The hunt for outliers

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The pp collisions and plasma a long history!

van Hove: Phys Lett B, 118 (1) (1982), pp. 138-140 followed by many experimentalists Alexopoulos et alhttps://doi.org/10.1016/S0370-2693(02)01213-3,

Charged Particle Spectra in ~ and ~p Collisions at the CERN ISR CERN-Heidelberg-Lund Collaboration. W. Bell et al

Presently, it is widely believed that in pp collisions in the studied energy range a hot QCD matter is not produced in the typical inelastic minimum bias events due to small energy density. But in high multiplicity (HM) pp events the energy density may be comparable to that in AA collisions at RHIC and LHC energies. And if the thermalization time, τ0, is small enough, say τ0 ∼ < 0.5 fm, the mini-QGP with size of ∼ 2 − 3 fm should be formed quite likely to the large-size plasma in AA collisions

- Until B.G Zakharov https://doi.org/10.48550/arXiv.1311.1159

The mean will most probably not help us

- The means are the result of many contributions – like the landau distribution for the energy loss – several effects contribute.
- The models can get the most prominent features but never the details of the interactions
- IMHO they serve to compare models and measurement

The hedgehogs

- If all the earlier works were focused to low multiplicities there is a reported feature by UA1 and CDF Tha occurs at the other end of the multiplicity spectrum

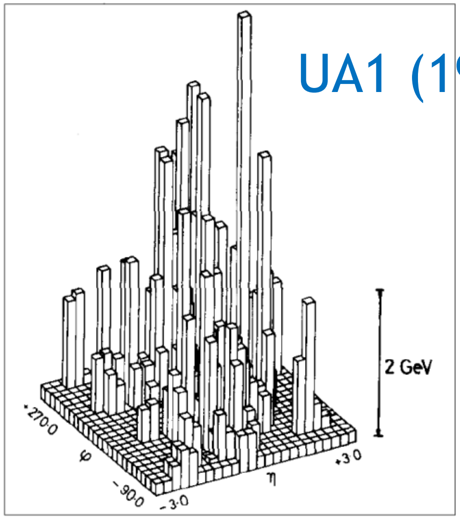
Introduction to “hedgehog” events

- The UA1 and CDF collaborations have reported the presence of events with a very extended structure of low momentum tracks filling in a uniform way the pseudorapidity-azimuth (η-φ) phase space.

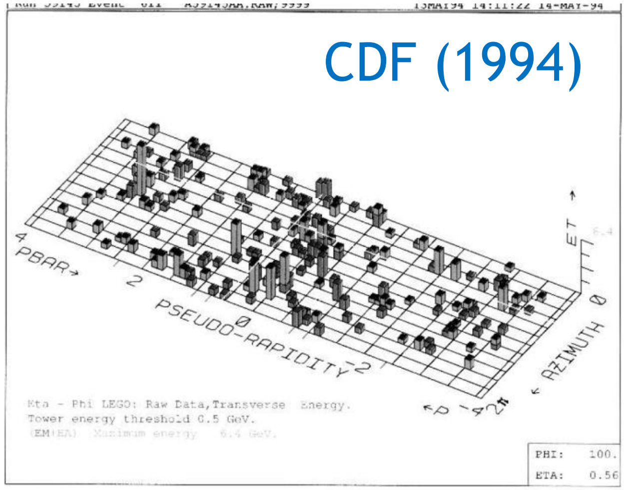
- First dedicated analysis of highest E_T events seen in the UA1 detector at √s = 630 GeV (with isotropic events with E_T ~ 210 GeV) – no evidence for non-QCD mechanism for these events.

- Unusual events observed in ppbar collisions at √s = 1.8 TeV by CDF’s Run 1 detector with more than 60 charged particles and ~320 GeV of transverse energy (E_T) – called “**hedgehog**” events by C. Quigg.

- Taken for granted that in these events with high E_T perturbative aspects of QCD dominate the event properties: multi-jet events.



UA1 Collaboration, Zeit. für Phys. C, V. 36, p. 33 (1987)



C. Quigg, Il Nuovo Cimento, V. 33C, N. 5 p. 327 (2010)

Characterisation of high-multiplicity events

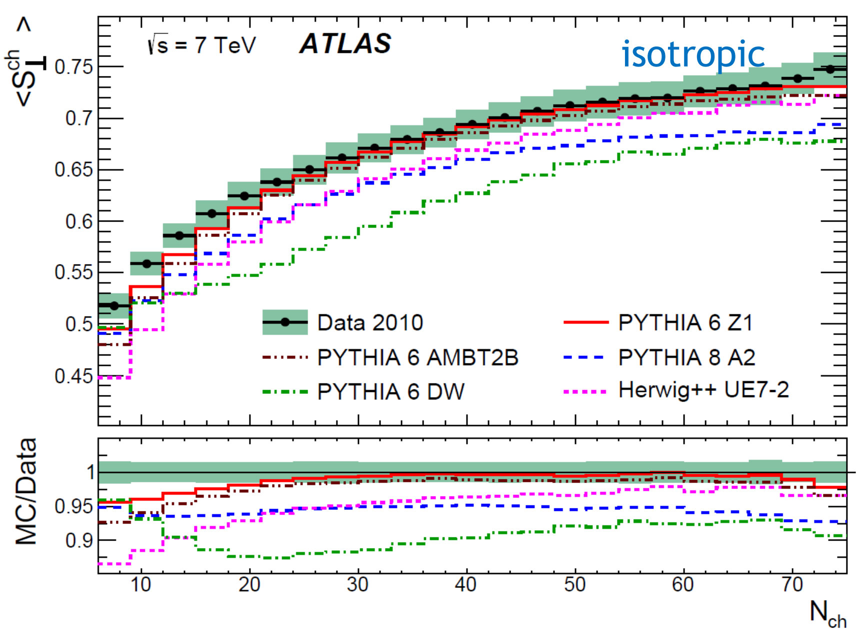
- Attempts to characterise these high-multiplicity events: use of event shapes, i.e. using transverse sphericity:

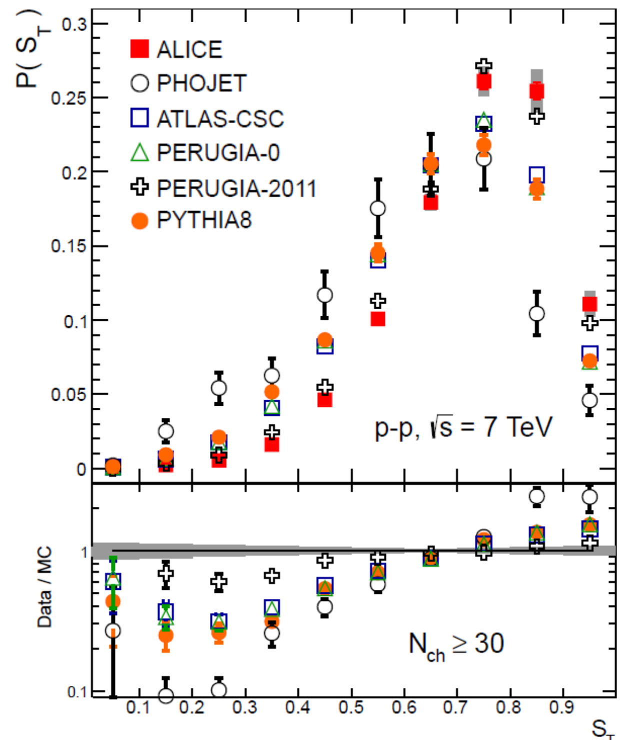
$$S_{\perp} = \frac{2\lambda_2^{xy}}{\lambda_1^{xy} + \lambda_2^{xy}}\,, \qquad S^{xy} = \sum_i \frac{1}{|\vec{p}_{\mathrm{T},i}|^2} \begin{bmatrix} p_{x,i}^2 & p_{x,i}\,p_{y,i} \\ p_{x,i}\,p_{y,i} & p_{y,i}^2 \end{bmatrix}$$

- Both ALICE and ATLAS observed an **under-estimation** of isotropic events by MC generators at high charged multiplicity ($N_{ch} \geq 30$)

  ✓ Suggest that a very active underlying event (UE) is needed by the MC event generators in order to explain these high-multiplicity events

ATLAS Collaboration, Phys. Rev. D 88, 032004 (2013)





