Measurement of the ridge correlations in pp and p+Pb collisions with the ATLAS detector at the LHC

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on behalf of the ATLAS Collaboration

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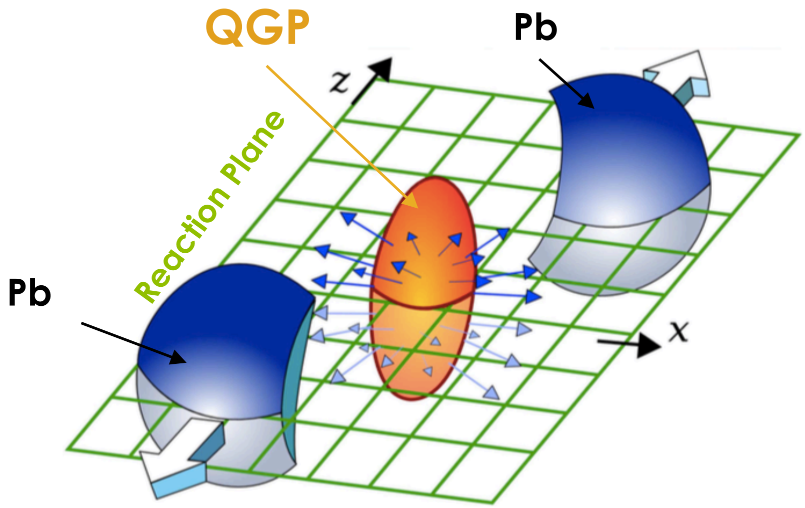
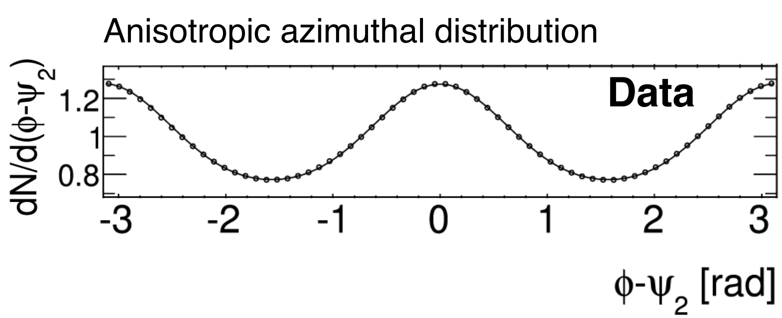
Motivation

- Quark Gluon Plasma (QGP) produced and probed in heavy ion collisions
- Signatures of QGP: collective expansion (radial flow, elliptic flow, ...), jet quenching, etc.





<u>Study plasma properties:</u>

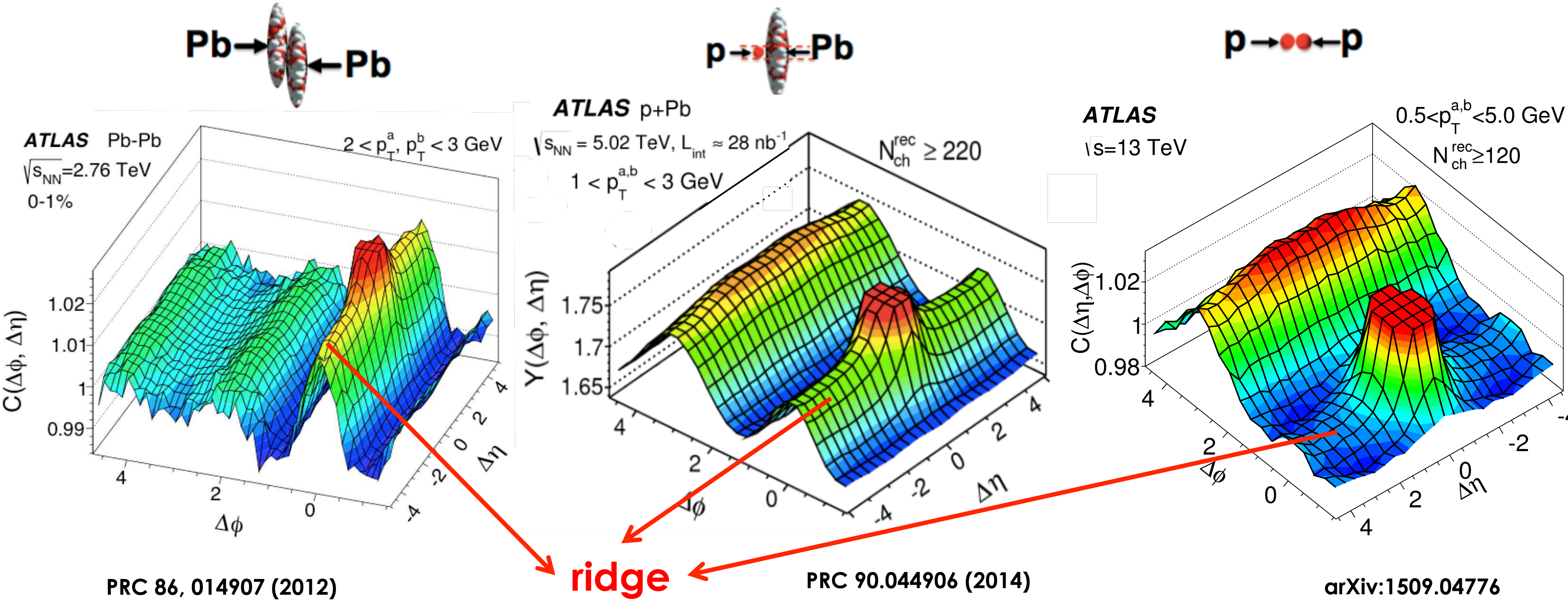
- particle azimuthal distribution
  → using v_n Fourier coefficients
- two/multi – particle correlations

Singles: $$\frac{dN}{d\phi} \propto 1 + \sum_n 2v_n \cos[n(\phi - \Phi_n)]$$

Pairs: $$\frac{dN}{d\Delta\phi} \propto 1 + \sum_n 2v_n^a v_n^b \cos[n(\Delta\phi)]$$

v_2 – elliptic flow

The **ridge** in **Pb+Pb**, **p+Pb** and **pp** collisions



PRC 86, 014907 (2012) | PRC 90.044906 (2014) | arXiv:1509.04776

- **Two-particle correlations show long-range correlation structure along $\Delta\eta$ at $\Delta\Phi \approx 0$ → the near-side ridge**
- **What is the origin of ridge structures in small systems? Is it the same mechanism as in Pb+Pb? Is it single-particle azimuthal anisotropy?**
- **Detailed ridge studies are performed:**
  - **p_T, η, N_{ch}, energy dependence, single-particle v_n**

