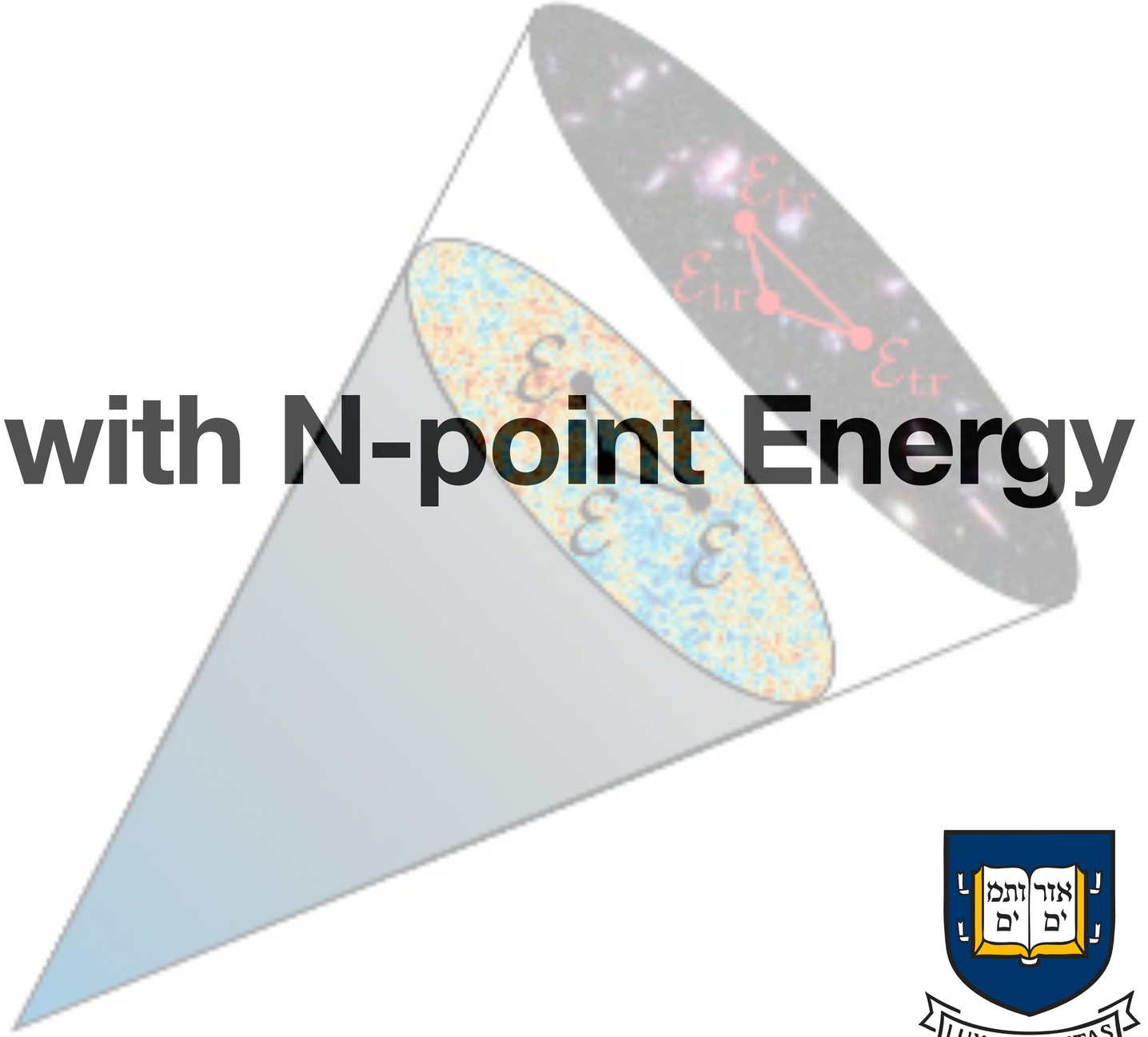
Wright Laboratory

Exploring the Invisible Universe

Probing QCD with N-point Energy Correlators

MITP EEC Workshop 2024



Ananya Rai, 10th July 2024

LUX ET VERITAS

Imaging the Wakes of Jets with EEECs: Roadmap

What are wakes and what is the hybrid model?

How can projected correlators be used to probe QCD?

See Hannah's talk next!

What new things can the shape-dependent energy-energy-energy correlator add?

How do these results depend on coordinate choices and the superposition of wakes?

Talk outline

Two sub-talks

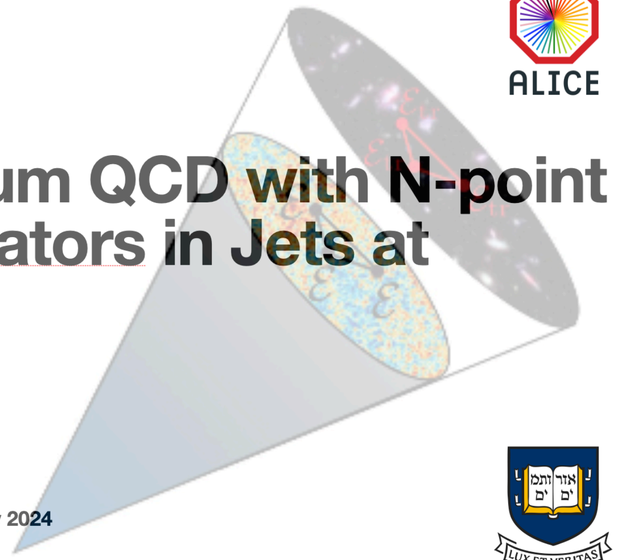
* **Probing vacuum QCD using energy correlators**

Wright Laboratory

ALICE

Probing vacuum QCD with N-point Energy Correlators in Jets at ALICE

MITP EEC Workshop 2024



Ananya Rai (on behalf of ALICE), 10th July 2024

* **Probing QCD matter using energy correlators**

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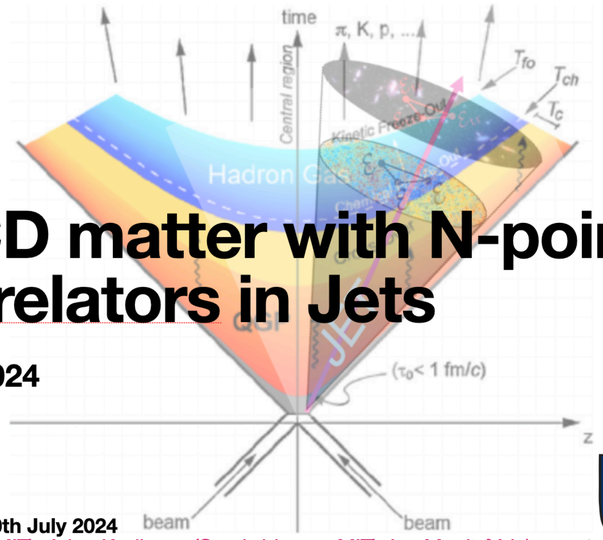


Probing QCD matter with N-point Energy Correlators in Jets

MITP EEC Workshop 2024

Ananya Rai (on behalf of herself), 10th July 2024

**Based on work with Hannah Bossi (MIT), Arjun Kudinoor (Cambridge → MIT), Ian Moult (Yale), Daniel Pablos (Santiago), Krishna Rajagopal (MIT)*

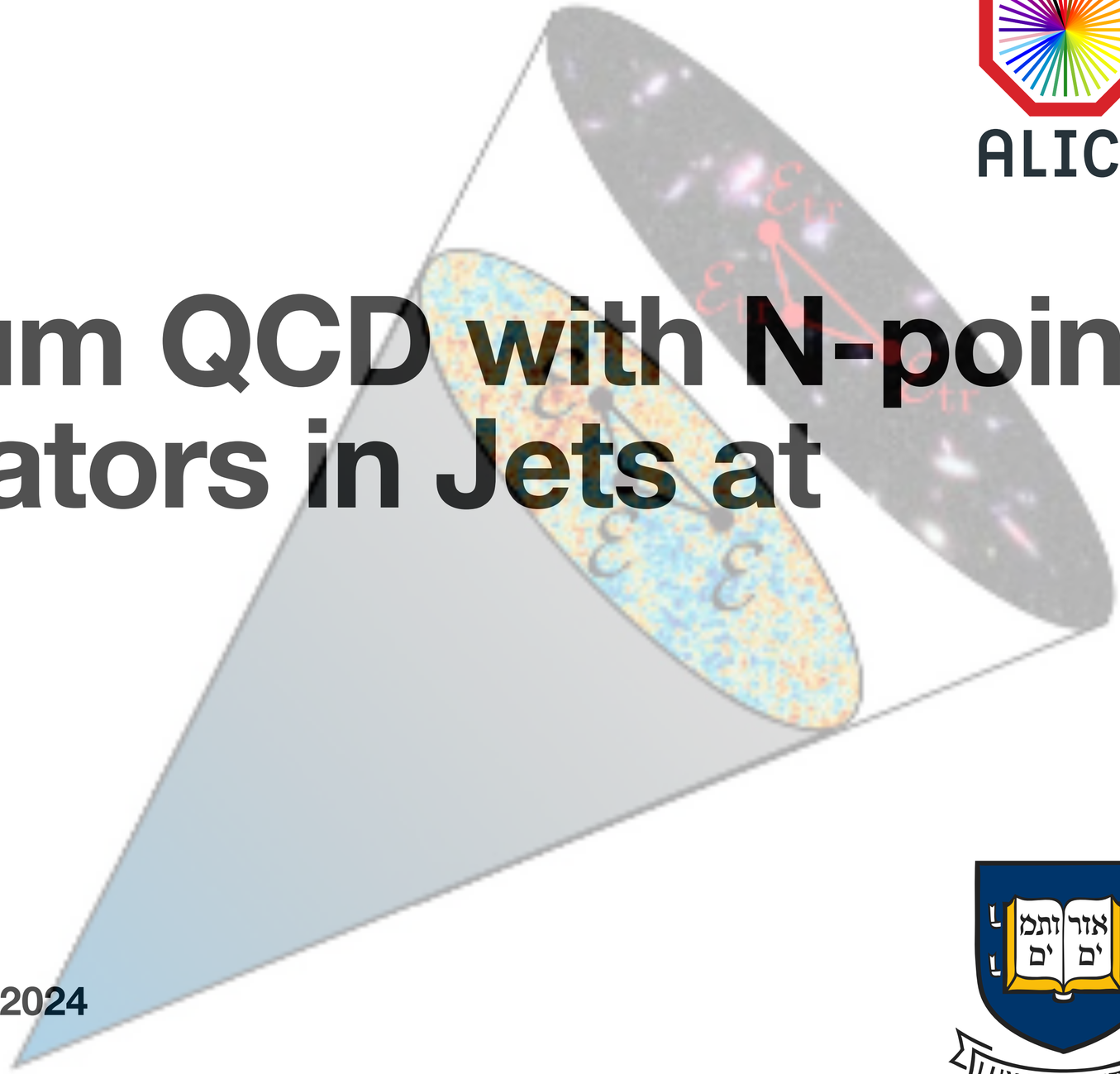
Wright Laboratory

Exploring the Invisible Universe

ALICE

Probing vacuum QCD with N-point Energy Correlators in Jets at ALICE

MITP EEC Workshop 2024



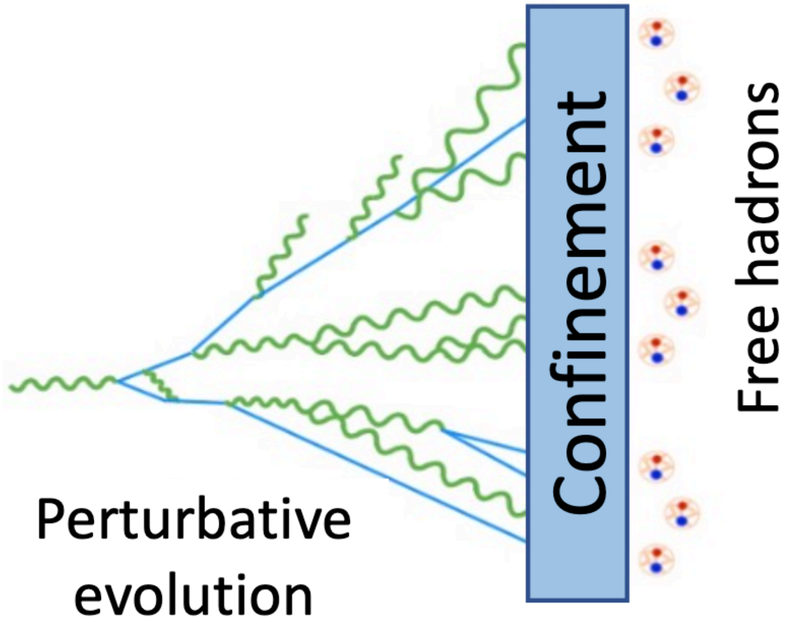
Ananya Rai (on behalf of ALICE), 10th July 2024

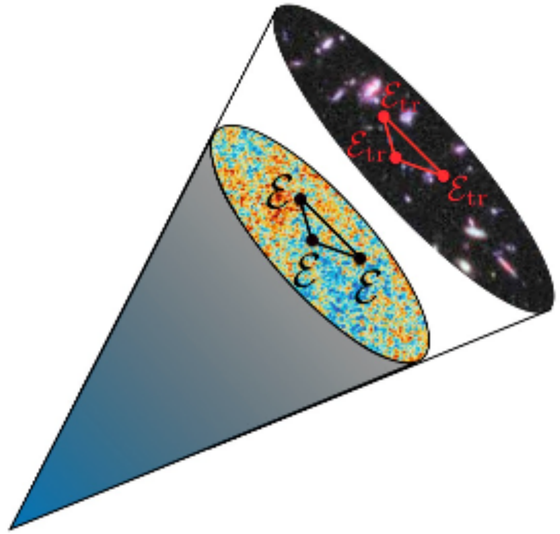
LUX ET VERITAS

Jets and Jet Substructure

Looking inside jets

* Created from iterative splittings of hard scattered partons during the initial collision



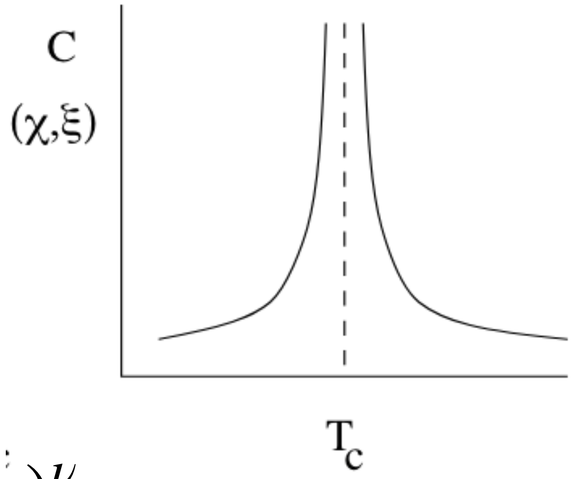


* **Multi-scale objects**: QCD evolution imprinted on jets as they go from perturbative to non-perturbative scales

Correlation Functions

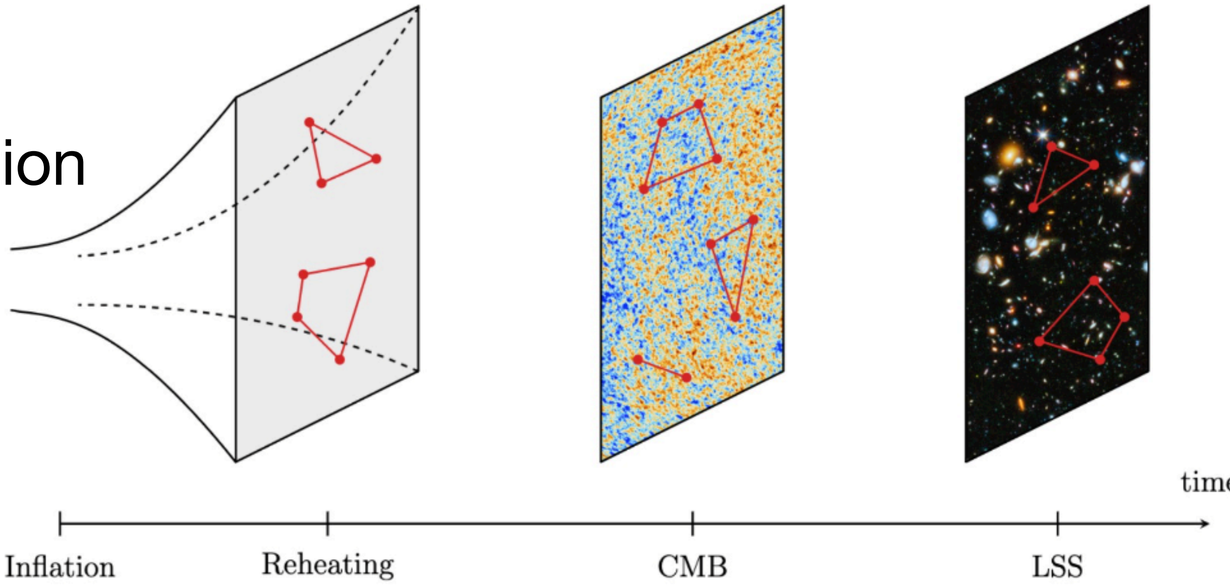
Some intuition from other systems

* Correlation functions indicate **phase transitions**
  Eg 1: Ferromagnetic transition, correlation length $\rightarrow \infty$



$$\xi \sim 1/(T - T_C)^{\nu}$$

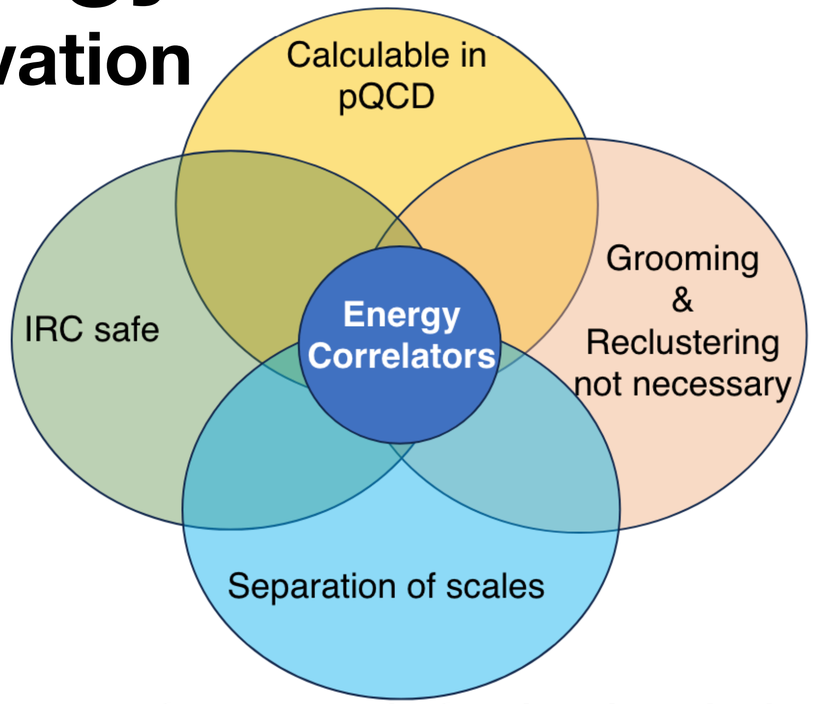
Image Credit: Austin Joyce

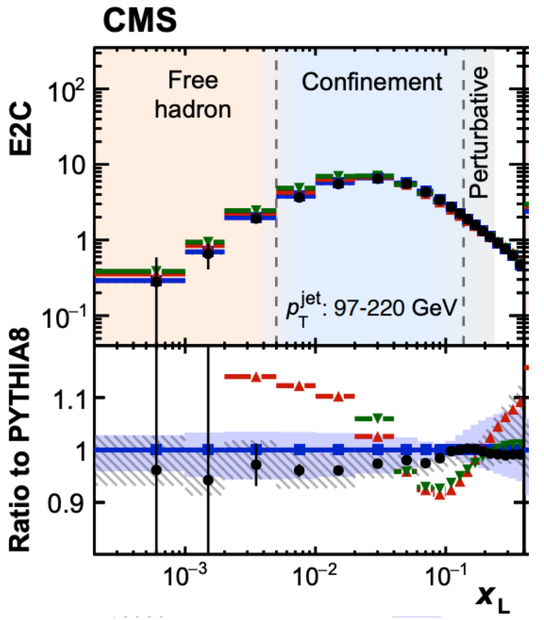


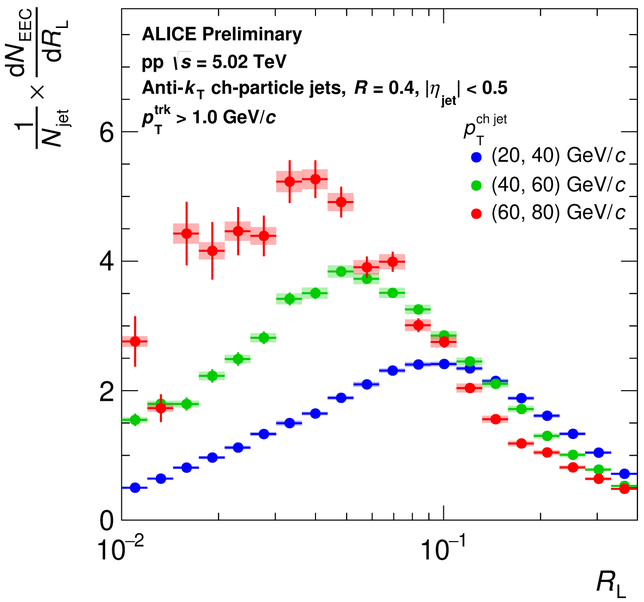
Eg 2: Use correlations to trace back to possible inflation scenarios

