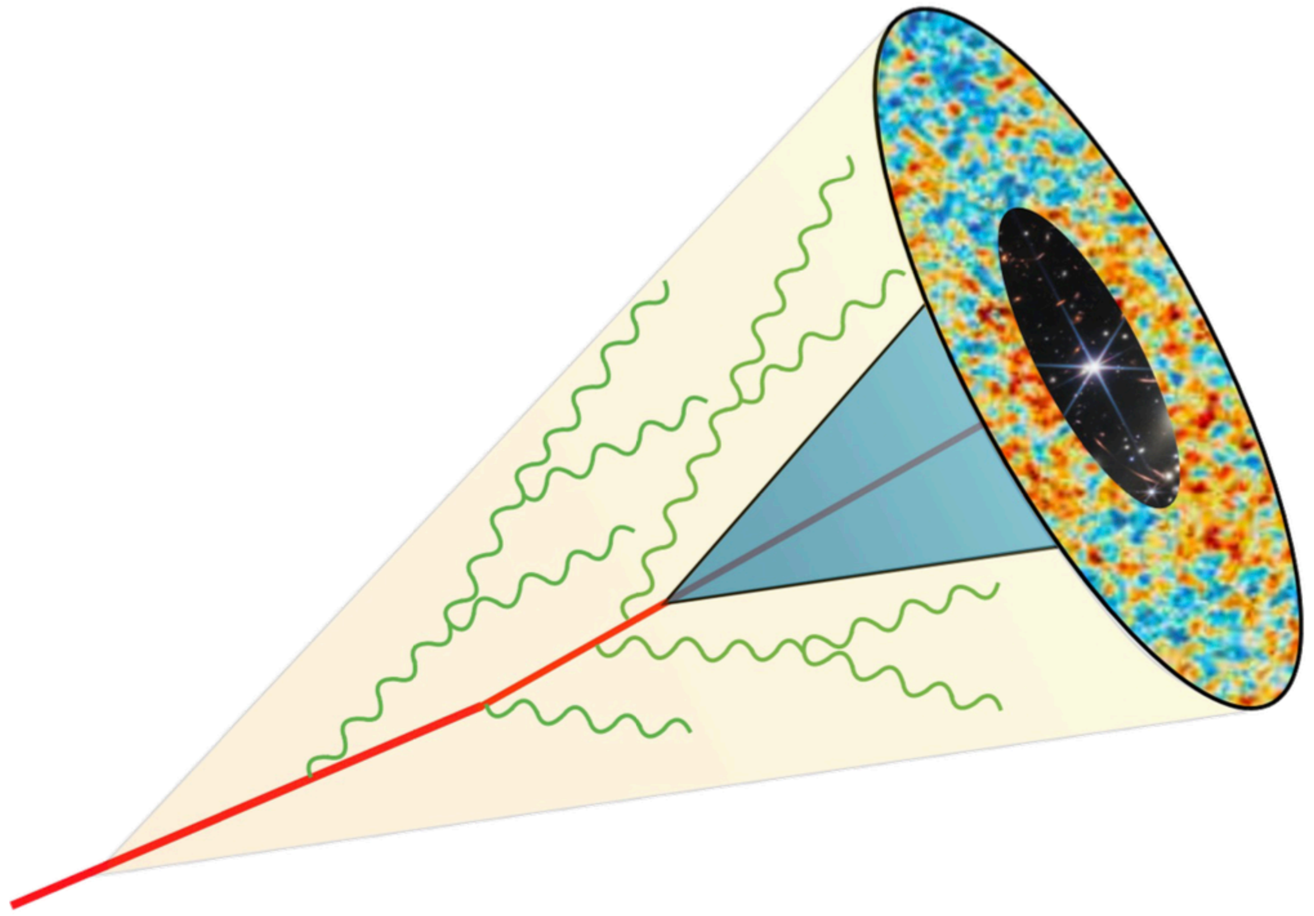
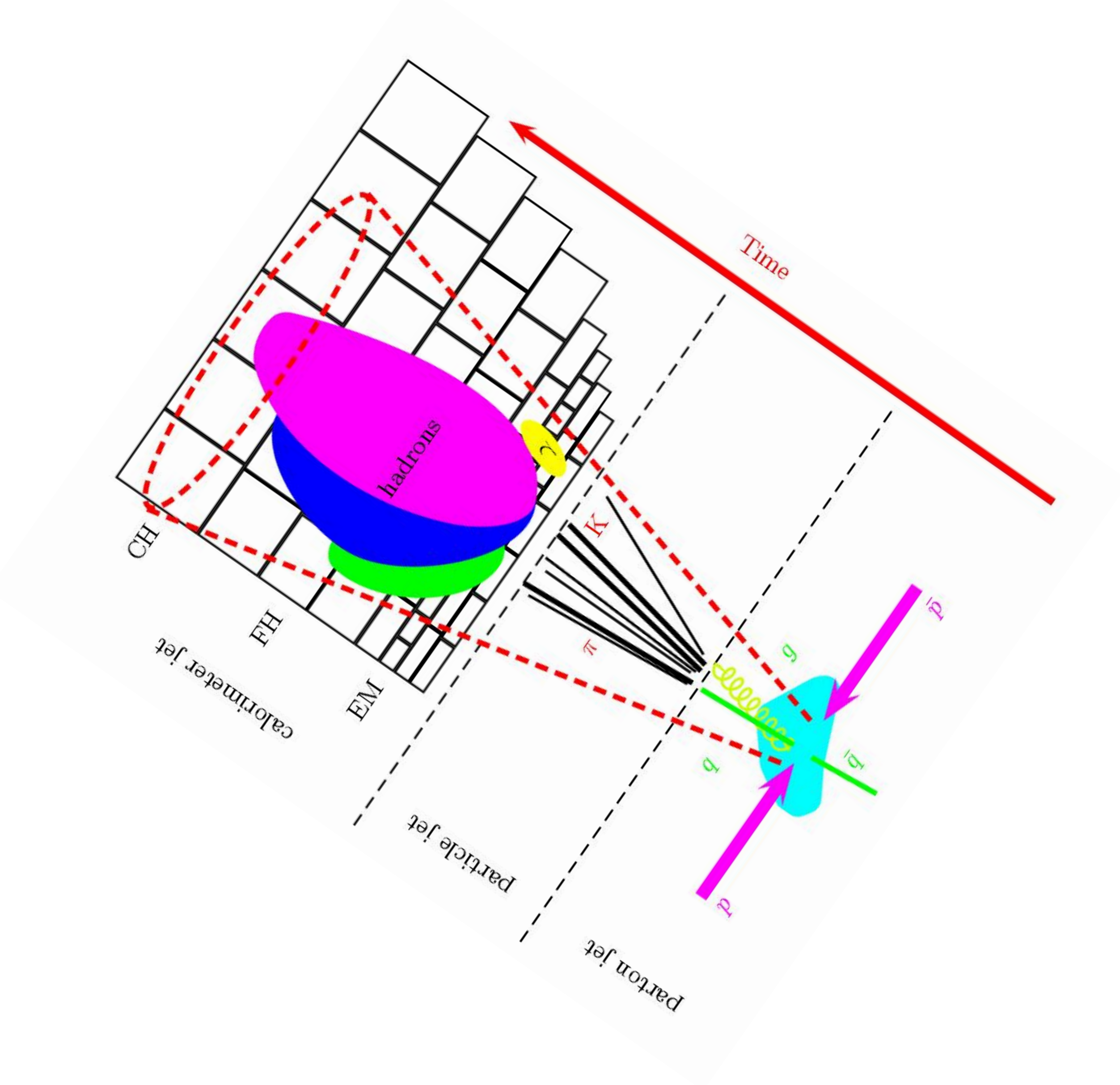
N-point Energy Correlators and why/how we measure them



Raghav (**Rithya**)
Kunnawalkam Elayavalli (she/they)
Vanderbilt University
raghavke.me

NPP Seminar @ BNL, Nov 4th 2025



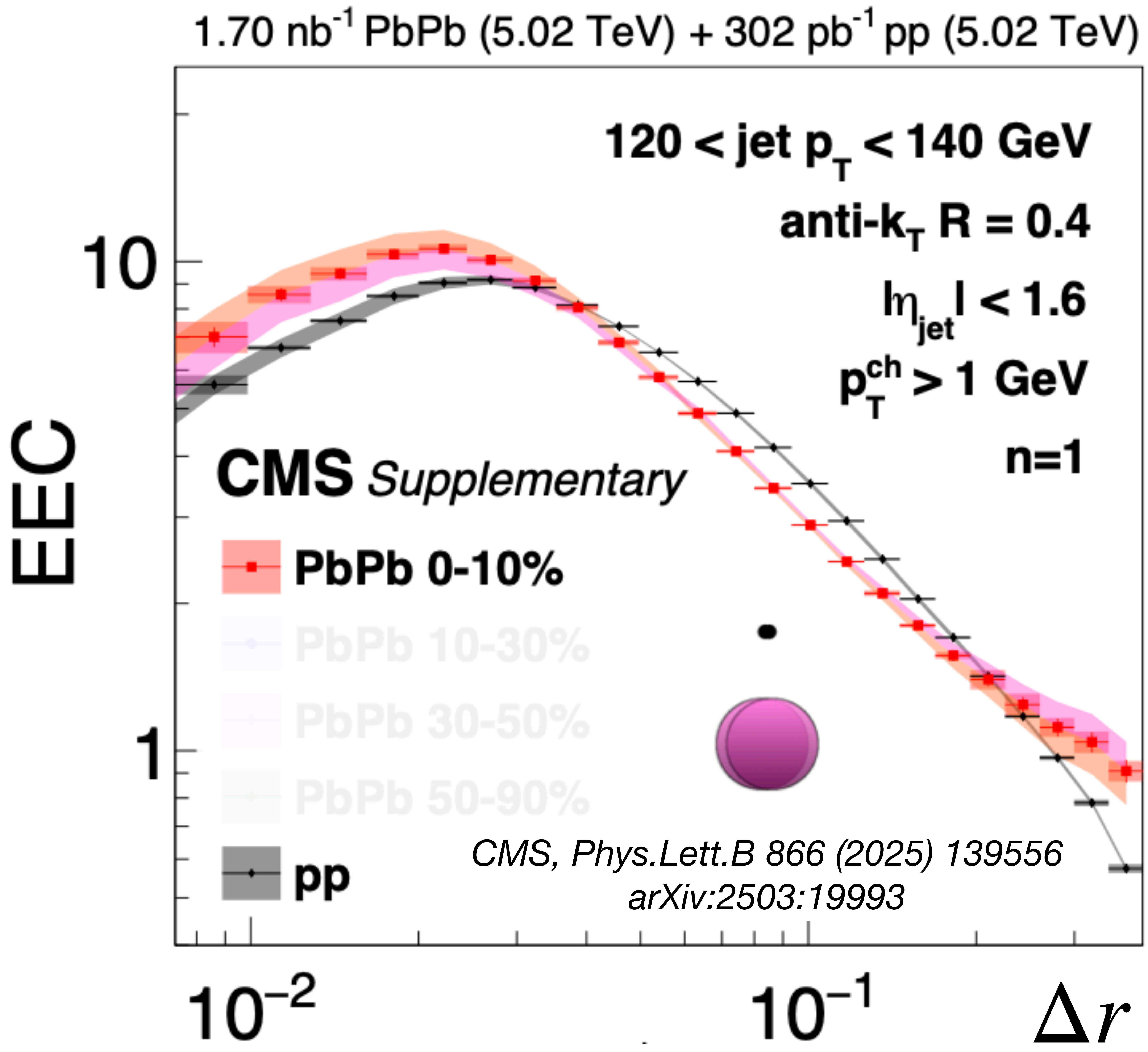
Disclaimer

- This is NOT a theoretical description of what the N-point energy correlators are! - see recent comprehensive review article by Hua Xing Xu and Ian Moult - https://arxiv.org/abs/2506.09119

- Experimental and phenomenology point of view - why should we spend the time to measure something?

- This is evolving! We are learning more about these features and we will see some steps for the future!

- This is also not an exhaustive review of *all* measurements



Plan for today

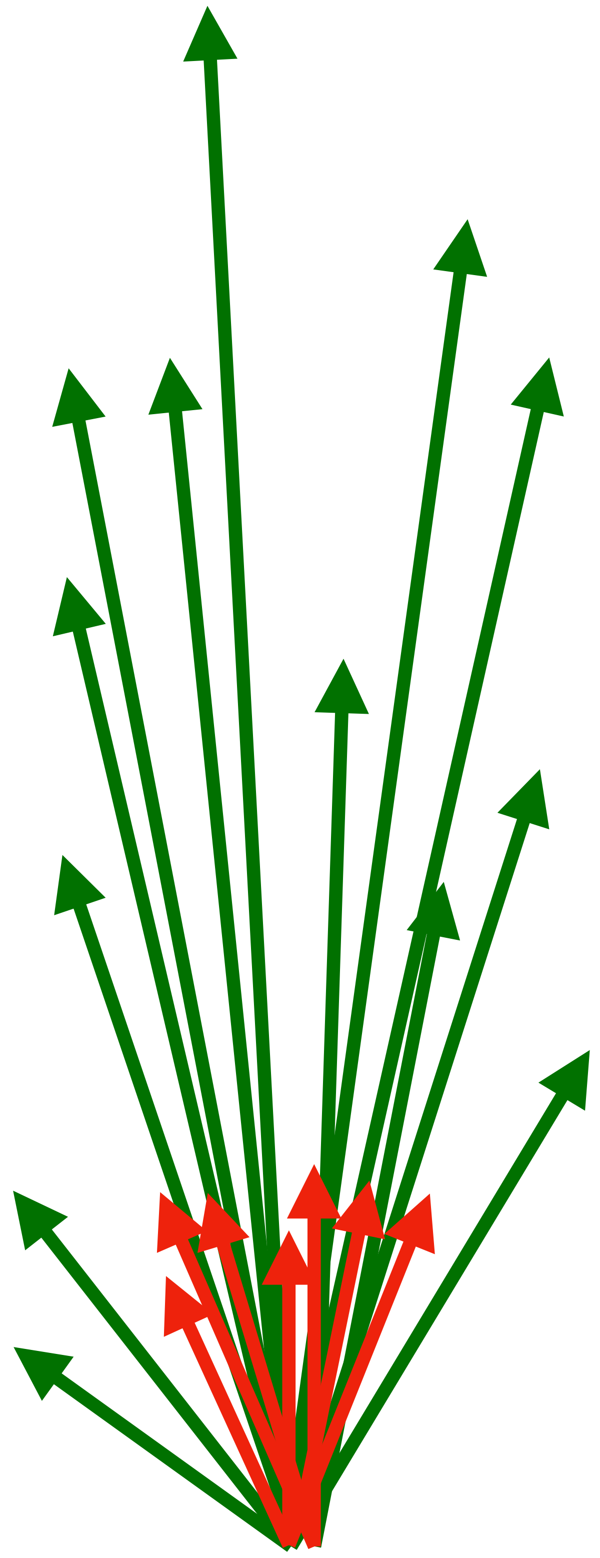
- Why did we do this measurement?
- What are the different feature spaces of this observable?
- How did we do this measurement?
- What have we done to understand what we see?
- What are some next steps?

Projected ENC

$$\text{Normalized EEC} = \frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_i E_j}{{p_{T,Jet}}^2}} \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_i E_j}{{p_{T,Jet}}^2}\right)}{d\,(\Delta R)}$$

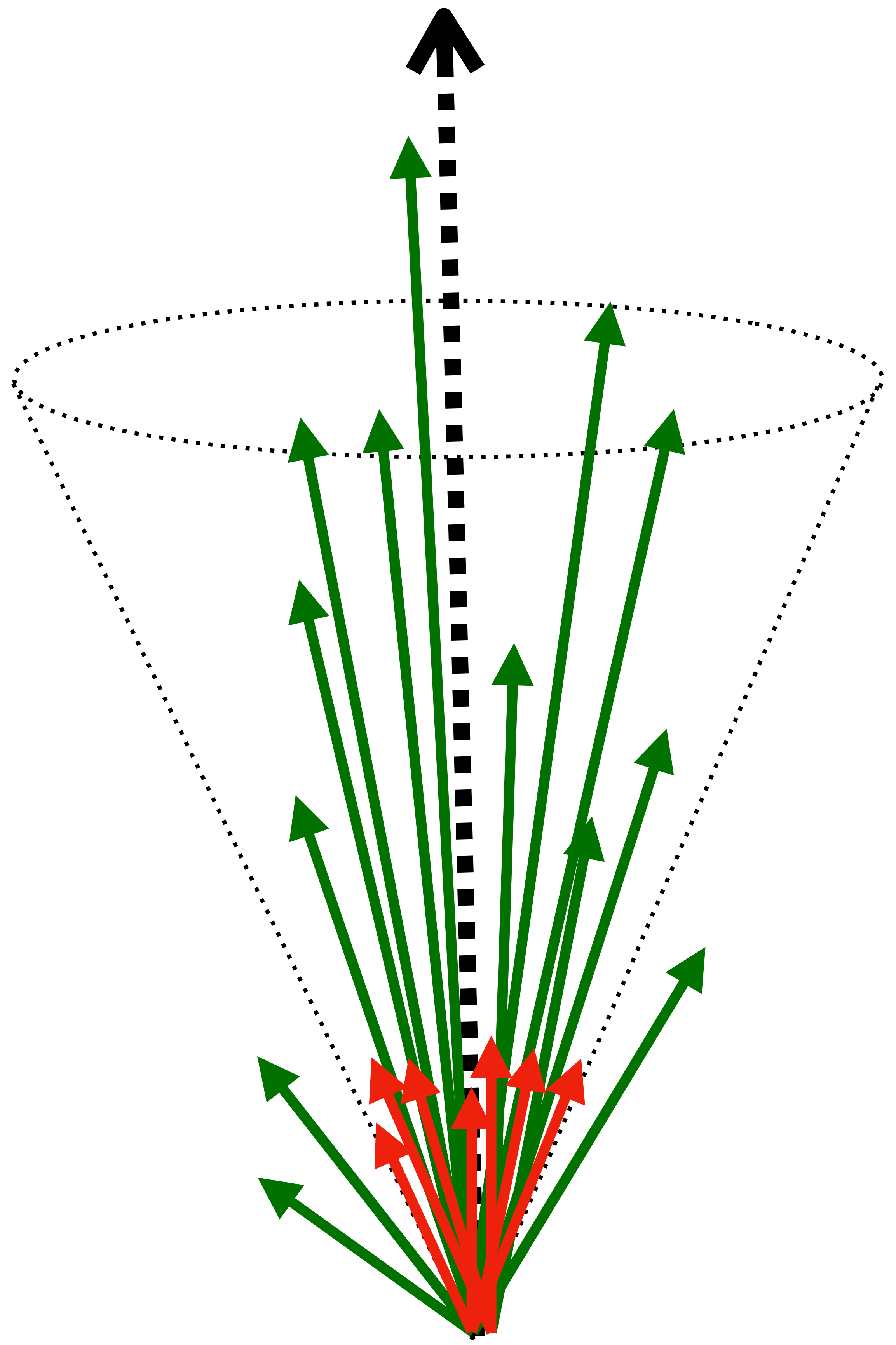
Energy weighted pairwise distance of particles within your jet (or the event!)

How exactly do we plot this?



Step 1 - reconstruct your jets!

How exactly do we plot this?

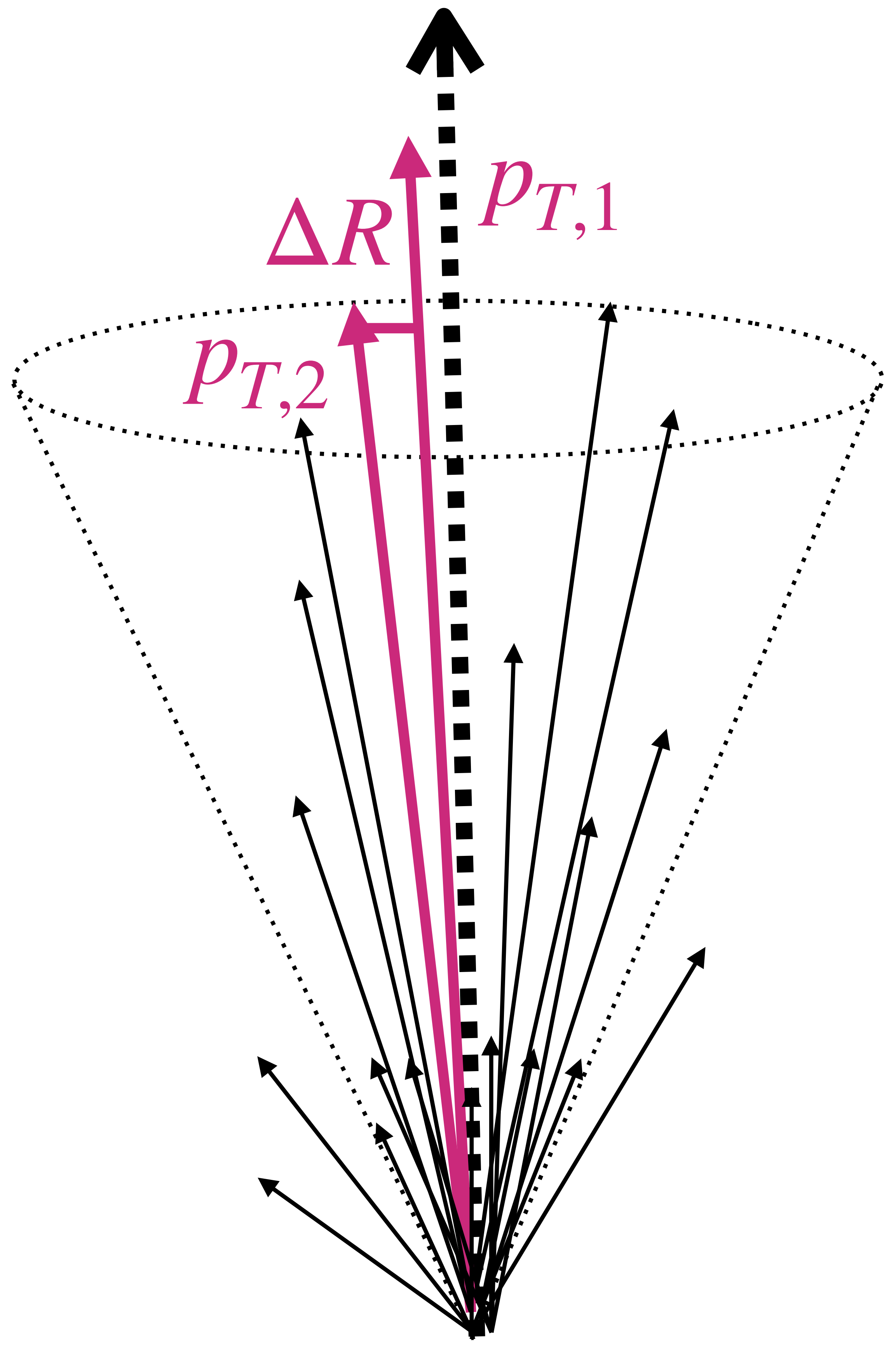


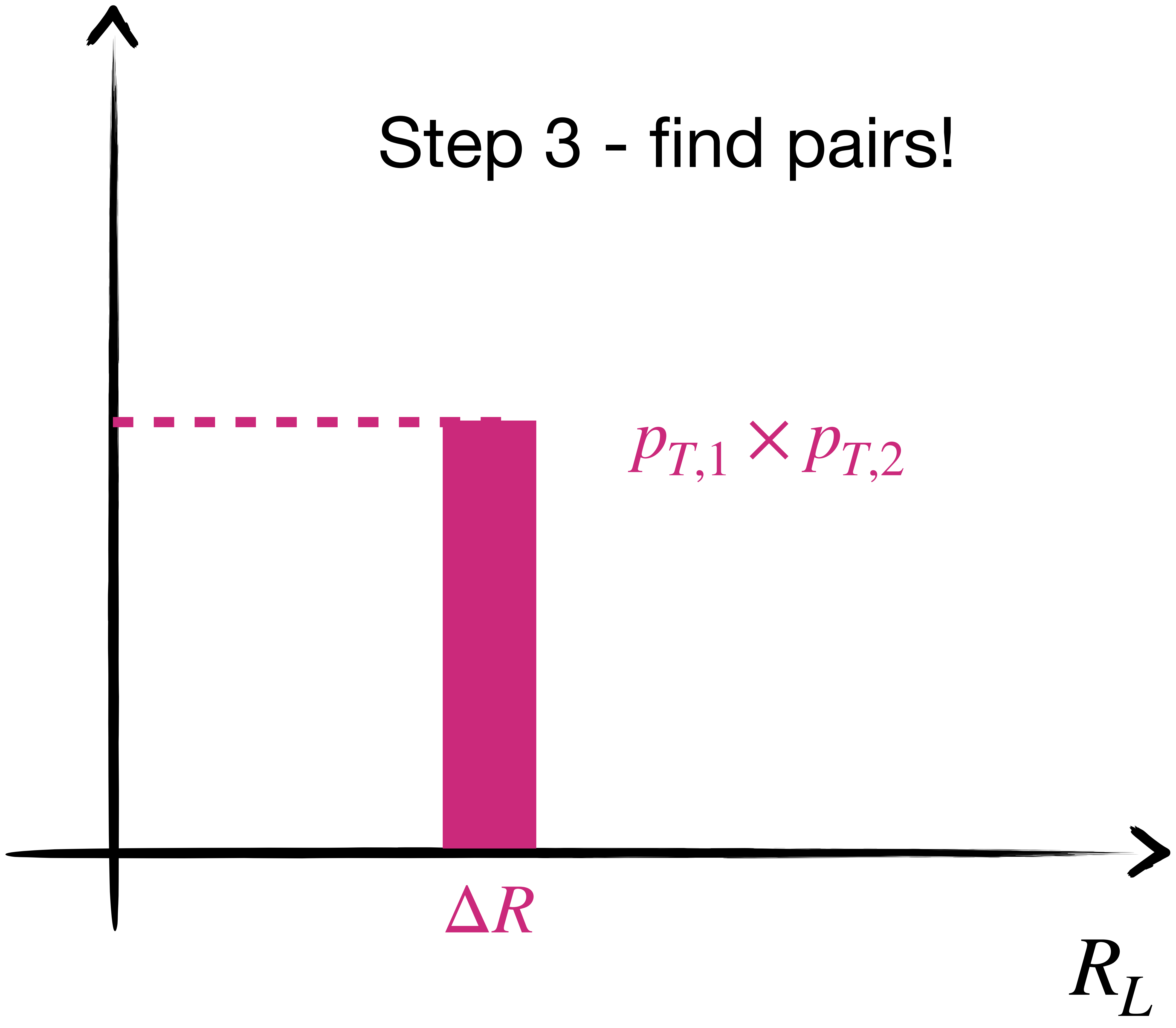
Step 1 - reconstruct your jets!

Step 2a - decide on an axis - jet $\vec{p}$ or WTA

Step 2b - draw a circle around the jet axis
and choose your particles

How exactly do we plot this?





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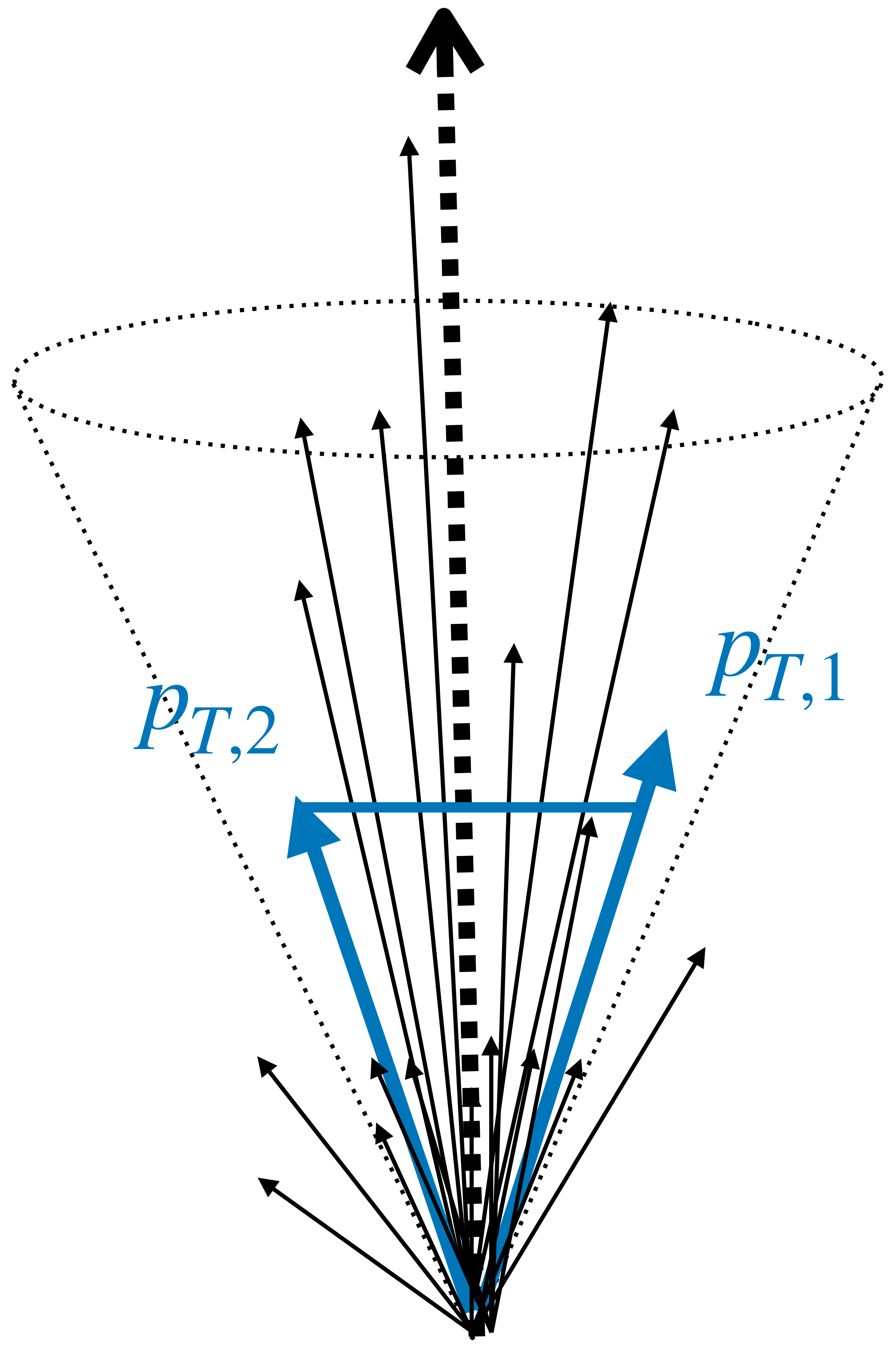
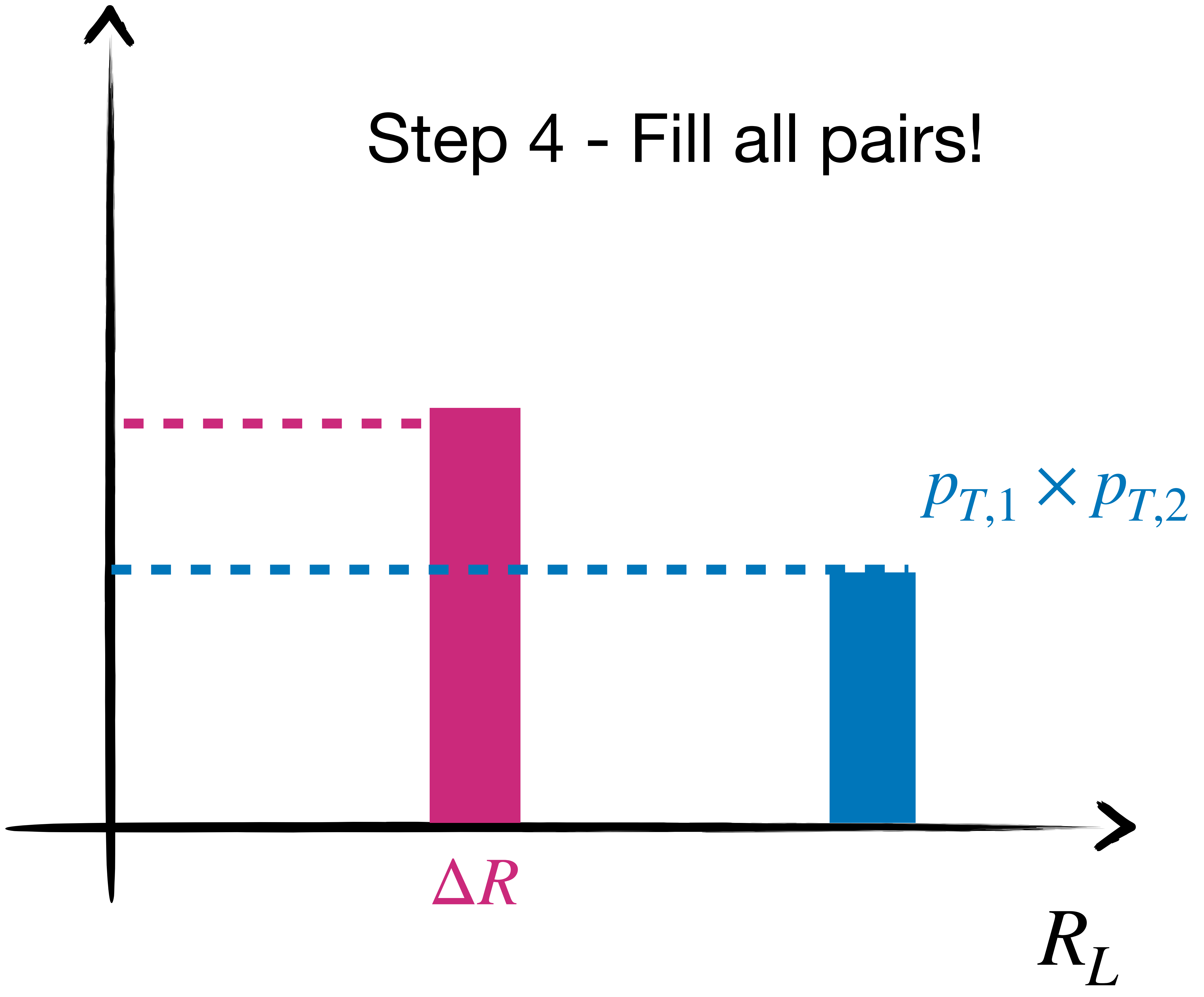




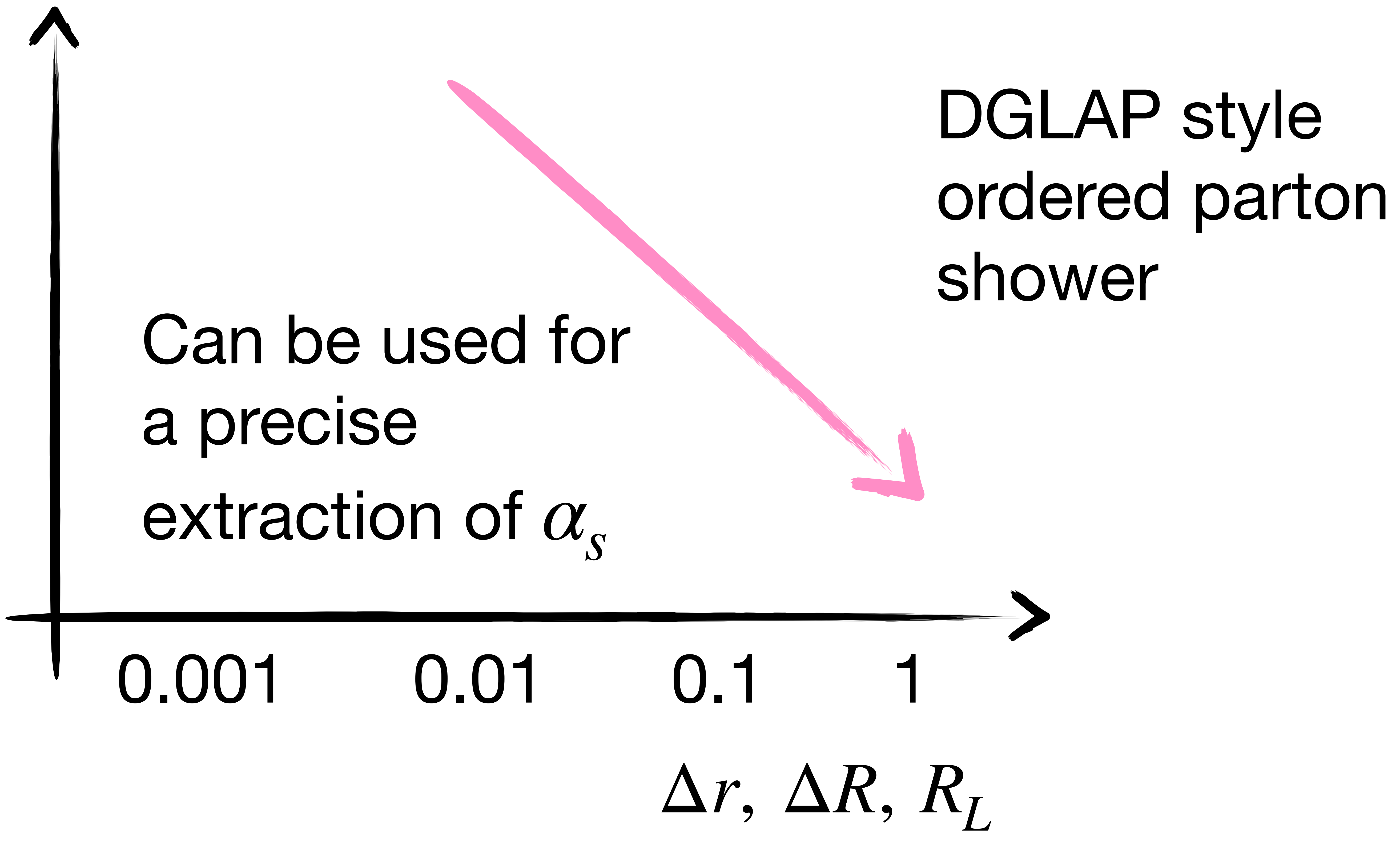
Feature space for projected ENC

$$\text{Normalized EEC} = \frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{p_{T,Jet}{}^2}}\frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_iE_j}{p_{T,Jet}{}^2}\right)}{d\,(\Delta R)}$$

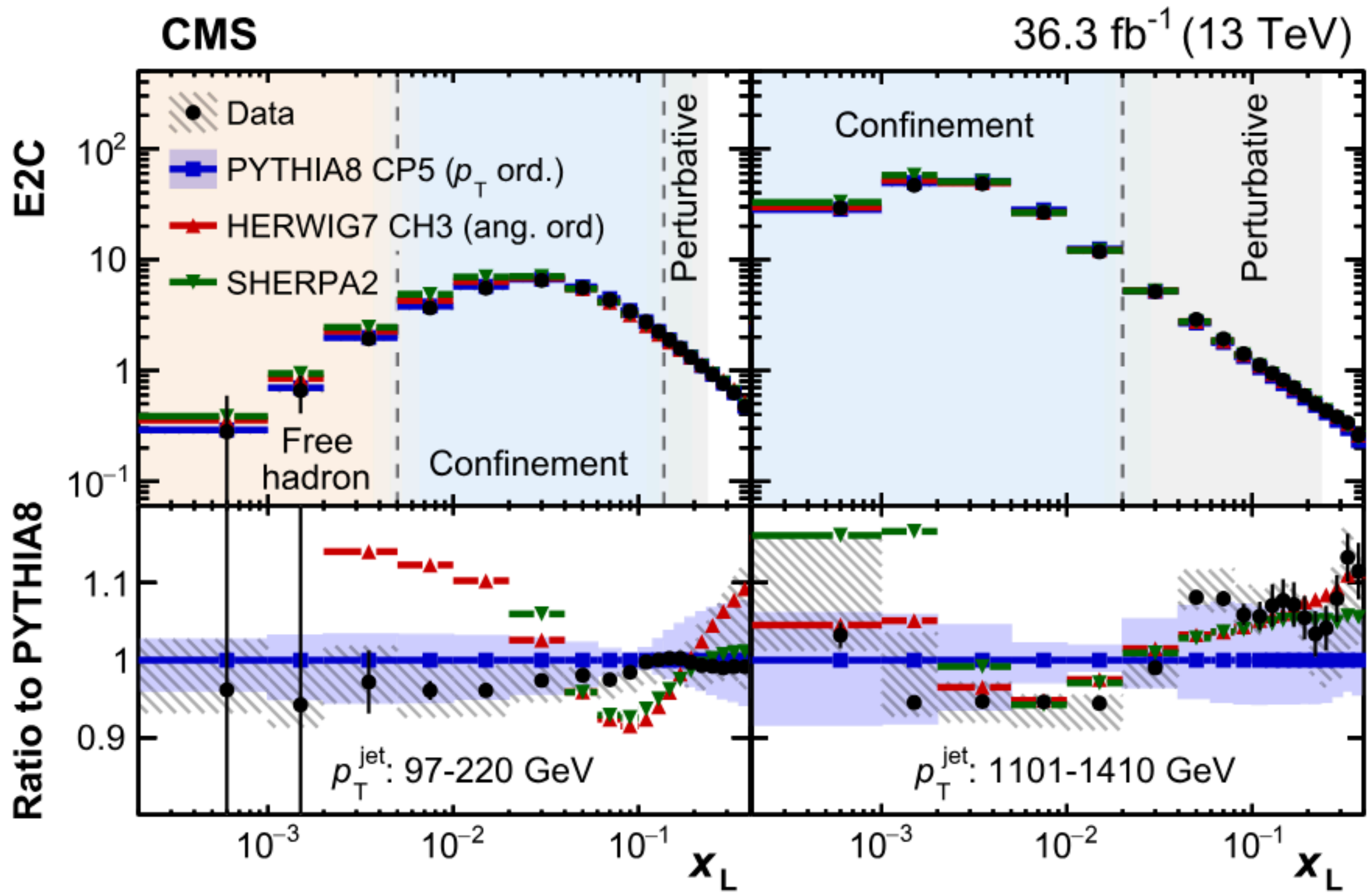
- Energy weighted pairwise distance of particles within your jet (or the event!)