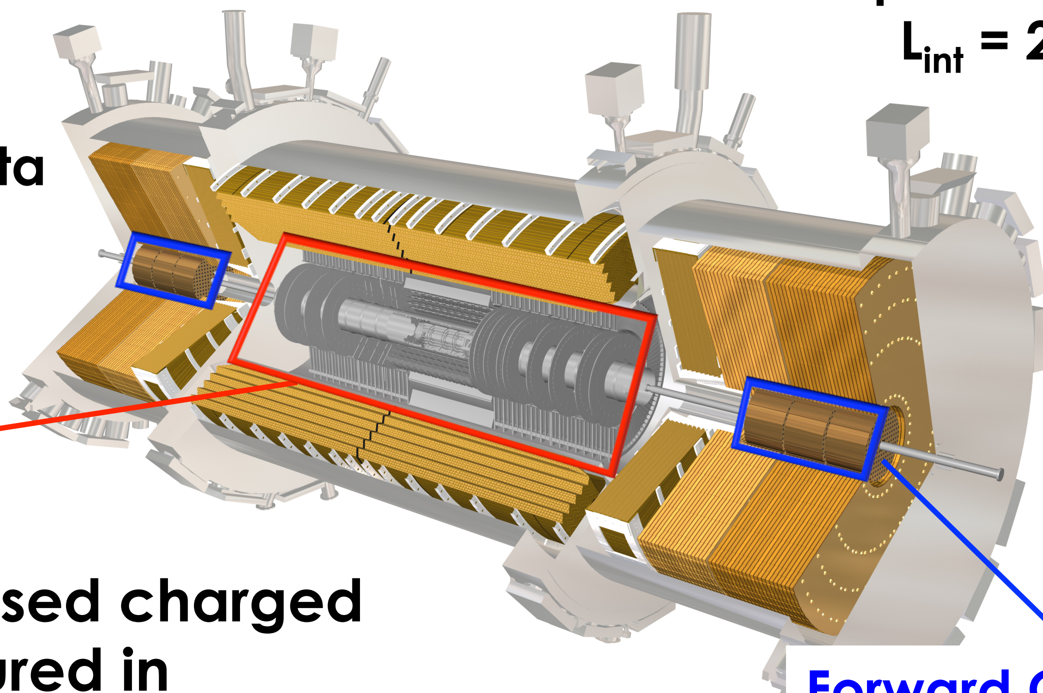
ATLAS detector and datasets

ATLAS pp 2.76 TeV data
L_{int} = 4 pb^{-1}

ATLAS pp 13 TeV data
L_{int} = 14 nb^{-1}

ATLAS p+Pb 5.02 TeV data
L_{int} = 28 nb^{-1}

p: 4 TeV
Pb: 1.57 TeV/N



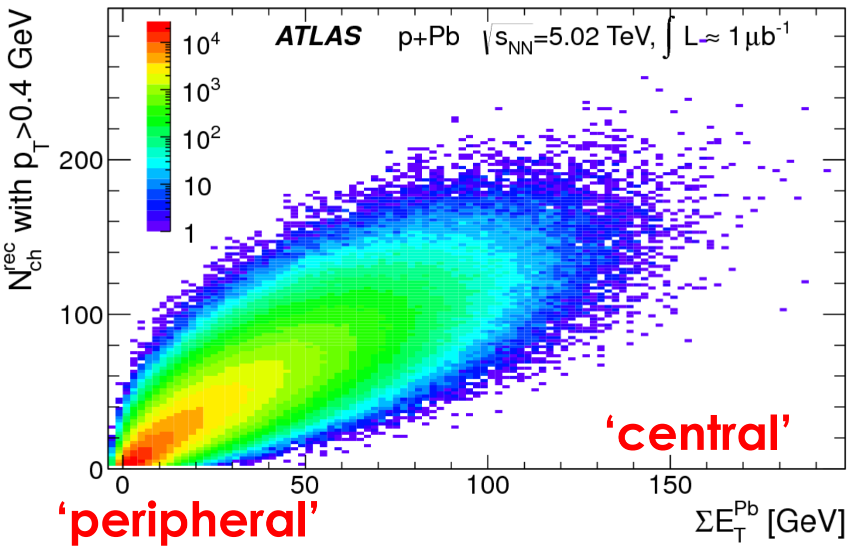
Inner Detector (ID)
$|\eta| < 2.5$

Forward Calorimeter (FCal)
$3.2 < |\eta| < 4.9$

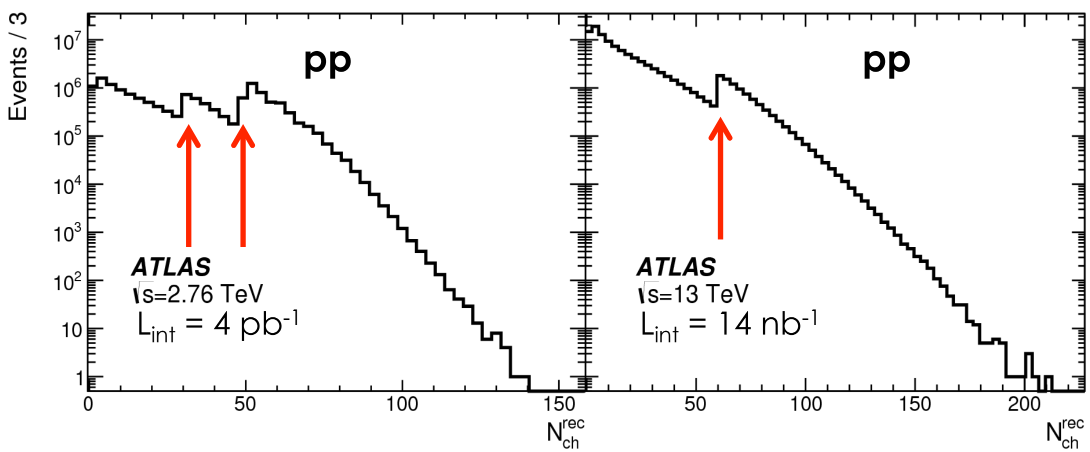
- **Both analyses used charged particles measured in Inner Detector (ID) with tracking coverage $|\eta| < 2.5$ and $p_T > 0.4$ GeV**

- **Forward Calorimeter (FCal) is used to define "event activity" of p+Pb collisions**

Event activity in **p+Pb** and **pp** collisions



- **Event activity** in p+Pb collisions is defined in two ways:
  - **E_T^{Pb}: Total transverse energy in the FCal on Pb-going side**
  - **N_{ch}^{rec}: number of charged particles with p_T > 0.4 GeV in ID**



- **For pp collisions only N_{ch}^{rec} intervals are used to characterize event activity**
- **High multiplicity events in pp:**
  2.76 TeV → N_{ch}^{rec} > 50
  13 TeV → N_{ch}^{rec} > 60

Two-particle correlation (**2PC**) function

$$C(\Delta\eta, \Delta\phi) = \frac{S(\Delta\eta, \Delta\phi)}{B(\Delta\eta, \Delta\phi)}$$

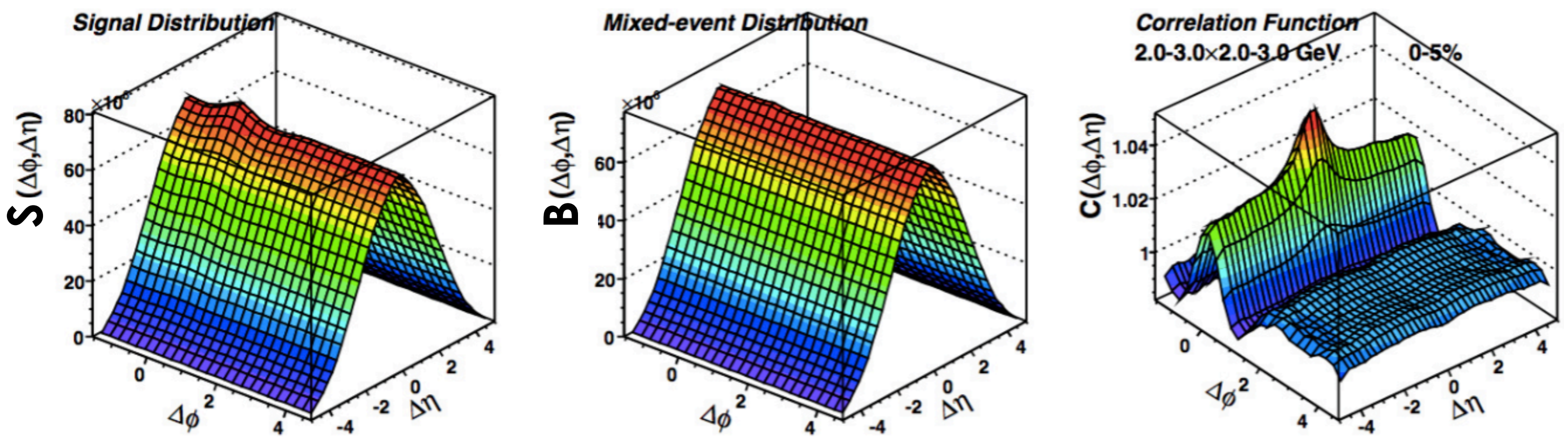
The same event pairs

Mixed event pairs (background)

$$\Delta\phi \equiv \phi^a - \phi^b$$

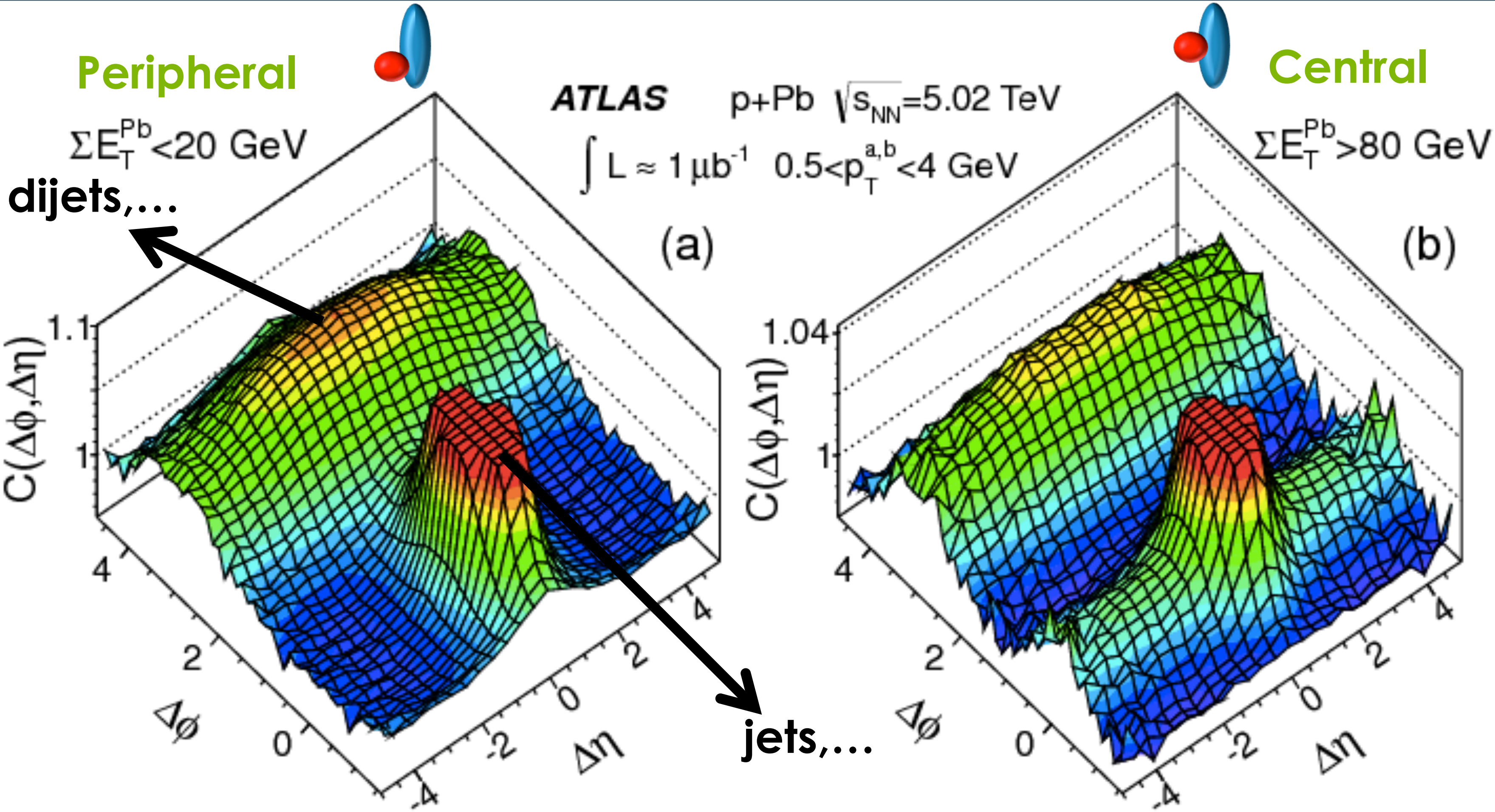
$$\Delta\eta \equiv \eta^a - \eta^b$$

Pb+Pb example:



