Correlation of flow harmonics and mean transverse momentum in 5.02 TeV *p+Pb* and *Pb+Pb* collisions
and
event-plane dependence of HBT radii in high-multiplicity *p+Pb* collisions with the ATLAS detector

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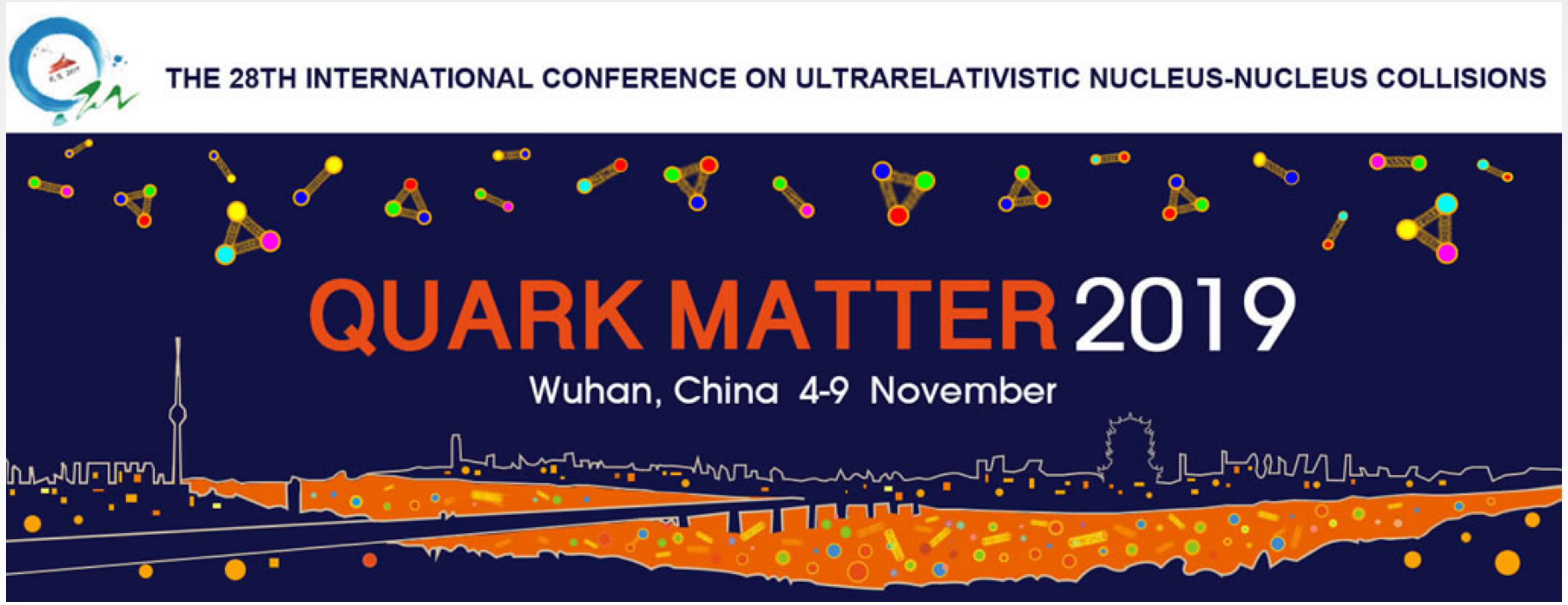
on behalf of the ATLAS Collaboration



Correlation of flow harmonics and mean transverse momentum in 5.02 TeV *p+Pb* and *Pb+Pb* collisions

arXiv:1907.05176

The idea

- Relate initial state quantity (event mean $[p_\mathrm{T}]$) with evolution towards the final state (flow harmonics)
- Known that the correlation exists (ALICE Phys. Rev. C93, 034916)
- Pearson correlation coefficient R distorted by the limited event multiplicity
- A modified correlator ρ proposed (P. Bozek Phys. Rev. C93 044908)
  - Replaces variances by dynamic counterparts $\mathrm{Var}_\mathrm{dyn}$, c_k
  - Reproduces true R even with limited event multiplicity
    → detector independent measurement

$$R = \frac{\mathrm{cov}(v_n\{2\}^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_n\{2\}^2)}\sqrt{\mathrm{Var}([p_\mathrm{T}])}},$$

$$\rho = \frac{\mathrm{cov}(v_n\{2\}^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_n\{2\}^2)_\mathrm{dyn}}\sqrt{c_k}}.$$

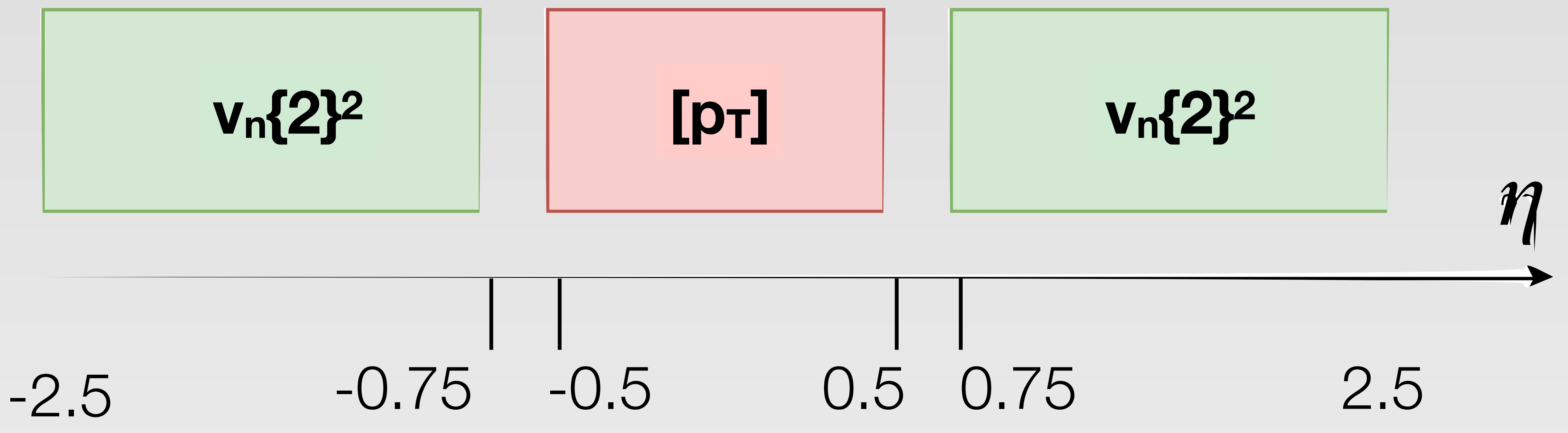
- **Is the correlation present & positive or negative?**
  Is it strong? Is it the same for all harmonics?
  Is it the same in Pb+Pb an p+Pb?

$$\mathrm{Var}(v_n\{2\}^2)_\mathrm{dyn} = \langle corr\{4\}\rangle - \langle corr\{2\}\rangle^2$$

$$c_k = \left\langle \frac{1}{N_\mathrm{pair}} \sum_i \sum_{j\neq i} (p_{\mathrm{T},i} - \langle [p_\mathrm{T}]\rangle)(p_{\mathrm{T},j} - \langle [p_\mathrm{T}]\rangle) \right\rangle$$

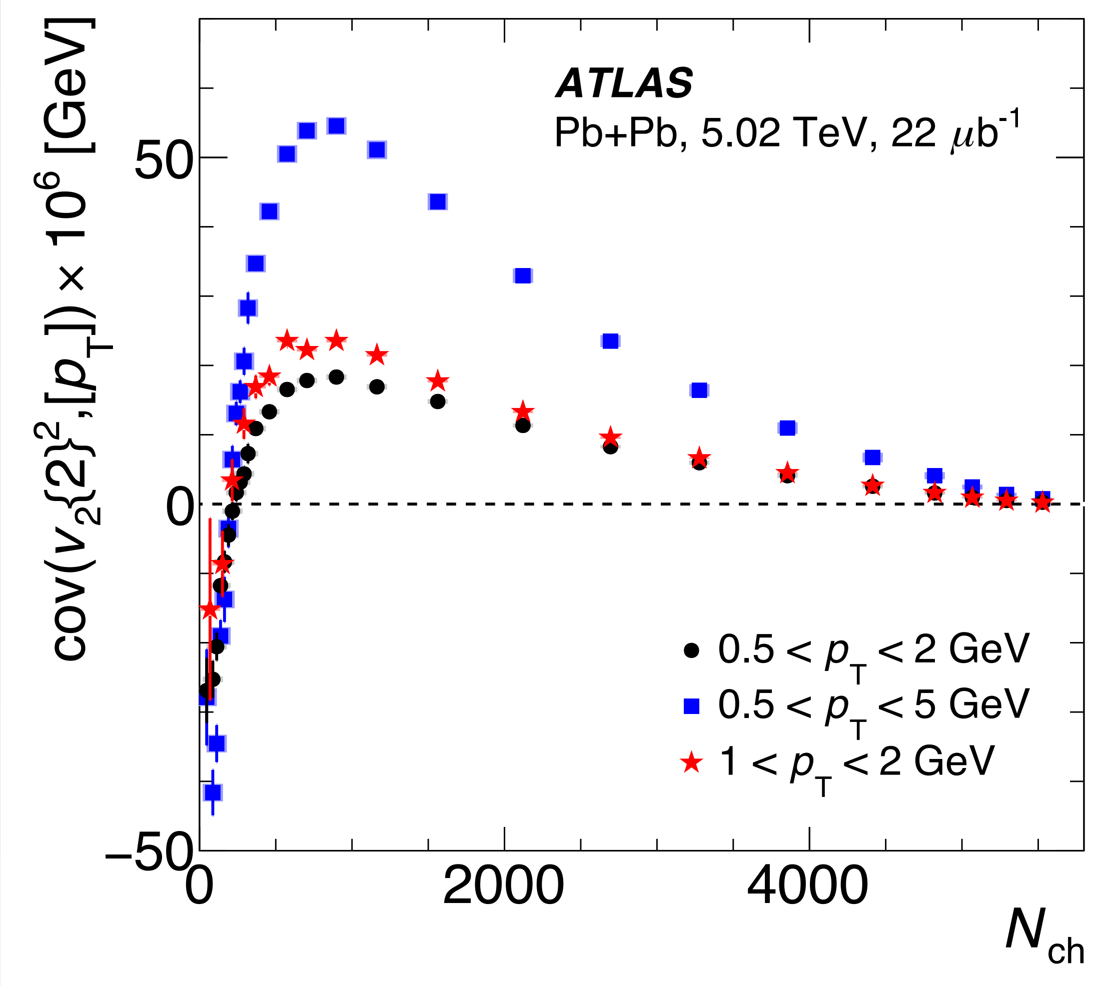
Details

$$\rho = \frac{\mathrm{cov}(v_n\{2\}^2, [p_\mathrm{T}])}{\sqrt{\mathrm{Var}(v_n\{2\}^2)_\mathrm{dyn}}\sqrt{c_k}}.$$