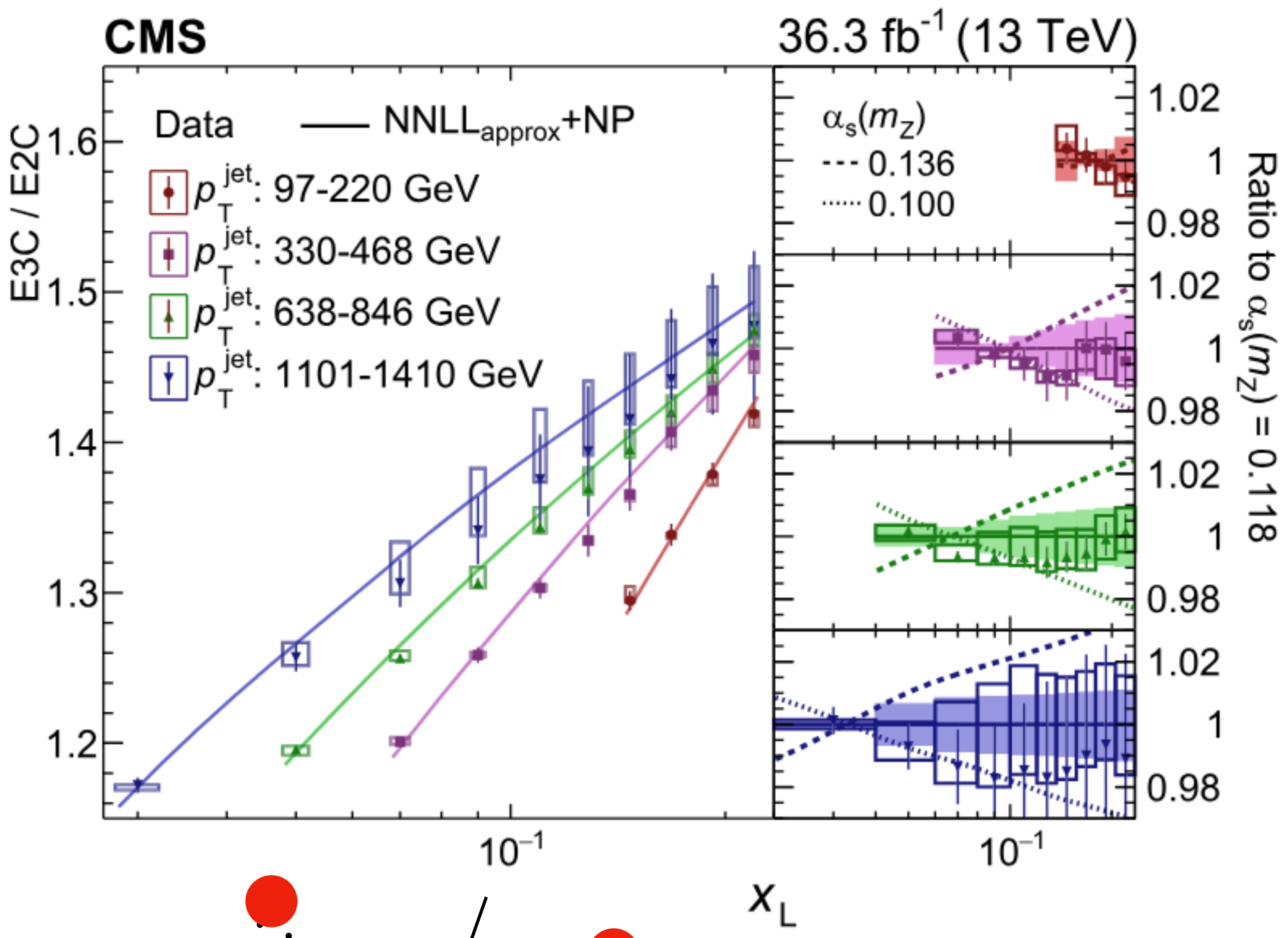
Hofman, Maldacena JHEP 0805 (2008) 012
Dixon, Moult, Zhu PRD 100, 014009 (2019)
Andres, Holguin et. al PRL. 130, 26, 262301 (2023)
Andres, Holguin et. al JHEP 09 (2023) 088

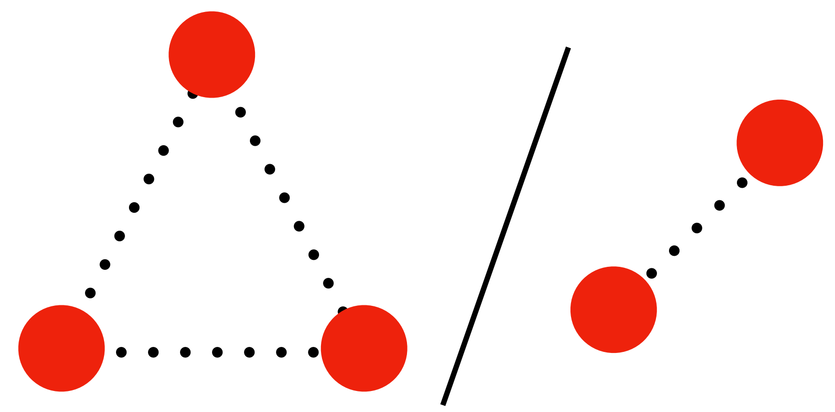
Large Angle



ENC ratios in the large angle region



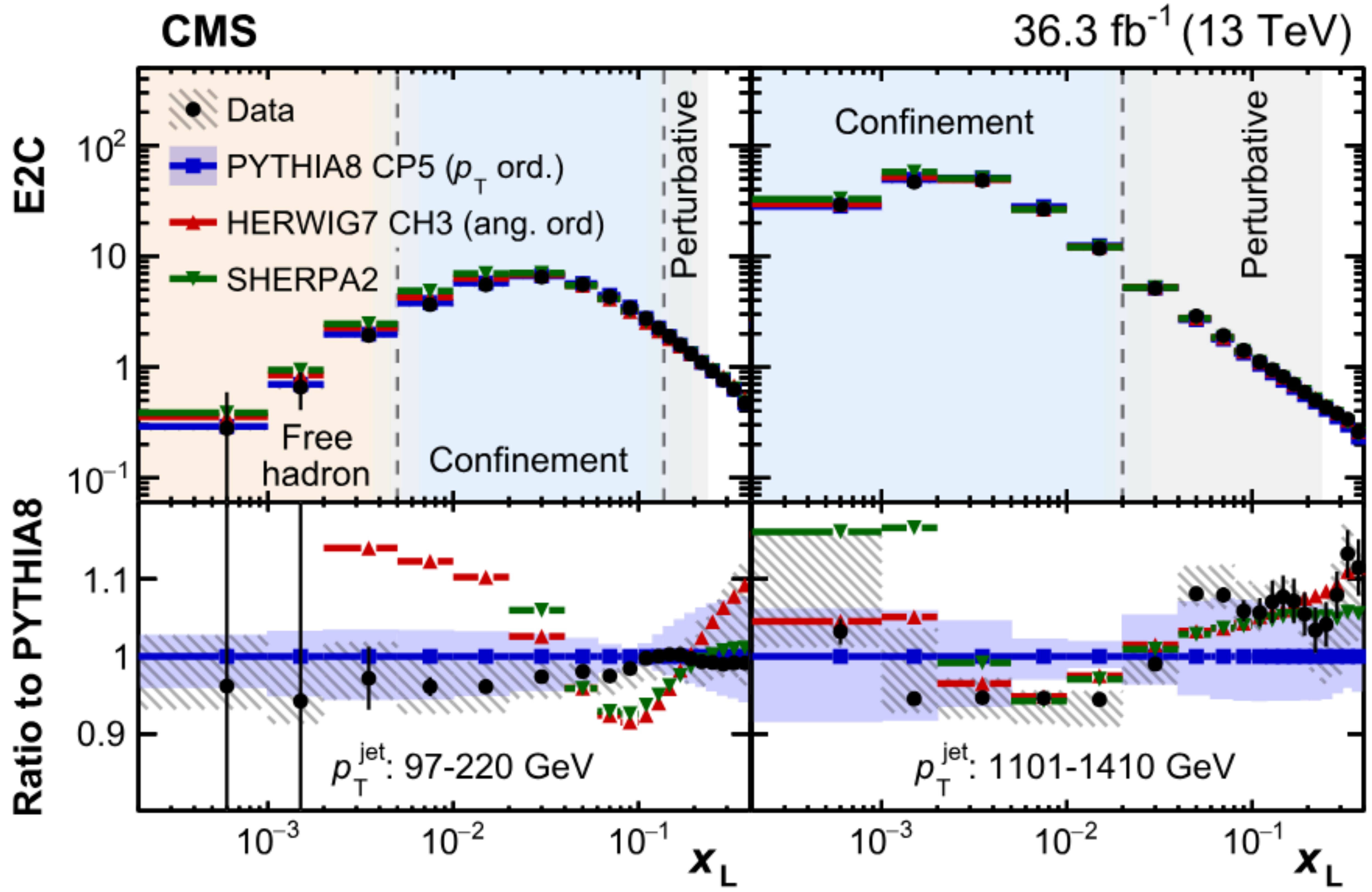


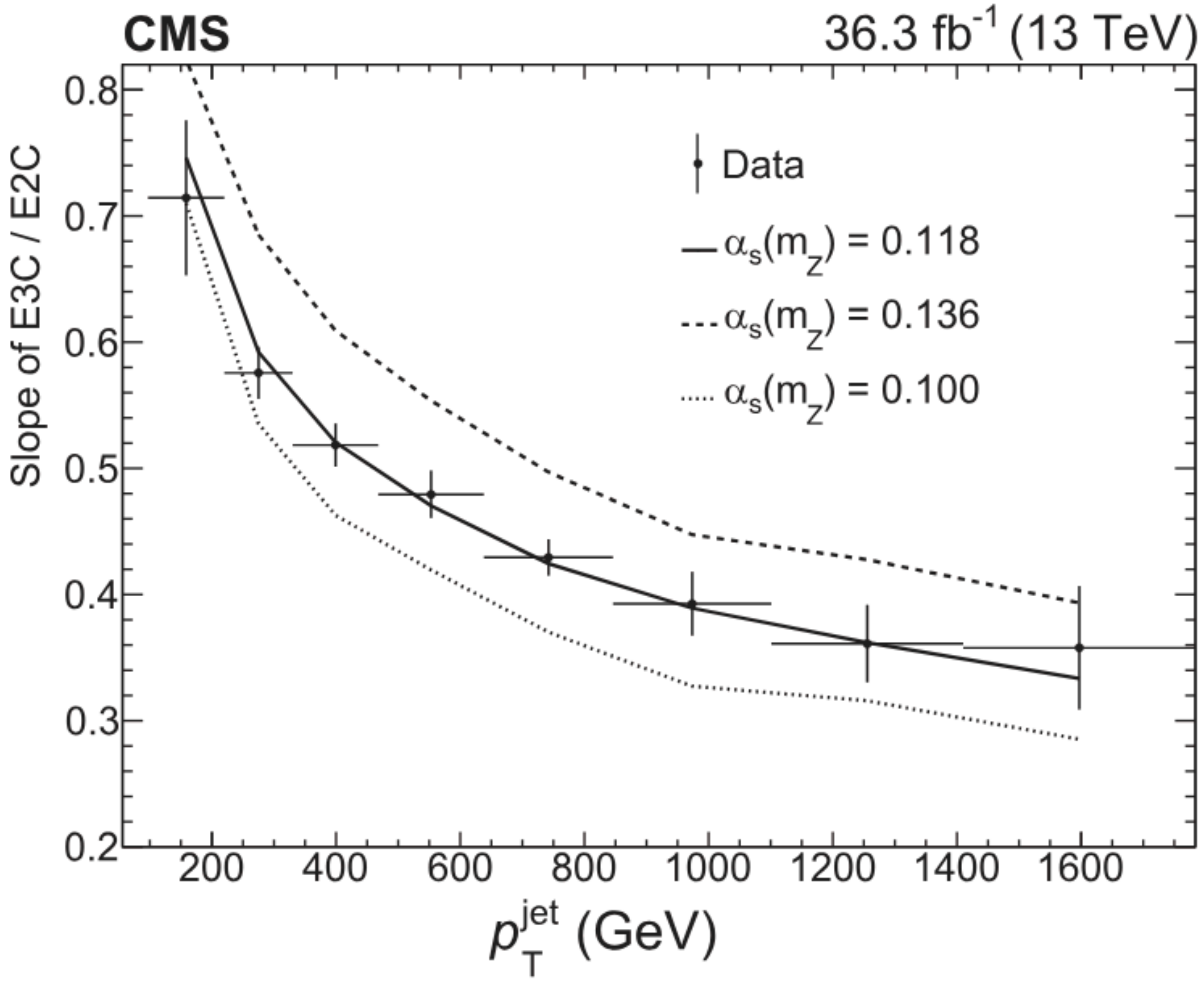


- Measurements from 100 - 1000 TeV jets! includes both tracks and calorimeter towers

CMS Phys. Rev. Lett. 133 (2024) 7, 071903
(81 citations as of yesterday)

ENC ratios in the large angle region

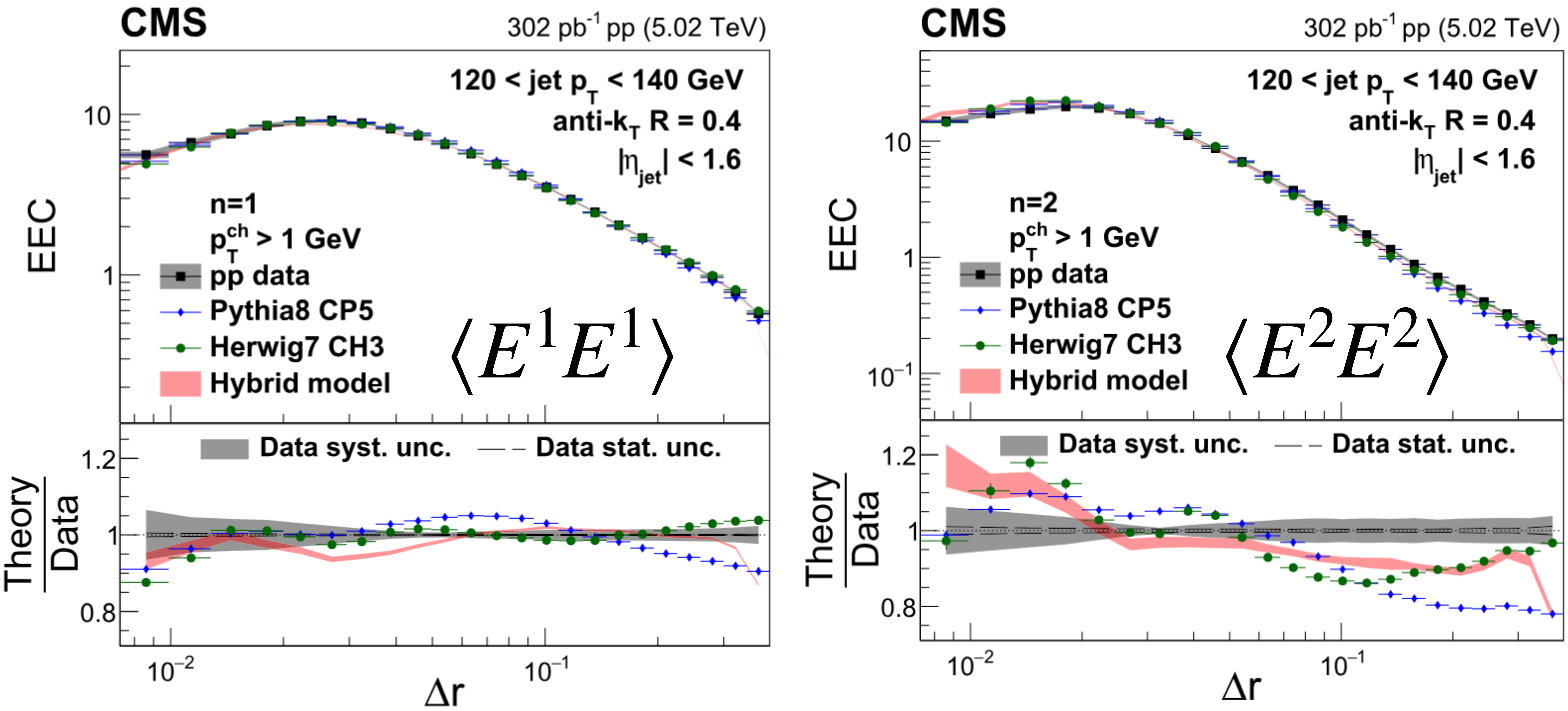




CMS Phys. Rev. Lett. 133 (2024) 7, 071903
(81 citations as of yesterday)

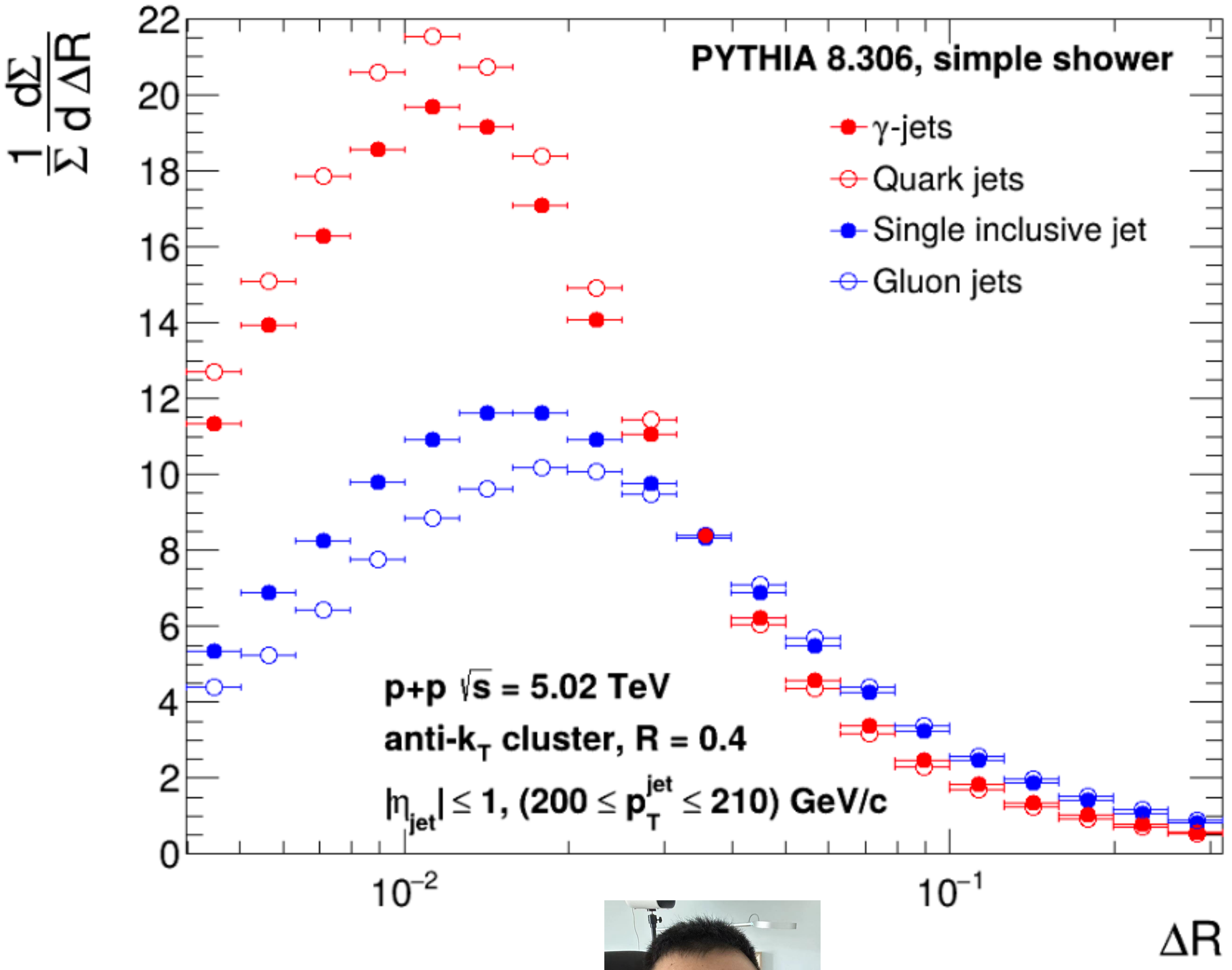
- $\alpha_s = 0.1229 \pm {}^{+0.0014}_{-0.0012}\,\text{stat}\ {}^{+0.0030}_{-0.0033}\,\text{th}\ {}^{+0.0023}_{-0.0036}\,\text{exp}$

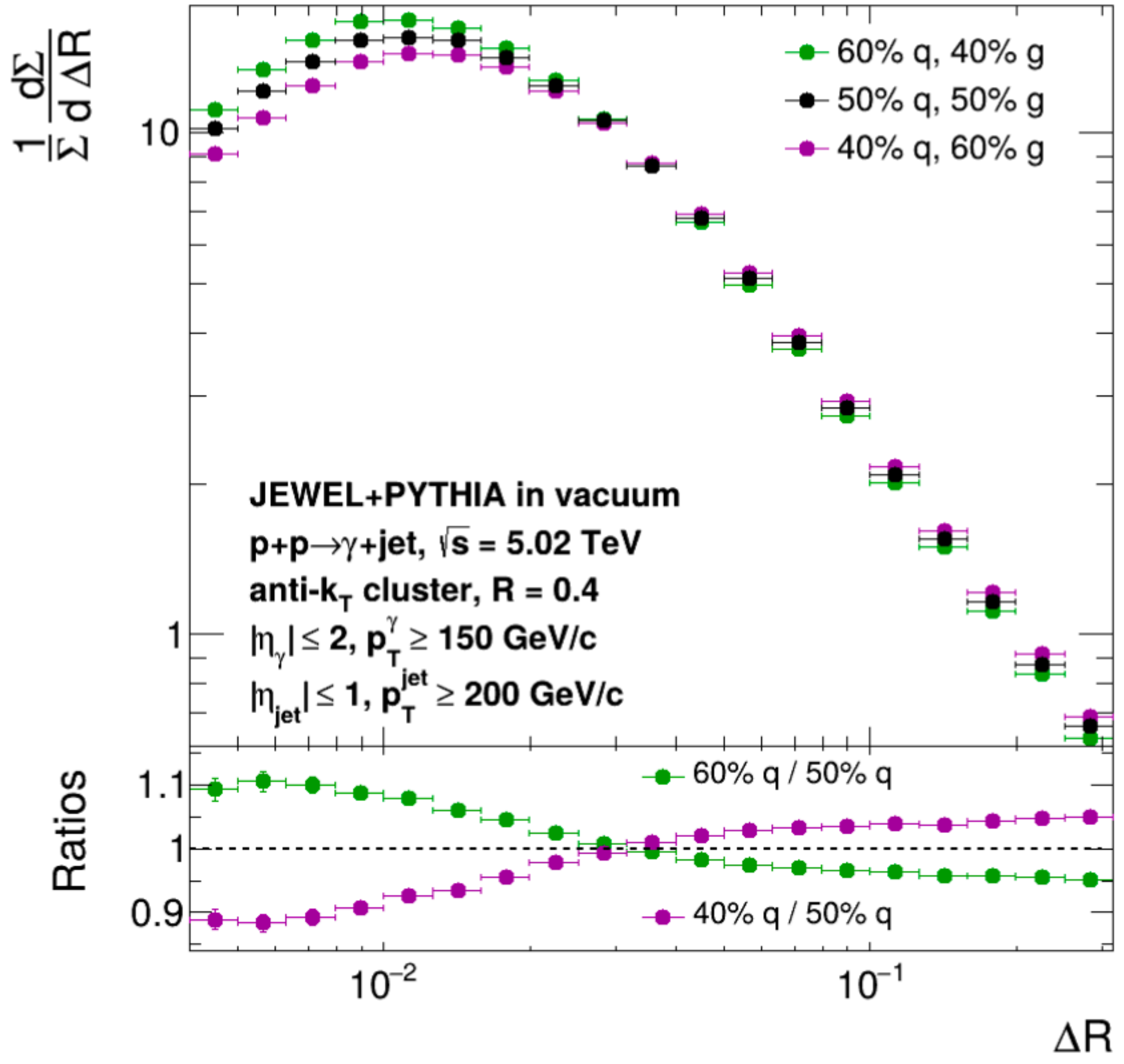
Differences in MC with higher exponents!



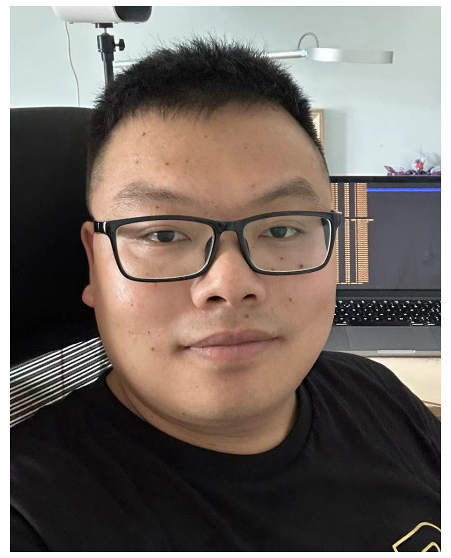
CMS, Phys.Lett.B 866 (2025) 139556
arXiv:2503:19993

Parton flavor dependence!





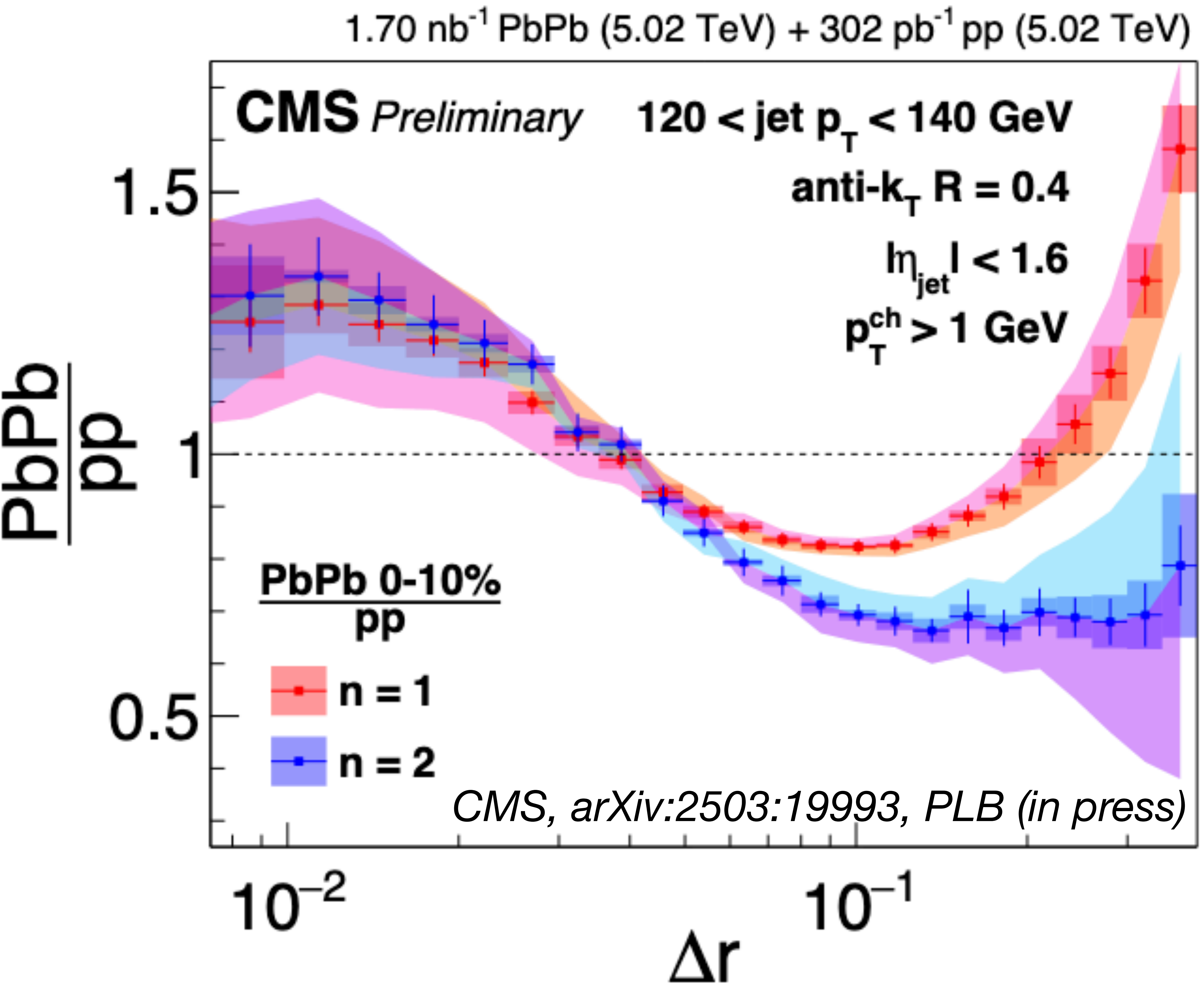
- Having a quark vs gluon fraction results in varying shapes at large *AND* small angles!



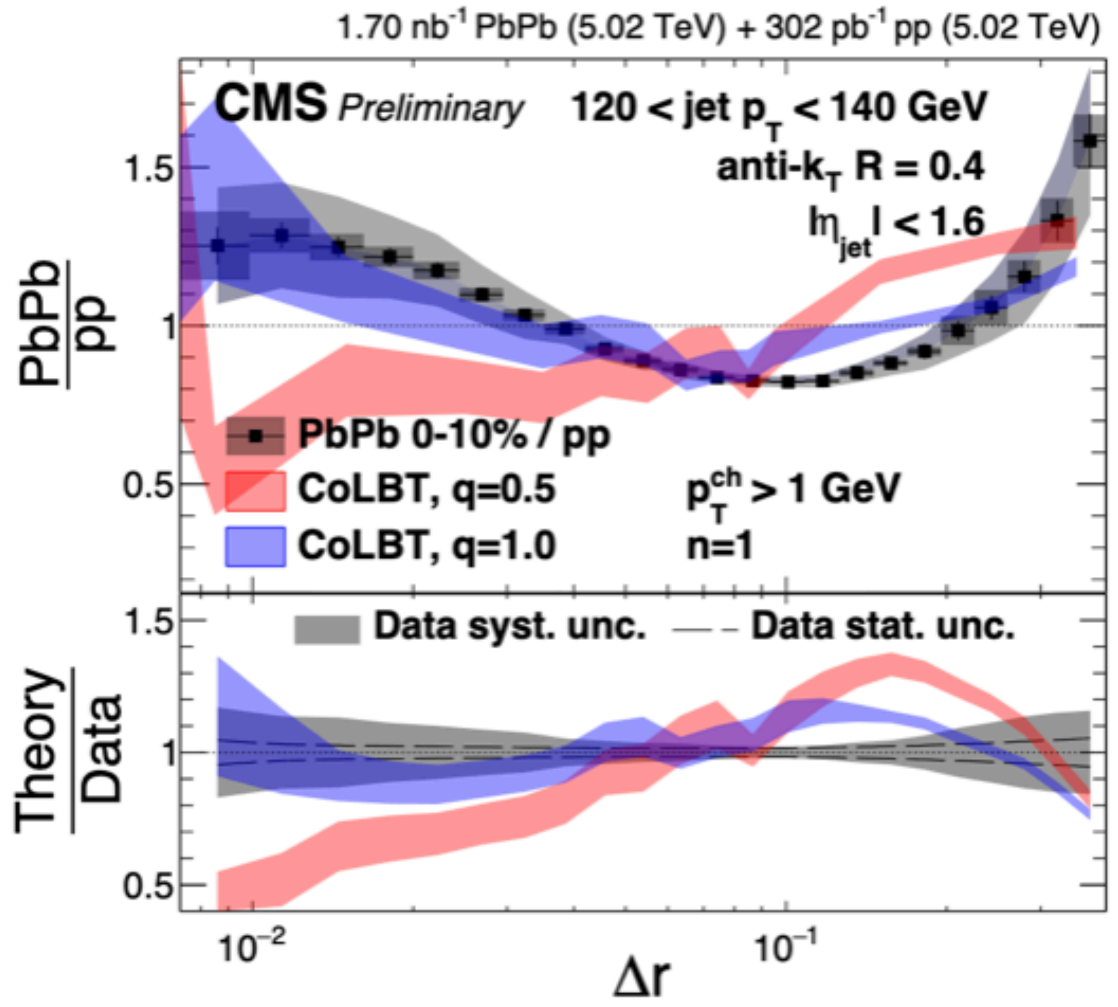
Zhong Yang [he/him]
zhong.yang@vanderbilt.edu

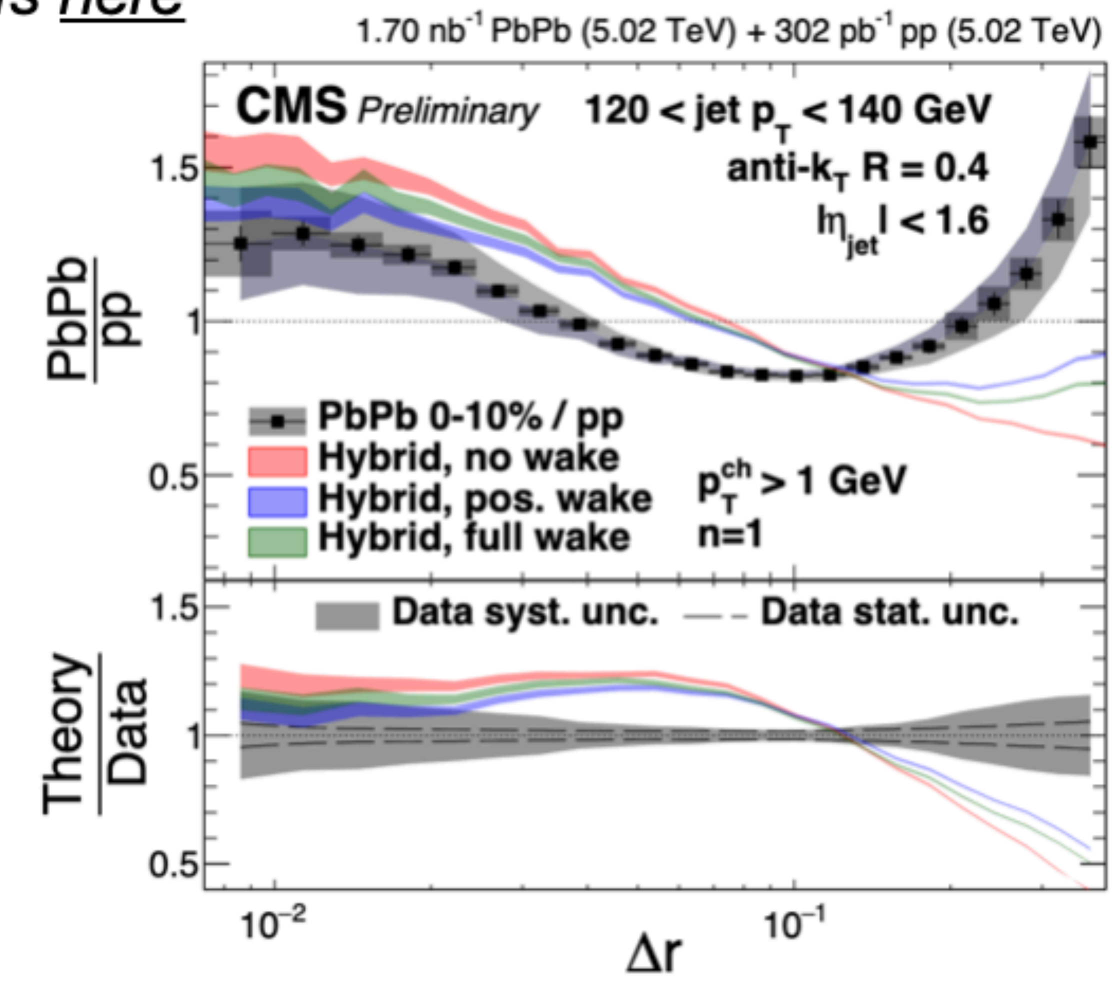
Zhong Yang, Nuno Madureira, LA, RKE, XNW arXiv:2502.11406

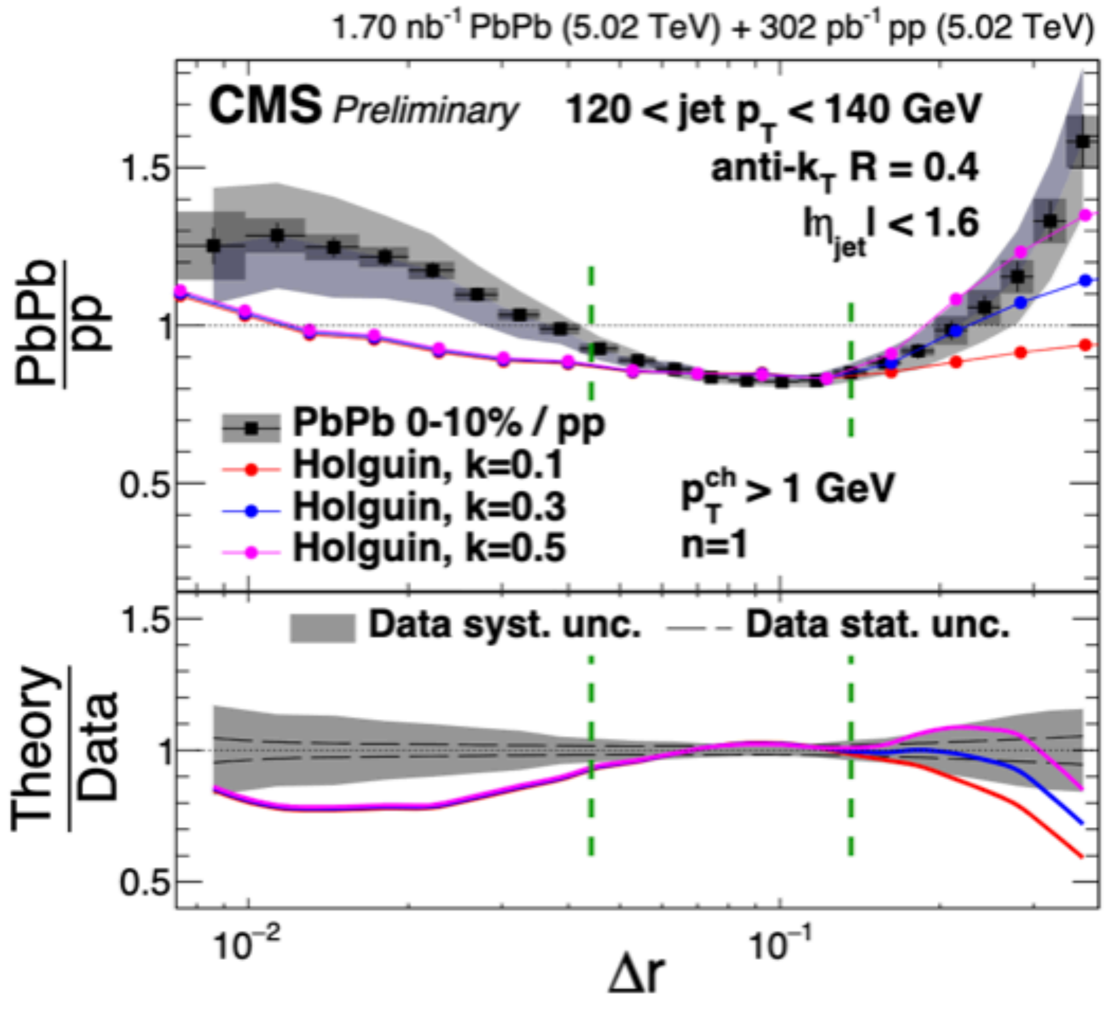
Back to data



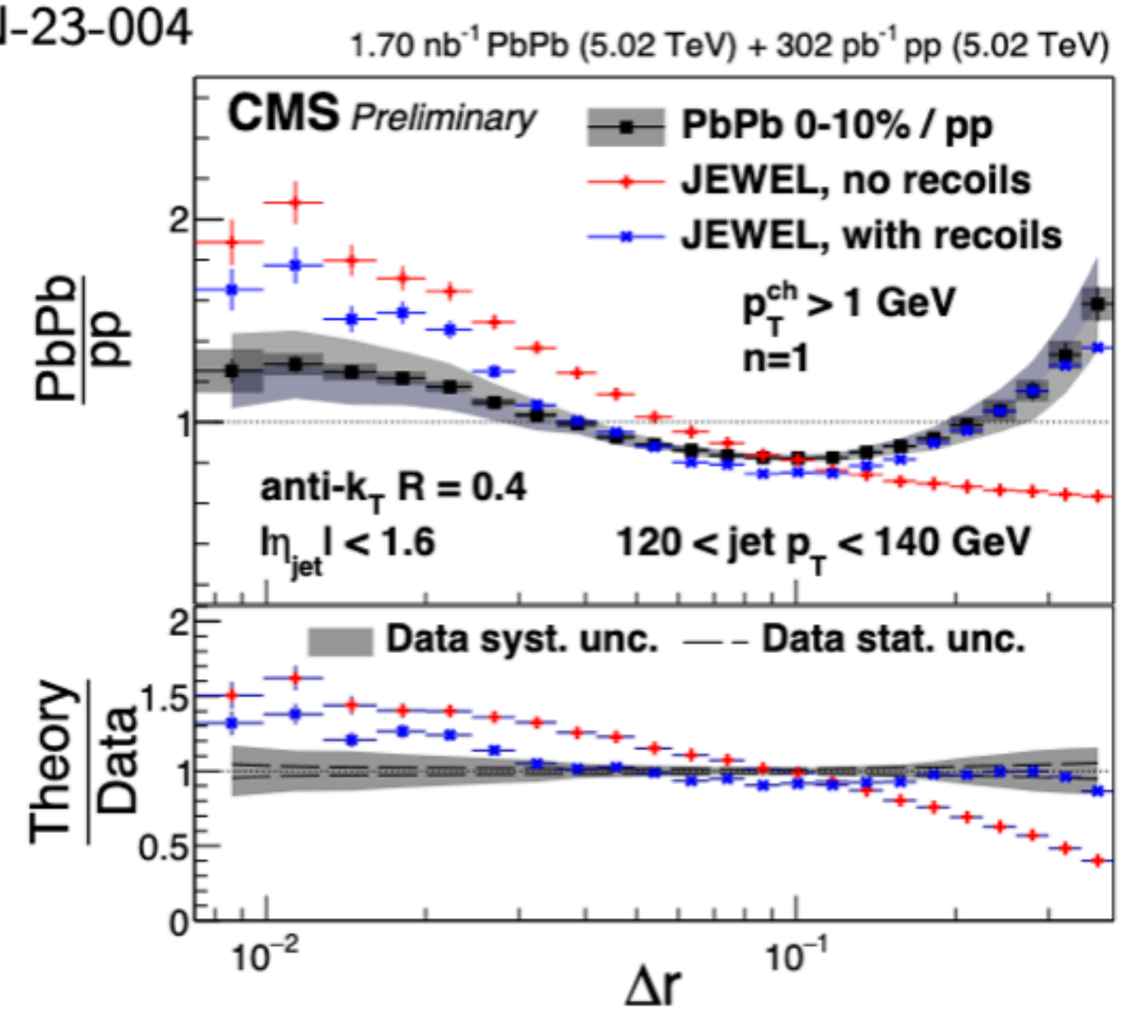
See refs here







IN-23-004

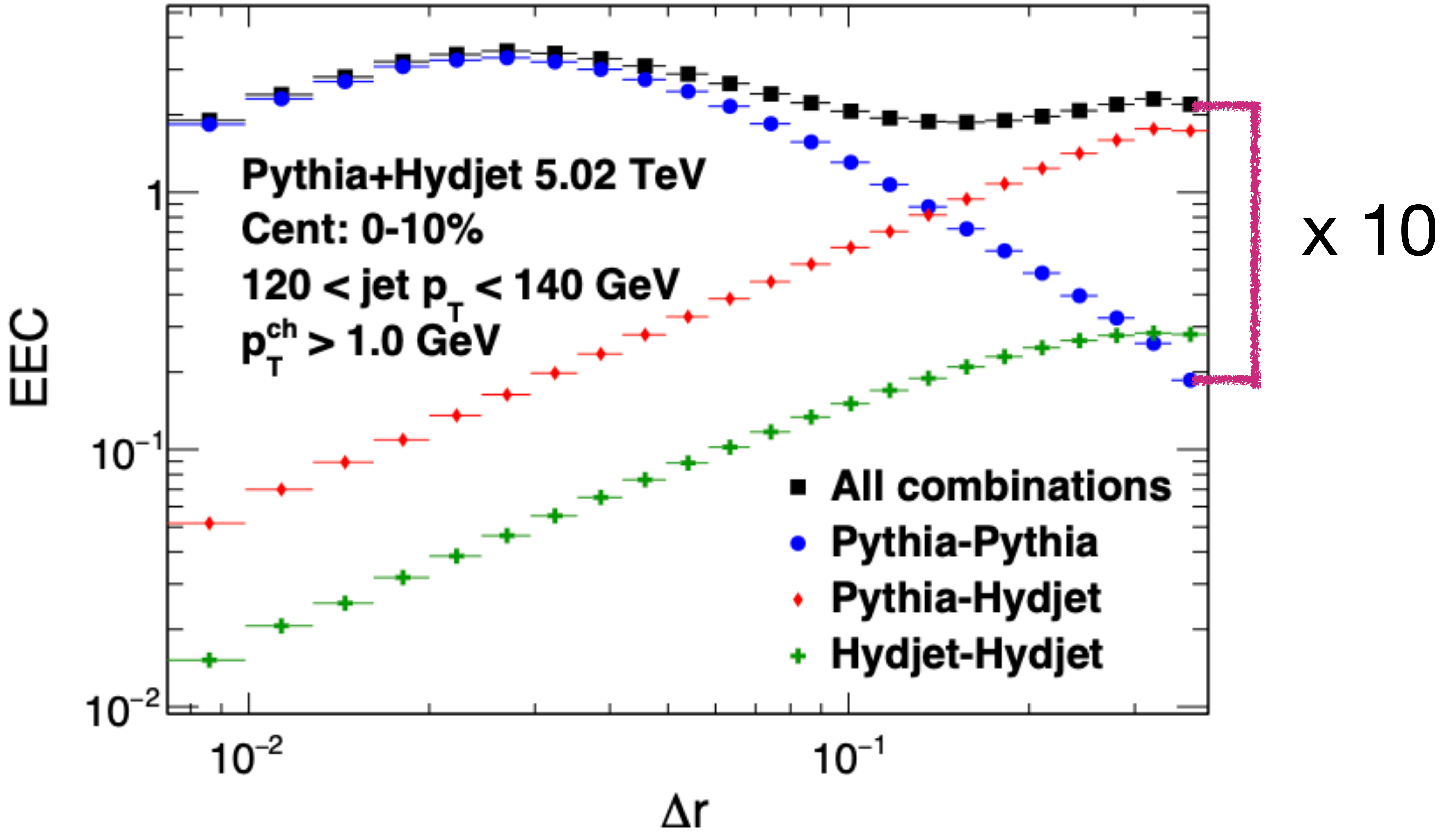


- Enhancement at the large angle - indicative of medium response and recoils but unclear if there are other effects - such is reality!

