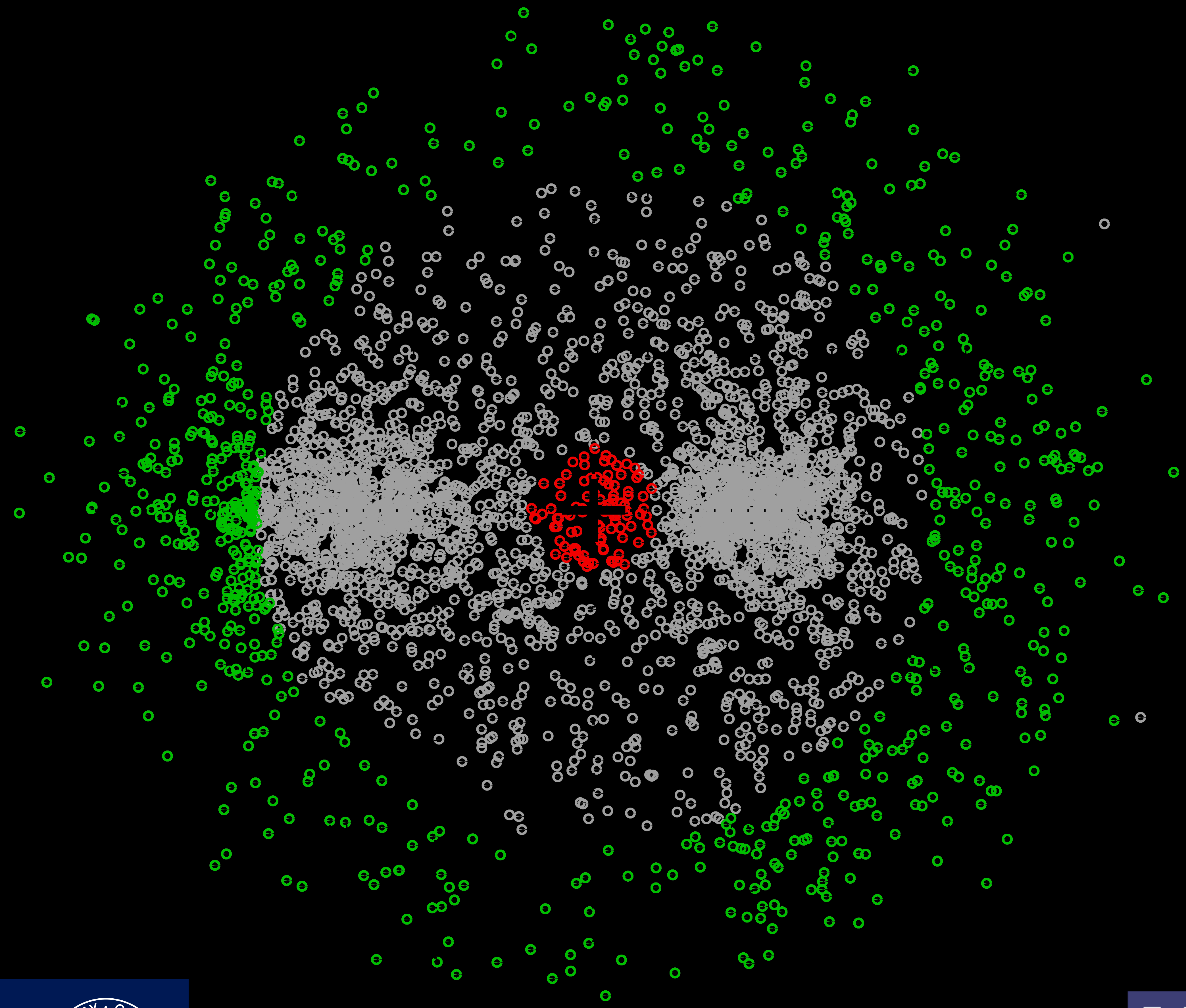
Dissecting jets for insight into flow-like signals

Work in progress with Alba Soto Ontoso

5th International Workshop on Emergent QCD Collectivity Across Scales: From Small System Collisions to Jets
Rice Global Paris Center
30 June 2026

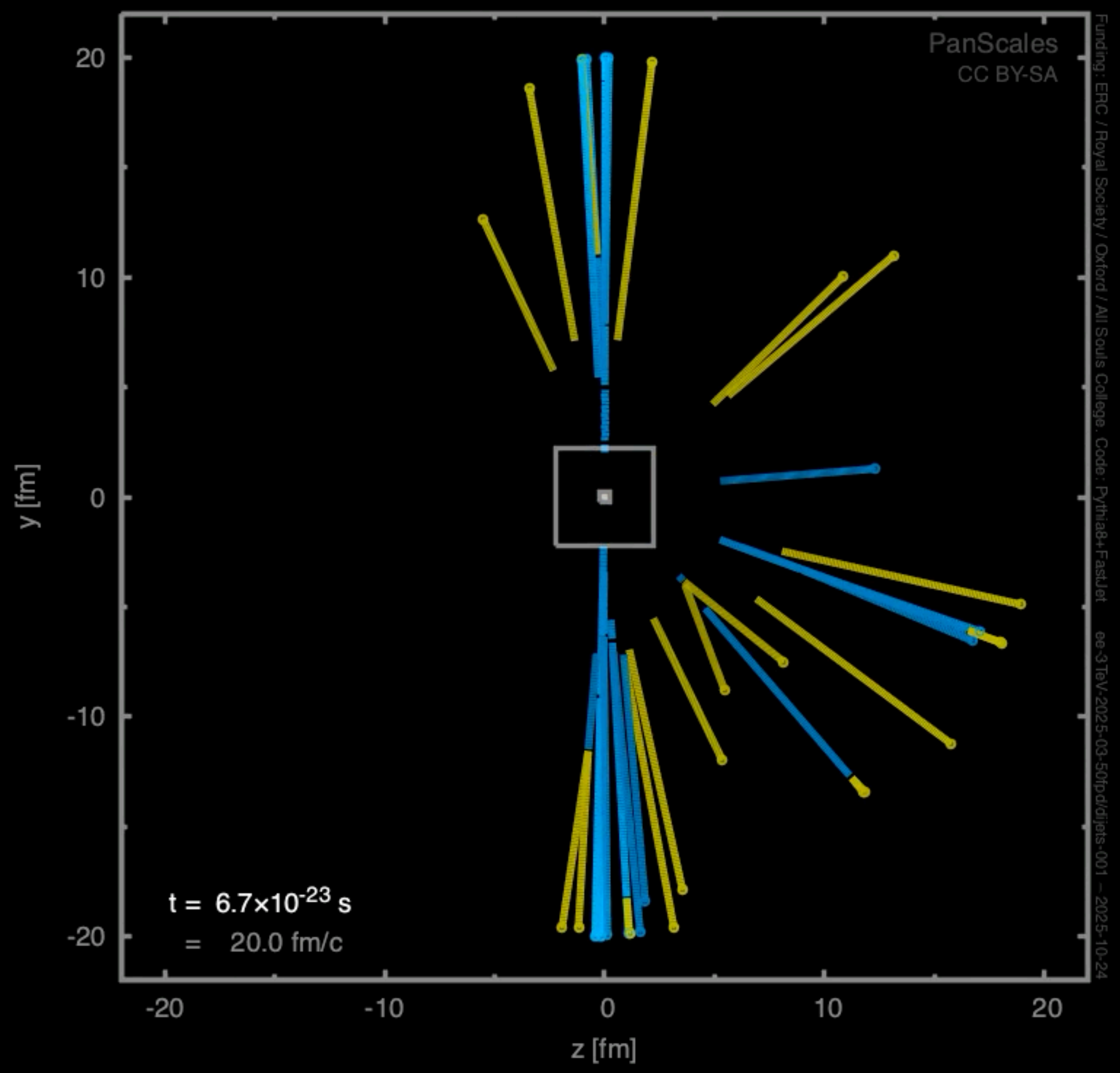


Gavin Salam
Rudolf Peierls Centre for Theoretical Physics
& All Souls College, Oxford

UNIVERSITY OF OXFORD

UKRI
Science and Technology Facilities Council

THE ROYAL SOCIETY



incoming beam particle

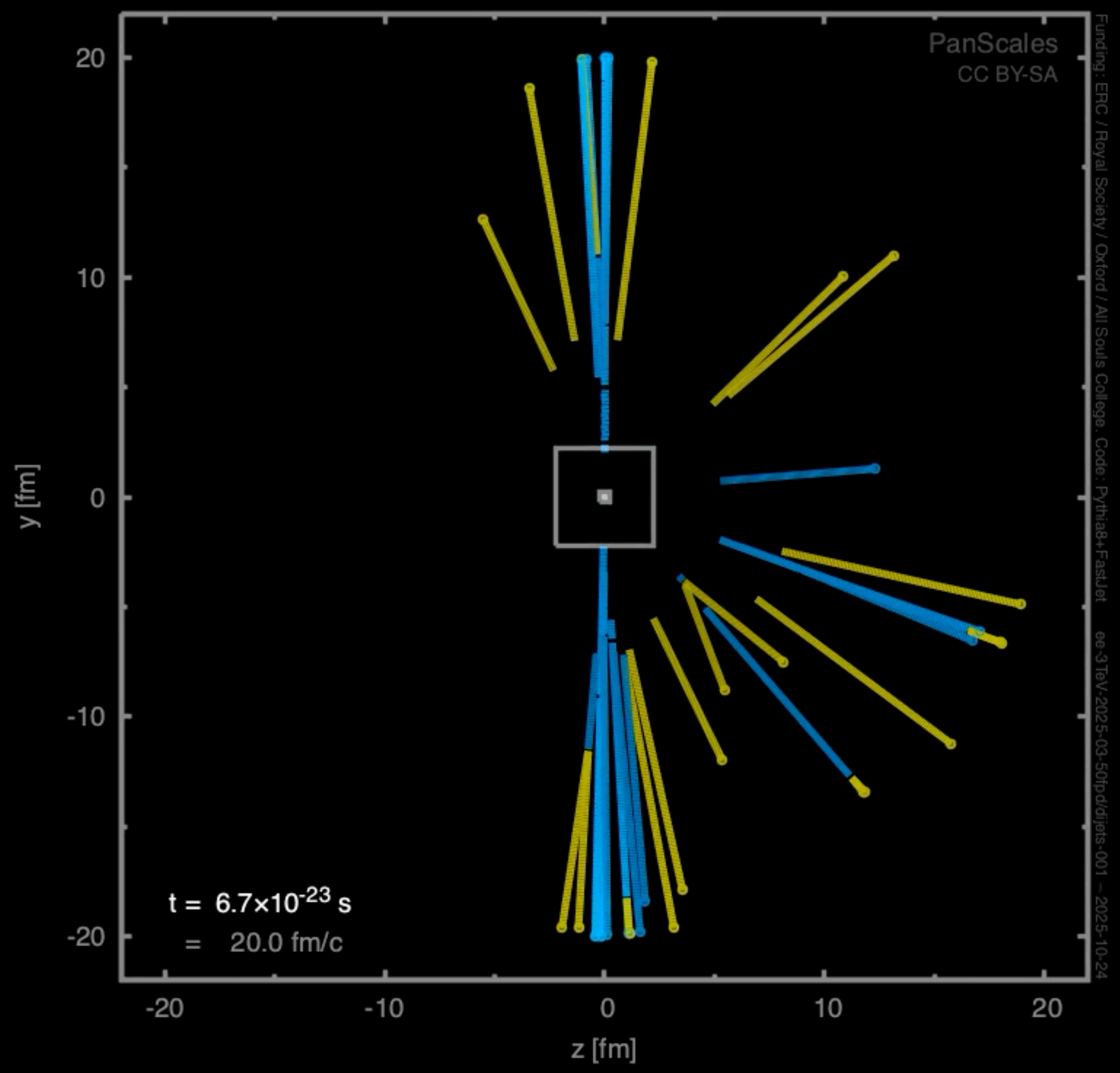
intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans up to 7 orders of magnitude in space-time.

Different parts of a jet are causally disconnected by the time hadronisation takes place.

A challenge for interpretations involving final-state collective effects.



incoming beam particle

intermediate particle (quark or gluon)

final particle (hadron)

Event evolution spans up to 7 orders of magnitude in space-time.

Different parts of a jet are causally disconnected by the time hadronisation takes place.

A challenge for interpretations involving final-state collective effects.

Focus is on analysis in CMS PAS HIN-24-024

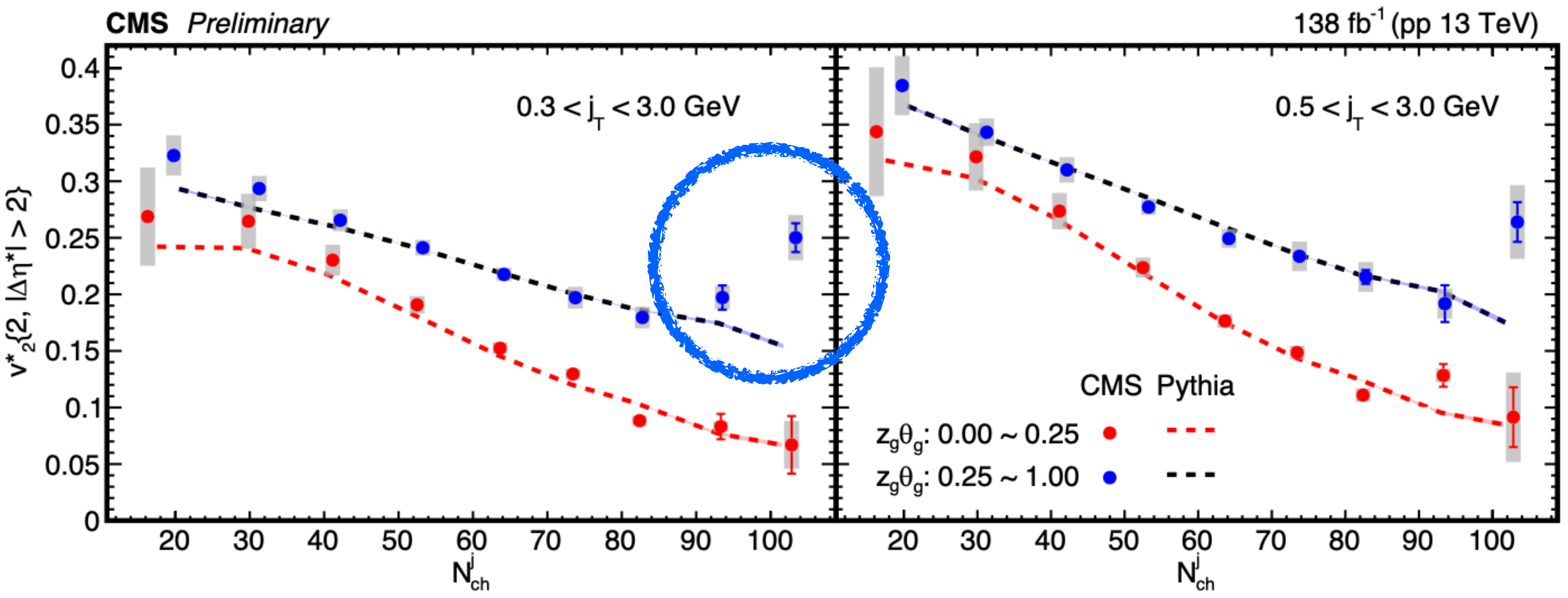


Figure 9: The elliptic anisotropy v_2^*, obtained from two-particle correlations, as a function of $N_{\mathrm{ch}}^{\mathrm{j}}$ for two jet substructure classes, $z_g\theta_g^\beta < 0.25$ (red) and $z_g\theta_g^\beta > 0.25$ (blue). Results are presented for two transverse momentum ranges, $0.3 < j_{\mathrm{T}} < 3\,\mathrm{GeV}$ (left) and $0.5 < j_{\mathrm{T}} < 3\,\mathrm{GeV}$ (right), using anti-k_{T} jets with $\mathrm{R} = 0.8$, $p_{\mathrm{T}}^{\mathrm{jet}} > 550\,\mathrm{GeV}$, and $|\eta^{\mathrm{jet}}| < 1.6$ in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$. The data points include statistical uncertainties (vertical bars), while systematic uncertainties are indicated by shaded boxes. The shaded envelopes around the PYTHIA 8 curves represent statistical uncertainties.

v_2 enhancement at high multiplicities

Evidence of flow or something else that we're missing?

