The two-point energy correlator in the QGP: from gamma+jet to inclusive jets

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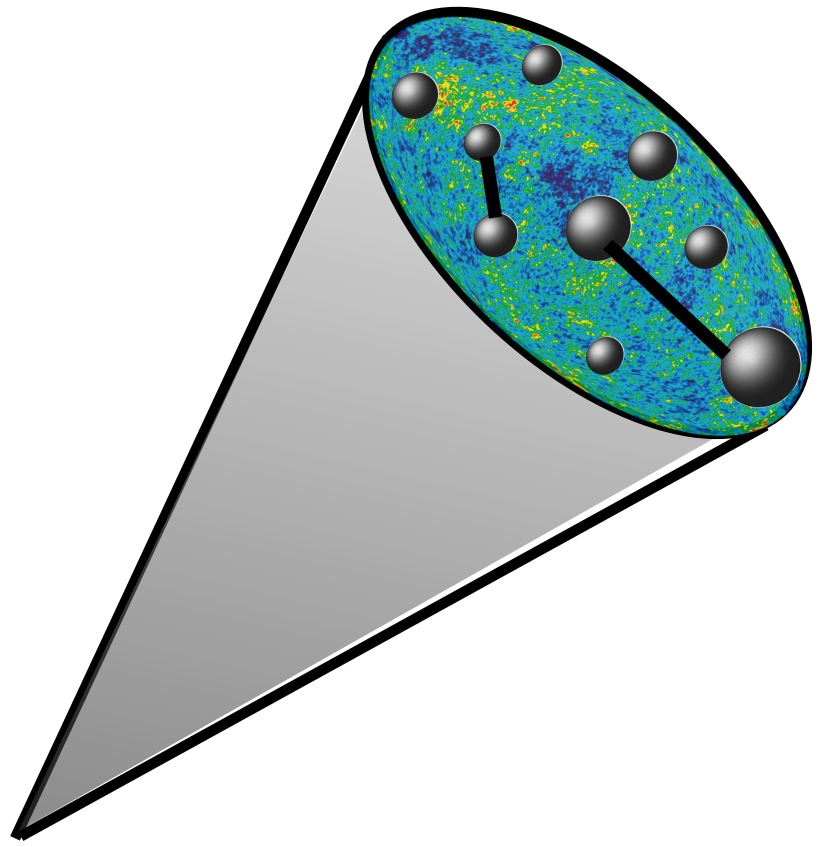
Massachusetts Institute of Technology

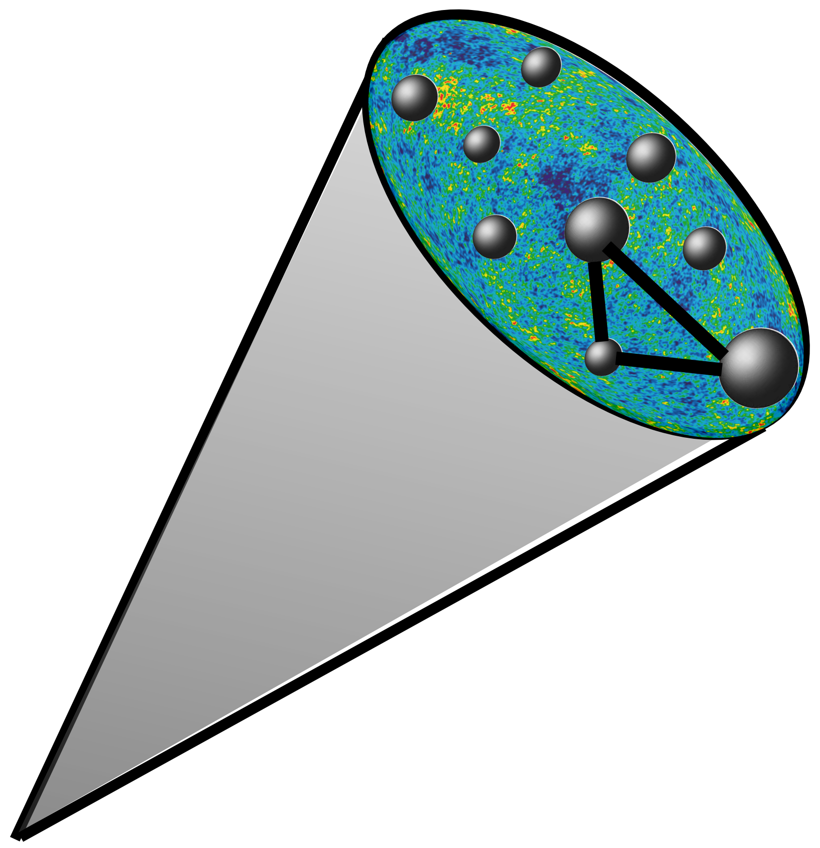
Energy correlators within jets

- Correlators $\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\cdots\mathcal{E}(\vec{n}_k)\rangle$ of the **energy flux**:
- **Exceptional angular resolution** of modern detectors provide us with an unprecedented opportunity to analyze the **energy flow within jets**

Jet substructure: energy flow operators are brought together (collinear limit)



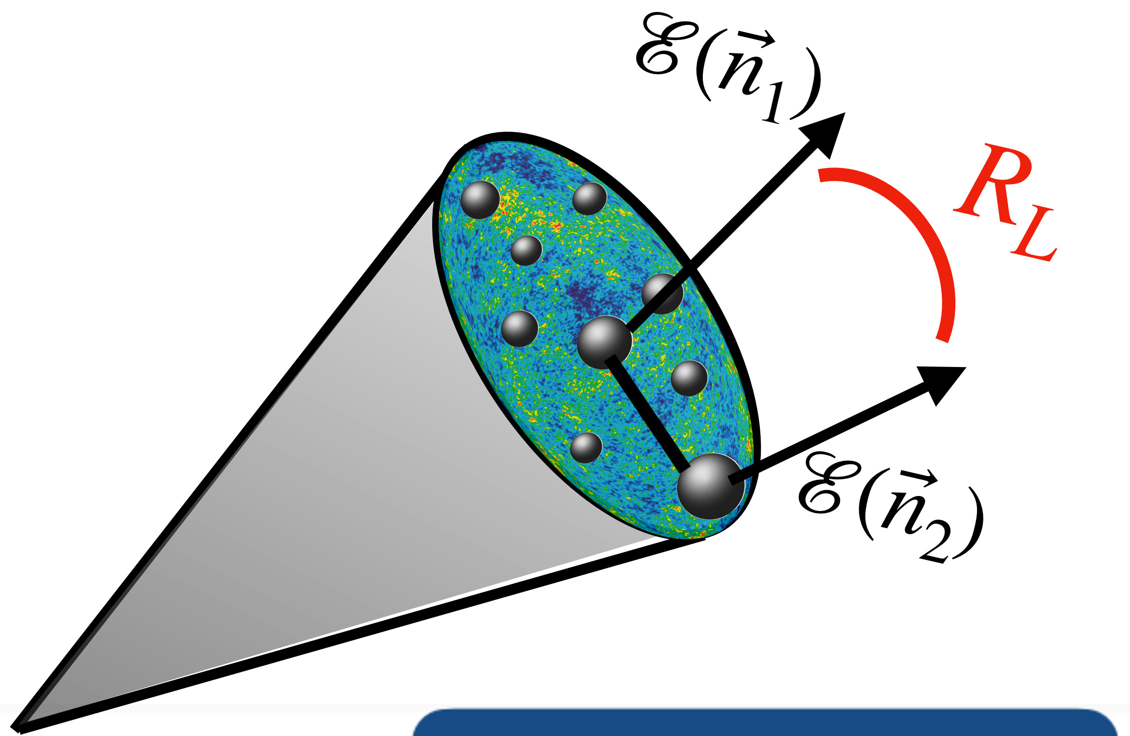
$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\rangle$



$\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\mathcal{E}(\vec{n}_3)\rangle$

- Jet substructure: **study of multi-point energy correlators** within jets (collinear limit)

E2C within p-p jets



$$\frac{d\Sigma_{E2C}}{dR_L} = \frac{1}{\sigma}\sum_{i,j}\int dE_i\, dE_j \frac{d\sigma}{dE_i\, dE_j\, dR_L}\frac{E_i E_j}{Q^2}$$

- Within jets: **collinear** (or OPE) limit of E2C

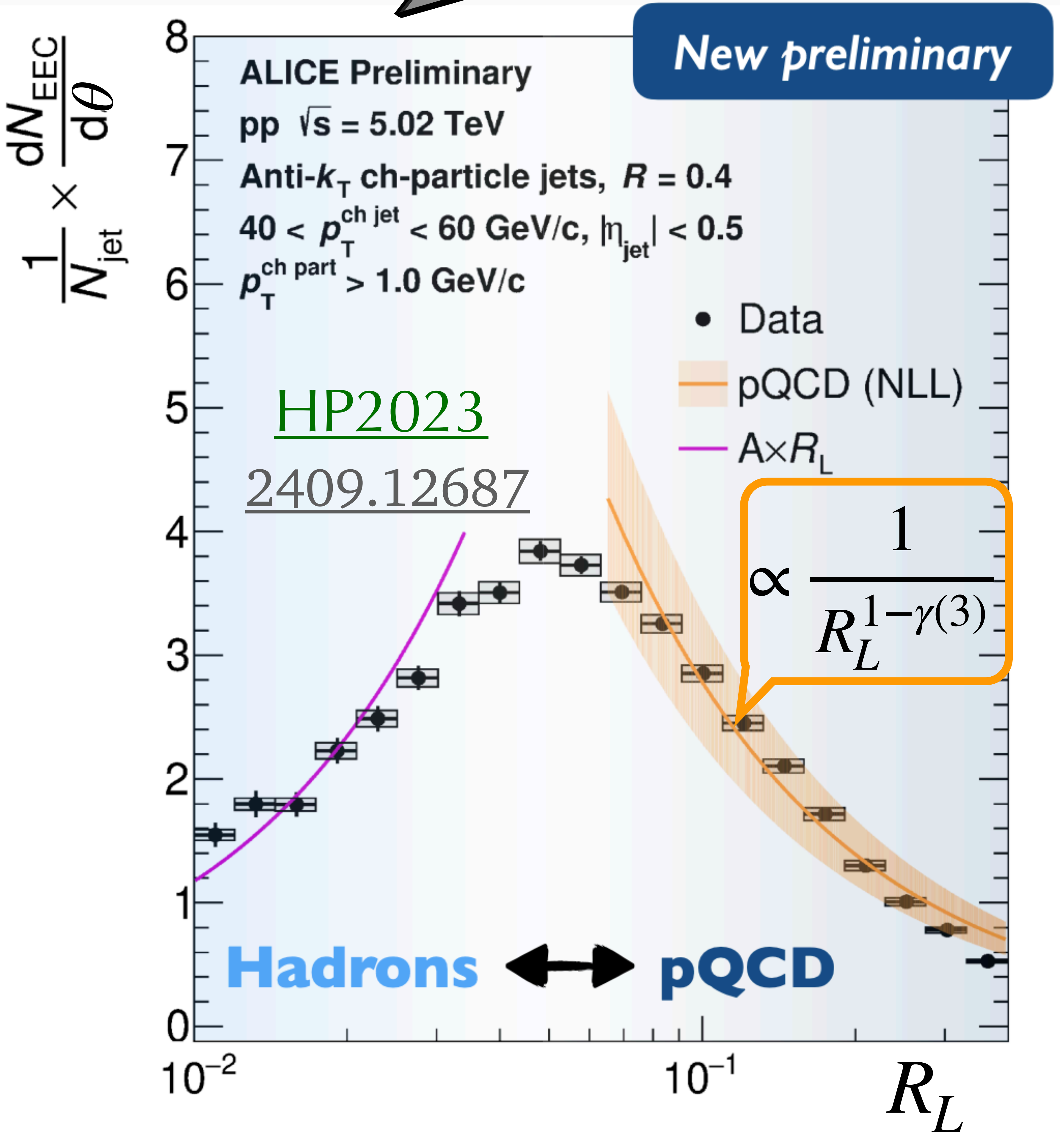
$$\langle X | \mathscr{E}(\vec{n}_1)\mathscr{E}(\vec{n}_2) | X\rangle \xrightarrow{R_L\to 0} \sum_i R_L^{(\tau_i-4)/2}\,\mathcal{O}_i(\vec{n}_1)$$

Hoffman, Maldacena, 0803.1467

Dixon, Moult, Zhu, 1905.01310

$$\frac{d\Sigma_{E2C}}{dR_L} \propto \frac{1}{R_L^{1-\gamma(3)}}$$

Power-law scaling according to CFT!

