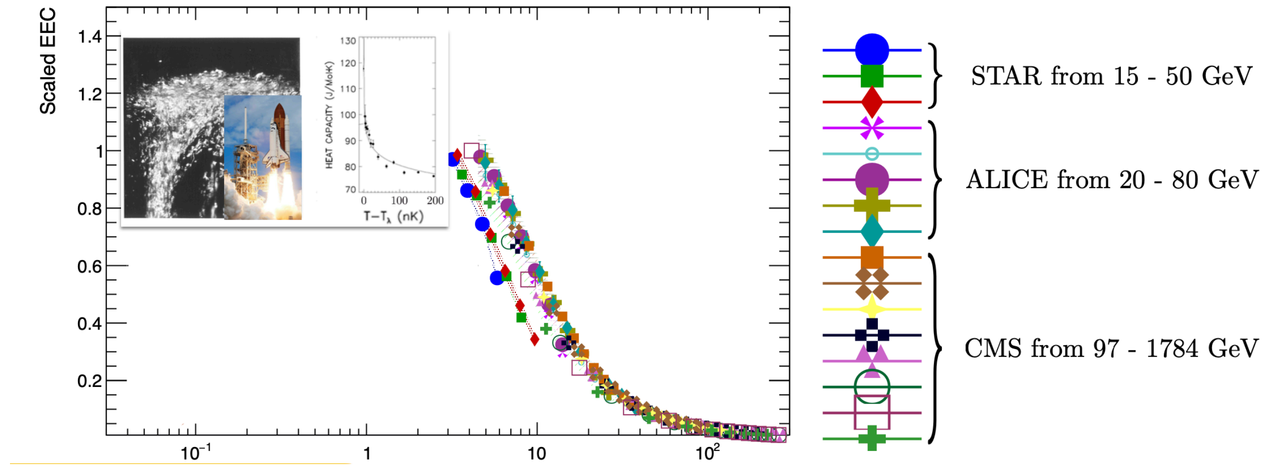
$$\text{EEC} = \frac{1}{\sigma}\int d\sigma \sum_{ij} \frac{E_i E_j}{Q^2}\delta(\chi - \theta_{ij})$$

Sterman, 1975

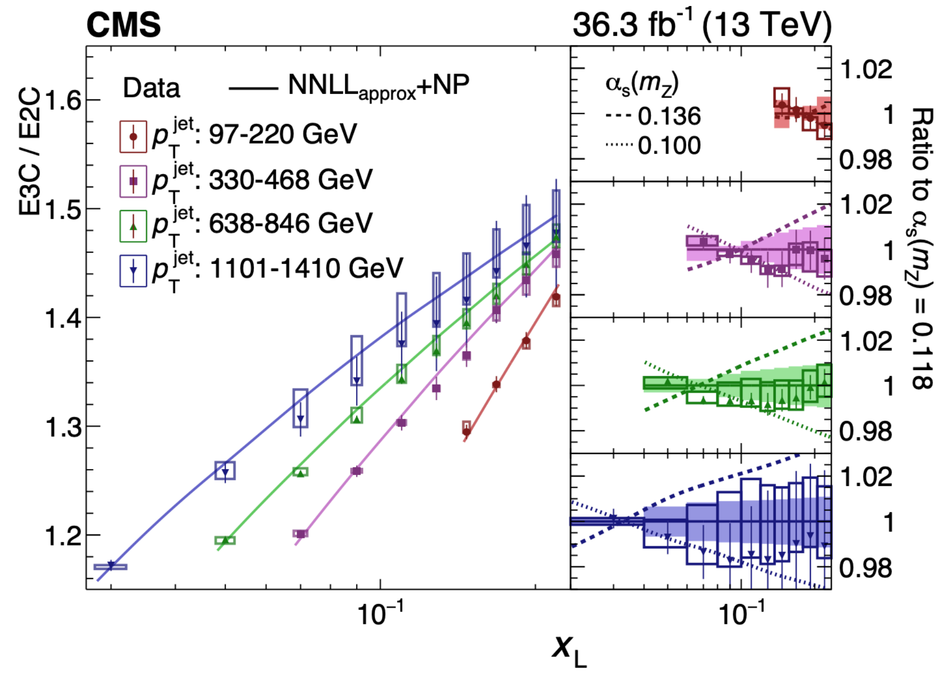
Bashman, et al. 1978

Collider Phenomenologies:

