Studies of particle production in $pp \rightarrow$jets using transverse multiplicity estimators

Clear observations of **strangeness enhancement** and **"flow"-like** effects with **pp charged multiplicity** in **minimum-bias events**

Recently, ALICE presented similar measurements in events **with a hard (jet) trigger: complementary probe of central impact parameters.**

Used "KNO-like" variable $R_T = N_{\mathrm{ch}}^{\mathrm{TRNS}} / \langle N_{\mathrm{ch}}^{\mathrm{TRNS}} \rangle$ as activity classifier (Martin, PS, Farrington, ***Eur.Phys.J.C* 76 (2016) 5, 299**), with TRNS a geometric region transverse to the leading jets ~ a measure of **underlying-event** activity.

I comment on R_T, on the ALICE measurements, and on wishes for the future.

Peter Skands (Monash University)
ALICE Week, November 2020, CERN

What is the "TRANSVERSE" Region?

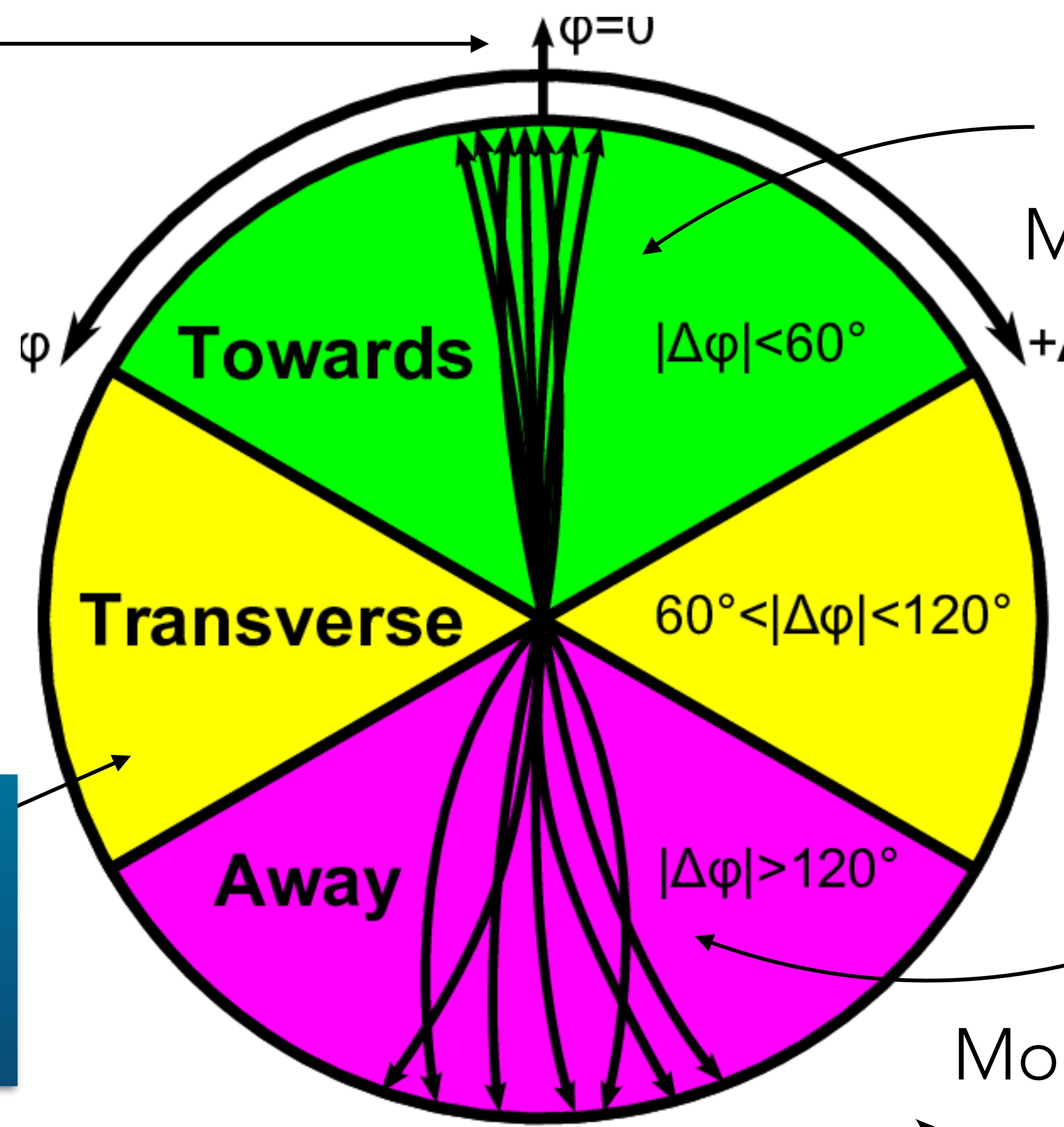
In events with a hard trigger

(Not infrared safe)	(More infrared safe)	(Infrared safe)
= Hardest Track	Hardest track-jet	Hardest jet

(+ generalisations to Drell-Yan, $t\bar{t}$, …)

Let hard trigger define $\varphi = 0$ (in x-y plane)

Beam axis: ⊗



TOWARDS region: Multiplicity dominated by hard trigger (jet)

TRANSVERSE region: Useful observable definition of the "Underlying Event"

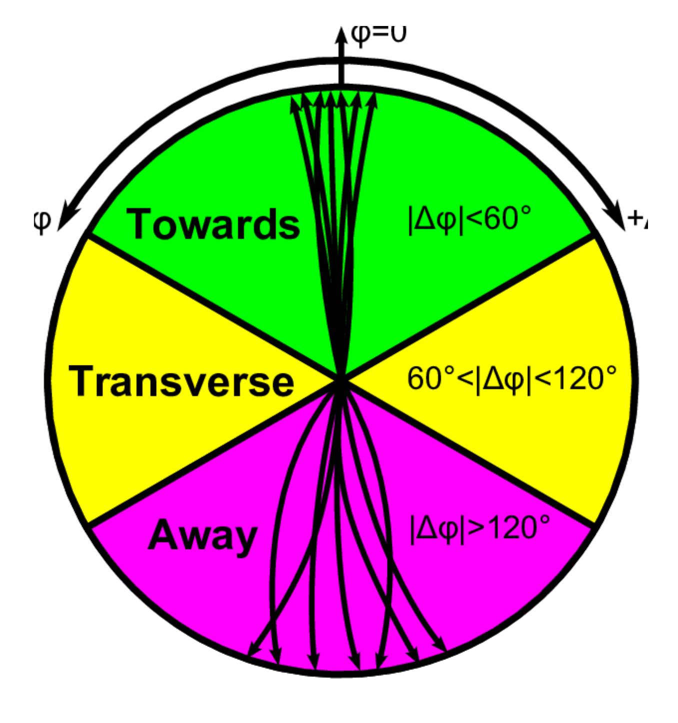
(Pioneered by R. Field, CDF)

AWAY region: Momentum conservation ➤ contains recoil jet (at LO)

Issue: Transverse region can be sensitive to contamination from **bremsstrahlung** from the hard scattering; will get back to that.

Note: prefer to express contents as **densities** (per unit $\Delta\varphi\Delta\eta$) ➤ easier comparisons

om Minimum-Bias (MB) to the Underlying Event (UE)



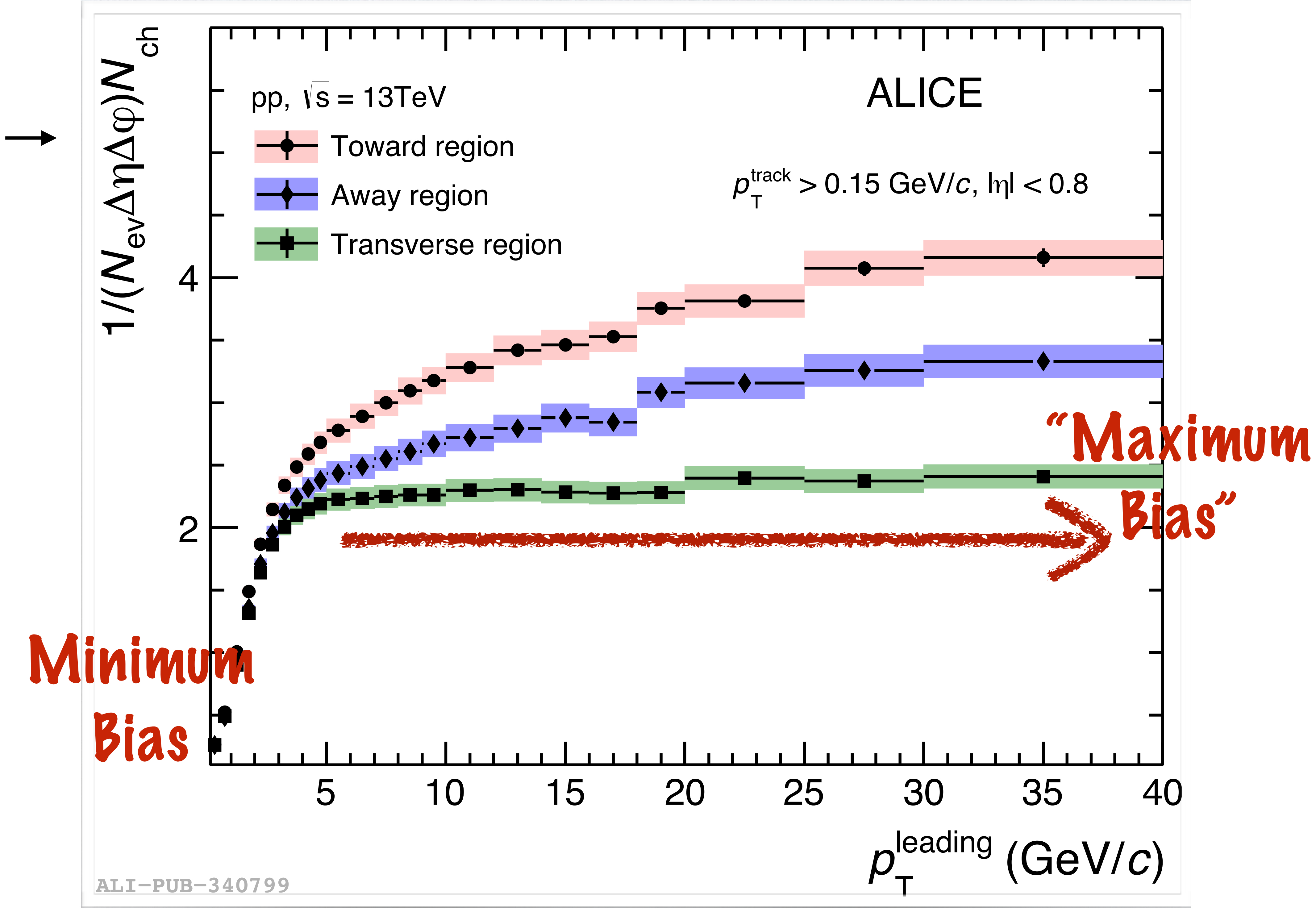
Pedestal effect (1983):

UA1, Phys. Lett. B 132 (1983) 214-222

> "Outside the [jet], a constant E_T plateau is observed, whose height is independent of the jet E_T. Its value is **substantially higher** than the one observed for minimum bias events."

