Collectivity in Jets: Experiment

Austin Baty
University of Illinois Chicago

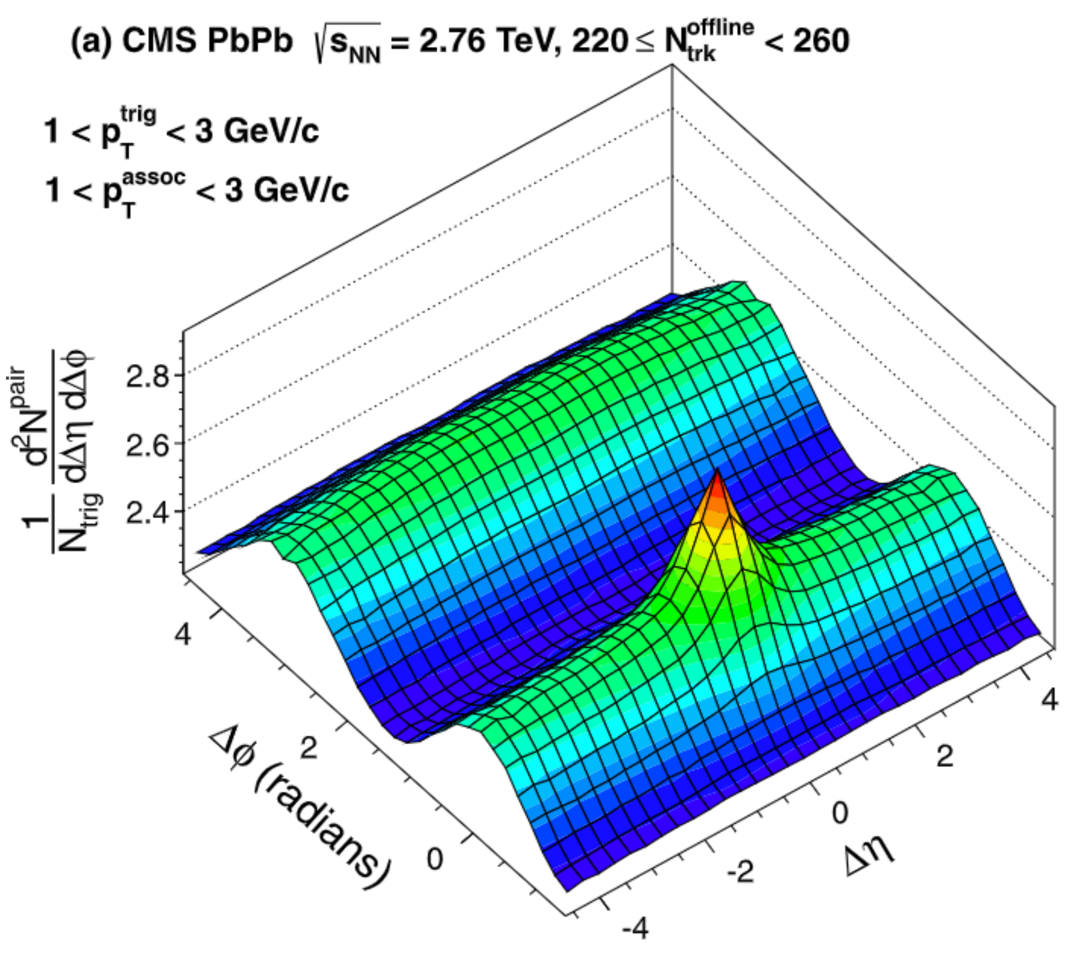
June 25, 2024
4th International Workshop on QCD
Collectivity at the Smallest Scales
Qingdao, China

UIC UNIVERSITY OF ILLINOIS CHICAGO

Motivation

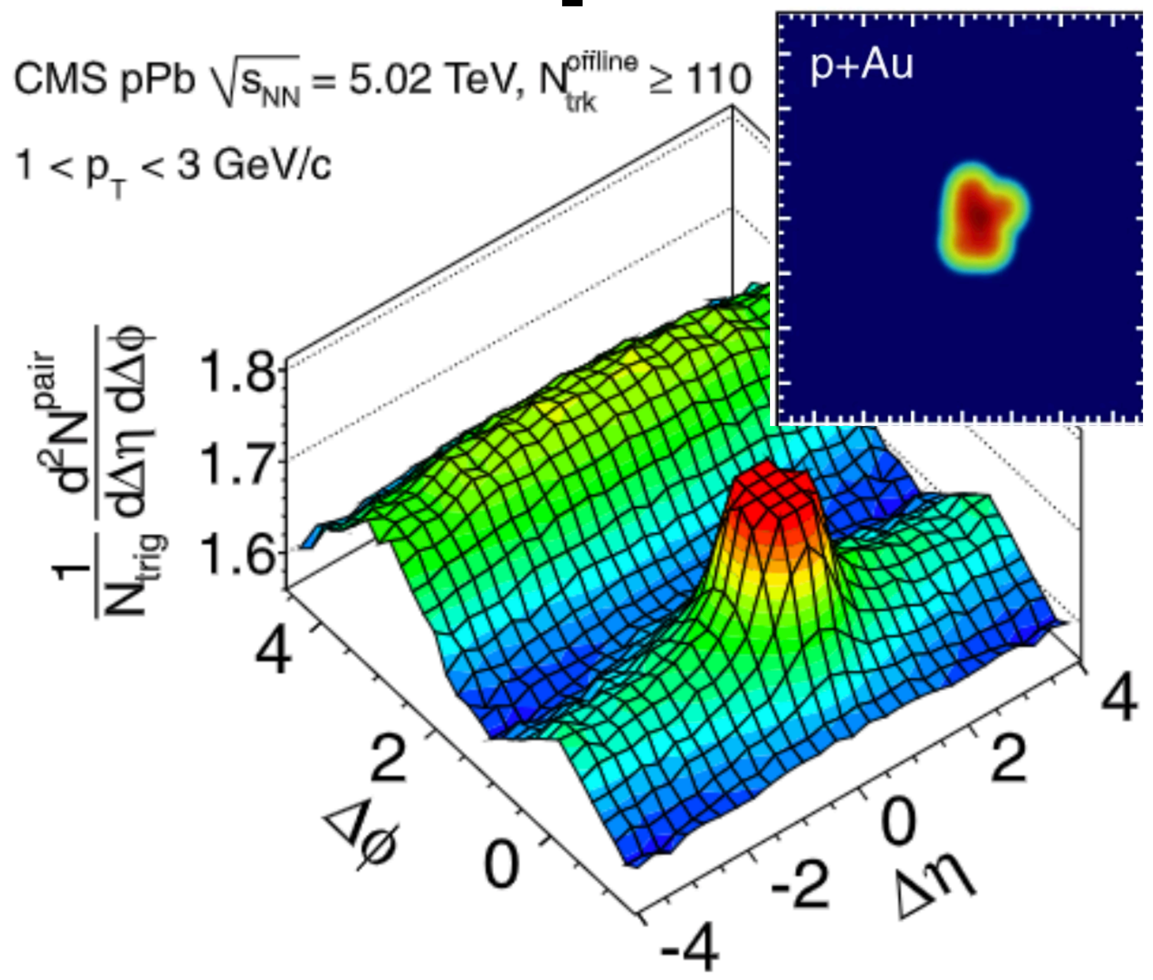
- ‘Fluid-like’ signal observed in both pPb and high-multiplicity pp collisions, not e^+e^-
  - Perhaps a small drop of QGP is formed!
  - One of the major discoveries at the LHC
- Alternative interpretations
  - Parton rescattering, initial-state effects, ‘escape mechanism’

PbPb



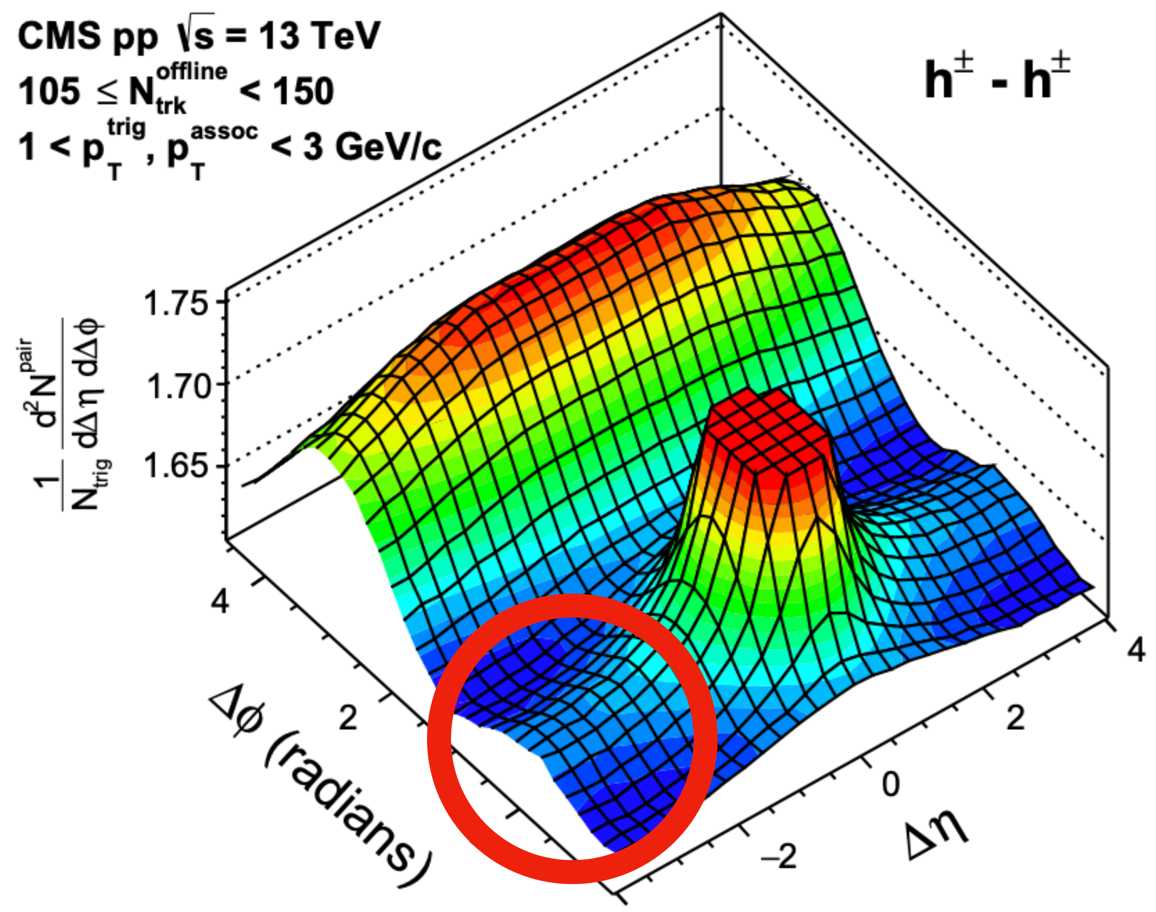
Phys. Lett. B 724 (2013) 213

pPb



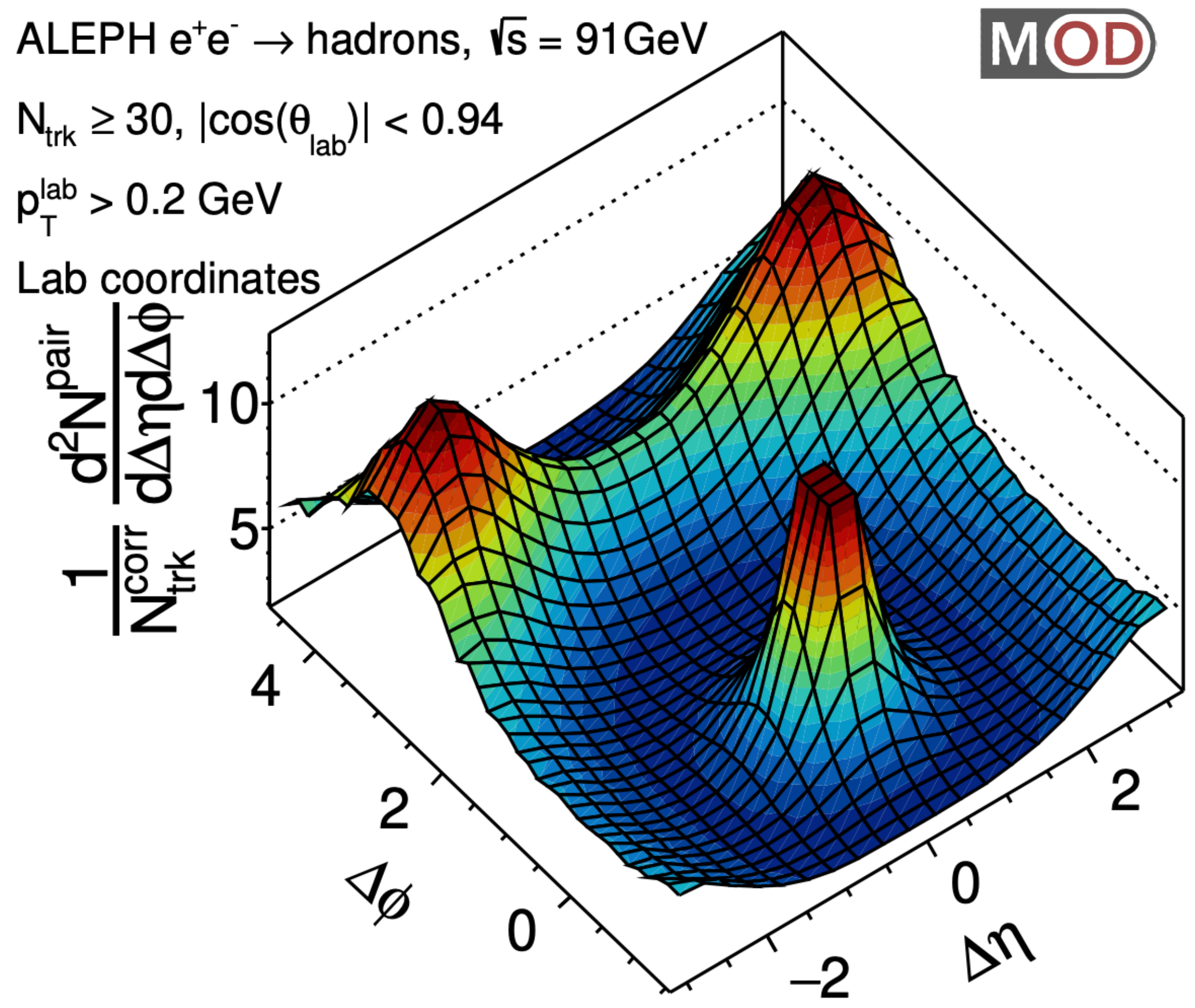
Phys. Lett. B 718 (2013) 795

High-multiplicity pp



Phys. Lett. B 765 (2017) 193

High-multiplicity e+e-



Badea, A., AB, et. al. PRL 123, 212002 (2019)

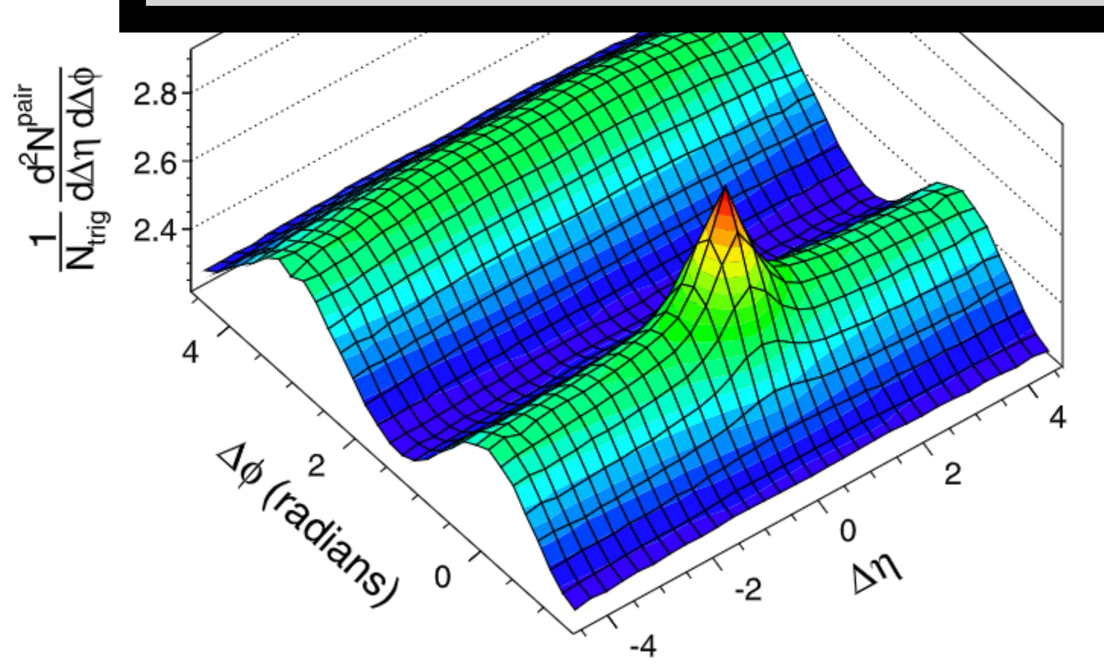
Motivation

- ‘Fluid-like’ signal observed in both pPb and high-multiplicity pp collisions, not e^+e^-
  - Perhaps a small drop of QGP is formed!
  - One of the major discoveries at the LHC

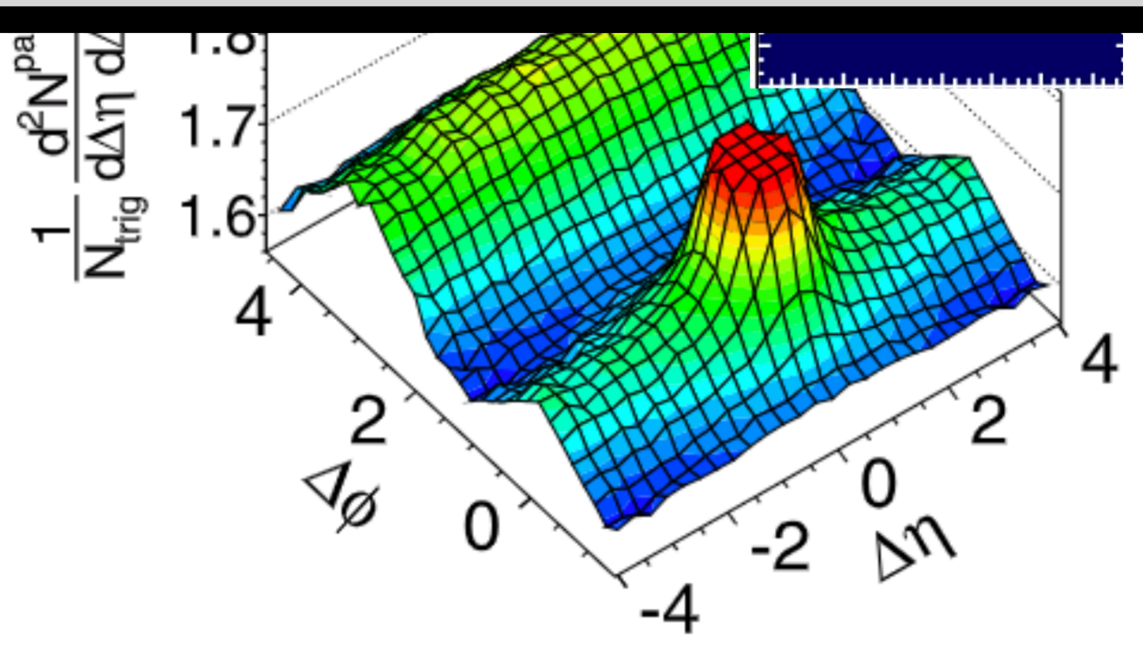
Are correlations in dense systems a general consequence of QCD?

From how small of a system can collectivity emerge?

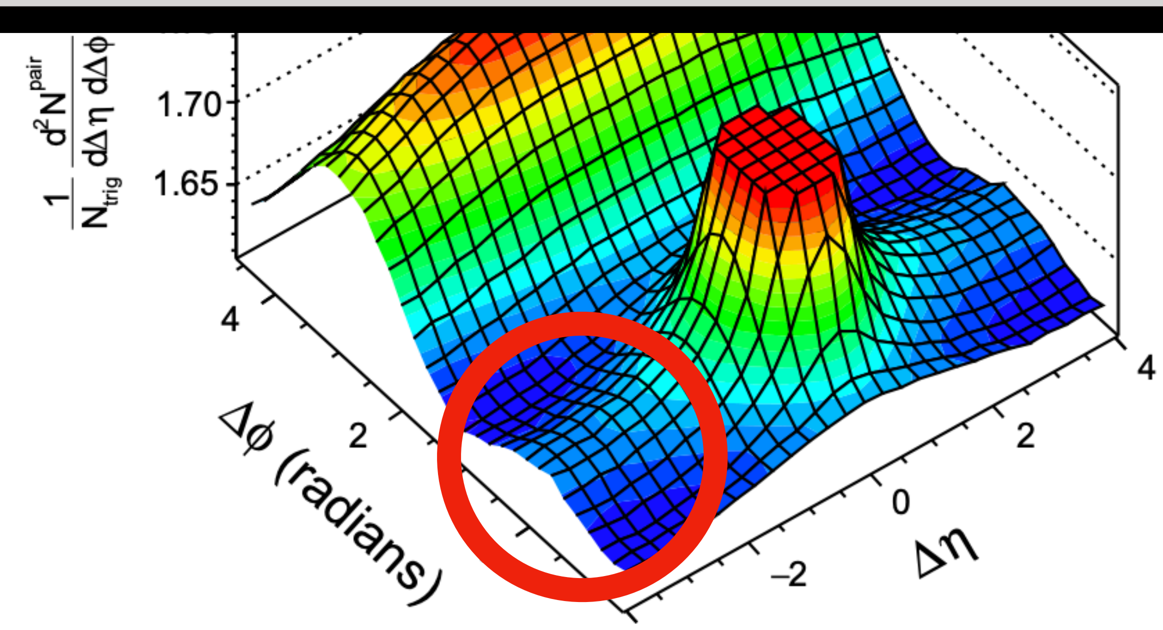
Can hydrodynamics be applied on other non-perturbative processes?



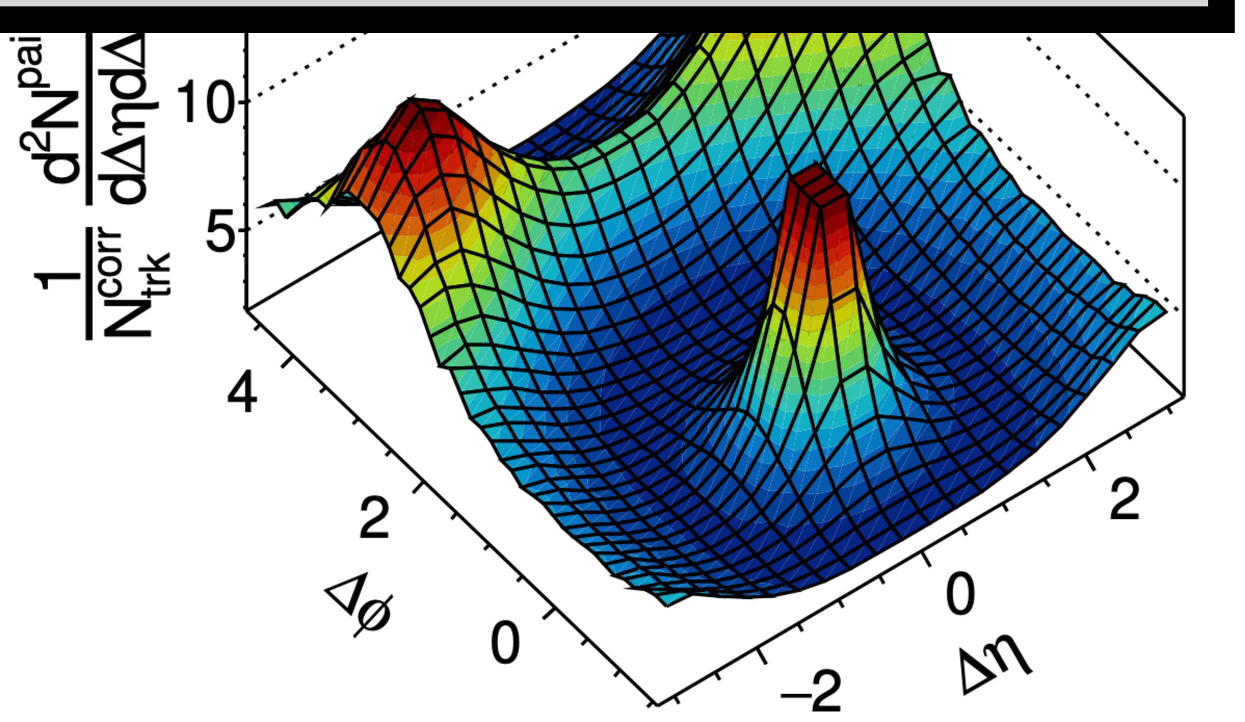
Phys. Lett. B 724 (2013) 213



Phys. Lett. B 718 (2013) 795



Phys. Lett. B 765 (2017) 193

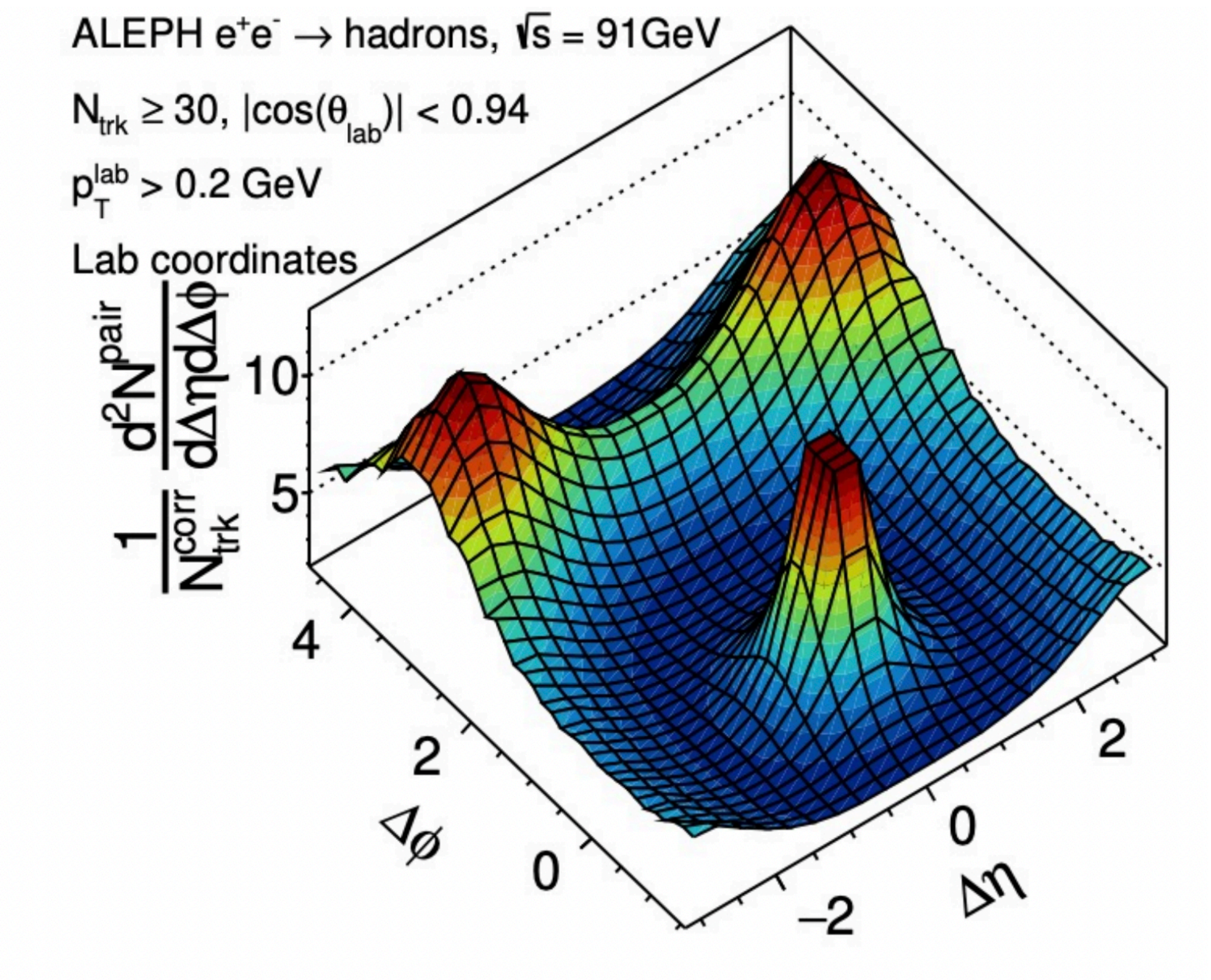


Badea, A., AB, et. al. PRL 123, 212002 (2019)

Even smaller systems

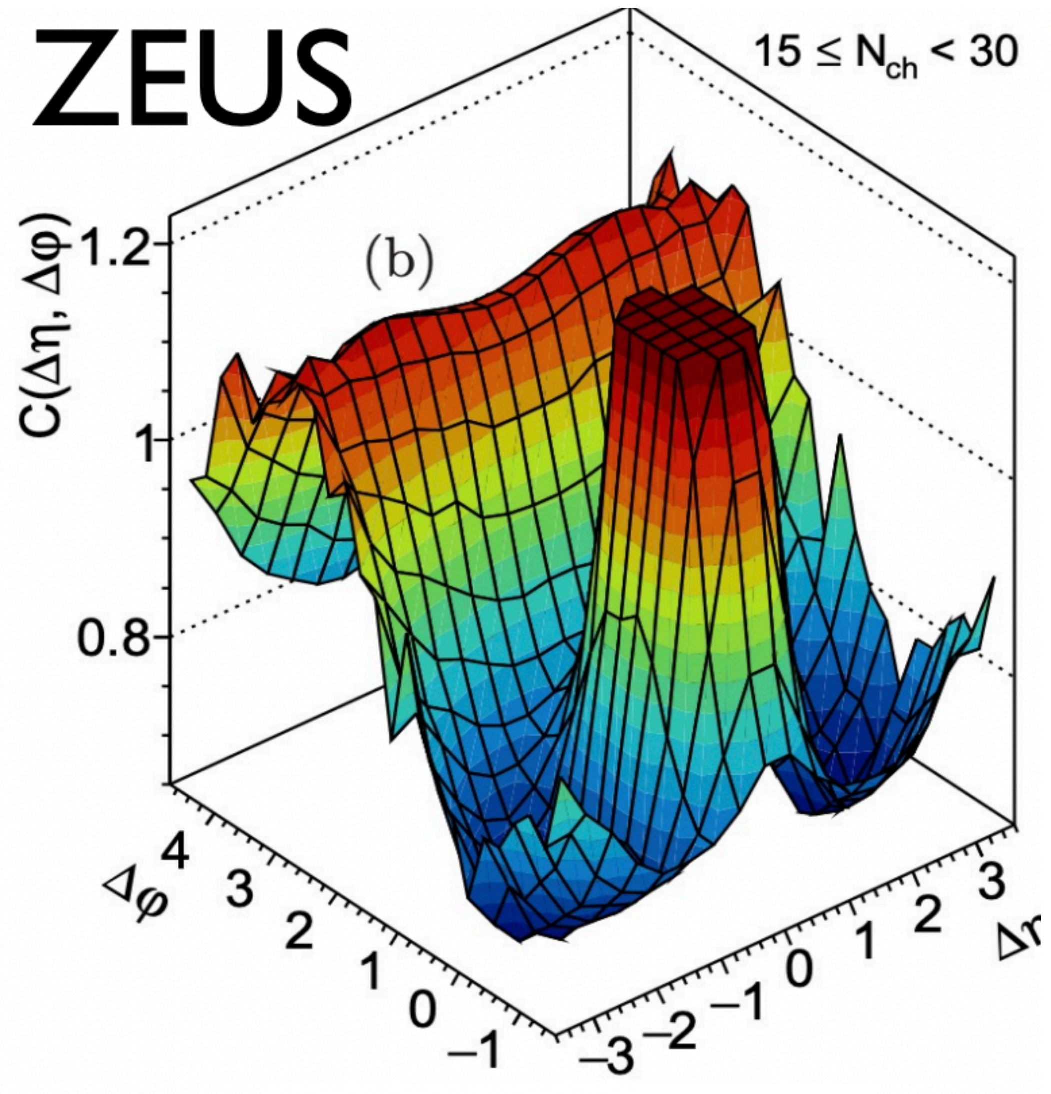
- **Many measurements trying to push boundaries to smaller systems**
  - **No unambiguous observation of collectivity yet**
- **Generally limited in multiplicity reach from limited luminosities/energies**
- **Not clear if no effect or systems are just too dilute**

e^+e^- **N_{ch}~30**



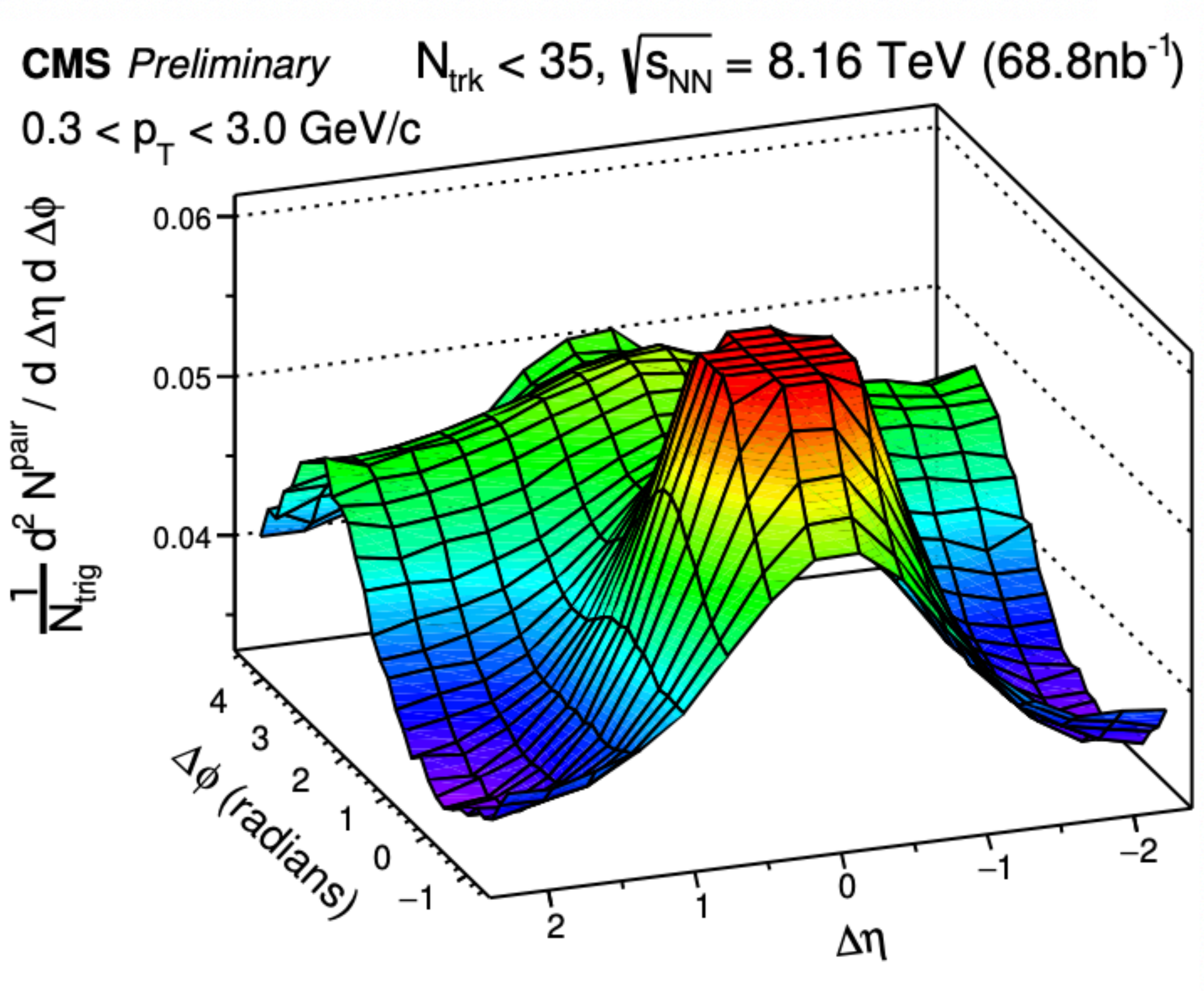
PRL 123, 212002 (2019)

ep **N_{ch}~30**



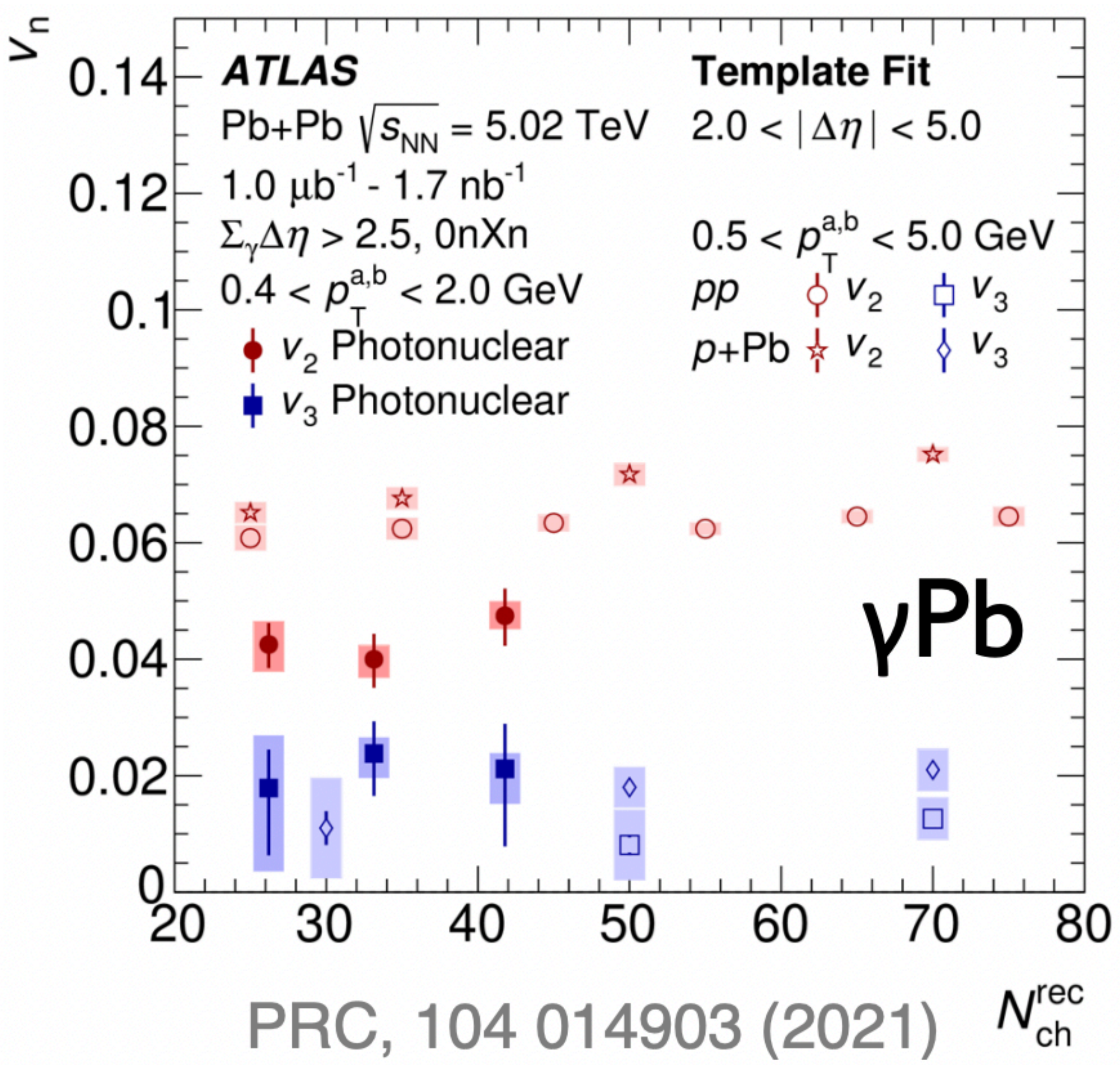
JHEP 04 (2020) 070

γp **N_{ch}~20**



arXiv:2204.13486

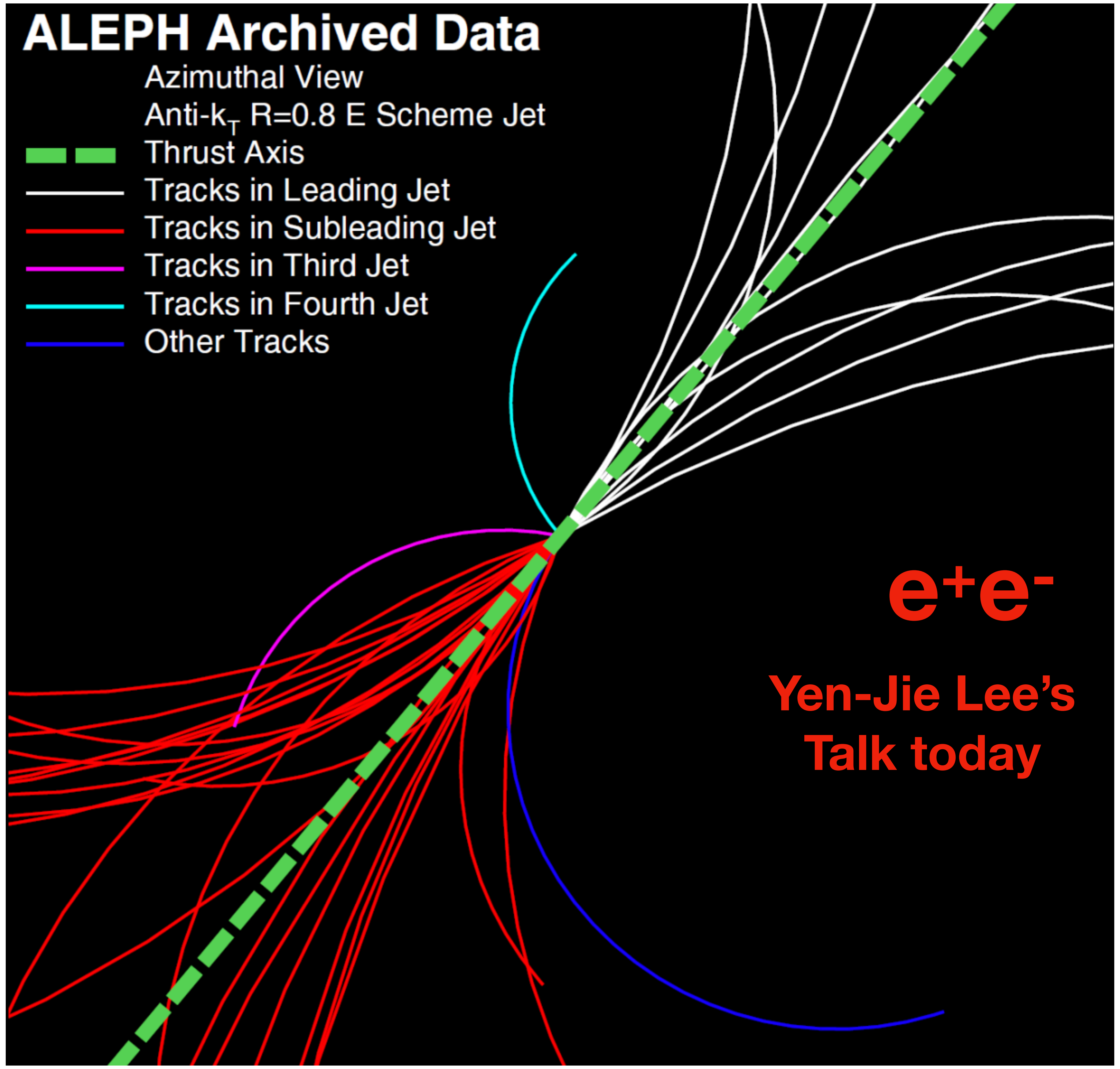
γPb **N_{ch}~40**



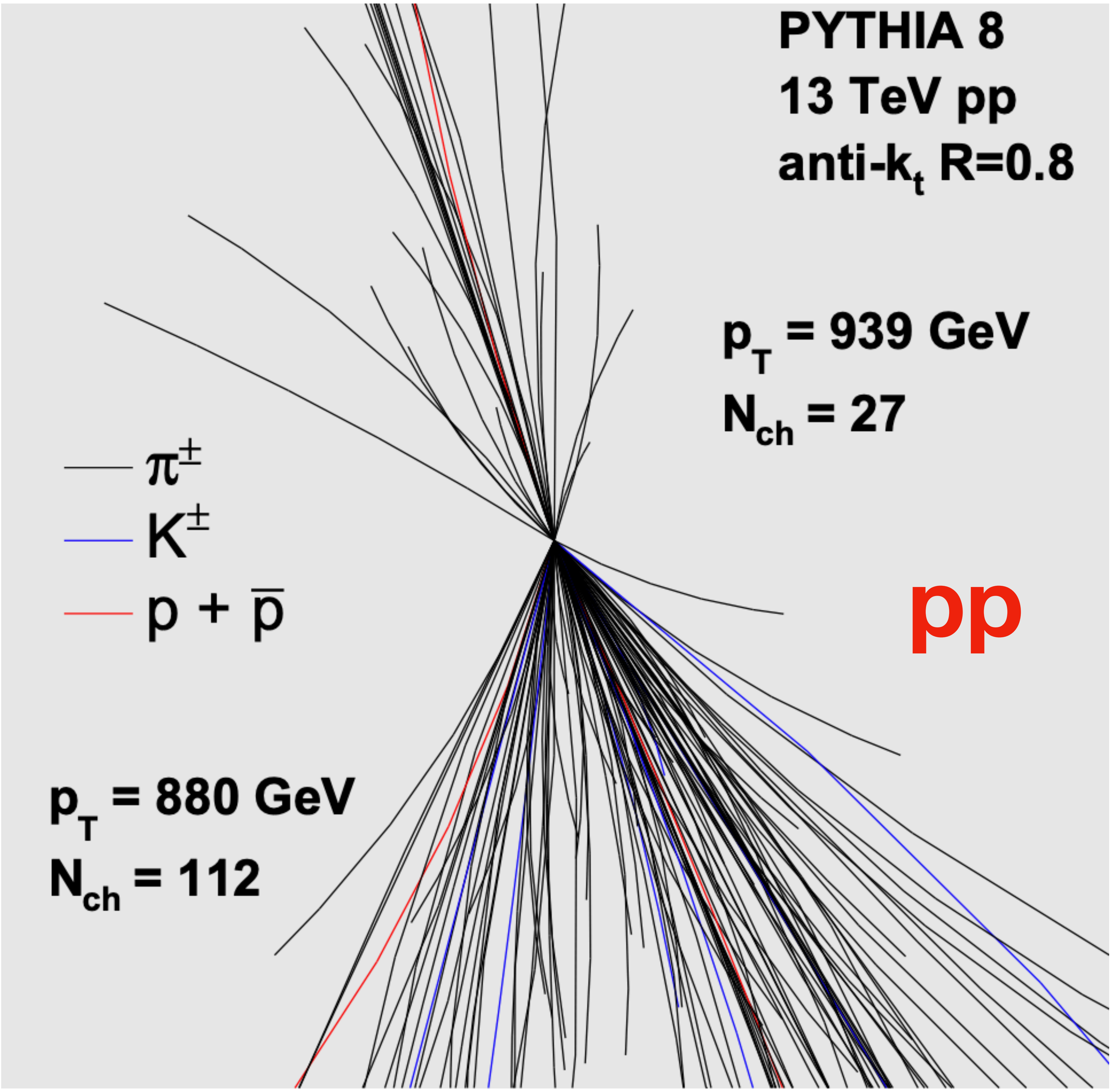
PRC, 104 014903 (2021)

High multiplicity jets?

