Massachusetts Institute of Technology

mitp

First investigations of the shape-dependent energy correlators in heavy-ion collisions

Hannah Bossi (MIT)

Energy Correlators at the Collider Frontier, Mainz, Germany

July, 10th, 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

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?

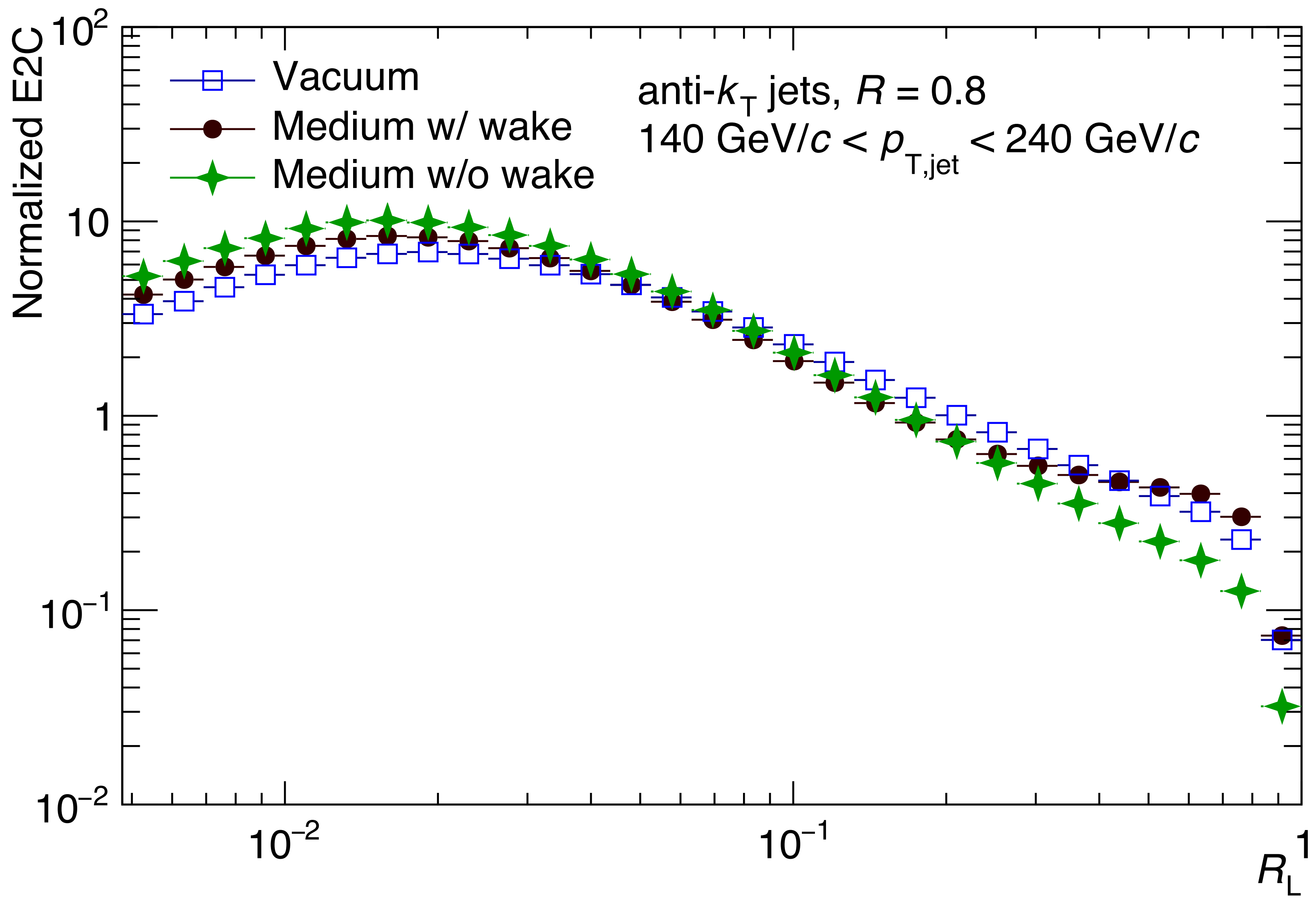
What new things can the shape-dependent energy-energy-energy correlator add?

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

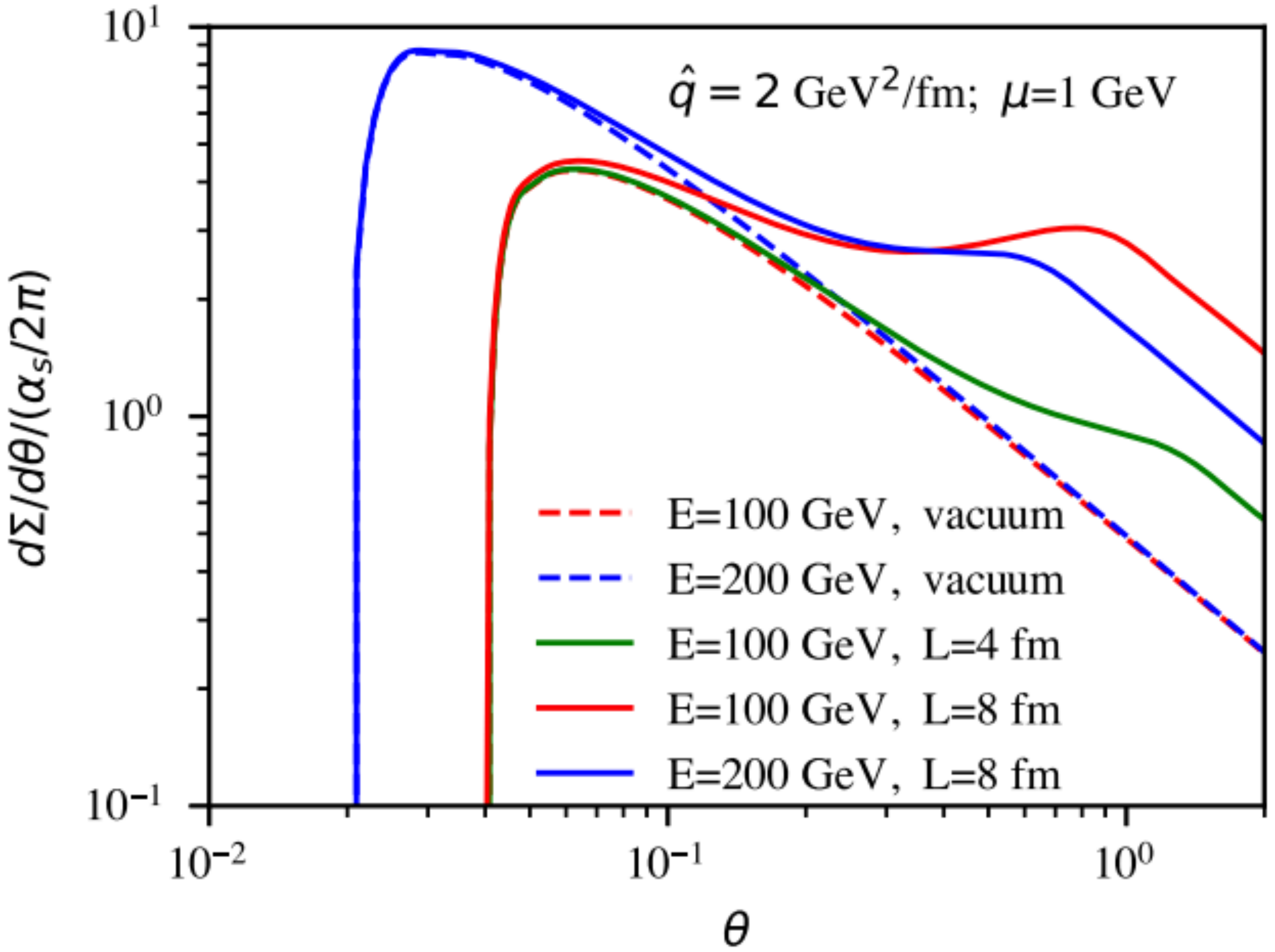
See Arjun's talk next!

Scaling of in-medium effects

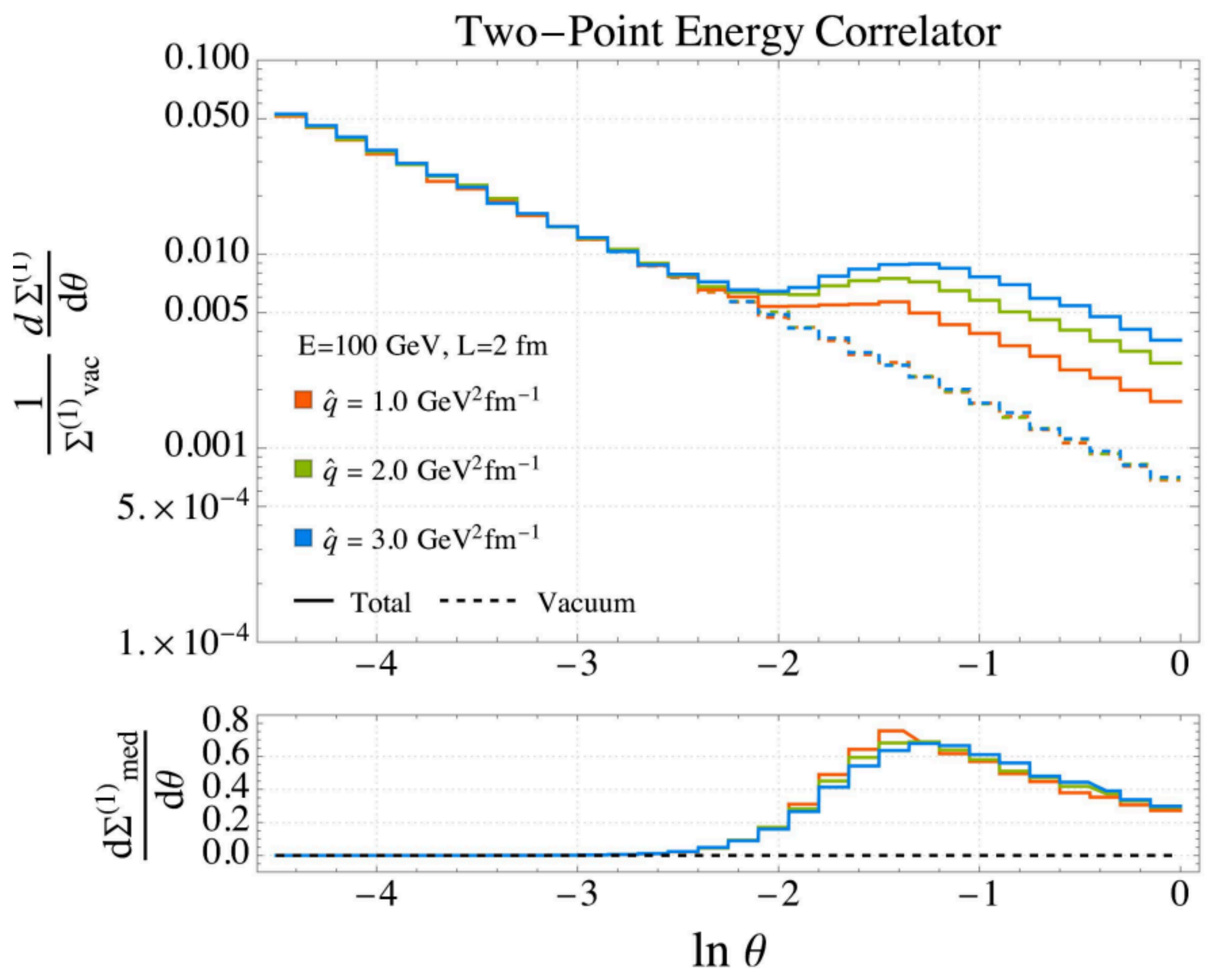
See Ananya's talk



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



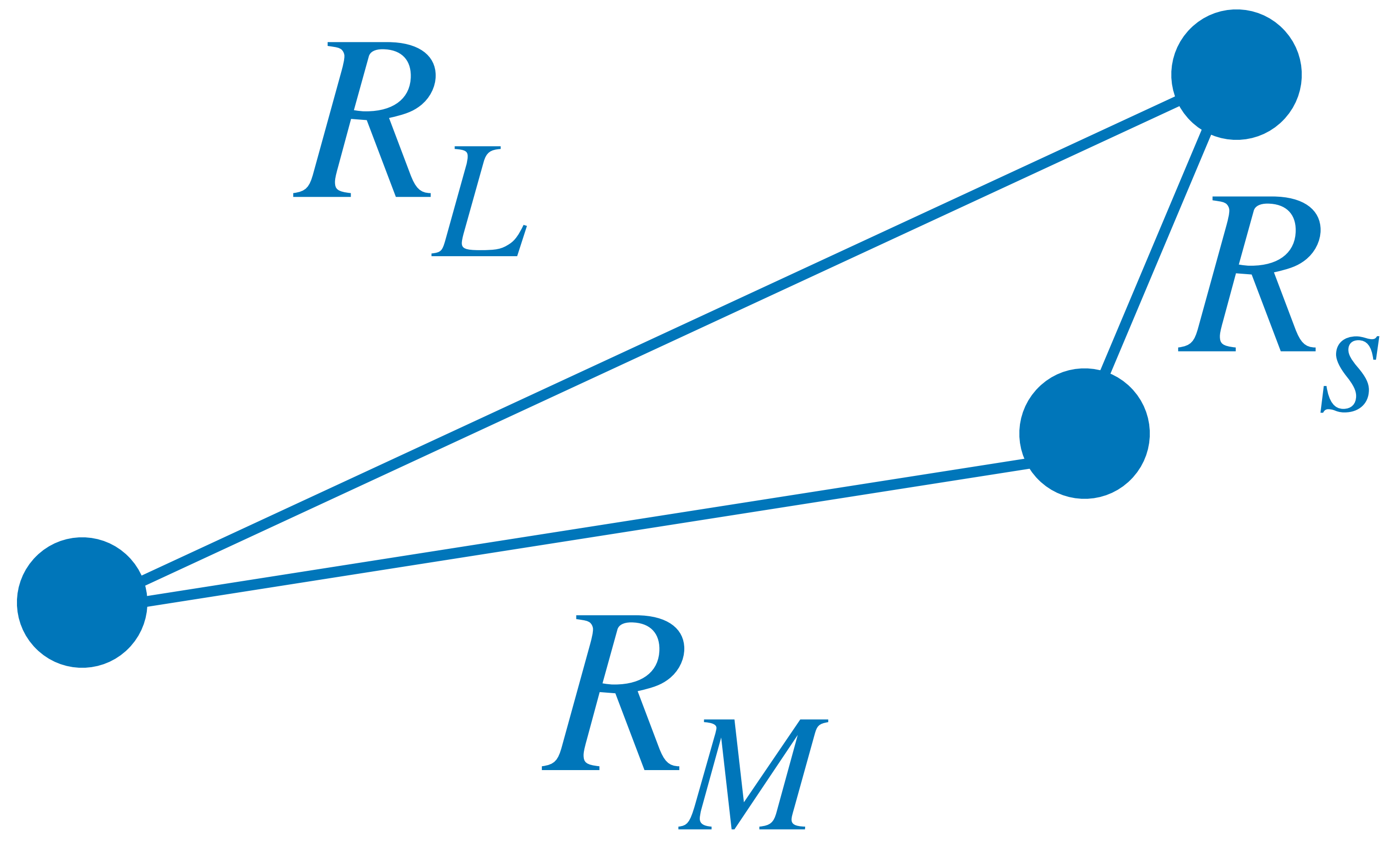
[Andres et al. Phys. Rev. Lett. 130, 262301]



- ✽ Medium effects appear at a similar characteristic scale

Can we distinguish these different physical mechanisms? What about higher orders of N? What if we also included the full shape information?

Higher-Point Correlators

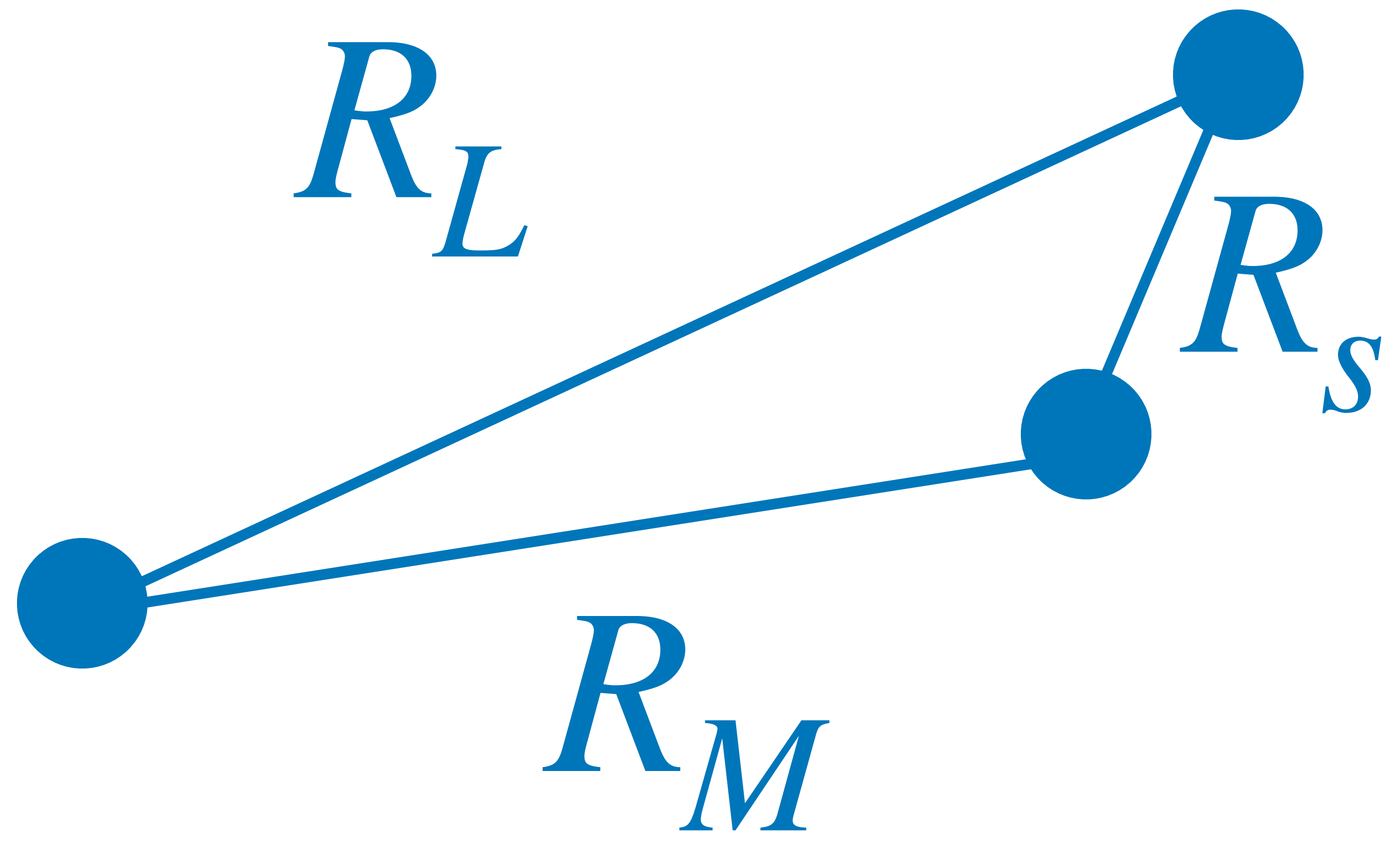


- Simplest example is the 3-point correlator

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

- 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, EEEC) and the scaling (projected correlator, ENC)!

