QCD Collectivity in High-Multiplicity Jets from pp Collisions

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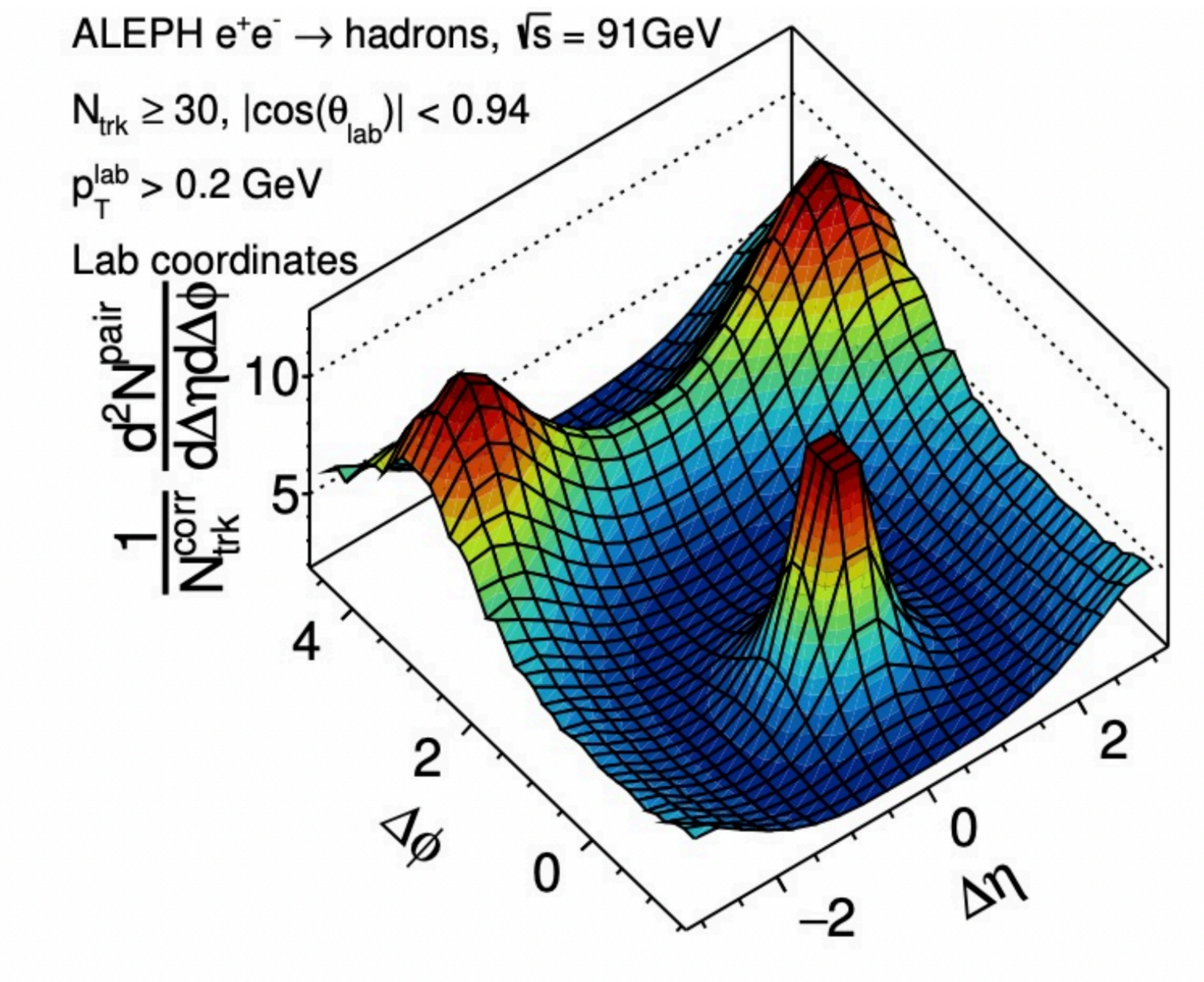
Brookhaven National Lab

UIC UNIVERSITY OF ILLINOIS CHICAGO

Very small systems

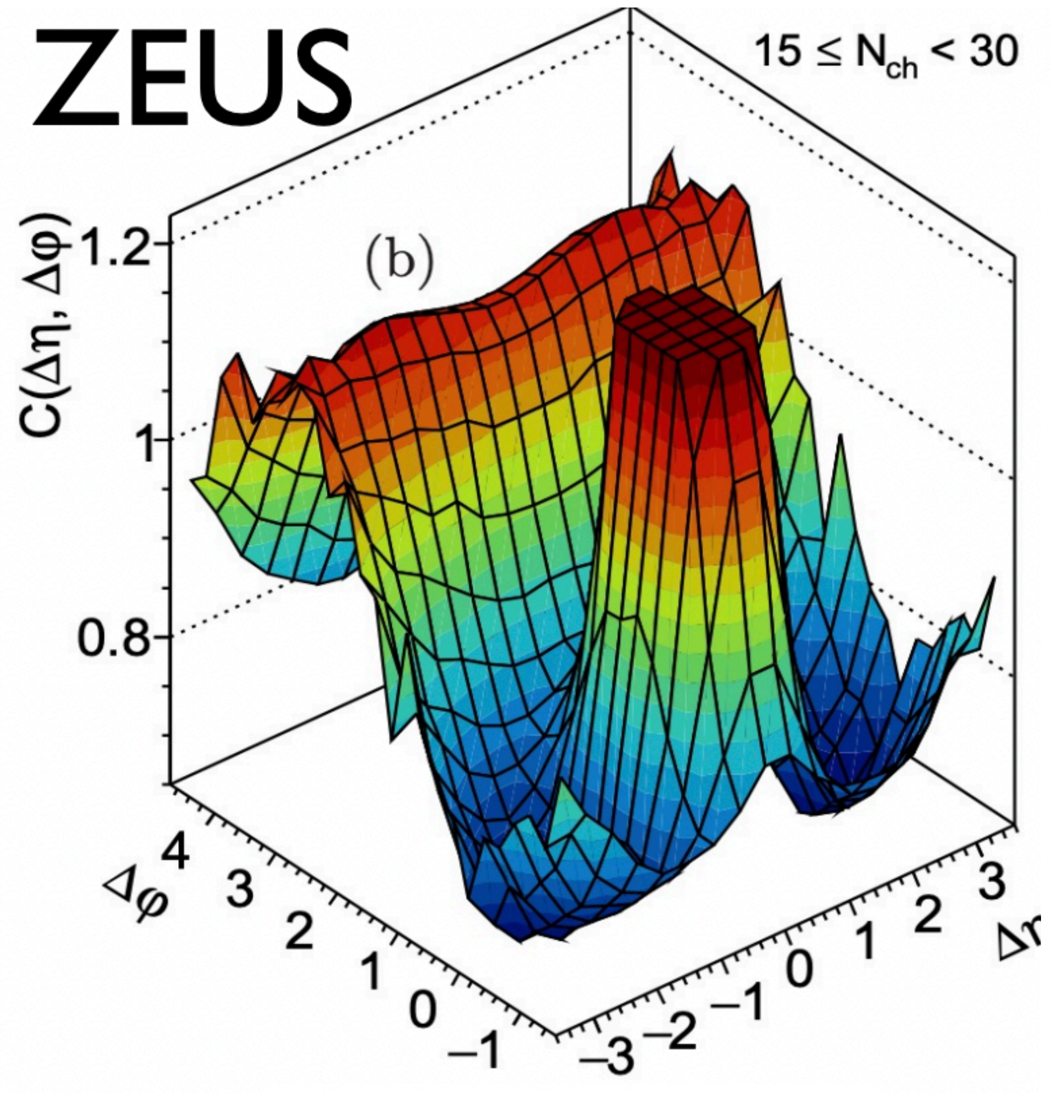
- **Well established 'Fluid-like' signal observed in both pPb and high-multiplicity pp**
- **Many measurements pushing boundaries to smaller systems in last ~ 5 years**
  - **Are correlations in dense systems a general consequence of QCD?**
  - **From how small of a system can collectivity emerge?**
  - **Can hydrodynamics be applied on other non-perturbative processes?**

e^+e^- — **N_{ch}~30**



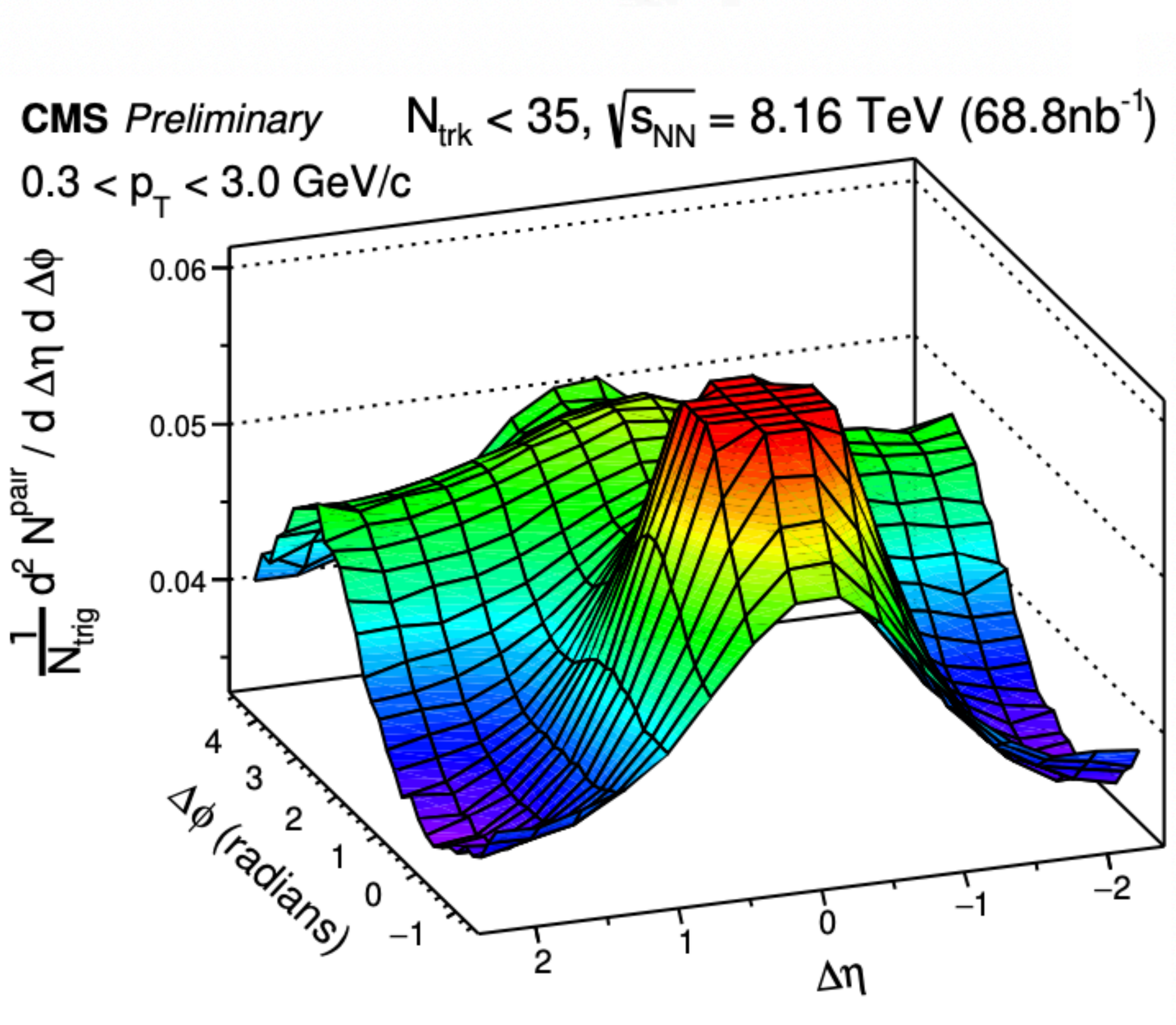
PRL 123, 212002 (2019)

ep — **N_{ch}~30**



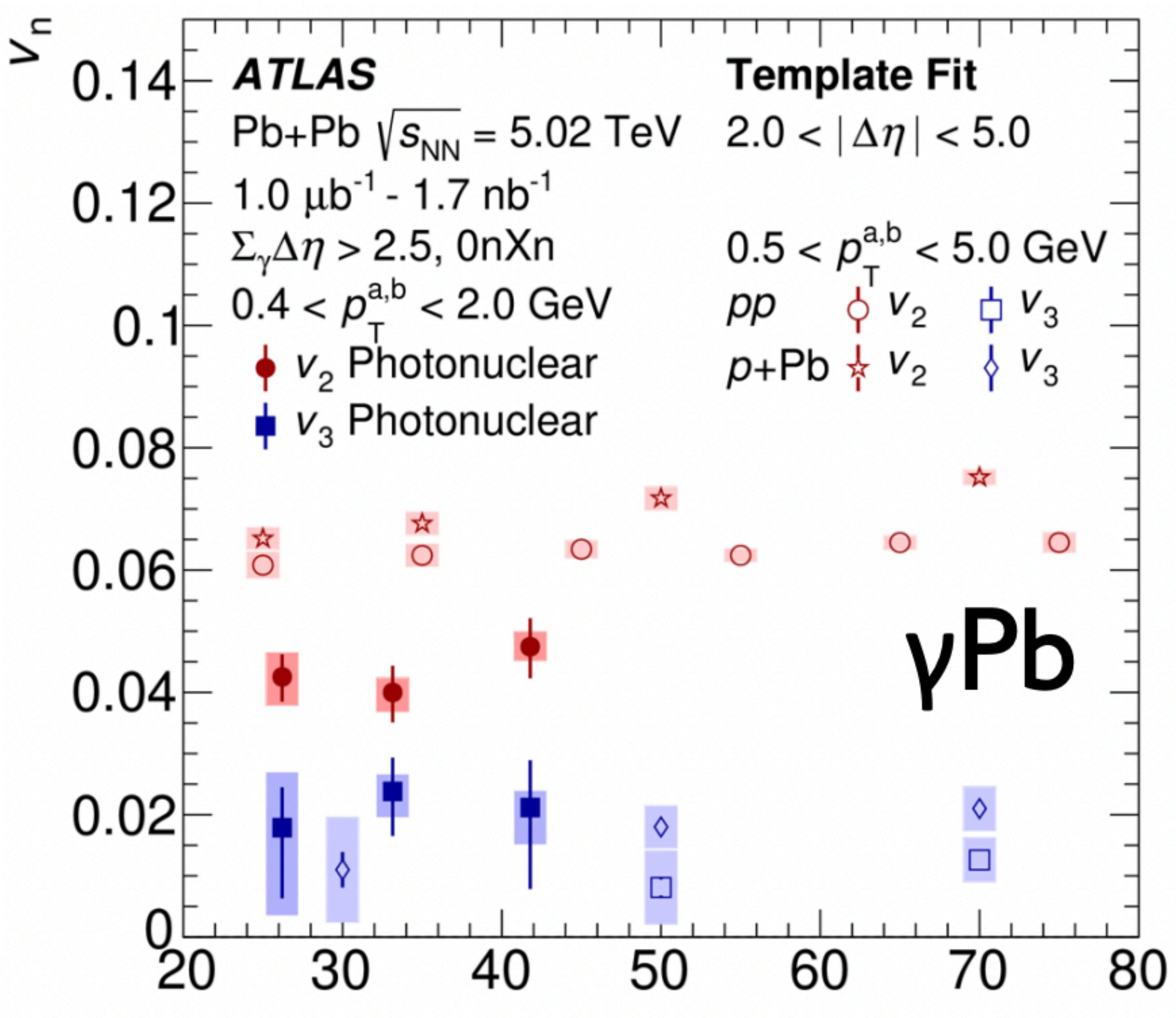
JHEP 04 (2020) 070

γp — **N_{ch}~20**



arXiv:2204.13486

γPb — **N_{ch}~40**

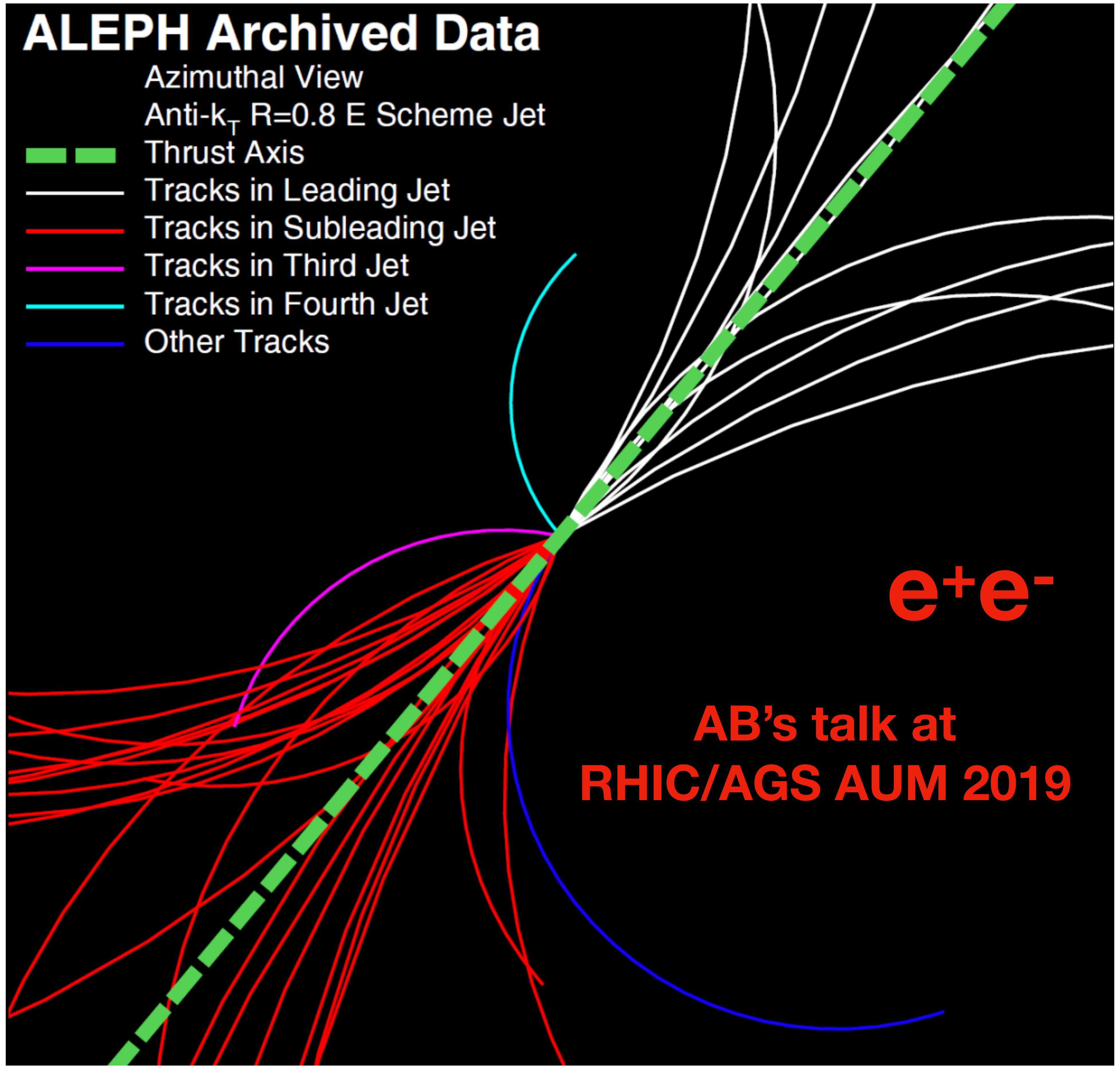


N_{ch}^{rec}

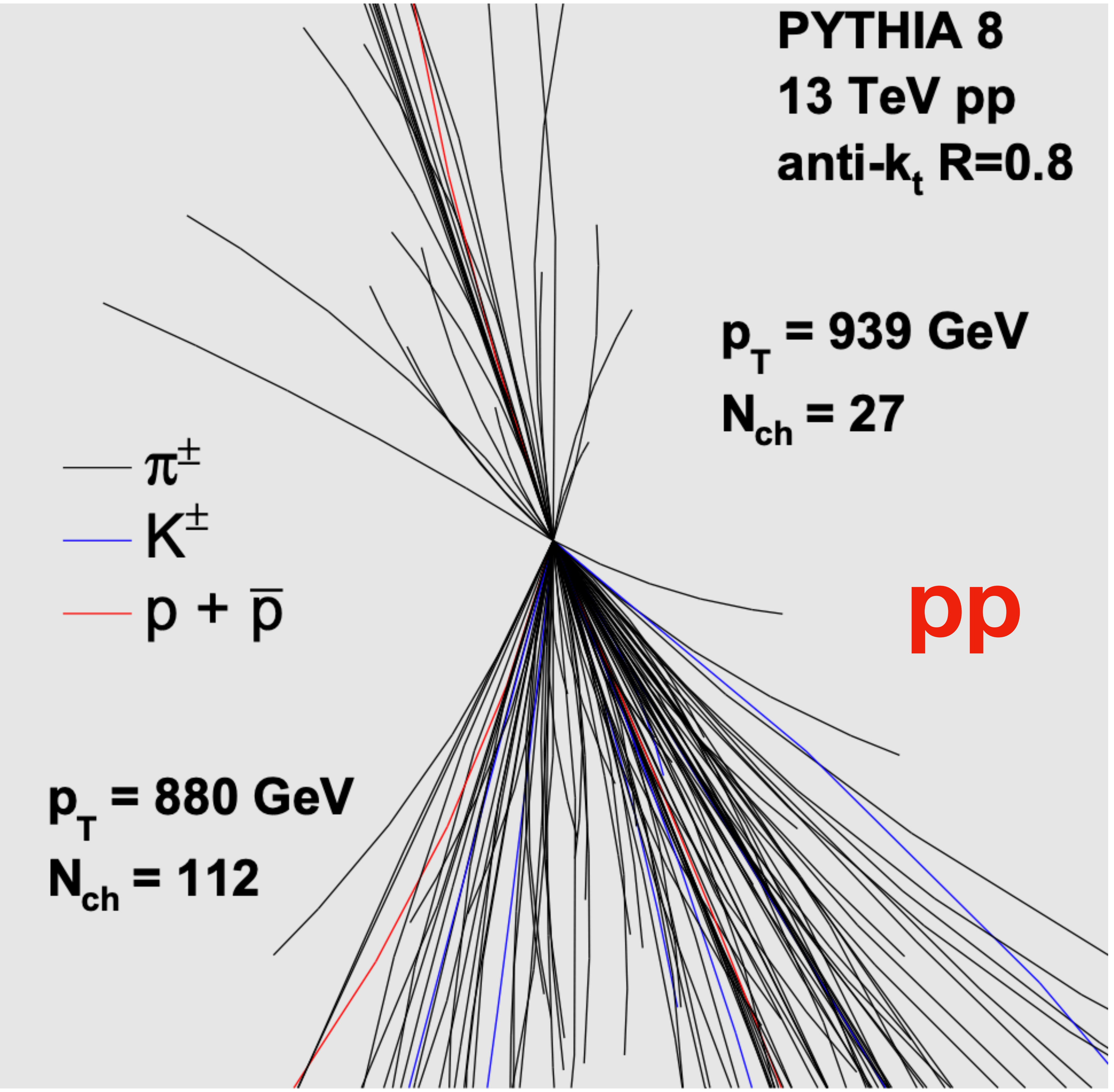
PRC, 104 014903 (2021)

High multiplicity jets?

- Do parton interactions/rescatterings in *localized* high-density region cause any effect?
- e^+e^- produces very clean jets, but limited in statistics
- Huge number of jets at LHC!

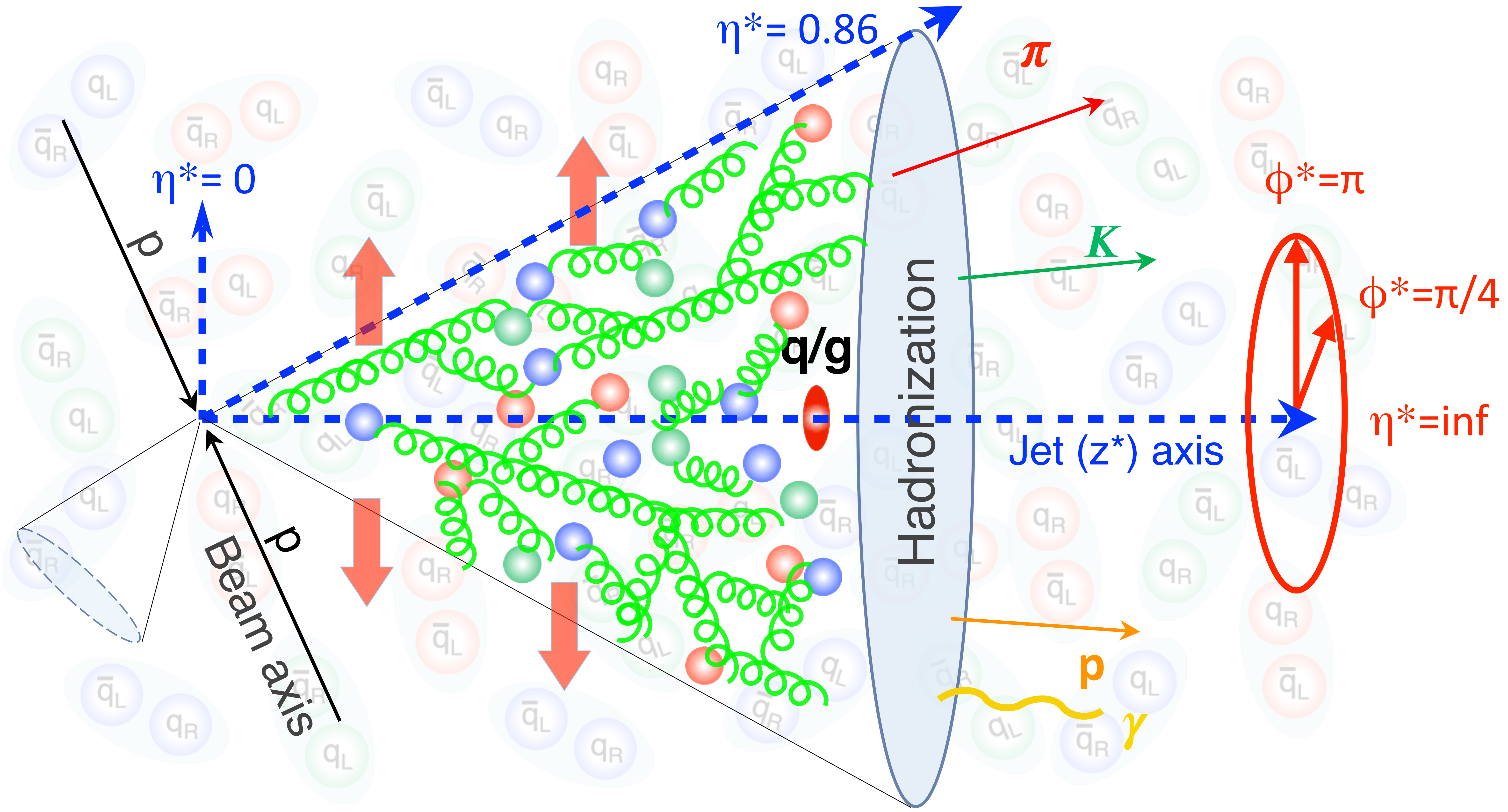


Badea A., <u>AB</u>, et al.. PRL 123, 212002 (2019)



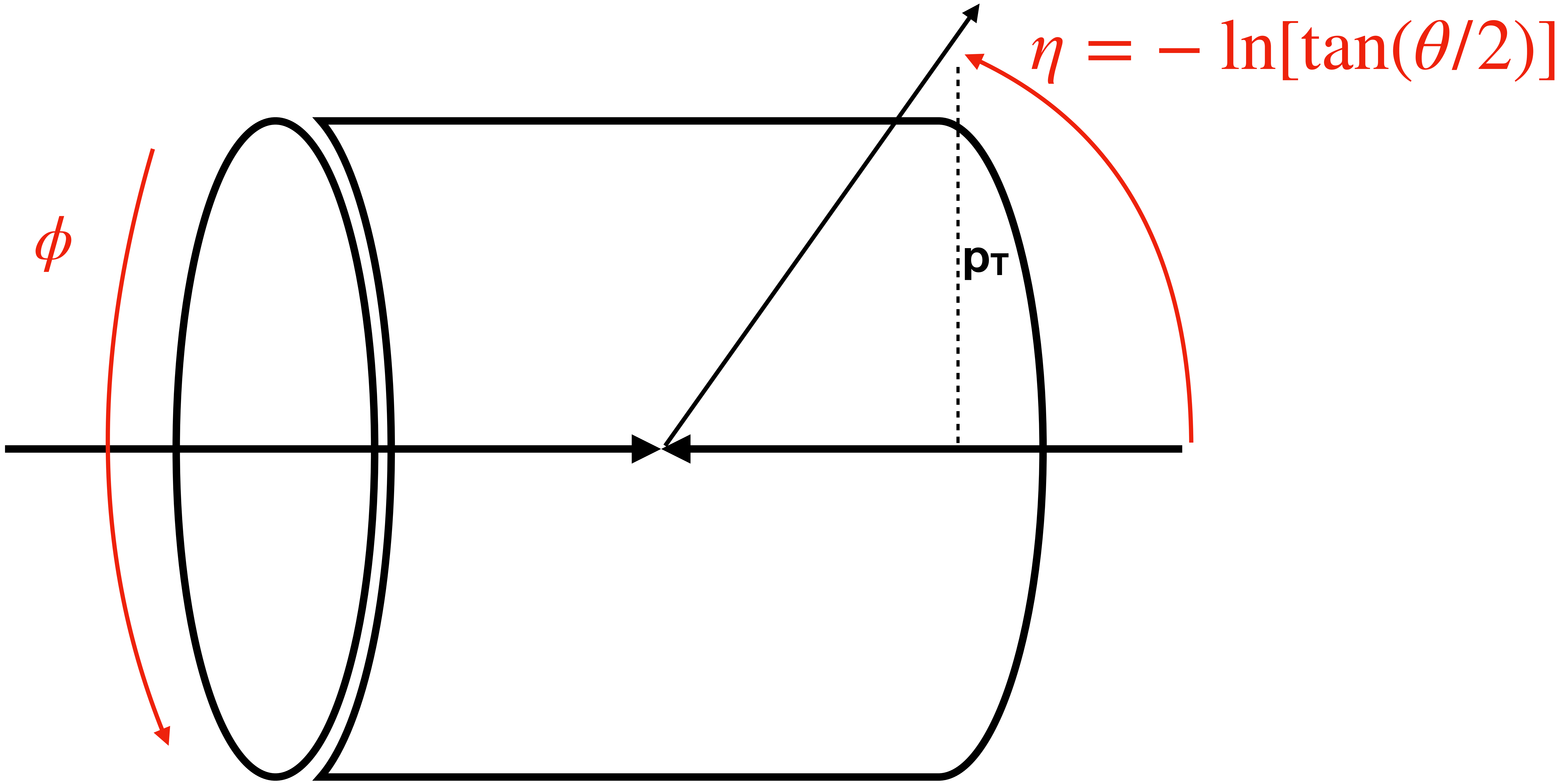
<u>AB</u>, Gardner P., Li W. PRC 107, 064908 (2023)

Postulated mechanism for collectivity



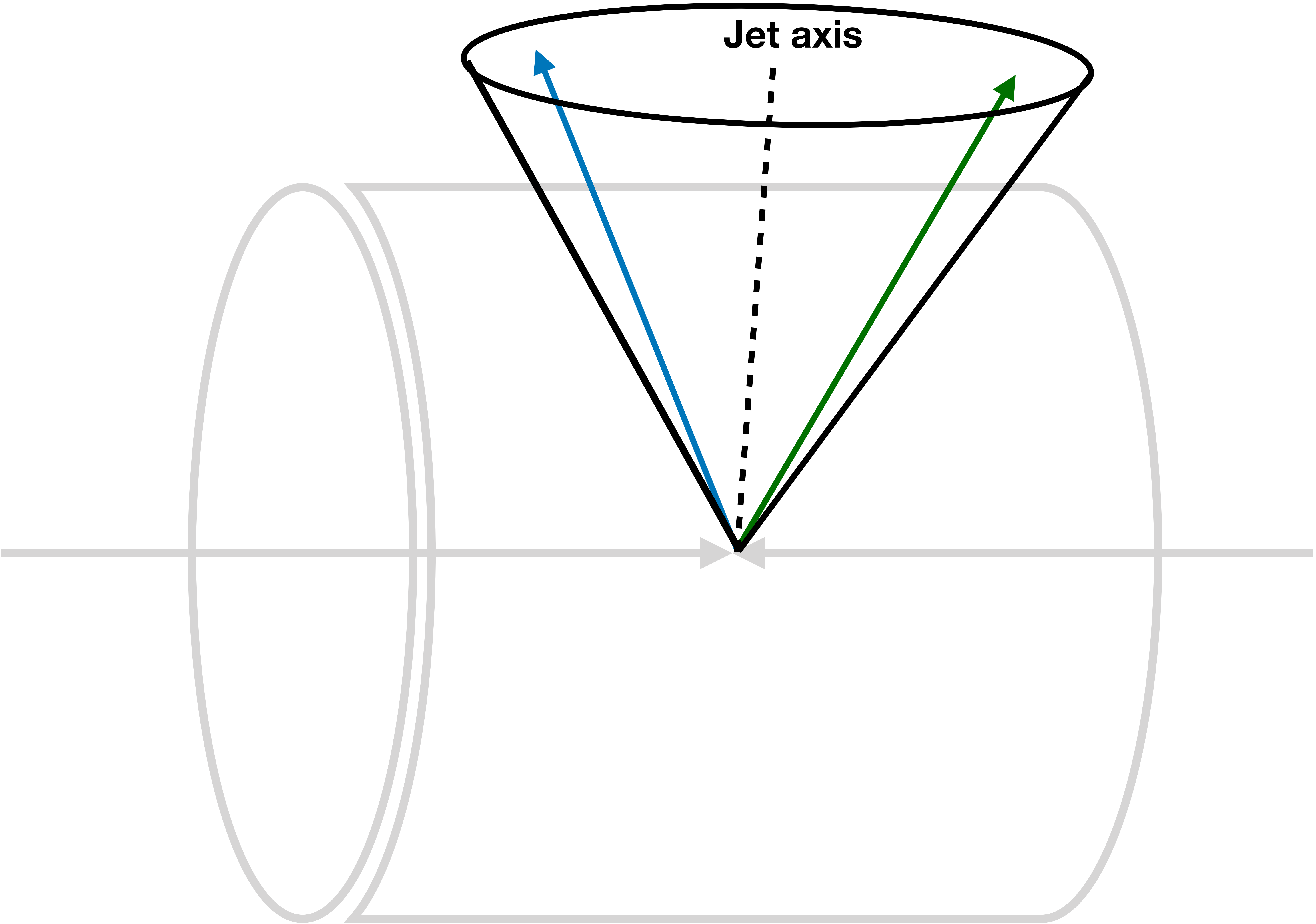
- **Single parton propagating *along jet axis* generates dense parton collection**
- **Interactions/rescattering between resulting partons could generate collectivity**
  - **Analysis must be with respect to jet axis - need to align jets**

Redefinition of coordinates



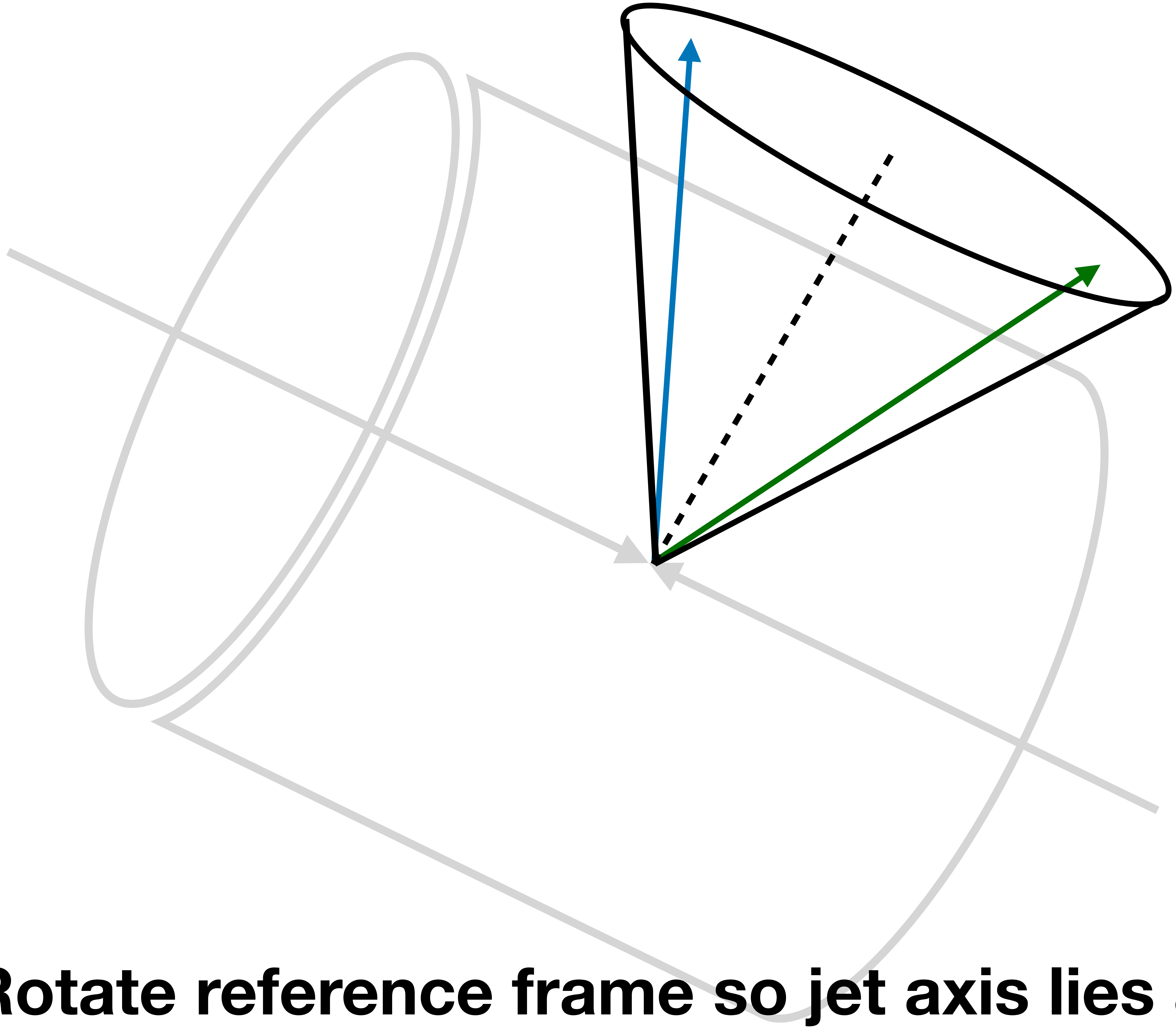
Start with standard lab coordinates

Rotation of reference frame



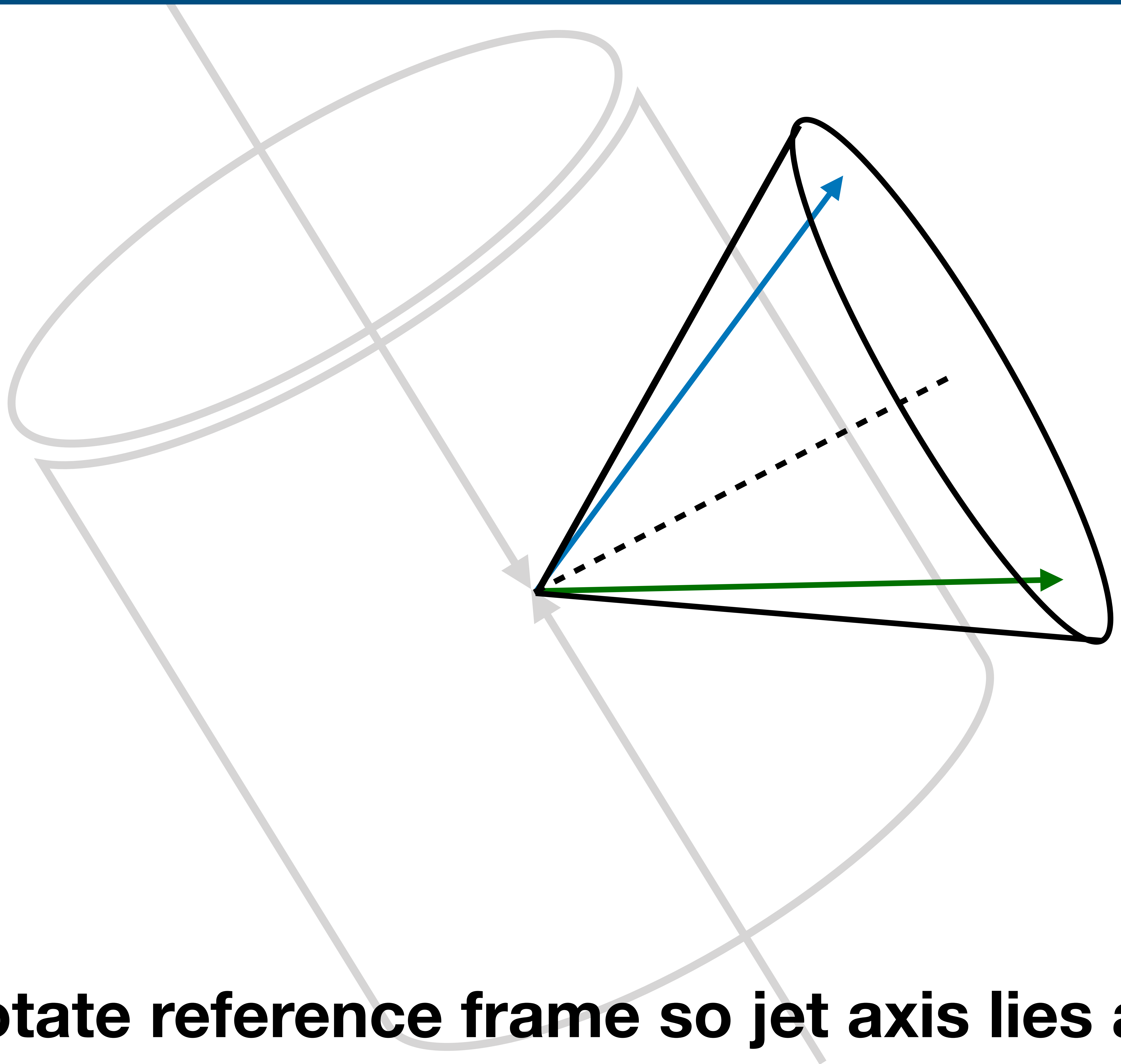
Consider a simplified jet with 2 constituents

Rotation of reference frame



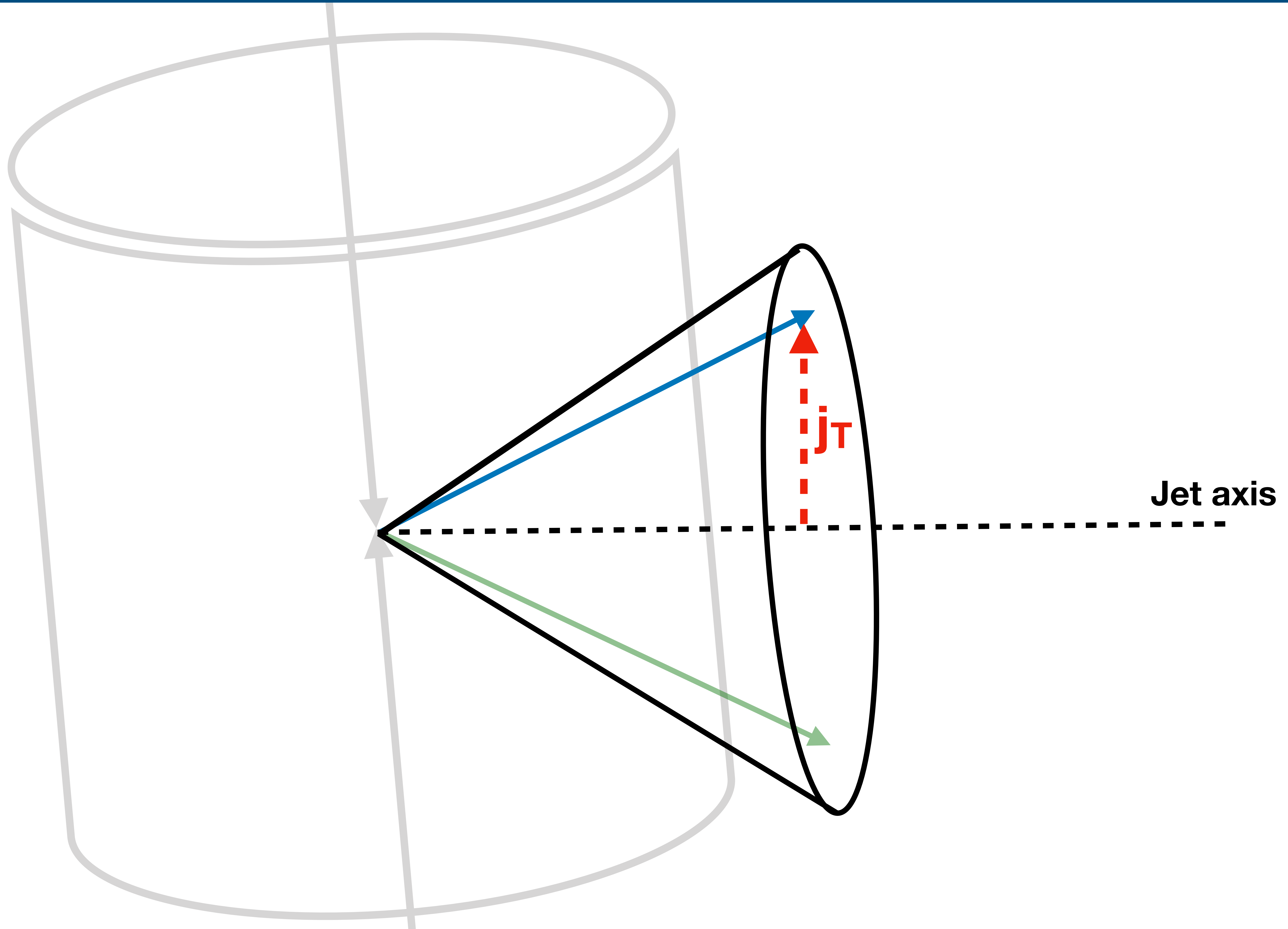
Rotate reference frame so jet axis lies along z axis

Rotation of reference frame



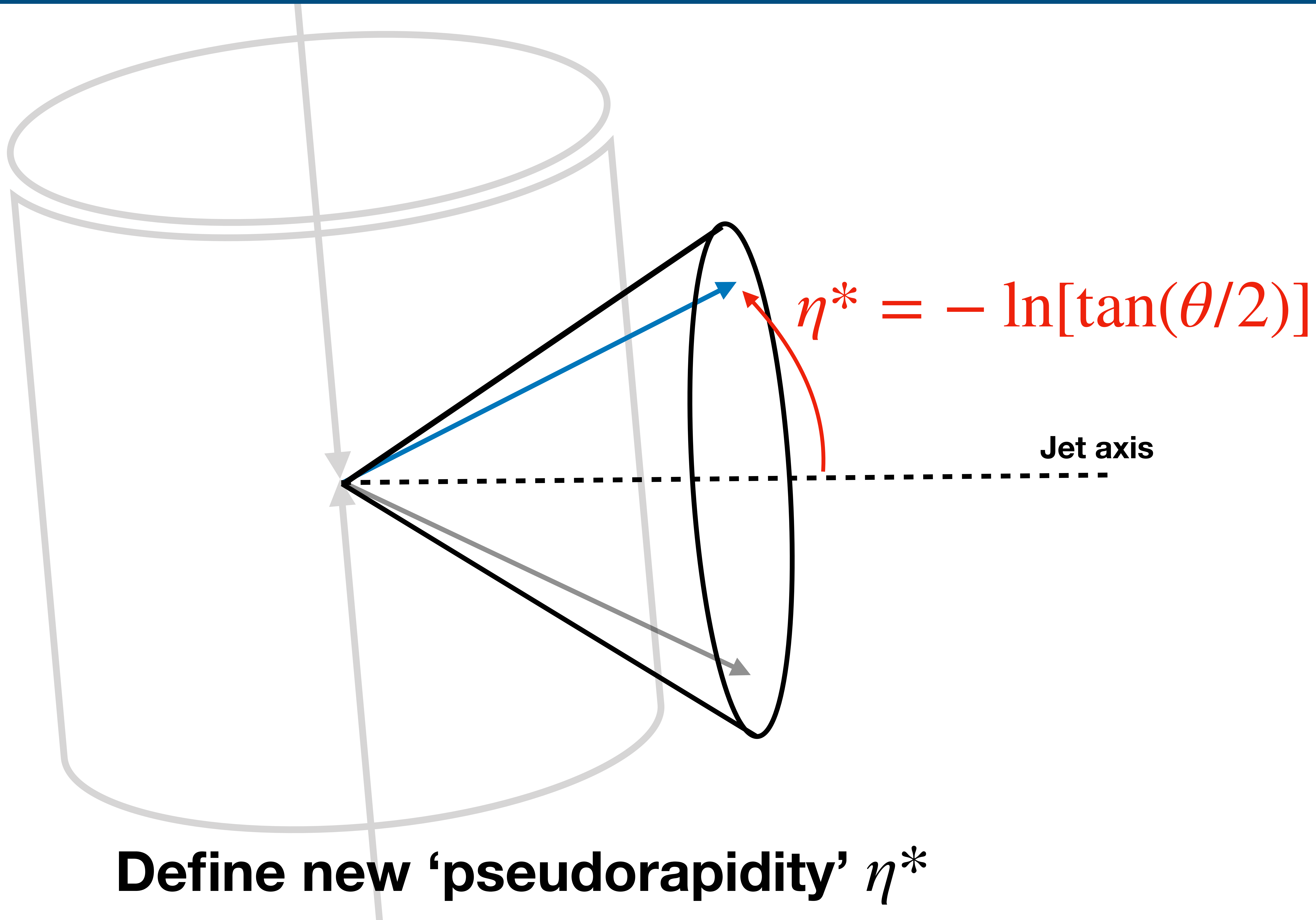
Rotate reference frame so jet axis lies along z axis

Coordinates in the jet frame



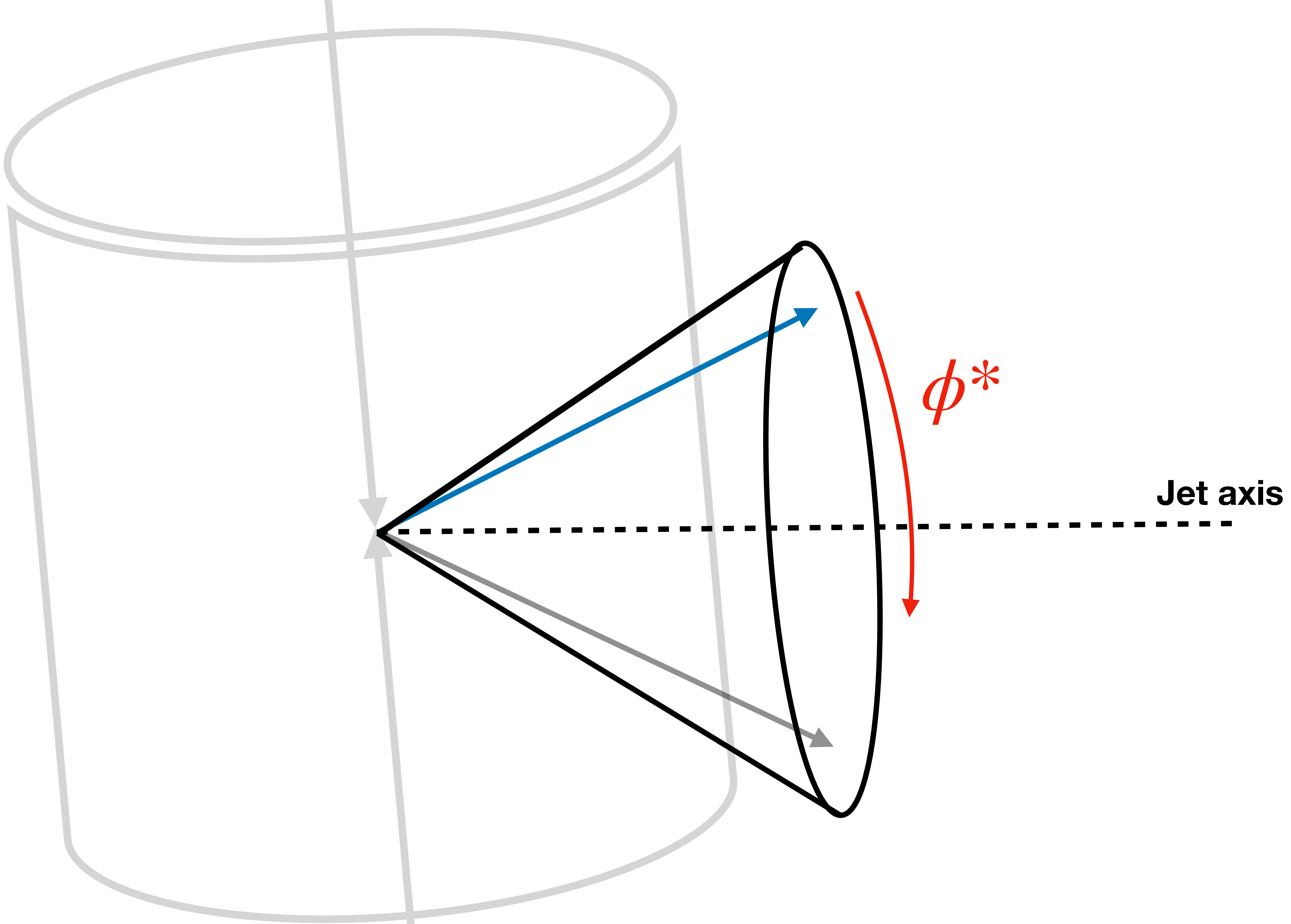
Define new 'transverse momentum' j_T

Coordinates in the jet frame



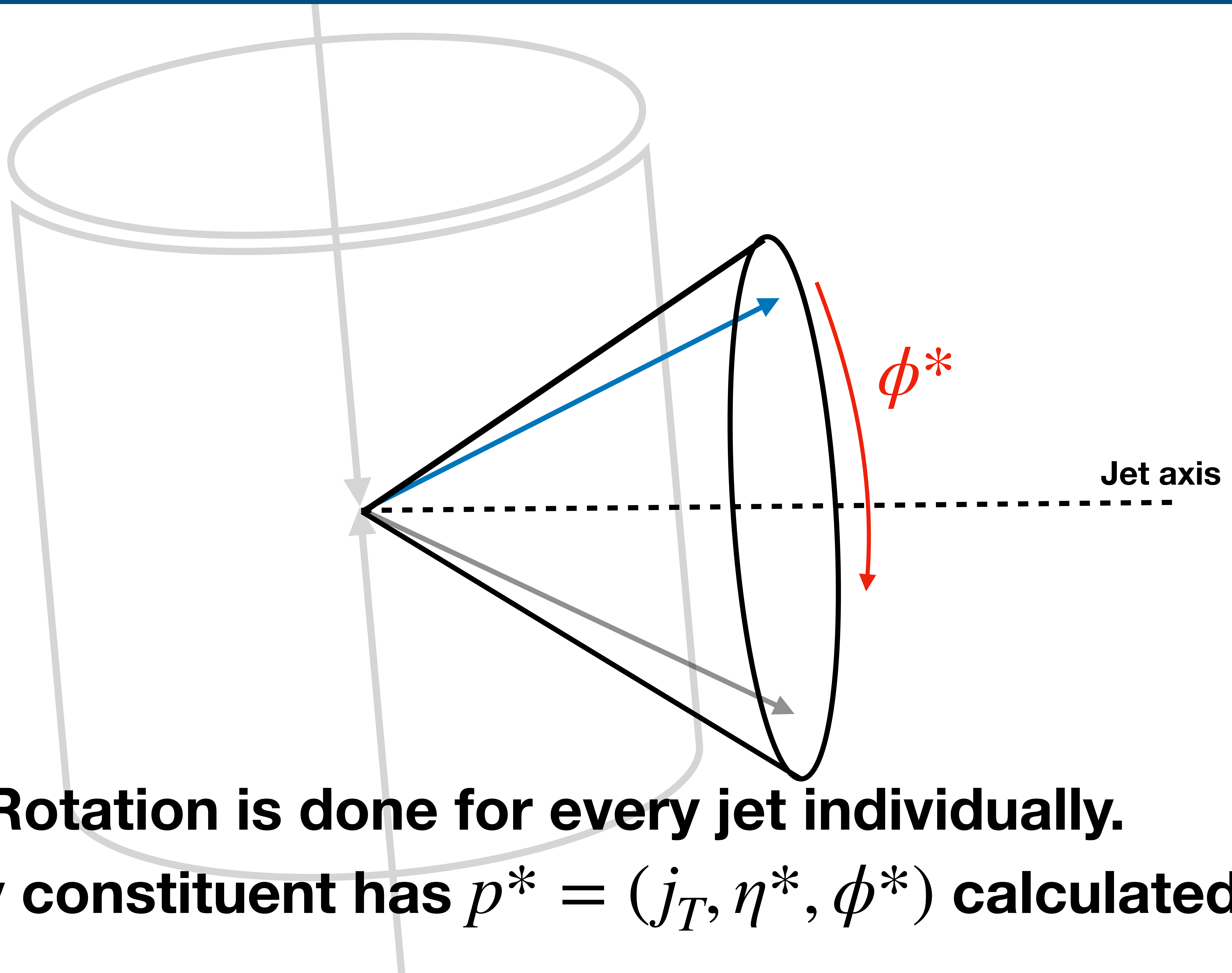
Define new 'pseudorapidity' η^*

Coordinates in the jet frame



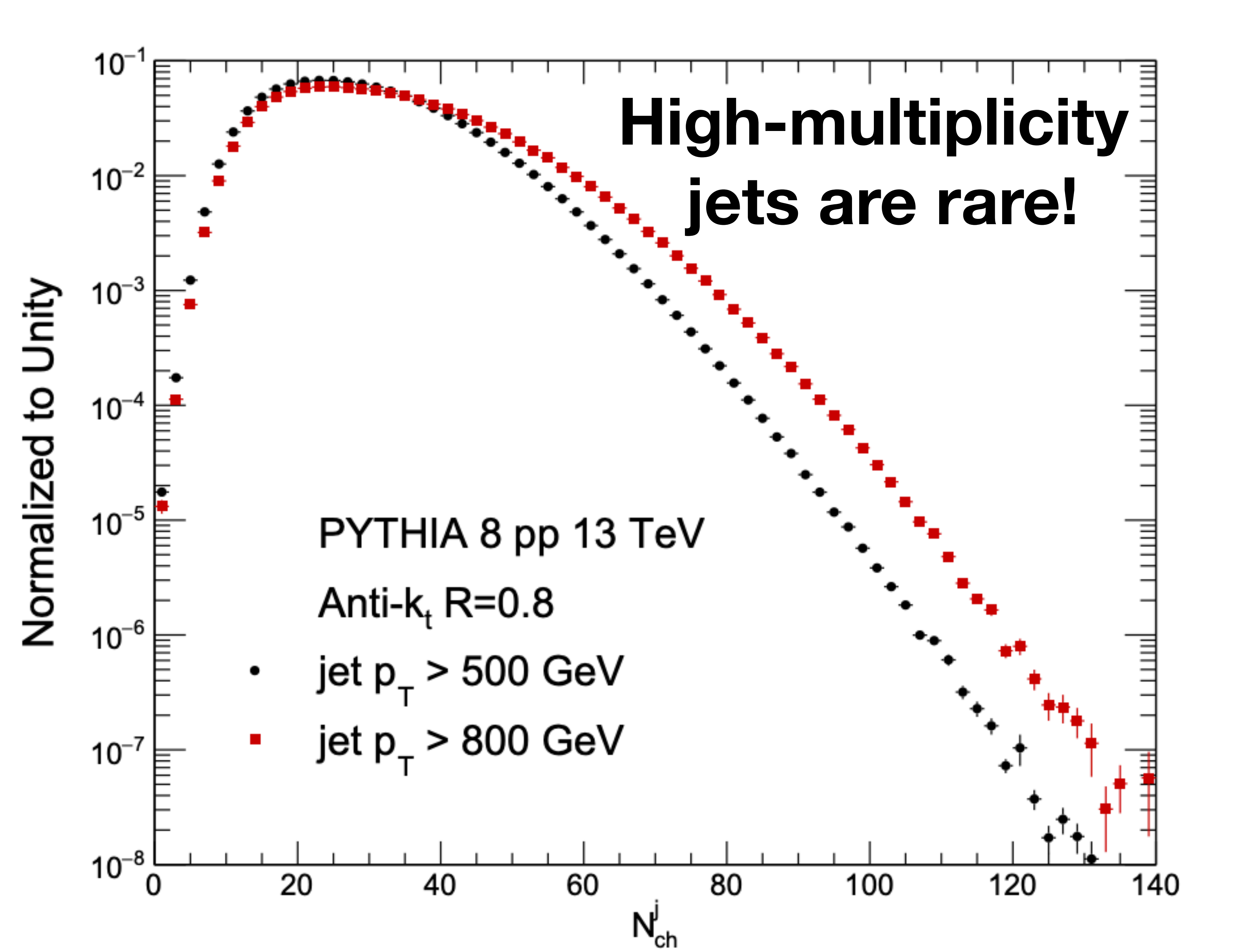
Define new 'azimuth' ϕ^*

Coordinates in the jet frame



Rotation is done for every jet individually.