Now called the **"Underlying Event"**

density →



Multiple Parton Interactions with **impact-parameter** dependence (eg PYTHIA):

Rise from minimum-bias to UE interpreted as a **biasing effect**.

Small pp impact parameters → larger matter overlaps → **more MPI**

→ higher probability for a **hard interaction**.

MPI in Minimum-Bias and UE

⟹ **Main idea:** UE in events triggered by a **hard scattering** = complementary probe of small impact parameters

+ **input** to **high-p_T** program @ **LHC**

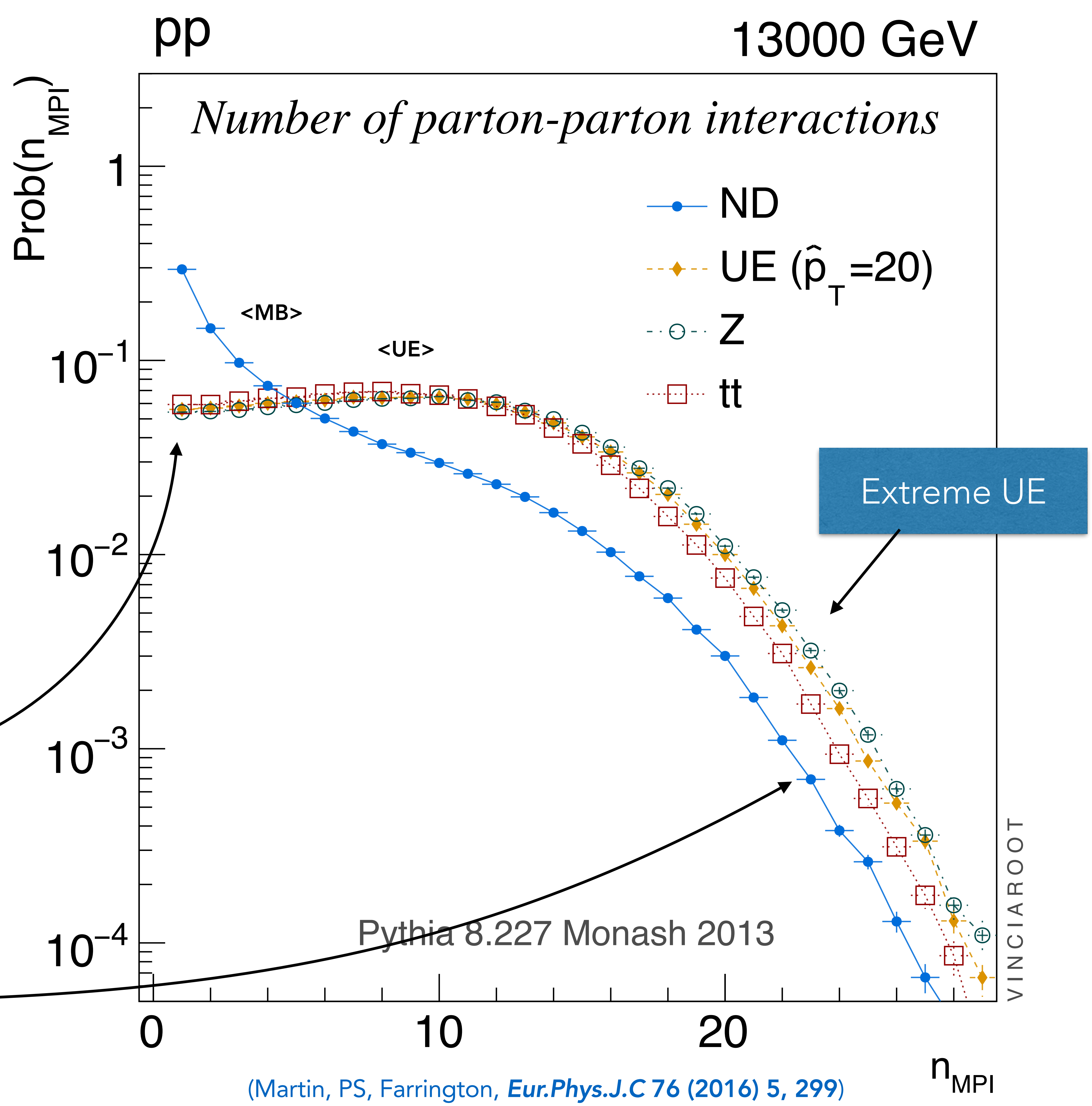
The Underlying Event

(here defined with hard scattering at $p_T > 20$ GeV, but no significant dependence on specific hard process; similar story for Drell-Yan and $t\bar{t}$)

Has substantially **larger average** number of MPI than minimum-bias
(as modelled by PYTHIA)

Still some events have **few MPI**
~ **jets without pedestals?**

Tail towards **high numbers of MPI**
↔ high-N_{ch} tail of Min-Bias?

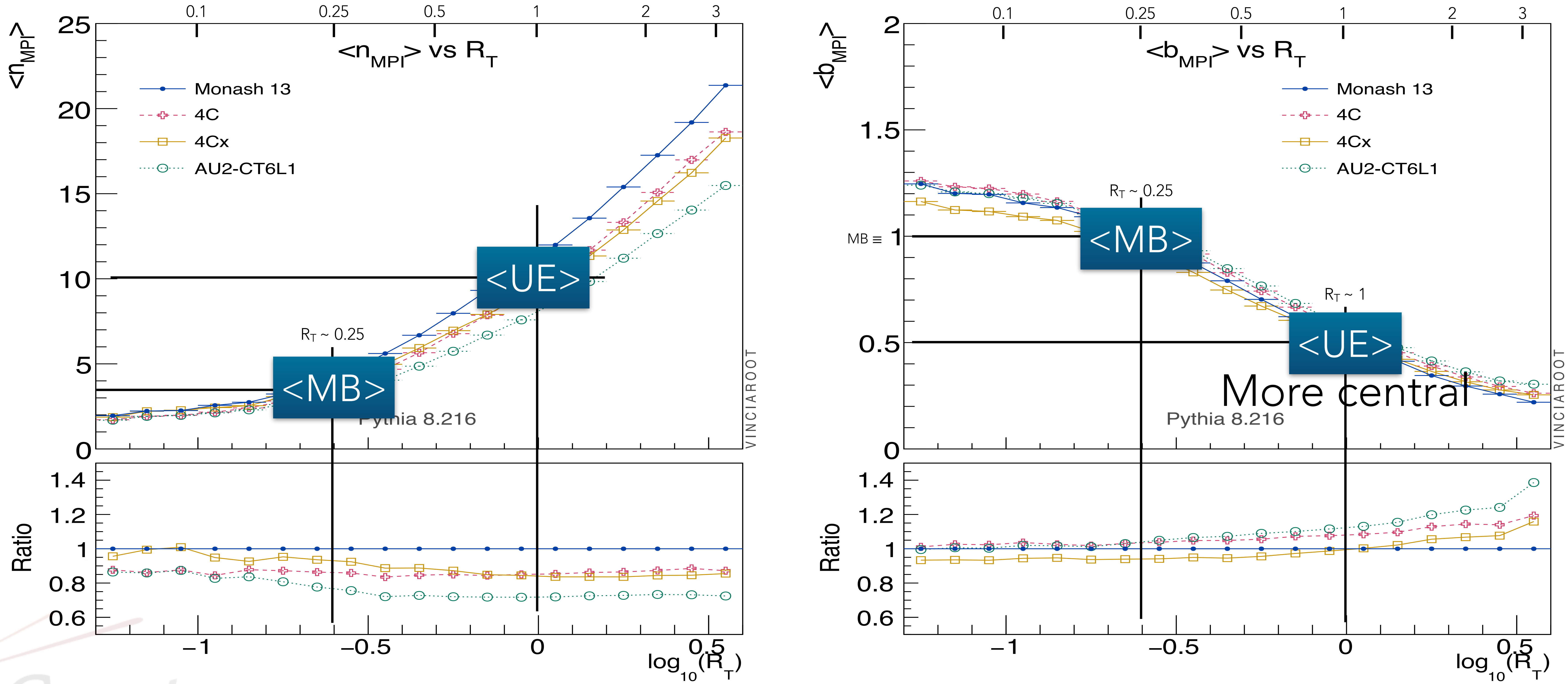


(Martin, PS, Farrington, **Eur.Phys.J.C 76 (2016) 5, 299**)

The Transverse Activity Classifier R_T

Aim: **study** **UE properties** (<p_T>, strangeness, …) **as function of UE multiplicity** ~ like we do in min-bias

Normalise by average value $\Longrightarrow$ "KNO-style" variable $R_T = \dfrac{N^{\mathrm{TRNS}}}{\langle N^{\mathrm{TRNS}} \rangle}$



