Measurement of the azimuthal anisotropy of muons from heavy-flavour decays in *p*+Pb collisions

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ATLAS EXPERIMENT

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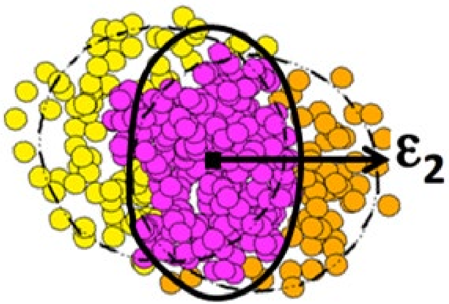
Quark-gluon plasma in *p*+A collisions

- In heavy-ion collisions, quark-gluon plasma (QGP) is formed, which expands hydrodynamically.
- Moments of deformation in the initial geometry are transferred to azimuthal anisotropy of final particle distributions.
- Strong evidence demonstrates that in ultra-relativistic proton+ion (*p*+A) collisions, a tiny droplet of QGP is also formed.
- Our goal is to study azimuthal anisotropy of heavy flavour particles in *p*+A collisions.
- We use *p*+Pb data collected by ATLAS at 8.16 TeV (L_{int} = 171 nb^{-1}).



Initial geometry

Hydrodynamic expansion

$$\frac{dN}{d\phi} = \frac{N_0}{2\pi}\left(1 + 2\sum_n v_n \cos\left(n\phi - n\Psi_n\right)\right)$$

Final particle distributions

Anisotropic flow (v_n) from heavy flavour decay

- Prior measurements demonstrate significant azimuthal anisotropy of inclusive and light hadrons in *p*+A collisions.

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Anisotropic flow (v_n) from heavy flavour decay

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- Why do we study the azimuthal anisotropy from heavy-flavour decay?
  - Heavy quarks (charm and bottom) are produced at earlier times in *p*+A collisions.
  - The mass of the heavy quarks are larger than the temperature of the QGP, so they may not be fully thermalized.
    - m_{charm} = 1.28 GeV, m_{bottom} = 4.18 GeV
    - T_{QGP} = 200-500 MeV
  - Measurements can determine if heavy quarks couple strongly or weakly to the QGP.
    - Are the QGP dynamics in p+A similar to that in A+A collisions?
- Measure heavy flavour azimuthal anisotropy via semileptonic decays to muons.
  - Muons can also be created from pion and kaon decays: "background" that needs to be removed.

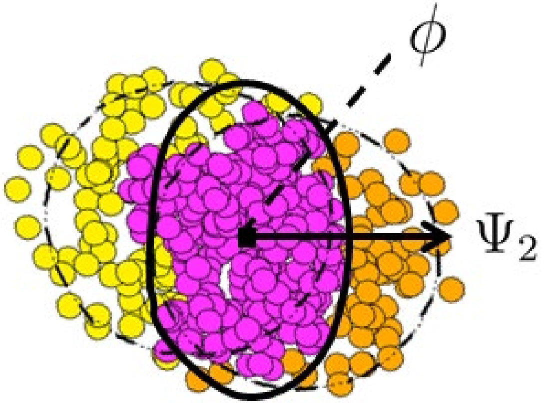
Event-plane method

- v_2 measurements are performed using the "event-plane" method:
    - The azimuthal angle of particles are correlated with the event-plane angle.
    - After summing over many events, this is then fit to a cosine function

$$\frac{d\mathrm{N}}{d\phi} = \frac{\mathrm{N}_0}{2\pi}\left(1 + 2\sum_n v_n \cos\left(n\phi - n\Psi_n\right)\right)$$