Every constituent has $p^* = (j_T, \eta^*, \phi^*)$ calculated.



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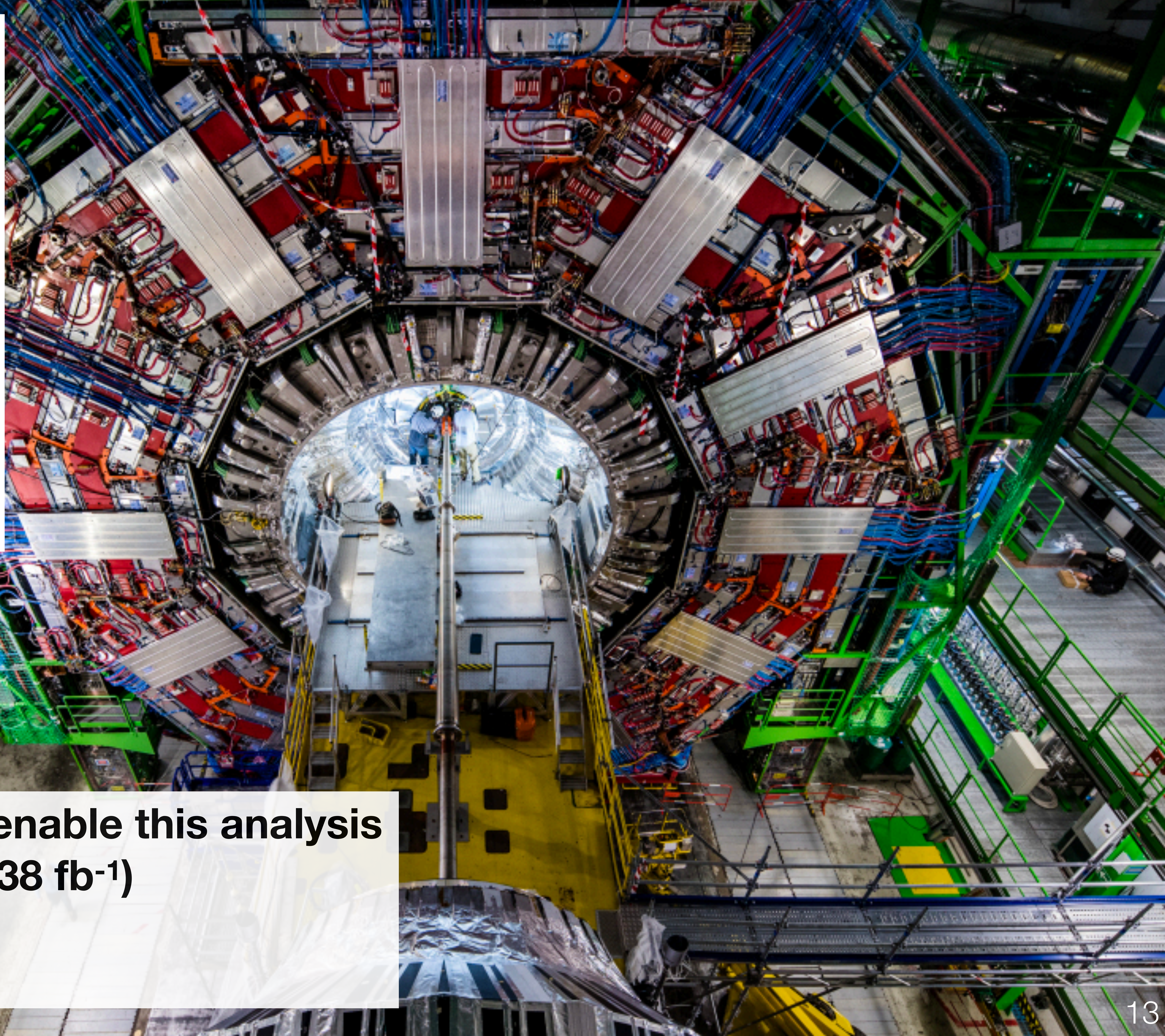
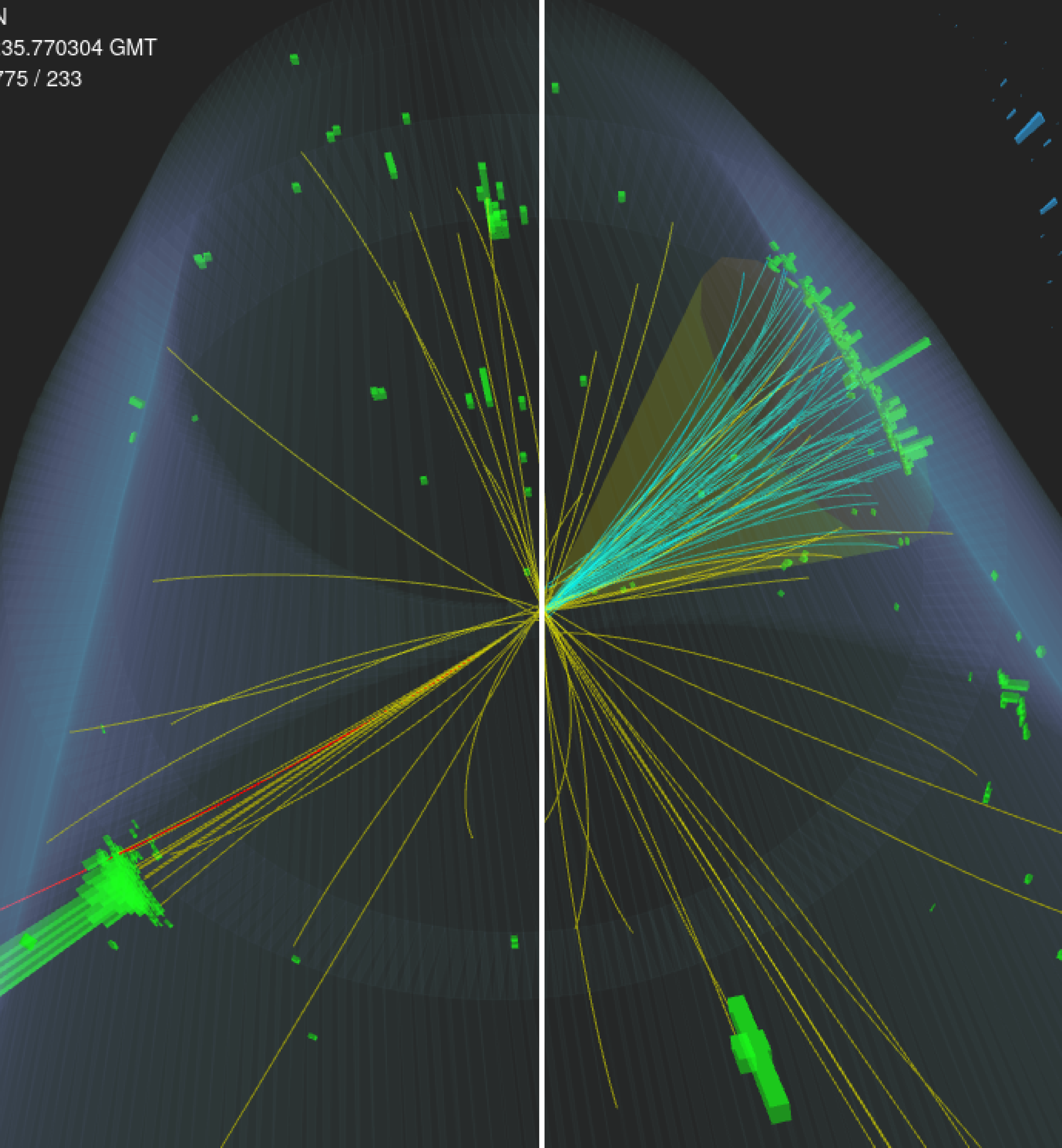


- CMS 13 TeV high-pileup data enable this analysis
  - Large sampled luminosity (138 fb^{-1})
  - Good jet acceptance
  - High quality tracking

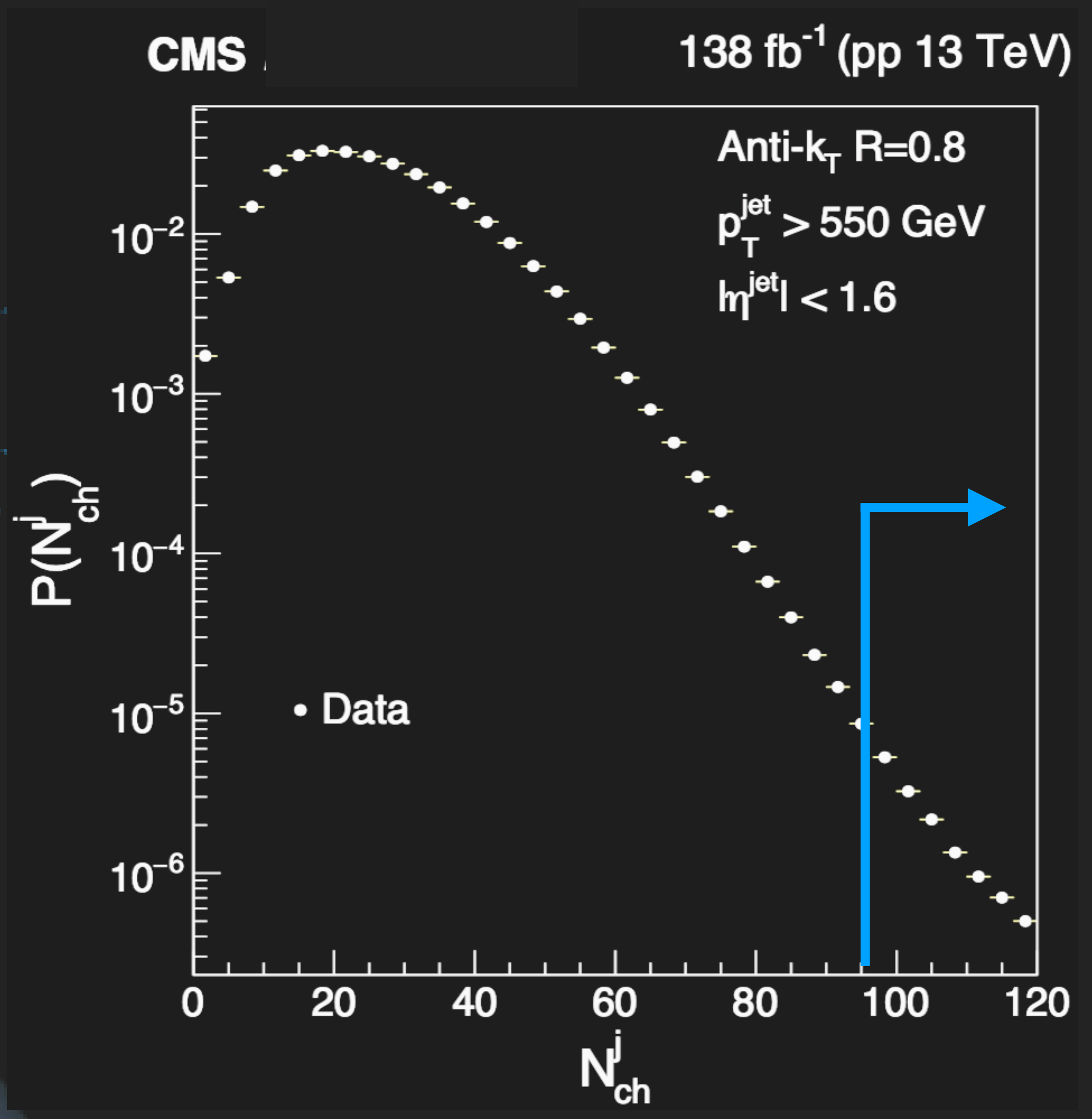


$p_T^{jet} > 550\ GeV$

$|\eta_{jet}| < 1.6$

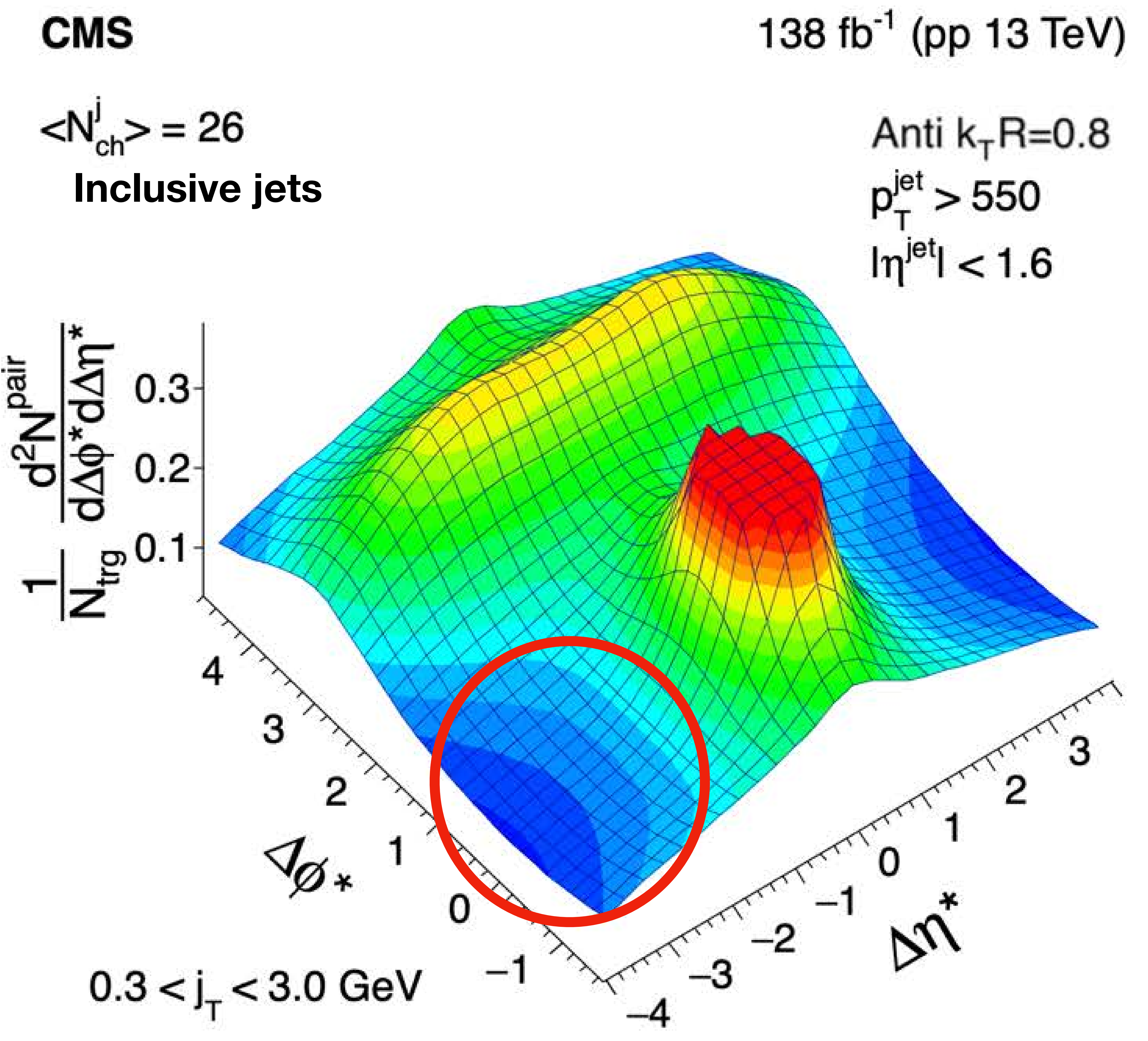
R=0.8 anti-k$_T$

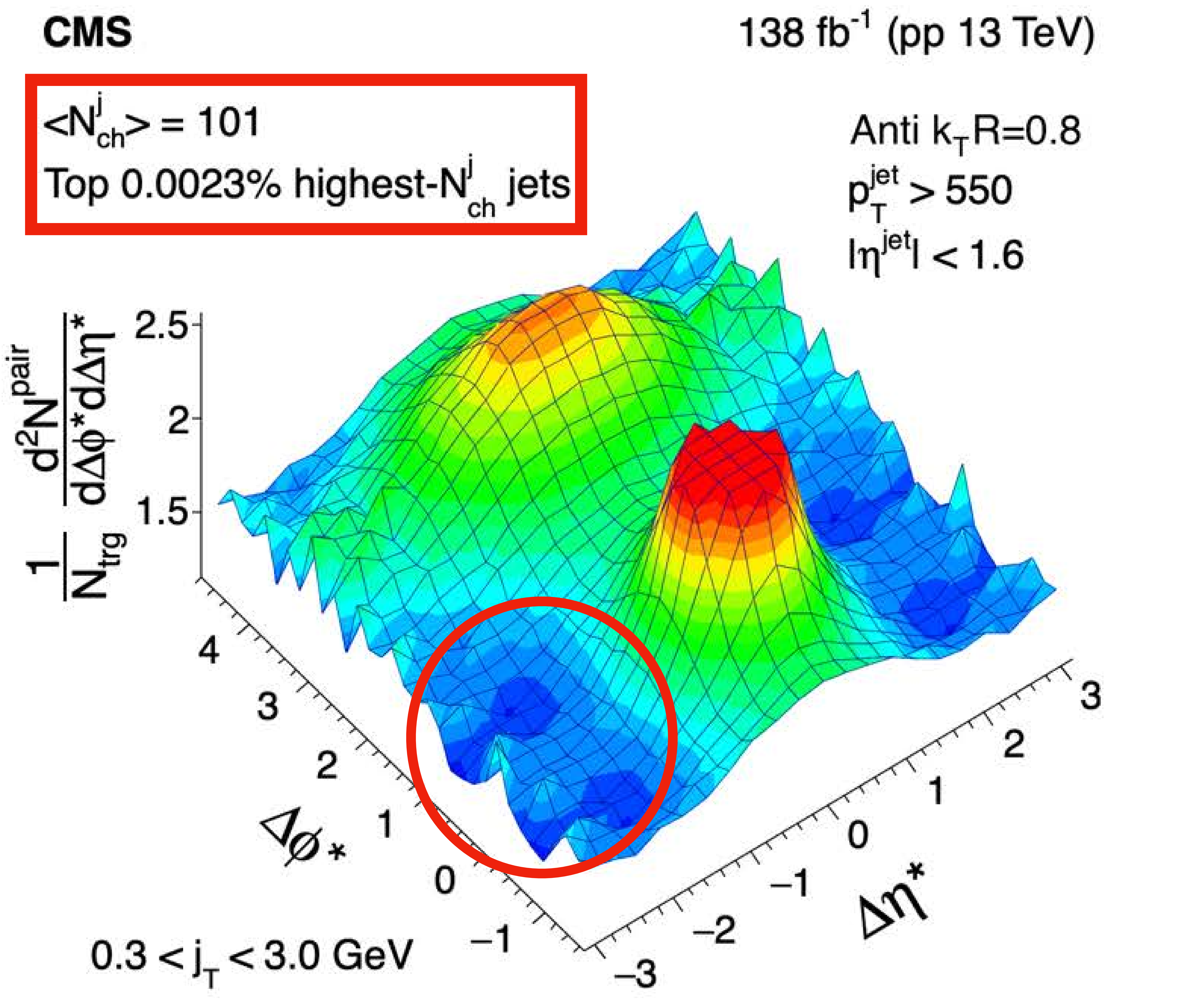
Analyze >10^8 jets



Select top ~2,500 jets in N$_{ch}$

High-Multiplicity 2D correlation



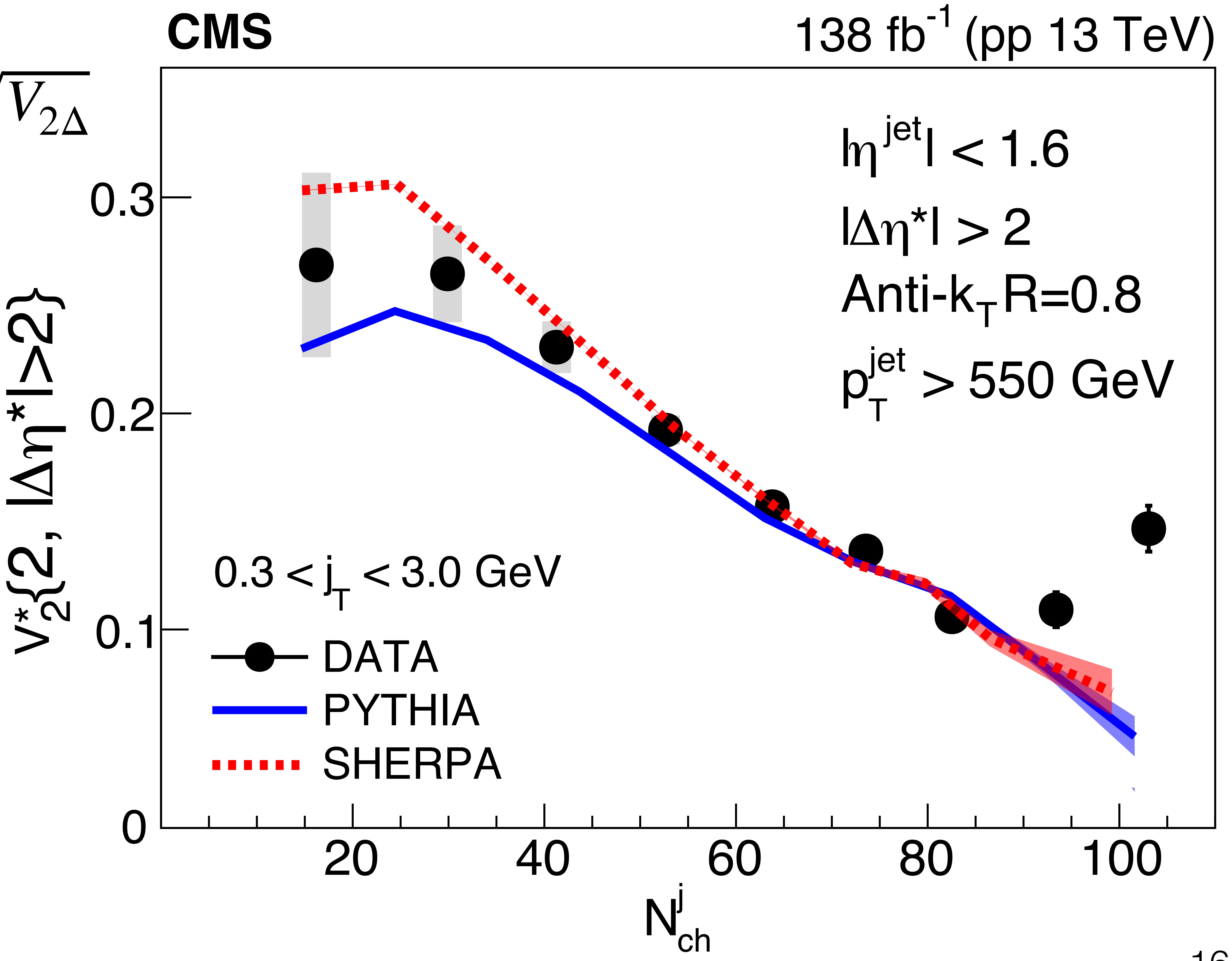


Potential 'ridge' in high-multiplicity jets?

v_2 vs jet N_{ch}

- **Quantify size of bump with** $v_2 = \sqrt{V_{2\Delta}}$
- **N_{ch}<80 trend captured by MC**
- **Rising trend for last few points**

- **Data deviates from MC by >5σ**
- **Observation of QGP-like effects above some critical density?**
- **What can explain such effect?**

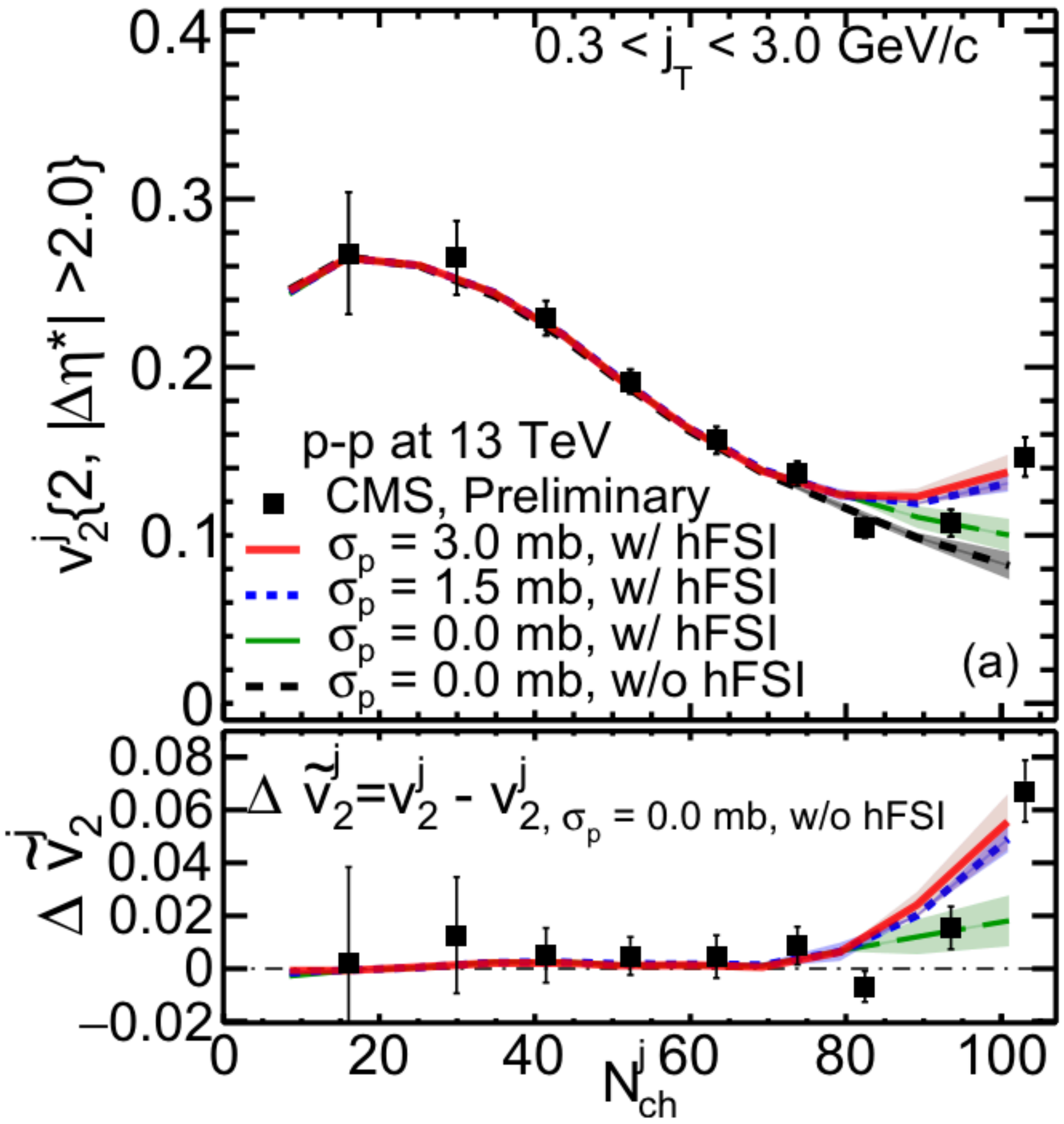


Potential collectivity explanation

W. Zhao, et. al., arxiv:2401.13137

- **Test 'collectivity' interpretation by adding final-state interactions to parton shower**
- **No effect in low N_{ch} region**
  - **consistent with HEP studies**

- **Only hadronic final state interactions can't describe data**
- **Need partonic rescatterings**
  - **Cross section similar to that needed to describe pPb v_n data**



$\Delta\eta*$ Dependence

- **Test 'collectivity' interpretation by adding final-state interactions to parton shower**
- **No effect in low N_{ch} region**
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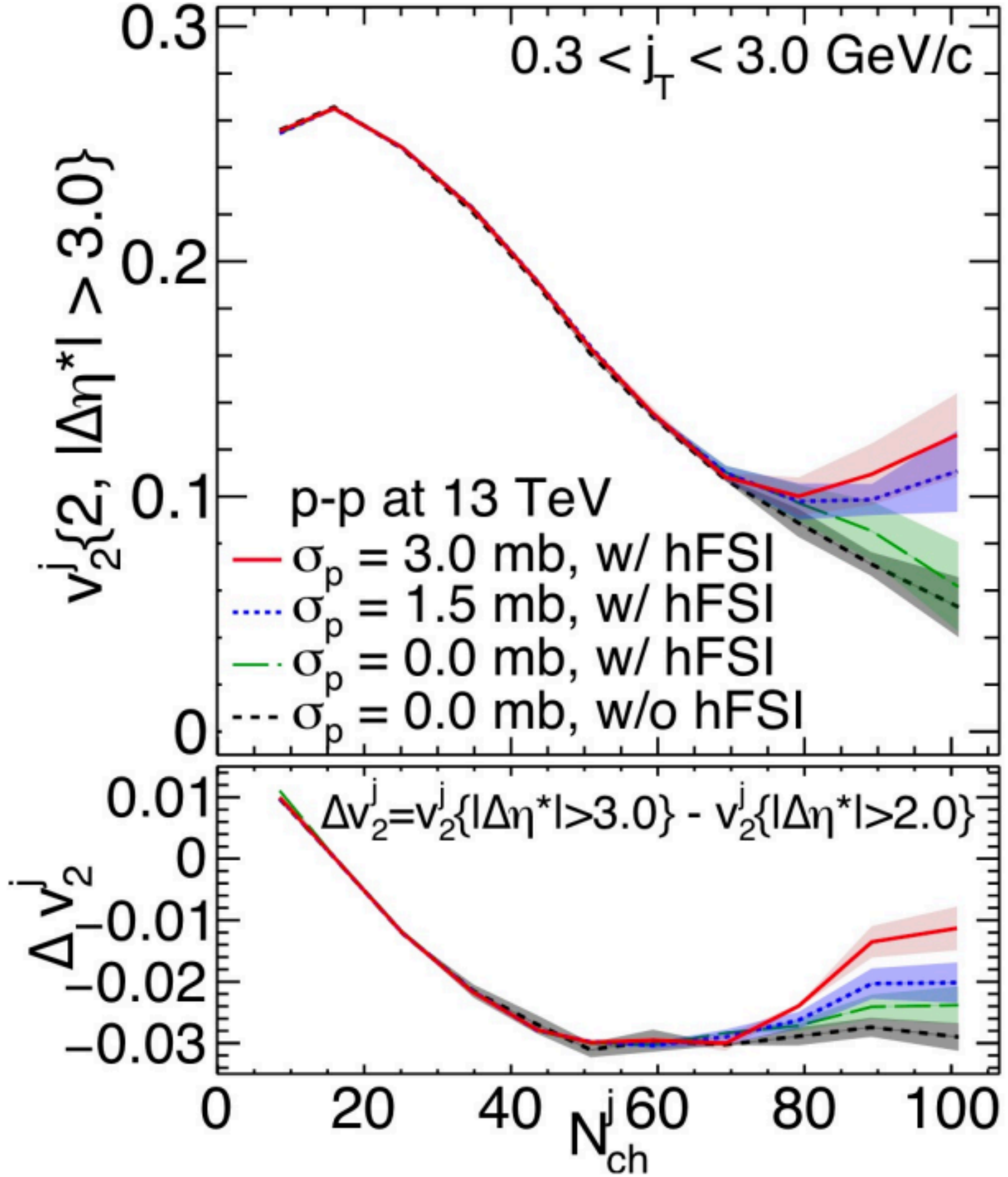
- **Only hadronic final state interactions can't describe data**
- **Need partonic rescatterings**
  - **Cross section similar to that needed to describe pPb v_n data**
- **Predicted a flattening of $\Delta\eta*$ dependence for N_{ch}>80**

W. Zhao, et. al., arxiv:2401.13137



New CMS analysis

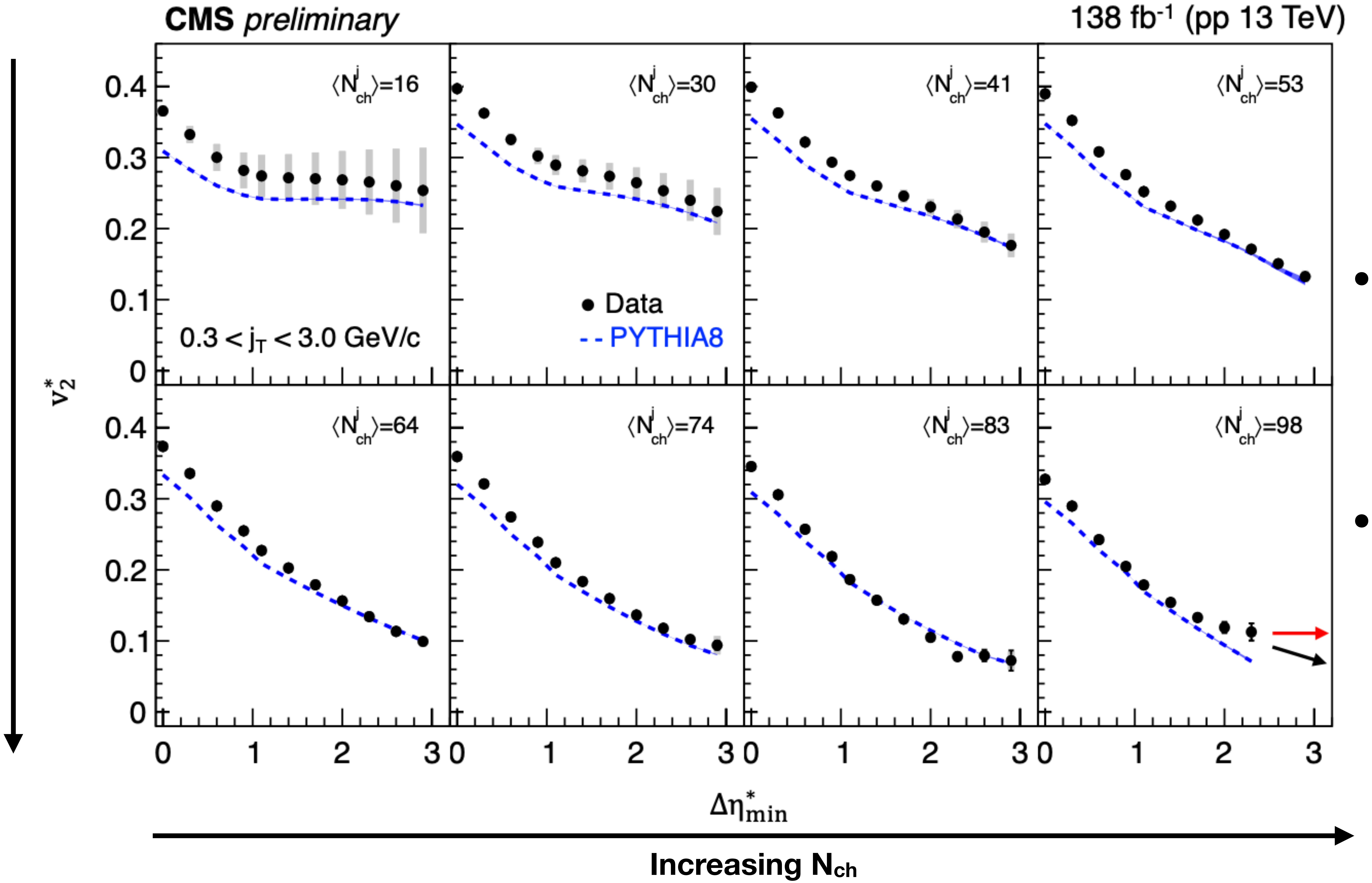
Unveiling the dynamics of long-range correlations in high-multiplicity jets through substructure engineering in pp collisions at CMS

The CMS Collaboration

CMS-PAS-HIN-24-024

- **New CMS follow-up analysis trying to provide more input to interpretations**

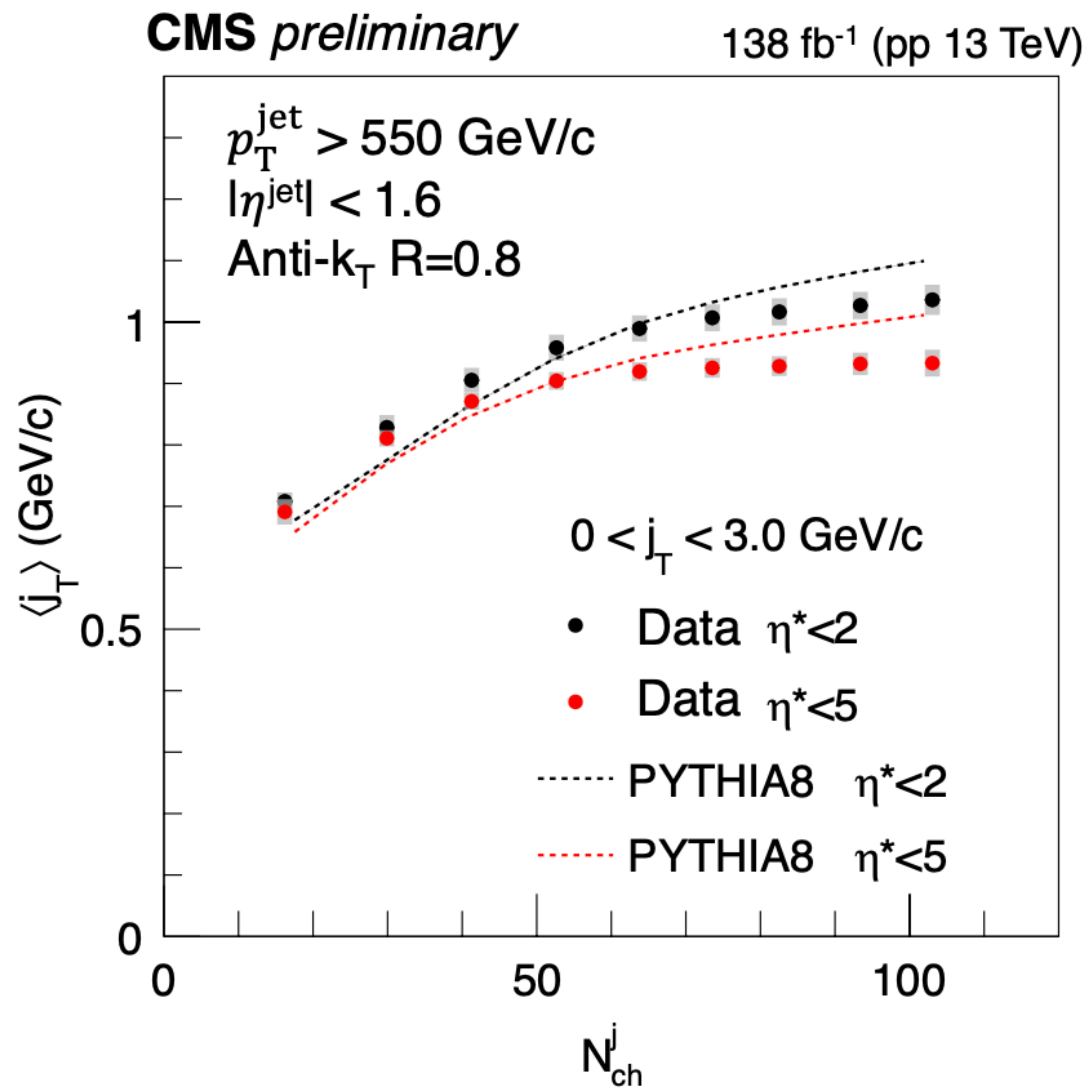
$\Delta\eta*$ Dependence - data



- **Qualitative flattening vs. $\Delta\eta*$ seen in data**
- **Rather small effect**

Average j_T Dependence

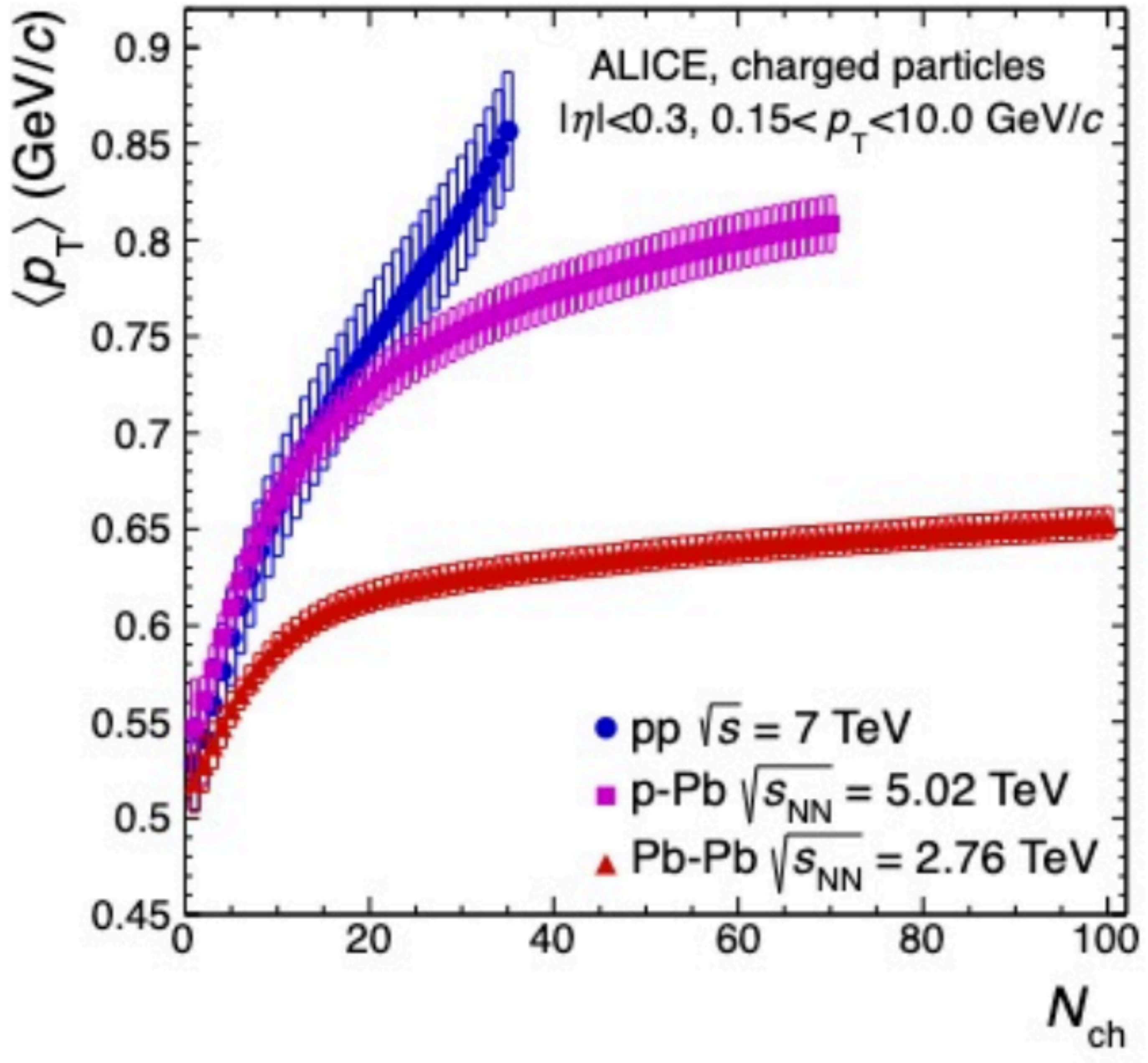
- ‘p_T’ with respect to jet axis
- **Lower average values than Pythia 8 for high N_{ch}**

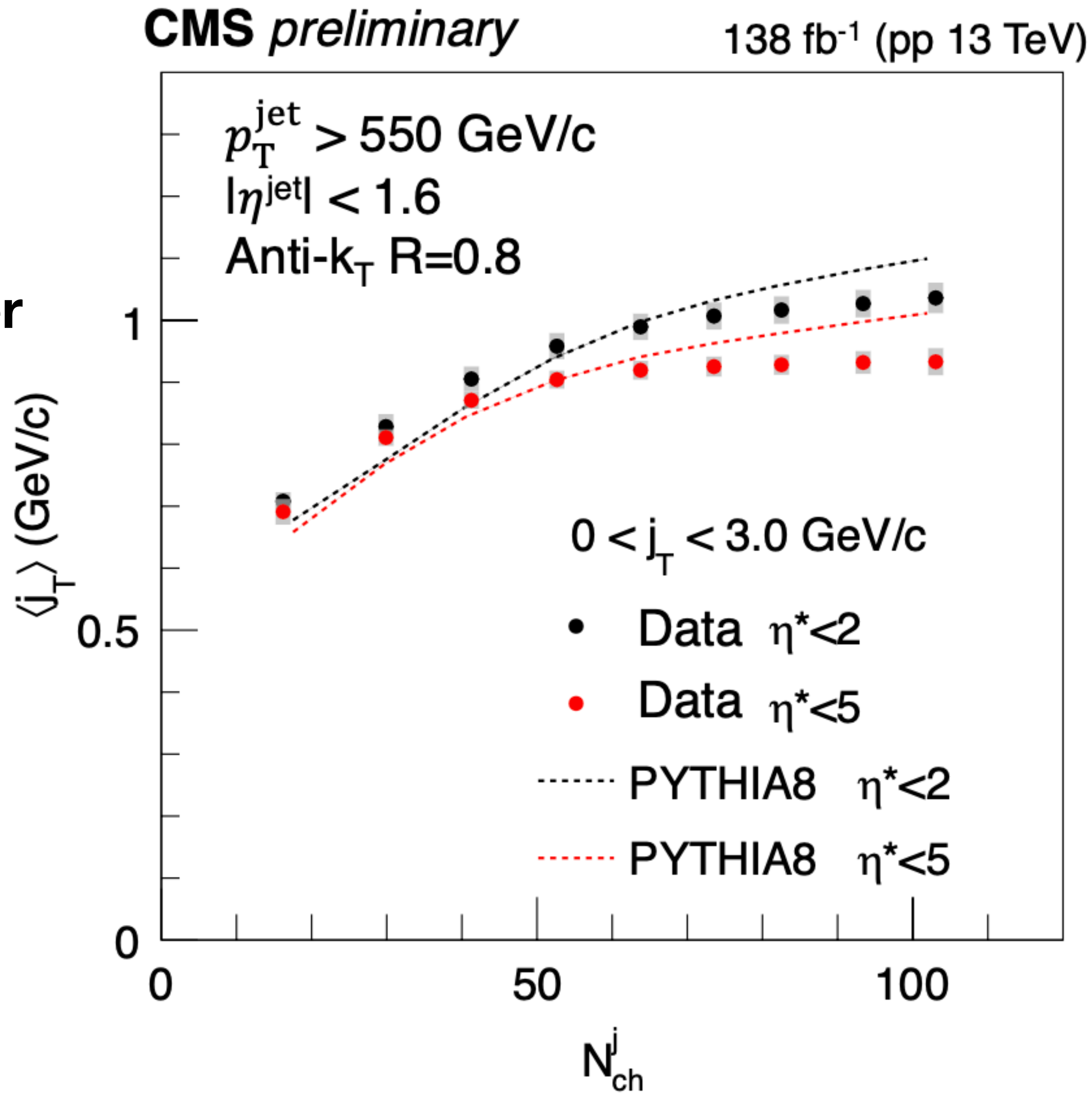


Average j_T Dependence

- 'p_T' with respect to jet axis
- Lower average values than Pythia 8 for high N_{ch}
- Suggestive of behavior in HI where other particle production mechanisms kick in