Flow arguably difficult to justify in space-time picture of jets (cf. Dokshitzer-Webber 2505.00652)

We have a mystery
Something is going on!
How do we get more clues?

Focus is on analysis in CMS PAS HIN-24-024

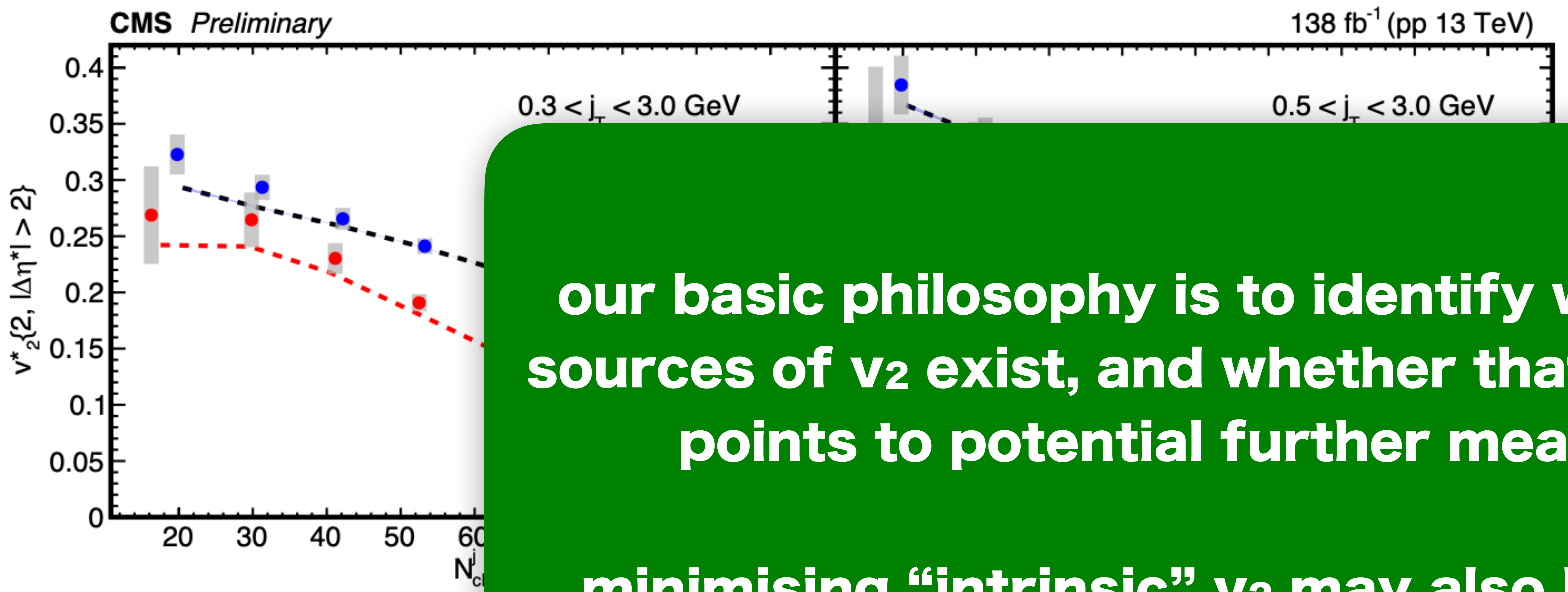


Figure 9: The elliptic anisotro[...]
for two jet substructure classe[...]
for two transverse momentu[...]
using anti-k_T jets with R = 0.[...]
The data points include statistical uncertainties (vertical bars), while systematic uncertainties are indicated by shaded boxes. The shaded envelopes around the PYTHIA 8 curves represent statistical uncertainties.

our basic philosophy is to identify what "intrinsic" sources of v₂ exist, and whether that understanding points to potential further measurements

minimising "intrinsic" v₂ may also help maximise relative size of flow-like signals

v_2 enhancement at high multiplicities

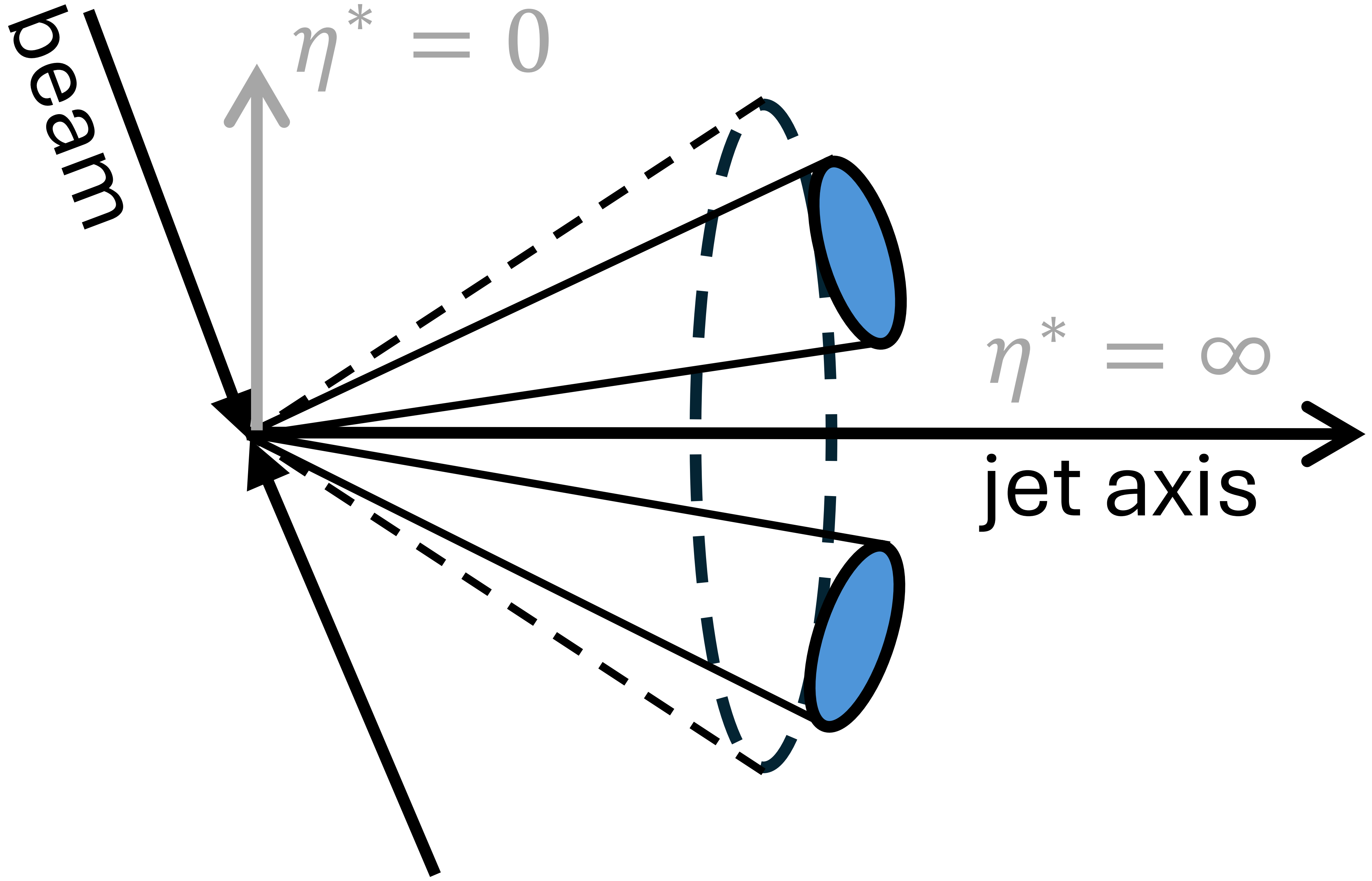
[...]ce of flow or [...]hing else that [...]e missing?

[...]ably difficult to [...]in space-time [...]e of jets (cf. [...]itzer-Webber [...]05.00652)

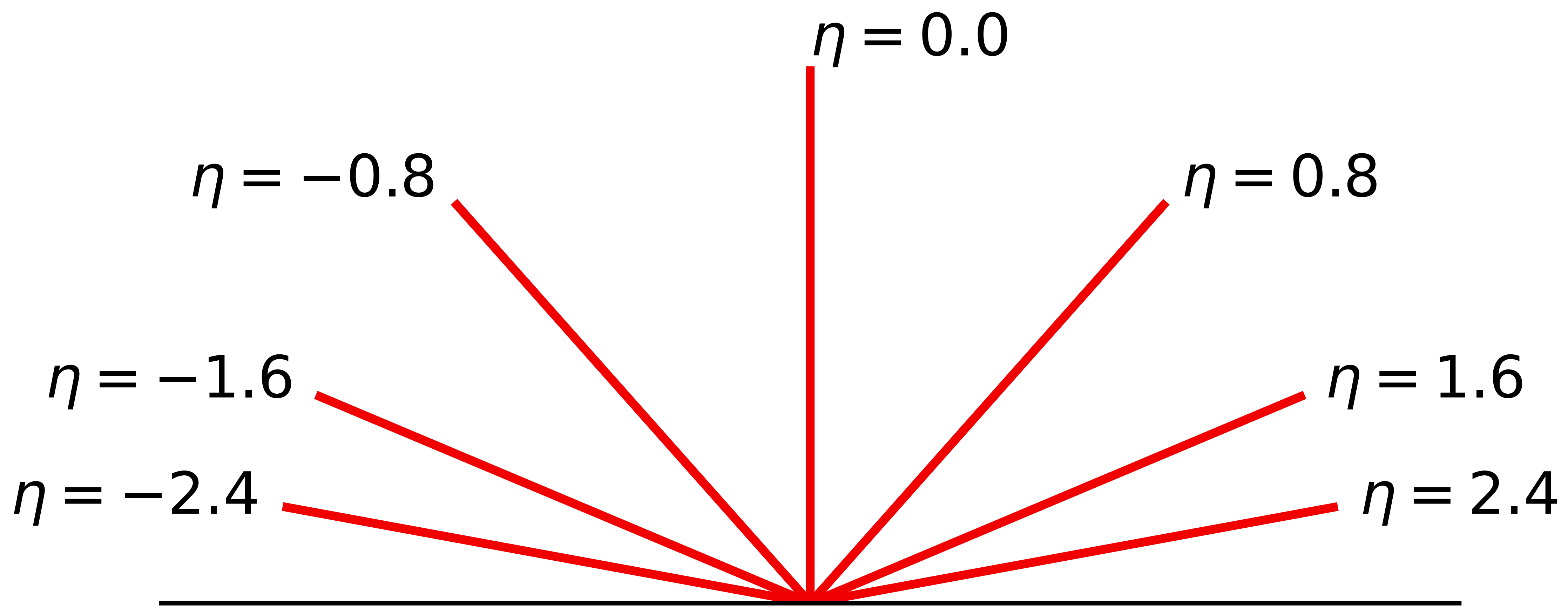
We have a mystery
Something is going on!
How do we get more clues?

an example:
jet frame coordinates

Step 1: transforming a jet (jet frame)

