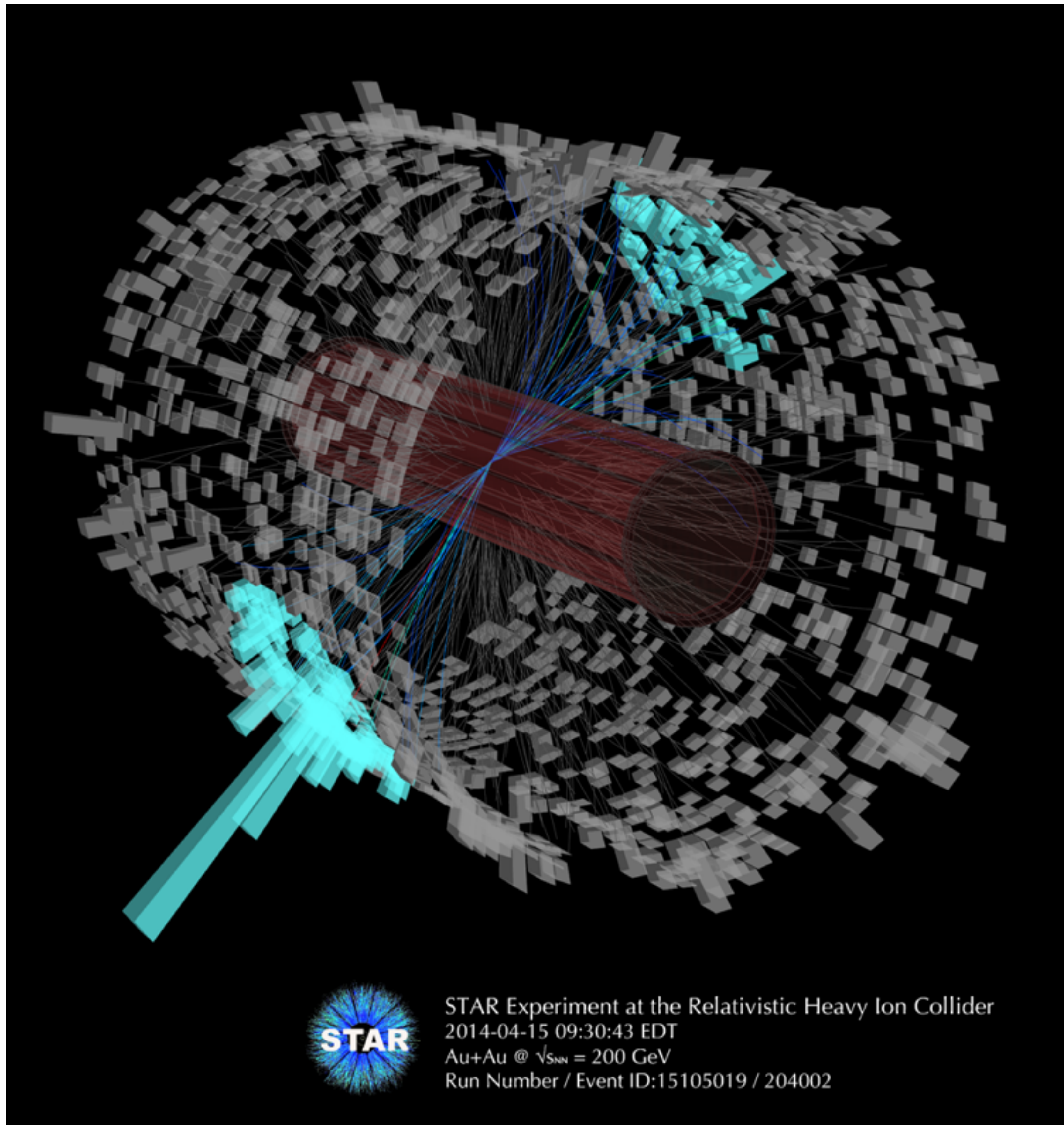
Jet theory highlights

Carlota Andres (she/her)

MIT

2025 RHIC&AGS Annual Users' Meeting

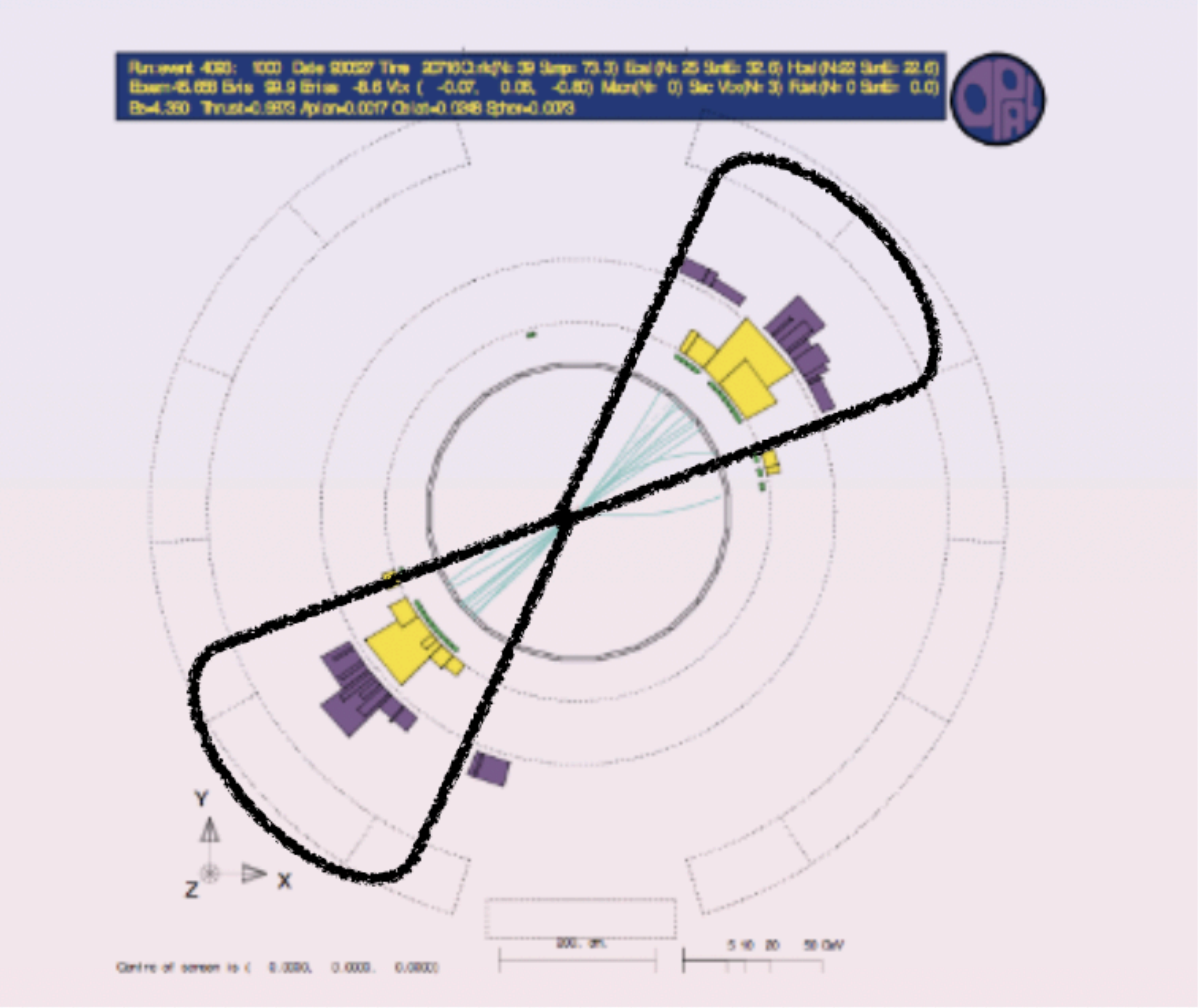
Massachusetts Institute of Technology

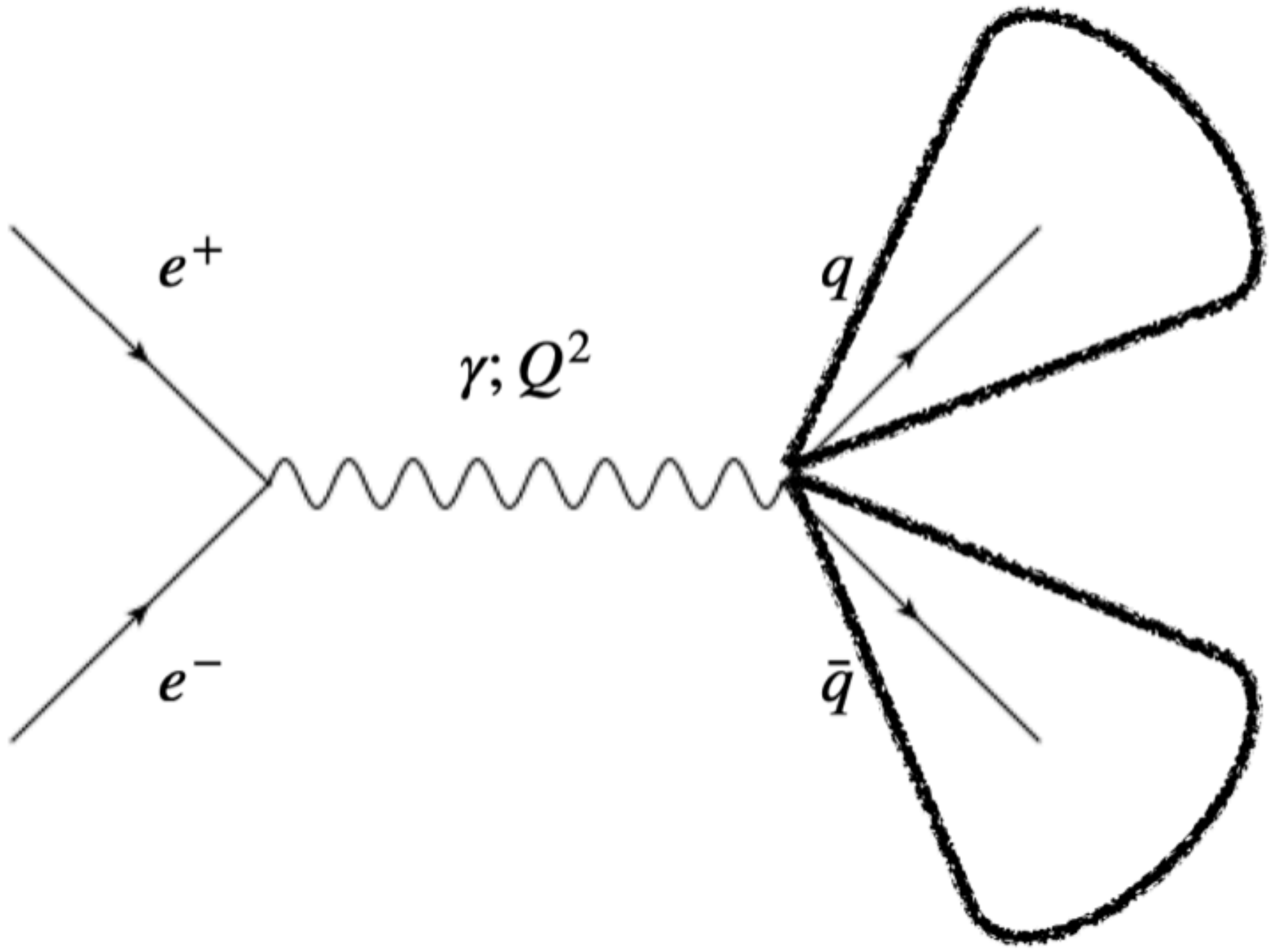


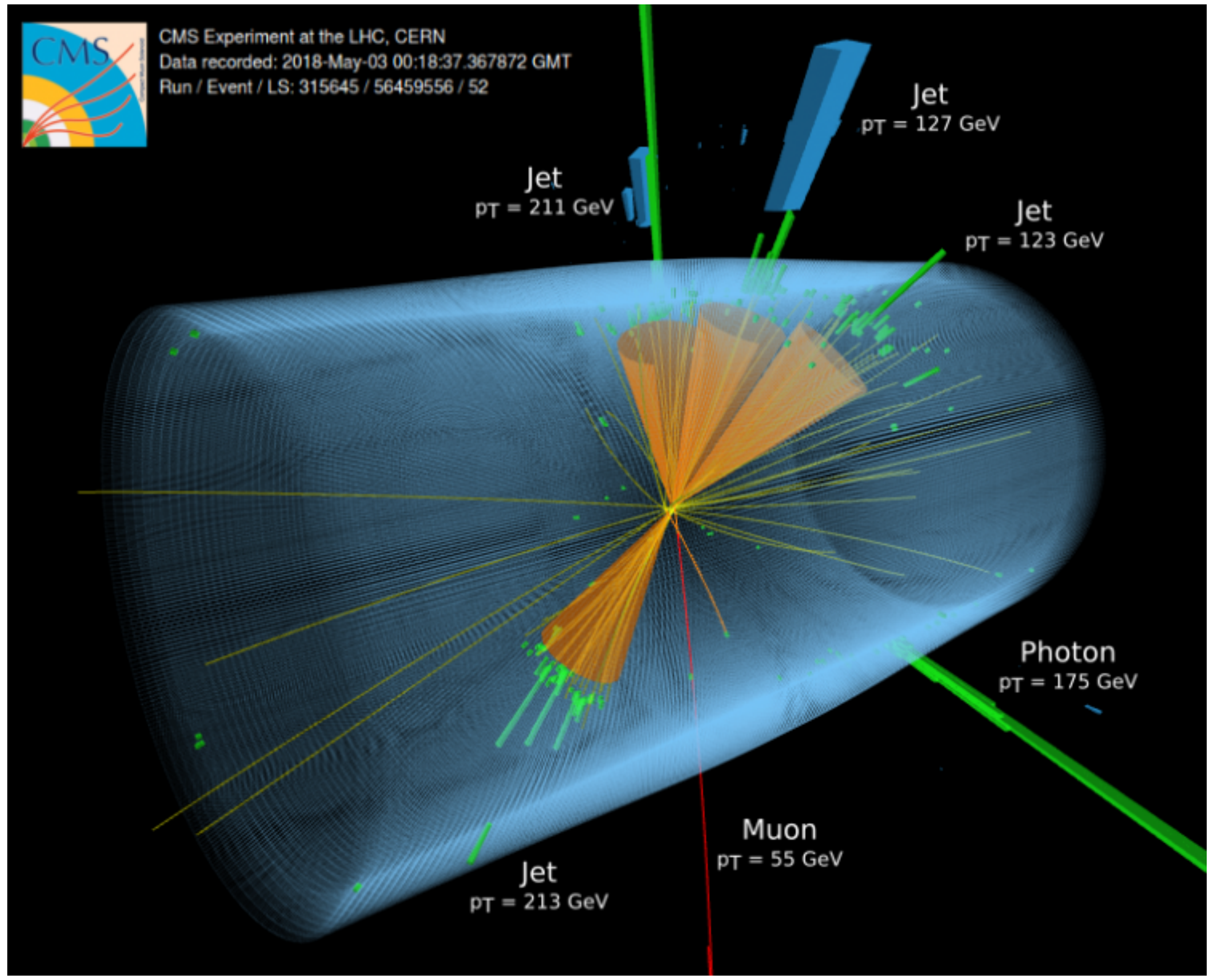
Jets at colliders

Jets are **proxies** of the **partons** produced in the **hard scattering**

OPAL Phys. Lett, B 265 462-474 (1991)



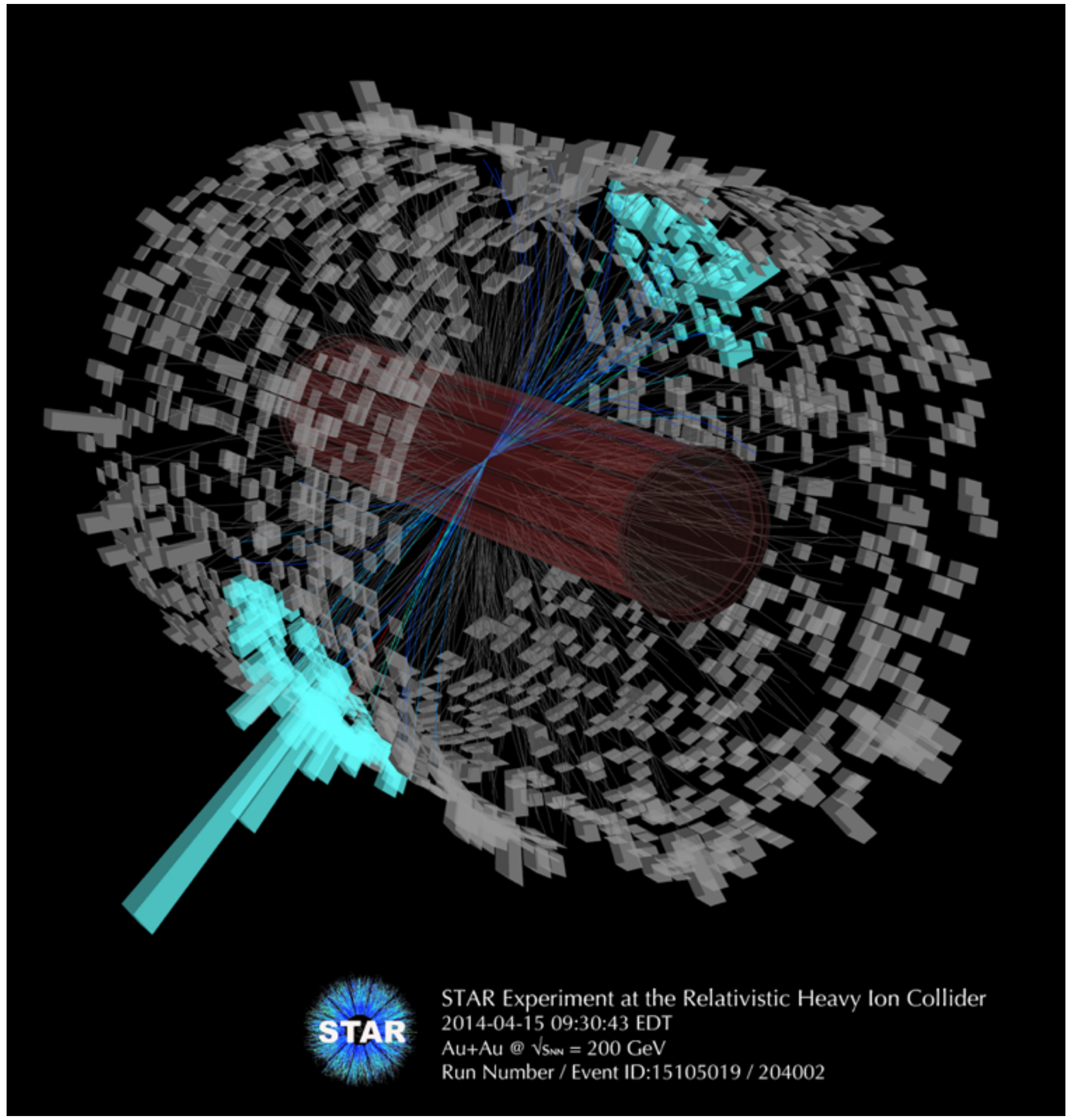


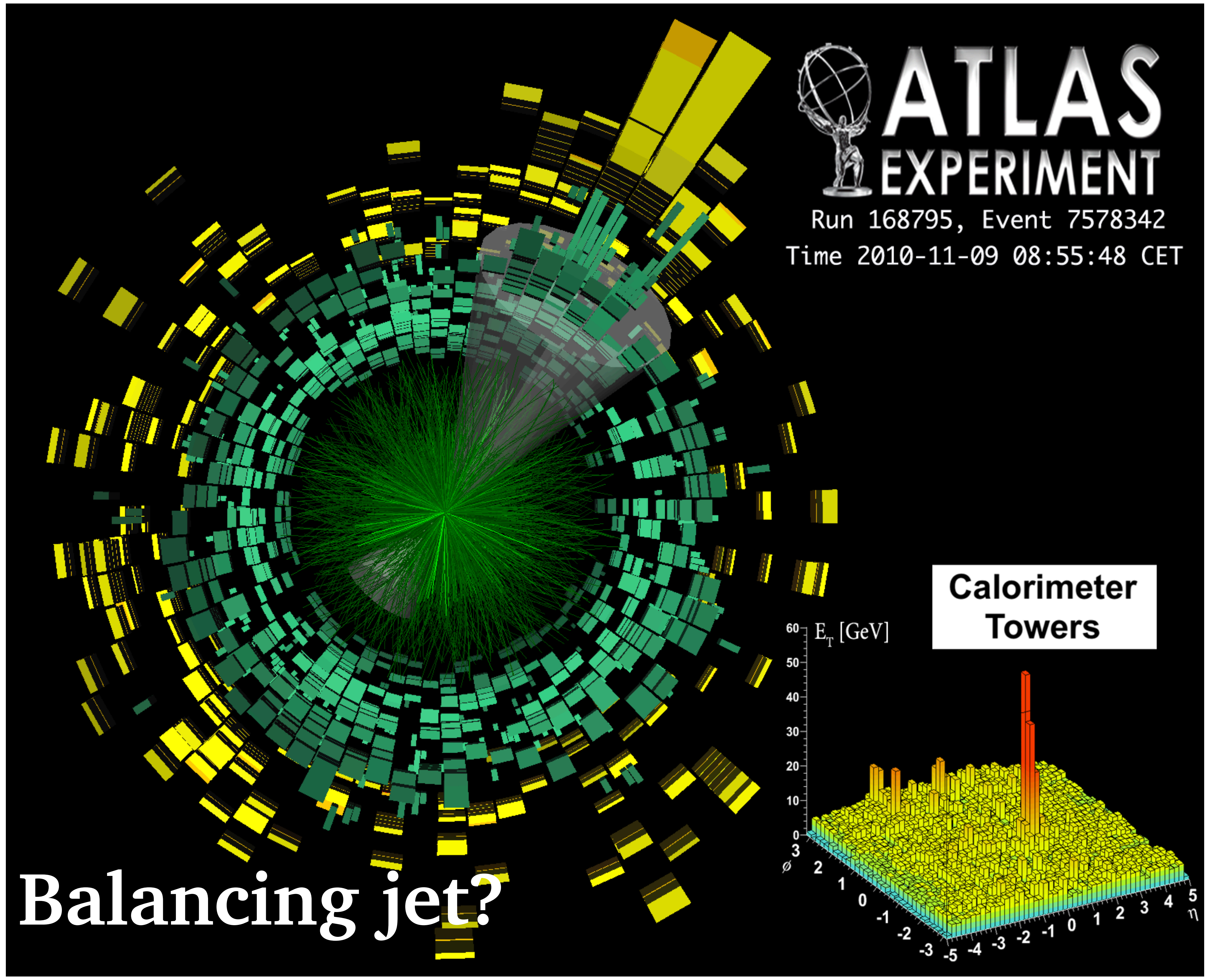


QCD **jets** are **fundamental tools** in collider physics

Jets in heavy ion collisions

Jet quenching

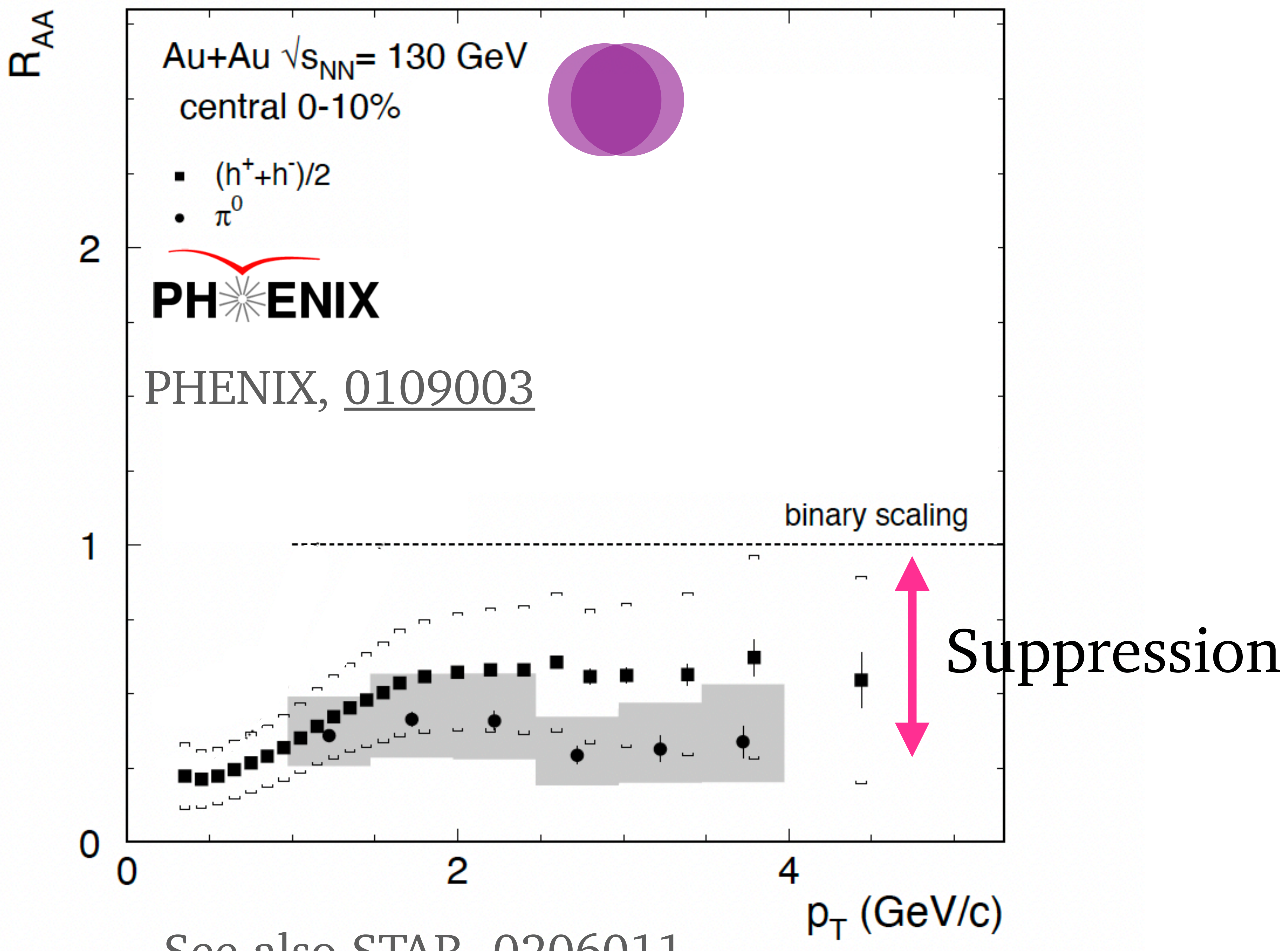




Jets in heavy ion collisions: quenching

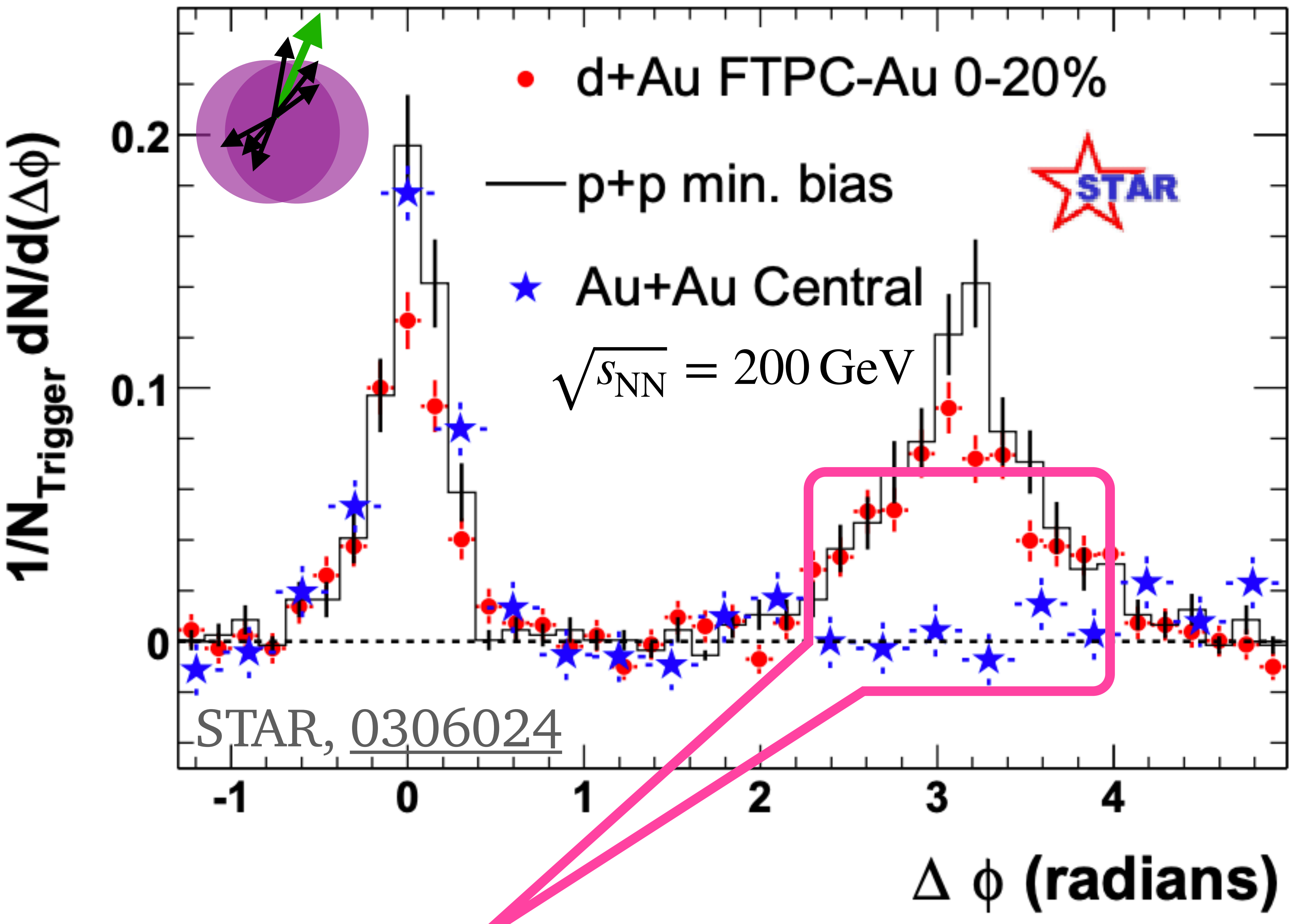
First observations of **jet quenching** at RHIC!

Inclusive hadron suppression



See also STAR, 0206011

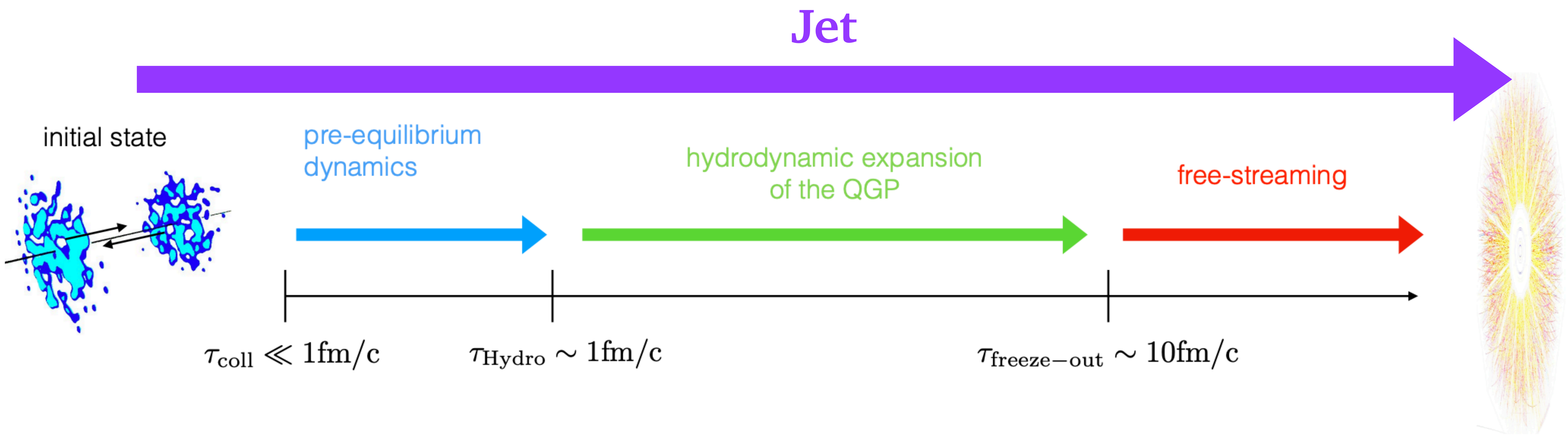
Di-hadron correlations



Back-to-back peak disappears in Au-Au

Why jets?

