# Exploring the extremes of the Underlying Event

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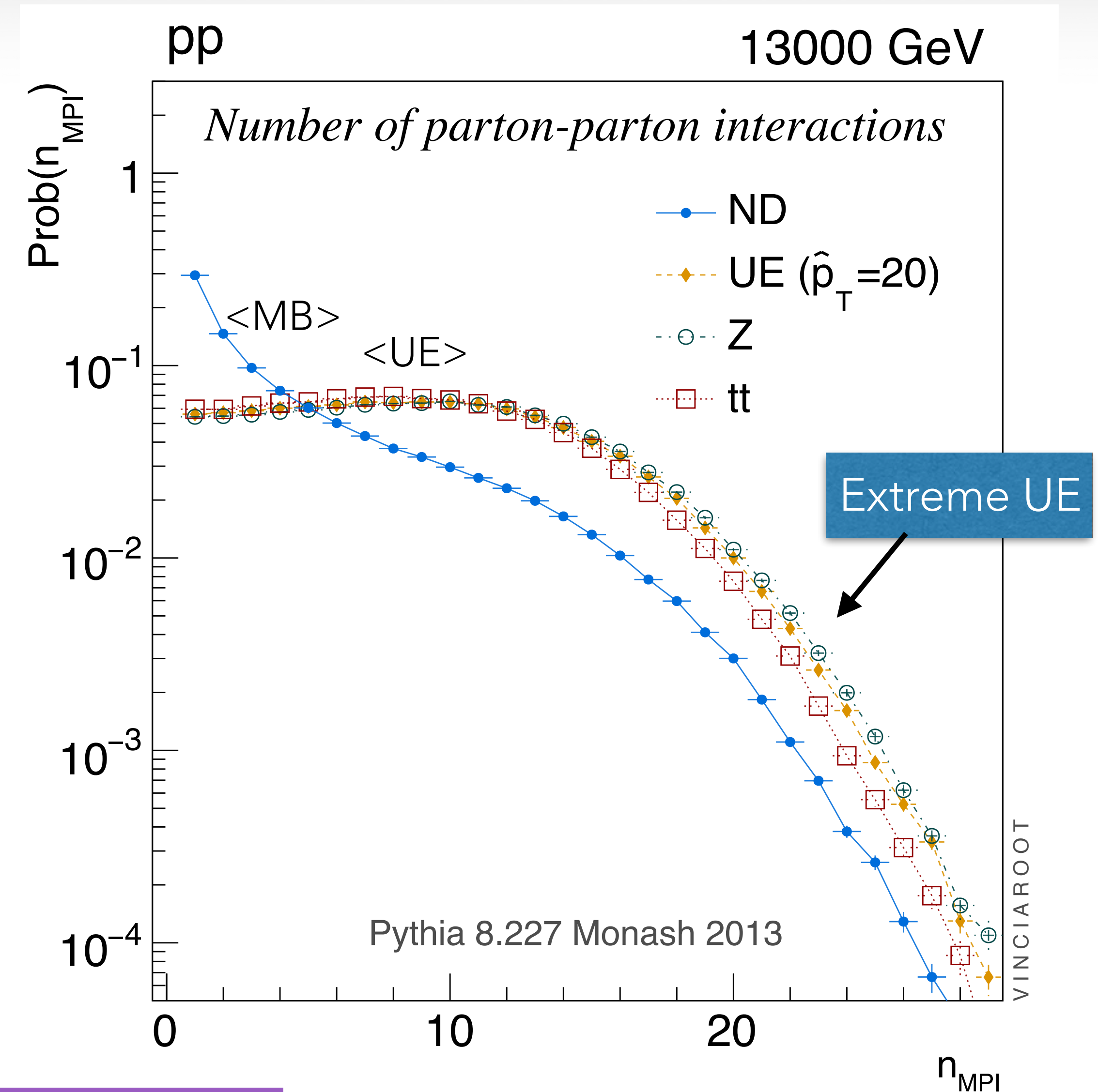
***Strange things*** have been observed in high-multiplicity minimum-bias events

Associated with small impact parameters

Jet trigger → bias to small b (pedestal effect)
(→ <UE> is larger than <MB>)

Complementary studies can be carried out in UE. Fluctuates from event to event. Studies as function of UE $N_{ch}$ (density) analogous to MB studies vs $N_{ch}$ (density)

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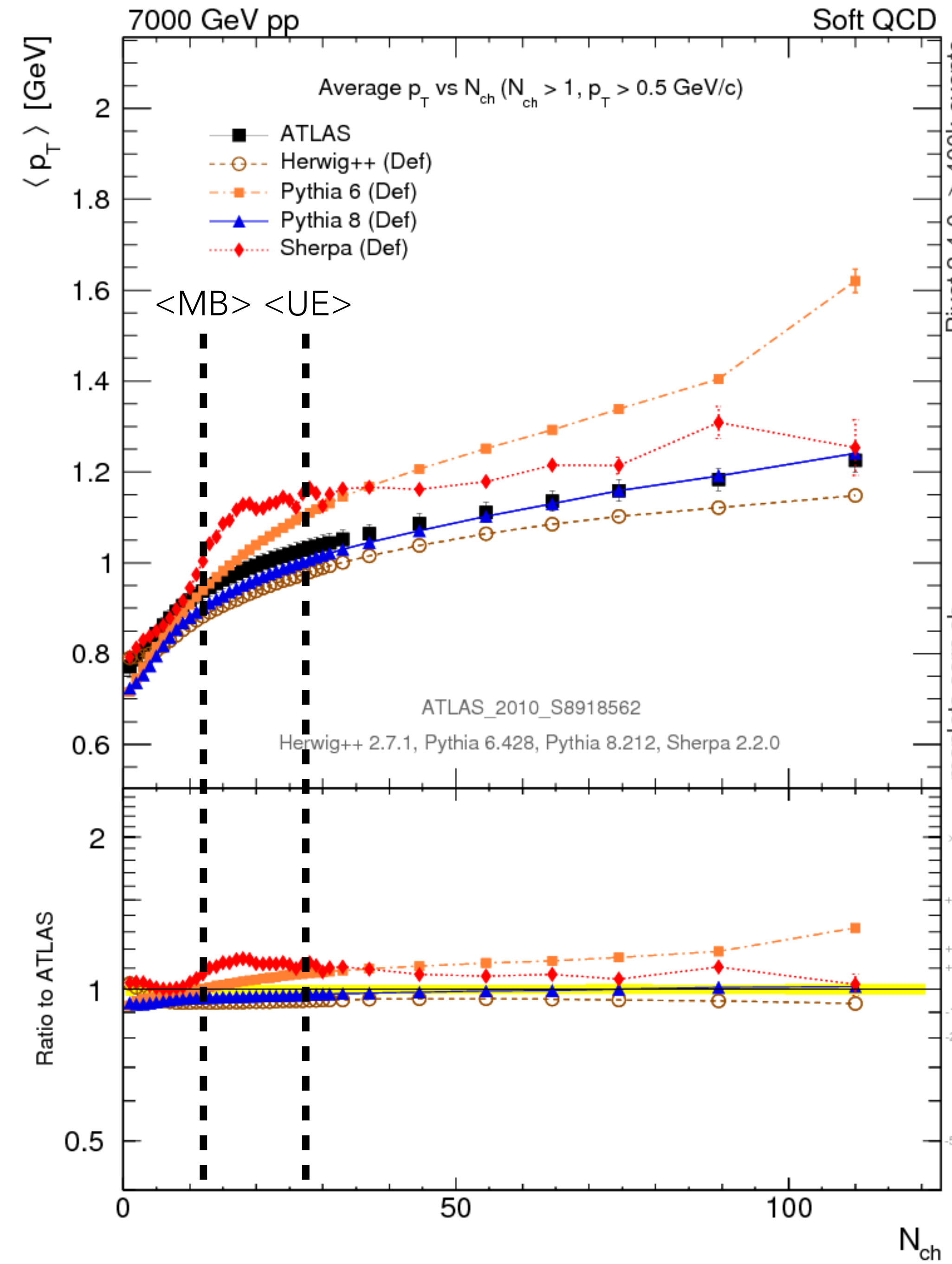
# MIN-BIAS VS THE UNDERLYING EVENT