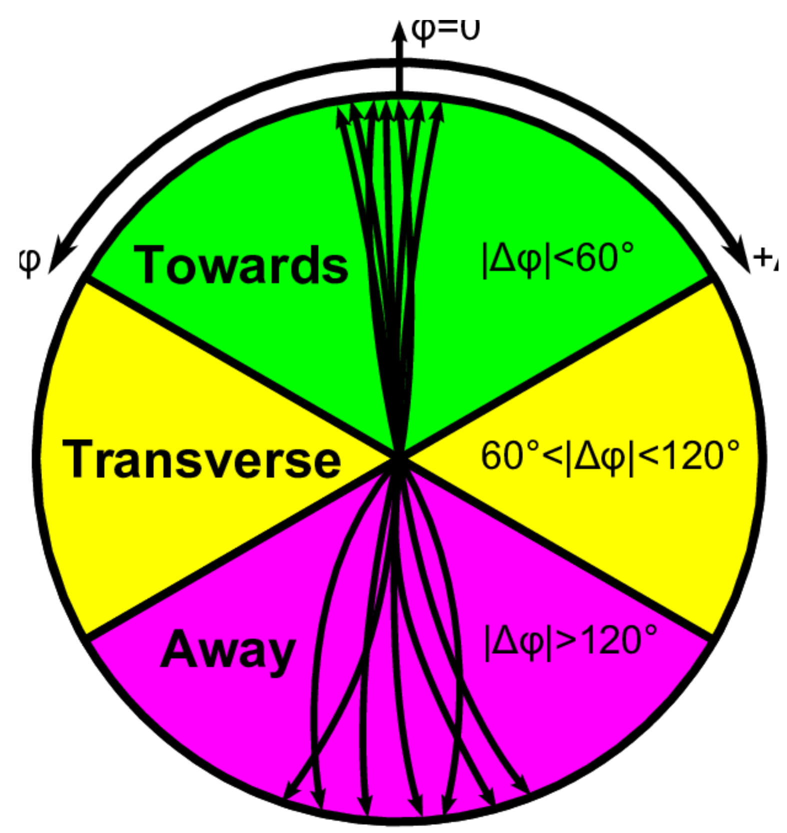
(Martin, PS, Farrington, *Eur.Phys.J.C* **76 (2016) 5, 299**)

TOWARD region - p_T spectrum

TOWARD region

Somewhat analogous to a **jet**

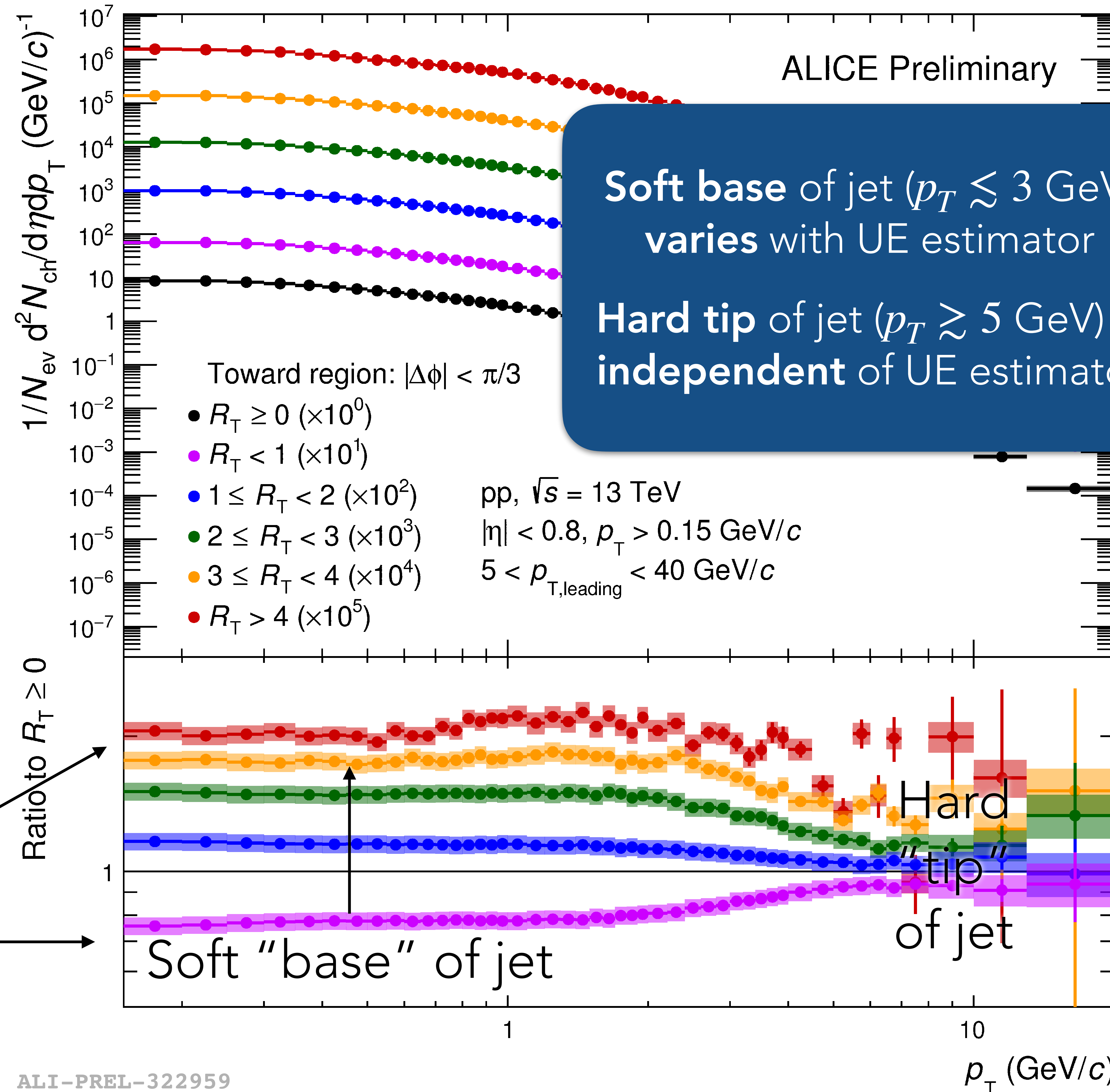
(with $\Delta R \sim 1$)



The UE fluctuates:

High UE ➤ **"Polluted"** jet

Low UE ➤ **"Clean"** jet



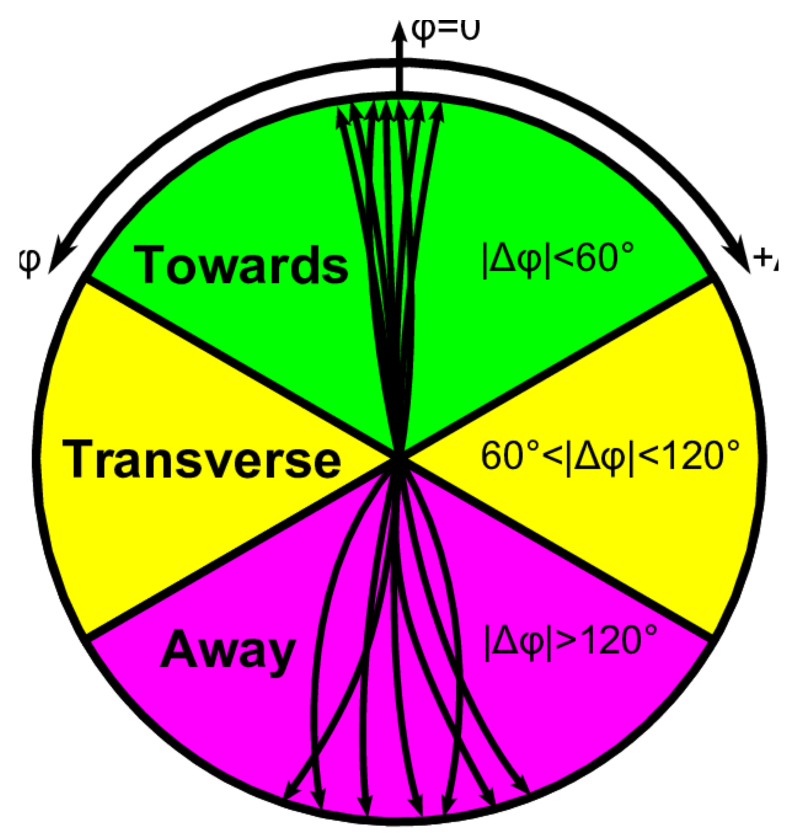
Soft base of jet ($p_T \lesssim 3$ GeV) **varies** with UE estimator

Hard tip of jet ($p_T \gtrsim 5$ GeV) ~ **independent** of UE estimator

Low UE ➤ **cleaner** jets ➤ Interesting for **precision jet studies**? Better **calibrations**?