- **S is constructed using all pairs of charged particles in the same event**
- **B obtained from "mixed events", measures distribution of uncorrelated pairs**
- **Both S and B are corrected for tracking inefficiencies – detector acceptance effects largely cancel in the *S/B* ratio**

2PC analysis – **p+Pb** collisions



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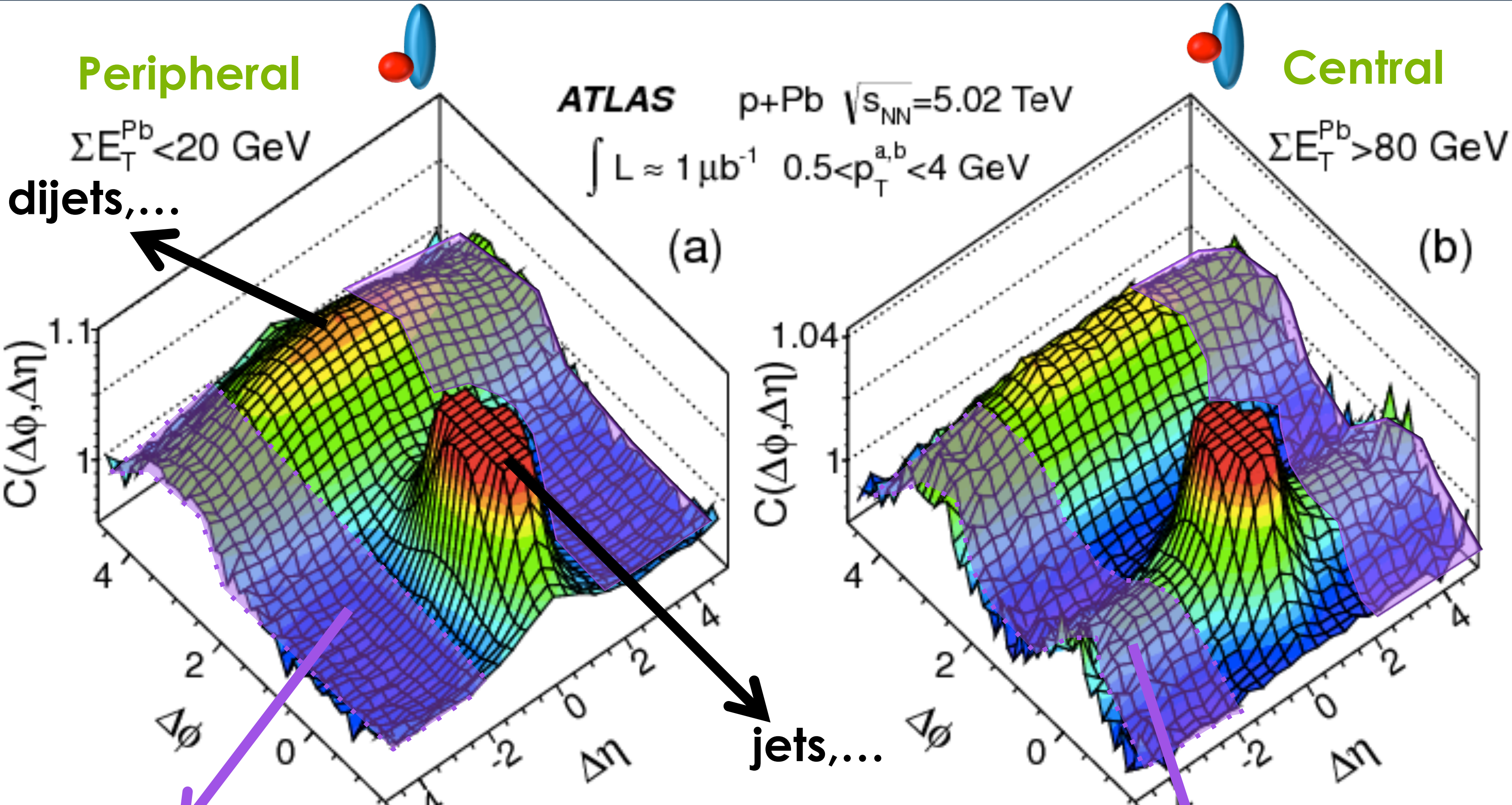


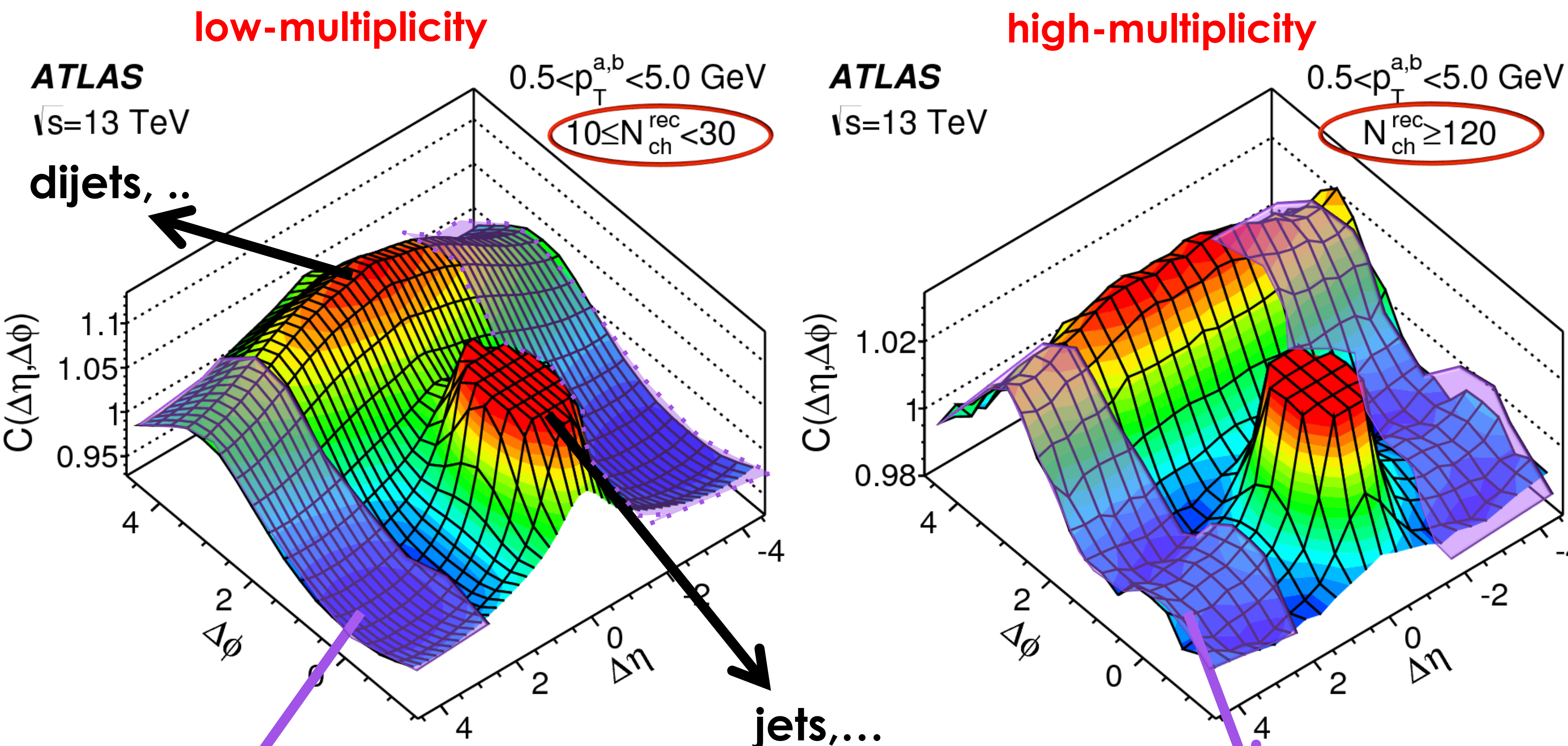
2 < | Δ η | < 5

Long range correlation concave-up

→ no ridge observed

Ridge develops in central events

2PC analysis – **pp** collisions



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Long range correlation concave-up
→ no ridge observed