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

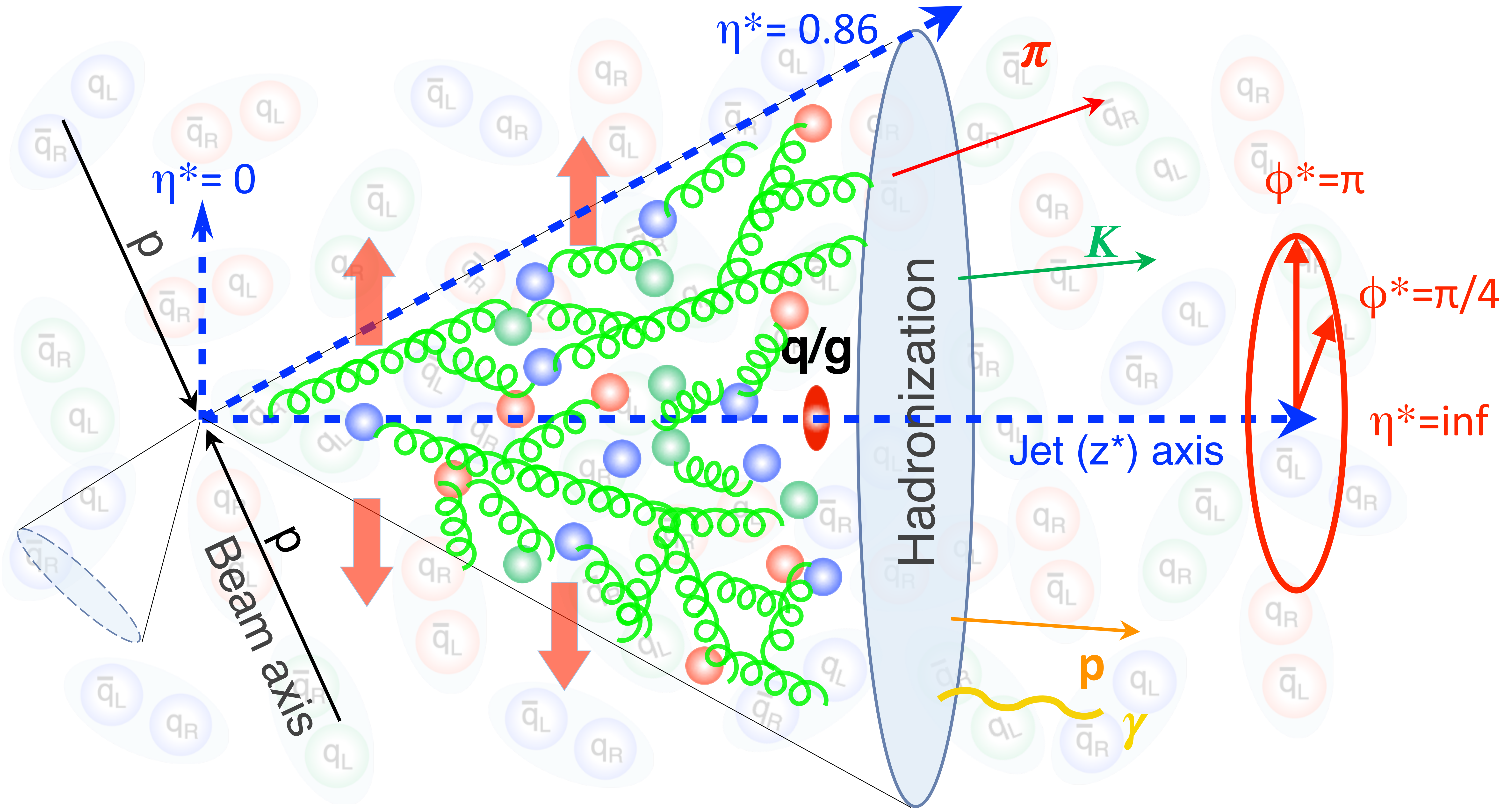


Badea A., AB, et al.. PRL 123, 212002 (2019)



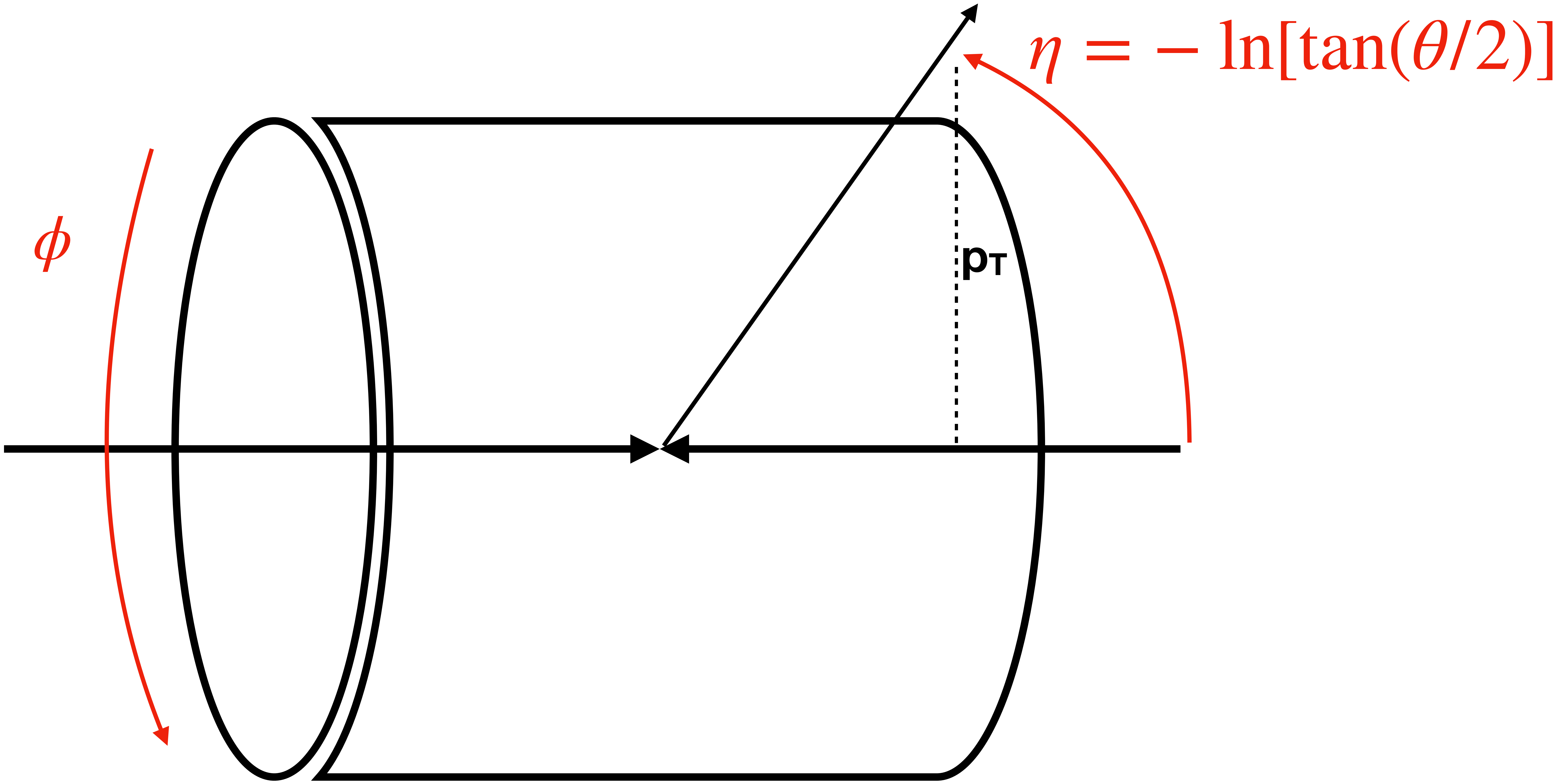
AB, Gardner P., Li W. PRC 107, 064908 (2023)

Postulated mechanism for collectivity



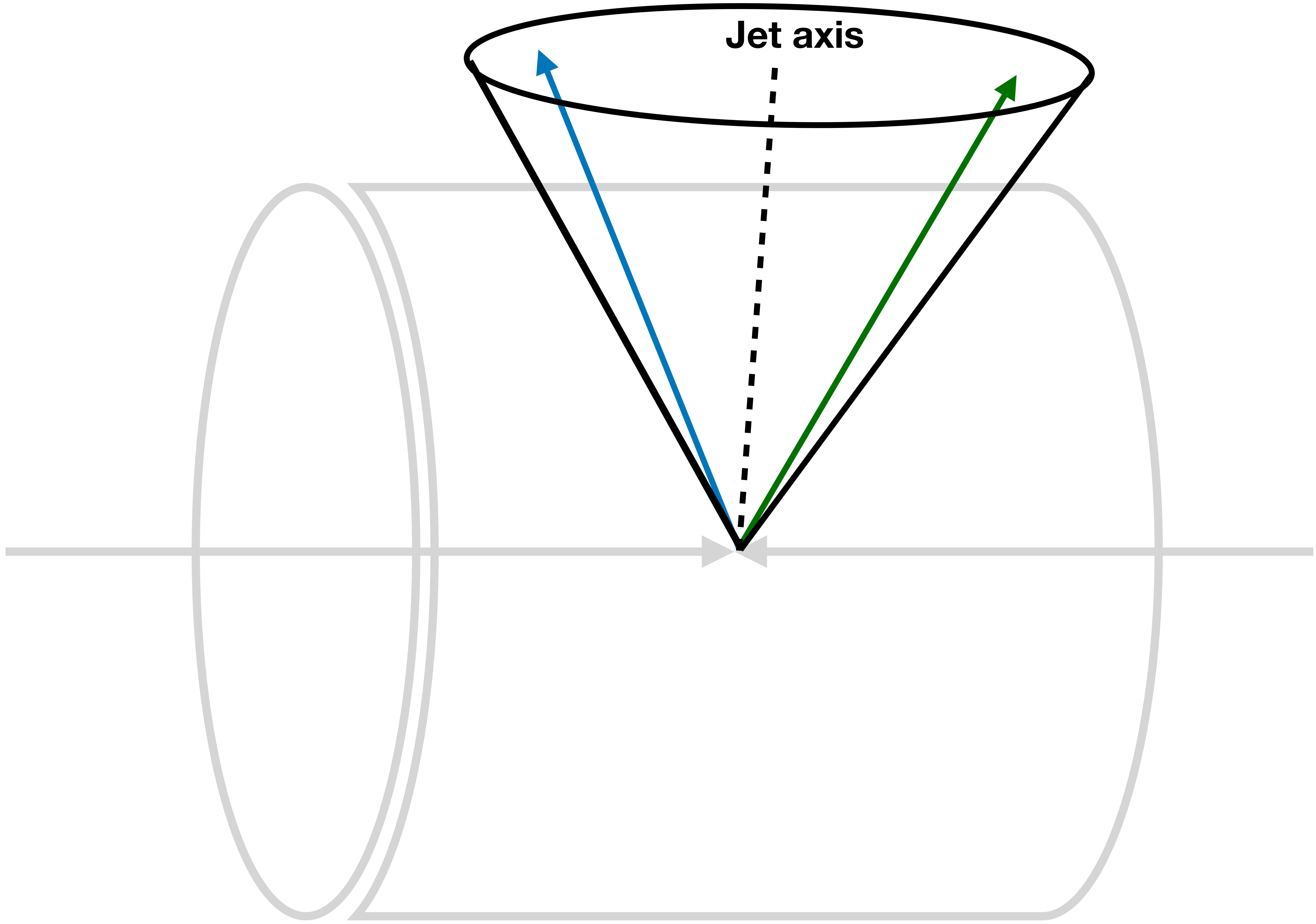
- **Single parton propagating *along jet axis* generates dense parton collection**
- **Interactions/rescattering between resulting partons could generate collectivity**
  - **Analysis must be with respect to jet axis - need to align jets**

Redefinition of coordinates



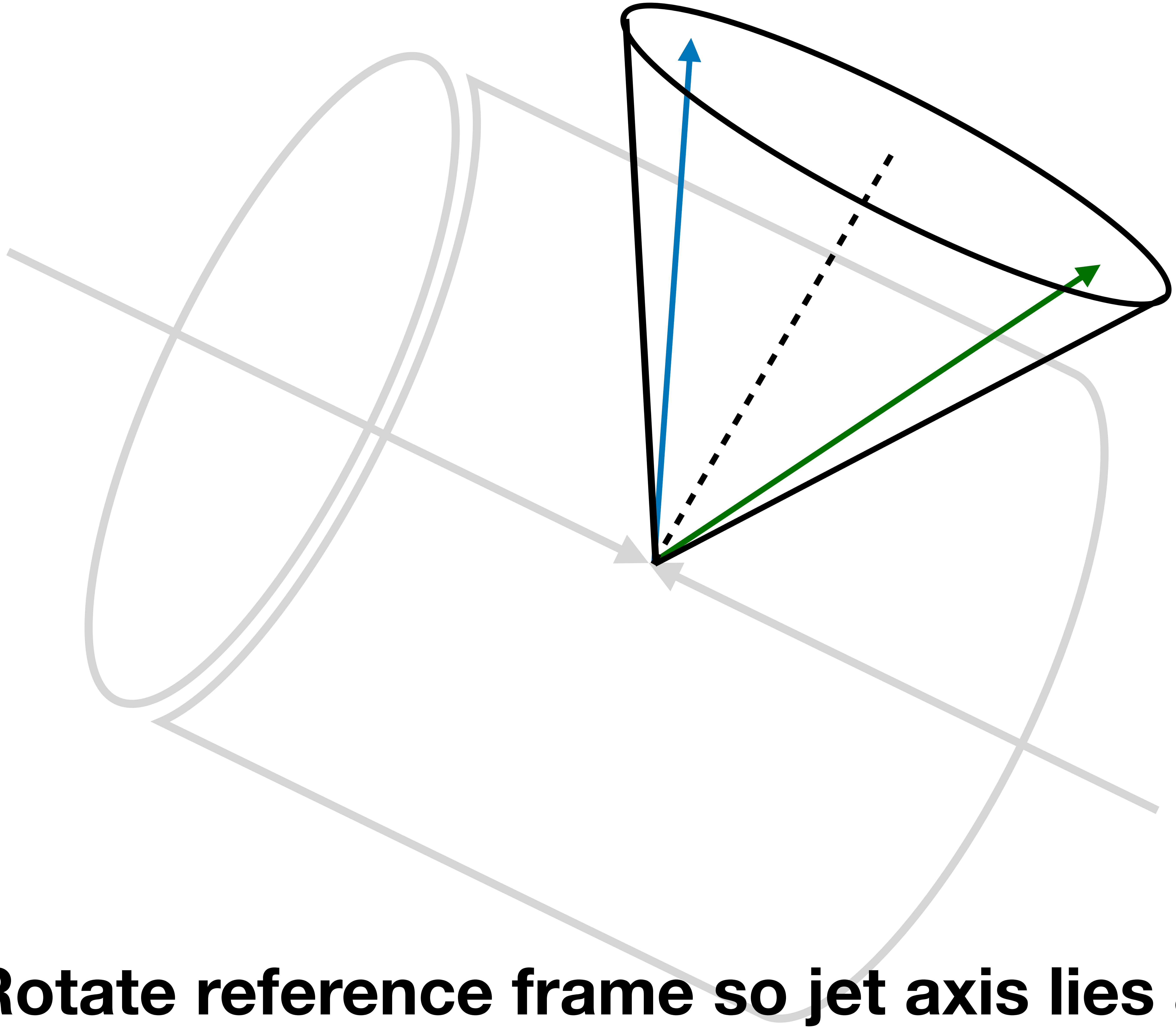
Start with standard lab coordinates

Rotation of reference frame



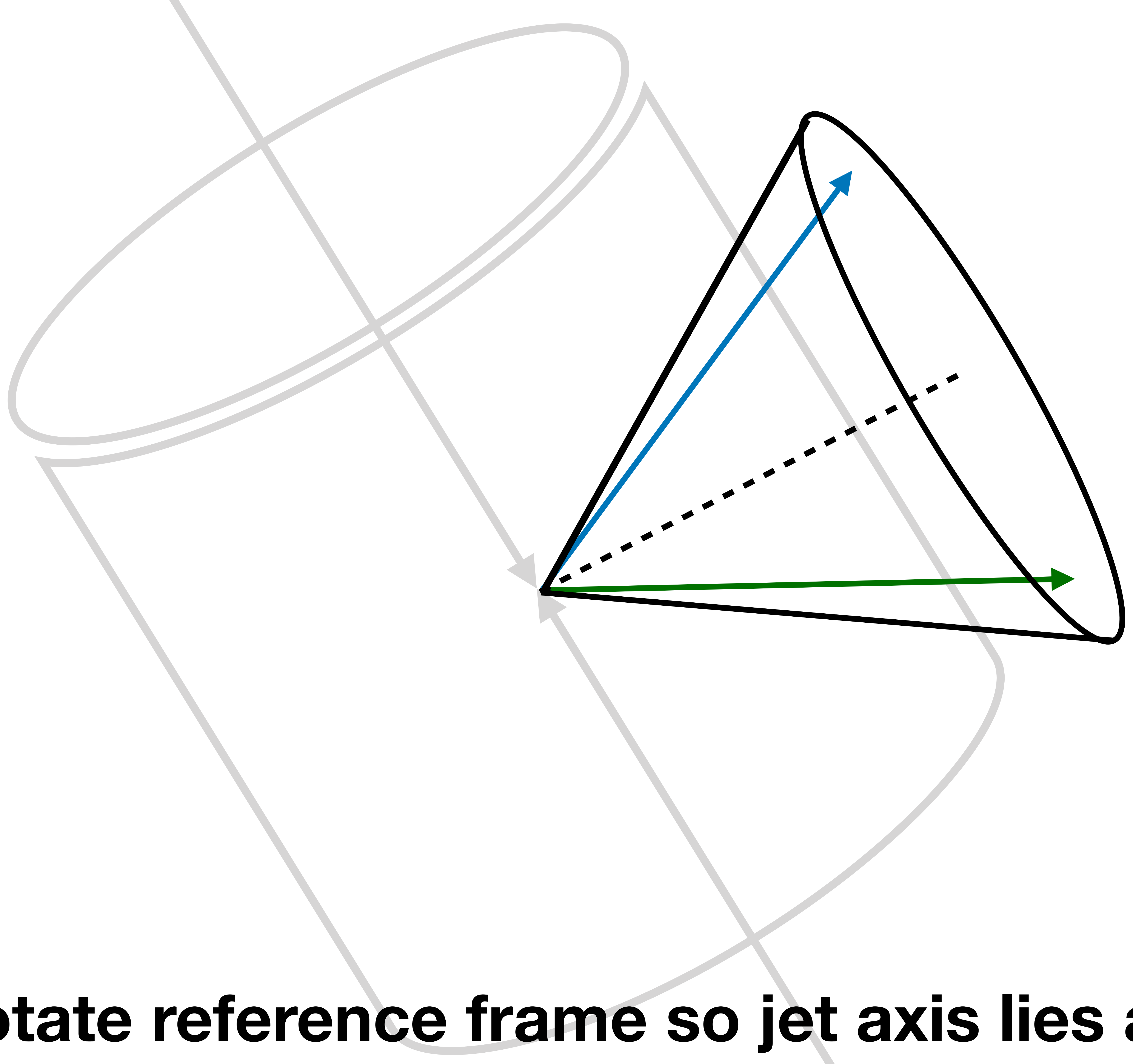
Consider a simplified jet with 2 constituents

Rotation of reference frame



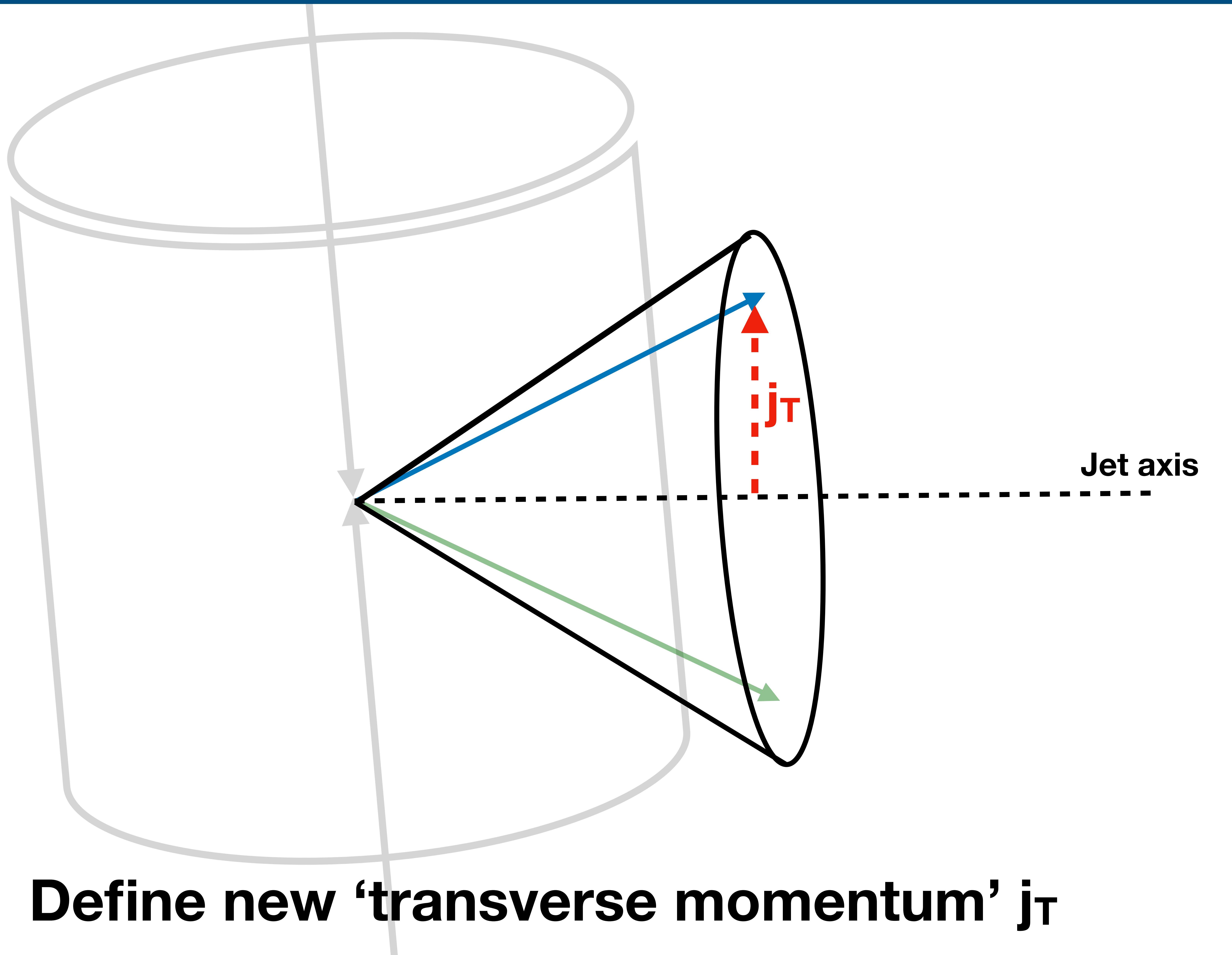
Rotate reference frame so jet axis lies along z axis

Rotation of reference frame



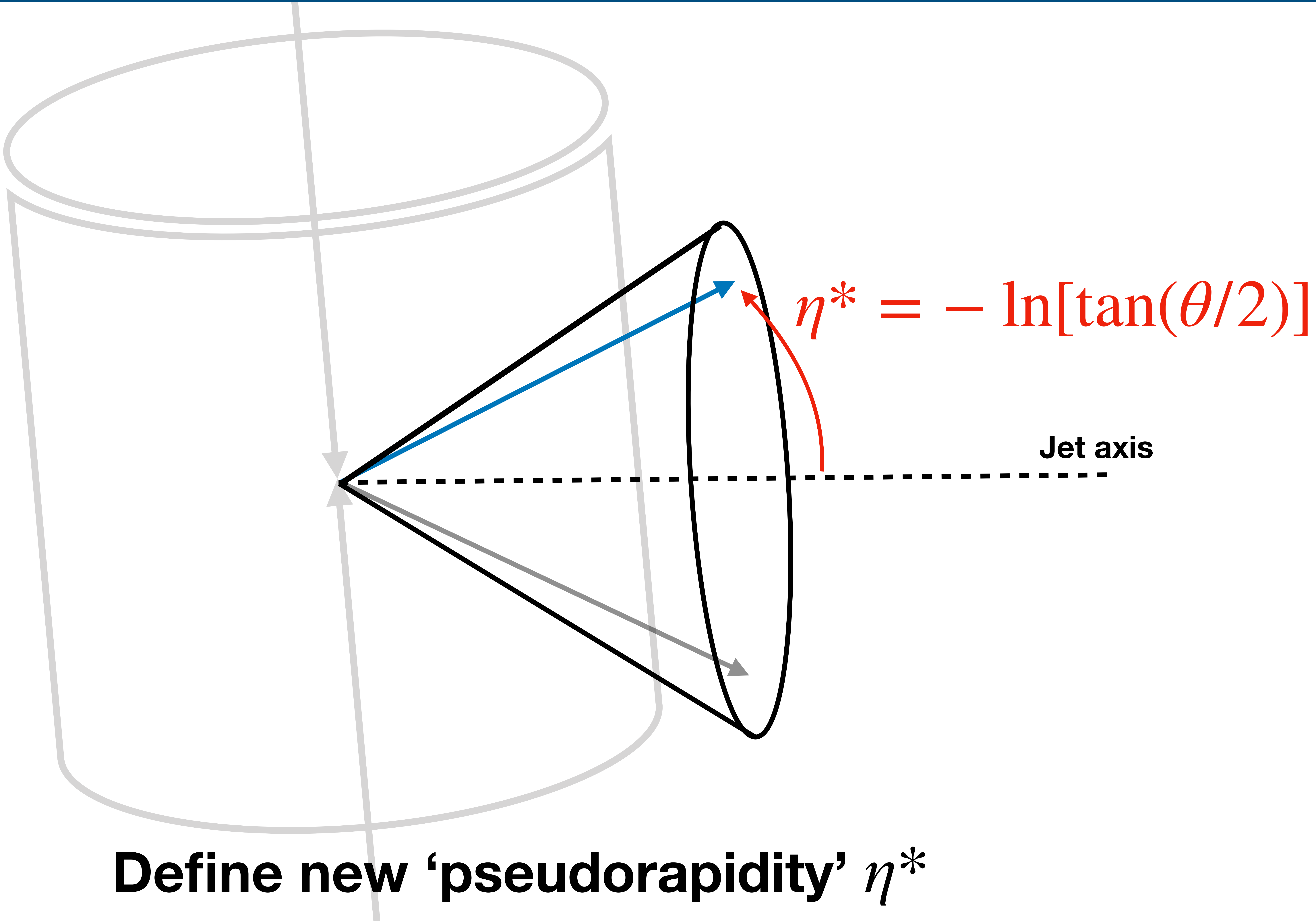
Rotate reference frame so jet axis lies along z axis

Coordinates in the jet frame



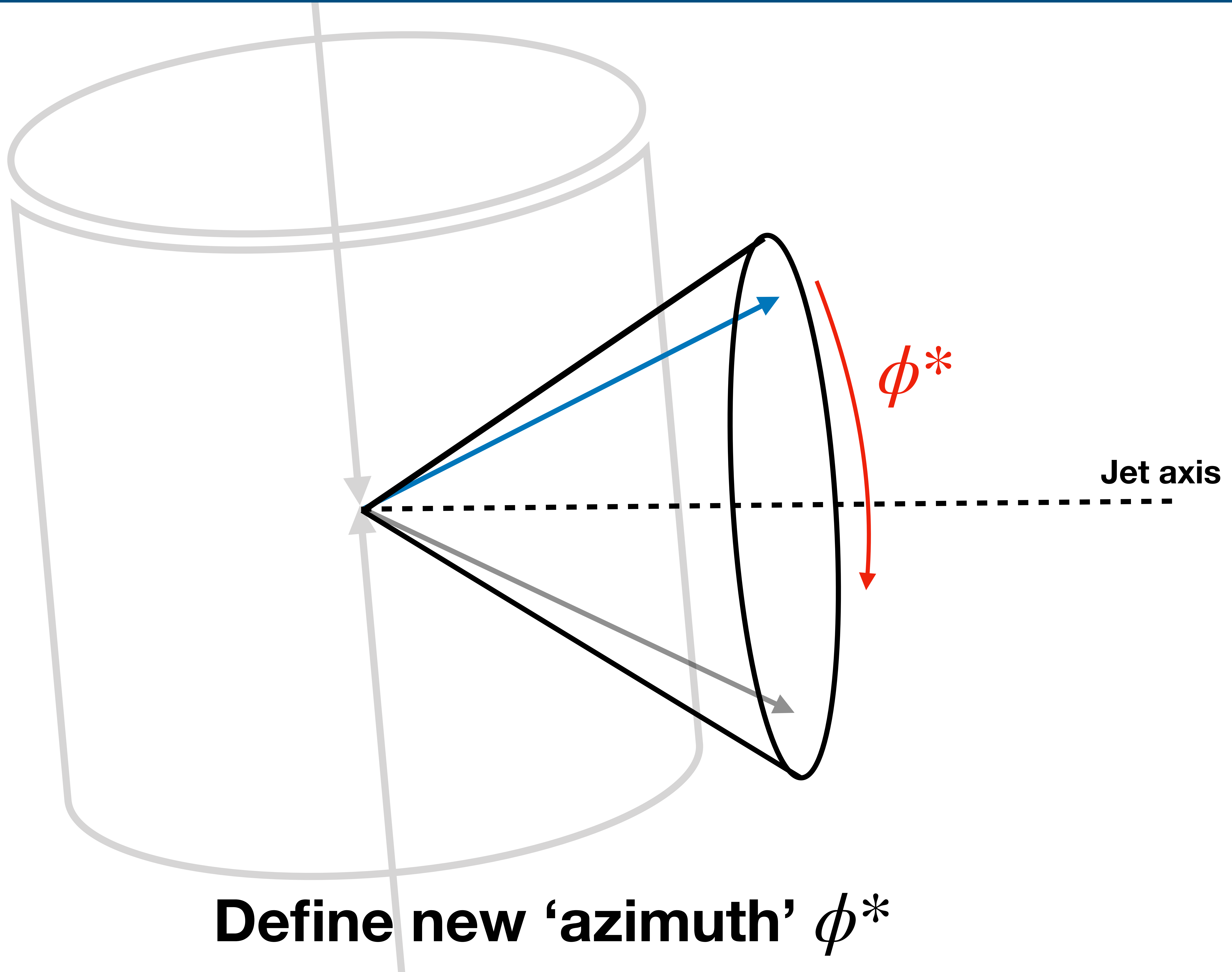
Define new 'transverse momentum' j_T

Coordinates in the jet frame



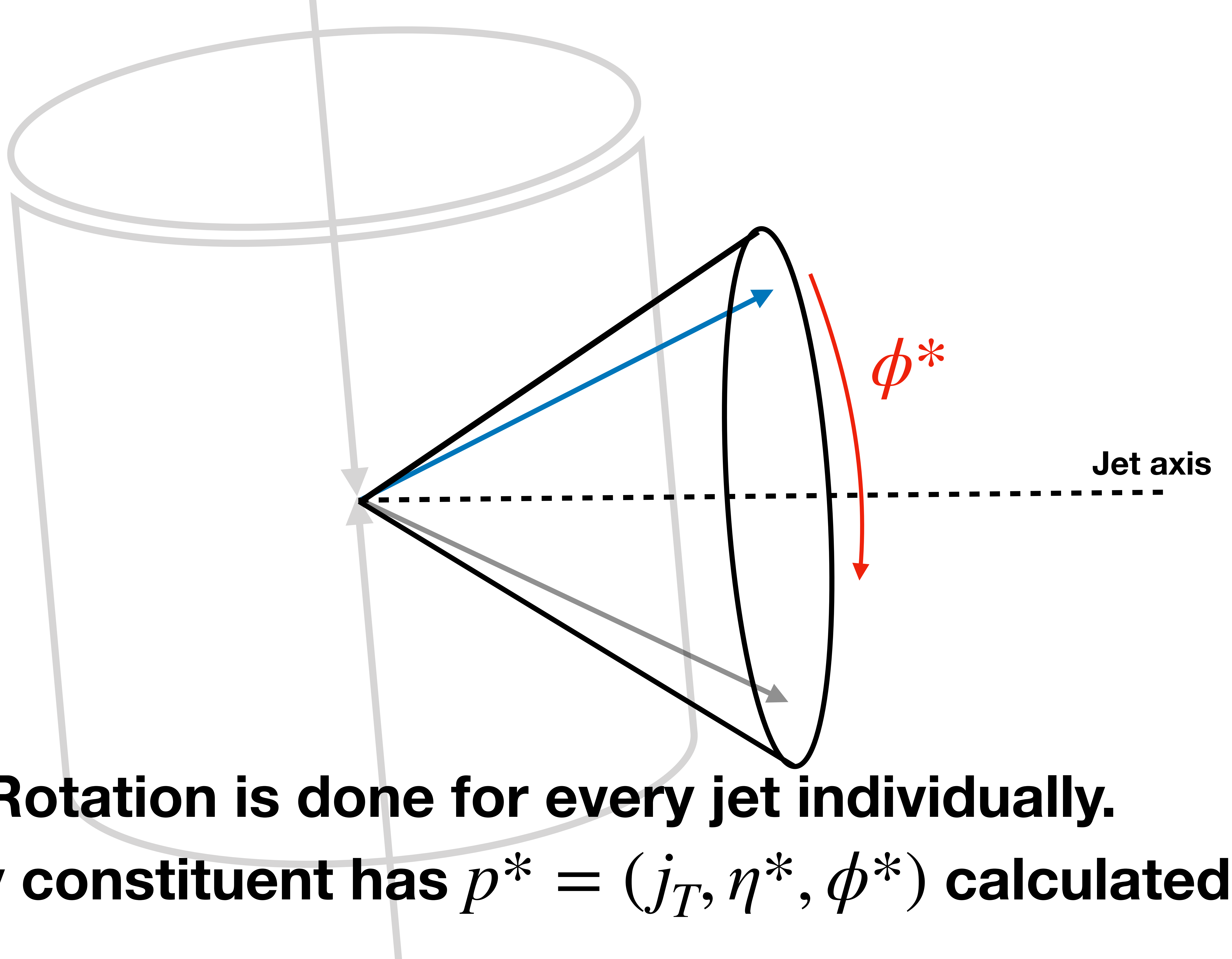
Define new 'pseudorapidity' η^*

Coordinates in the jet frame



Define new 'azimuth' ϕ^*

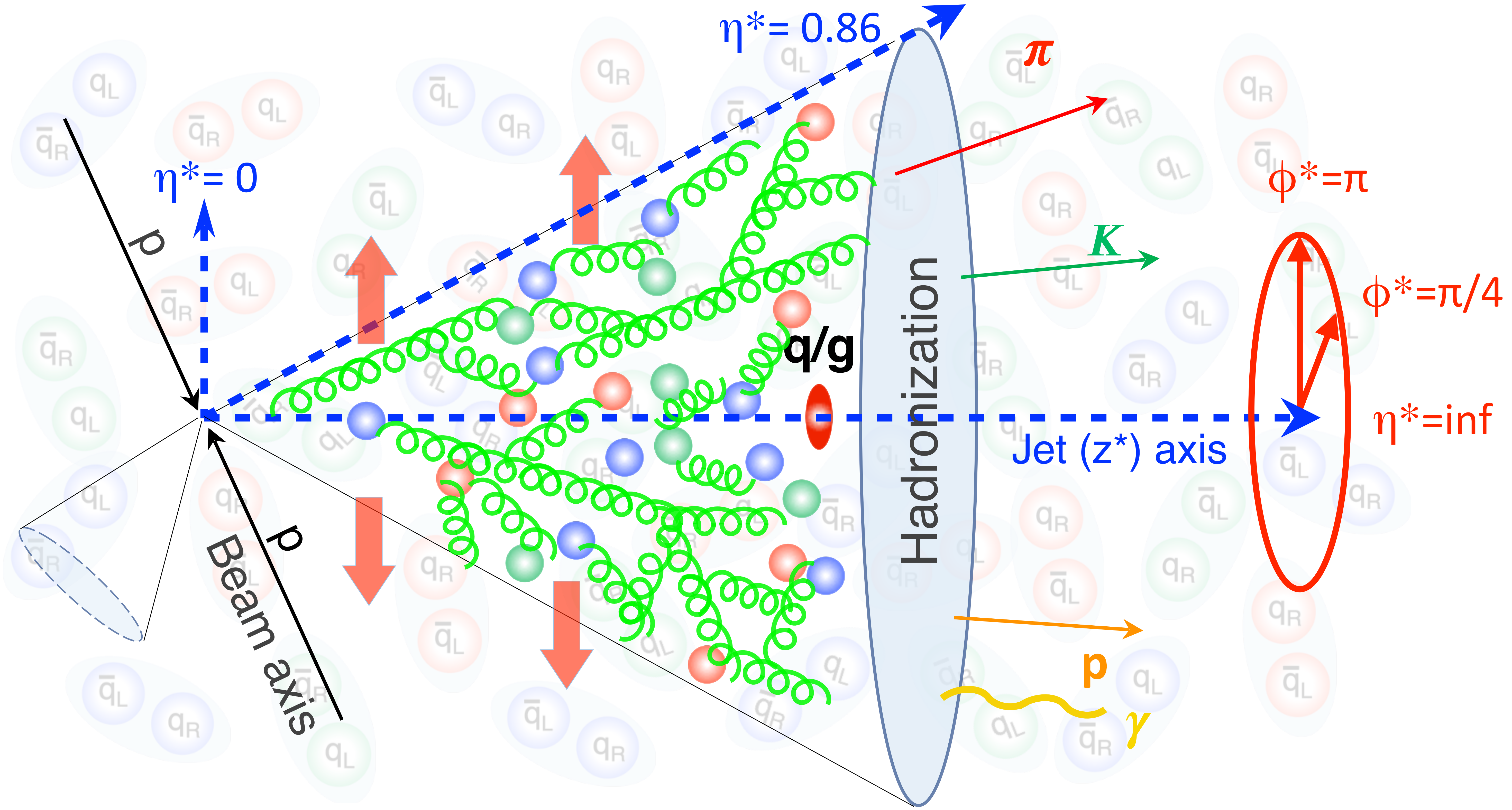
Coordinates in the jet frame

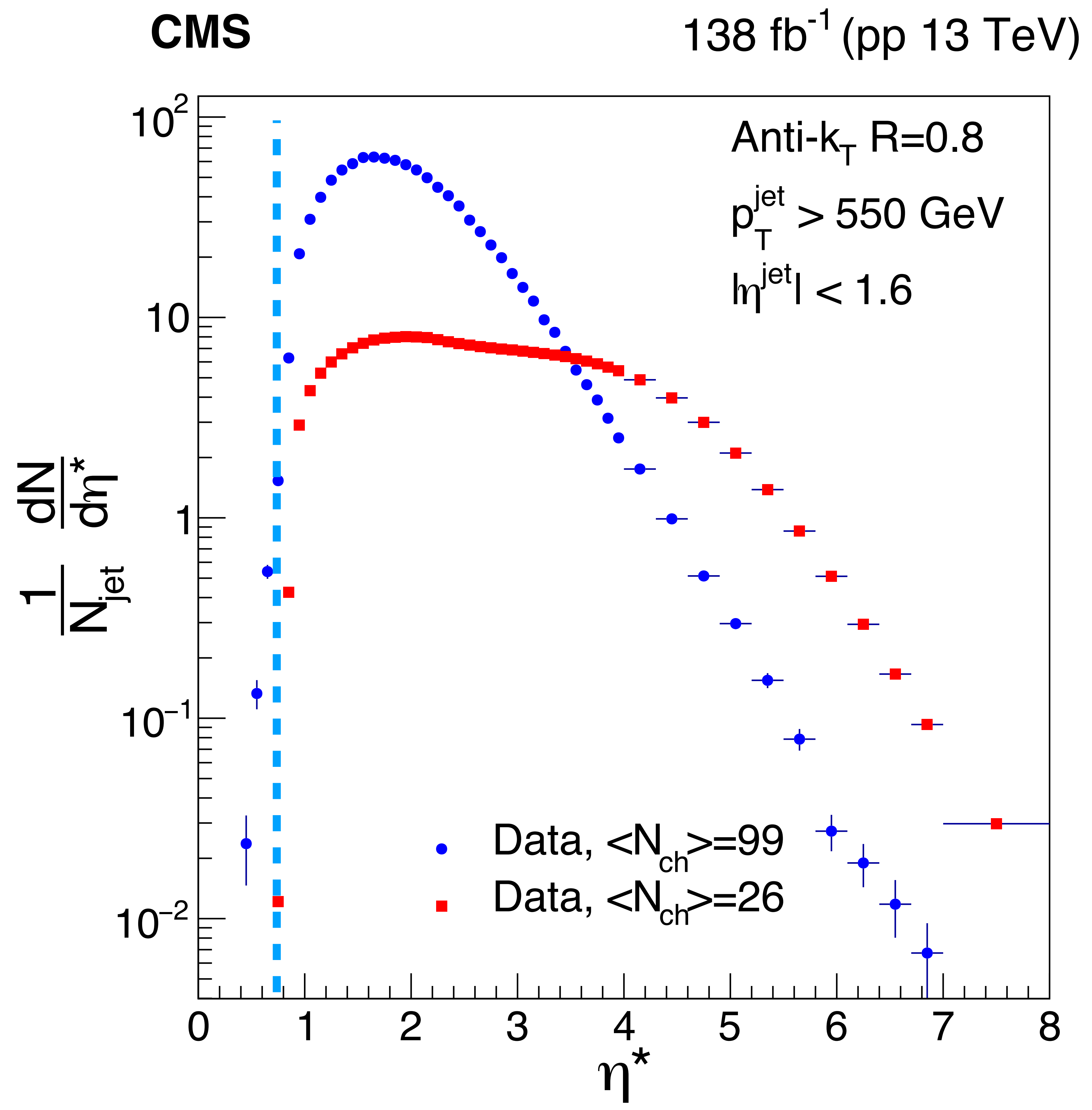


Rotation is done for every jet individually.