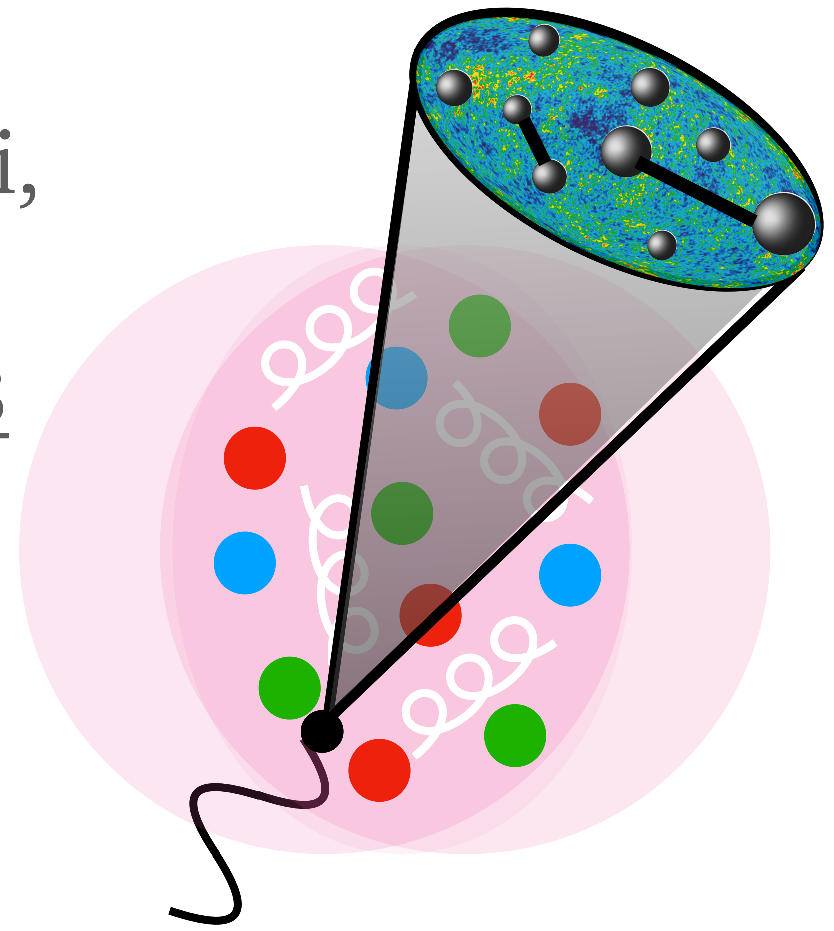


QCD scaling observed by STAR, ALICE, and CMS in jets **from 15 GeV to ~2TeV!**

See also: CMS, 2402.13864, and STAR 2309.0576

Proof of principle in HICs

CA, Dominguez, Elayavalli, Holguin, Marquet, Moult
2209.11236, 2303.03413



- Quark-initiated jet with **known initial energy** $Q = E$ (γ/Z-jet)

$$\frac{d\Sigma_{\mathrm{E2C}}}{dR_L} = \frac{1}{\sigma_{qg}} \int dz \left(\frac{d\sigma_{qg}^{\mathrm{vac}}}{dz dR_L} + \frac{d\sigma_{qg}^{\mathrm{med}}}{dz dR_L} \right) z(1-z) + \mathcal{O}\left(\frac{\mu_s}{E}\right)$$

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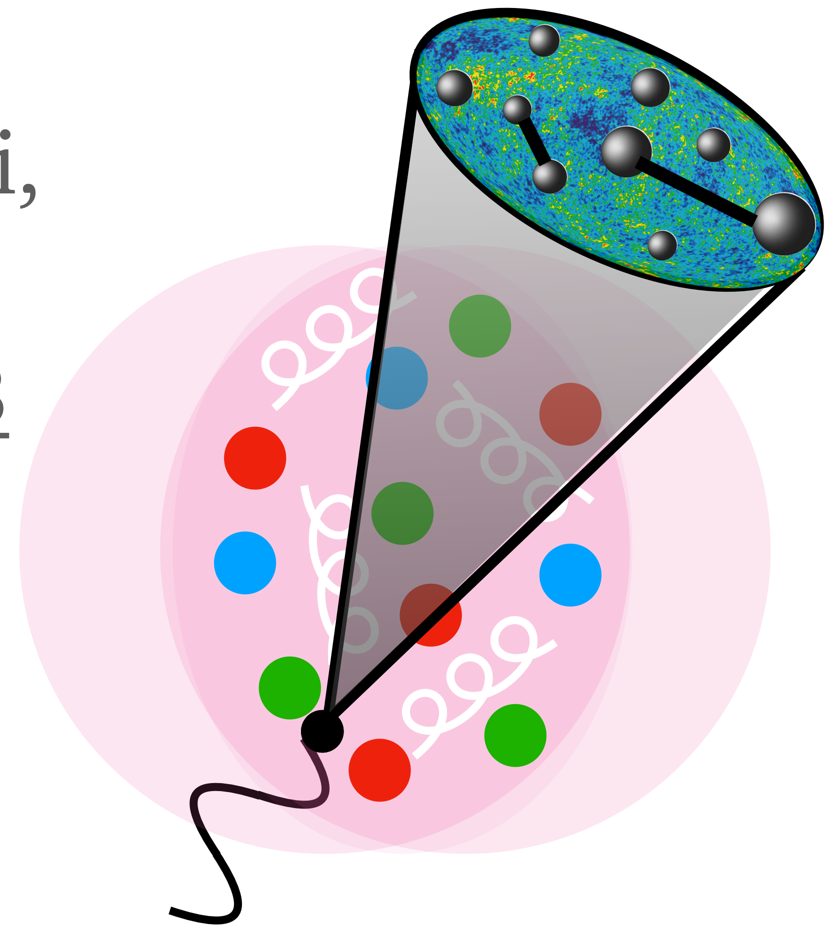

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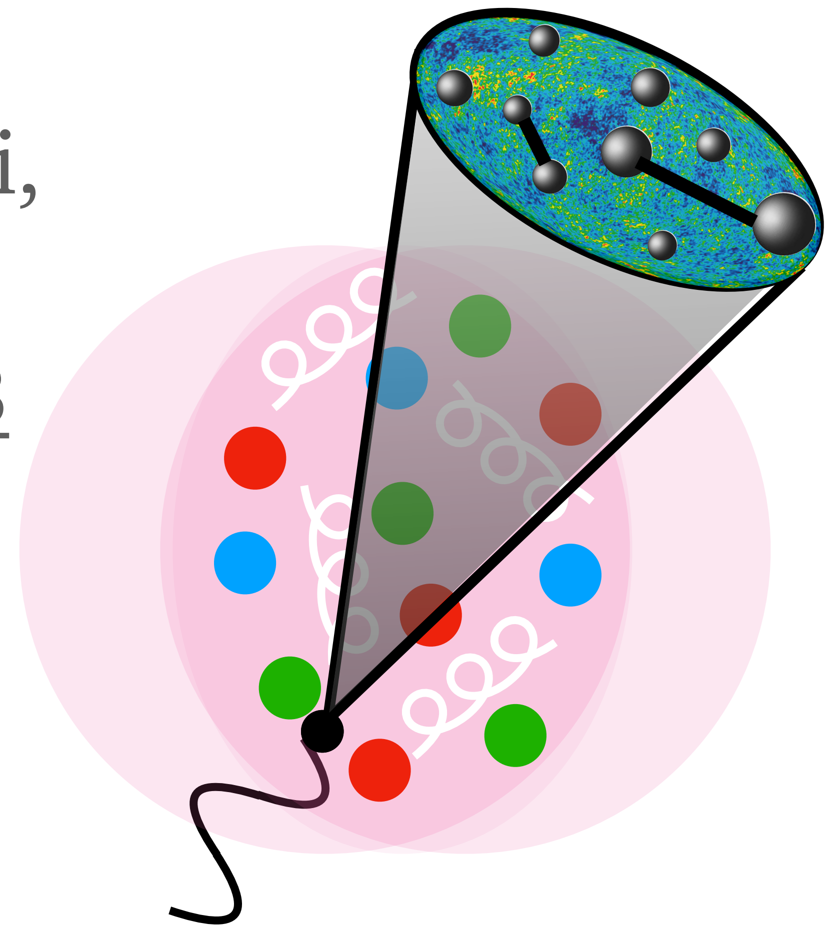

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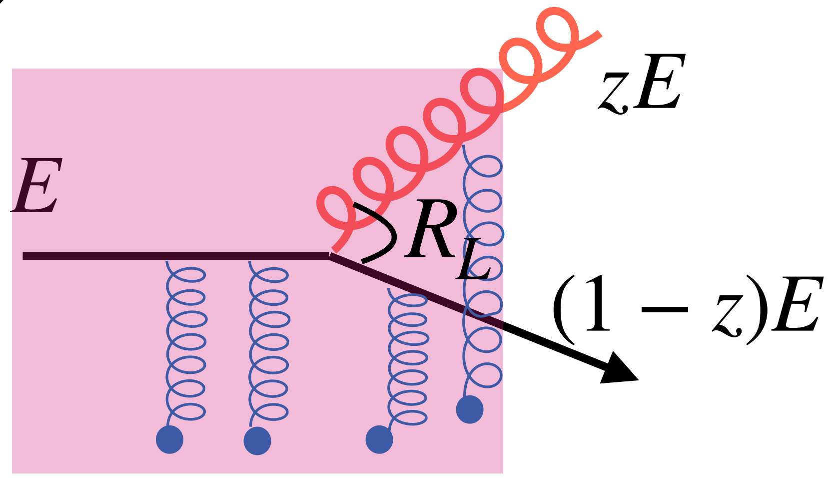
LO in the number of splittings



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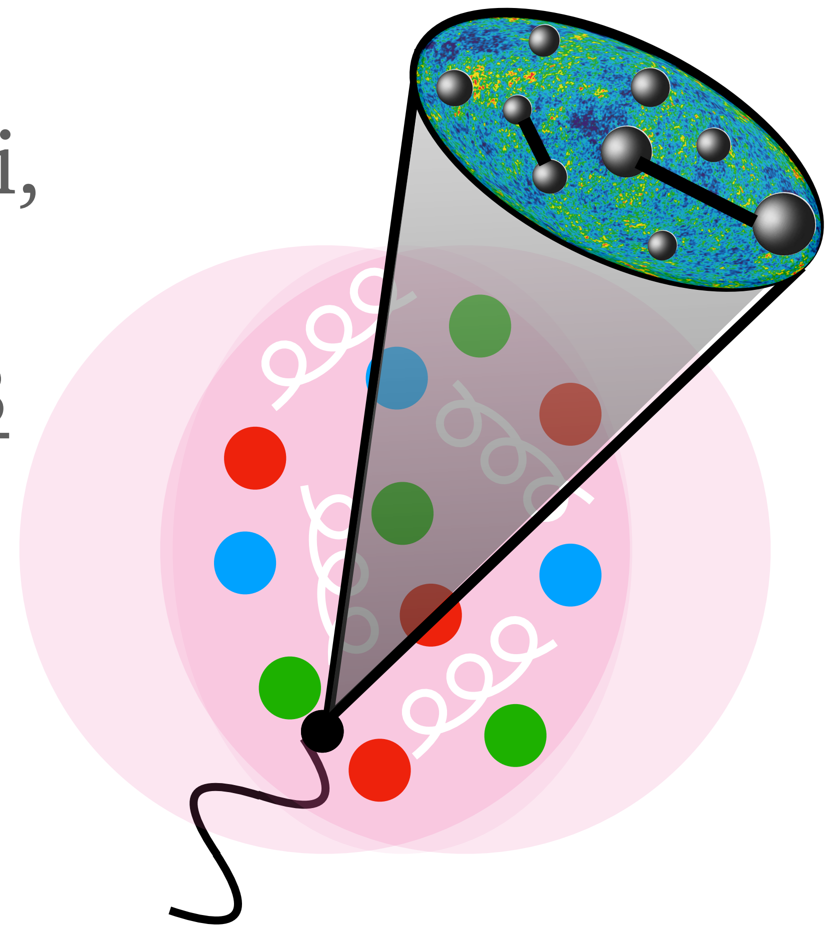

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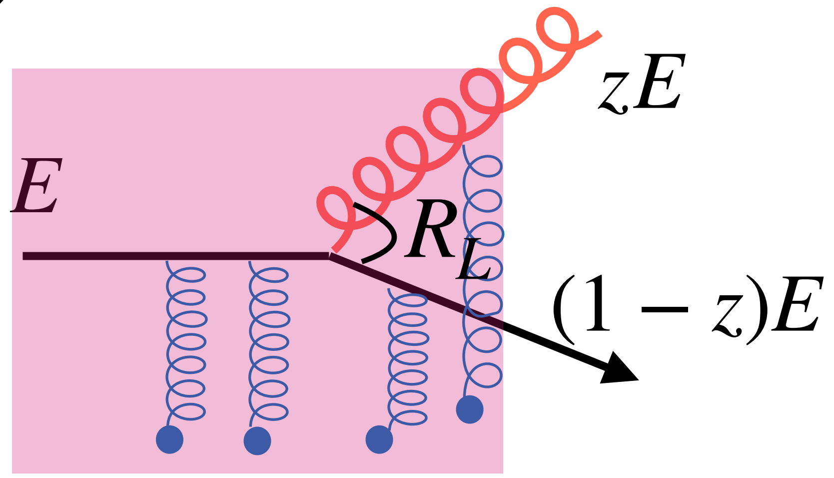

- Soft approximation ($z \to 0$, zE finite) not suitable
- Two available approximations:
  - ***Semi-hard* splittings**: eikonal trajectories. Ignores broadening Isaksen, Tywoniuk, 2107.02542

    Dominguez, Milhano, Salgado, Tywoniuk, Vila, 1907.03653
  - **Opacity expansion (GLV)**. No eikonal assumptions

    Sievert, Vitev, 1807.03799

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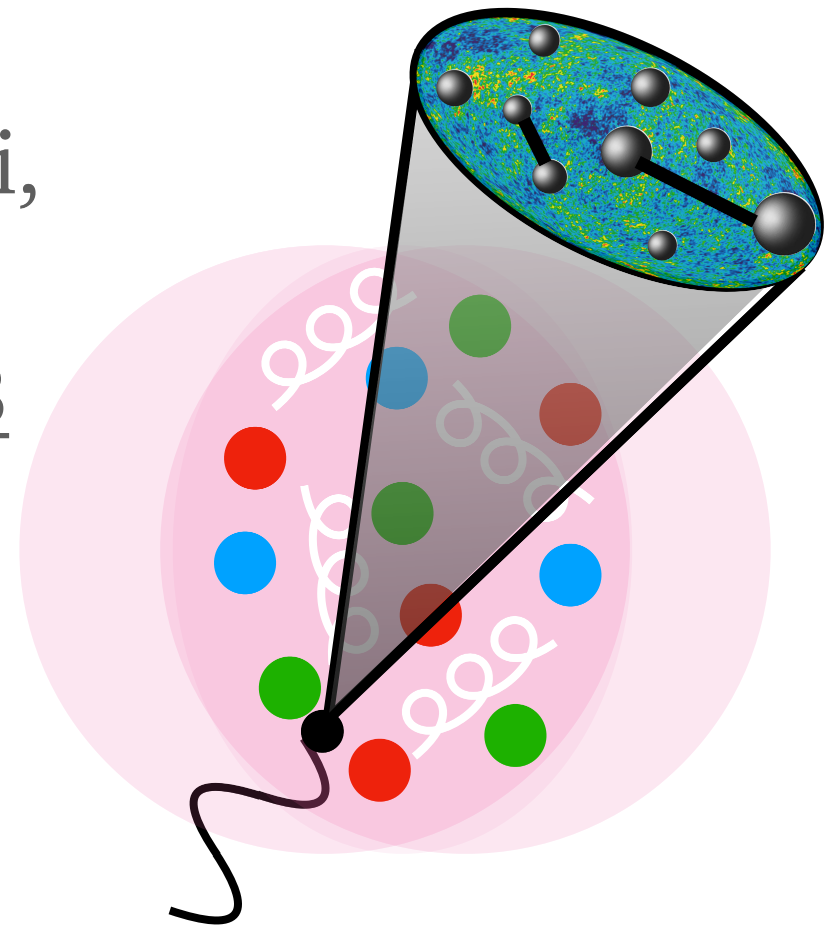