Ridge develops in high-multiplicity events

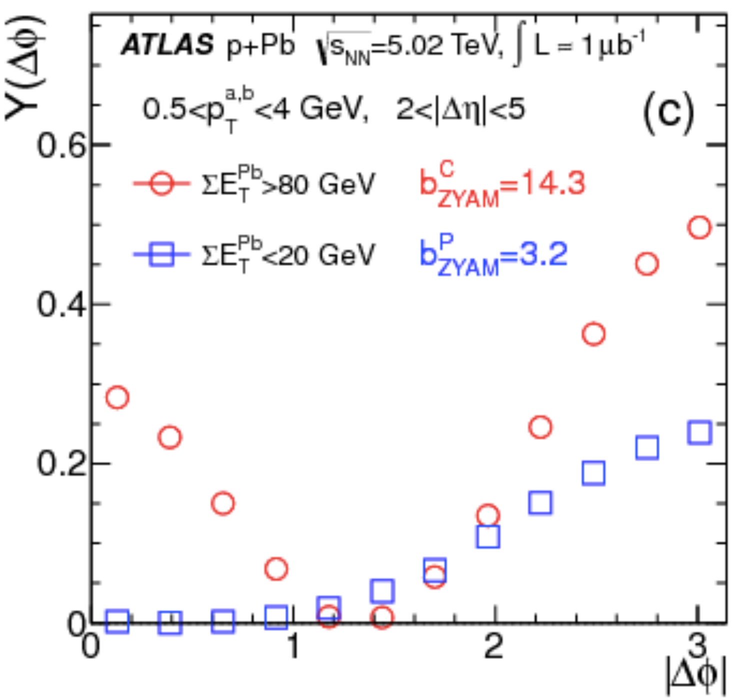
Per-Trigger Yields: **p+Pb**

- **$Y(\Delta\phi)$ is used to measure the strength of the long-range component**

$$Y(\Delta\phi) = \left(\frac{\int B(\Delta\phi) d\Delta\phi}{N^a \int d\Delta\phi}\right) C(\Delta\phi) - b_{ZYAM}$$

N^a - total number of trigger particles

b_{ZYAM} – pedestal arising from uncorrelated pairs



- **Compared central and peripheral PTY for $2<|\Delta\eta|<5$**
- **Peripheral events show 'away-side' peak → dijets contribution**
- **Central events feature the ridge (near-side peak) and excess on away-side**
- **Excess on near-side and away-side independent on event activity, E_T^{Pb}**

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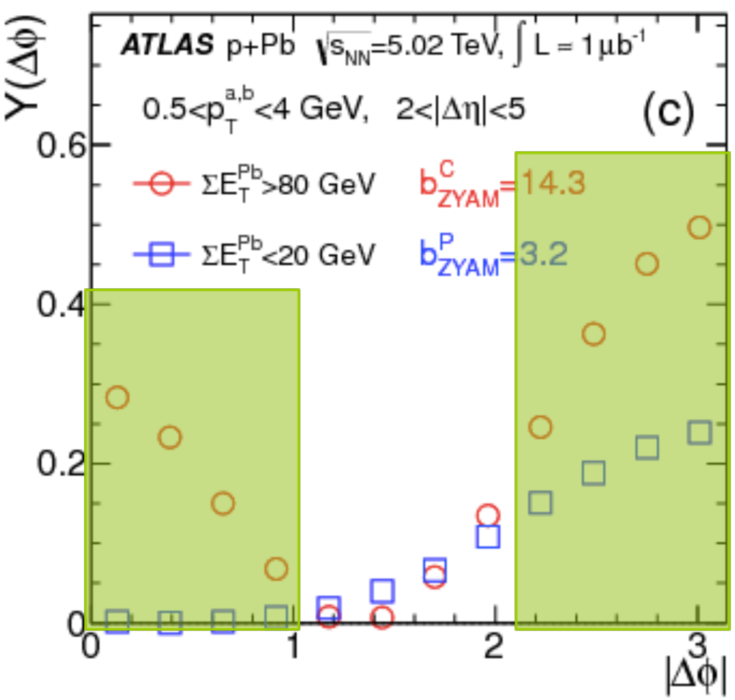

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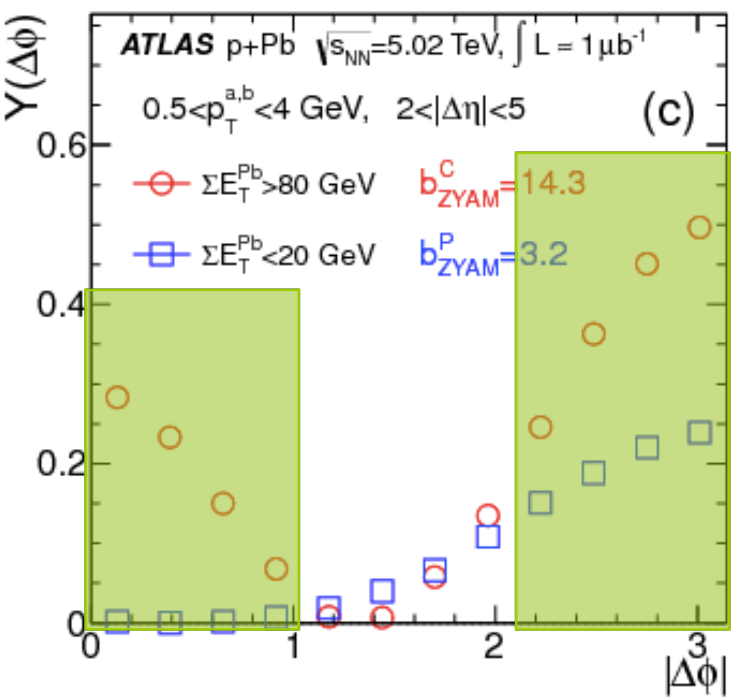

- **Compared central and peripheral PTY for $2 < |\Delta\eta| < 5$**
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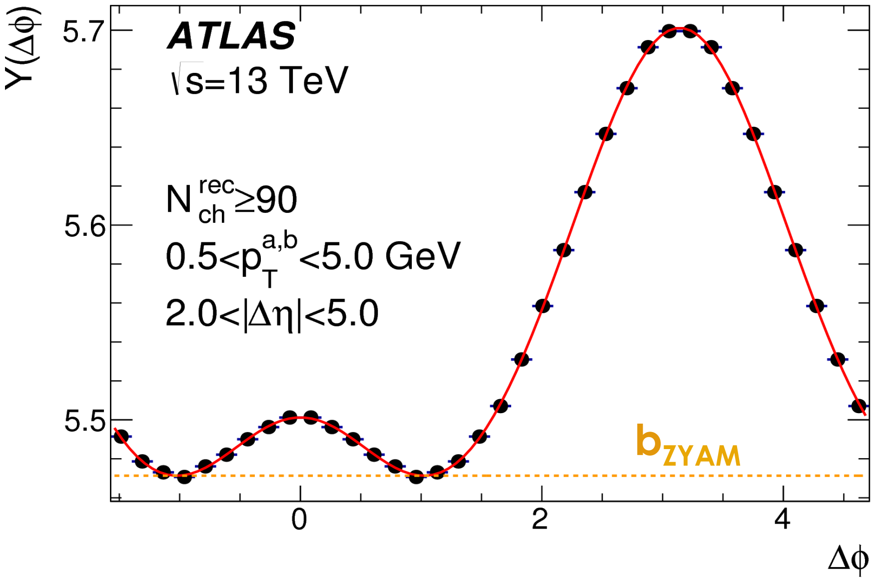
- **Excess on near-side and away-side independent on event activity, E_T^{Pb}**

$$Y^{sub}(\Delta\phi) = Y(\Delta\phi) - \alpha Y^{corr}_{peri}(\Delta\phi) \propto \left[1 + \sum_n 2 v_{n,n} cos(n\Delta\phi)\right]$$