- Jets ($Q \sim p_{\rm T}$) are **produced** in the **earliest phase of the collision** $\tau_{\rm p} \sim \frac{1}{Q} \ll \frac{1}{Q_s} \ll \tau_{\rm hydro}$



- They **interact with the medium** through the strong interaction **getting modified**

Jets are extended objects: ideal to **probe the medium at different times** and **resolution scales**

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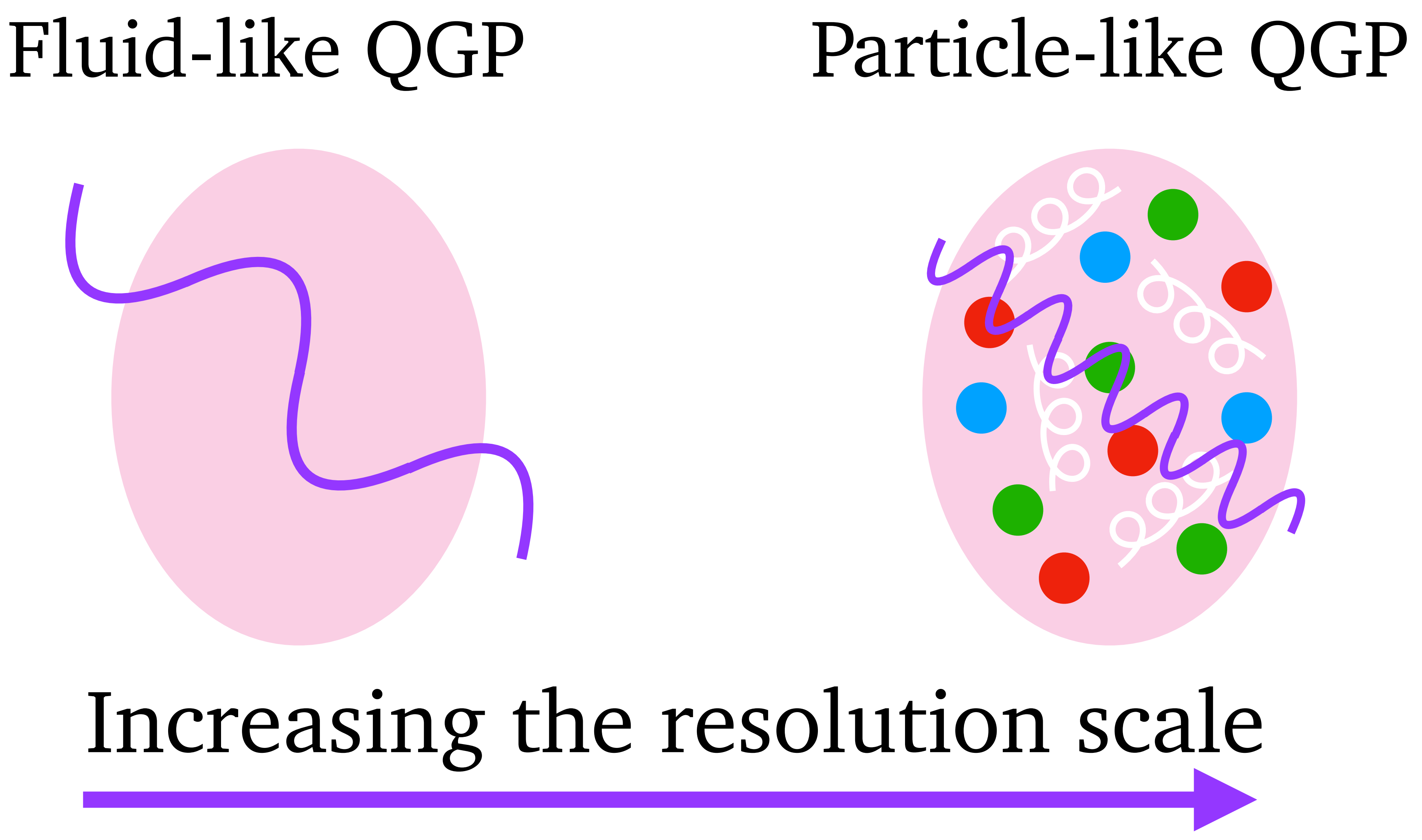
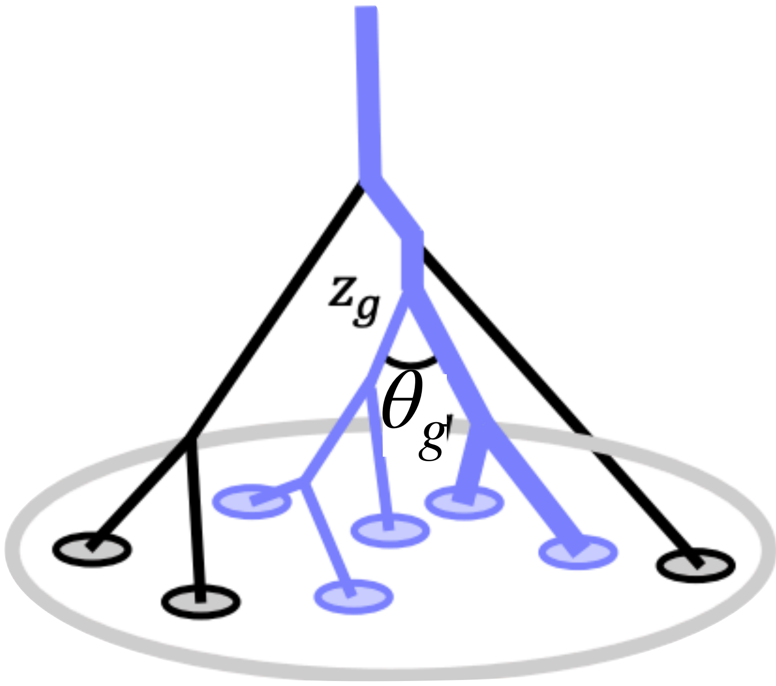
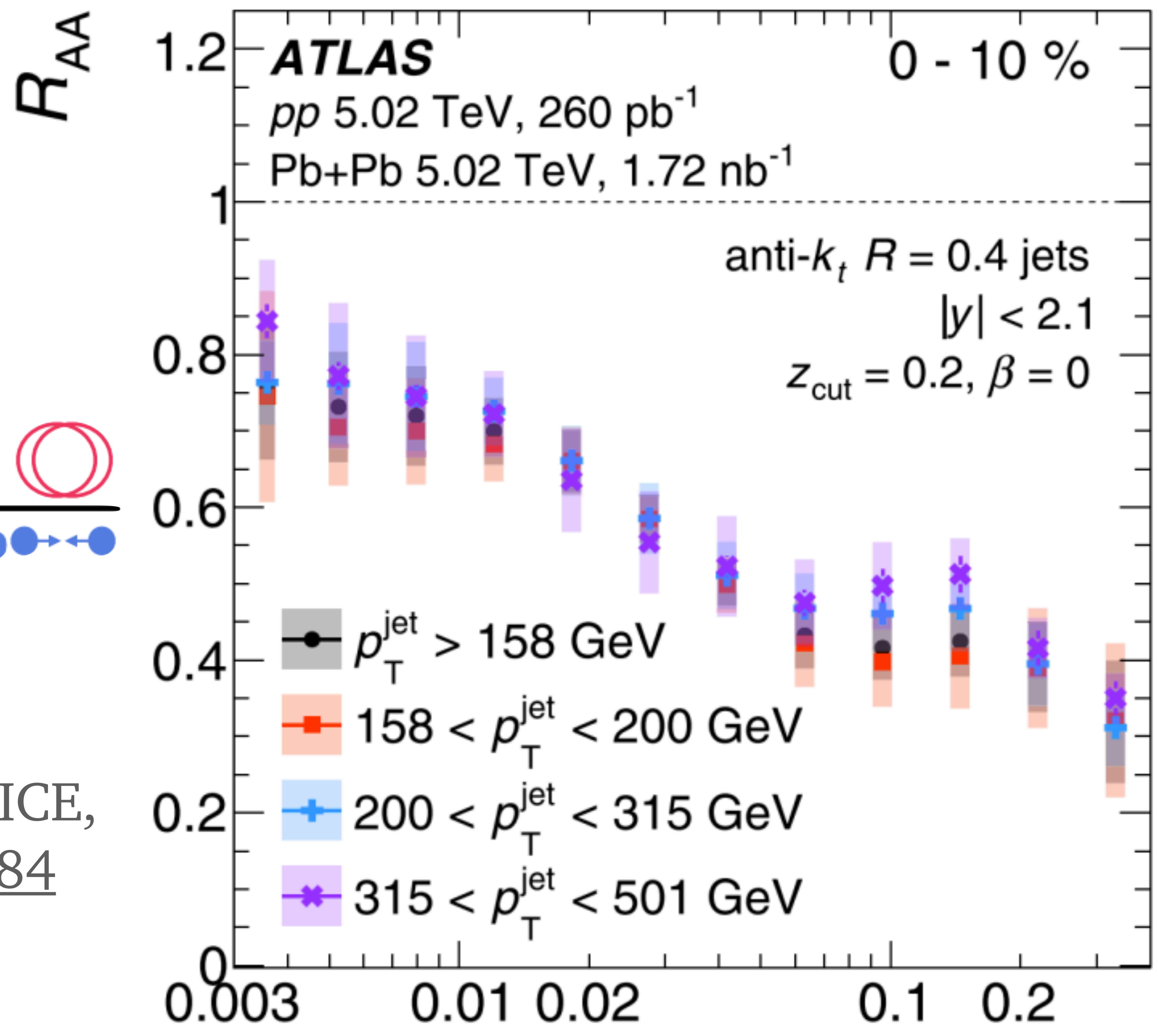


Groomed jet radius [Soft Drop grooming]



ATLAS, 2211.11470



$r_g = R\theta_g$

$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled}\otimes\text{pp}}$$

See also ALICE, 2107.12984

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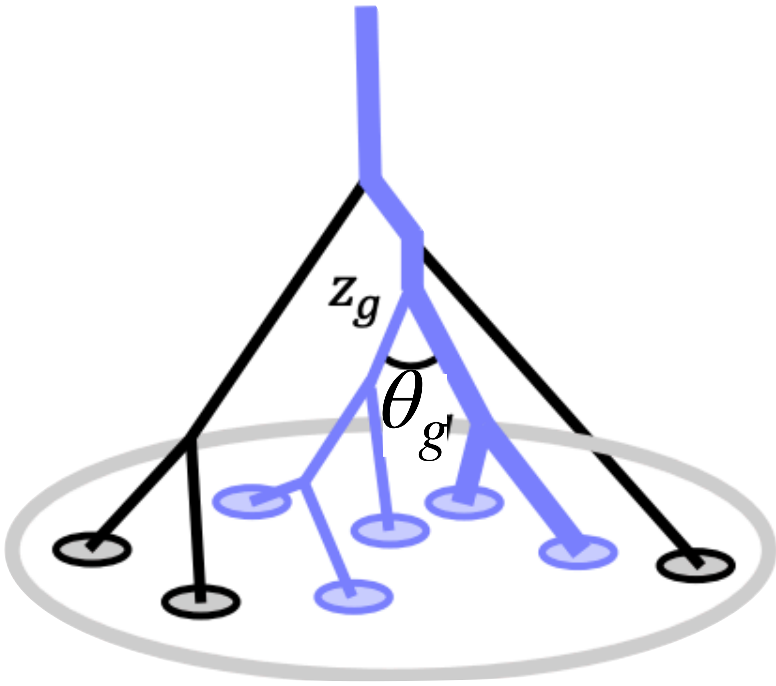

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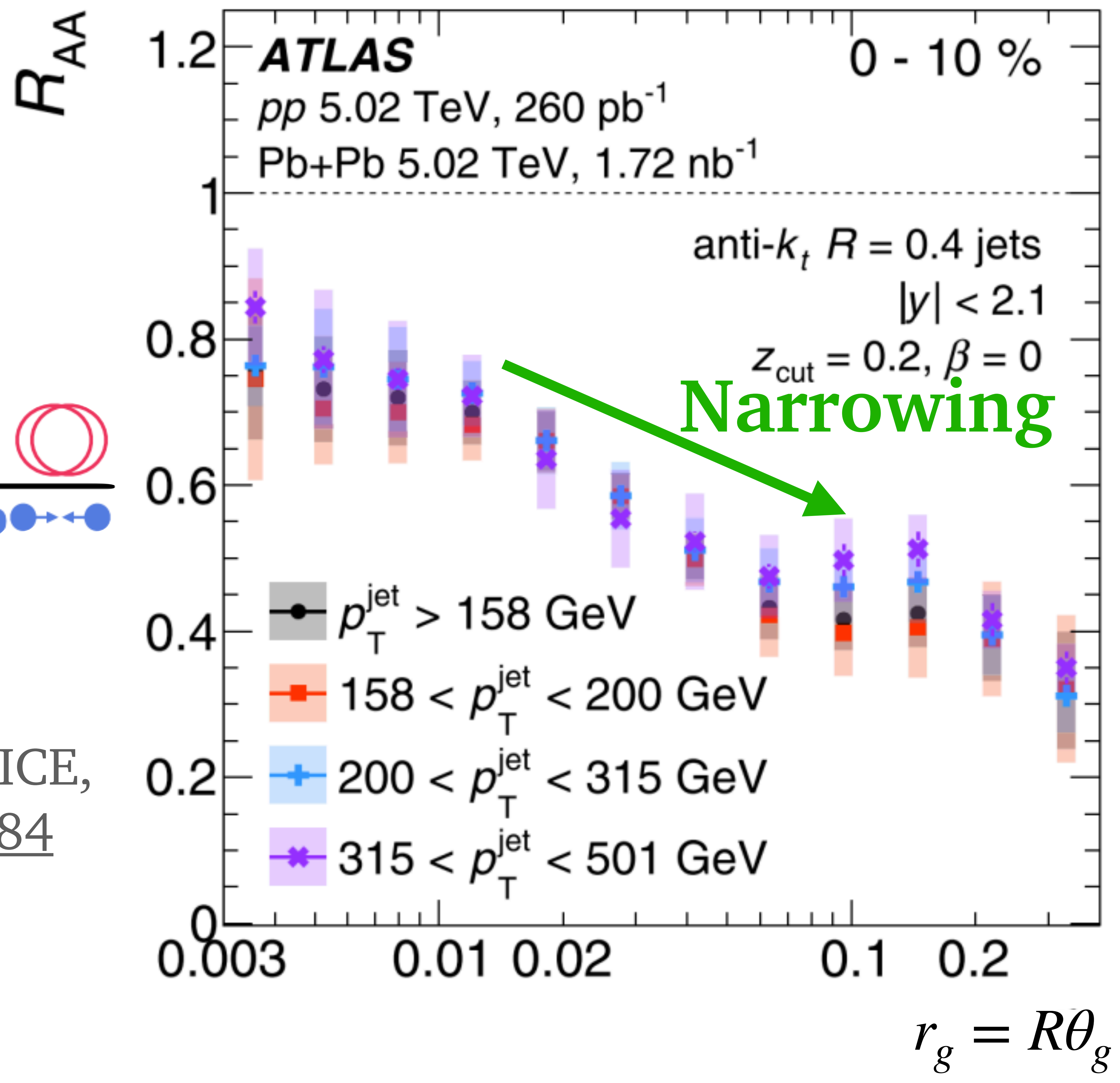

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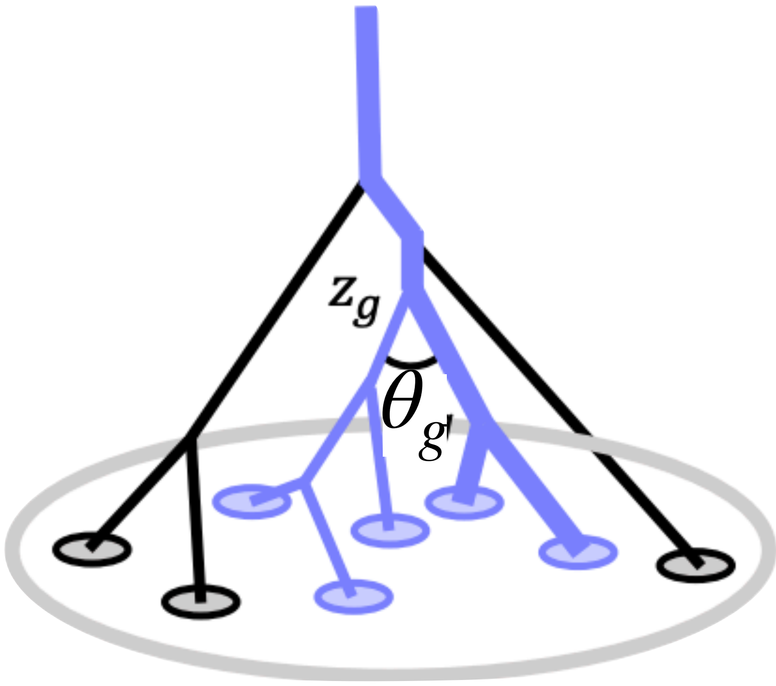

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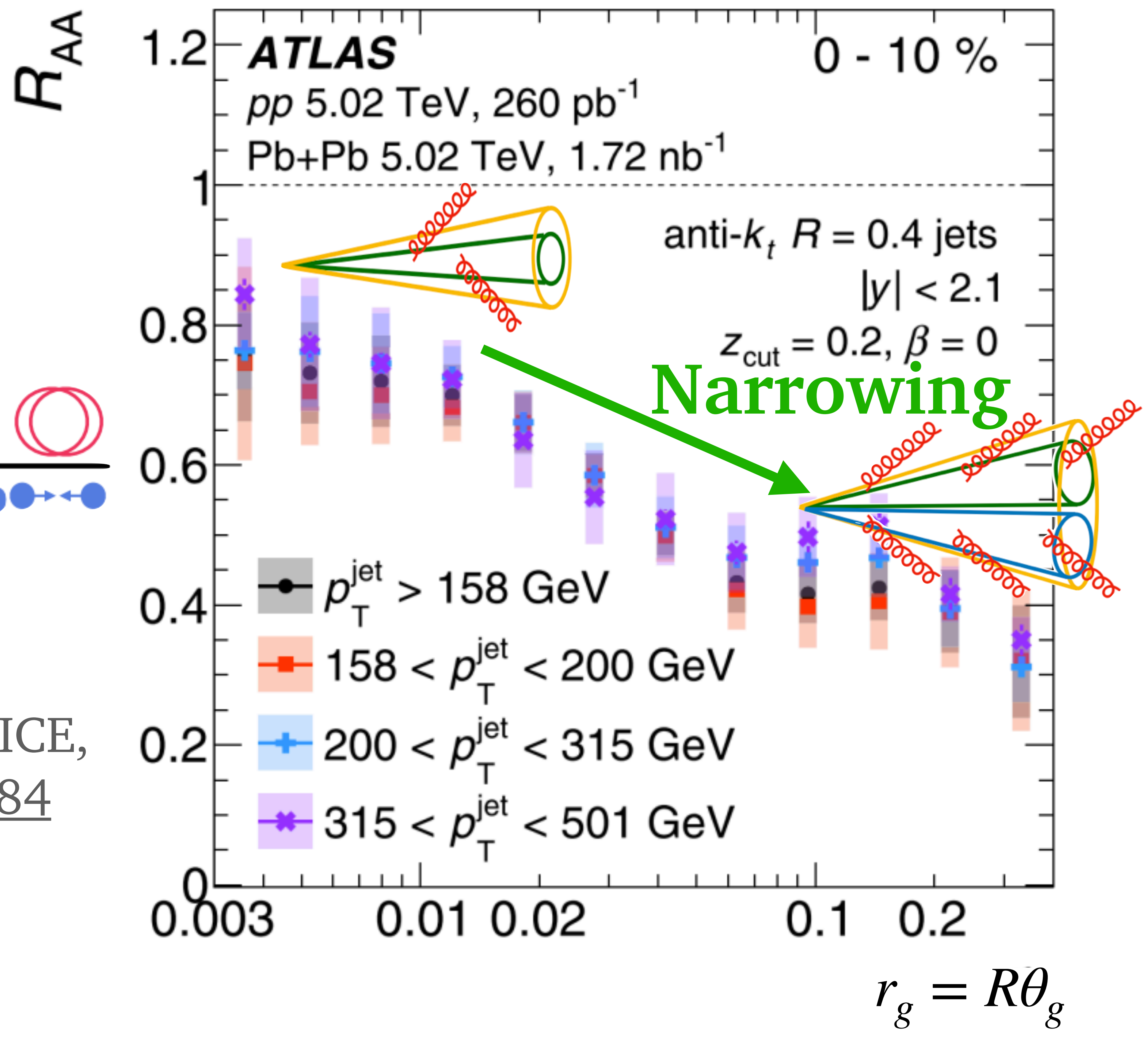

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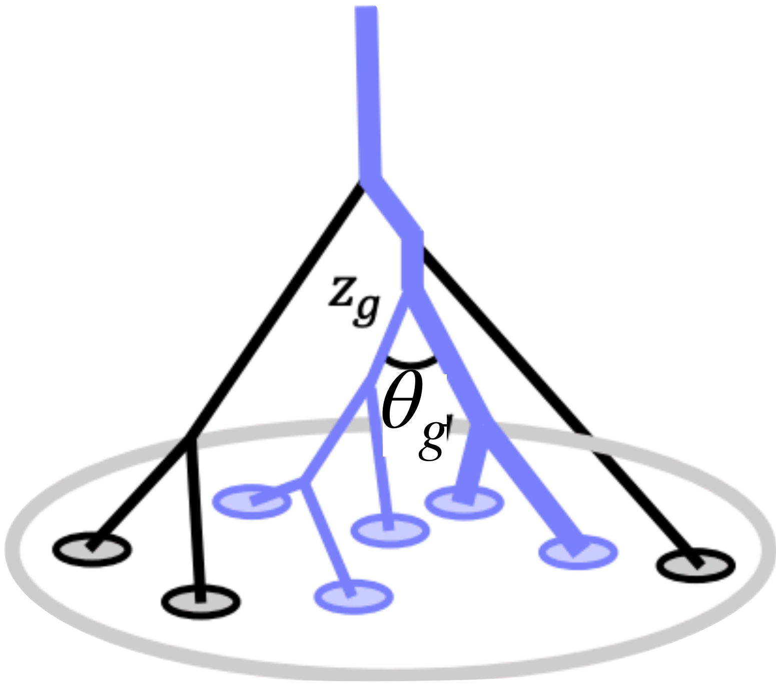

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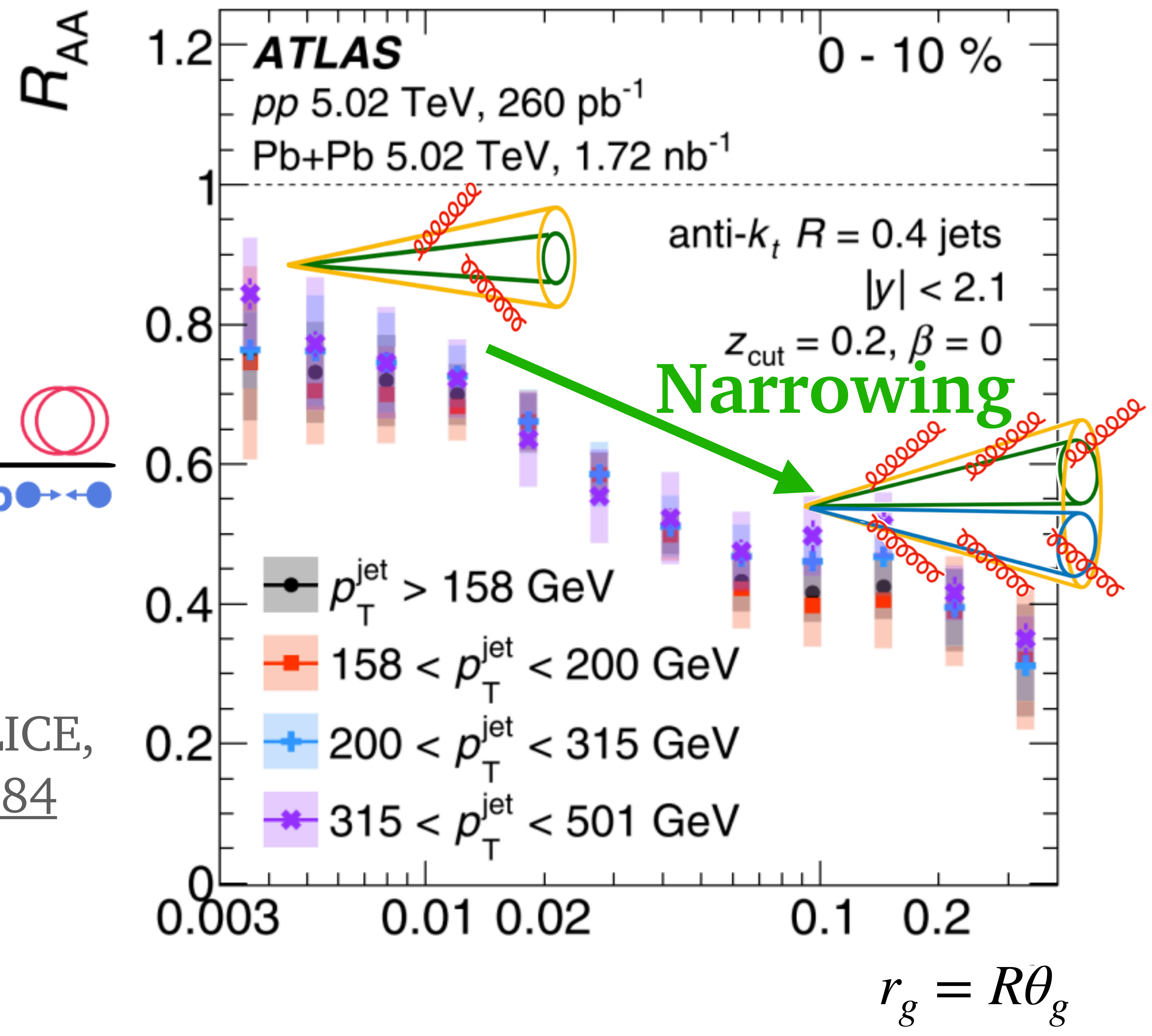

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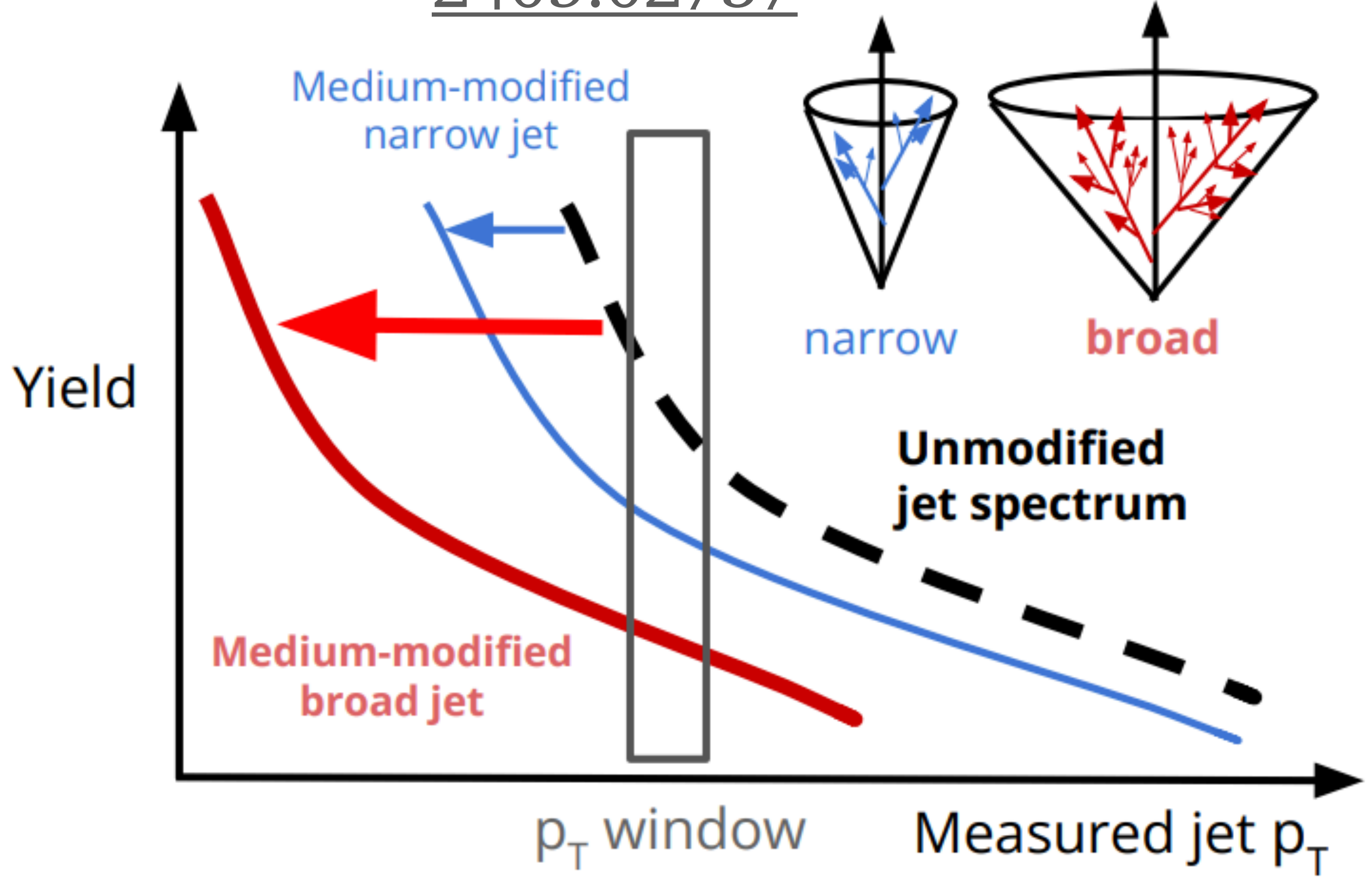
Selection bias

2405.02737



See also CMS, θ_g in γ-tagged jets 2405.02737

ALICE, θ_g balanced vs. unbalanced in HP2024

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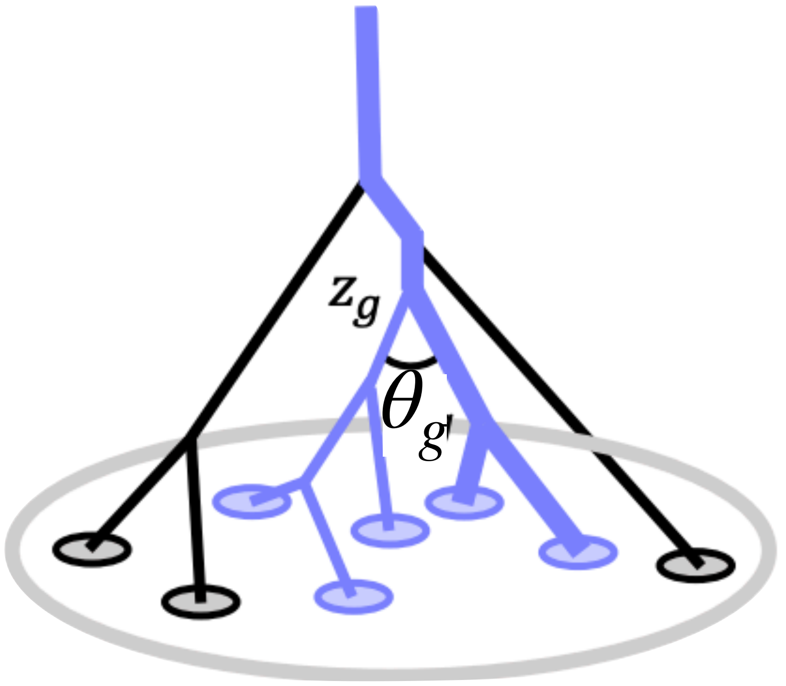

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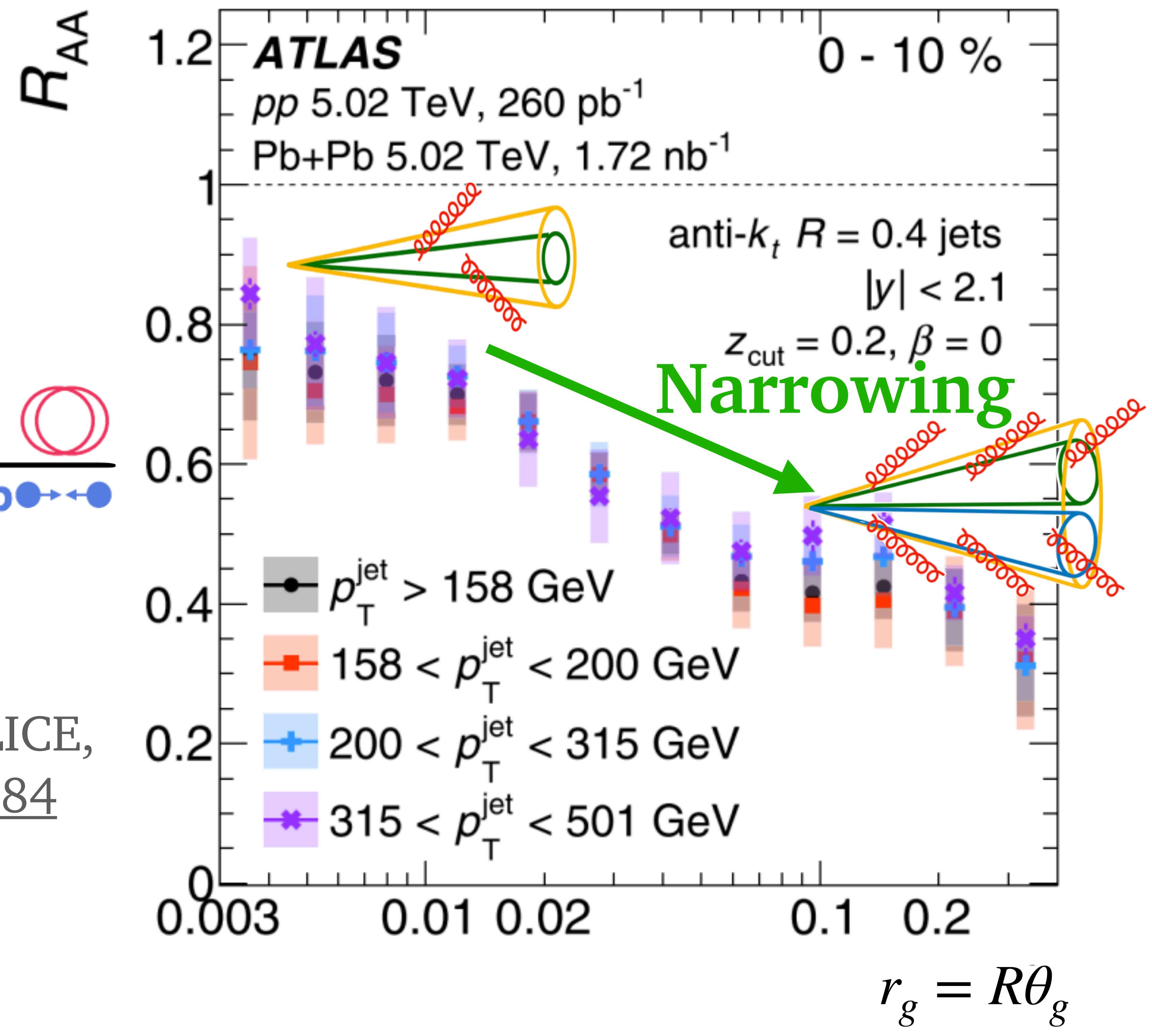

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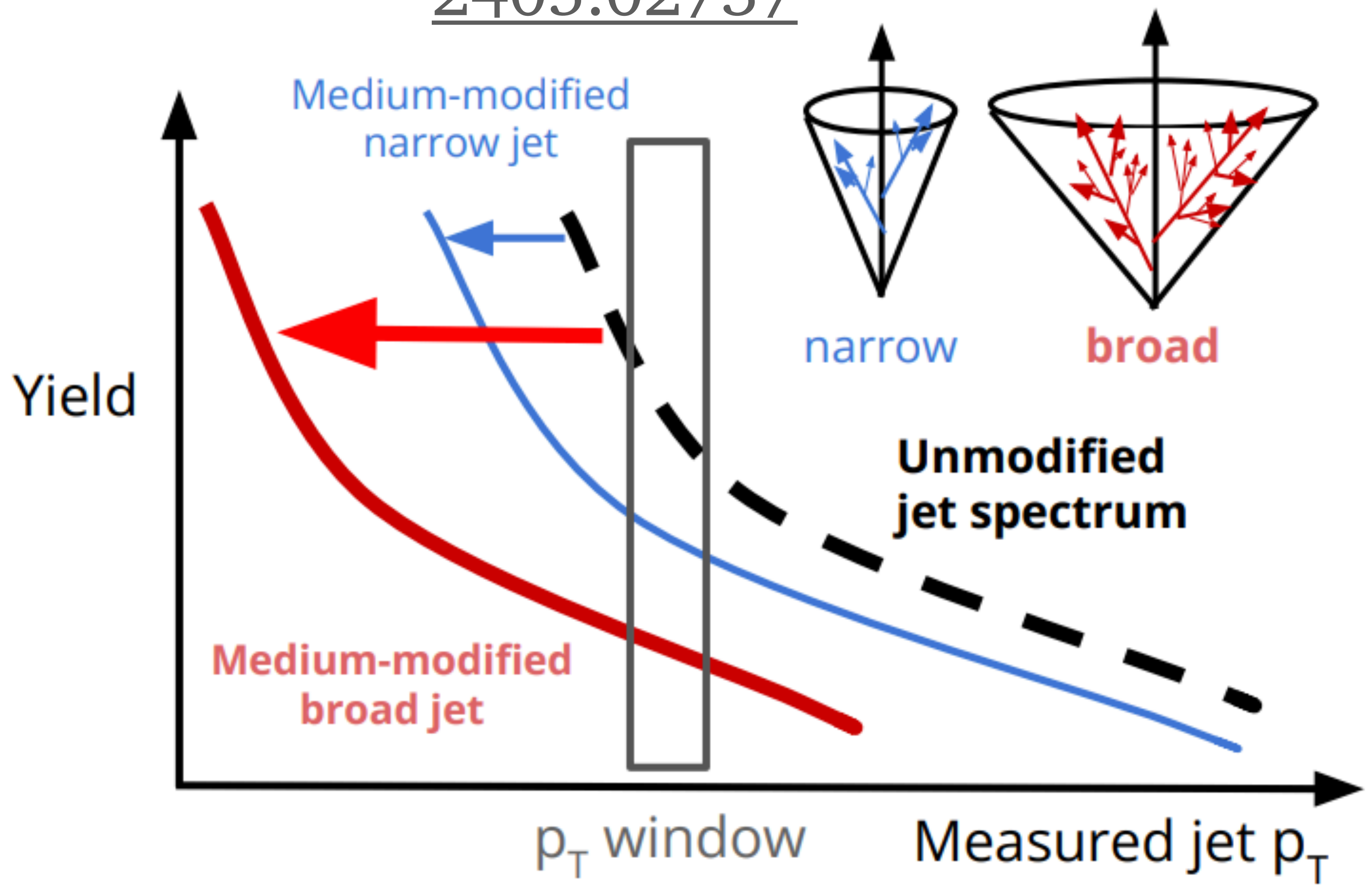