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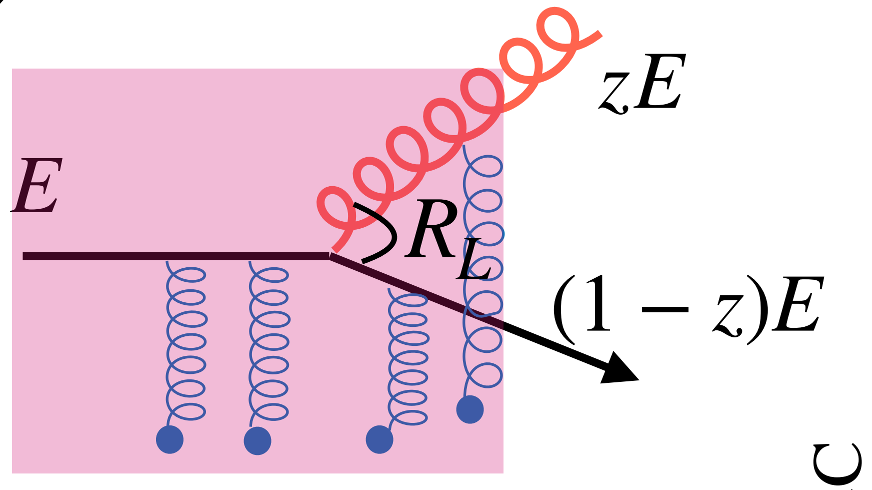

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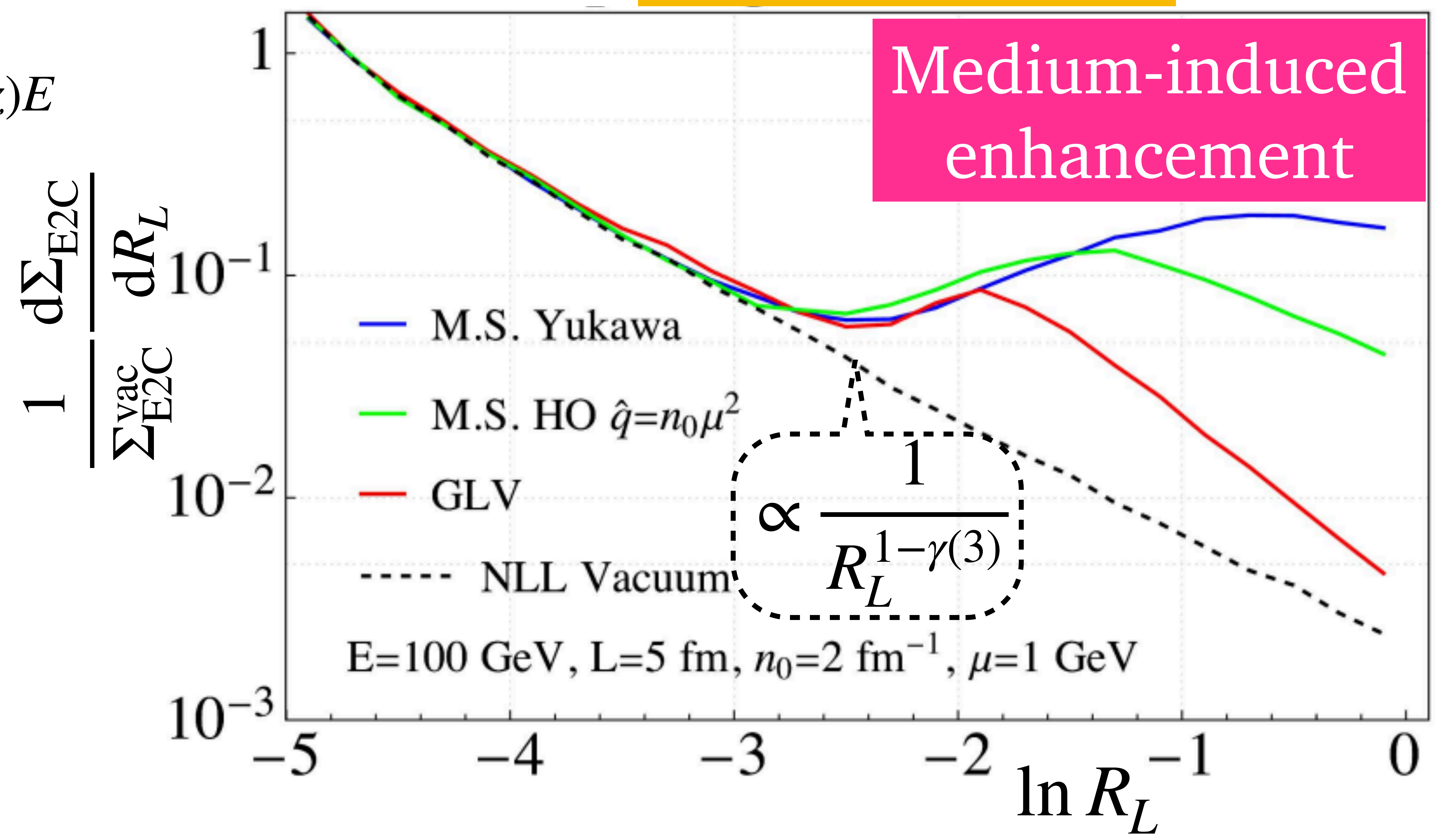
E2C for γ/Z-jets

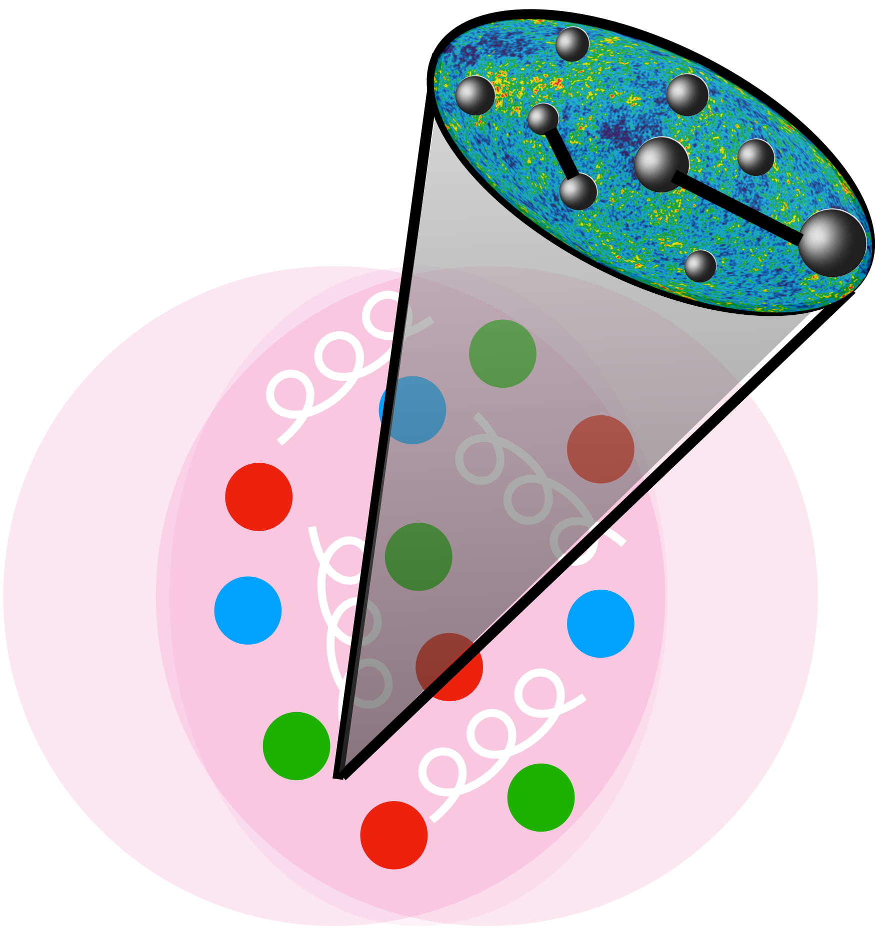


Energy loss and medium response not included!

Toward a qualitative comparison to inclusive jets data

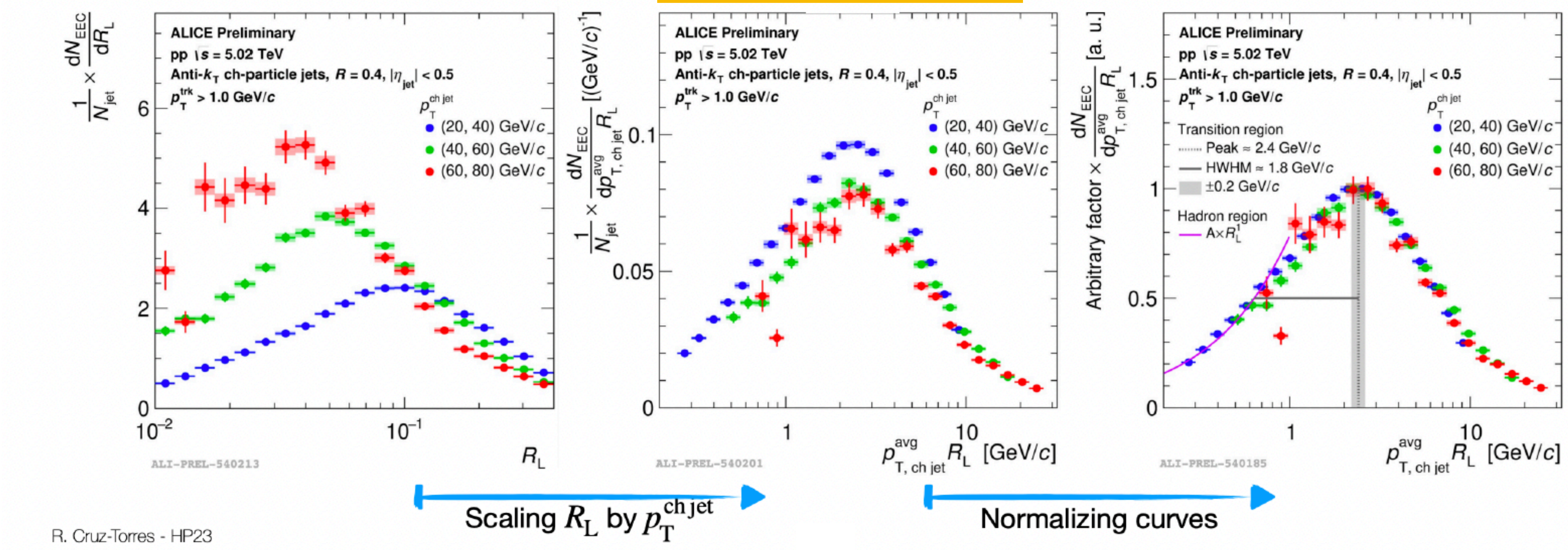
CA, Dominguez, Holguin, Marquet, Moult, 2407.07936

Energy loss



- Energy loss must be included at LO in inclusive measurements due to the **dependence of the E2C on the hard scale**
- Shift in the hard scale. **Selection bias**

E2C within p-p jets



Energy loss and hadronization transition

- Analytical model of the **hadronization transition**

$$\left.\frac{d\Sigma^{\mathrm{E2C}}}{dR_L}\right|_{\mathrm{pQCD}} \sim R_L^{-1+\mathcal{O}(\alpha_s)}$$

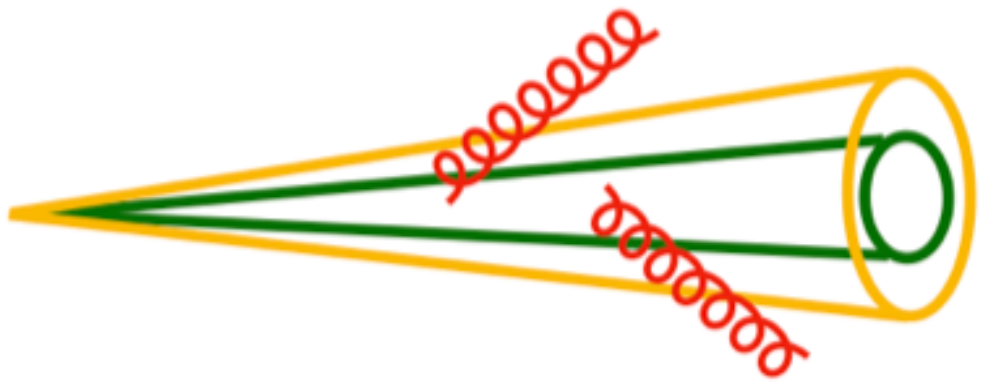
$$\left.\frac{d\Sigma^{\mathrm{E2C}}}{dR_L}\right|_{\text{free had}} \sim R_L$$

$$\Rightarrow \quad \left.\frac{d\Sigma^{\mathrm{E2C}}}{dR_L}\right|_{\mathrm{pQCD}} = \frac{R_L}{B_0 + B_2\, R_L^2} \qquad \frac{B_0}{B_2} \sim \frac{\Lambda^2_{\mathrm{QCD}}}{Q^2}$$

- Rough estimate of **energy loss** through Quenching Weights distribution (totally coherent)

Salgado, Wiedemann, hep-ph/0302184

$$P_\xi(\epsilon) = \sum_{N=0}^{\infty} \frac{1}{N!} \prod_{i=1}^{N} \left[\int d\omega_i \frac{dI_\xi}{d\omega}\right] \delta\left(\epsilon - \sum_{i=1}^{N} \omega_i\right) \exp\left[-\int_0^\infty d\omega \frac{dI_\xi}{d\omega}\right]$$



For corrections to this approach due to fluctuations see: Mehtar-Tani, Tywoniuk, 1707.07361