Azimuthal angle of the muon

Event-plane angle, obtained using Pb-going side FCal



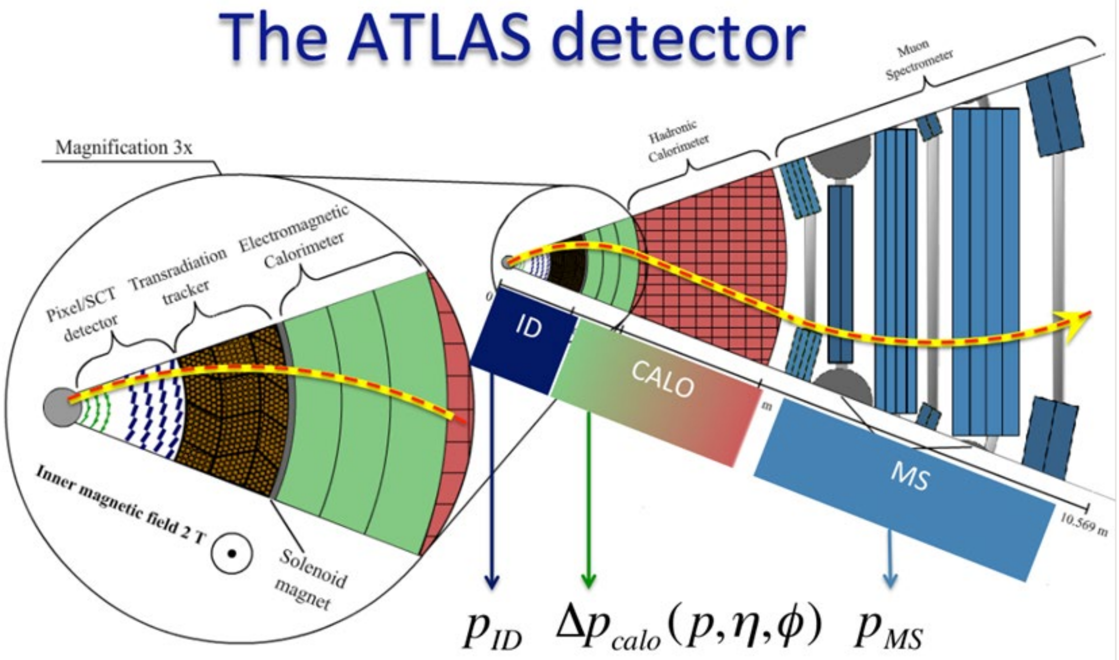
- In this analysis, we investigate the n = 2 harmonic (elliptic flow).

Momentum imbalance (Δ*p*/*p*)

Momentum imbalance describes the mismatch of momentum as measured in the inner detector (ID) and muon spectrometer (MS) after accounting for energy loss in the calorimeter.

We use this to separate the signal and background muons.

- Distribution of signal muons: Gaussian centered at zero.
- Distribution of background muons: Gaussian with a positive mean.

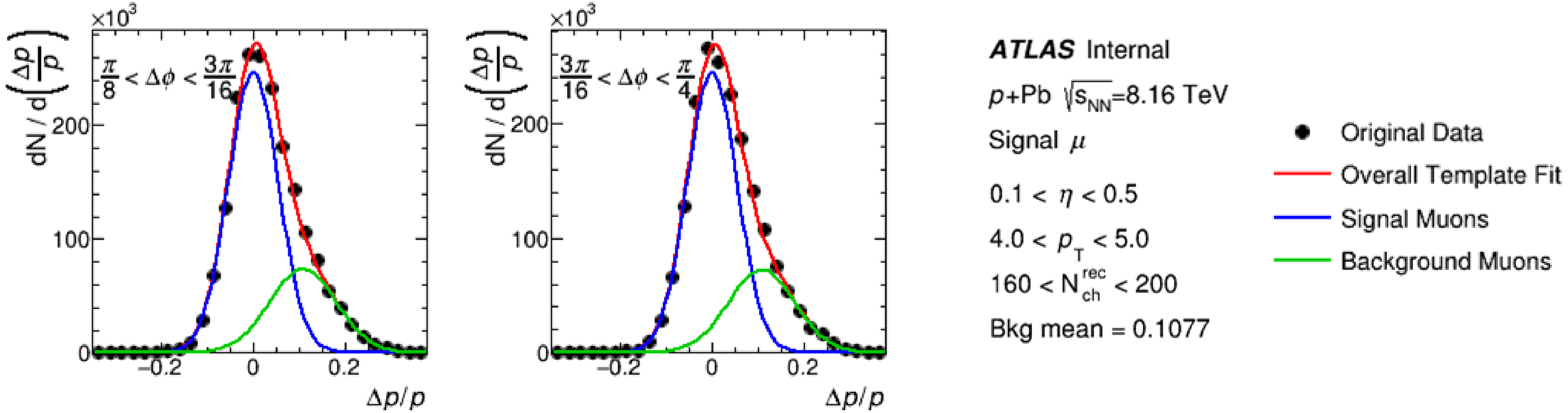


$$\frac{\Delta p}{p_{ID}} = \frac{p_{ID} - p_{MS} - \Delta p_{calo}(p,\eta,\phi)}{p_{ID}}$$

Two methods of obtaining Δφ distributions

Define Δφ as $2(\phi - \Psi_2)$, which is the correlation between the azimuthal angle and event-plane angle.