pencil-like isotropic

ALICE Collaboration, Eur. Phys. J. C 72 (2012) 2124

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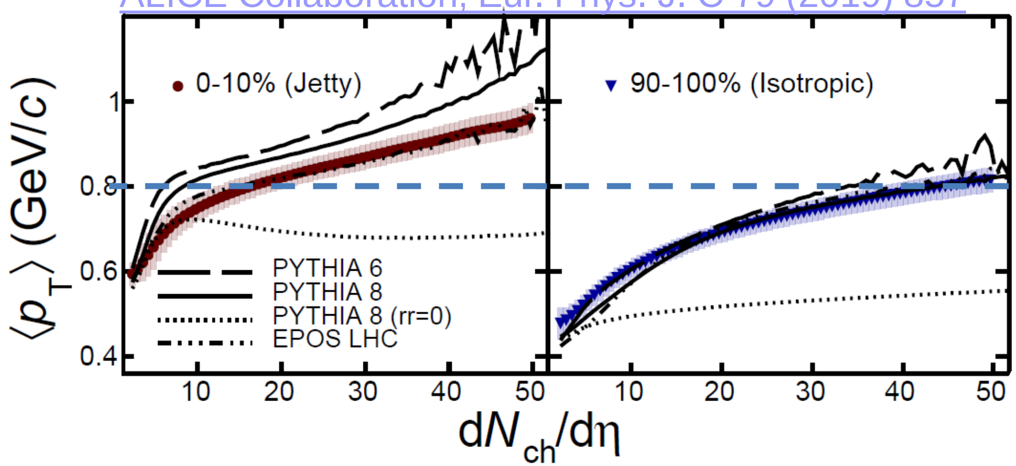
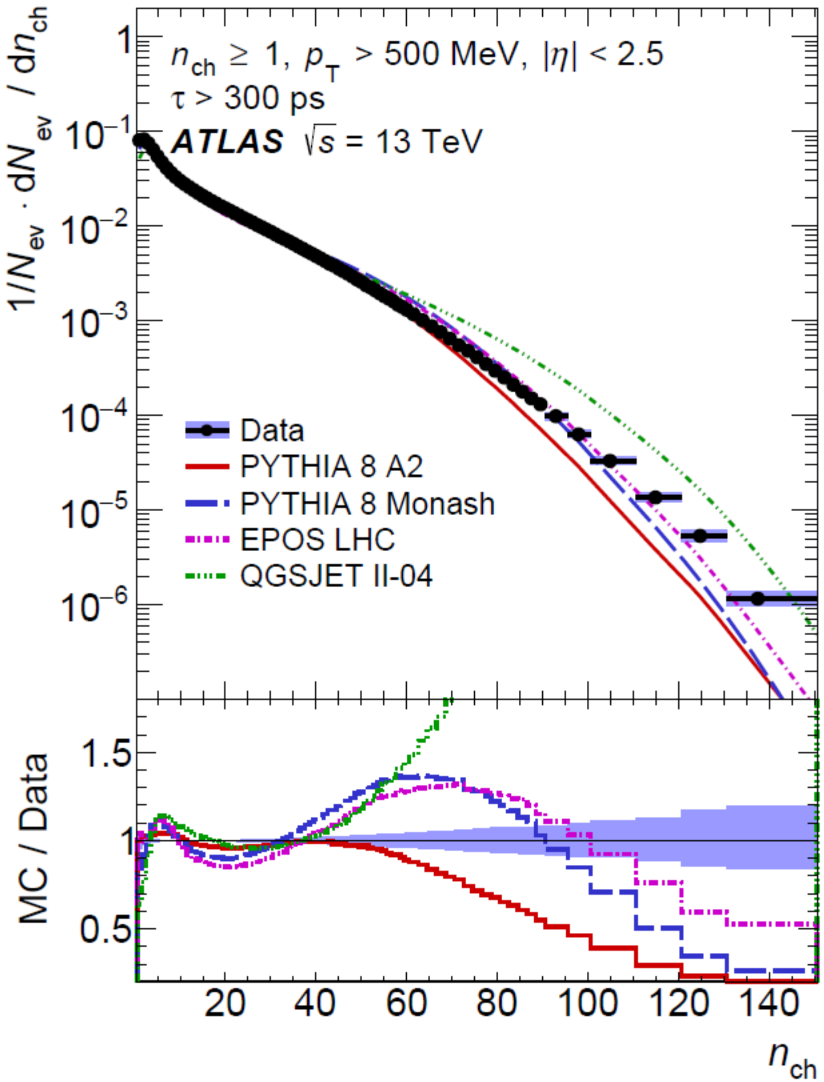
- ALICE measurement shows that $\langle p_T \rangle$ as a function of N_{ch} in isotropic events was found to be **smaller** than that measured in jet-like events, and that for jet-like events, the $\langle p_T \rangle$ is **over-estimated** by PYTHIA 6 and 8 models.

ALICE Collaboration, Eur. Phys. J. C 79 (2019) 857



Comparing to ATLAS measurement

ATLAS Collaboration, Phys. Lett. B 758 67-88 (2016)



- Early 2016 charged-particle distributions measured in proton-proton collisions at 13 TeV, using a data sample of nearly 9 million events (L ~170 μb^{-1})
- Selection: charged particles with $|\eta|$< 2.5 and p_T > 0.5 GeV
- Comparisons made to

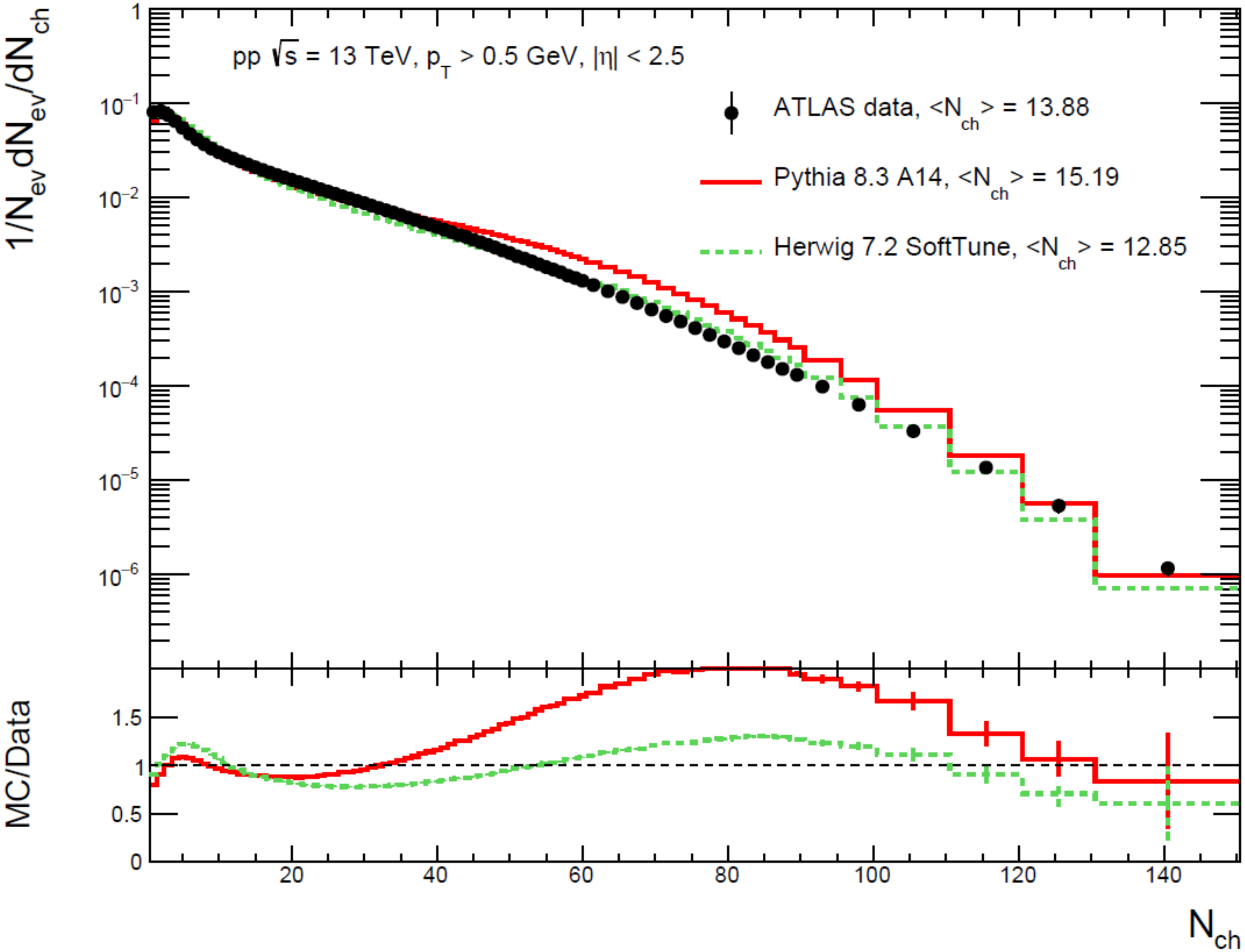
Pythia 8.185 (A2 tune)

Pythia 8.186 (Monash tune)

Epos (LHCv3400)

Our simulation comparison

- Data from ATLAS
- Simulation with latest Pythia 8.309 (A14 tune) and latest Herwig 7.2 (soft tune)



Our simulation comparison

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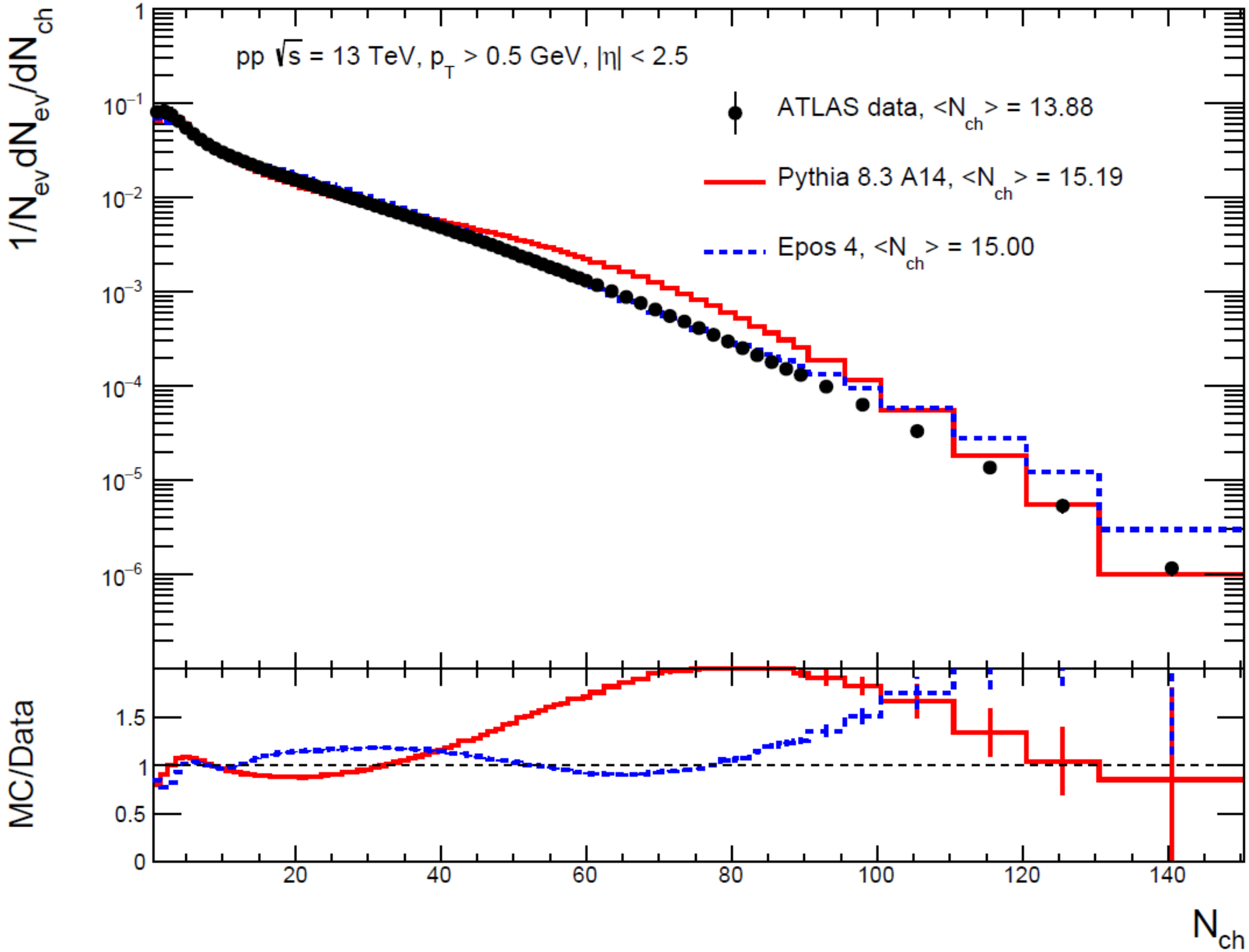