Barata, Caucal, Soto-Ontoso, Szafron, 2312.12527

E2C in inclusive heavy-ion jets

- **Convolution** of this the **Quenching Weights** with the **E2C at a higher hard scale** and averaged over trajectories

$$\frac{\mathrm{d}\Sigma_{\mathrm{E2C}}(p_T)}{\mathrm{d}R_L} = \int \mathrm{d}\epsilon \left\langle P_\xi(\varepsilon) \frac{\mathrm{d}\Sigma^{\mathrm{NP}}_{\mathrm{E2C},\xi}(p_T+\epsilon)}{\mathrm{d}R_L} \right\rangle_\xi \frac{1}{\sigma_{q+X}} \frac{\mathrm{d}\sigma_{q+X}}{\mathrm{d}p_{T,q}} \Bigg|_{p_{T,q}=p_T+\varepsilon}$$

- Predictions within two approaches to compute E2C:
  - Multiple scatterings: ***Semi-hard* + leading broadening corrections** $\hat{q}(t) = k_{\mathrm{HO}} T^3(\xi(t))$

    CA, Dominguez, Holguin, Marquet, Moult, 2407.07936
  - Single scattering: **GLV** $n(t) = k_{\mathrm{GLV}} T(\xi(t))$ $\mu^2(t) = 6\pi\alpha_s T^2(\xi(t))$

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E2C at the hard scale $p_T + \epsilon$

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Energy loss — E2C at the hard scale $p_T + \epsilon$

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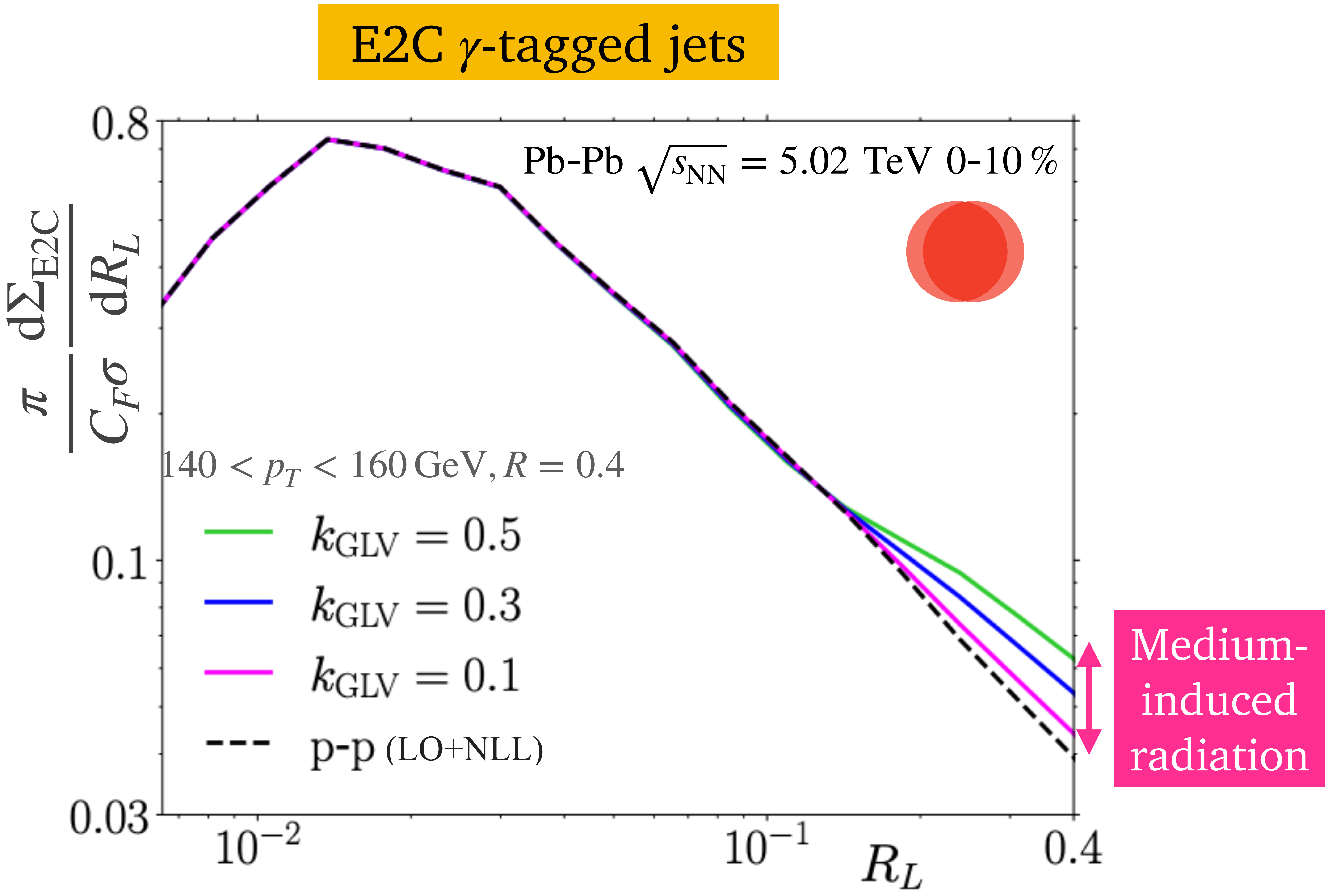
$k_{\rm GLV}$ and normalization are free parameters!

E2C in heavy-ions

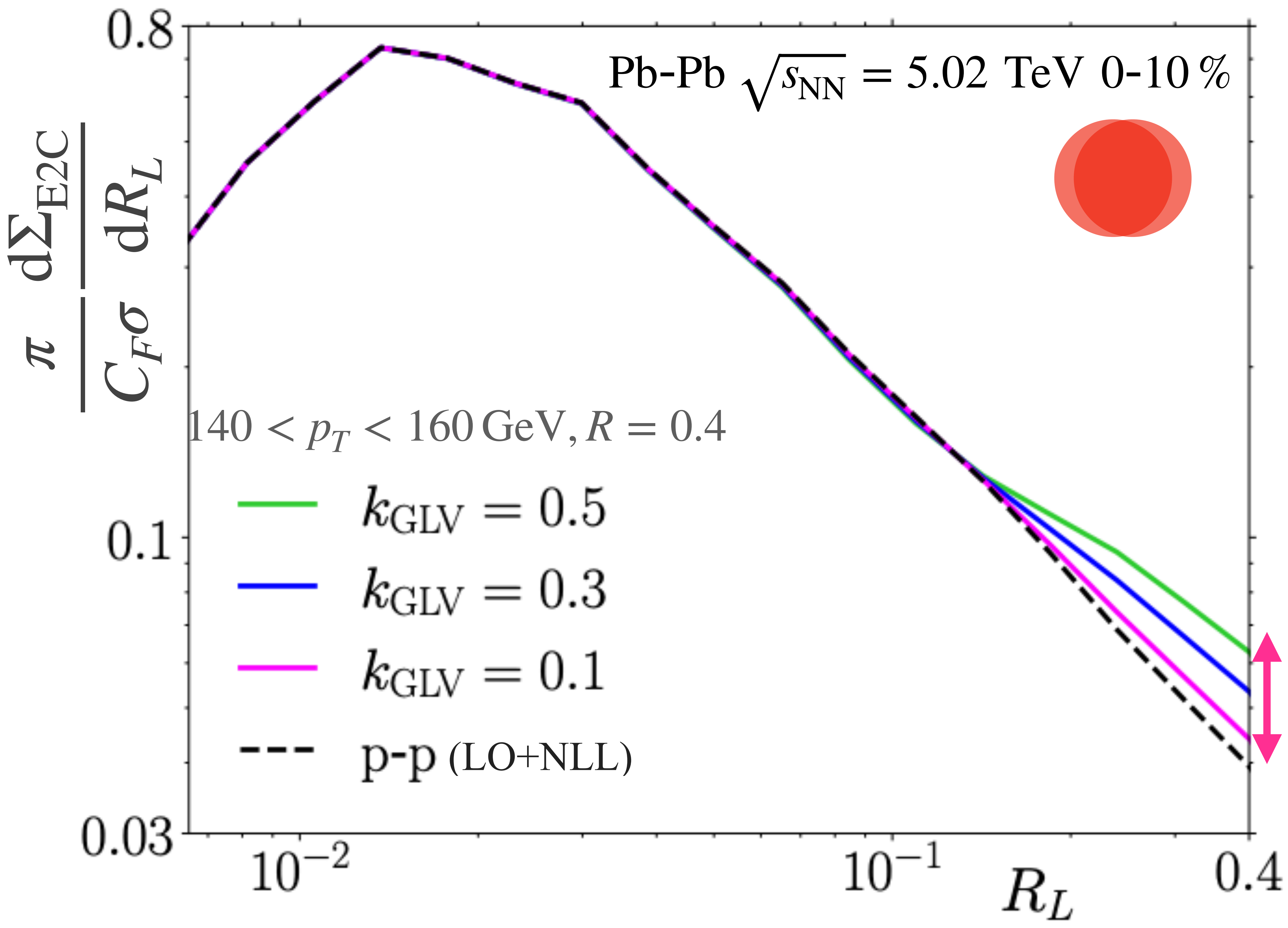


Medium response: can also appear at large angles!

Yang, He, Moult, Wang, 2310.01500 Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal, 2407.13818