See also CMS, θ_g in γ-tagged jets 2405.02737

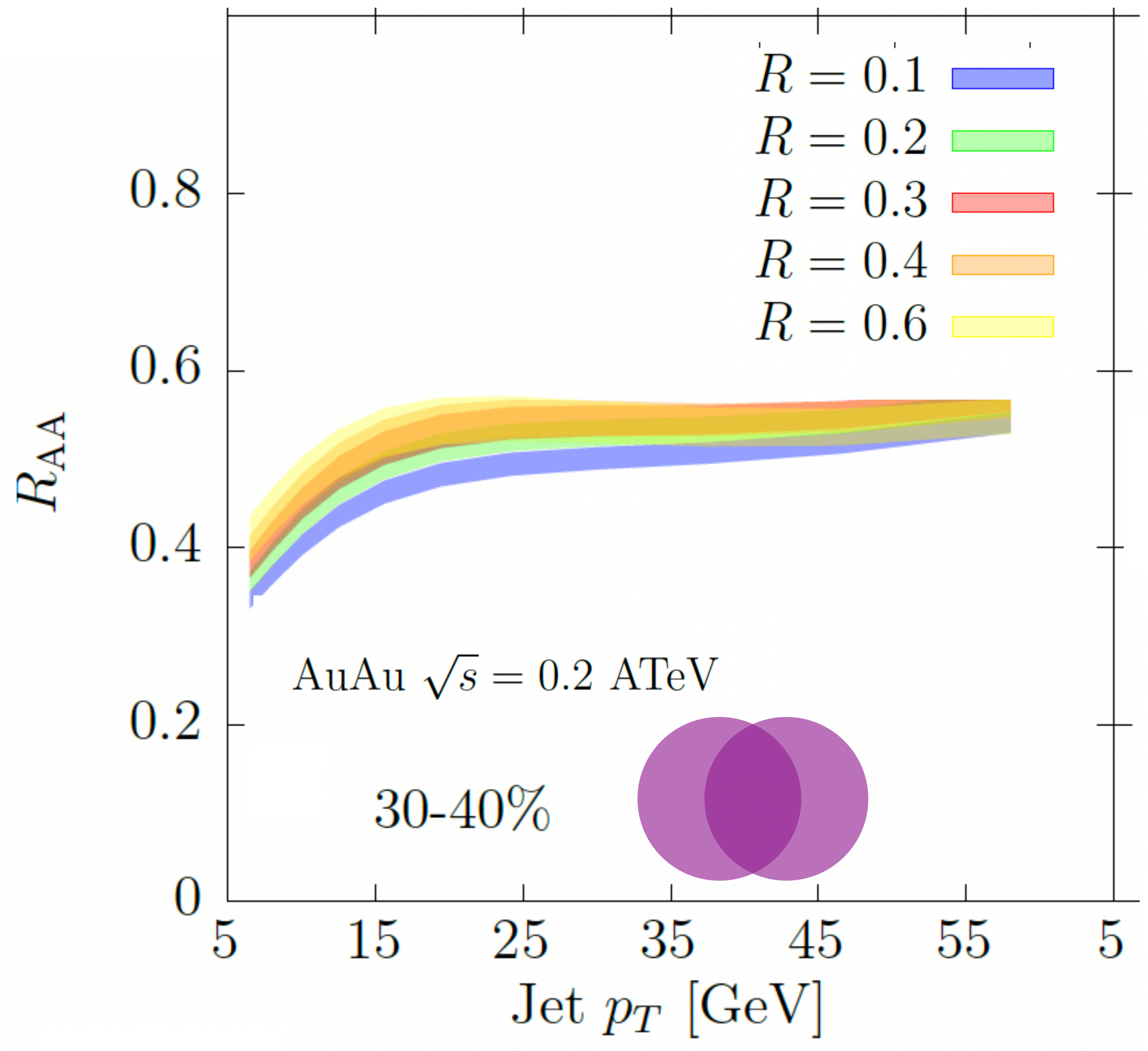
ALICE, θ_g balanced vs. unbalanced in HP2024

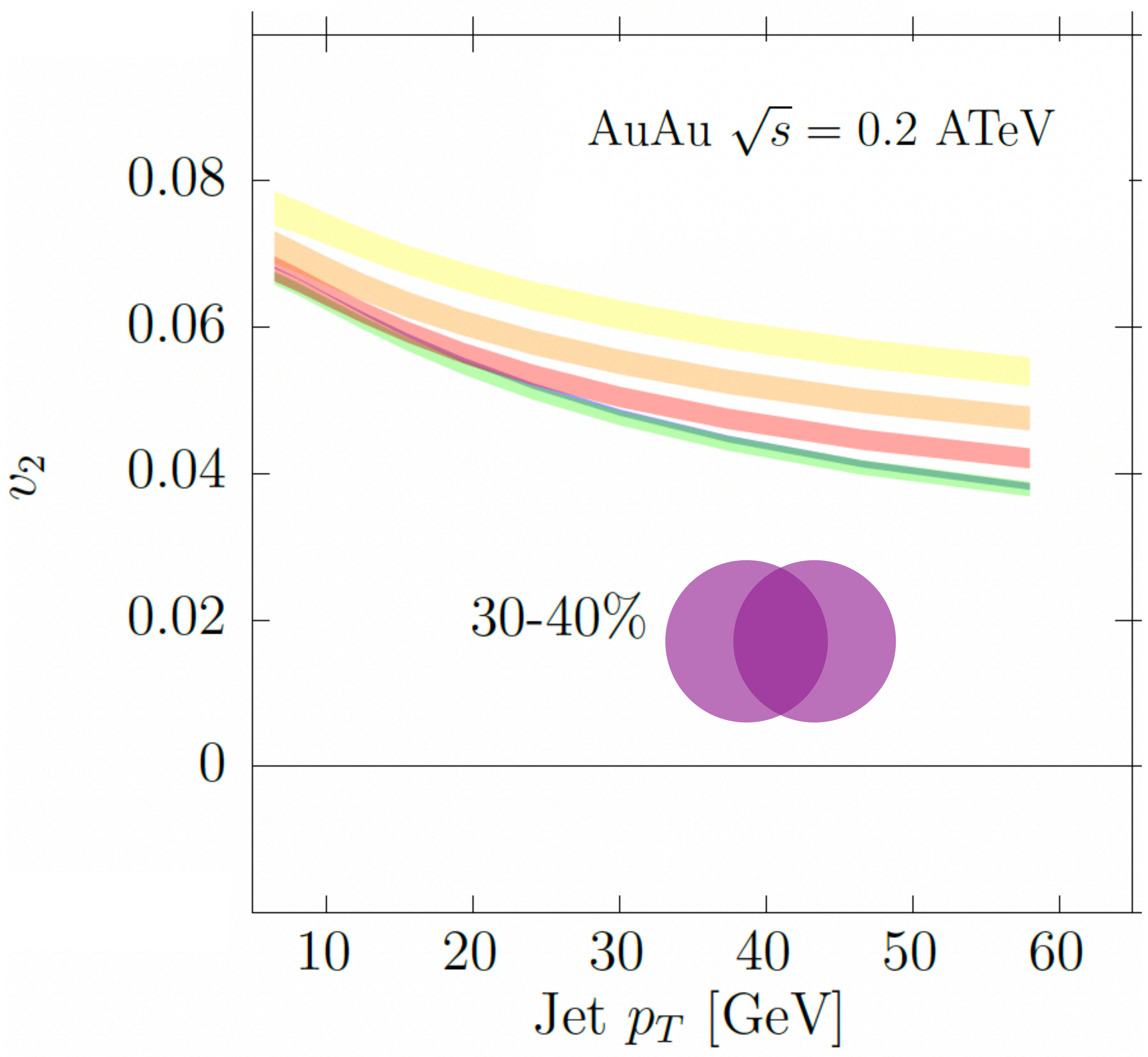
Jets **narrowed by the QGP** or **wider jets less likely to survive**?

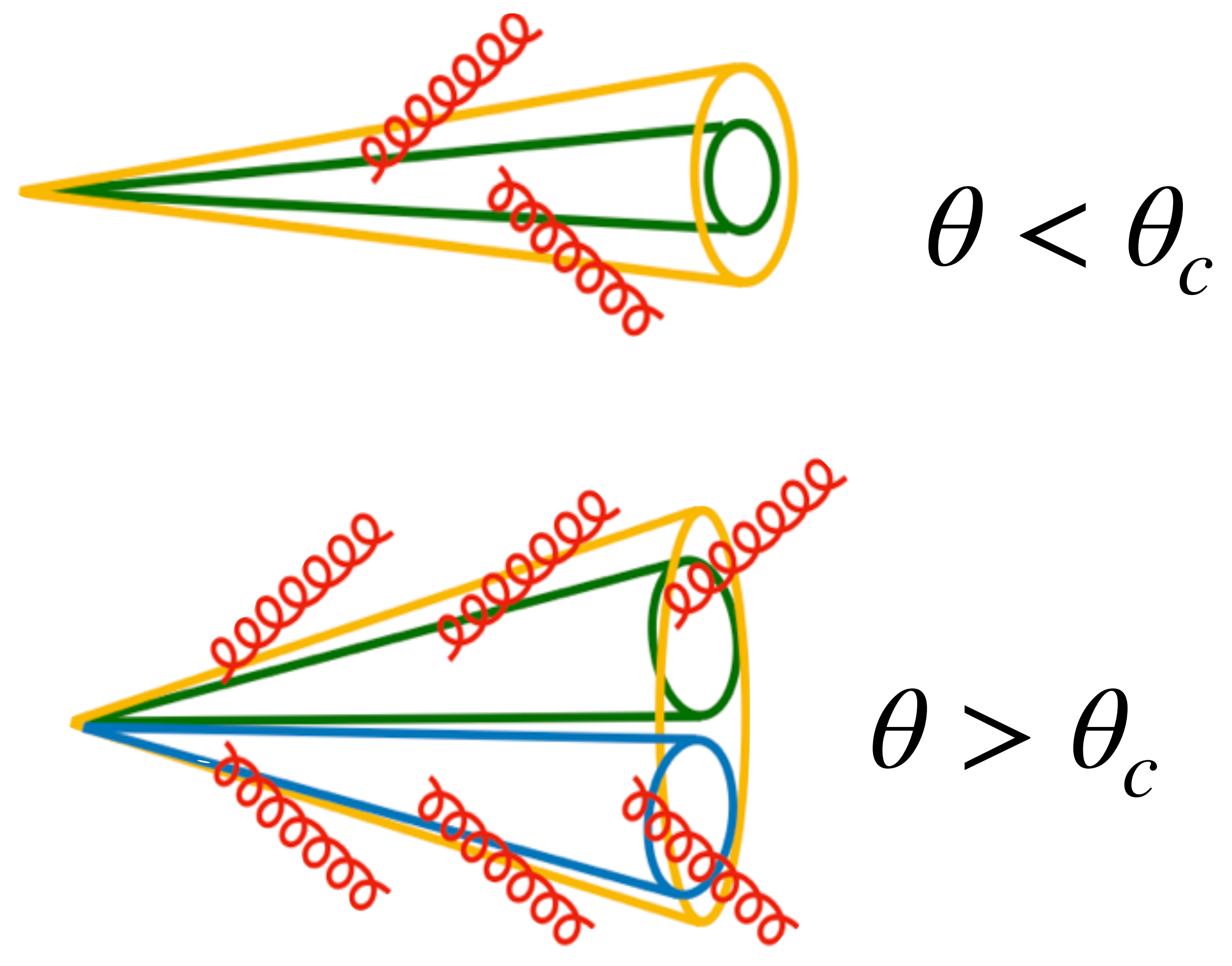
Inclusive jets and v_2

Mehtar-Tani, Pablos, Tywoniuk, 2402.07869
2101.01742

Jet v_2: stronger dependence on the dynamics of color coherence







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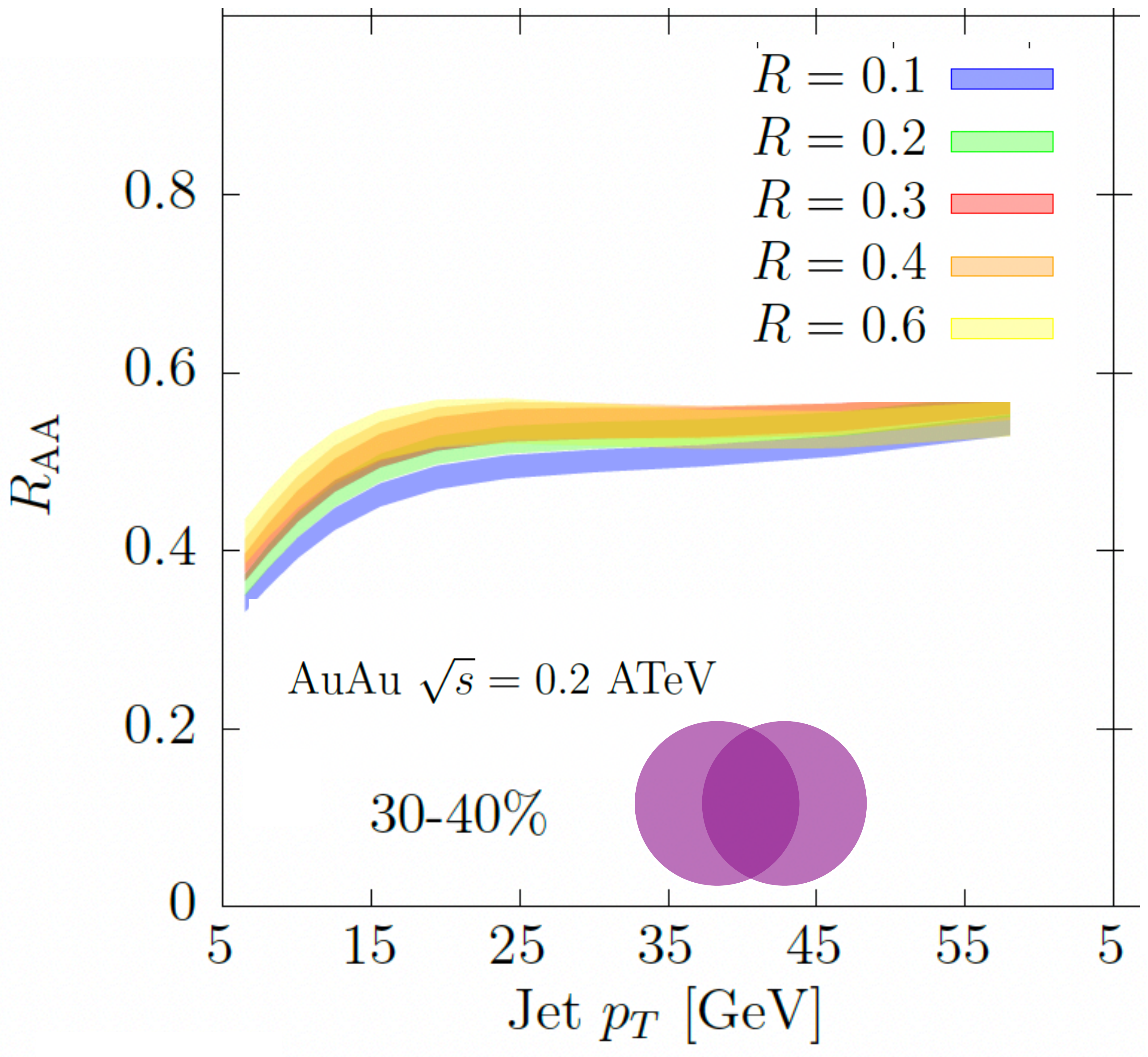

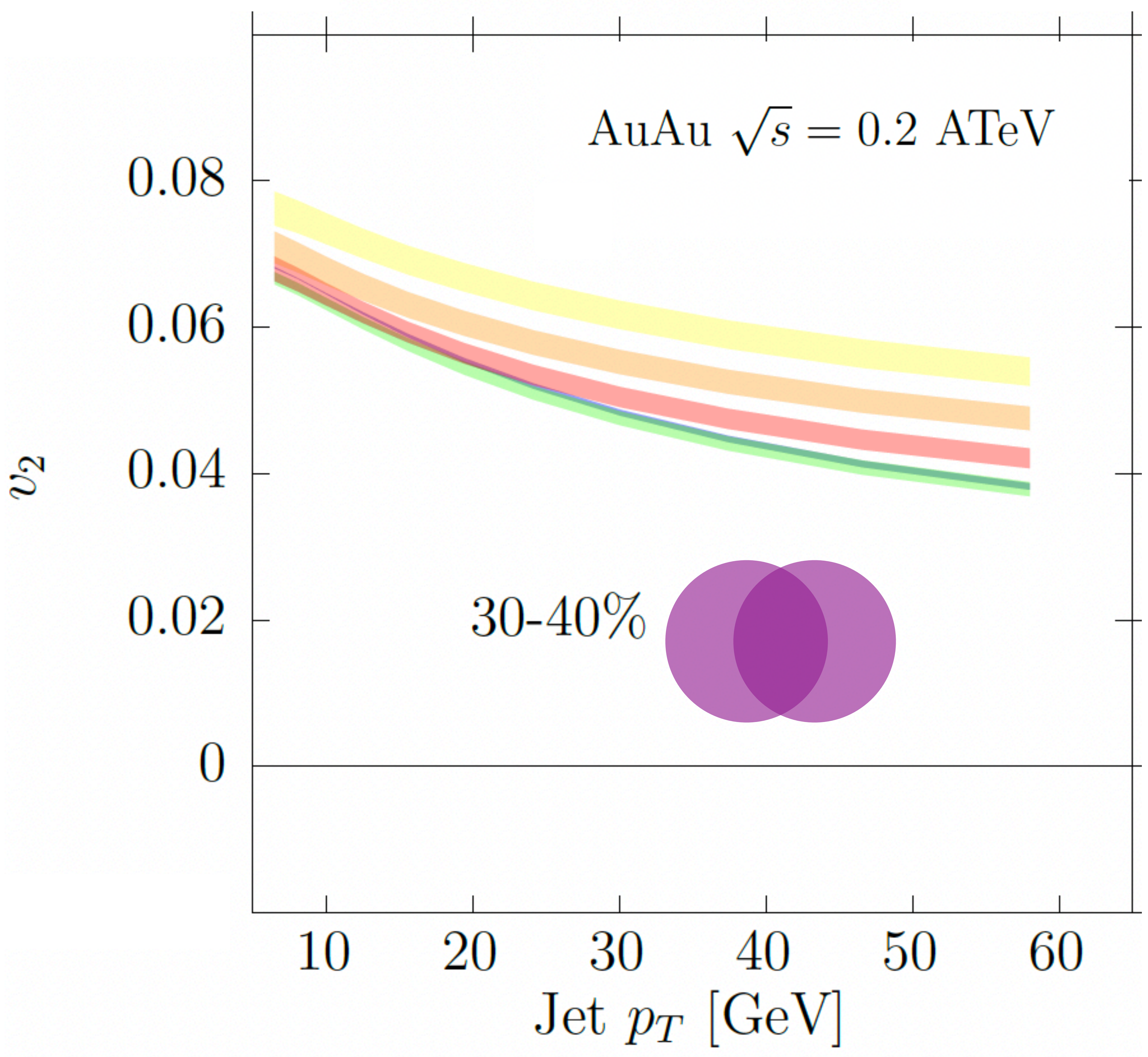

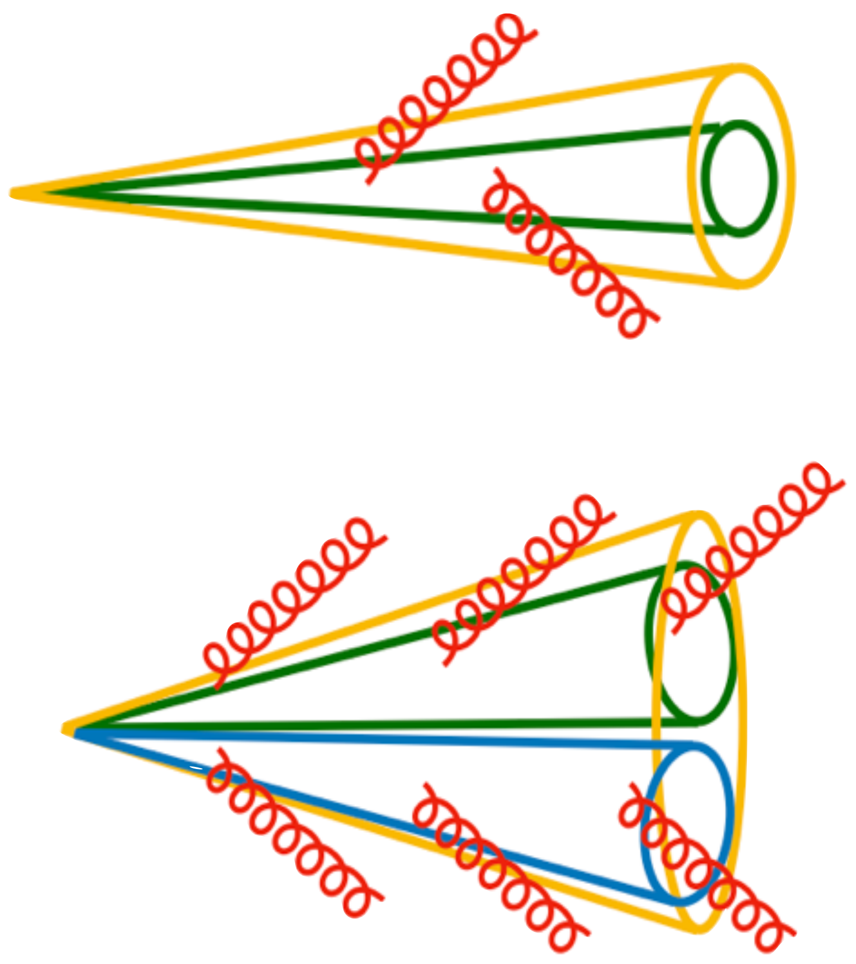

$\theta < \theta_c$

$\theta > \theta_c$

$$\theta_c \sim \frac{1}{\sqrt{\hat{q}L^3}}$$

Carlota Andres

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Mehtar-Tani, Pablos, Tywoniuk, 2402.07869
2101.01742

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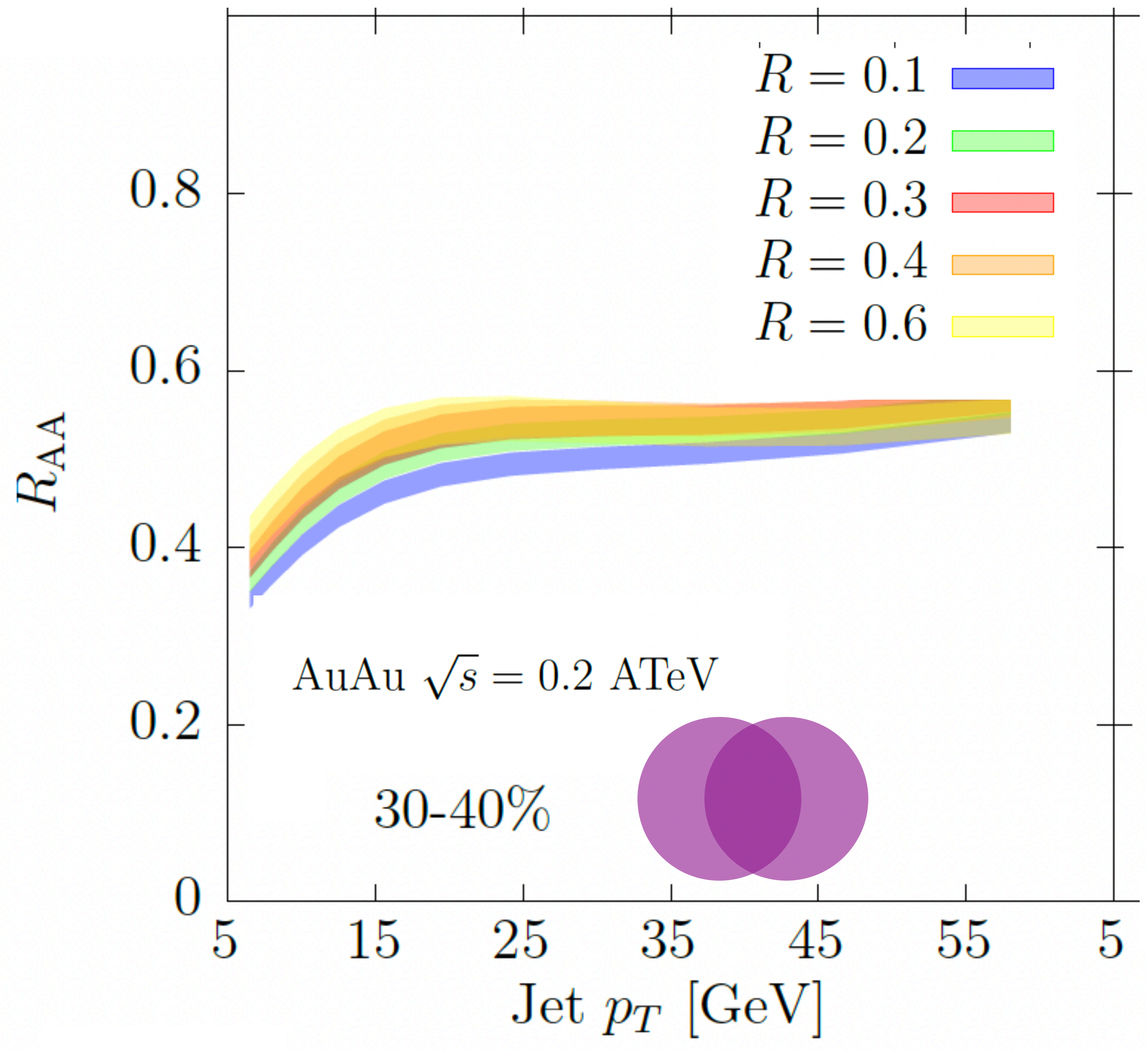
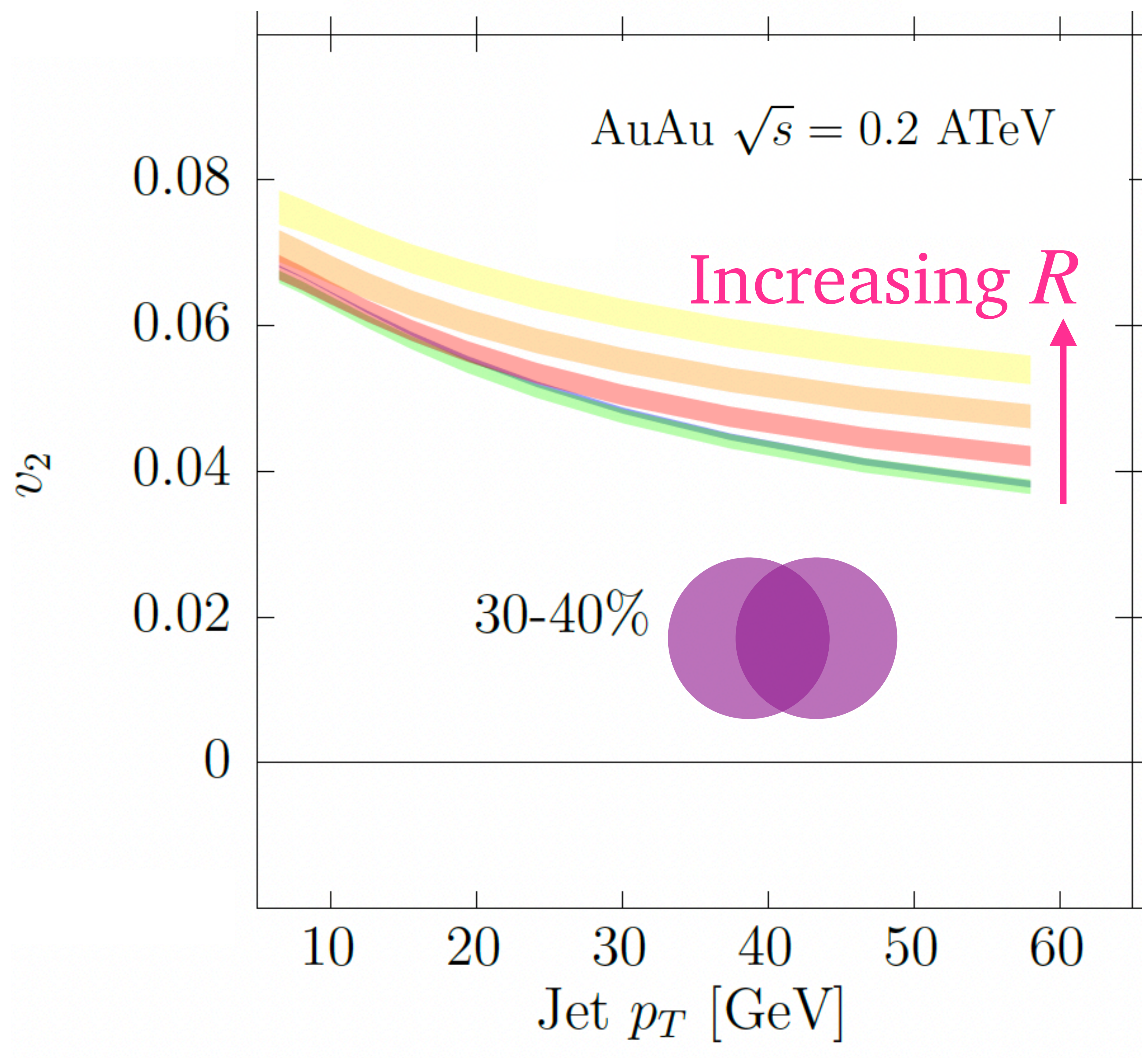
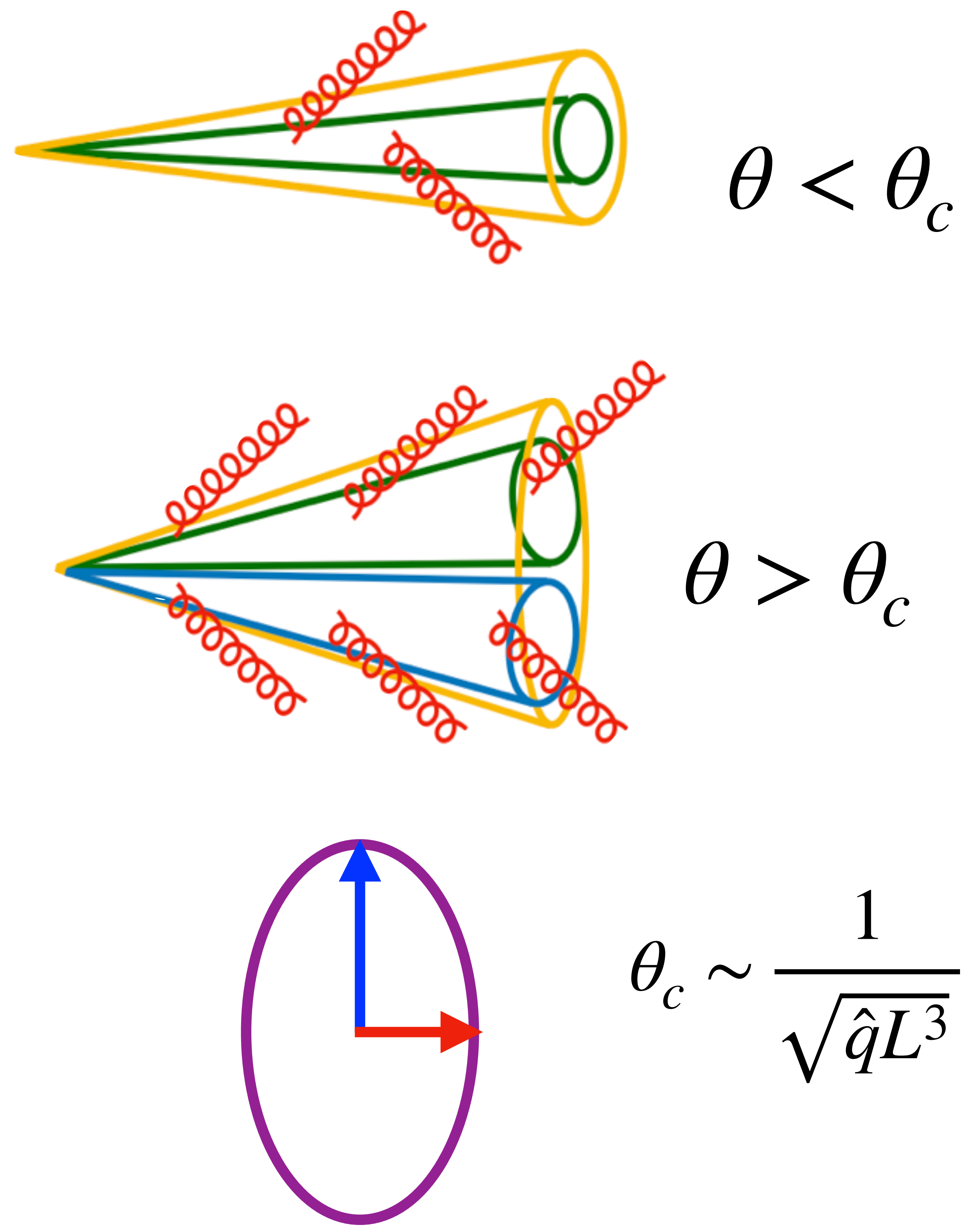




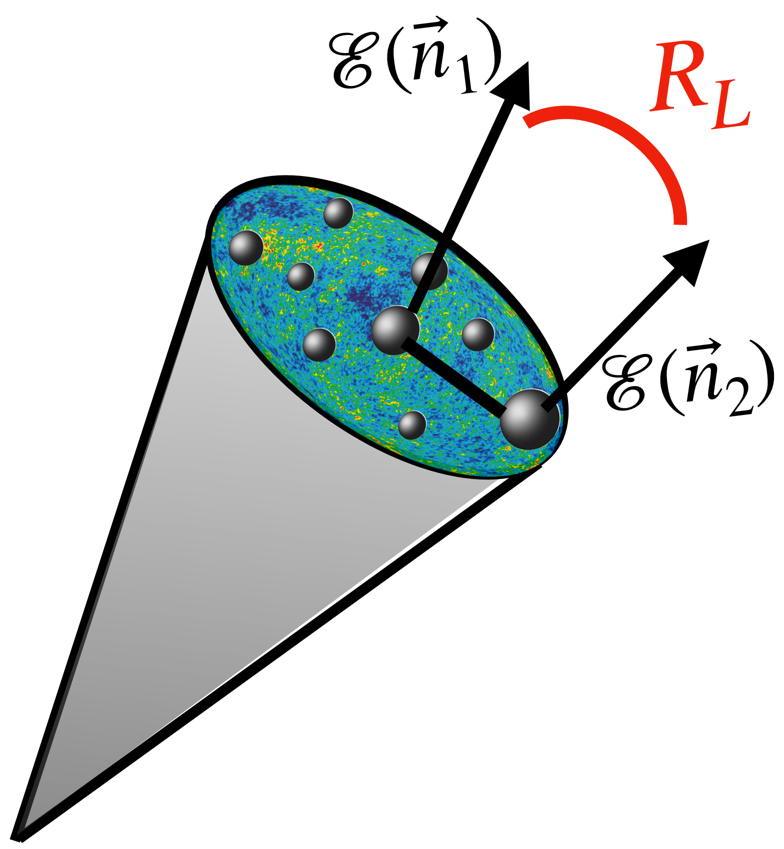


Energy correlators

Energy correlators

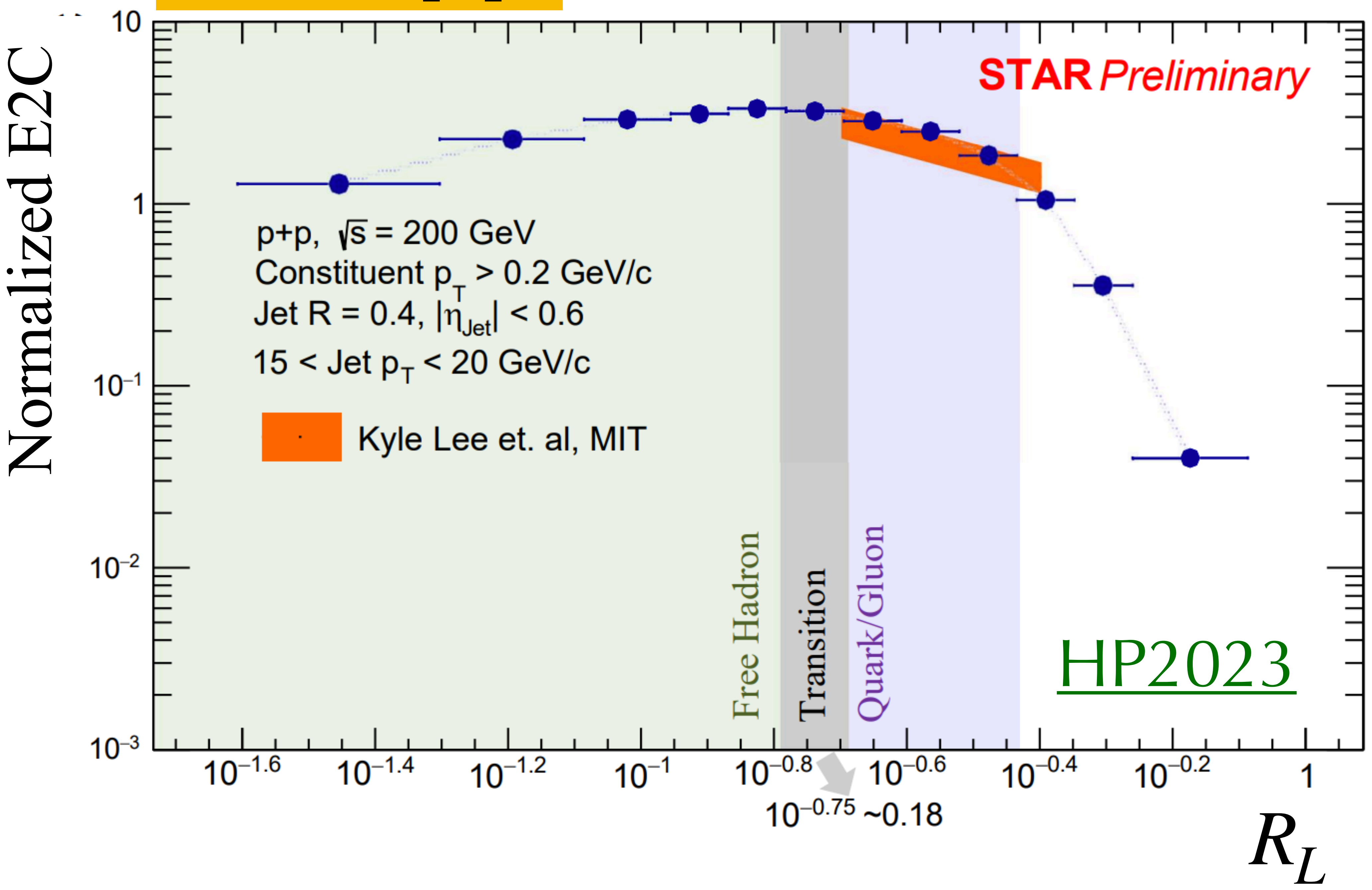
- Correlators of the **energy flux** $\langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\cdots\mathcal{E}(\vec{n}_k)\rangle$

$$\text{E2C} \propto \sum_{\text{jets}} \sum_{i,j} \frac{P_{T,i}P_{T,j}}{P_{T,\text{jet}}^2}\,\delta(R_{ij}-R_L)$$