- Dataset: $\sqrt{s_{NN}} = 5.02\ TeV$,
  2015 *Pb+Pb* 22$\mu\mathrm{b}^{-1}$, 2013 *p+Pb* 28nb^{-1}
- Distinct sets of particles for $[p_\mathrm{T}]$ and $v_n\{2\}^2$
- Rapidity gaps to suppress non-flow
- Analysis in narrow bins of multiplicity in froward regions
  - Mapped to N_ch and N_part
- Several p_T intervals: hydrodynamics region, energy loss region & region to test sensitivity to multiplicity change

Ingredients of the ρ for v_2 in $Pb+Pb$



$\longrightarrow$ $0.5 < p_T < 5$ GeV, $|\eta| < 2.5$

Significant variation with centrality

Trend follows the v_2 magnitude

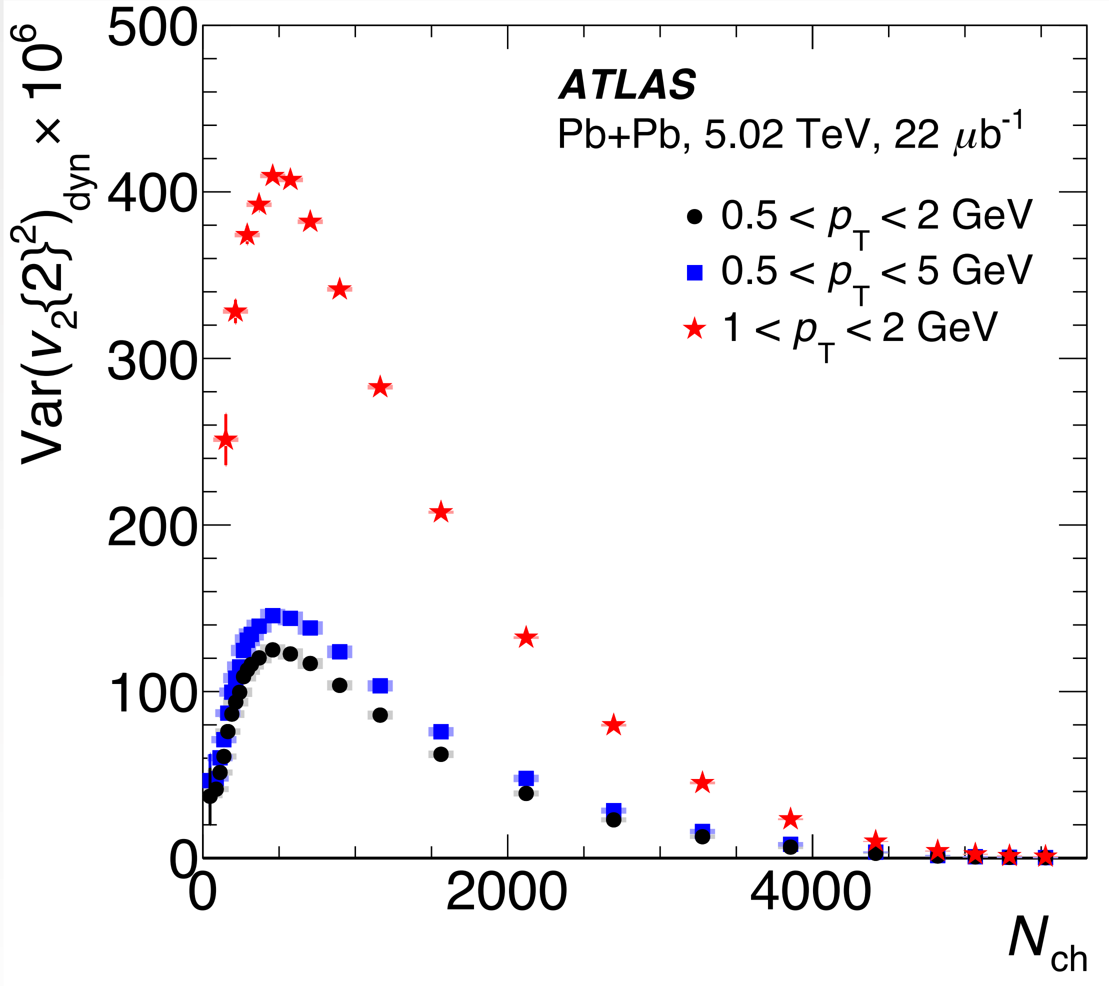
Negative in peripheral events!