## Tautology: a jet trigger provides a bias(ed subsample of min-bias)

## Pedestal effect:

Events with a hard jet trigger are accompanied by a higher plateau of ambient activity (extending far from the jet cores)

MPI: interpreted as a biasing effect. Small impact parameters → larger matter overlaps → more MPI → higher chances for a hard one (and the trigger throws out any events that didn't have at least one)

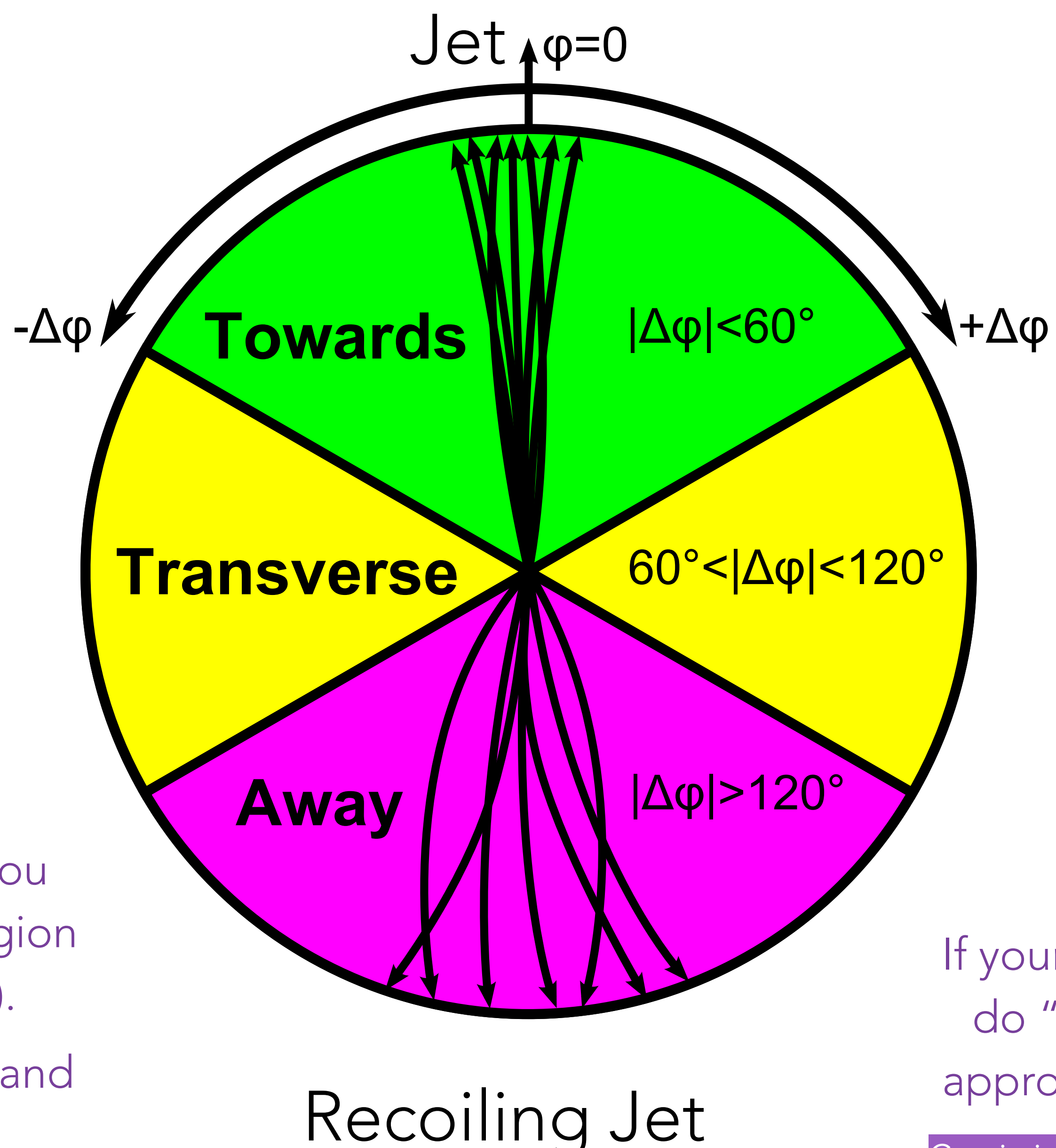


# DEFINING THE UNDERLYING EVENT

## Jet trigger (or other hard probe but want high statistics)

Consider event in transverse plane (x,y)

Look at 90 degrees to leading jet direction:




Operational definition of UE = "Transverse Region"

Note: if your hard probe is a Z, you can also look in the "Towards" region (subtracting the decay leptons).

UE in Drell-Yan studies by ATLAS and CMS

If your hard probe is a ttbar pair, can do "Swiss Cheese" or jet median approach (also generally applicable)

Cacciari, Salam, Sapeta, "On the characterisation of the underlying event," *JHEP*04(2010)065,arXiv:0912.4926 [hep-ph].

# THE (AVERAGE) UE

By now lots of measurements of the average properties of the underlying event, and of its (non)-evolution* with $p_{T\mathrm{trigger}}$

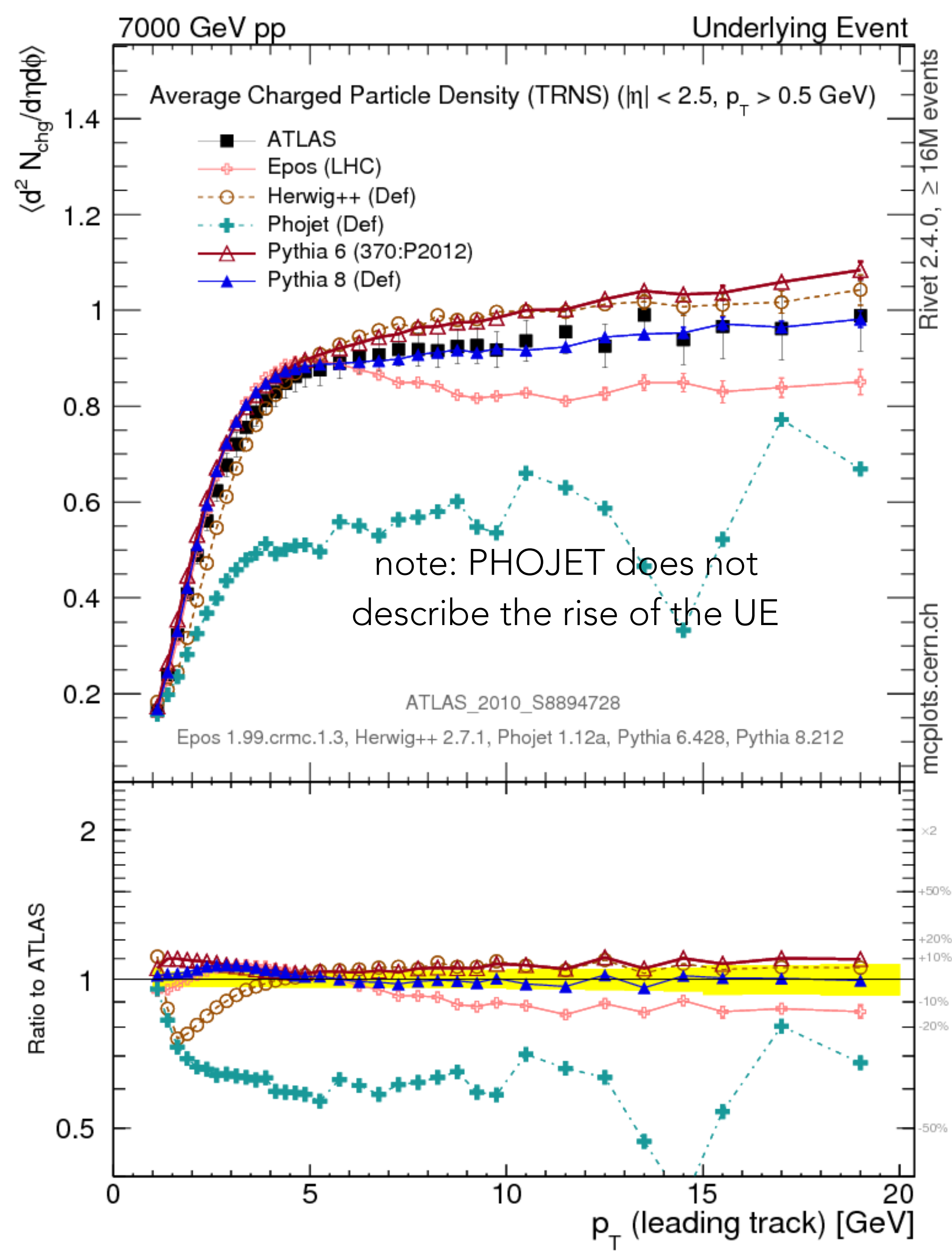
NB: trigger can be:

