Probing jet substructure with energy correlators in pp collisions at 13 TeV with ALICE

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for the ALICE collaboration

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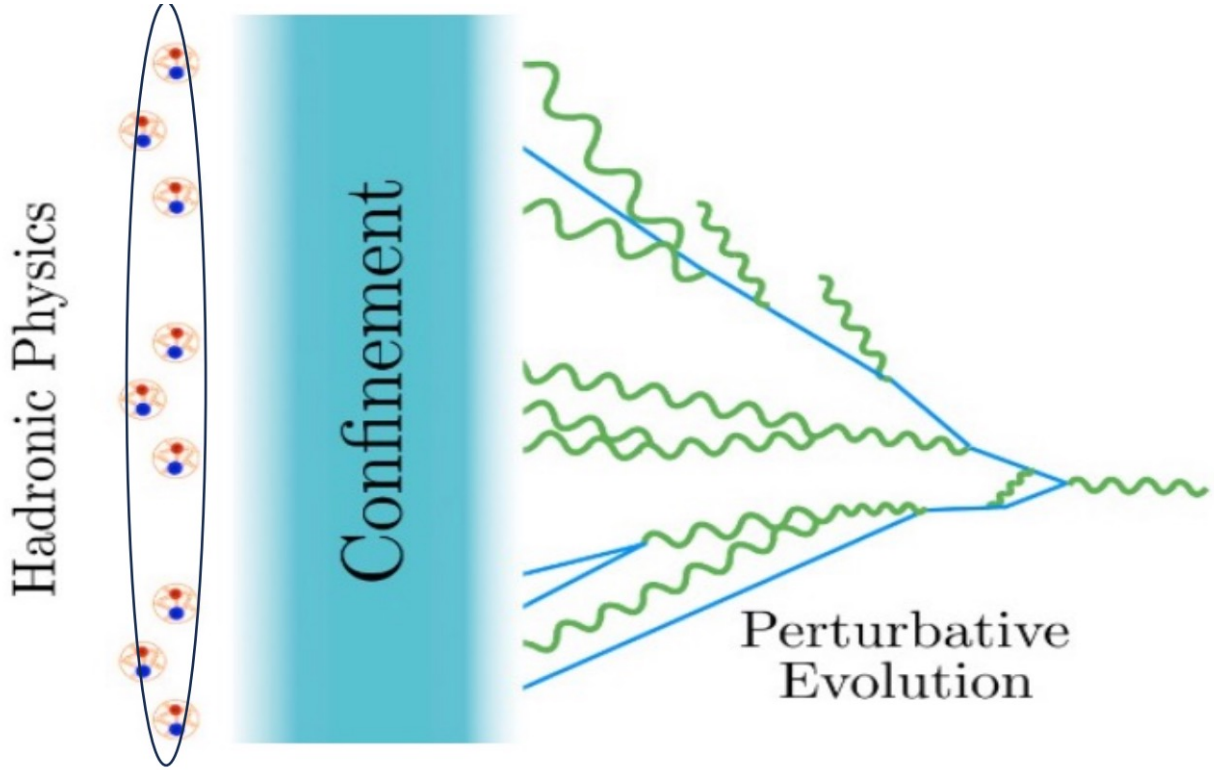
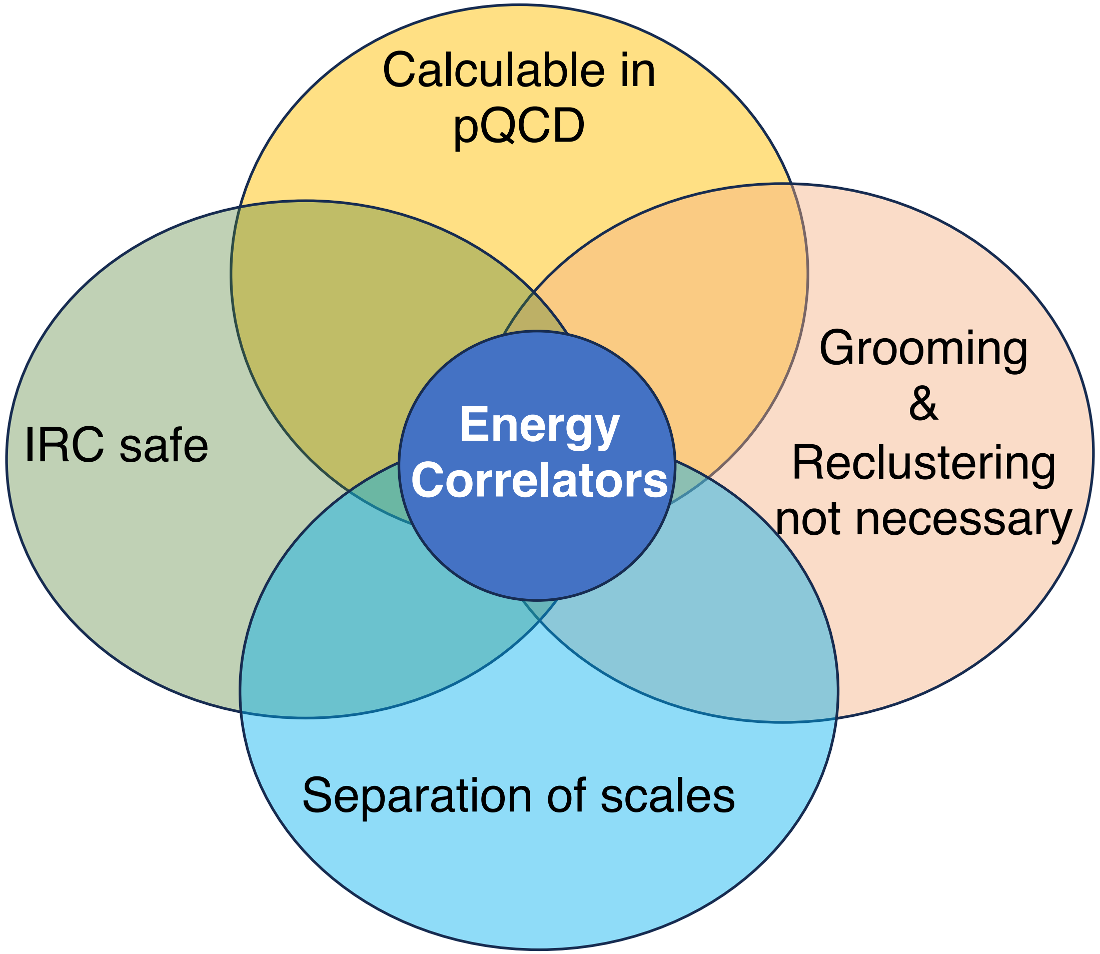
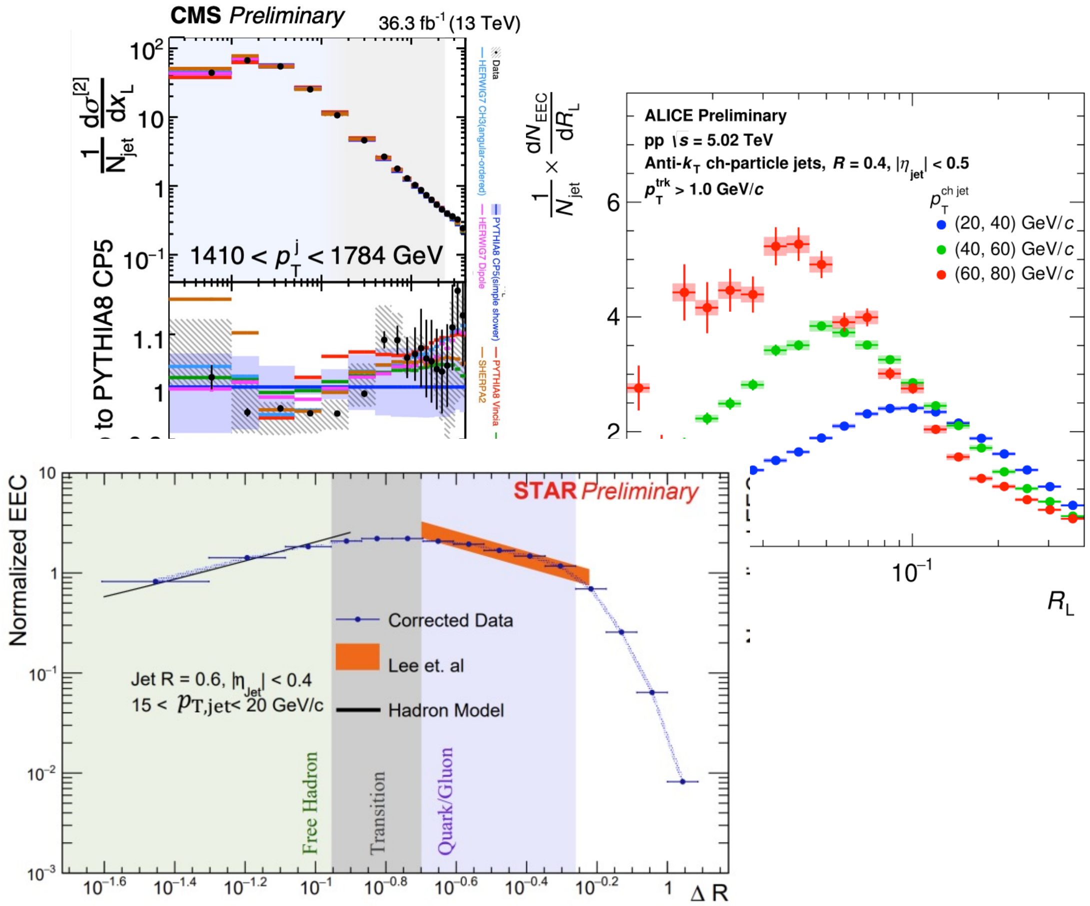
Jets and Jet Substructure



- Useful probe of QCD.
- Jets are **multiscale** objects.
- Jet substructure allows us to trace back to the initial hard scattering.

Energy correlators to study jet substructure





Active area of research for hadronic jets
– results from STAR, CMS, ALICE
– many theory papers

Projected N-point Energy Correlators (ENC)

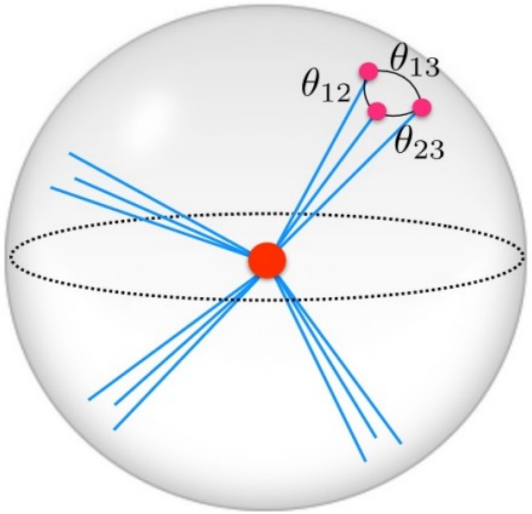
- N-point energy correlators: “Detectors at infinity”

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

$$\mathcal{E}(\hat{n}) = \lim_{r\to\infty} \int_0^{\infty} \mathrm{d}t\, r^2\, n^i T_{0i}(t, r\hat{n})$$

Energy flux operator

Stress-energy tensor

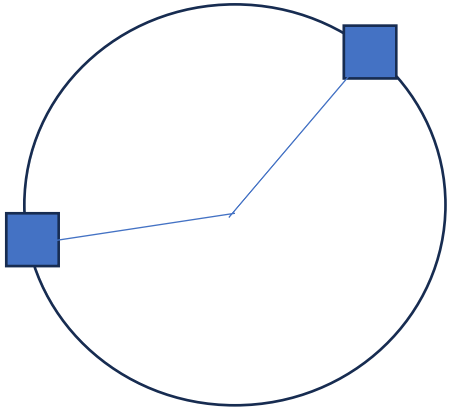


- In experiment – create a weighted histogram as a function of R_L (largest distance between N particles) with weights

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

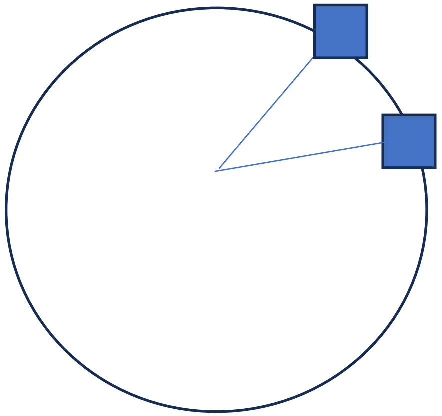
Projected N-point Energy Correlator

Event shape observable

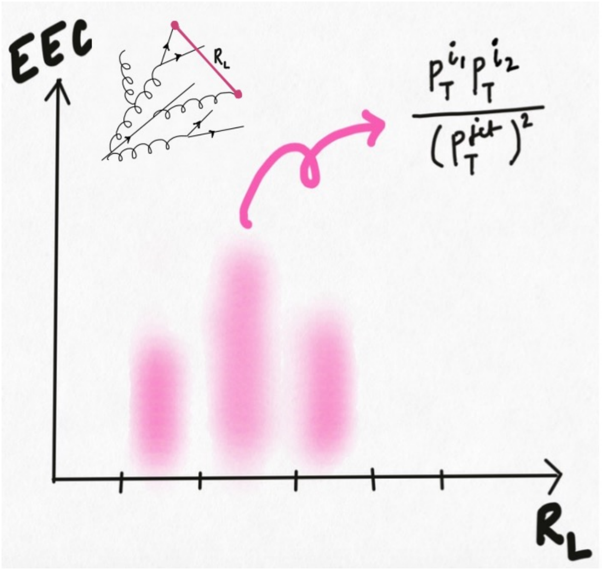


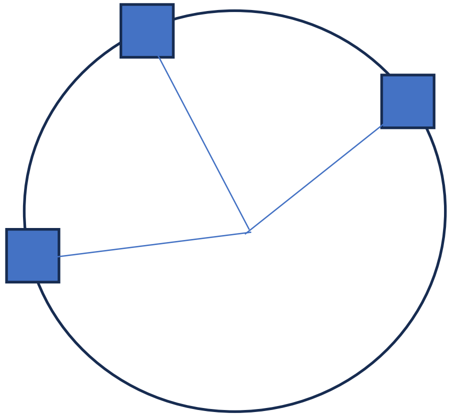
In jets

Collinear limit

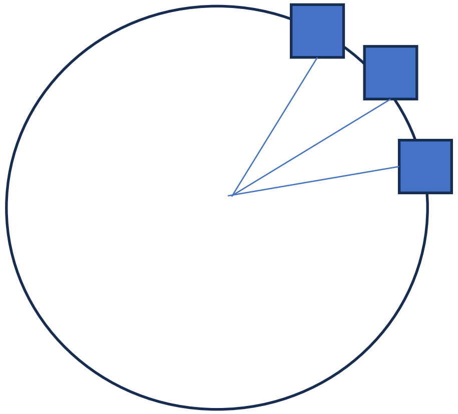


In experiment

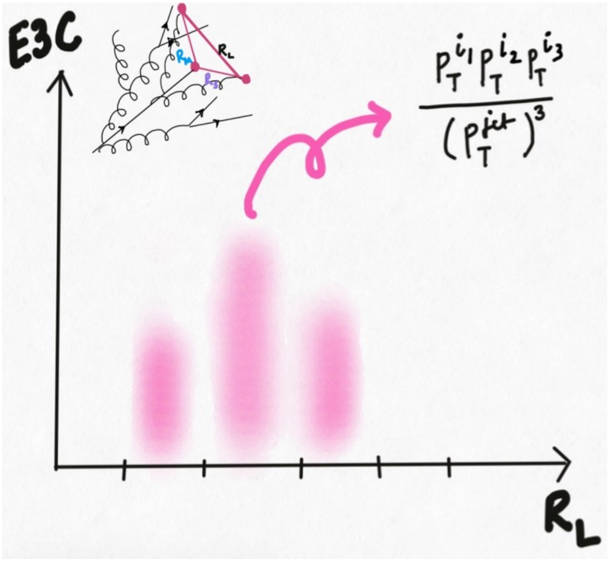




In jets



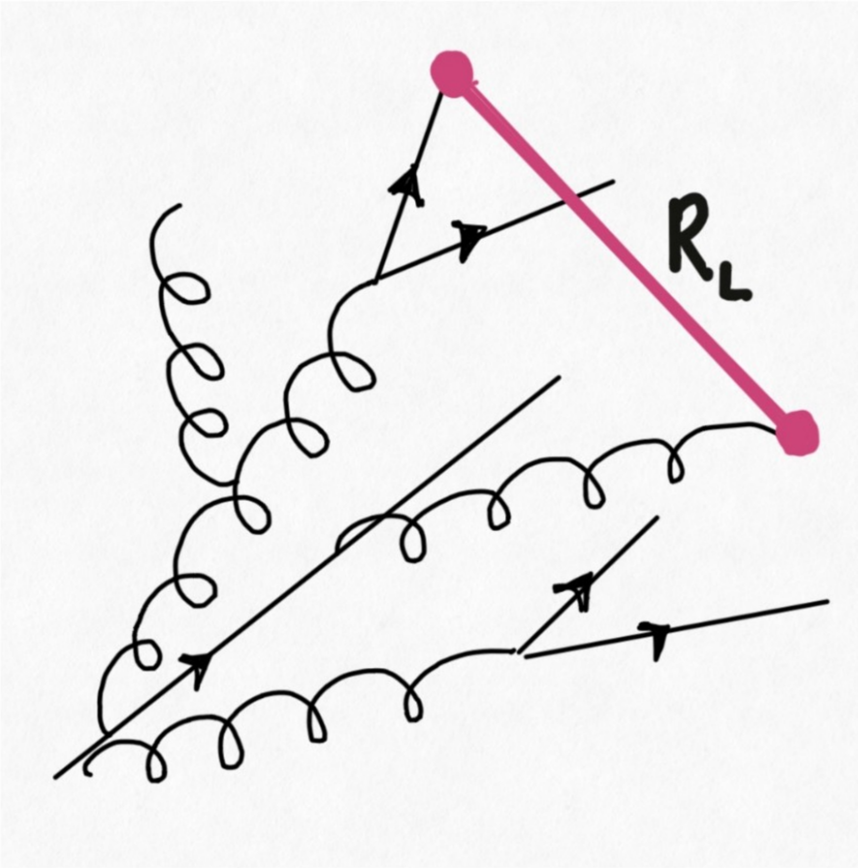
In experiment



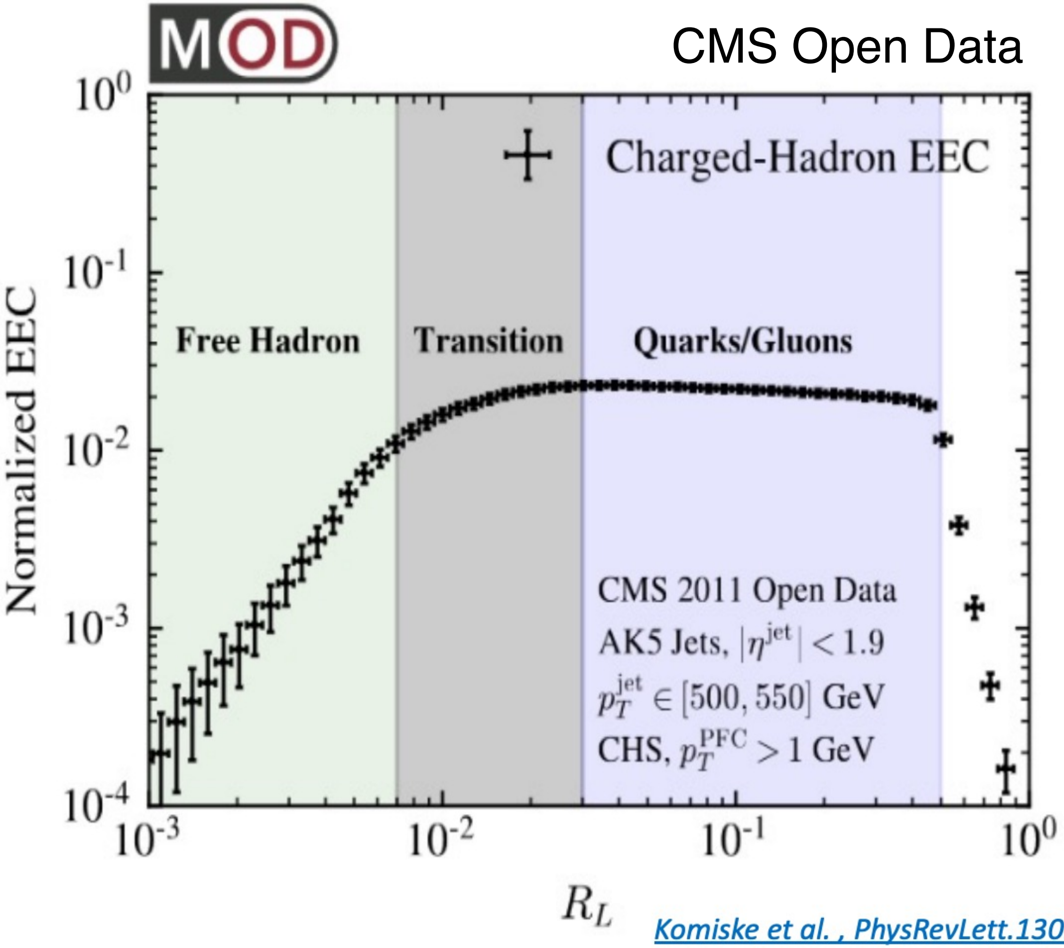
Energy Energy Correlator (EEC)

Correlations between 2 particles in a jet.