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

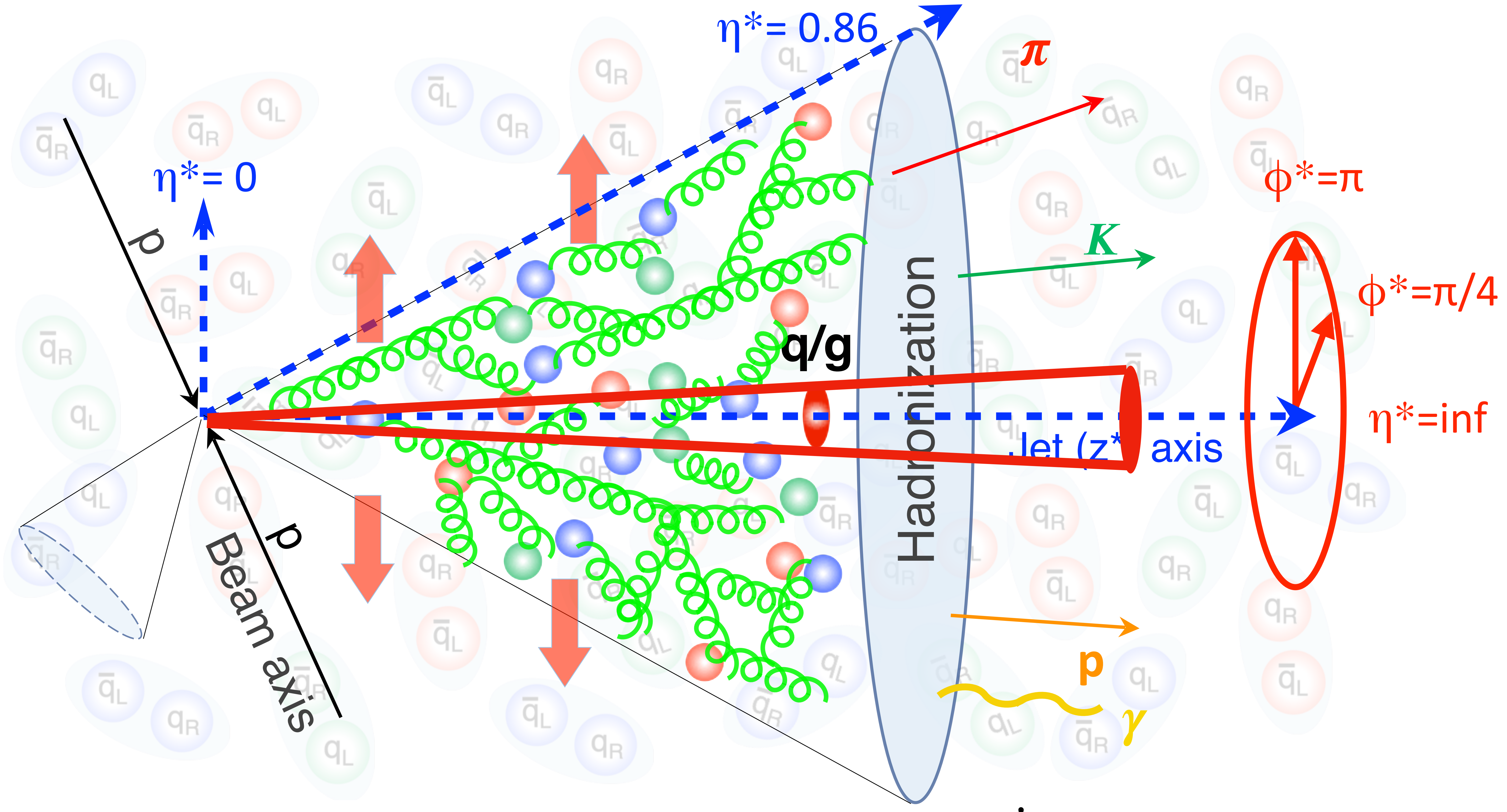
Properties of η^*

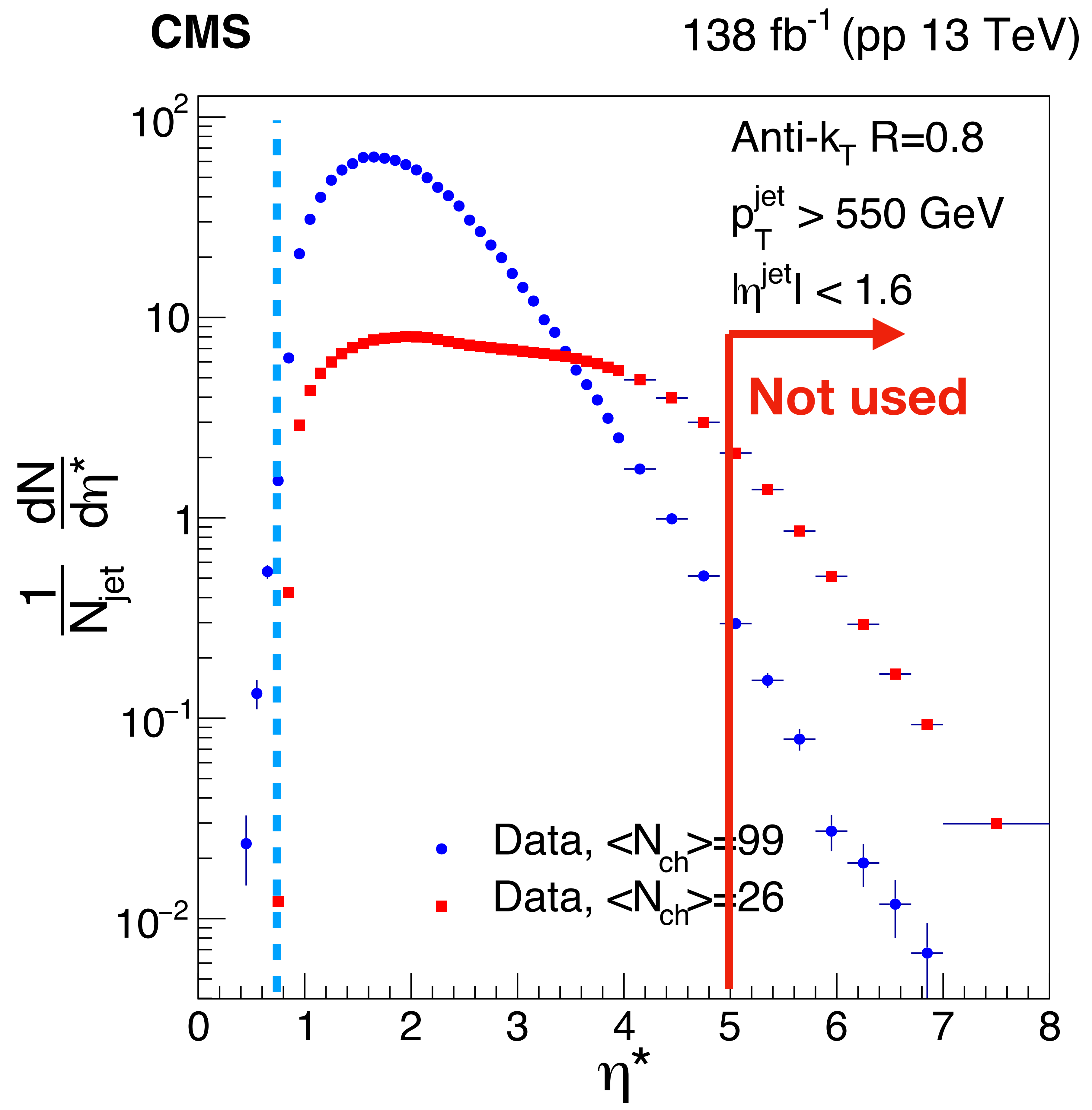




- **Wide angle radiation → smaller η^***
  - $\eta^* > 0.86$ **for an R=0.8 jet**

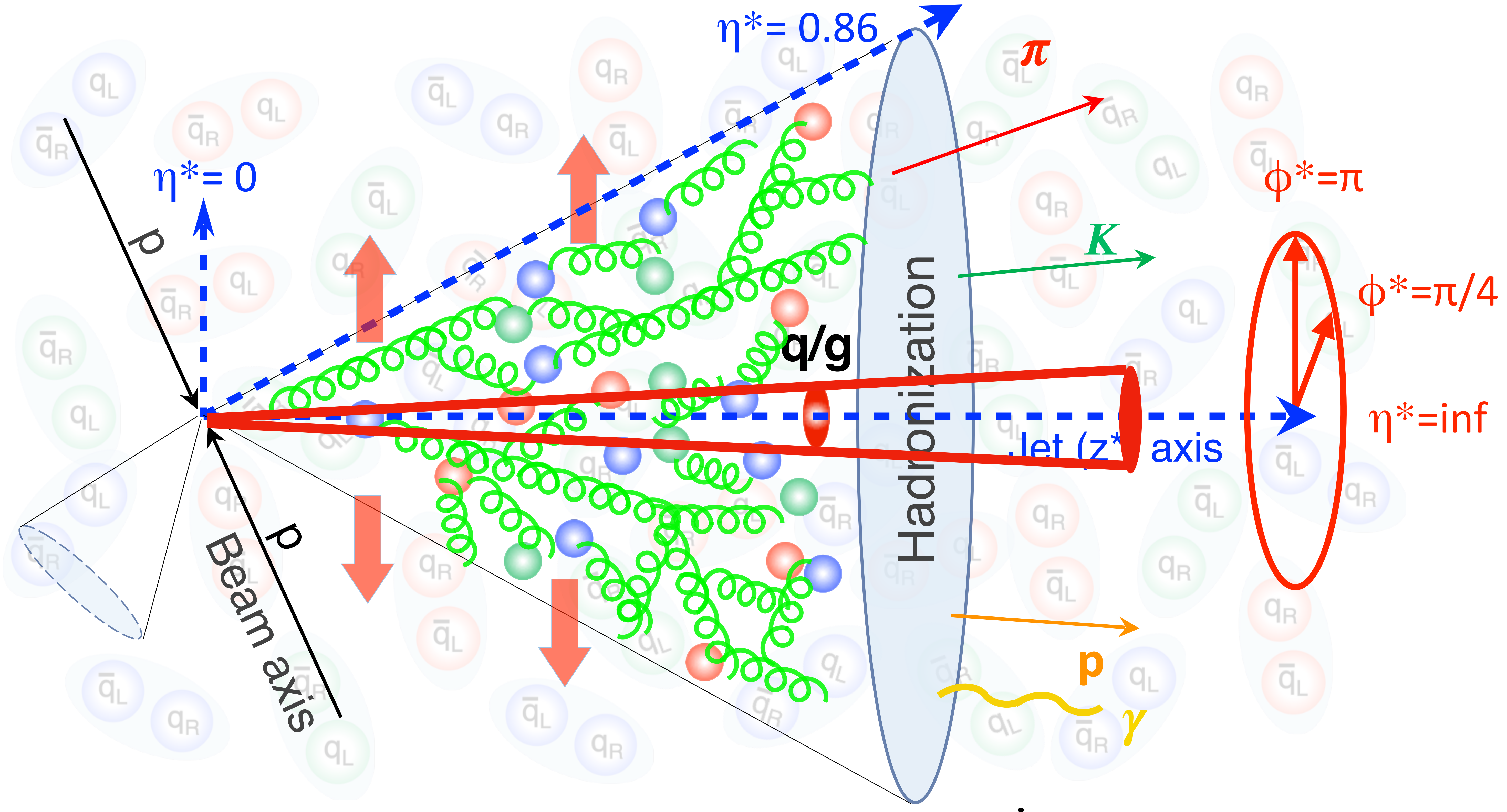
Properties of η^*

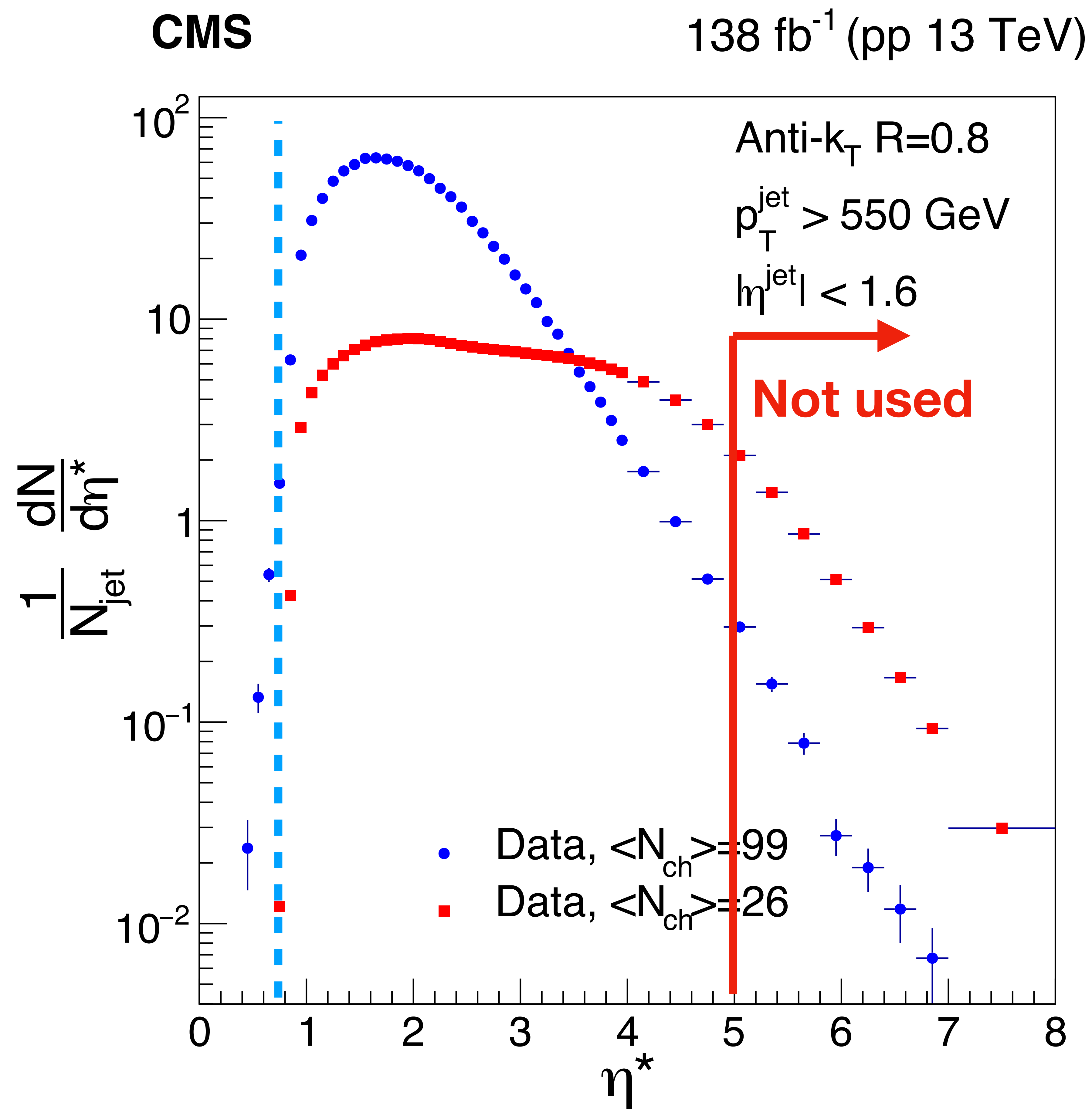




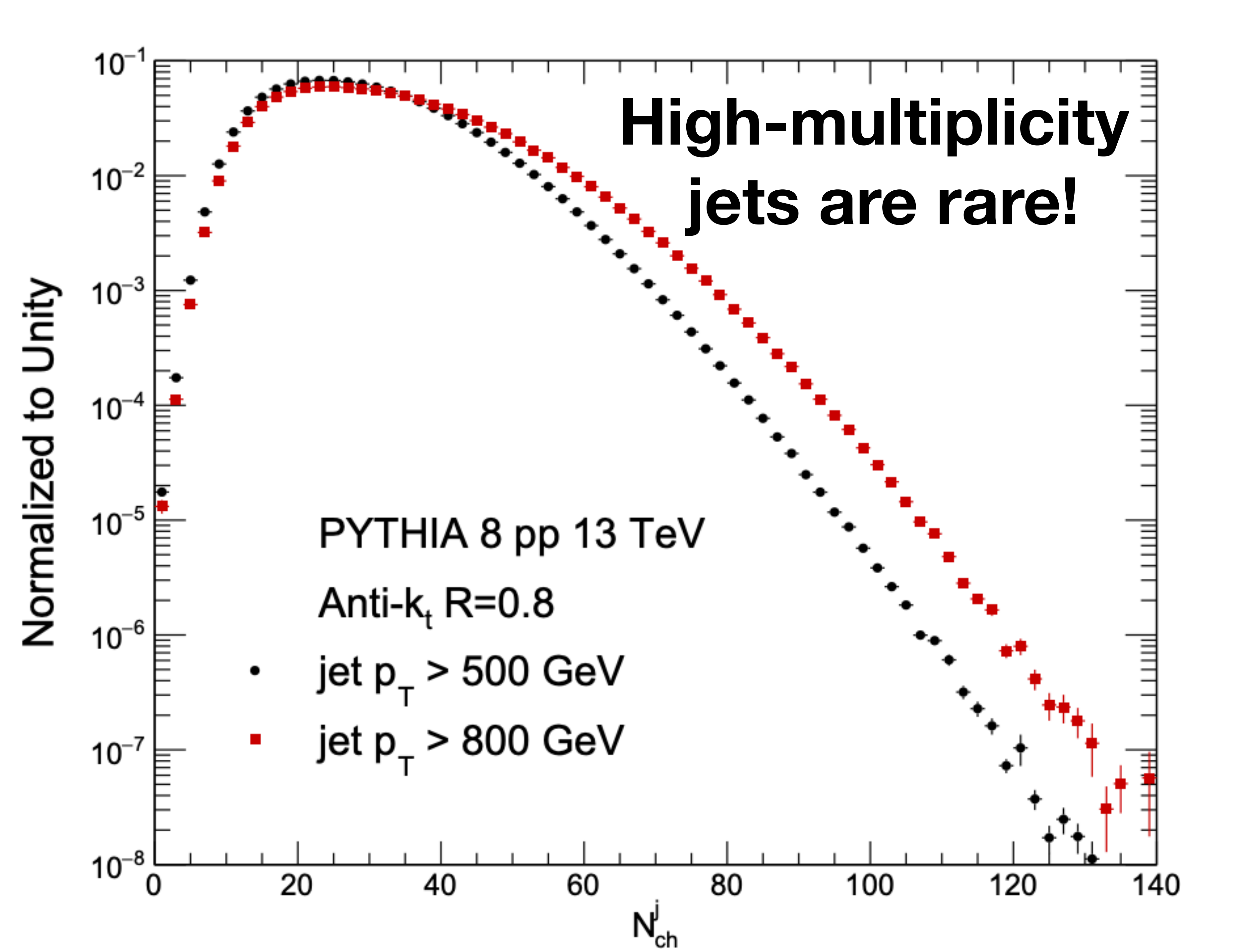
- **Wide angle radiation → smaller η^***
  - $\eta^* > 0.86$ **for an R=0.8 jet**
- $\eta^* > 5$ **excluded from analysis - sensitive to jet axis resolution**

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!**

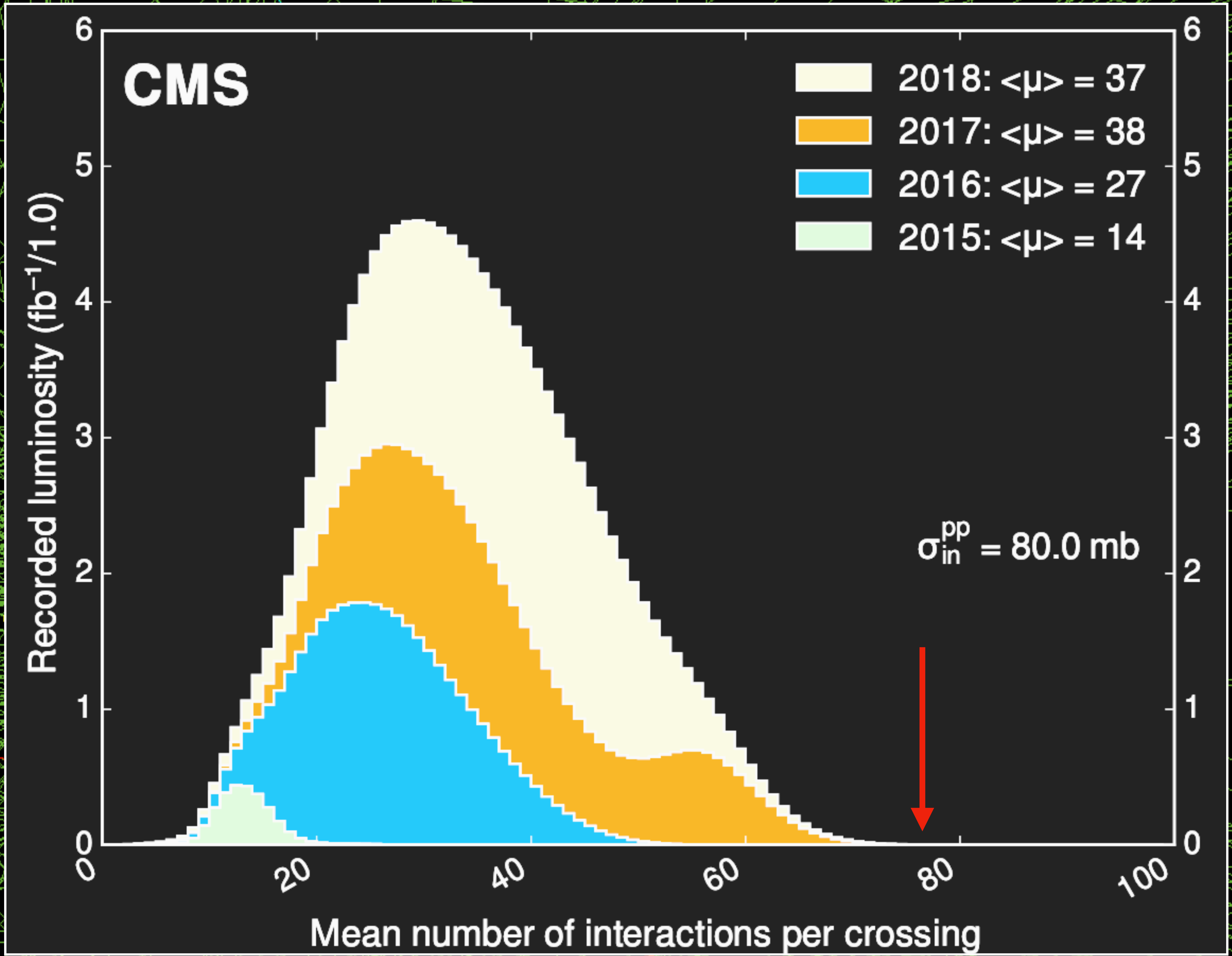


AB, Gardner P., Li W. PRC 107, 064908 (2023)

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

Pileup distribution

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

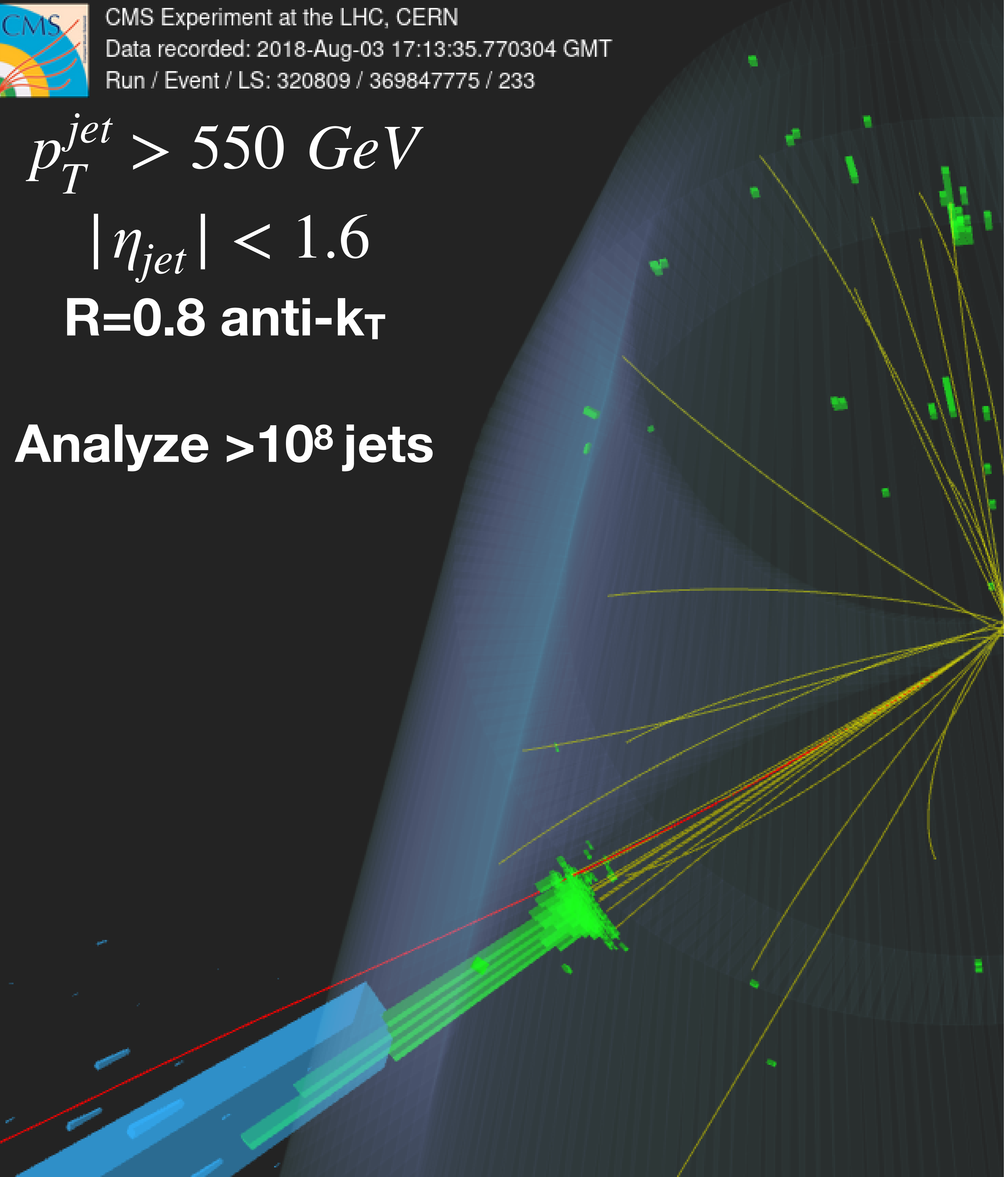


78 vertices: ~2x more than the average for this analysis

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



$p_T^{jet} > 550\ GeV$

$|\eta_{jet}| < 1.6$

R=0.8 anti-k_T

Analyze >10^8 jets

Only tracks with p_T > 1.5 GeV shown for clarity.

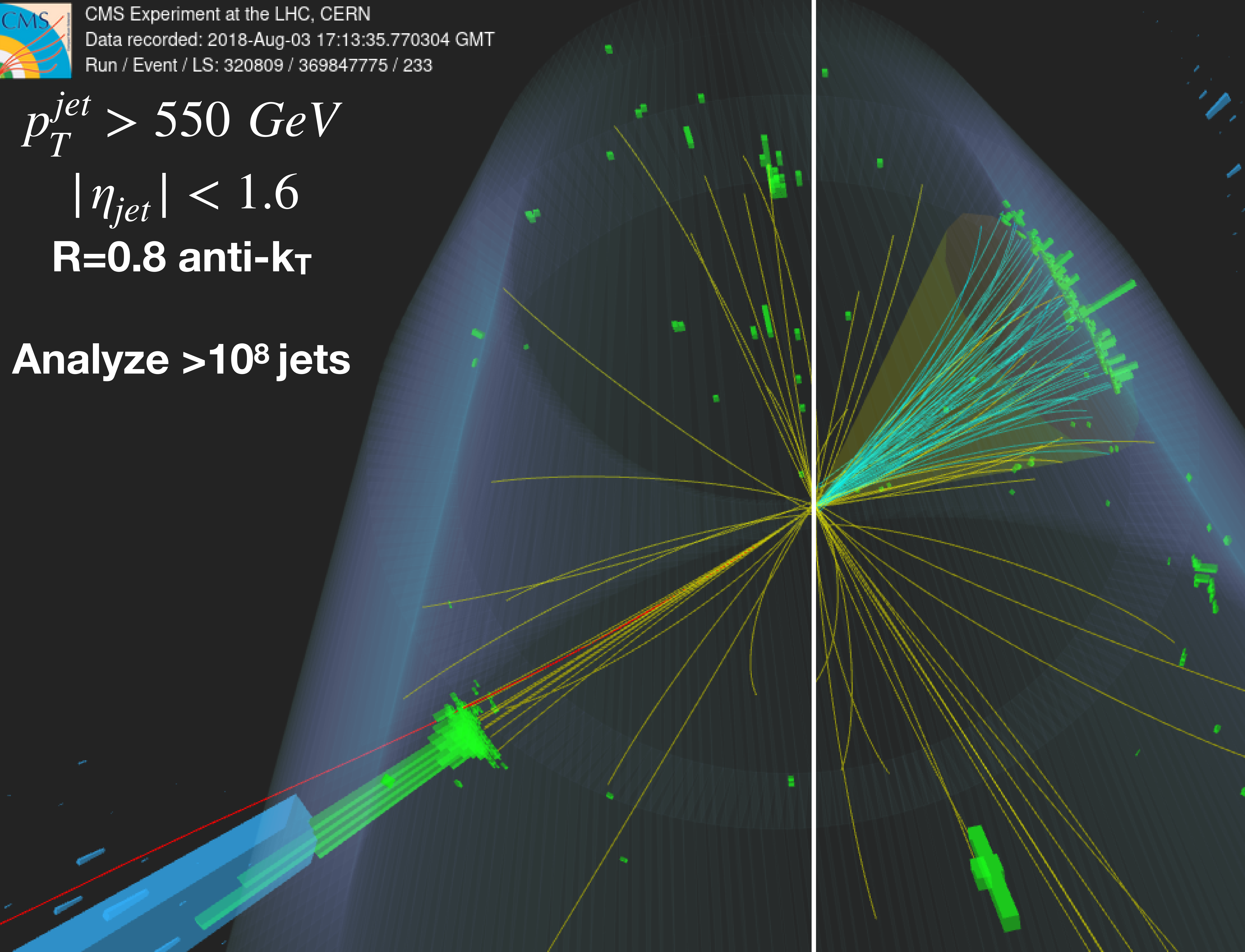
Full p_T range used in analysis!

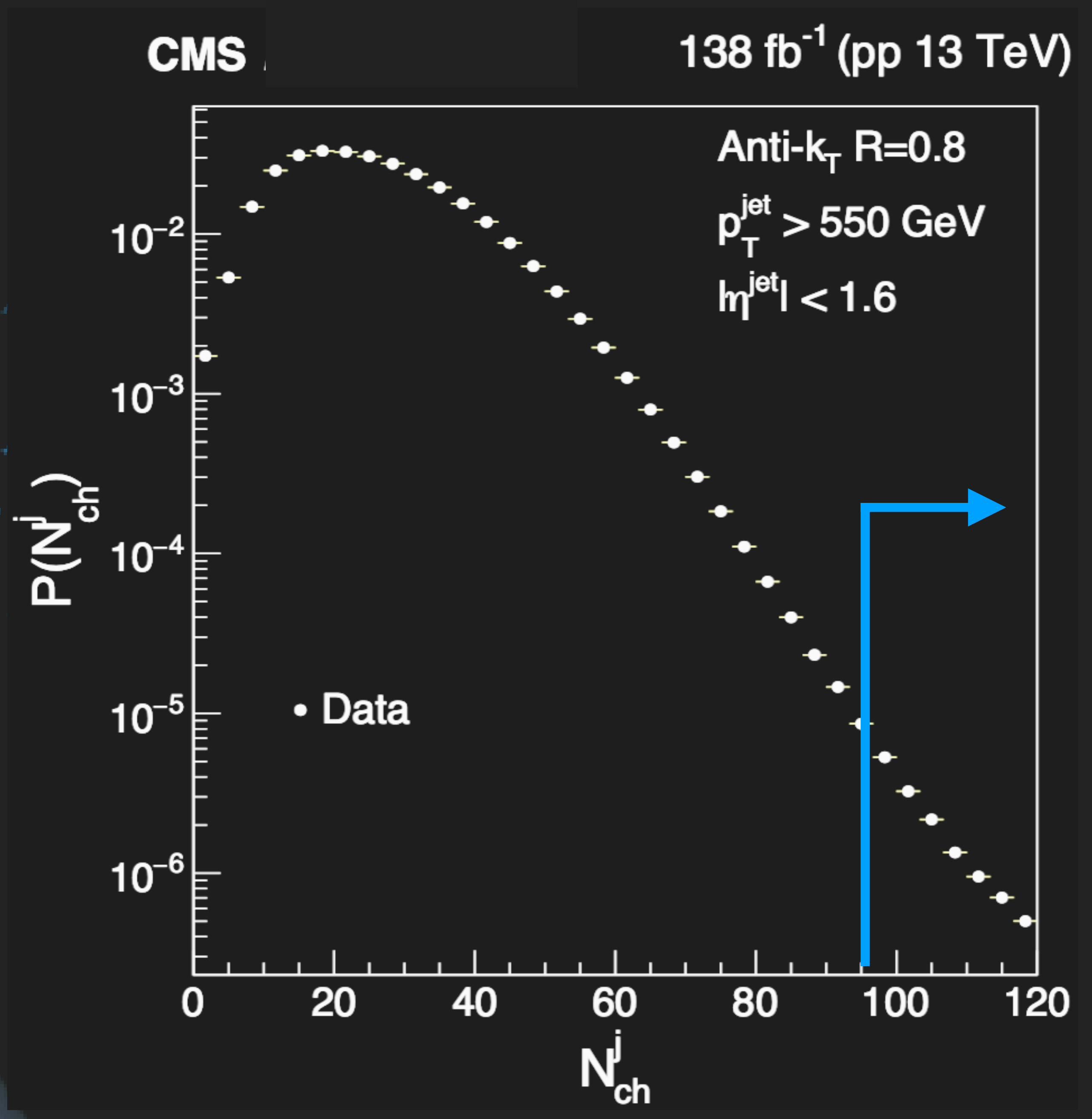
$p_T^{jet} > 550\ GeV$

$|\eta_{jet}| < 1.6$

R=0.8 anti-k_T

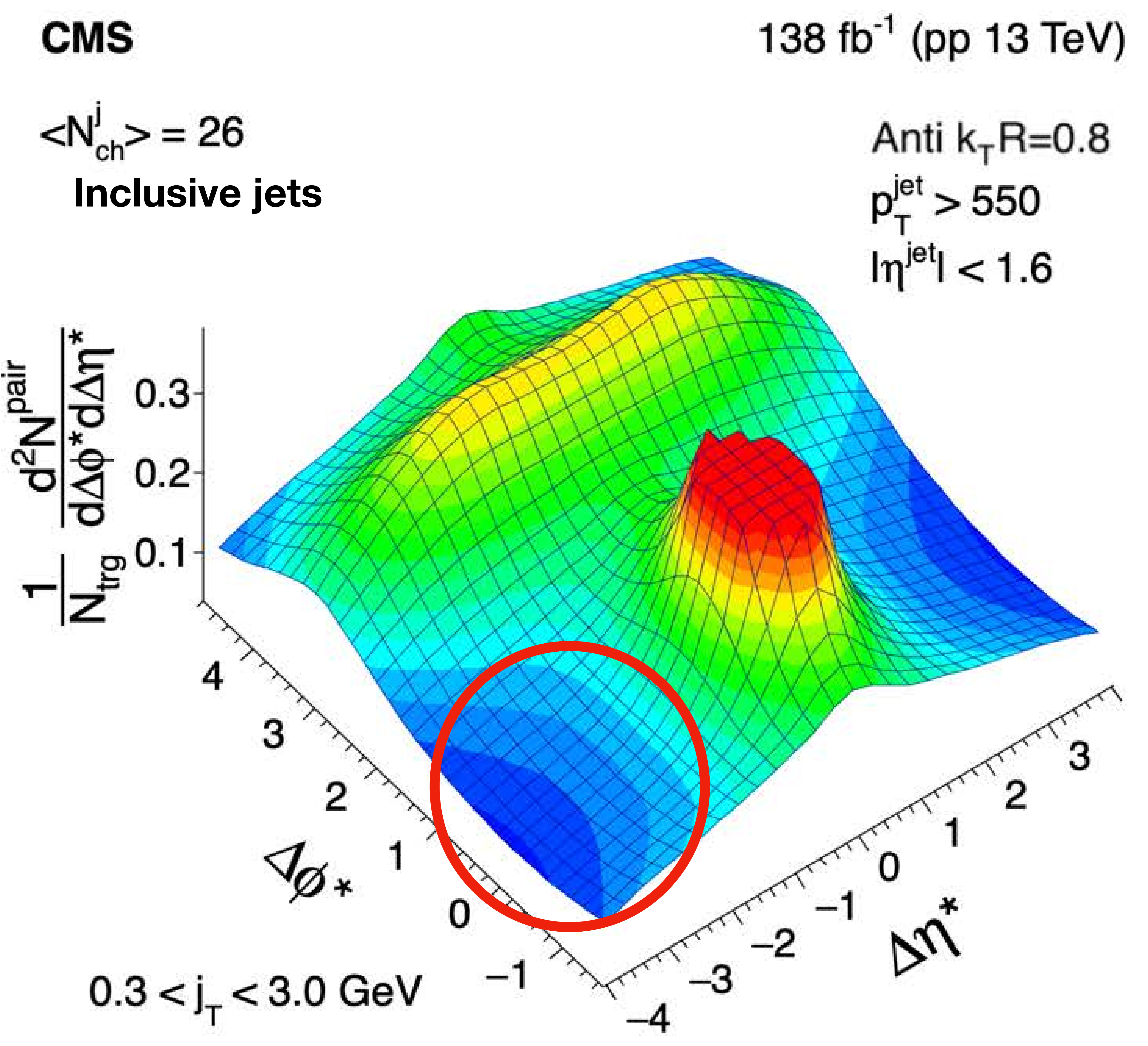
Analyze $>10^8$ jets

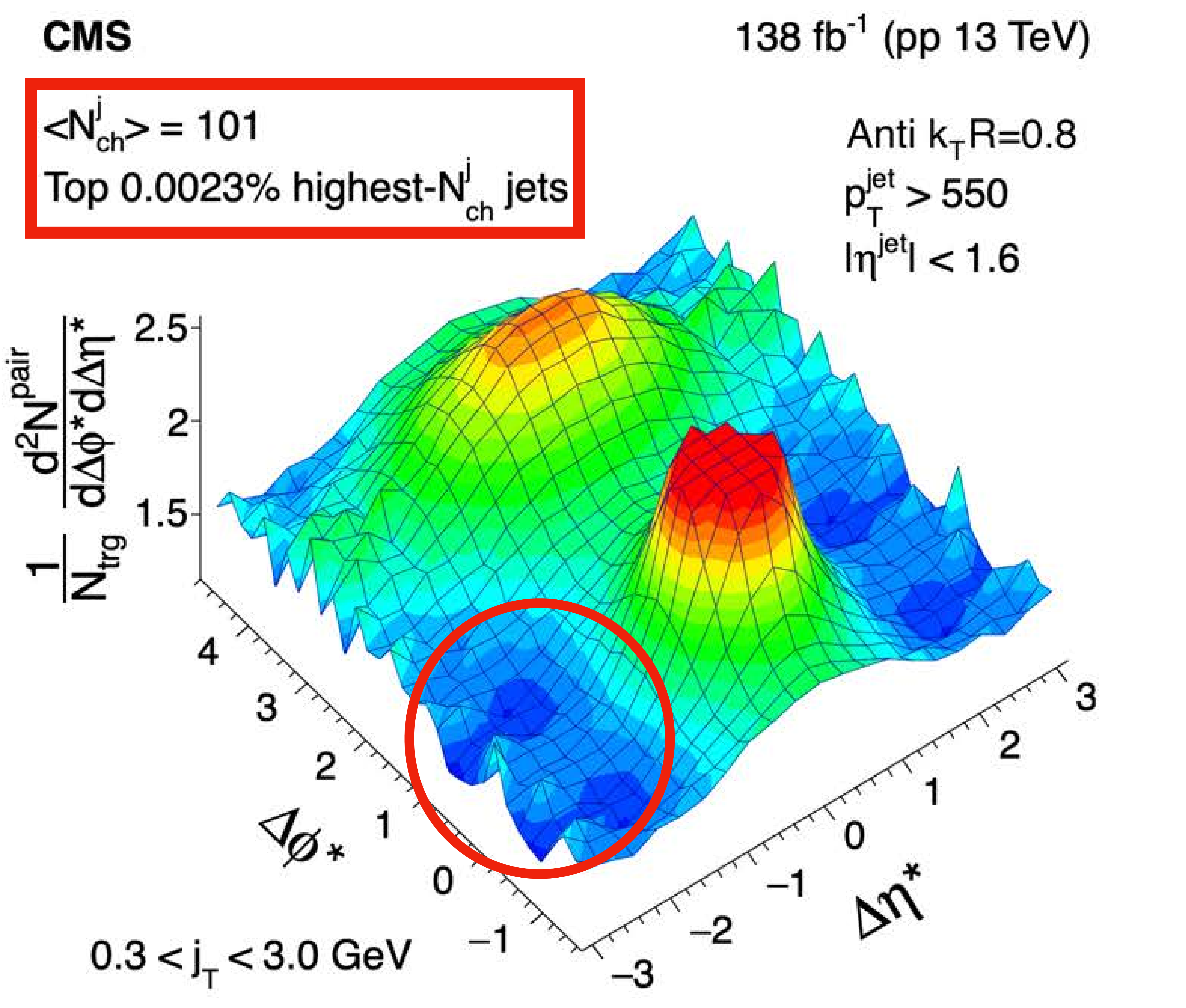




Select top ~2,500 jets in N_{ch}

High-Multiplicity 2D correlation



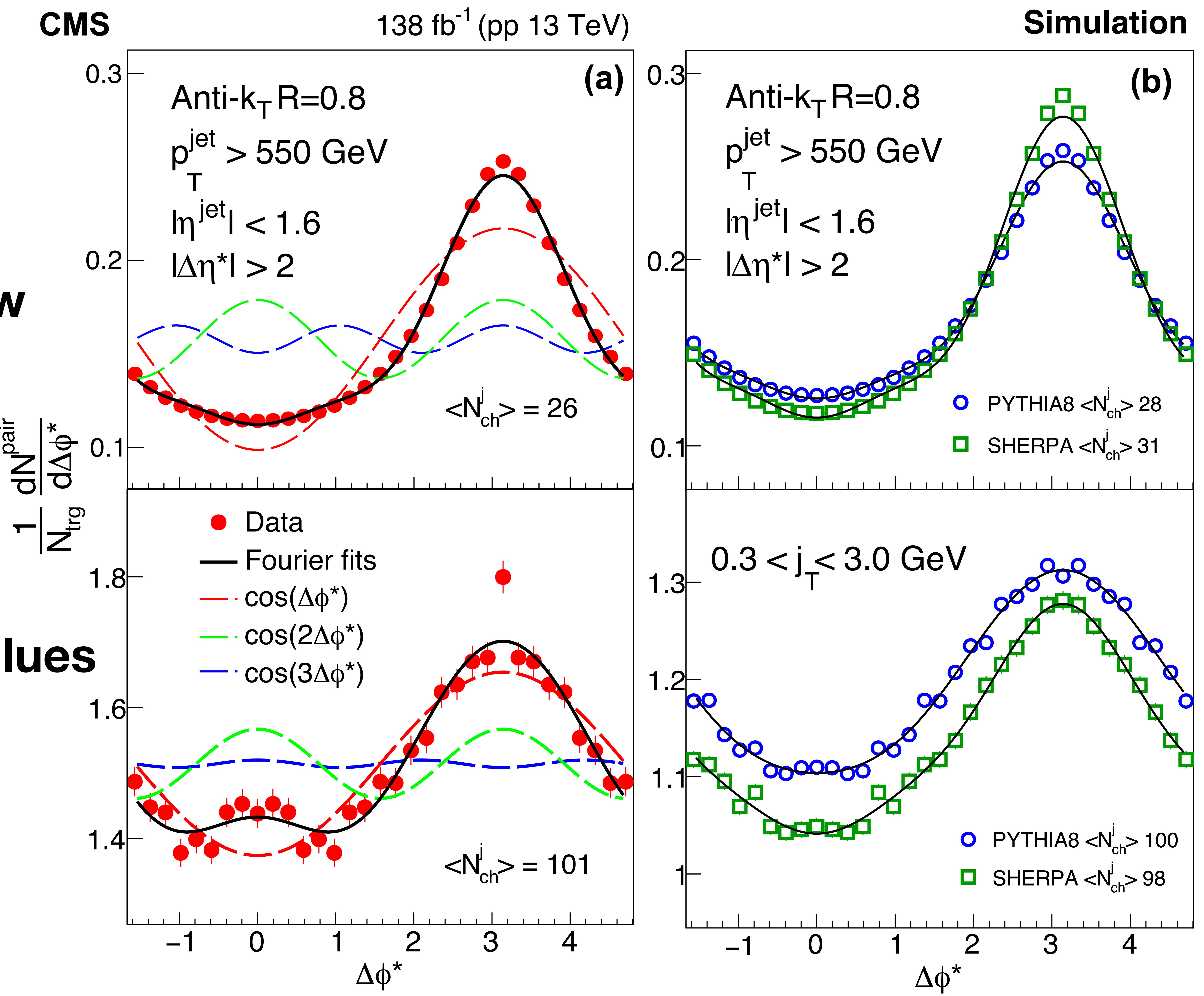


Potential 'ridge' in high-multiplicity jets?