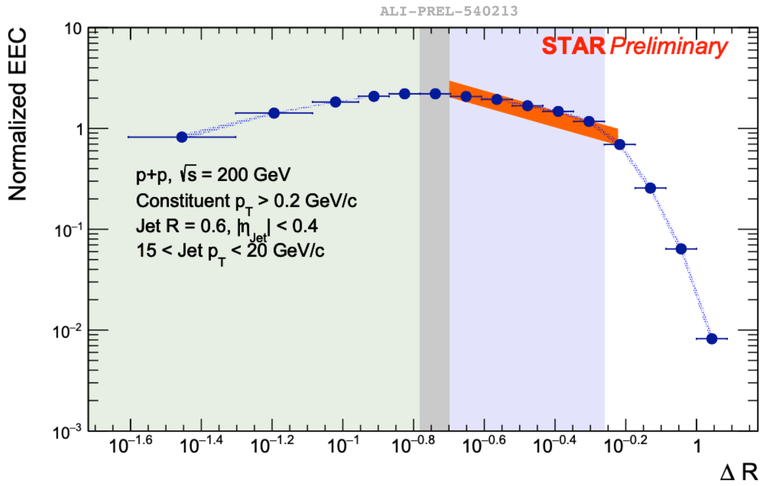
Energy Correlators in Jets

Motivation





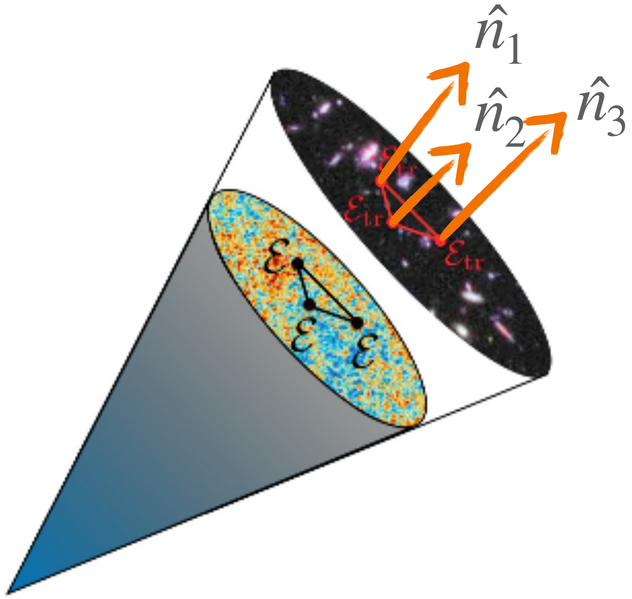




- Active area of research for hadronic jets
- Recent results from ALICE, CMS, STAR — wide energy range!
- Extension to complex systems — this workshop!

Energy Correlators in Jets

Definition



Number of particles in the correlation

Power on energy weight

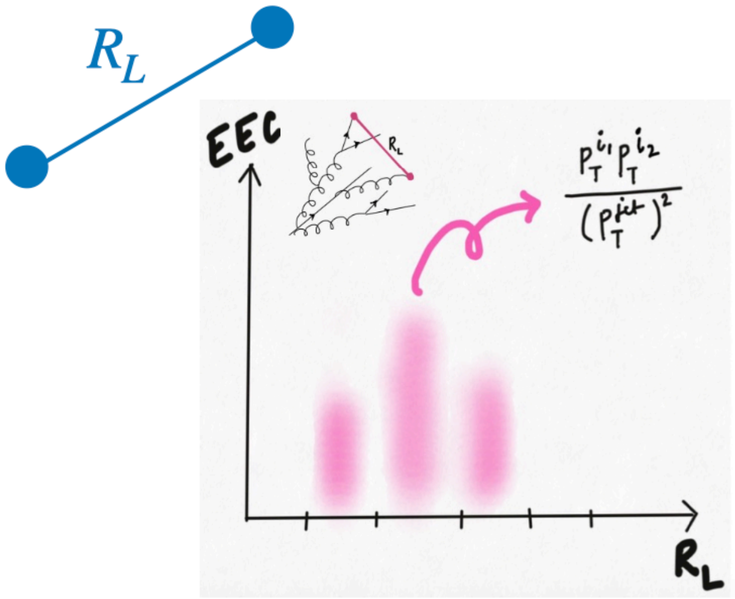
$$\mathrm{ENC}(R_L) = \left(\prod_{k=1}^{N}\int d\Omega_{\vec{n}_k}\right)\delta(R_L - \Delta\hat{R}_L)\cdot\frac{1}{(E_{\mathrm{jet}})^{(n*N)}}\left\langle\mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\ldots\mathcal{E}^n(\vec{n}_N)\right\rangle$$

Largest distance between N particles

Energy Correlators in Jets

Constructing the correlators

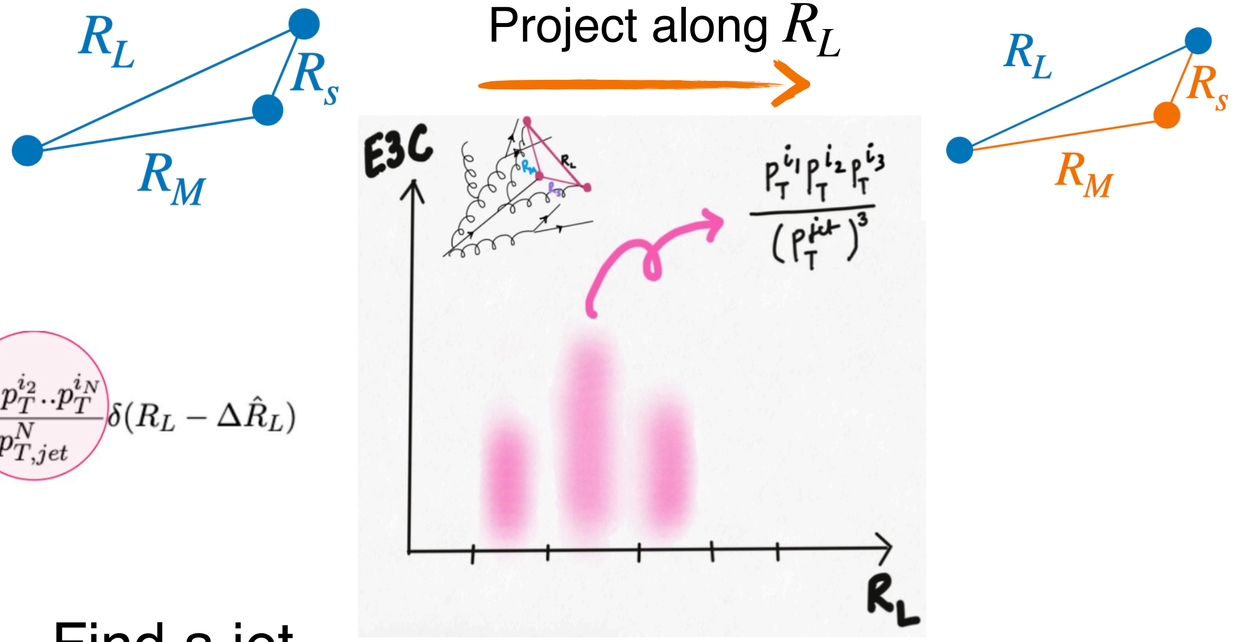
EEC (or E2C): 2-point correlator



$$ENC(R_L) = \sum_{i_1, i_2, .. i_k}^{i_N} \int dR_L \frac{p_T^{i_1} p_T^{i_2} .. p_T^{i_N}}{p_{T,jet}^N} \delta(R_L - \Delta \hat{R}_L)$$

1. Find a jet
2. Create pairs with jet constituents
3. Fill an energy-weighted histogram

E3C: Projected 3-point correlator



1. Find a jet
2. Create triplets with jet constituents
3. Find the largest distance between the triplets
4. Fill an energy-weighted histogram

QFT Detour: Anomalous Dimensions

What they are and why they matter

QFT operators have a scaling/mass dimension $\Delta_{\mathbb{O}}$.
For e.g., in 3+1D, scalar field $[\phi] = 1$,
fermion field $[\psi] = 3/2$.
Quantum mechanical effects $\longrightarrow$ $\Delta_{\mathbb{O}}$ gets shifted by "anomalous dimensions", $\gamma_{\mathbb{O}}$:

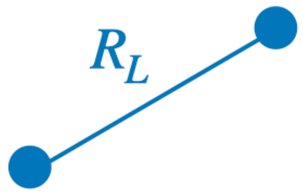
$$\boxed{\Delta_{\mathbb{O}} = \Delta_{\mathbb{O},\,classical} + \gamma_{\mathbb{O}}}$$

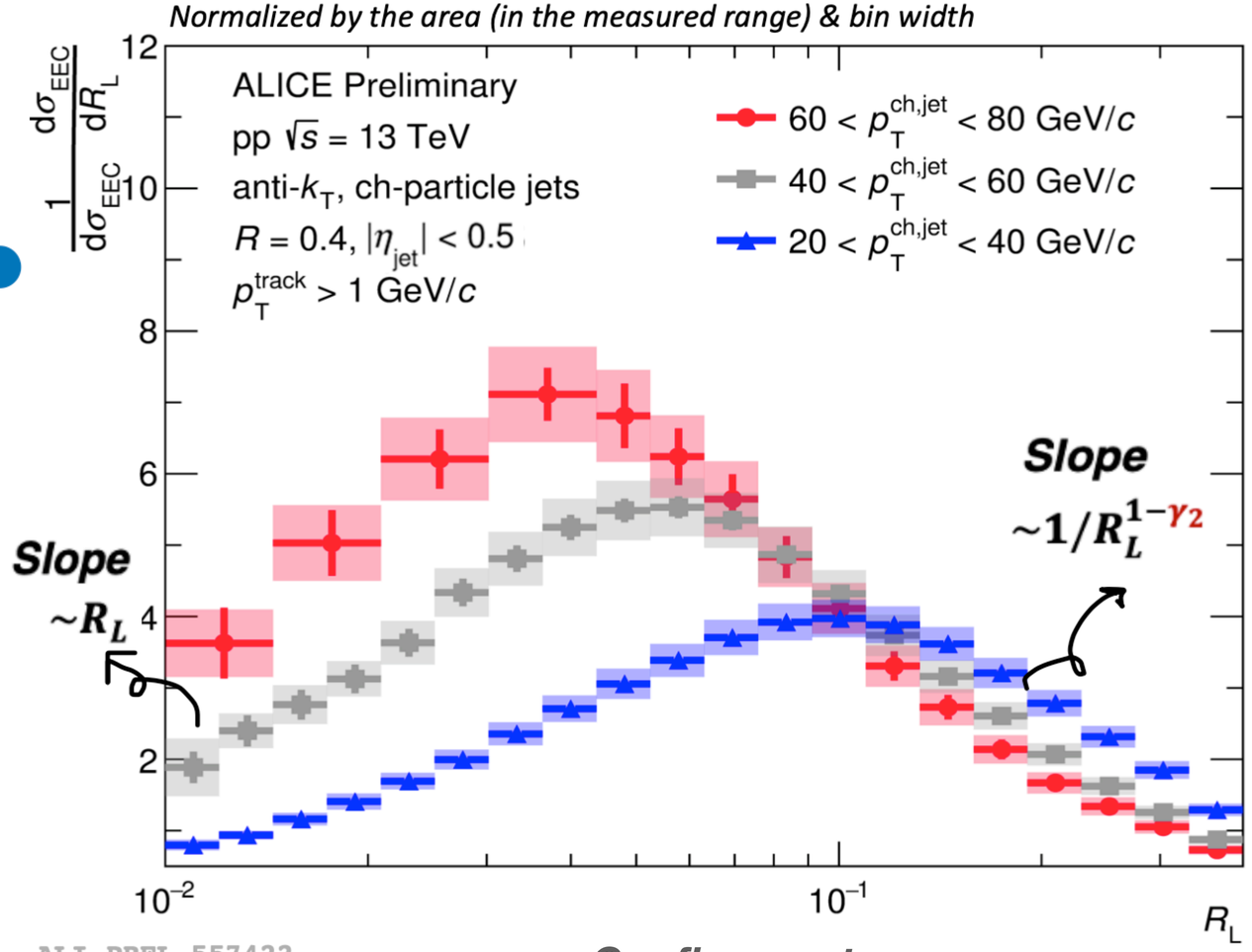
Allow us to probe quantum mechanical corrections!
Measuring and extracting these is a great way to prove to ourselves that we live in a quantum world

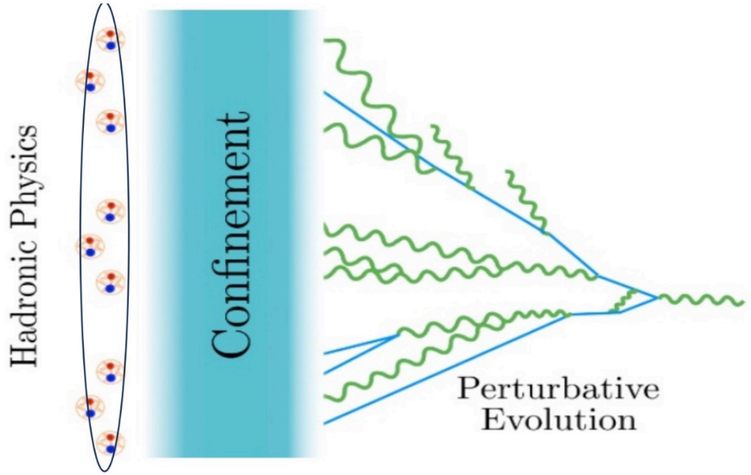
We will discuss how in the case of energy correlators, extracting these allows us to probe the strong coupling constant, α_S !

Preliminary Results: EEC

pp $\sqrt{s} = 13\ TeV$







- QCD evolution from right (perturbative partons) to left (non-perturbative, free streaming hadrons), with the peak region representing confinement transition.
- Curve shifts to the left with increasing jet p_T – elongating the perturbative regime.
- γ_2 is the anomalous dimension of EEC operator - quantum correction!
  Powers of the slope ***"Scaling behavior"***