Probes scale dependence of energy flow.



CMS Open Data

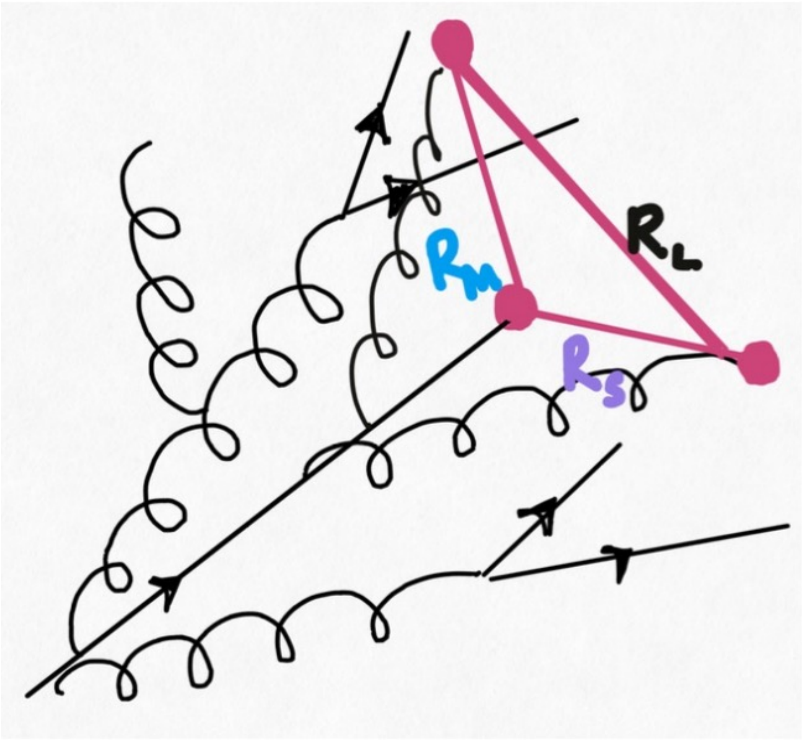


Komiske et al. , PhysRevLett.130.051901

Energy Energy Energy Correlator: EEEC

- What other information can we access?

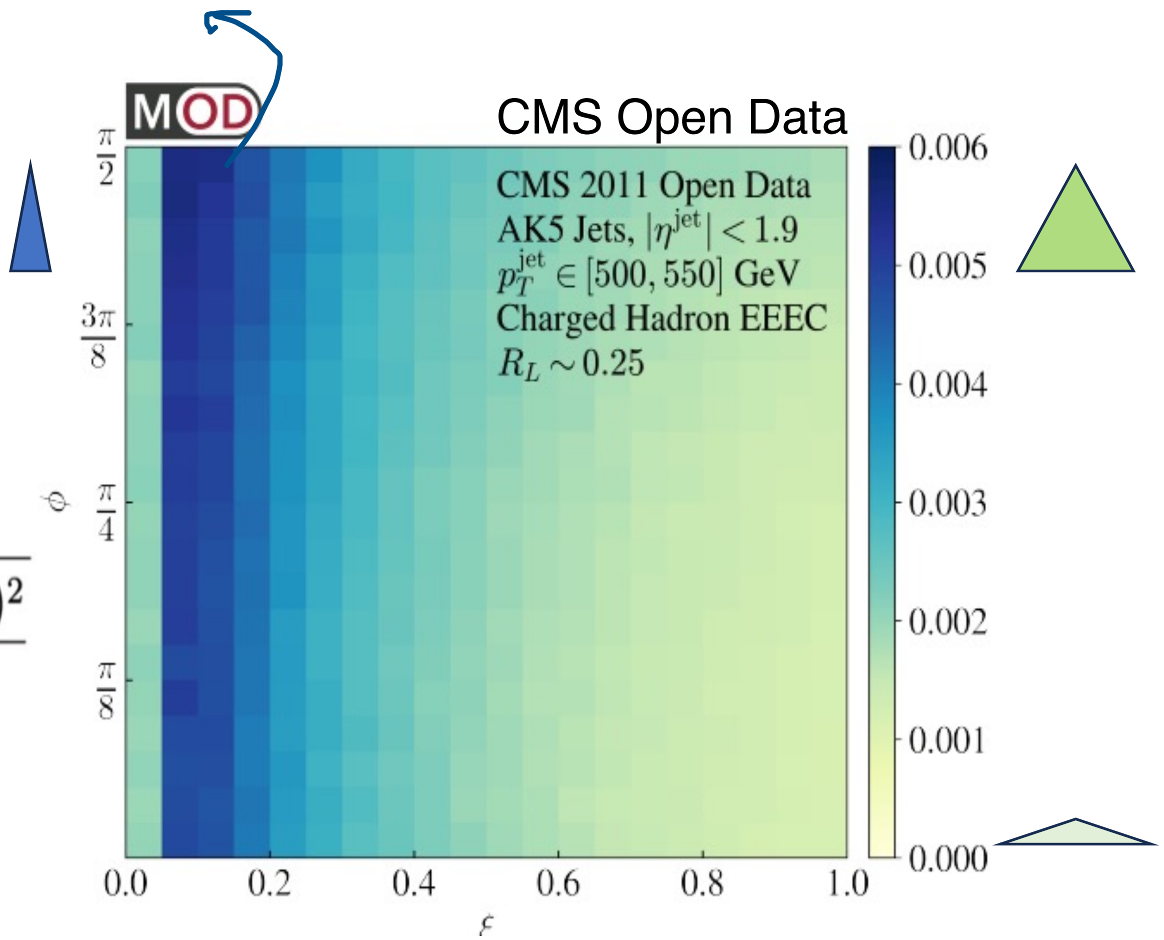
Shape of energy flow.
1 → 3 splitting functions.



$$\xi = \frac{R_S}{R_M}$$

$$\phi = \arcsin\sqrt{1 - \frac{(R_L - R_M)^2}{R_S^2}}$$

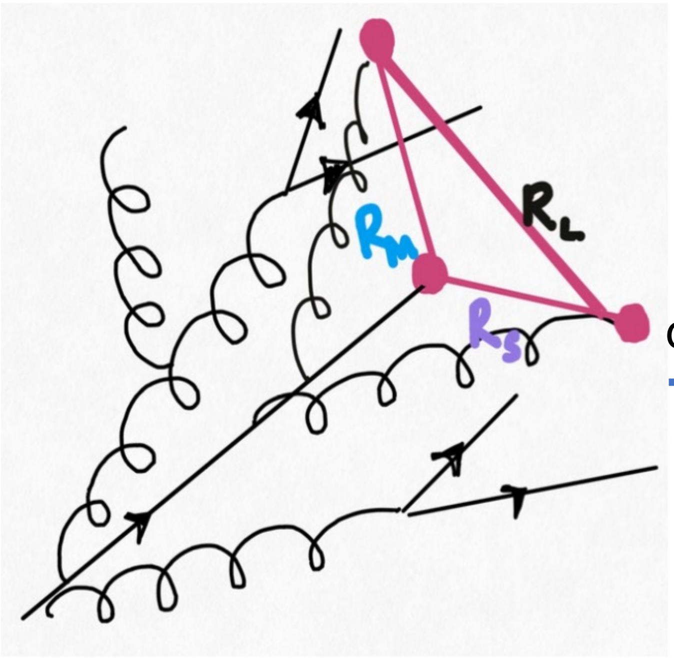
Enhancement of collinear emissions.



Komiske et al. , PhysRevLett.130.051901

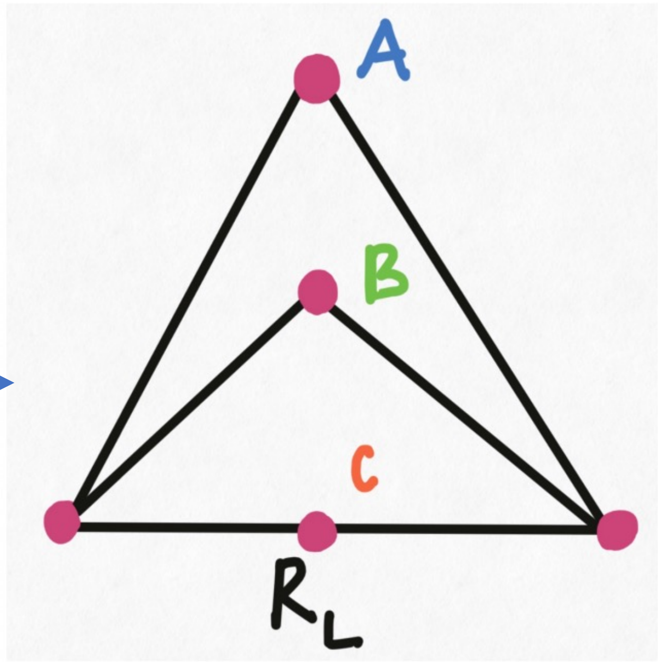
E3C: Taking a middle step

EEEC

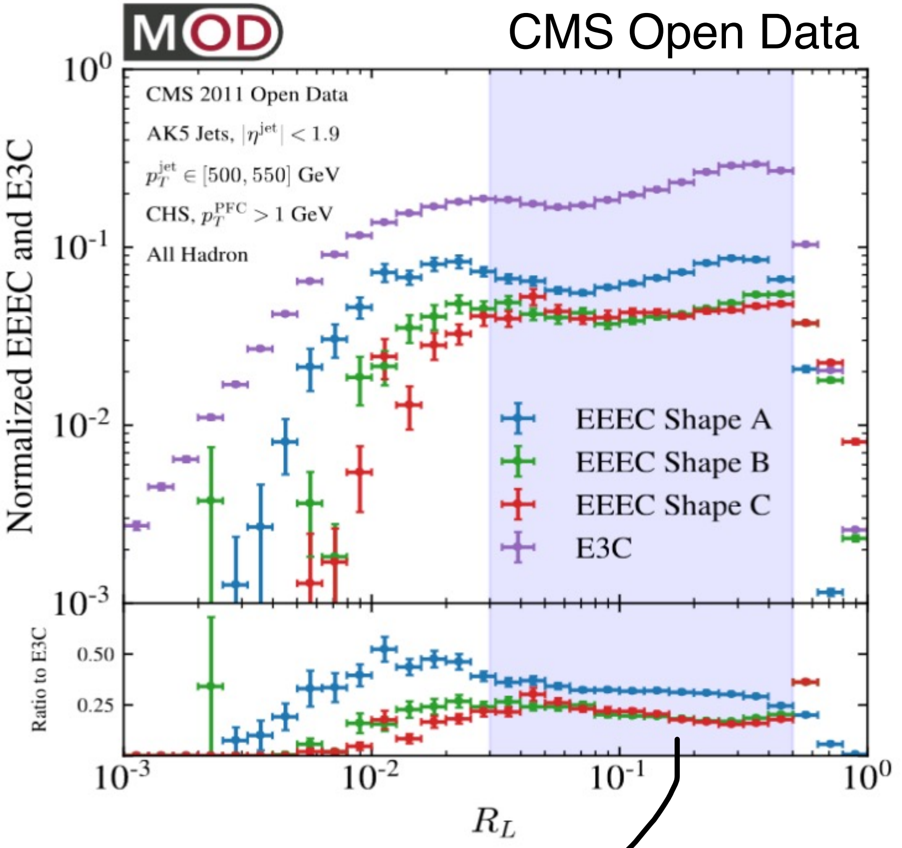


Integrate over R_M & R_s

E3C



CMS Open Data

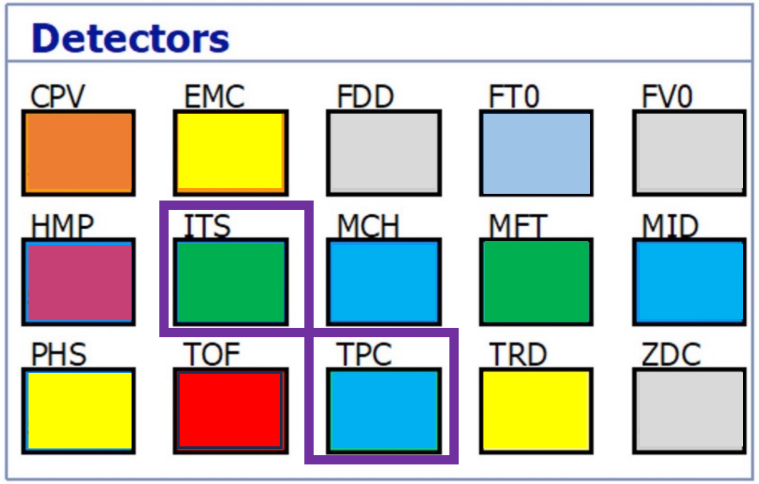


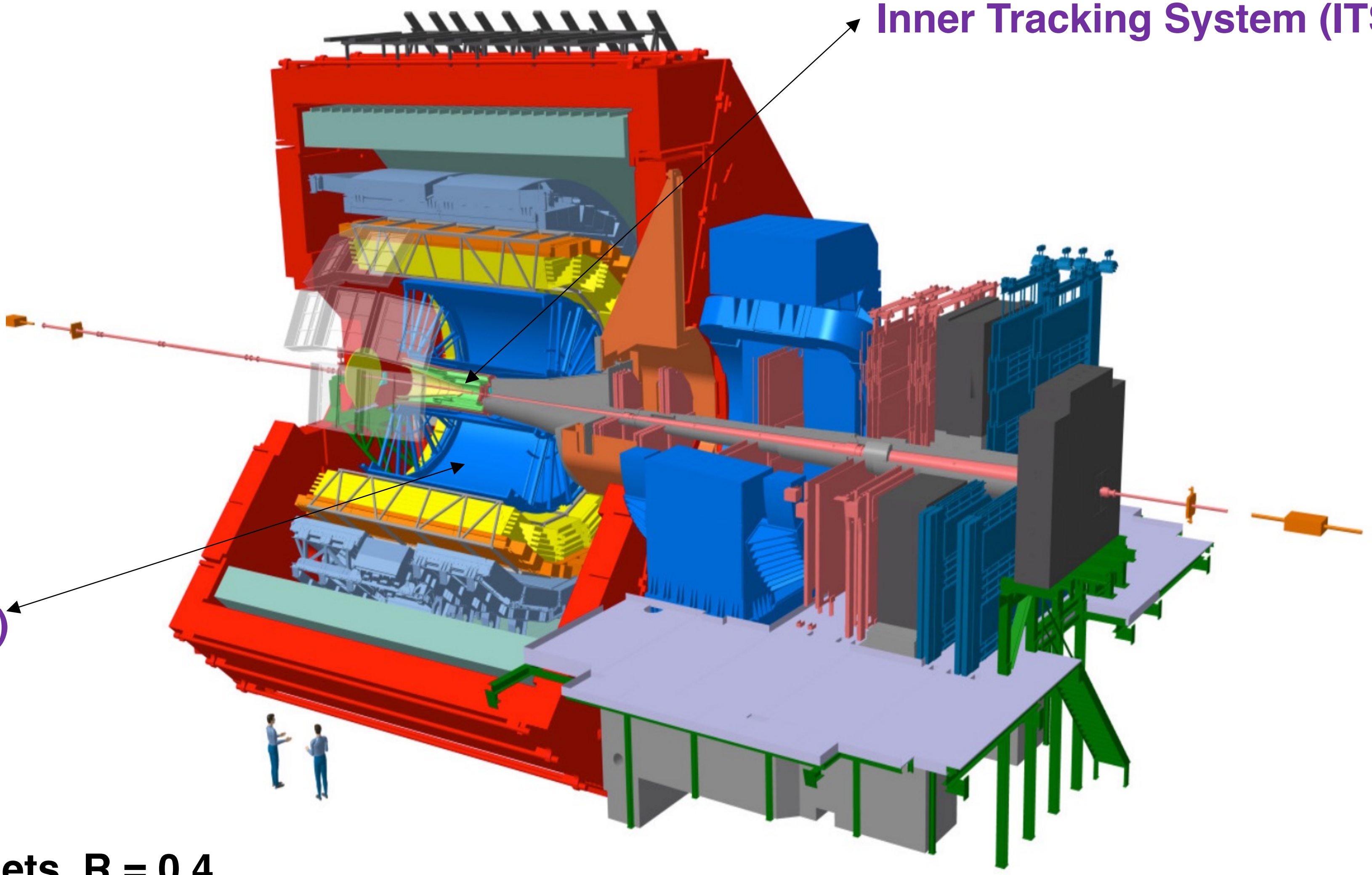
Constant slope → Probes the scaling behavior of the EEEC (theory & open data).*

Not reproduced by MC generators. E3C measurements can be useful to tune MC generators.

*Not confirmed experimentally (yet).

ALICE Detector



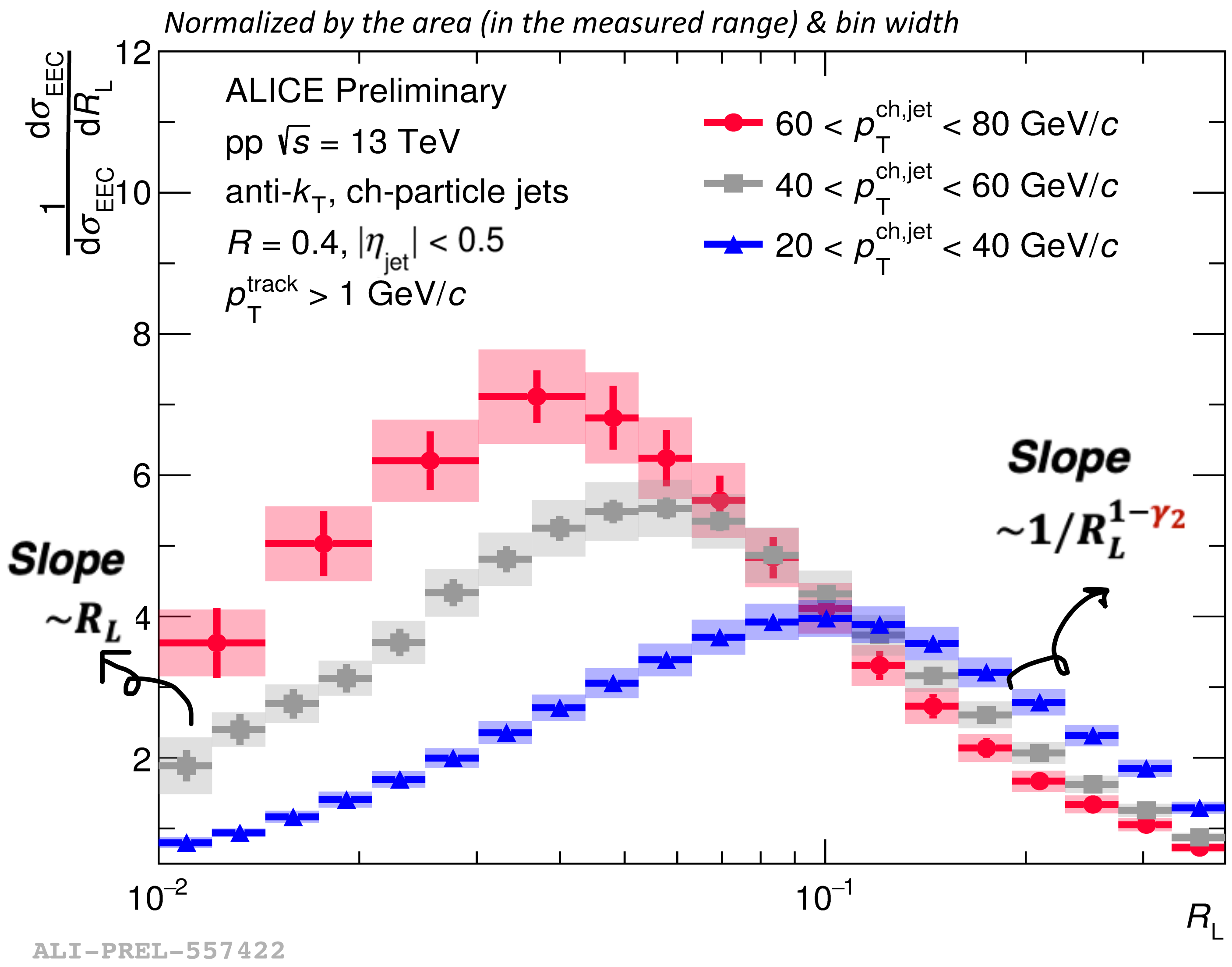


ALICE_PreTrainingSlides.pdf

Time Projection Chamber (TPC)
Jet reconstruction.
Great angular resolution
(~ 1mrad for p_T^{track} = 1 GeV).

This analysis: Charged anti-k_T jets, R = 0.4

Results: EEC at 13 TeV



Increasing jet p_T – curve shifts to the left – elongating the perturbative regime.

Depicts ***angular ordering*** of QCD!

γ_2 is the anomalous dimension of the EEC operator.