High-Multiplicity 1D correlation

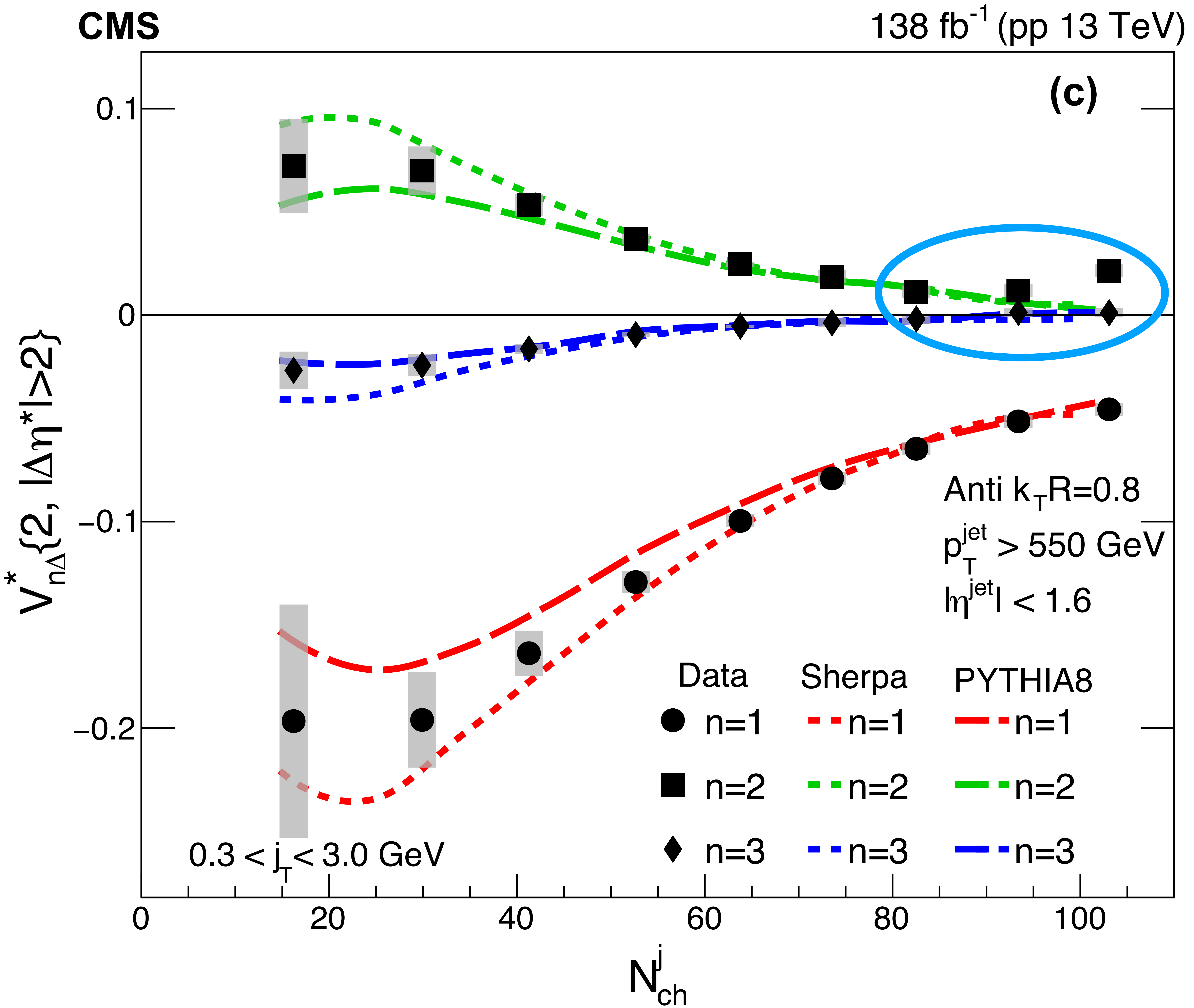
- **Project into $\Delta\phi*$ for $|\Delta\eta^*| > 2$**
- **Similar shape between data/MC**
- **Clear minimum at $\Delta\phi^* = 0$ at low multiplicity**

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



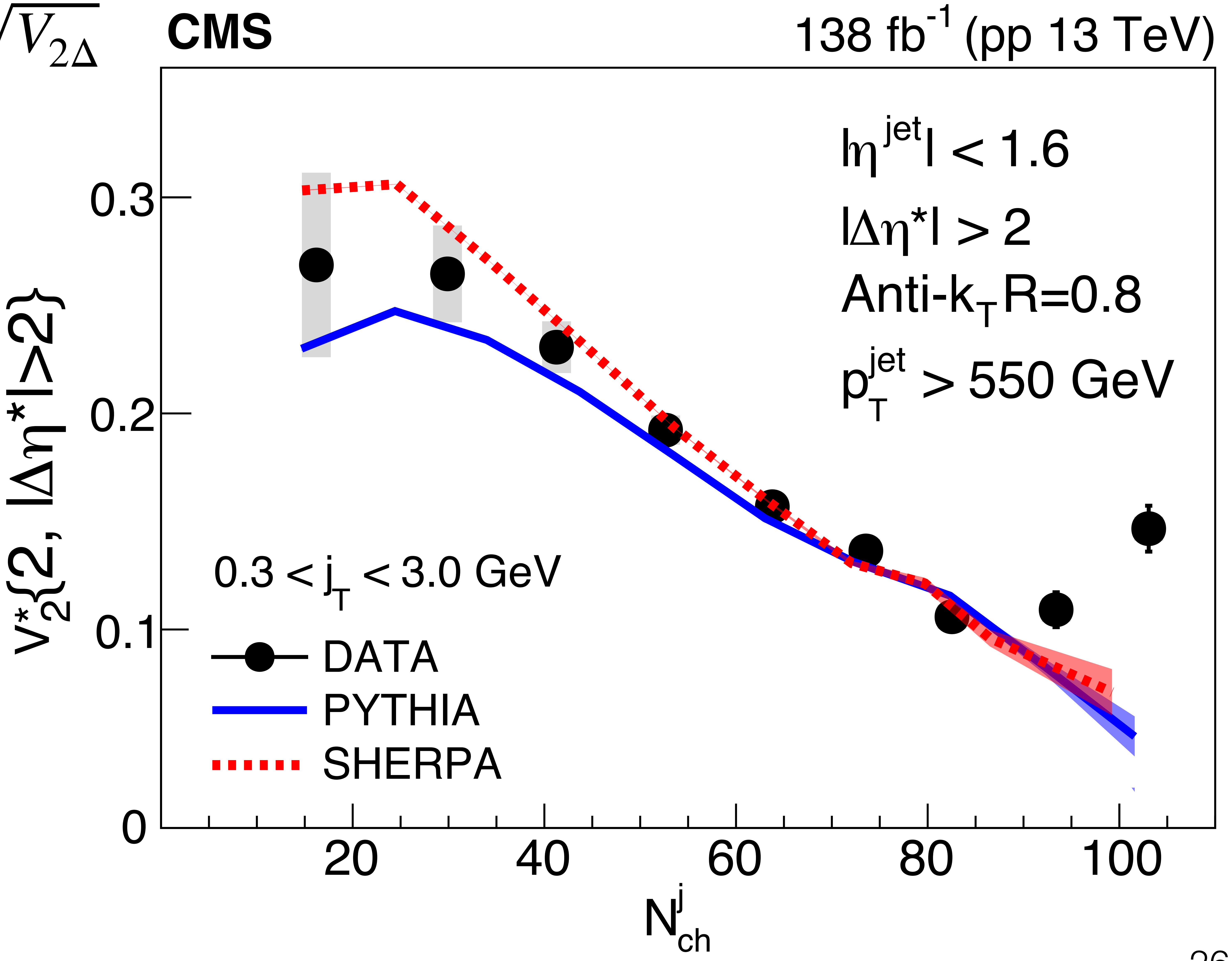
Fourier Harmonics vs N_{ch}

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



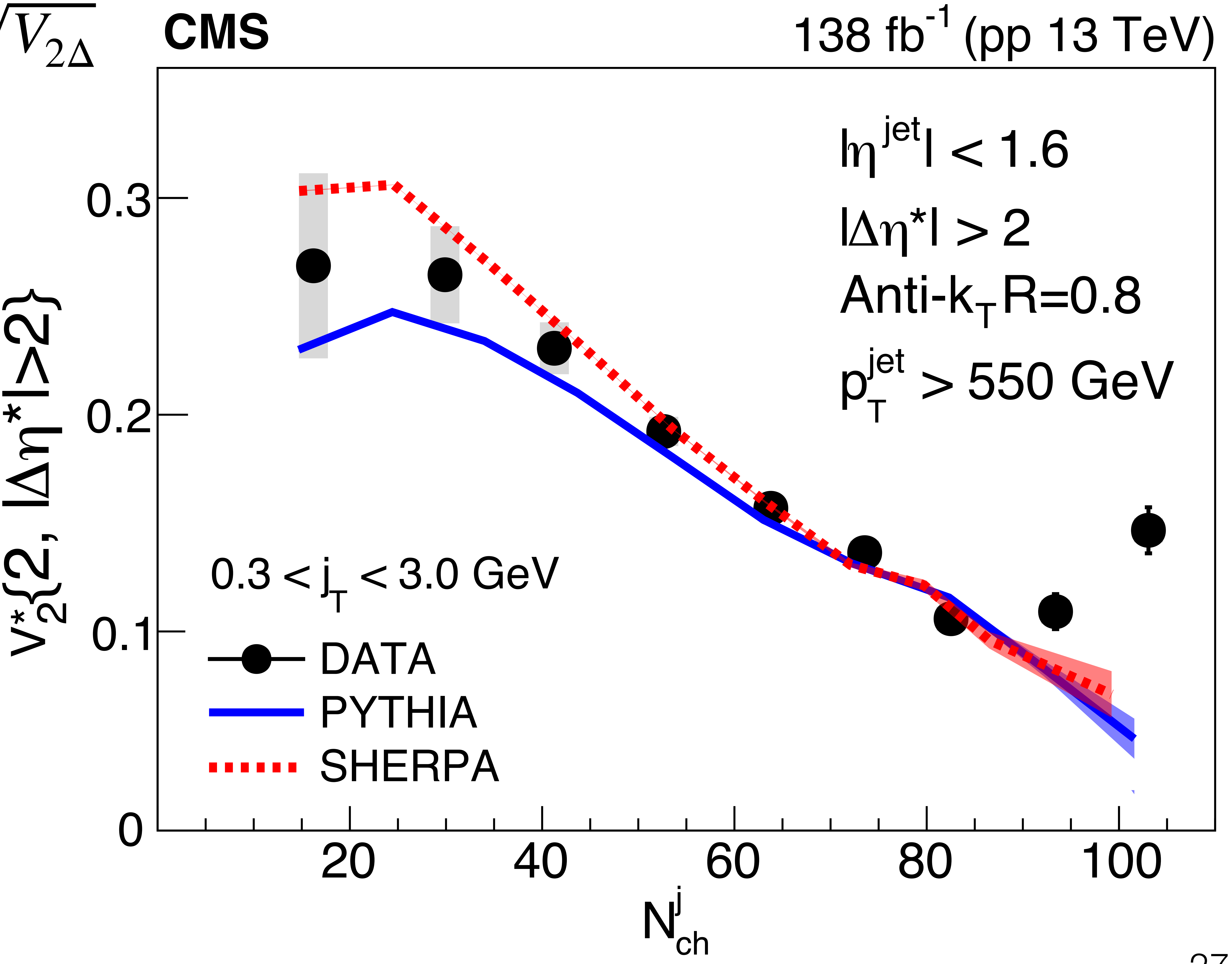
Single particle v_2

- **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**



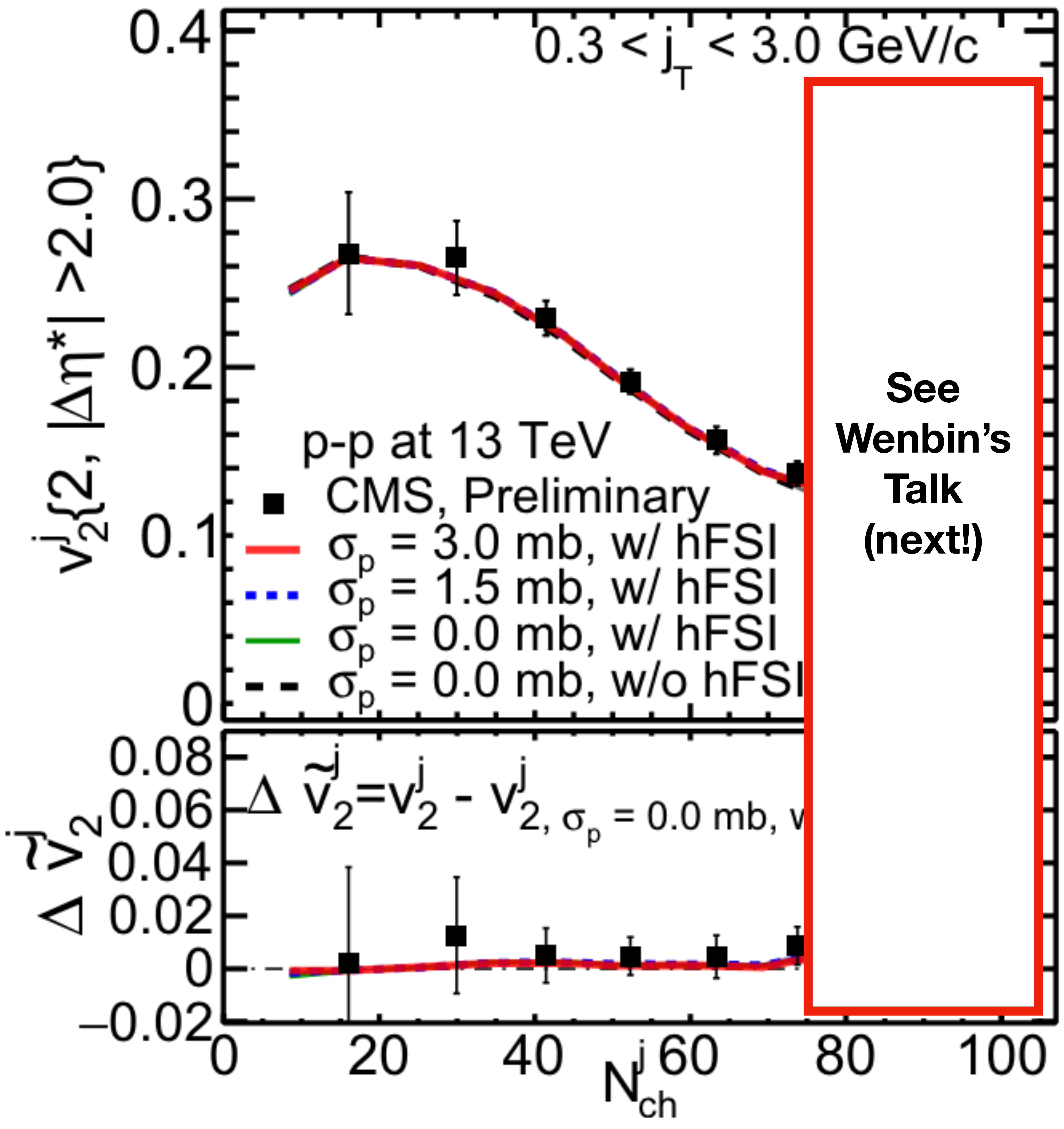
- **Data deviates from MC by >5σ**
- **Observation of QGP-like effects above some critical density?**
- **What can explain such effect?**

Collectivity explanation

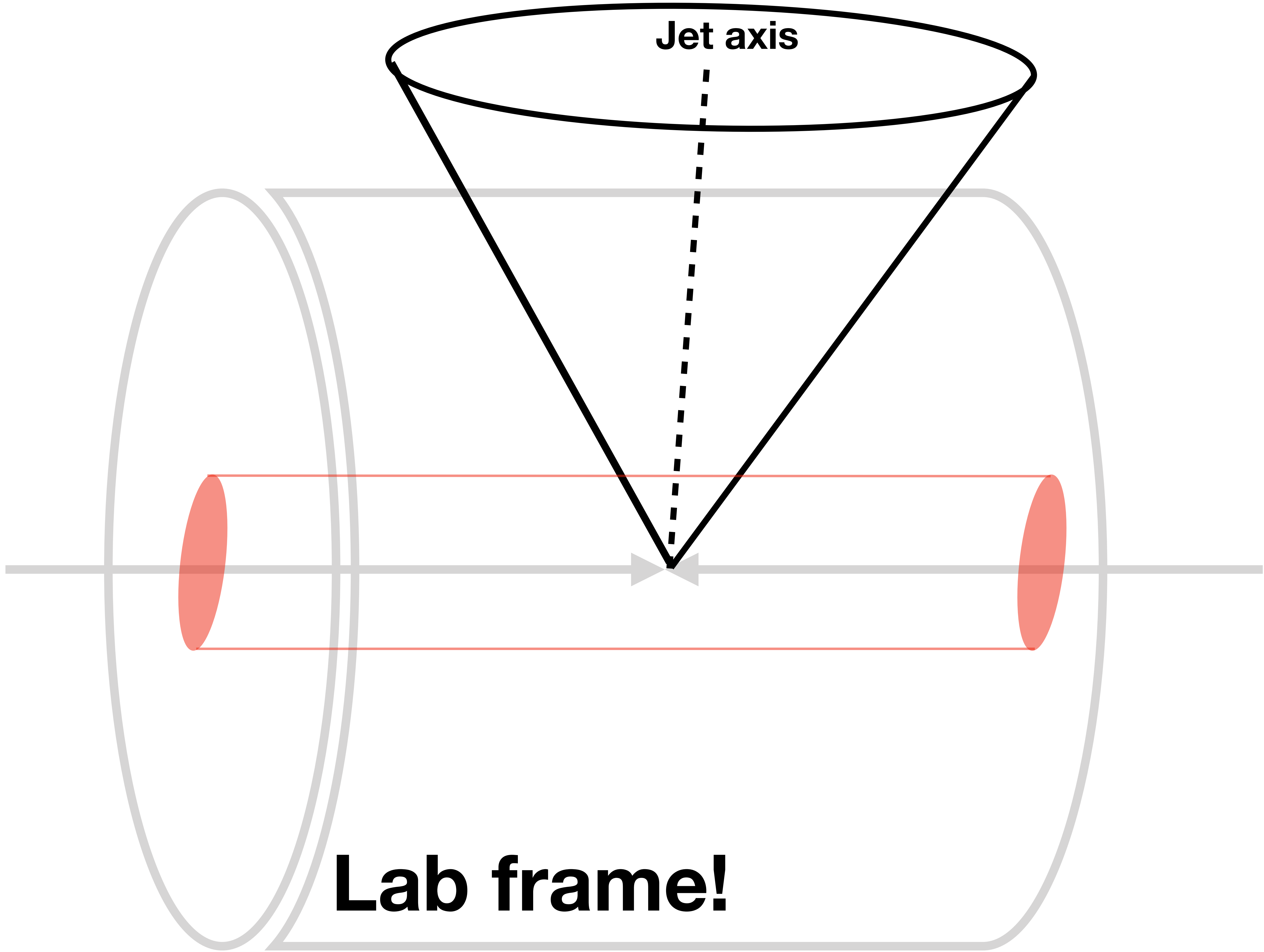
- **Test 'collectivity' interpretation by adding final-state interactions to parton shower**

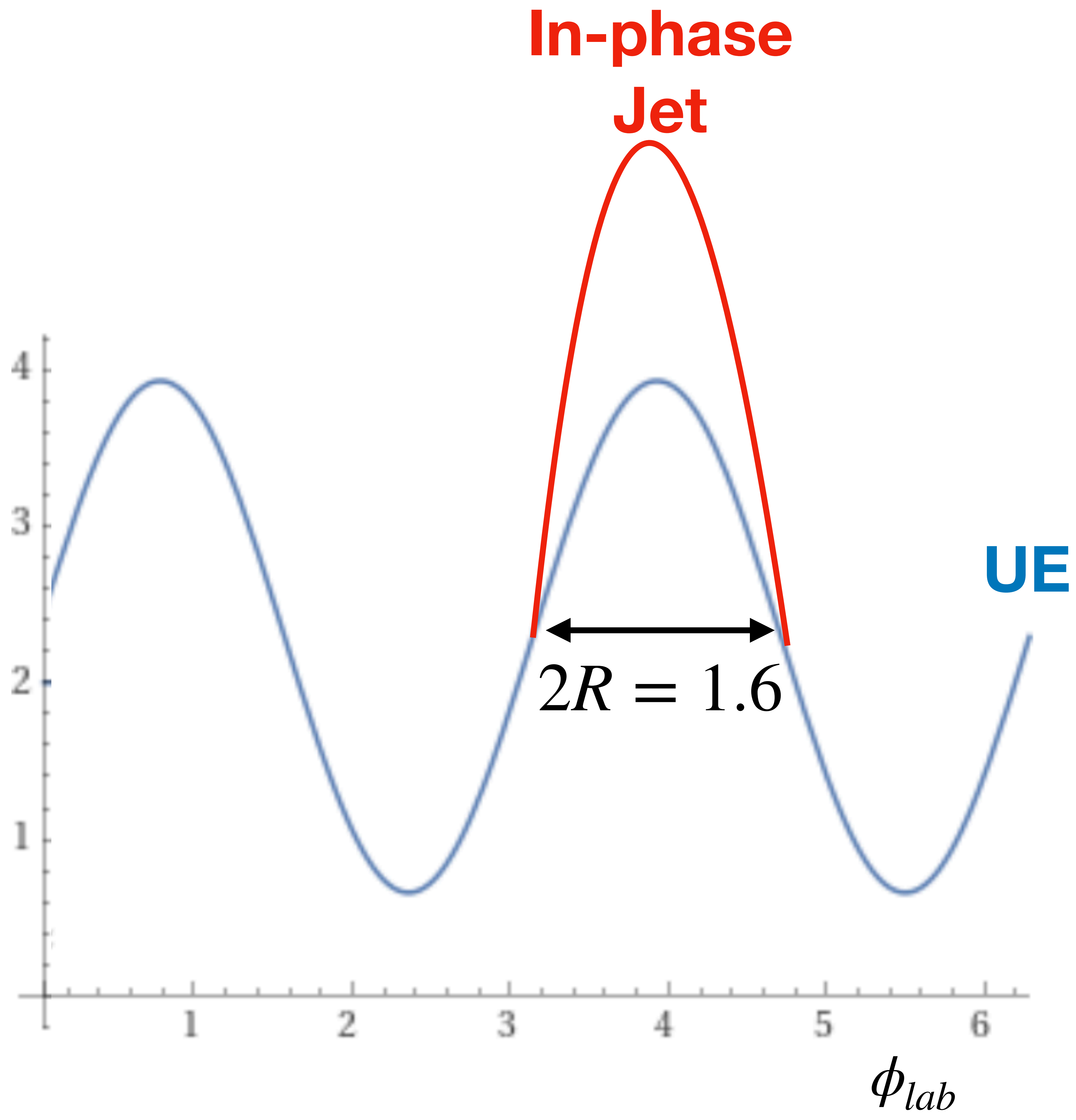
- **Does not seem to affect lower N_{ch} region significantly - consistent with no effect seen in HEP studies**
- **High-multiplicity trend - see next talk!**

arxiv:2401.13137



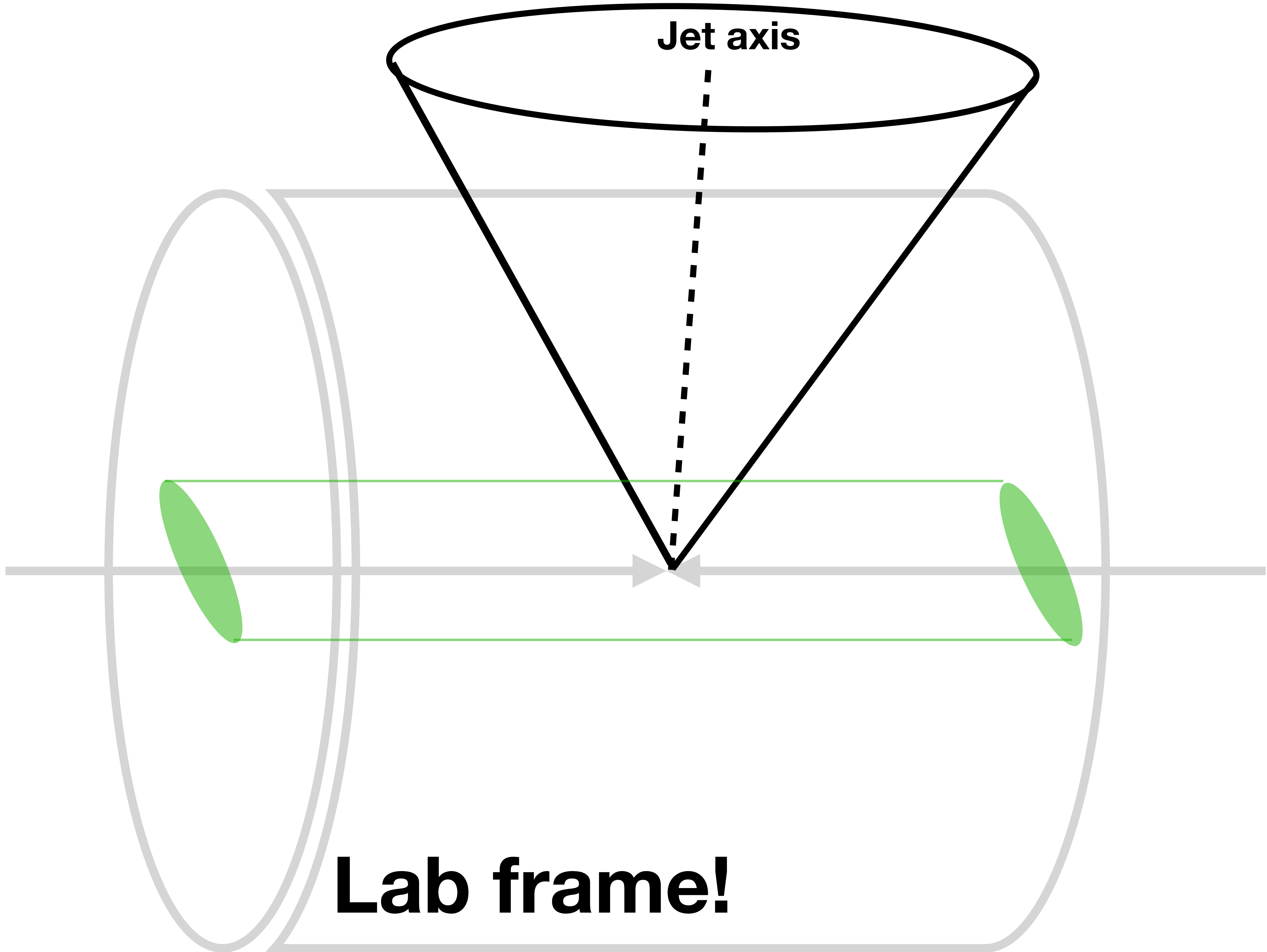
Underlying Event Explanation?

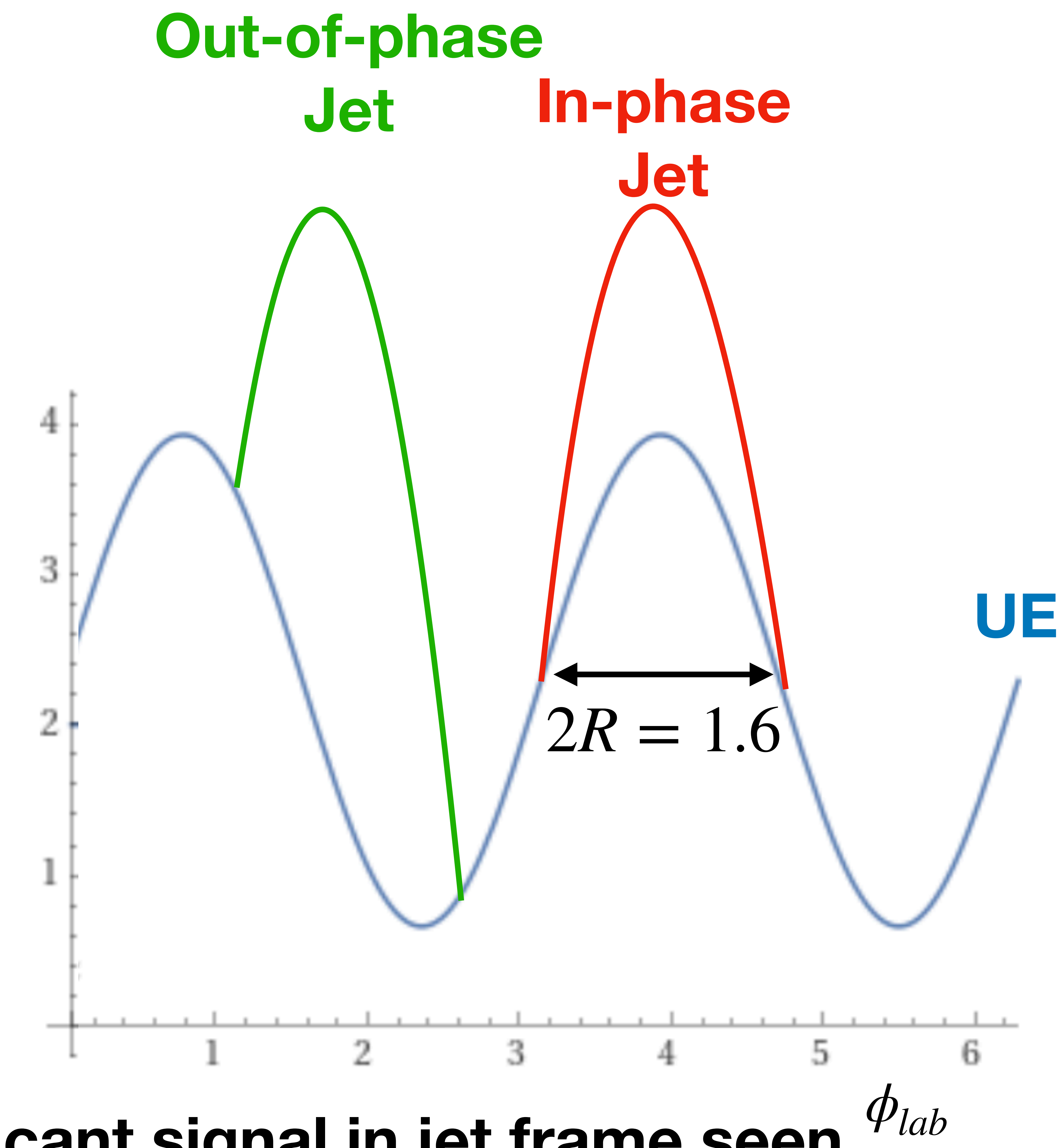




- **Can underlying event generate a signal?**
- **Inject signal into UE and study effect on signal**

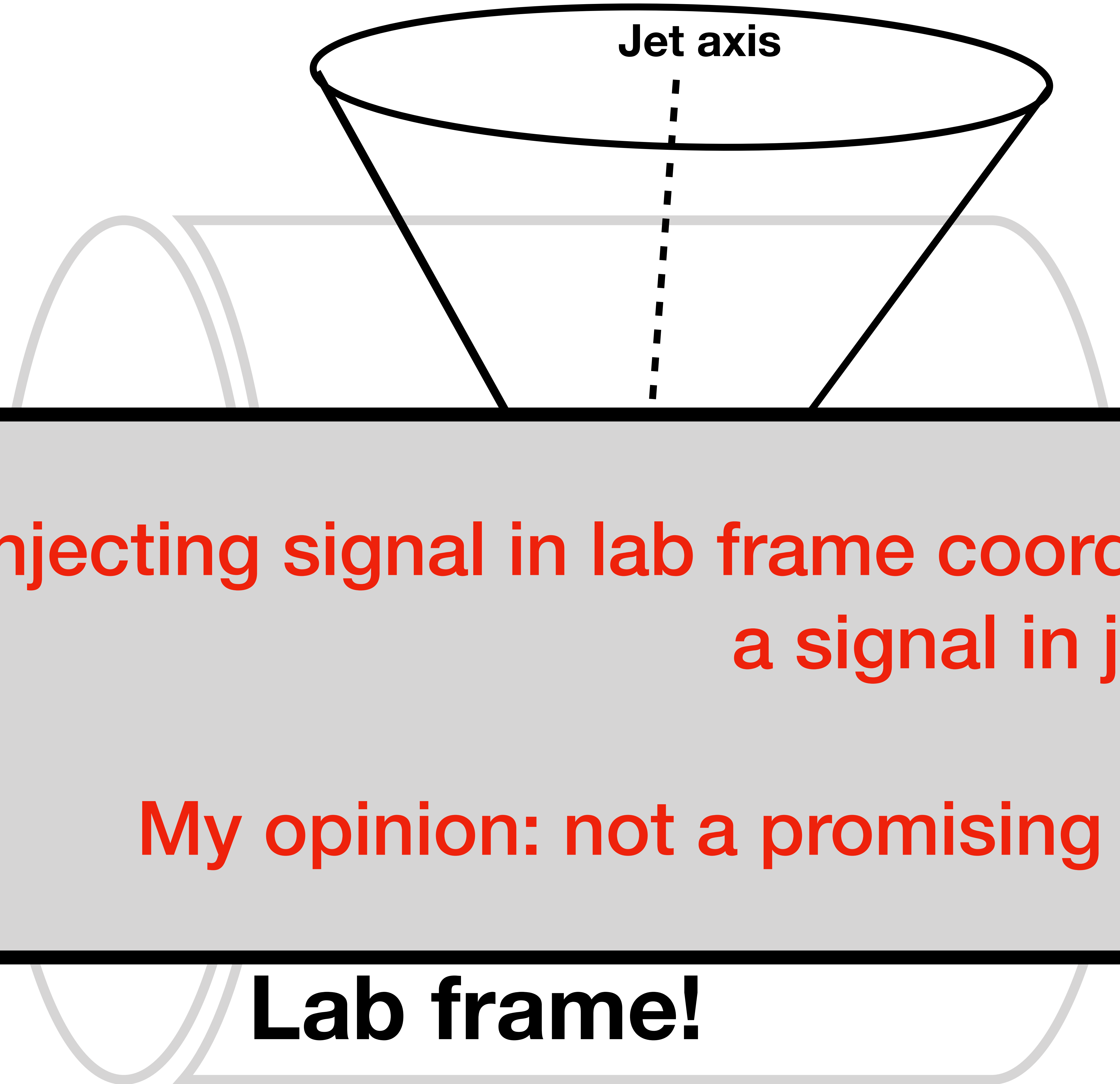
Underlying Event Explanation?

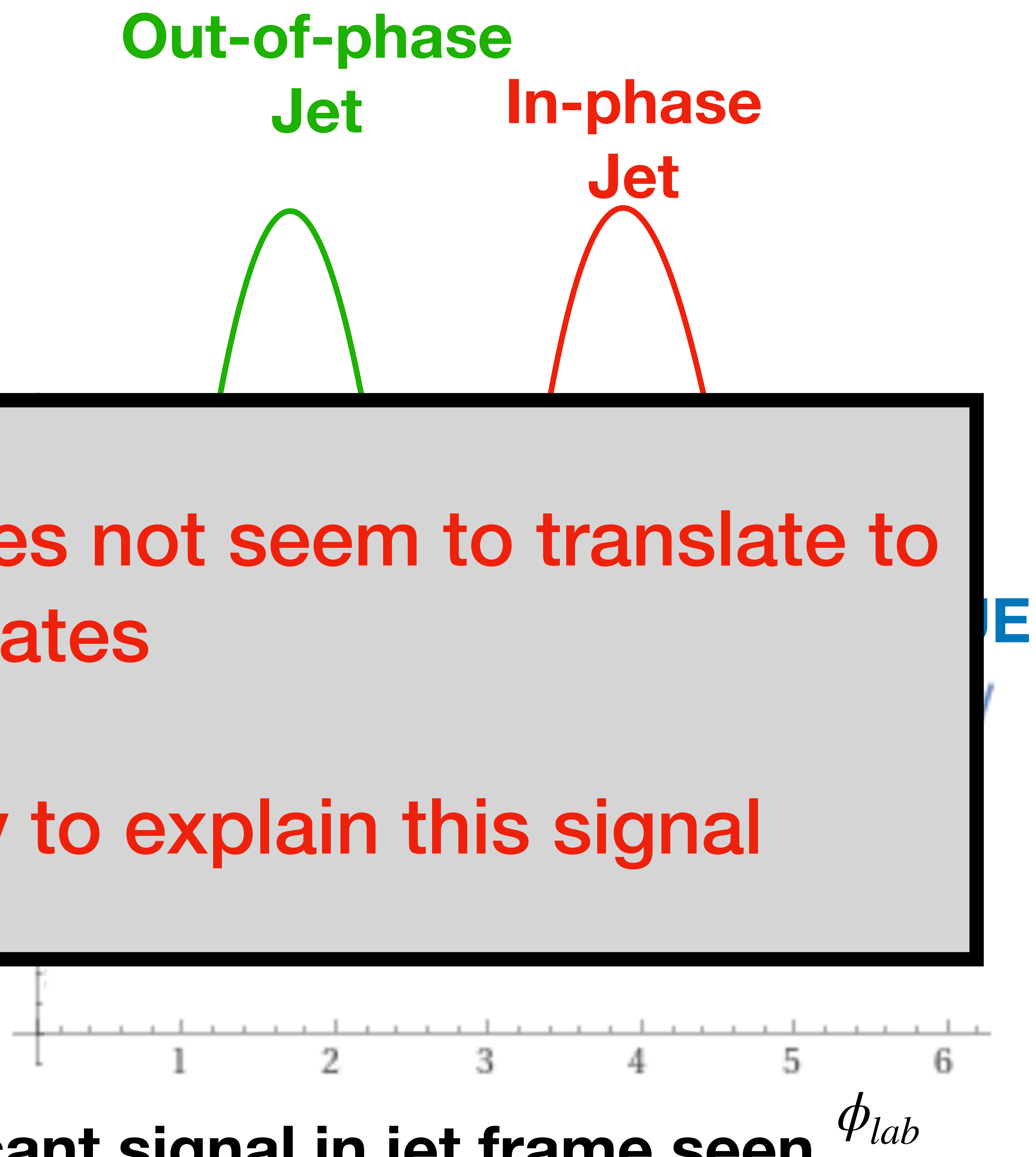




- **Regardless of phase between jet and UE, no significant signal in jet frame seen**
- **Different UE tunes also have no effect**

Underlying Event Explanation?





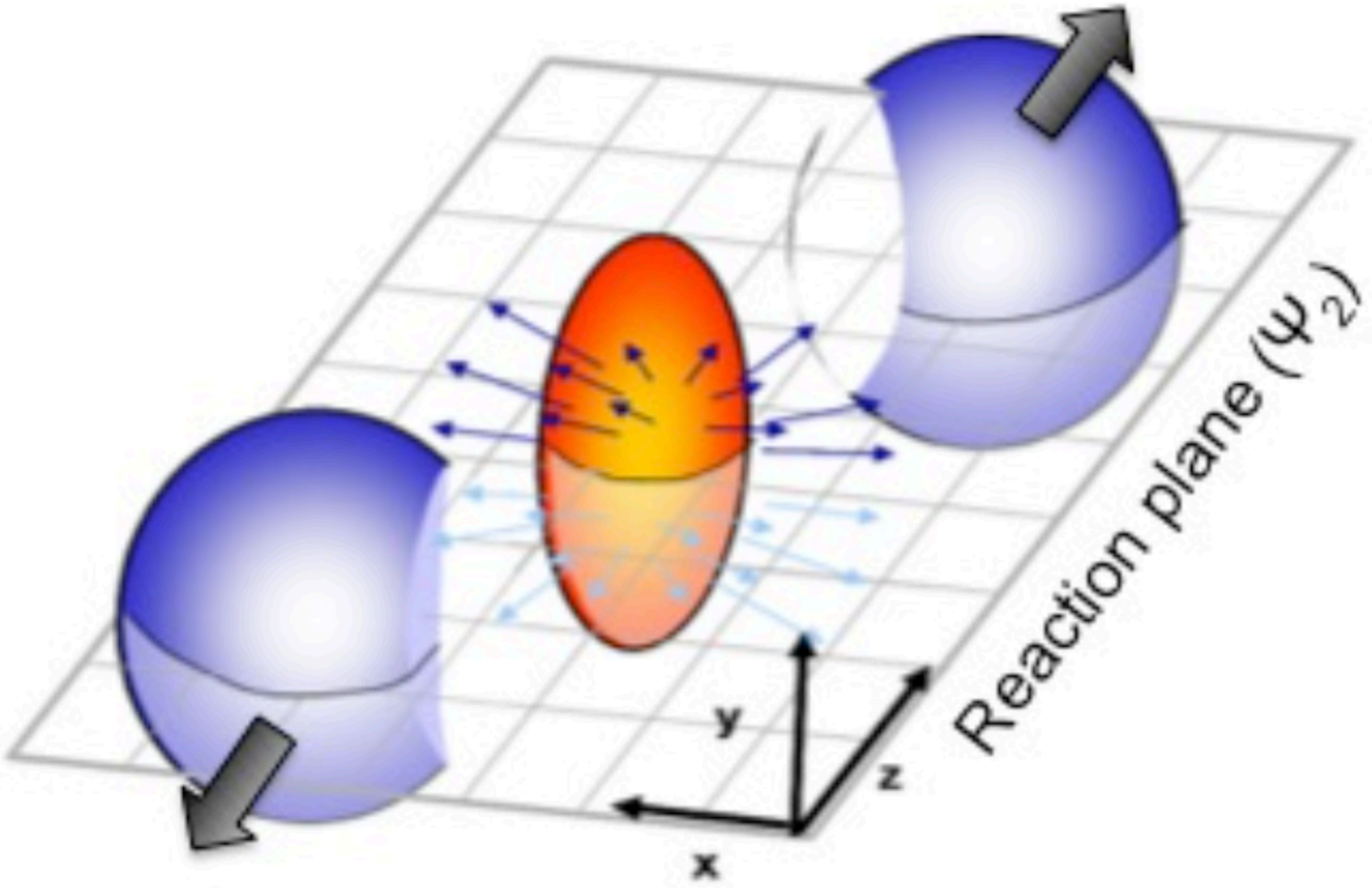
Injecting signal in lab frame coordinates does not seem to translate to a signal in jet coordinates

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**

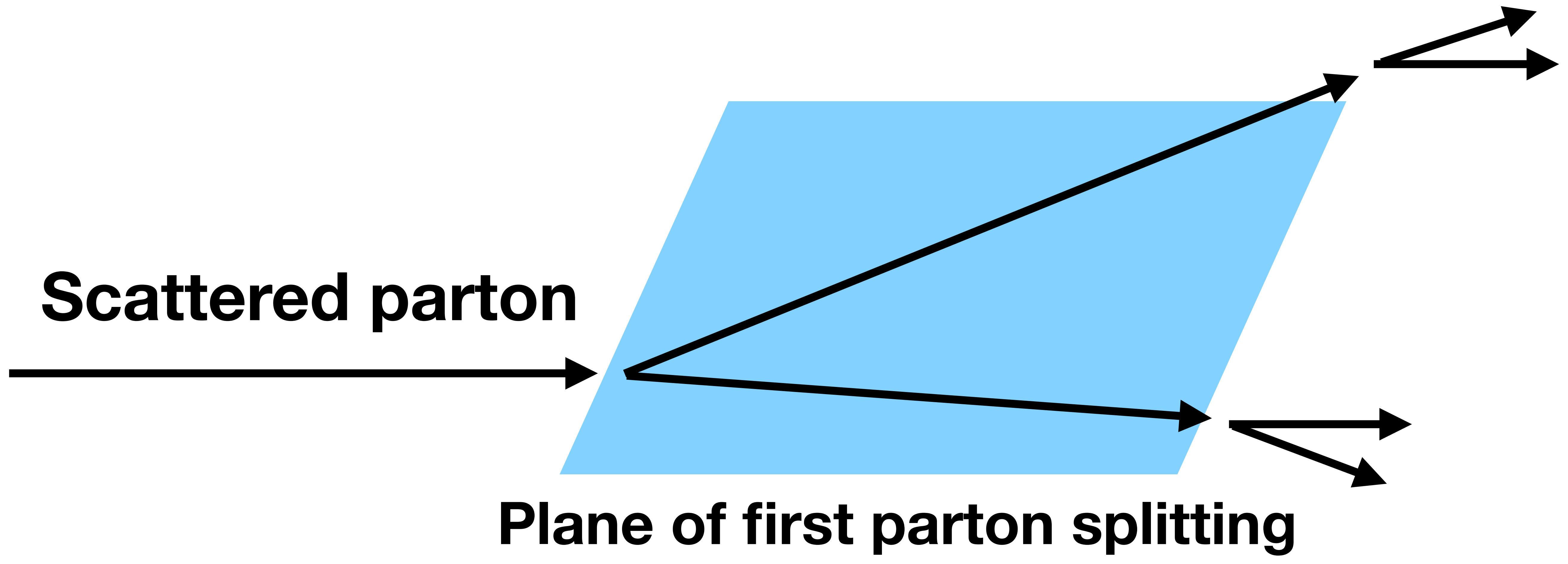
Preferred plane of production

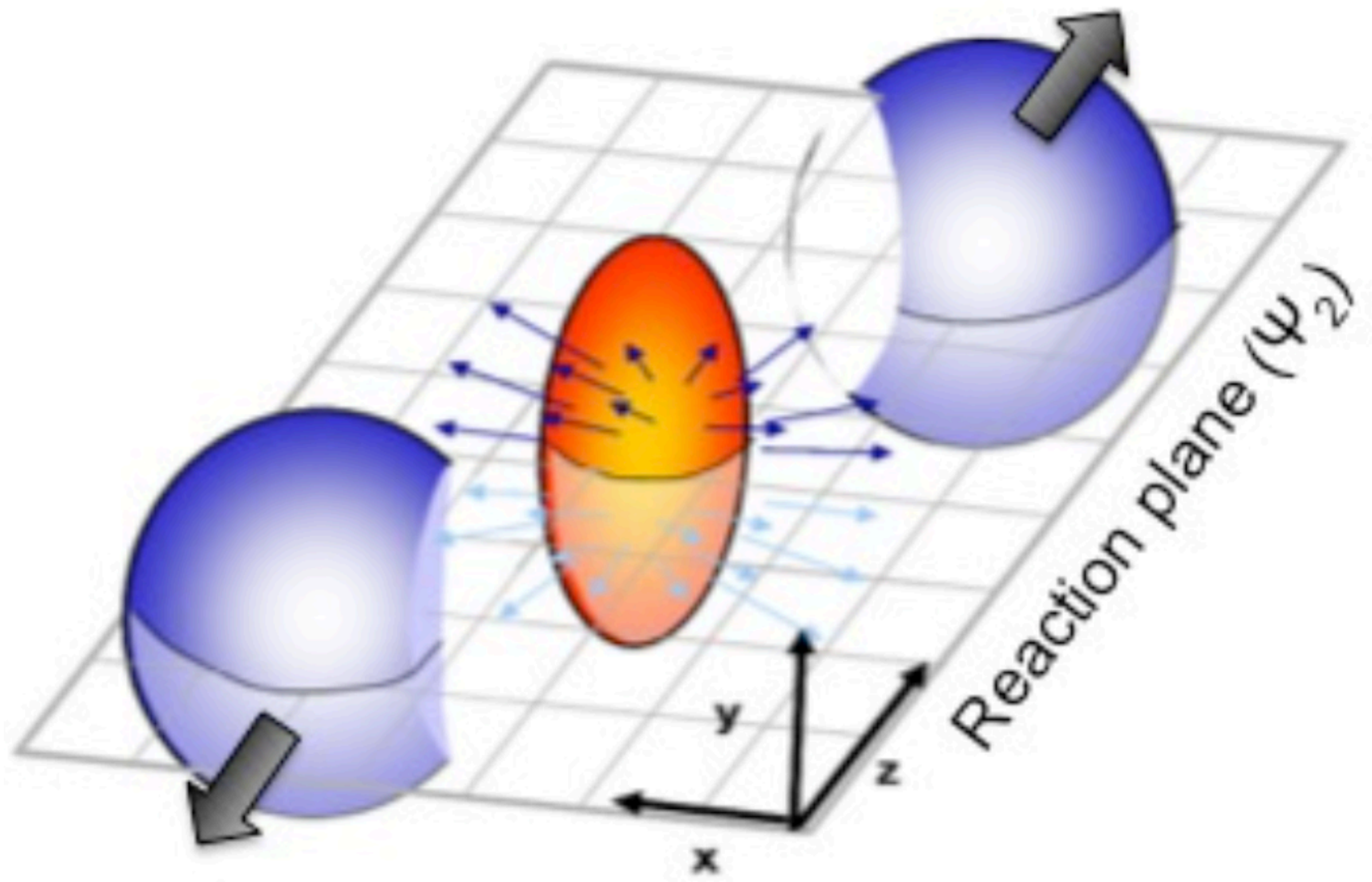
Scattered parton



- **Initially scattered parton has no preferred direction - azimuthal symmetry**
- **How is some 'preferred direction' generated (the "reaction plane")**

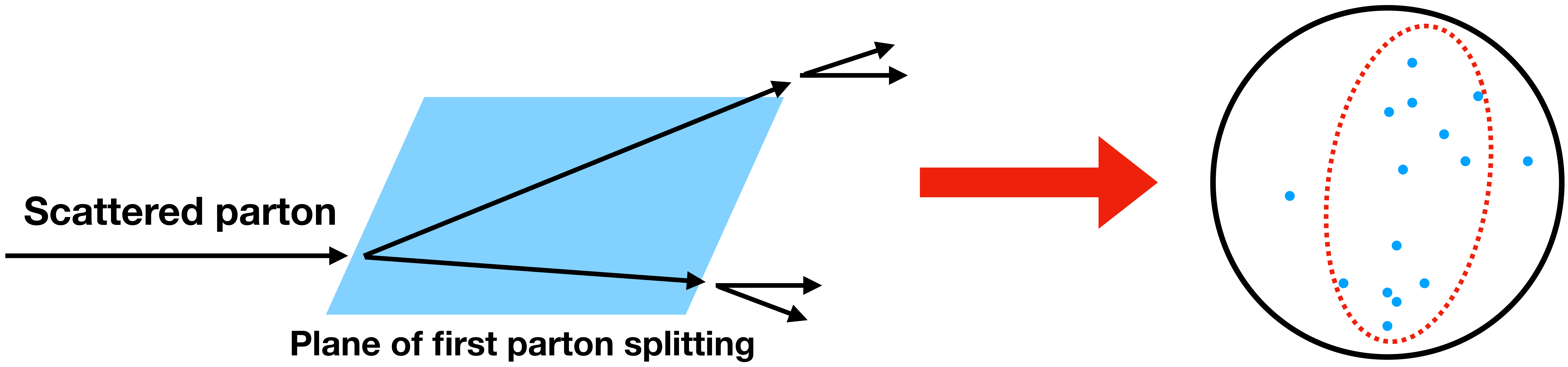
Preferred plane of production





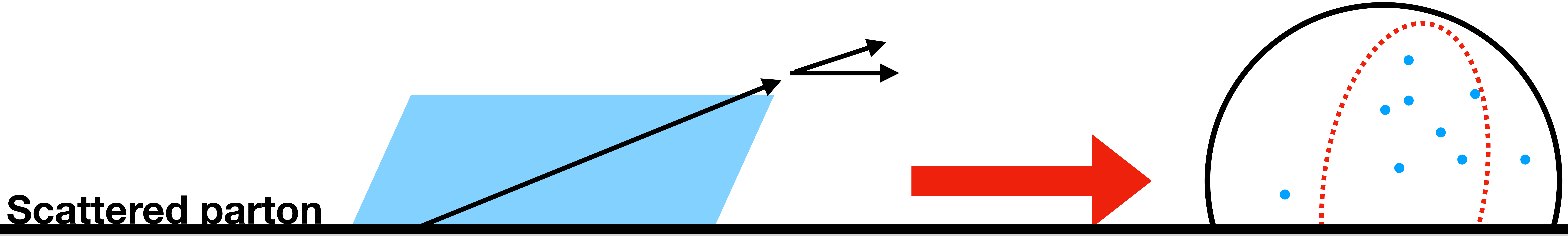
- Initially scattered parton has no preferred direction - azimuthal symmetry
- How is some ‘preferred direction’ generated (the “reaction plane”)
- First parton splitting in jet shower creates a preferred plane
  - From formation time arguments, this splitting will be harder/wider

Nonflow contributions



- Initially scattered parton has no preferred direction - azimuthal symmetry
- How is some ‘preferred direction’ generated (the “reaction plane”)
- First parton splitting in jet shower creates a preferred plane
  - From formation time arguments, this splitting will be harder/wider
- First and subsequent splittings result in final particle distribution - governed by pQCD

Nonflow contributions

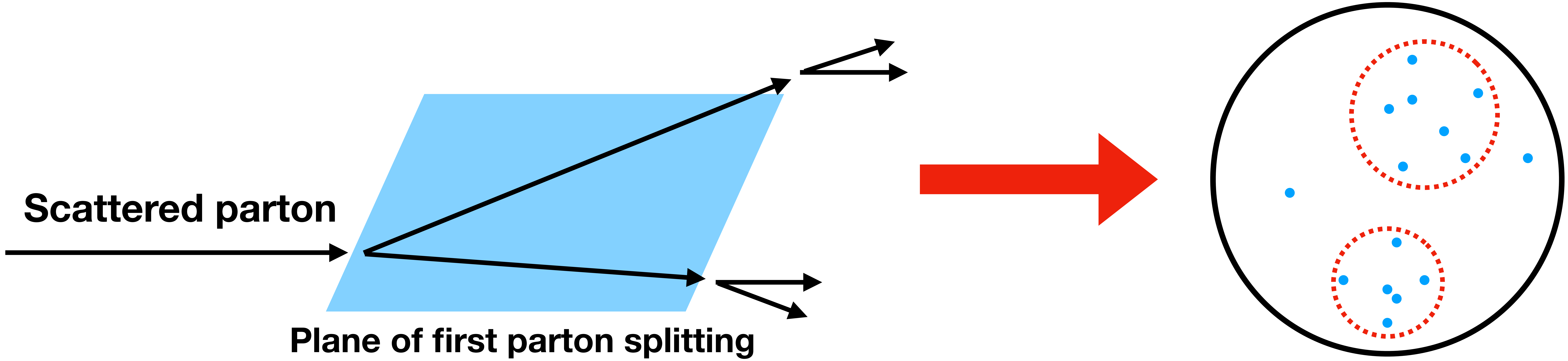


“Nonflow” in jet coordinate frame has huge component from well-understood pQCD jet evolution.