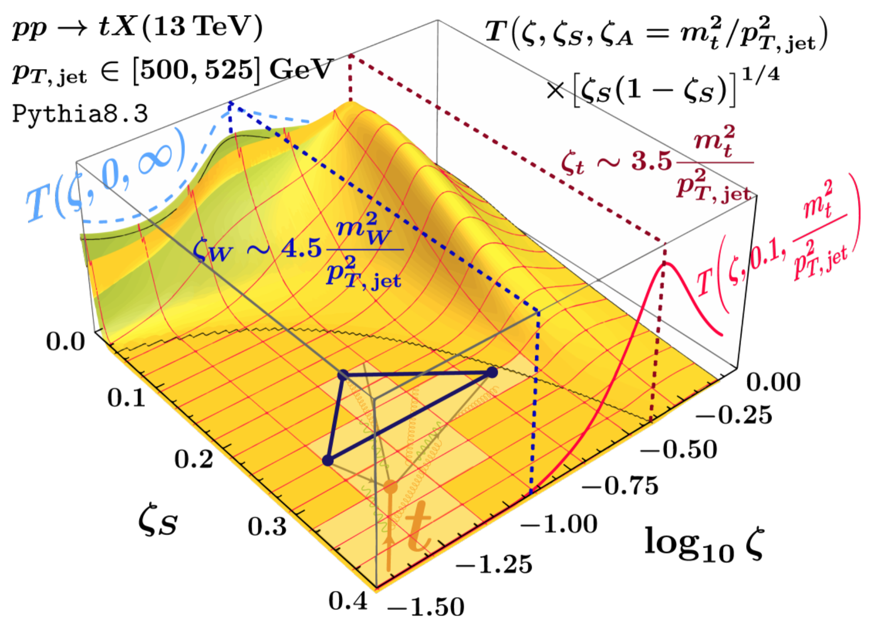
Conformal meets collider



α_s measure

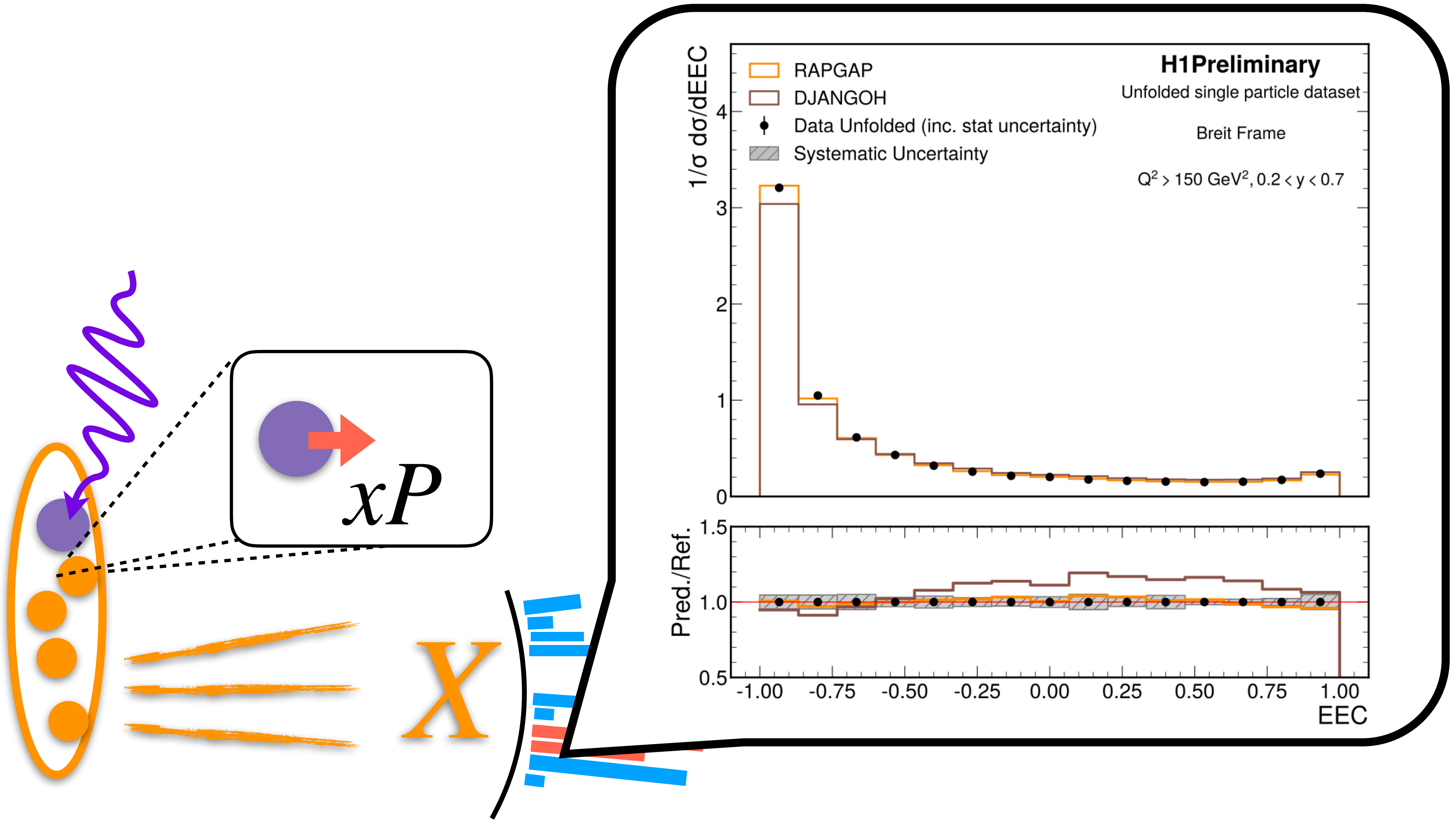


Top mass



Cracks NP Physics

Adapted to Hadron Structure Studies

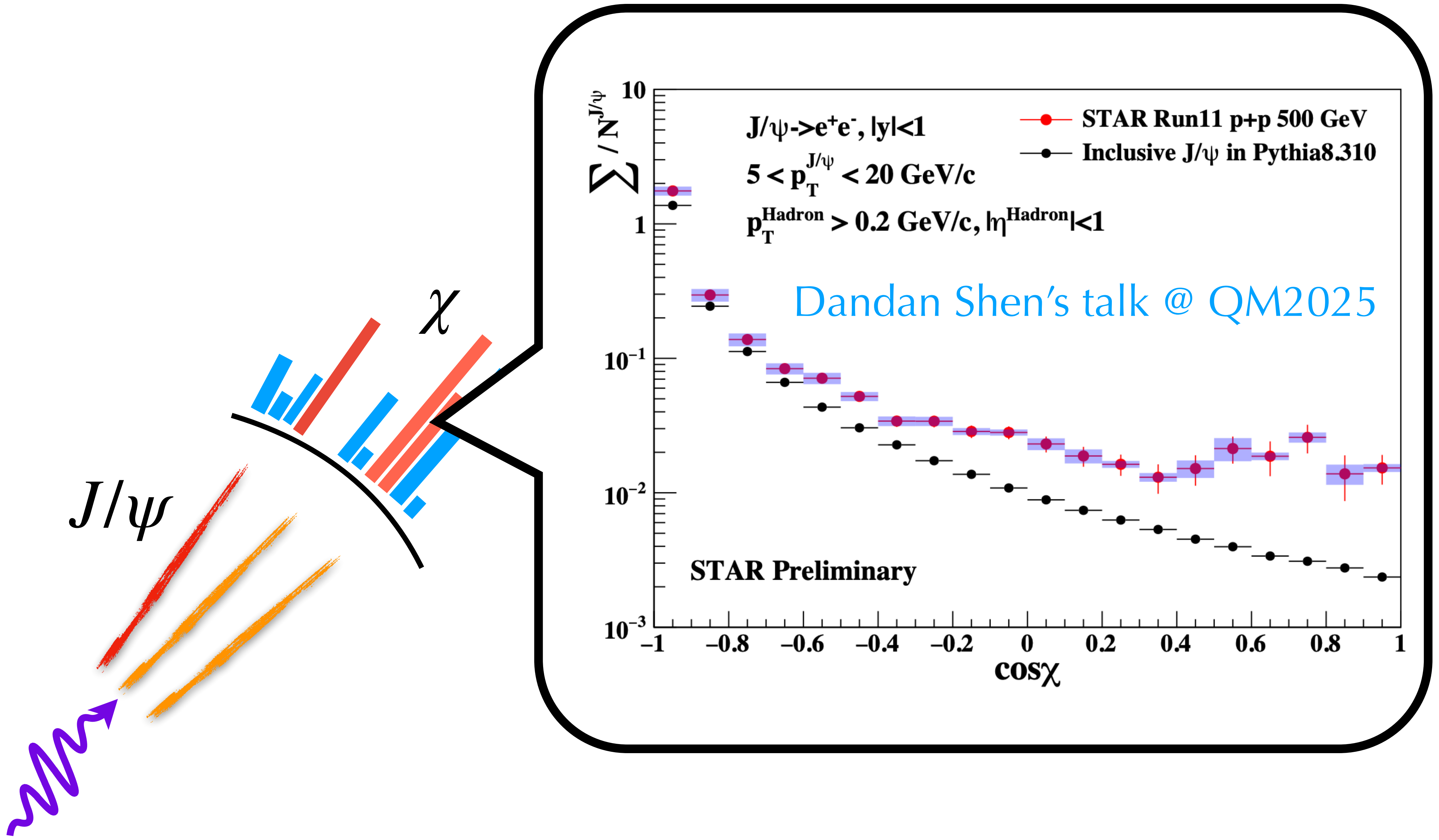


Nucleon EEC **Liu, XL, Pan, Feng, Zhu, PRL 2023**

XL, Zhu, PRL 2023

TMD **Li, Makris, Vitev PRD 2021**

Adapted to HF Hadronization studies



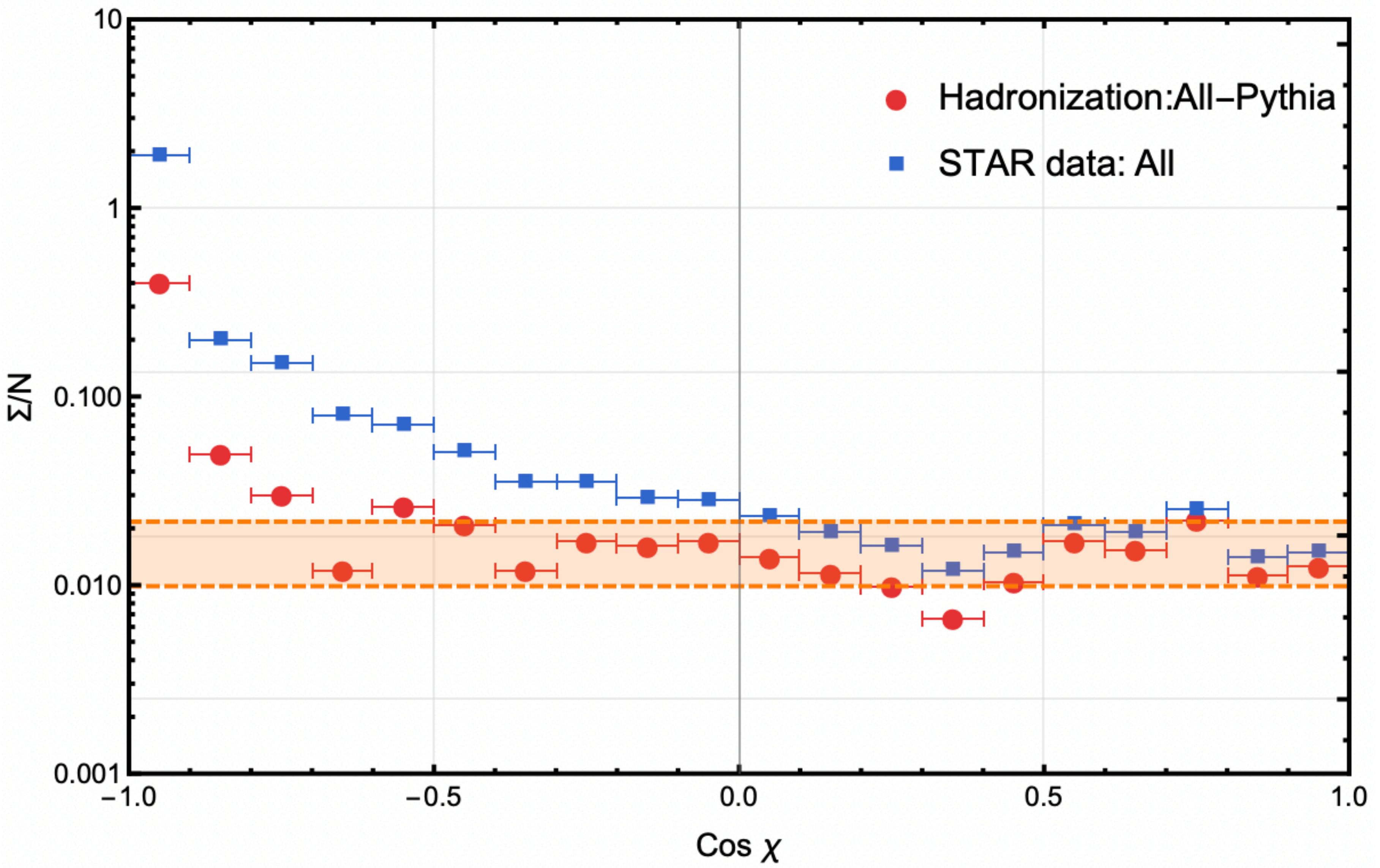
Quarkonium EC

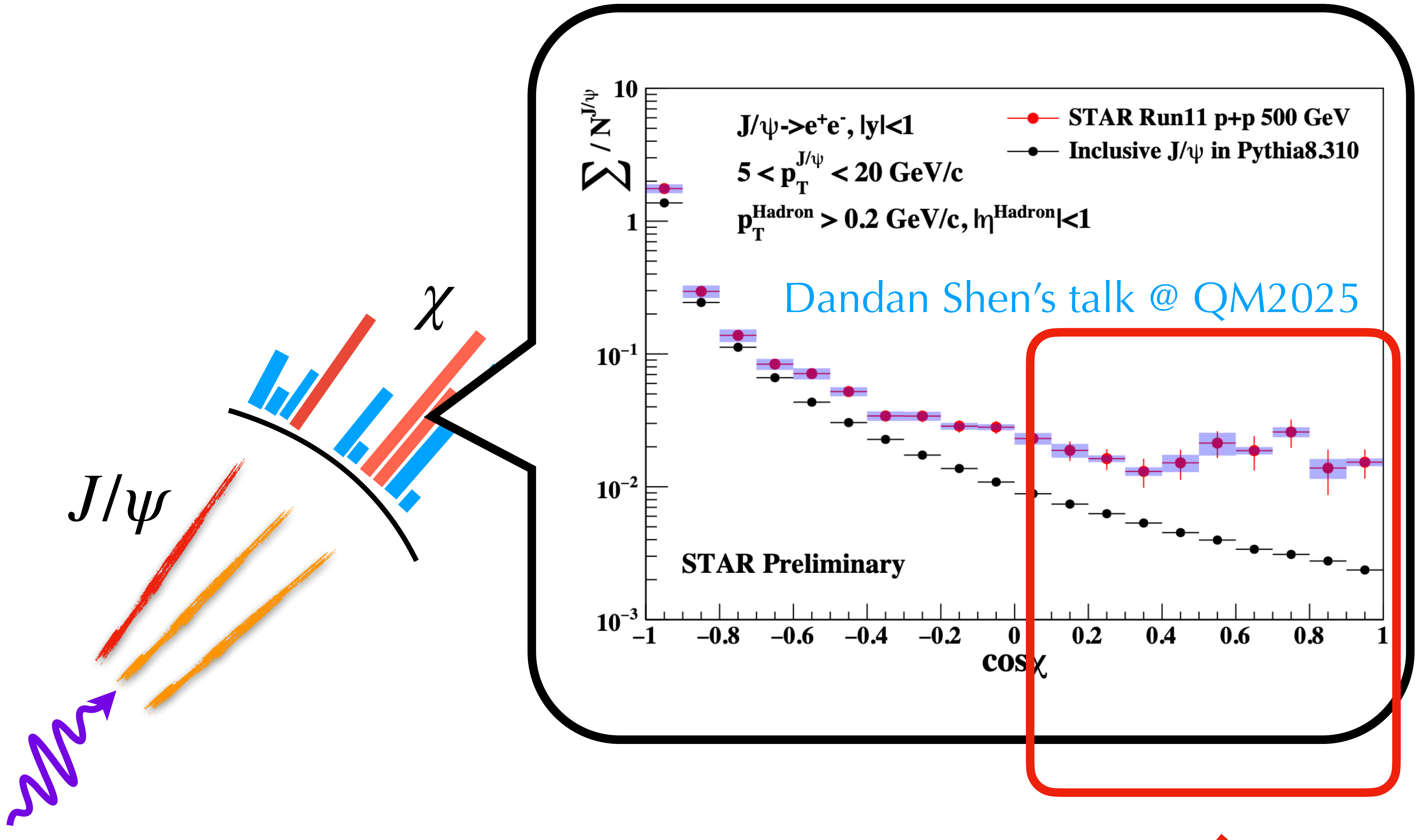
Chen, XL, Ma, PRL 2024

Cracks NP Physics

- Pythia shape agrees with generic expectation
- Data - Pythia, Compatible with the NRQCD power counting model. See energy emitted by hadronization ?

Adapted to HF Hadronization studies

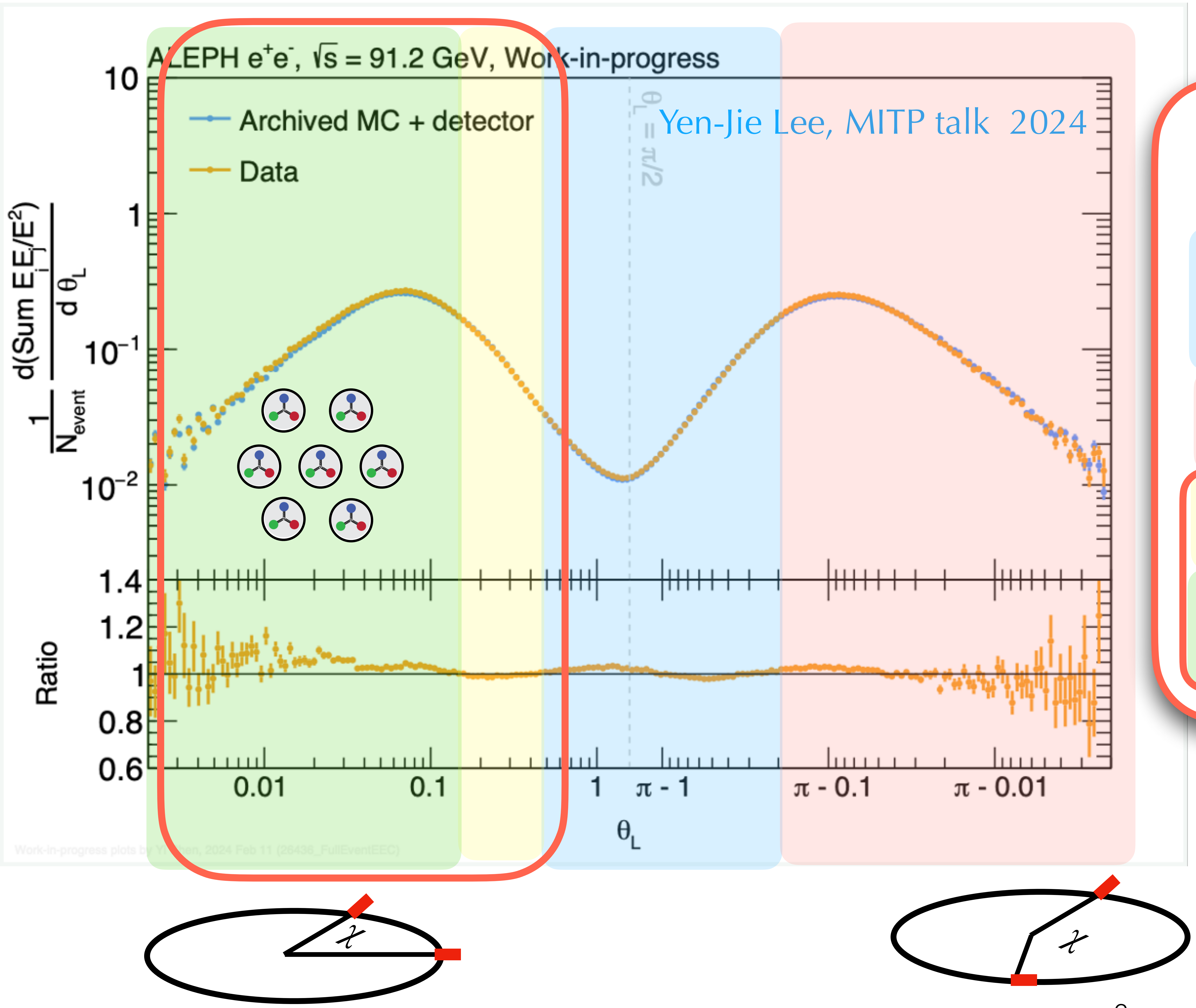




Quarkonium EC

Chen, XL, Ma, PRL 2024

Near-side features



Probe different dynamics @ $Q\chi$

- $\chi \to \frac{\pi}{2}$, UV physics, fixed order
- $\chi \to \pi$, TMD soft, $\sim e^{a \ln^2 \frac{1}{\chi}} e^{-2S_{NP}}$
- $\Lambda_{QCD} \ll Q\chi \ll Q$, Collinear, $\sim \theta^{-1+\gamma[3]}$
- $Q\chi \lesssim \Lambda_{QCD}$, **free hadron?, transition?**

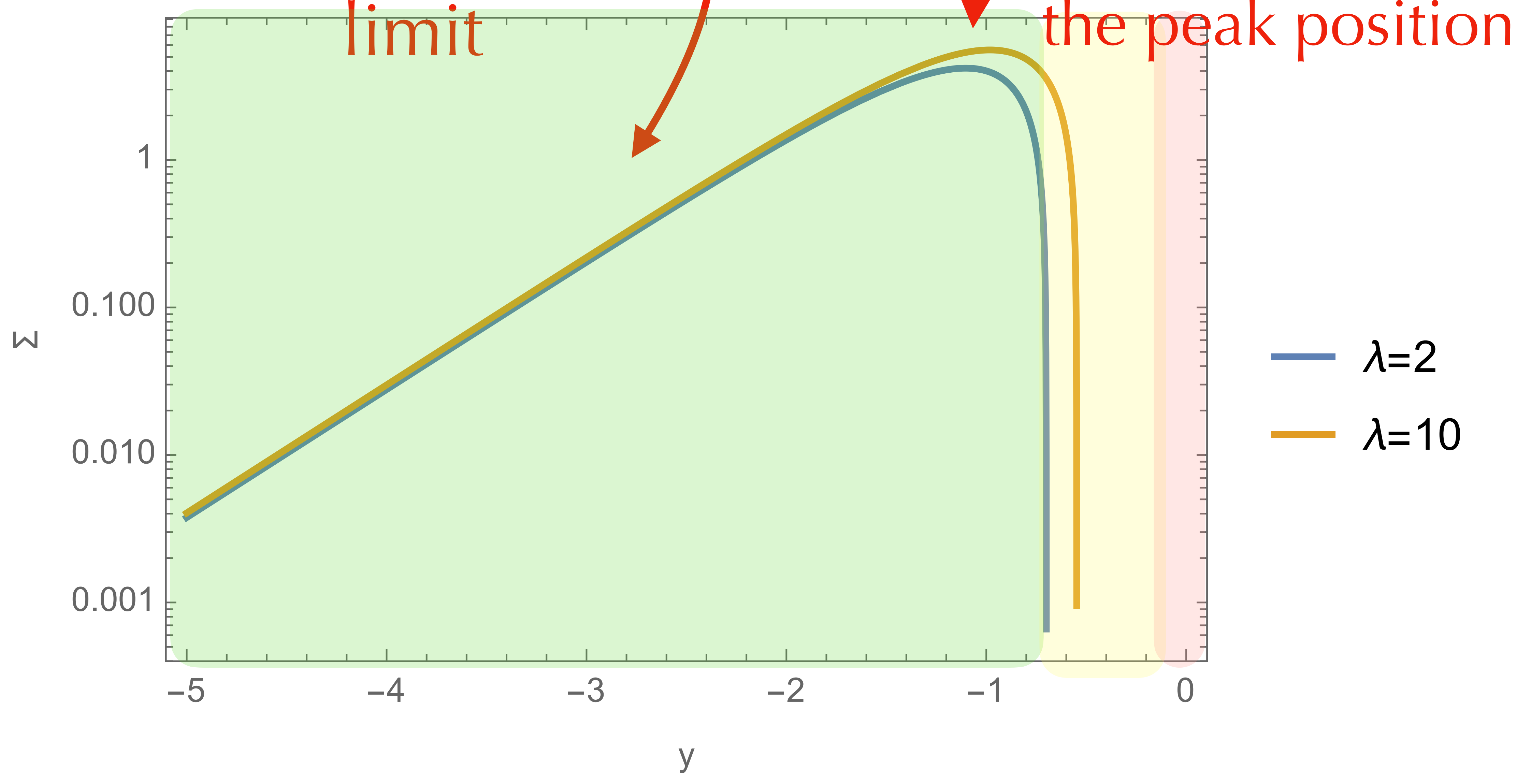
Near-side features

AdS/CFT prediction: Hofman, Maldacena, 2008

$$\langle \mathcal{E}(\vec{n}_1')\mathcal{E}(\vec{n}_2')\rangle = (\frac{q^0}{4\pi})^2 \left[1 + \frac{6\pi^2}{\lambda}(\cos^2\theta_{12} - \frac{1}{3}) + \cdots\right]$$

Infinite coupling limit

Hard to predict the peak position



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But treating QCD as a CFT is questionable

Other alternative models within QCD?

Near-side features

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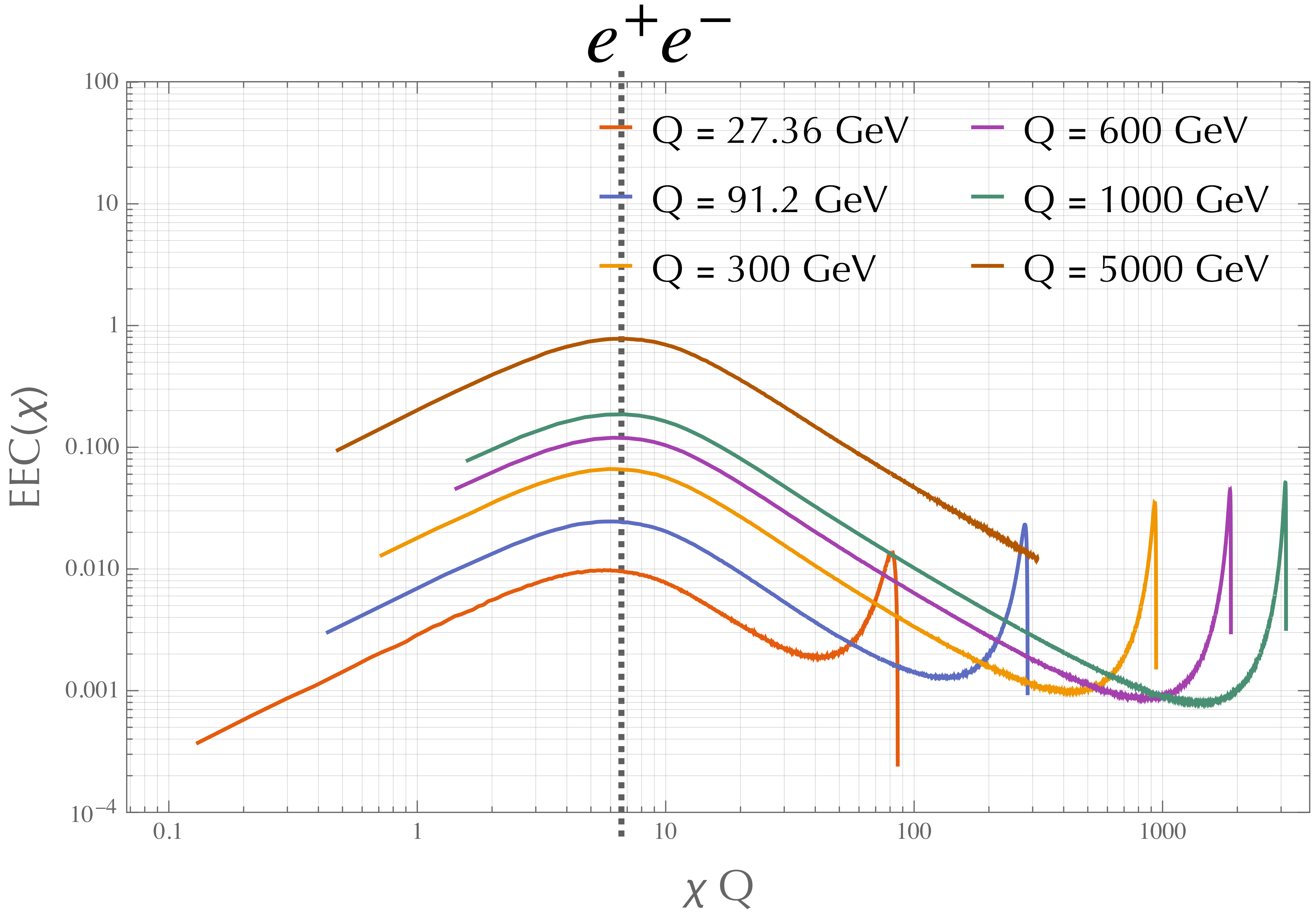
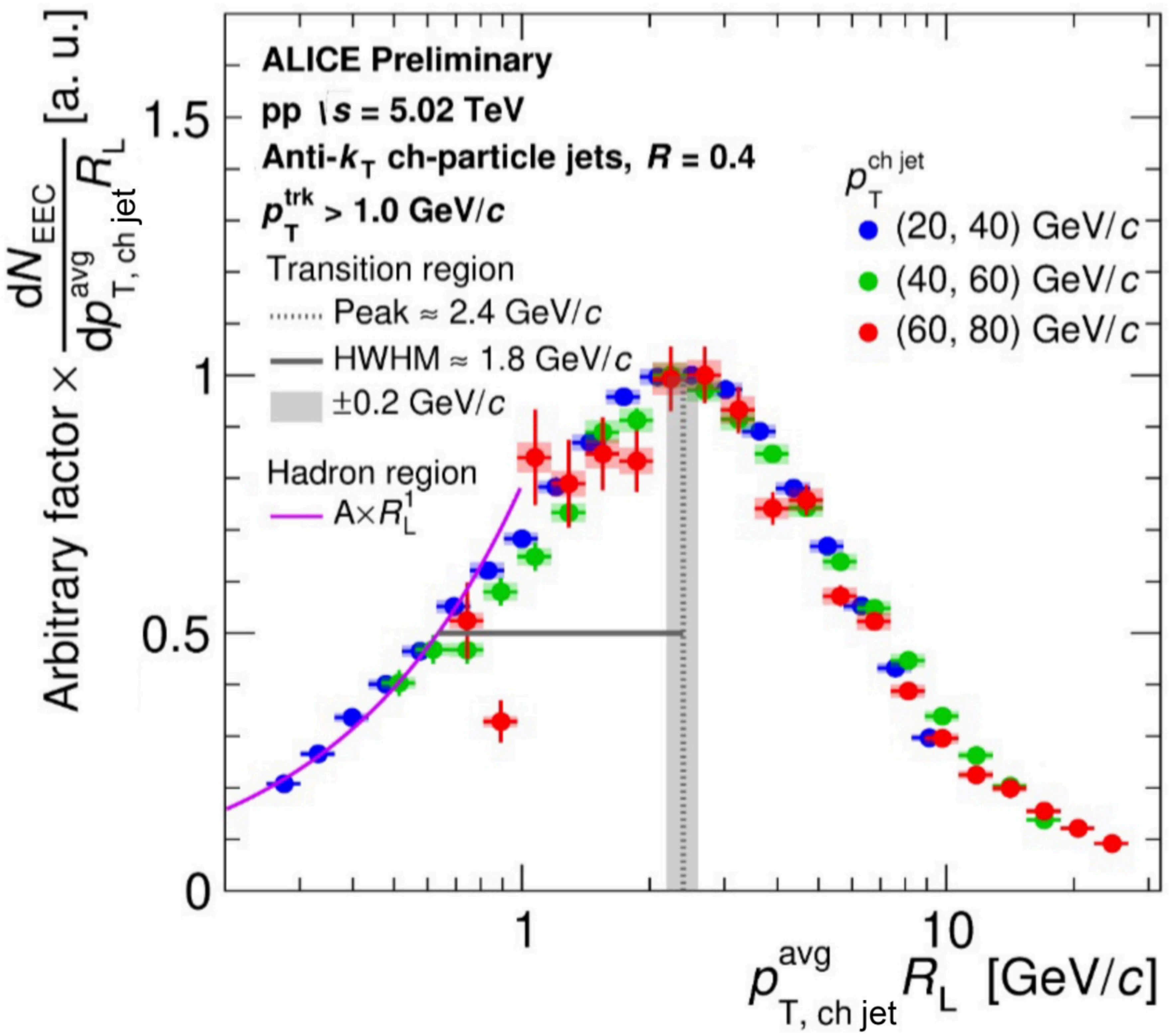


