Coordinates for, and Explorations of, Jet Wakes in Energy-Energy-Energy Correlators

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Imaging the Wakes of Jets with EEECs: Roadmap

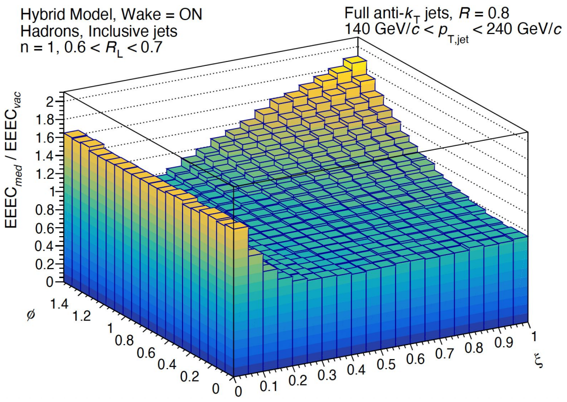
What are wakes and what is the hybrid model?

How can projected correlators be used to probe QCD?

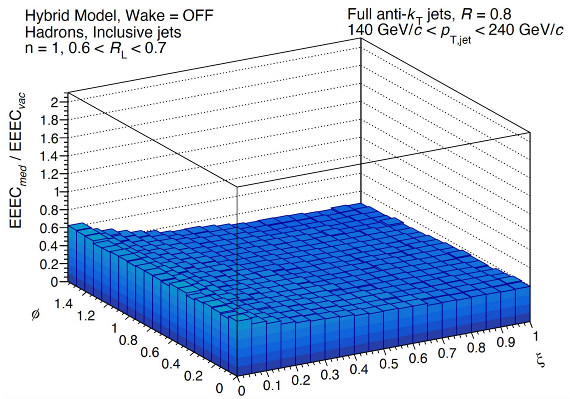
What new things can the shape-dependent energy-energy-energy correlator add?

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

Pb+Pb with wake / vacuum



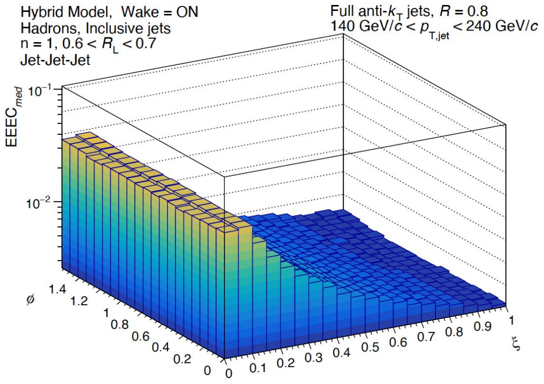
Pb+Pb without wake / vacuum



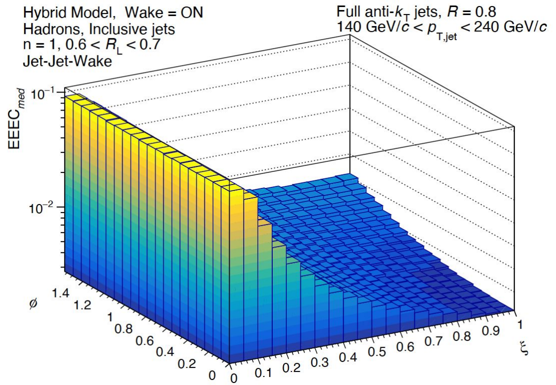
- Correlations involving wake particles populate the equilateral and collinear regions of the Pb+Pb EEEC at a fixed R_L slice of $0.6 < R_L < 0.7$.
- So, we see an enhancement in these regions of the (ξ, ϕ) space when we take the ratio of the Pb+Pb EEEC (with wake) to the vacuum EEEC.

CONTRIBUTIONS TO THE Pb+Pb EEEC… (SEE HANNAH'S TALK)

jet-jet-jet

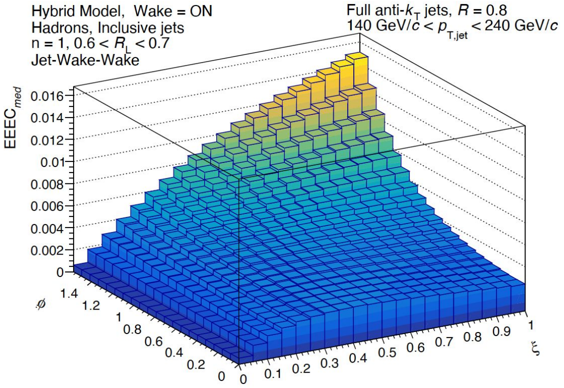


jet-jet-wake

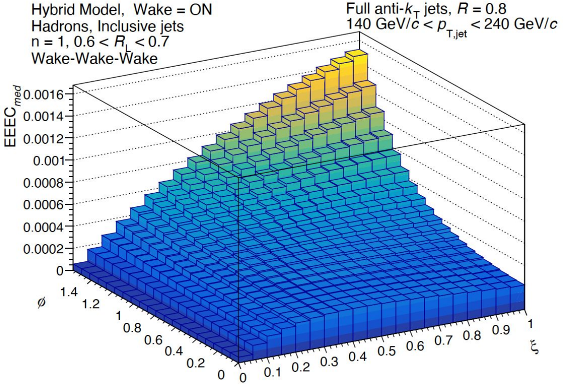


The jet-jet-wake correlators are the source of the collinear enhancement.

jet-wake-wake



wake-wake-wake



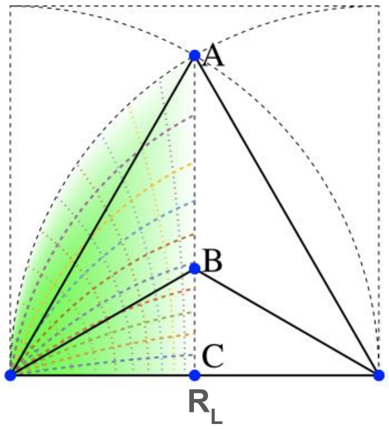
The jet-wake-wake and wake-wake-wake correlators are the source of the equilateral enhancement.

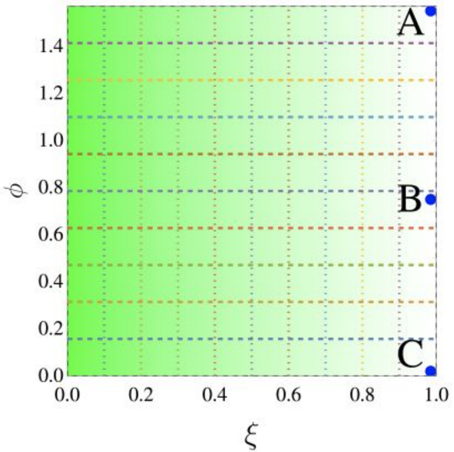
Why do wake particles favor equilateral structures over others (e.g. flat triangles)?

Why do wake particles favor equilateral structures over others (e.g. flat triangles)?

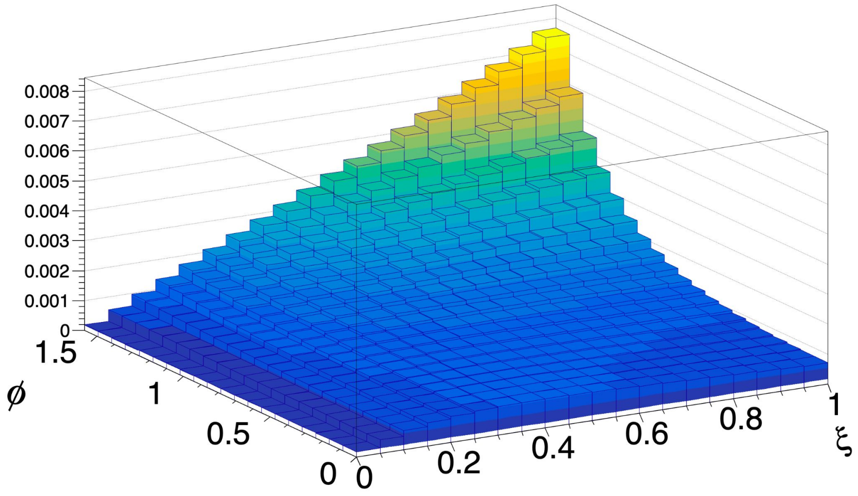
- The area of a (ξ, ϕ) bin, in a Cartesian (η, ϕ) plane, close to equilateral triangles is significantly larger than the area of a (ξ, ϕ) bin in the collinear (or even flat) region.
- A uniform distribution in (η, ϕ) yields a large peak in the equilateral triangles region.

Is the equilateral enhancement from wake correlations a coordinate artifact?





arXiv: 2201.07800 [Komiske, Moult, Thaler, Zhu]



Area of the Cartesian bin corresponding to each (ξ, ϕ) bin, after having set $R_L = 1$