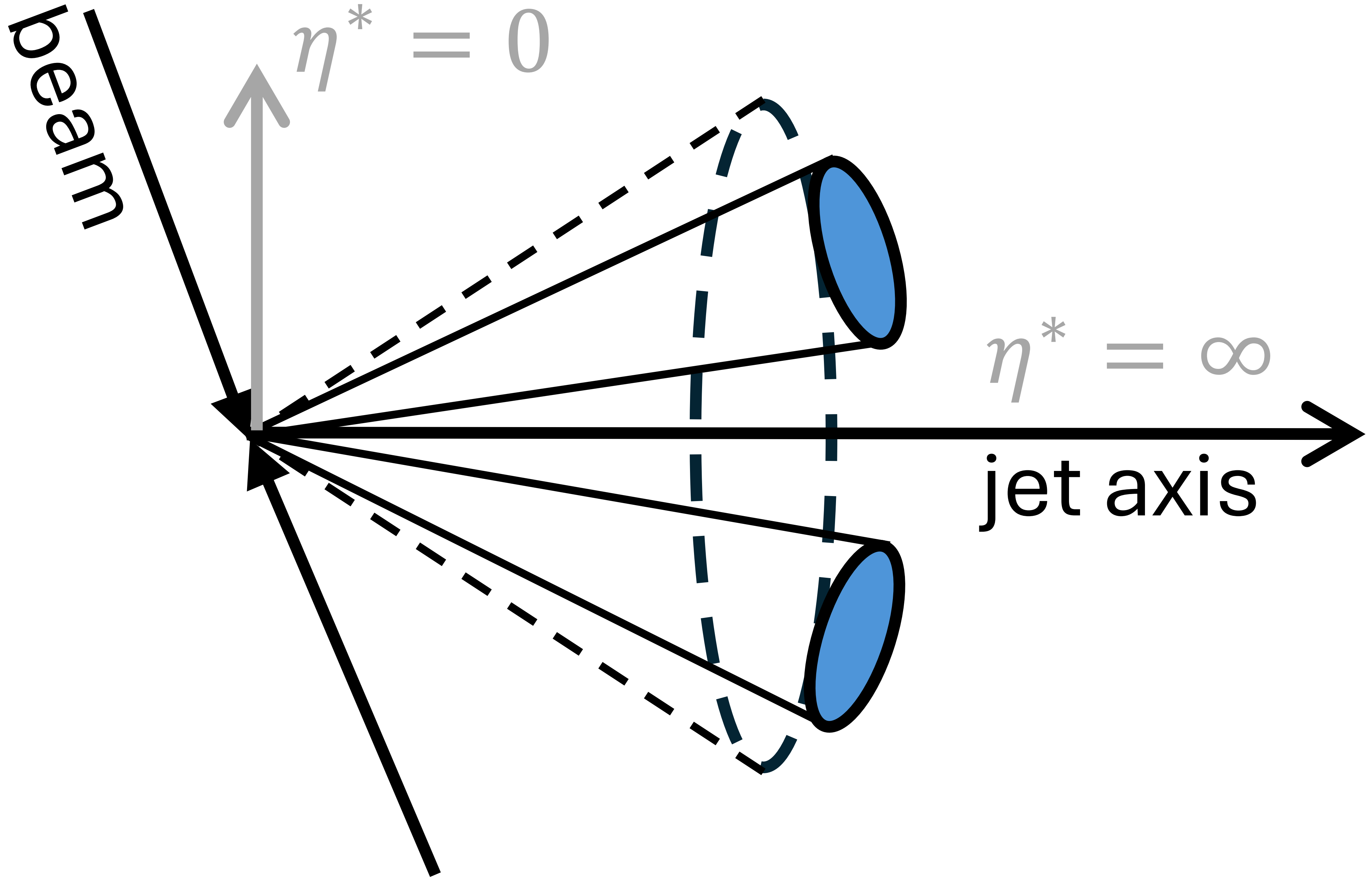


Jet frame: rotate the jet so that its axis aligns with the z axis

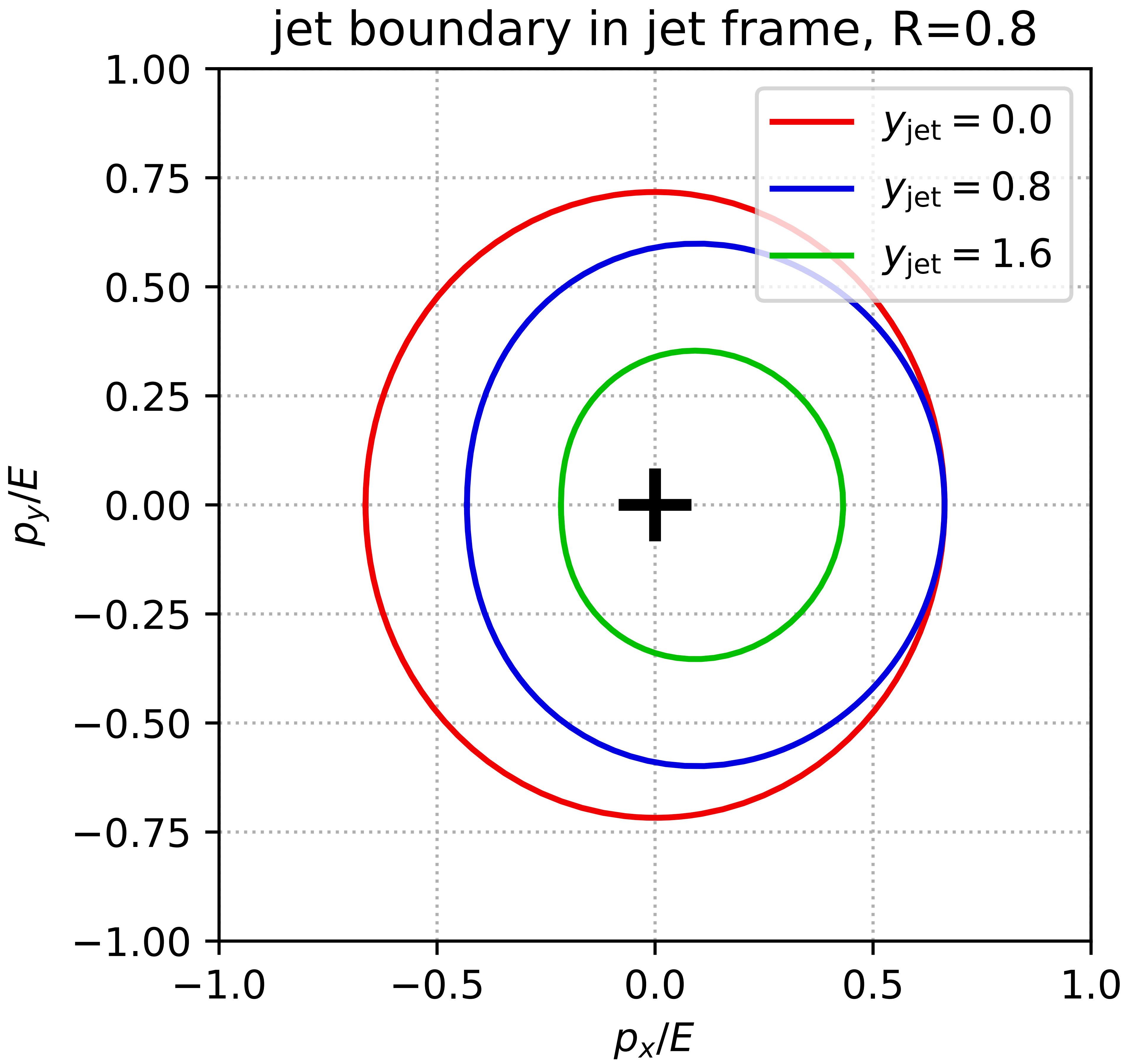


forward jets are narrower

Step 1: transforming a jet (jet frame)



Jet frame: rotate the jet so
that its axis aligns with the z axis



forward jets also have a squeezed shape
(with potential intrinsic v_2)

Step 1 alternative: transformation based on longitudinally invariant coordinates

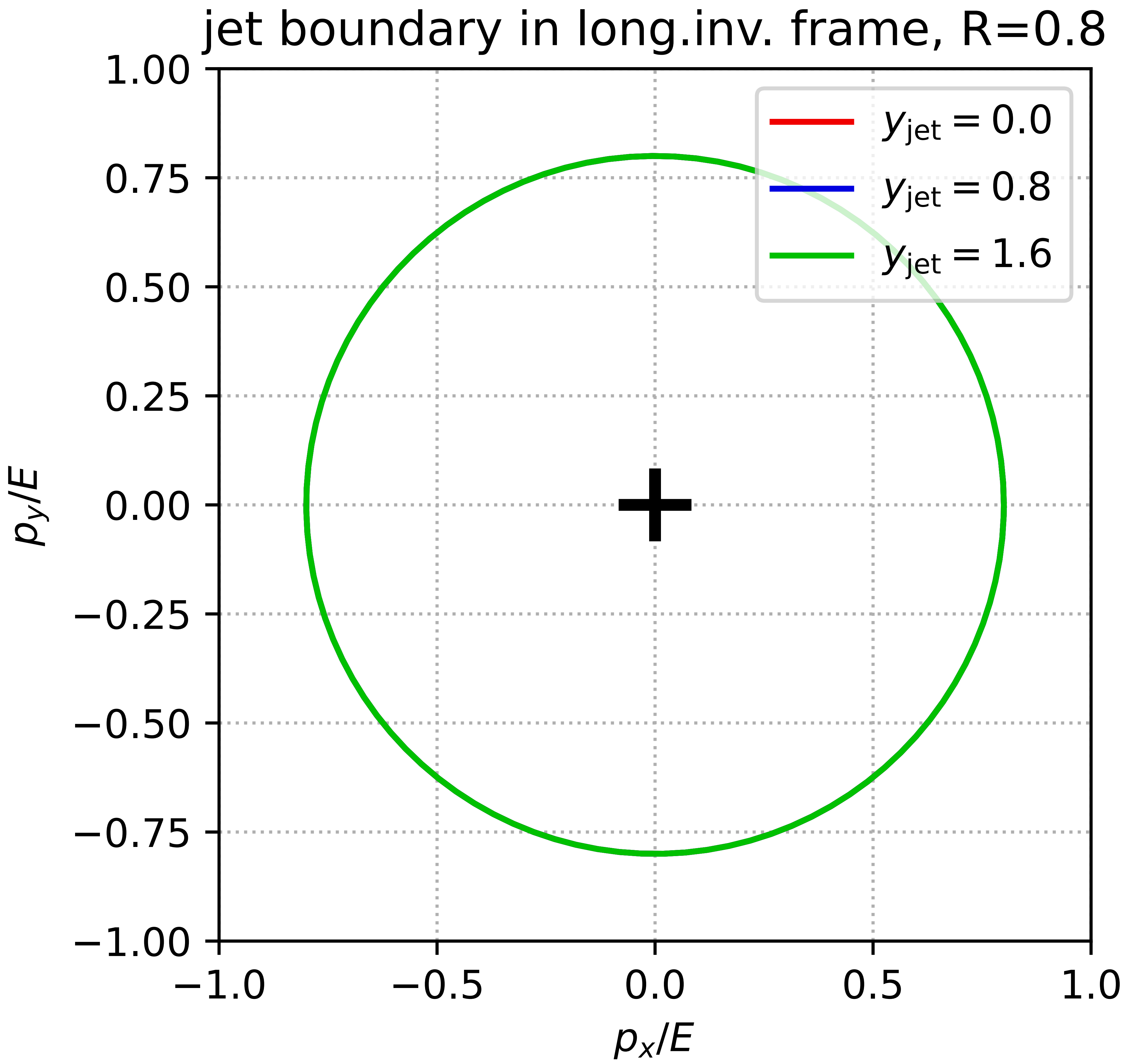
$$\theta_i^2 \equiv \Delta y_{i,\text{jet}}^2 + \Delta\phi_{i,\text{jet}}^2,$$

$$\eta_i^* = -\log\tan\frac{\theta_i}{2},$$

$$\phi_i^* = \tan^{-1}\frac{\Delta y_{i,\text{jet}}}{\Delta\phi_{i,\text{jet}}},$$

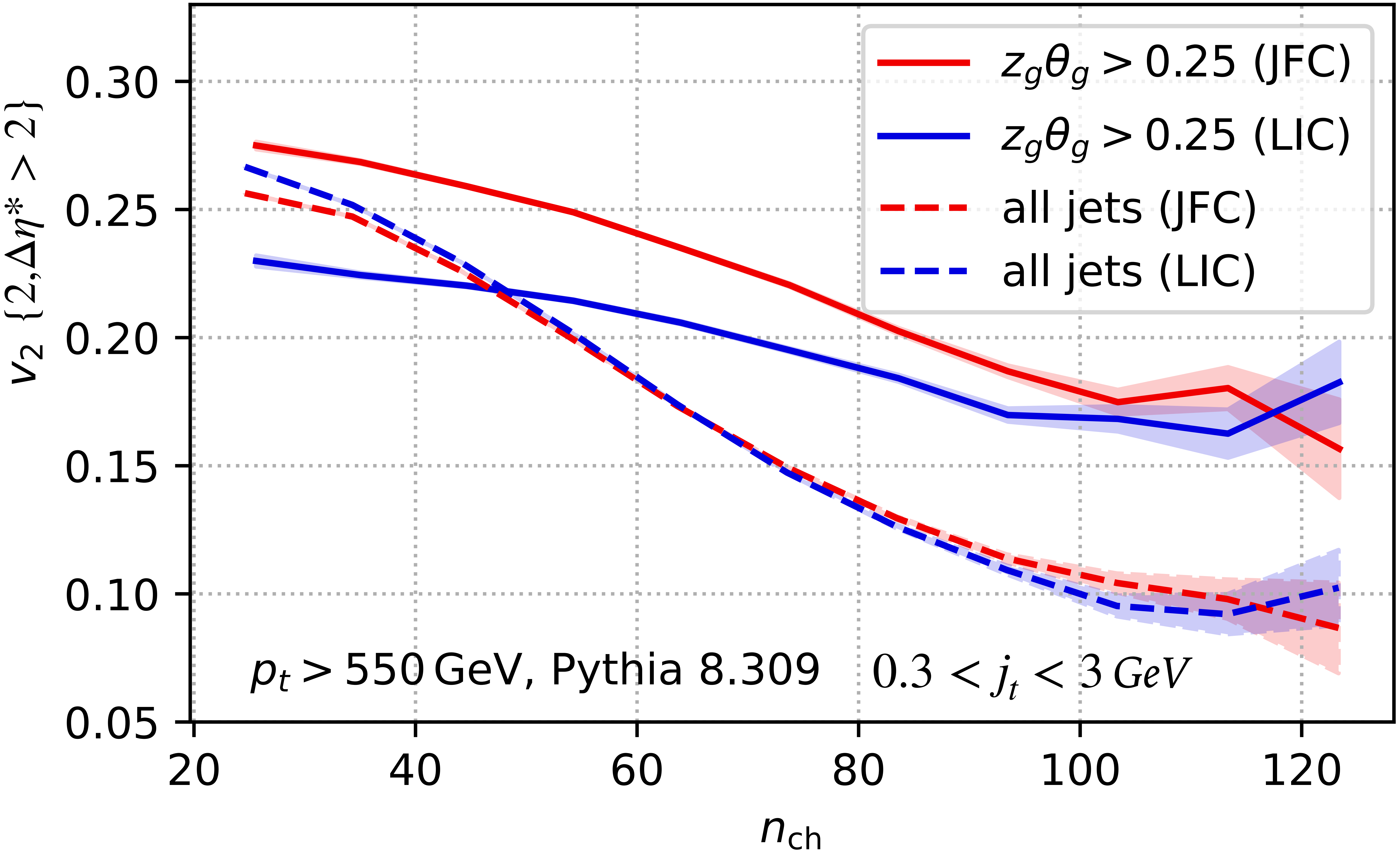
$$j_{ti} = p_{ti}\theta_i$$

long. inv. constituents:
use Δy and $\Delta\phi$ of particles wrt jet axis



forward and central jets both circular
(no intrinsic v_2)

jet-frame ("JFC") v. long-inv ("LIC"): v_2 vs. n_{ch}

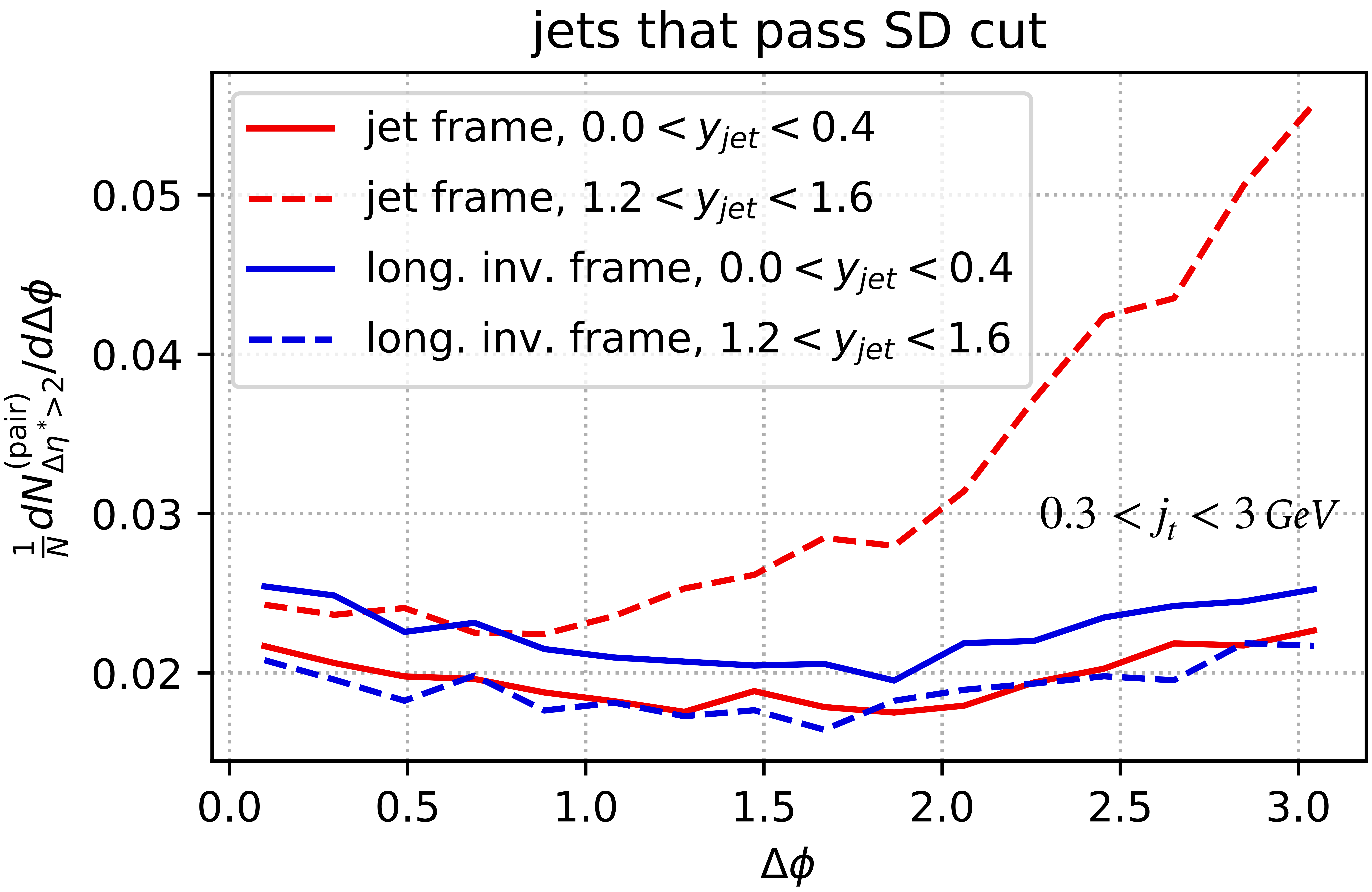


Little impact in full-jet sample (i.e. no soft-drop cut)

Some reduction of v_2 for jets that pass the SD cut (≡ less background for "signals")

Question: does the v_2 effect persist with LIC rather than JFC?

