Massachusetts Institute of Technology

Imaging the wake of the jet with Energy Correlators

Hannah Bossi (MIT)

ECT* Jet Tools Workshop, Trento, Italy

February, 13th, 2024

Based on work in progress with Ian Moult (Yale), Dani Pablos (Santiago), Ananya Rai (Yale), Krishna Rajagopal (MIT), and Arjun Srinivasan Kudinoor (Cambridge)

MIT HIG's work was supported by US DOE-NP

Jet quenching

***This categorization scheme is largely based off of great talk by Jing Wang.*

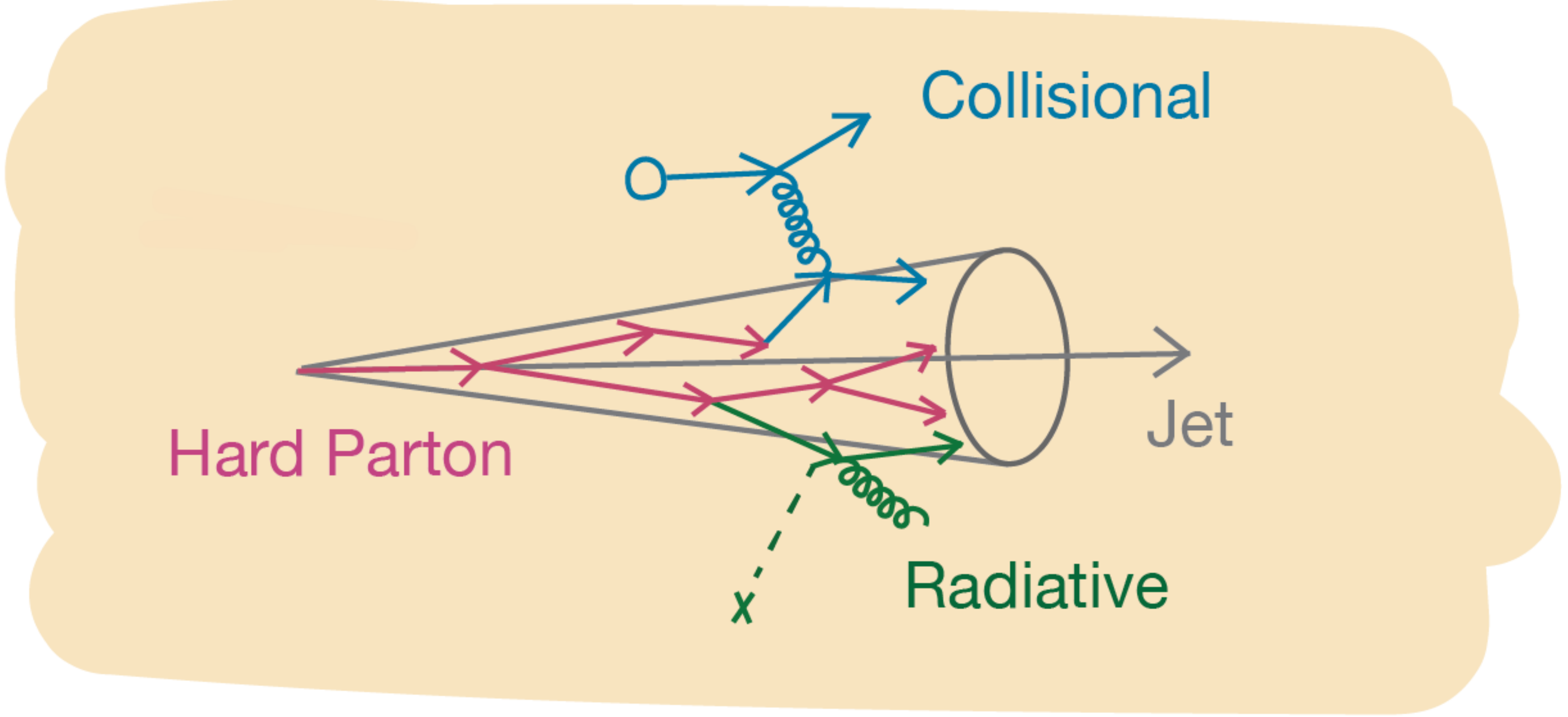
① Impact of the medium on the jet → jet energy loss

Ⓐ Weak coupling limit

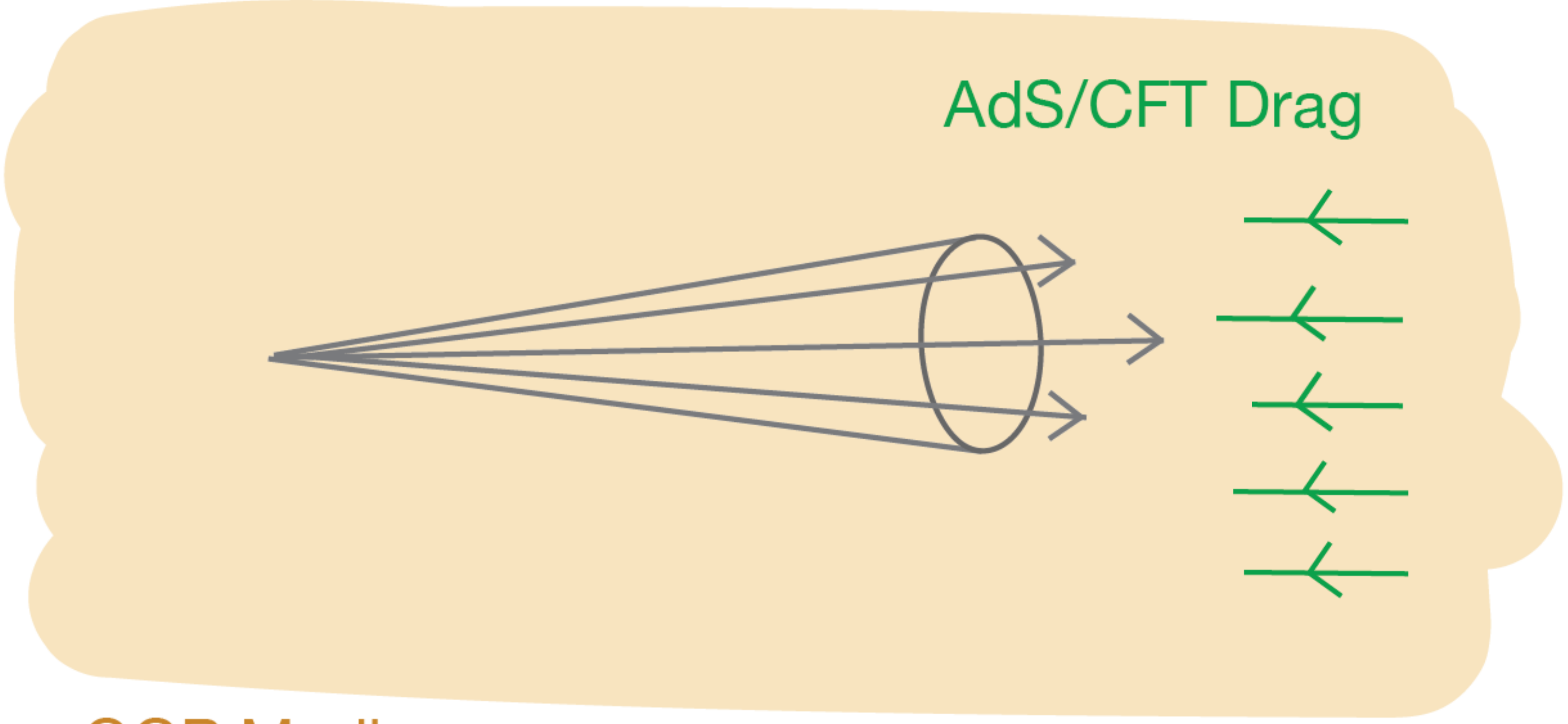
- ✽ Collisional
- ✽ Radiative

Ⓑ Strong coupling limit

- ✽ AdS/CFT drag force



QGP Medium



QGP Medium

Variety of ways to implement each category →all theories won't behave the same!

Jet quenching

***This categorization scheme is largely based off of great talk by Jing Wang.*

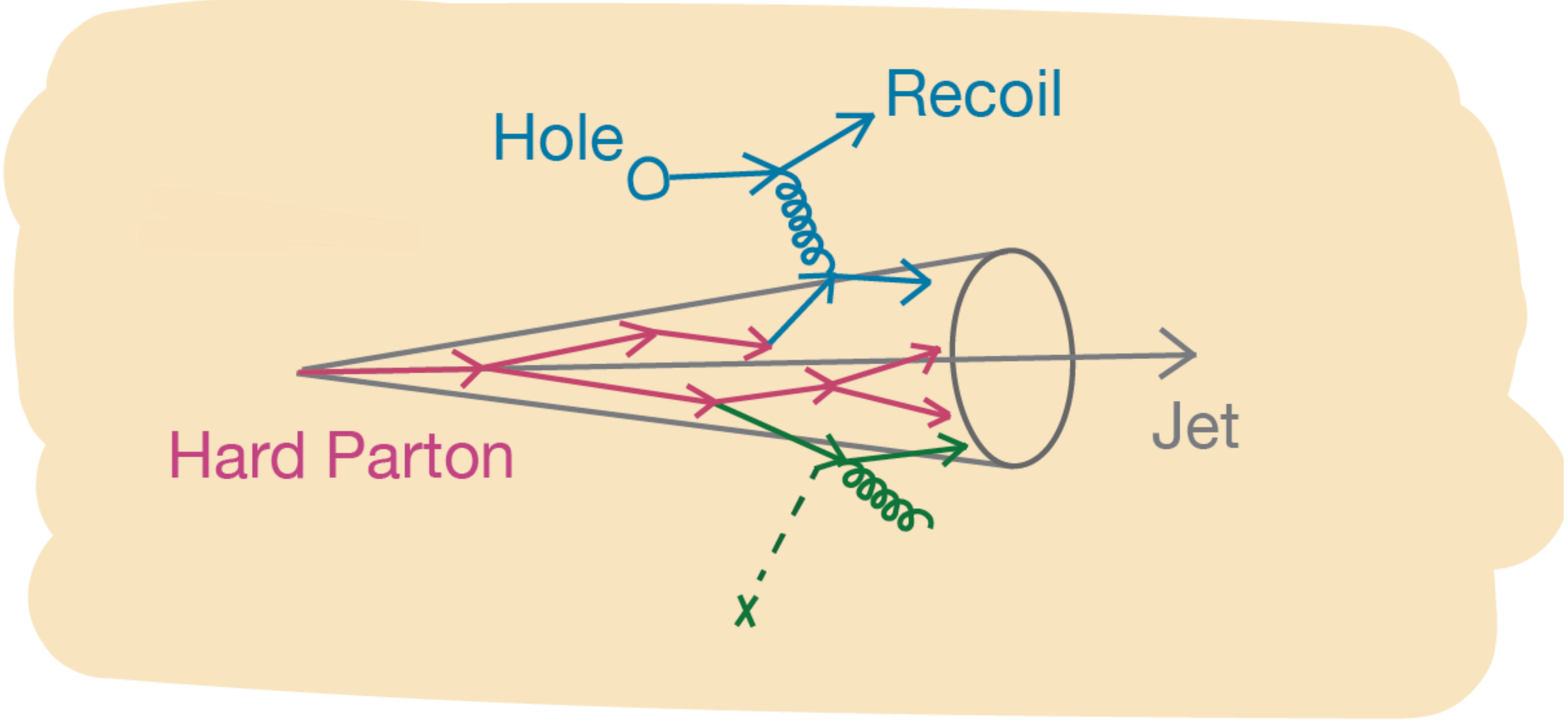
② Impact of the jet on the medium → medium response

Ⓐ Weak coupling limit

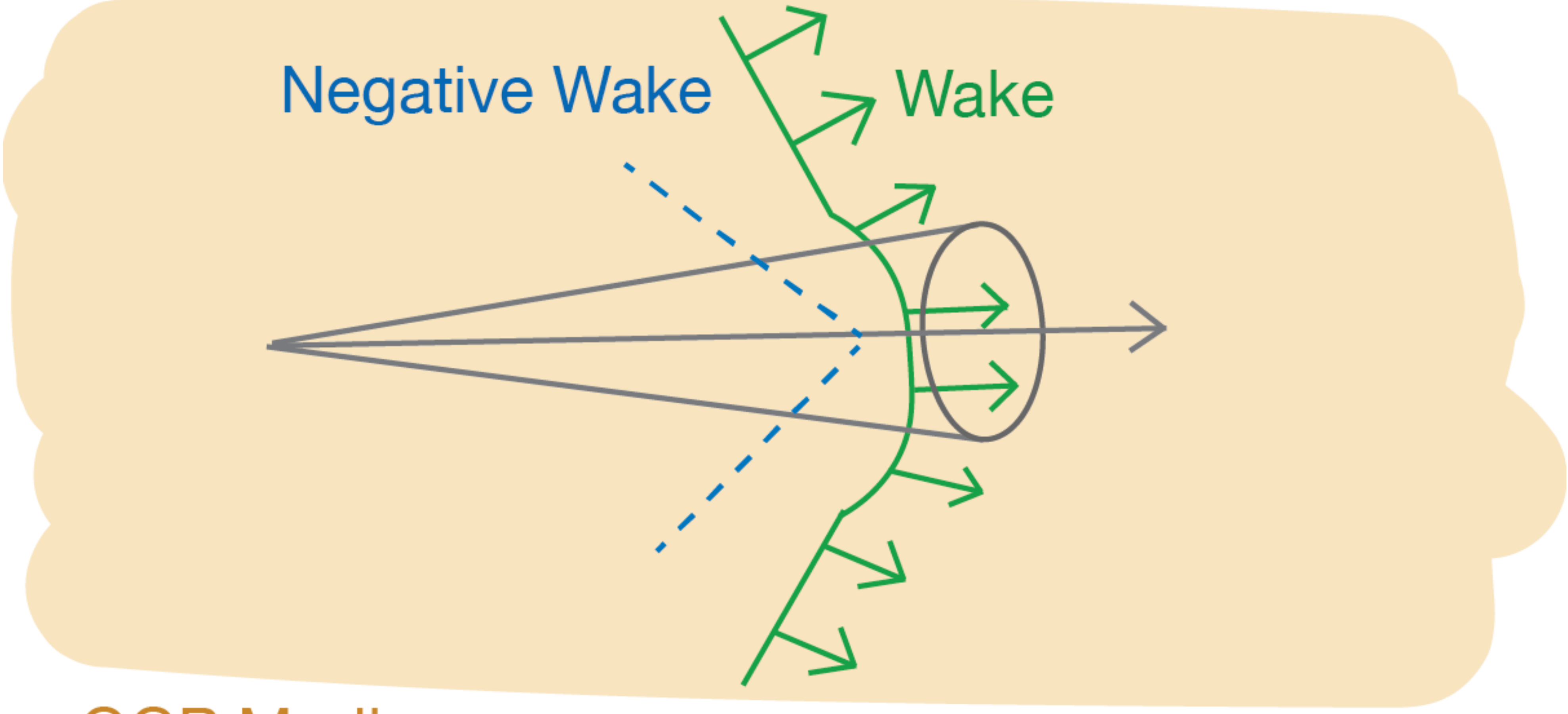
- ❃ Recoils (Kinetic based approach)

Ⓑ Strong coupling limit

- ❃ Wake (Hydrodynamics based approach)
- ❃ Includes positive and negative contributions



QGP Medium



QGP Medium

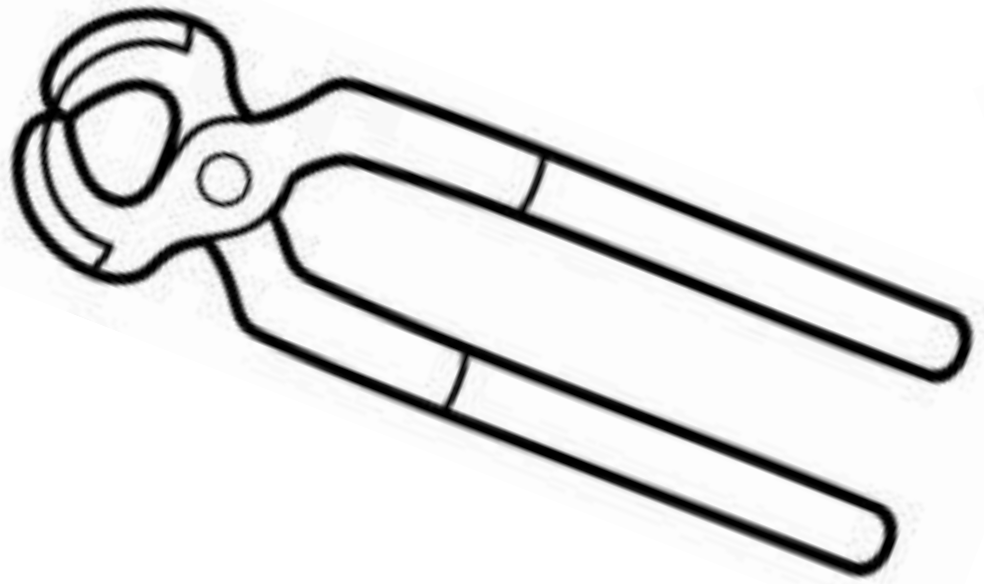
*** Cartoon of the wake in position space*

Focus of this talk: study medium response effects!

Tools to search for the medium response

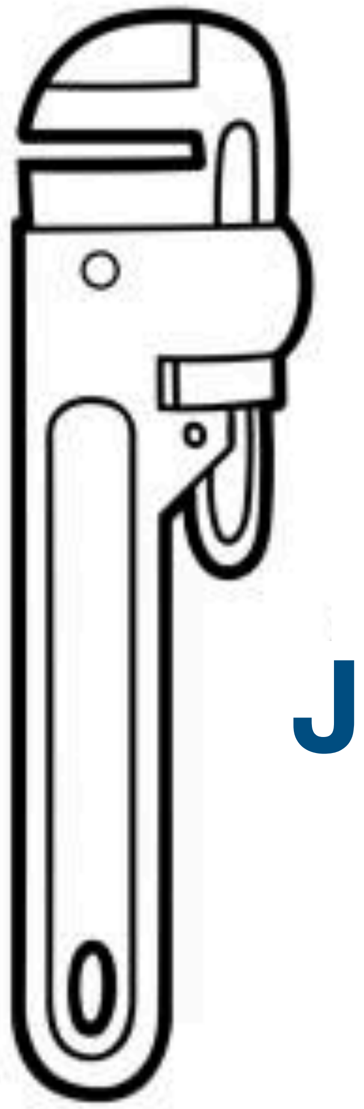
What tools exist to study the medium response?

Z-hadron

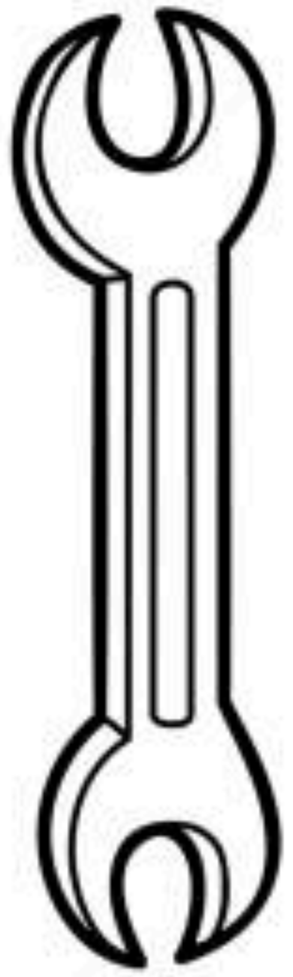


γ/Z-jet

(Groomed) jet substructure

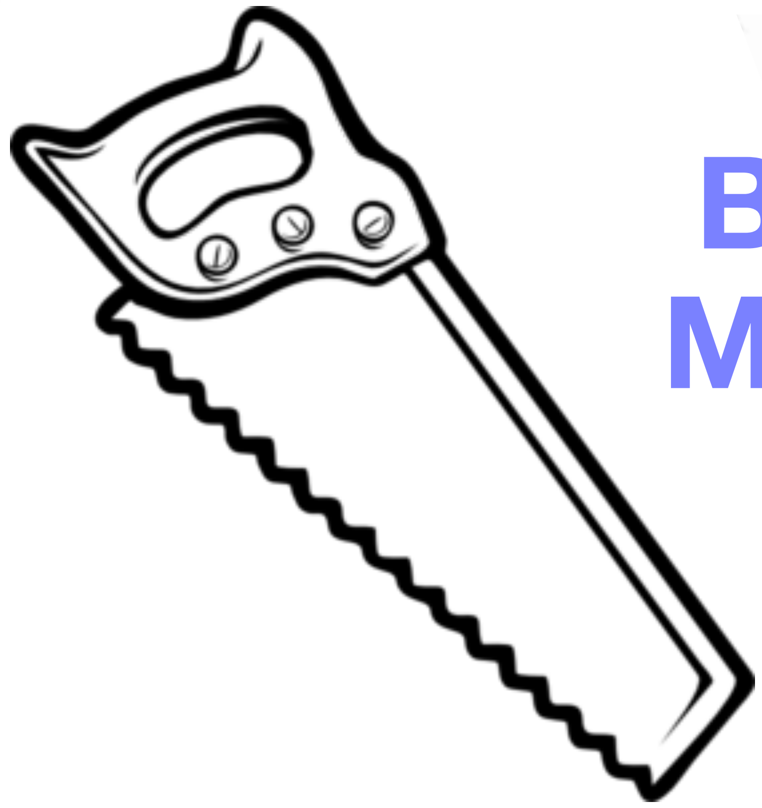


Jet Shapes



R-dependent inclusive jet measurements

Jet-Hadron correlations



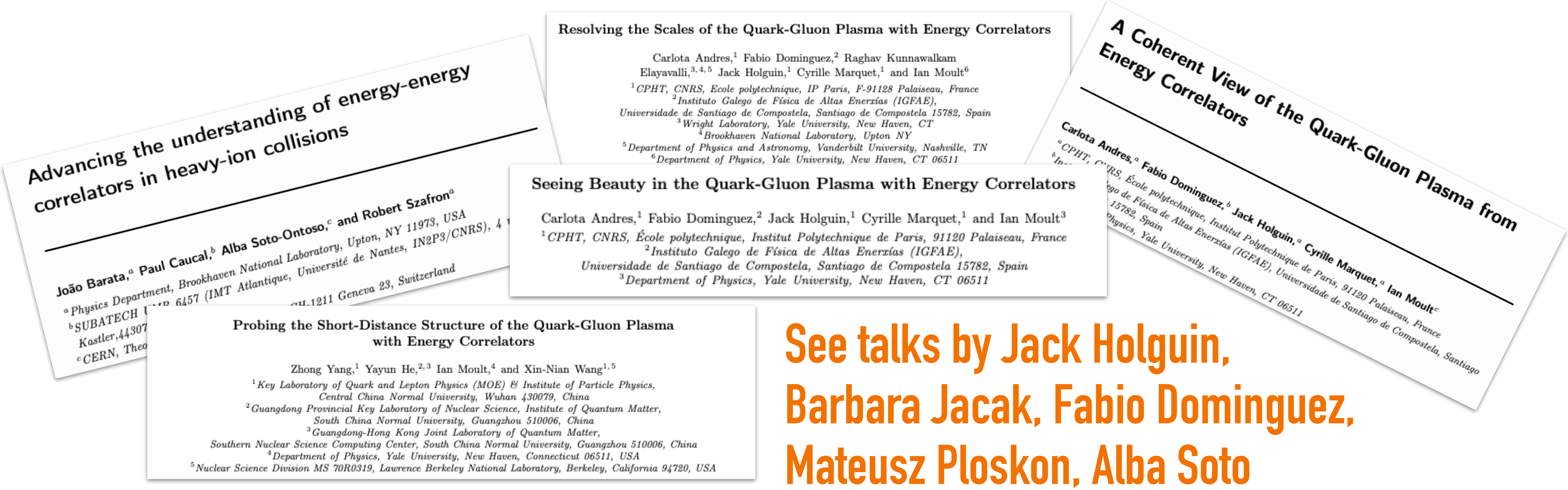
Baryon-to-Meson ratio near jets

See Yeonju's talk (Mon 2:30pm) for more!

Some tools are better than others!

New tools or a combination often needed!

Energy Energy Correlators


Advancing the understanding of energy-energy correlators in heavy-ion collisions

João Barata,[a] Paul Caucal,[b] Alba Soto-Ontoso,[c] and Robert Szafron[a]
[a] Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA
[b] SUBATECH UMR 6457 (IMT Atlantique, Université de Nantes, IN2P3/CNRS), 4
Kastler, 44307
[c] CERN, Theo ... CH-1211 Geneva 23, Switzerland

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] Department of Physics and Astronomy, Vanderbilt University, Nashville, TN
[6] Department of Physics, Yale University, New Haven, CT 06511

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 ... 15782, Spain
[c] ... Physics, Yale University, New Haven, CT 06511

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

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) & Institute of Particle Physics, Central China Normal University, Wuhan 430079, China
[2] Guangdong Provincial Key Laboratory of Nuclear Science, Institute of Quantum Matter, South China Normal University, Guangzhou 510006, China
[3] Guangdong-Hong Kong Joint Laboratory of Quantum Matter, Southern Nuclear Science Computing Center, South China Normal University, Guangzhou 510006, China
[4] Department of Physics, Yale University, New Haven, Connecticut 06511, USA
[5] Nuclear Science Division MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

See talks by Jack Holguin, Barbara Jacak, Fabio Dominguez, Mateusz Ploskon, Alba Soto Ontoso, Yen-Jie Lee (and more)!

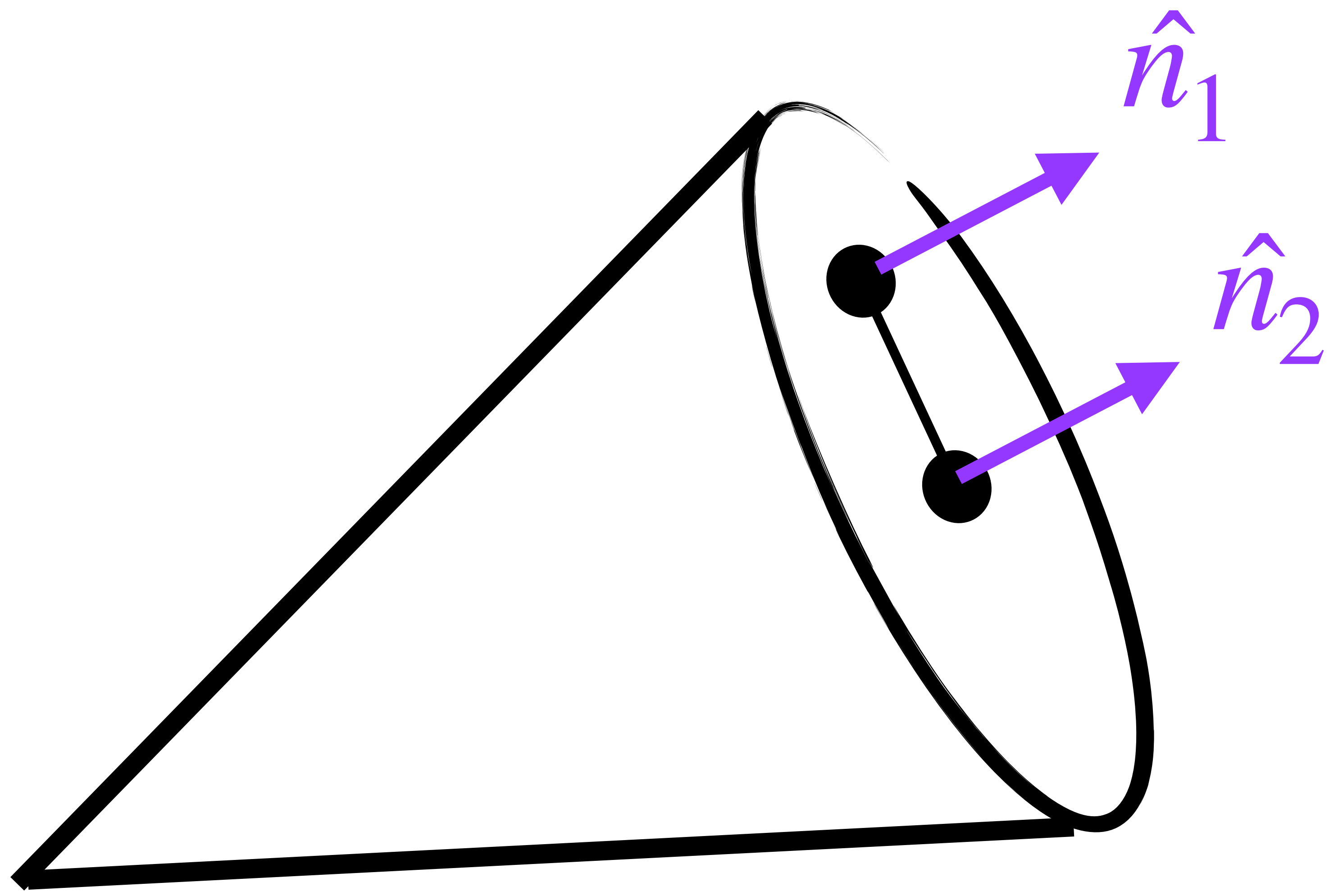
Energy energy correlators are a new emerging tool for heavy-ion collisions!

Can EECs be a new tool for the medium response?

Energy Correlators

Define as the correlation of energy flow operator $\langle\Psi|\mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\cdots\mathcal{E}(\vec{n}_k)|\Psi\rangle$

where $\mathcal{E}(\vec{n}_1) = \lim_{r\to\infty}\int \mathrm{d}t r^2 n_1^i T_{0i}(t, r\vec{n}_1)$



Characterizes the energy flux in the direction of $\hat{n}$

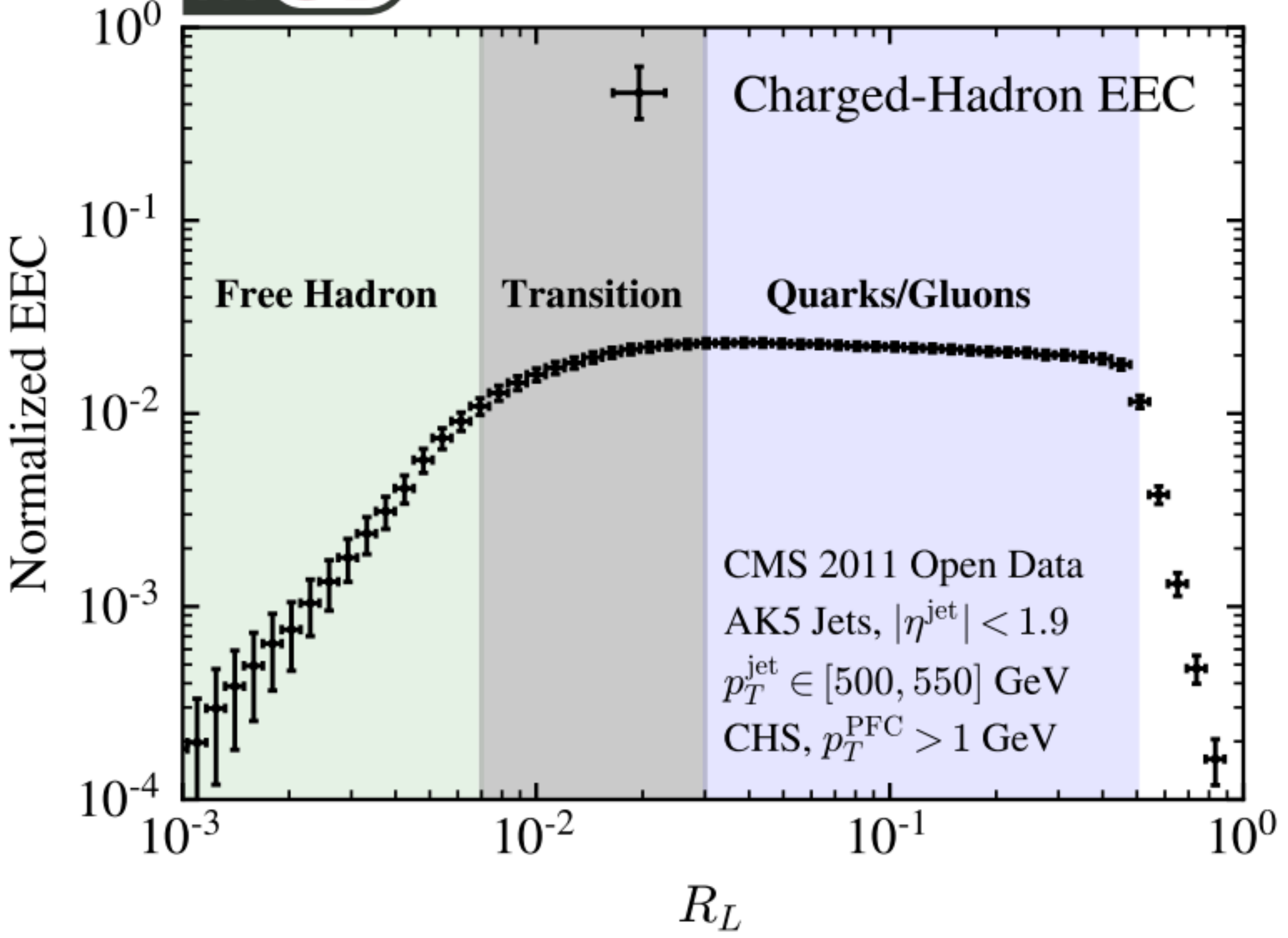
In hadron collider environments, instead of $\hat{n}_1$ use

$$\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$$

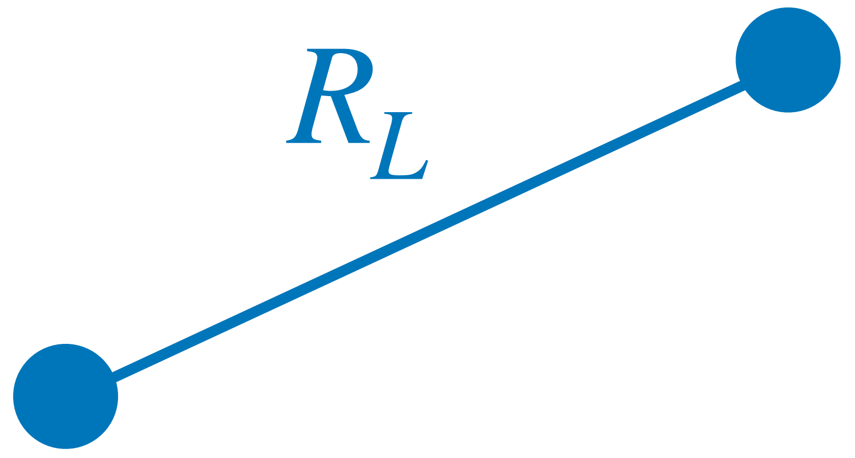
Projected N-point Correlators

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

MOD [Moult et al., PRL 130 (2023) 5, 051901]



- All shape information is integrated out, keep longest side R_{L} fixed

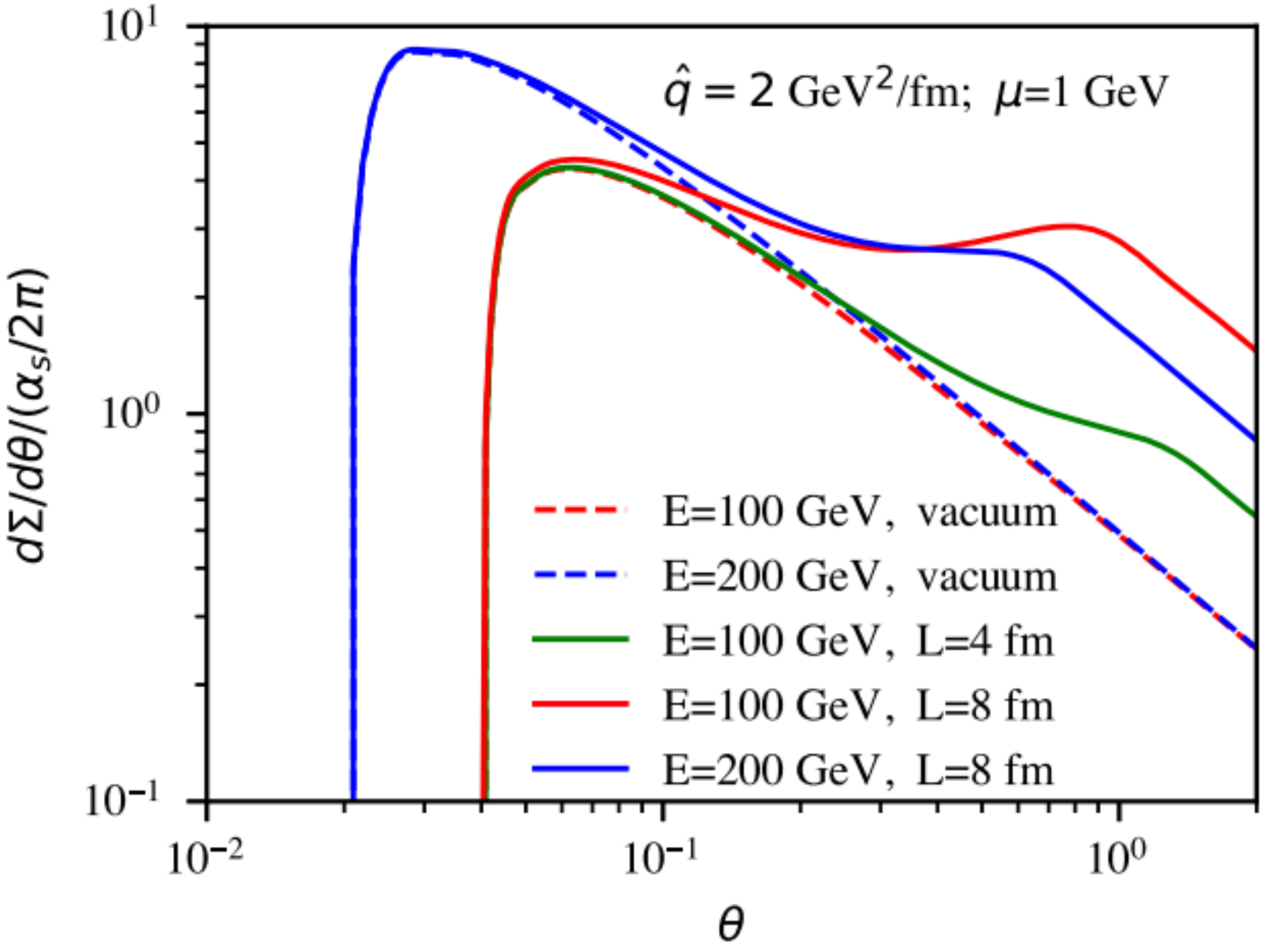


- ***Projected correlators are useful for isolating the scaling behavior!***

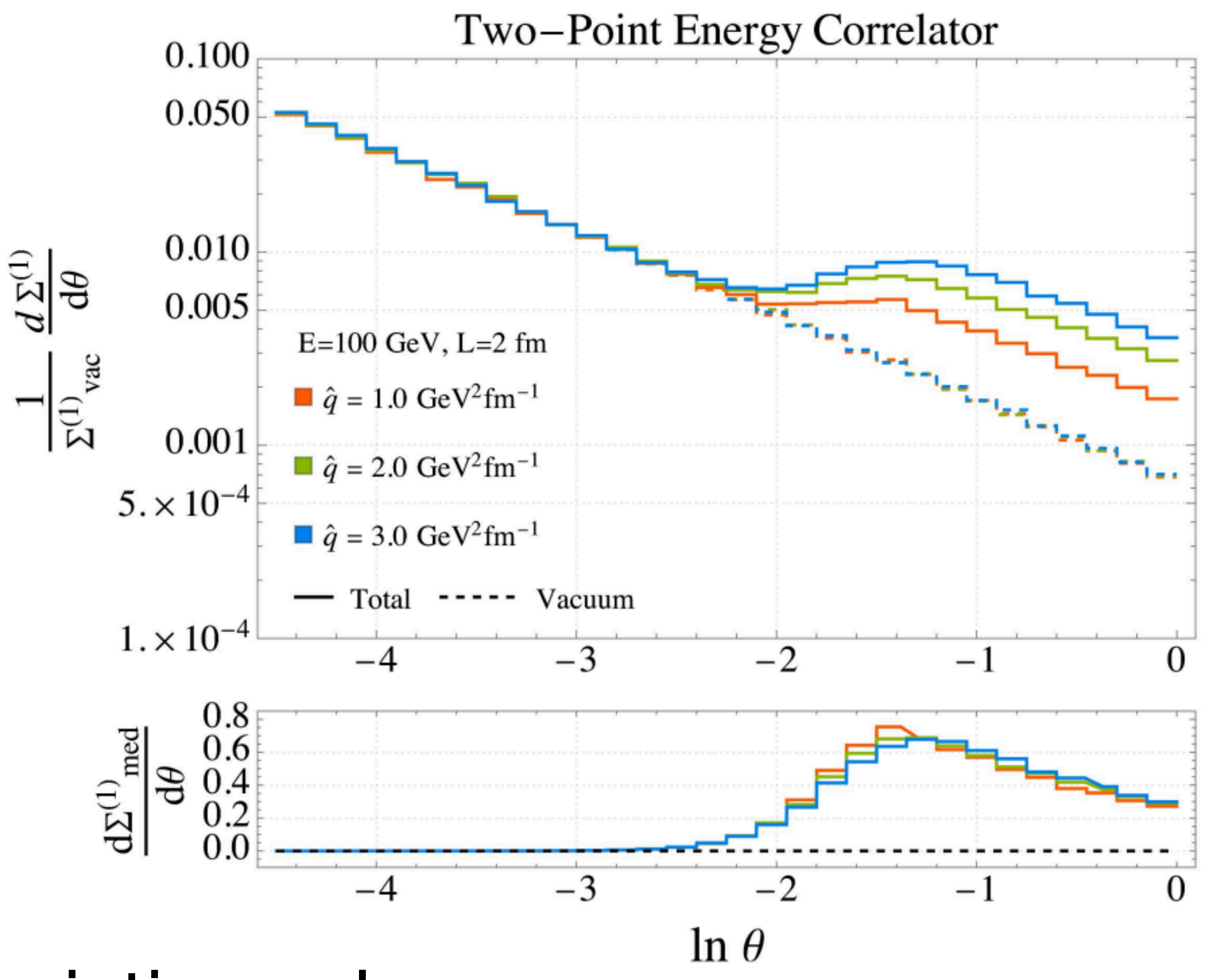
- Transition region happens roughly at $\Lambda_{\text{QCD}}/p_{\text{T,jet}}$

Scaling of in-medium effects

[Yang et al., Phys. Rev. Lett. 132, 011901]



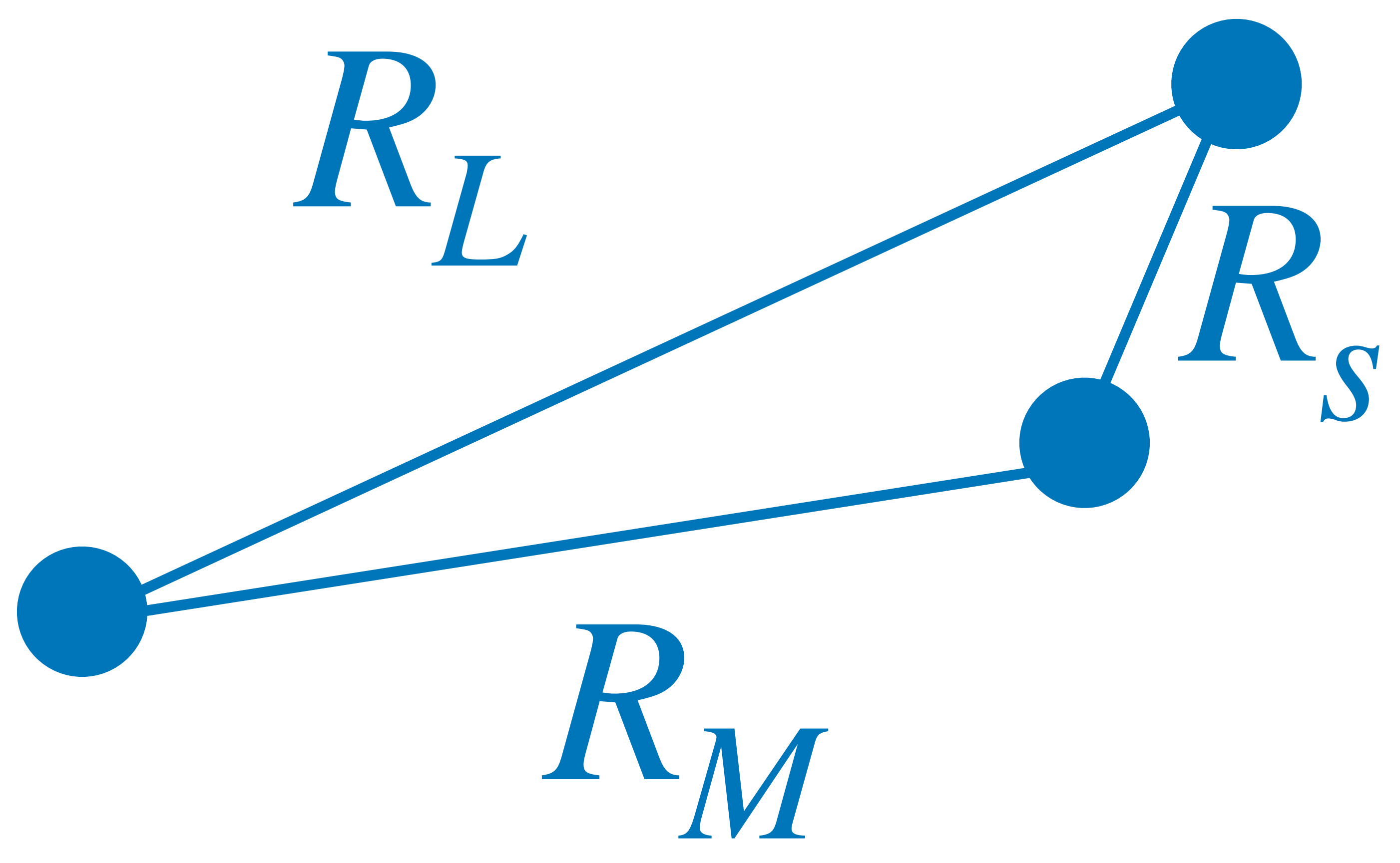
[Andres et al. Phys. Rev. Lett. 130, 262301]



✽ Medium effects appear at a similar characteristic scale

What about higher orders of N? What if we also included the full shape information?

Higher-Point Correlators

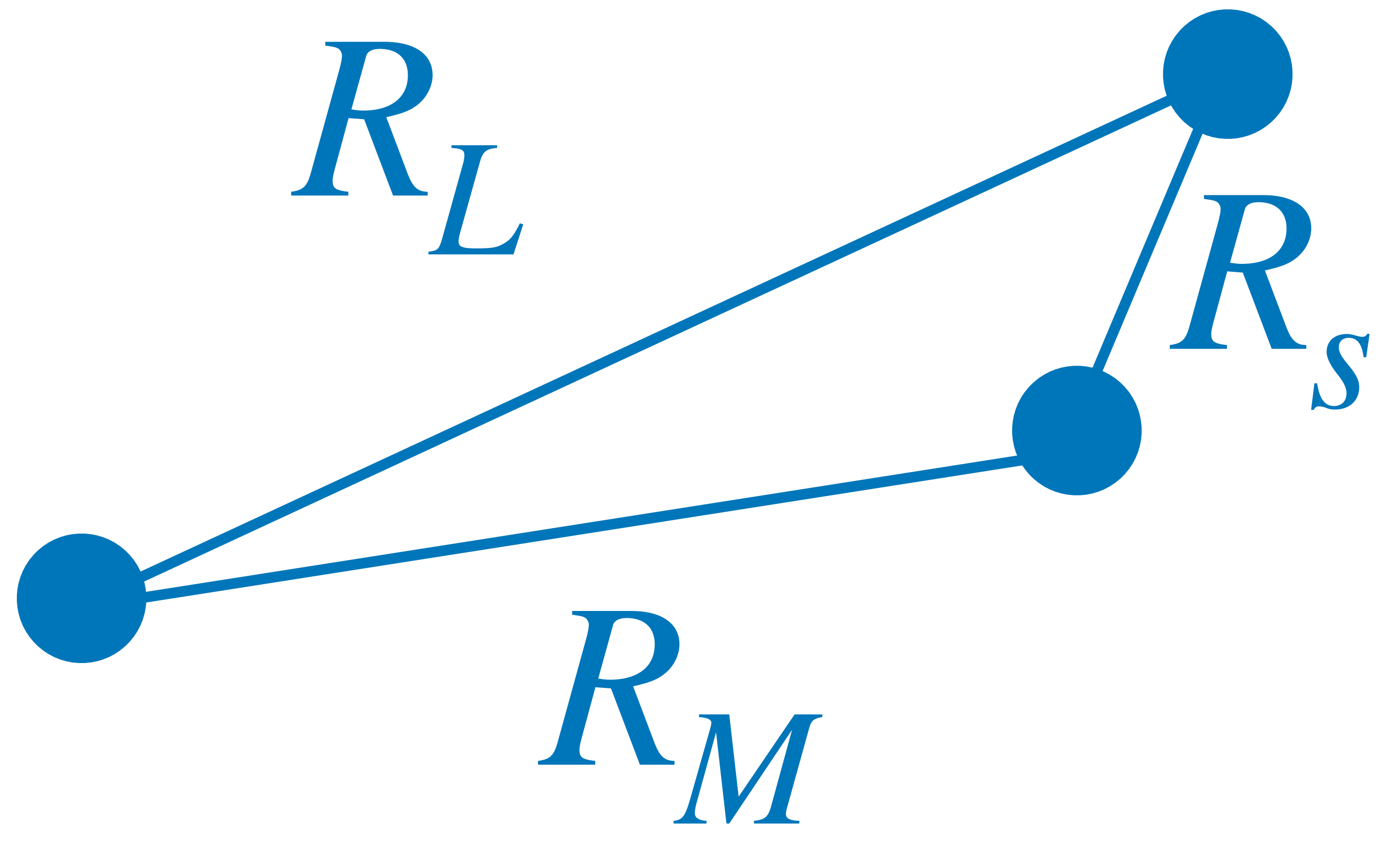


- Simplest example is the 3-point correlator

Interesting to study both the shape (full correlator) and the scaling (projected correlator)!