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

Visualize the shape in 3D space where the dimensions are

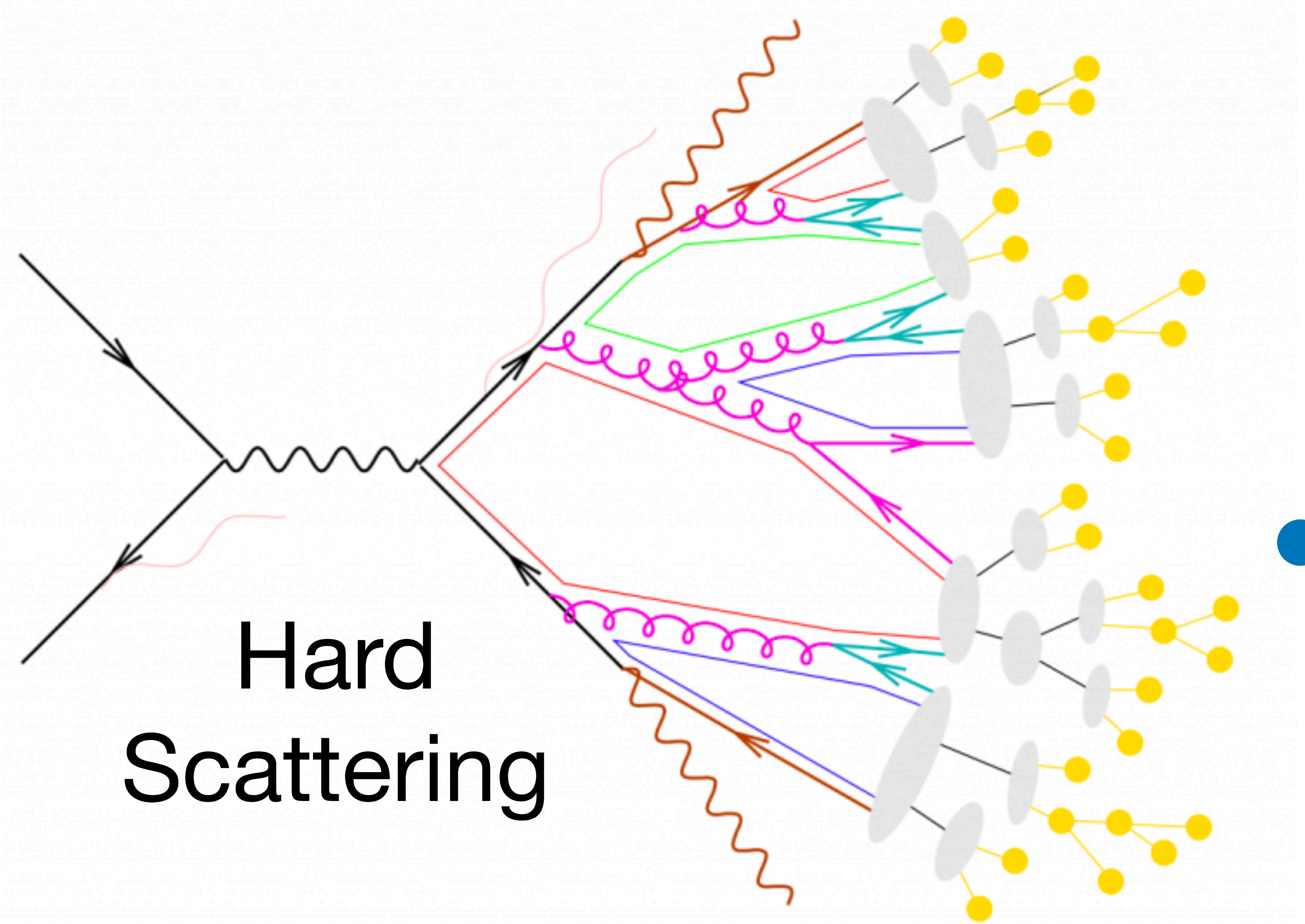
$$R_\mathrm{L} \qquad \xi = \frac{R_\mathrm{S}}{R_\mathrm{M}} \qquad \phi = \arcsin\sqrt{1 - \frac{(R_\mathrm{L} - R_\mathrm{M})^2}{R_s^2}}$$

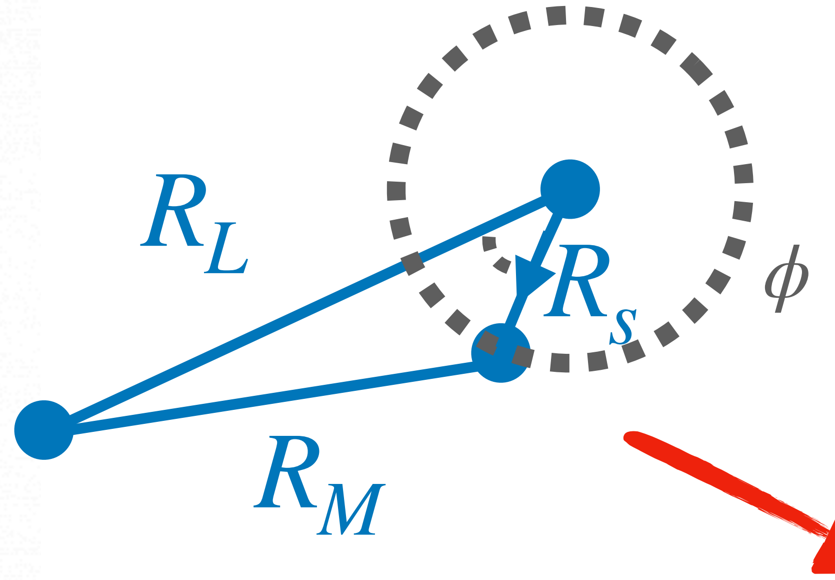
See Bianka's talk from yesterday

3-point correlator in vacuum

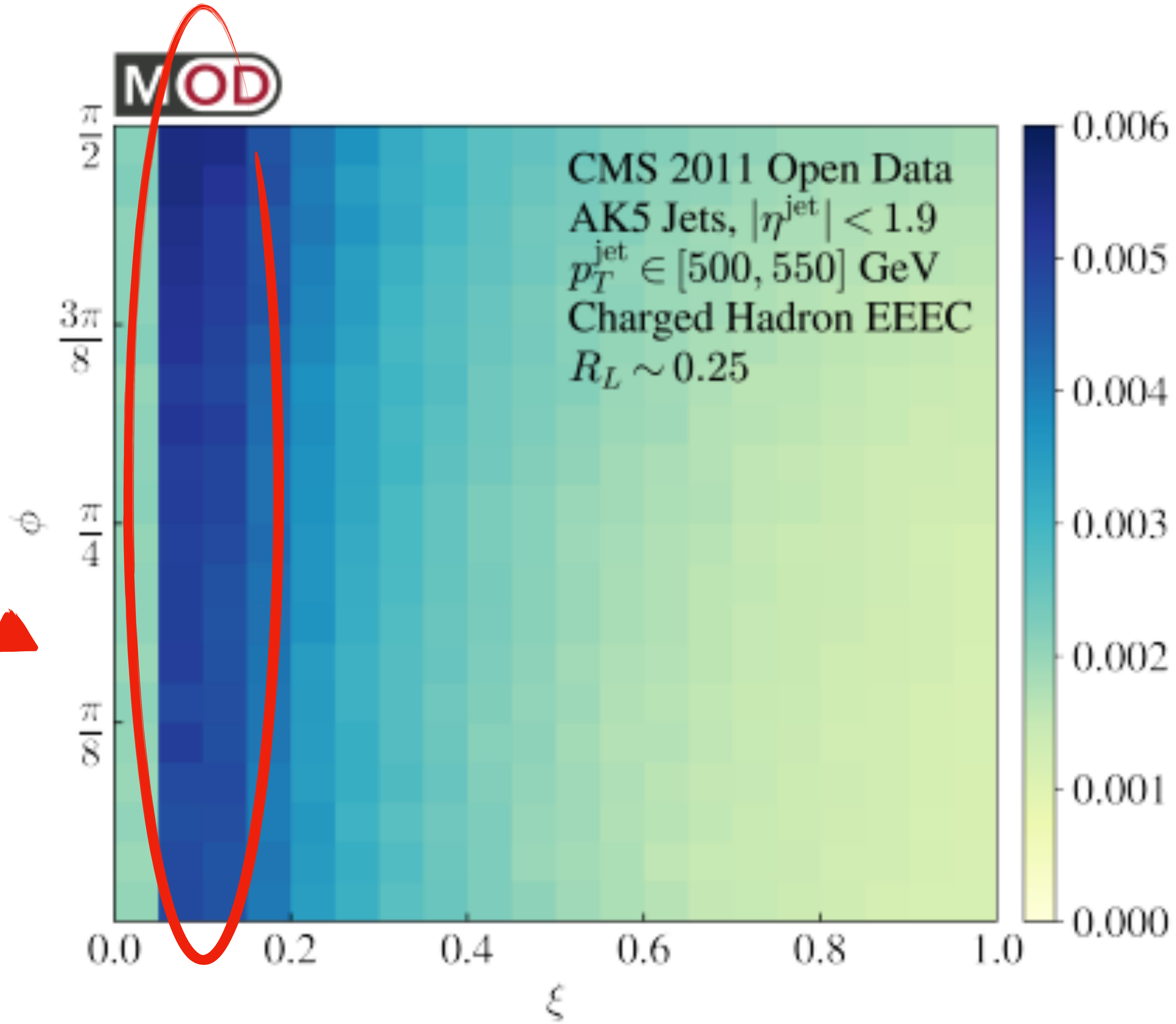
- Let's explore the 3-point correlator in vacuum at a fixed $R_{\rm L}$ slice!

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





"squeezed" triangles



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

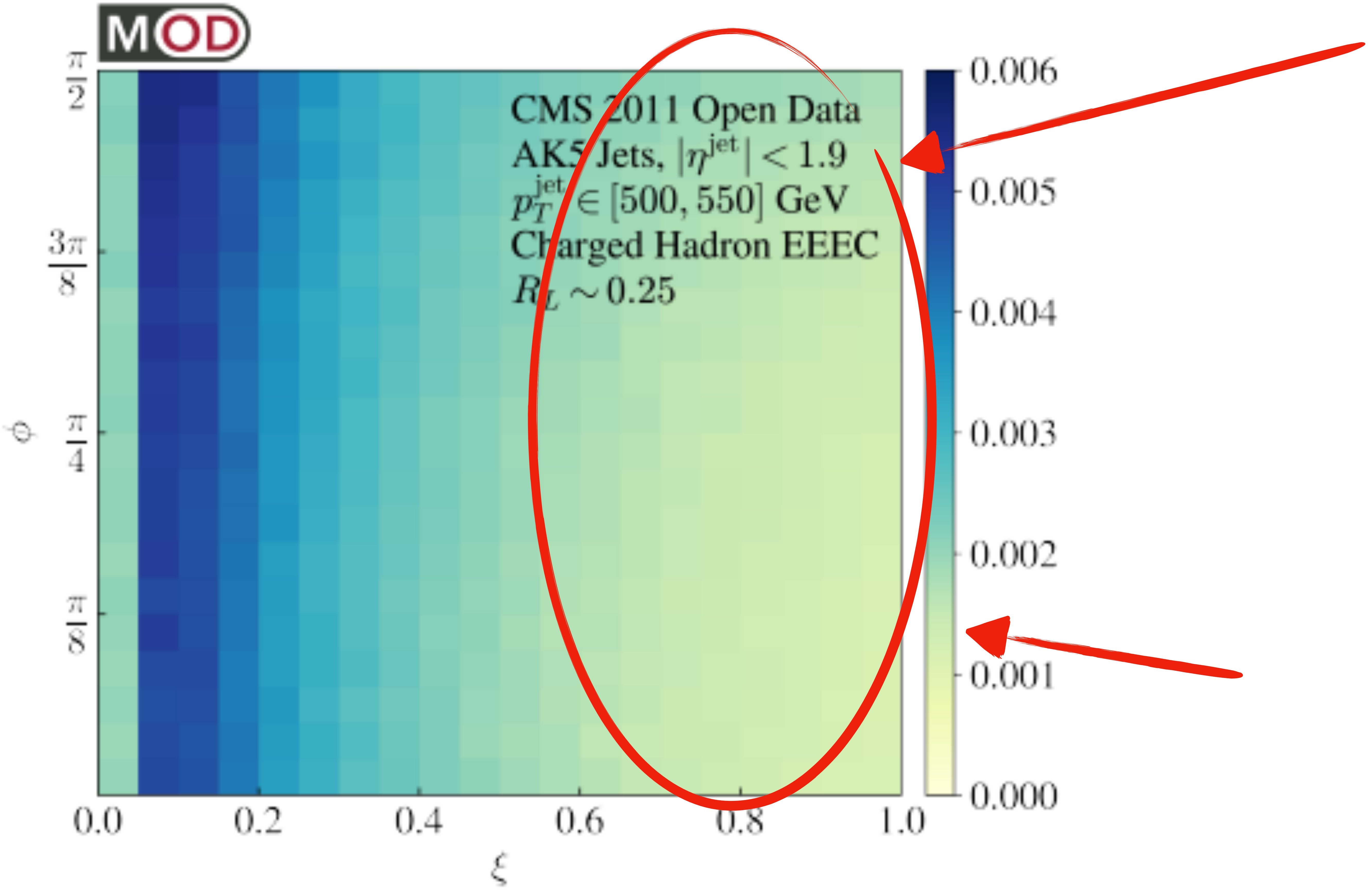
When ξ is small, behavior similar for all ϕ

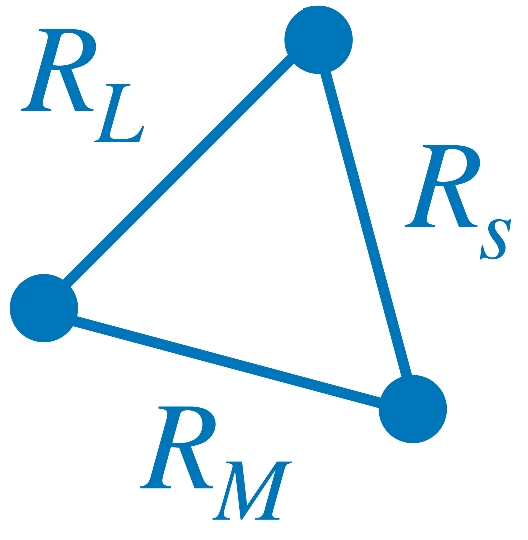
In collinear limit, reflect 2-point correlator.

3-point correlator in vacuum

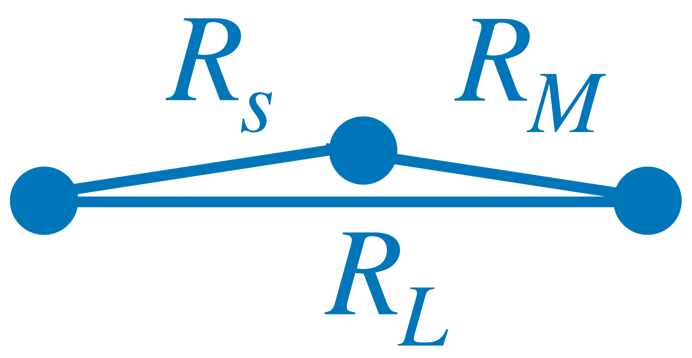
- Let's explore the 3-point correlator in vacuum at a fixed R_L slice!

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





Upper right corner is populated with equilateral triangles

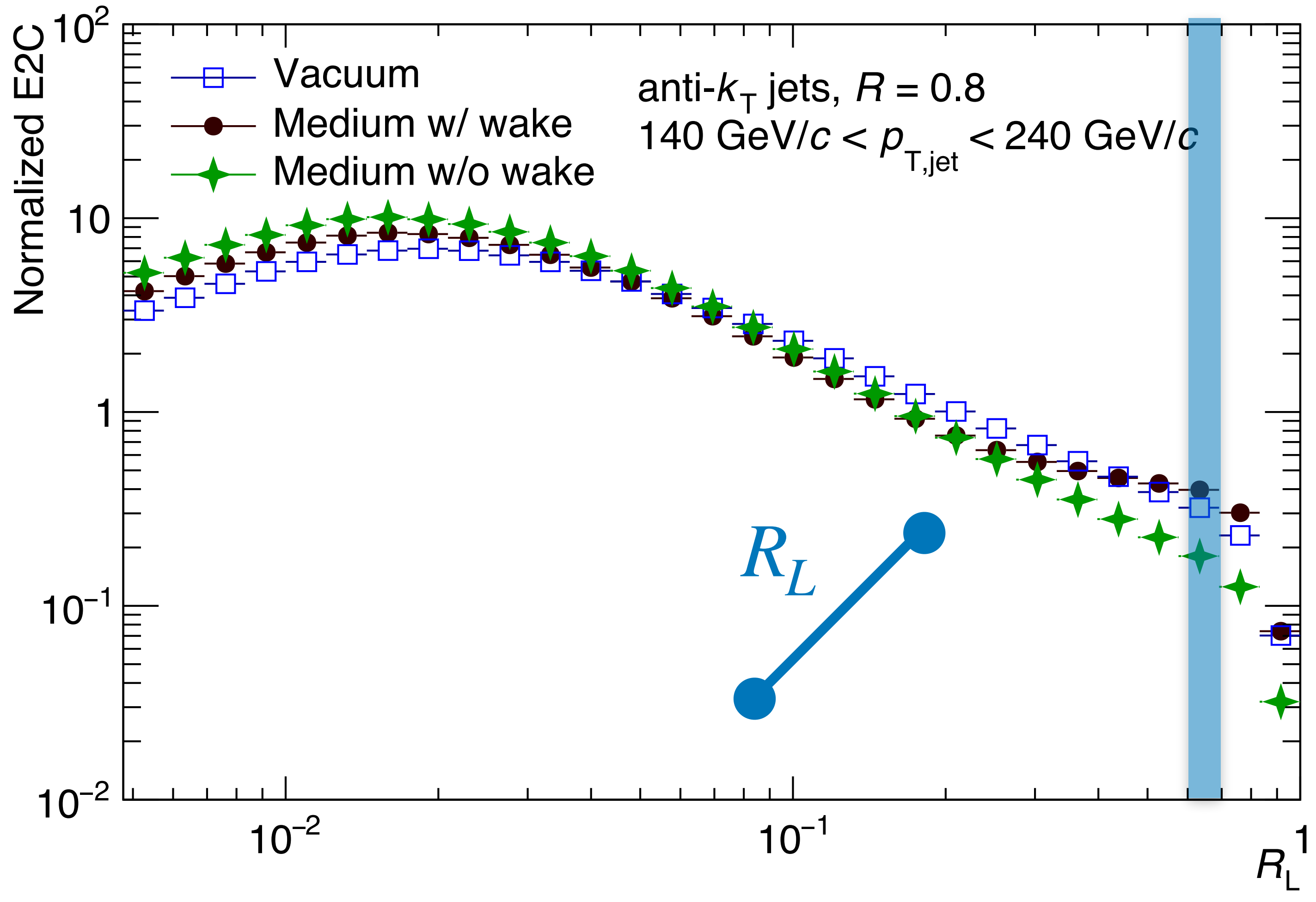


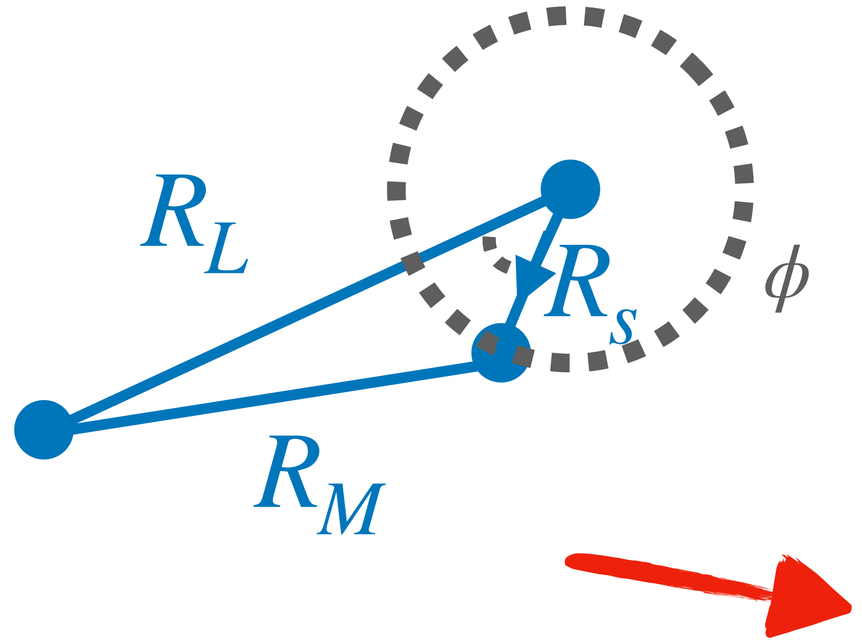
Bottom right corner is populated with "flat" triangles