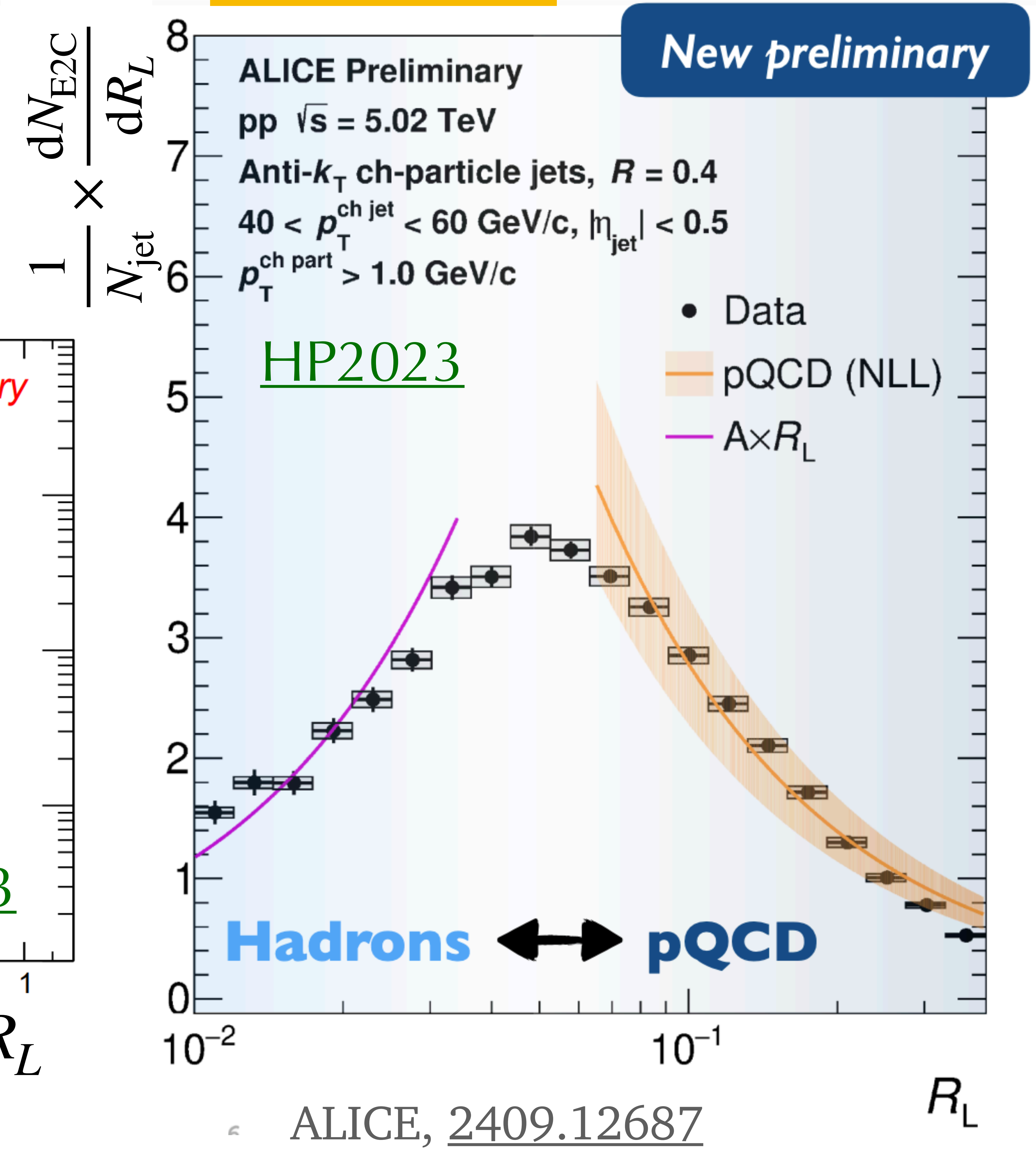
$$R_{ij}=\sqrt{\Delta\phi_{ij}^2+\Delta\eta_{ij}^2}$$

E2C in p-p



STAR, 2502.15925

E2C in p-p



ALICE, 2409.12687

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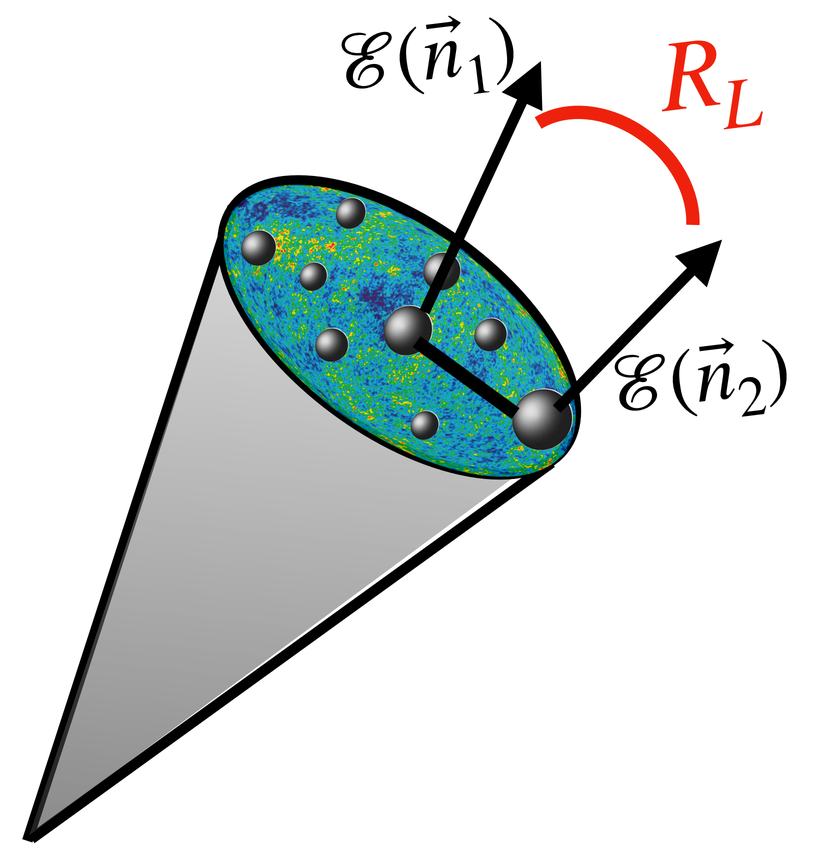
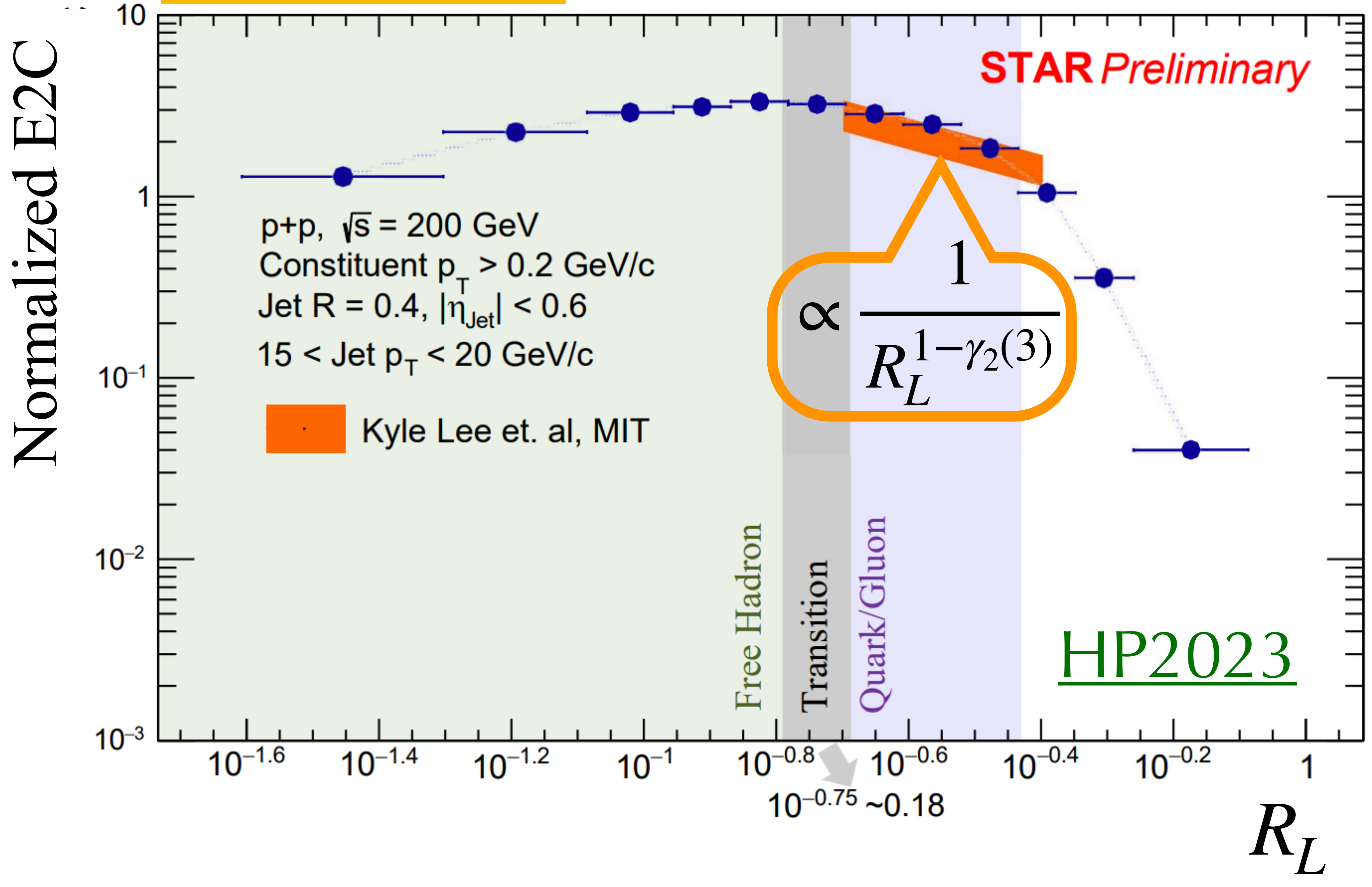


$$R_{ij} = \sqrt{\Delta\phi^2_{ij} + \Delta\eta^2_{ij}}$$

E2C in p-p



STAR, 2502.15925

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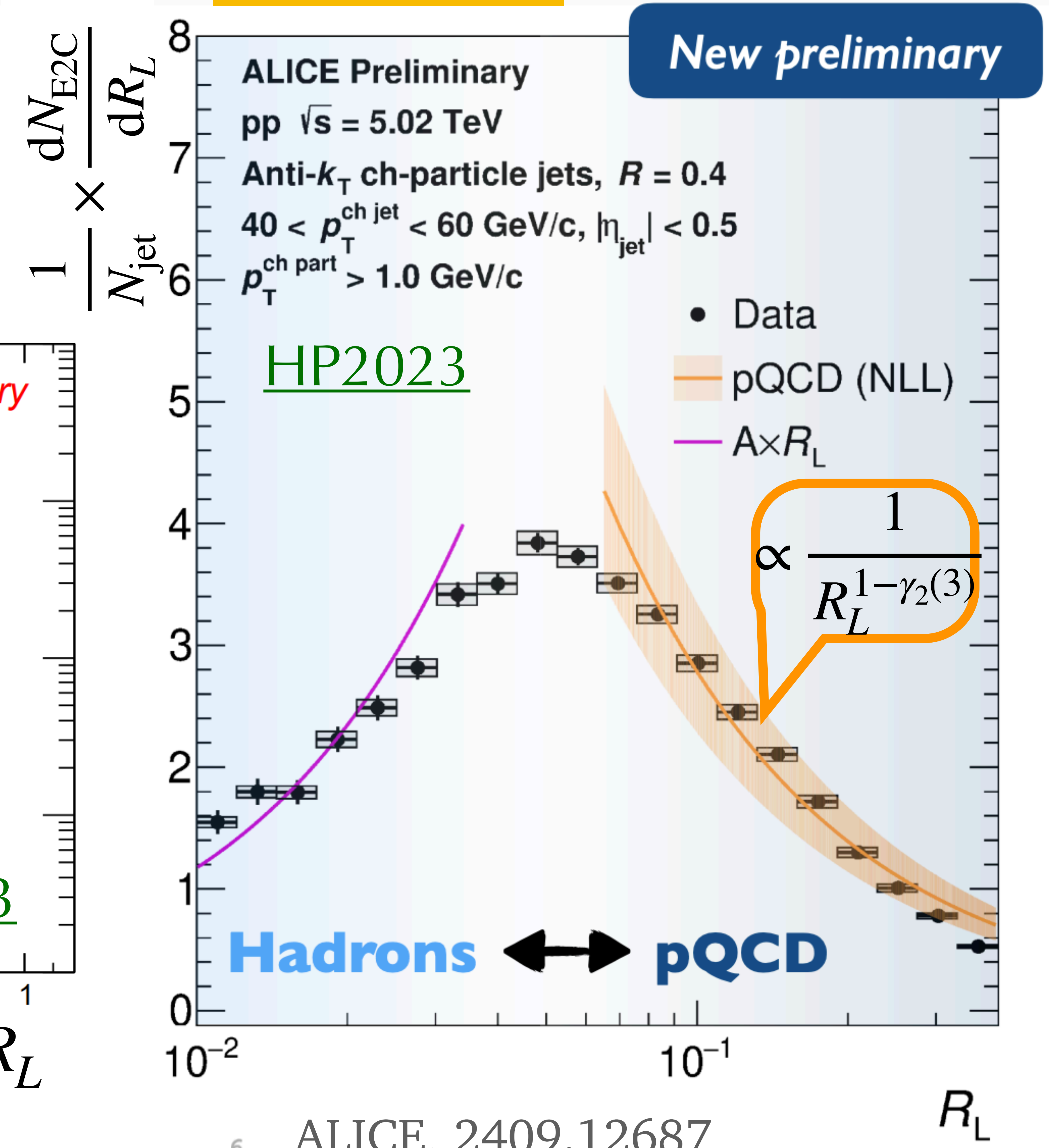
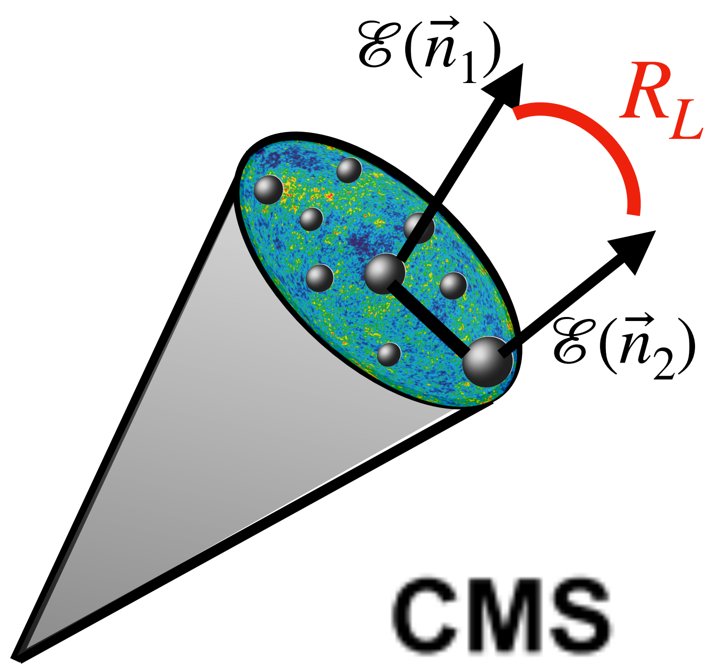


ALICE, 2409.12687

Universal scaling in p-p



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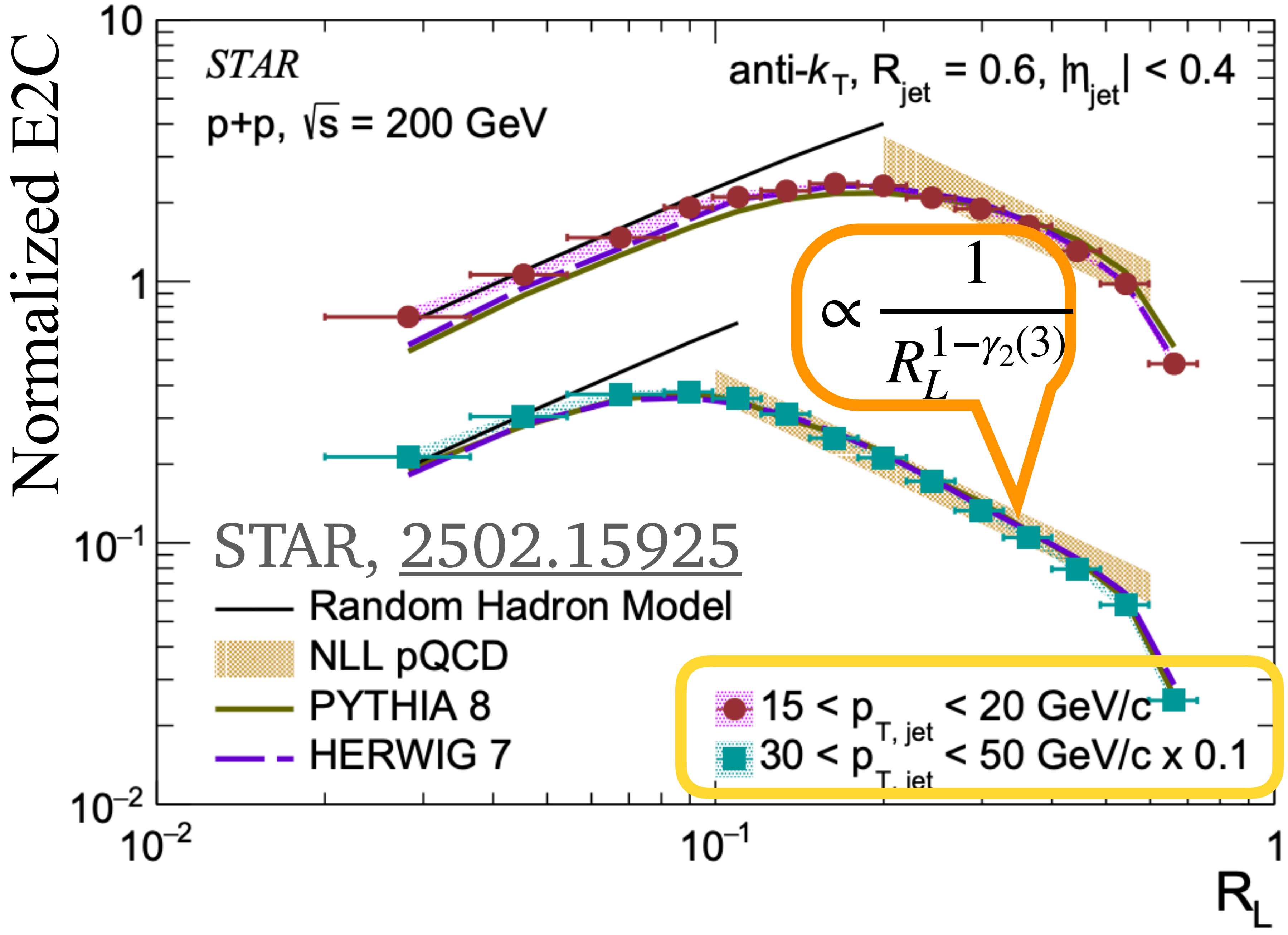

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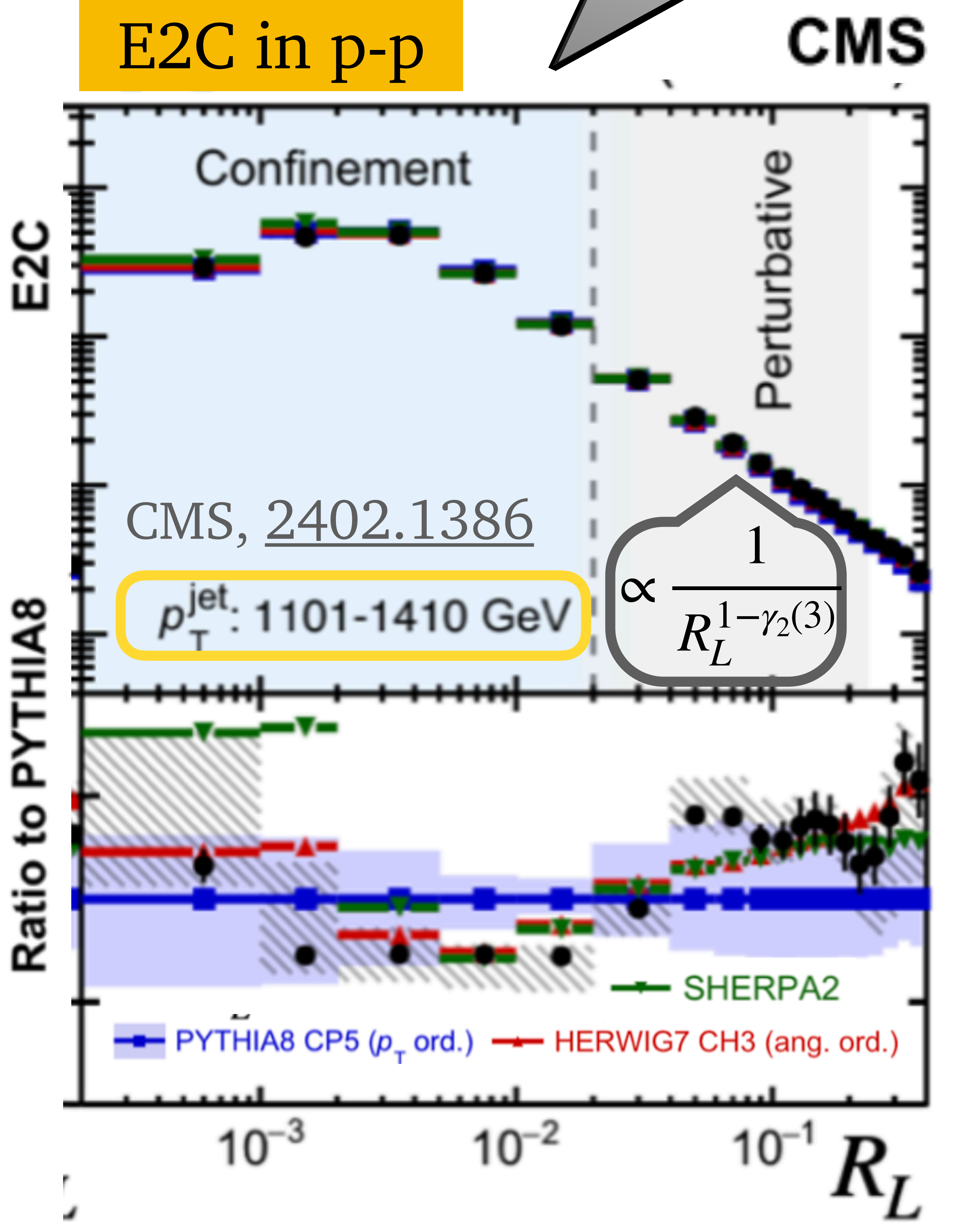

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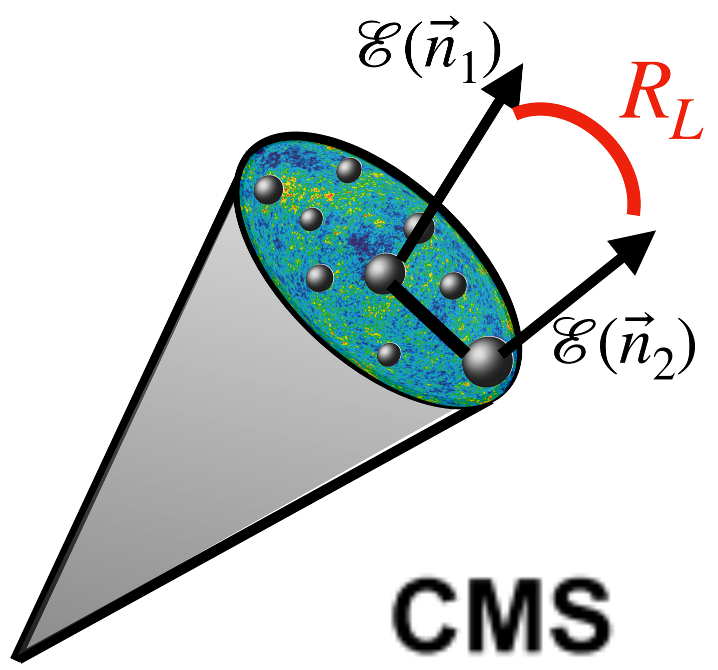


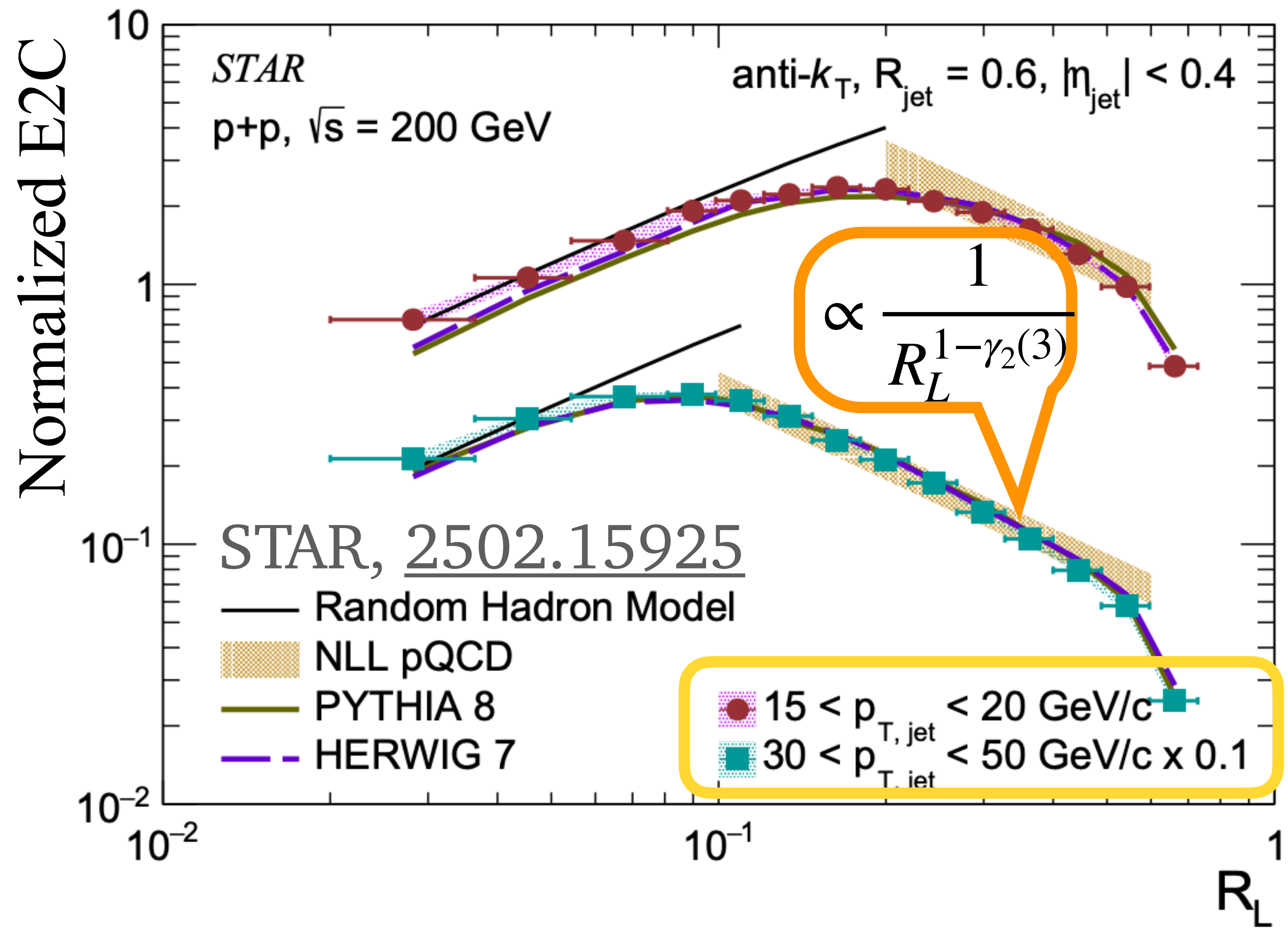
Hoffman, Maldacena, 0803.1467

Chen, Moult, Sandor, Zhu, 2202.04085

Light-Ray OPE

$$\mathscr{E}(\vec{n}_1)\mathscr{E}(\vec{n}_2) \xrightarrow{\vec{n}_1 \to \vec{n}_2} \sum_i \mathscr{C}_i R_L^{\tau_i - 4 + \hat{\gamma}_i(3)} \mathbb{O}_i^{[J=3]}(\vec{n}_1)$$

E2C in p-p



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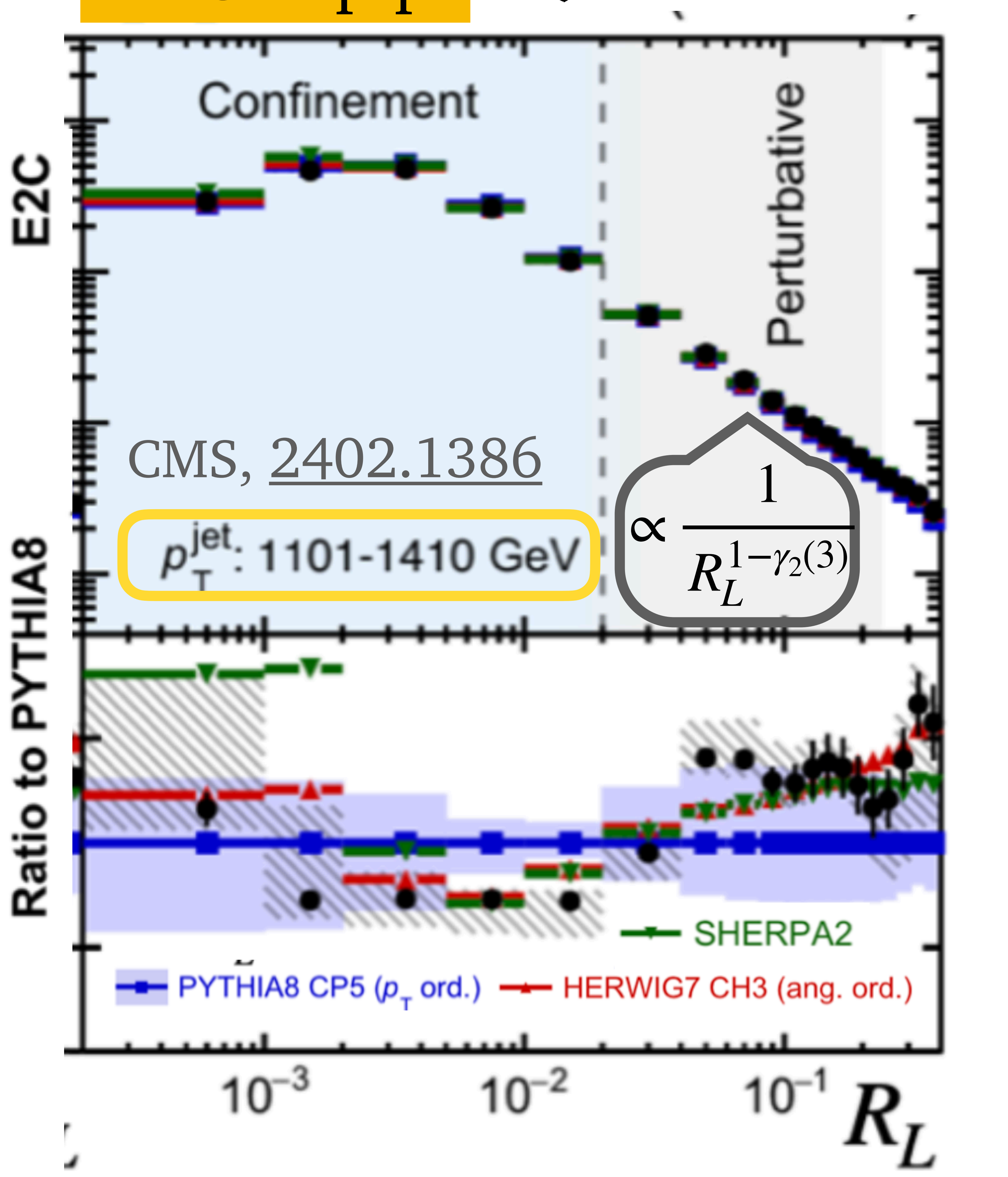

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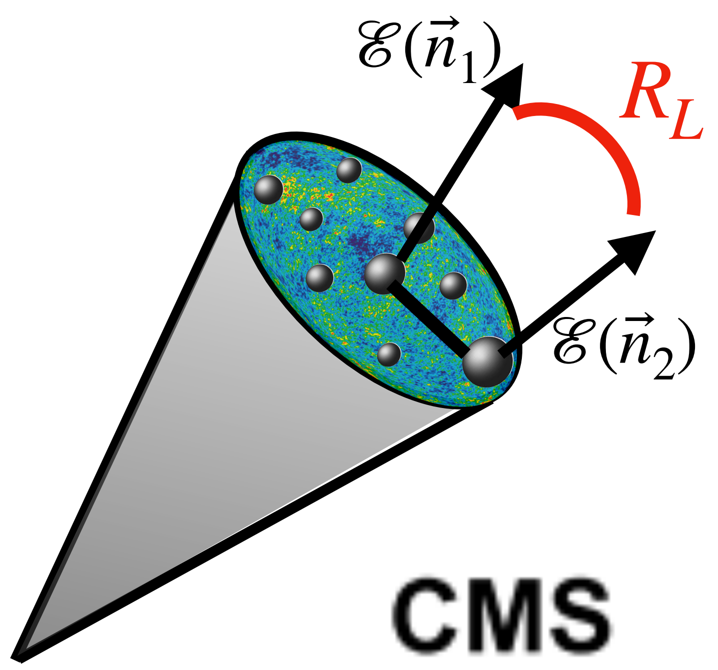