- When $N > 2$ there are non-trivial shape dependencies in collinear limit.

Higher-Point Correlators



- Simplest example is the 3-point correlator

Interesting to study both the shape (full correlator) and the scaling (projected correlator)!

- When $N > 2$ there are non-trivial shape dependencies in collinear limit.

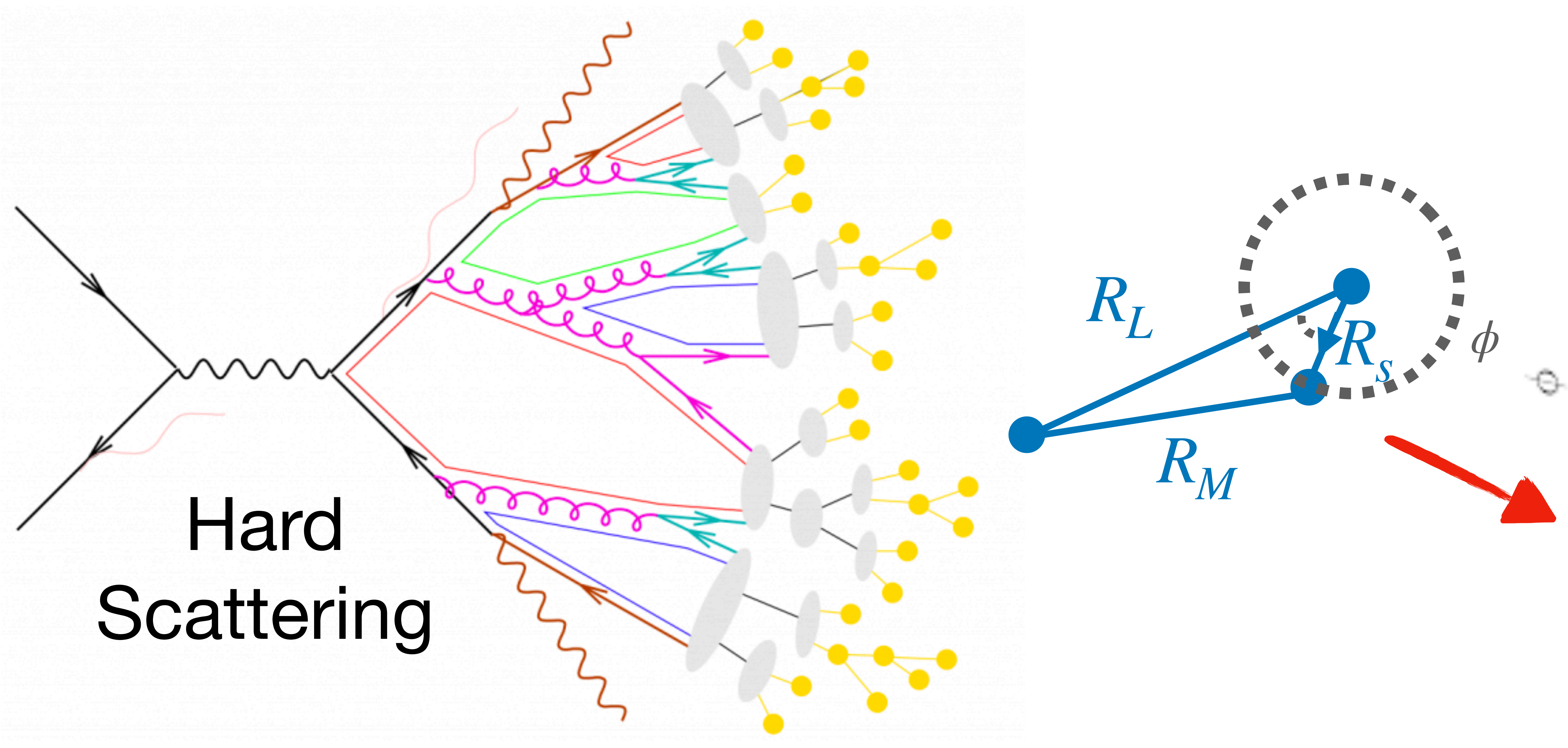
Visualize the shape in 3D space where the dimensions are

$$R_{\mathrm{L}} \qquad \xi = \frac{R_{\mathrm{S}}}{R_{\mathrm{M}}} \qquad \phi = \arcsin\sqrt{1 - \frac{(R_{\mathrm{L}} - R_{\mathrm{M}})^2}{R_s^2}}$$

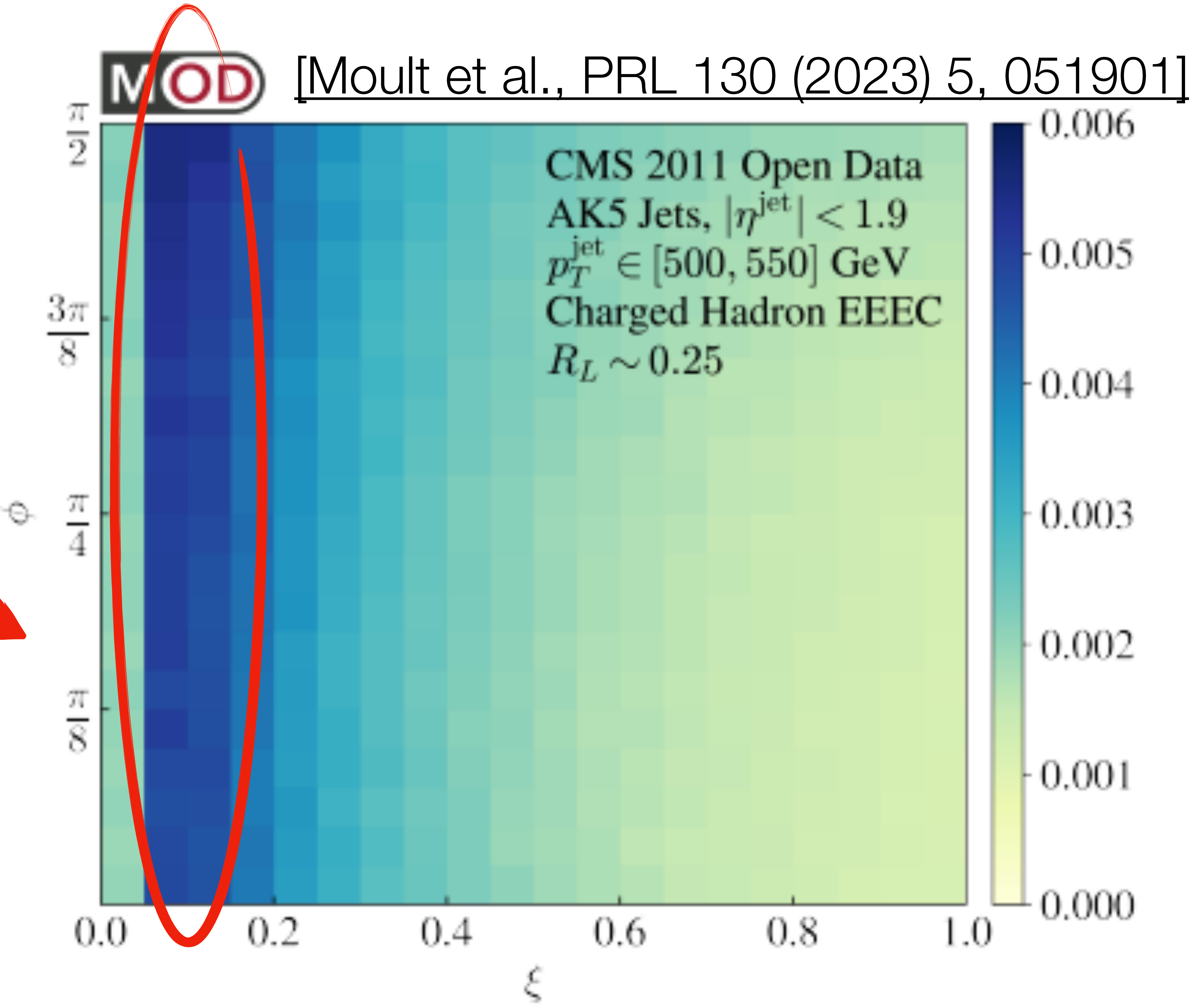
3-point correlator in vacuum

- Let's explore the 3-point correlator in vacuum at a fixed R_L slice!

In vacuum all emissions are correlated with the same source (parton shower)!



[Moult et al., PRL 130 (2023) 5, 051901]



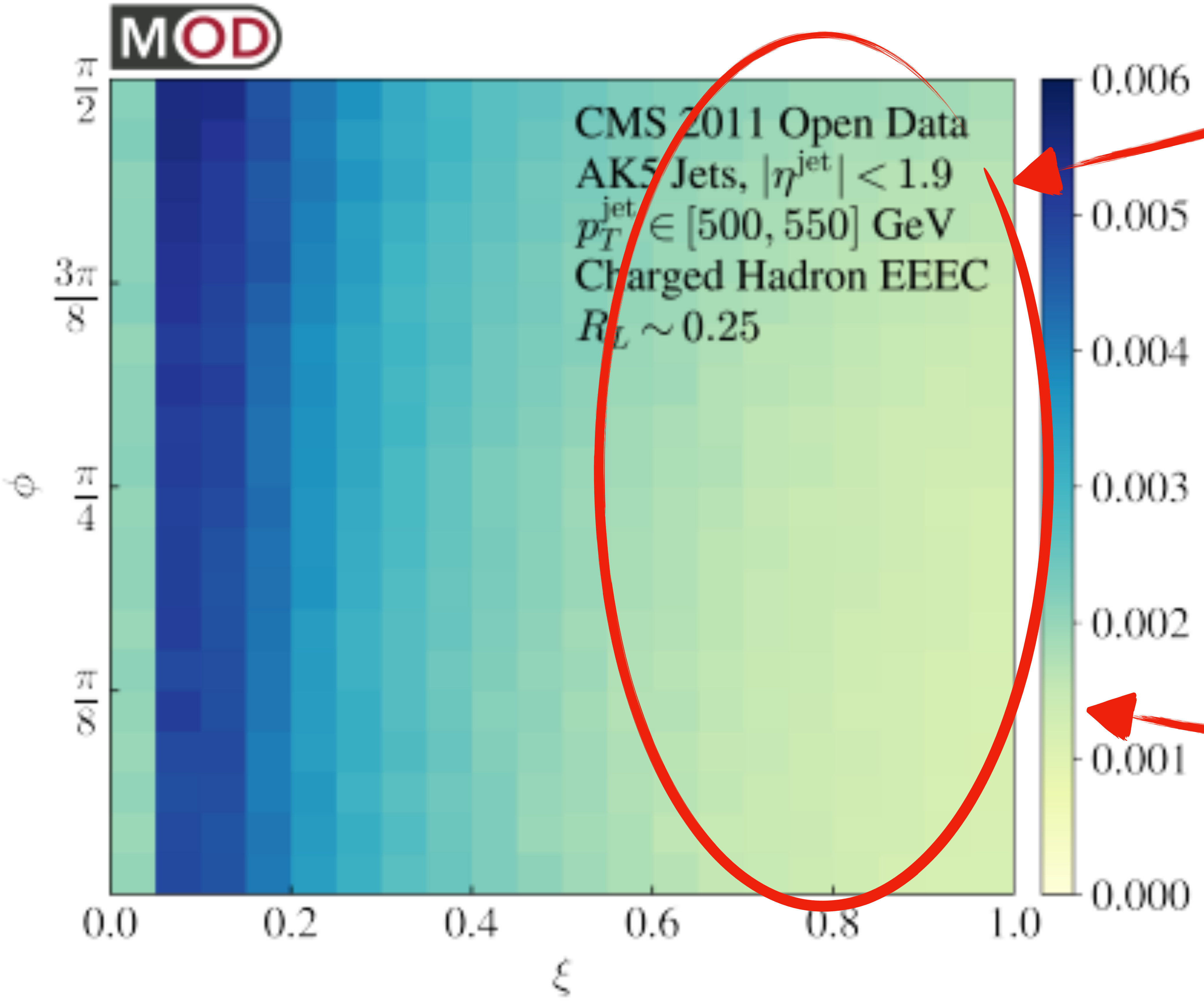
When ξ is small, behavior similar for all ϕ

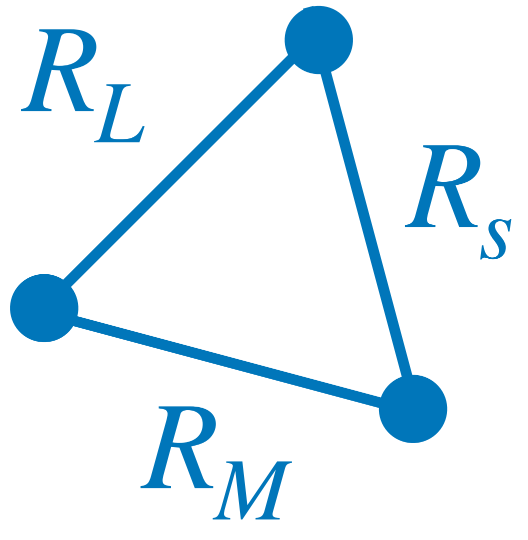
In small angle limit, reflect 2-point correlator

3-point correlator in vacuum

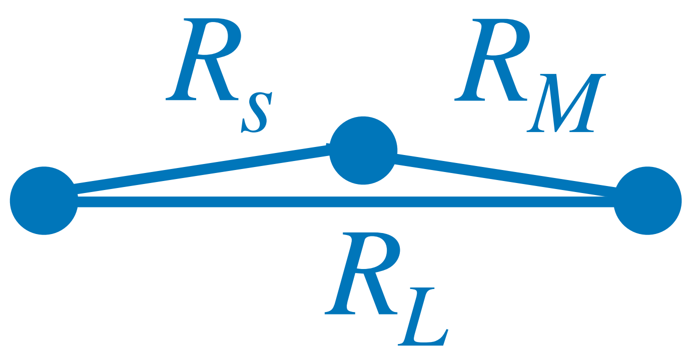
- Let's explore the 3-point correlator in vacuum at a fixed R_L slice!

[Moult et al., PRL 130 (2023) 5, 051901]





Upper right corner is populated with equilateral triangles

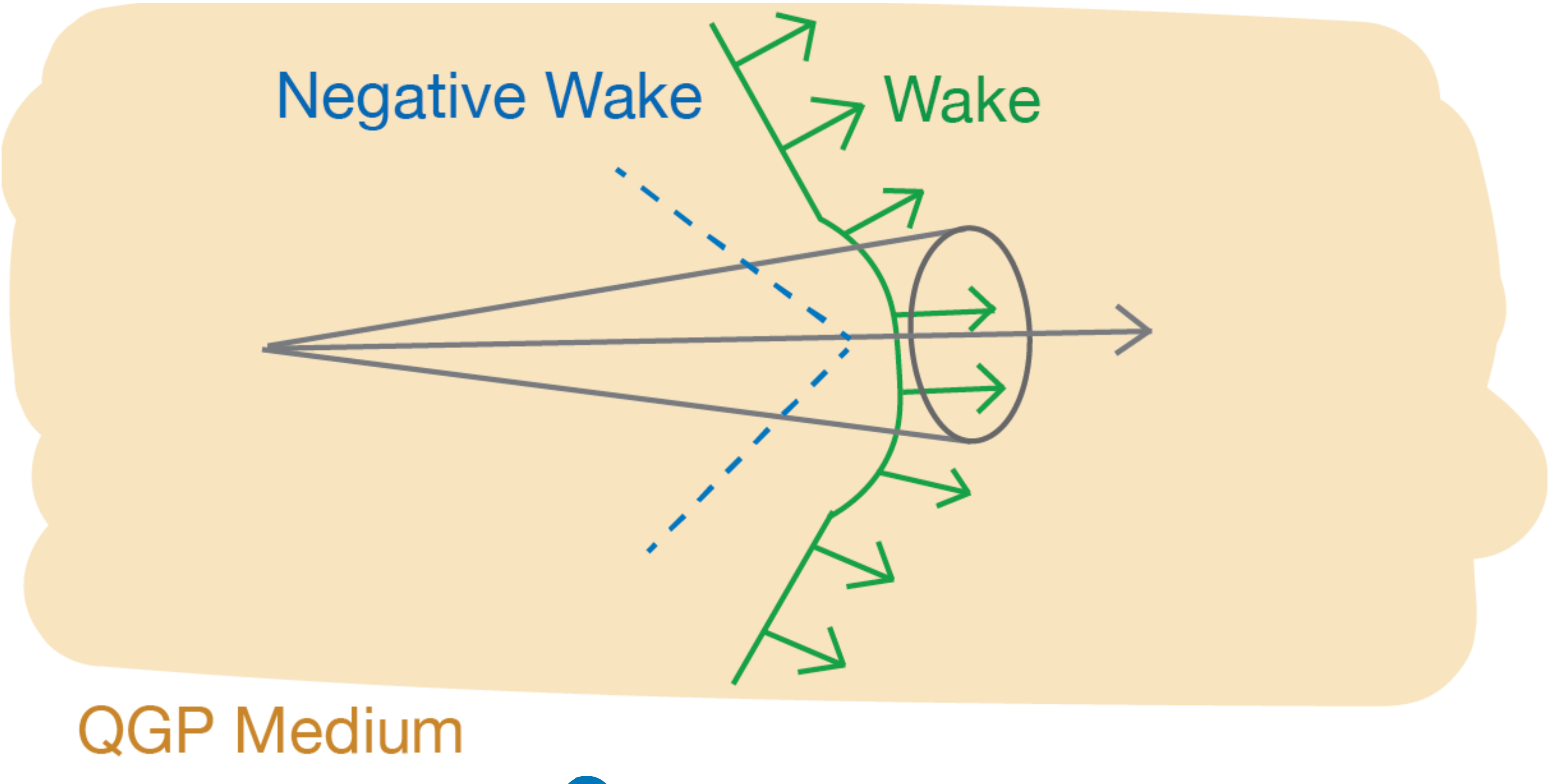


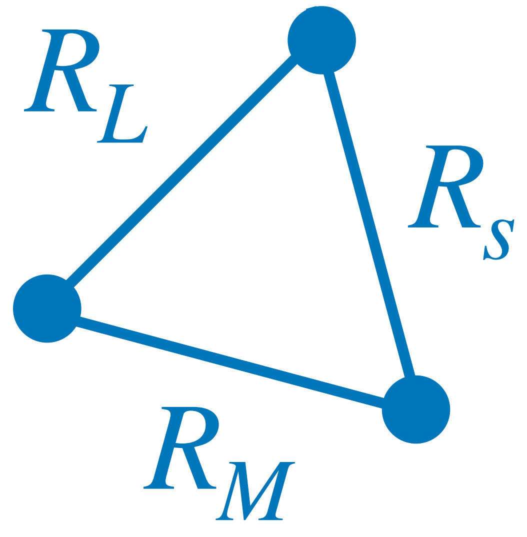
Bottom right corner is populated with "squished" triangles

These features are not prominent in vacuum!

Exposing the wake with 3-point correlators

Idea: Study one type of medium response (wake) via its distinct shape dependence in the 3-point correlator





Wake should "fill in" region unpopulated in vacuum!

Still will have parton shower contributions, but now in addition have a broader and softer contribution from the wake.

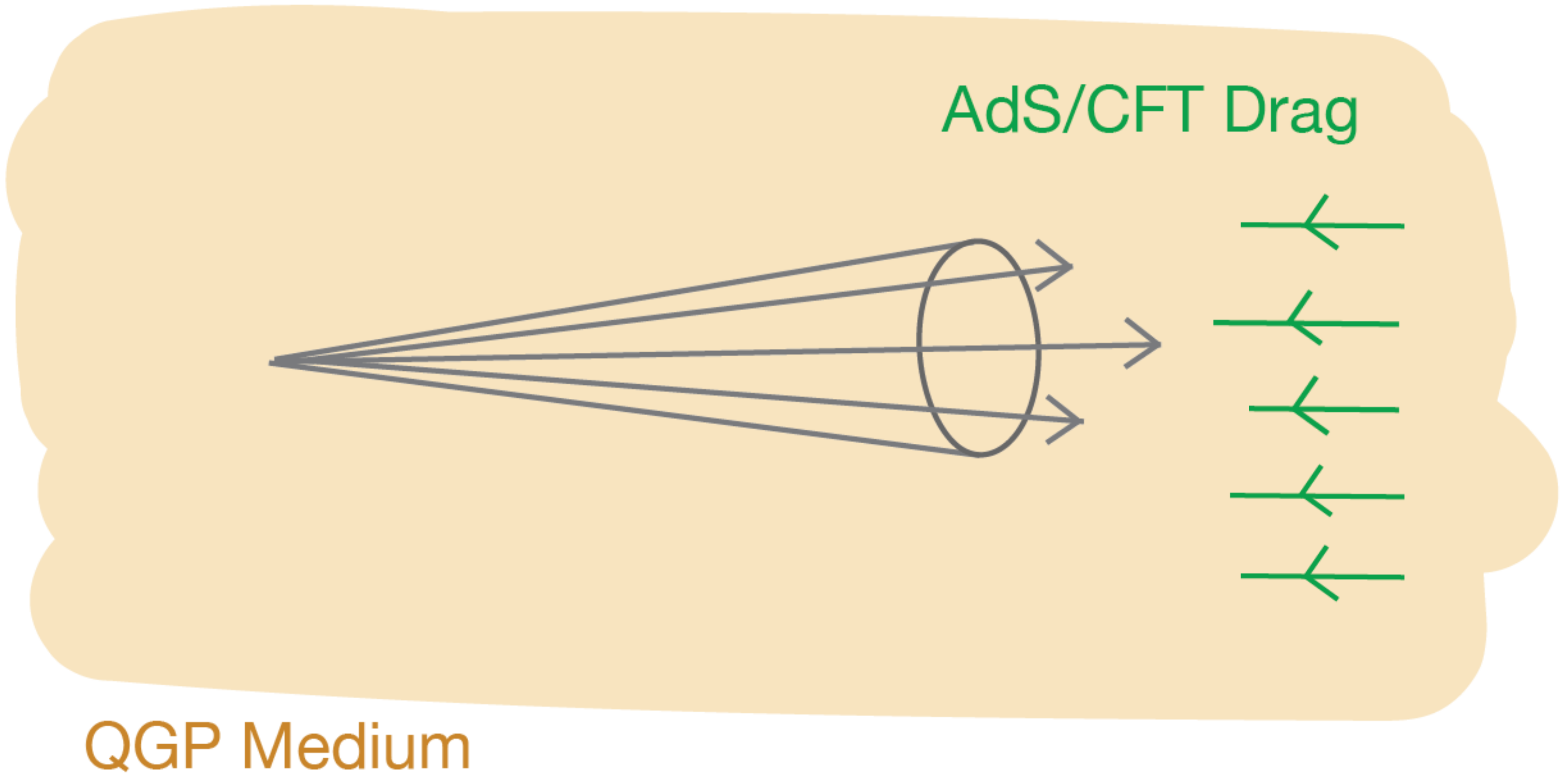
Outline: first discuss an idealized case, then go over some practical considerations for experimental applications!

Hybrid Model

[JHEP 10 (2014) 019]

To study the wake we will use the hybrid model! This is a jet quenching model where…

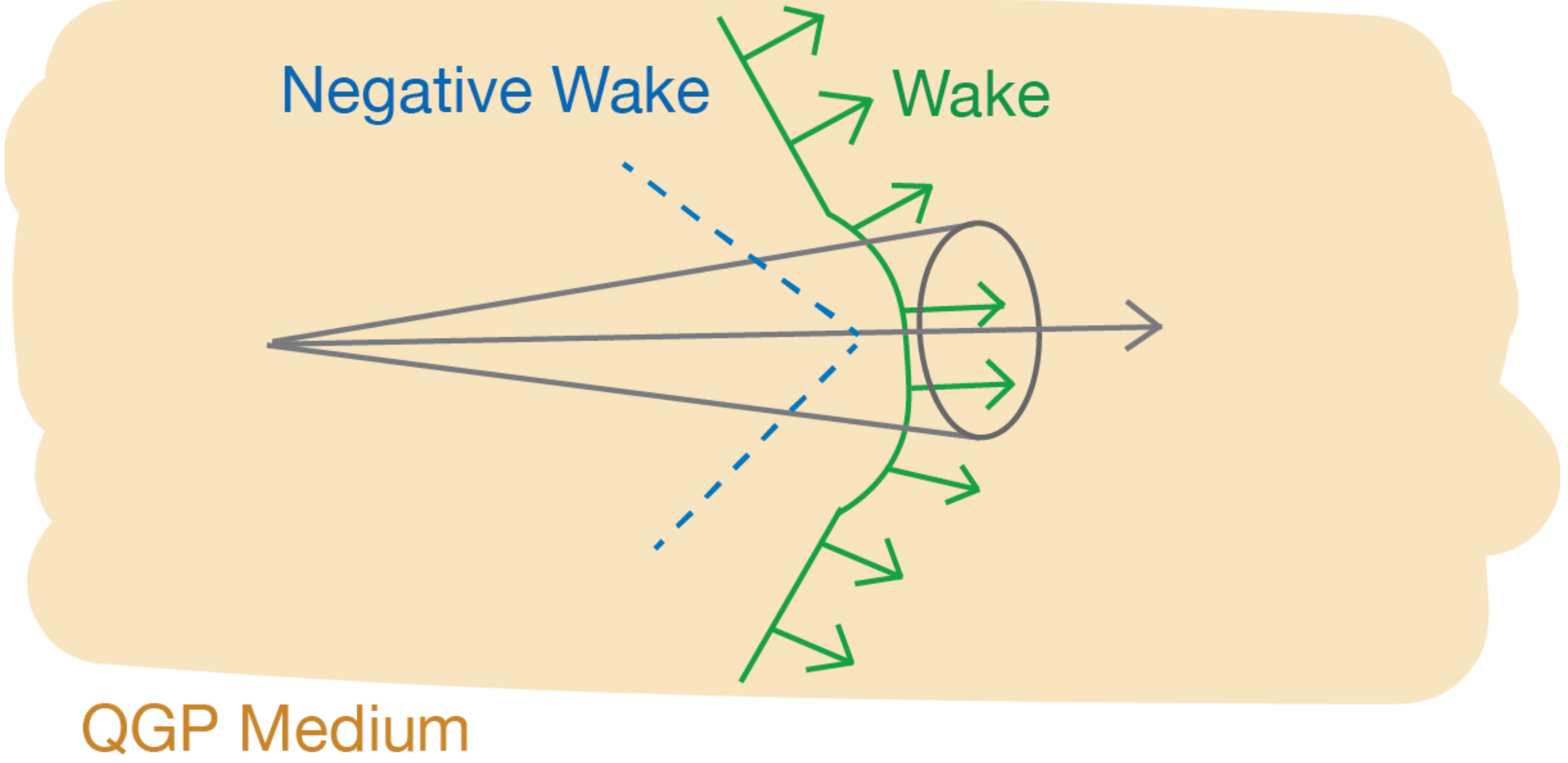
Impact of the medium on the jet → jet energy loss



Strong coupling limit

- ❃ AdS/CFT drag force

Impact of the jet on the medium → medium response



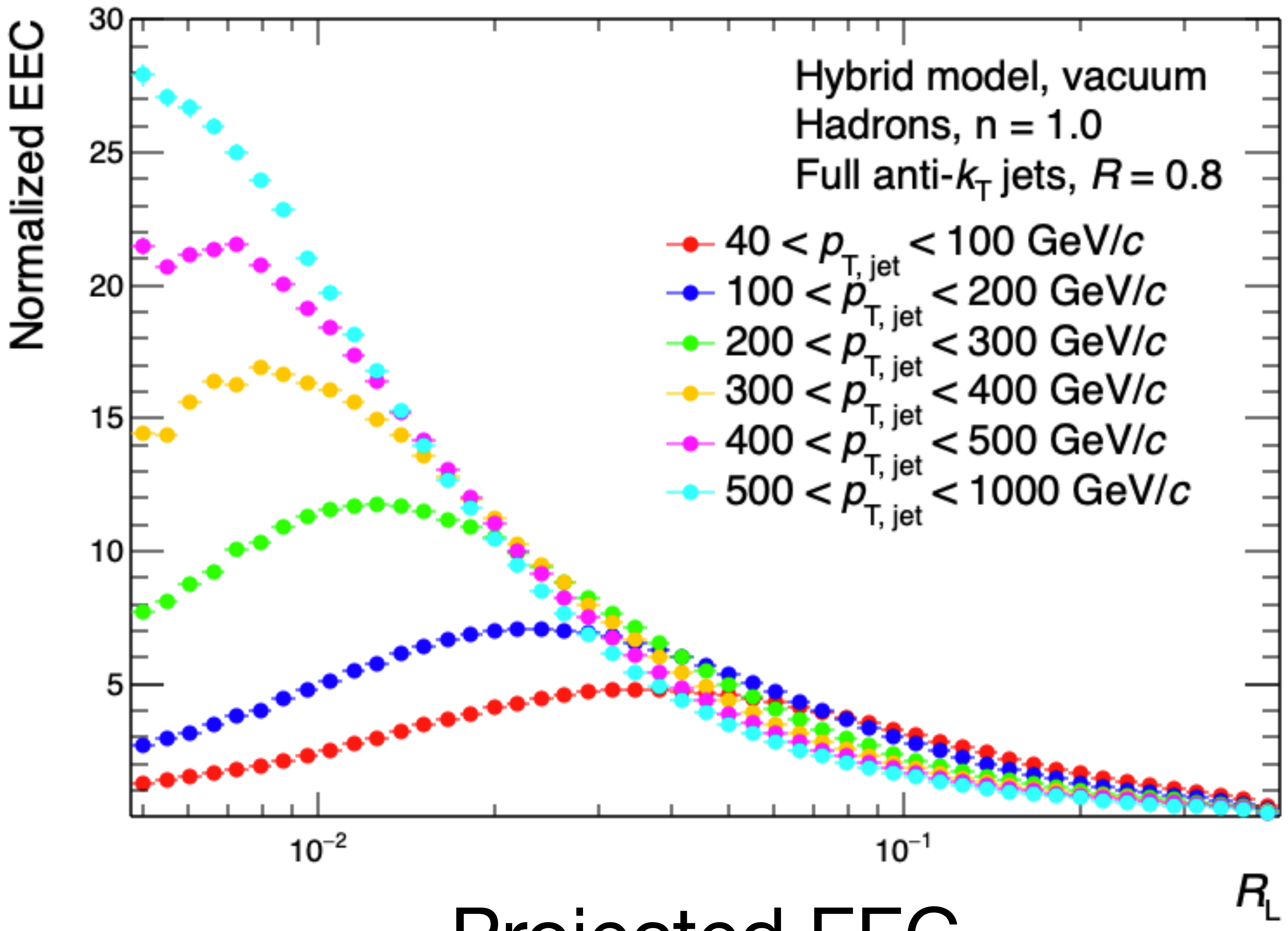
Strong coupling limit

- ❃ Wake (Hydrodynamics based approach)

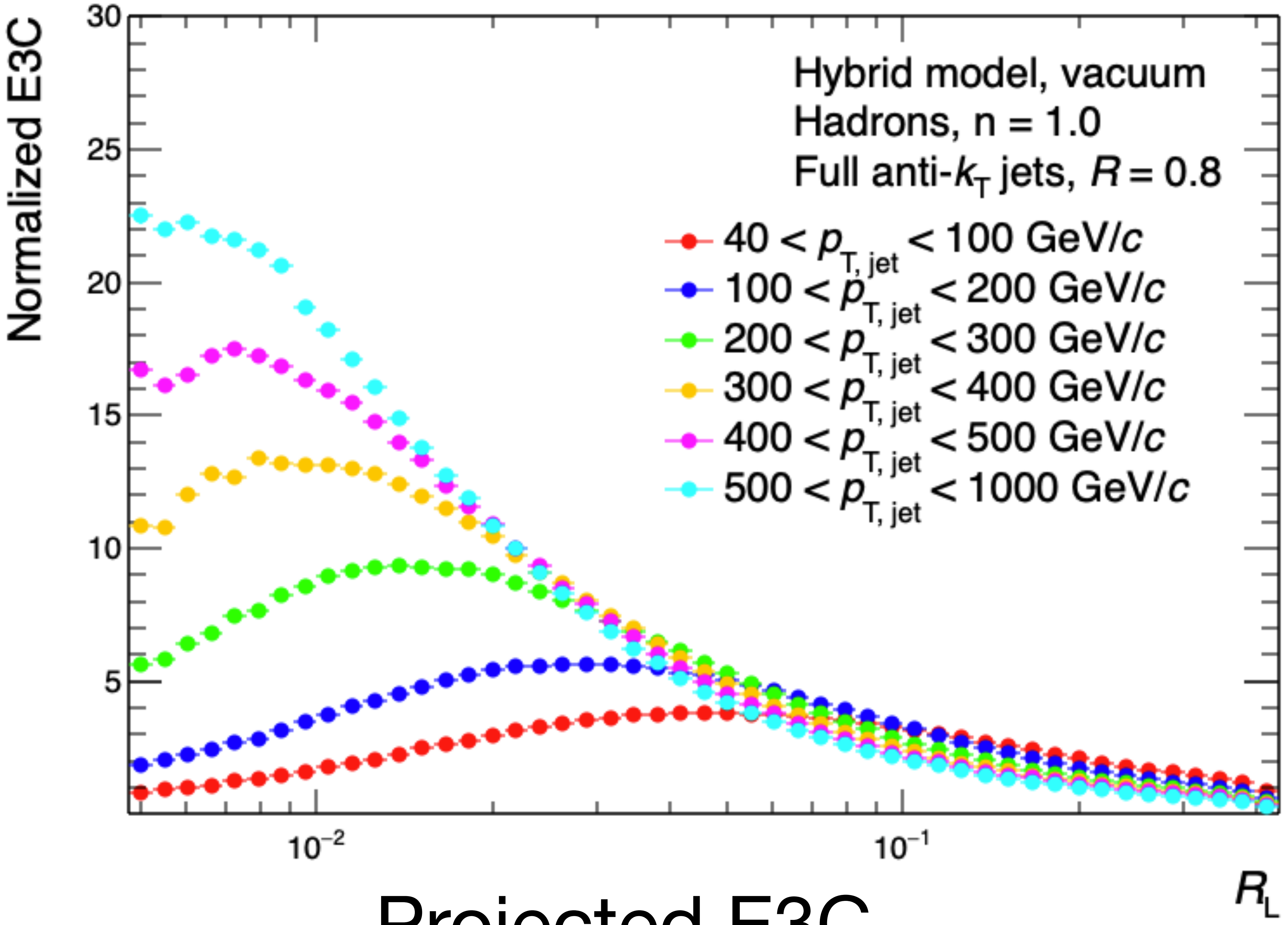
See Krishna's (Mon 3:30pm) talk for a more comprehensive overview!

Projected correlators in vacuum

- Showing the projected 2 and 3 point correlators in vacuum as a function of jet p_T



Projected EEC



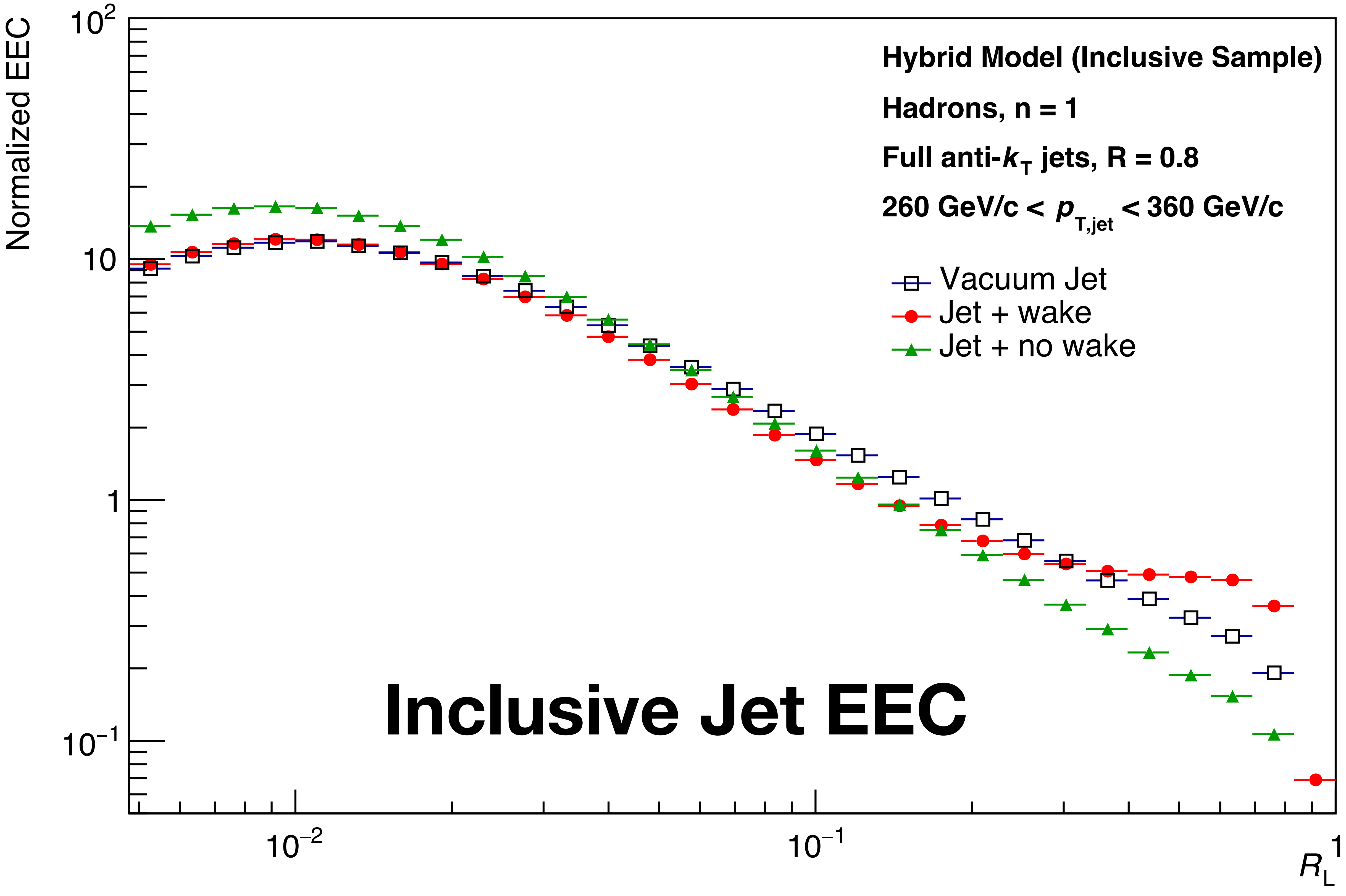
Projected E3C

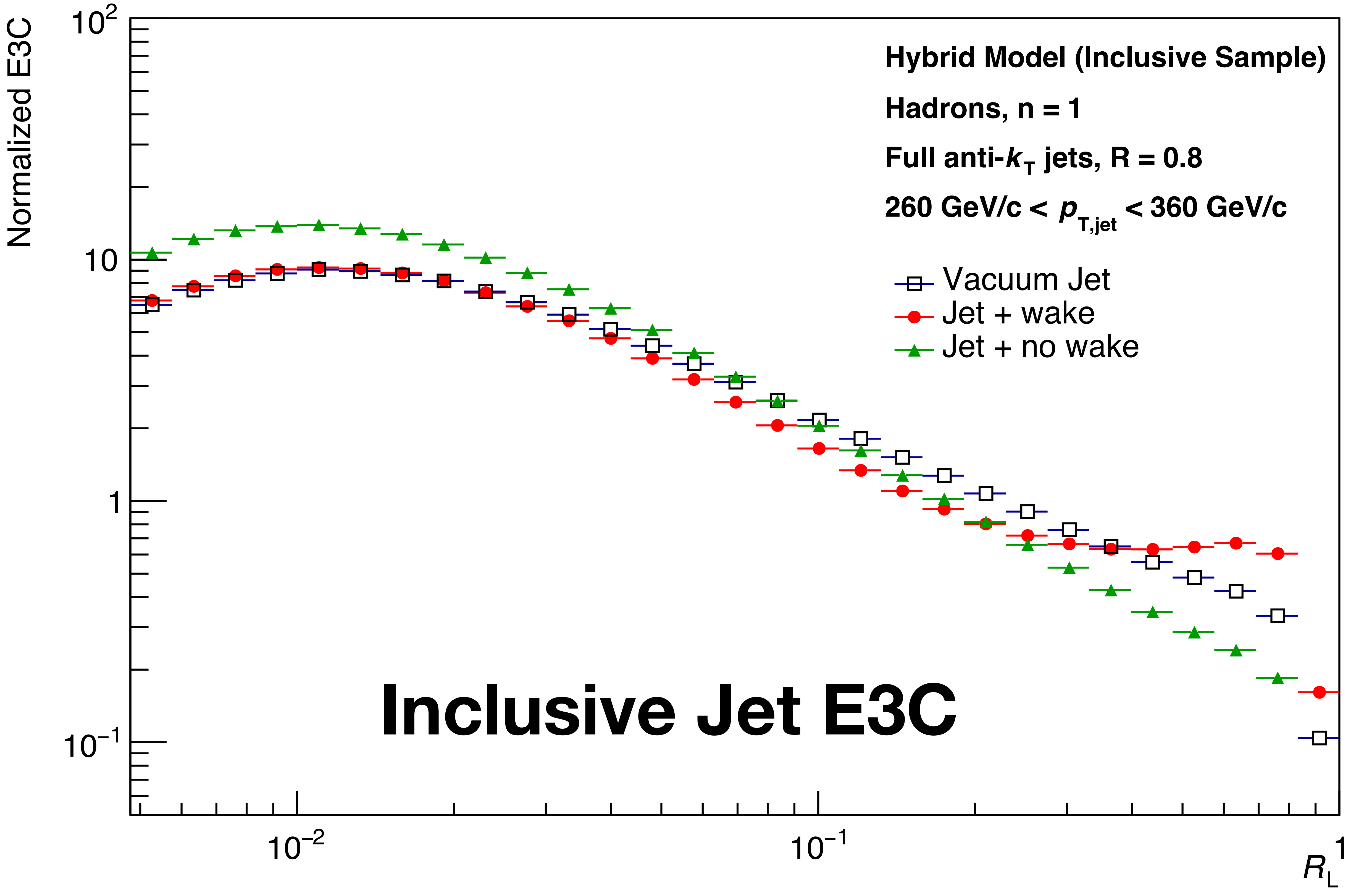
- Projected EEC and E3C show similar features.
- Peak position is roughly $\Lambda_{QCD}/p_{T,jet}$

What happens when we include the wake?