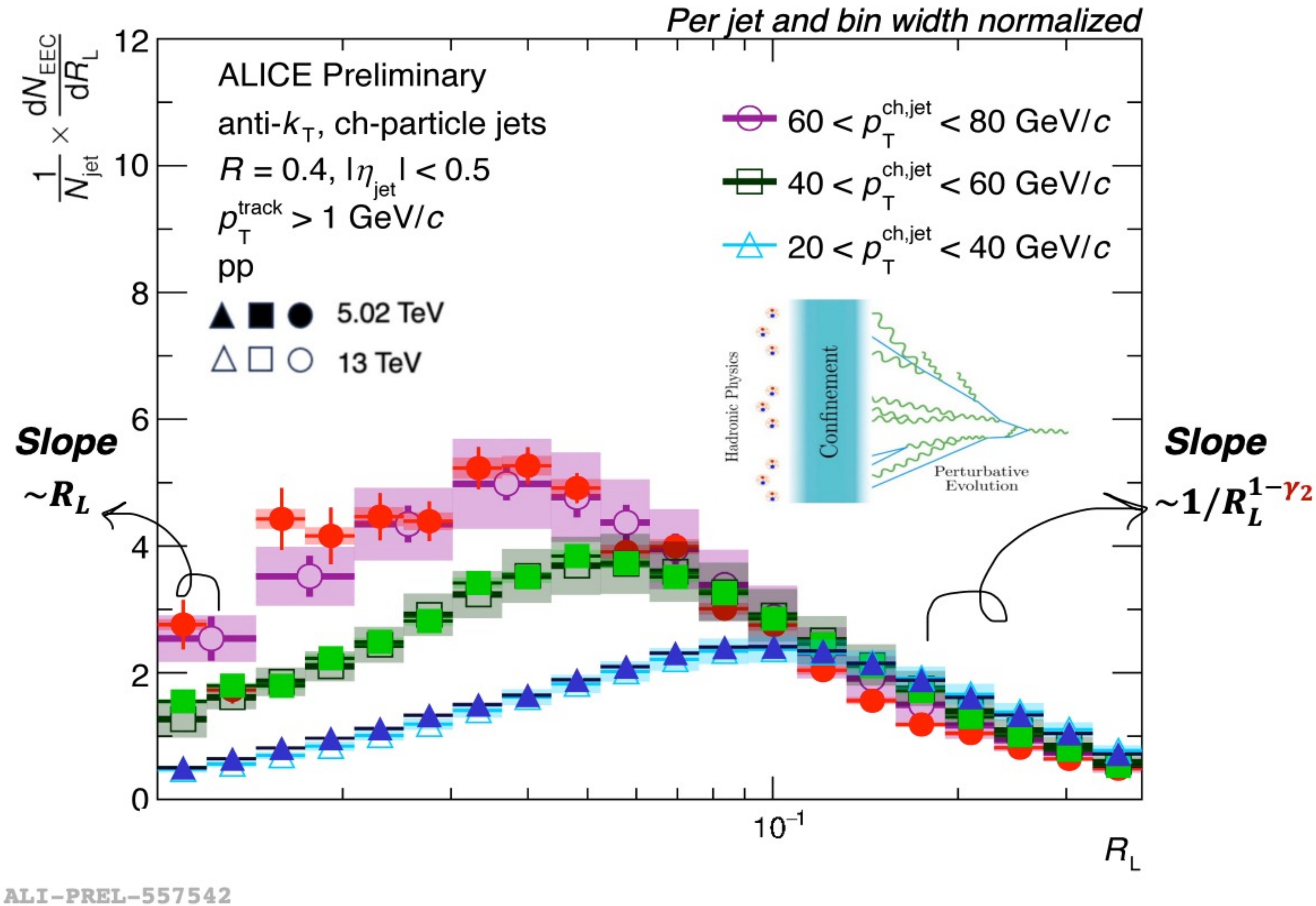
Powers of the slope: ***"Scaling behavior"***.

Results: EEC comparison at 13 TeV and 5 TeV

Almost $\sqrt{s}$ independent

↓

q/g fractions at play!

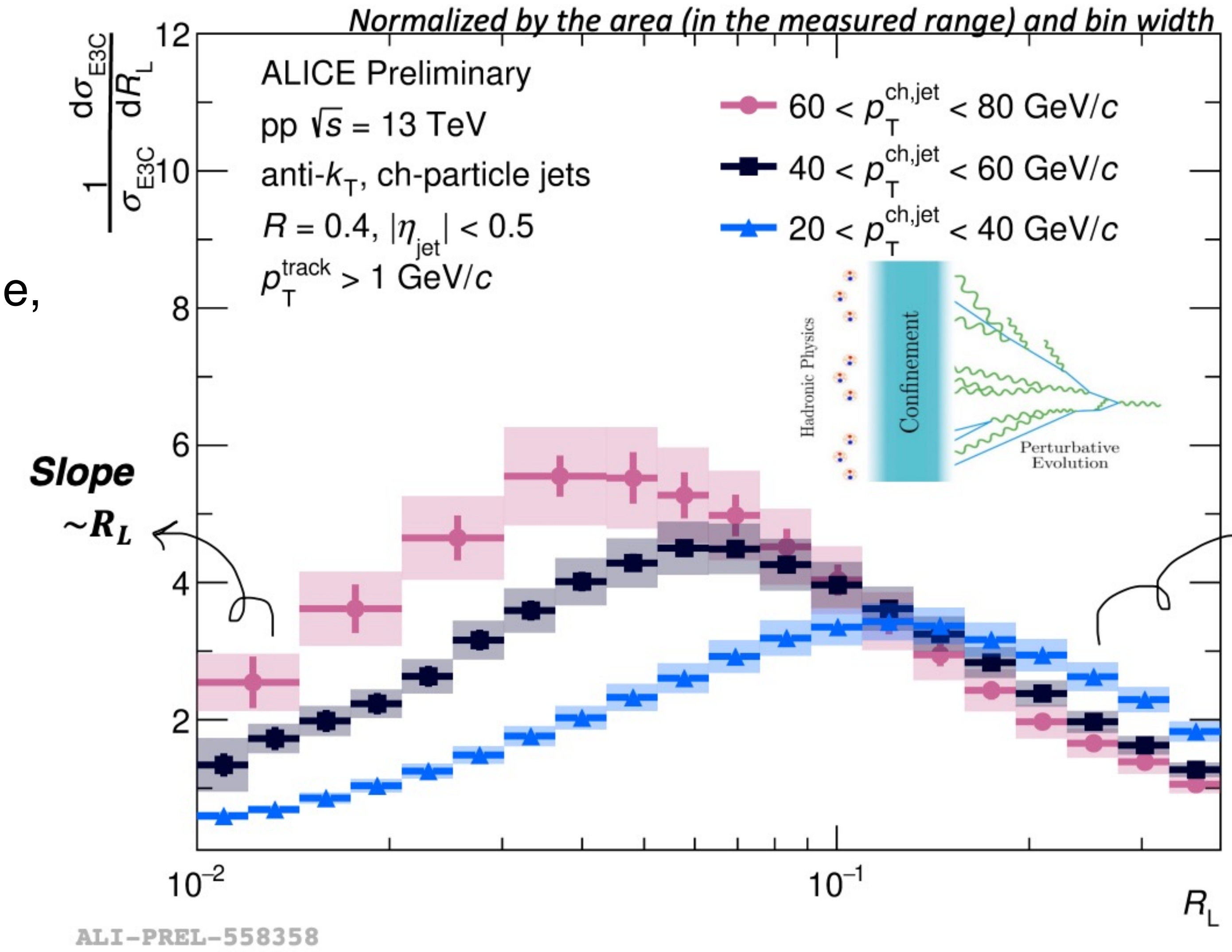


Results: E3C at 13 TeV

First measurement of E3C at ALICE!

Similar to the EEC, depicts angular ordering of QCD.

Hadronization regime, npQCD effects.

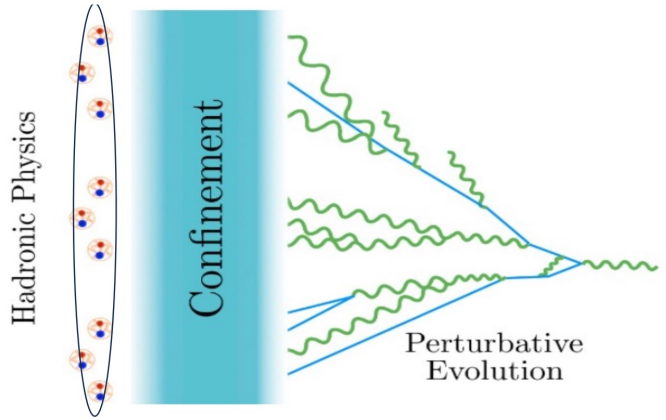


Slope in this regime is **different** from the EEC.

Leading order behavior dominates because $\gamma_3 \ll 1$.

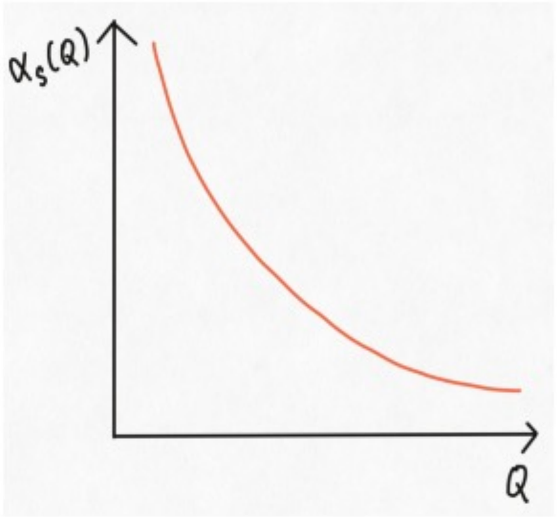
What can ratios of projected correlators tell us?

- Clear separation of energy scales: different slopes in different regimes are highlighted.



- Access to the strong coupling constant: ratio is proportional to $\boldsymbol{\alpha_S}$.

  Recently measured by CMS (BOOST – 2023).



- Highlight quantum mechanical corrections by directly probing anomalous dimensions.

Results: E3C/EEC at 13 TeV

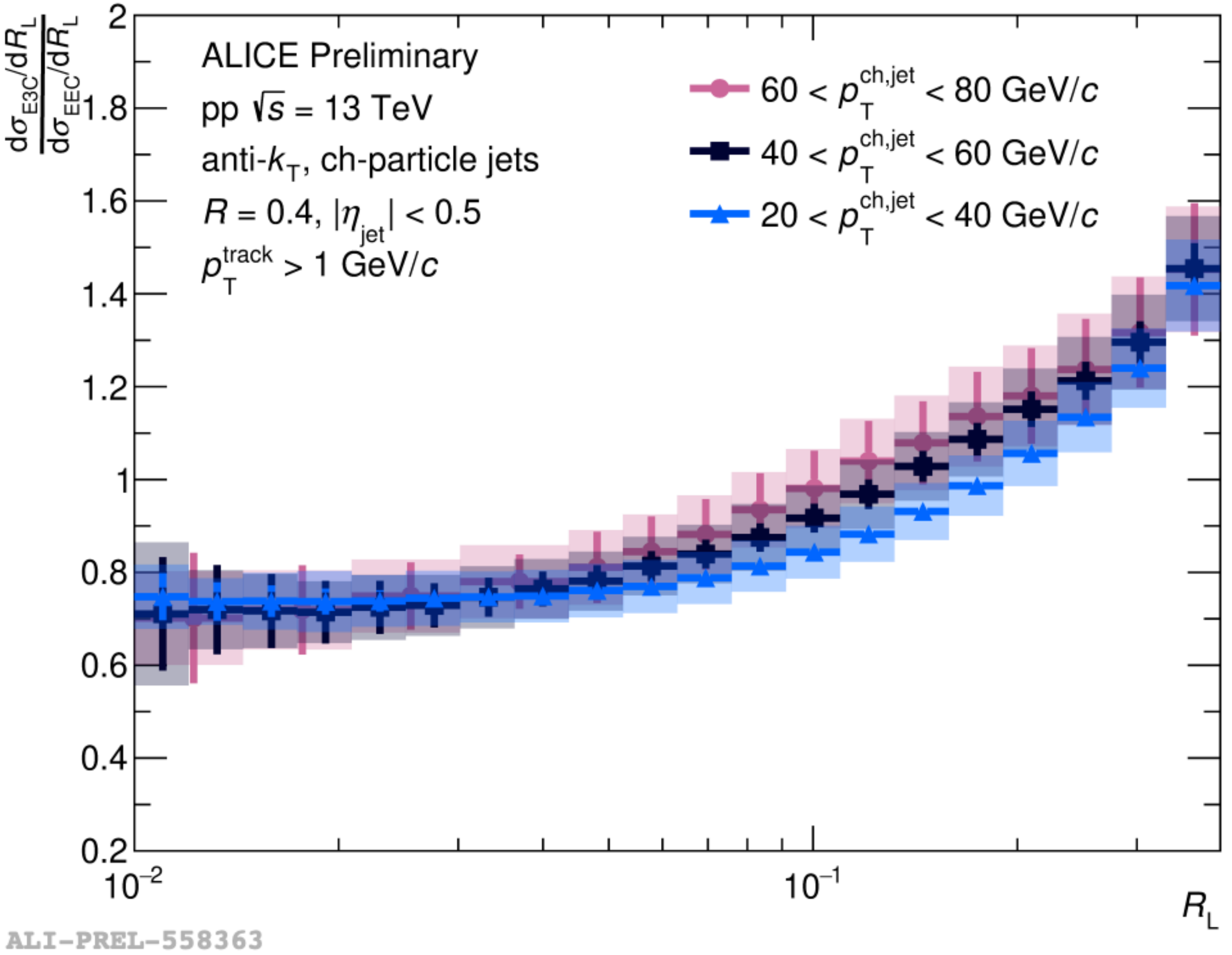
First measurement of E3C/EEC at ALICE!

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

More sensitive to QM corrections.
Slope in perturbative regime ~ $(R_L)^{\gamma_3 - \gamma_2}$

pQCD prediction: $\gamma_{N+1} > \gamma_N$
Reproduced in data: $\gamma_3 > \gamma_2$, positive slope in the perturbative regime!

Change in slope with jet p_T indicates running of coupling, α_S.

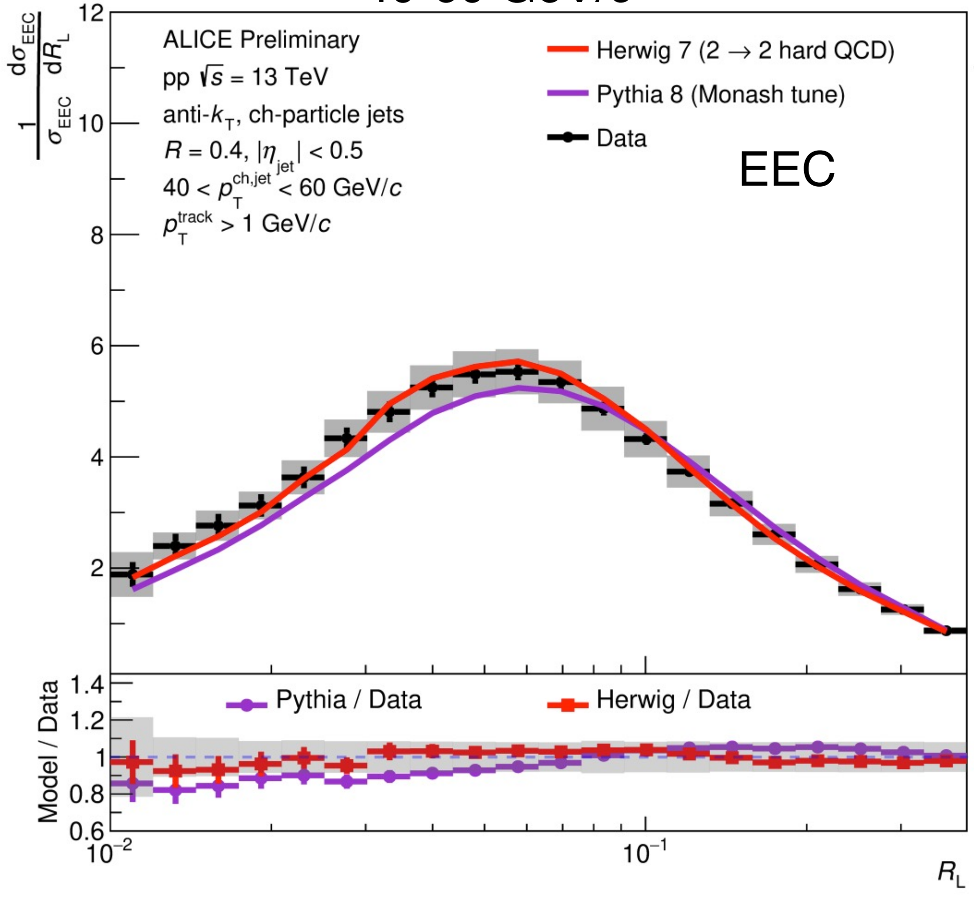


Both E3C & EEC are normalized by the area (in the measured range) and bin width.

Model Comparisons: EEC & E3C

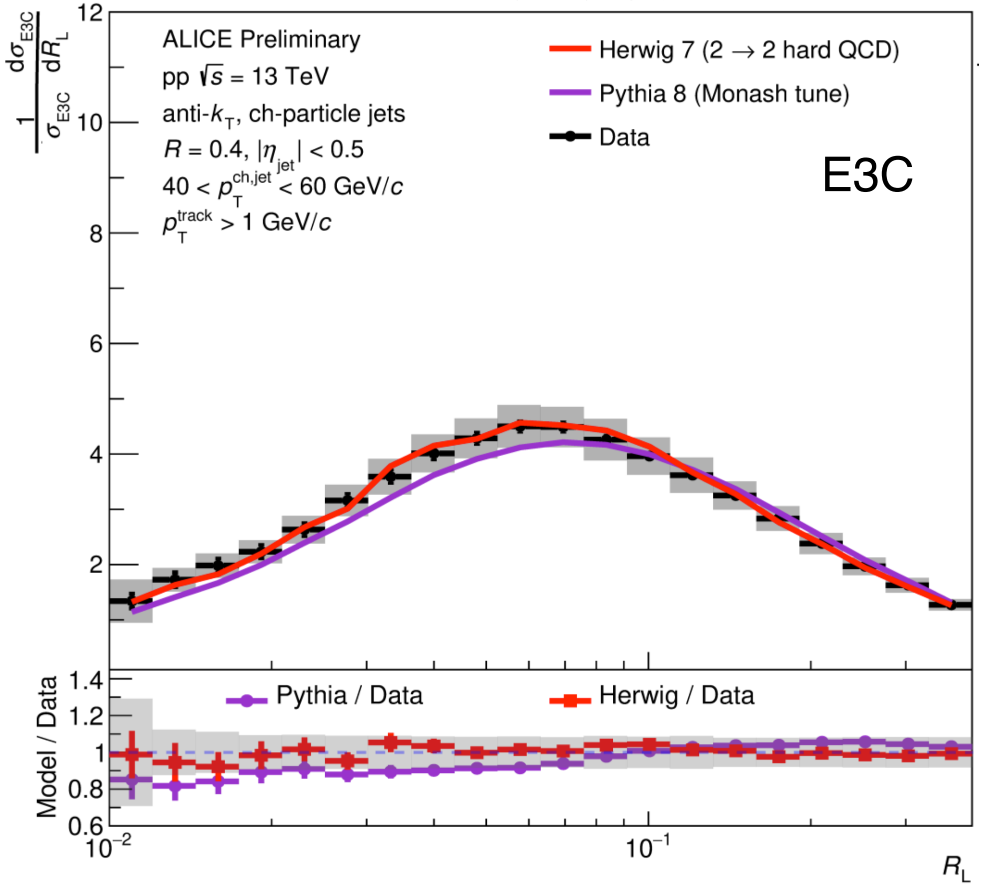
Herwig describes data better for all jet p_T bins (backup).
Pythia underestimates the width of the transition region.