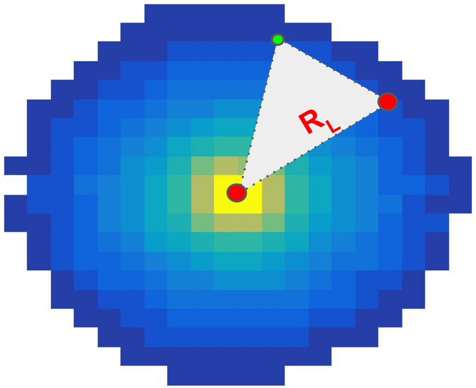
A NEW COORDINATE SYSTEM

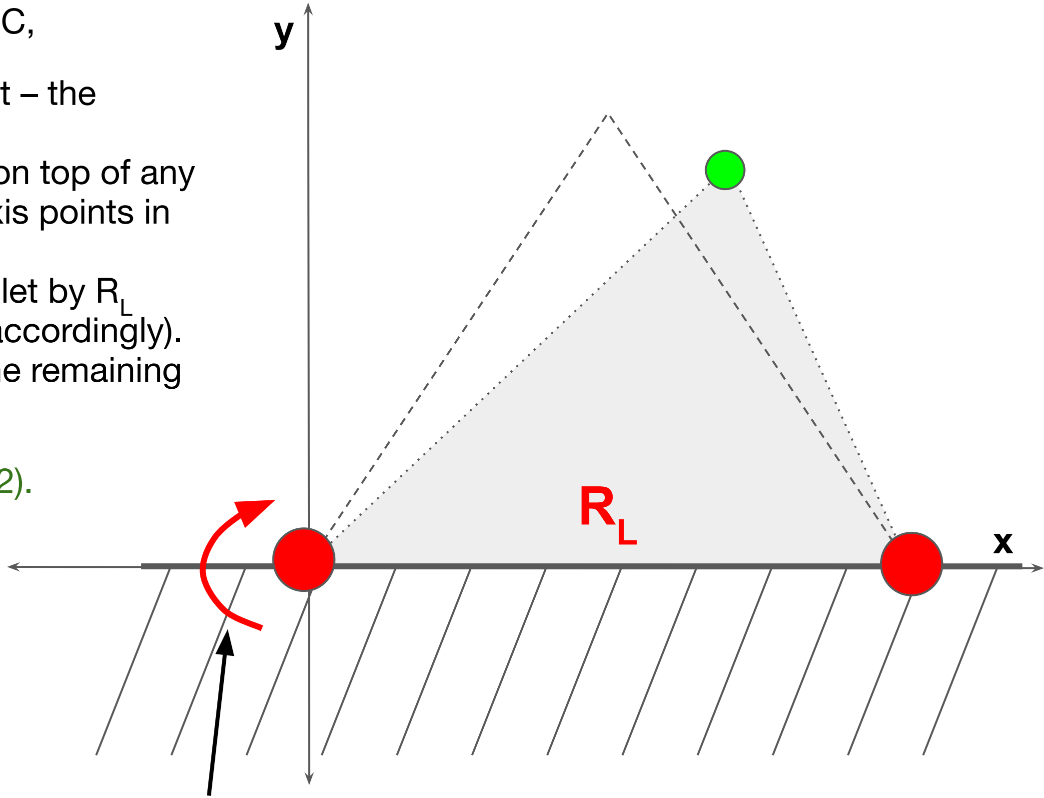
A NEW COORDINATE SYSTEM

For each triplet of particles that contribute to the EEEC,

1) Find the two particles that are separated the most – the distance between them defines R_L.
2) Define (x, y) coordinates such that the origin lies on top of any one of the two particles from step 1, and the x-axis points in the direction of the other particle from step 1.
3) Scale all lengths of the triangle formed by the triplet by R_L (equivalently, set $R_L = 1$ and rescale the triangle accordingly).
4) Fill the EEEC in bins of the (x, y) coordinates of the remaining third particle in the triplet

Ex: Equilateral triangles correspond to $(x, y) = (½, \sqrt{3}/2)$.

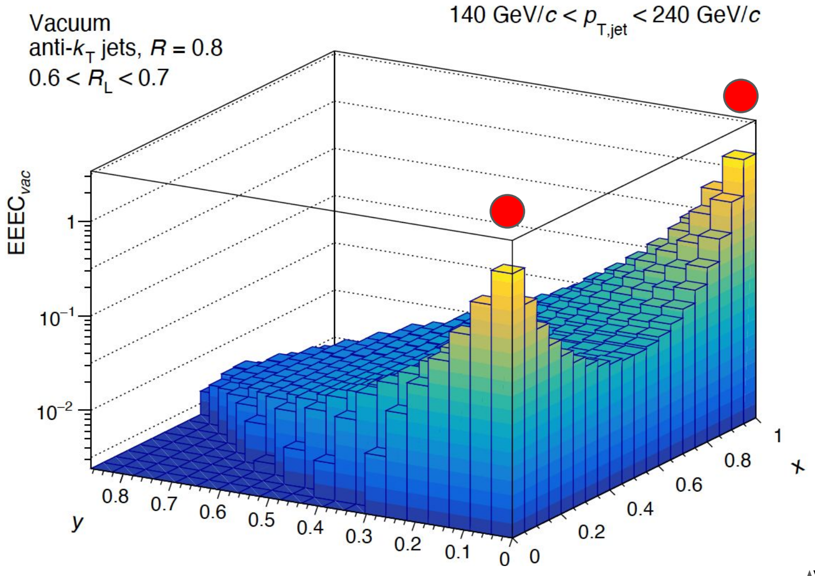




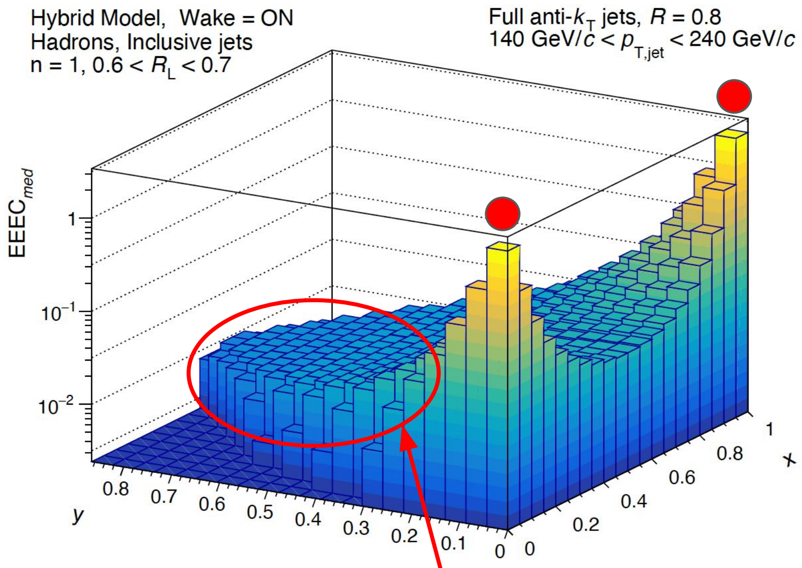
Green points below this line are equivalent to green points symmetrically above this line

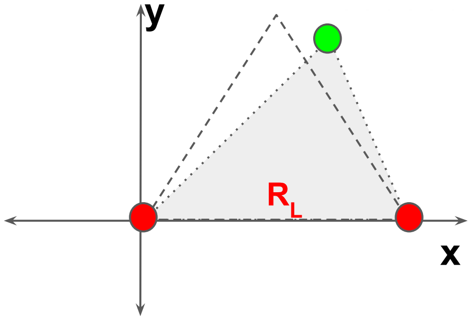
EEECs IN (x , y) COORDINATES

Vacuum EEEC



Pb+Pb with wake EEEC

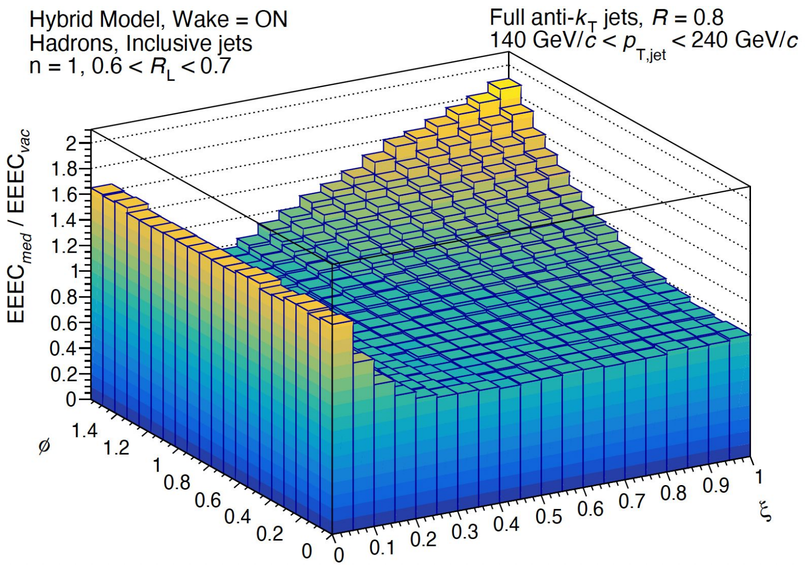




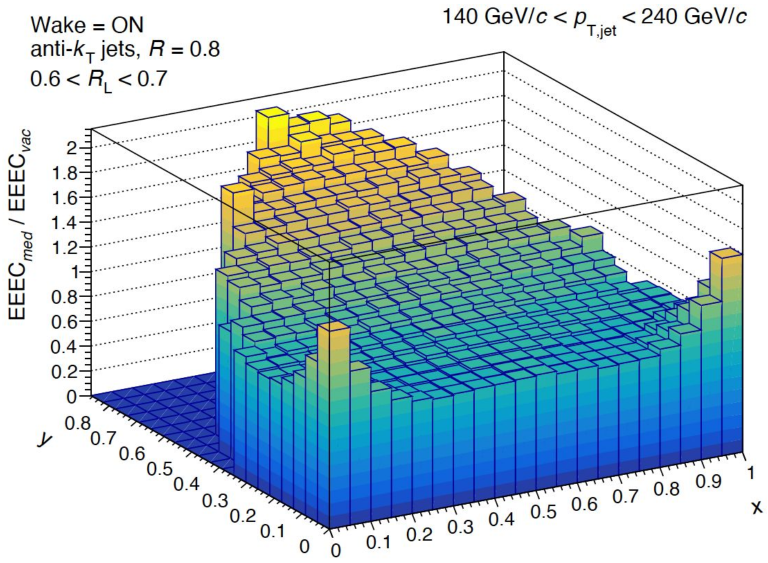
The wake fills in the phase space relatively unpopulated in vacuum.

Pb+Pb WITH WAKE / VACUUM EEEC RATIO IN DIFFERENT COORDINATES

(ξ, ϕ) COORDINATES



(x, y) COORDINATES

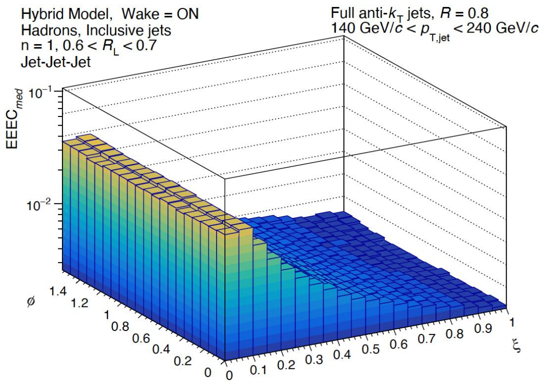


- The equilateral enhancement in the Pb+Pb/vacuum ratio encodes the shape of the wake, and is not a coordinate artifact.
- In the Pb+Pb EEEC (not in ratio to vacuum), we can be tricked because the equilateral region is dominated by the coordinate Jacobian, not the physics.