PLB 727 (2013) 371-380

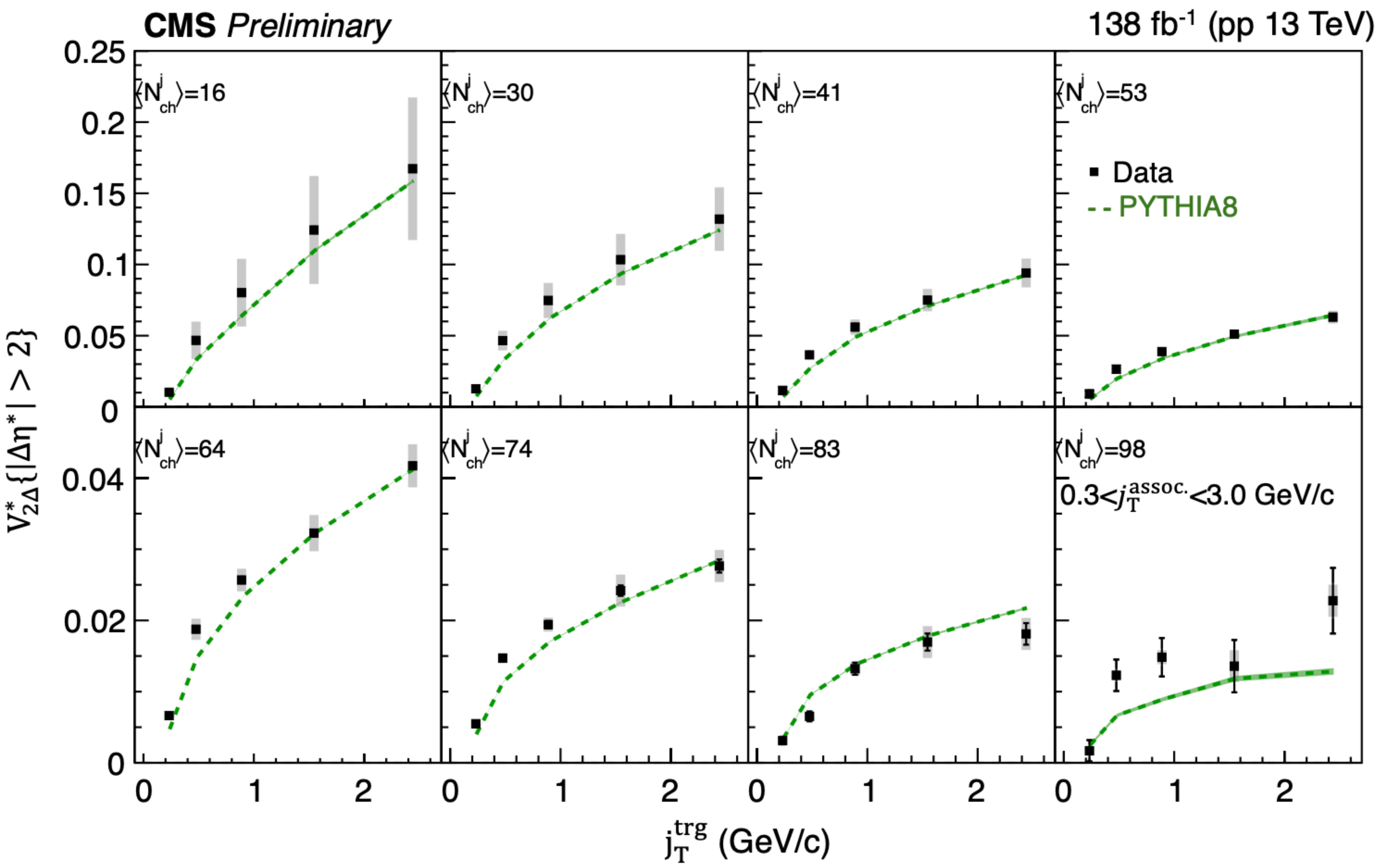




Scan of trigger particle j_T

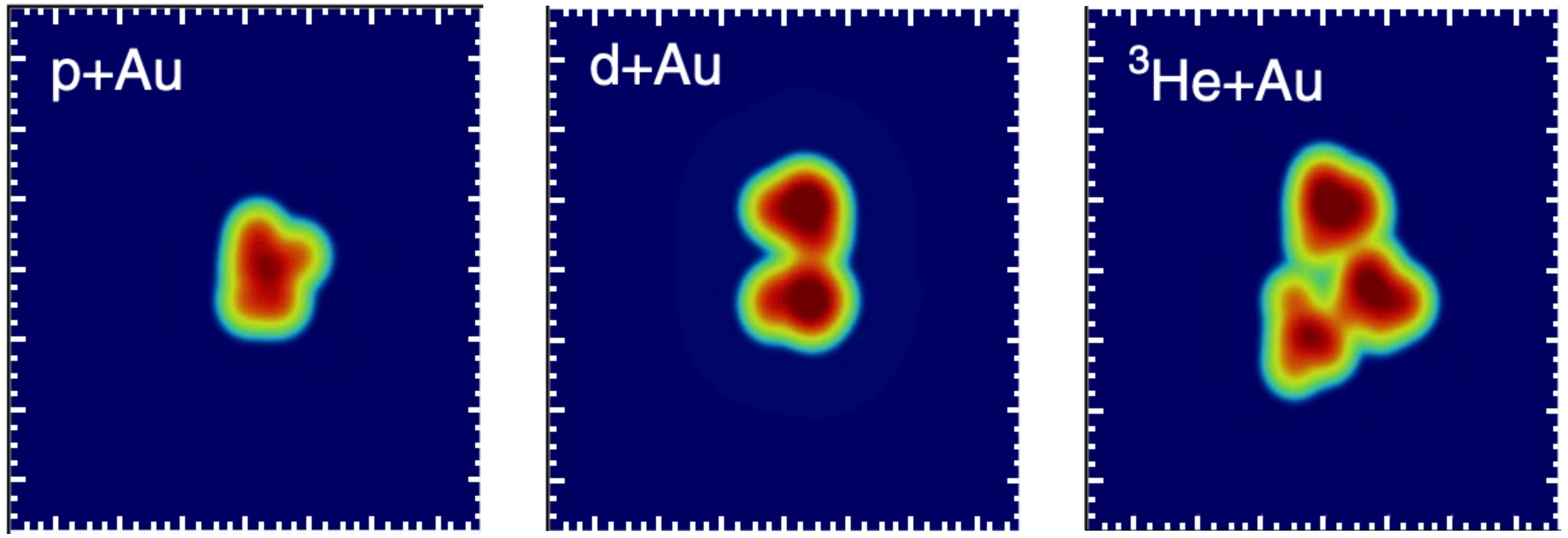
- **V_2 vs. j_T^{trig} has largest deviations >0.3 GeV**

- **Effect comes from particles with greater separation from jet axis**



Role of initial geometry

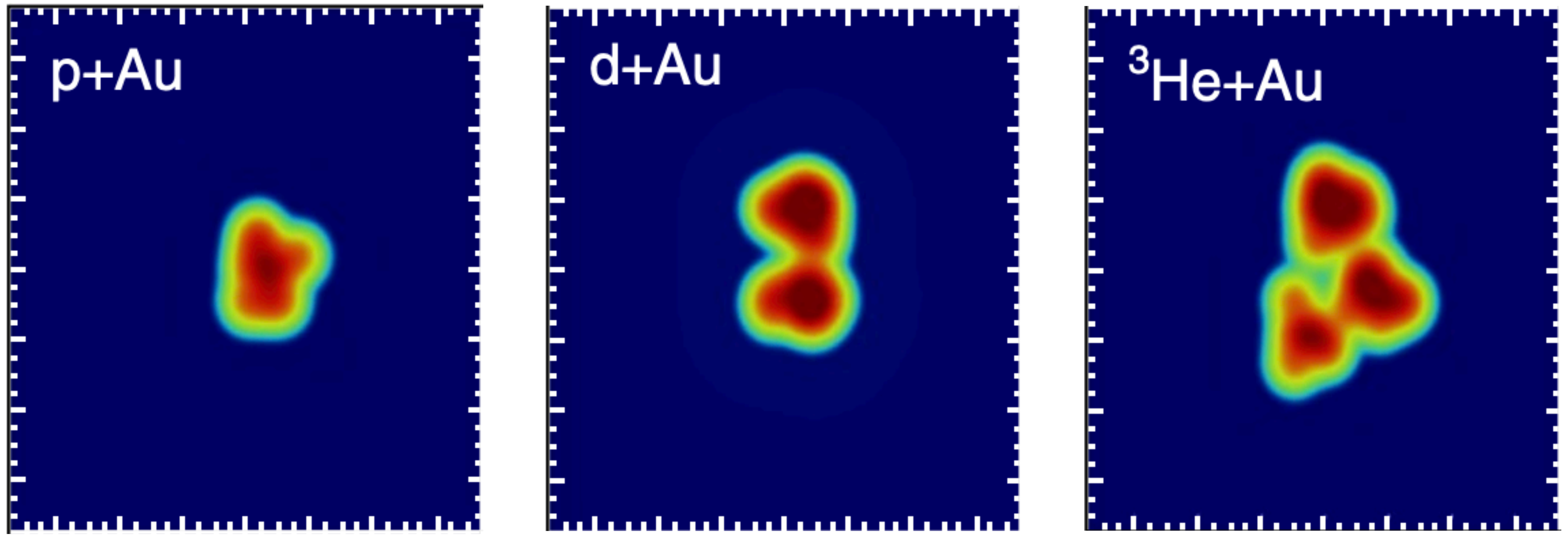
- **In Heavy Ions, we know initial geometry is of key importance**
- **Is there any ‘initial parton geometry’ analogue for jets?**



Nature Physics 15, 214-220 (2019)

Role of initial geometry

- **In Heavy Ions, we know initial geometry is of key importance**
- **Is there any 'initial parton geometry' analogue for jets? - domain of jet substructure**



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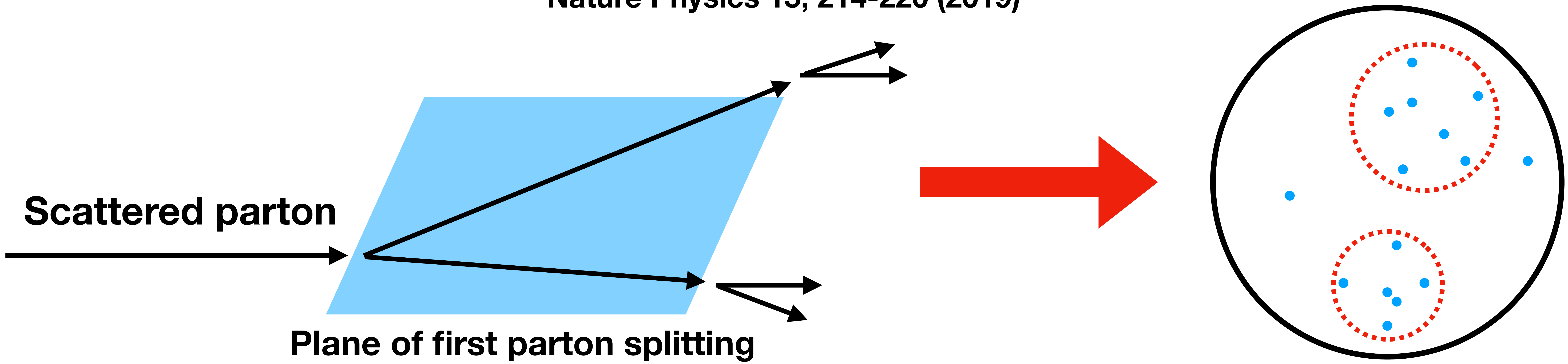
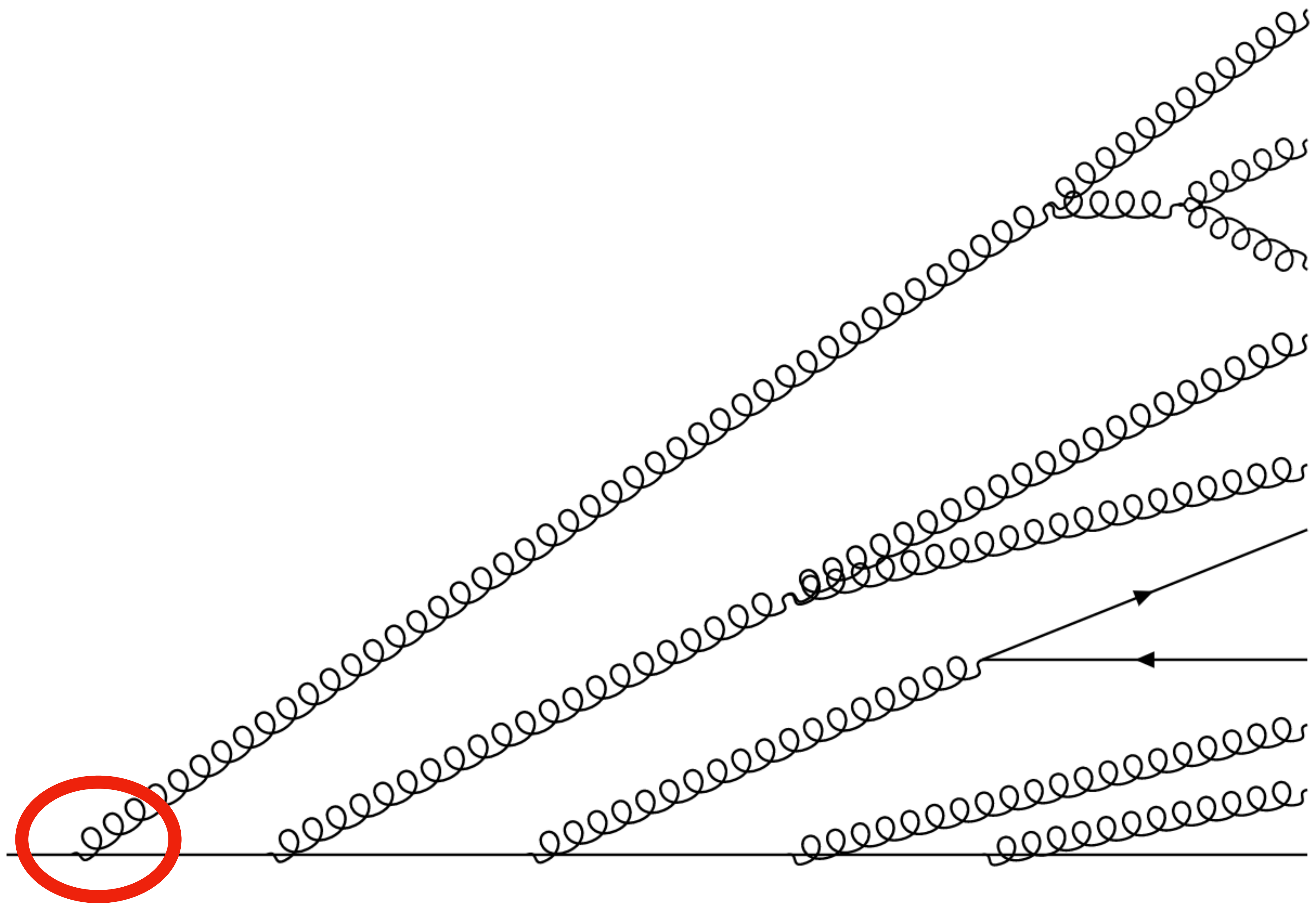
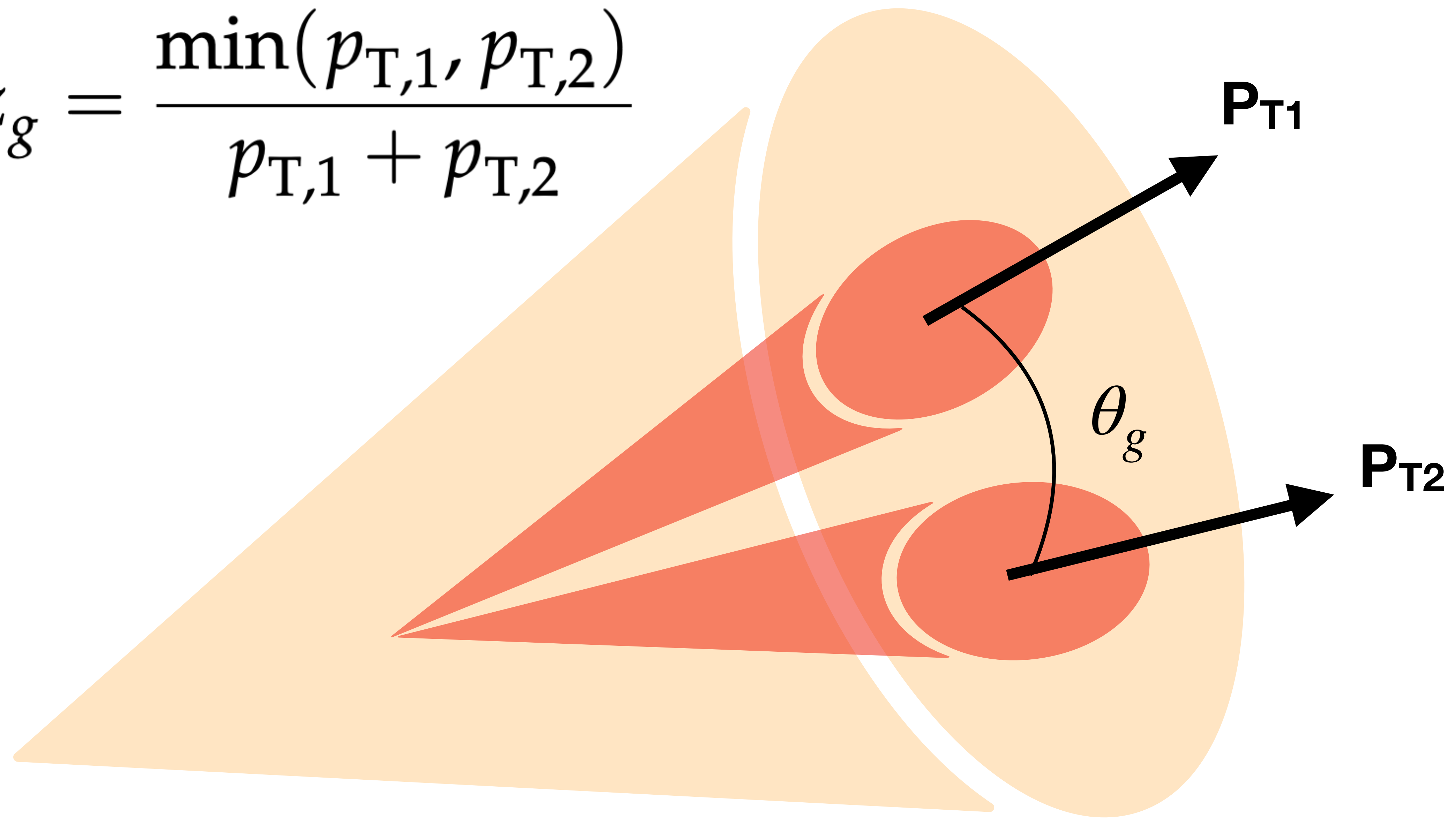


Jet substructure engineering

- **Use SoftDrop grooming algorithm to access** **early parton splitting kinematics**

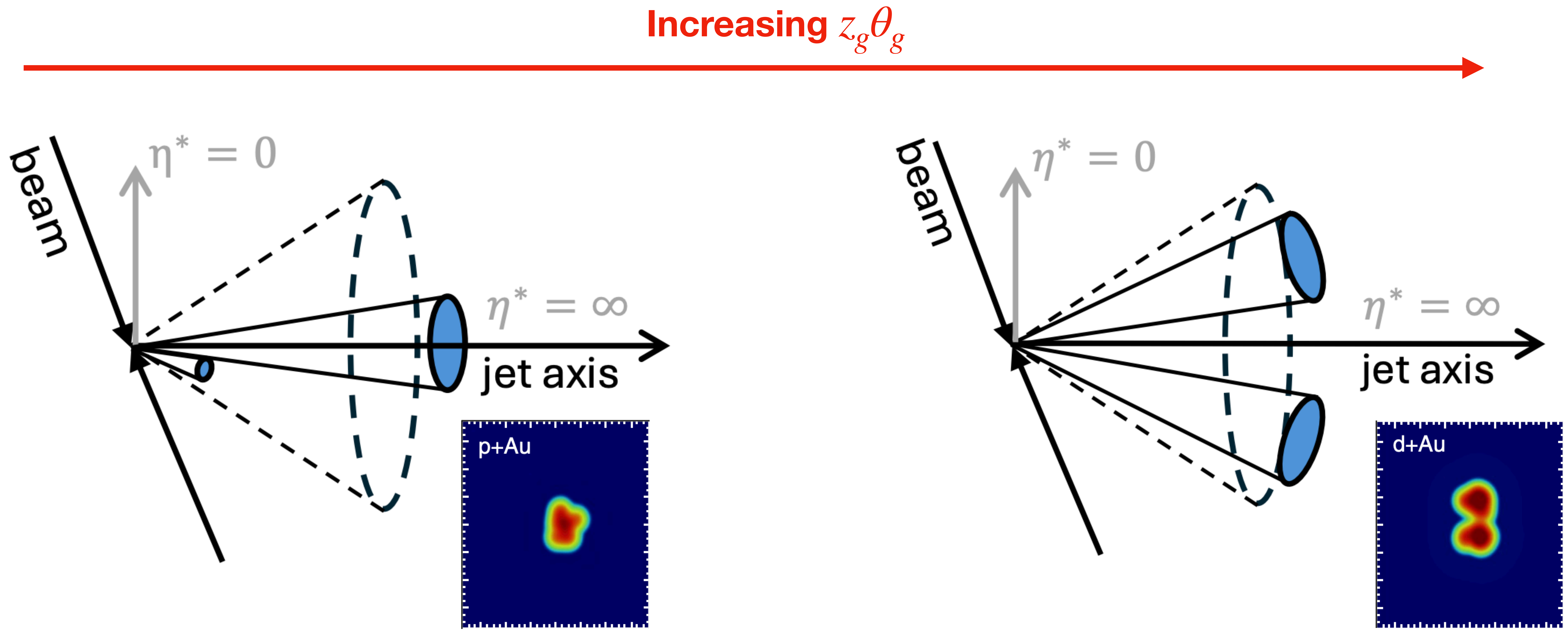


$$z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$$



Jet substructure engineering

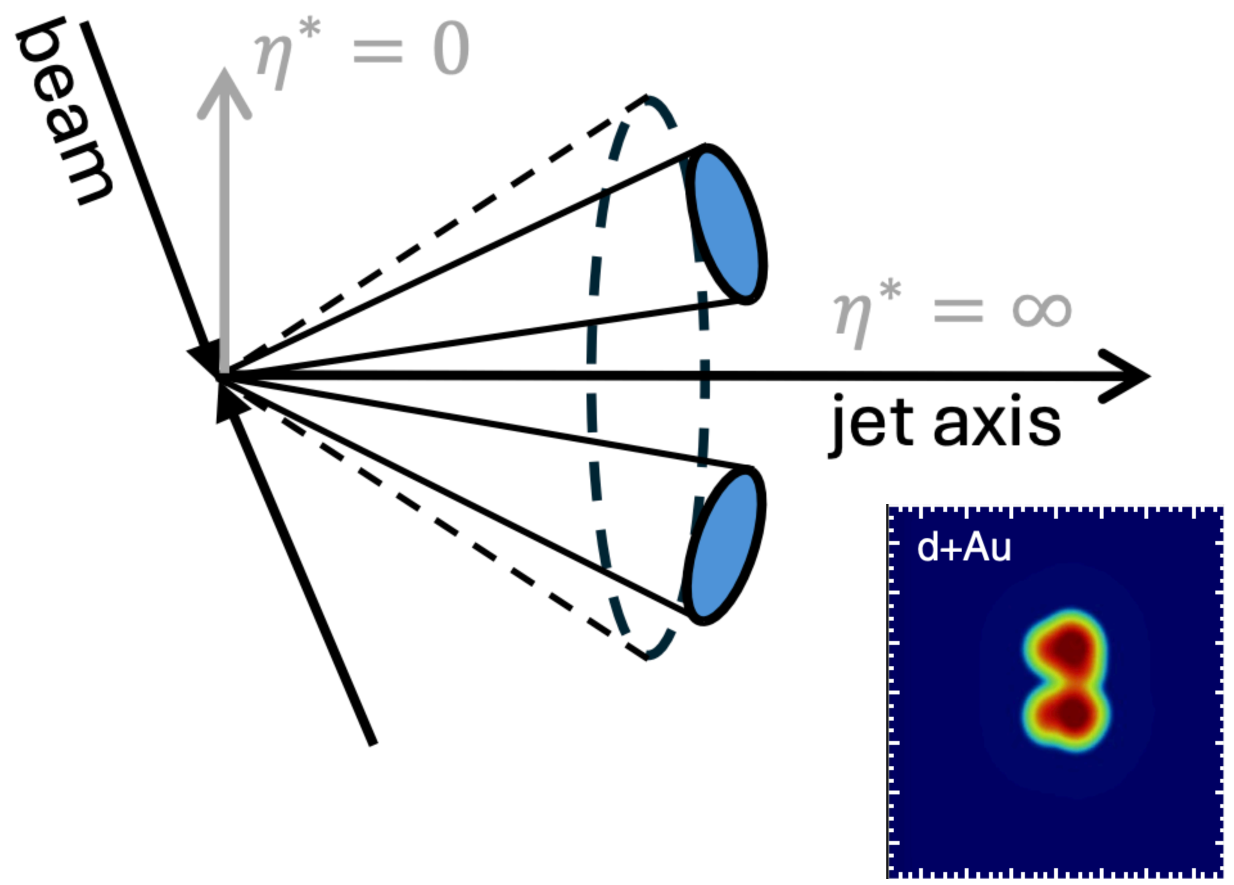
- **Use SoftDrop grooming algorithm to access early parton splitting kinematics**
- **Quantify how separated + balanced two-prongs in jet is with** $z_g\theta_g$

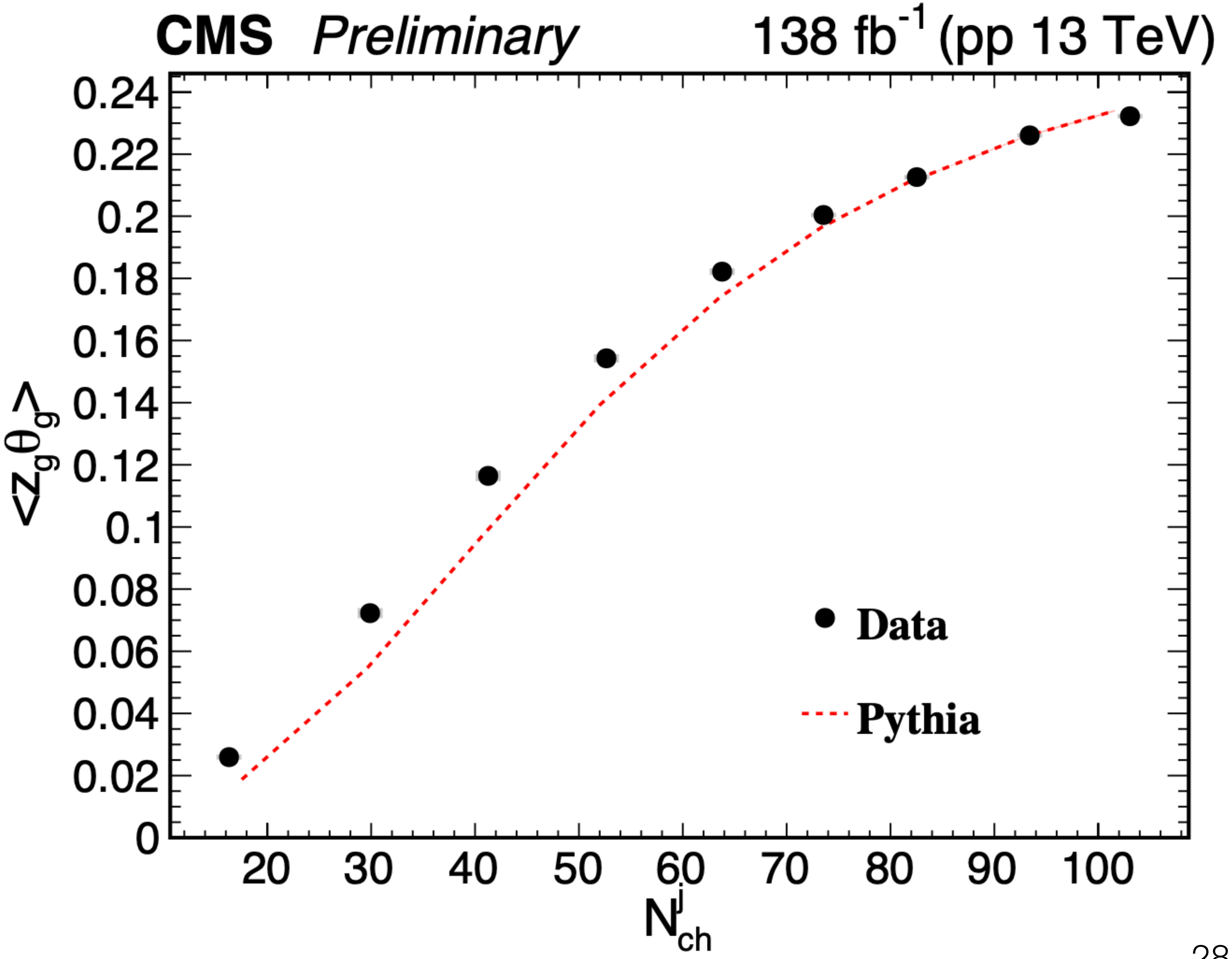


$\langle z_g\theta_g \rangle$ vs N_{ch} in data

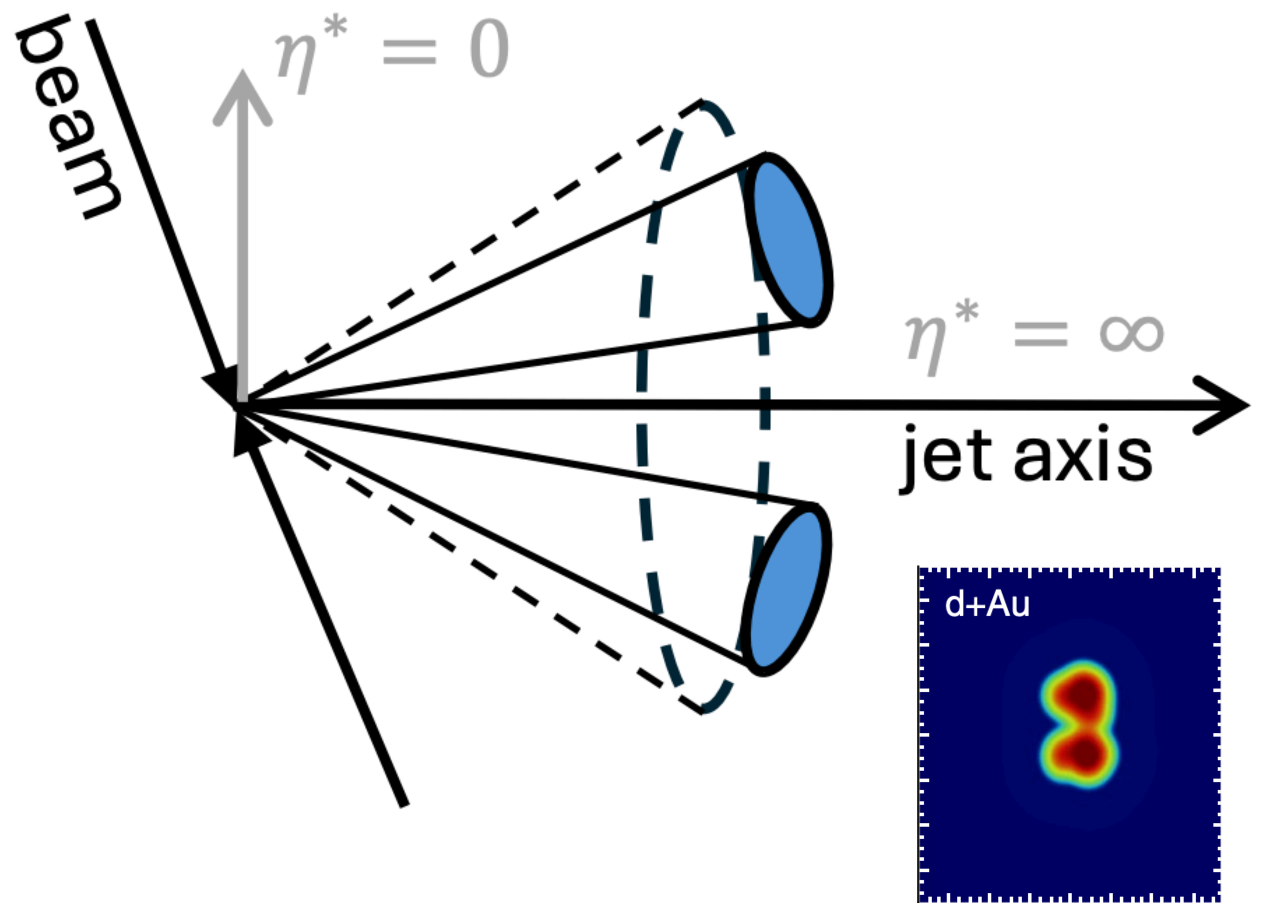
- Average $z_g\theta_g$ distribution well-described by Pythia 8

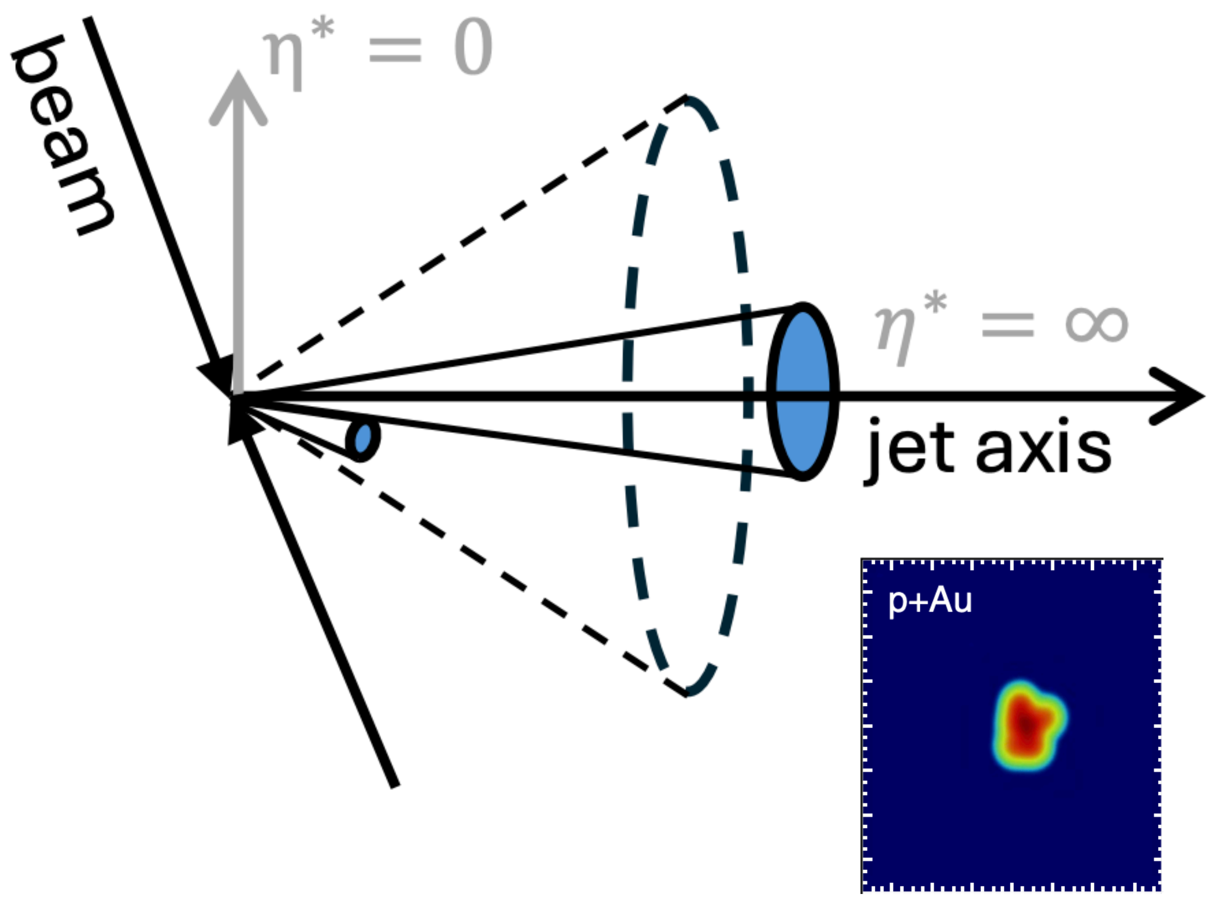
- N_{ch} is correlated with more balanced and separated subjets
  - More ‘elliptic’ initial parton geometry

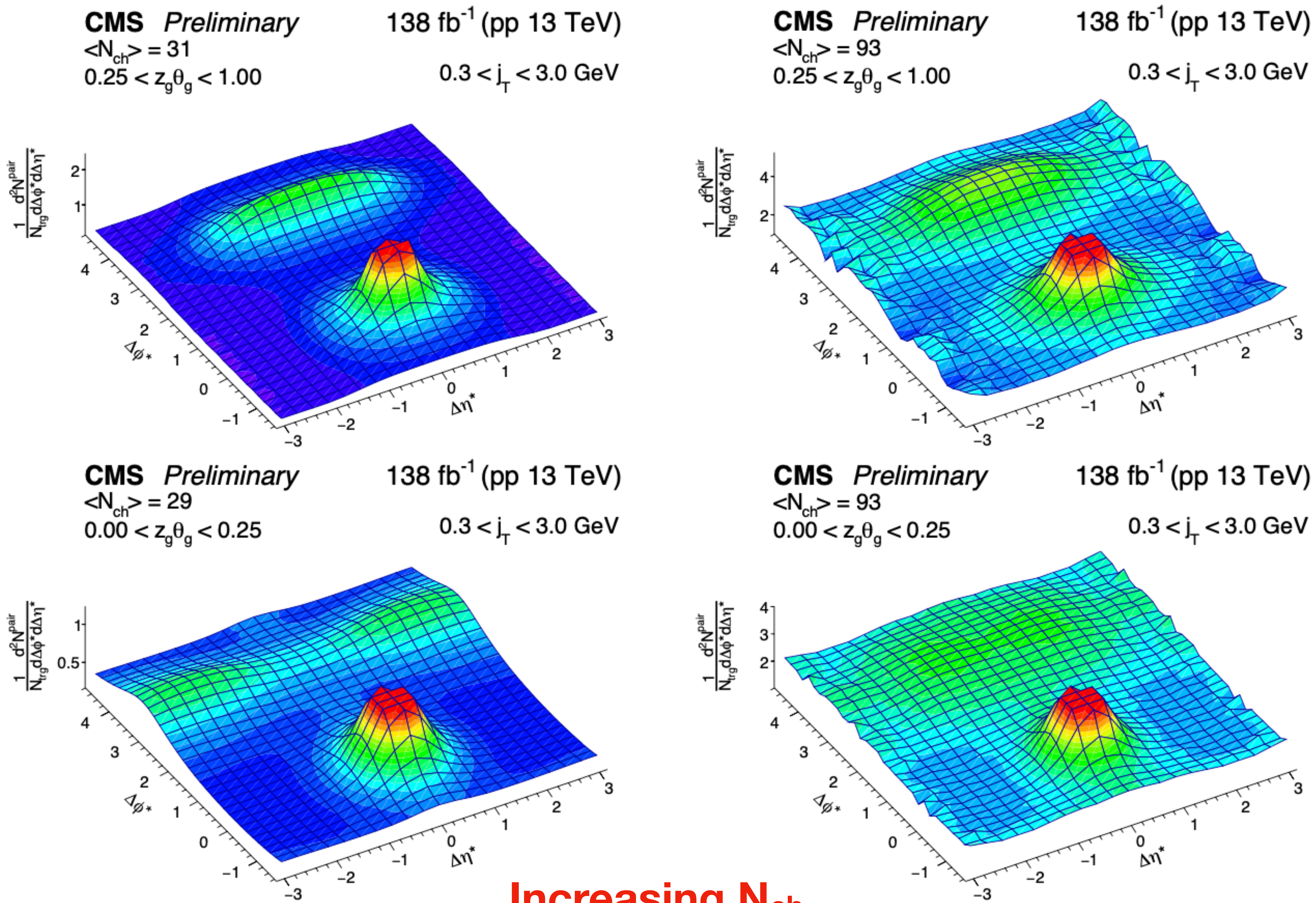




Correlations for different geometries





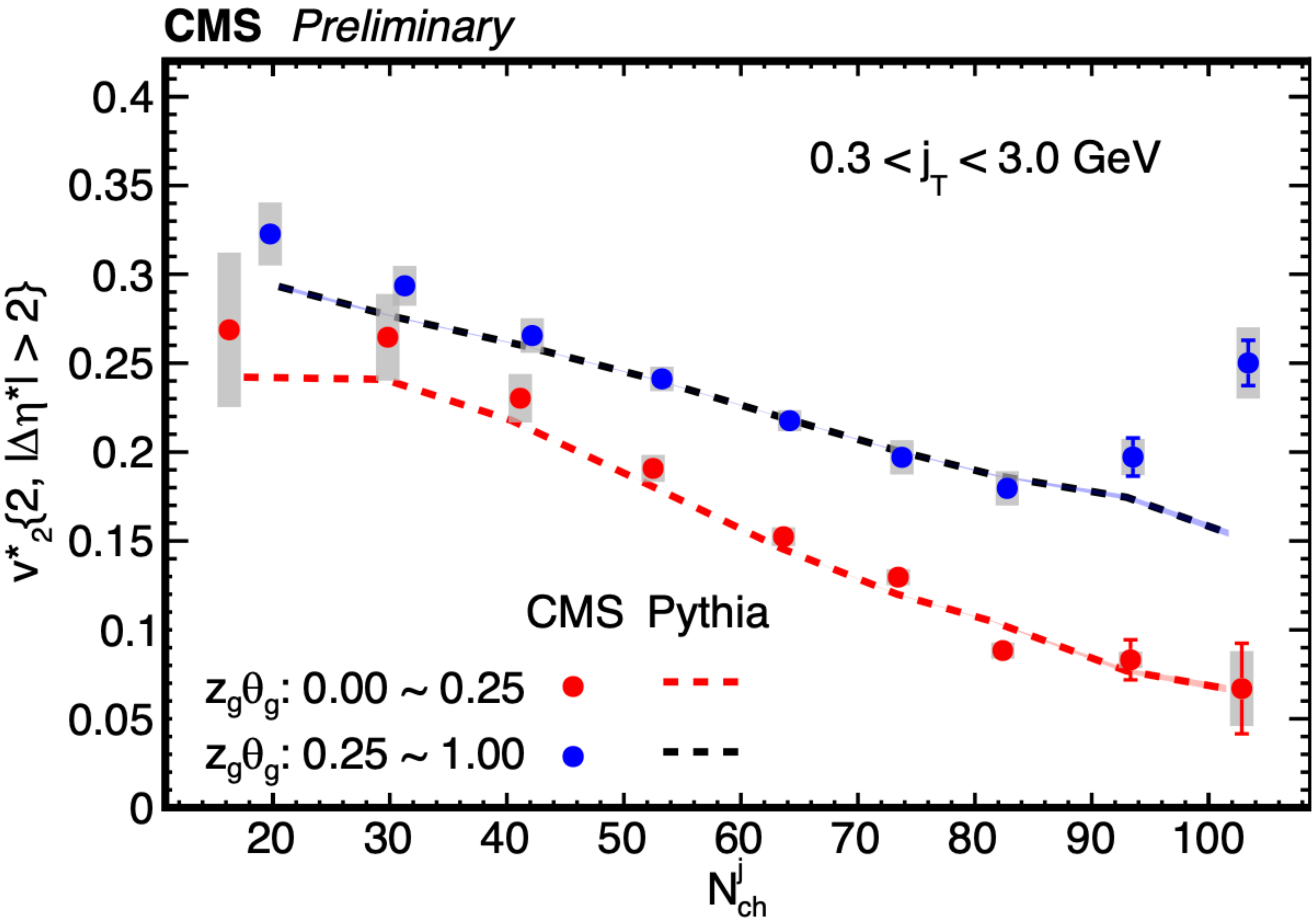


Increasing N_{ch}

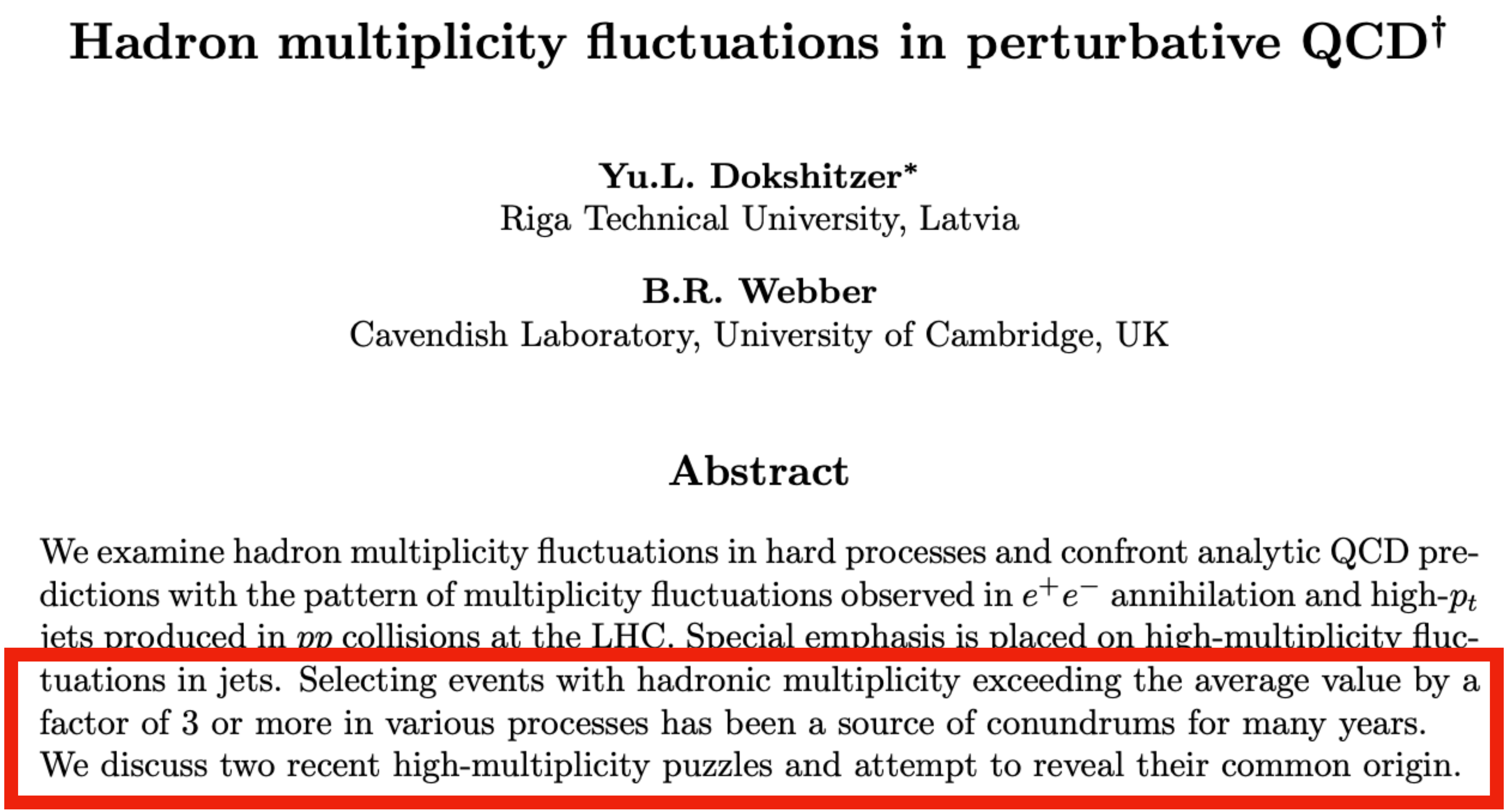
v_2 for different 'parton geometry'

- **'Single prong' jets show no v_2 enhancement, match Pythia**
- **'Two prong' jets cause v_2 rise**

- **Clearly treatment of initial hard splittings very important for this observable**
  - **Establish 'geometry' for collectivity?**
  - **Simply a jet selection bias?**



A recent paper on this topic



Hadron multiplicity fluctuations in perturbative QCD†

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B.R. Webber
Cavendish Laboratory, University of Cambridge, UK

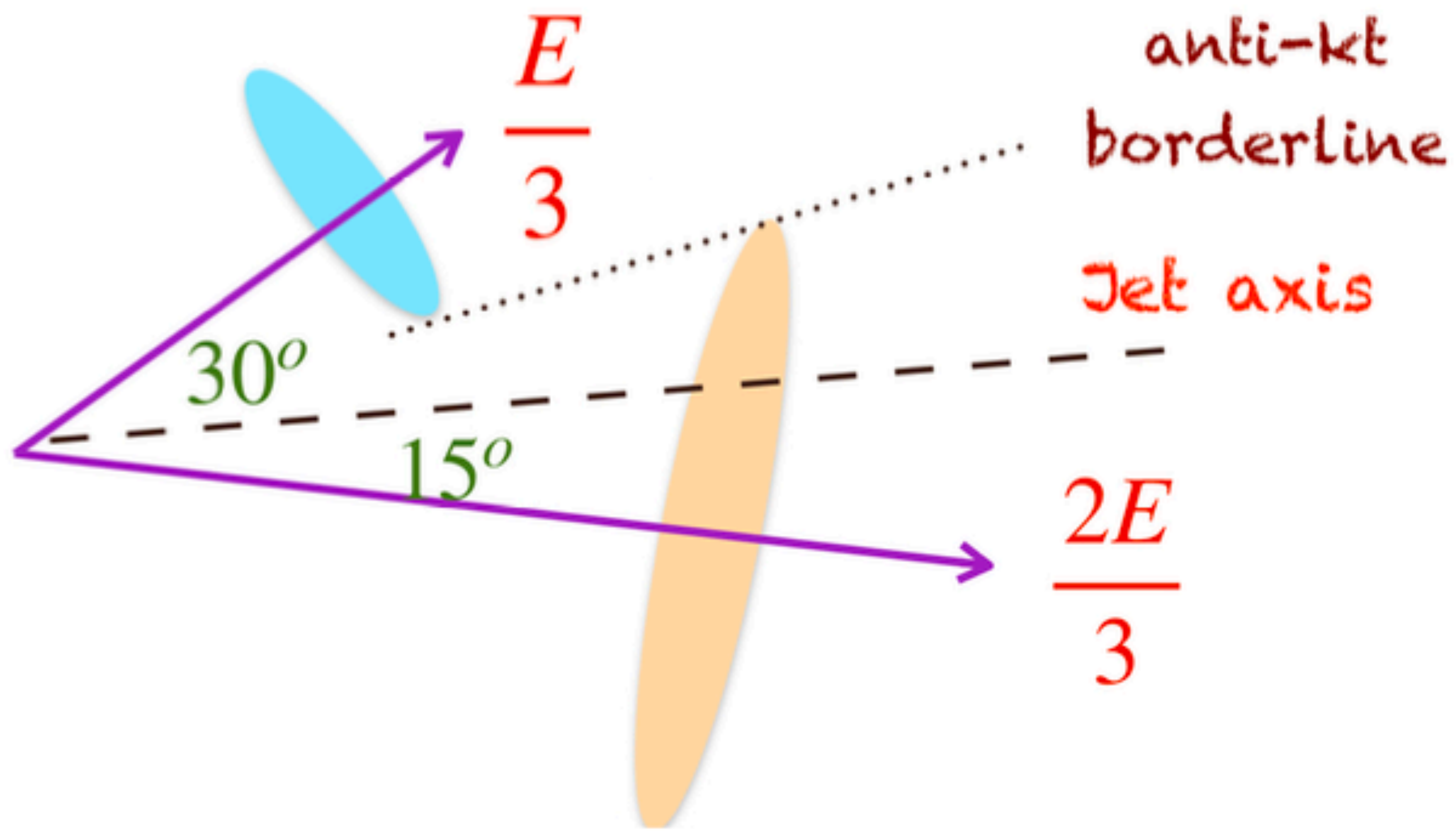
Abstract

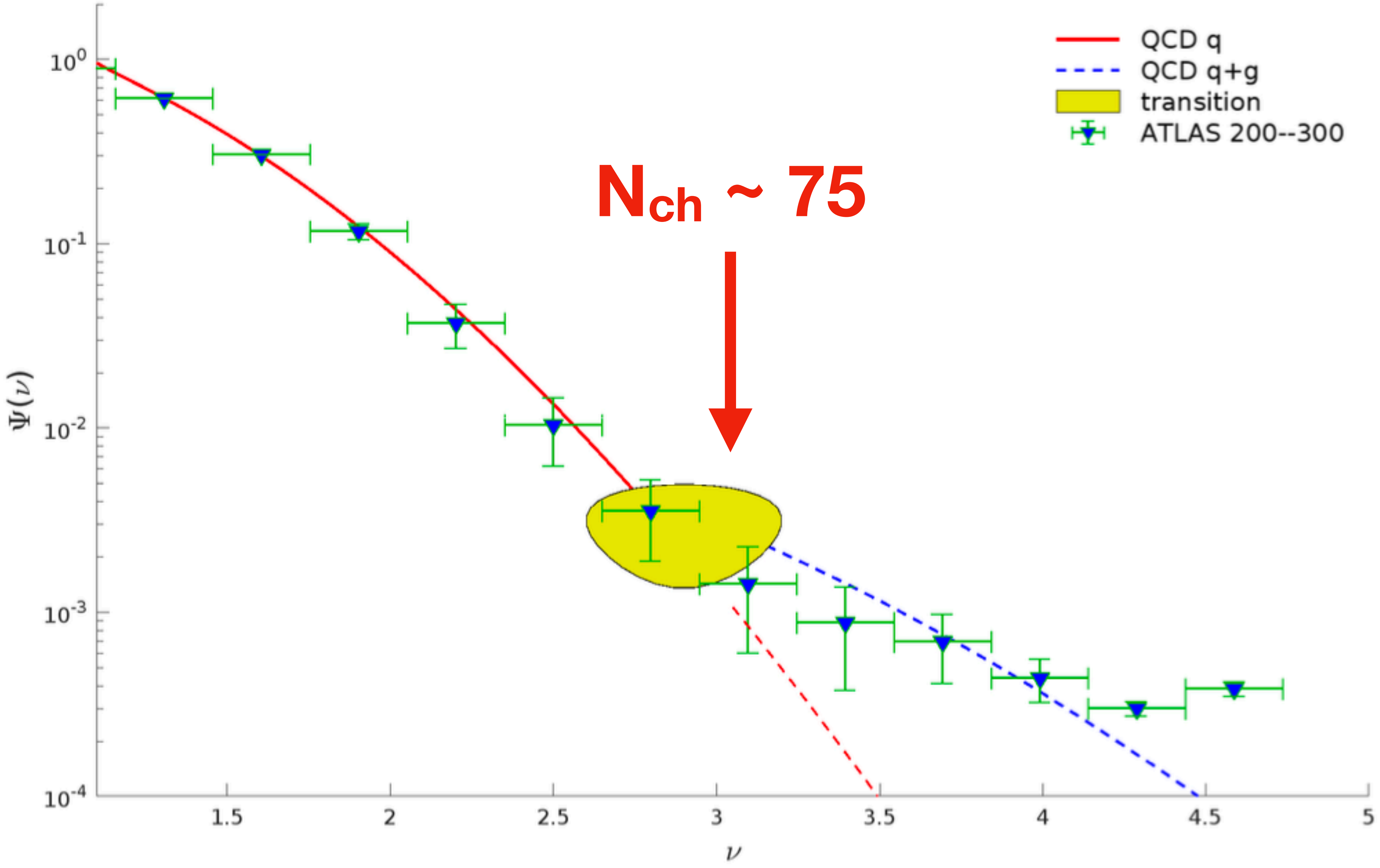
We examine hadron multiplicity fluctuations in hard processes and confront analytic QCD predictions with the pattern of multiplicity fluctuations observed in e^+e^- annihilation and high-p_t jets produced in pp collisions at the LHC. Special emphasis is placed on high-multiplicity fluctuations in jets. Selecting events with hadronic multiplicity exceeding the average value by a factor of 3 or more in various processes has been a source of conundrums for many years. We discuss two recent high-multiplicity puzzles and attempt to reveal their common origin.