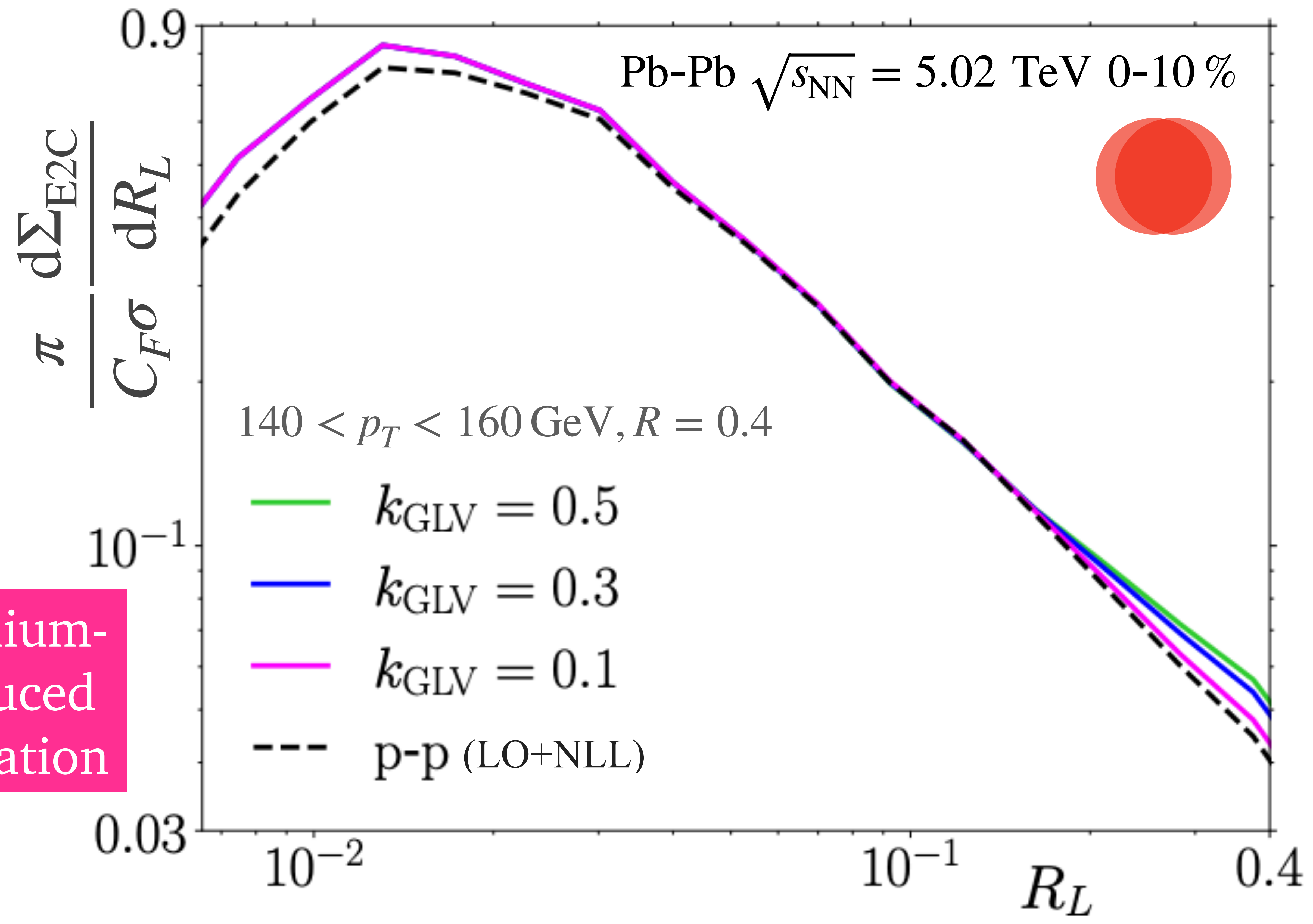
E2C in heavy-ions

E2C γ-tagged jets



Medium-induced radiation

E2C Inclusive jets



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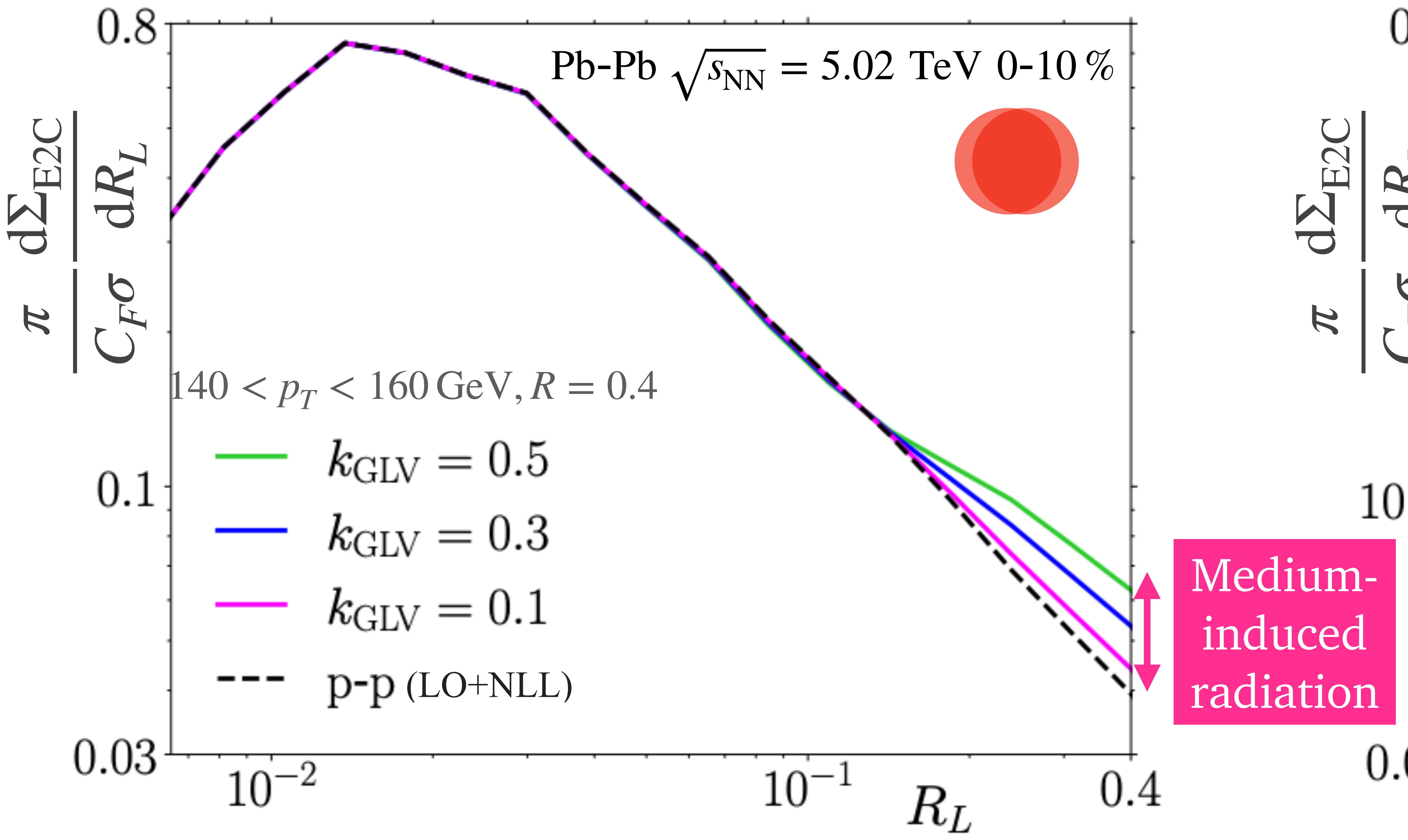
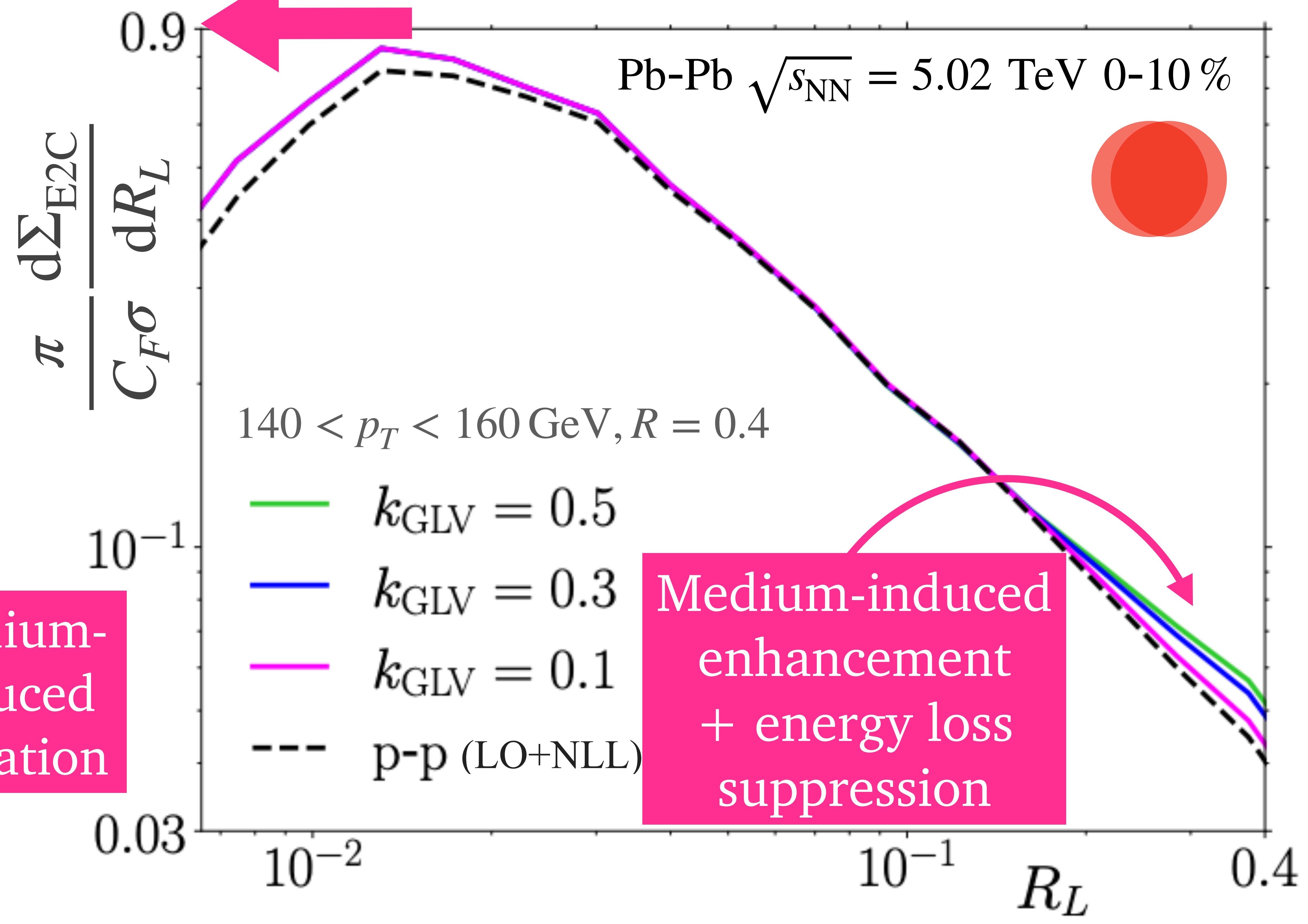


Energy loss

E2C Inclusive jets



See also: Barata et al. 2312.12527

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E2C: Pb-Pb/p-p ratio

Selection bias: non-trivial angular estructure at small angles and some reduction of the enhancement at large angles

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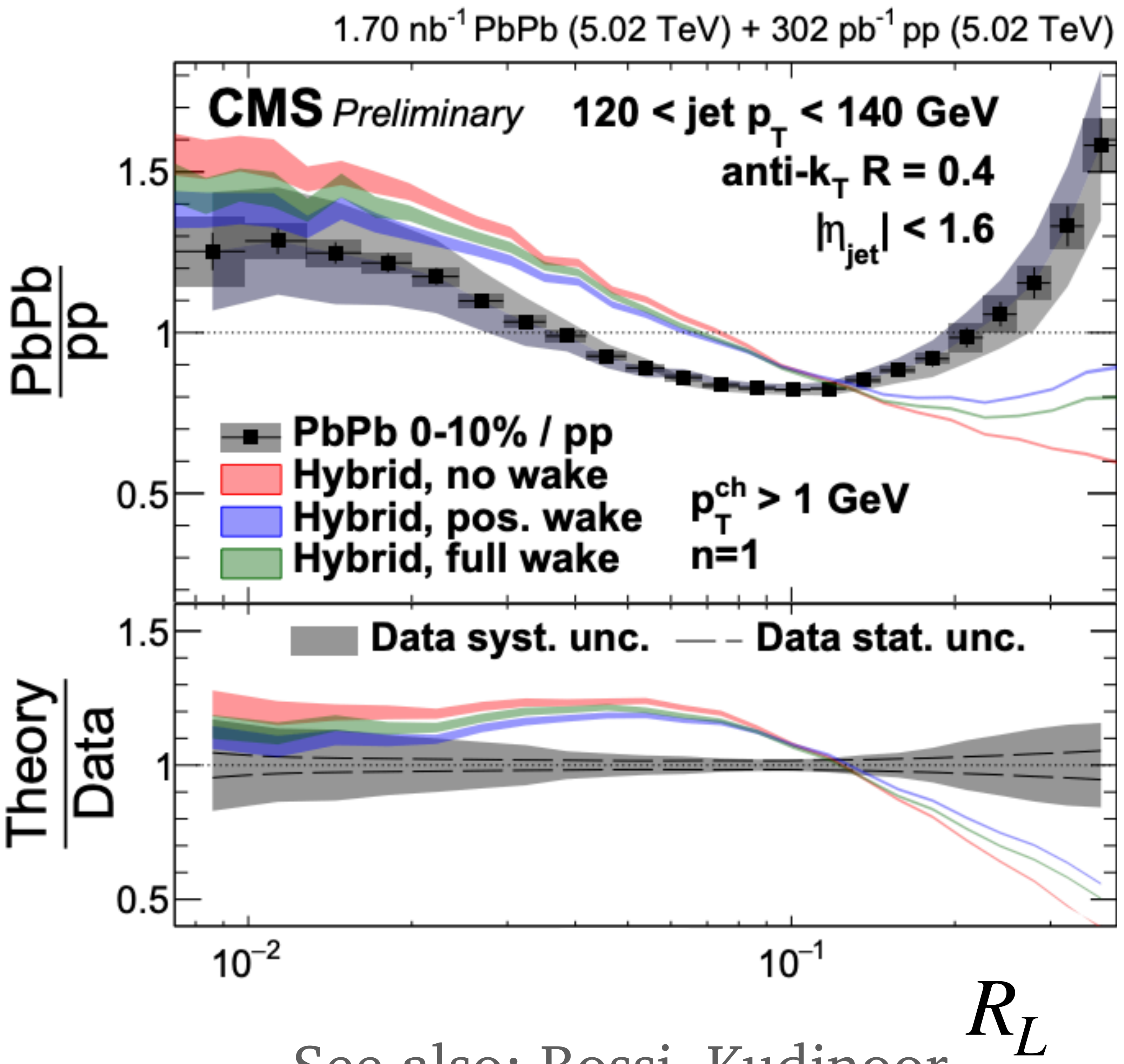
E2C: A-A/p-p ratio predictions

CMS-PAS-HIN-23-004

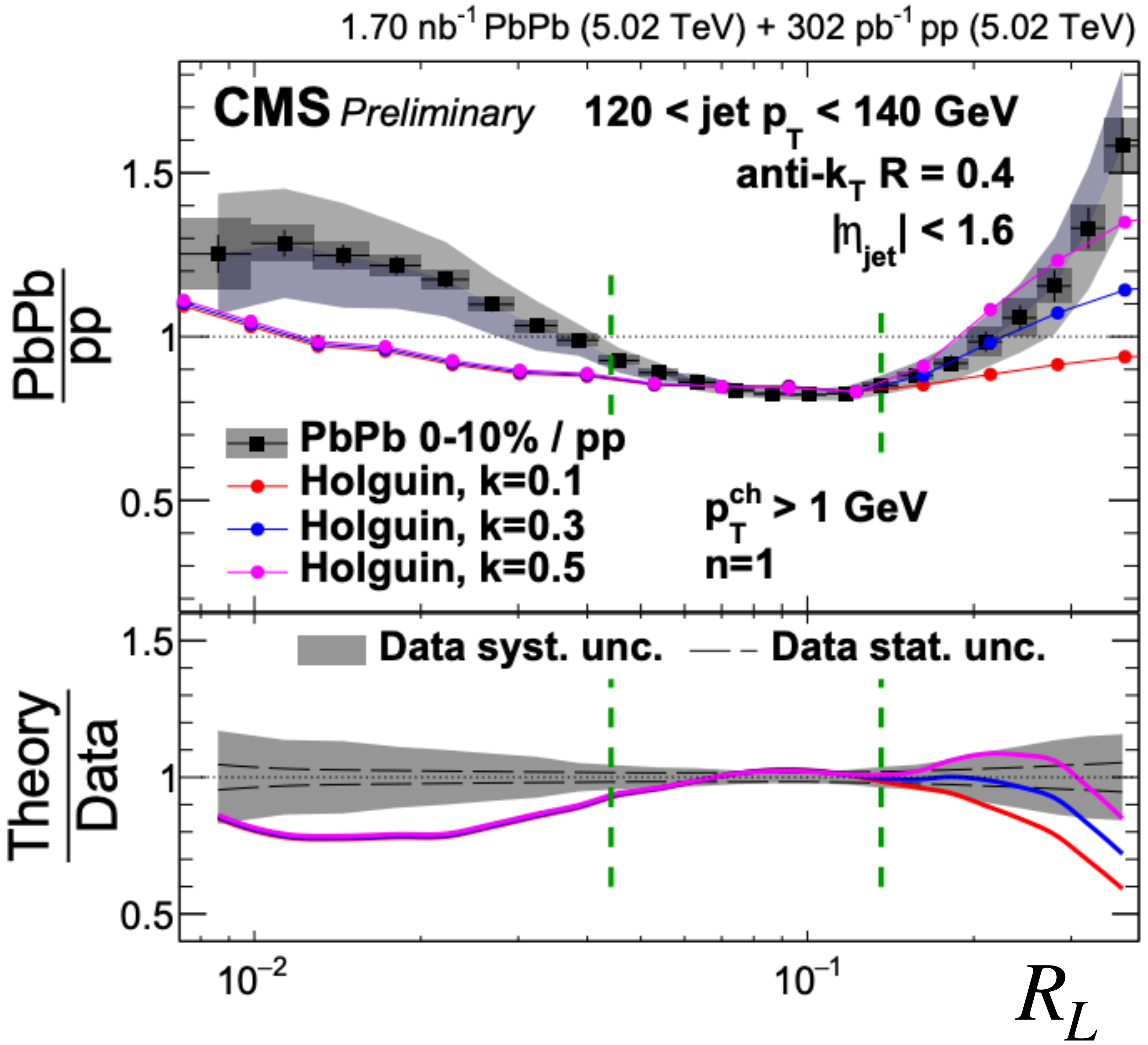
From Jussi Viinikainen's talk at the Energy Correlators at the Collider Frontier workshop