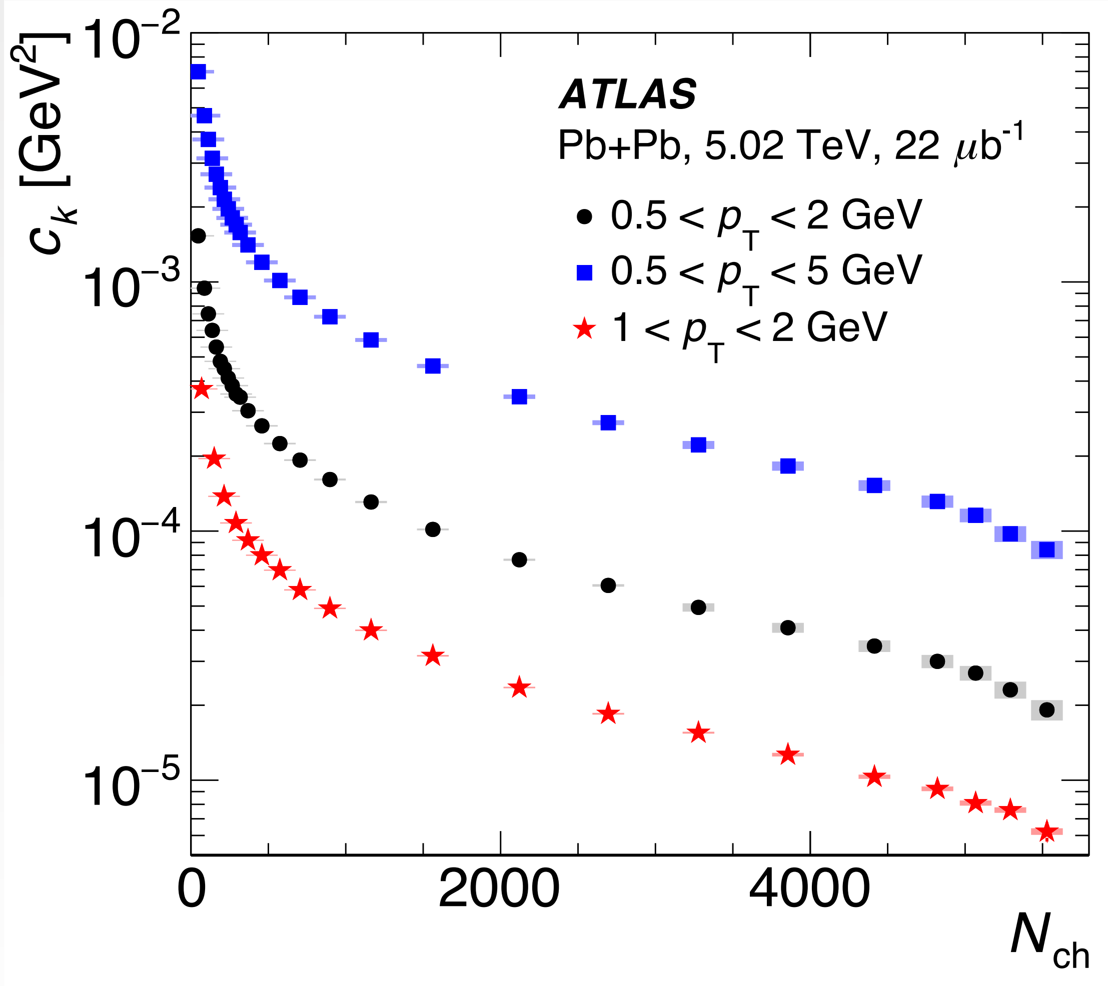
$$\rho = \frac{}{\sqrt{}}$$

Magnitude of v_2 fluctuations

Similar trend to v_2

Different p_{T} ordering as compared to cov

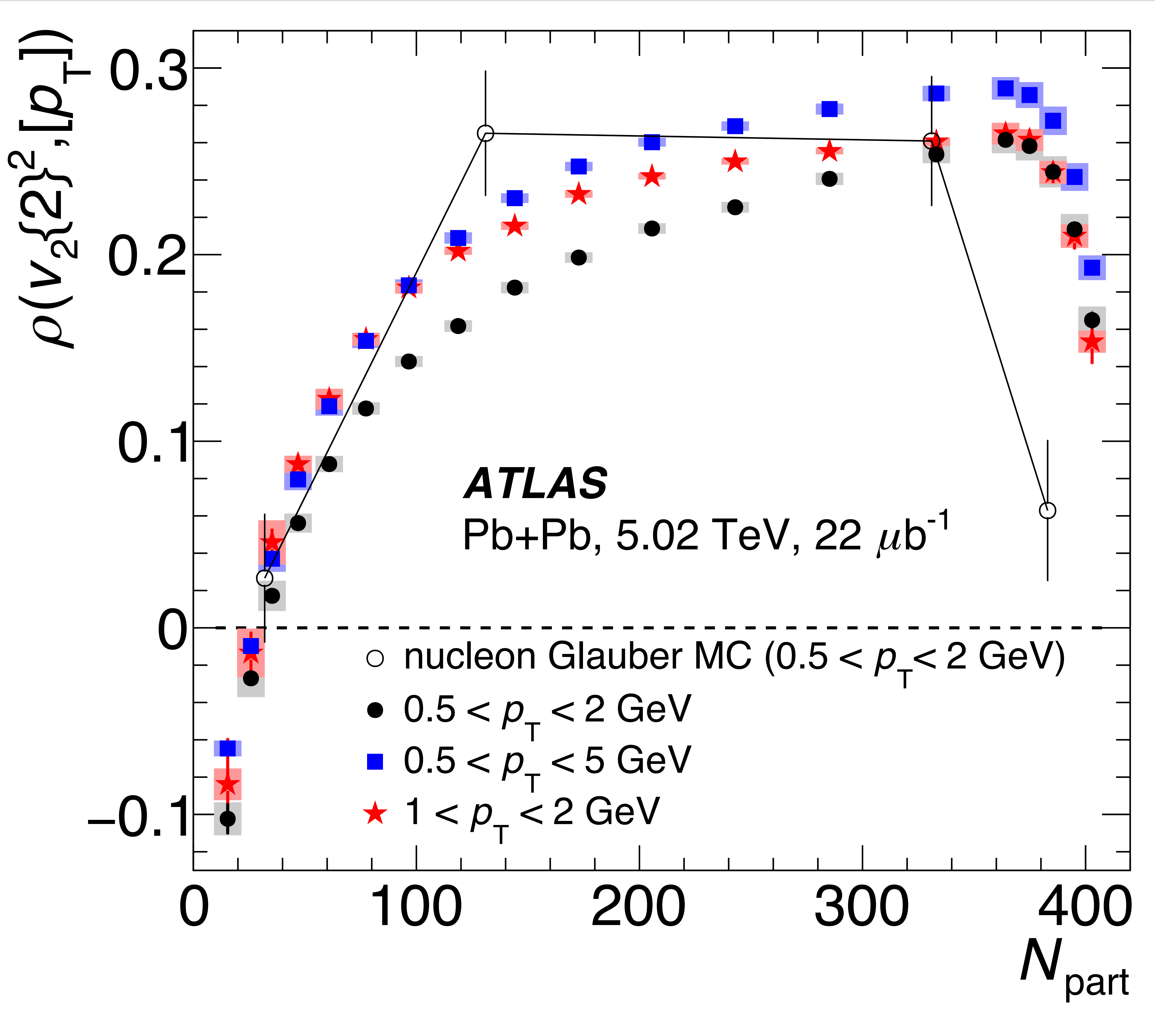




c_k quantifies magnitude of $[p_{\mathrm{T}}]$ fluctuations

Nontrivial p_{T} interval ordering, different than for *cov* and $\mathrm{Var}_{\mathrm{dyn}}$

Correlation coefficient ρ for v_2



Negative correlation for v_2 in peripheral collisions

→ related to ecc. ~ 1/r

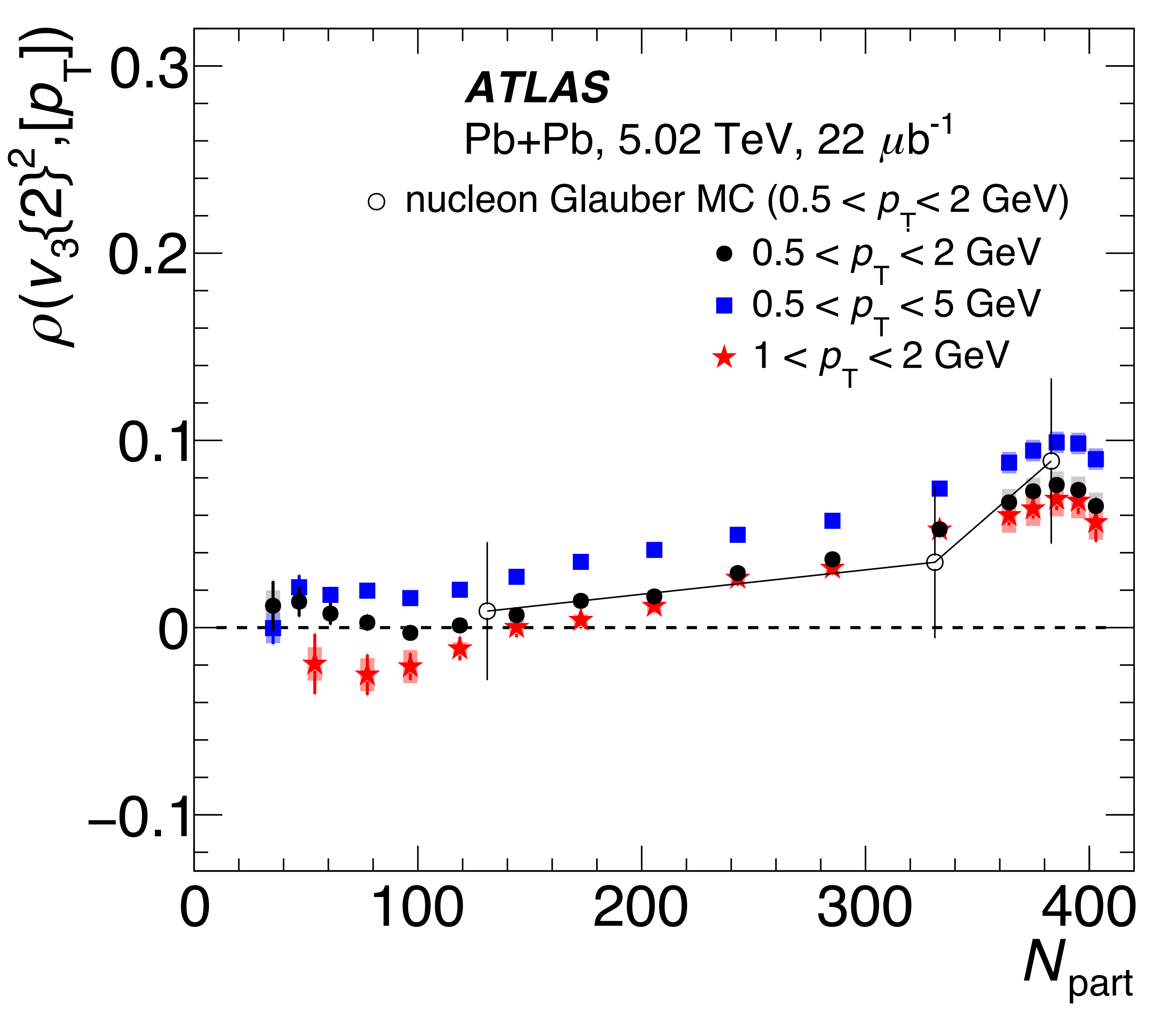
Gentle rise in mid central

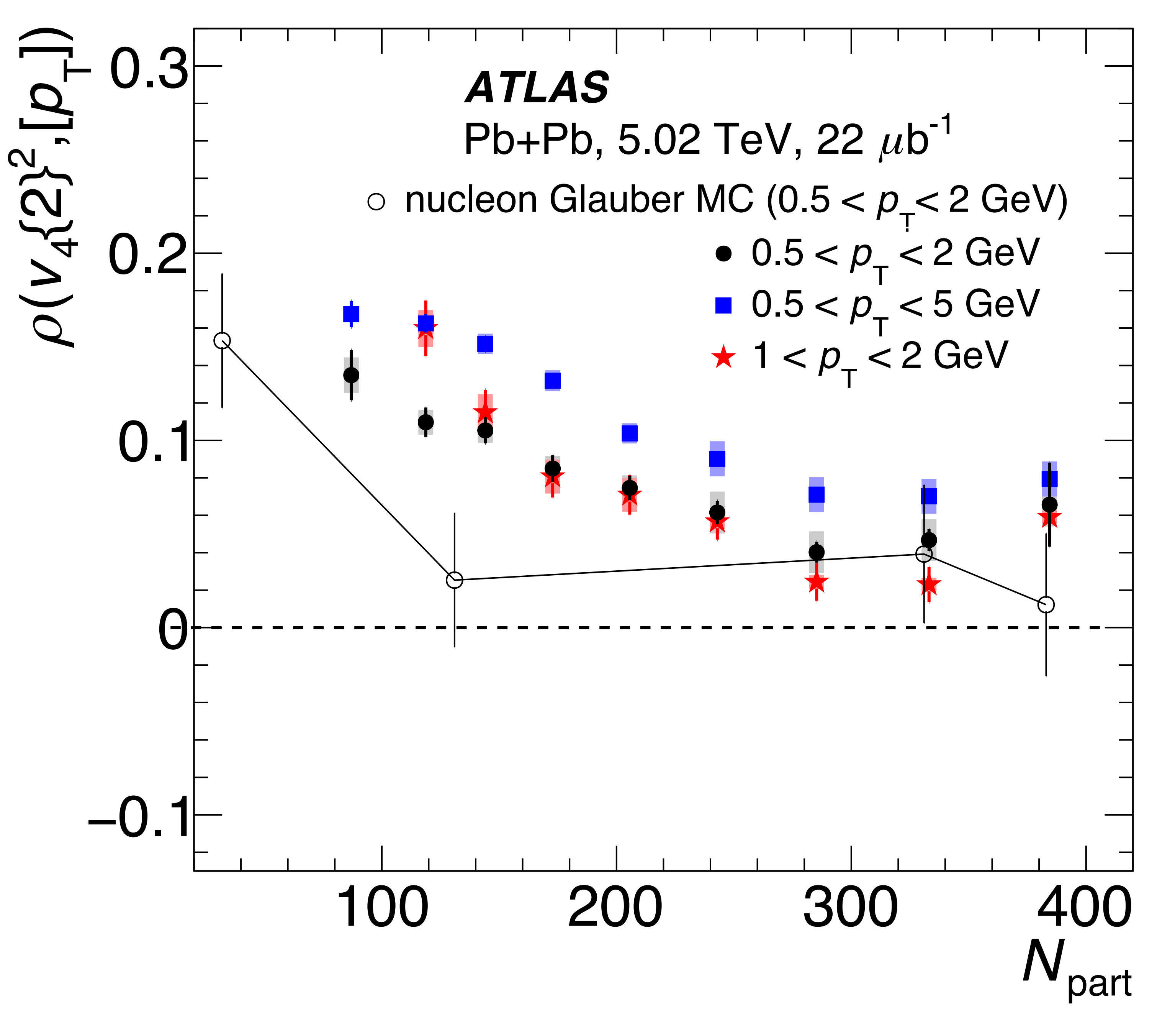
→ stronger hydrodynamic response to initial eccentricities - interplay between radial and elliptic flow

Fall in most central events

Hydrodynamics 1+3D (Phys. Rev. C93 044908), reproduces the behaviour qualitatively

