Using the Hybrid Model to Learn How to Visualize, or See Through, Jet Wakes

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How you can learn from a model

- There are things you can do with a model (here, the Hybrid Model) that you cannot do with experimental data. (Eg, turn physical effects off and on) . . .
- . . . but that nevertheless teach us important lessons for how to look at, and learn from, experimental data.
- TODAY: findng jet observables that are (i) dominated by, or (ii) insensitive to, wakes that jets make in the soup.
- Parton shower loses momentum. Medium gains momentum in the jet direction. Medium is a hydrodynamic liquid → jet excites a wake.
- After freezeout, momentum conservation means wake becomes soft hadrons with net momentum in jet direction.
- What an experimentalist reconstructs as a jet necessarily includes hadrons originating from the (modified) parton shower and from the wake in the droplet of QGP.
- In a model, though, the wake can be turned off and on.
- First, a brief intro to the Hybrid Model. . .

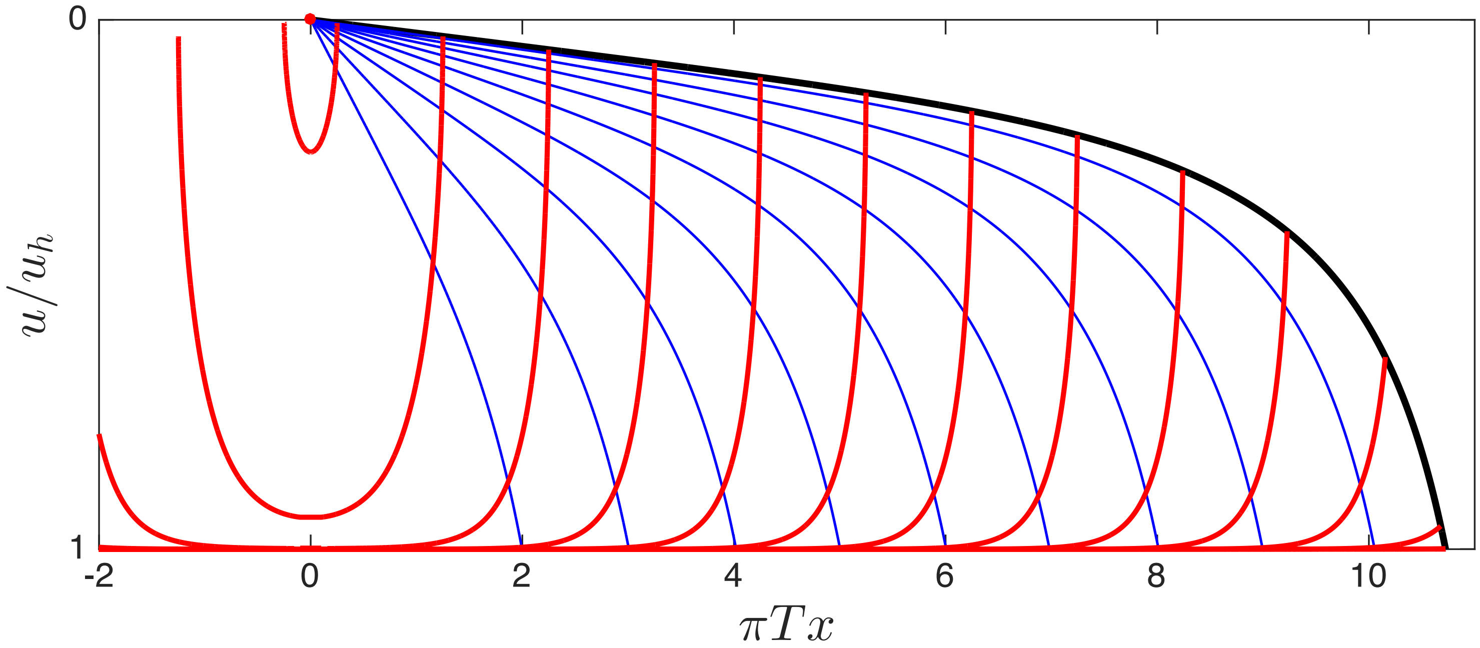
A Hybrid Approach

Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 2014,15,16; Hulcher, DP,KR, ’17; JCS,ZH,GM,DP,KR, ’18; JCS,GM,DP,KR, ’19; JCS,GM,DP,KR, Yao, ’20

- **Hard scattering and the fragmentation of a hard parton produced in a hard scattering are weakly coupled phenomena, well described by pQCD.**
- **The medium itself is a strongly coupled liquid, with no apparent weakly coupled description. And, the energy the jet loses seems to quickly become one with the medium.**
- **Try a hybrid approach. Think of each parton in a parton shower à la PYTHIA losing energy à la dE/dx for light quarks in strongly coupled liquid.**
- **Look at R_{AA} for jets and for hadrons, dijet asymmetry, jet fragmentation function, photon-jet and Z-jet observables. Upon fitting one parameter, *lots* of data described well. Value of the fitted parameter is reasonable: x_{therm} (energetic parton thermalization distance) 3-4 times longer in QGP than in $\mathcal{N} = 4$ SYM plasma at same T.**
- **Then: add the wake in the plasma; add resolution effects; look at jet shapes, jet masses jet substructure observables; add Molière scattering…**

Quenching a Light Quark "Jet"

Chesler, Rajagopal, 1402.6756, 1511.07567



- **Take a highly boosted light quark and shoot it through strongly coupled plasma...**
- **A fully geometric characterization of energy loss. Which is to say a new form of intuition. Energy propagates along the blue curves, which are null geodesics in the bulk. When one of them falls into the horizon, that's energy loss! Precisely equivalent to the light quark losing energy to a hydrodynamic wake in the plasma.**

Implementation of Hybrid Model

Casalderrey-Solana, Gulhan, Milhano, Pablos, KR, 1405.3864,1508.00815

- **Jet production and showering from PYTHIA.**
- **Embed the PYTHIA parton showers in hydro background. (2+1D hydro from Heinz and Shen.)**
- **Between one splitting and the next, each parton in the branching shower loses energy according to**

$$\frac{1}{E_{\mathrm{in}}}\frac{dE}{dx} = -\frac{4x^2}{\pi x_{\mathrm{therm}}^2}\frac{1}{\sqrt{x_{\mathrm{therm}}^2 - x^2}}$$

  where $x_{\mathrm{therm}} \equiv E_{\mathrm{in}}^{1/3}/(2\kappa_{\mathrm{sc}}T^{4/3})$ **with** κ_{sc} **one free parameter that to be fixed by fitting to one experimental data point. (**$\kappa_{\mathrm{sc}} \sim 1 - 1.5$ **in** $\mathcal{N} = 4$ **SYM; smaller** κ_{sc} **means** x_{therm} **is longer in QGP than in** $\mathcal{N} = 4$ **SYM plasma with same** T**.)**
- **Turn energy loss off when hydrodynamic plasma cools below a temperature that we vary between 145 and 170 MeV. (This, plus the experimental error bar on the one data point, becomes the uncertainty in our predictions.)**
- **Reconstruct jets using anti-**k_T**.**

Perturbative Shower … Living in Strongly Coupled QGP

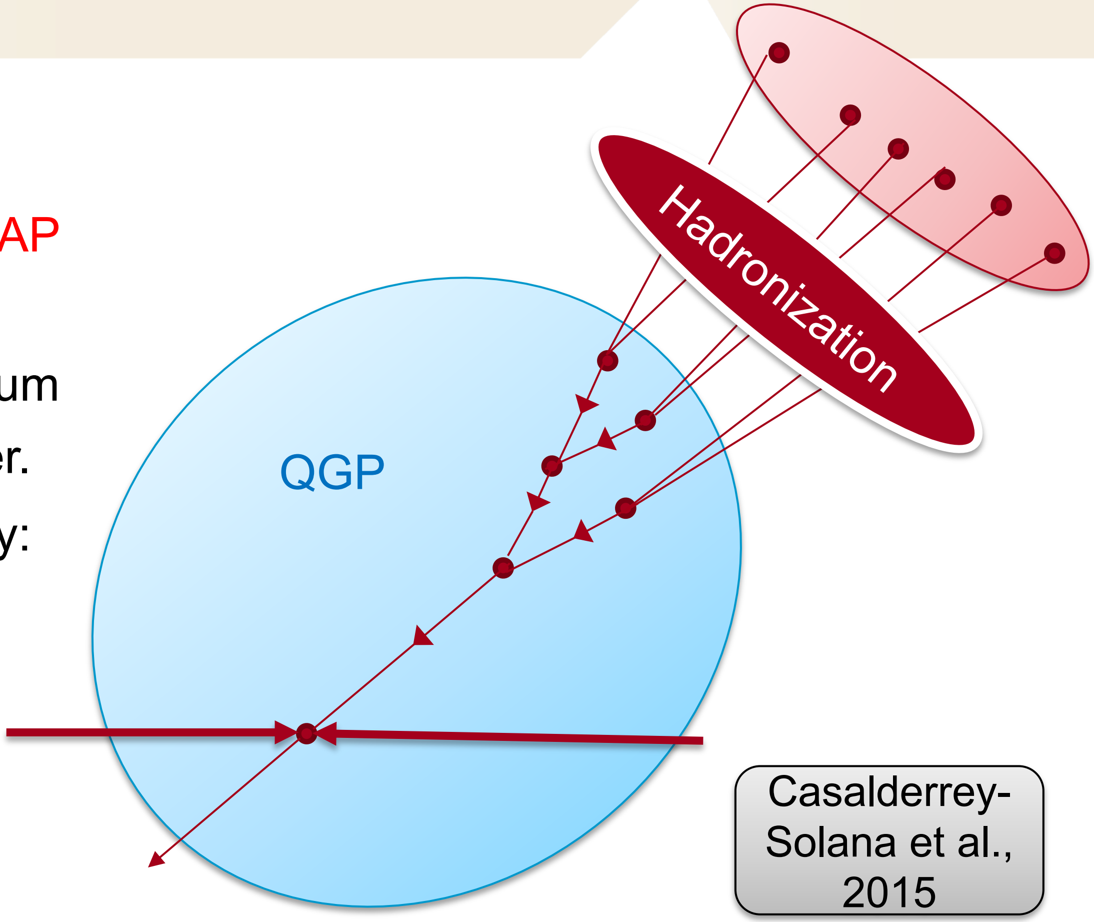
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

O(1) fit const.

$$x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}}$$

$$\tau = \frac{2E}{Q^2}$$



Casalderrey-Solana et al., 2015

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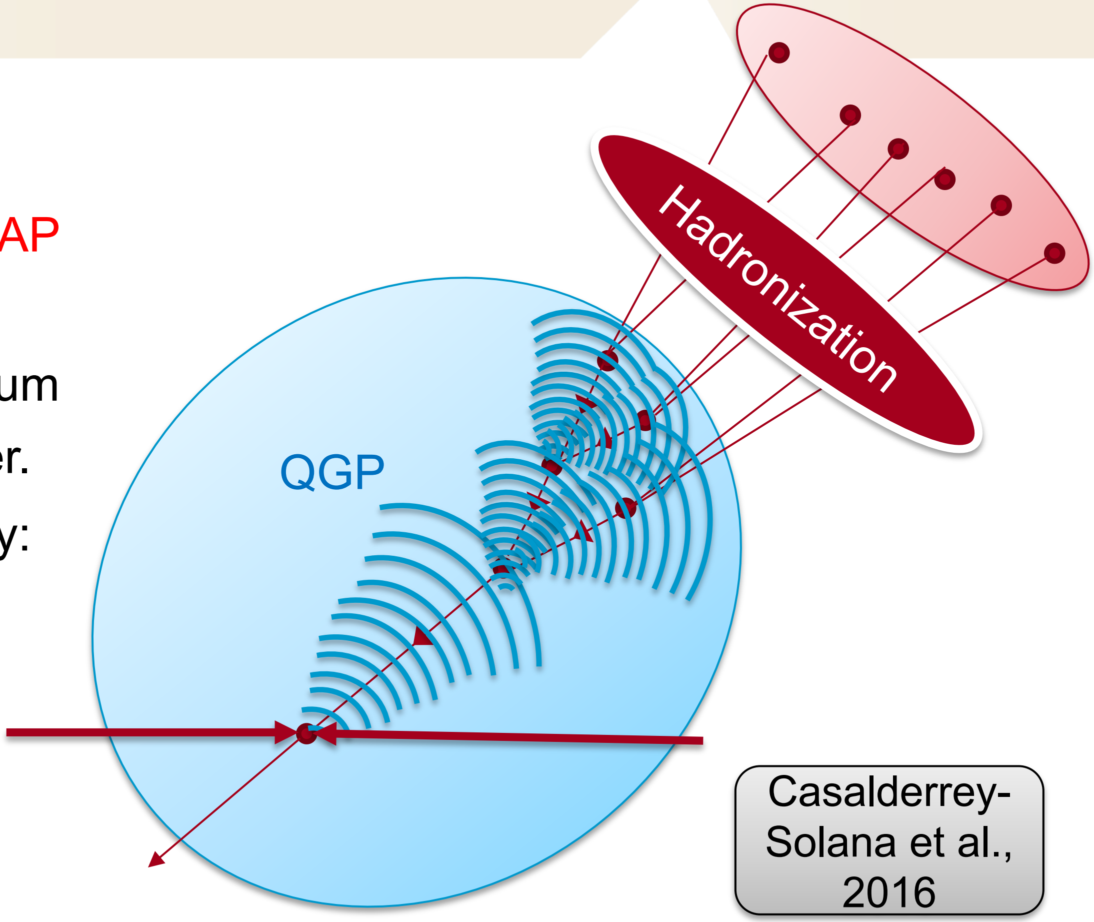


Casalderrey-Solana et al., 2016

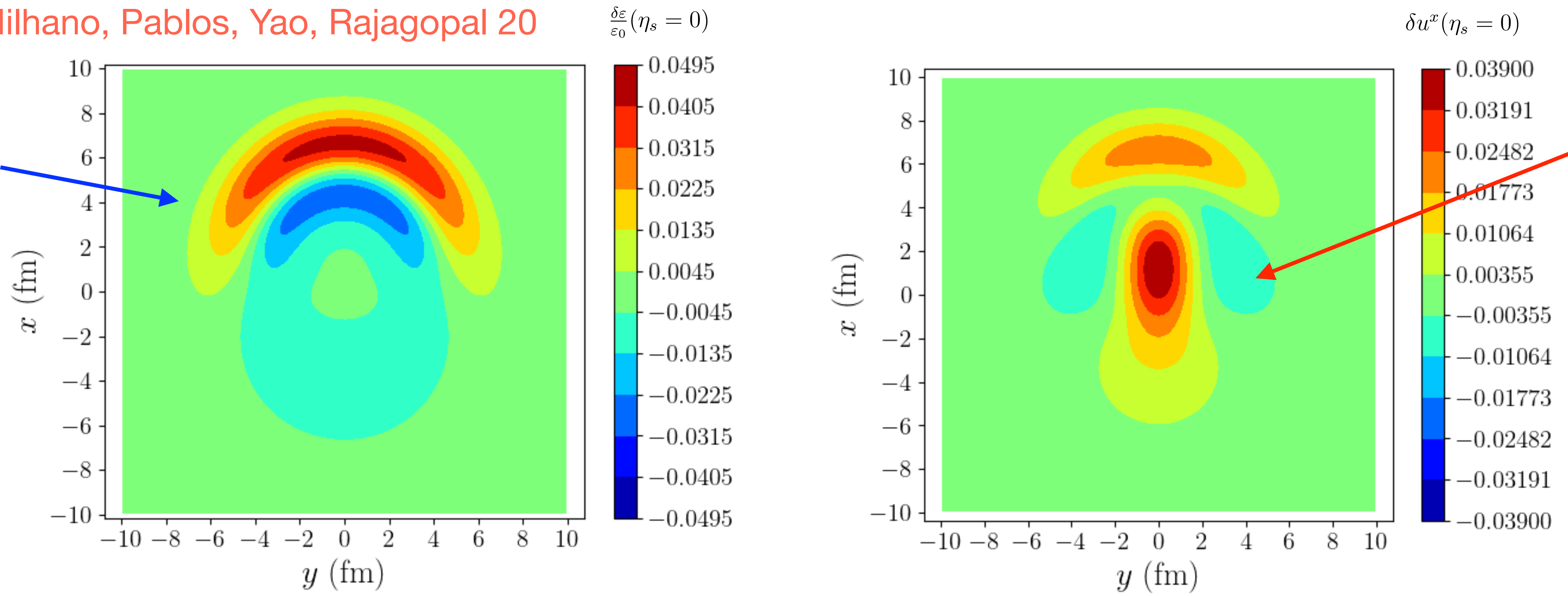
Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f+\delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

Response without Transverse Flow

- Building block: perturbation on-top of Bjorken flow

JCS, Milhano, Pablos, Yao, Rajagopal 20



Sound waves

Diffusion wake

- Sound waves ⇒ take energy away from jet
- Diffusion wake

  ⇒lost momentum becomes moving fluid along the jet path
- On average:

JCS, Teaney and Shuryak 05

diffusion wake dominates over sound waves in particle production

See for Yang, He, Chen, Ke, Pang and Wangattempts to disentangle Mach and wake in COLBT

Estimation of the Hadrons from the Wake

- Assuming:
  - small perturbations on top of Bjorken flow.
  - perturbation stays localised near jet’s rapidity.

Expand Cooper-Frye spectrum to first order in perturbations:

$$E\frac{d\Delta N}{d^3p} = \frac{1}{32\pi}\,\frac{m_T}{T^5}\,\cosh(y-y_j)\exp\left[-\frac{m_T}{T}\cosh(y-y_j)\right]$$

$$\left\{p_T\Delta P_T\cos(\phi-\phi_j)+\frac{1}{3}m_T\,\Delta M_T\,\cosh(y-y_j)\right\}$$

$$\Delta P^i_\perp = w\,\tau\int d^2x_\perp\,d\eta\,\delta u^i_\perp$$

$$\Delta S = \frac{s\,\tau}{c_s^2}\int d\eta\,d^2x_\perp\,\frac{\delta T}{T}$$

Velocity pert.

Temperature pert.

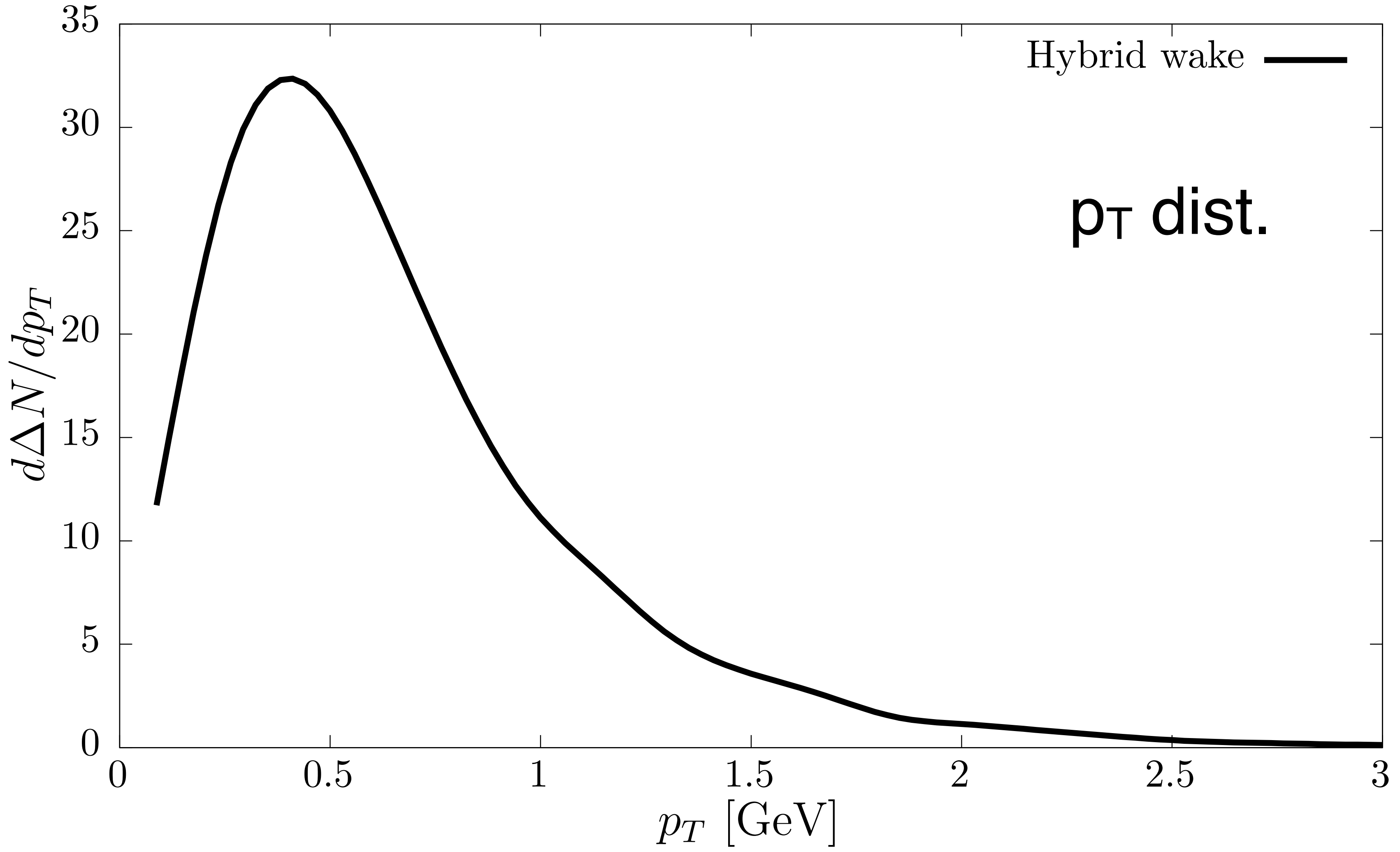
✓ Fully constrained by energy-momentum conservation.

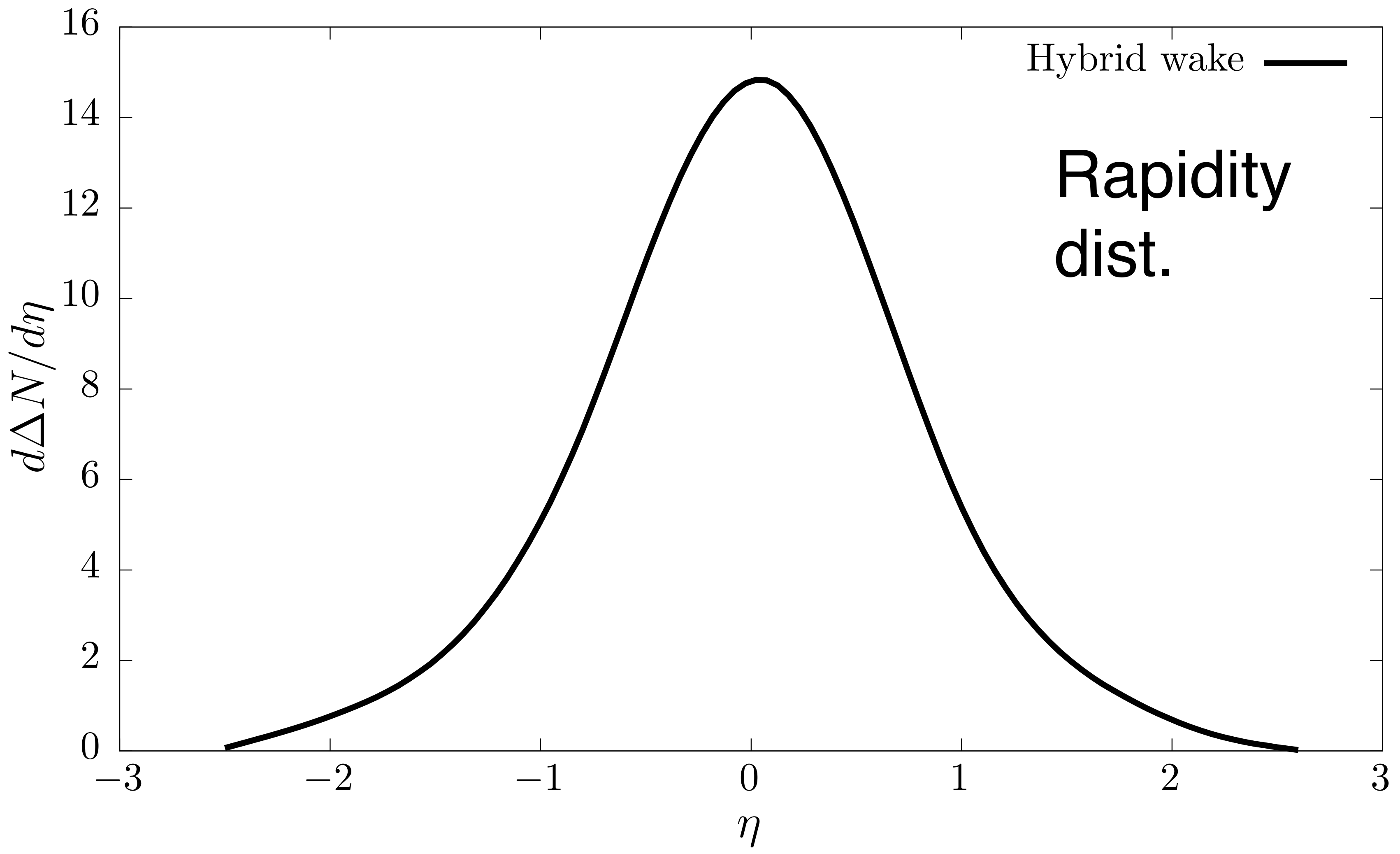
✓ Computationally efficient.

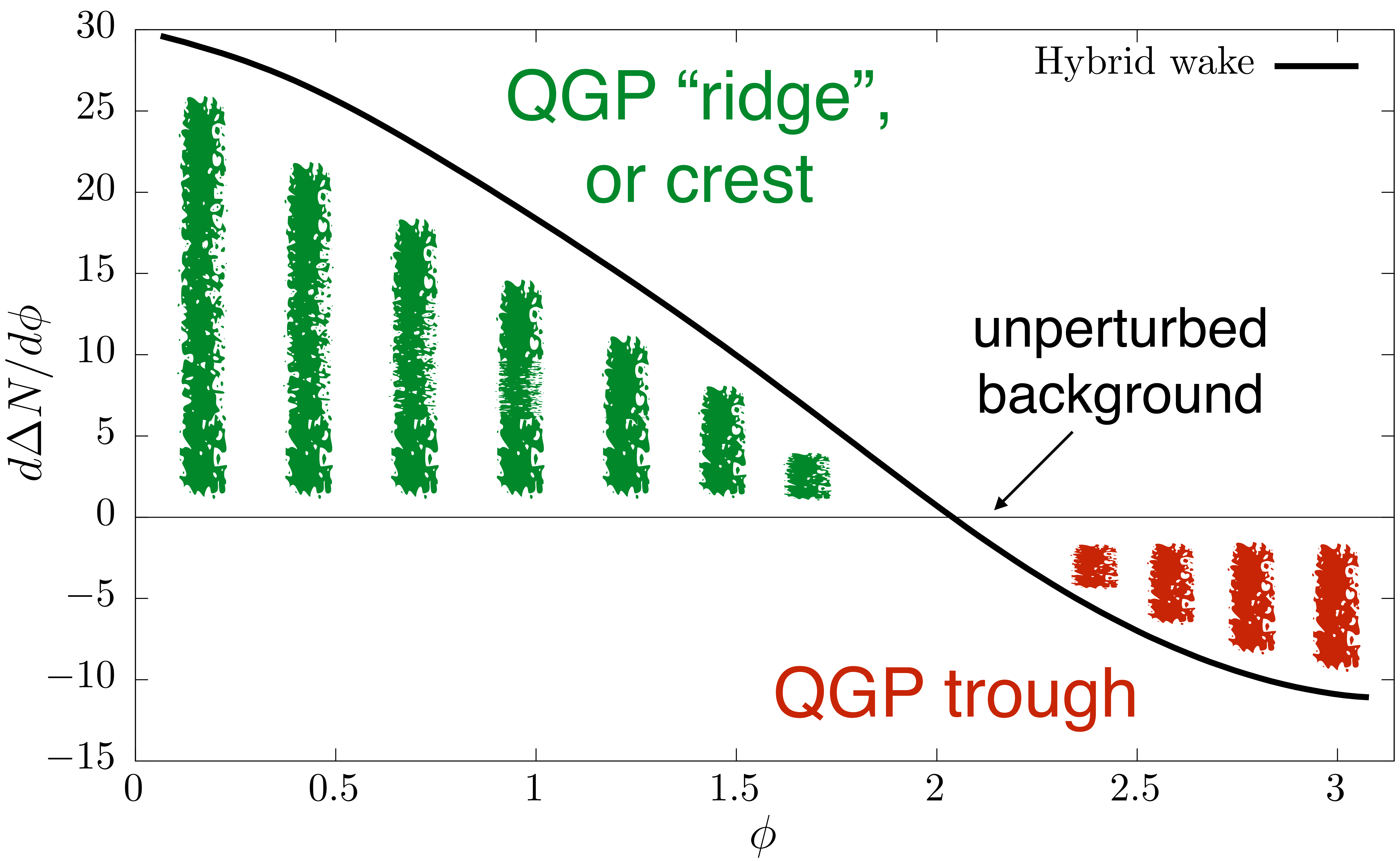
⊗ Neglects important effects from local flow.

Estimation of the Hadrons from the Wake

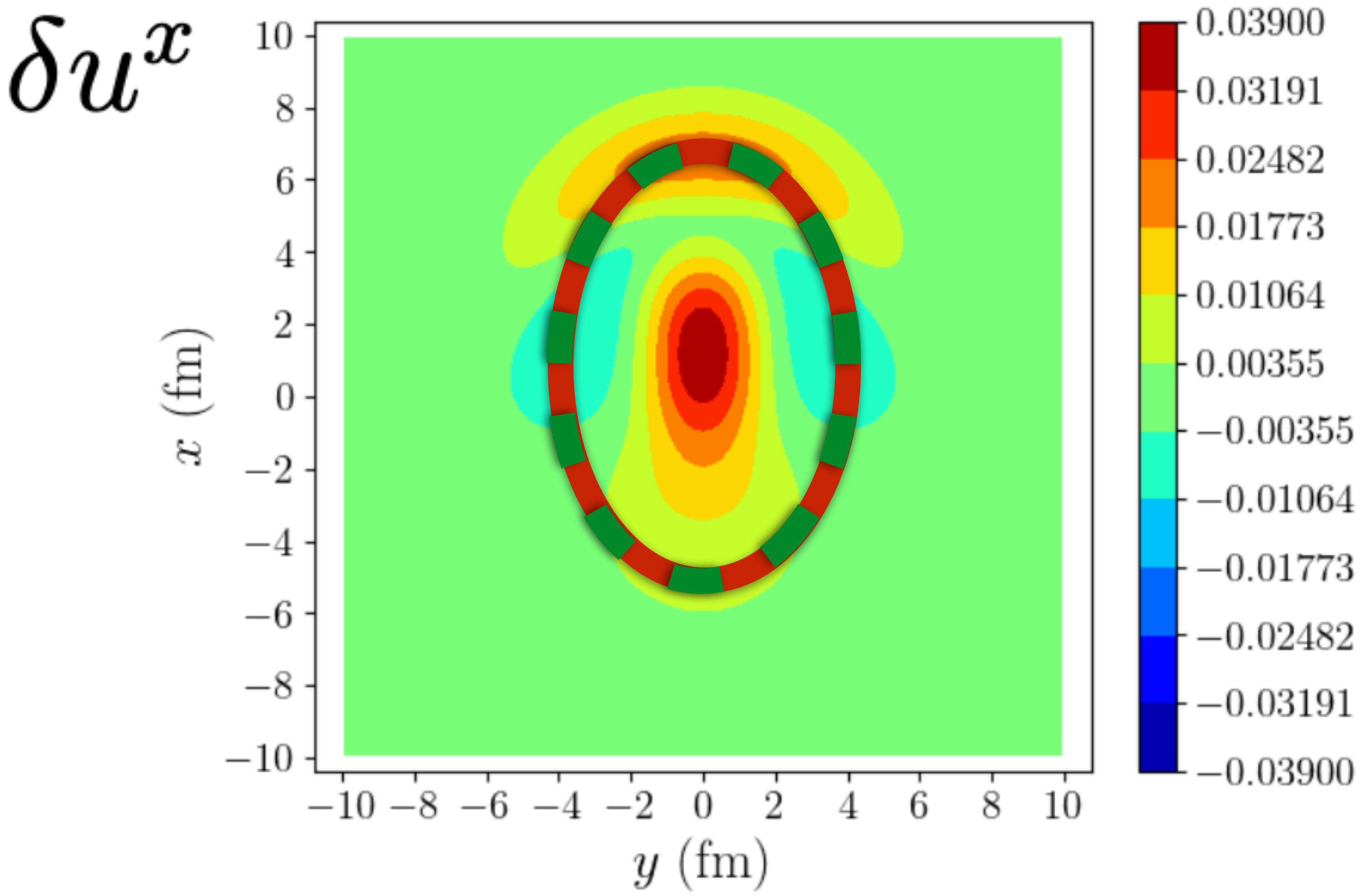
- Sample hadrons from one body dist.
- Energy-momentum conservation through Metropolis.





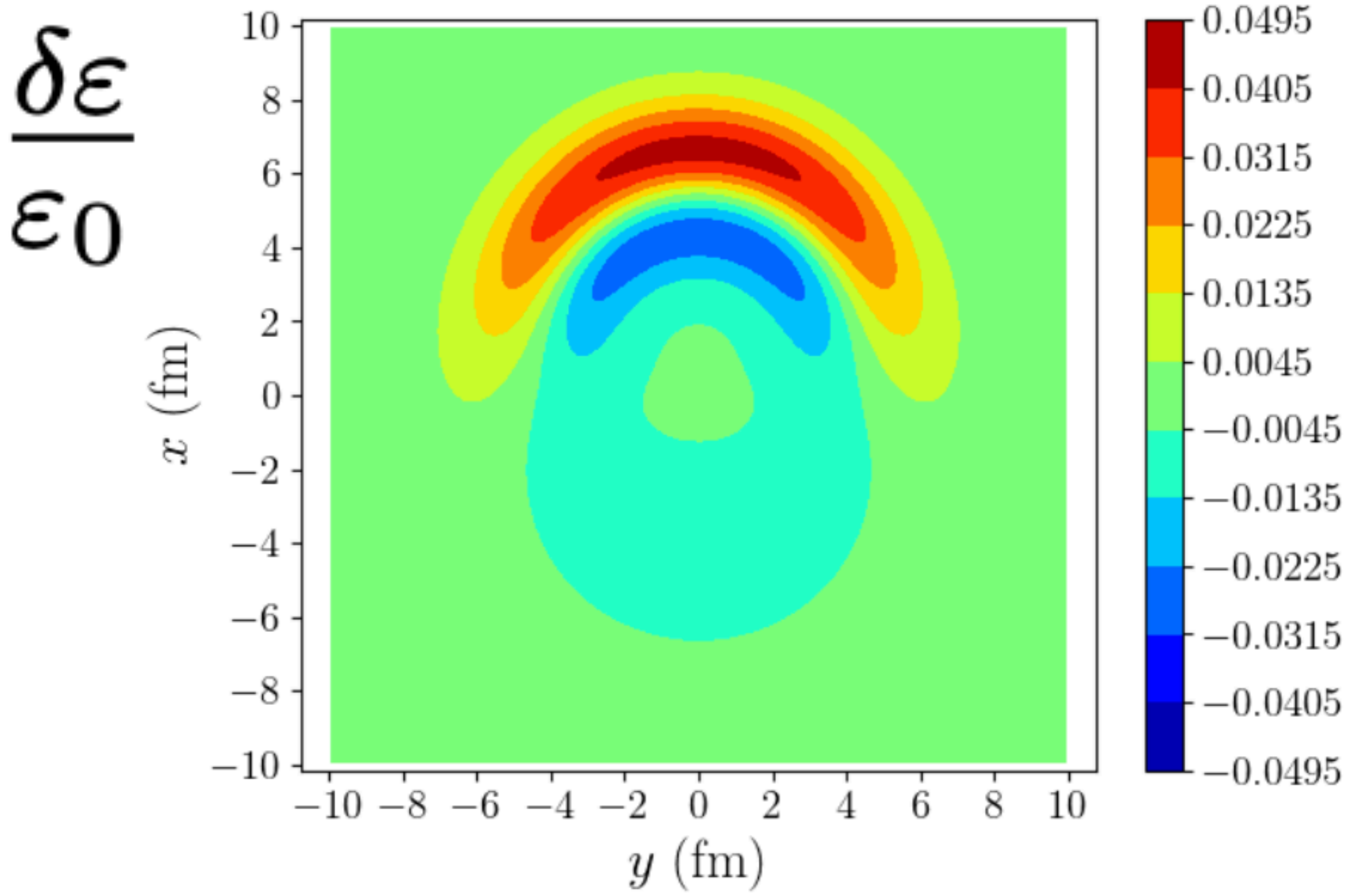


Dragging the QGP



Increase particle production in jet direction, **decrease** in opposite direction (boosted fluid cells).

Cooper-Frye



Increase particle production isotropically.

With respect to unperturbed background

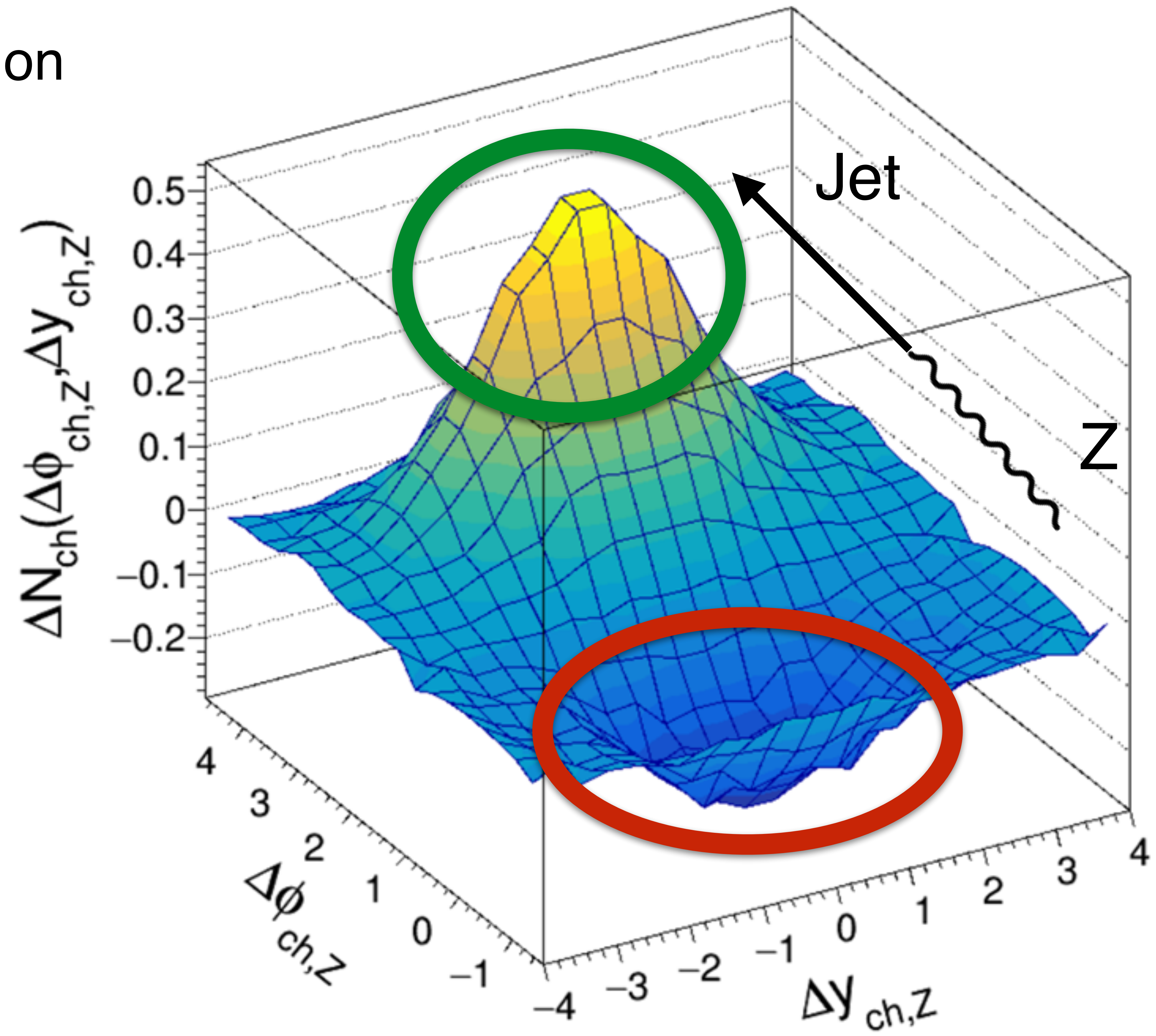
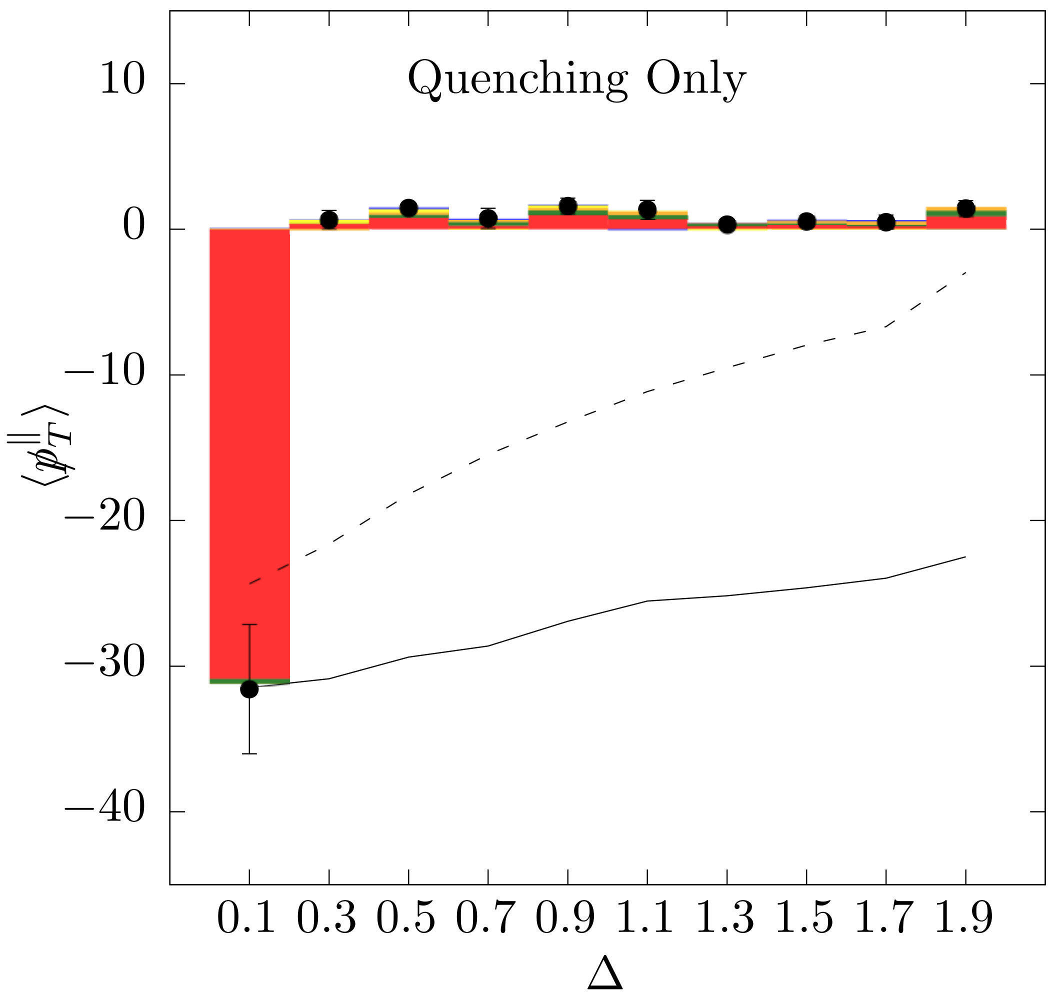


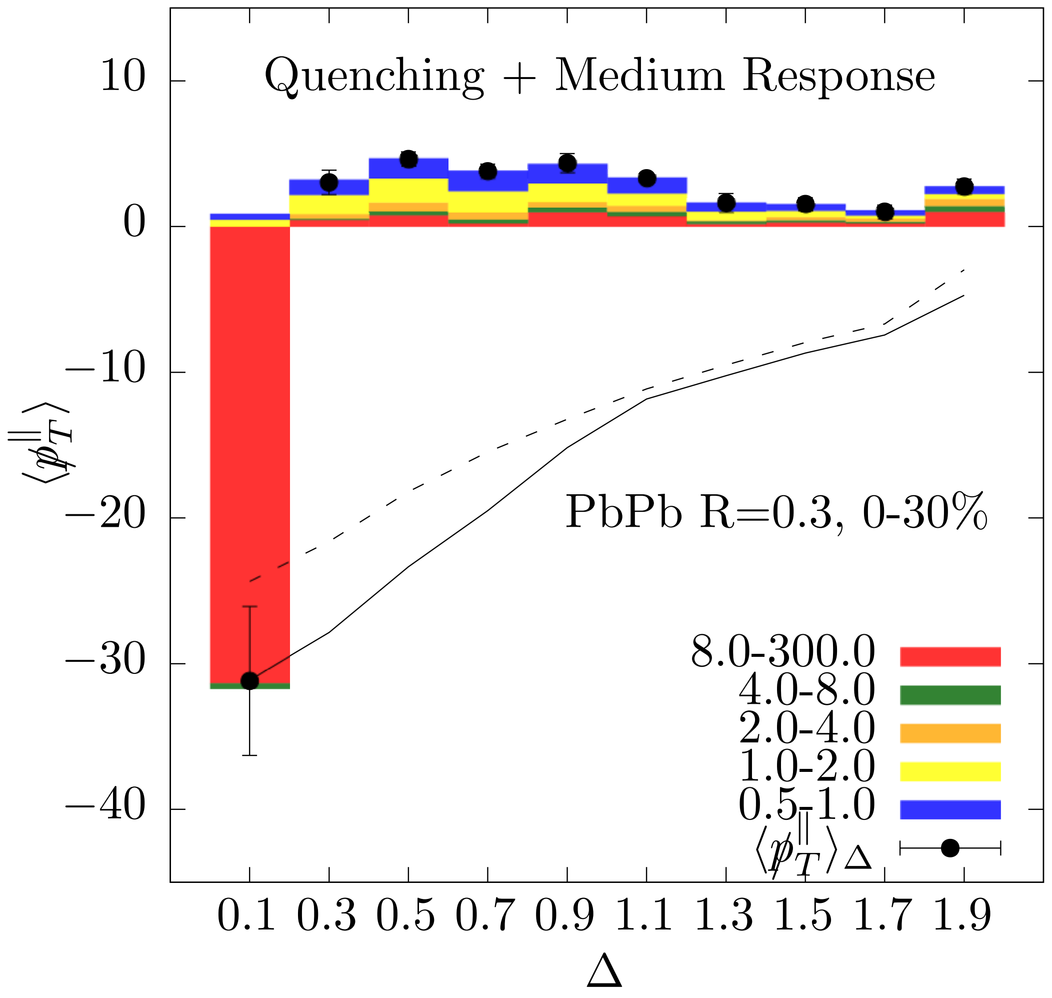
Fig. from Yen-Jie's slides

Missing p_T observables – 2016

- Adding the soft particles from the wake is necessary if we aim to describe data. It also seems that our treatment of the wake does not fully capture what the data calls for.
- If goal is seeing larger angle scattering of partons in the jet, ignore the wake, look at observables sensitive to 5-20 GeV partons; groomed jet substructure observables.
- Lets focus on wake: what was key oversimplification?
- We *assumed* that the wake rapidly equilibrates, and becomes a small perturbation on the hydro flow and hence a small perturbation to the final state particles. The only thing the thermalized particles in the final state remembers is the energy and net momentum deposited by the jet. This is natural at strong coupling.
- We assumed the perturbations to the final state spectra due to the wake are small at all p_T. Need not be so at intermediate p_T.