Too much background on top of your signal!

Jussi Viinikainen [he/him]
jussi.viinikainen@vanderbilt.edu

See his talks @ QM25, HP24, Mainz 24



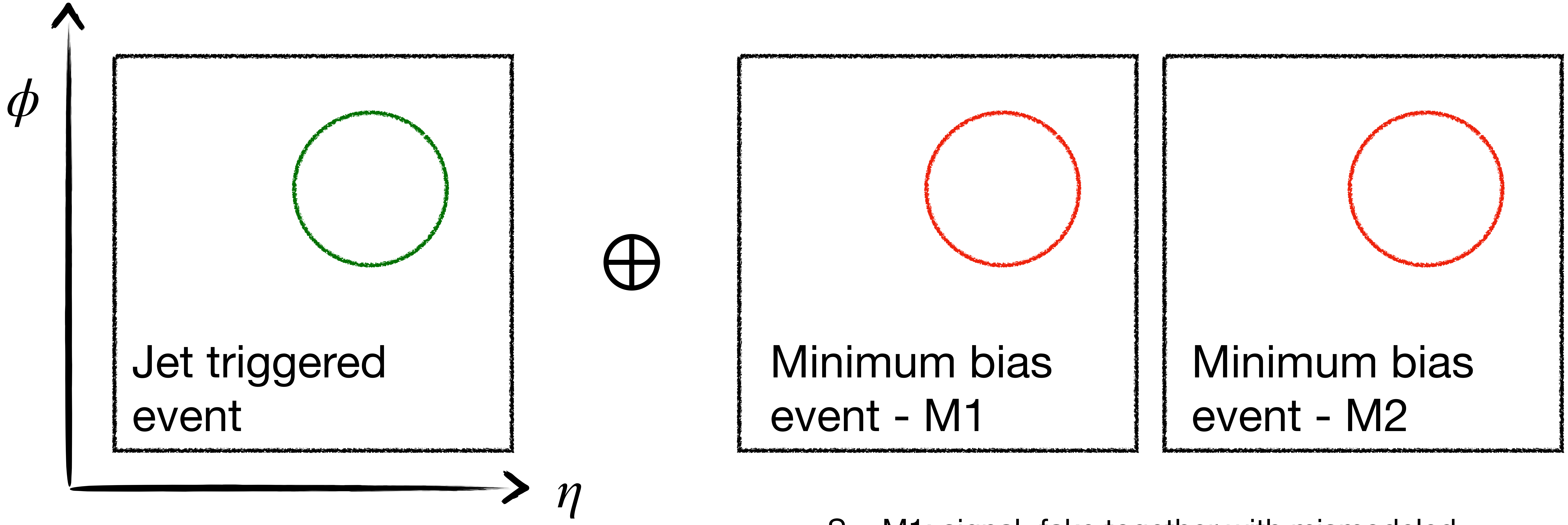
- Different pairings in the simulation
  - All pairs
  - Signal+signal pairs
  - Signal+background pairs
  - Background+background pairs
- Background contributions dominant at large Δr
- Background subtraction needed

The good 

The bad 

The ugly 

Background subtraction method

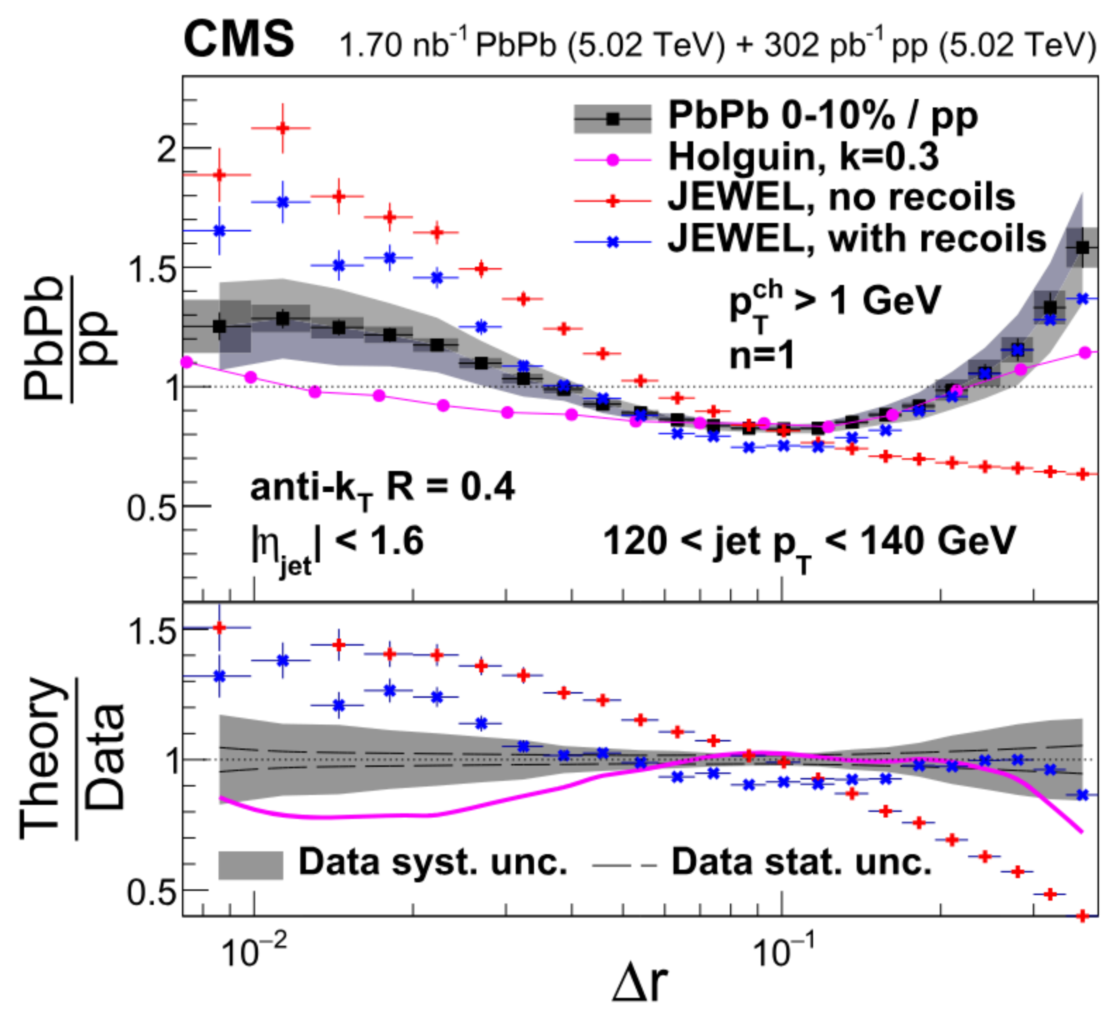


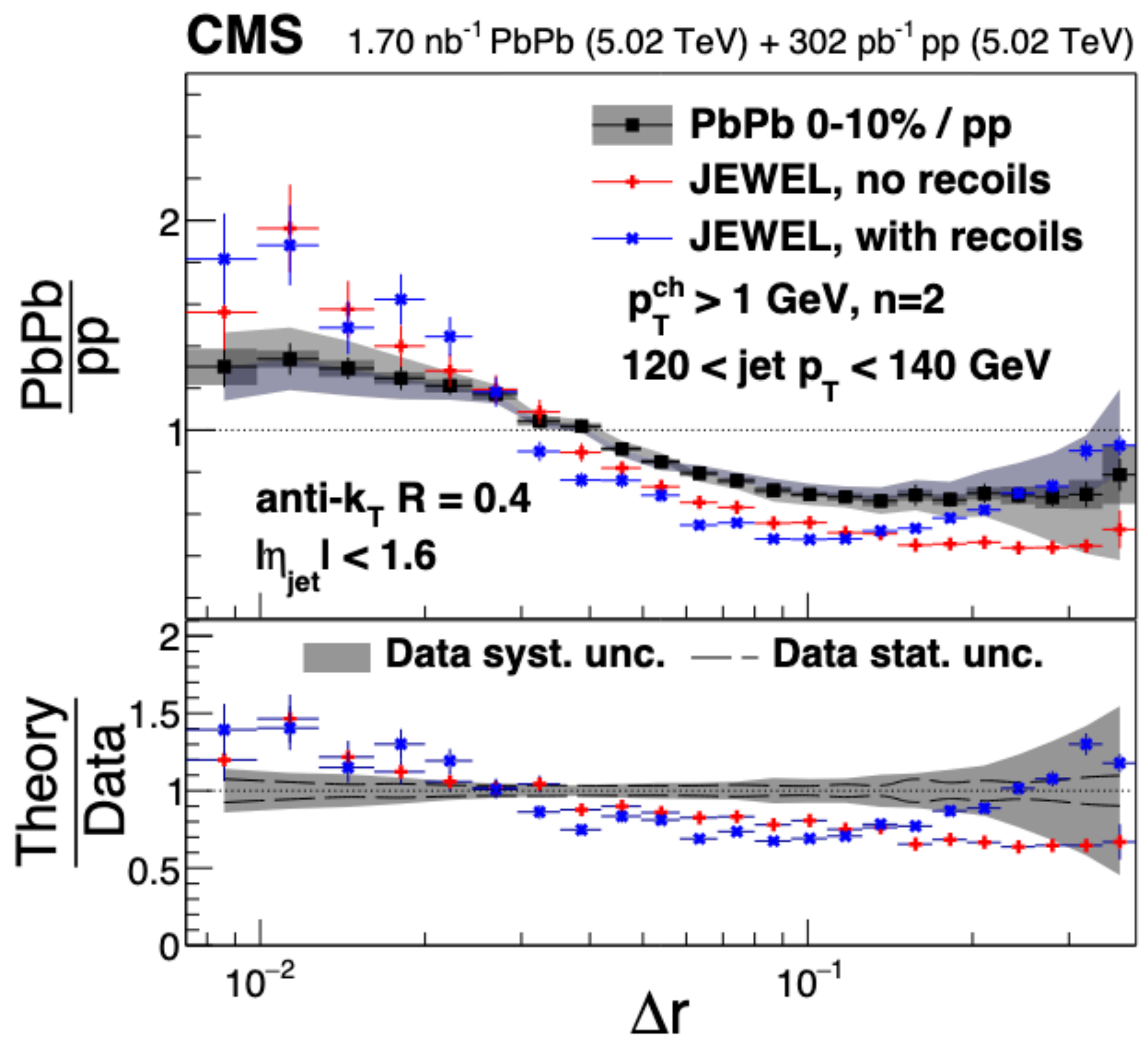
- SS + SB + BB - thats what we start with in Data
- SM1 + M1M1 – M1M2 - gives us the background we need the subtract!

- S + M1: signal+fake together with mismodeled fake+fake
- M1+ M1: properly modeled fake+fake
- M1+ M2: mismodeled fake+fake

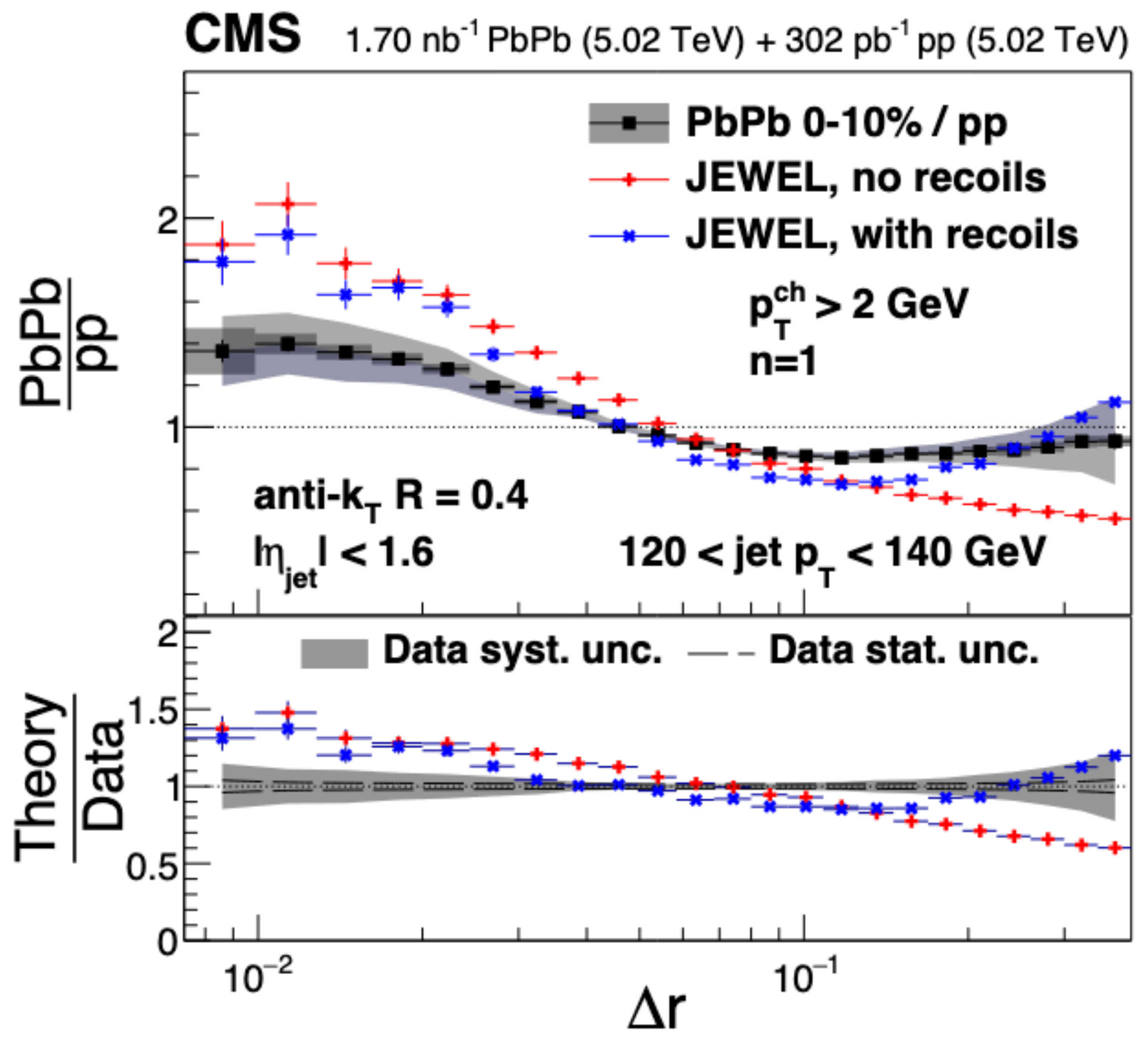
n = 1 n = 2

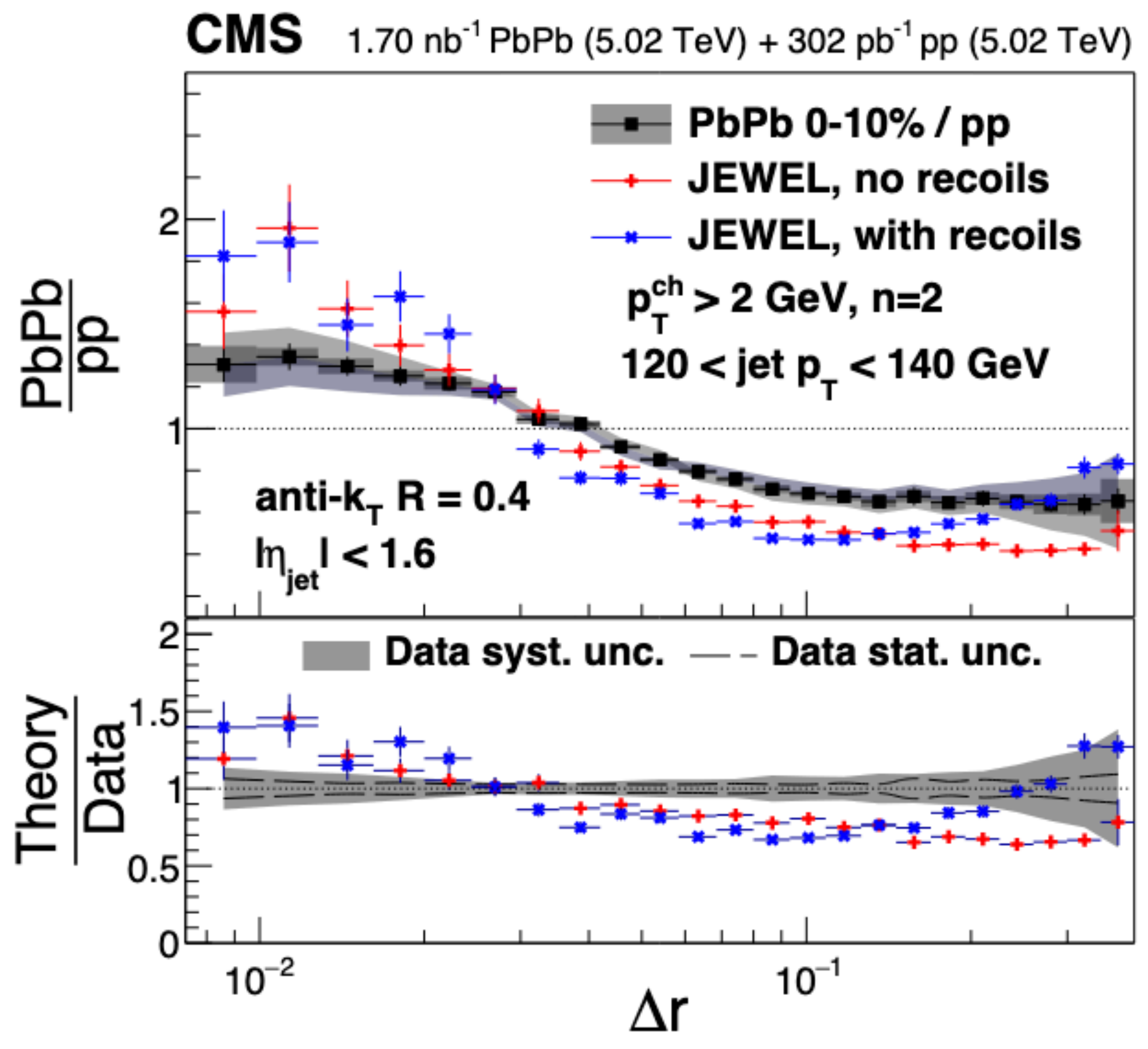
$p_T > 1$





$p_T > 2$





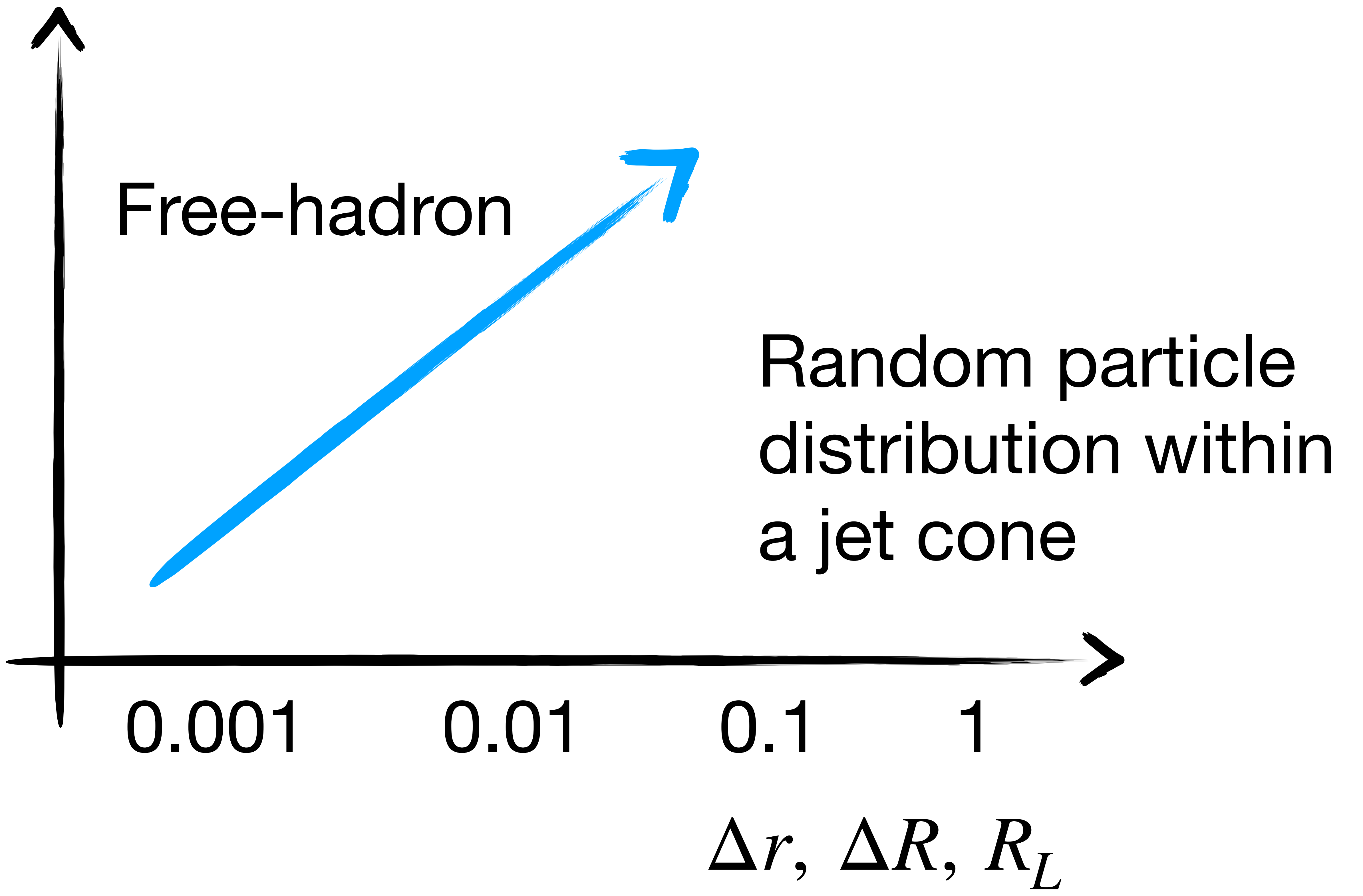
- Similar physics as one increases the exponents or adds in a track p_T threshold
- Models do not all reproduce the variations in the observables

Feature space for projected ENC

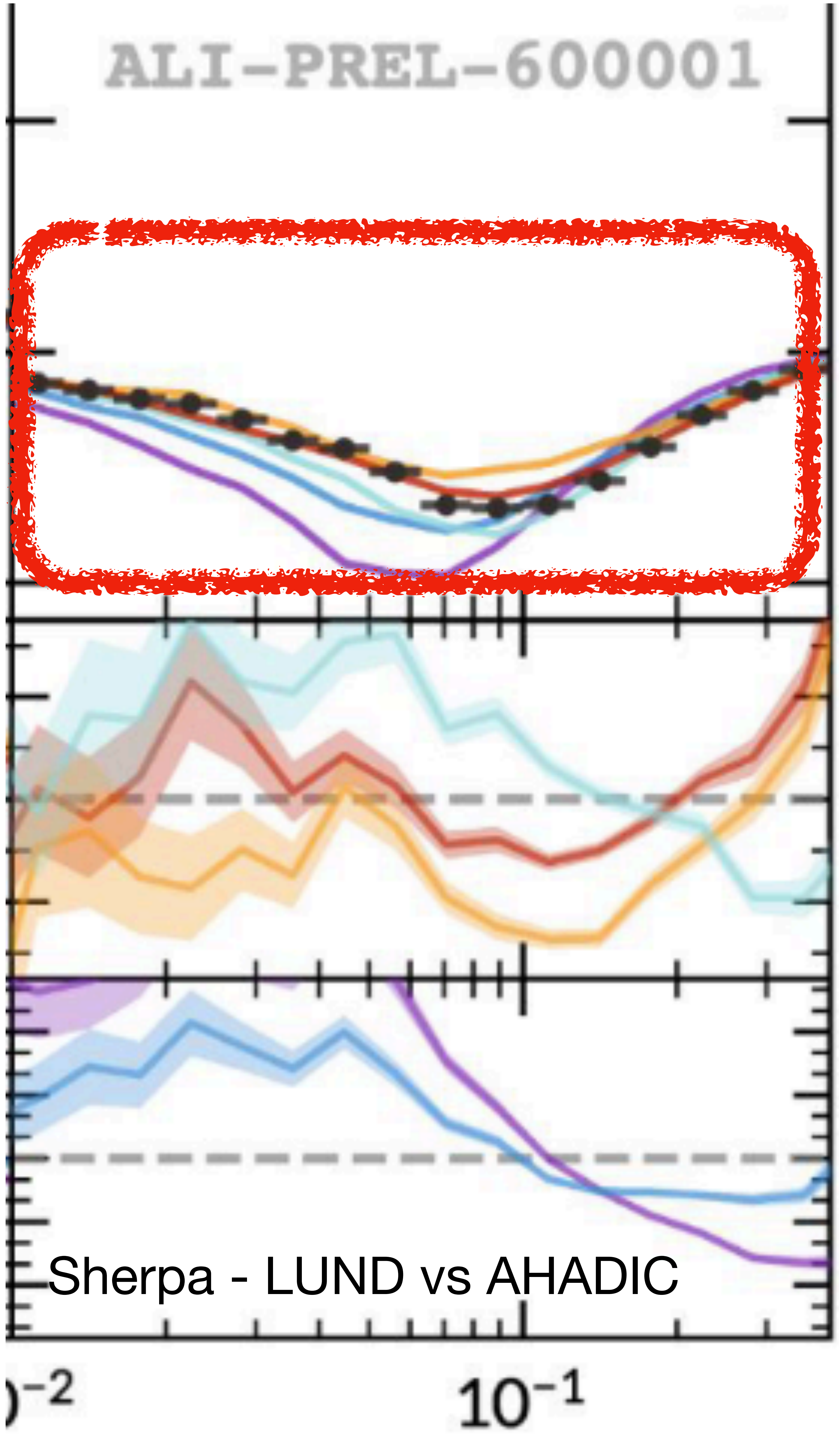
$$\text{Normalized EEC} = \frac{1}{\sum_{Jets}\sum_{i\neq j}\frac{E_i E_j}{{p_{T,Jet}}^2}} \frac{d\left(\sum_{Jets}\sum_{i\neq j}\frac{E_i E_j}{{p_{T,Jet}}^2}\right)}{d\,(\Delta R)}$$

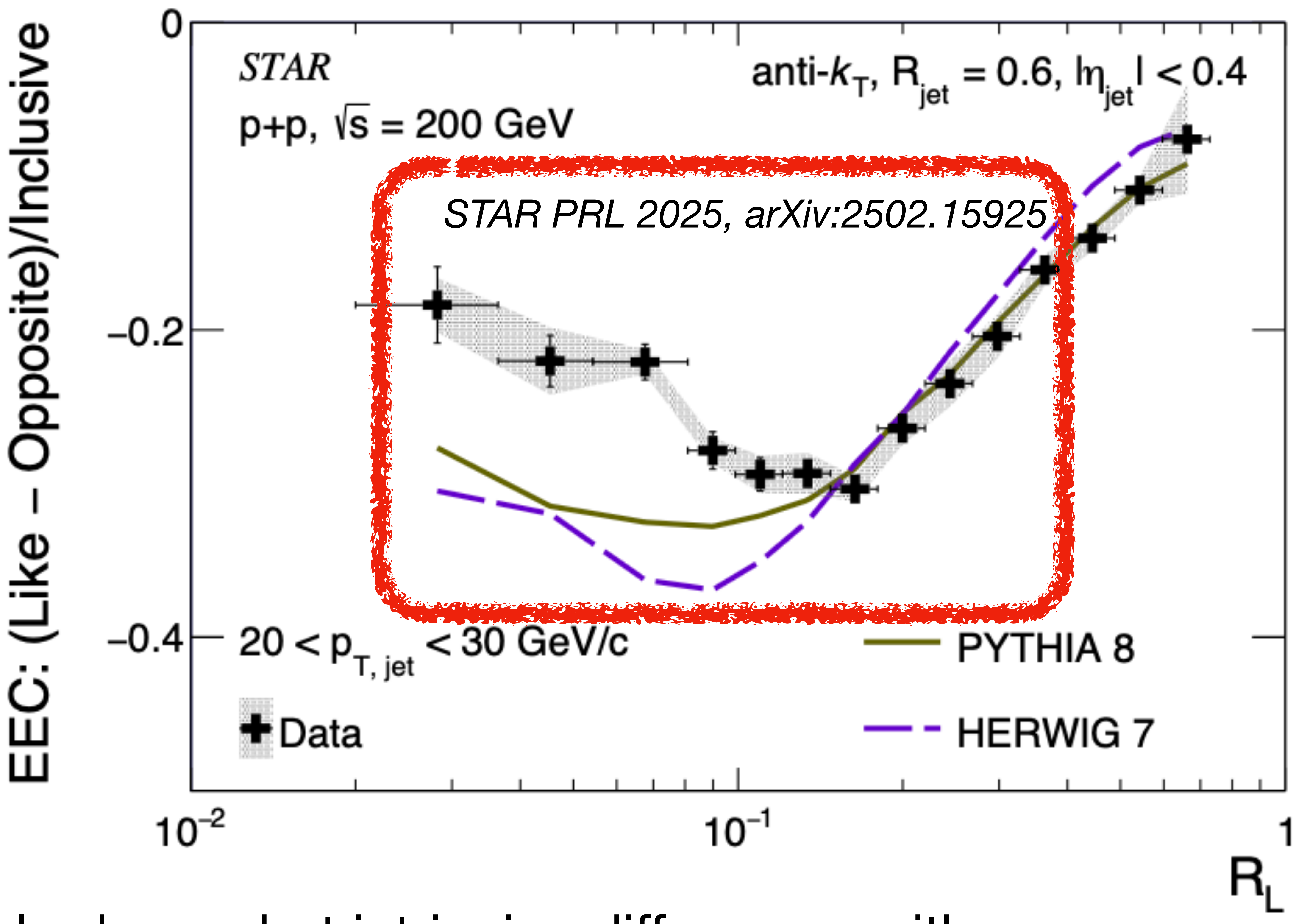
- Energy weighted pairwise distance of particles within your jet (or the event!)

Small angle



Highlighting hadronization effects





- Similarly shapes but intriguing differences with pQCD based shower variations

Feature space for projected ENC

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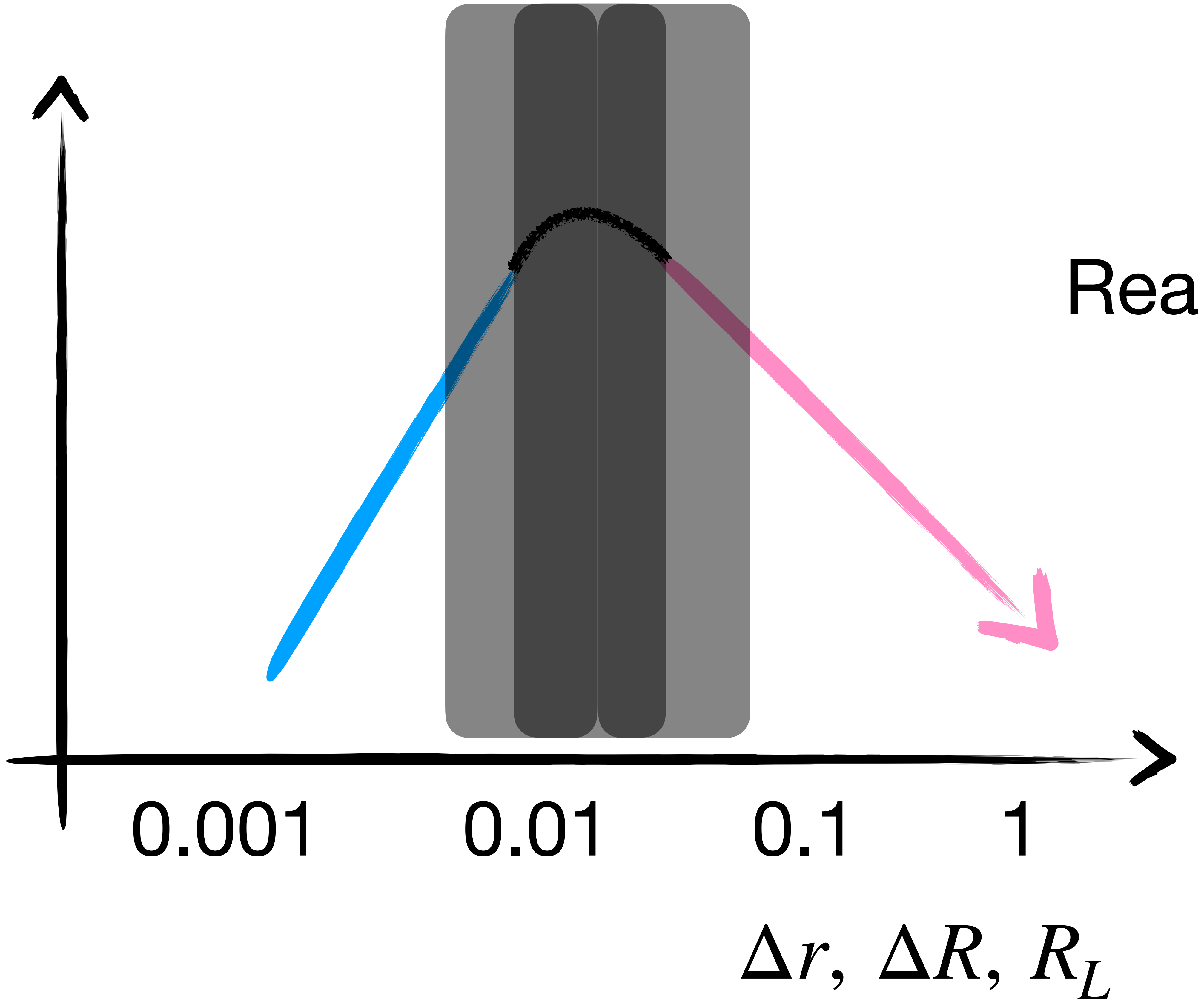
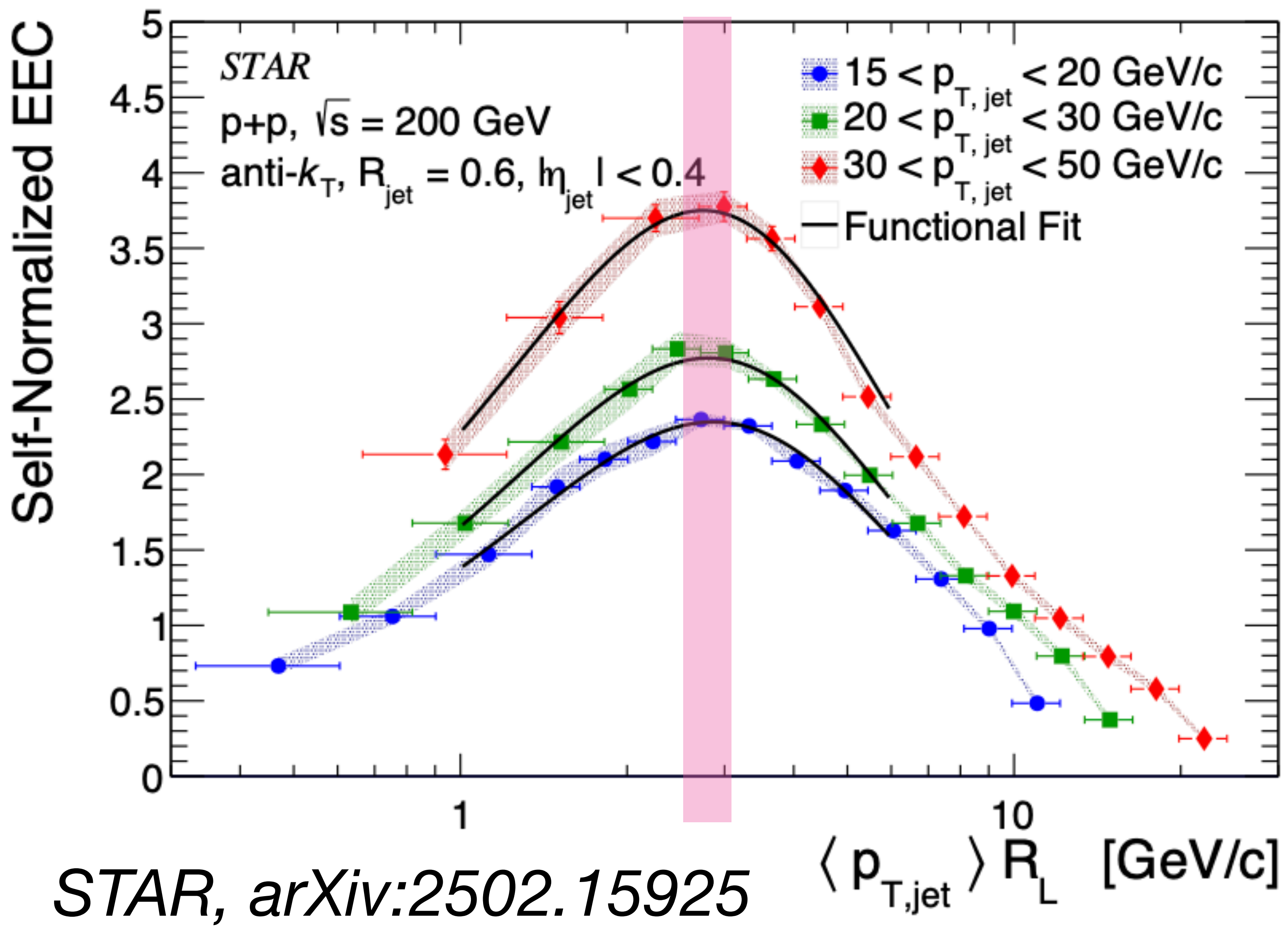
- Energy weighted pairwise distance of particles within your jet (or the event!)
- Potential separation of scales - can we actually visualize physics of multi-scale processes?