Δφ distribution for different rapidities and jet-frame choices



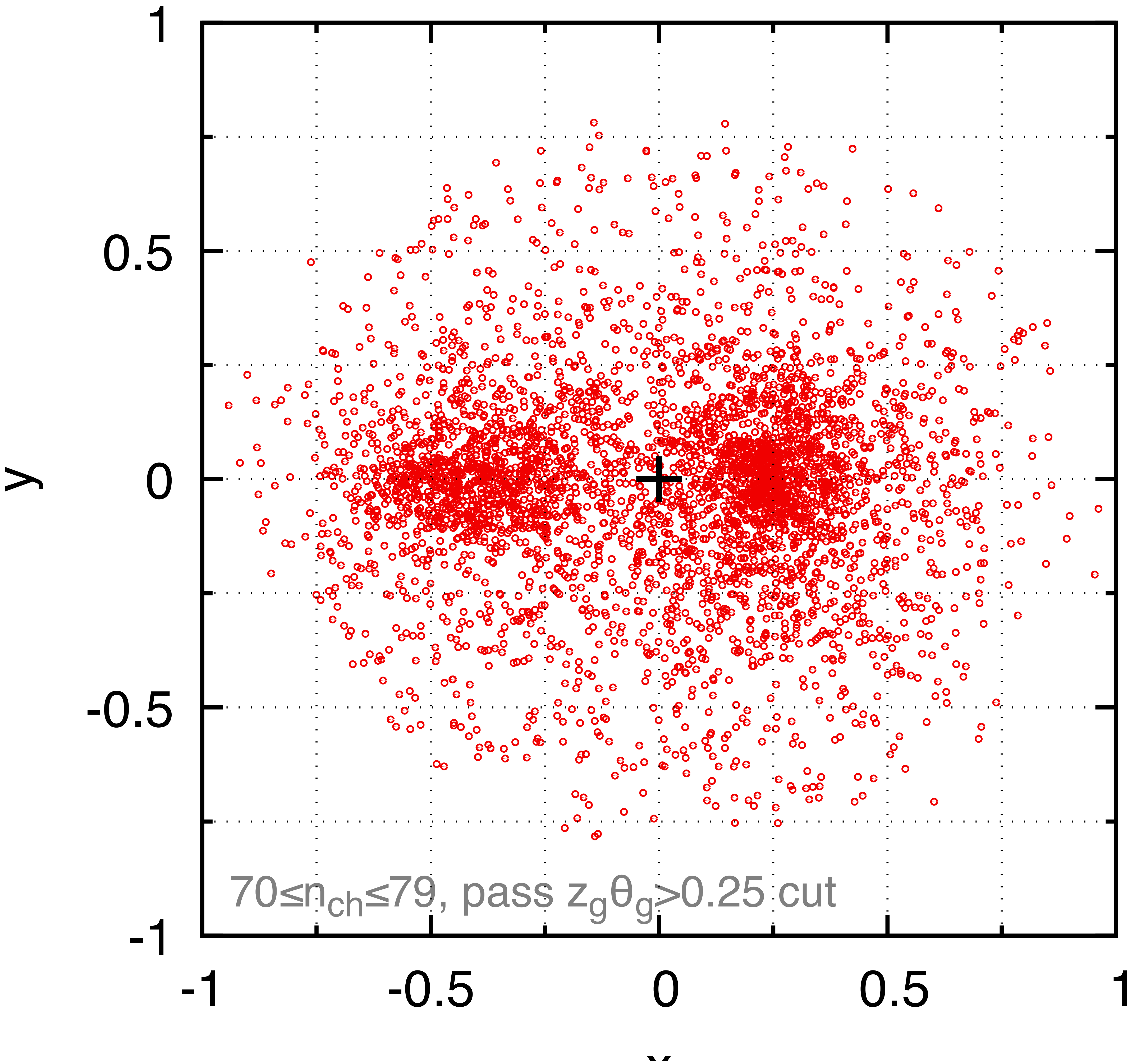
"SD cut" means

$z_g \theta_g > 0.25$

transverse jet profile

all plots done with longitudinally invariant coordinates

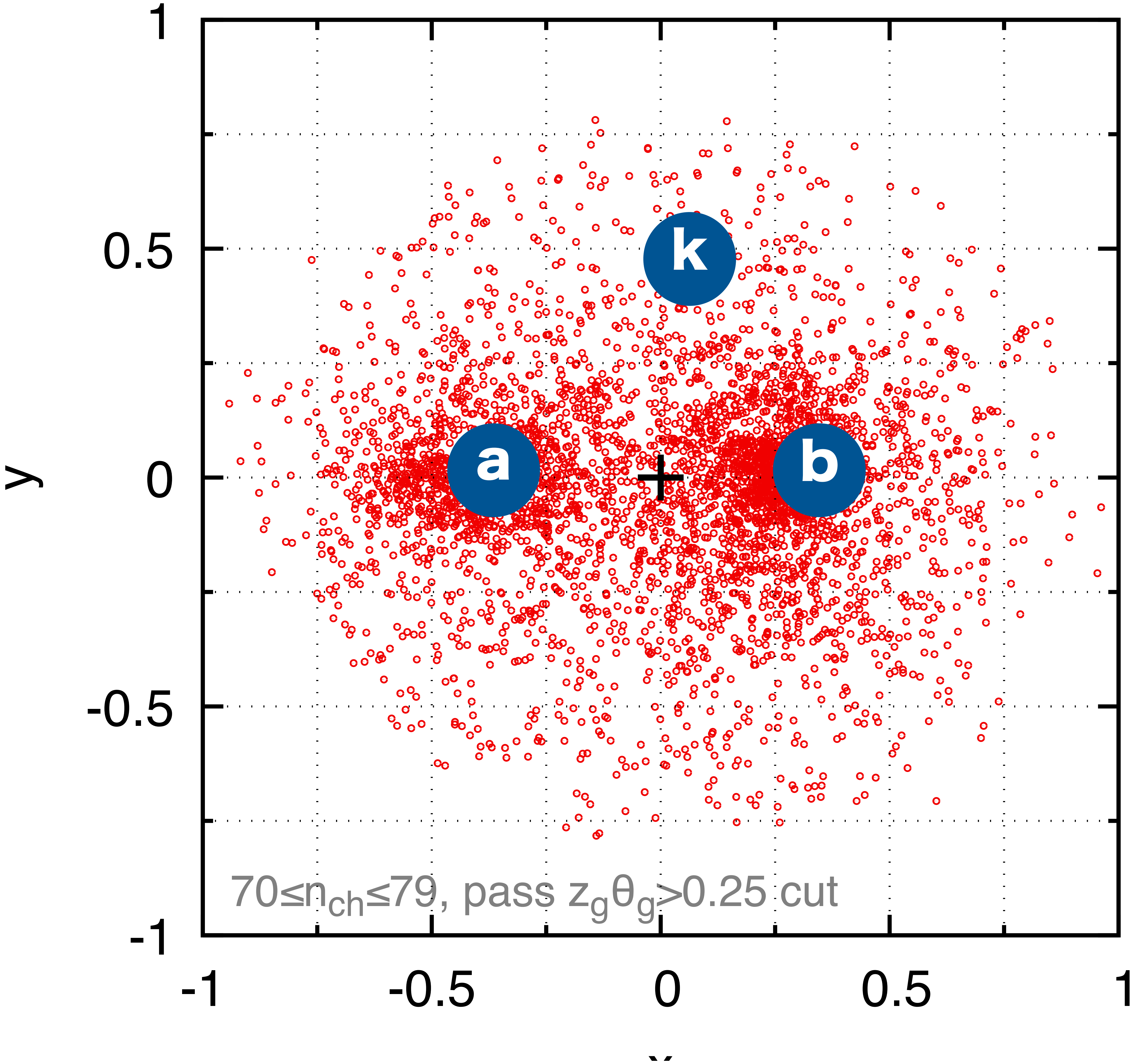
A first key question: why is there any v_2 at all, even at low multiplicity?



- Take a jet in a given n_{ch} bin & that passes the $z_g\theta_g > 0.25$ cut
- Rotate each jet azimuthally around its axis so that the soft-drop declustering line is horizontal
- Plot all charged constituents
- repeat for many jets, to build up a coherent picture

Particles distributed according to a **dipole-radiation pattern**; that is the source of

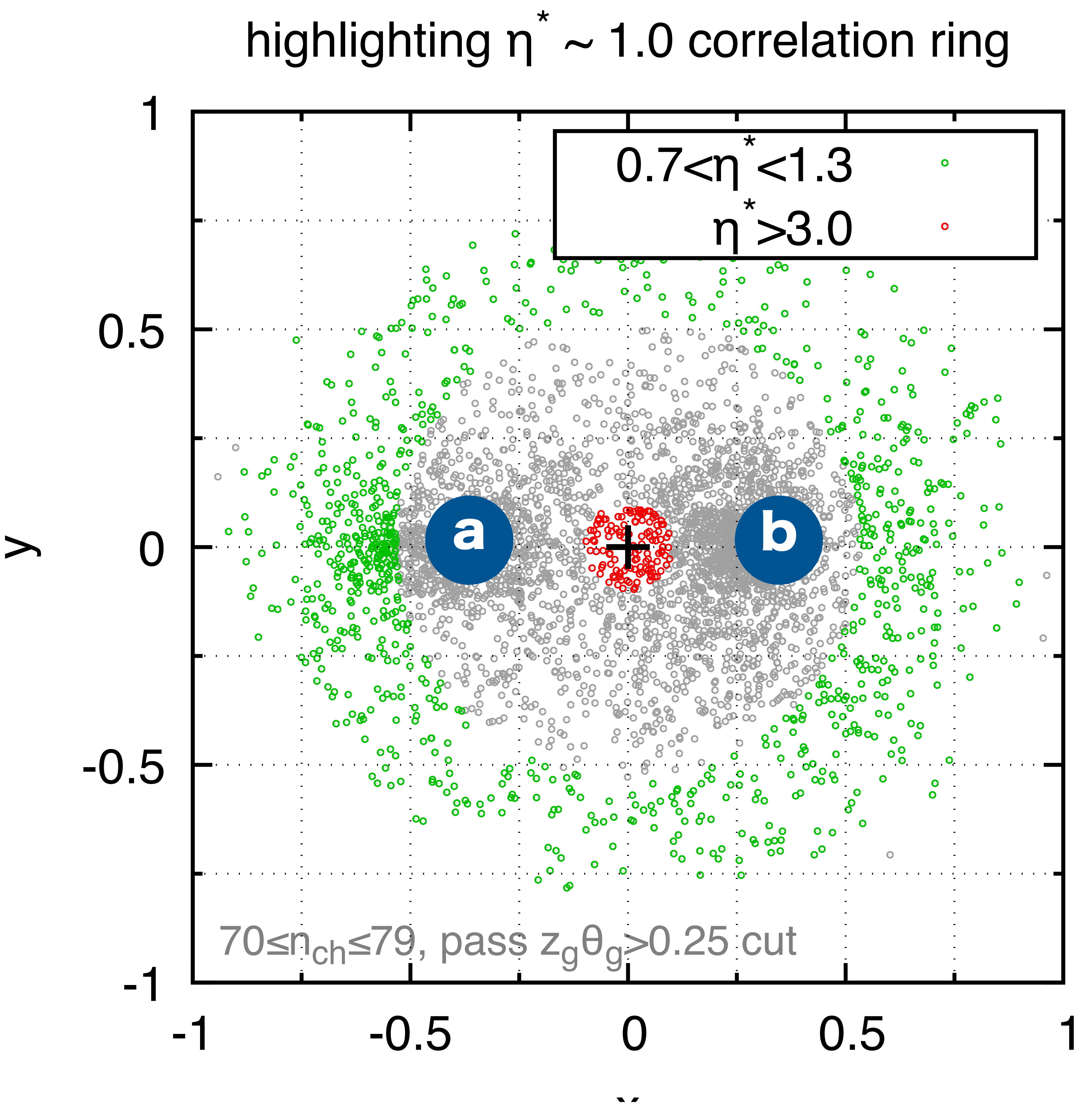
A first key question: why is there any v_2 at all, even at low multiplicity?



Antenna pattern for soft radiation k from a hard dipole of particles a and b:

$$\frac{p_a \cdot p_b}{(p_a \, . \, k)(k \, . \, p_b)}$$

$\Delta\eta^* > 2$ cut and antenna effect

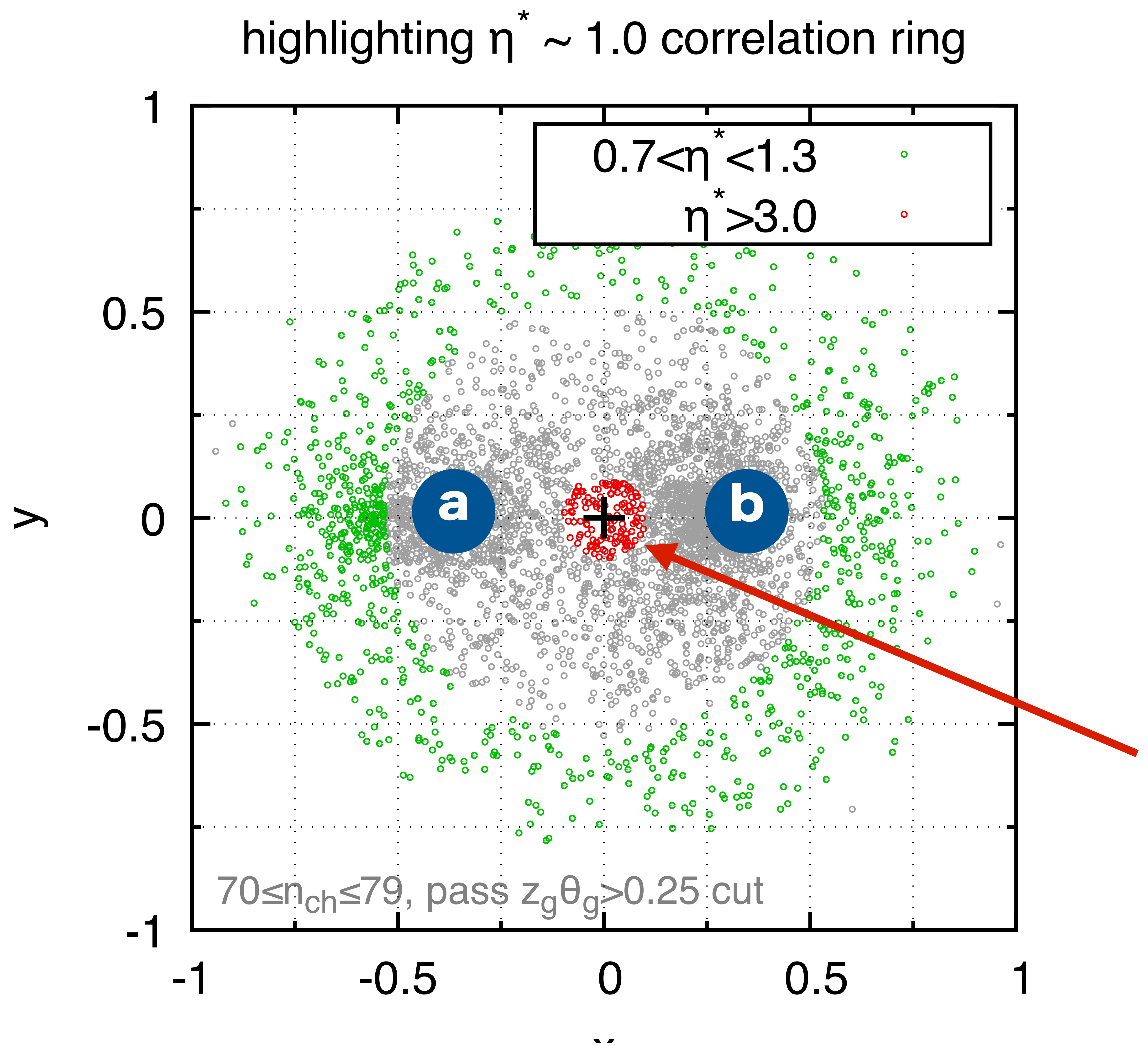


Antenna pattern for soft radiation k from a hard dipole of particles a and b:

$$\frac{p_a \cdot p_b}{(p_a \cdot k)(k \cdot p_b)}$$

$\Delta\eta^* > 2$ cut means correlation stretches between large angles and small angles.