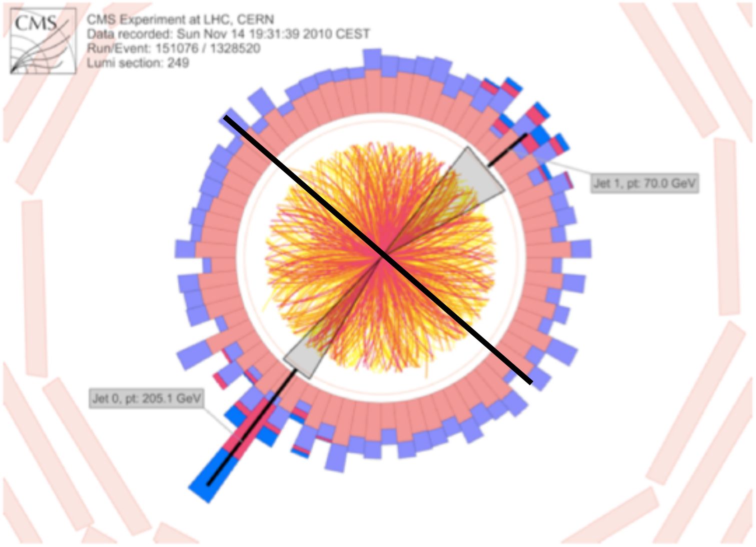
Recovering Lost Energy: Missing Pt





- Energy is recovered at large angles in the form of soft particles

- Adding medium response is essential for a full understanding of jet quenching



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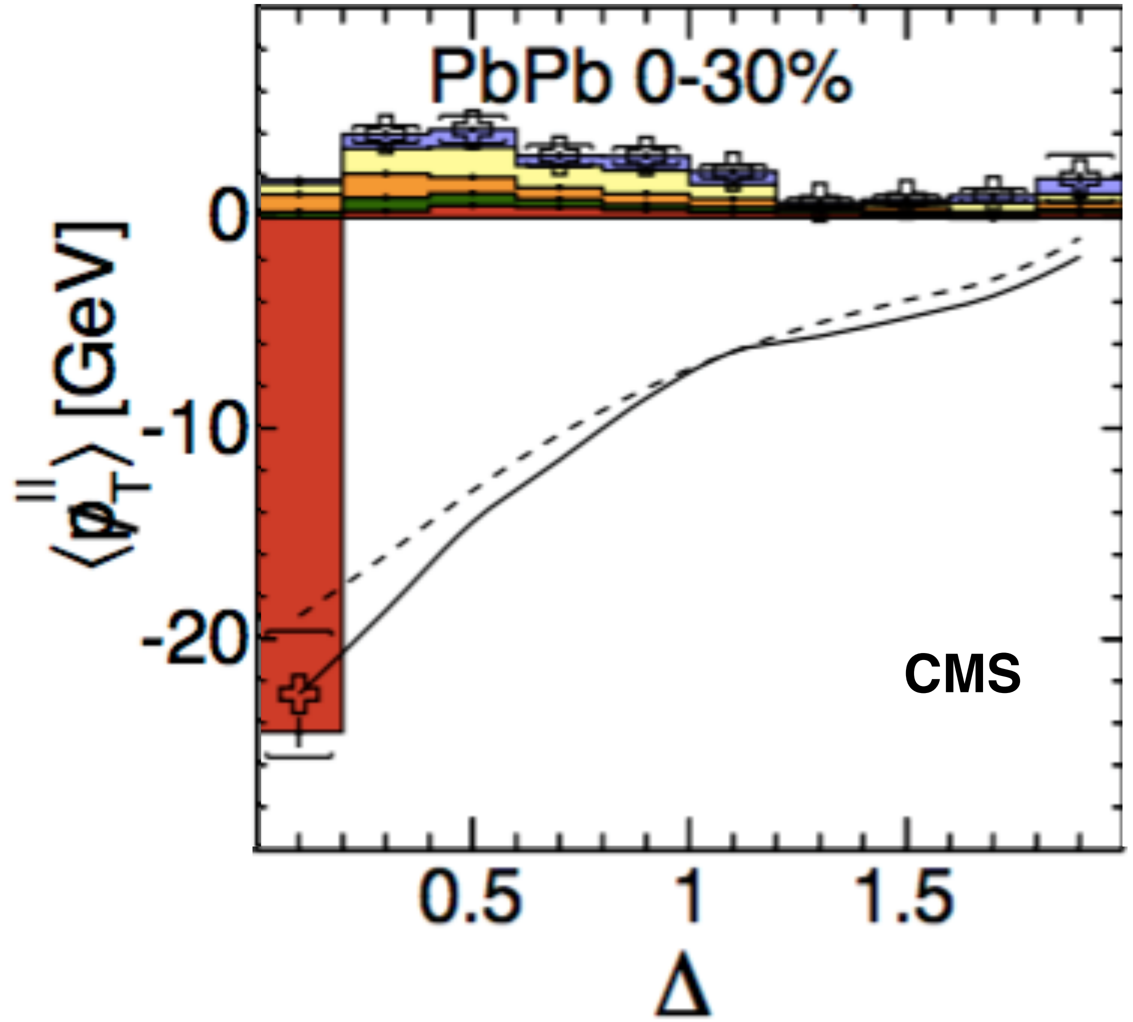

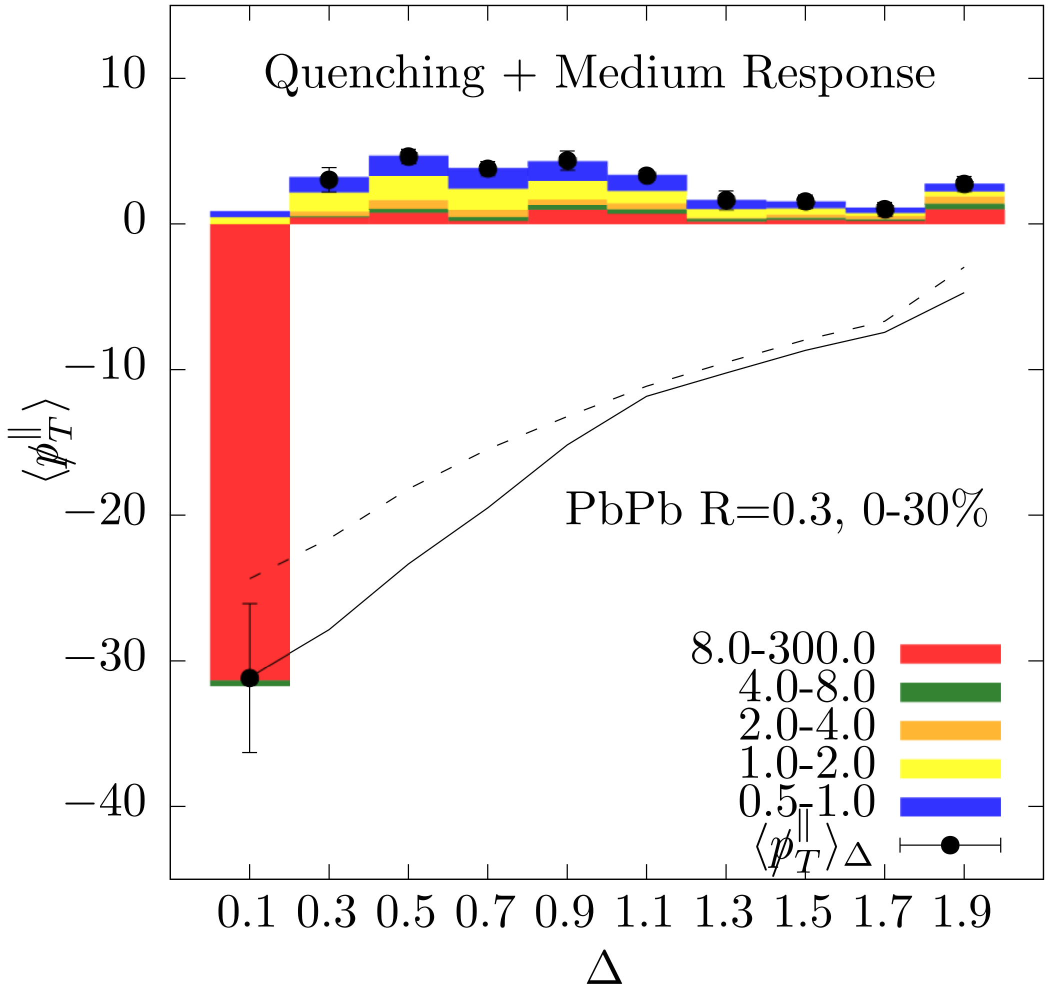

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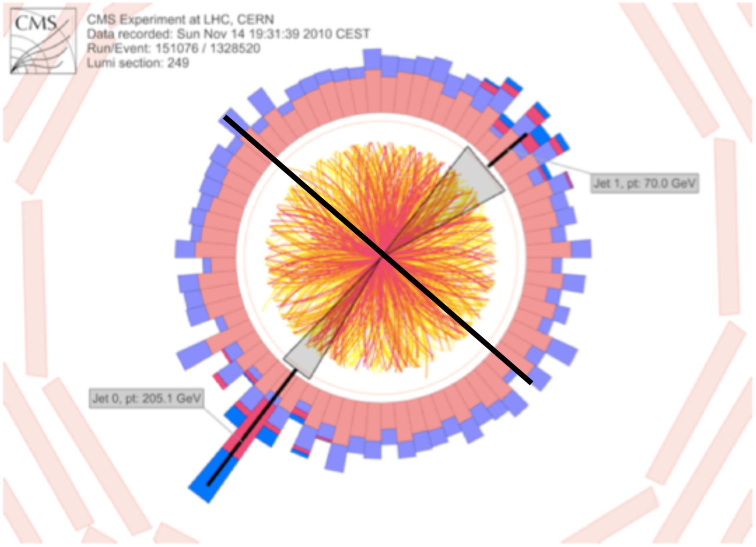

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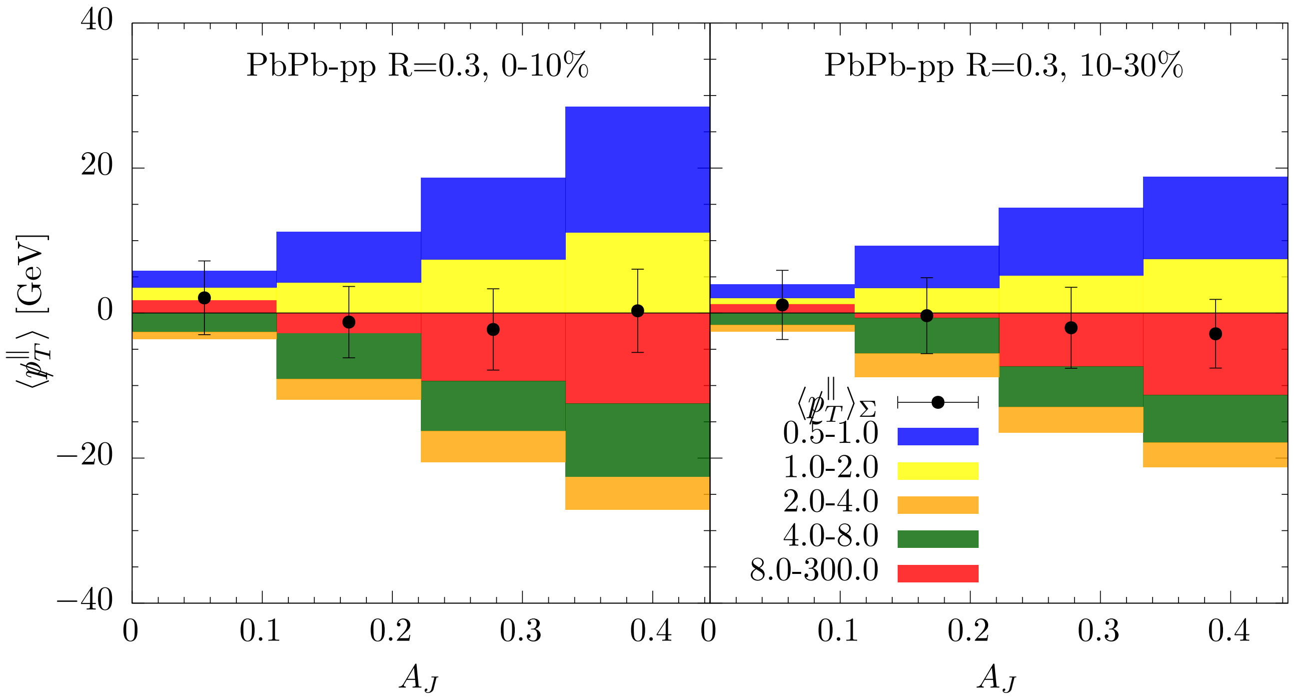
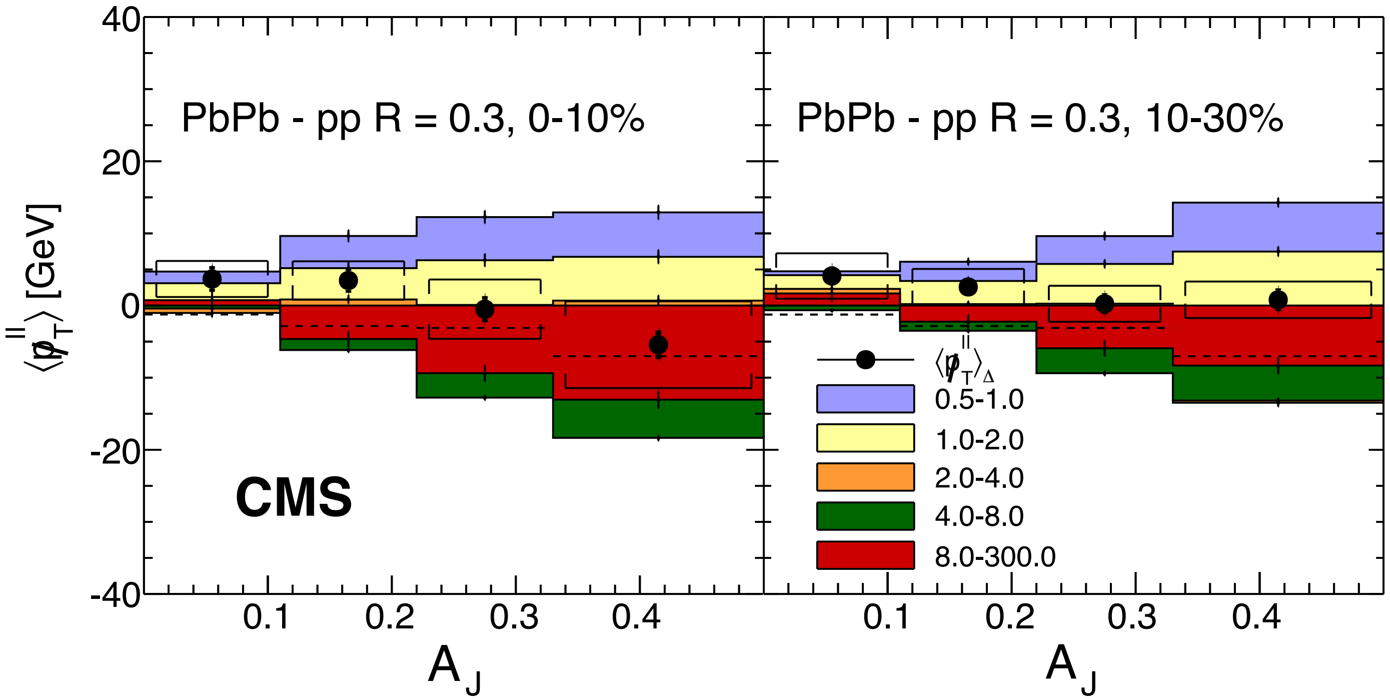
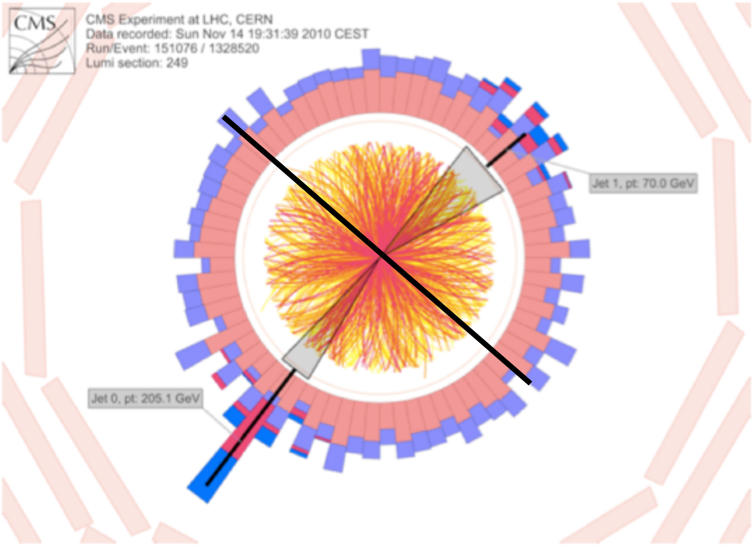


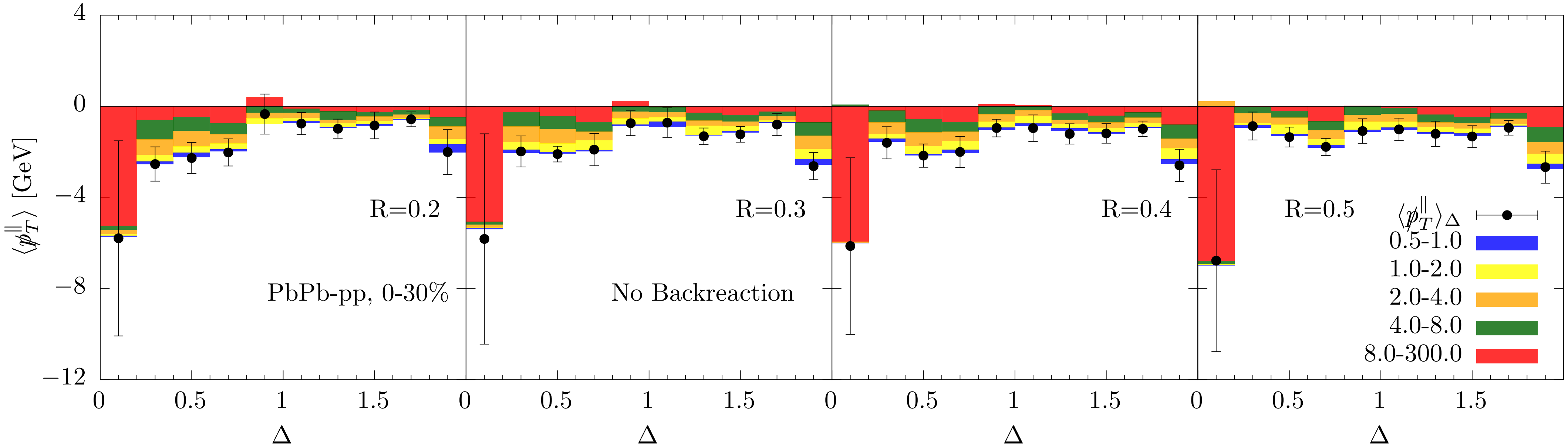


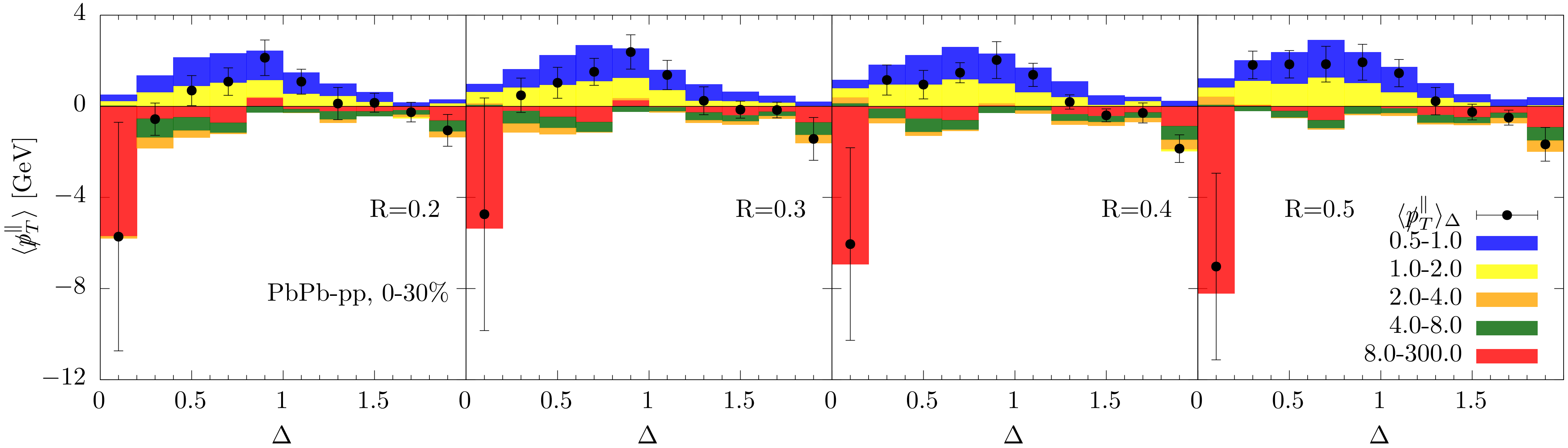
- In PbPb, more asymmetric dijet events are dominated by soft tracks in the subleading jet side

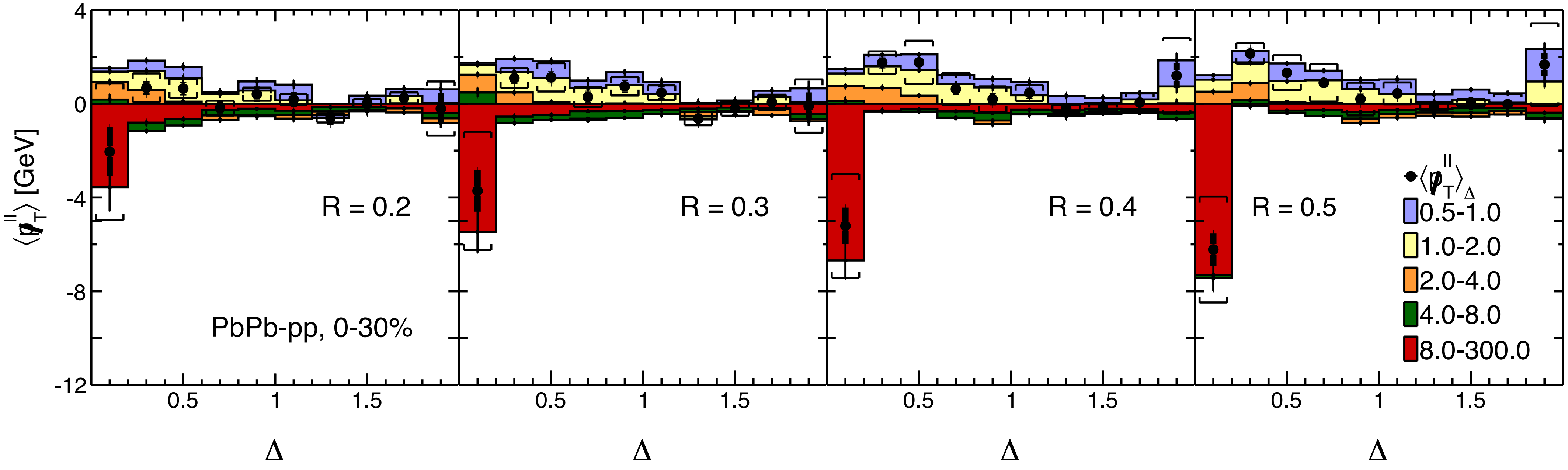
- Discrepancies w.r.t. data in the semi-hard regime motivate improvements to our model



Jet radius dependence of Missing Pt







On the Right Track

- Crude calculation of particles in jet originating from wake has been part of the Hybrid Model since 2016. Weaknesses and strengths known. On the right track, but...
- We have too many particles with 0.5 GeV$< p_T <$2 GeV.
- We have too few particles with 2 GeV$< p_T <$4 GeV.
- Further improving our description of the low-p_T component of jets, as reconstructed, requires full-fledged calculation of the wake. And, the energy and momentum given to the plasma by the jet may not fully thermalize.
- Full hydrodynamic calculation of wake due to every parton in every jet in a sample of 100,000 jets is expensive. Jet wake from linearized hydrodynamics will suffice, and will modify Hybrid Model predictions in the direction indicated by data. Use the linearity of linearized hydro to speed up calculation of wake. Casalderrey-Solana, Milhano, Pablos, KR, Yao 2010.01140 and in progress.

An Implementation Problem

- Monte Carlo analysis: millions of events
- Full hydro analysis of back-reaction:

  Simulating an event is very time consuming

$\Big\}$ Hard to combine

We need approximations!

- Energy injection is small as compared to the fireball $\Longrightarrow$ linearization
  - COLBT: linearised Boltzman equation
  - Here: linearized hydro response
  - But not everything is linear:
    - Deposition rate
    - Particle production E$\gg$ T

$\Big\}$ Non-linear dependence on jet energy

Incorporating Transverse Flow

- Linearized solution on top of radial flow is inefficient:
    - Different simulations for each collision configuration

- An efficient approximate procedure
    - Compose wake from linearised Bjorken solutions by locally boosting to a frame with no transverse flow
    - Correct for the direction of the jet after this boost
    - Compute time between deposition time and freezeout depending on transverse flow
  - Applicable to any transverse flow
  - Fast generation of flow fields induced by jets
    - Library of cases for each deposition point + linear superposition

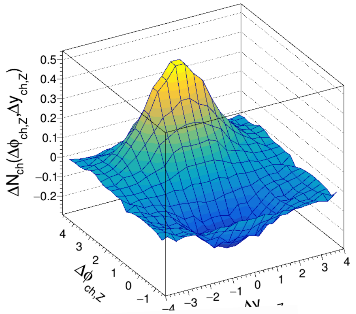
Visualizing Jet Wakes

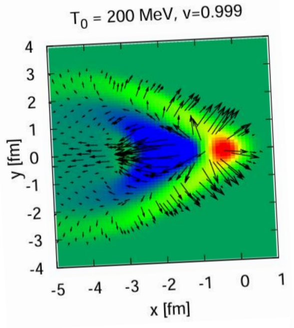
- Three recent (HP2024) examples of observables that we can use to visualize jet wakes, in different ways.
- In all cases, use Hybrid Model to assess sensitivity to jet wakes by turning them off and on.
- Yen-Jie's talk.
- Arjun's talk.
- Energy-energy-energy correlators…
  Bossi, Kudinoor, Moult, Pablos, Rai, KR 2407.13818

Summary and Outlook

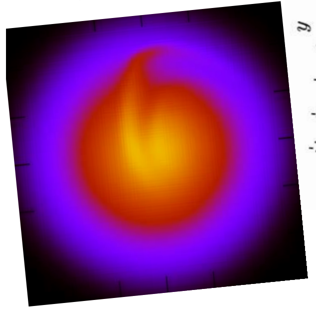
- First p_T^{ch} differential measurement of Z^0-hadron correlation in azimuthal angle and rapidity
- We report the **first direct evidence of medium response in QGP**
- High statistics analysis with Run3+4 data in the near future

Hybrid Model

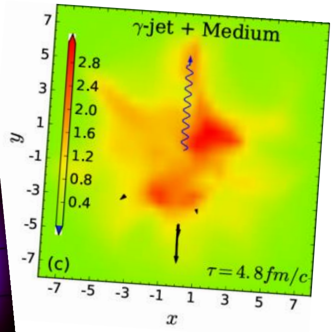


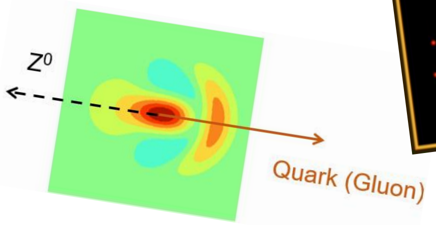


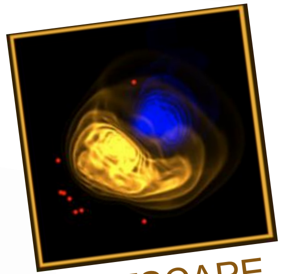
Jet-Fluid



Co-LBT

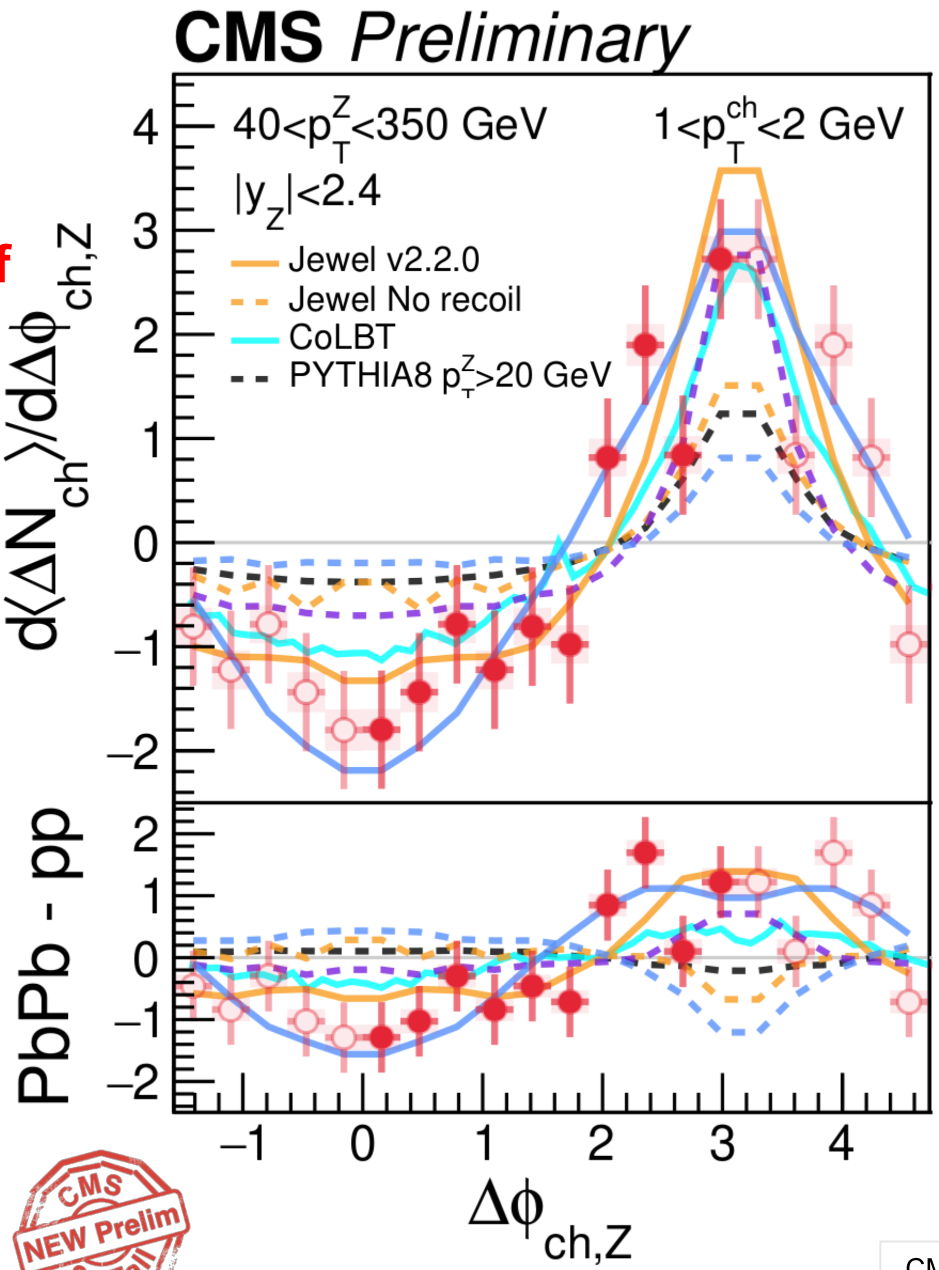


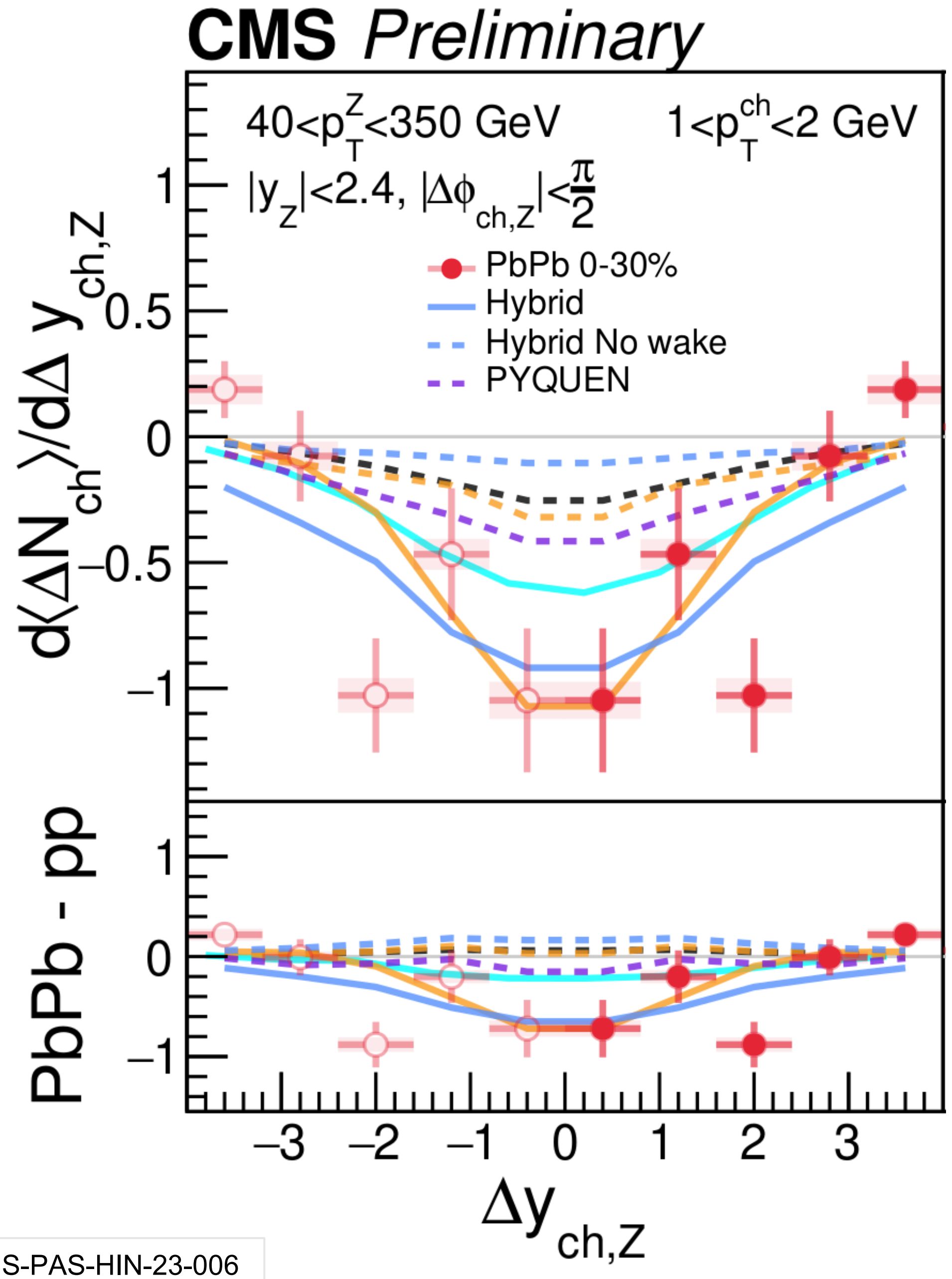




JETSCAPE

CMS NEW Prelim 24'Fall





CMS-PAS-HIN-23-006

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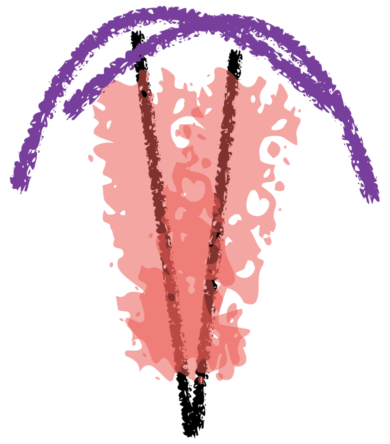
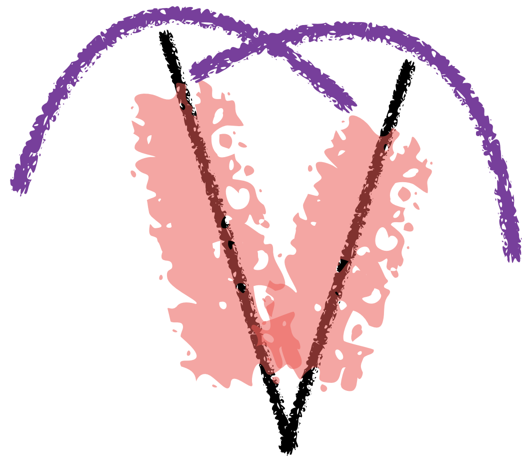
- Yen-Jie's talk.
- Arjun's talk.
- Energy-energy-energy correlators...
  Bossi, Kudinoor, Moult, Pablos, Rai, KR 2407.13818

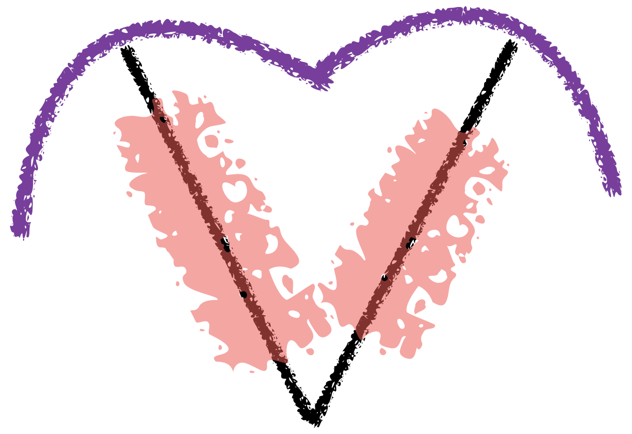
Multiple Wakes

We have learned that wider structures tend to be more suppressed, but can we analyze the medium response to these multiple structures?

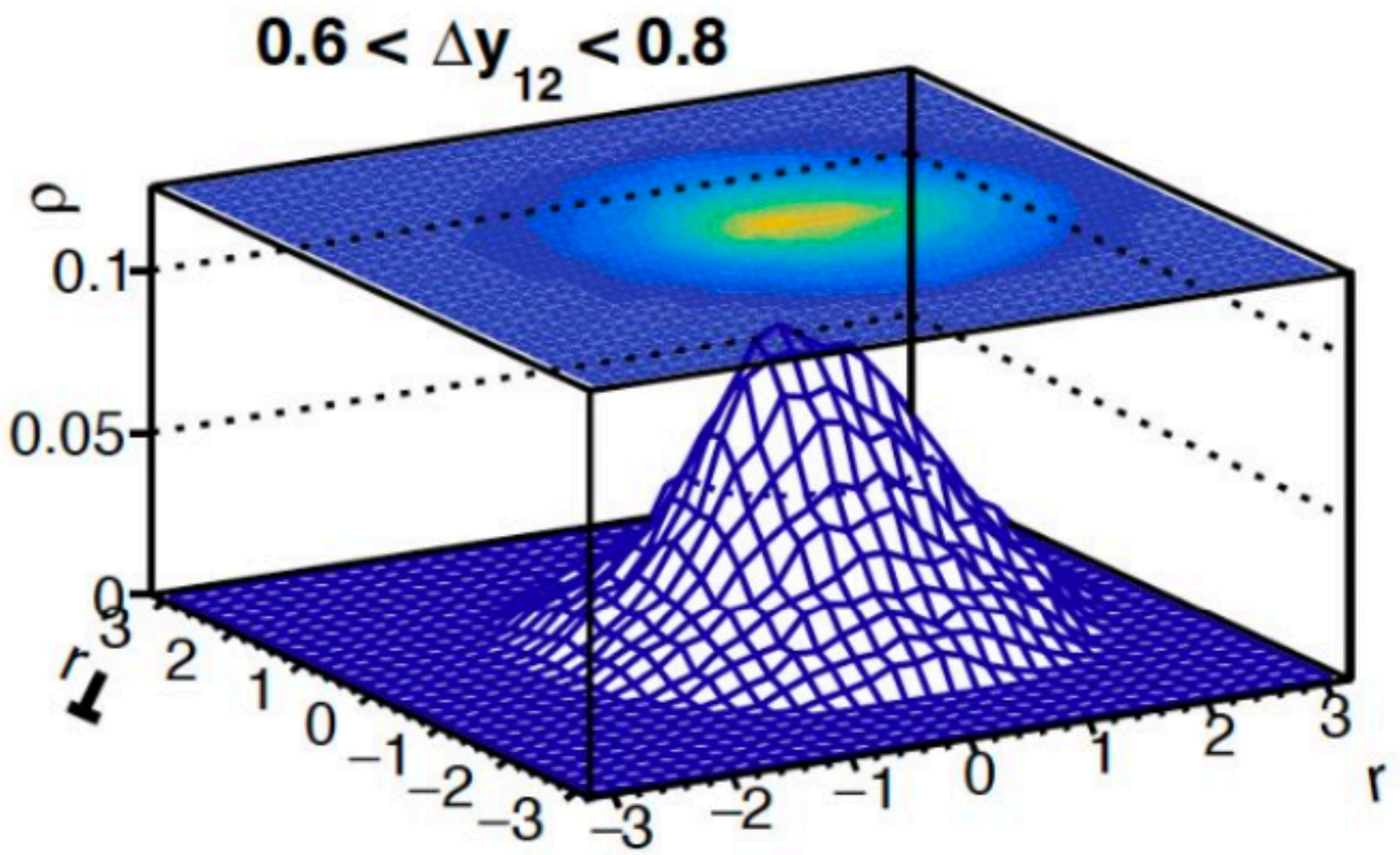
See M. Park’s talk
See M. Nguyen’s talk
See B. Hofman’s talk

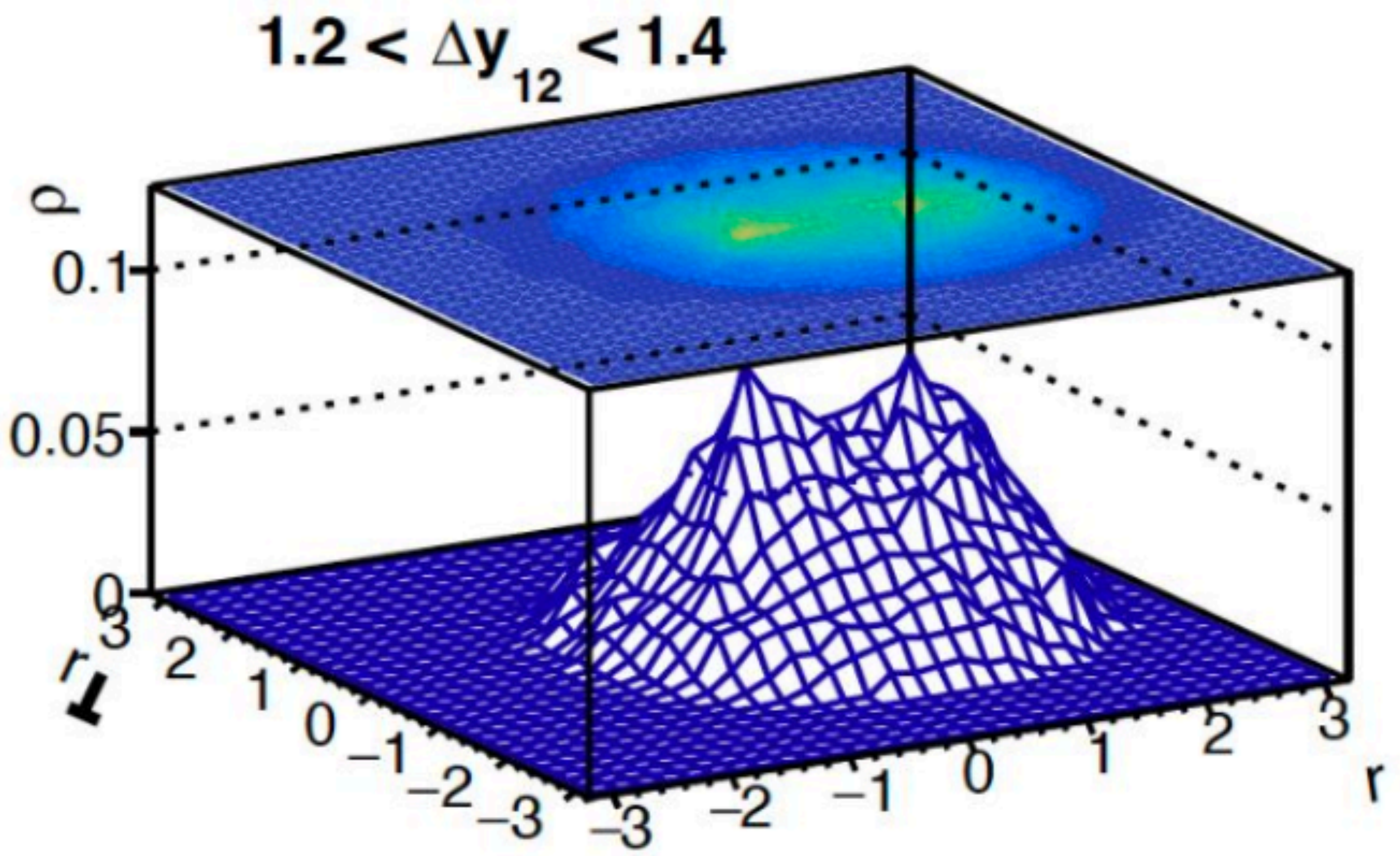


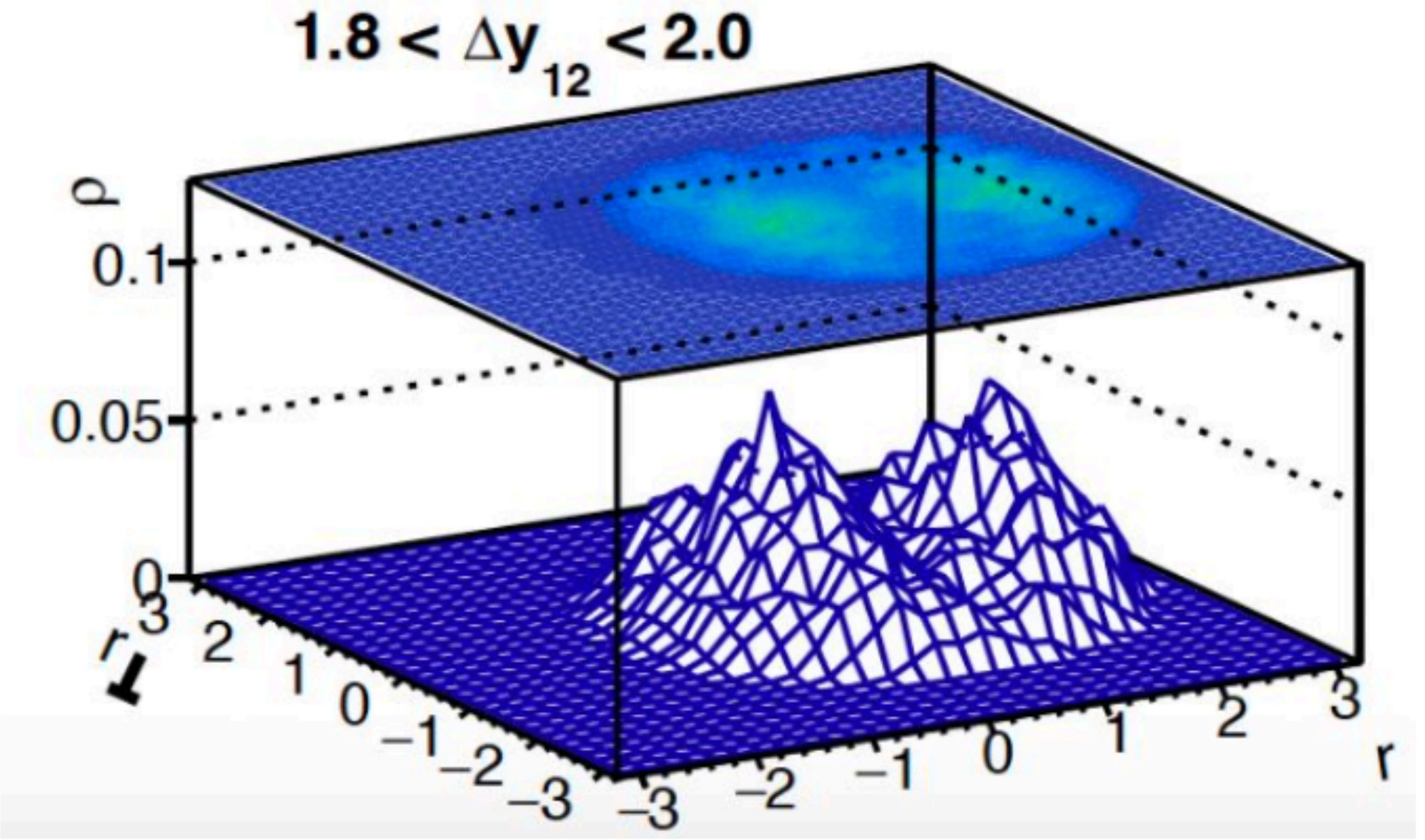




See A. Kudinoor’s talk







Just wake particles

Exploit ATLAS’ reconstruction of large R jets via hard small R jets.