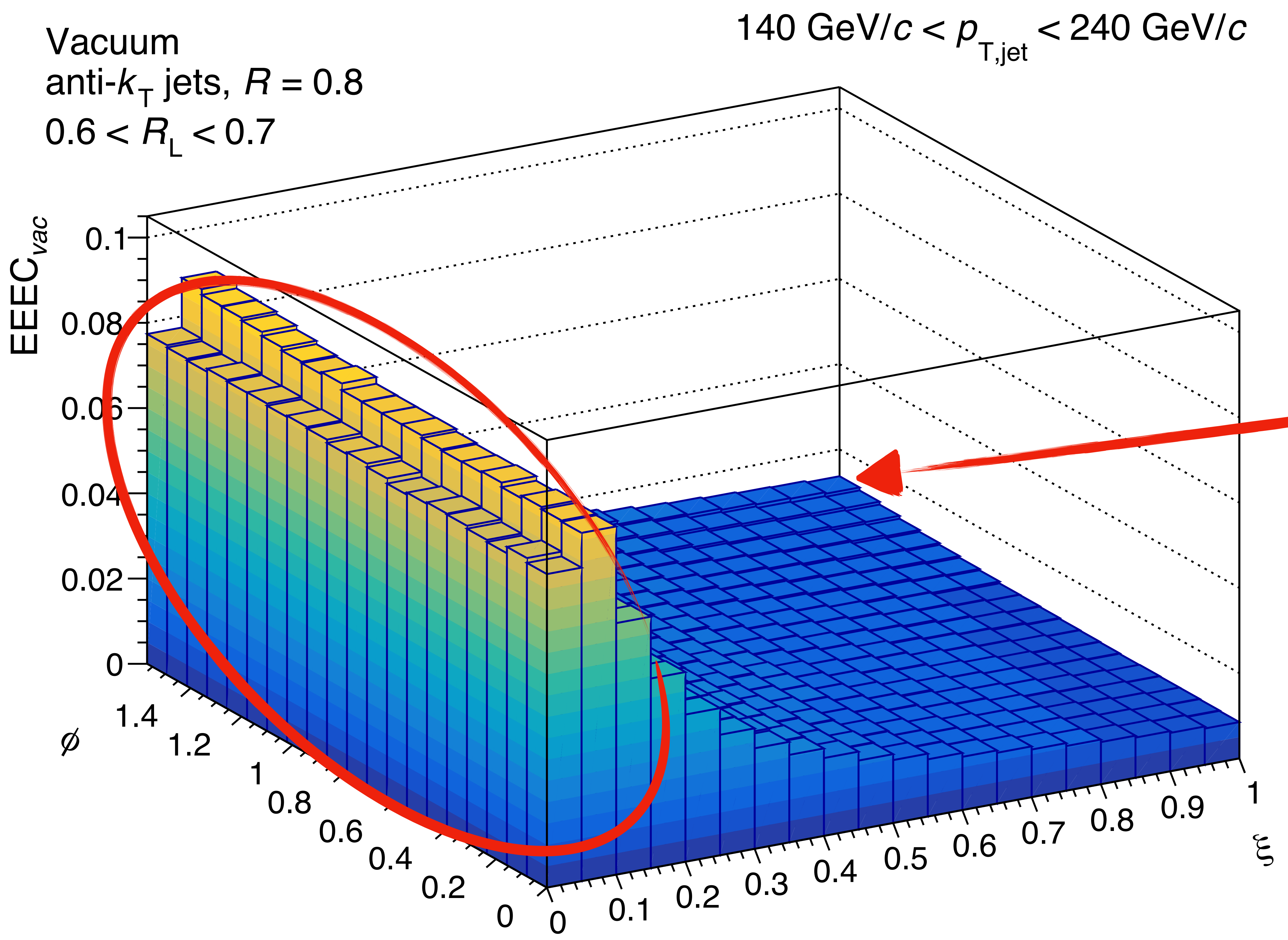
These features are not prominent in vacuum!

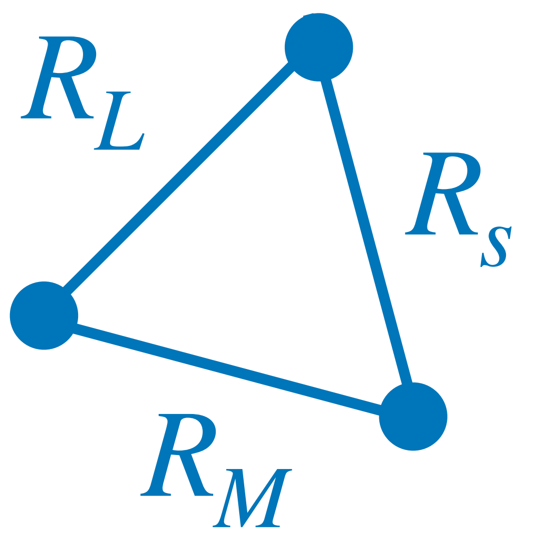
Shape dependence in vacuum

Can also visualize this in 3D with the kinematics we will use for our nominal case!







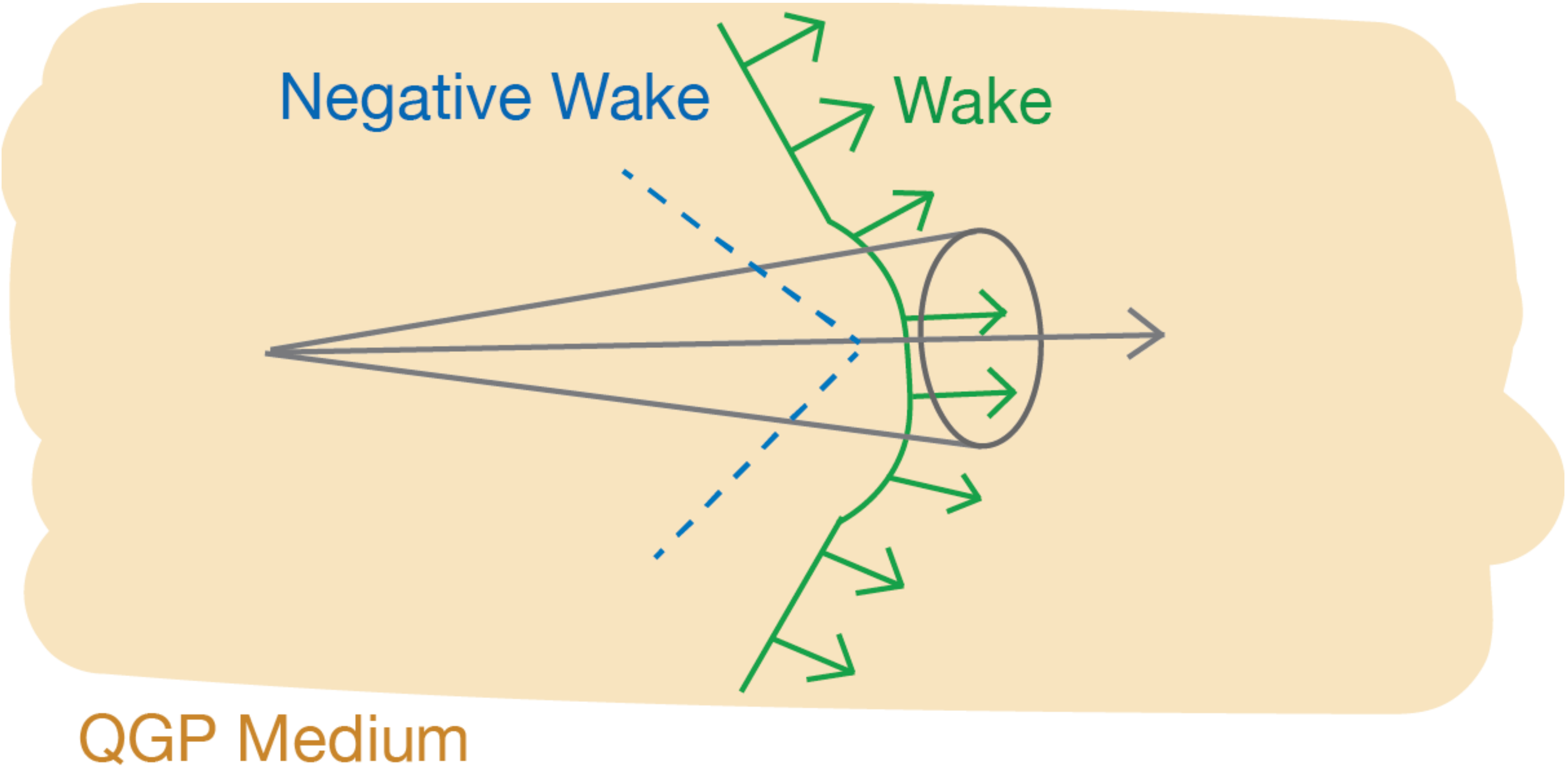


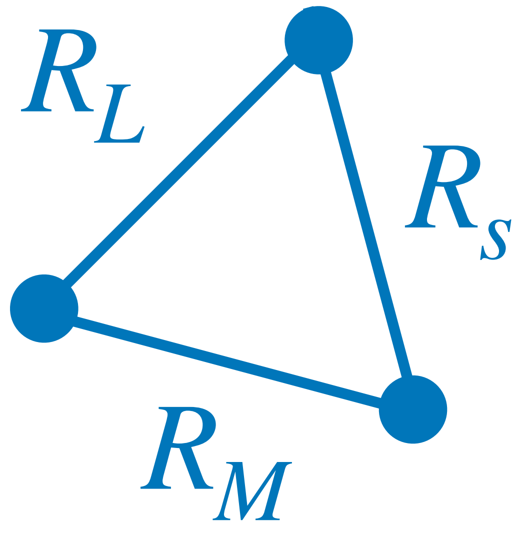
All other shapes not prominent in vacuum!

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

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



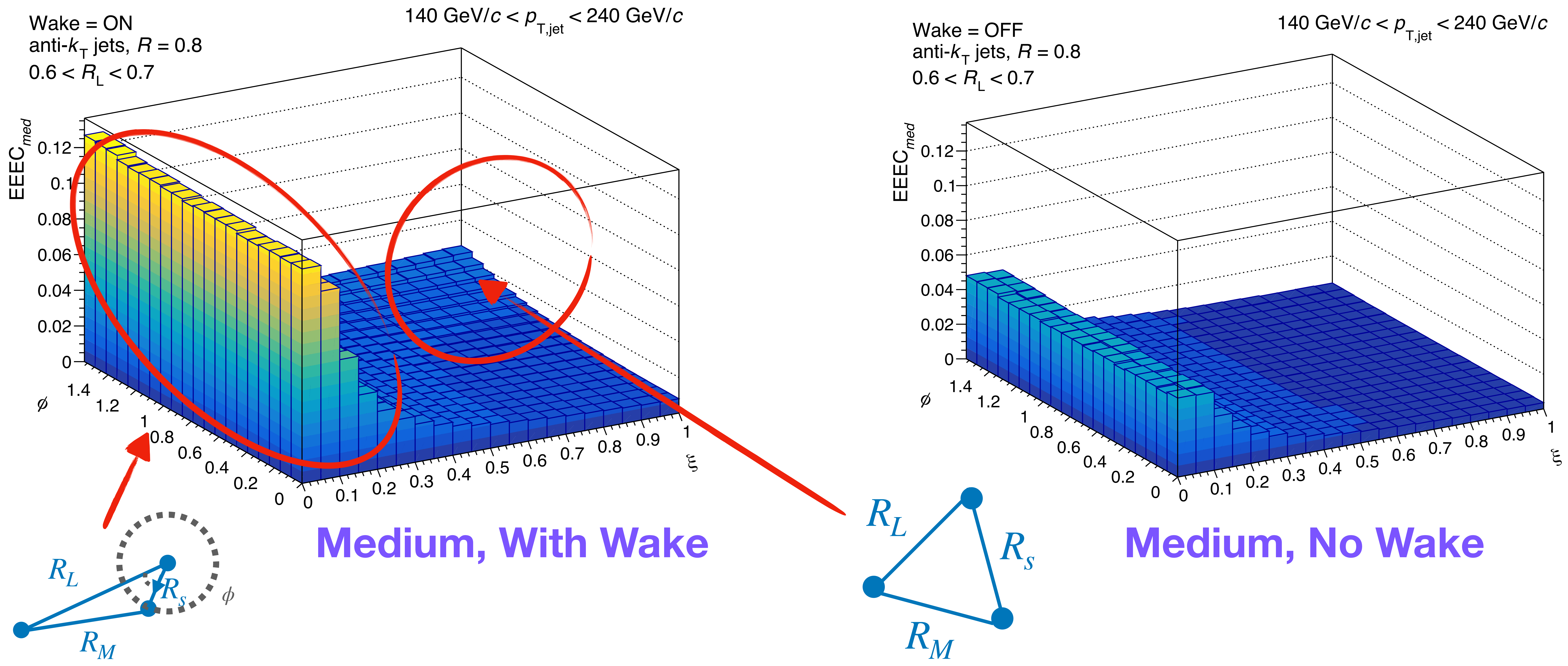


Wake should "fill in" region unpopulated in vacuum!

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

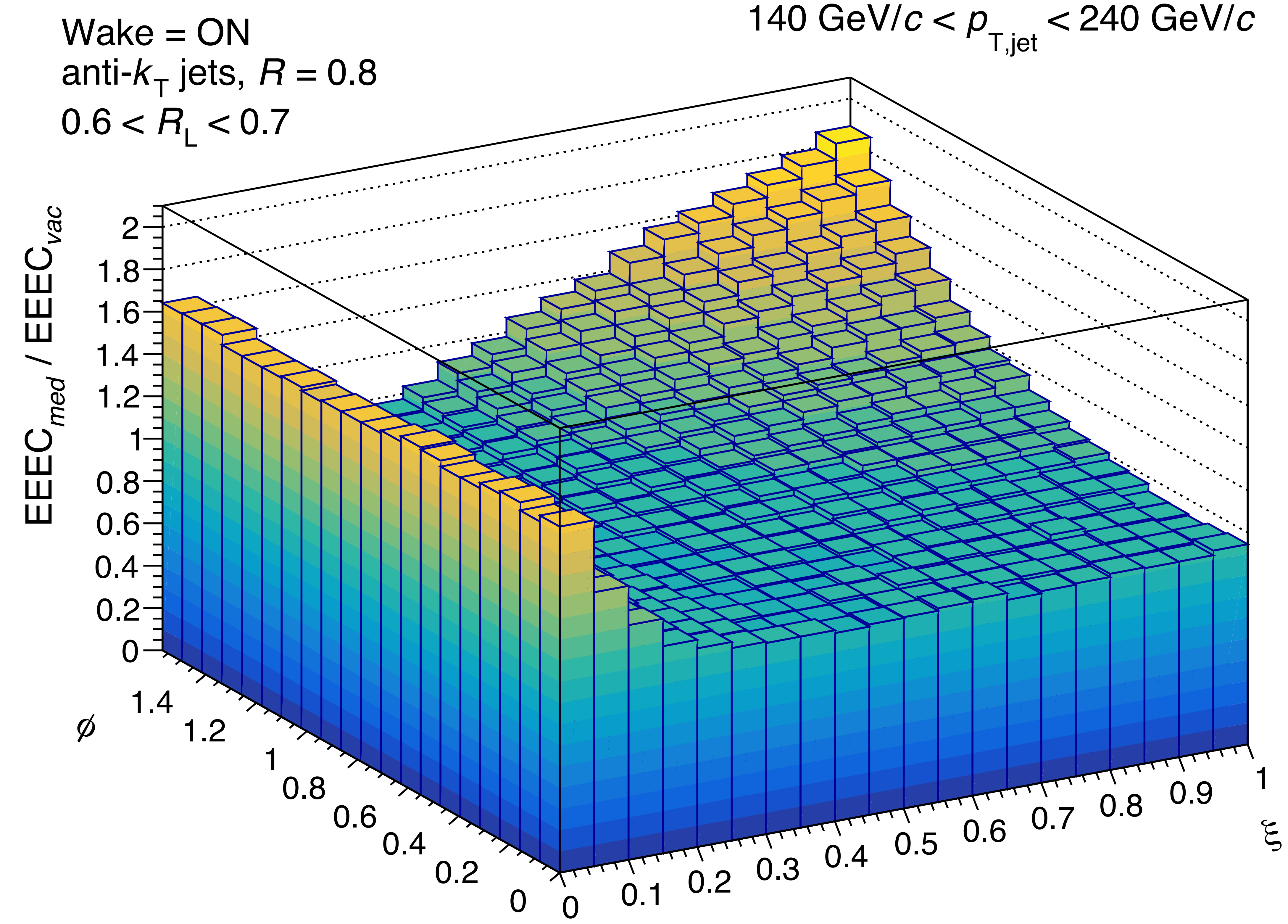
Outline: first discuss an idealized case, then go over some practical considerations for experimental applications!