Δη* > 2 cut and antenna effect



Antenna pattern for soft radiation k from a hard dipole of particles a and b:

$$\frac{p_a \cdot p_b}{(p_a \, . \, k)(k \, . \, p_b)}$$

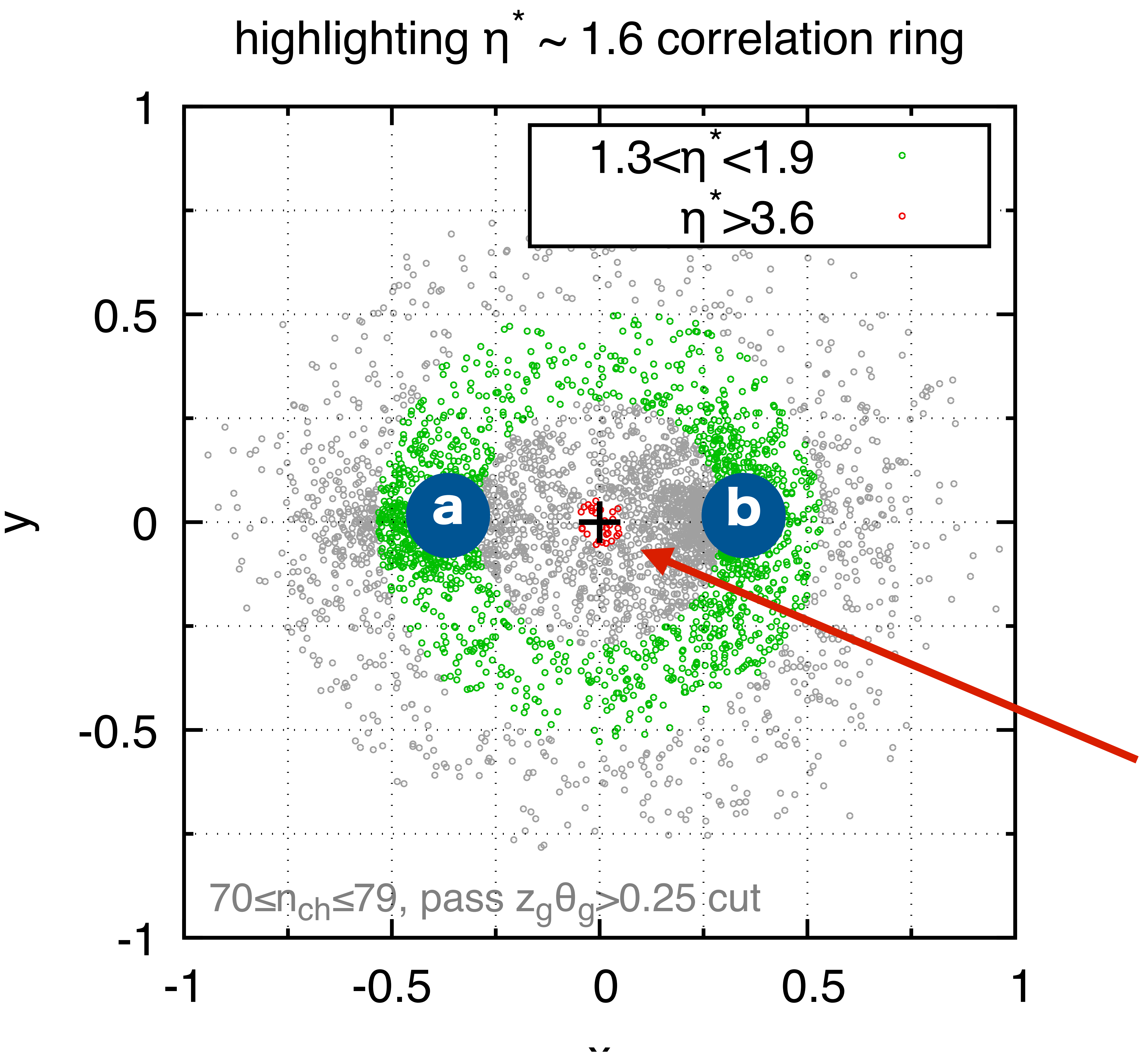
$\Delta\eta^* > 2$ cut means correlation stretches between large angles and small angles.

If a and b at angles $\pm R/2$, distribution of radiation at distance $r \ll R$ from jet center is

$$\propto 1 + 8\,\frac{r^2}{R^2}\,\cos 2\phi^*$$

Vanishes as $e^{-2\Delta\eta^*}$, contained in Pythia

$\Delta\eta^* > 2$ cut and antenna effect



Antenna pattern for soft radiation k from a hard dipole of particles a and b:

$$\frac{p_a \cdot p_b}{(p_a \,.\, k)(k \,.\, p_b)}$$

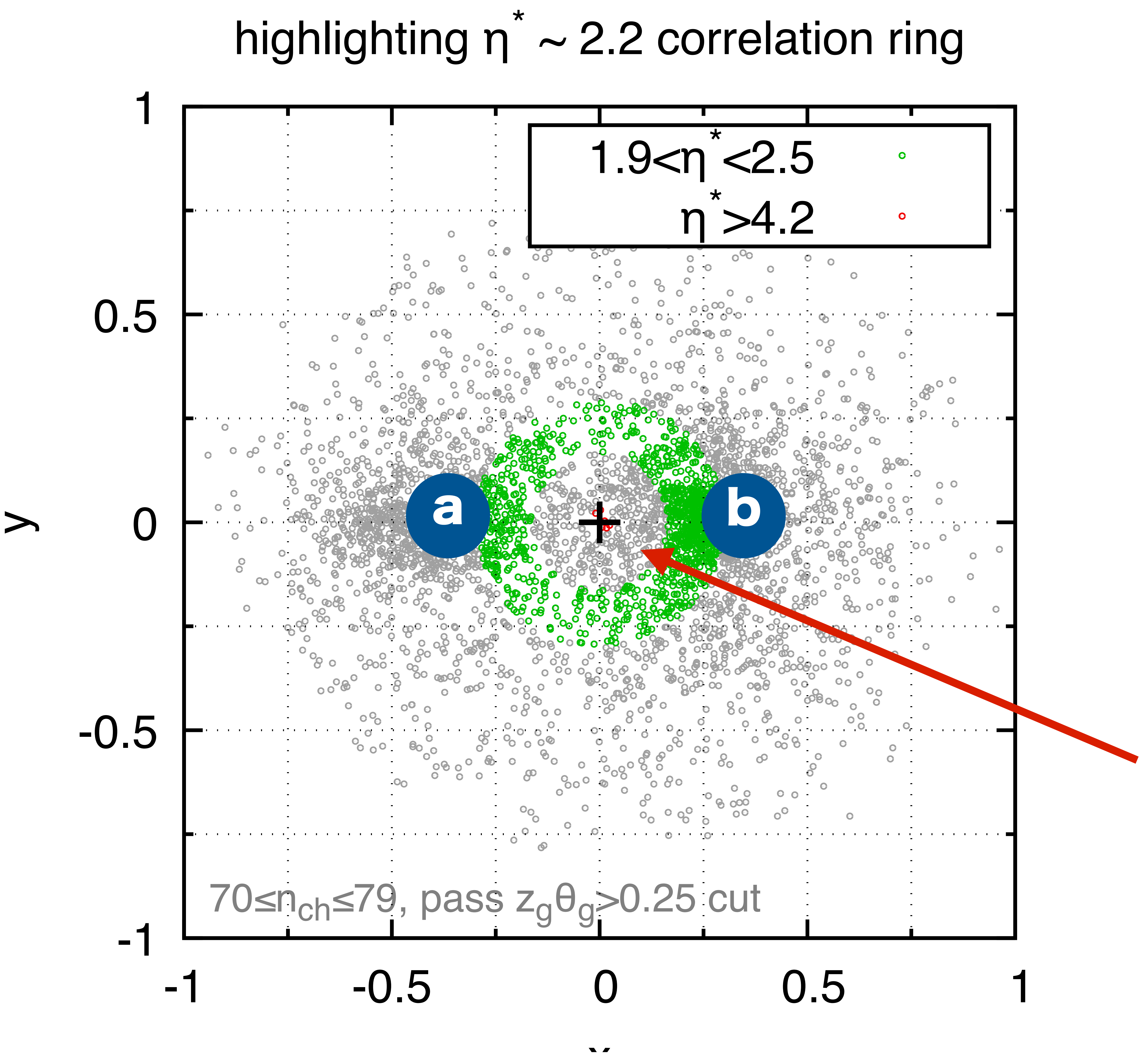
$\Delta\eta^* > 2$ cut means correlation stretches between large angles and small angles.

If a and b at angles $\pm R/2$, distribution of radiation at distance $r \ll R$ from jet center is

$$\propto 1 + 8\,\frac{r^2}{R^2}\,\cos 2\phi^*$$

Vanishes as $e^{-2\Delta\eta^*}$, contained in Pythia

$\Delta\eta^* > 2$ cut and antenna effect



Antenna pattern for soft radiation k from a hard dipole of particles a and b:

$$\frac{p_a \cdot p_b}{(p_a \,.\, k)(k \,.\, p_b)}$$

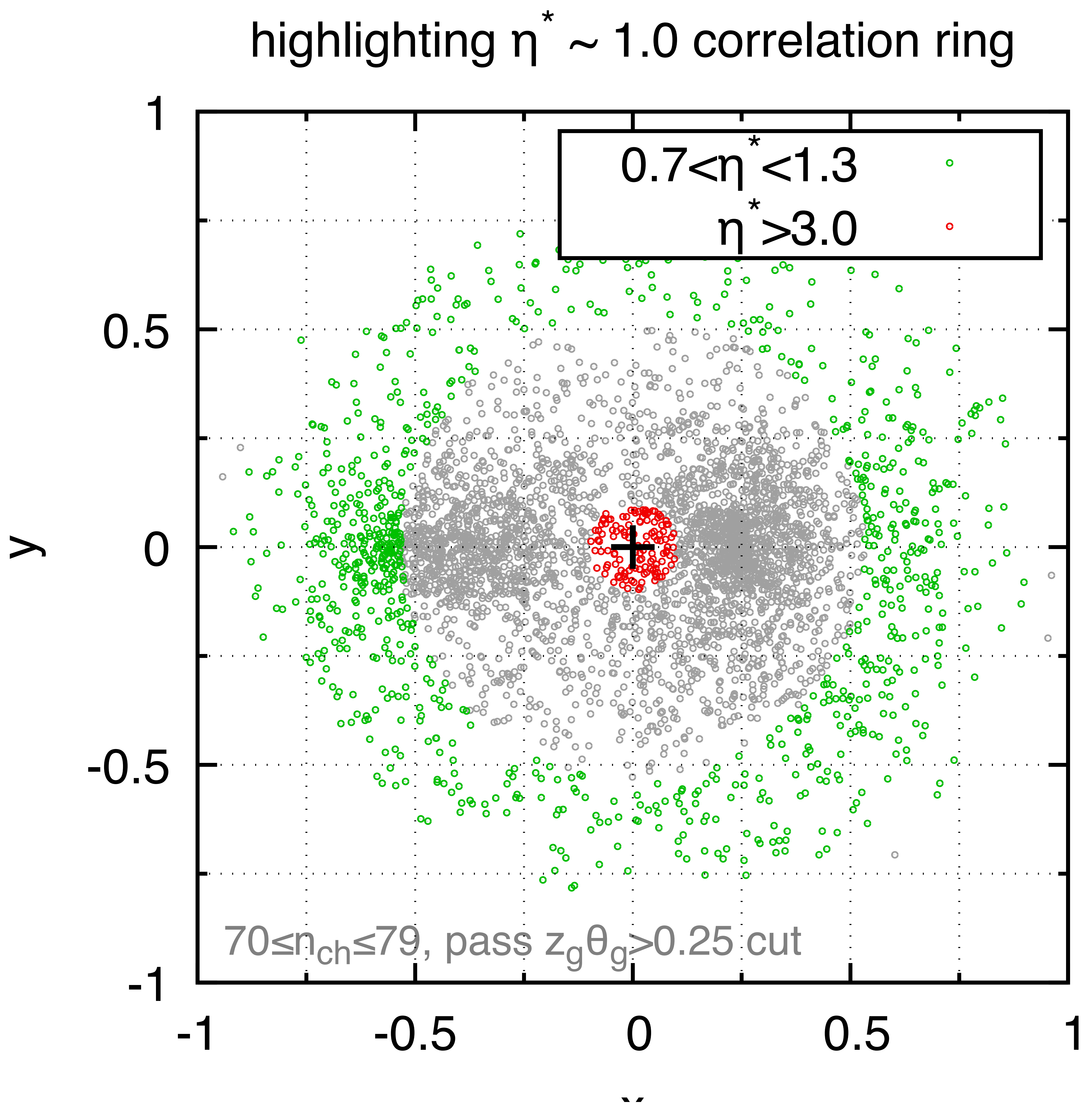
$\Delta\eta^* > 2$ cut means correlation stretches between large angles and small angles.

If a and b at angles $\pm R/2$, distribution of radiation at distance $r \ll R$ from jet center is