if you don't have (good) calorimetry → Hardest track, Hardest track-jet

more inclusive → Hardest calo-jet

...

*: radiation spillover into the UE does provide a (slow) evolution with $p_{T\mathrm{trigger}}$

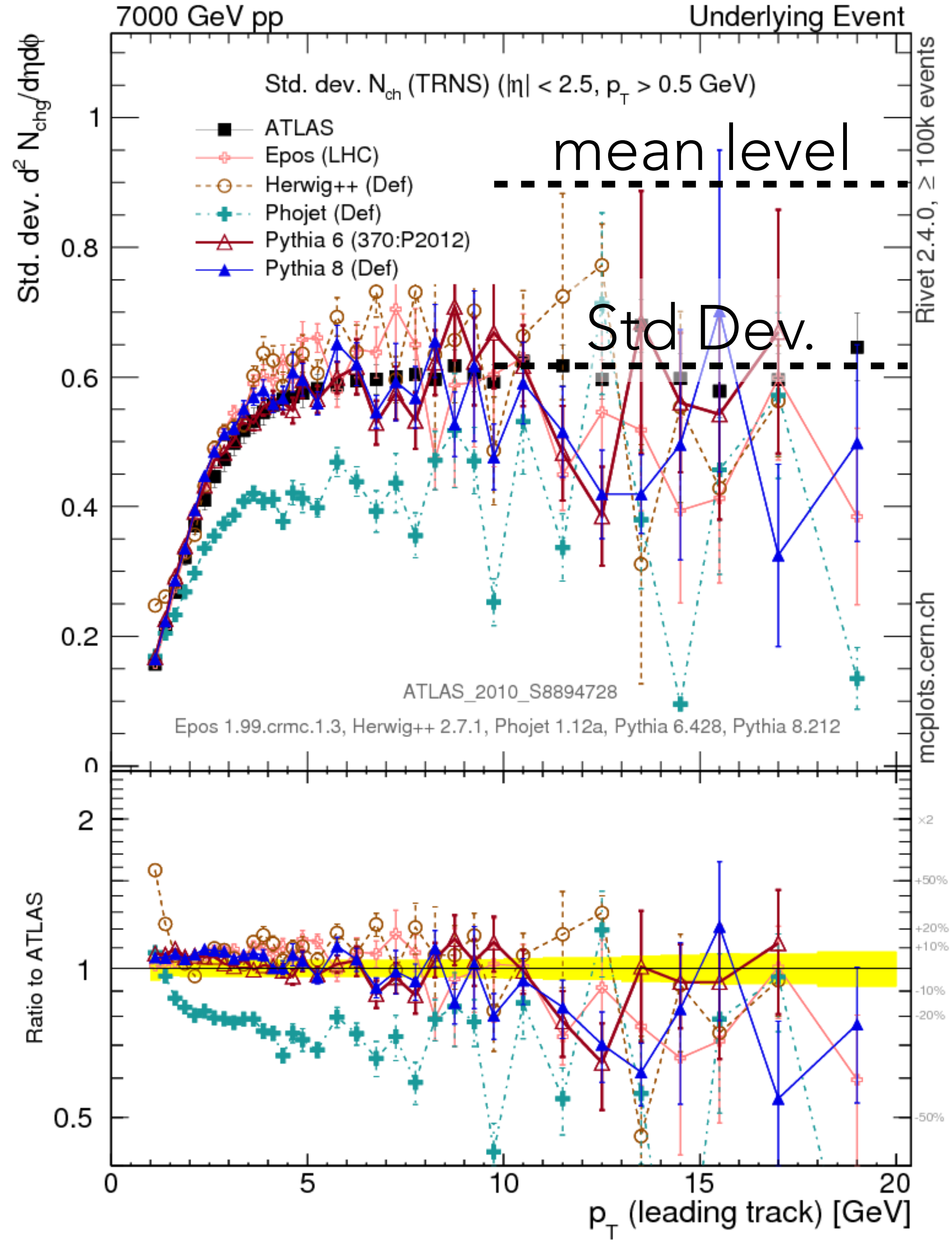


ATLAS: UE fluctuates a lot from event to event

(similarly to the large width of the $N_{ch}$ distribution in min-bias)

Implies that there are "quiet" events with $N_{TRNS}$ << <N>
Does the UE in those events look like min-bias? or LEP?

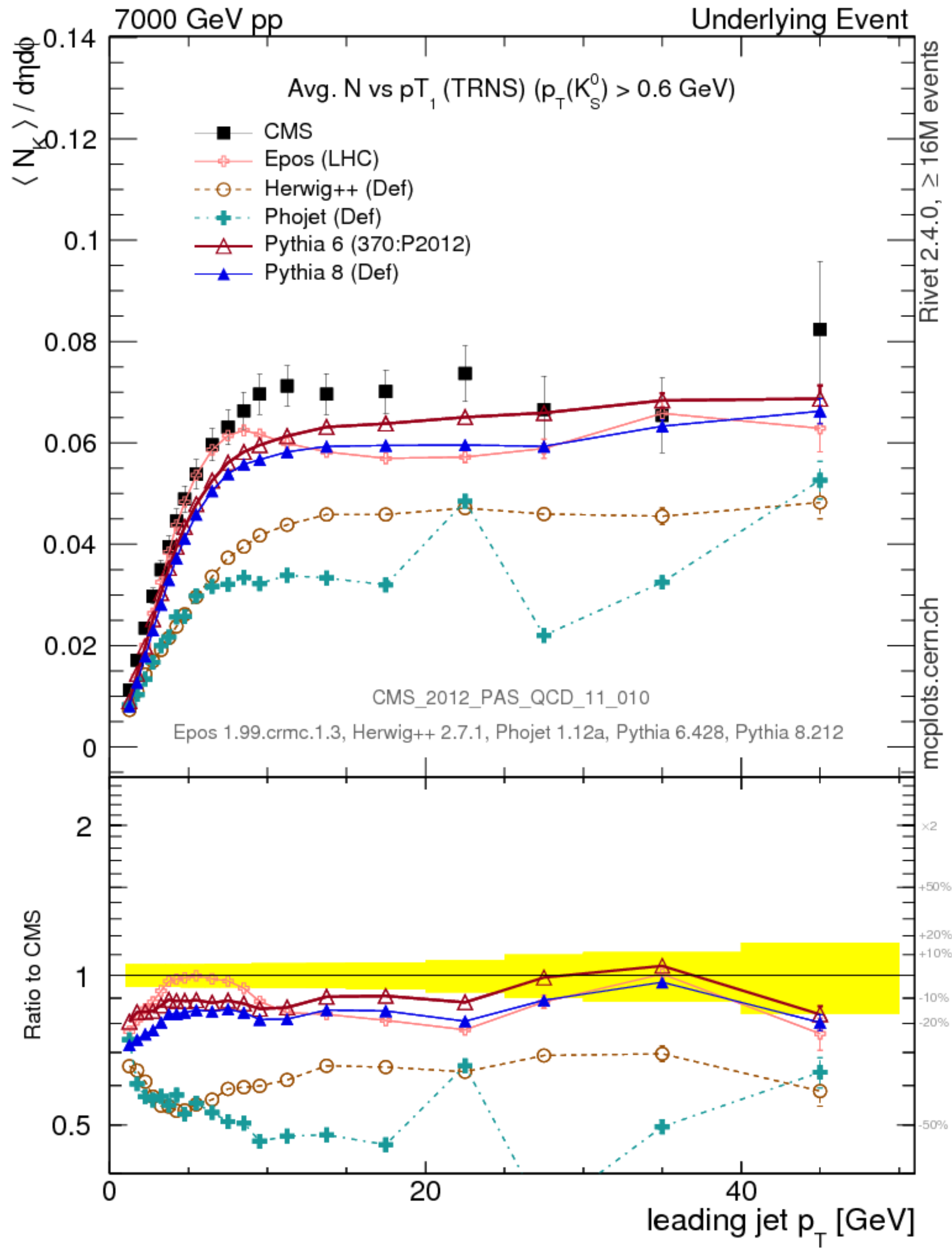
Implies that there are "extreme UE" events with $N_{TRNS}$ >> <N>
Does the UE in those events exhibit same effects as high-$N_{ch}$ min-bias?