Intermediate angle



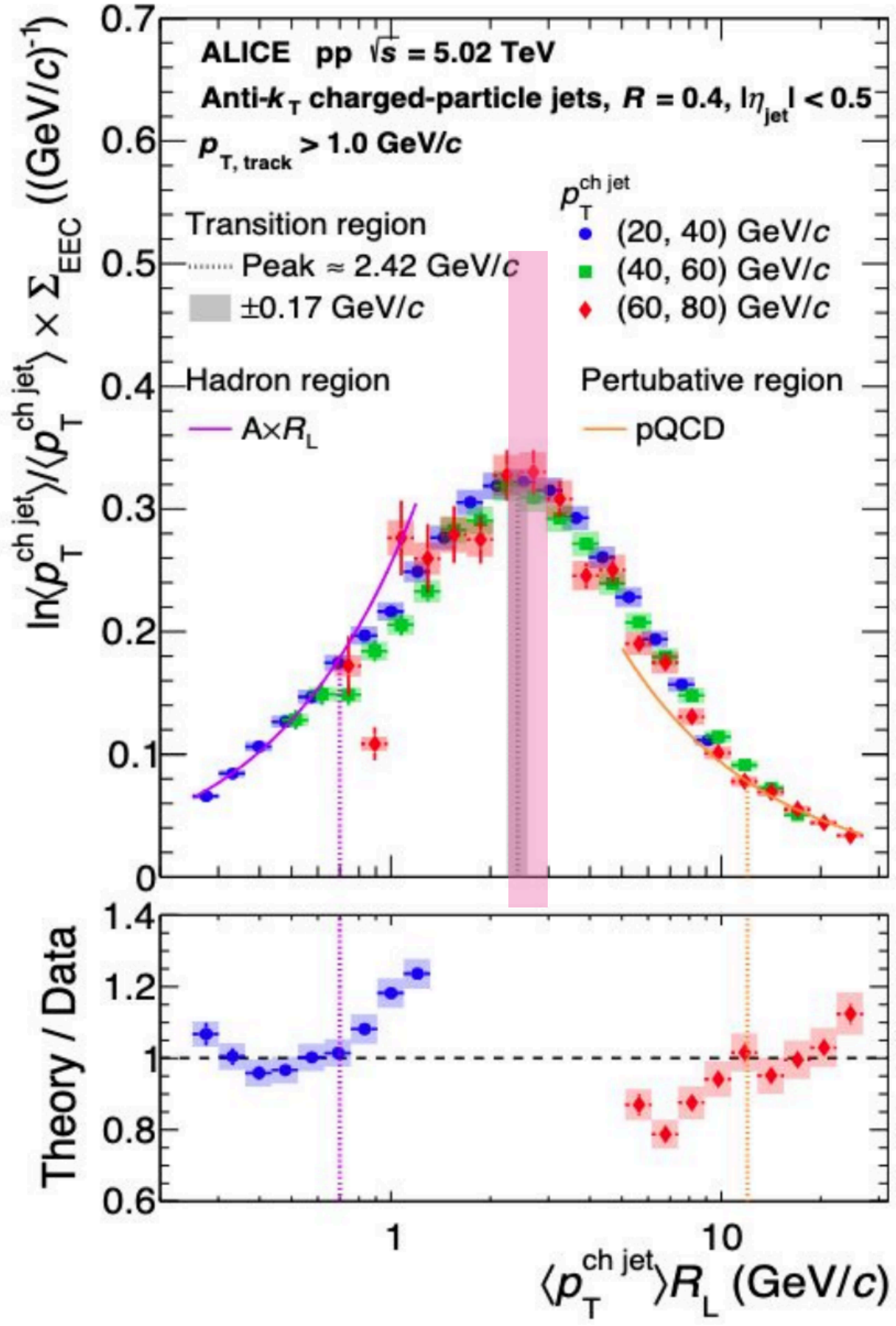
Realistic jet!

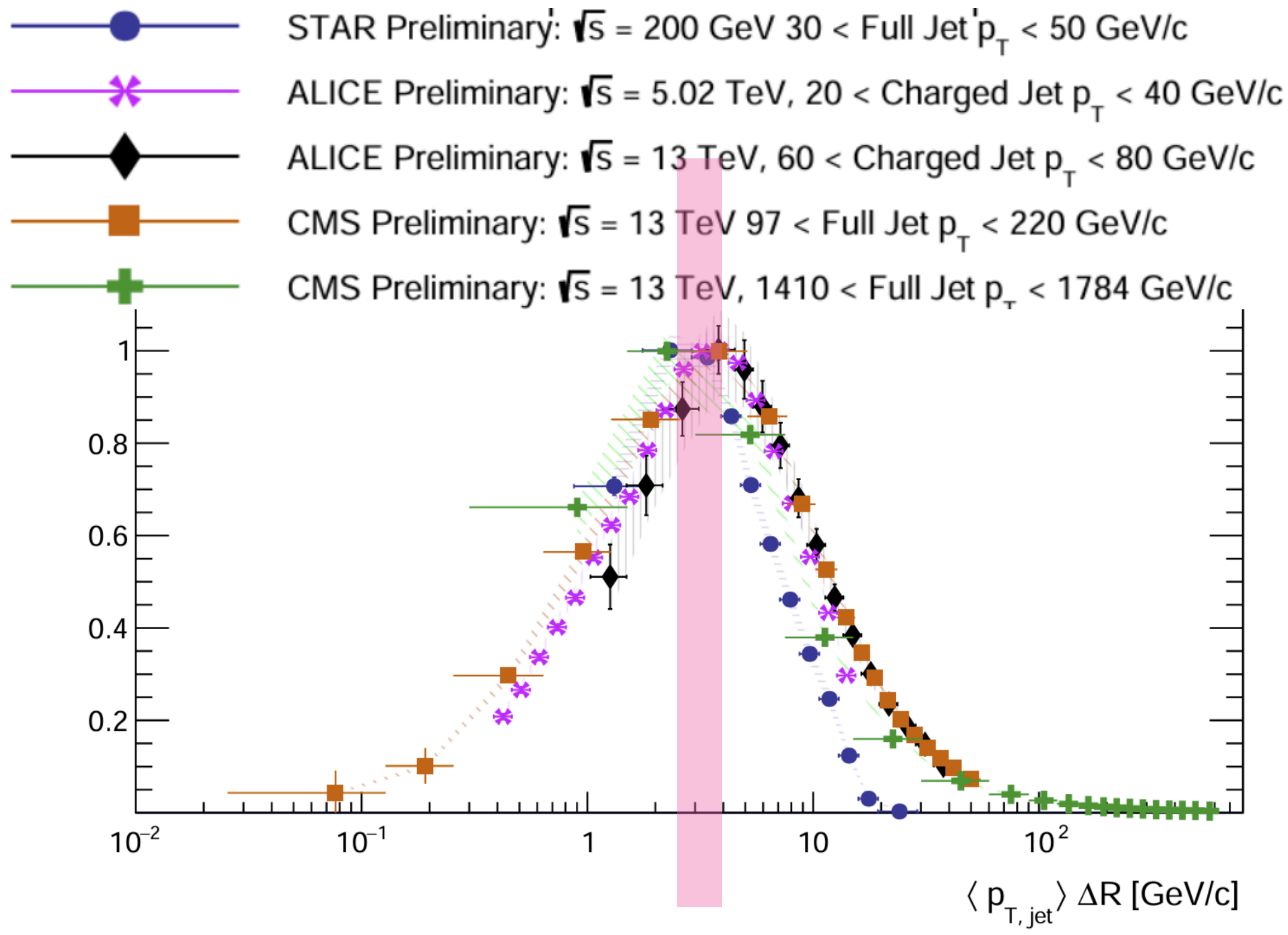
Potential common scale for the transition



STAR, arXiv:2502.15925

$$F(R_L) = C\frac{R_L}{(R_L^2 + T)^{3/2}}$$



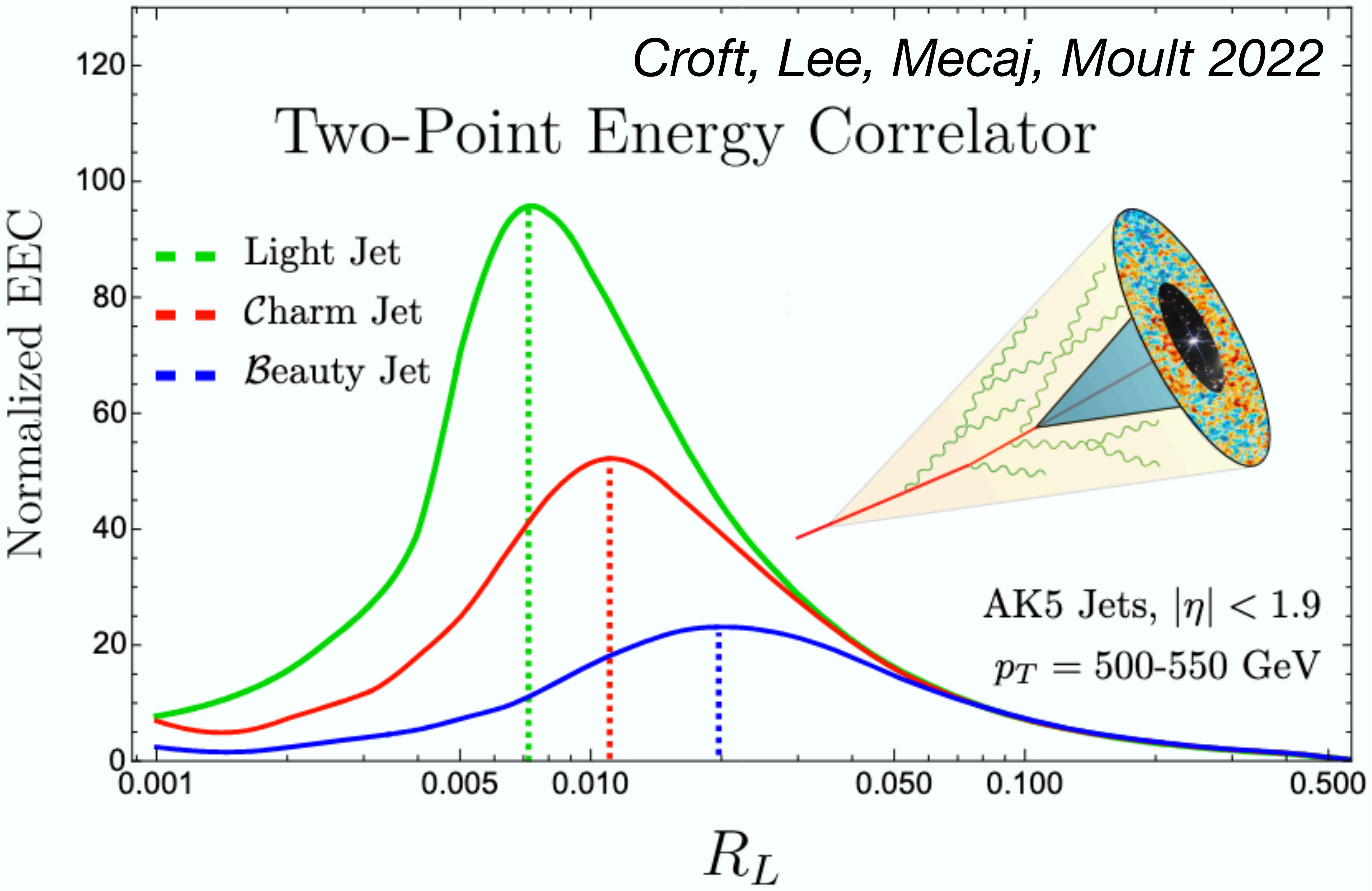


pQCD calculation from K. Lee: arXiv:2205.03414

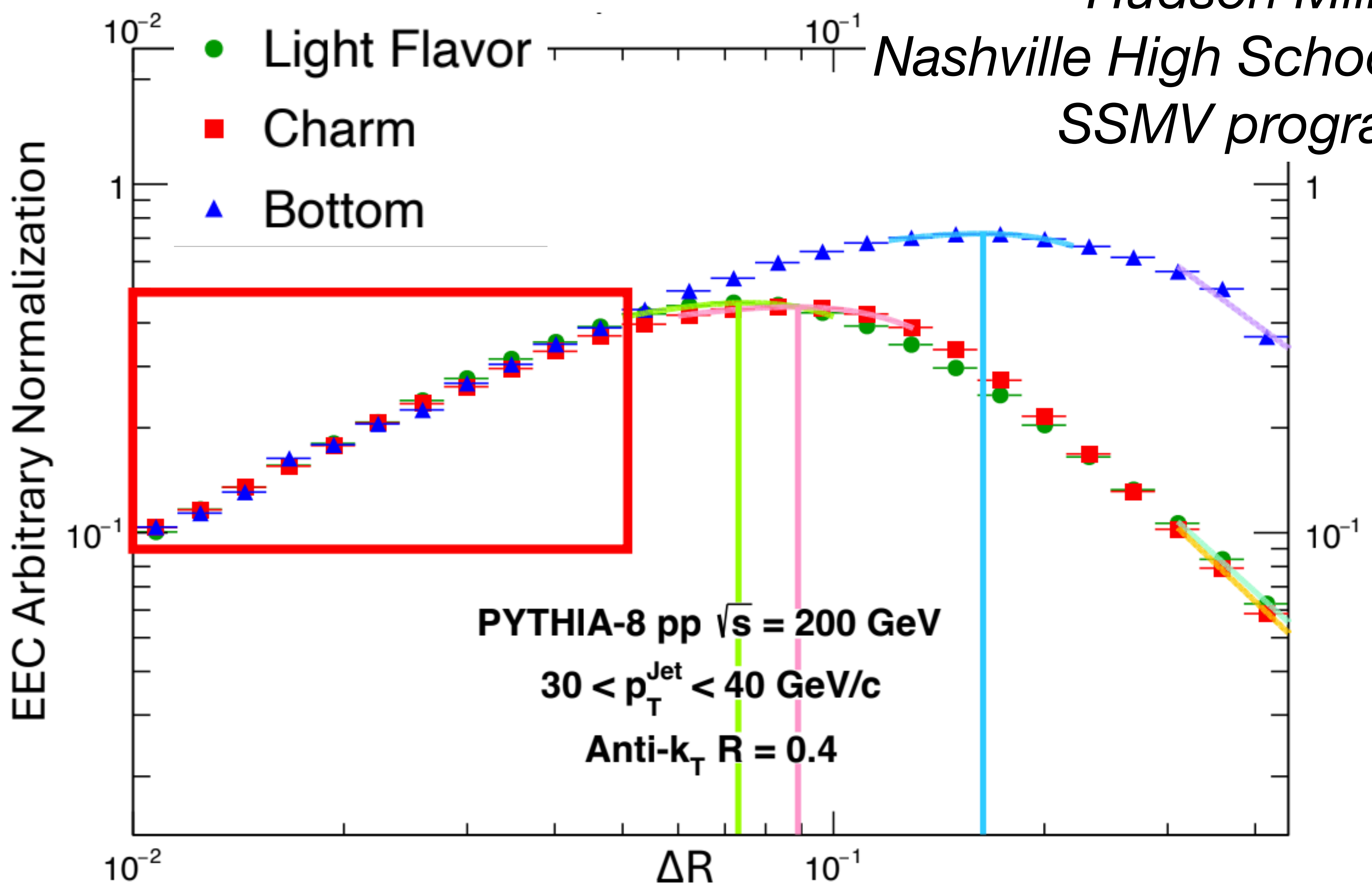
4

- Turnover happens $R_L \approx 2-3$ GeV
- universal with important differences…

Light vs Heavy Flavor jets!



Hudson Mills
Nashville High School Student
SSMV program

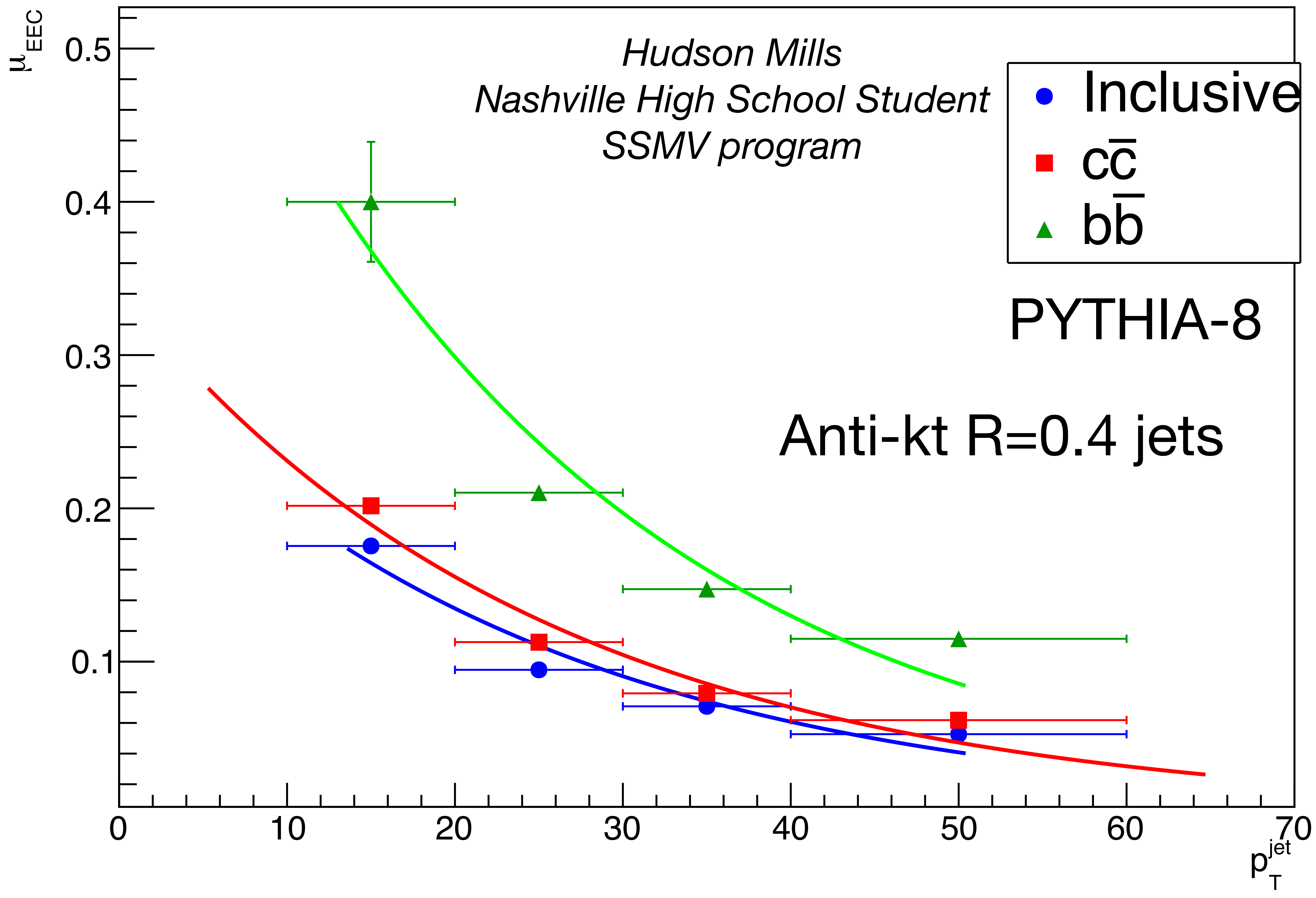


DNP 2025 (Chicago), Hudson Mills (Vanderbilt)

- Clear shift in the peak at fixed jet momenta for varying parton mass!
- Scale of the peak is no longer ~ Λ_{QCD}/p_T but its rather $\Lambda_{QCD}/p_T + F(m_q, E)$

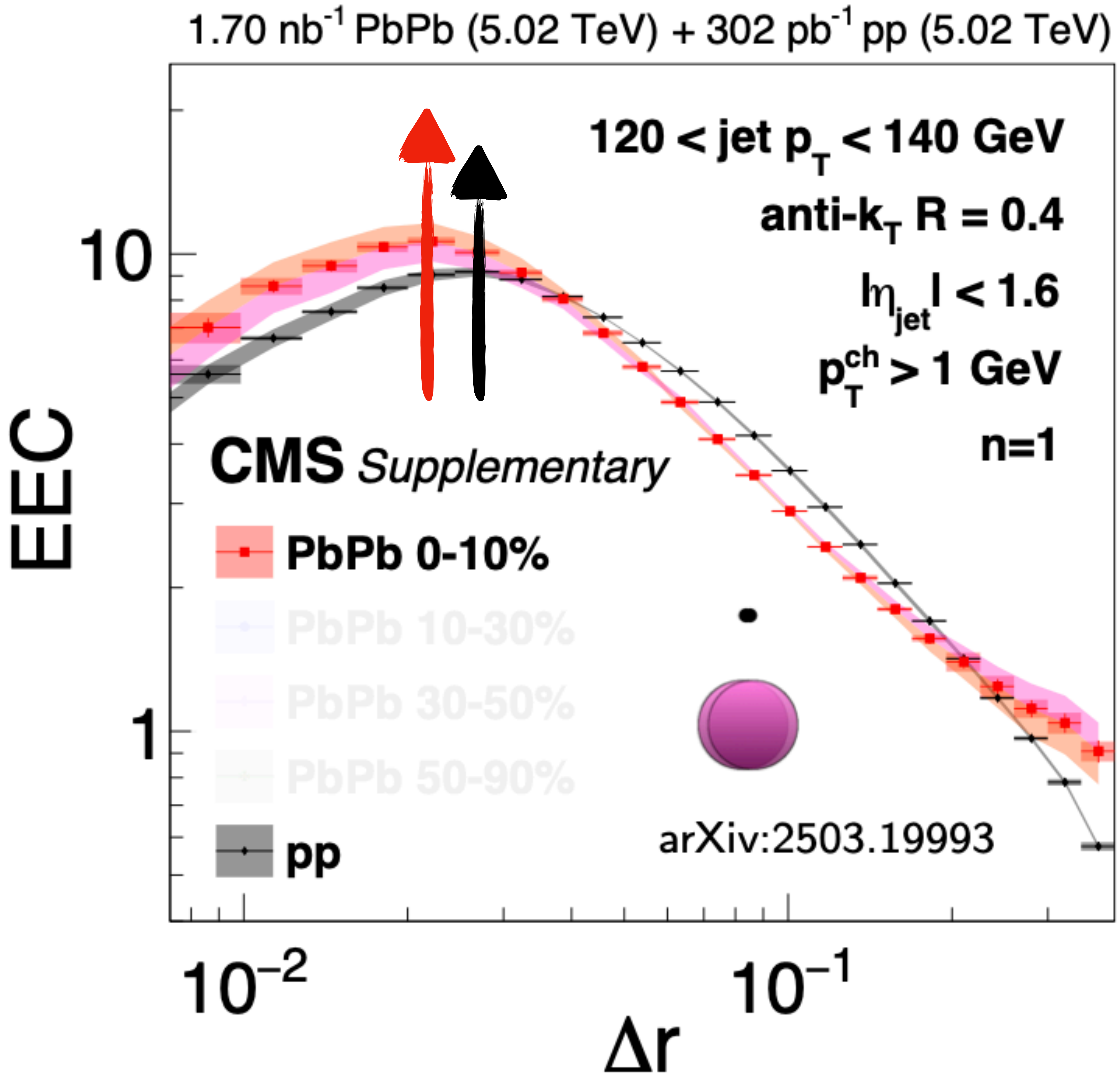
Light vs Heavy Flavor jets!

Resurrection of the dead cone!



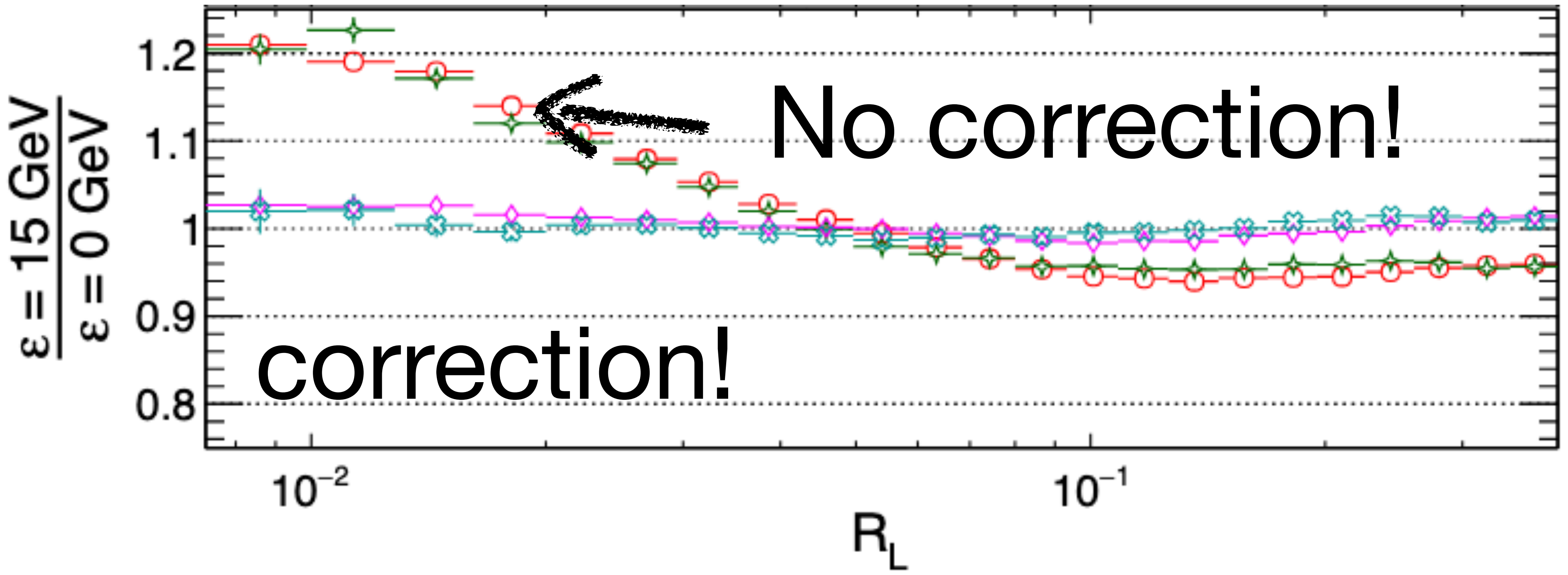
- Fitting the EEC transition peak with an exp decay!
- Potentially stronger dependence on HF jets at RHIC as we are much closer to the b-quark mass energy
- Accessible at RHIC but unsure if it will be done - definite discovery potential at the EIC

Back to Data



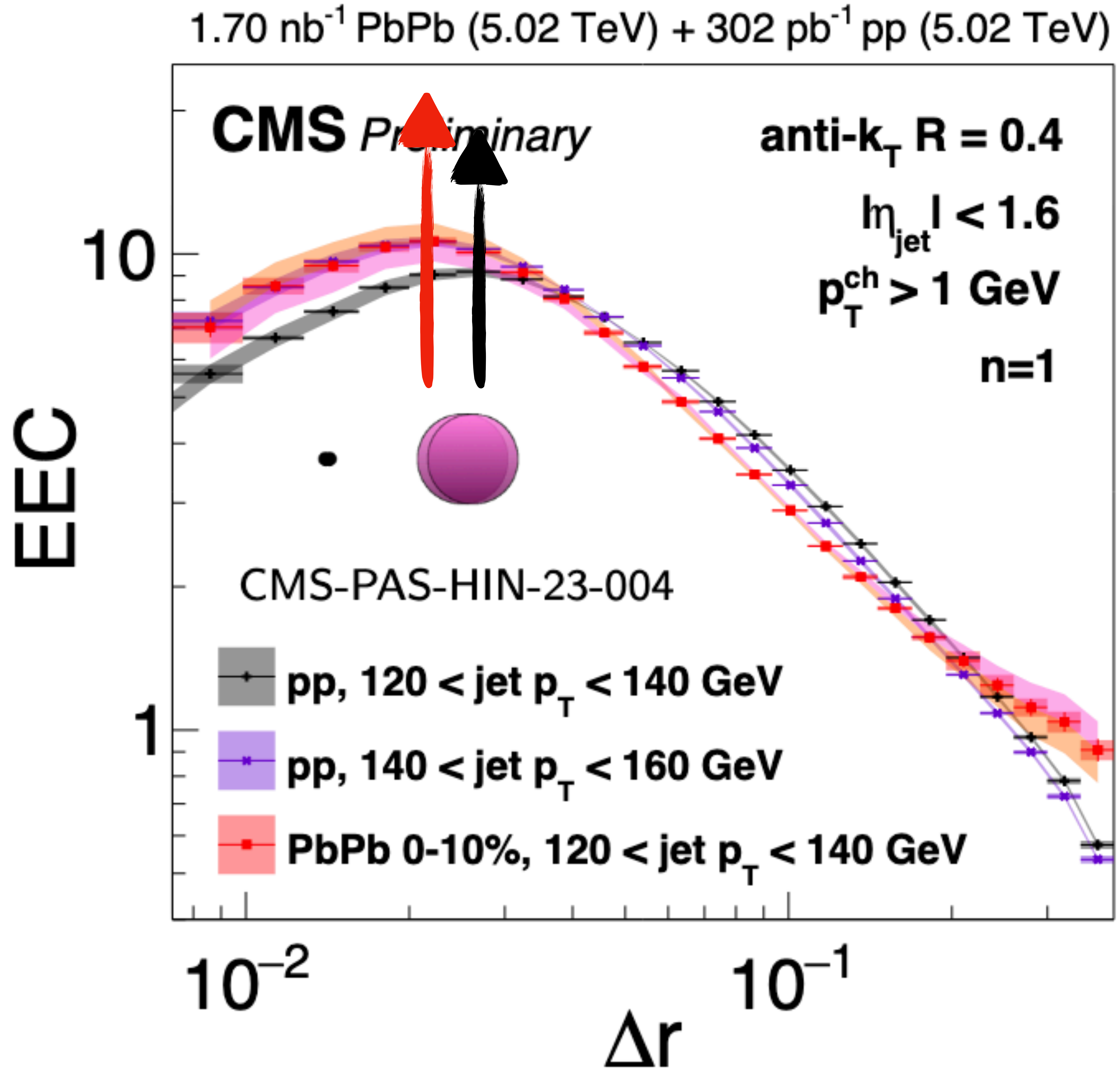
- We now have a direct evidence of PbPb jets starting at higher virtuality
- Shows selection bias which is isolated to a specific region and can be corrected

$$f^{AA}_{\rm ENC}(R_L) = \int d\varepsilon\, \bar{p}(\varepsilon) f^{\rm pp}_{\rm ENC}\left(R_L\left(1+\frac{\varepsilon\, P(R_L)}{p_T}\right)\right)$$



J Holguin, C Andres, J Viinikainen, RKE PRL 134 (2025) 8, 082303

Back to Data



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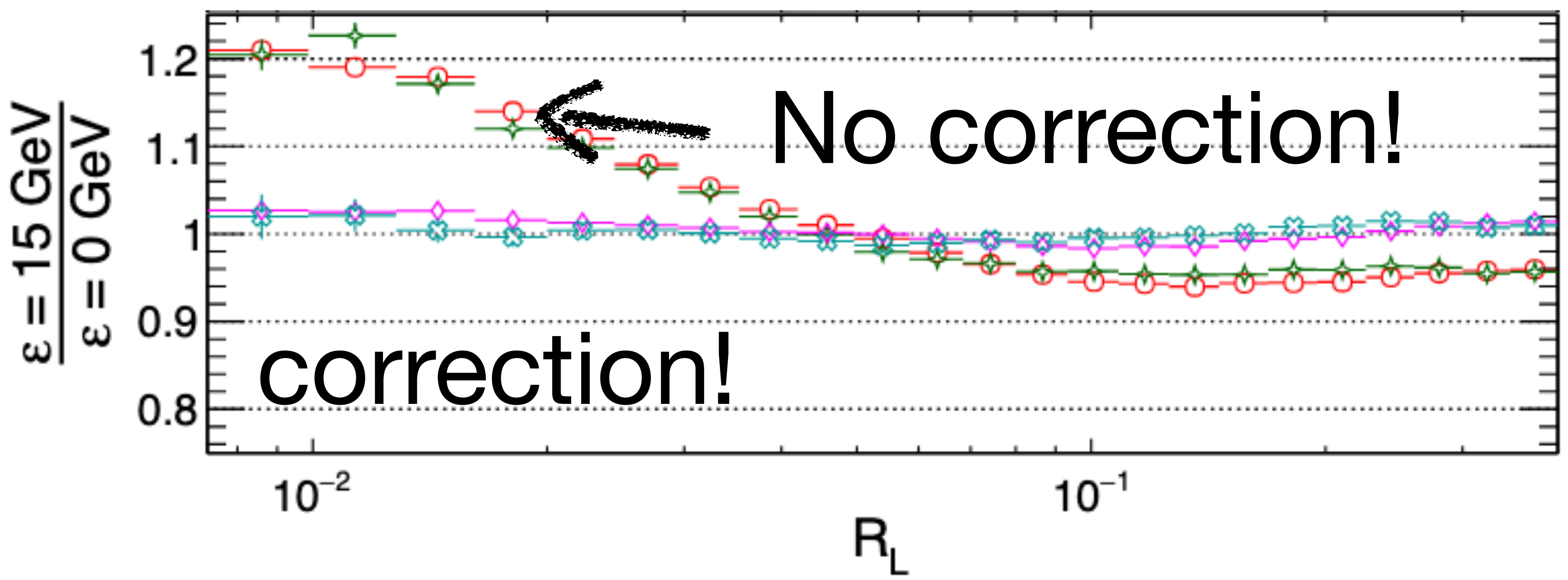


J Holguin, C Andres, J Viinikainen, RKE PRL 134 (2025) 8, 082303

On the way!

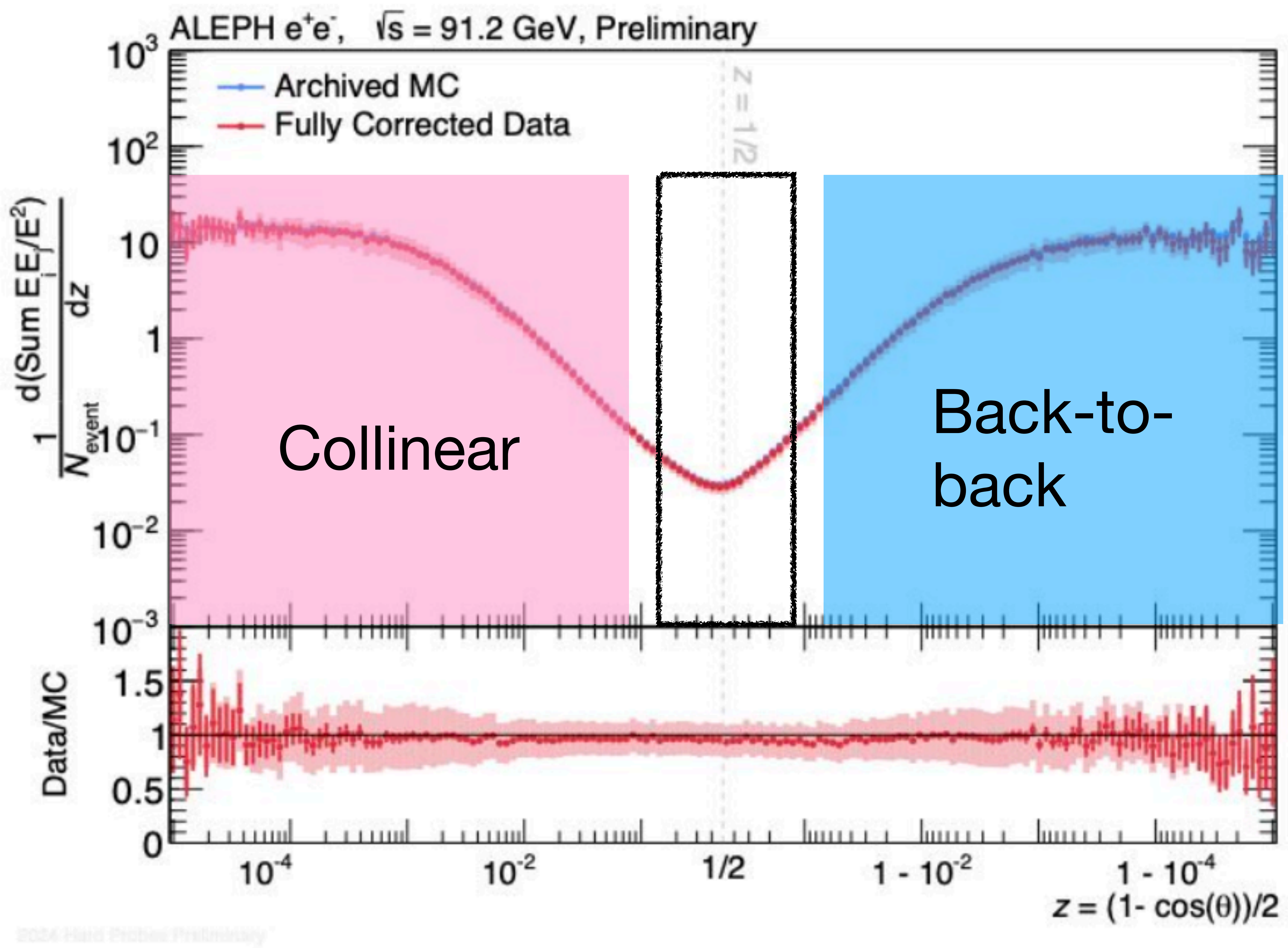
Differential studies on jets out to larger angles

Increasing the E exp-power (1,2), (1.5, 1.5)

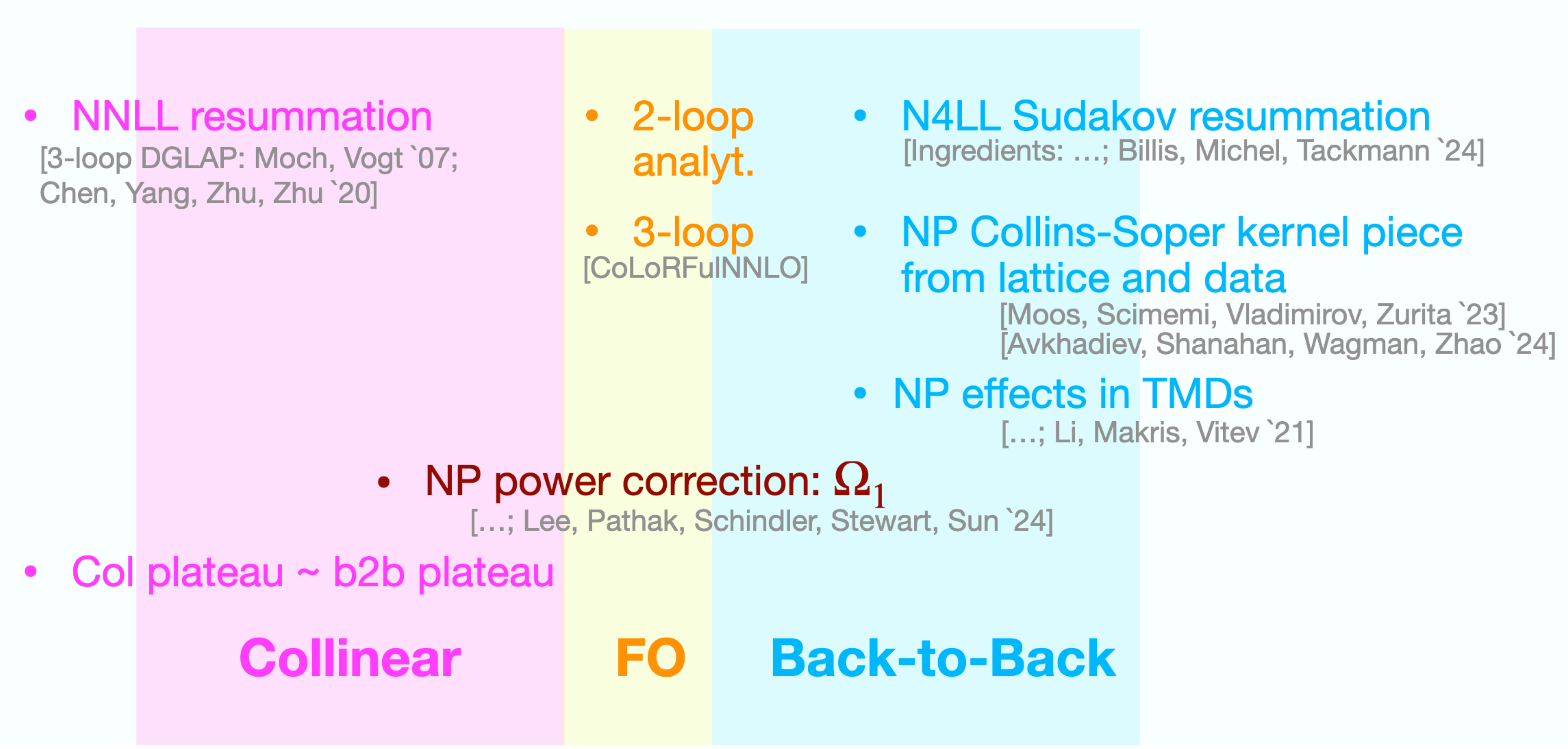
Full event EEC and also transverse EECs

Going to higher N point correlators (1,1,1)