$$\propto 1 + 8\,\frac{r^2}{R^2}\,\cos 2\phi^*$$

Vanishes as $e^{-2\Delta\eta^*}$, contained in Pythia

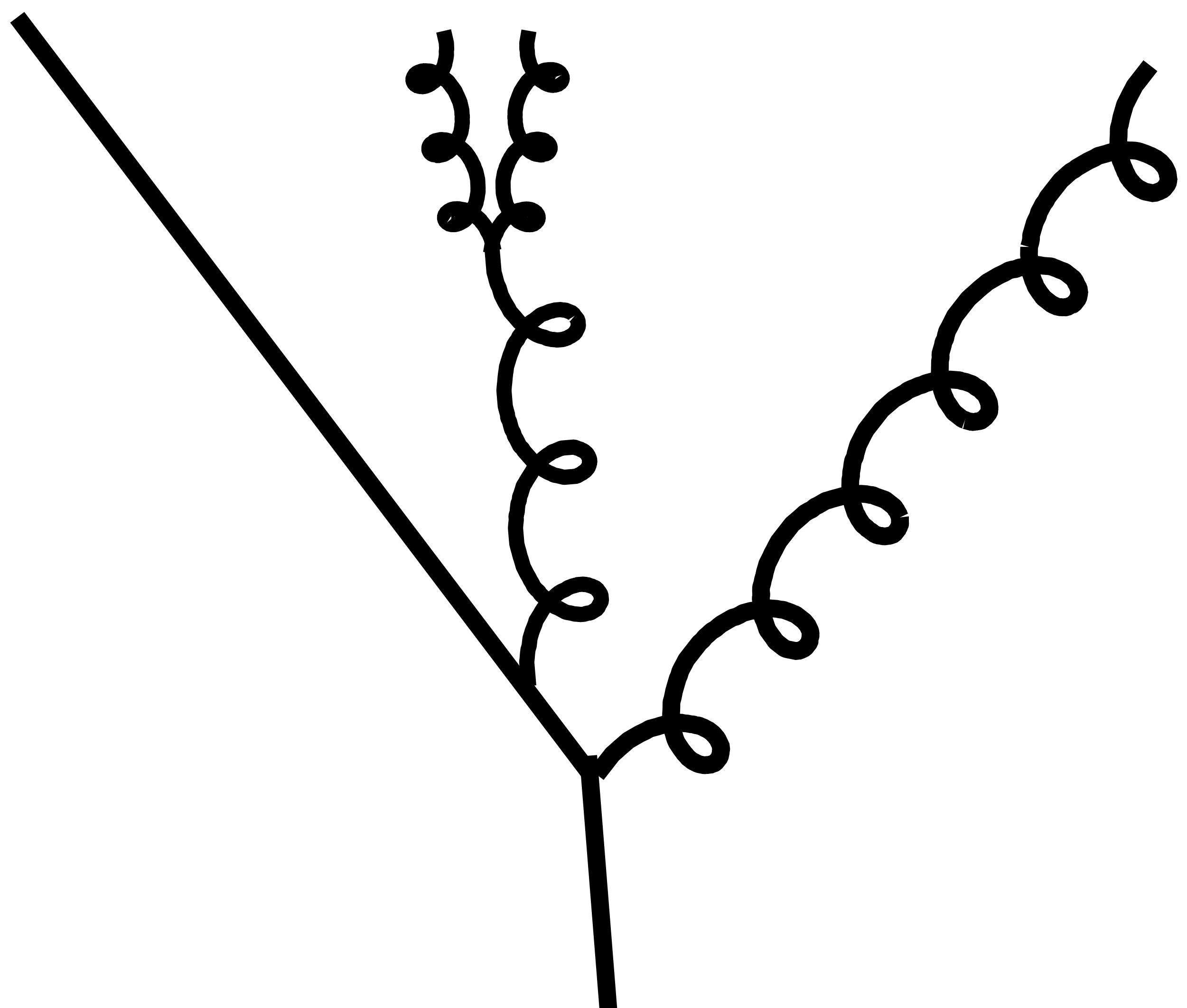
Spin correlations



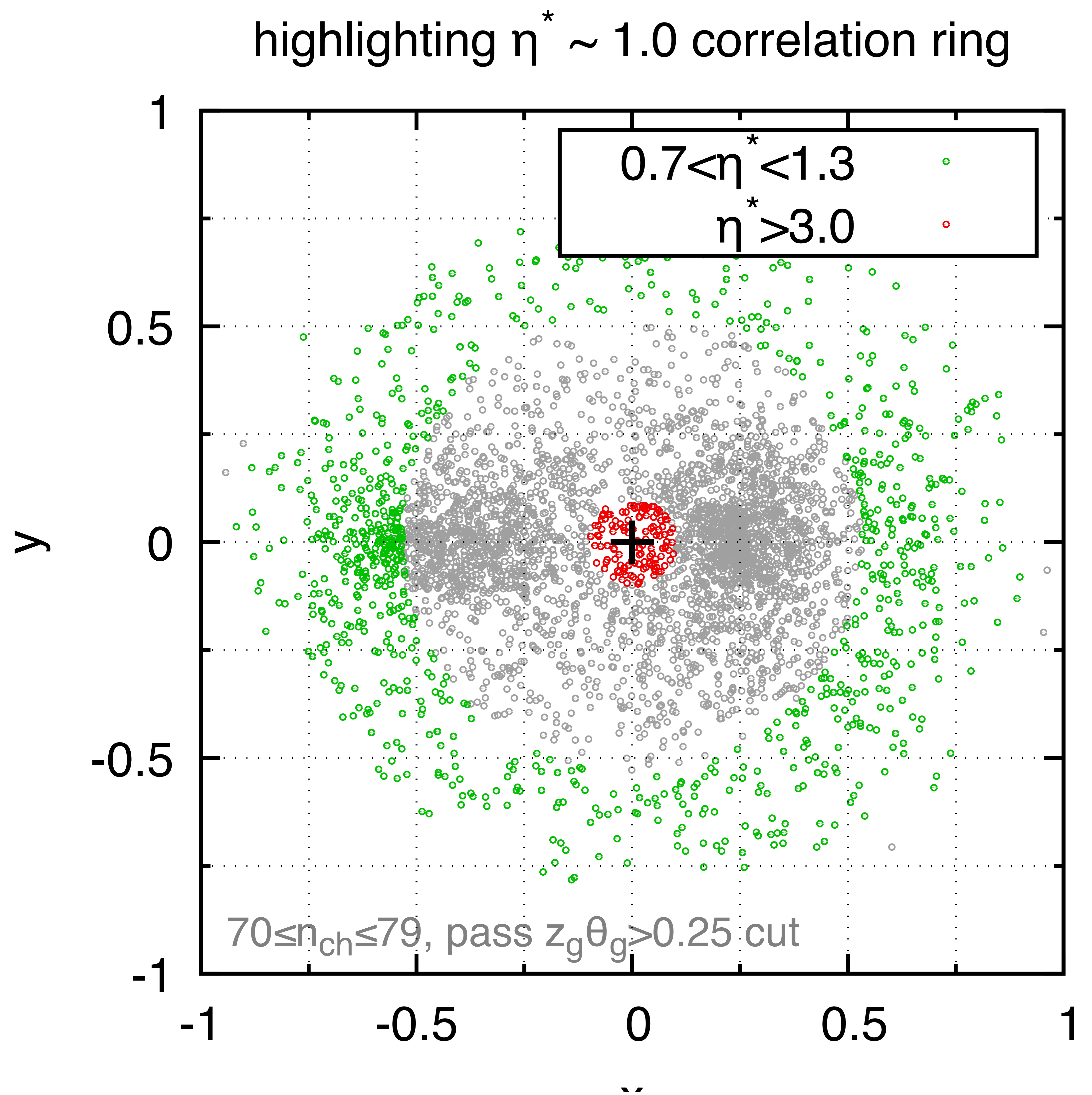
At next perturbative order, gluon polarisation in $g \to gg$ gives correlation that persists for $r/R \to 0$.

$$\propto 1 + \frac{A}{9}\cos 2\phi^*, \qquad A \leq 1$$

Could it be especially relevant at high multiplicity (involves multiple gluons)?



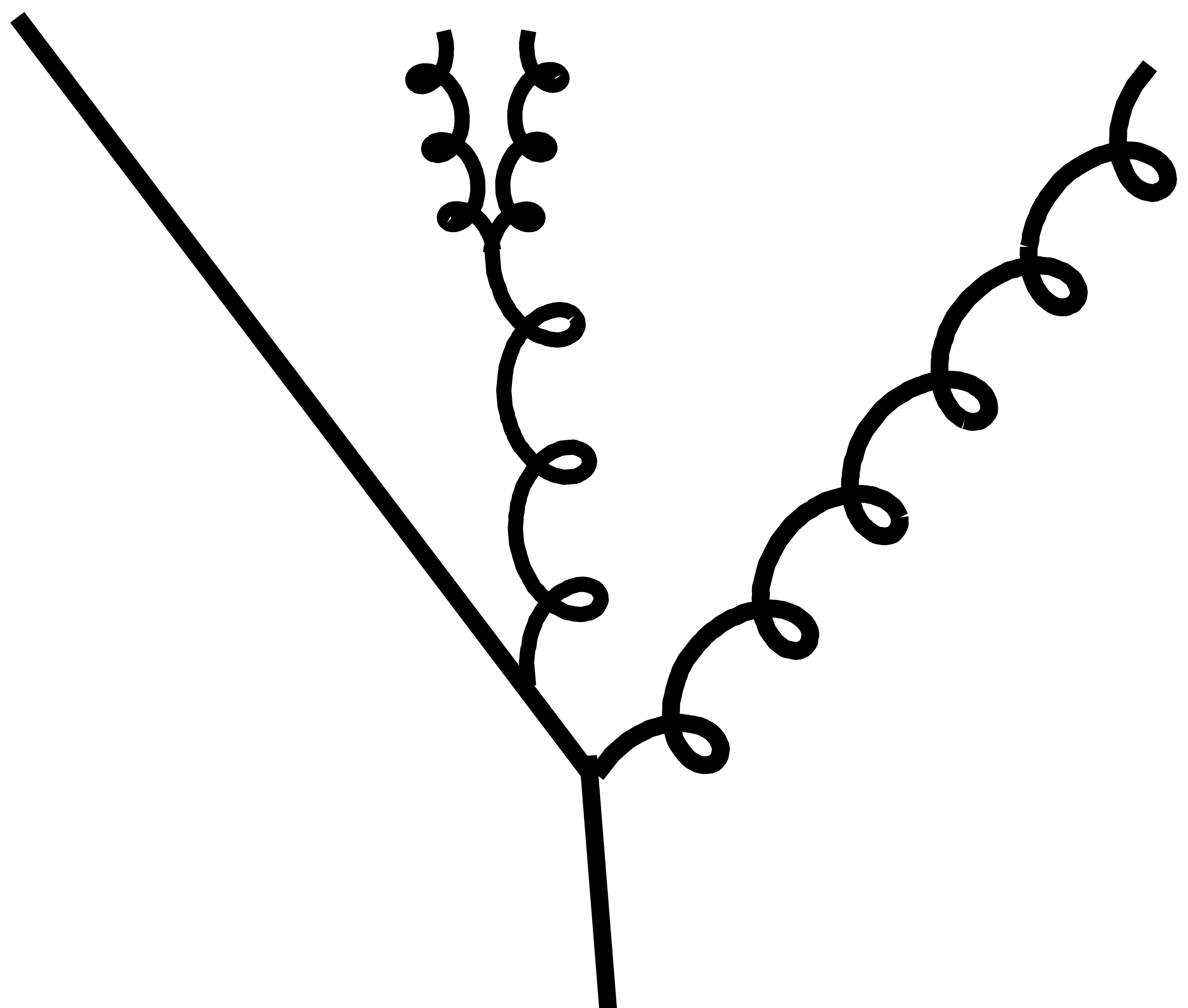
Spin correlations



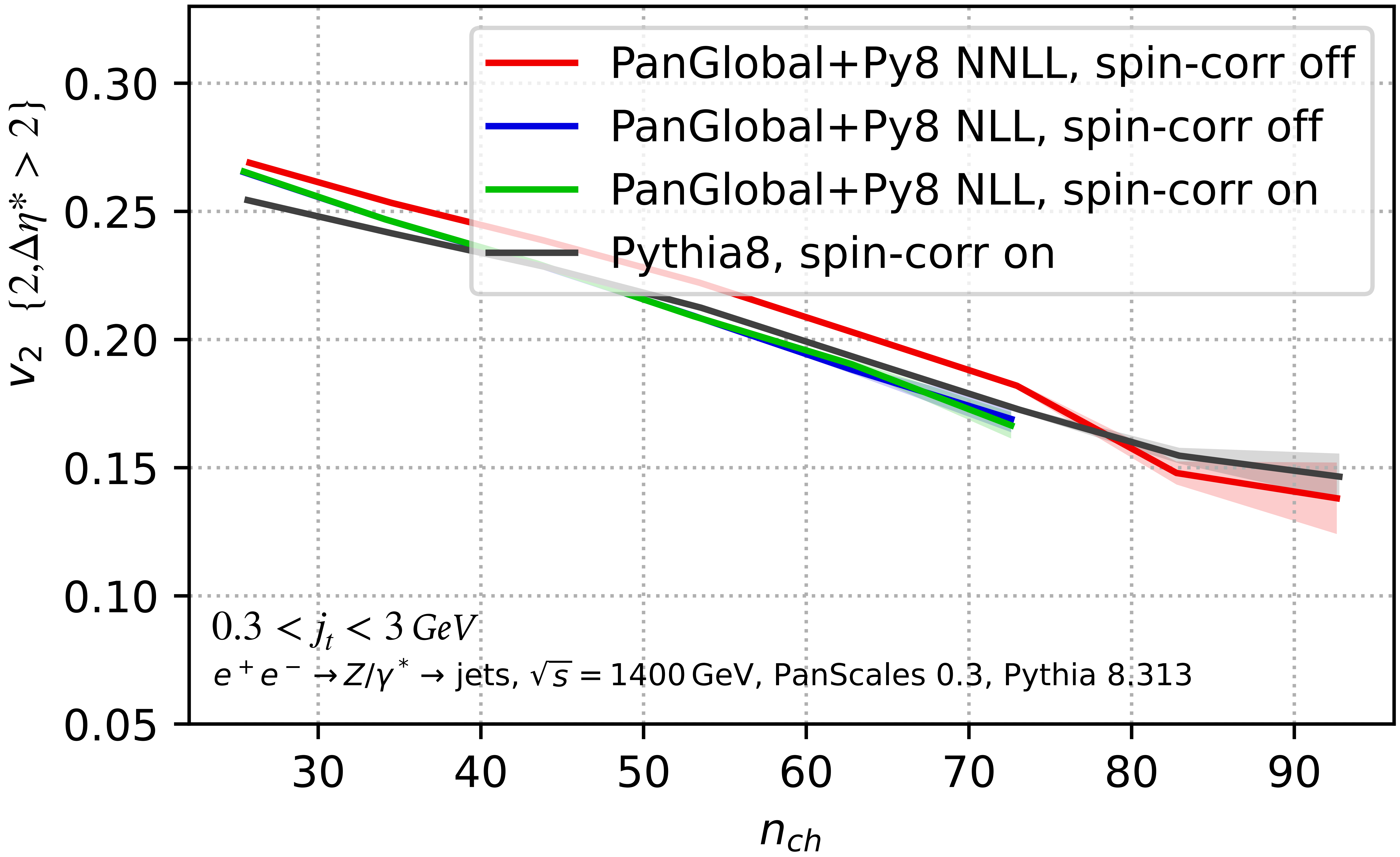
At next perturbative order, gluon polarisation in $g \to gg$ gives correlation that persists for $r/R \to 0$.

$$\propto 1 + \frac{A}{9}\cos 2\phi^*, \qquad A \leq 1$$

Could it be especially relevant at high multiplicity (involves multiple gluons)?



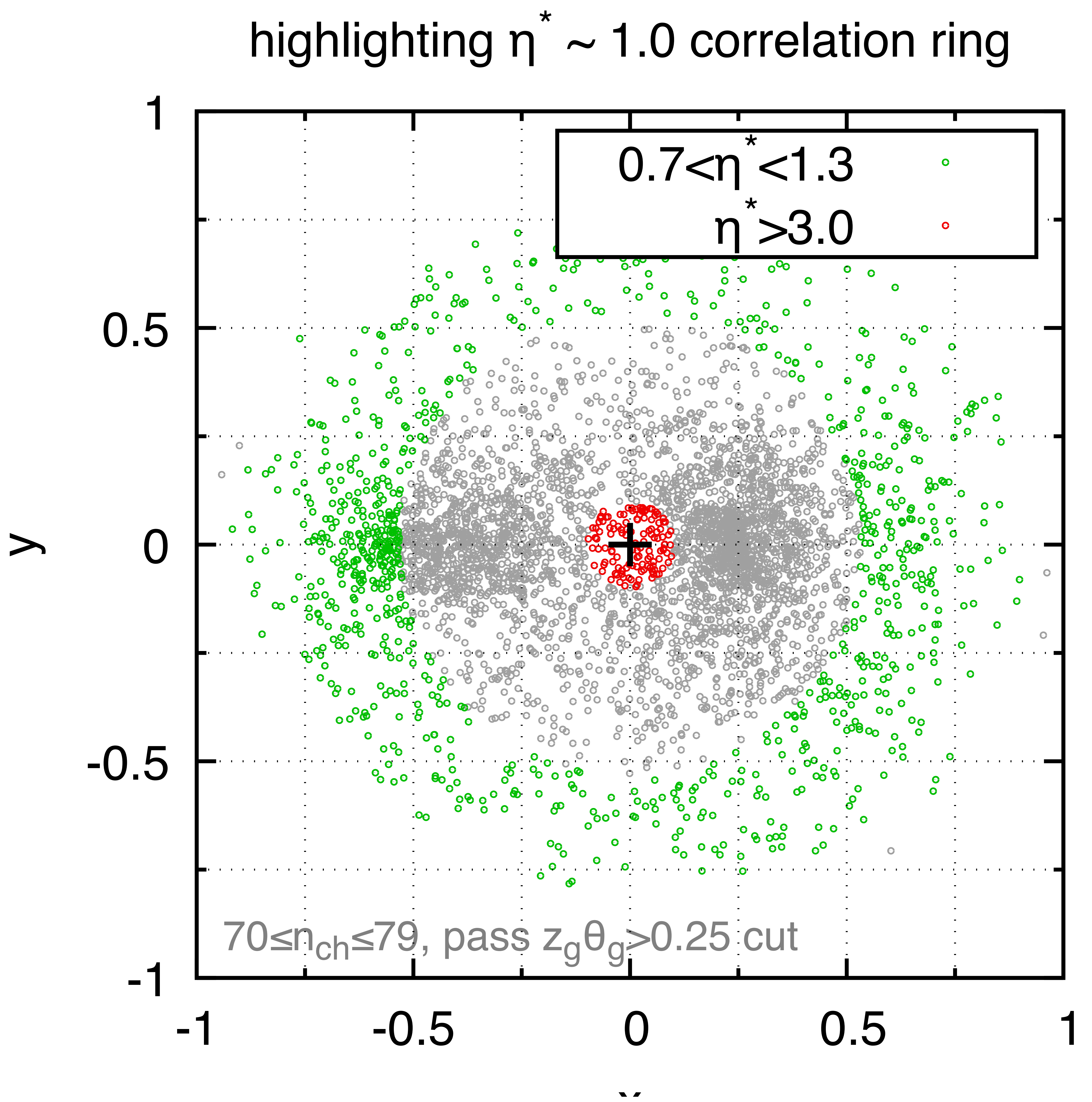
Studying higher-order effects, in e^+e^- analogue