Projected correlators w/ Wake

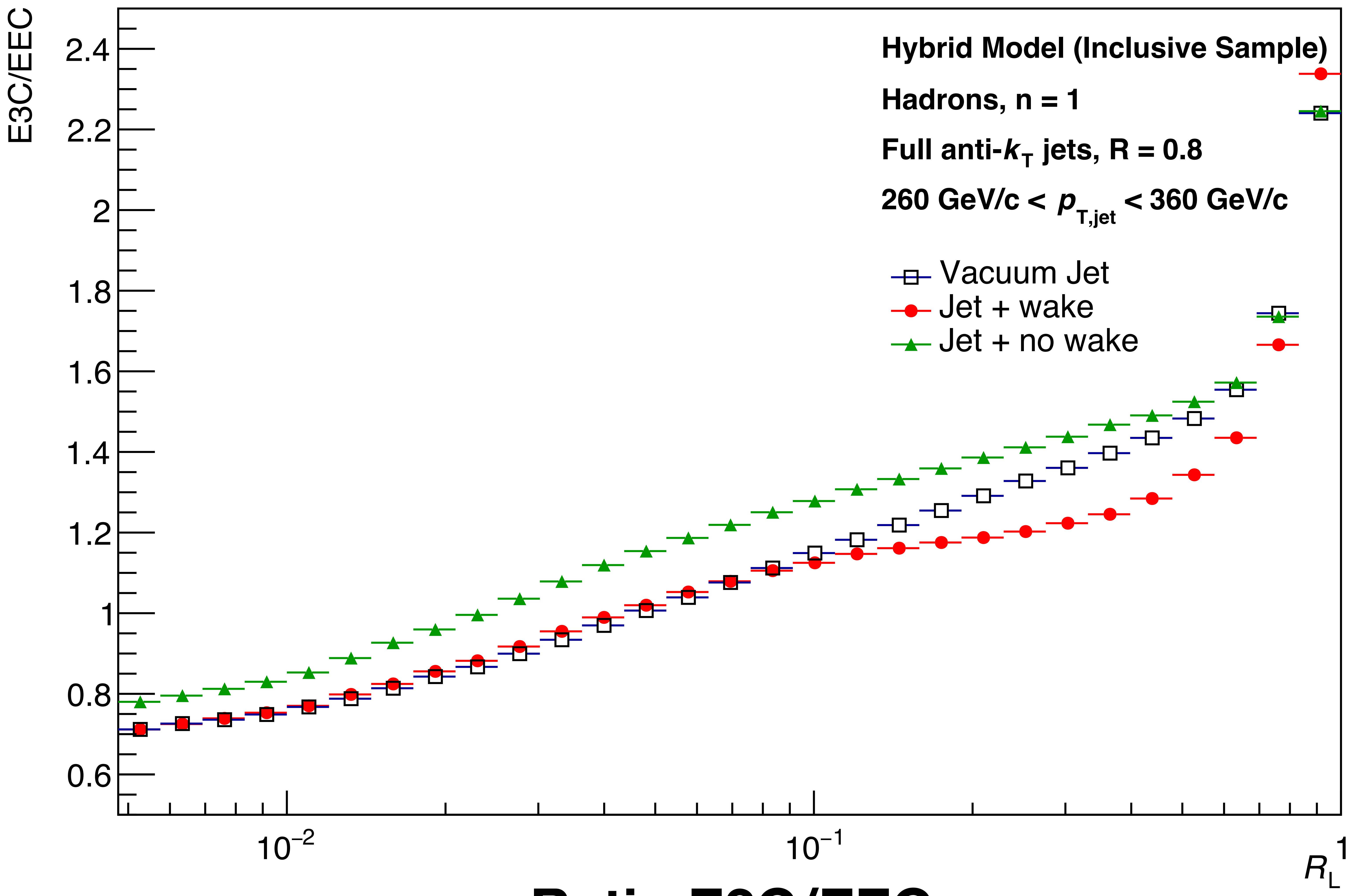
- Look at projected correlators in vacuum compared to jet + wake and jet + no wake





- ***Scaling behavior at large values of R_L different when wake is included!***
- Wake shows up similarly to other medium effects.
- **No track p_T cut included in this sample (will show effect later)**

Ratio of projected correlators

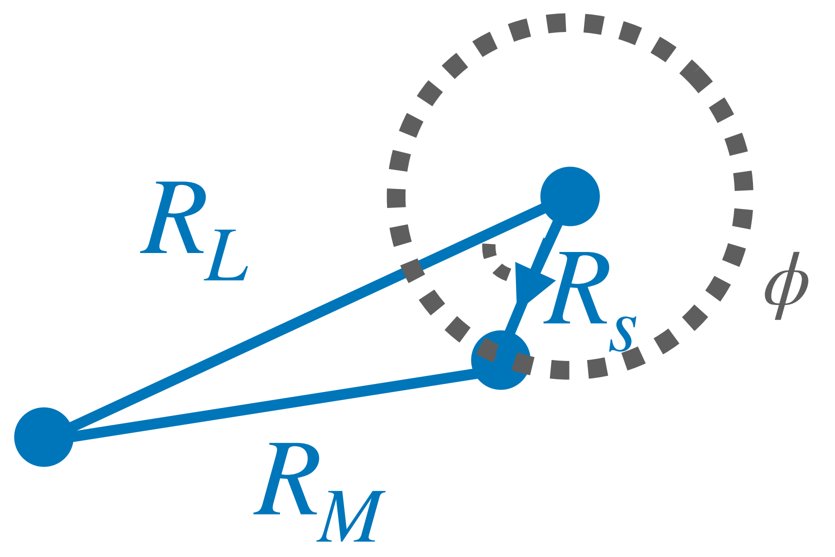


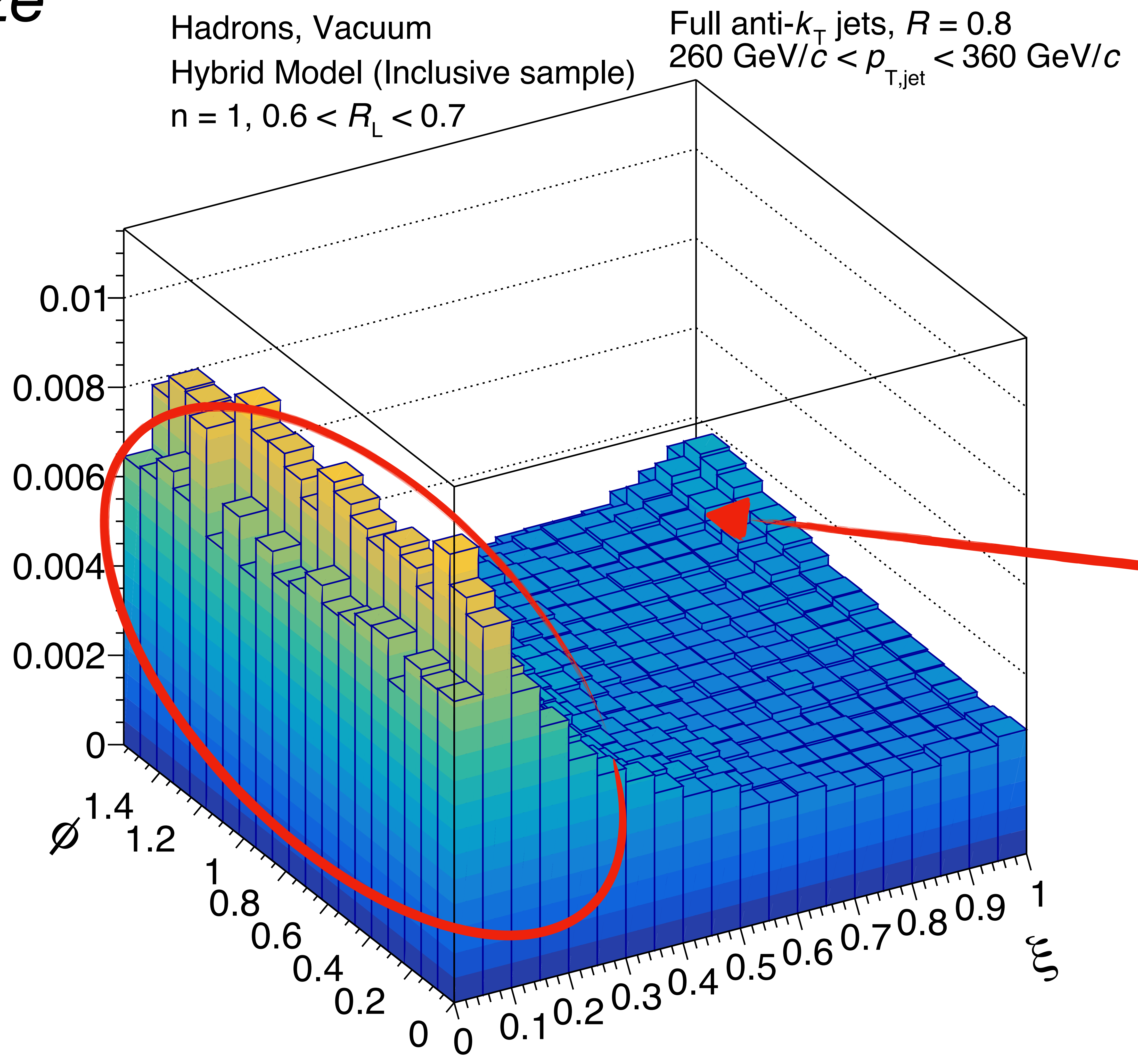
Ratio E3C/EEC

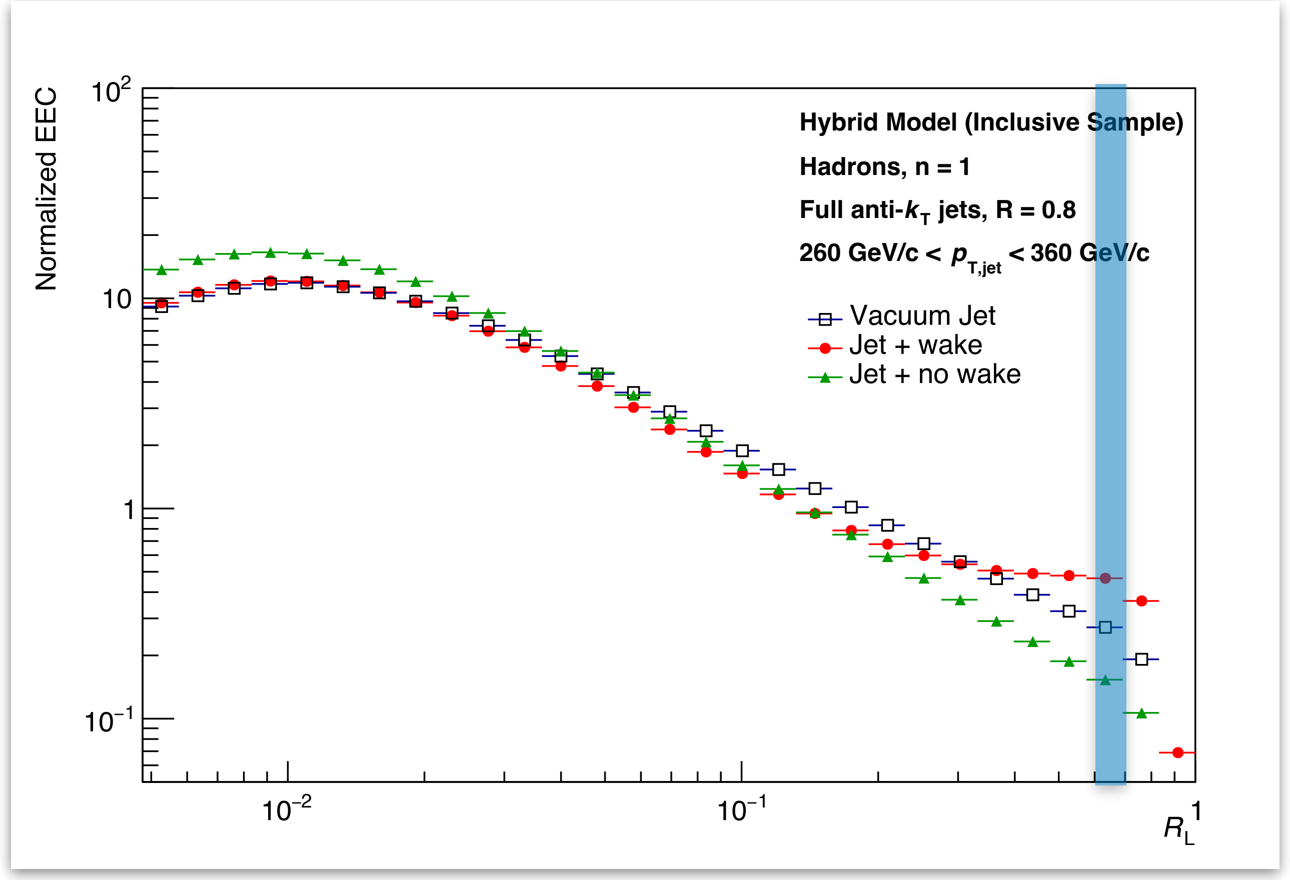
- Can also elucidate the wake using the ratios!
- Beneficial if systematics can be cancelled in the ratio.

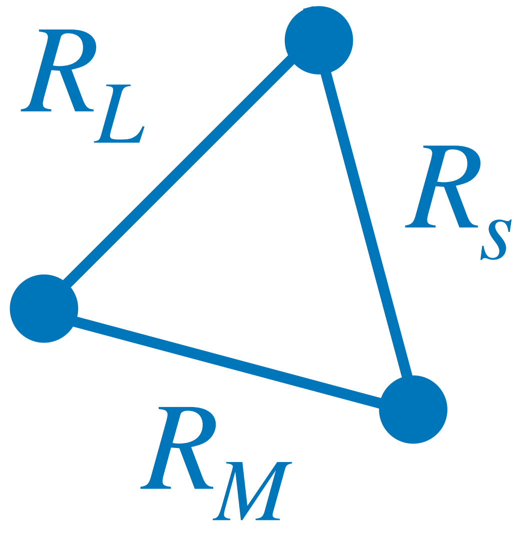
Shape dependence in vacuum

Can also visualize this in 3D!





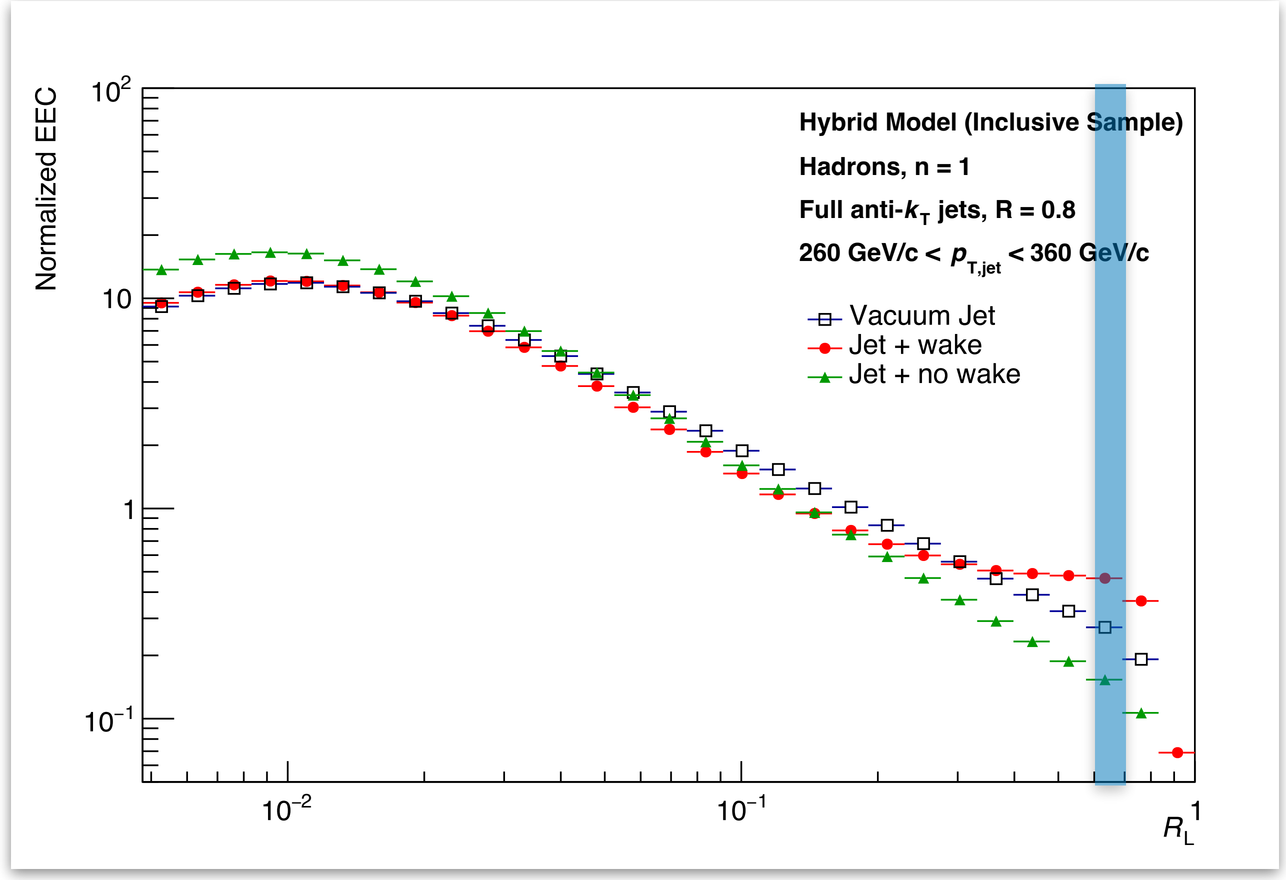


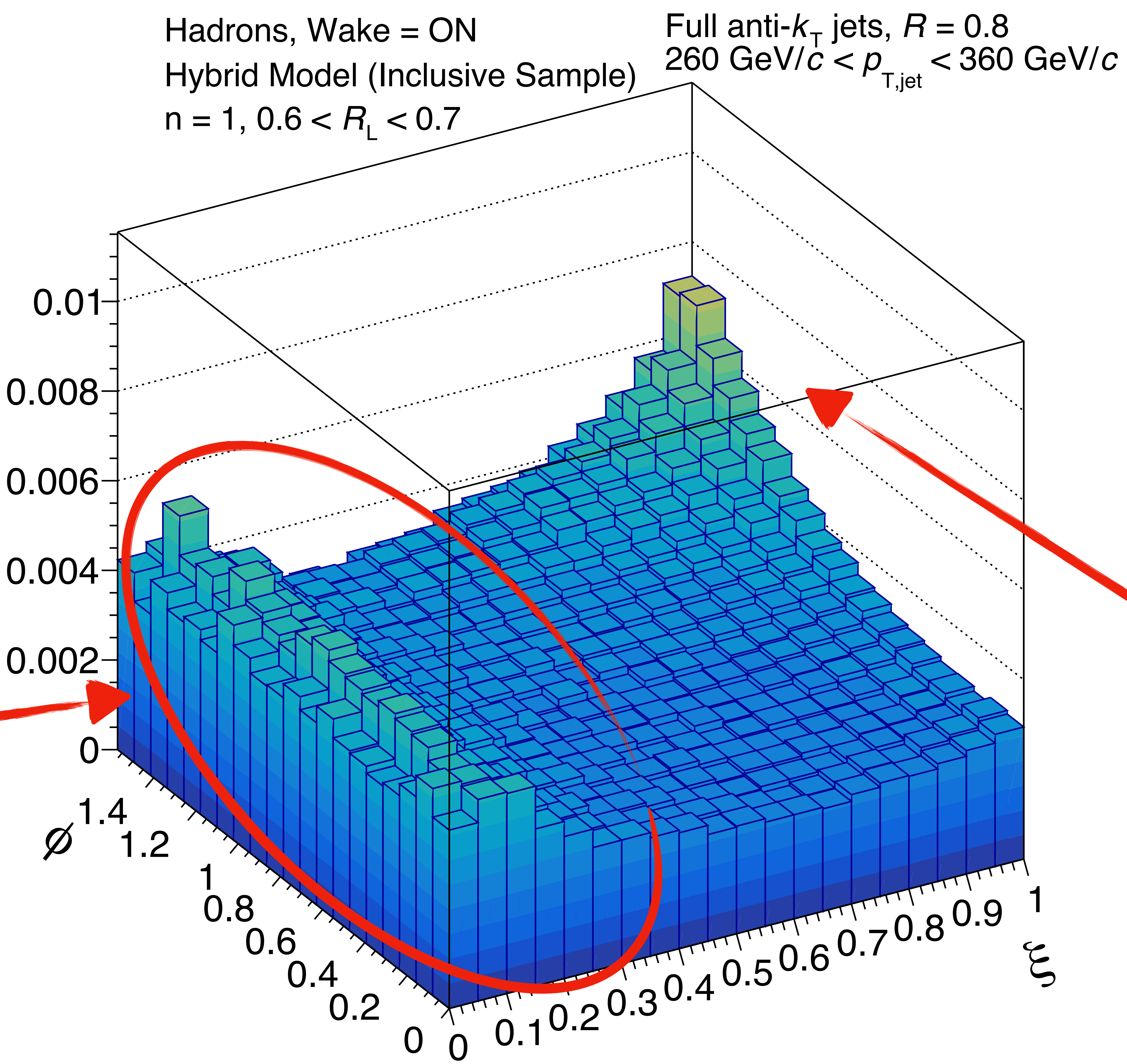


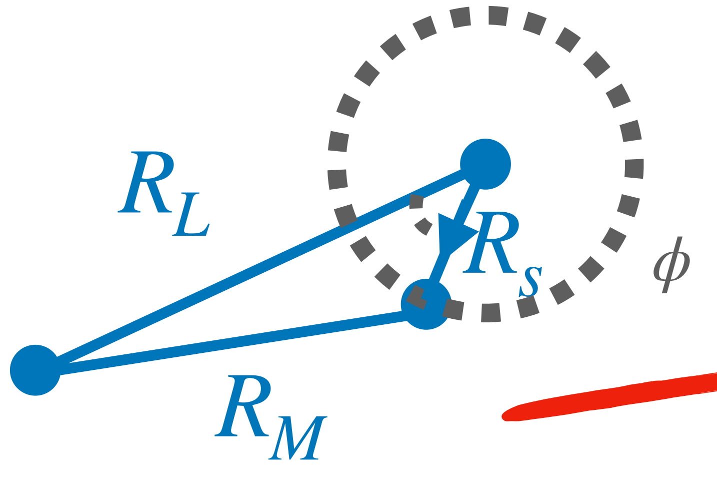
- All other shapes not prominent in vacuum!

- All emissions correlated with the same source (parton shower)

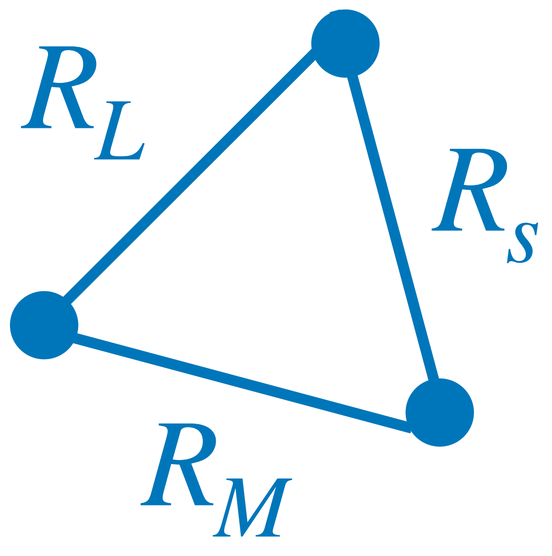
Shape dependence in medium (with wake)





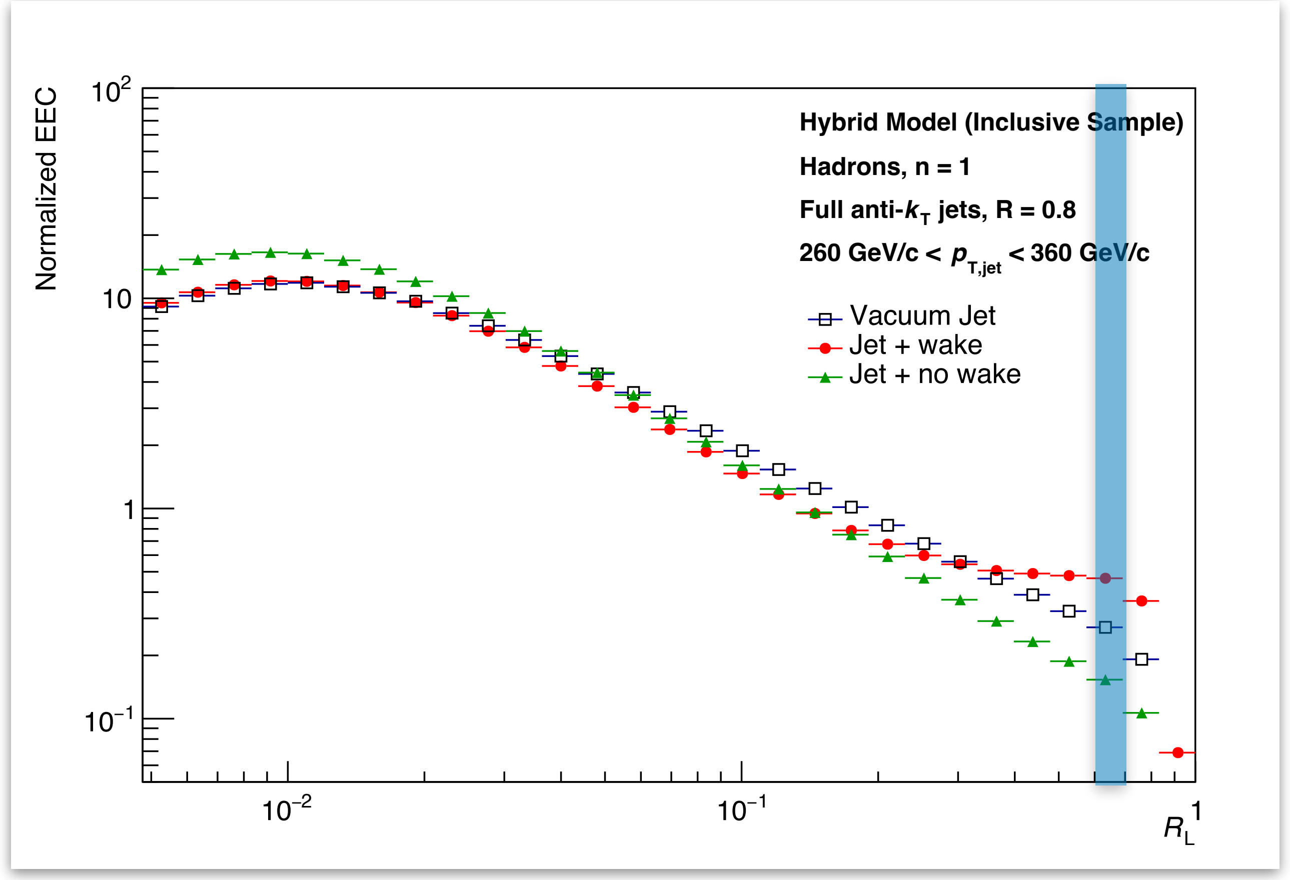


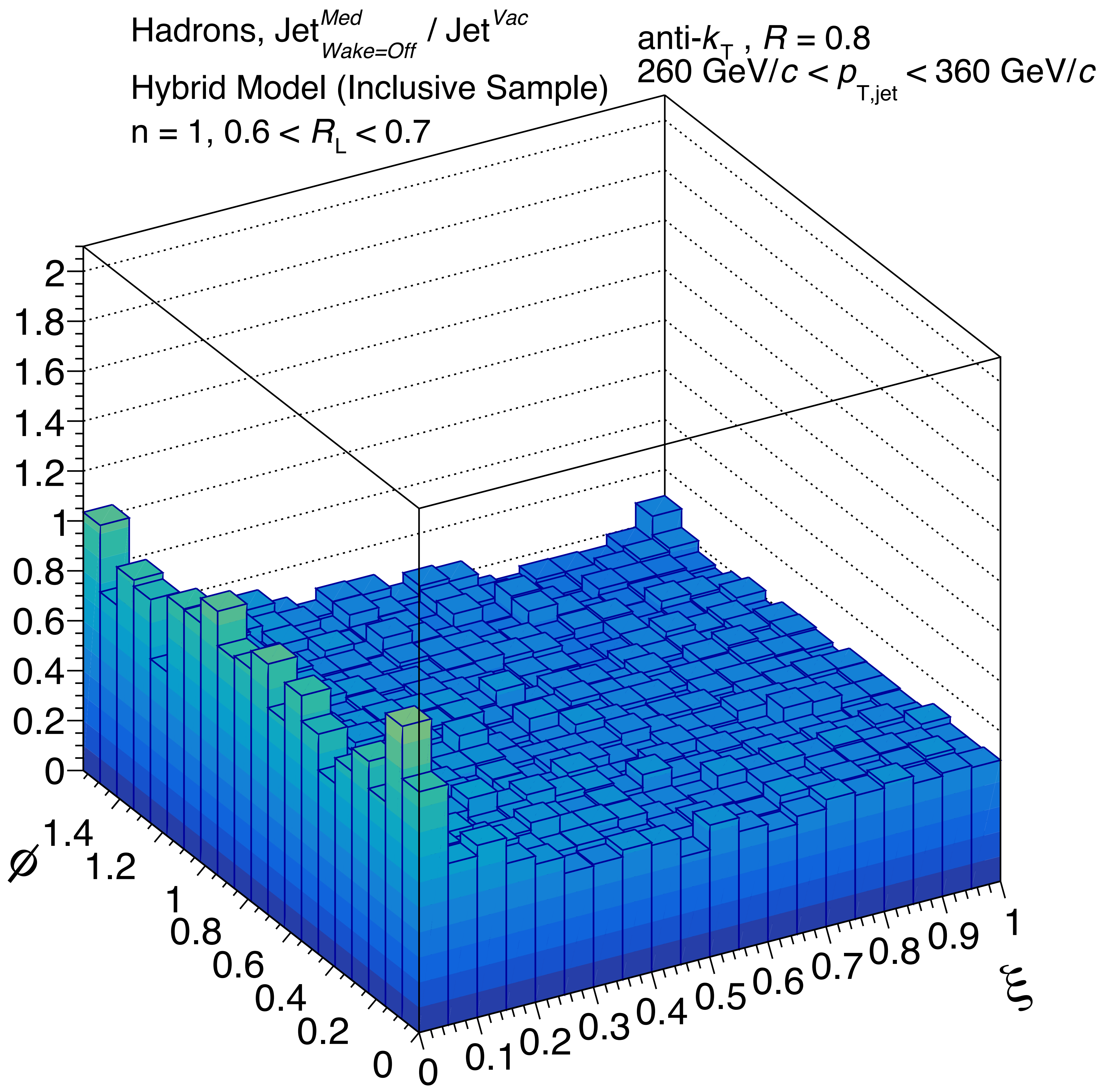
- Large rise in equilateral structures due to the presence of the uncorrelated wake!



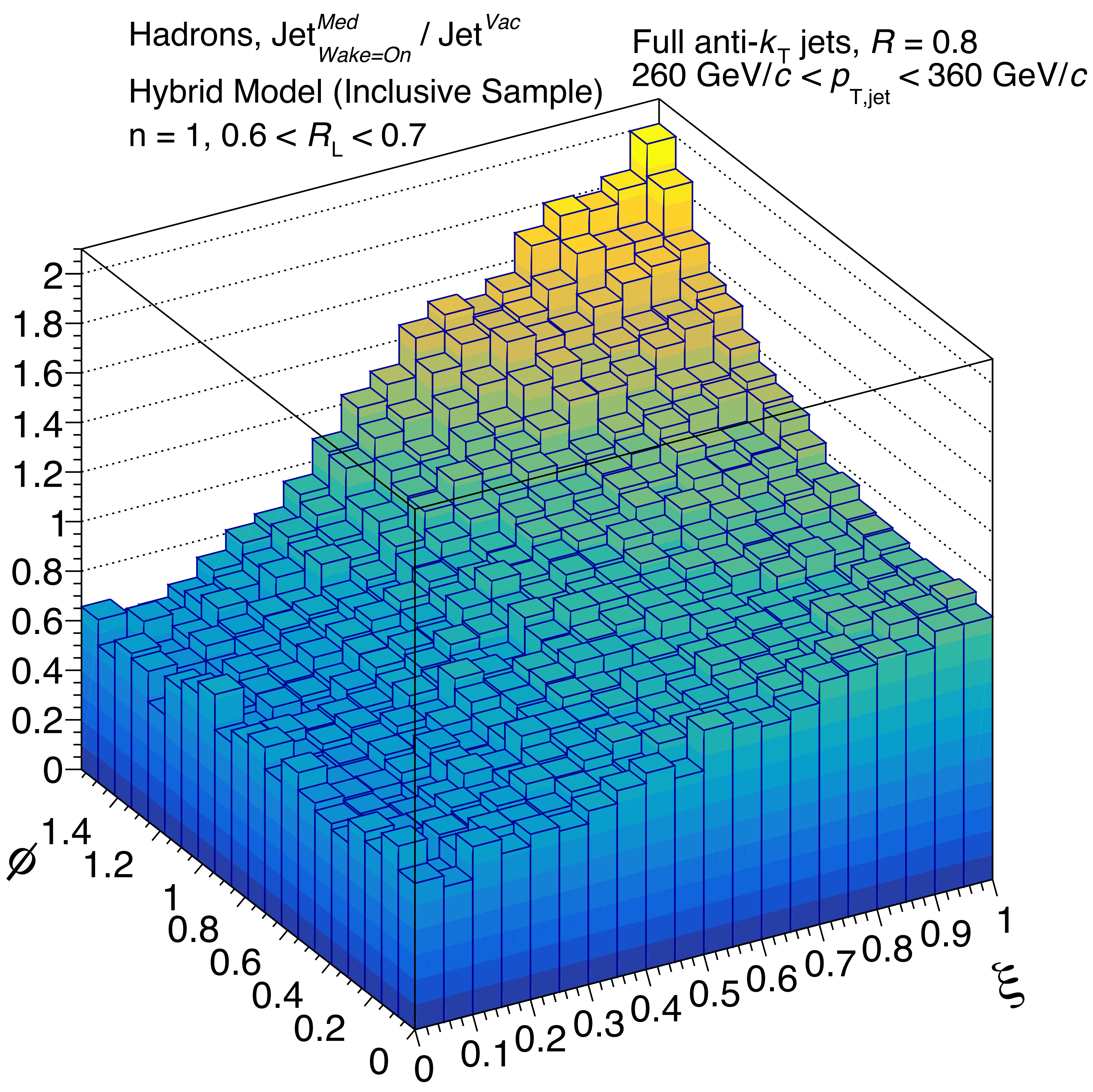
- ***Dramatically different shape dependence when the wake is included!***

Ratios to vacuum





No wake / vacuum

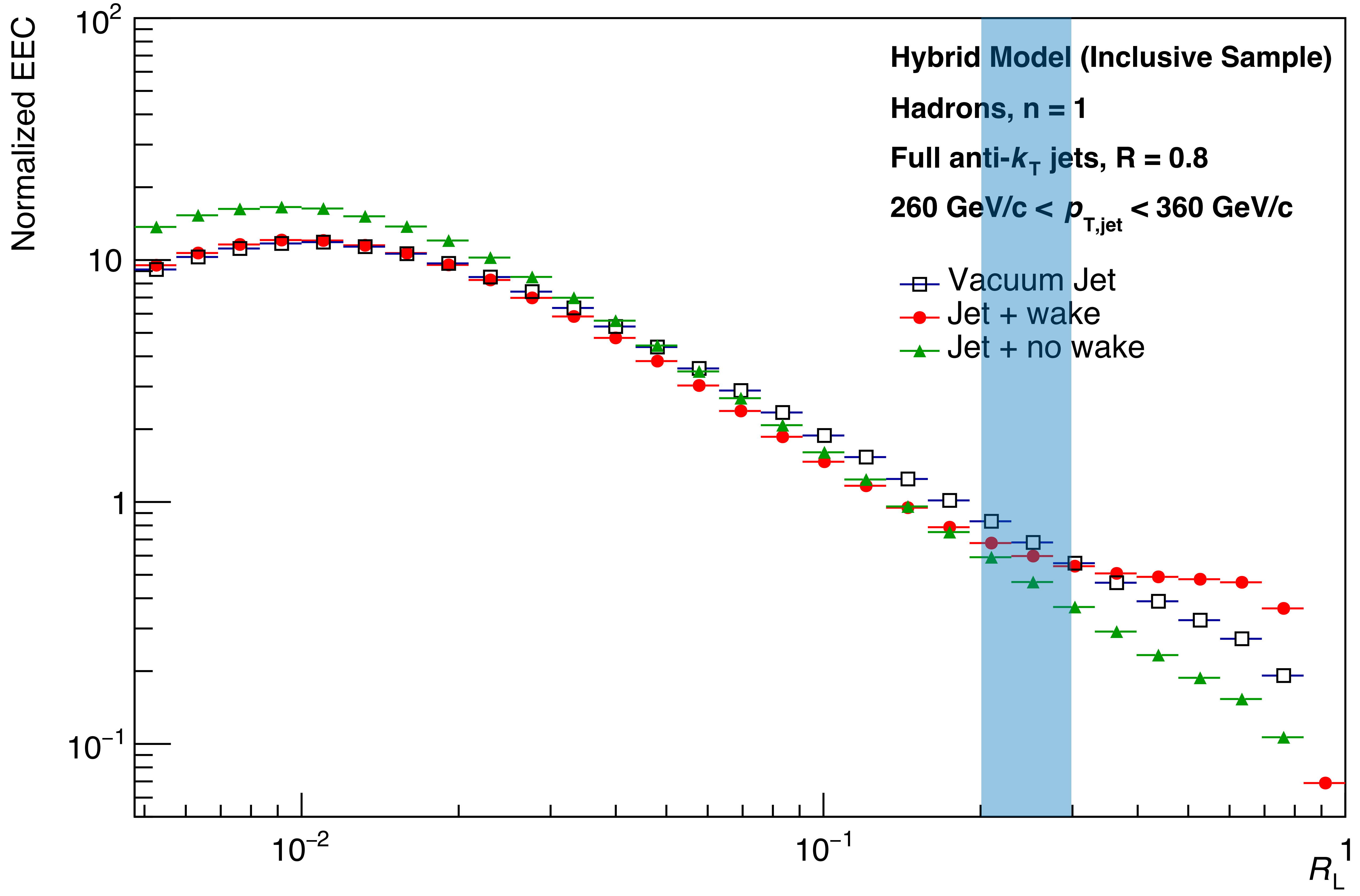


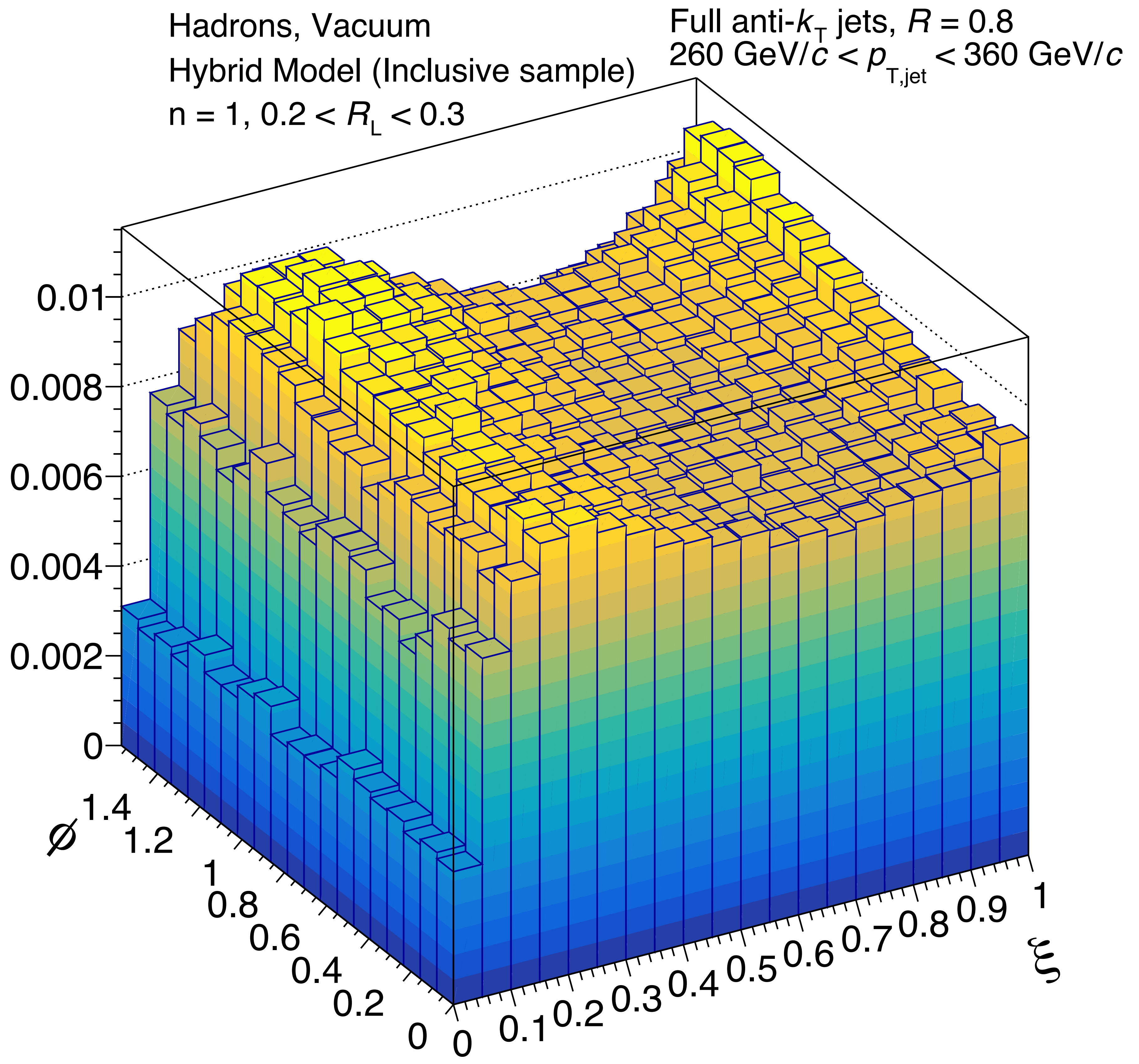
Wake / vacuum

- ***Wake leaves clear signatures in comparison to vacuum!***

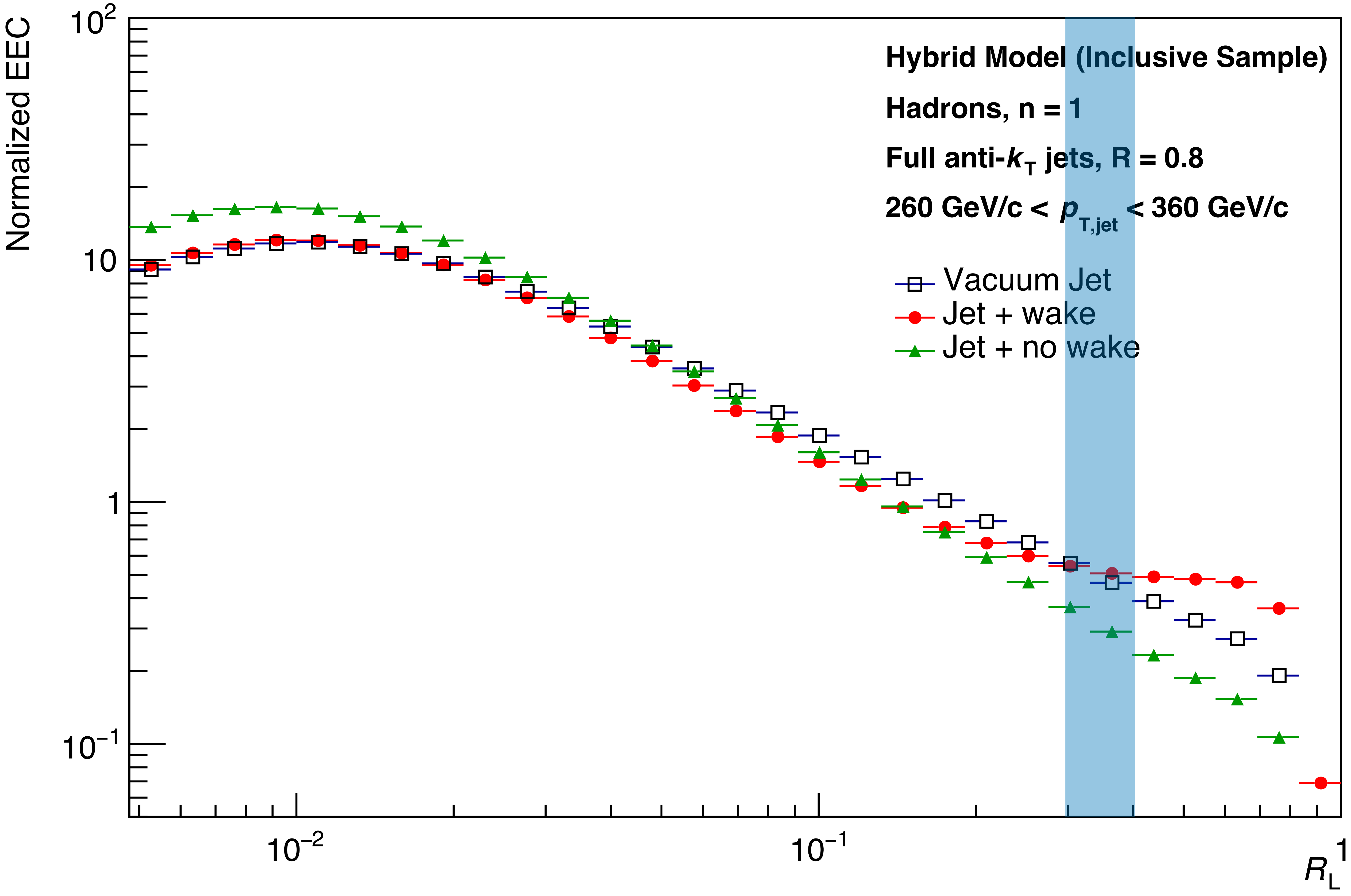
- Shape of medium response is encoded in these ratios!

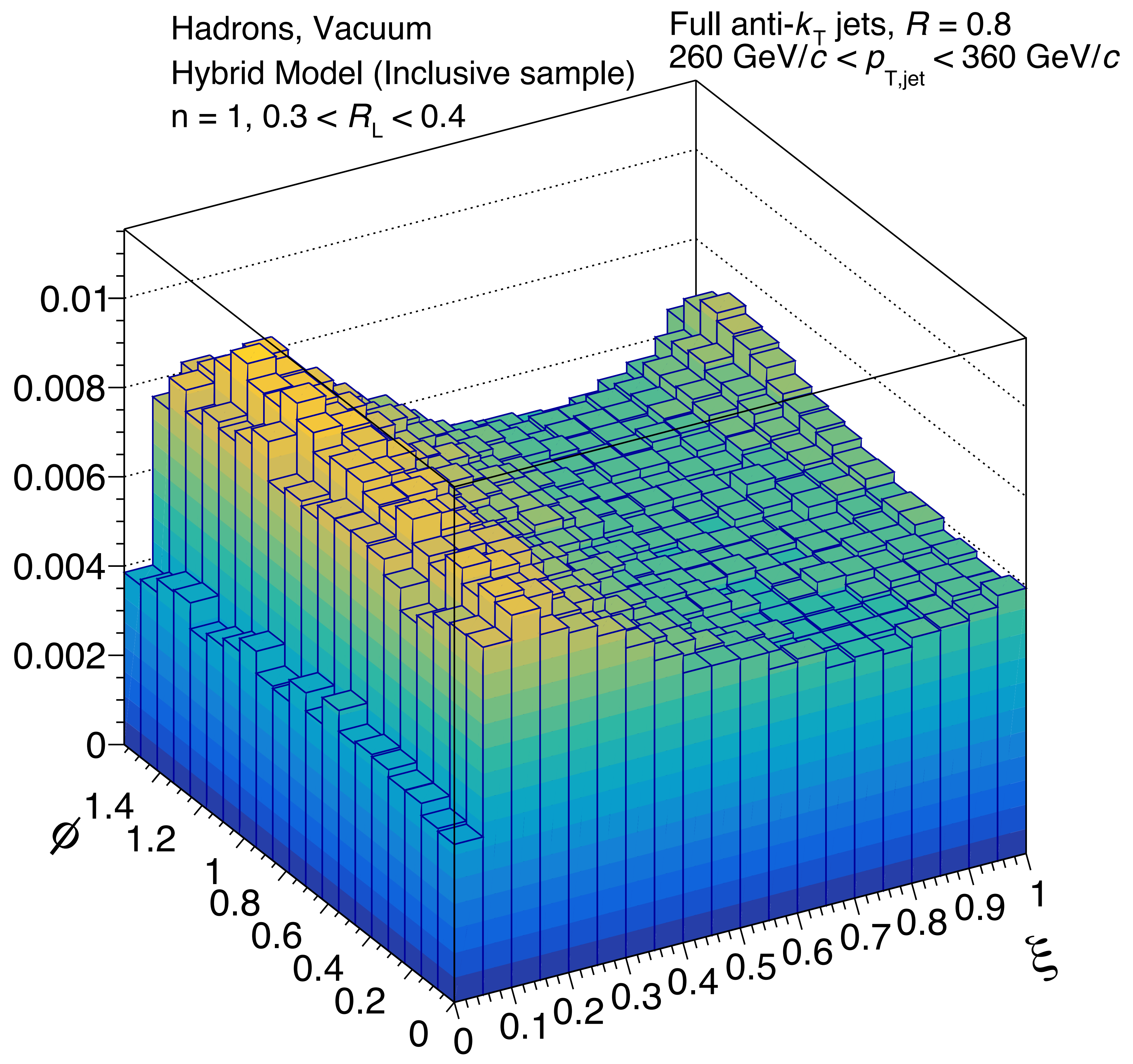
Progression with R_L (vacuum)



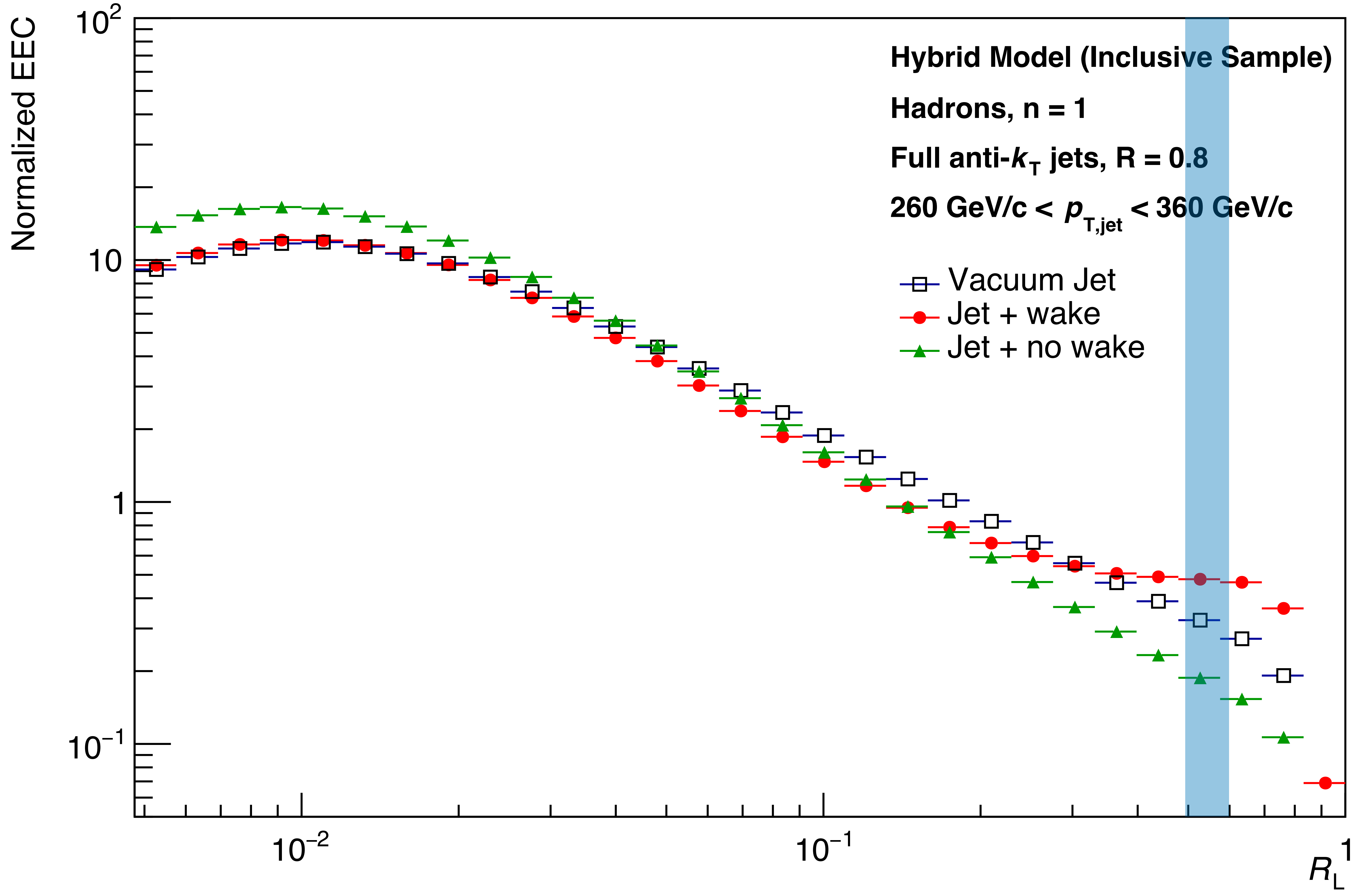


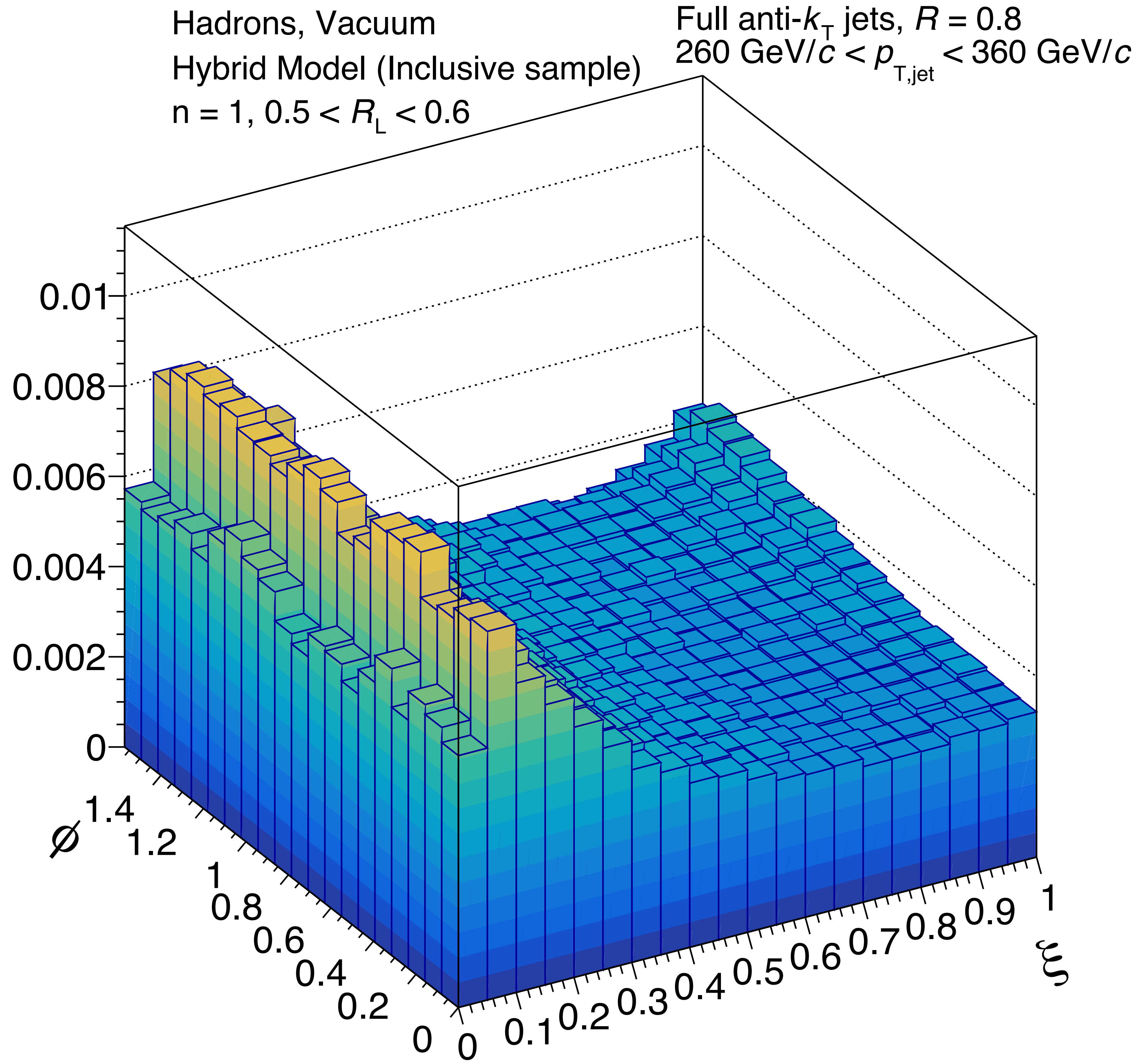
Progression with R_{L} (vacuum)