Shape dependence in medium

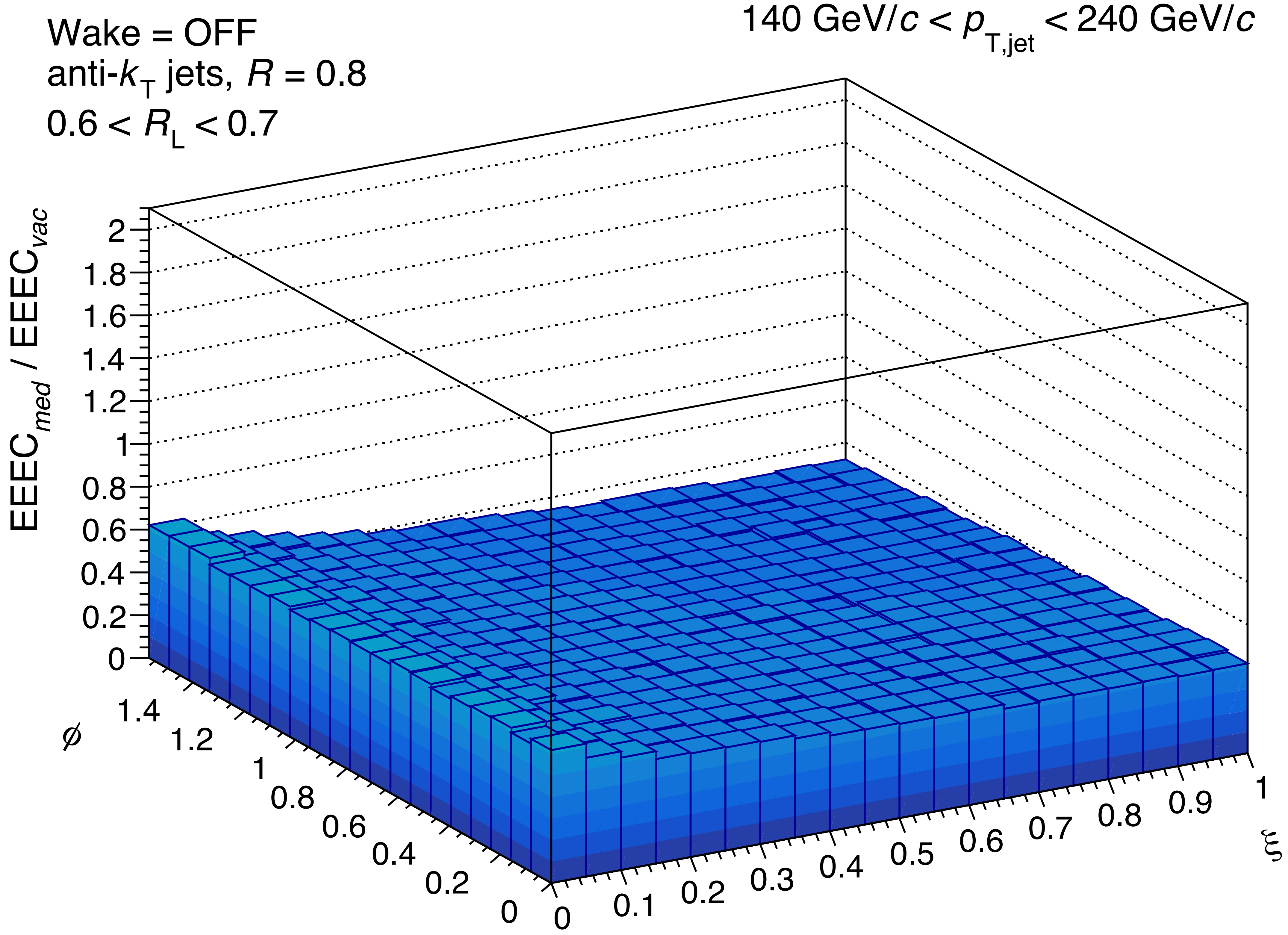


Rise in equilateral and collinear structures due to the presence of the uncorrelated wake!

Ratios to vacuum



Wake / vacuum



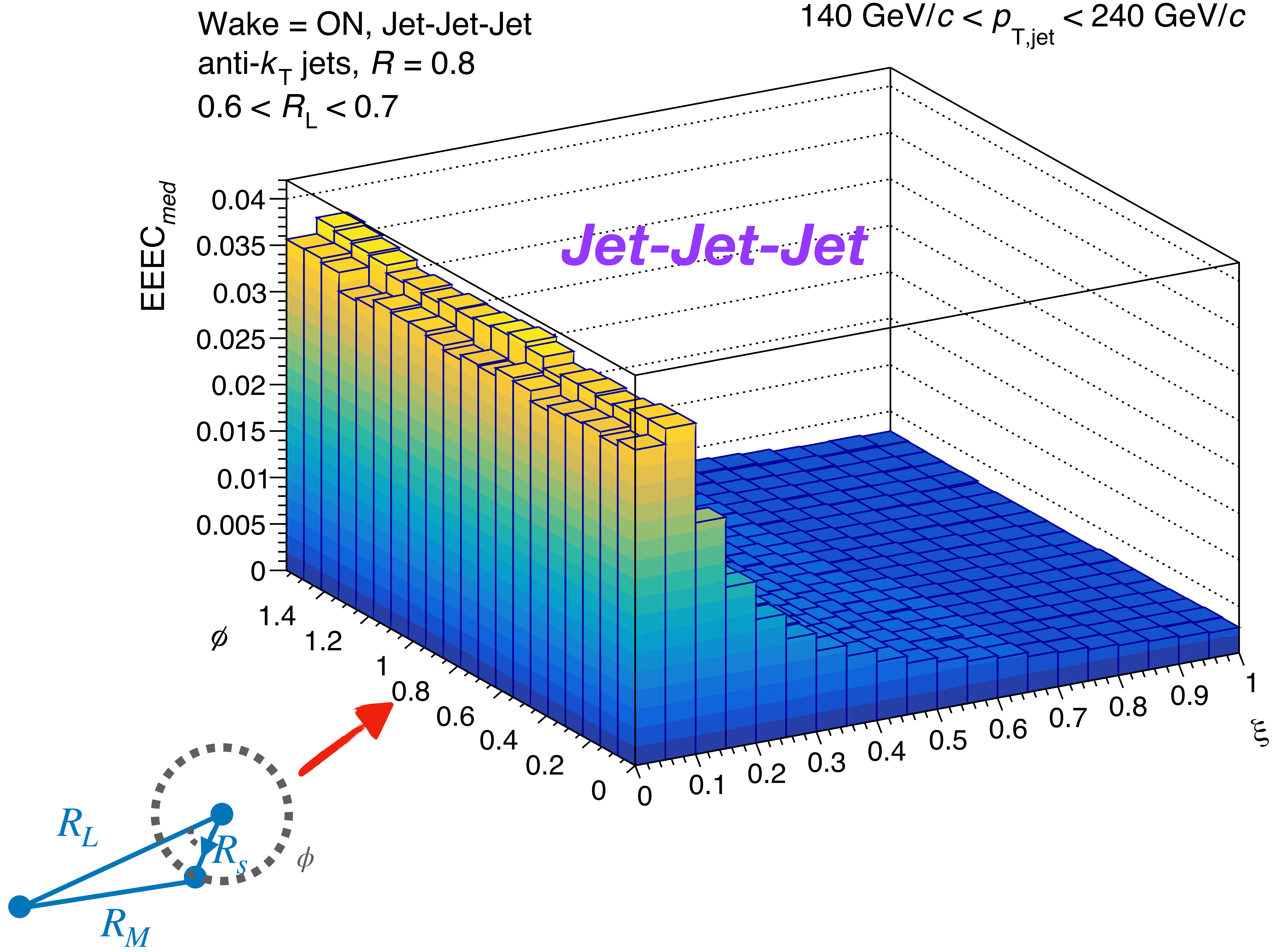
No wake / vacuum

Wake leaves clear signatures in comparison to vacuum!

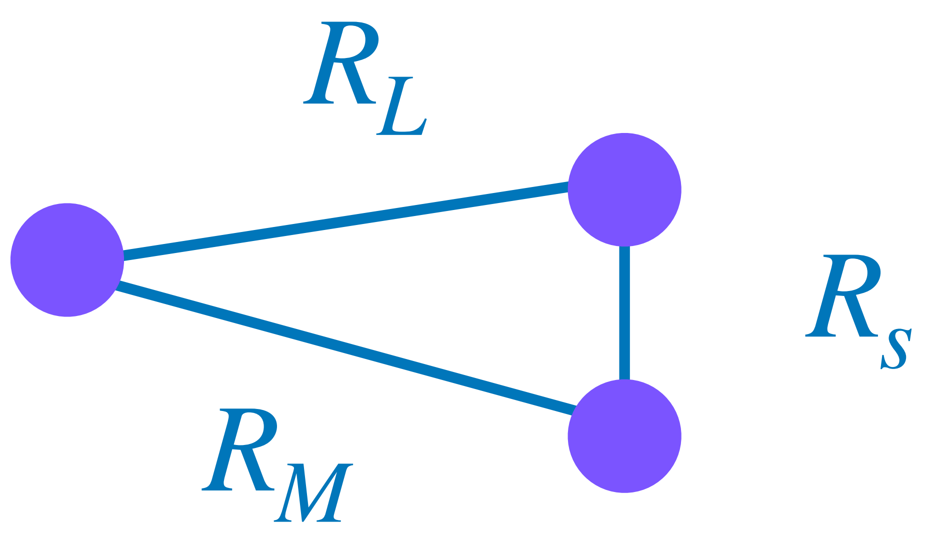
❃ Shape of medium response is encoded in these ratios!

Breaking down the contributions

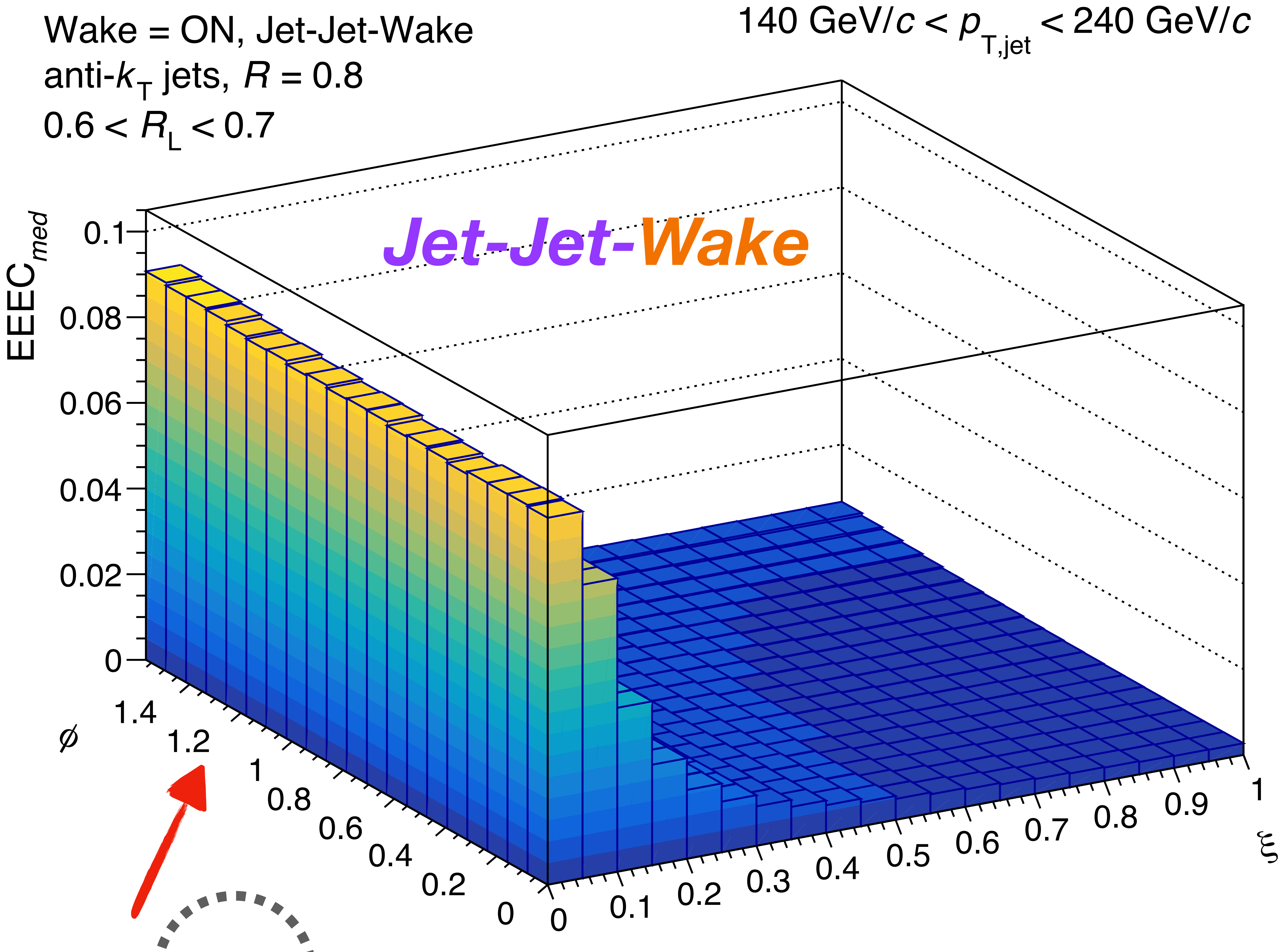
With hybrid model, we know which particles are from jet and which are from the wake! Show how each type of correlation contributes to the distribution!

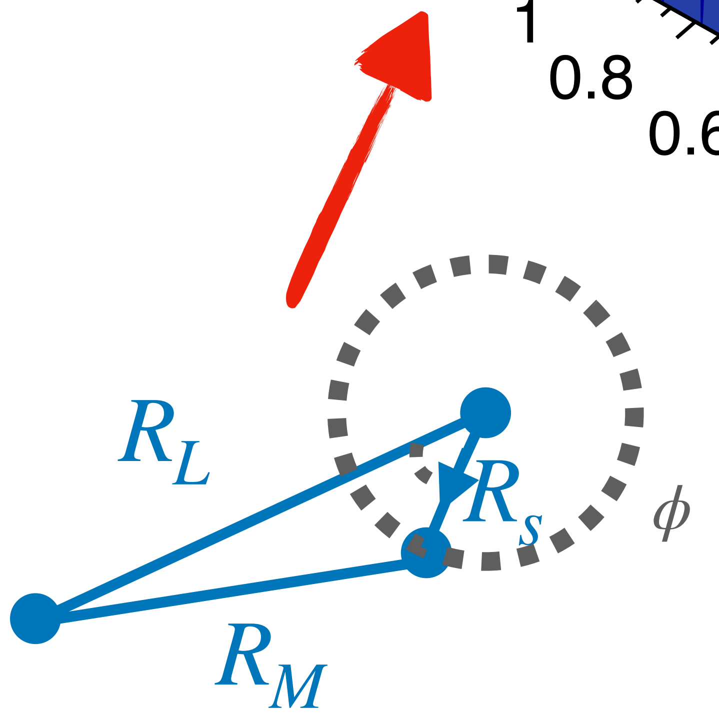


Jet correlations populate the collinear region, as expected.

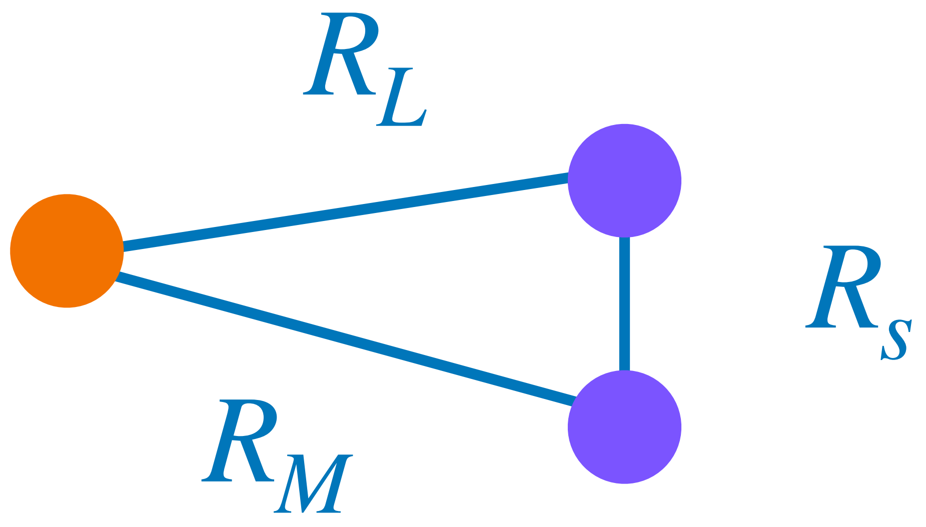


Breaking down the contributions

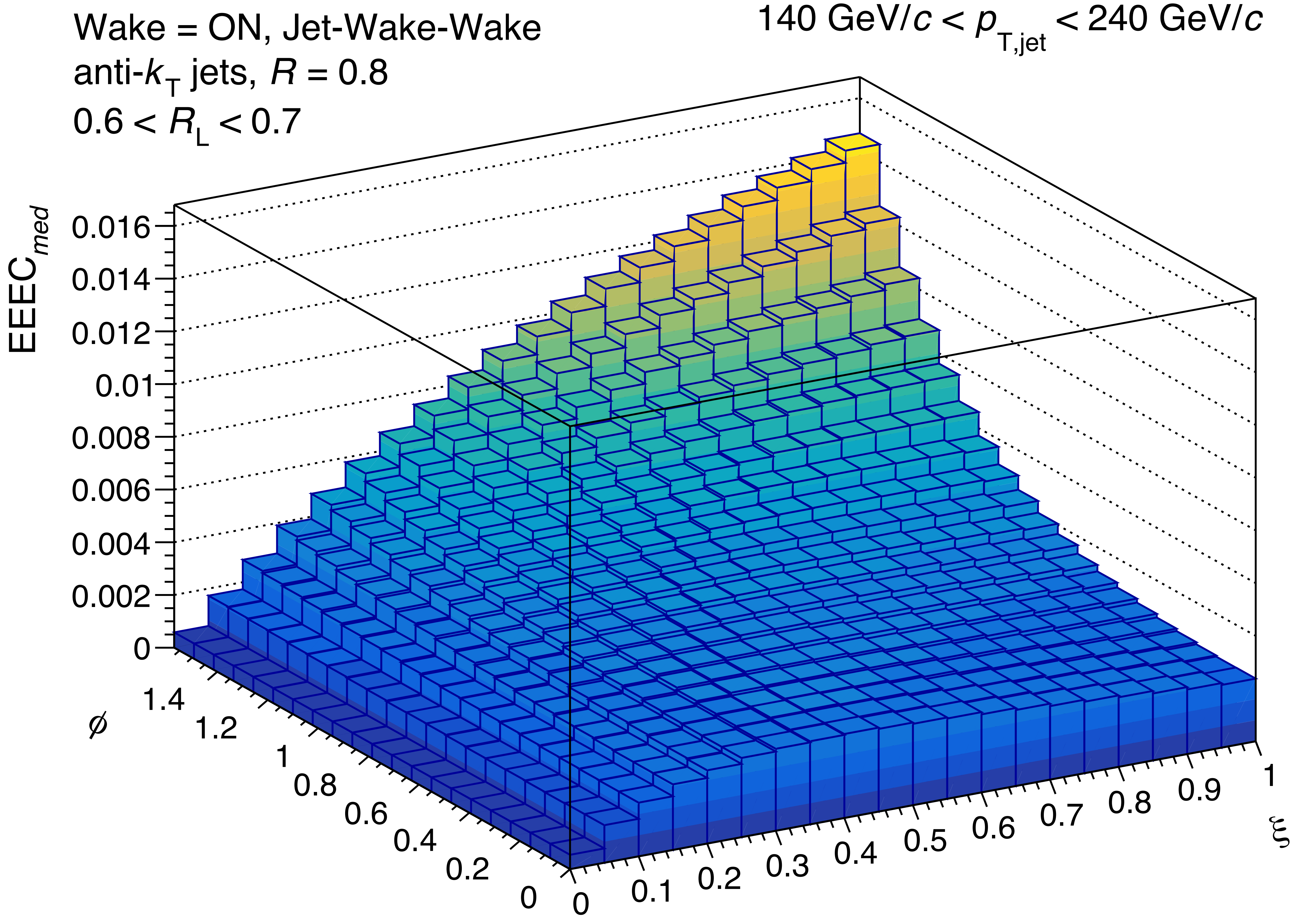




Correlations between the **jet** and the **wake** also populate the collinear region, leading to the enhancement seen in the ratio.