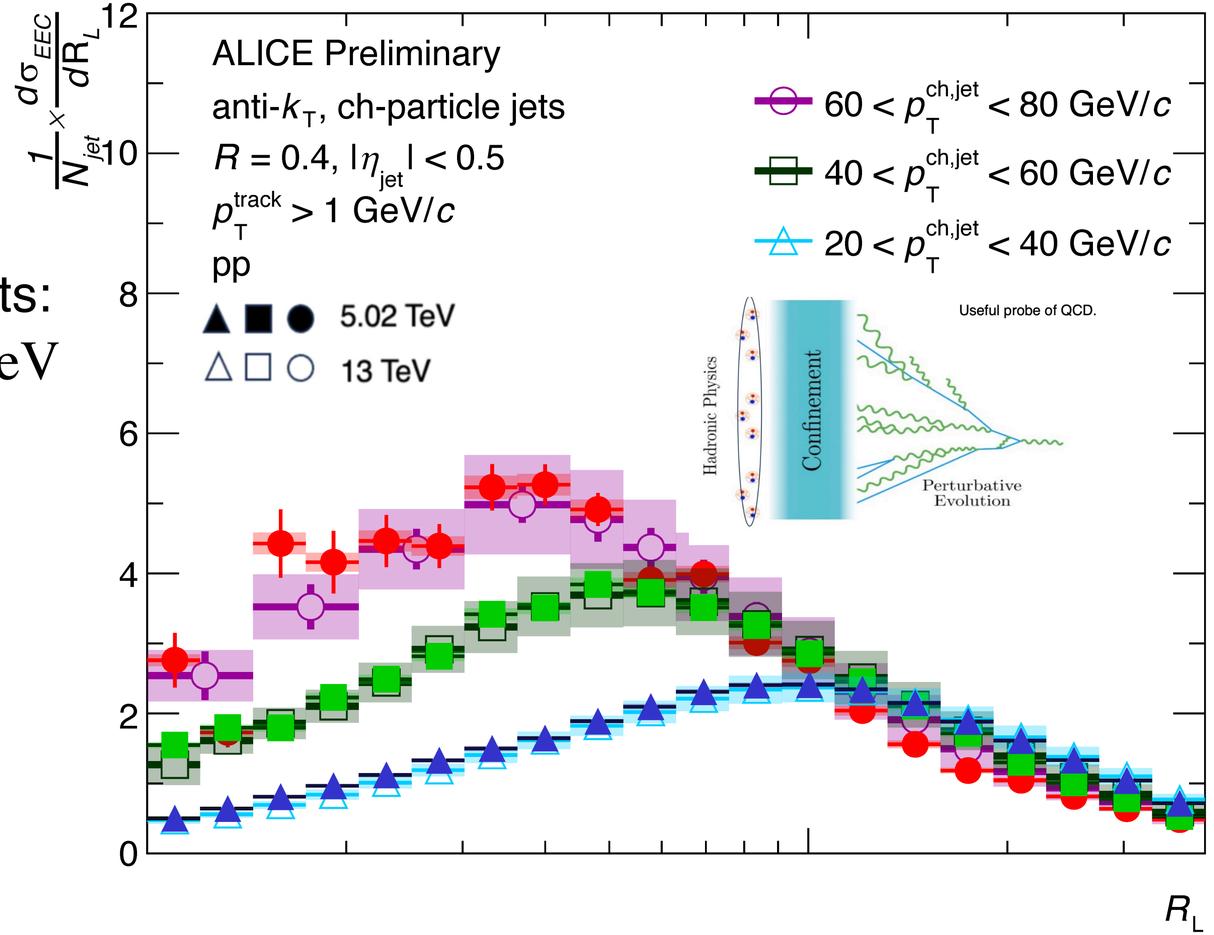
Confinement

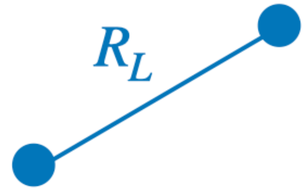
Non-perturbative ← ***Perturbative***

Preliminary Results: EEC

Dependence on $\sqrt{s}$

- Two ALICE measurements: $\sqrt{s} = 5.02$ TeV and 13 TeV

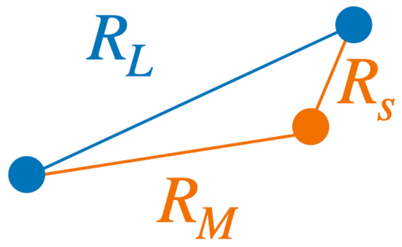




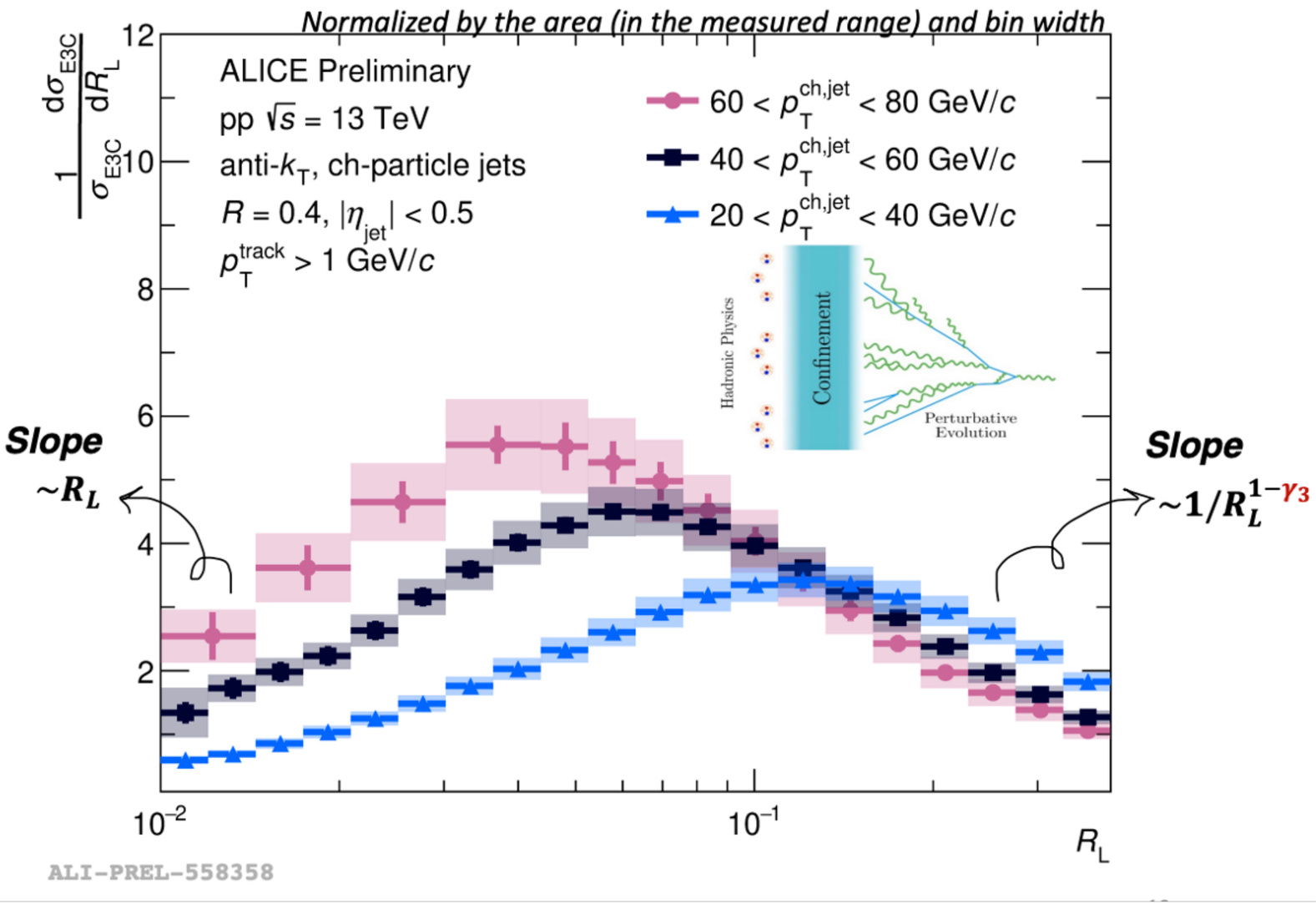
- Small dependence on $\sqrt{s}$ — **quark/gluon fractions** at play

Preliminary Results: E3C

pp $\sqrt{s} = 13\ TeV$

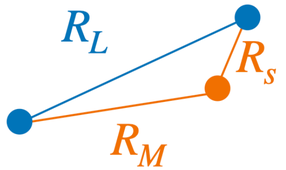


- Preserve the “size” of the correlation
- Similar behavior as the EEC
- γ_3 is the anomalous dimension of E3C operator

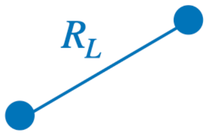


Preliminary Results: E3C/EEC Ratio

pp $\sqrt{s} = 13\ TeV$

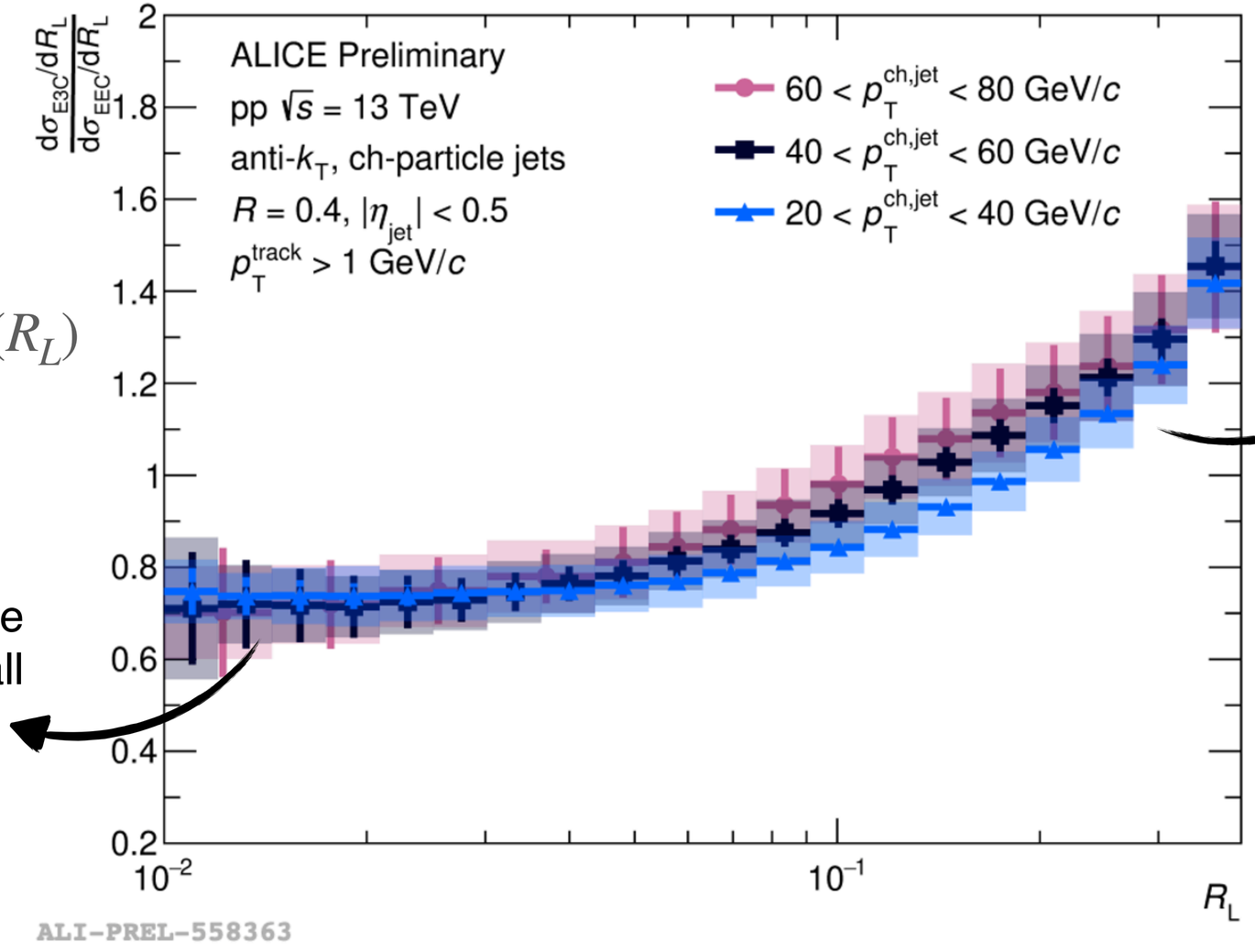


$$\propto \alpha_S ln(R_L)$$



Slope in non-perturbative regime is the same for all jet p_T bins.

- Trivial correlation in this regime comes from free streaming hadrons



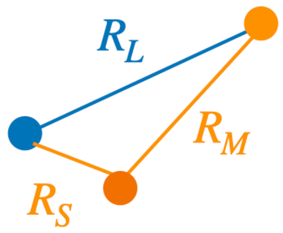
Both E3C & EEC are normalized by the area (in the measured range) and bin width.

Slope in perturbative regime ~ $R_L^{\gamma_3-\gamma_2}$

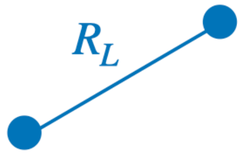
- Change in slope **indicative of running of coupling**
- pQCD prediction: $\gamma_{N+1} > \gamma_N$ Reproduced in data!

α_S extraction : E3C/EEC Ratio

pp $\sqrt{s} = 13\ TeV$

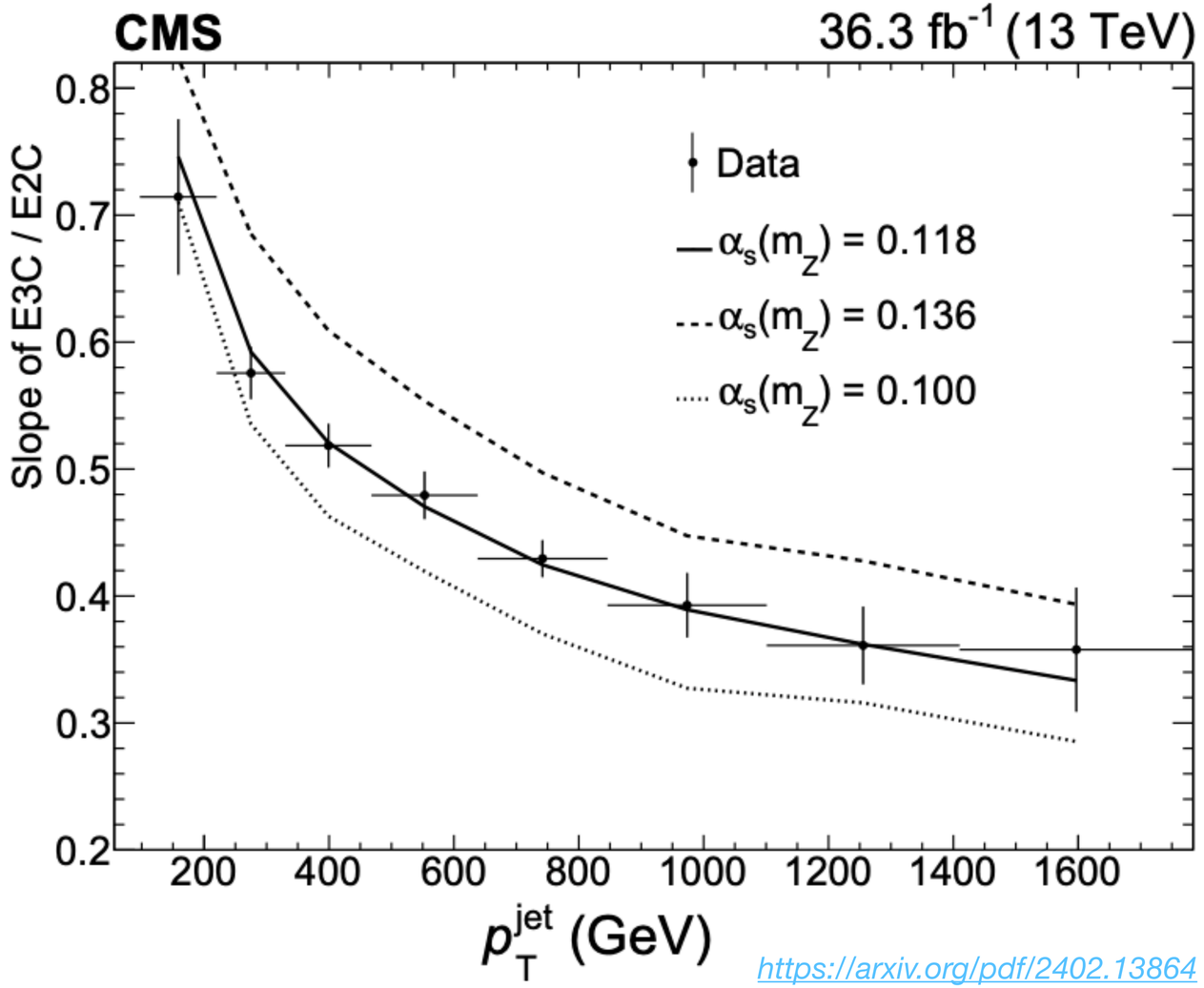


$$\propto \alpha_S ln(R_L)$$



$$\alpha_S(m_Z) = 0.1229^{+0.0014}_{-0.0012}\,(\text{stat})^{+0.0030}_{-0.0033}\,(\text{theo})^{+0.0023}_{-0.0036}(\text{exp})$$

4% precision!