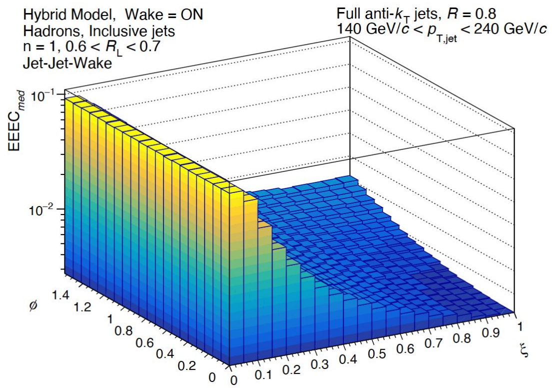
COLLINEAR ENHANCEMENT

(ξ, ϕ)

jet-jet-jet

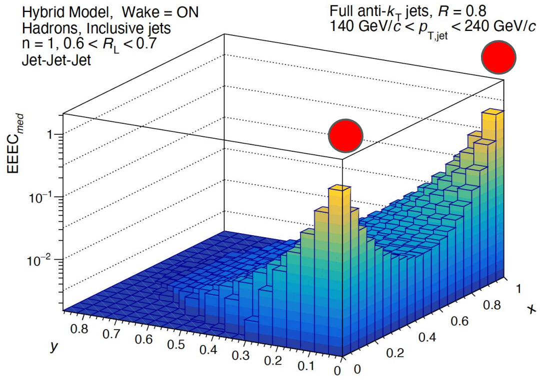


jet-jet-wake

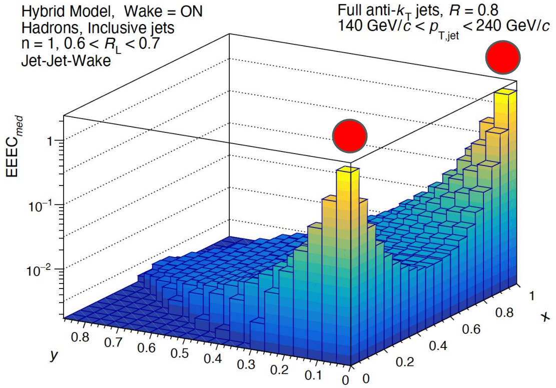


(x, y)

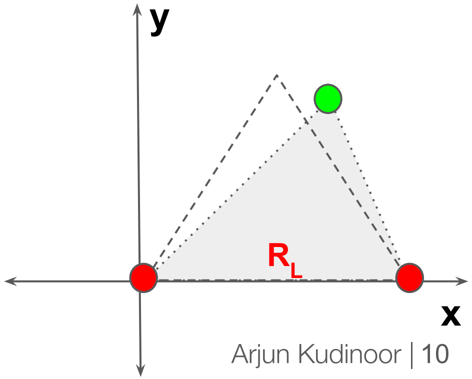
jet-jet-jet



jet-jet-wake

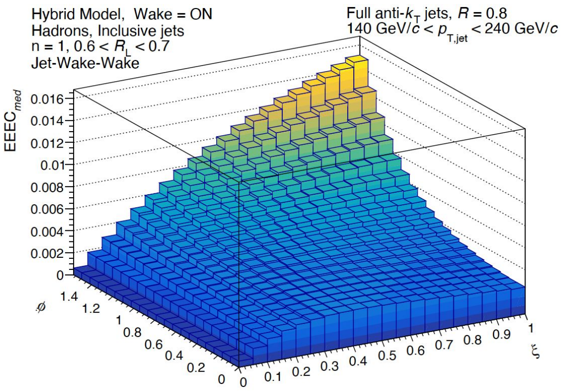


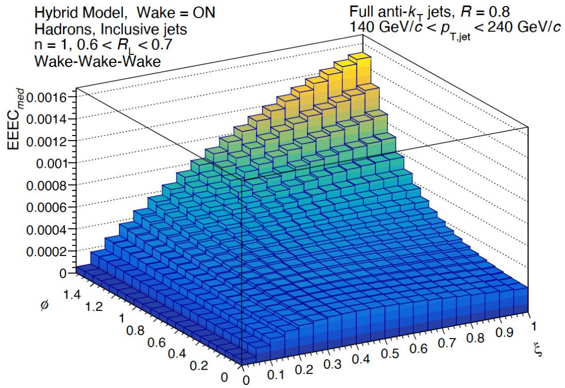
Can see collinear contributions in both coordinates ✅



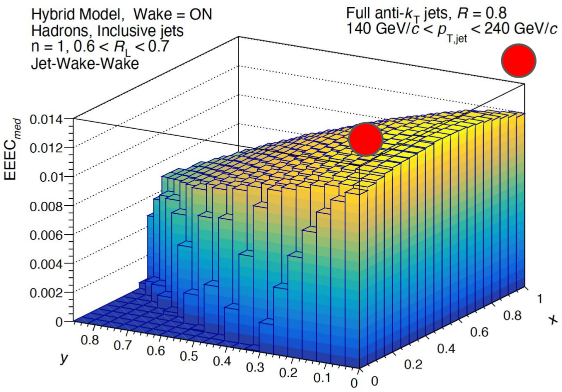
EQUILATERAL ENHANCEMENT

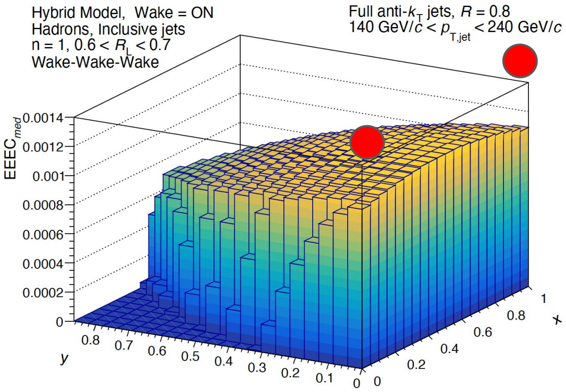
jet-wake-wake **(ξ, ϕ)** **wake-wake-wake**





jet-wake-wake **(x, y)** **wake-wake-wake**



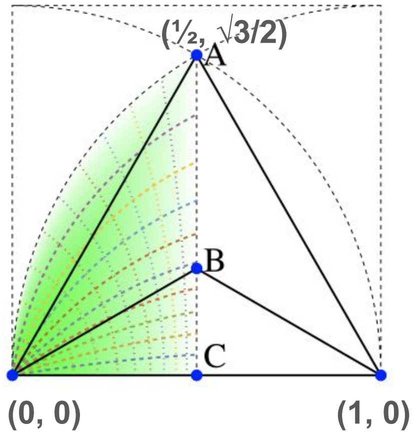


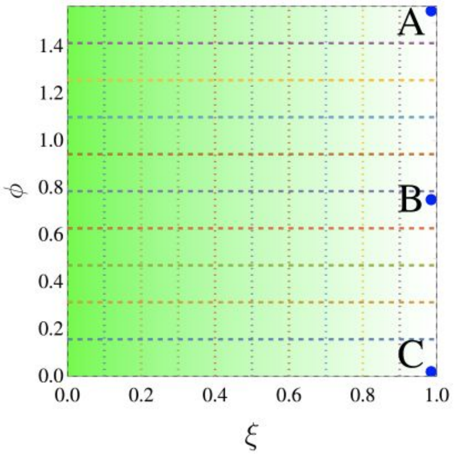
Since the Jacobian is flat in the (x, y) coordinates, these coordinates offer a more faithful representation of the three-point correlator in heavy ion collisions.

TRANSLATING BETWEEN (ξ , ϕ) AND (x , y) COORDINATES

The Jacobian of the (x, y) coordinate system is flat; the Jacobian of the (ξ, ϕ) coordinate system is not flat.

We can translate between the two coordinate systems by dividing the (ξ, ϕ) EEEC by the area that each (ξ, ϕ) bin occupies in (x, y) coordinates.





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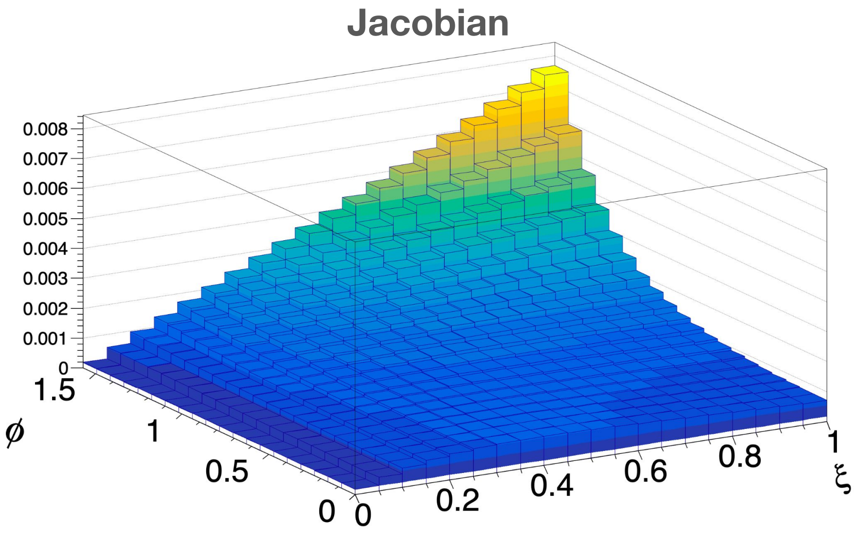
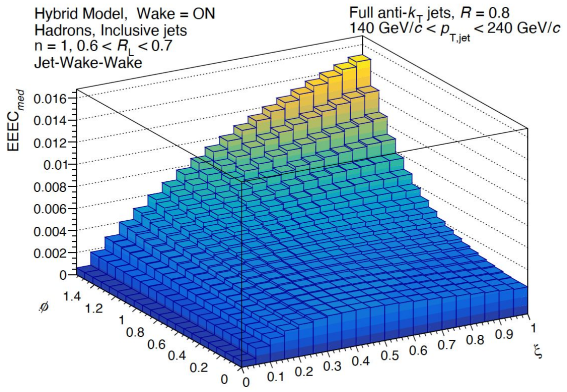
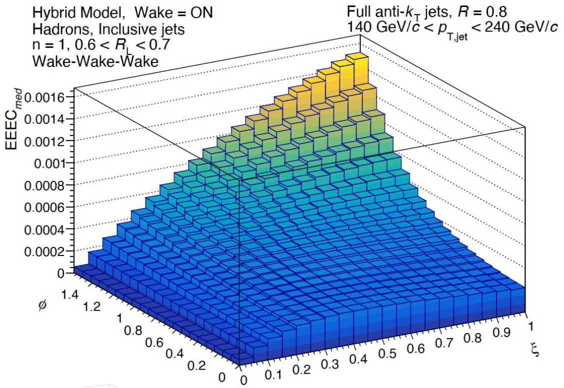