Correlation coefficient ρ for v_3 and v_4





Correlation for v_3 is weaker compared to v_2

Positive except for $N_{\mathrm{part}} < 100$ and $p_{\mathrm{T}} > 1$GeV

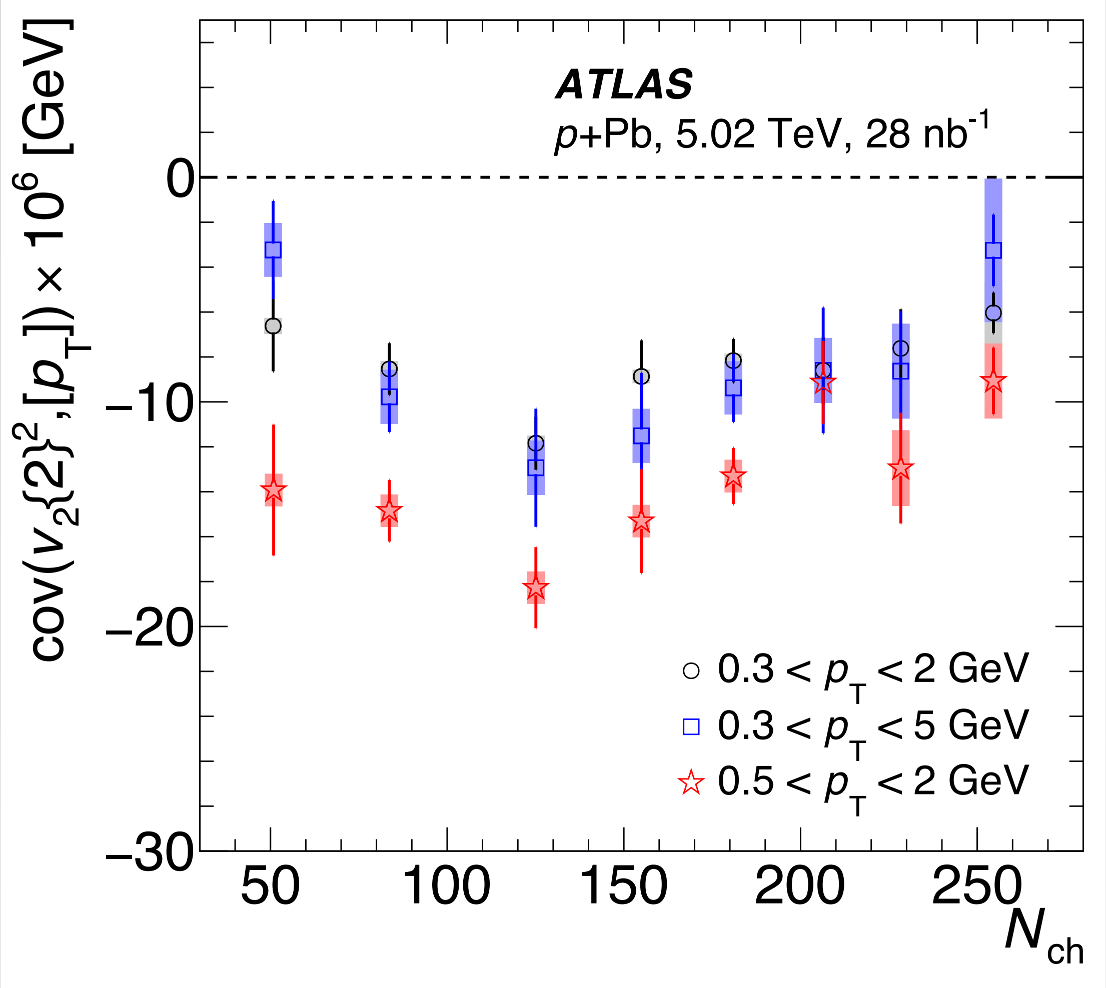
Above $N_{\mathrm{part}} \simeq 100$ steady rise

Significant correlation for v_4

The trend is inverted as compared to v_2 and v_3

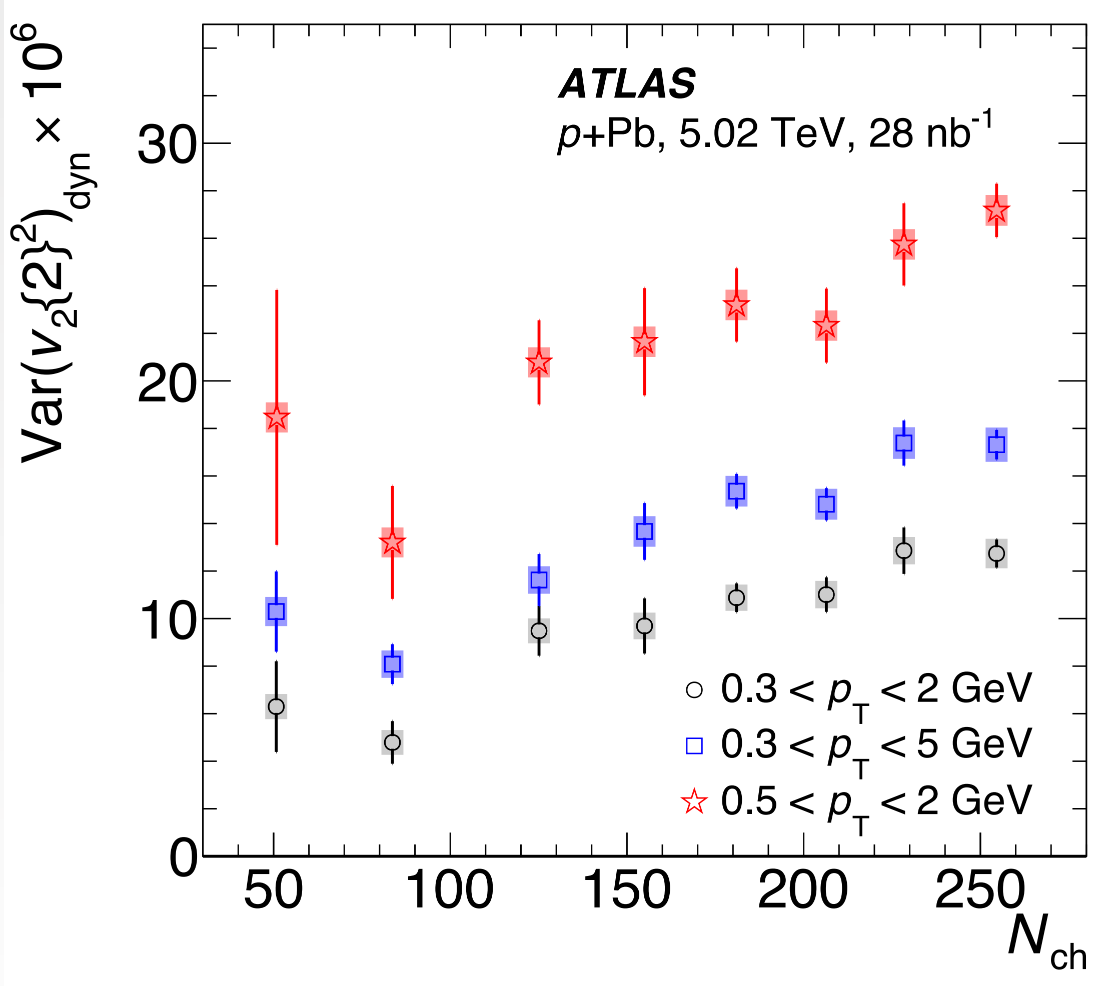
Change of the trend in central events
→ nonlinear hydro response to initial geometry fluctuations?