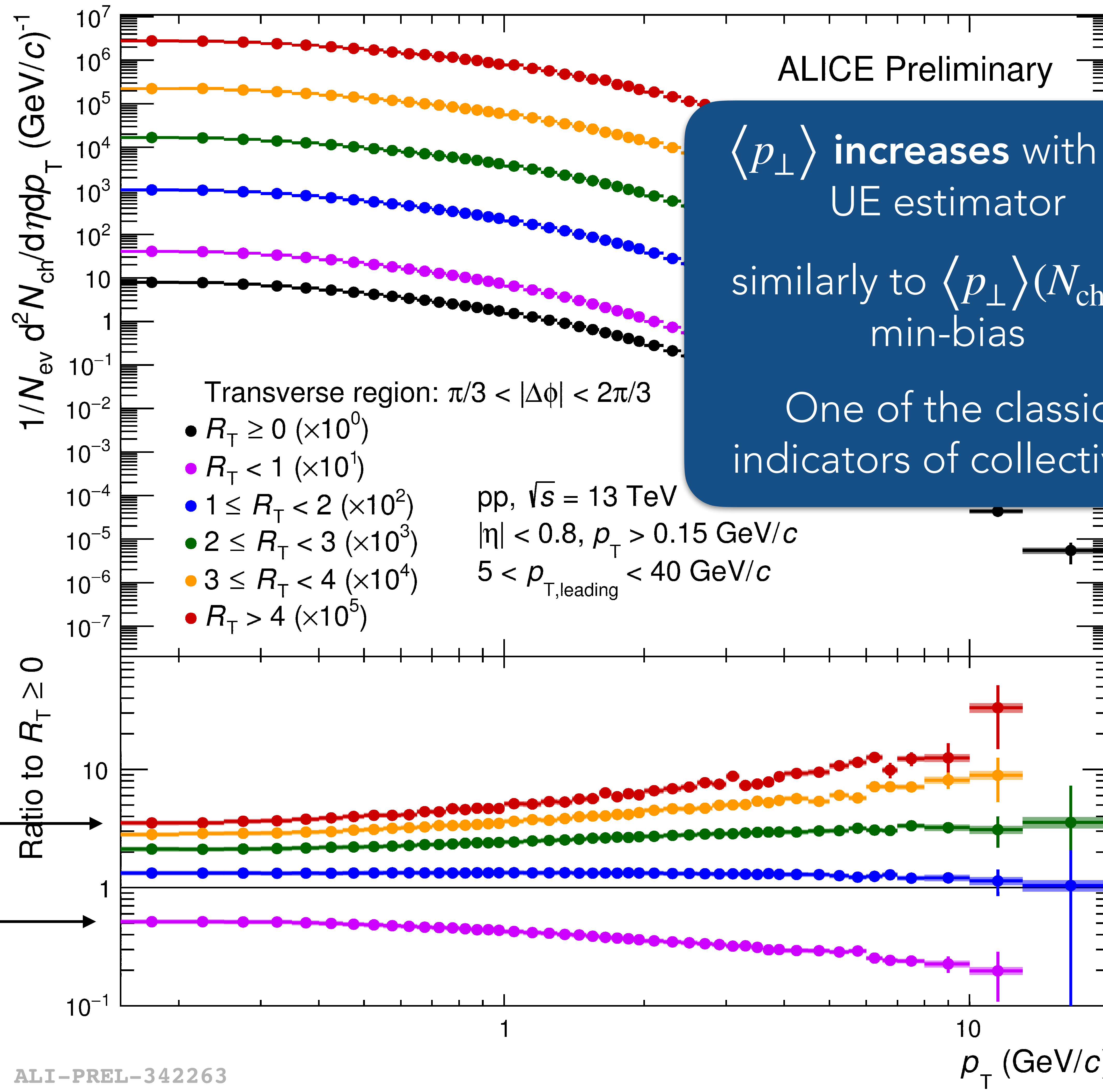
TRANSVERSE region

~ the "Underlying Event"



High UE ➤ **Harder** Spectra

Low UE ➤ **Softer** Spectra

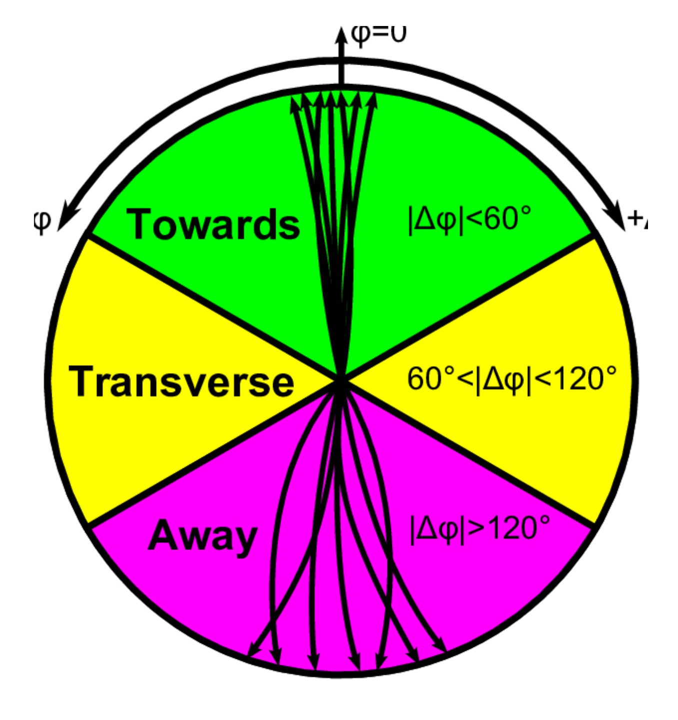


$\langle p_\perp \rangle$ **increases** with the UE estimator

similarly to $\langle p_\perp \rangle (N_{ch})$ in min-bias

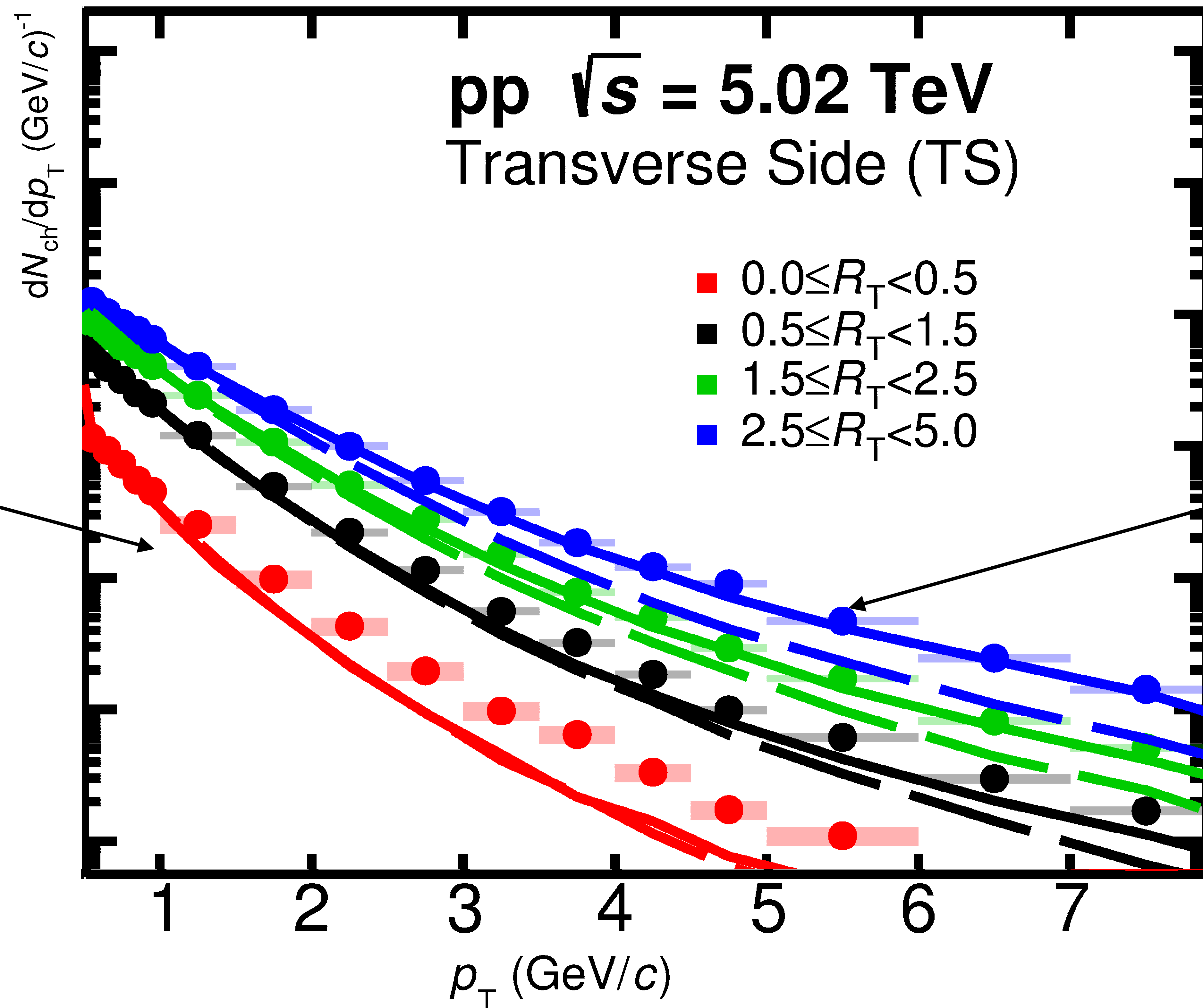
One of the classic indicators of collectivity

TRANSVERSE region: MC Comparison



Solid lines: PYTHIA 8.244

Dashed Lines: EPOS LHC



In **low-UE events**, both Pythia and EPOS predict a **too soft p_T spectrum** in the transverse region

Especially for $p_T > 1$ GeV/c

Naively, could have expected PYTHIA good at modelling a **single jet with low UE** ~ LEP?

In **high-UE events**, PYTHIA does a reasonable job of modelling the p_T spectrum in the transverse region

(Probably at least in part due to MPI and CR modelling tuned to high-N_{ch} tail of min-bias)

But remember: here we look TRANSVERSE to the jet.
More challenging than collinear fragmentation.