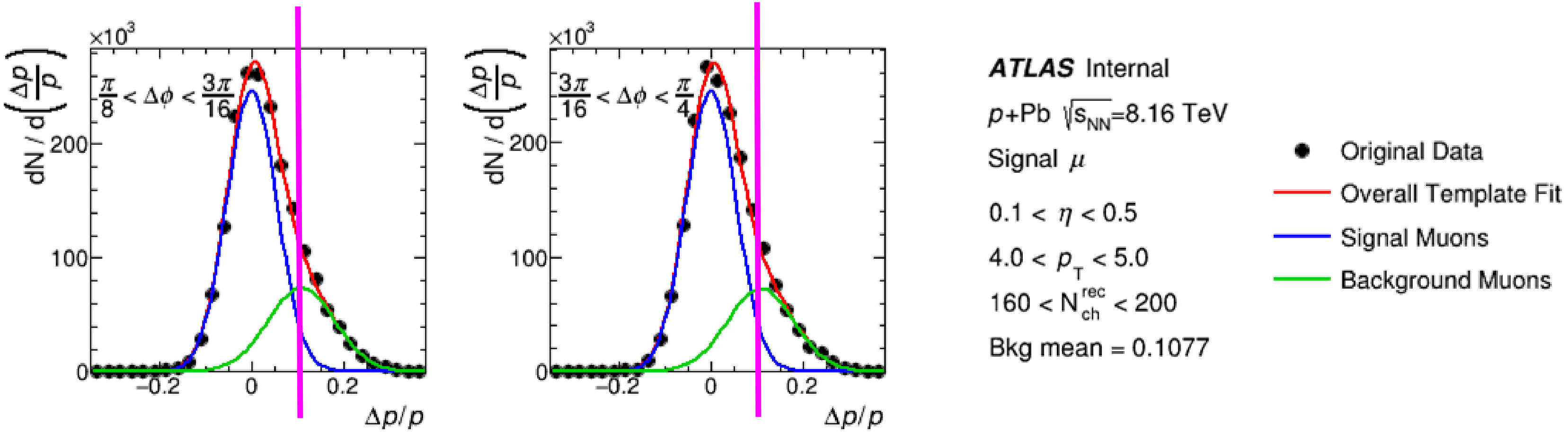
1. Template-fit method
   - Assume Δ*p*/*p* distribution is a double Gaussian
   - Signal muons: Gaussian centered at Δ*p*/*p* = 0
   - Background muons: Gaussian centered at positive Δ*p*/*p*
2. Cut-based method



Two methods of obtaining Δ*φ* distributions

Define Δ*φ* as $2(\phi - \Psi_2)$, which is the correlation between the azimuthal angle and event-plane angle.