Seen in the LHC data



- Uncorrelated distribution in the deep NP regime, $d\Sigma/d\cos\theta \sim$ const.
- $\chi \to 0$ peaks almost position at the same $Q\chi$ →probing the same NP scale Λ_{QCD}
- Universal behavior in the near side region → probing the same NP physics

Near-side features

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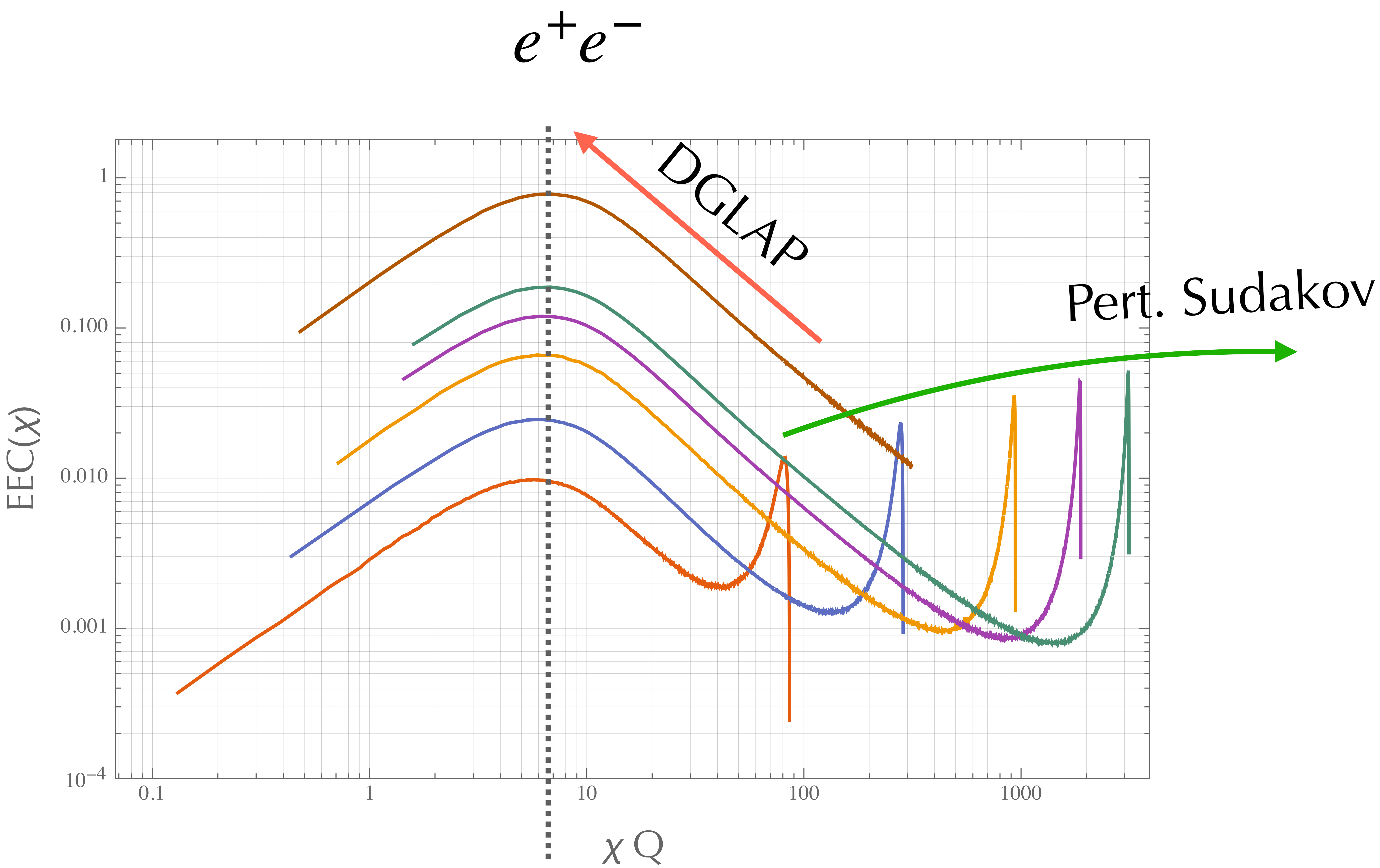

- $\chi \to 0$ peaks rise more dramatically than $\chi \to \pi$, $\leftarrow$ collinear vs pert. soft
  - $\theta Q \gg \Lambda_{QCD}$, Collinear splitting (ignoring intrinsic soft) predicts a forever lasting rising shape $\sim \theta^{-1+\gamma[3]}$. No turn-over in pQCD in near side
  - $\chi \to \pi$, Pert. Sudakov (soft) suppression
  - $\theta Q \lesssim \Lambda_{QCD}$, Intrinsic transverse momentum (NP soft) becomes important and may lead to the turn over in the near-side

Near-side features

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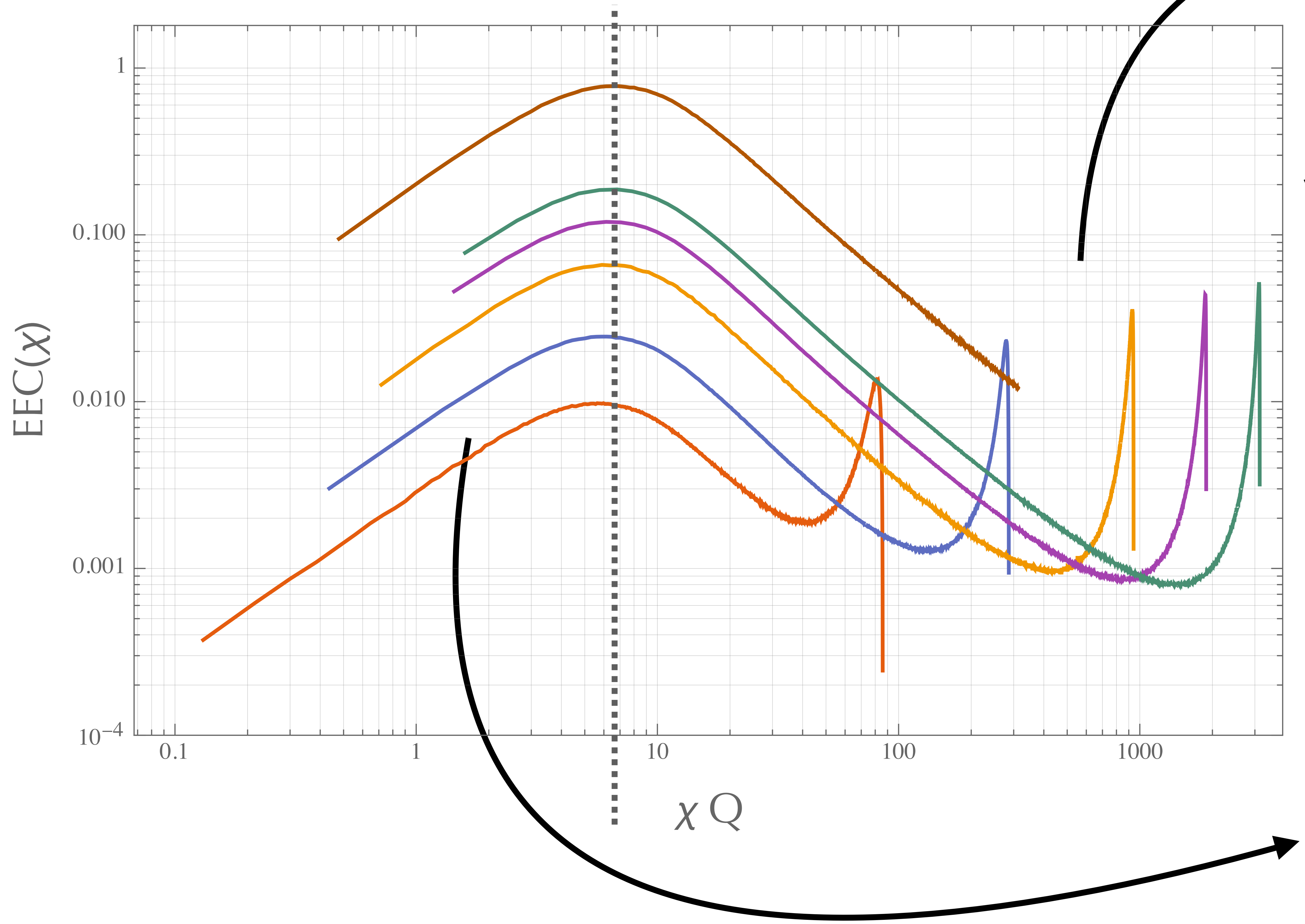
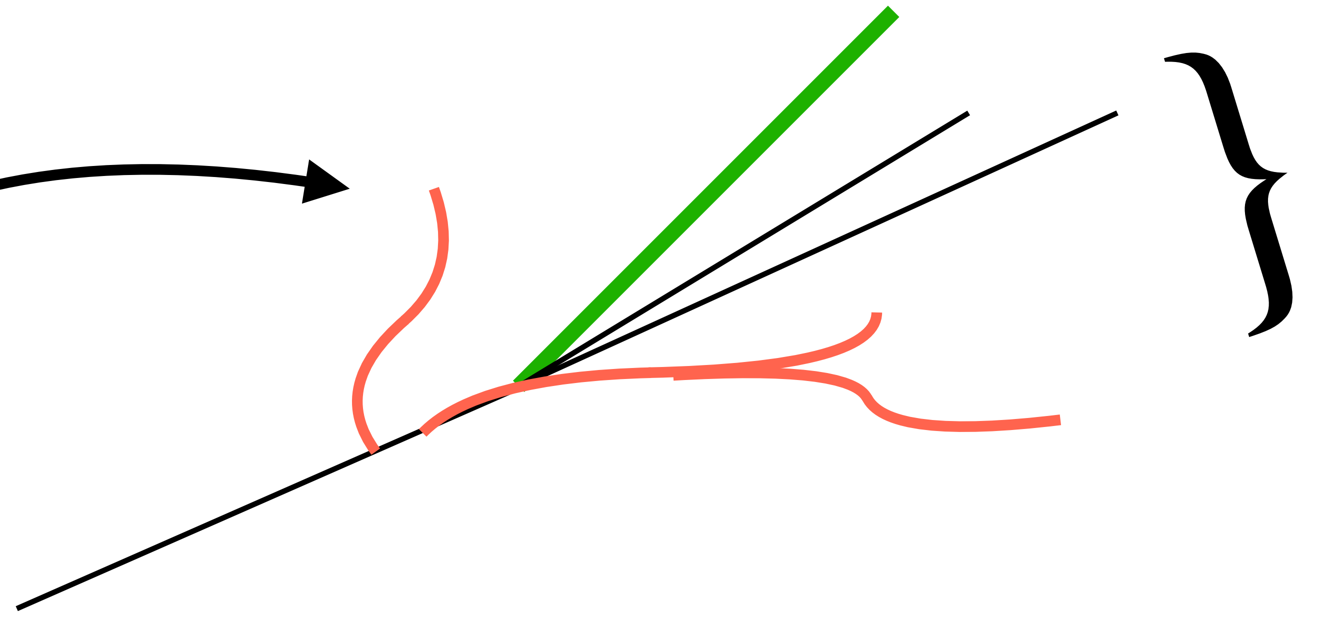
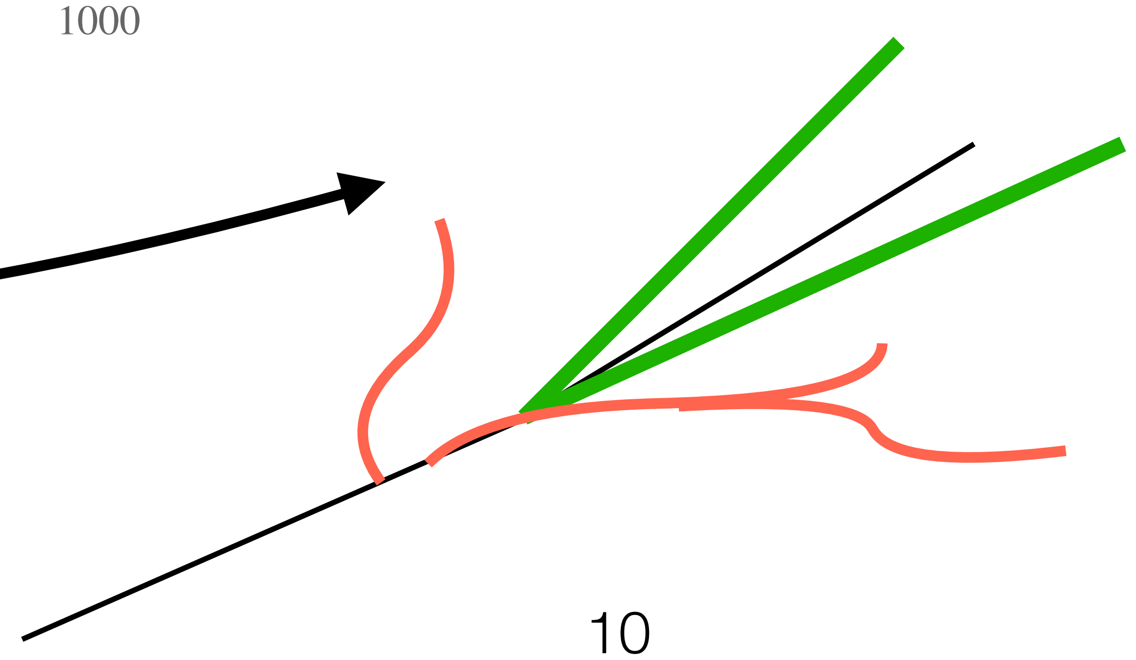
e^+e^-





$$p_t = -\sum_X p_{X,t}$$

- TMD is semi-inclusive, knows only one hadron and inclusive over the rest
- EEC needs to know 2 hadrons, likely to be modeled by a di-hadron fragmentation, but less known …