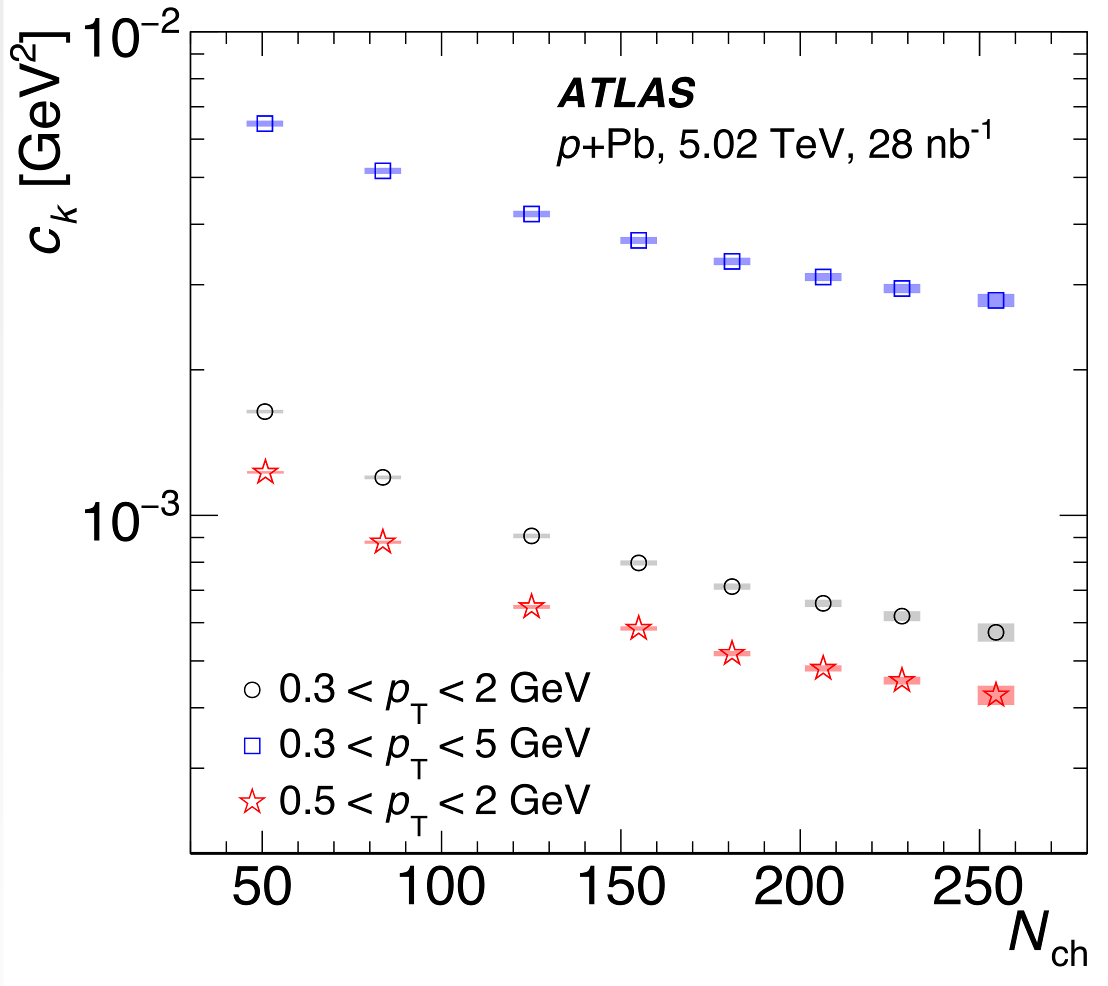
Ingredients of ρ for v_2 in p+Pb



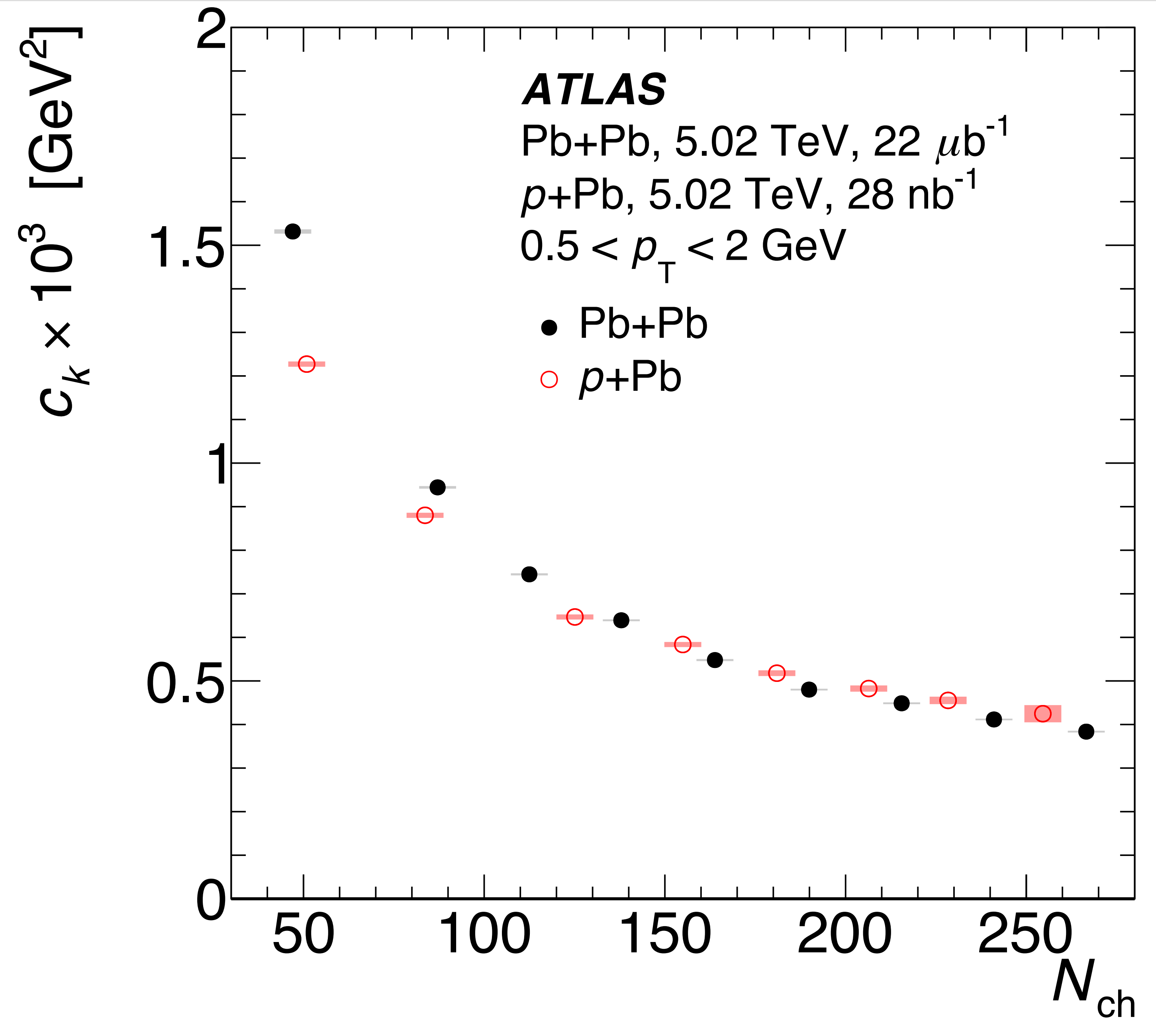
Negative covariance, will determine sign of ρ

$$\rho = \frac{}{\sqrt{}}$$





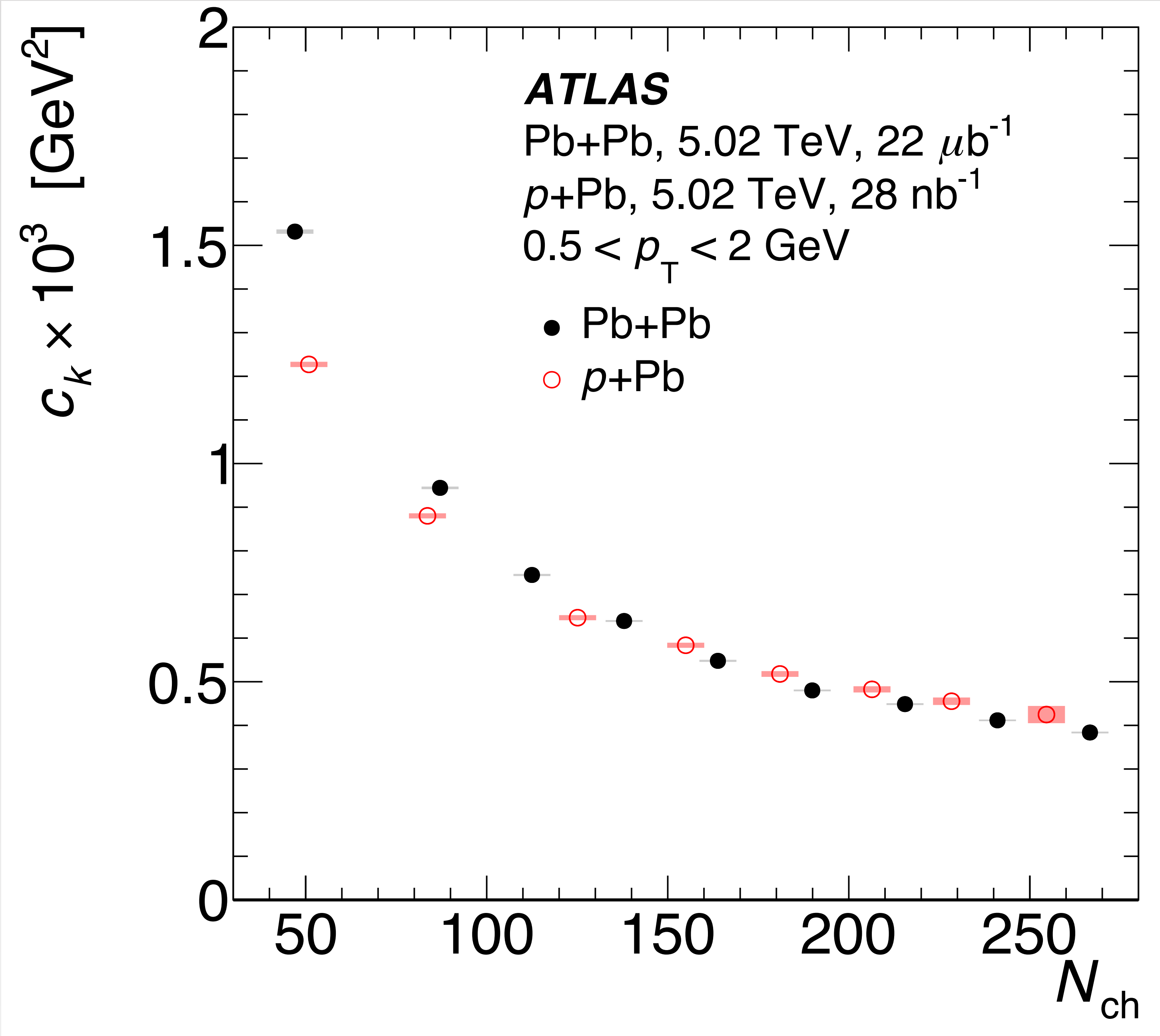
The ρ for v_2 in *p+Pb* vs *Pb+Pb*

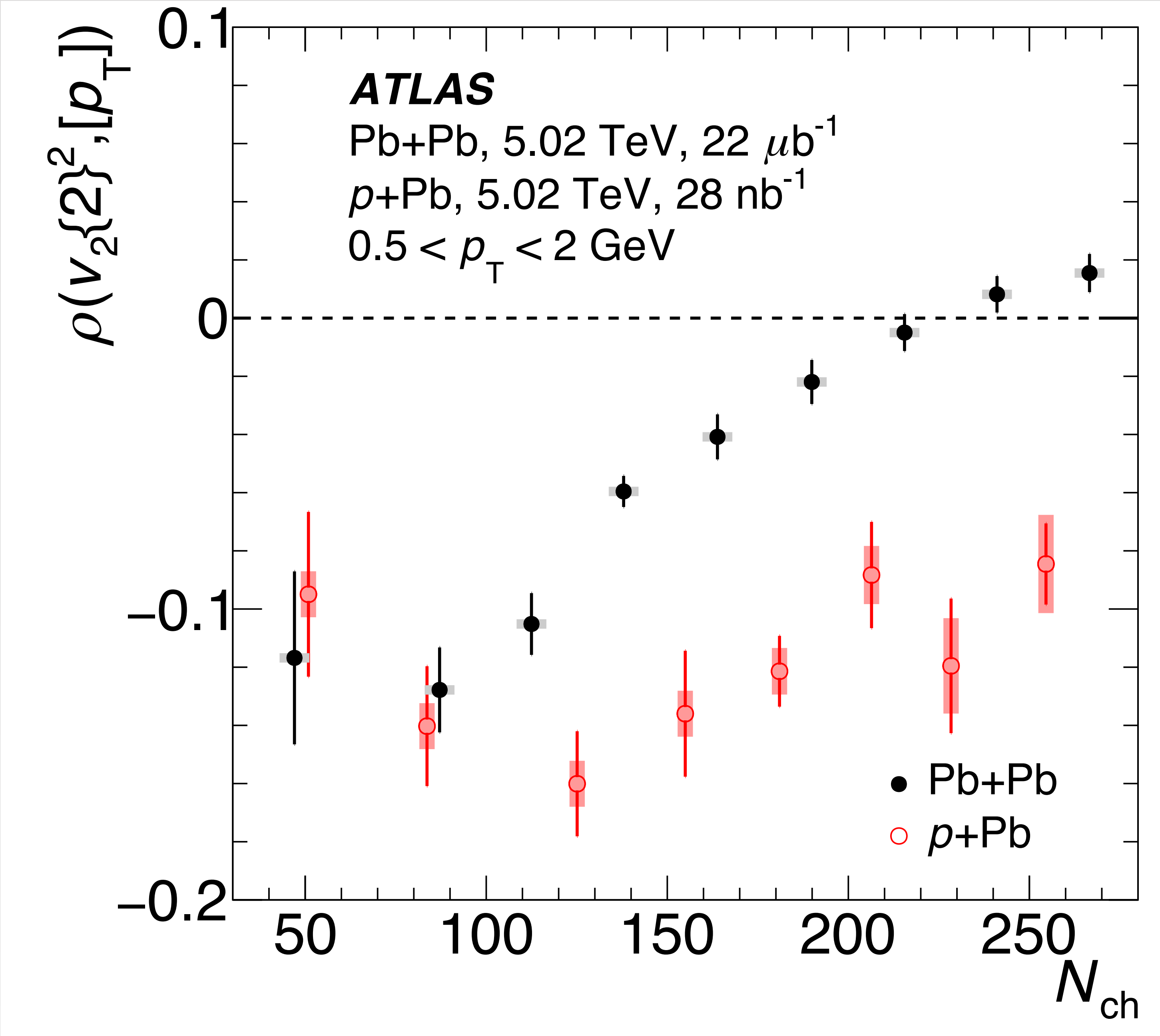


The $[p_T]$ fluctuations are of similar magnitude in *p+Pb* and peripheral *Pb+Pb* when matched N_{ch}