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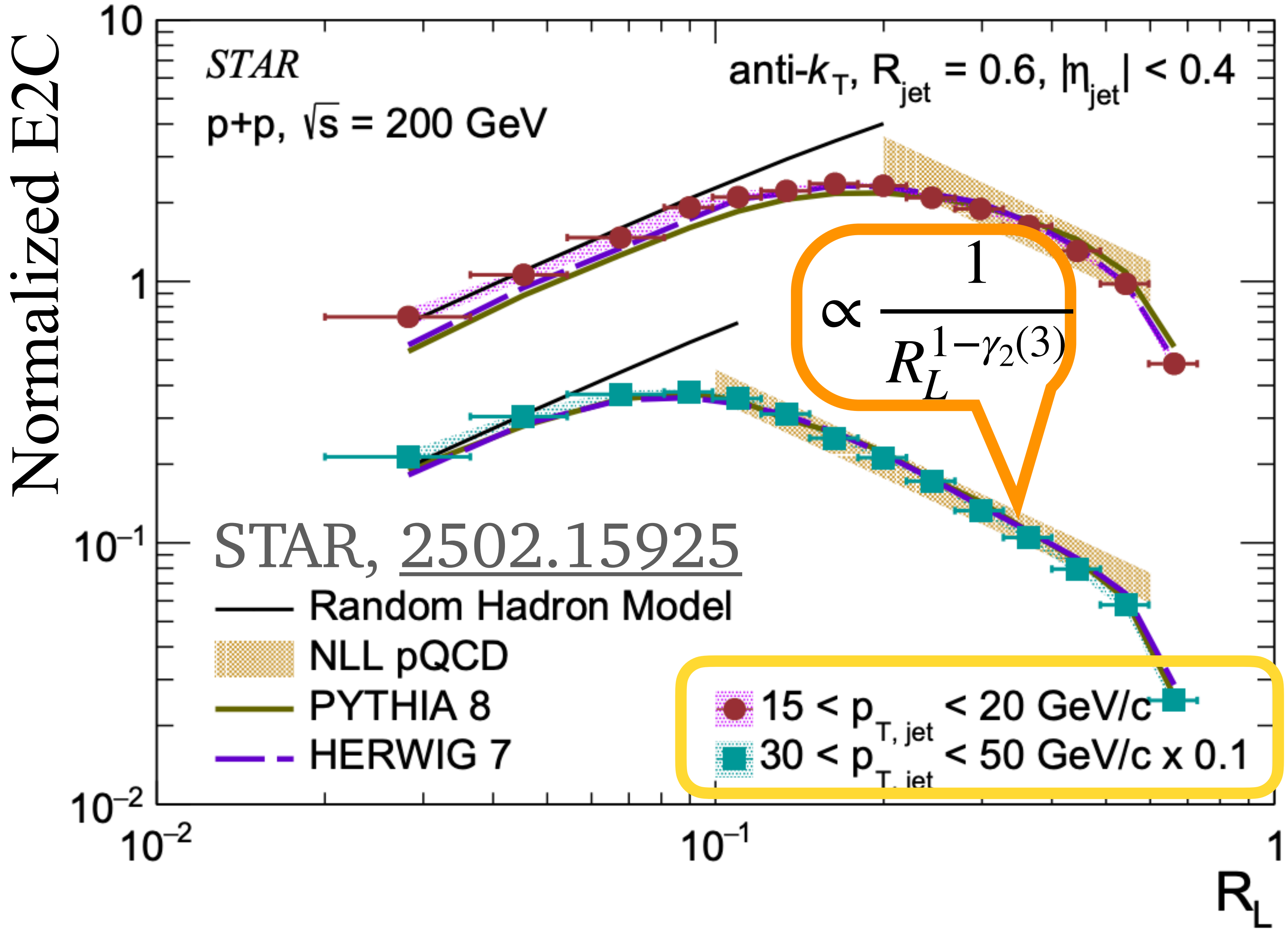
Leading term dominates!

$$\frac{d\Sigma_{E2C}}{dR_L} \propto \frac{1}{R_L^{1-\gamma_2(3)}}$$

E2C in p-p



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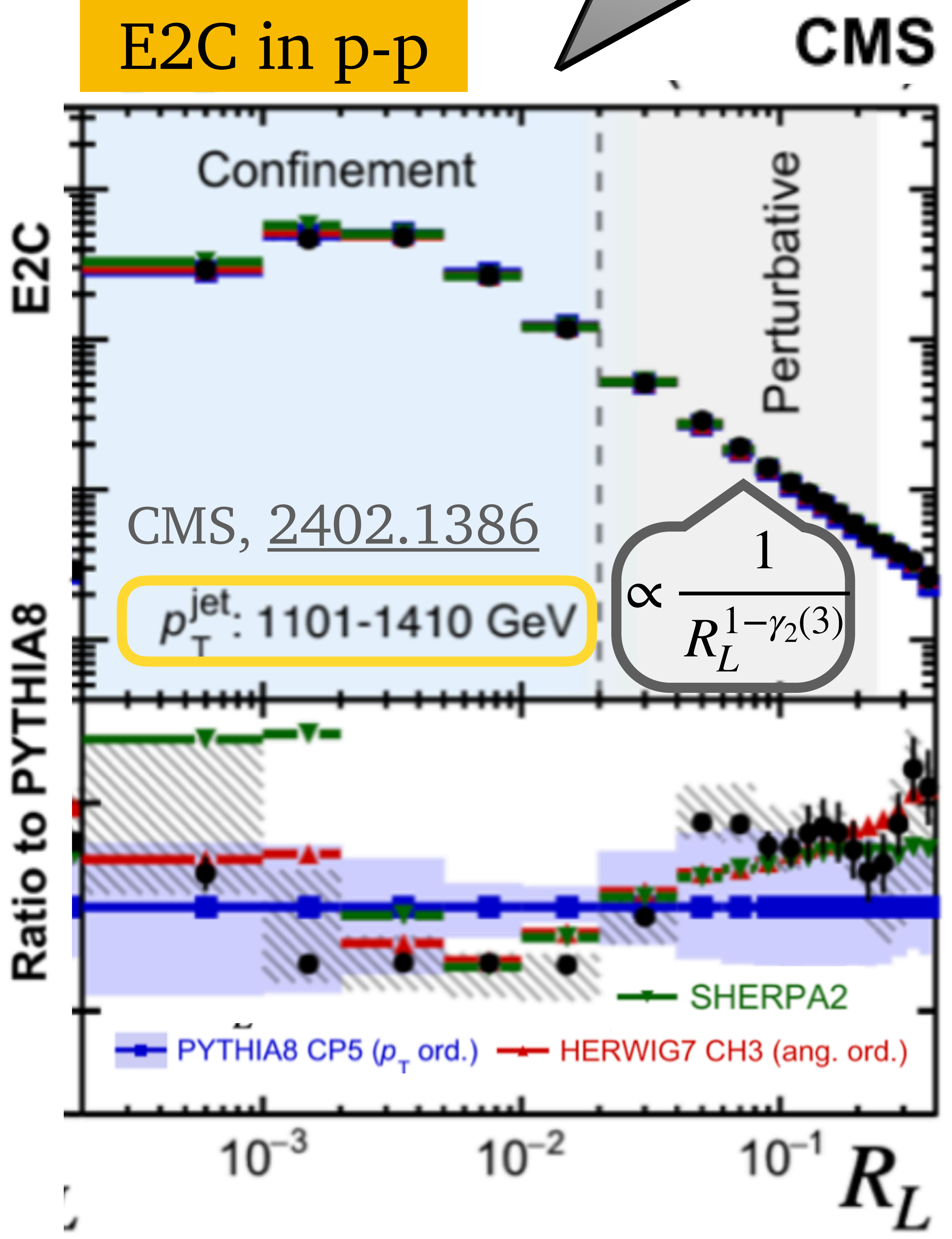

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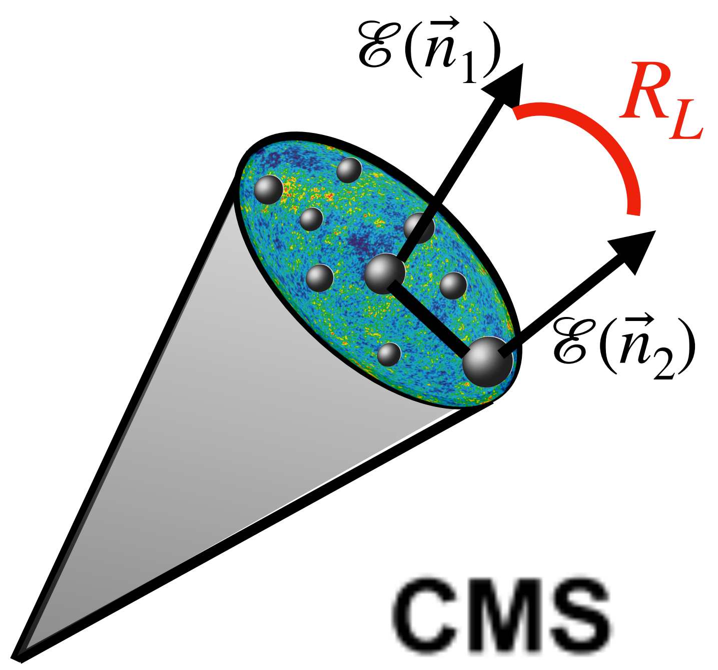

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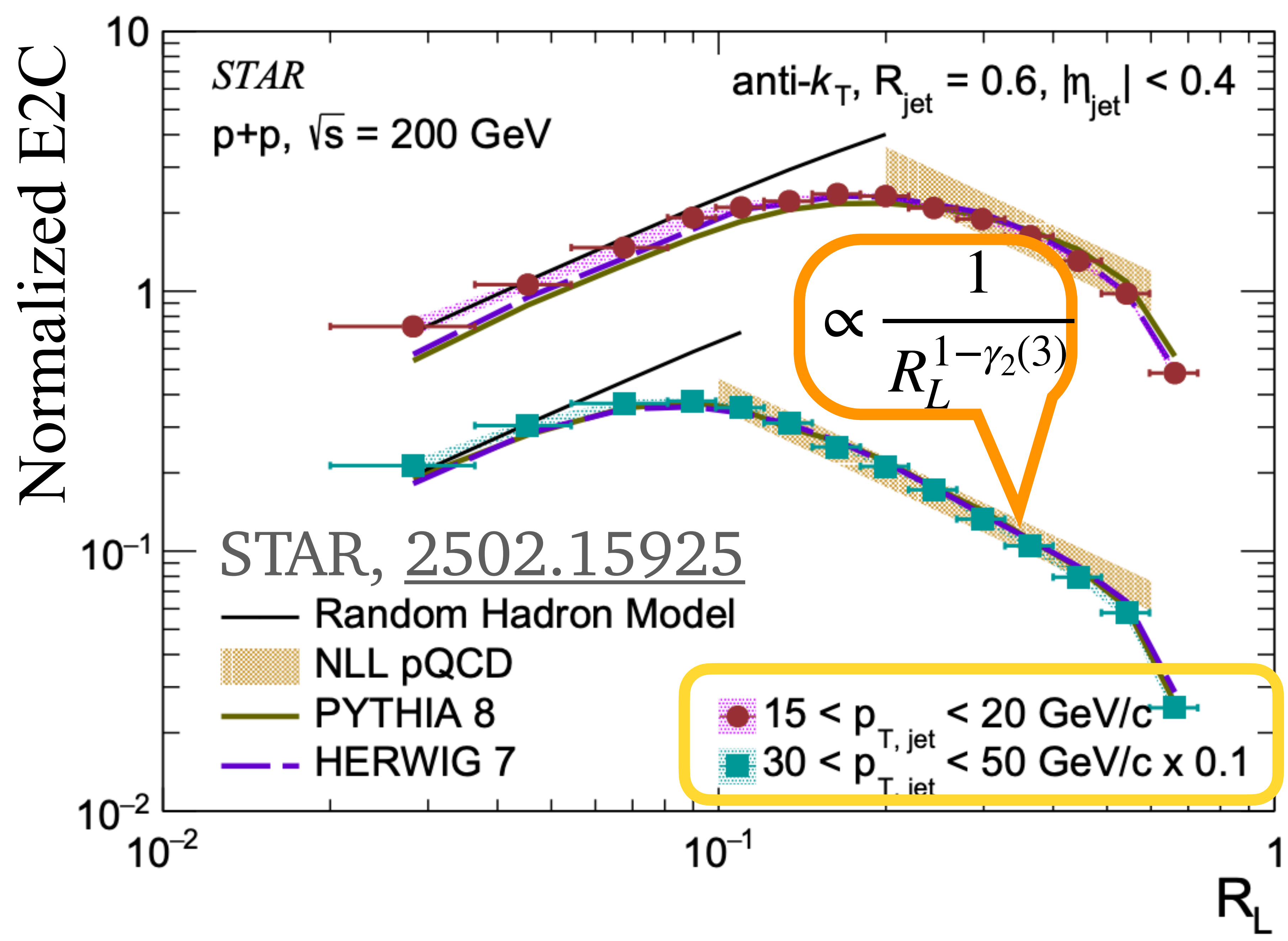
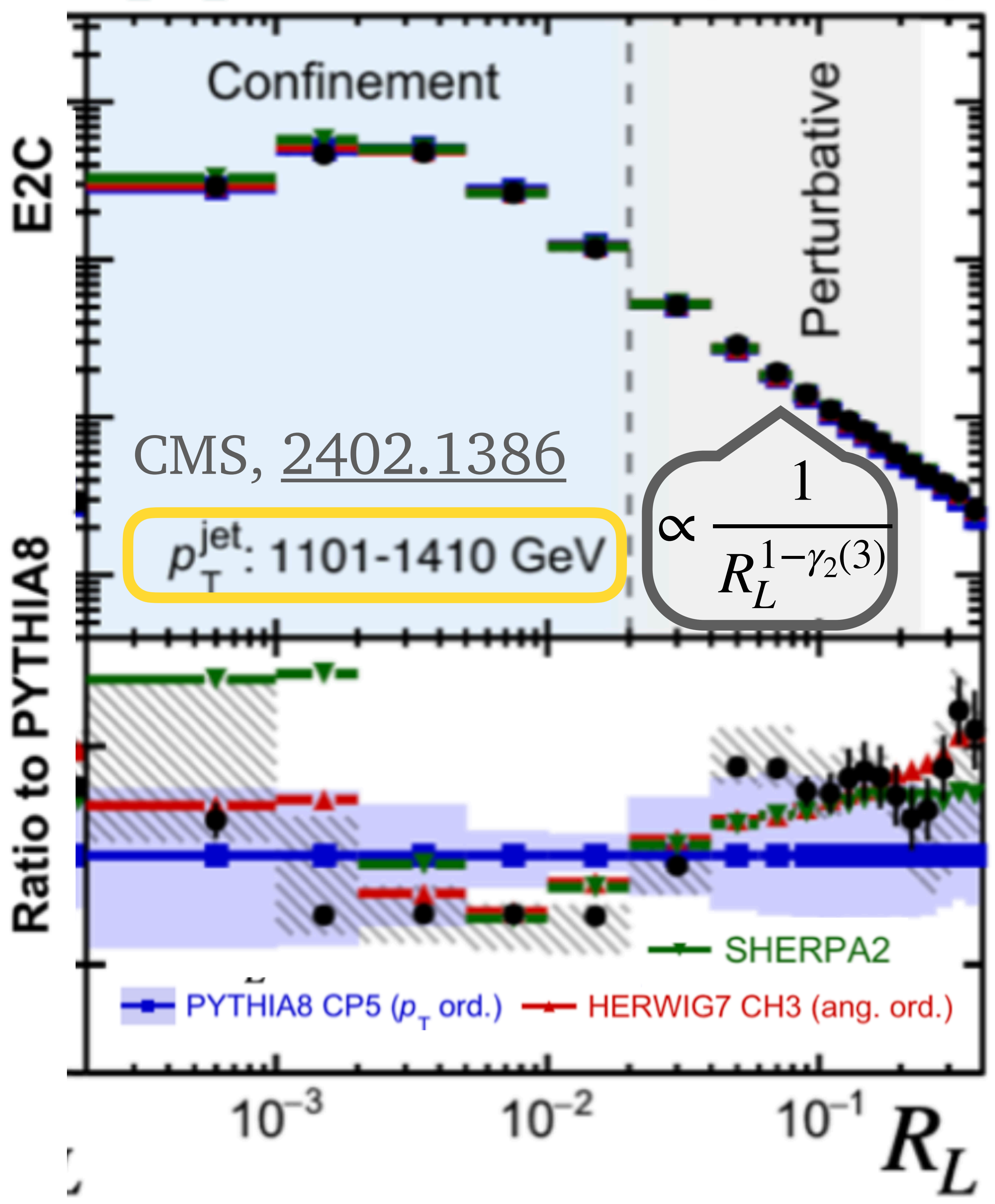
E2C in p-p



Leading term dominates!

$$\frac{d\Sigma_{E2C}}{dR_L} \propto \frac{1}{R_L^{1-\gamma_2(3)}}$$

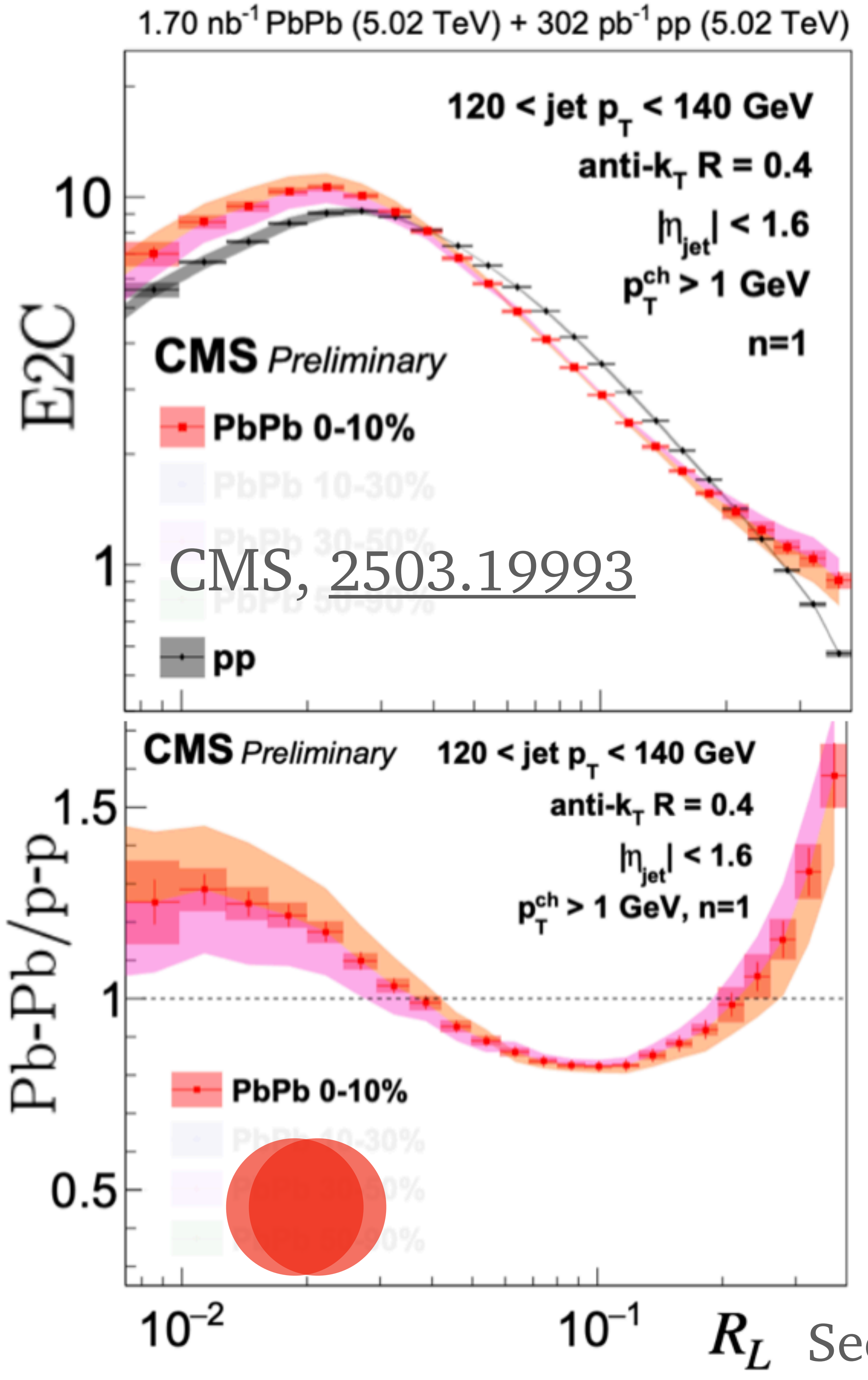
E2C in p-p



Light-ray OPE scaling observed by STAR, ALICE, and CMS in jets **from 15 GeV to ~2TeV!**

E2C in PbPb

E2C in inclusive jets

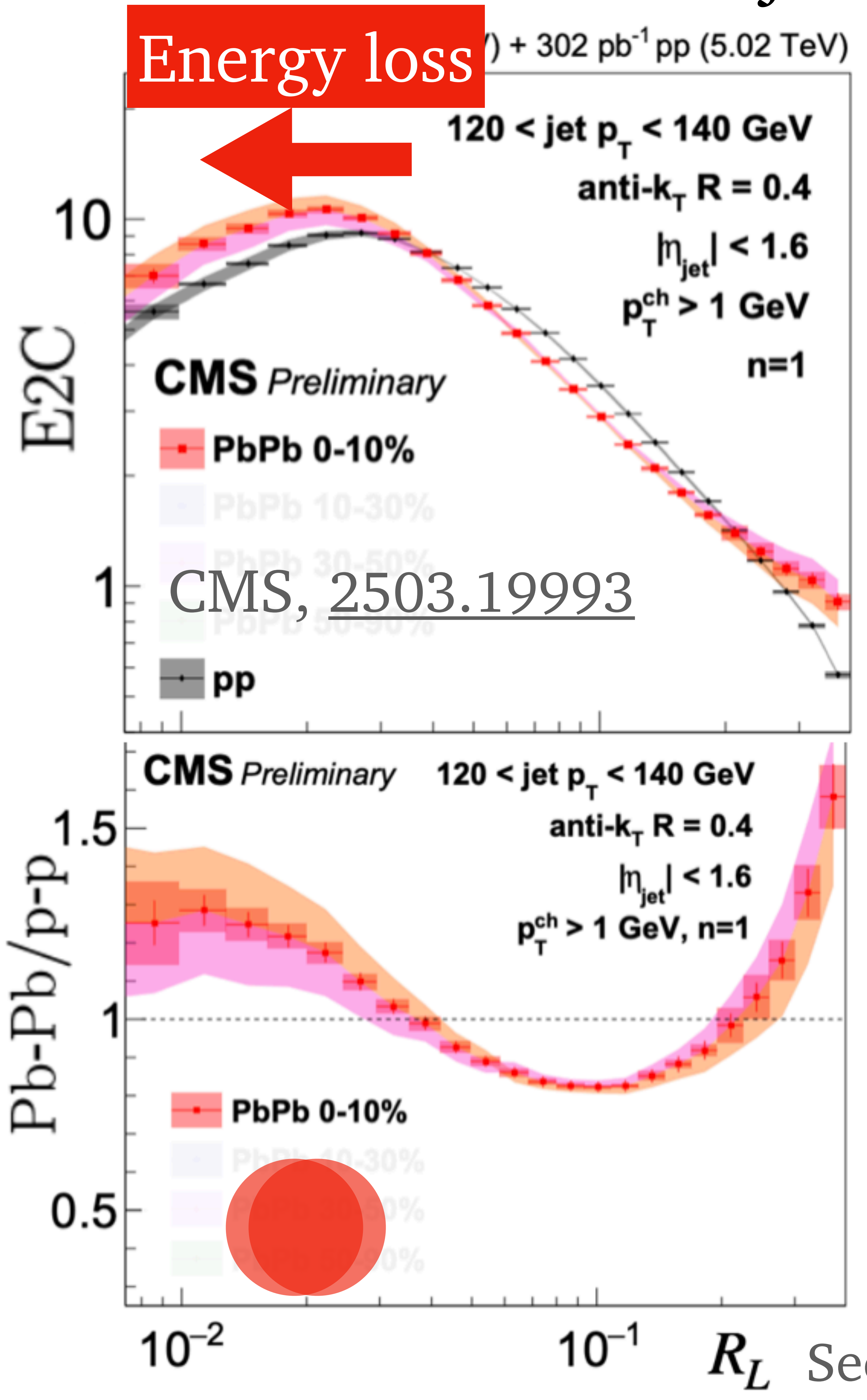


CMS, 2503.19993

See also ALICE PbPb QM2025

E2C in PbPb

E2C in inclusive jets



CMS, 2503.19993

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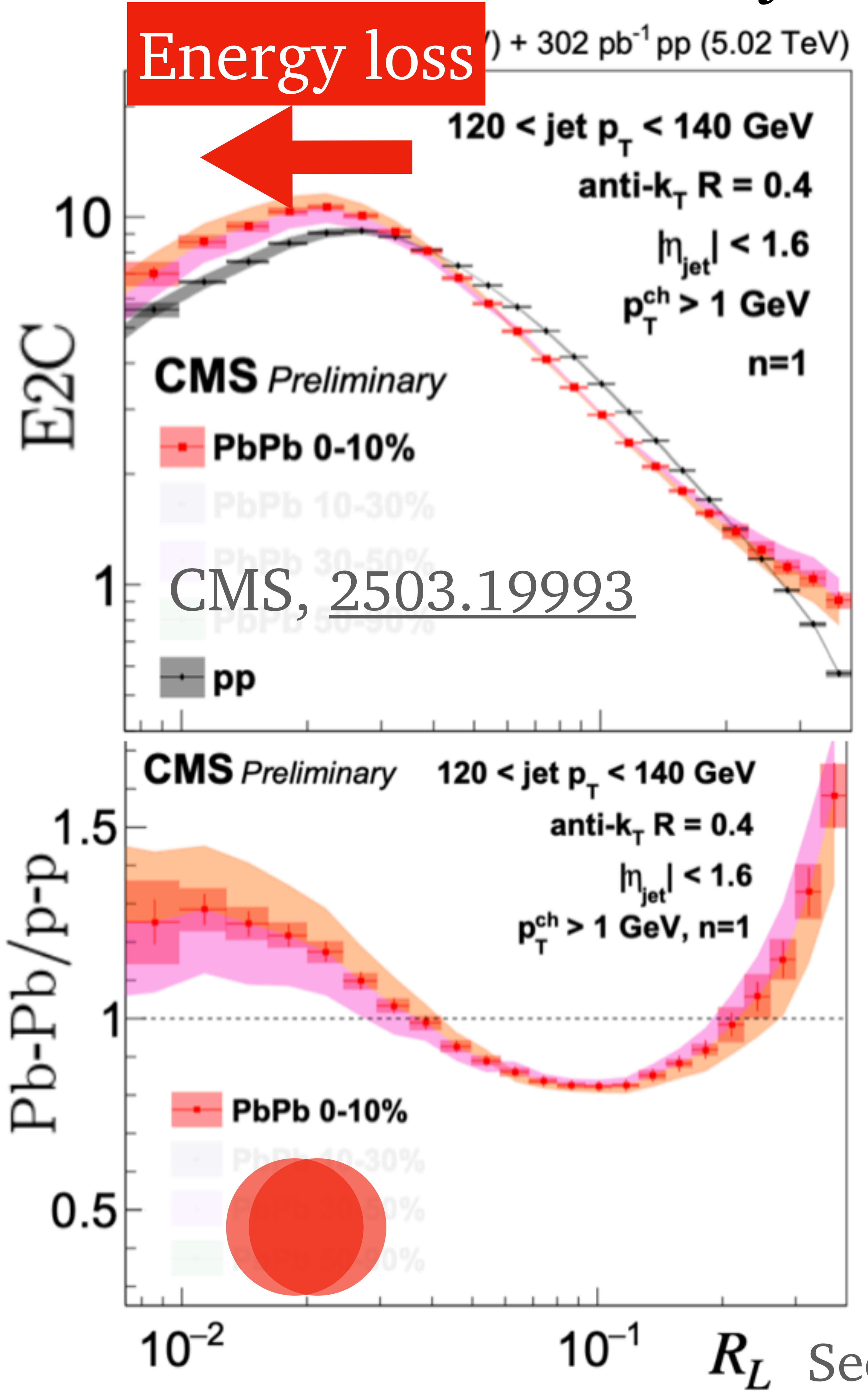
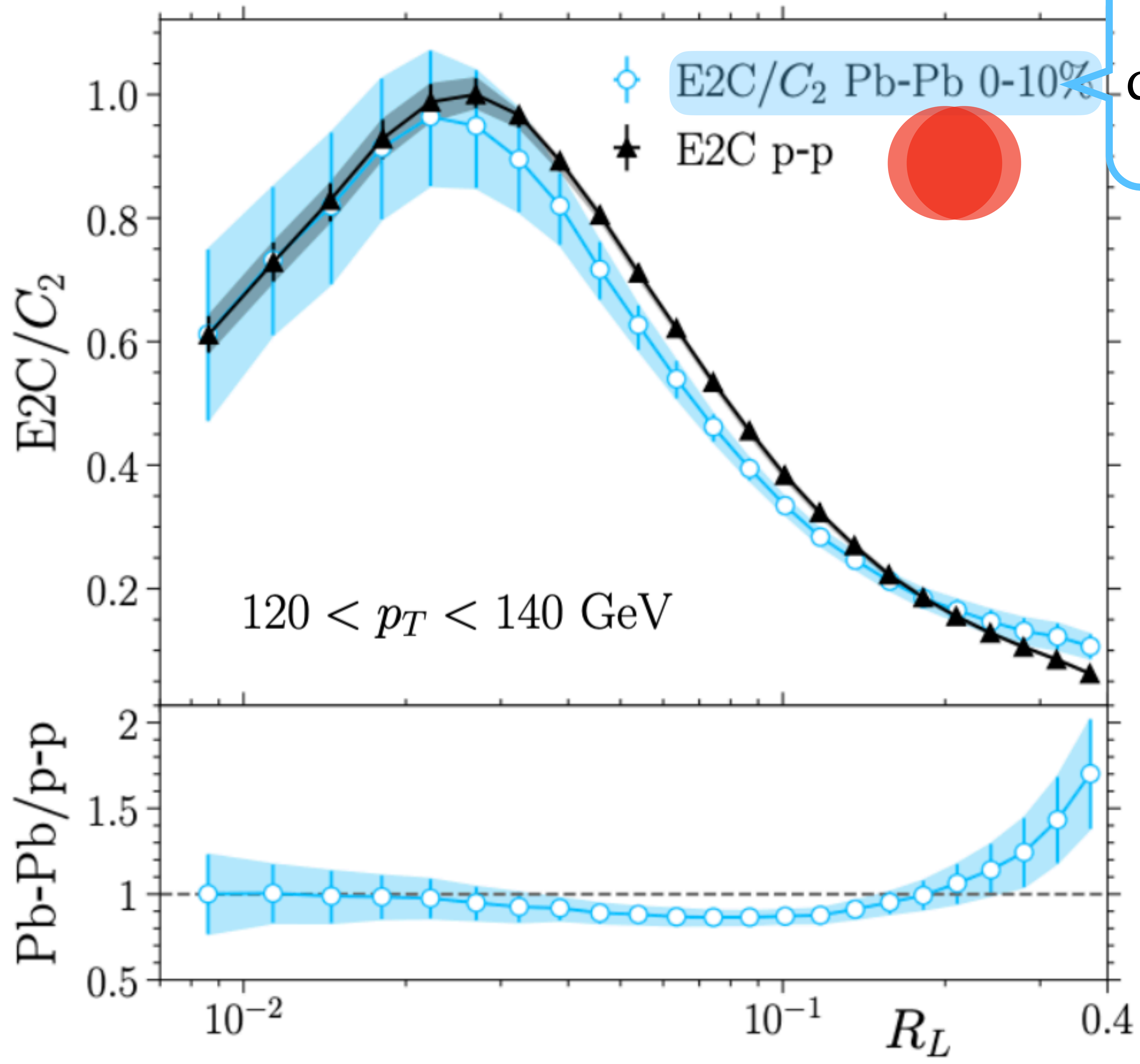
E2C in PbPb

CA, Holguin, Kunnawalkam Elayavalli, Viinikainen, 2409.07514, 2409.07526

E2C in inclusive jets



Unbiased E2C in inclusive jets



C_2 can be directly obtained from the E2C!