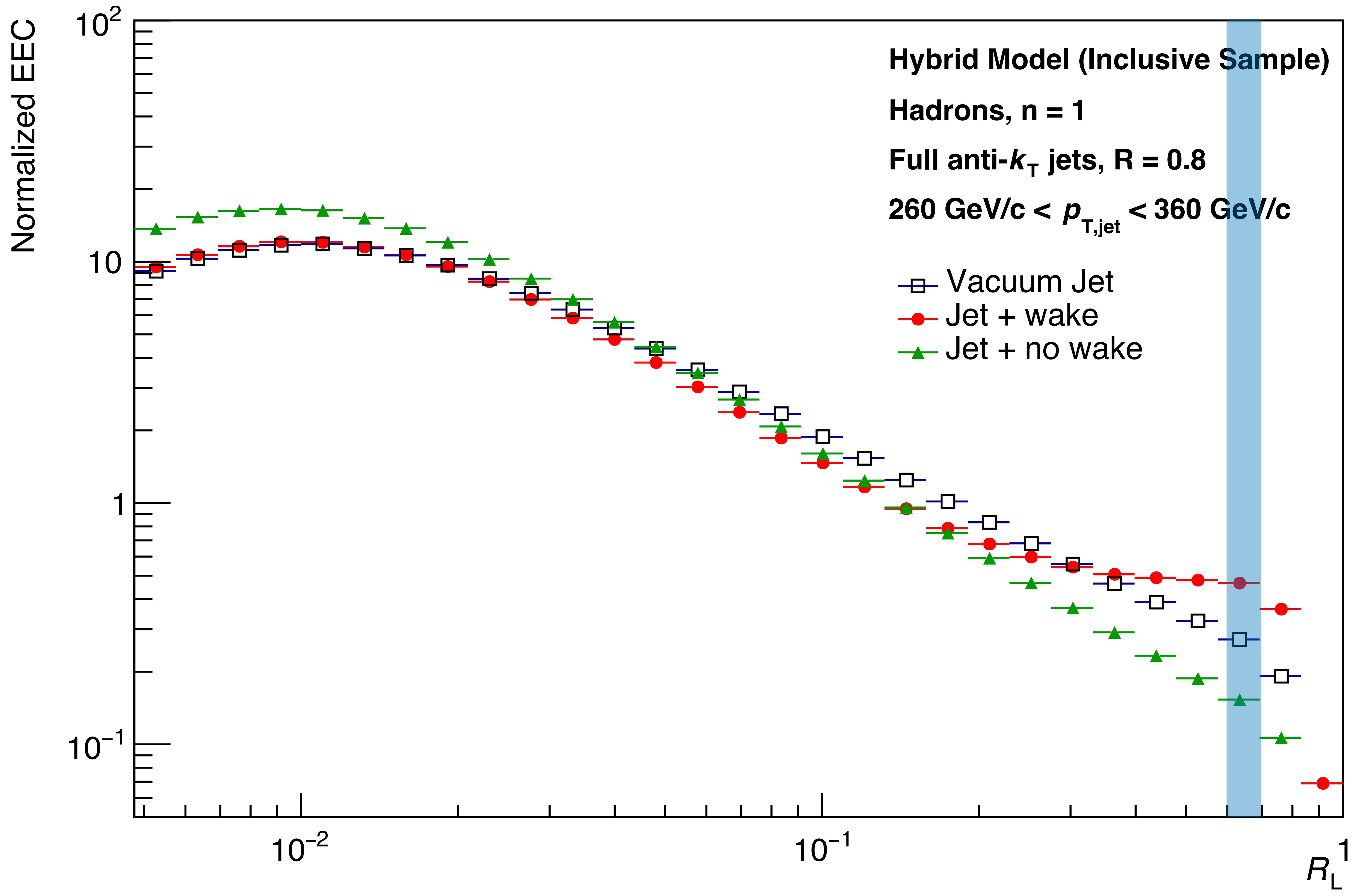


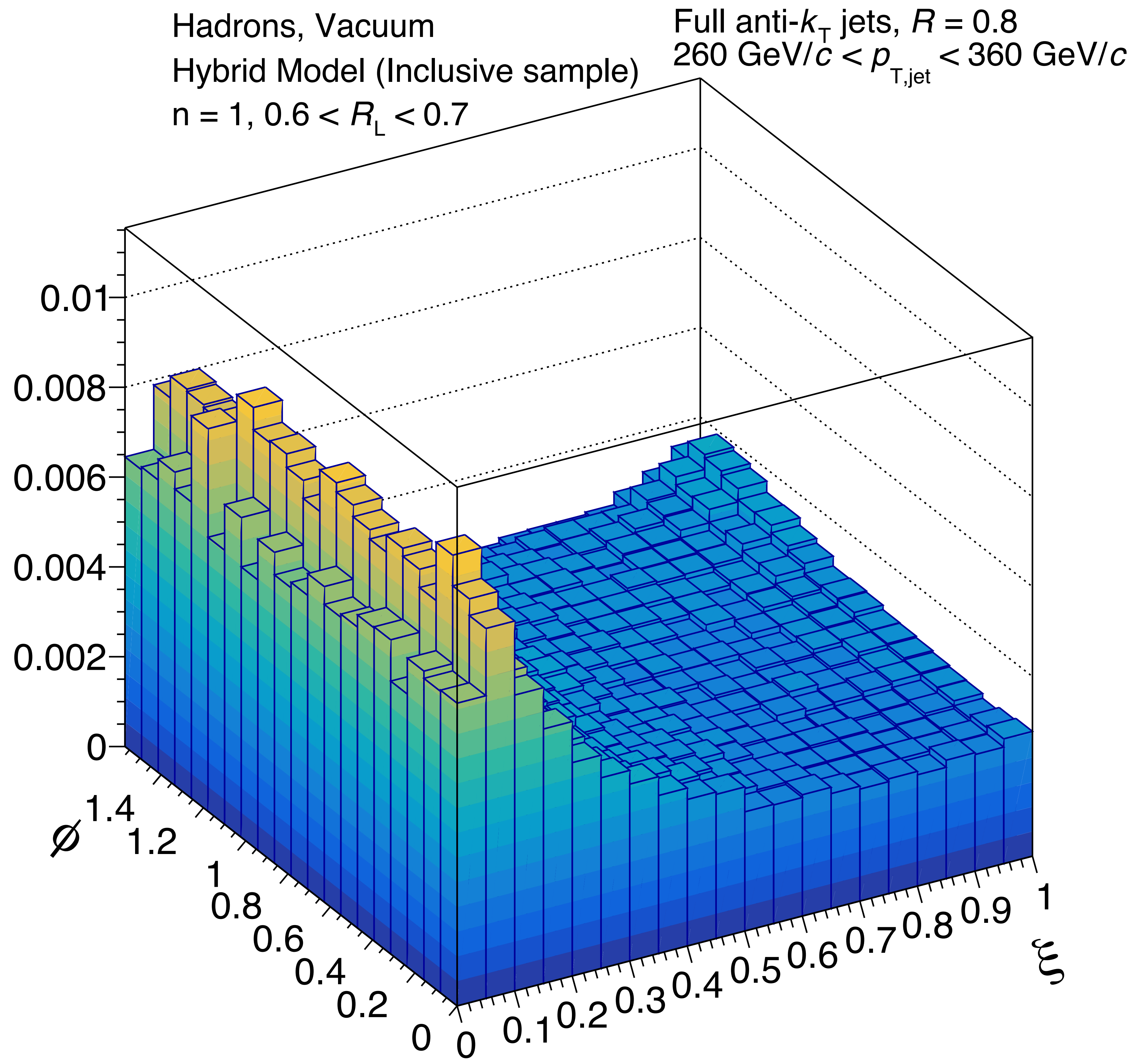
Progression with R_{L} (vacuum)





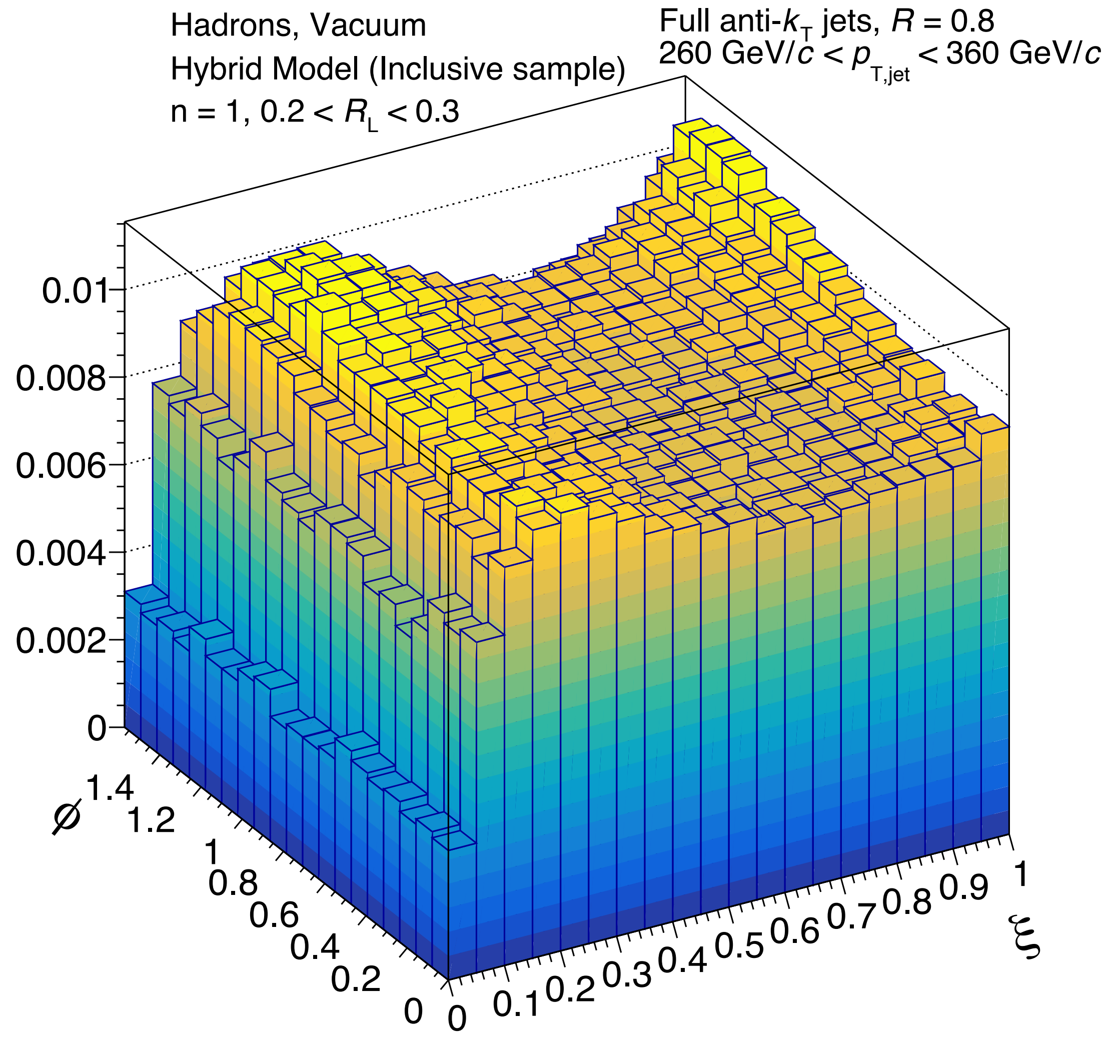
Progression with R_{L} (vacuum)



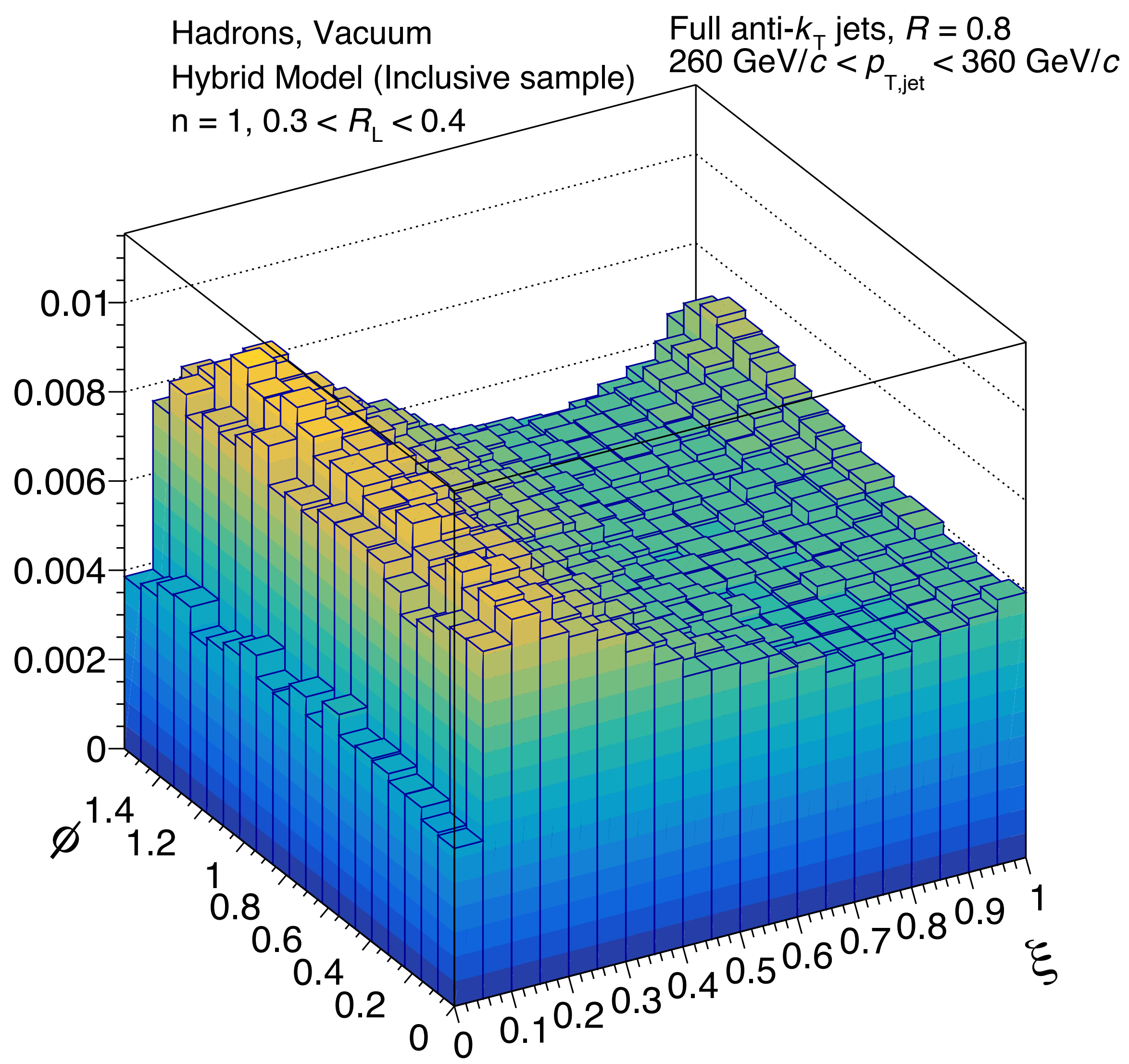


Progression with R_L (vacuum)

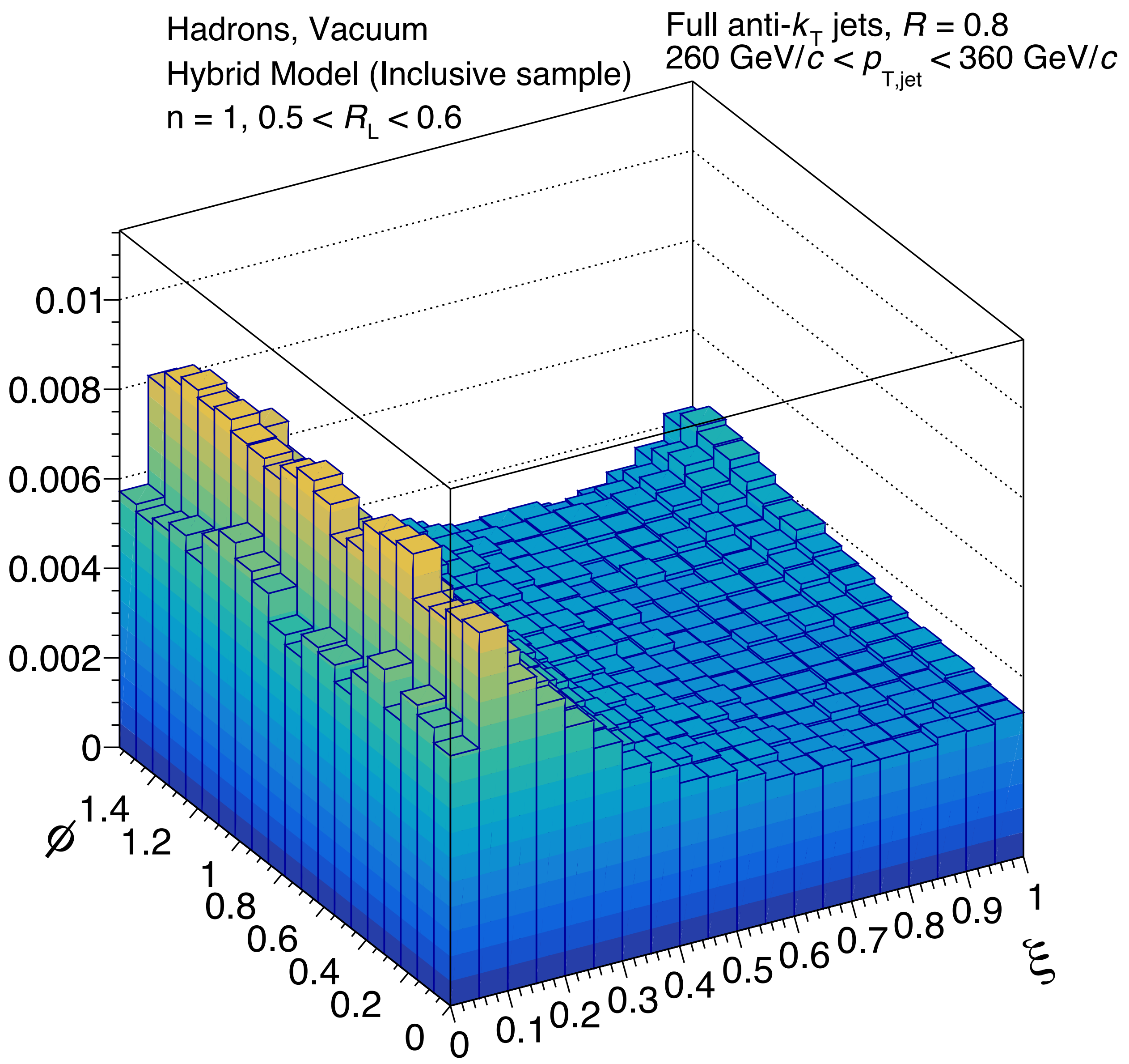
$0.2 < R_L < 0.3$



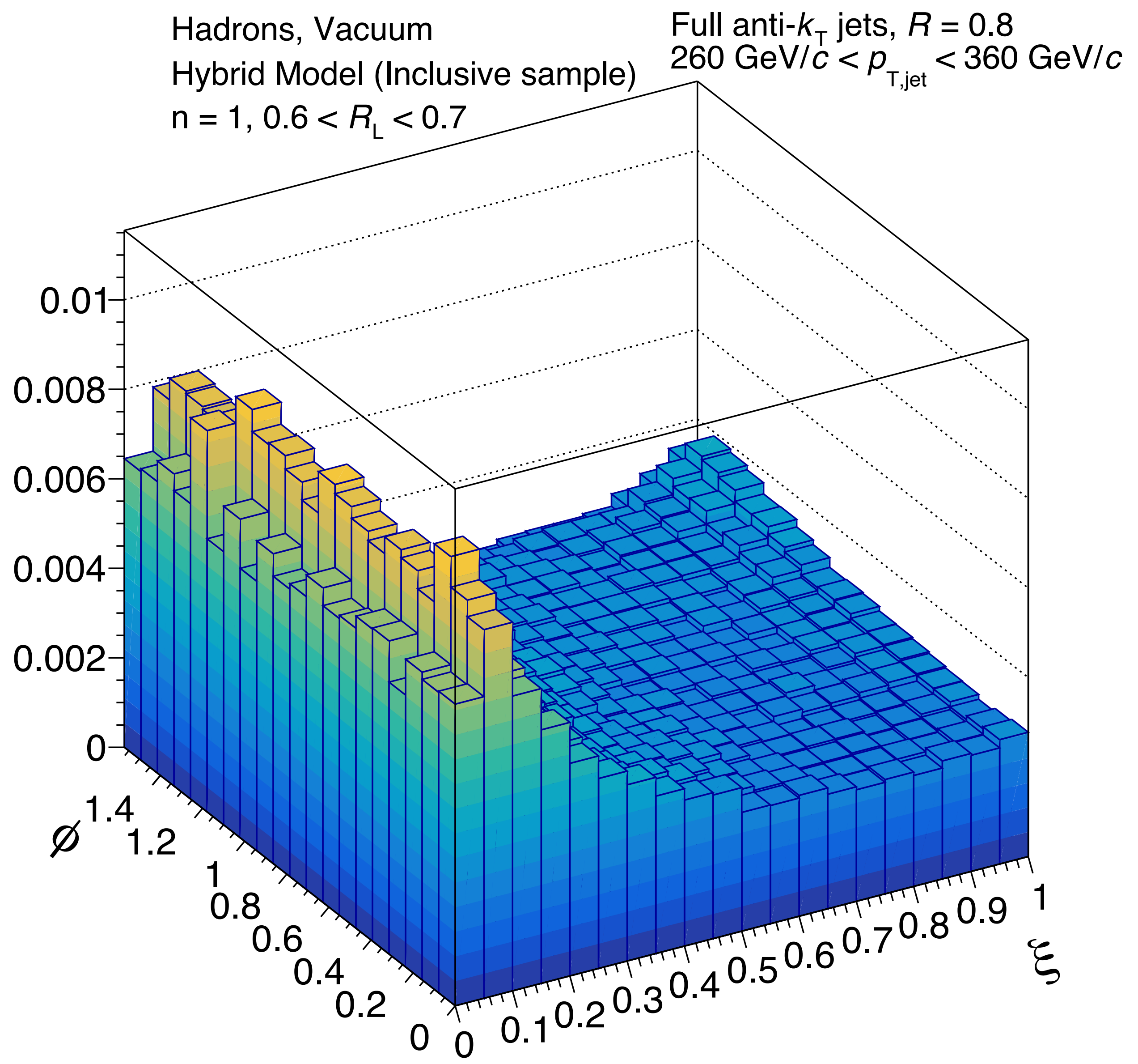
$0.3 < R_L < 0.4$



$0.5 < R_L < 0.6$



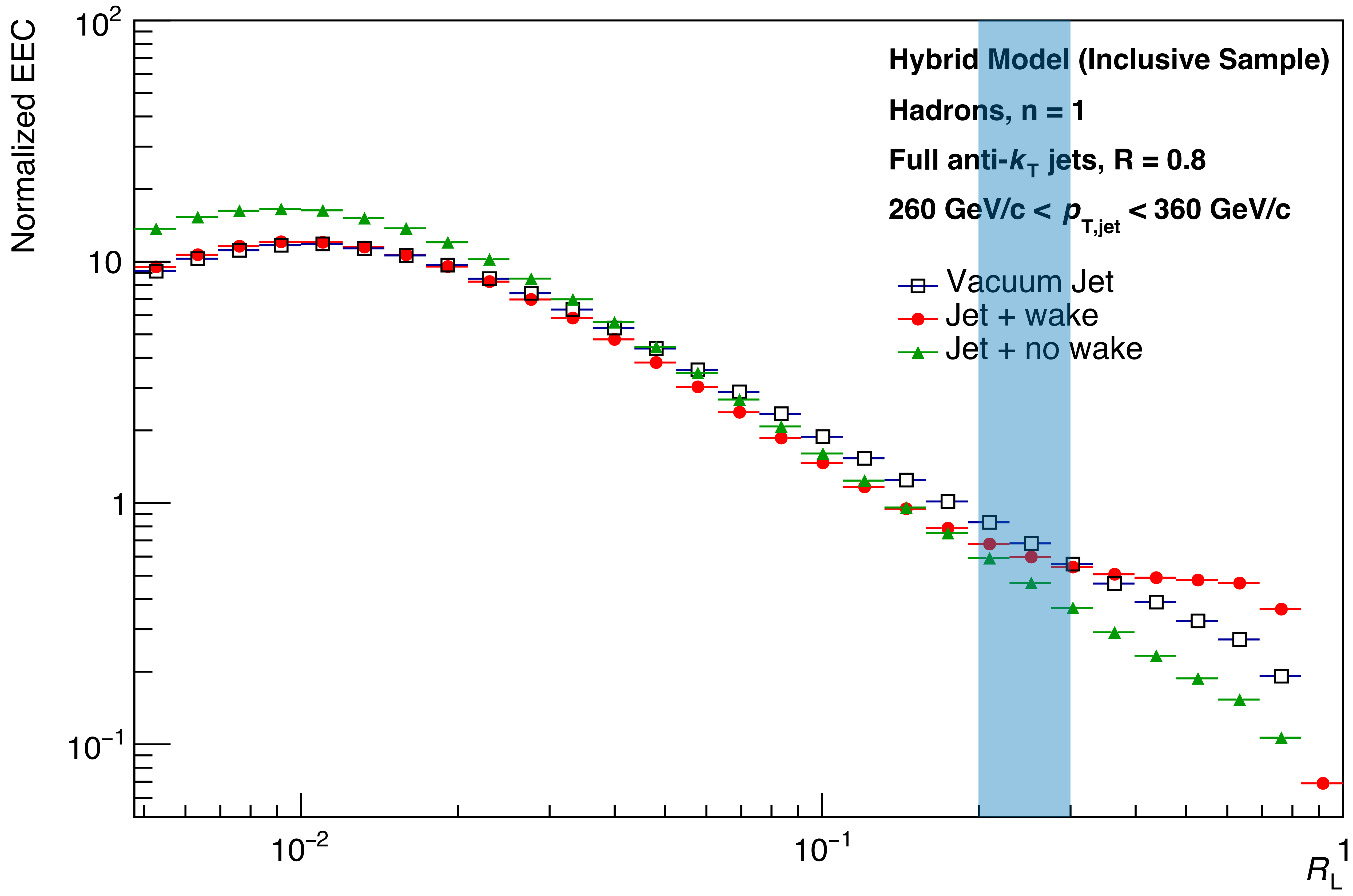
$0.6 < R_L < 0.7$

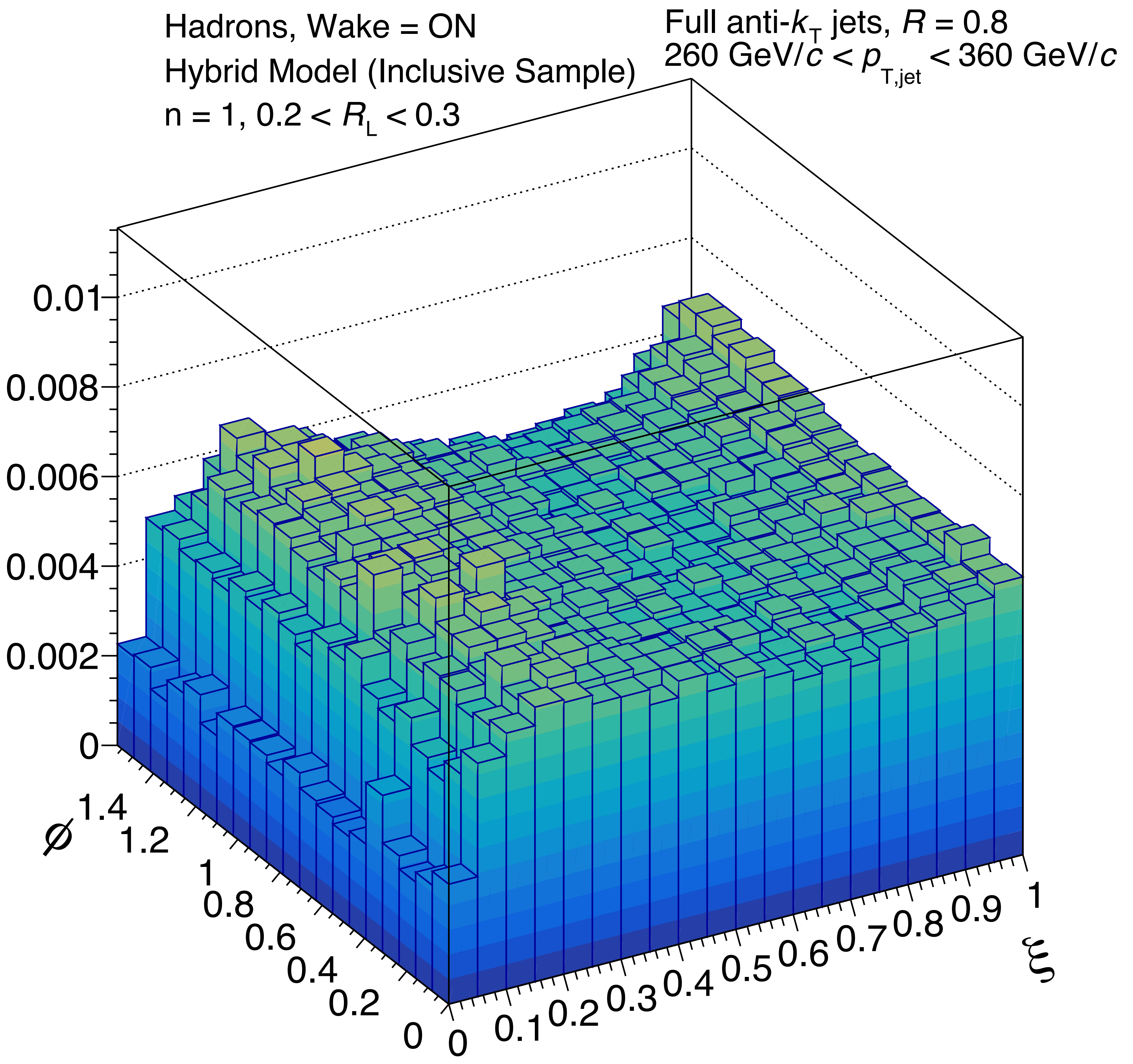


Increasing R_L

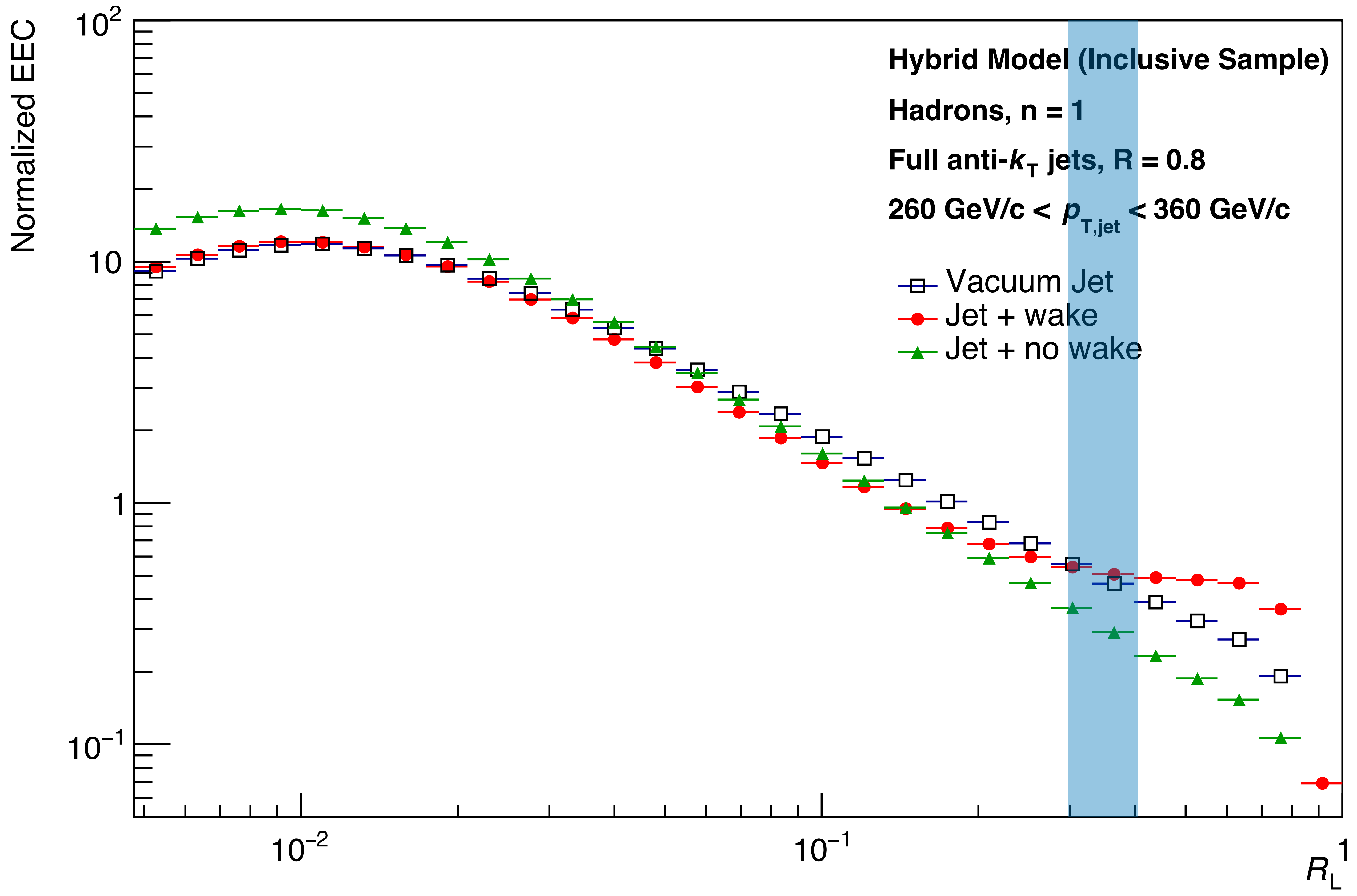
- Larger $R_L \rightarrow$ more perturbative
- See perturbative features enhanced at large R_L

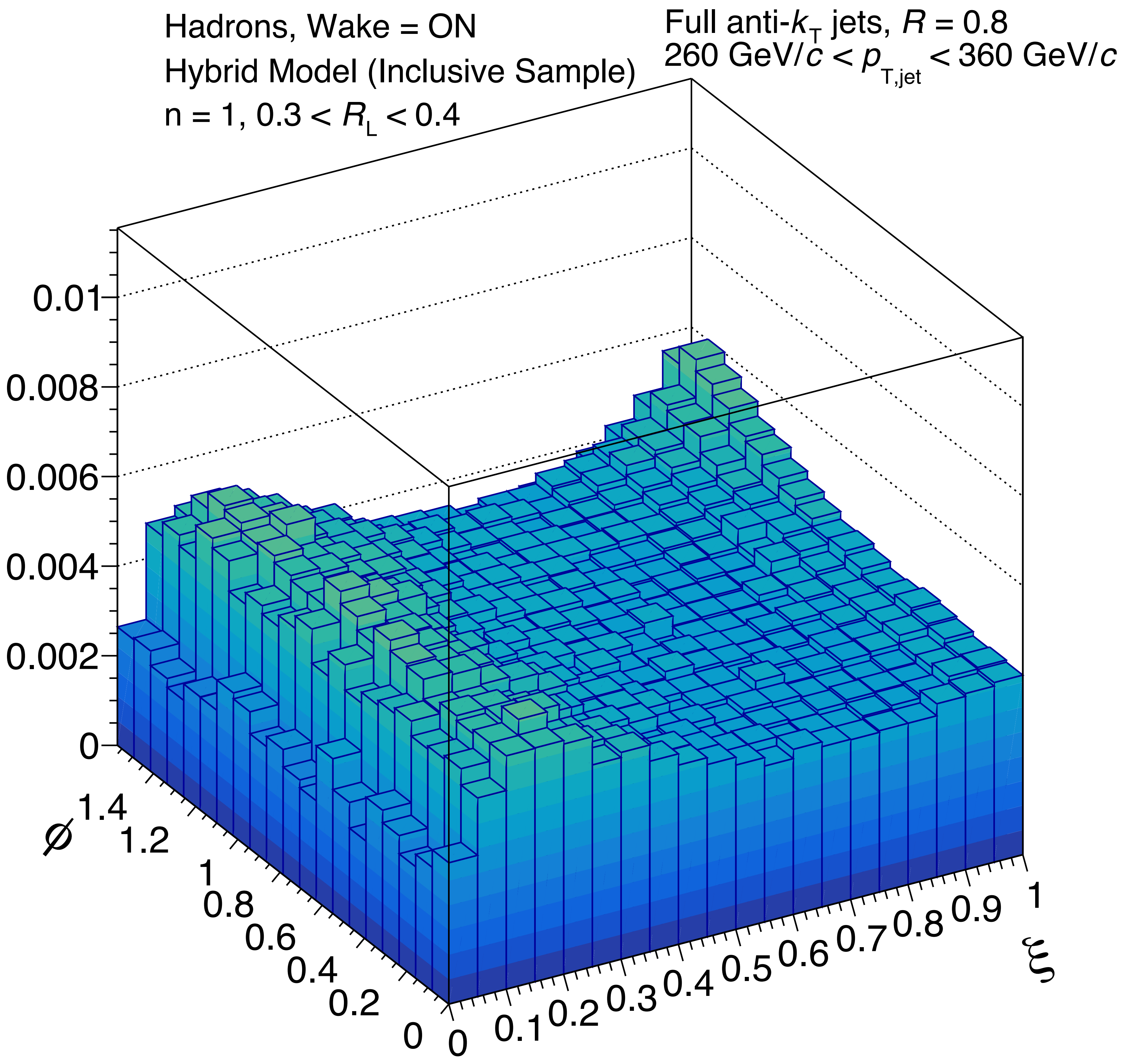
Progression with R_L (medium, wake)



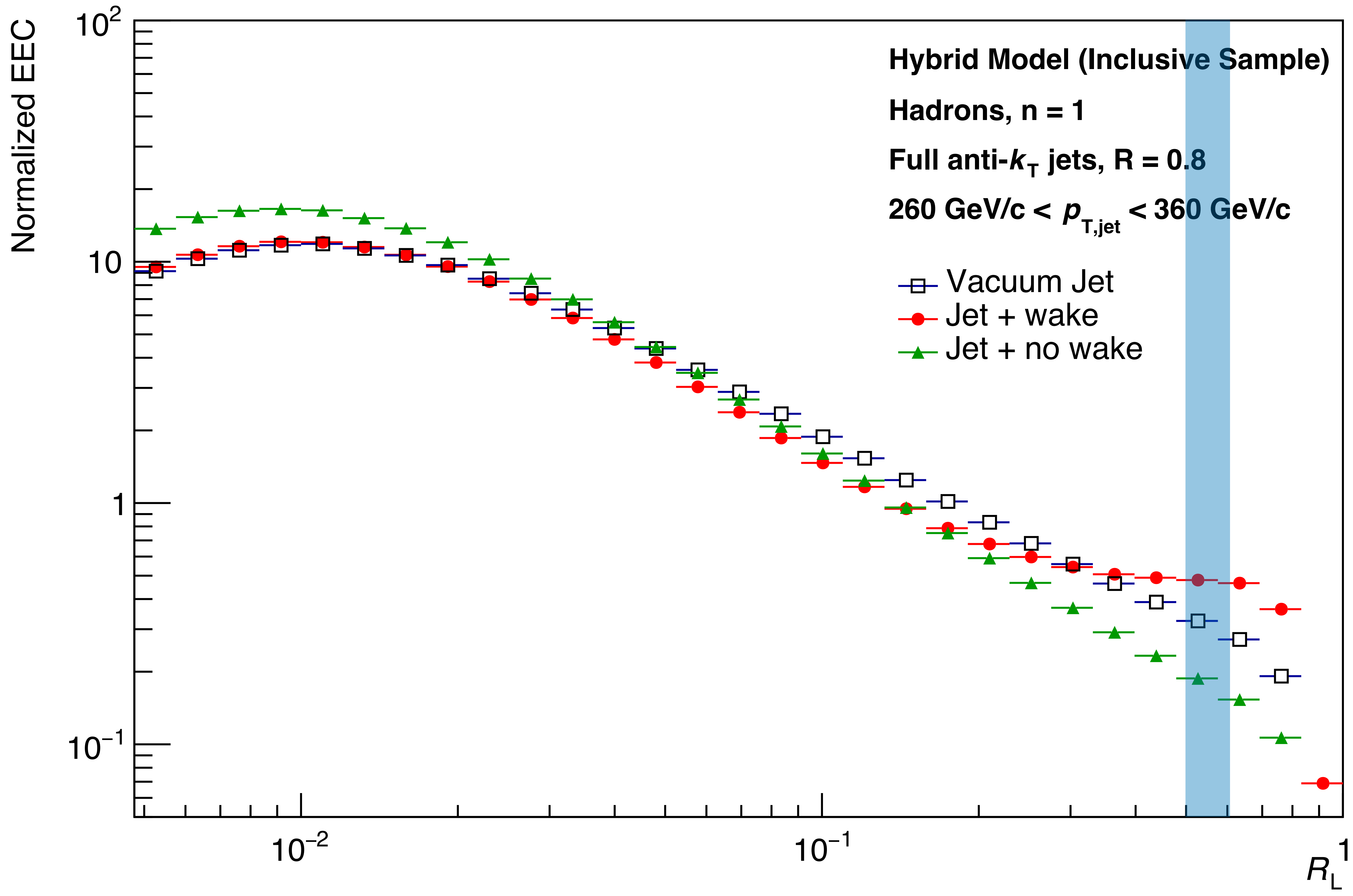


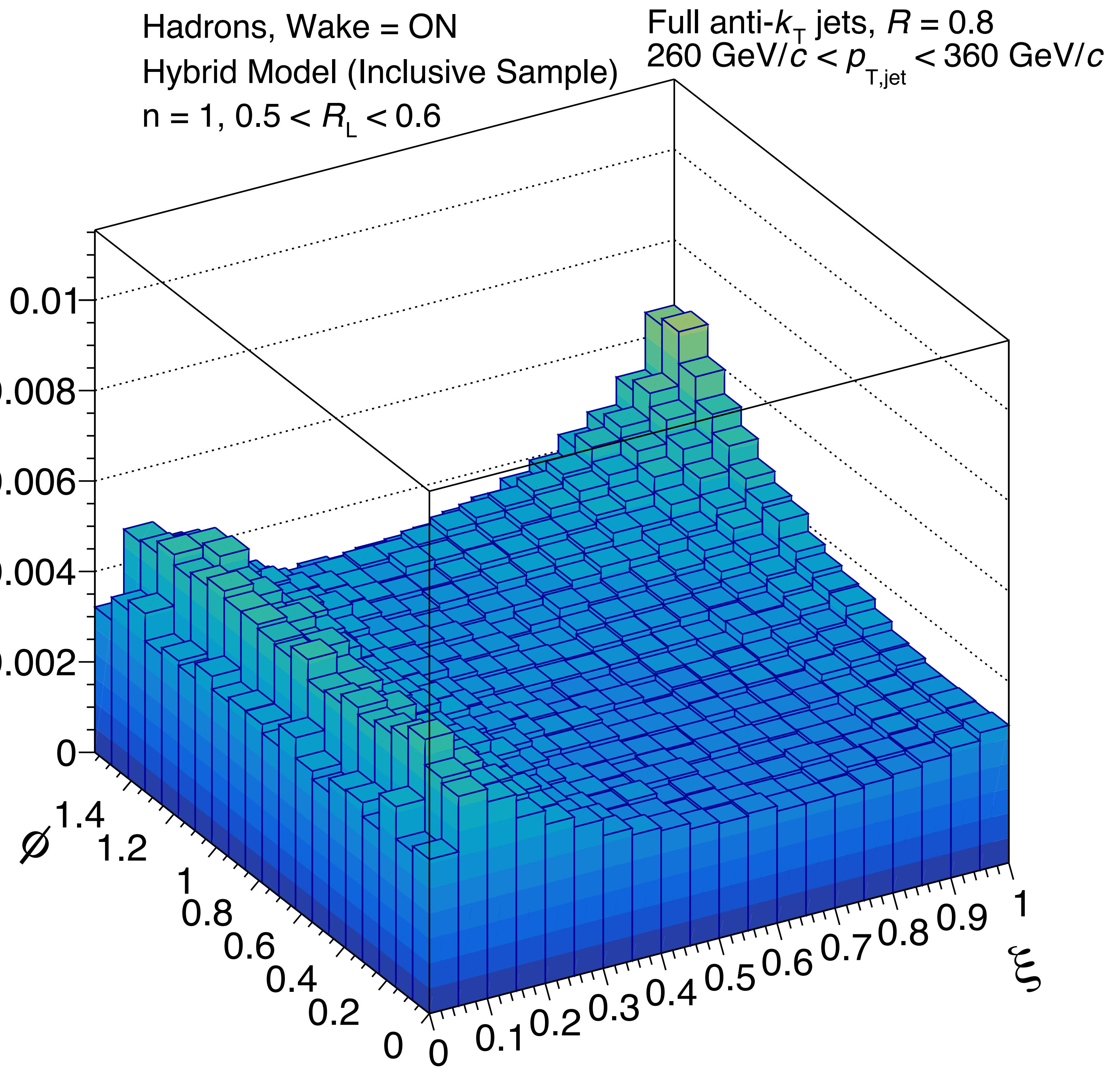
Progression with R_L (medium, wake)