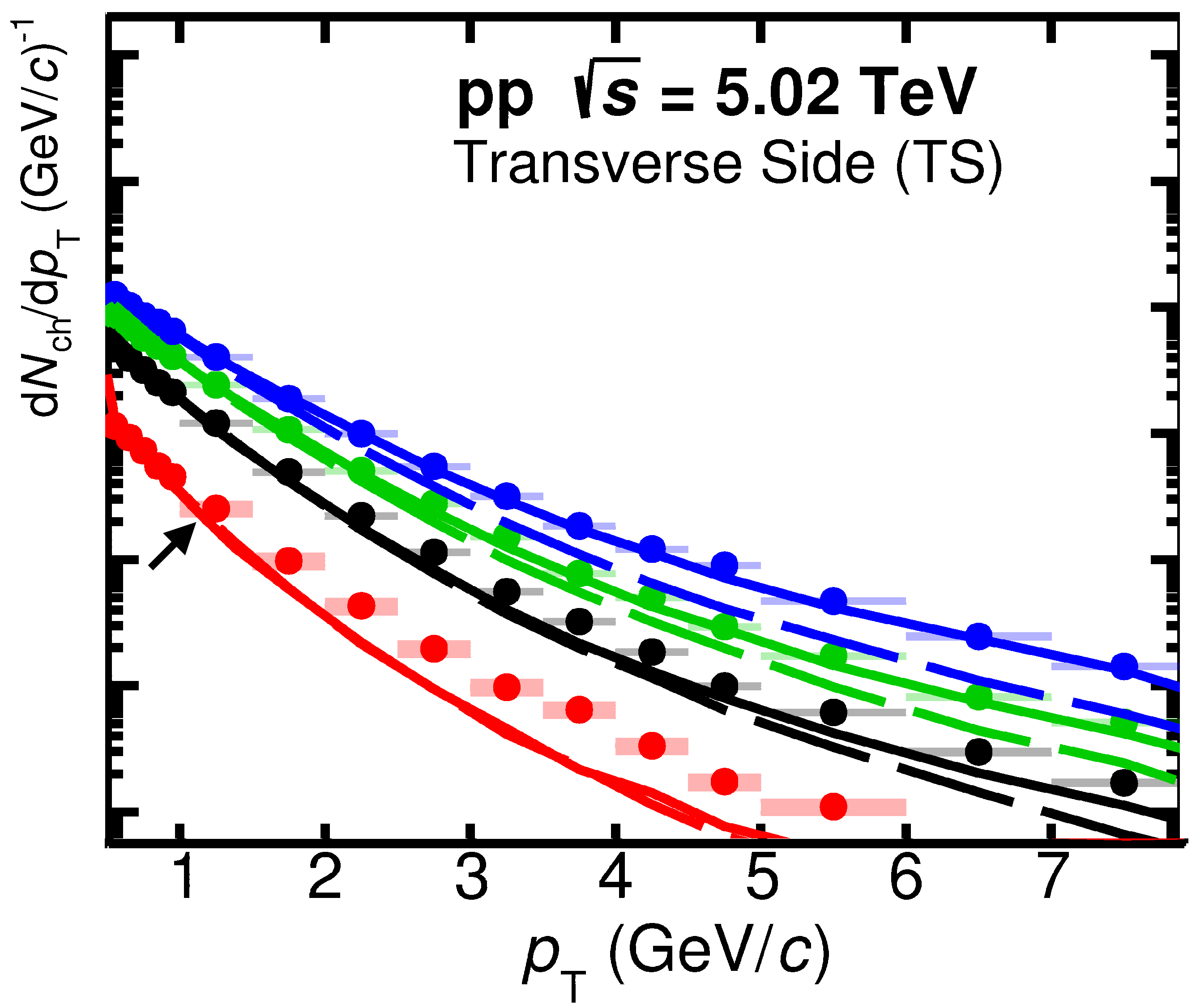
Interestingly (?) something similar was seen at LEP

TRANSVERSE region: Comparison to LEP?

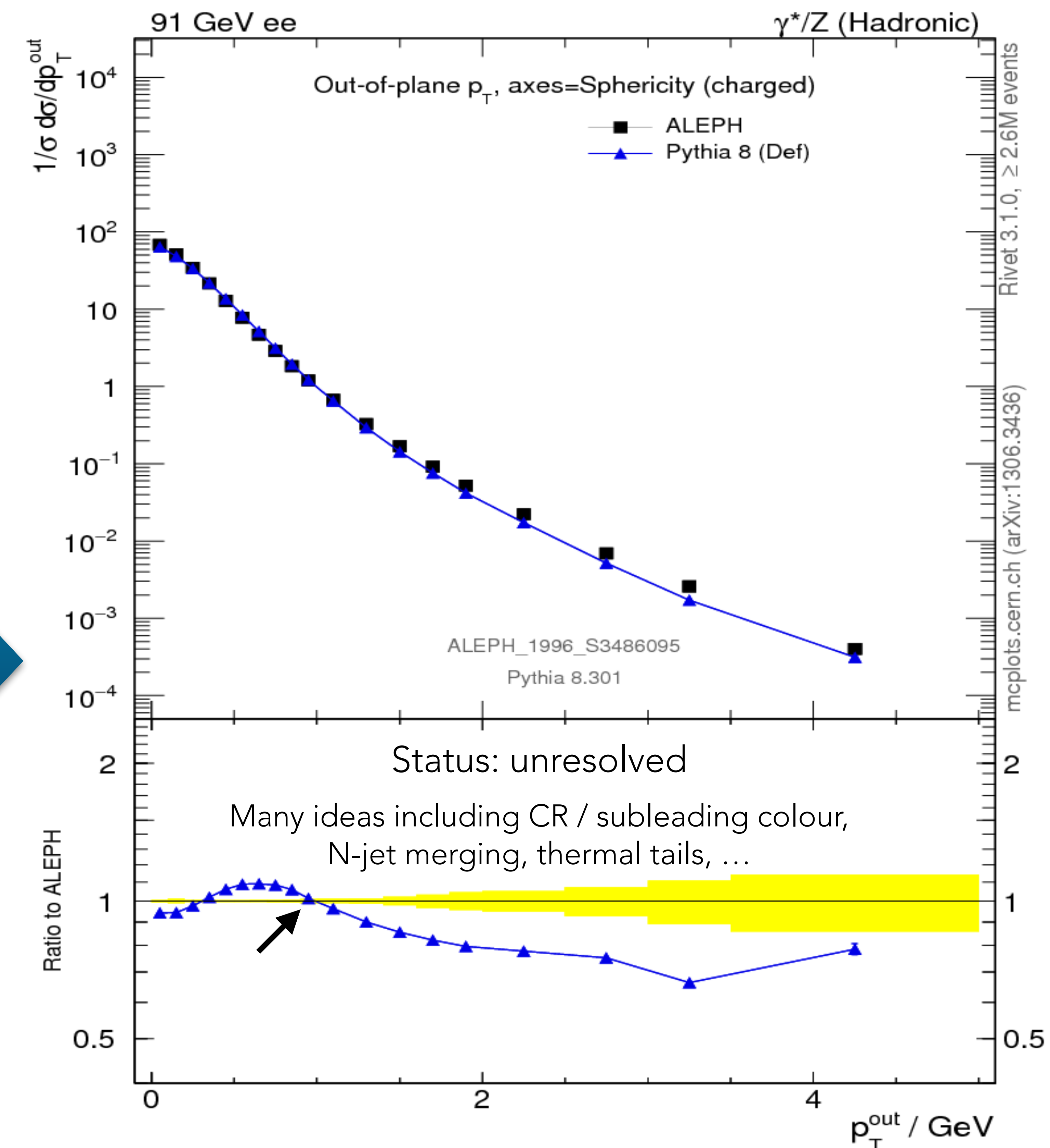
Pythia describes a wide range of LEP event shapes, jet rates, and particle spectra well

See eg PS et al., Eur.Phys.J.C 74 (2014) 8, 3024

A longstanding significant exception are the p_T distributions transverse to the main jet axis →



Related?



Highlights that **low-UE** events are particularly interesting to compare with the **no-UE** events we have in e^+e^-

(However as defined here, these observables are not directly comparable. They cover different regions, have different trigger biases, different q vs g Born-level starting points, and different contributions from extra jets)

2019 analysis: strangeness ratios **as functions of p_T**

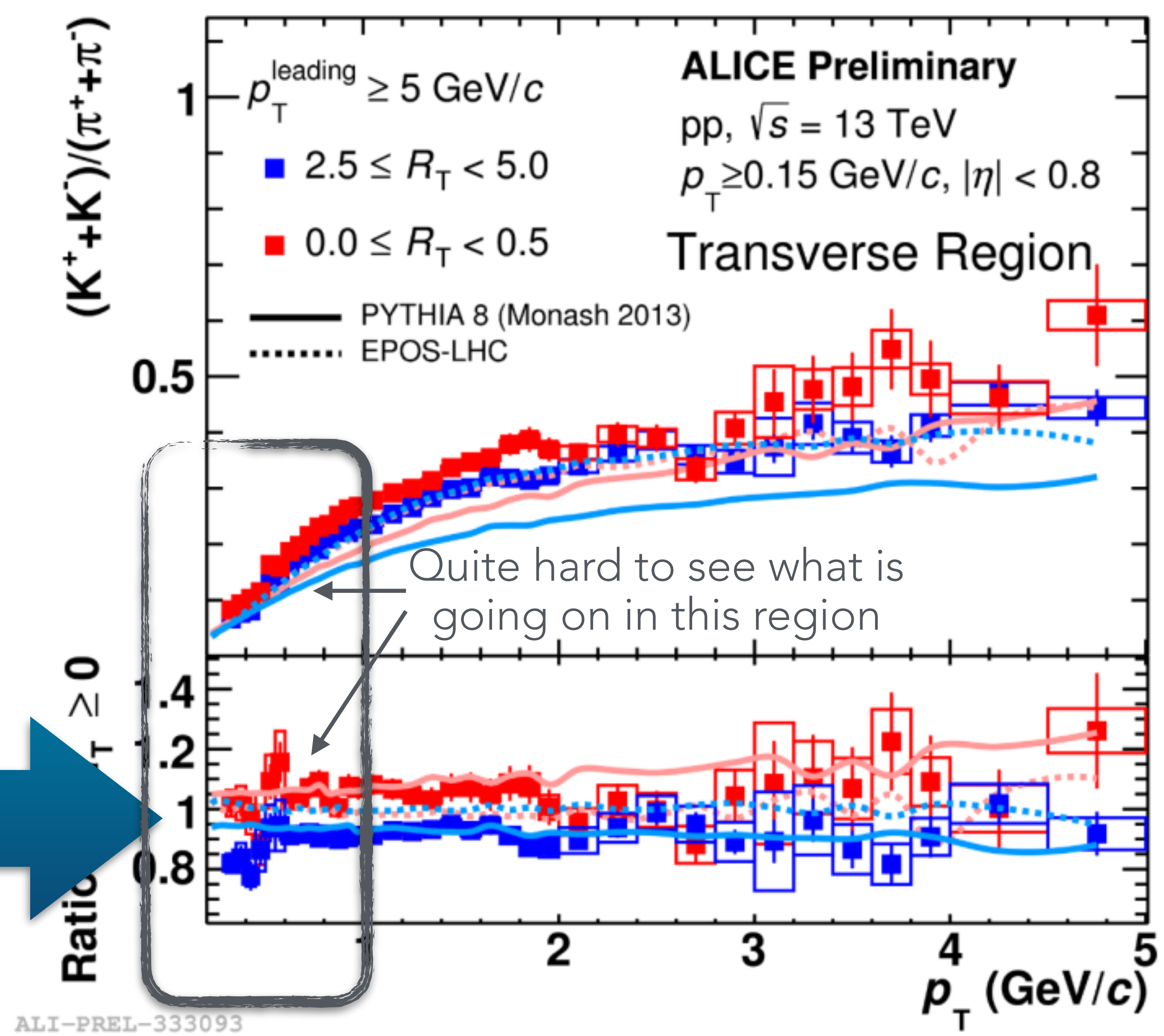
Would have liked to start from **p_T-integrated** $\langle N_X \rangle / \langle N_Y \rangle$ as functions of R_T