## CMS: average strangeness (K0) as a function of trigger jet $p_T$

10% - 20% strangeness deficit also in UE

(Ideally, should show strangeness *fraction* to avoid concluding that e.g., the PHOJET result is just due to strangeness; recall PHOJET was low on total N as well)



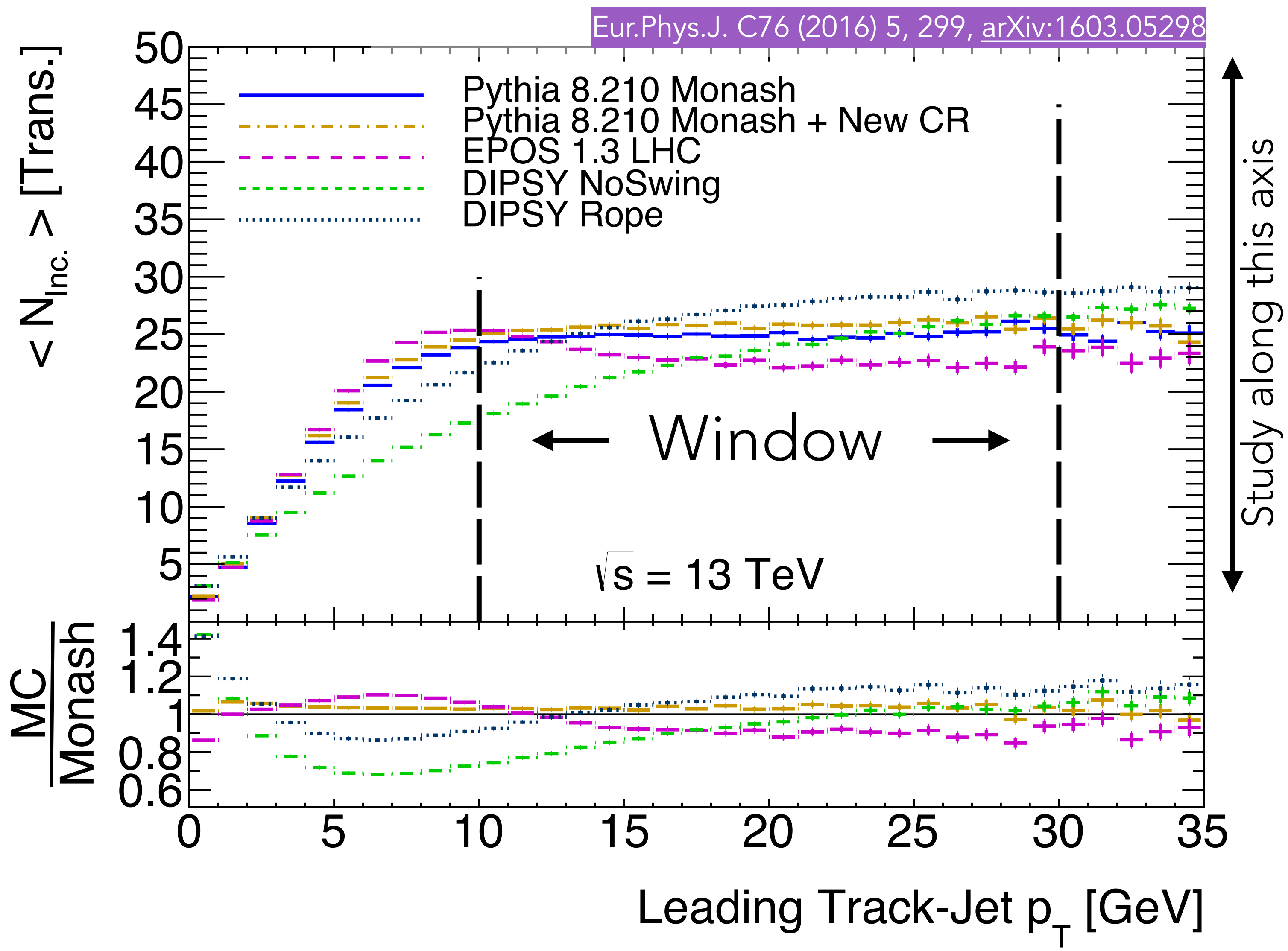

Do extreme events have even larger deficits? What about quiet ones? What about other PIDs?

## Instead of plotting UE plateau as function of trigger jet $p_T$,

⇨ Plot salient quantities (e.g., strangeness) as function of event-by-event UE level, for some window of trigger jet $p_T$

We propose a window just above the turn-on of the plateau; maximises rates and minimises contamination of the UE by radiation

10 GeV < $p_{T\text{trigger}}$ < 30 GeV




Note: $N_{inc}$ is ATLAS jargon for a particular combination of charged tracks and long-lived strange hadrons that they can reconstruct well. Think of it as $N_{ch}$.