C_2 **corrects** for the **shift** in the **hard scale**

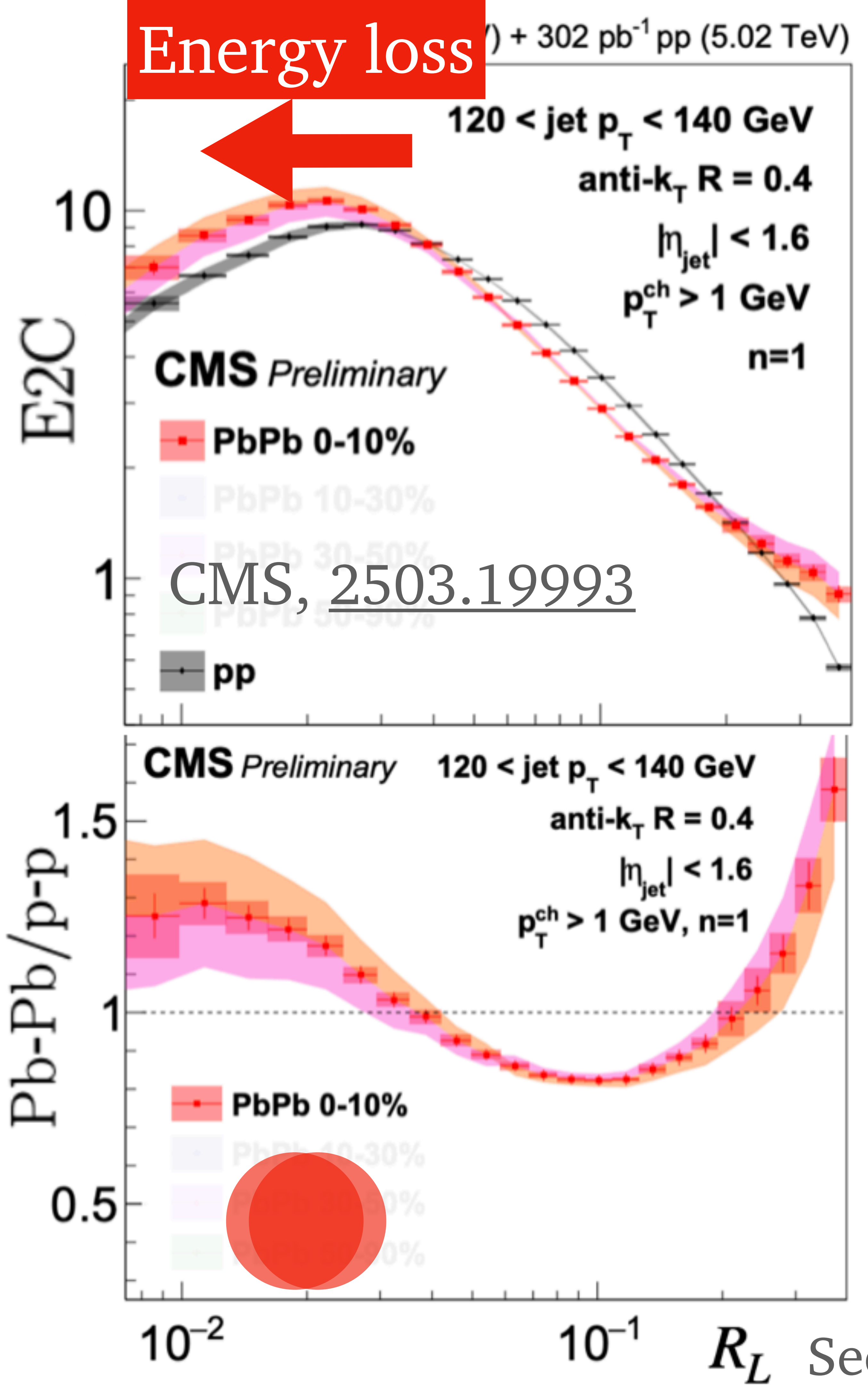
See also ALICE PbPb QM2025

E2C in PbPb

CA, Holguin, Kunnawalkam Elayavalli, Viinikainen, 2409.07514, 2409.07526

E2C in inclusive jets

Energy loss



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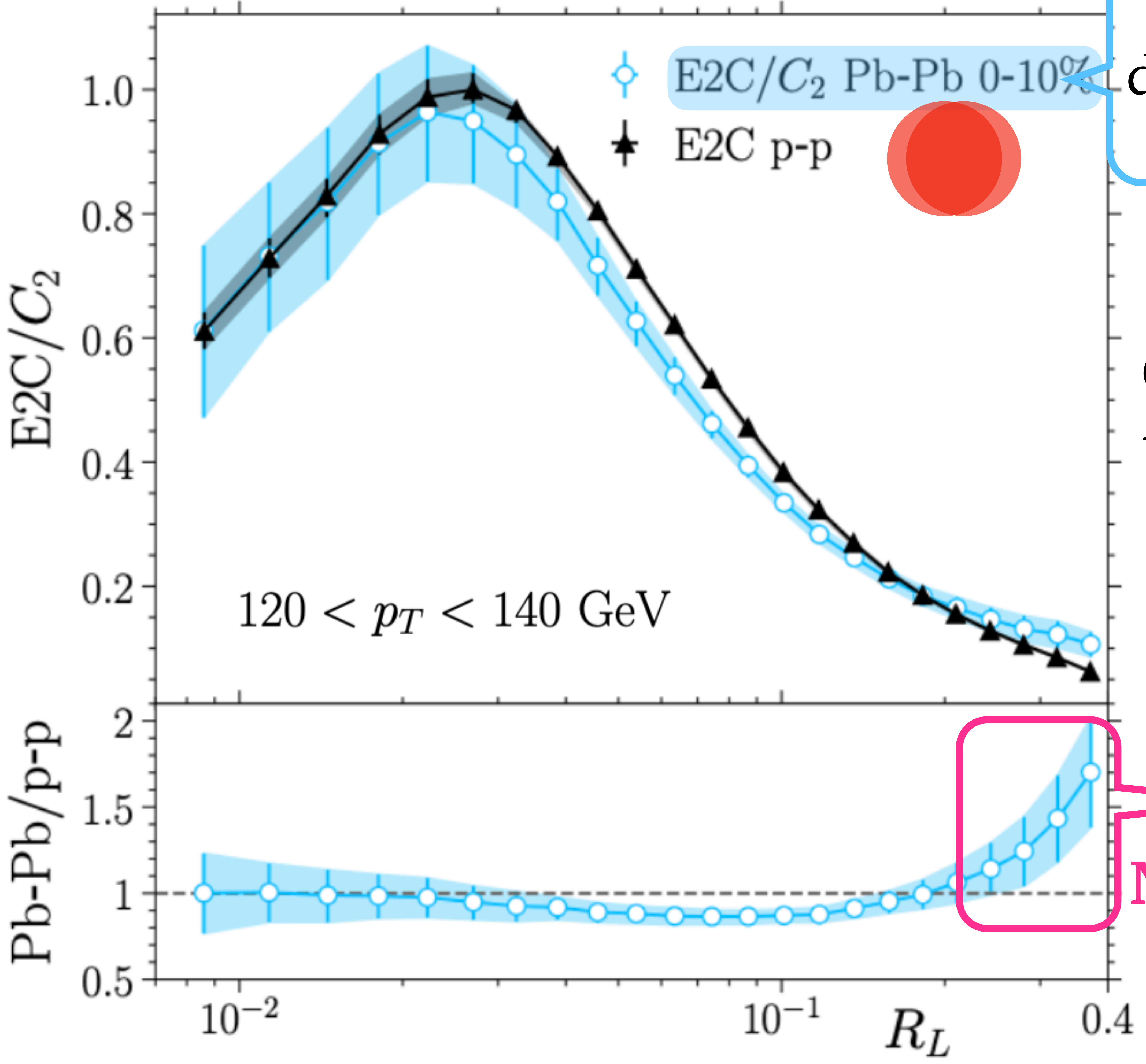

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C_2 **corrects** for the **shift** in the **hard scale**

?

Not energy loss!!

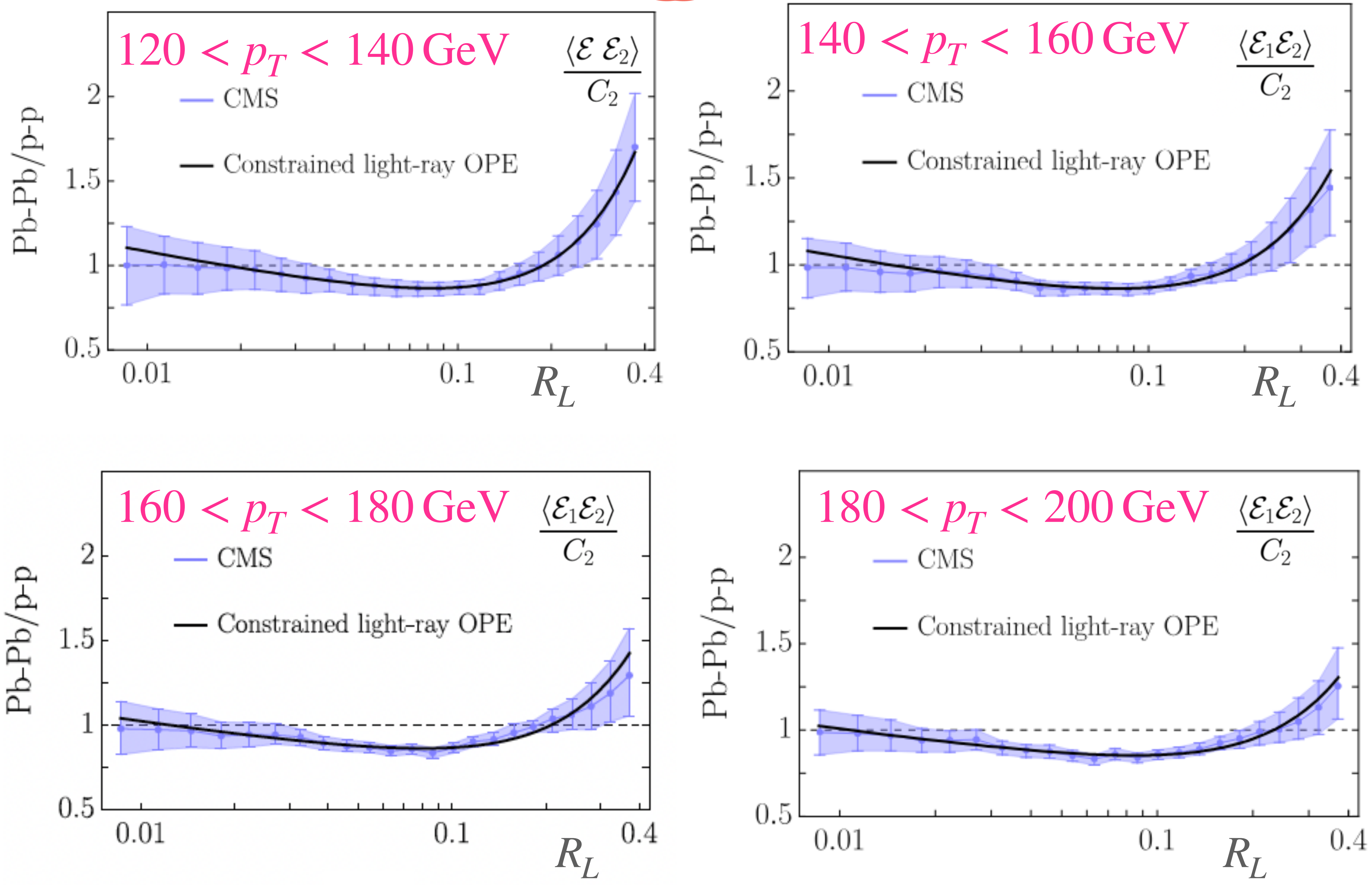
See also ALICE PbPb QM2025

Light-ray OPE in AA

CA, Dominguez, Holguin, Marquet, and Moult, 2411.15298

Unbiased E2C

Pb-Pb $\sqrt{s_{\rm NN}}$ = 5.02 TeV 0-10 %



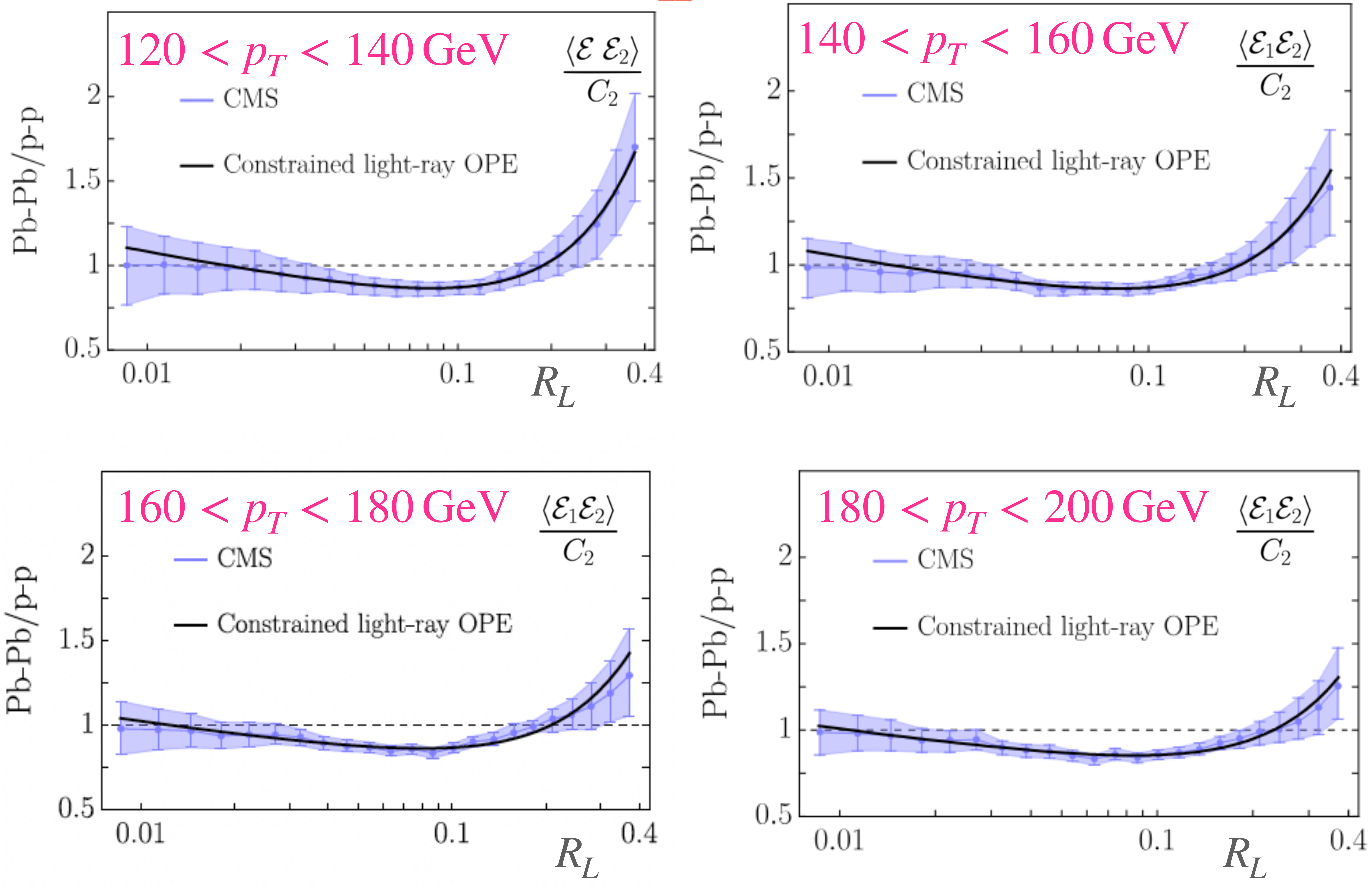
$$\mathscr{E}(\vec{n}_1)\mathscr{E}(\vec{n}_2) \xrightarrow{\vec{n}_1 \to \vec{n}_2} \sum_i \mathscr{C}_i R_L^{\tau_i - 4} \mathbb{O}_i^{[J=3]}(\vec{n}_1)$$

Light-ray OPE in AA

CA, Dominguez, Holguin, Marquet, and Moult, 2411.15298

Unbiased E2C

Pb-Pb $\sqrt{s_{\rm NN}} = 5.02$ TeV 0-10 %



$$\mathscr{E}(\vec{n}_1)\mathscr{E}(\vec{n}_2) \xrightarrow{\vec{n}_1\to\vec{n}_2} \sum_i \mathscr{C}_i R_L^{\tau_i-4}\, \mathbb{O}_i^{[J=3]}(\vec{n}_1)$$

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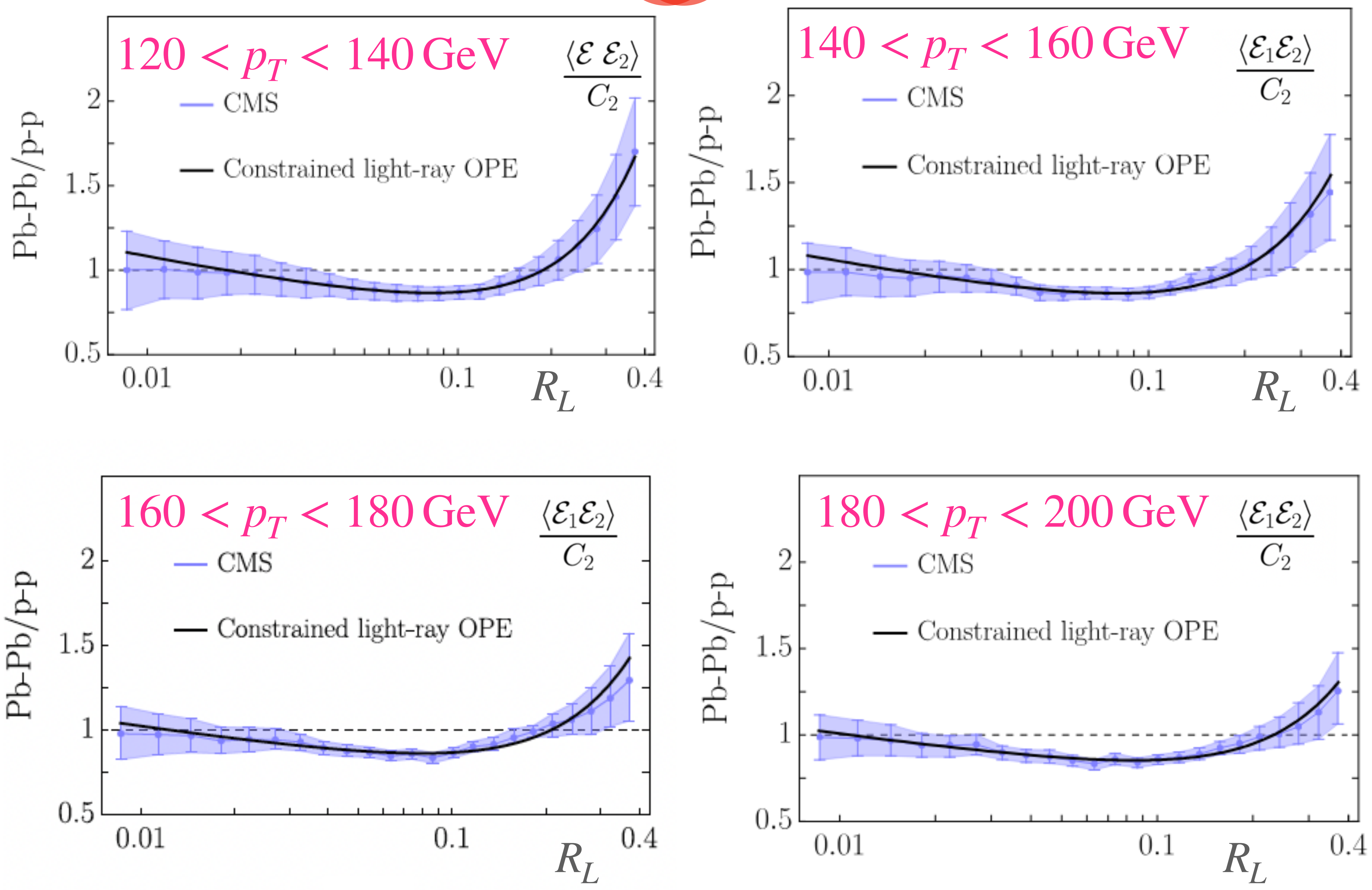


$$\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \xrightarrow{\vec{n}_1 \to \vec{n}_2} \sum_i \mathcal{C}_i\, R_L^{\tau_i - 4}\, \mathbb{O}_i^{[J=3]}(\vec{n}_1)$$

$$\mathrm{E2C}^{\text{Pb-Pb}} \sim 1/R_L^2 + a \qquad \mathrm{E2C}^{\text{p-p}} \sim 1/R_L^2$$

$$\frac{\mathrm{E2C}^{\text{Pb-Pb}}}{\mathrm{E2C}^{\text{p-p}}} \sim 1 + aR_L^2$$

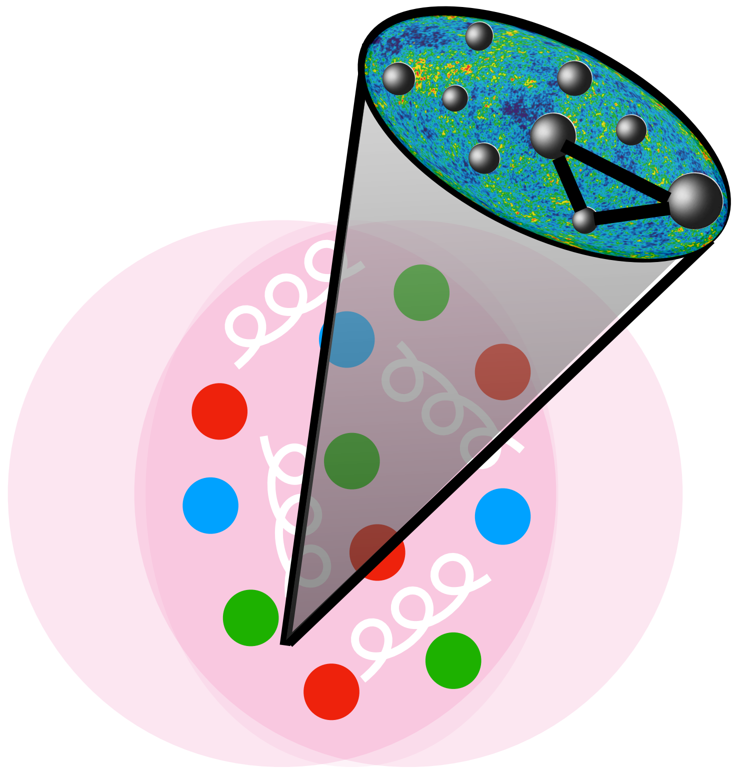
$$\text{Pb-Pb/p-p} = \frac{M_2\, R_L^{\gamma_N} + \left(\frac{p_{T,0}}{p_T}\right)^2 M_4(p_{T,0})\, R_L^2}{R_L^{\gamma}}$$

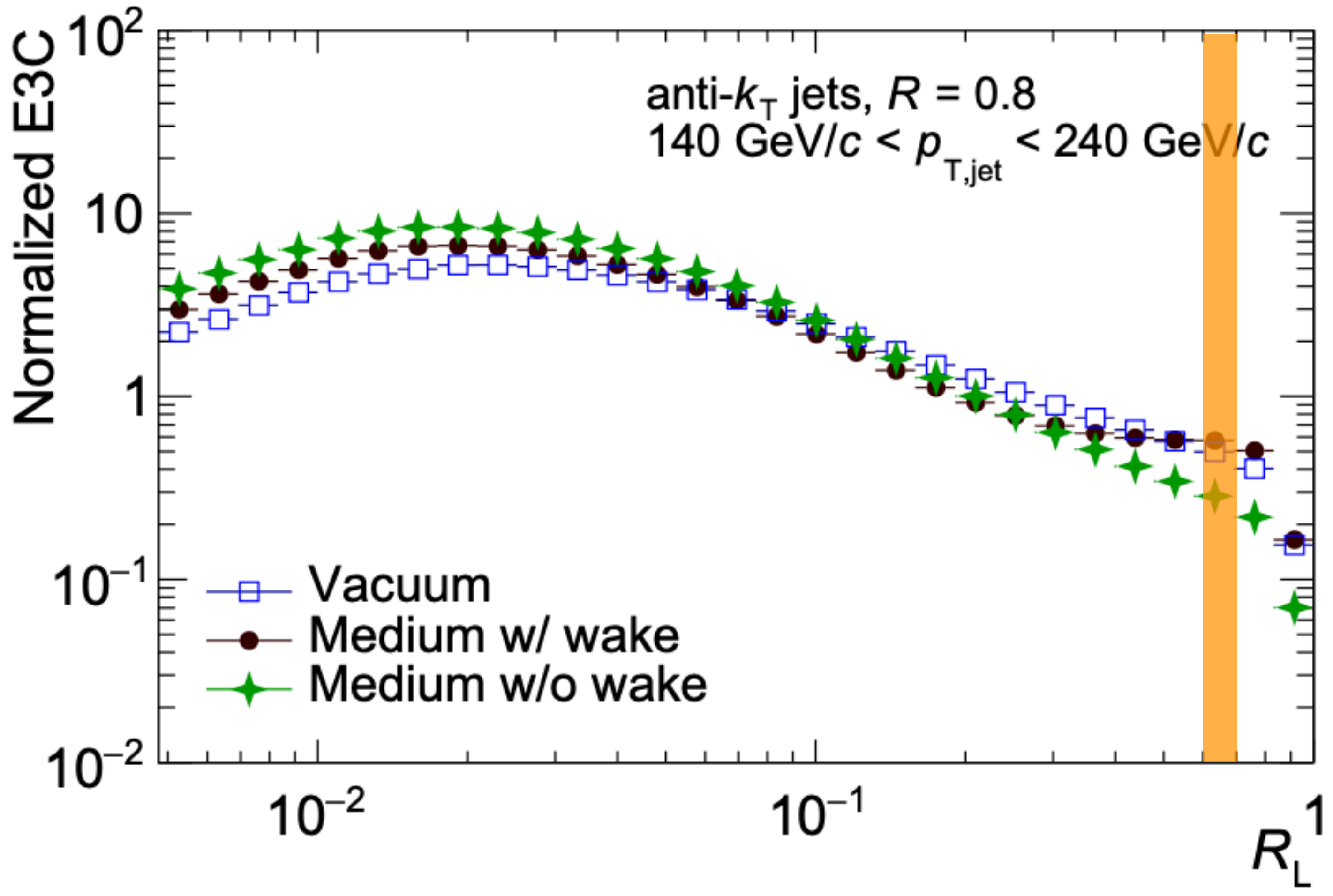
Behavior of the **enhancement** with the **jet** p_T predicted by the light-ray **OPE**

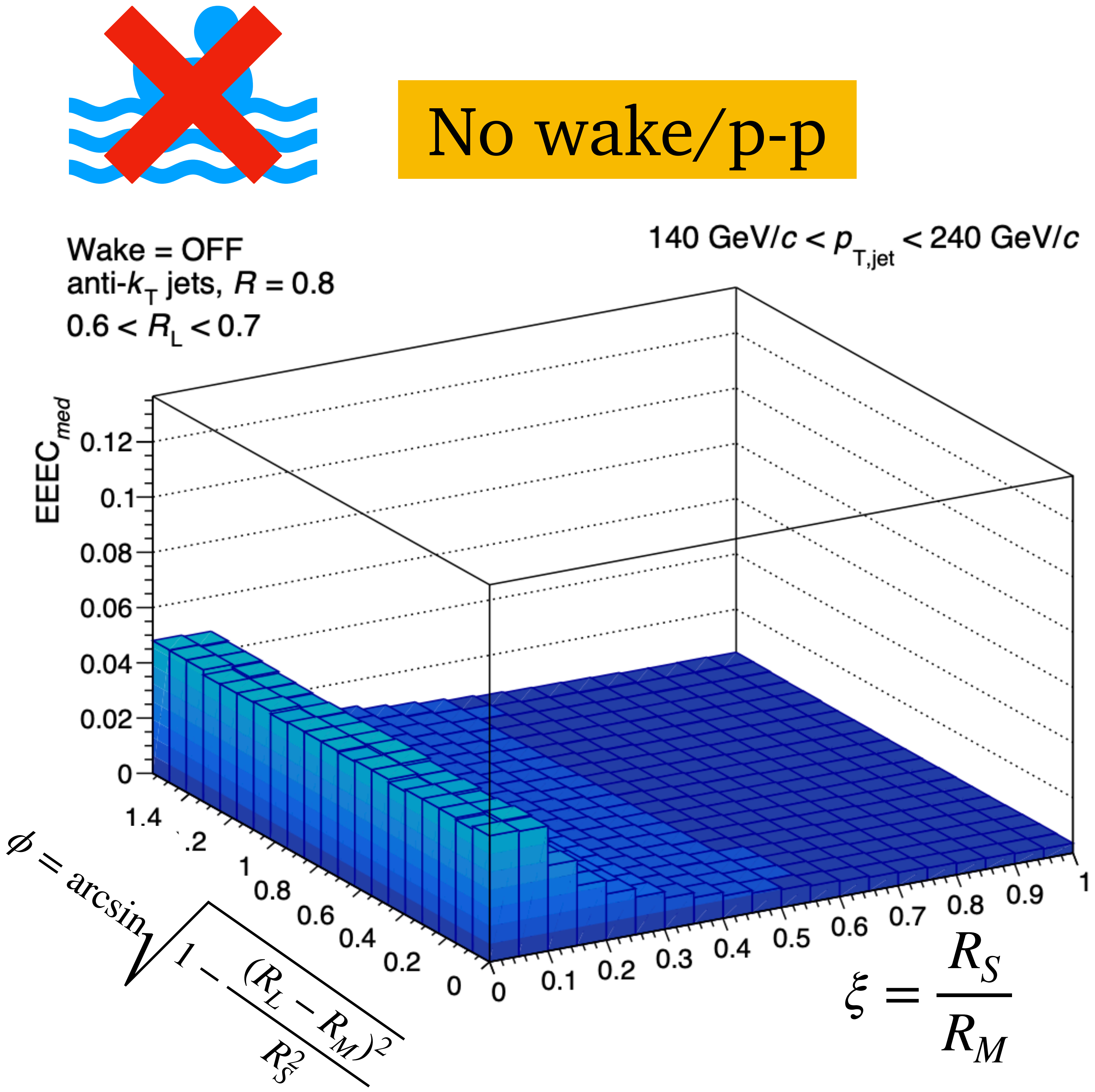
E3C in heavy-ions

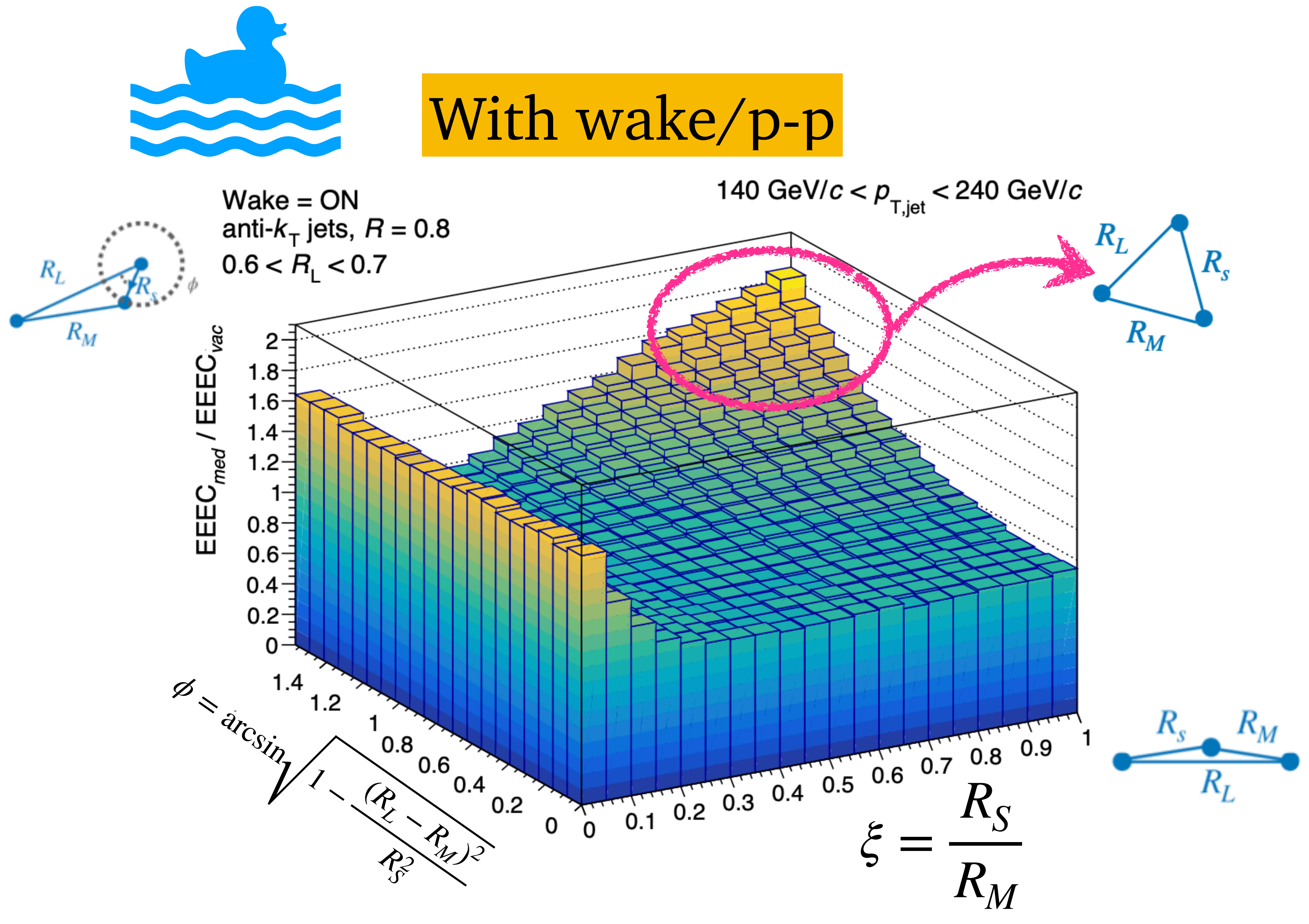
- First studies of the shape of the E3C

Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal, 2407.13818





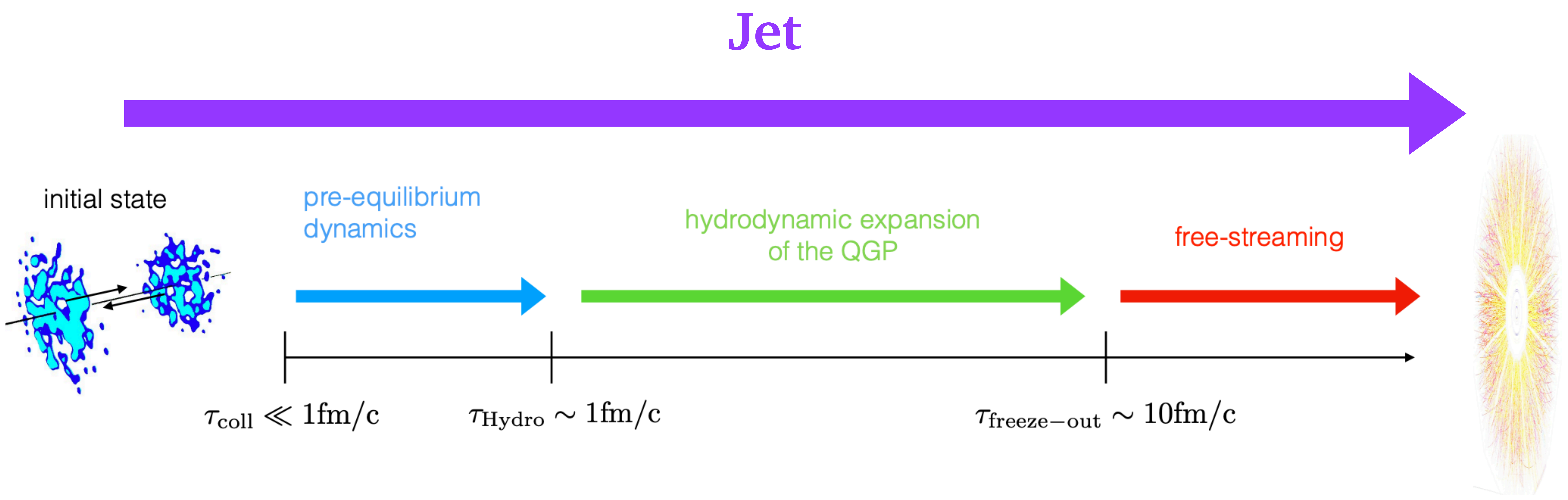




See also Barata, Moult, Sadofyev and Silva 2503.13603

Jets are extended objects: ideal to **probe the medium at different times** and **resolution scales**

Jets are extended objects: ideal to **probe the medium at <u>different times</u>** and **resolution scales**