See M. Rybar’s talk

Multiple Wakes

We have learned that wider structures tend to be more suppressed, but can we analyze the medium response to these multiple structures?

See M. Park's talk
See M. Nguyen's talk
See B. Hofman's talk

⬛ Wake + Nonwake (Pb+Pb)
🟥 Wake (Pb+Pb)
🟦 Non-Wake (Pb+Pb)
🟩 Vacuum (pp)

Soft particles contribution dominated by wake(s).

See A. Kudinoor's talk

Outlook: Non-trivial interference patterns? Event plane correlations?

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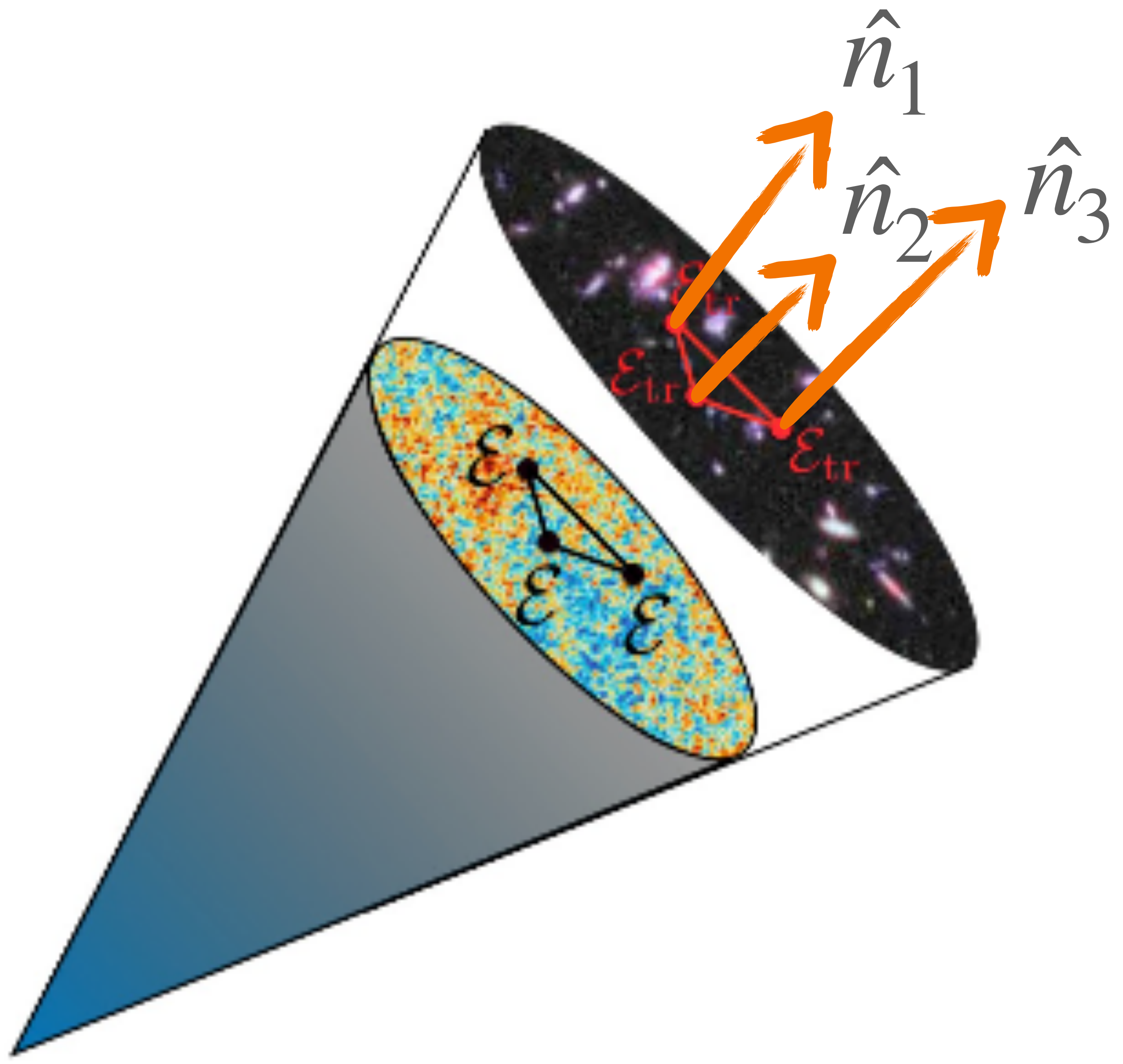
Energy Correlators in Jets

Definition



Number of particles in the correlation

Power on energy weight

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

Largest distance between N particles

Lessons for Energy Correlators

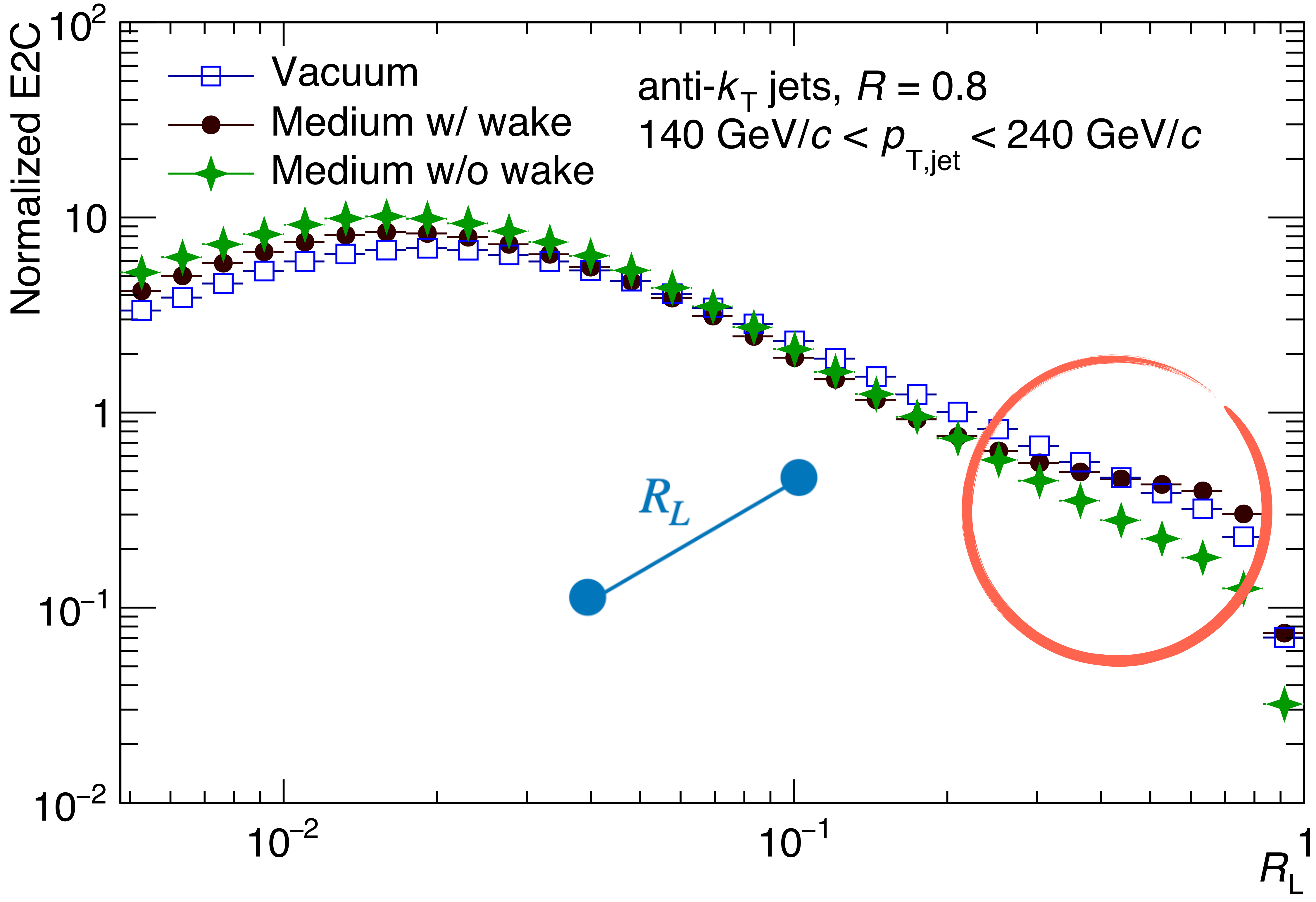
- Hadrons coming from the response of the medium to the parton shower *are* a component of what is reconstructed as a jet in heavy ion collisions. But to date (before HP2024) it has been difficult to find and measure jet observables that are unambiguously dominated by this component.
- Physics of energy correlators in jets in vacuum will be modified in heavy ion collisions, as parton shower is modified. In some kinematic regimes, this beautiful physics will be obscured by particles coming from the wake.
- If wake can obscure, perhaps in some kinematic regimes it can dominate? Not for E2C or projected E3C; they depend only on R_L. Modification of the shower, and wake, both modify E2C and E3C in same large-R_L regime.
- If the wake can obscure, perhaps in some kinematic regimes it can dominate! → Imaging the “shape” of the wake via energy-energy-energy correlators!
- Long term: use event selection and correlator engineering to see how wake evolves/dissipates by comparing smaller/larger collisions, smaller/larger path length.

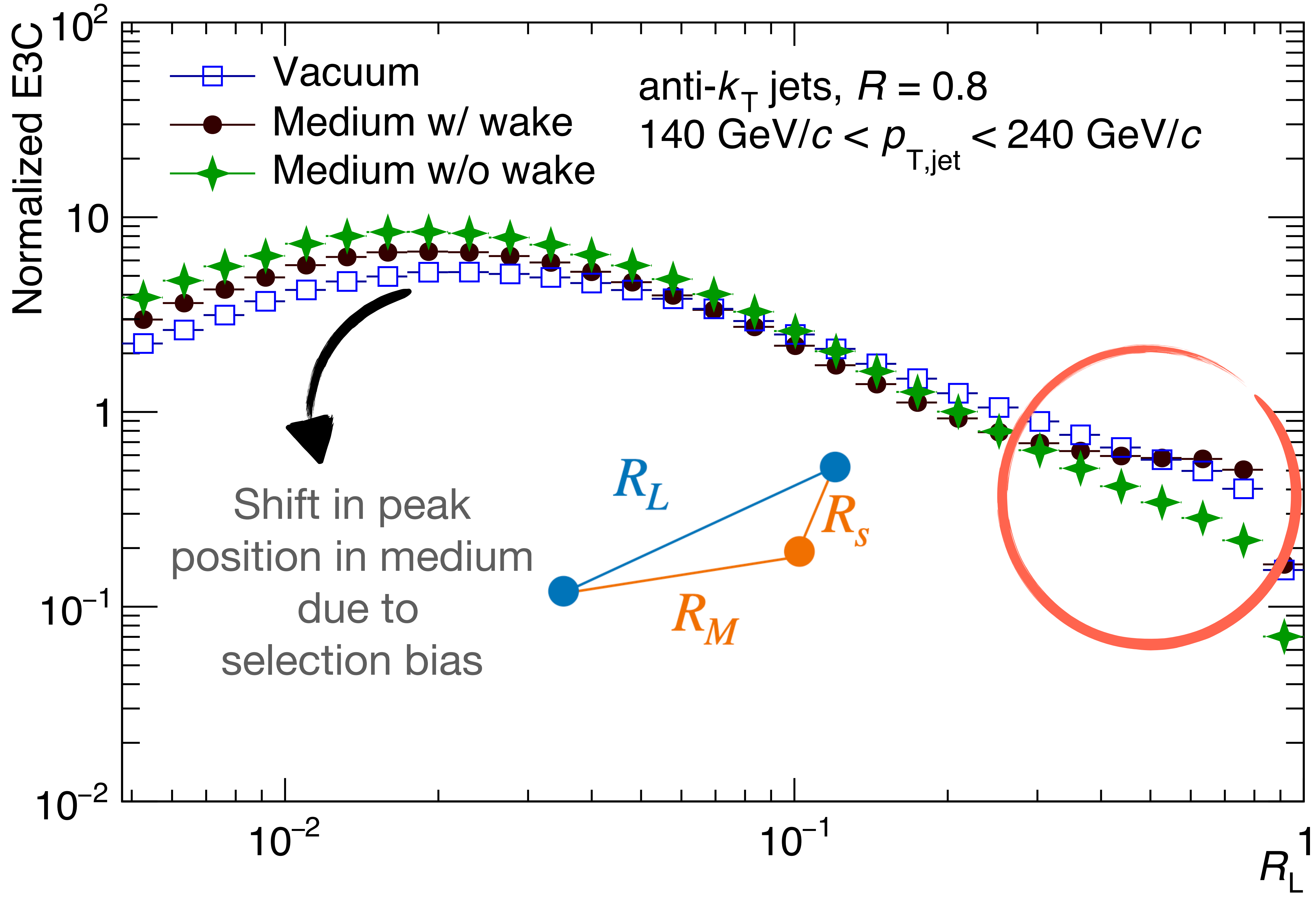
E2C and E3C in Heavy Ion Collisions

Looking for interesting physics

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

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





Shift in peak position in medium due to selection bias

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

Lessons for Energy Correlators

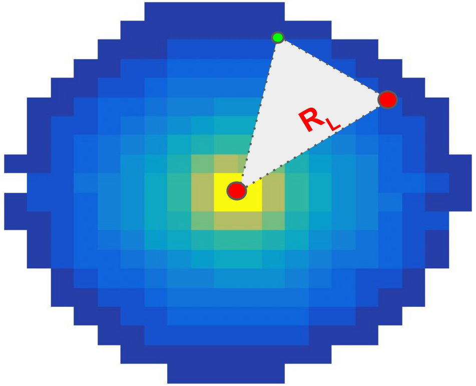
- Hadrons coming from the response of the medium to the parton shower *are* a component of what is reconstructed as a jet in heavy ion collisions. But to date (before HP2024) it has been difficult to find and measure jet observables that are unambiguously dominated by this component.
- Physics of energy correlators in jets in vacuum will be modified in heavy ion collisions, as parton shower is modified. In some kinematic regimes, this beautiful physics will be obscured by particles coming from the wake.
- If wake can obscure, perhaps in some kinematic regimes it can dominate? Not for E2C or projected E3C; they depend only on R_L. Modification of the shower, and wake, both modify E2C and E3C in same large-R_L regime.
- If the wake can obscure, perhaps in some kinematic regimes it can dominate! → Imaging the "shape" of the wake via energy-energy-energy correlators!
- Long term: use event selection and correlator engineering to see how wake evolves/dissipates by comparing smaller/larger collisions, smaller/larger path length.

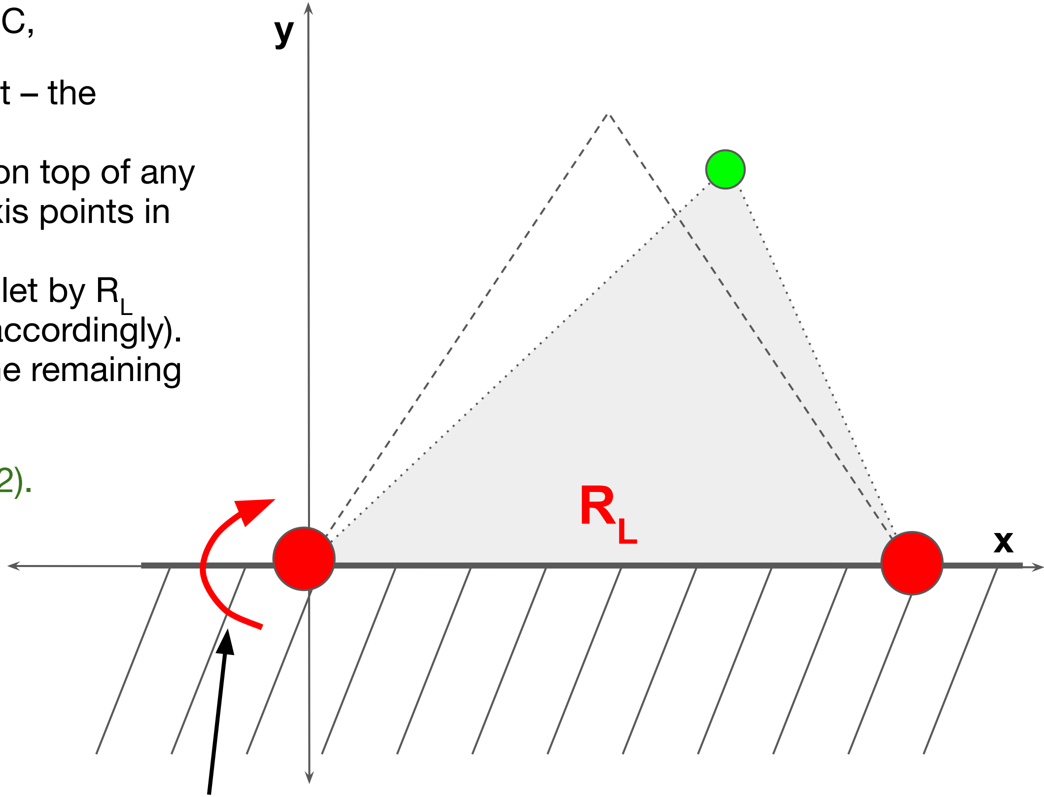
A NEW COORDINATE SYSTEM

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 $(x, y) = (\frac{1}{2}, \sqrt{3}/2)$.

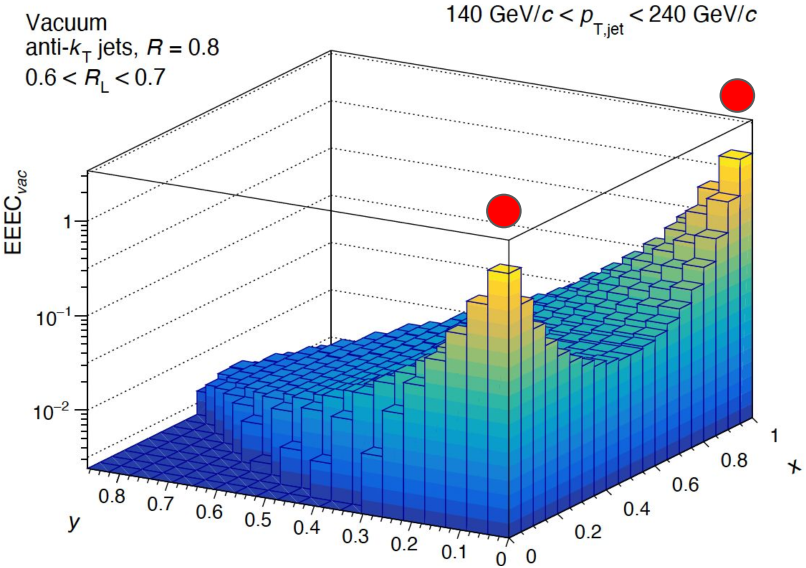




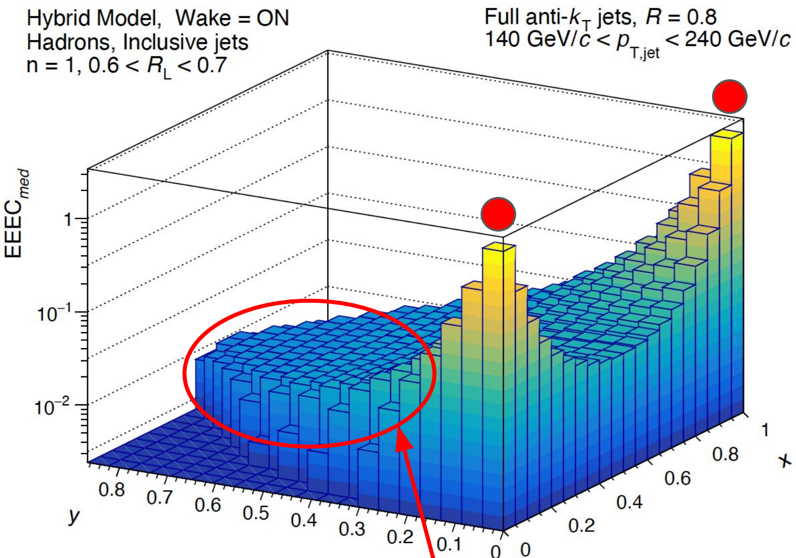
Green points below this line are equivalent to green points symmetrically above this line

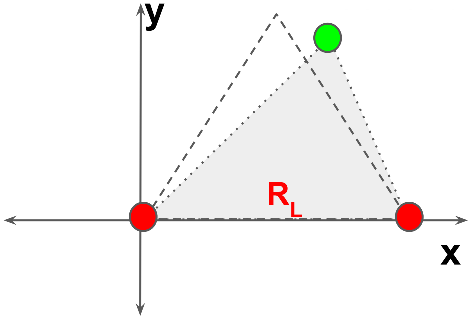
EEECs IN (x , y) COORDINATES

Vacuum EEEC



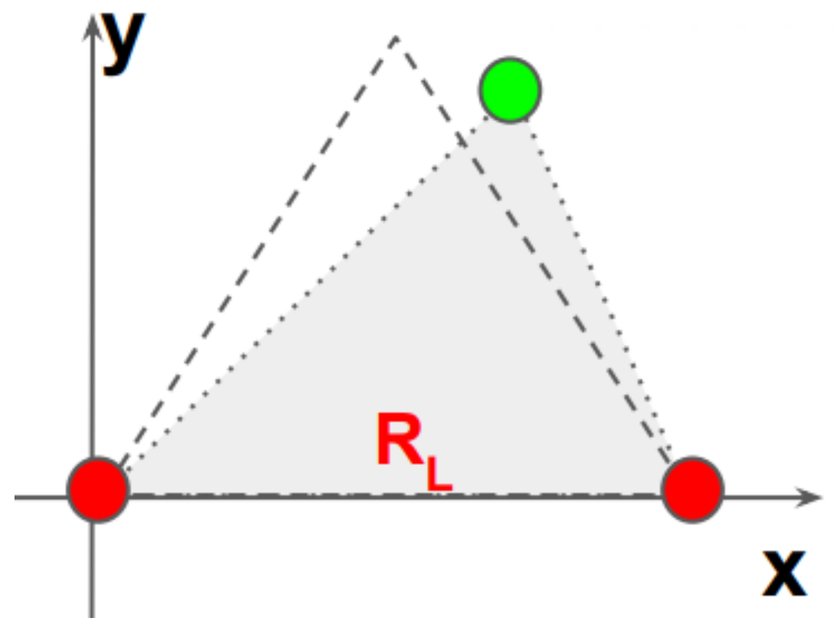
Pb+Pb with wake EEEC





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

The Wake on the EEEC



$0.6 < R_L < 0.7$

then rescaled to 1

3-point energy correlator (EEEC) in PbPb:

- Striking dependence on the wake.
- Specially manifest in the *equilateral region*.
- Dominated by jet-wake-wake correlations.

See A. Rai's poster

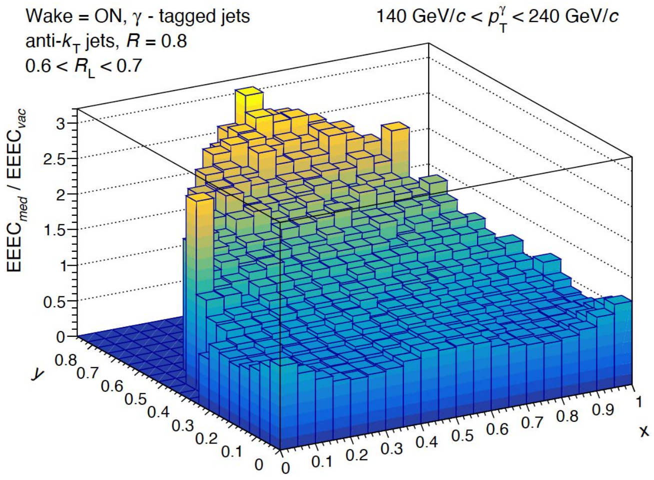
Bossi et al. - 2407.13818

EFFECT EVEN MORE PRONOUNCED IN GAMMA-JETS

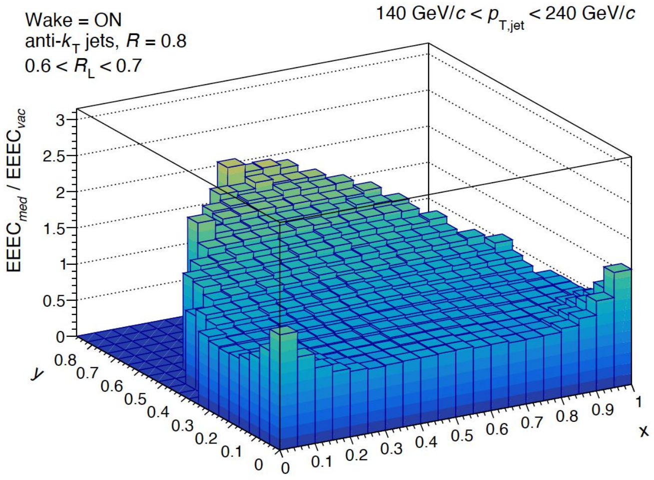
γ-jet Selection Criteria

- 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

Gamma-Jets



Inclusive Jets



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**.

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Jets as Probes of QGP

- Model calculations enabling key steps. . .
- Disentangling jet modification from jet selection.
- Showing that QGP *can* resolve structure within jet shower.
- Identification of new experimental observables, and predictions, that are enabling new experimental measurements to "see" the particles originating from jet wakes. Points the way toward visualizing dynamics of jet wakes in droplets of QGP and how they hydrodynamize.
- Identifying those jet substructure observables that *are* sensitive to scattering of jet quarks/gluons off QGP quarks/gluons, "seeing the latter à la Rutherford, and are *not* sensitive to particles coming from the wake.
- Next several years will be the golden age of HIC jet physics: sPHENIX, LHC runs 3 and 4, new substructure observables. *Many* theoretical and experimental advances are whetting our appetite for the feast to come.
- We can learn about the microscopic structure of QGP, and the dynamics of rippling QGP.

Identifying Jet Observables with which to “See” the Short-Scale Structure of QGP

Krishna Rajagopal
MIT

with
Zach Hulcher (Stanford)
Dani Pablos (INFN Torino)

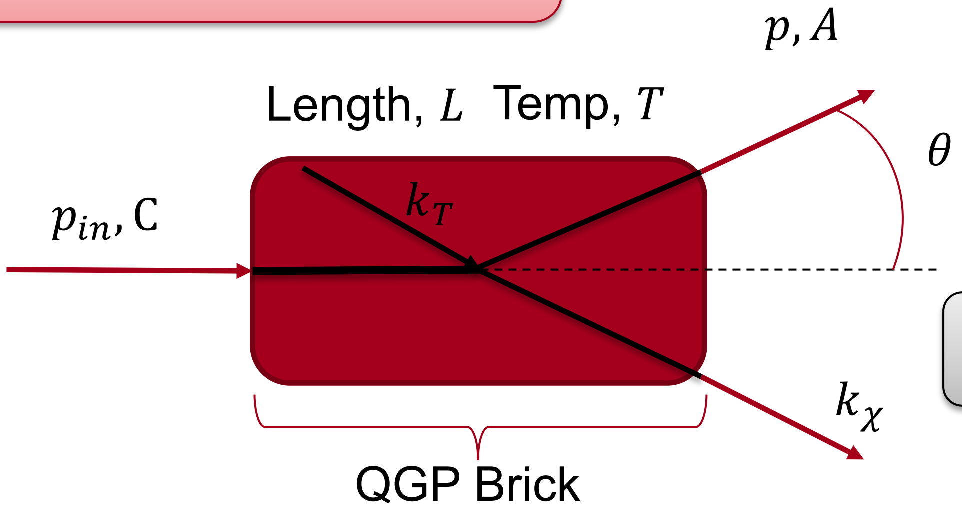
Why Molière scattering?
Why add to Hybrid Model?

- QGP, at length scales $\mathcal{O}(1/T)$, is a strongly coupled liquid. Flow, and jet observables sensitive to parton energy loss, are well-described (eg in hybrid model) in such a fluid, without quasiparticles.
- At shorter length scales, probed via large momentum-exchange, asymptotic freedom → quasiparticles matter.
- High energy partons in jet showers *can* probe particulate nature of QGP. Eg via power-law-rare, high-momentum-transfer, large-angle, Molière scattering
- “Seeing” such scattering is first step to probing microscopic structure of QGP.
- What jet observables are sensitive to effects of high-momentum-transfer scattering? To answer, need to turn it off/on.
- Start from Hybrid Model – in which any particulate effects are definitively off! Add Molière, and look at effects...

Moliere Scattering in a brick of QGP (D'Eramo, KR, Yin, 2019)

Power-law-rare medium kicks which can probe particle constituents of QGP

In JEWEL, LBT, MARTINI, harder to turn off



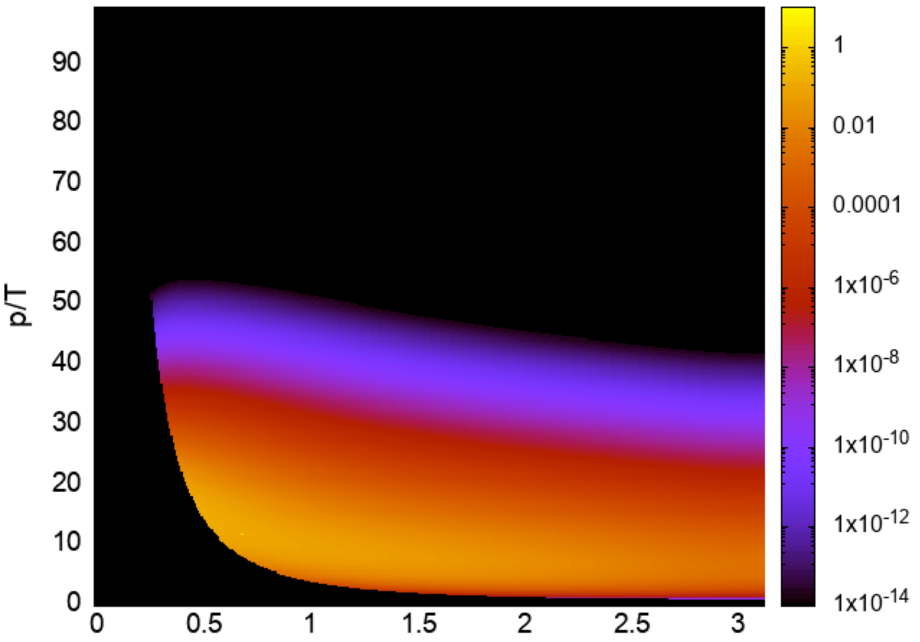
D'Eramo et al., 2019

- Sufficiently hard scattering should be perturbative.
- High p_T particle can be deflected, changing its energy and direction.
- Recoiling particle, k_χ, a new particle to be quenched
- Thermal particle, k_T, from BE/FD distribution, removed from medium.

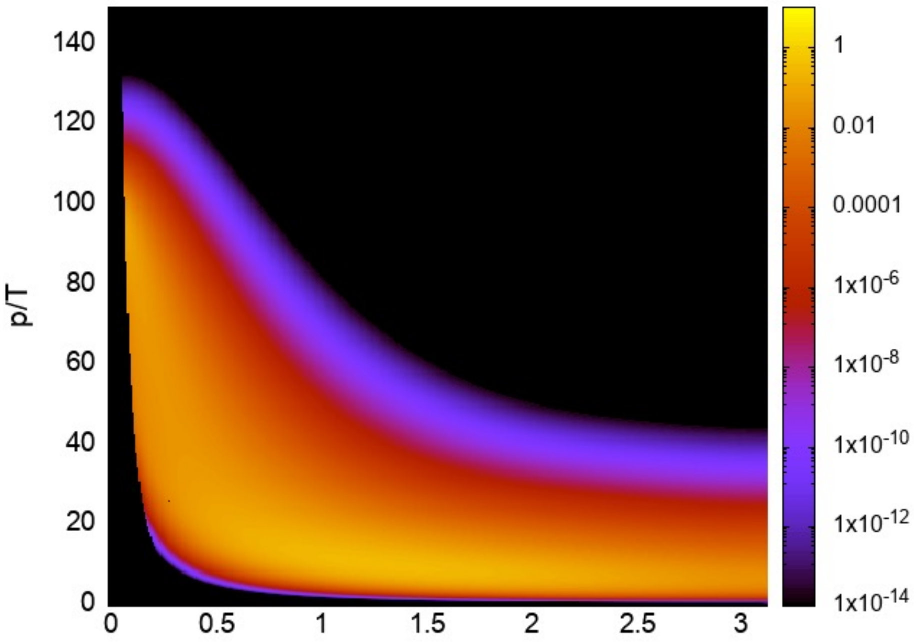
Tree-Level 2-2 massless scattering amplitudes

$$F^{C\to A}(p,\theta;p_{in}) = \sum_{nDB} \frac{c_{DBn}^{C\to A}}{2(4\pi)^3}\left(\frac{p\sin(\theta)}{p_{in}|\boldsymbol{p}-\boldsymbol{p_{in}}|T}\right)\int_{k_{min}}^{\infty} dk_T\, n_D(k_T)\left[1 \pm n_B(k_\chi)\right]\int_0^{2\pi}\frac{d\phi}{2\pi}\frac{\left|M^{(n)}\right|^2}{g_s^4}$$

Results (for a QGP brick)



Incoming gluon, $p_{in} = 20T, \mathrm{L} = 15/T$



Incoming gluon, $p_{in} = 100T, \;\; \mathrm{L} = 15/T$

- Excluding $\tilde{u} > 10\, m_D^2$ not a simple curve on this plot, but effects visible
- Restricting to $\tilde{u}, \tilde{t} > 10\, m_D^2$ excludes soft scatterings; justifies assumptions made in amplitudes; avoids double counting. Can vary where to set this cut…
- Analytical results → fast to sample
- Apply at every time step, to every rung, in every shower, in Hybrid Model Monte Carlo…. And, if a scattering happens, two subsequent partons then lose energy a la Hybrid

Gaussian Broadening vs Large Angle Scattering

Elastic scatterings of exchanged momentum $\sim m_D$

→ Gaussian broadening due to multiple soft scattering

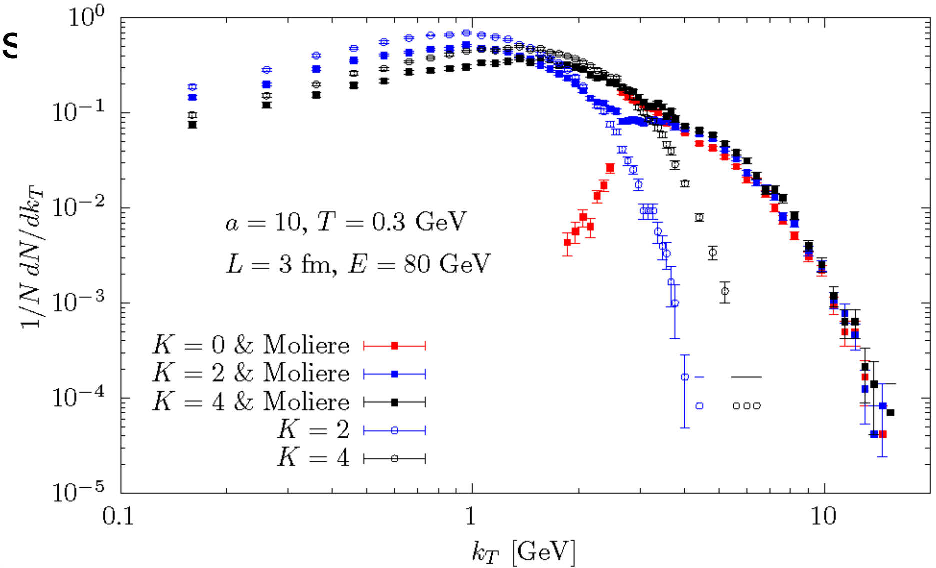
At strong coupling, holography predicts Gauss broadening without quasi-particles (eg: N=4 SYM)

$$P(k_\perp) \sim \exp\left(-\frac{\sqrt{2}k_\perp^2}{\hat{q}L^-}\right) \qquad \hat{q} = \frac{\pi^{\frac{3}{2}}\Gamma\left(\frac{3}{4}\right)}{\Gamma\left(\frac{5}{4}\right)}\sqrt{\lambda}T^3$$

Adding this in hybrid model (C-S et al 2016) yielded little effect on jet observables.

Today, Bayesian inference from hadron R_{AA} data indicates $P(k_\perp) \sim K\,T^3$ with $K \sim 2-4$. This need not have anything to do with quasiparticles.

- Add Moliere scattering with momentum exchanges $> m_D$; here, $a = 10$ and 80 GeV incident jet parton



Perturbative Shower … Living in Strongly Coupled QGP

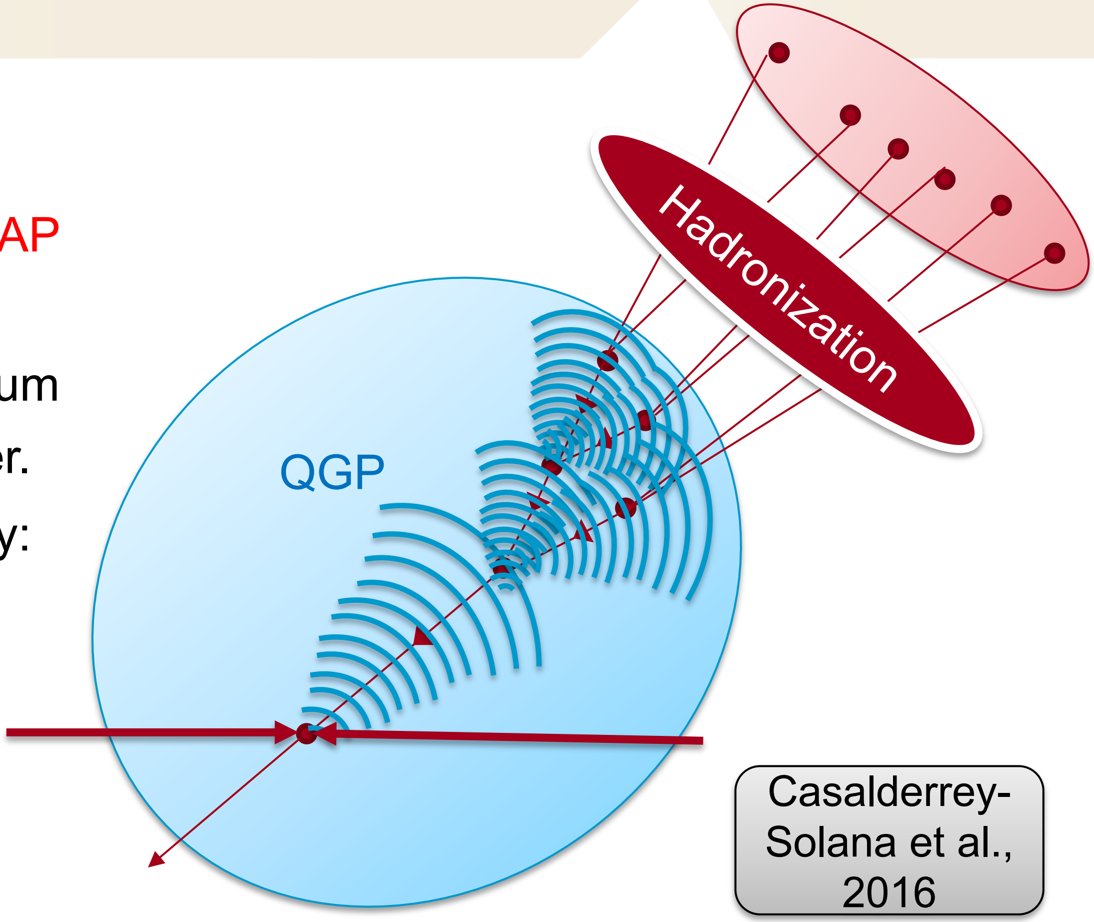
- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
  - Energy loss from holography:

$$\frac{1}{E_{in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{stop}^2}\frac{1}{\sqrt{x_{stop}^2 - x^2}}$$

O(1) fit const.

$$x_{stop} = \frac{1}{2\kappa_{sc}}\frac{E_{in}^{\frac{1}{3}}}{T^{\frac{4}{3}}}$$

$$\tau = \frac{2E}{Q^2}$$



Casalderrey-Solana et al., 2016

Energy and momentum conservation → deposit hydrodynamic wake in QGP liquid

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f+\delta T}\right) - f\left(\frac{\mu_0^\mu p_\mu}{T_f}\right)\right]$$

Adding Moliere Scattering to Hybrid Model

- High Q^2 parton shower up until hadronization described by DGLAP evolution (PYTHIA).
- For QGP with $T \sim \Lambda_{QCD}$, the medium interacts strongly with the shower.
    - Energy loss from holography:

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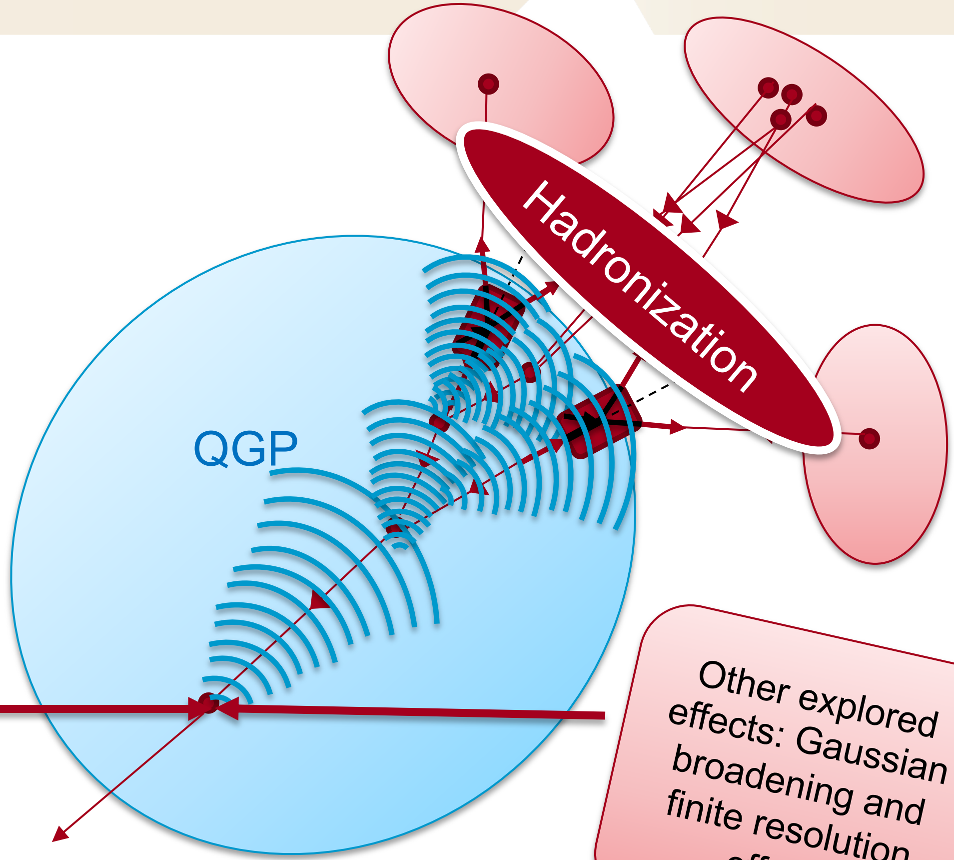
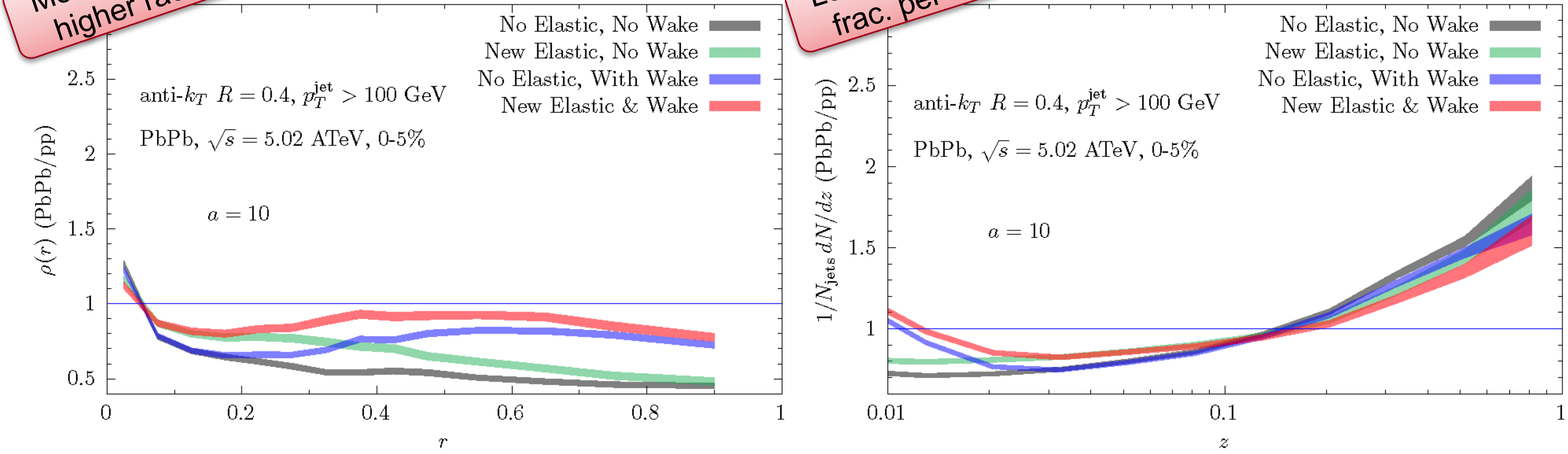


Other explored effects: Gaussian broadening and finite resolution effects

Energy and momentum conservation → activate hydrodynamic modes of plasma

$$\frac{d\Delta N}{p_T dp_T d\phi dy} = \frac{1}{(2\pi)^3}\int \tau dx dy d\eta_s m_T \cosh(y-\eta_s)\left[f\left(\frac{u^\mu p_\mu}{T_f + \delta T}\right) - f\left(\frac{u_0^\mu p_\mu}{T_f}\right)\right]$$

Jet Shapes and Fragmentation Functions

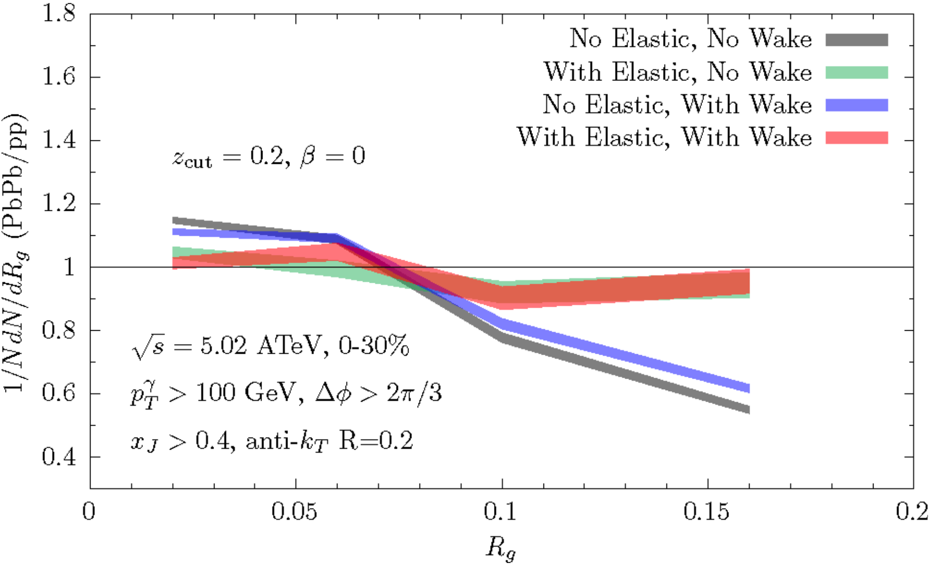

More energy at higher radius

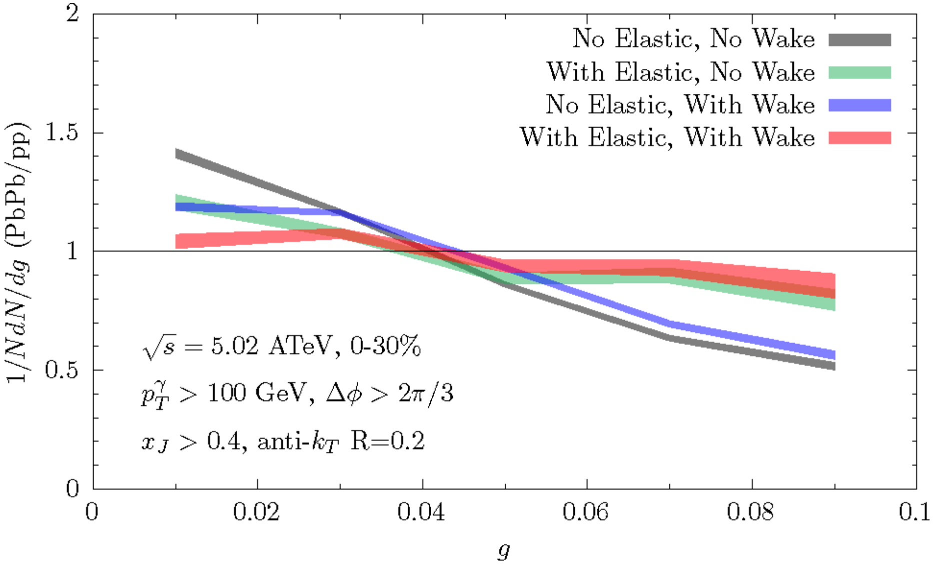
Lower momentum frac. per hadron

→ Elastic scattering effects look very similar to wake effects, but smaller.