# WHAT MIGHT YOU SEE?

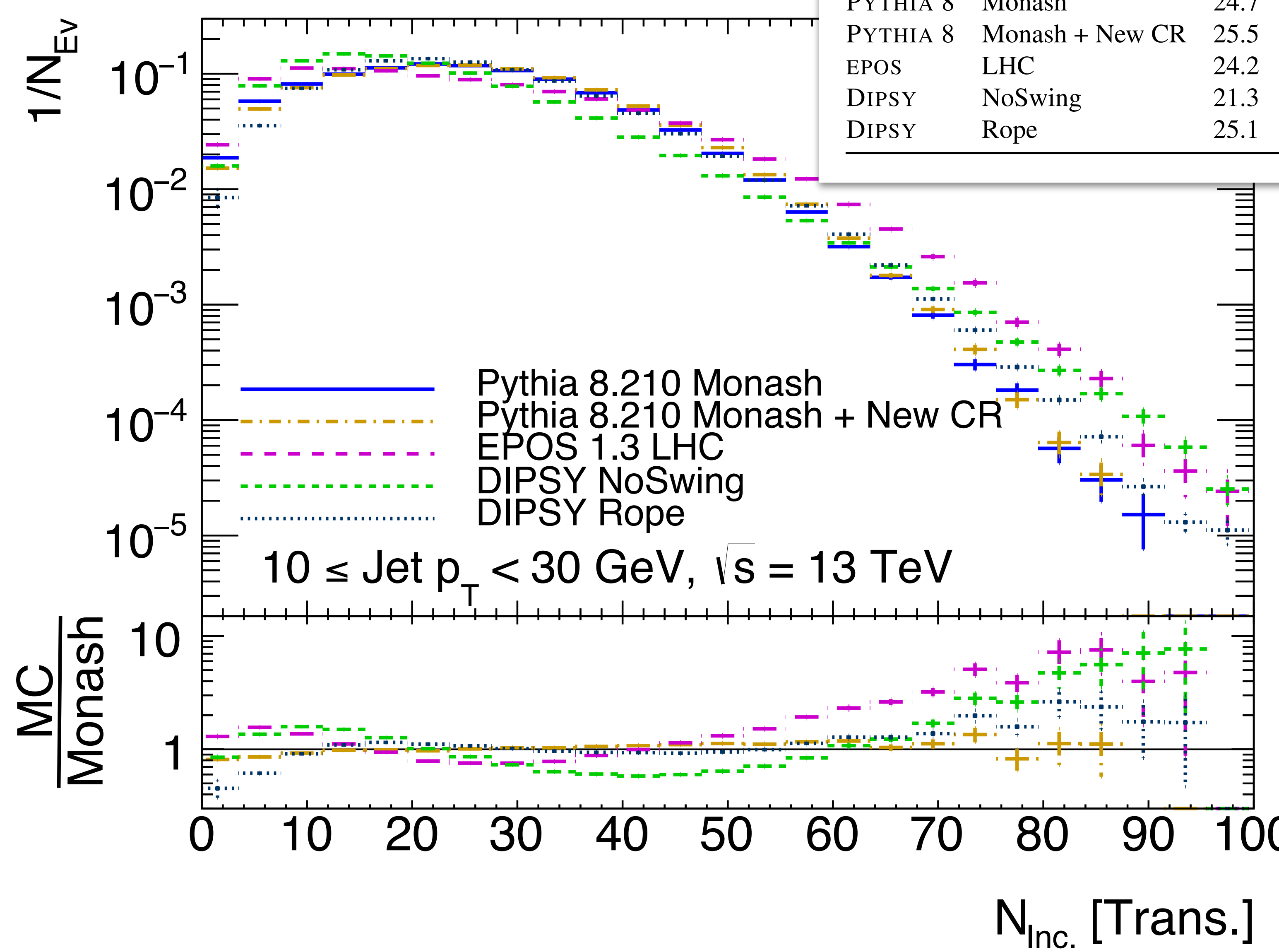
## Bear in mind: models only represent a subset of the possibilities in nature

Here is basically an $N_{ch}$ spectrum (but for the UE)

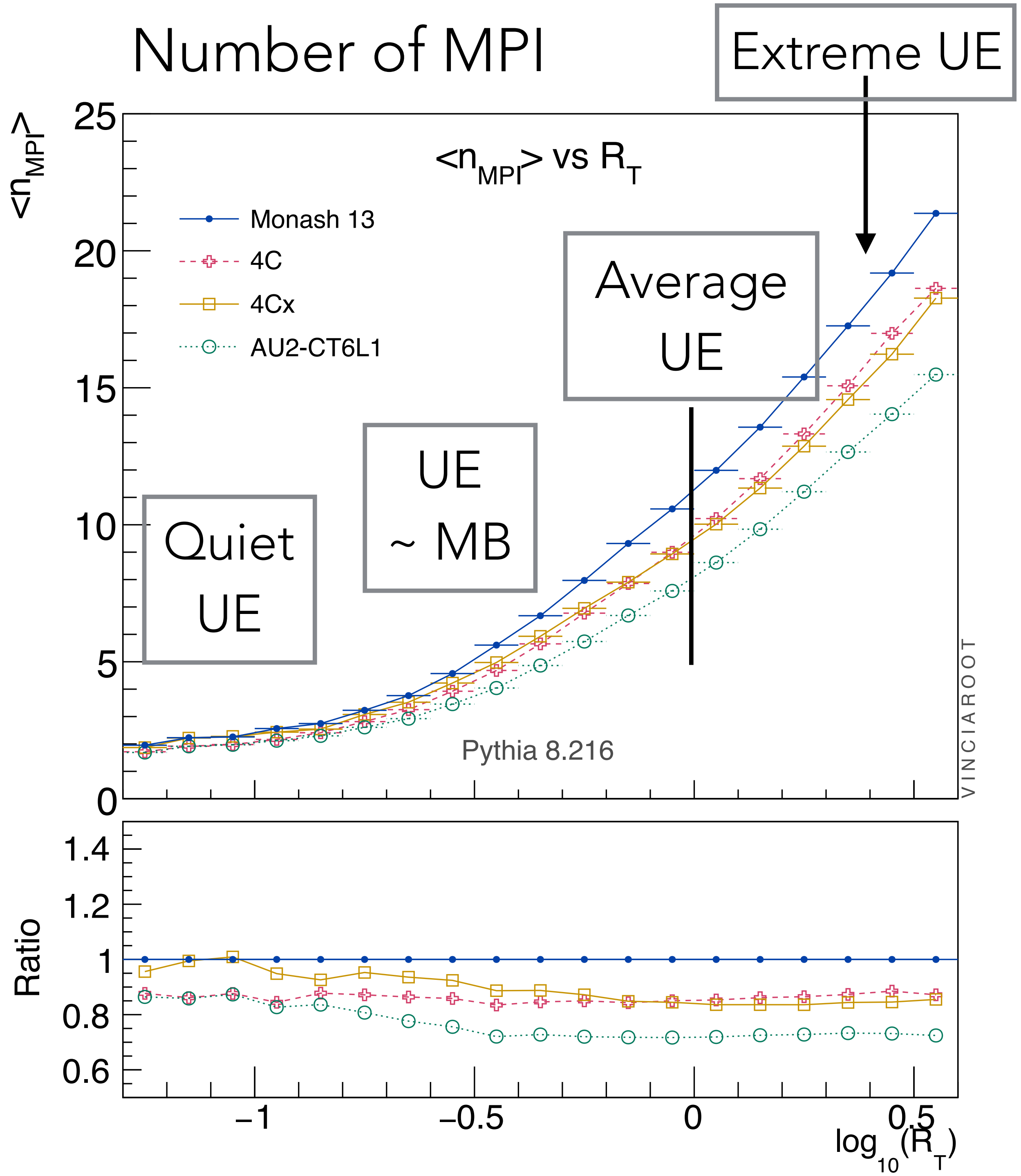
Use average to define AVERAGE UE LEVEL and $R_T = N / \langle N \rangle$