Direct connection with existing HEP studies, with the caveat that extremely high-multiplicity jets are understudied

- First parton splitting in jet shower creates a preferred plane
  - From formation time arguments, this splitting will be harder/wider
- First and subsequent splittings result in final particle distribution - governed by pQCD

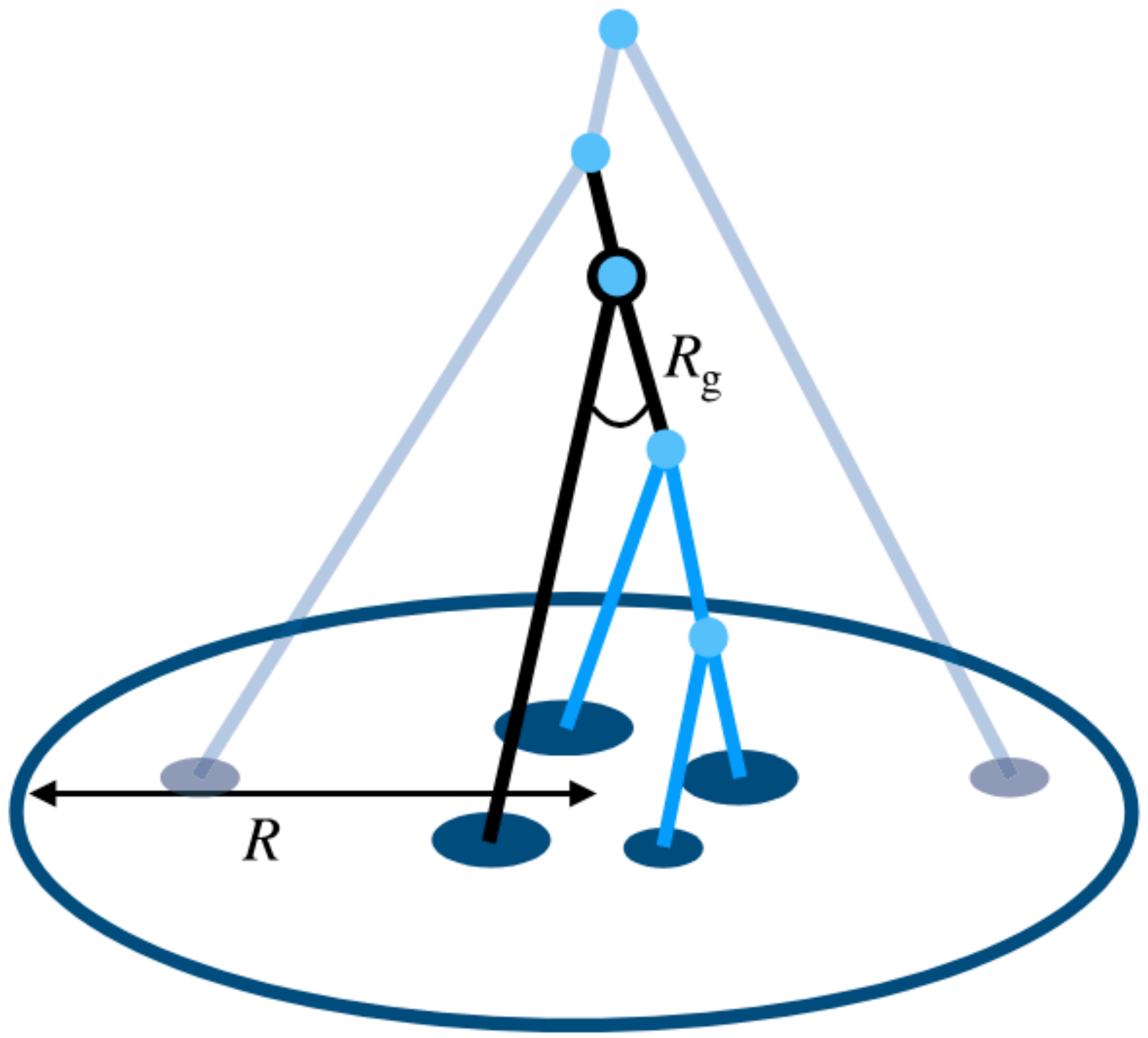
Nonflow contributions



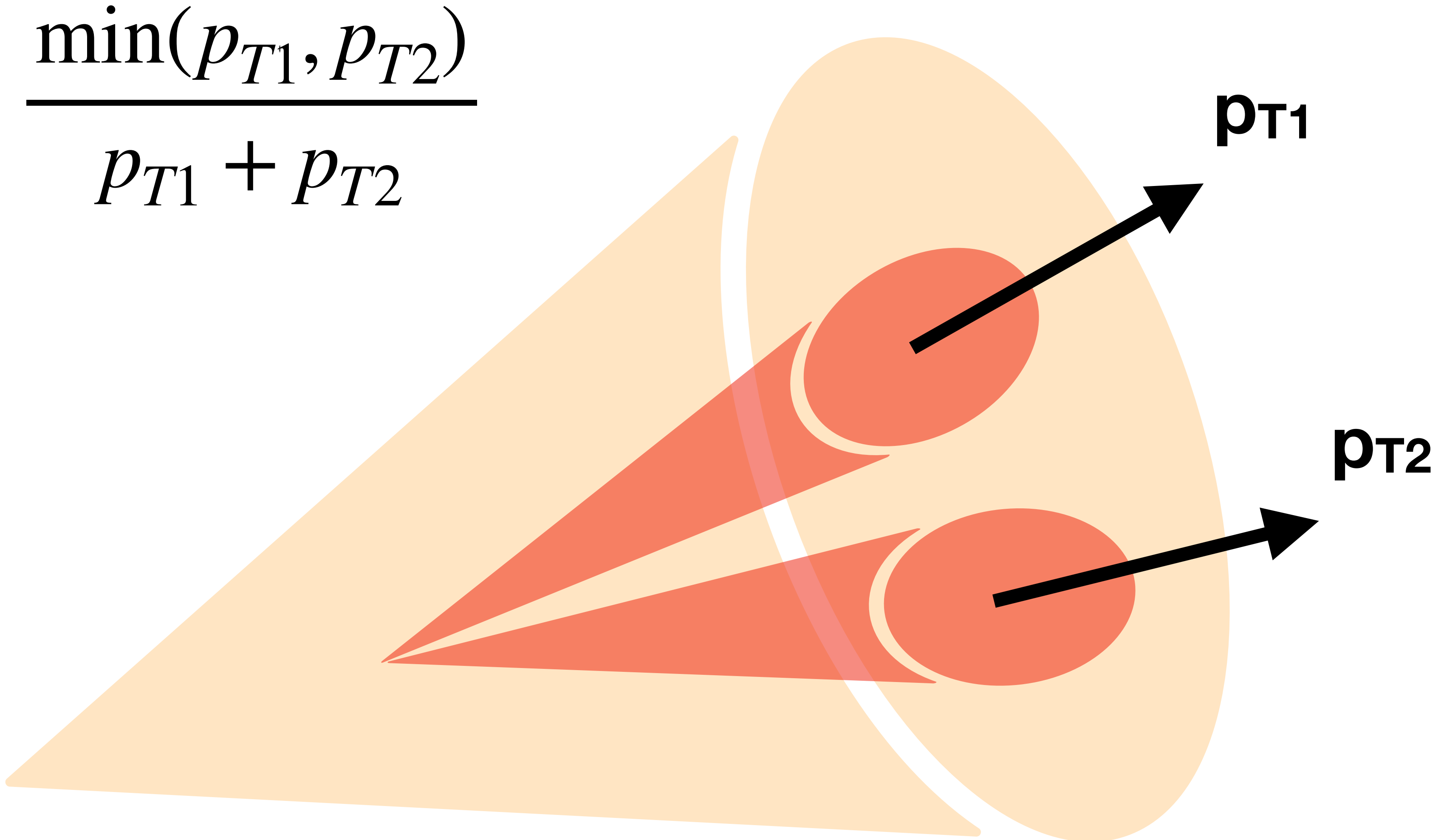
- **Another way of looking at this picture - studying substructure of jets**

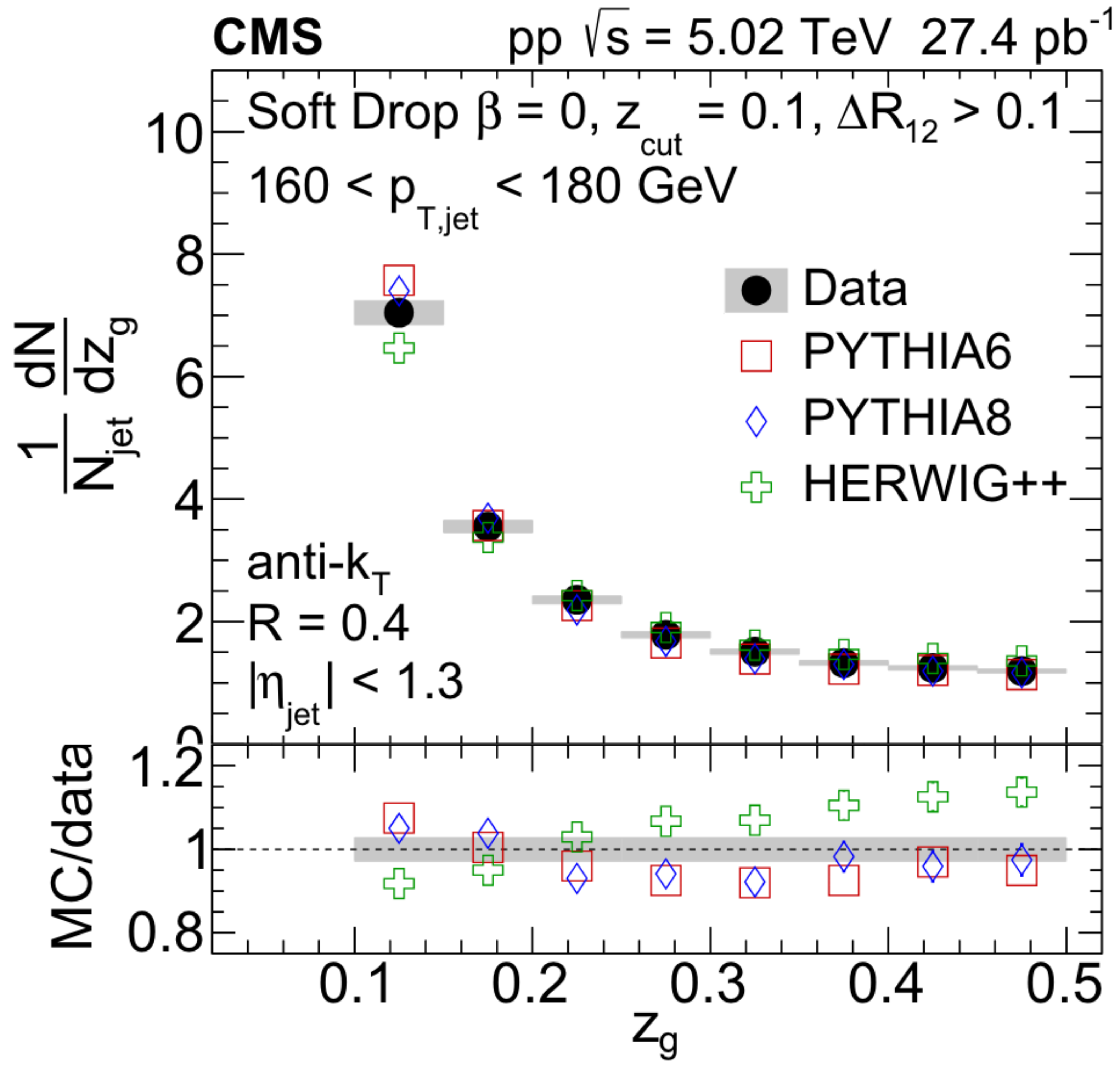
Relation to jet substructure

PRL 128, 102001 (2022)



$$z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}}$$

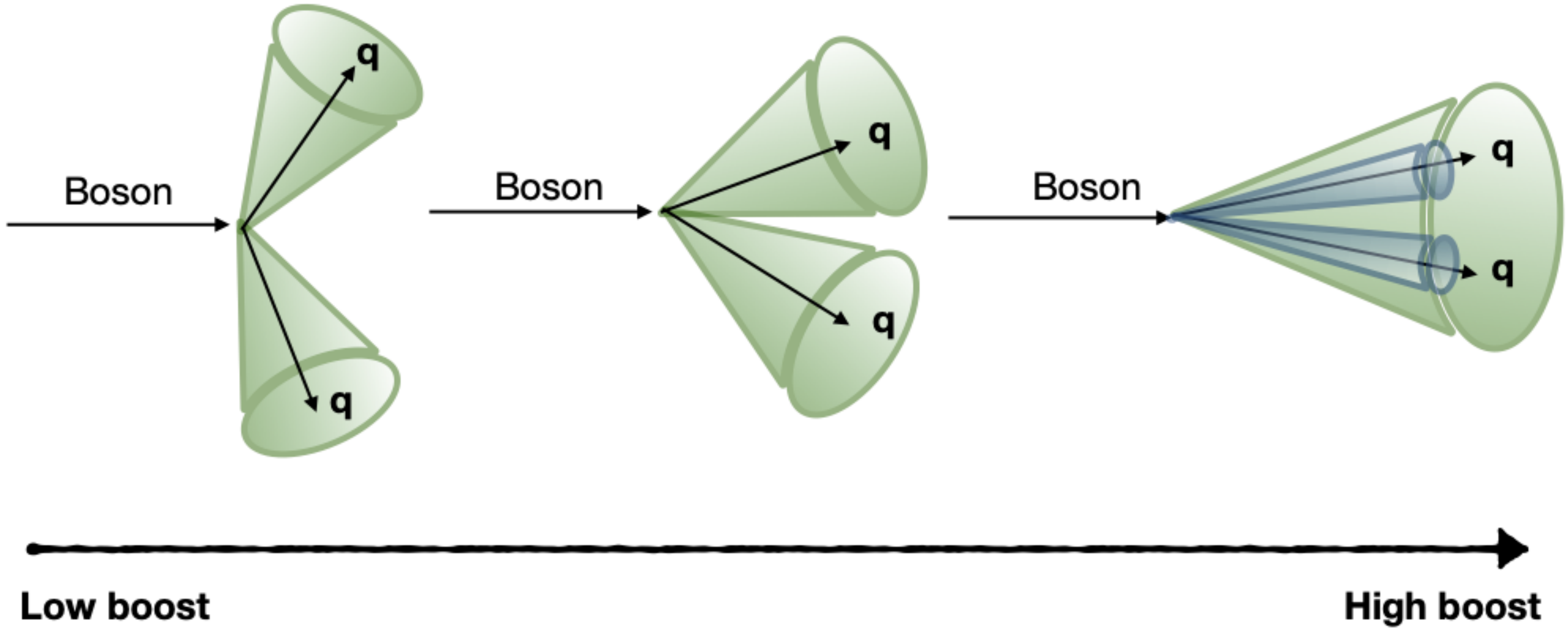


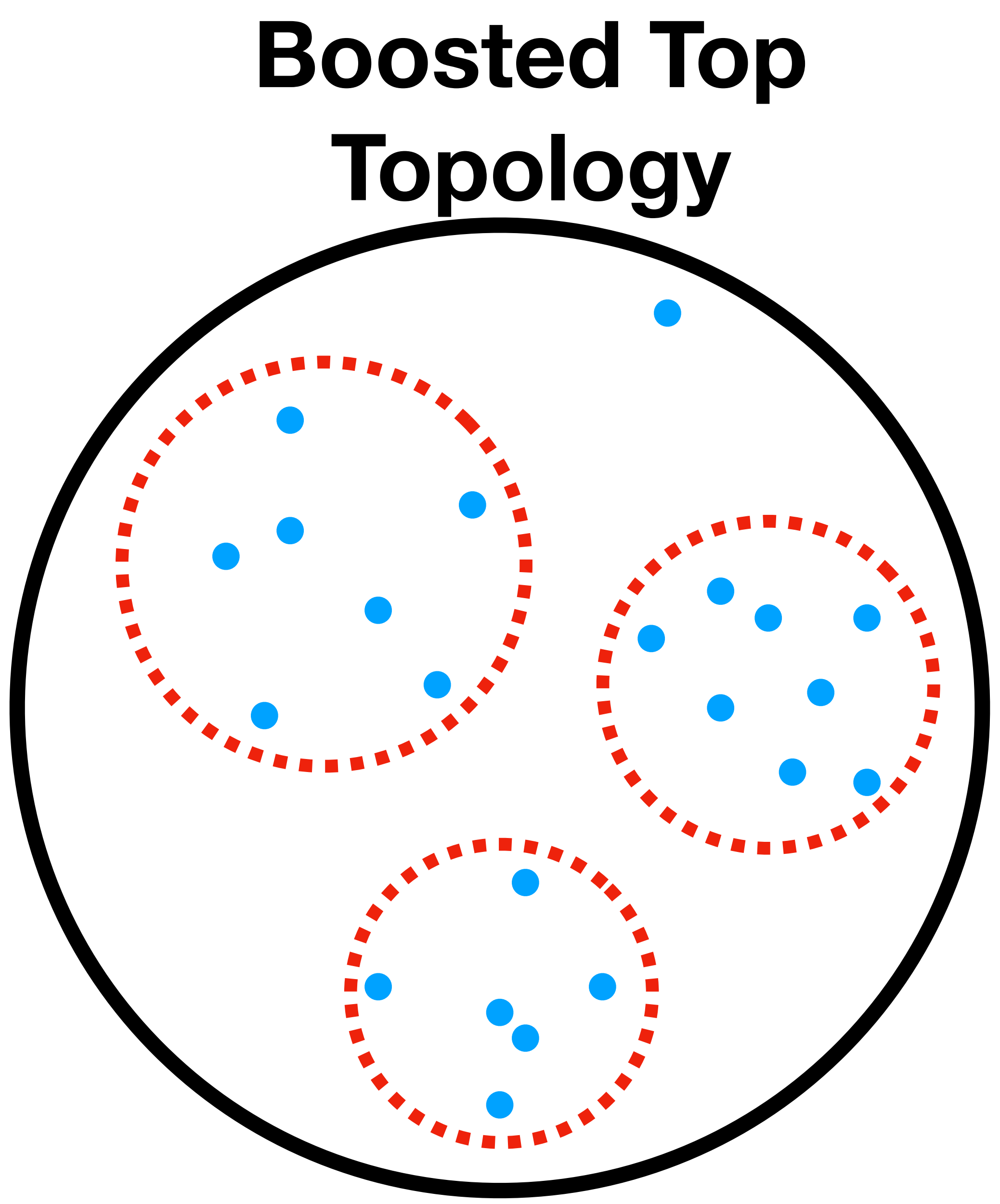


PRL 120, 142302 (2018)

- 2-pronged structure of jets well-studied with groomed substructure observables now
- Grooming removes soft emissions
  - What happens to high-multiplicity jets with different grooming settings?
  - Is v_2 related to multiple hard cores within a jet, or more uniform particle production?

Boosted Topologies



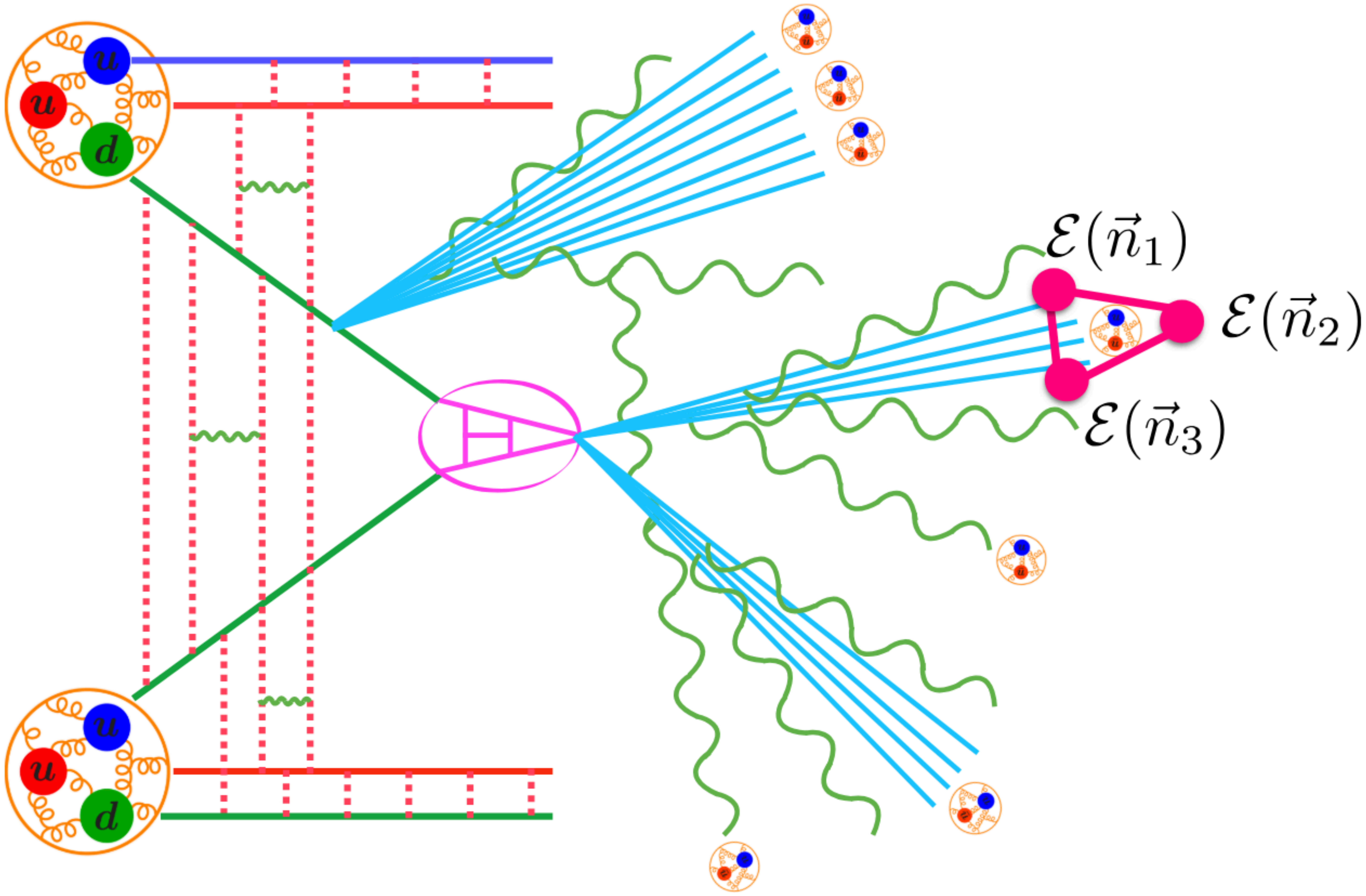


- **Hadronic decays from boosted W/Z could give 2-prong structure**
  - **Very rare, but so are high-multiplicity jets!**
- **Boosted top also possible contribution**
  - **Top known to produce higher constituent multiplicities (large mass)**
- **What fraction of high-multiplicity jets are W/top tagged?**

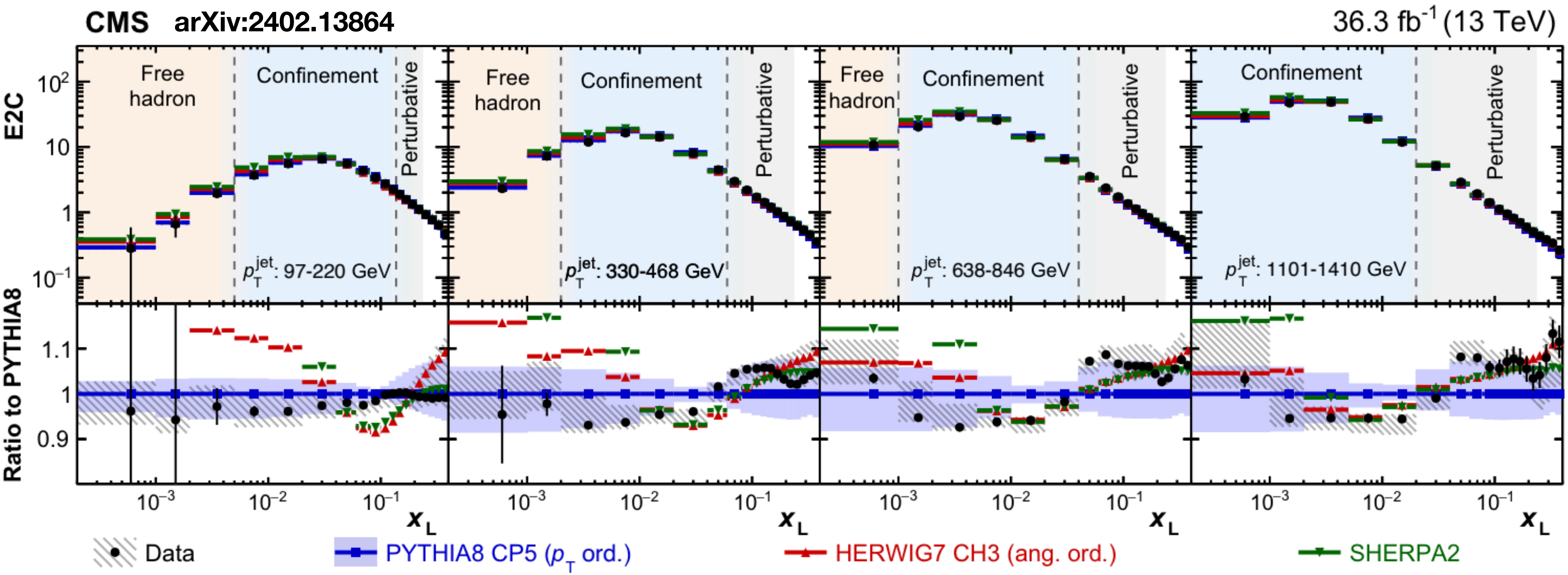
Energy-energy correlators

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**



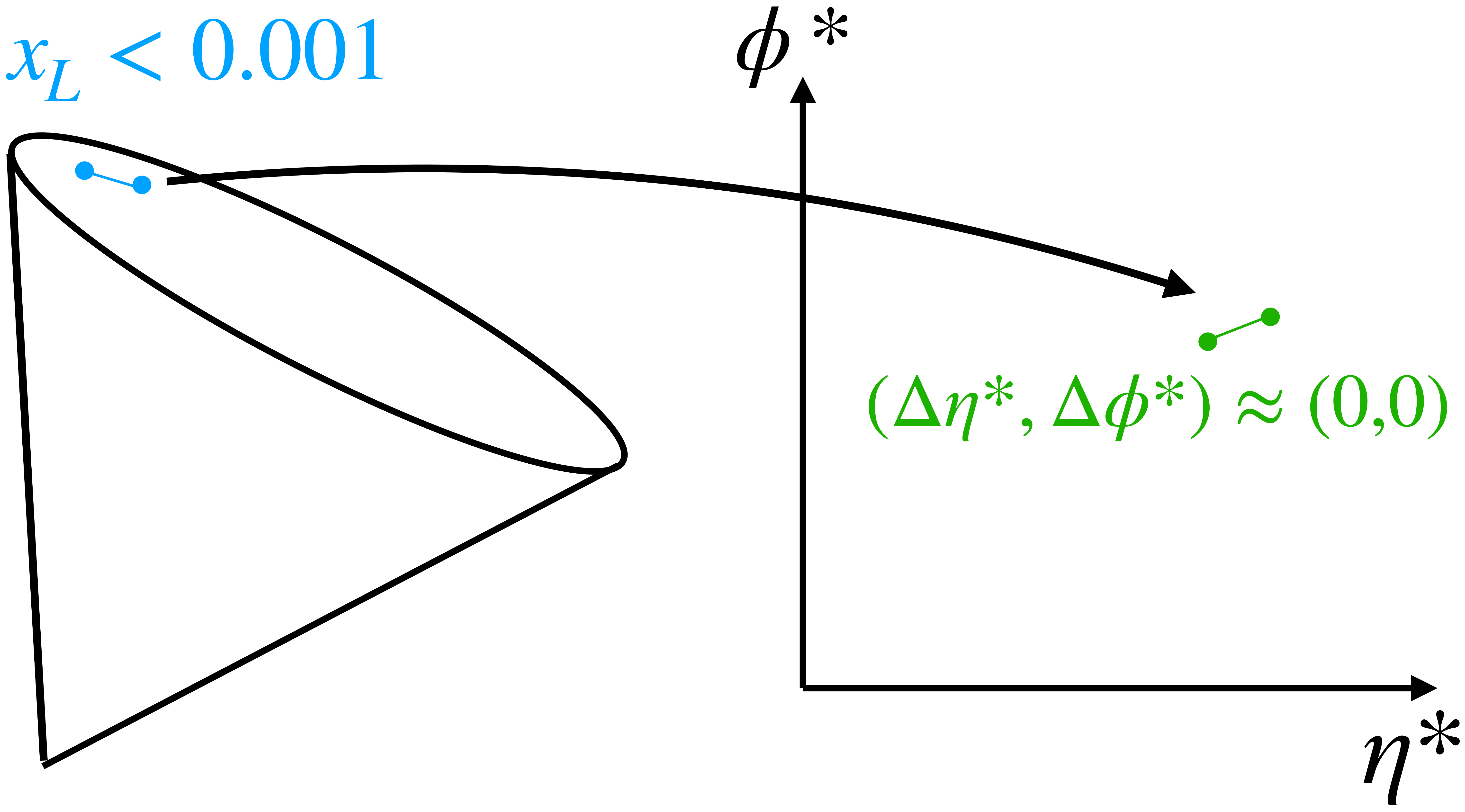
2-point pp Energy-energy correlators



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

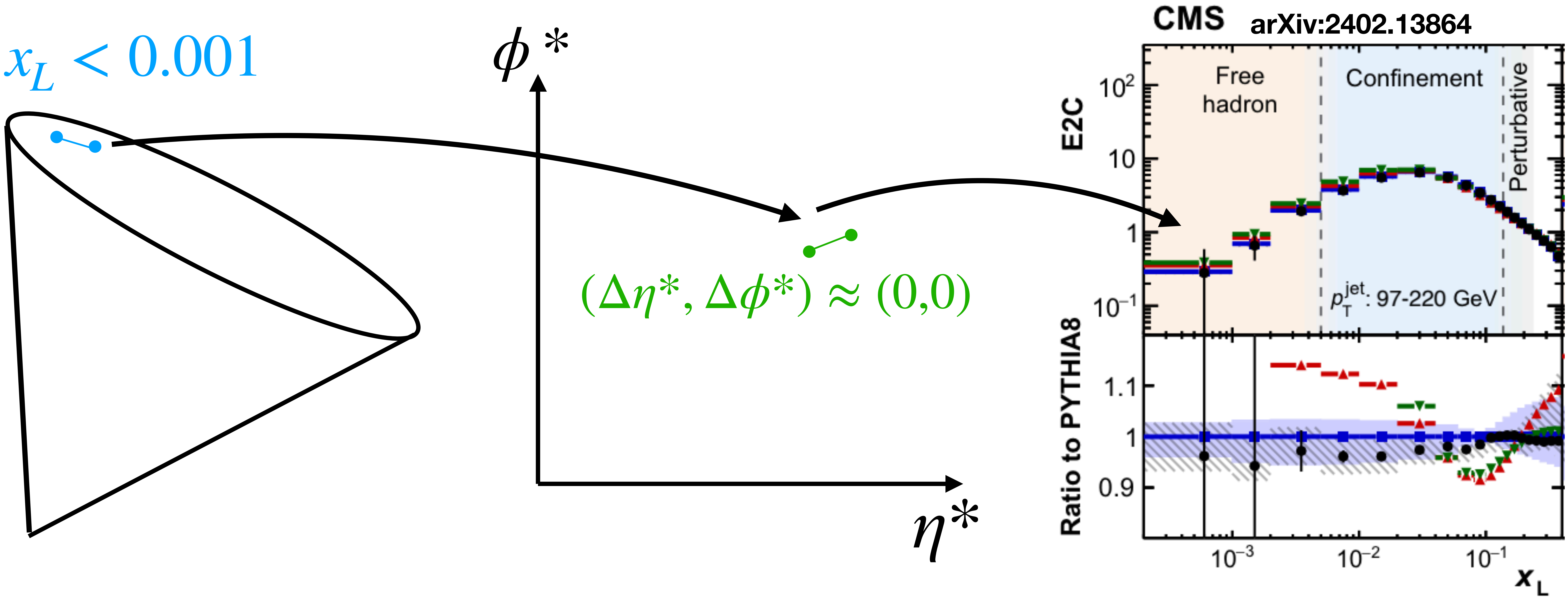
$$x_L = \Delta r_{i,j} = \sqrt{\Delta\phi_{lab}^2 + \Delta\eta_{lab}^2}$$

Mapping between coordinates



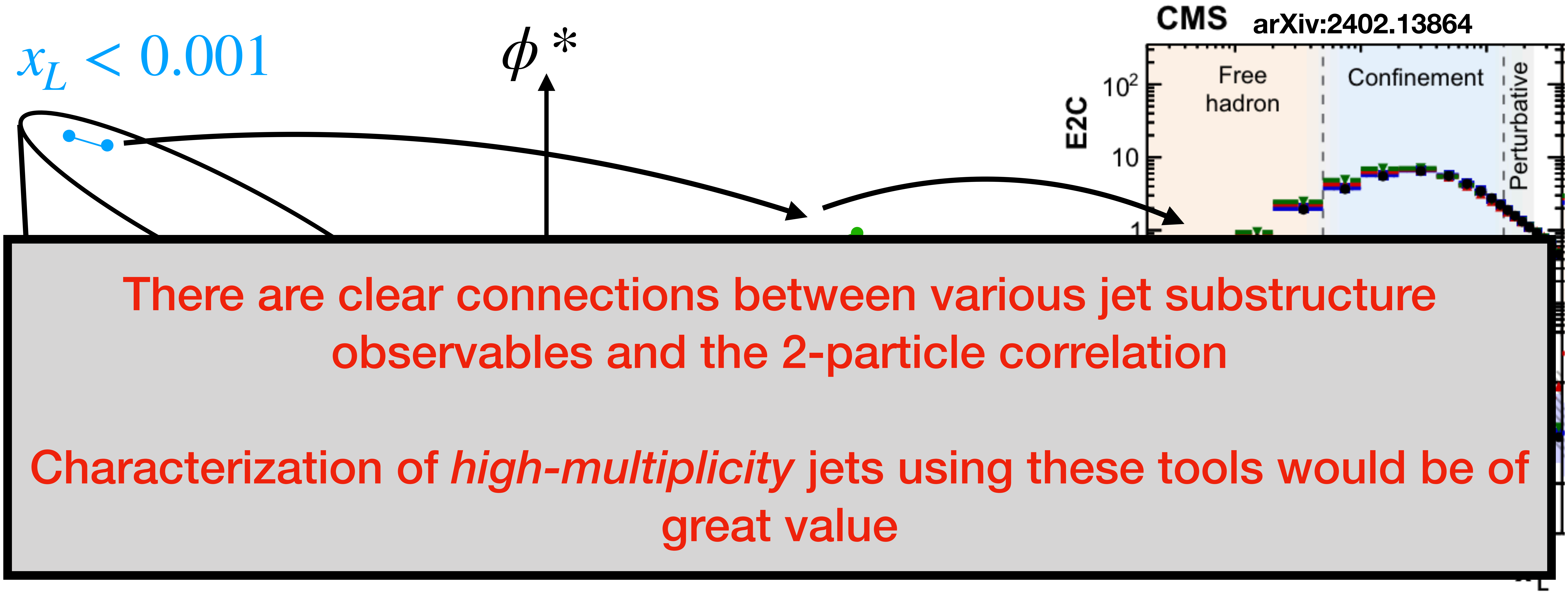
- **Particles close to each other in lab frame are also close to each other in jet coordinates**

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



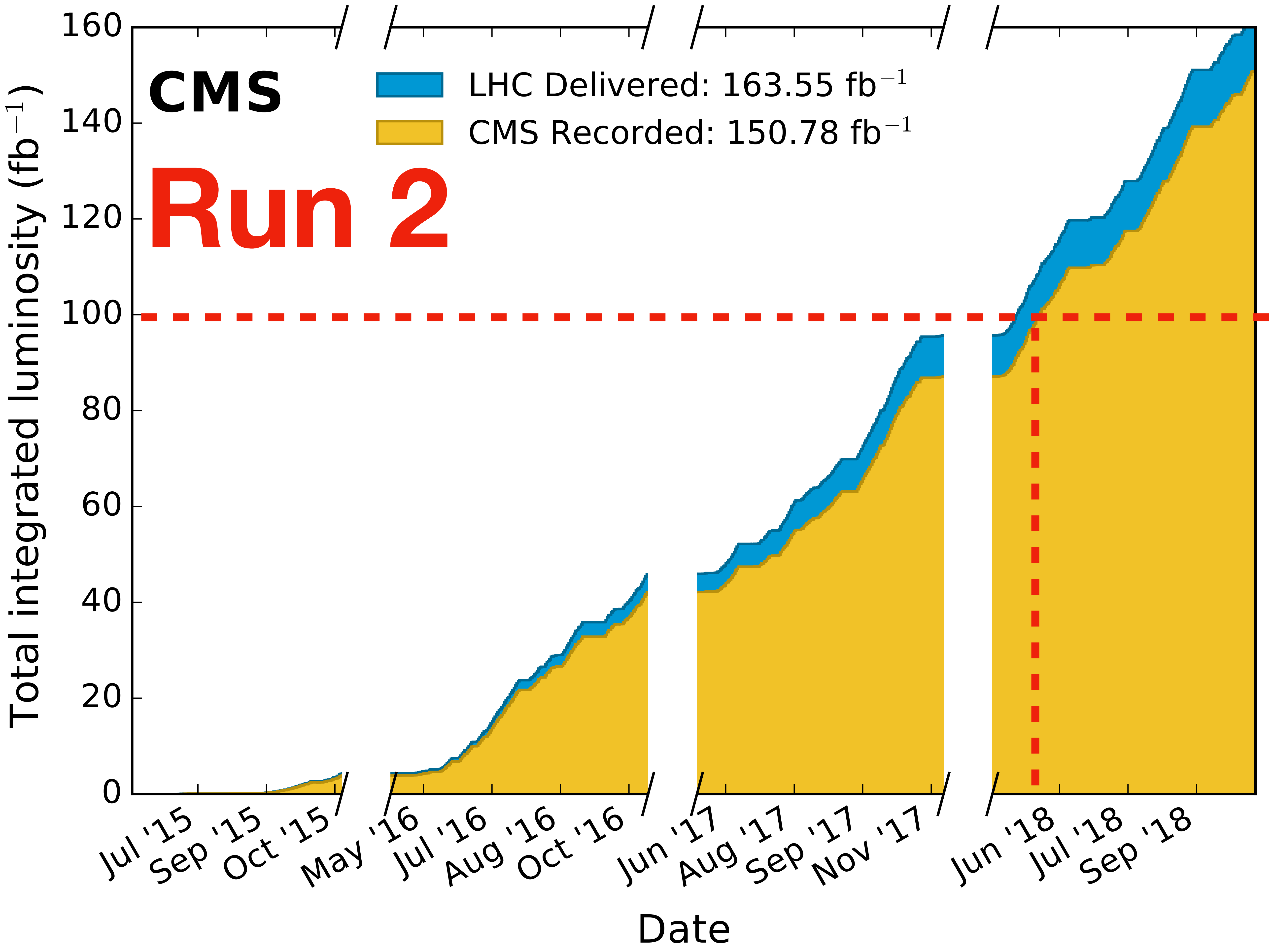
There are clear connections between various jet substructure observables and the 2-particle correlation