(A great read for fans of <u>Alice in Wonderland</u>)

arXiv:2505.00652v1

An intressssssssssssting connection





$$\nu = N_{ch}/\langle N_{ch}\rangle$$

A 'forked-tongue' initial parton splitting:
Leads to CMS data

Could also lead to KNO scaling violations:
A 'raised tail' in ATLAS jet data

arXiv:2505.00652v1

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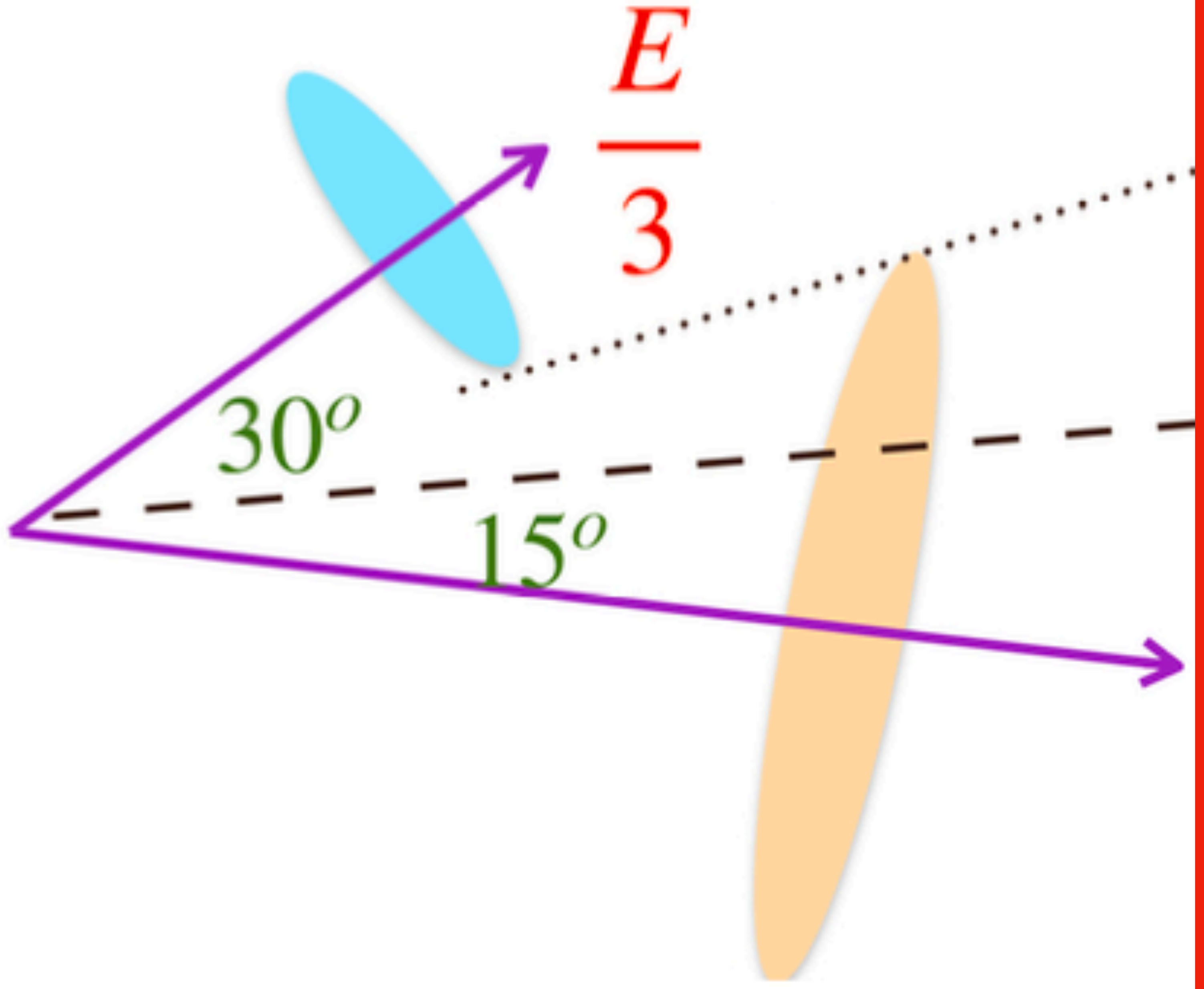
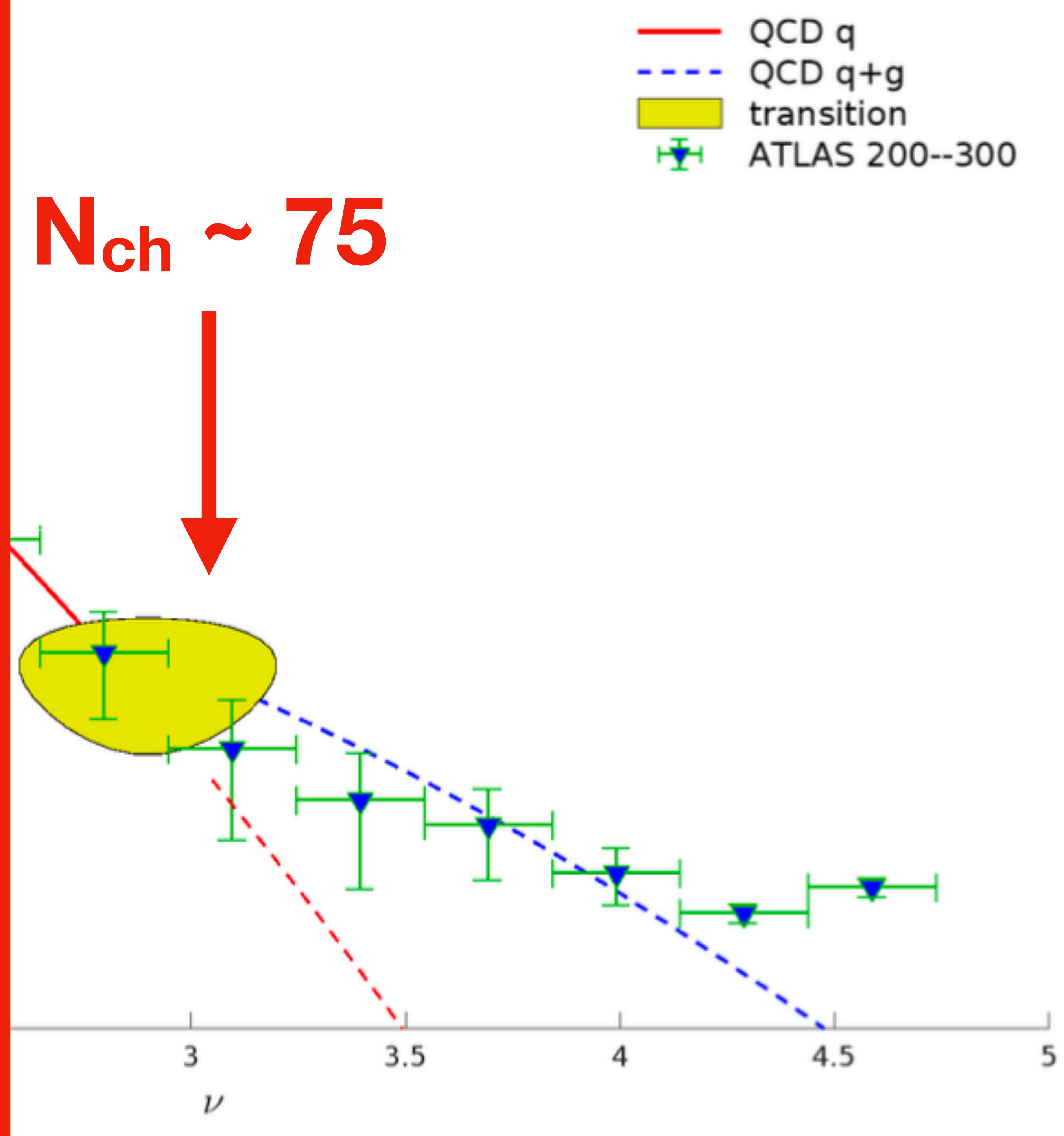




$= N_{ch}/\langle N_{ch}\rangle$

A ‘forked-tongue’ initial parton
Leads to CMS data

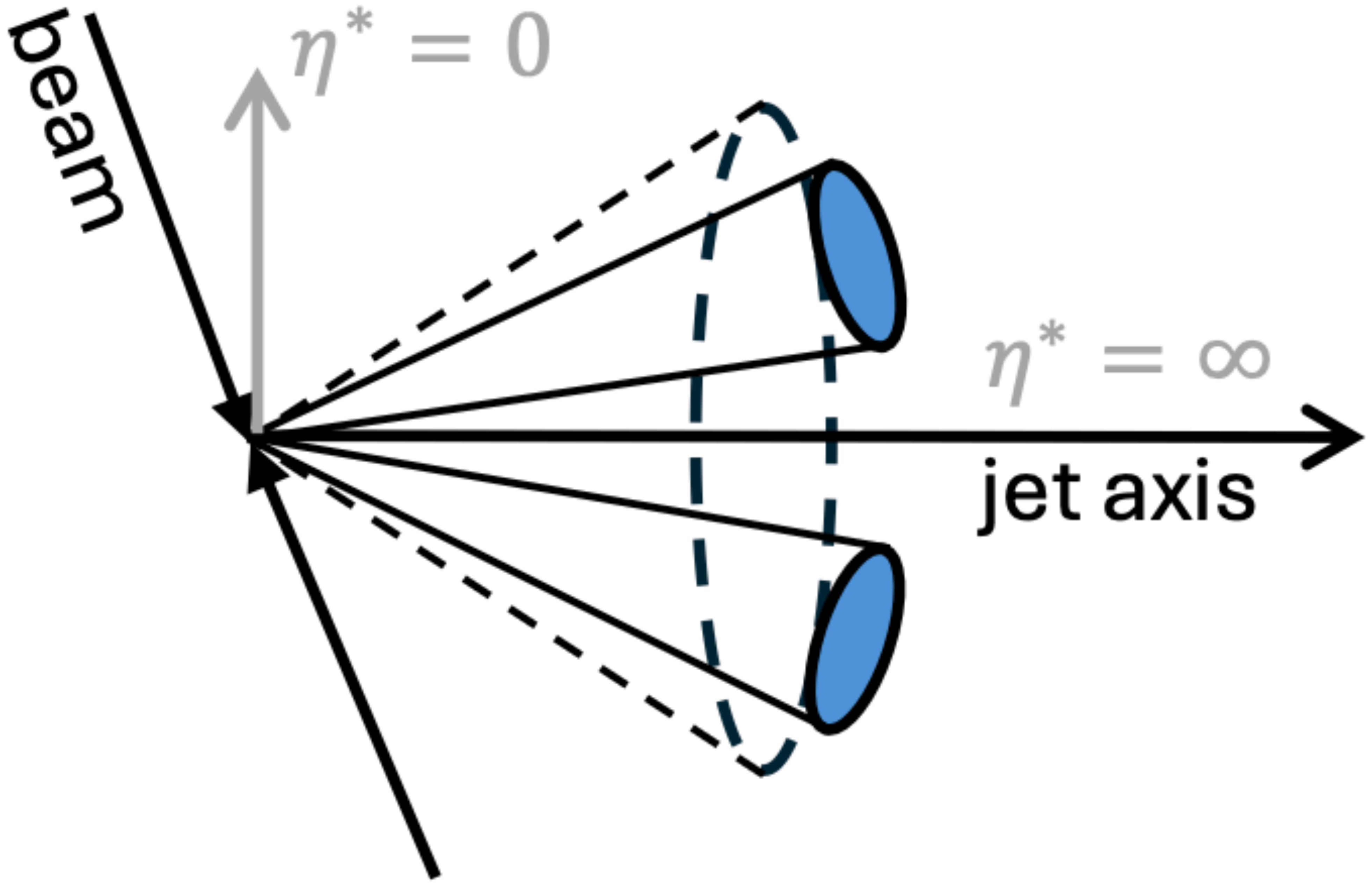
o KNO scaling violations:
il’ in ATLAS jet data

[3] After this paper was completed, we learned of a forthcoming CMS publication [33] in which the possibility of two-pronged structure of ellipticity generating events is put under scrutiny.

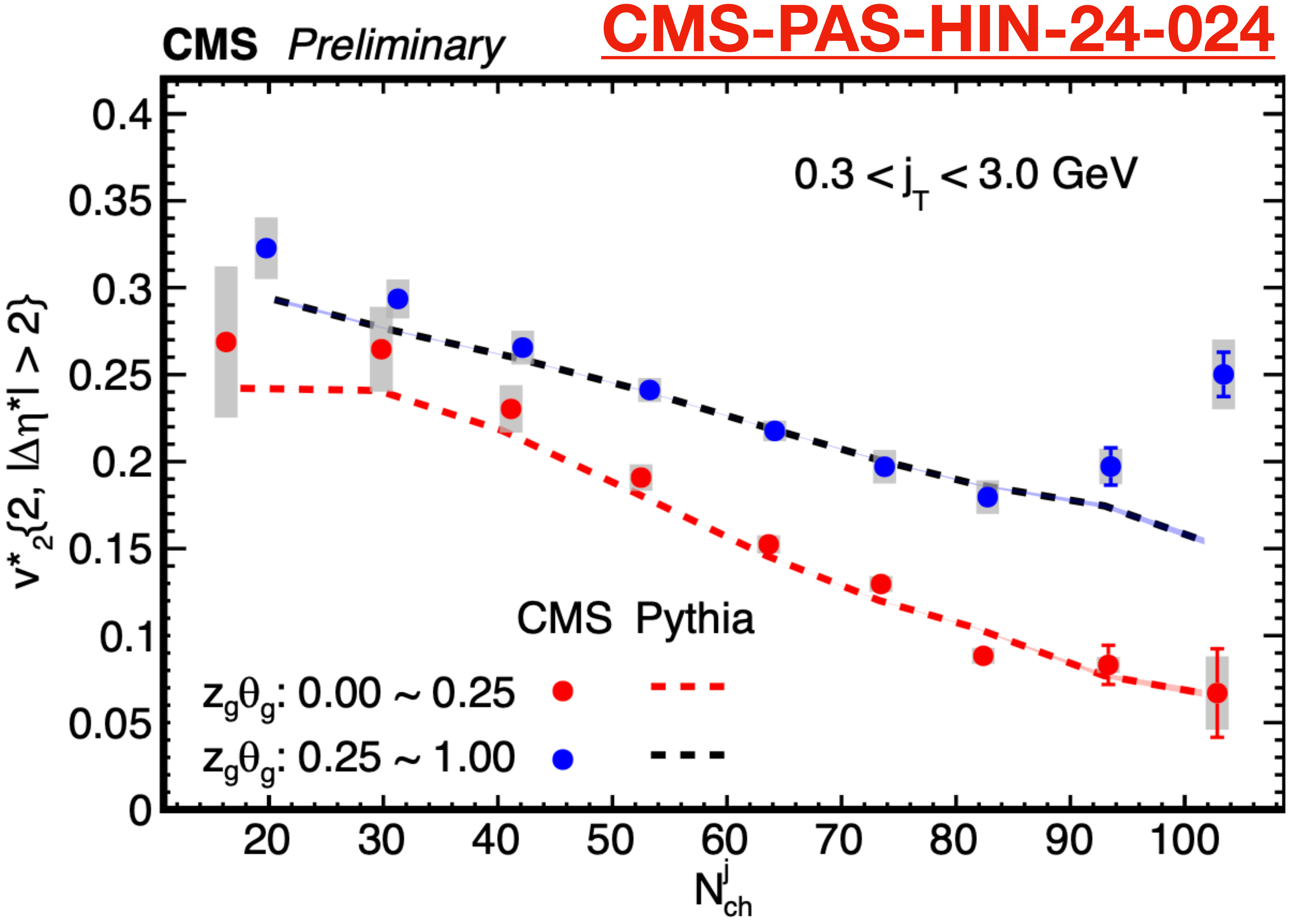
arXiv:2505.00652v1

Summary

- New detailed examination of high-multiplicity jet v_2 vs $\Delta\eta^*$, j_T
- 'Jet substructure engineering' to understand initial 'parton geometry'
- Rise in v_2 seems to originate from 2-pronged jets
- Collectivity vs. rattlesnake (or some combination) still undetermined
  - Much more Run 3 data on disk - stay tuned!

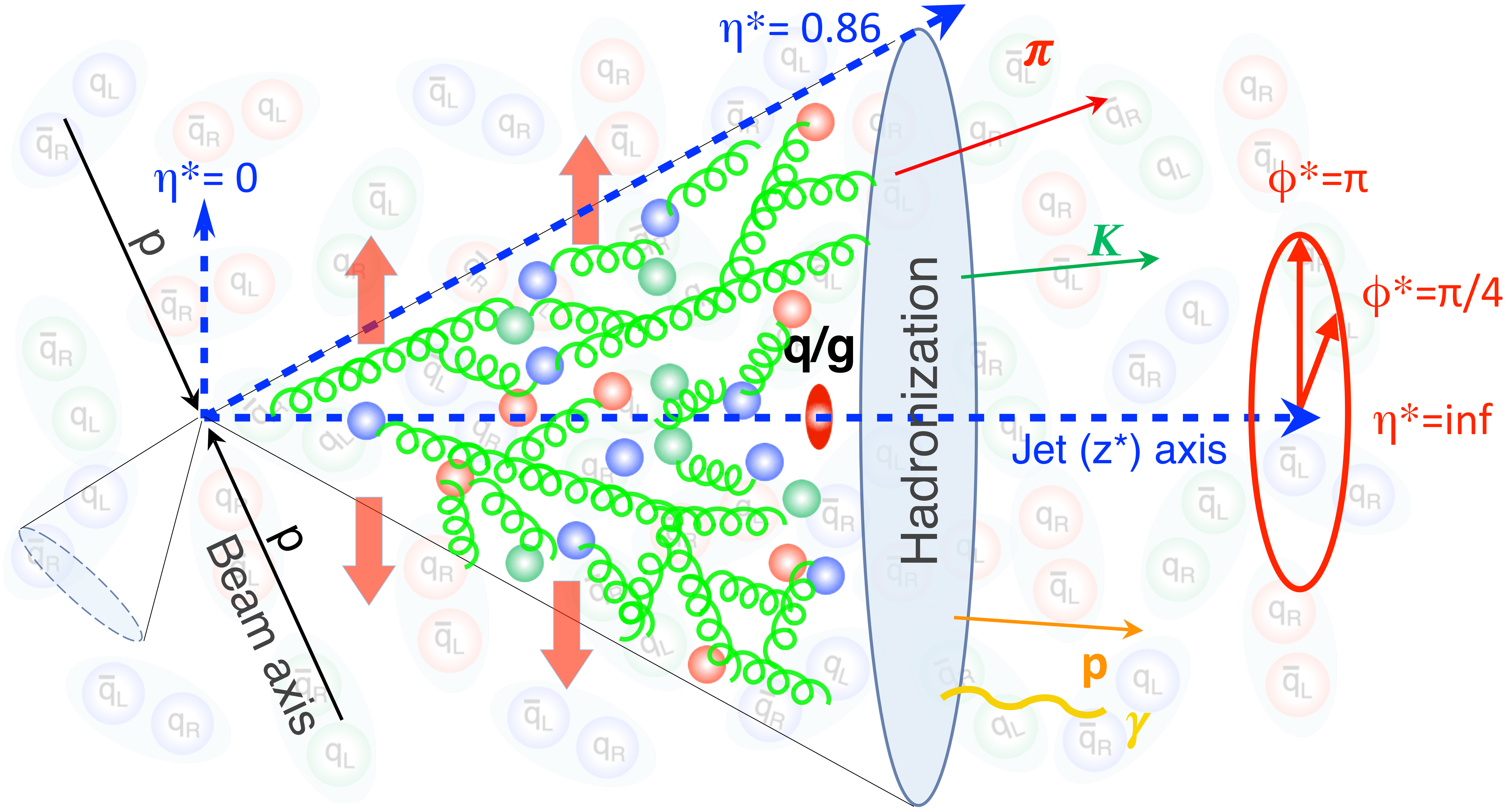


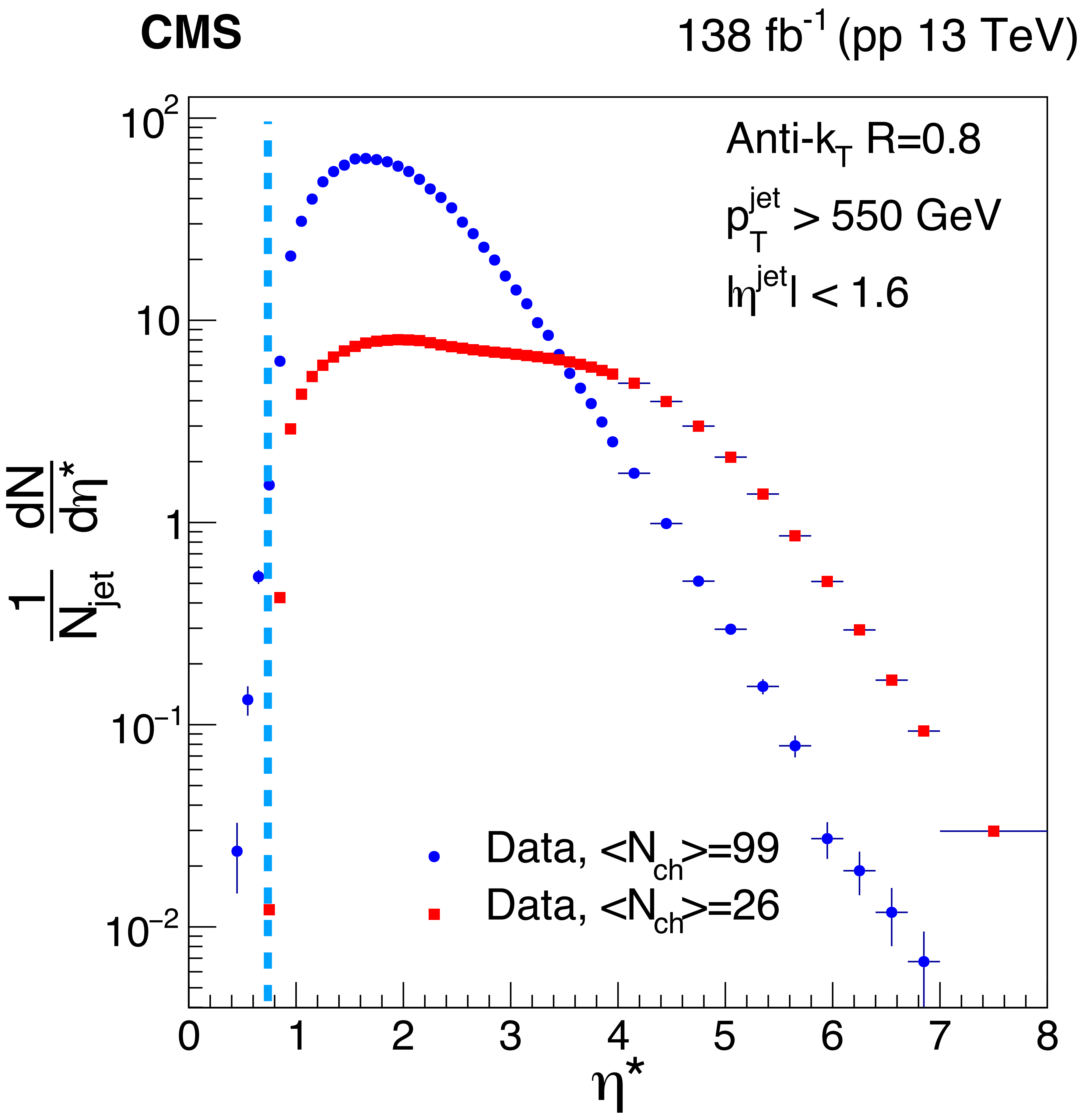
CMS-PAS-HIN-24-024



Backup

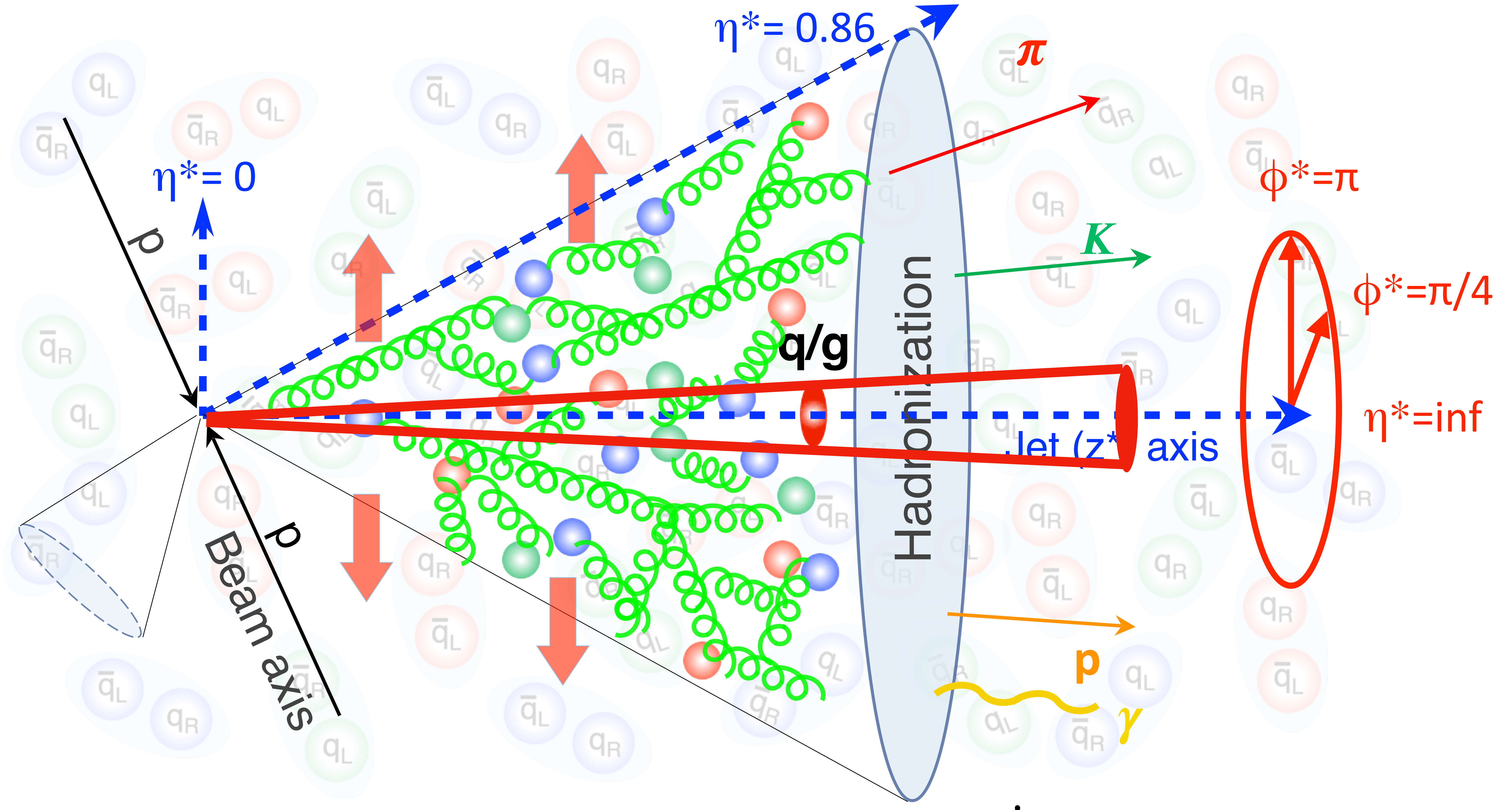
Properties of η^*

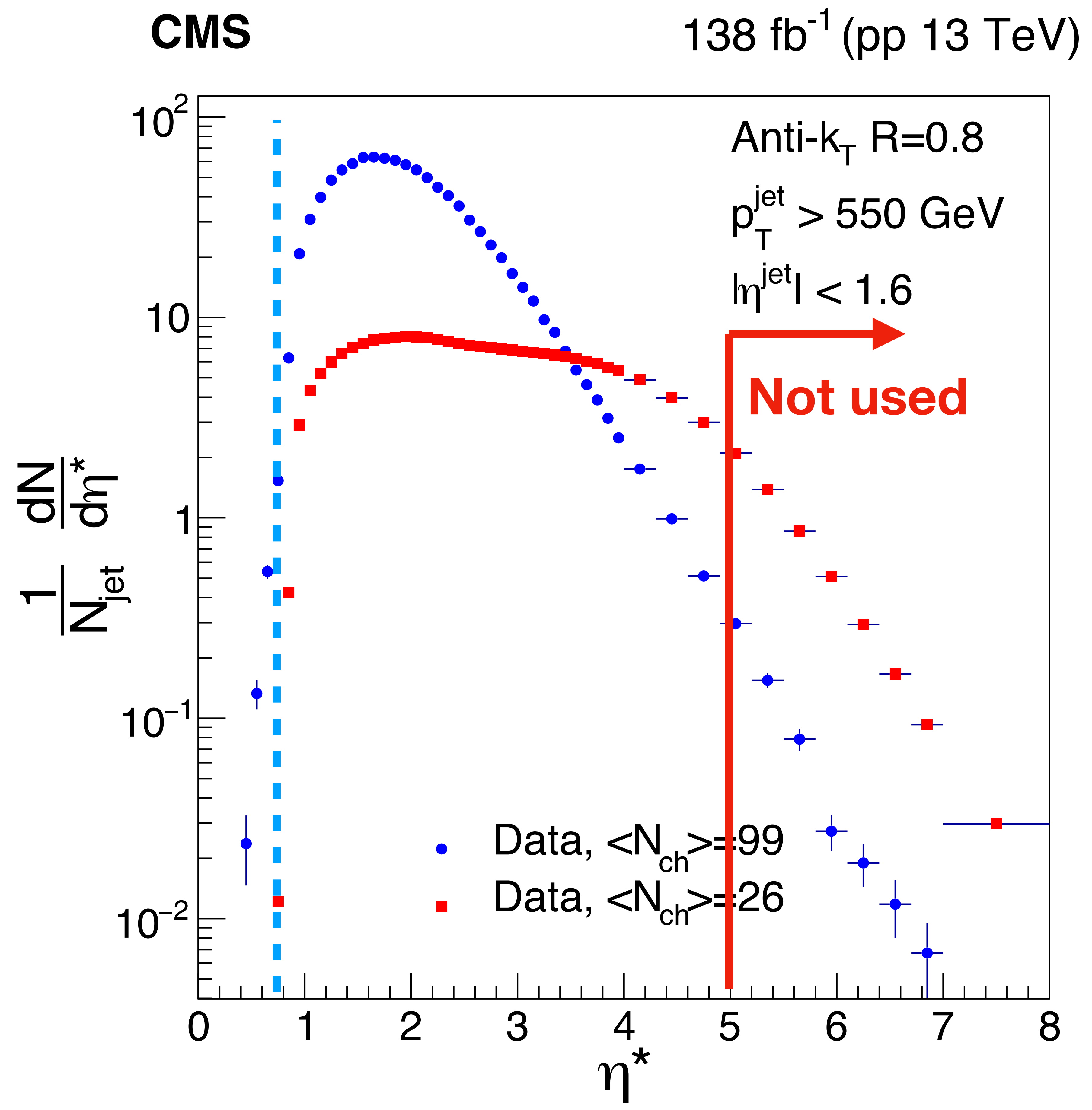




- **Wide angle radiation → smaller η^***
  - $\eta^* > 0.86$ **for an R=0.8 jet**

Properties of η^*





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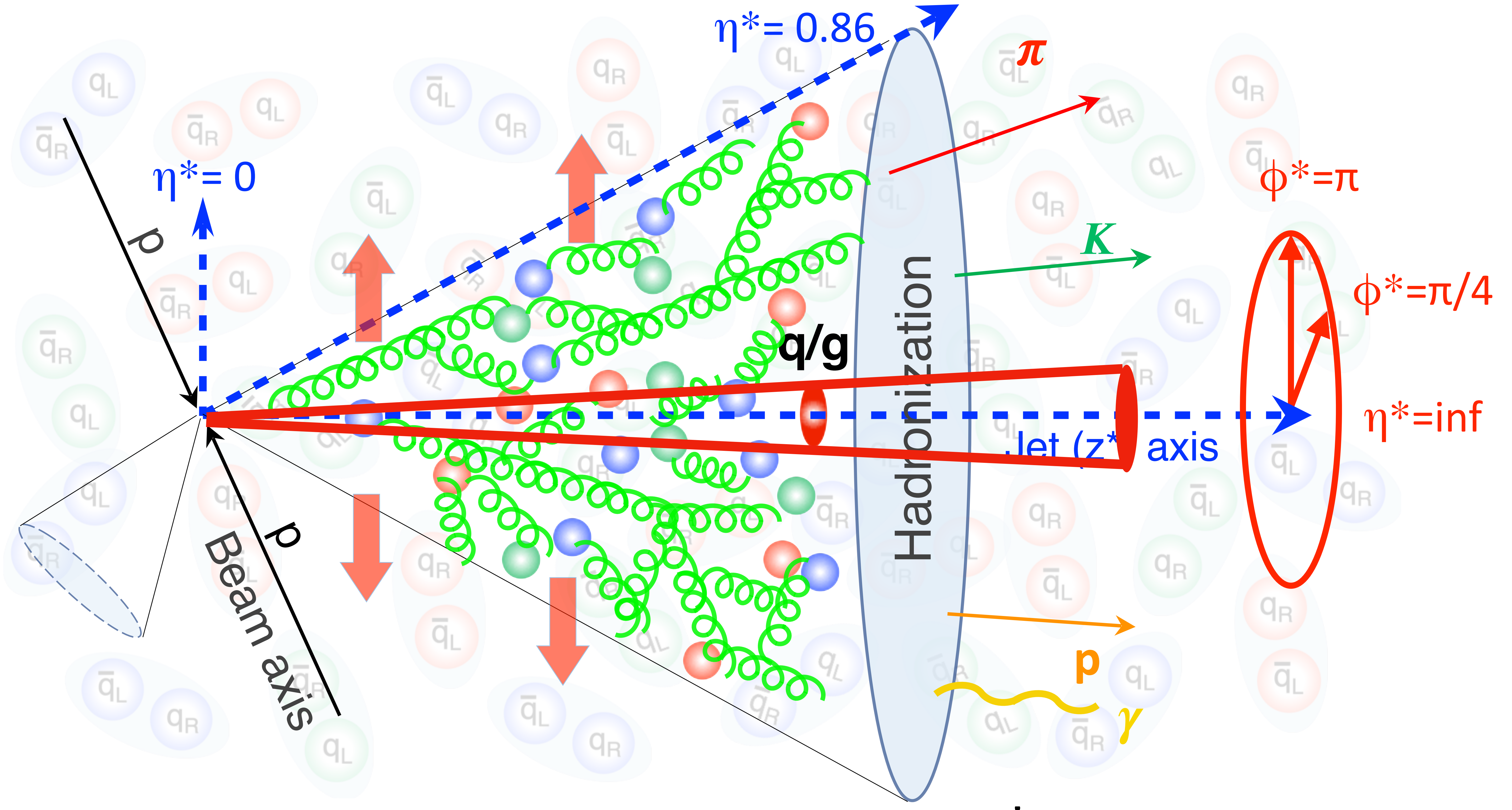
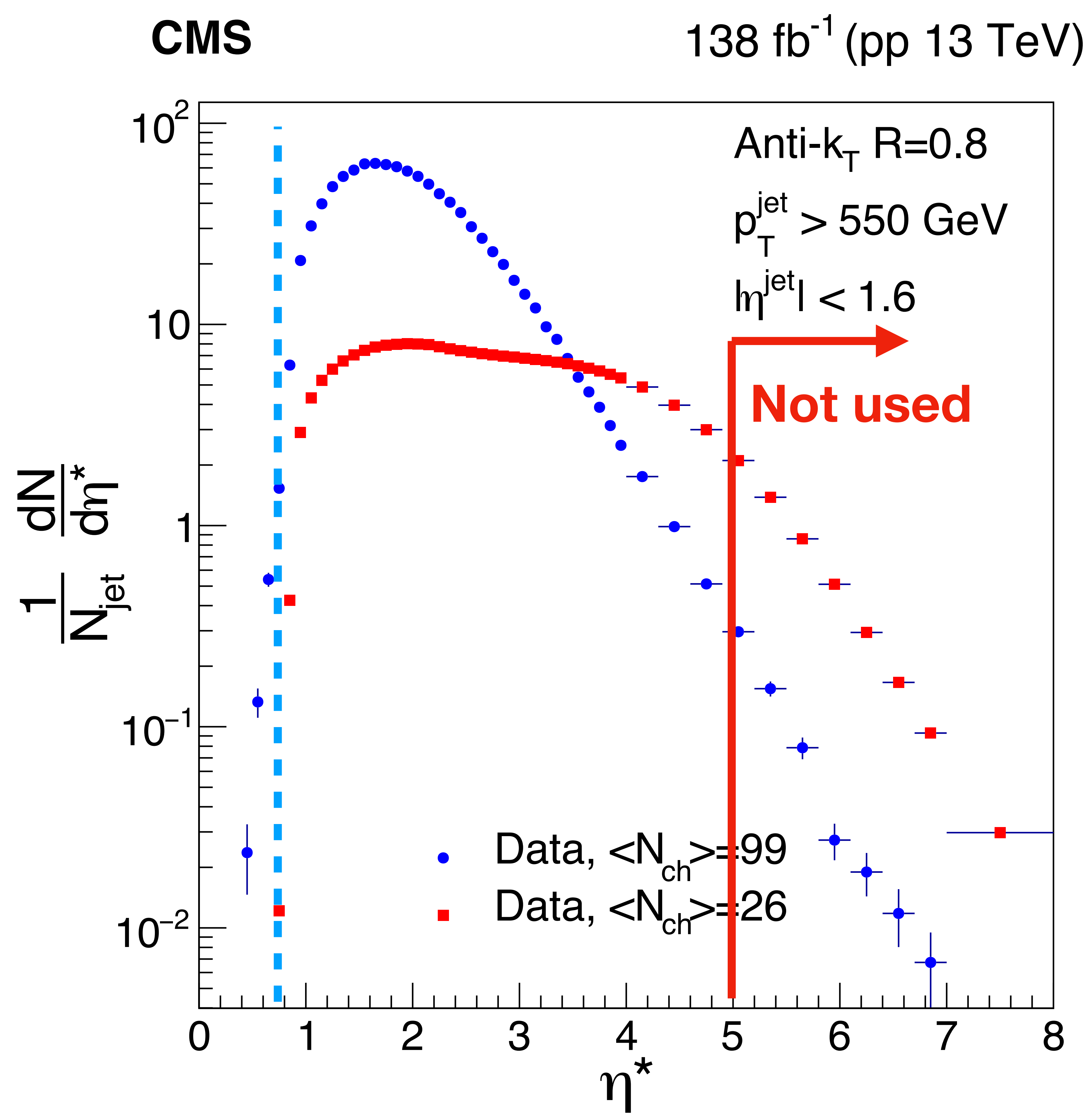
- $\eta^* > 5$ **excluded from analysis - sensitive to jet axis resolution**

Properties of η^*



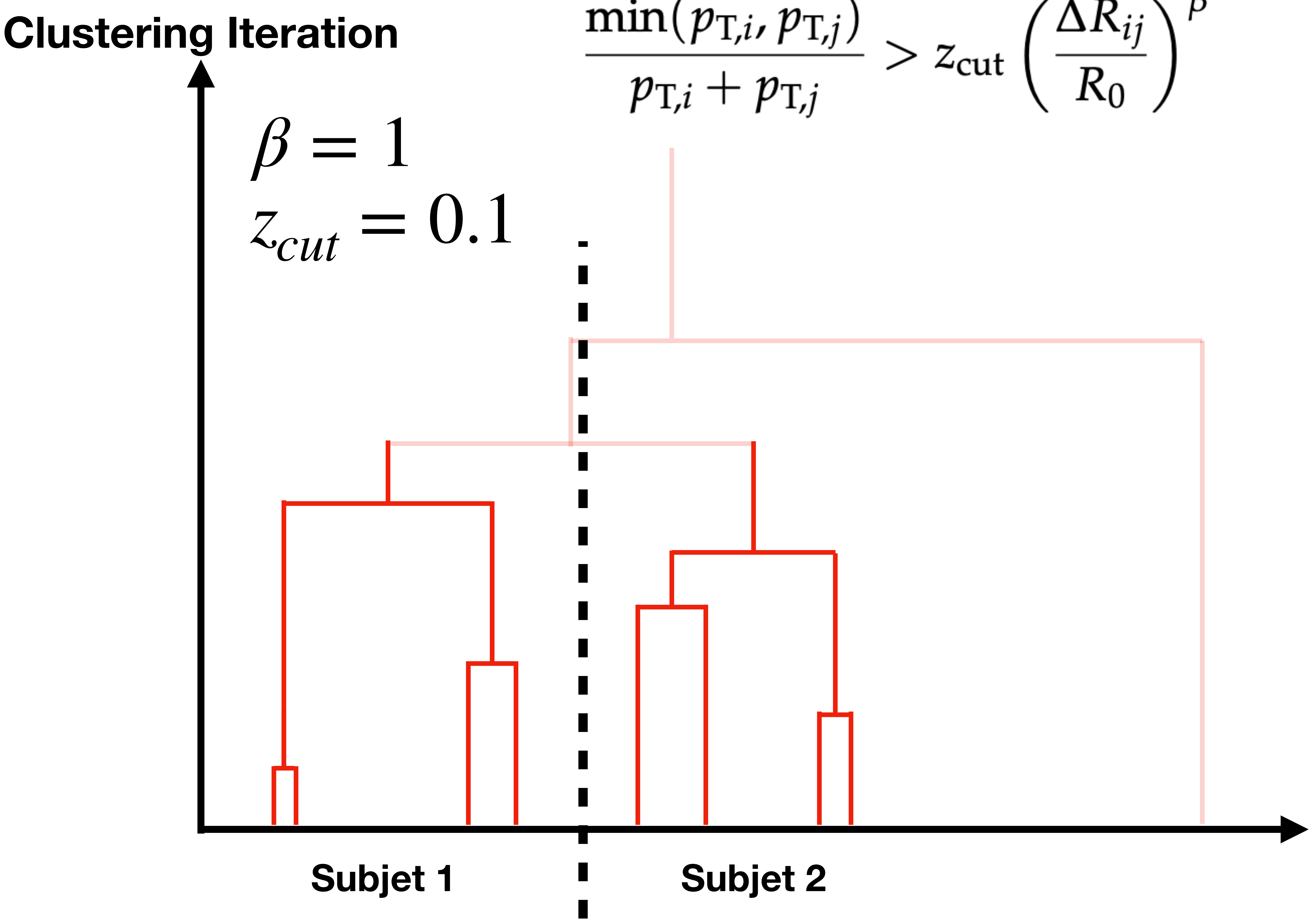


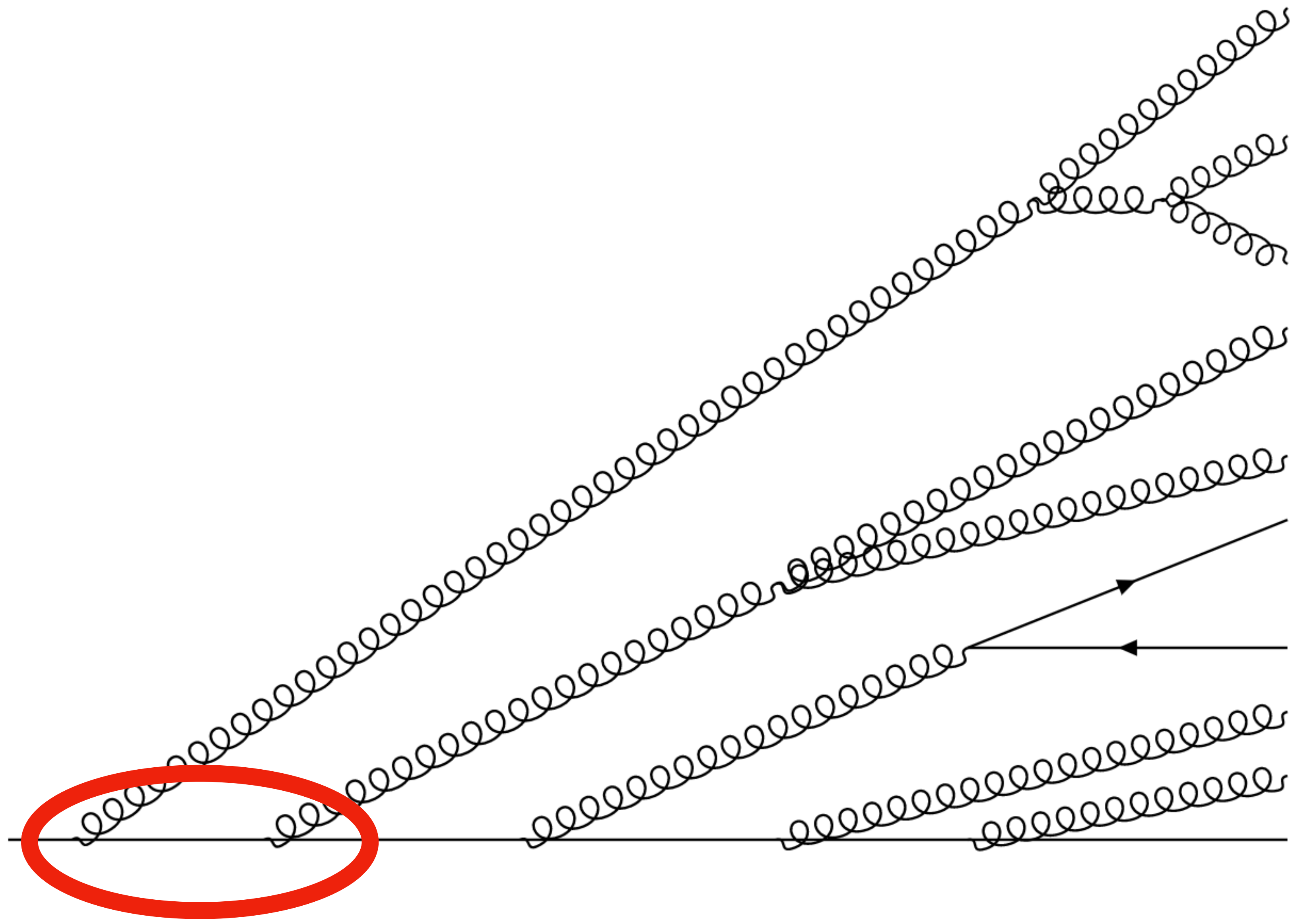
- **Wide angle radiation → smaller η^***
  - $\eta^* > 0.86$ **for an R=0.8 jet**
- $\eta^* > 5$ **excluded from analysis - sensitive to jet axis resolution**
- $dN/d\eta^*$ **up to 80 in jet frame - similar particle density to peripheral heavy ion collision!**