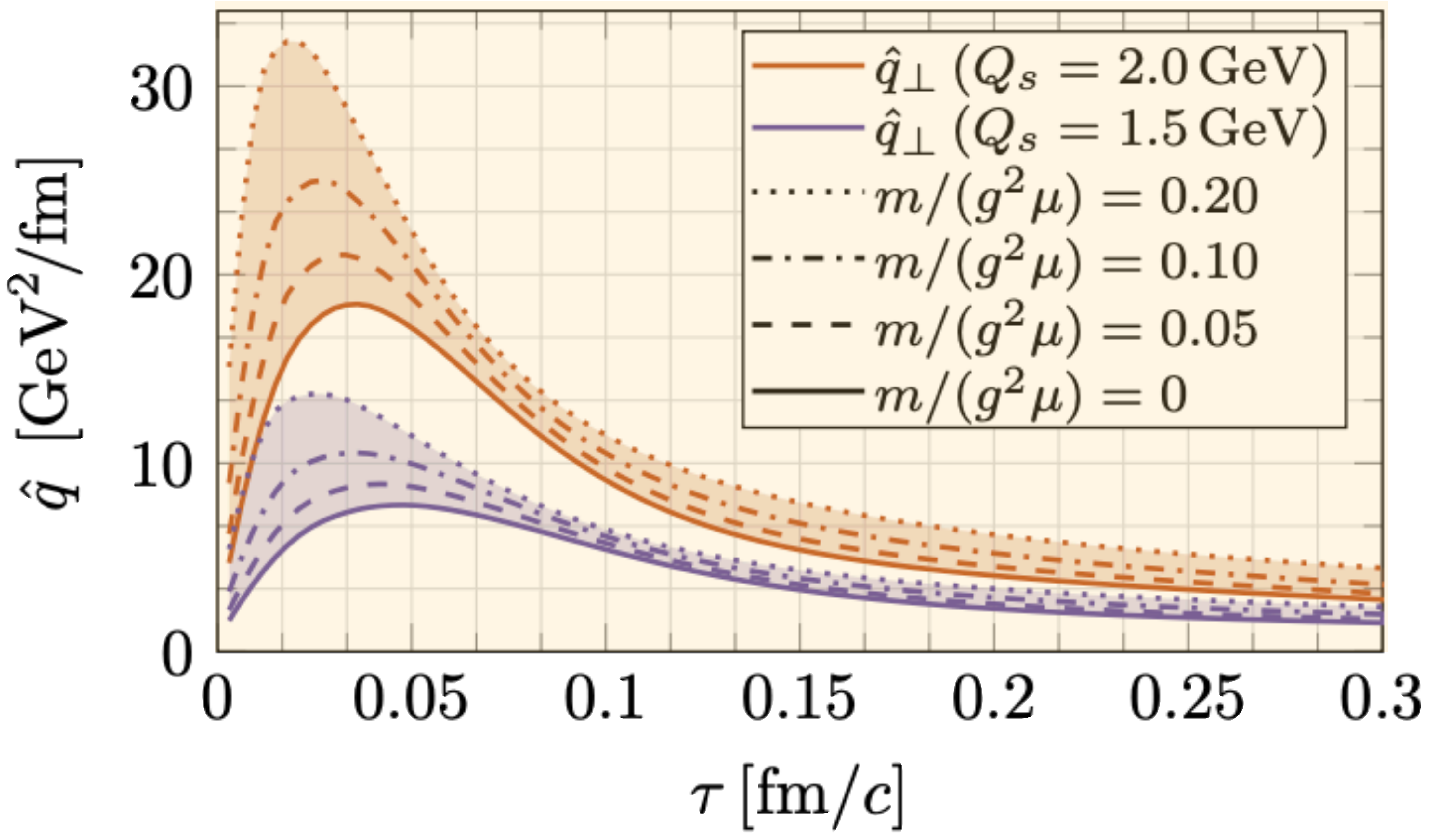


Broadening in the pre-hydro stages

First computations of **broadening in the pre-hydrodynamic stages**

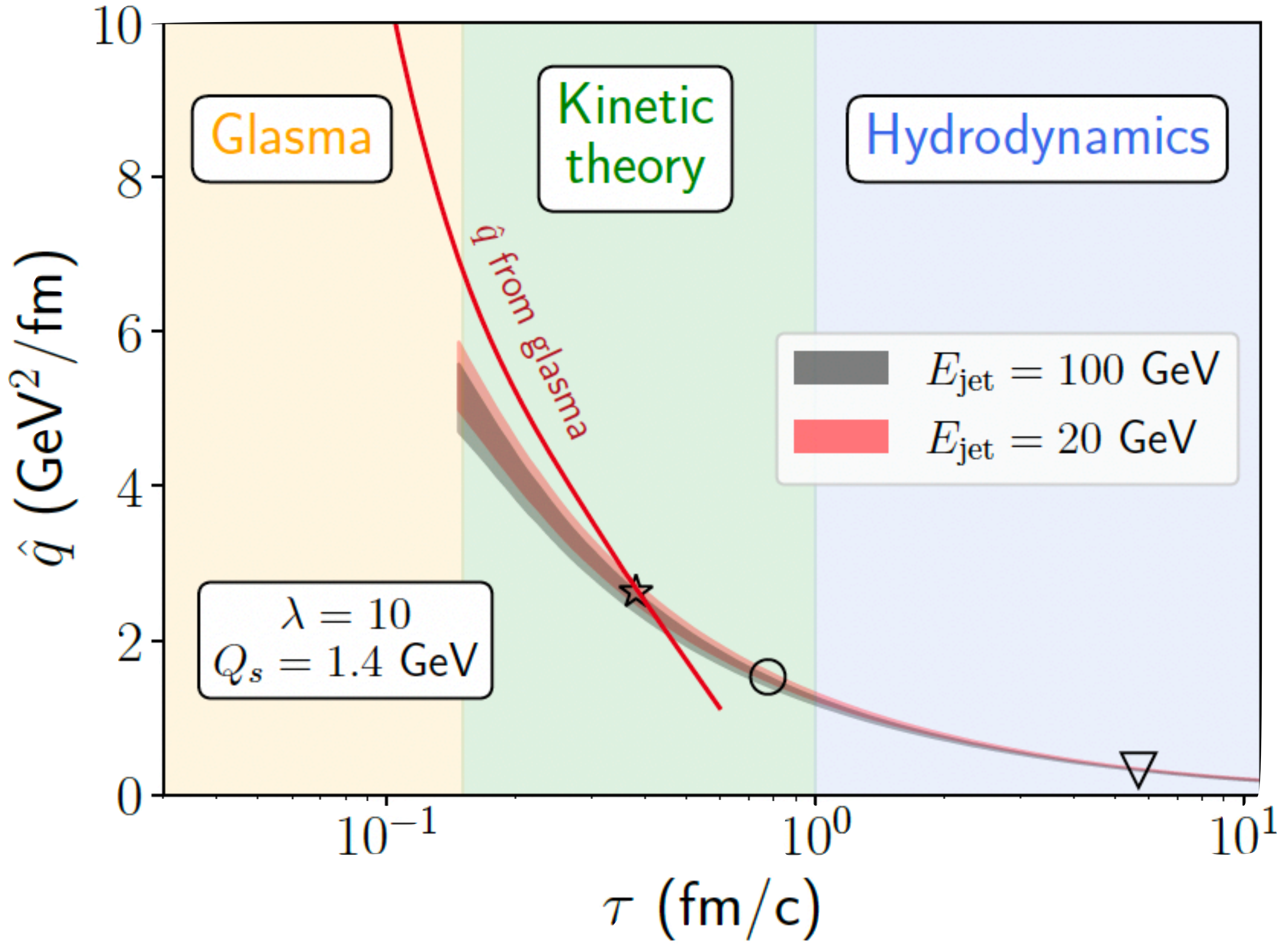
Ipp, Müller, Schuh
2001.10001 2009.14206

Glasma



See also:
Carrington, Czajka, Mrówczynski, 2112.06812 2202.00357
Avramescu, Baran, Greco, Ipp, Müller, Ruggieri, 2303.05599

Kinetic theory

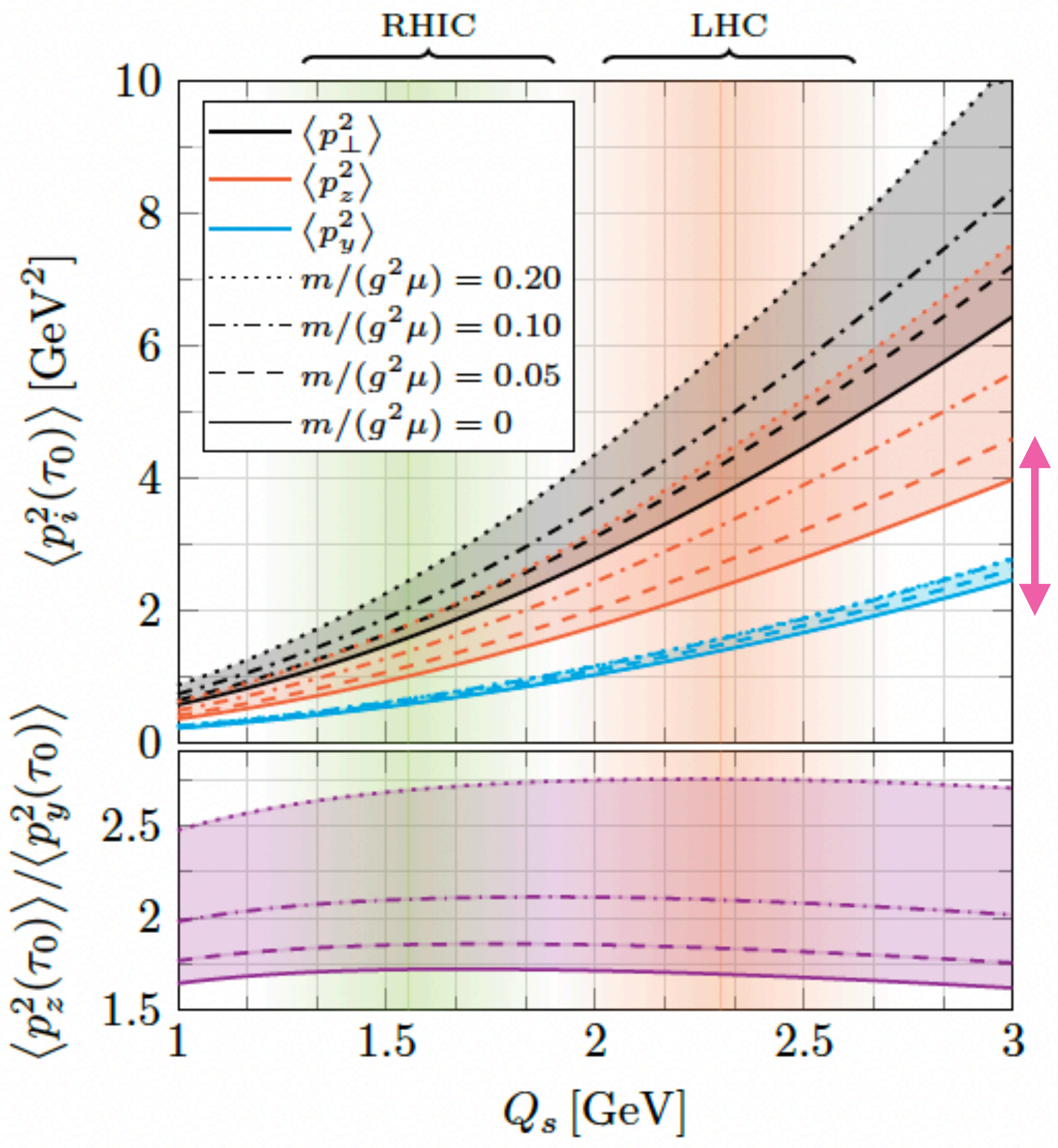


Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron, 2303.12595

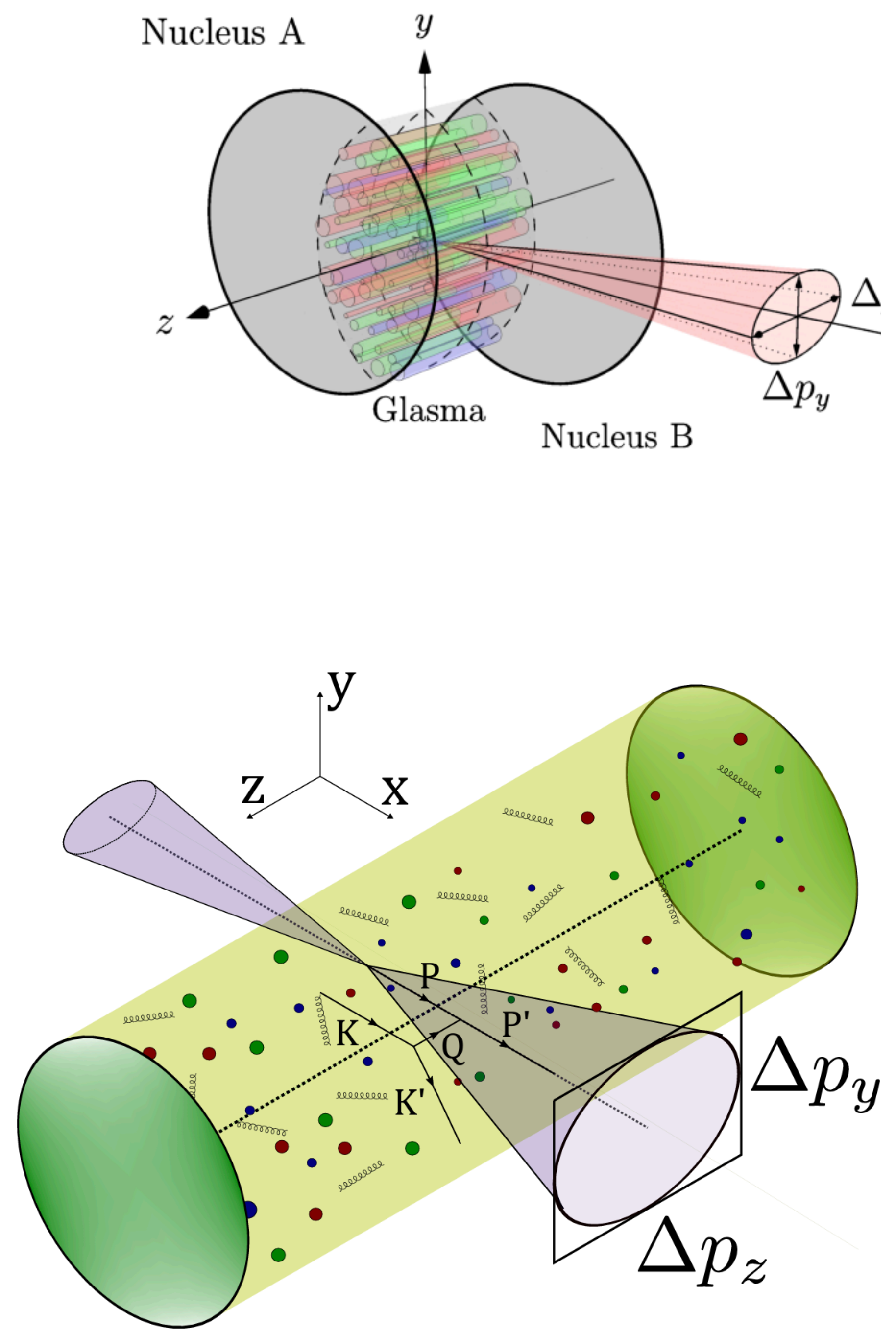
Broadening in the pre-hydro stages

Glasma

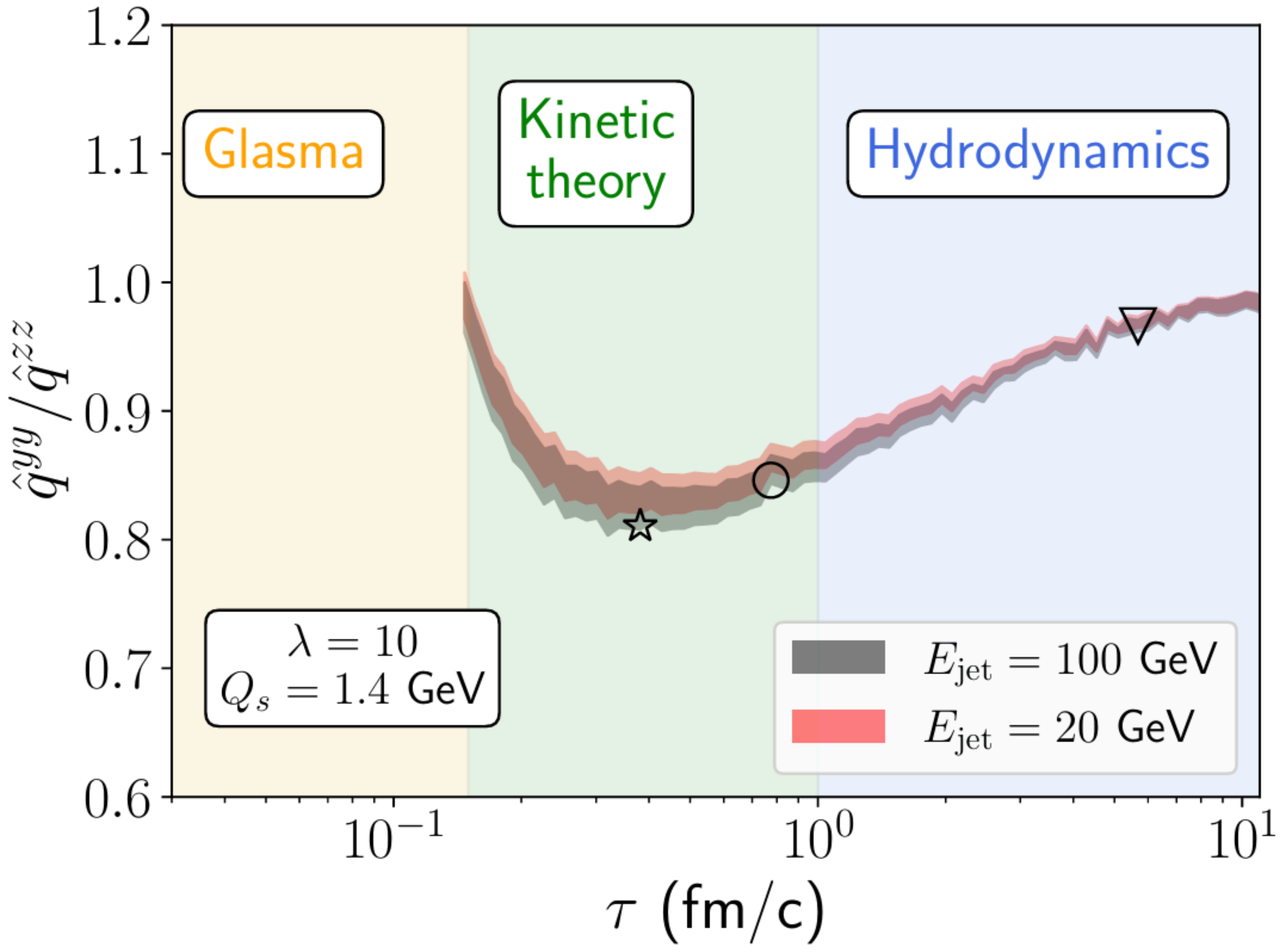
Accumulated broadening at $\tau_0 = 0.6$ fm



Ipp, Müller, Schuh 2009.14206



Kinetic theory



Boguslavski, Kurkela, Lappi, Lindenbauer, Peuron, 2303.12595

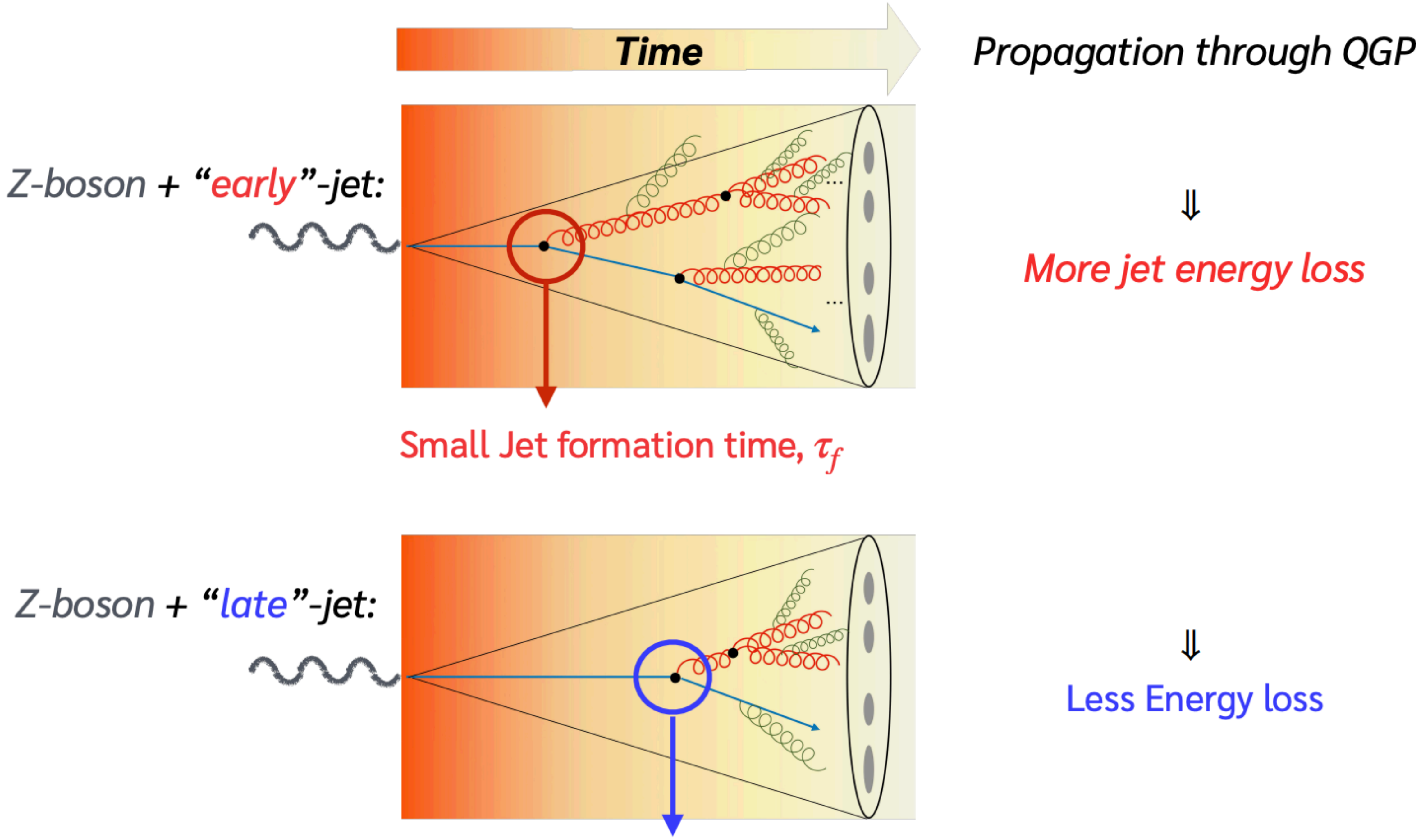
Anisotropic broadening: **larger along the beam axis** than transverse to it

Early jets vs. *Late* jets

- τ algorithm: select jets based on **formation times**

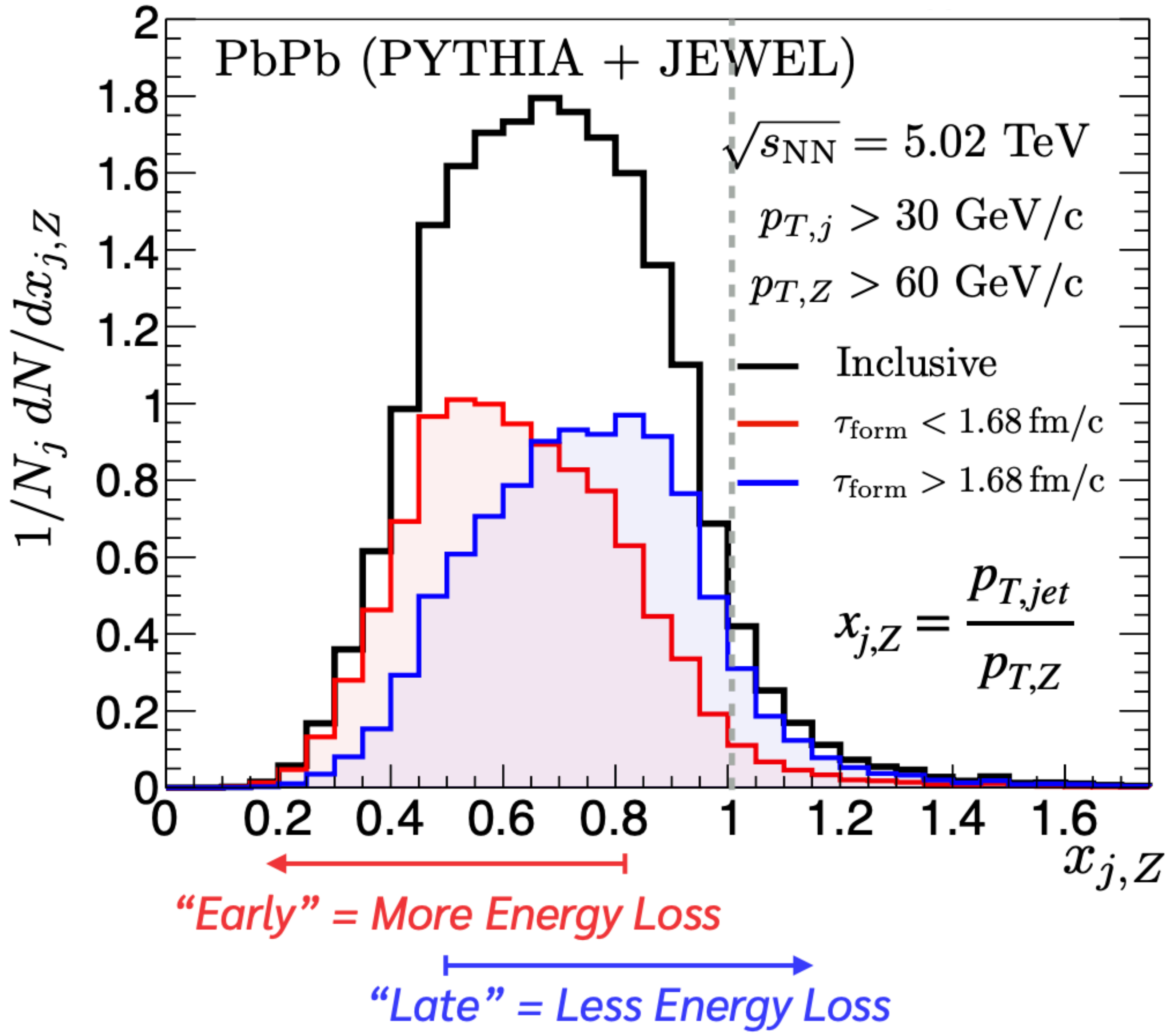
Apolinário, Cordeiro, Zapp, 2012.02199

$$d_{ij} = \min(p_{t,i}^{2p}, p_{t,j}^{2p})\frac{\Delta R_{ij}^2}{R^2} \qquad p = 0.5 \rightarrow d_{ij} \sim \frac{1}{\tau_f}$$



Courtesy of L. Apolinário

Apolinário, Guerrero-Rodriguez, Zapp, 2401.14229



Allows us to select populations of strong energy loss

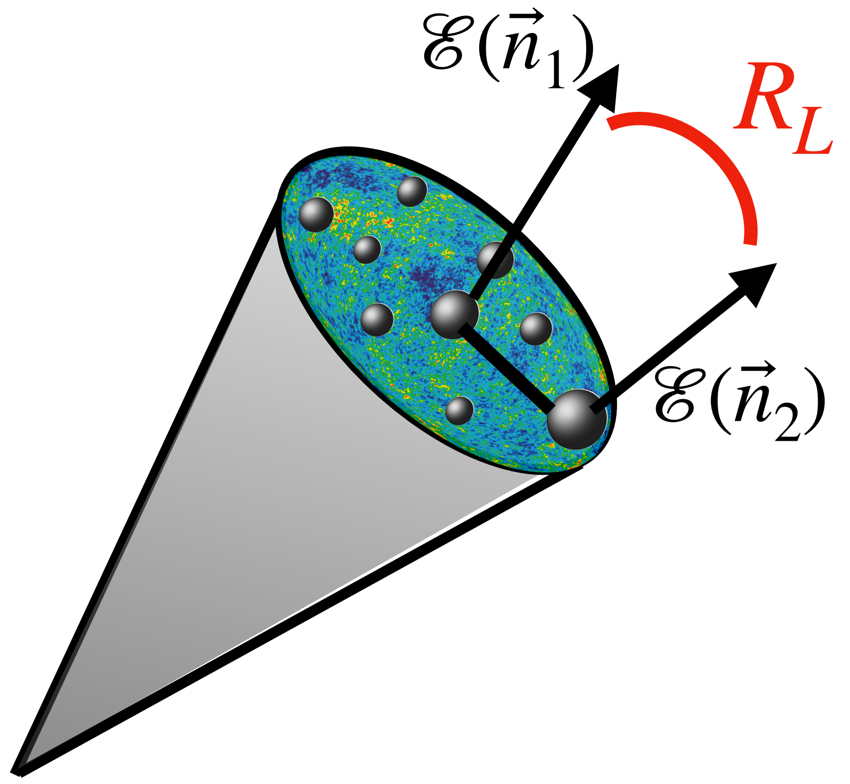
Conclusions

- Since the 1970s, **jets** have played a **central role** in **collider physics**
- Almost 25 years of **jet quenching at RHIC**
- **Jet substructure:** probe the QGP at **different resolution scales**
    - Recent focus on **Energy Correlators**
        - Access to **transverse scales** + good theoretical control thanks to the **light-ray OPE**
        - **Enhancement** of the E2C in PbPb **cannot be** due to **selection bias**
- Many open questions, including: how can we use jets to probe the pre-QGP stages?

Thank you!

E2C within p-p jets

Hoffman, Maldacena, 0803.1467
Chen, Moult, Sandor, Zhu, 2202.04085



- Within jets: **Light-ray OPE expansion**

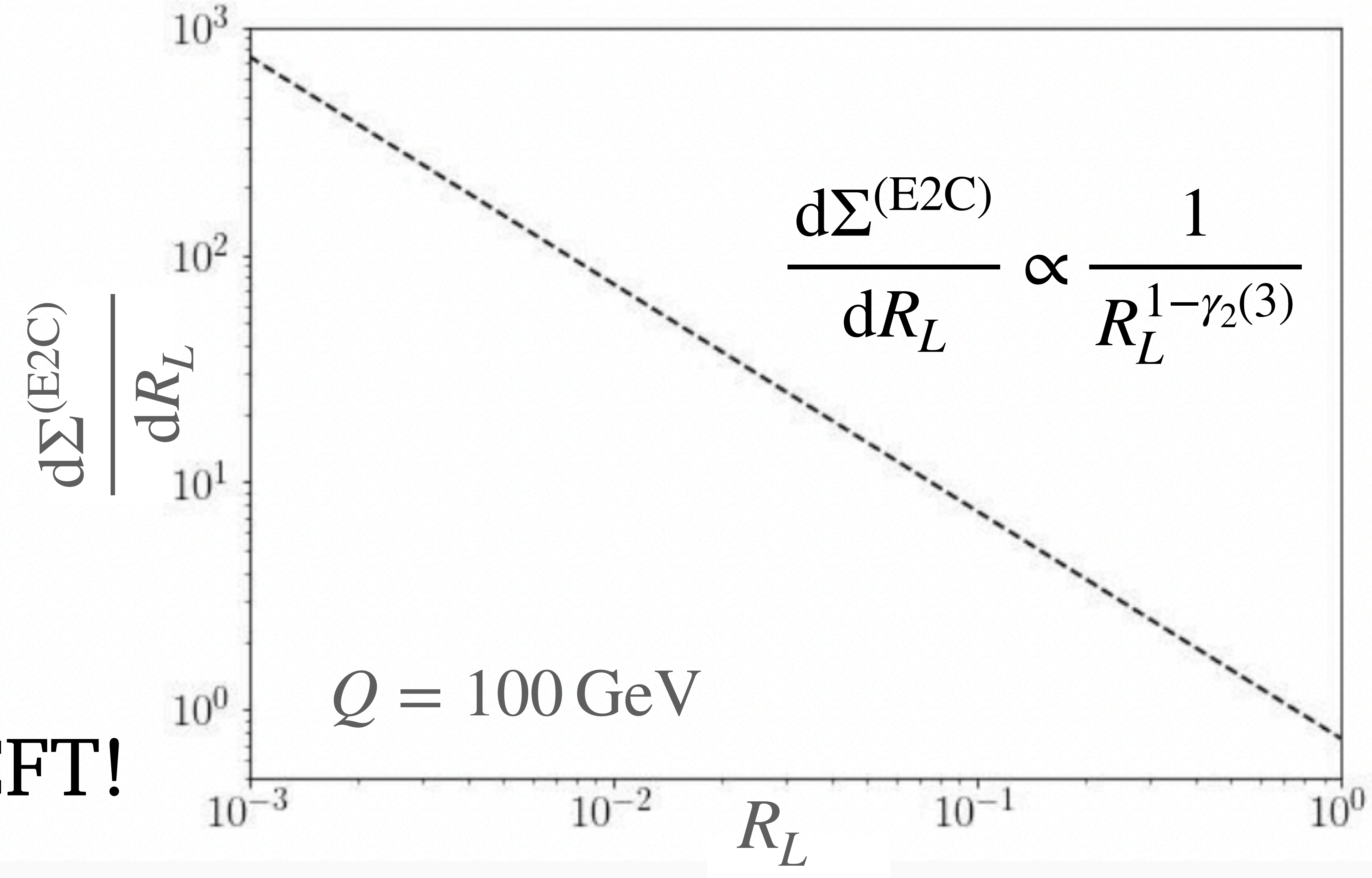
$$\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) \xrightarrow{\vec{n}_1 \to \vec{n}_2} \sum_i \mathcal{C}_i R_L^{\tau_i - 4 + \hat{\gamma}_i(J=3)} \mathbb{O}_i^{[J=3]}(\vec{n}_1)$$

Twist = mass dimension - spin

- Renormalization introduces the anomalous dimension matrix

$$\langle X | \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2) | X \rangle \equiv \frac{d\Sigma^{(\mathrm{E2C})}}{dR_L^2}$$

- **Leading twist** dominates: $\boxed{\dfrac{d\Sigma_{\mathrm{E2C}}}{dR_L} \propto \dfrac{1}{R_L^{1-\gamma_2(3)}}}$

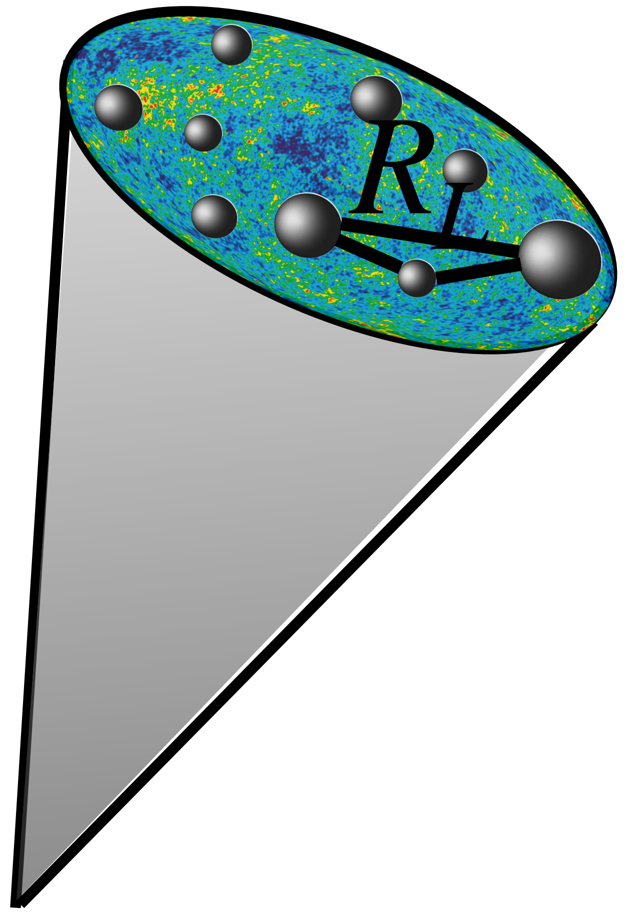


Power-law scaling according to CFT!