Hybrid model
Pablos, Kudinoor, Rajagopal



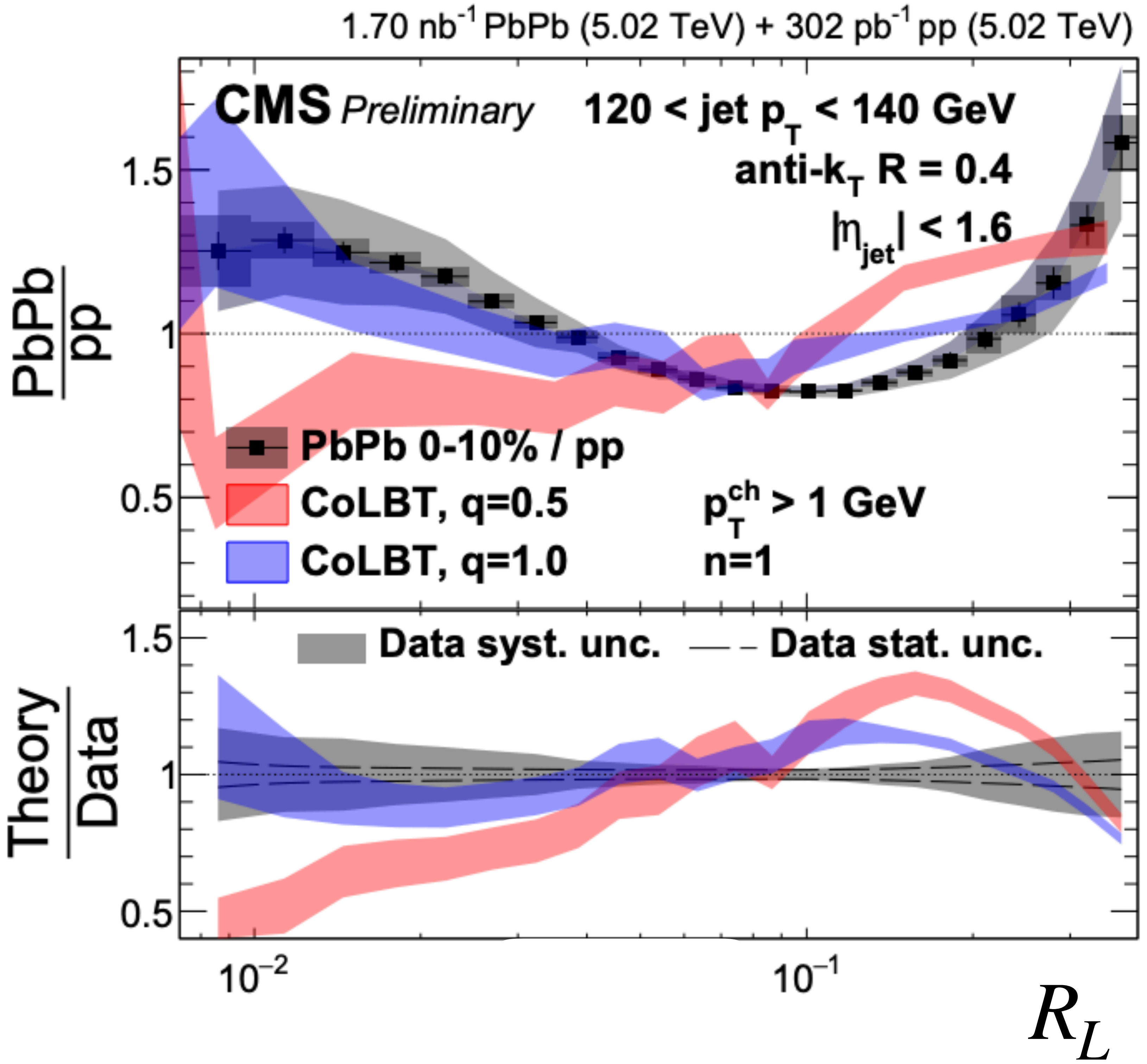
See also: Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal, 2407.13818

CA, Dominguez, Holguin, Marquet, Moult



CA, Dominguez, Holguin, Marquet, Moult, 2407.07936

CoLBT
Yang, He, Wang

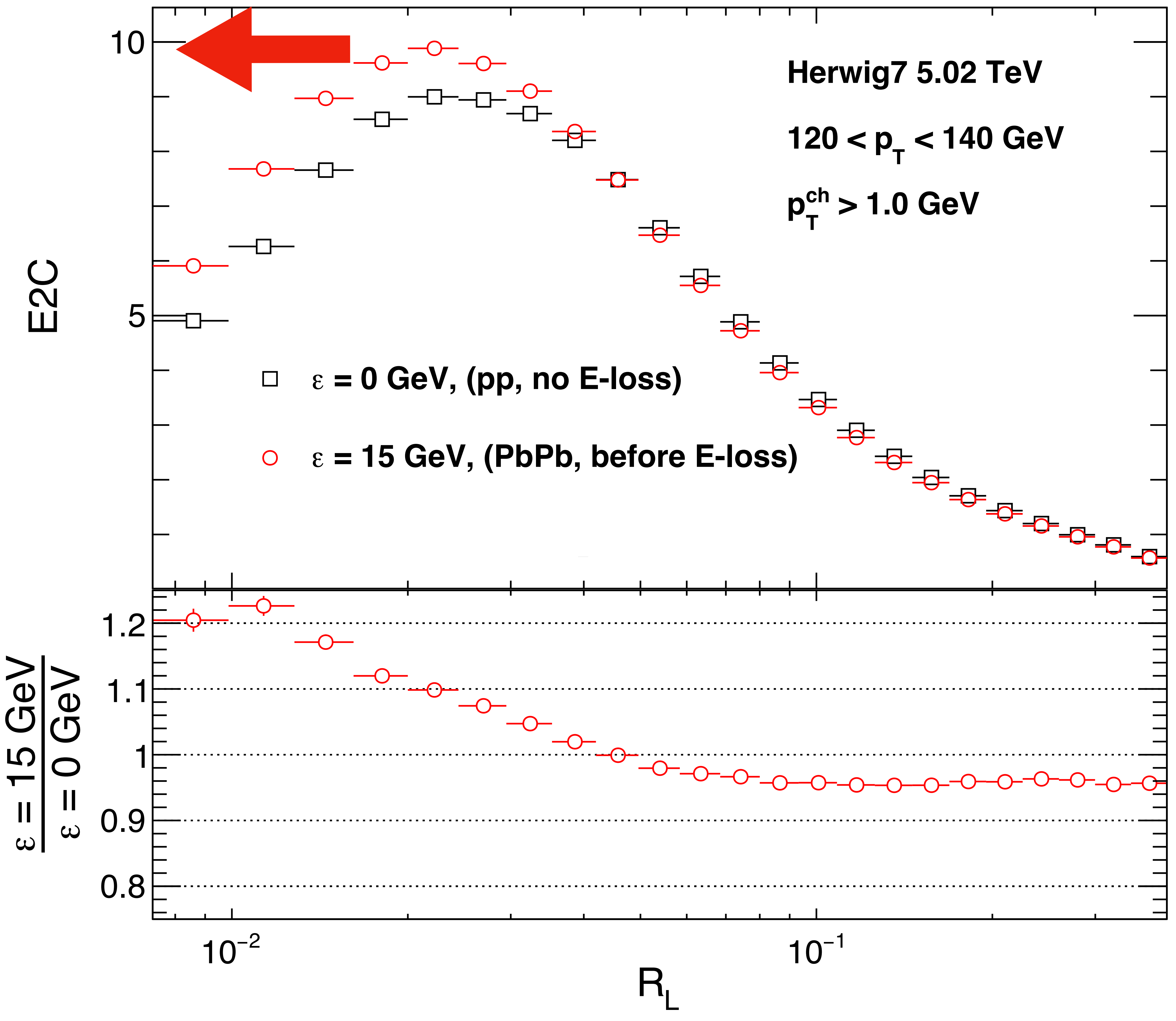


See also: Yang, He, Moult, Wang, 2310.01500

Mitigating energy loss

CA, Holguin, Kunnawalkam Elayavalli, Viinikainen, 2409.07514

15 GeV shift



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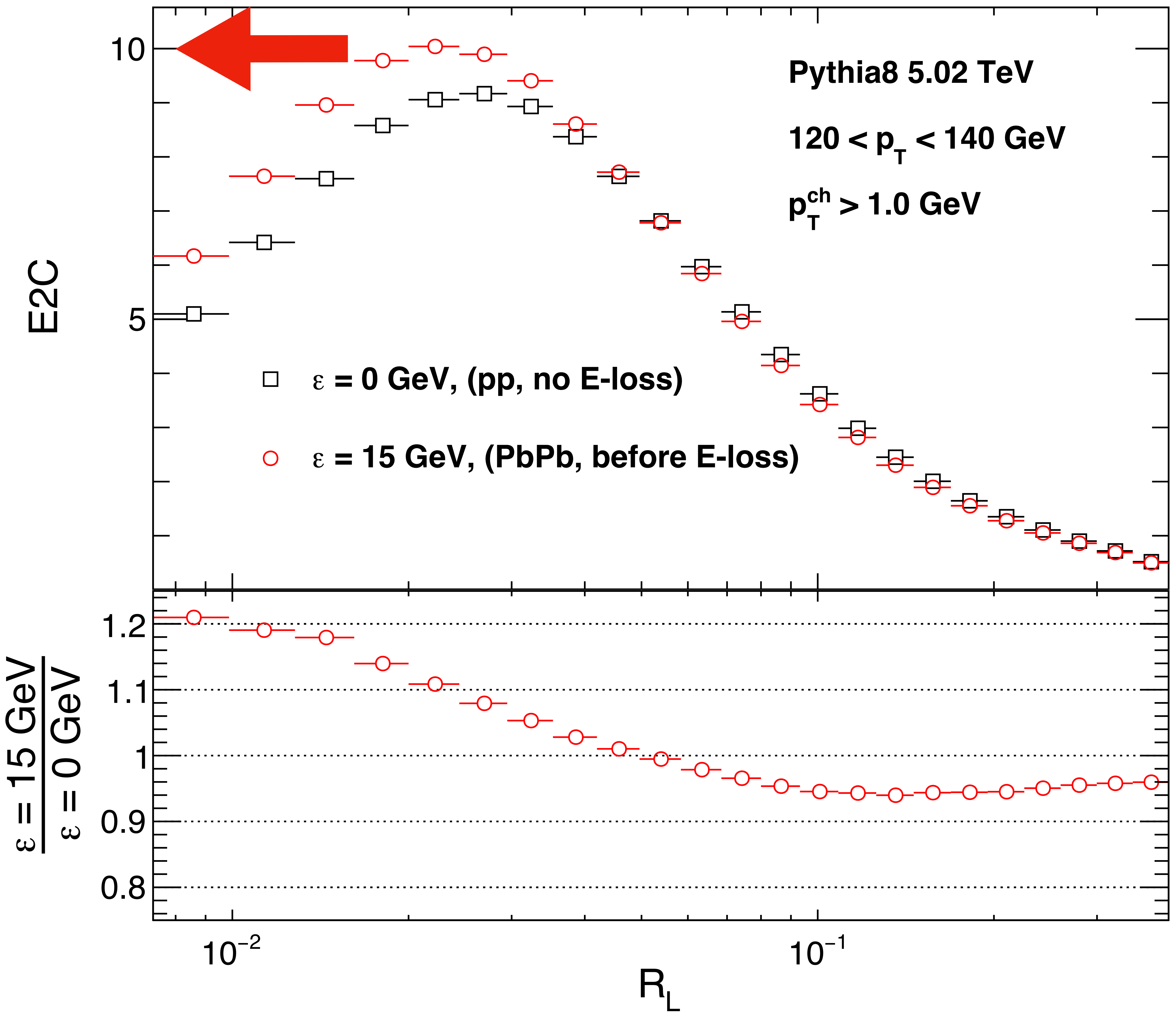