Near-side features

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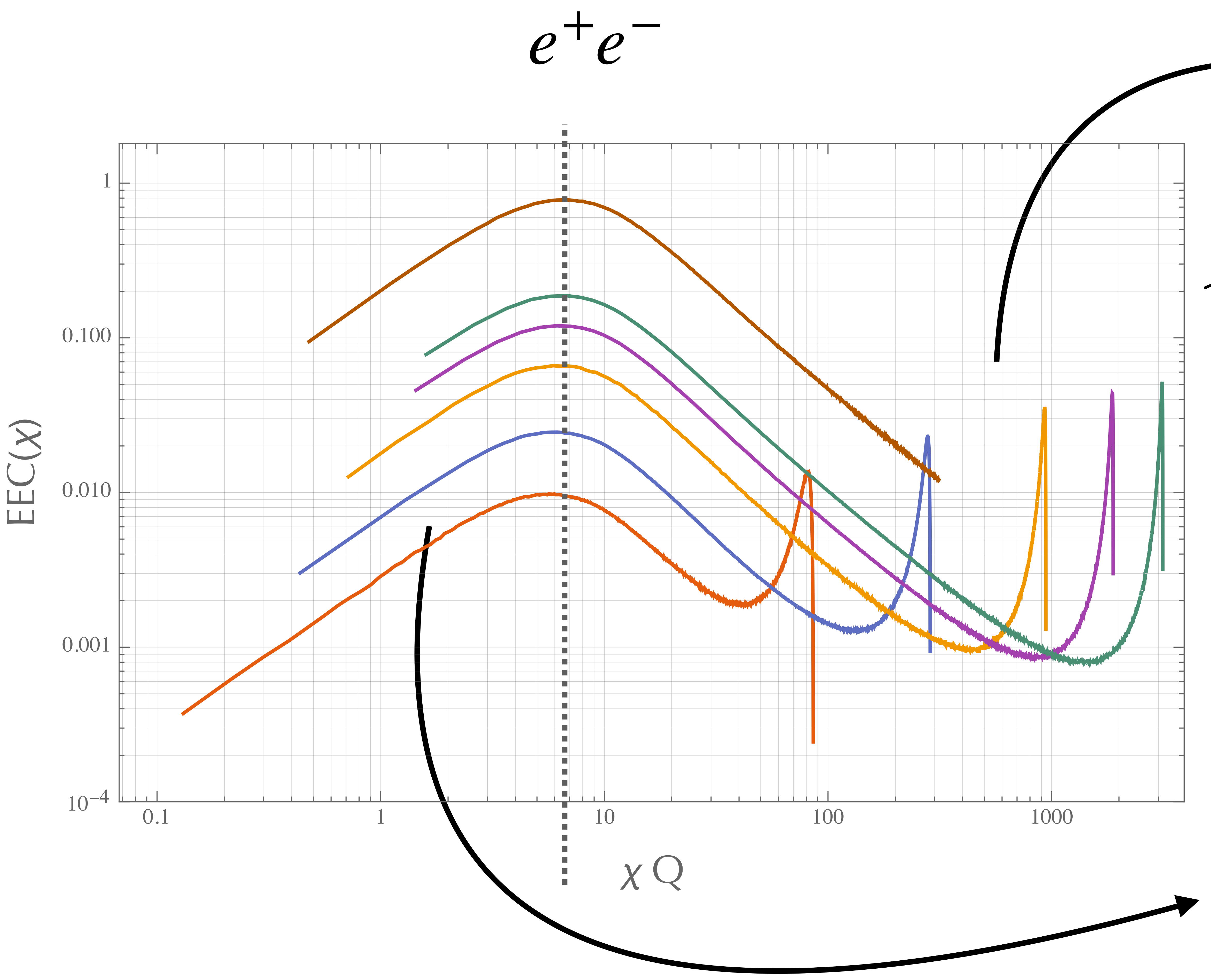
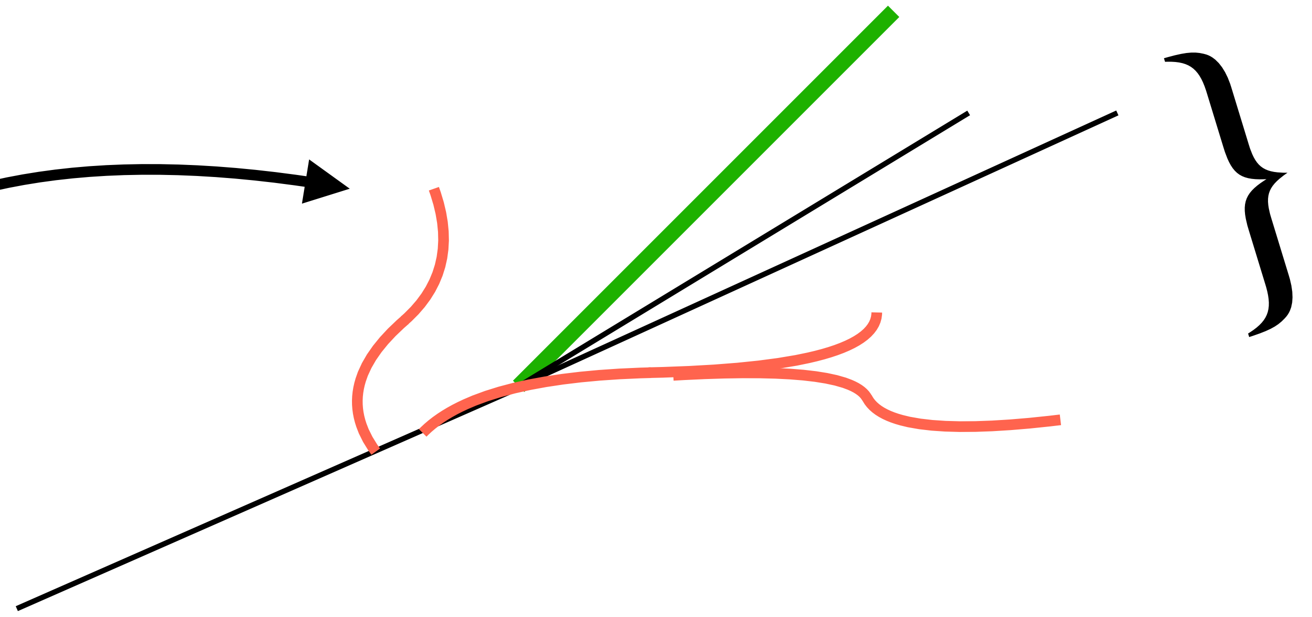
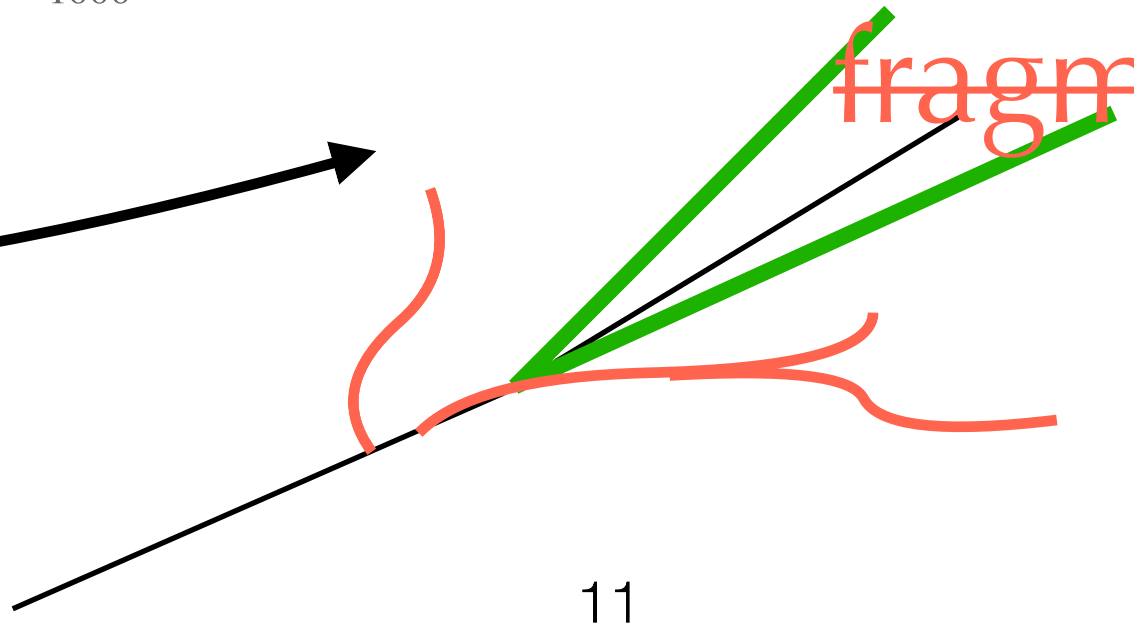




$$p_t = -\sum_X p_{X,t}$$

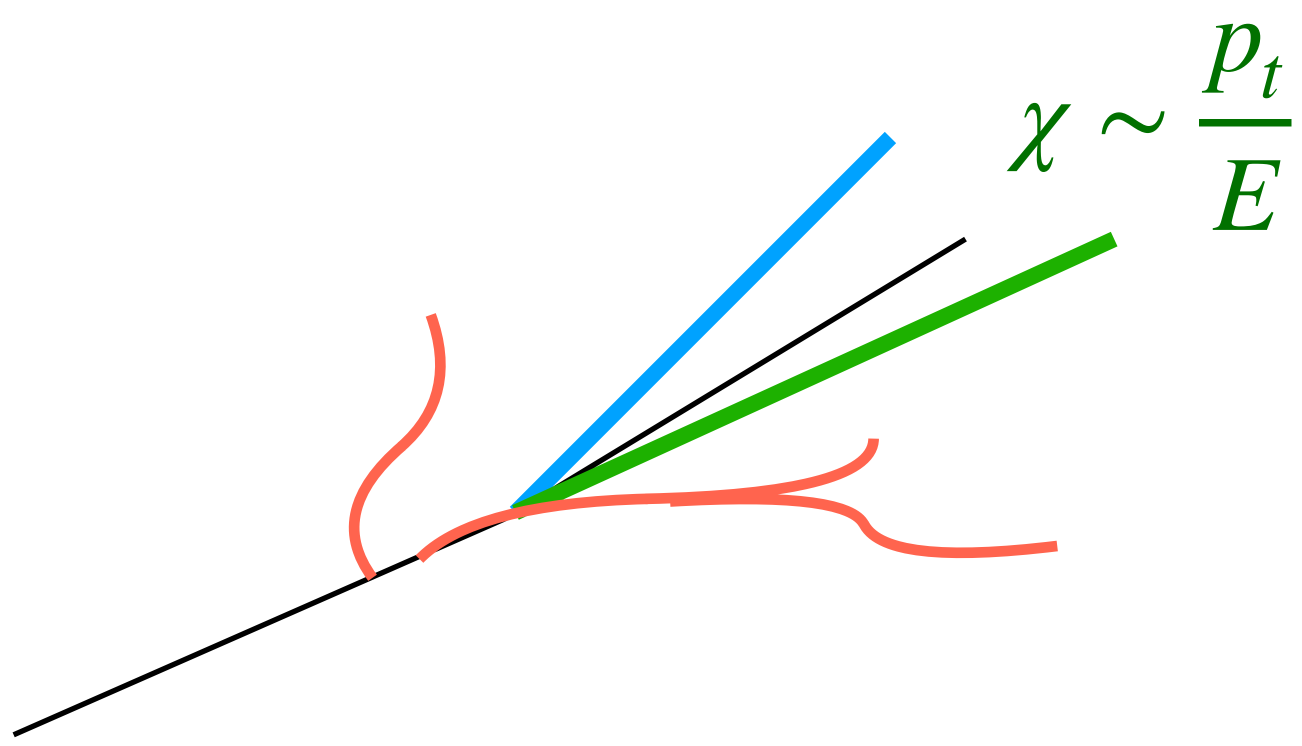
- TMD is semi-inclusive, knows only one hadron and inclusive over the rest, **encoding FULL info. on the NP transverse dynamics, how to extract?**
- ~~EEC needs to know 2 hadrons, likely to be modeled by a di-hadron fragmentation, less known …~~



XL and Zhu, 2403.08874

An NP Model in the Small χ Regime

- Pick an arbitrary hadron h with momentum fraction z
- The angle between h and a collinear hadron near h is $\chi \sim \frac{p_t}{E}$
- **The transverse kinematics w.r.t h, is driven by emitting soft quanta**
- The transverse momentum of an arbitrary collinear hadron follows the transverse momentum distribution of the soft quanta
- Assuming the soft quanta are emitted identically and un-correlatedly



XL, Vogelsang, Yuan, Zhu, PRL 2025

An NP Model in the Small χ Regime

a lonely boat drifting on a soft river

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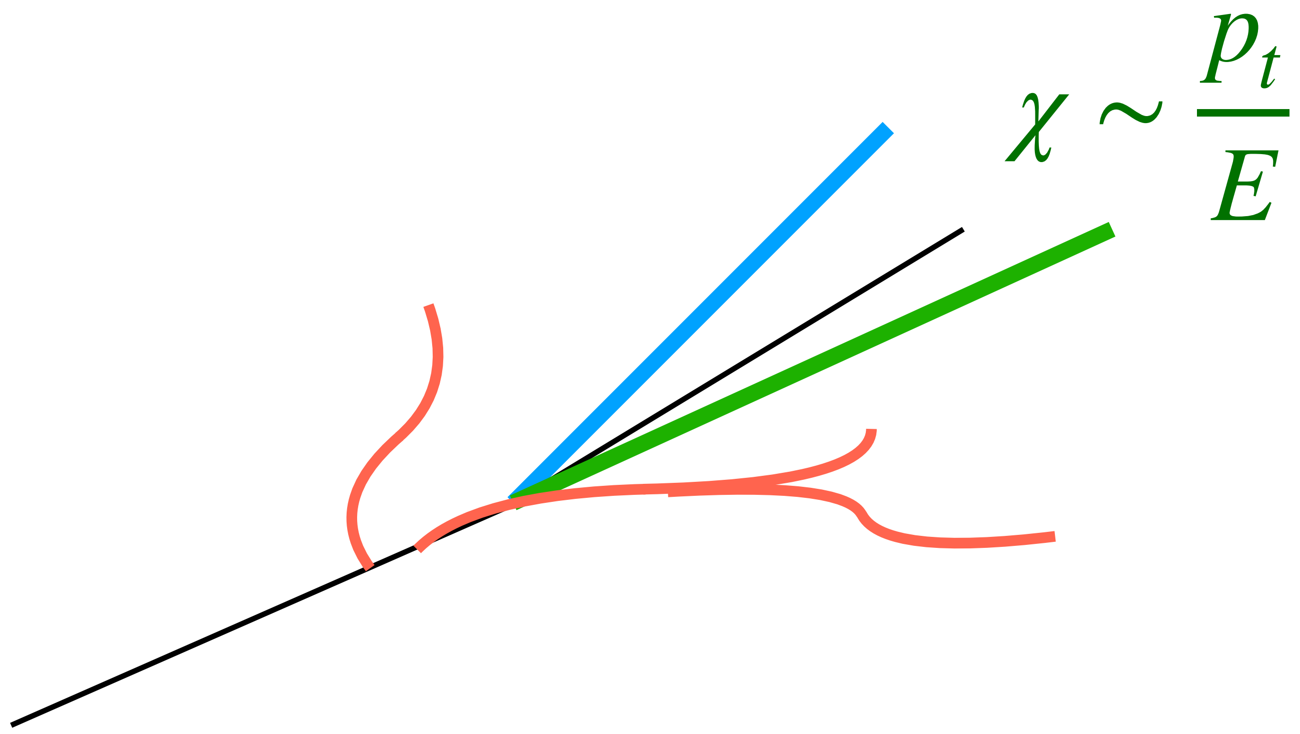

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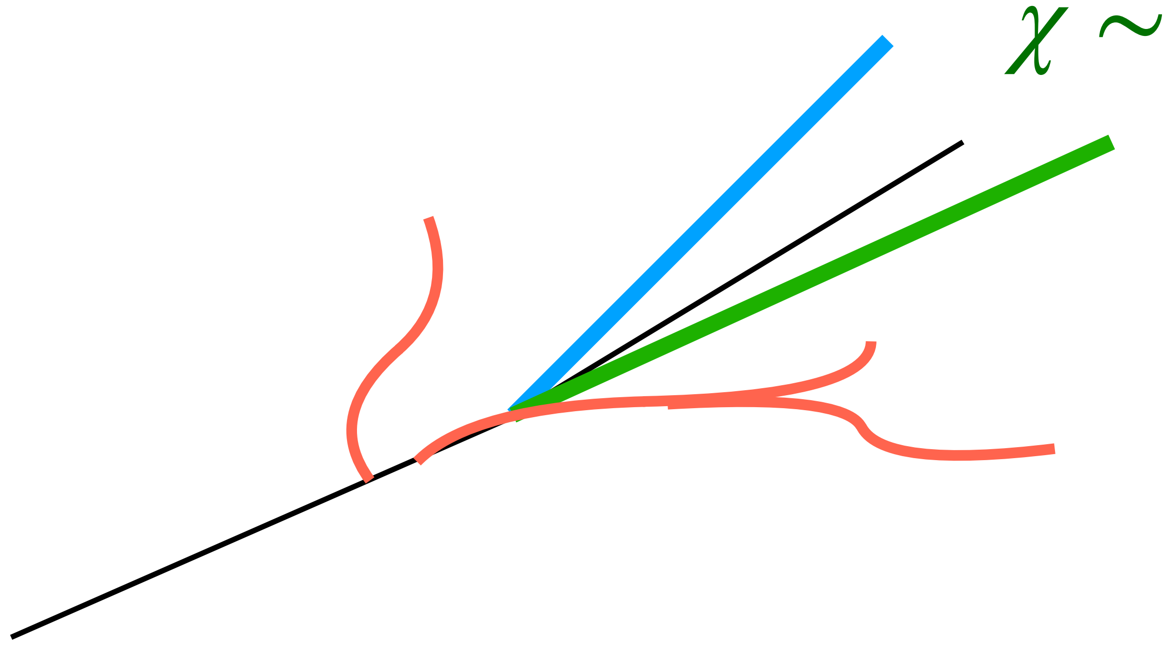

$$\frac{1}{\sigma}\frac{d^3\sigma}{dz d^2\mathbf{p}_t} = d_h(z) \times$$

$$\sum_{n=0}^{\infty}\frac{1}{n!}\int\prod_i^n [dk_i]\, M_{NP}(k_i)\left[\delta(\mathbf{p}_t - \sum_i \mathbf{k}_{i,t}) - \delta(\mathbf{p}_t)\right]$$