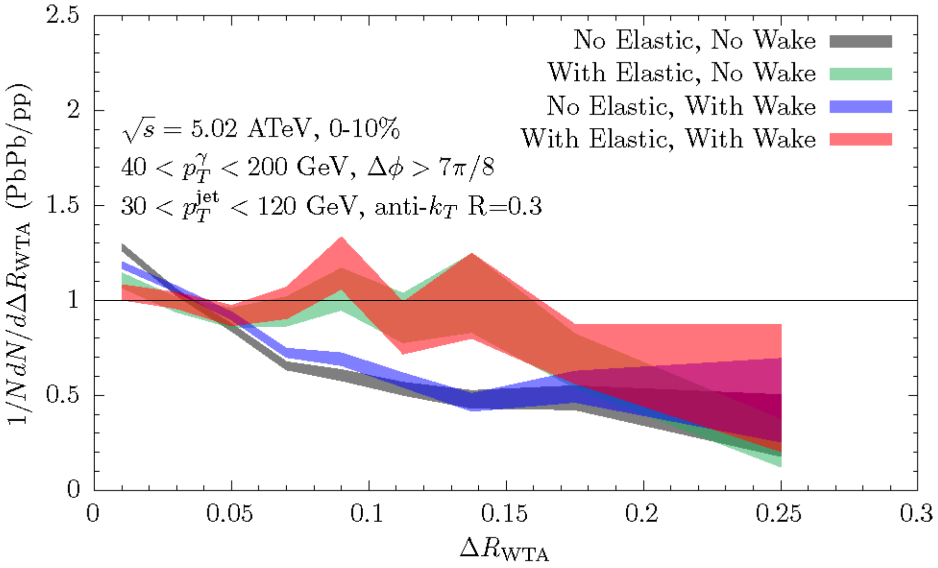
- Moliere scattering transfers jet energy to high angle and lower momentum fraction particles. So does energy loss to wake in fluid.
- In **these observables**, effect of Moliere looks like just a bit more wake.
- In principle sensitive to Moliere, but in practice not: more sensitive to wake.
- Moliere effects are even slightly smaller if $\tilde{u}, \tilde{t} > \mathrm{a}\, m_D^2$ with a=10.
- What if we look at groomed observables? Less sensitive to wake…

Three “groomed” gamma-Jet Observables: R_g , Girth, and angle between standard and WTA axes

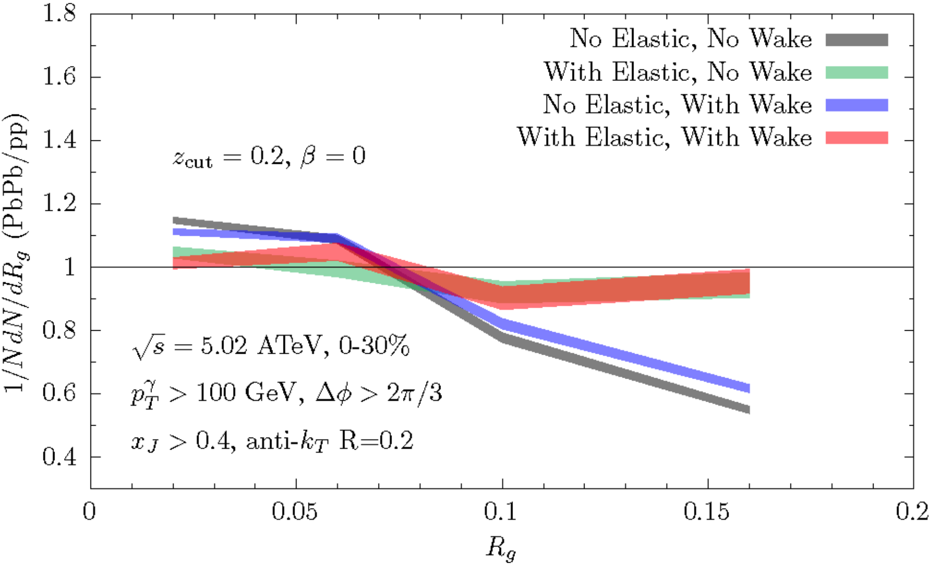


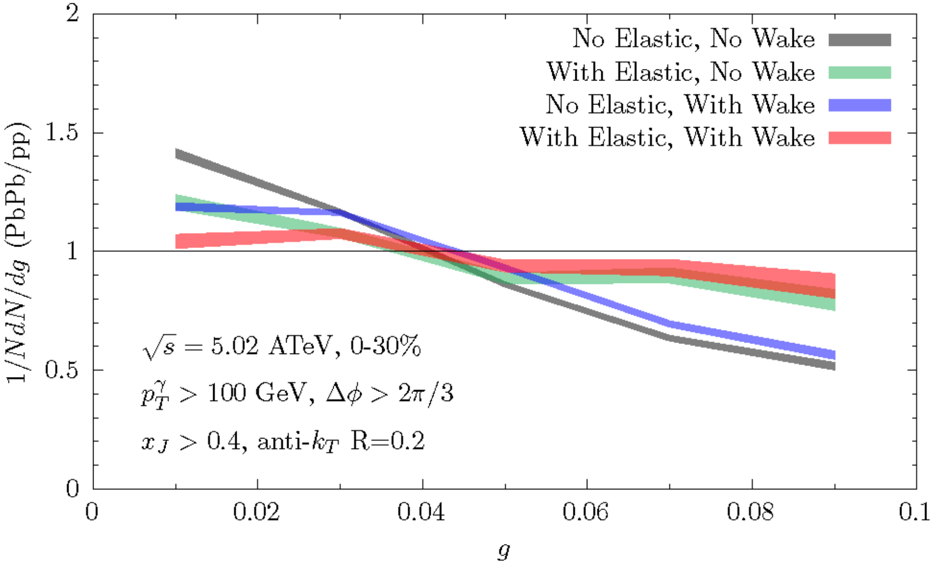


All show much less sensitivity to wake: R=0.2; Moliere scattering shows up; effects of Moliere and wake are again similar in shape, but here effects of Moliere are very much dominant.



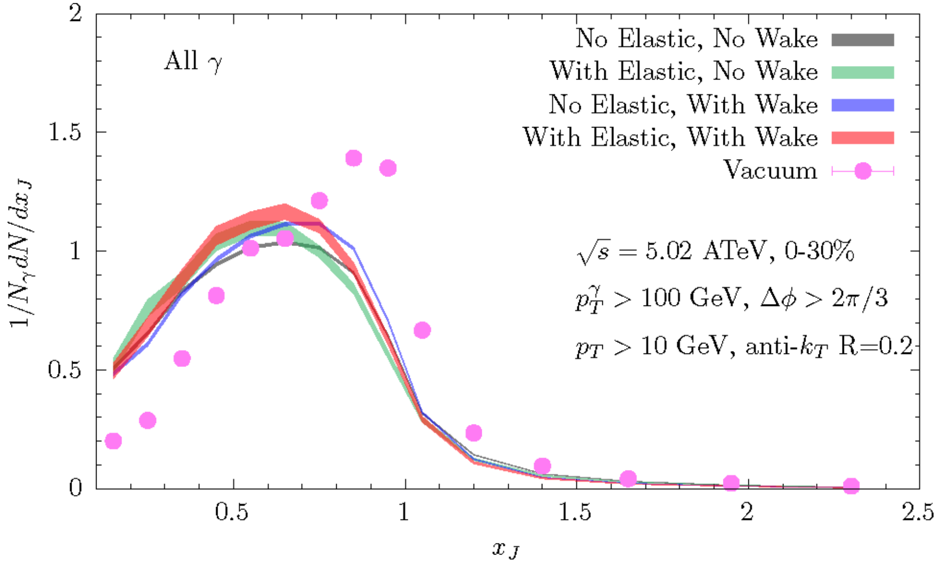
Gamma-Jet Observables: R_g and Girth



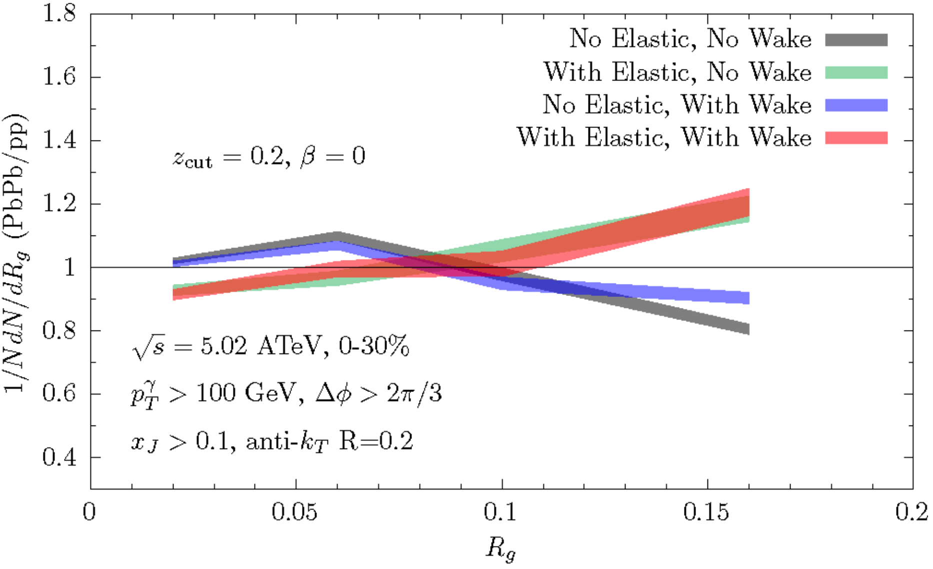


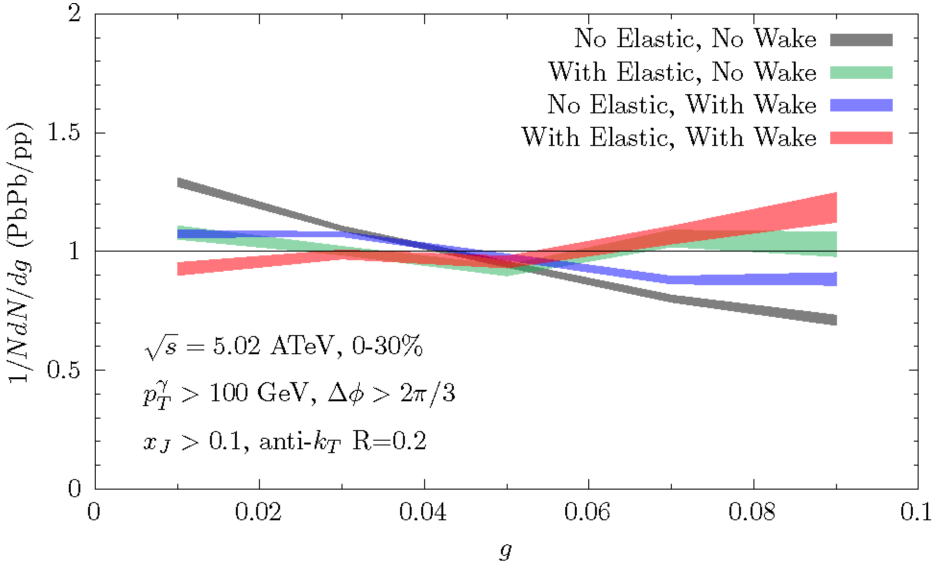
All show much less sensitivity to wake: R=0.2; Moliere scattering effects are very much dominant.

But why is R_{AA} below 1? Selection bias! With x_J>0.4 selection, missing too many of the most modified jets.



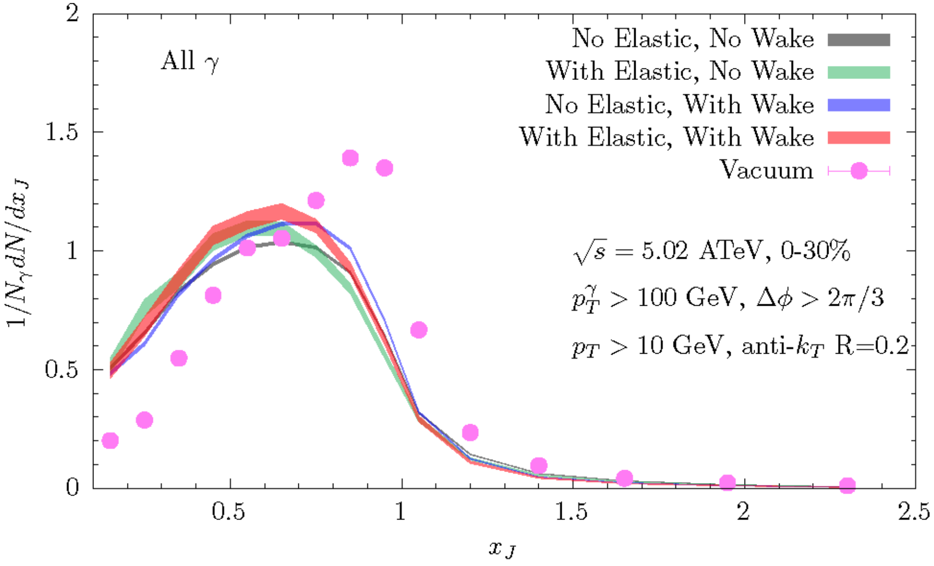
Gamma-Jet Observables: R_g and Girth, with $x_J>0.1$



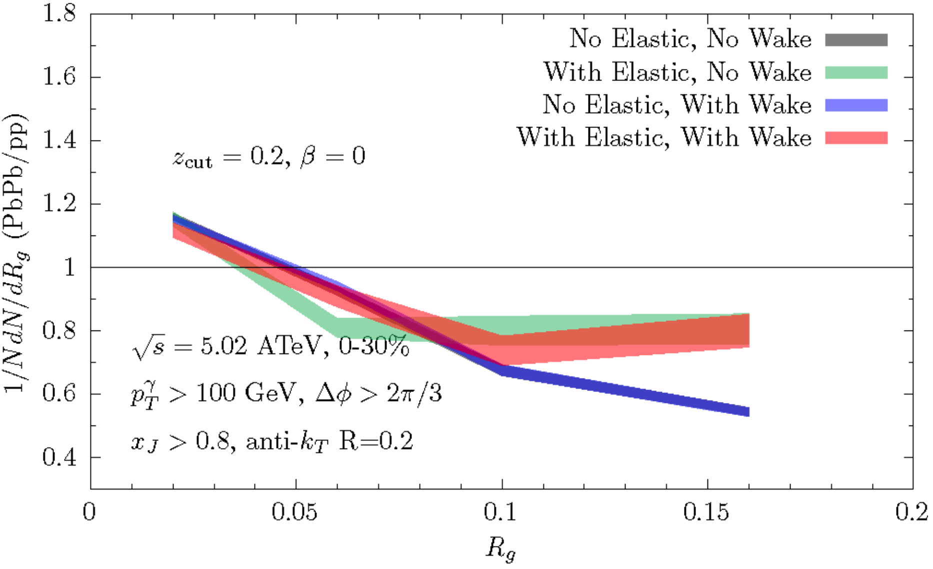


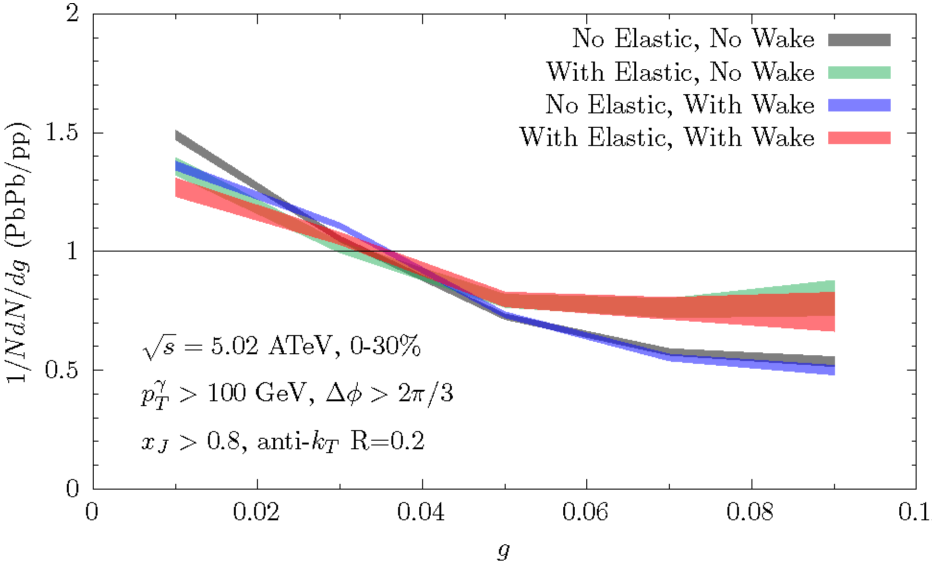
On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.1. Moliere scattering important, and causes R_{AA} >1.

Selection bias reduced (cf Brewer+Brodsky+KR); some effects of wake visible.



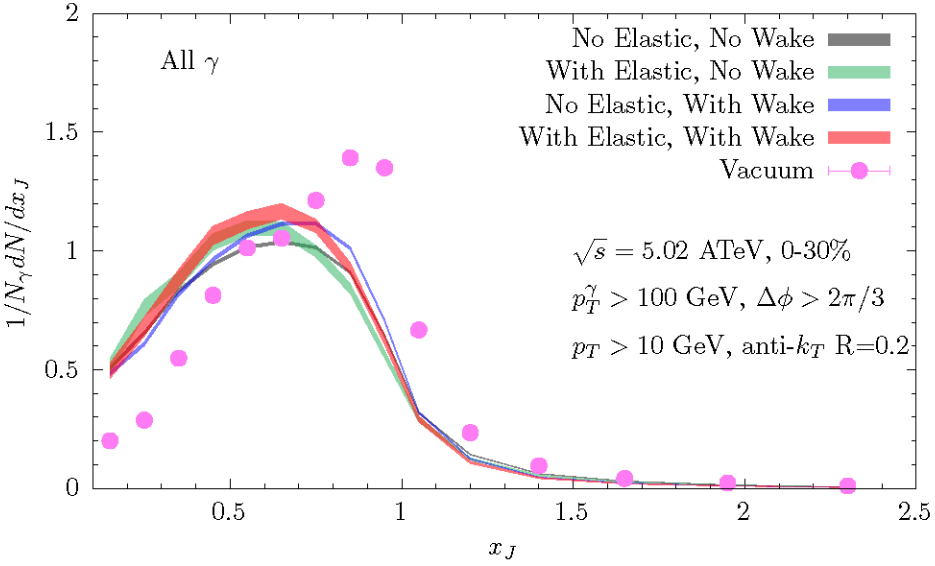
Gamma-Jet Observables: R_g and Girth, with x_J>0.8



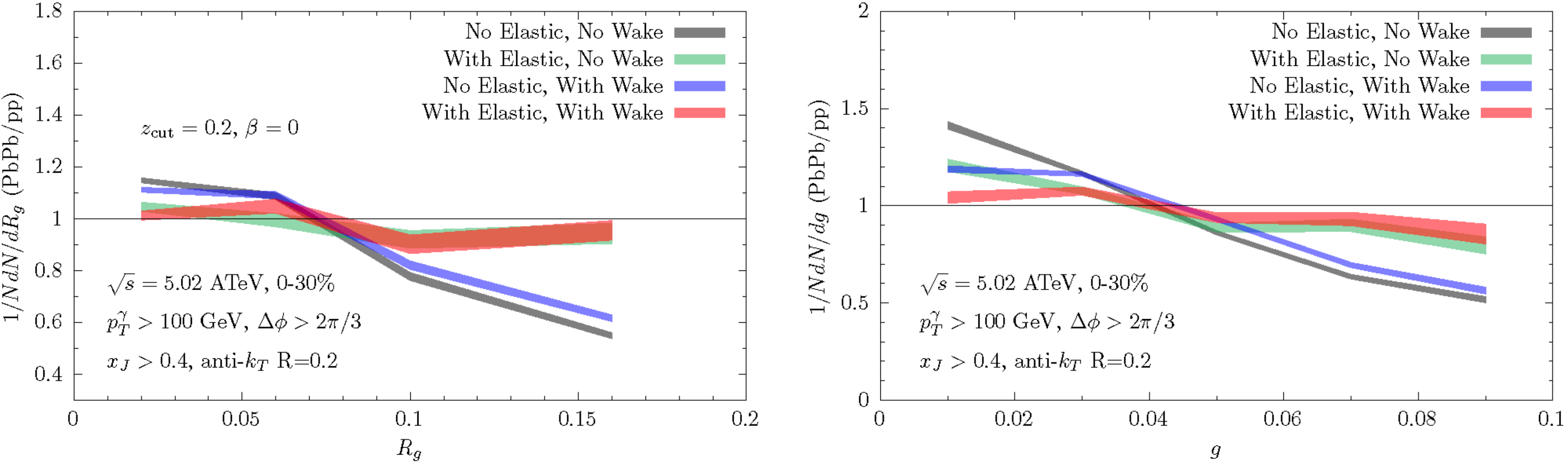


On previous slides, Rg and Girth with xJ>0.4: missing the most modified jets. Here, xJ>0.8. Selection bias increased.

Moliere scattering still important, and but selection bias so strong that it does not yield R_{AA} >1.



Gamma-Jet Observables: R_g and Girth, with x_J>0.4



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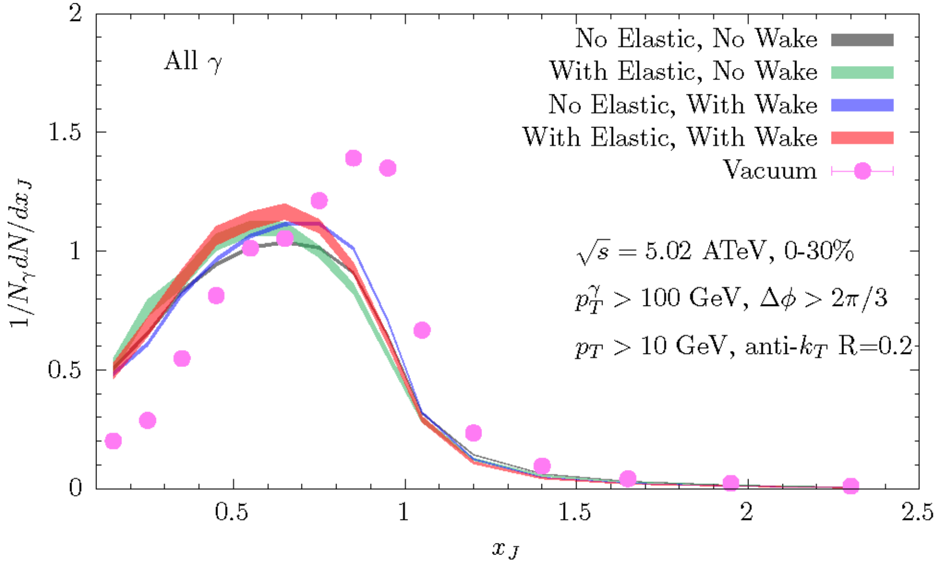
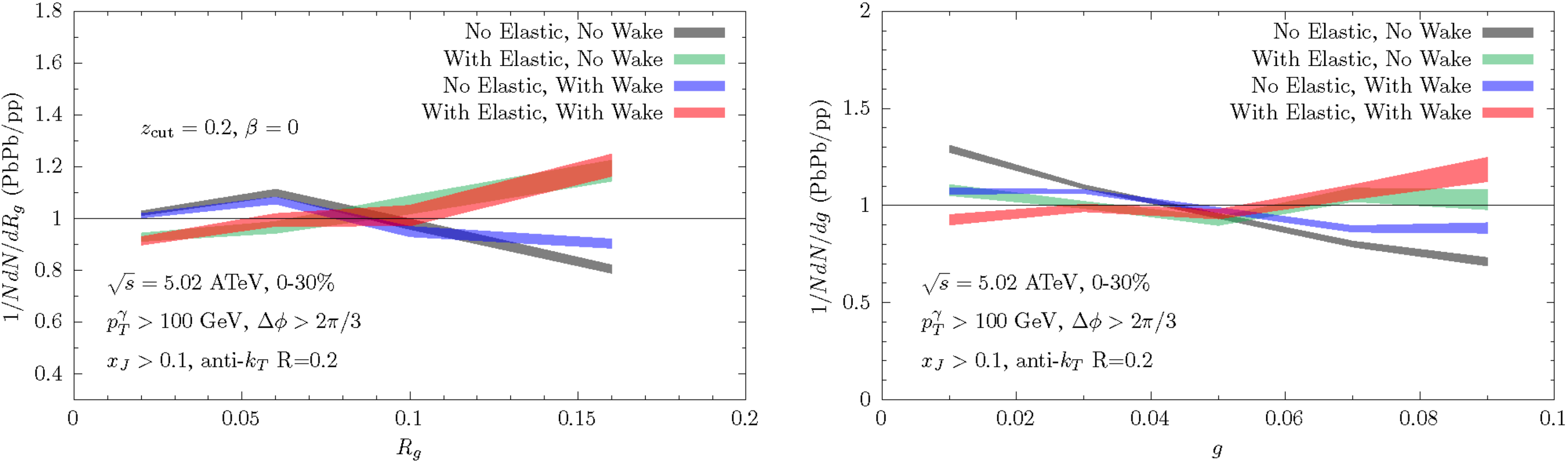


Gamma-Jet Observables: R_g and Girth, with x_J>0.1



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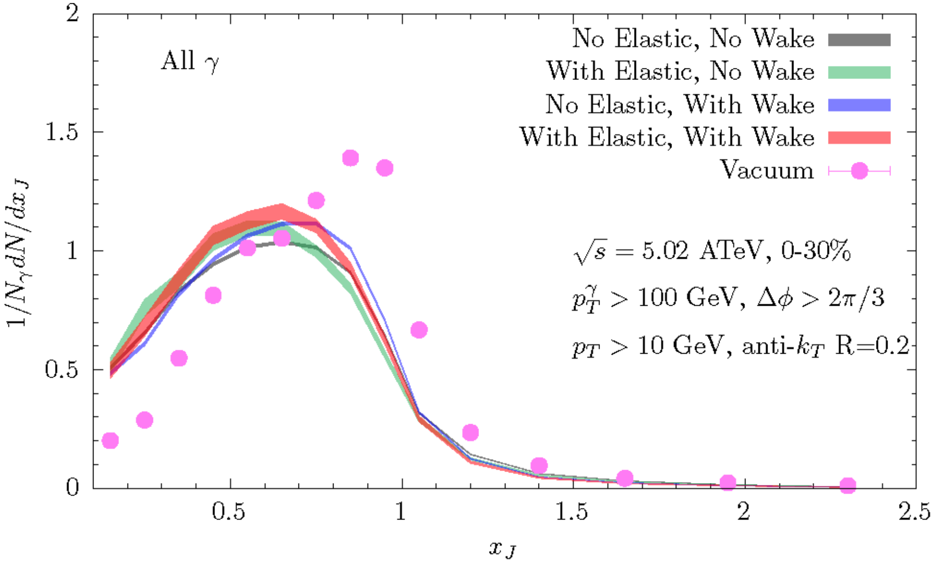
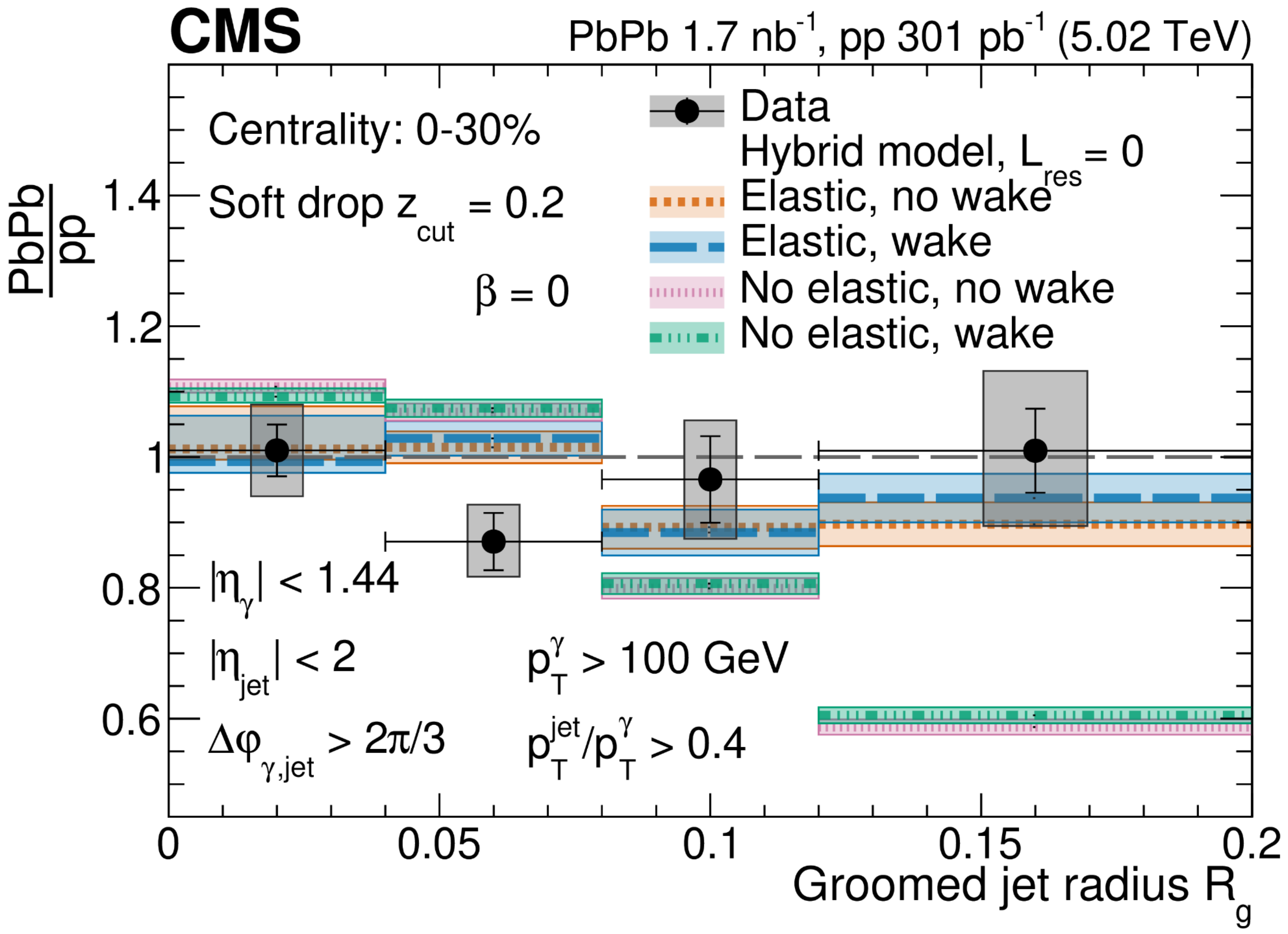


Summary

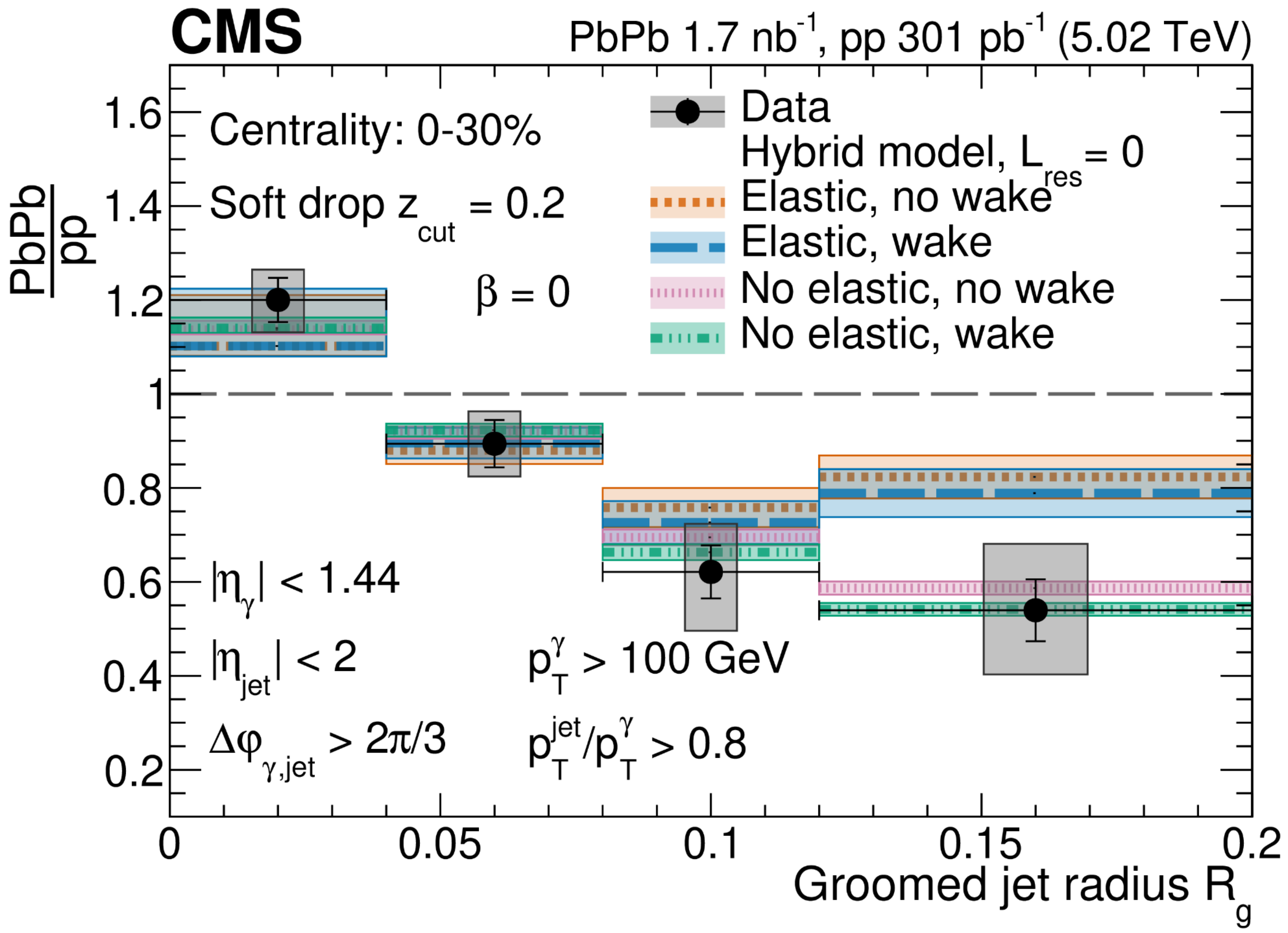
- Groomed jet radius and girth measured in γ+jet events in pp and PbPb

‣Leading recoil jet from p_T > 100 GeV photons studied for two selections:

$x_{\gamma j} > 0.4$ (w/ quenched jets):
no narrowing observed



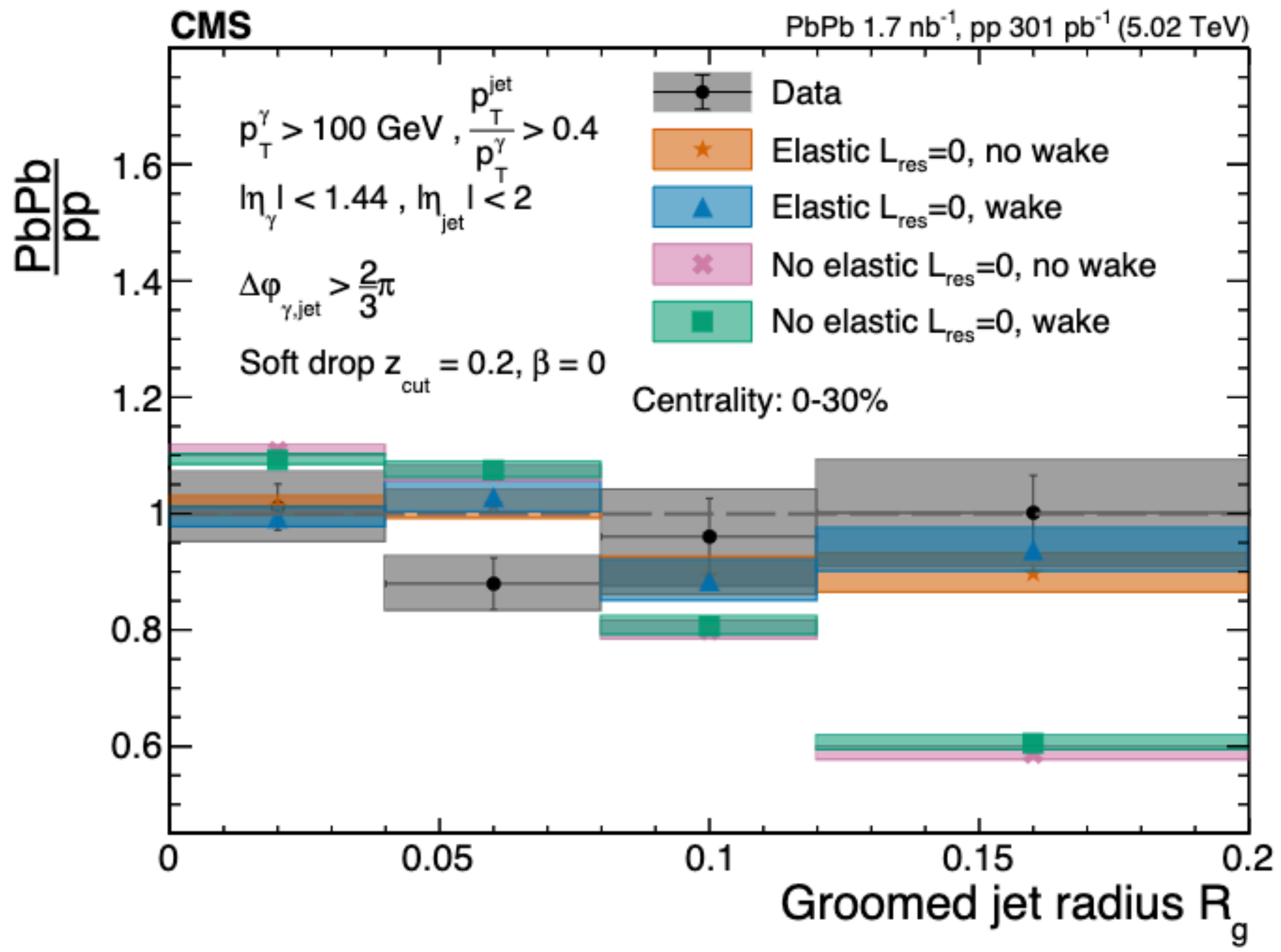
$x_{\gamma j} > 0.8$ (less quenched jets):
narrowing is restored



CMS, arXiv:2405.0273

γ-jet substructure, prospects

xJ>0.4



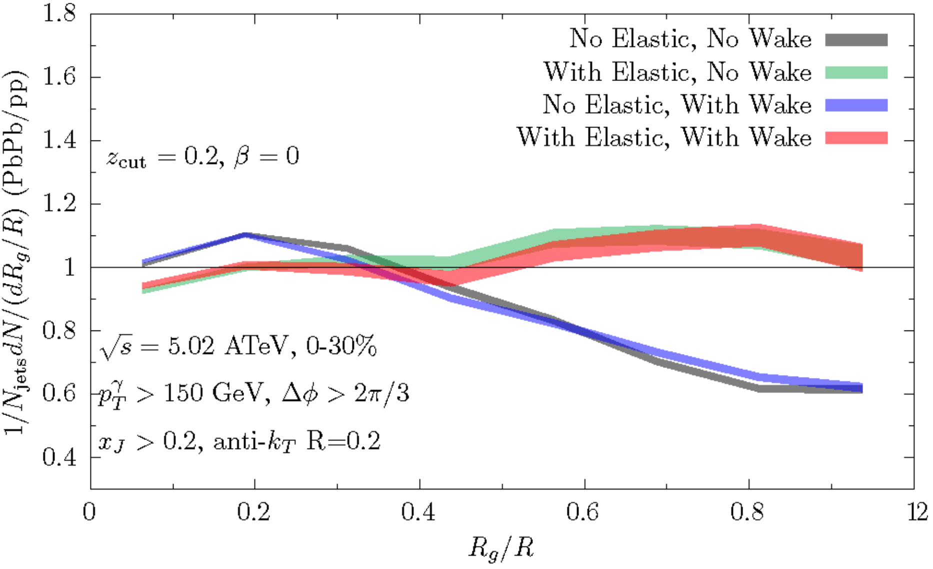
The survivor bias can be fully suppressed when $x_J \to 0$
(the model has a strong survivor bias down to xJ=0.1)

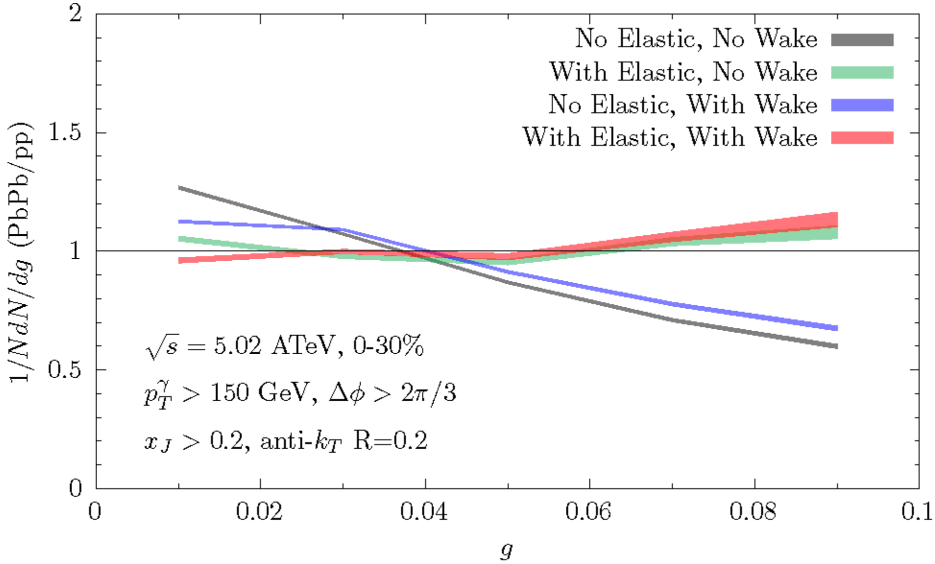
Since low jet p_T is limited by detector effects, such zero bias limit can be achieved by increasing the energy of the photons

Ideally, **simultaneous measurement of x_J and substructure** ,current results are statistically limited

CMS-PAS-HIN-23-001

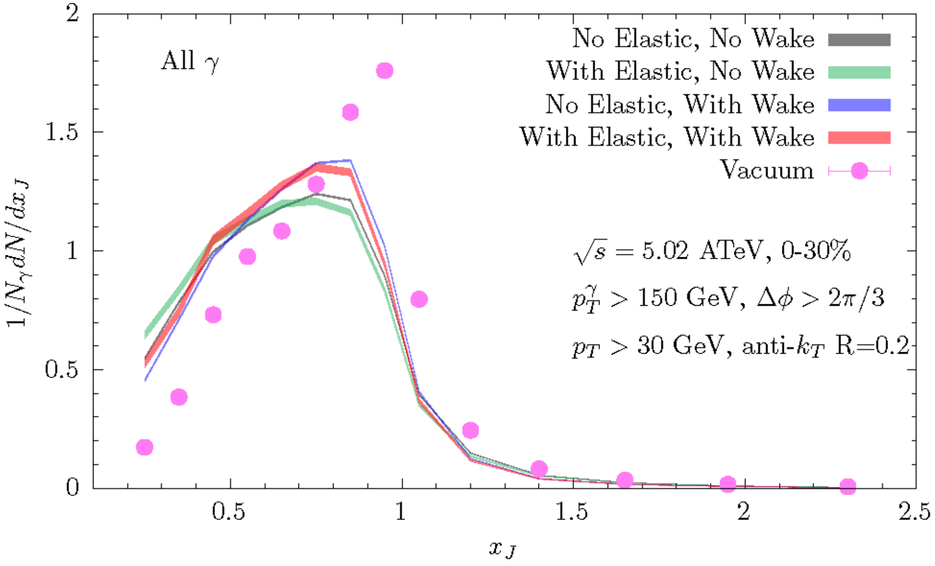
Gamma-Jet Observables with $p_T^\gamma > 150$ GeV: R_g and Girth, with $x_J > 0.2$



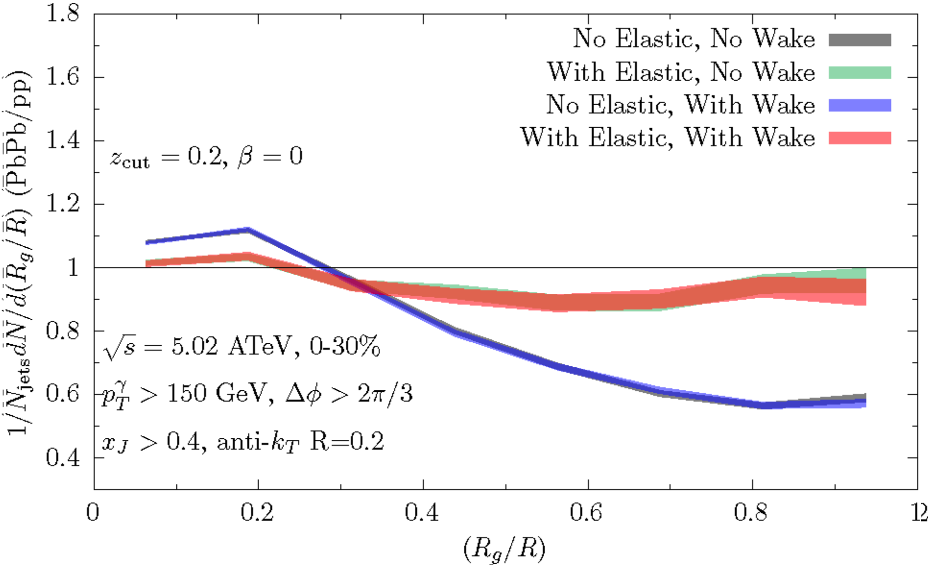


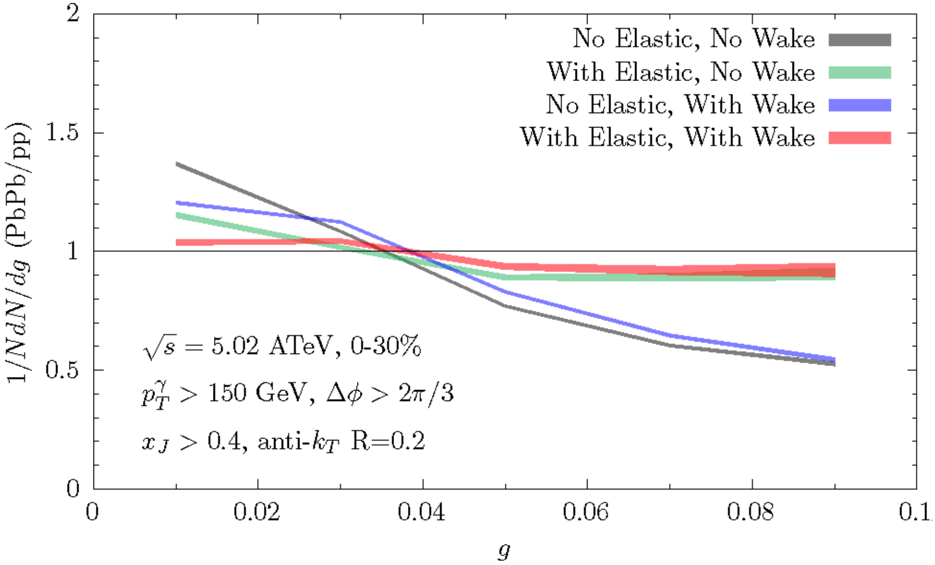
On previous slides, $p_T^\gamma > 100$ GeV; here, $p_T^\gamma > 150$ GeV. Means $x_J > 0.2$ corresponds to $p_T^{\rm jet} > 30$ GeV. And, no need to go down to $x_J > 0.1$.