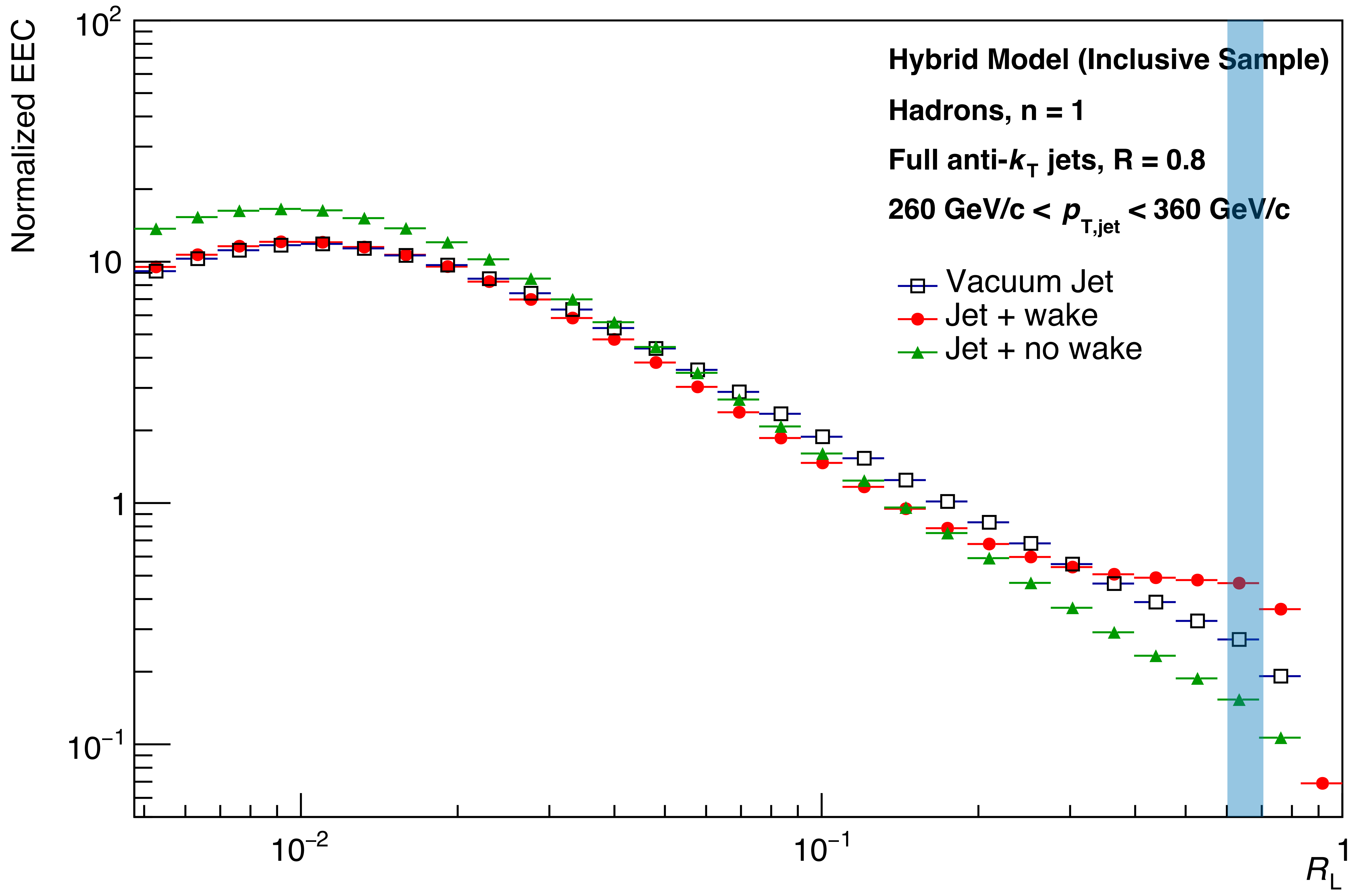


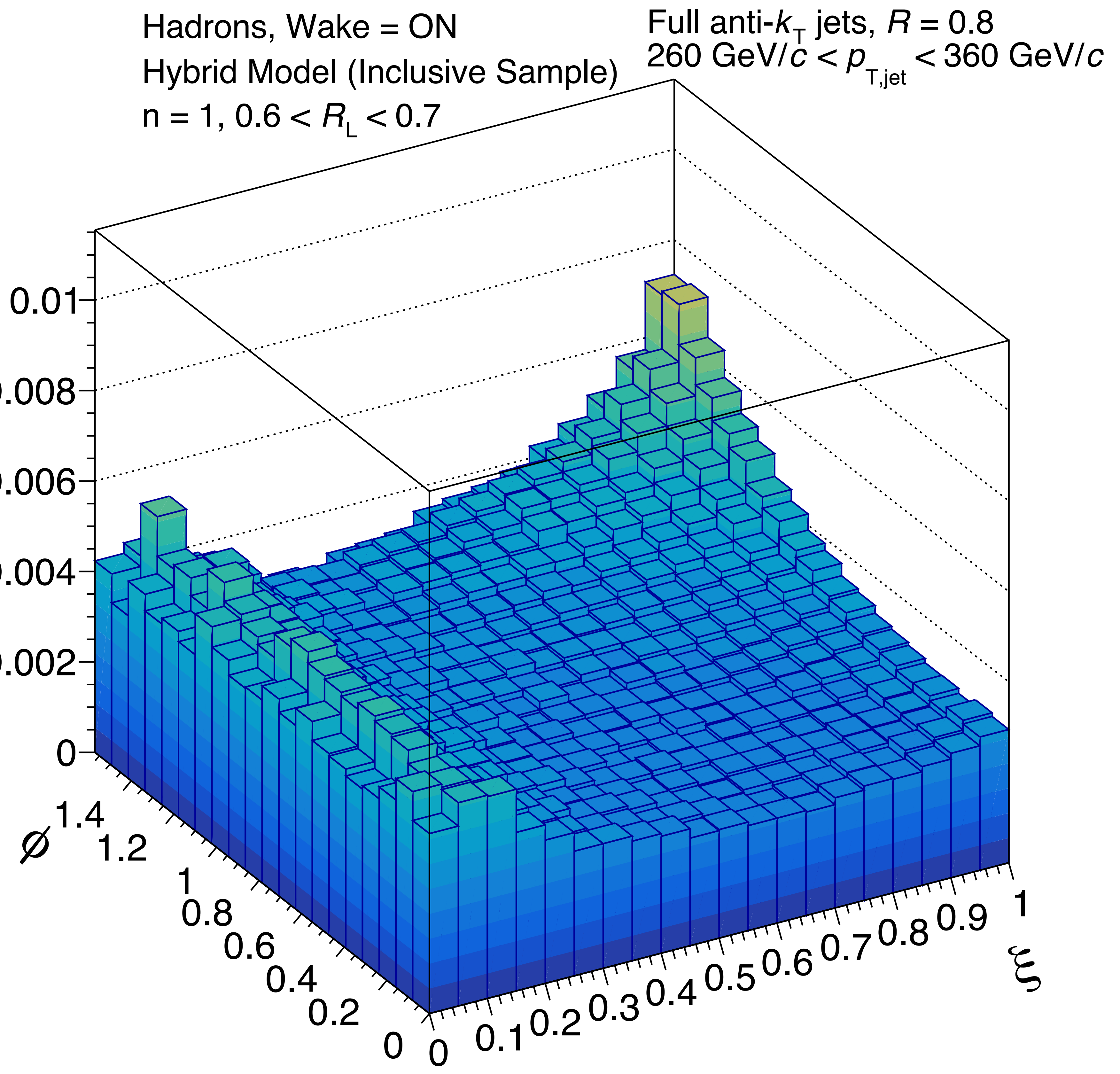
Progression with R_L (medium, wake)





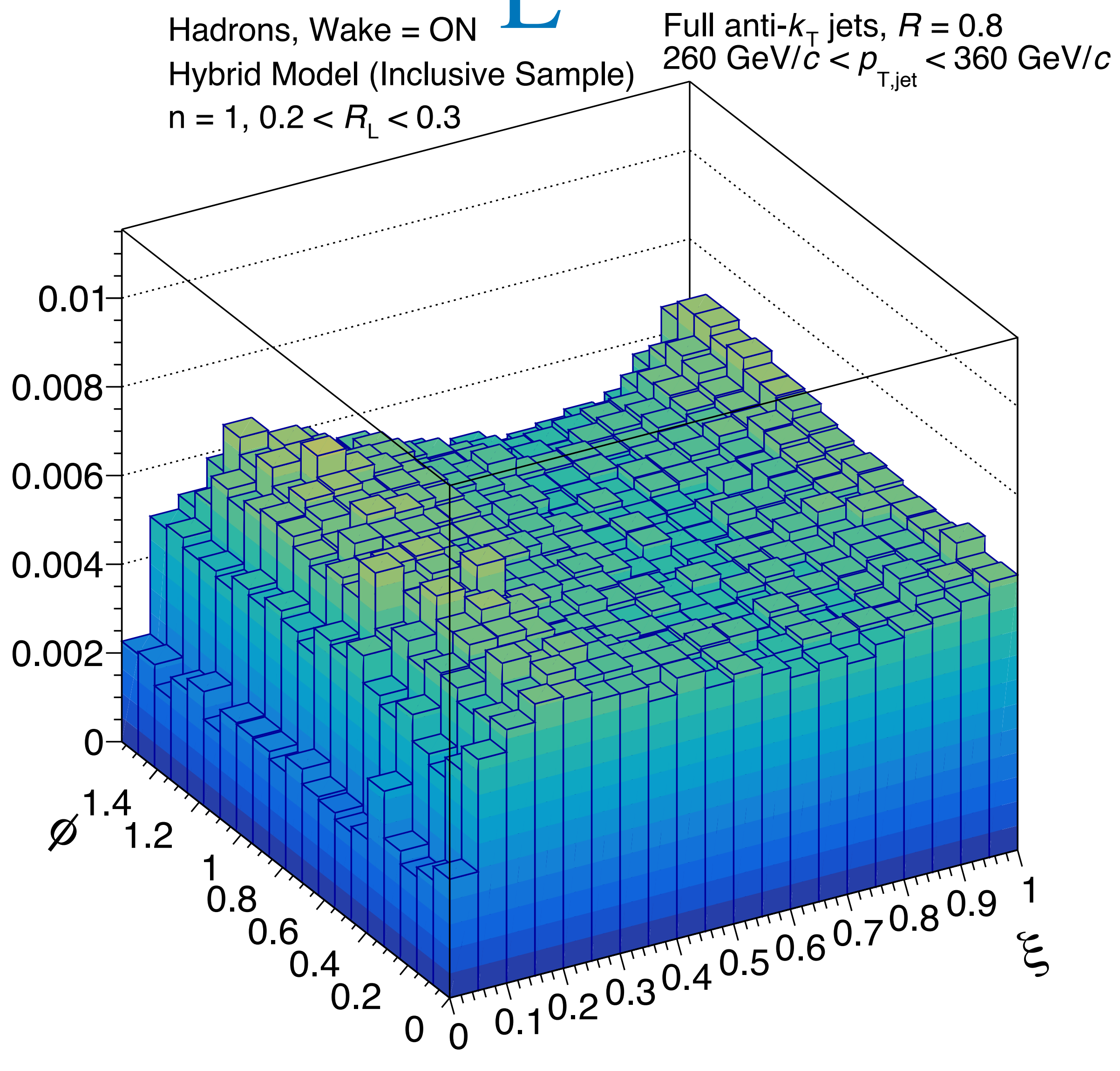
Progression with R_L (medium, wake)



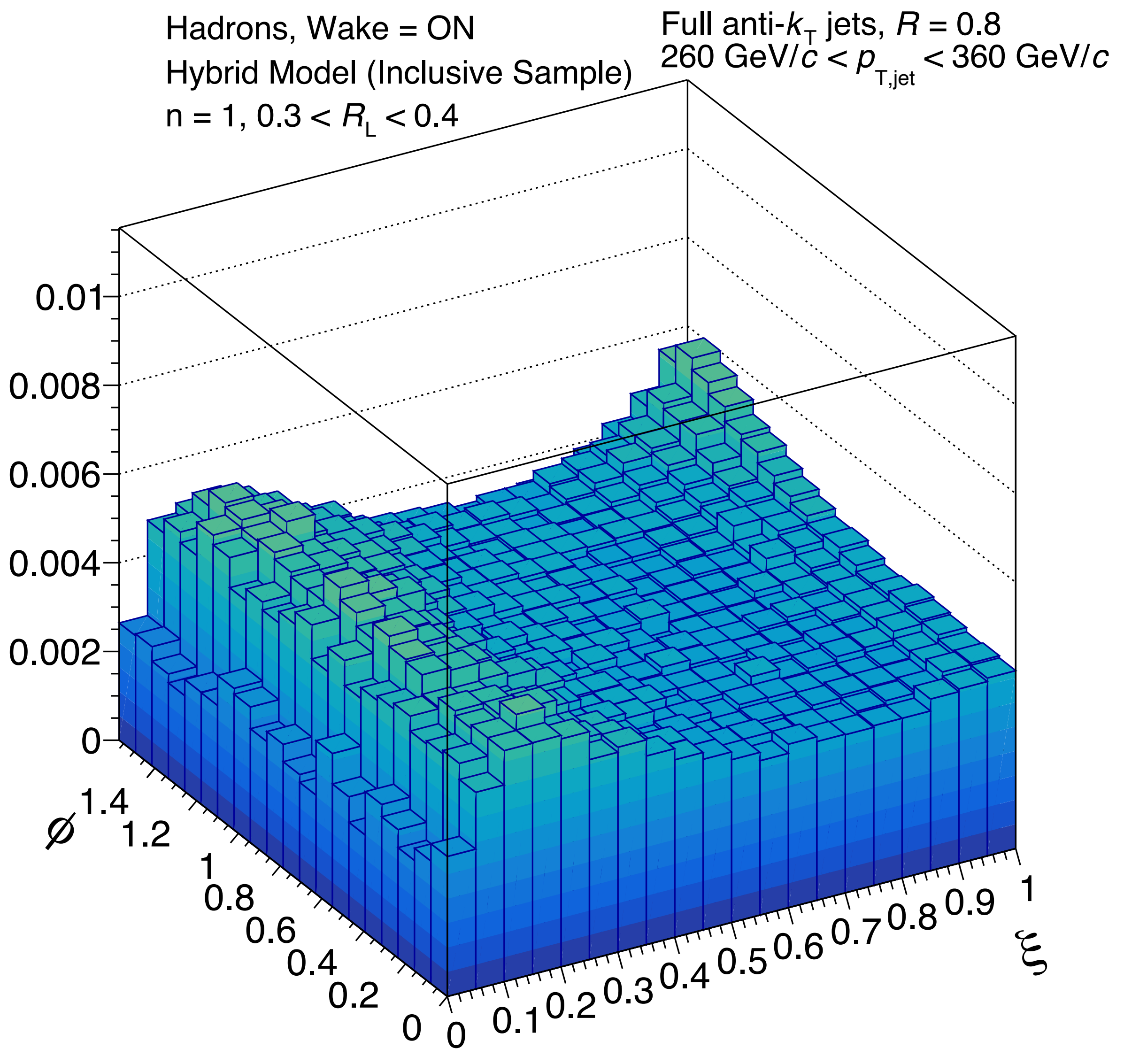


Progression with R_L (medium, wake)

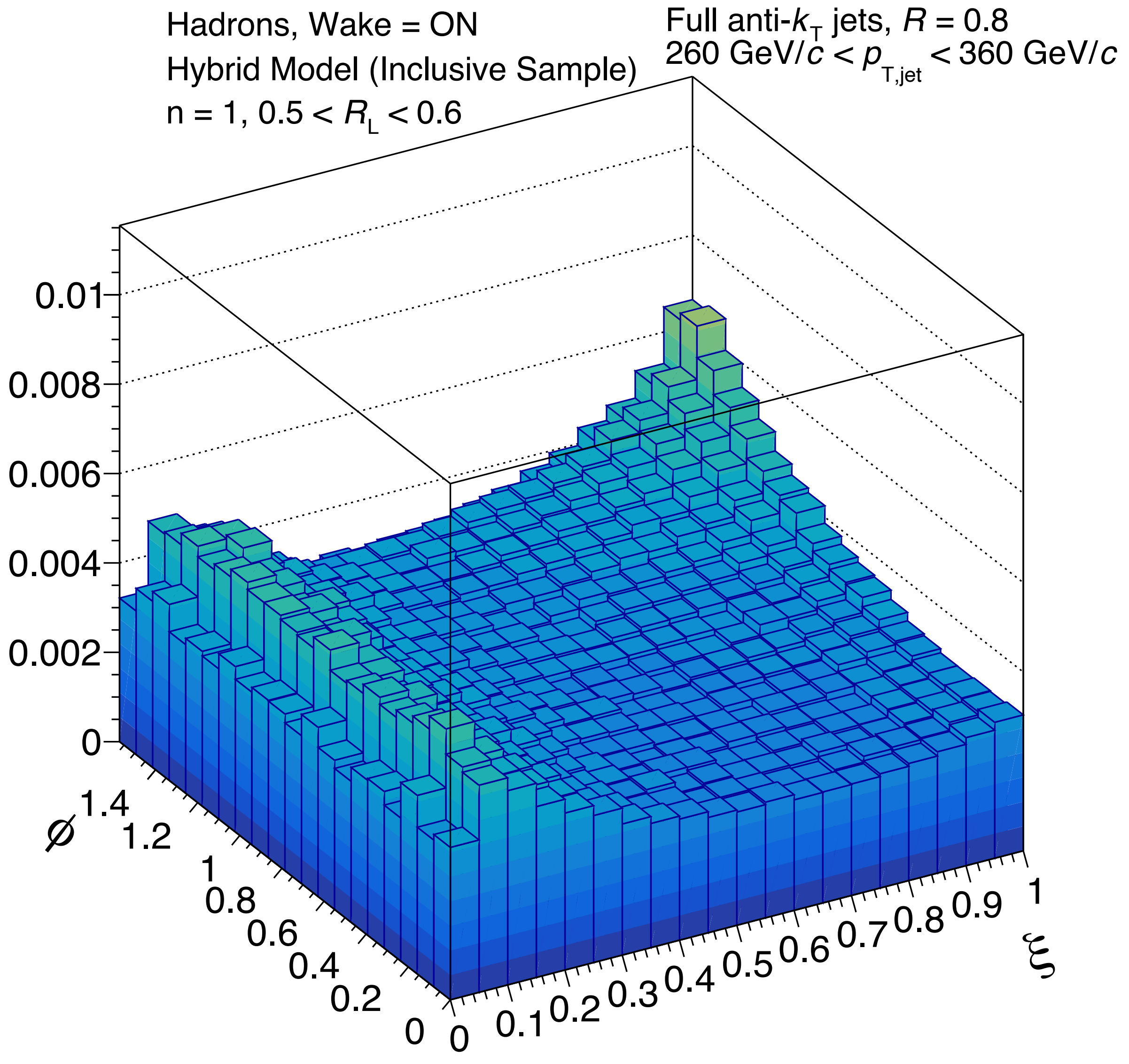
$0.2 < R_\mathrm{L} < 0.3$



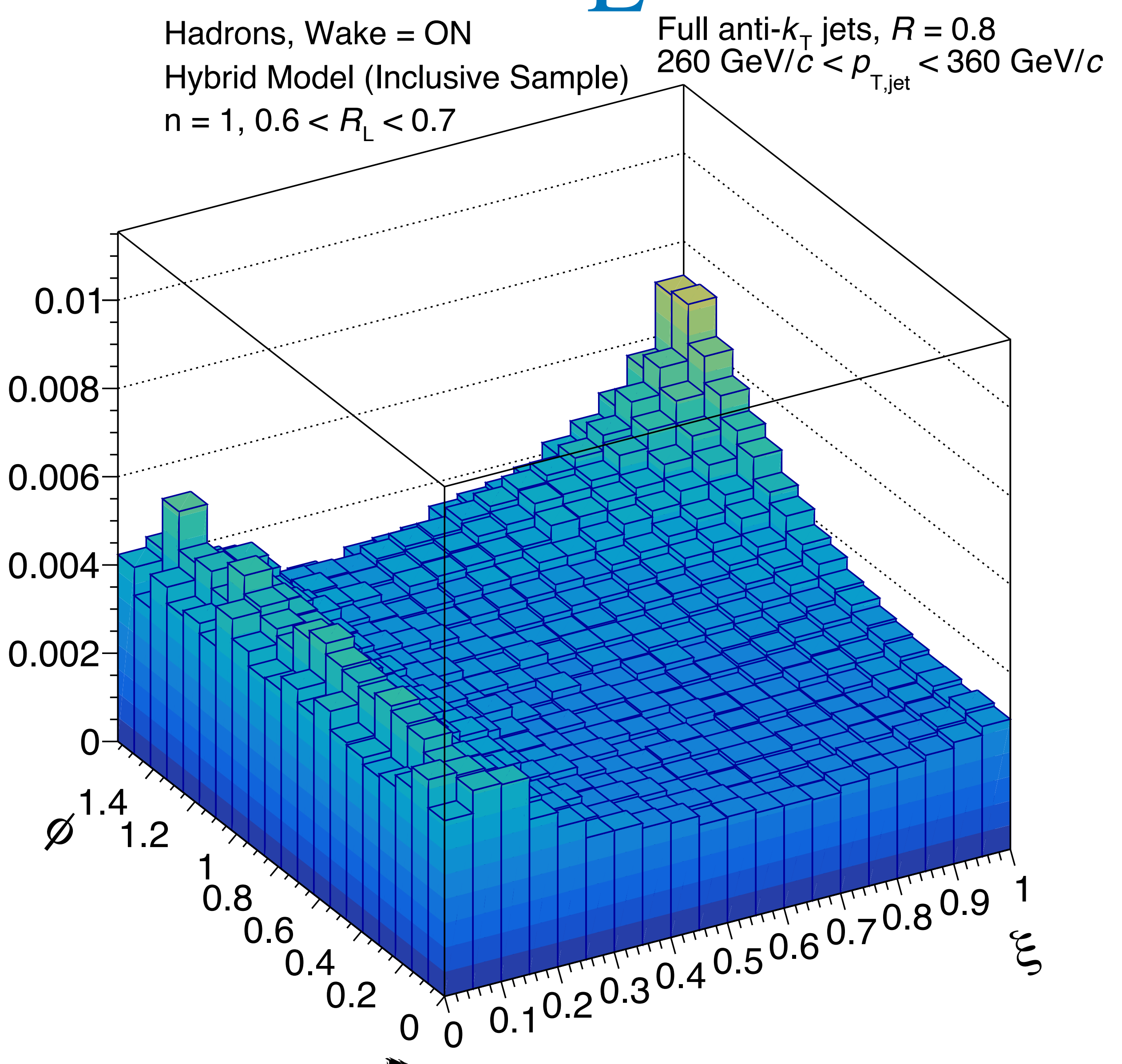
$0.3 < R_\mathrm{L} < 0.4$



$0.5 < R_\mathrm{L} < 0.6$



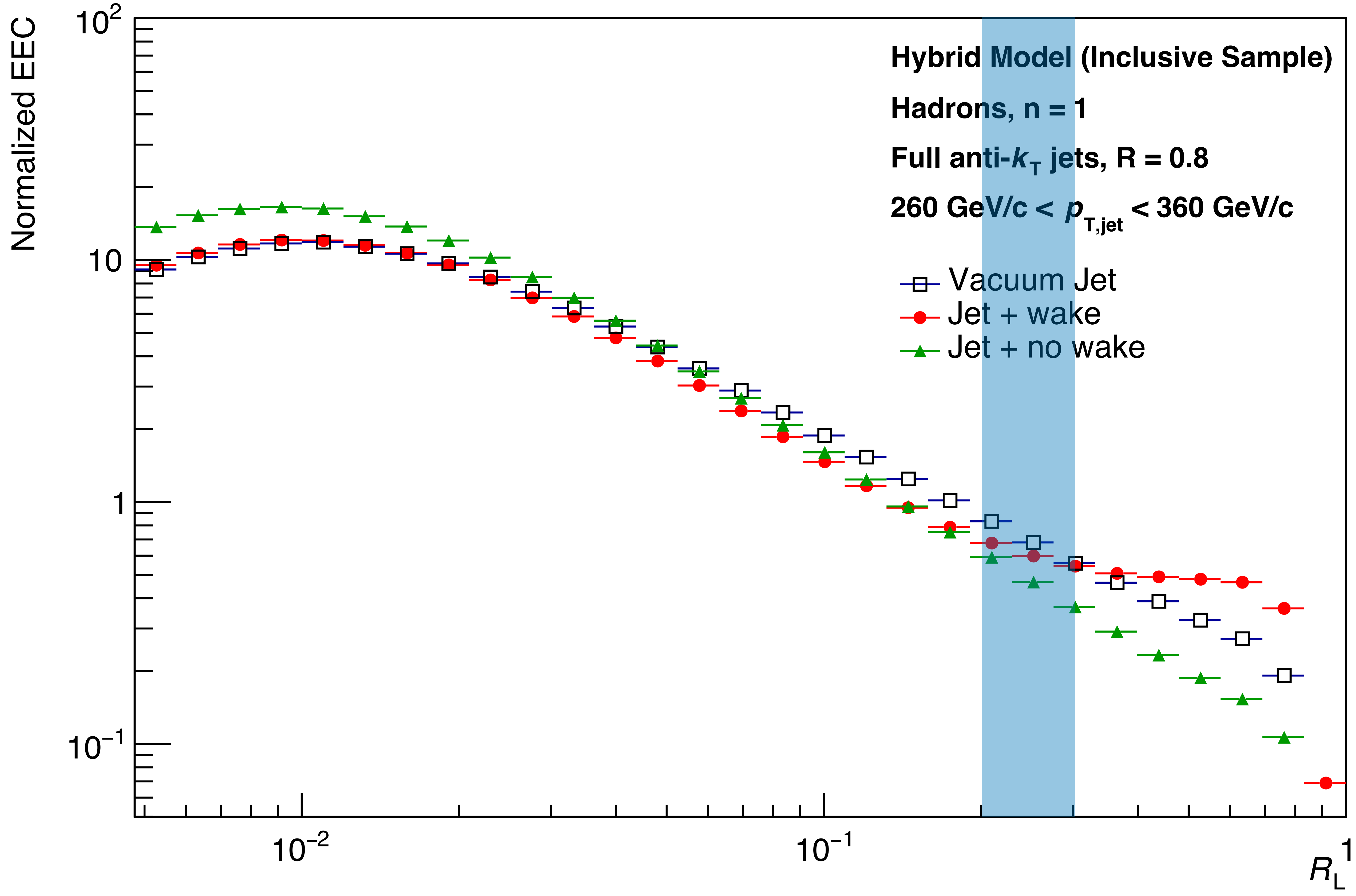
$0.6 < R_\mathrm{L} < 0.7$

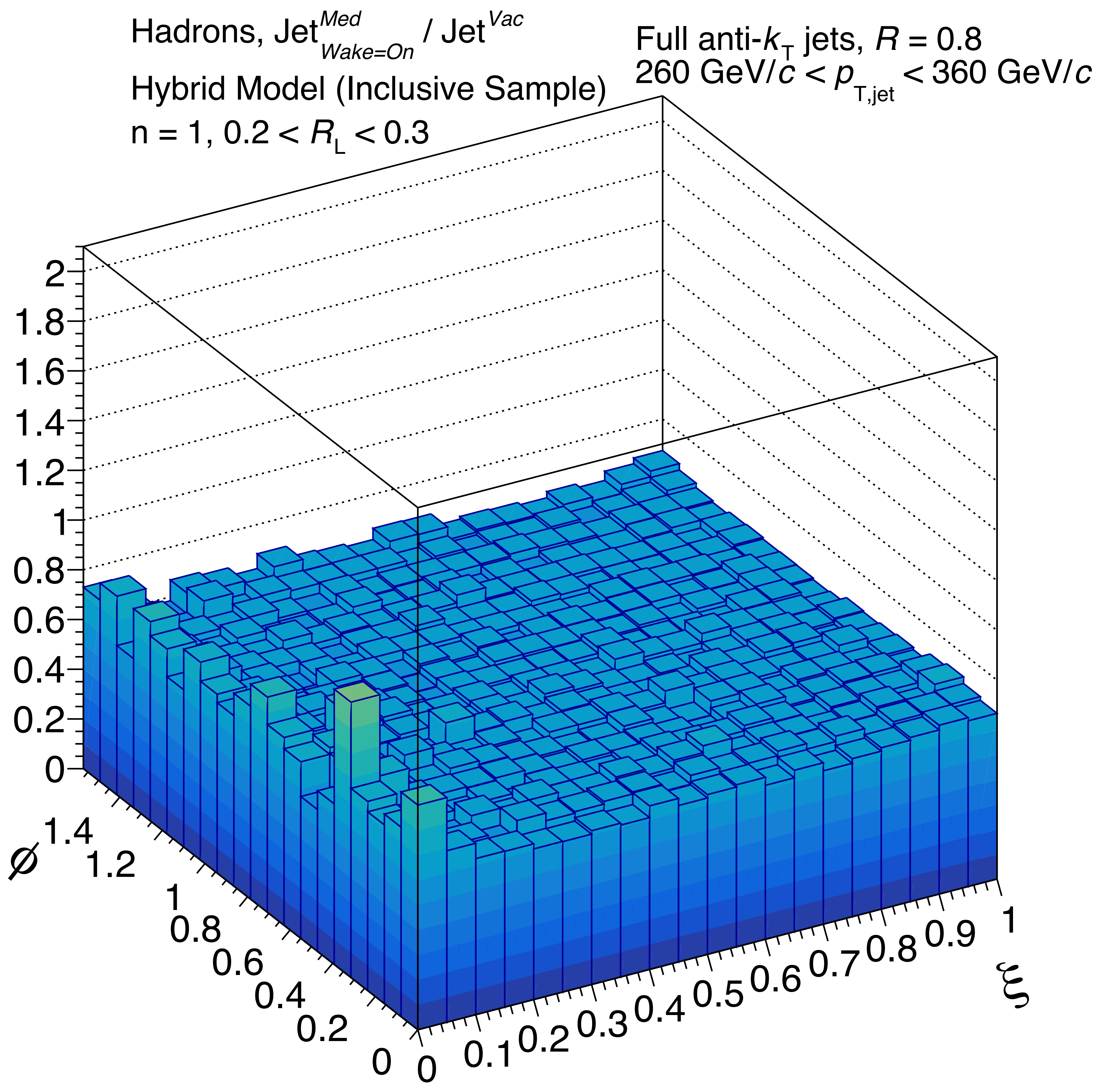


Increasing R_L

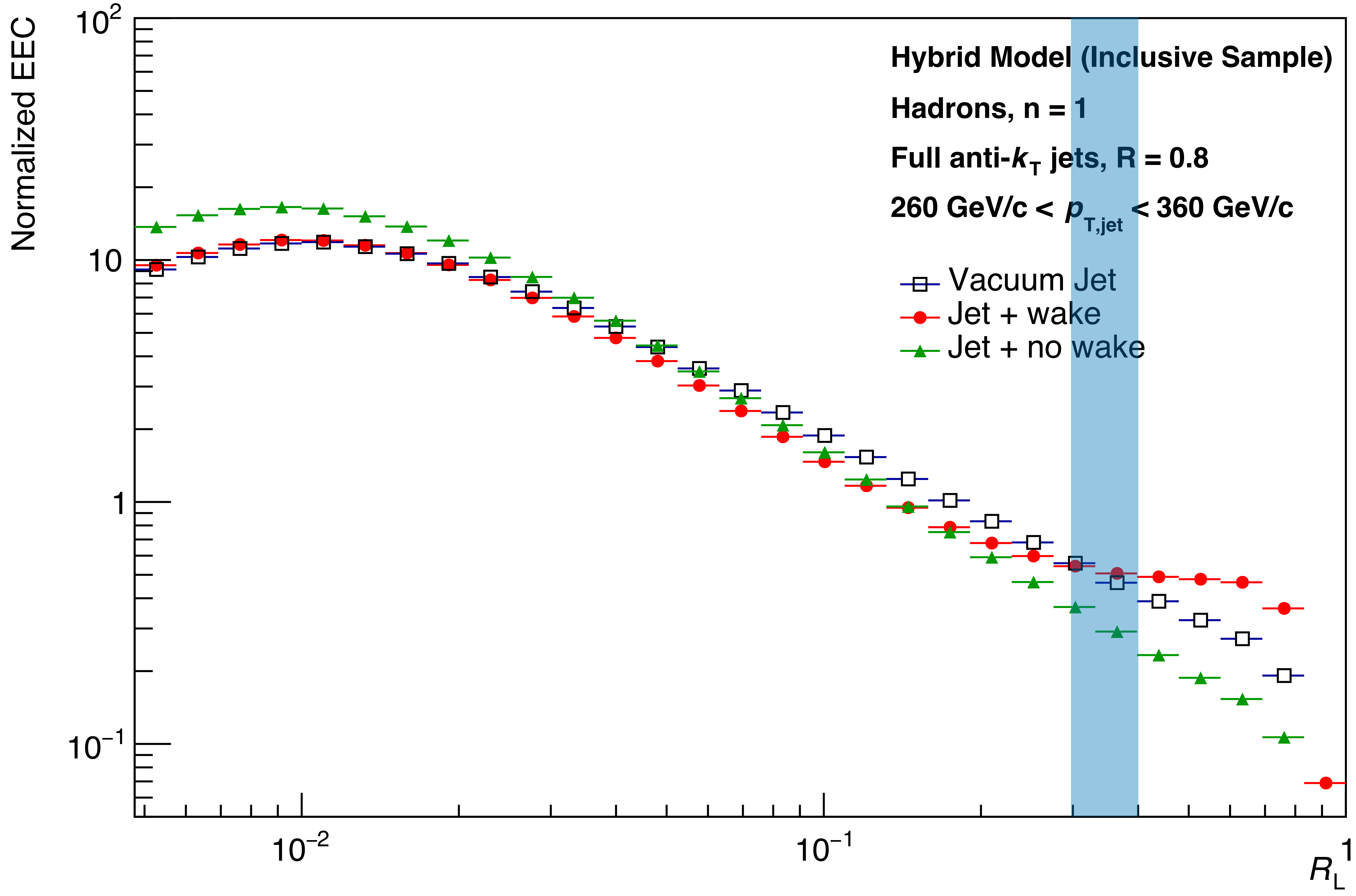
- Wake effects populate regions unfilled, relative effect becomes larger at large R_L

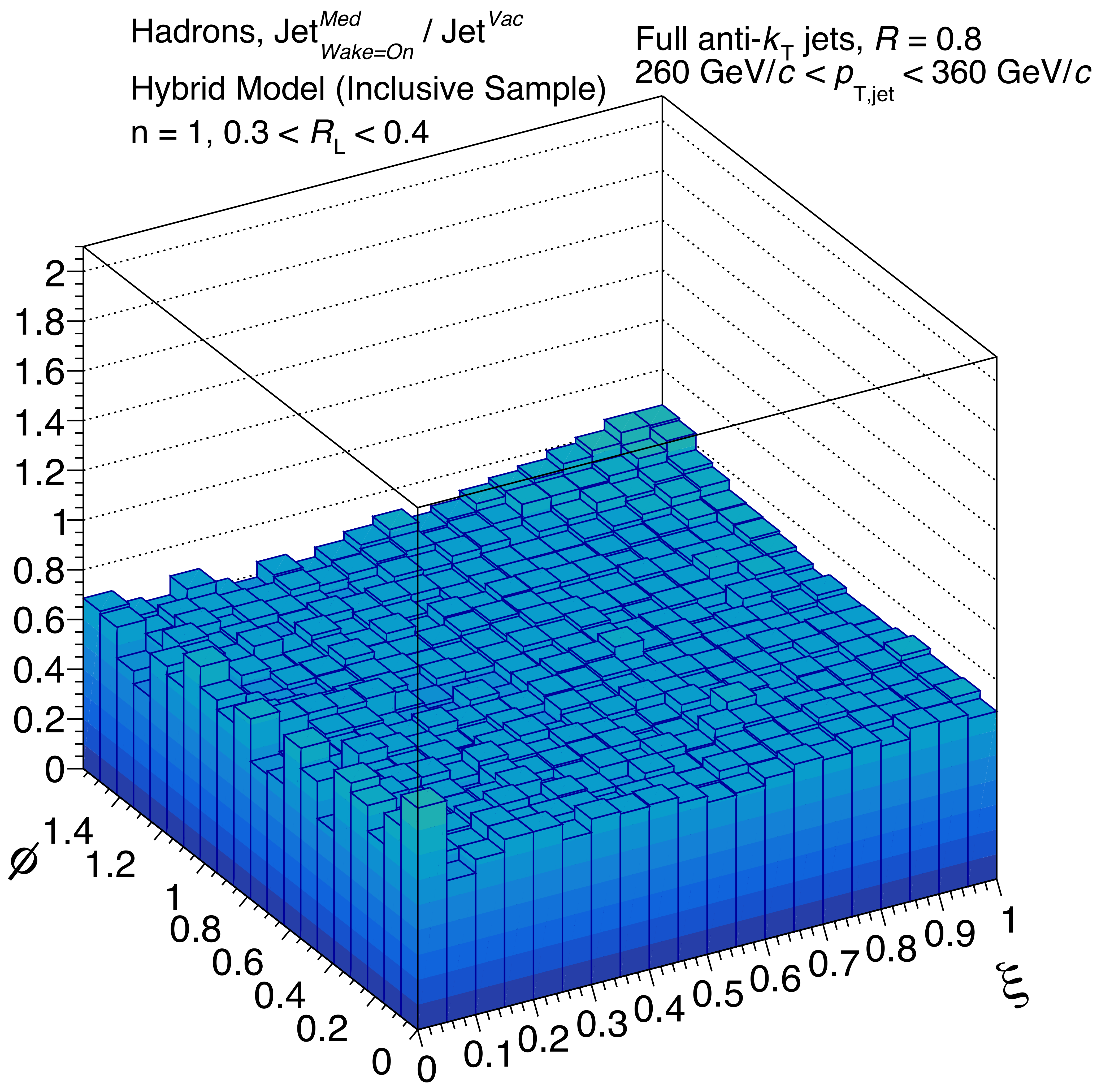
Progression with R_{L} (wake/vacuum)



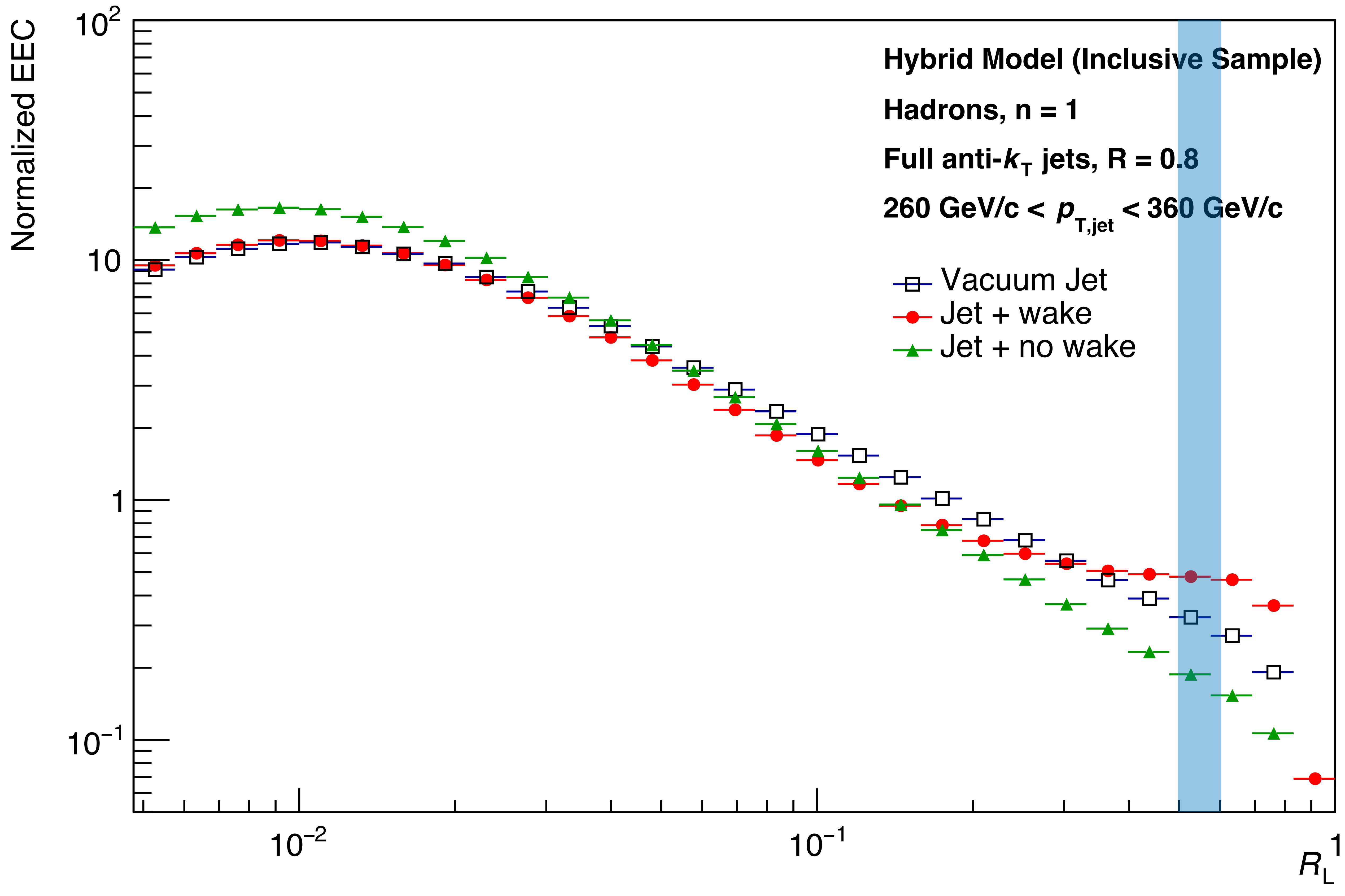


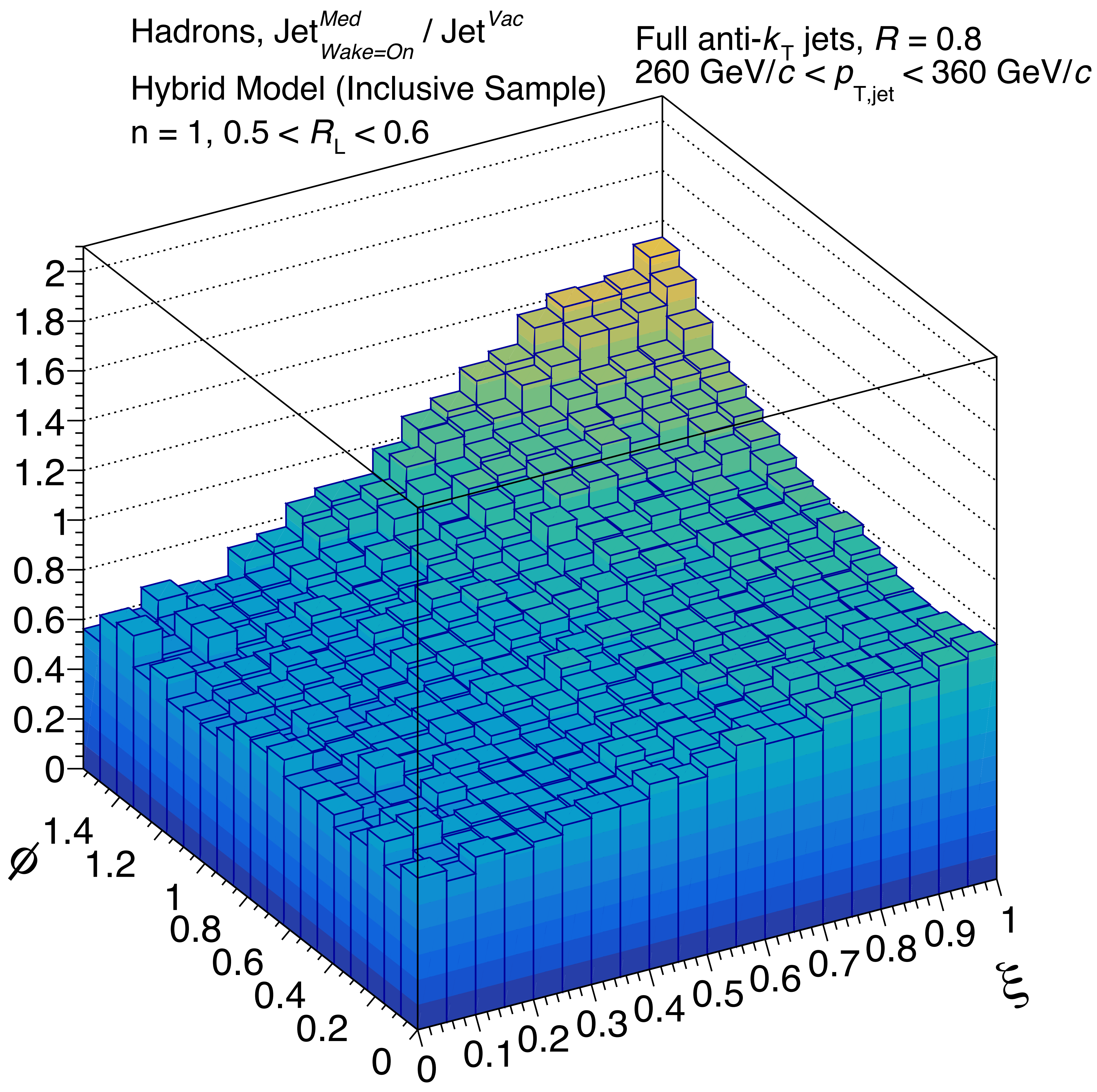
Progression with R_L (wake/vacuum)



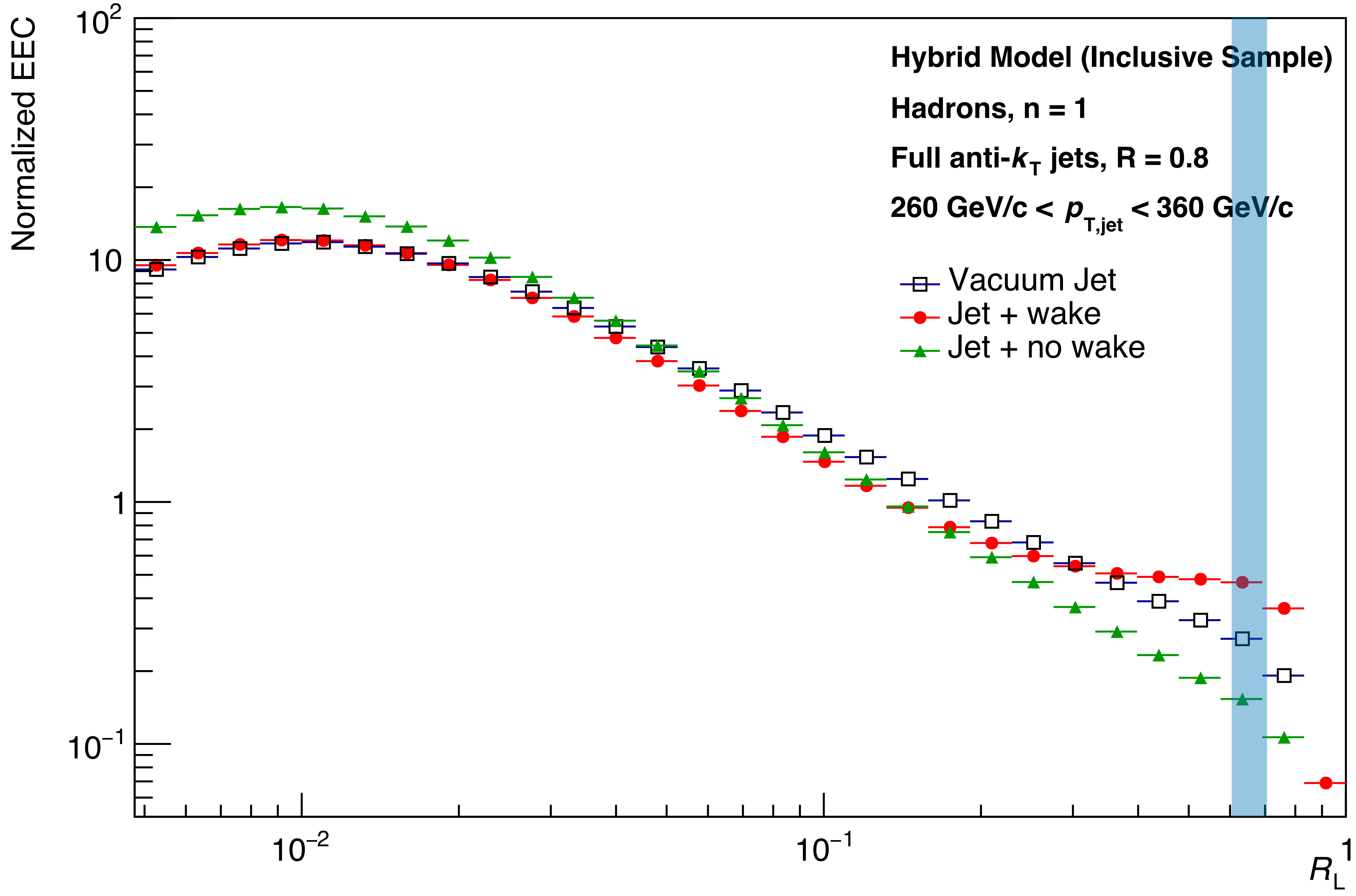


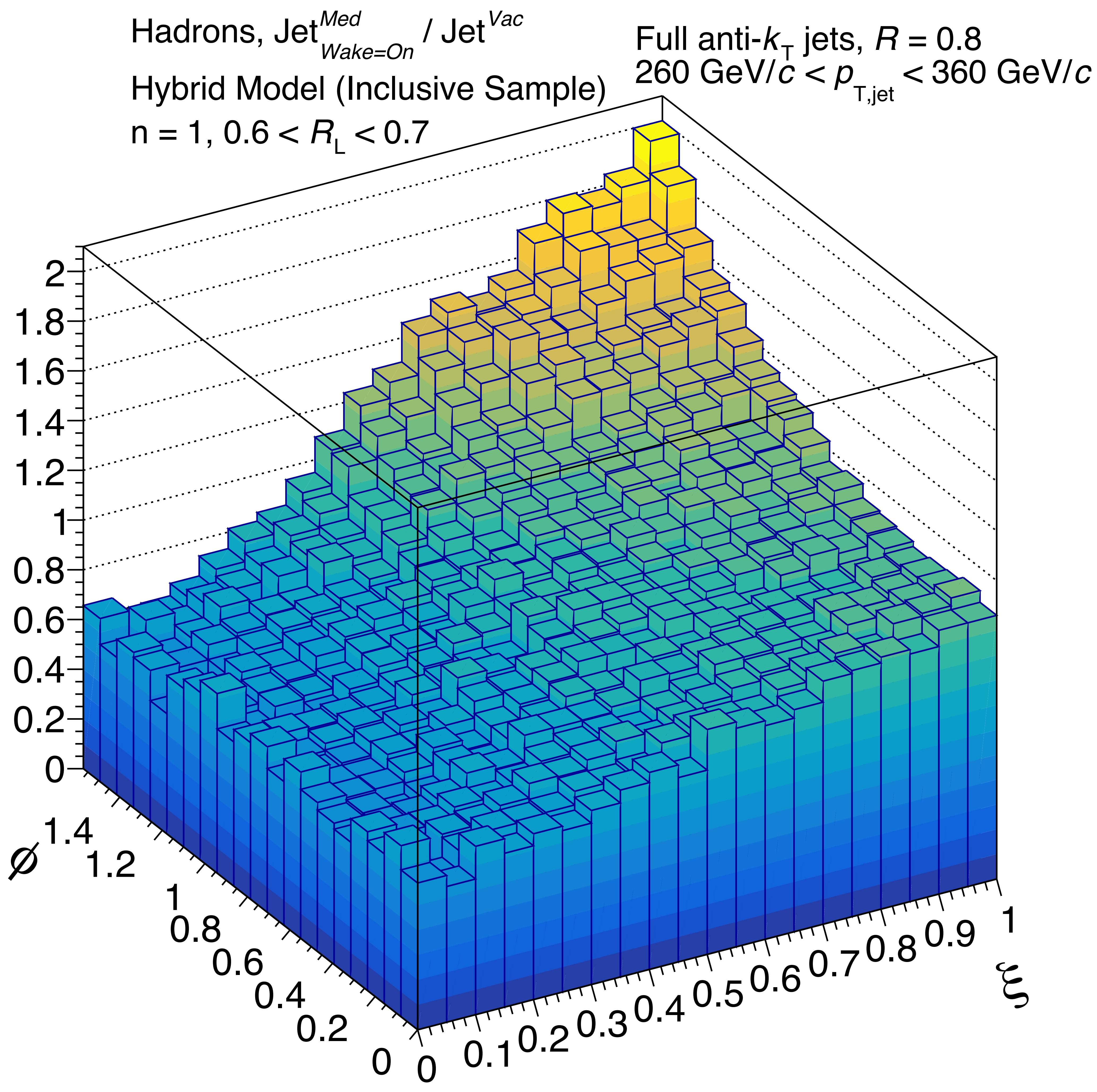
Progression with R_L (wake/vacuum)