XL, Vogelsang, Yuan, Zhu, PRL 2025

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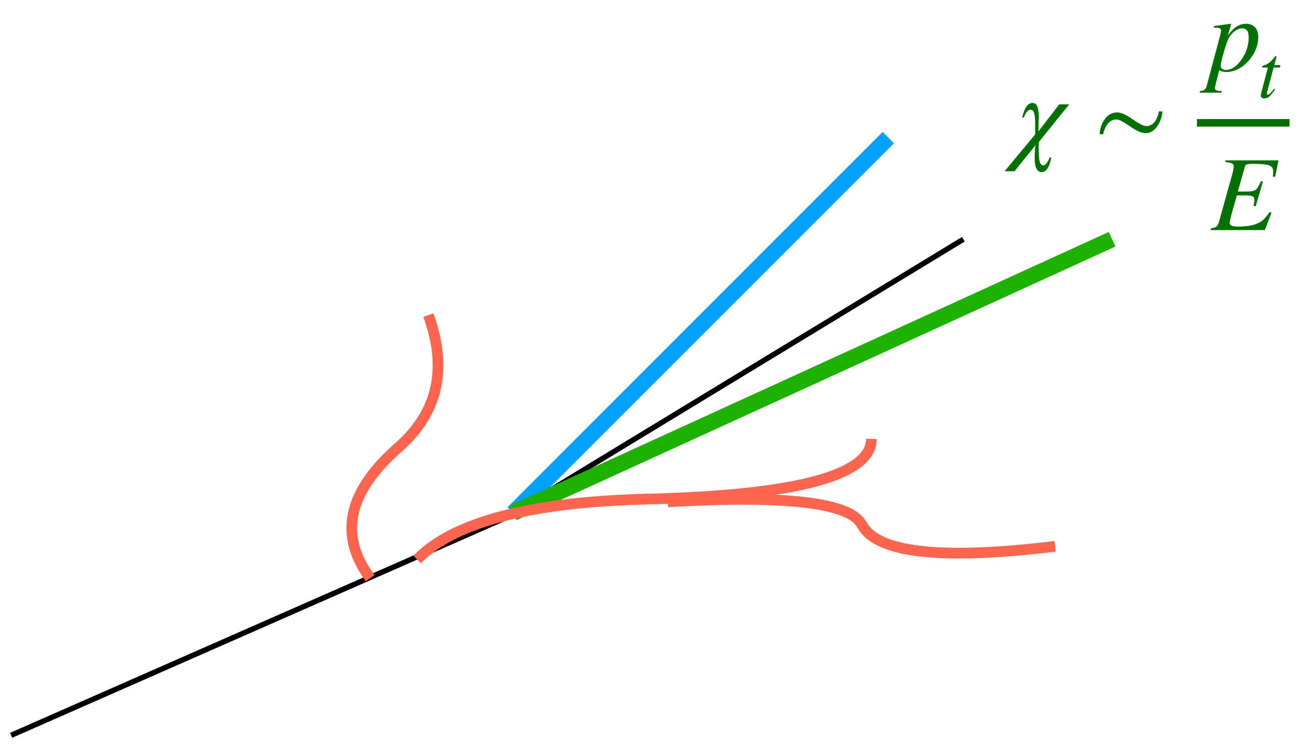

$$\frac{1}{\sigma}\frac{d^3\sigma}{dz d^2\mathbf{p}_t} = d_h(z)\int \frac{d^2\mathbf{b}}{(2\pi)^2} e^{-i\mathbf{b}\cdot\mathbf{p}_t}$$

$$\times \sum_{n=0}^{\infty} \frac{1}{n!}\left(\int [dk_i] M_{NP}(k_i)\left(e^{i\mathbf{k}_{i,t}\cdot\mathbf{b}} - 1\right)\right)^n$$

$$= d_h(z)\int \frac{db}{2\pi} b J_0(bp_t) e^{-S_{NP}(b,\mu)}$$

$p_t \approx cE_J\chi$ Purely NP Sudakov

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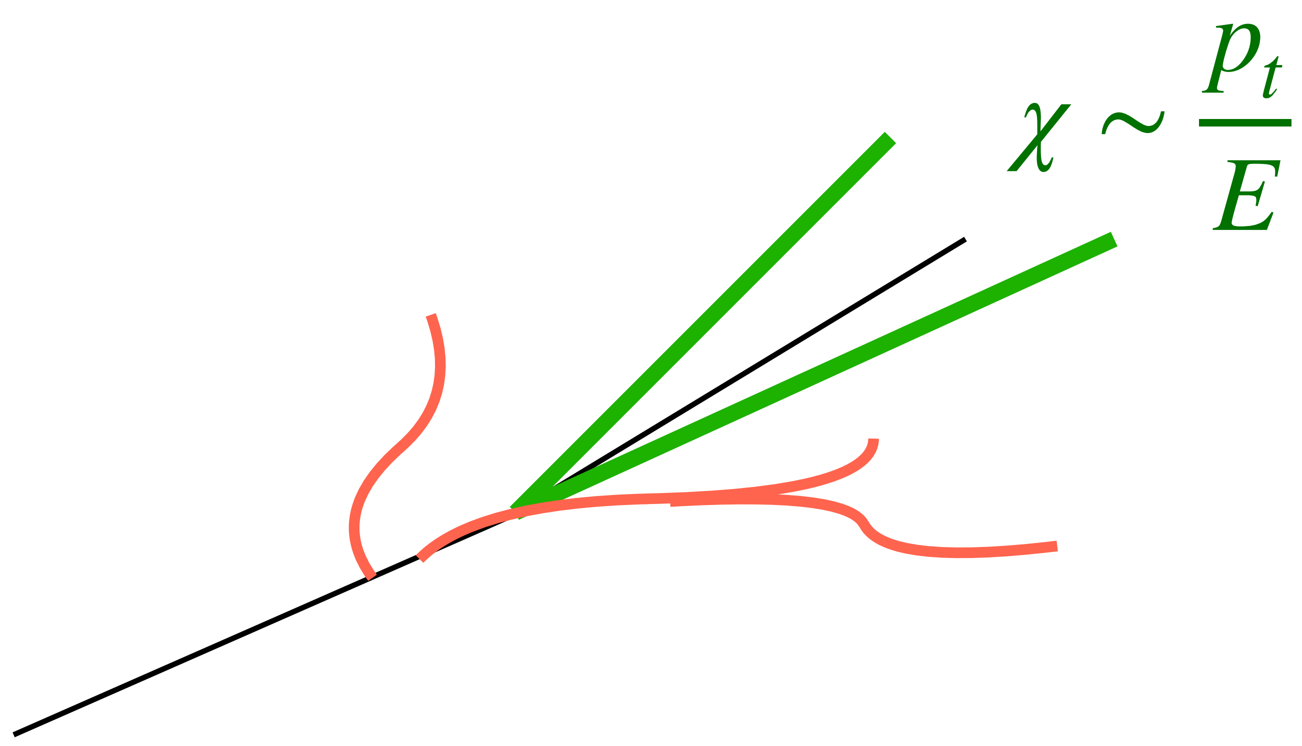
An NP Model in the Small χ Regime

$$\mathrm{EEC}(\chi) = E_J^2 c^3 \chi \int dz z d_h(z) \int db\, b J_0(cE_J\chi b) e^{-S_{NP}(b,\mu)}$$

$$= E_J^2 c^3 N \chi \int db\, b J_0(cE_J\chi b) e^{-\frac{g_1}{c^2}b^2} e^{-\frac{g_2}{2}\ln\frac{b}{b_*}\ln\frac{cE_J}{\mu_0}}$$

with $S_{NP} = \frac{g_1}{z^2}b^2 + \frac{g_2}{2}\ln\left(\frac{b}{b_*}\right)\ln\frac{cE_J}{\mu_0}$, $\quad Ne^{-\frac{g_1}{c^2}b^2} \approx \int dz \sum_h z d_h(z) e^{-\frac{g_1}{z^2}b^2}$



$c, N, g_1, g_2, \mu_0, b_*$, **6 parameters!!**

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An NP Model in the Small χ Regime

$$\text{EEC}(\chi) = E_J^2 c^3 \chi \int dz z d_h(z) \int db\, b J_0(cE_J \chi b) e^{-S_{NP}(b,\mu)}$$

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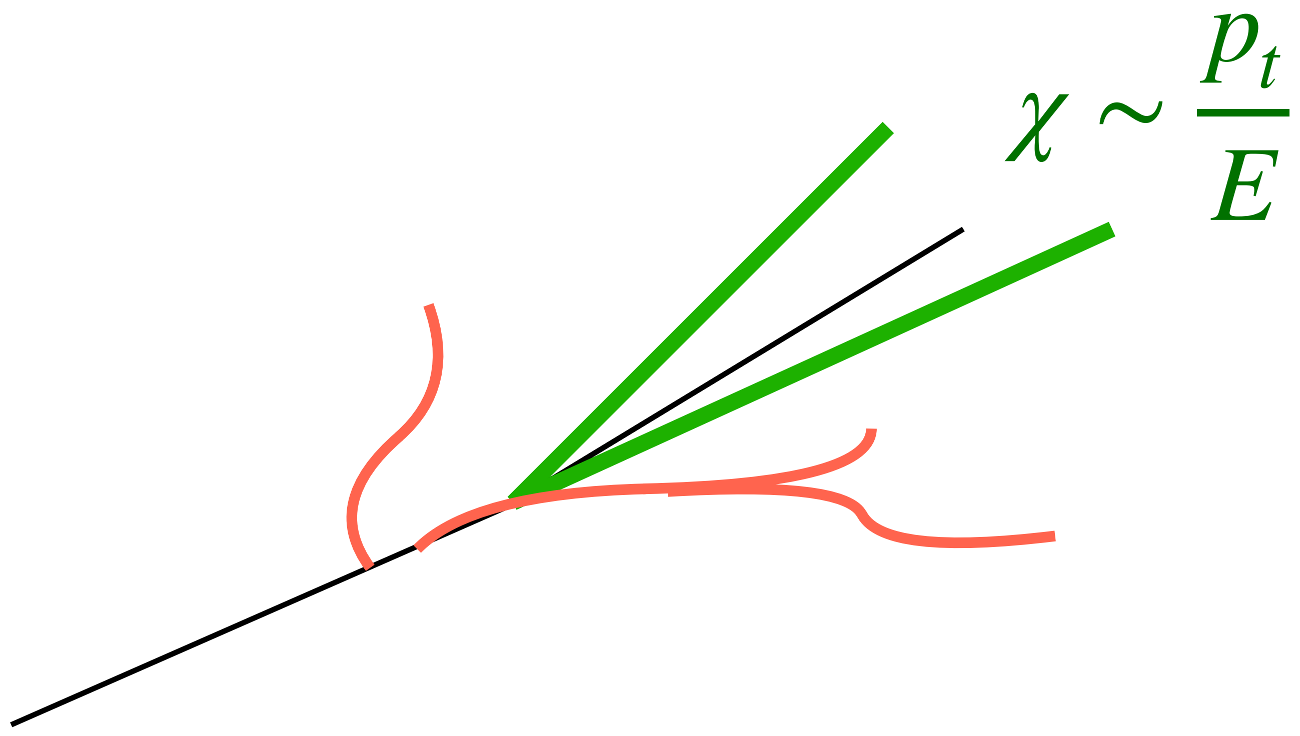

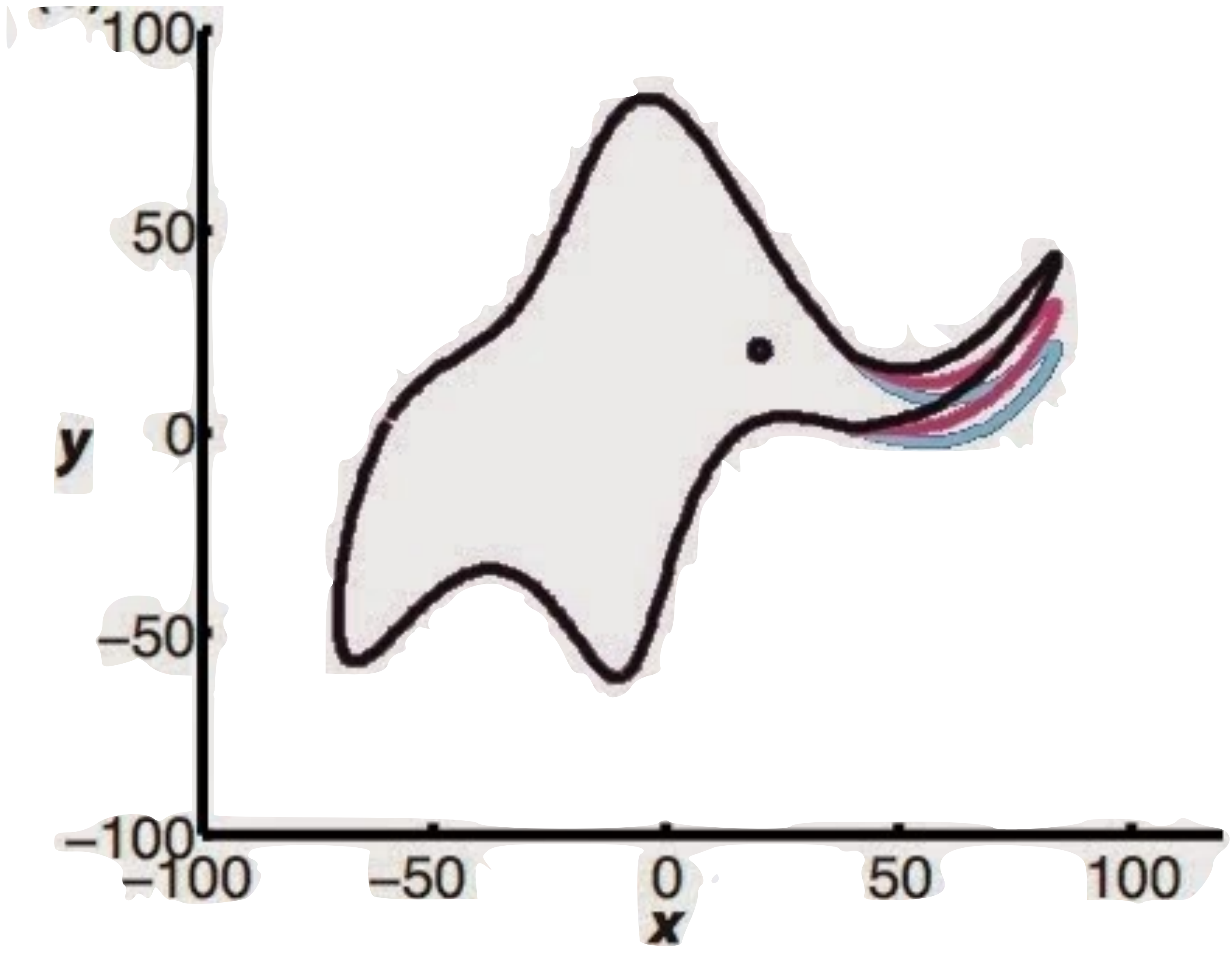

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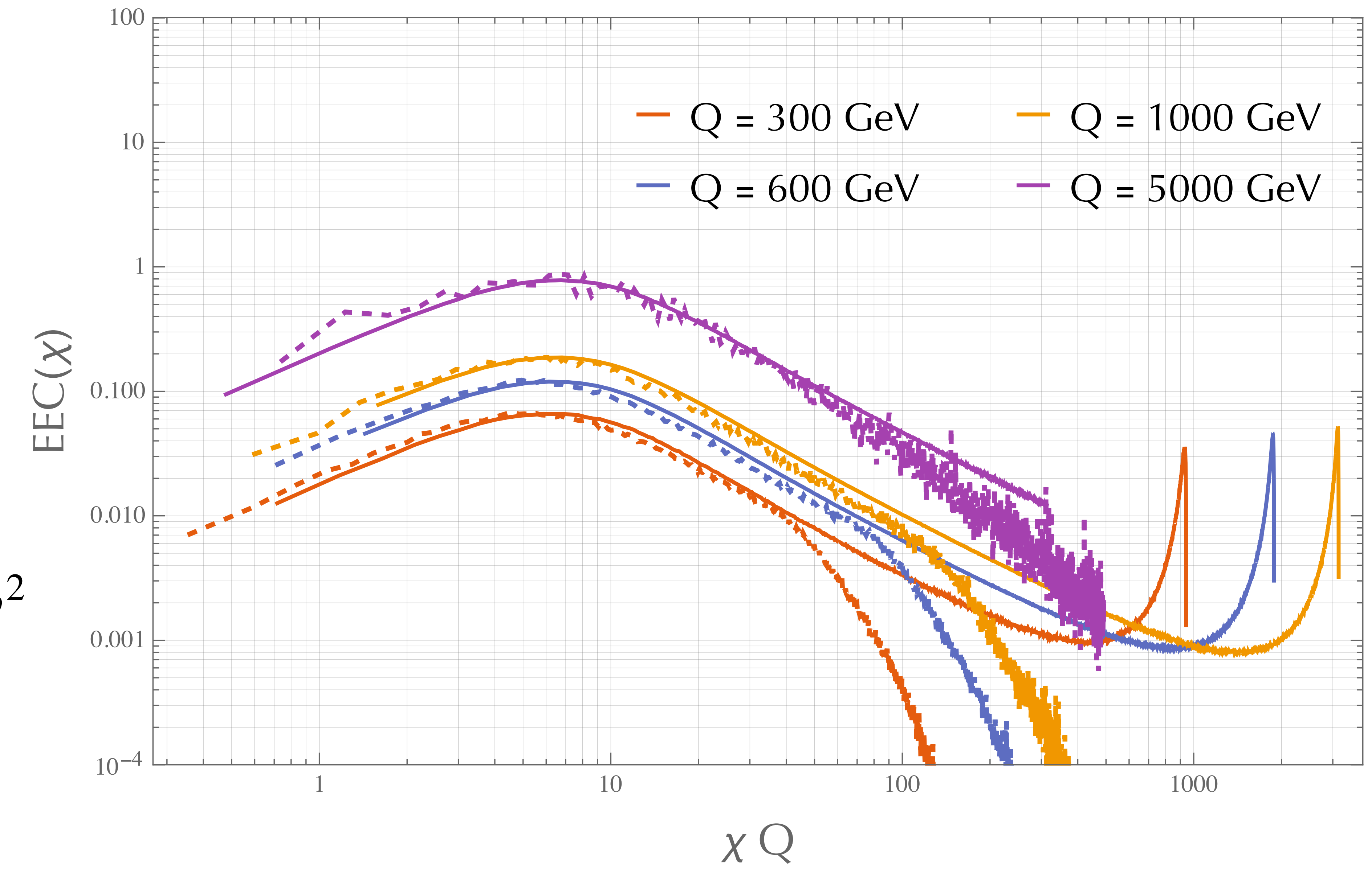

$c, N, g_1, g_2, \mu_0, b_*,$ 6 parameters!! Too many!!