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- Both ALICE and ATLAS observed an **under-estimation** of isotropic events by MC generators at high charged multiplicity ($N_{ch} \geq 30$)

    ✓ Suggest that a very active underlying event (UE) is needed by the MC event generators in order to explain these high-multiplicity events

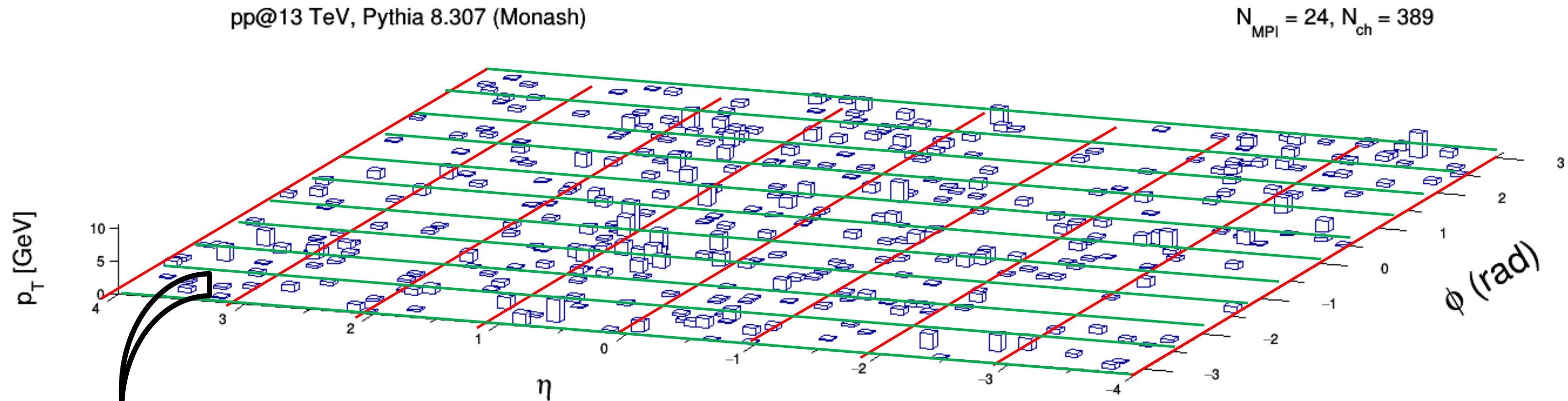
- ALICE measurement shows that $\langle p_T \rangle$ as a function of N_{ch} in isotropic events was found to be **smaller** than that measured in jet-like events, and that for jet-like events, the $\langle p_T \rangle$ is **over-estimated** by PYTHIA 6 and 8 models.

- Recently, a new event shape parameter, **flattenicity**, was proposed [A. Ortiz, G. Paic, Rev. Mex. Fis. Suppl. 3 (2022) 4, 040911] that allows one to identify and characterise high-multiplicity events with a quasi-isotropic distribution in a wide pseudorapidity range in proton-proton collisions.

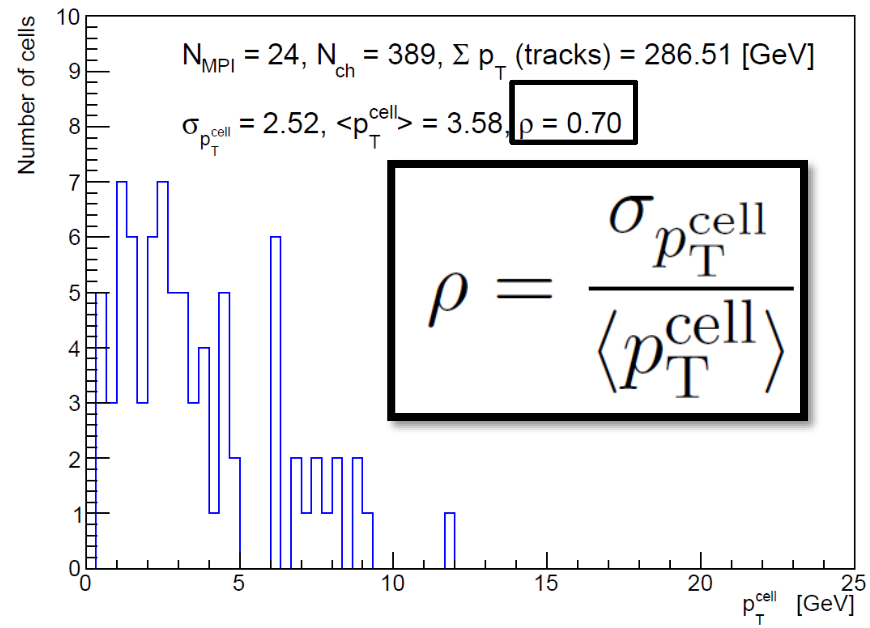
- MC event generators are able to model "hedgehog" events, which opens the possibility to study their properties and find a potential way to experimentally trigger these events.

Calculating flattenicity

- Build **8** x **10** grid in (η-φ) space:



In each cell, the average transverse momentum is calculated: $p_{\mathrm{T}}^{\mathrm{cell}}$



$$\rho = \frac{\sigma_{p_{\mathrm{T}}^{\mathrm{cell}}}}{\langle p_{\mathrm{T}}^{\mathrm{cell}} \rangle}$$

- Event-by-event, the relative standard deviation of the $p_{\mathrm{T}}^{\mathrm{cell}}$ distribution is obtained – flattenicity.

- Events with isotropic distribution of particles (“**hedgehogs**”) are expected to have **a small value of flattenicity** (ρ < 1).

Re-defining flattenicity

- Take the usual flattenicity definition: $$\rho = \frac{\sigma_{p_{\mathrm{T}}^{\mathrm{cell}}}}{\langle p_{\mathrm{T}}^{\mathrm{cell}} \rangle}$$

- Re-normalise (divide by an additional factor 1/sqrt(Ncell)) the value of ρ, such that it goes from 0 to 1.

- Plot flattenicity as (1 – ρ), so that events with values close to 1 are associated with the isotropic hedgehog topology.

- Build a larger grid of **10 cells** in η-space and **12 cells** in φ-space (120 in total):

    - allows the area of each cell ($\Delta\eta = 0.50$, $\Delta\varphi \sim 0.52$) to be closely related to a jet area defined with $\Delta R = 0.4$.

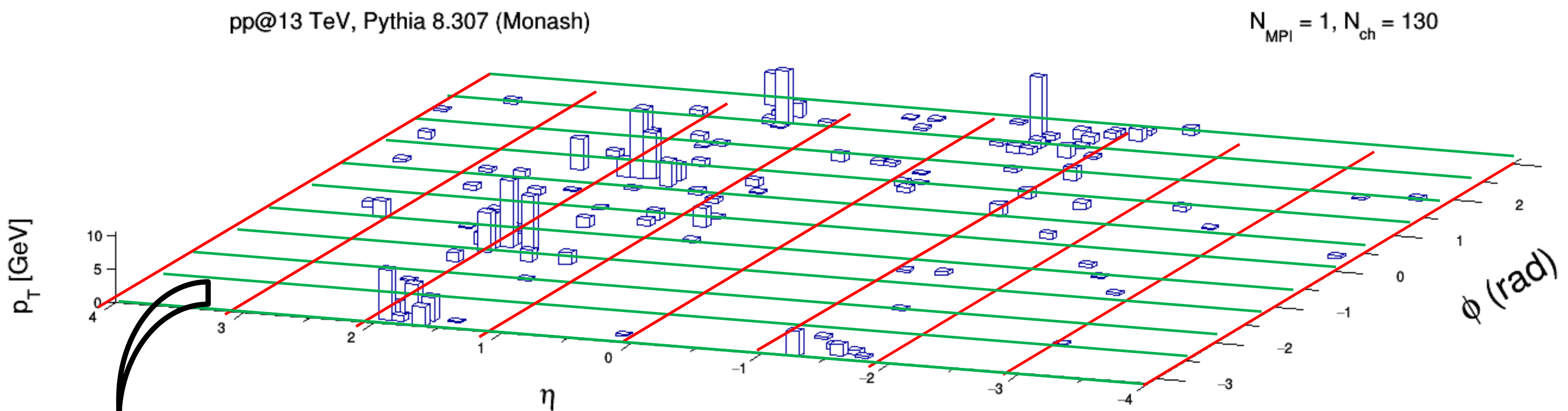
- Selection of charged particles as in ATLAS (and CMS): $|\eta| < 2.5$ and $p_T > 0.5$ GeV.