JACOBIAN-NORMALIZED Pb+Pb EEEC IN (ξ , ϕ) COORDINATES

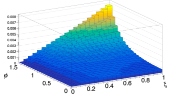
jet-wake-wake

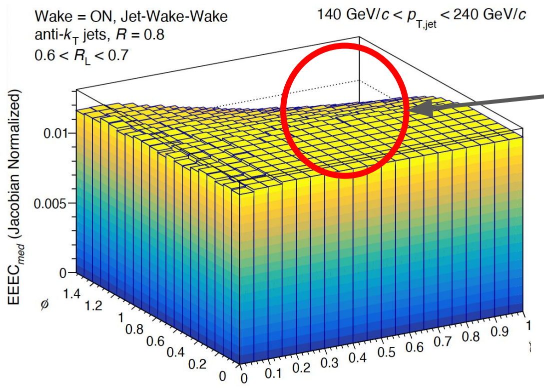


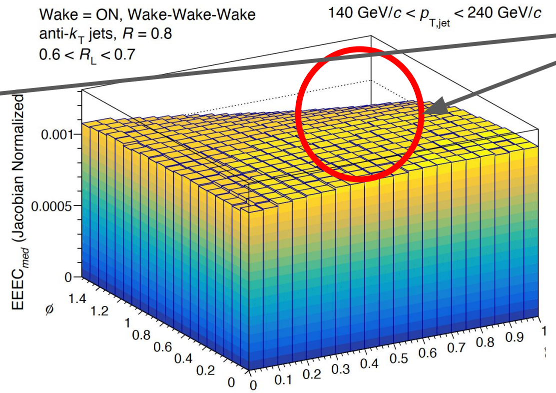
wake-wake-wake



Divide by the Jacobian







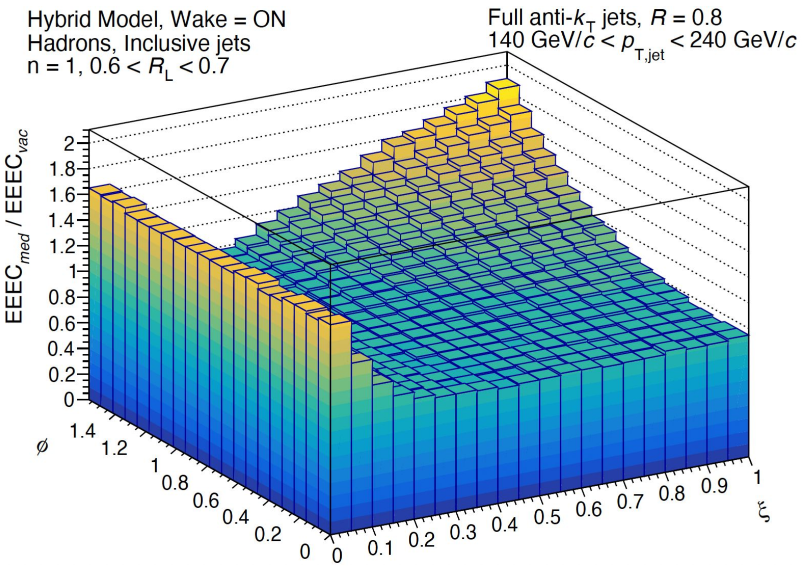
Now, this dip looks like what we saw in (x, y) ✅

There are more equilateral structures in a uniform distribution of particles than there are in the wake.

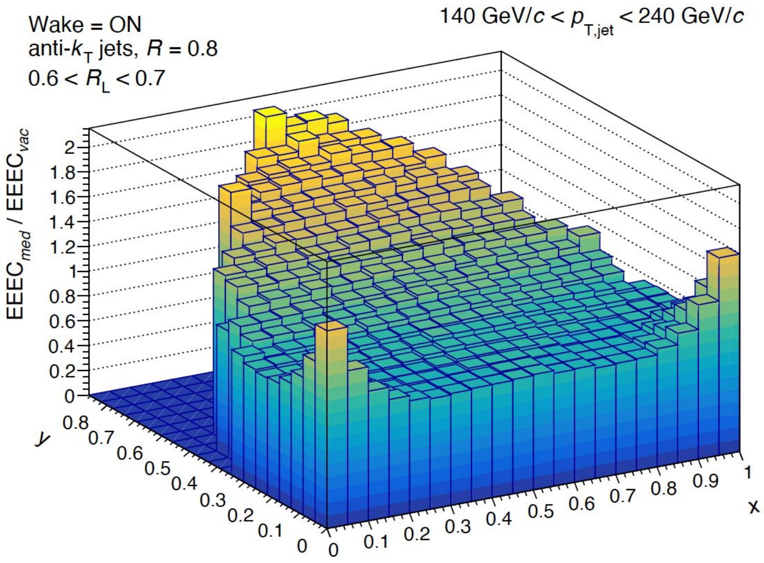
Pb+Pb WITH WAKE / VACUUM EEEC RATIO IN DIFFERENT COORDINATES

Equilateral structures relatively unpopulated in vacuum → Large enhancement in Pb+Pb/vacuum ratio!

(ξ, ϕ) COORDINATES



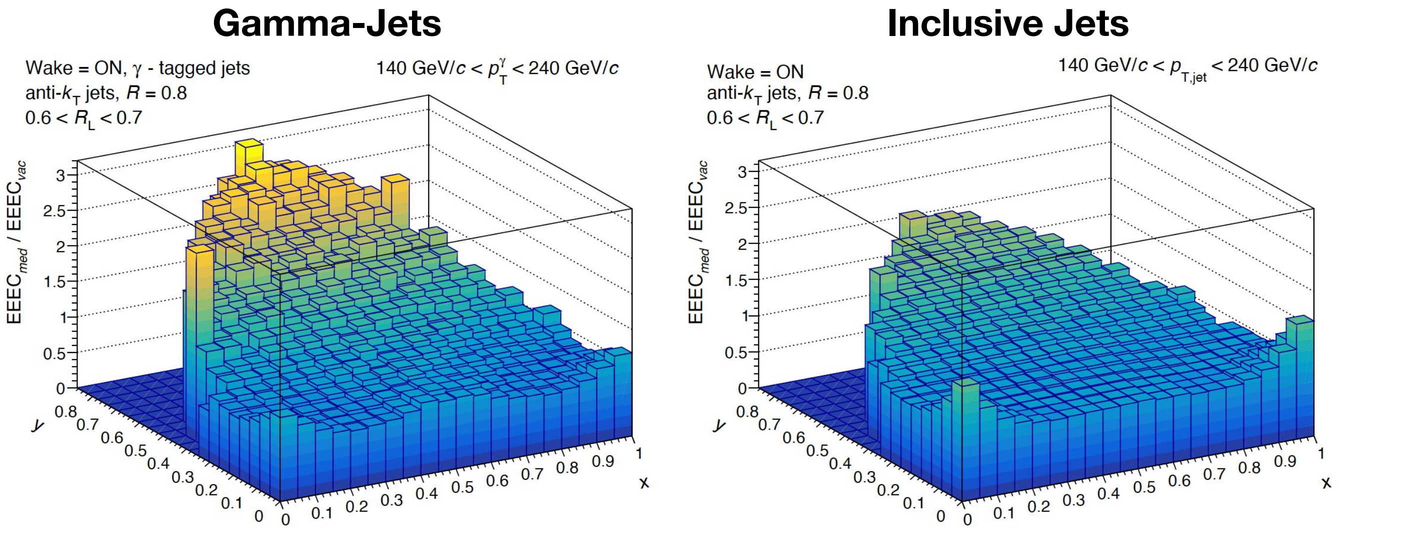
(x, y) COORDINATES



EFFECT EVEN MORE PRONOUNCED IN GAMMA-JETS

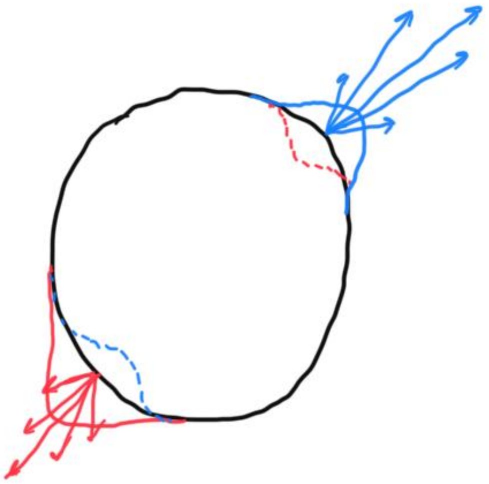
γ-jet Selection Criteria

- Photon $p_T > 40$ GeV
- $\Delta\phi_{\gamma,\,jet} > 2\pi/3$
- $\Sigma\, E_T < 5$ GeV in an R = 0.4 cone around γ



What factors contribute to these differences?

- Different jet selection criteria
- Inclusive jet events largely contain jets that are roughly back-to-back with other jets that produce their own wakes. So, in inclusive jets we have to worry about the **effects coming from the wake of an away-side jet**.



THE WAKE

Hypothesis: The equilateral enhancement of inclusive jet EEECs is reduced in magnitude by the superposition of the wake of the jet we have selected and the wake of one or more other jets going in roughly the opposite direction.

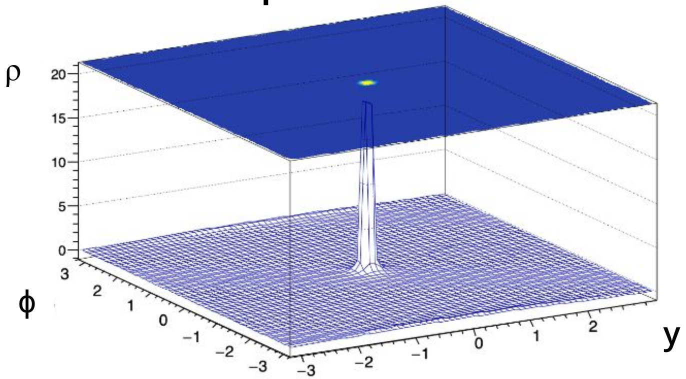
THE WAKE IN THE HYBRID STRONG/WEAK COUPLING MODEL OF JET QUENCHING

- As a jet traverses the QGP, it loses momentum to the plasma. By momentum conservation, this momentum is carried by a wake, in the direction of the jet.