40-60 GeV/c



ALI-PREL-557442

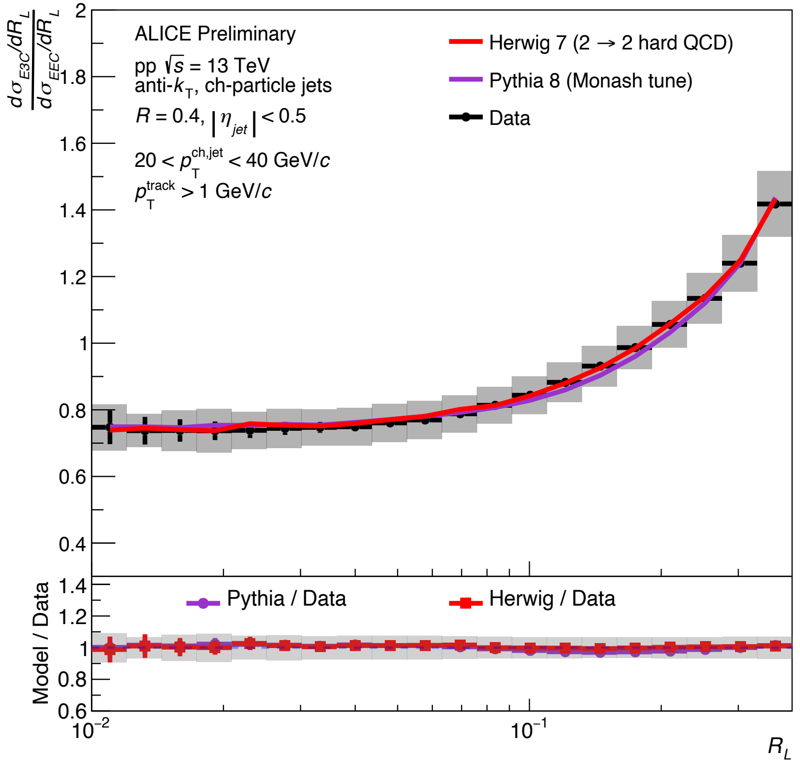
40-60 GeV/c



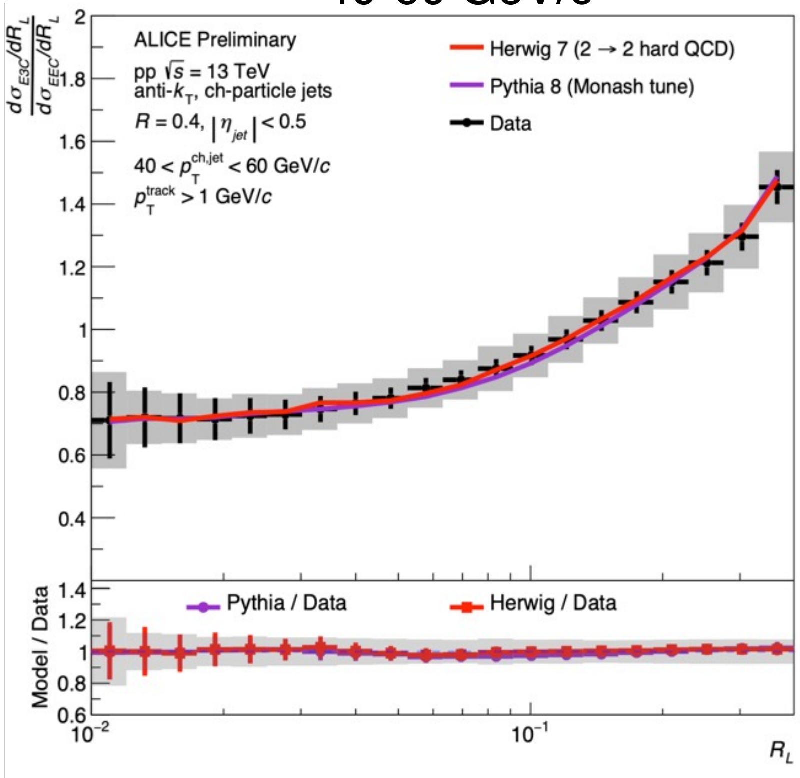
ALI-PREL-557457

Model Comparisons: E3C/EEC

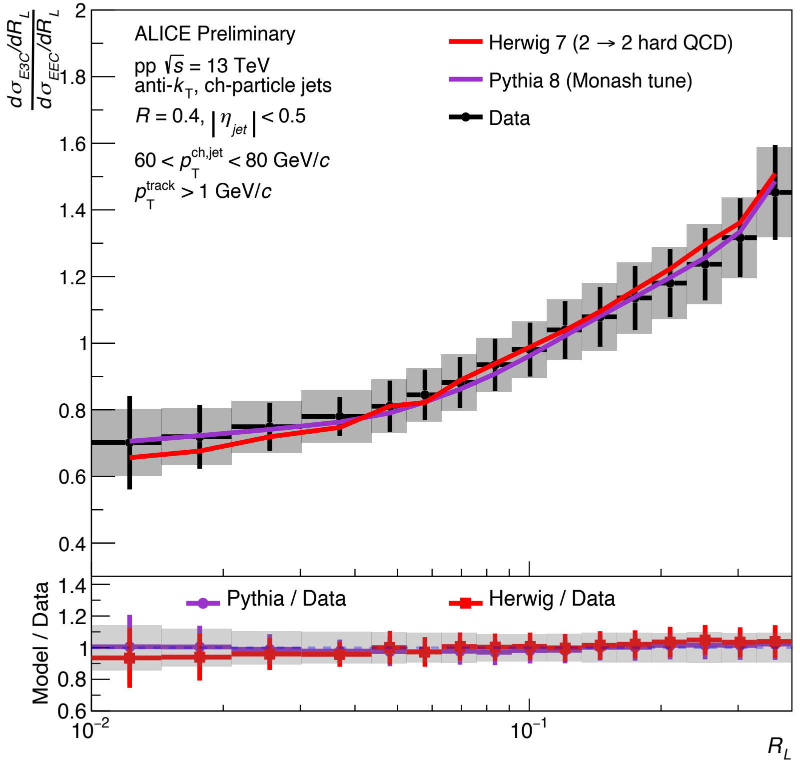
20-40 GeV/c



40-60 GeV/c

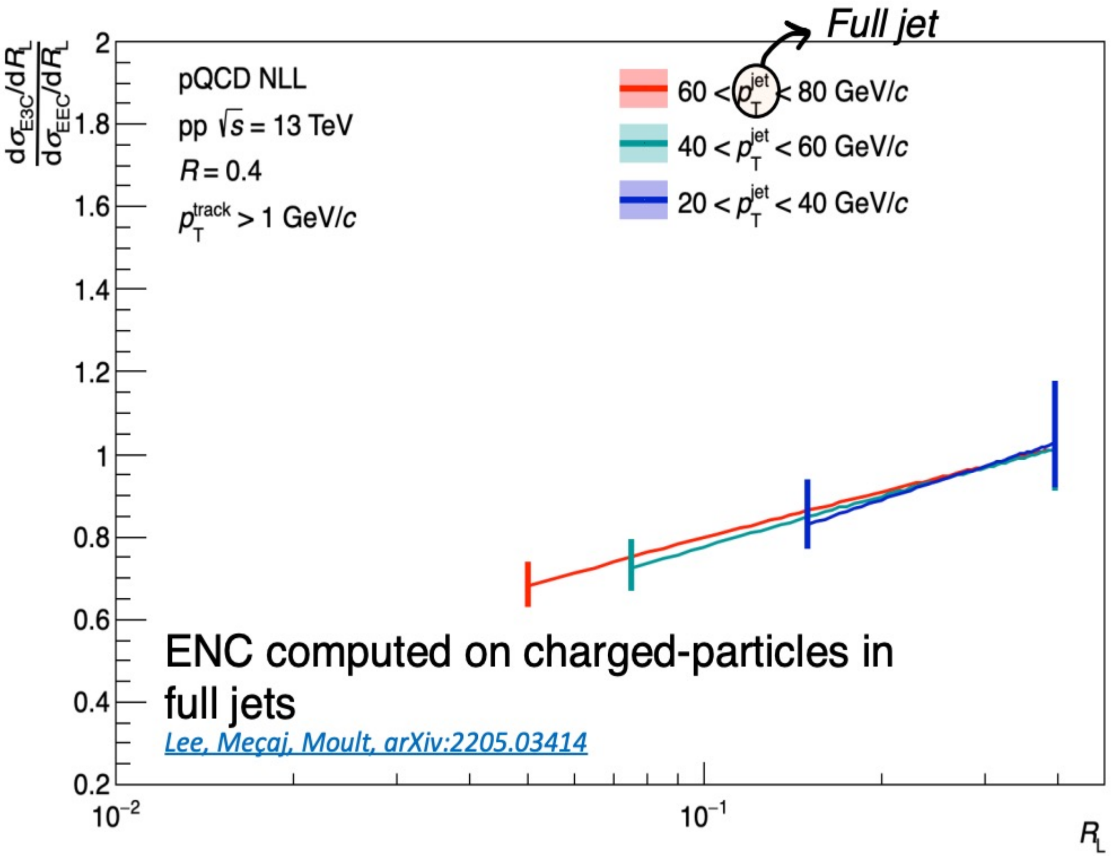


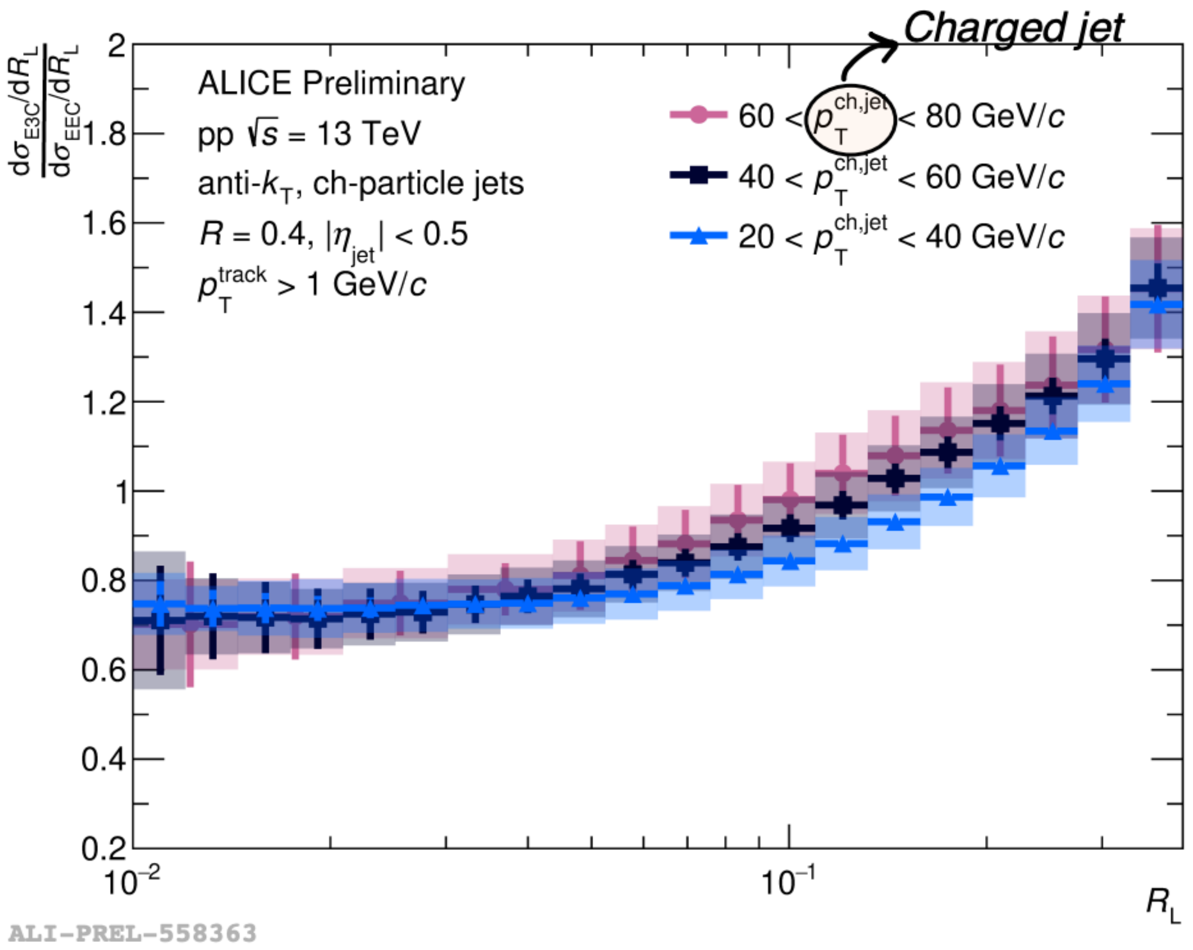
60-80 GeV/c



Models agree well in all jet p_T ranges → Independence from non-perturbative effects of hadronization.

Comparisons to pQCD predictions: E3C/EEC





At LL collinear in pQCD

Jet p_T scale — q/g fraction

$$ENC(R_L) = -\frac{d}{dR_L}\left[(1,1)\exp\left(\frac{-\gamma^{(0)}(N+1)}{\beta_0}\ln\frac{\alpha_S(R_L\mu)}{\alpha_S(\mu)}\right)(x_q, x_g)\right]H_J(\mu)$$

Komiske et al. , PhysRevLett.130.051901

QCD beta function (1 loop) — Jet production crossx

Trends between theory and data agree!
Work is ongoing to make a “direct” comparison.

Moving towards complex systems

Jets in heavy ion collisions: great tool to understand medium evolution via jet-medium interactions.

Many medium effects –
- Transverse Momentum Broadening
- Color coherence effects
- **Wake**

actively being explored with EECs in models
Andres et al., arXiv:2209.11236, *Yang et al., arxiv:2310.01500*

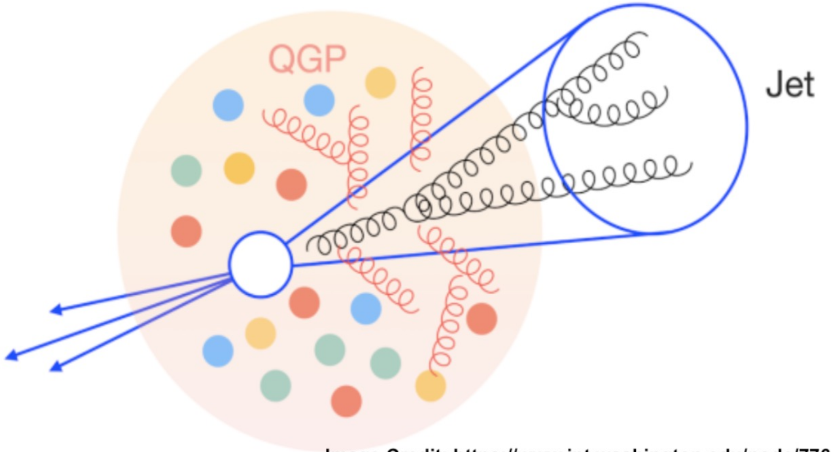


Image Credit: https://www.int.washington.edu/node/776

Are the ENCs sensitive to the medium response?

Illustrate this in the **Hybrid Model**:
Wake in the Hybrid model adds soft particles from the medium to the jet.

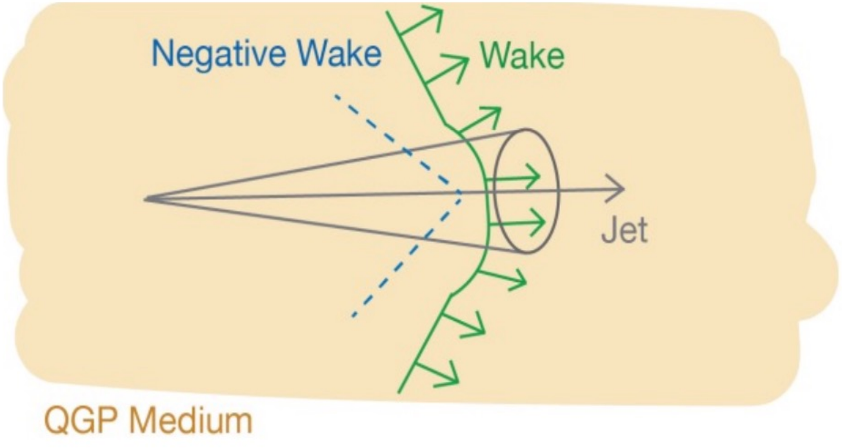
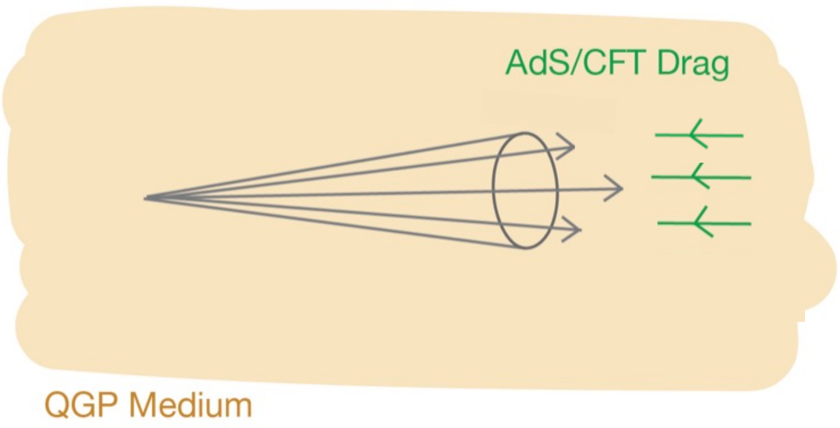


Fig Credit: H.Bossi Thesis, 2023

What can we learn about the QGP from ENCs?

ENCs are a scale sensitive probe that can be **tuned** to highlight the type of physics we are interested in.

Medium impacts jet: **Energy Loss**



Jet impacts medium: **Wake**

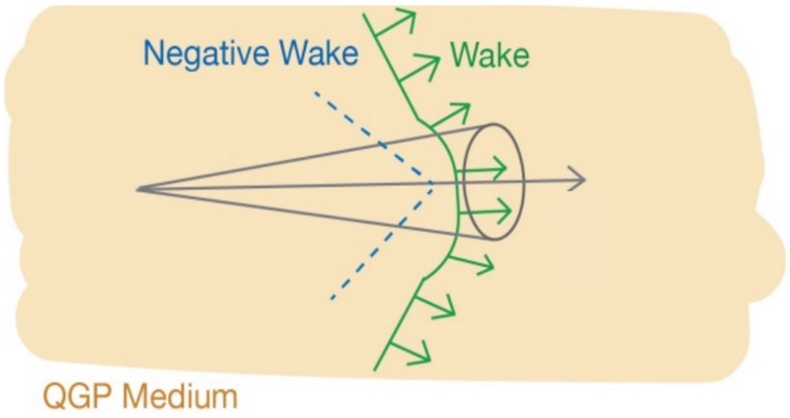


Fig Credit: H.Bossi Thesis, 2023

- Q1. Can we see the wake?
- Q2. Can we amplify its effect?
- Q3. What can give us a clear experimental signature?

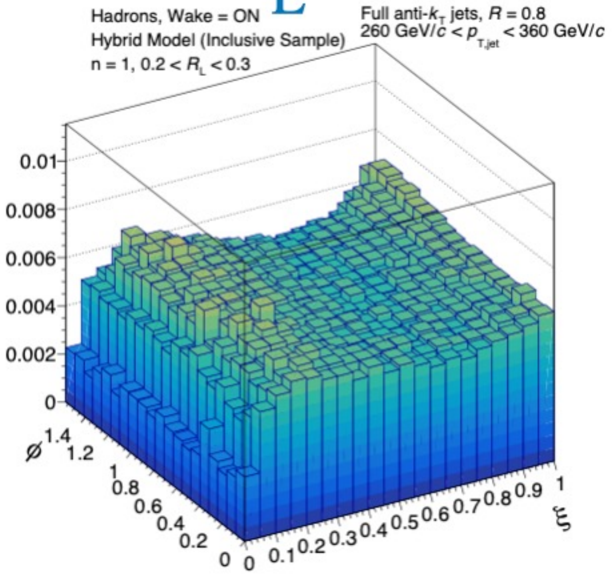
**Work in collaboration with Ian Moult (Yale), Hannah Bossi (MIT), Arjun Kudinoor (Cambridge), Krishna Rajagopal (MIT), Daniel Pablos (Universidad de Santiago de Compostela)*

EEC in the Hybrid Model

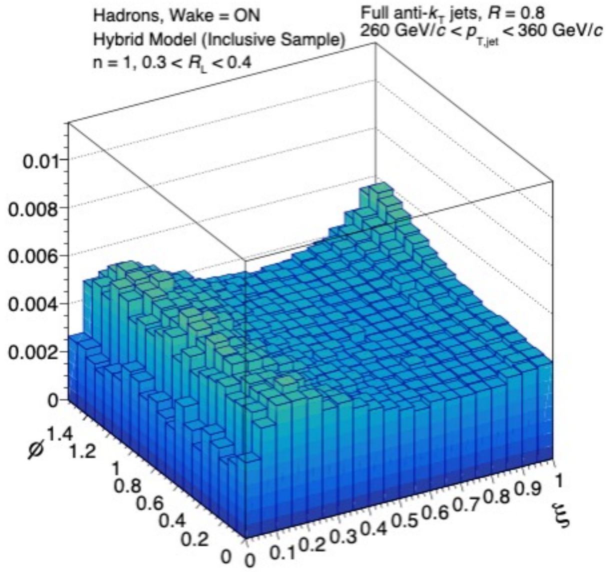
The wake shows up in the ***equilateral regime*** (which was unpopulated in vacuum) as we scan through R_L.

$$\xi = \frac{R_S}{R_M} \qquad \phi = \arcsin\sqrt{1 - \frac{(R_L - R_M)^2}{R_S^2}}$$