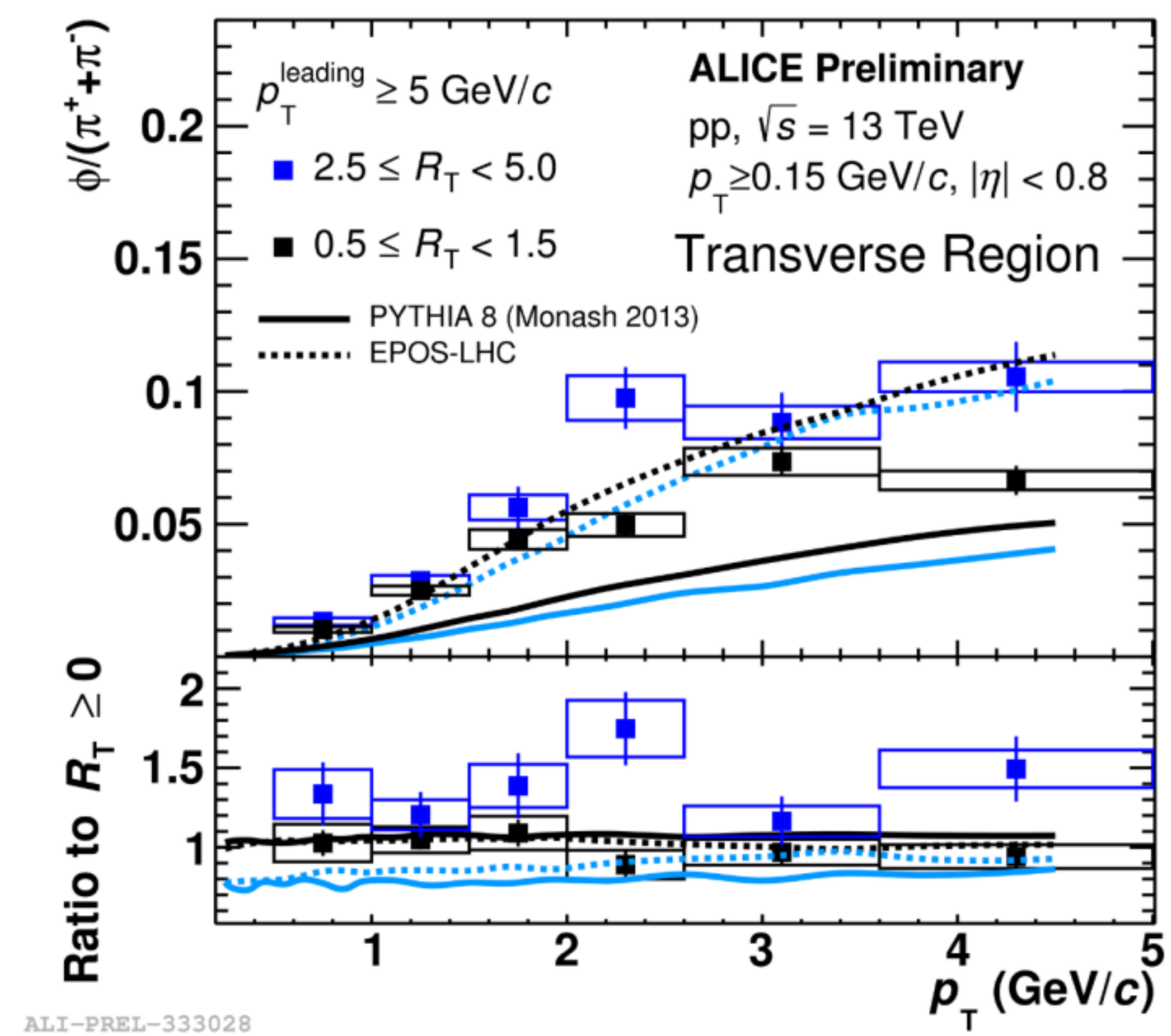
(that would still be useful; Yields are changing at the same time as the p_T spectra. Yields first, then spectra.)