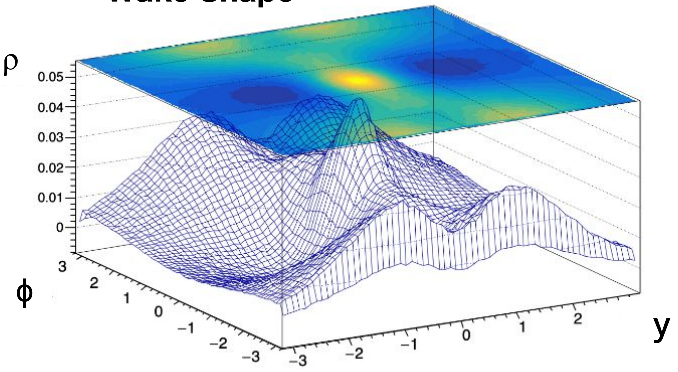
- A way to think of this is that the jet pulls some amount of QGP in the direction of the jet. So, when you compare the freezeout of a QGP droplet containing a jet wake will have:

1) Additional soft particles in the jet direction
2) A depletion of soft particles in the direction opposite the jet

Jet Shape

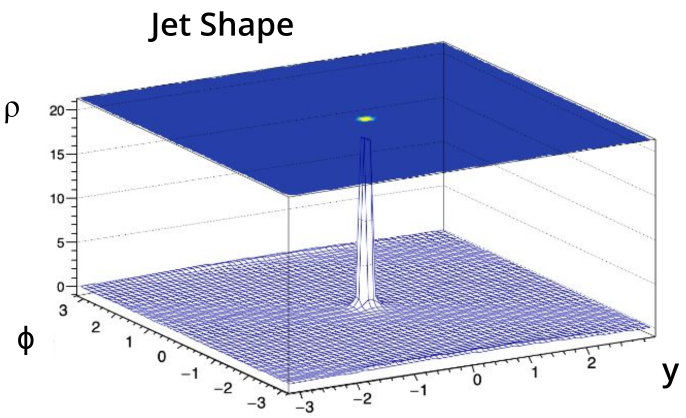


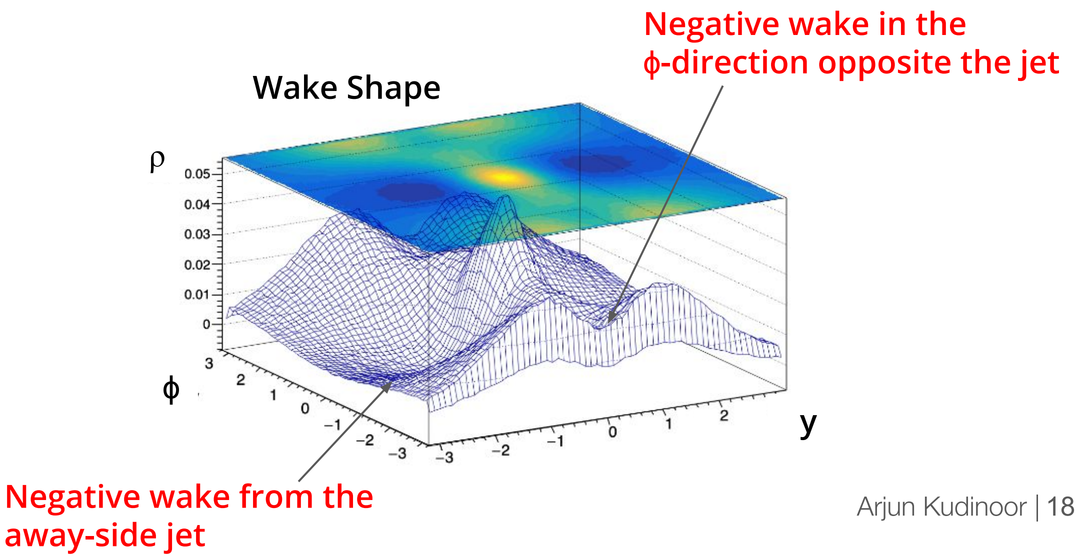
Wake Shape



After running the Hybrid Model Monte Carlo for Pb+Pb collisions, a list containing three types of outgoing hadrons is produced:

- **Non-wake** particles: Hadrons that result from jet fragmentation
- **Positive wake** particles: Wake hadrons due to a jet pulling the plasma in its direction
- **Negative wake** particles: Wake “hadrons” that represent a depletion of the momentum distribution of the hadrons from the plasma in the direction opposite a jet



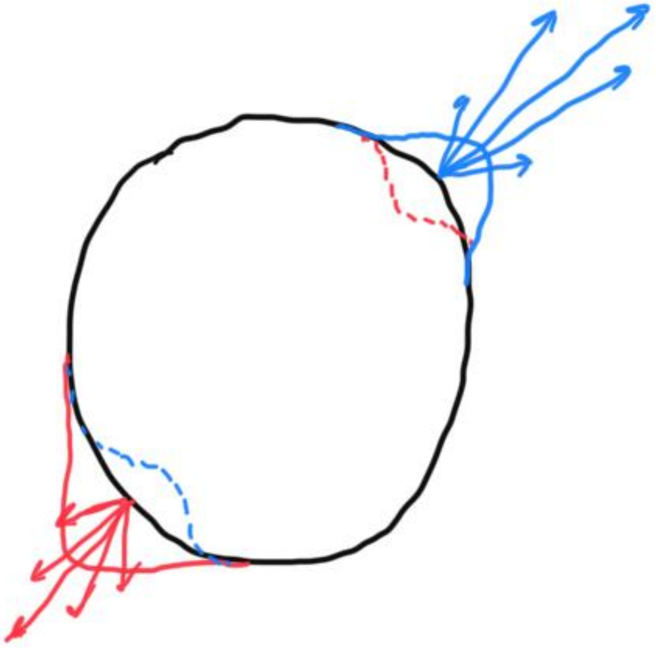


THE WAKE IN THE HYBRID STRONG/WEAK COUPLING MODEL OF JET QUENCHING

- Now, think of an inclusive jet event. Select a jet in an event. This jet will produce a wake.

- The event will have at least one additional jet going in approximately the opposite direction. This jet will also produces its own wake.

- The negative wake associated with away-side jet(s) gets superposed with the positive wake coming from the jet we initially selected. **This poses an issue…**



THE ISSUE OF NEGATIVE WAKE PARTICLES

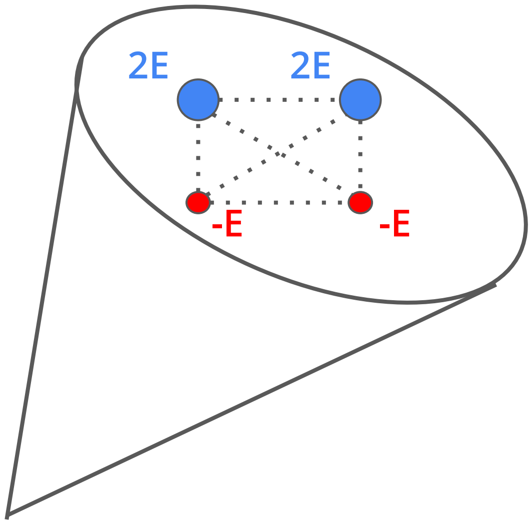
When calculating quantities that are linear in particle momentum, like jet shape or jet reconstruction, we simply count the negative wake particles with negative energy.

BUT… how do we calculate an energy-correlation between two negative particles?

$$\mathrm{EEEC}_{R_L}(\xi, \phi) = \frac{1}{\delta\xi\ \delta\phi} \frac{1}{(p_T^{\mathrm{jet}})^3} \sum_{\substack{i<j<k\in\mathrm{jet} \\ \max(R_{ij}, R_{jk}, R_{ik}) \approx R_L}} p_T^i p_T^j p_T^k$$

If both negatives contribute negatively, their product will be positive. But the correlation between two depletions of the plasma should not be positive…

AN EXAMPLE



Let's calculate the 2-point energy correlator for this "jet" with 4 constituent particles.

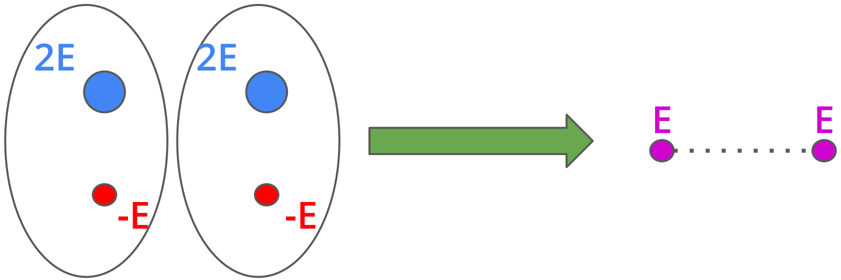
$$\text{EEC} = (2E)(2E) + 4\,(2E)(-E) + (-E)(-E)$$

$$= 4E^2 - 4(2E^2) + E^2$$

$$= -3E^2$$ 👀 👀 👀

We need to subtract the negatives from each event before calculating the energy-correlators.

AN EXAMPLE



First, we subtract negative wake particles from nearby positive particles, i.e. from the positive wake or from jet fragmentation. Then, we calculate the energy-correlator.

EEC = E^2 

SUBTRACTION PROCEDURE

Each particle has 4-momentum $p^\mu = (E, p_x, p_y, p_z) = \big((p_T + m_\delta)\cosh(y),\ p_T\cos(\phi),\ p_T\sin(\phi),\ (p_T + m_\delta)\sinh(y)\big)$,

where y is its rapidity, ϕ azimuthal angle, p_T transverse momentum, and $m_\delta = \sqrt{m^2 + p_T^2} - p_T$ its mass.

Based on arXiv 2207.14814 [Milhano, Zapp], we do a constituent subtraction of particles in each event:

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Based on arXiv 2207.14814 [Milhano, Zapp], we do a constituent subtraction of particles in each event:

1) Create a list of all possible pairs consisting of a negative particle i and a non-negative particle k in the event. Order the list in increasing distance $\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$ between the particles in each pair.

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2) Remove all pairings with $\Delta R > R_{\text{sub}}$, where R_{sub} is a chosen "subtraction radius", which ensures that negatives are locally subtracted from the event. In our analysis we chose $R_{\text{sub}} = 0.5$.

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3) Beginning with the first pair (k, i) in the ordered-list, subtract p_T and m_δ as

$$p_T^{(i)} \geq p_T^{(k)} \Rightarrow p_T^{(i)} \to p_T^{(i)} - p_T^{(k)} \text{ and } p_T^{(k)} \to 0, \qquad m_\delta^{(i)} \geq m_\delta^{(k)} \Rightarrow m_\delta^{(i)} \to m_\delta^{(i)} - m_\delta^{(k)} \text{ and } m_\delta^{(k)} \to 0,$$

$$p_T^{(i)} < p_T^{(k)} \Rightarrow p_T^{(k)} \to p_T^{(k)} - p_T^{(i)} \text{ and } p_T^{(i)} \to 0, \qquad m_\delta^{(i)} < m_\delta^{(k)} \Rightarrow m_\delta^{(k)} \to m_\delta^{(k)} - m_\delta^{(i)} \text{ and } m_\delta^{(i)} \to 0.$$

SUBTRACTION PROCEDURE

Each particle has 4-momentum $p^\mu = (E, p_x, p_y, p_z) = \big((p_T + m_\delta)\cosh(y),\ p_T\cos(\phi),\ p_T\sin(\phi),\ (p_T + m_\delta)\sinh(y)\big)$,

where y is its rapidity, ϕ azimuthal angle, p_T transverse momentum, and $m_\delta = \sqrt{m^2 + p_T^2} - p_T$ its mass.