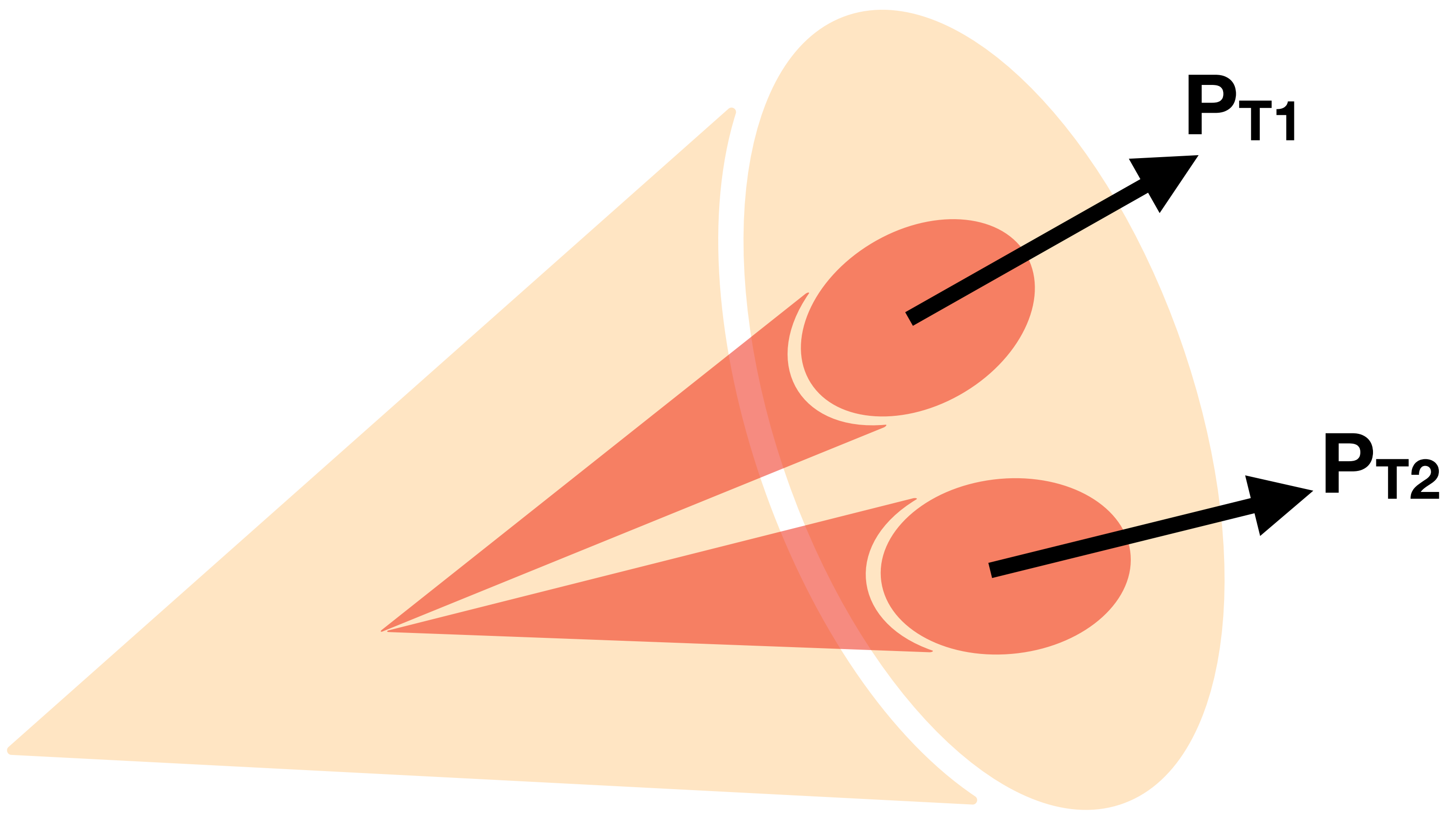
SoftDrop Jet Grooming

Softdrop condition

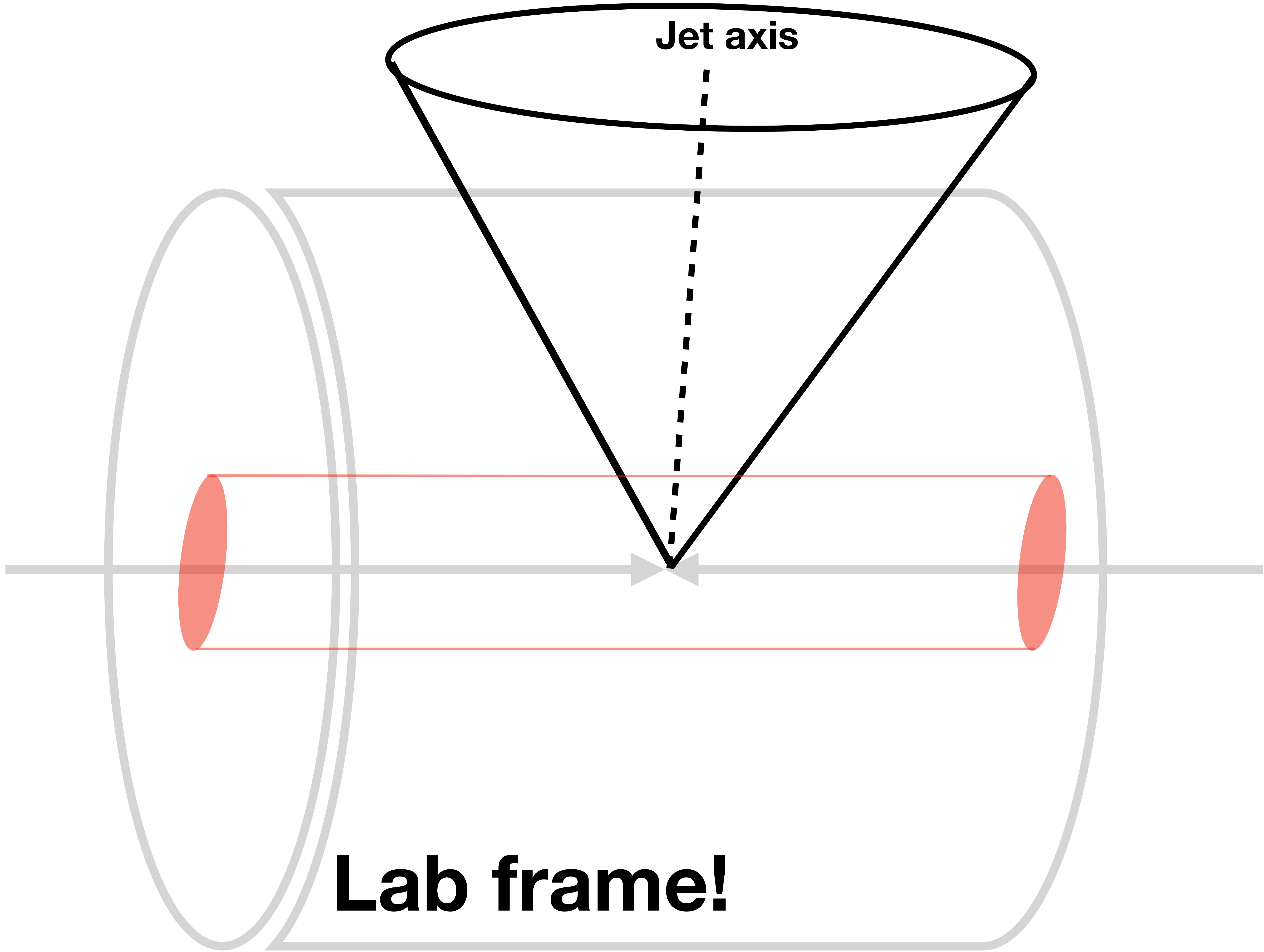
$$\frac{\min(p_{\mathrm{T},i}, p_{\mathrm{T},j})}{p_{\mathrm{T},i} + p_{\mathrm{T},j}} > z_{\mathrm{cut}} \left(\frac{\Delta R_{ij}}{R_0}\right)^{\beta}$$

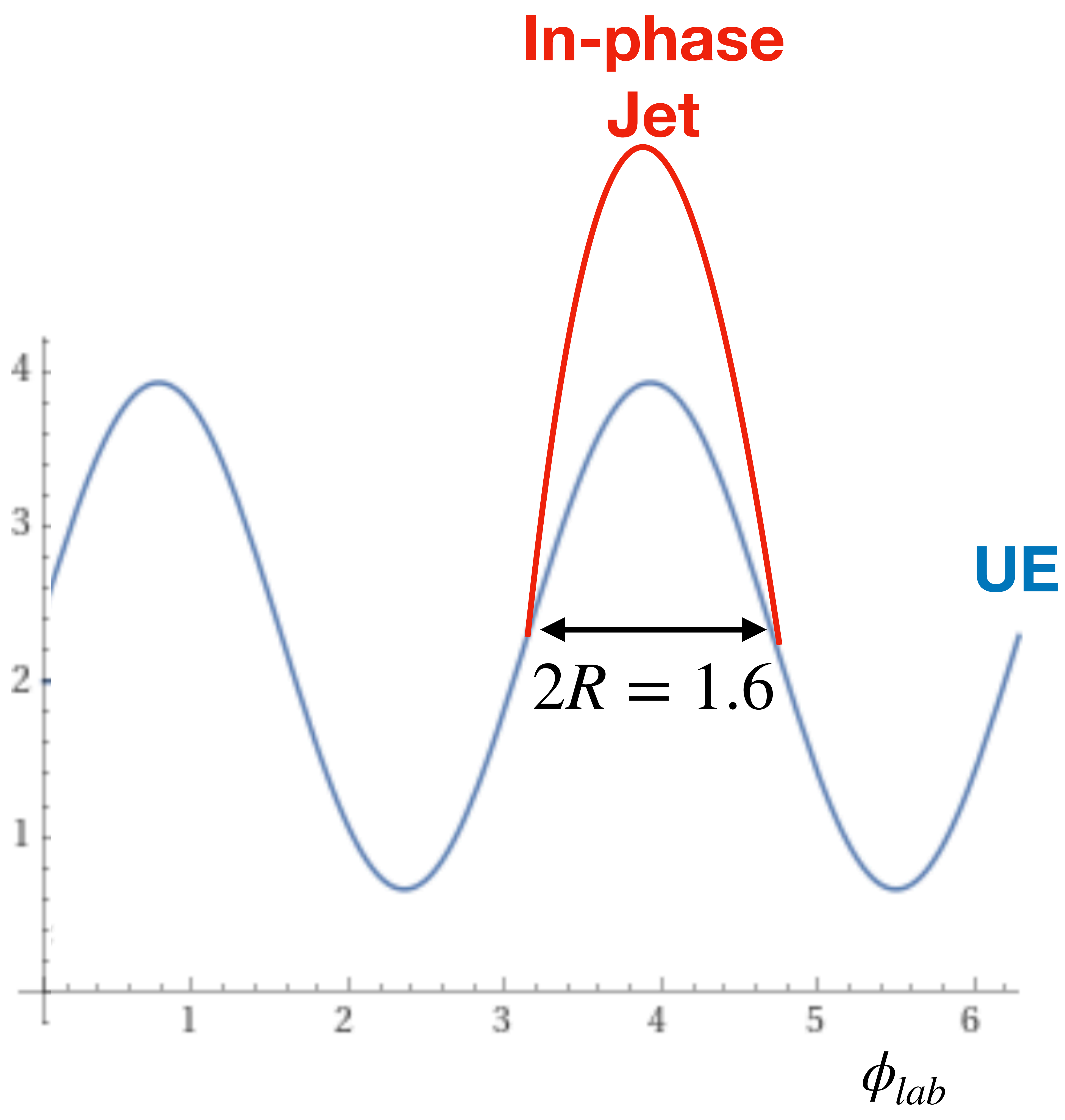






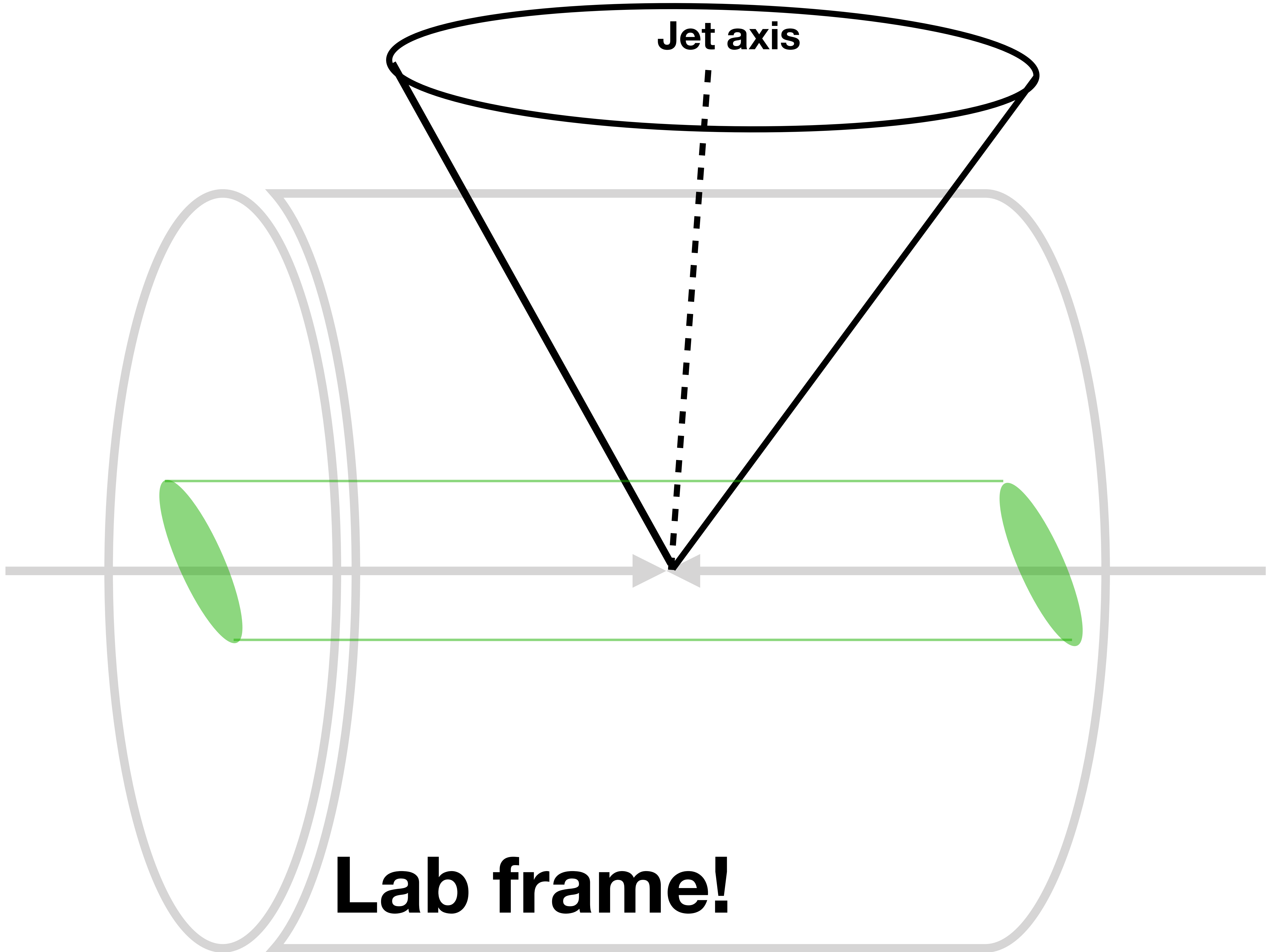
Underlying Event Explanation?

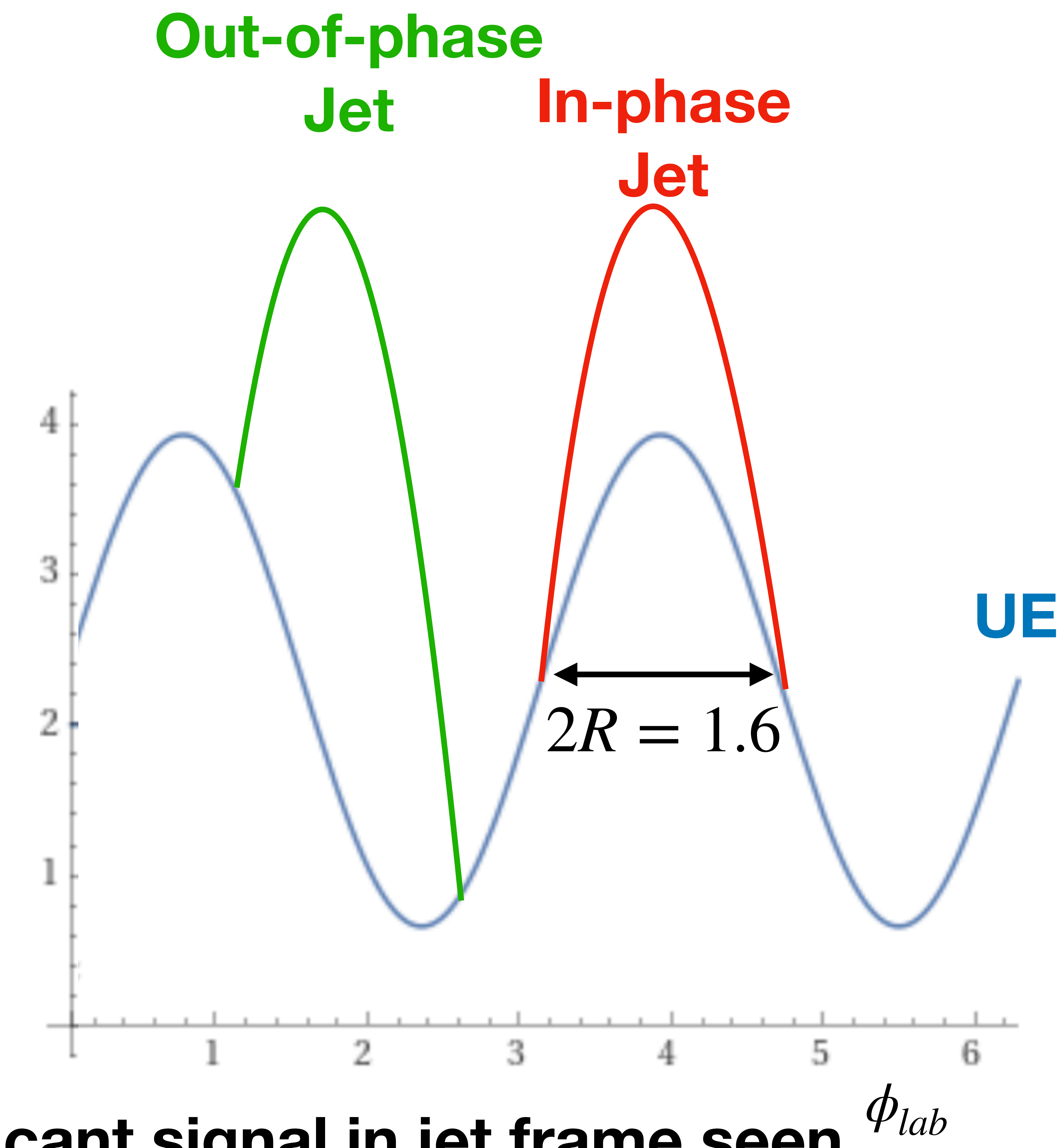




- **Can underlying event generate a signal?**
- **Inject signal into UE and study effect on signal**

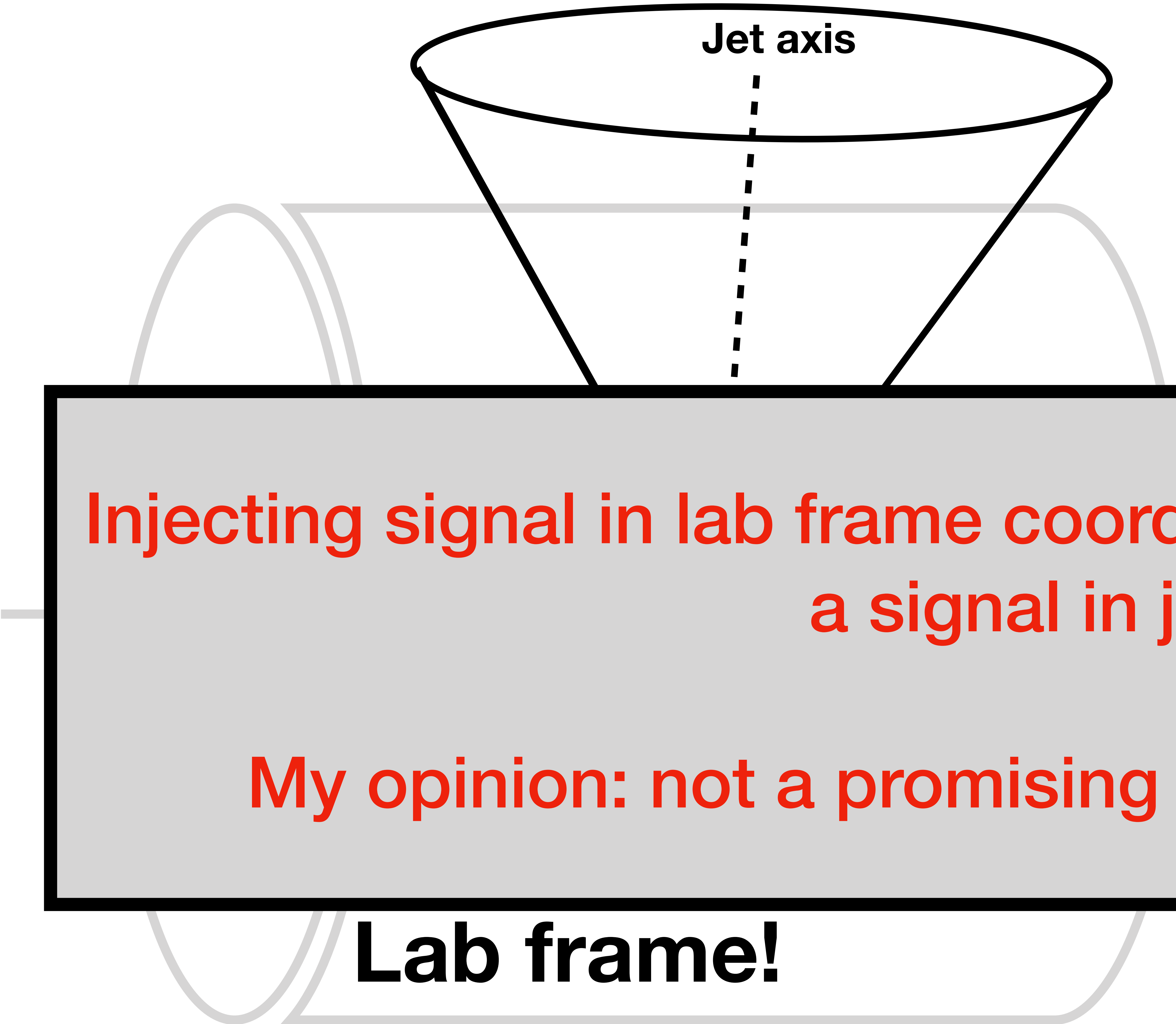
Underlying Event Explanation?

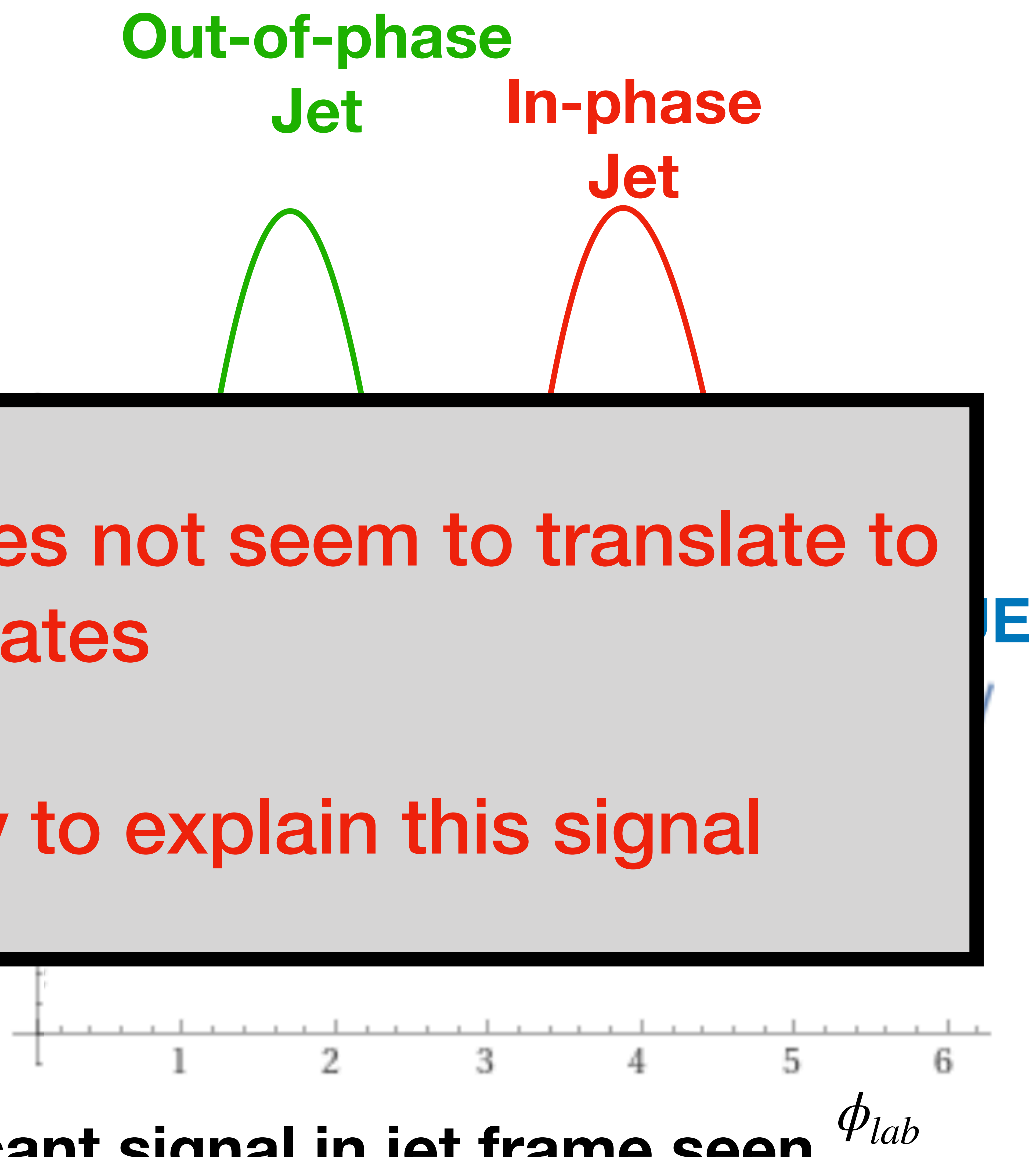




- **Regardless of phase between jet and UE, no significant signal in jet frame seen**
- **Different UE tunes also have no effect**

Underlying Event Explanation?





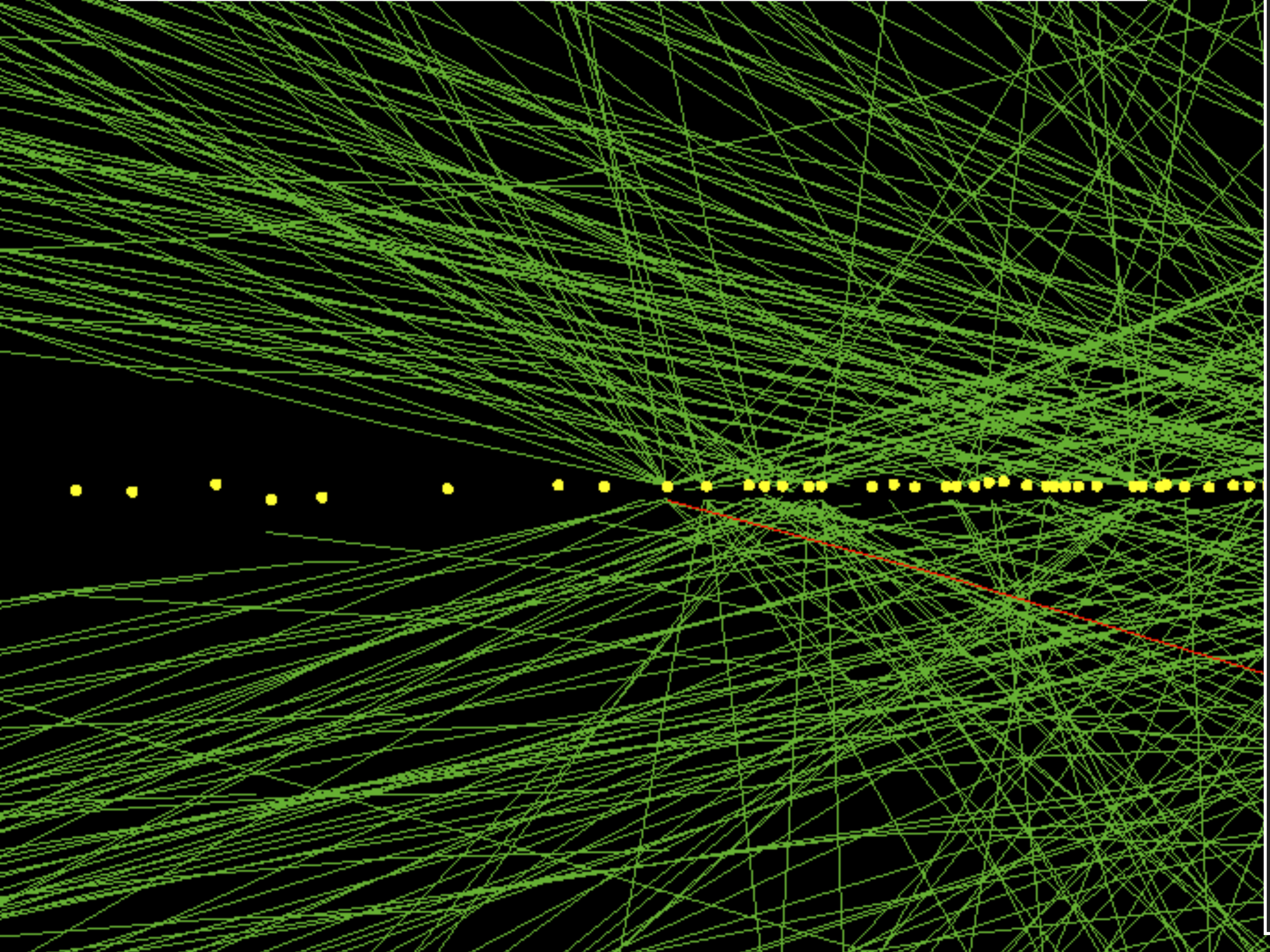
Injecting signal in lab frame coordinates does not seem to translate to a signal in jet coordinates

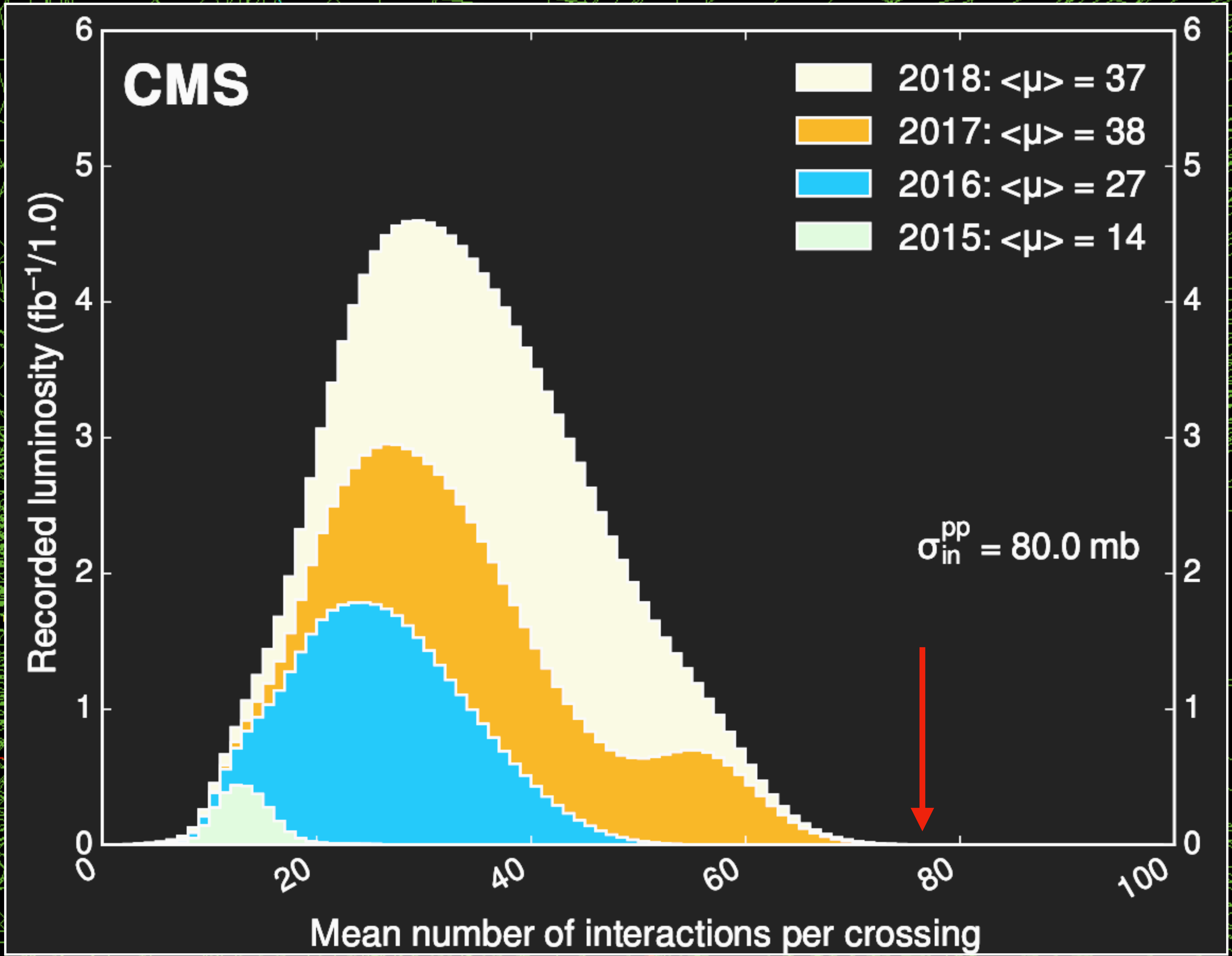
My opinion: not a promising path to try to explain this signal

- **Regardless of phase between jet and UE, no significant signal in jet frame seen**
- **Different UE tunes also have no effect**

Pileup distribution

- **Use 2016-2018 Run 2 data**
- **Only interested in jet events**
  - **Must deal with pileup!**





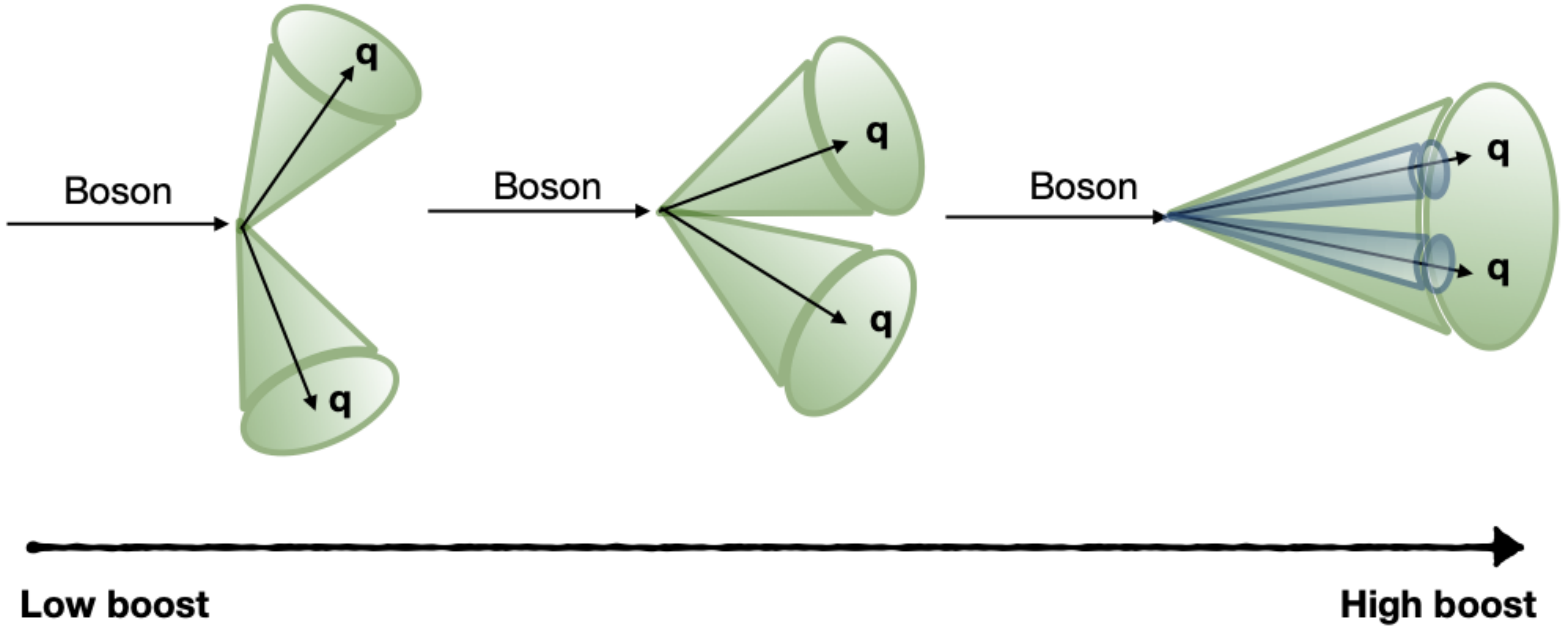
78 vertices: ~2x more than the average for this analysis

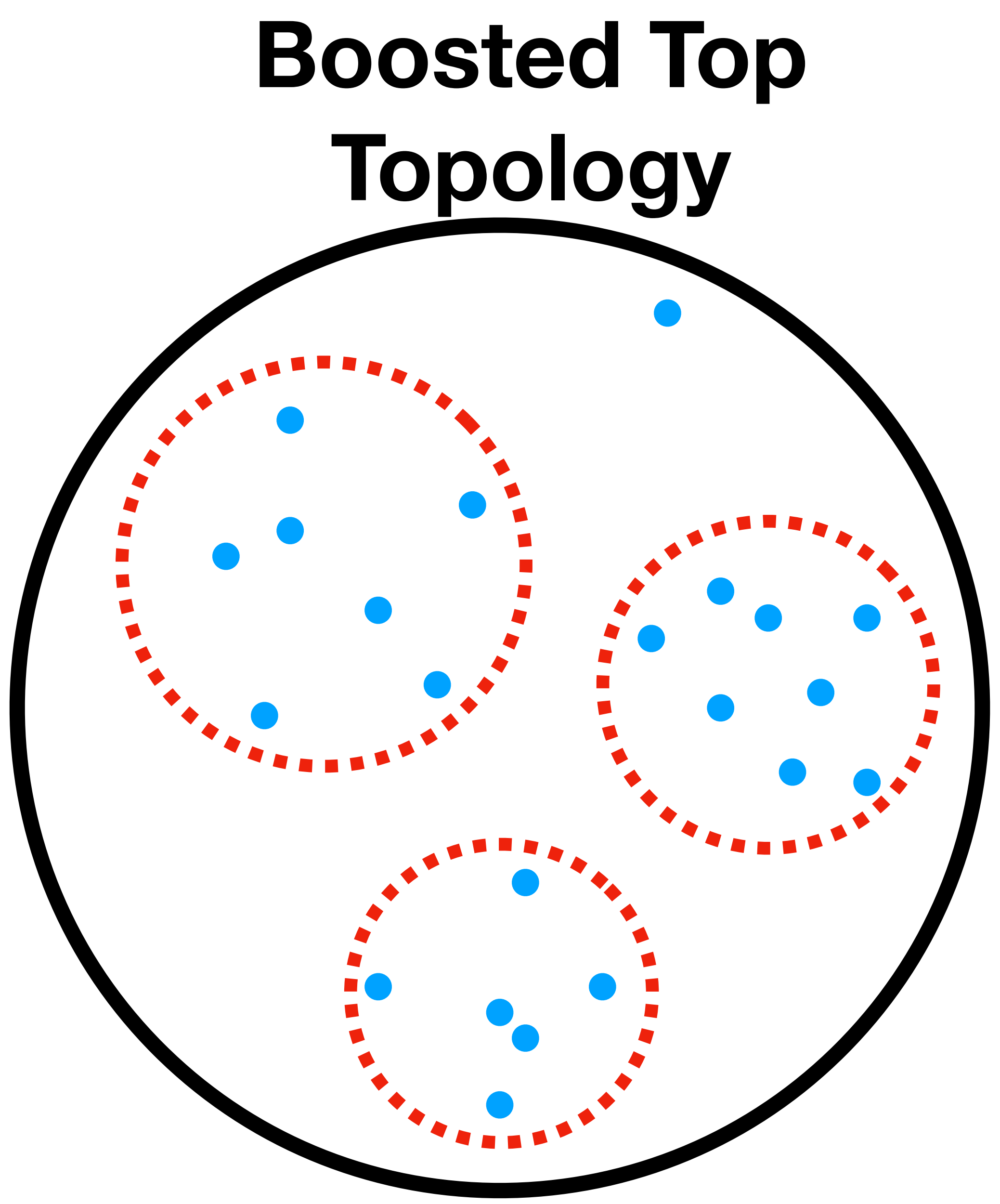
Pileup Mitigation

- Pileup Per Particle Identification (PUPPI) subtraction
  - Use track/vertex info to remove obvious pileup tracks
  - Ambiguous tracks weighted by probability of being signal
    - Included in analysis (negligible effect)
  - Similar weighting for neutral particles

78 vertices: ~2x more than the average for this analysis

Boosted Topologies

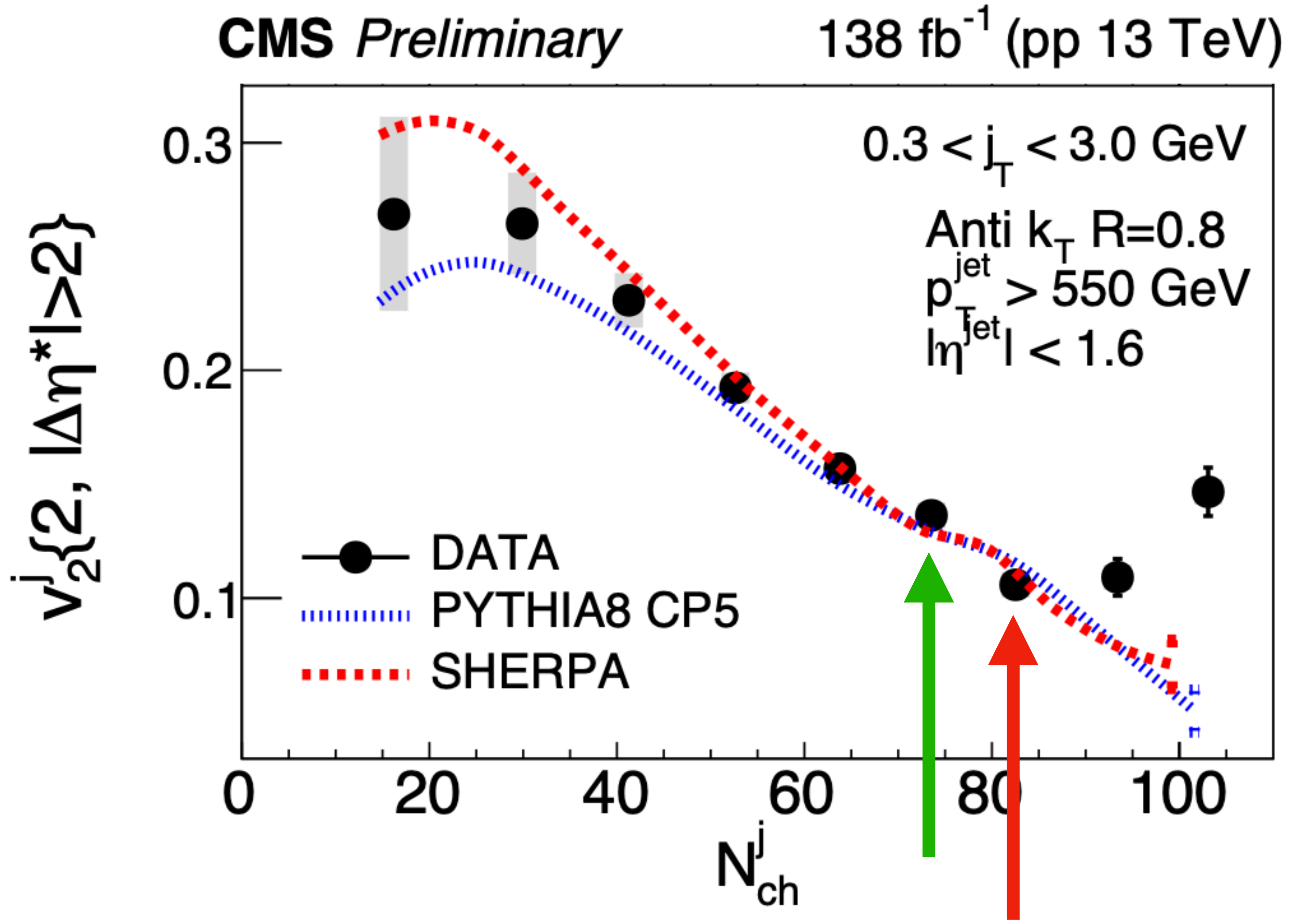


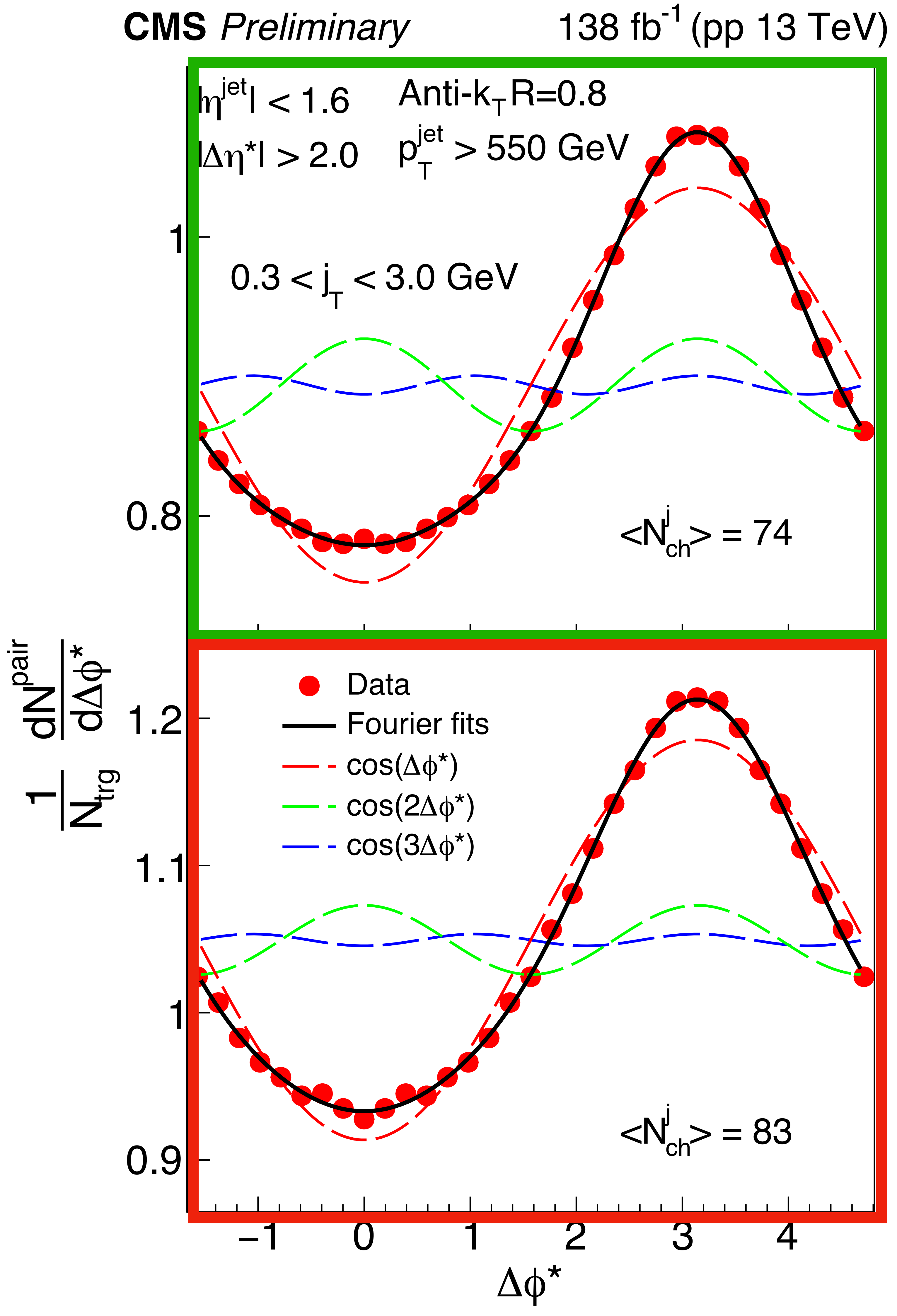


- **Checks of groomed W mass indicate W's are not origin of signal**

Closer inspection of 1D correlations

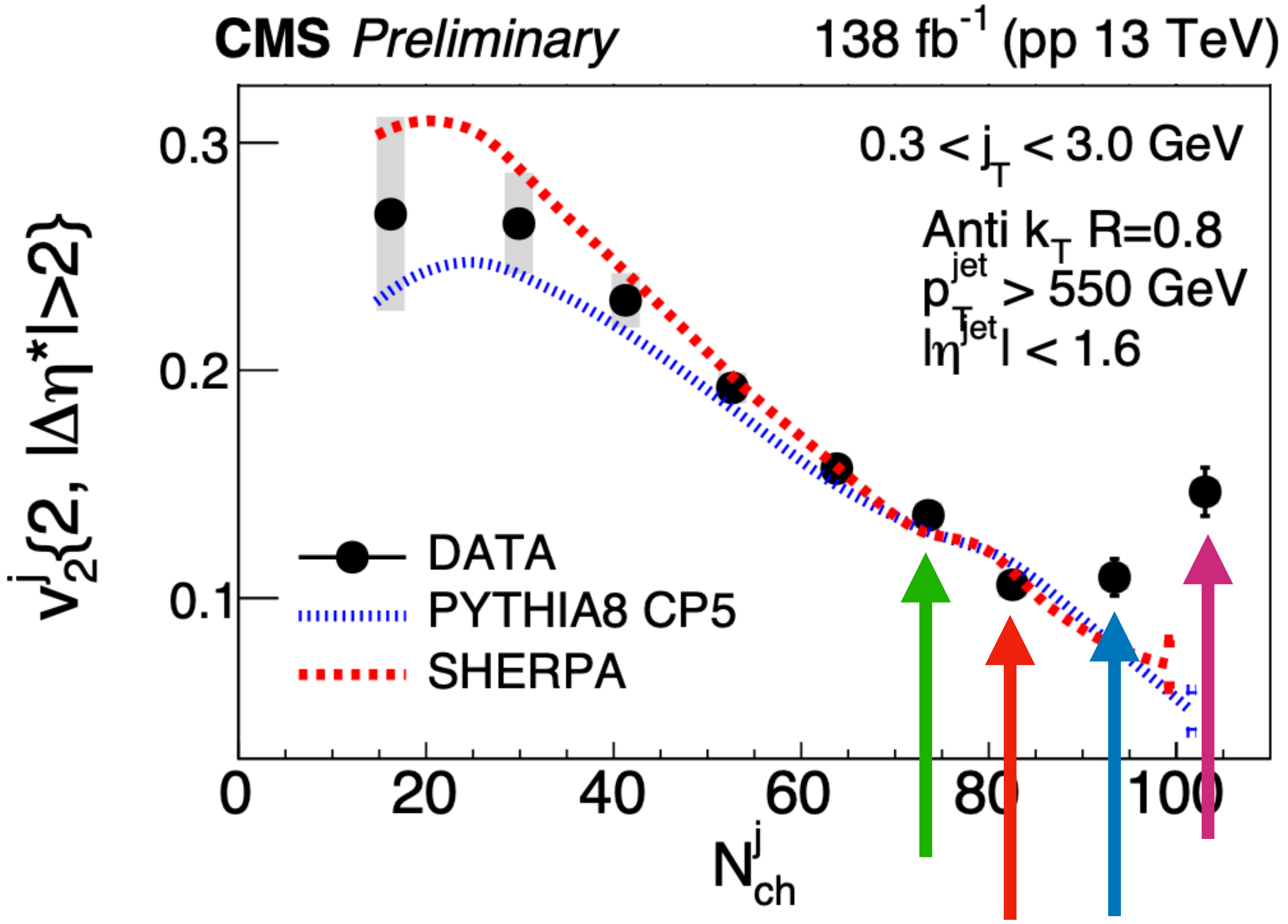
- **Smoothly varying 1D correlation up to N_{ch} ~ 85**

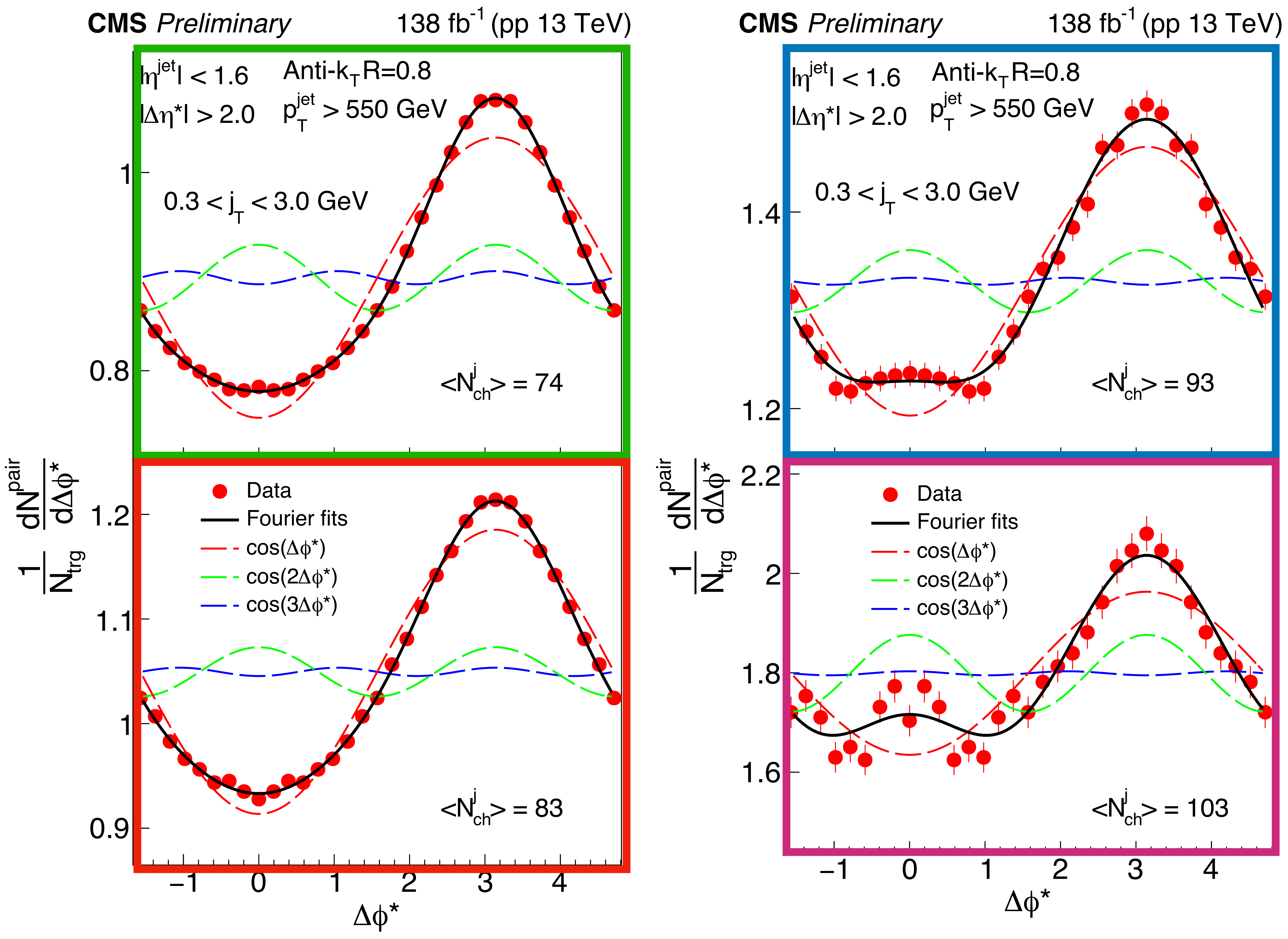




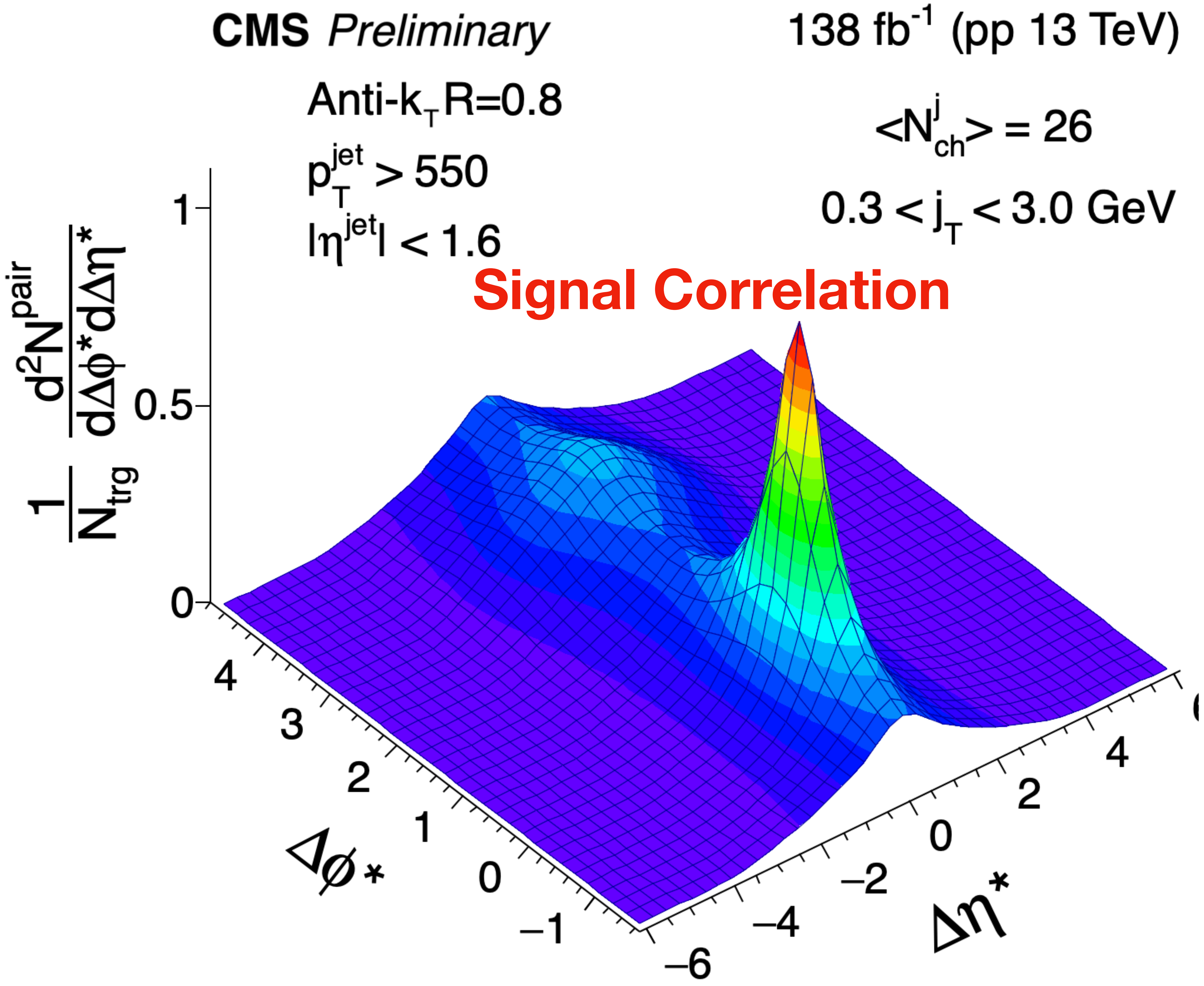
Closer inspection of 1D correlations

- **Bump around $\Delta\phi^* = 0$ emerges around $N_{ch} > 90$**
- **Hallmark behavior of 'near side ridge' in previous analyses**



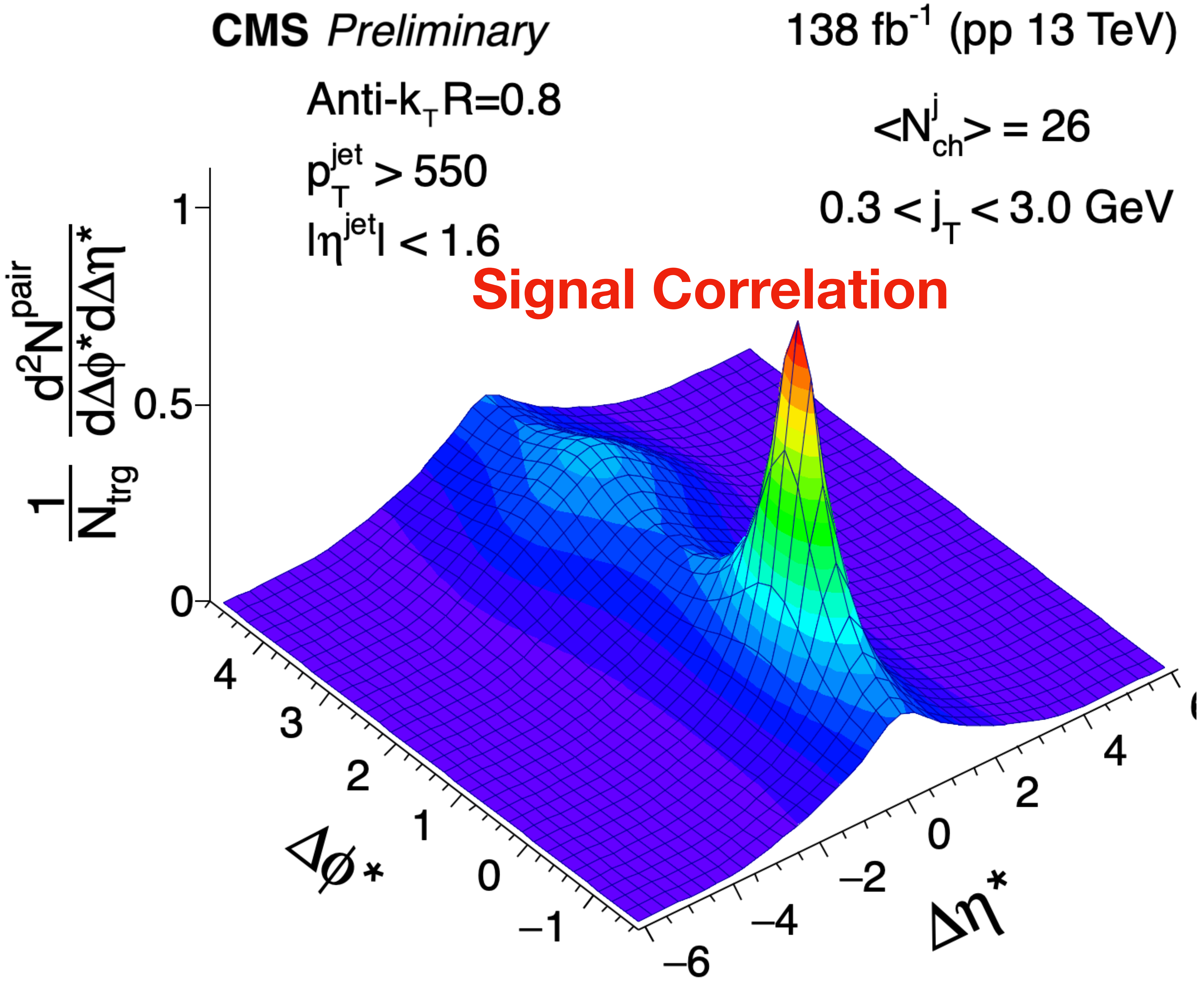


Particle pair correlations



Built from all pairs of jet constituents.
Particles not clustered into the jet ignored.