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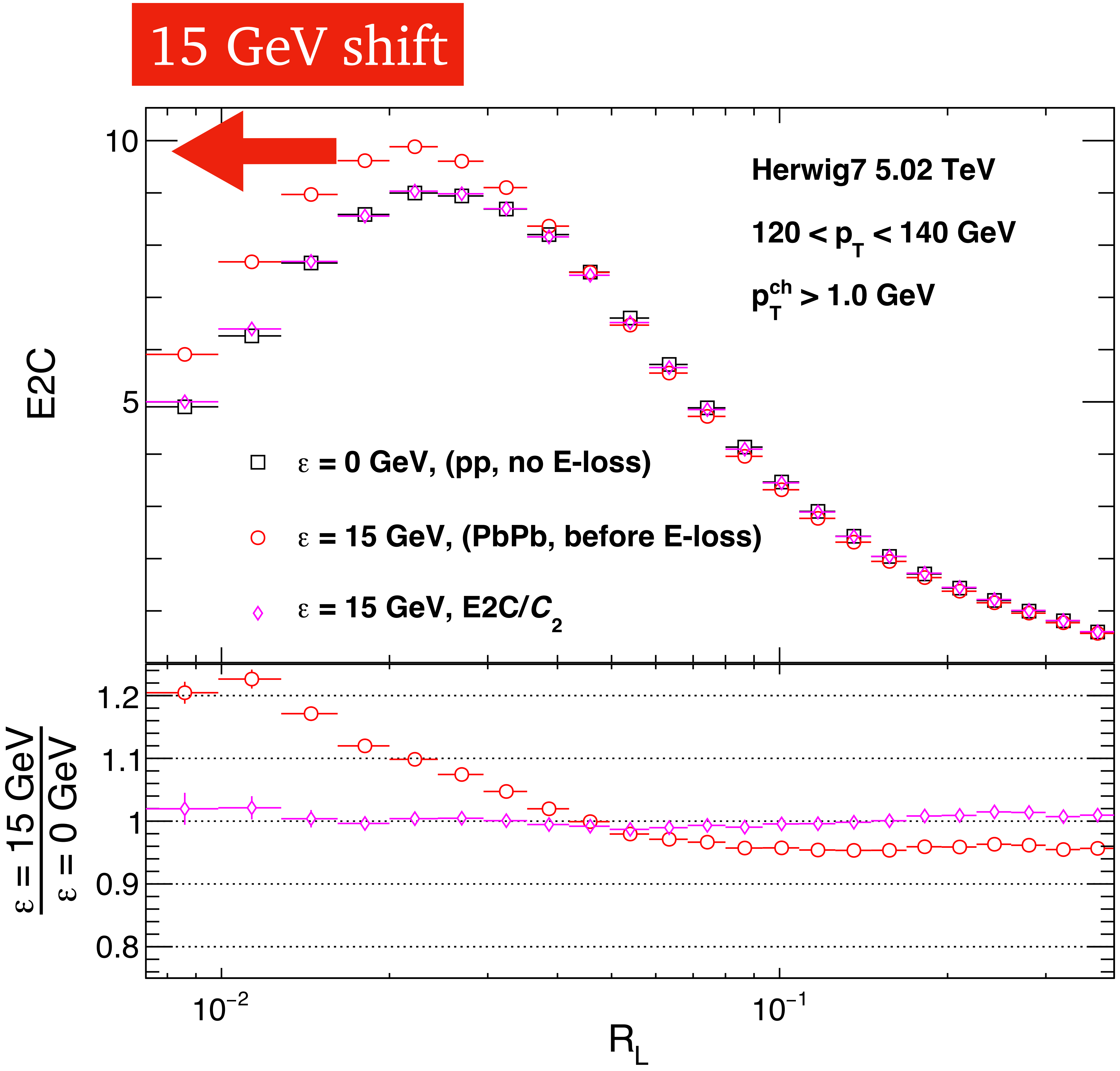
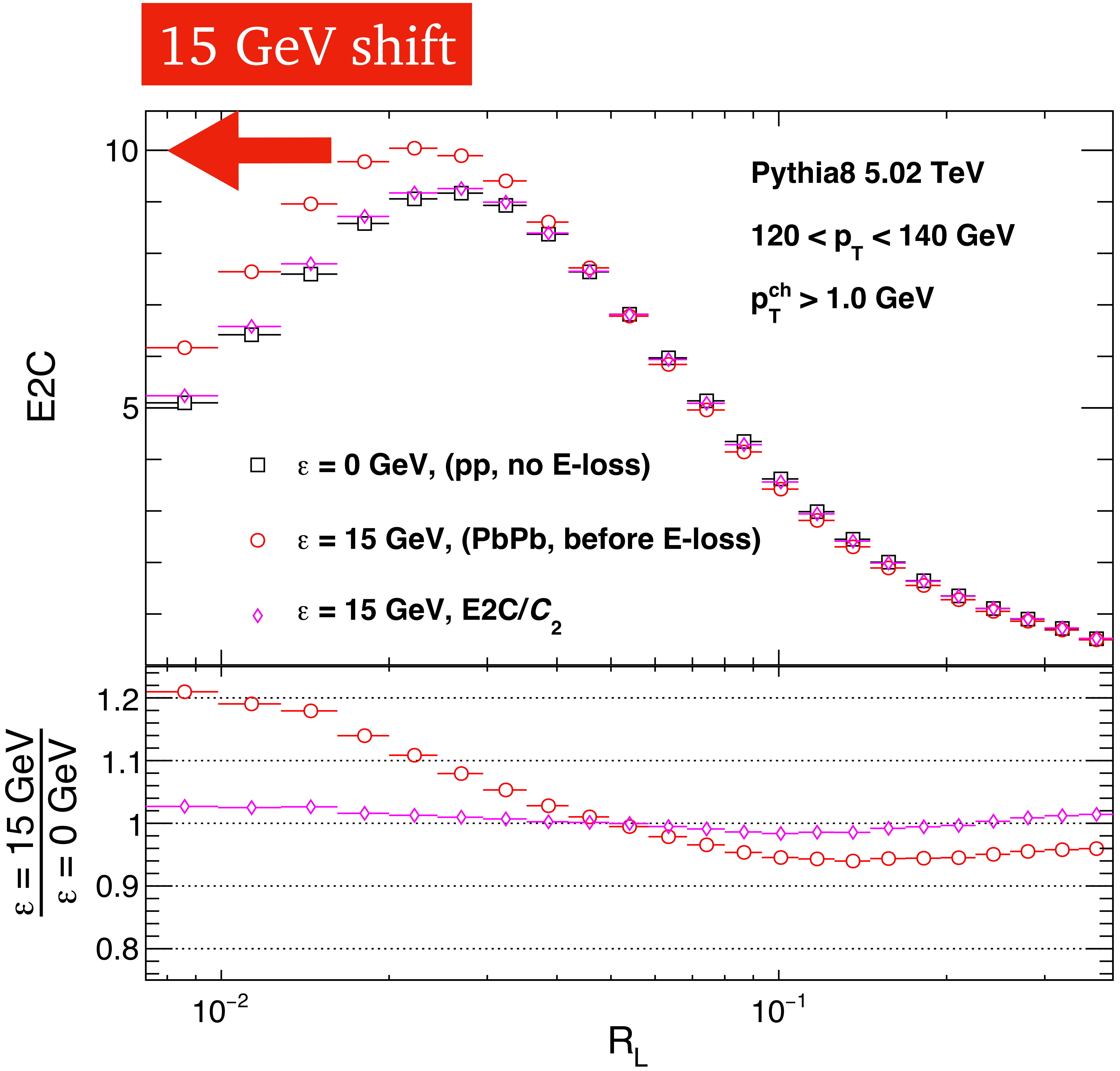


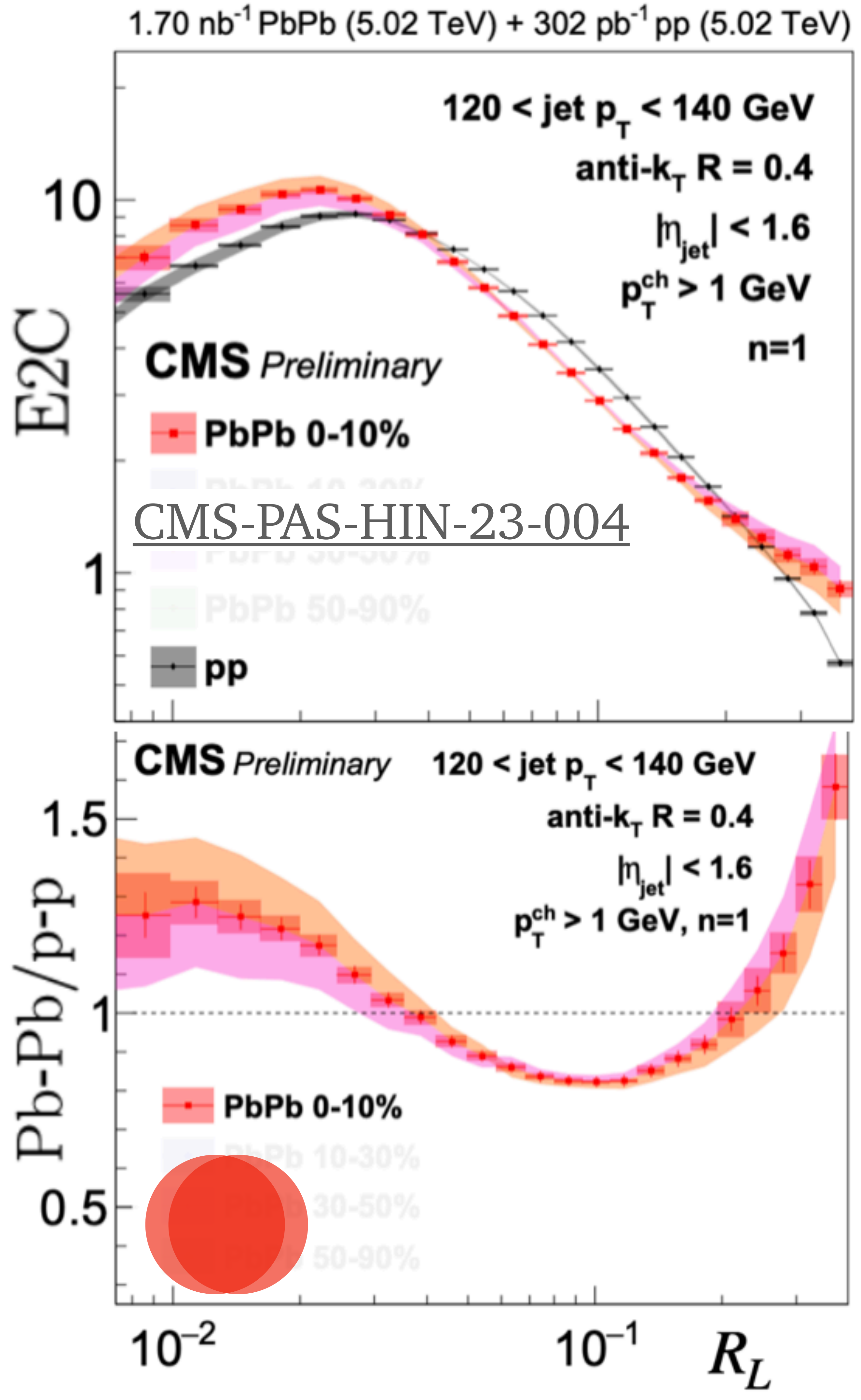


E2C/C_2: almost no selection bias effect!

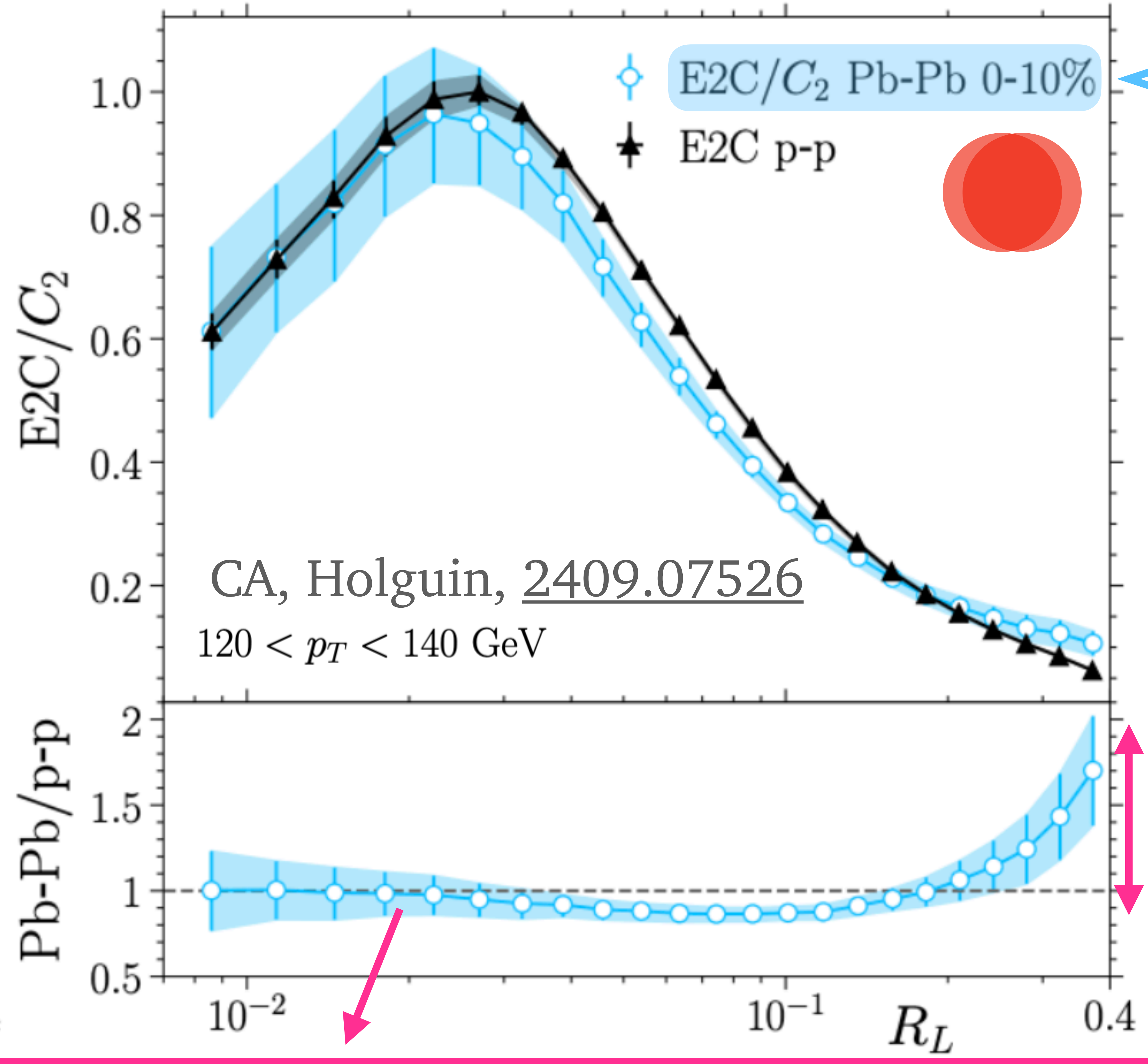
Mitigating energy loss

$$C_2(R_L) \equiv \left(\frac{F^{AA}_{E2C}(R_L,2)}{F^{pp}_{E2C}(R_L,2)}\right)^{\frac{2}{3}} - \left(\frac{F^{AA}_{E2C}(R_{peak},2)}{F^{pp}_{E2C}(R_{peak},2)}\right)^{\frac{2}{3}} + 1$$

E2C in inclusive jets



Unbiased E2C in inclusive jets



C_2 can be directly obtained from the E2C!