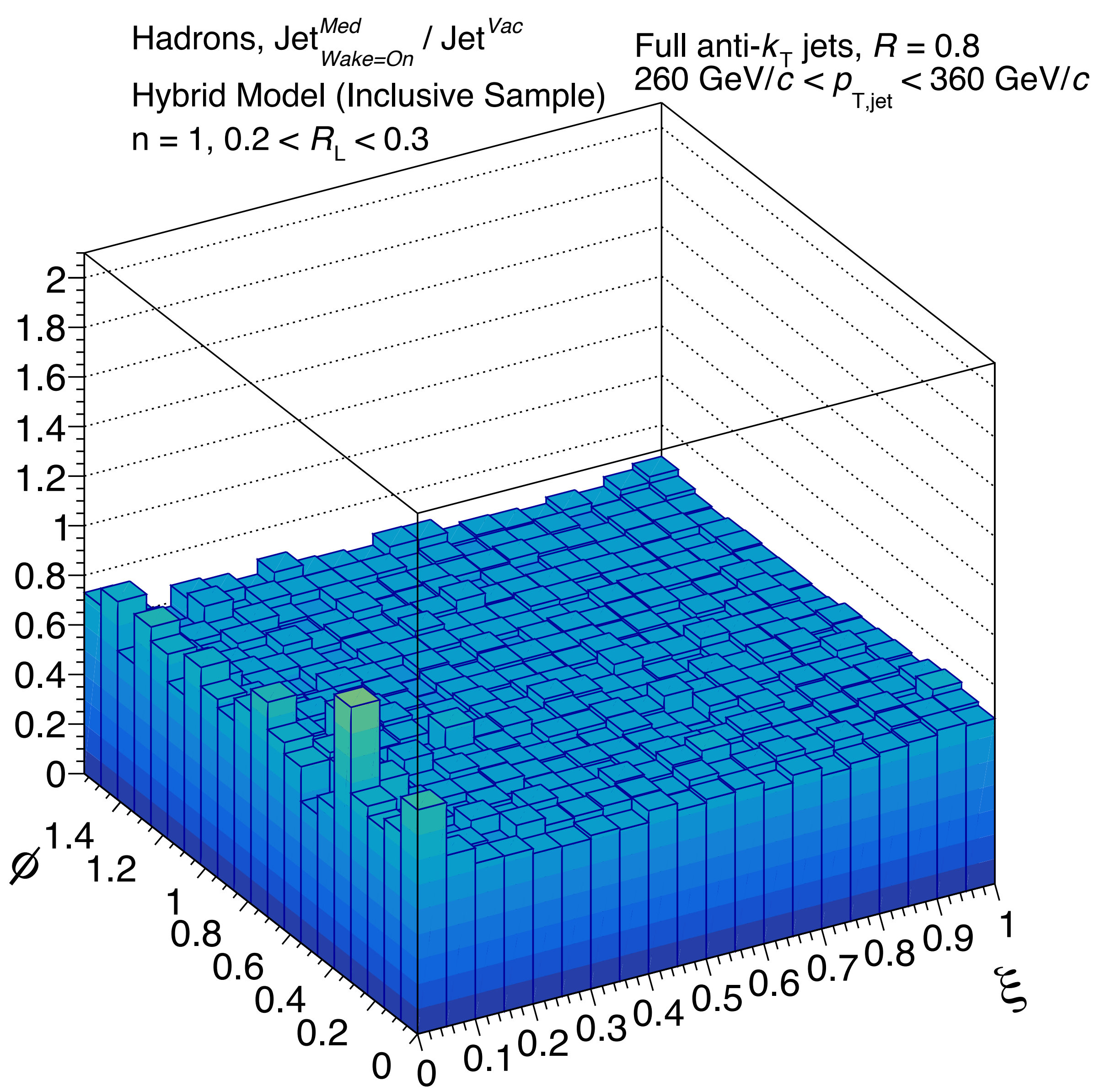
Progression with R_L (wake/vacuum)

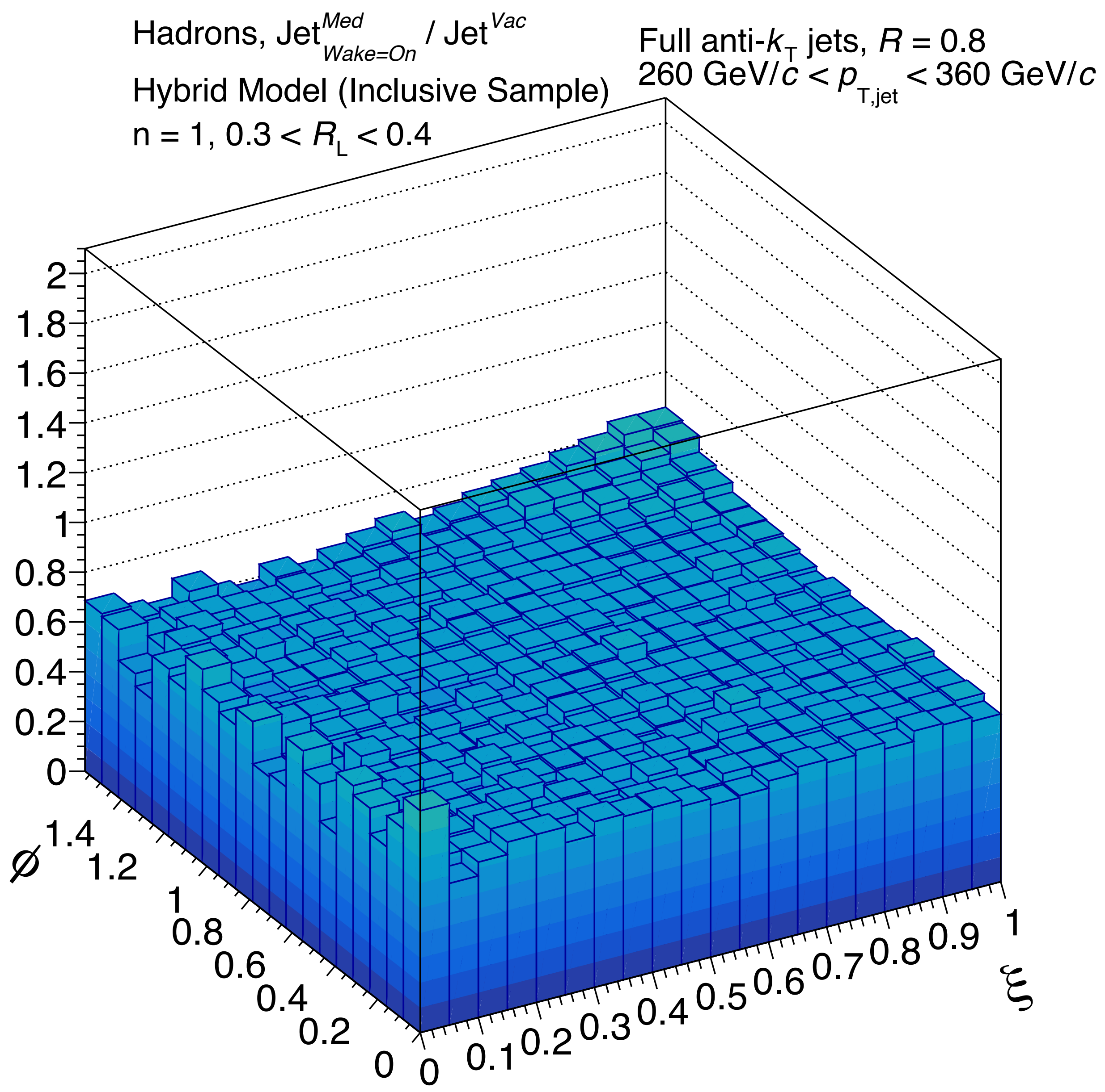


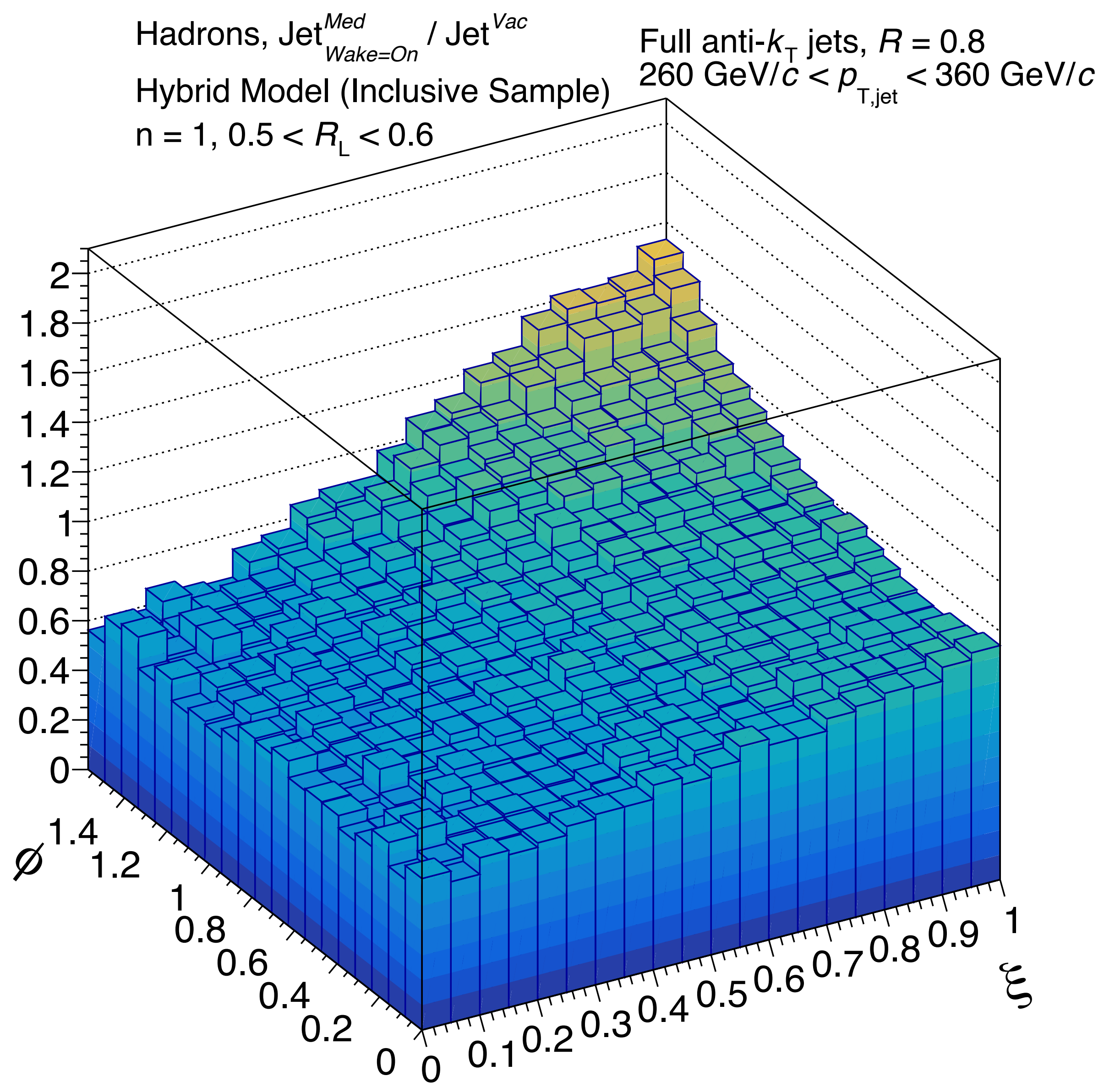


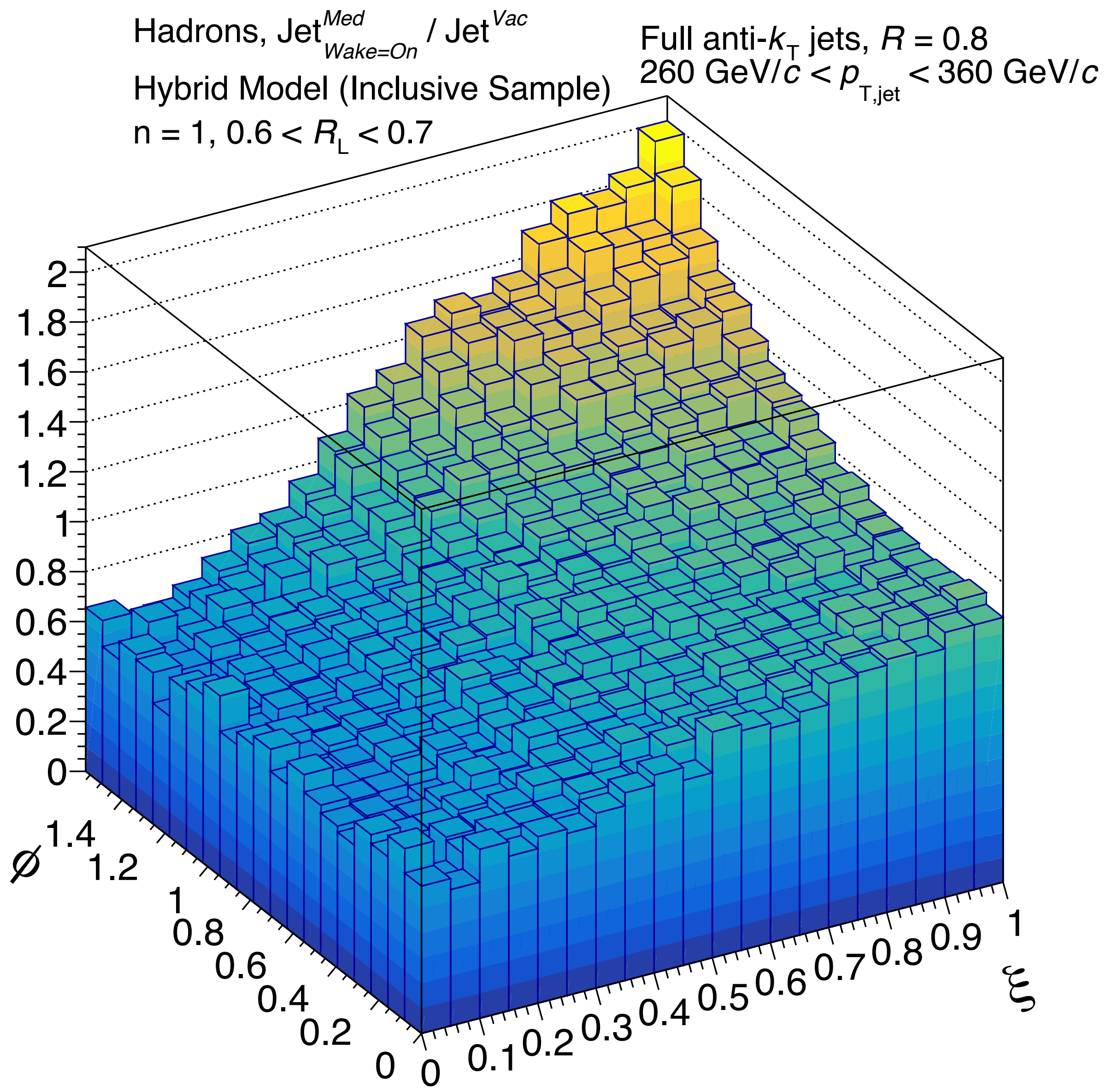
Progression with R_L (wake /vacuum)

$0.2 < R_L < 0.3$ $0.3 < R_L < 0.4$ $0.5 < R_L < 0.6$ $0.6 < R_L < 0.7$









Increasing R_L

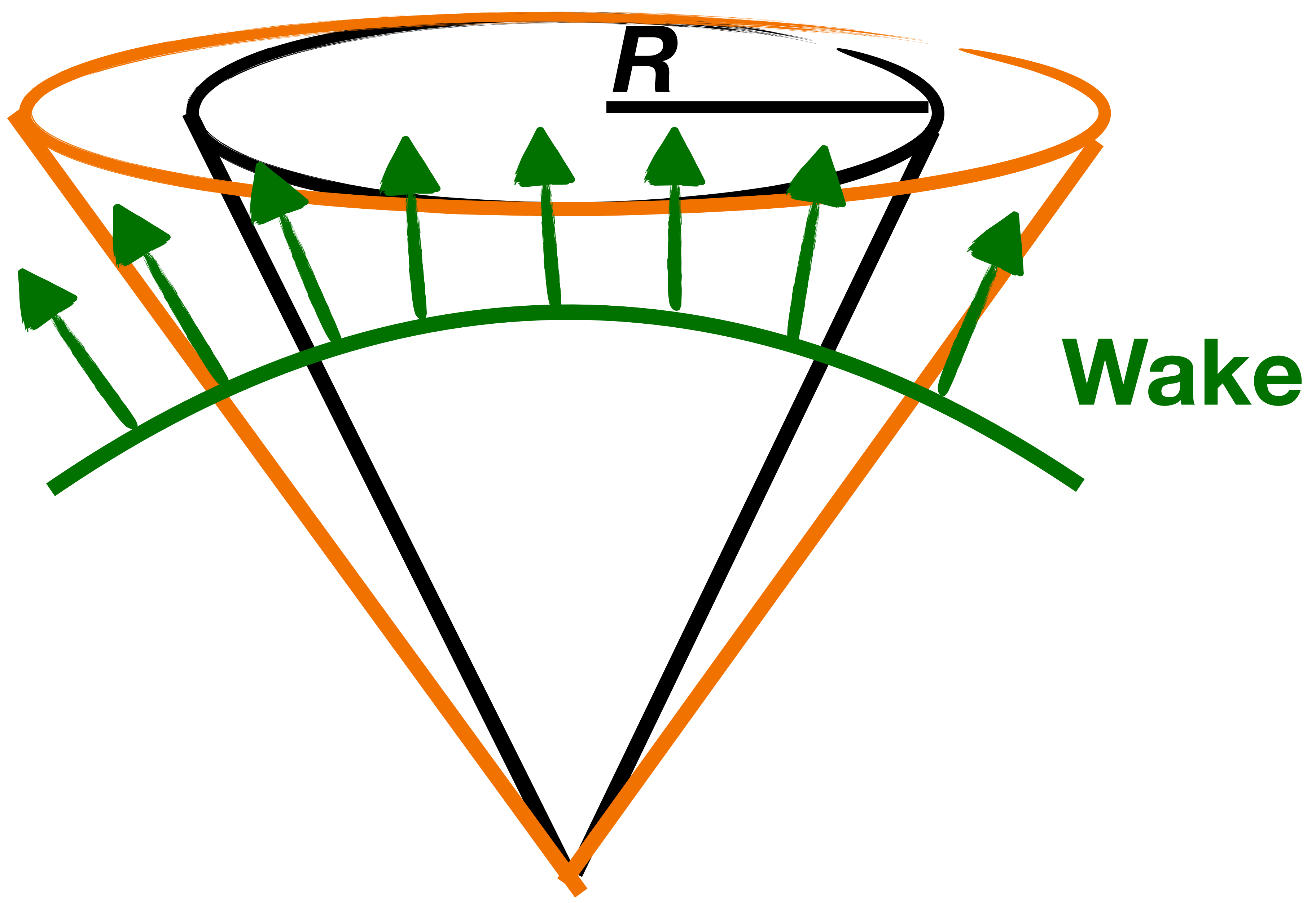
- Clear observable for isolating and exploring the medium response!

Experimental considerations

We presented an idealized case, but experimental measurements will have some differences…

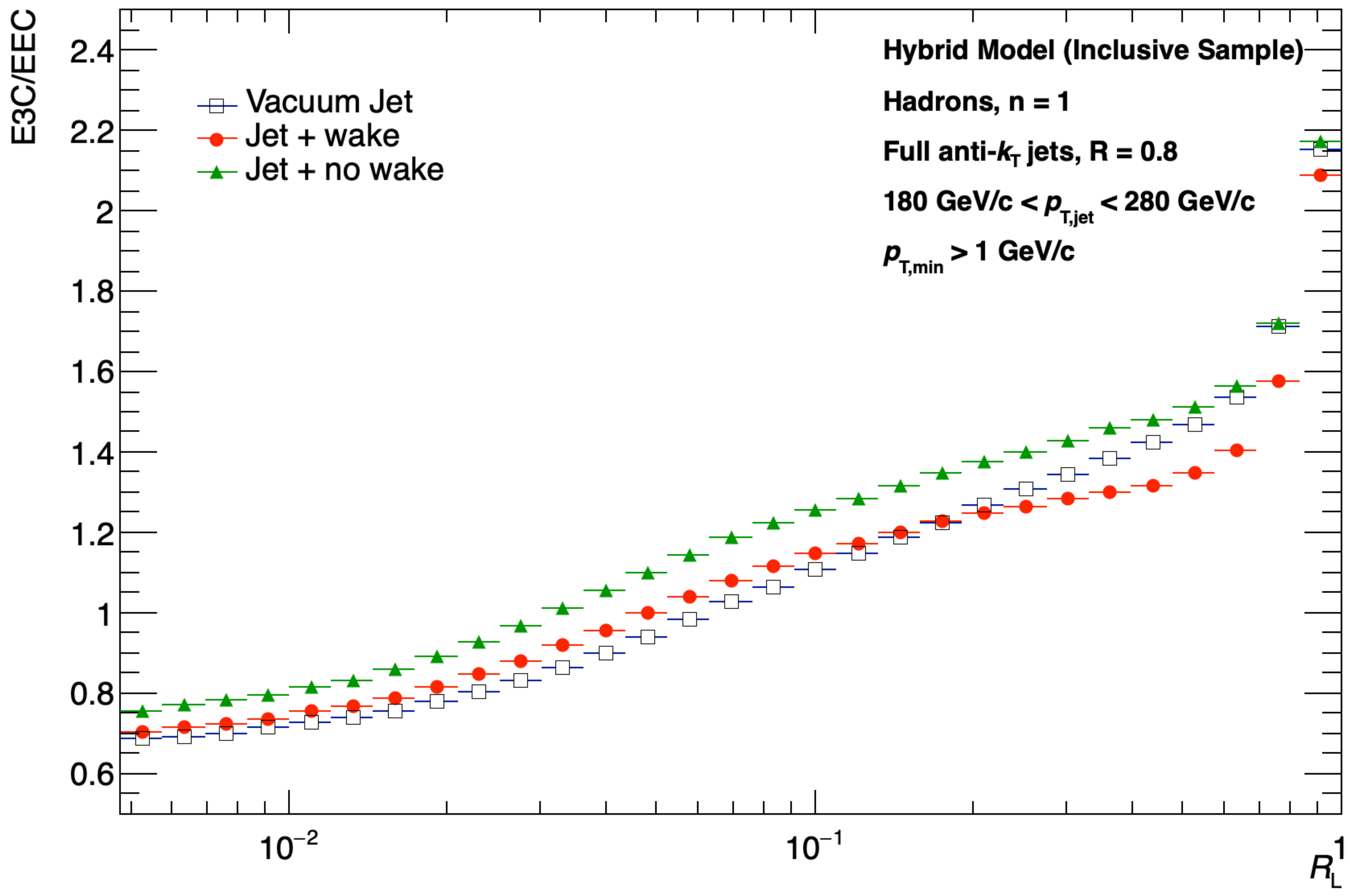
- Wake effects will be largest for large *R* (we showed *R* = 0.8), but this is more difficult to measure experimentally

→ Detector acceptance and large background contributions $\propto R^2$

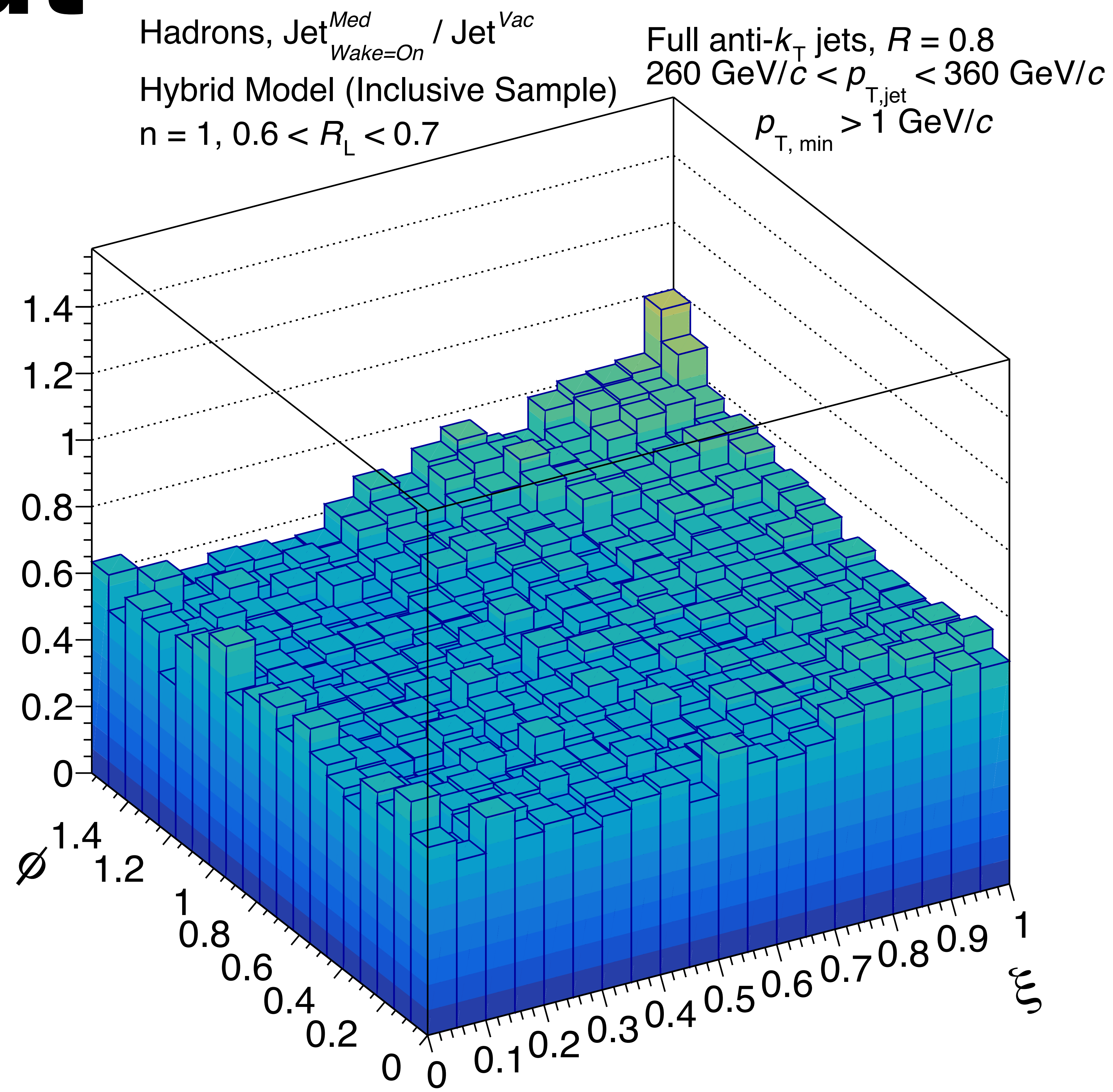


- No cut on the constituent p_{T}, often necessary in experiment due to worsening resolution effects.

Introducing a constituent cut



E3C/EEC Ratio w/ p_T cut



Wake/Vacuum

- Size of signal is reduced with a p_T cut.

Ratio is the ideal observable to use in experiment to maximize signal!

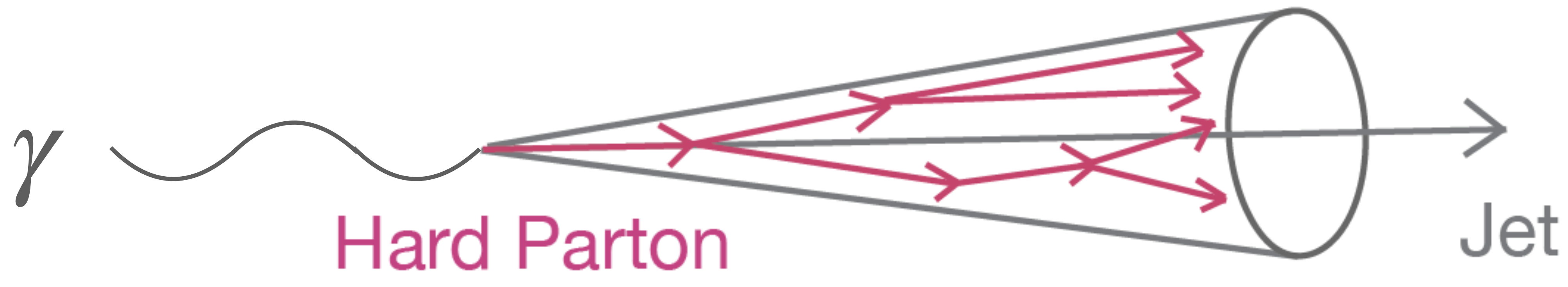
What dials can we turn?

There are a few dials we can turn to maximize experimental signal!

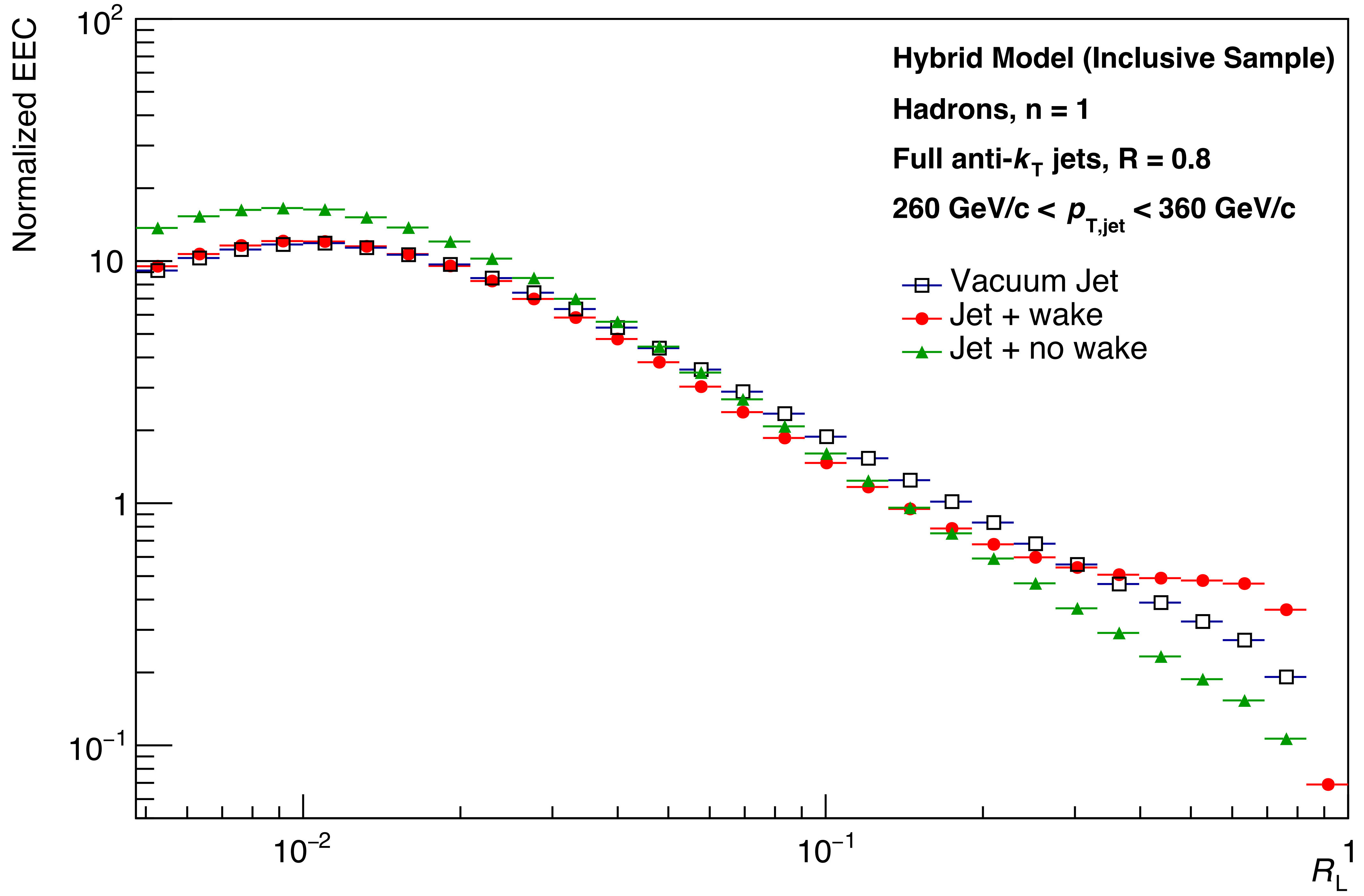
- Can use different energy weighting (ex: n = 0.5) to amplify features!

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

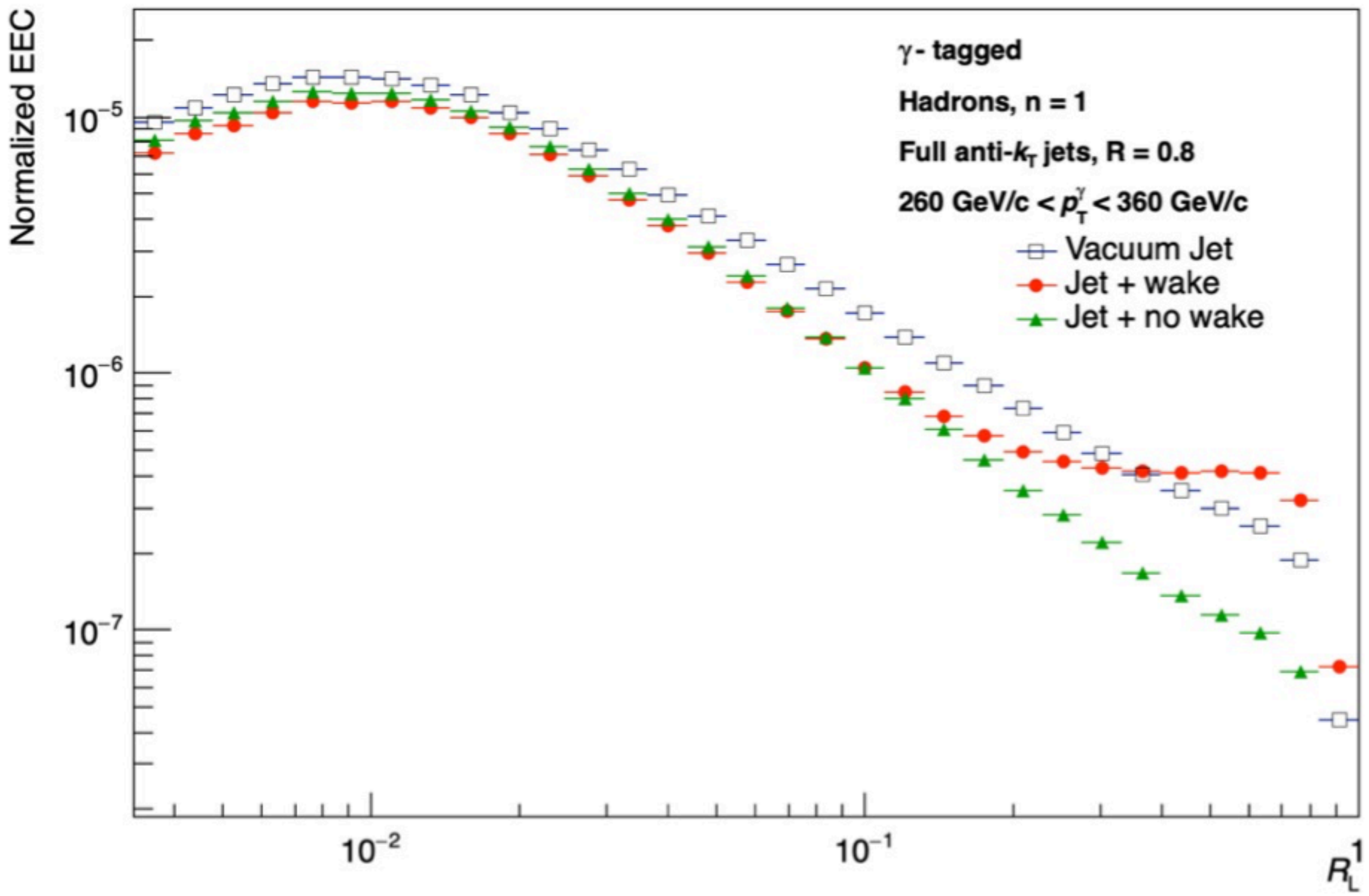
- Use gamma-tagged jets!



γ-tagged 2 point correlors



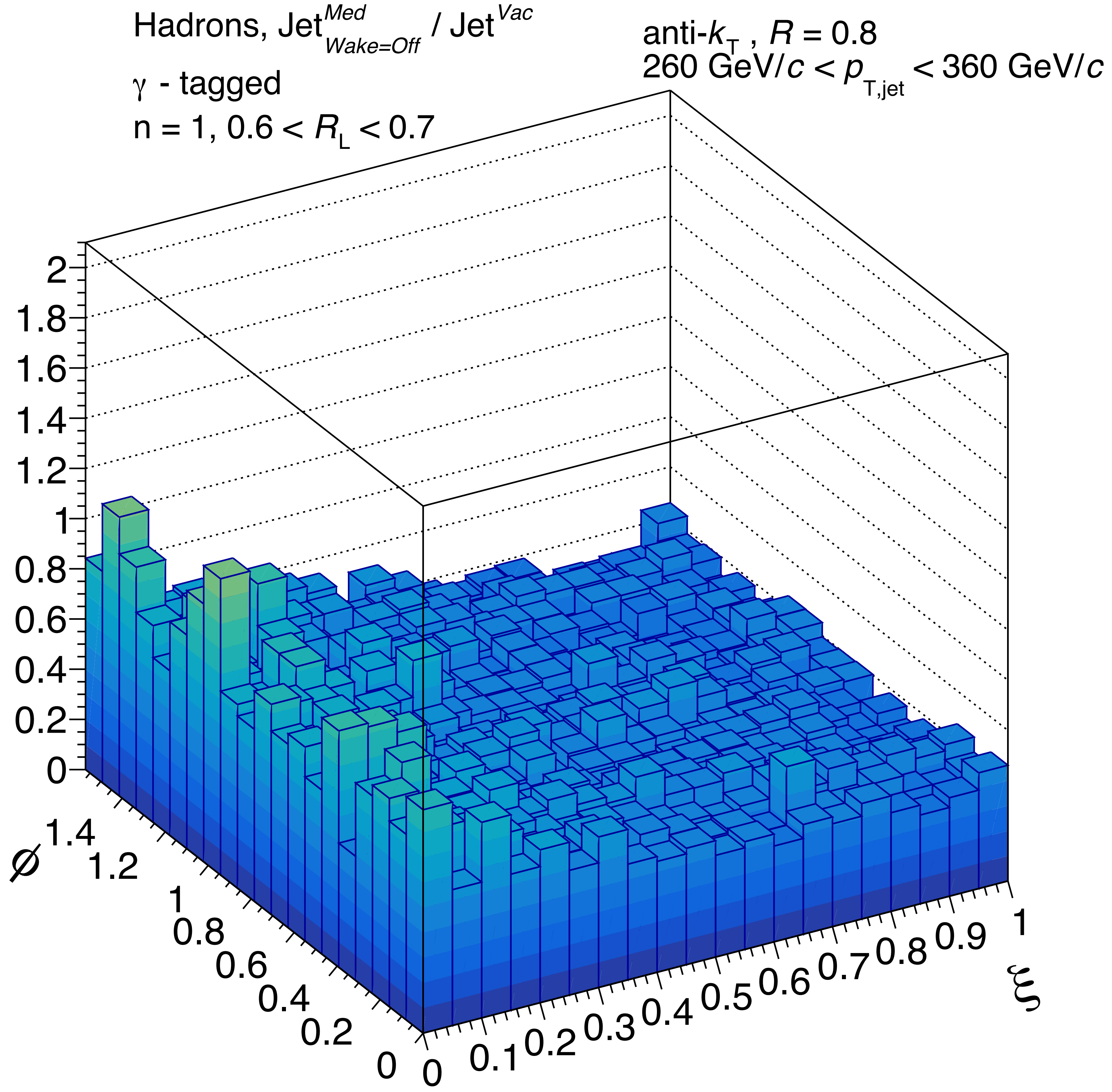
Inclusive Jet EEC



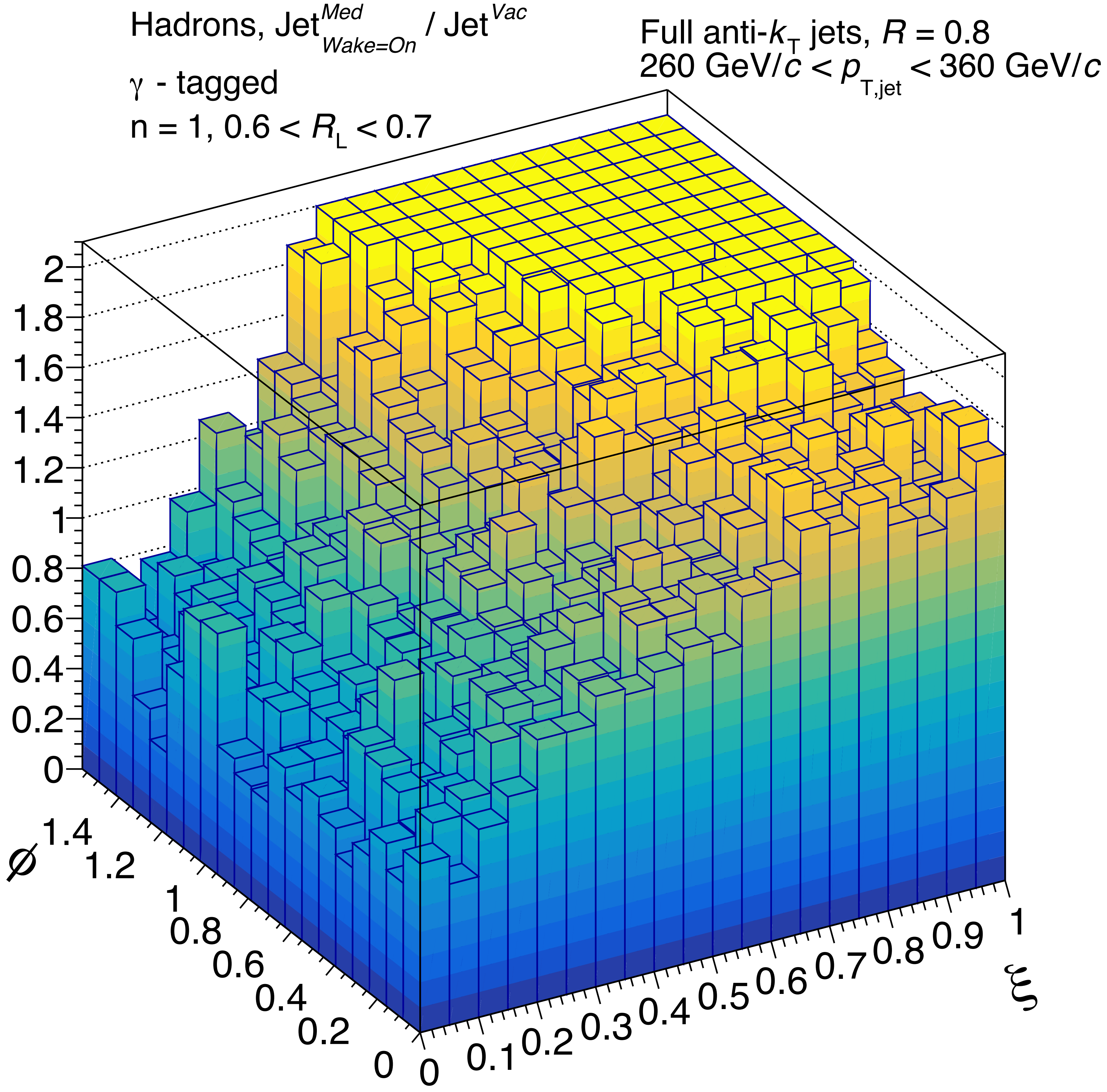
γ-tagged jet EEC

γ-tagged jets dramatically increases difference between wake + vacuum!