Particle pair correlations



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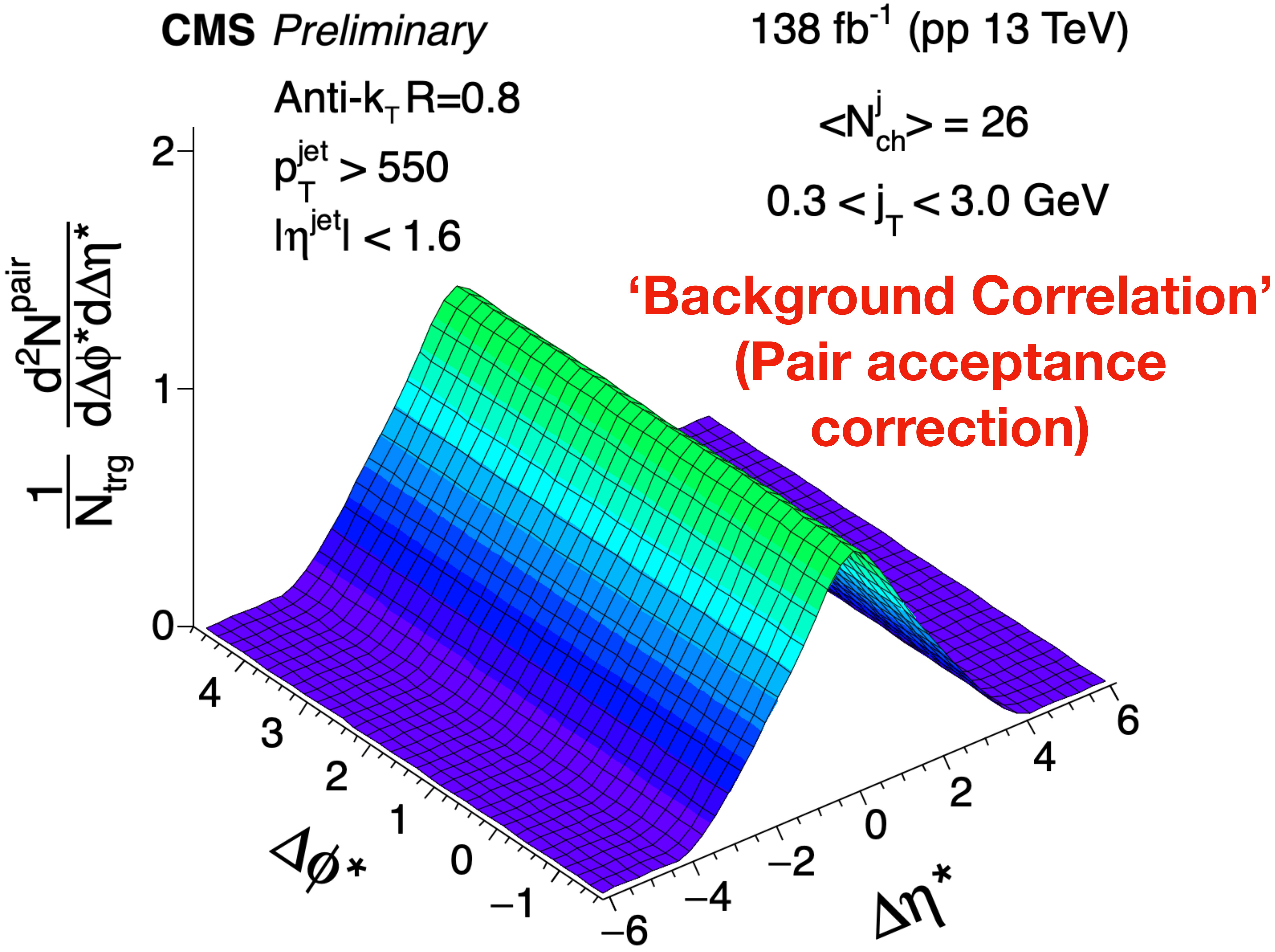
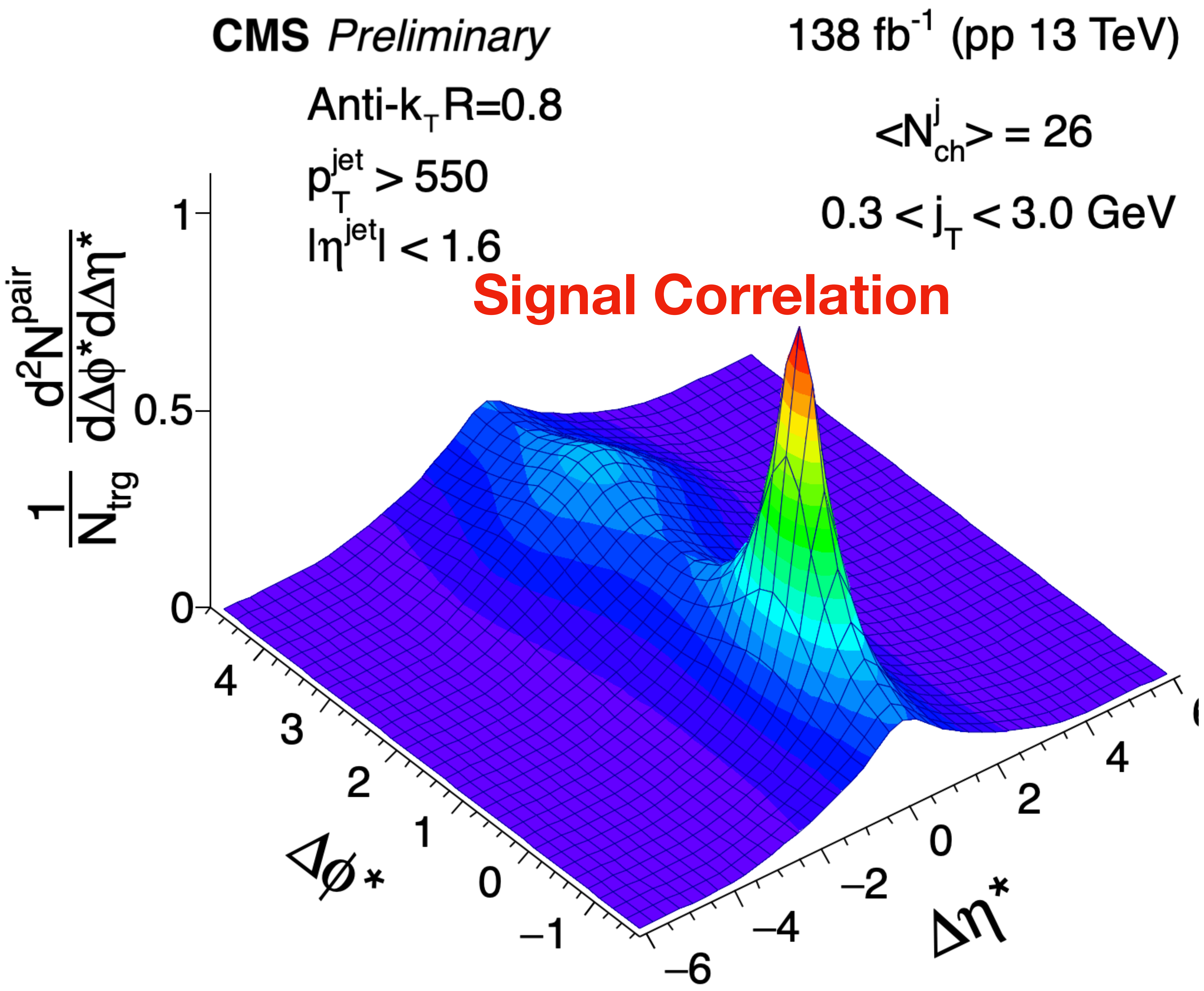
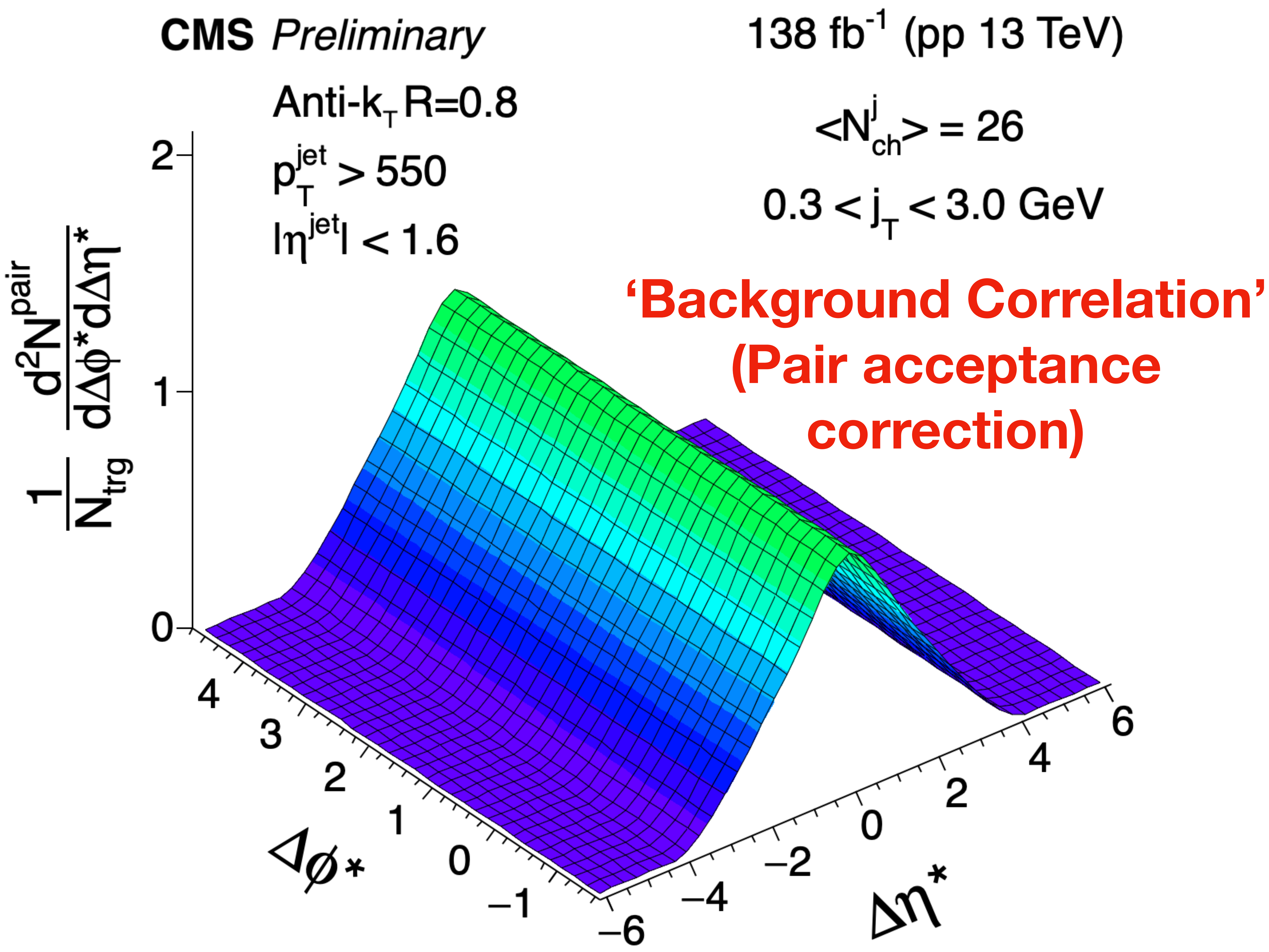
Particles not clustered into the jet ignored.



Built from random sampling of 1-D distributions (no physics correlations by construction)

Particle pair correlations

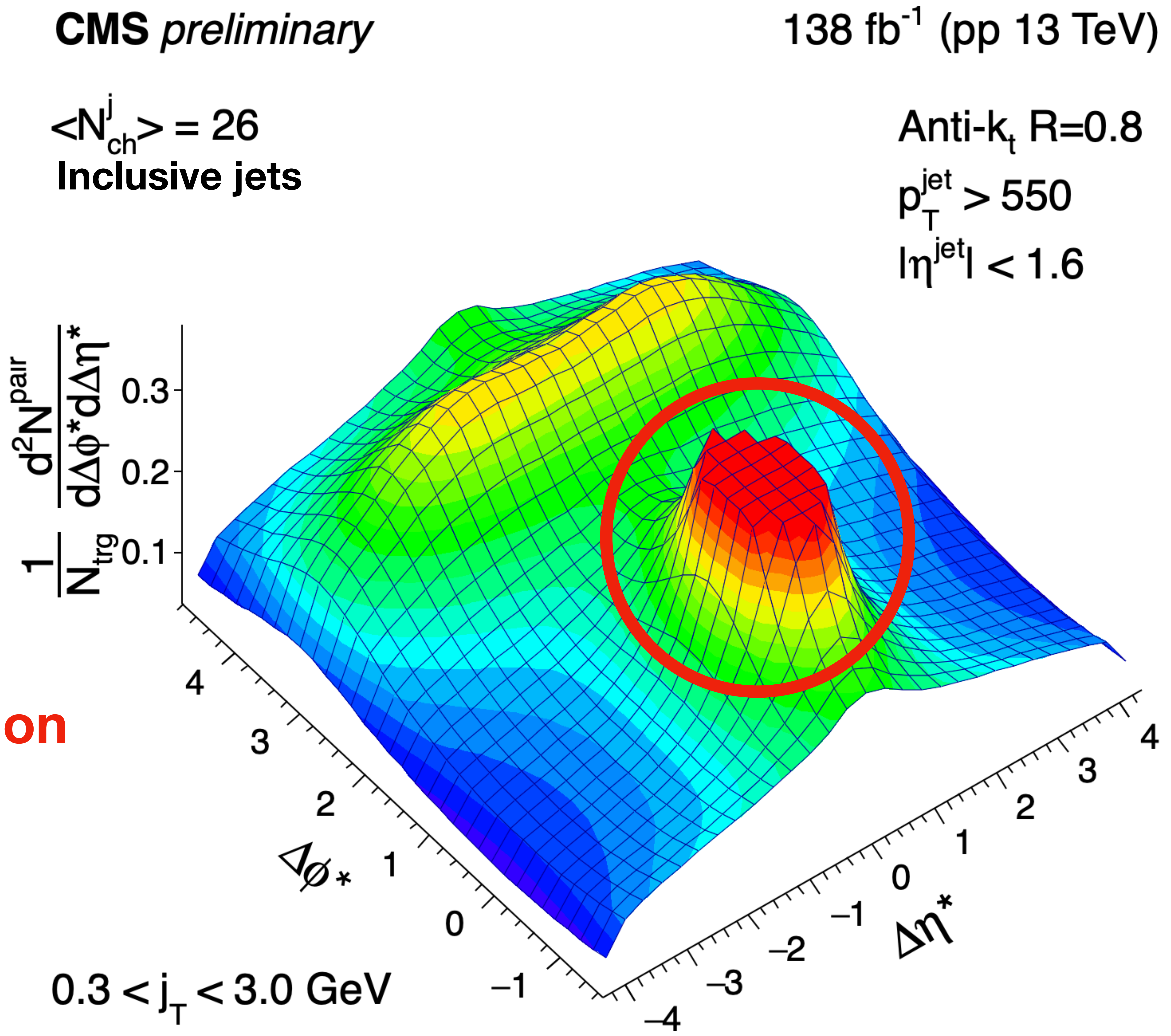




$$\frac{1}{N_{\mathrm{ch}}^{\mathrm{trg}}}\frac{\mathrm{d}^2 N^{\mathrm{pair}}}{\mathrm{d}\Delta\eta^*\mathrm{d}\Delta\phi^*} = B(0,0)\frac{S(\Delta\eta^*,\Delta\phi^*)}{B(\Delta\eta^*,\Delta\phi^*)}$$

2 Particle Correlation Function

$$\frac{1}{N_{\rm ch}^{\rm trg}} \frac{d^2 N^{\rm pair}}{d\Delta\eta^* d\Delta\phi^*} = B(0,0) \frac{S(\Delta\eta^*, \Delta\phi^*)}{B(\Delta\eta^*, \Delta\phi^*)}$$

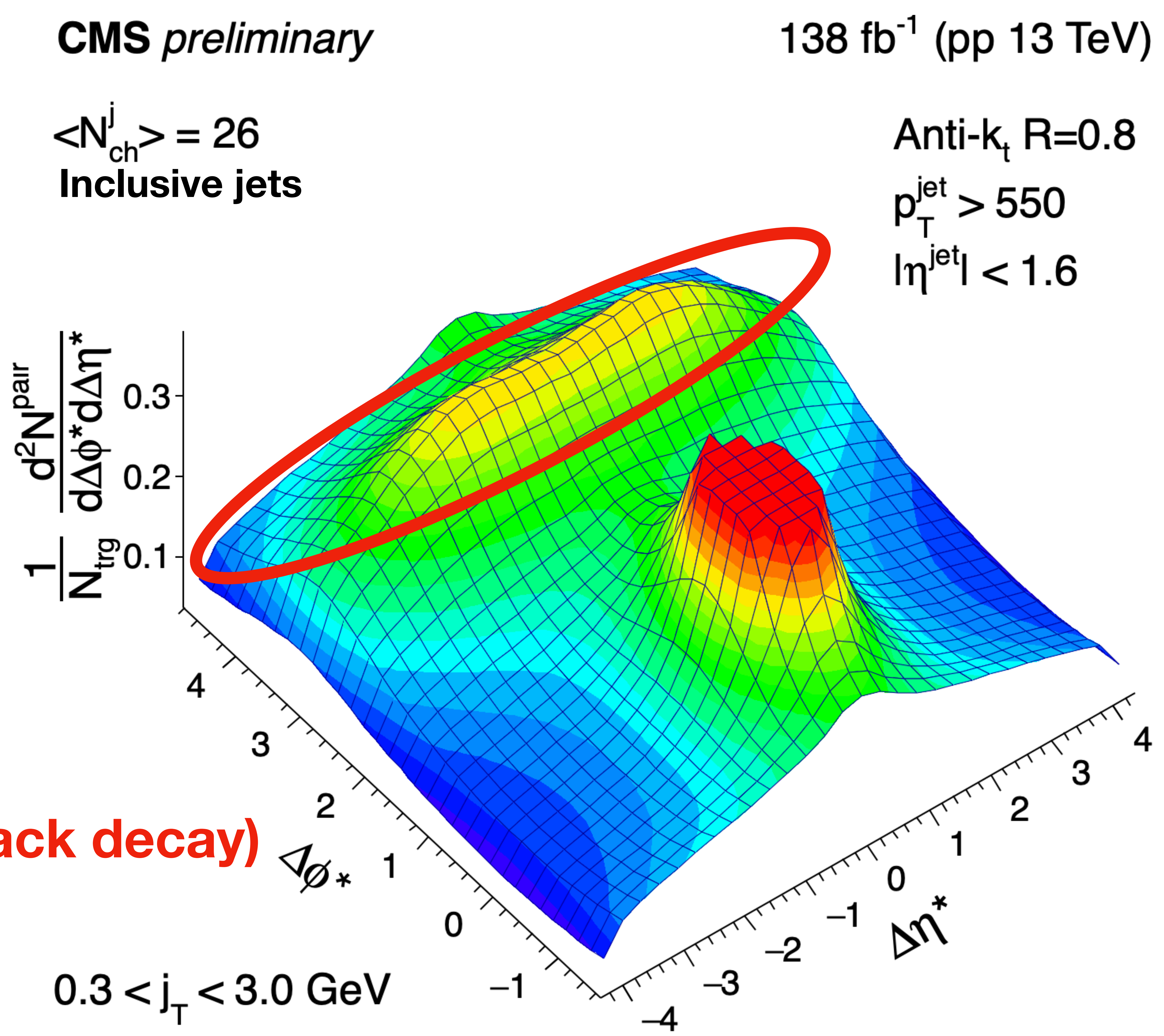


- **Similar features as lab-frame analysis!**
- **Peak at (0,0)**
    - **Hadron decays, collinear fragmentation**

2 Particle Correlation Function

$$\frac{1}{N_{\text{ch}}^{\text{trg}}}\frac{d^2N^{\text{pair}}}{d\Delta\eta^* d\Delta\phi^*} = B(0,0)\frac{S(\Delta\eta^*,\Delta\phi^*)}{B(\Delta\eta^*,\Delta\phi^*)}$$

- **Similar features as lab-frame analysis!**
- **Peak at (0,0)**
- **Away-side enhancement at $\Delta\phi^* = \pi$**
    - **Momentum conservation (back-to-back decay)**



2 Particle Correlation Function

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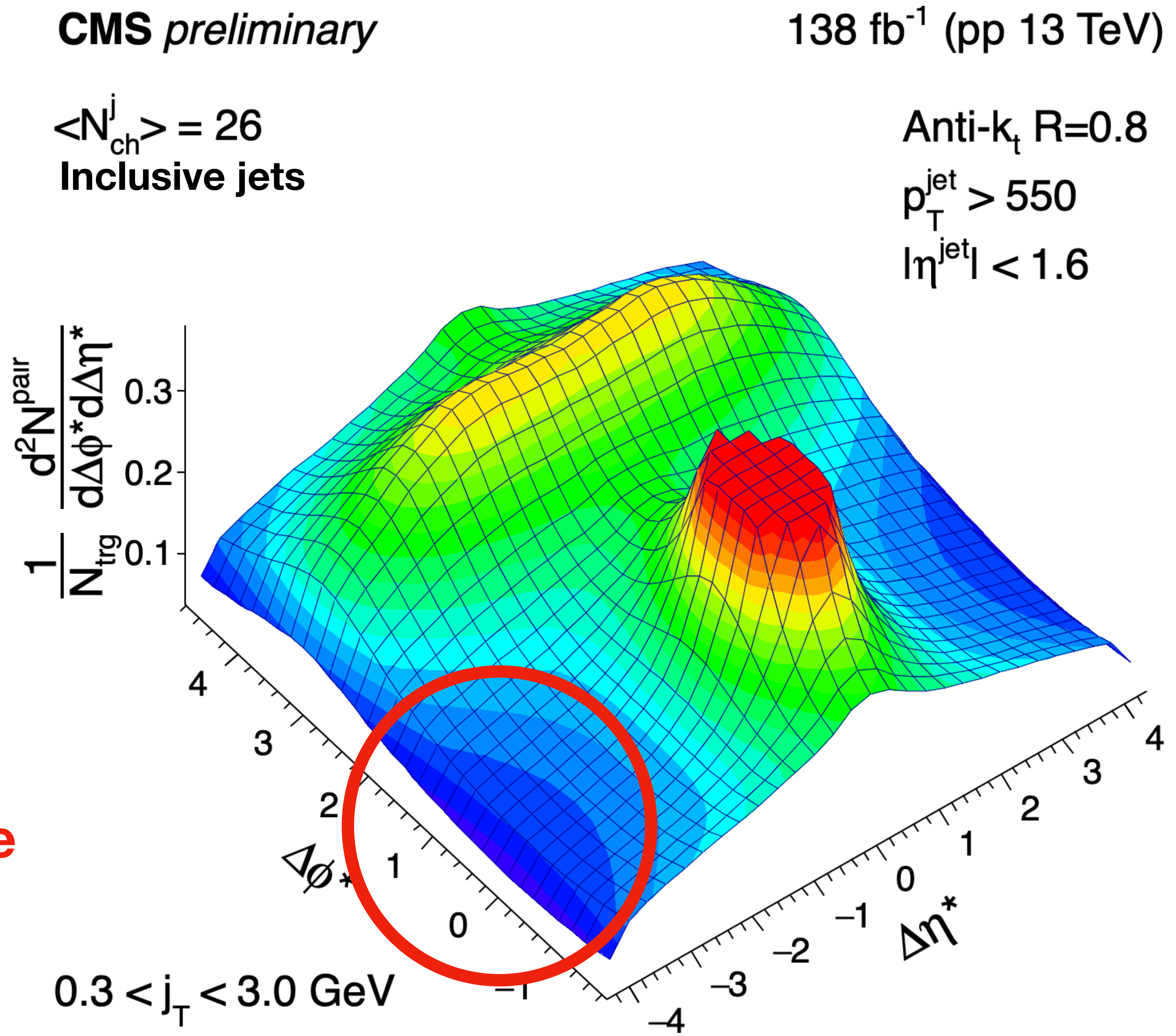
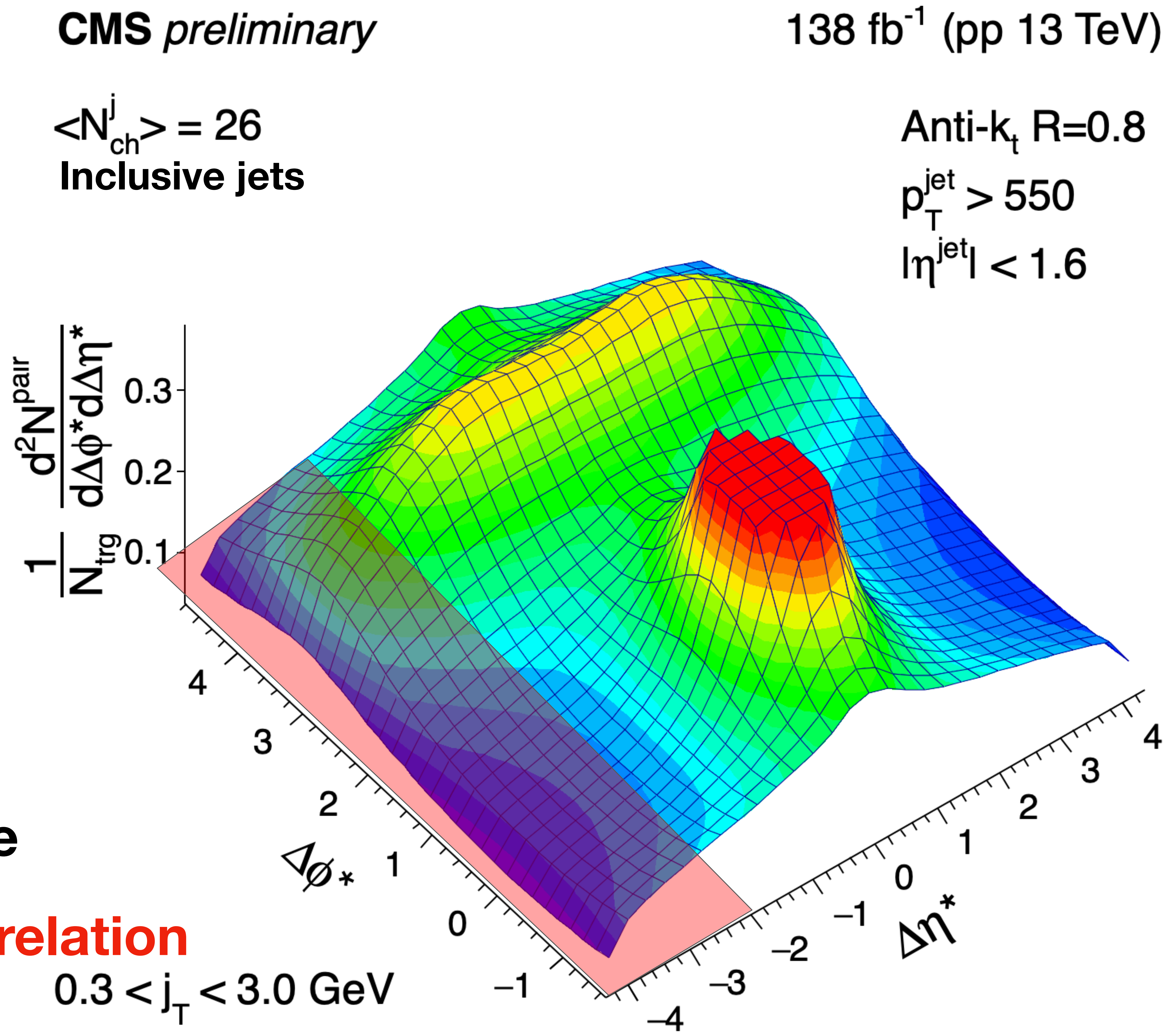
- **Similar features as lab-frame analysis!**
- **Peak at (0,0)**
- **Away-side enhancement at $\Delta\phi^* = \pi$**
- **No near-side ridge for inclusive sample**



2 Particle Correlation Function

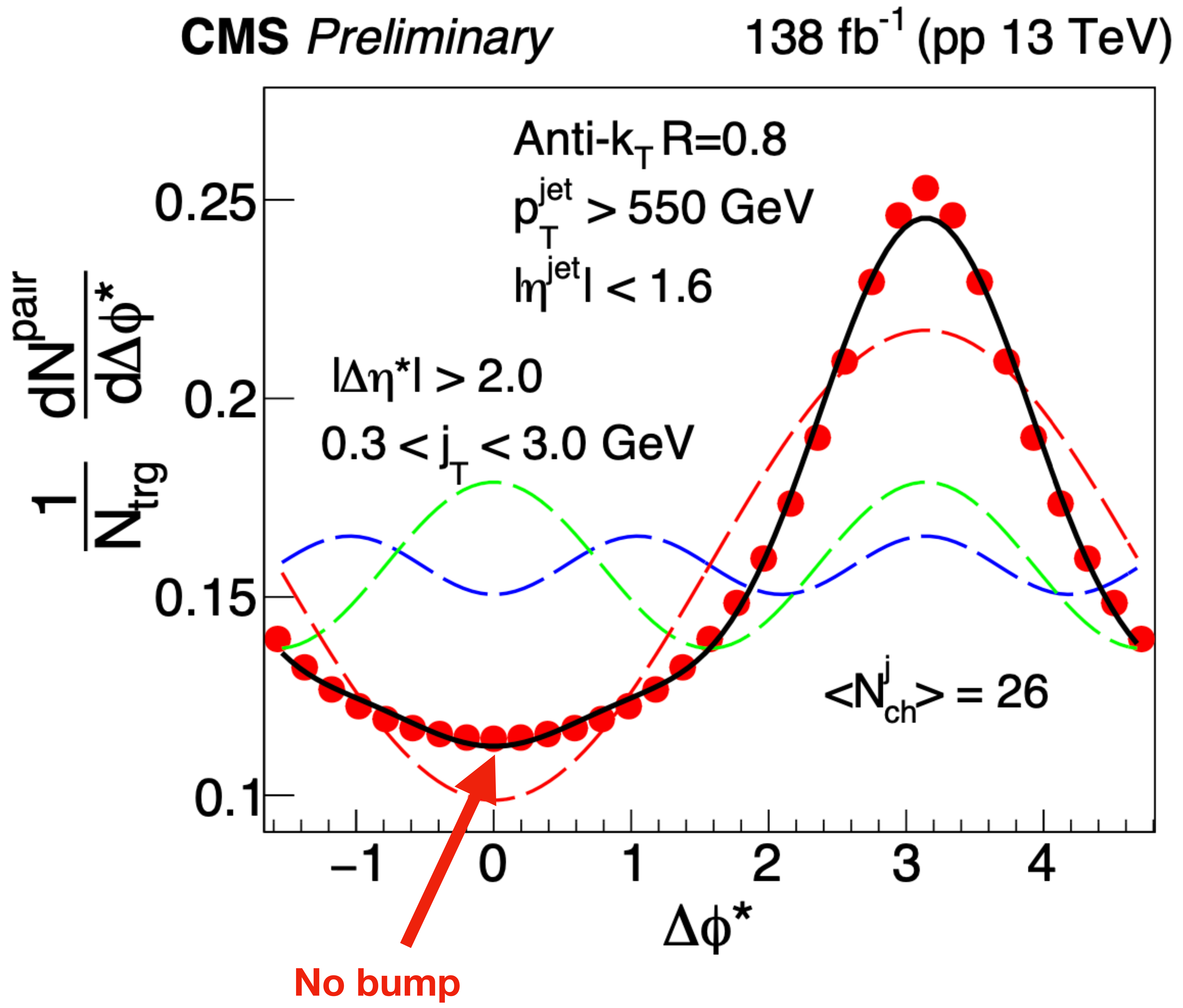
$$\frac{1}{N_{\rm ch}^{\rm trg}}\frac{{\rm d}^2N^{\rm pair}}{{\rm d}\Delta\eta^*{\rm d}\Delta\phi^*} = B(0,0)\frac{S(\Delta\eta^*,\Delta\phi^*)}{B(\Delta\eta^*,\Delta\phi^*)}$$



- **Similar features as lab-frame analysis!**
- **Peak at (0,0)**
- **Away-side enhancement at $\Delta\phi * = \pi$**
- **No near-side ridge for inclusive sample**
- **Project long-range portion into 1D correlation**

1D Correlation Function

- **Data from [0,π] range symmetrize**
- **Look for a bump around** $\Delta\phi* = 0$



1D Correlation Function

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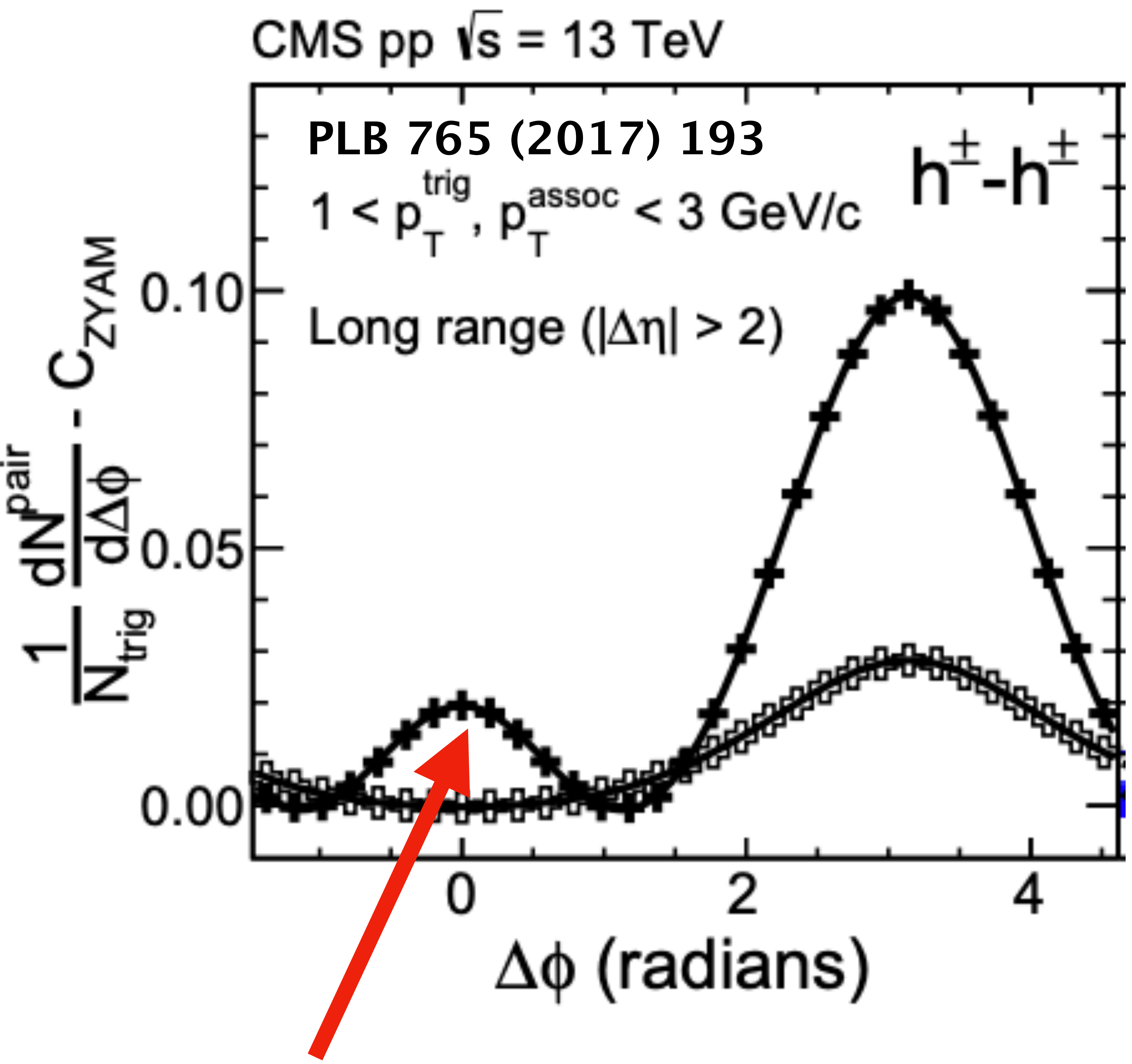
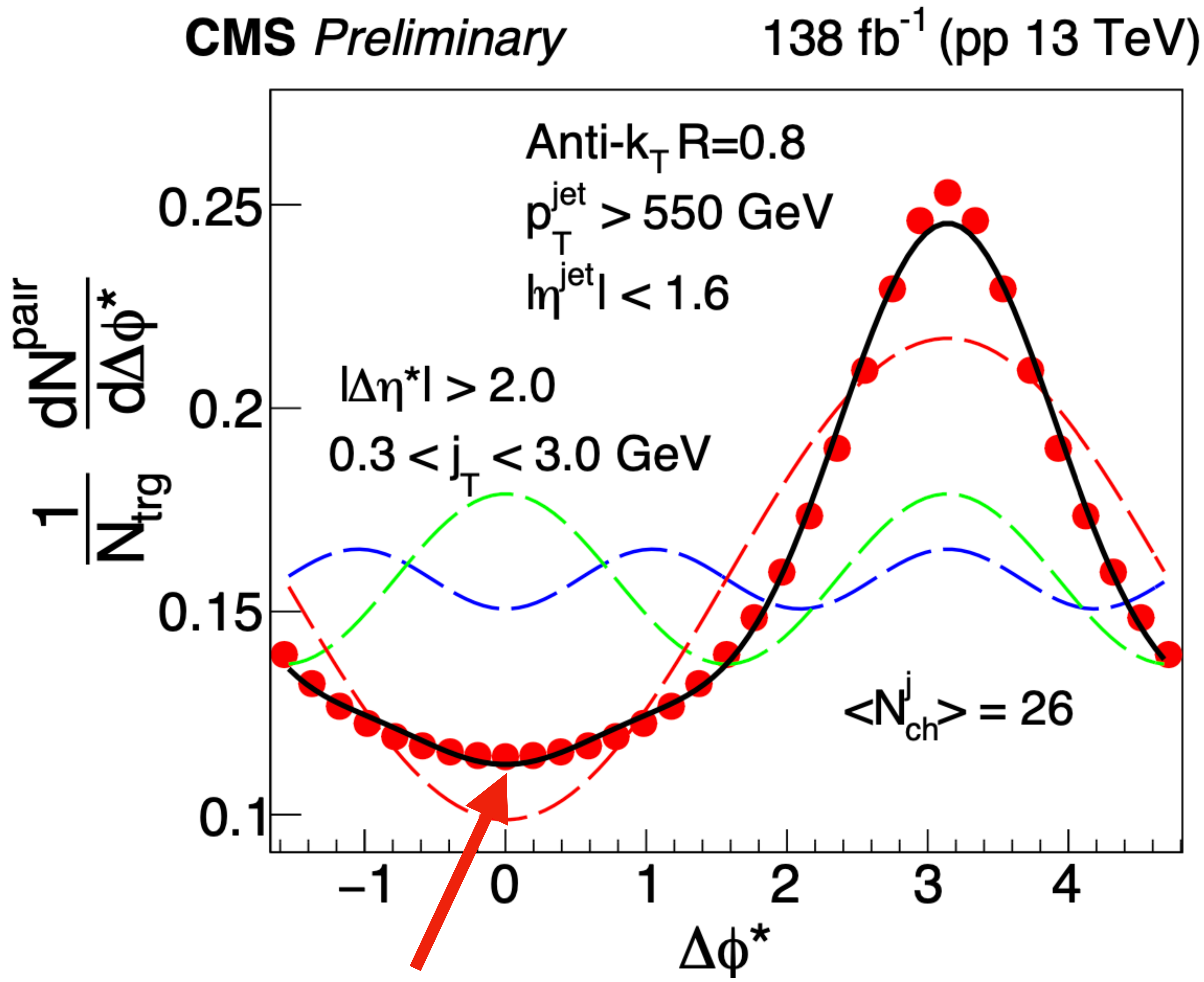


Example of a 'ridge' bump in high-multiplicity pp events (not jets)

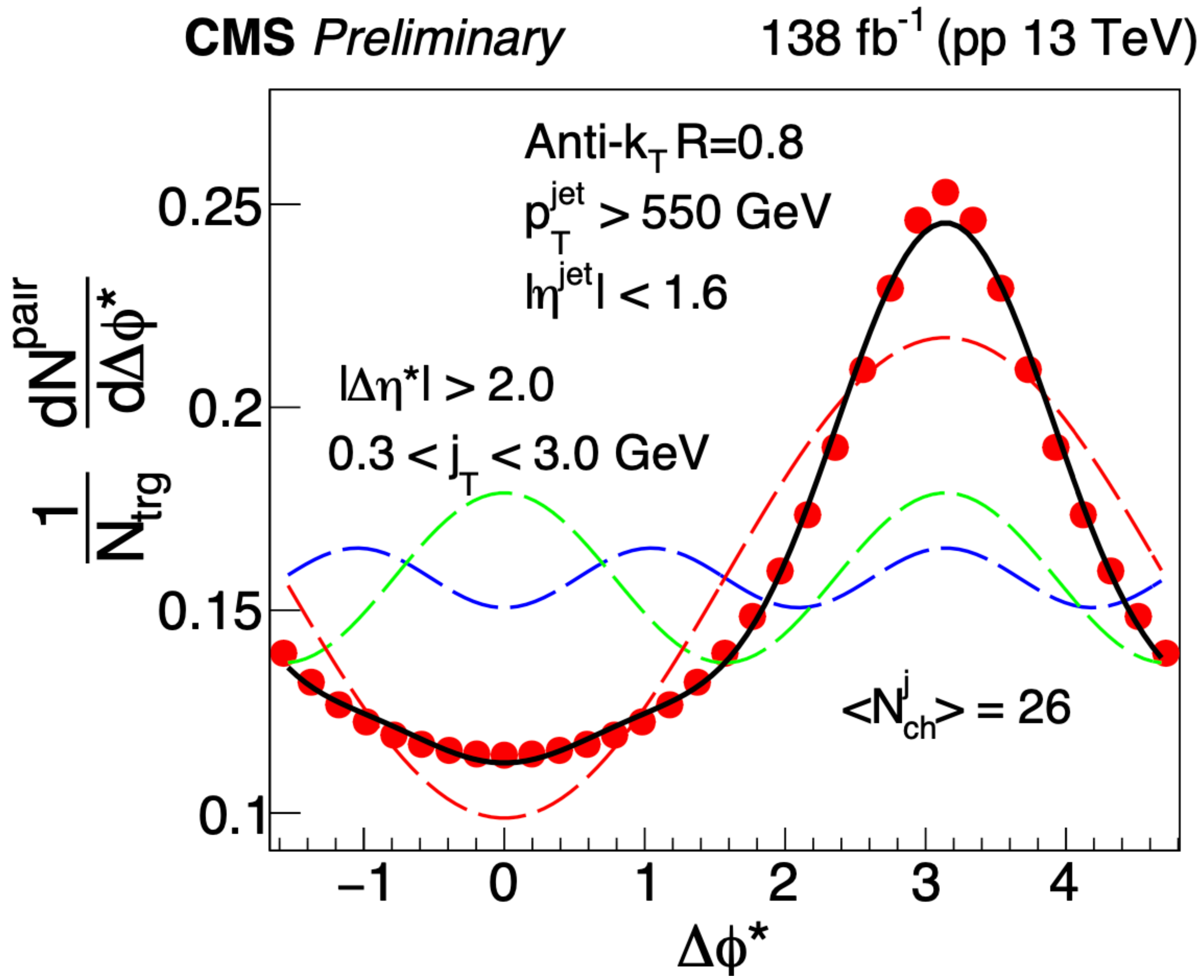


No bump

Fourier Fits

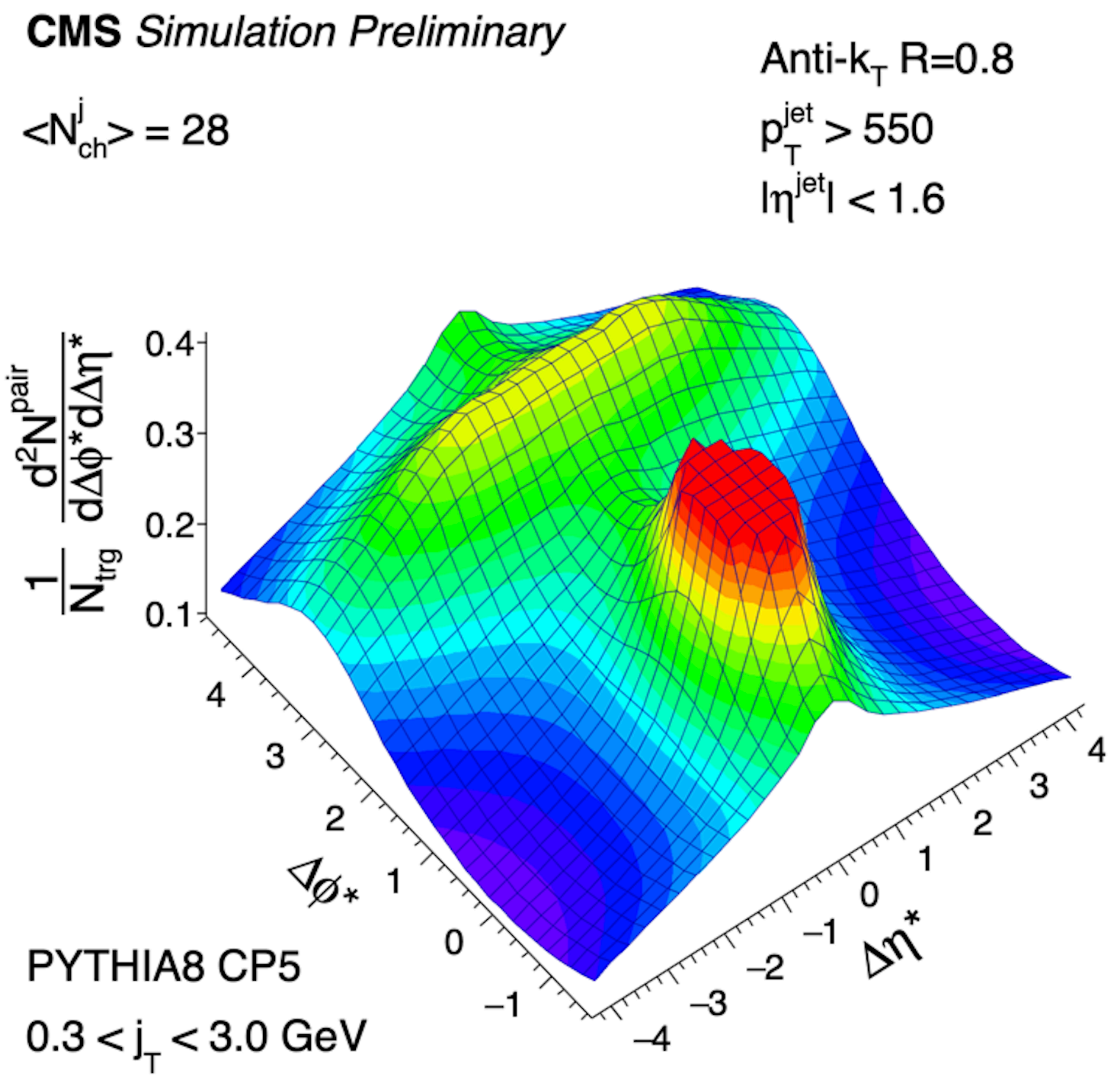
- **Fourier fit to 1D correlation function**
- **Coefficients $V_{n\Delta}$ are free parameters**
- **Can be nonzero even with no bump**
  - **Will come back at the end of talk!**