The difference in the ρ values driven by the flow

The ρ for v_2 in *p+Pb* vs *Pb+Pb*





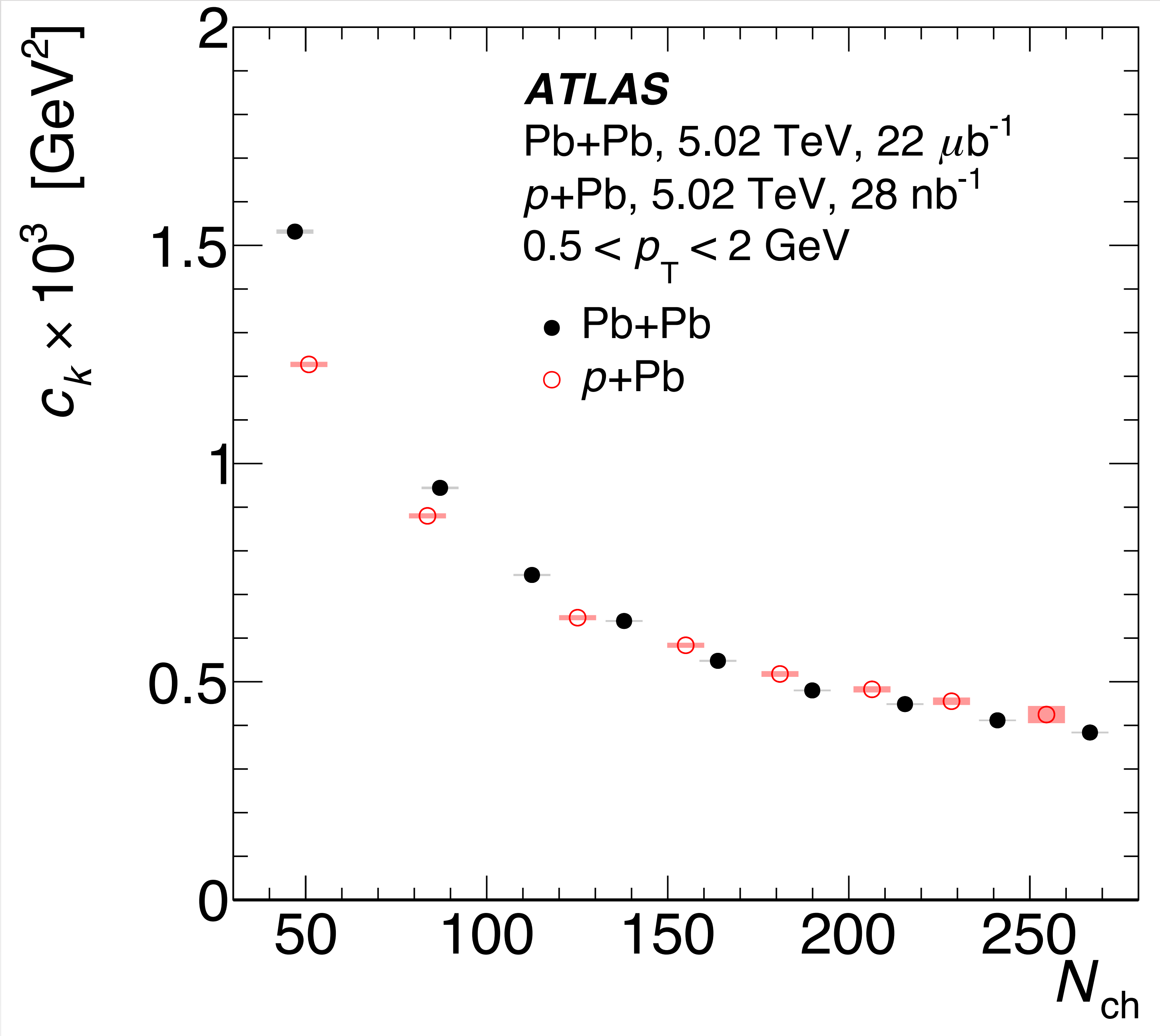
The $[p_{\mathrm{T}}]$ fluctuations are of similar magnitude on *p+Pb* and peripheral *Pb+Pb* when matched N_{ch}

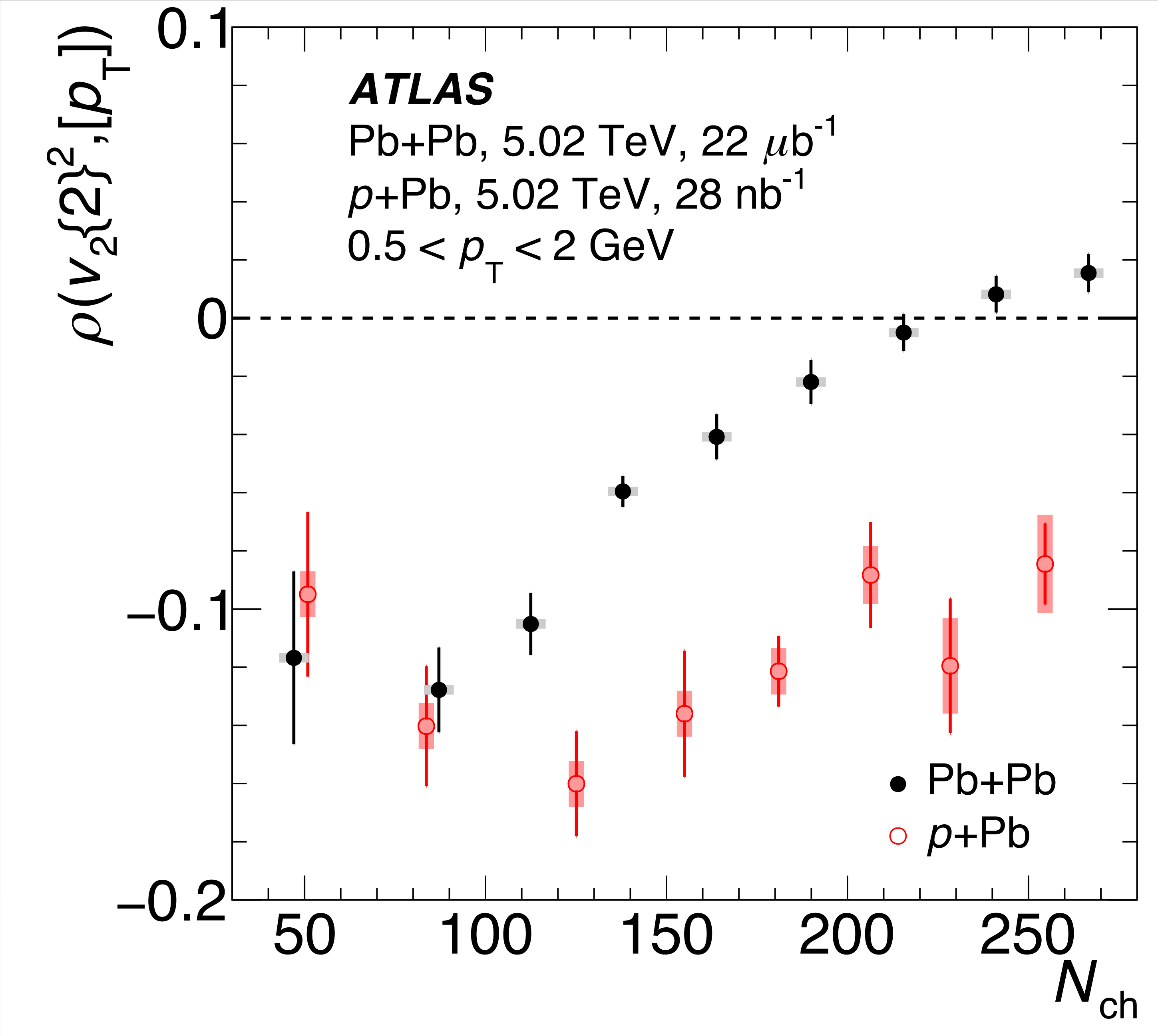
The difference in the ρ values driven by the flow