Extending to the full event



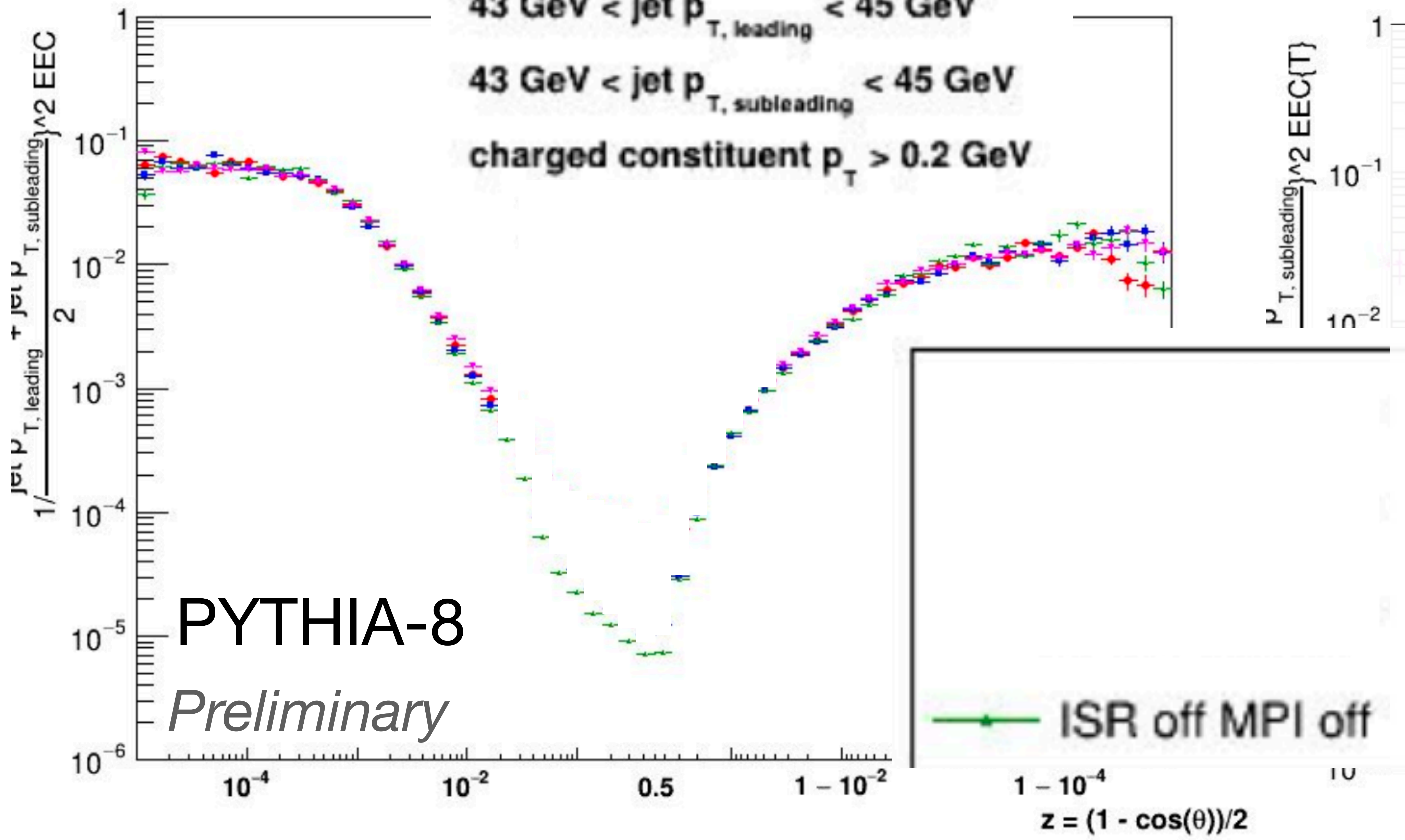
Very nice compilation by Yibei Li



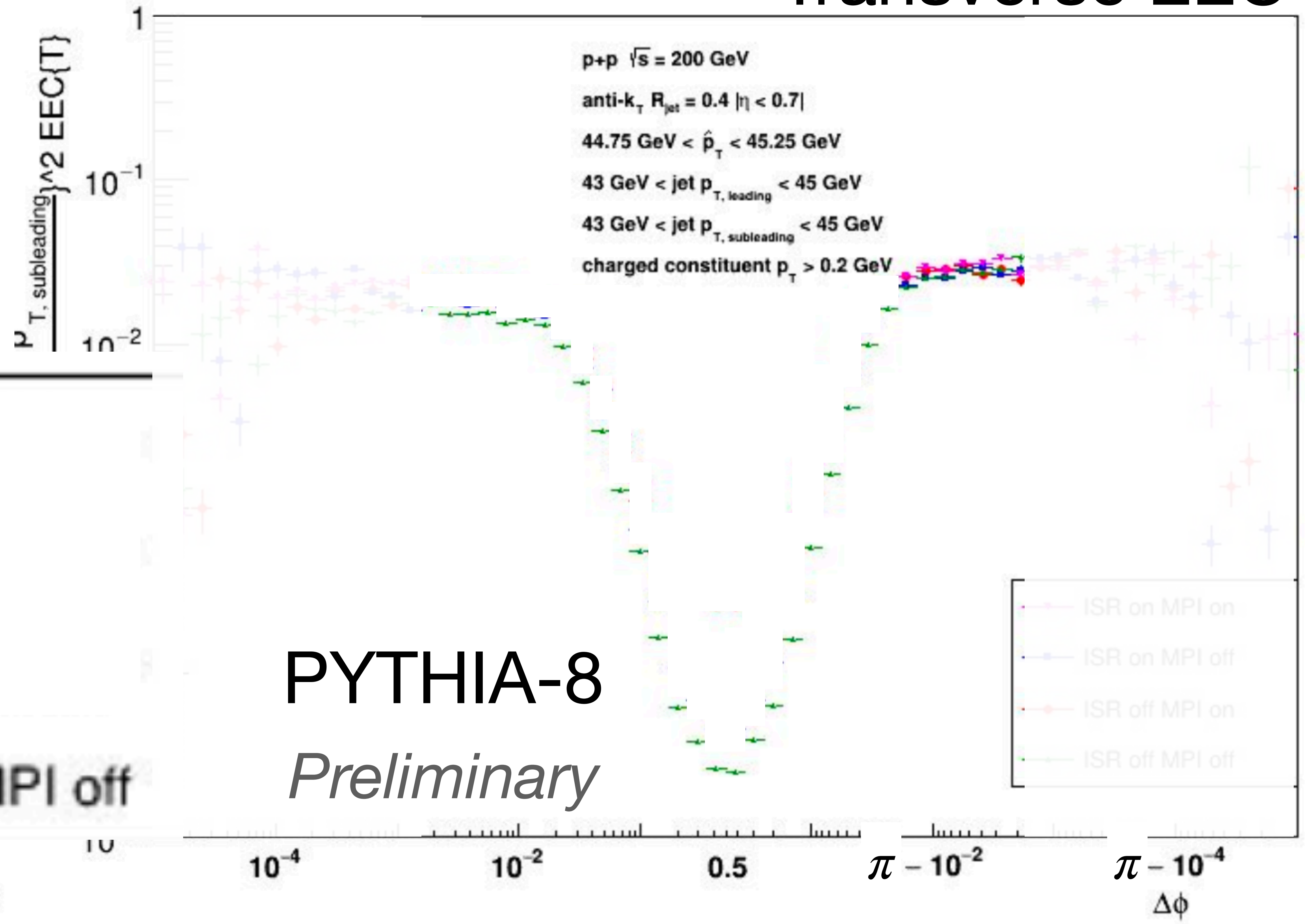
- Very clear separation of the physics in this setup
- See talks by Yibei Li, Max Jaarsma @ C3NT workshop

WEEC in p-p

Laurynette Griffin [she/they]
laurynette.griffin@vanderbilt.edu



Transverse EEC



- Whole event EEC in z does not have the similar shape as e^+e^- due to rapidity spread along the beam axis - Transverse EEC removes this effect and looks perfect!

WEEC in p-p

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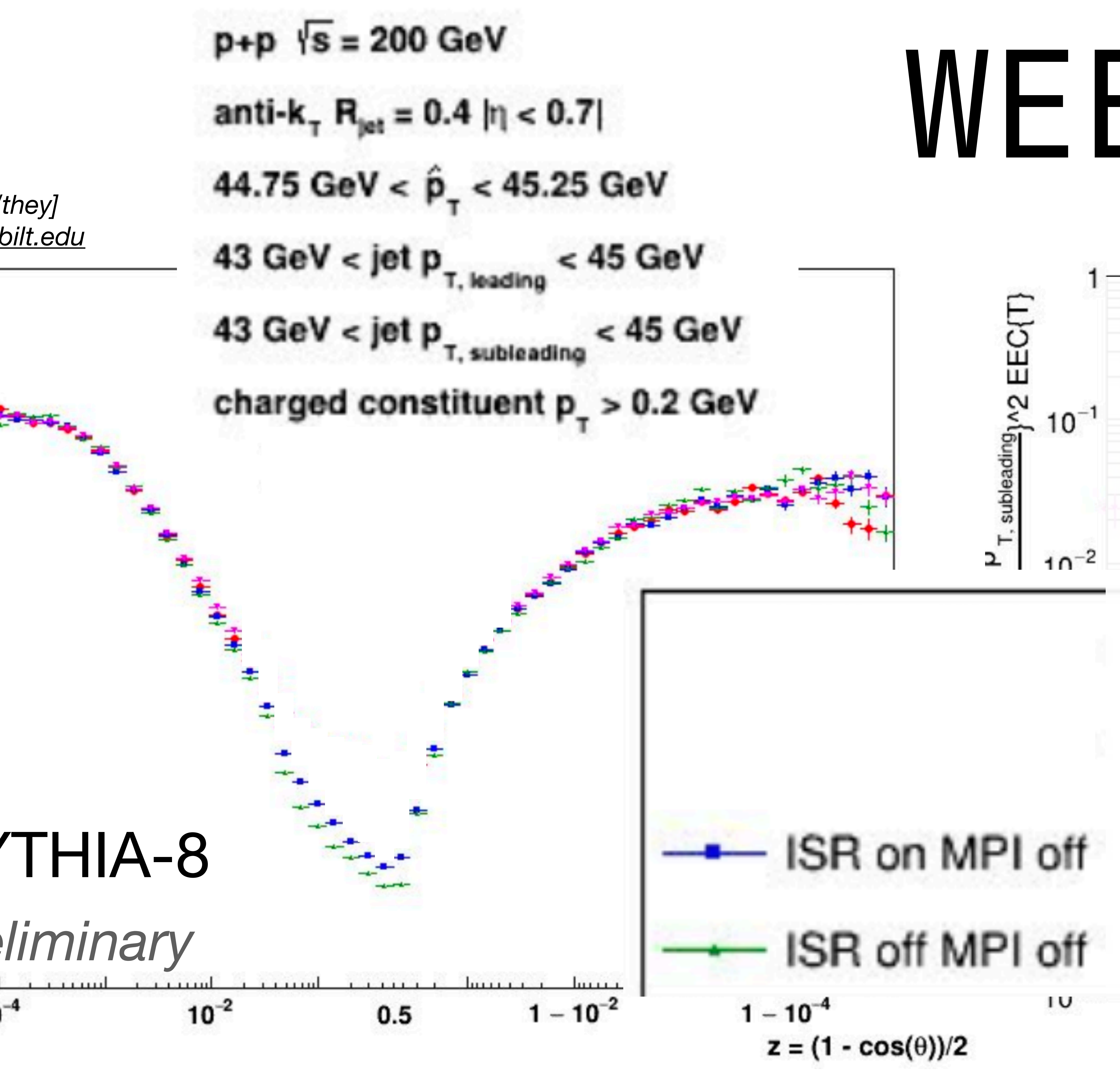
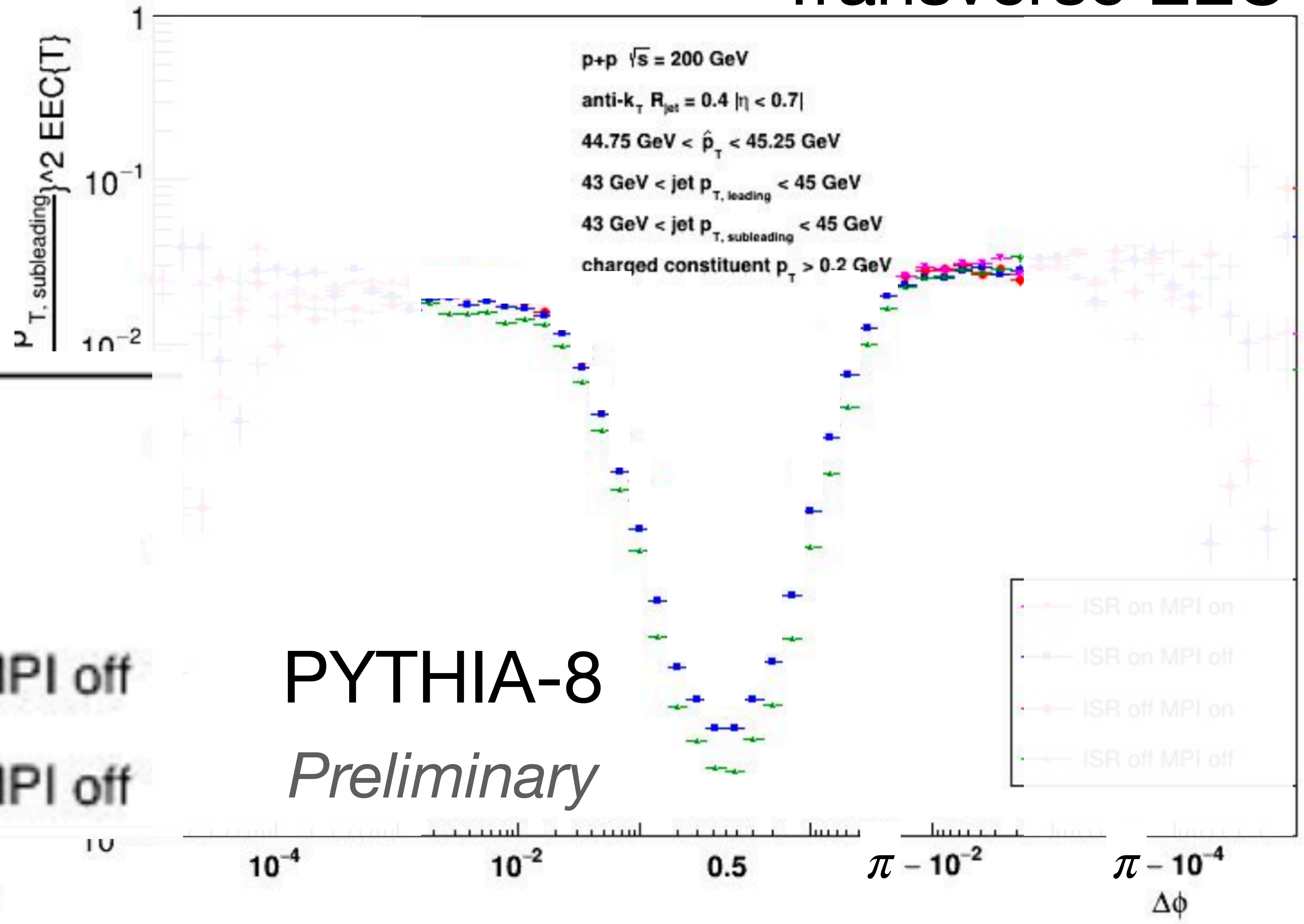


Transverse EEC



- Adding ISR - similar to adding a small background in the middle region but doesnt overall effect the shape

WEEC in p-p

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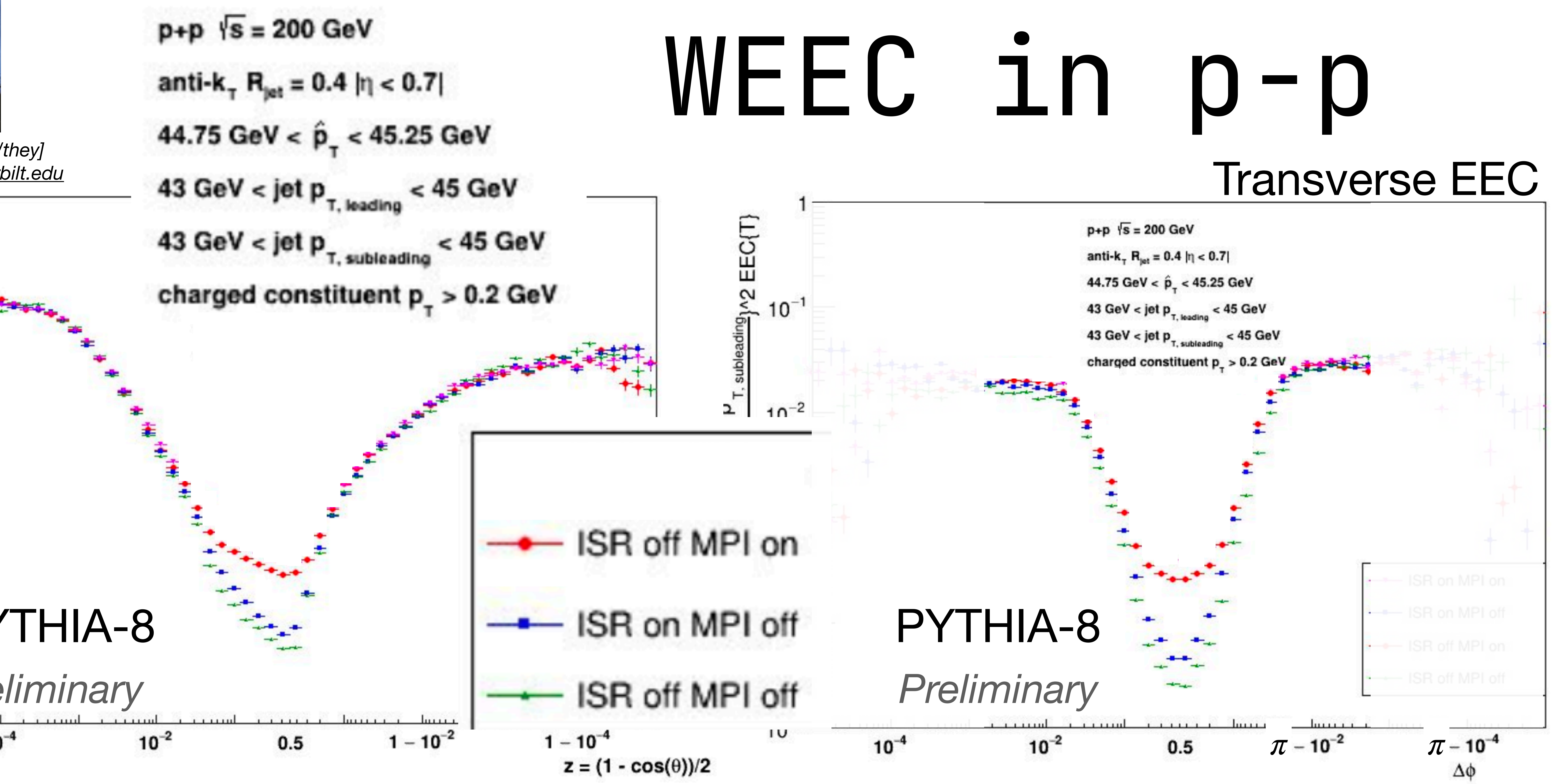

- Turning on MPI - Huge increase in overall background! Shape modification consistently across a very wide region in z and $\Delta\phi$

Laurynette Griffin [she/they]
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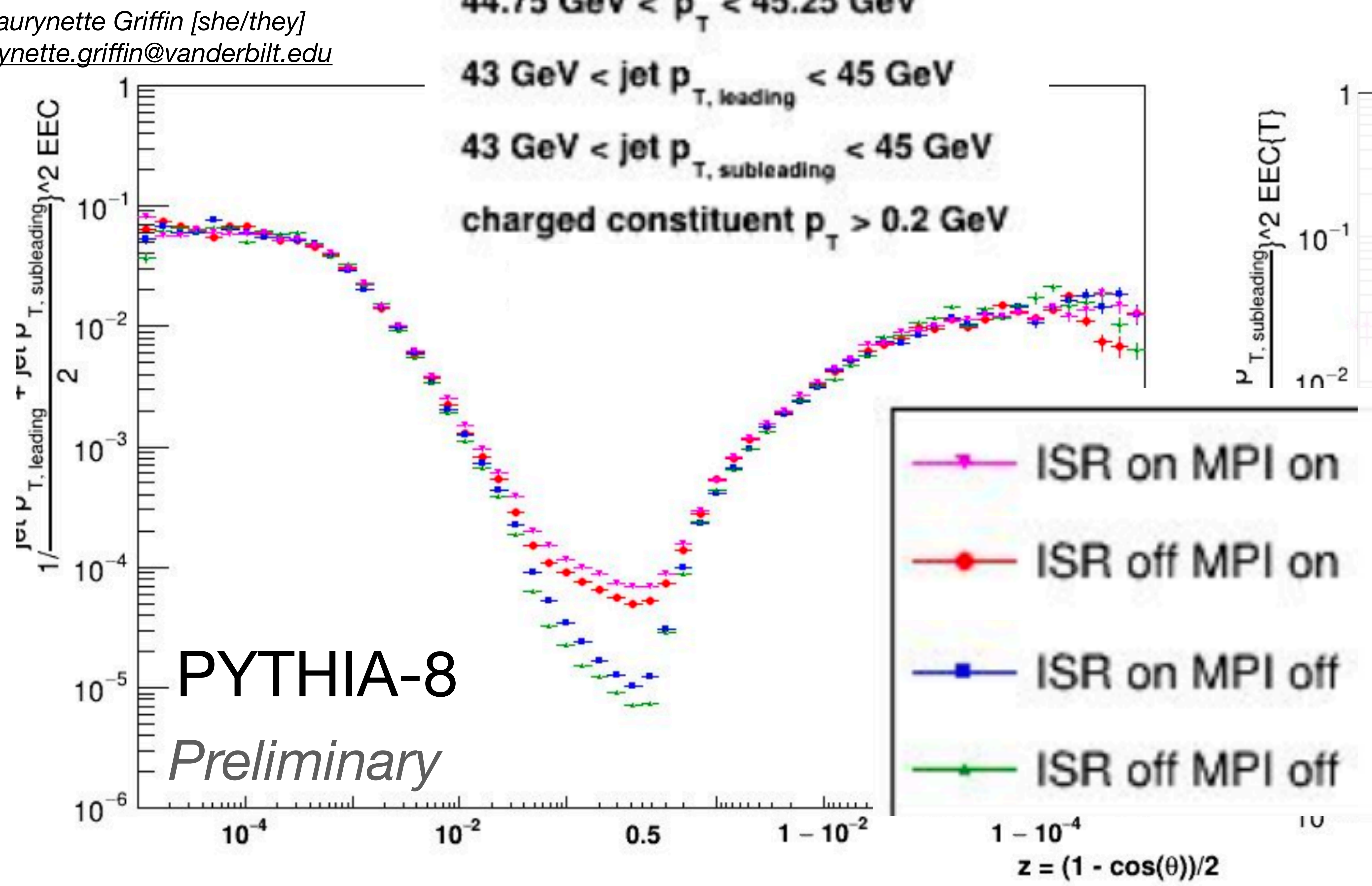
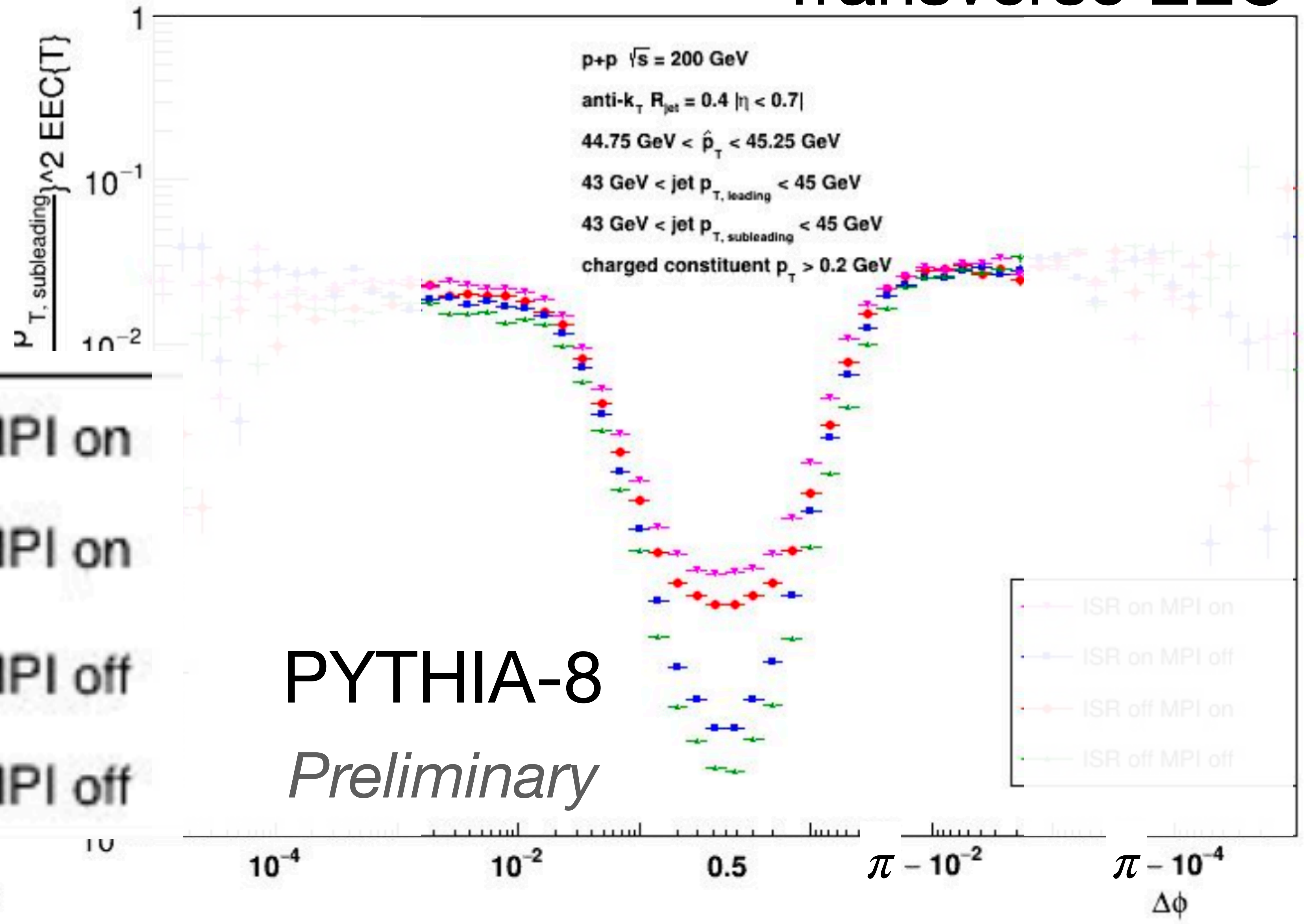
WEEC in p-p



Transverse EEC



- This is still not a realistic pp di-jet event! We selected significantly narrow jet momenta range in both the leading and sub-leading jets!

WEEC in Au-Au

Laurynette Griffin [she/they]
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Benjamin Kimelman [he/him]
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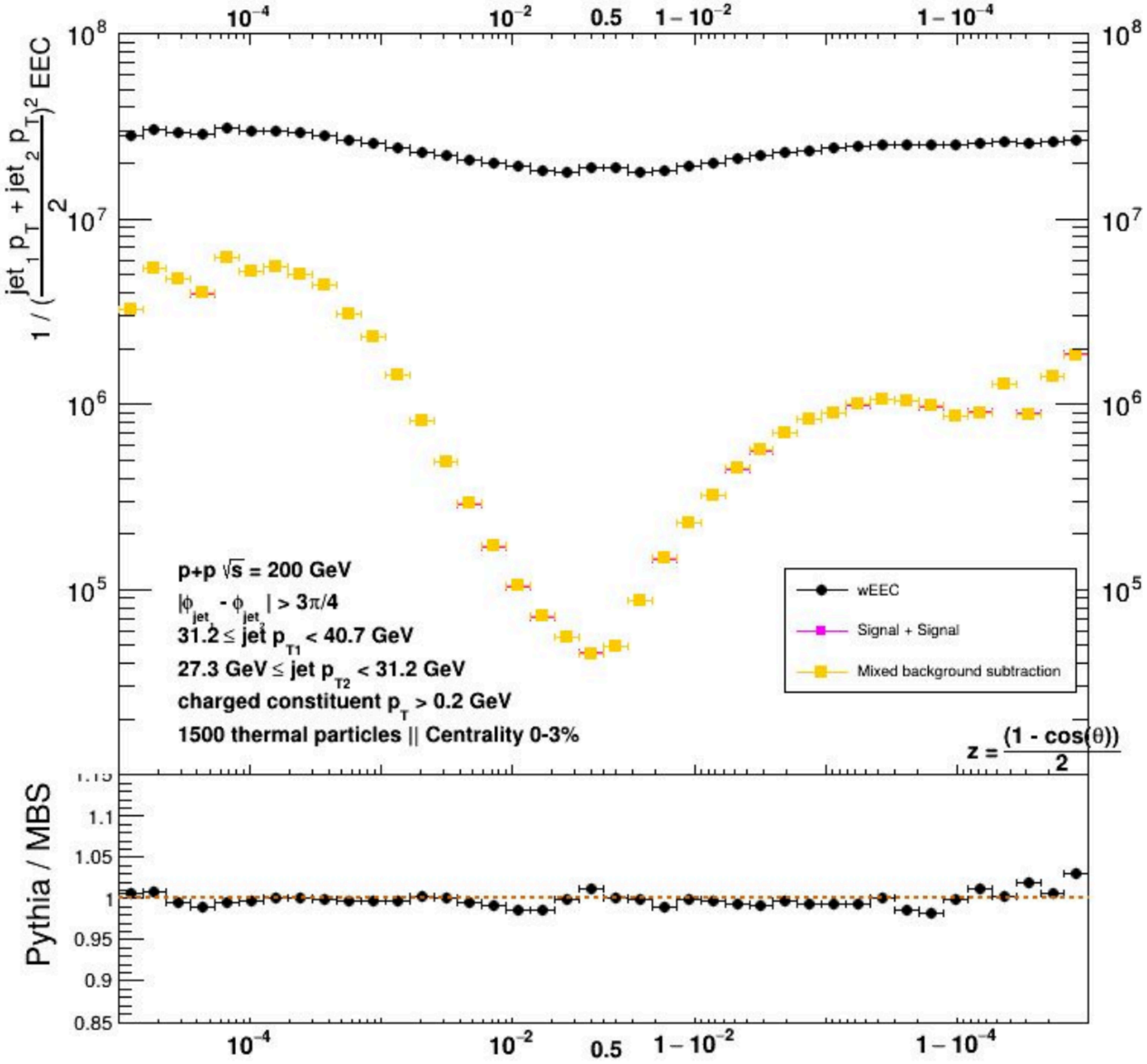
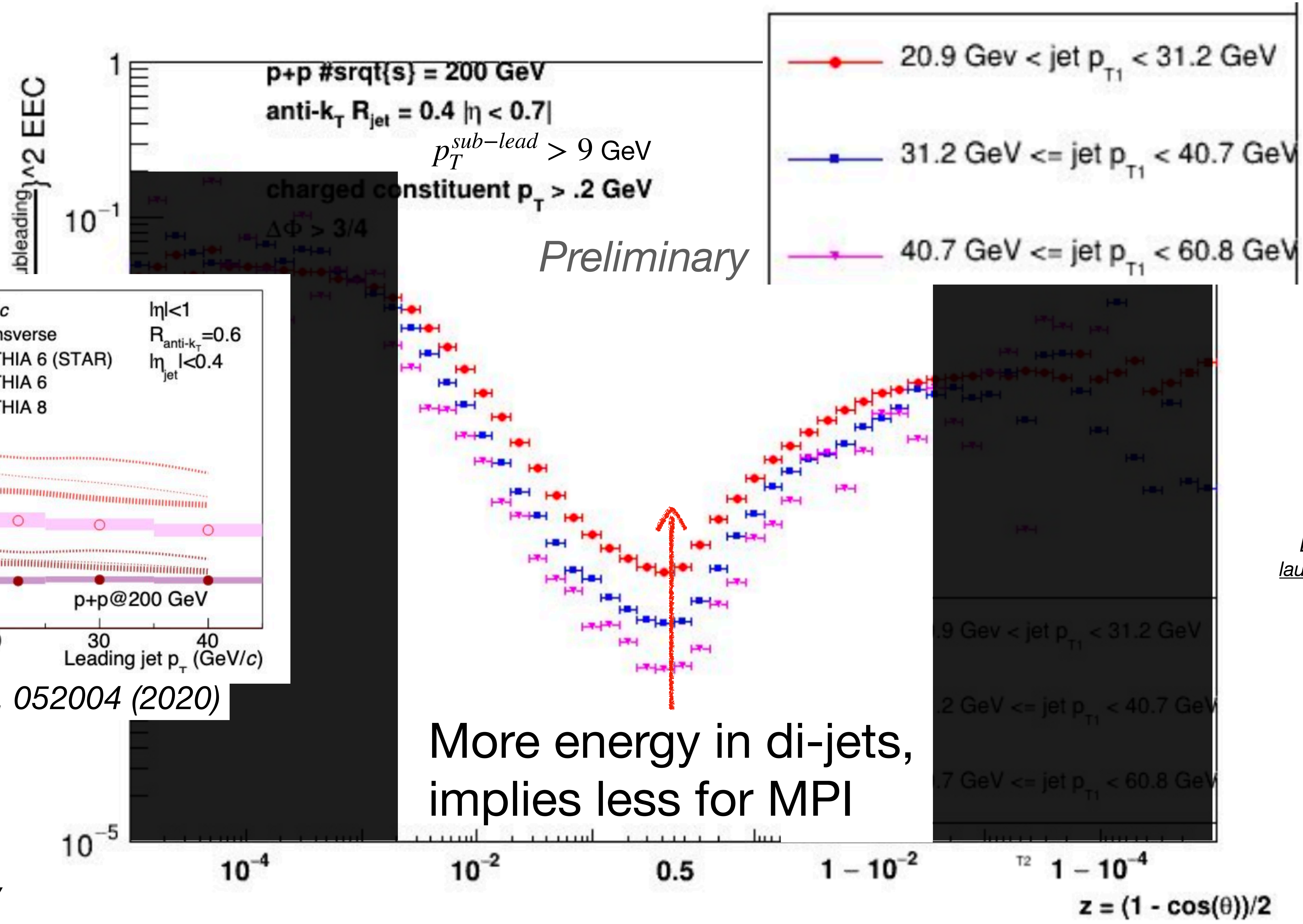
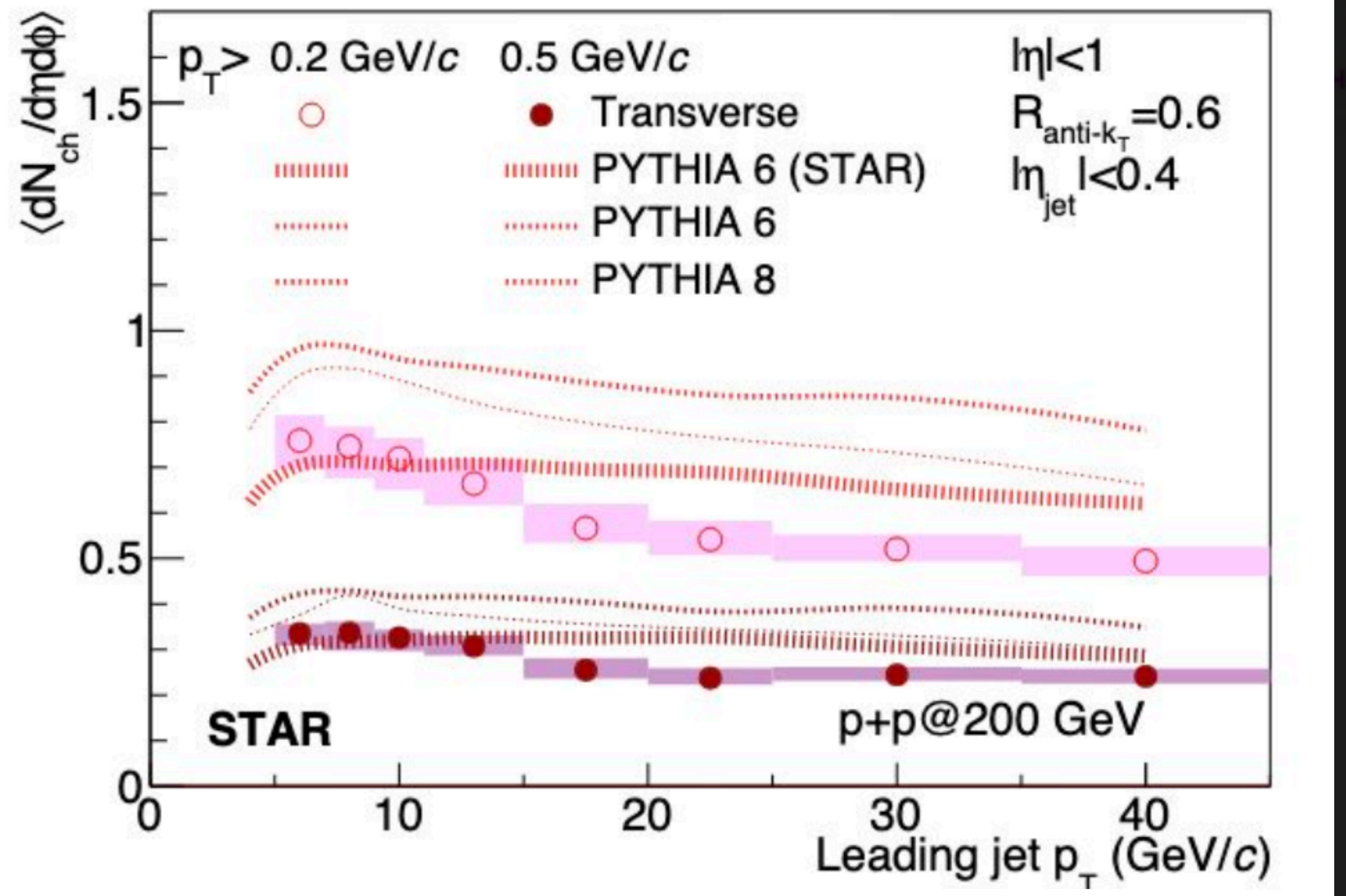
- Realistic background at RHIC energies completely destroys the signal!
- We need to subtract O(1e3) background
- Our methodology reproduces the signals with percent level deviations



How about a more realistic case?