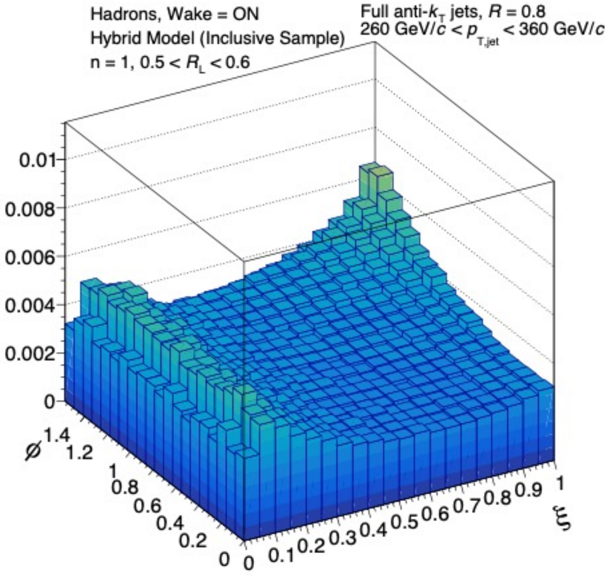
$0.2 < R_L < 0.3$



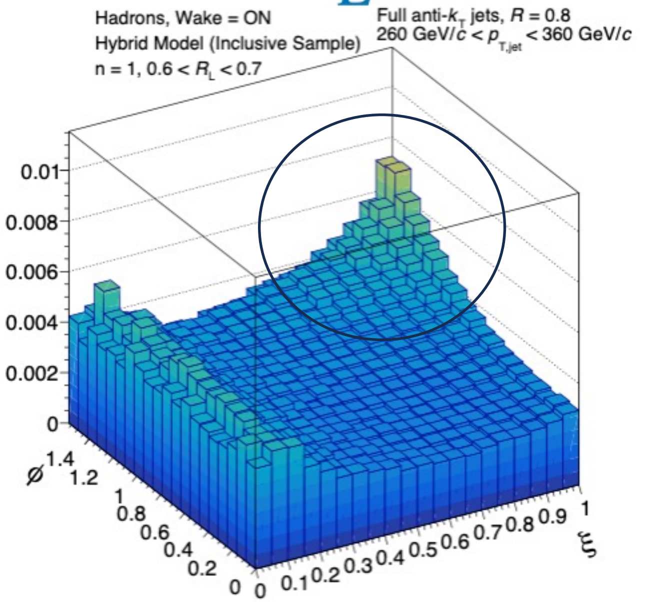
$0.3 < R_L < 0.4$



$0.5 < R_L < 0.6$



$0.6 < R_L < 0.7$



Increasing R_L

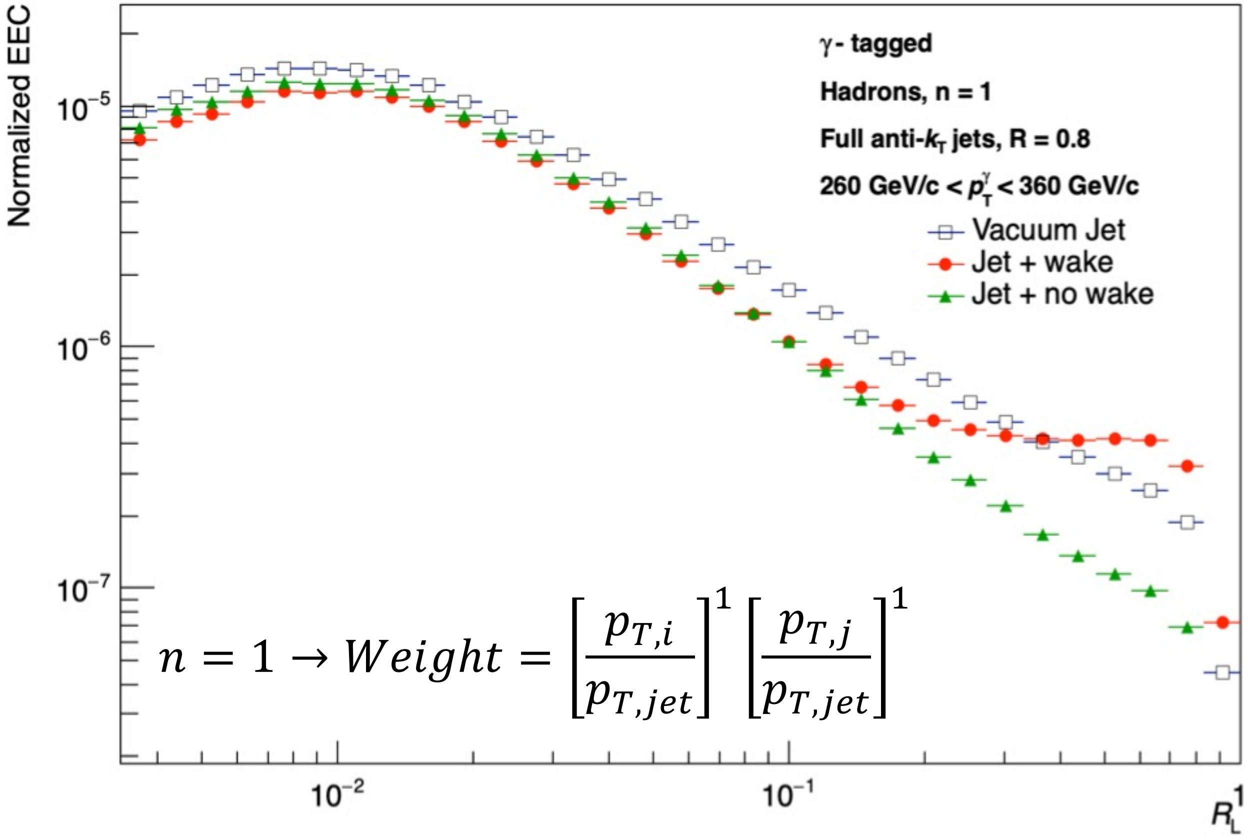
See Ian Moult's talk (earlier this session)!

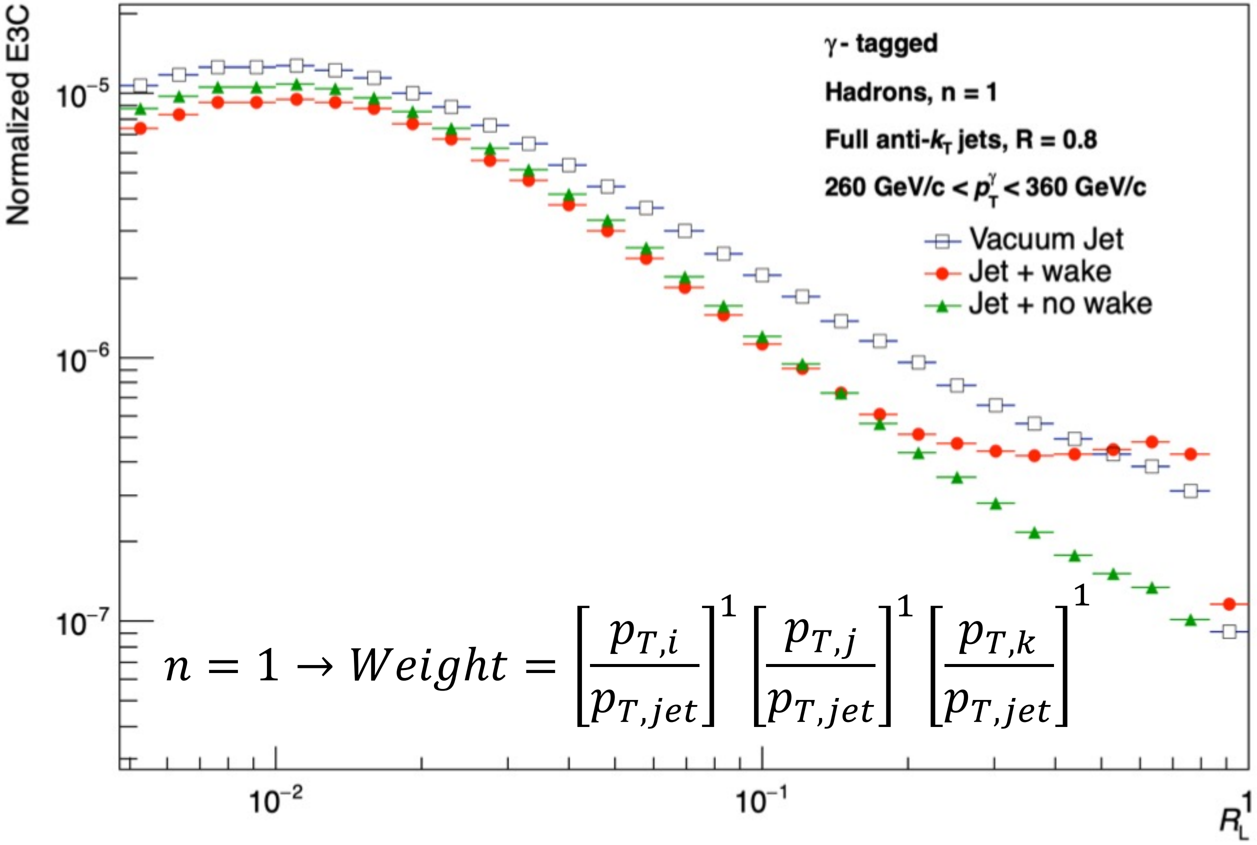
ENCs in the Hybrid Model

First exploration of higher-point correlators in models!

Very large jets at very high p_T, no track cuts, unlimited statistics.

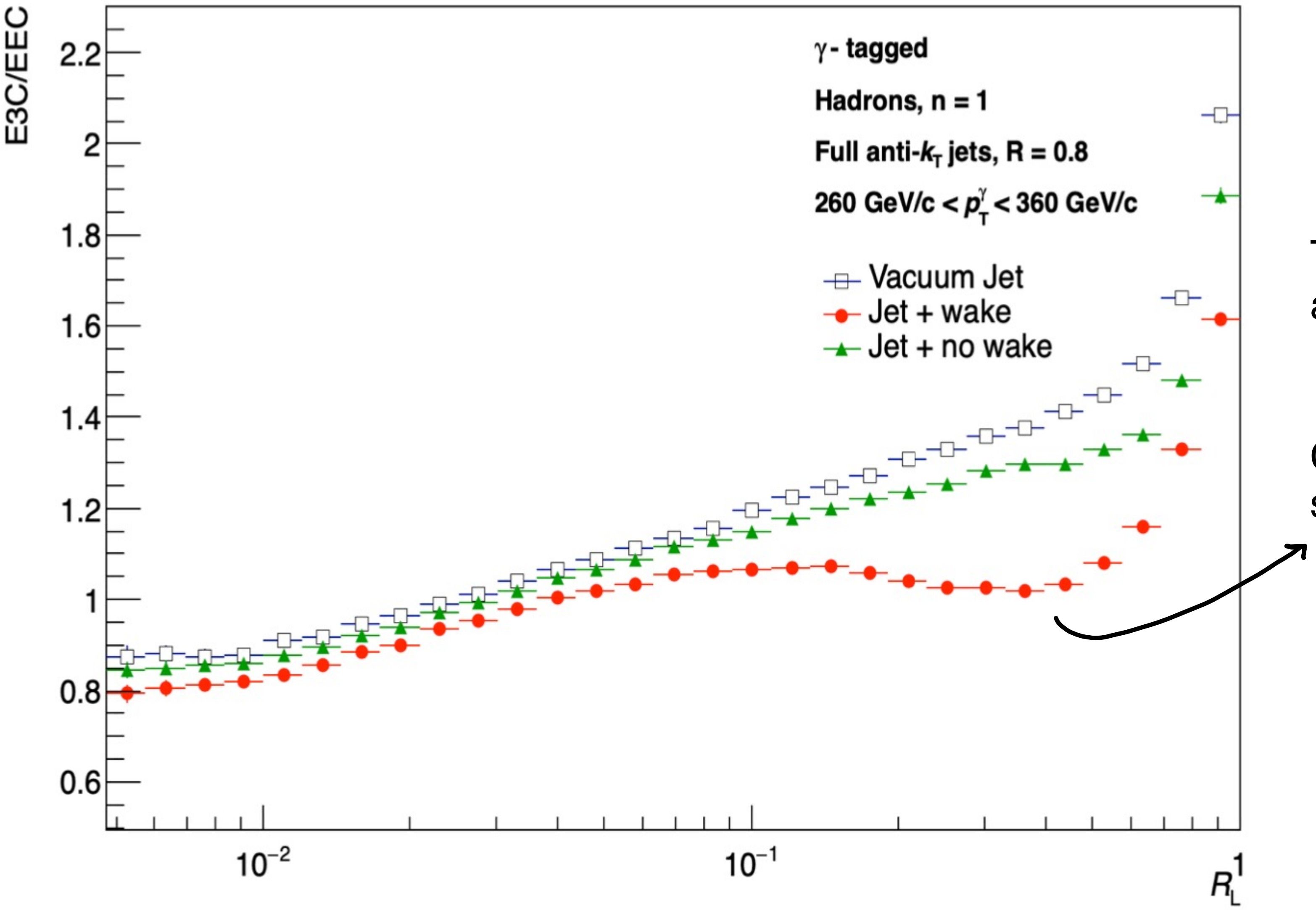
Using p_T^{γ} to construct the correlator as a proxy for unquenched p_T^{jet} .





▲ Only jet energy loss implemented **without** energy conservation – unphysical.

E3C/EEC in the Hybrid Model



Using $p_T^{jet} = p_T^\gamma$ to construct the correlator as a proxy for unquenched p_T^{jet} .

The crucial point is the **change in slope** at large R_L.

Change in slope, deviation from vacuum scaling – effect of the **wake**.

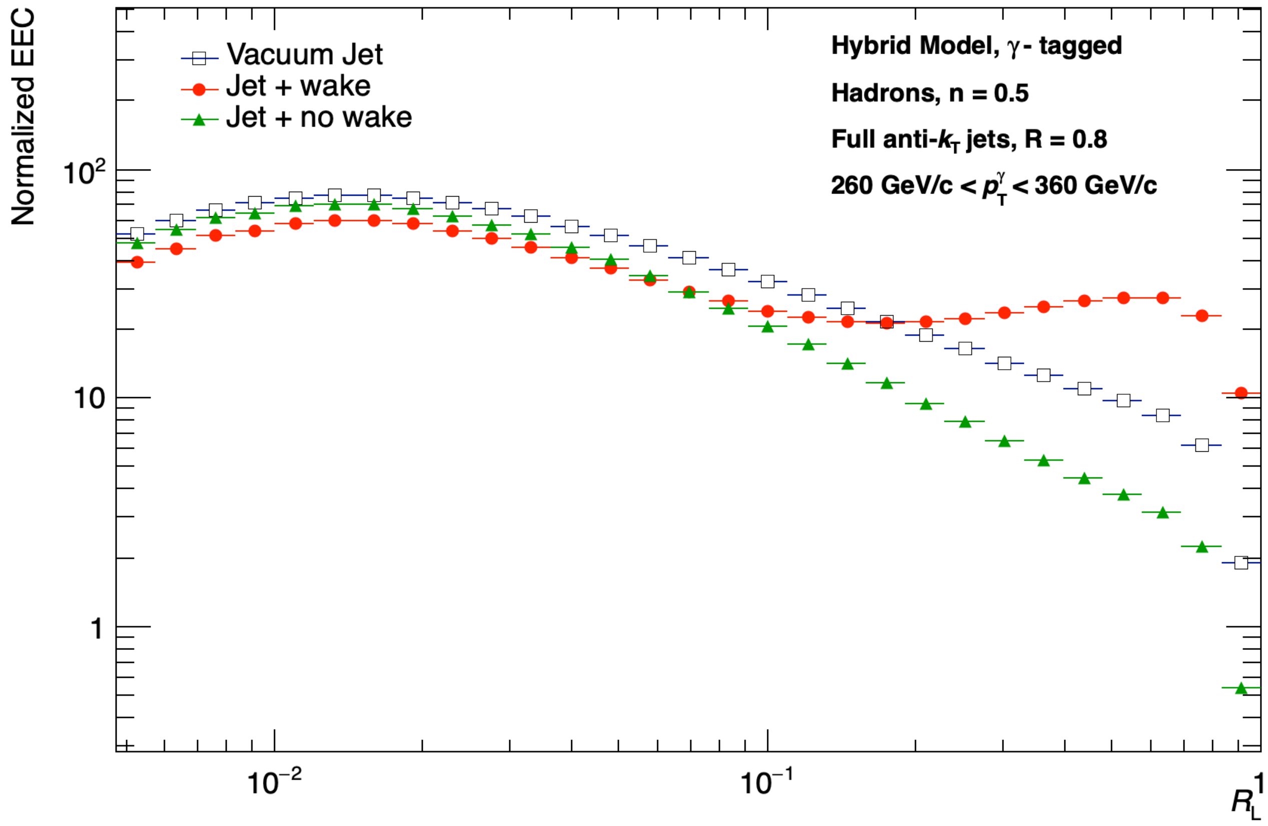
E3C/EEC might be a great experimental tool to study medium response effects!

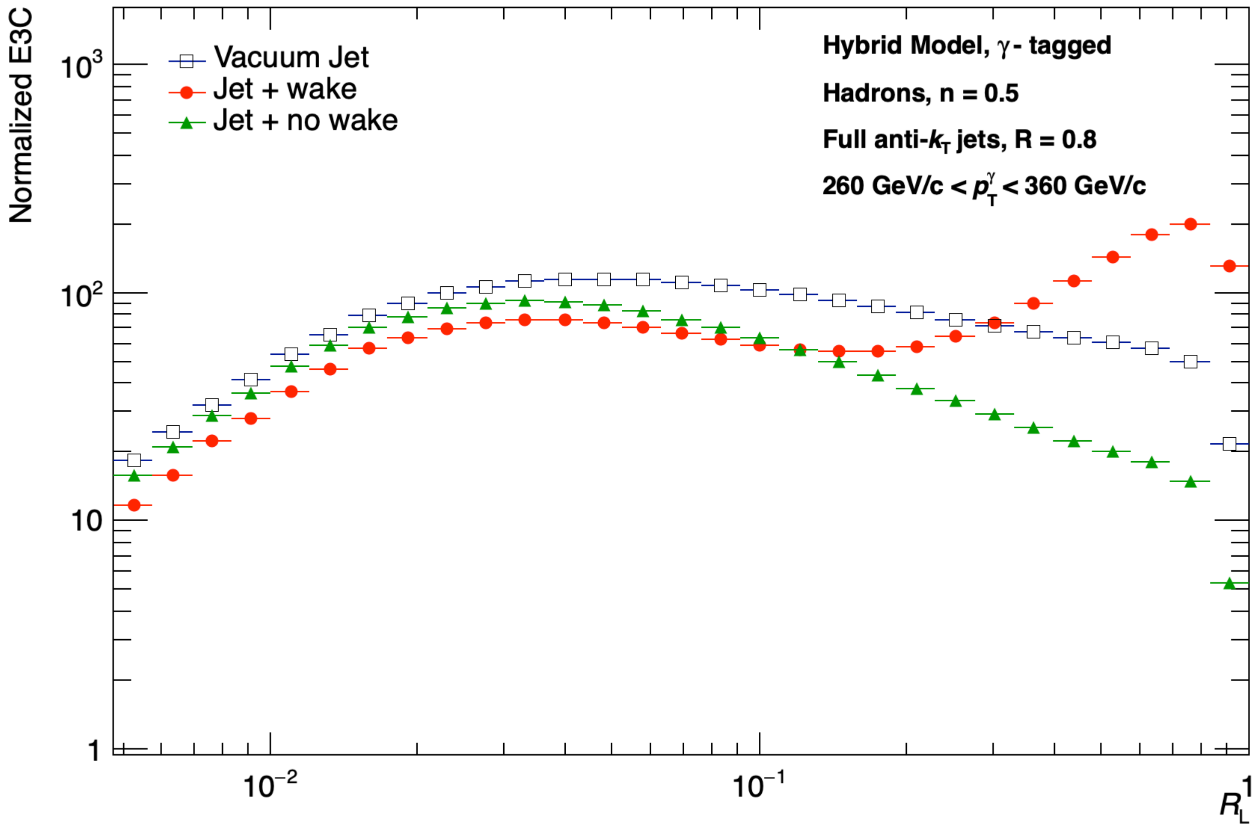
ENC: tuning energy weightings

n = 0.5, enhances the soft particles → we can tune to the physics we are interested in.

$$Weight = \left[\frac{p_{T,i}}{p_{T,jet}}\right]^{0.5}\left[\frac{p_{T,j}}{p_{T,jet}}\right]^{0.5}$$

$$Weight = \left[\frac{p_{T,i}}{p_{T,jet}}\right]^{0.5}\left[\frac{p_{T,j}}{p_{T,jet}}\right]^{0.5}\left[\frac{p_{T,k}}{p_{T,jet}}\right]^{0.5}$$