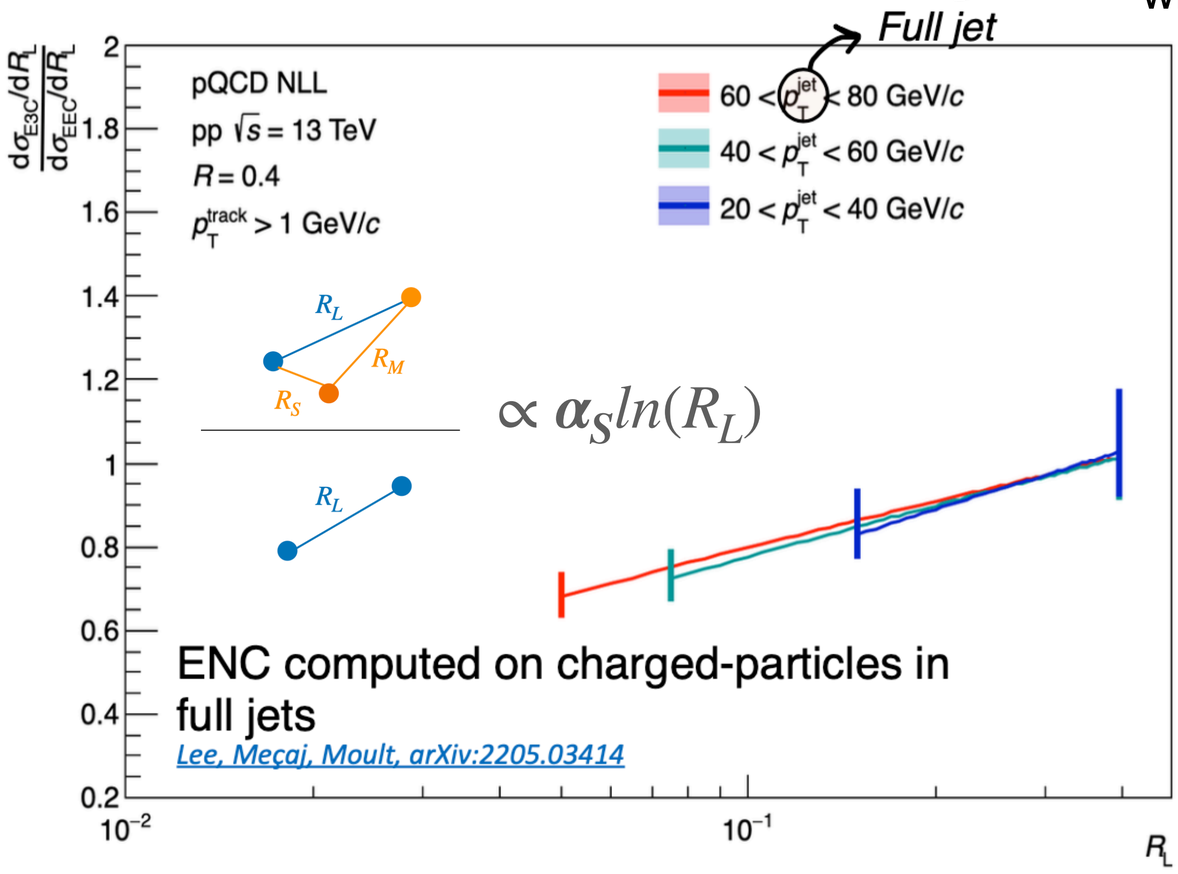


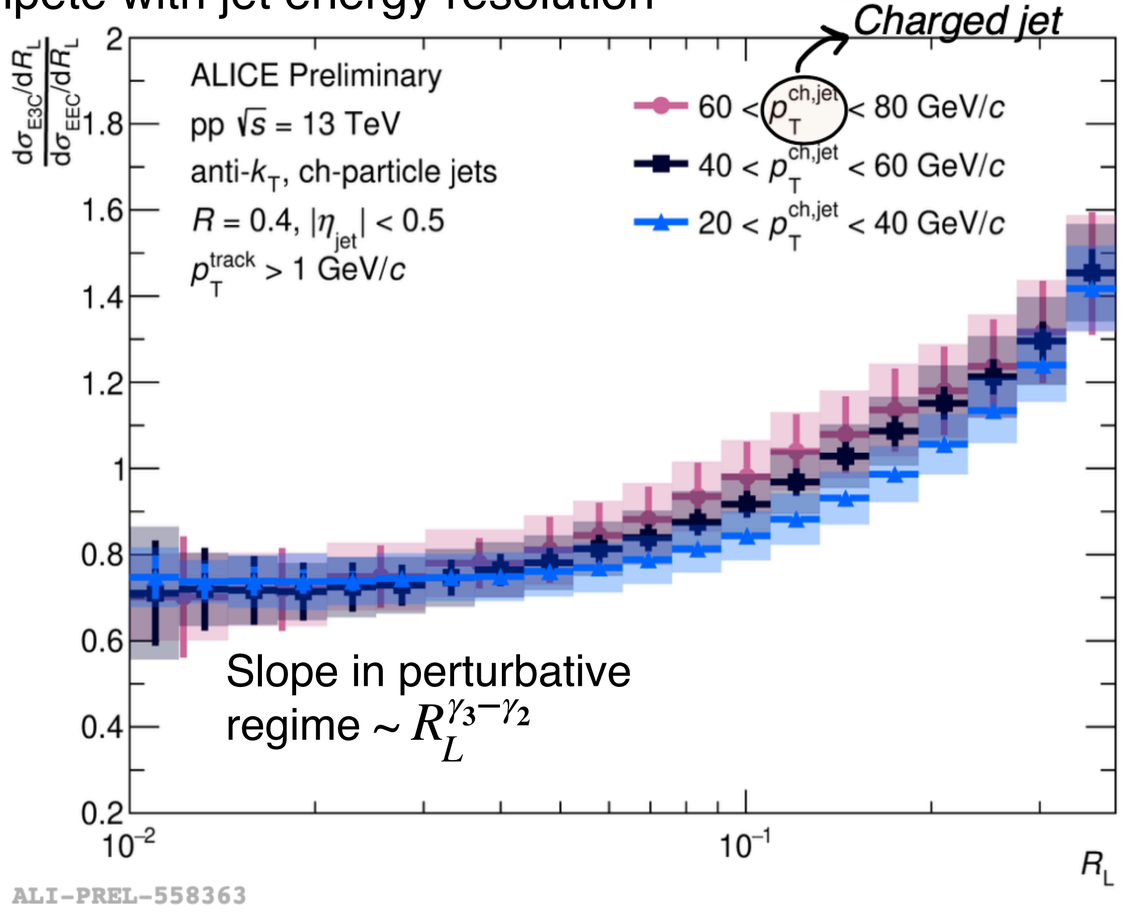
https://arxiv.org/pdf/2402.13864

α_S extraction : E3C/EEC Ratio

pp $\sqrt{s} = 13\ TeV$

Cause uncertainty in mapping, will compete with jet energy resolution

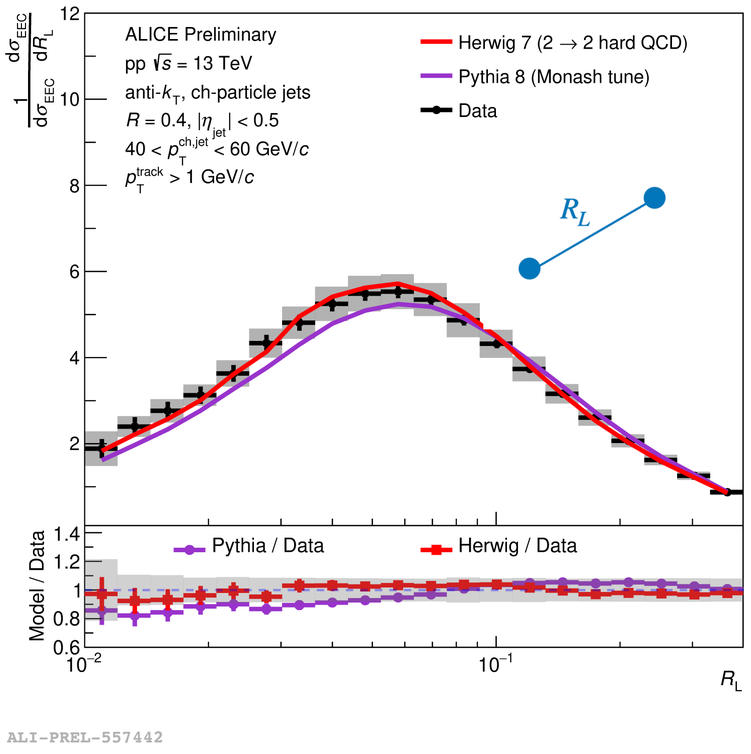




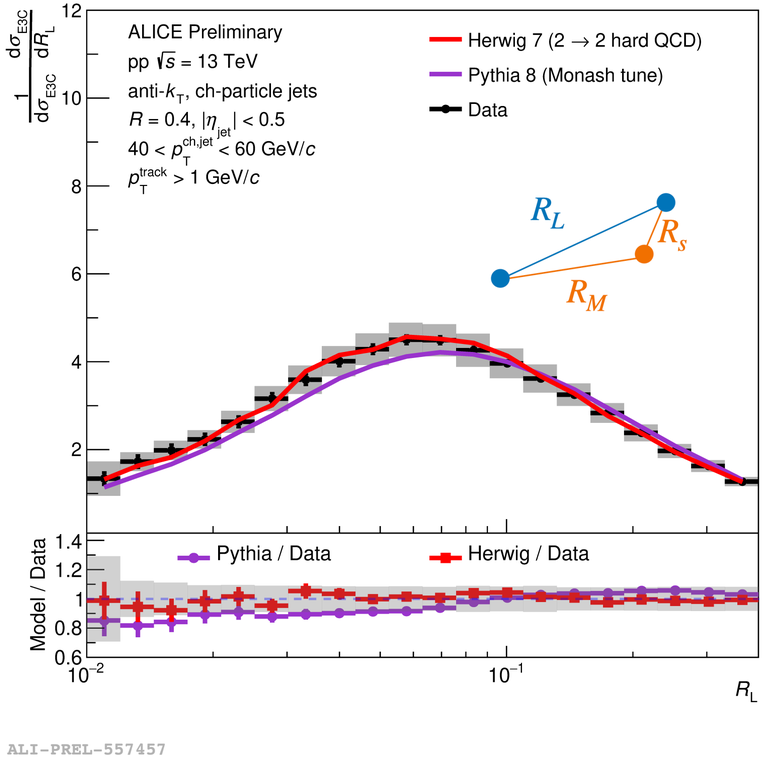
- **Trends between theory and data agree**
- Current work: extracting the anomalous dimensions and attempting to map them to α_S

Comparison to MC generators

pp $\sqrt{s} = 13\ TeV$



ALI-PREL-557442



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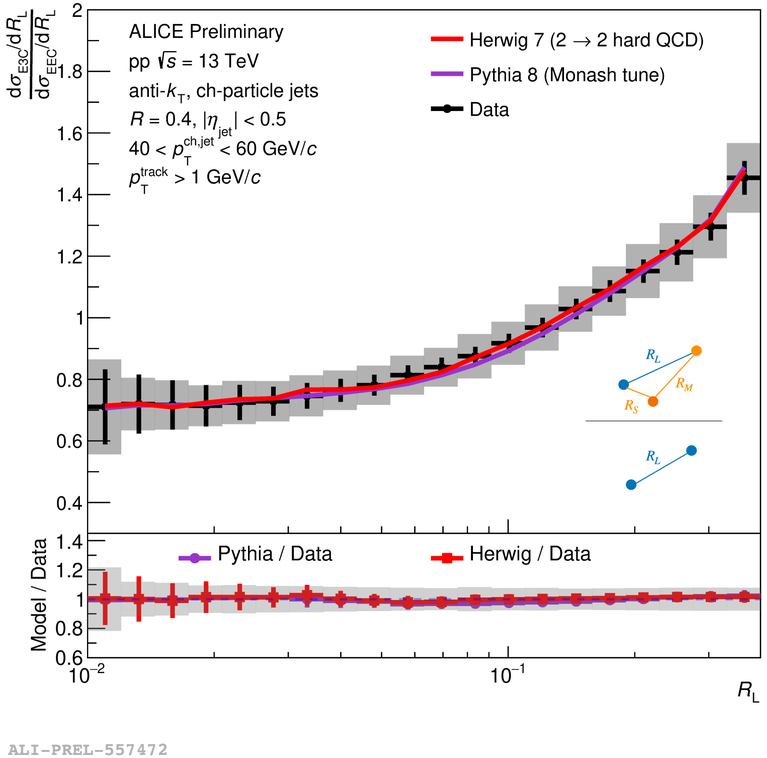


ALI-PREL-557472

- Herwig shows better agreement than Pythia for EEC and E3C. Differences are more pronounced in the hadronization region.
- The ratio to MC sits at unity for E3C/EEC — signifying that non-perturbative power corrections cancel and E3C/EEC isolates perturbative physics.

Ongoing work

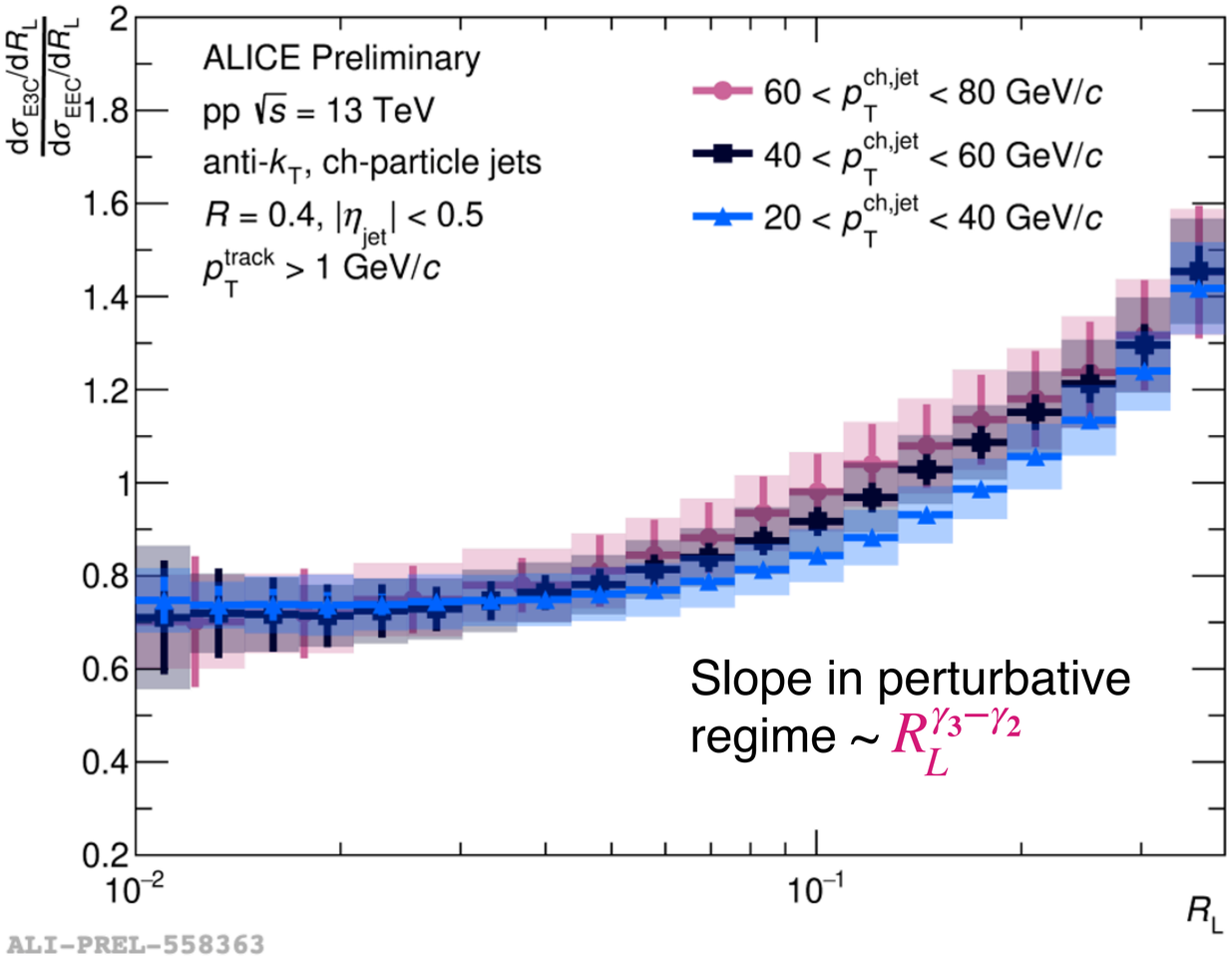
pp $\sqrt{s} = 13\ TeV$

- Preliminary results used ***bin-by-bin*** correction method (possible due to excellent R_{L} resolution at ALICE)

$$f_{corr}\left(R_L^{det}, p_{\mathrm{T,jet}}^{det}\right) = ENC_{det}/ENC_{true}$$

$$ENC_{true}\left(p_{\mathrm{T,jet}}^{true}\right) = (1/f_{corr})ENC_{det}(p_{\mathrm{T,jet}}^{det})$$

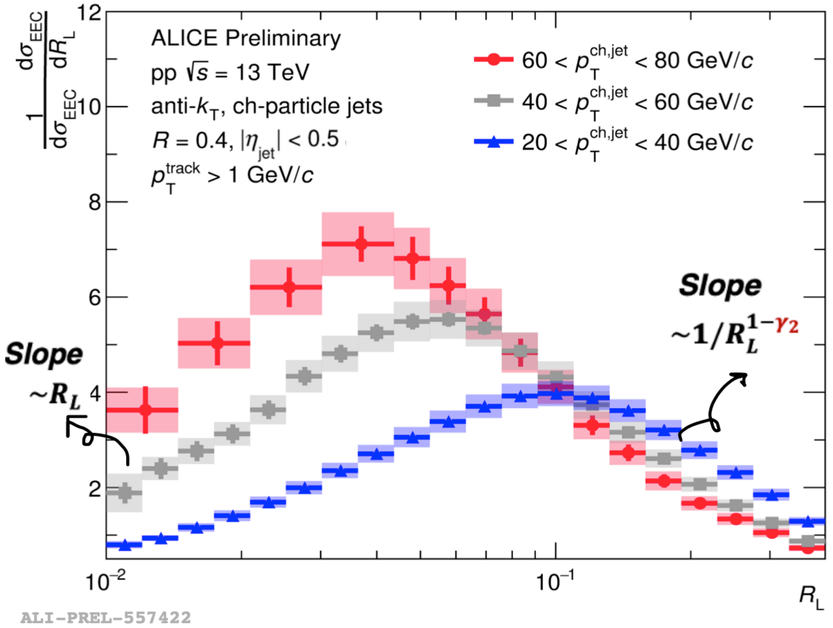
- Unfold to extract anomalous dimensions and relate to α_{S}.

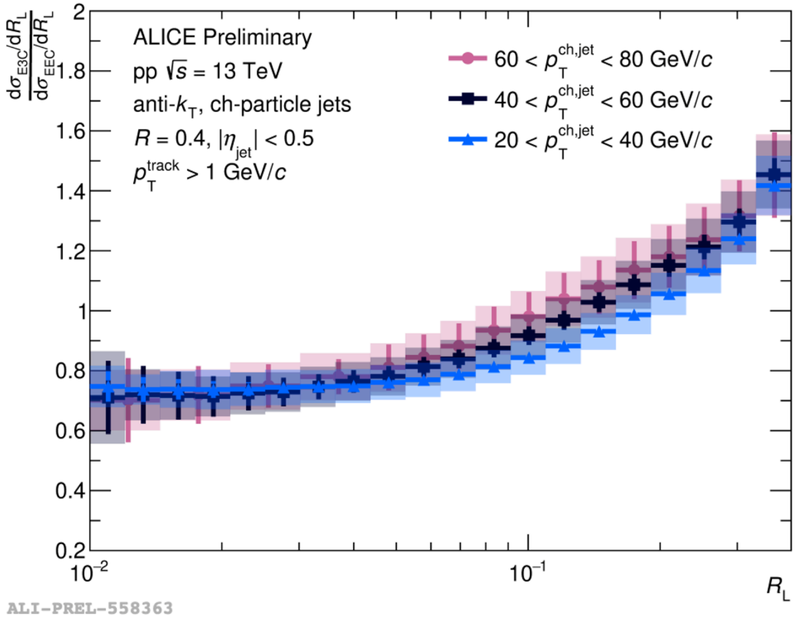


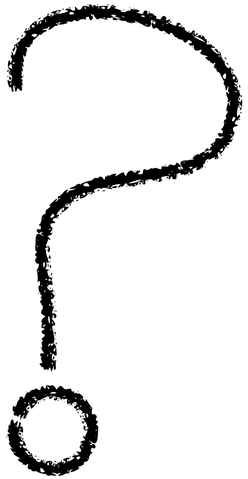
Both E3C & EEC are normalized by the area (in the measured range) and bin width.

Goal: Extract the anomalous dimensions γ_3 and γ_2

Summary and Outlook
Energy Correlators in vacuum QCD and beyond







Energy Correlators show clear ***separation of energy scales*** inside jets

Ratios of projected correlators are ***sensitive to running of the strong coupling,*** α_S. We can extract the slopes of E3C/EEC and relate them to α_S.

Energy correlators in the QGP

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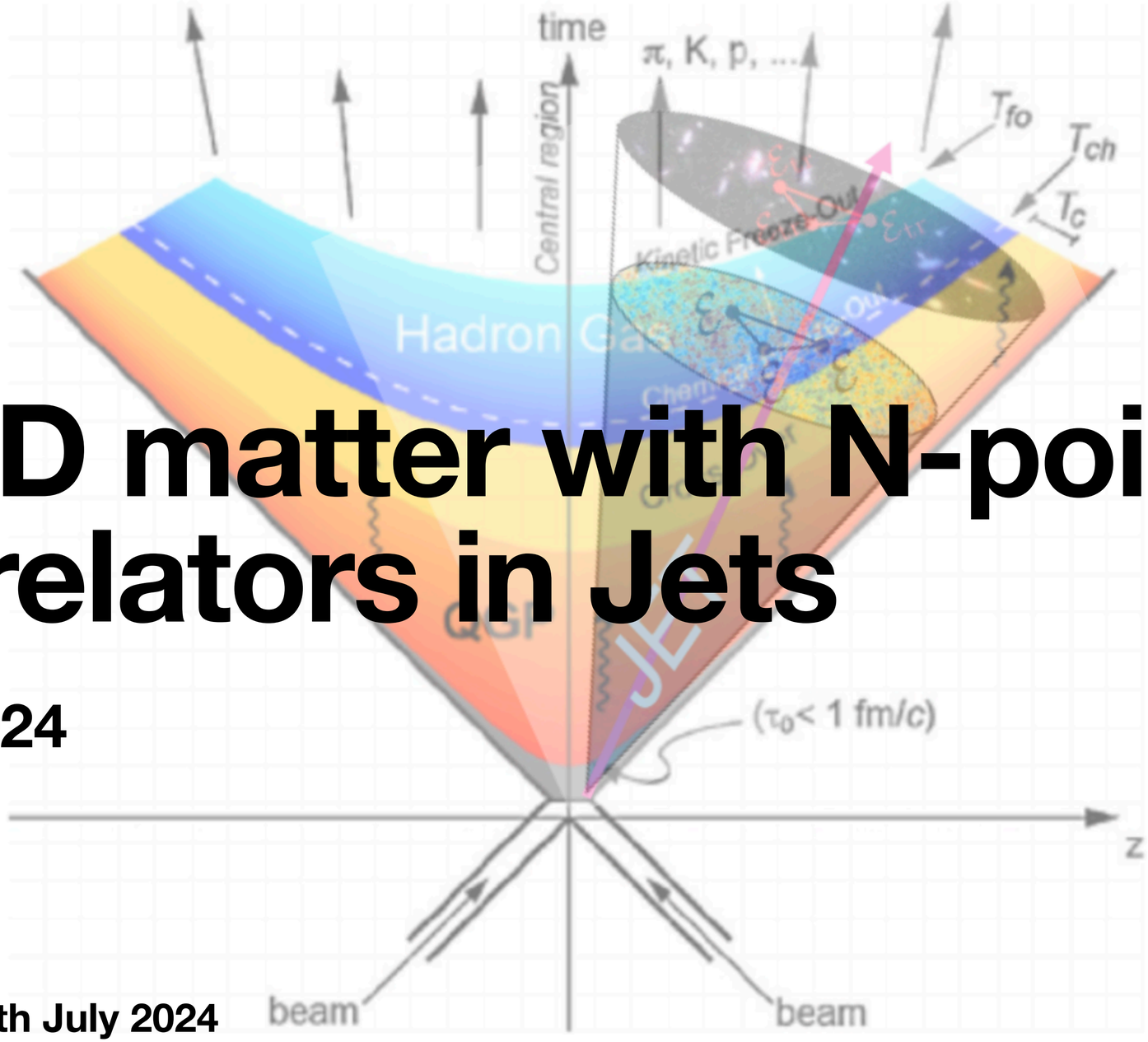


Probing QCD matter with N-point Energy Correlators in Jets

MITP EEC Workshop 2024

Ananya Rai (on behalf of herself), 10th July 2024

**Based on work with Hannah Bossi (MIT), Arjun Kudinoor (Cambridge → MIT), Ian Moult (Yale), Daniel Pablos (Santiago), Krishna Rajagopal (MIT)*

LUX ET VERITAS

Energy Correlators in Heavy Ion Collisions

Active area of research!