Moliere effects substantial; selection bias reduced; wake effects negligible.



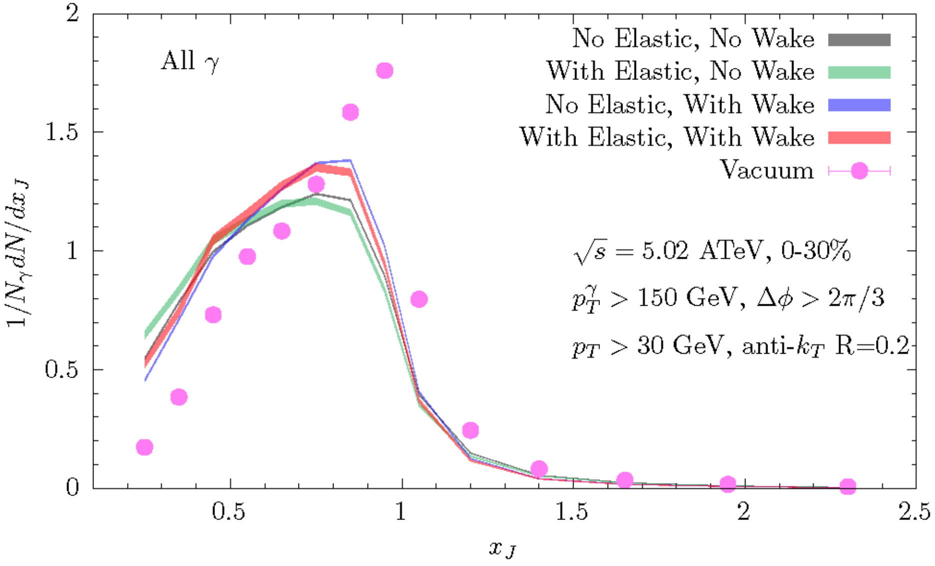
Gamma-Jet Observables with $p_T^\gamma > 150$ GeV: R_g and Girth, with $x_J > 0.4$



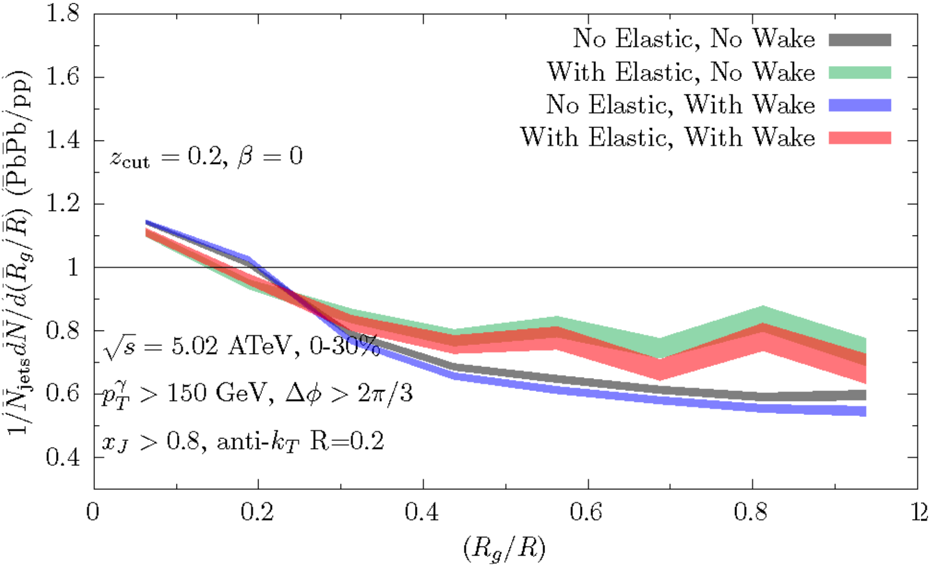


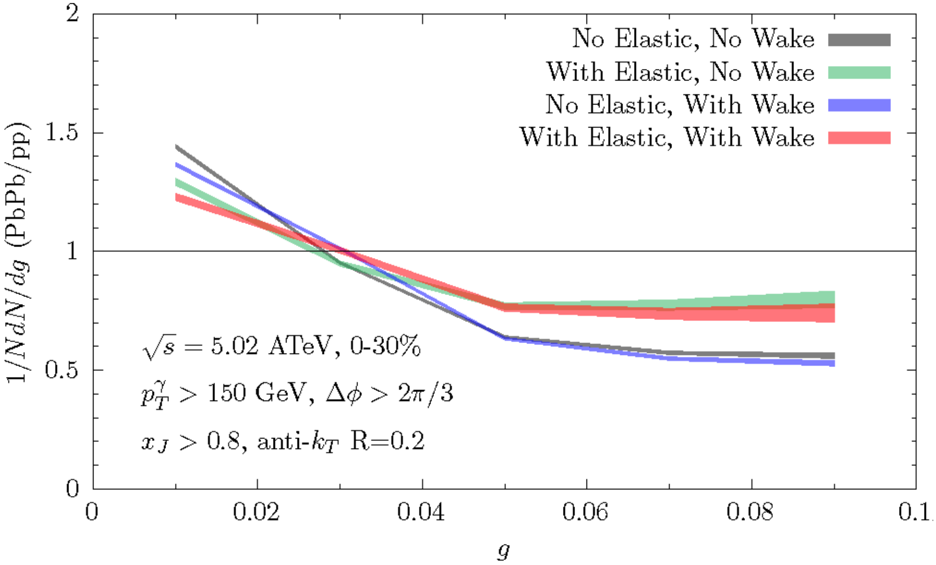
On previous slides, $p_T^\gamma > 100$ GeV; here, $p_T^\gamma > 150$ GeV.
Means $x_J > 0.4$ corresponds to $p_T^{\rm jet} > 60$ GeV.

Moliere effects substantial; selection bias significant; wake effects negligible.



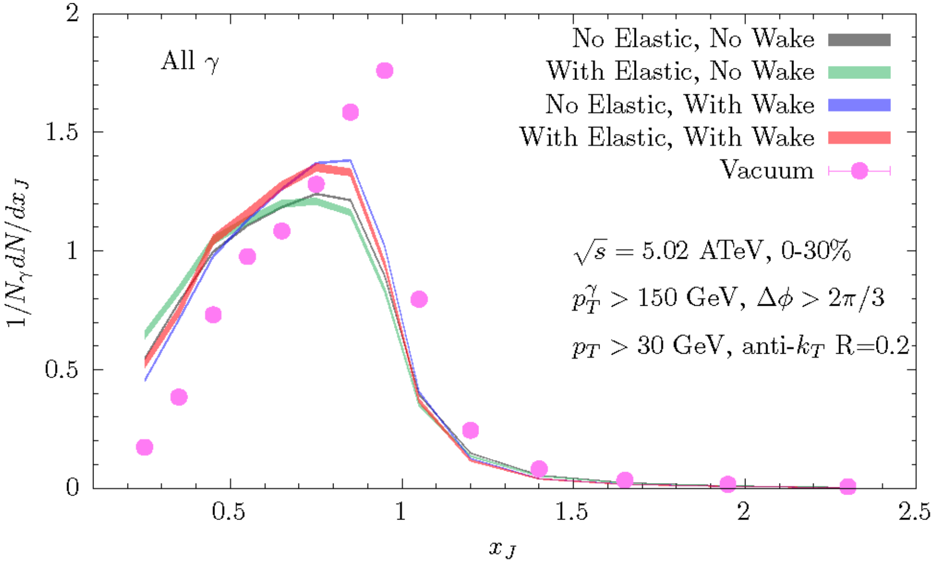
Gamma-Jet Observables with $p_T^\gamma > 150$ GeV: R_g and Girth, with $x_J > 0.8$



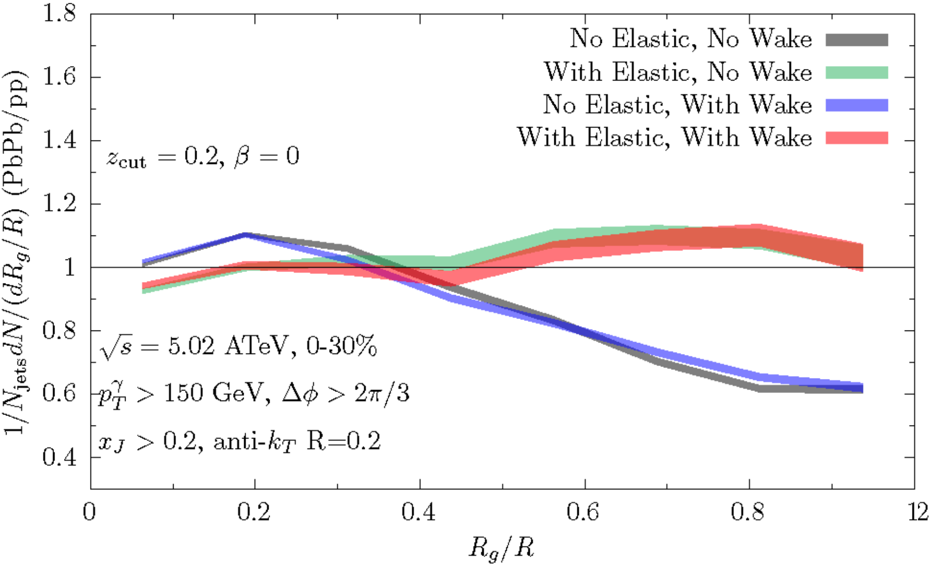


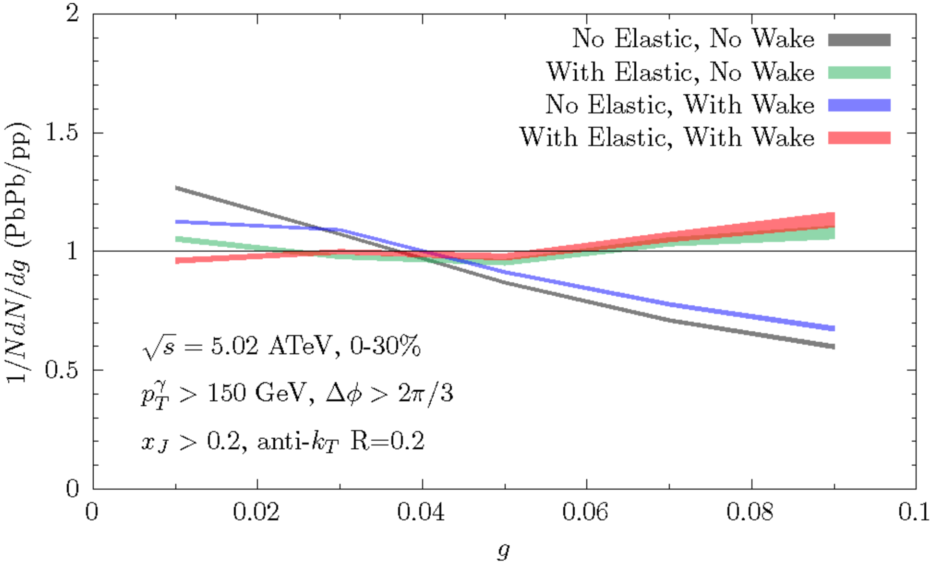
On previous slides, $p_T^\gamma > 100$ GeV; here, $p_T^\gamma > 150$ GeV.
Means $x_J > 0.8$ corresponds to $p_T^{\rm jet} > 120$ GeV.

Moliere effects substantial; selection bias dominant; wake effects negligible.



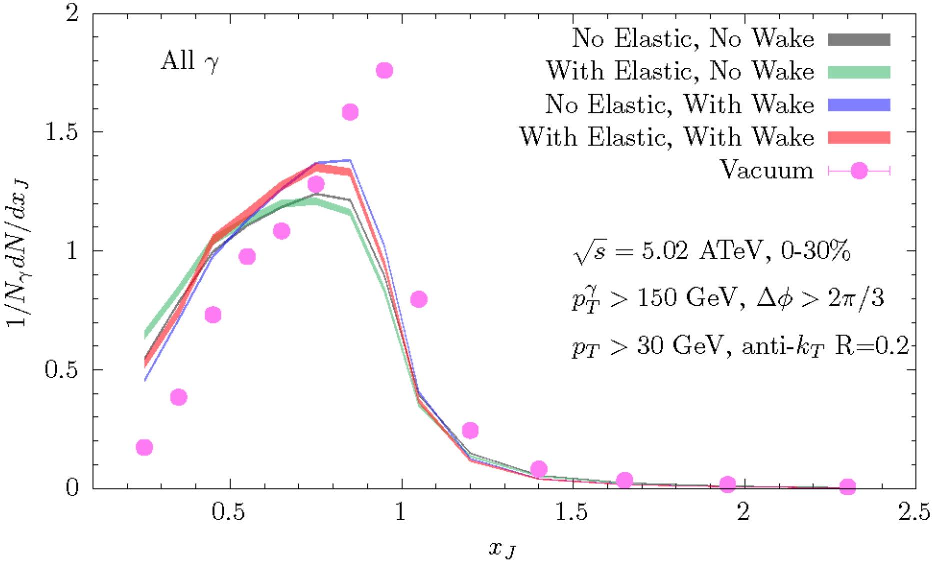
Gamma-Jet Observables with p_T^{γ} >150 GeV: R_g and Girth, with x_J>0.2



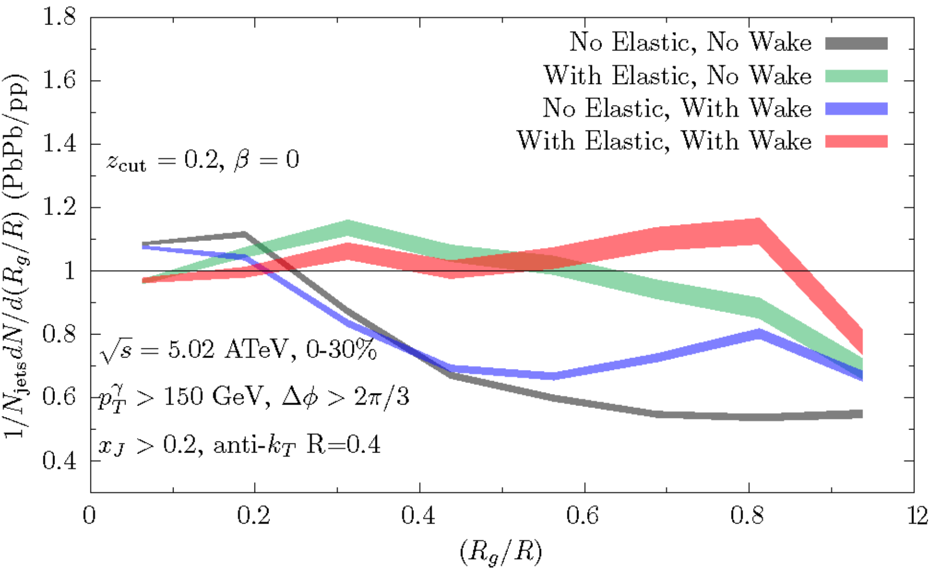


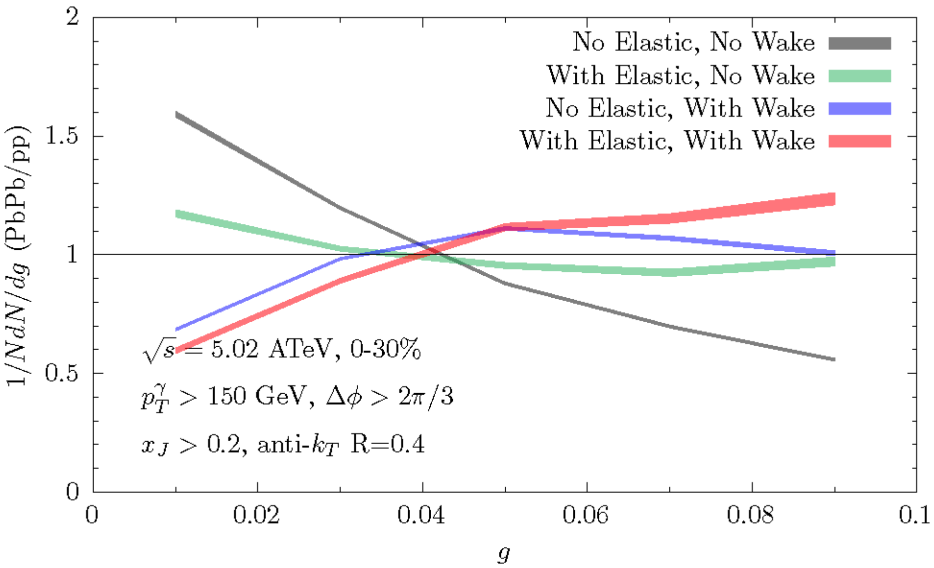
On previous slides, p_T^{γ} >100 GeV; here, p_T^{γ} >150 GeV.
Means x_J>0.2 corresponds to $p_T^{\rm jet}$>30 GeV. And, no need to go down to x_J>0.1.

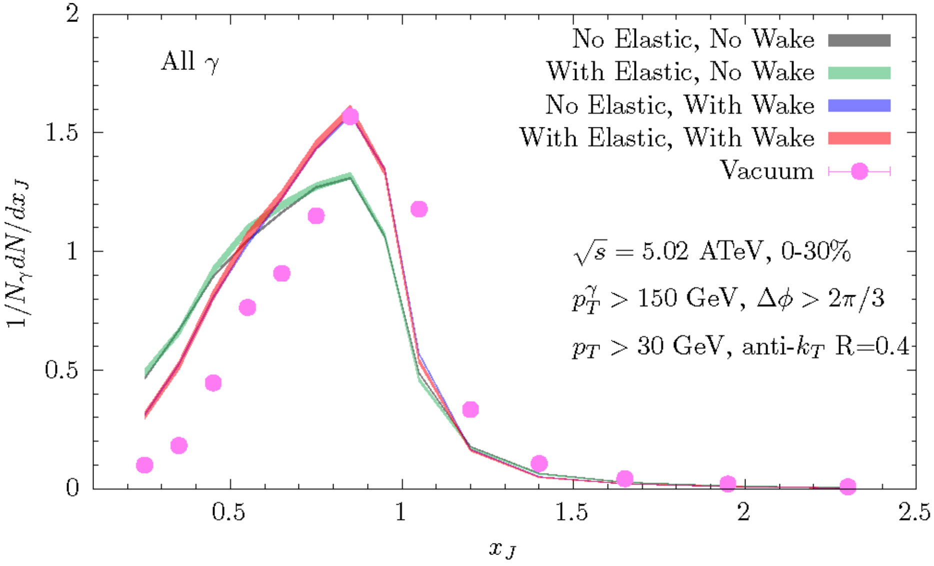
Moliere effects substantial; selection bias reduced; wake effects negligible.



Gamma-Jet Observables with p_T^{γ} >150 GeV and R=0.4: R_g and Girth, with x_J>0.2



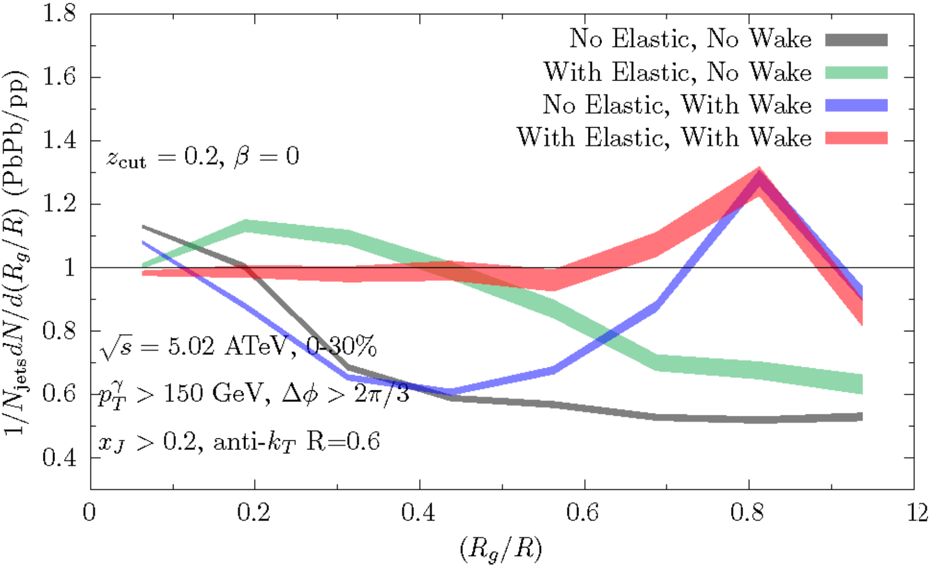


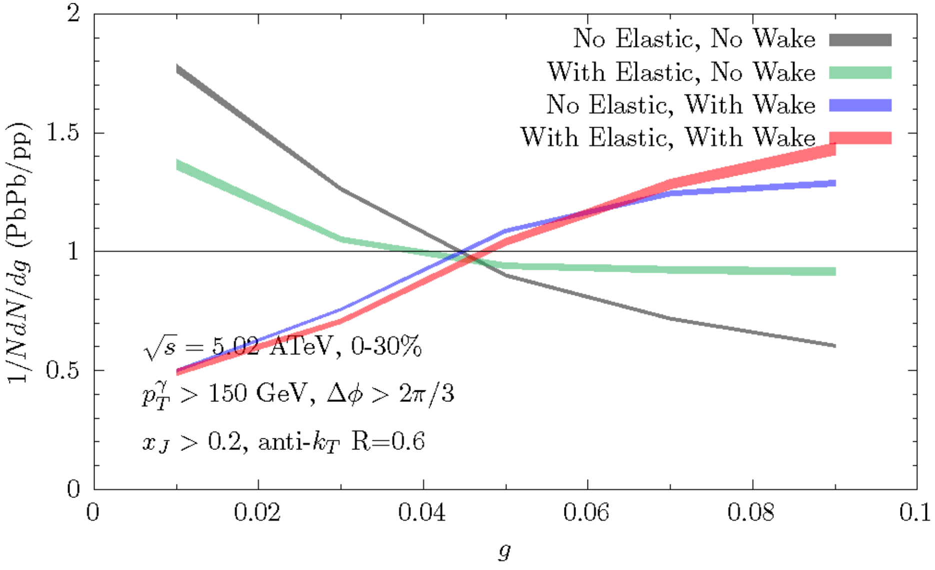


On previous slides, p_T^{γ} >150 GeV with R=0.2. Here, R=0.4, so that we can "catch" more wake, with little selection bias.

Moliere effects substantial; selection bias reduced; wake effects significant.

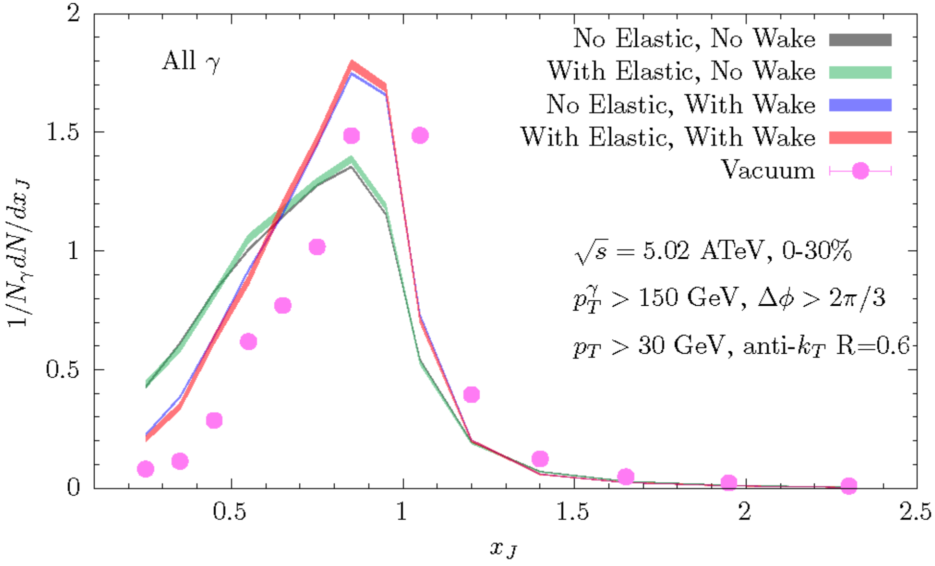
Gamma-Jet Observables with p_T^γ >150 GeV and R=0.6: R_g and Girth, with x_J>0.2



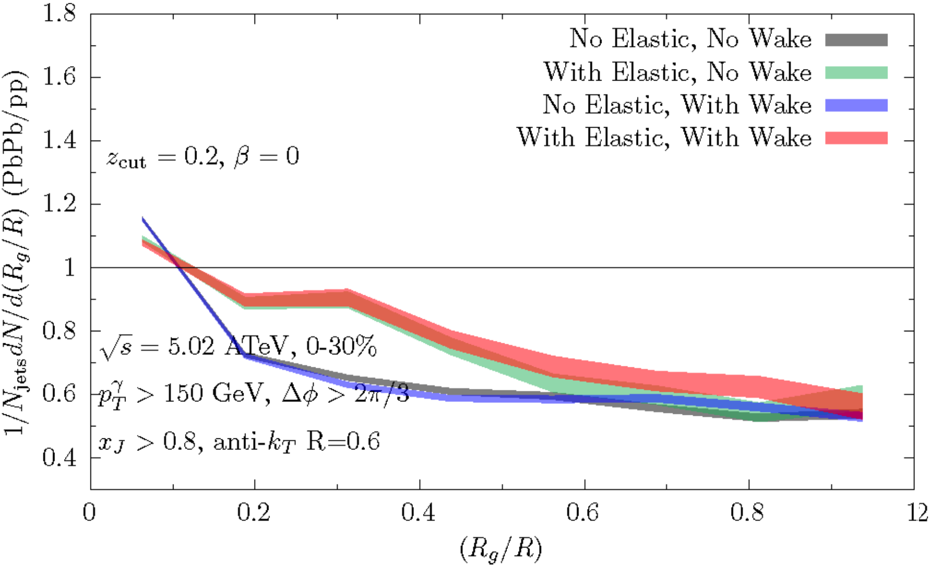


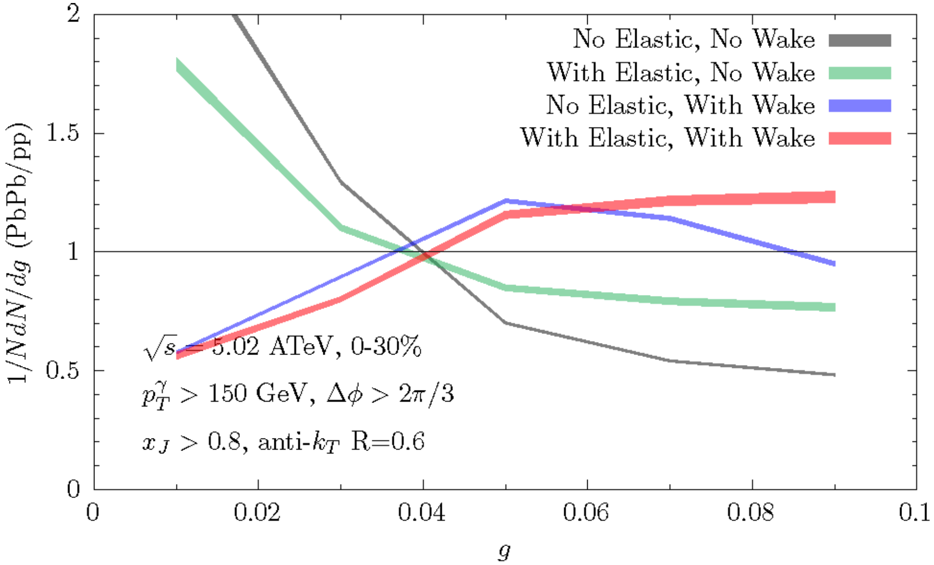
On previous slides, p_T^γ >150 GeV with R=0.2. Here, R=0.6, so that we can “catch” *even more* wake, with little selection bias.

Moliere effects substantial; selection bias reduced; wake effects enormous, and as in Brewer+Brodsky+KR.



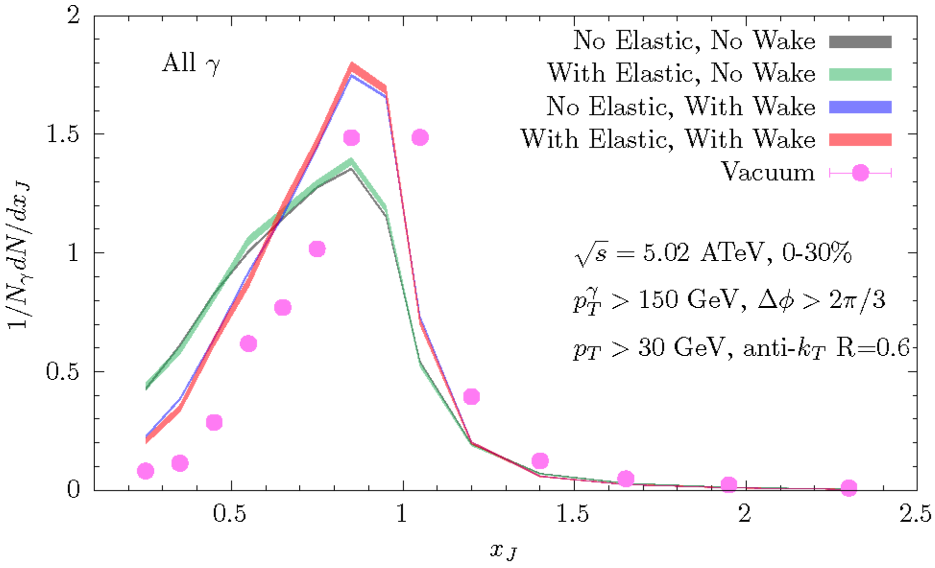
Gamma-Jet Observables with p_T^γ >150 GeV and R=0.6: R_g and Girth, with x_J>0.8





On previous slides, p_T^γ >150 GeV with R=0.2. Here, R=0.6. But, we've turned the selection bias back ON.

Moliere effects still substantial; selection bias dominant; wake effects *greatly reduced*, as in Brewer+Brodsky+KR.



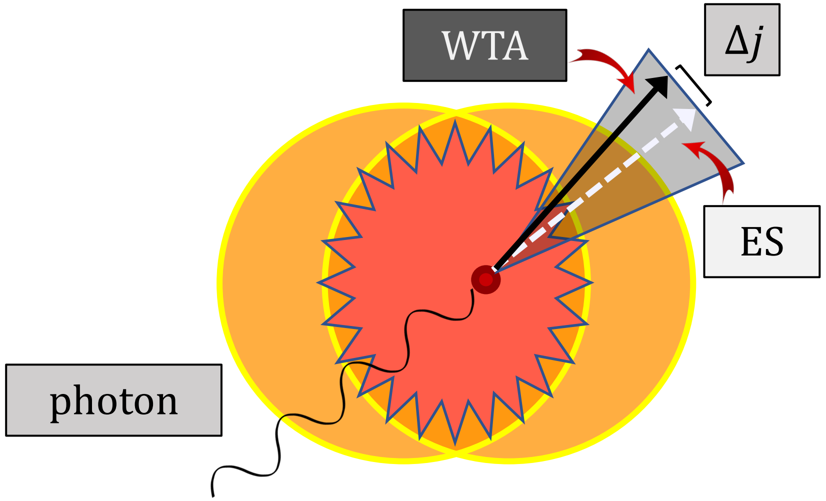
Jet axis difference

Studying the jet axis decorrelation, which is the angular difference between the WTA and E-Scheme jet axes

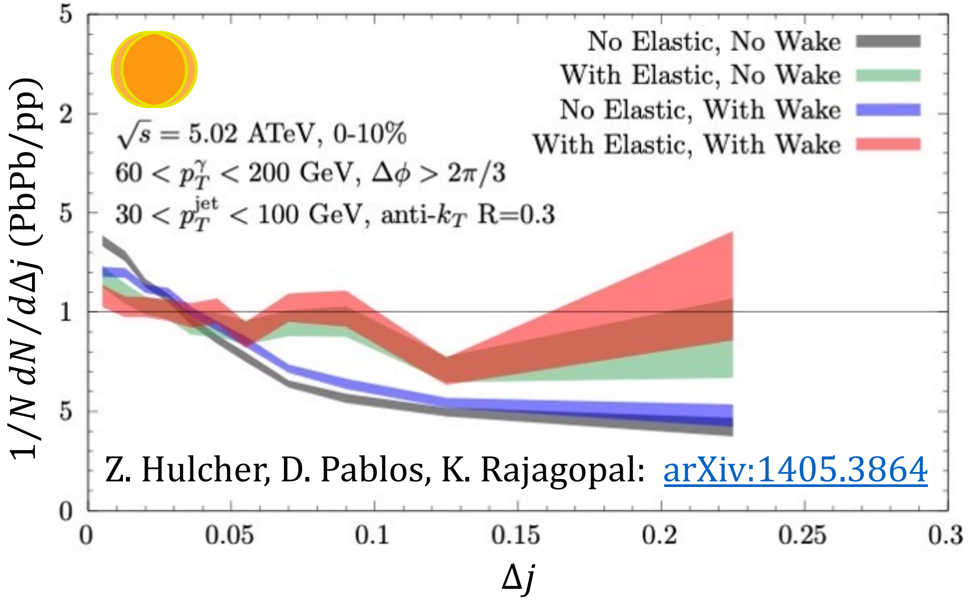
WTA axis = direction of leading energy flow in jet **E-Scheme axis** = direction of average energy flow in jet

$$\Delta j = \sqrt{(\eta^{E-Scheme} - \eta^{WTA})^2 + (\phi^{E-Scheme} - \phi^{WTA})^2}$$

Photon-jet schematic



Hybrid model prediction



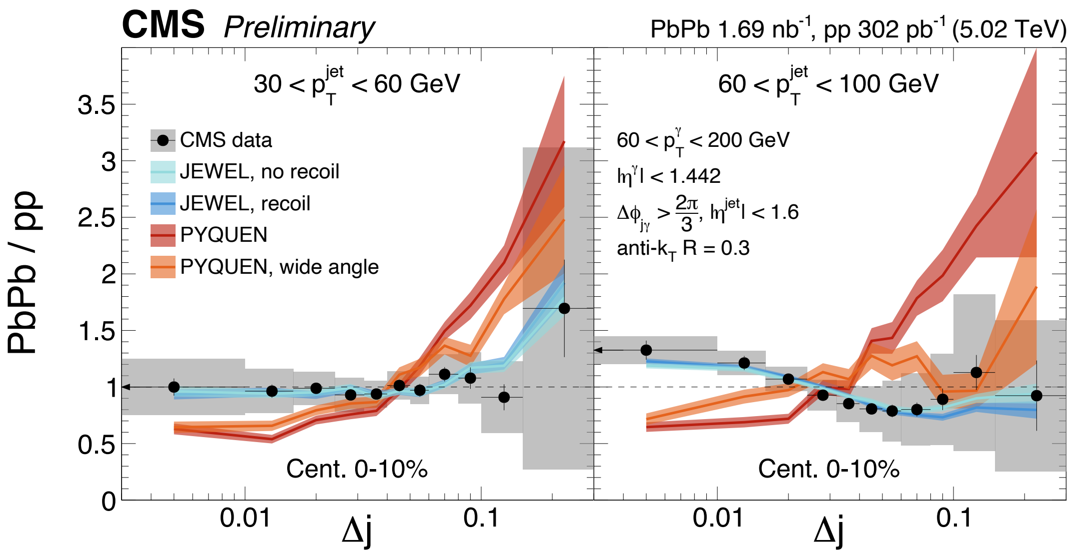
Z. Hulcher, D. Pablos, K. Rajagopal: arXiv:1405.3864

Potentially sensitive to **elastic scattering** effects in the QGP

Photon tags hard scattering energy and constrains the quark/gluon fraction of recoiling jets

Result: Δj shape ratio theory comparison

$30 < p_T^{jet} < 60$ GeV $\quad$ $60 < p_T^{jet} < 100$ GeV



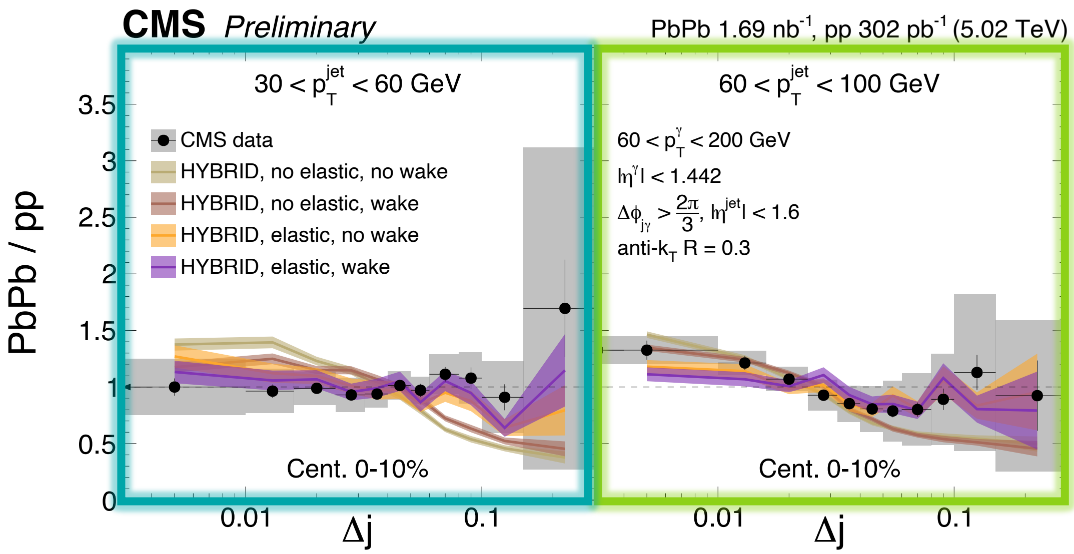
Jewel, recoil: medium recoil particles included and subtracted

Jewel, no recoil: medium recoil particles ignored

Pyquen: baseline model of jet quenching

Pyquen, wide angle: additional wide angle gluon radiation

$30 < p_T^{jet} < 60$ GeV $\quad$ $60 < p_T^{jet} < 100$ GeV



CMS: PAS-HIN-21-019

Hybrid, no elastic, no wake: strongly-coupled model of jet quenching

Hybrid, no elastic, wake: conservation of energy imposed

Hybrid, elastic, no wake: scattering from medium particles

Hybrid, elastic, wake: conservation of energy + scattering within medium

- Data agrees well with **Jewel** and with **Hybrid** with elastic scattering effects
- **Pyquen** overpredicts broadening effects
- Shapes are relatively insensitive to wake affects, which appear to mostly affect the overall jet yield

Seeing Through Jet Wakes

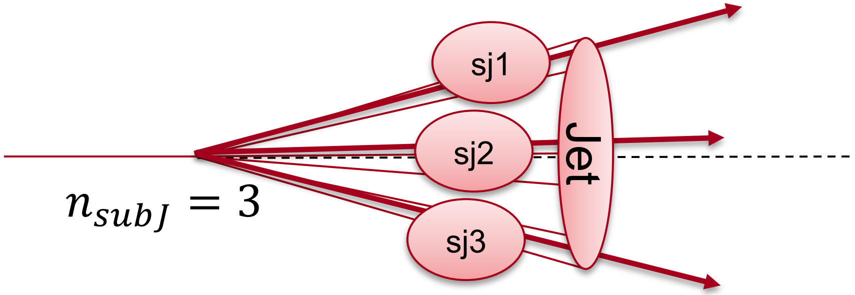
- Identifying observables that are insensitive to jets' wakes lets us see effects of elastic Molière scattering of jet partons off medium partons in the perturbative regime.
- R_g, girth, leading k_T, WTA axis, D or B mesons within jets.
- Can "engineer" R_g and girth observables in γ+jet events to reduce (enhance) selection bias by selecting with $x_J >$ a low (high) threshold. When selection bias is reduced, elastic scattering yields $R_{\mathrm{AA}} > 1$.
- Can also "engineer" these observables to reduce (enhance) effects of the wake by choosing small (large) R jets.
- Need to make sure models and measurements have same selection bias, which is to say for γ-jet observables need to make sure we have same $x_{J\gamma}$ distribution.

Seeing Through Jet Wakes

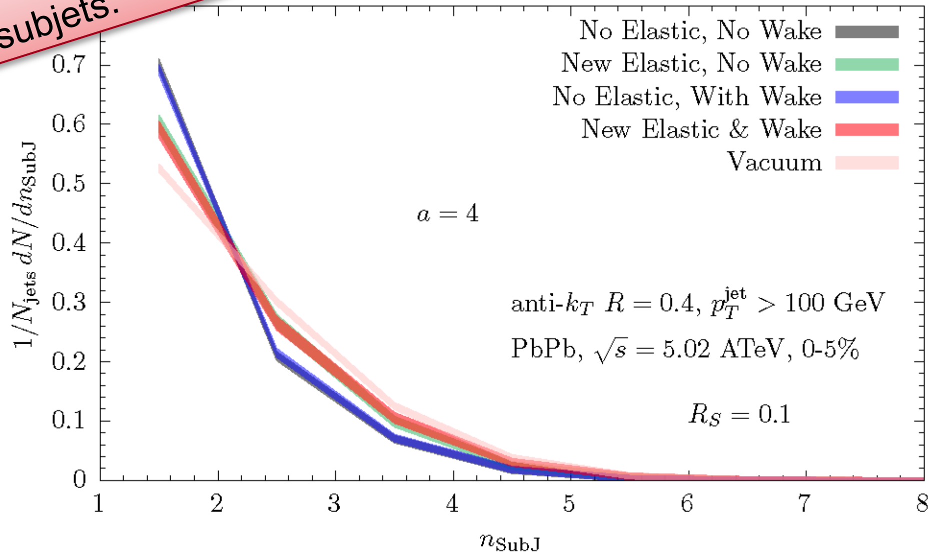
- Identifying observables that are insensitive to jets' wakes lets us see effects of elastic Molière scattering of jet partons off medium partons in the perturbative regime.
- R_g, girth, leading k_T, WTA axis, D or B mesons within jets.
- Impressive new experimental measurements. At HP2024, and coming soon. More than I had time to show.
- Modification of inclusive subjet observables (number, and angular spread, of subjets within inclusive jets) are especially sensitive to elastic scattering. And are unaffected by the wake. They reflect what it is that makes the effects of scattering different from those of the wake.
- Now enough different substructure measurements and hybrid model calculations of observables that are sensitive to elastic scattering and resolution length (and insensitive to wake) that a Bayesian study is motivated.
- All these observables may also be influenced by other ways in which jet shower partons "see" particulate aspects of QGP. That's great!

Inclusive Jets within Inclusive Jets: Inclusive Subjets

1. Reconstruct jet with R=0.6
2. Recluster each jet's particle content into subjets with R=0.15



Increase in number of subjets.



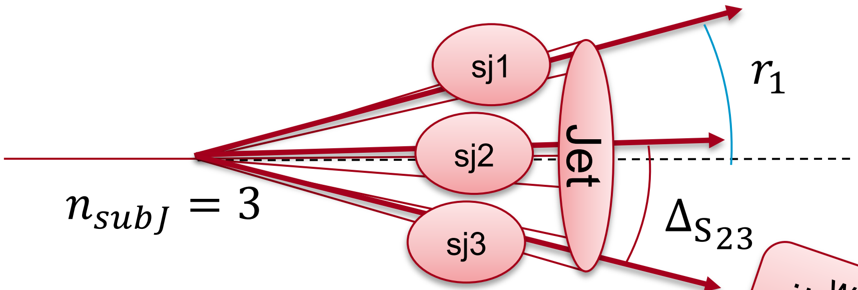
Moliere scattering visible as increase in number of subjets; no such effect coming from wake at all.

Moliere scattering also yields more separated subjets…

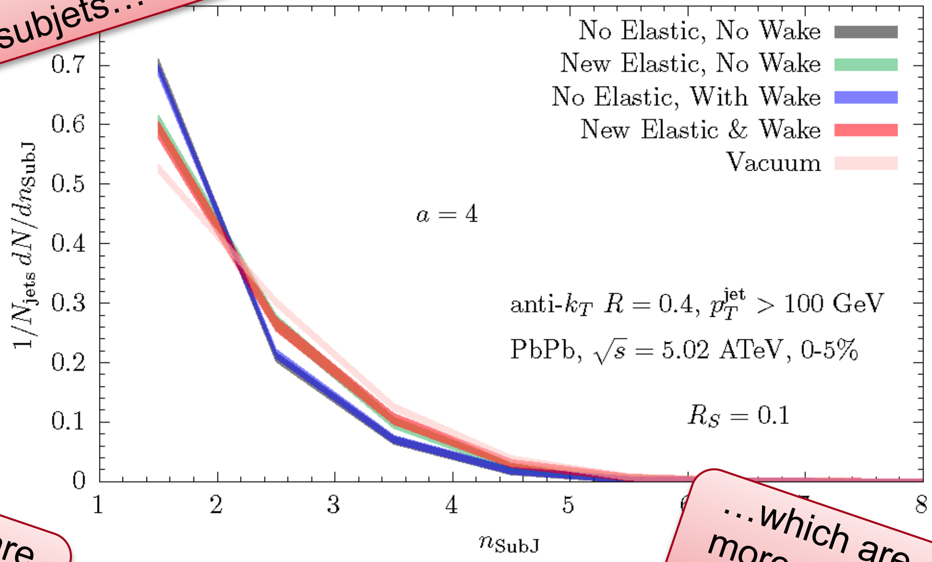
These observables are directly sensitive to "sprouting a new subjet" the intrinsic feature of Moliere scattering which makes it NOT just a bit more wake.

Inclusive Subjets

1. Reconstruct jet with R=0.4
2. Recluster each jet's particle content into subjets with R=0.1

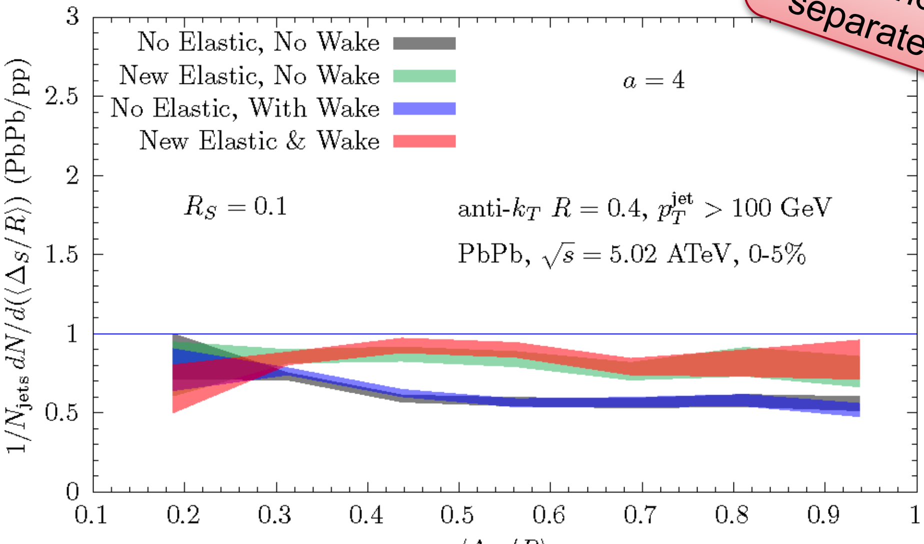


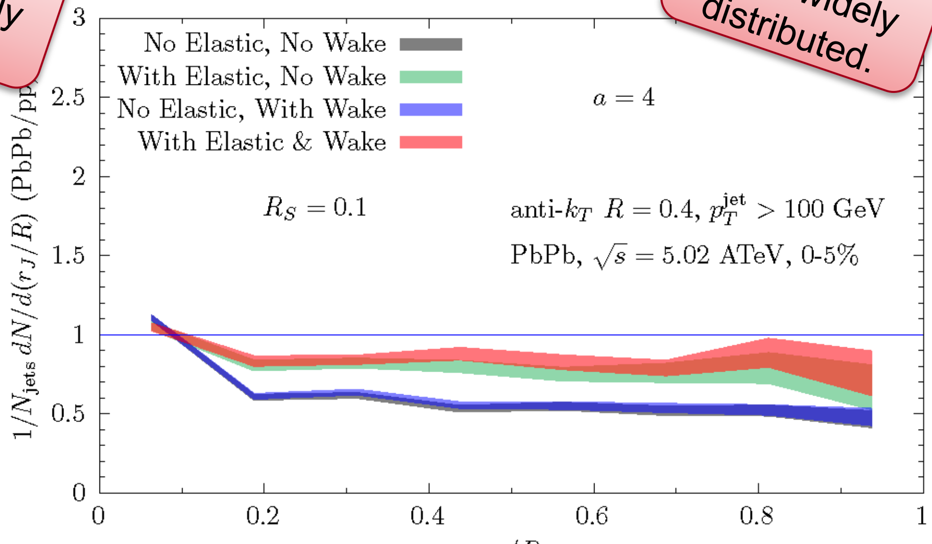
Increase in number of subjets…



…which are more widely separated.