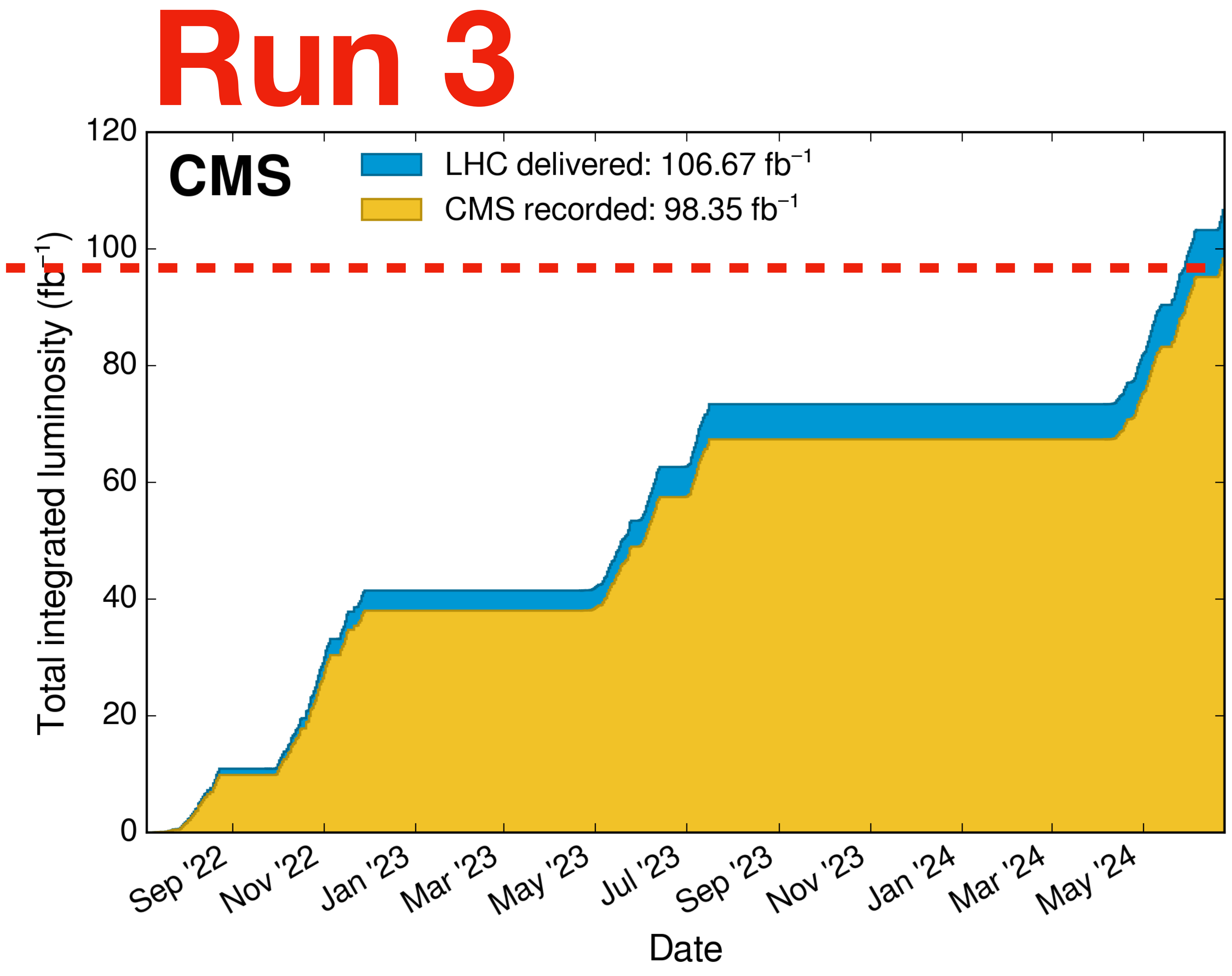
Characterization of *high-multiplicity* jets using these tools would be of great value

- **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**

Run 3 status

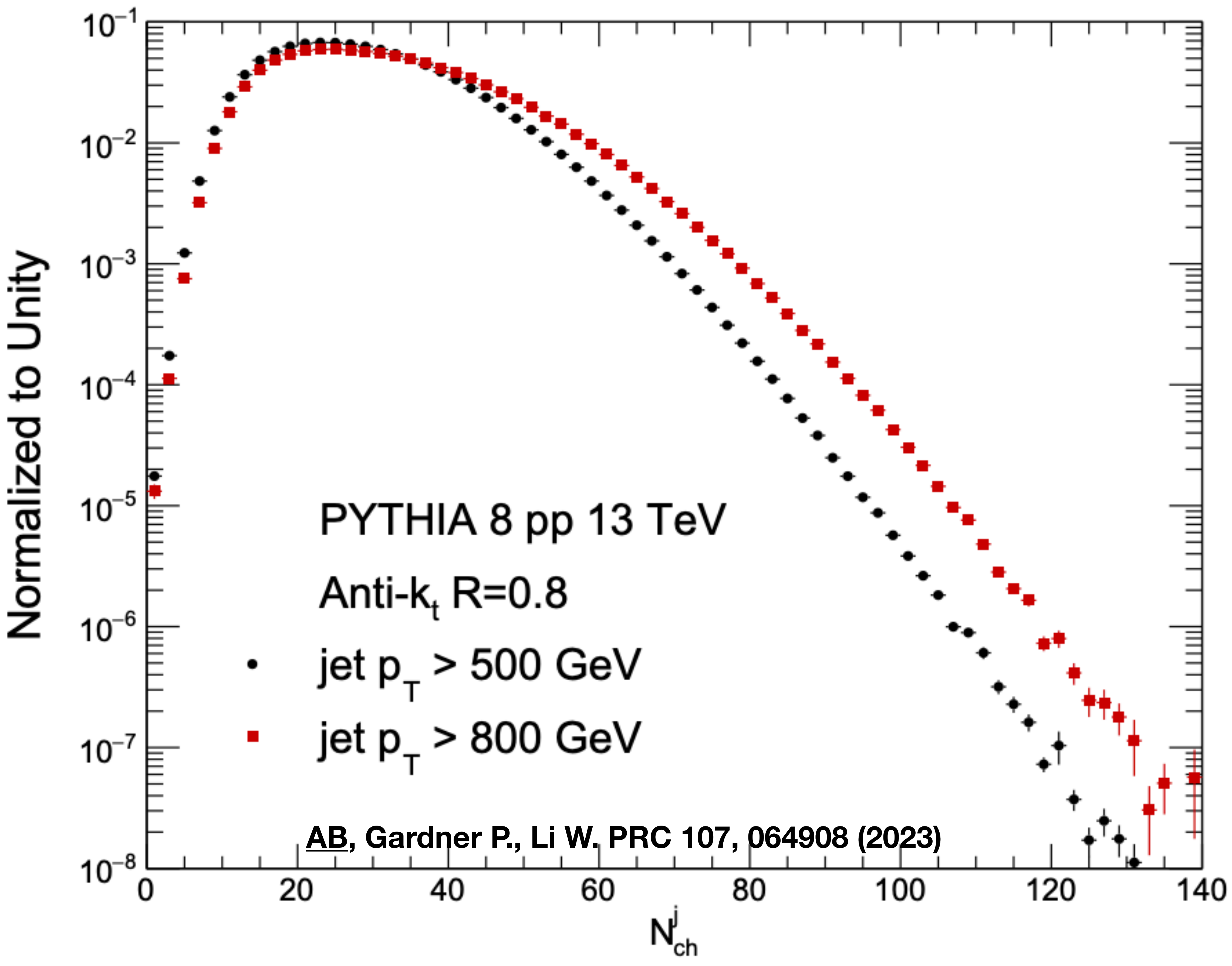
- **Run 3 lumi quickly increasing**
- **Will be challenging to have >2x Run 2 lumi**





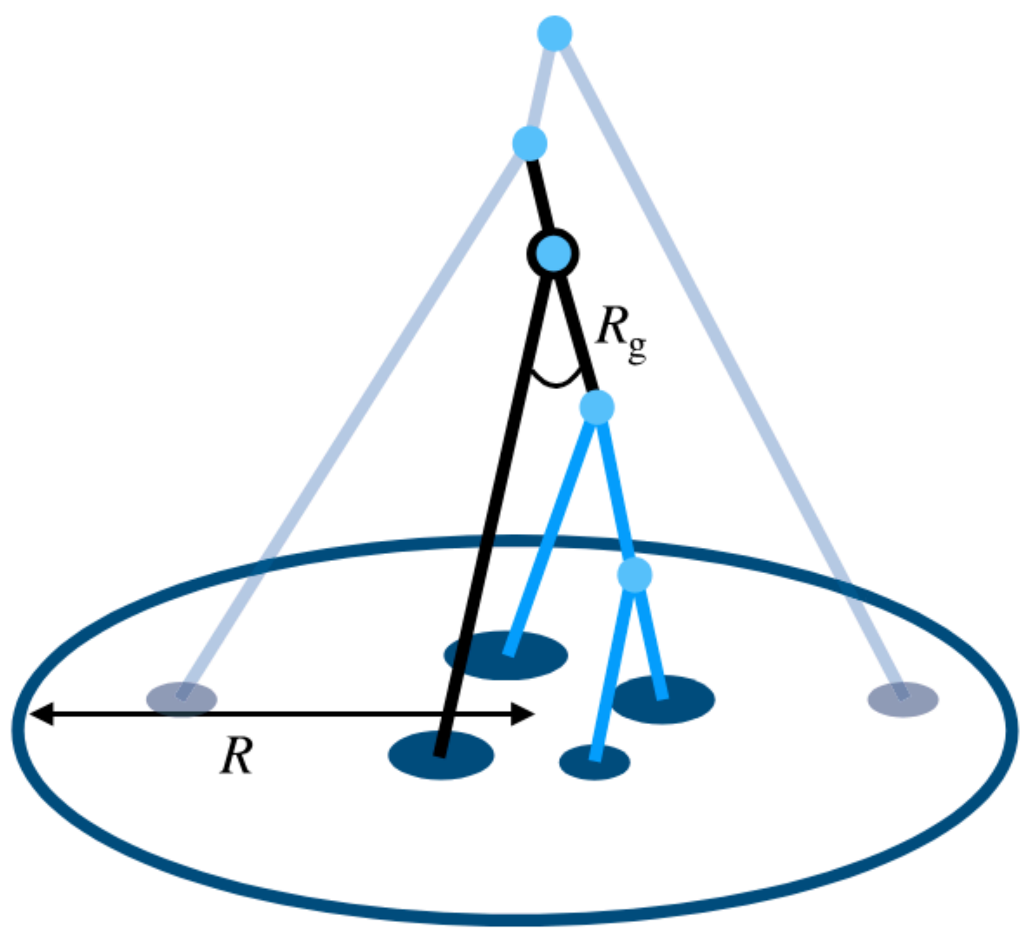
Future Directions

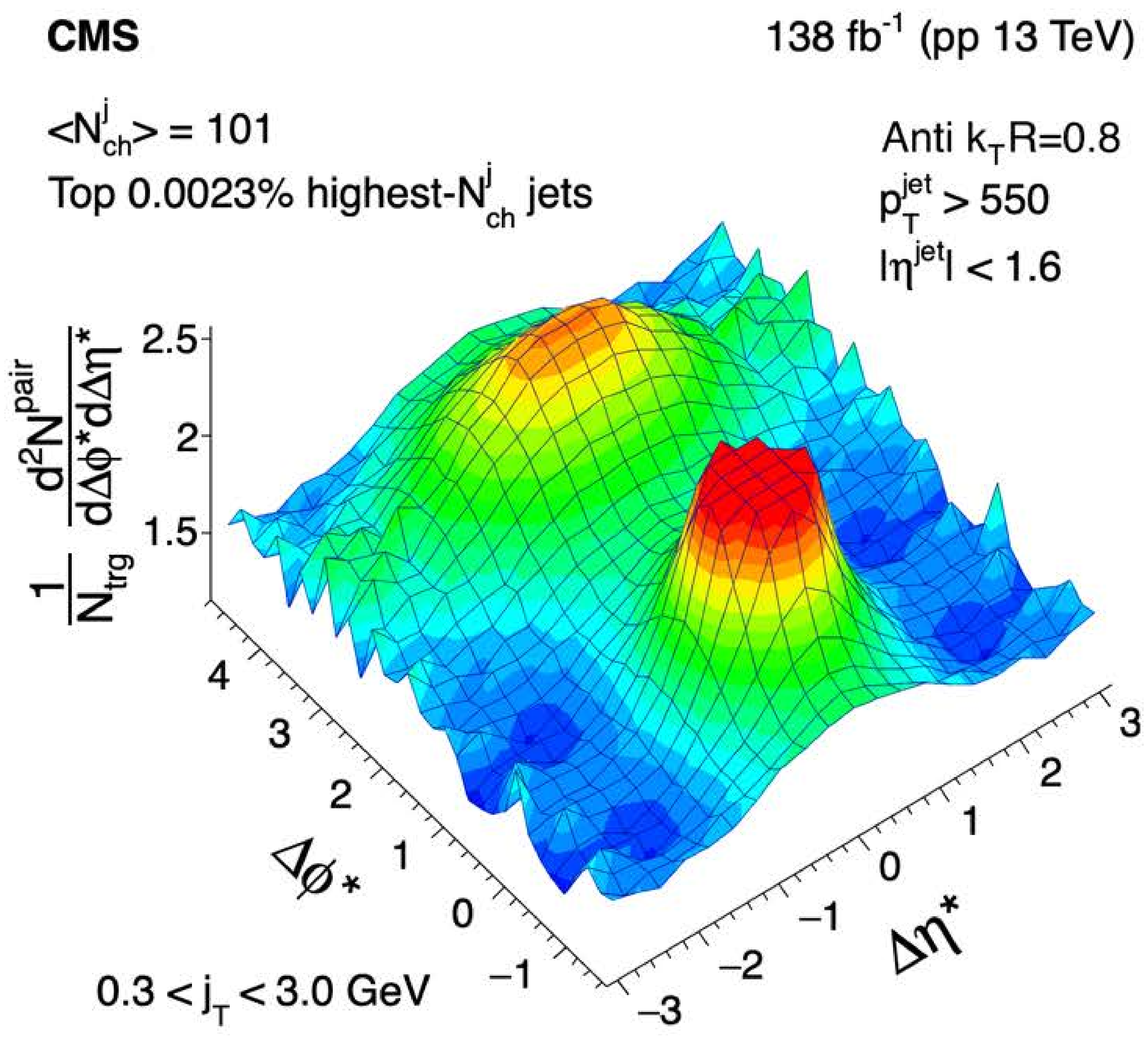
- **Leveraging Run 3 data**
- **Increasing multiplicity reach**
  - **Lower-pt high-multiplicity jets?**
- **Characterization of high-multiplicity jets using substructure**
  - **W/top tagging**
  - **Grooming observables**
  - **Relation to EECs**
- **More input from theory also welcome!**

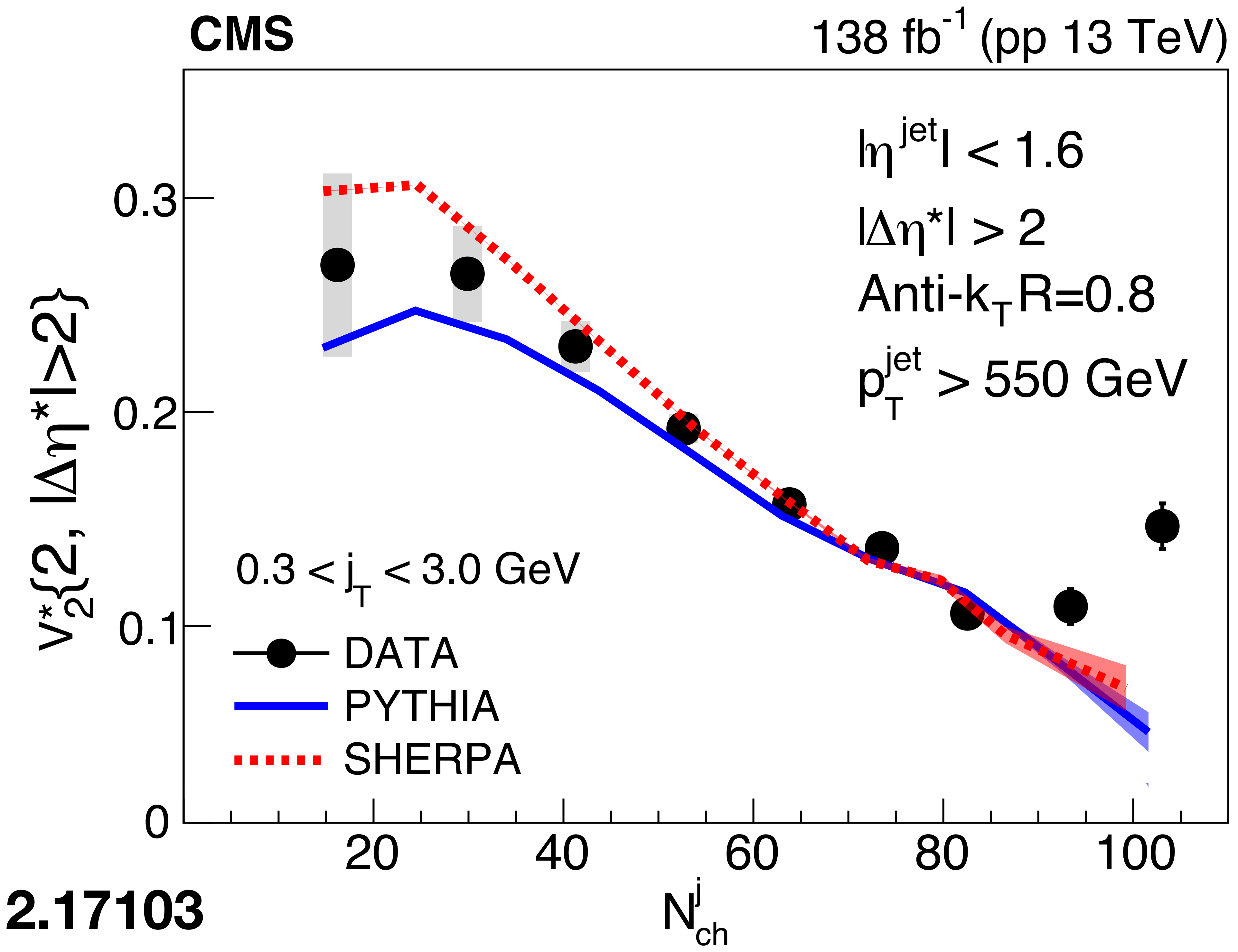


Summary

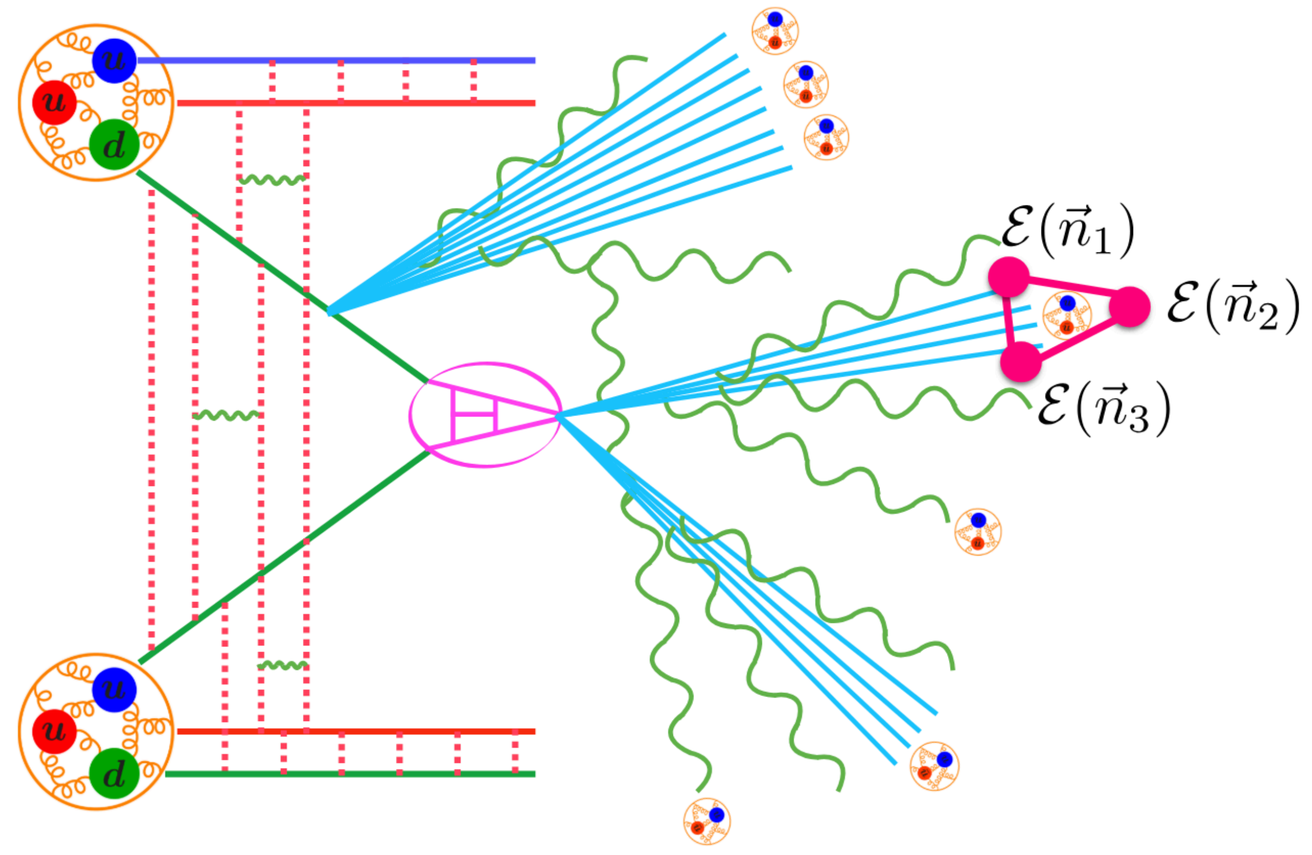
- **Interesting upward trend for in-jet v_2 for N_{ch}>80**
  - **Clear connections to substructure observables to understand pQCD ‘non flow’ contributions**
- **More studies of high-multiplicity jets needed!**







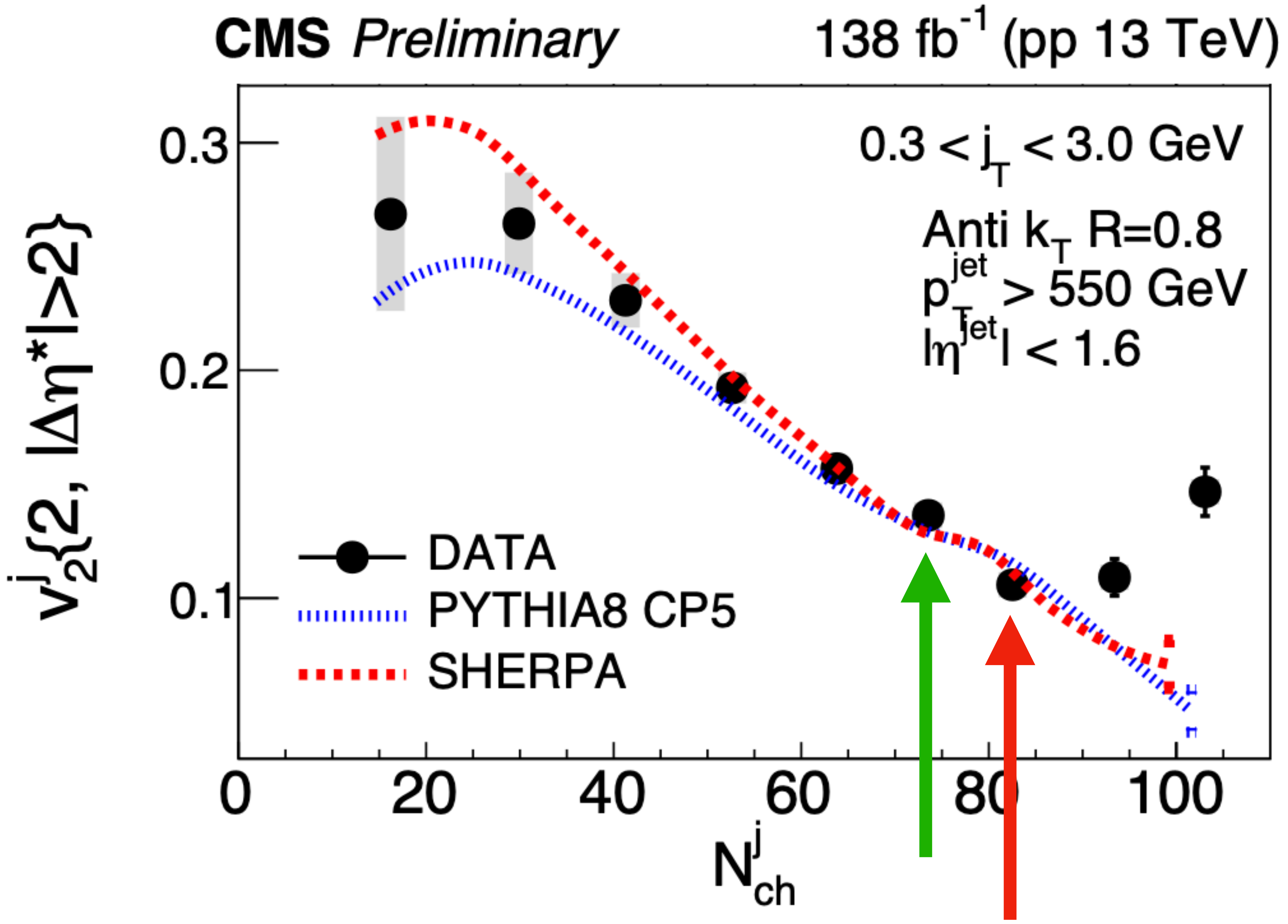
arXiv:2312.17103

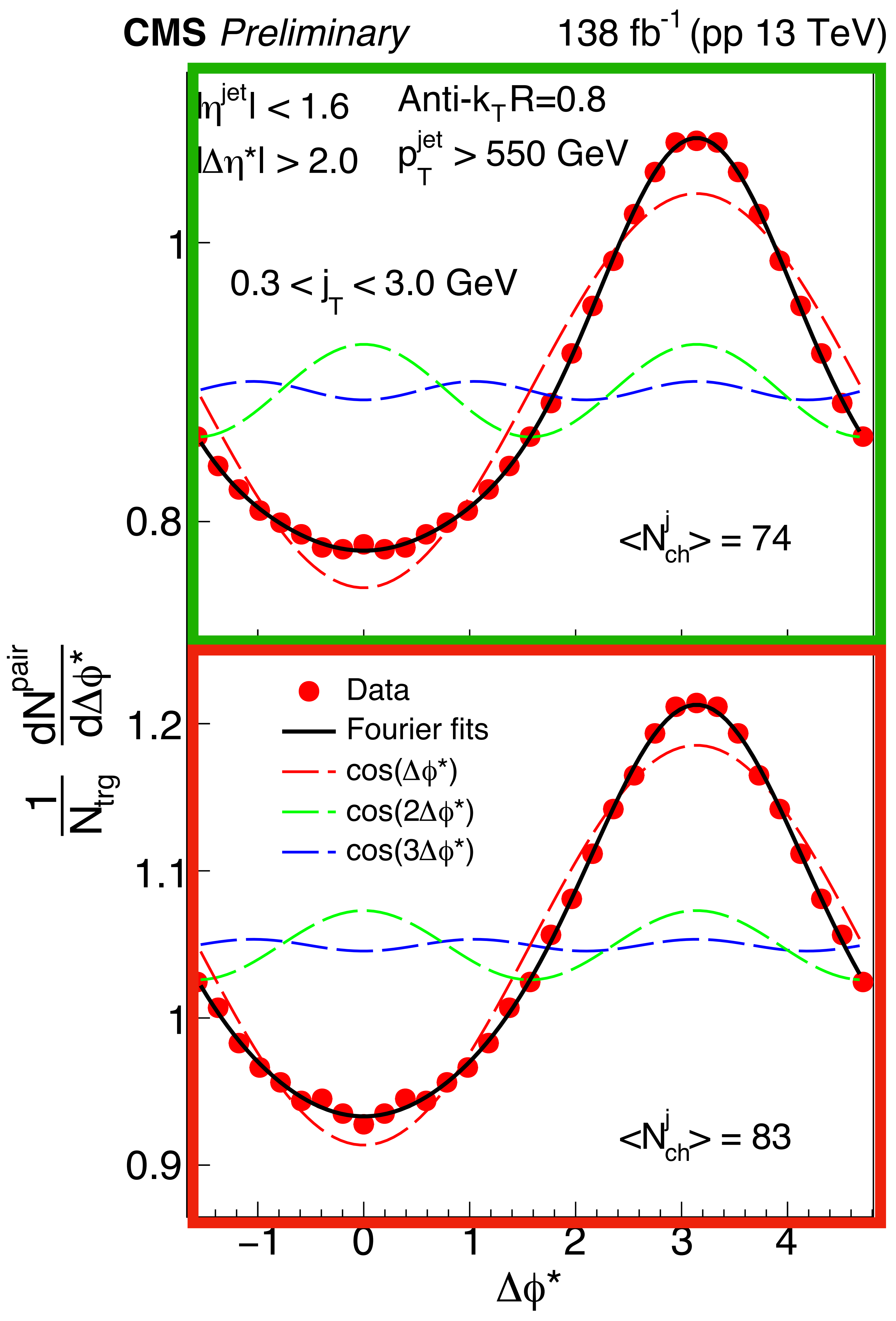


Backup

Closer inspection of 1D correlations

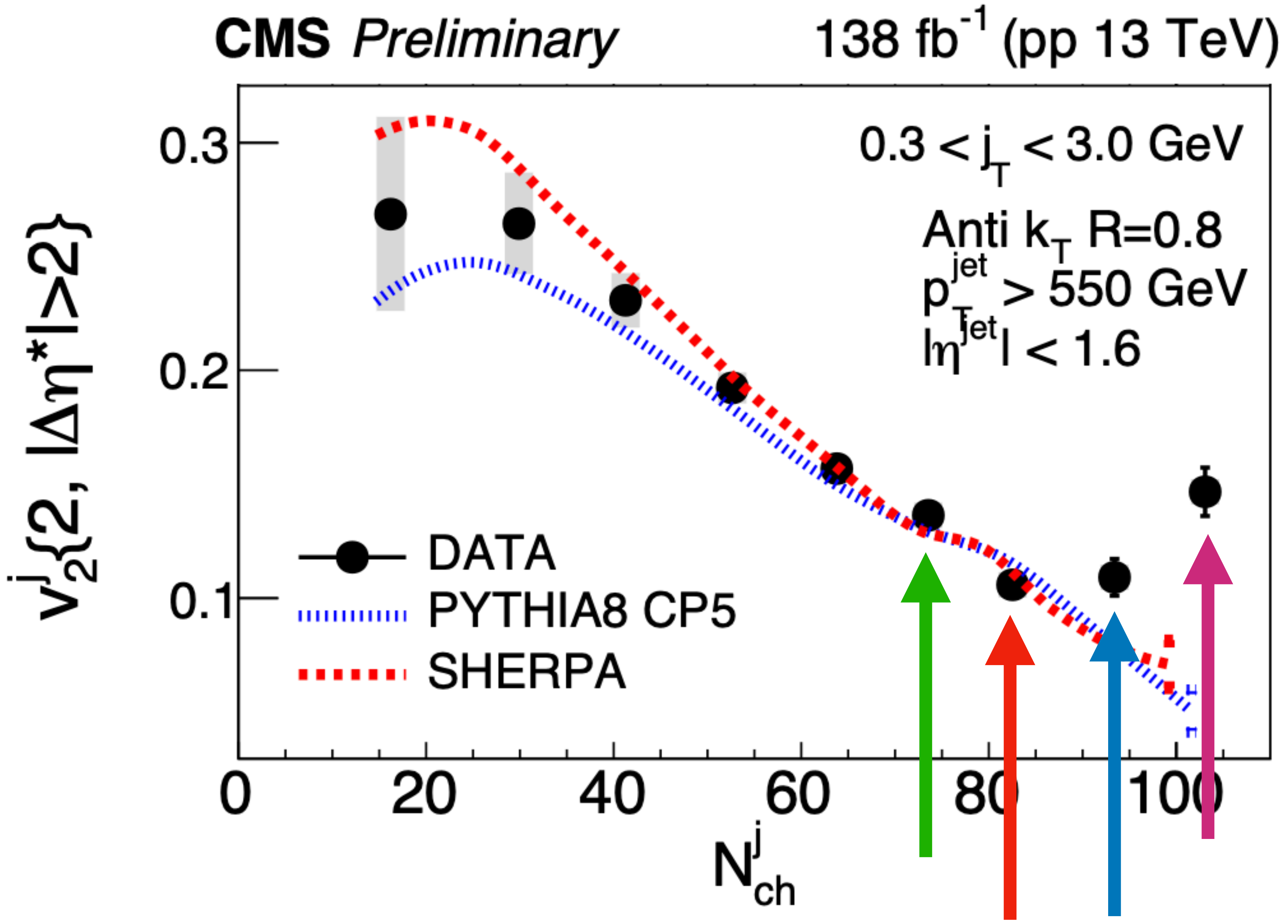
- **Smoothly varying 1D correlation up to N_{ch} ~ 85**

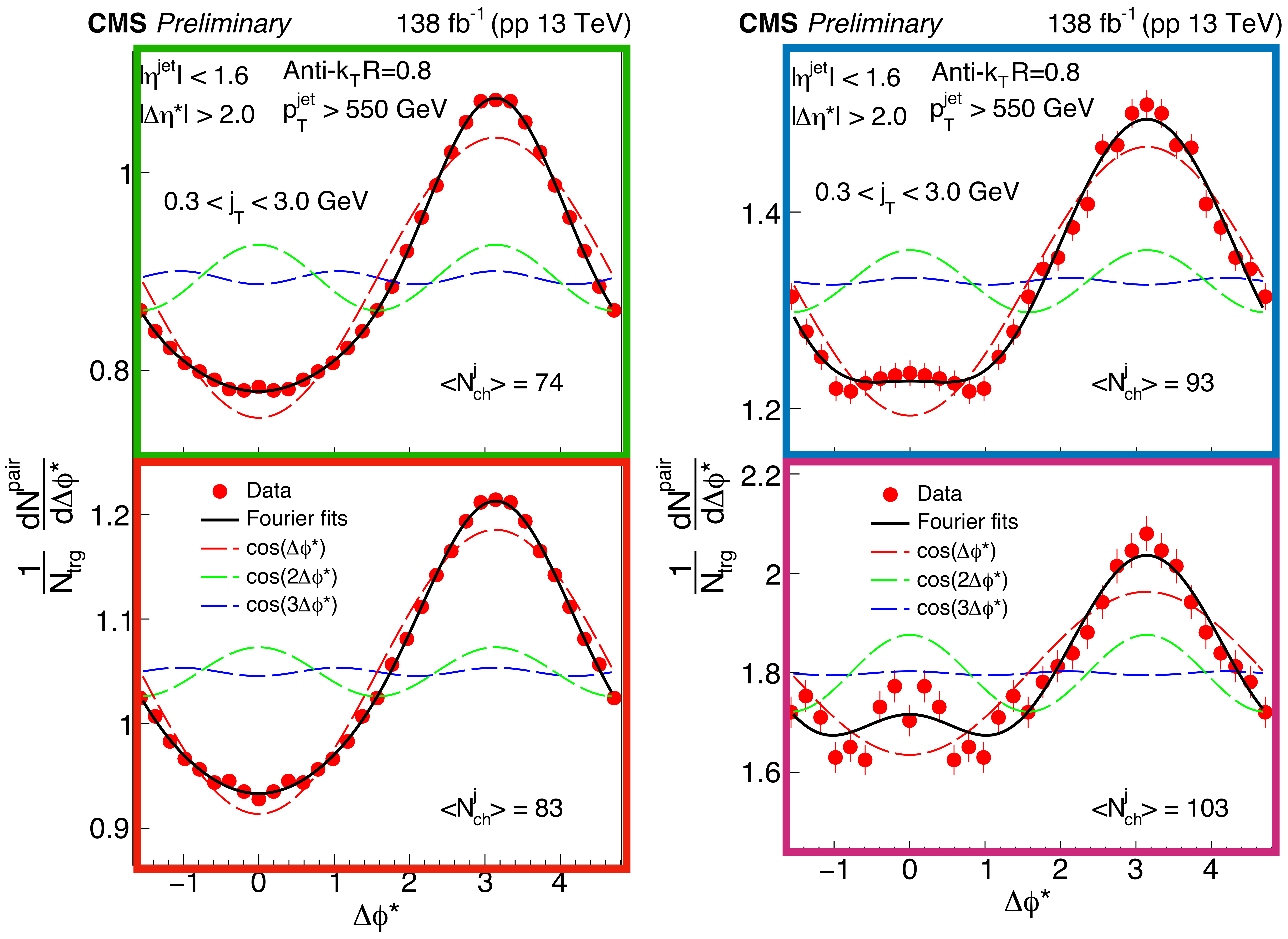




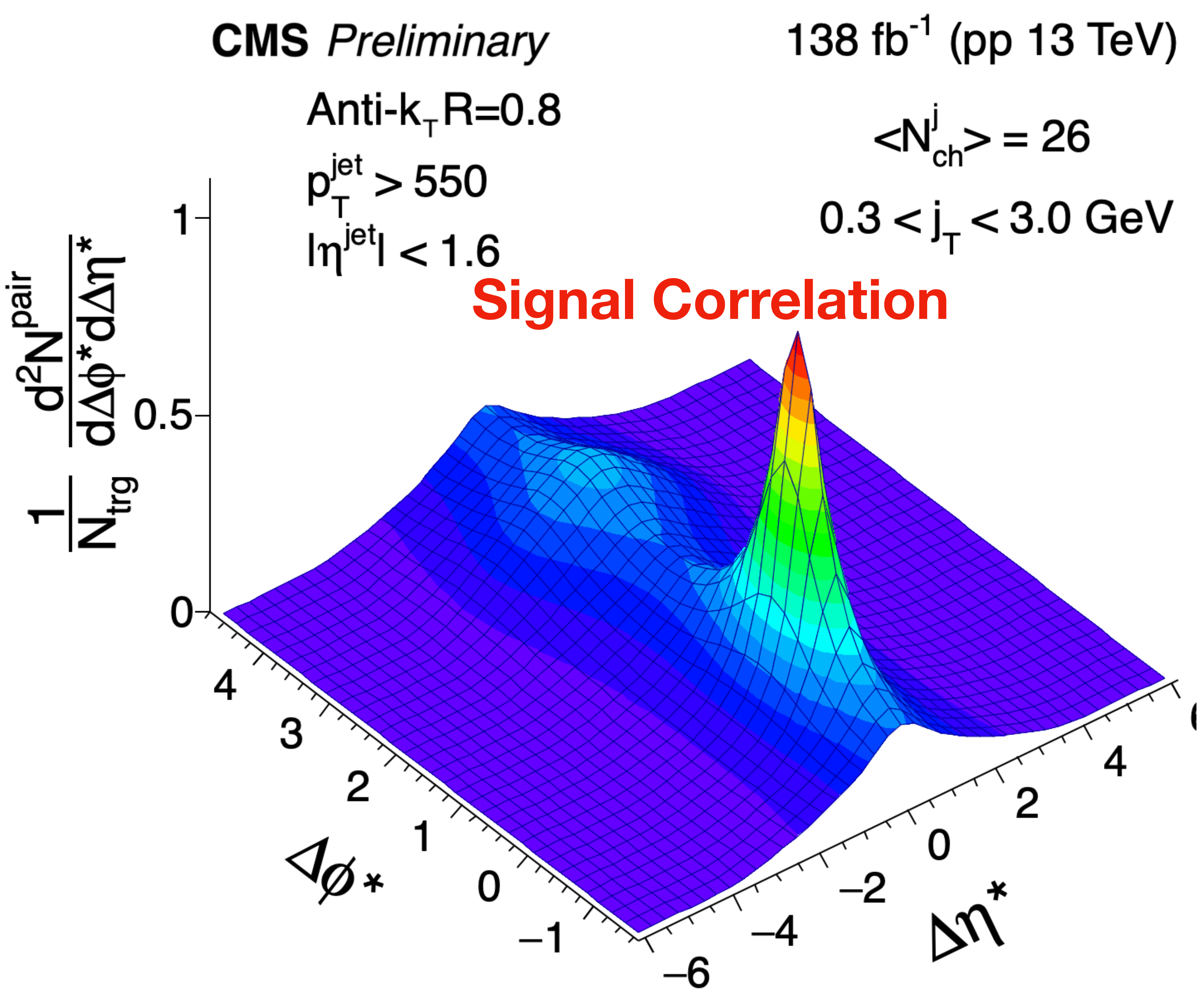
Closer inspection of 1D correlations

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



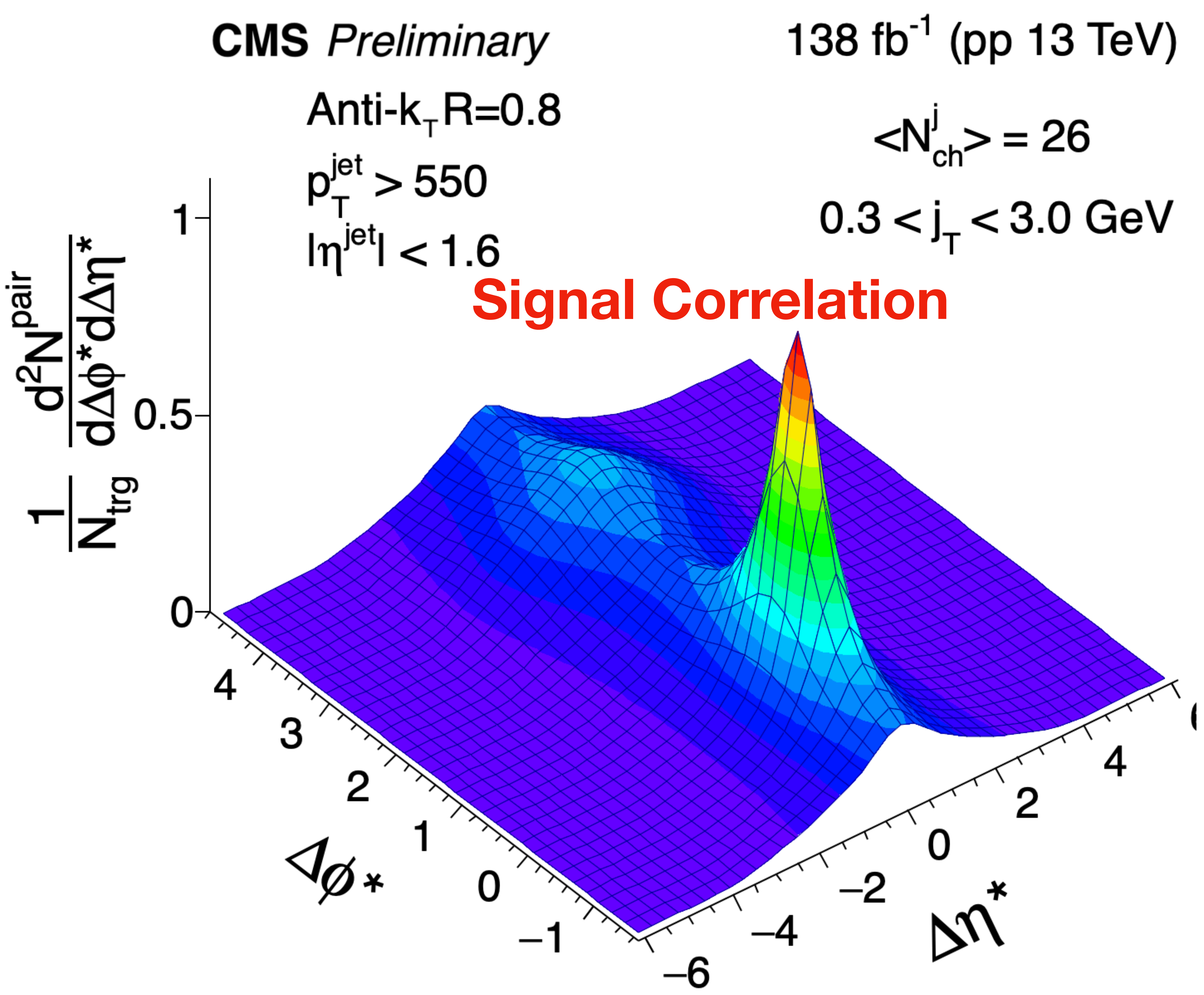


Particle pair correlations

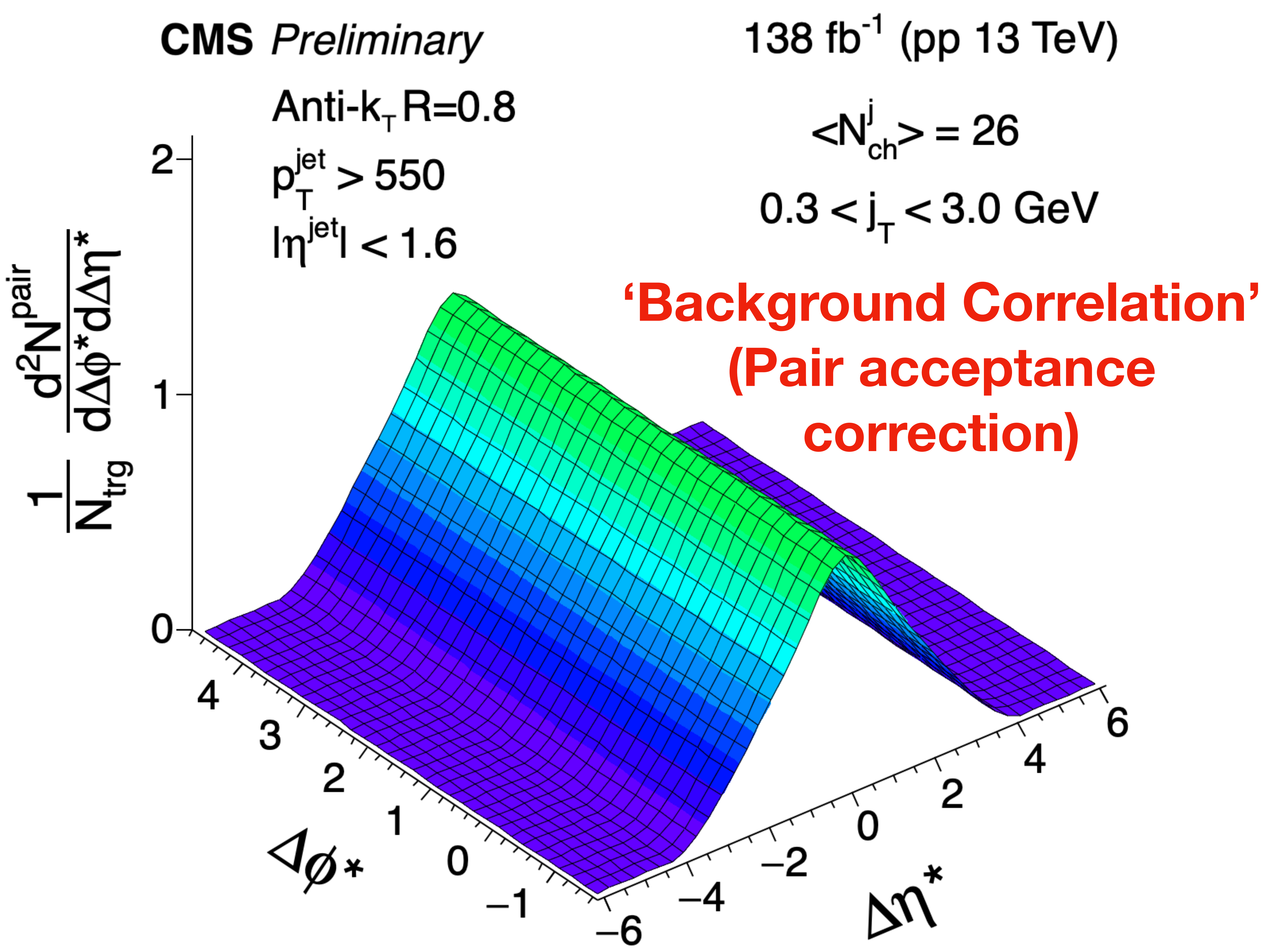


Built from all pairs of jet constituents.
Particles not clustered into the jet ignored.