STAR PRD 101, 052004 (2020)

More energy in di-jets, implies less for MPI

Laurynette Griffin [she/they]
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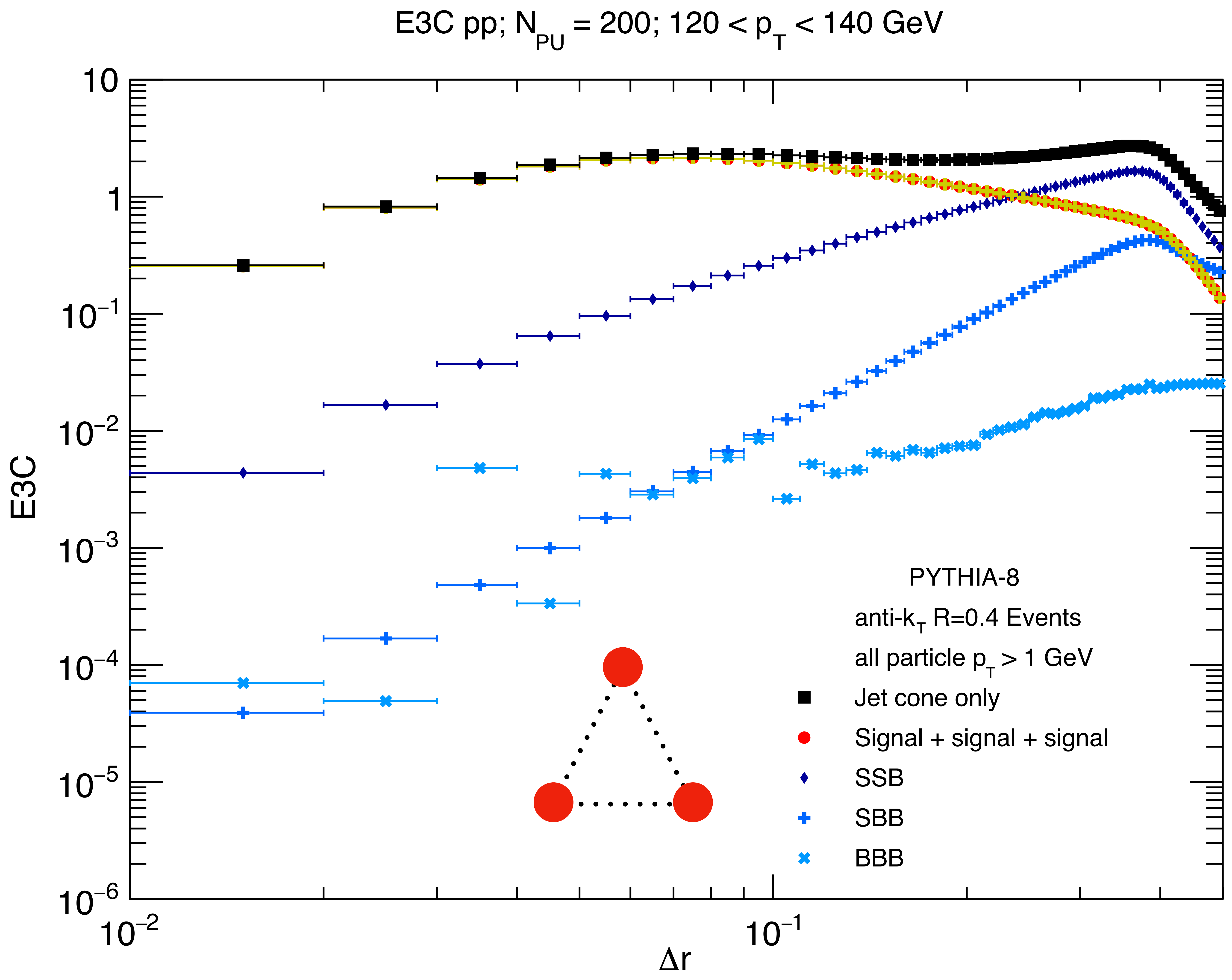
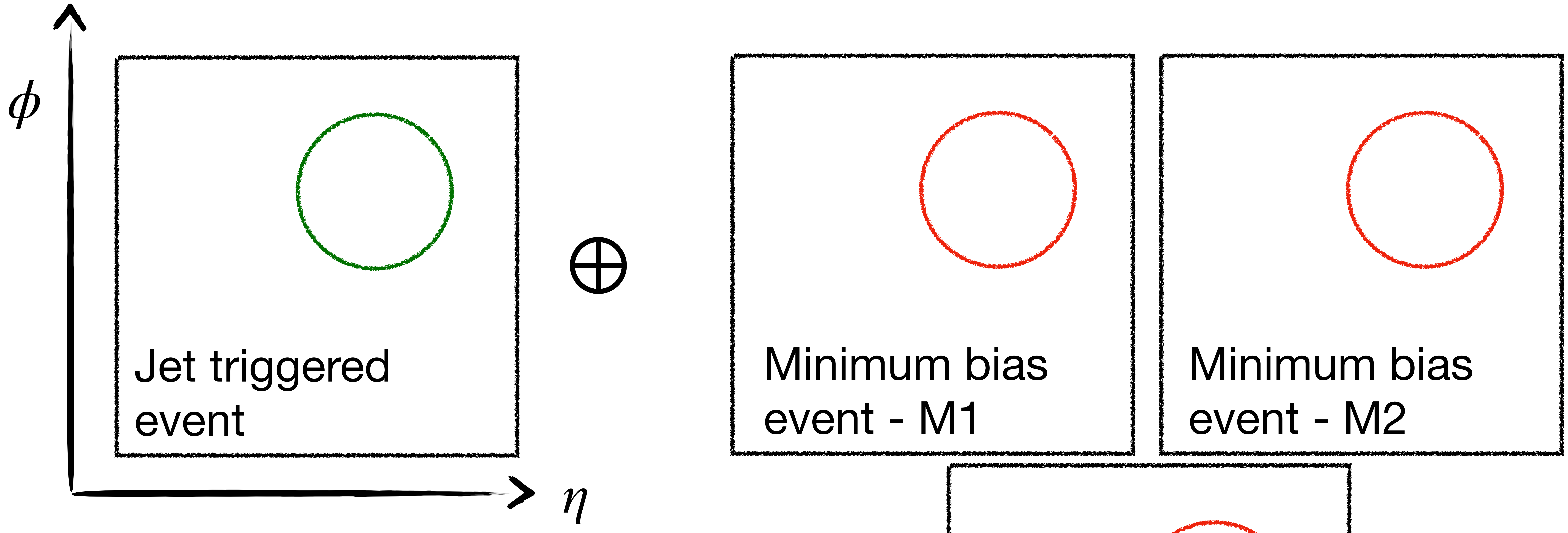
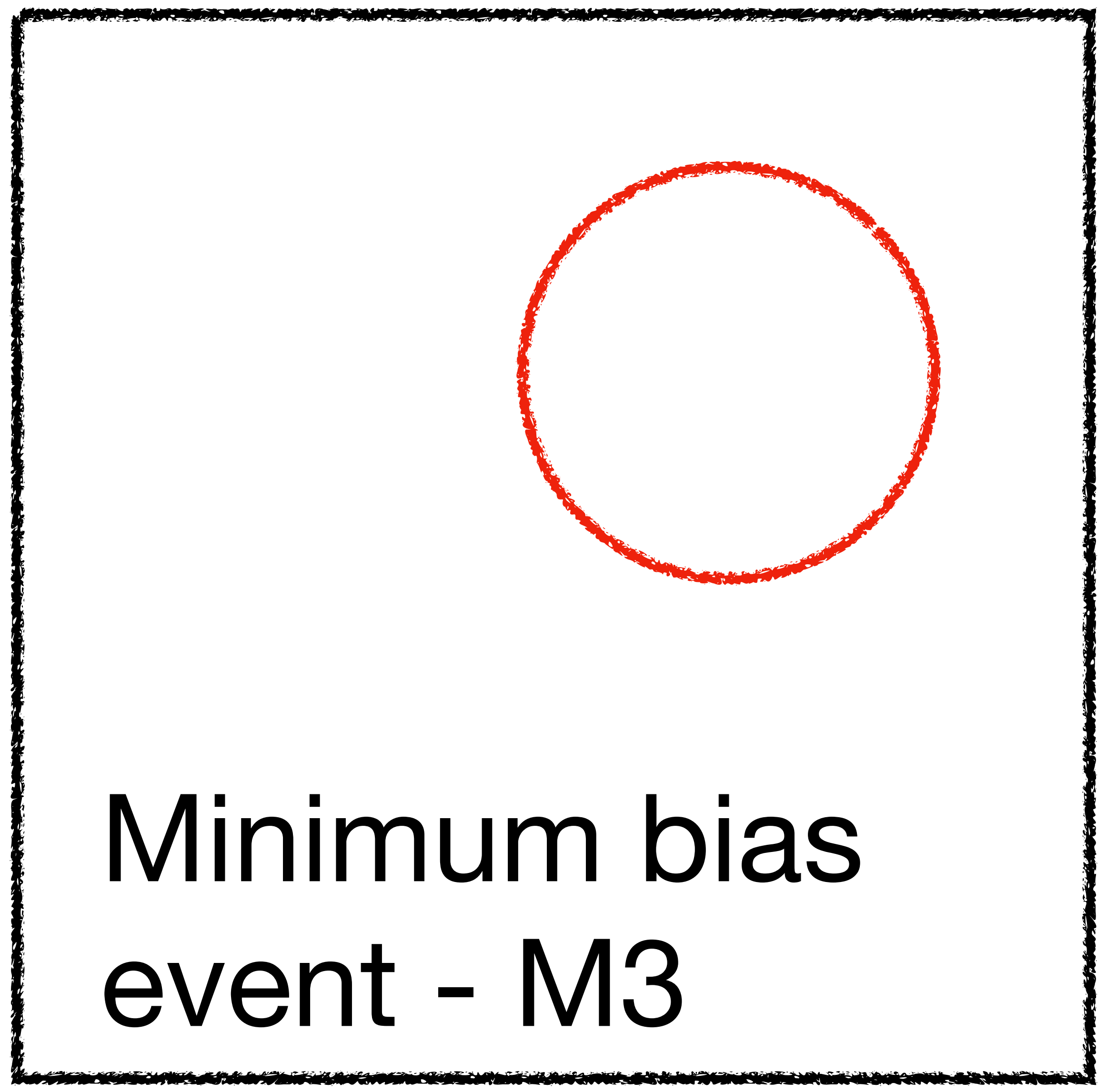
Dealing with triplets!



- Estimate the impact of the heavy ion underlying event with multiple pileup minimum bias events
- Significant correction needed especially when one considers the amount
- Lets try with the existing bkg sub method and see if we can expand it!



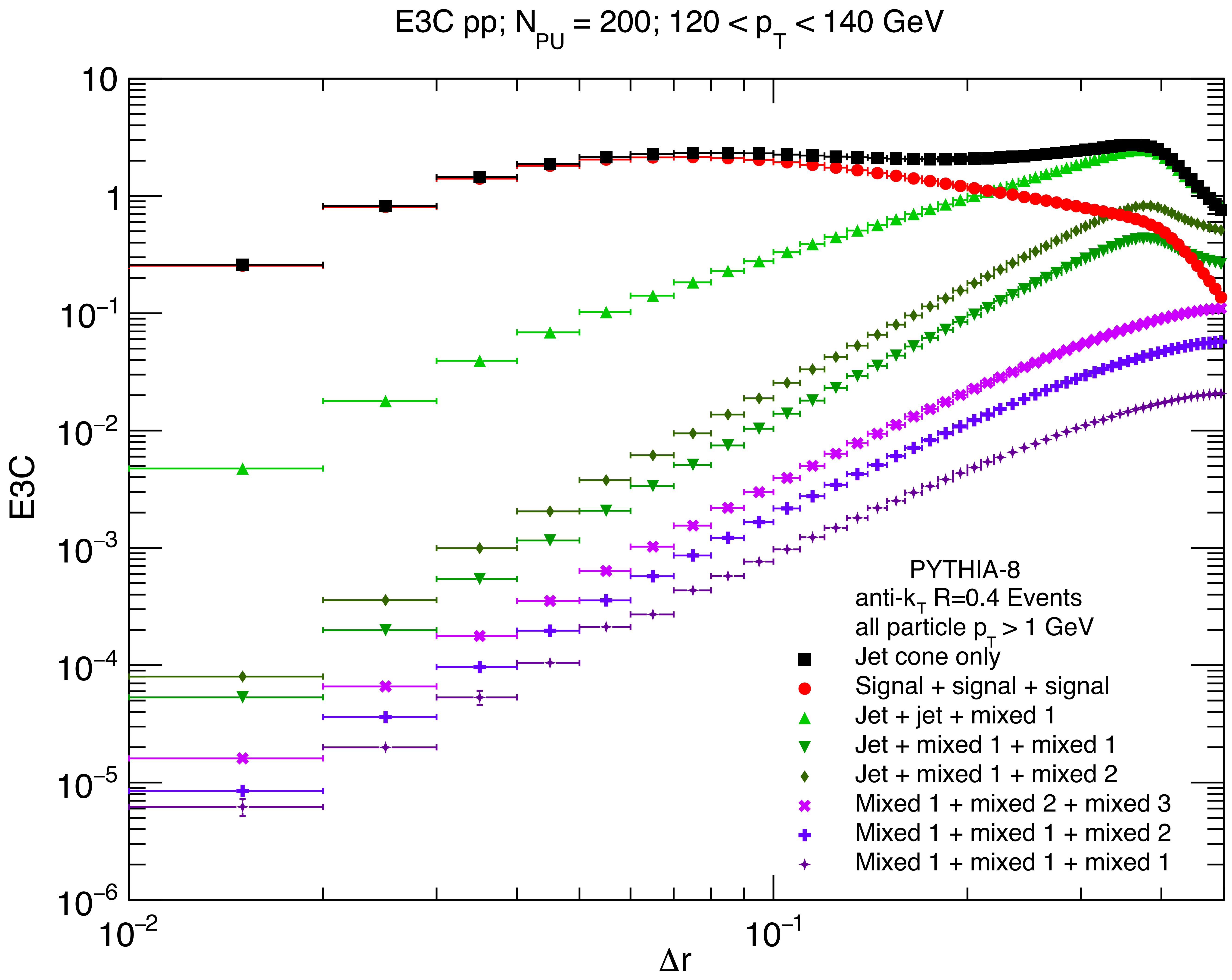


- What you measure = SSS + SSB + SBB + BBB

- Total Background = SSB + SBB + BBB [SSM1] + SBB + BBB [SM1M1] + BBB [M1M1M1] - 2 * BBB [M1M1M2] - SBB - BBB [SM1M2] + BBB [M1M2M3]

Note: these are from unique triplets!

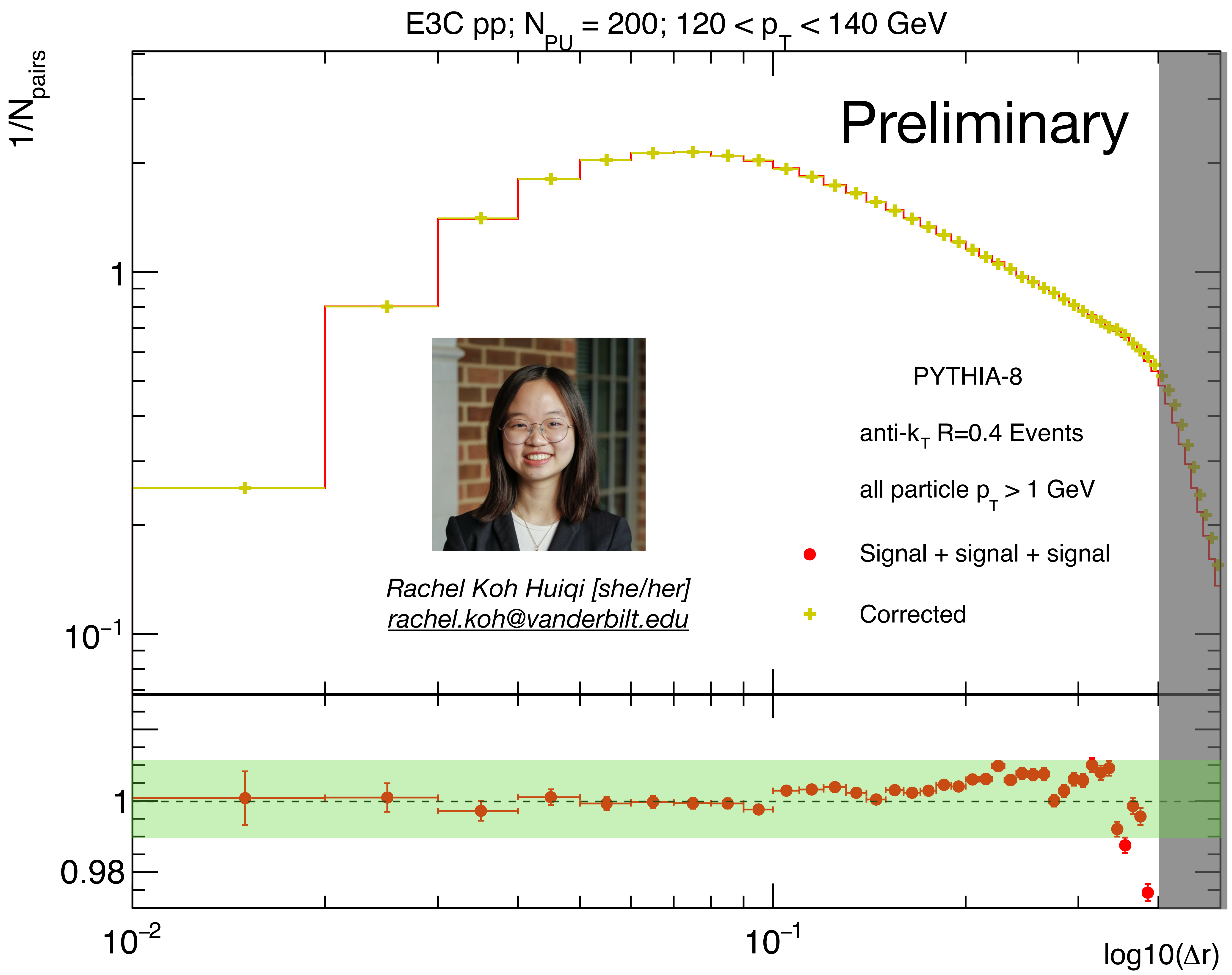
Performance of the subtraction



- These are all the relevant combinations
- There is a specific condition that we need to correct for -
- The mere fact that you do jet finding results in your background estimate needing to be adjusted

Note: these are from unique triplets!

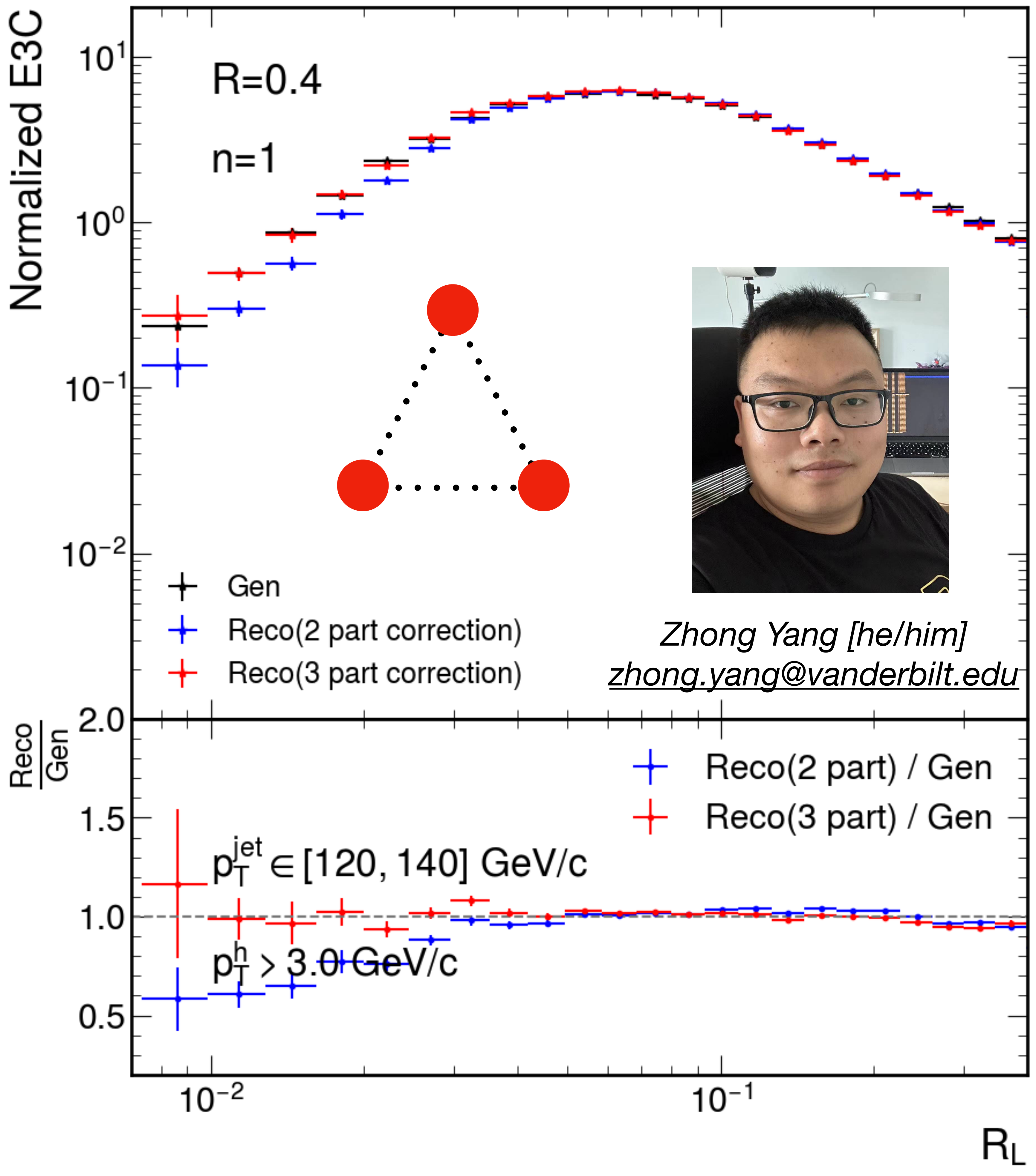
Performance of the subtraction

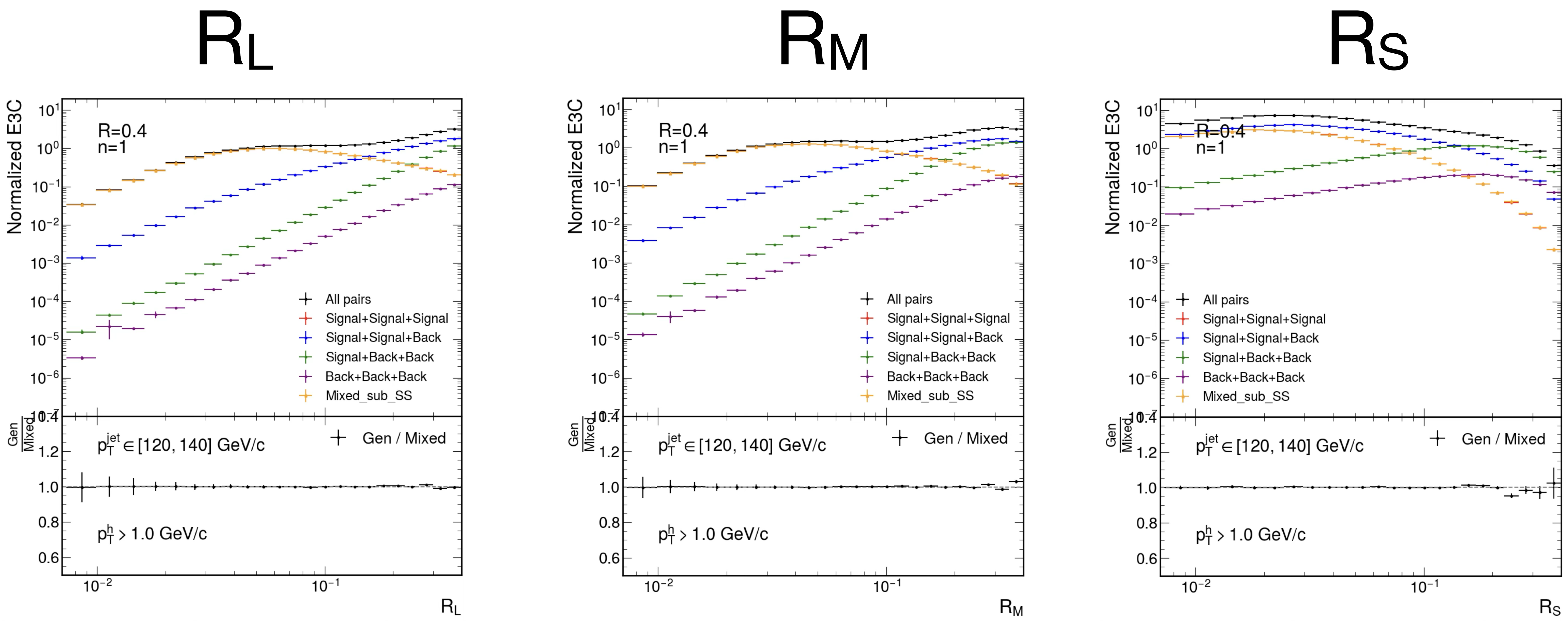


- Very good estimate of the background through the entire region of accessibility (experimentally)
- Sub percent non-closure until we get to the large angular region (which is the region of interest for wake physics)
- RS, RM, RL should be measurable similarly!
  (ξ, ϕ not clear at this point..)

Note: these are from unique triplets!

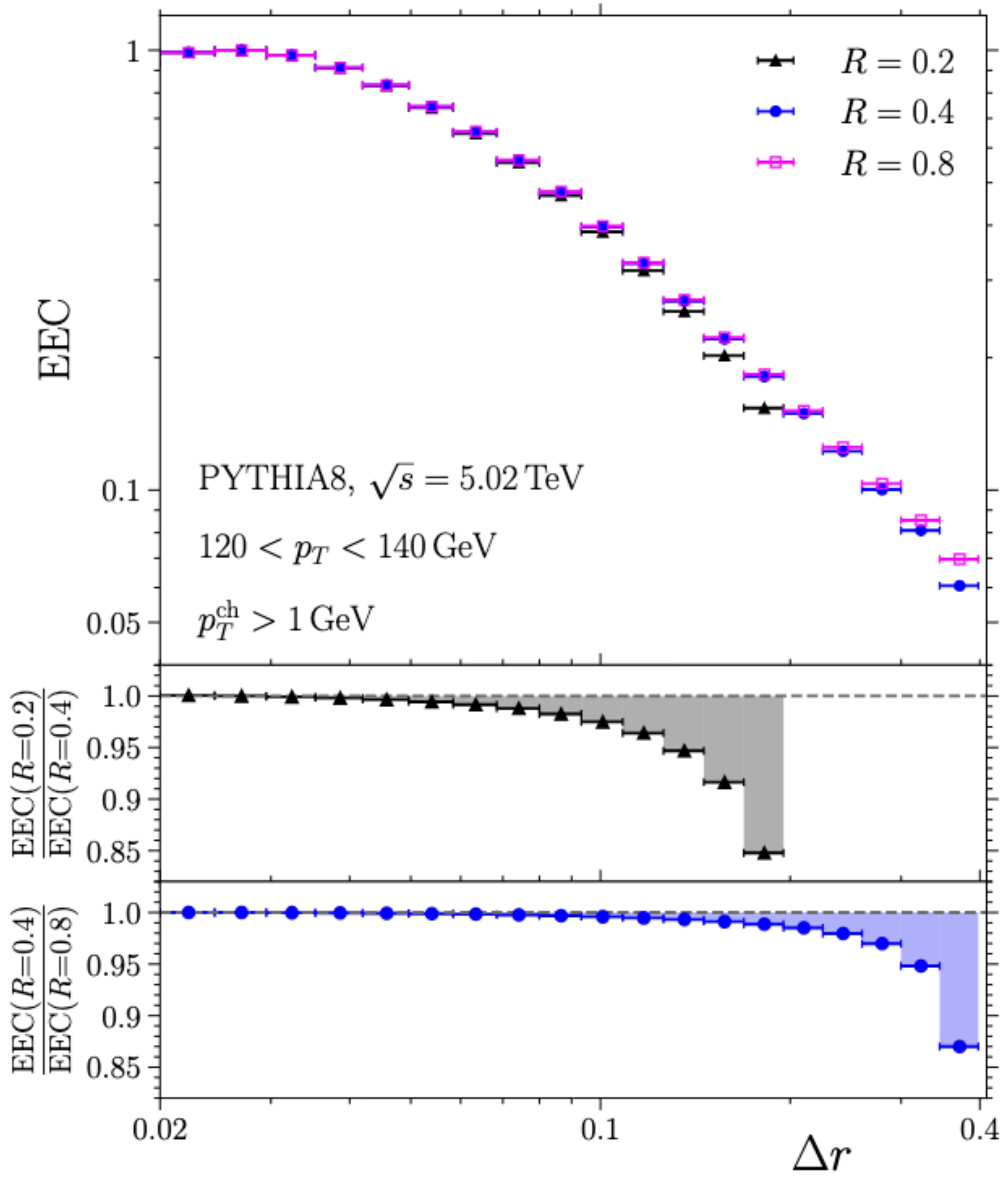
Correcting 3-track correlations



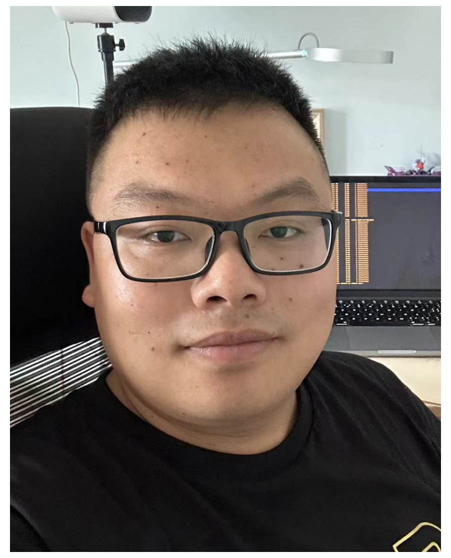


- Need to develop new set of 3-track corrections which are inherently multidimensional (jet momentum, track 1,2,3 momenta)
- Methodology seems sound at the simulation level - currently underway in measurement!

Measuring till the edge of the jet!



- Selecting a jet axis and extending out to much larger angle results in significant loss due to jet finding not giving you a perfect circle!
- This effect is intrinsic to anything that uses jet finding (can be calculated)
- This is a big issue for increasing the degree of precession in HI jet substructure



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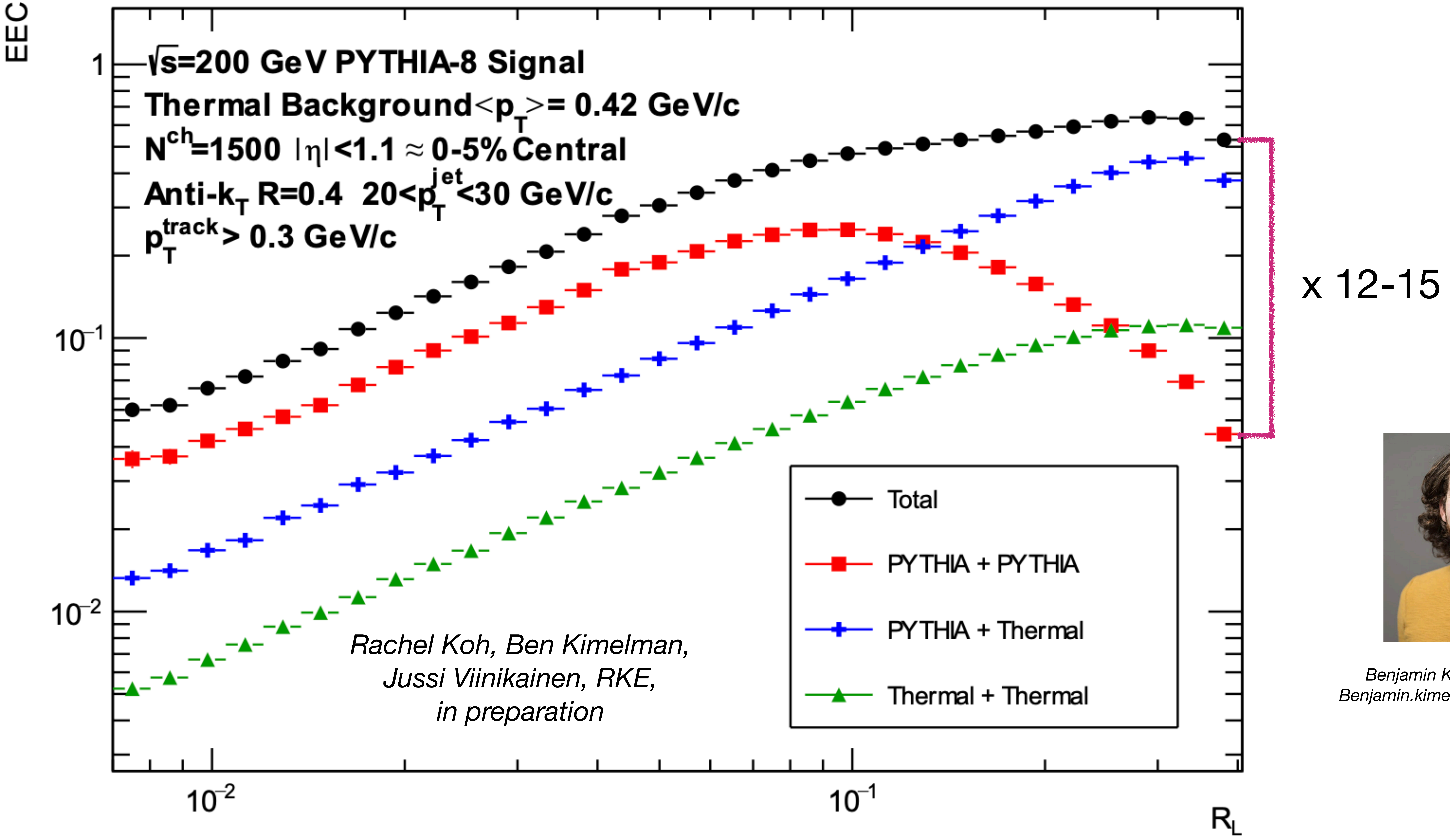
Z Yang, B Kimelman, J. Holguin, J. Viinikainen, C. Andres, RKE, in preparation

Where are we now!

- **Why did we do this measurement?**
- **What are the different feature spaces of this observable?**
- **How did we do this measurement?**
- **What have we done/are doing to understand what we see?**
- **What are some next steps?**

- **Expected to see unambiguous evidence of angular dependent energy loss - we did not**
- **Varying regions with dominant effects from pQCD, npQCD and a 'universal' scale - maybe**
- **Background subtraction was imperative and needed a statistical ensemble method - works**
- **Phenomenology studies of jet flavor, E exponents, edge effects… - many areas of exploration underway!**
- **Stay Tuned!**

Bonus Slides



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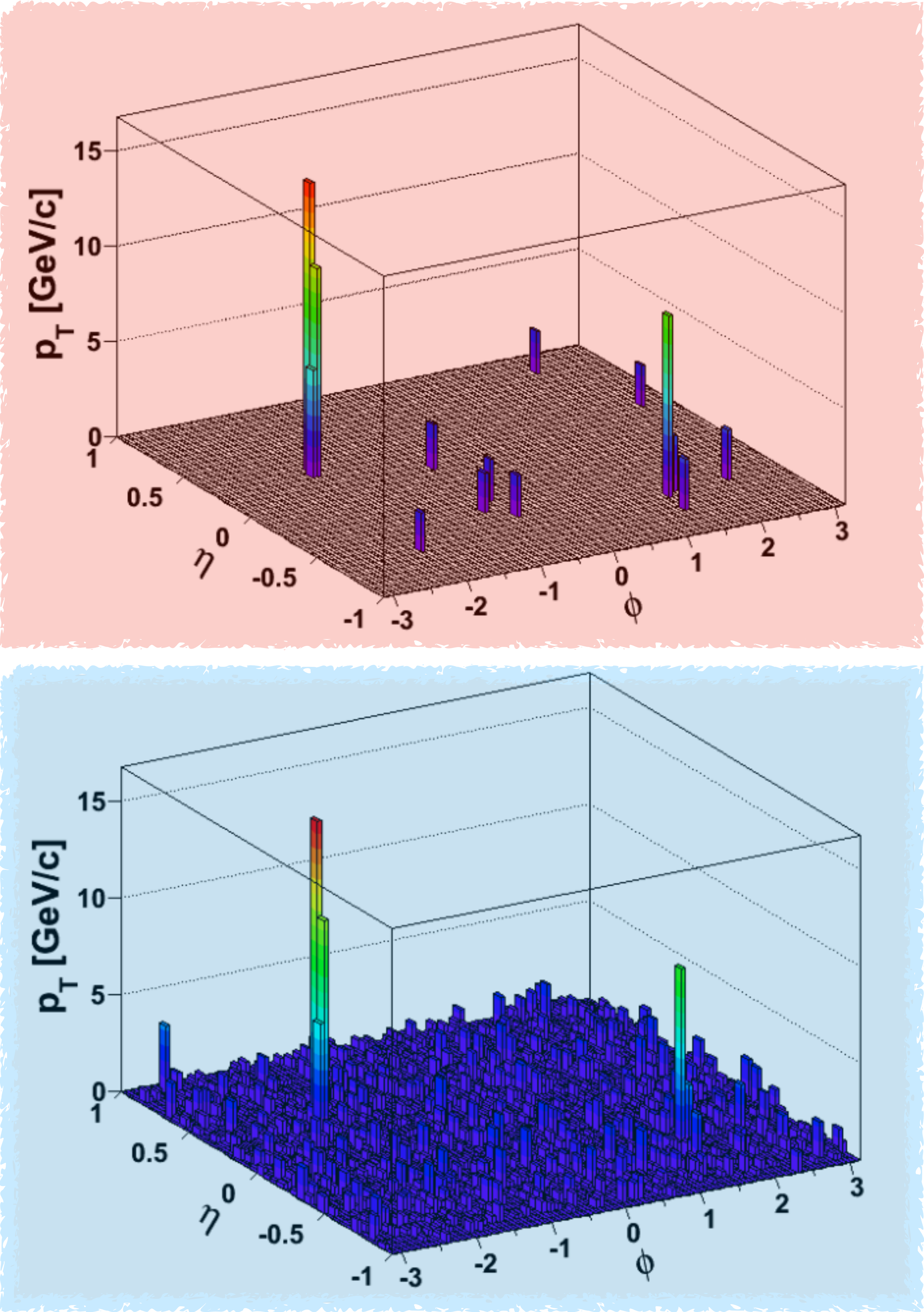

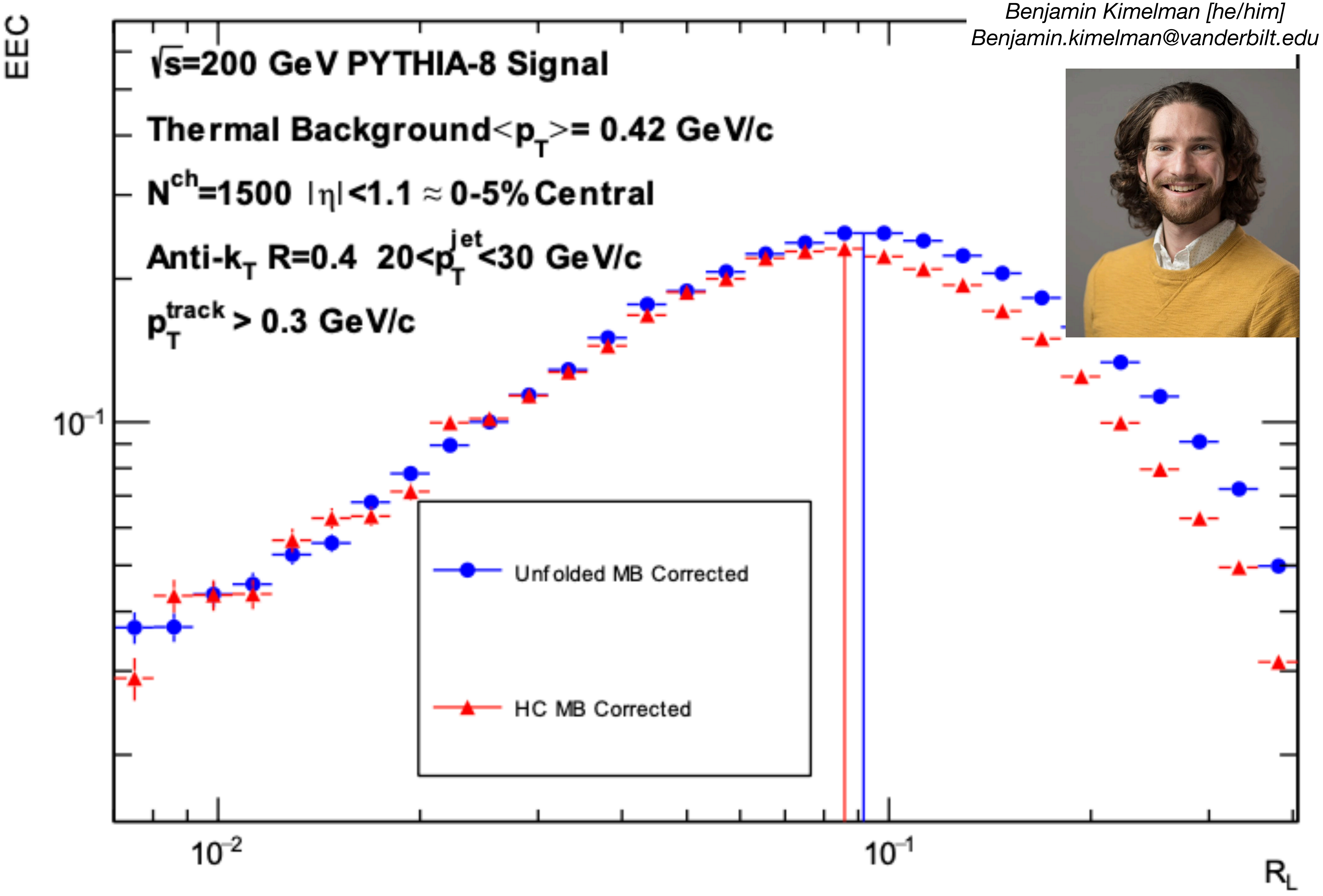

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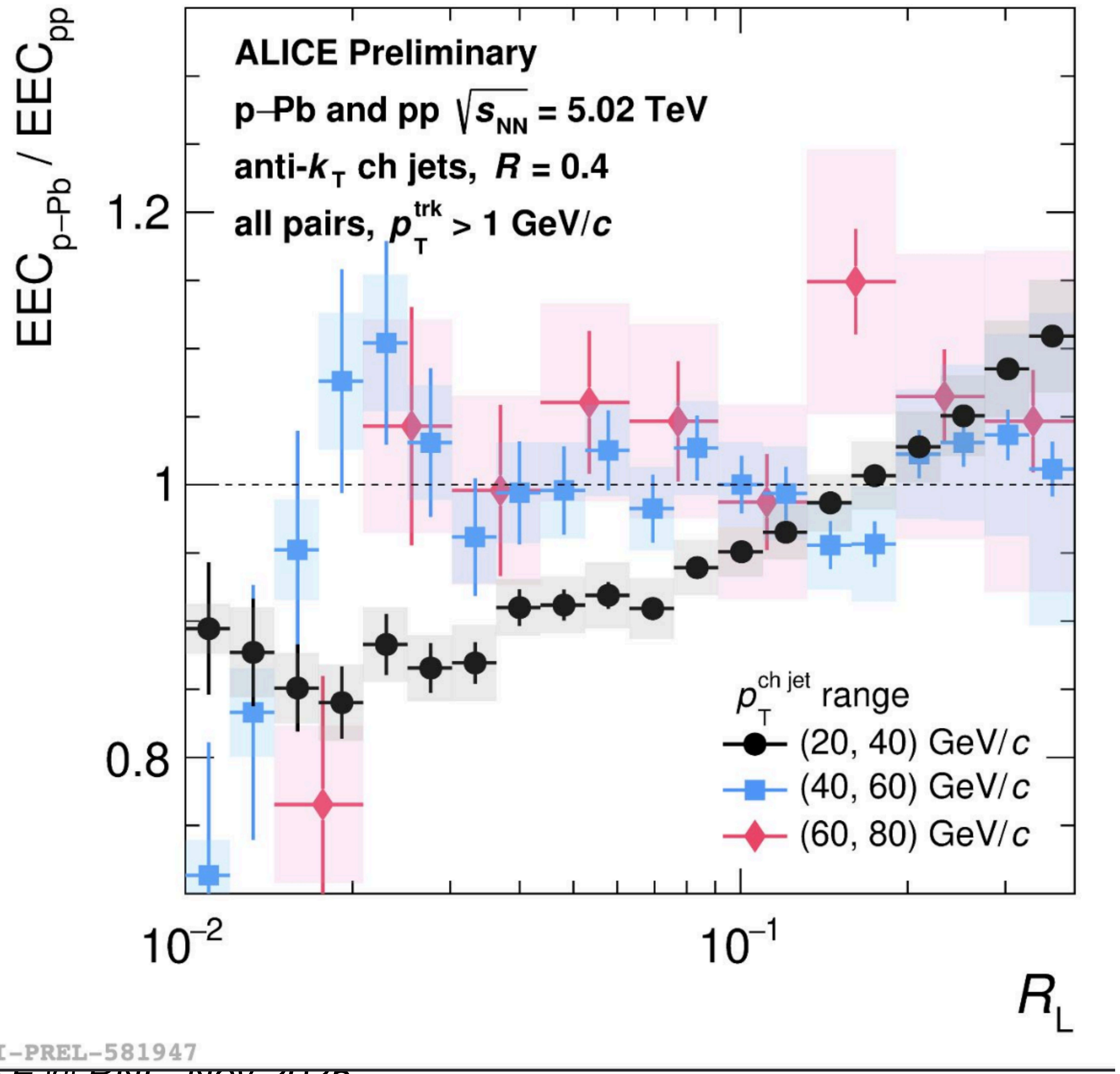
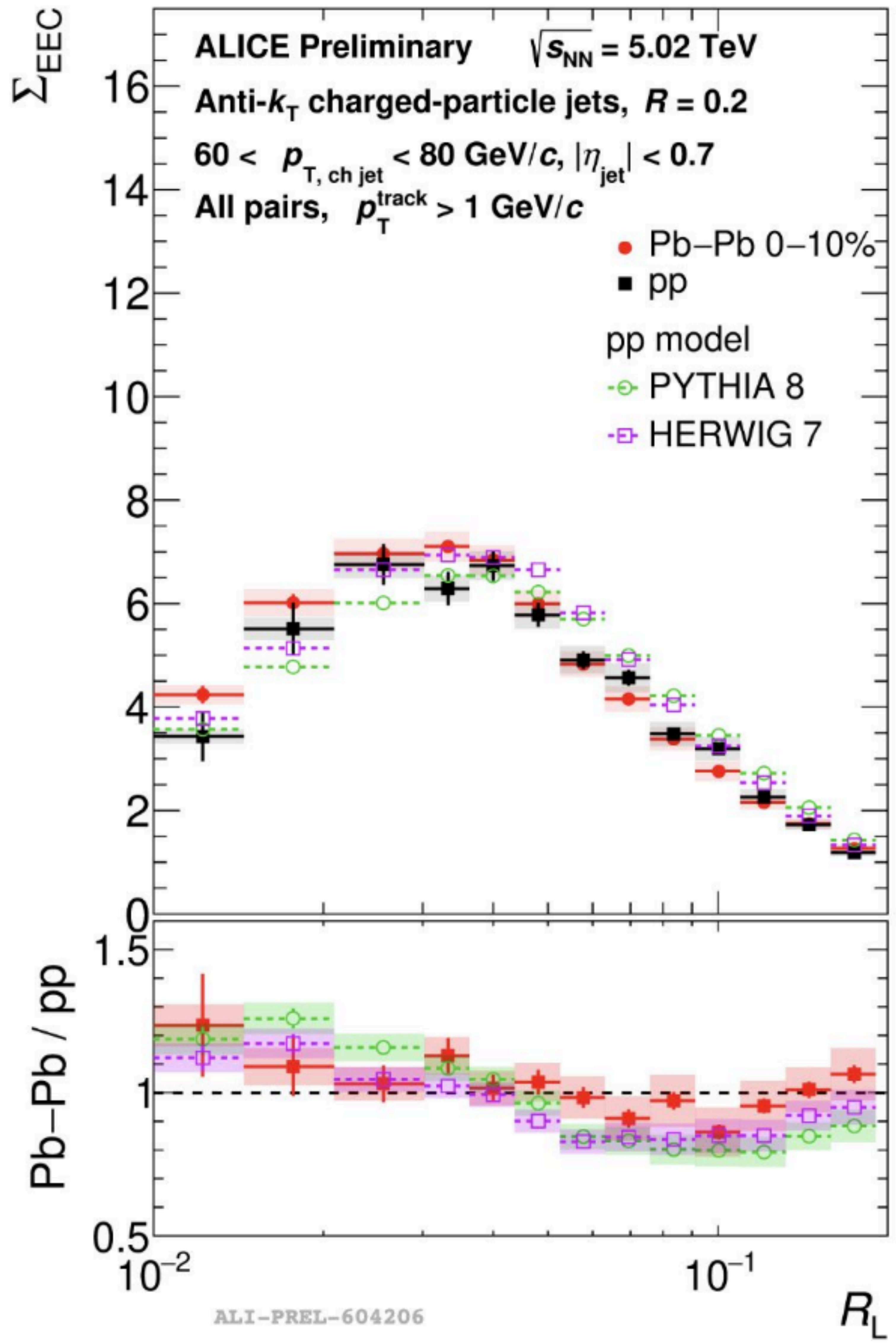
- Two ways select and fully correct for observable.
- Quantify the bias!