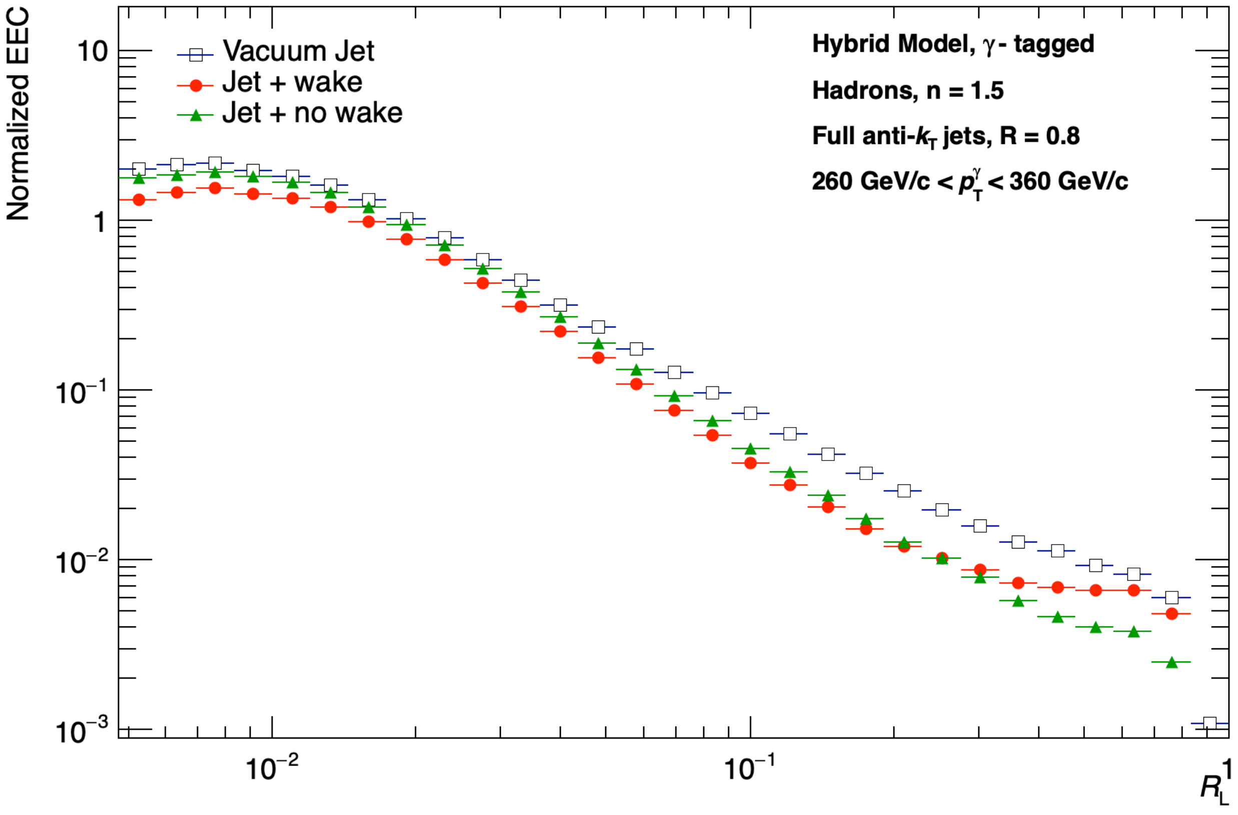


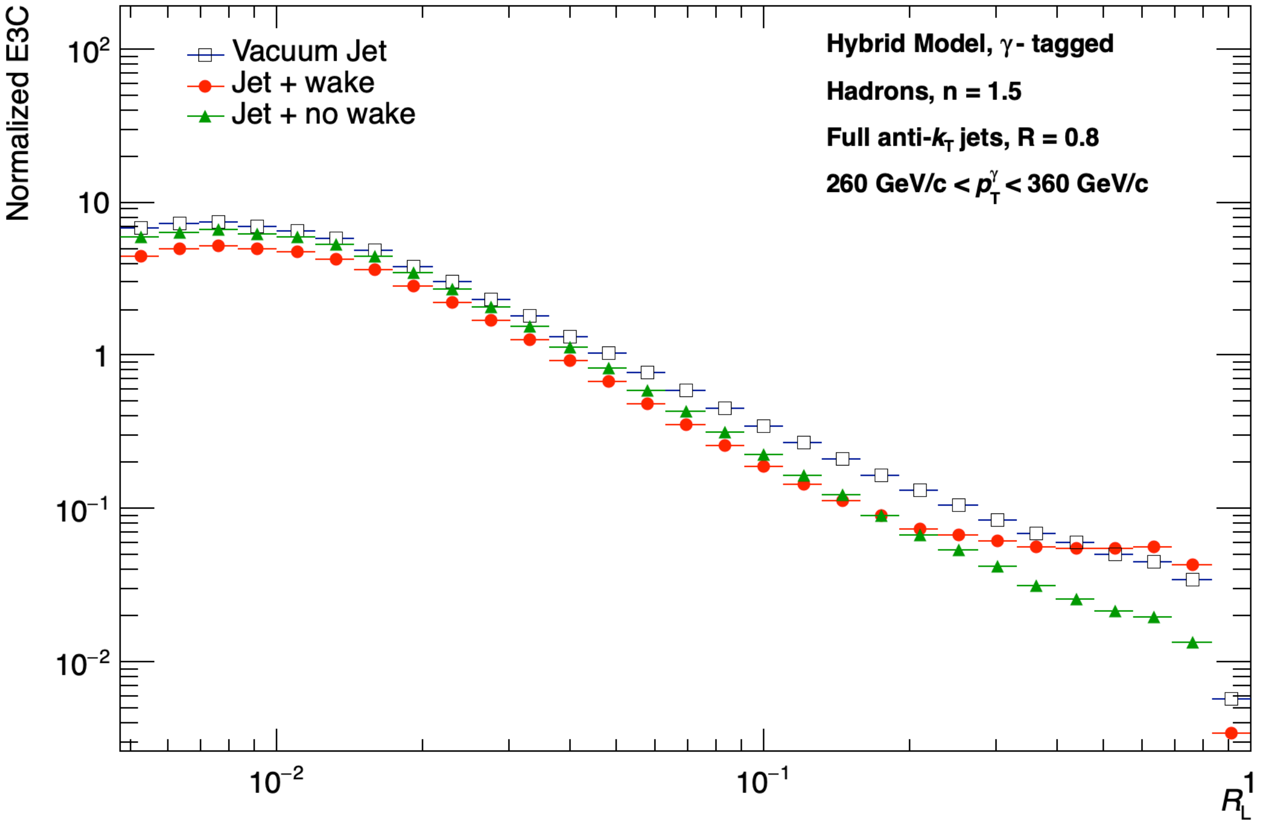
ENC: tuning energy weightings

n = 1.5, suppresses the soft particles → we can tune to the physics we are interested in.

$$Weight = \left[\frac{p_{T,i}}{p_{T,jet}}\right]^{1.5}\left[\frac{p_{T,j}}{p_{T,jet}}\right]^{1.5}$$

$$Weight = \left[\frac{p_{T,i}}{p_{T,jet}}\right]^{1.5}\left[\frac{p_{T,j}}{p_{T,jet}}\right]^{1.5}\left[\frac{p_{T,k}}{p_{T,jet}}\right]^{1.5}$$

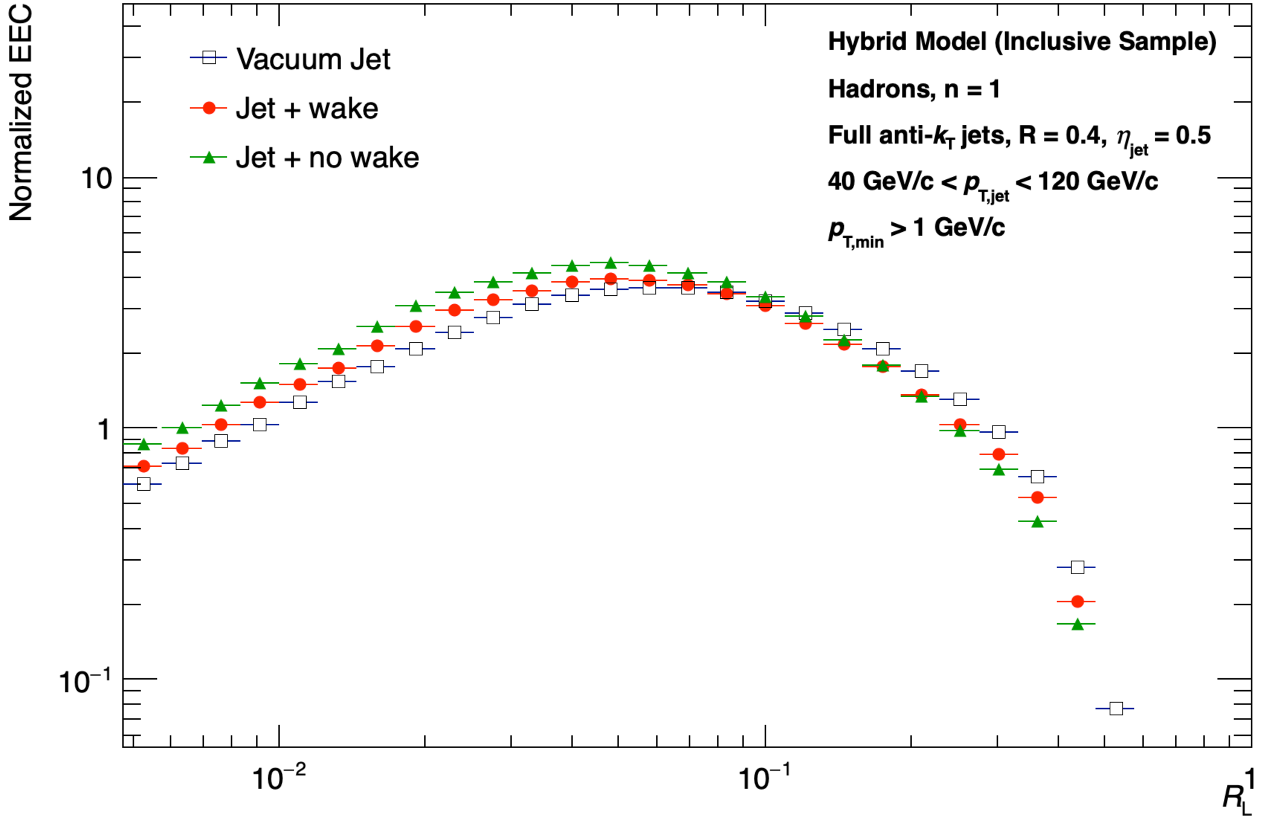


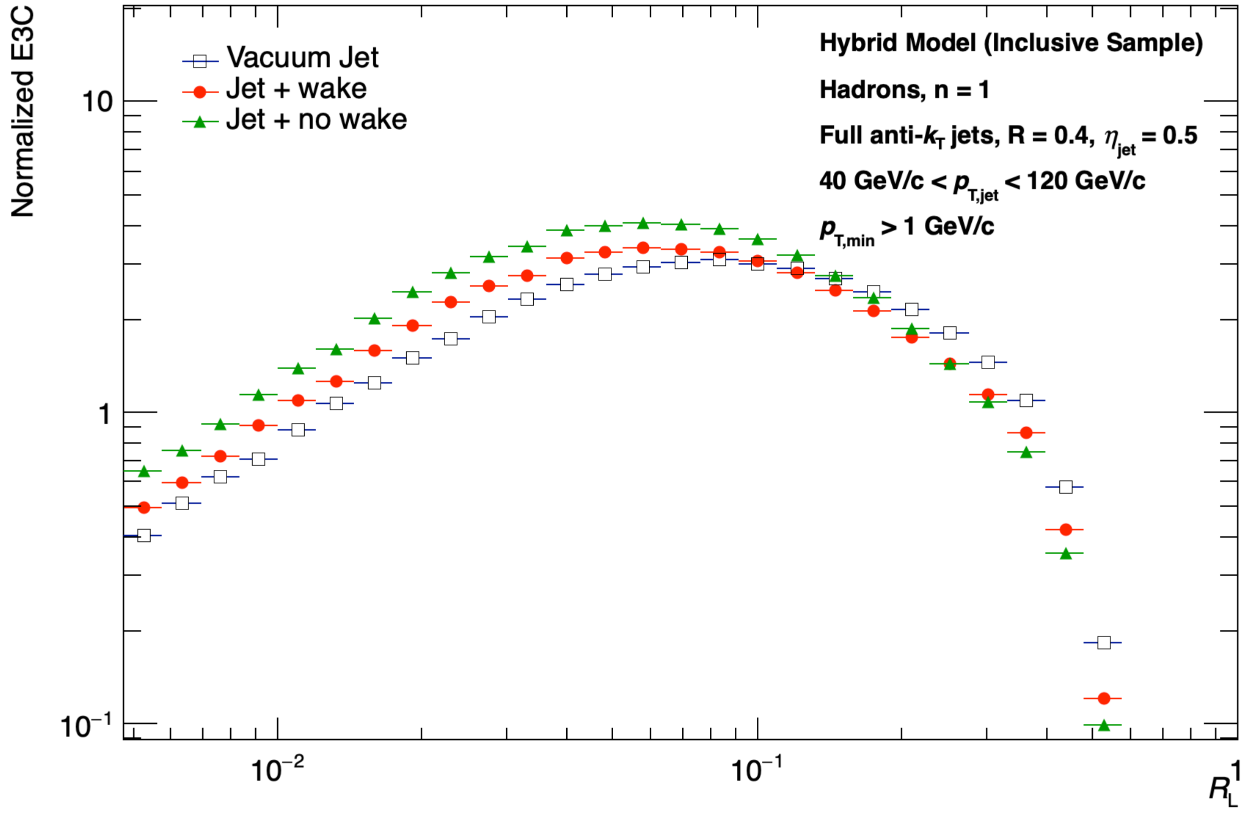


ENCs in the Hybrid Model: ALICE kinematics

Inclusive jets, ALICE kinematics, track cuts applied (still no background).

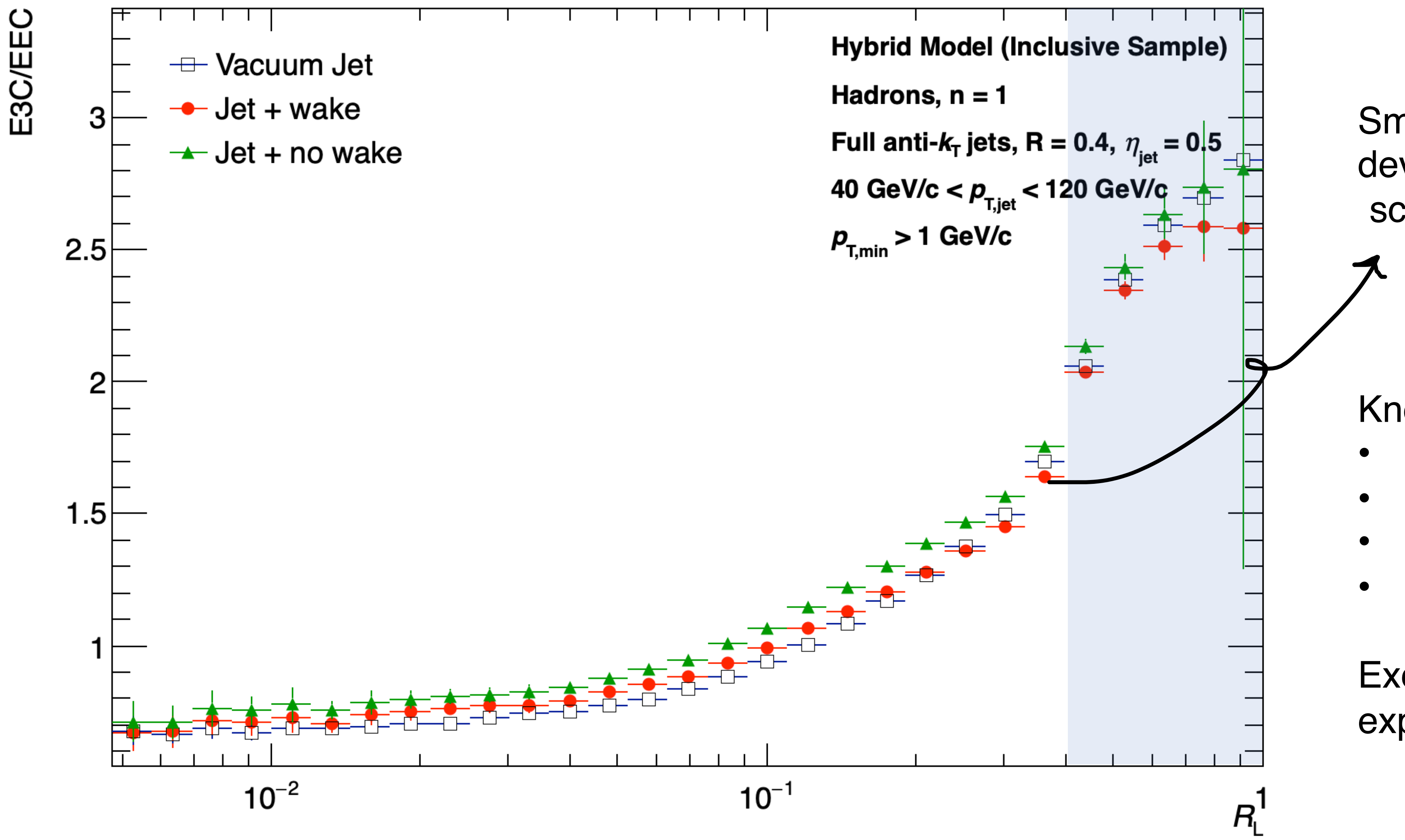
Effects are no longer as pronounced because we hit the edge of the jet.





Per jet and bin-width normalized.

E3C/EEC in the Hybrid Model: ALICE kinematics



Small change in slope, deviation from vacuum scaling – effect of the **wake**.

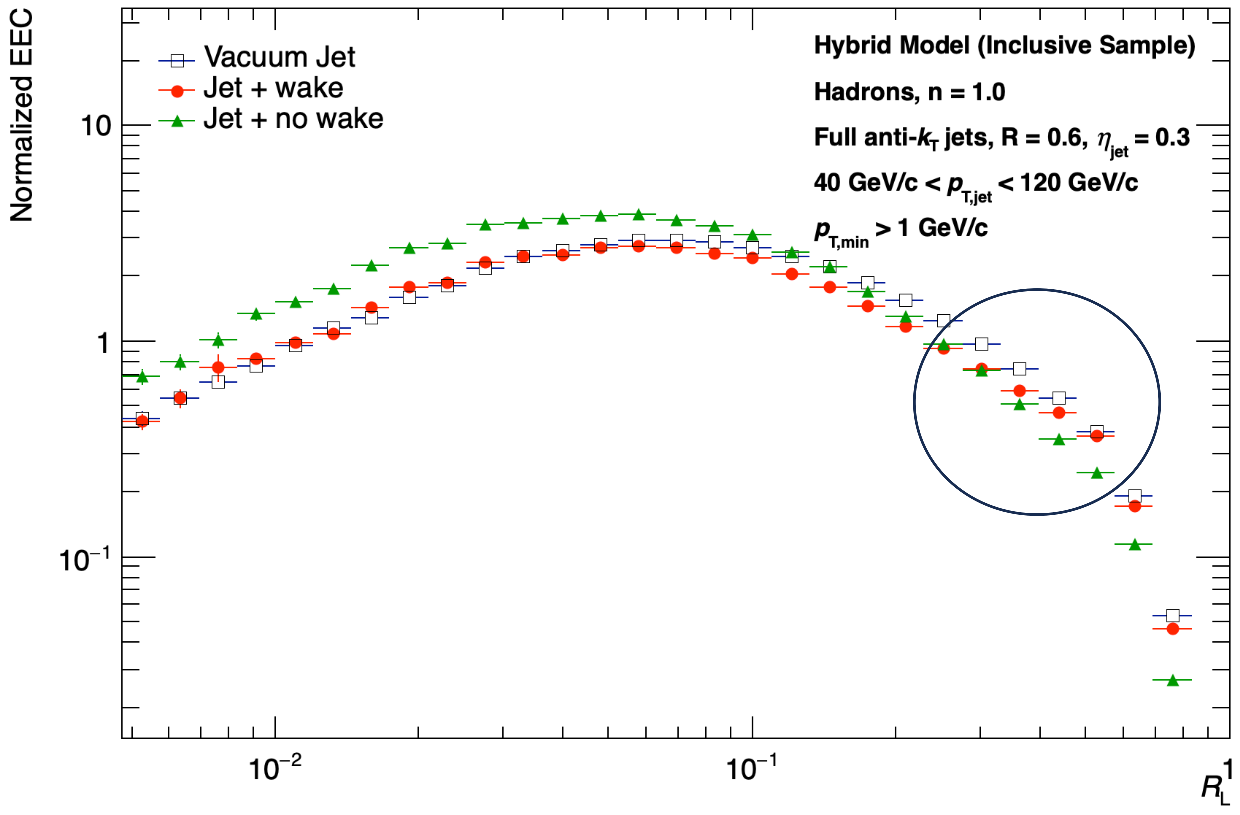
Knobs we can we turn –

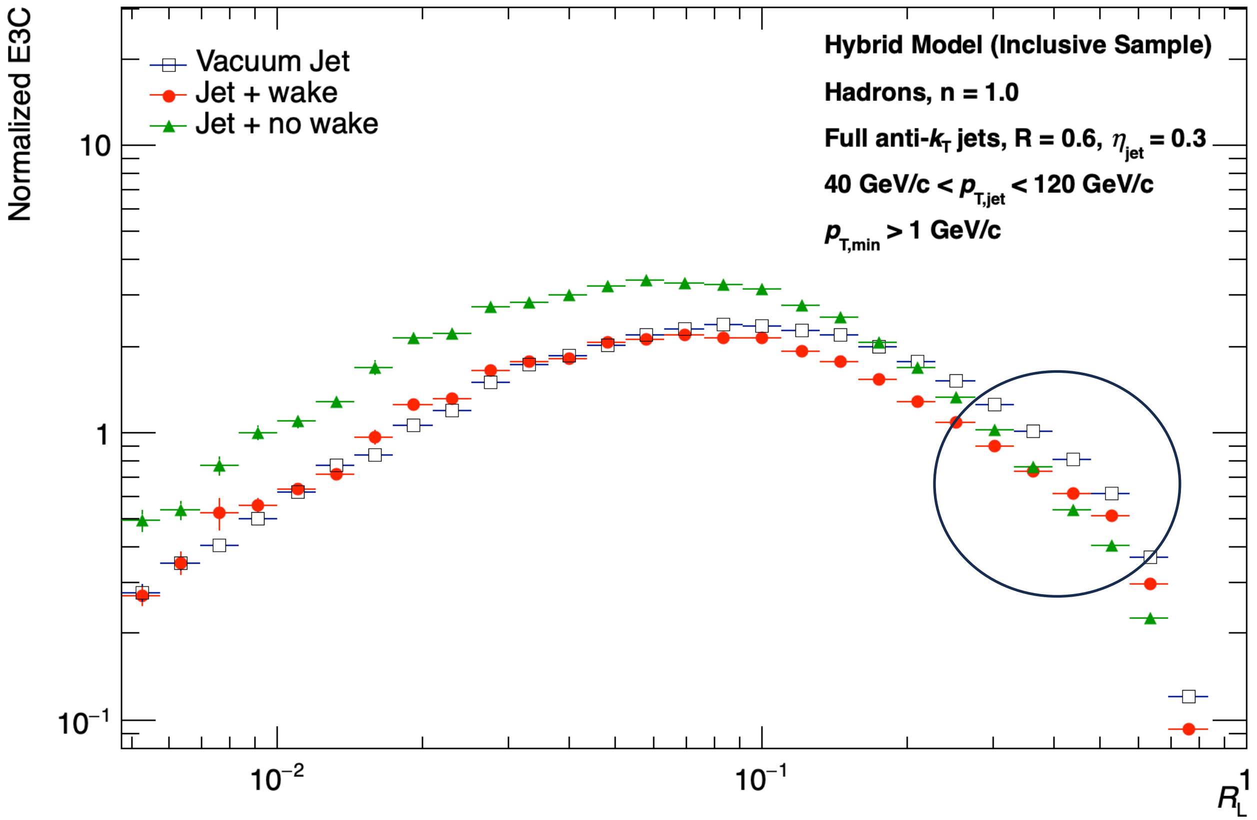
- Play with energy weights?
- Larger jet radius?
- Play with track p_T cuts?
- Isolate phase space?