- Require at least 10 charged particles in this phase-space:

    - in order to further compare other event shape variables

Calculating flattenicity

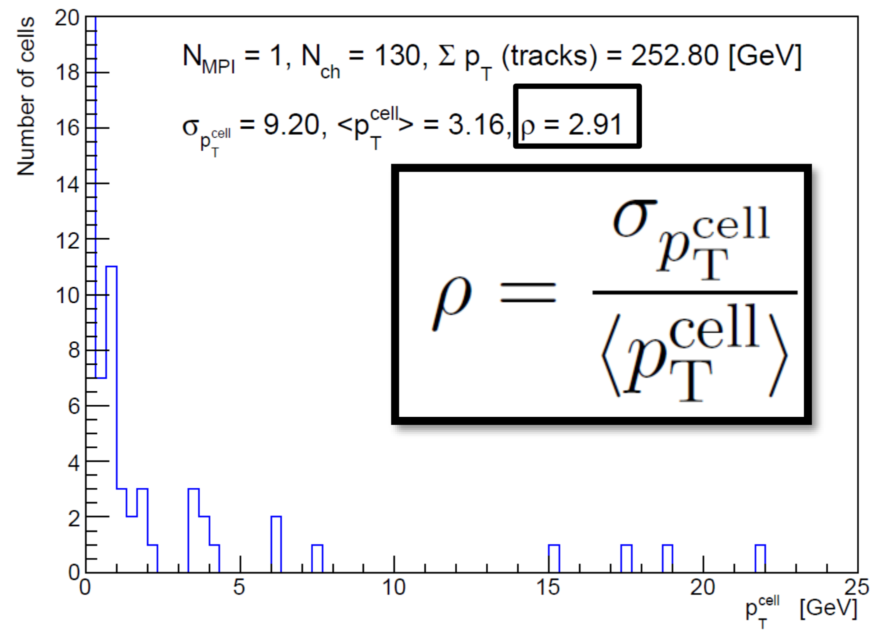
- Build 8 x 10 grid in (η-φ) space:



In each cell, the average transverse momentum is calculated: $p_{\mathrm{T}}^{\mathrm{cell}}$

- Event-by-event, the relative standard deviation of the $p_{\mathrm{T}}^{\mathrm{cell}}$ distribution is obtained – flattenicity.

- Events with **jet-like** structures are expected to have **larger values** of ρ.



$$\rho = \frac{\sigma_{p_{\mathrm{T}}^{\mathrm{cell}}}}{\langle p_{\mathrm{T}}^{\mathrm{cell}} \rangle}$$

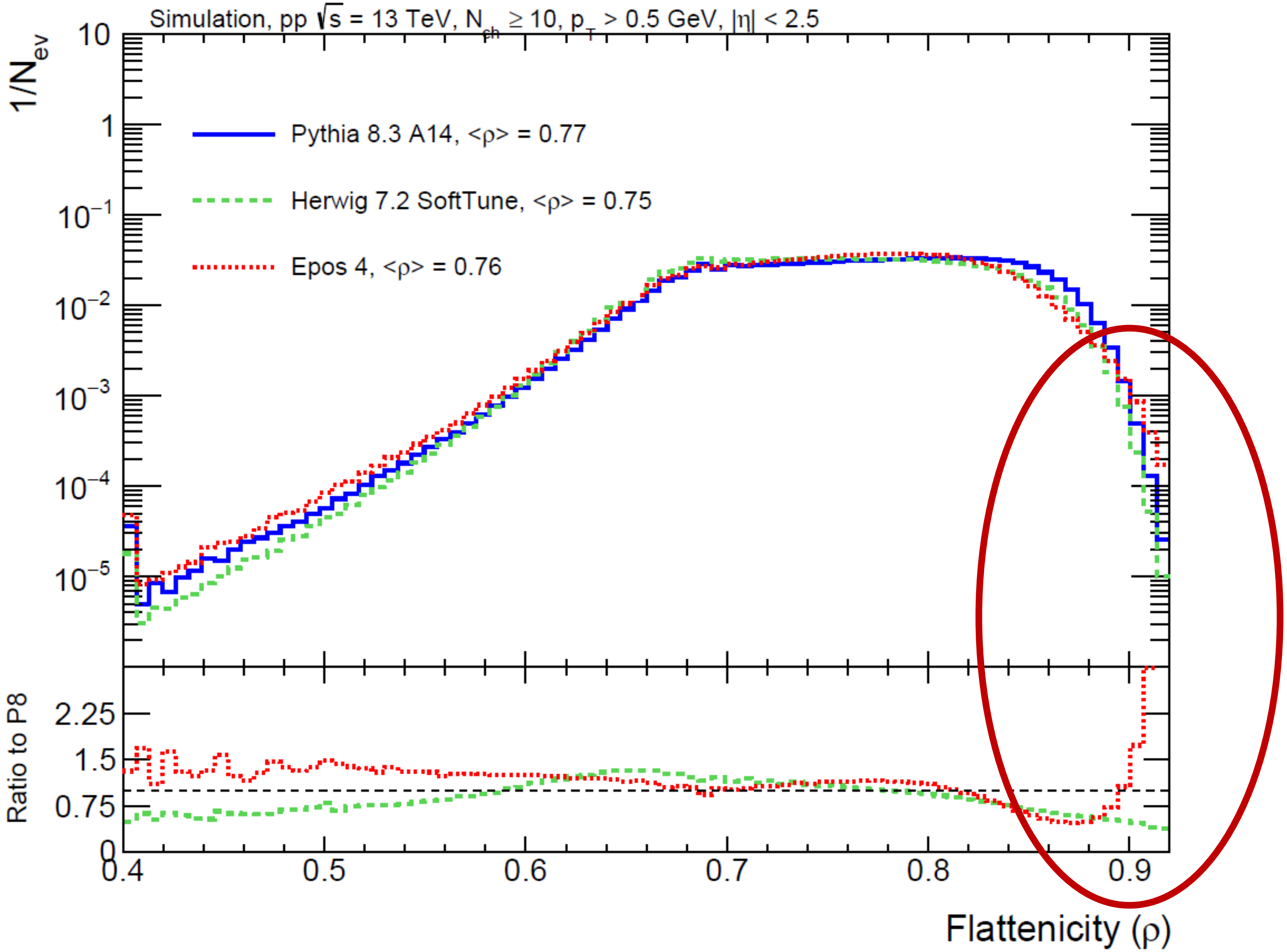
Calculating flattenicity

- Flattenicity: $$\rho = 1 - \frac{\sqrt{\sum_i \left(p_T^{cell,i} - < p_T^{cell} >\right)^2 / N_{cell}^2}}{< p_T^{cell} >}$$

- By using this definition, the values of ρ go from 0 to 1 (as other event shapes).
- Events with **values close to 1** are associated with the **hedgehog** topologies.
- Events with **jet-like** structures are expected to have **smaller values** of ρ.
- A total of 120 cells (stability of flattenicity against variations in the size of the cells was studies anf found consistent within a few percent) allows the area of each cell ($\Delta\eta = 0.50$, $\Delta\varphi \sim 0.52$) to be closely related to a jet area defined with $\Delta R = 0.4$.

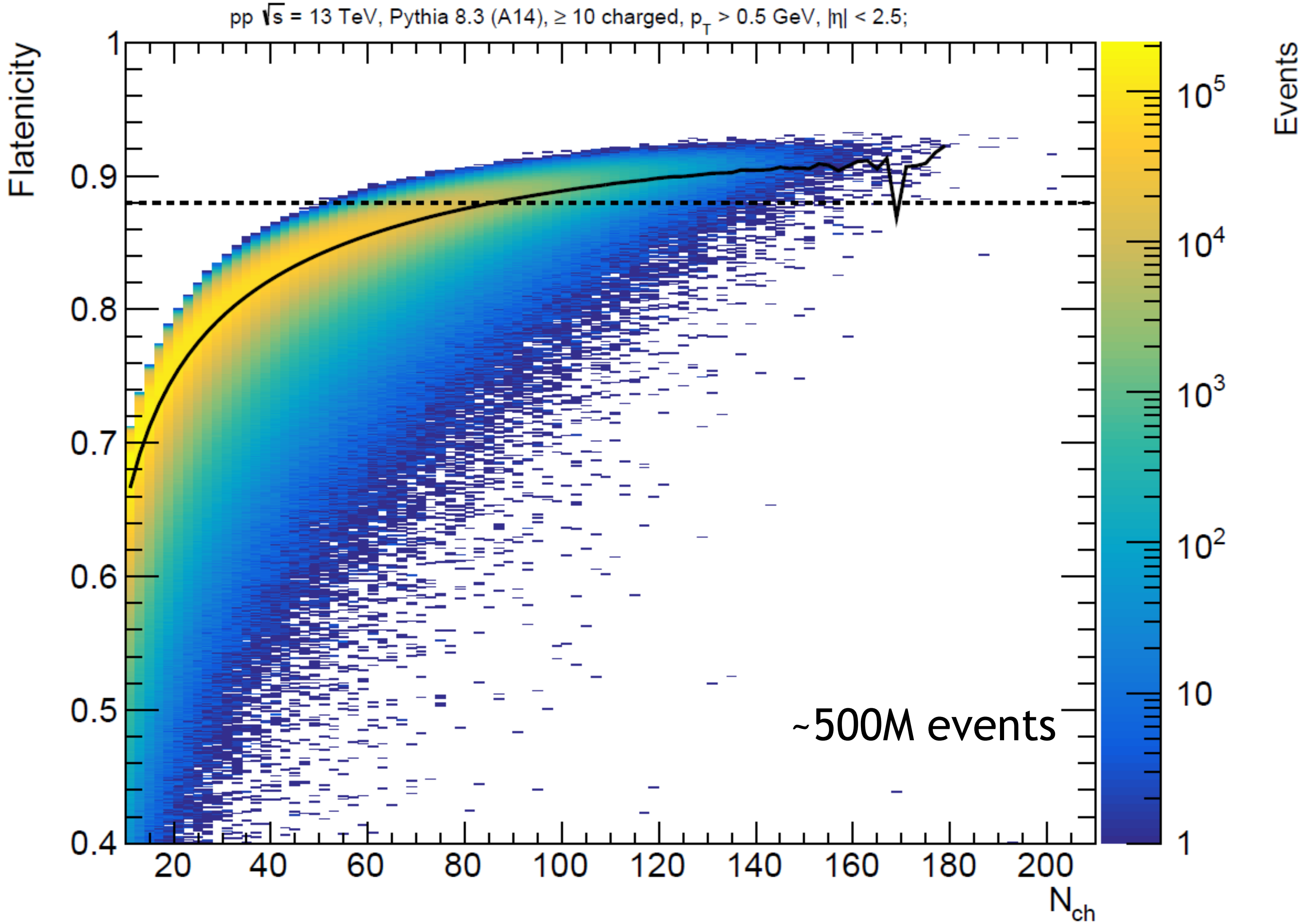
Comparing flattenicity in different MC generators