Resolving the Scales of the Quark-Gluon Plasma with Energy Correlators

Carlota Andres,[1] Fabio Dominguez,[2] Raghav Kunnawalkam Elayavalli,[3,4,5] Jack Holguin,[1] Cyrille Marquet,[1] and Ian Moult[6]

[1] *CPHT, CNRS, Ecole polytechnique, IP Paris, F-91128 Palaiseau, France*
[2] *Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela 15782, Spain*
[3] *Wright Laboratory, Yale University, New Haven, CT*
[4] *Brookhaven National Laboratory, Upton NY*
[5] *Dep...*

A Coherent View of the Quark-Gluon Plasma from Energy Correlators

Carlota Andres,[a] **Fabio Dominguez,**[b] **Jack Holguin,**[a] **Cyrille Marquet,**[a] **Ian Moult**[c]

[a] *CPHT, CNRS, École polytechnique, Institut Polytechnique de Paris, 91120 Palaiseau, France*
[b] *Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela 15782, Spain*

Probing the Short-Distance Structure of the Quark-Gluon Plasma with Energy Correlators

Zhong Yang,[1] Yayun He,[2,3] Ian Moult,[4] and Xin-Nian Wang[1,5]

[1] *Key Laboratory of Quark and Lepton Physics (MOE) and Institute of Particle Physics, Central China Normal University, Wuhan 430079, China*
[2] *Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Q...*

Seeing Beauty in the Quark-Gluon Plasma with Energy Correlators

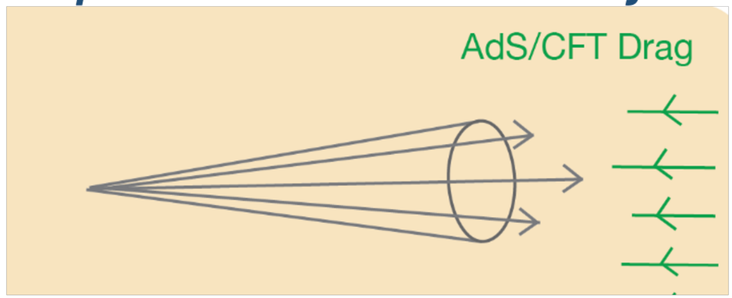
Carlota Andres,[1] Fabio Dominguez,[2] Jack Holguin,[1] Cyrille Marquet,[1] and Ian Moult[3]

[1] *CPHT, CNRS, École polytechnique, Institut Polytechnique de Paris, 91120 Palaiseau, France*
[2] *Instituto Galego de Física de Altas Enerxías (IGFAE), Universidade de Santiago de Compostela, Santiago de Compostela 15782, Spain*
[3] *Department of Physics, Yale University, New Haven, CT 06511*

Energy Correlators in Heavy Ion Collisions

Looking for interesting physics

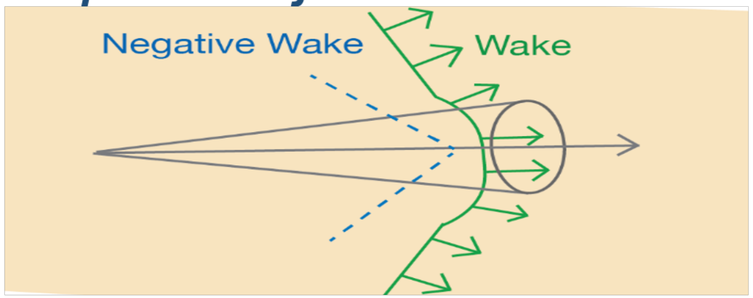
Impact of medium on jet



"Jet Energy Loss"

Drag Force

Impact of jet on medium



"Medium Response"

Hydrodynamic Wake

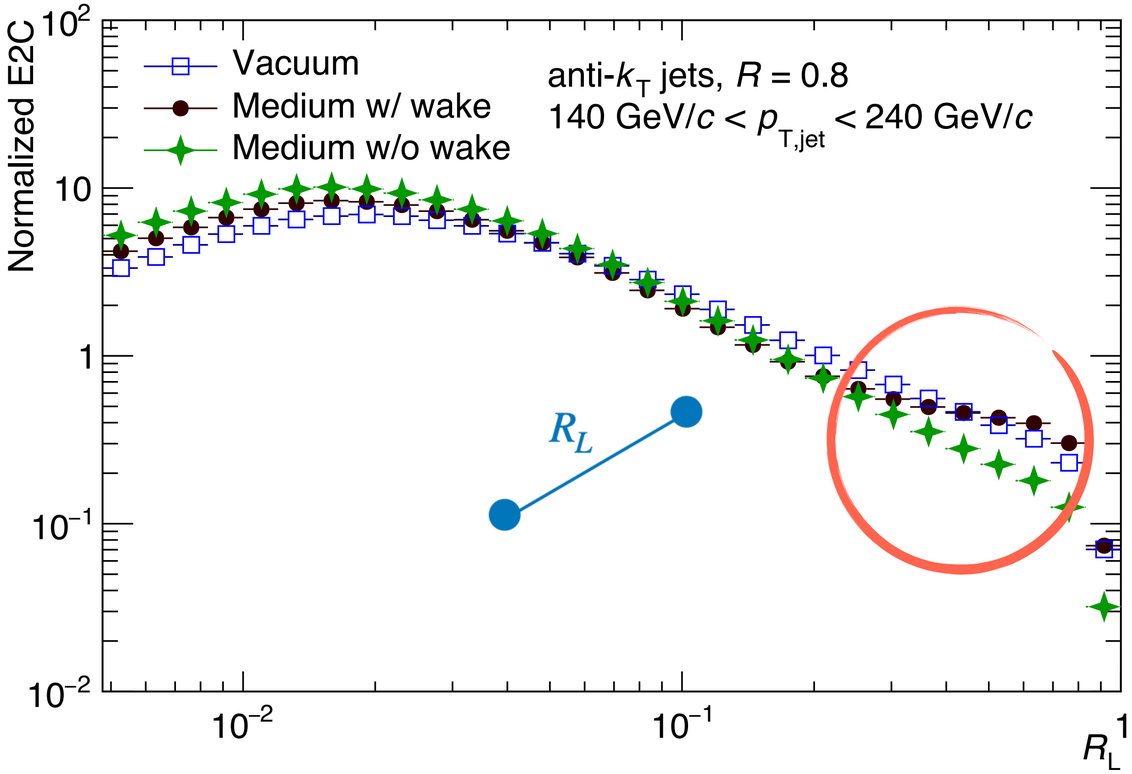
- Can we measure the medium response with energy correlators?
- What is the best observable for experiments?

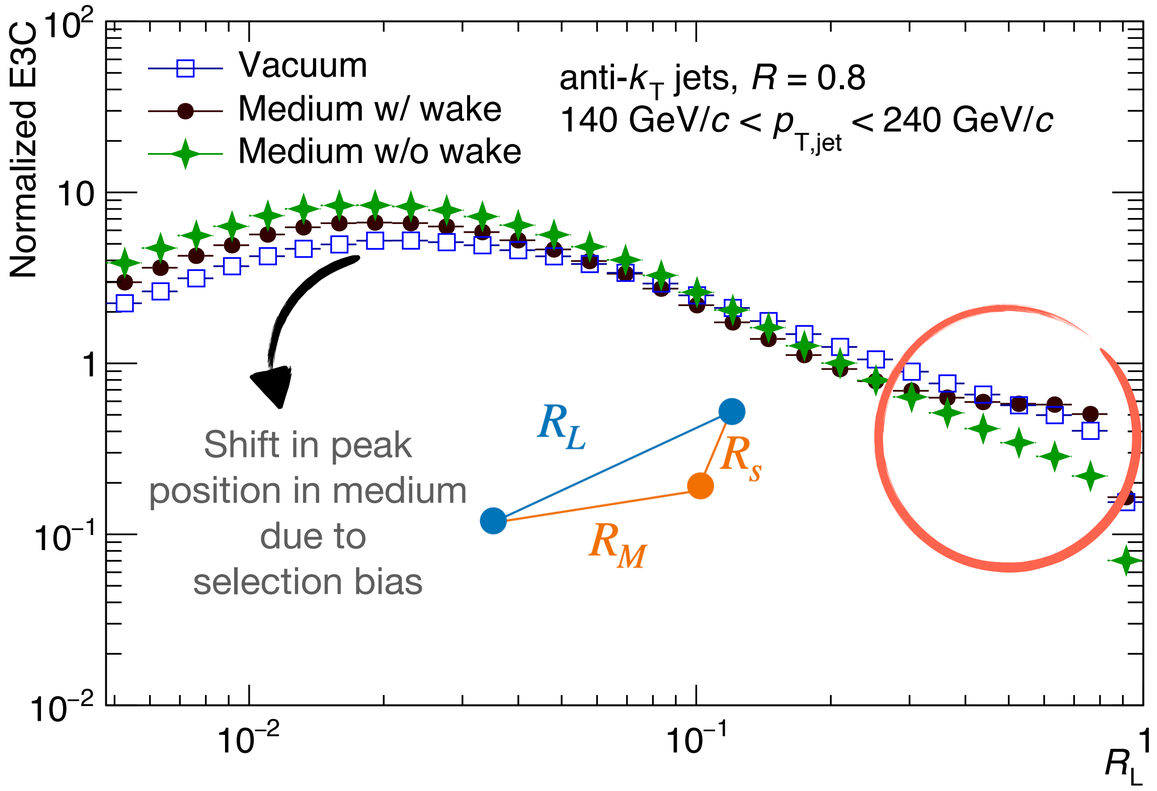
E2C and E3C in Heavy Ion Collisions

Looking for interesting physics

Wake effects appear at ***large angles***

Effects are further ***enhanced*** for E3C!

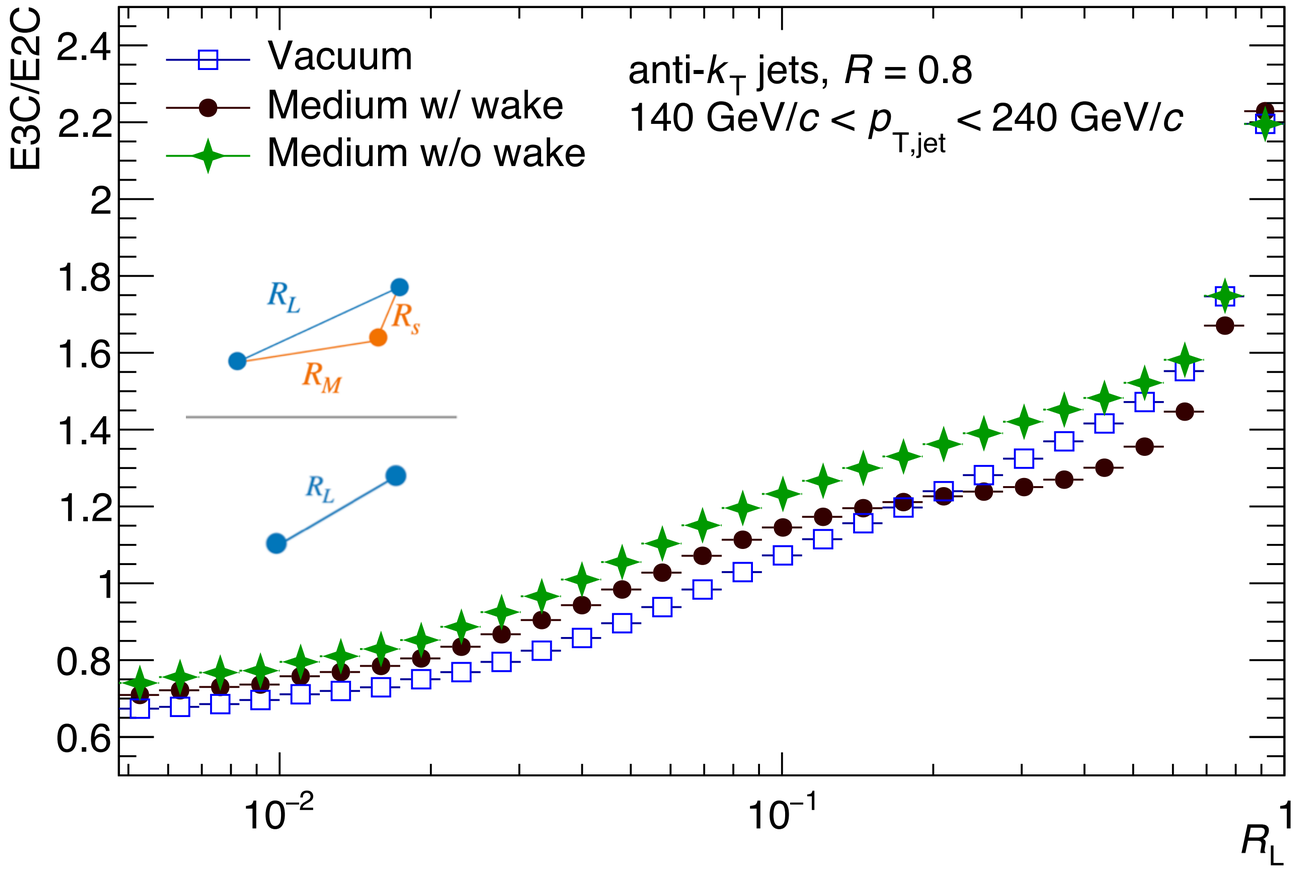




***Green (solid diamonds) curve implements unphysical energy loss*

E3C/E2C in Heavy Ion Collisions

Looking for interesting physics

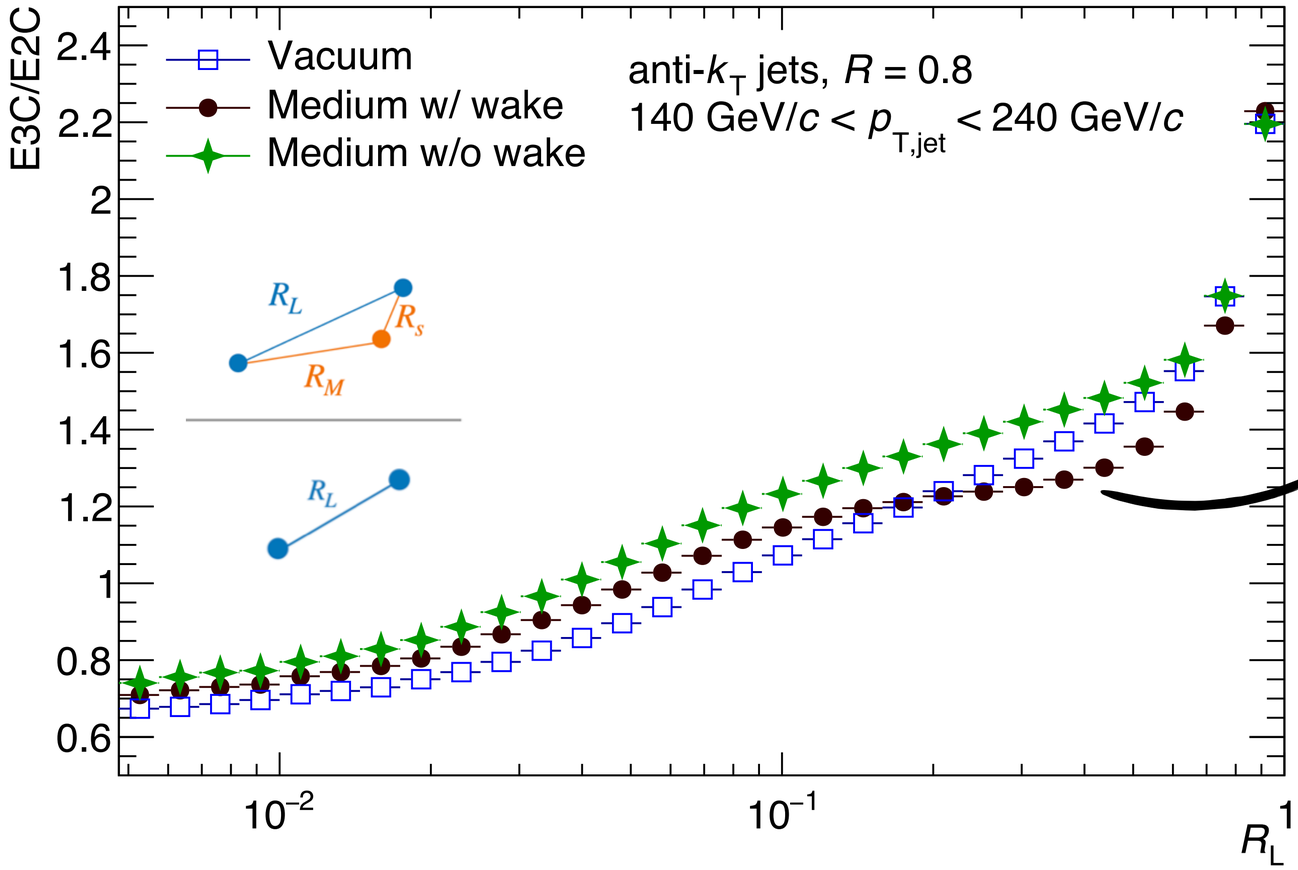


- We see deviation from vacuum behavior at **large** R_L
- **Experimentally interesting** because ratios are more robust to detector effects!
- Ratios will also cancel some uncorrelated background effects

***Green (solid diamonds) curve implements unphysical energy loss*

E3C/E2C in Heavy Ion Collisions

Some open questions



- We see deviation from vacuum behavior at **large** R_L
- **We think that this "flat" region corresponds to the presence of the wake**
- In pp, we access the anomalous dimensions of vacuum QCD. How should we interpret the scalings in this picture here?