…which are more widely distributed.





Jets as Probes of QGP

- Model calculations enabling key steps…
- Disentangling jet modification from jet selection.
- Showing that QGP *can* resolve structure within jet shower.
- Identification of new experimental observables, and predictions, that are enabling new experimental measurements to “see” the particles originating from jet wakes. Points the way toward visualizing dynamics of jet wakes in droplets of QGP and how they hydrodynamize.
- Identifying those jet substructure observables that *are* sensitive to scattering of jet quarks/gluons off QGP quarks/gluons, “seeing the latter à la Rutherford, and are *not* sensitive to particles coming from the wake.
- Next several years will be the golden age of HIC jet physics: sPHENIX, LHC runs 3 and 4, new substructure observables. *Many* theoretical and experimental advances are whetting our appetite for the feast to come.
- We can learn about the microscopic structure of QGP, and the dynamics of rippling QGP.

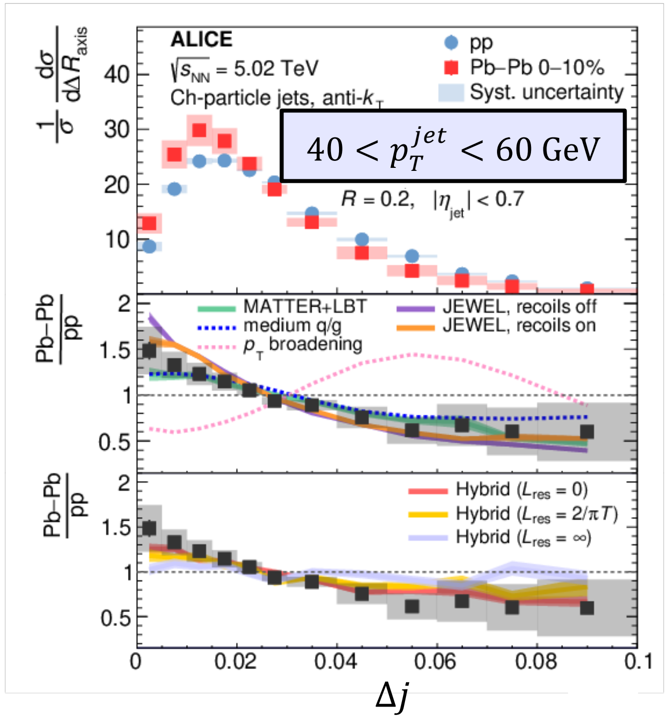
BACKUP SLIDES

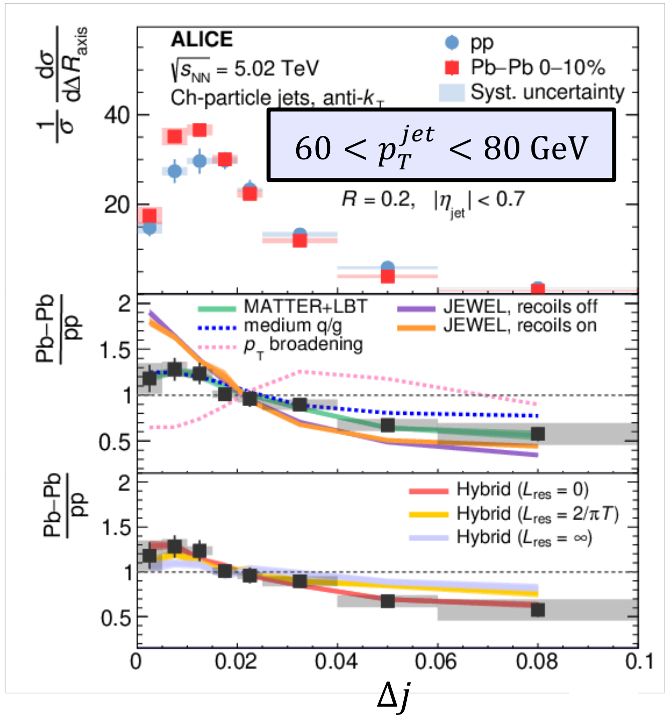
Previous measurement in inclusive jets

Studying the jet axis decorrelation, which is the angular difference between the WTA and E-Scheme jet axes

WTA axis = direction of leading energy flow in jet **E-Scheme axis** = direction of average energy flow in jet

$$\Delta j = \sqrt{(\eta^{E-Scheme} - \eta^{WTA})^2 + (\phi^{E-Scheme} - \phi^{WTA})^2}$$



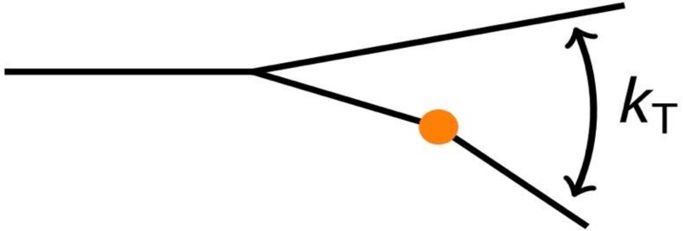


ALICE: arXiv:2303.13347

Inclusive jet measurements of Δj show signs of narrowing in PbPb compared to pp collisions

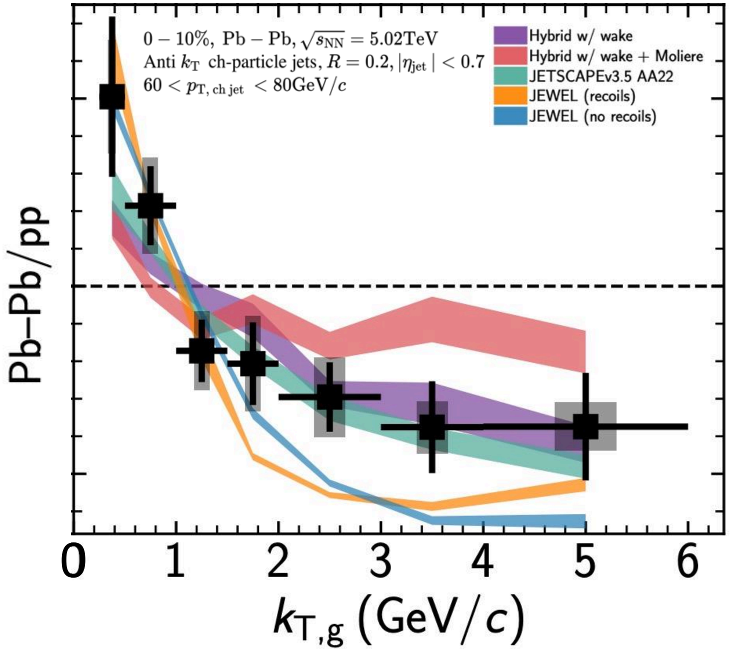
In other jet measurements such as R_g, narrowing in inclusive jets likely due to **selection bias**

Searching for the quasi-particle in QGP



$$k_T = p_{T,\text{subleading}} \sin \Delta R$$

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



New publication

arXiv:2409.12837

Bas Hofman 23/09 14:40

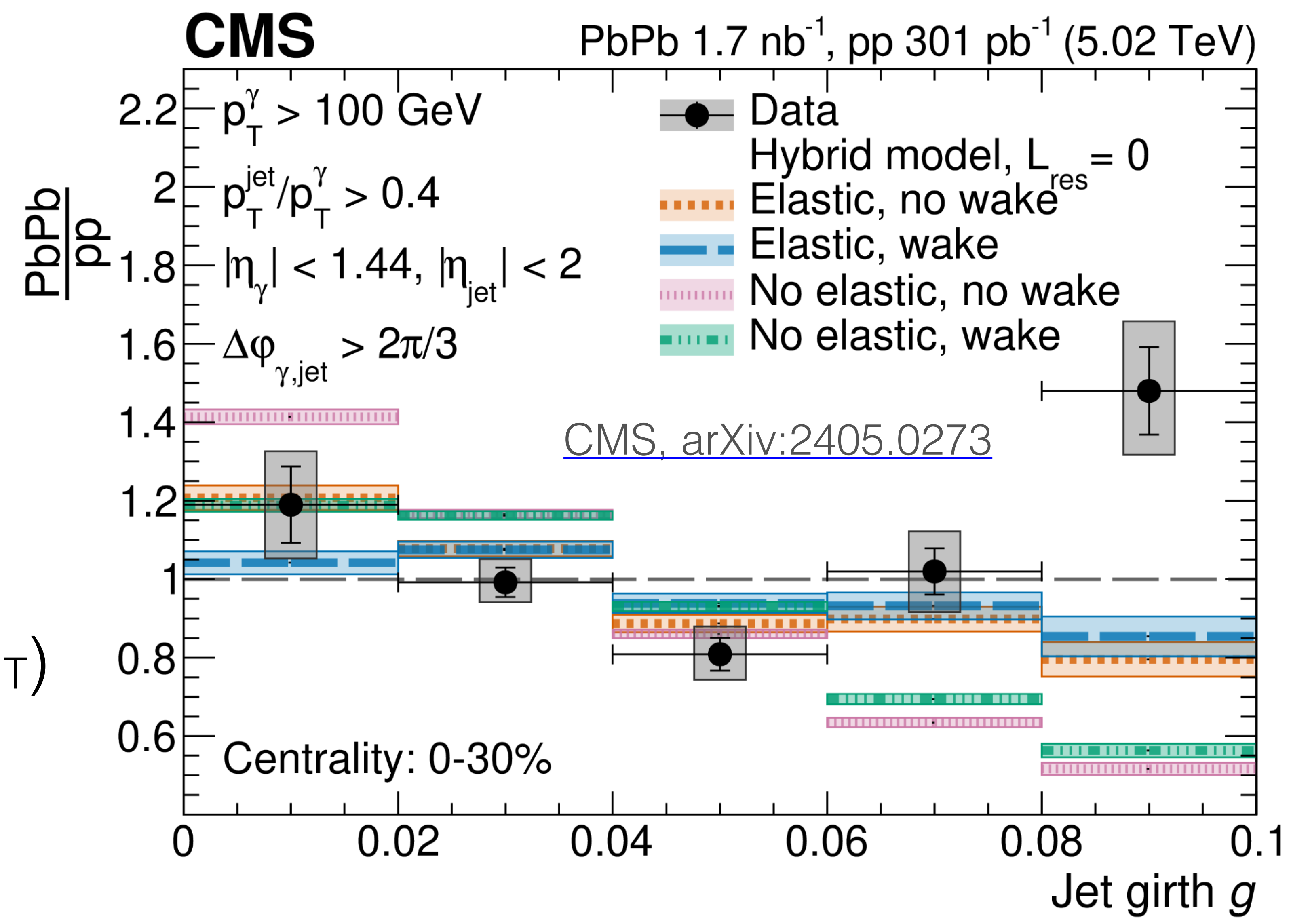
- First measurement of the hardest relative transverse jet splitting
- **Need well-controlled models baseline** from theory to investigate Moliere effects to search quasi-particle in QGP
- Provide new constrain on the microscopic structure and dynamics of the quark–gluon plasma

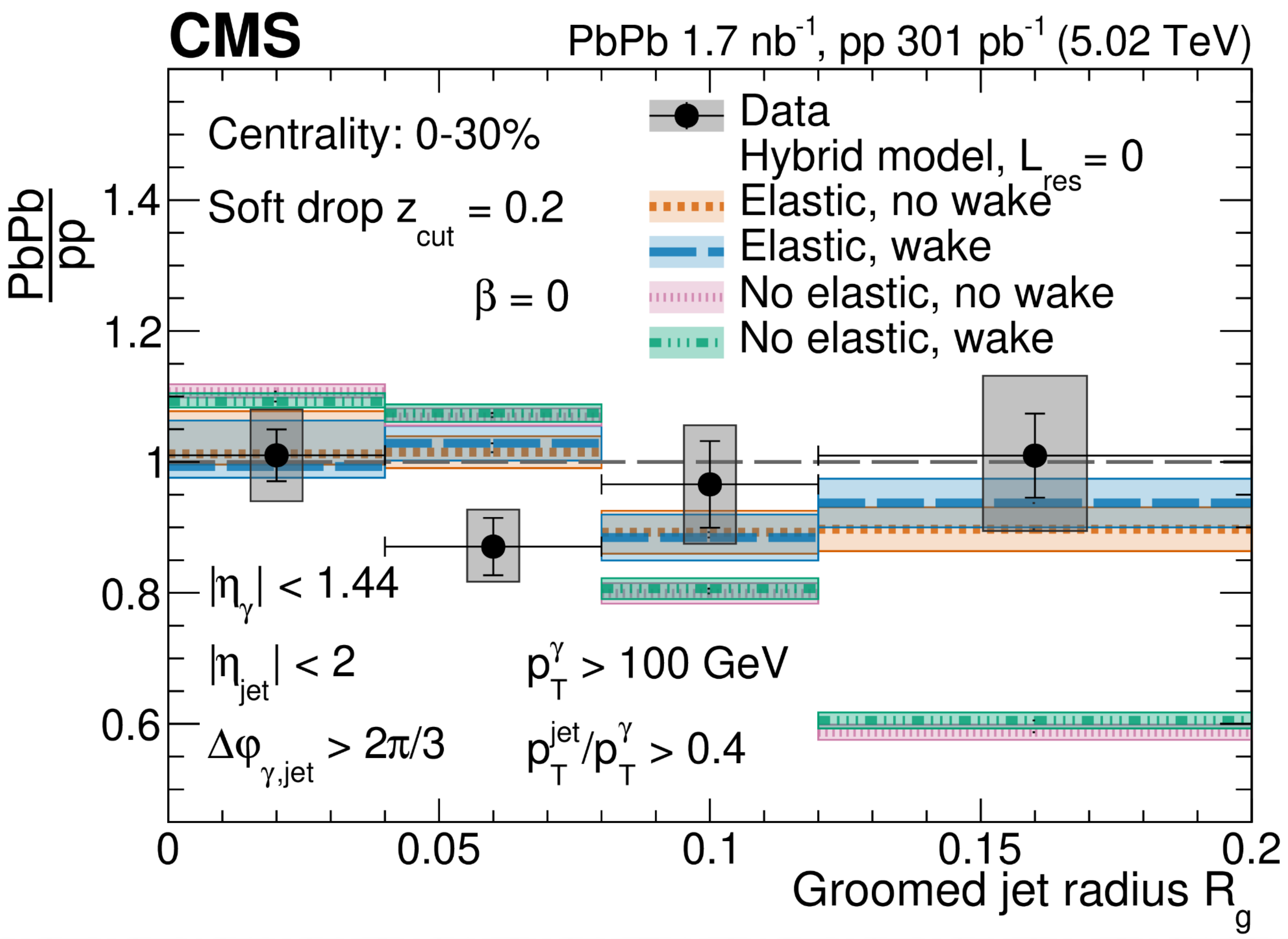
Quenching model comparison (hybrid)

Hybrid: weak+strong coupling model of jet quenching

Calculations w/o coherence (L_{res} = 0)

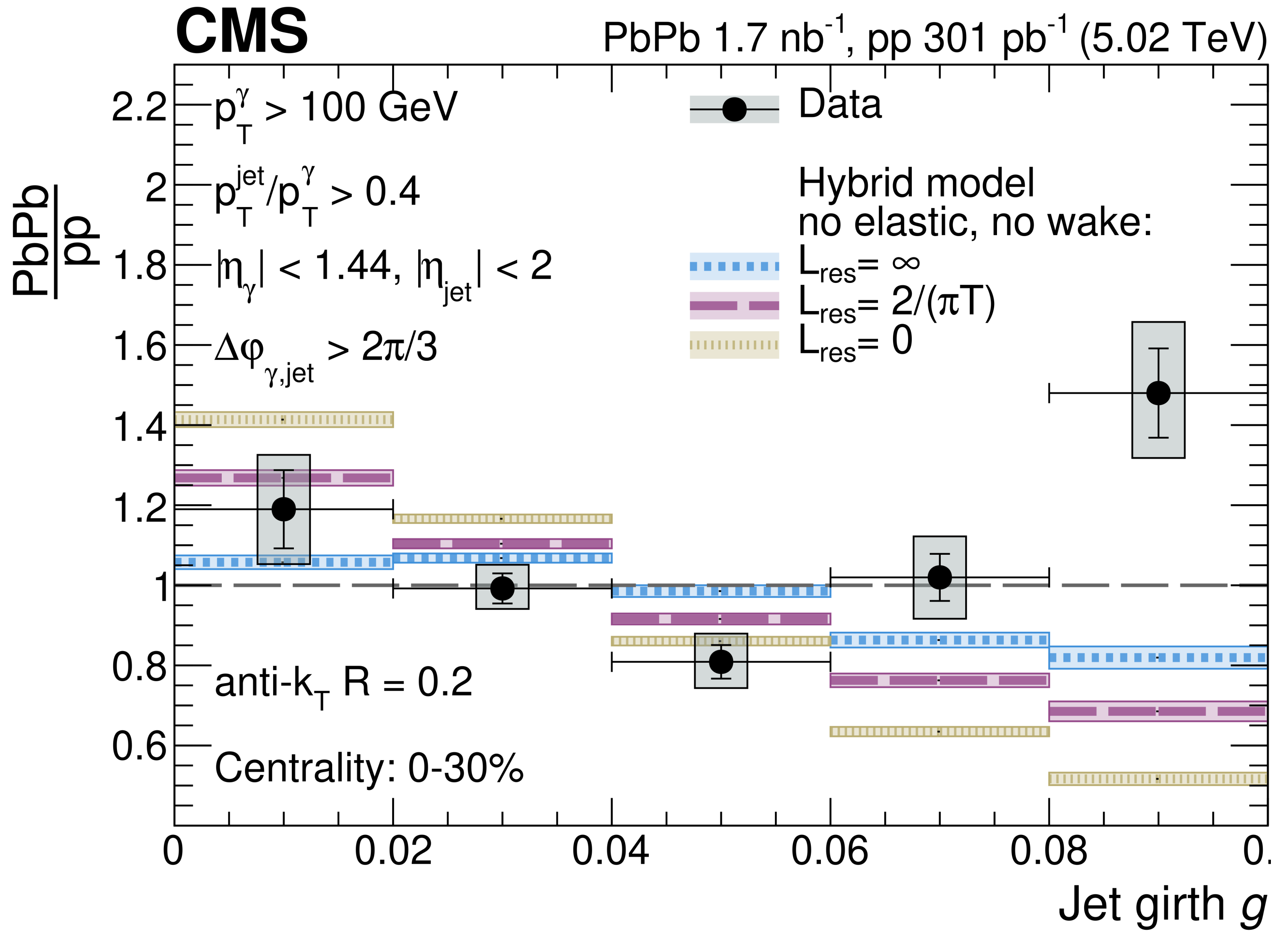
- Wake plays no role for these jet kinematics (R, p_T)
- Elastic scattering improves agreement w/ model

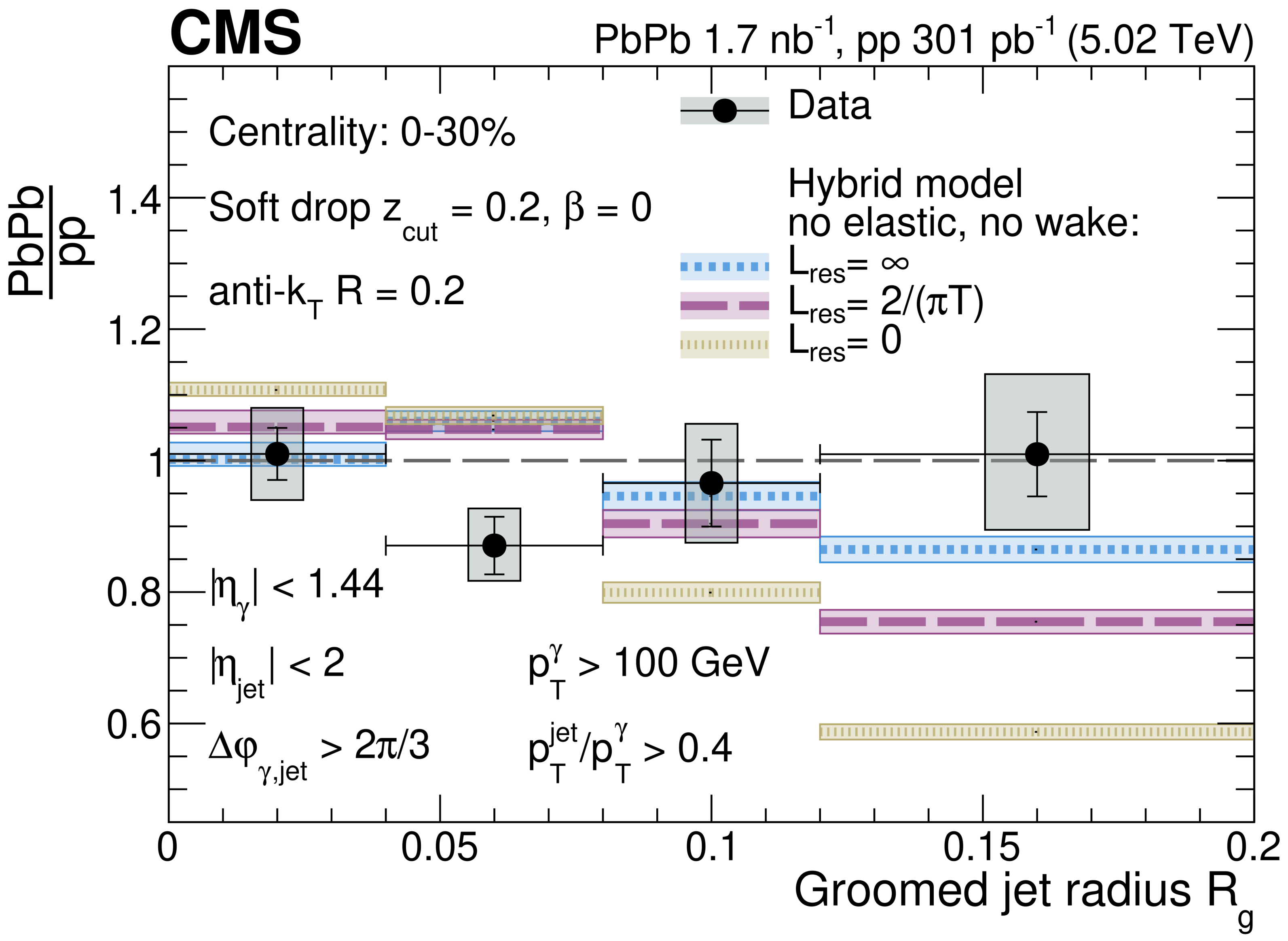




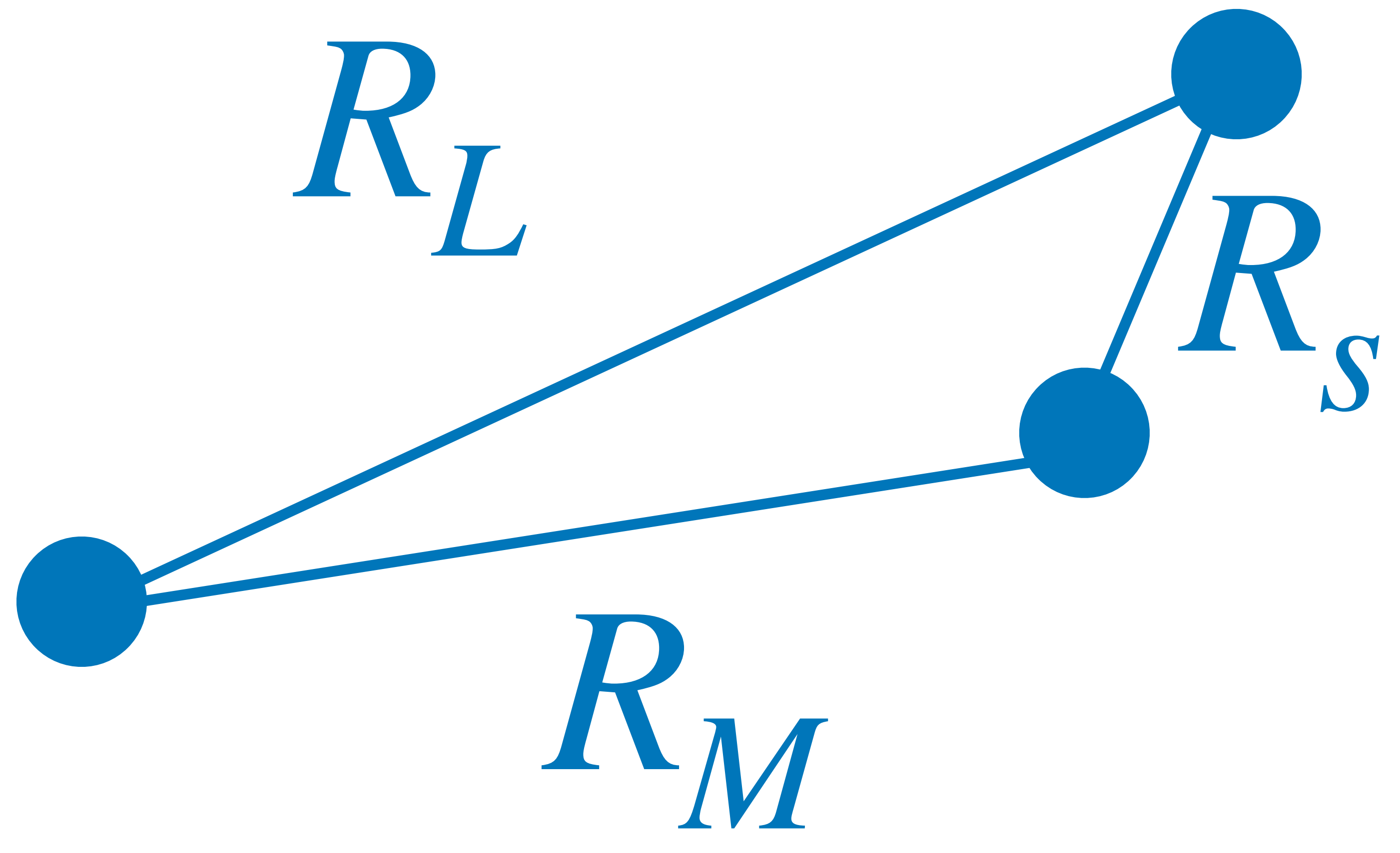
Varying coherence length

- L_{res} = 0: incoherent limit
- L_{res} = 2/(πT): intermediate
- L_{res} → ∞: coherent 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

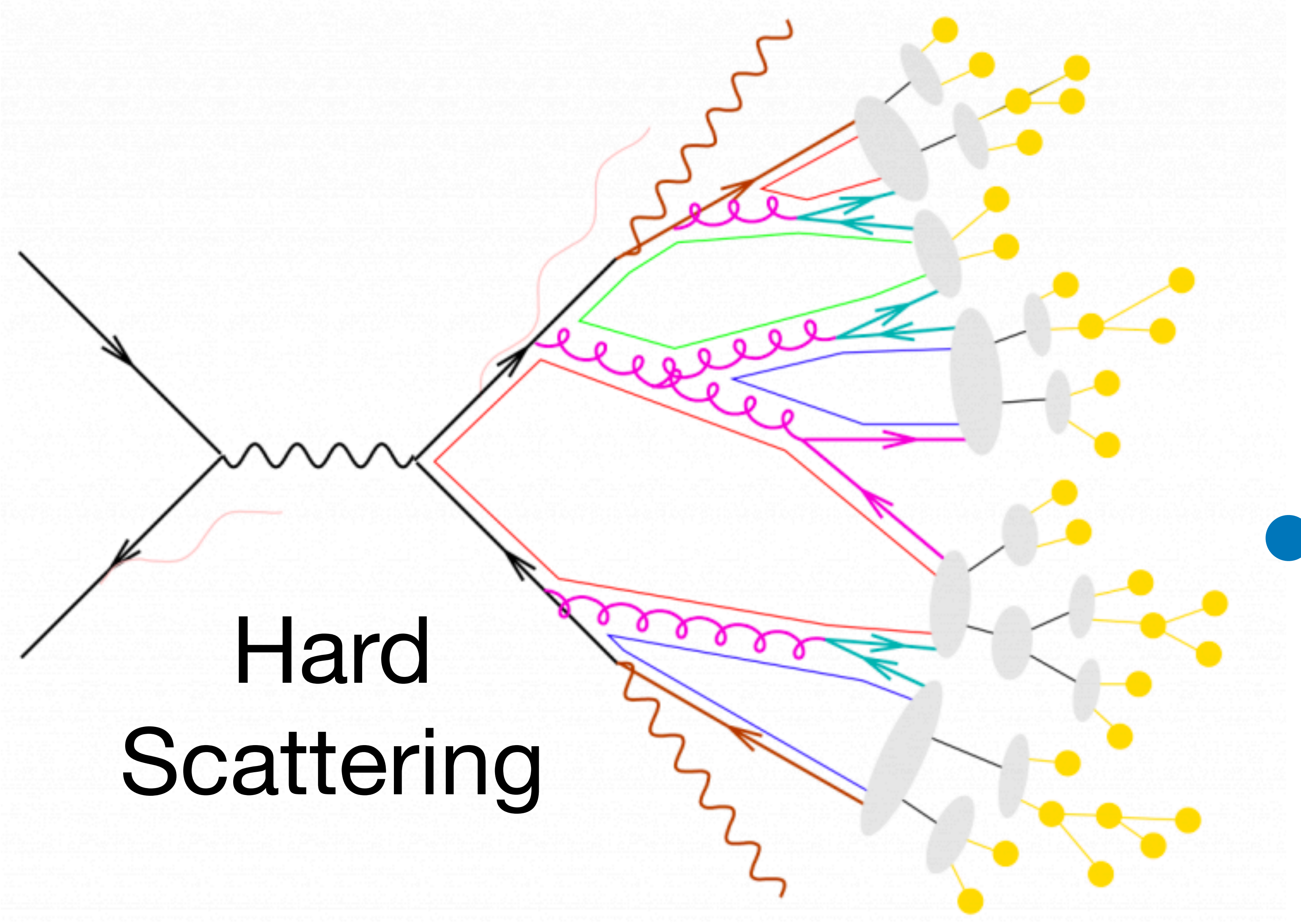
$$R_L \qquad \xi = \frac{R_S}{R_M} \qquad \phi = \arcsin\sqrt{1 - \frac{(R_L - R_M)^2}{R_s^2}}$$

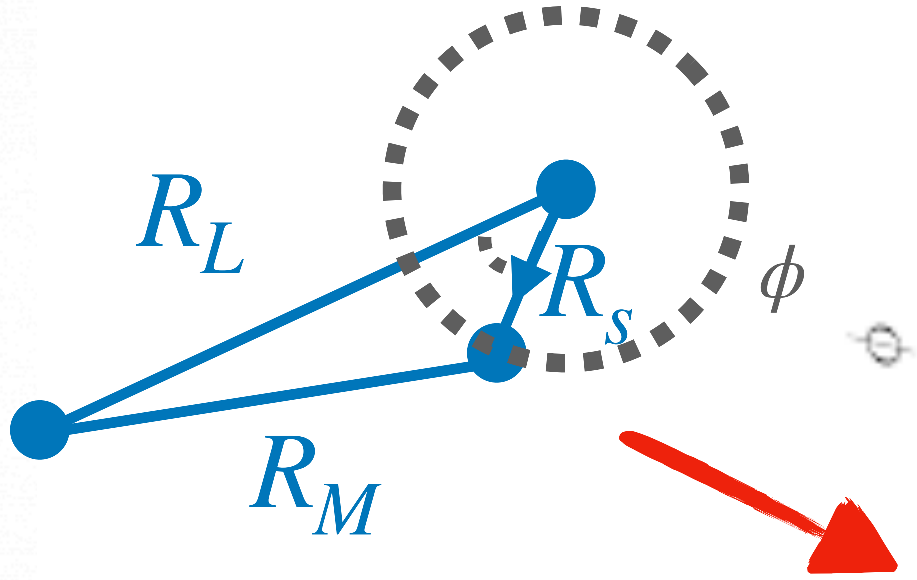
See Bianka's talk from yesterday

3-point correlator in vacuum

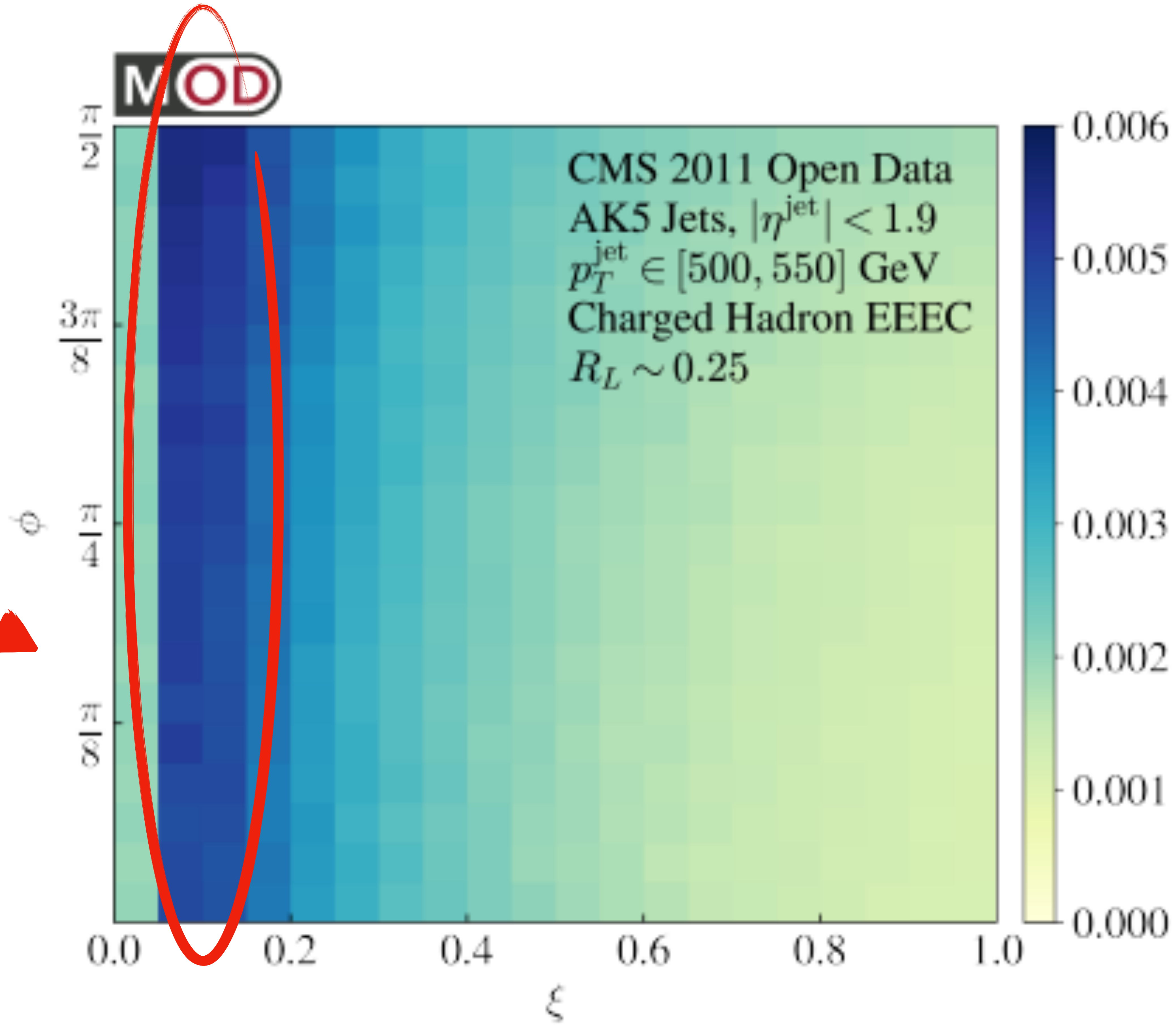
- Let’s explore the 3-point correlator in vacuum at a fixed R_{L} slice!

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





“squeezed” triangles



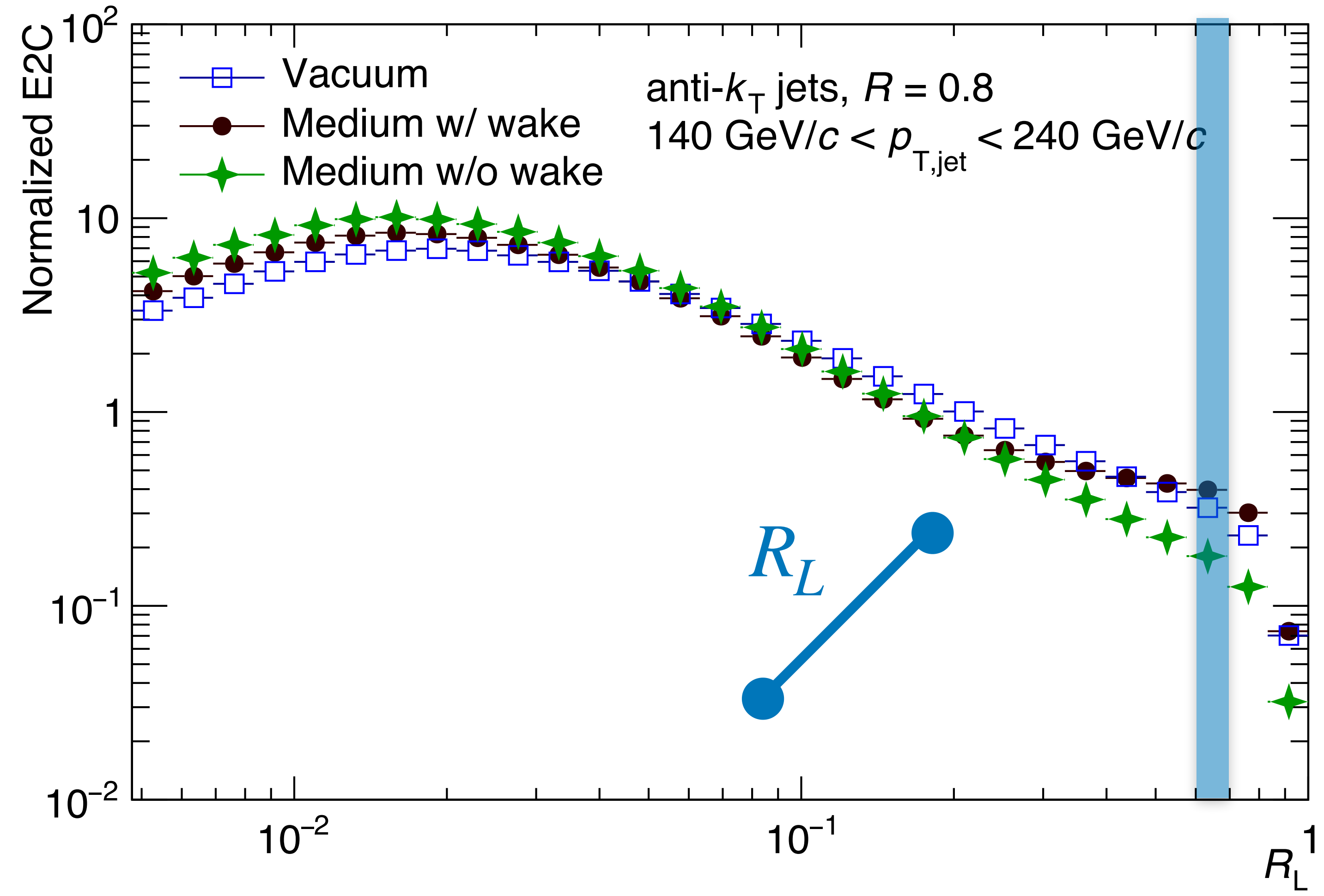
[Komiske et al., PRL 130 (2023) 5, 051901]

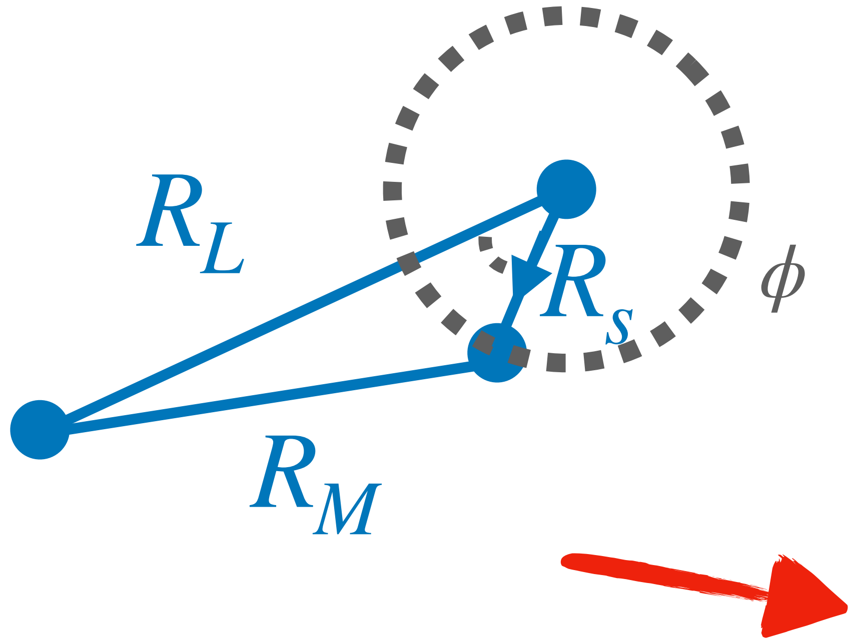
When ξ is small, behavior similar for all ϕ

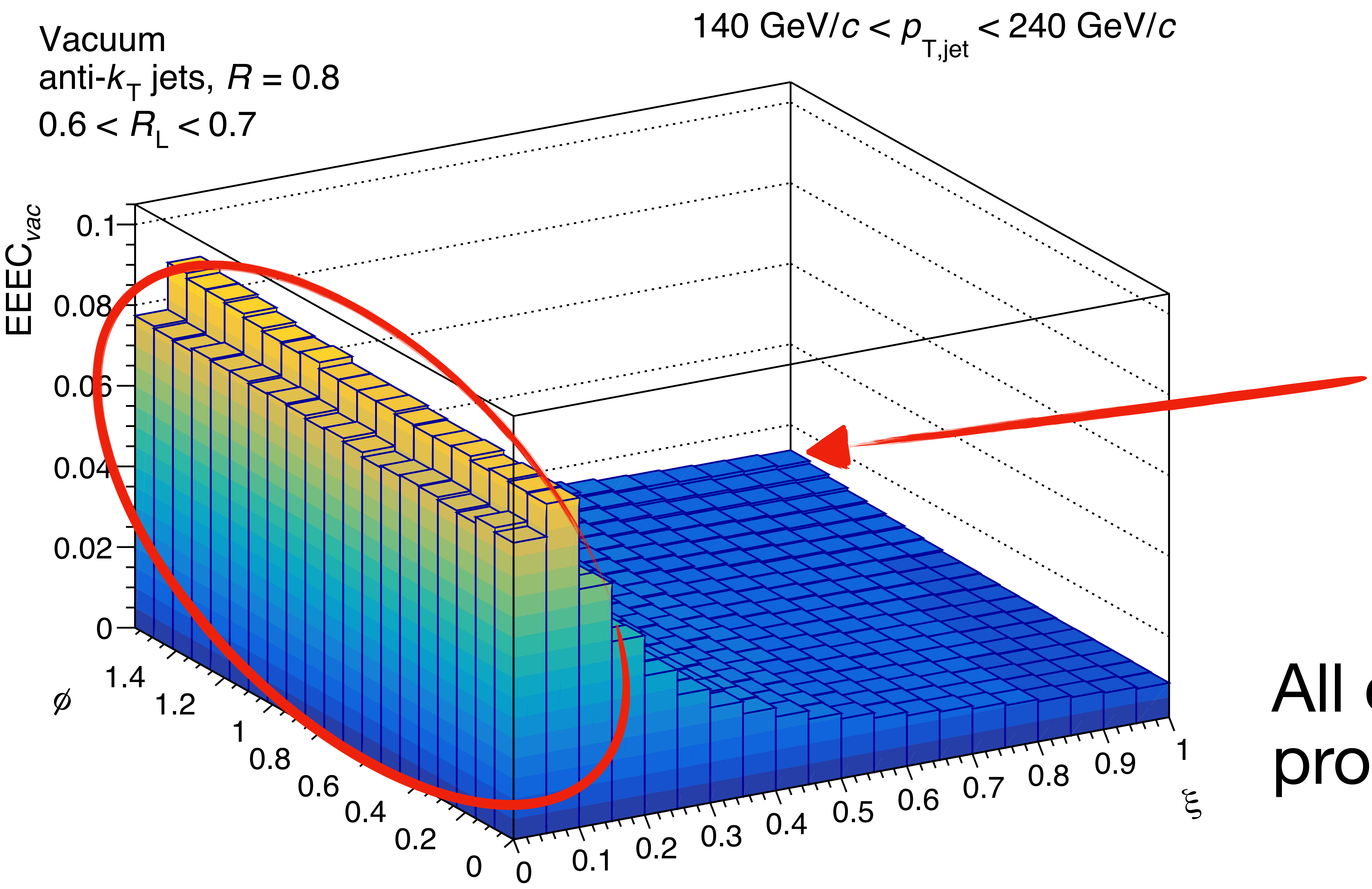
In collinear limit, reflect 2-point correlator.