- Using samples of 25 million events for each MC generator



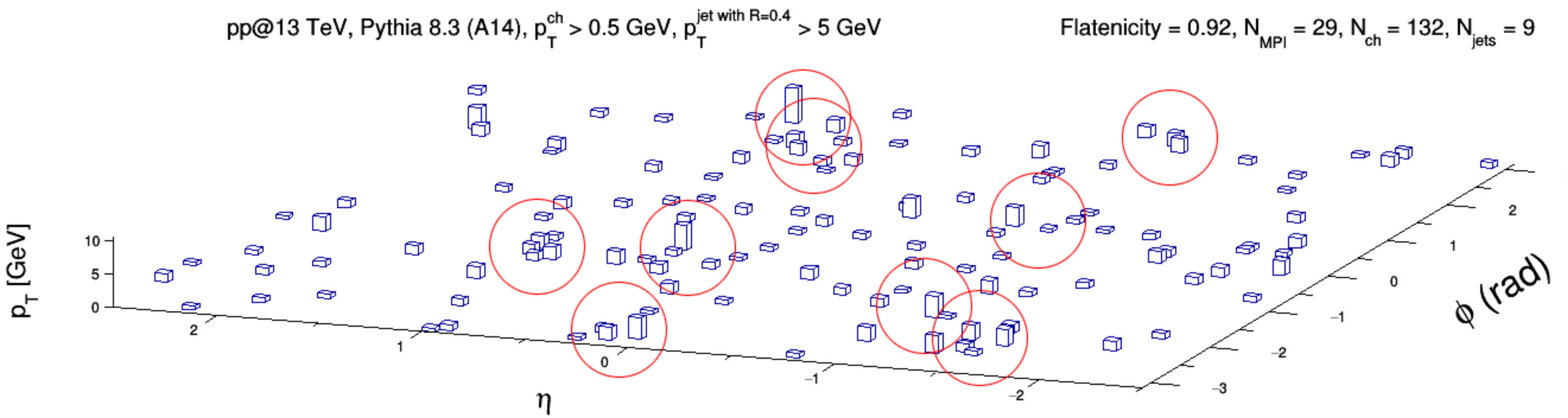
Analysing flattenicity vs N_{ch}

- We can select the 0 – 1% percentile event class based on the flattenicity value of ρ > 0.88, denoted with dashed line in the N(charged) vs ρ map:

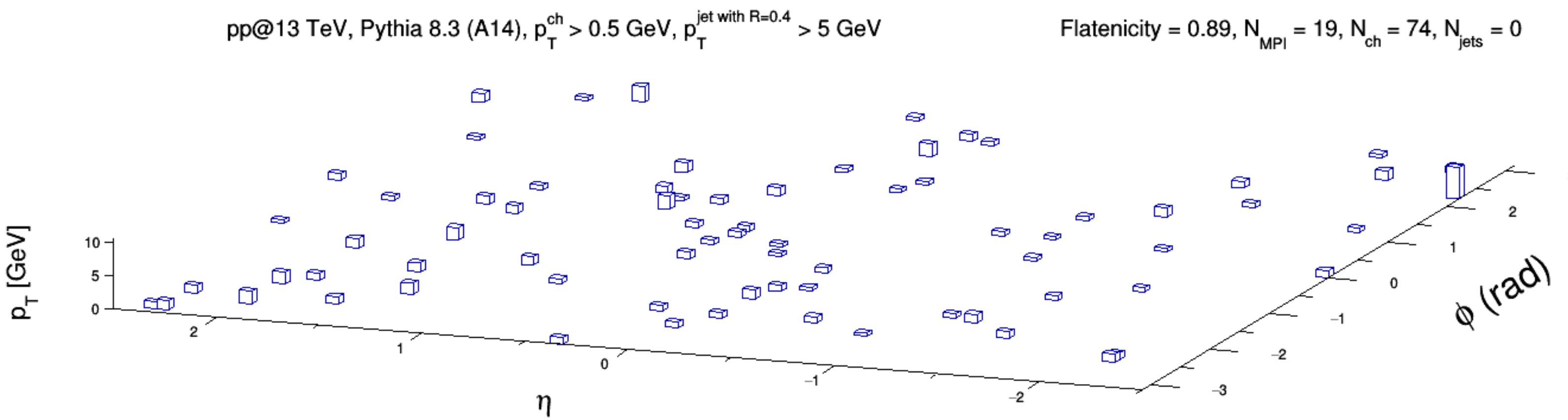


Analysing flattenicity vs N_{ch}

- With the **0 - 1% flattenicity percentile selection**, we can clearly see **hedgehogs:**
  - with high N(charged) and jet production:



  - with lower N(charged) and **no jet production:**

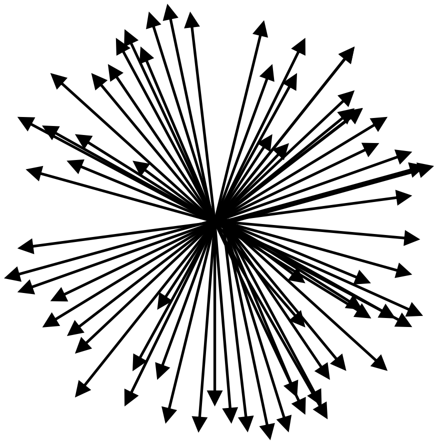


Event shape variables

- The basic idea of the event shape variables is to give more information by defining the "shape" of an event (pencil-like, planar, spherical etc.) [arXiv:1001.4082v1 [hep-ph], arXiv:2206.13431 [hep-ph]]
- Event shape variables describe the patterns and correlations of energy flow resulting from the particle collisions.
- Additional global information is obtained from the full momentum tensor M of the event via its eigenvalues, where i,j are the spatial indices and the sum runs over all particles.

$$M_{ij} = \frac{\sum_{a=1}^{n_j} p_{ia} p_{ja}}{\sum_{a=1}^{n_j} |\vec{p}_a|^2},$$

- The ordered eigenvalues λ_i ($\lambda_1 > \lambda_2 > \lambda_3$) with the normalisation condition ($\lambda_1+\lambda_2+\lambda_3=1$) define different event shapes.



Event shape variables

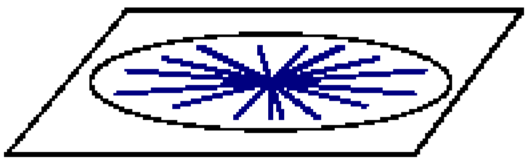
- Sphericity, defined as: $S = \frac{3}{2}(\lambda_2 + \lambda_3), 0 \leq S \leq 1$

describes the three dimensional distribution by an expression involving the eigenvectors defining the three axes of a spheroid representing the energy flow of the scattered particles.

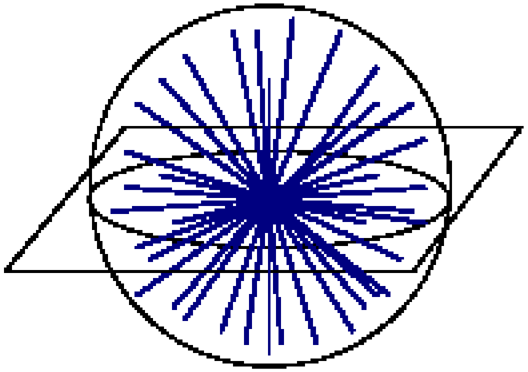
- Aplanarity, defined as $A = \frac{3}{2}\lambda_3, 0 \leq A \leq \frac{1}{2}$

describes the energy flow out of the shpericity event plane, i.e. it is a mesure of p_T out of plane