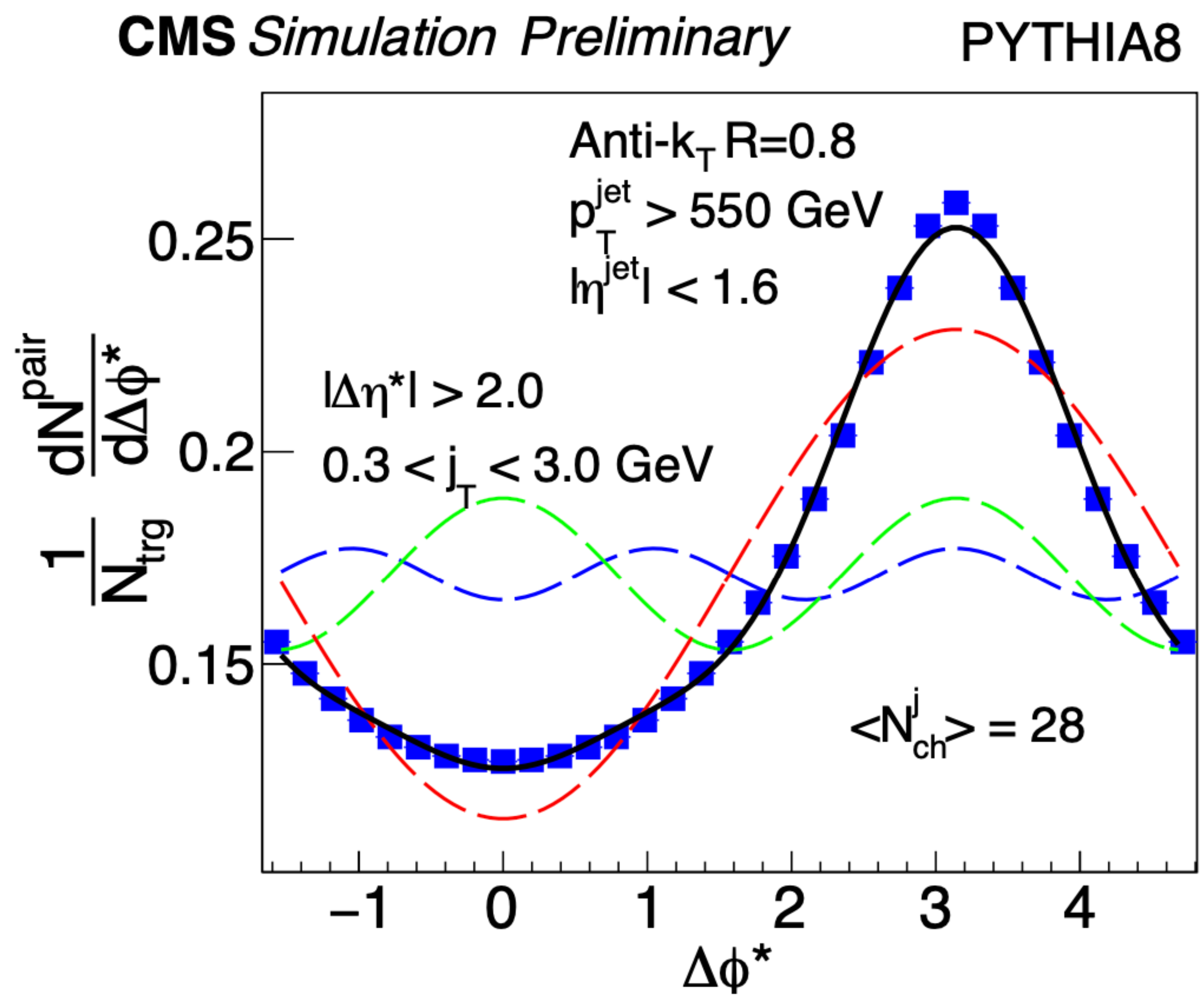
$$\frac{1}{N_{\mathrm{ch}}^{j}} \frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi^{*}} \propto \sum_{n=1}^{\infty} \boxed{V_{\mathrm{n}\Delta}} \cos(\mathrm{n}\Delta\phi^{*})$$



Pythia 8 Correlation

- **String hadronization model**

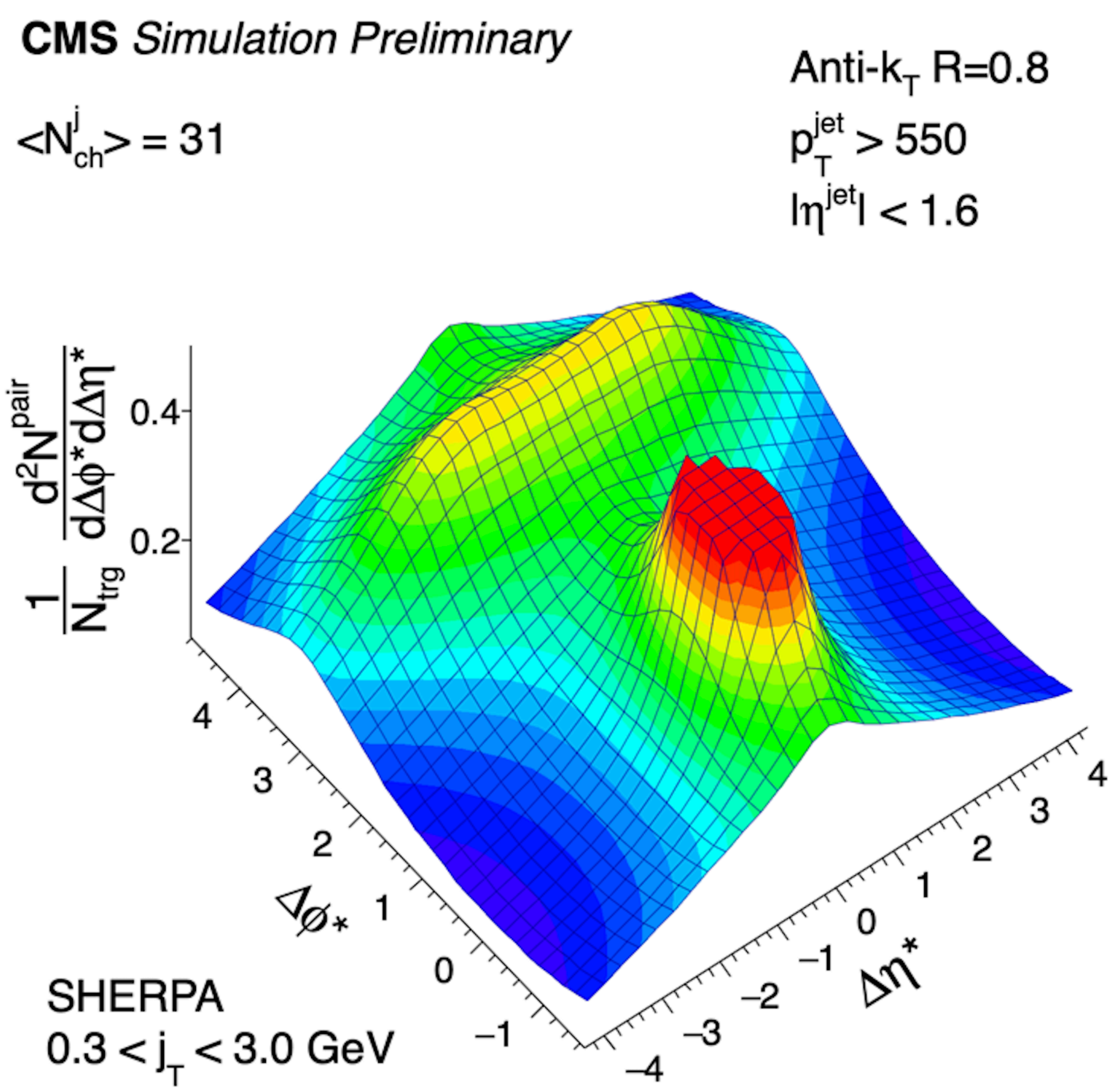


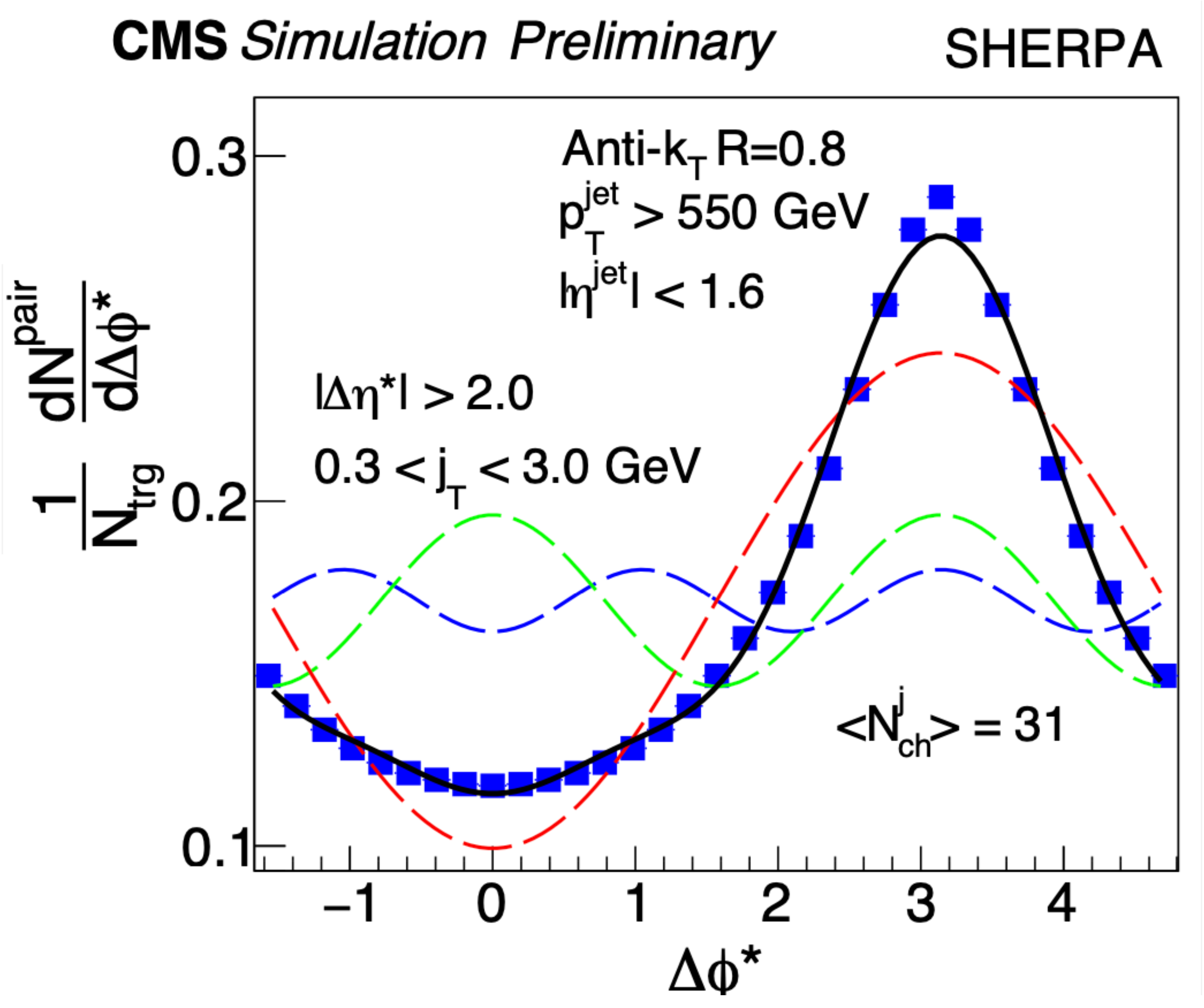


Overall features of low-multiplicity correlation captured by MC models

Sherpa Correlation

- **Cluster hadronization model**



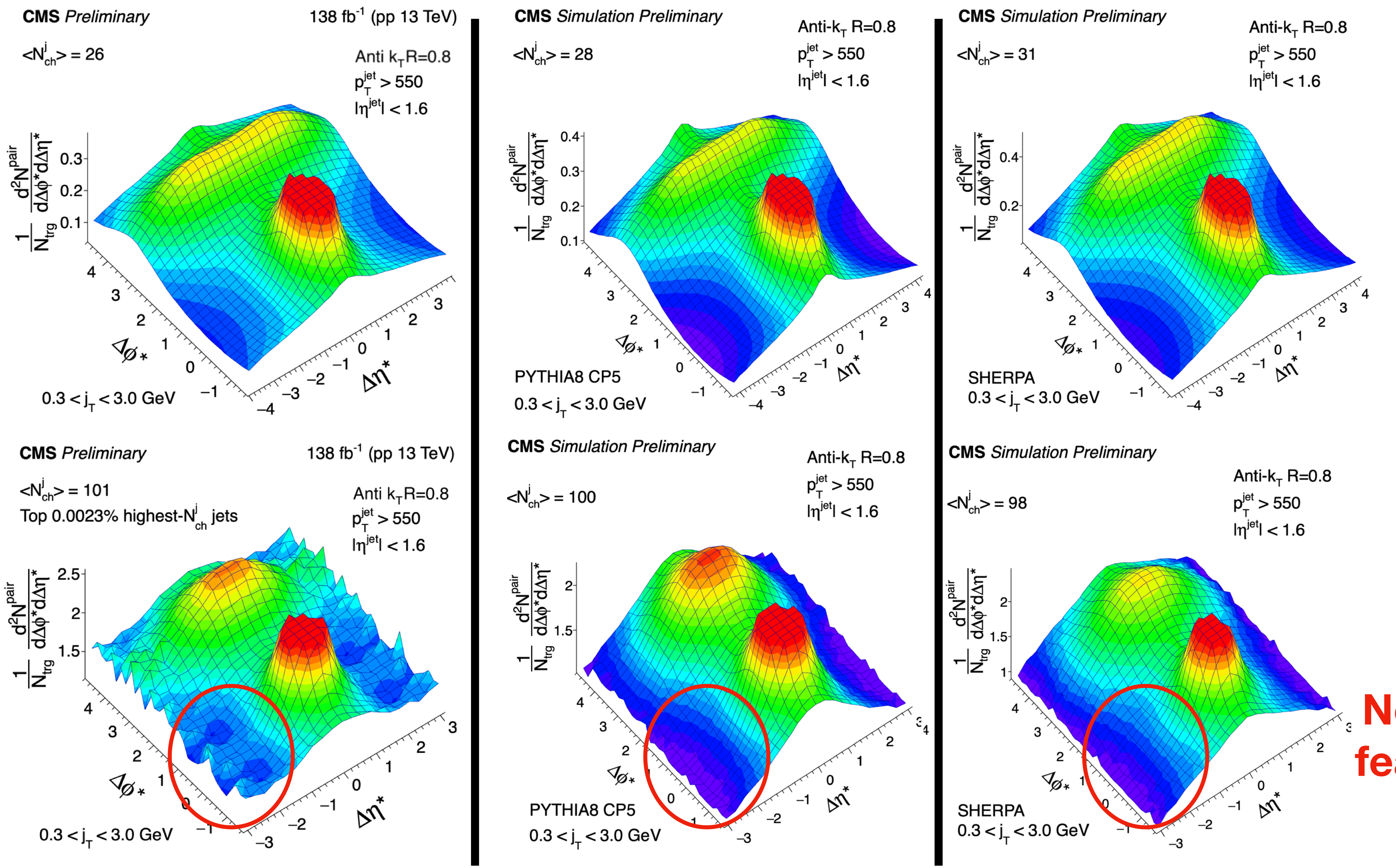


Overall features of low-multiplicity correlation captured by MC models

Comparison to MC

N_{ch} ~ 26

N_{ch} ~ 100

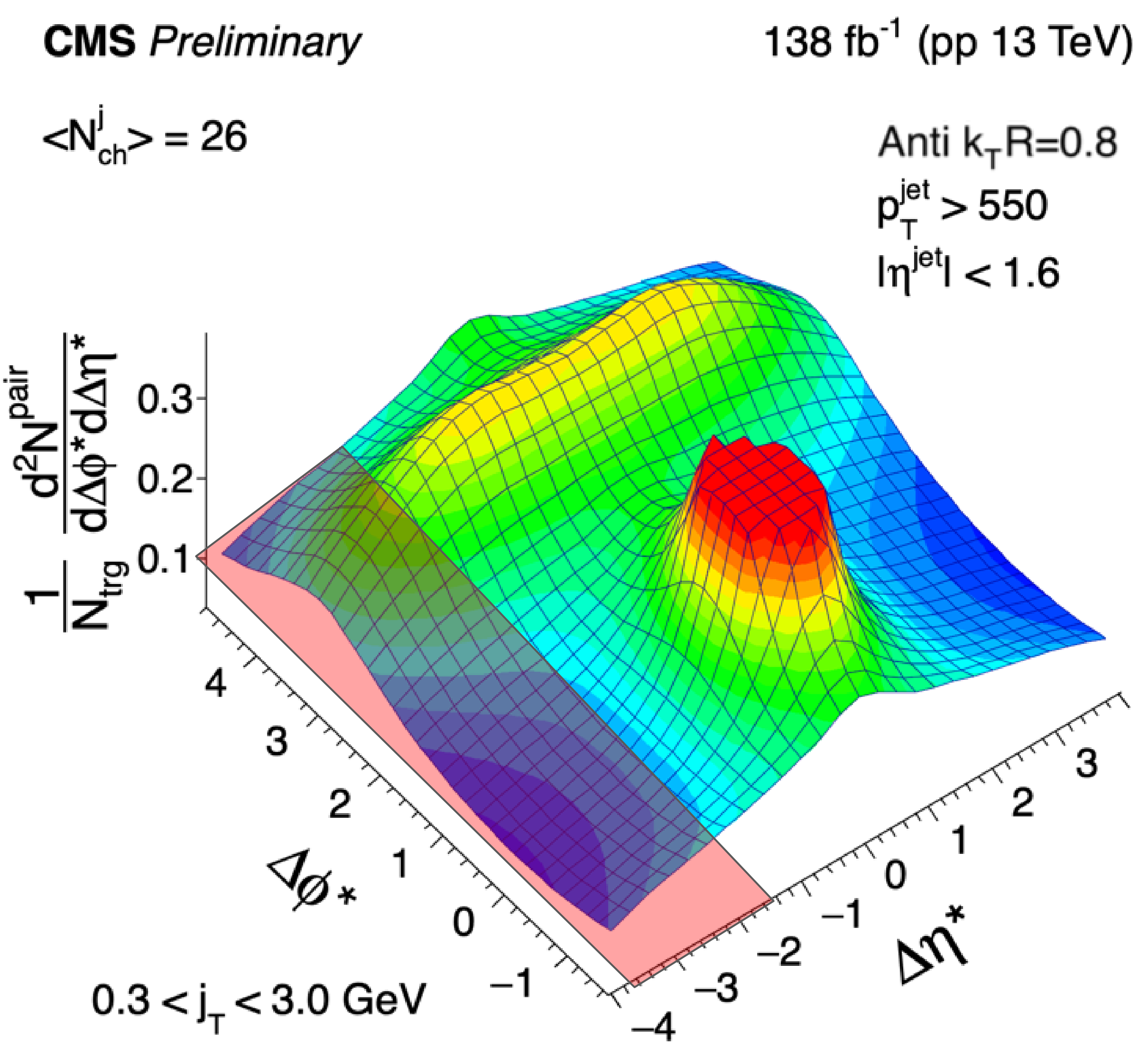


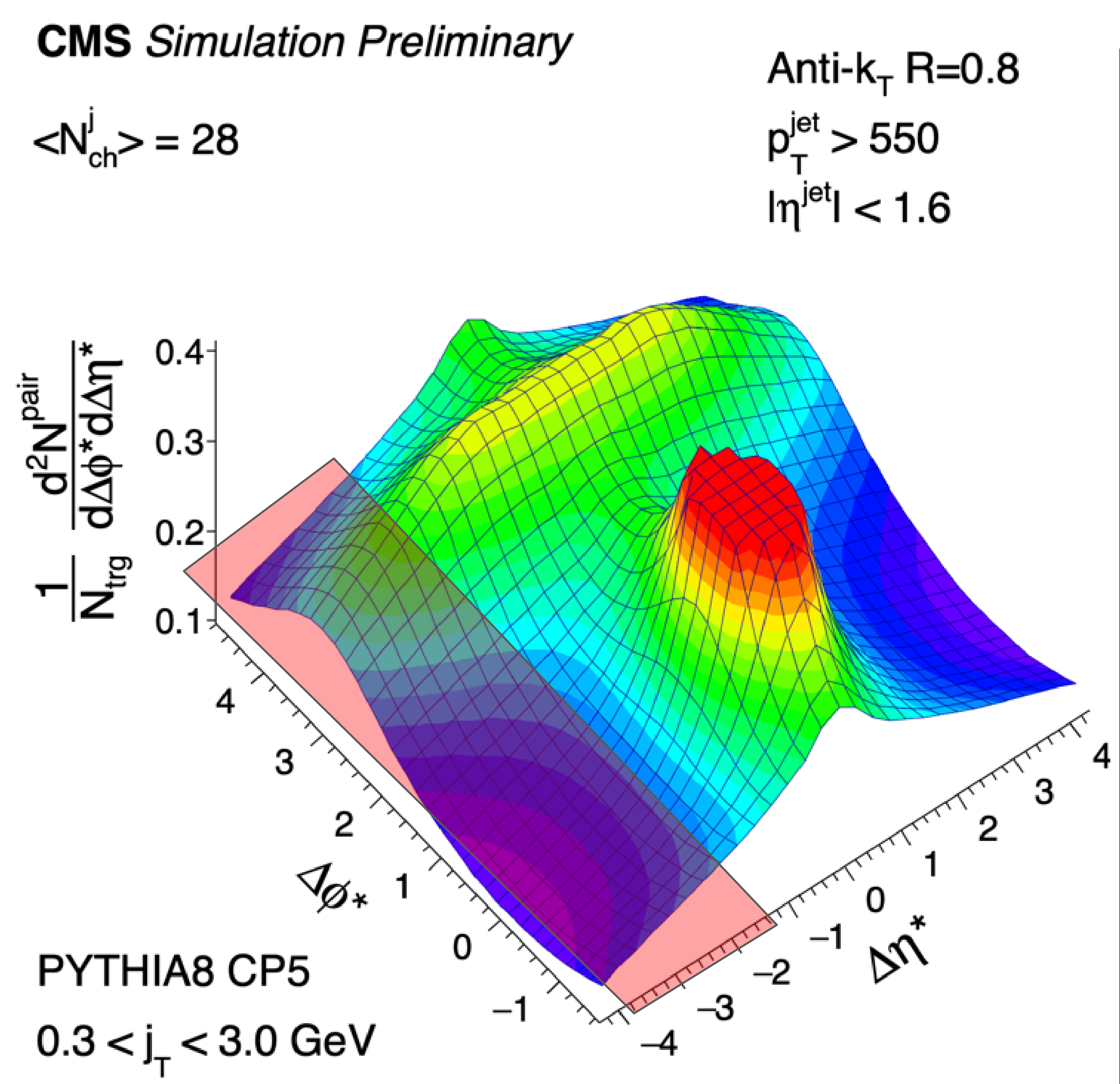
Data **PYTHIA** **SHERPA**

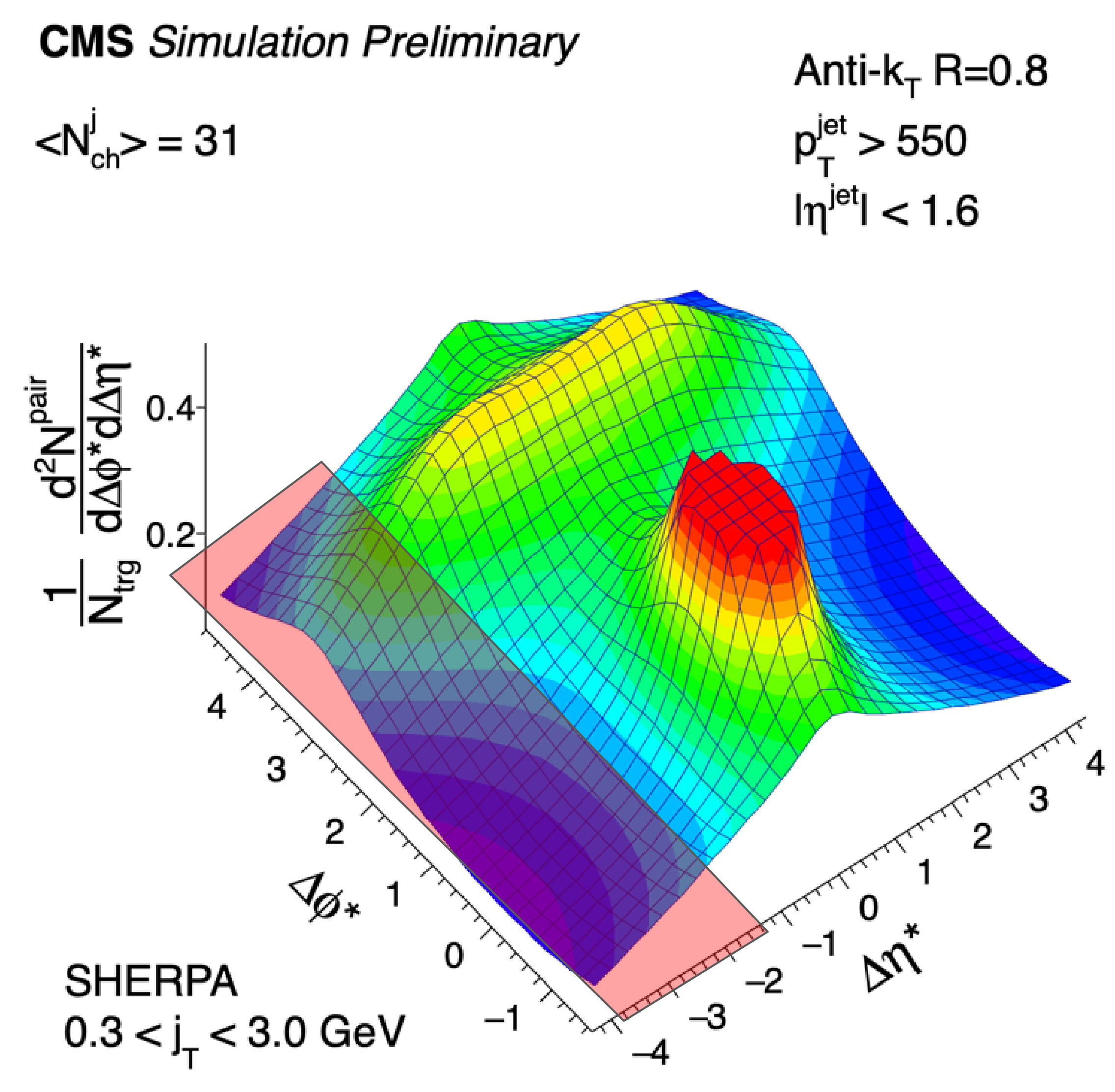
No near-side feature in MC

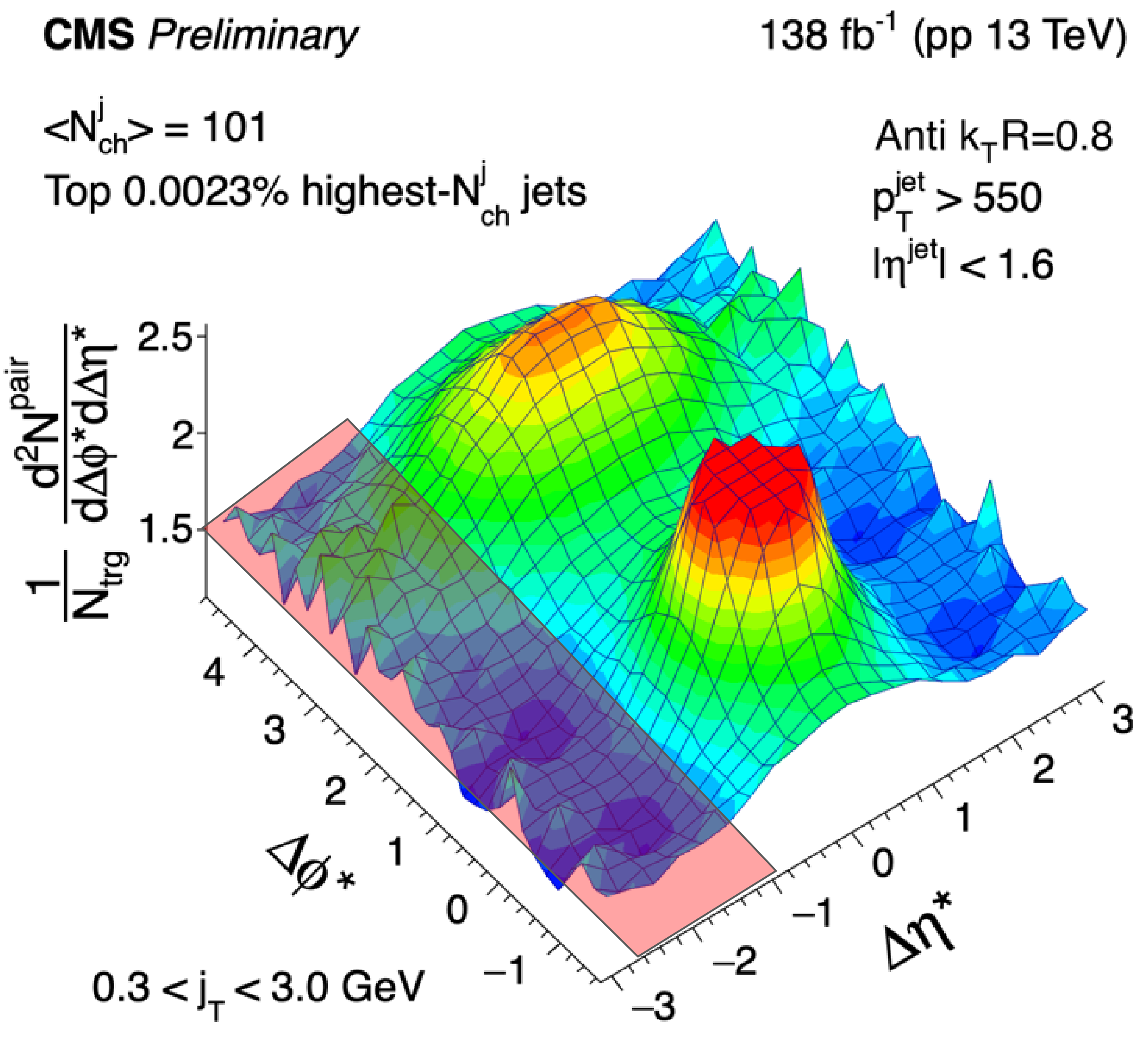
Comparison to MC

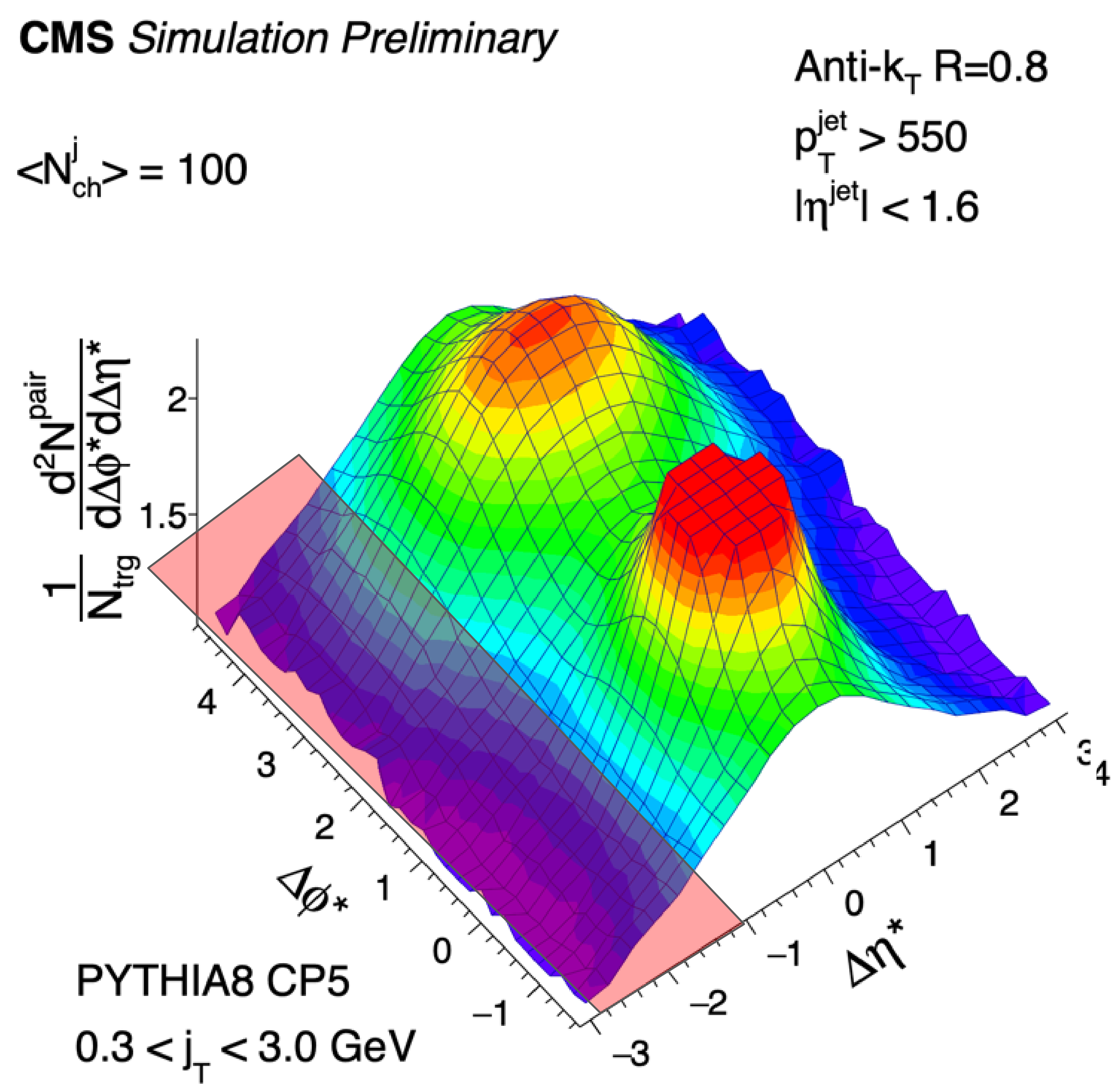
N_{ch} ~ 26

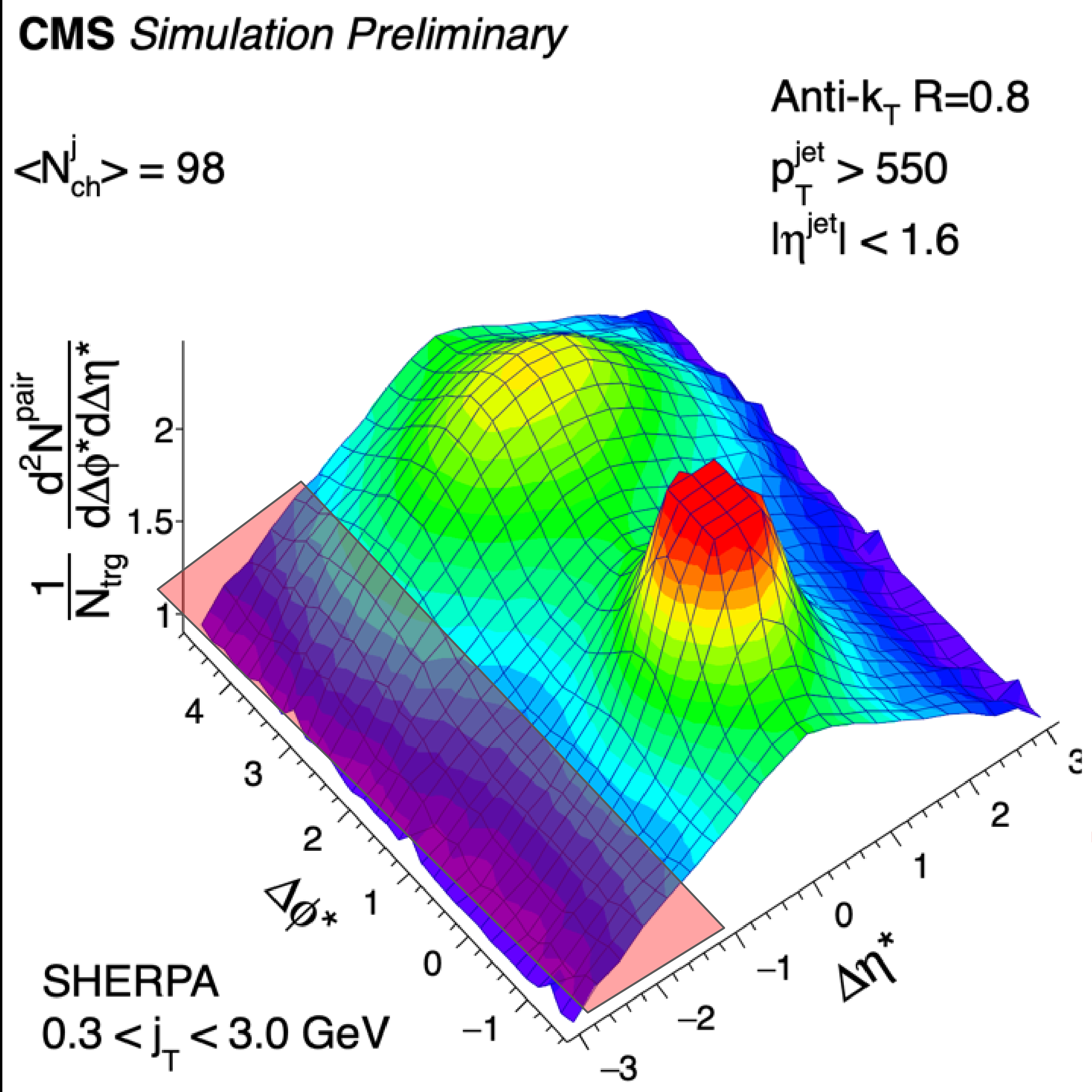










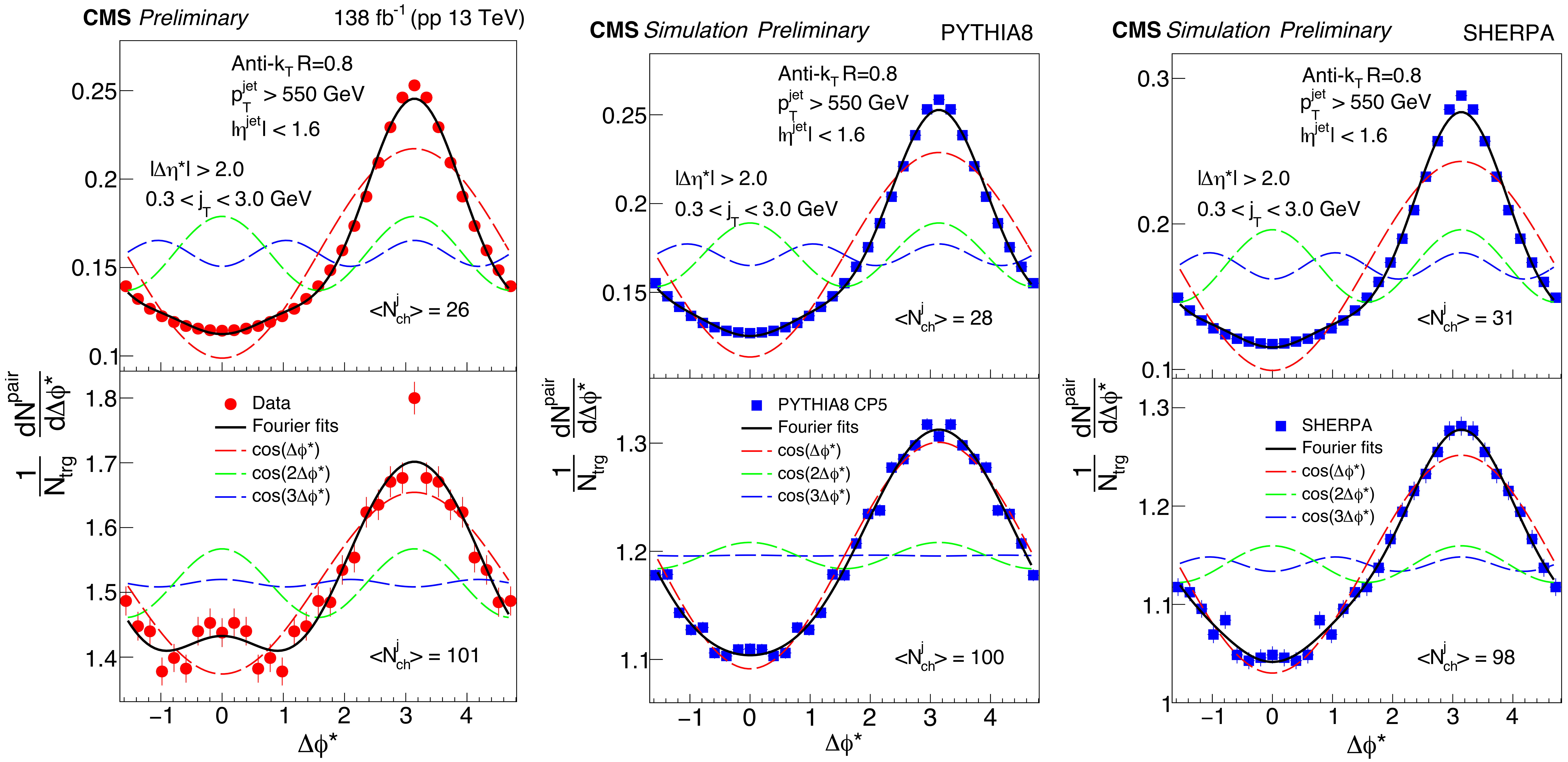


N_{ch} ~ 100

No near-side feature in MC

Data **PYTHIA** **SHERPA**

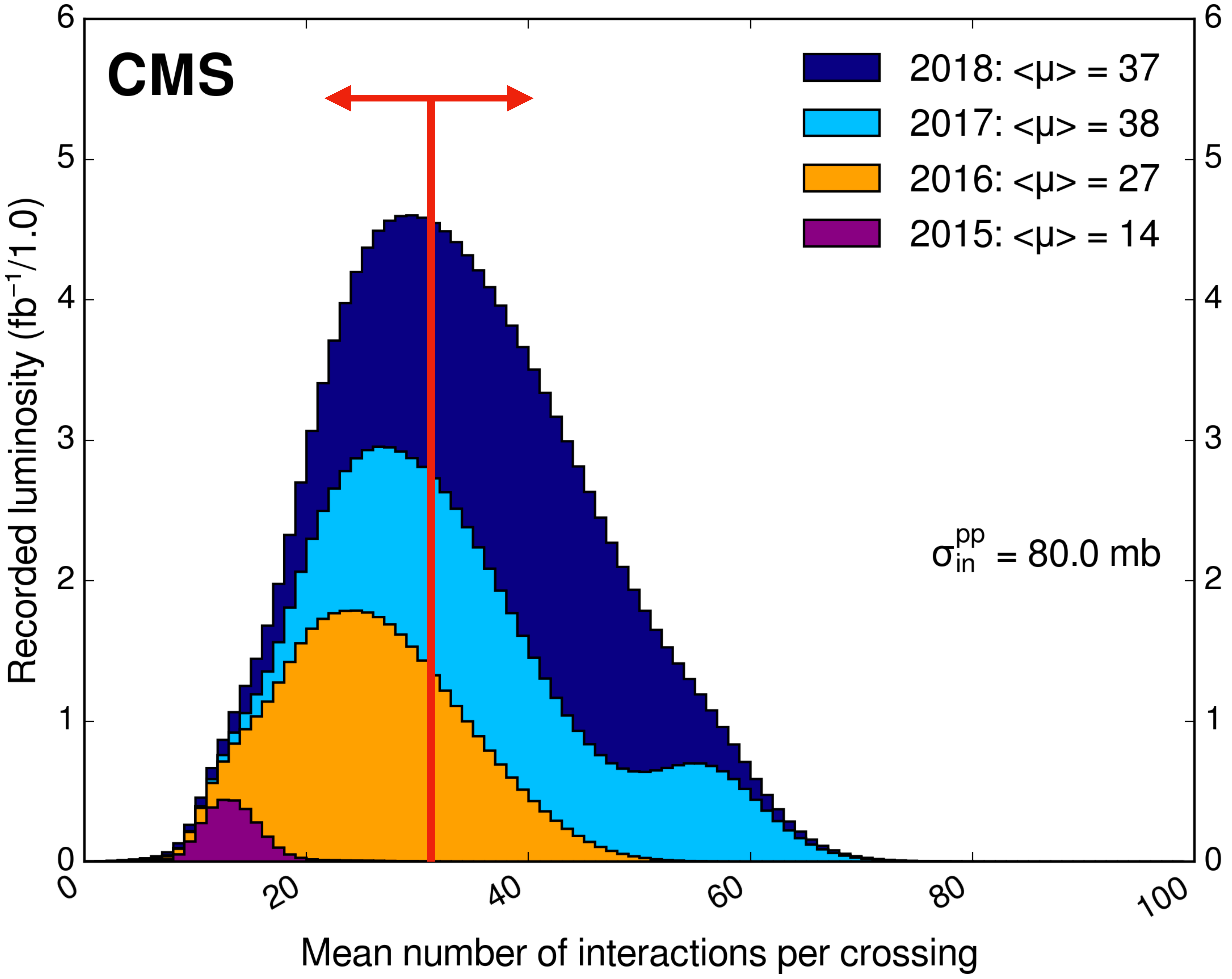
1D Correlations with MC



Pileup Uncertainty

- **Effect of pileup studied by splitting data sample into subsamples**
  - **By year**
  - **By μ**
- **Leading systematic in high-N_{ch} region**

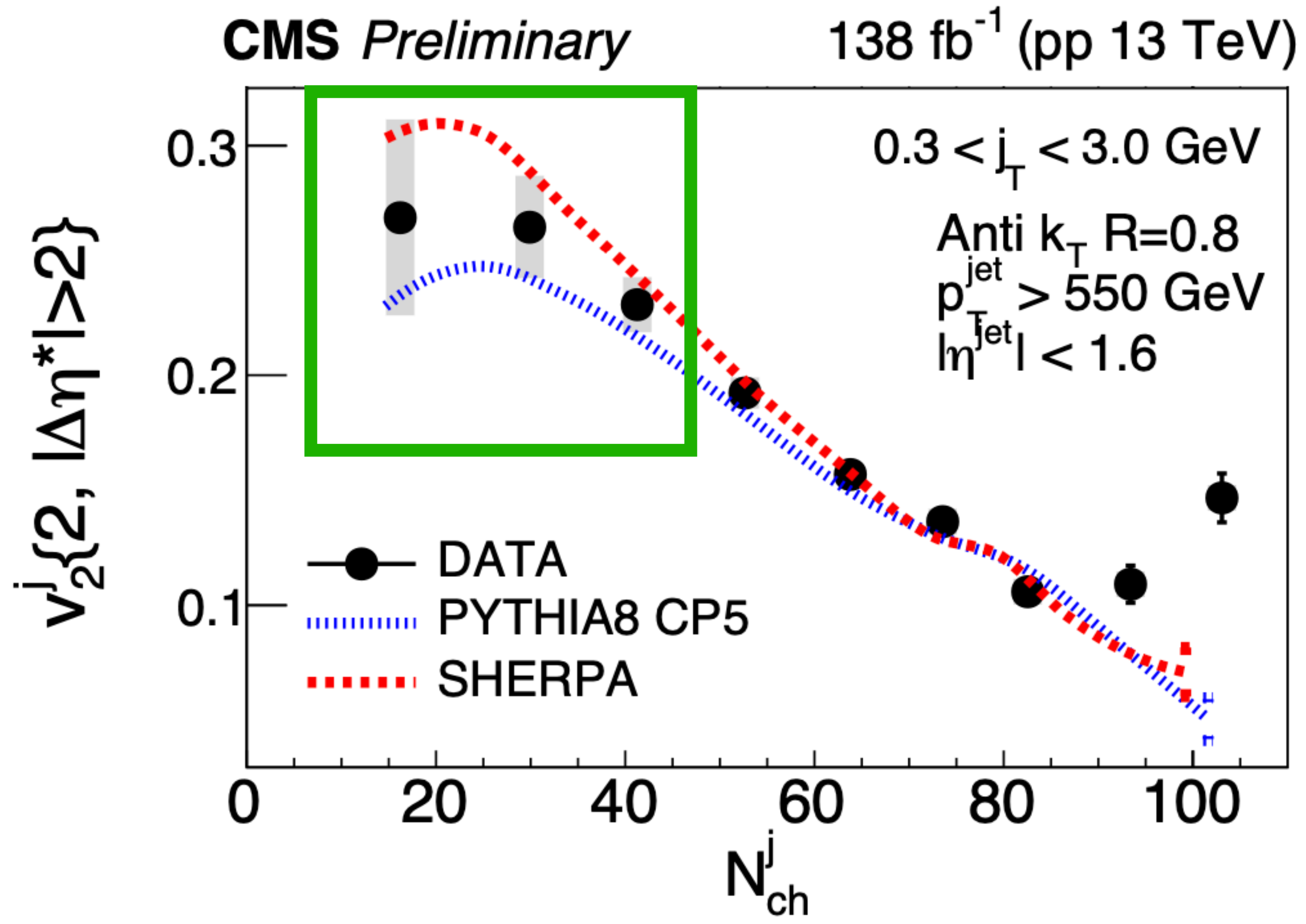
- **Variation of allowed PUPPI weight for 'ambiguous' tracks**
  - **Negligible effect**

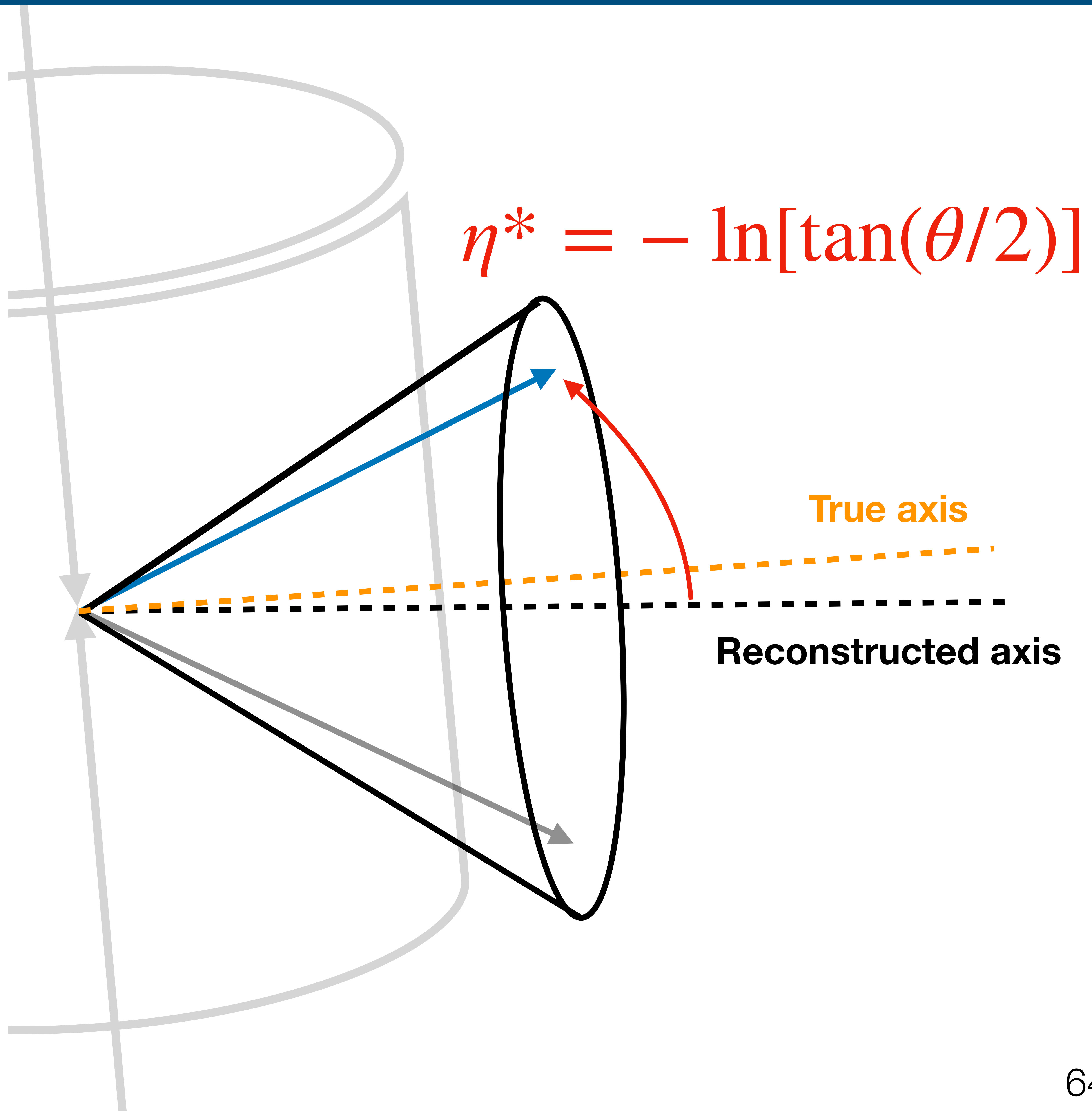


Jet axis resolution uncertainty

- **Resolution effects in the jet axis reconstruction affect $p^* = (j_T, \eta^*, \phi^*)$**
- **Tracks close to jet axis are more sensitive**
- **Evaluated systematic by smearing jet axis**