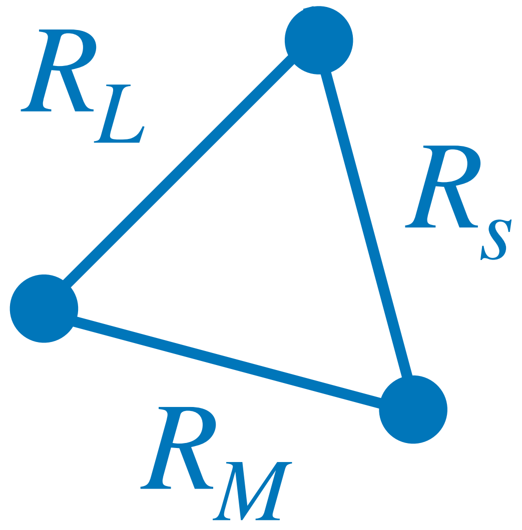
Shape dependence in vacuum

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





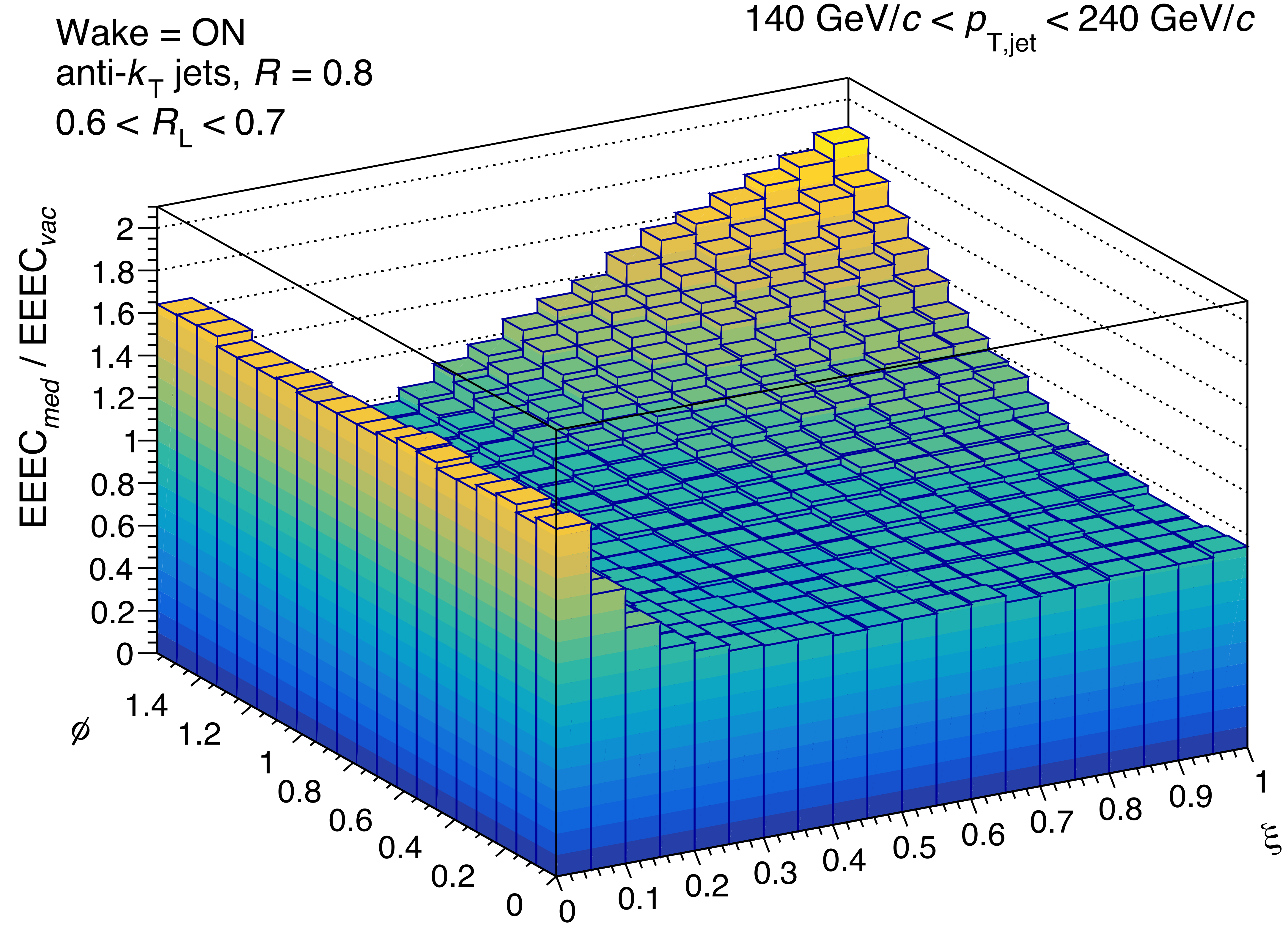




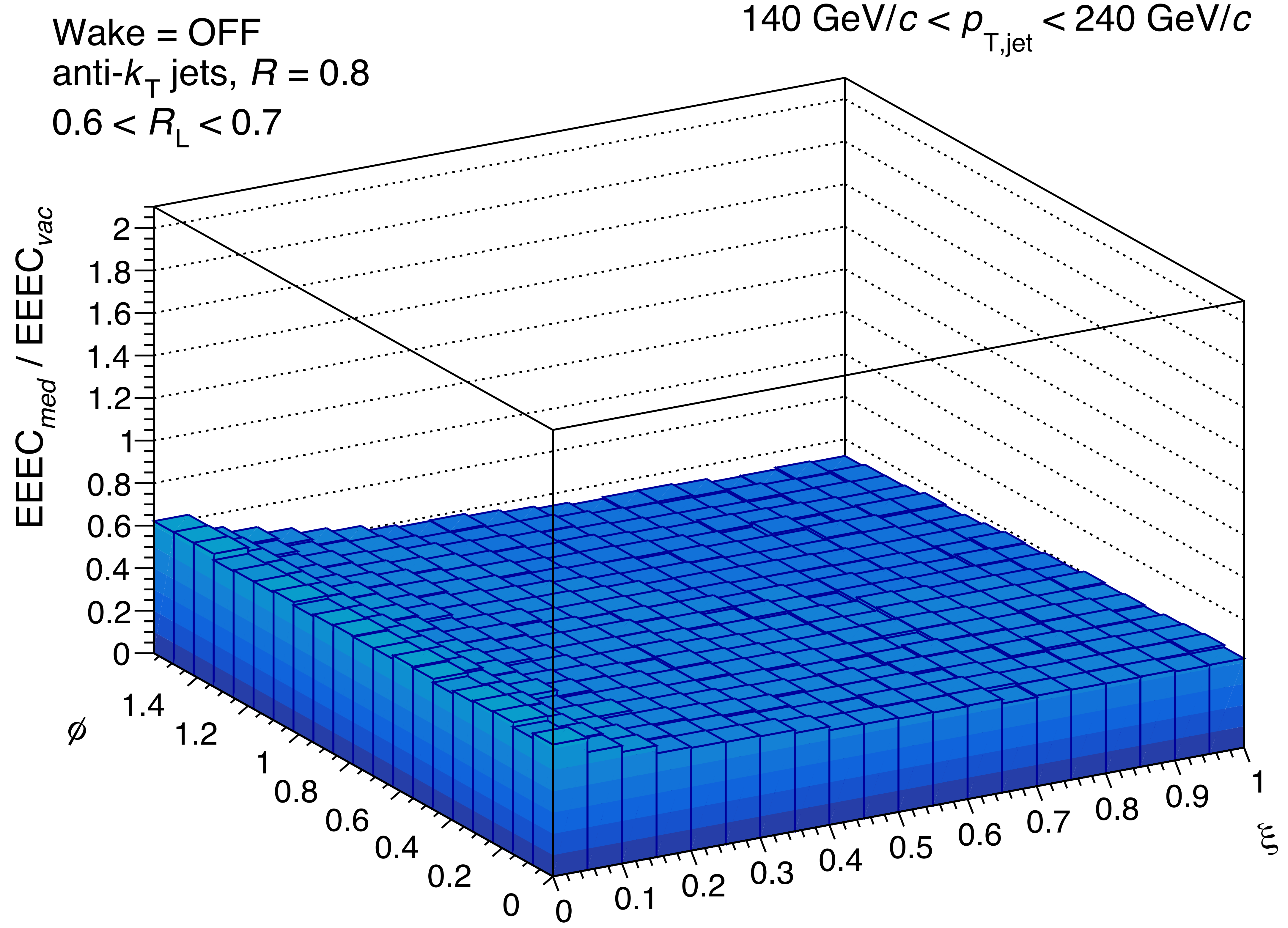
All other shapes not prominent in vacuum!

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

Ratios to vacuum



Wake / vacuum



No wake / vacuum

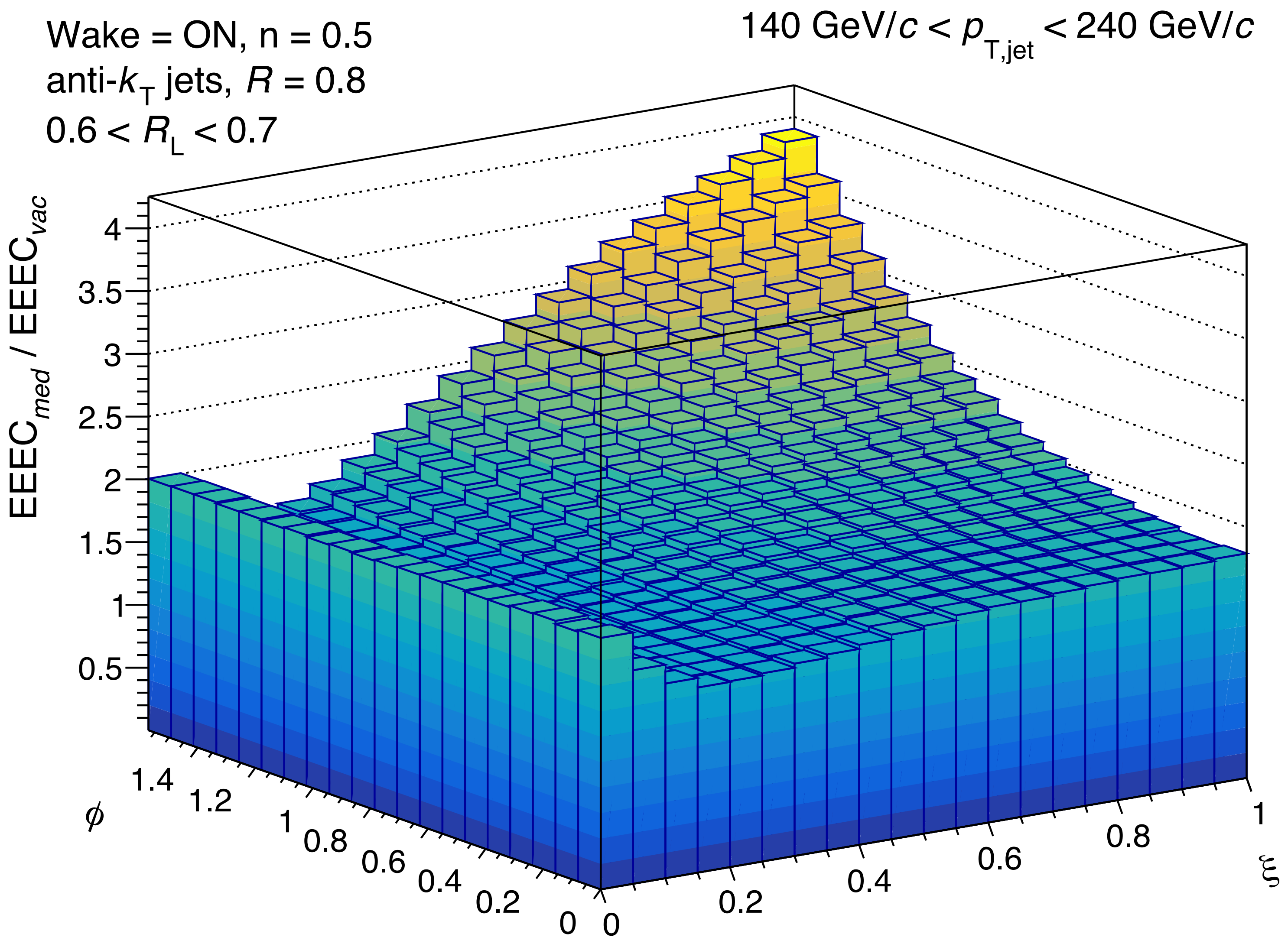
Wake leaves clear signatures in comparison to vacuum!

- Shape of medium response is encoded in these ratios!

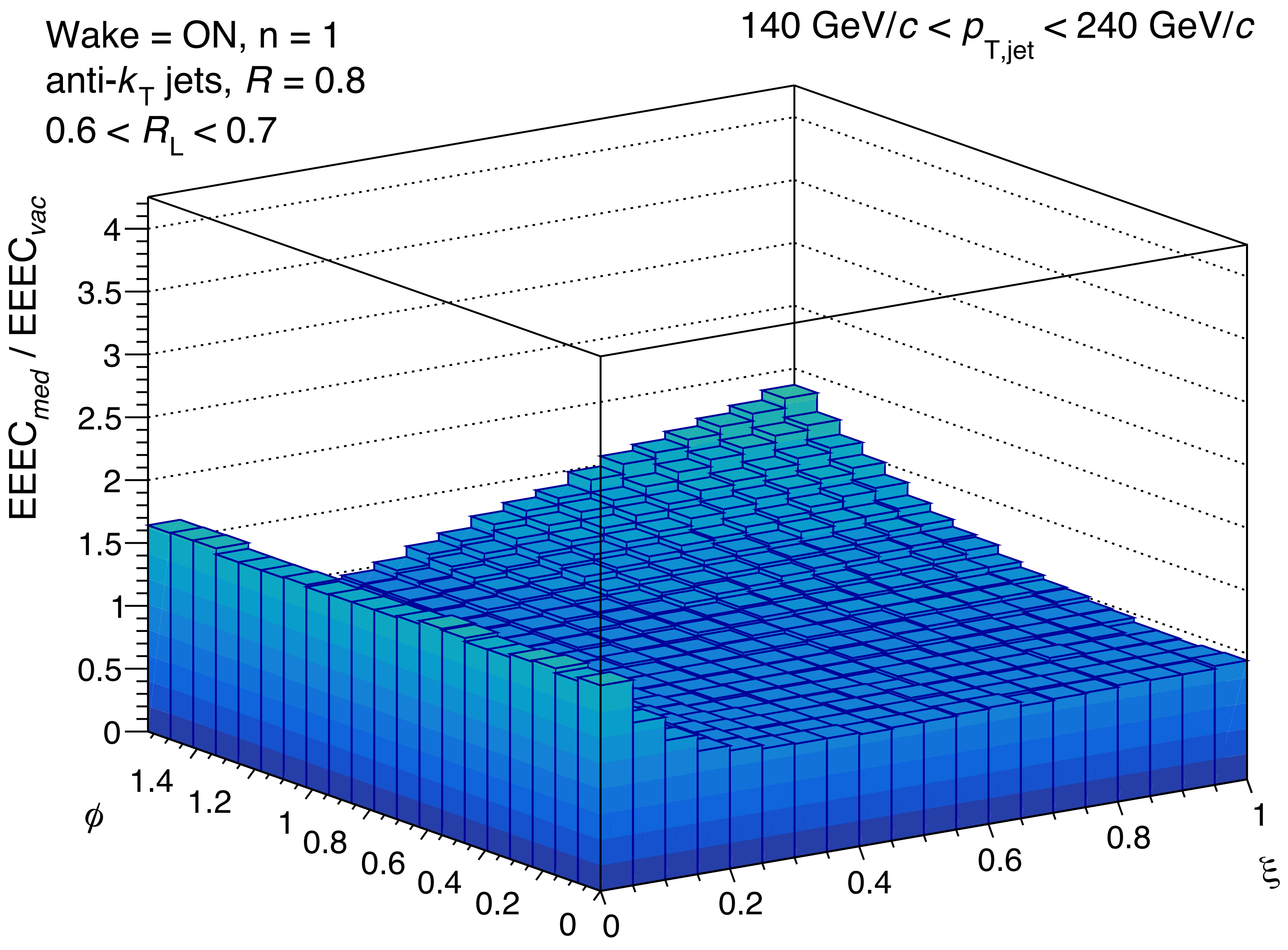
Energy weighting

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

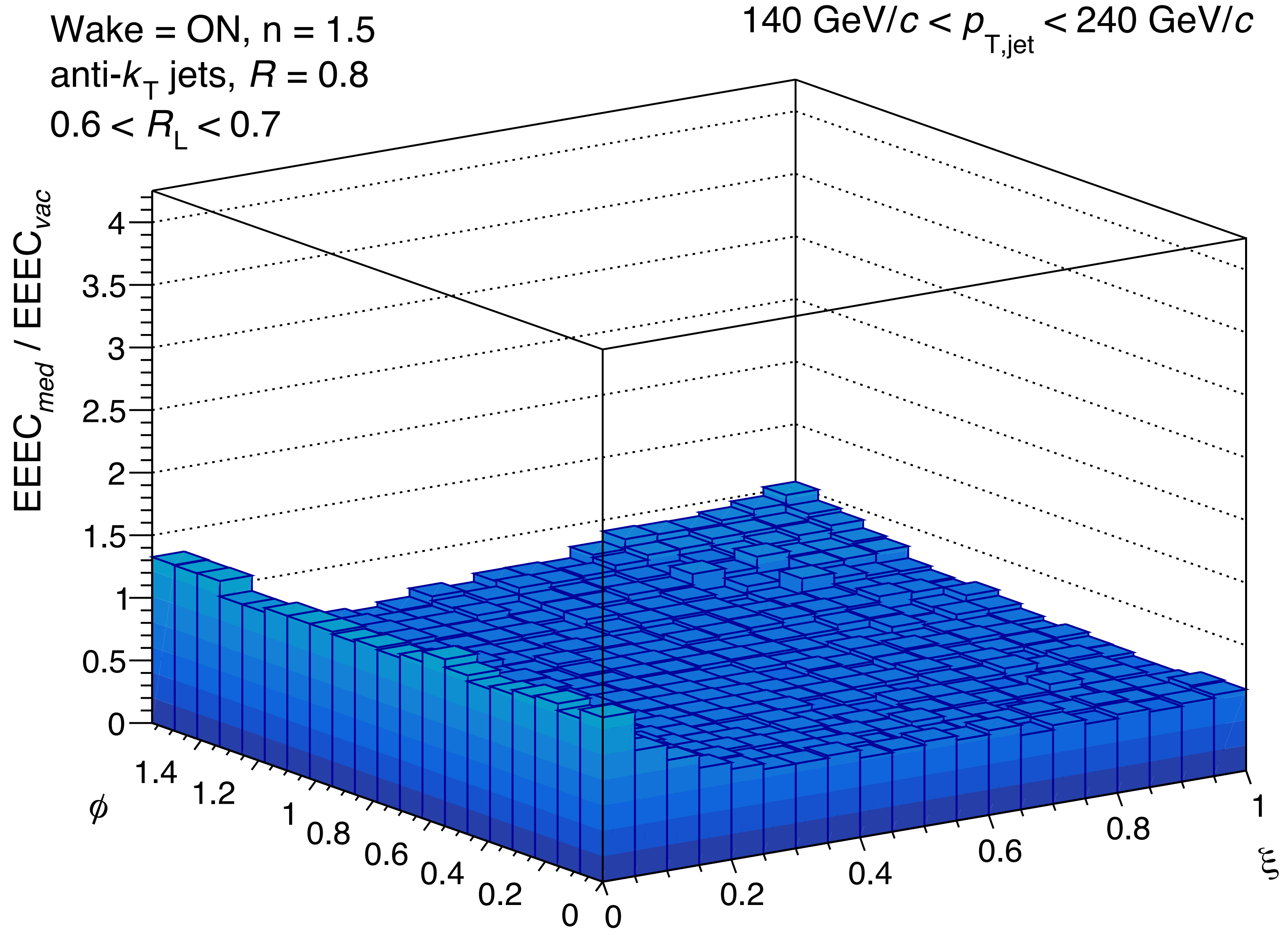
Energy weight → $$\frac{1}{(E_{\text{jet}})^{(n*N)}}\langle \mathcal{E}^n(\vec{n}_1)\mathcal{E}^n(\vec{n}_2)\ldots\mathcal{E}^n(\vec{n}_N)\rangle$$



***n* = 0.5**



***n* = 1.0**

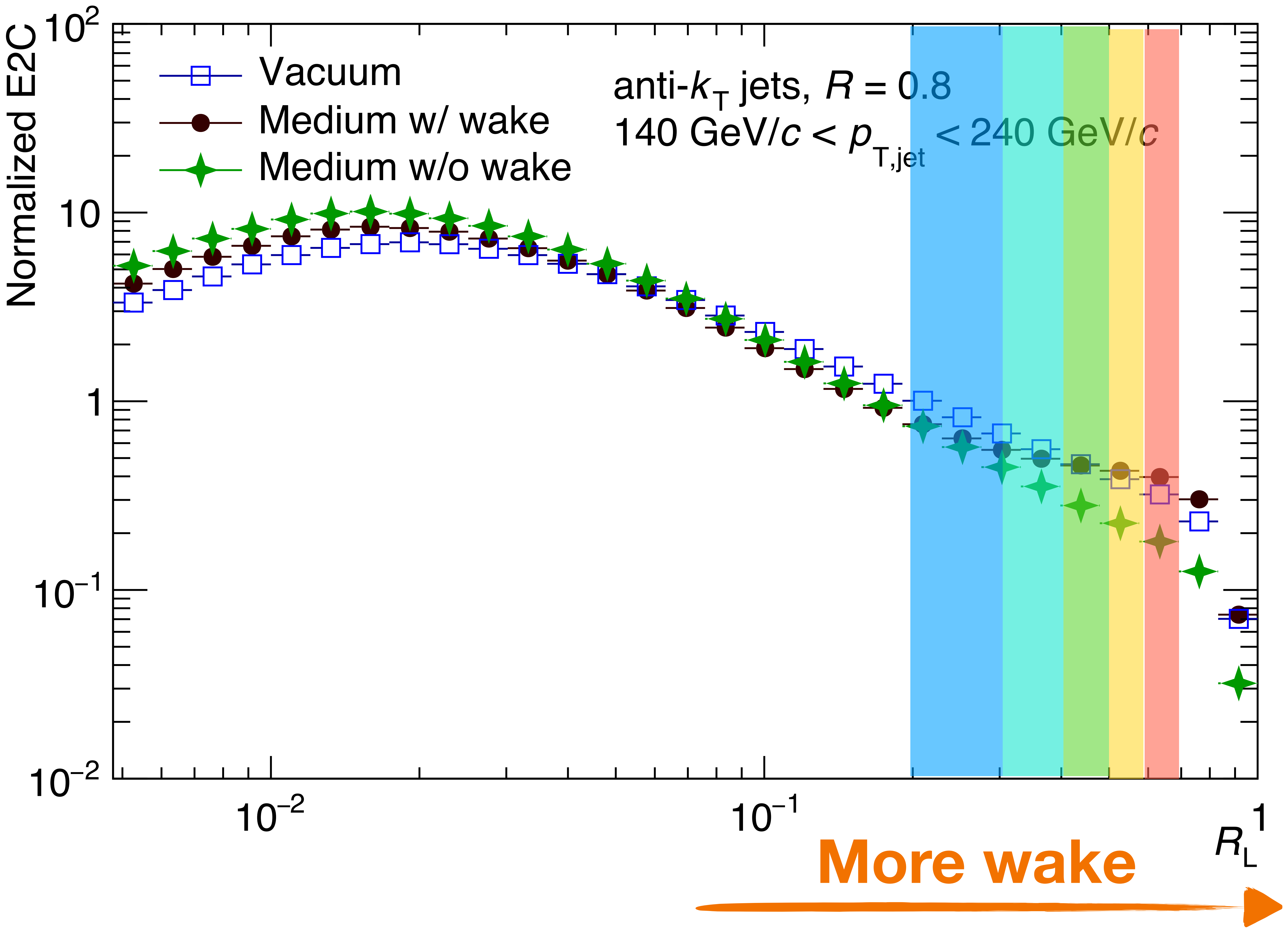


***n* = 1.5**

More wake

R_{L} scan

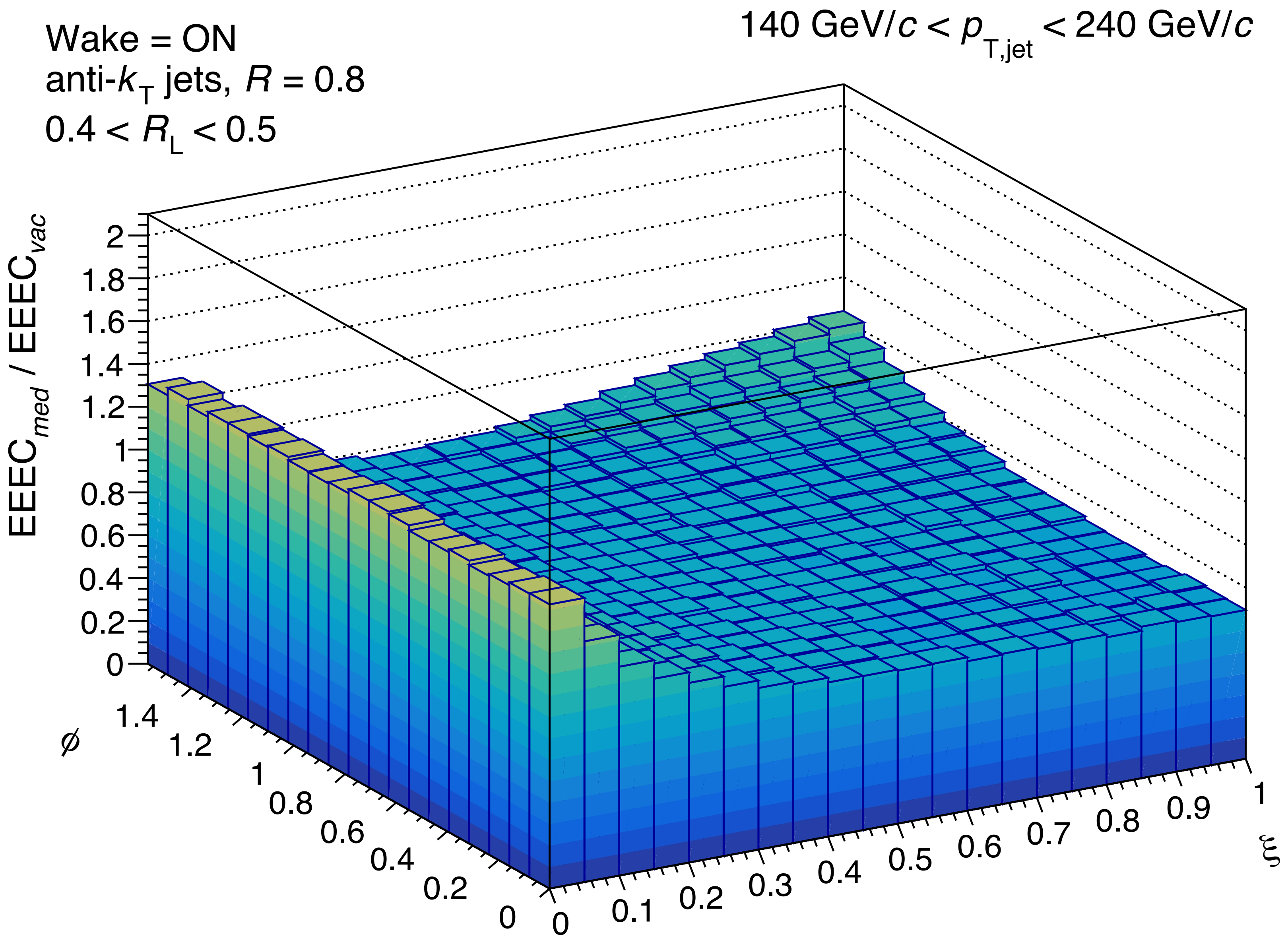
- Can use projected correlator to see which R_{L} values enhance sensitivity.



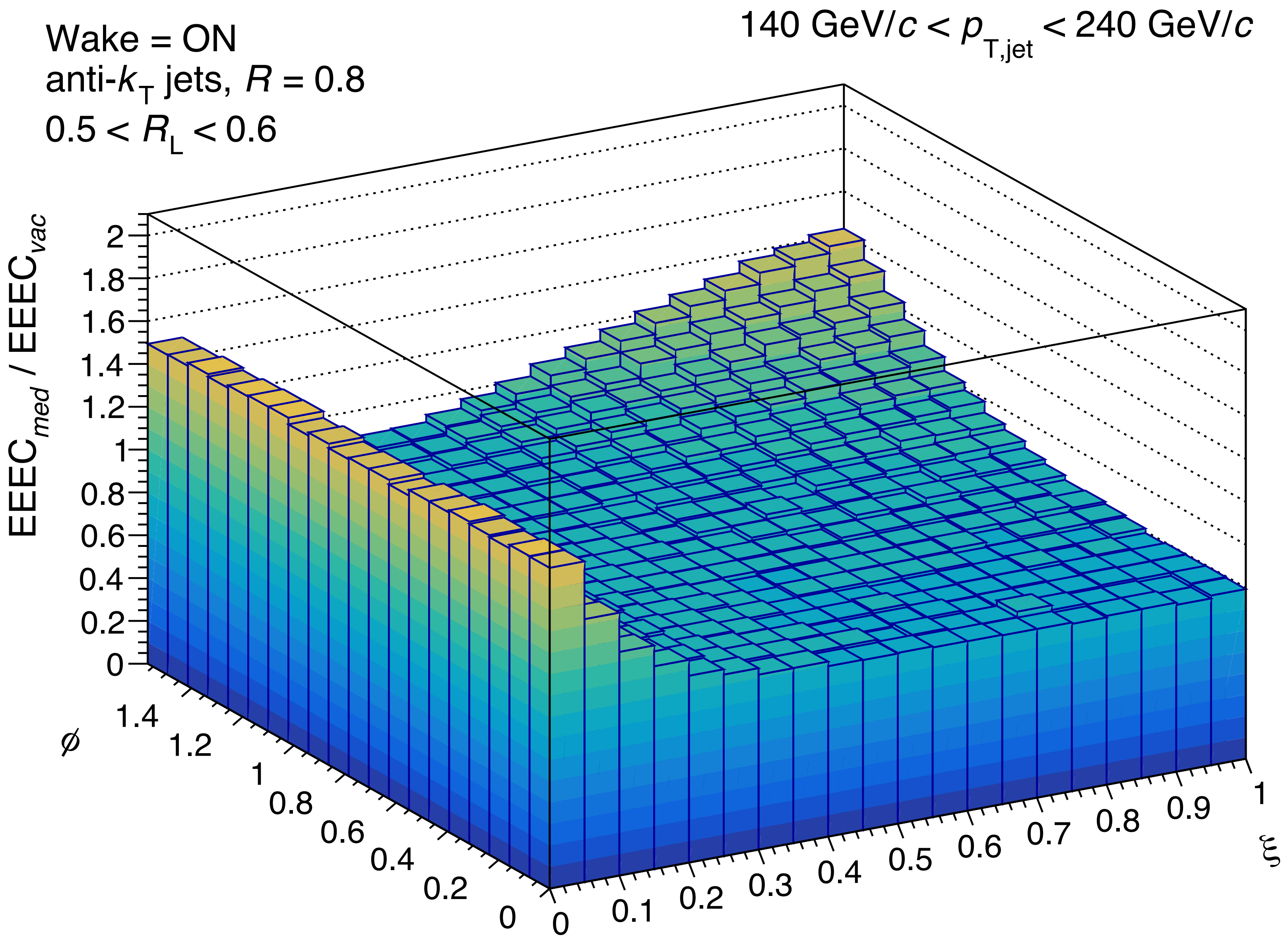
By shifting R_{L} , we expect to change sensitivity to the wake!

R_{L} scan

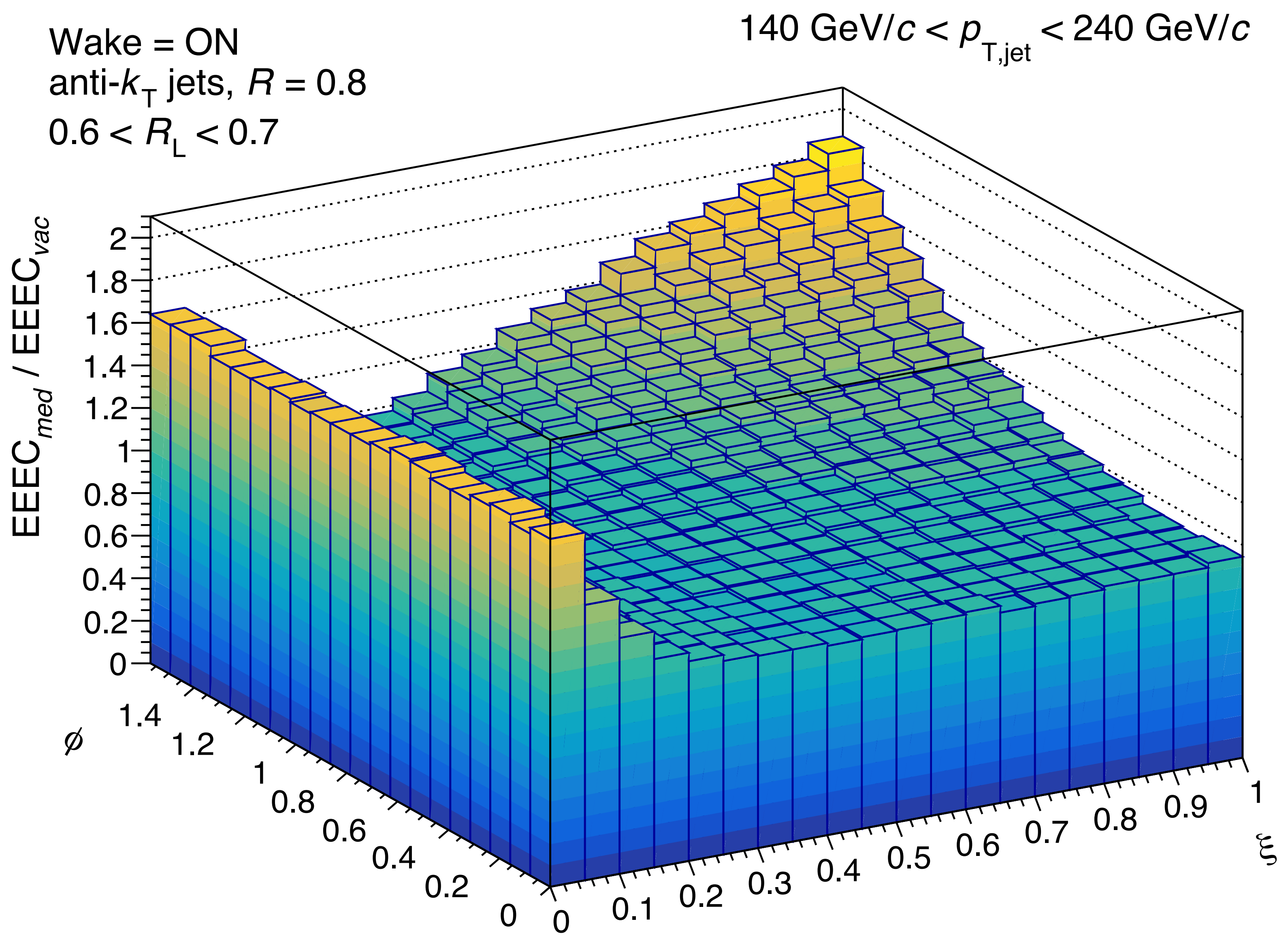
- Wake becomes more prominent at large angles (large R_{L})



$0.4 < R_{\mathrm{L}} < 0.5$



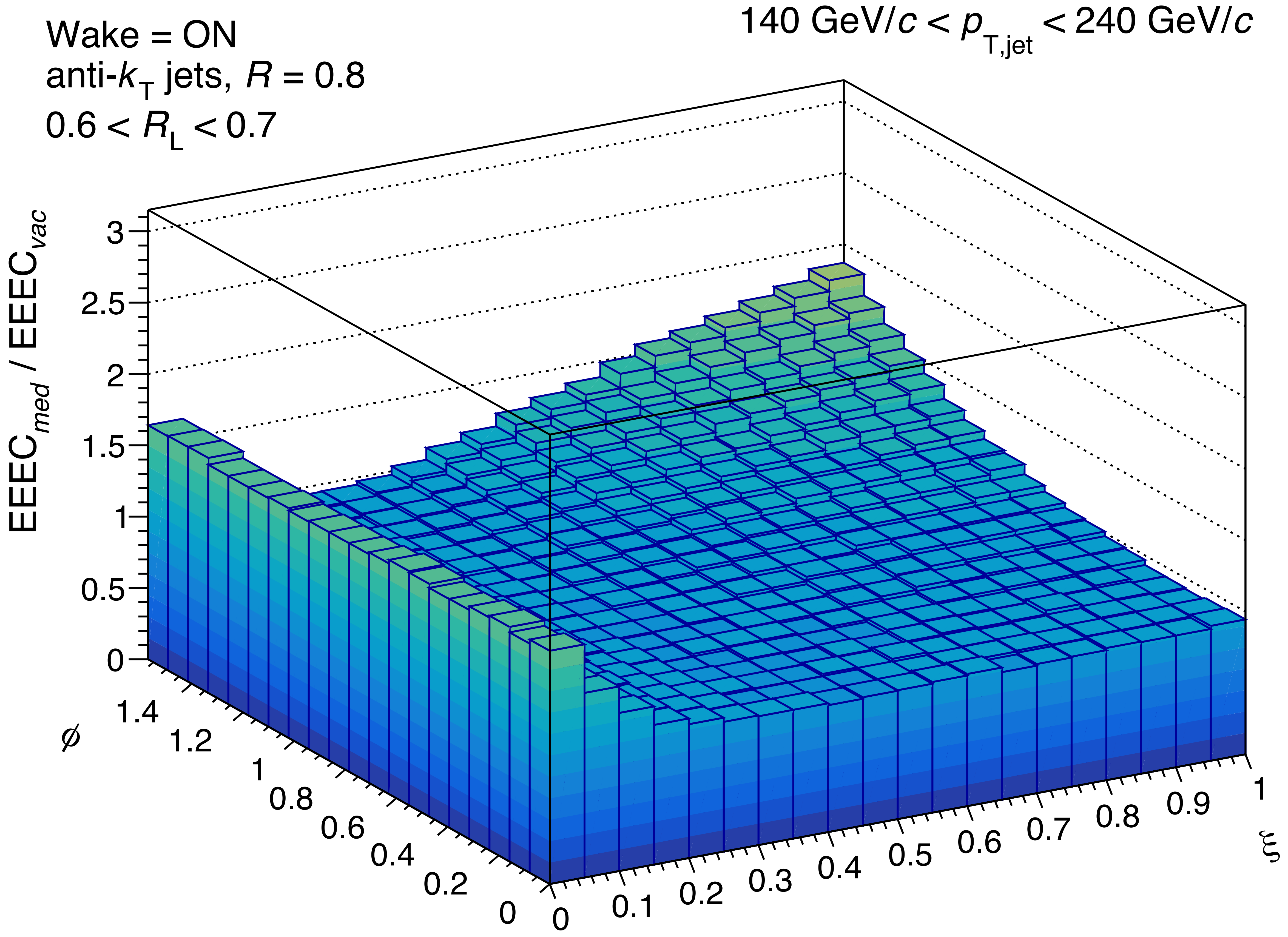
$0.5 < R_{\mathrm{L}} < 0.6$



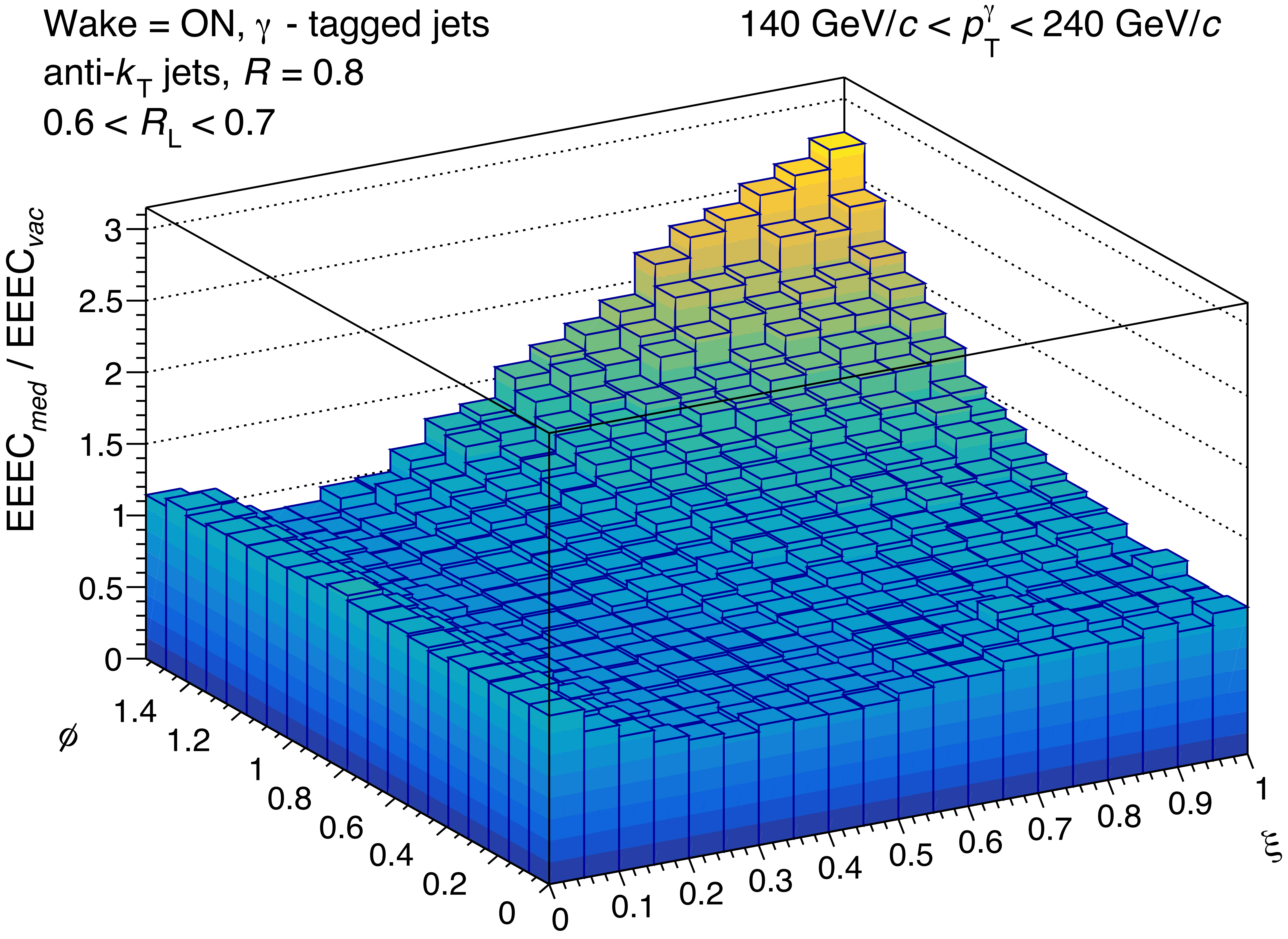
$0.6 < R_{\mathrm{L}} < 0.7$

More wake

γ - tagged EEEC



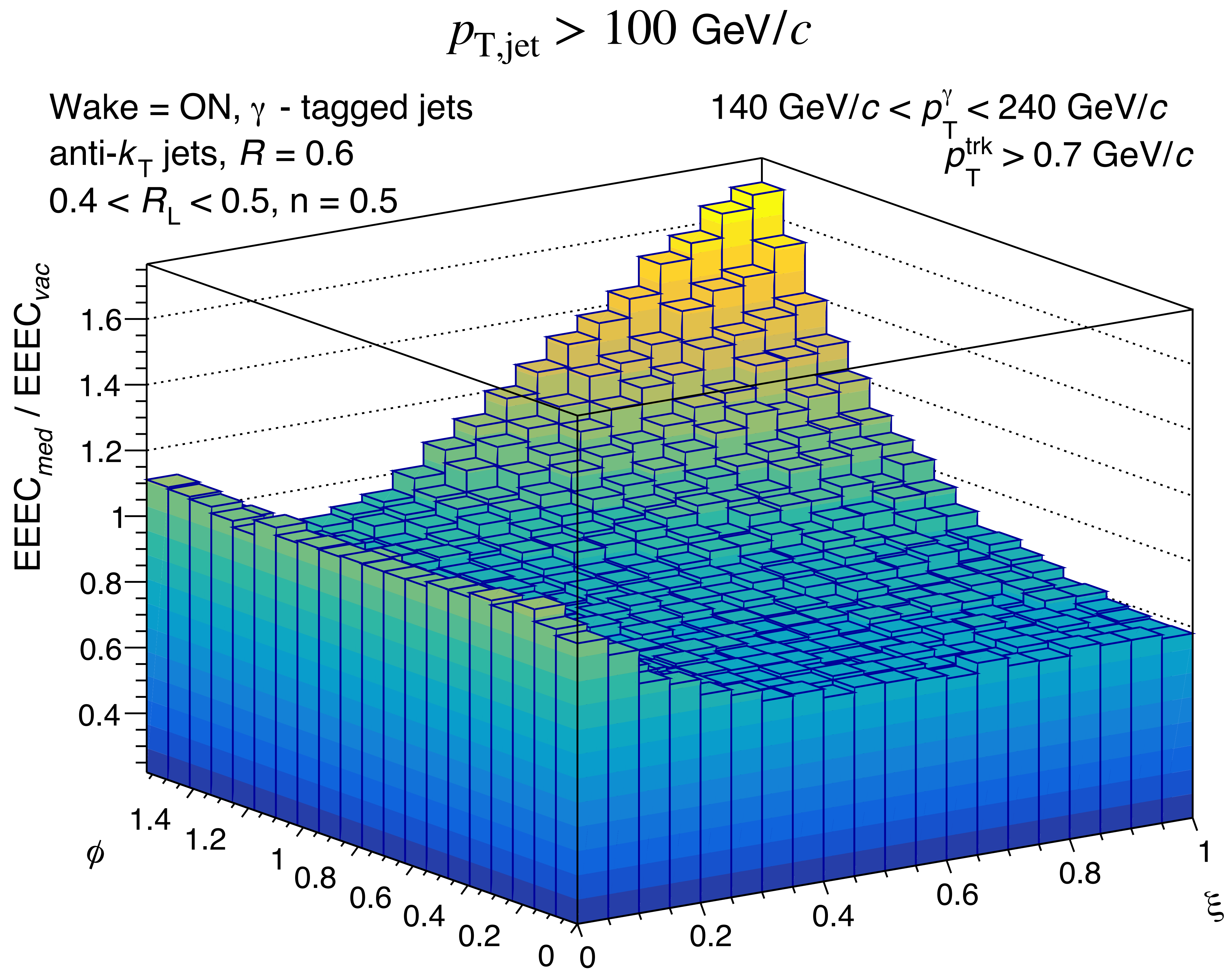
Inclusive Sample



γ-tagged Sample

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

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)]

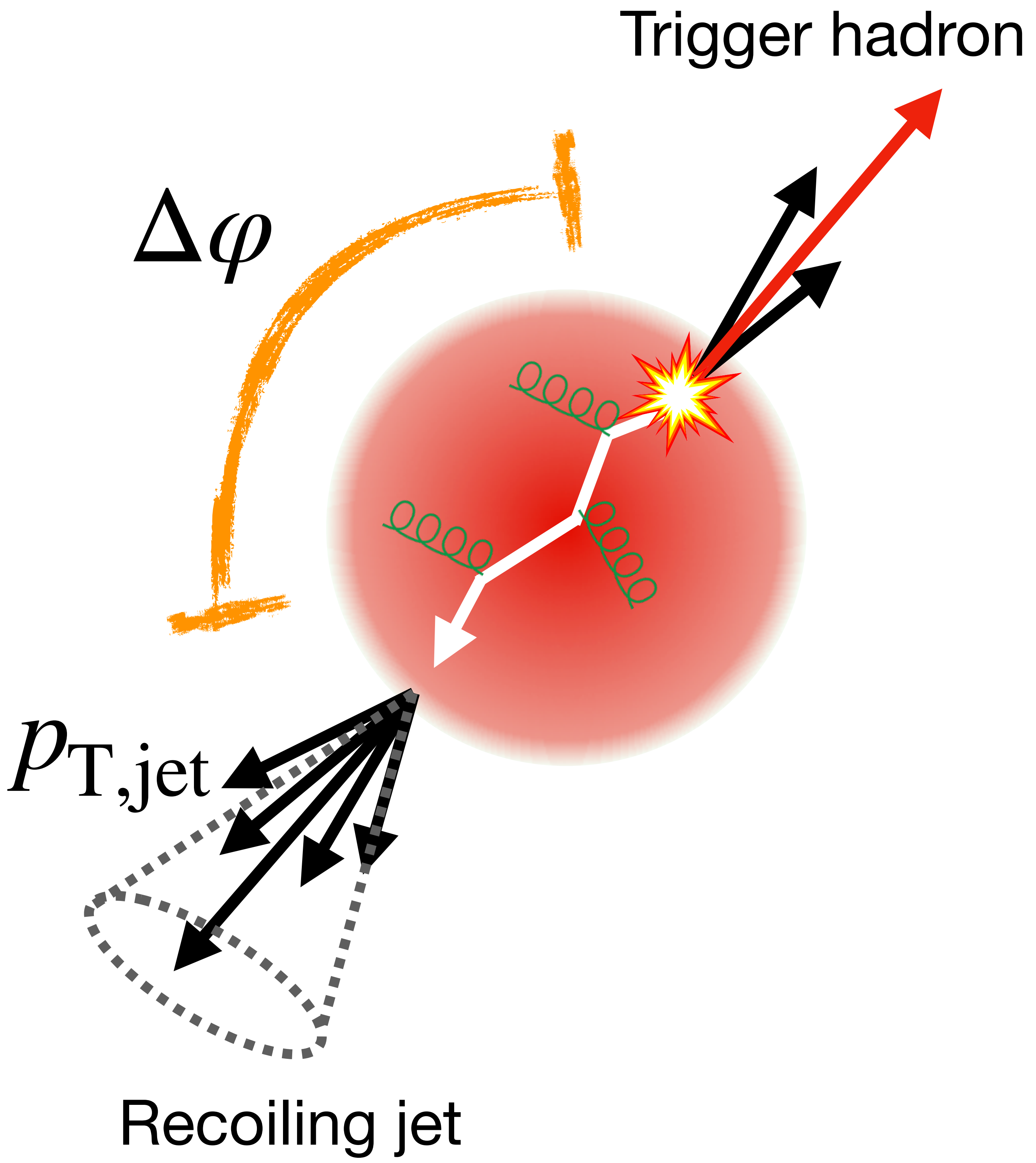
Wake effects still visible even in more realistic experimental environment!