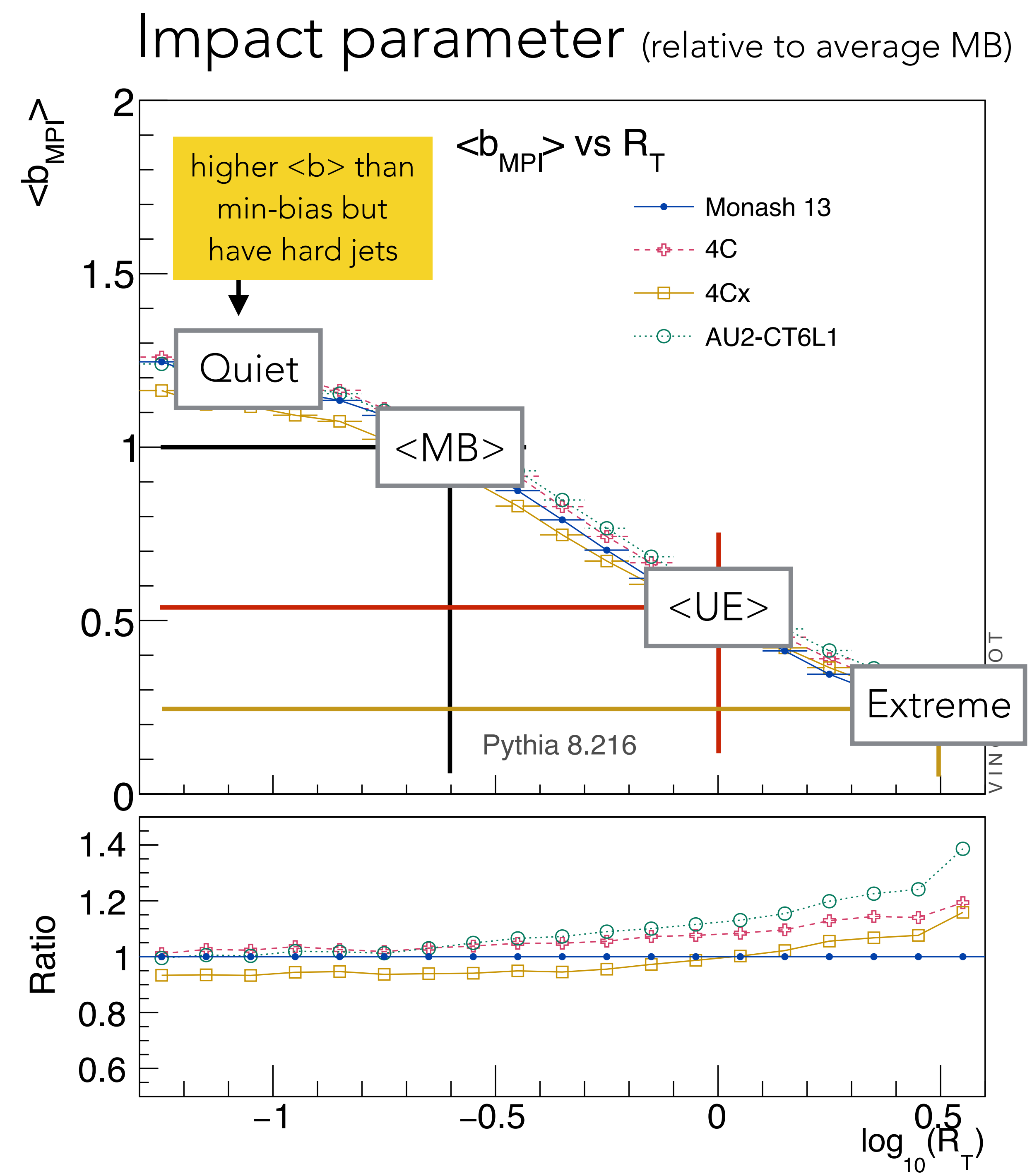
(analogous to the KNO z variable)

| Generator | Tune | $\langle N_{\text{Inc.}} \rangle$ | $\sigma$ |
|---|---|---|---|
| PYTHIA 8 | Monash | 24.7 | 12.5 |
| PYTHIA 8 | Monash + New CR | 25.5 | 12.6 |
| EPOS | LHC | 24.2 | 14.6 |
| DIPSY | NoSwing | 21.3 | 12.2 |
| DIPSY | Rope | 25.1 | 12.0 |