Mesons

TRNS

All ~ constant



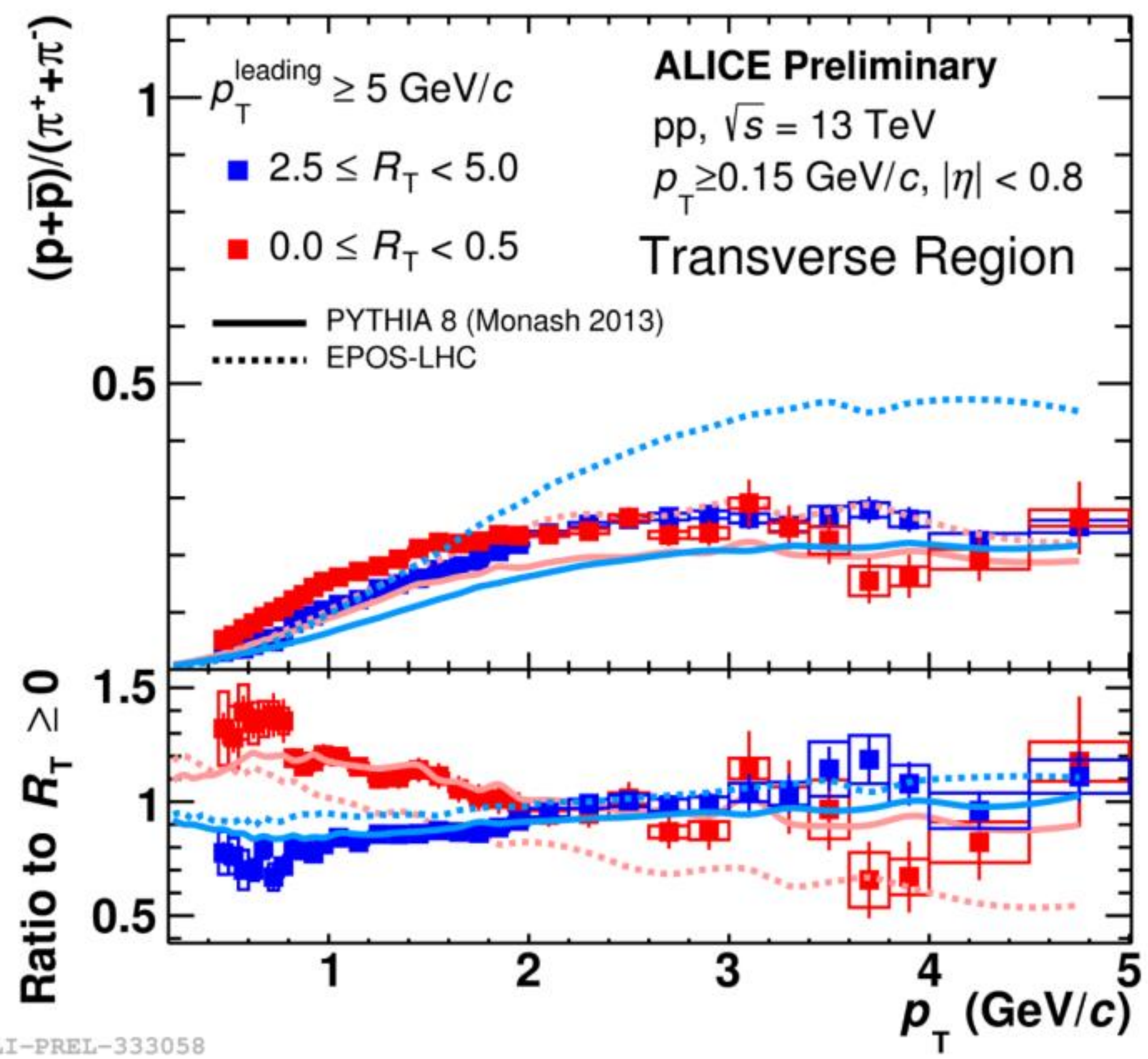


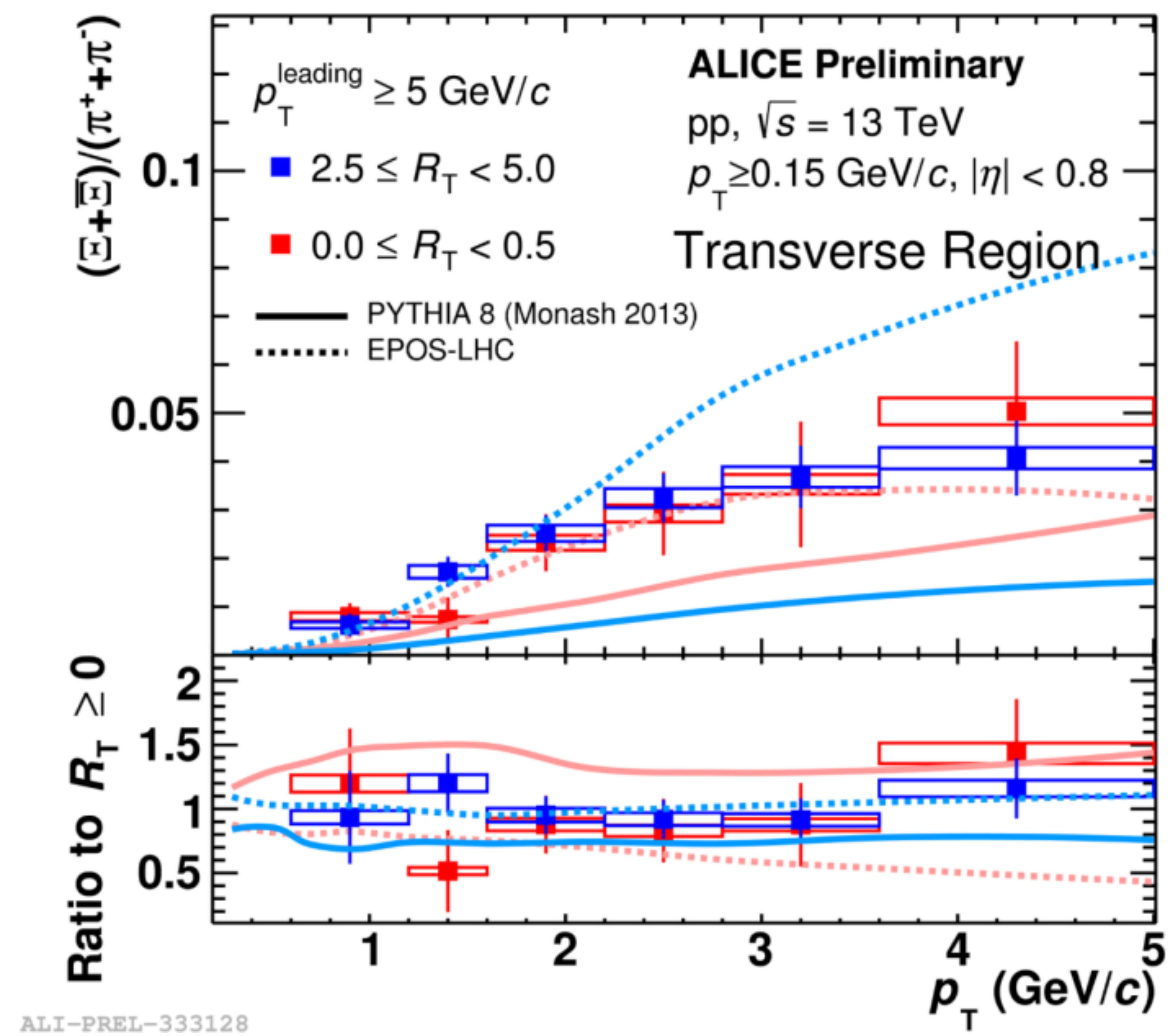
Overall trends: PYTHIA underpredicts strangeness, **even at low R_T**

EPOS has the <strangeness> but not the right R_T dependence.

Baryons: **crucial to get full picture**; require the formation of diquarks and/or **colour-epsilon structures** in the confinement field.

Baryons TRNS





EPOS predicts large high-p_T baryon fractions at high R_T not seen in data

PYTHIA underpredicts baryon fractions, especially Ξ at high R_T

Would be interesting to test with QCD CR, Rope Hadronisation, and Shoving

Comments & Subtleties: N_{ch} vs N_{inc} vs track-jets vs jets

N_{ch}: cleanest / easiest to meausure

But quite "infrared unsafe". E.g., a K^+ always counts as one particle, but a K^0_S either counts as zero (if treated as stable or decaying to $\pi^0\pi^0$) or 2 if decaying to $\pi^+\pi^-$.

Can lead to counter-intuitive biases eg in strangeness fractions vs R_T

Alternatively N_{inc} = Identifiable **weakly decaying strange hadrons** ($K^0_S, \Lambda, \Sigma, \bar{\Sigma}, \Xi, \Omega$) + long-lived **prompt charged hadrons** ($\pi^\pm, K^\pm, p^\pm$)

Less weird biases (but prompt π^0 still "invisible"; use EM information?)

Alternatively measure UE activity in complementary (non-overlapping) region (eg $N_{\mathrm{ch}}^{\mathrm{FWD}}$)

Must be correlated with activity in measurement region to be useful.

If using $N_{\mathrm{ch}}^{\mathrm{FWD}}$ how to distinguish between **low-angle ISR jets** and events with **many MPI**?

Require Forward AND Backward coincidence? Forward AND Inclusive Central? Exploit momentum-conservation (anti-)correlation between ISR and jet(s) from hard scattering?

Using Jets to Define $\varphi = 0$:

Instead of hardest track, use a clustered (track) **jet** to define $\varphi = 0$.

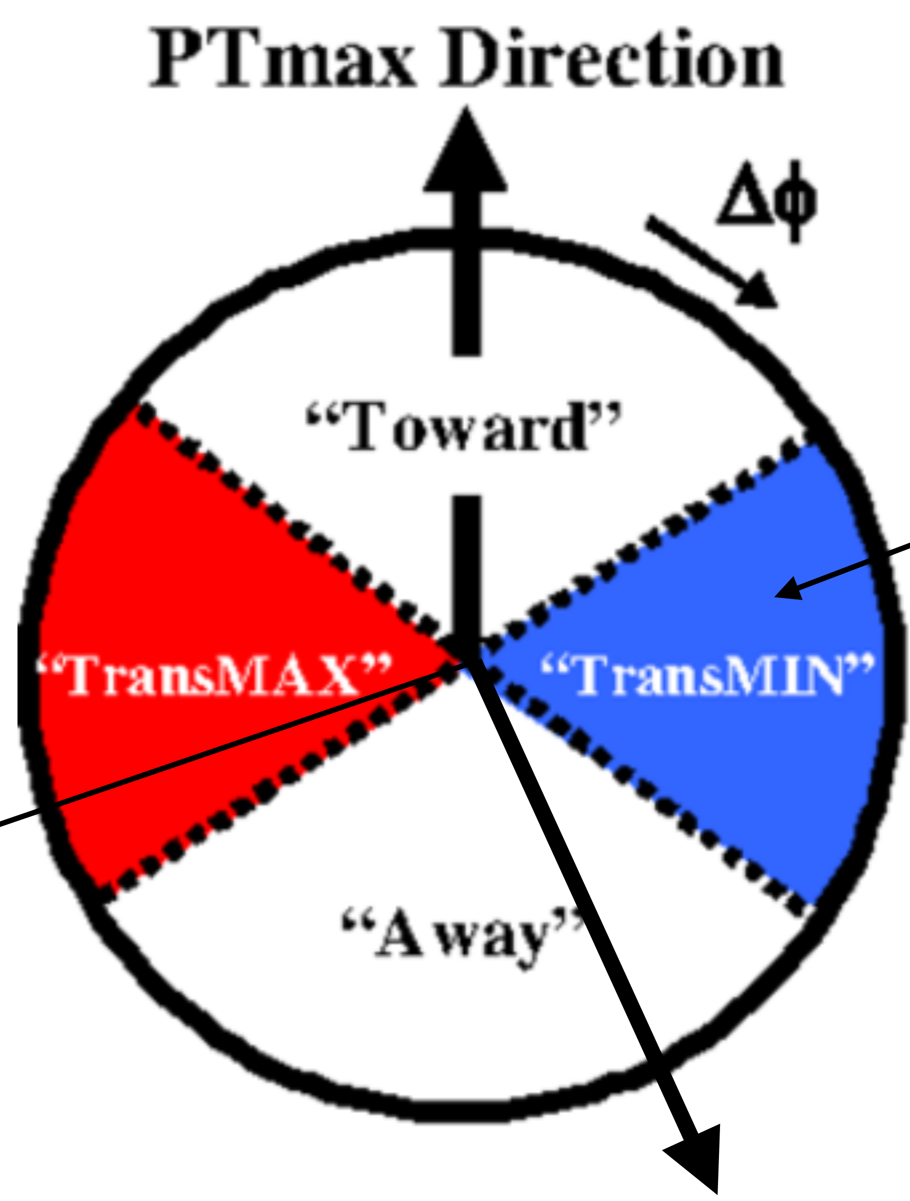
Brings in information from more than a single (charged) particle.