S=A=0



S=3/4 A=0



S=1 A=1/2

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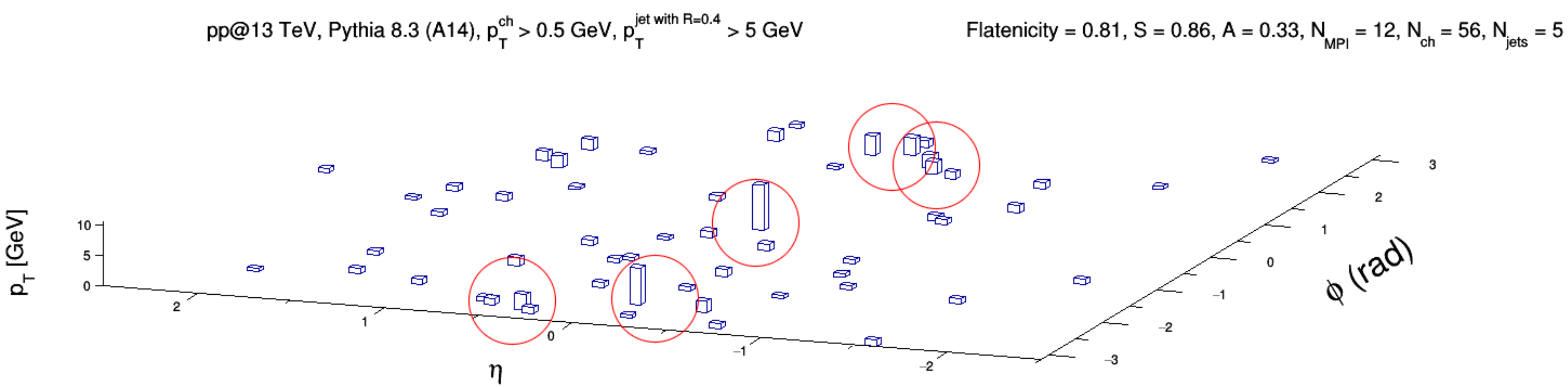
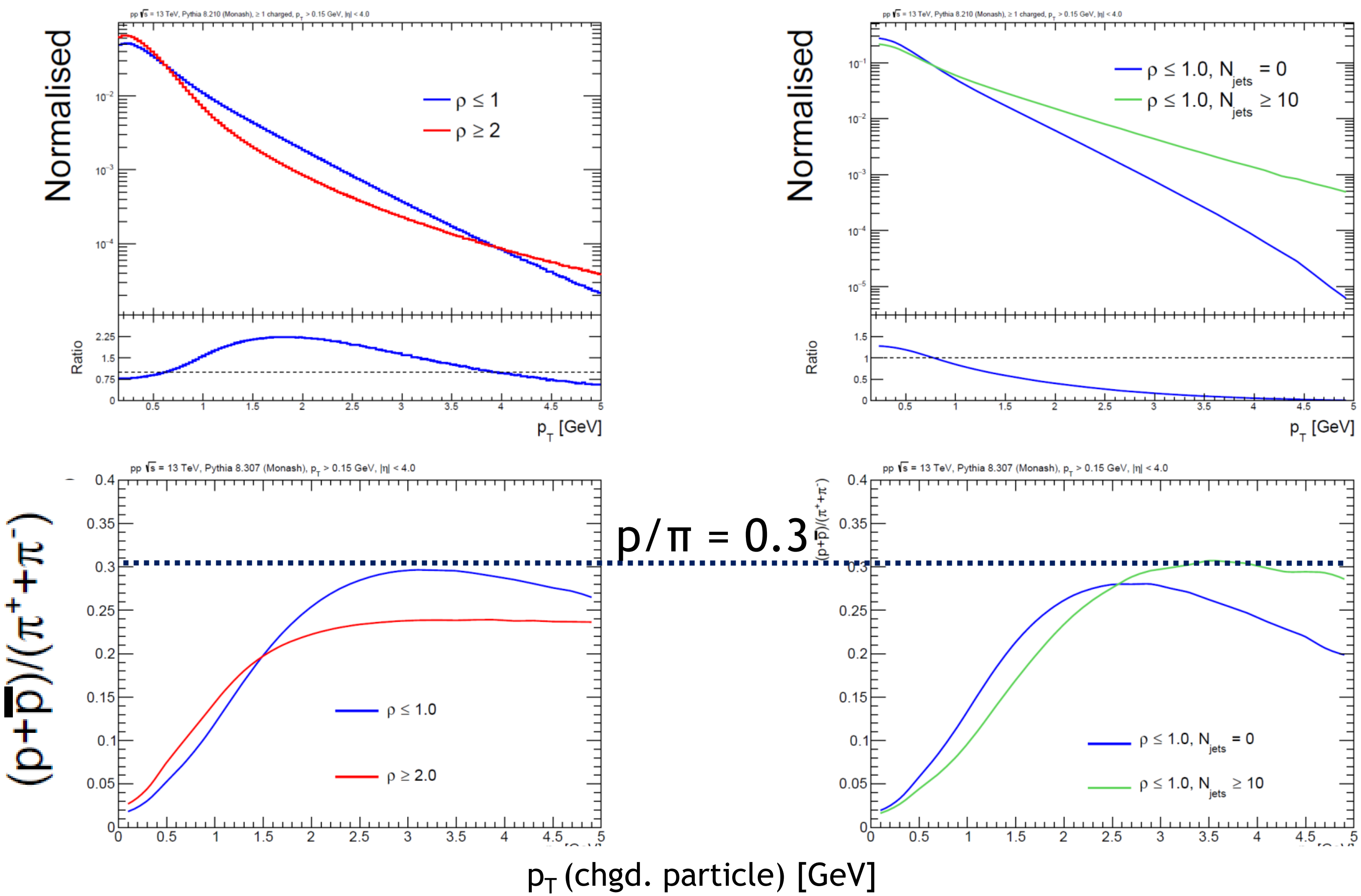


ρ=0.81, S=0.86, A=0.33

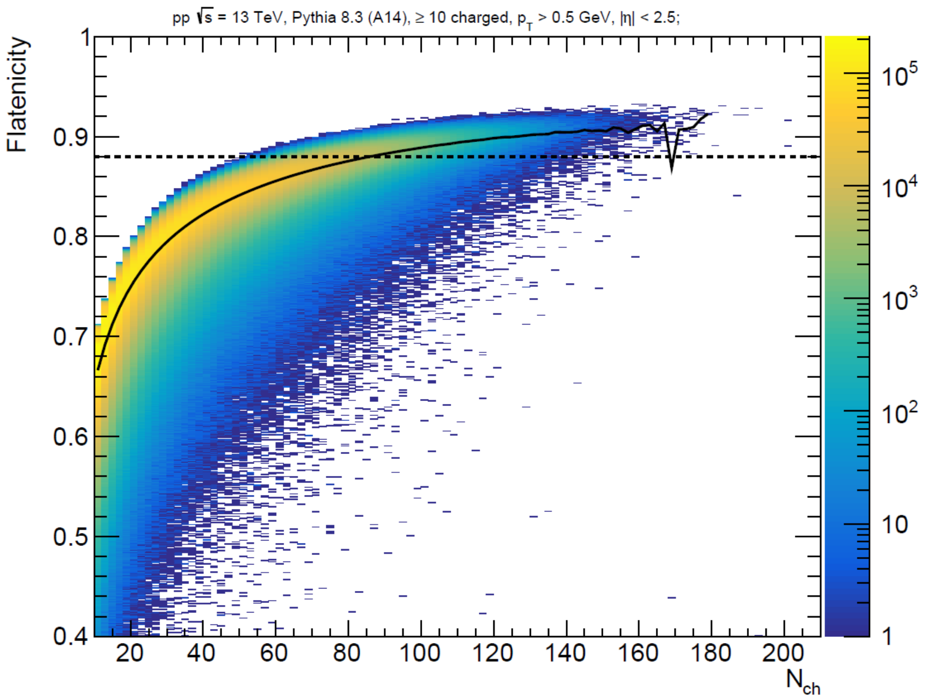
Analysing flattenicity vs chgd. particle p_T and p/π ratio

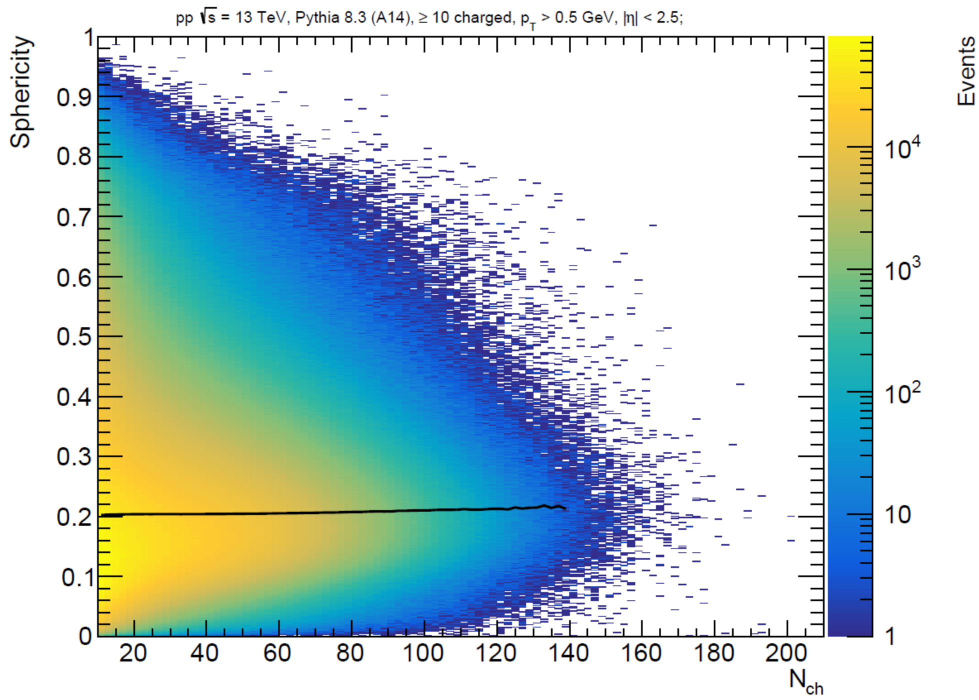
- We study the p_T (particle) as well as the proton-to-pion ratio in 0.15 to 5 GeV interval by selecting events with $\rho < 1$ and $\rho > 2$. For events with $\rho < 1$, we also select jetty events (≥10 jets with min p_T(jet) = 5 GeV) and events with no jets at all.



Flattenicity and sphericity vs N_{ch}

- We can see a completely different behaviour in flattenicity and sphericity wrt to the charge particle multiplicity