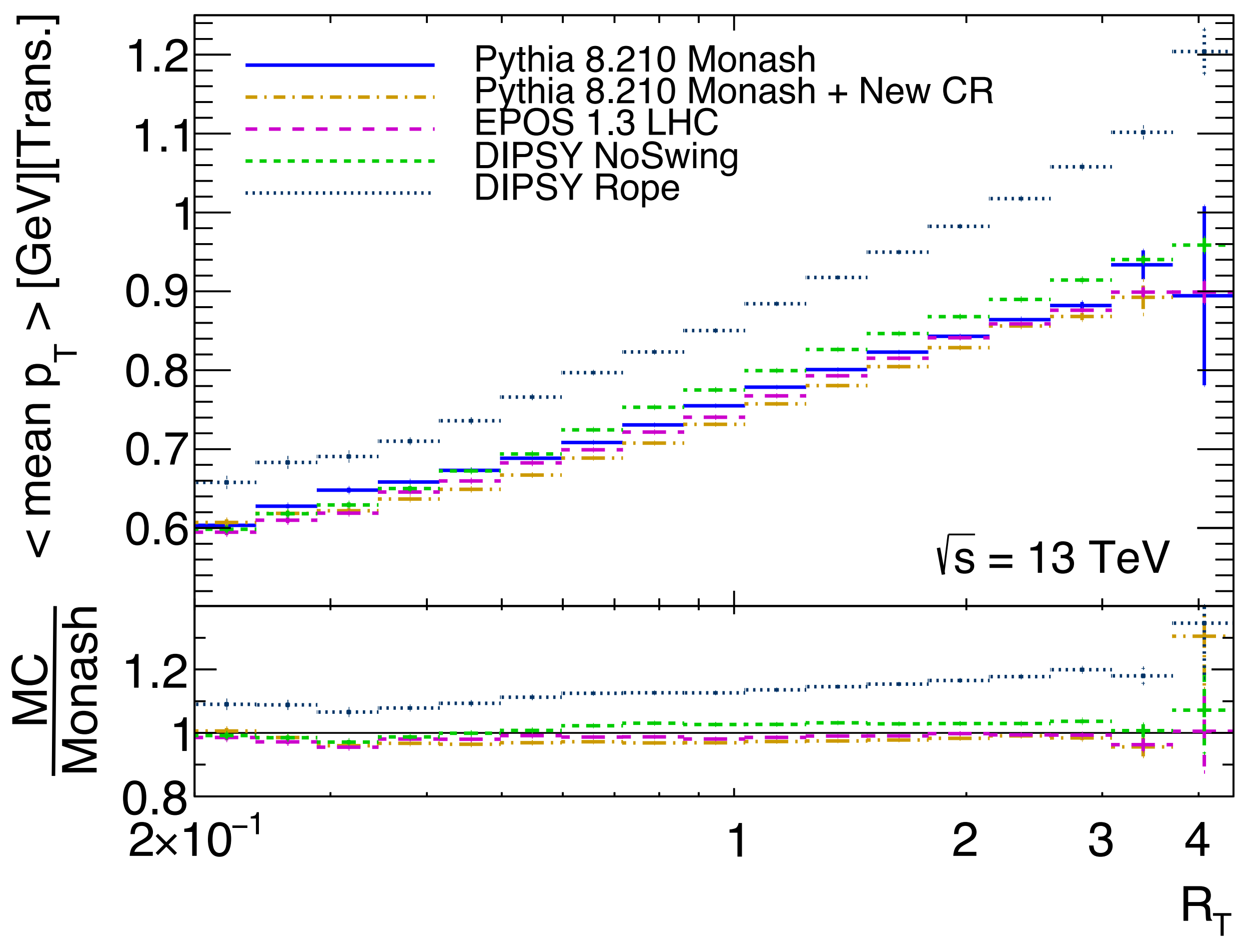
# THEORY: UNDER THE HOOD



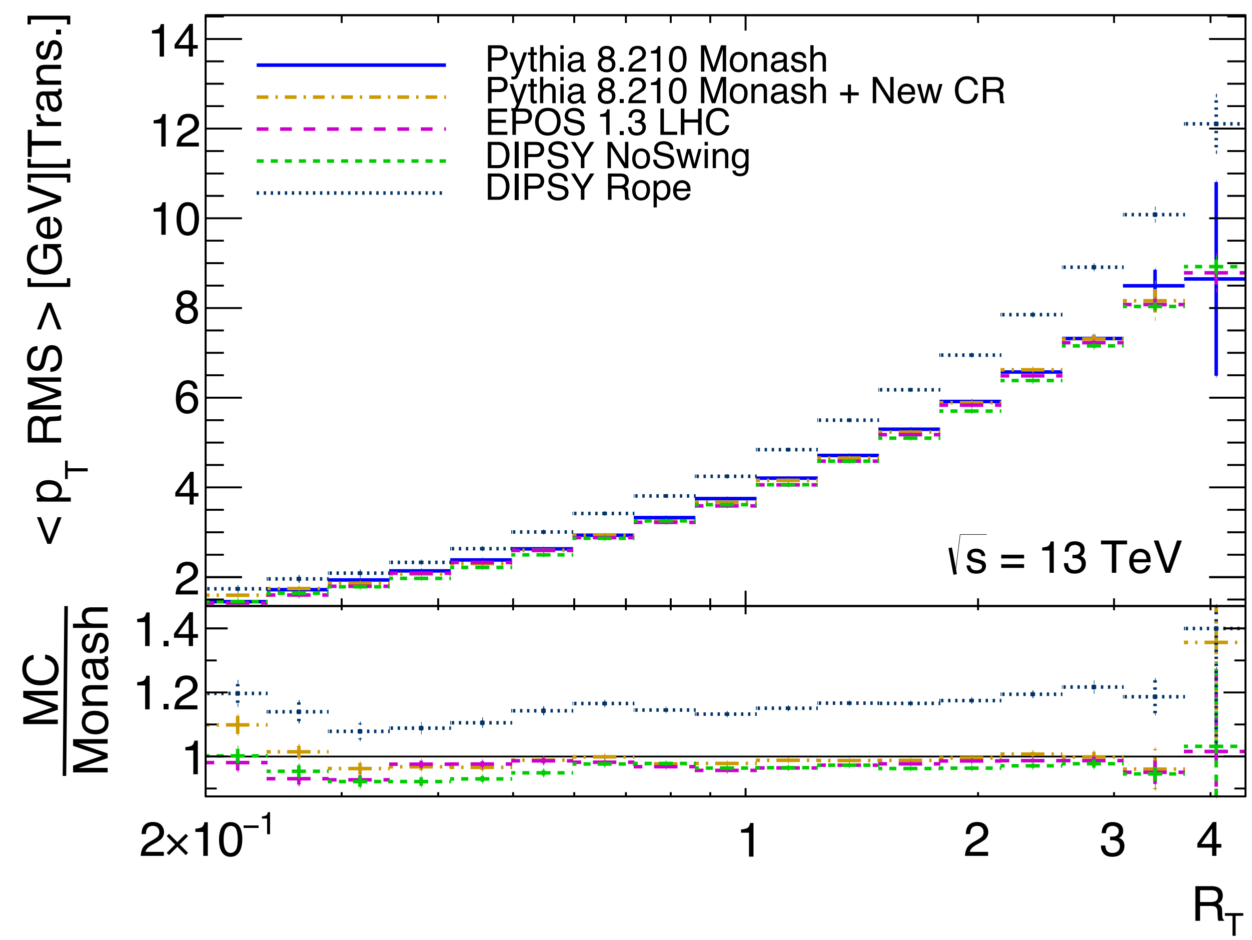



# THE UE ANALOGUE OF <PT>(NCH)

## Rising trend in minimum-bias taken as indicative of collectivity; how about in UE?

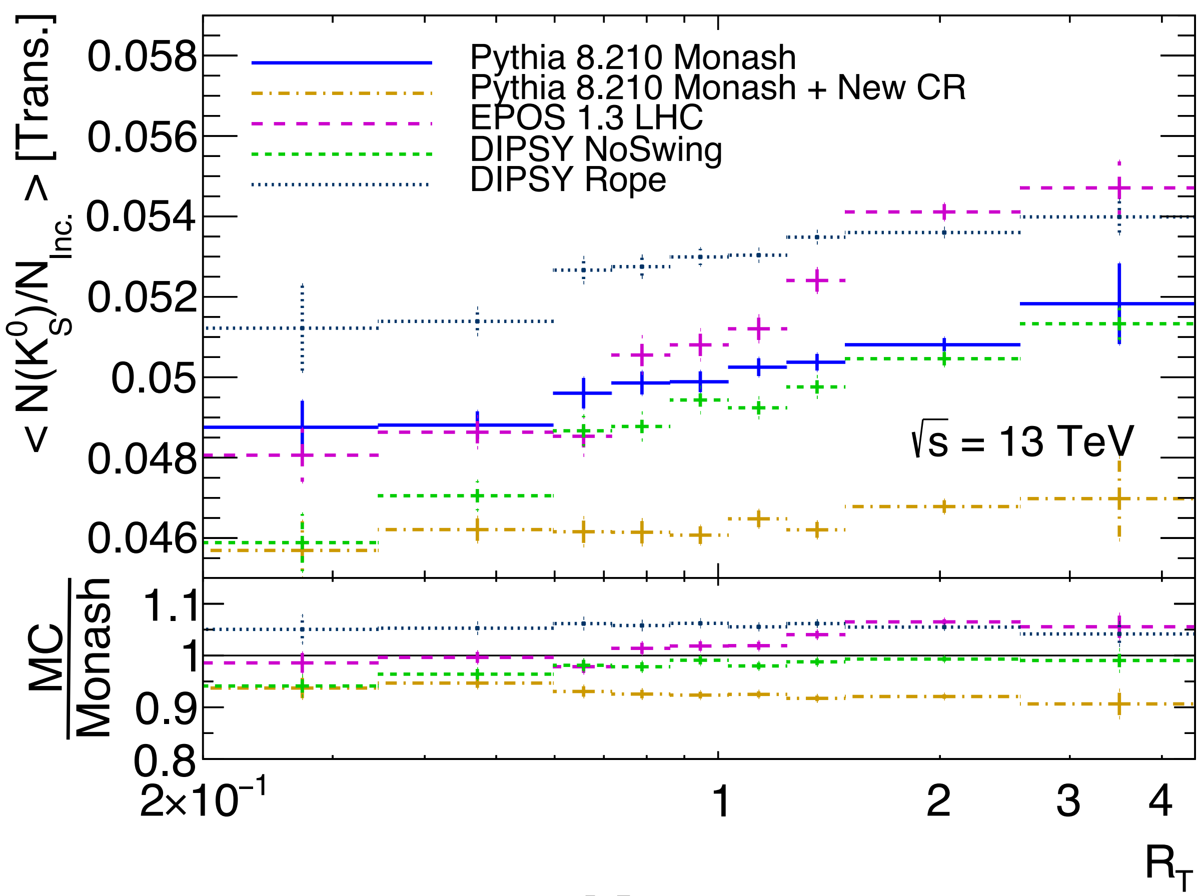



<pT>

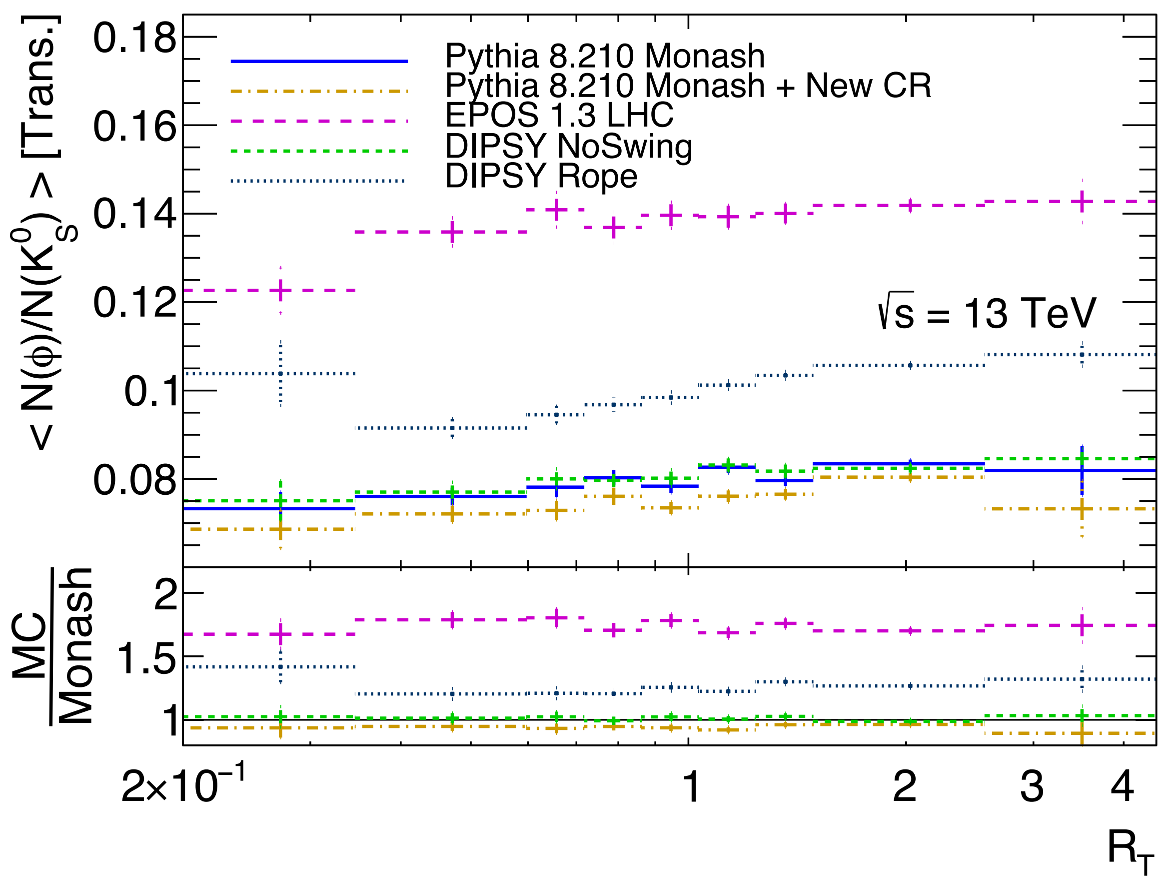



RMS

## Significant power to separate different physics mechanisms

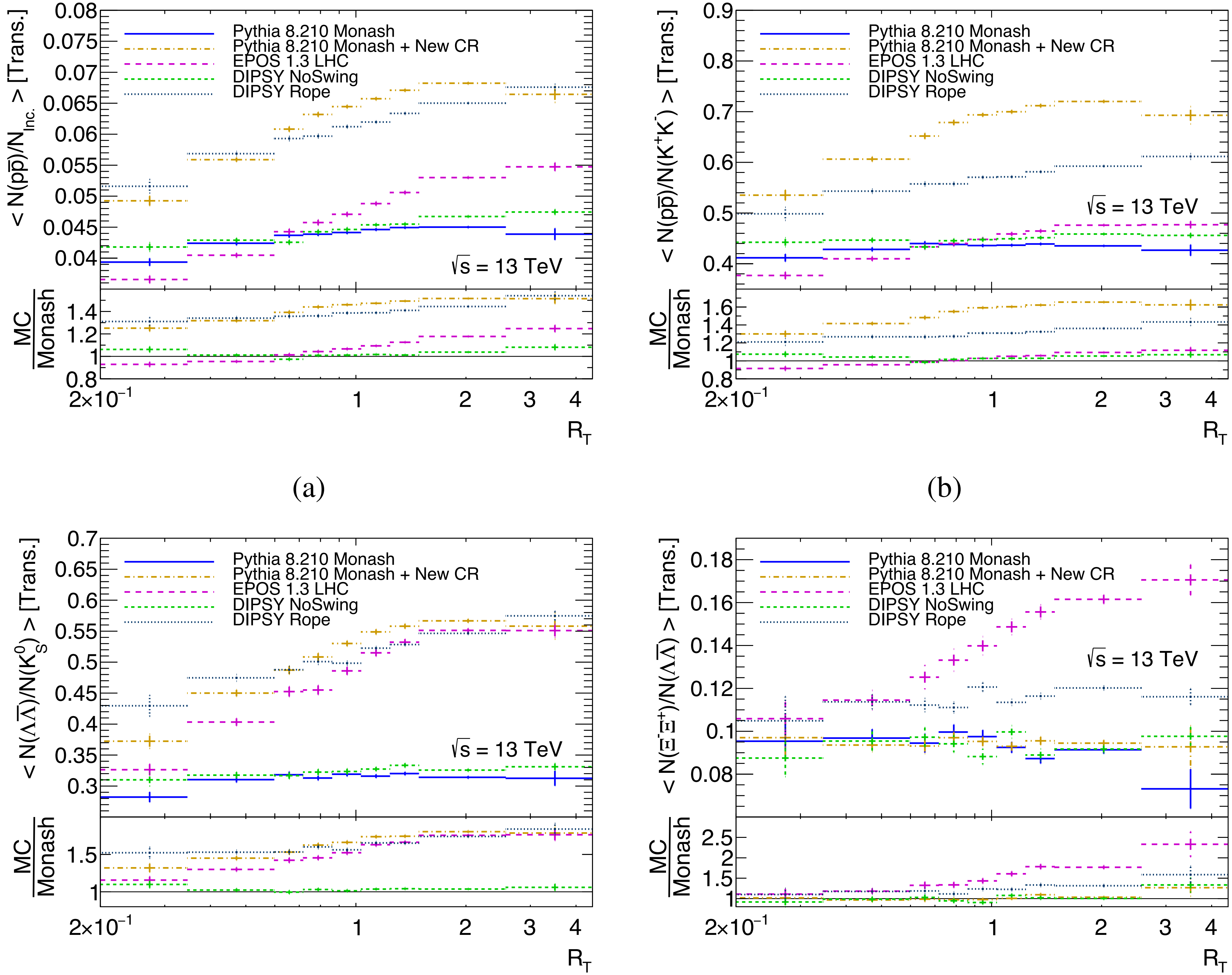



**Kaons**




**Phi mesons**

# IT'S EVEN MORE FUN WITH BARYONS




(a)

(b)

# SUMMARY / OUTLOOK

## The UE provides a complementary phase-space region to min-bias which could well exhibit similar phenomena as high-mult min-bias

- Hard trigger biases selection to small impact parameters
  - But can find "ultra-quiet" UE levels with even less activity / higher b, than MB (LEP-like?)
  - Can explore events with "extreme" UE levels → collectivity?
- Models based on different principles predict ***qualitatively*** different trends for the various particle ratios, as functions of the UE level
  - NB: so far, we only studied particle multiplicities (*ratios*) and spectra; particle *correlations* would provide additional information

## Work is ongoing in ATLAS; but limited by PID capabilities

- CMS similar? (but not aware of any measurement underway?)

## ALICE and LHCb have the PID to do it

- What is the status of UE studies?