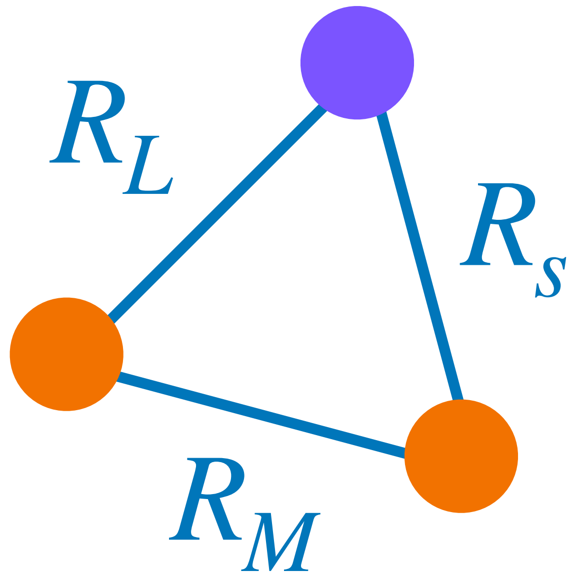


Breaking down the contributions

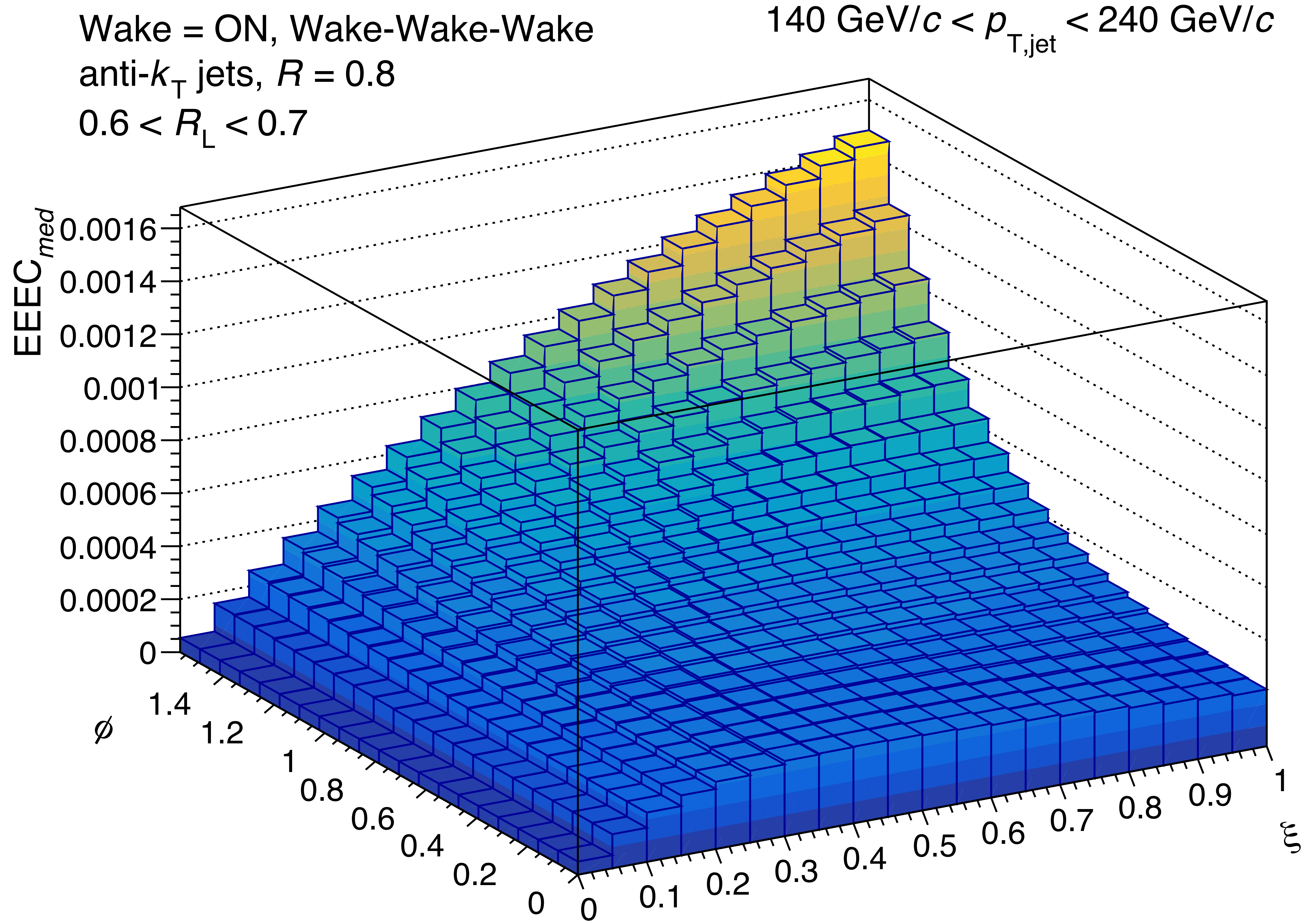


Jet-Wake-Wake

Correlations of **wake** particles with the **jet** fills in the equilateral structures!



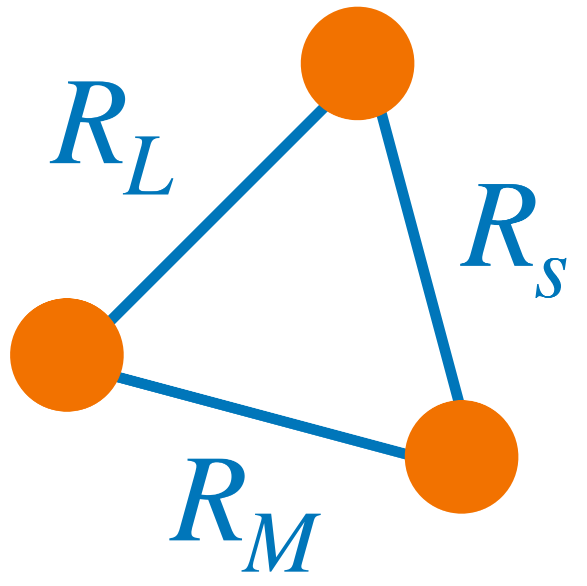
Breaking down the contributions



Wake-Wake-Wake

Wake correlations are dominated by equilateral structures!

Due to energy weighting, contribution to the total is small.



What to do in experiment?

- In experiment, we won't know which particles are from the wake and which are from the jet!

- Strategy will be to vary the EEEC in a way that is expected to enhance/suppress the wake and see what that does to the correlator.

  - Ex: Energy weighting (*n*), R_L

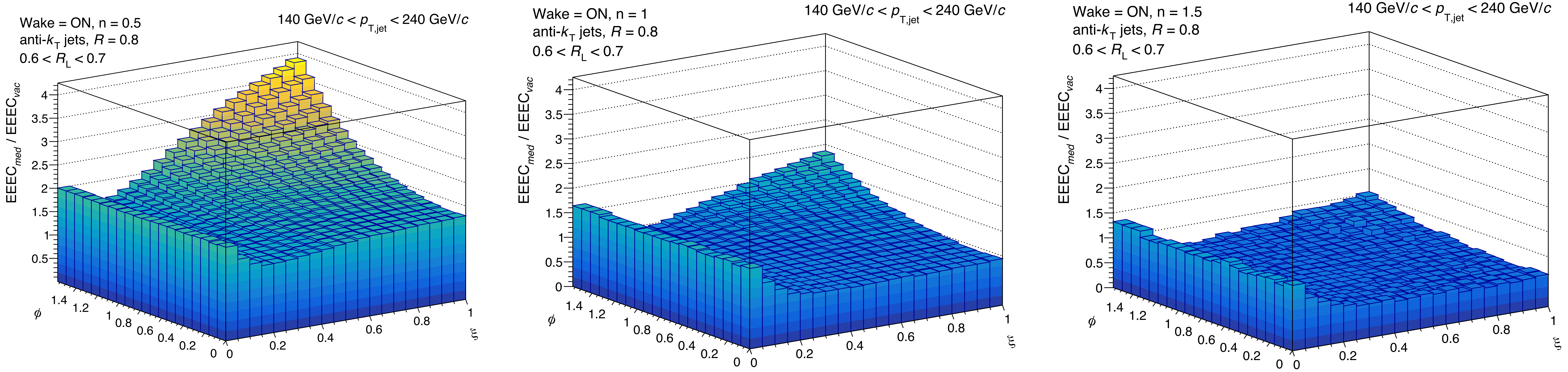
$$\mathrm{ENC}(R_L) = \left(\prod_{k=1}^{N}\int d\Omega_{\vec{n}_k}\right)\delta(R_L - \Delta\hat{R}_L)\cdot\frac{1}{(E_{\mathrm{jet}})^{(n*N)}}\langle\mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\ldots\mathcal{E}^n(\vec{n}_N)\rangle$$

Looking for dials that we can turn in experiment to show that there is sensitivity to the wake.

Energy weighting

- Can tune the energy weighting (*n*) to enhance or suppress contributions of low p_{T} particles **(where the wake sits)**

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

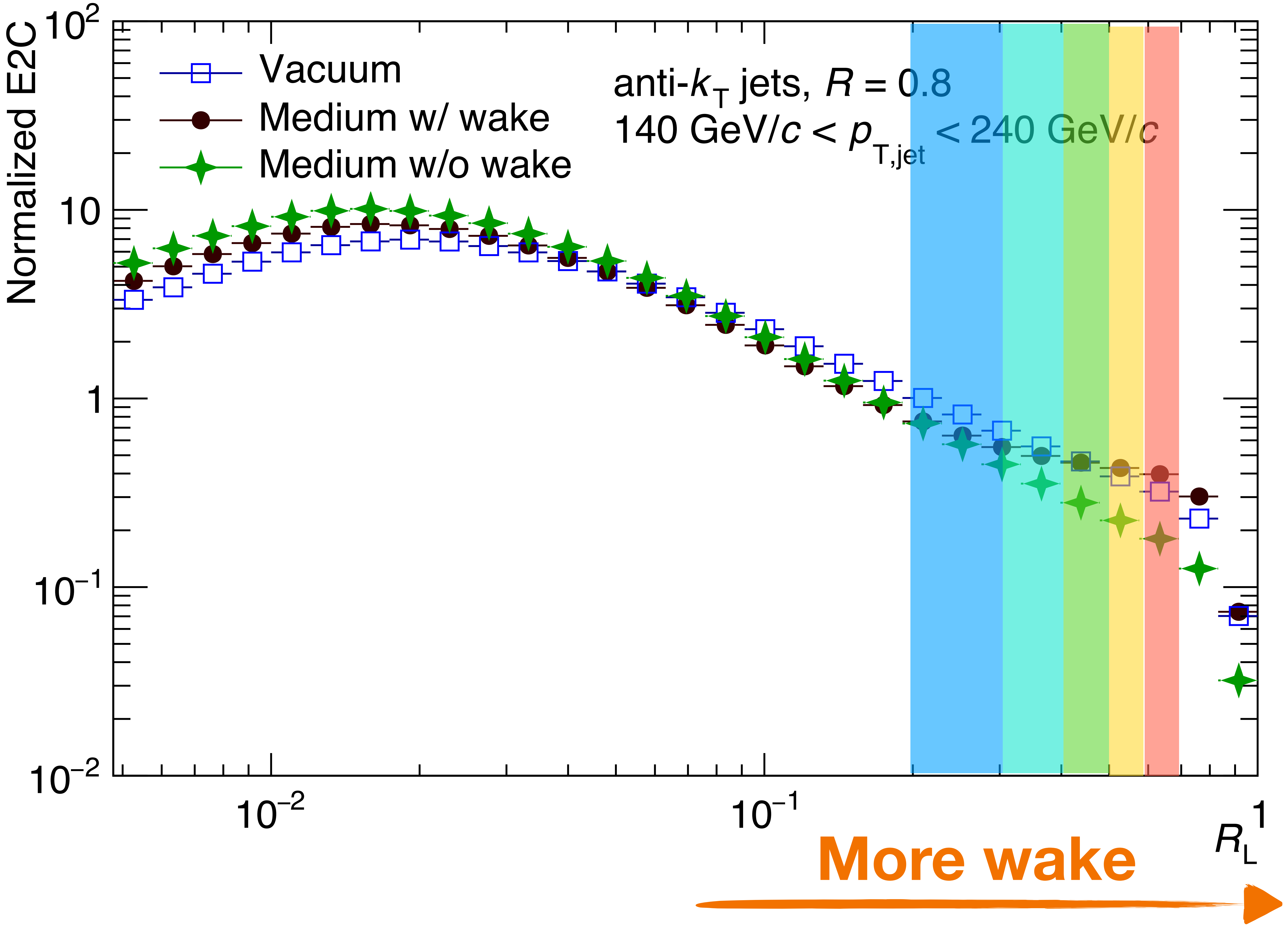


***n* = 0.5** ***n* = 1.0** ***n* = 1.5**

More wake

R_{L} scan

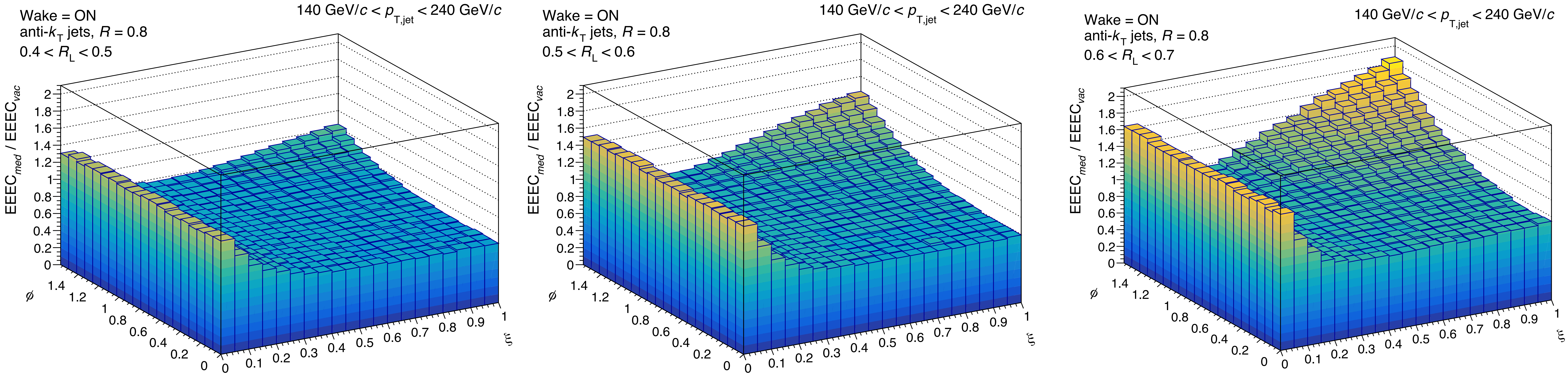
- Can use projected correlator to see which R_{L} values enhance sensitivity.



By shifting R_{L} , we expect to change sensitivity to the wake!

R_L scan

- Wake becomes more prominent at large angles (large R_L)



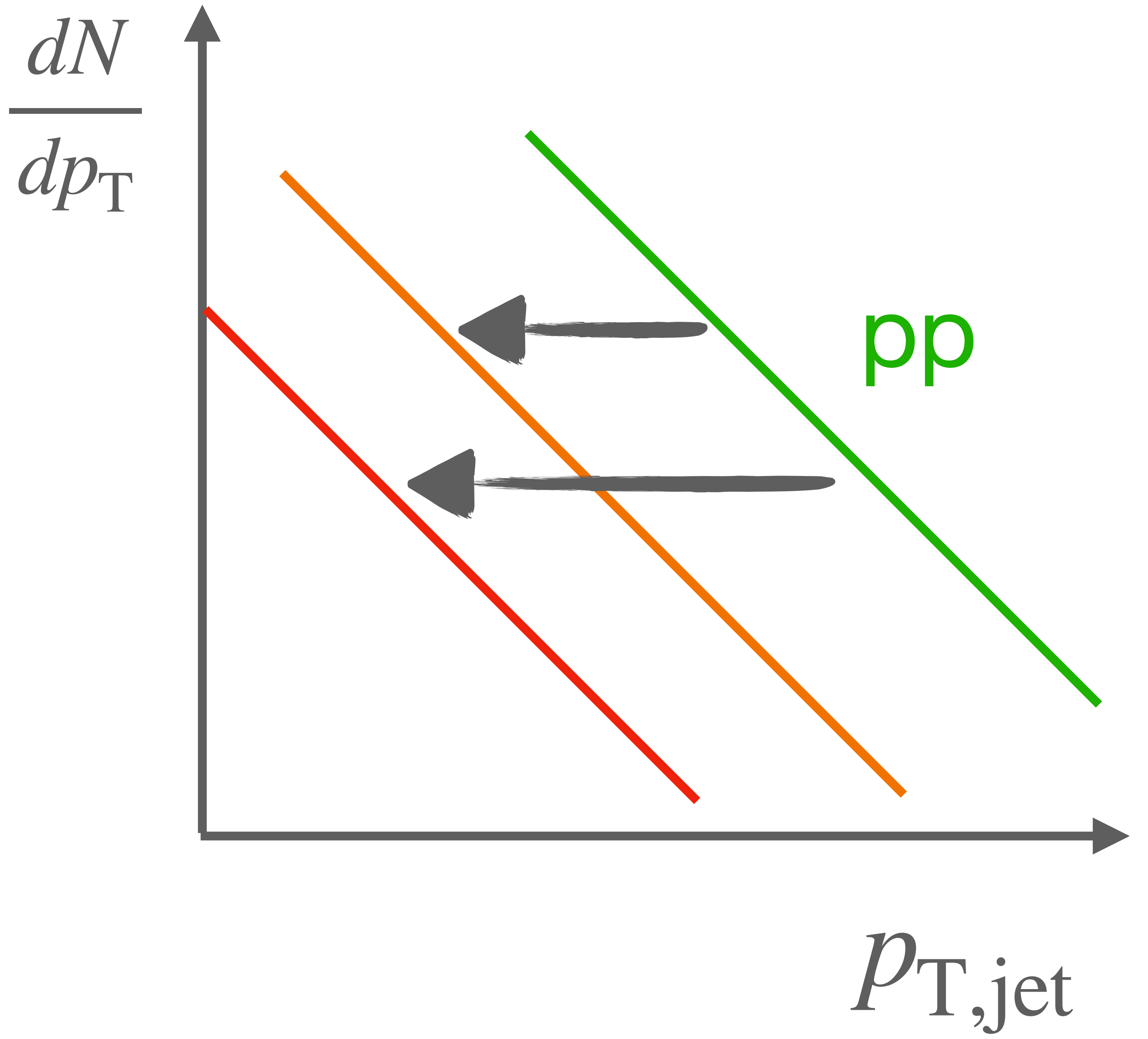
$0.4 < R_\mathrm{L} < 0.5$ $\quad$ $0.5 < R_\mathrm{L} < 0.6$ $\quad$ $0.6 < R_\mathrm{L} < 0.7$

More wake →

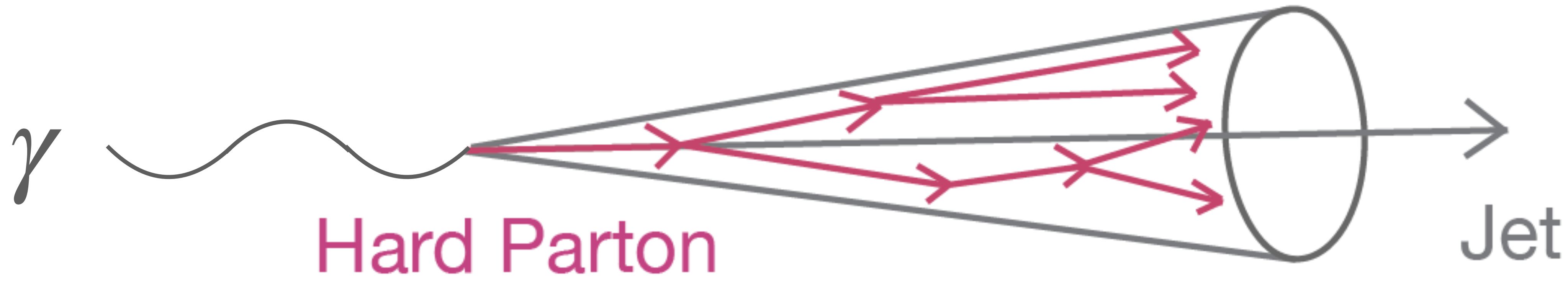
Selection bias

See [Fabio's talk](#) from yesterday!