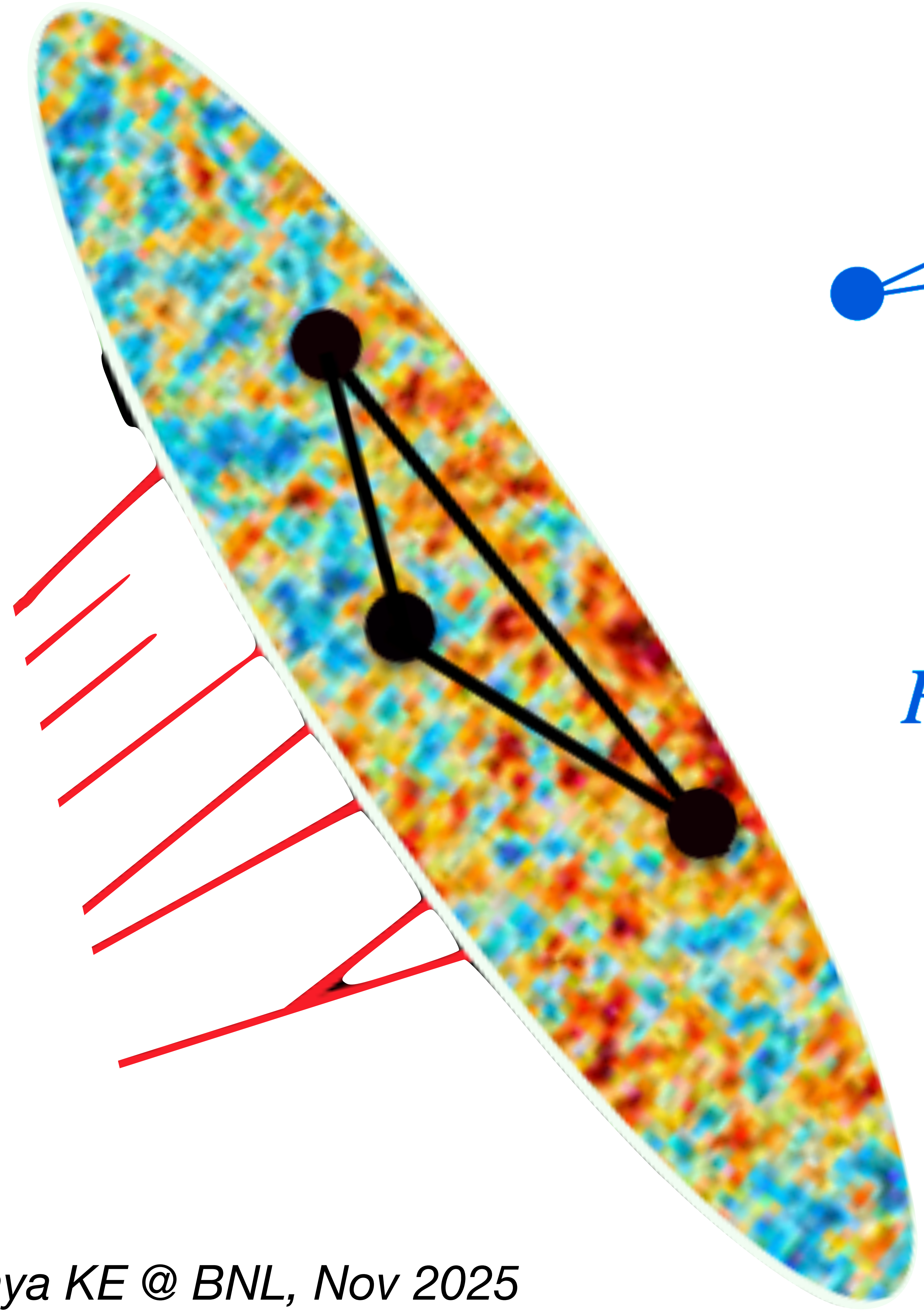
- Selecting on harder fragmenting particles reduces your background but biases your jet selection!

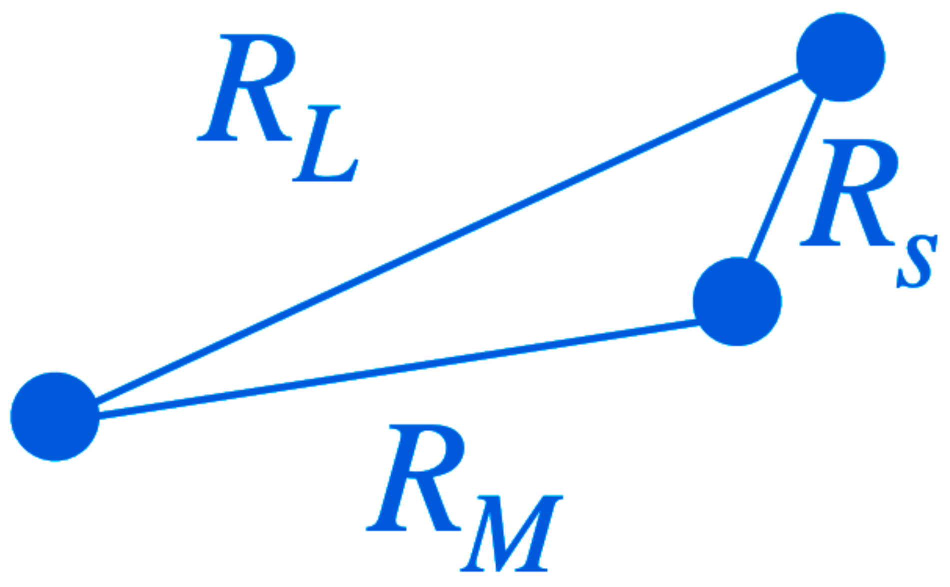
ALICE's EEC in pPb and PbPb



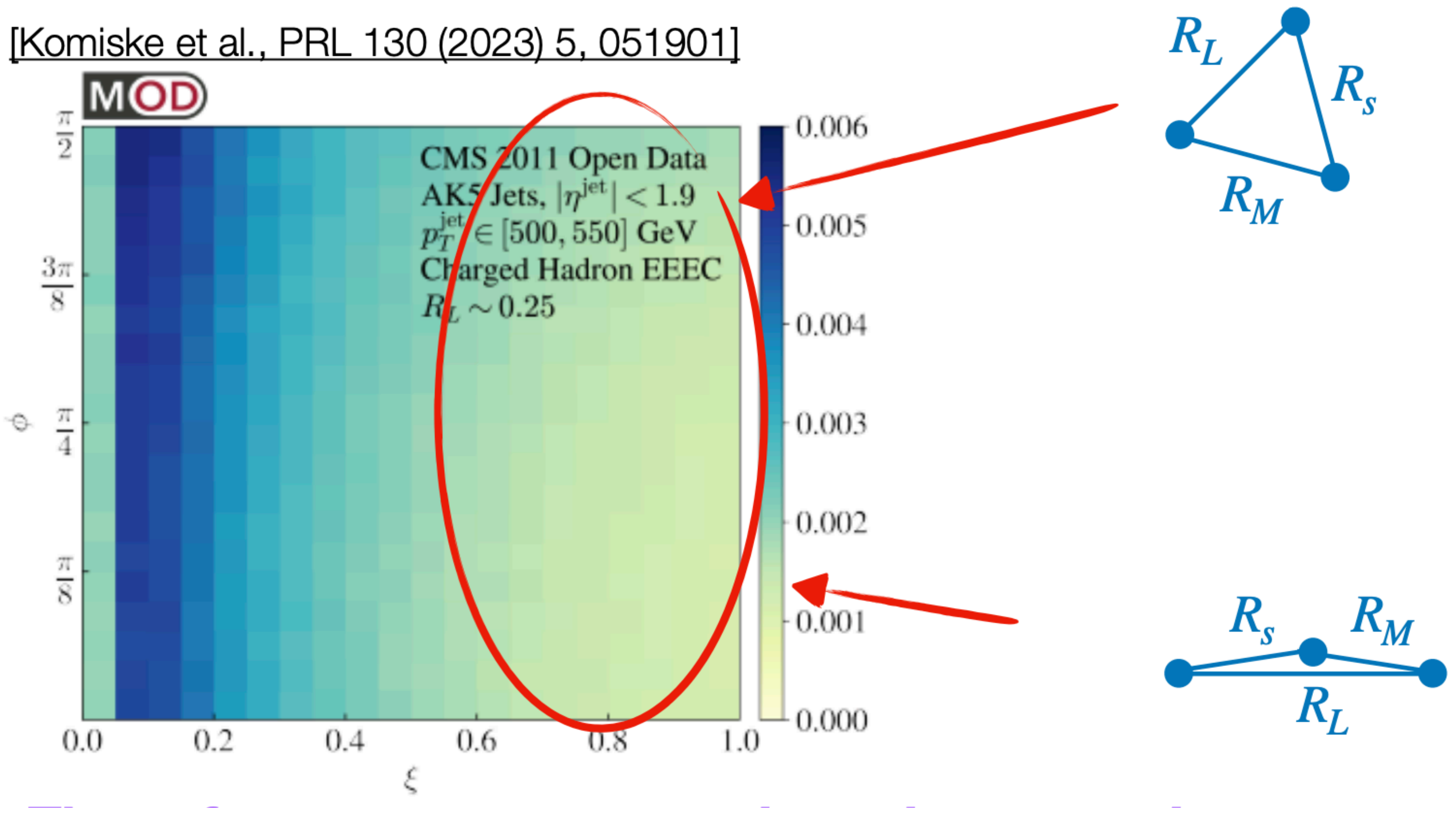


What are 3-point correlators?





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



Upper right corner is populated with equilateral triangles

Bottom right corner is populated with "flat" triangles

Compilation by Hannah Bossi and Ananya Rai

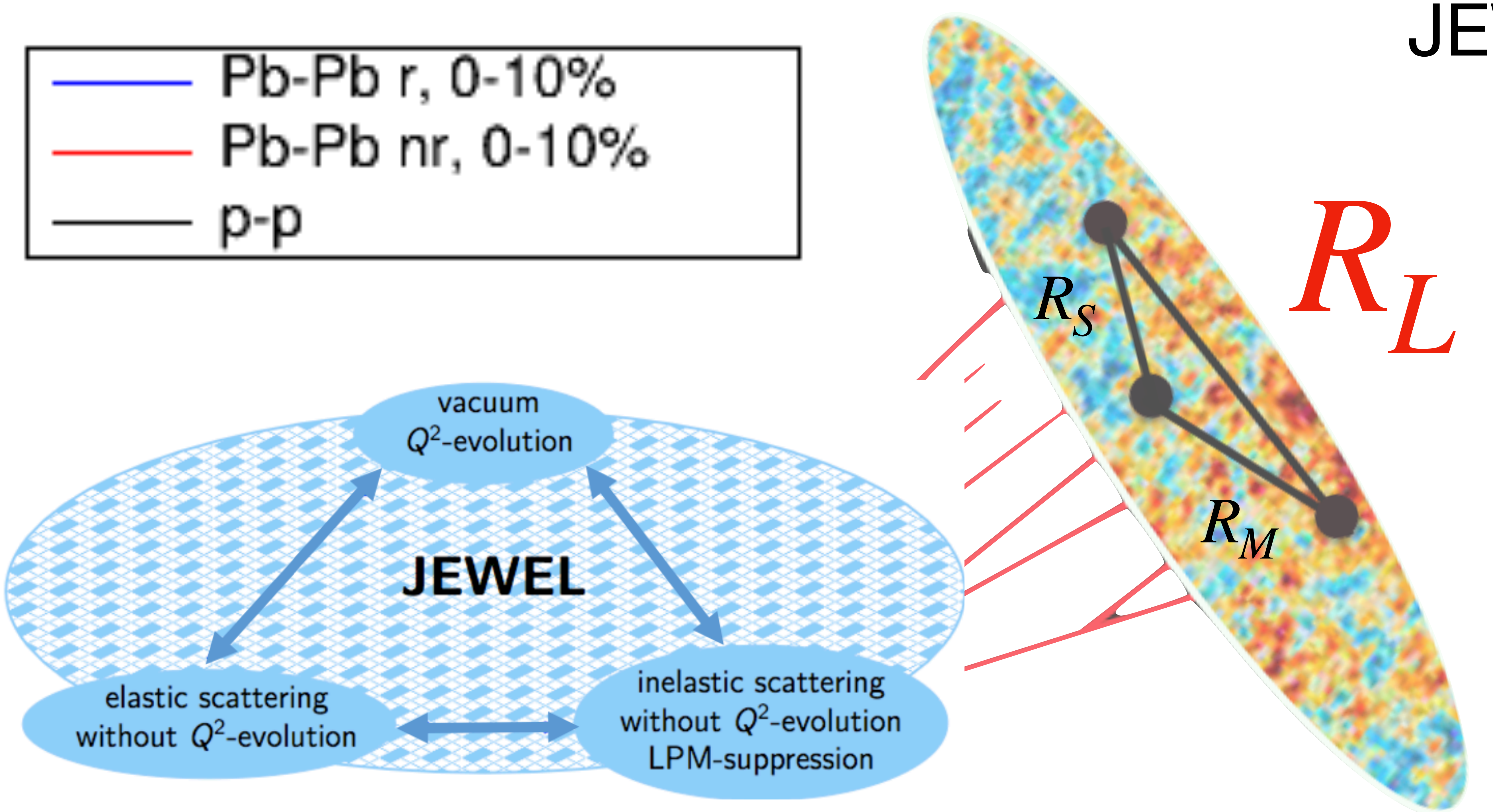
R_L

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

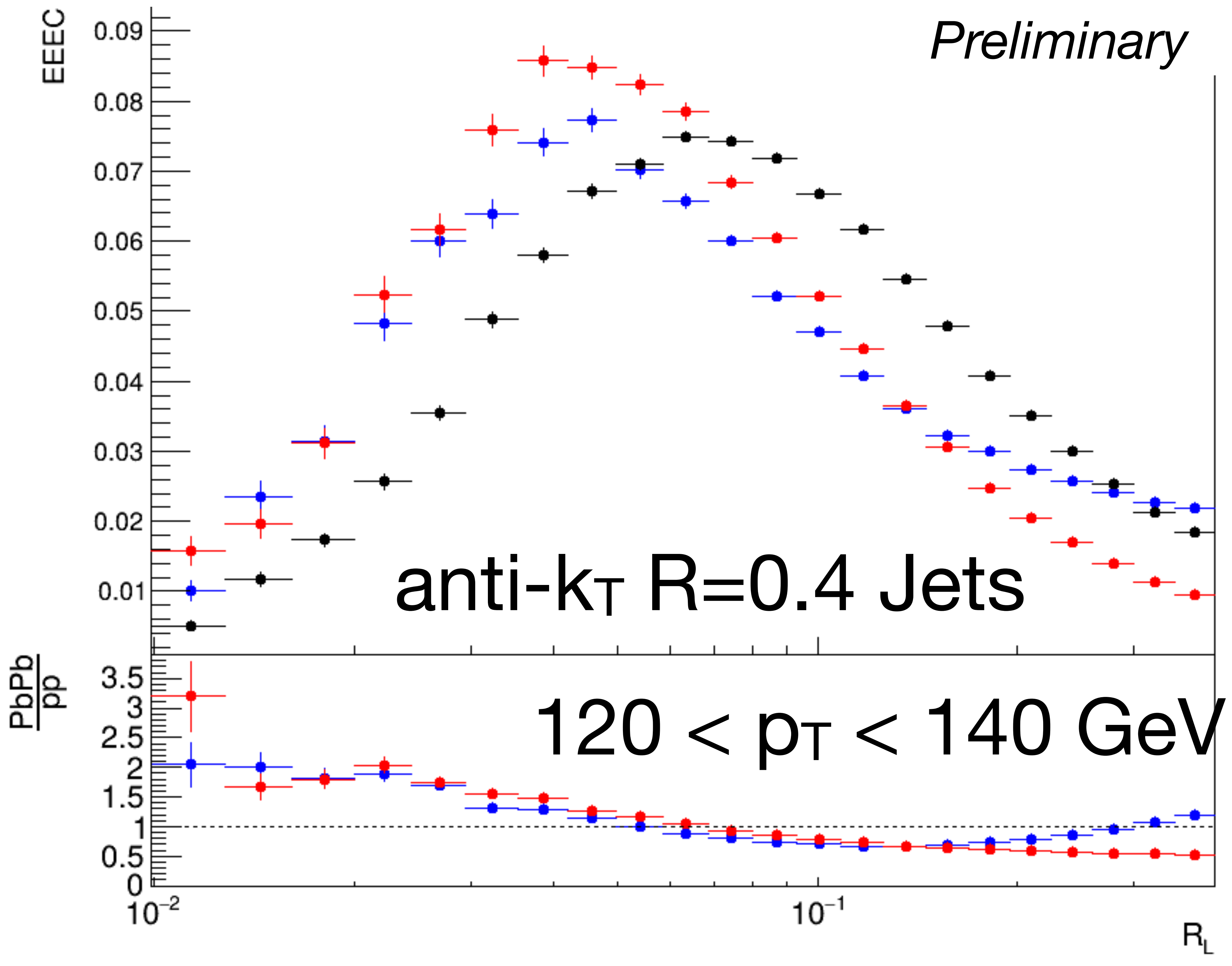
$$\phi = \arcsin\sqrt{1 - \frac{(R_L - R_M)^2}{R_s^2}}$$

- Projected 3-point correlators onto the larger angle side RL can asymptote to 2-point
- ϕ and ξ are sensitive to different shapes of particle fragmentation within jets

R_L, R_S, R_M



JEWEL 2.4.0 + PYTHIA $\sqrt{s} = 5.02$ TeV



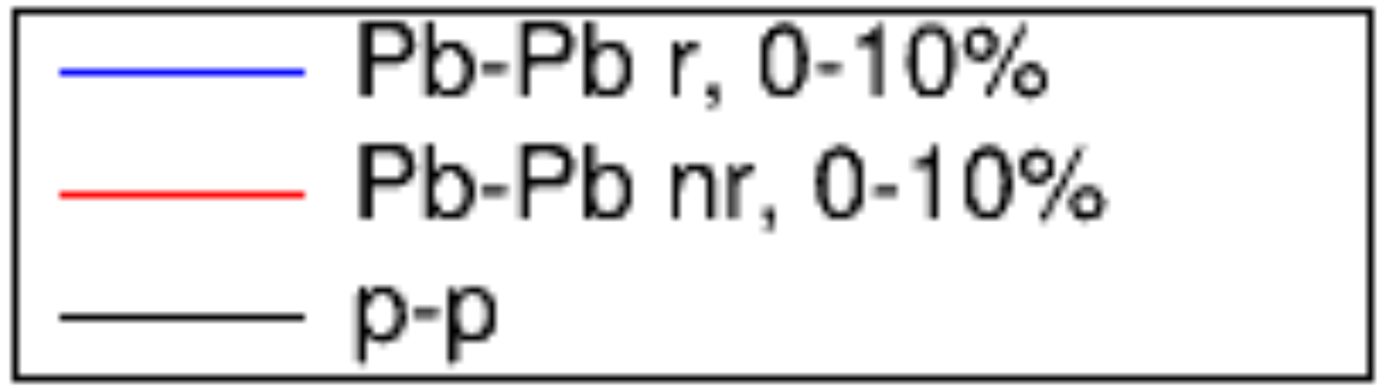
w/ recoils + thermal subtraction

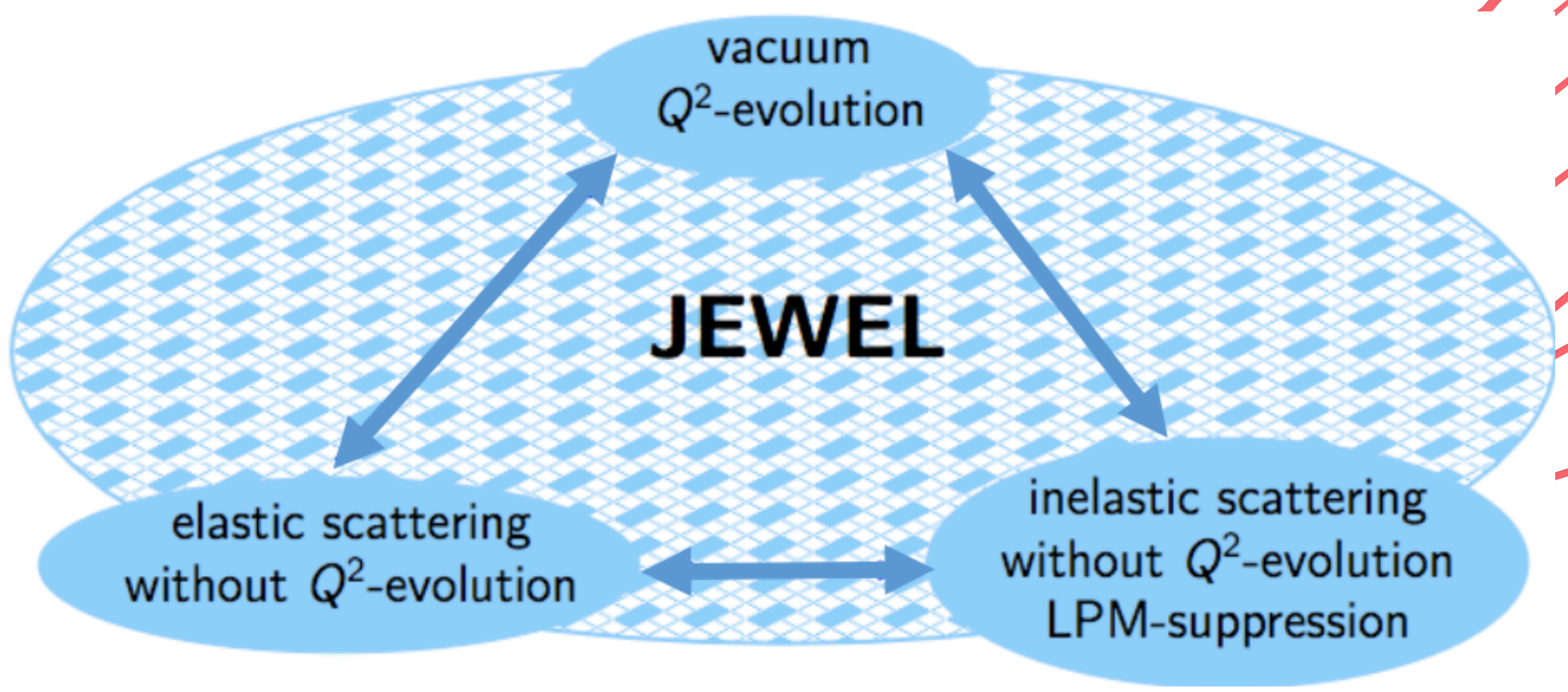
w/o recoils

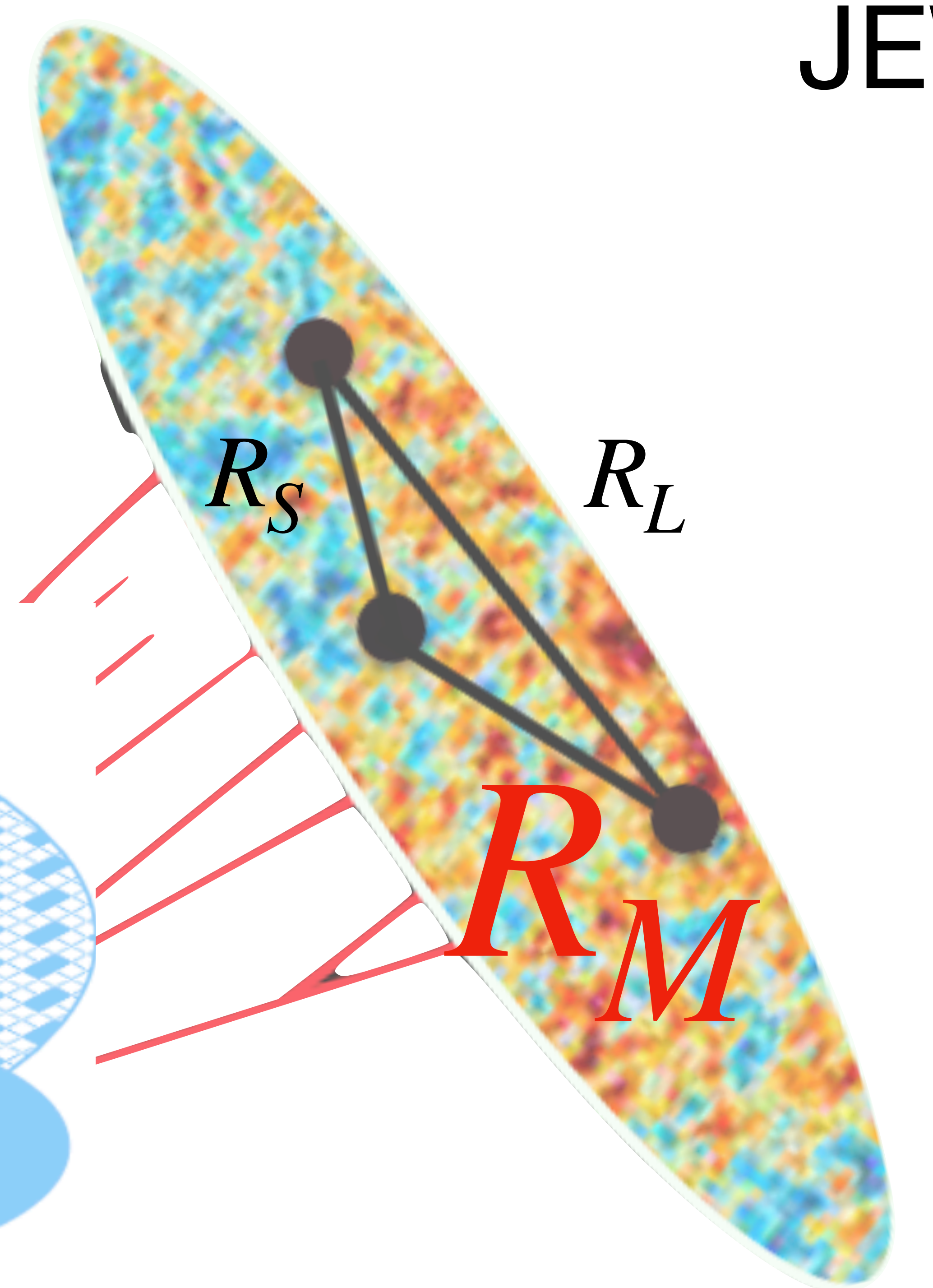
- Similar behavior to 2-point correlators with slight difference at the larger angles - enhancement seems to be smaller with 3-particles!

Note: these are from unique triplets!

R_L, R_S, R_M







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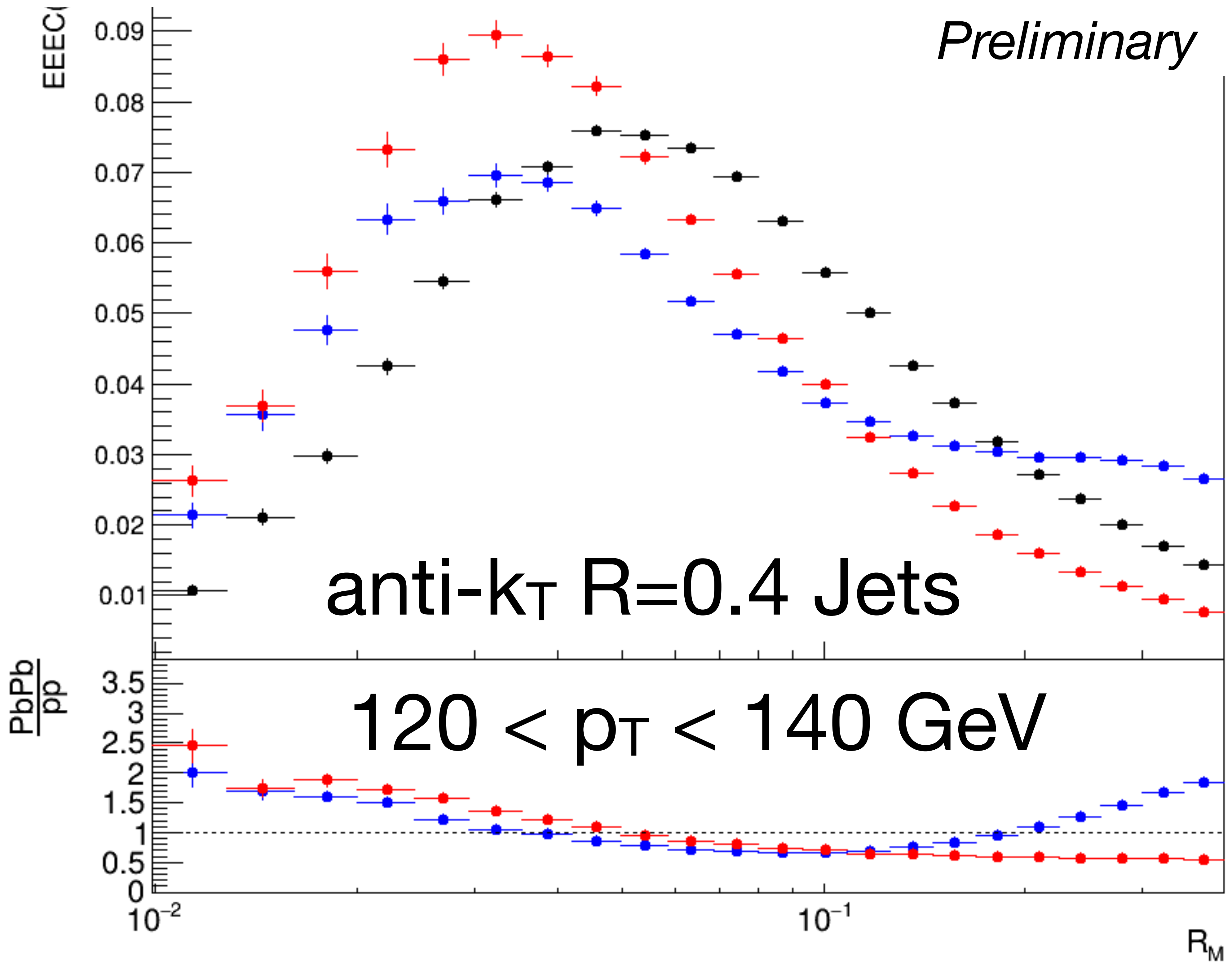
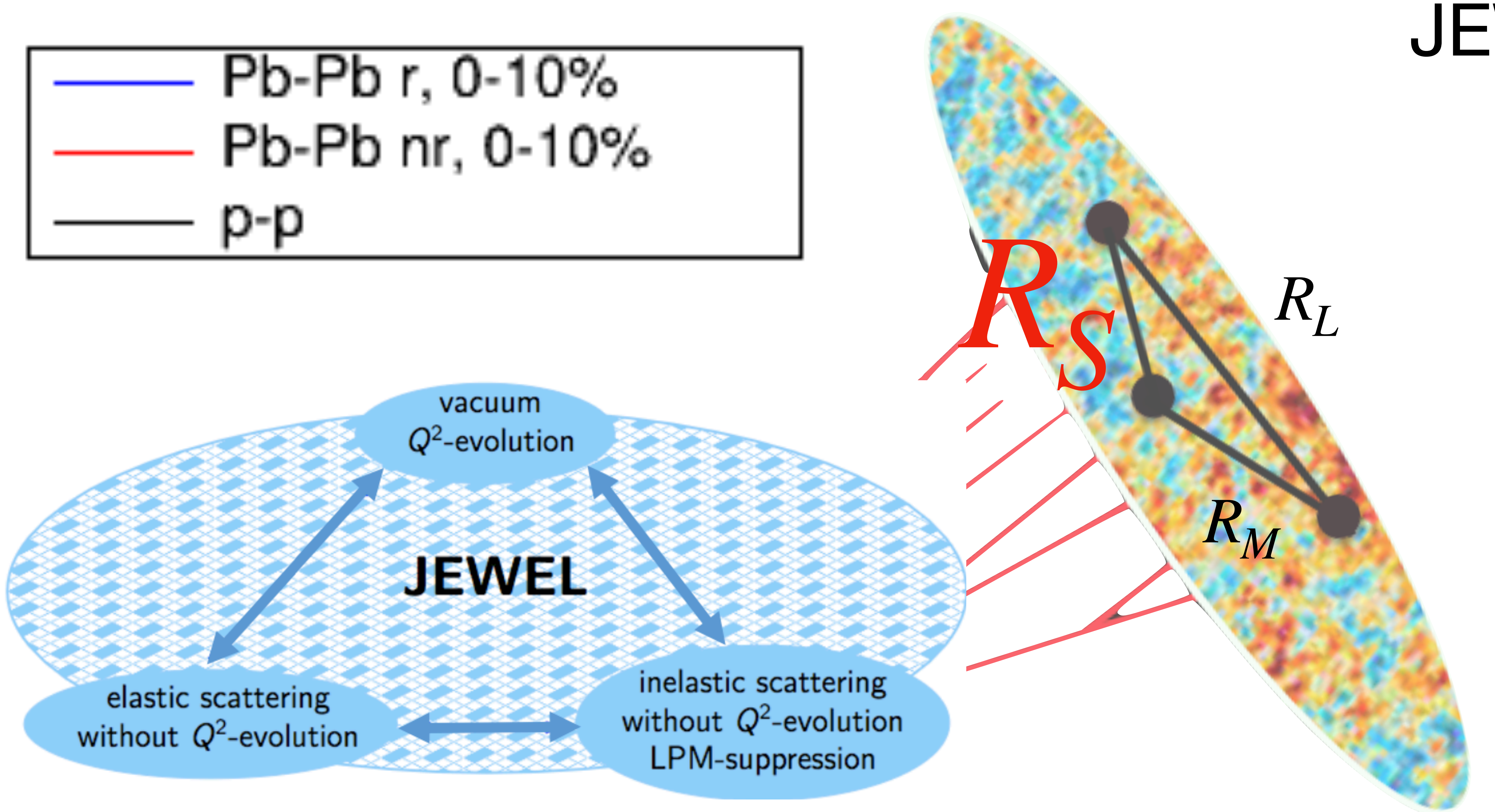


w/ recoils + thermal subtraction

w/o recoils

- As we go to smaller distances - R_M - we see enhancement start to creep up again! Deviation from w/o recoils happens at larger angles…

R_L, R_S, R_M



w/ recoils + thermal subtraction

w/o recoils

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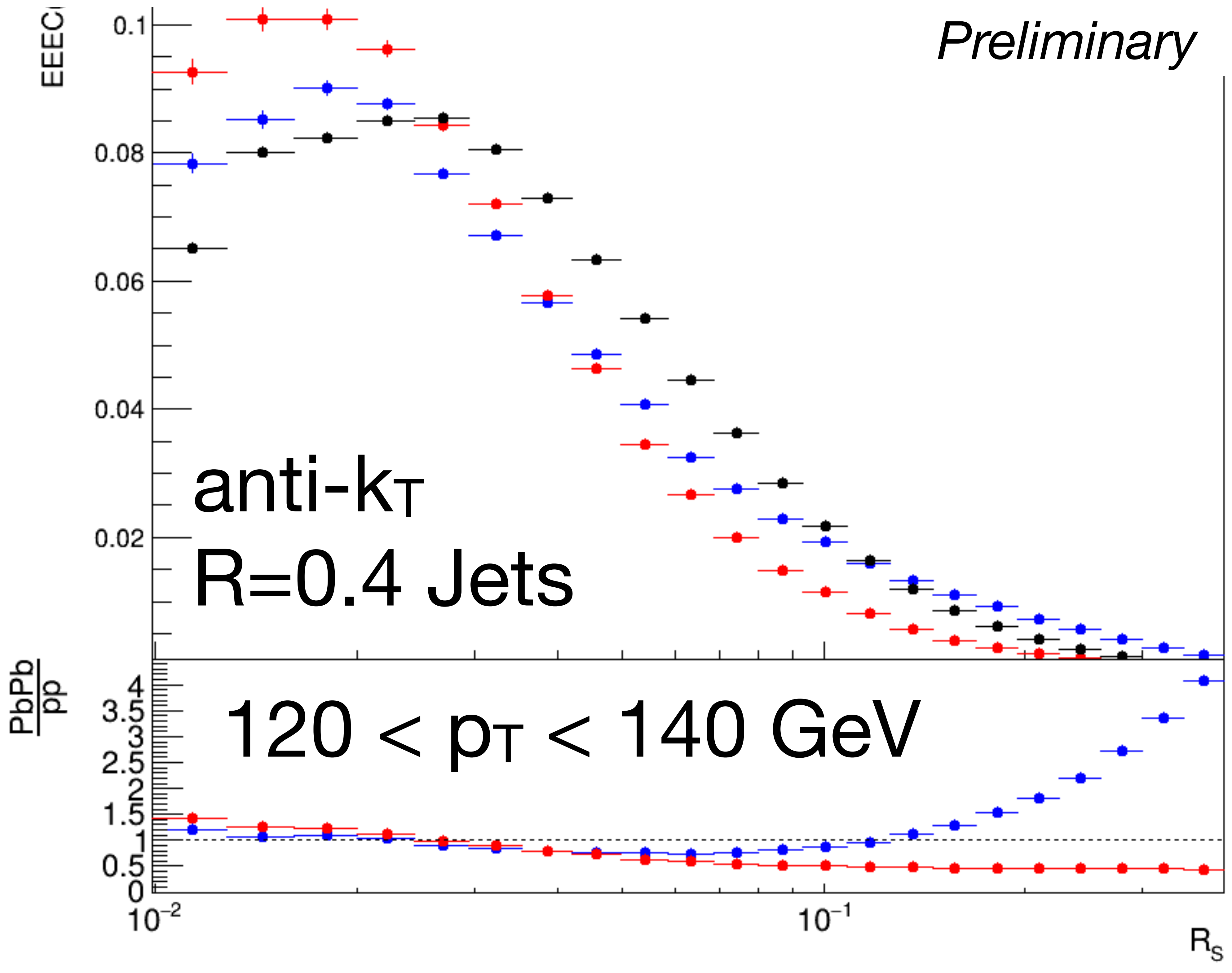
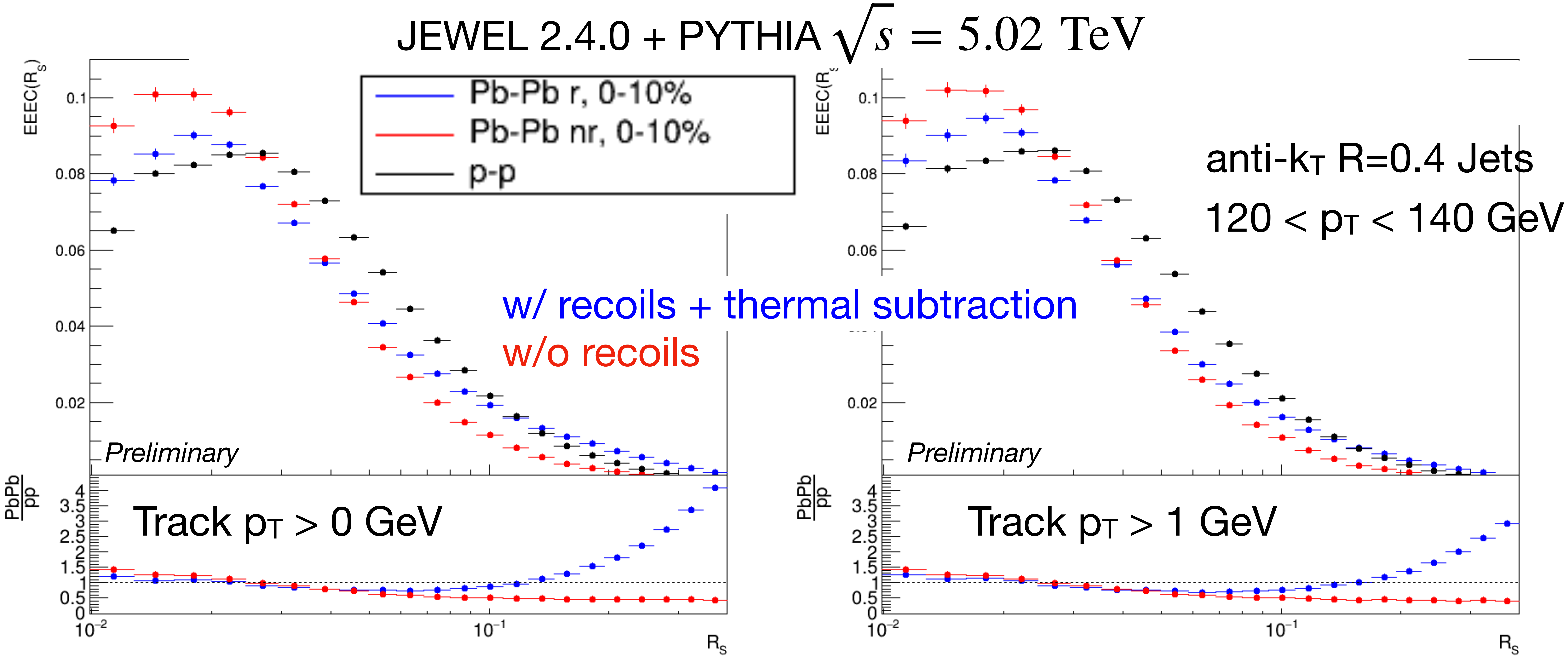


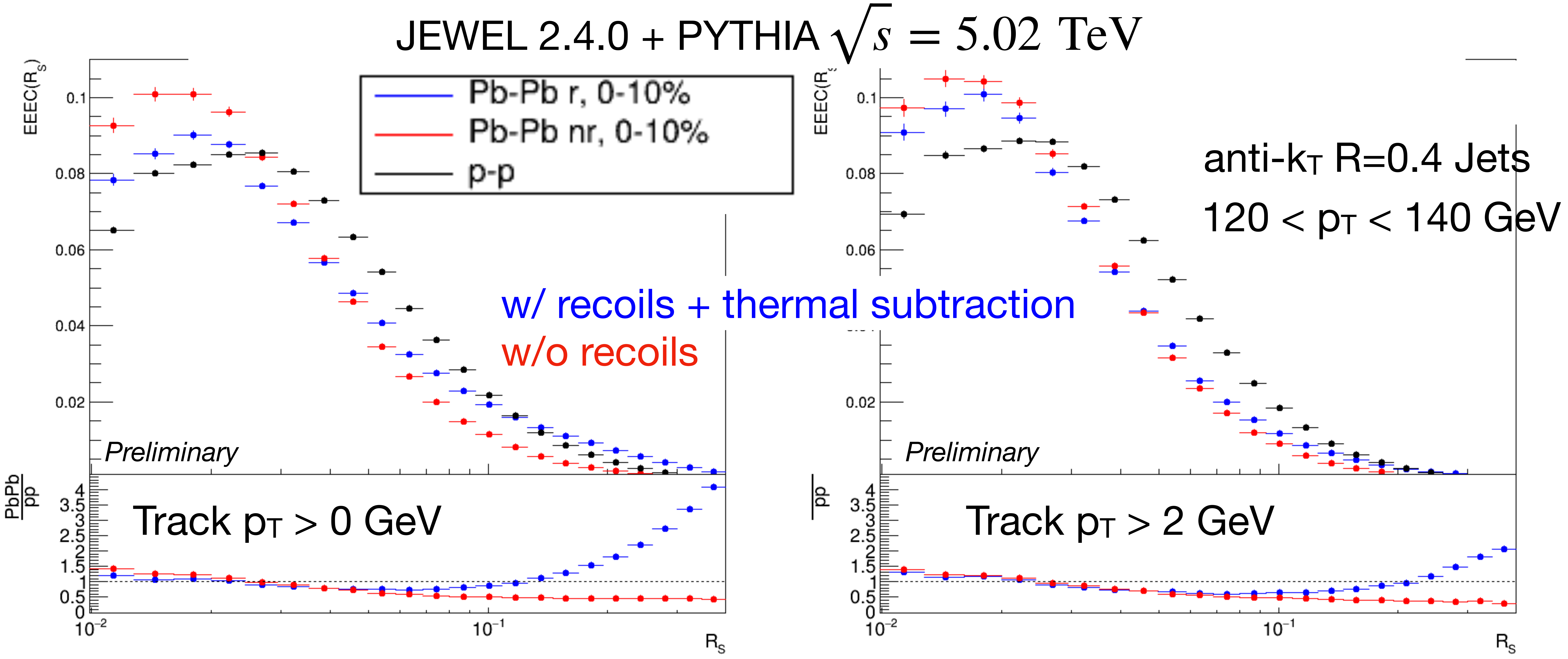
- Largest enhancement reserved for the smallest side of the triangle! And also showcases the deviation goes to smaller angles!!