Larger enhancement

Within current uncertainties: the free hadron region is flat

Conclusions

- **Qualitative good description** of the CMS E2C data in **inclusive jets** for the 0-10% centrality and all p_T bins

- **Medium-induced splittings** create an **enhancement at large angles**

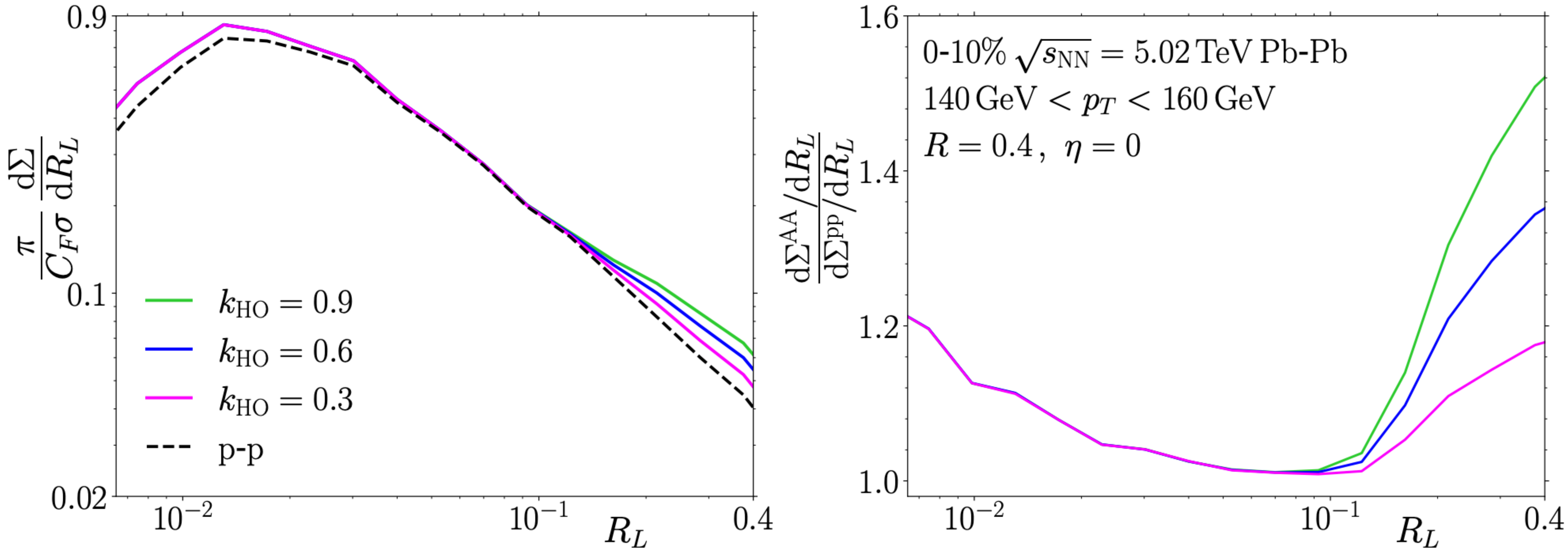
- **Energy loss**: **shifts** the E2C in Pb-Pb **towards small angles** w.r.t. the p-p result

  reduces the enhancement at large angles

- **E2C/C_2**: **new E2C-based** observable that **removes leading order energy loss effects!**

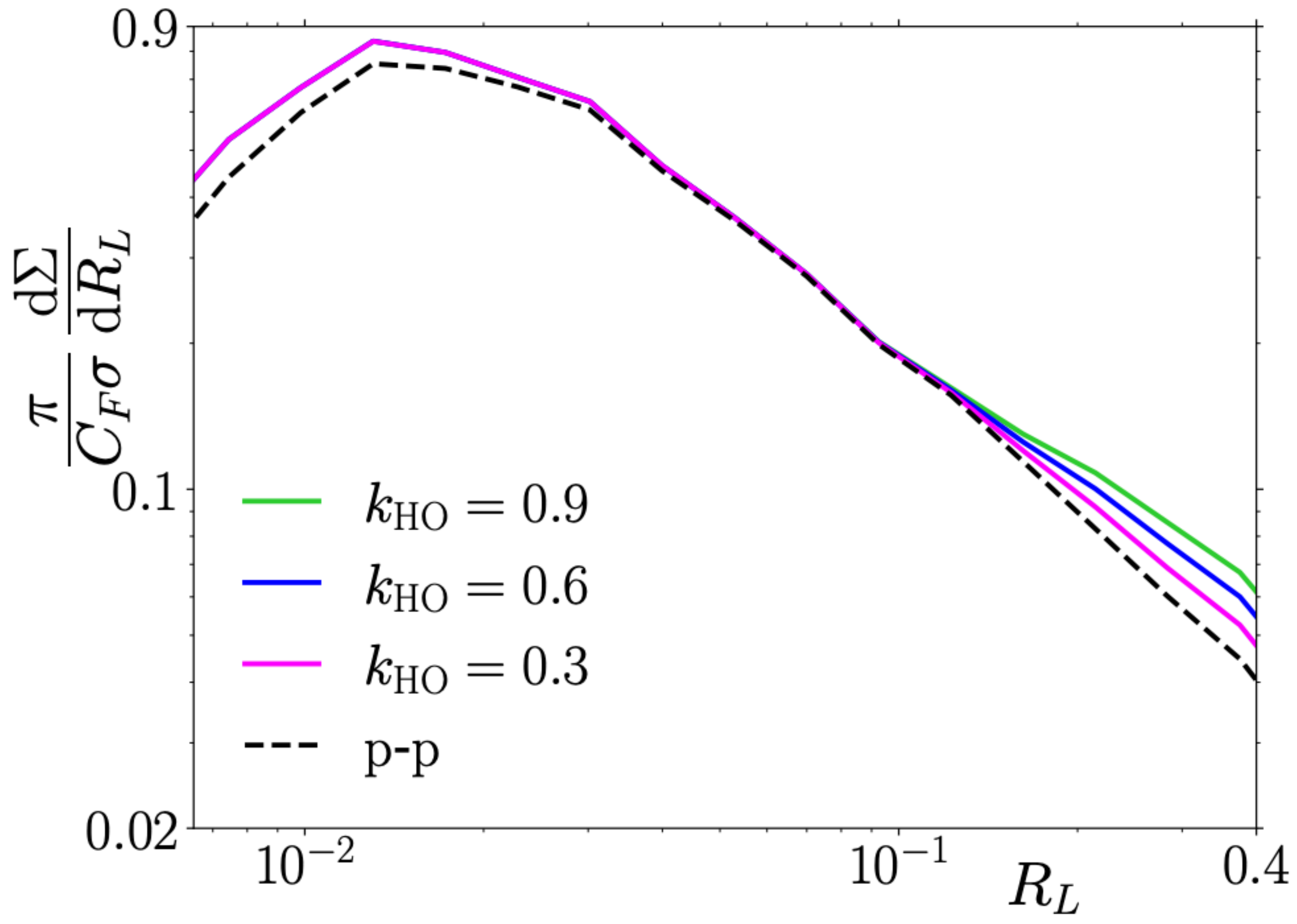
Thank you!

Multiple scatterings

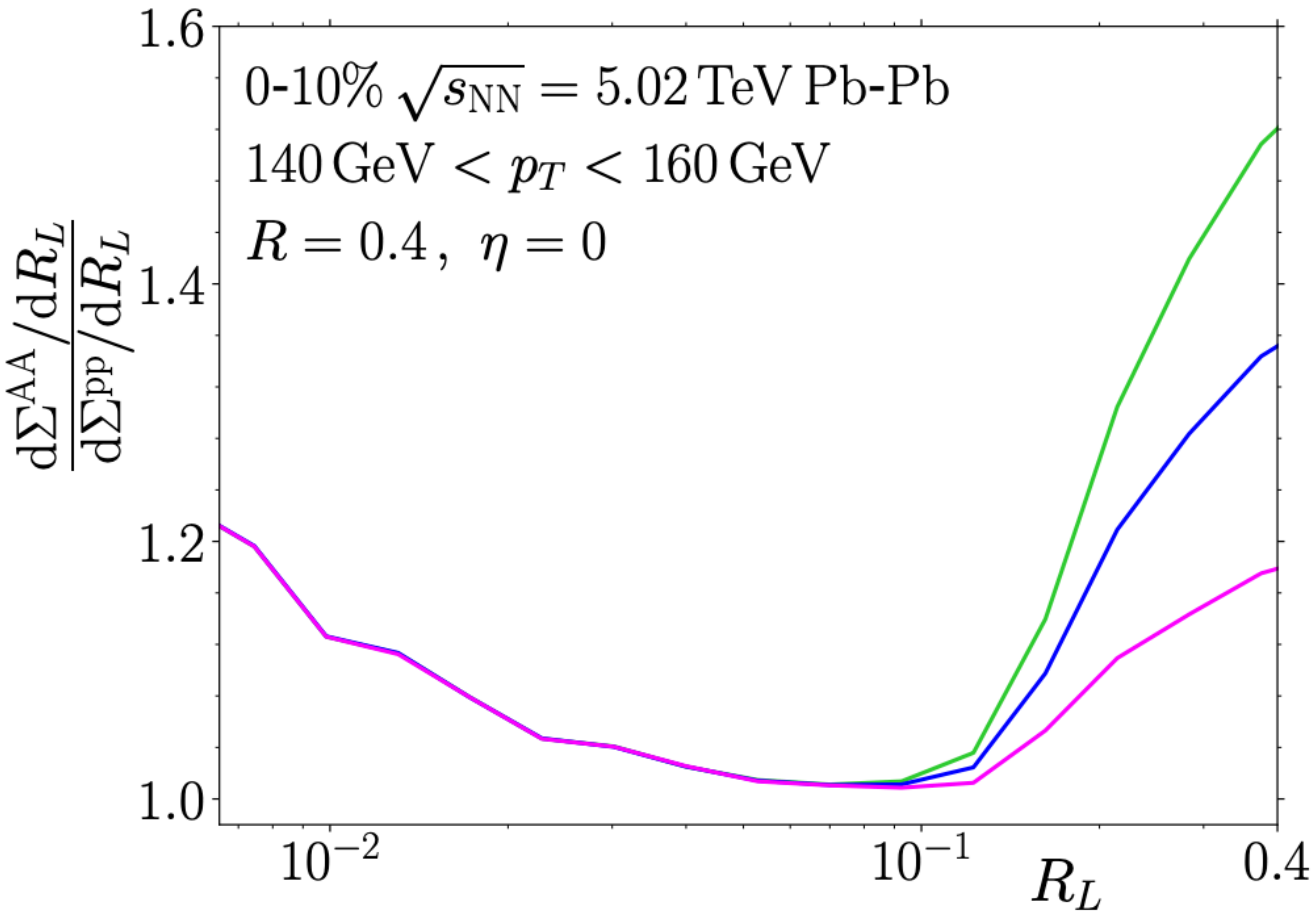


Multiple scatterings

Inclusive jets

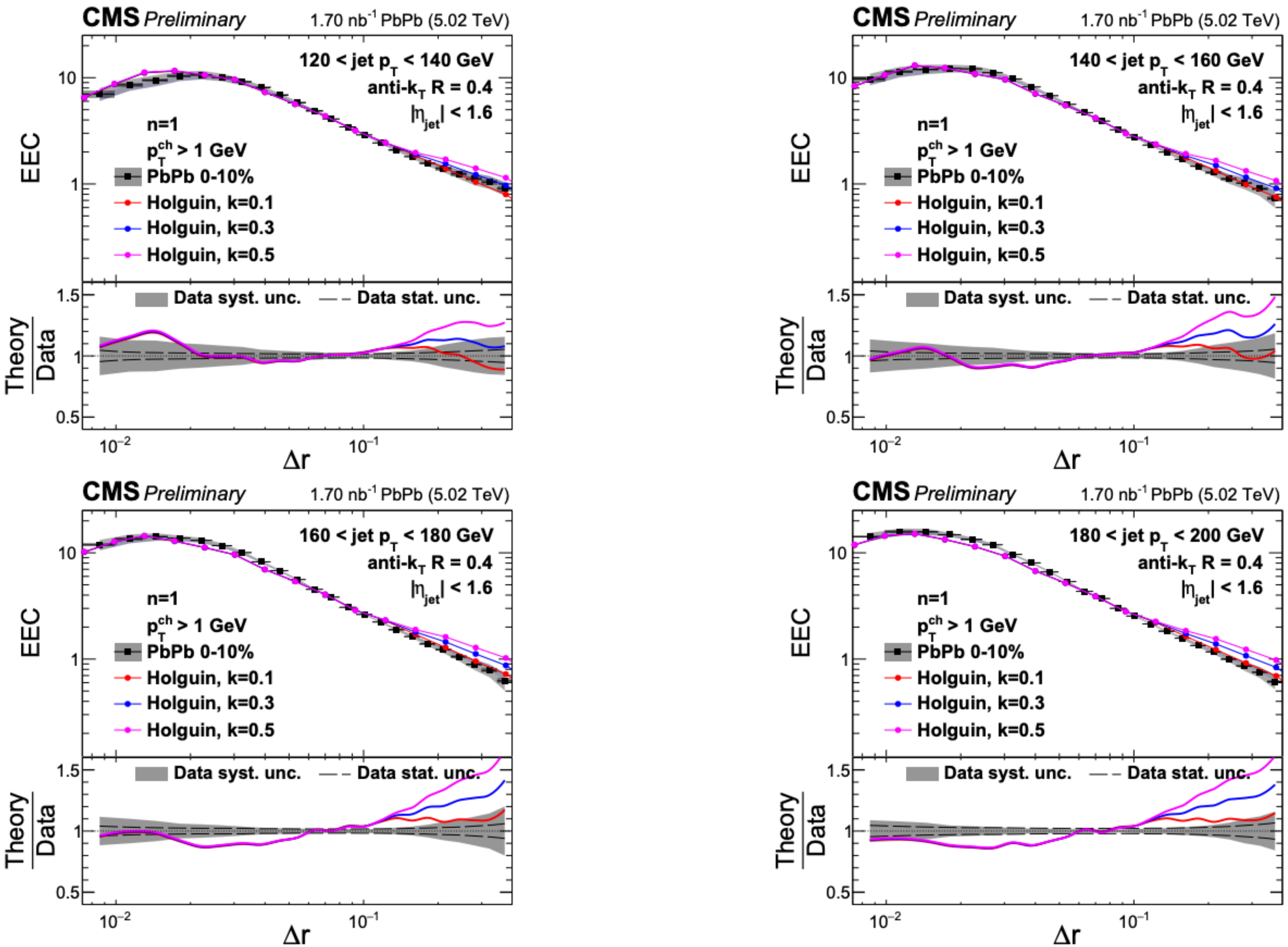


Inclusive jets



p_T dependence

From Jussi Viinikainen's talk unveiling the measurement at the Energy Correlators at the Collider Frontier workshop



Mitigating energy loss

Mitigating energy loss