- Important additional check how the behaviour seen in the EEECs is impacted by selection bias where jet population at a fixed p_T changes in comparison to vacuum [Brewer et. al: PRL.122.222301]

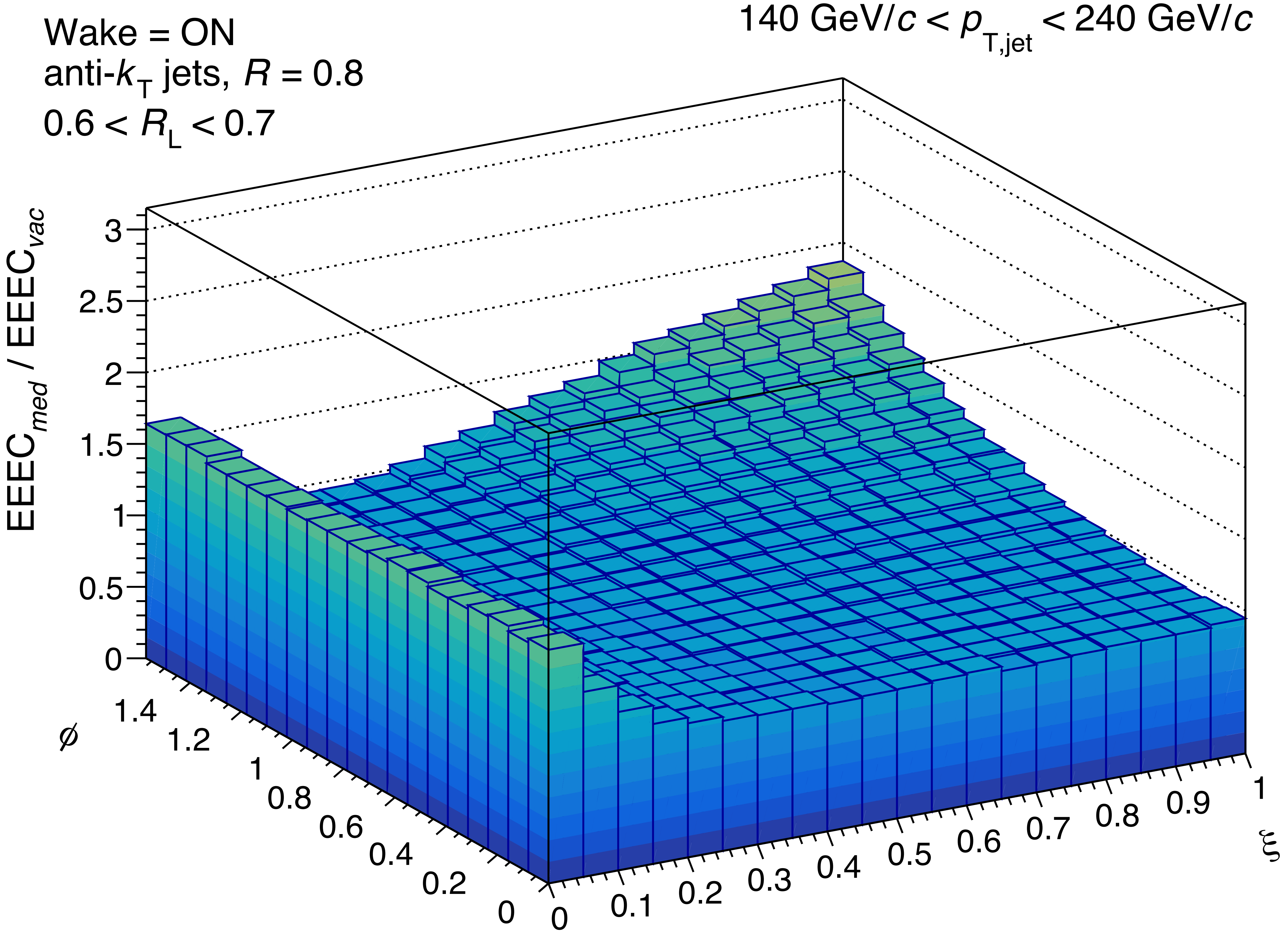


- γ-tagged jets are a good way to overcome this! EM probes have long mean free path relative to the size of the QGP (negligible interactions).

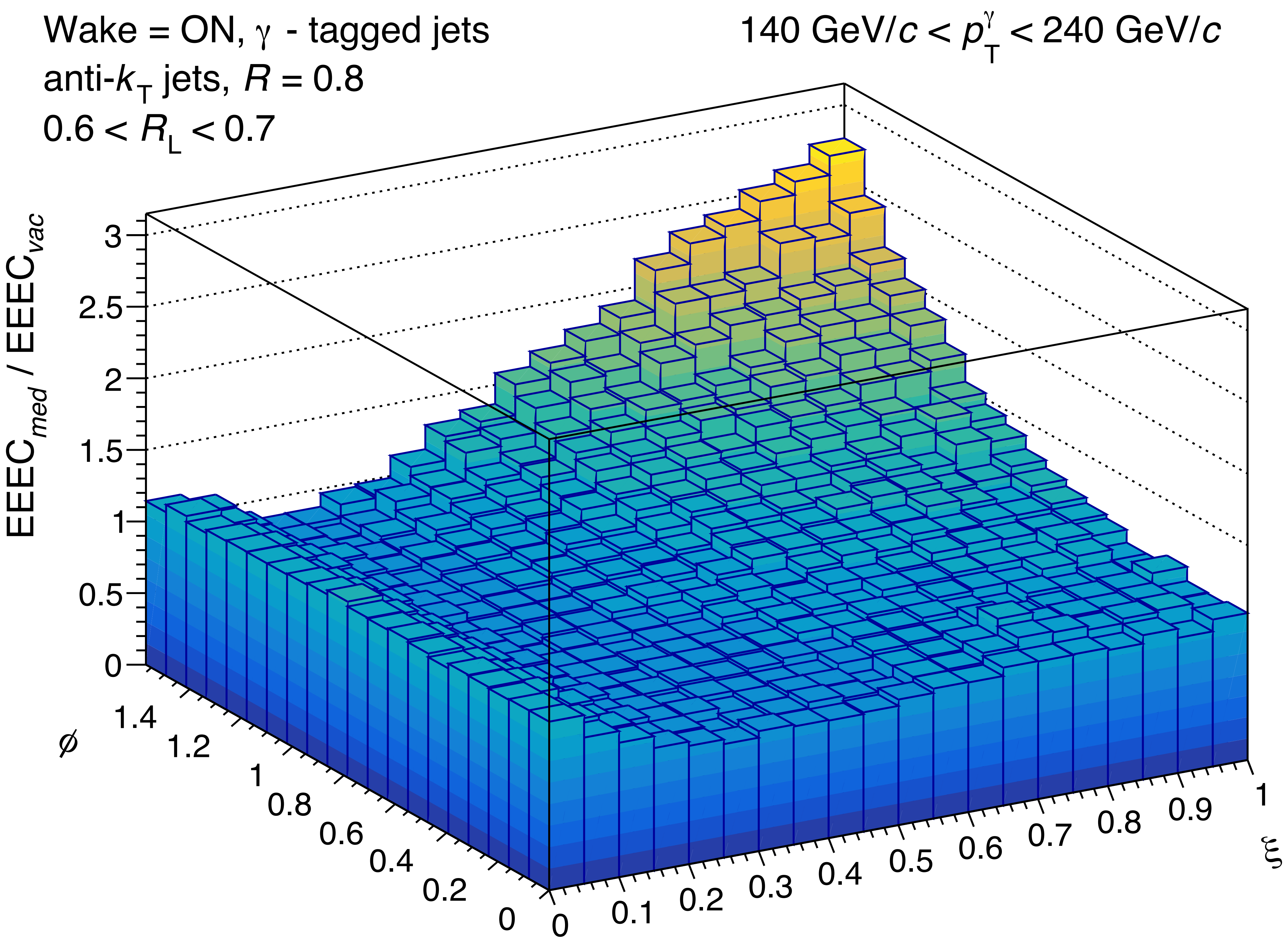


See Yen-Jie's talk

γ - tagged EEEC



Inclusive Sample



γ-tagged Sample

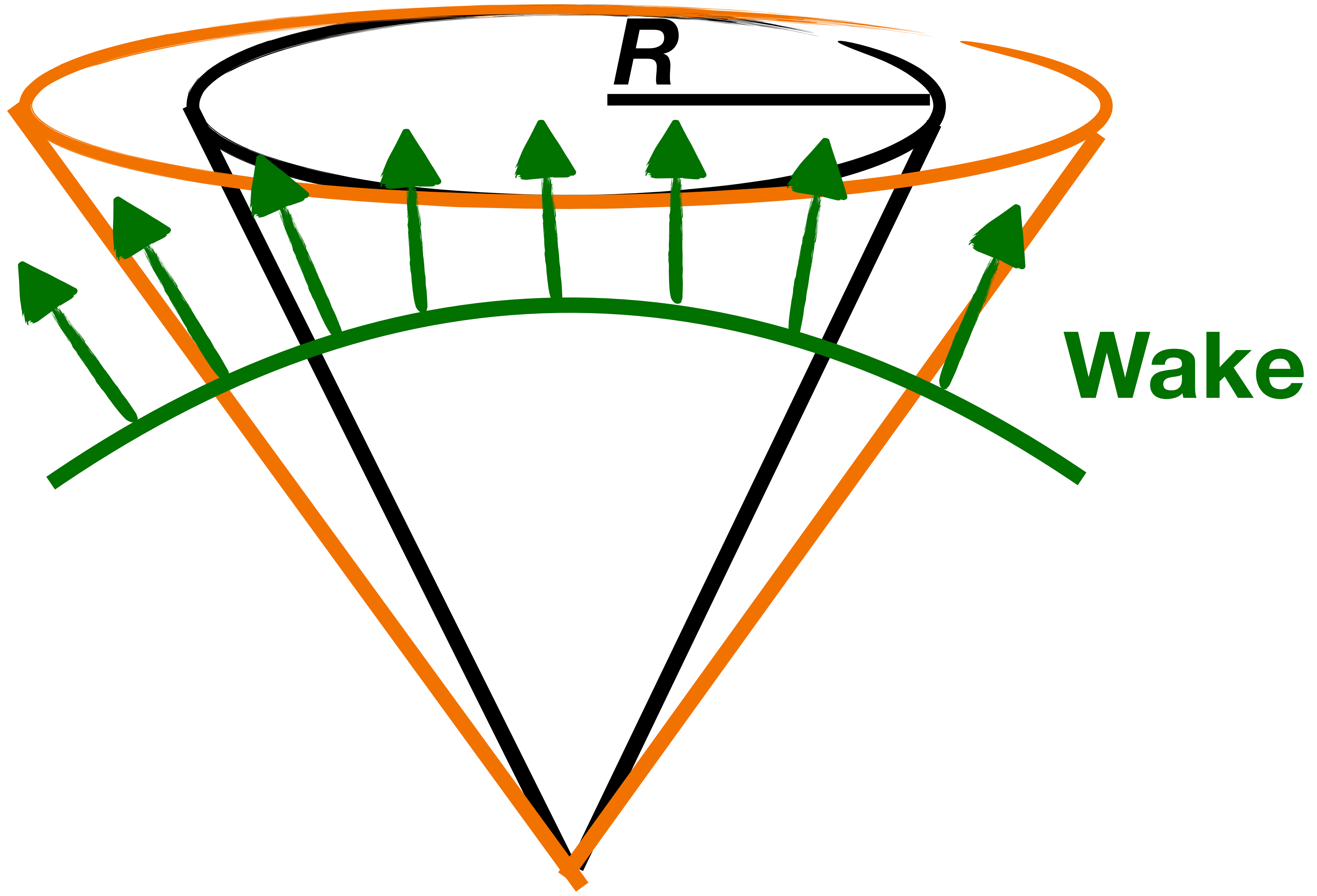
Using γ-tagged jets removes selection bias and greatly enhances sensitivity to the wake!

Experimental considerations

We presented an idealized case, but experimental measurements of EEECs in heavy-ions will have some challenges (opportunities).

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

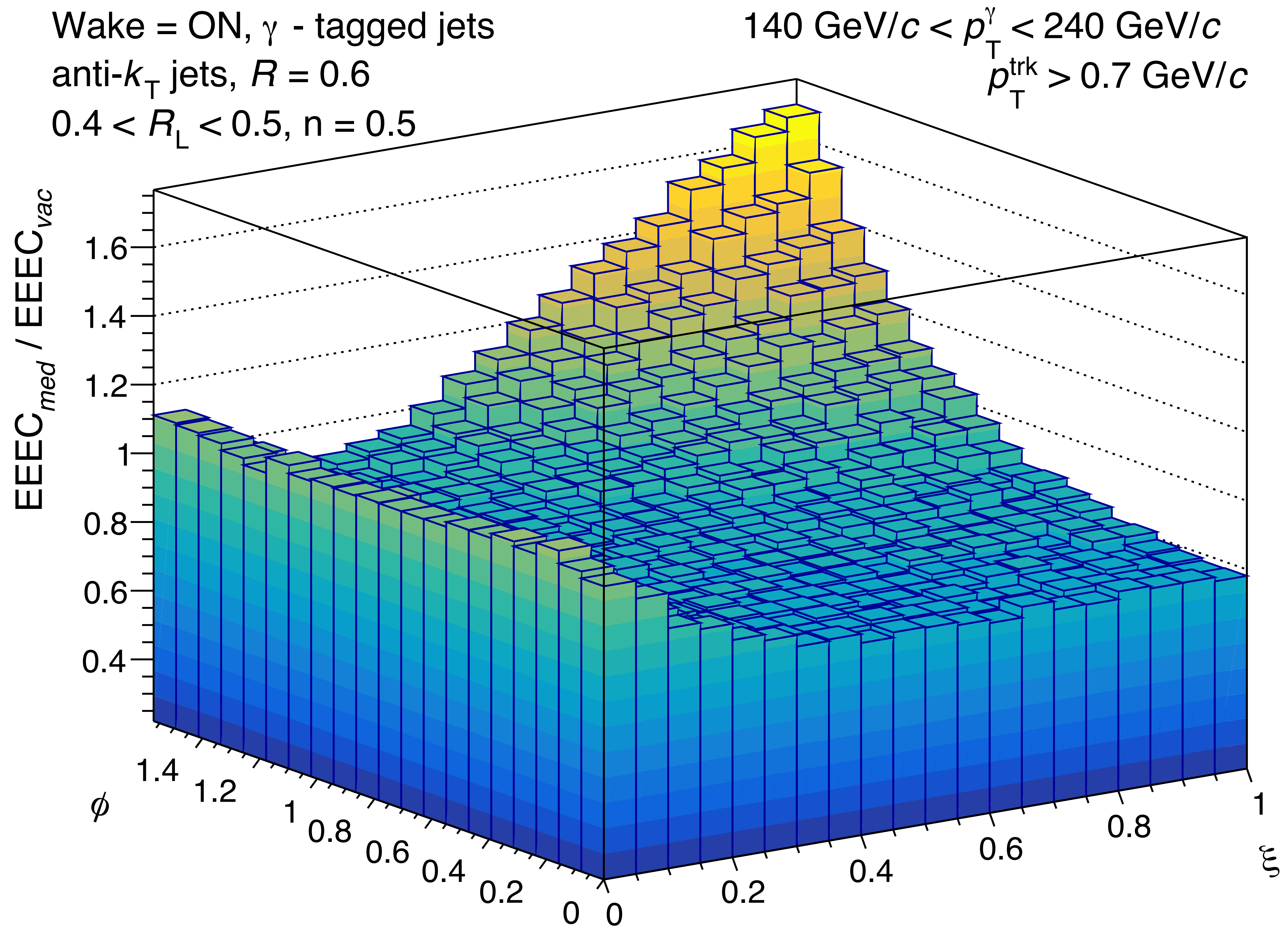
→ Detector acceptance and large background contributions $\propto R^2$



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

Let's present a more realistic experimental case!

Experimental case



- R = 0.6 inclusive jets measured in experiments

  ALICE: [PLB 849 (2024) 138412]

  CMS: [JHEP 05 (2021) 284]

- Recent progress on γ/Z-tagged jets

  ATLAS: [PLB 846 (2023) 138154]

  STAR: [arXiv:2309.00145]

  CMS: [arXiv:2405.02737]

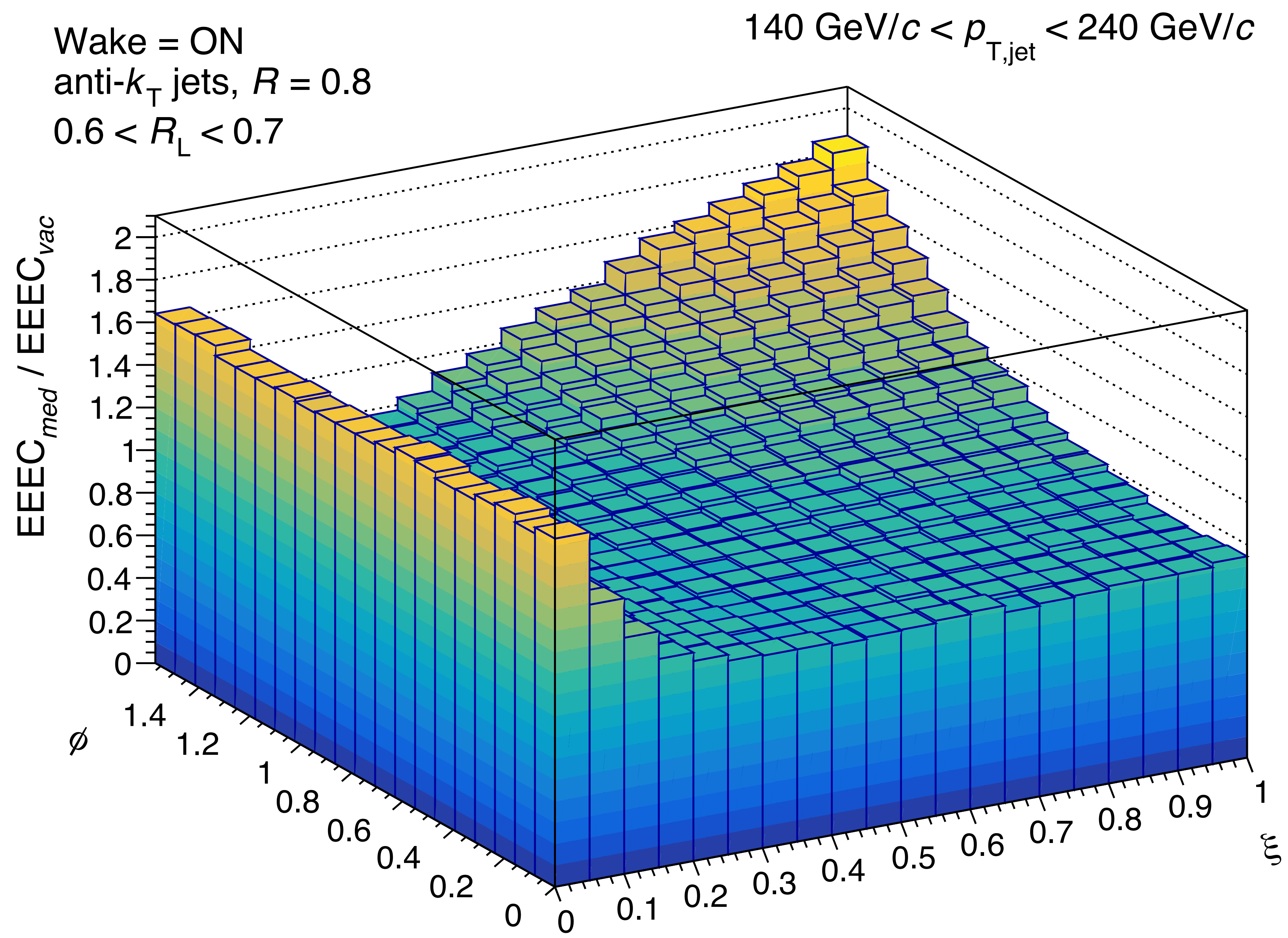
  [PRL 128 122301 (2022)]

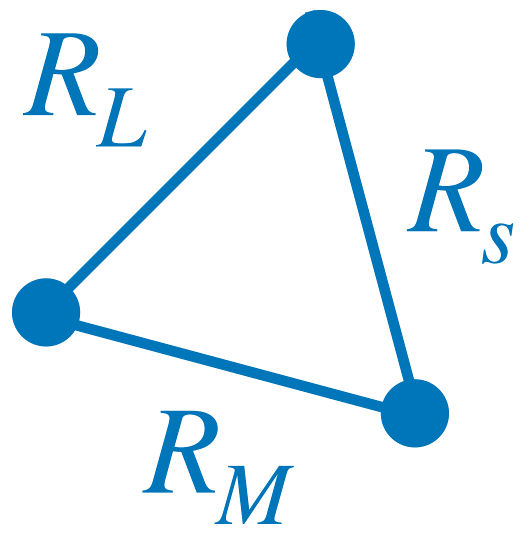
Wake effects still visible even in more realistic experimental environment!