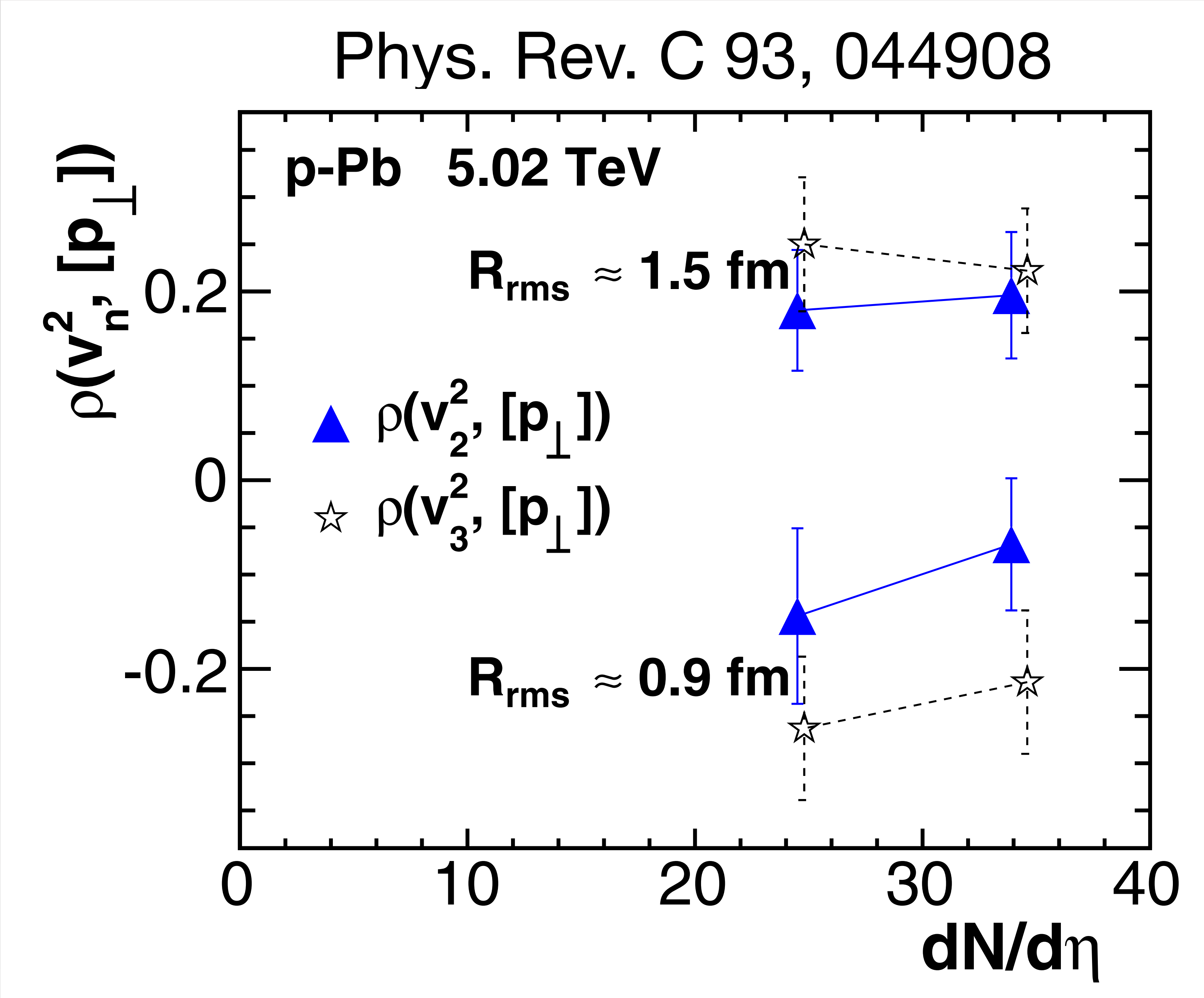
The ρ for v_2 is negative in high multiplicity *p+Pb* collisions, for N_{ch} < 100, compatible with *Pb+Pb*

No geometry driven trend observed in *p+Pb* compared to a clear effect in *Pb+Pb*

The ρ for v_2 in *p+Pb* vs *Pb+Pb*







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The difference in the ρ values driven by the flow

The ρ for v_2 is negative in high multiplicity *p+Pb* collisions, for $N_{ch} < 100$, compatible with *Pb+Pb*

No geometry driven trend observed in *p+Pb* compared to a clear effect in *Pb+Pb*

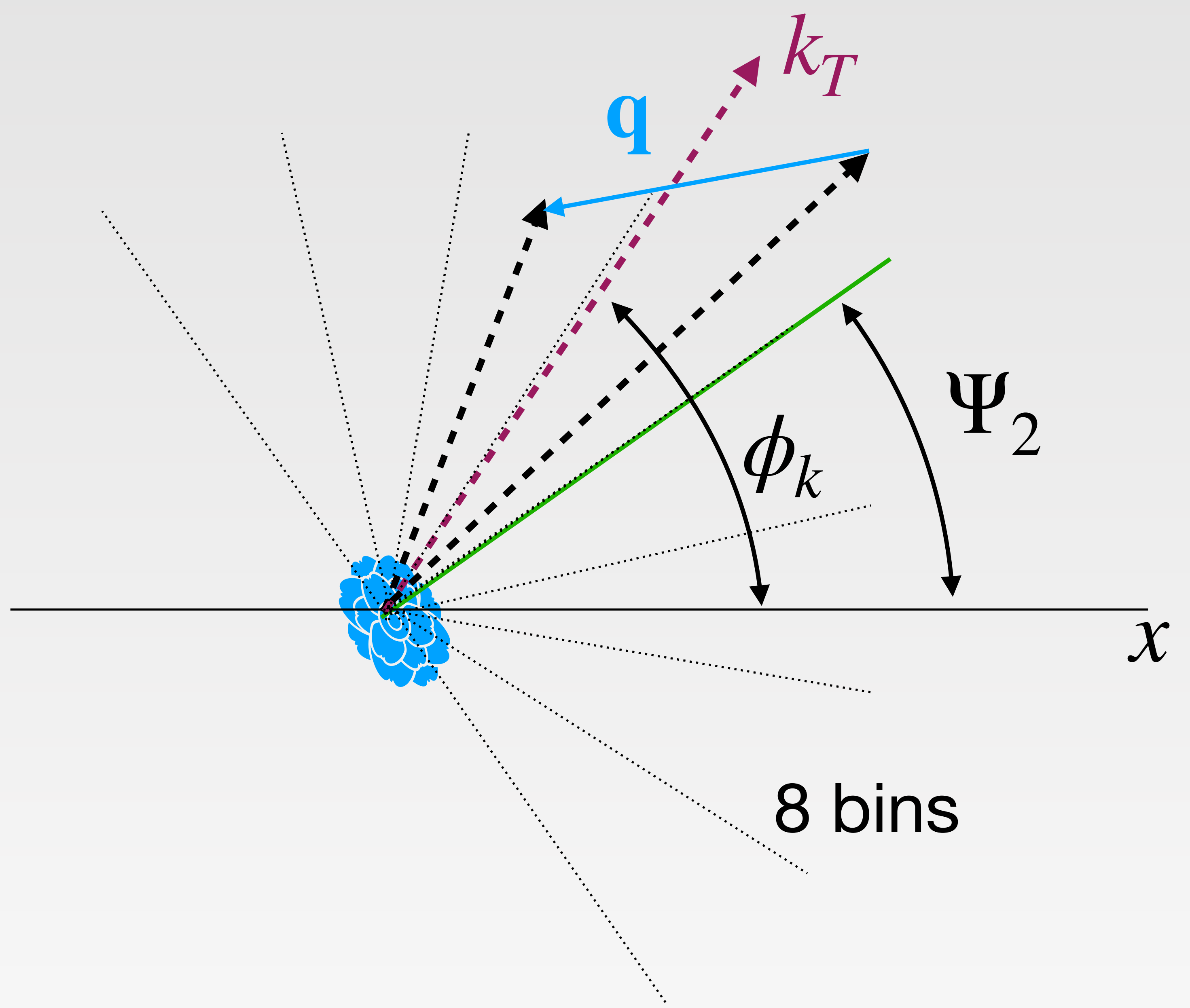
Favours small dimensions of the initial state -> higher pressure ($[p_T]$), low eccentricity (v_2)

Event-plane dependence of HBT radii in high-multiplicity in 5.02 TeV *p+Pb* collisions with the ATLAS detector

ATLAS-CONF-2017-008

The idea

- Many observables point to the collective behaviour of the system created in *p+Pb* collisions
  - Competitive theoretical explanations available, hydrodynamics vs “glasma” models
  - By measuring the shape of the fireball we can provide useful input
- Technique:
  - Measure the HBT radii with pions ($0.2 < k_T < 0.3$ GeV - late ev. stag) as a function of angular distance of k_T from Ψ_2 - $2(\phi_k - \Psi_2)$
  - In bins of flow vector magnitude $|\vec{q}_2|$

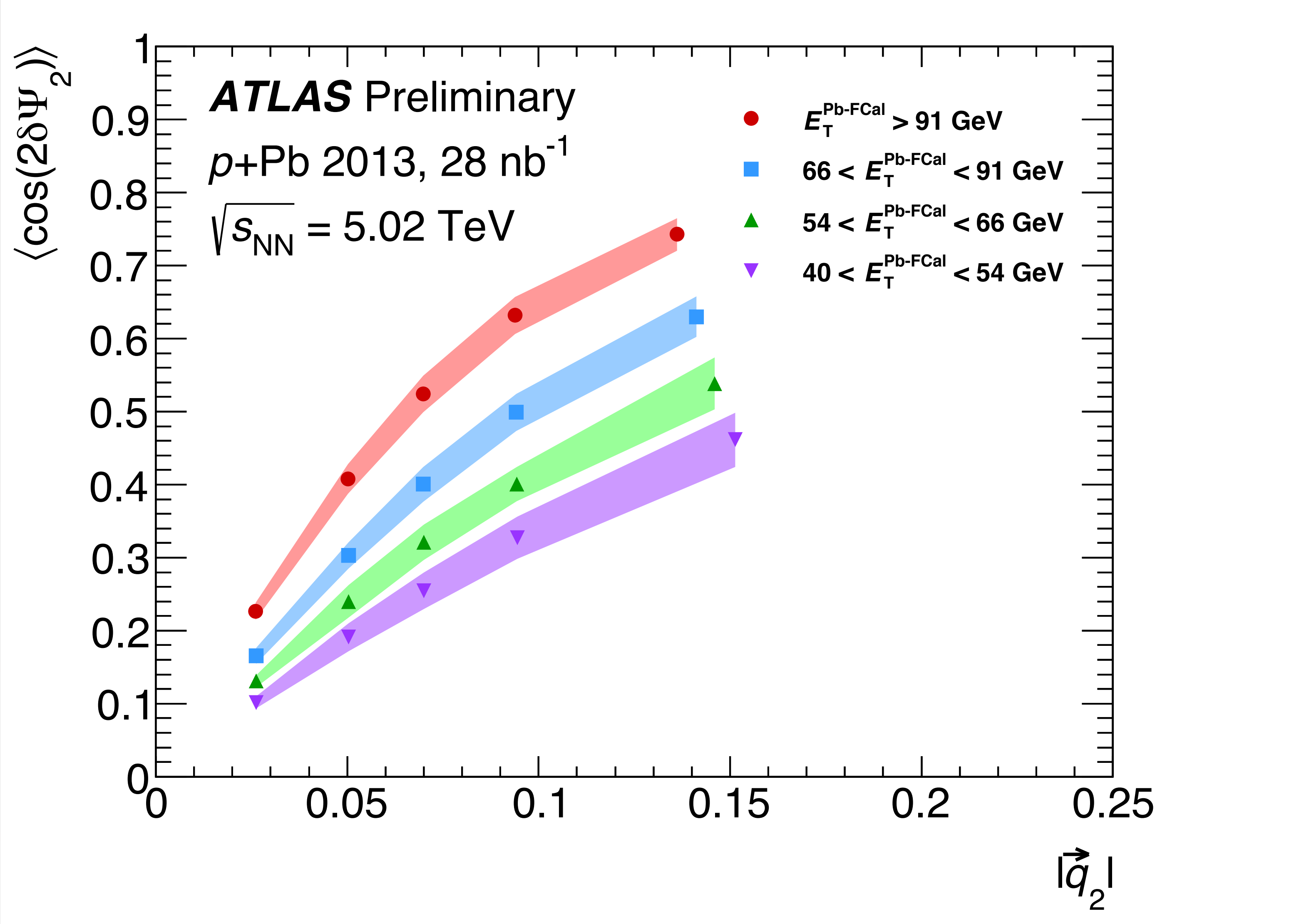


- **Is there any modulation visible in *p+Pb*? How significant?**
- **Does it depend on the $|\vec{q}_2|$, does it become $\simeq 0$ for $|\vec{q}_2| \simeq 0$?**
- **Does it resemble the modulation in *A+A*?**