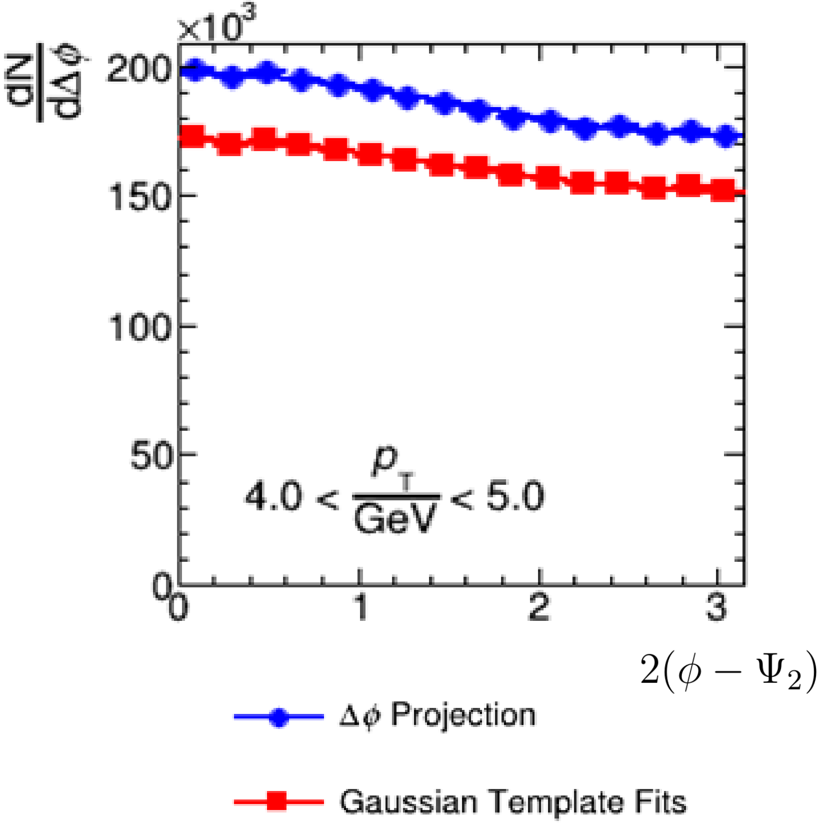
1. Template-fit method
   - Assume Δ*p*/*p* distribution is a double Gaussian
   - Signal muons: Gaussian centered at Δ*p*/*p* = 0
   - Background muons: Gaussian centered at positive Δ*p*/*p*
2. Cut-based method
   - Signal muons: -0.3 < Δ*p*/*p* < 0.1
   - Background muons: 0.15 < Δ*p*/*p* < 1.0



Obtaining v_2 from $\Delta\varphi$ distributions

ATLAS Internal
p+Pb $\sqrt{s_{NN}}$=8.16 TeV

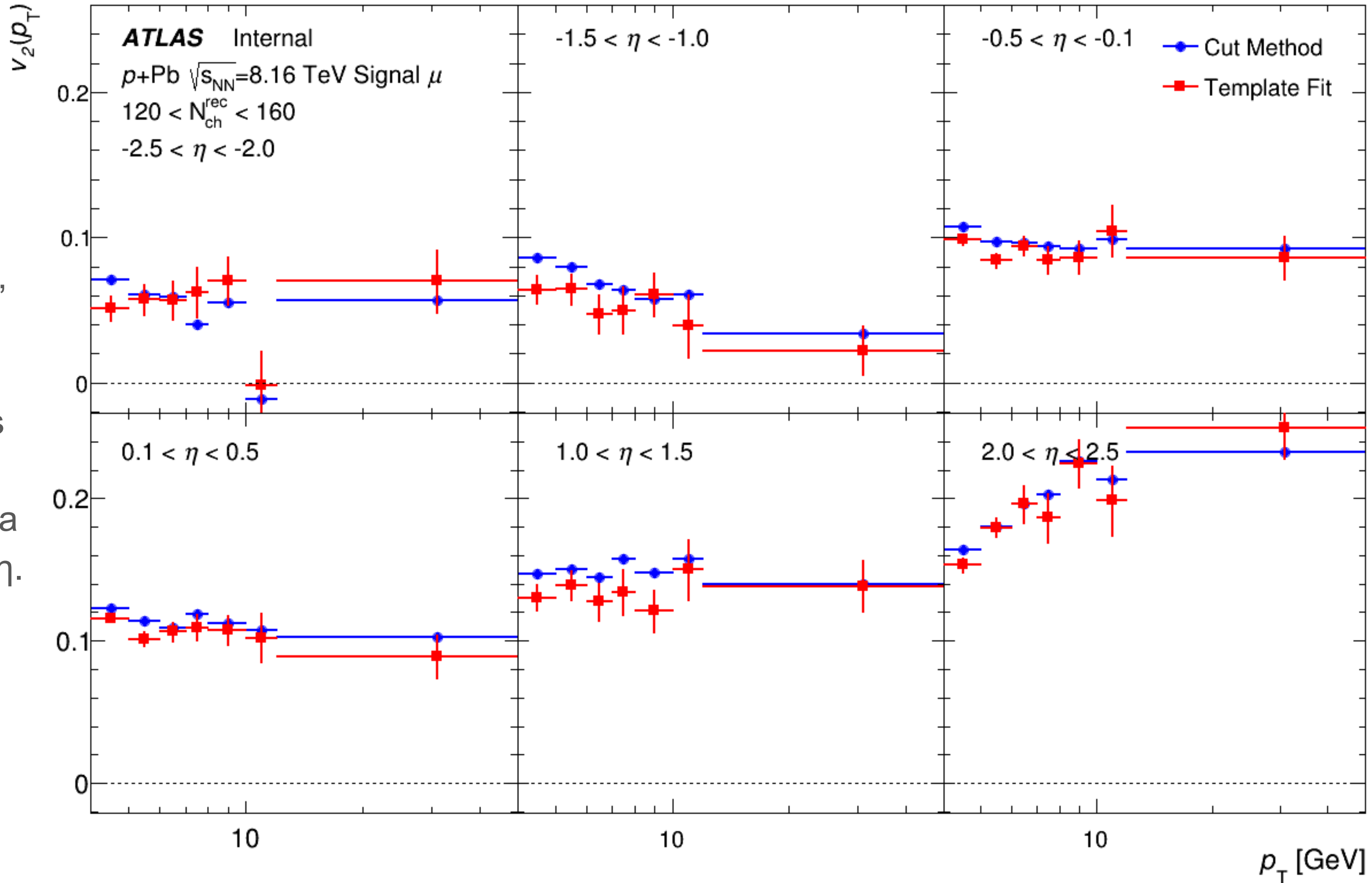
Signal μ
$0.1 < \eta < 0.5$
$160 < N_{ch}^{rec} < 200$