Per-Trigger Yields: **pp**

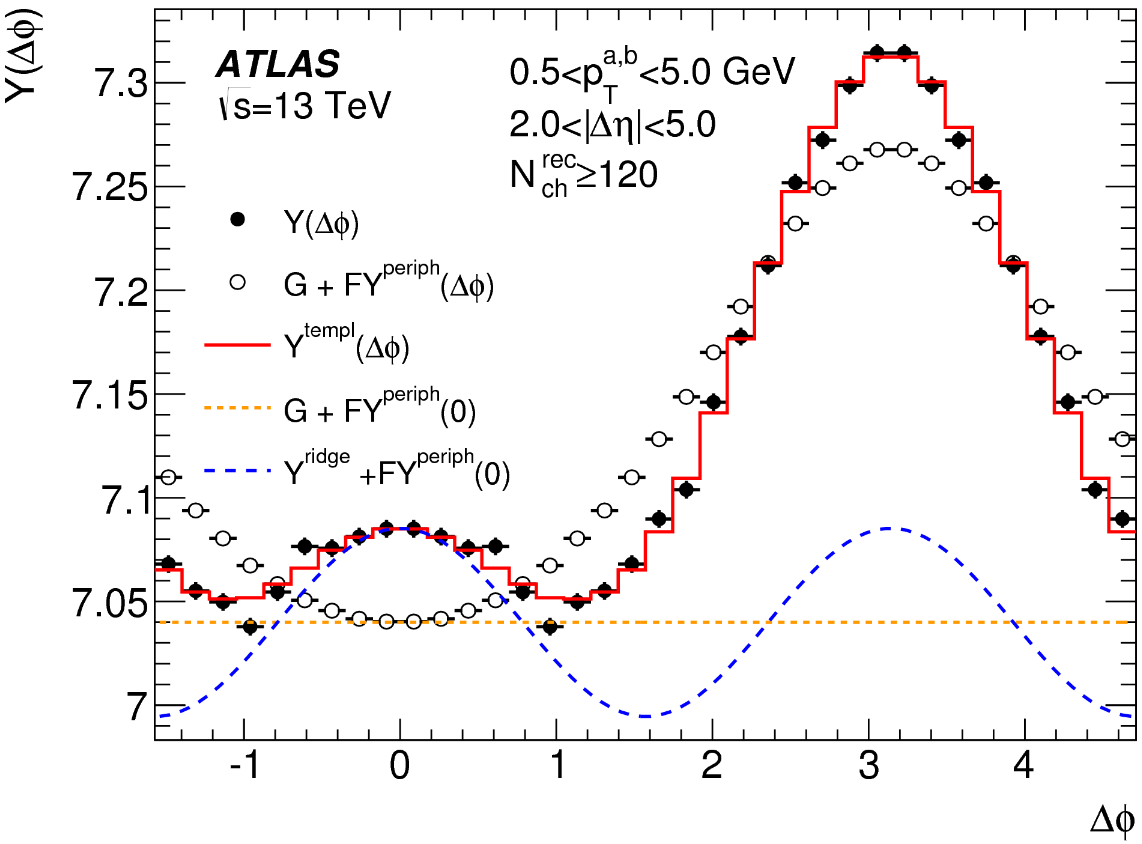


$$Y(\Delta\phi) = \left(\frac{\int B(\Delta\phi)d\Delta\phi}{N^a \int d\Delta\phi}\right) C(\Delta\phi) - \cancel{b_{ZYAM}}$$

N^a - total number of trigger particles

- **ZYAM assumes that number of correlated pairs is zero at minimum**
- **The minimum of Y(Δ ϕ) may be modulated due to long-range correlations**
- **Only near-side long range correlation can be extracted → away-side Y(Δ ϕ) dominated by dijets**
- **No information about full Δ ϕ dependence → new template fitting method**

Template fitting method - pp



- **Y(Δ ϕ) are assumed to result from a superposition of a 'peripheral' Y^{periph}(Δ ϕ), scaled by multiplicative factor, F, and an elliptic flow-like modulation with an amplitude $v_{2,2}$**

$$0 \leq N_{ch}^{rec} < 20$$

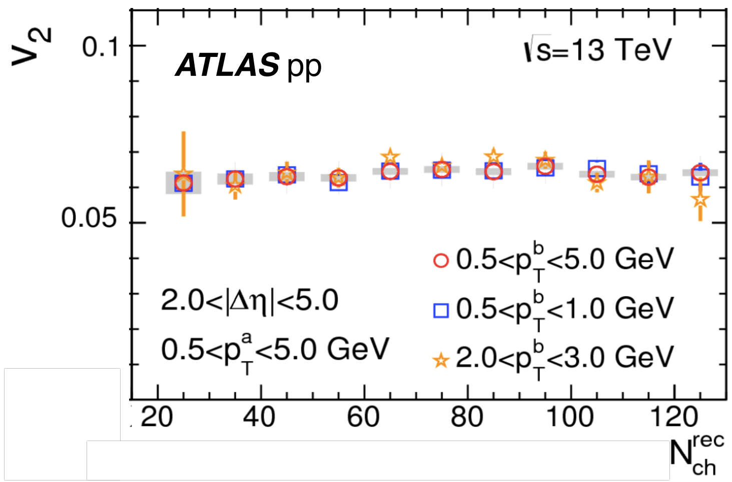
$$Y^{templ}(\Delta\phi) = FY^{periph}(\Delta\phi) + Y^{ridge}(\Delta\phi)$$

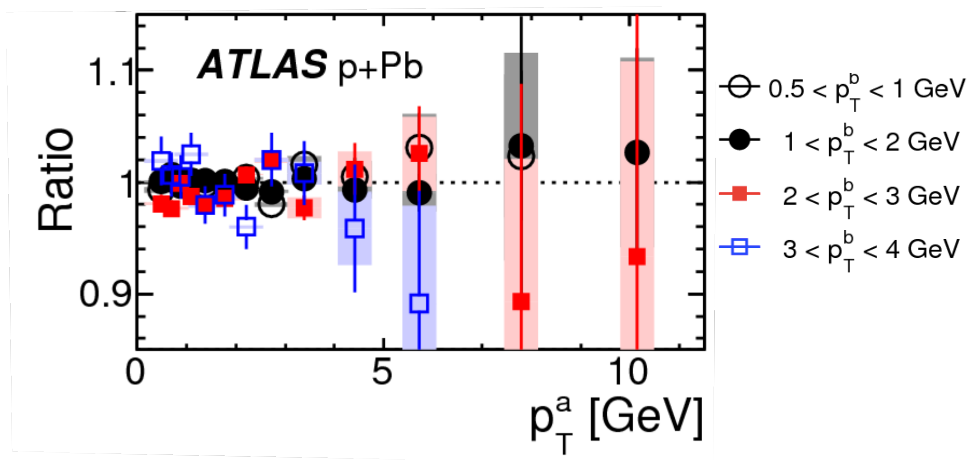
$$Y^{ridge}(\Delta\phi) = G\,(1 + 2\,v_{2,2}\cos(2\Delta\phi))$$

Single-particle anisotropies v_2 in **pp & p+Pb**

- **If ridge in pp and p+Pb collisions also results from modulation of the single particle ϕ-distribution, measured $v_{2,2}$ should factorize:**

$$v_{2,2}(p_T^a, p_T^b) = v_2(p_T^a)v_2(p_T^b) \quad \Rightarrow \quad v_2(p_T^a) = v_{2,2}(p_T^a, p_T^b)/\sqrt{v_{2,2}(p_T^b, p_T^b)}$$

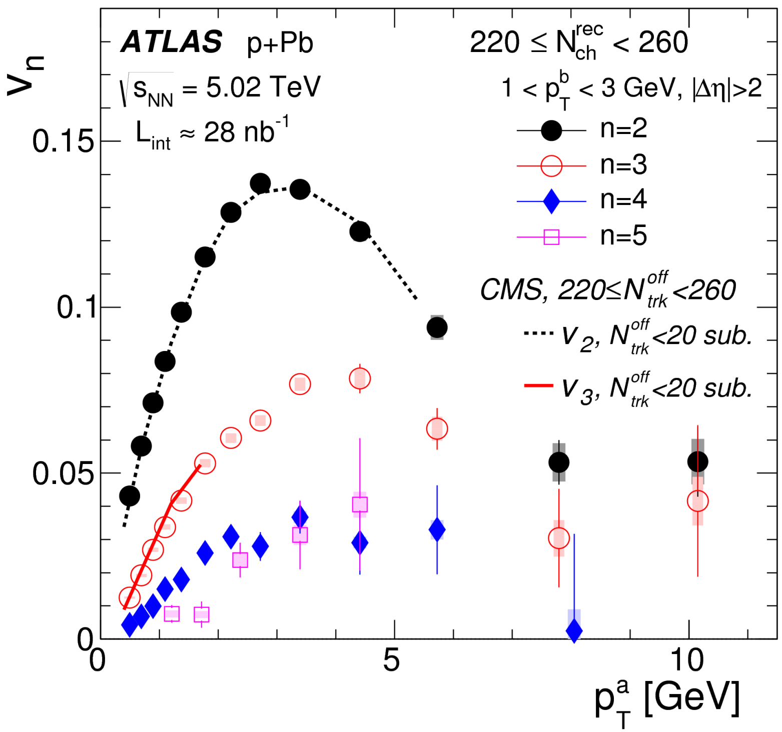


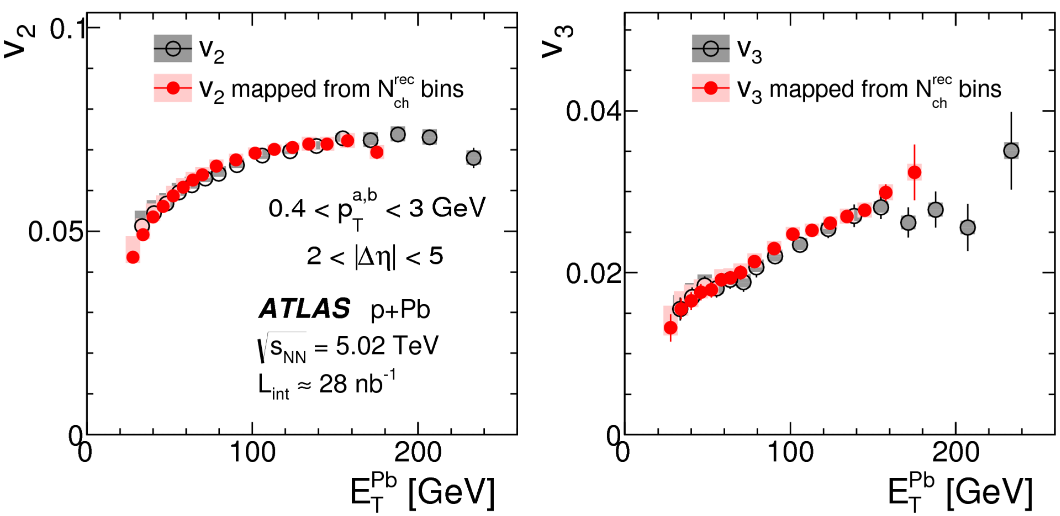


- **$v_{2,2}$ depends on both, *a* and *b*, particles but v_2 (p_T^a) should be independent of reference p_T^b**