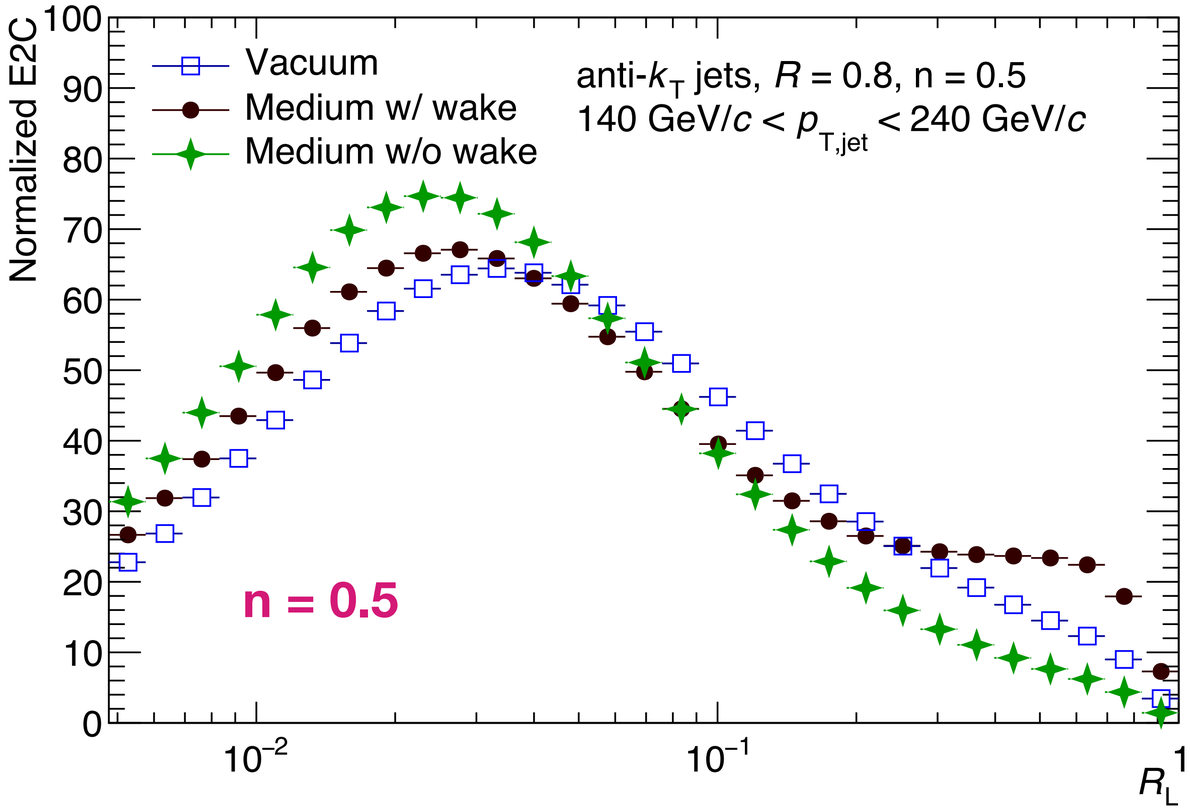
***Green (solid diamonds) curve implements unphysical energy loss*

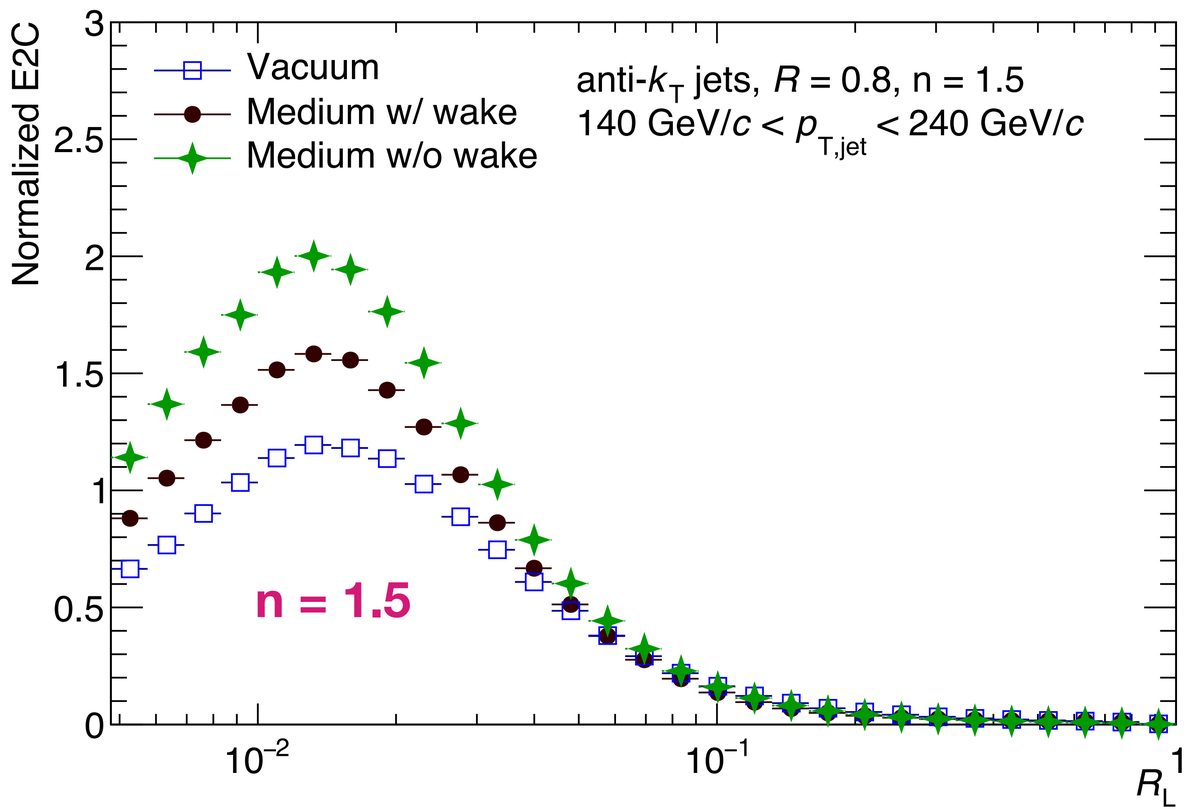
Tuning the wake signal: E2C

Enhancing and suppressing soft physics

$$\text{Energy Weight} = \frac{1}{(E_{\text{jet}})^{(n*N)}} \langle \mathscr{E}^n(\vec{n}_1)\mathscr{E}^n(\vec{n}_2)\ldots\mathscr{E}^n(\vec{n}_N)\rangle$$

We can tune the correlator to **isolate** hard or soft physics via energy weights!

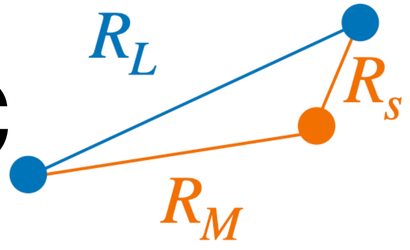




**By doing so we lose IRC safety and become more susceptible to non-perturbative effects*

Tuning the wake signal: E3C

Enhancing and suppressing soft physics



Energy Weight = $\frac{1}{(E_{\text{jet}})^{(n*N)}} \langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\ldots\mathcal{E}^n(\vec{n}_N)\rangle$

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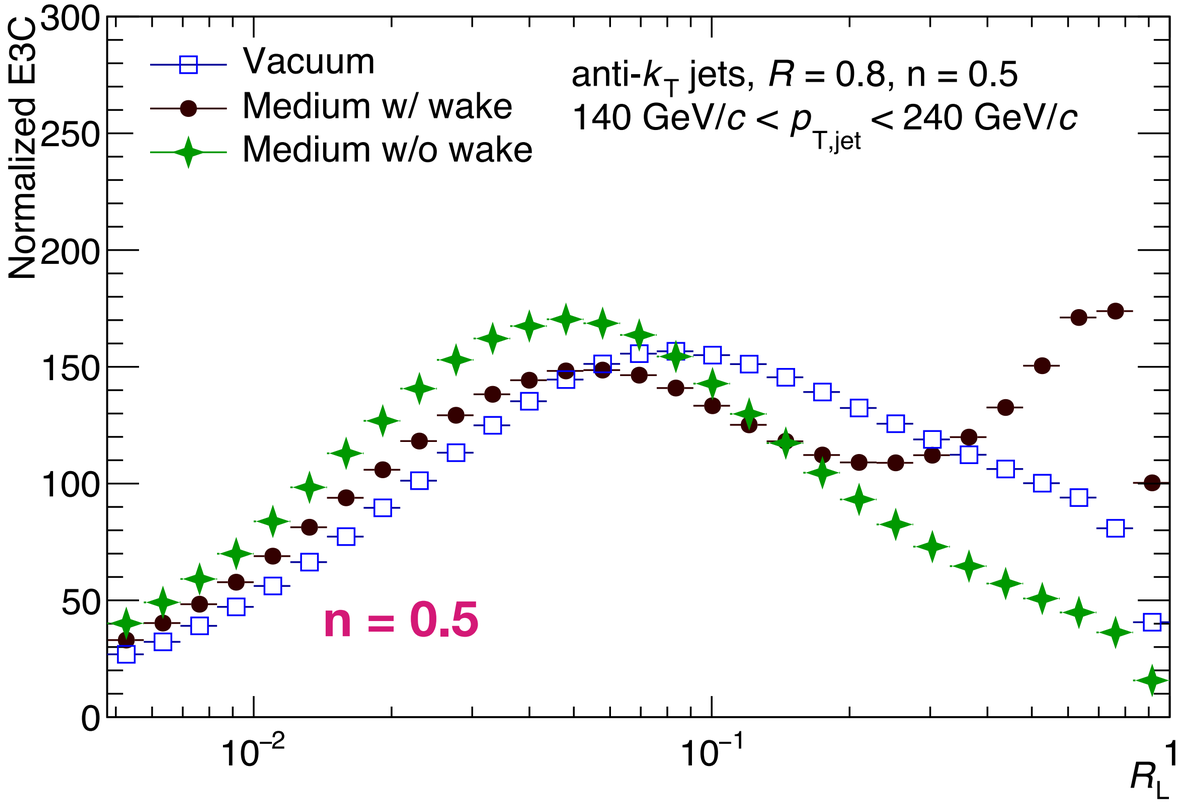
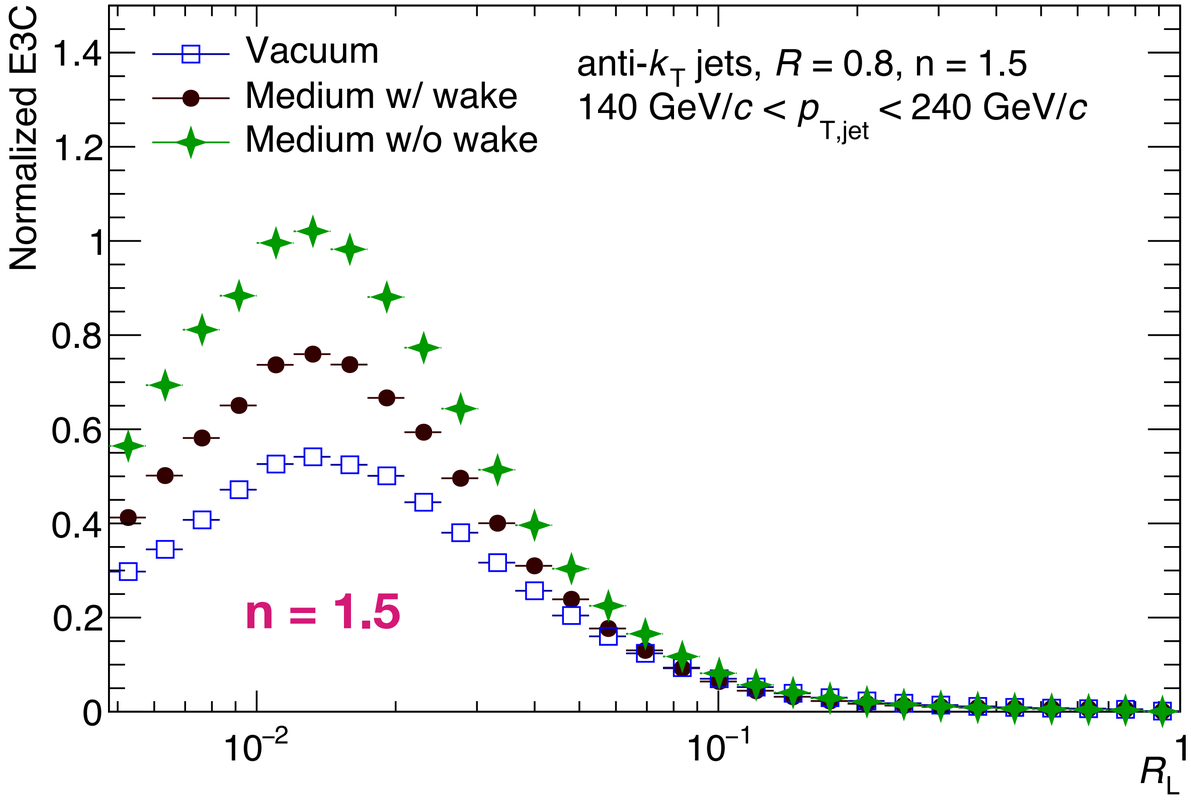
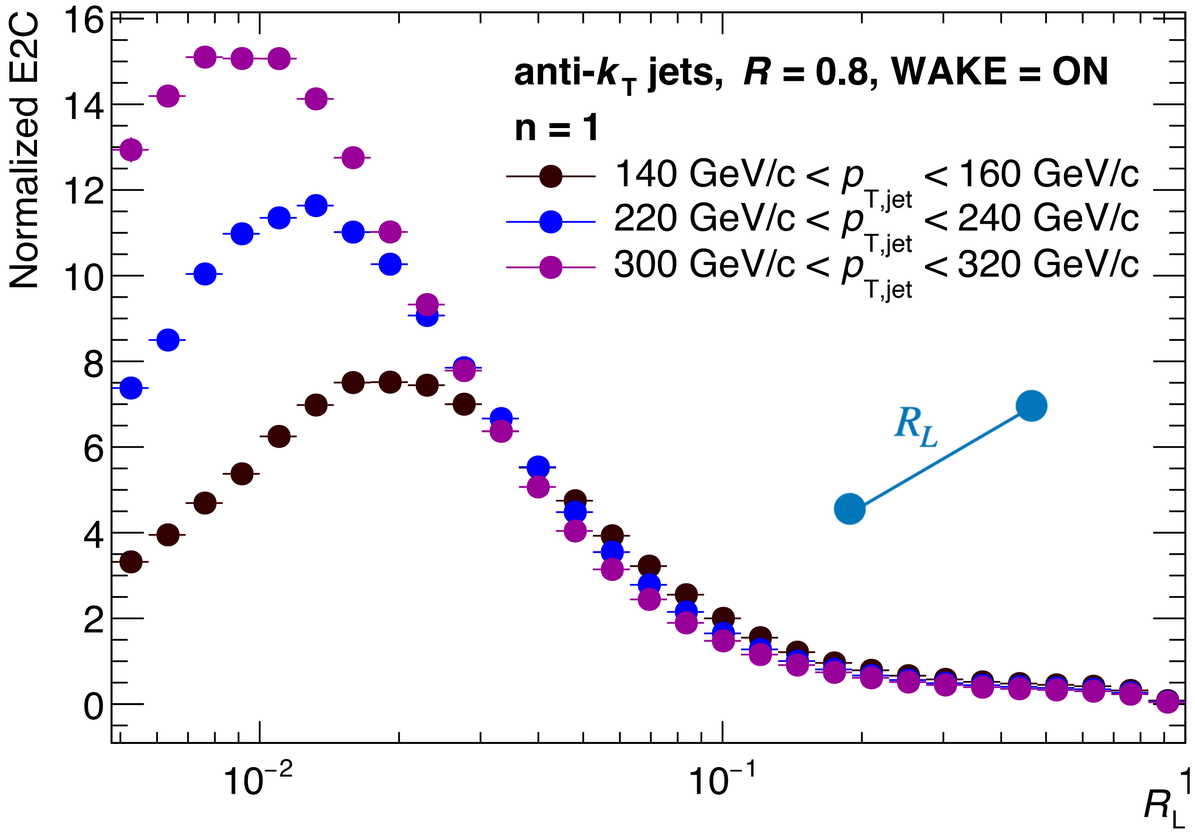