Capability to use jets can then also be used e.g. to define **exclusive 2-jet events**…

The TransMIN Region and Exclusive 2-Jet Events

TransMIN region:

The "TRANSVERSE" region is really two separate regions



highest-p_T particle/jet in the transverse region

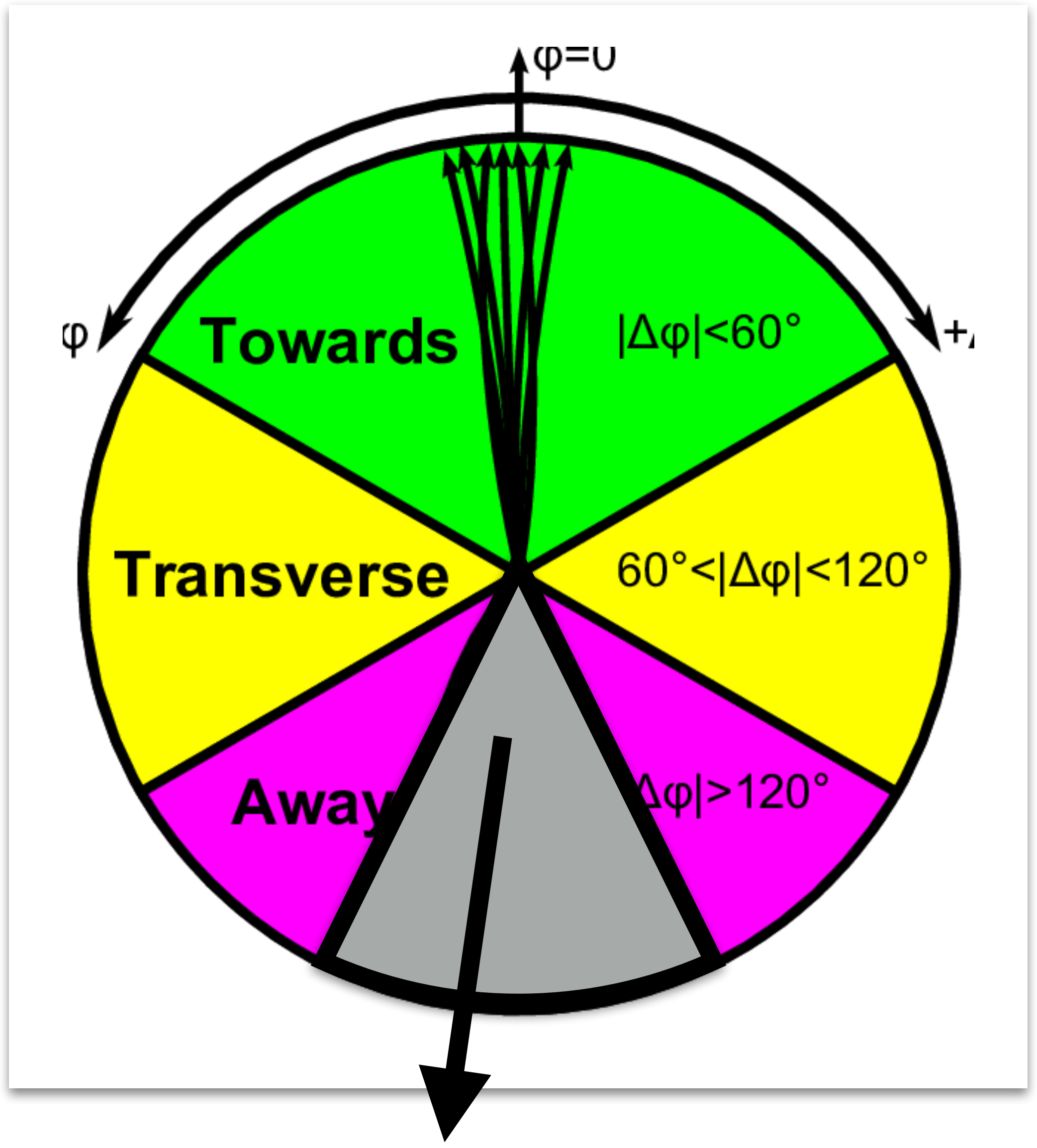
TransMIN region:

Less contaminated by bremsstrahlung jets

a.k.a. "back-to-back" events

Exclusive 2-jet events

Less contaminated by bremsstrahlung jets



Require **observed away-side jet** (with similar p_T and in angular region that prevents overlap with TRNS)

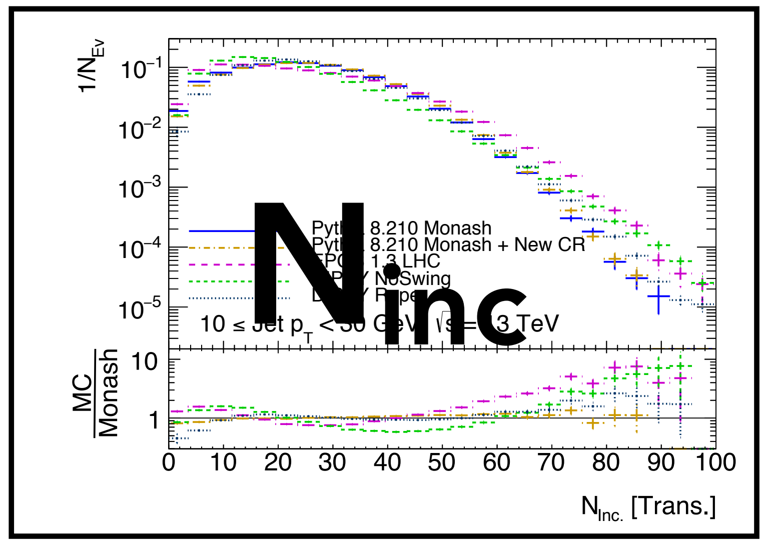
Both types studied at CDF, but I haven't seen them much since.

Start with most inclusive measures of activity ~ sum(p_T) , N_{inc}

Express next-level quantities as ratio to first, and so on

Emphasises broad event features first ➤ progressively finer details

Similarly, spectra in order of mean, width, then (de)tails of spectrum.



Strangeness Ladder

$$\frac{N_K}{N_{inc}} \rightarrow \frac{N_\phi}{N_K}$$

(+ Spin ladder!)

Baryon Ladder

$$\frac{N_p}{N_{inc}} \quad \frac{N_\Lambda}{N_p} \quad \frac{N_\Lambda}{N_K} \quad \frac{N_\Xi}{N_\Lambda} \quad \frac{N_\Xi}{N_K} \quad \frac{N_\Xi}{N_\phi}$$

Super Exciting: Correlations !

Eagerly awaiting baryon-meson correlations and Λ/K studies

+ baryon-(anti)baryon + dependence on activity estimator ($N_{ch}/N_{inc}/R_T$)?

Correlations are key to understanding detailed particle production mechanisms.

Further complementary studies by ALICE:

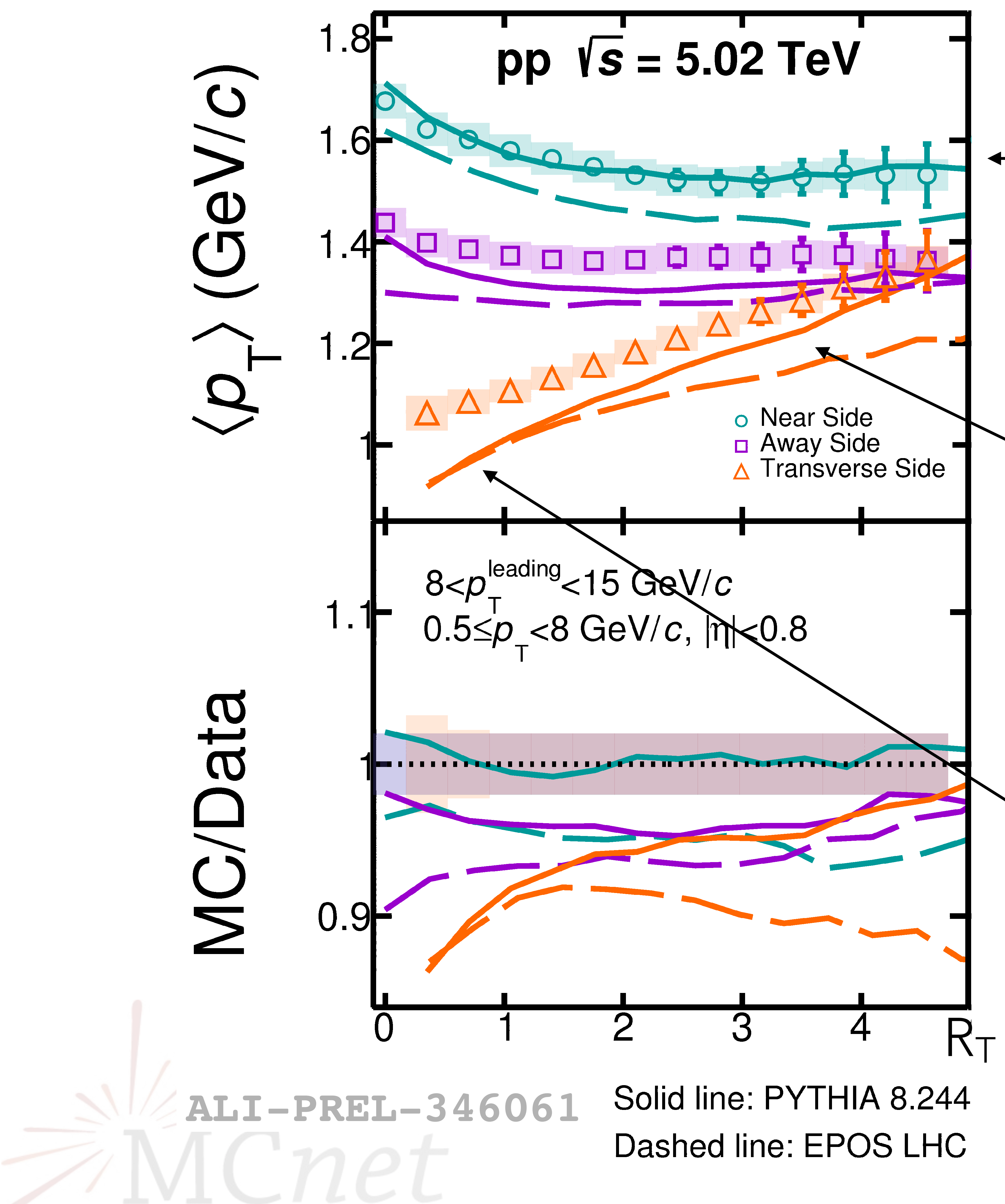
In min-bias context, interesting to probe **"jetty"** vs isotropic events at high multiplicities. Several studies carried out by ALICE using **transverse spherocity** classifier; not covered here.

Charm Baryon fractions (**huge** enhancements up to ~ 20 times e^+e^-!)

THANK YOU!

Extra Slides

Summary: <pT> Comparison between regions



NEAR: $<p_T>$ drops as more soft UE is added underneath the jet, then flattens

AWAY ~ washed-out version of NEAR

TRNS: $<p_T>$ increases ~ linearly with R_T, similar to trend in high-N_{ch} min-bias?

Eventually "catches up" with the other regions (& then presumably dominates there too)

Interesting that both models (PYTHIA and EPOS) **fail** at lowest R_T

Interesting to follow up on!

Related (or not) to LEP p_{Tout} discrepancy?