We tried a simpler setup in PanScales e^+e^- with spin correlations on/off and impact was small and not enhanced at high multiplicity

[all curves include 3-jet matrix element corrections]

Meaning of j_t cut: $0.3 < j_t < 3$ GeV

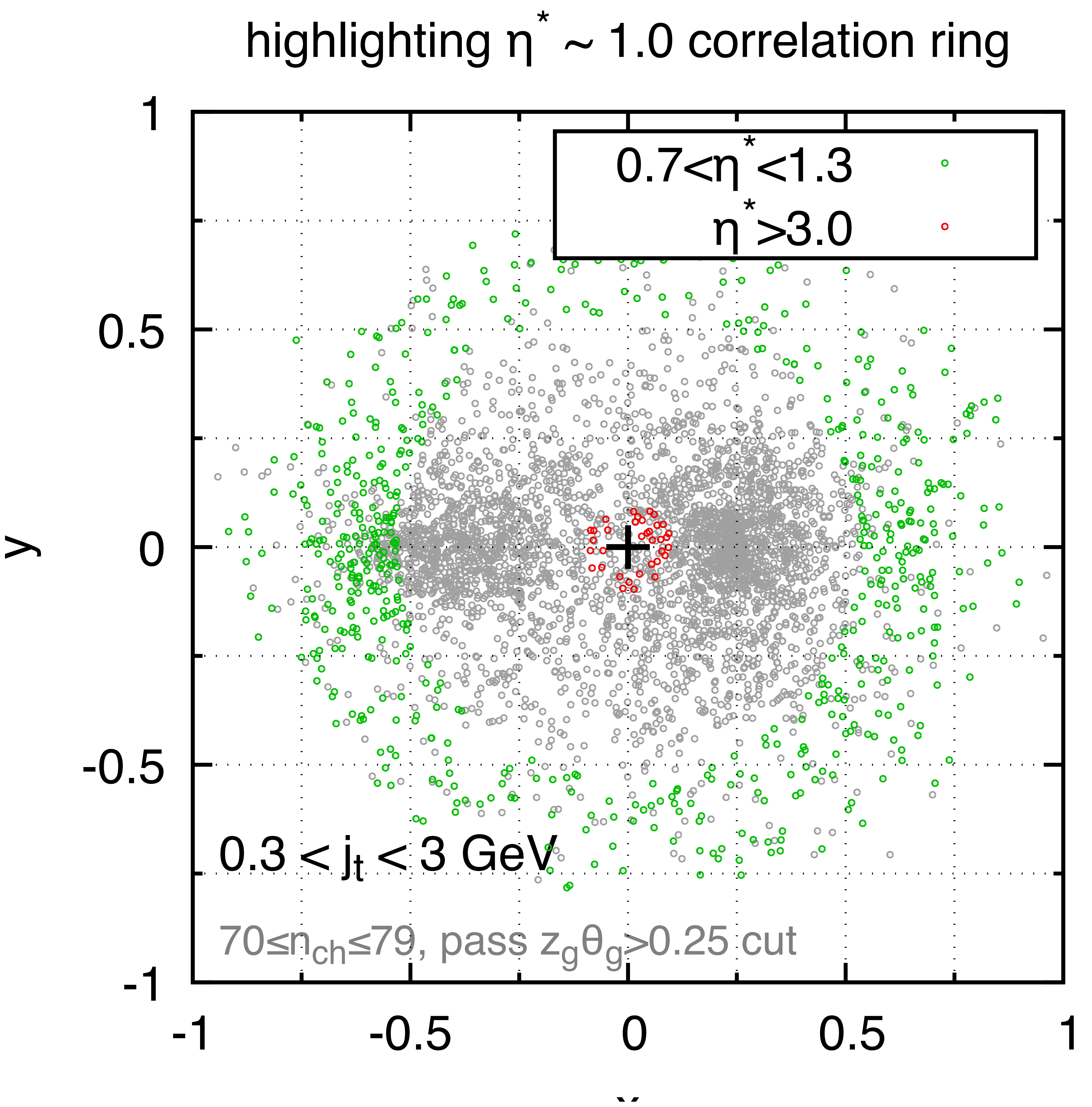


$$j_{ti} \sim \theta_{i,jet}\, p_{ti}$$

In the outer ring, the j_t cut selects genuinely soft particles, since $\theta_{i,jet} \sim 0.5$. A large fraction of the particles pass the j_t cut.

In the inner disc (high η^*), selected particles are not soft: $\theta_{i,jet} \ll 1$ implies $p_{ti} \gg 1$ GeV. Few of the particles pass the cut.

Meaning of j_t cut: $0.3 < j_t < 3$ GeV

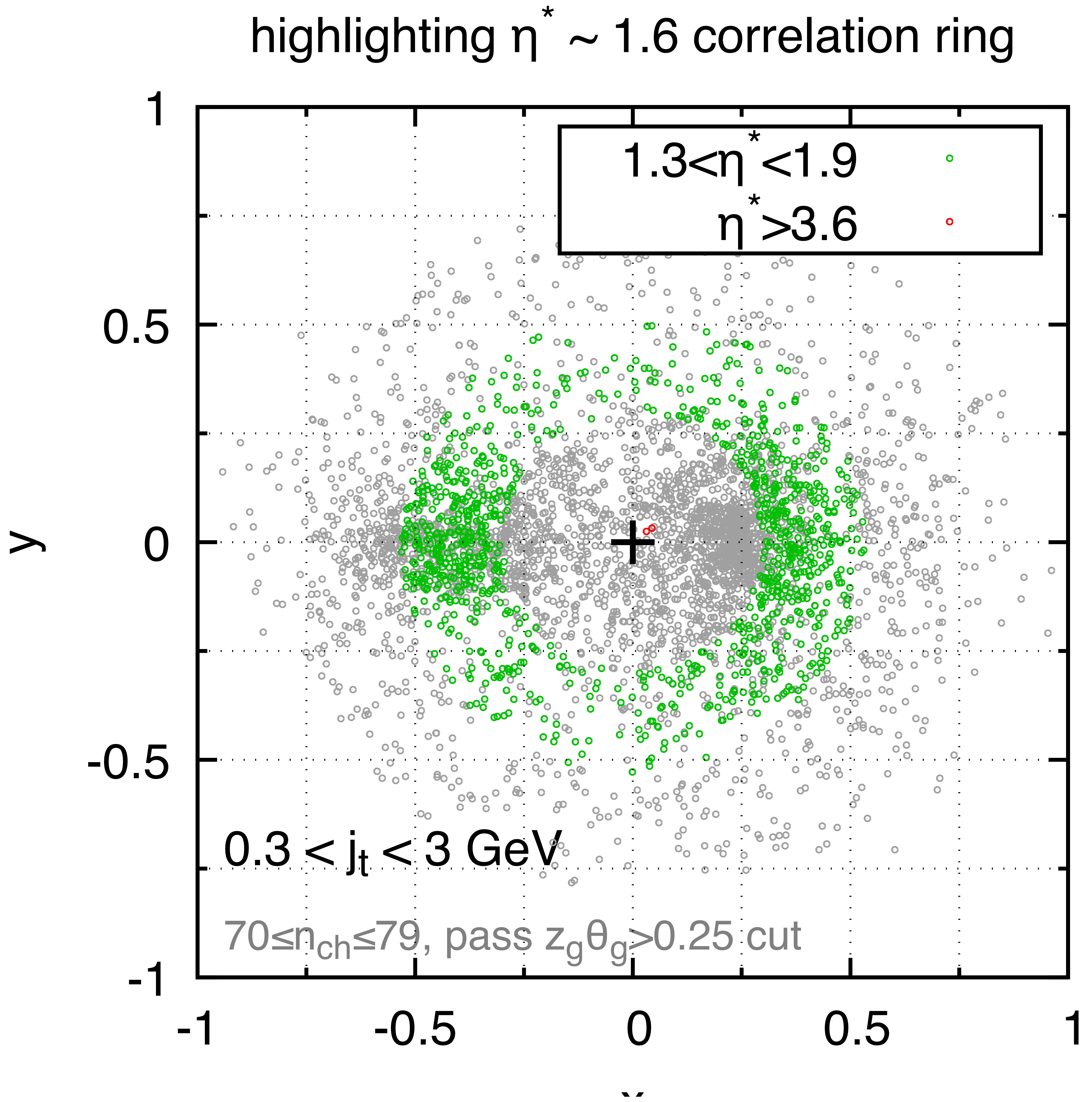


$$j_{ti} \sim \theta_{i,jet}\, p_{ti}$$

In the outer ring, the j_t cut selects genuinely soft particles, since $\theta_{i,jet} \sim 0.5$. A large fraction of the particles pass the j_t cut.

In the inner disc (high η^*), selected particles are not soft: $\theta_{i,jet} \ll 1$ implies $p_{ti} \gg 1$ GeV. Few of the particles pass the cut.

Meaning of j_t cut: $0.3 < j_t < 3$ GeV

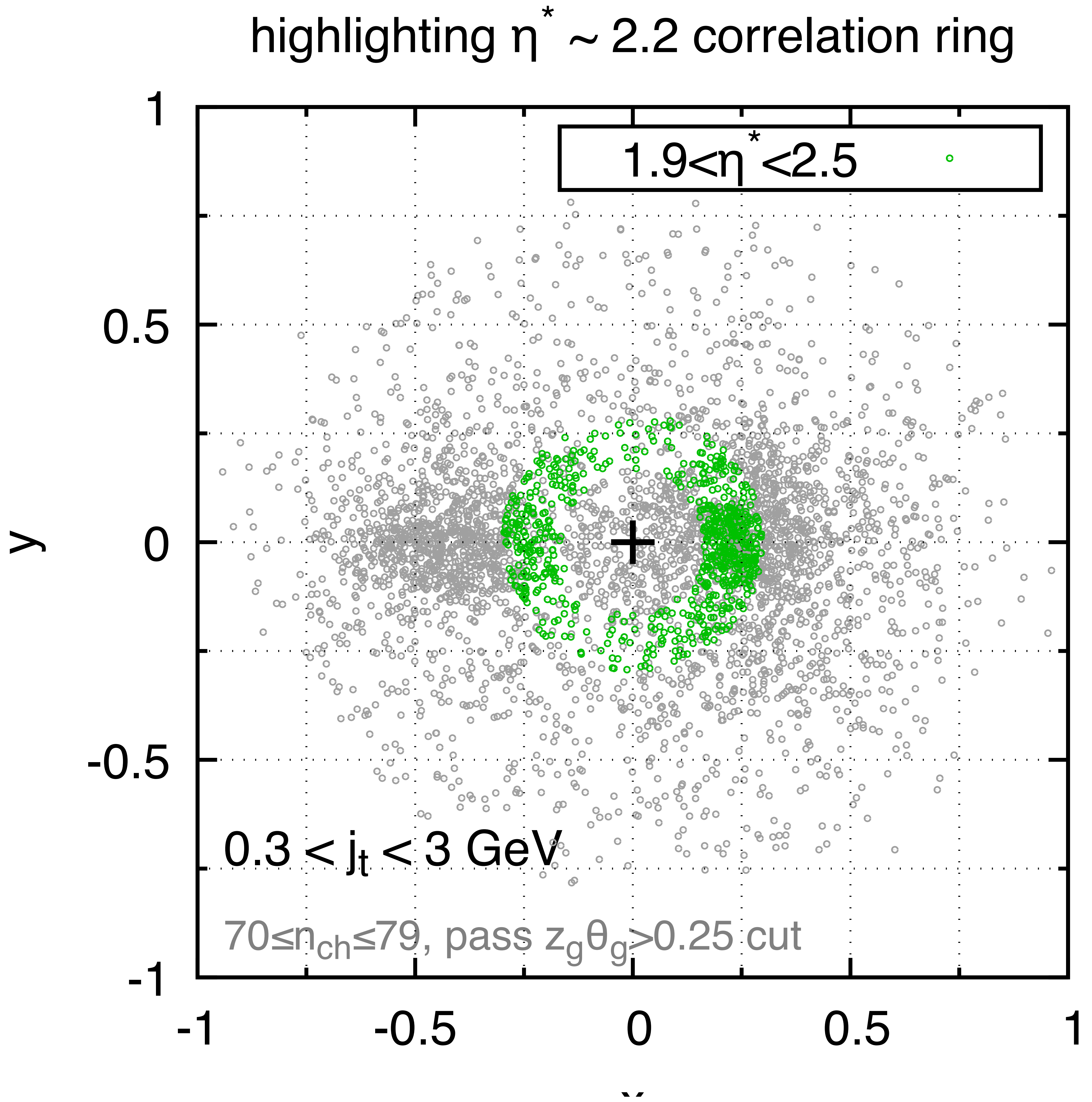


$$j_{ti} \sim \theta_{i,jet}\, p_{ti}$$

In the outer ring, the j_t cut selects genuinely soft particles, since $\theta_{i,jet} \sim 0.5$. A large fraction of the particles pass the j_t cut.

In the inner disc (high η^*), selected particles are not soft: $\theta_{i,jet} \ll 1$ implies $p_{ti} \gg 1$ GeV. Few of the particles pass the cut.