4 parameters have already been determined, by SIDIS. Sun, Isaacson, Yuan, and Yuan, 2018

Only 2 free parameters left, can be soley determined by the overall normalization and position with just one energy input

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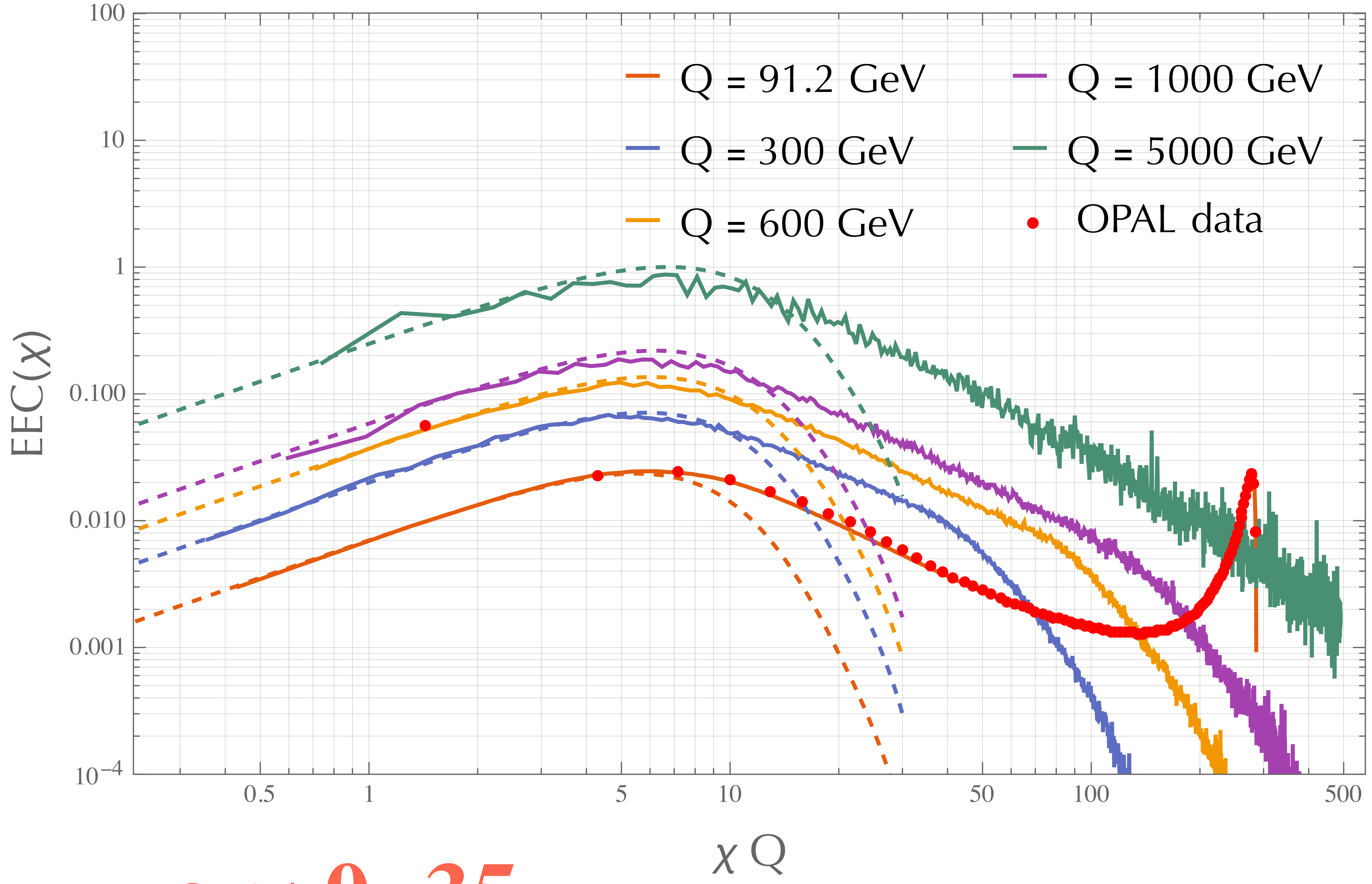
Comparison with Pythia and Data

EEC from **quark** Jet



c ≈ 0.35

- determine c, N using $Q = 300\,\text{GeV}$ curve, others are obtained by varying $E_J = Q/2$
- Correct Q scaling, Good agreement between model and Pythia/data in the transition region, turning point driven by NP physics
- Larger χ region requires matching with pQCD calculations

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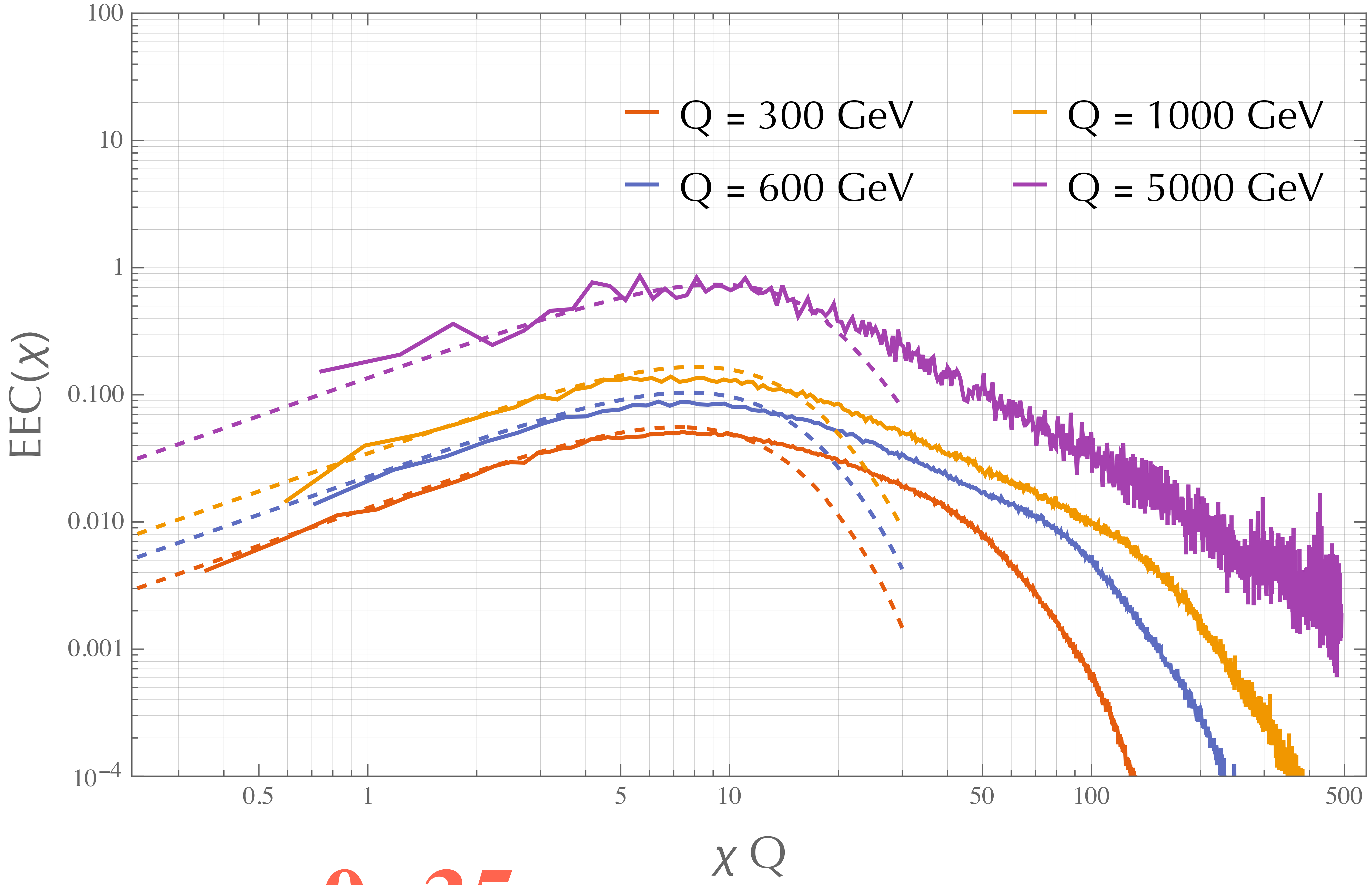
Comparison with Pythia and Data

EEC from **gluon** Jet



c ≈ 0.35

- Everything is fixed, simply replace $\frac{g_2}{2} \ln \frac{b}{b_*} \ln \frac{cE_J}{\mu_0} \to g_2 \frac{C_A}{C_F} \ln \frac{b}{b_*} \ln \frac{cE_J}{\mu_0}$
- Correct Q scaling, Good agreement between model and Pythia, turning point driven by NP physics
- Larger χ region requires matching with pQCD calculations

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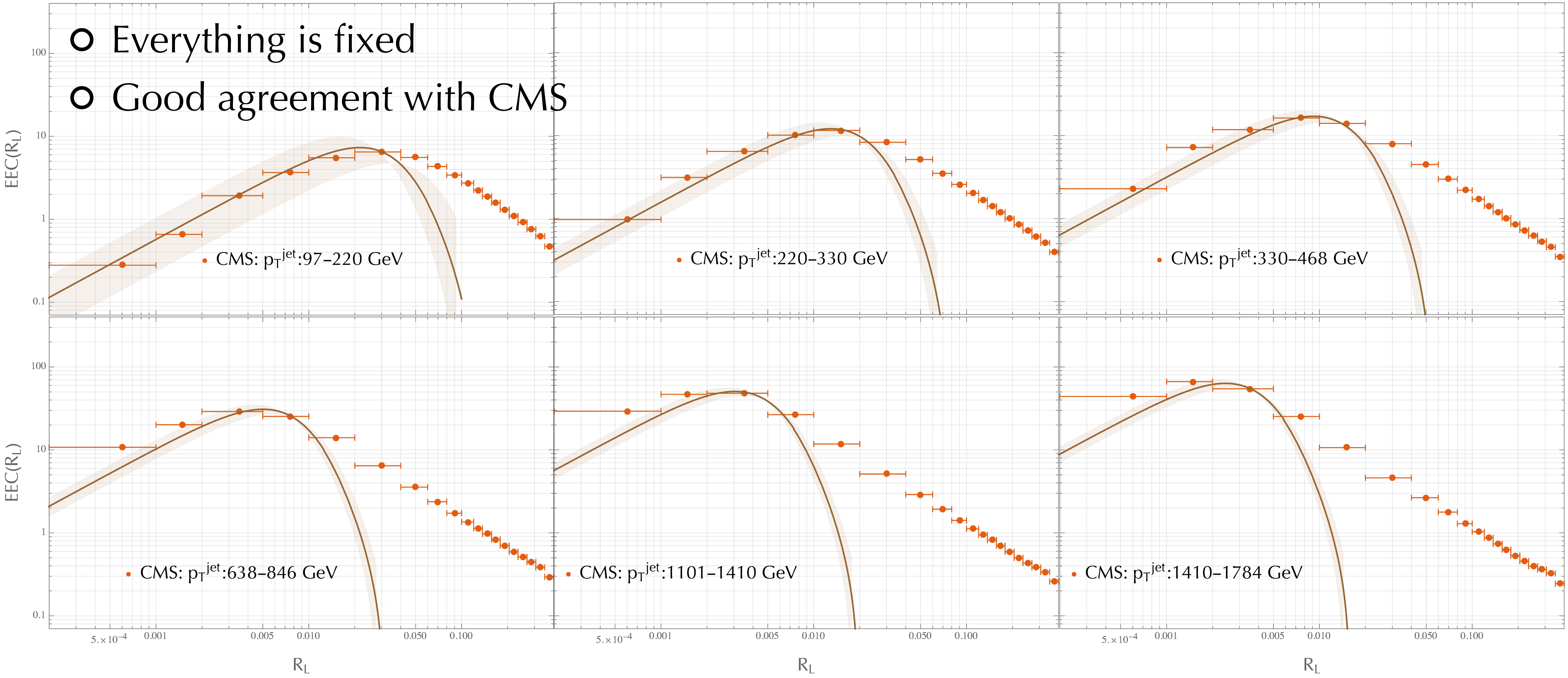
Comparison with Pythia and Data

- Everything is fixed
- Good agreement with CMS



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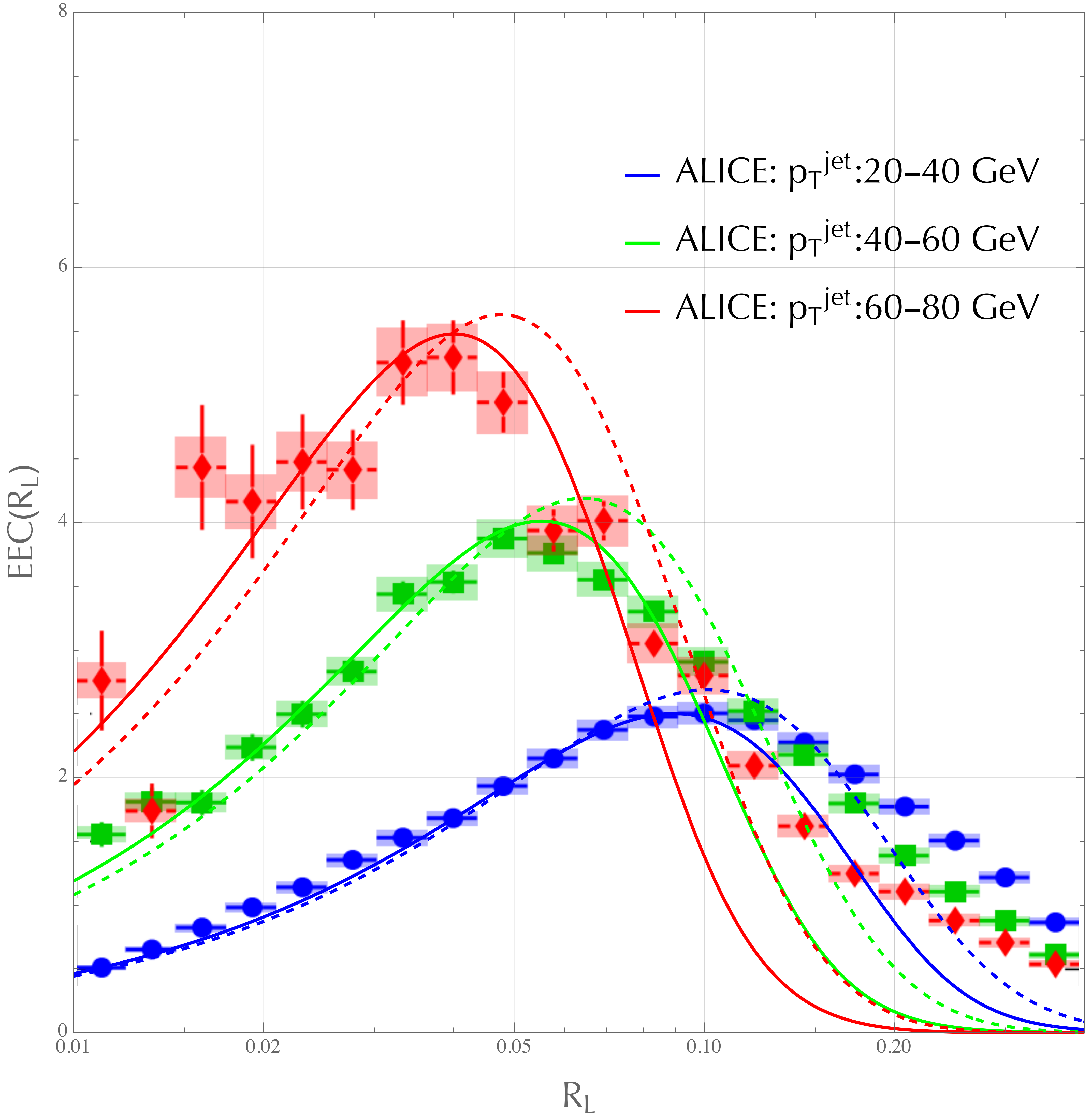
Comparison with Pythia and Data