γ-tagged shape



No wake / vacuum

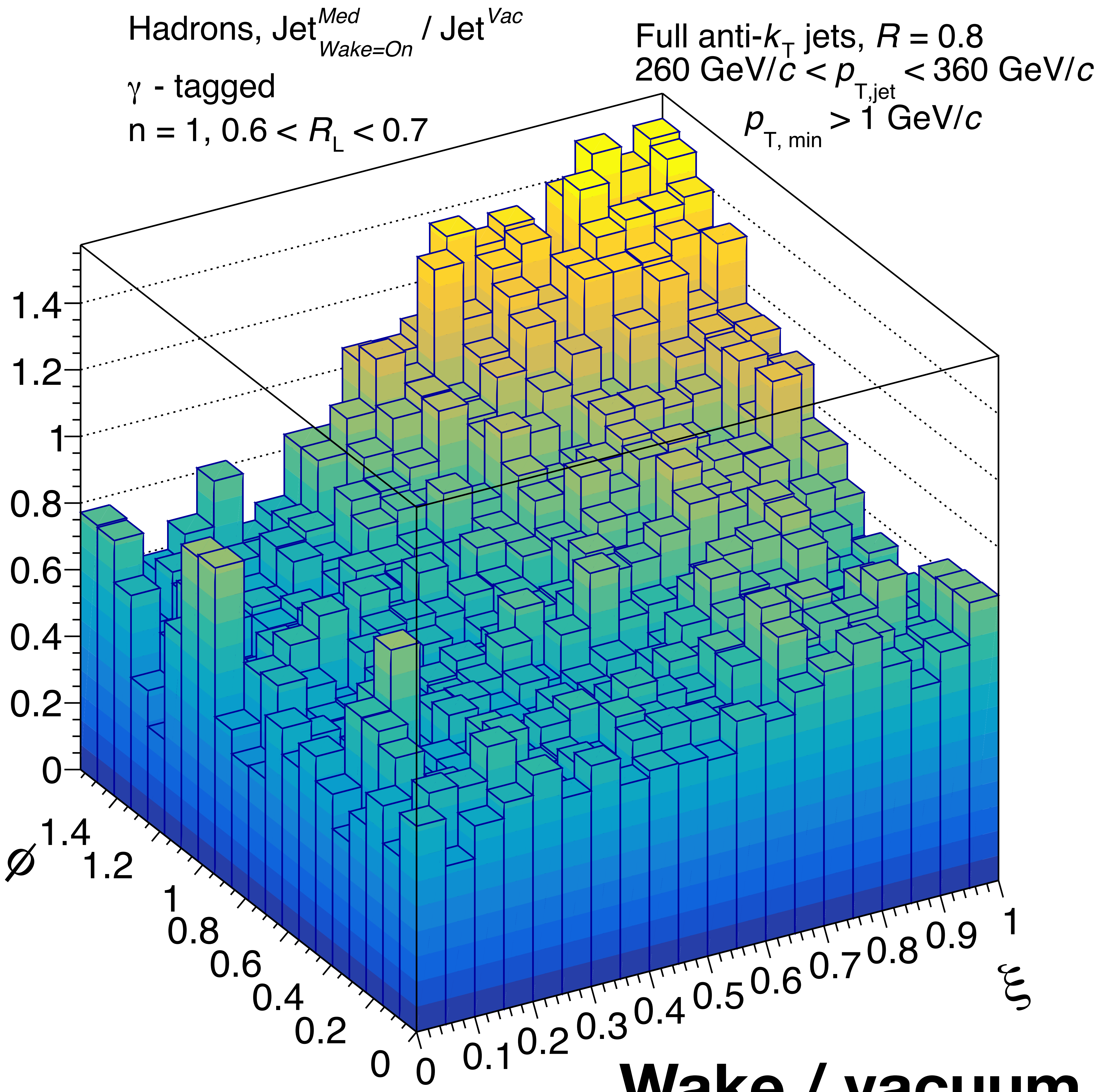


Wake / vacuum

γ-tagged jets dramatically increases difference between wake + vacuum!

What if we added in the track p_T cut?

Shape of γ-jet w/ track pT cut

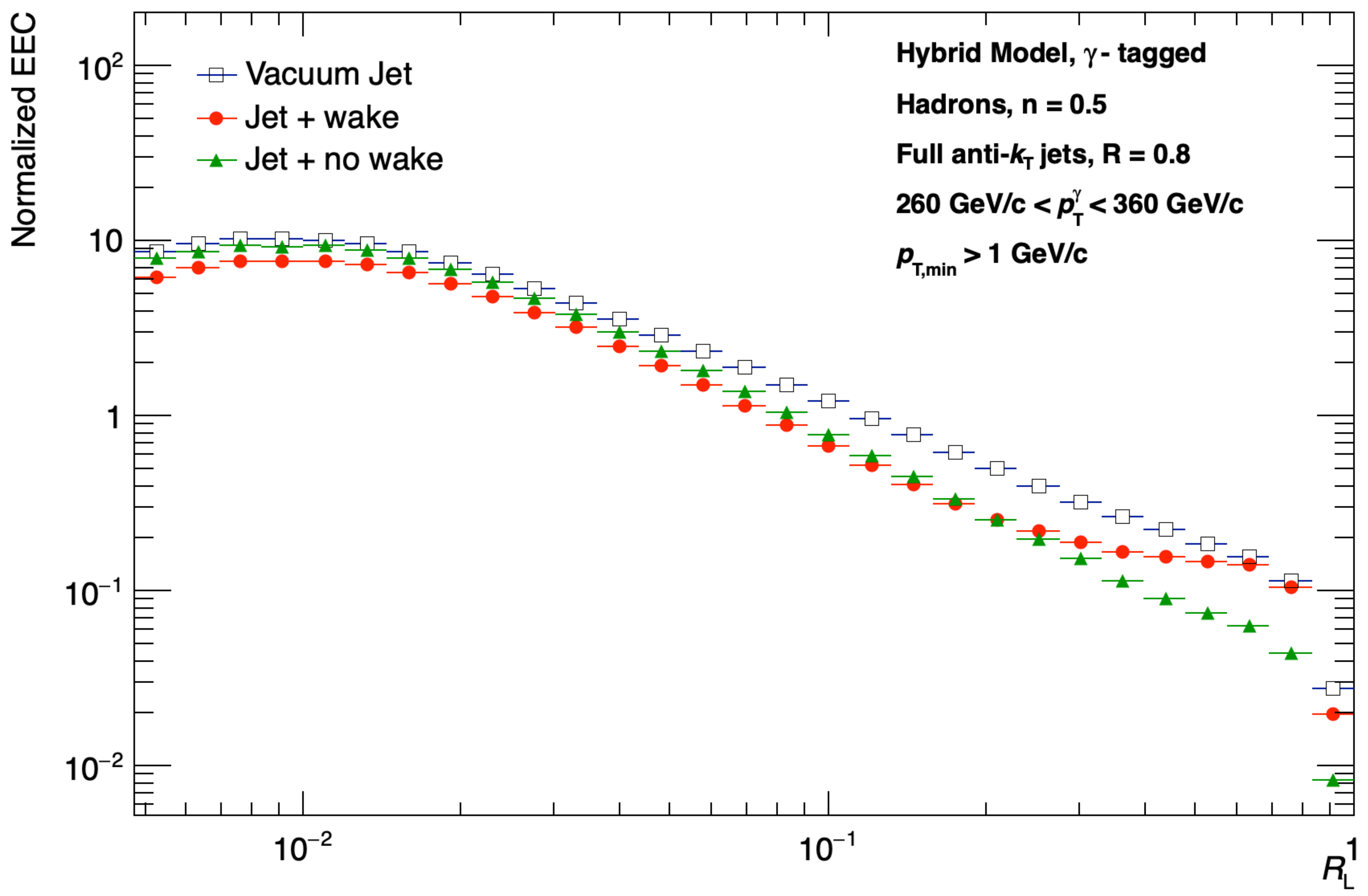


Wake / vacuum

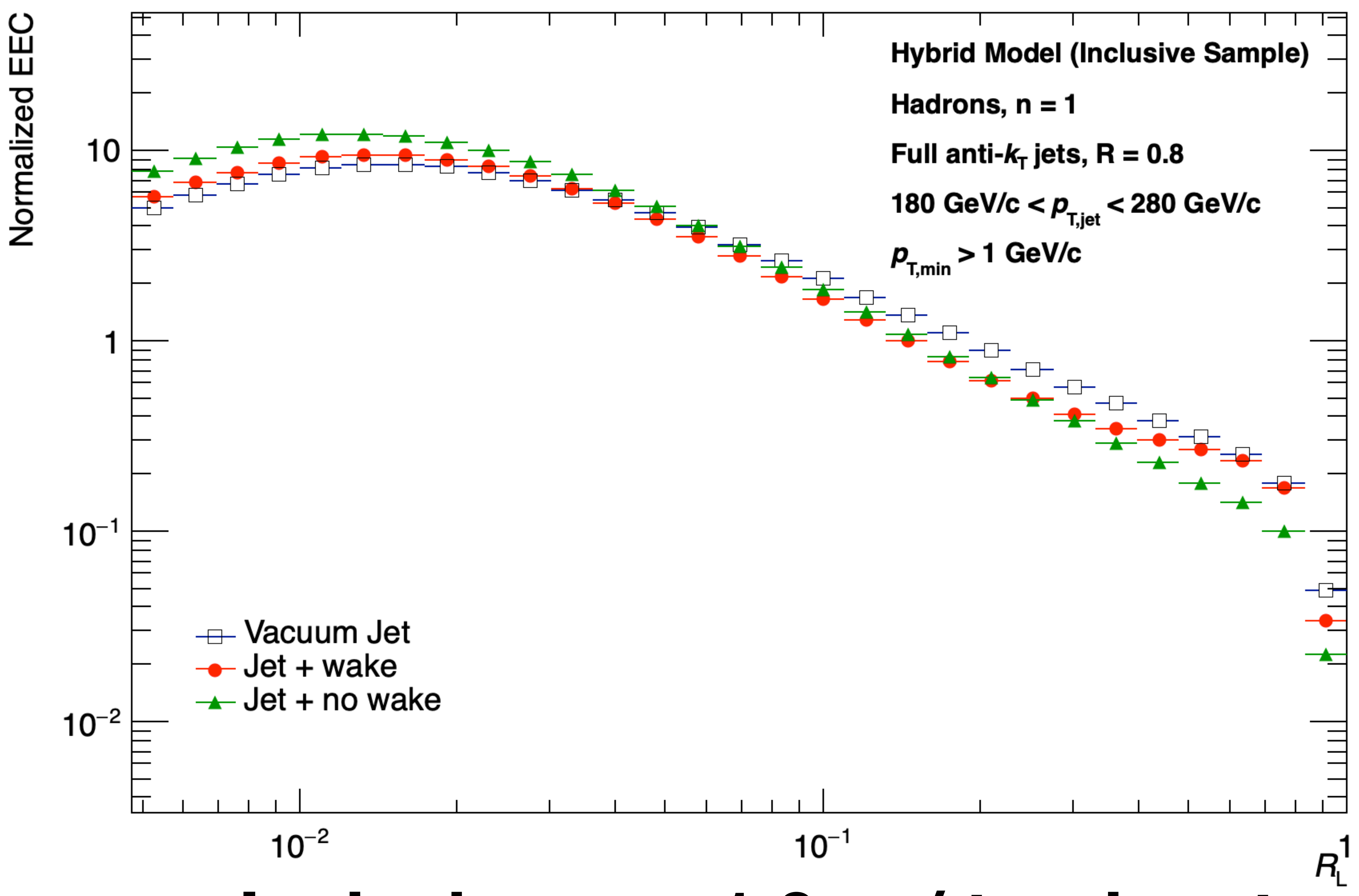
With a track p_T cut - still large differences with the vacuum case!

What else can we do?

Changing the energy weighting



γ-tagged, n = 0.5, w/ track cut

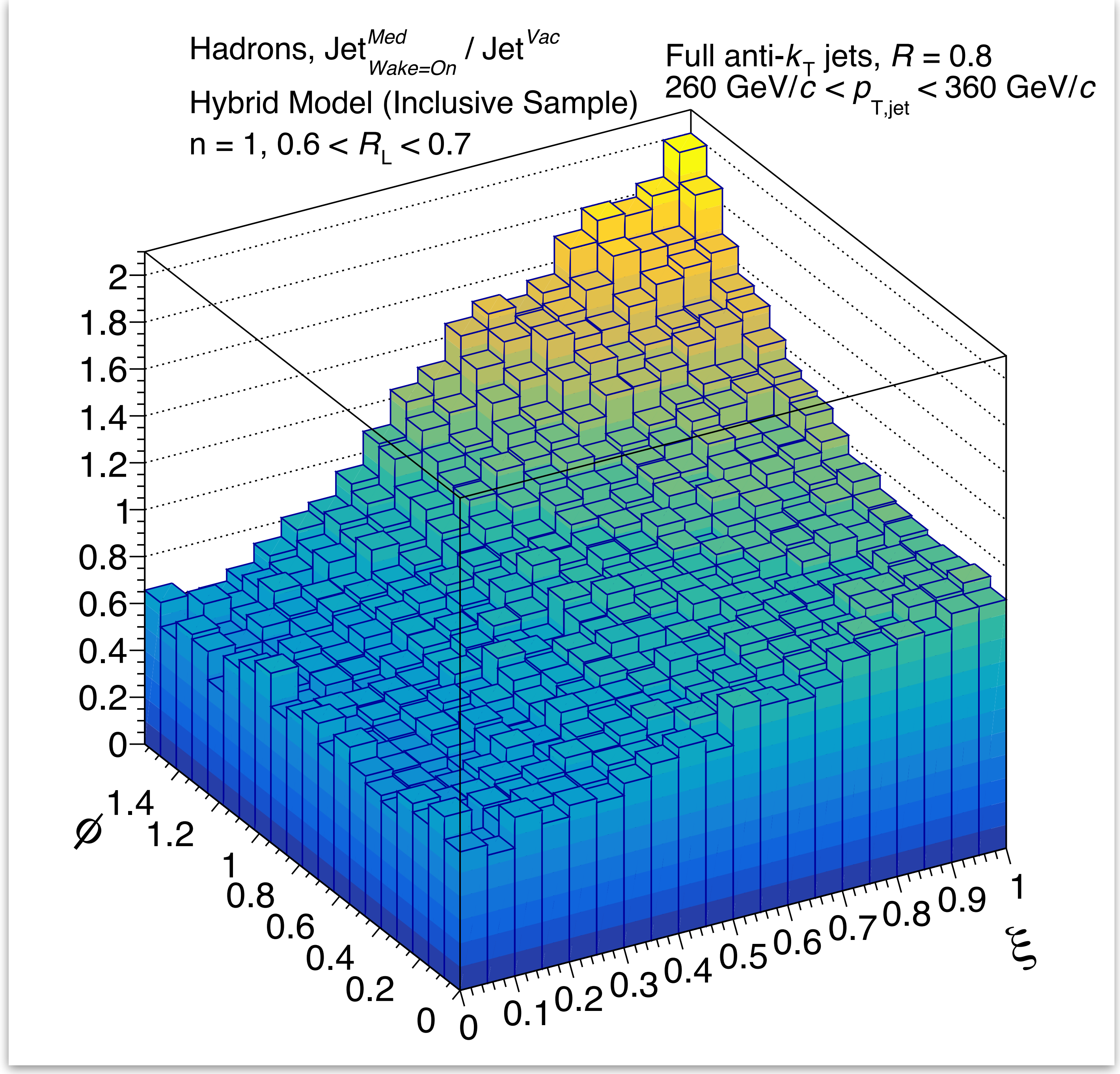


Inclusive, n = 1.0, w/ track cut

Energy weight can increase size of the wake signal!

Summary & Conclusions

- We have presented the first exploration of the shape dependence of full higher point energy correlators in heavy-ion collisions!
- Ideal way to study the shape of the medium response!
- We did this using the hybrid model with a hydrodynamical wake as the medium response effect.
- When comparing in-medium distributions to vacuum, we see a large and clear wake signal!

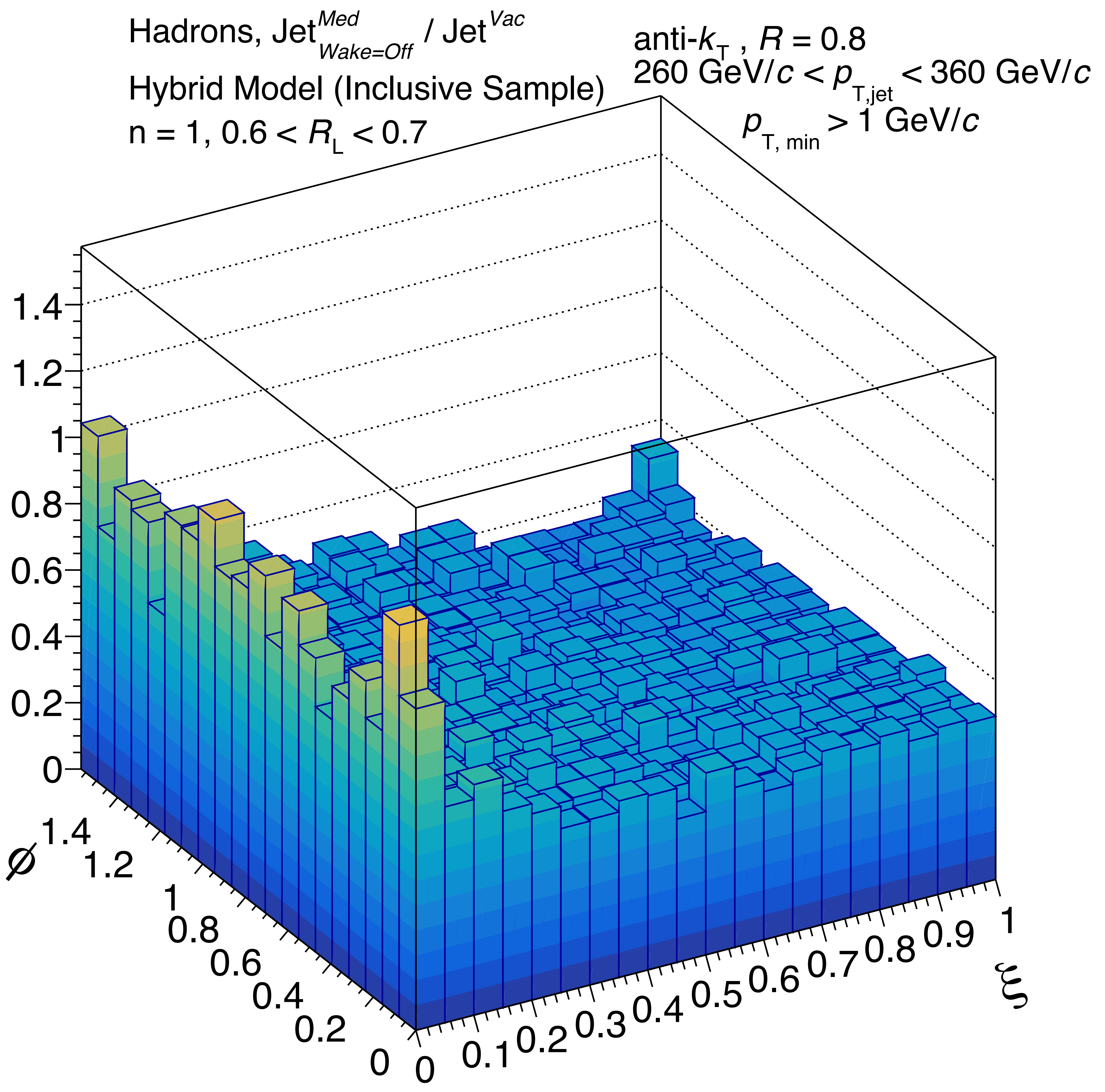


This is a new promising tool to expose and characterize the medium response!

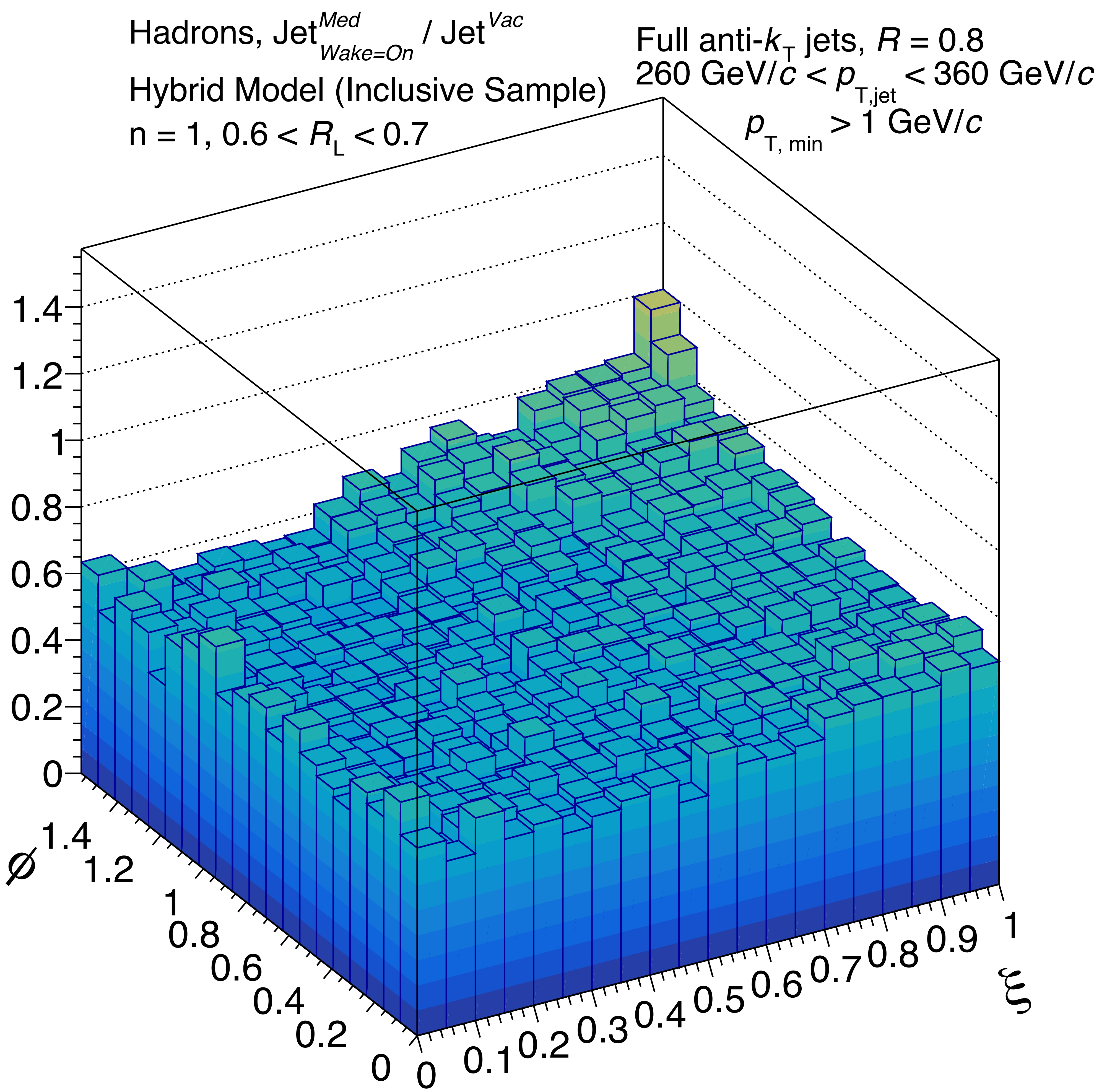
Let's go looking for this large signal in data/models!

Backup

Shape of inclusive sample w/ track pT cut

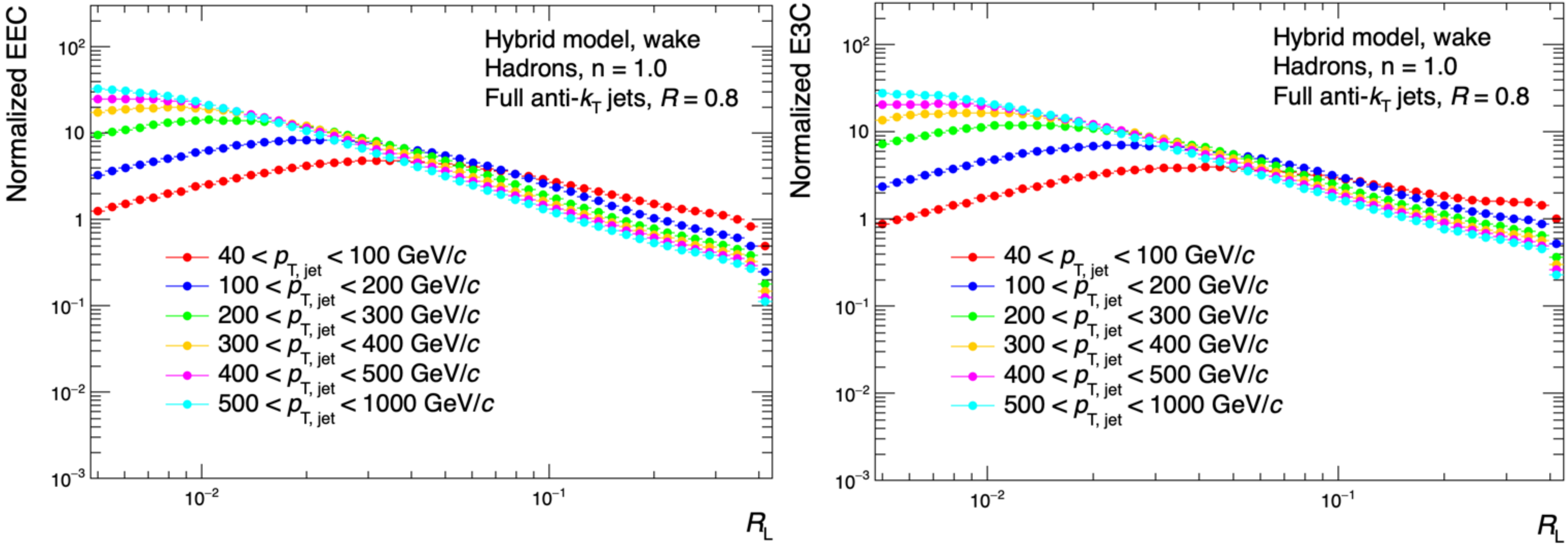


No wake / vacuum



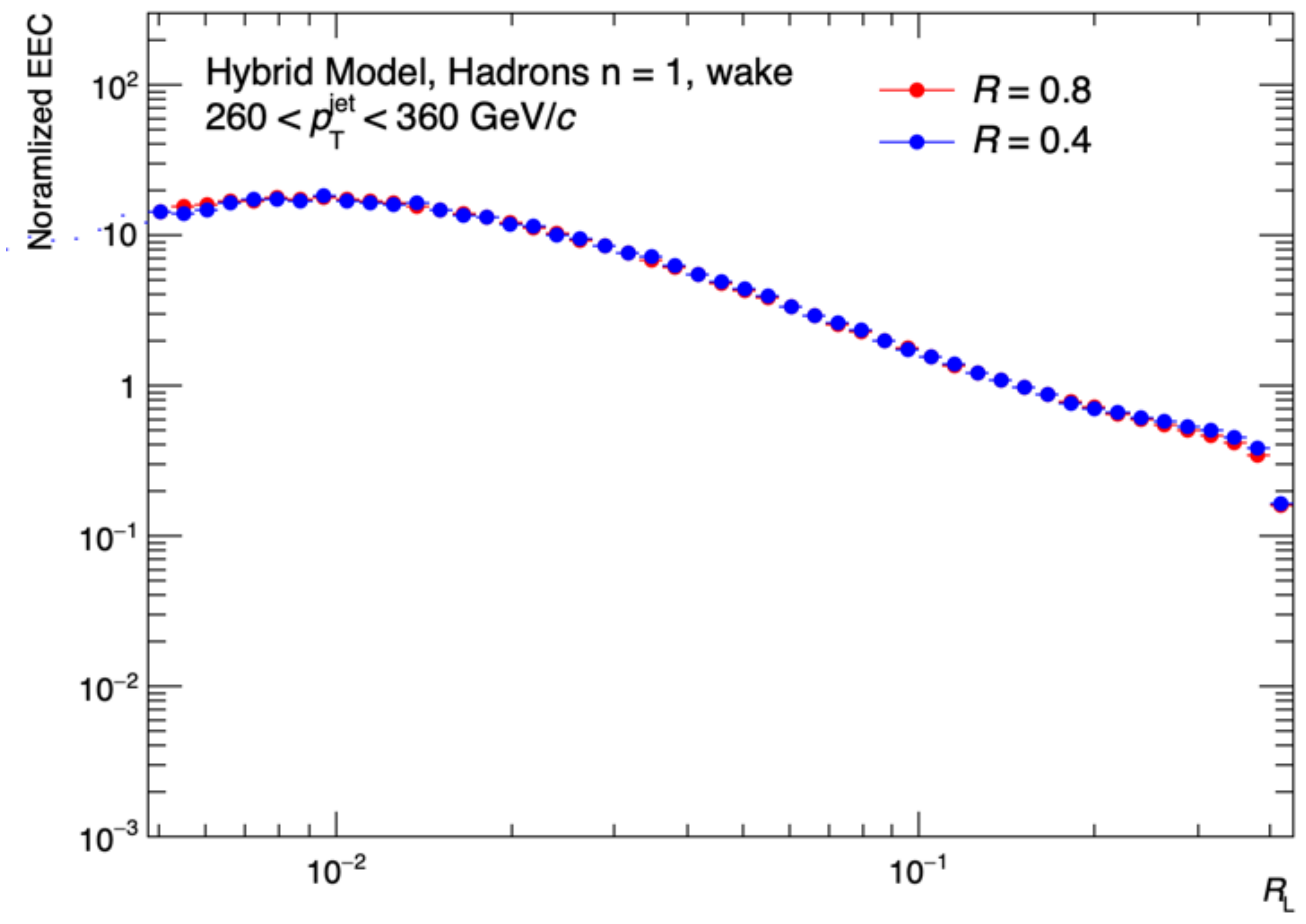
Wake / vacuum

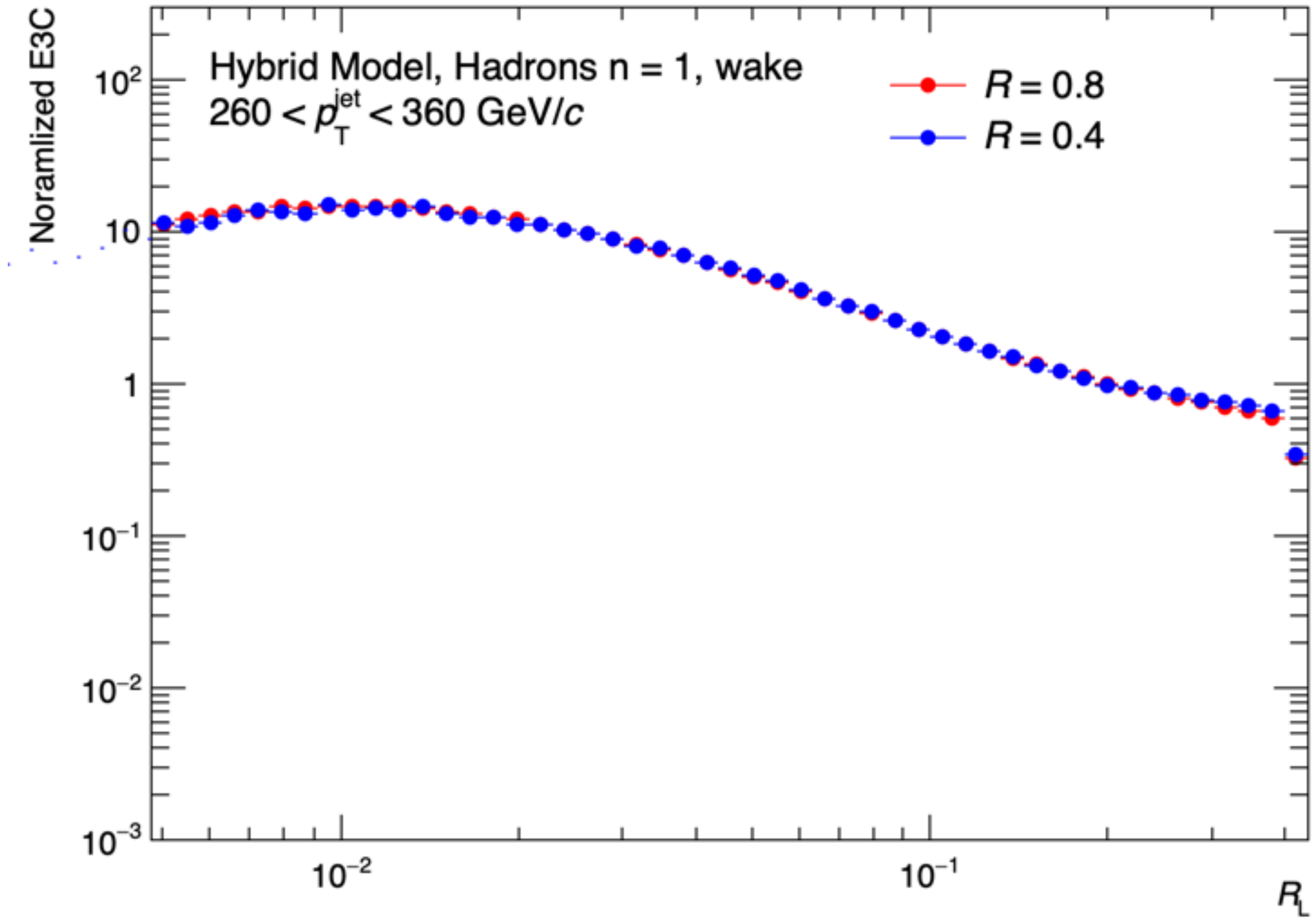
Prominence of the wake with p_T



Wake signal is more prominent at low p_T!

Prominence of the wake with *R*





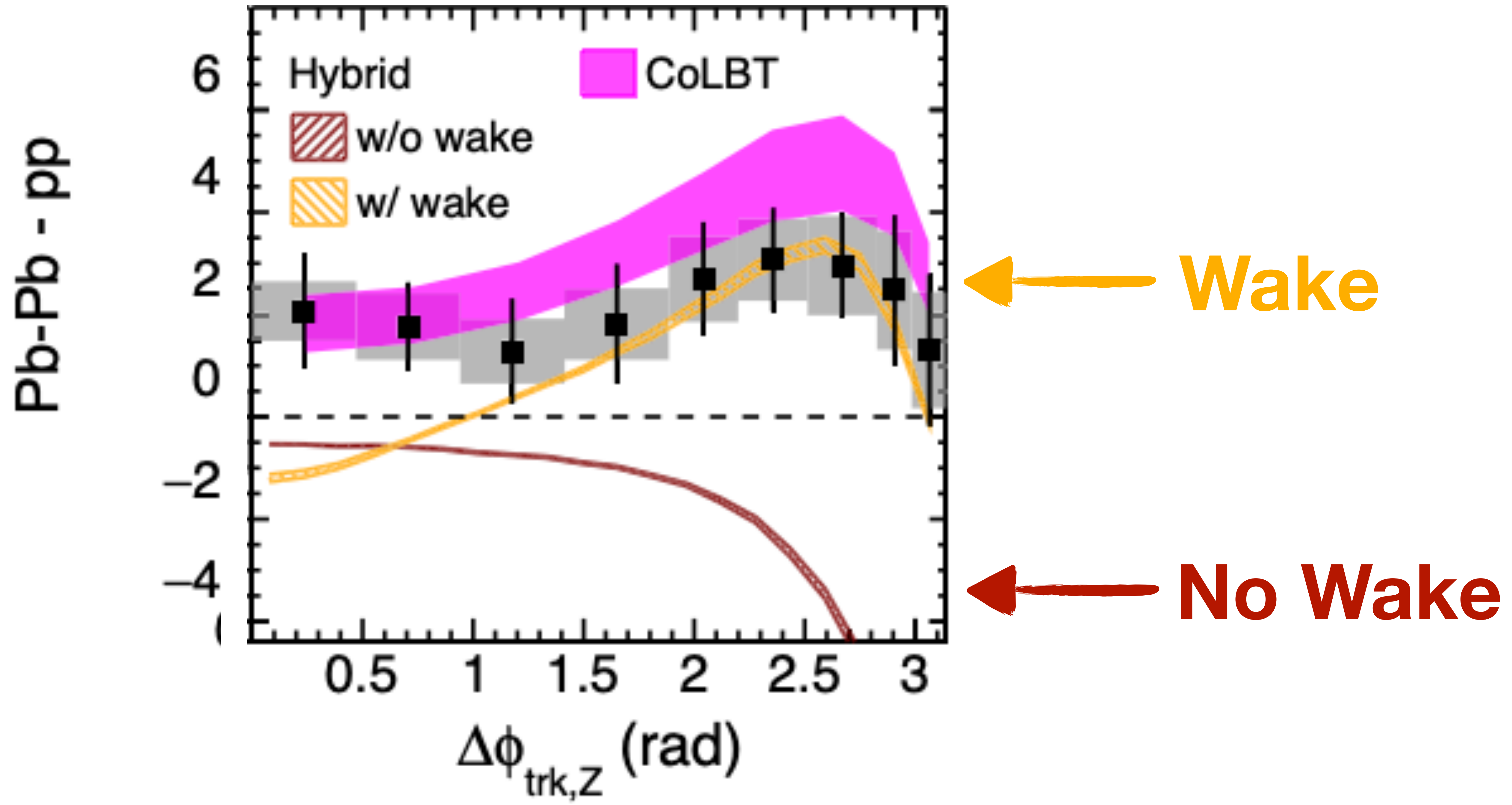
Very small differences with R!

Search for the medium response

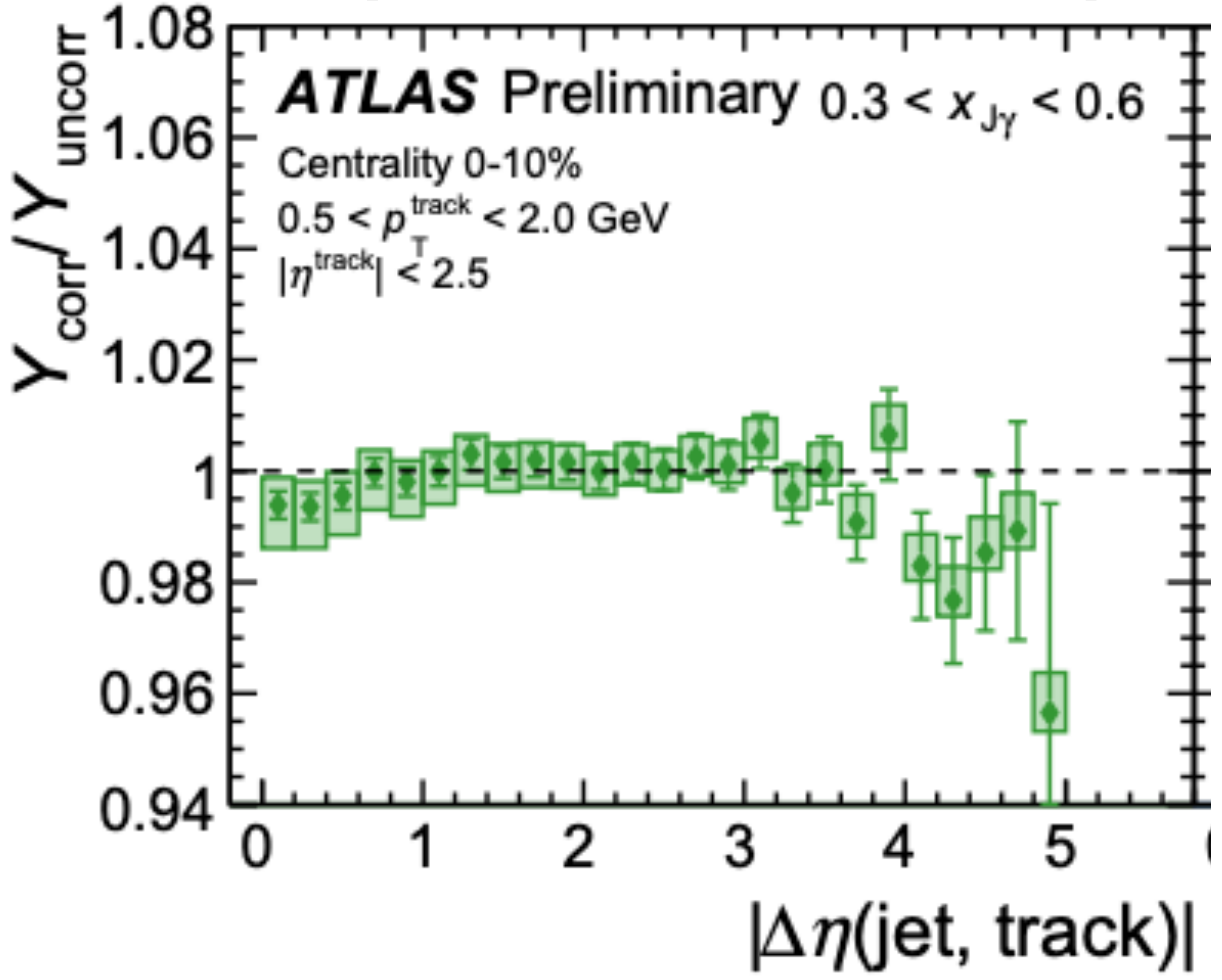
Difficult to experimentally separate

- Modification of parton shower (broadening)
- Medium response effects (even harder to separate wake vs. recoils)

[CMS, PRL 128 122301 (2022)]



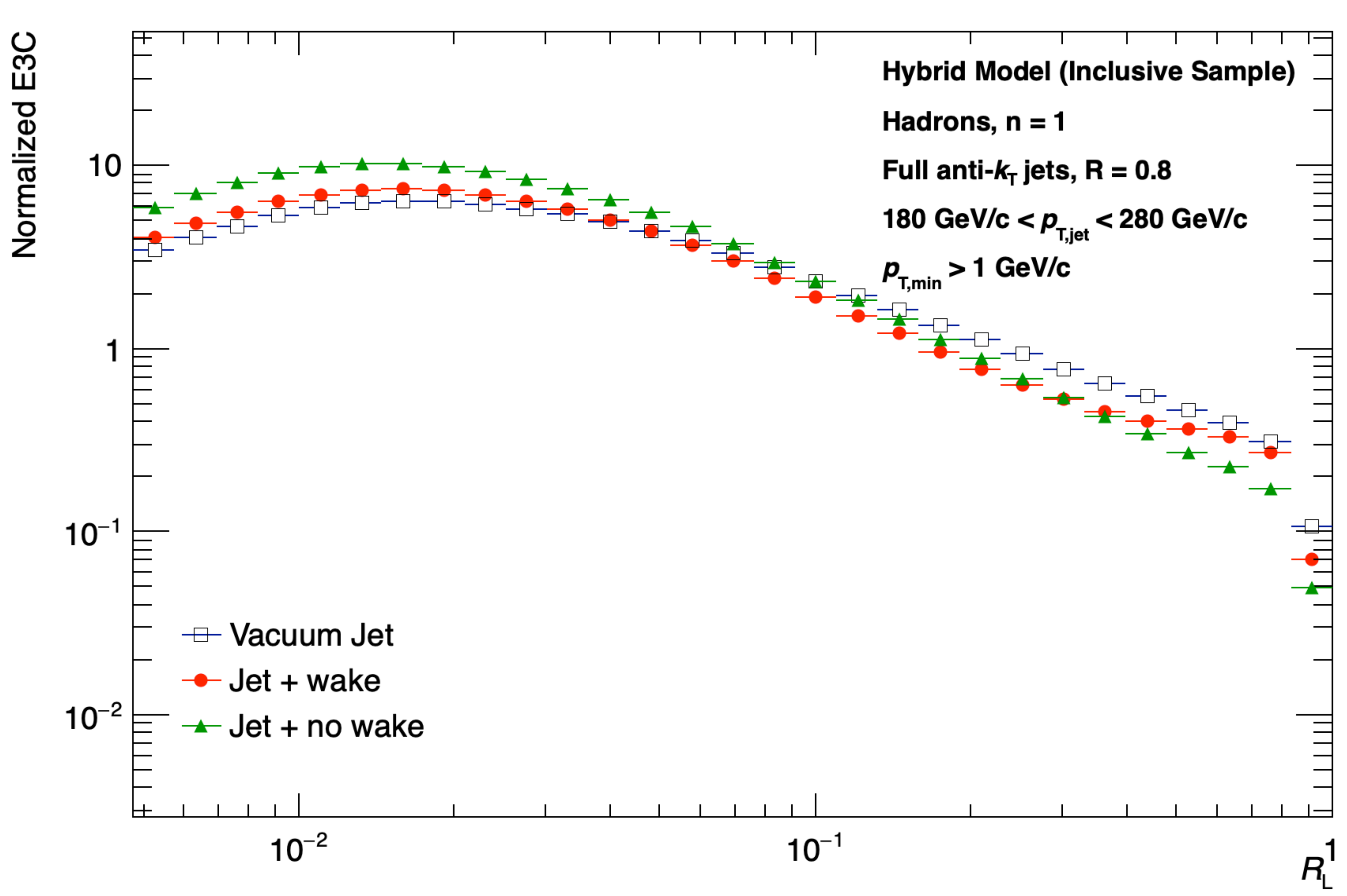
[ATLAS-CONF-2023-054]



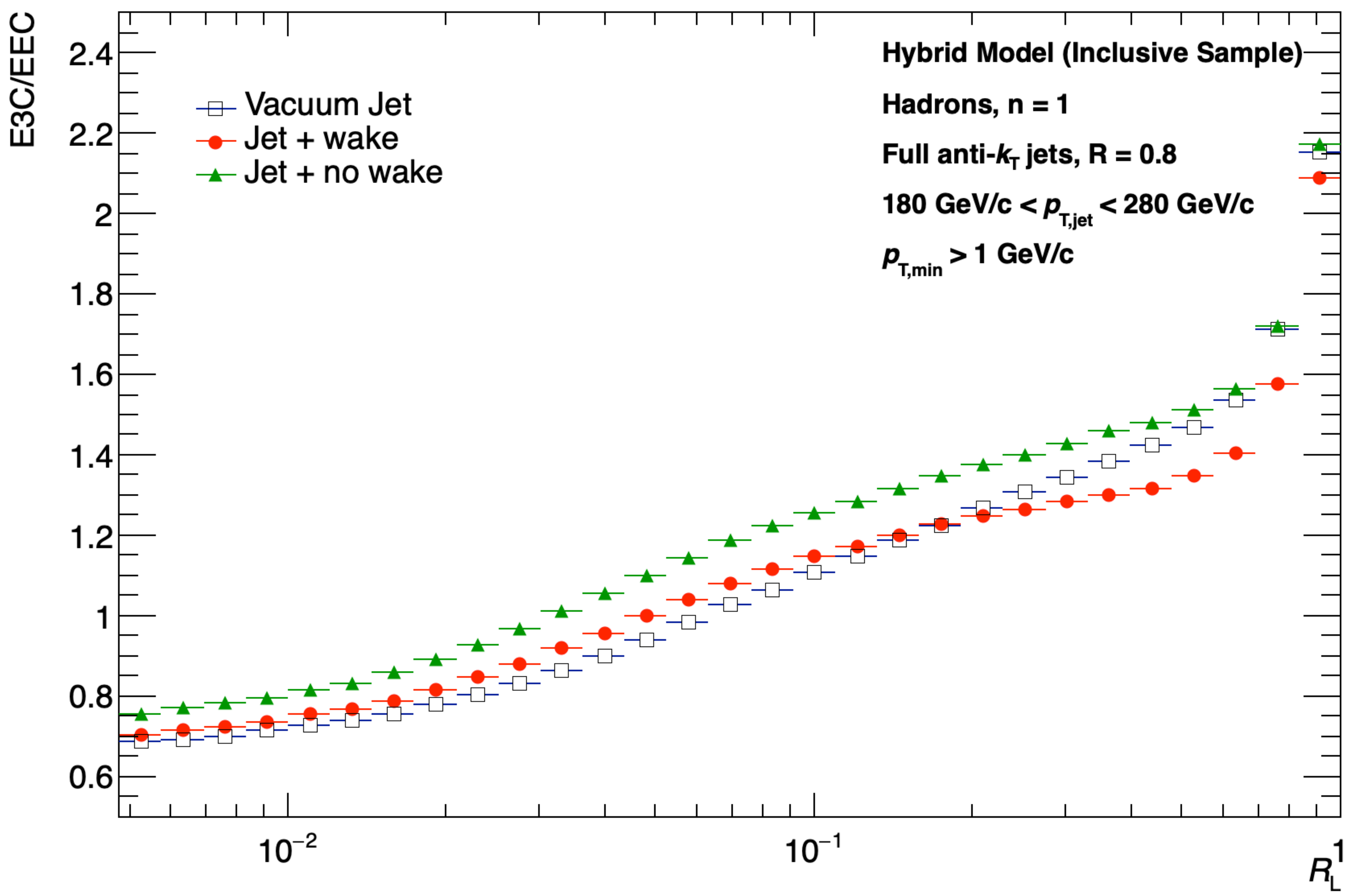
Z-hadron clean probe! Low $\Delta\phi$ consistent with CoLBT (w/ MPI)