Meaning of j_t cut: $0.3 < j_t < 3$ GeV

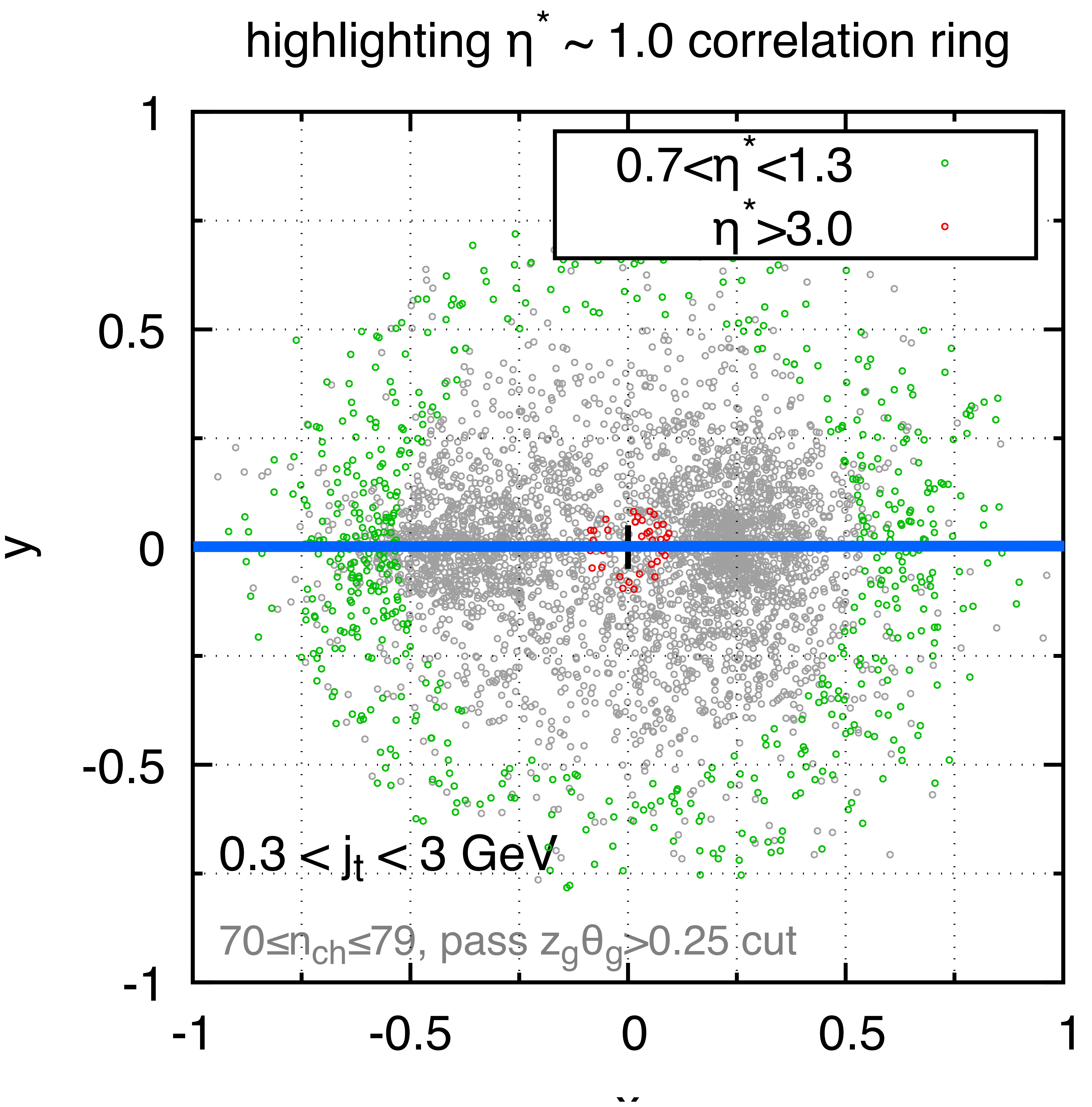


$$j_{ti} \sim \theta_{i,jet}\, p_{ti}$$

In the outer ring, the j_t cut selects genuinely soft particles, since $\theta_{i,jet} \sim 0.5$. A large fraction of the particles pass the j_t cut.

In the inner disc (high η^*), selected particles are not soft: $\theta_{i,jet} \ll 1$ implies $p_{ti} \gg 1$ GeV. Few of the particles pass the cut.

What further investigations?



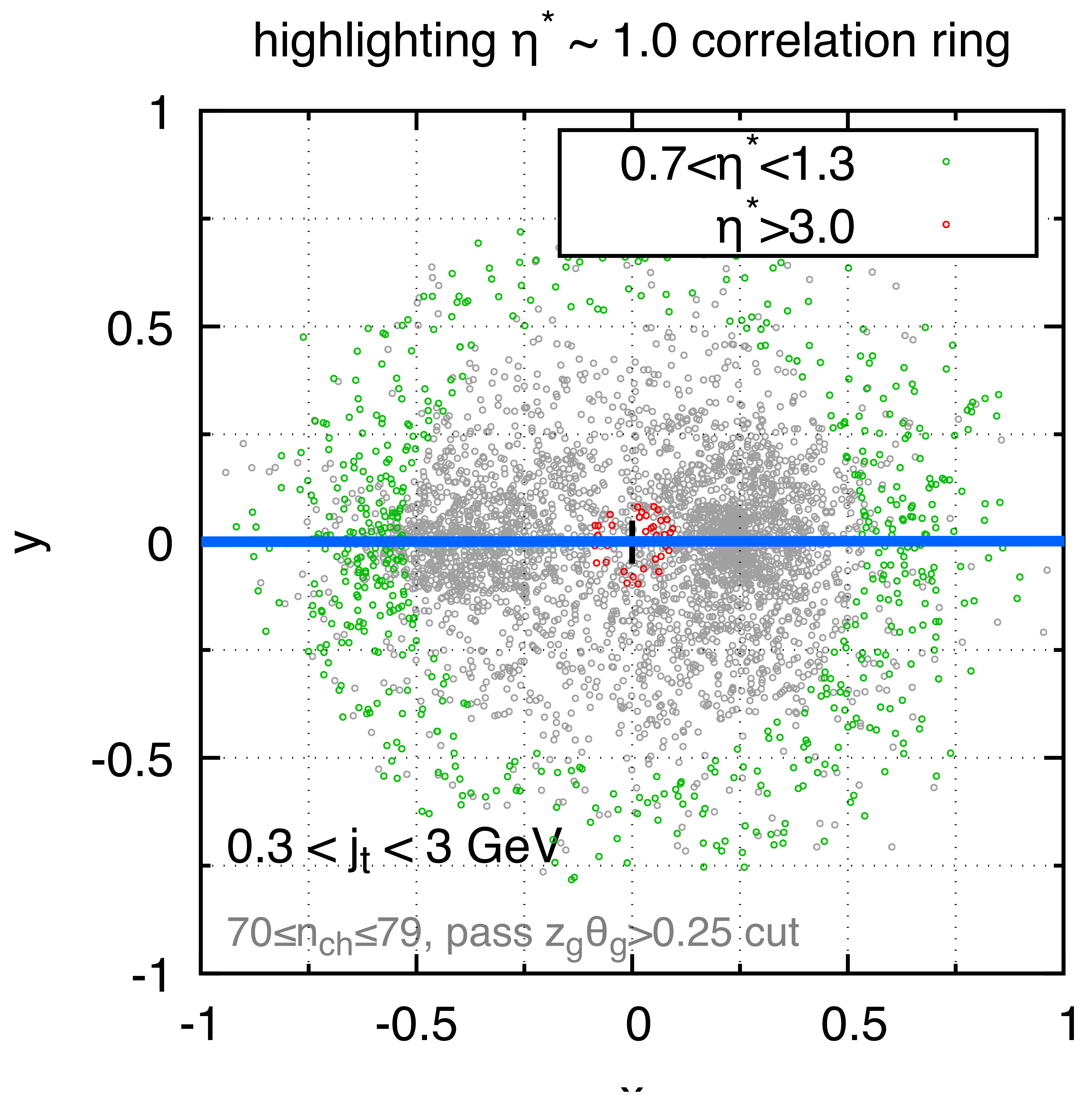
The soft-drop splitting provides an effective [plane]

That means one can take rings in η^*, and calculate the single-particle v_2 with respect to the plane

Is the 2-particle v_2 compatible with the convolution of the single-particle v_2's in distinct rings?

Can the the rise in v_2 at high n_{ch} be attributed to a specific η^* region?

What further investigations?



The soft-drop splitting provides an effective plane

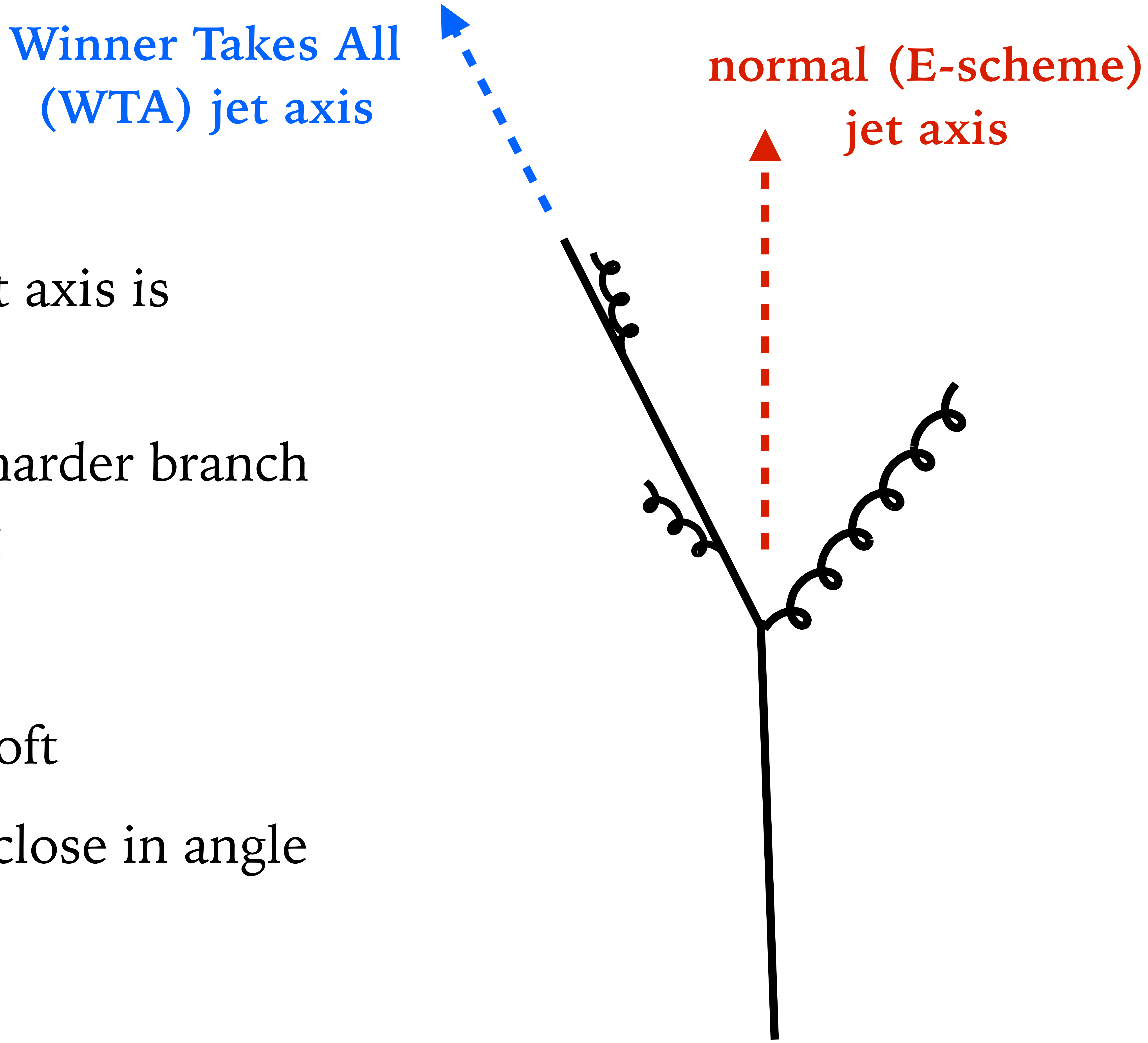
That means one can take rings in η^*, and calculate the single-particle v_2 with respect to the plane

Is the 2-particle v_2 compatible with the convolution of the single-particle v_2's in distinct rings?

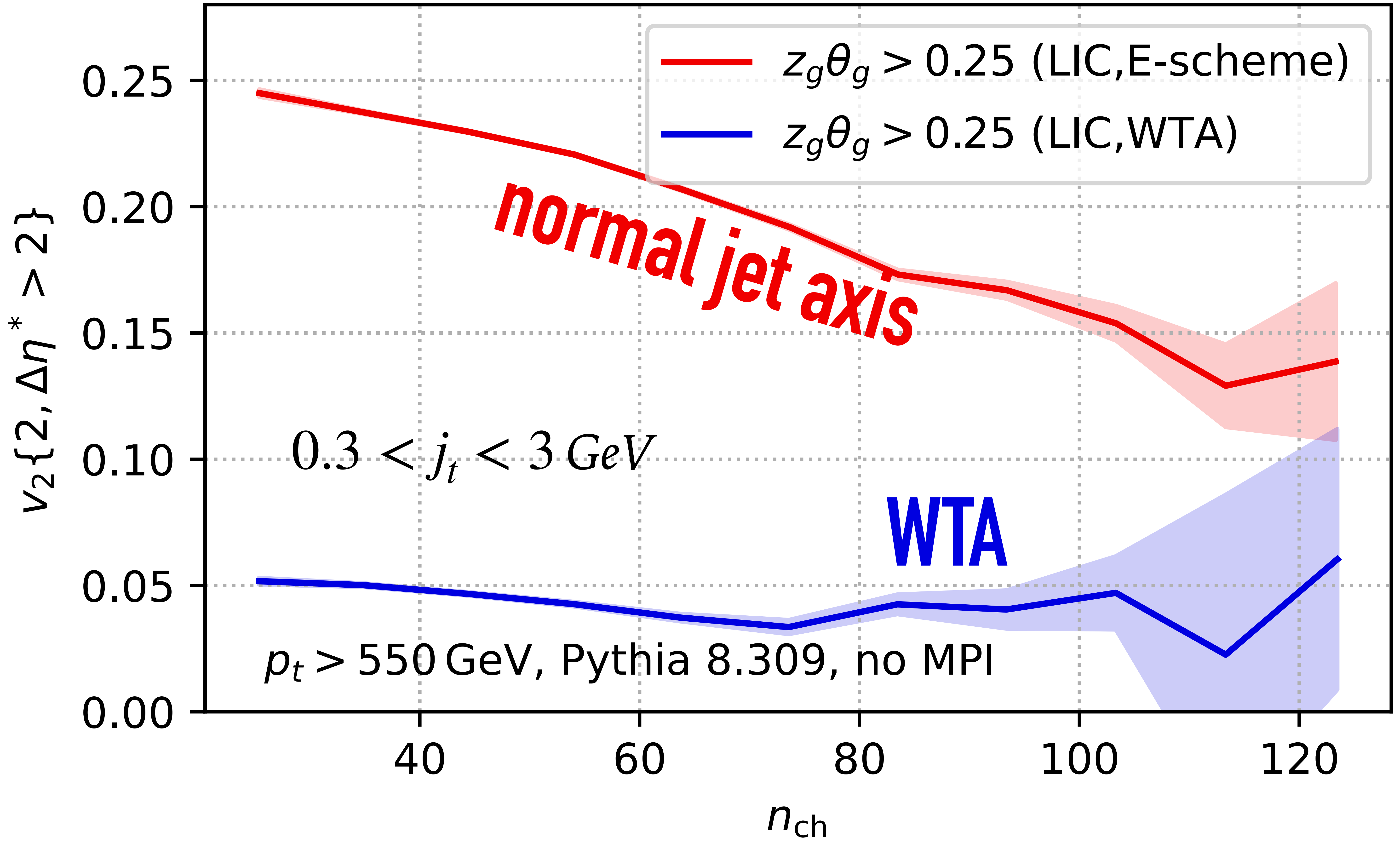
Can the the rise in v_2 at high n_{ch} be attributed to a specific η^* region?

WTA

- for a 2-pronged jet, normal jet axis is mostly empty
- WTA instead sets axis along harder branch at each stage of the clustering
- Only with WTA does:
  - small j_t mean a particle is soft
  - large η^* mean a particle is close in angle to its parent



v_2 with WTA versus normal (E-scheme) jet axis



- WTA has much smaller baseline v_2
- Presumably because large η^* region is genuinely collinear to the hard parton, azimuth mostly uncorrelated with direction of hard SD prong

conclusions

Conclusions

There are arguments that "collective" effects don't make sense in the final state: by the time hadronisation takes place the jet is sparse and many parts are causally disconnected

Can we get extra clues to the origin of the observed v_2 effect?

- longitudinally-invariant v. jet-frame coordinates: the former would reduce non-trivial kinematic correlation with the beam direction
- single-particle v_2, in η^* slices: this is possible given the soft-drop splitting defines a "jet plane", and might tell us if v_2 enhancement is coming from the outer or inner parts of the jet
- WTA limits intrinsic v_2 from dipole antenna structure of jets that pass the SD condition. More similar to initial-state flow observables. Does high-multiplicity v_2 enhancement persist?

backup