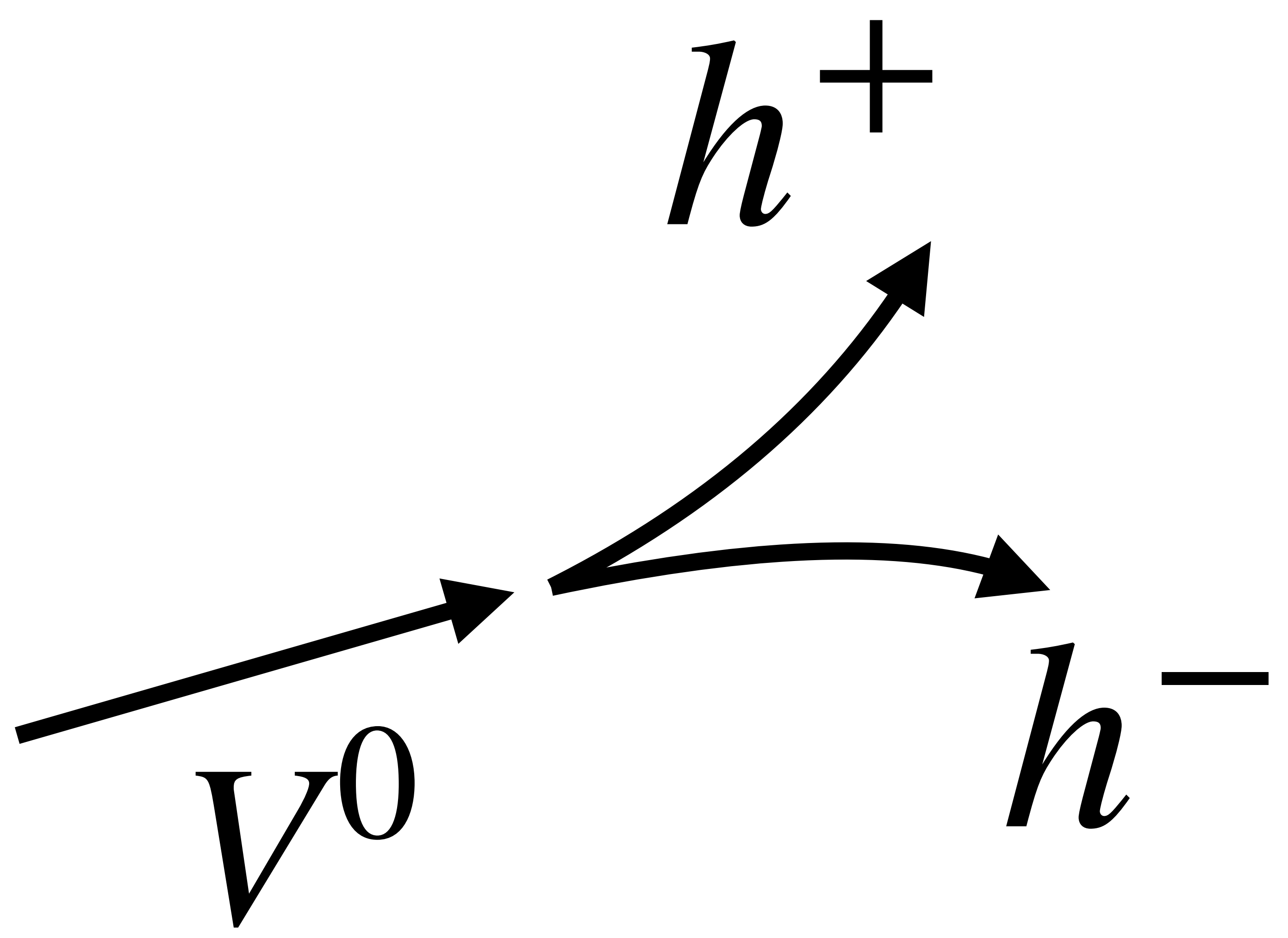
- **Large uncertainty for low N_{ch} jets**
- **High N_{ch} are wider → less sensitive**

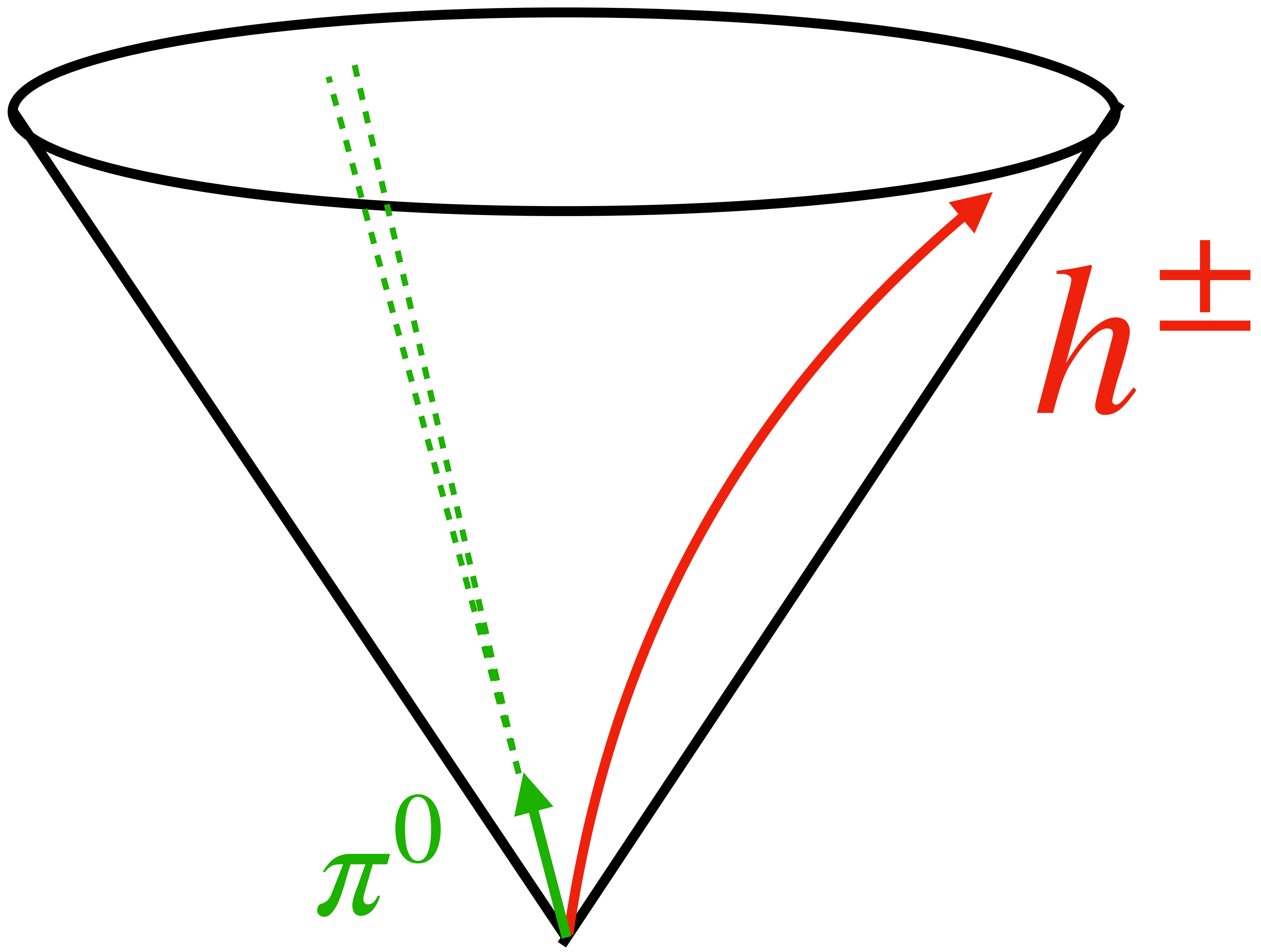




Other cross checks

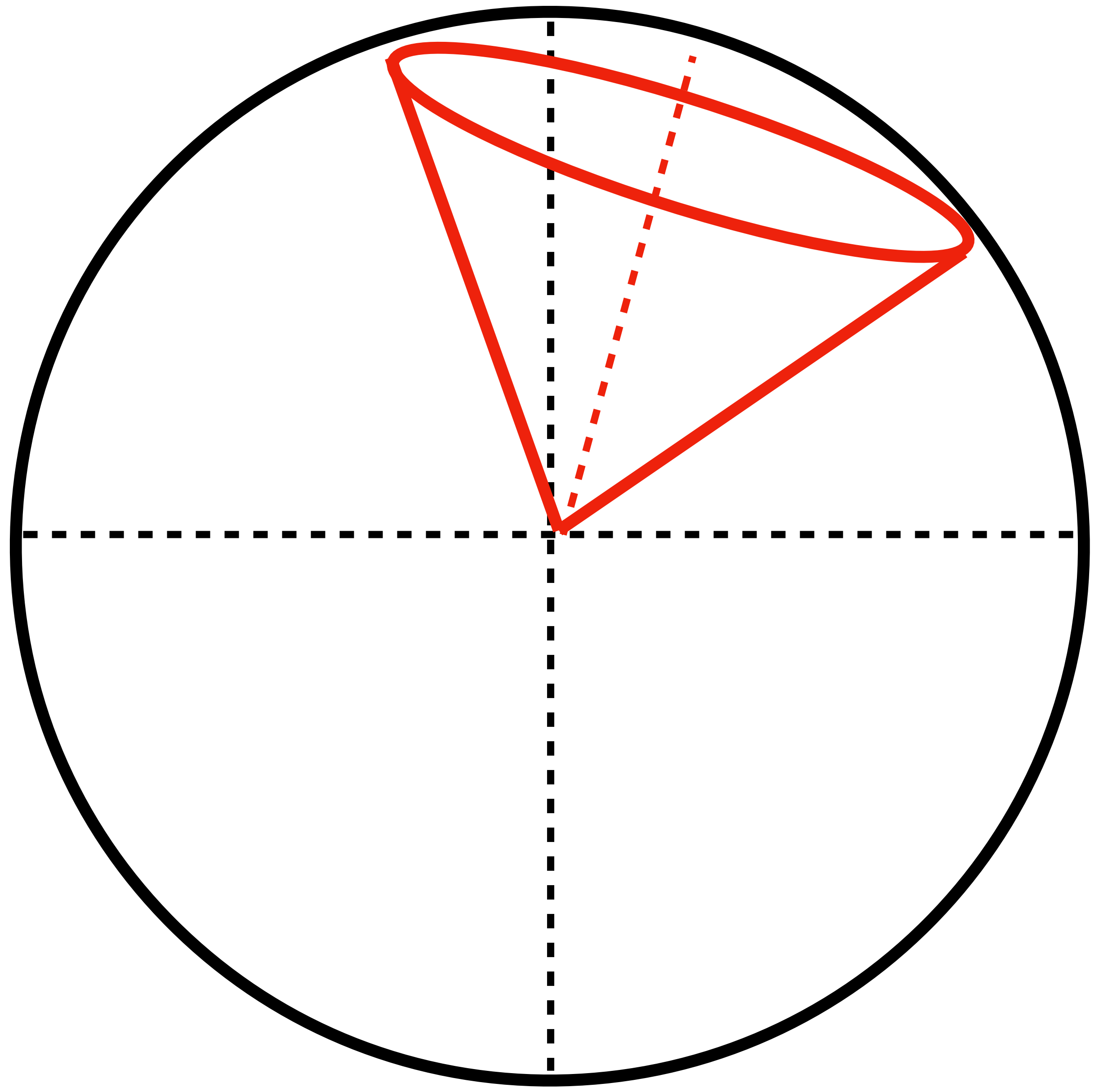
- **Signal found to be robust to:**
  - **Correlating same-sign tracks (suppresses particle decay contributions)**
  - **Correlating tracks w/ neutral deposits (from π^0 decays)**
    - **Signal is weaker, potentially from less effective of pileup mitigation**





Other cross checks

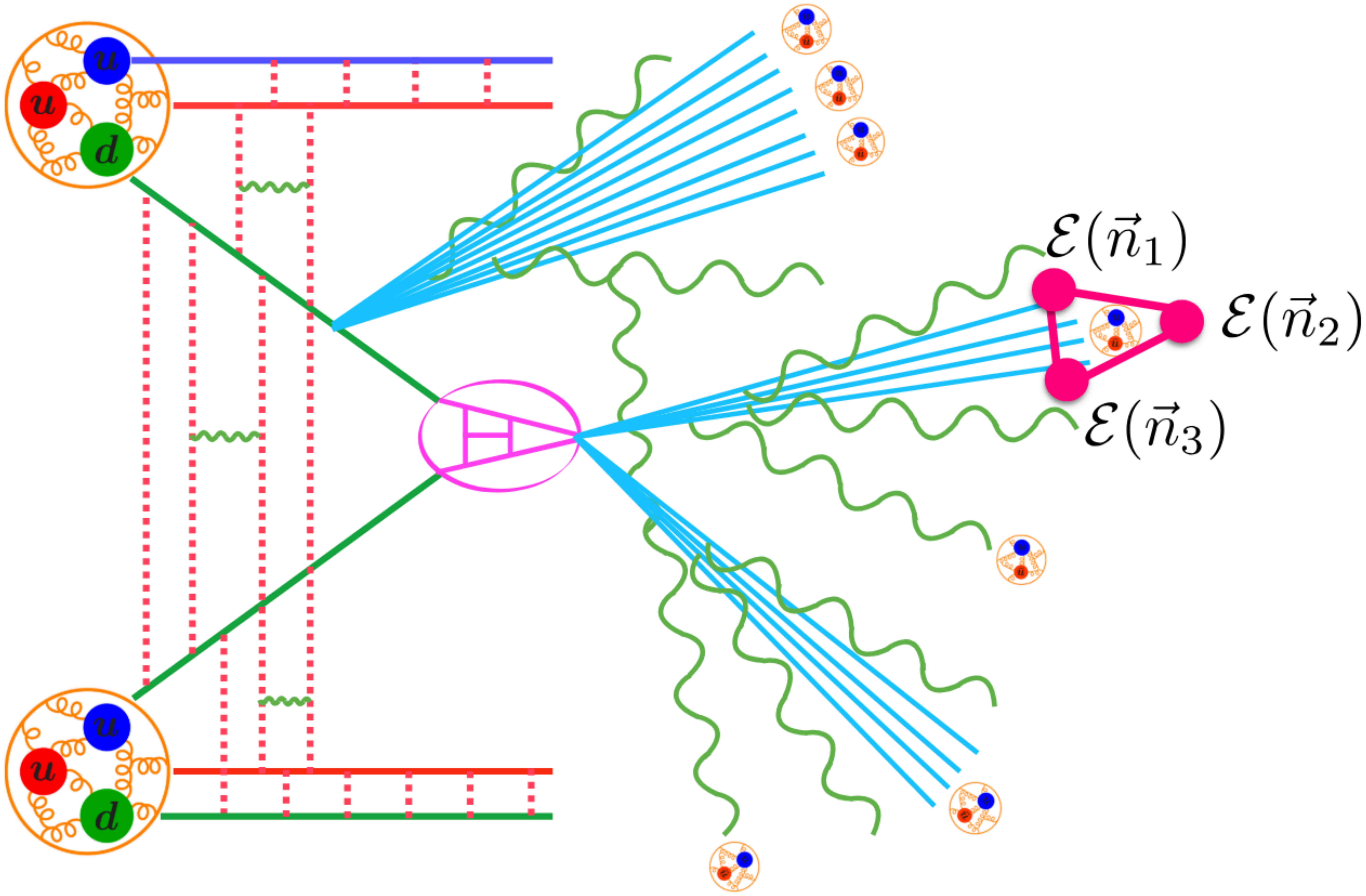
- Signal found to be robust to:
  - Correlating same-sign tracks (suppresses particle decay contributions)
  - Correlating tracks w/ neutral deposits (from π^0 decays)
    - Signal is weaker, potentially from less effective of pileup mitigation
  - Variations in track quality selections
  - Details of jet energy reconstruction and trigger efficiency
  - Selection of only leading (subleading) jets
  - Changes in jet area to alter UE contributions
  - Repeating analysis using different azimuthal quadrants of CMS



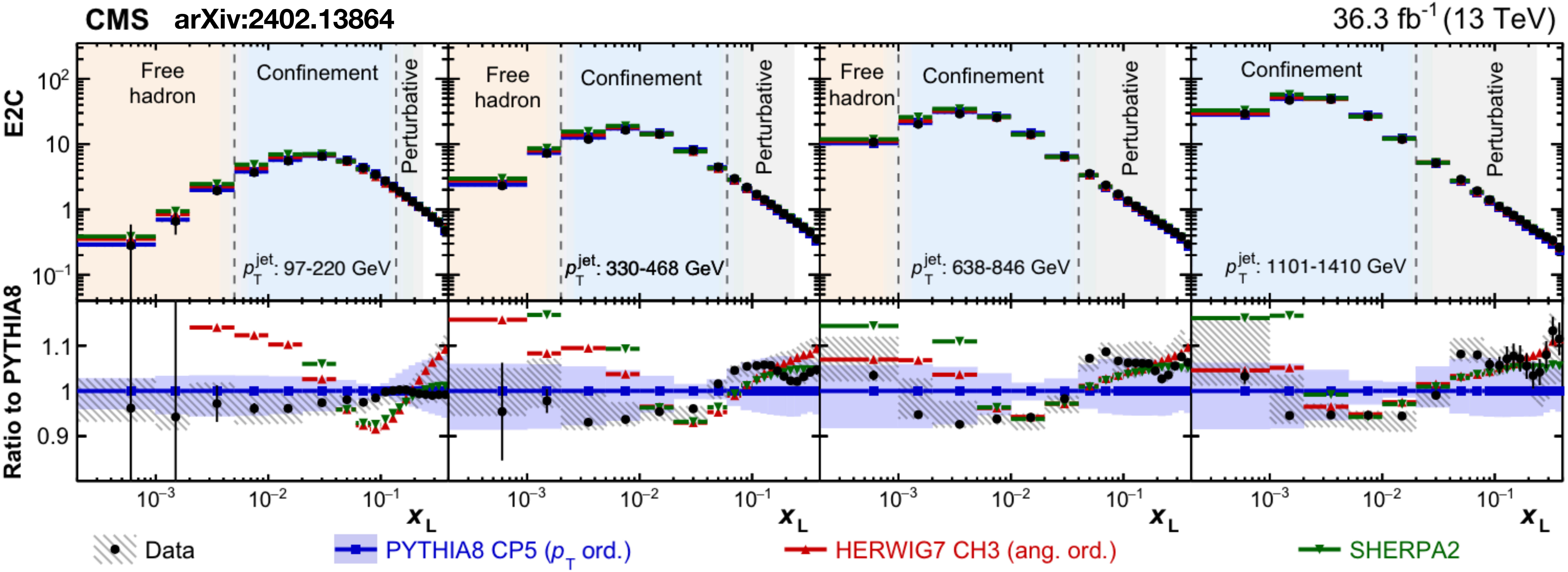
Energy-energy correlators

Phys. Rev. D 102, 054012 (2020)

- **EECs are n-particle correlators that factorize from the whole event in the collinear limit**
- **Calculated to very good precision**
- **Clear connection to various stages of jet evolution**
- **Inputs are p_T and angular separations of particles in jets**
  - **2-point EEC contains very similar input info as as 2 particle correlation analysis**



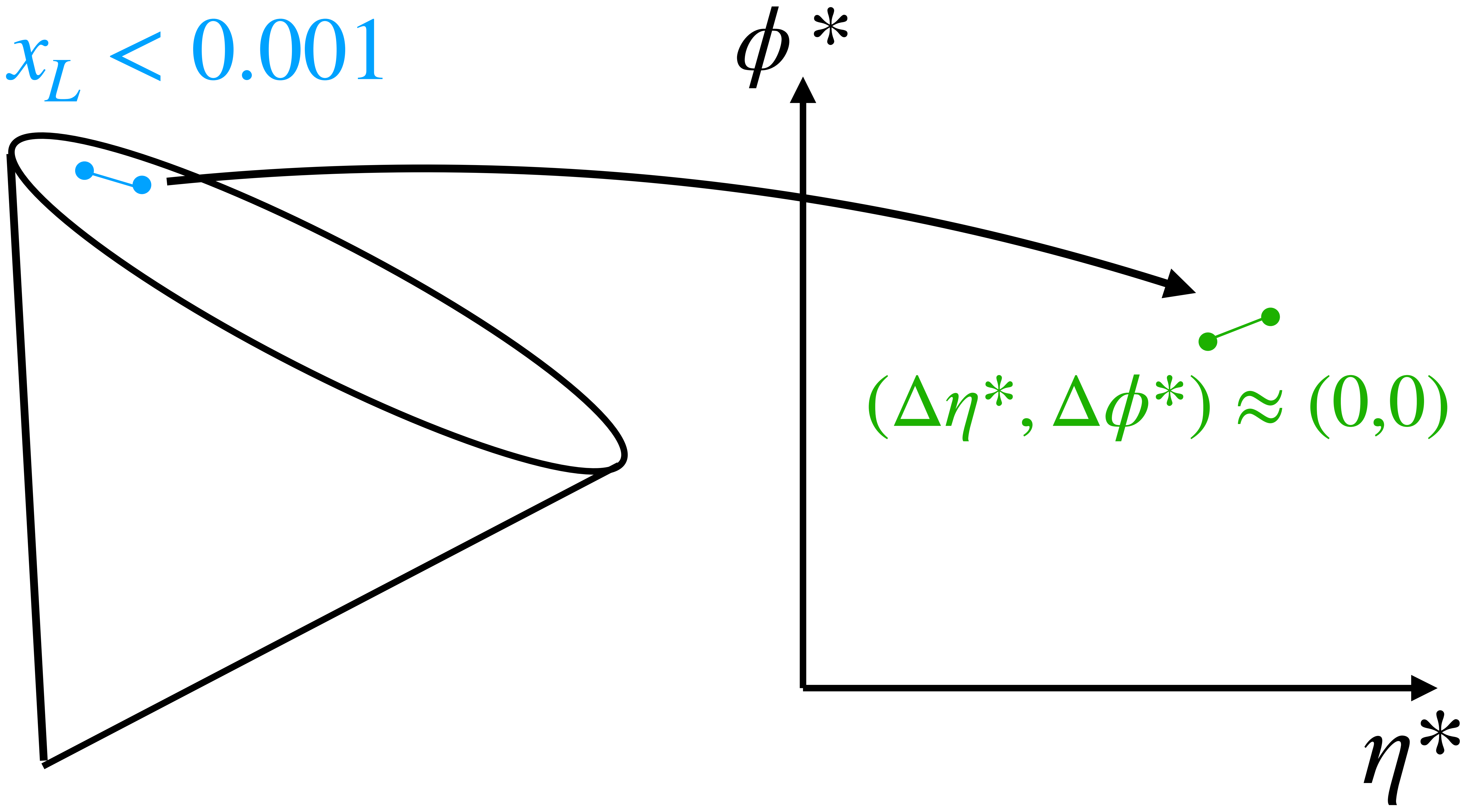
2-point pp Energy-energy correlators



$$\mathrm{EEC}(\Delta r) = \frac{1}{N_{\mathrm{pairs}}} \sum_{\mathrm{jets} \in [p_{\mathrm{T},1}, p_{\mathrm{T},2}]} \sum_{\mathrm{pairs}} (p_{\mathrm{T},i}\, p_{\mathrm{T},j})^n\, \Delta r_{i,j}$$

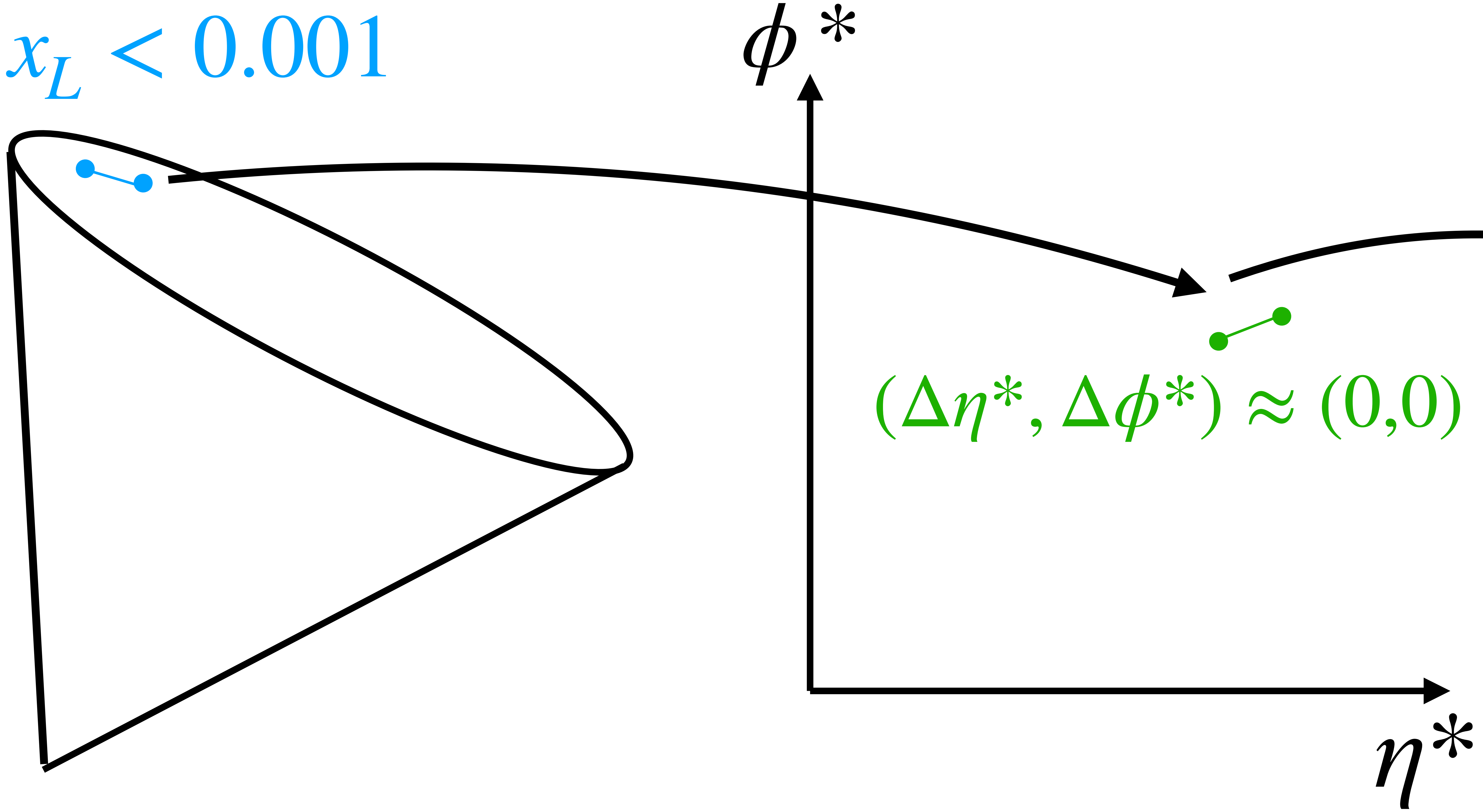
$$x_L = \Delta r_{i,j} = \sqrt{\Delta\phi_{lab}^2 + \Delta\eta_{lab}^2}$$

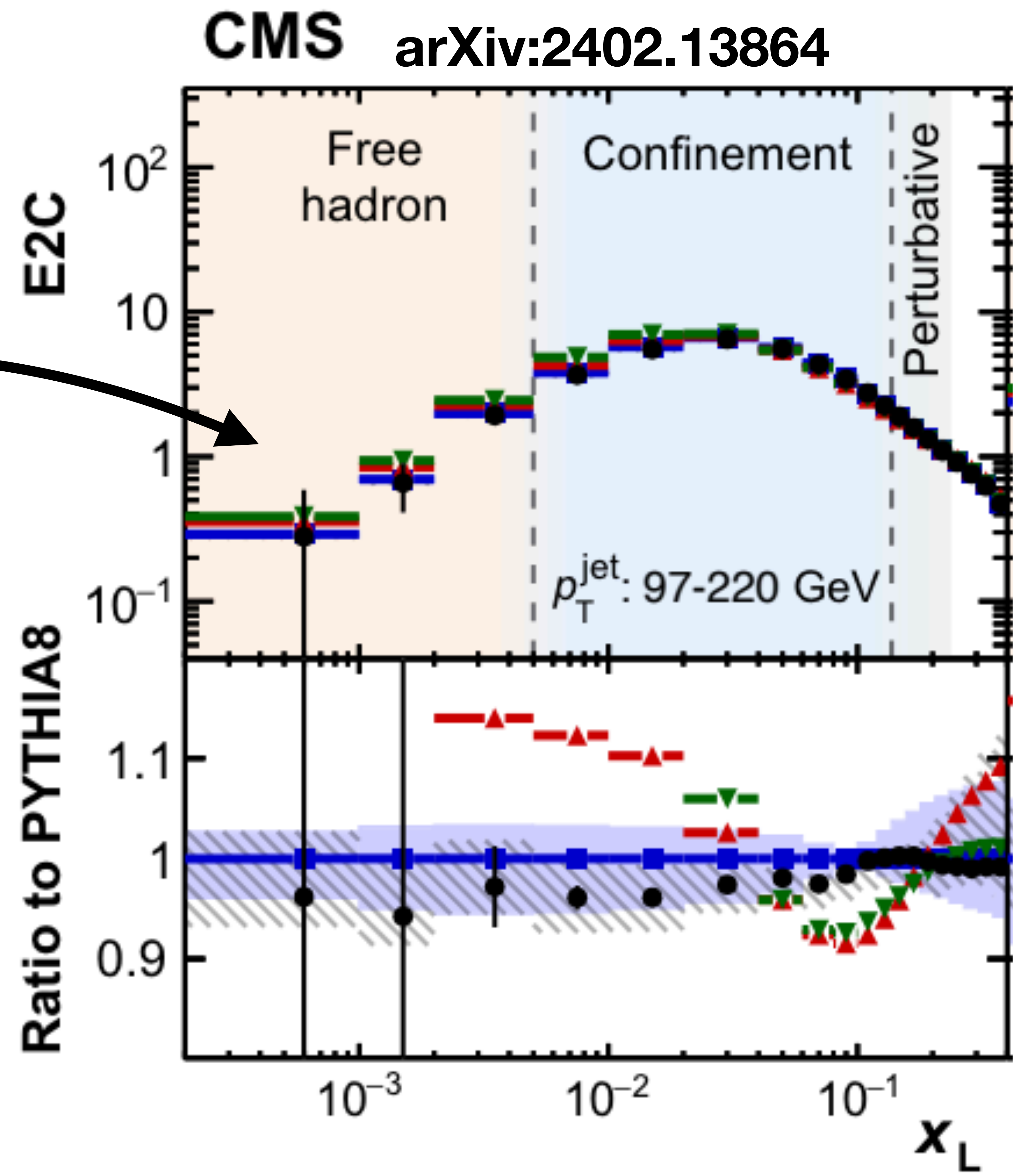
Mapping between coordinates



- **Particles close to each other in lab frame are also close to each other in jet coordinates**

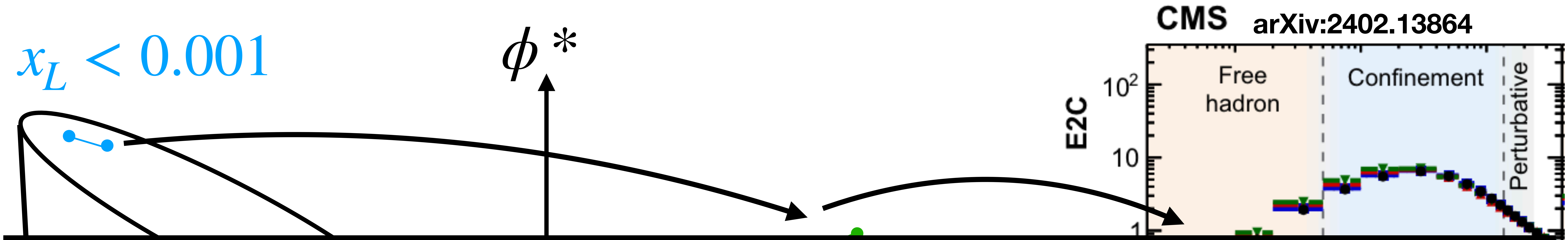
Mapping between coordinates





- **Particles close to each other in lab frame are also close to each other in jet coordinates**
  - **These contribute to central peak around (0,0) -> excluded with $\Delta\eta^*$ cut**
- **'Long-range' correlation corresponds to perturbative/confinement component of E2C**

Mapping between coordinates



There are clear connections between various jet substructure observables and the 2-particle correlation

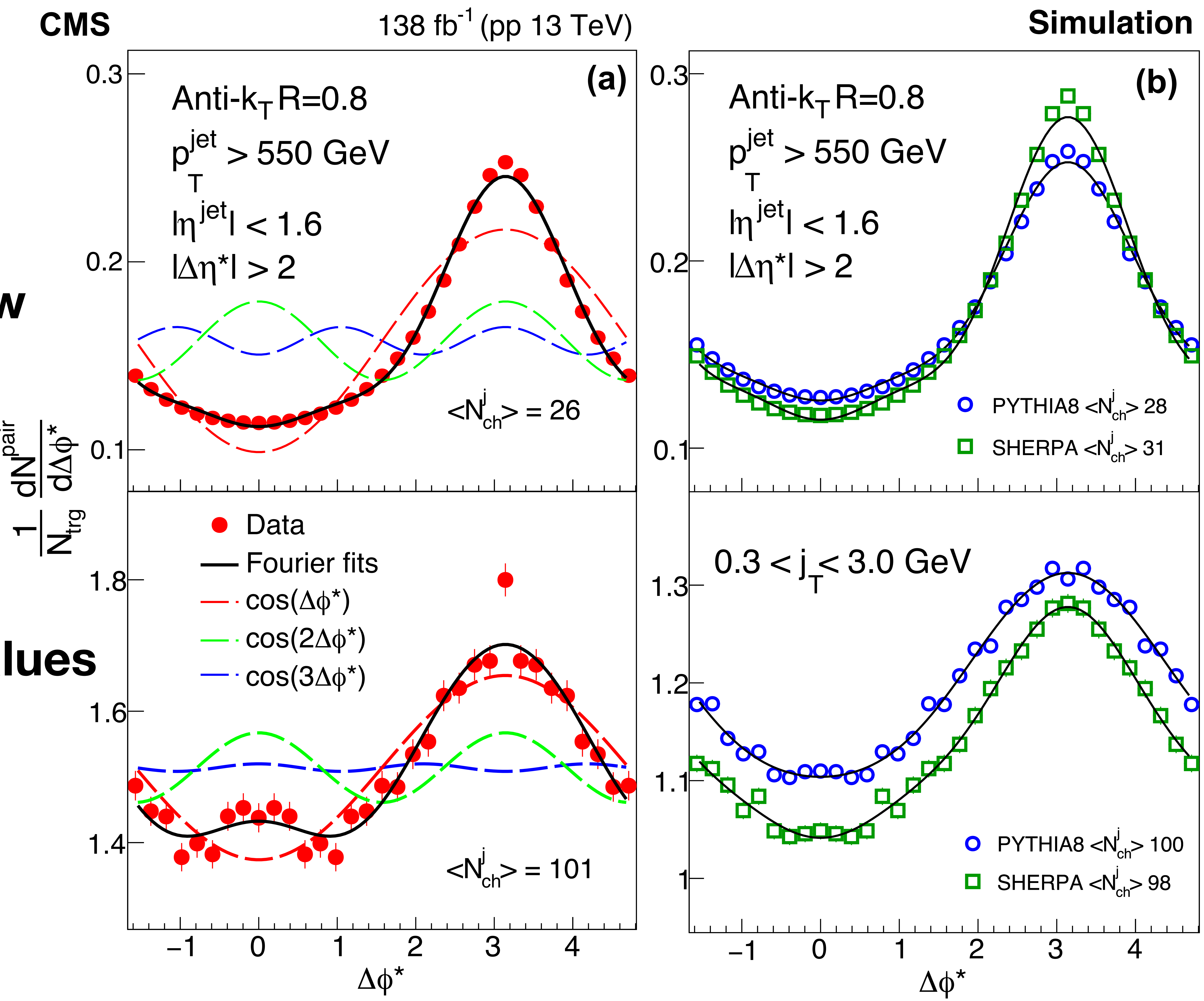
Characterization of *high-multiplicity* jets using these tools would be of great value

- **Particles close to each other in lab frame are also close to each other in jet coordinates**
  - **These contribute to central peak around (0,0) -> excluded with $\Delta\eta^*$ cut**
- **'Long-range' correlation corresponds to perturbative/confinement component of E2C**

High-Multiplicity 1D correlation

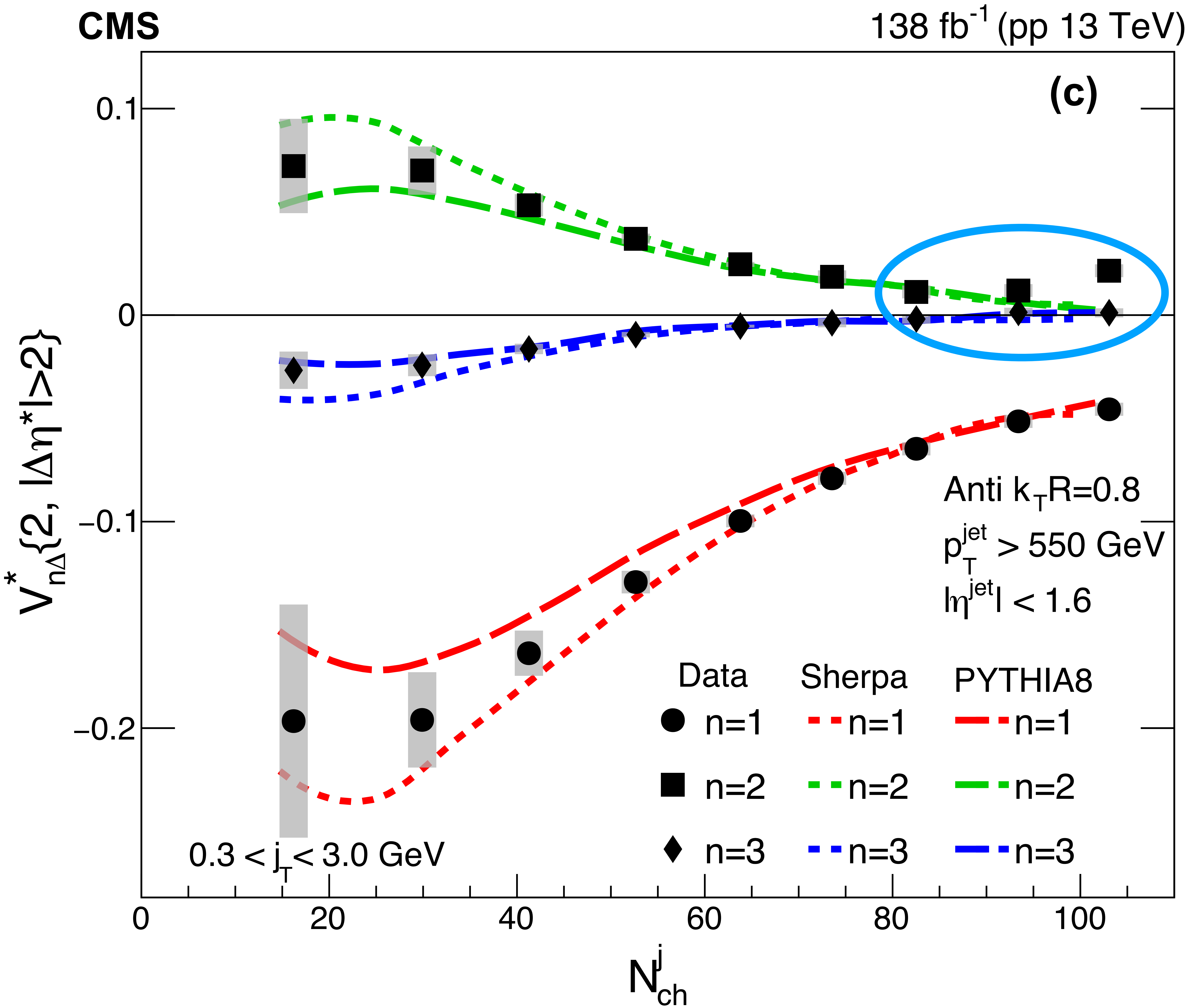
- **Project into $\Delta\phi*$ for $|\Delta\eta*| > 2$**
- **Similar shape between data/MC**
- **Clear minimum at $\Delta\phi* = 0$ at low multiplicity**

- **Perform Fourier fit to get V_ns**
- **Bump seen in fit for higher N_{ch} values**



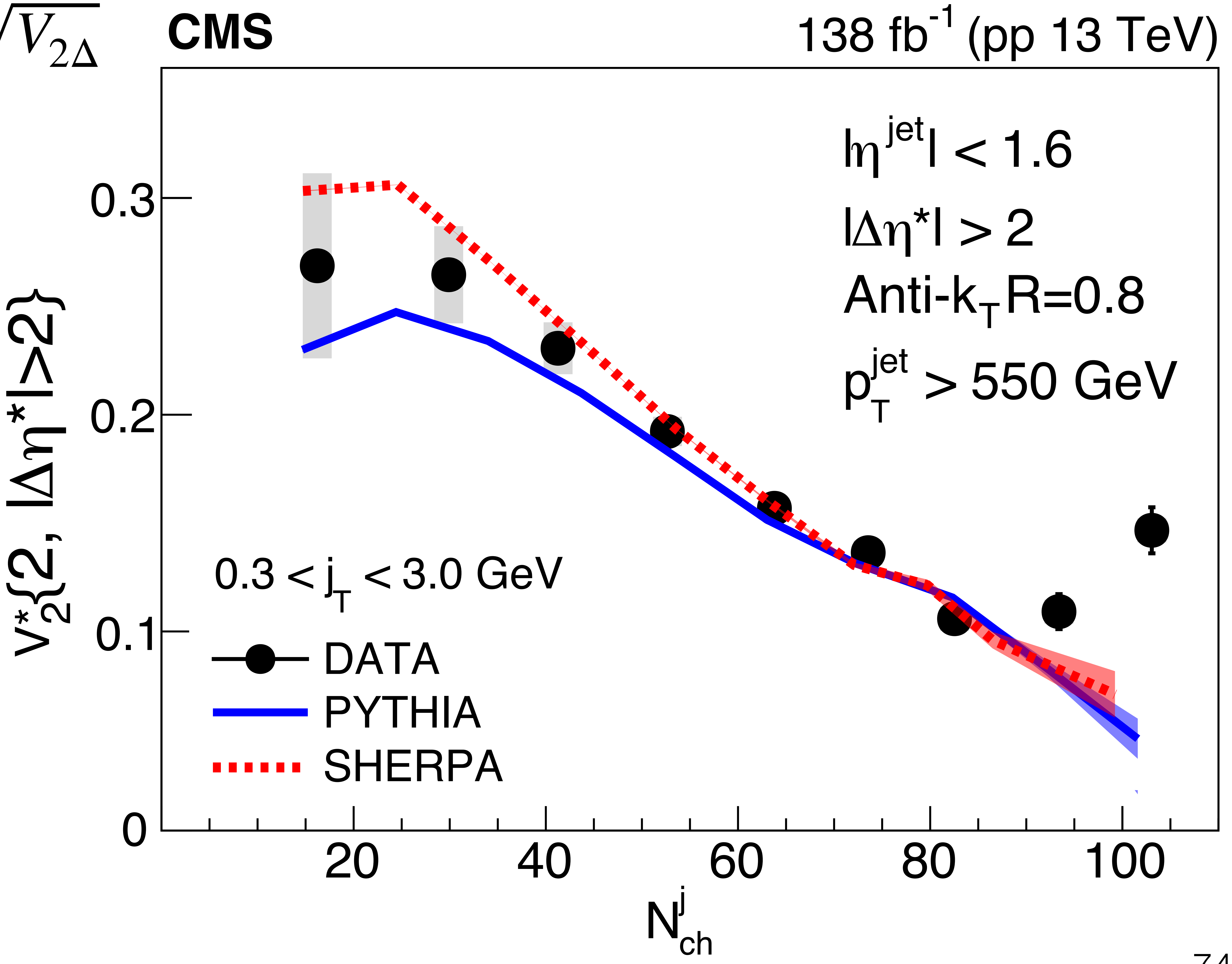
Fourier Harmonics vs N_{ch}

- **Magnitude of $V_{n\Delta}$ decreases with $N_{ch} < 80$**
  - **Agrees with MC predictions**
- **Deviation of $V_{2\Delta}$ for $N_{ch} > 80$**



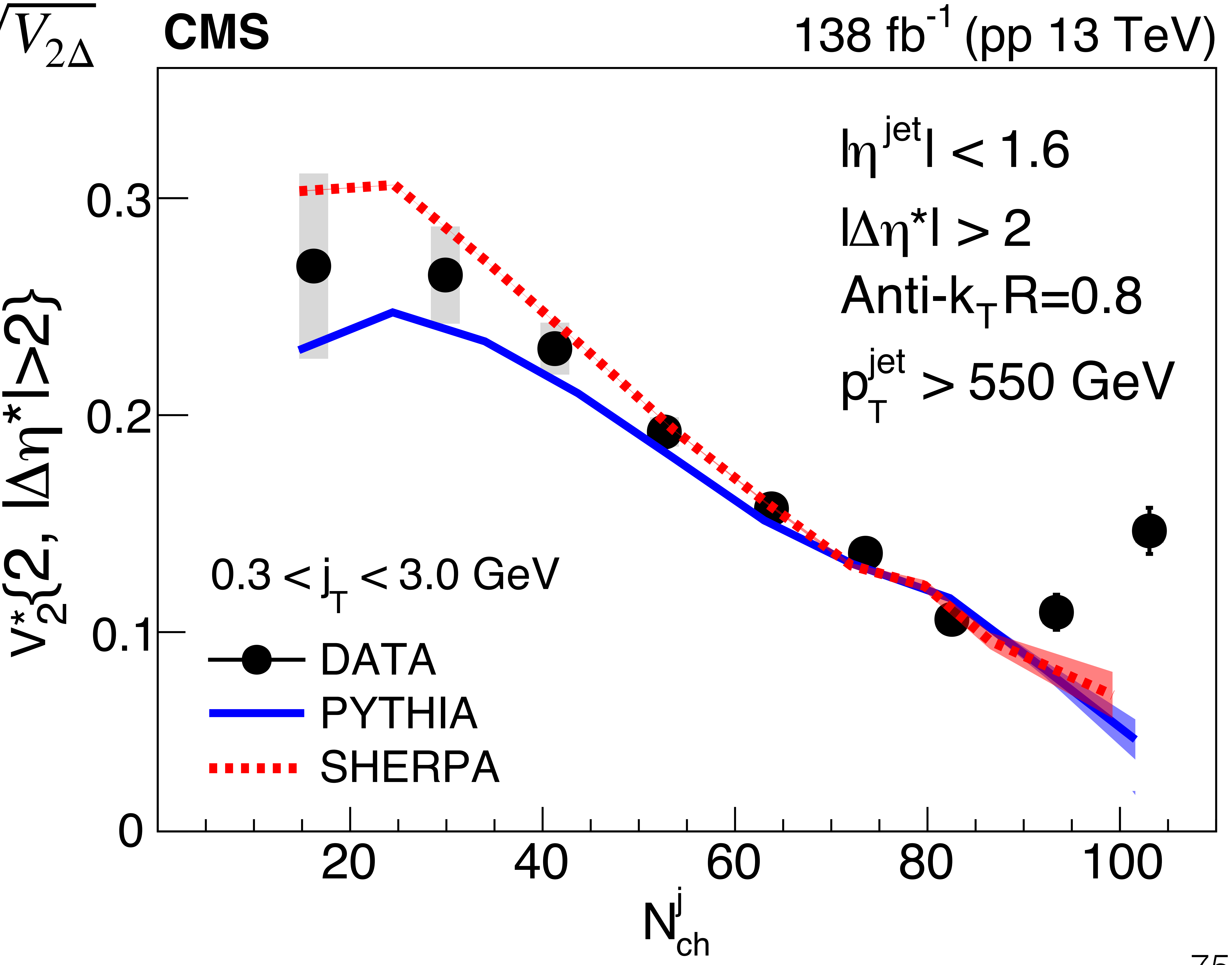
Single particle v_2

- **Quantify size of bump with** $v_2 = \sqrt{V_{2\Delta}}$
- **N_{ch}<80 trend captured by MC**
- **Rising trend for last few points**



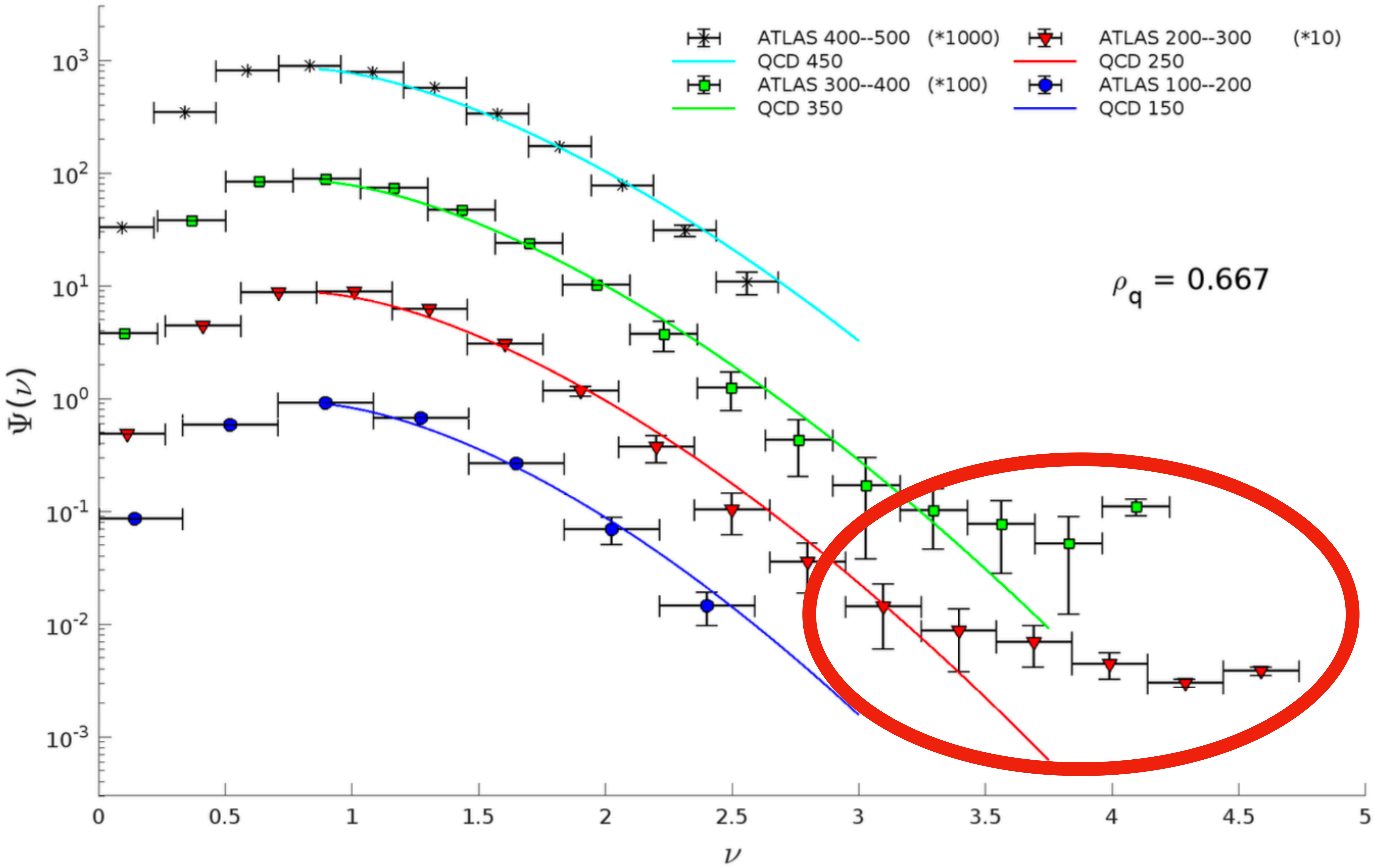
Significance of trend

- Quantify size of bump with $v_2 = \sqrt{V_{2\Delta}}$
- N_{ch}<80 trend captured by MC
- Rising trend for last few points



- Data deviates from MC by >5σ
- Observation of QGP-like effects above some critical density?
- What can explain such effect?

ATLAS jet multiplicity data



$$\nu = N_{ch}/\langle N_{ch}\rangle$$

arXiv:2505.00652v1