- **Factorization works fine for both, pp & p+Pb, systems → global anisotropy**

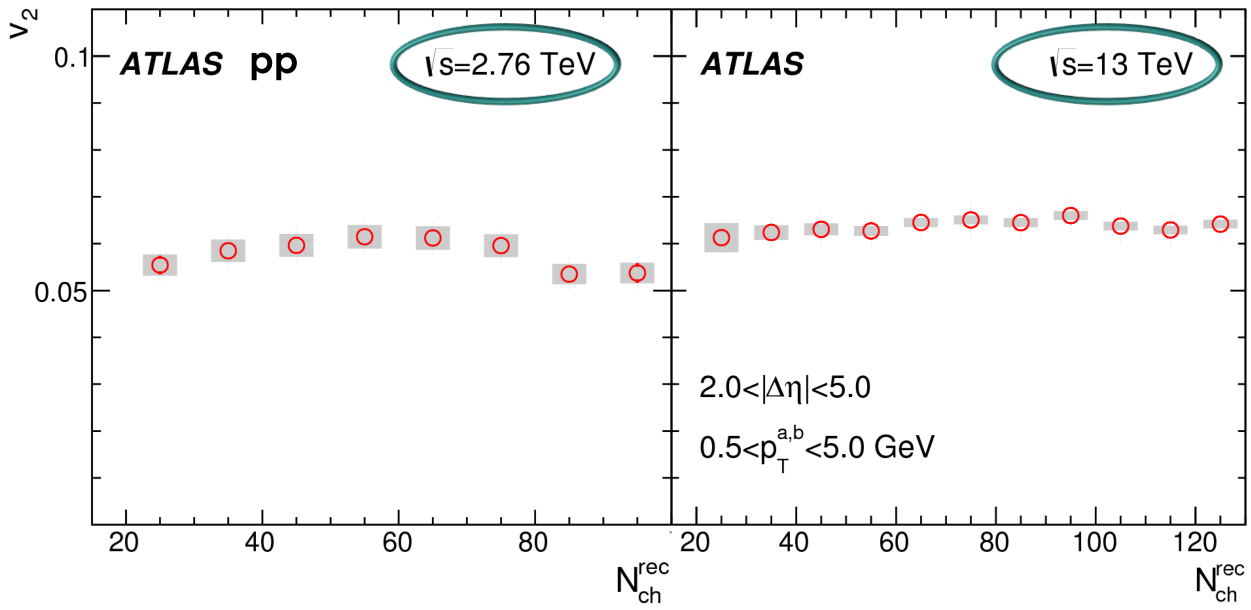
v_n (p_T) and event activity dependence in **p+Pb**

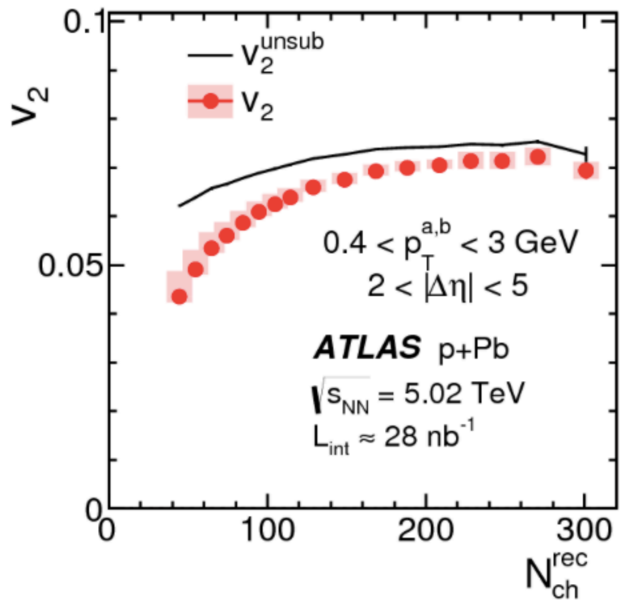




- v_n decreases with increasing n
- Rapid rise reaching maximum at p_T~3GeV
- v_n decreases at higher p_T
- v_n is dependent on event activity
- v_n increases with E_T^{Pb}
- v_2 saturates for central events while v_3 continues rising

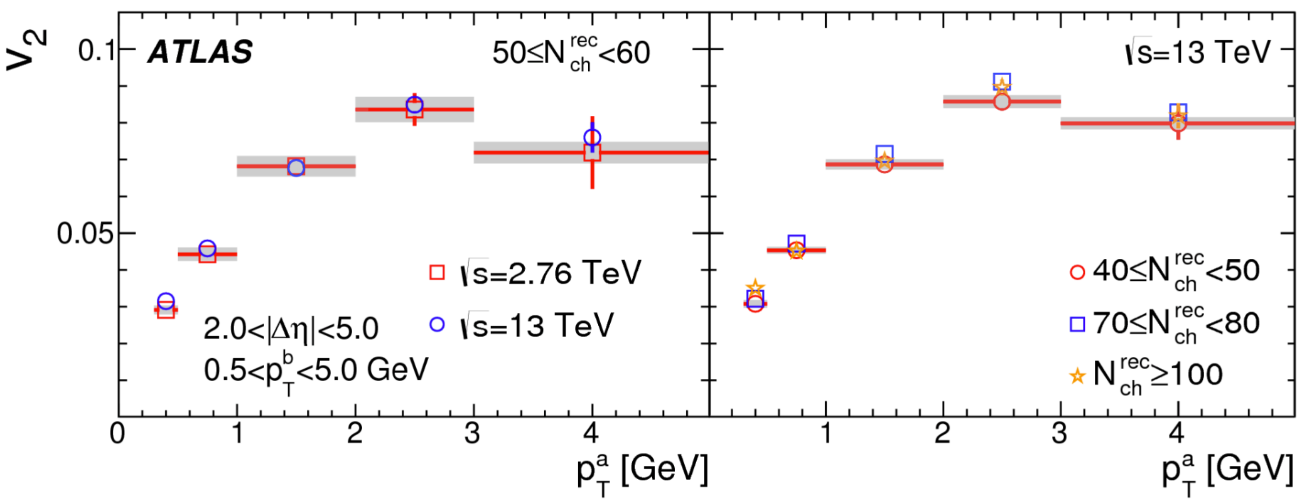
v_2 integrated over p_T in **pp** and **p+Pb**

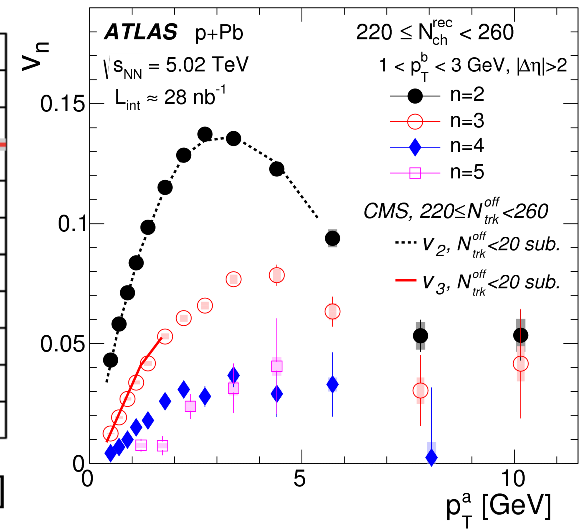




- **In pp system v_2 shows very weak dependence on energy and track multiplicity**
- **In p+Pb multiplicity dependence is stronger**
  → v_2 grows with N_{ch}^{rec}

N_{ch}^{rec} and p_T dependence of v_2 in **pp** and **p+Pb**





- **v_2 in pp system behaves similar as v_2 in Pb+Pb and p+Pb:**
  - **Increase with p_T up to ~3 GeV**
  - **Decreases at higher p_T**
- **v_2 (p_T) shows very weak dependence on energy and track multiplicity (in pp)**

Summary

- Ridge was observed in high-multiplicity *pp* collisions at 2.76 and 13 TeV as well as in *p+Pb* collisions at 5.02 TeV

- ZYAM and template fitting methods were applied to extract long range correlations $v_{2,2}$ modulated by $\cos(2\Delta\phi)$ in *p+Pb* and *pp* systems respectively

- $v_{2,2}$ exhibits factorization into single particle v_2

- Elliptic flow, v_2, was measured for both systems
  → higher harmonics measured in p+Pb