Excellent opportunity for experimental ingenuity!

ENCs in the Hybrid Model: Turning knobs

Extending to larger radius (R = 0.6)

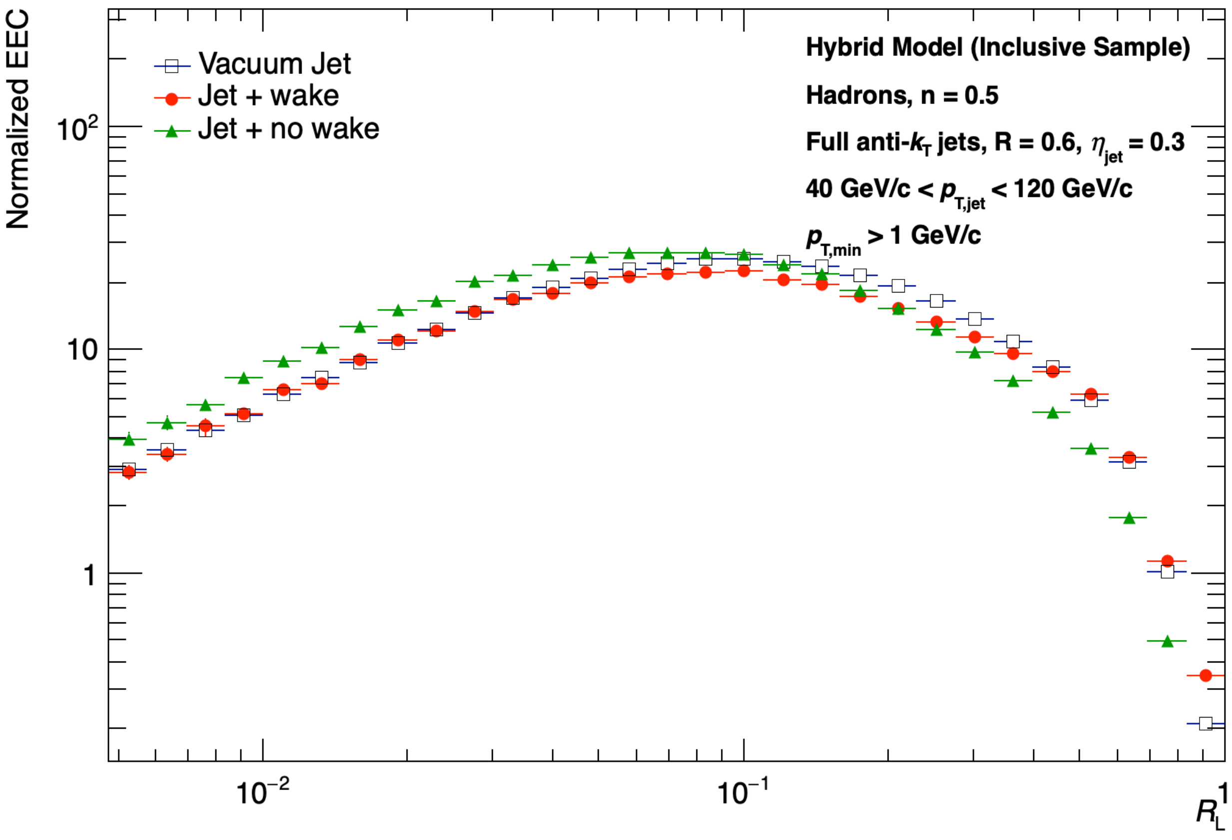


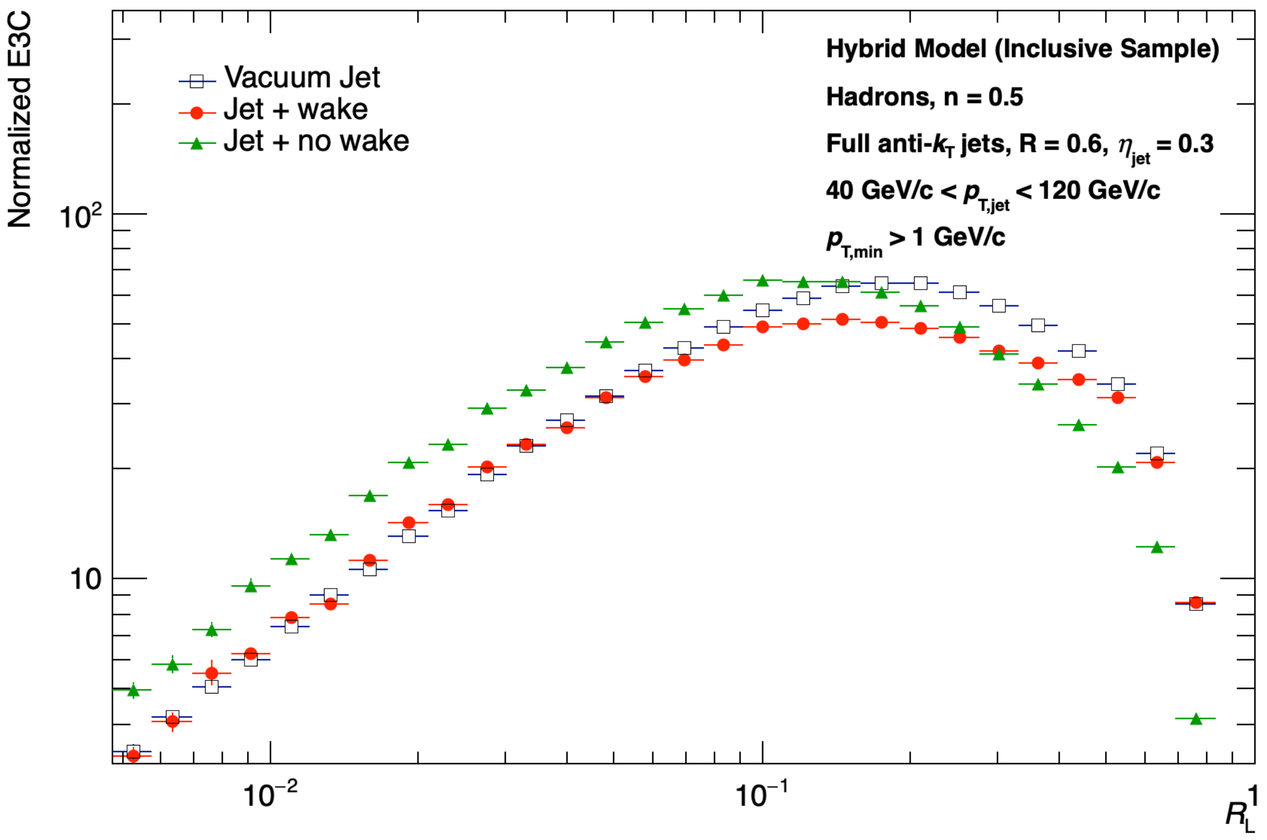


Per jet and bin-width normalized.

ENCs in the Hybrid Model: Turning knobs

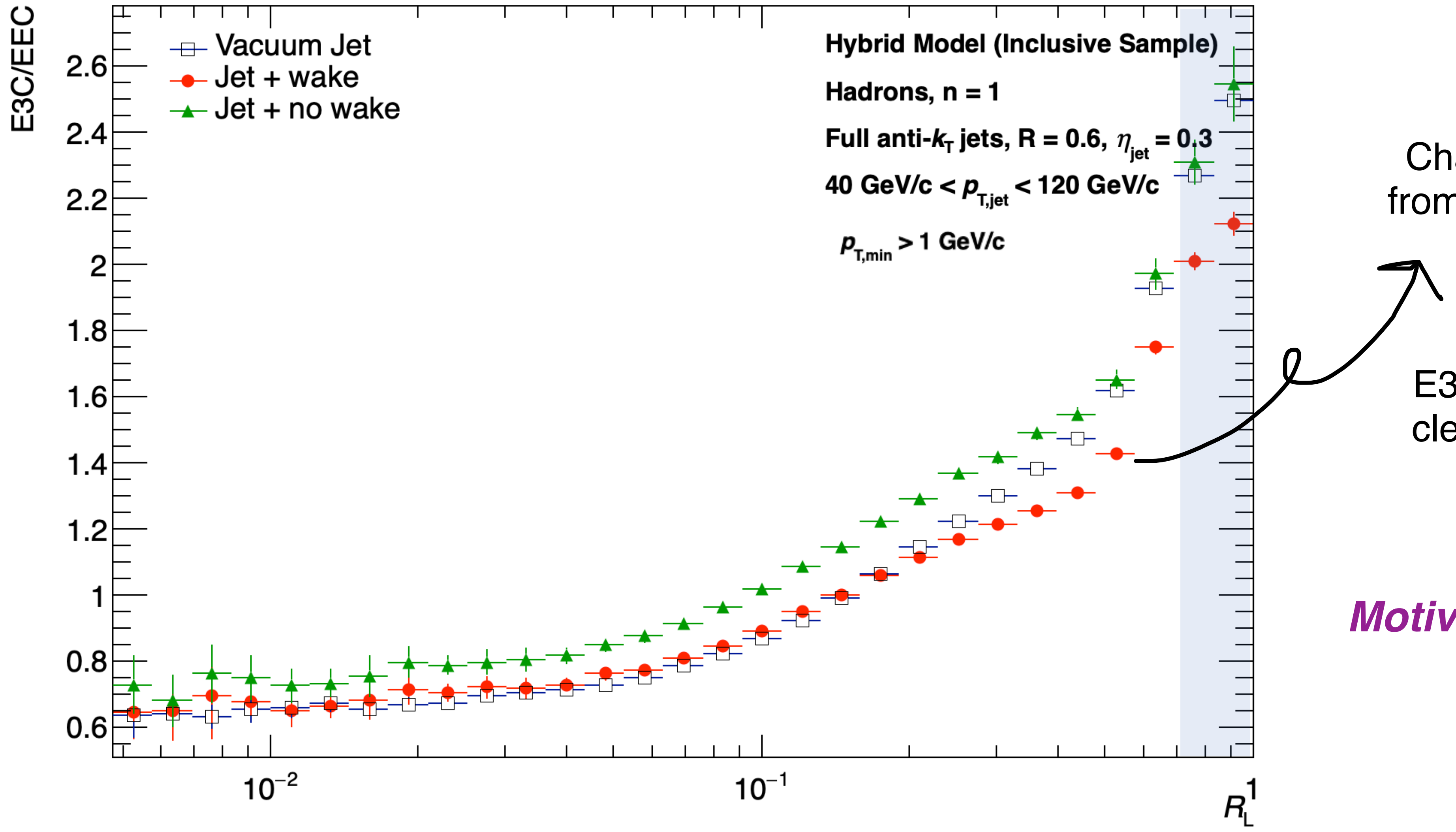
Extending to larger radius (R = 0.6) and playing with energy weights (n = 0.5)





Per jet and bin-width normalized.

E3C/EEC in the Hybrid Model: Turning knobs



Change in slope, deviation from vacuum scaling is more visible.

E3C/EEC might provide a cleaner signal for medium response effects!

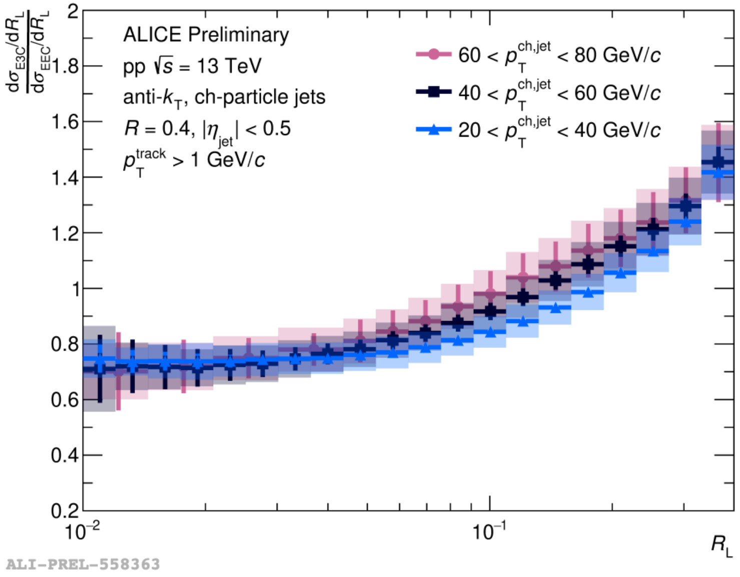
Motivates jet substructure at larger R!!!

Summary and outlook

- ENCs are a **scale sensitive** probe of QCD.
- E3C/EEC → clear signature of pQCD effects (α_S, γ_N).
- Access both **hard & soft** physics via playing with energy weightings.
- It looks promising to use E3C/EEC ratios to study **medium response effects** such as the wake – Pb-Pb analysis is ongoing.

Energy Correlators

Other substructure observables



HARD

SOFT

BACKUP

Analysis Method/Overview:

- Compute ENCs on charged anti-k_T jets, R = 0.4
- Bin-by-bin correction: ALICE has great angular resolution ($\approx$ 1mrad for $p_T^{track} \approx$ 1GeV)

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

- Dominant systematic: p_T migration effects (unfolding checks – ongoing)

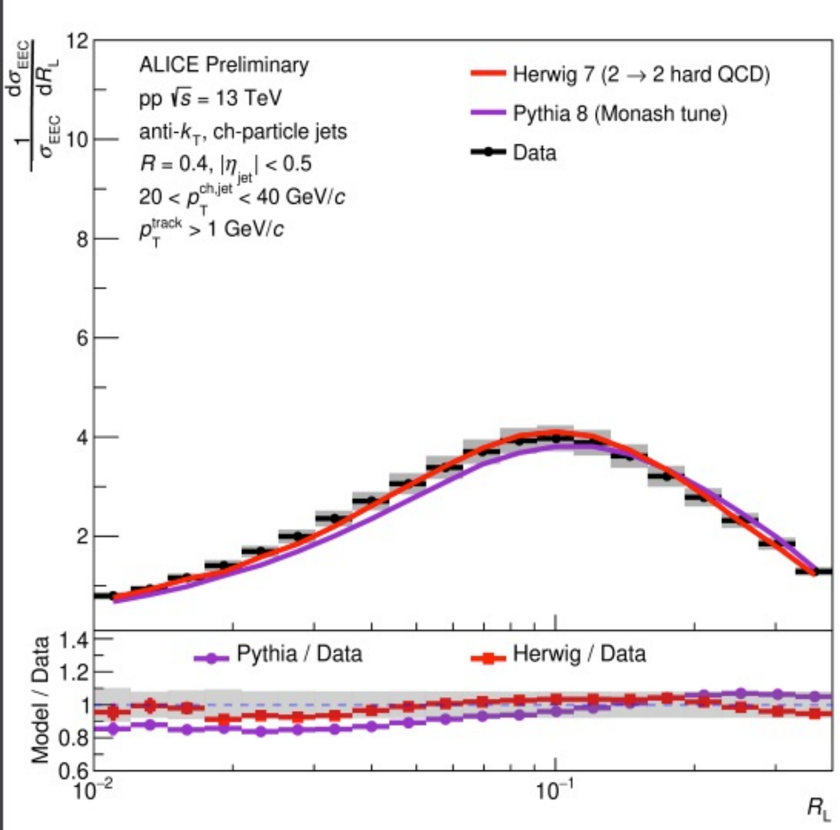
Systematics
p_T migration
Single particle tracking efficiency
Pair efficiency
Generator dependence

Anomalous Dimensions: QFT review

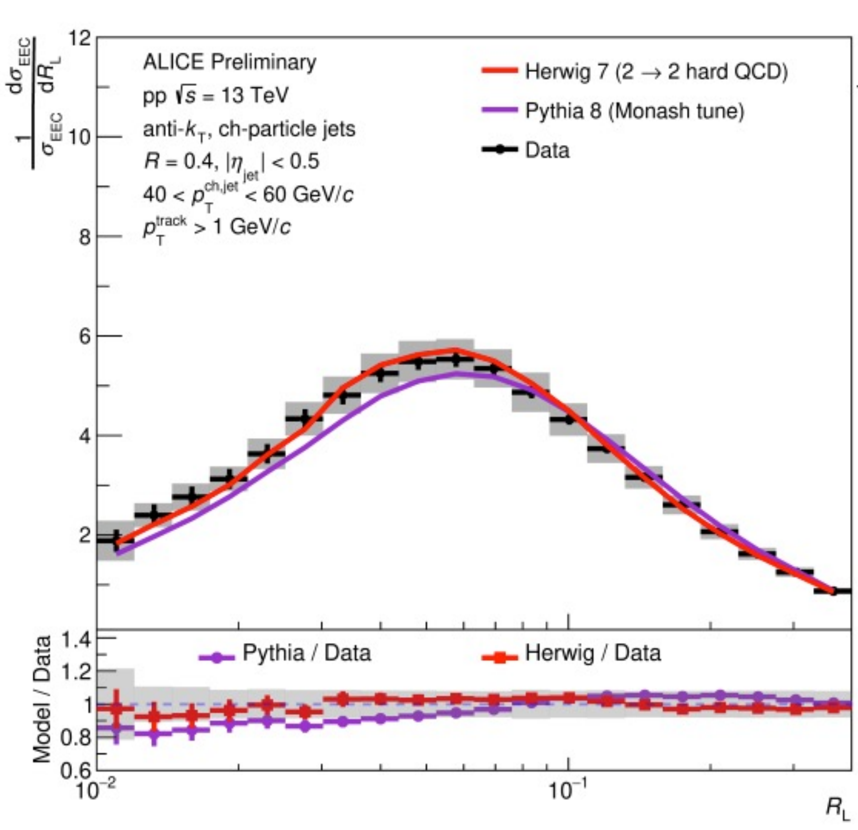
QFT operators have a scaling/mass dimension $\Delta_{\mathbb{O}}$.
For e.g., in 3+1D, scalar field $[\phi] = 1$, fermion field $[\psi] = 3/2$.
Quantum mechanical effects ⟶ $\Delta_{\mathbb{O}}$ *gets shifted by "anomalous dimensions", $\gamma_{\mathbb{O}}$:*