- This figure shows the $\Delta\varphi$ distributions from the cut-based (blue) and template fit (red) methods.
- Each point in the template fit series (red) is computed by integrating the signal Gaussian curves, as obtained from the template fits.
- Both distributions are fit to a cosine function to extract the flow value.
- This fitting process is repeated across all bins in p_T, η, and multiplicity.

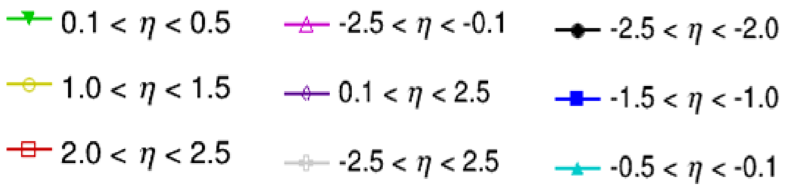
Signal v_2 for multiplicity between 120 and 160

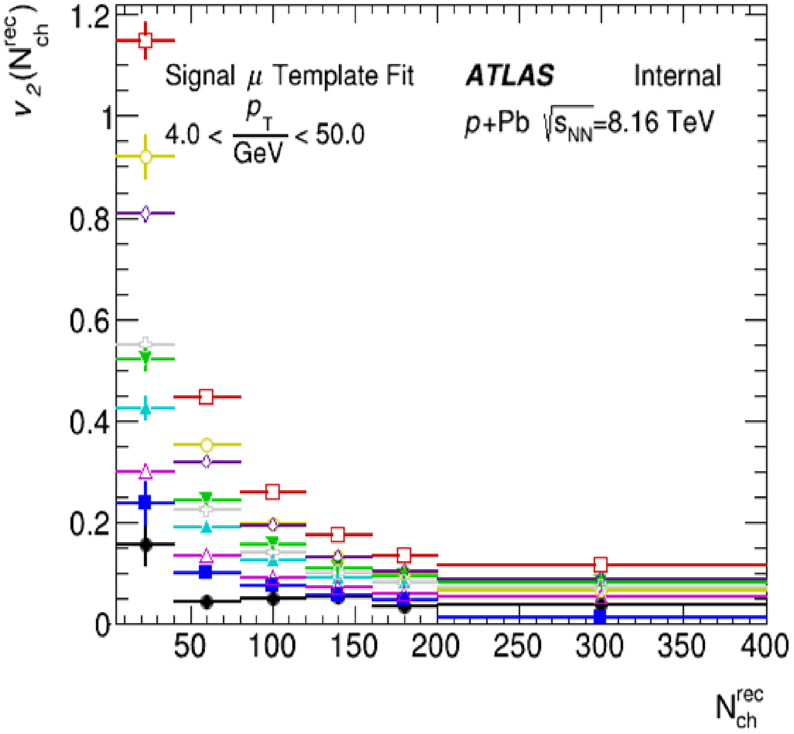
- Cut-based (blue) and template-fit (red) produce consistent results.
- At backward rapidities, v_2 decreases with p_T, but at forward rapidities, v_2 increases with p_T.
- The flow values show a marked increase with η. This is caused by autocorrelation effects due to jets in the forward calorimeter.