See Yen-Jie's and Jussi's talk for experimental progress!

Summary & Conclusions

- We have presented the first exploration of the shape dependence of full higher-point energy correlators in heavy-ion collisions!
- Encode the shape of the medium response!
- When comparing in-medium distributions to vacuum, we see a large and clear wake signal!





Why does the wake prefer equilateral triangles??

See Arjun's talk next!

Backup

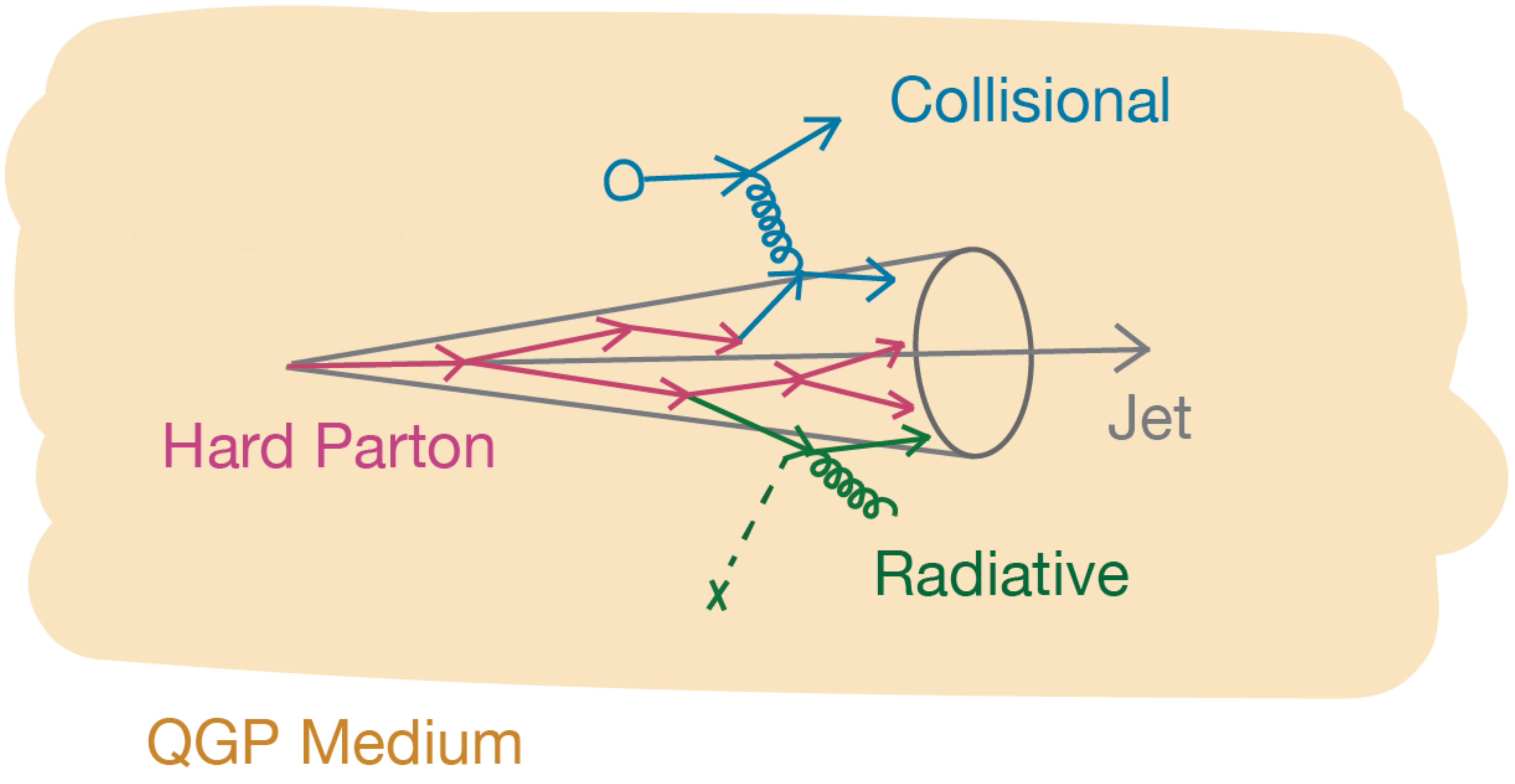
Jet quenching

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

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

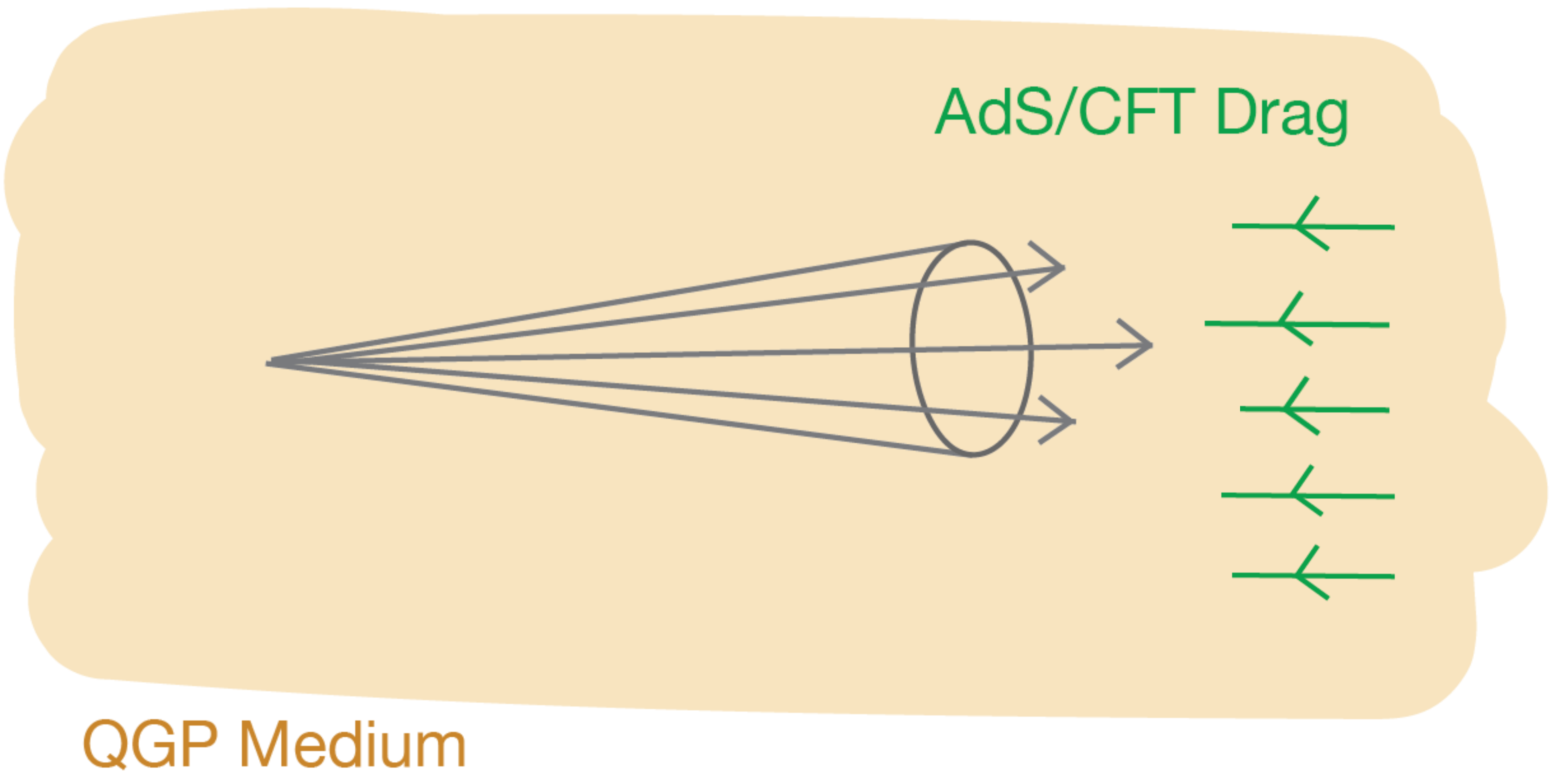
Ⓐ Weak coupling limit

- ❃ Collisional
- ❃ Radiative



Ⓑ Strong coupling limit

- ❃ AdS/CFT drag force



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

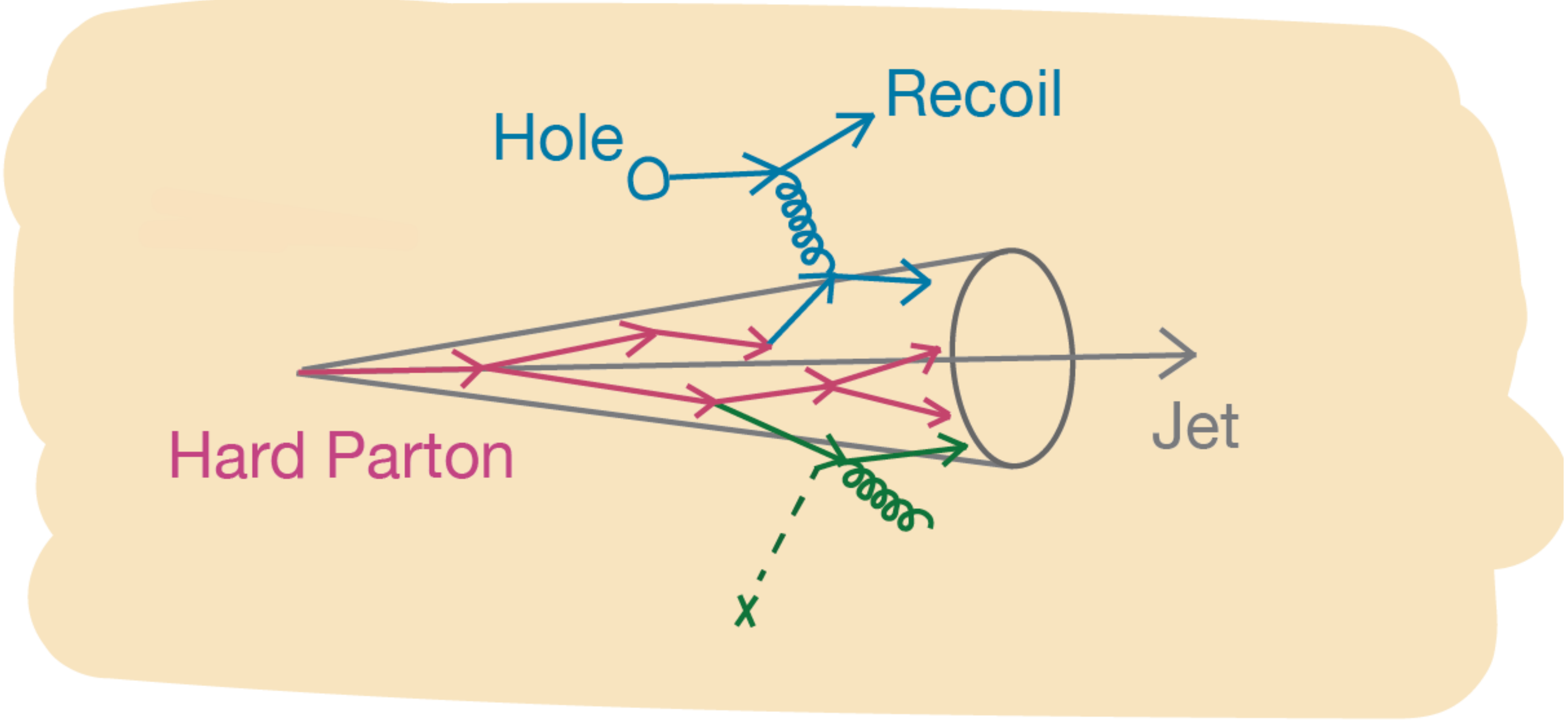
Jet quenching

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

② Impact of the jet on the medium → medium response

Ⓐ Weak coupling limit

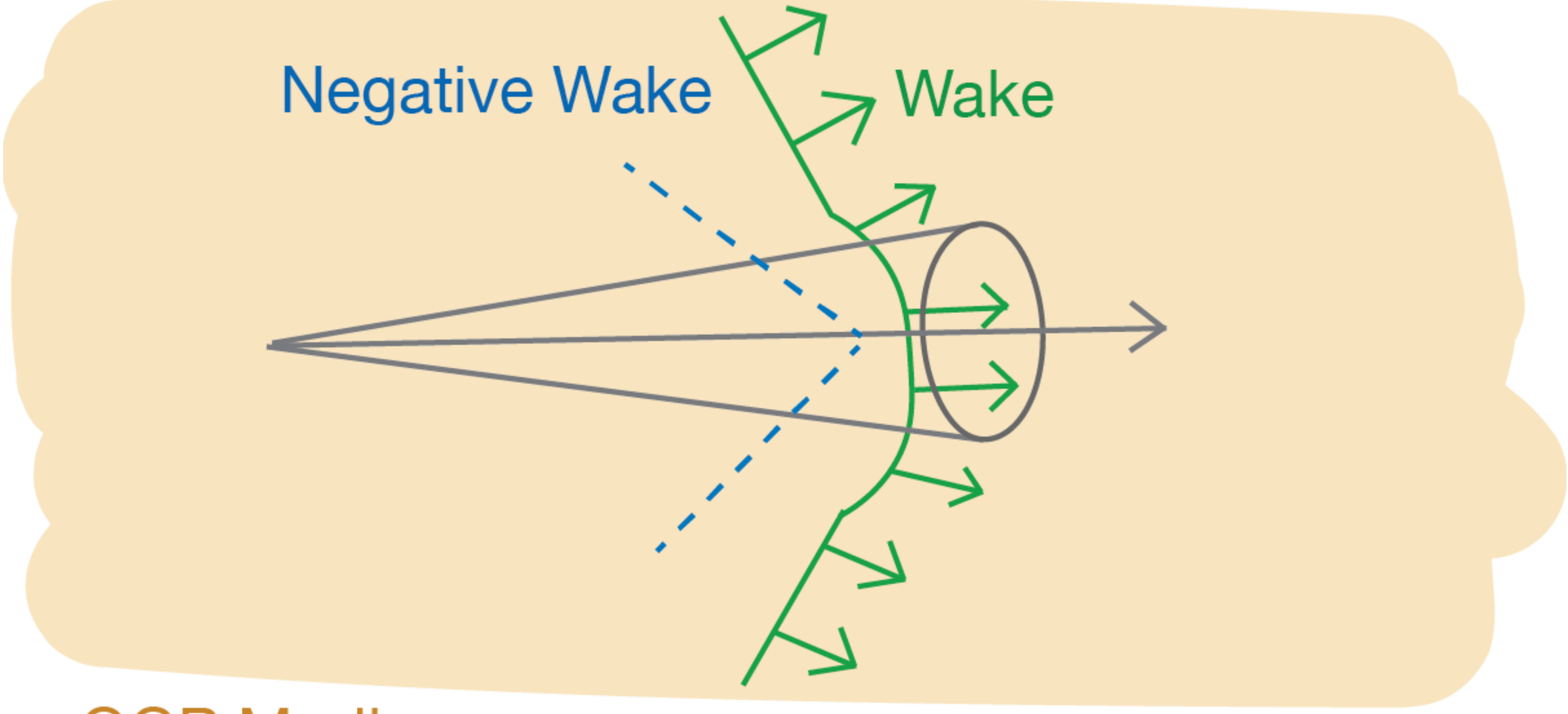
- ✽ Recoils (Kinetic based approach)



QGP Medium

Ⓑ Strong coupling limit

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



QGP Medium

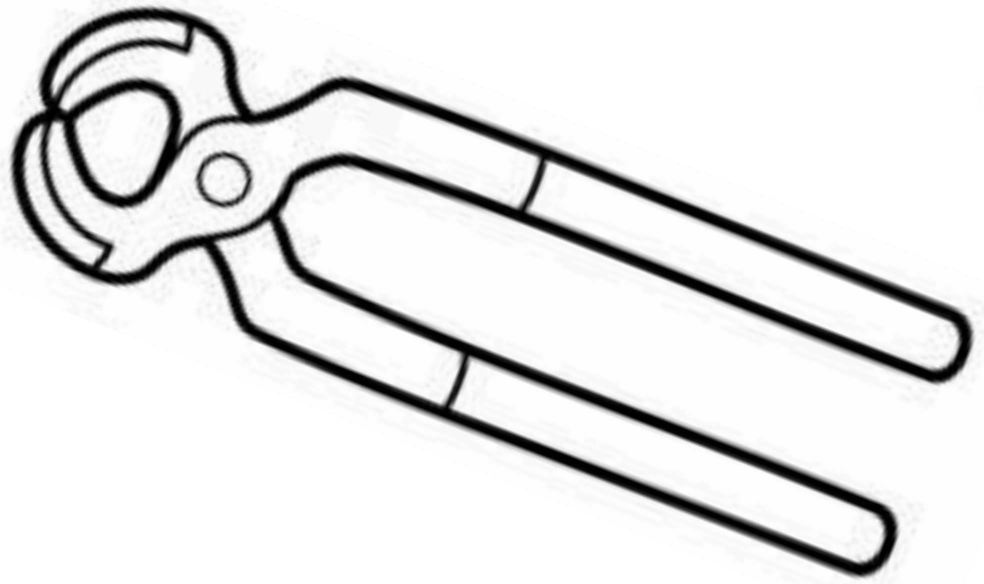
*** Cartoon of the wake in position space*

Focus of this talk: study medium response effects!