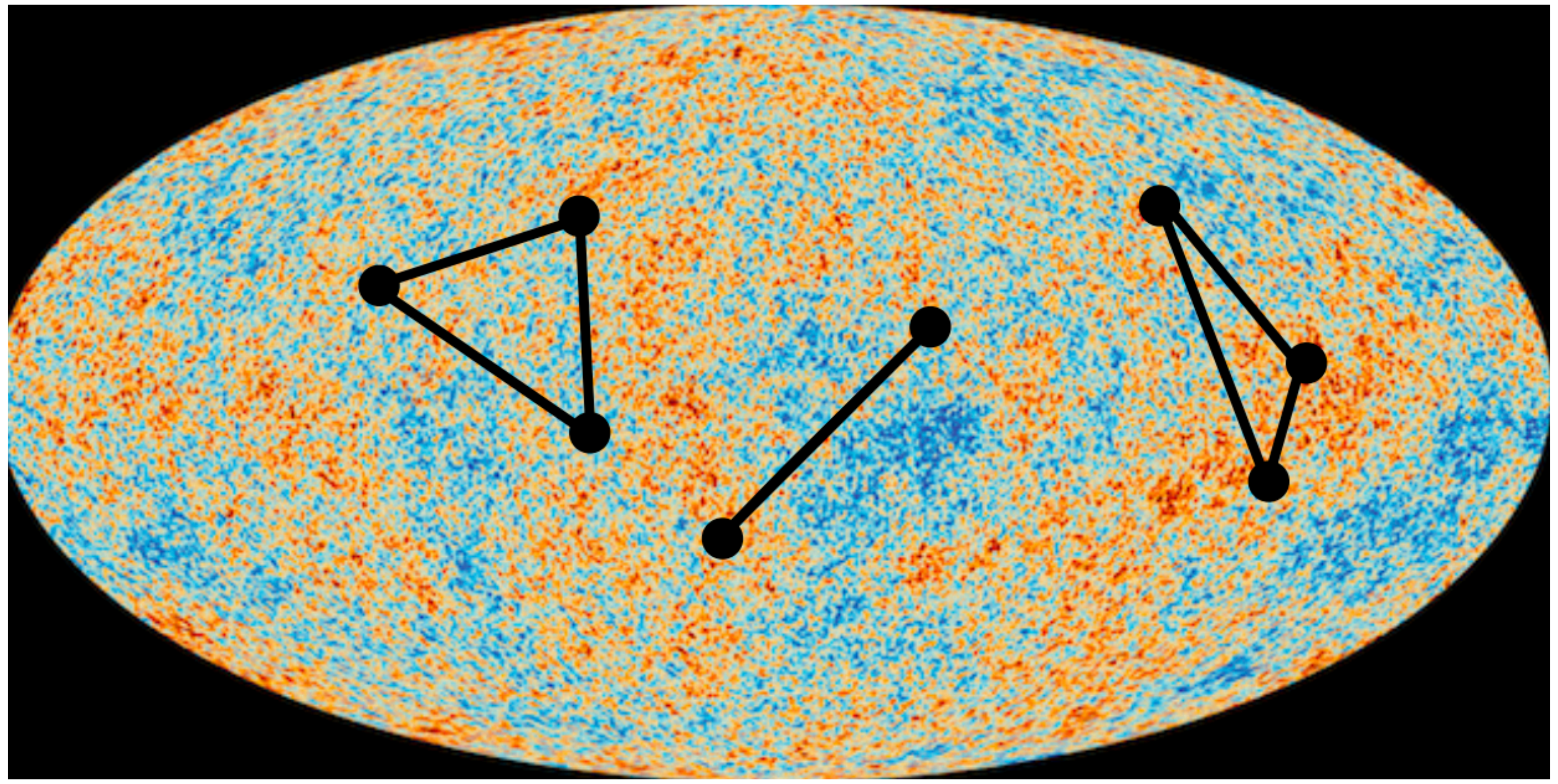
- ALICE used different normalization.
- Re-determine N, but fix other para.
- Gluon and quark jet fraction unknown in their measurements
- Correct Q scaling, good agreement with ALICE



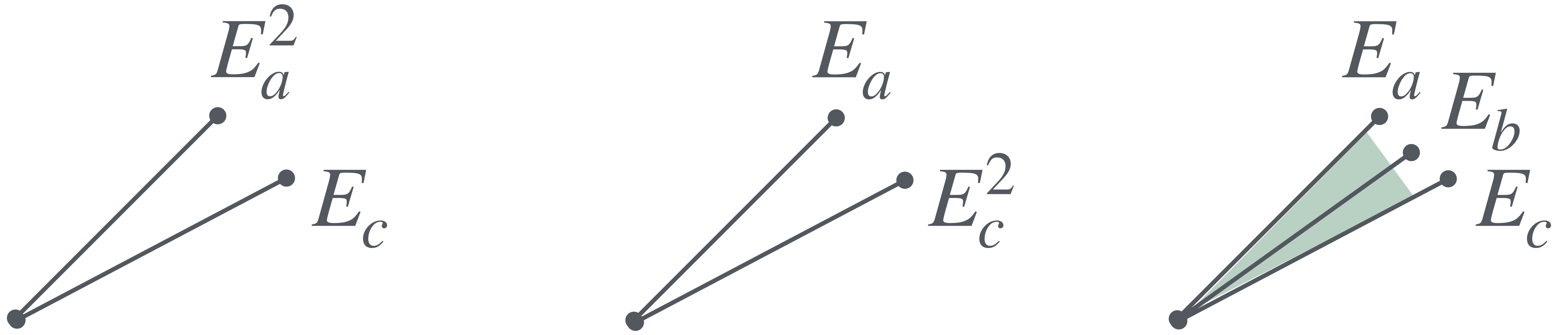
XL, Vogelsang, Yuan, Zhu, 2410.16371

E3C

- Go beyond EEC



$$\mathrm{E3C}(\chi) = \frac{1}{\sigma}\int \frac{E_a E_b E_c}{Q^3} d\sigma \delta(\chi - \max(\theta_{ab}, \theta_{ac}, \theta_{bc}))$$



Model prediction:

$\propto c\mathrm{EEC}(\chi)$ $\propto c\mathrm{EEC}(\chi)$ $\propto \chi^2$

$\mathbf{E3C}(\chi)/\mathbf{EEC}(\chi)|_{\chi\to 0} \to 2c \approx 0.7$

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E3C

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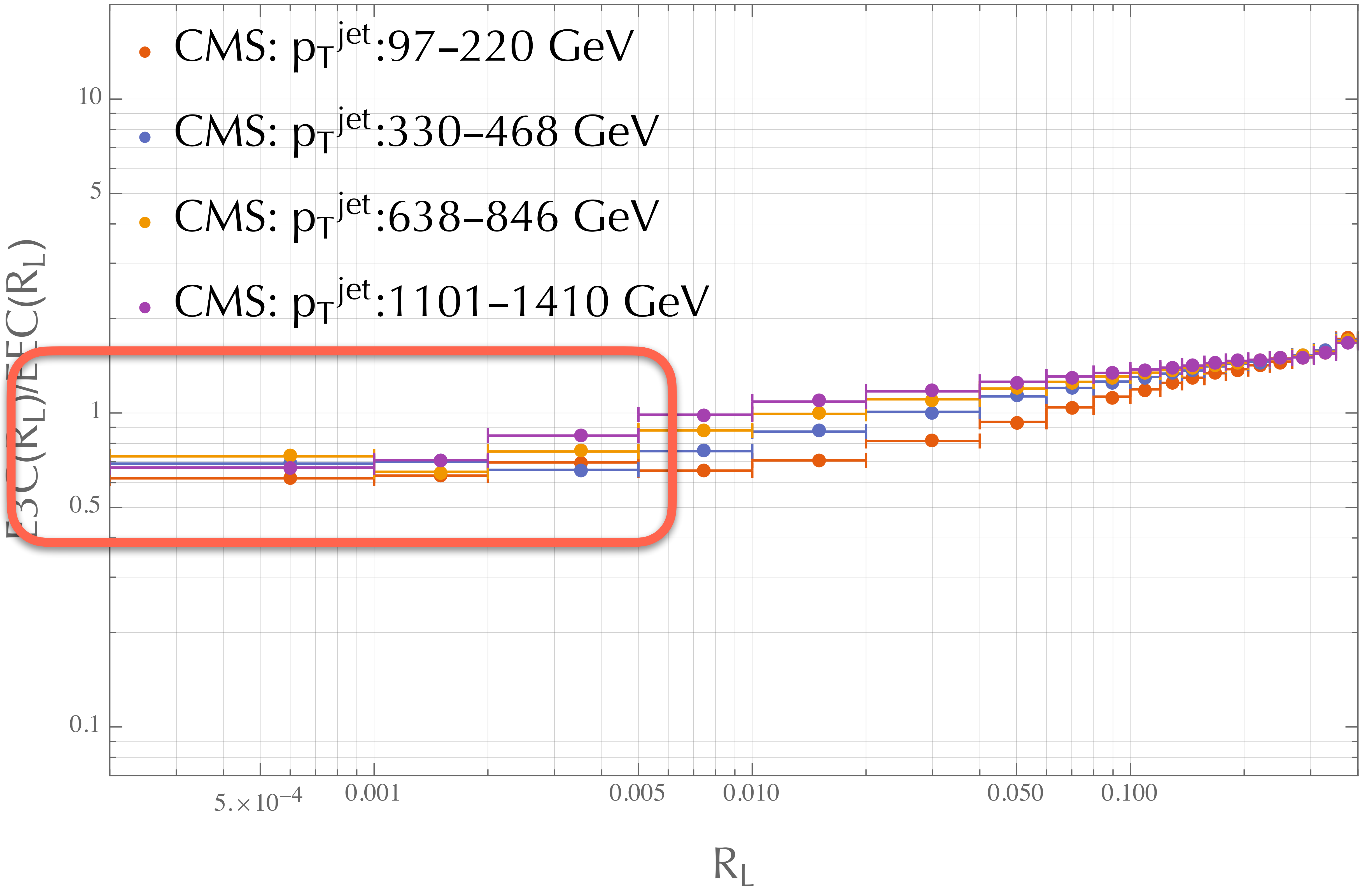

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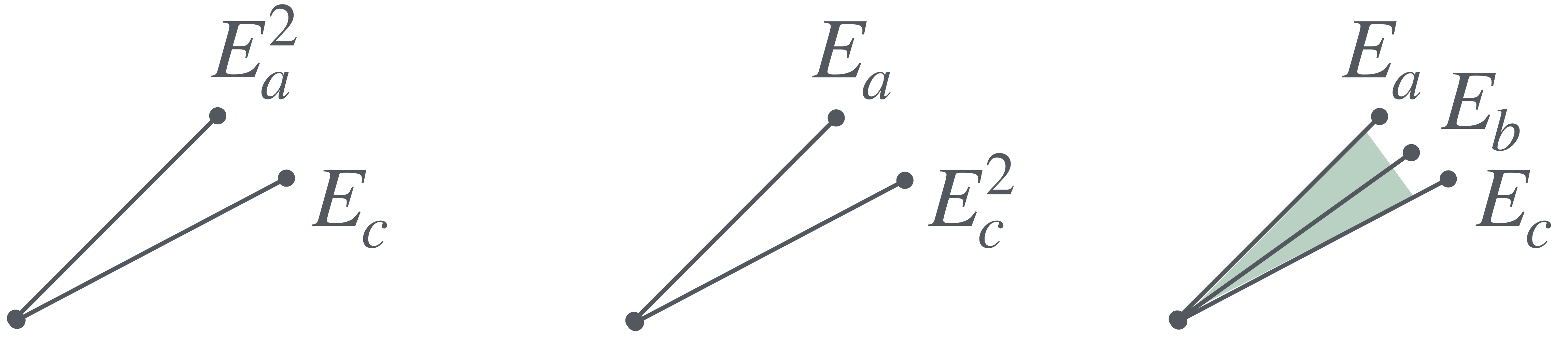

Model prediction:

$\propto c\mathrm{EEC}(\chi)$ $\propto c\mathrm{EEC}(\chi)$ $\propto \chi^2$

- **c determined from an entirely unrelated observable !**

$\mathrm{E3C}(\chi)/\mathrm{EEC}(\chi)|_{\chi\to 0} \to 2c \approx 0.7$

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E3C

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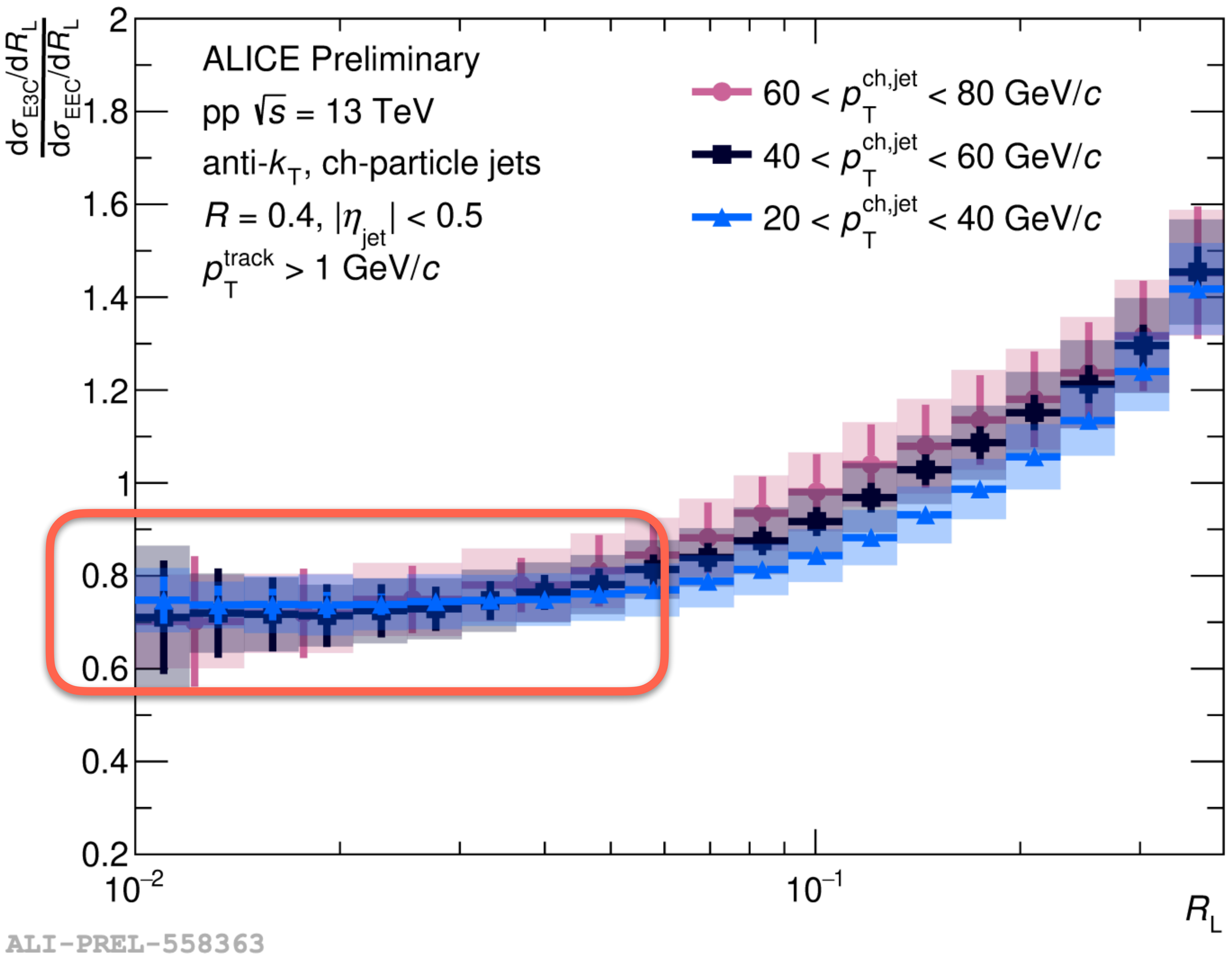

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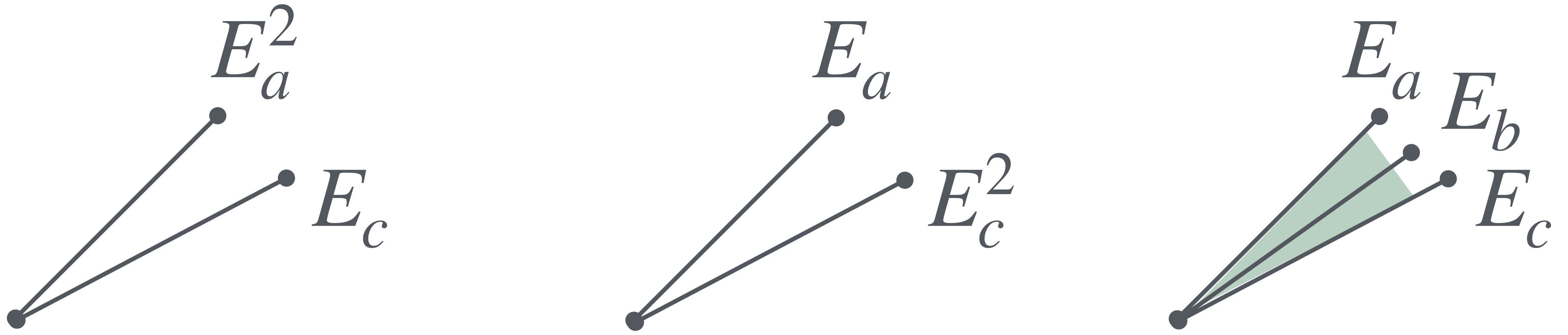