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

Analysis procedure

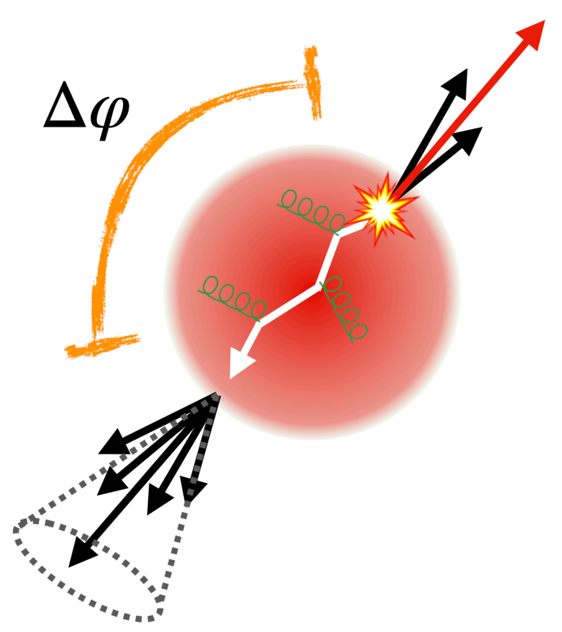
1. **Select events** based on the **presence of a high-p_T 'trigger' hadron**
2. **Do jet reconstruction** on these events
3. **Count jets recoiling from the trigger hadron** as function of:
   - opening angle ($\Delta\varphi$) of jet relative to trigger axis
   - transverse momentum ($p_\mathrm{T,jet}$) of recoil jet
4. **Define observable:**

$$\frac{1}{N_\mathrm{trig}^\mathrm{AA}} \frac{\mathrm{d}^3 N_\mathrm{jet}^\mathrm{AA}}{\mathrm{d}p_\mathrm{T,jet}^\mathrm{ch}\mathrm{d}\Delta\varphi\mathrm{d}\eta_\mathrm{jet}}\Bigg|_{p_\mathrm{T,h}\in\mathrm{TT}} = \left(\frac{1}{\sigma^{\mathrm{AA}\to\mathrm{h+X}}} \cdot \frac{\mathrm{d}^3\sigma^{\mathrm{AA}\to\mathrm{h+jet+X}}}{\mathrm{d}p_\mathrm{T,jet}^\mathrm{ch}\mathrm{d}\Delta\varphi\mathrm{d}\eta}\right)\Bigg|_{p_\mathrm{T,h}\in\mathrm{TT}}$$



- **Perturbatively calculable**
  Ratio between high-p_T hadron and jet production cross sections
- **Semi-inclusive**
  events selected based on presence of trigger → count all recoil jets in defined acceptance

$\Delta_{\mathrm{recoil}}(\Delta\varphi)$ distributions in pp and Pb-Pb collisions

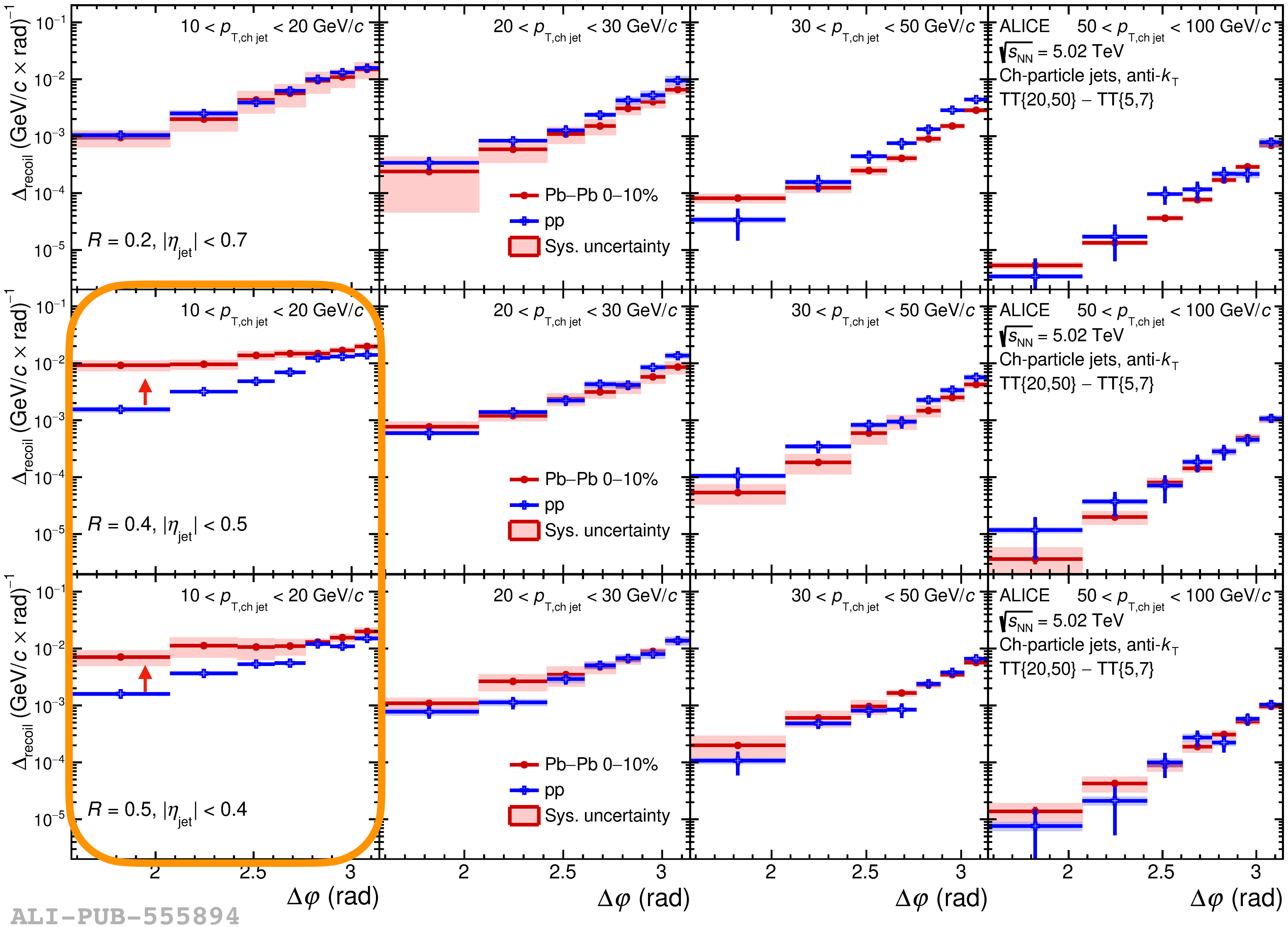


$p_{\mathrm{T,ch\,jet}}$: **[10,20] GeV/c** **[20,30] GeV/c** **[30,50] GeV/c** **[50,100] GeV/c**

***R*=0.2**

***R*=0.4**

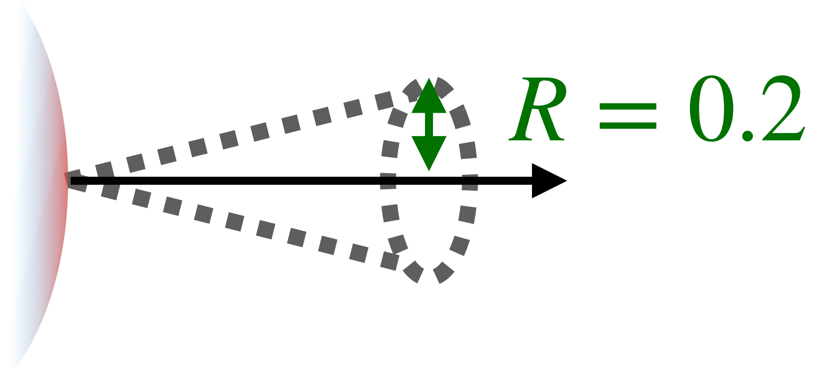
***R*=0.5**



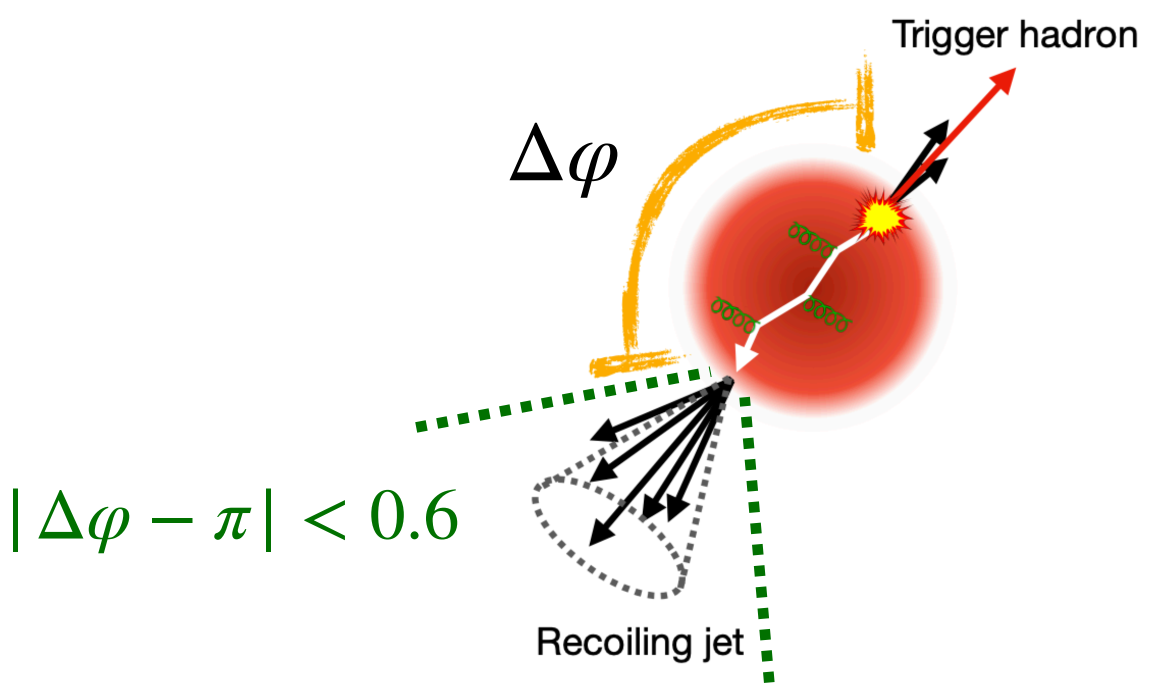
ALI-PUB-555894

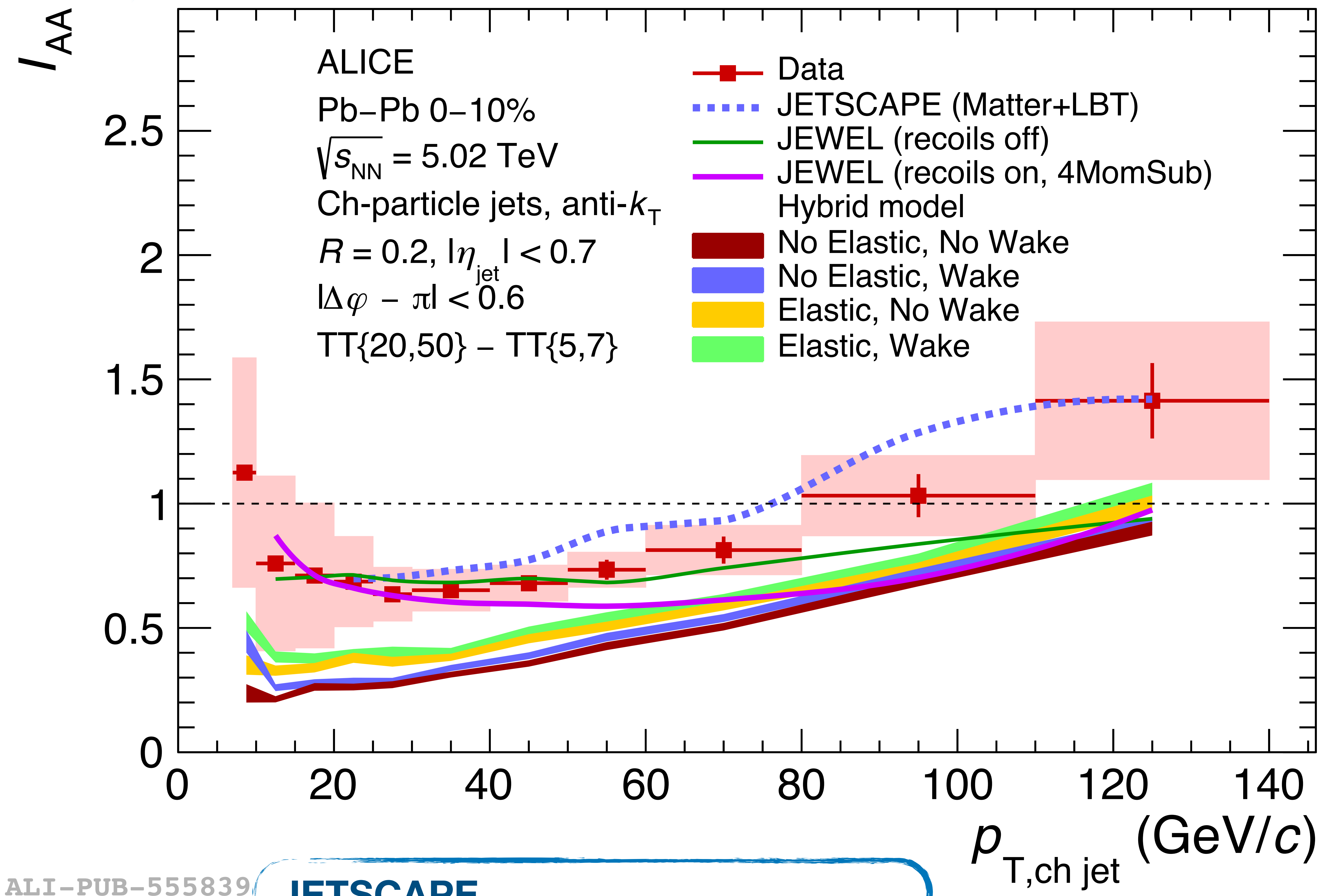
- **Significant azimuthal broadening** for R=0.4 and R=0.5 at low $p_{\mathrm{T,ch\,jet}}$

$I_{\mathrm{AA}}(p_{\mathrm{T,ch\,jet}})$ - recoil jet yield modification in Pb-Pb collisions



$$I_{\mathrm{AA}} = \frac{\Delta_{\mathrm{recoil}}(\mathrm{Pb-Pb})}{\Delta_{\mathrm{recoil}}(\mathrm{pp})}$$





ALI-PUB-555839

- **Suppression** at 20 < $p_{\mathrm{T,ch\,jet}}$ < 80 GeV/c
  → jet energy loss
- **Rising trend with $p_{\mathrm{T,ch\,jet}}$**
  → interplay between hadron and jet energy loss?
  Less trigger surface bias when $p_{\mathrm{T,jet}} >> p_{\mathrm{T,trig}}$?
- Models (Hybrid, JETSCAPE) capture rising trend
- JEWEL describes low-$p_{\mathrm{T,jet}}$ I_{AA}

JETSCAPE

Energy loss based on MATTER (high virtuality) and LBT (low virtuality)

JETSCAPE, Phys. Rev. C 107, 034911

JEWEL

Medium response effects via treatment of 'recoils'

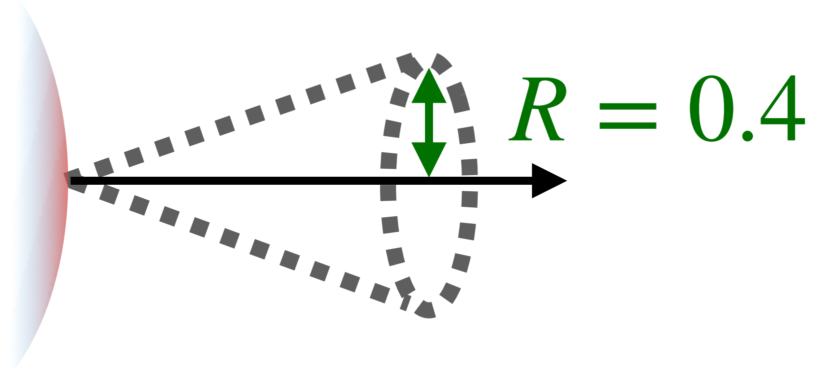
K. Zapp, EPJ C, Volume 74, Issue 2, 2014
R. Elanavalli, K. Zapp, JHEP 1707 (2017) 141

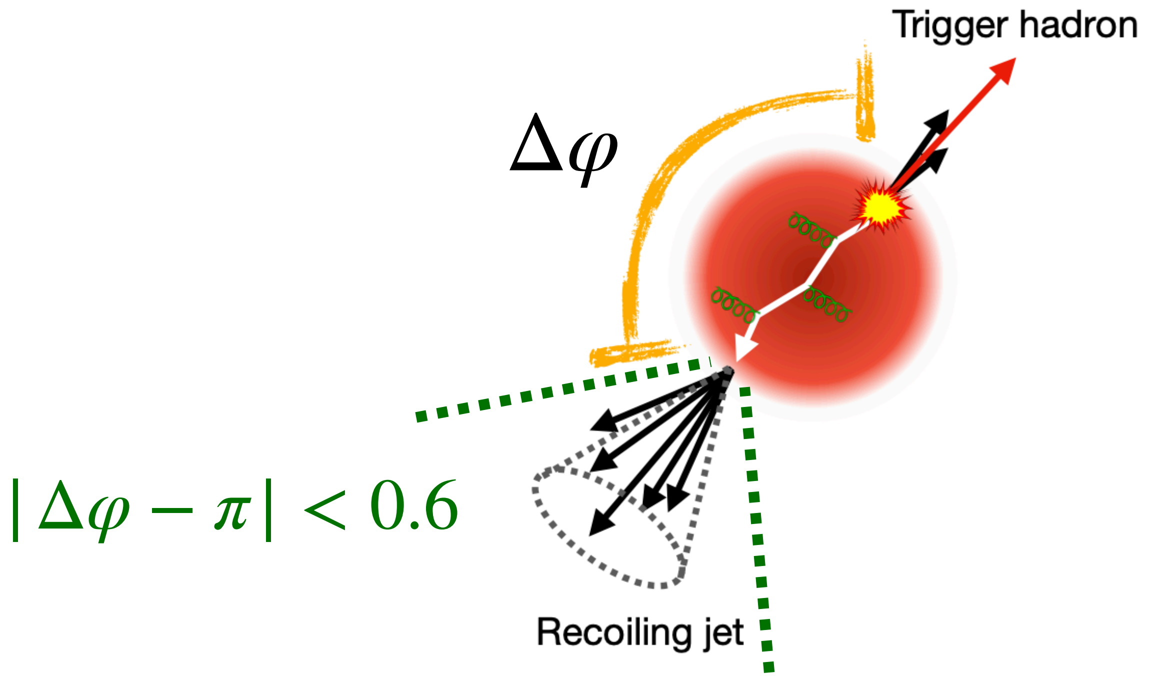
Hybrid model

Elastic (Moliére) scatterings and wake (medium response) included

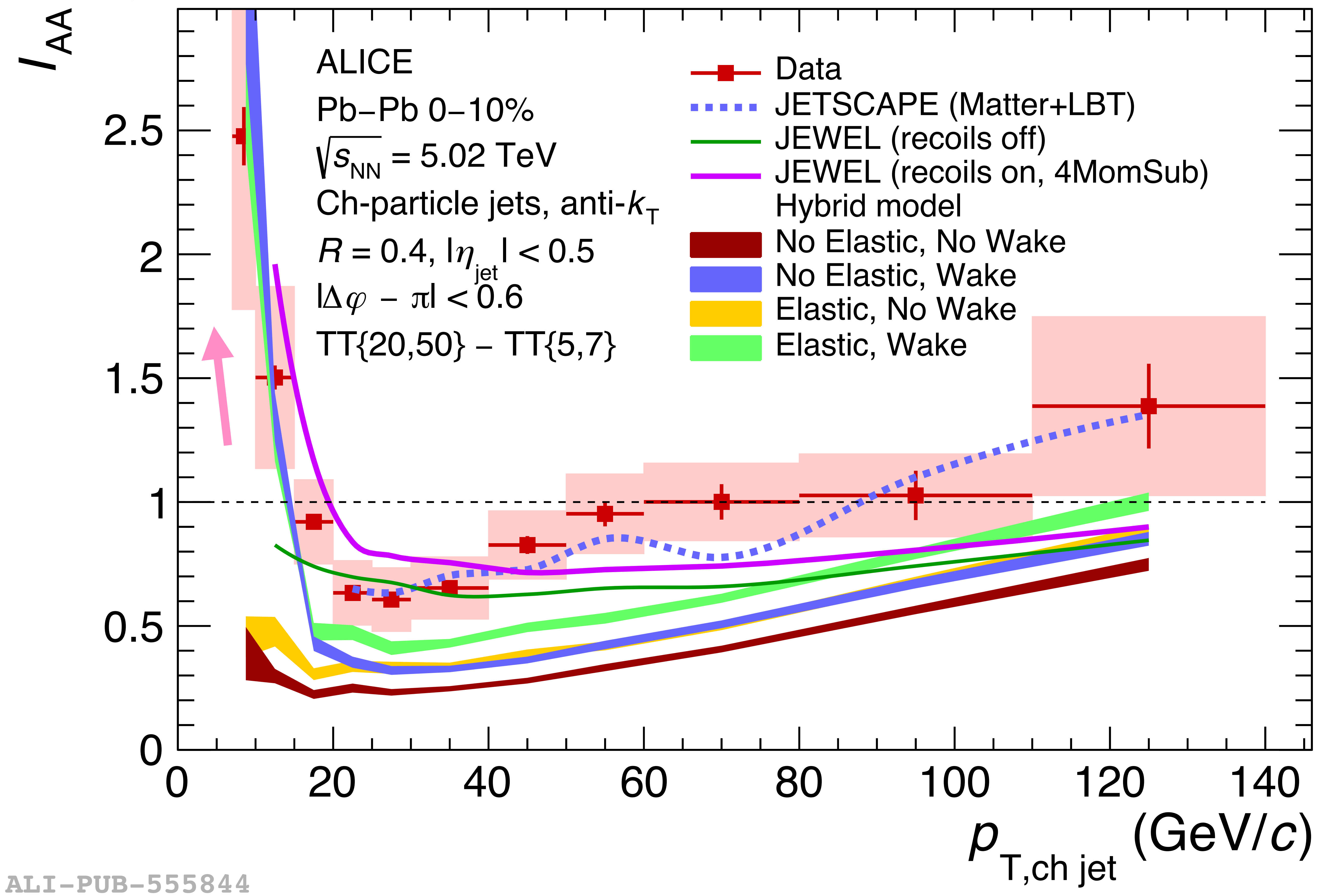
F. d'Eramo, K. Rajagopal, Y. Yin, *JHEP* 01 (2019) 172
Z. Hulcher, D. Pablos, K. Rajagopal, 2208.13593 (QM22)

$I_{\mathrm{AA}}(p_{\mathrm{T,ch\,jet}})$ - recoil jet yield modification in Pb-Pb collisions





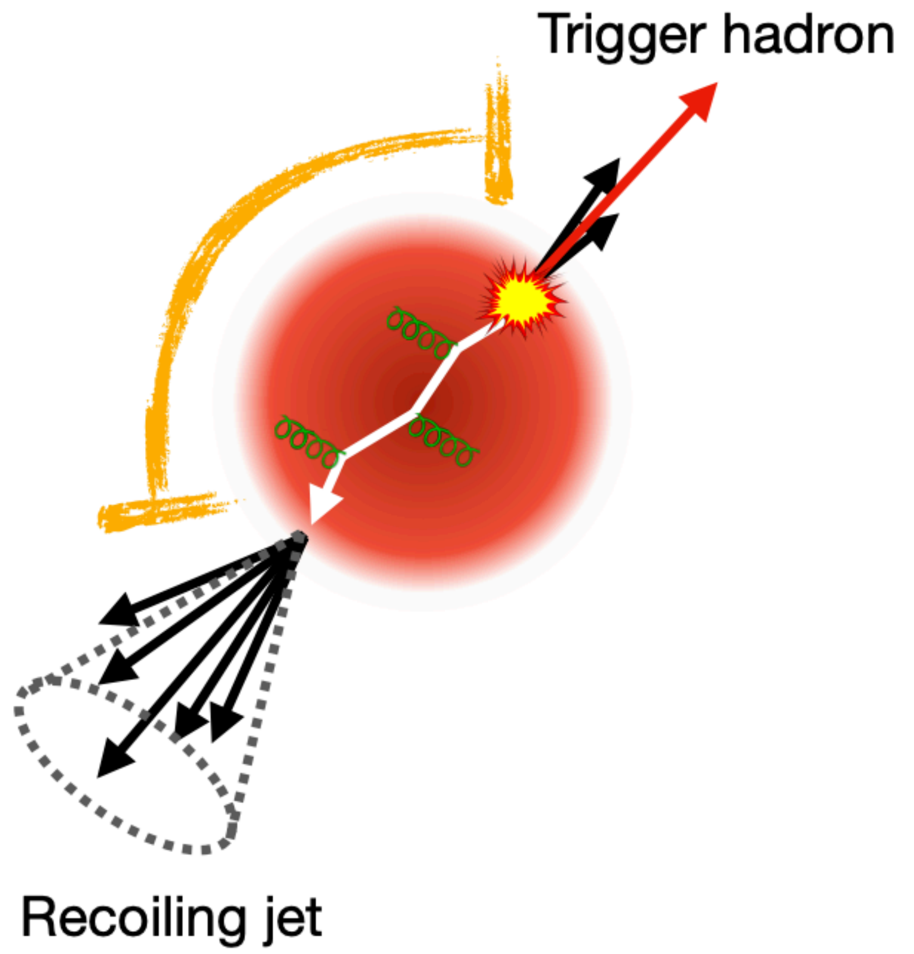
$$I_{\mathrm{AA}} = \frac{\Delta_{\mathrm{recoil}}(\mathrm{Pb-Pb})}{\Delta_{\mathrm{recoil}}(\mathrm{pp})}$$

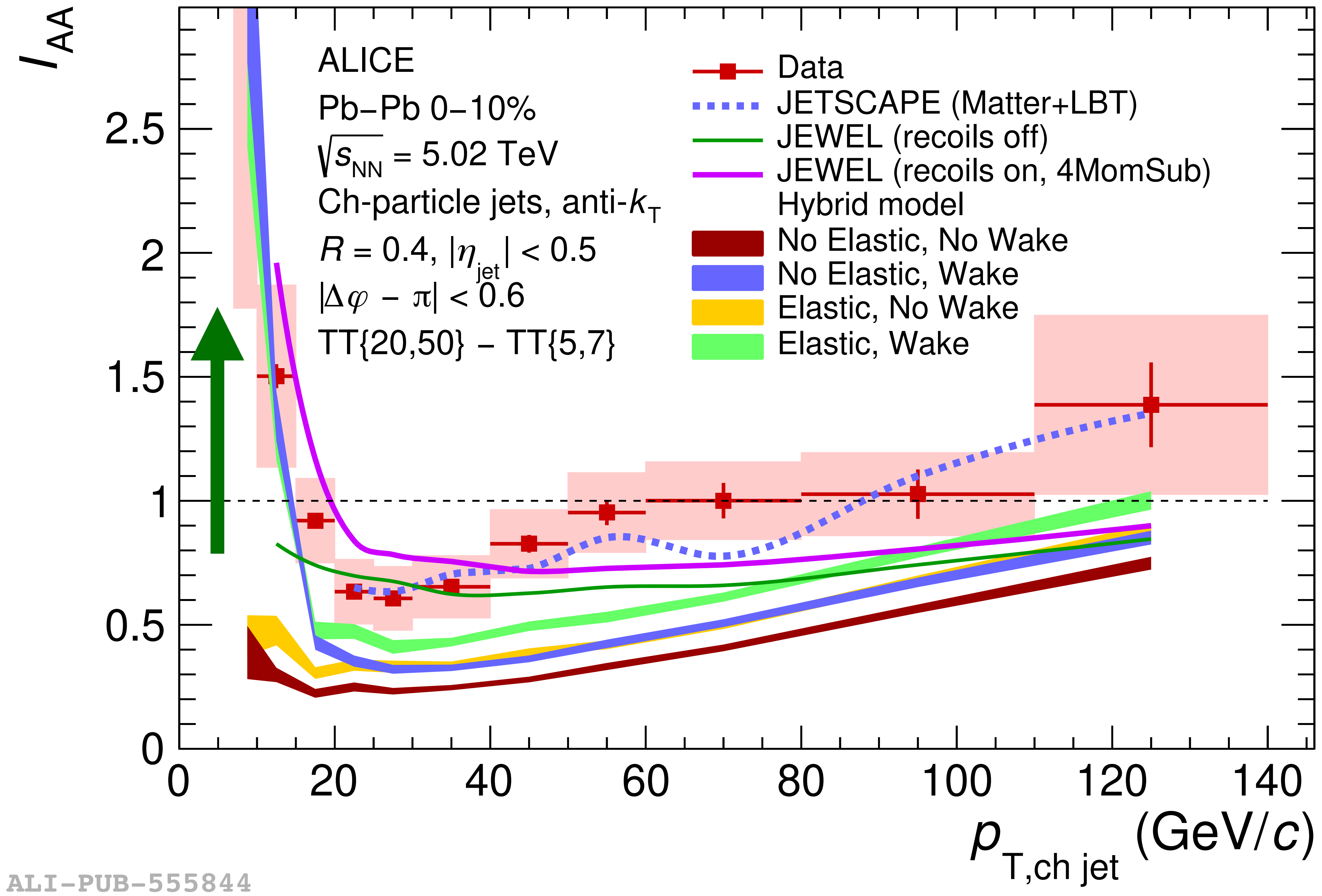


ALI-PUB-555844

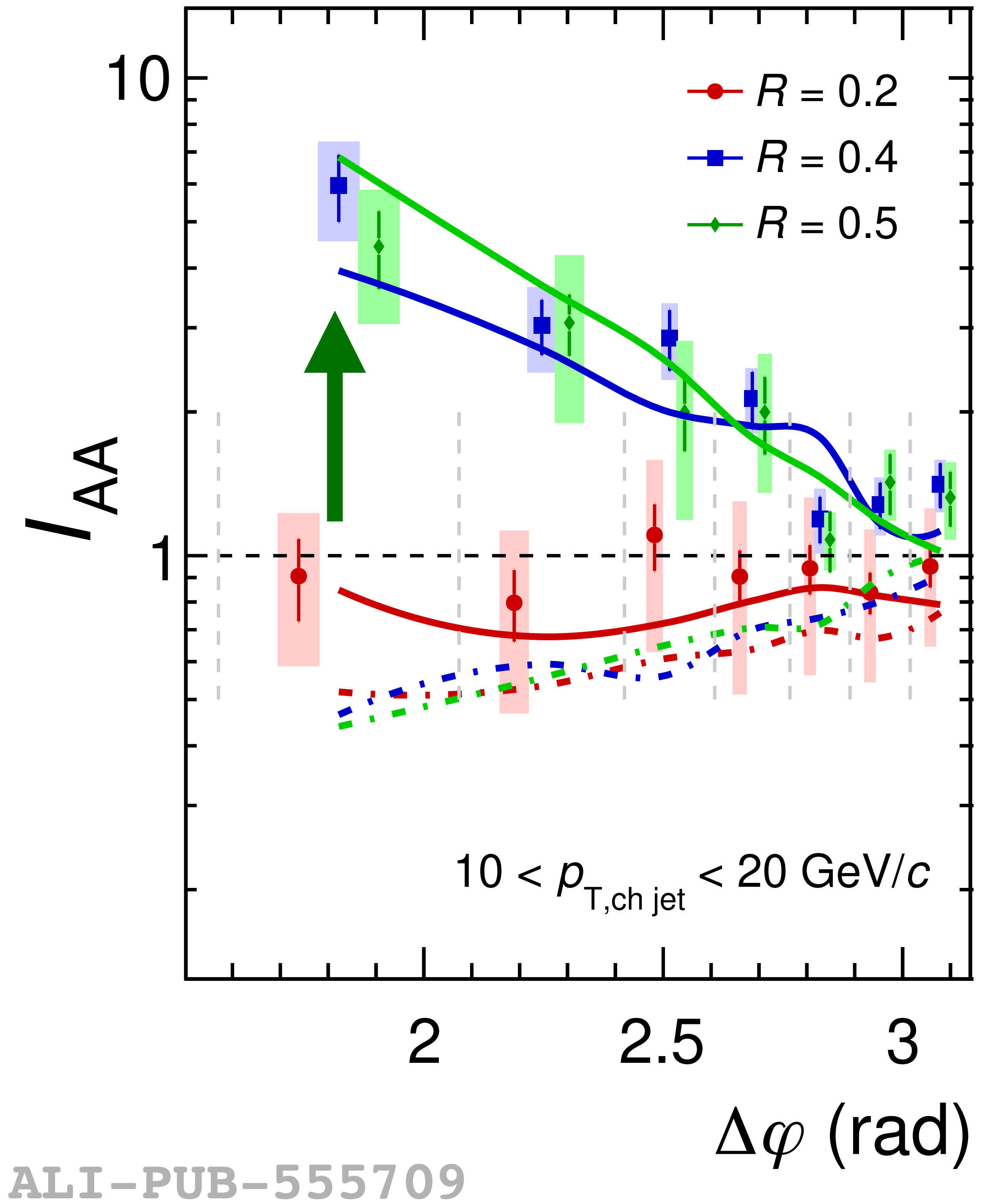
- **Suppression** at 20 < $p_{\mathrm{T,ch\,jet}}$ < 80 GeV/c
  → jet energy loss
- **Rising trend with $p_{\mathrm{T,ch\,jet}}$**
  → interplay between hadron and jet energy loss?
  Less trigger surface bias when $p_{\mathrm{T,jet}} >> p_{\mathrm{T,trig}}$?
- **Rise at low $p_{\mathrm{T,ch\,jet}}$**
  → Energy recovery? Reproduced by models including medium response

Summary and outlook





ALI-PUB-555844



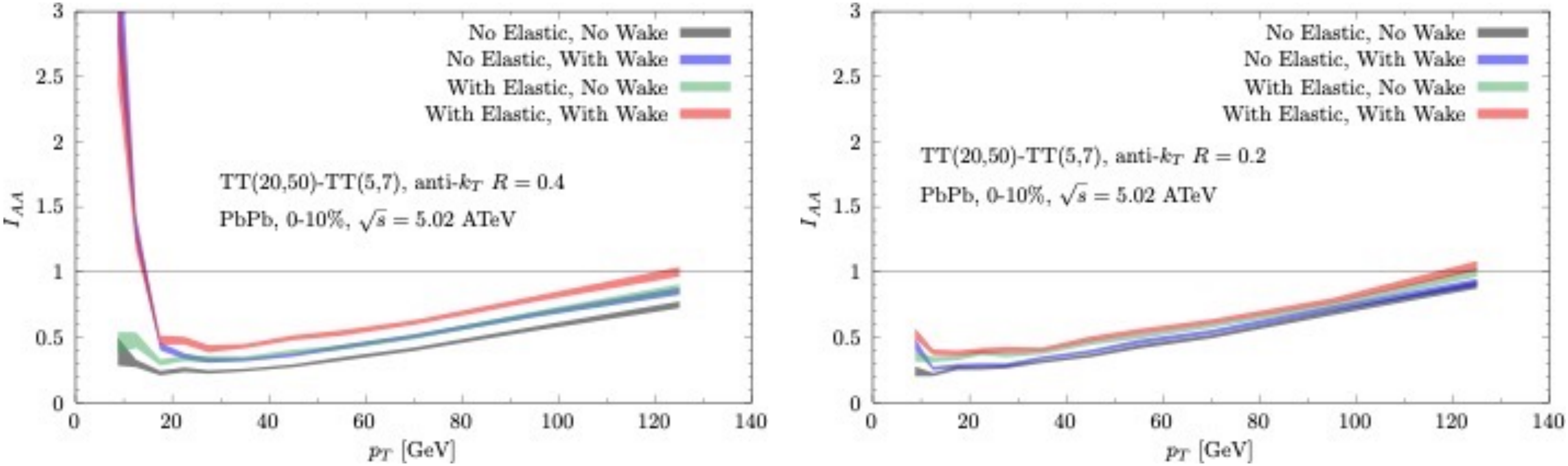
ALI-PUB-555709

- **First observation of significant low-$p_{\mathrm{T,jet}}$ jet yield and large-angle enhancement in Pb-Pb collisions with ALICE!**
- Medium response or medium-induced soft radiation favoured as cause for both measured effects
- Looking forward to further studies with Run 3 data with ALICE after significant upgrade programme

arXiv:2308.16128
arXiv:2308.16131

Hadron—Charge-Jet Acoplanarity, LHC energy

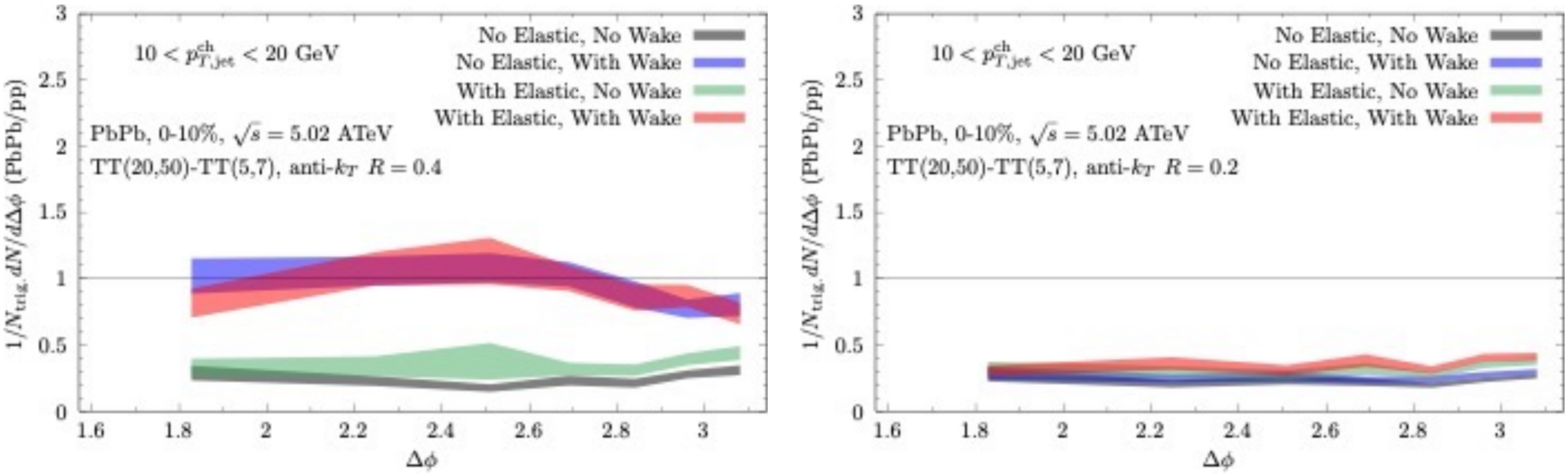
Preliminary



- Study acoplanarity in hadron - charged jet system.
- Parameters similar to ALICE
- Very little effect from Moliere scattering; increase in acoplanarity that we see is almost entirely due to the wake.
- Significant effect caused by the wake seen for R=0.4 jets, not for R=0.2
- I_{AA} indicates effect of wake enhances number of jets at these p_T
- And indeed effect of wake seen only in the lower charged jet p_T bin
- Moliere scattering: jet sprouts added prongs, not much overall deflection

Hadron--Charge-Jet Acoplanarity, LHC energy

Preliminary



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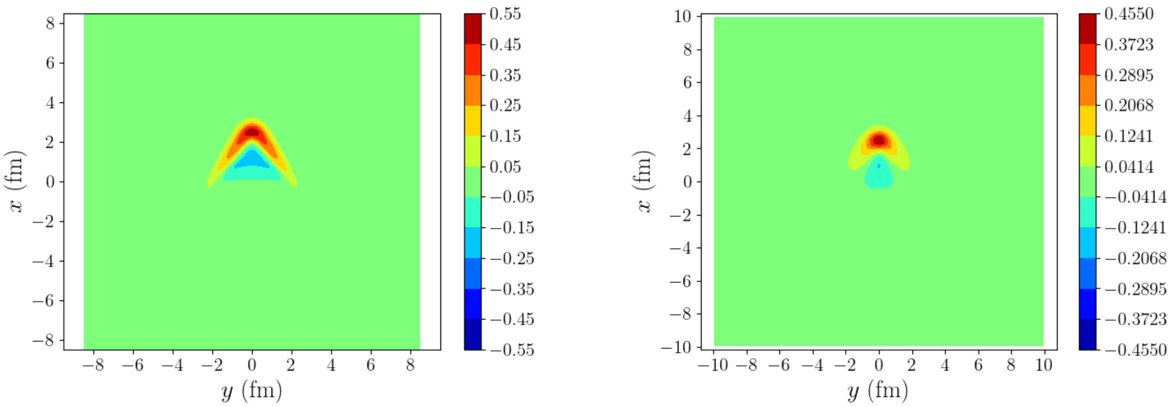
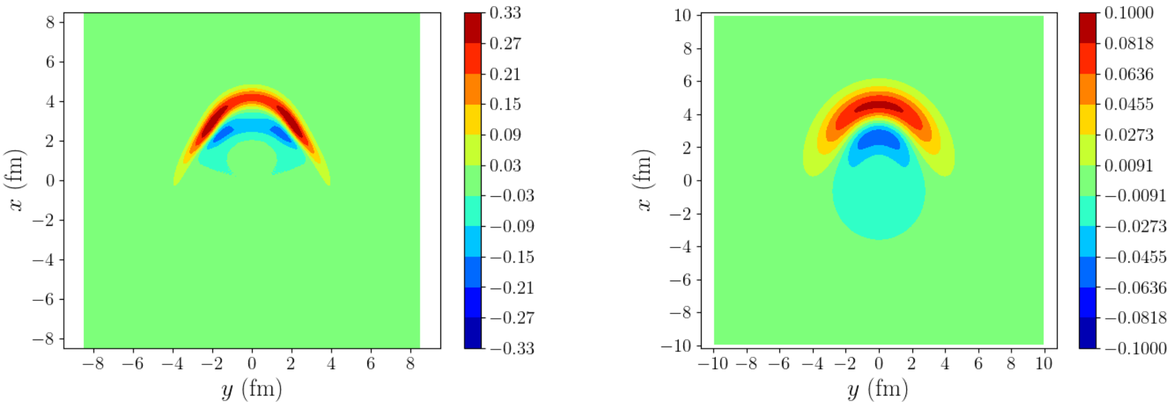


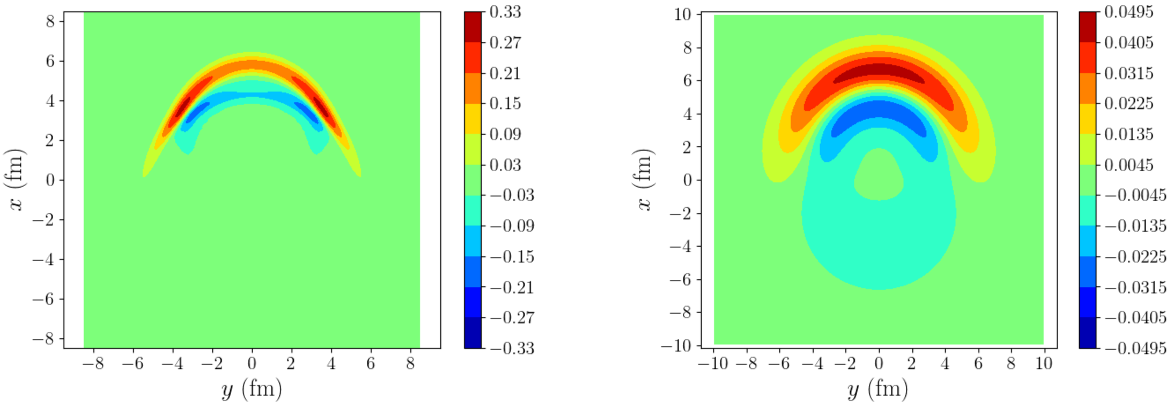
(a) Case 1 (ideal), $\tau = 4.9$ fm/c.

(b) Case 2 (viscous), $\tau = 4.9$ fm/c.



(c) Case 1 (ideal), $\tau = 7.7$ fm/c.

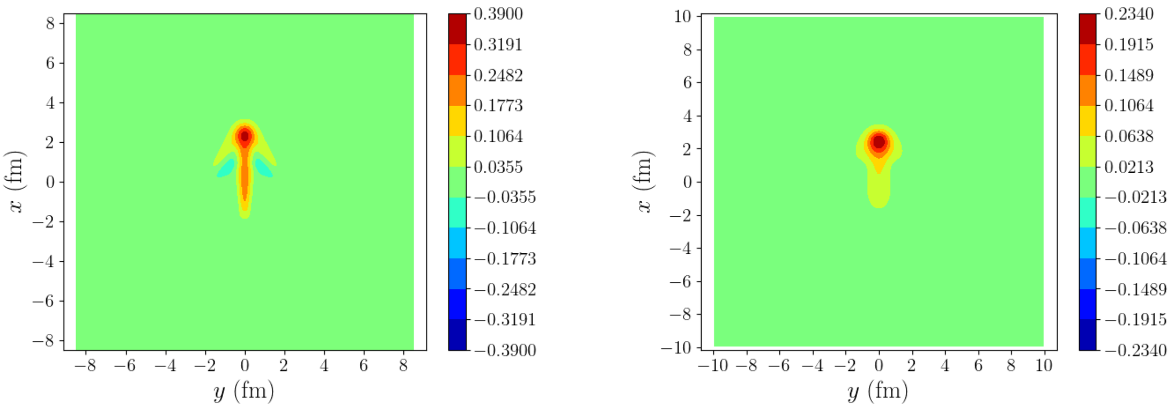
(d) Case 2 (viscous), $\tau = 8.3$ fm/c.



(e) Case 1 (ideal), $\tau = 10.5$ fm/c.

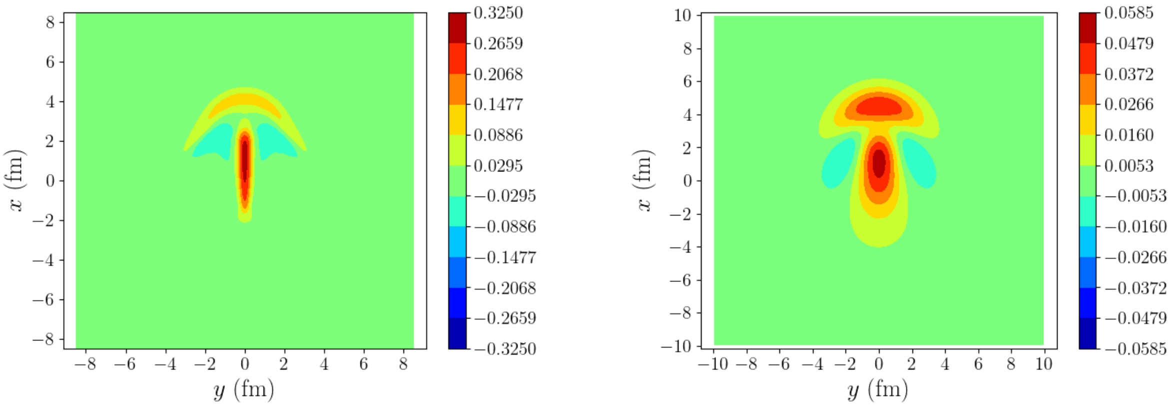
(f) Case 2 (viscous), $\tau = 11.7$ fm/c.

FIG. 4: Plots of $\frac{\delta\varepsilon}{\varepsilon_0}(\eta_s = 0)$ as functions of x and y at three different times τ for Case 1 (ideal fluid; left panels) and 2 (viscous fluid; right panels). Note that we have used different color bars in different panels; assessing the strength of the perturbations (in this and the next two Figures also) requires looking at the color bars to see the magnitudes corresponding to the reddest and bluest colors.



(a) Case 1 (ideal), $\tau = 4.9$ fm/c.

(b) Case 2 (viscous), $\tau = 4.9$ fm/c.



(c) Case 1 (ideal), $\tau = 7.7$ fm/c.

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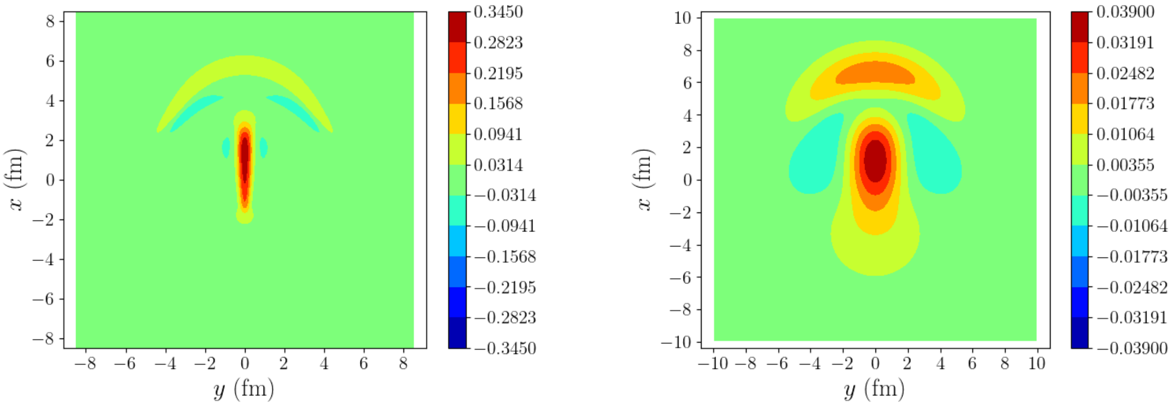

(e) Case 1 (ideal), $\tau = 10.5$ fm/c.

(f) Case 2 (viscous), $\tau = 11.7$ fm/c.

FIG. 5: Plots of $\delta u^x(\eta_s = 0)$ as functions of x and y at three different times τ for Case 1 (ideal fluid; left panels) and 2 (viscous fluid; right panels).