Sensitive to particle p_T?



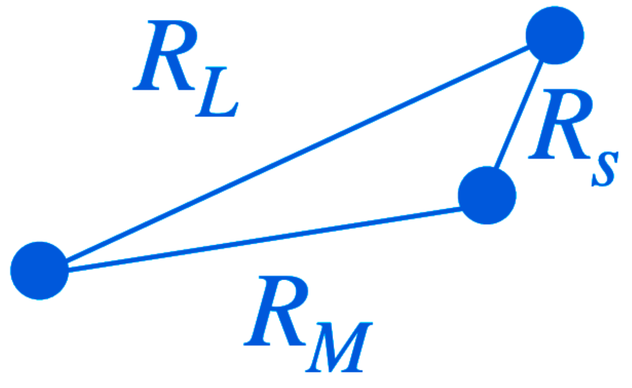
- Increasing the track p_T results in reduced enhancement at large R_S

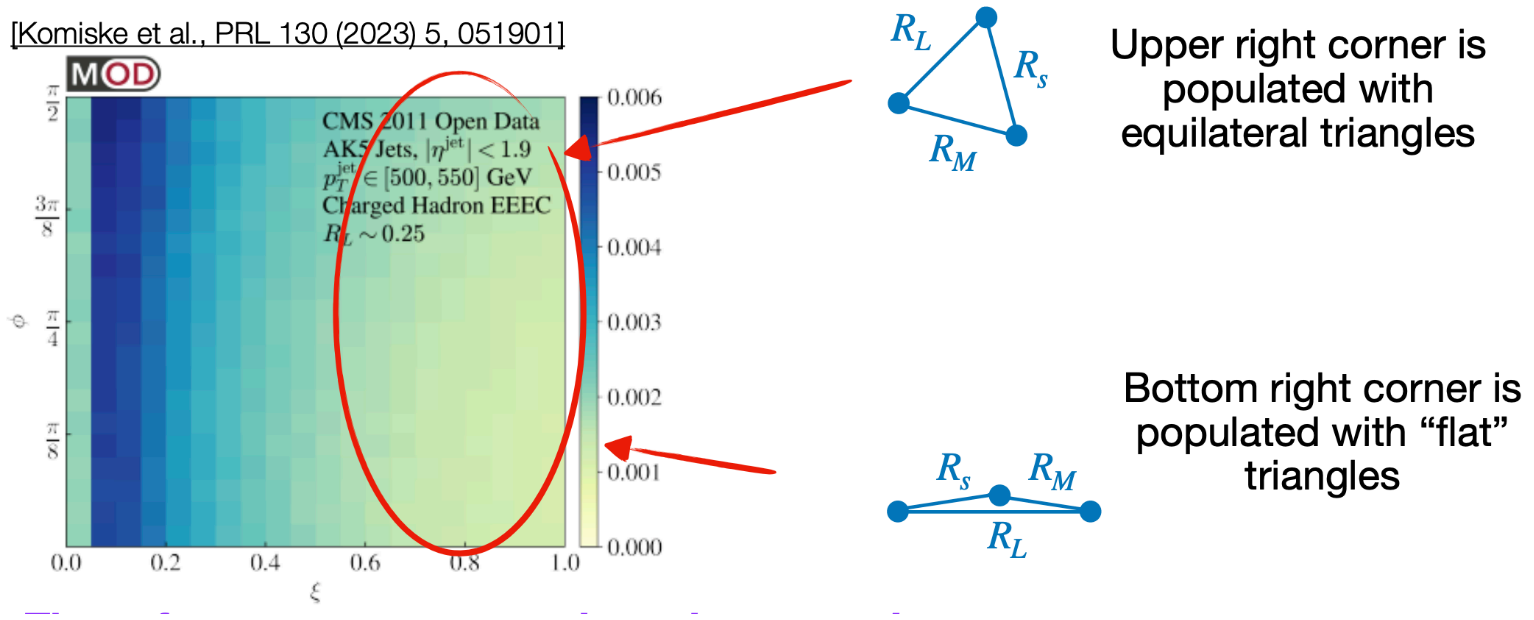
Sensitive to particle p_T?



- Even going to p_T > 2 GeV we still see modification - which we did not see in E2C!

How about the ratios of lengths? ξ

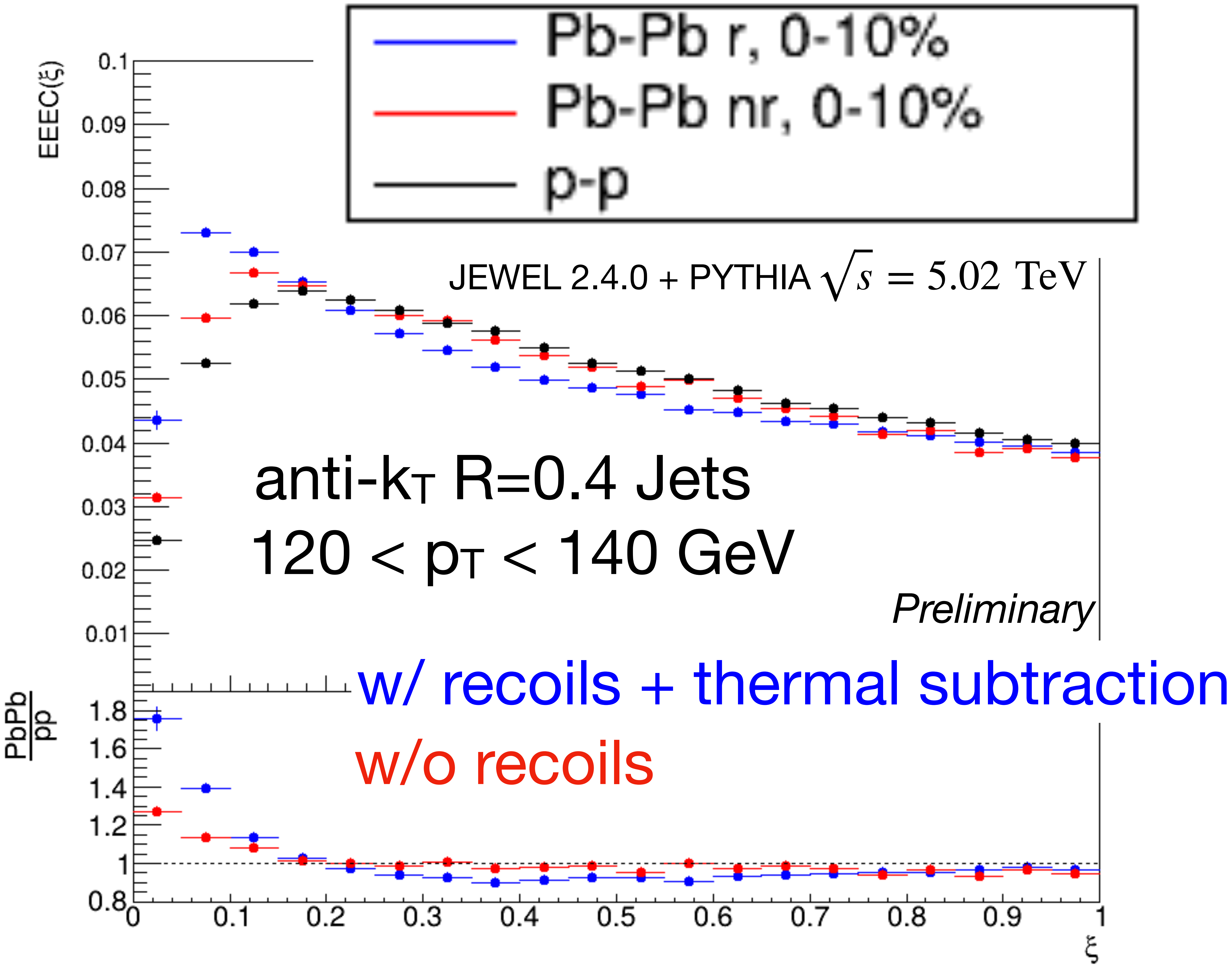




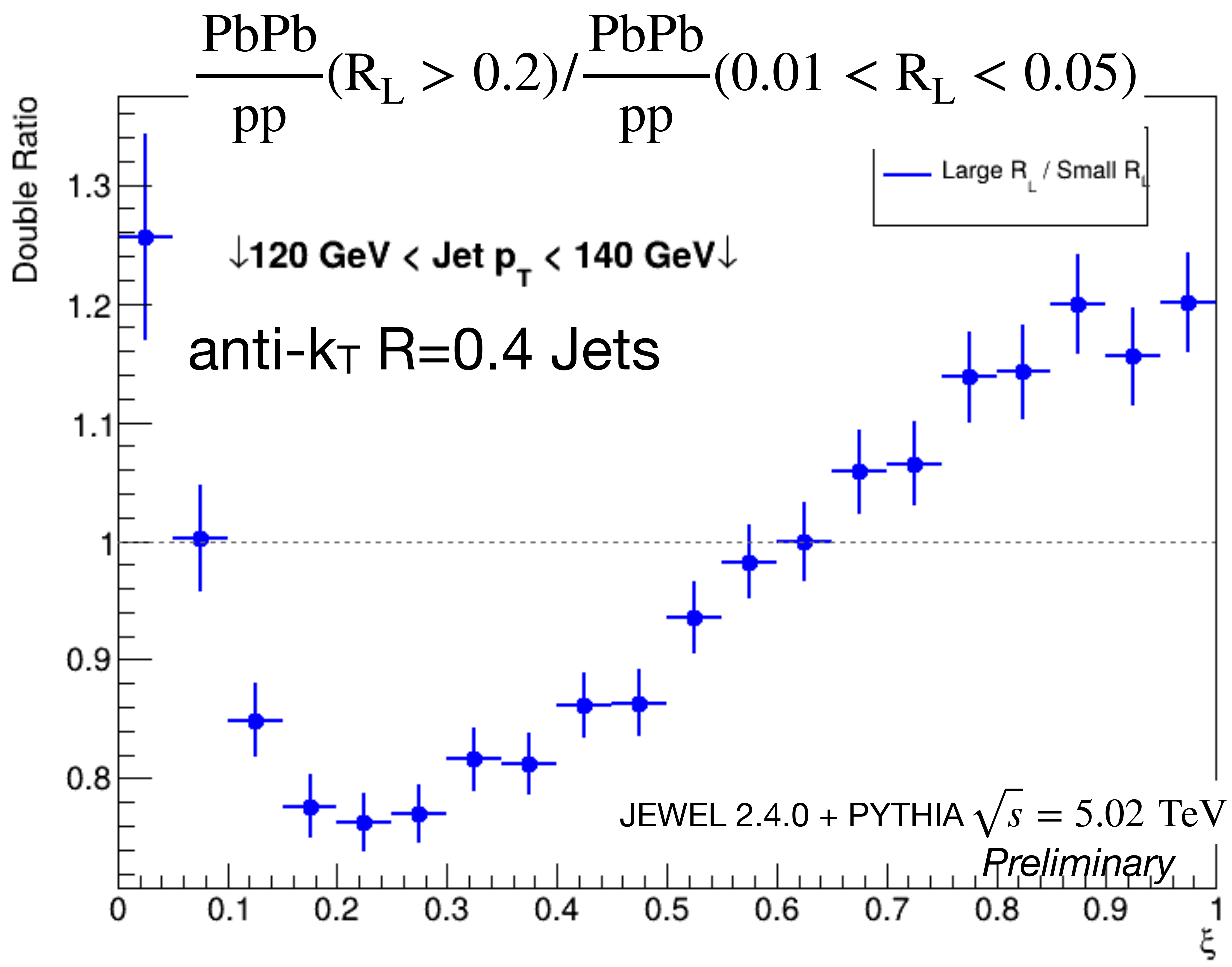
R_L $\quad$ $\xi = \dfrac{R_S}{R_M}$ $\quad$ $\phi = \arcsin\sqrt{1 - \dfrac{(R_L - R_M)^2}{R_s^2}}$

- Shows an enhancement at smaller ξ - we see larger smaller RS in heavy ions compared to pp - expected from having more lower p_T particles in the pbpb jet!

- What about ϕ?



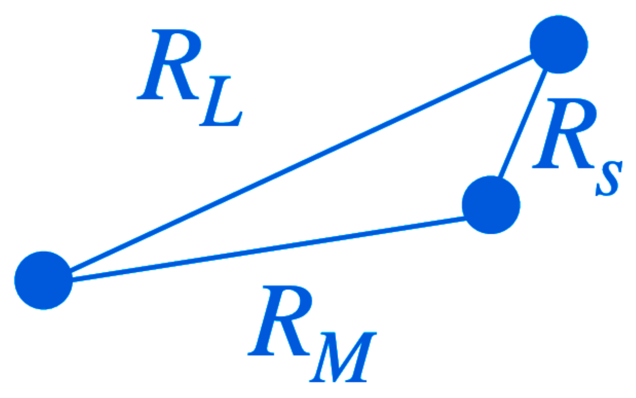
Double ratios!

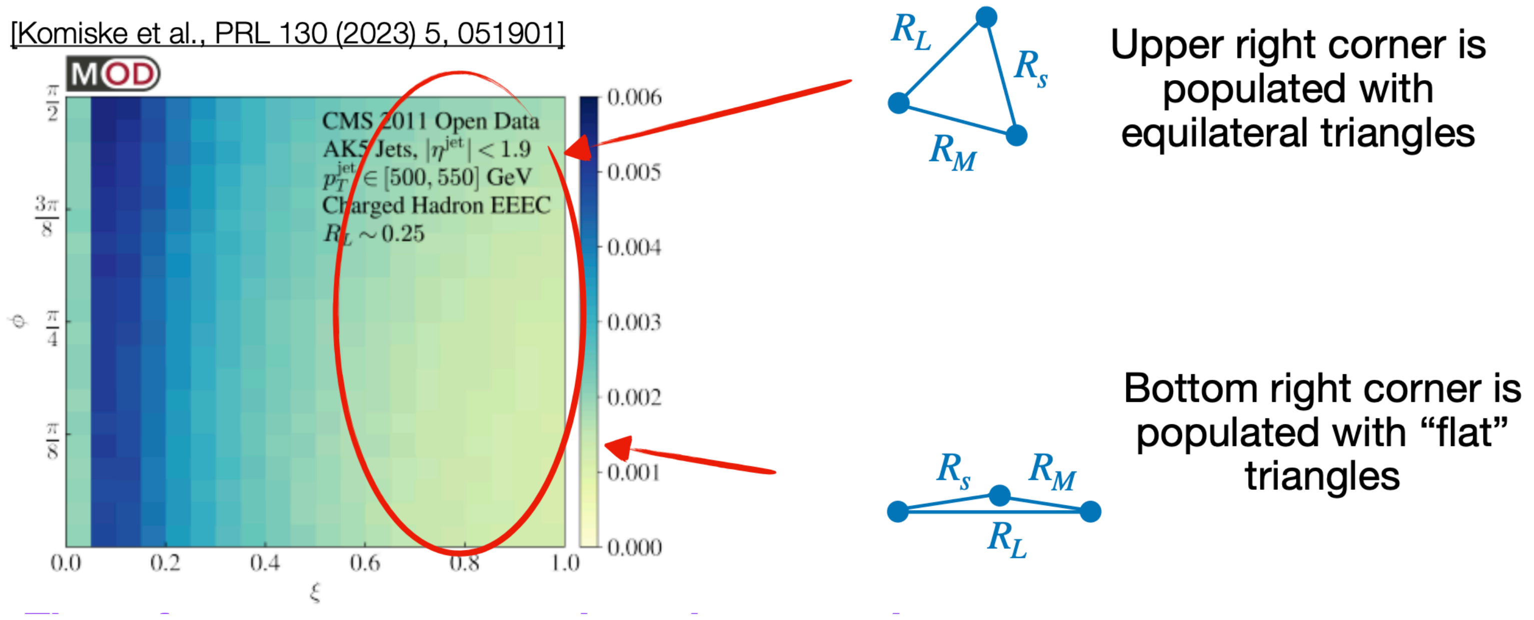


$$\xi = \frac{R_S}{R_M}$$

- Selection on RL seems to indicate a shape we are familiar with!
- These are ofcourse normalized so the integral is consistent

Controlling the shape of our triangles

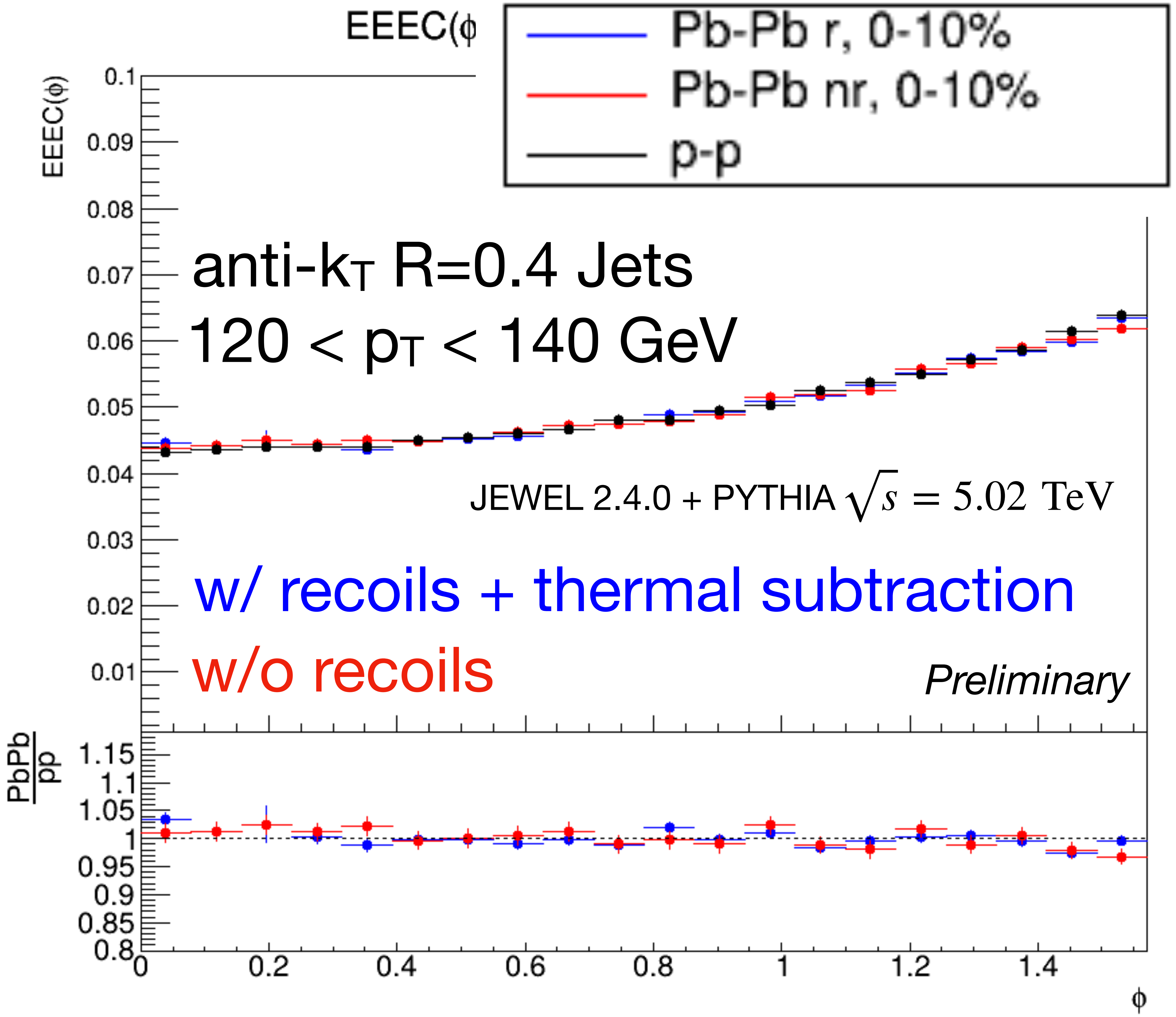




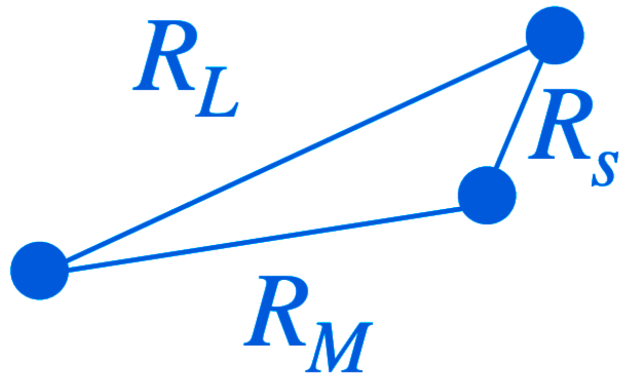
R_L $\quad \xi = \frac{R_S}{R_M}$ $\quad \phi = \arcsin\sqrt{1 - \frac{(R_L - R_M)^2}{R_s^2}}$

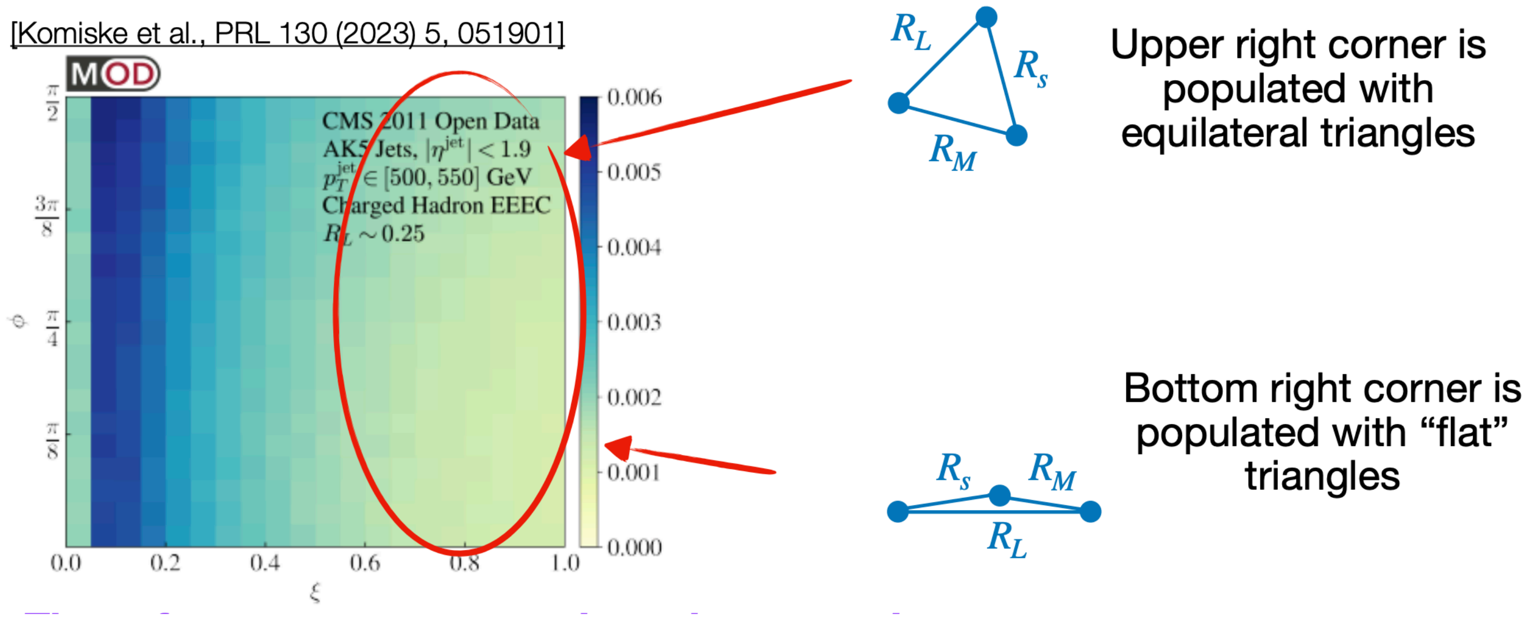
- Very surprising! Potential invariant under JEWEL's energy loss

- Why does this happen so? Is it a cancellation effect with change in jet p_T and possible quenching?



Controlling the shape of our triangles





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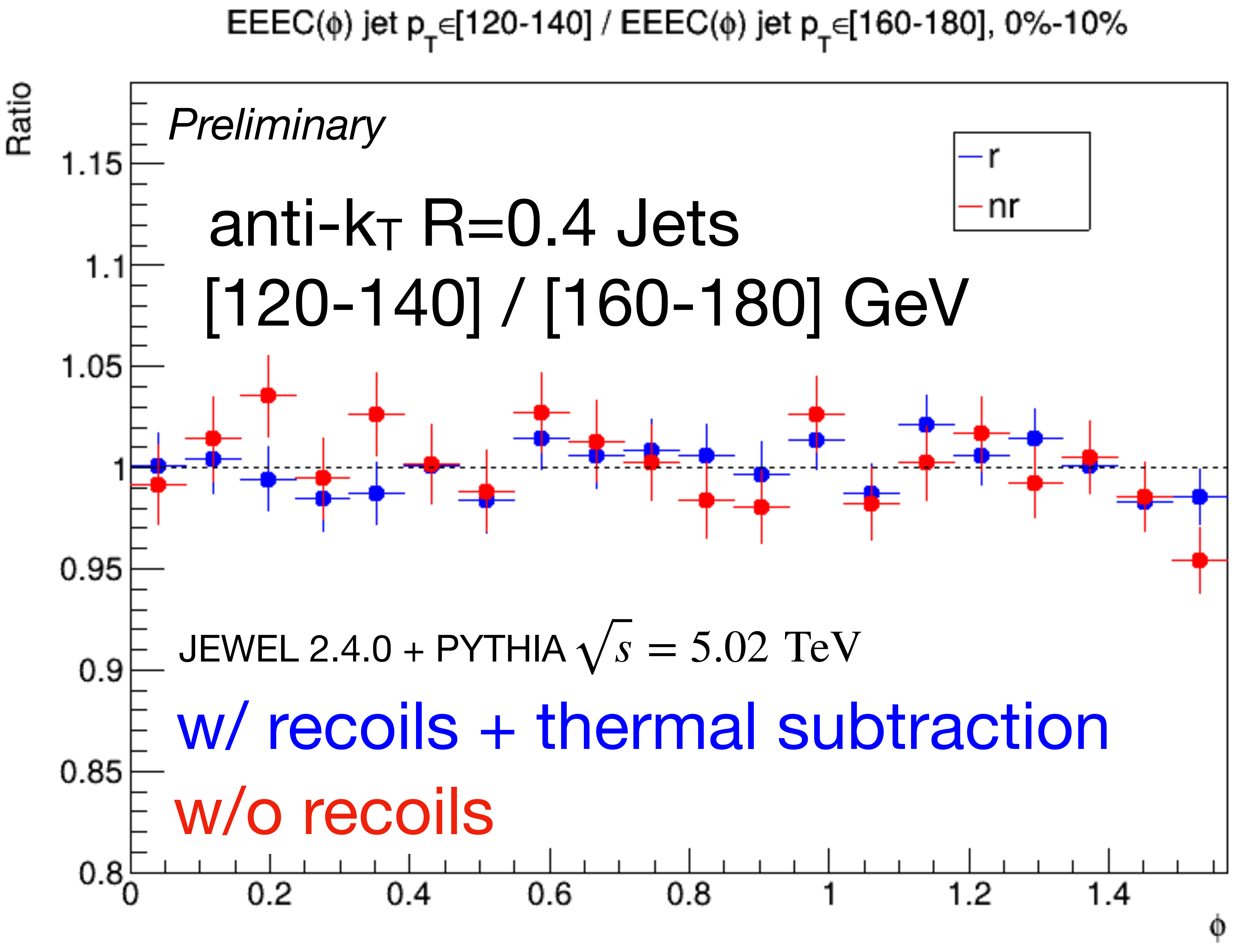
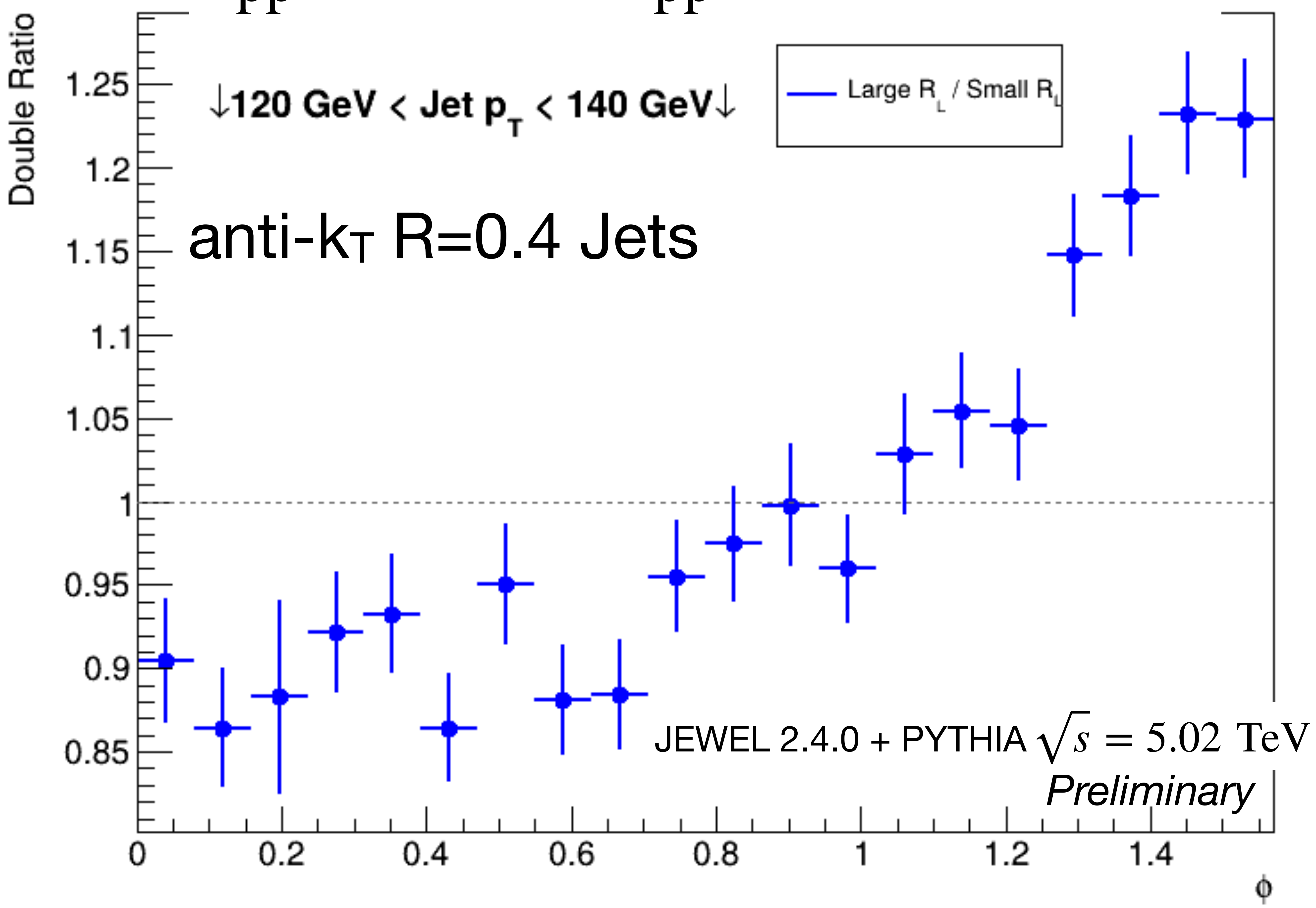


How to see modifications in phi?

$$\frac{\text{PbPb}}{\text{pp}}(R_L > 0.2) / \frac{\text{PbPb}}{\text{pp}}(0.01 < R_L < 0.05)$$

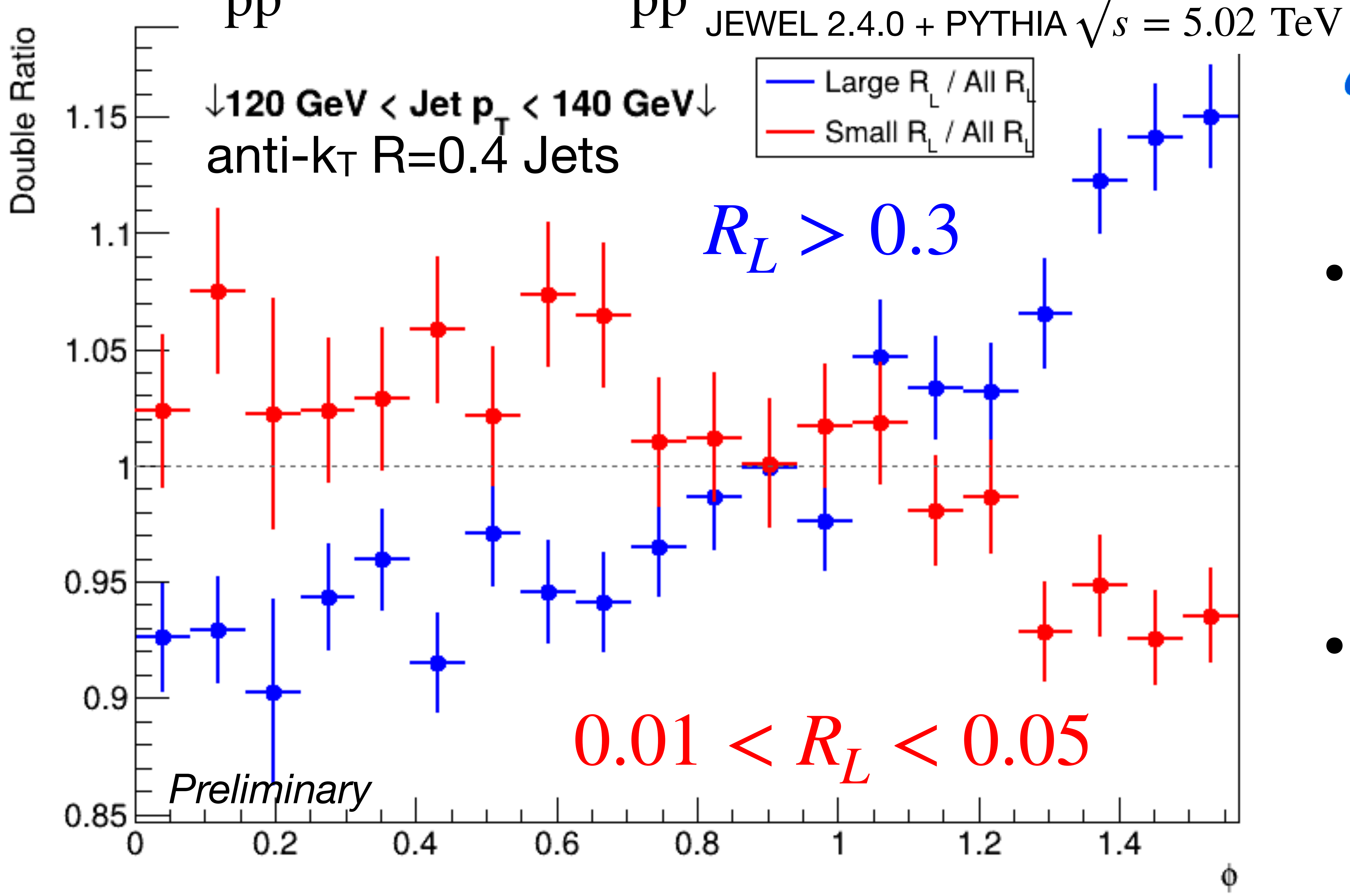


$$\phi = \arcsin\sqrt{1 - \frac{(R_L - R_M)^2}{R_s^2}}$$

- Selection on RL seems to indicate an enhancement of larger ϕ
- Relatively small effect - if you have larger RL, you end up with larger 'equilateral'-like triangles…
- These are ofcourse normalized so the integral is consistent

How to see modifications in phi?

$$\frac{\text{PbPb}}{\text{pp}}(R_L > 0.2) / \frac{\text{PbPb}}{\text{pp}}(0.01 < R_L < 0.05)$$



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

- Example of a cancellation effect that results in an RL integrated ϕ showing up as unmodified…
- Would be very interesting if different methods of energy loss show up differently in such observables!