Current γ-jet data not experimentally sensitive to negative wake

Introducing a constituent cut



Inclusive Jet E3C w/ p_T cut

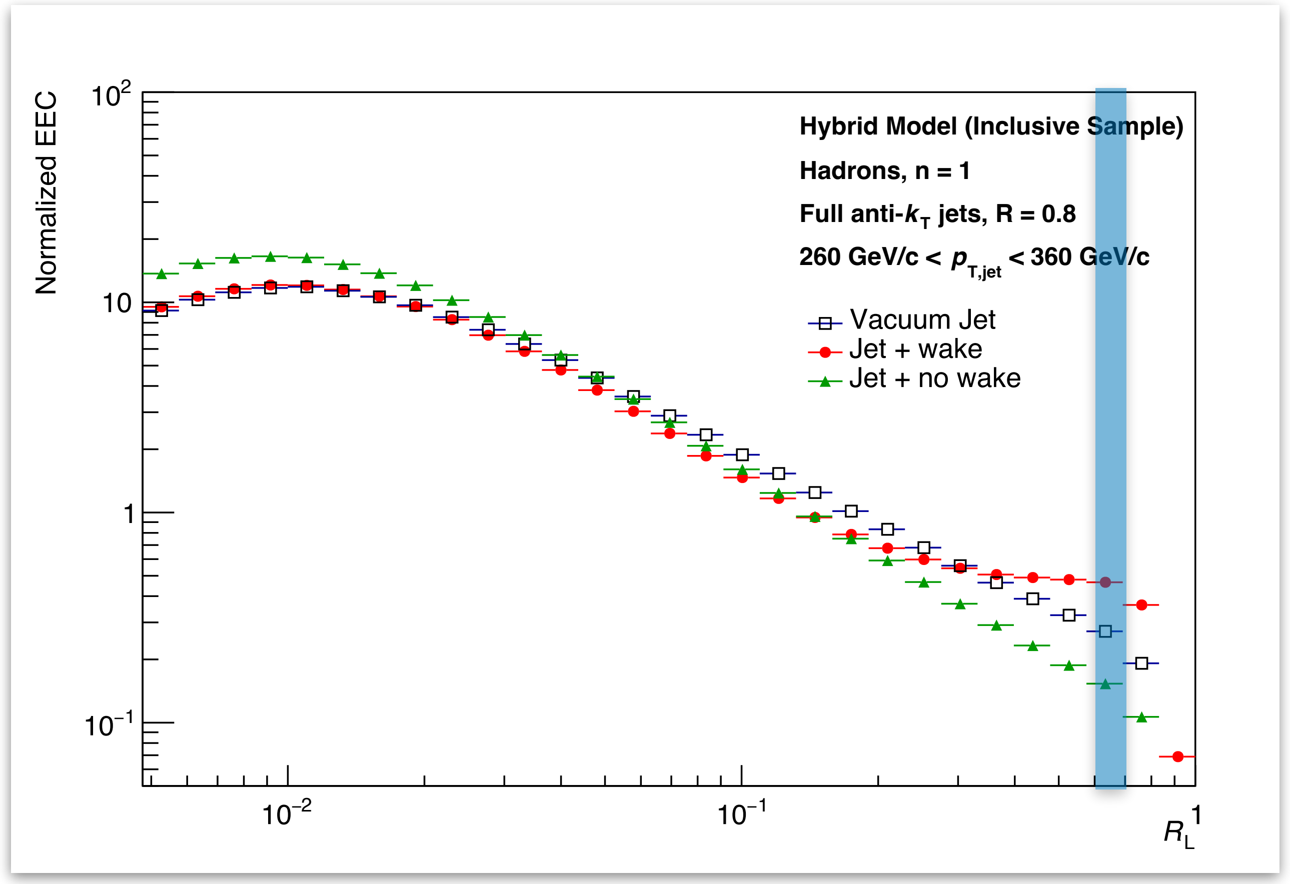


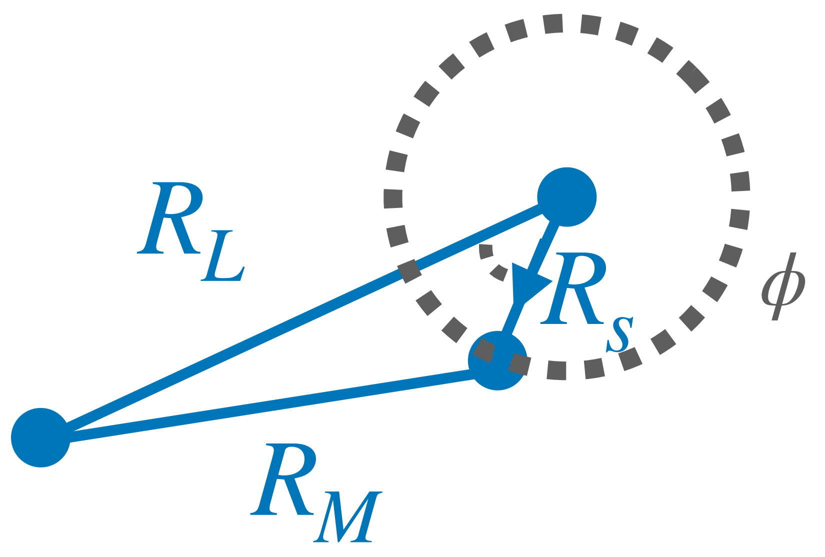
E3C/EEC Ratio w/ p_T cut

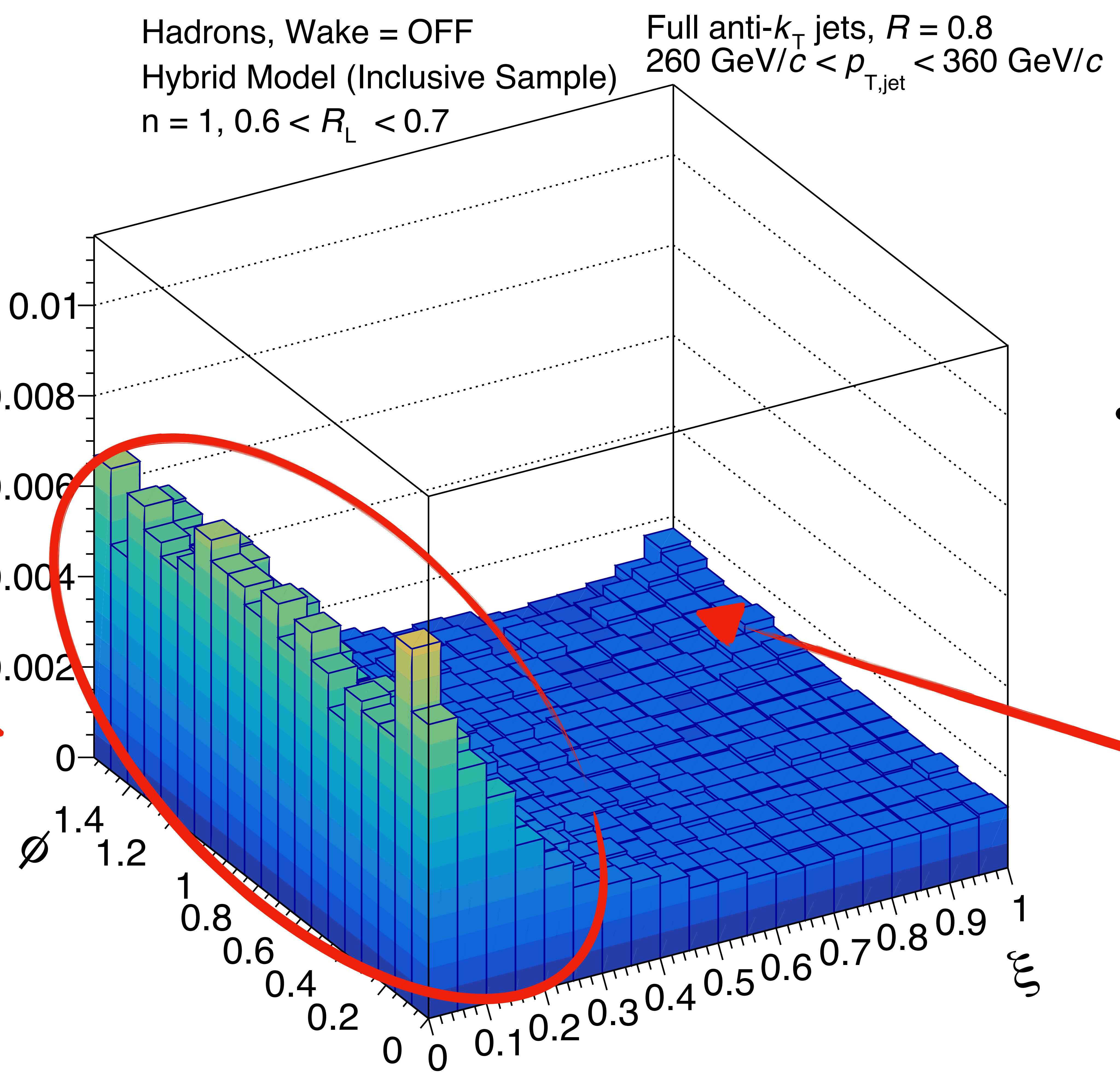
- Size of signal is reduced with a p_T cut.

Ratio is the ideal observable to use in experiment to maximize signal!

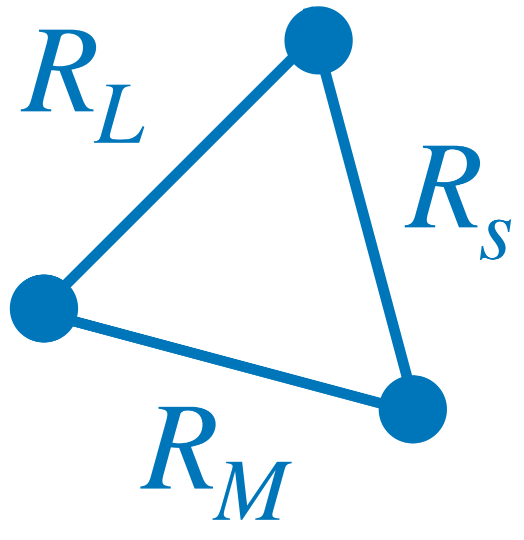
Shape dependence in medium (no wake)





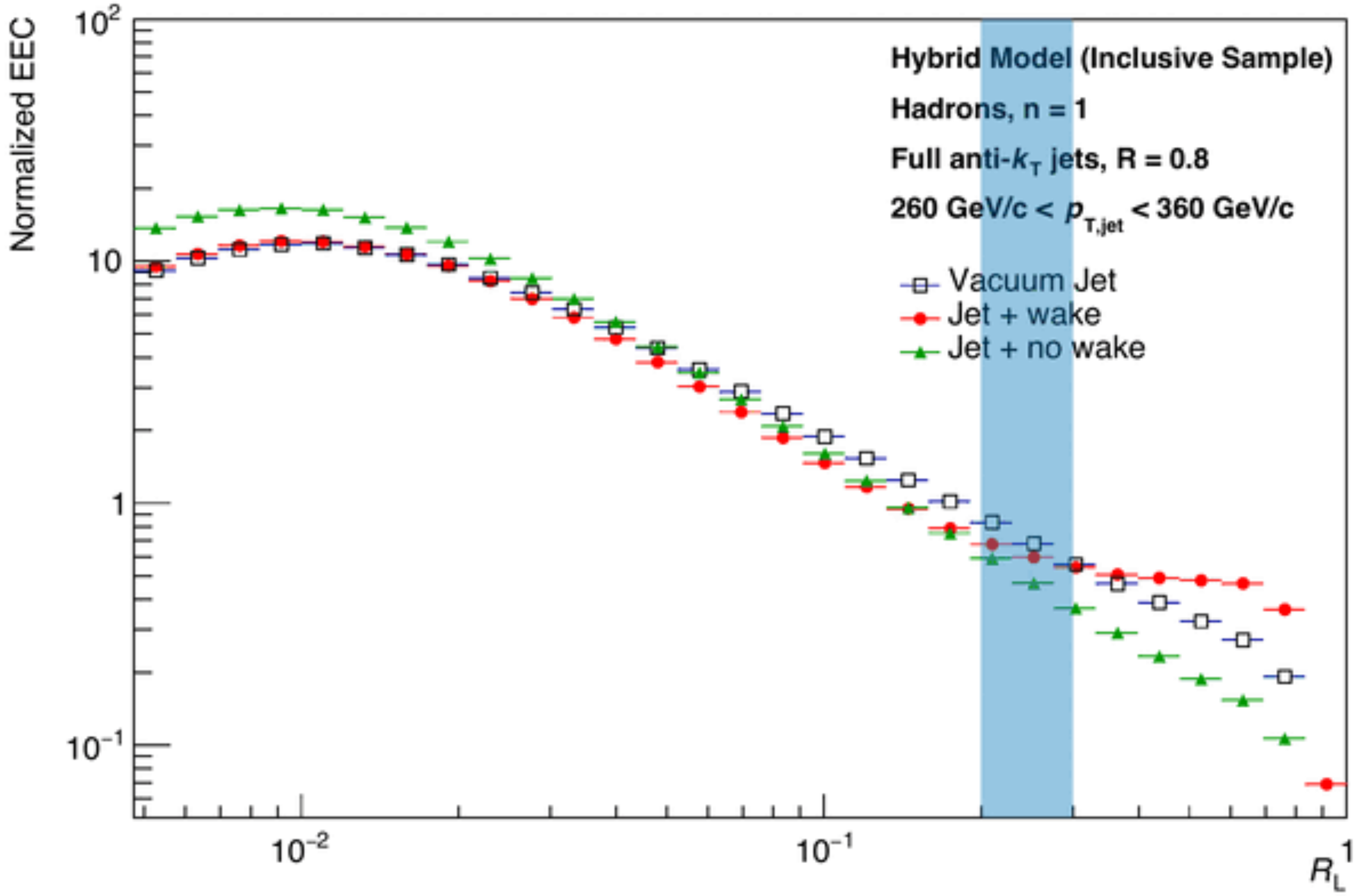


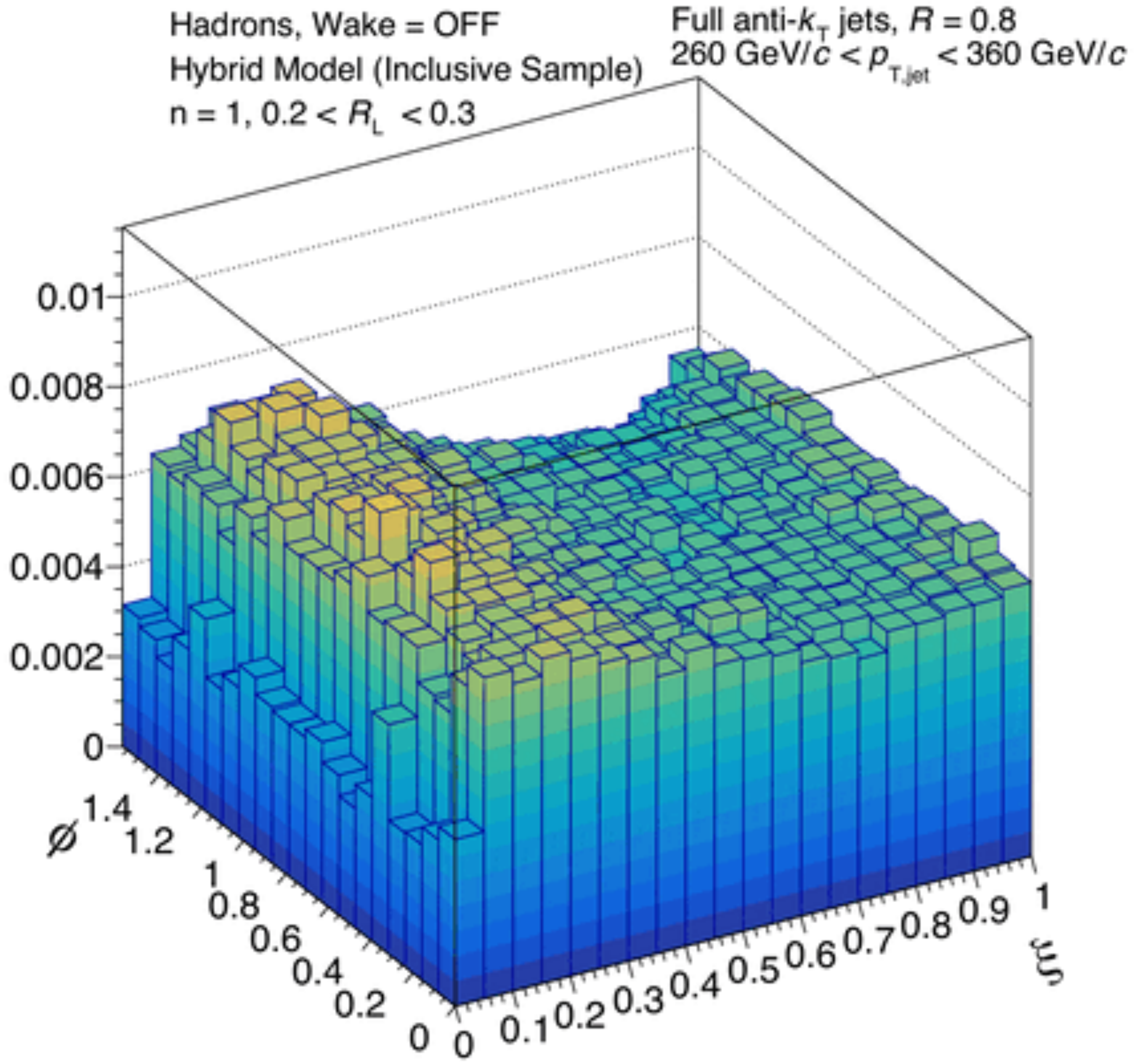
- Similar features to the vacuum case with peak slightly shifted due to energy loss.



- Could this be a good way to isolate effects from medium response?

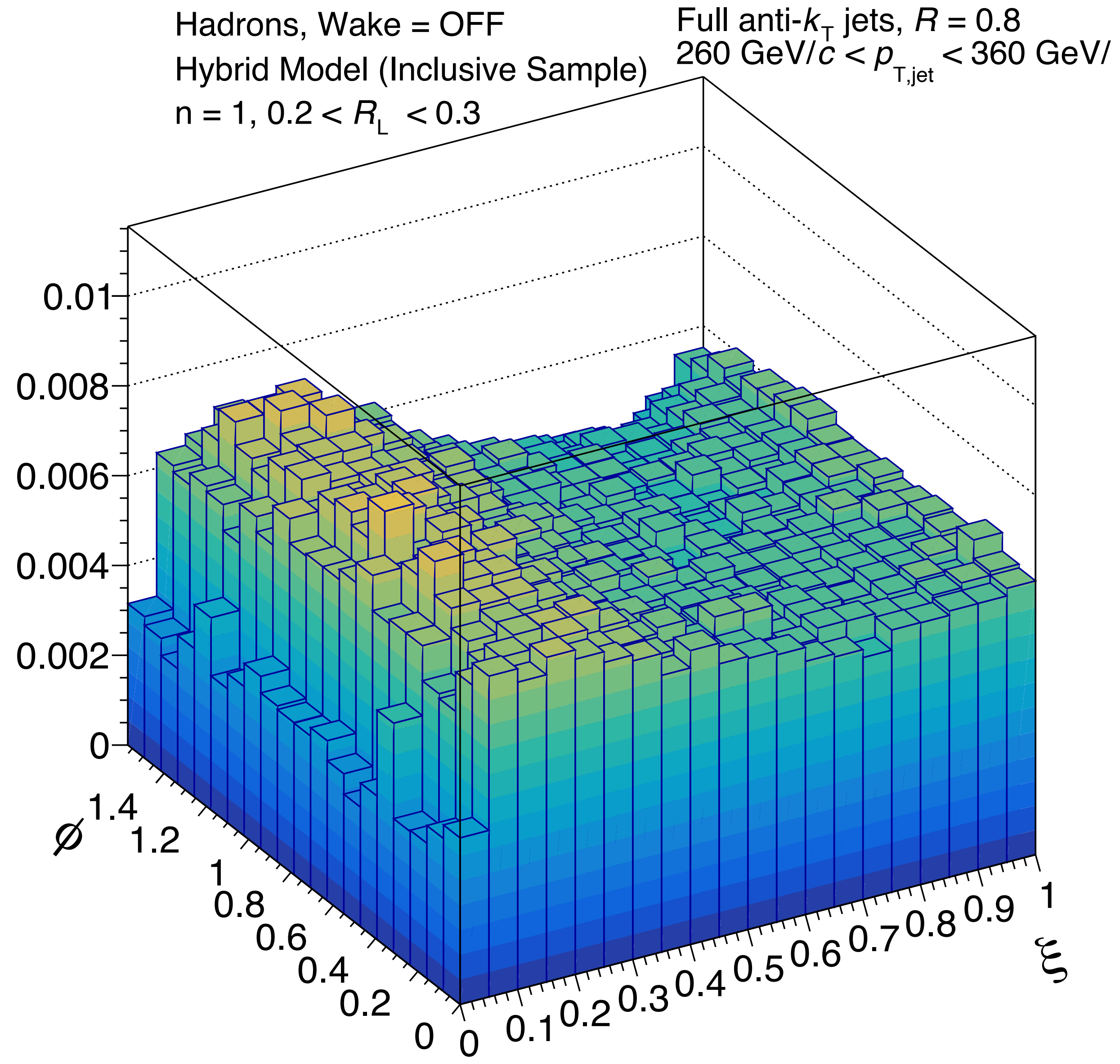
Progression with R_{L} (medium, no wake)



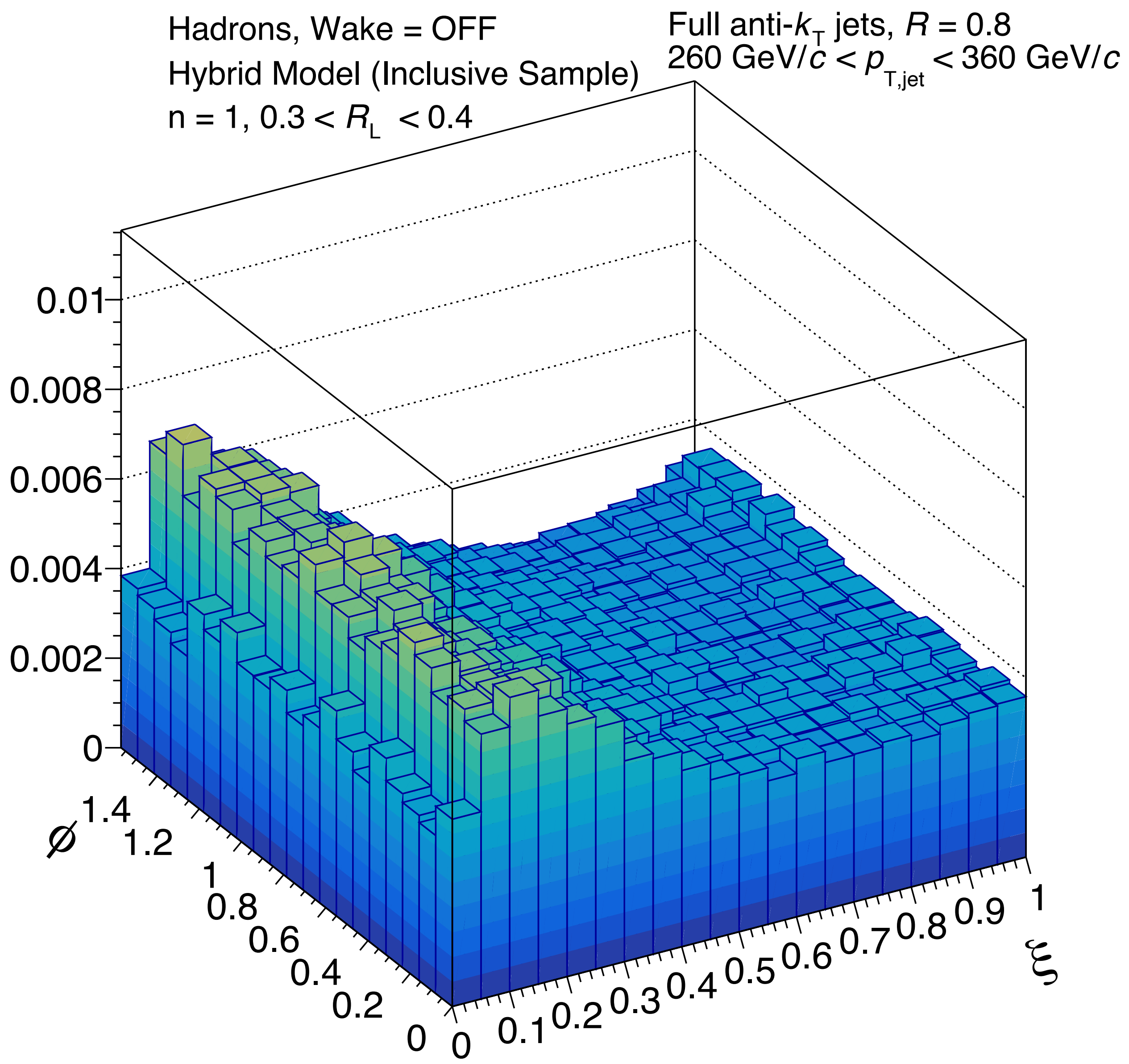


Progression with R_{L} (medium, no wake)

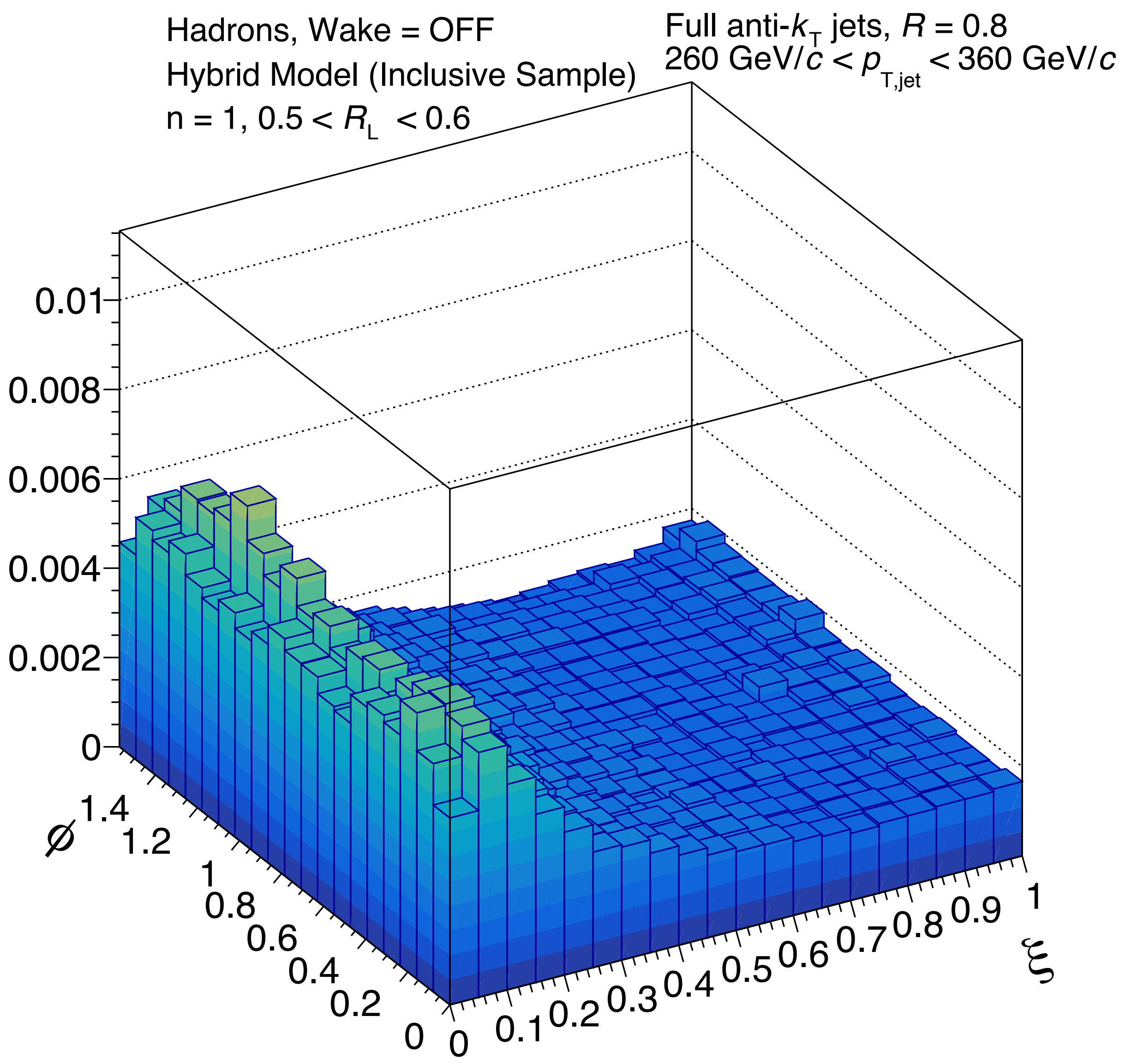
$0.2 < R_{\mathrm{L}} < 0.3$



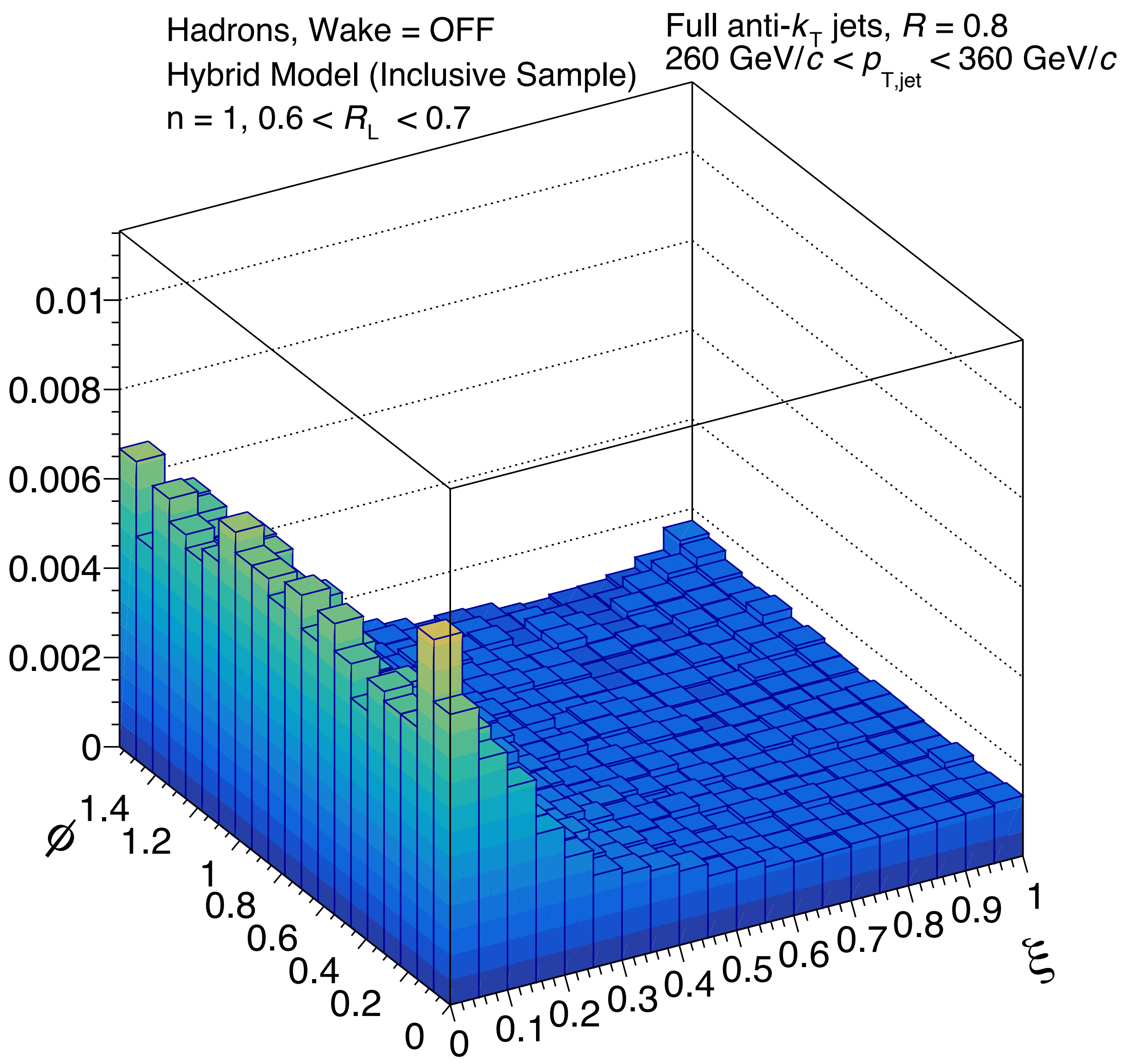
$0.3 < R_{\mathrm{L}} < 0.4$



$0.5 < R_{\mathrm{L}} < 0.6$



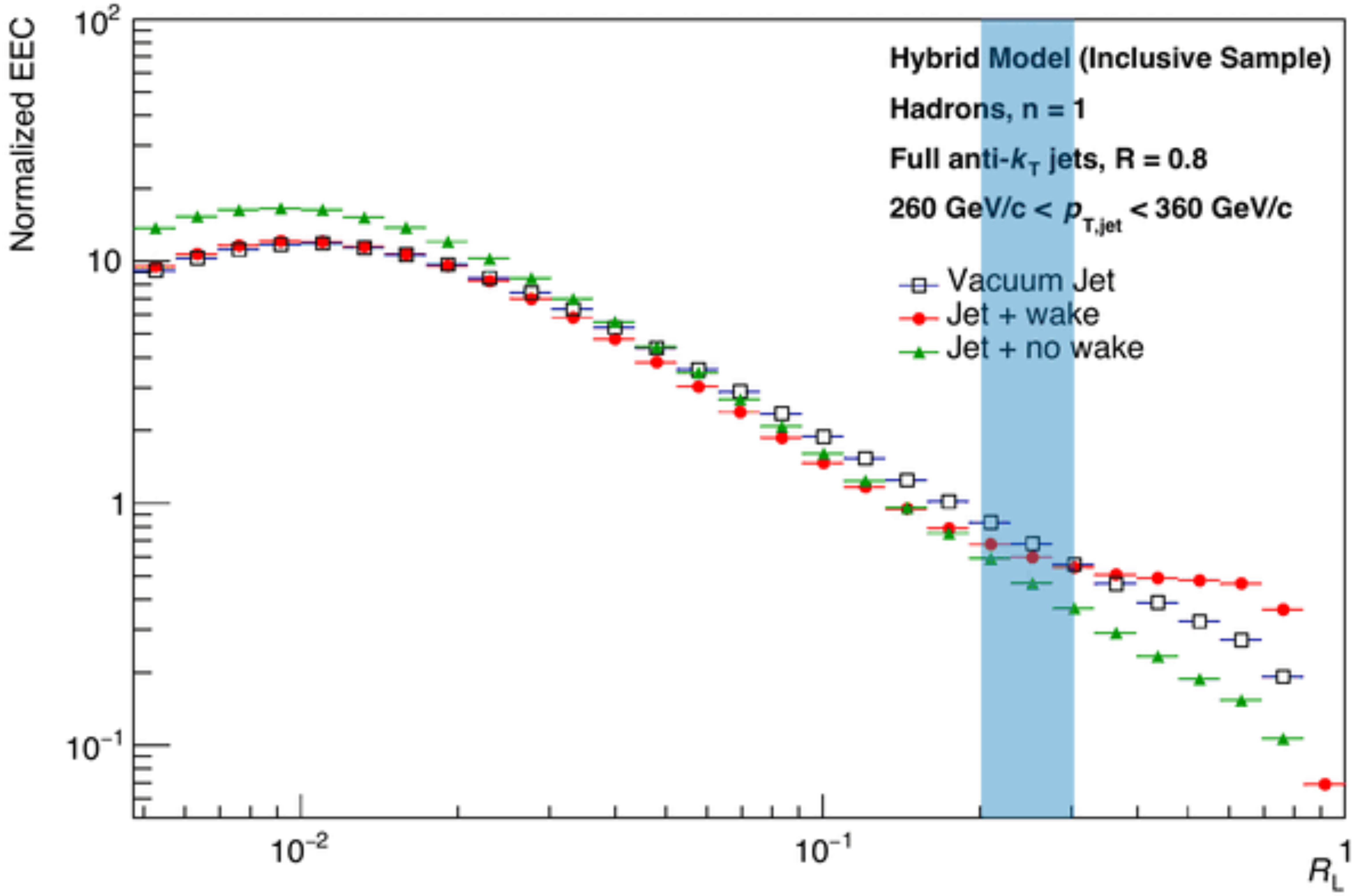
$0.6 < R_{\mathrm{L}} < 0.7$

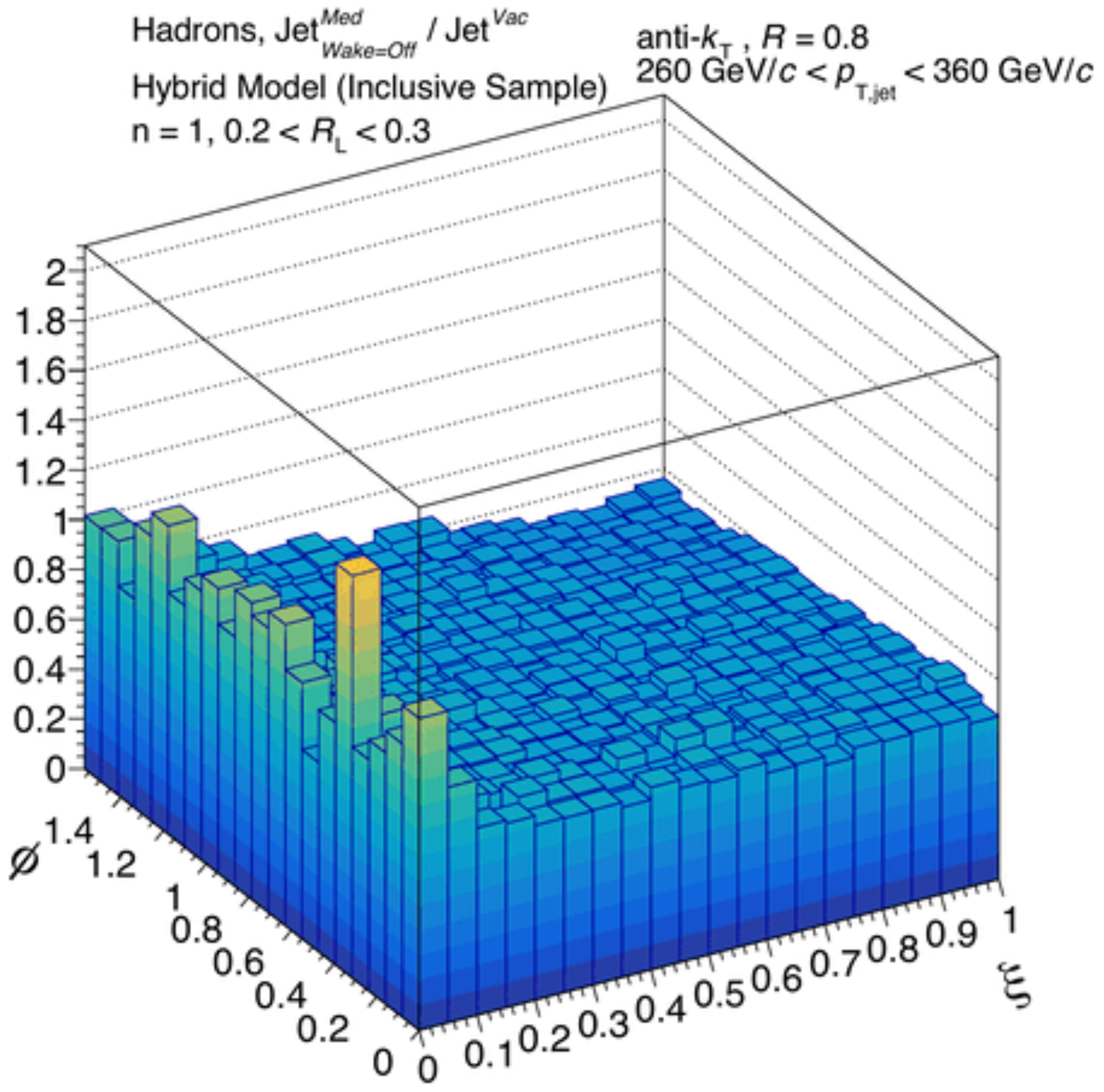


Increasing R_{L}

- Similar features to the vacuum case, positions shifted due to quenching

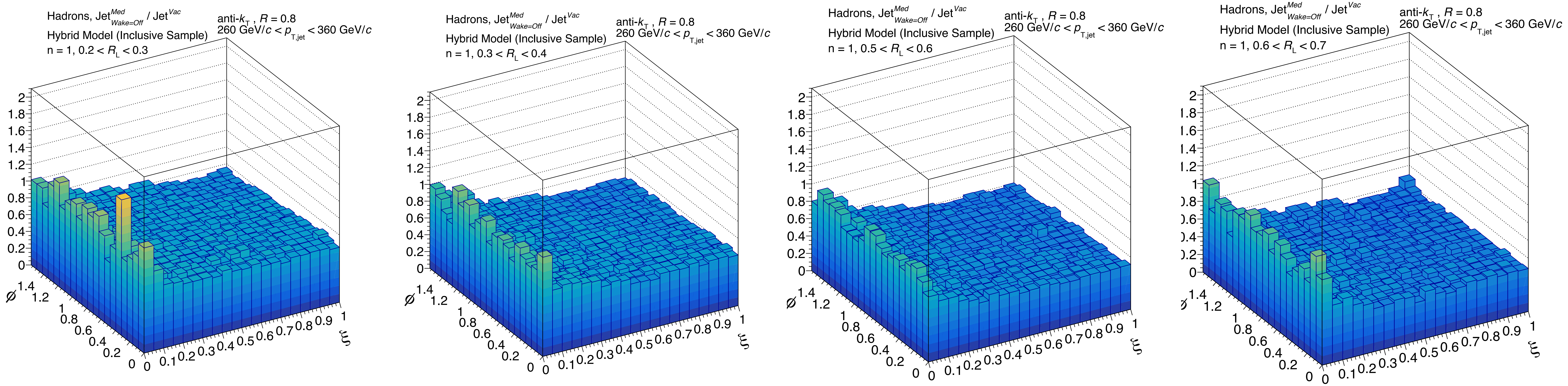
Progression with R_L (no wake /vacuum)





Progression with R_{L} (no wake /vacuum)

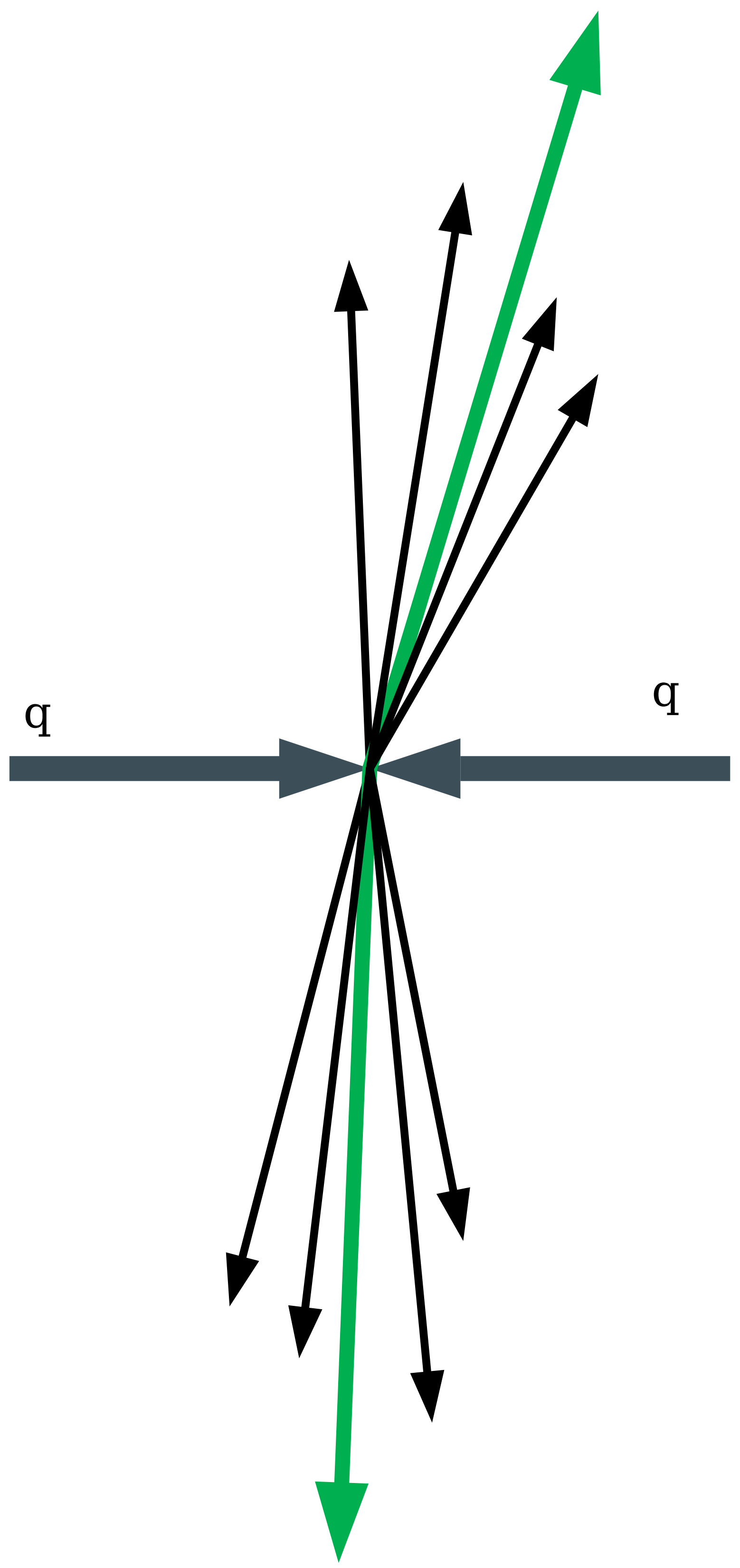
$0.2 < R_{\mathrm{L}} < 0.3$ | $0.3 < R_{\mathrm{L}} < 0.4$ | $0.5 < R_{\mathrm{L}} < 0.6$ | $0.6 < R_{\mathrm{L}} < 0.7$



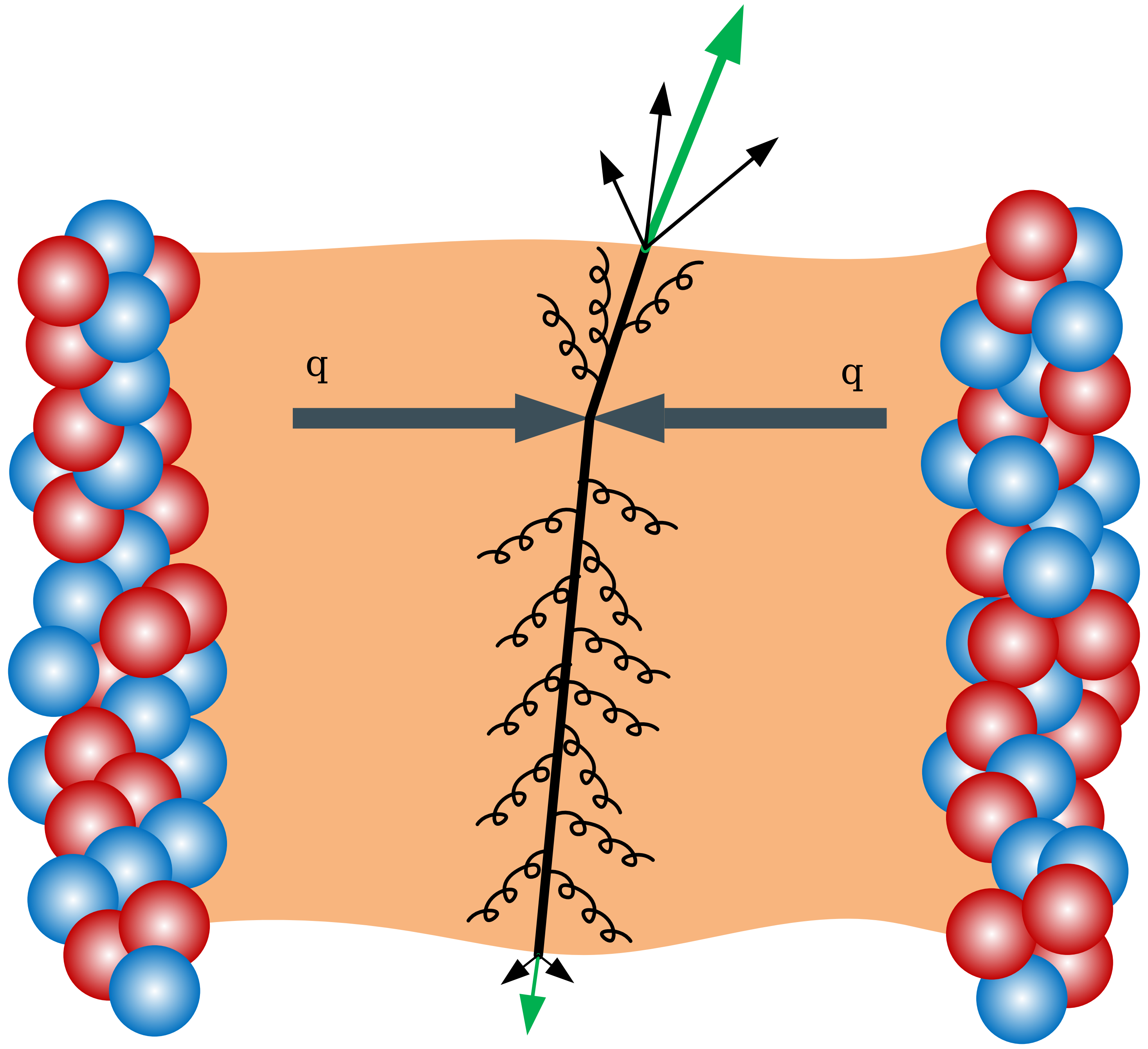
Increasing R_{L}

- Distributions appear to be very similar other than small quenching differences.

Jets as a probe of the QGP



pp



Heavy-Ions (Pb—Pb)

→ High p_{T} parton is expected to lose energy in interactions with the hot and dense medium in heavy-ion collisions **(jet quenching)**.

→ Jets are a colored probe of the colored QGP medium!

→ Use pp, where jets are measured in vacuum, as a reference for no QGP.

Jet quenching models

As of now, no clear winner for best description of jet quenching effects!

Different models are different!

We will come back to these later!