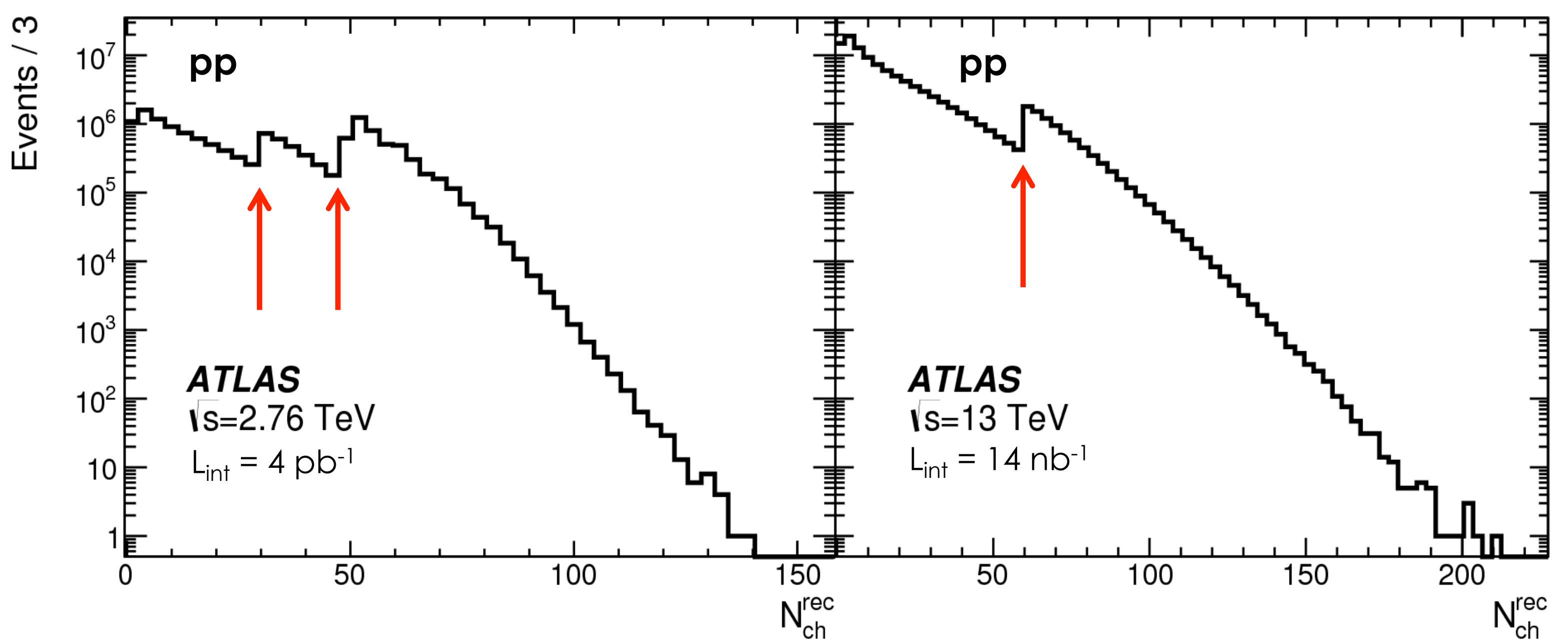
- The shape of $v_2(p_T)$ distribution in pp and p+Pb is similar to the shape of $v_2(p_T)$ distribution in Pb+Pb

  → This suggests that the ridge in pp, p+Pb and Pb+Pb collisions arises from similar dynamics ?

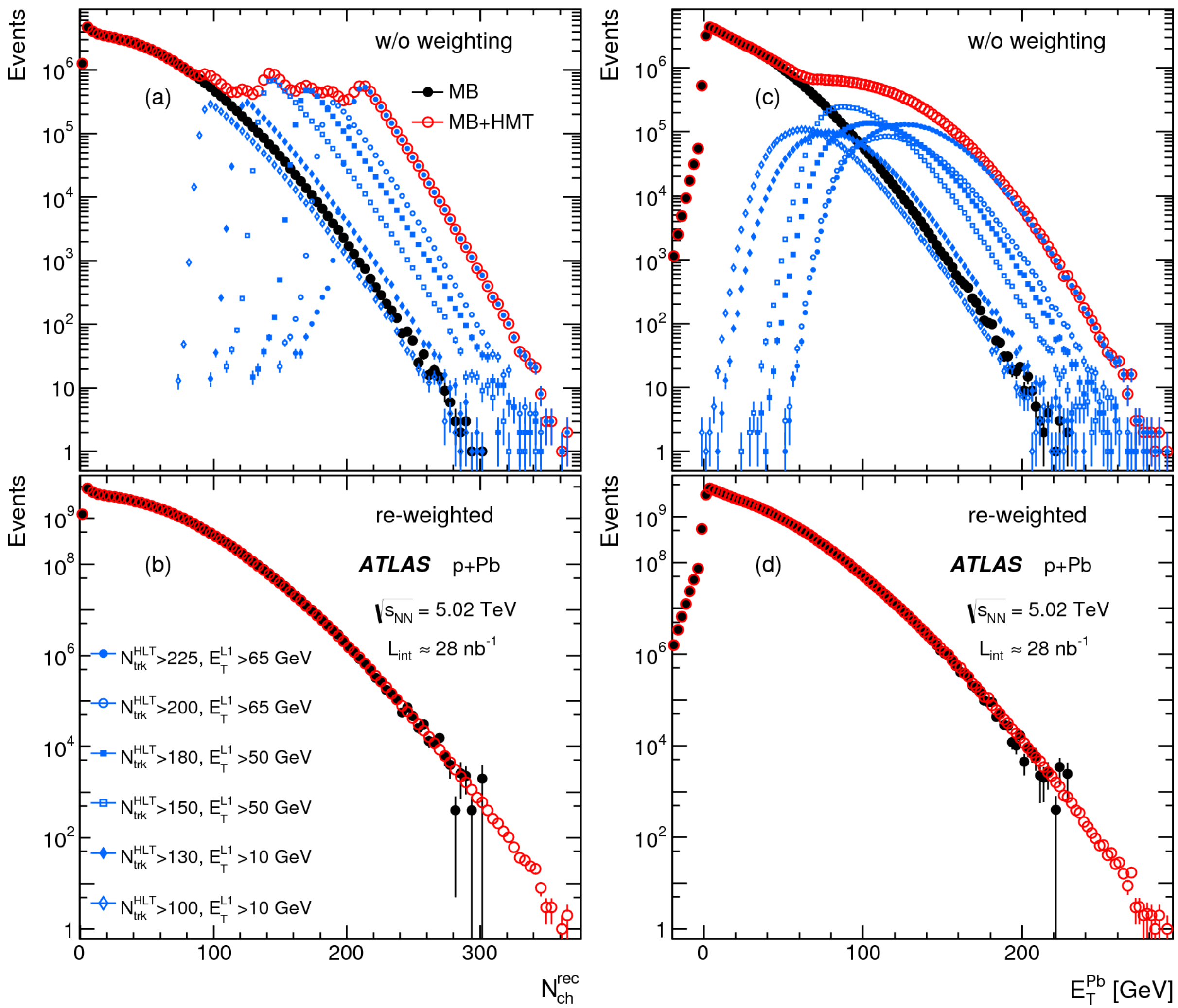
Backup slides

High Multiplicity Triggers in **pp** collisions

- **Dedicated triggers (HMT) implemented using ATLAS L1 & HLT systems to increase high multiplicity events**
- **The structures in the distributions result from the different HMT trigger thresholds**
- **High multiplicity events: 2.76 TeV → $N_{ch}^{rec} > 30$**
  13 TeV → $N_{ch}^{rec} > 60$

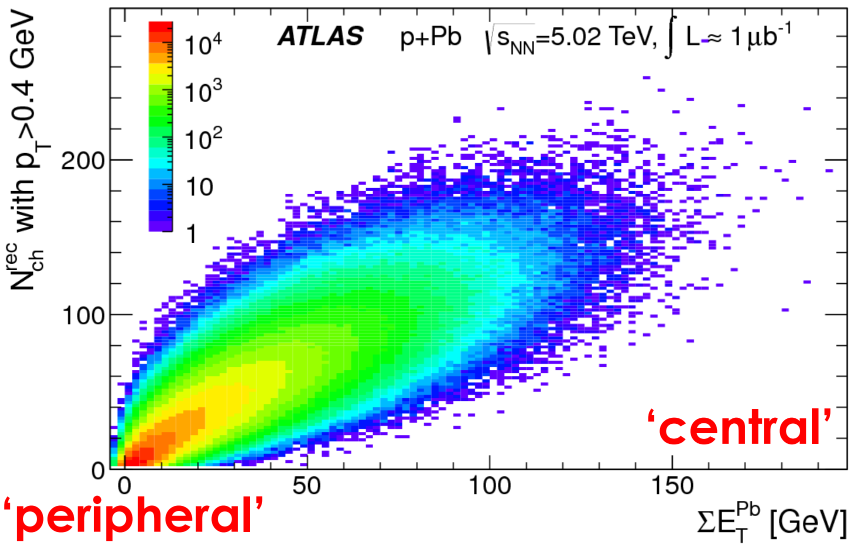


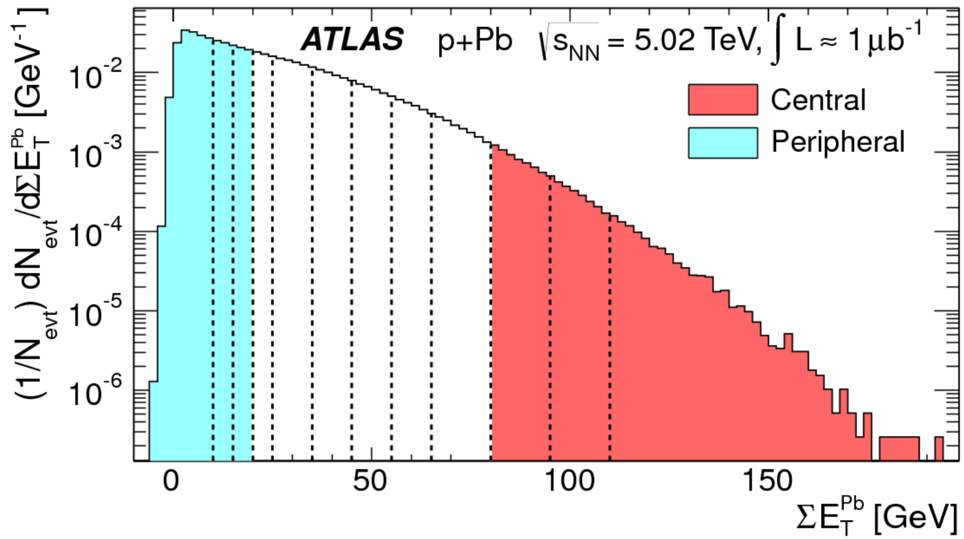
High multiplicity triggers in **p+Pb**



- **Six pairs of HMT thresholds**
- **Enhancement from individual HMT (top)**
- **Reweighted by MB +HMT distribution (bottom)**
- **Reweighting procedure comprise probability for a given event to be accepted by MB or HMT, prescale and trigger effiviency**