  - Jet or hard-track triggers? Other hard trigger probes?

# Backup Slides

# FIDUCIAL CUTS (FOR OUR EXAMPLES)

Fiducial cuts are applied to the MC generator output to approximate experimental sensitivity and this results in an inclusive set of particles formed of two components. The ‘prompt charged’ component of the inclusive set consists of charged particles with $p_\perp > 200$ MeV, $|\eta| < 2.5$, lifetime $\tau > 300$ ps and which are not created from the decay of a state with $30 < \tau < 300$ ps. This set is dominantly $\pi^\pm$, $K^\pm$, $p$ and $\bar{p}$. The definition is based around the ATLAS fiducial selection in ref. [76]. The second component consists of ‘identifiable prompt strange hadrons’; here both charged and neutral strange hadrons are included if they typically undergo weak decay to one or more charged particles. These states are also required to satisfy $p_\perp > 200$ MeV, $|\eta| < 2.5$ and for themselves to not be created from the decay of other states with $30 < \tau < 300$ ps[4]. This set is comprised of $K^0_\mathrm{s}$, $\Lambda$, $\bar{\Lambda}$, $\Xi^\pm$, $\Sigma^\pm$, $\bar{\Sigma}^\pm$ and $\Omega^\pm$.

Track jets are clustered from prompt charged and prompt identifiable strange hadrons. They are reconstructed with the anti-$k_t$ algorithm [77] using radius parameter $R = 0.4$, the leading jet is required to be within $|\eta| < 2.3$.