Particle pair correlations

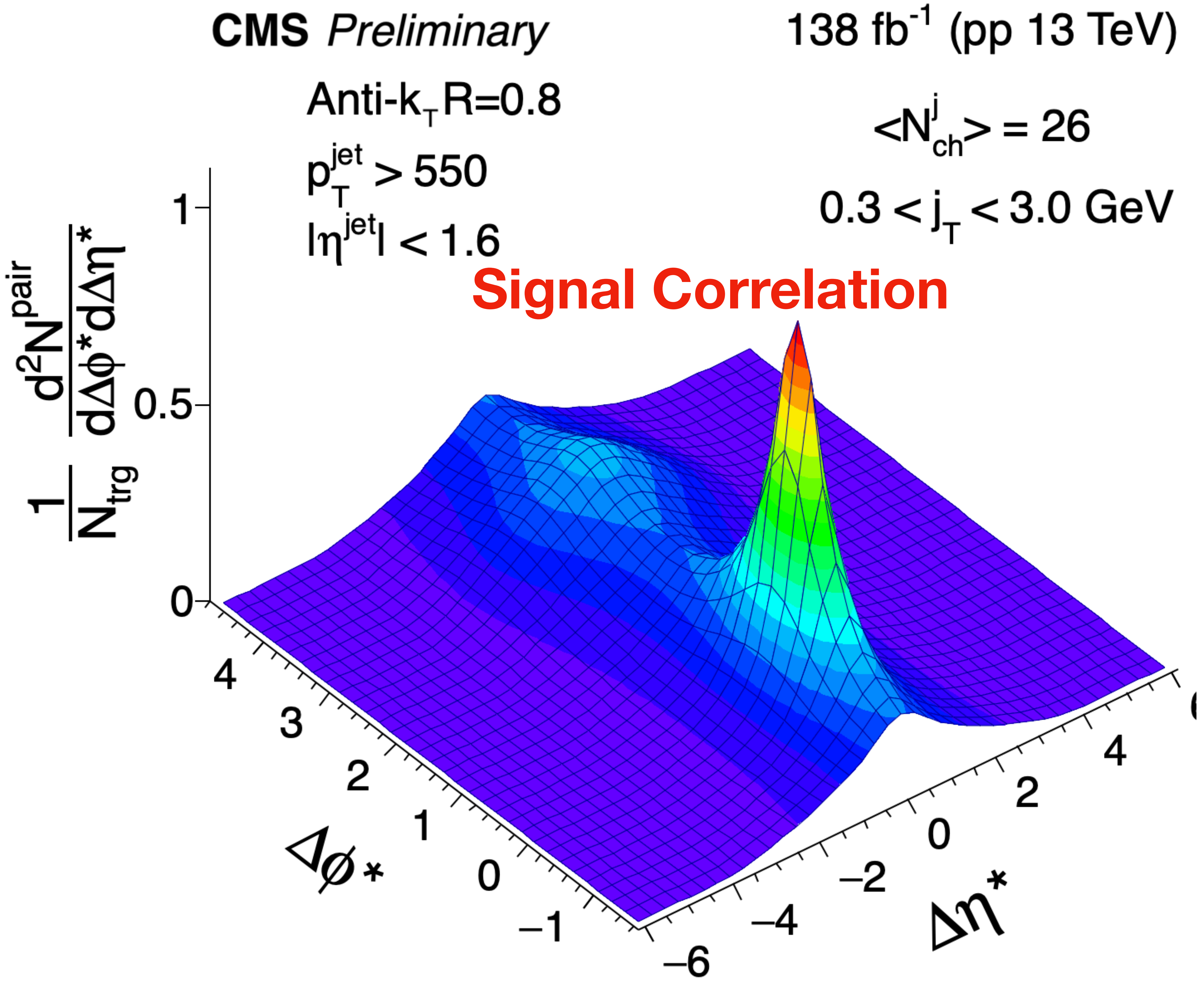


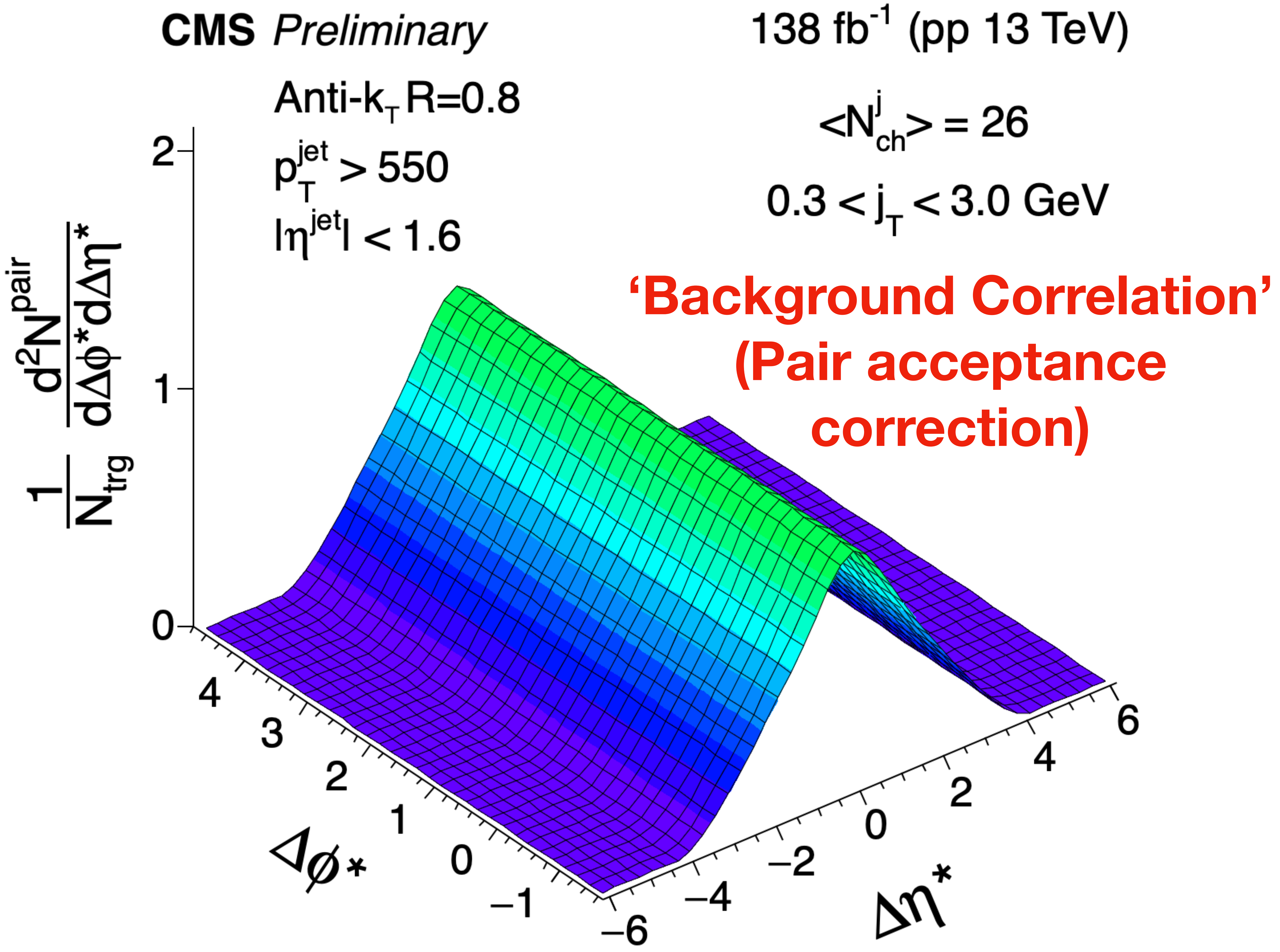
Built from all pairs of jet constituents.
Particles not clustered into the jet ignored.



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

Particle pair correlations

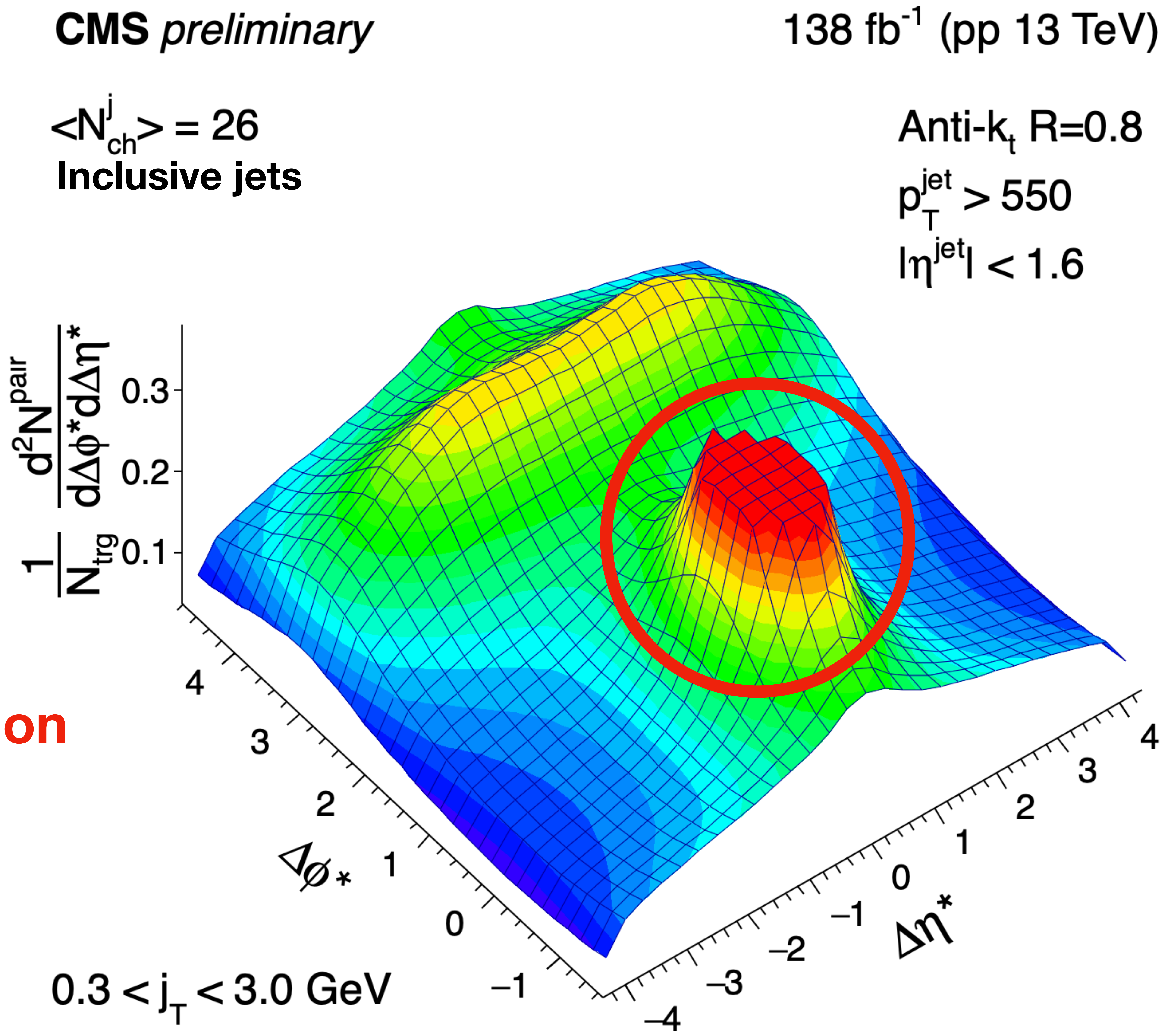




$$\frac{1}{N_{\mathrm{ch}}^{\mathrm{trg}}}\frac{\mathrm{d}^2 N^{\mathrm{pair}}}{\mathrm{d}\Delta\eta^*\mathrm{d}\Delta\phi^*} = B(0,0)\frac{S(\Delta\eta^*,\Delta\phi^*)}{B(\Delta\eta^*,\Delta\phi^*)}$$

2 Particle Correlation Function

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

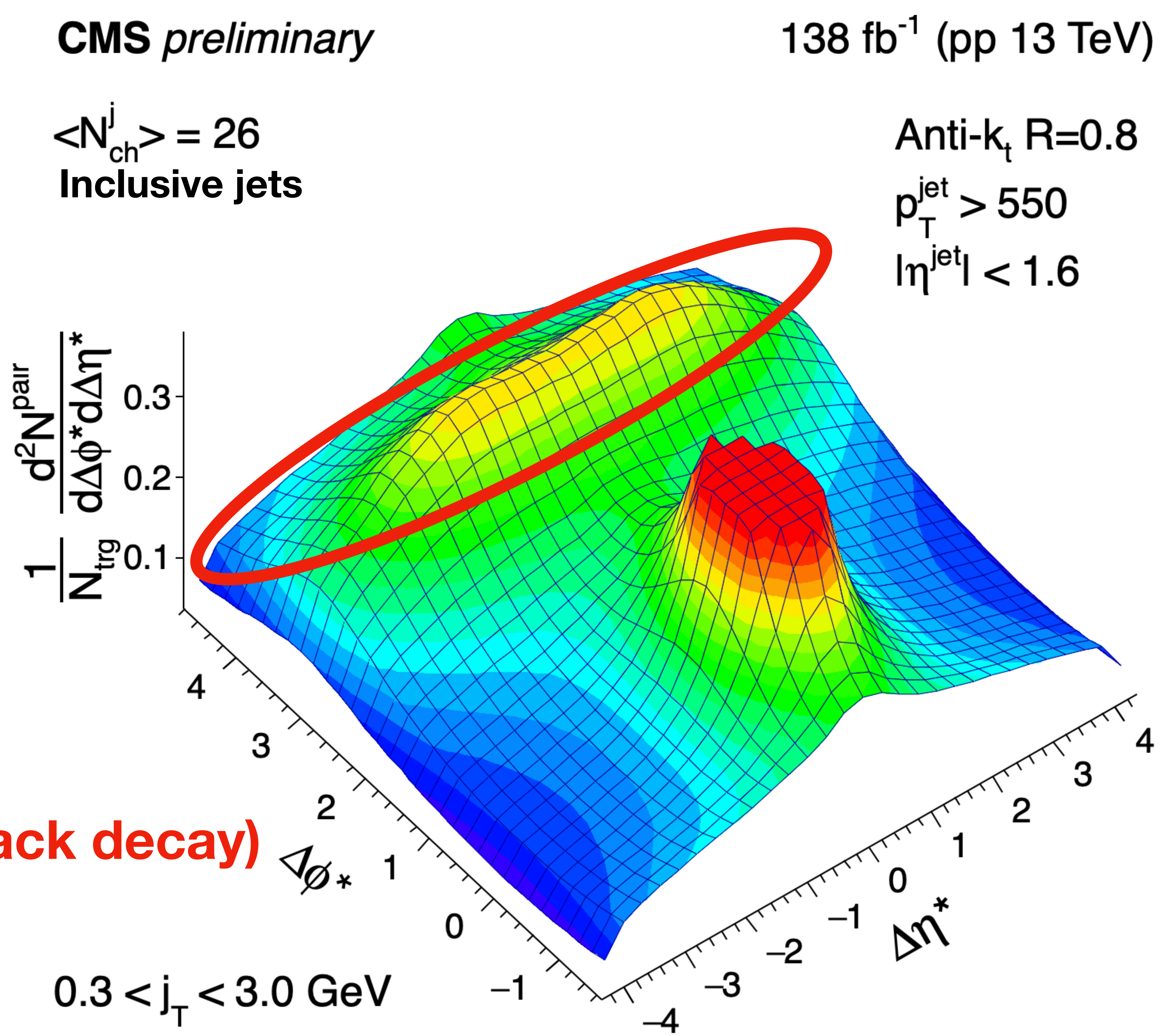


- **Similar features as lab-frame analysis!**
- **Peak at (0,0)**
  - **Hadron decays, collinear fragmentation**

2 Particle Correlation Function

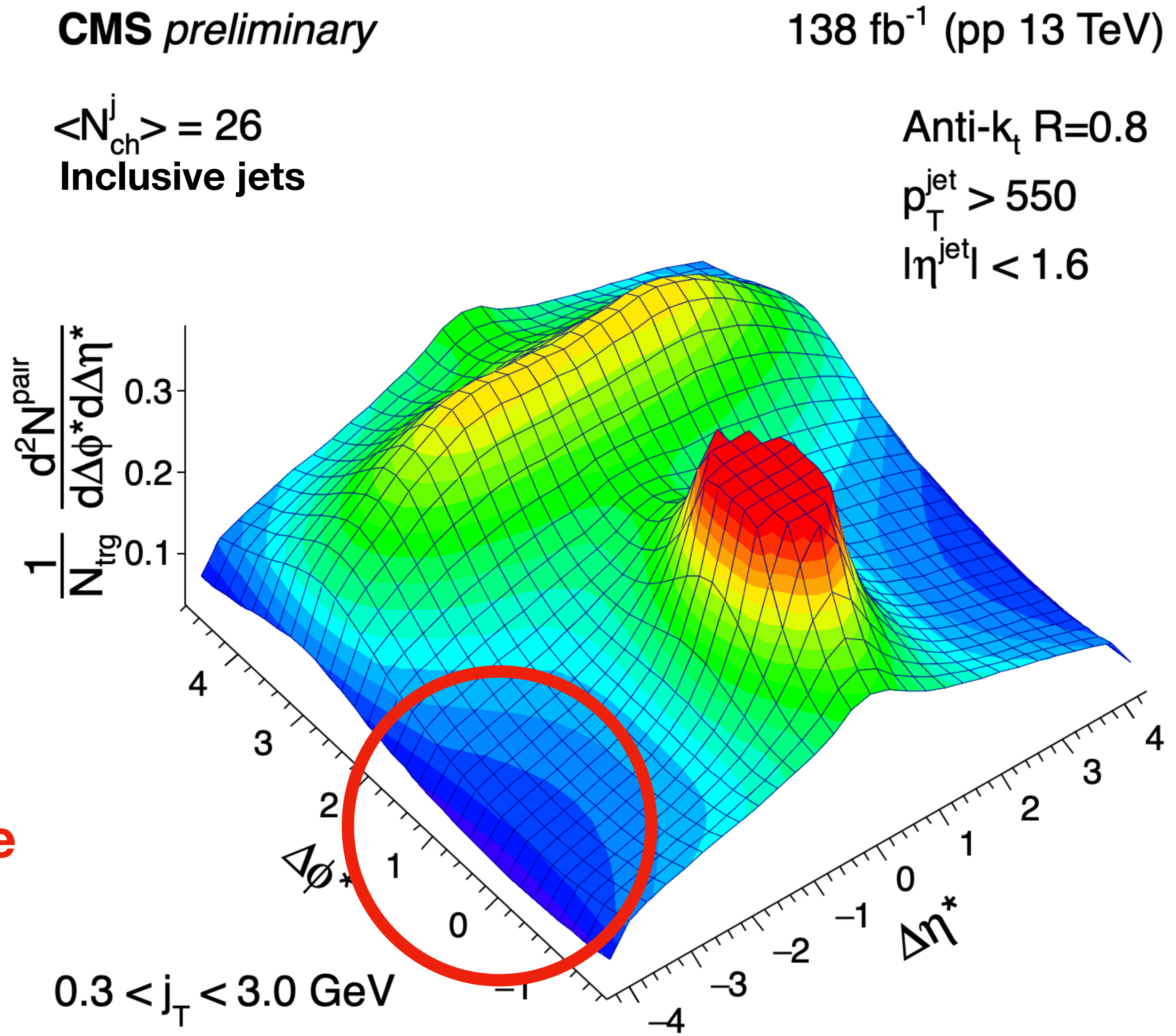
$$\frac{1}{N_{\rm ch}^{\rm trg}} \frac{d^2 N^{\rm pair}}{d\Delta\eta^* d\Delta\phi^*} = B(0,0) \frac{S(\Delta\eta^*, \Delta\phi^*)}{B(\Delta\eta^*, \Delta\phi^*)}$$

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



2 Particle Correlation Function

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

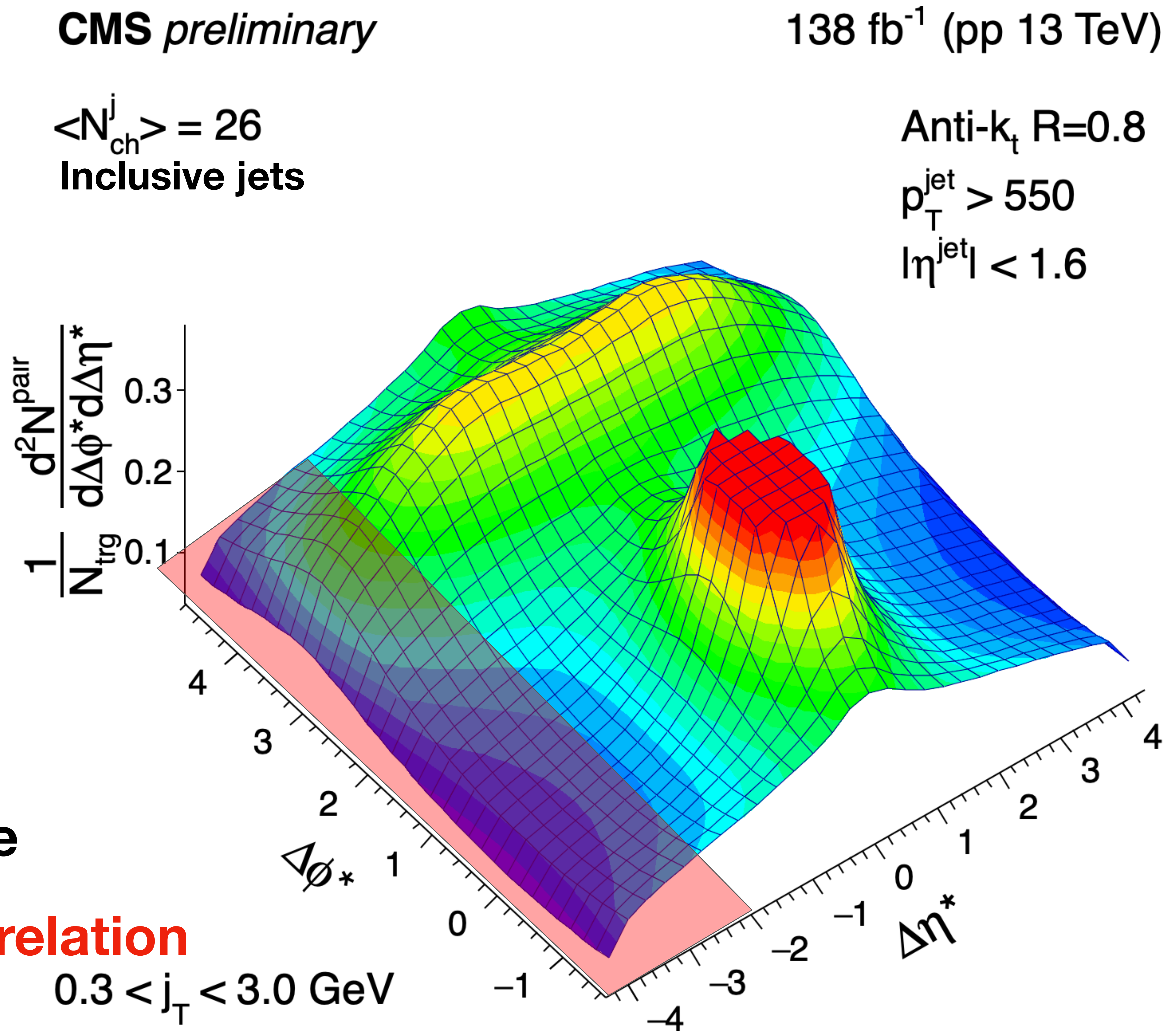


- **Similar features as lab-frame analysis!**
- **Peak at (0,0)**
- **Away-side enhancement at $\Delta\phi^* = \pi$**
- **No near-side ridge for inclusive sample**

2 Particle Correlation Function

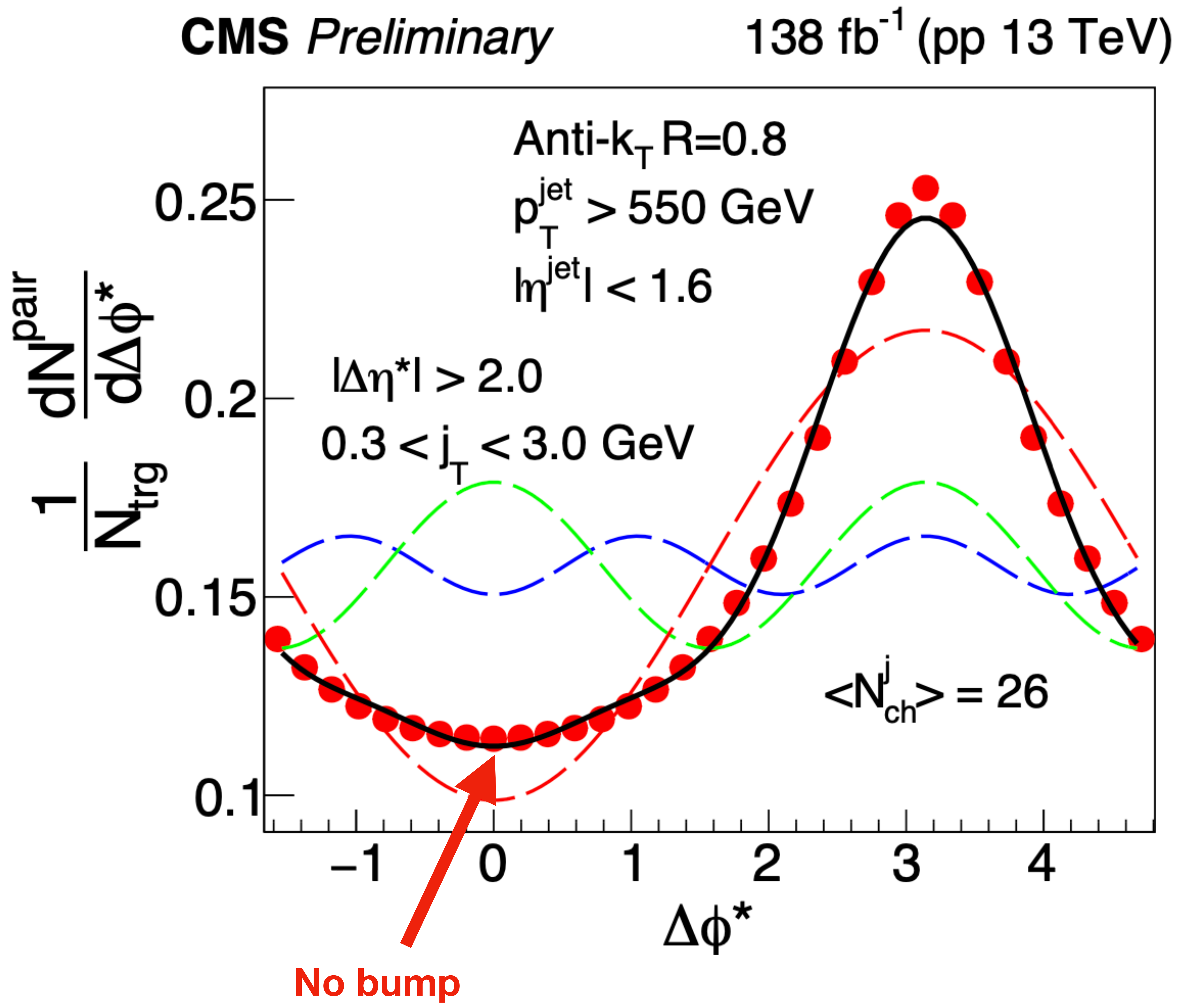
$$\frac{1}{N_{\mathrm{ch}}^{\mathrm{trg}}} \frac{\mathrm{d}^2 N^{\mathrm{pair}}}{\mathrm{d}\Delta\eta^* \mathrm{d}\Delta\phi^*} = B(0,0) \frac{S(\Delta\eta^*, \Delta\phi^*)}{B(\Delta\eta^*, \Delta\phi^*)}$$

- **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**



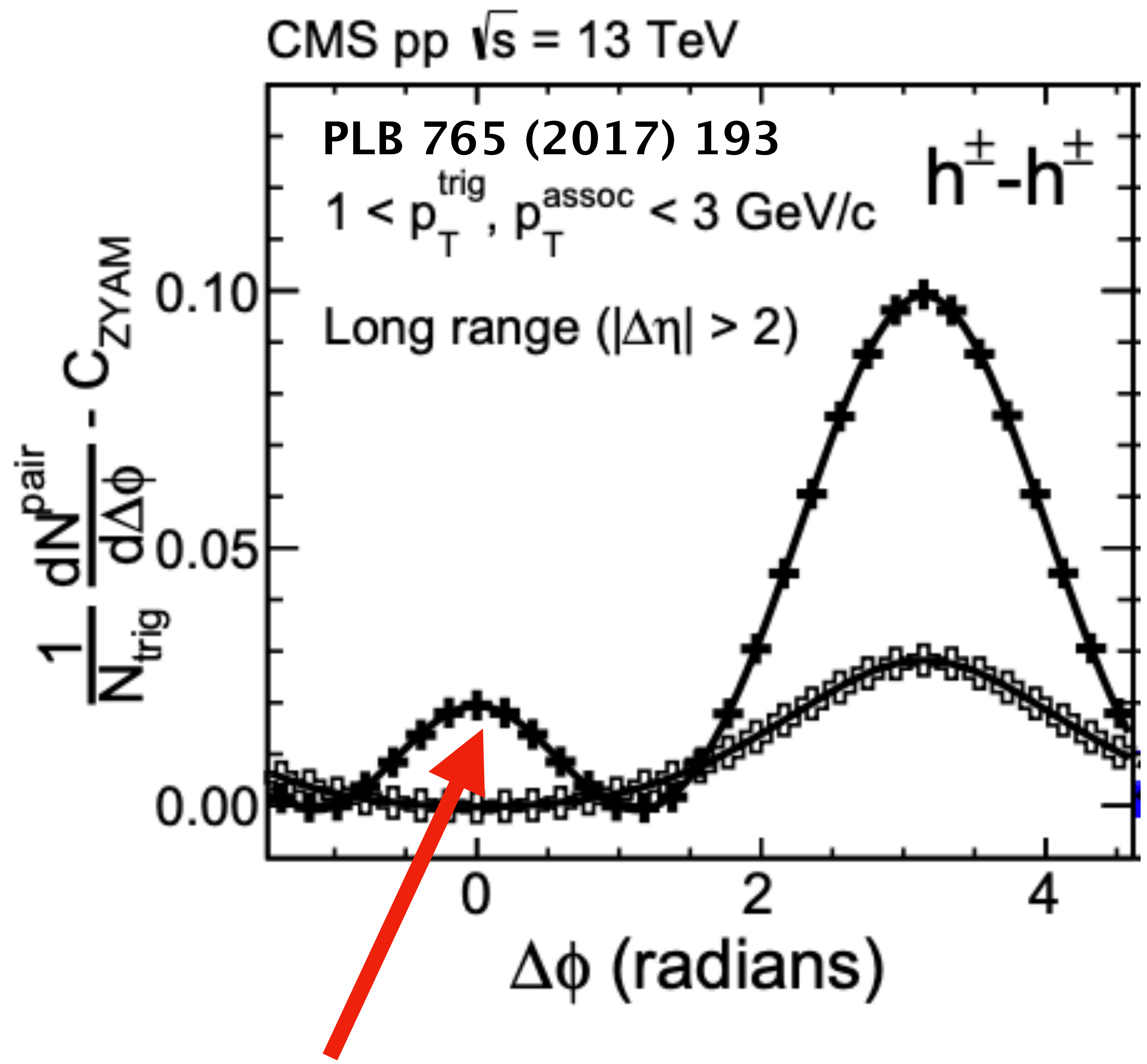
1D Correlation Function

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

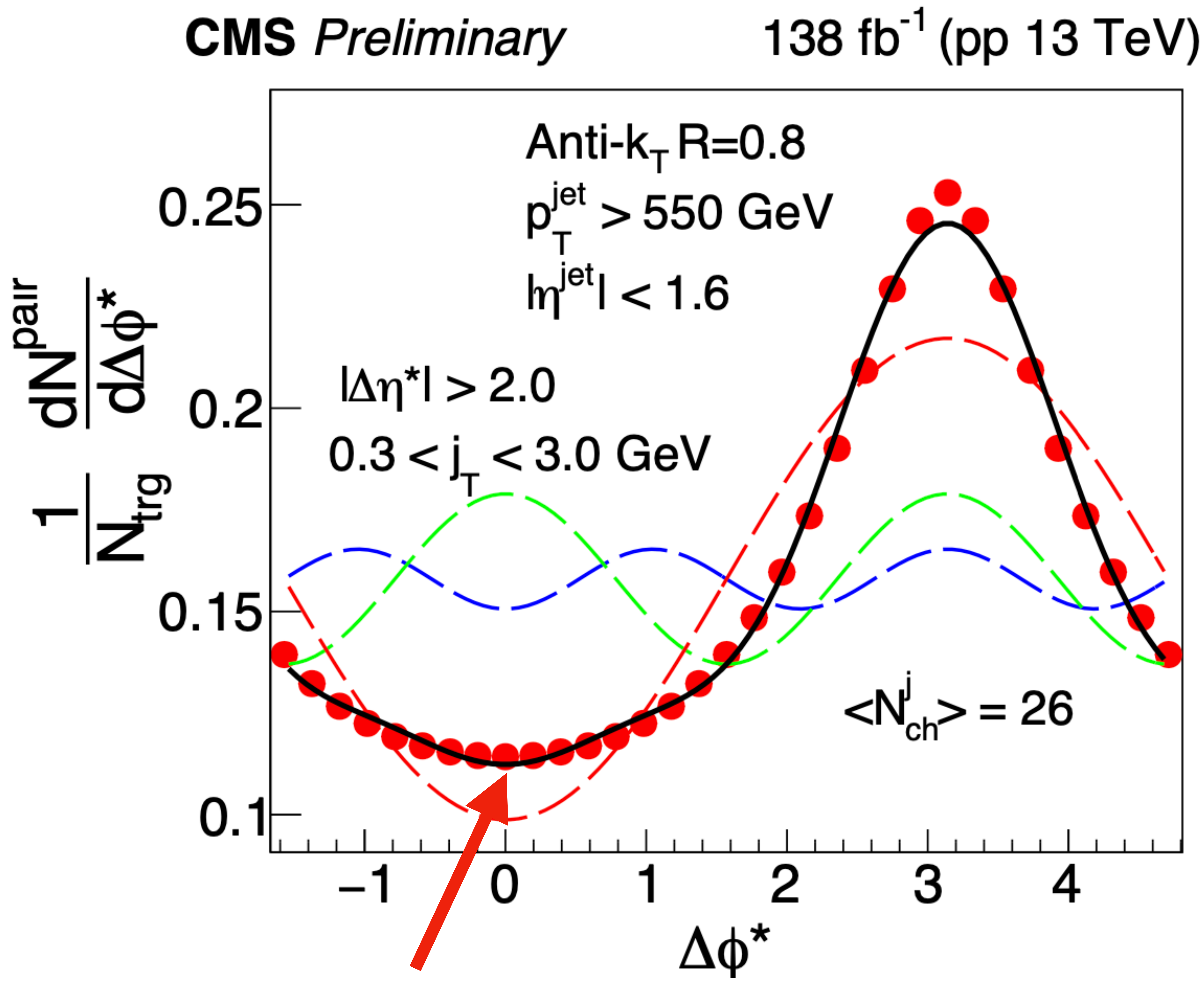


1D Correlation Function

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



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

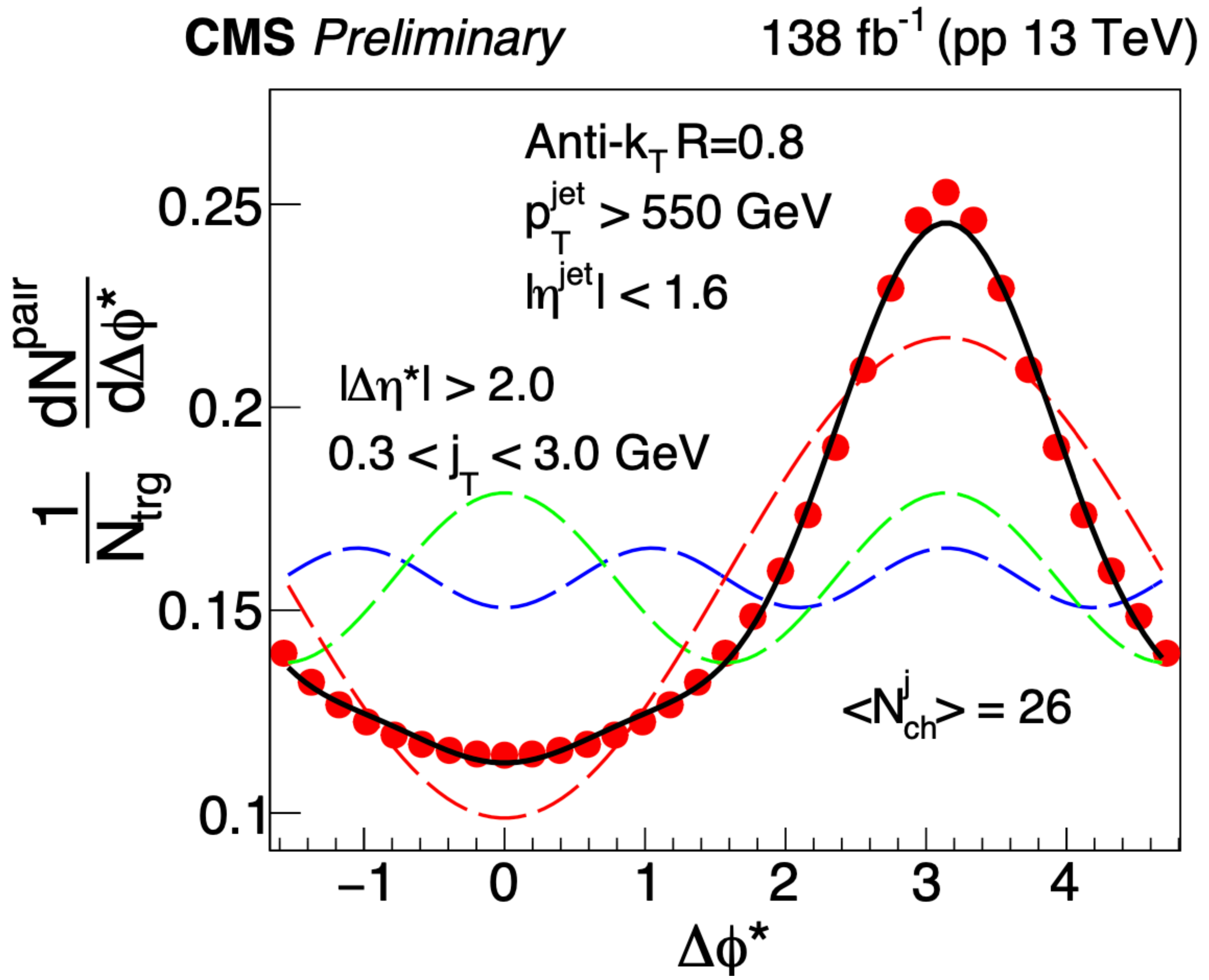


No bump

Fourier Fits

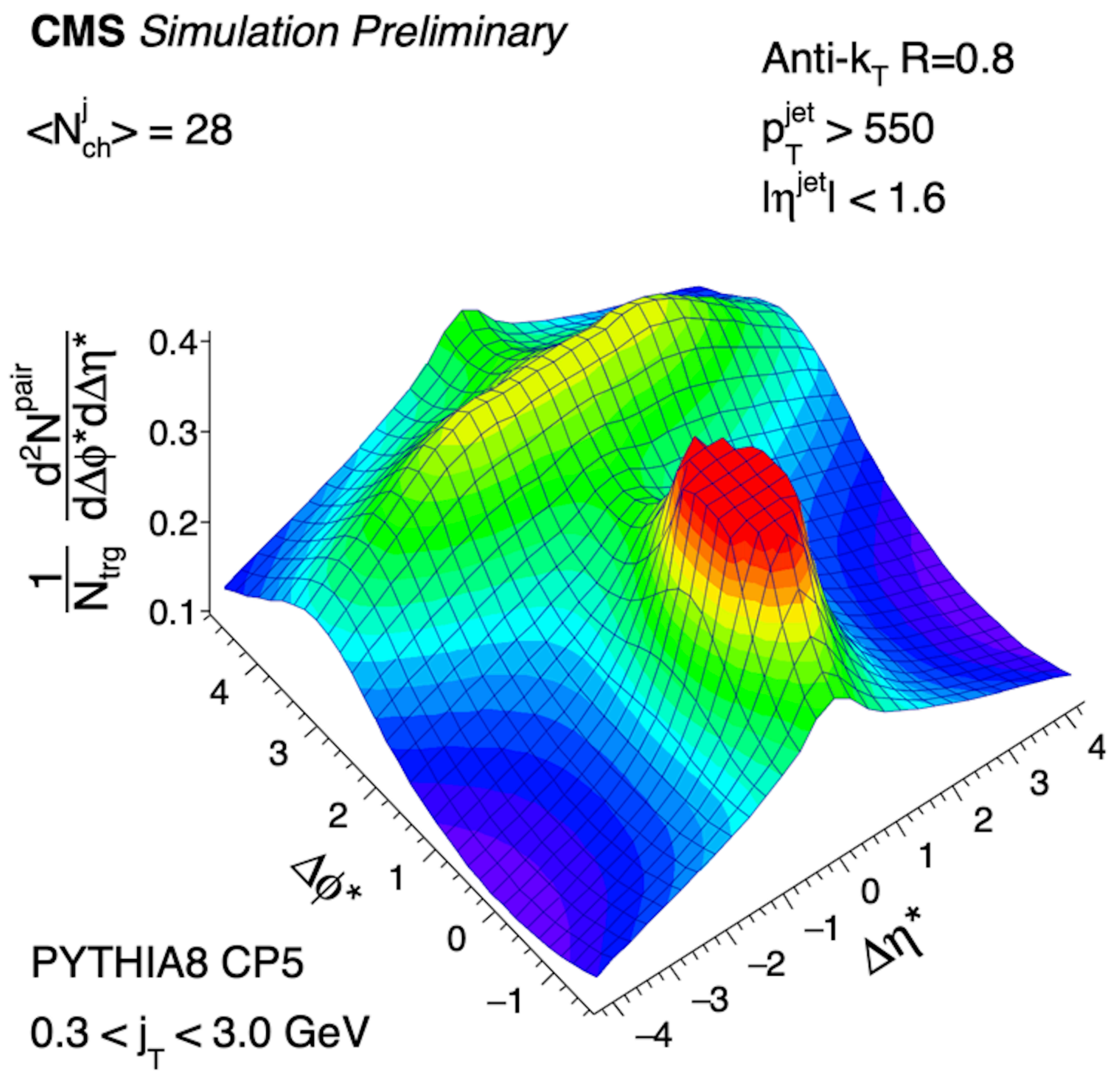
- **Fourier fit to 1D correlation function**
- **Coefficients $V_{n\Delta}$ are free parameters**
- **Can be nonzero even with no bump**
  - **Will come back at the end of talk!**