Summary of v_2 as a function of multiplicity (all p_T values)

- This figure summarizes v_2 values for muons of all p_T ranges, i.e. p_T > 4 GeV.
- There is significant bias in the most forward rapidity bins, as well as the low multiplicity bins. This is due to the aforementioned autocorrelation effects that bias the event plane.





Conclusion

- The v_2 values are calculated using the event-plane method over broad multiplicity, transverse momentum, and pseudorapidity ranges.
- We observed significant non-zero azimuthal anisotropy from muons produced in *p*+Pb collisions at 8.16 TeV.
- Future work:
  - Use a tighter cut for the cut-based method to eliminate more of the background muons.
  - Improve template fits replacing the Gaussians with MC templates.
  - Account for the bias caused by autocorrelation effects, especially in bins with forward rapidity and low multiplicity.

Event-plane method

- The flow vector (Q-vector) is measured by summing over calorimetric towers. These values are biased due to detector effects, and this bias is obtained by averaging the components over all events. The recentering correction is performed by subtracting this bias from each event.

$$Q_{n,x} = \sum_i E_{\mathrm{T}}^i \cos(n\phi^i) \qquad Q_{n,x} = \frac{Q_{n,x}^{\mathrm{raw}} - \langle Q_{n,x}^{\mathrm{raw}} \rangle}{E_{T_{n,x}}}$$

$$Q_{n,y} = \sum_i E_{\mathrm{T}}^i \sin(n\phi^i) \qquad Q_{n,y} = \frac{Q_{n,y}^{\mathrm{raw}} - \langle Q_{n,y}^{\mathrm{raw}} \rangle}{E_{T_{n,y}}}$$

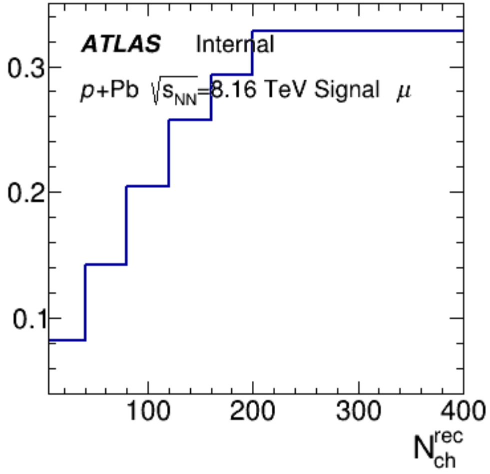
- The event plane angle can be obtained by taking the arctangent of the quotient of the Q-vector components:

$$\Psi_n = \frac{1}{n} \arctan\left(\frac{Q_{n,y}}{Q_{n,x}}\right)$$

Resolution correction (three sub-event method)

- Due to statistical limitations, the true event-plane differs from what is measured. Averaged over many events, these fluctuations can be accounted for by a factor.
- Three reference detectors located at different η values are used to calculate the resolution of detector A
  - A: Pb-going side FCal at $3.2 < \eta < 4.9$
  - B: p-going side FCal at $-4.9 < \eta < -3.2$
  - C: inner detector (ID) at $-1.0 < \eta < 1.0$
- The resolution is calculated by correlating the Ψ angles of each reference detector.

$$\mathrm{Res} = \sqrt{\frac{\langle\cos\left(\Psi_n^A - \Psi_n^B\right)\rangle\langle\cos\left(\Psi_n^A - \Psi_n^C\right)\rangle}{\langle\cos\left(\Psi_n^B - \Psi_n^C\right)\rangle}}$$



- Then, the raw flow values are divided by the resolution to obtain the corrected values.