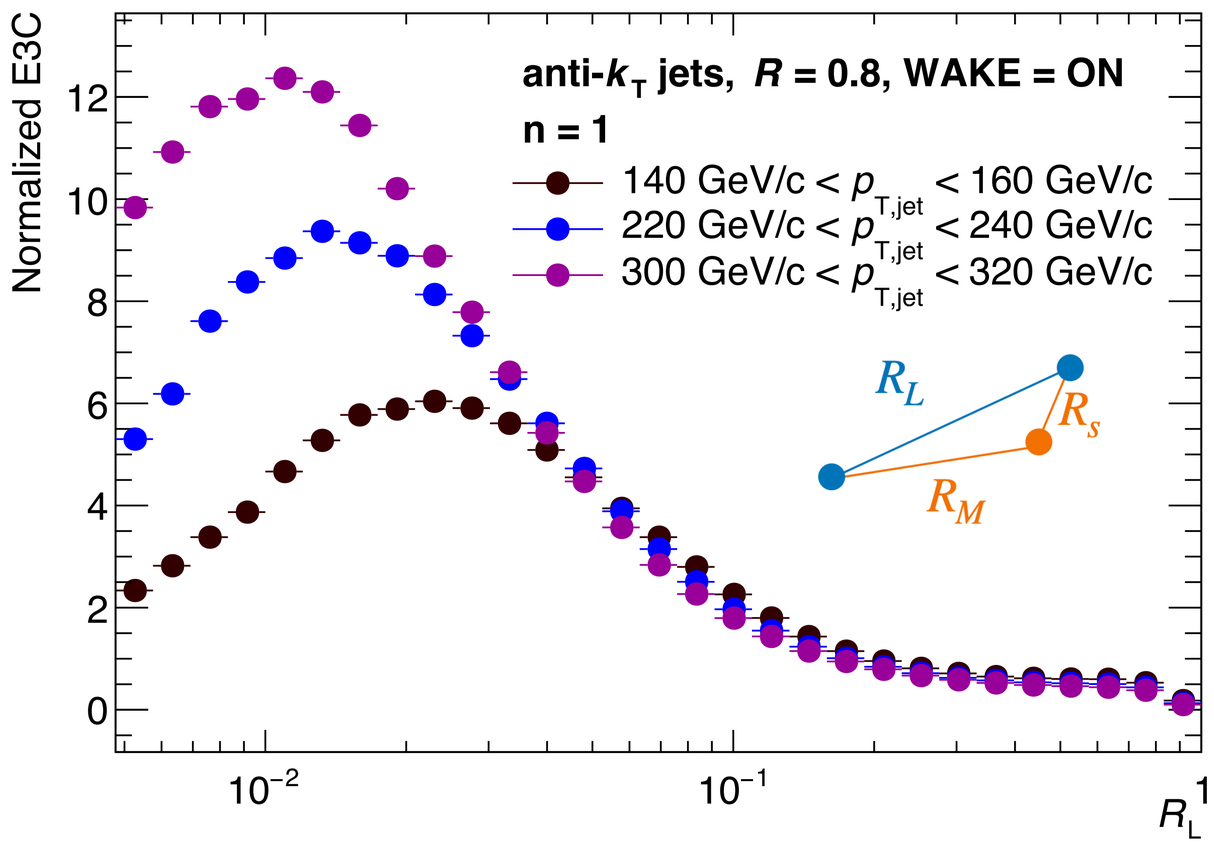


Studying jet p_{T} dependence

n = 1

Expectation: Lower p_{T} jets should show more medium modification



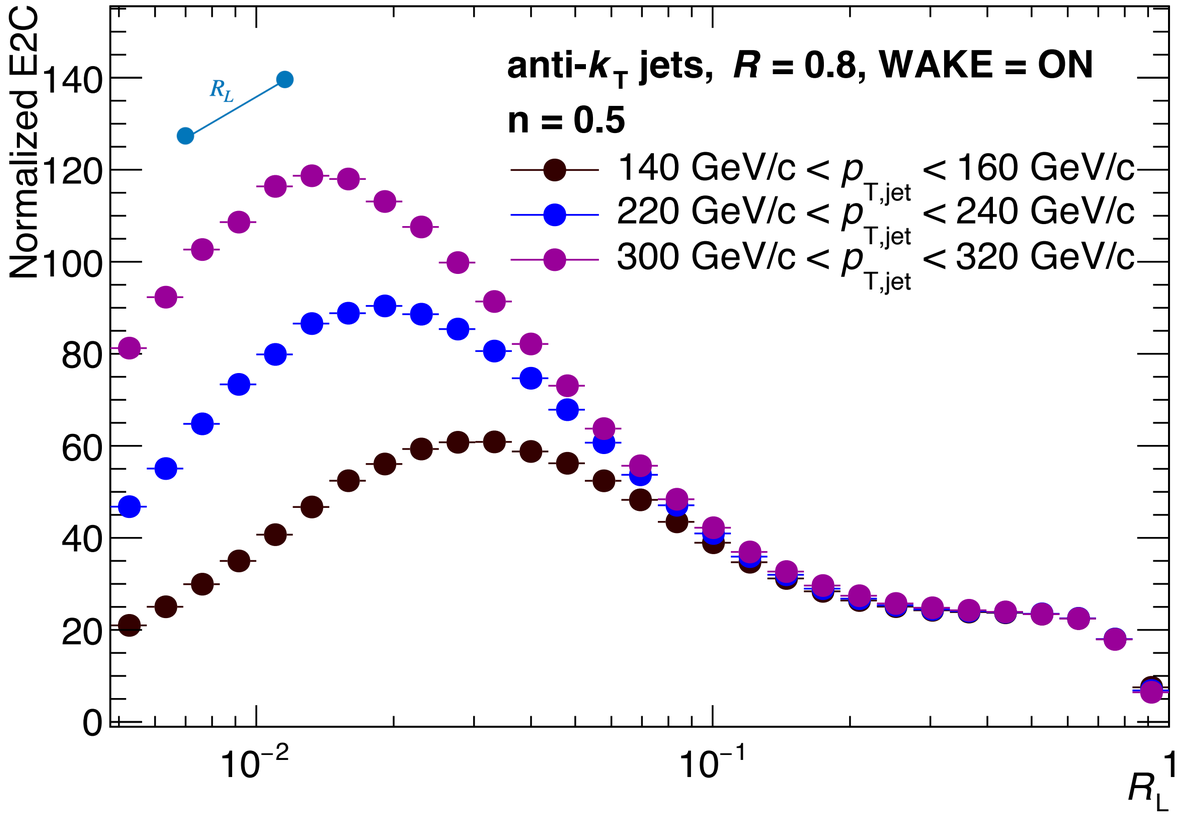


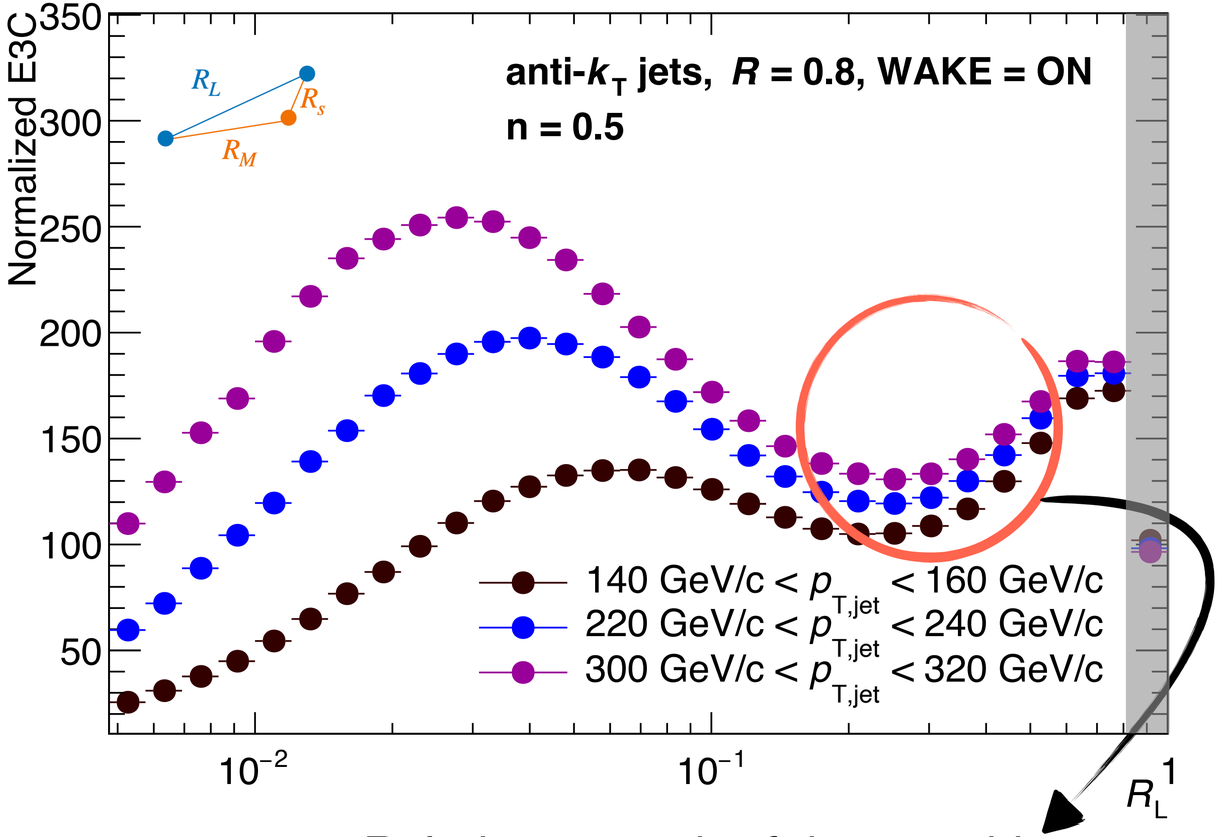
Difficult to see any differences by eye for both the E2C and E3C

Studying jet p_{T} dependence

n = 0.5

Expectation: Lower p_{T} jets should show more medium modification ✓



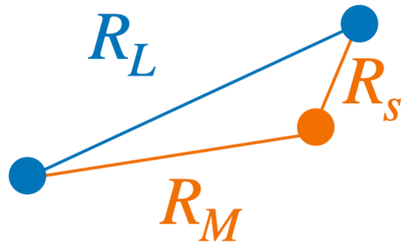


Relative to peak of the transition

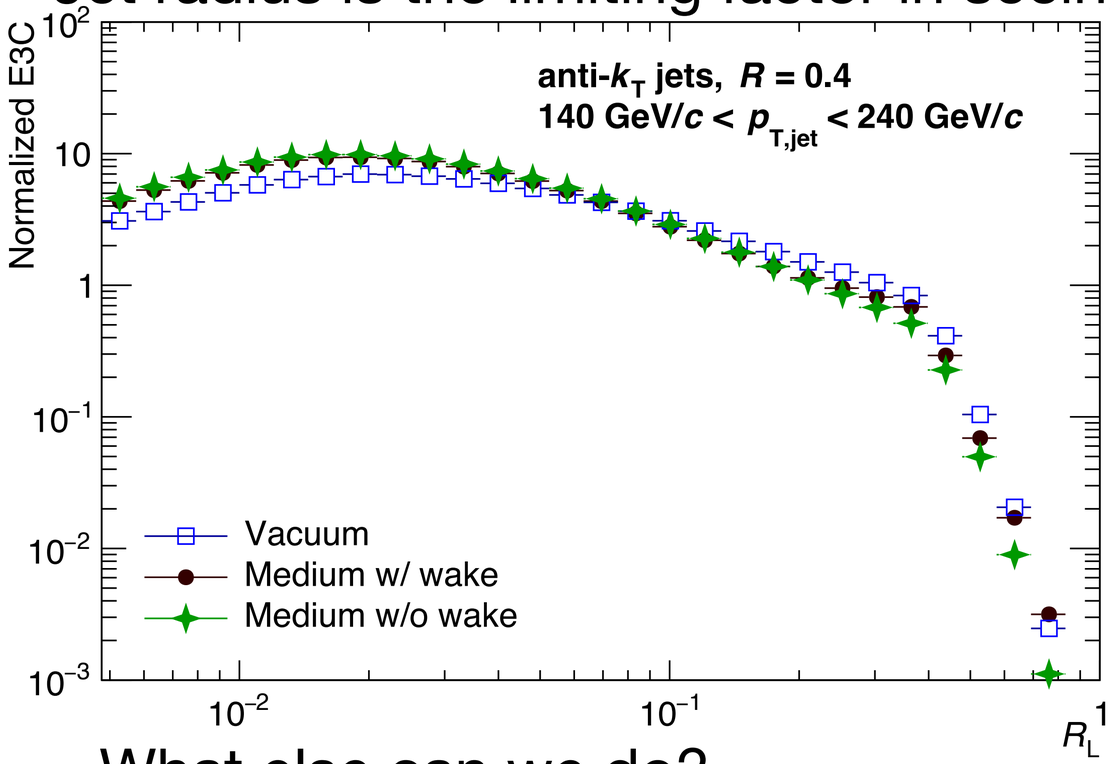
largest effect for lowest jet p_{T} bin

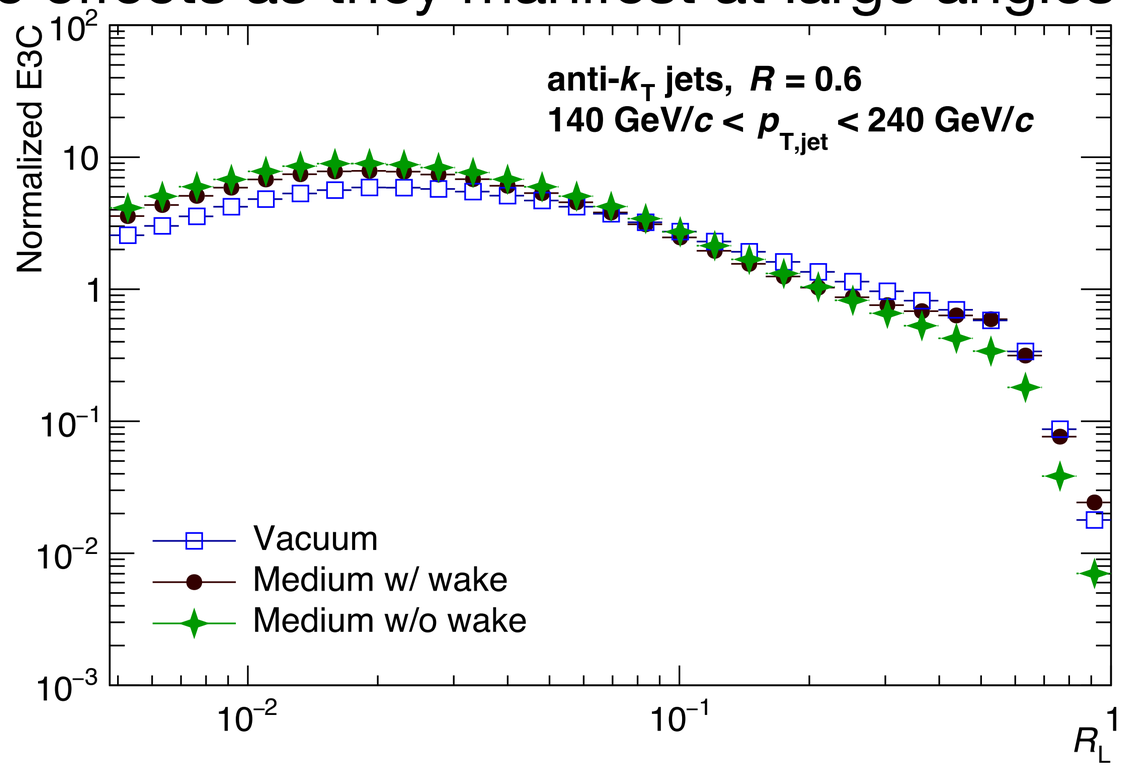
Studying R dependence

Can we see the wake?



Jet radius is the limiting factor in seeing wake effects as they manifest at large angles



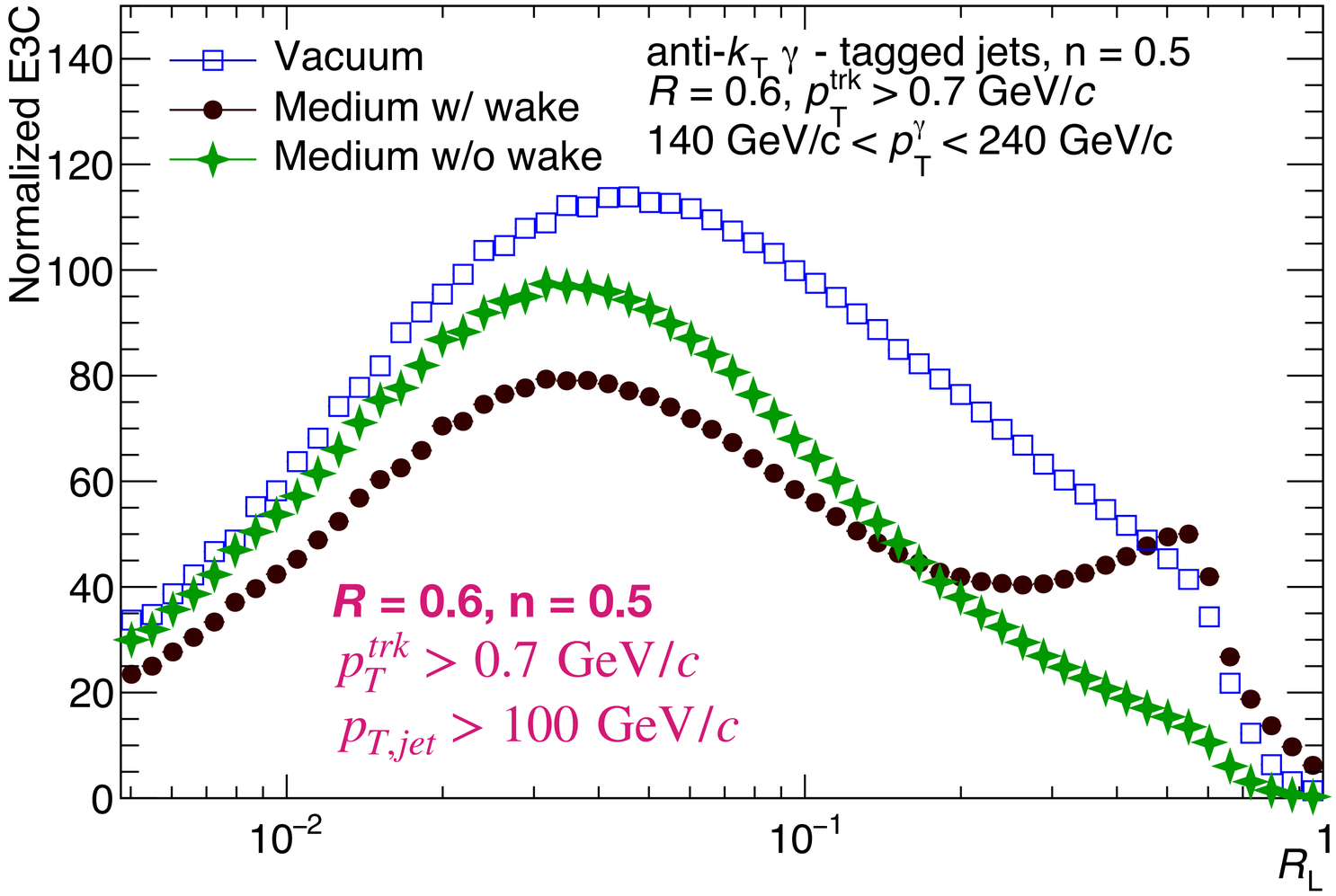


What else can we do?

- a radial profile measurement
- γ/Z-hadron correlations instead of jets to maximize effect (***Yen-Jie's talk on Monday***)

Experimental Outlook

How to maximize signal in data



Can turn knobs to see medium response effects at smaller *R*!

See Jussi's talk on Friday for results on E2C in data!

More to come, stay tuned!

What next?

We have identified the scale of the medium response (wake) using projected N-point correlators. Can we use the full EEEC to uniquely identify the wake?

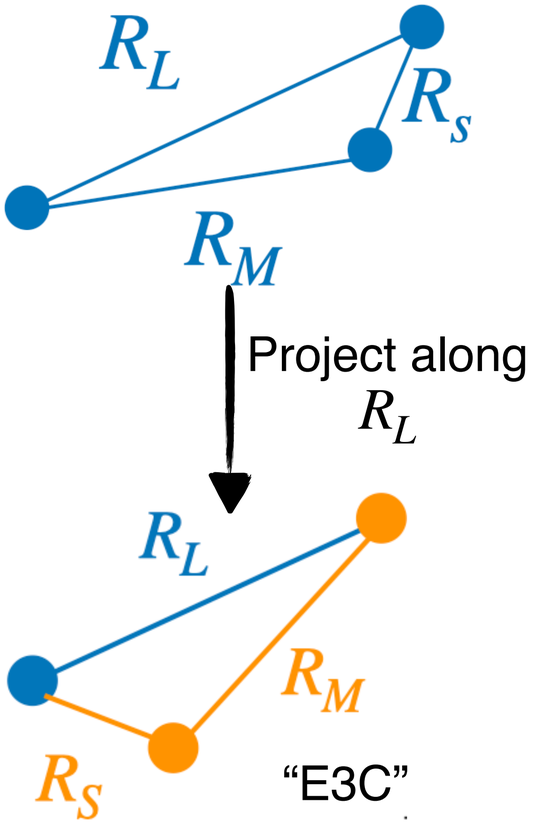
Hannah's talk! 