Based on arXiv 2207.14814 [Milhano, Zapp], we do a constituent subtraction of particles in each event:

1) Create a list of all possible pairs consisting of a negative particle i and a non-negative particle k in the event. Order the list in increasing distance $\Delta R = \sqrt{\Delta y^2 + \Delta\phi^2}$ between the particles in each pair.

2) Remove all pairings with $\Delta R > R_{\text{sub}}$, where R_{sub} is a chosen "subtraction radius", which ensures that negatives are locally subtracted from the event. In our analysis we chose $R_{\text{sub}} = 0.5$.

3) Beginning with the first pair (k, i) in the ordered-list, subtract p_T and m_δ as

$$p_T^{(i)} \geq p_T^{(k)} \quad \Rightarrow \quad p_T^{(i)} \to p_T^{(i)} - p_T^{(k)} \quad \text{and} \quad p_T^{(k)} \to 0, \qquad m_\delta^{(i)} \geq m_\delta^{(k)} \quad \Rightarrow \quad m_\delta^{(i)} \to m_\delta^{(i)} - m_\delta^{(k)} \quad \text{and} \quad m_\delta^{(k)} \to 0,$$

$$p_T^{(i)} < p_T^{(k)} \quad \Rightarrow \quad p_T^{(k)} \to p_T^{(k)} - p_T^{(i)} \quad \text{and} \quad p_T^{(i)} \to 0, \qquad m_\delta^{(i)} < m_\delta^{(k)} \quad \Rightarrow \quad m_\delta^{(k)} \to m_\delta^{(k)} - m_\delta^{(i)} \quad \text{and} \quad m_\delta^{(i)} \to 0.$$

4) Continue until the end of the list is reached. Then, remove all particles with $p_T = 0$ from the event. The final list of particles with nonzero p_T is the subtracted ensemble.

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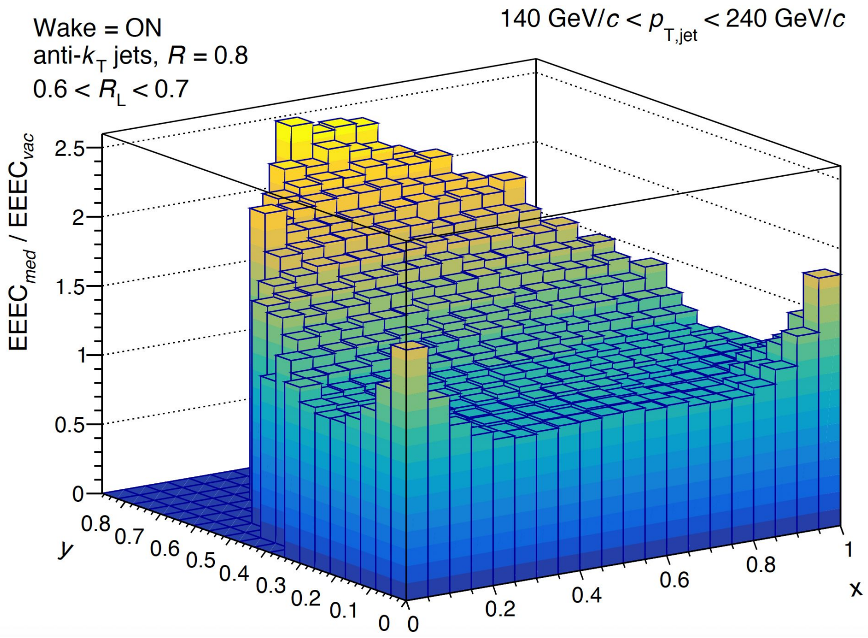
4) Continue until the end of the list is reached. Then, remove all particles with $p_T = 0$ from the event. The final list of particles with nonzero p_T is the subtracted ensemble.

5) If any negative particles still remain, remove them from the subtracted ensemble since they will be at least $R_{\rm sub}$ away from all remaining positive particles. This is the final ensemble of particles.

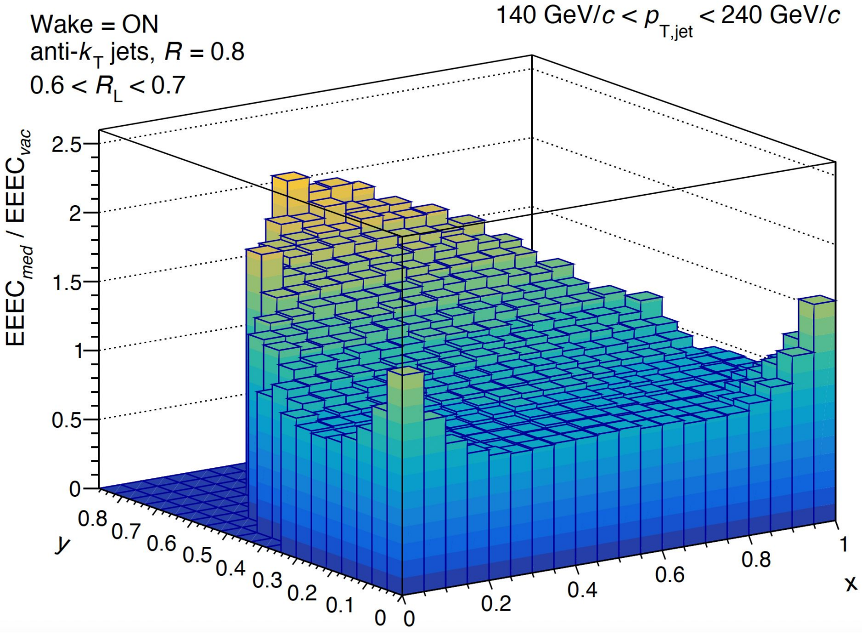
EFFECT OF SUBTRACTION ON INCLUSIVE JET EEEC RATIO

After subtracting the negative wake particles from inclusive-jet events, the equilateral enhancement is reduced, but still significant.

Ignoring negative wake particles altogether

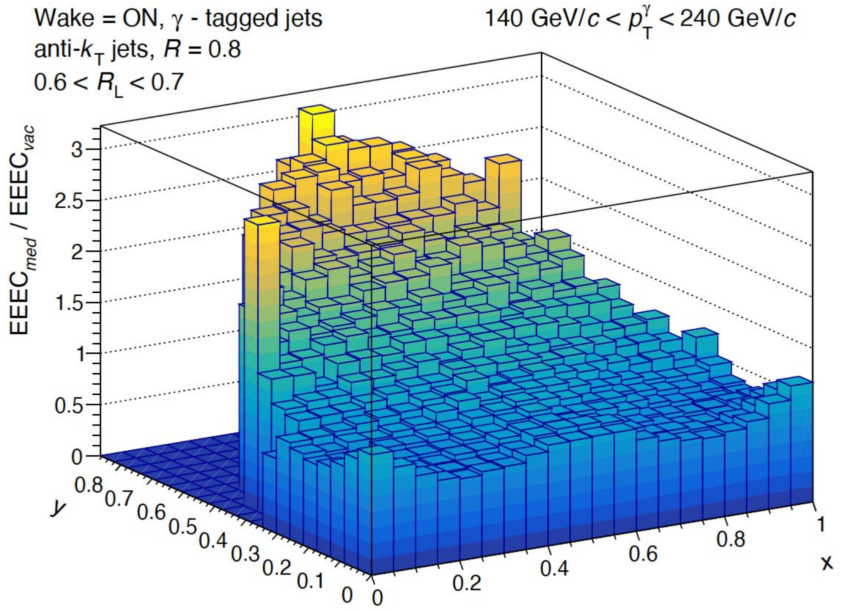


Negative wake subtracted

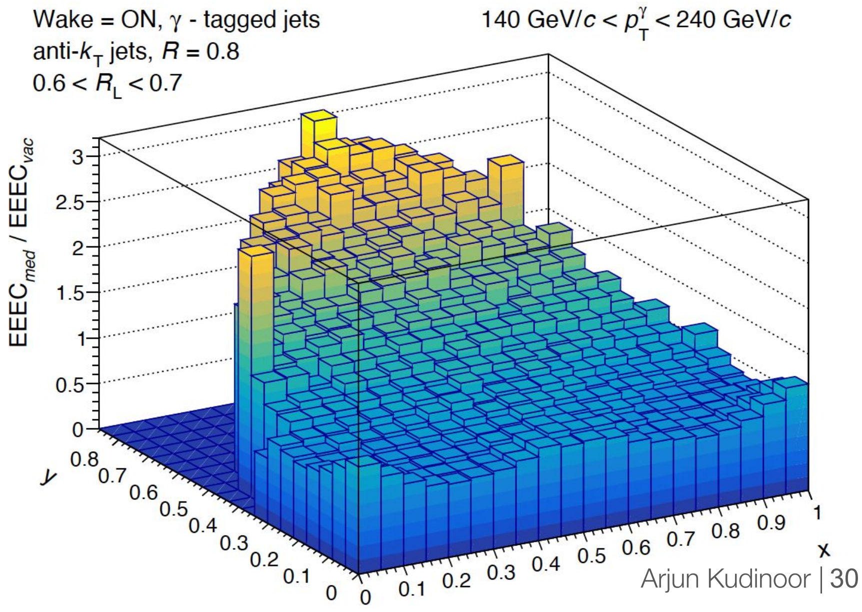


Negative wake has almost no effect on the equilateral enhancement of gamma-jet EEECs!

Ignoring negative wake particles altogether



Negative wake particles subtracted with R_{sub} = 0.5



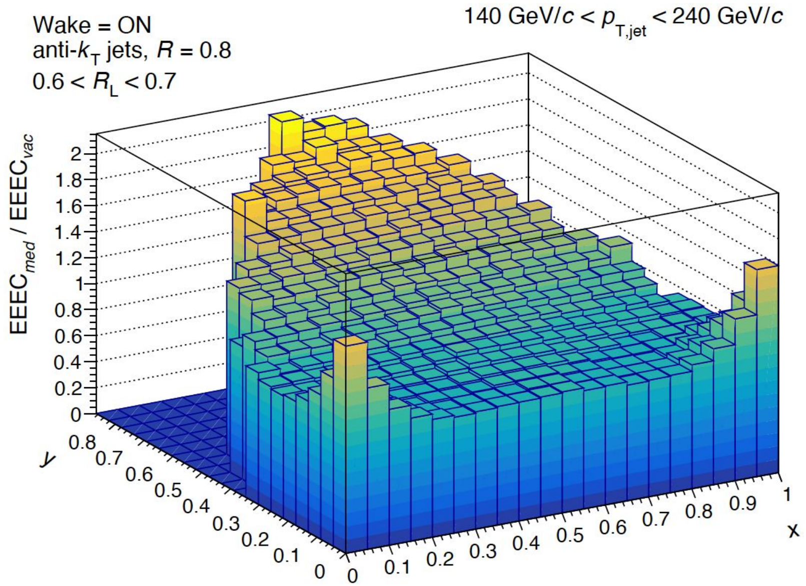
Hypothesis: The equilateral enhancement of inclusive jet EEECs is reduced in magnitude by the superposition of the wake of the jet we have selected and the wake of one or more other jets going in roughly the opposite direction.