Event activity in **p+Pb** collisions

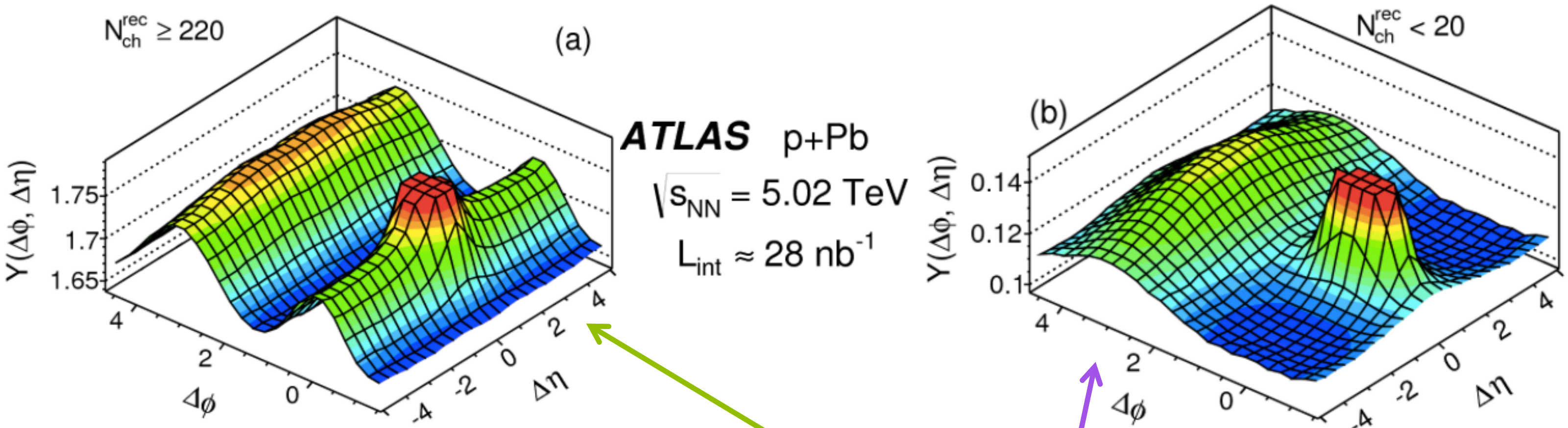




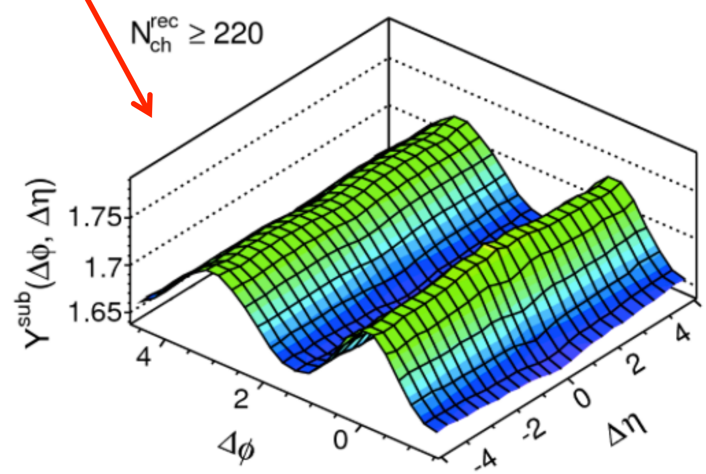
- **Event activity in p+Pb collisions is defined in two ways:**
  - **N_{ch}^{rec}: number of charged particles with p_T > 0.4 GeV in ID**
  - **E_T^{Pb}: Total transverse energy on the FCal on Pb-going side**
    - **E_T^{Pb} distribution is divided into 12 intervals**
- **For pp collisions only N_{ch}^{rec} intervals are used to characterize event activity**

Per-Trigger Yields: **p+Pb**

- **Jet & dijets peaks are estimated from the peripheral collisions and subtracted from Y(Δ ϕ)**

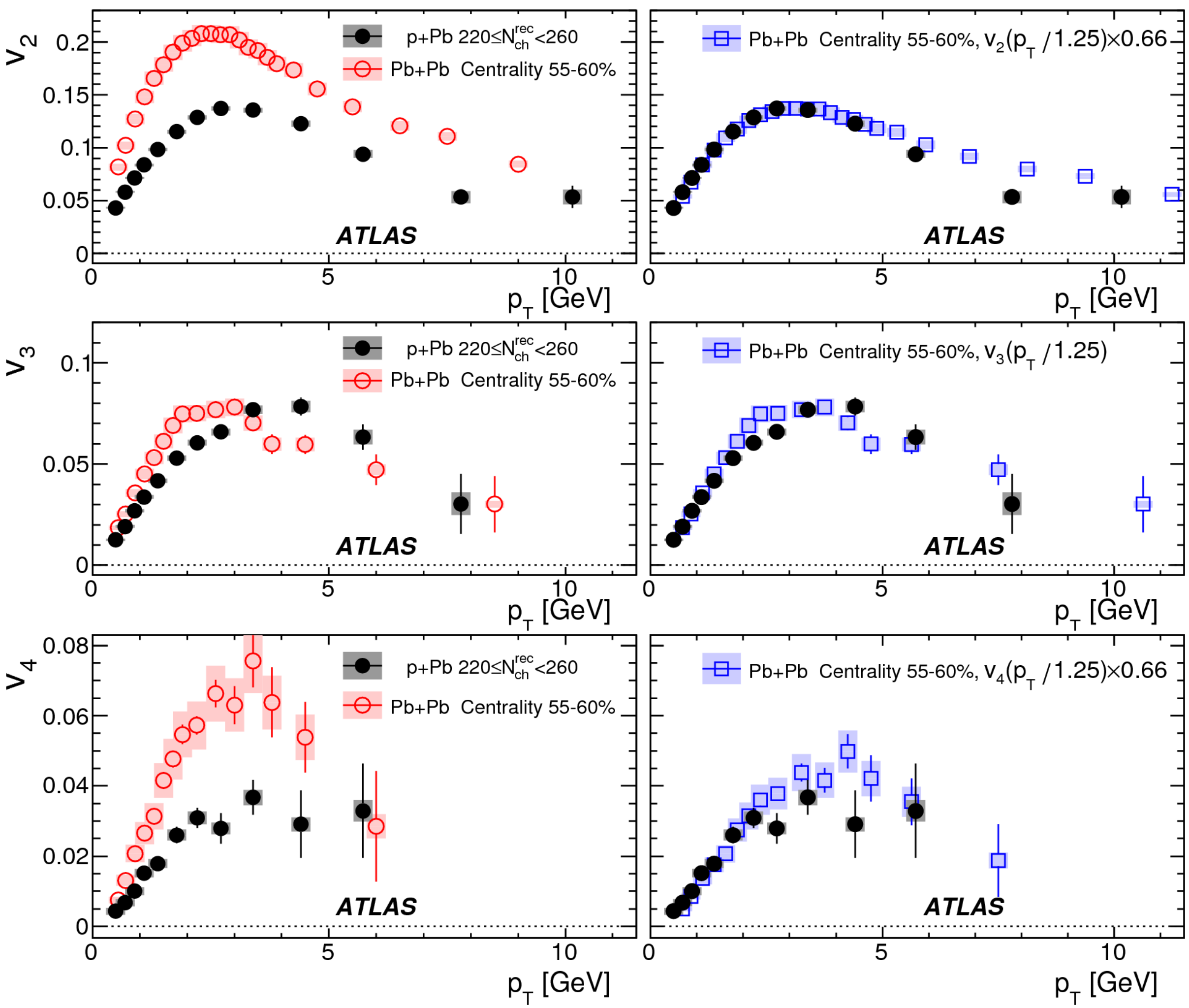


$$Y^{sub}(\Delta\phi) = Y(\Delta\phi) - \alpha Y^{corr}_{peri}(\Delta\phi)$$



Δ ϕ -symmetric double ridge → almost independent of Δ η .

$v_n(p_T)$ scaling between the **p+Pb** and **Pb+Pb**



- **Compare $v_n(p_T)_{p+Pb}$ with $v_n(p_T/1.25)_{Pb+Pb}$ (*Teaney et al. arXiv: 1312.6770[nucl-th]*)**
- **The shape after scaling is similar in both systems**
- **v_2 values differ only by a scale factor between the two systems**
- **This suggest similar origins of long range correlations**

2PC funcition and **Y(Δ φ)** in **p+Pb**