Projected ENCs

Hoffman, Maldacena, JHEP 05 012 (2008)

Chen, Moult, Sandor, Zhu, JHEP 09 199 (2022)



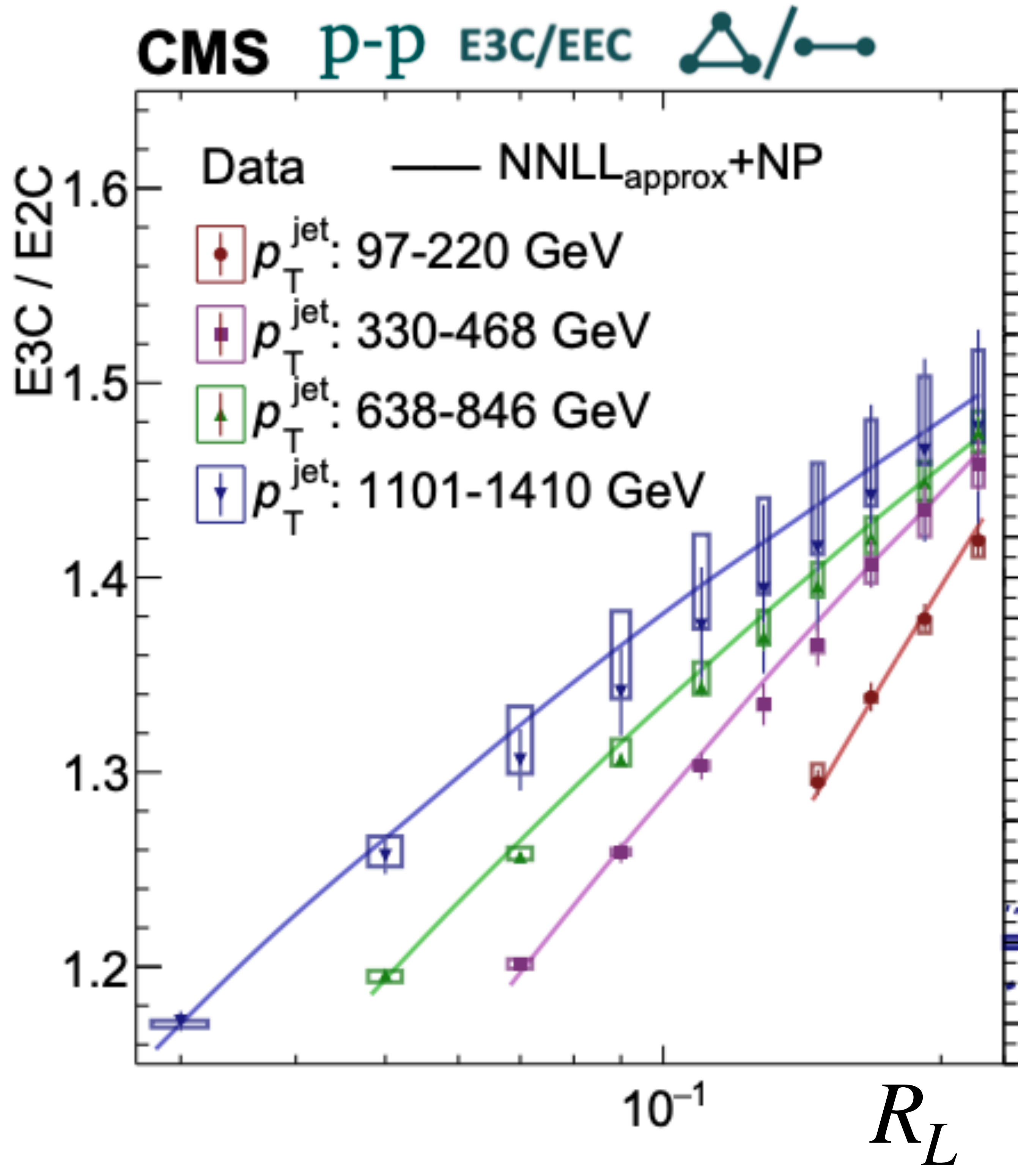
$$\mathscr{E}(\vec{n}_1)\mathscr{E}(\vec{n}_2) \sim R_L^{-2+\gamma_2(3)} \overrightarrow{\mathscr{C}}_2 \cdot \mathbb{O}_{\tau=2}^{[J=3]}(\vec{n}_1)$$

$$\mathscr{E}(\vec{n}_1)\ldots\mathscr{E}(\vec{n}_N) \sim R_L^{-2+\gamma_2(N+1)} \overrightarrow{\mathscr{C}}_2 \cdot \overrightarrow{\mathbb{O}}_{\tau=2}^{[J=N+1]}(\vec{n}_1)$$

$$\frac{\text{E3C}}{\text{E2C}} \sim R_L^{\gamma_2(4)-\gamma_2(3)}$$

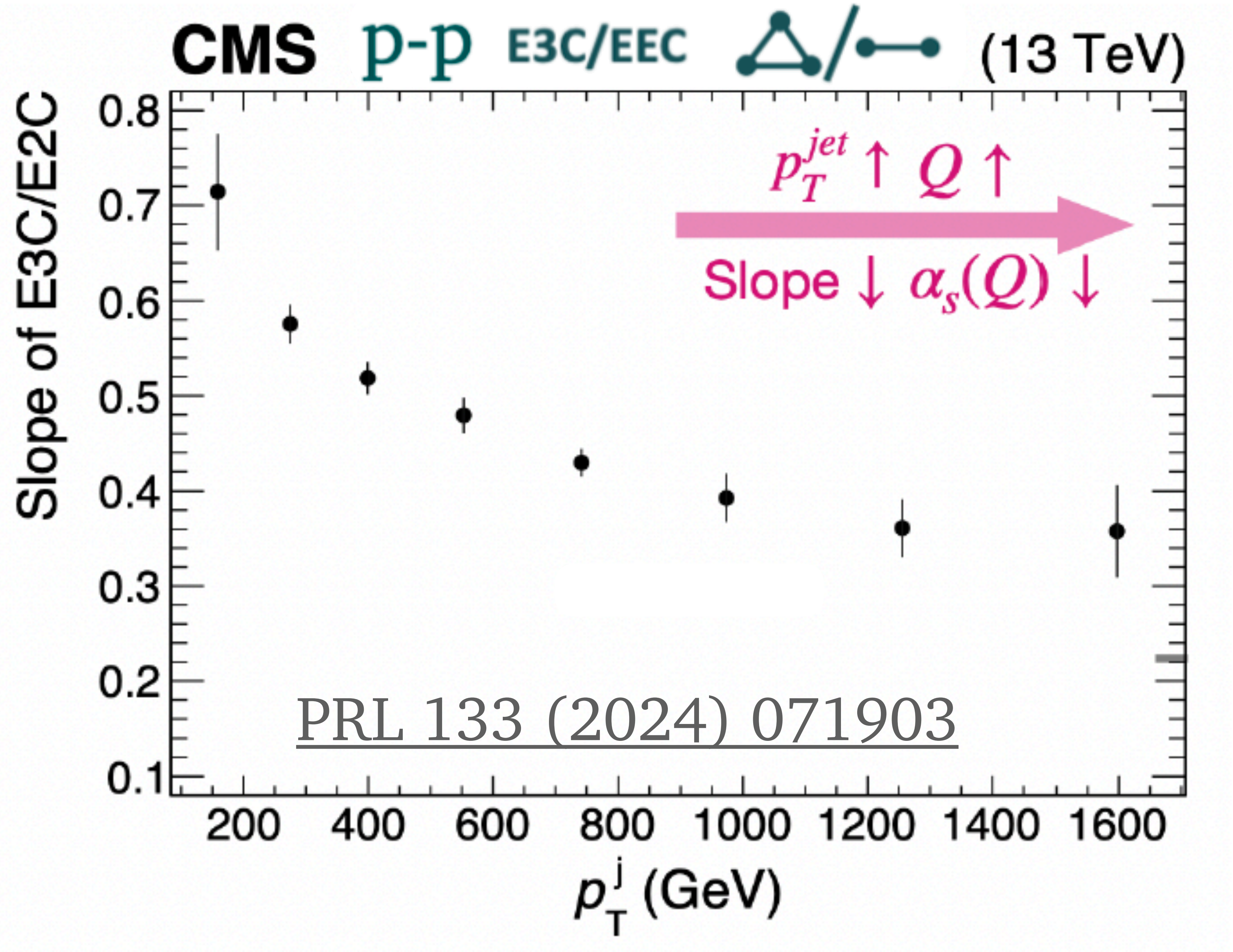
$$\left(\gamma_2(4) - \gamma_2(3)\right) \propto \alpha_s(p_T)$$

PRL 133 (2024) 071903



Most precise determination of α_s from jet substructure (4% accuracy)

$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$



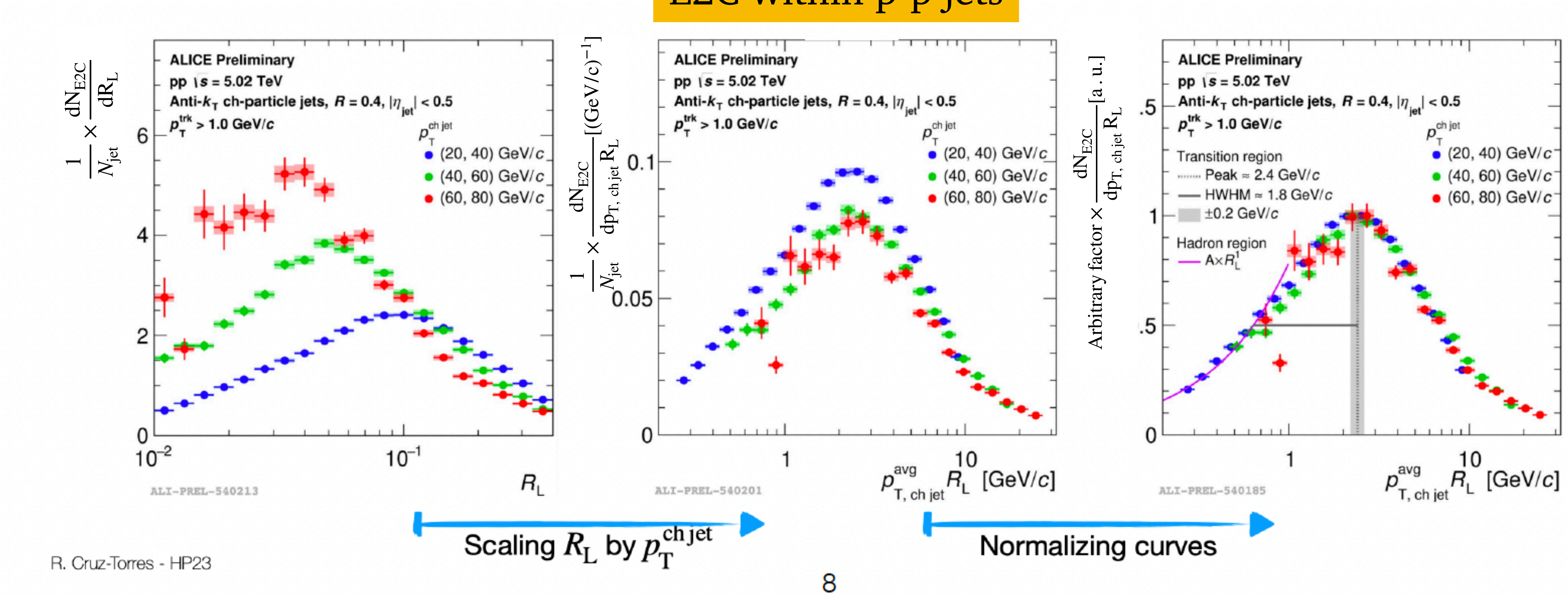
PRL 133 (2024) 071903

We can see **asymptotic freedom** by eye in data!

Selection bias due to energy loss

- Features in the E2C appear at scales related to the (initial) **hard scale**

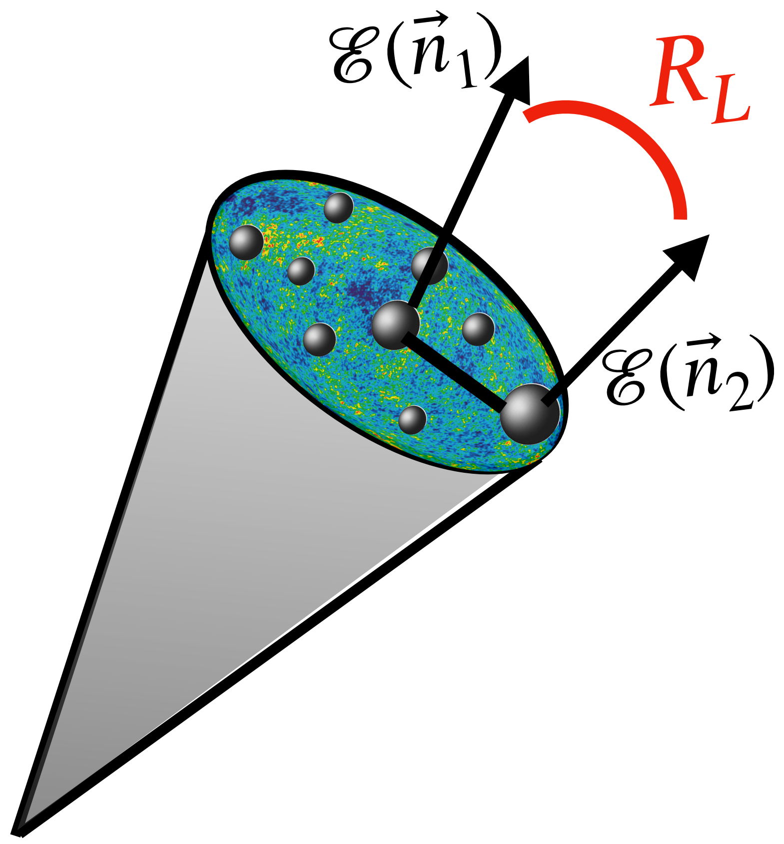
E2C within p-p jets



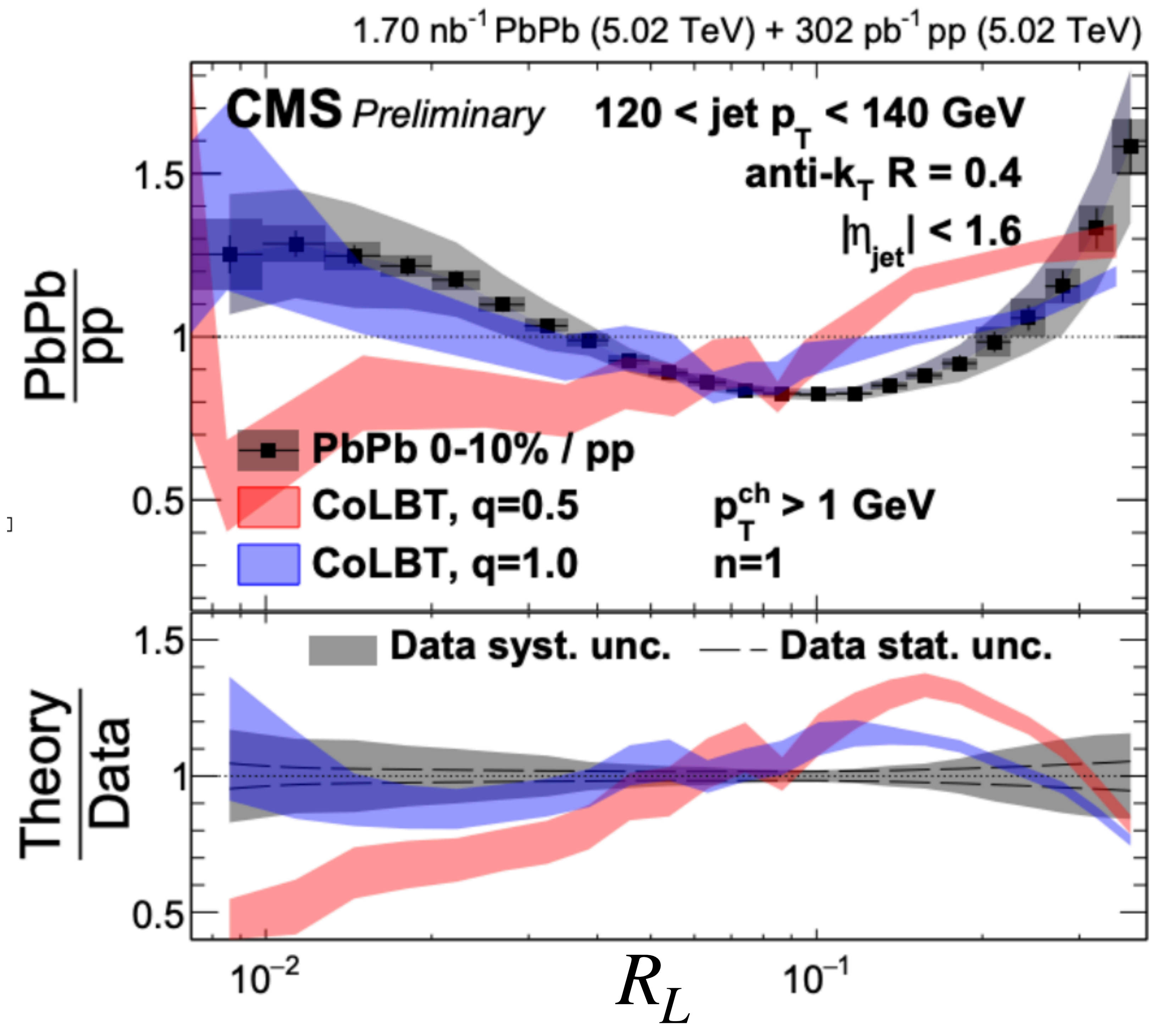
- Heavy ions: Shift in the hard scale due to energy loss. **Selection bias**

CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, 2407.07936

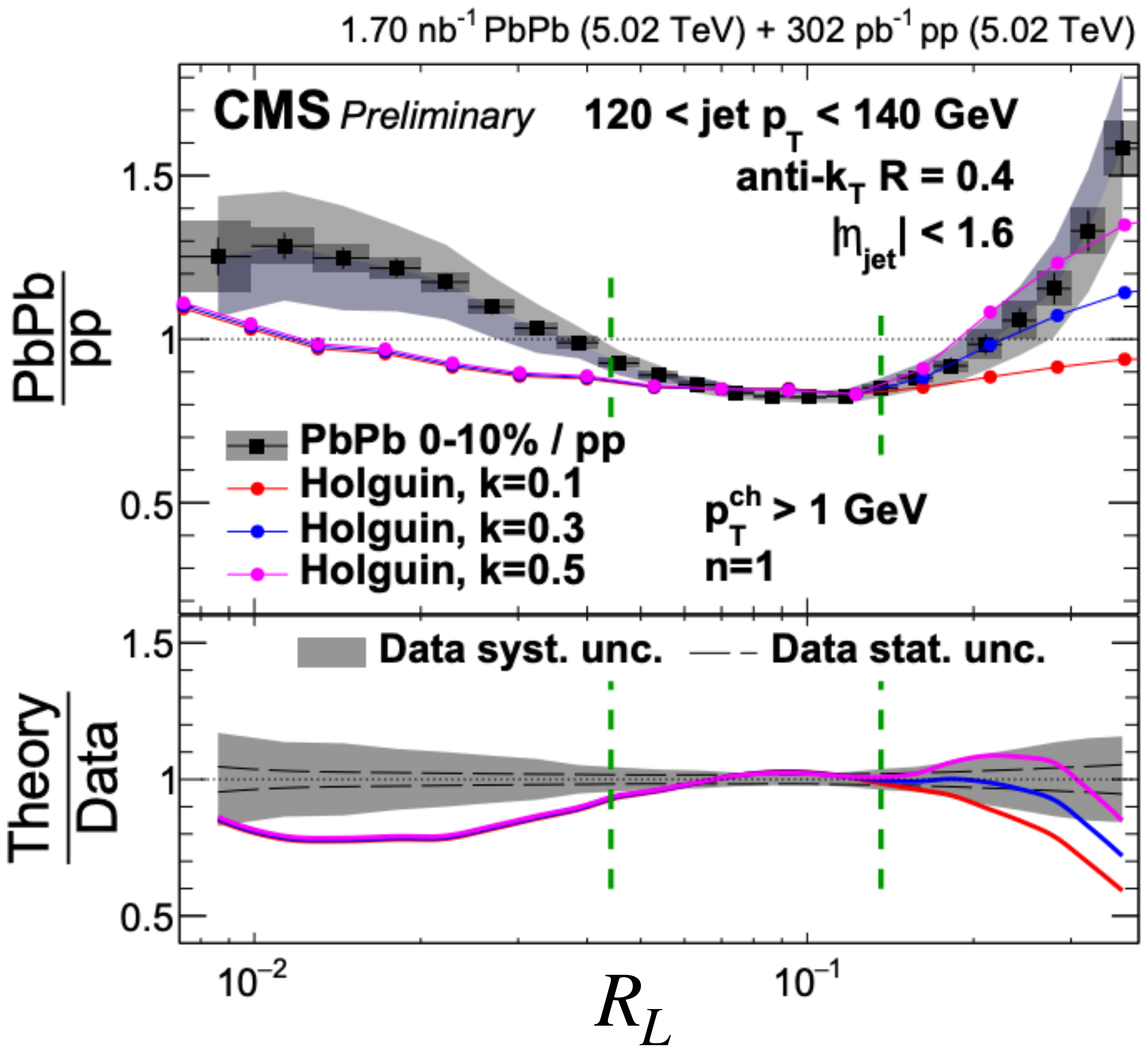
E2C in AA



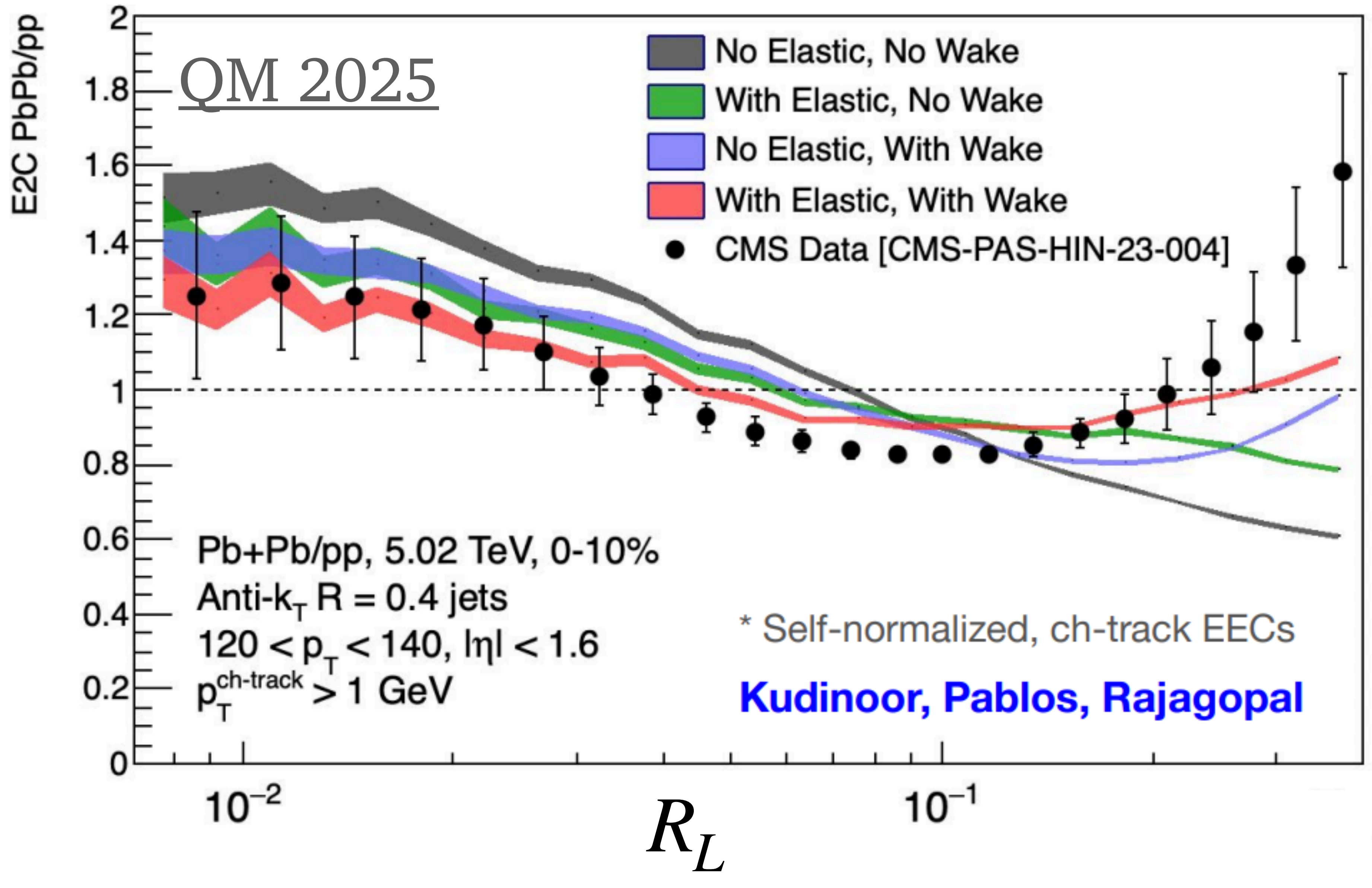
CMS, 2503.19993



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



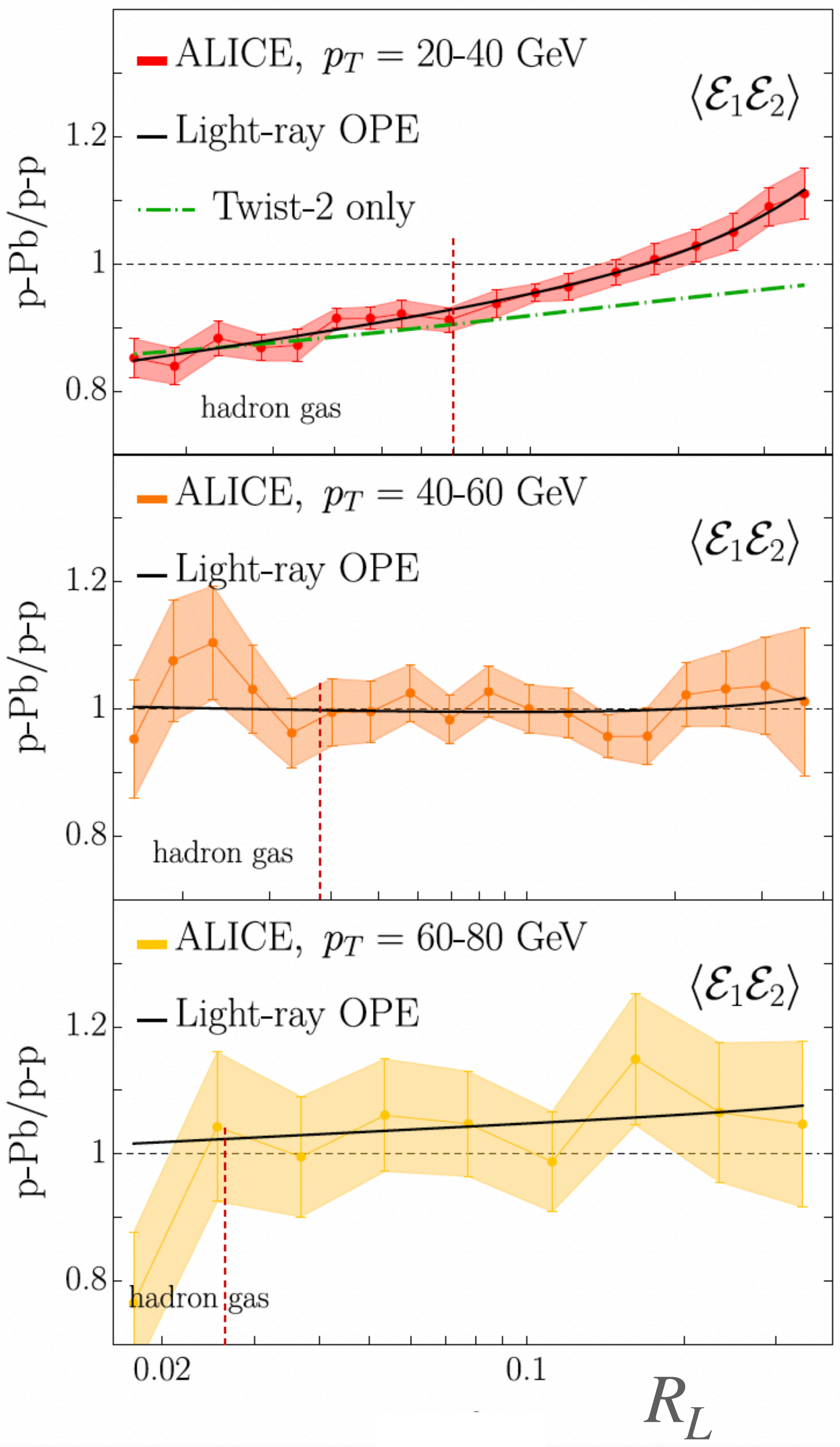
CA, Dominguez, Elayavalli, Holguin, Marquet, Moult, 2407.07936



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

Light-ray OPE: pPb

CA, Dominguez, Holguin, Marquet, and Moult, 2411.15298



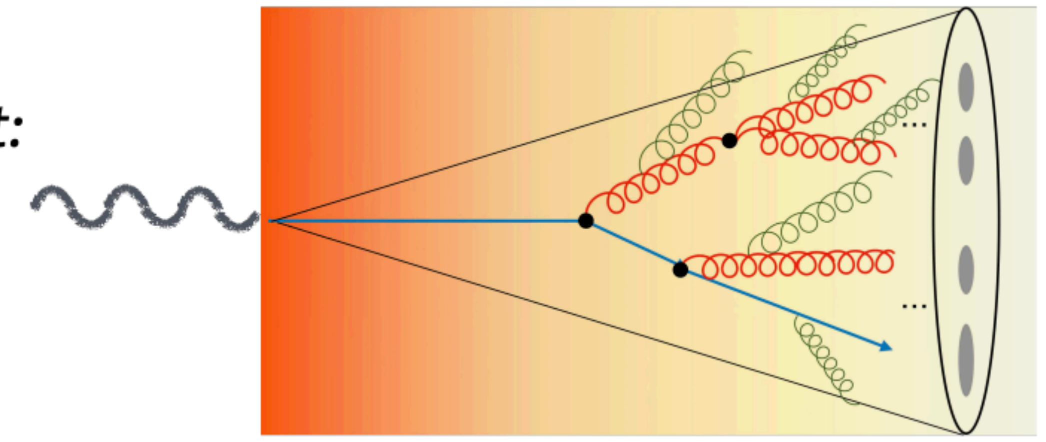
$$\frac{\mathrm{E2C}^{\text{p-Pb}}}{\mathrm{E2C}^{\text{p-p}}} \sim 1 + aR_L^2$$

$$\text{p-Pb/p-p} = \frac{M_2 R_L^{\gamma_N} + \left(\frac{p_{T,0}}{p_T}\right)^2 M_4(p_{T,0})\, R_L^2}{R_L^{\gamma}}$$

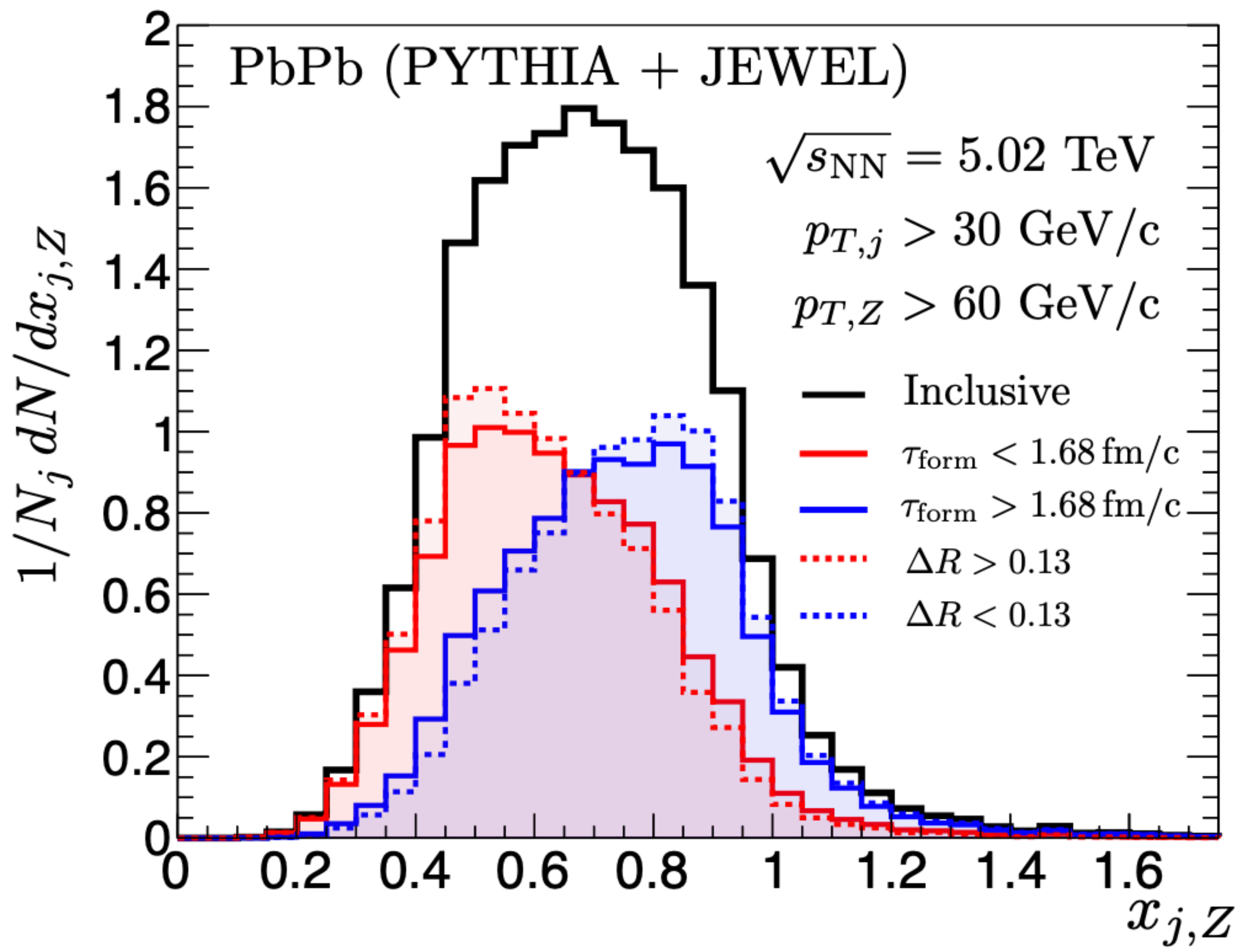
Behavior of the **enhancement** with the **jet** p_T predicted by the **OPE**

See also Fu, Müller, and, Sirimanna, 2411.04866

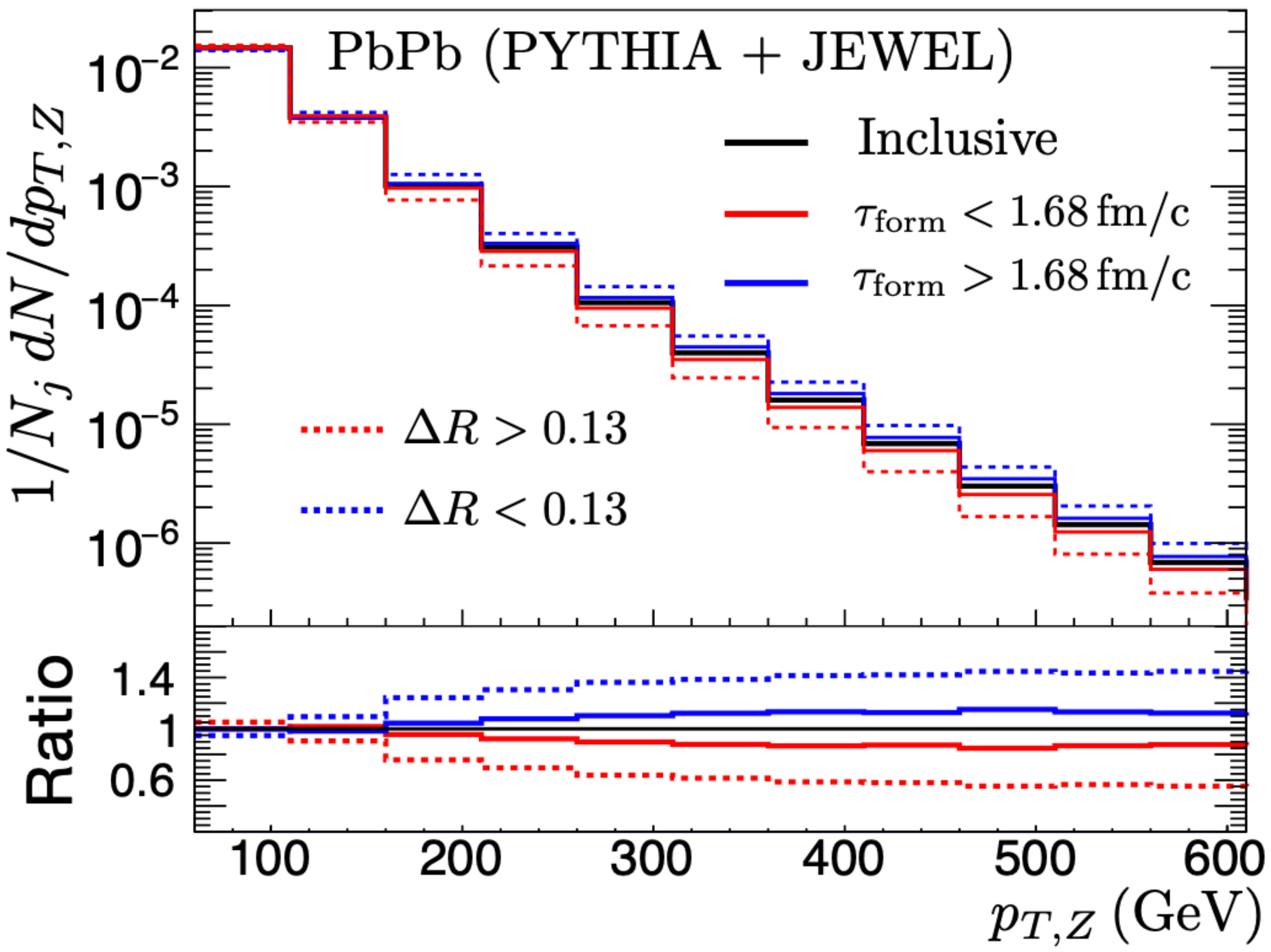
Selection bias



Apolinário, Guerrero-Rodriguez, Zapp, 2401.14229



Z-boson spectrum



Selecting on $\tau_{\rm form}$ significantly **reduces the bias** on the initial hard parton p_T