HYPOTHESIS CONFIRMED!

SUMMARY OF THIS TALK

- Compared to the (ξ, ϕ) coordinates, the new (x, y) coordinates we have introduced provide a more faithful visual representation of how the wake populates regions of the EEEC phase space that are largely unpopulated in vacuum.

- Regardless of our choice of coordinates, wake correlations result in an enhancement of equilateral structures in medium, when compared to vacuum.

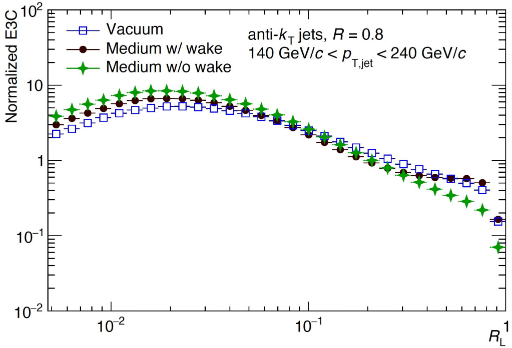


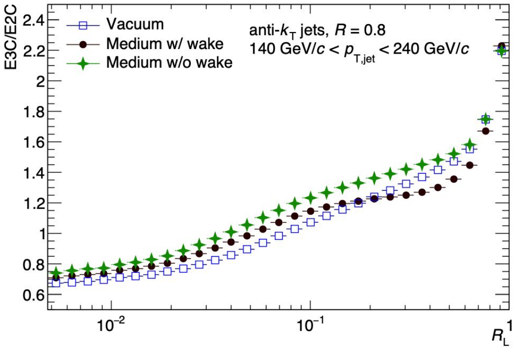
- Negative wake particles have a noticeable effect on energy-correlators and must be carefully handled.

- [Ongoing] EEEC analyses may reveal signatures of the negative wake
  - Gamma-jets vs. inclusive jets
  - [Ongoing] Dijets that are not back-to-back in η (arXiv: 1907.12301 [Pablos]) vs. those that are back-to-back

KEY TAKEAWAYS FROM THE DAY

- The scale of the medium response is imprinted on the projected E2C and E3C. This scale become most prominent when taking the ratio of the E3C/E2C.

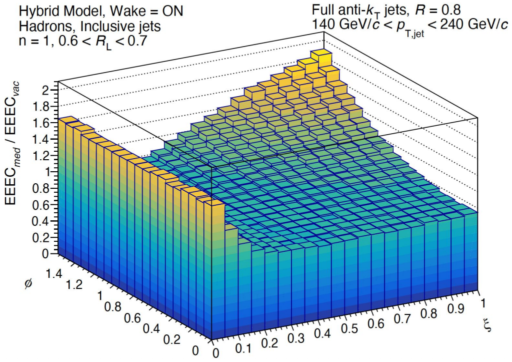


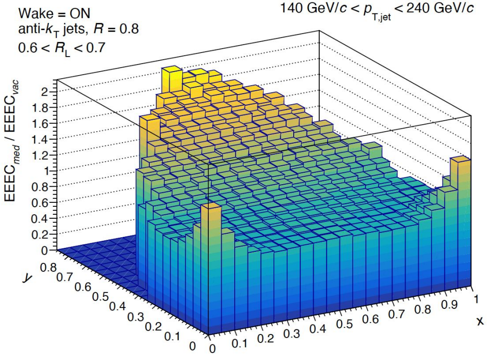


At large angles, over a broad kinematic range, medium/vacuum ratio is completely dominated by the wake

- The shape of the medium response is encoded in the full EEEC, seen most prominently in the medium/vacuum ratio. Coordinate choices and the effect of superposing wakes are important considerations when studying EEECs in a heavy-ion context.

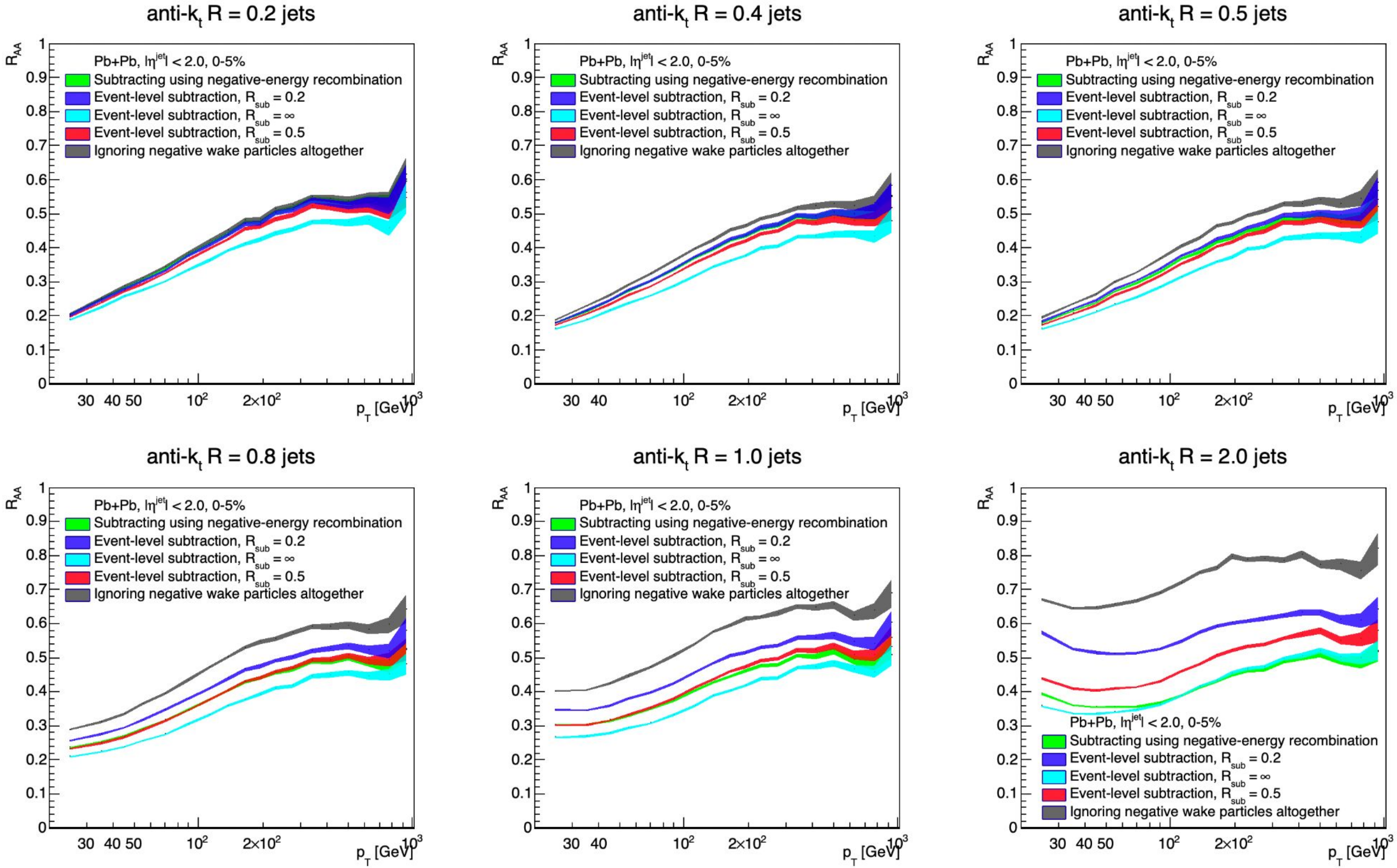
Let's look for this large signal in other models and experiment!





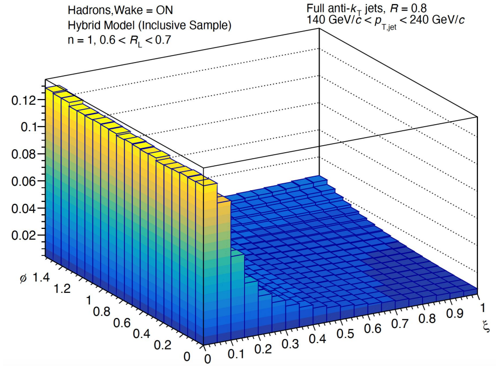
BACKUP

EFFECTS OF NEGATIVE WAKE SUBTRACTION ON JET SUPPRESSION

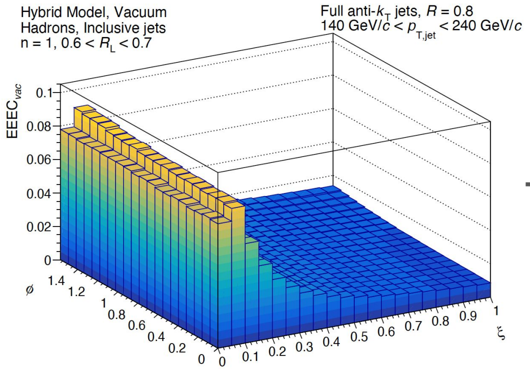


Pb+Pb/pp EEEC RATIO

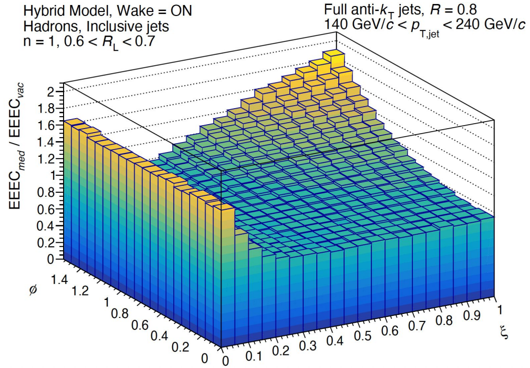
Pb+Pb with wake



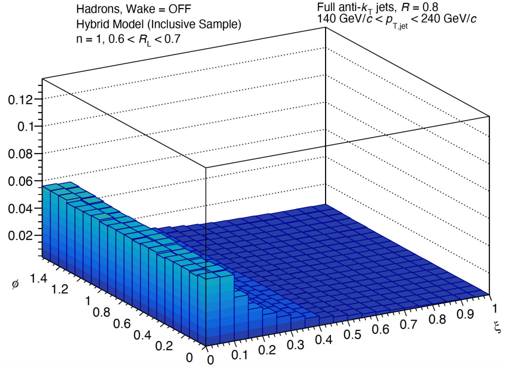
Vacuum (pp)