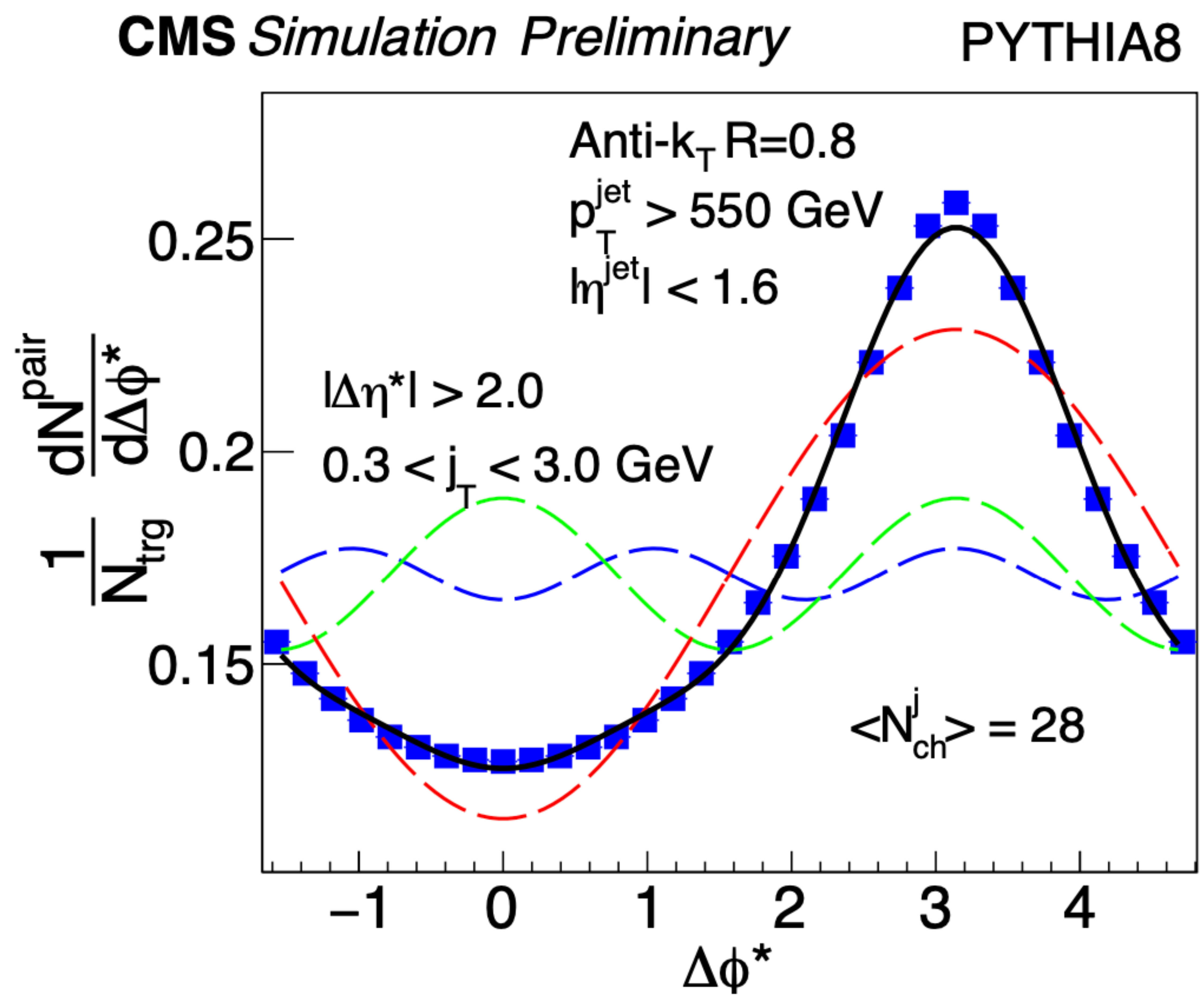
$$\frac{1}{N_{\mathrm{ch}}^{j}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi^{*}} \propto \sum_{n=1}^{\infty} \boxed{V_{\mathrm{n}\Delta}} \cos(\mathrm{n}\Delta\phi^{*})$$



Pythia 8 Correlation

- **String hadronization model**

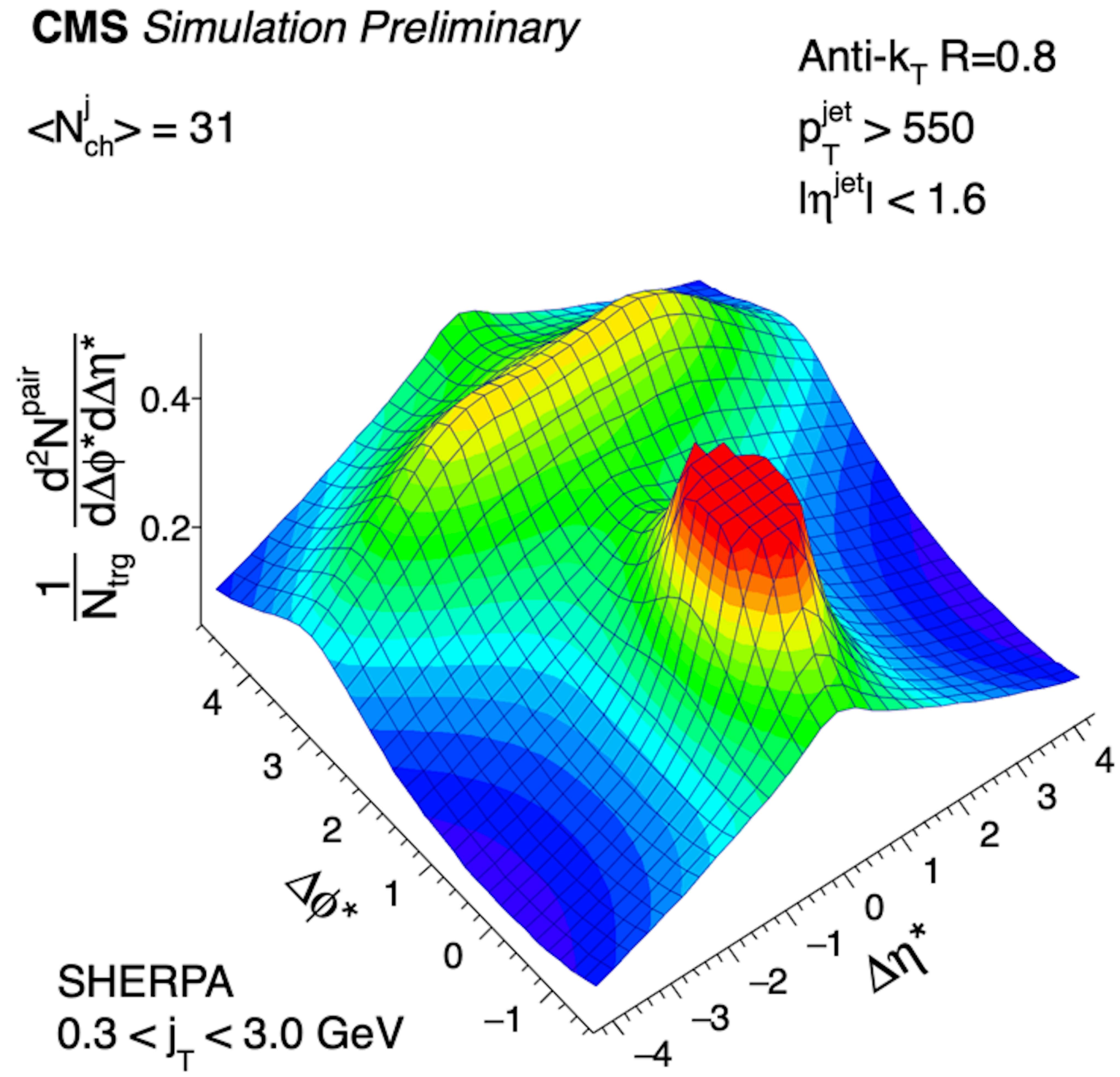


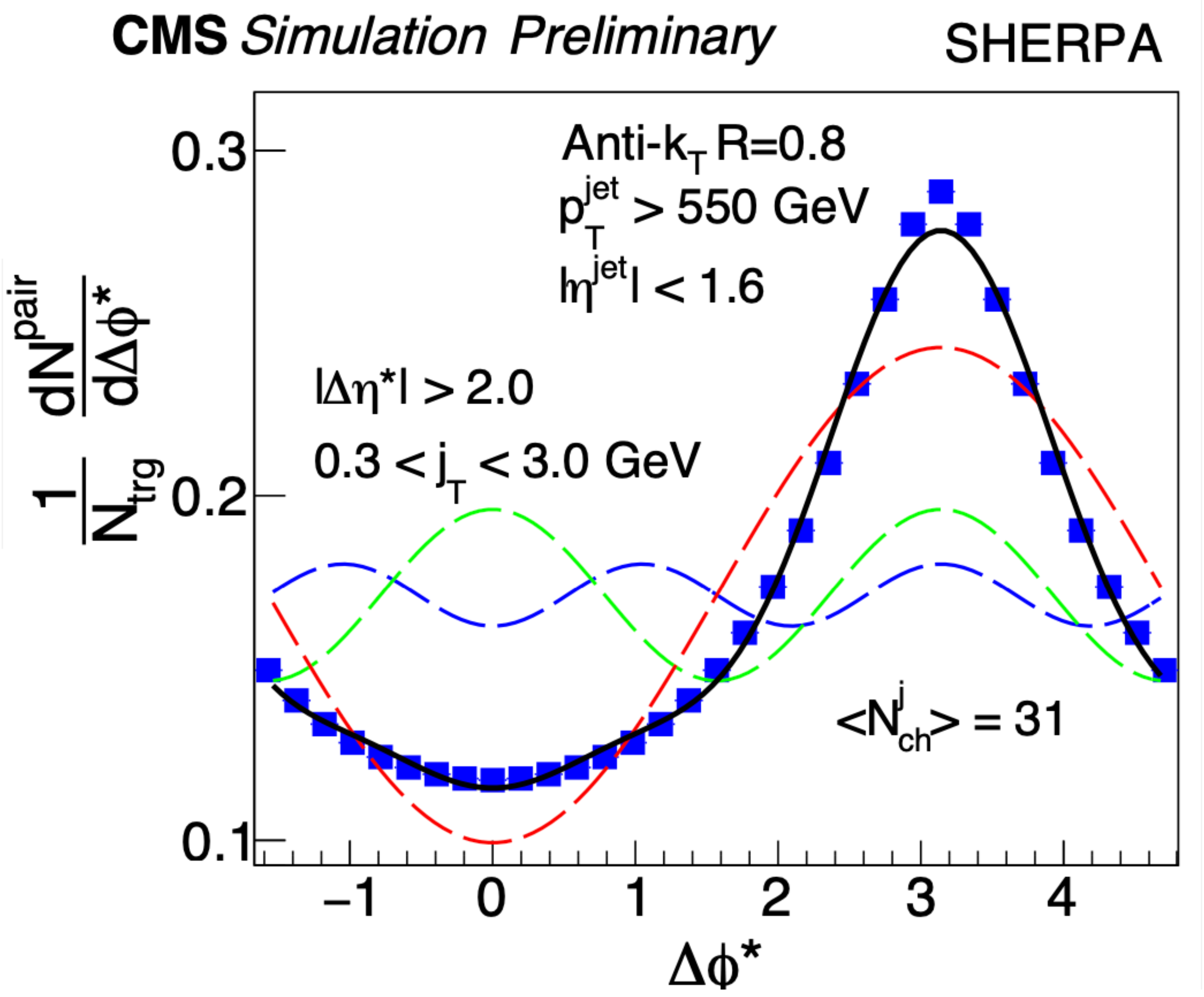


Overall features of low-multiplicity correlation captured by MC models

Sherpa Correlation

- **Cluster hadronization model**



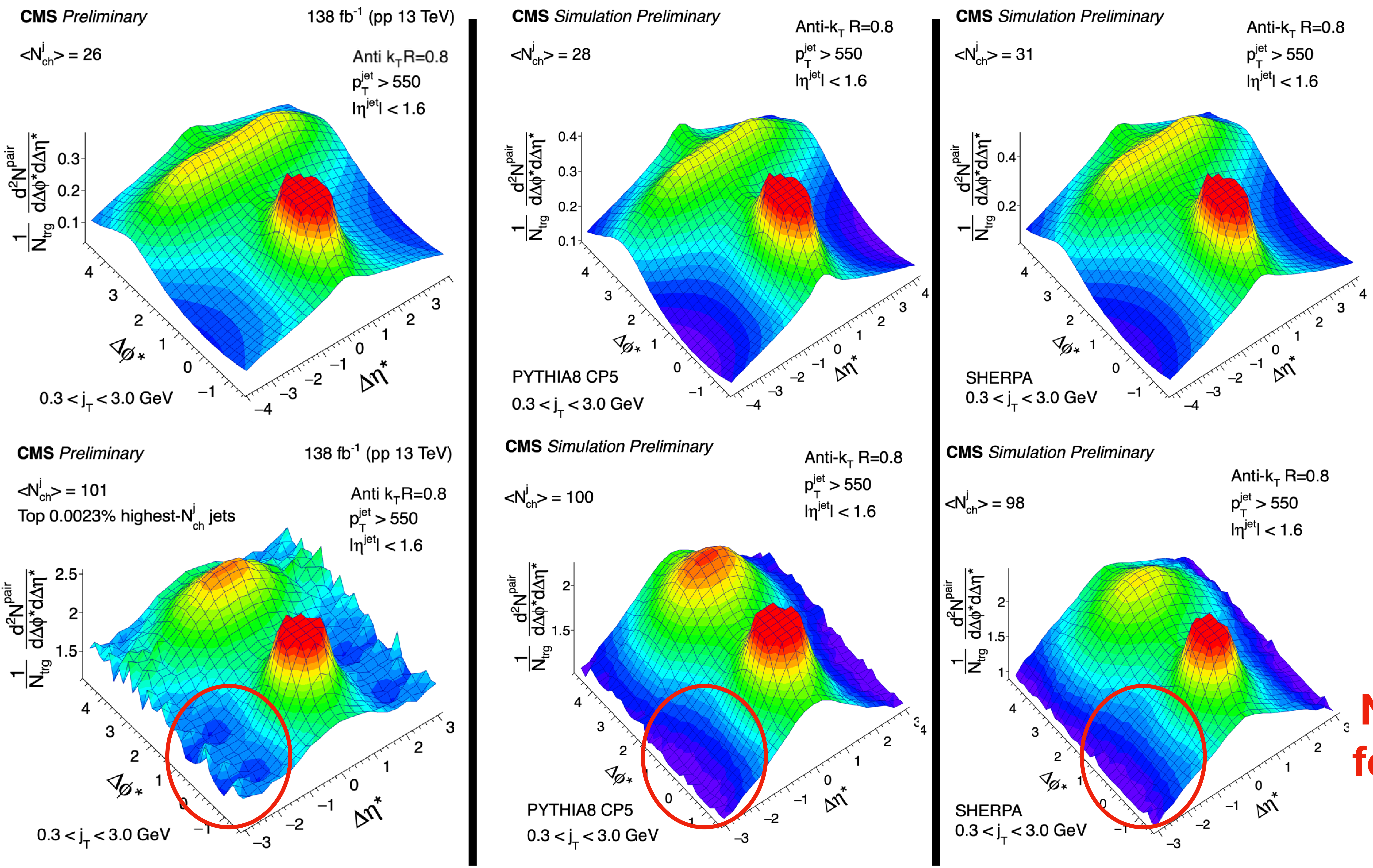


Overall features of low-multiplicity correlation captured by MC models

Comparison to MC

N_{ch} ~ 26

N_{ch} ~ 100



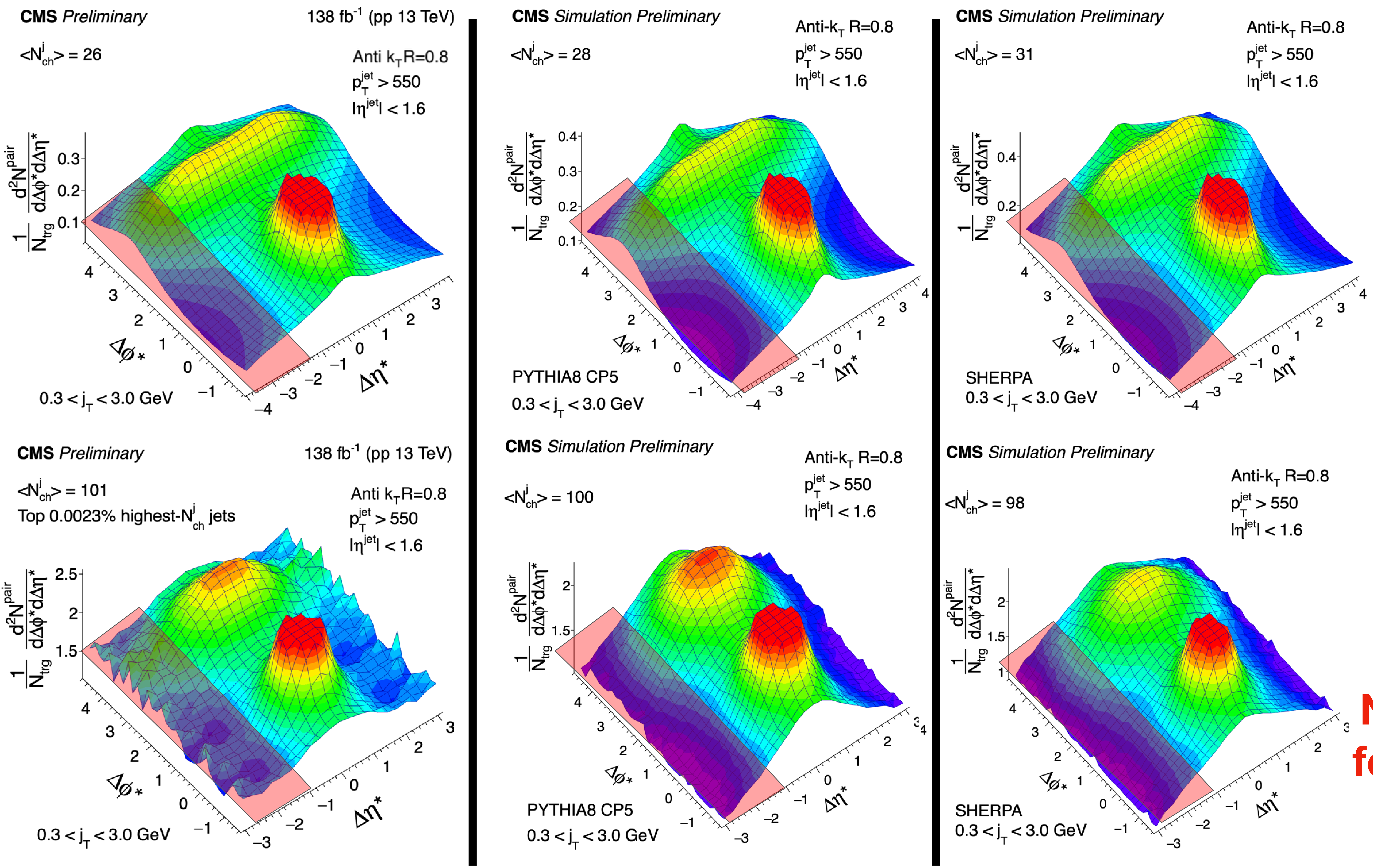
Data **PYTHIA** **SHERPA**

No near-side feature in MC

Comparison to MC

N_{ch} ~ 26

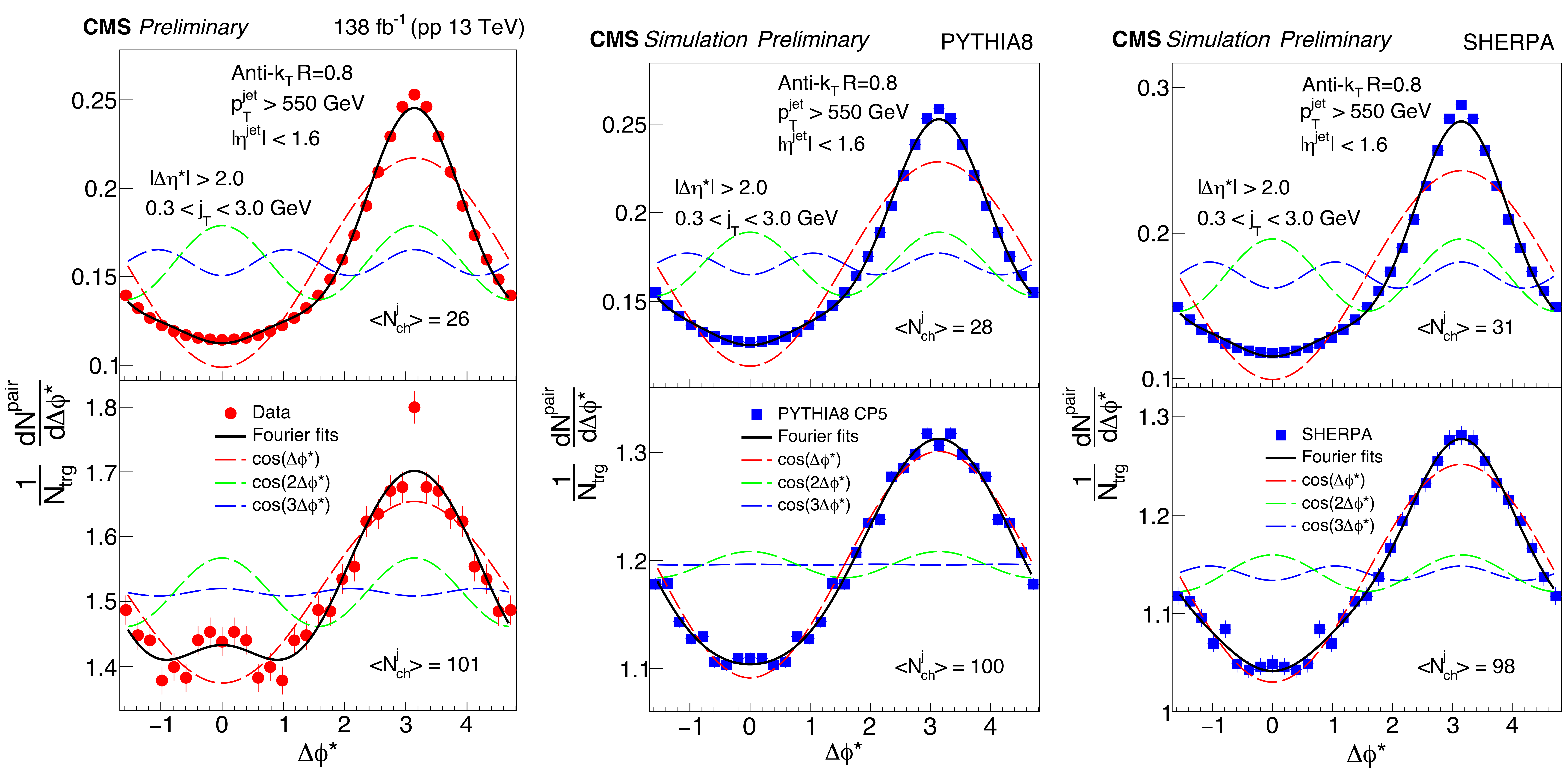
N_{ch} ~ 100



No near-side feature in MC

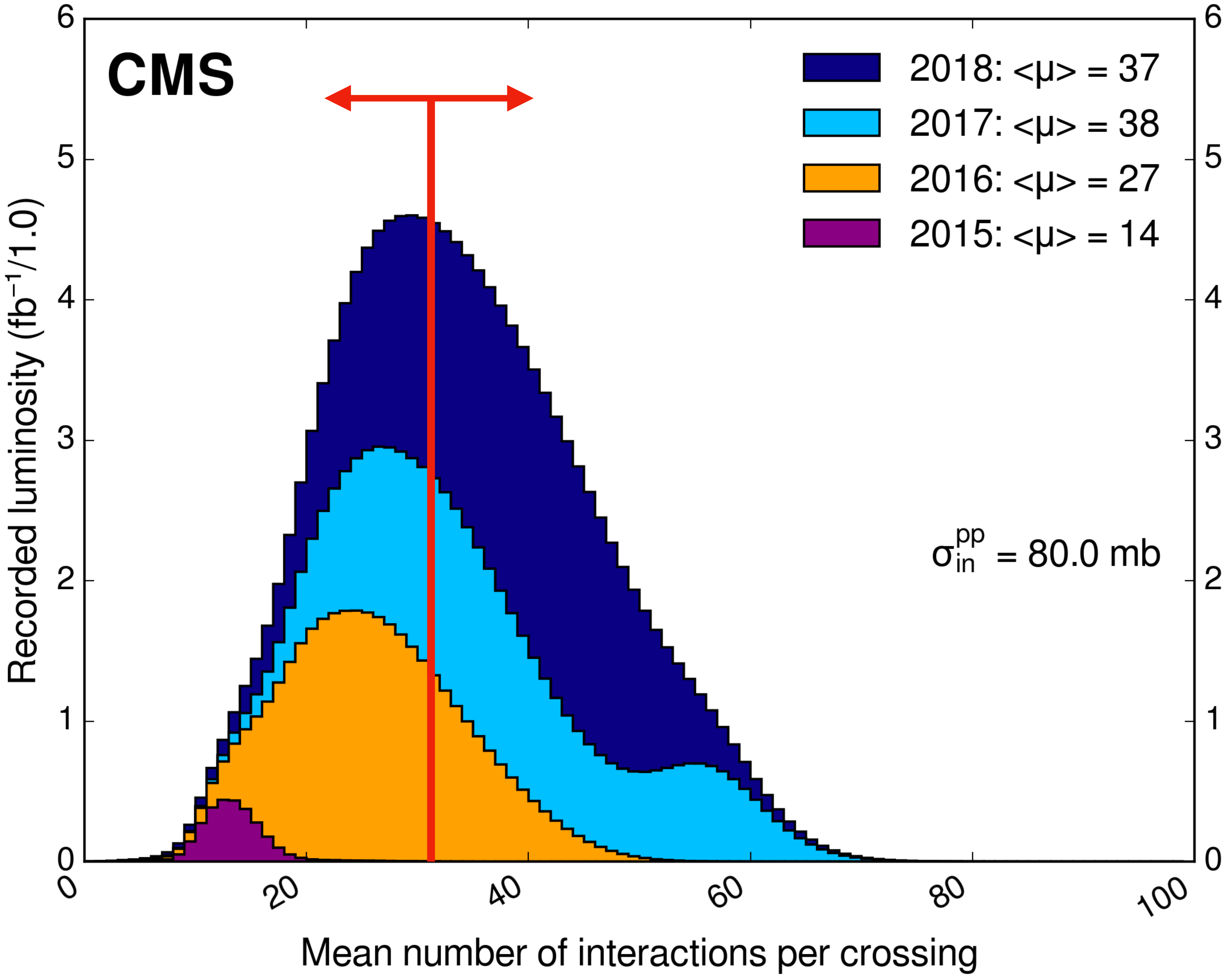
Data **PYTHIA** **SHERPA**

1D Correlations with MC



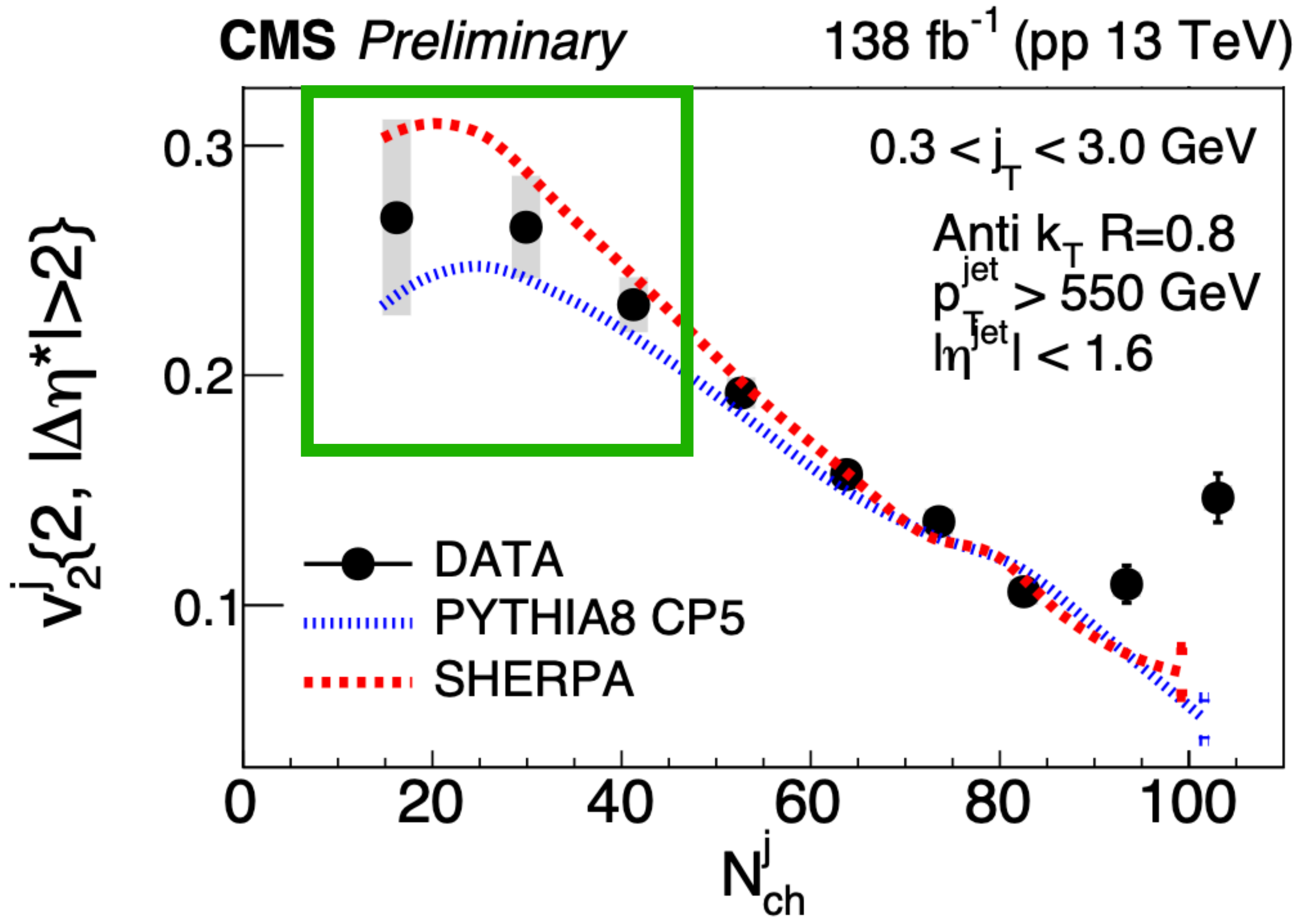
Pileup Uncertainty

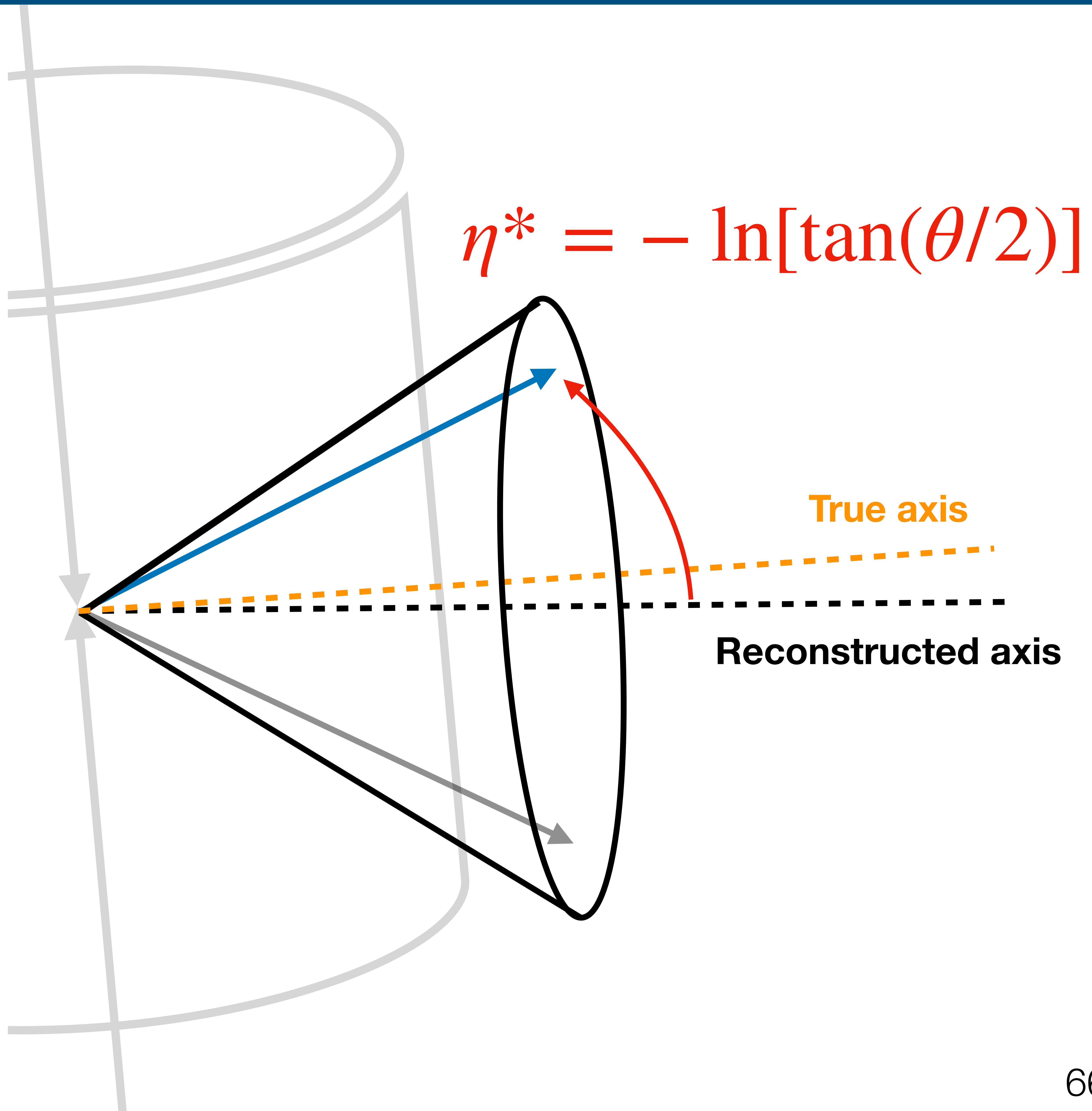
- **Effect of pileup studied by splitting data sample into subsamples**
  - **By year**
  - **By μ**
- **Leading systematic in high-N_{ch} region**
- **Variation of allowed PUPPI weight for 'ambiguous' tracks**
  - **Negligible effect**



Jet axis resolution uncertainty

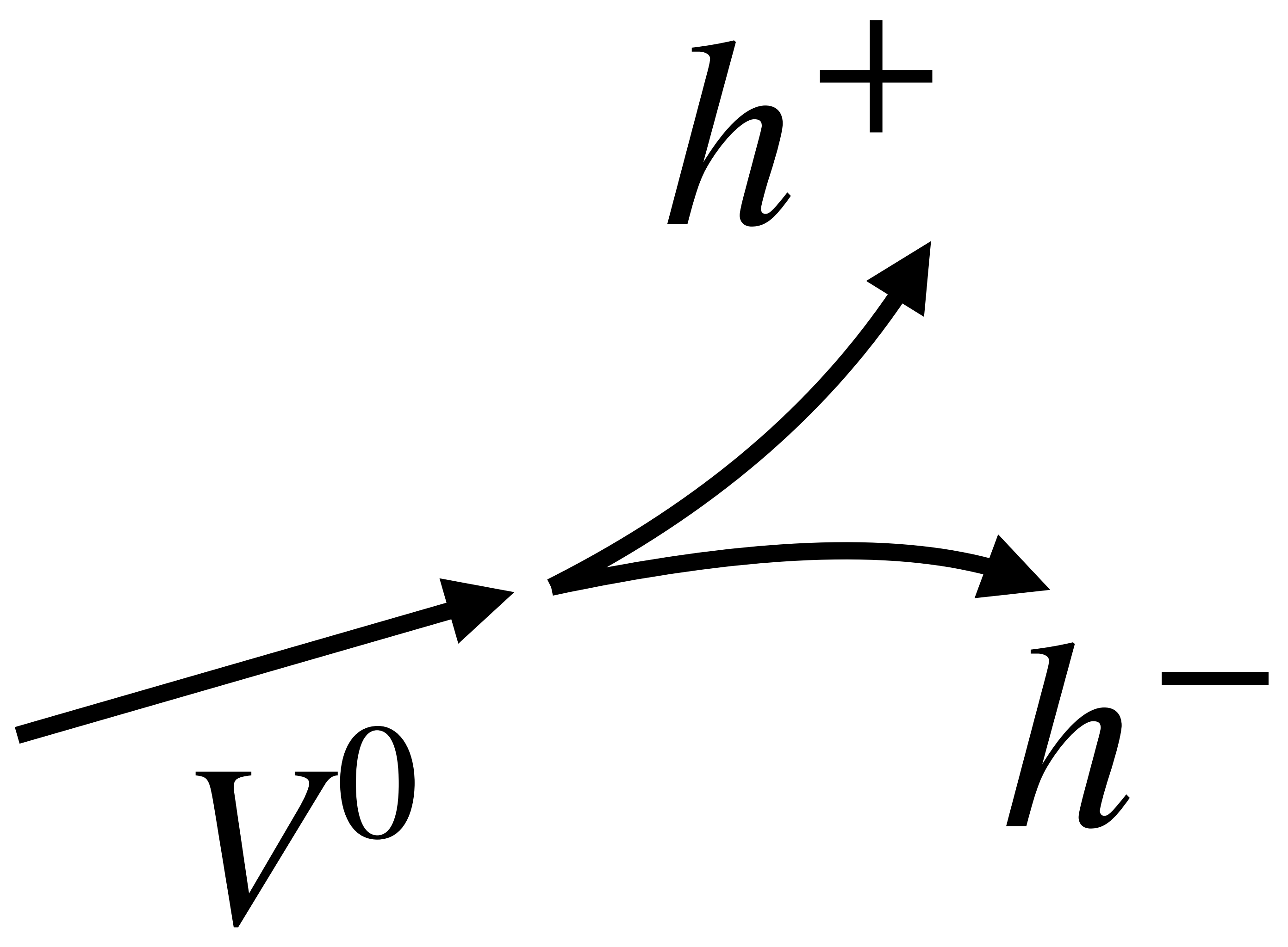
- **Resolution effects in the jet axis reconstruction affect $p* = (j_T, \eta^*, \phi^*)$**
- **Tracks close to jet axis are more sensitive**
- **Evaluated systematic by smearing jet axis**
- **Large uncertainty for low N_{ch} jets**
- **High N_{ch} are wider → less sensitive**

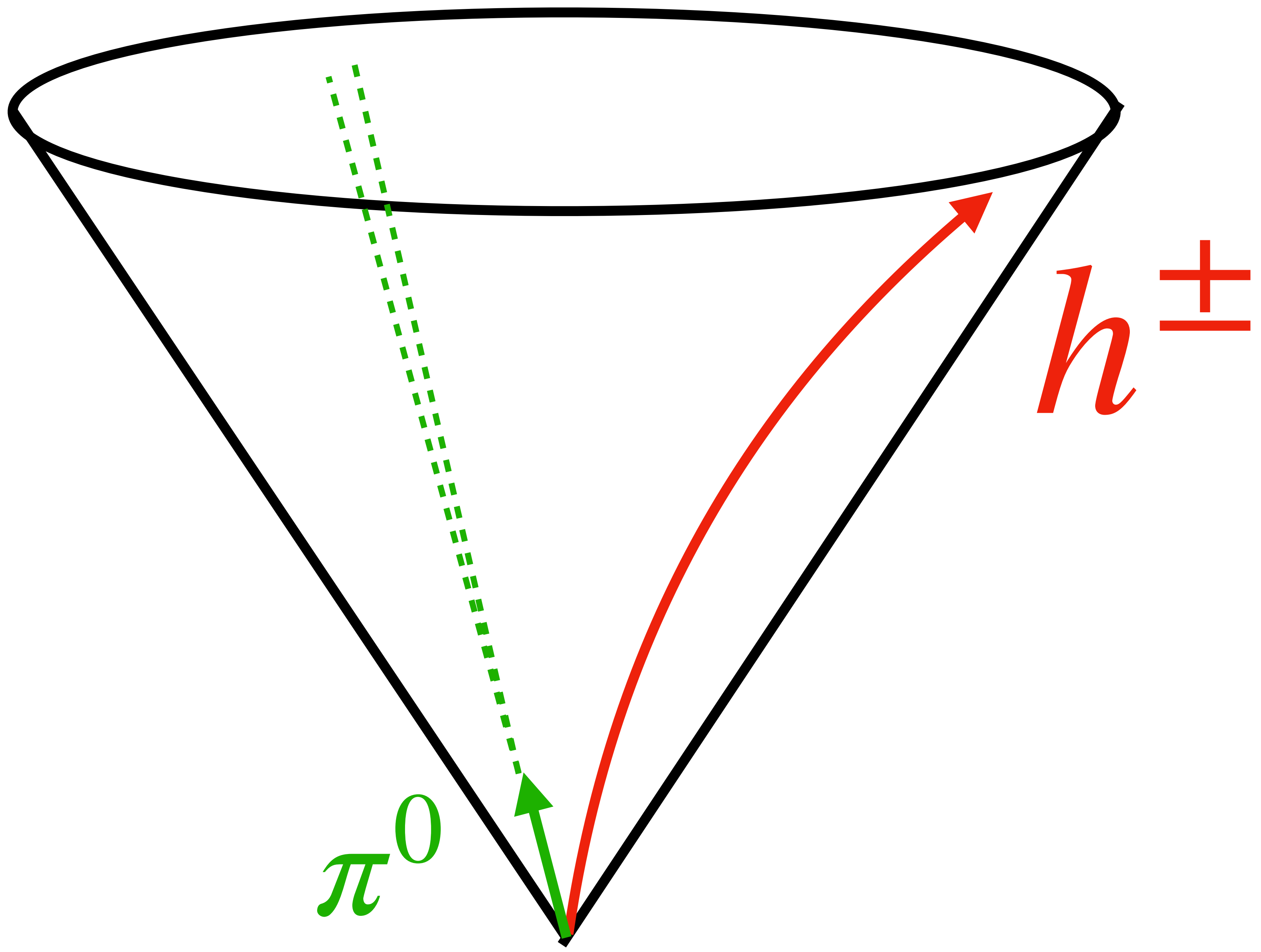




Other cross checks

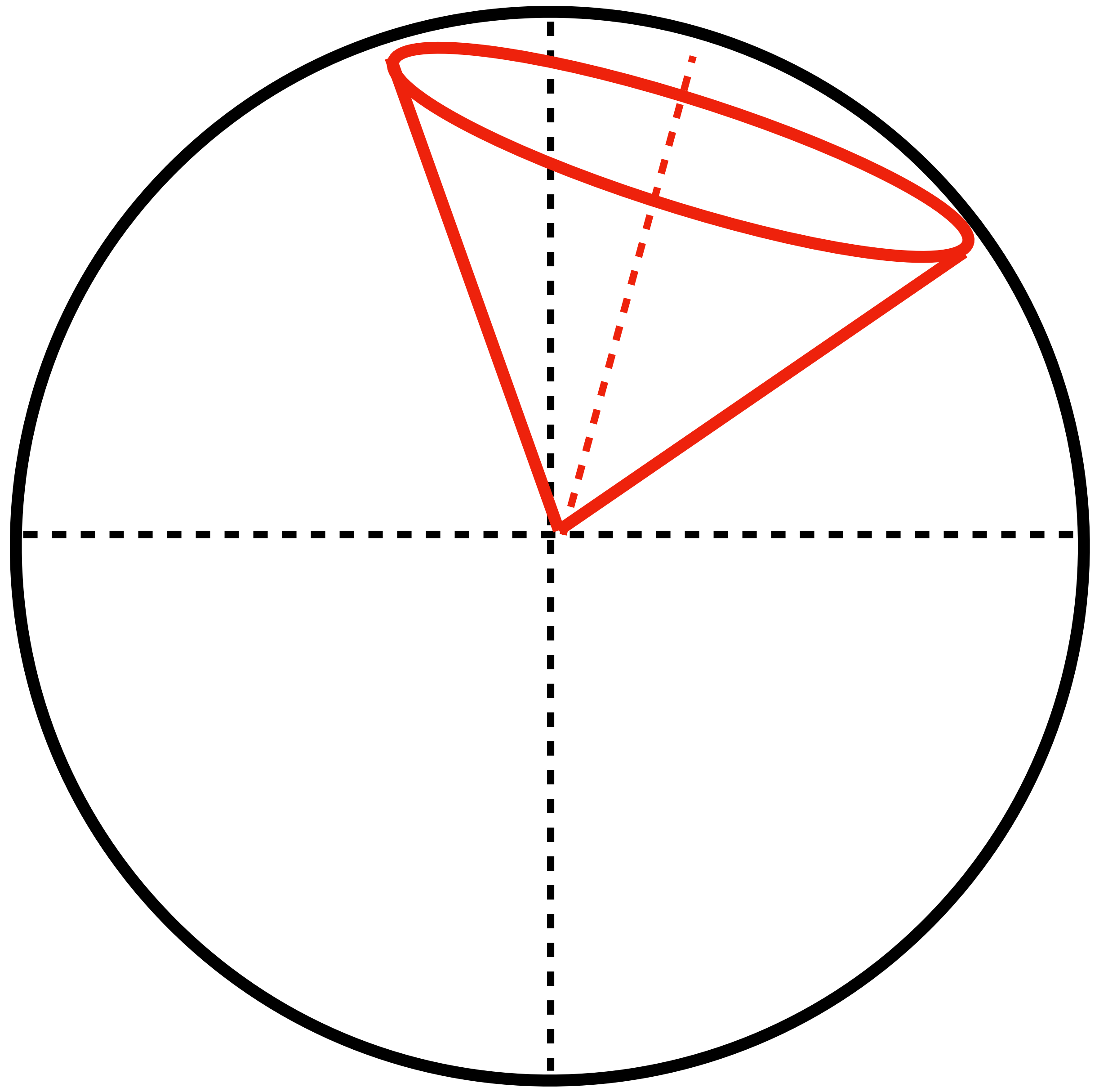
- **Signal found to be robust to:**
  - **Correlating same-sign tracks (suppresses particle decay contributions)**
  - **Correlating tracks w/ neutral deposits (from π^0 decays)**
    - **Signal is weaker, potentially from less effective of pileup mitigation**





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



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
- No obvious preferred N-pronged substructure in highest N_{ch} jets