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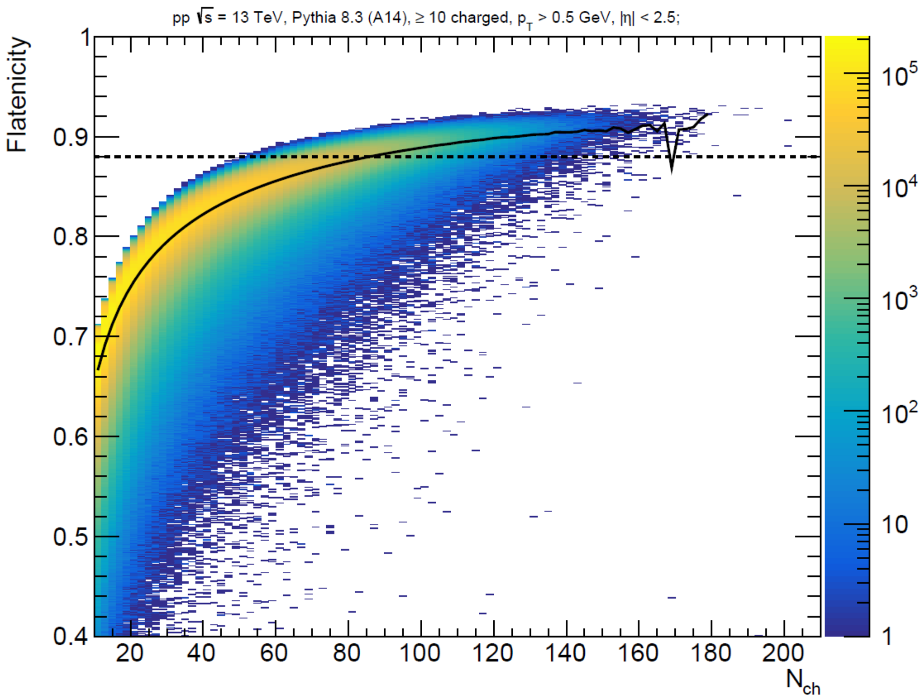
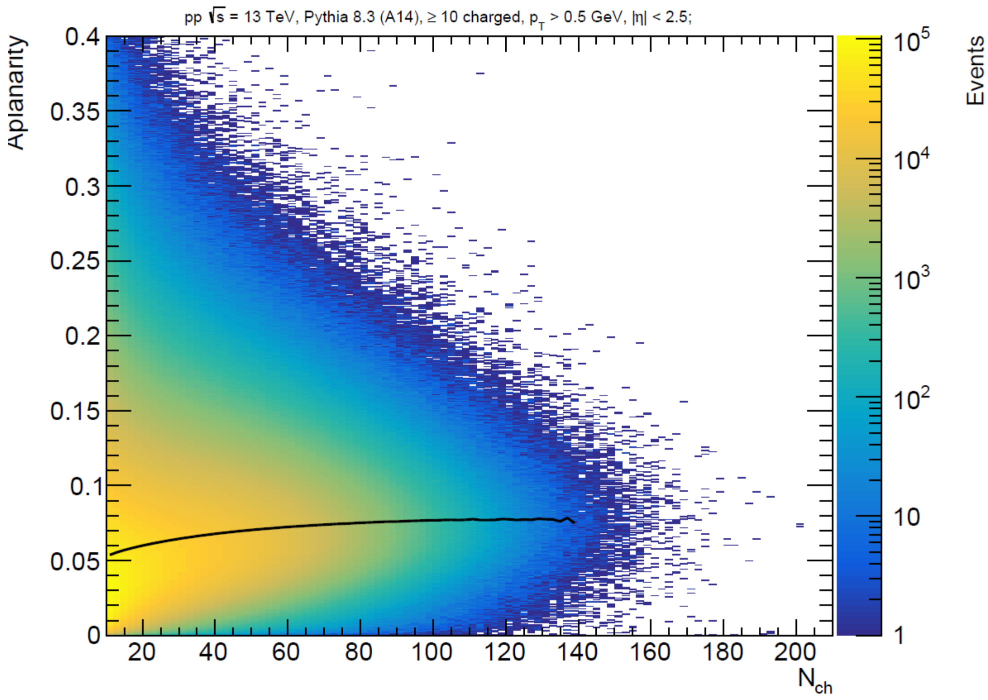
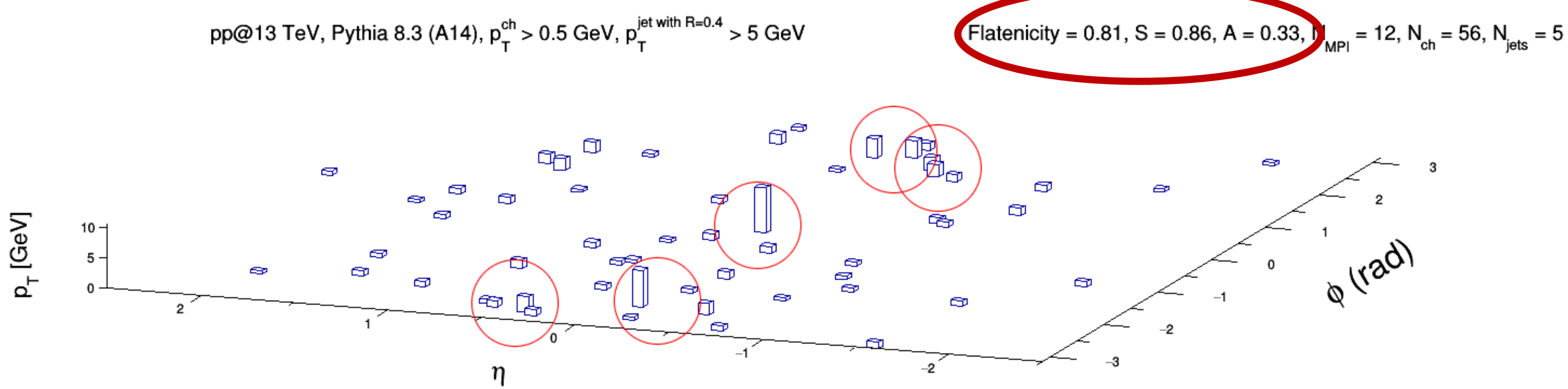