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

Model Comparison: EEC



ALI-PREL-557437



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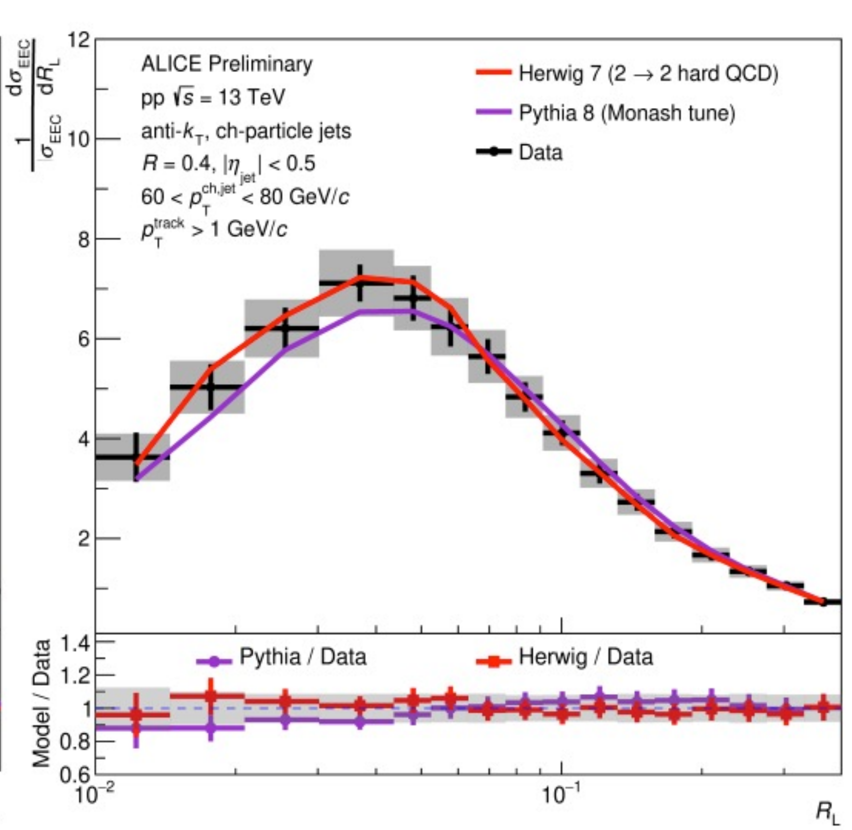
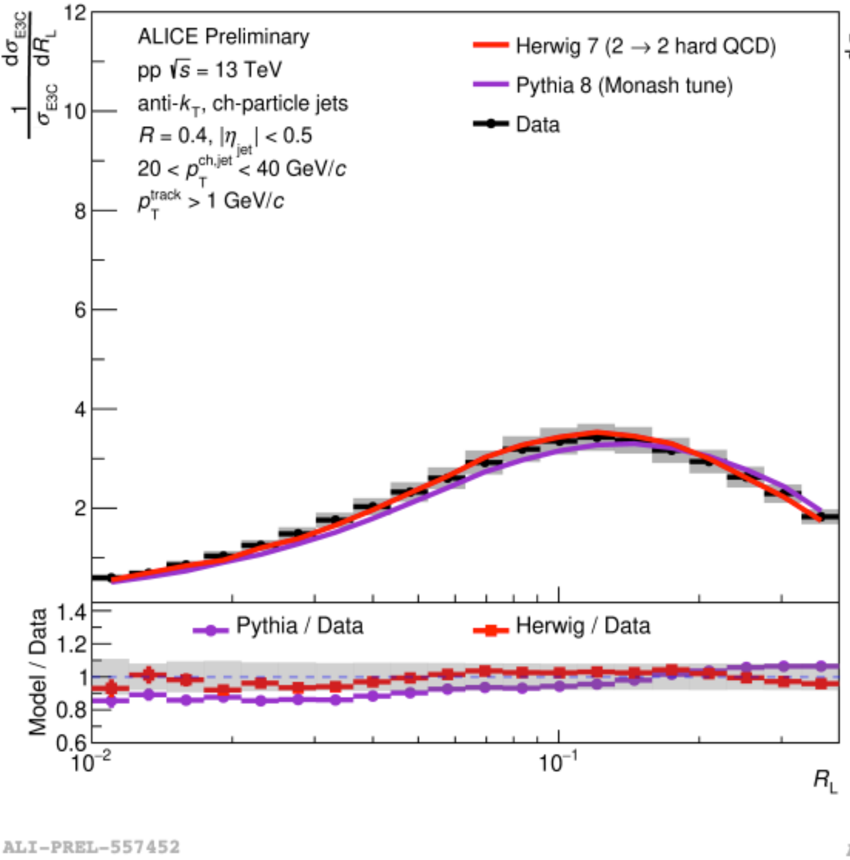
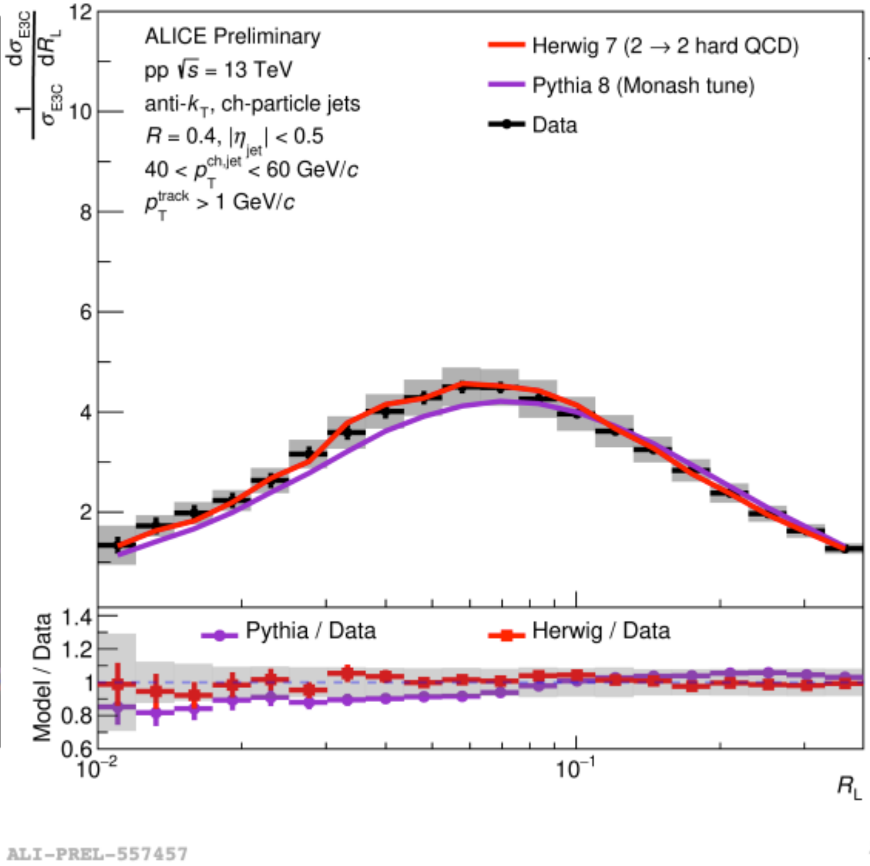


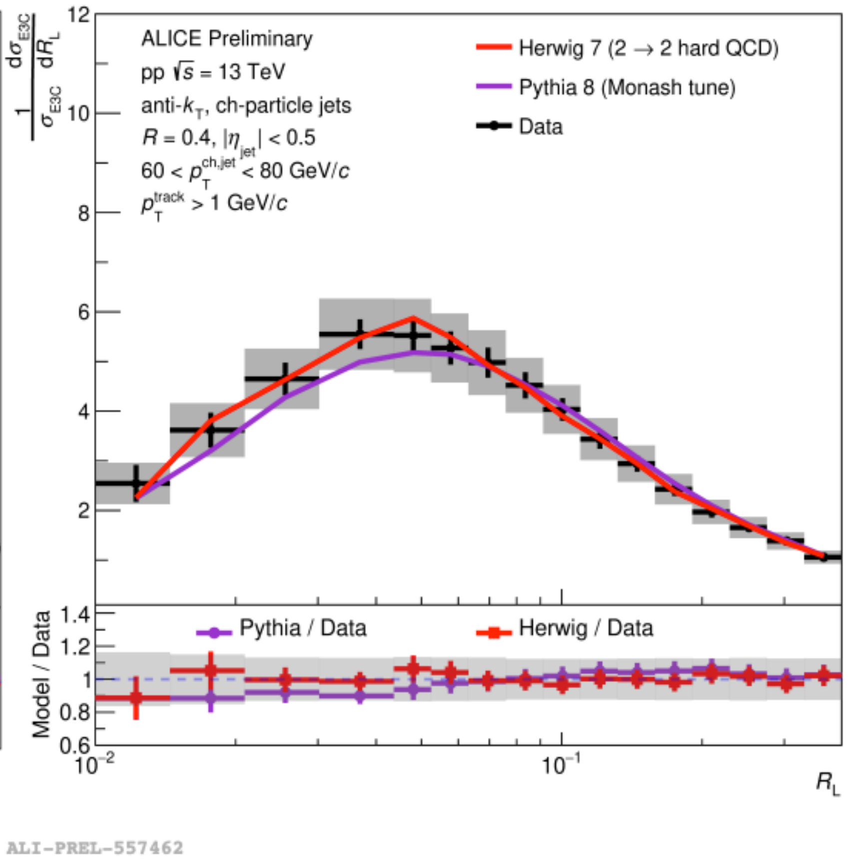
ALI-PREL-557447

Herwig shows better agreement
Differences more pronounced in the hadronic region
Possible due to different hadronization mechanisms?

Model Comparison: E3C

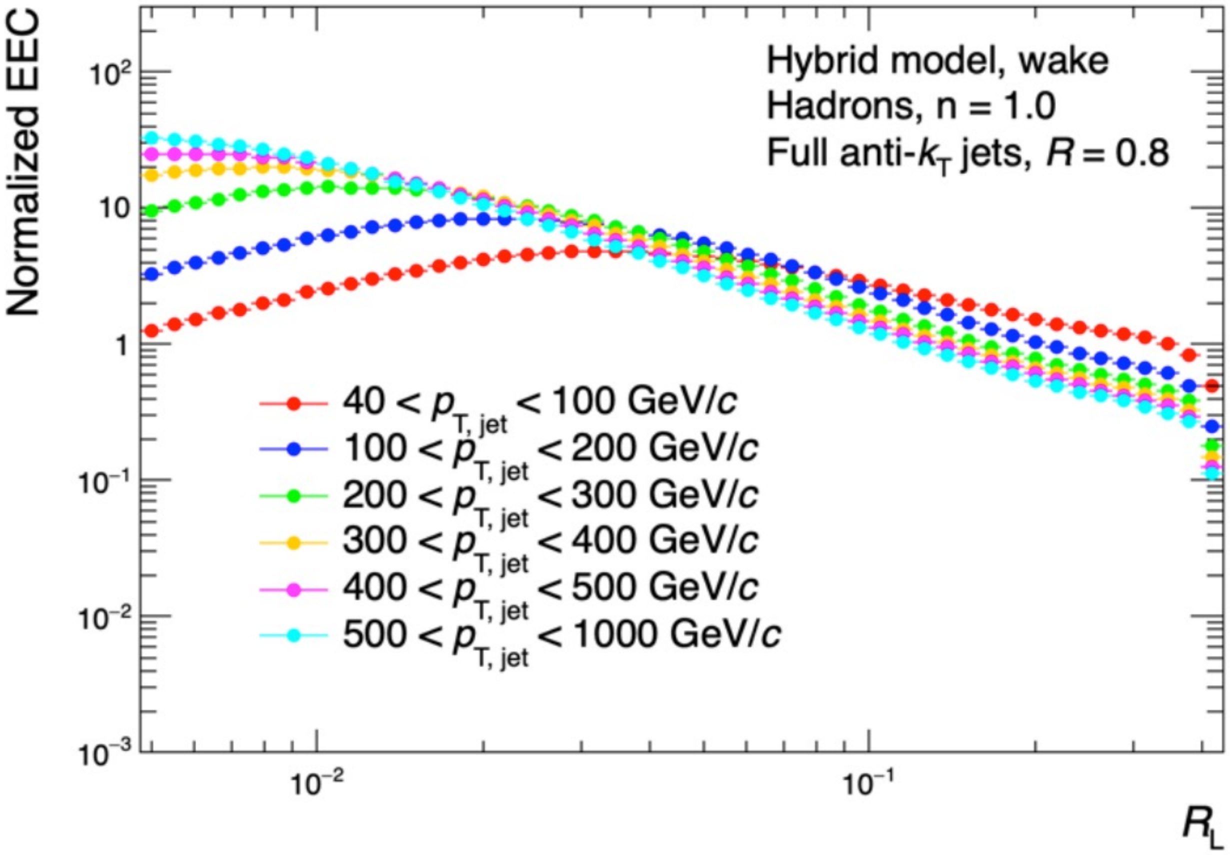


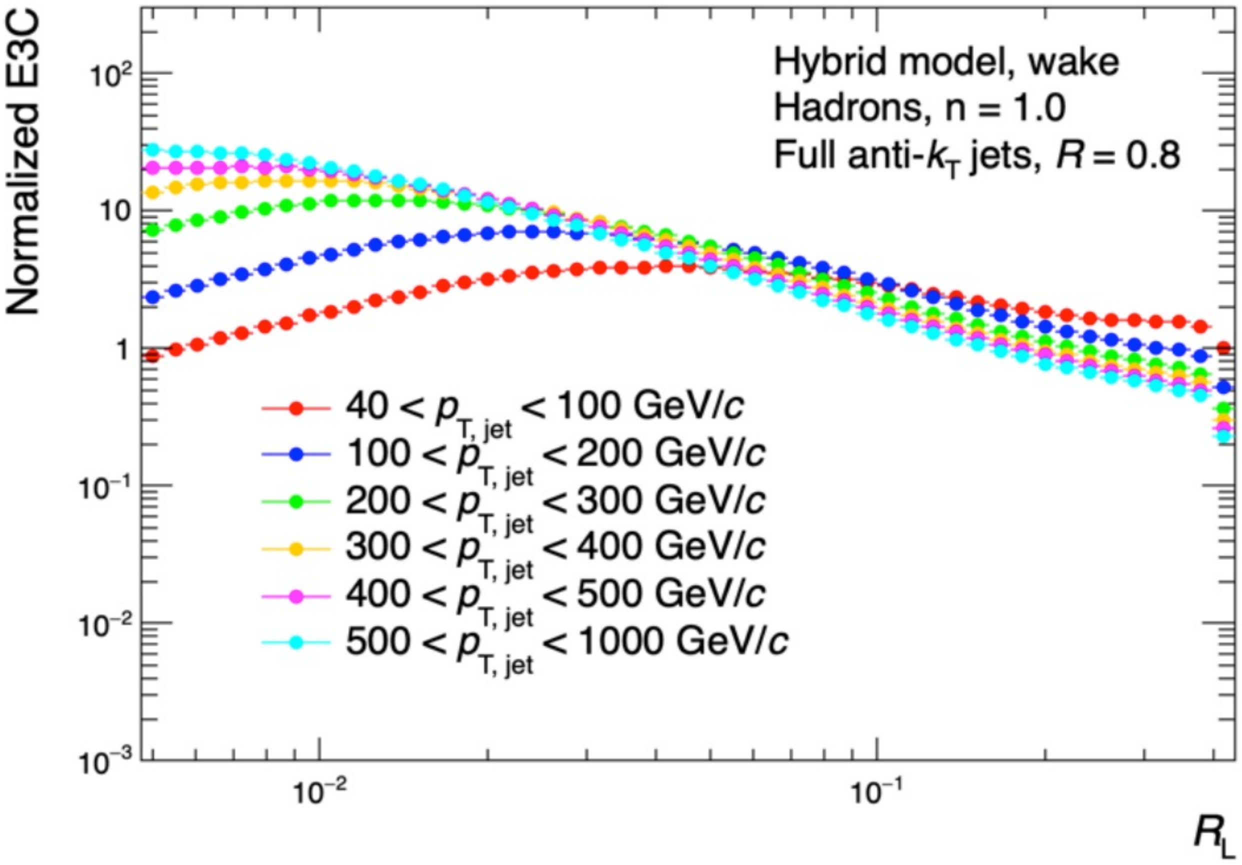




Trends remain similar to EEC. Herwig still agrees better

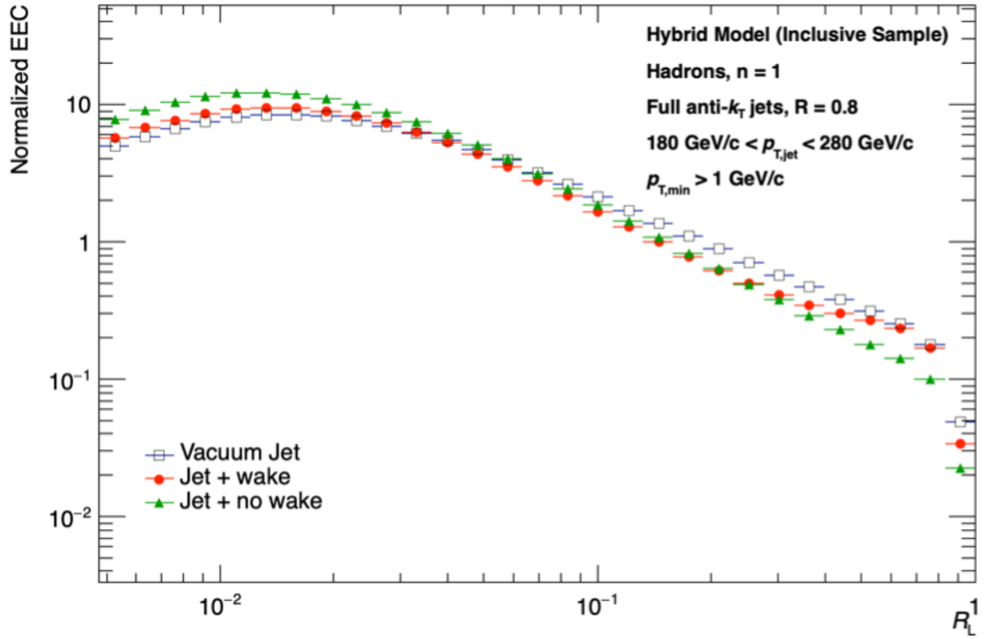
Dependence of wake signal on jet p_T

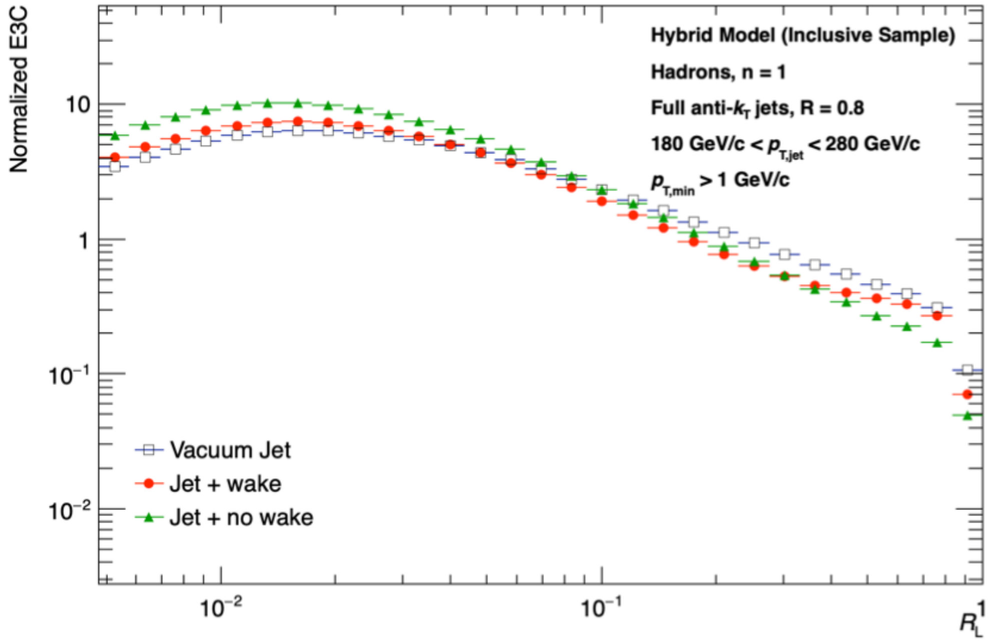


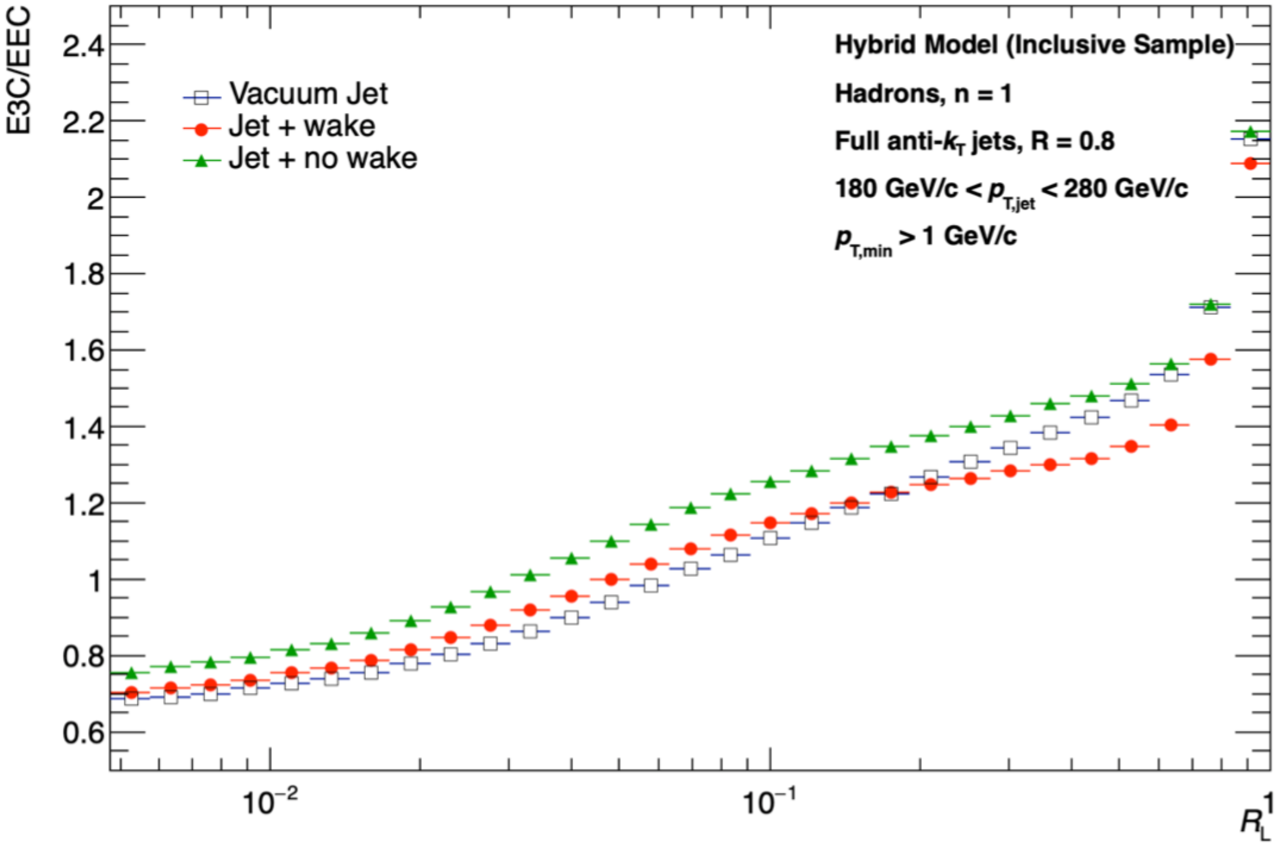


Wake is more prominent at lower jet p_T!

R = 0.8, η_{jet} = 2, track pT cut = 1 GeV







The ideal observable is E3C/EEC!!