Tools to search for the medium response

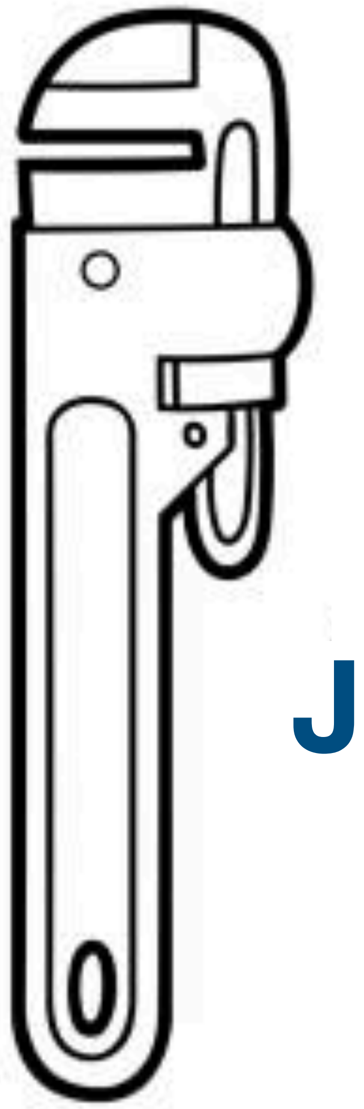
What tools exist to study the medium response?

Z-hadron

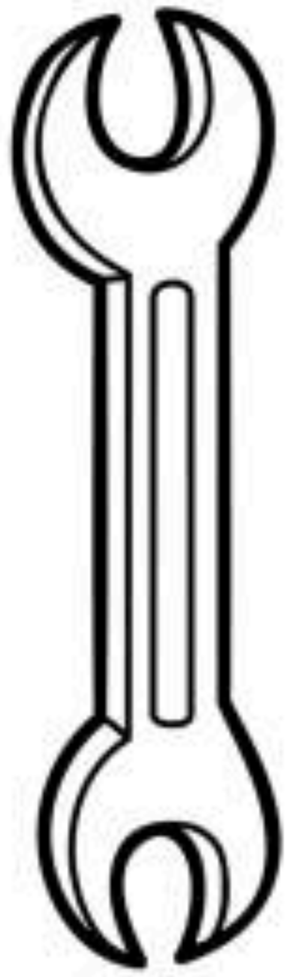


γ/Z-jet

(Groomed) jet substructure

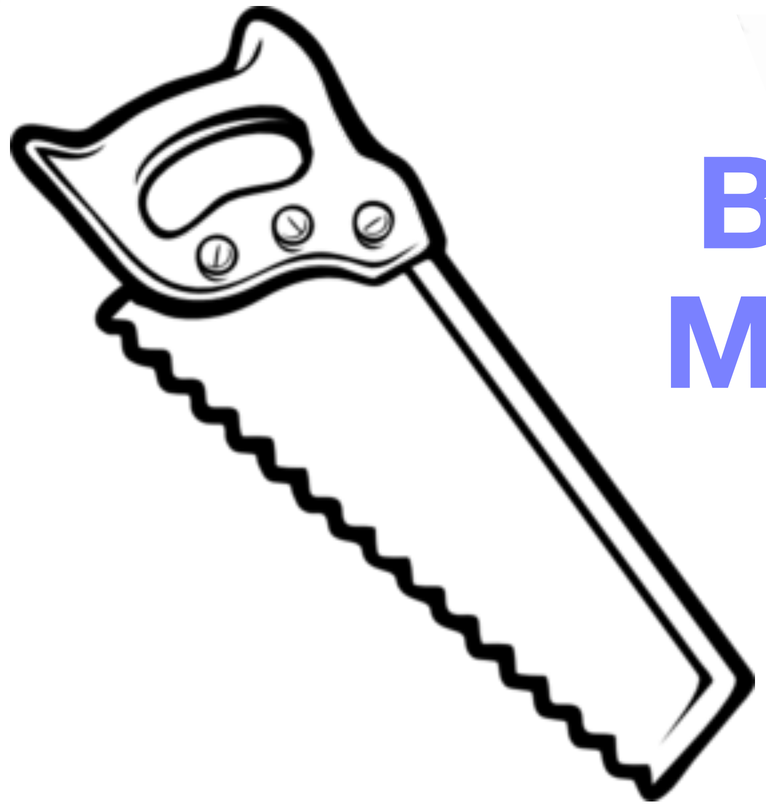


Jet Shapes



R-dependent inclusive jet measurements

Jet-Hadron correlations



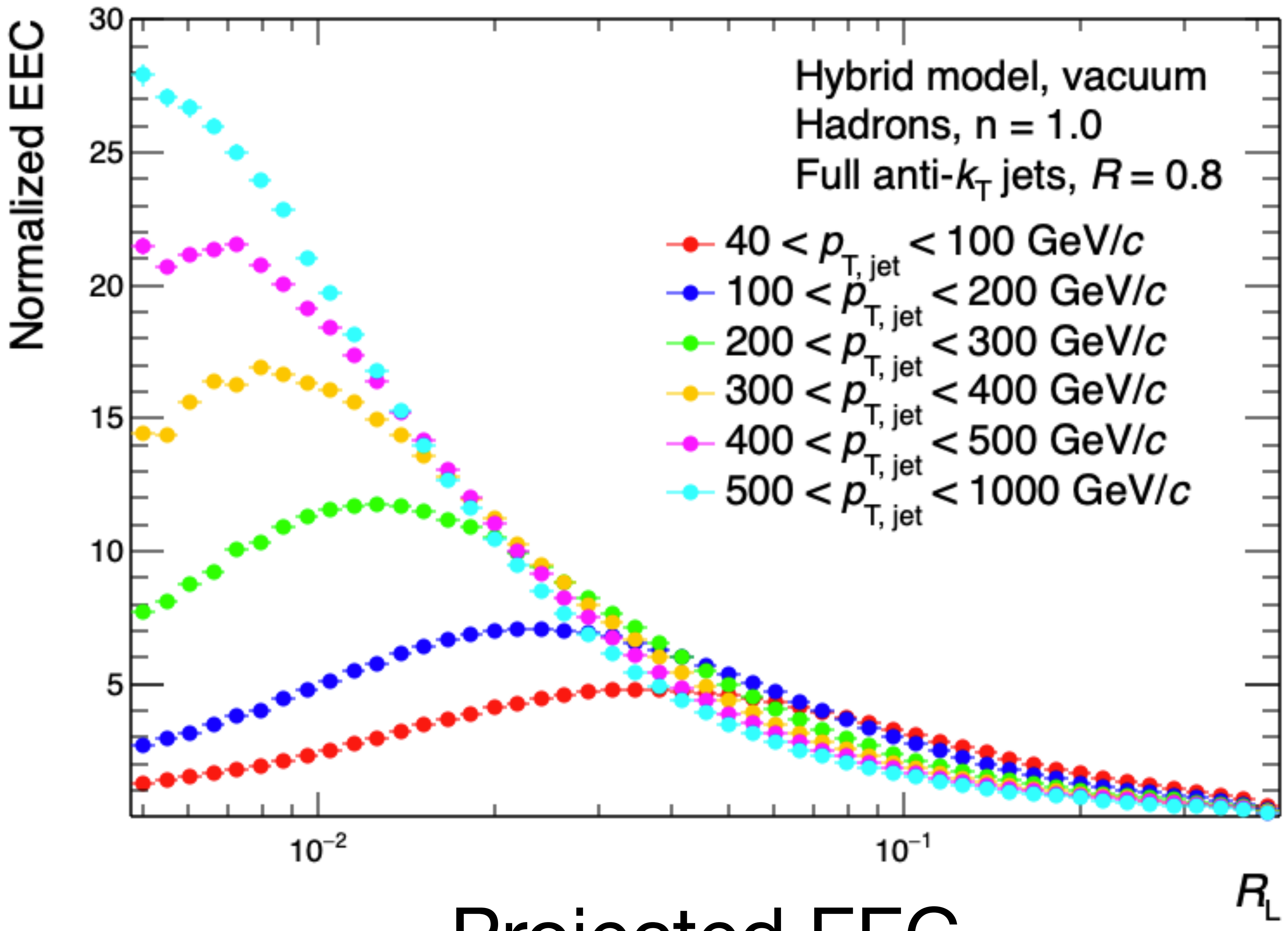
Baryon-to-Meson ratio near jets

Some tools are better than others!

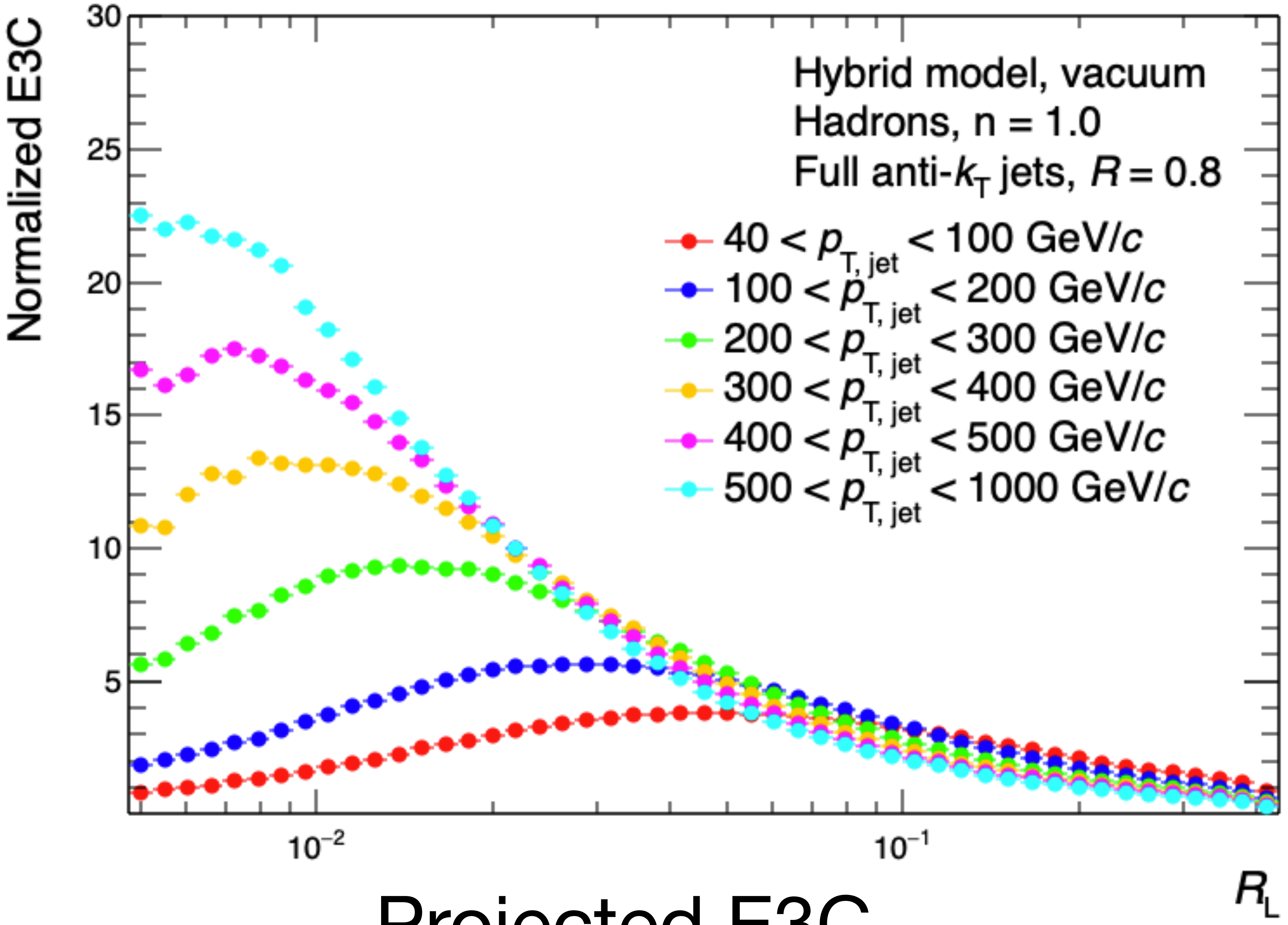
New tools or a combination often needed!

Projected correlators in vacuum

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



Projected EEC

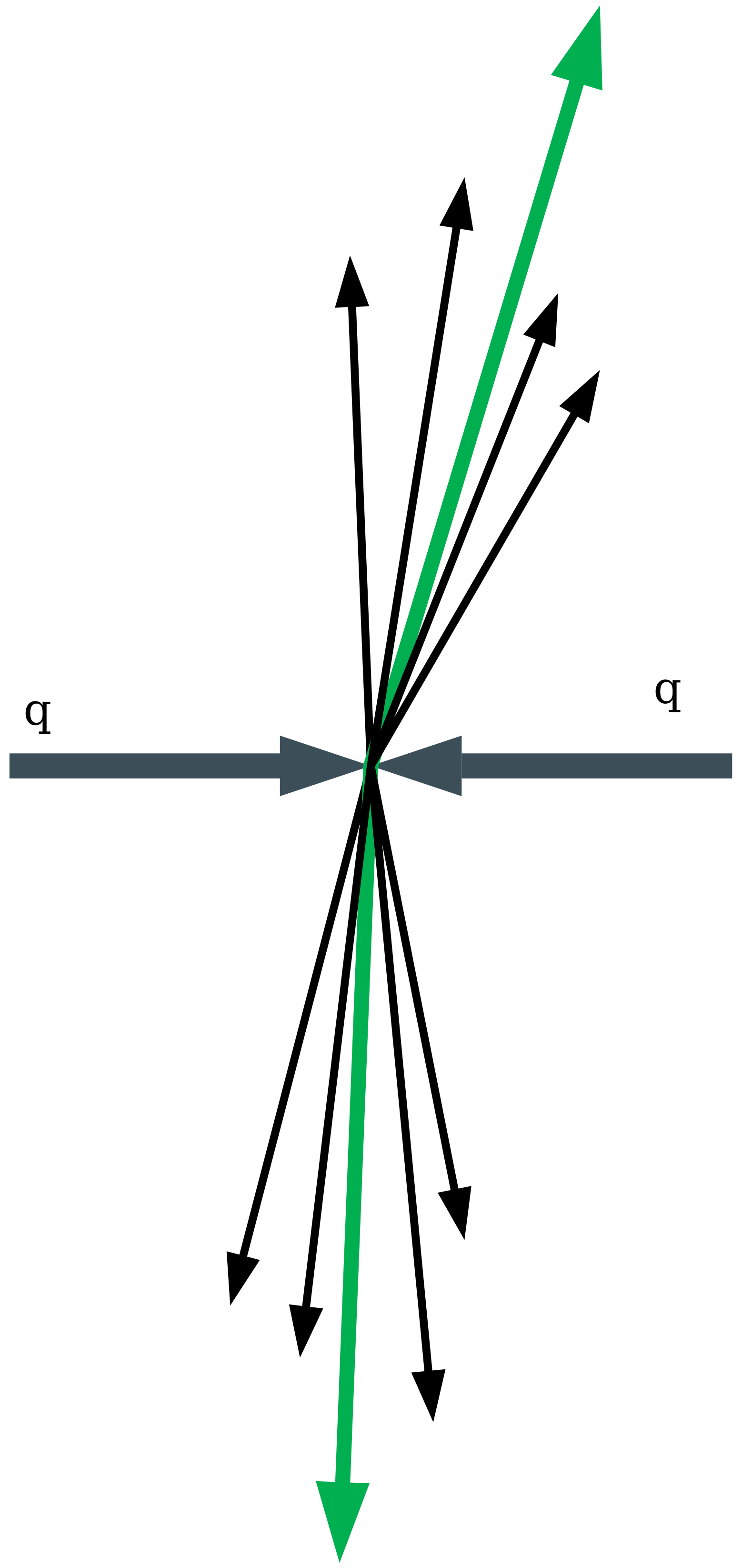


Projected E3C

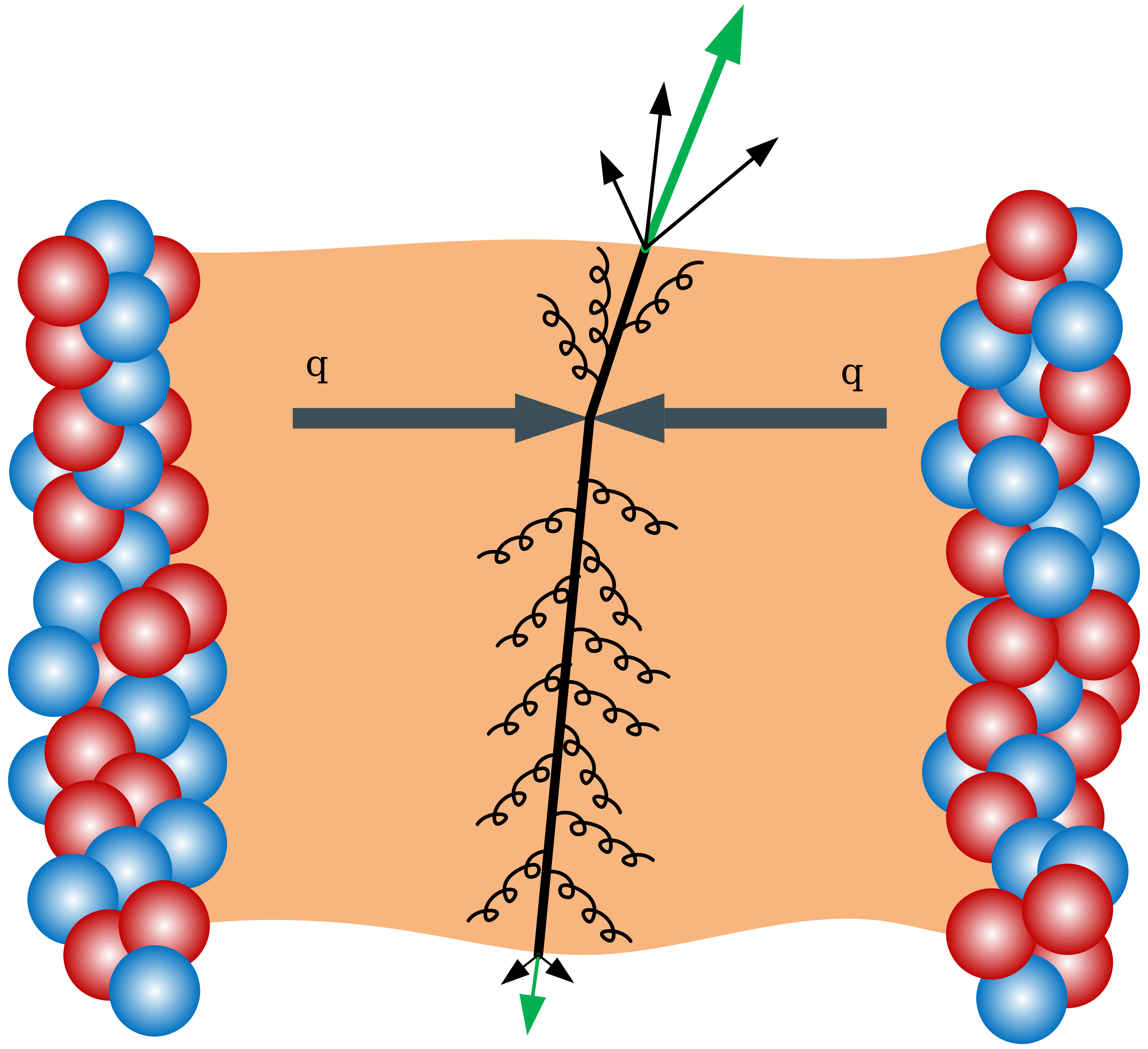
- Projected EEC and E3C show similar features.
- Peak position is roughly $\Lambda_{QCD}/p_{T,jet}$

What happens when we include the wake?

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!