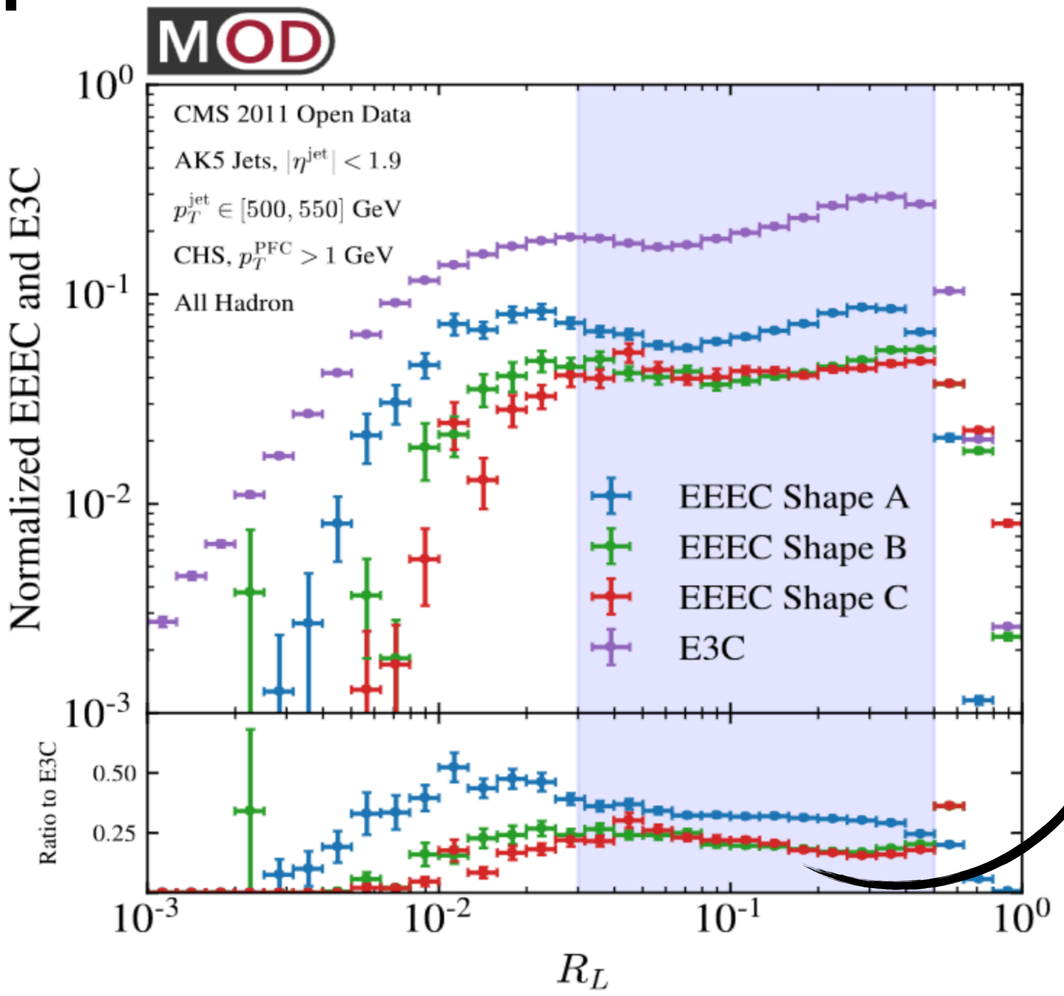
Backup

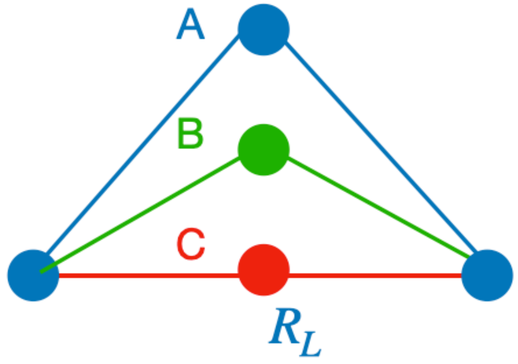
Higher Point Projected Correlators in Jets

Definition & Motivation

* Shape dependence of energy flow & 1→3 splittings



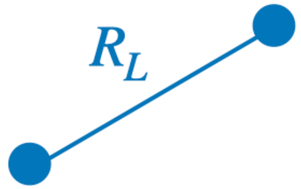




* **Flat ratio**: E3C encodes the behavior of the EEEC (yet to be verified experimentally!)

Tuning the wake signal: E2C

Enhancing and suppressing soft physics



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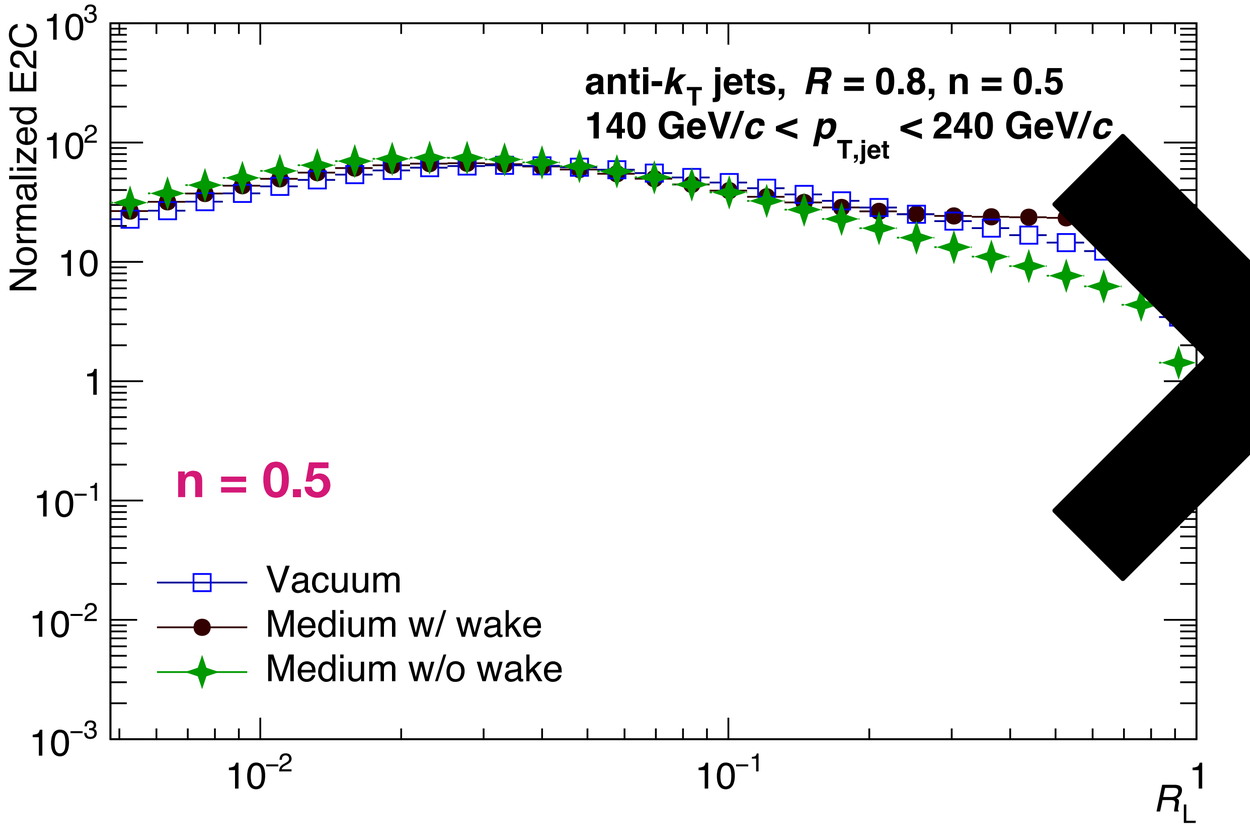

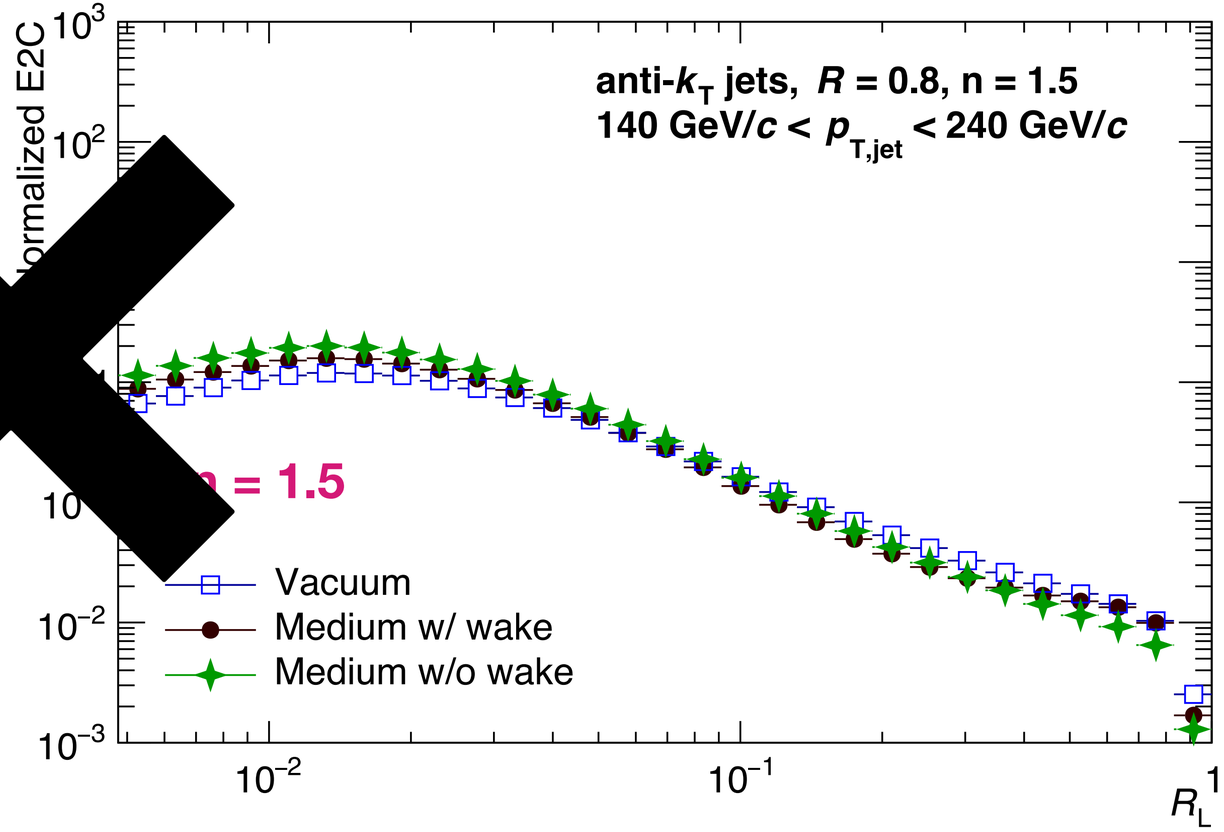

Tuning the wake signal: E3C

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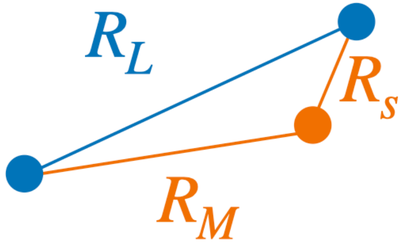

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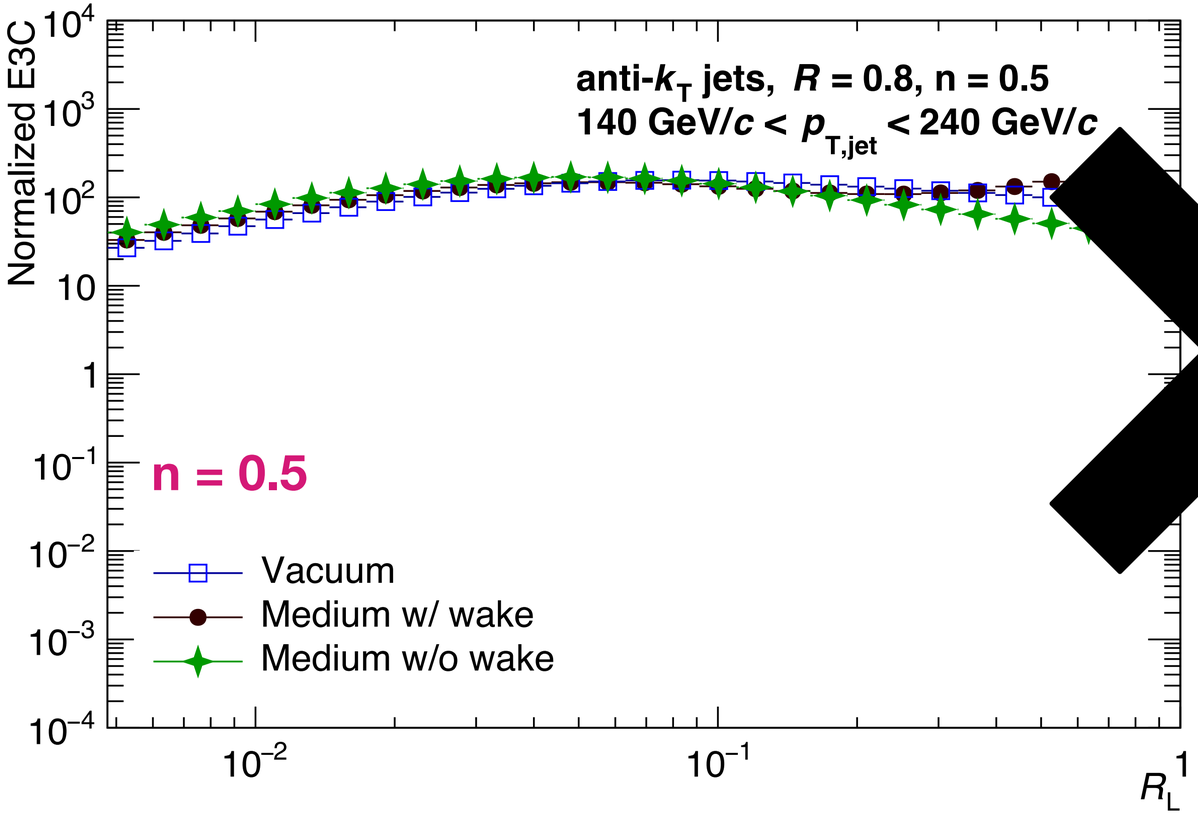
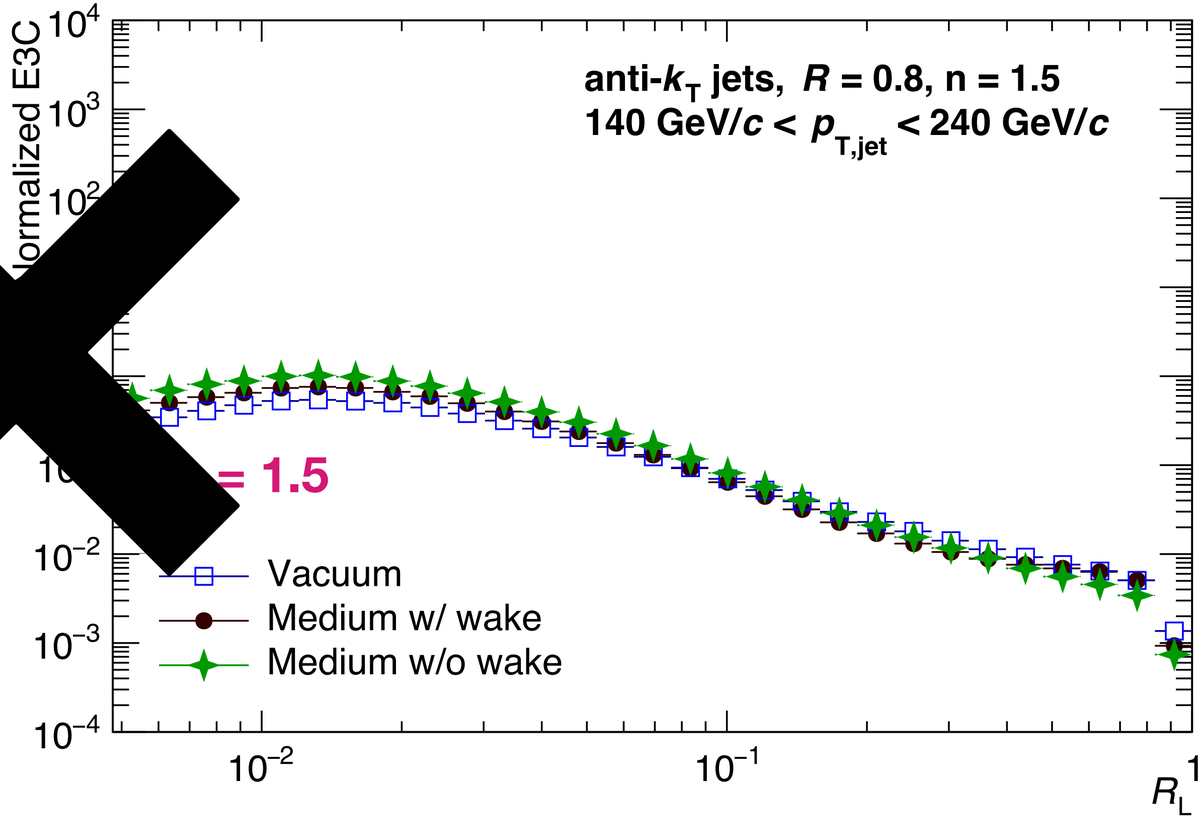


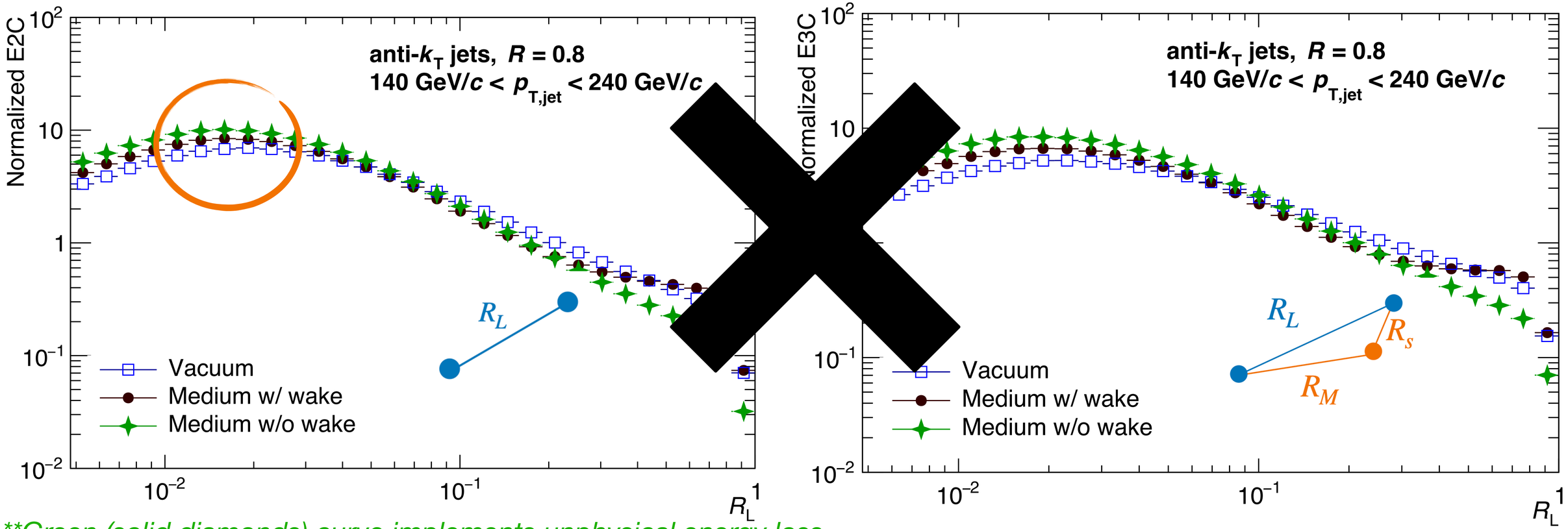


E2C and E3C in Heavy Ion Collisions

Looking for interesting physics

Wake effects appear at ***large angles***

Effects are ***enhanced*** for E3C!



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