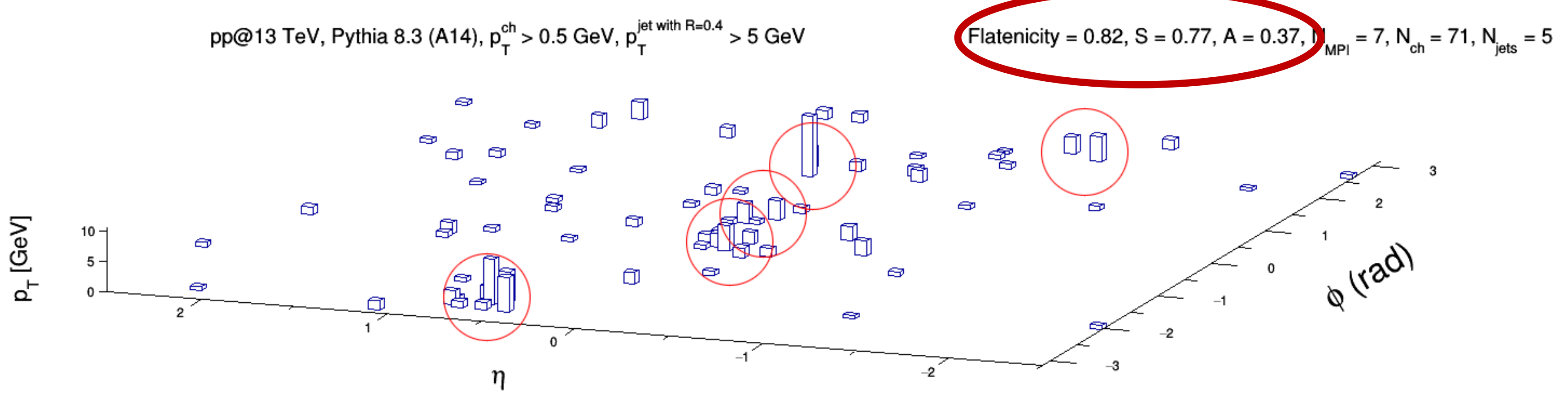


Spherical and aplanar events

Fully spherical (S > 0.85) events

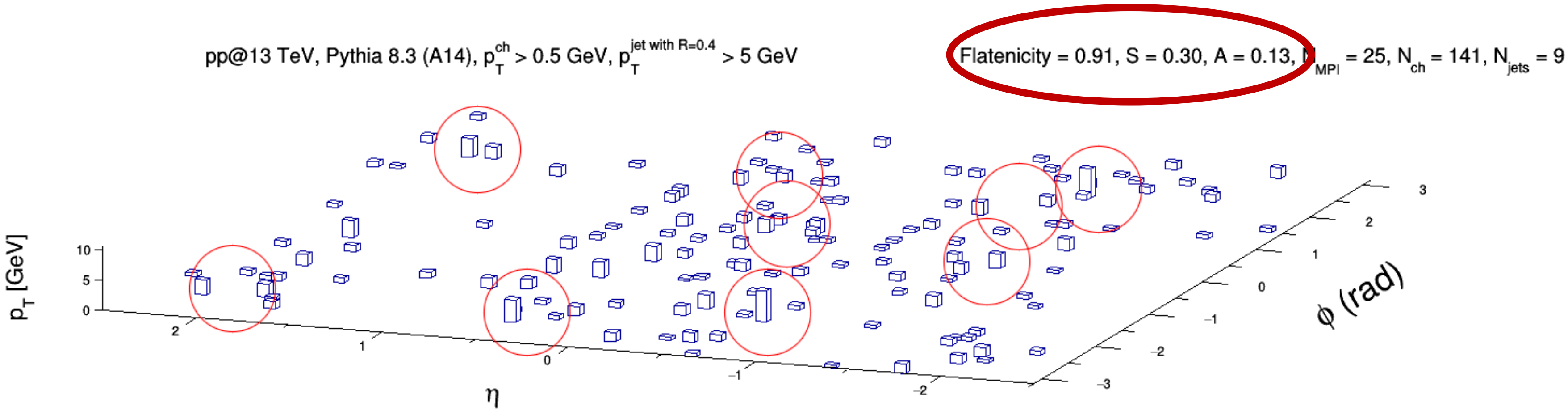


Fully aplanar (A > 0.30) events

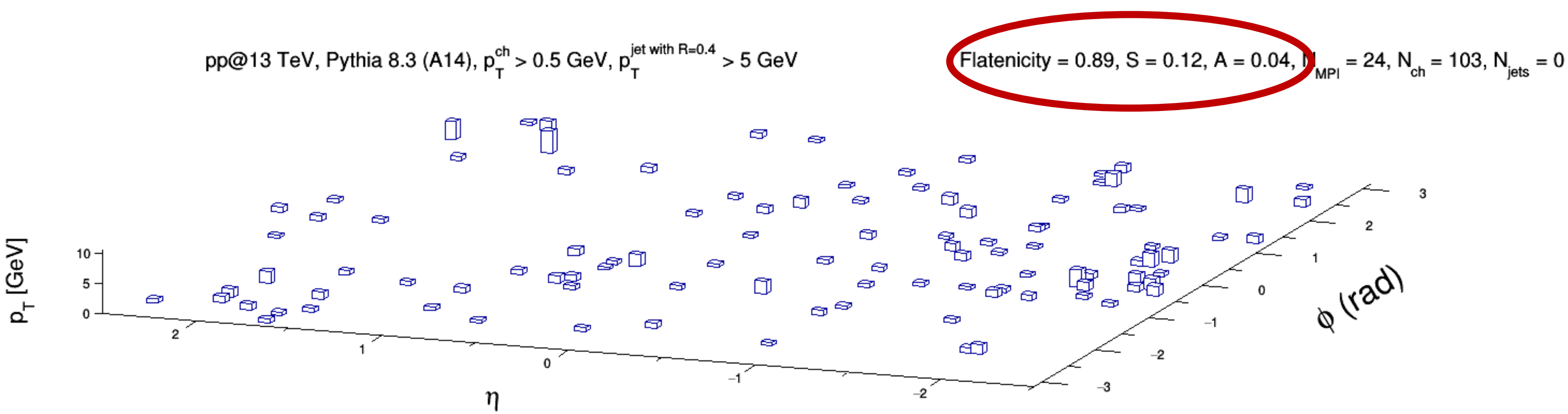


Hedgehog events

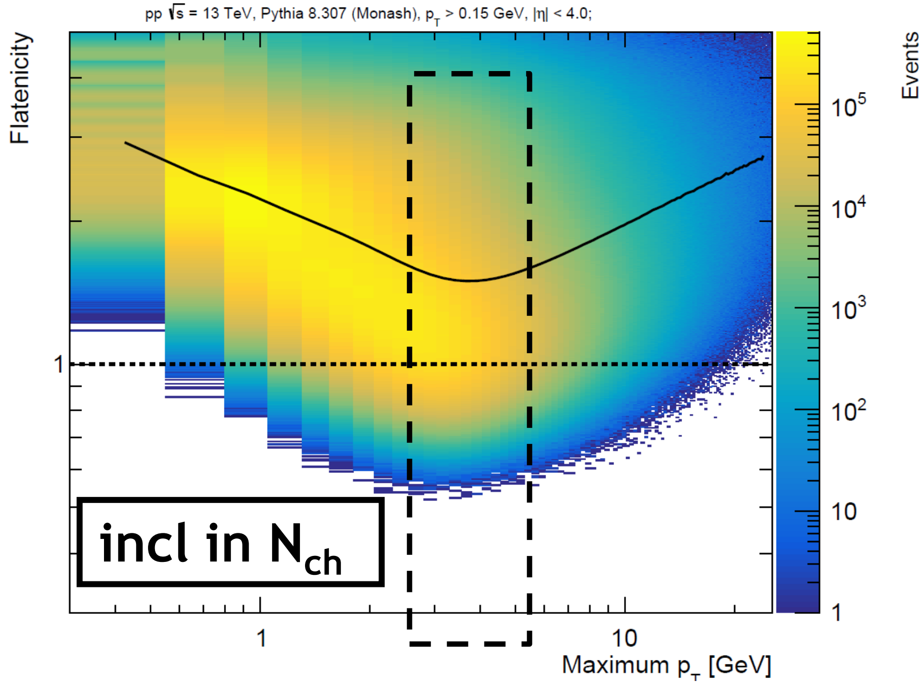
ρ > 0.88 and Nch > 140



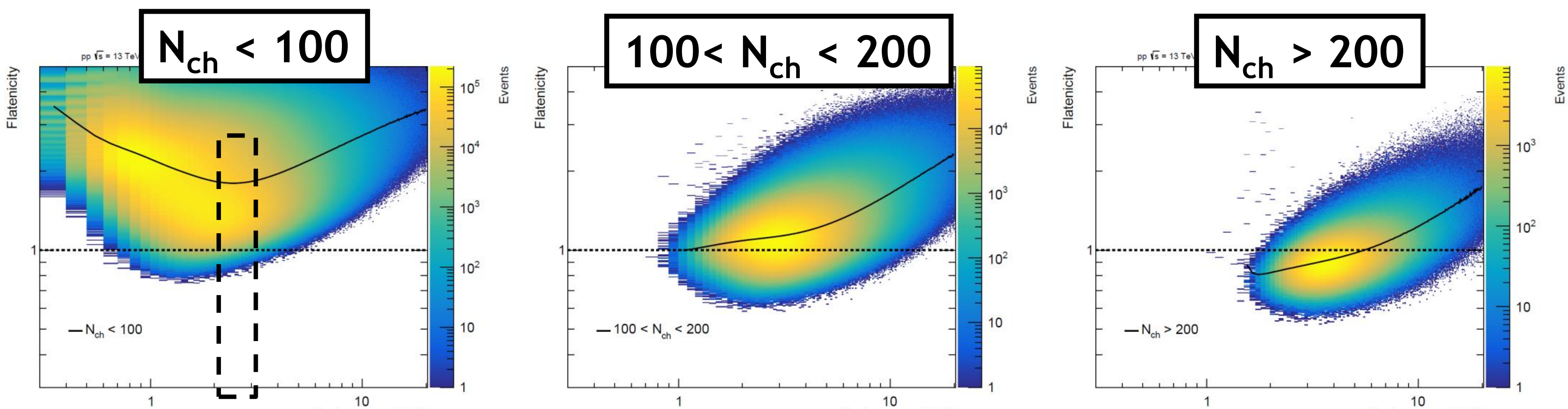
ρ > 0.88 and Nch > 100 and no jets



Analysing flattenicity vs leading chgd. particle p_T



- Leading charged particle p_T shows a prominent feature: <ρ> has a dip around 3-5 GeV, while events with lower multiplicity show a dip at lower values (~ 2-3 GeV)
- At higher N_{ch}, <ρ> shows a trend towards higher p_T values
- A step towards studying the underlying event by using the leading particle p_T



Leading p_T (chgd. particle) [GeV]

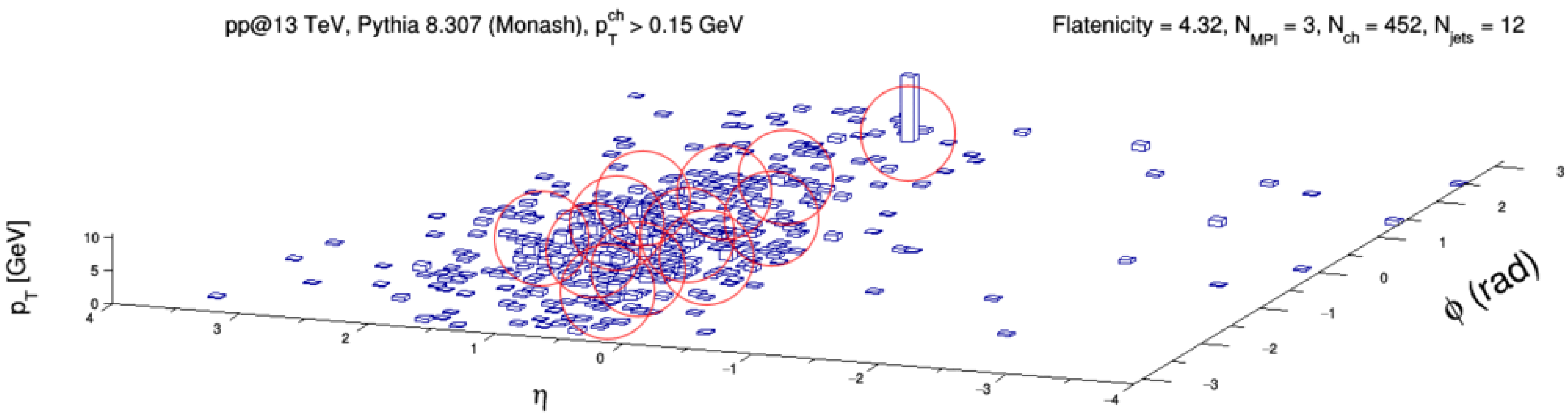
conclusion

- We found a region that has never been truly studied
- plenty of possibilities to study these events and it even may shed light on the “energy re-distribution” effect in pp collisions.

BACK-UP

Analysing very atypical events

- Flattenicity allows one to find quite atypical (and rare 1/100M) events:
    - i.e. high chgd. multiplicities (>300) and low number of hard-scatterings (MPI=3)



- In some events we see one very high p_T charged particle (around which a jet is usually build, and particle p_T divided by jet p_T approaches unity!) .
- Recoil jets are usually produced opposite in φ, and fragment into several particles.
- Nor the partonic hard-scattering p_T , nor the additional multiparton interactions p_T are high enough nor match the reconstructed energy for these events.
- Are we looking at the limit of fragmentation and/or ISR/FSR emissions?
- We are identifying an experimental way to find these events, and it would be a perfect place to study data and tune our generators!

- Hedgehog events have never been seriously studied in pp collisions at the LHC. These events are "rare" – but as rare as a Z-boson production!

Selection	Probability
$\rho < 1$	4×10^{-2}
$\rho < 0.75$, $N_{ch} > 100$, $N_{jets}=0$	2×10^{-6}
$\rho < 0.75$, $N_{ch} > 400$	6×10^{-8}

- Flattenicity - the new event structure parameter - allows one to identify the hedgehog events and is more detailed than sphericity/spherocity/RT, as one can observe the evolution of events from jetty to hedgehog type.

- We are able to identify different classes of hedgehog events: those with high jet multiplicity (jetty) and with no jet production.

- Events with low flattenicity show an enhancement in the proton-to-pion ratio compared to those with high flattenicity.

- Studying these events may shed light to the search for the "energy re-distribution" effect in pp collisions.

- Next step: look for hedgehog events in data!

Transverse sphericity

A. Ortiz, arXiv:1110.2278 [hep-ex]

sphericity is measured in the acceptance $|\eta| \leq 0.8$, for events with more than two tracks ($p_T \geq 0.5$ GeV/c). The observable is defined as follows:

$$S_T \equiv \frac{2\lambda_2}{\lambda_2 + \lambda_1} \tag{1}$$

where: $\lambda_1 > \lambda_2$ are the eigenvalues of the transverse momentum matrix:

$$\mathbf{S}^{\mathbf{L}}_{\mathbf{xy}} = \frac{1}{\sum_i p_{Ti}} \sum_i \frac{1}{p_{Ti}} \begin{pmatrix} {p_{xi}}^2 & p_{xi}p_{yi} \\ p_{xi}p_{yi} & {p_{yi}}^2 \end{pmatrix}$$

By construction, the limits of the variable are related to specific configurations in the transverse plane

$$S_T = \left(\begin{cases} = 0 & \text{"pencil-like" limit} \\ = 1 & \text{"isotropic" limit} \end{cases} \right. .$$

Analysing flattenicity vs N_{jets}