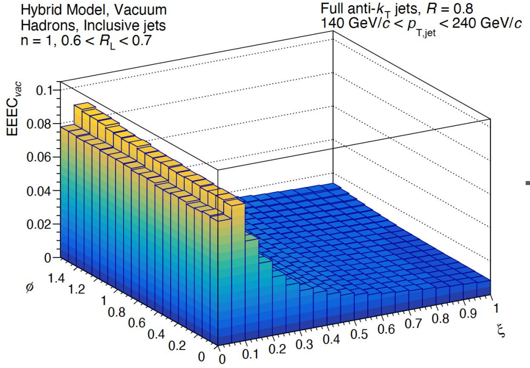
Pb+Pb/pp, with wake



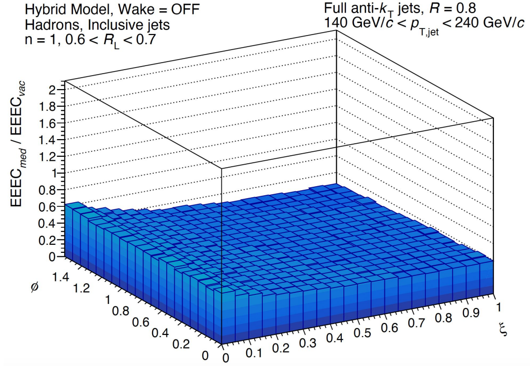
Pb+Pb without wake



Vacuum (pp)



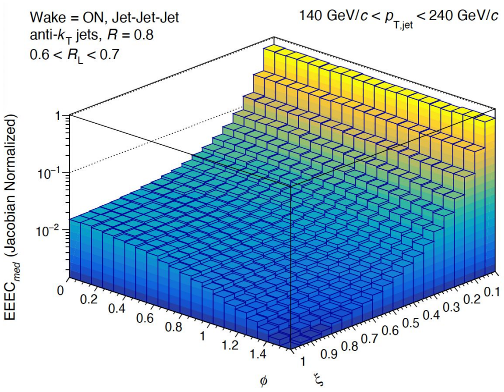
Pb+Pb/pp, without wake



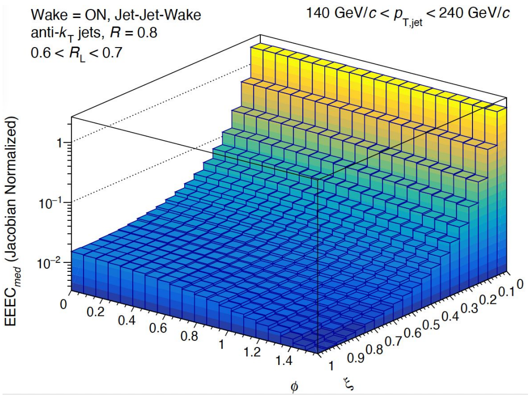
Correlations involving wake particles populate the equilateral region of the Pb+Pb EEEC.

JUST ROTATED… JACOBIAN-NORMALIZED Pb+Pb EEEC IN (ξ , ϕ) COORDINATES

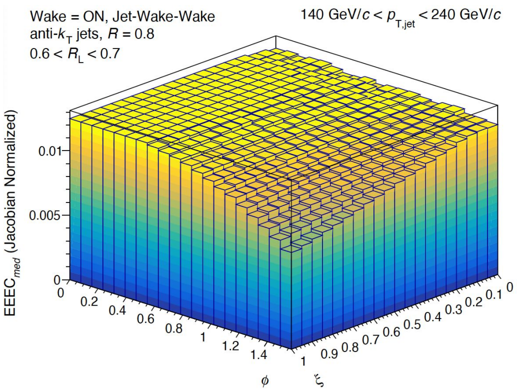
jet-jet-jet



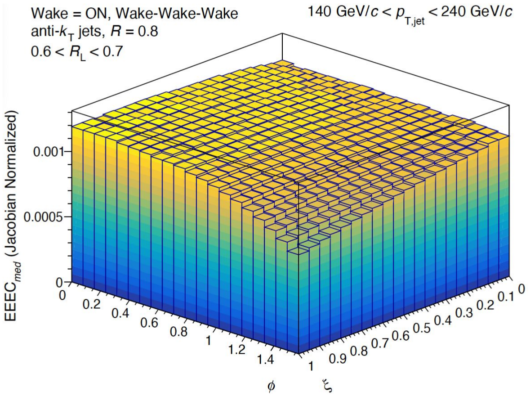
jet-jet-wake



jet-wake-wake

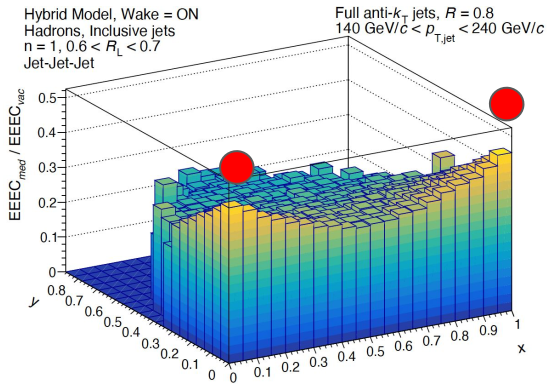


wake-wake-wake

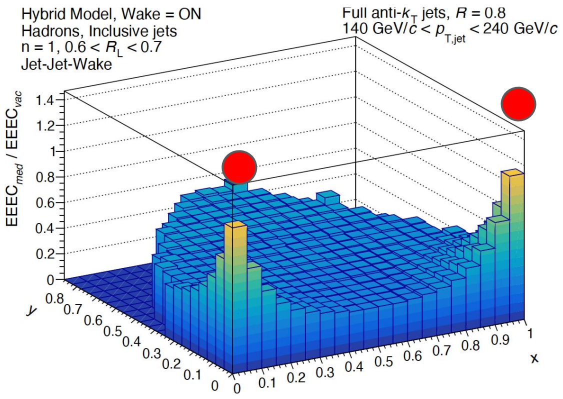


Pb+Pb WITH WAKE / VACUUM EEEC RATIO IN (x, y) COORDINATES

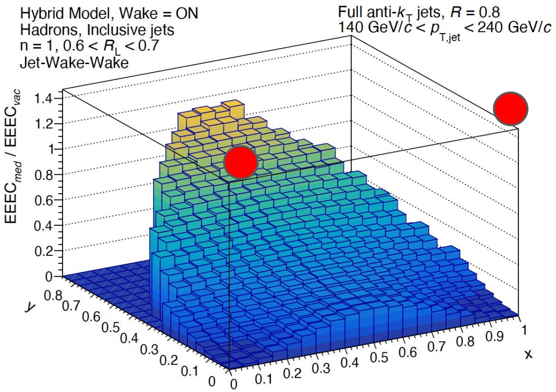
jet-jet-jet



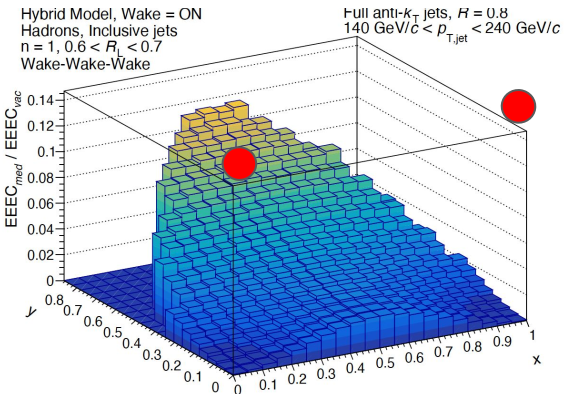
jet-jet-wake

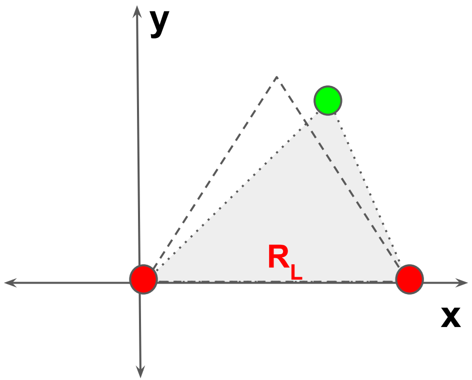


jet-wake-wake



wake-wake-wake

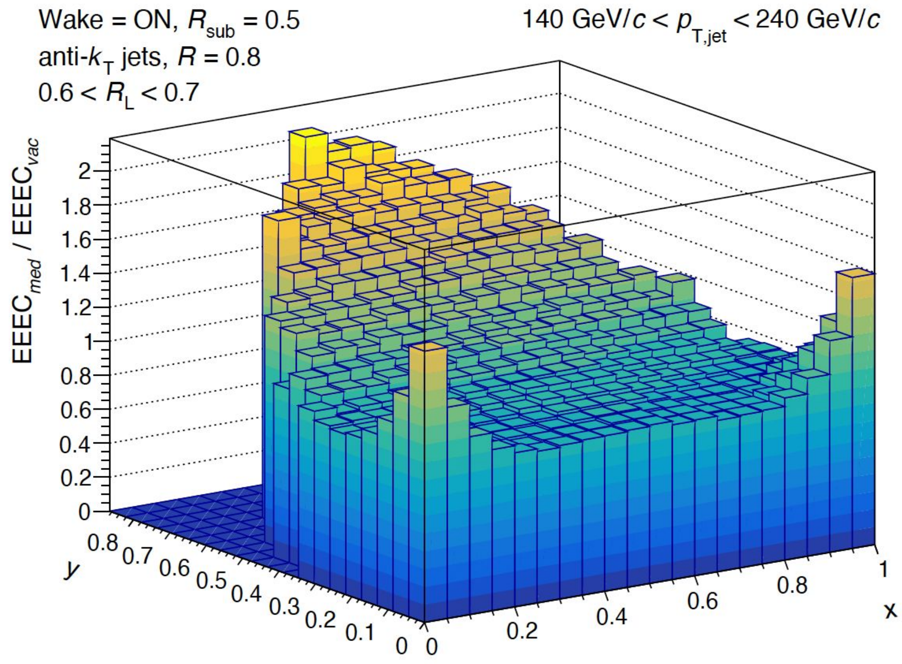




EFFECT OF SUBTRACTION ON INCLUSIVE JET EEEC RATIO

Varying the subtraction radius (above 0.5) has very little effect on the EEEC ratio.

R_{sub} = 0.5



R_{sub} = Infinity