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E3C

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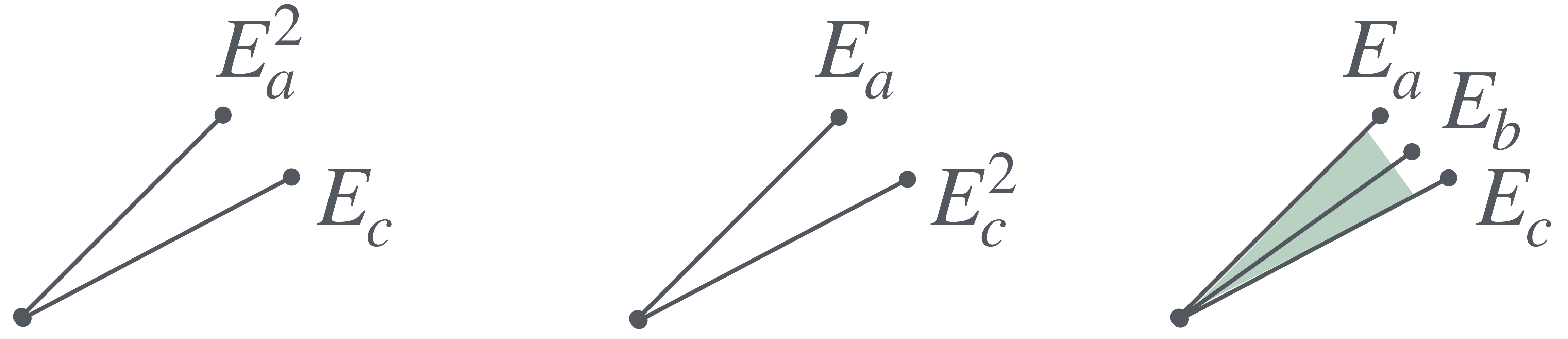
Model prediction:

$$\text{E3C}(\chi)/\text{EEC}(\chi)\,|_{\chi\to 0}$$

$$\to 2c$$

$$+c^3 E_J^2 \int d\Omega db b \Theta(\theta_{ab}, \theta_{ac} < \chi) J_0(cE_J\theta b) e^{-2S_{NP}}$$



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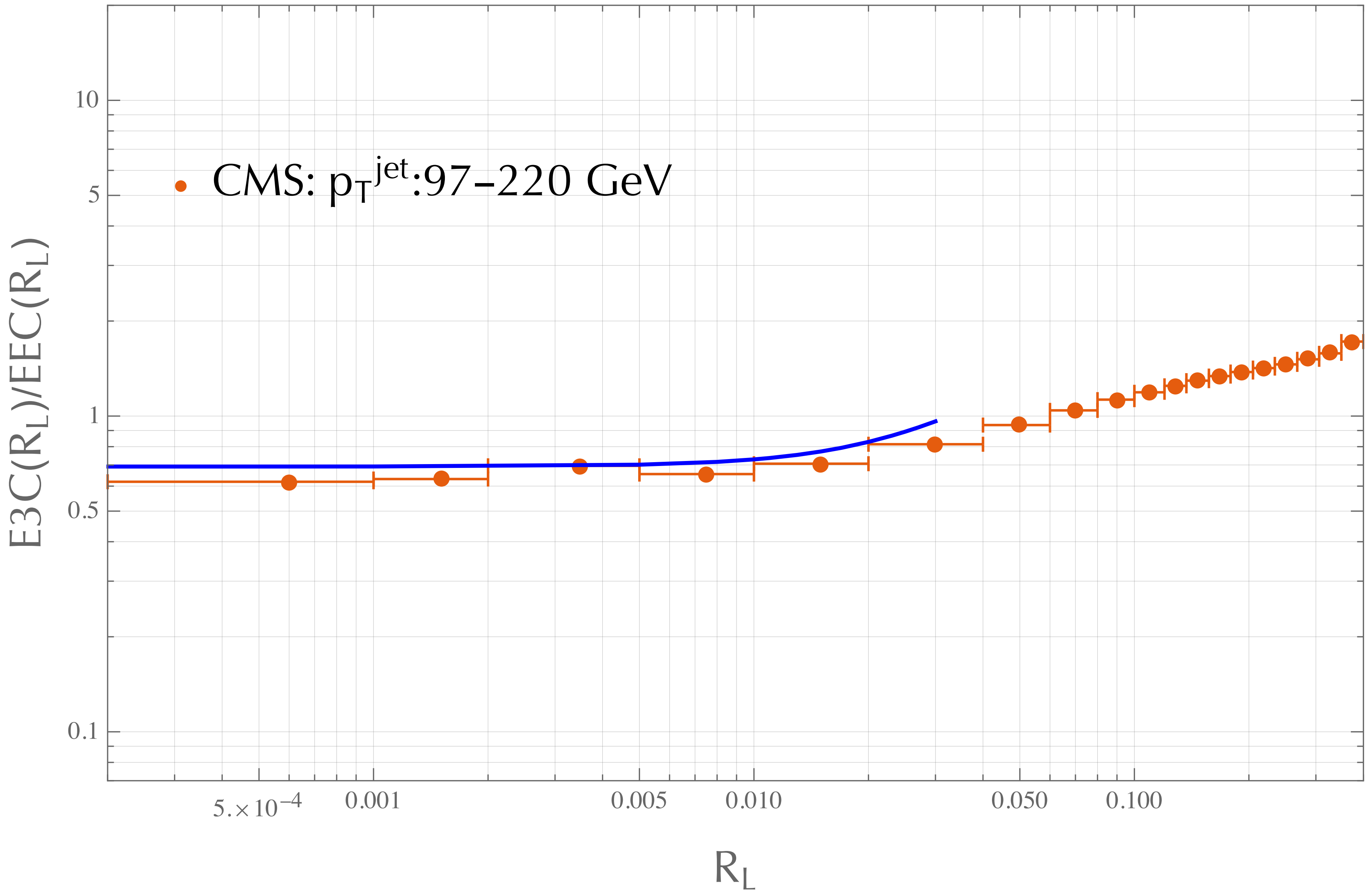
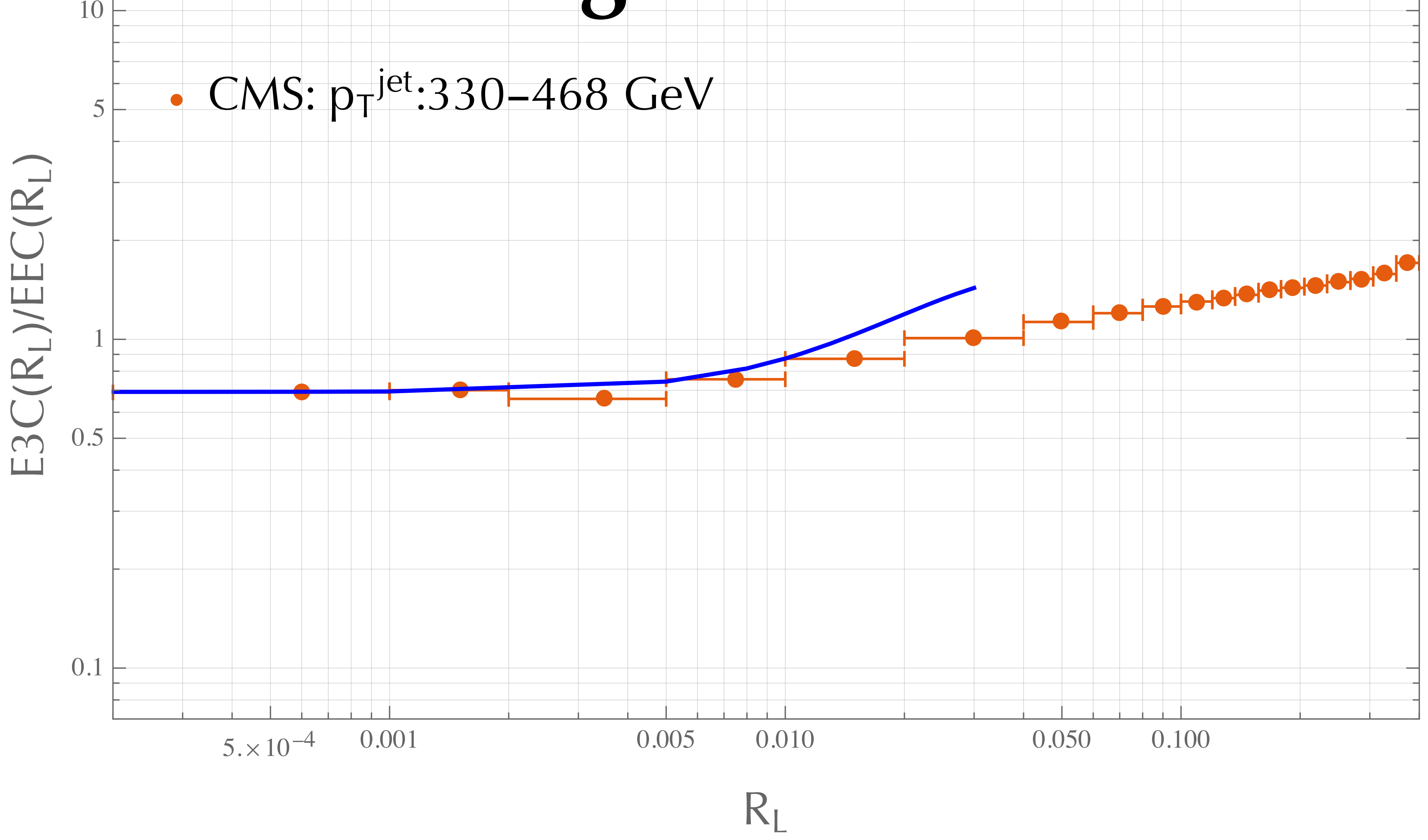
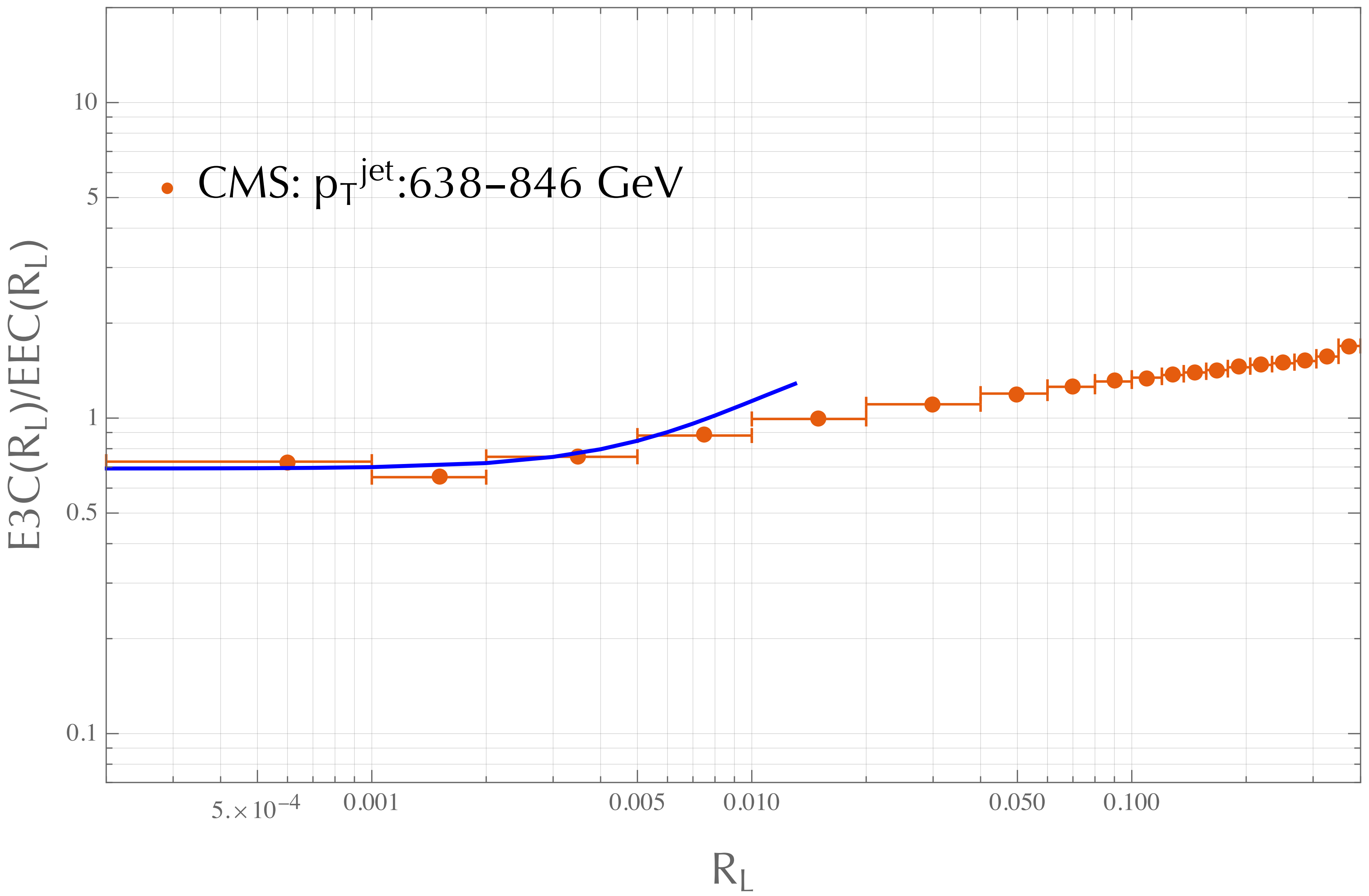
E3C

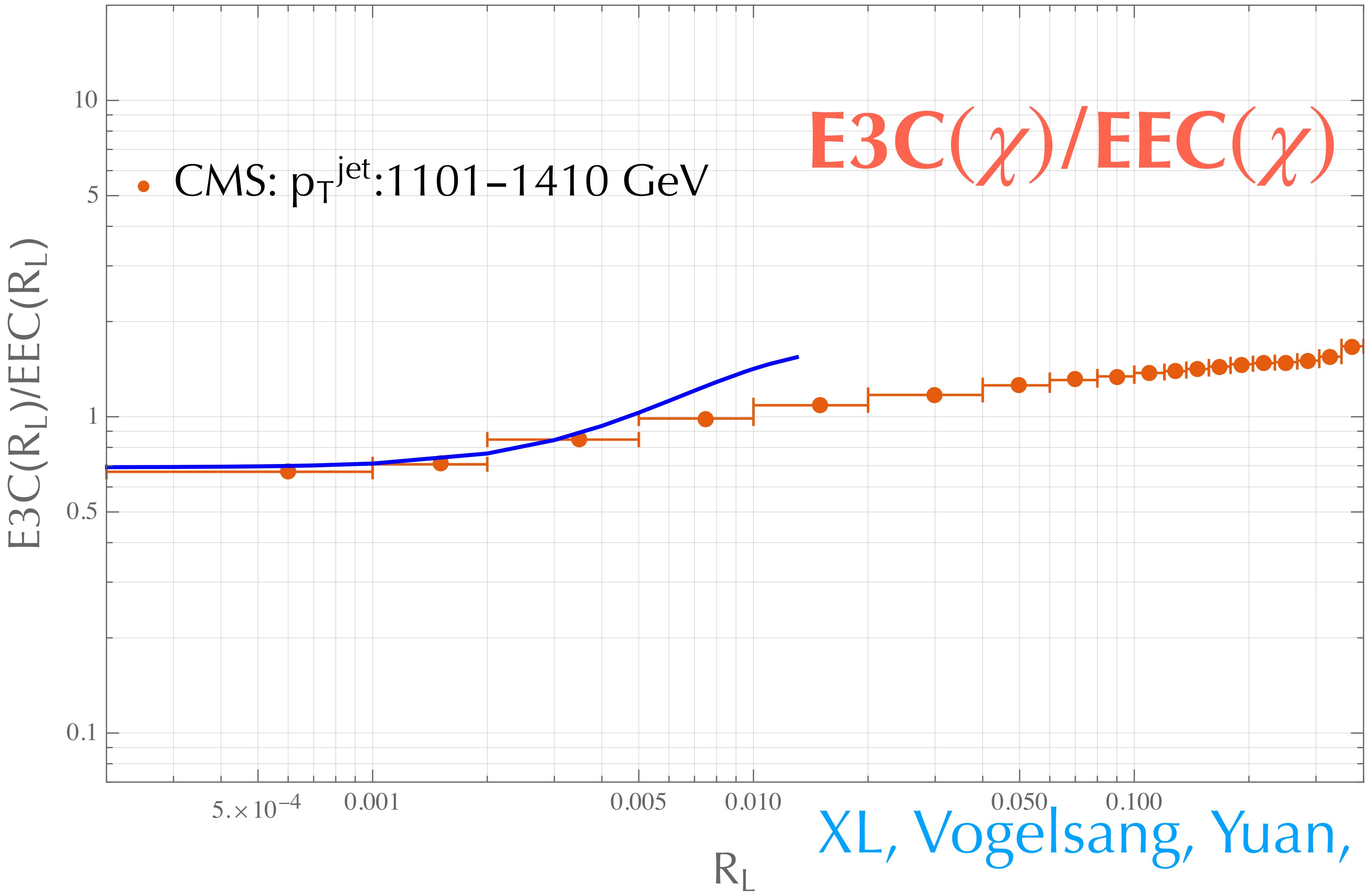


- **Good agreement with CMS**





E3C(χ)/EEC(χ)



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Conclusion

- Suggest a connection between the NP physics in the Near side Energy Correlator and NP TMD
- Agree with Pythia/LHC data across several orders of magnitude in the input energy
- Should be applicable to NEEC, di-hadron fragmentation
- This in turn may indicate the possibility of understanding TMD physics using formal field theoretical tools

Thanks