Analysis

- Events selection: $28\mathbf{nb}^{-1}$ of *p+Pb* data from 2013
- High multiplicity $N_{ch} > 130$
- Very careful treatment of detector effects applied
- $p_{T,min} = 0.1$ GeV, same-, mixed- events distribution corrected for Ψ_2 resolution
  (U. W. Heinz Phys. Rev. 044903),

  $c_{\mathrm{BE}}(\mathbf{q})$ includes corrections for:
  final state - Bowler-Sinyukov
  jets - opposite-sign + scaling from MC
- **Extracted modulation amplitude for:**
  R_{out} -along k_T, **R_{side}** - $\perp$ k_T, **R_{os}, R_{long}** - along z



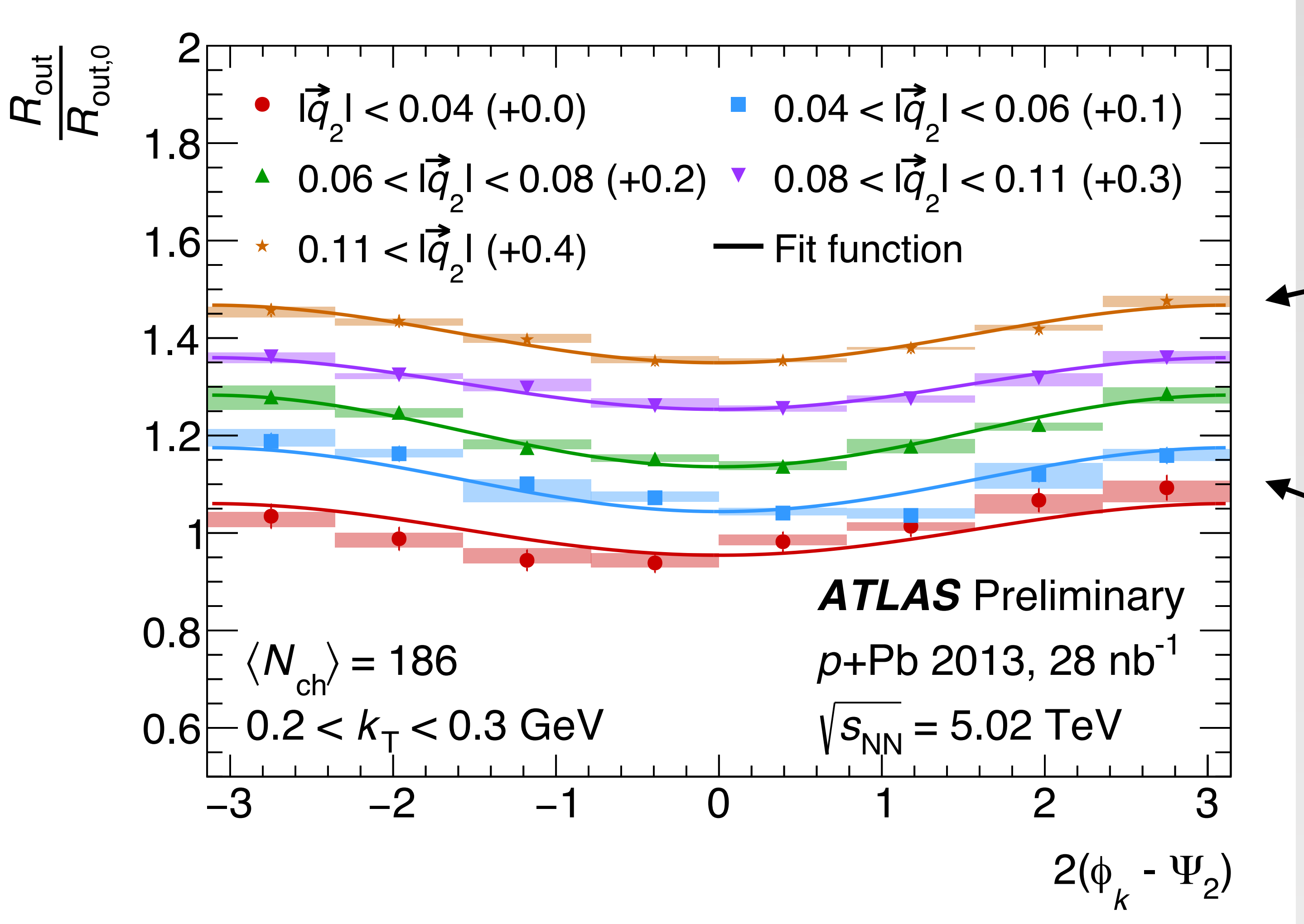
$$C_{\mathrm{BE}}(\mathbf{q}) = 1 + e^{-\|R\mathbf{q}\|}$$

$$R = \begin{pmatrix} R_{\mathrm{out}} & R_{\mathrm{os}} & 0 \\ R_{\mathrm{os}} & R_{\mathrm{side}} & 0 \\ 0 & 0 & R_{\mathrm{long}} \end{pmatrix}$$

$$R_i = R_{i,0}\left(1 + 2\frac{R_{i,2}}{R_{i,0}}\cos[2(\phi_k - \Psi_2)]\right)$$

$$R_{\mathrm{os}} = 2R_{\mathrm{os},2}\sin[2(\phi_k - \Psi_2)]$$

Extracted radii



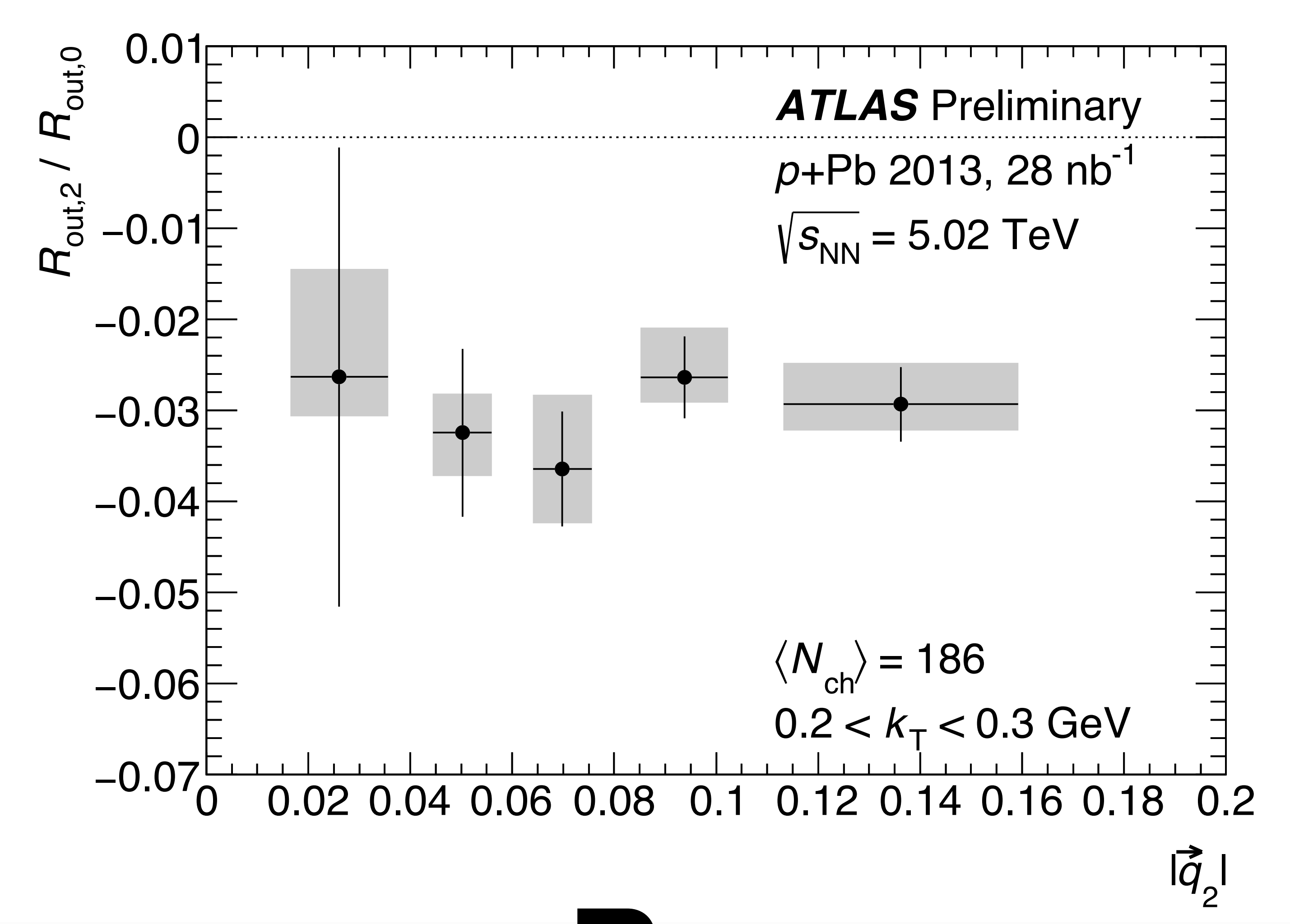
large $|\vec{q}_2|$

+arbitrary shifts for visibility

small $|\vec{q}_2|$

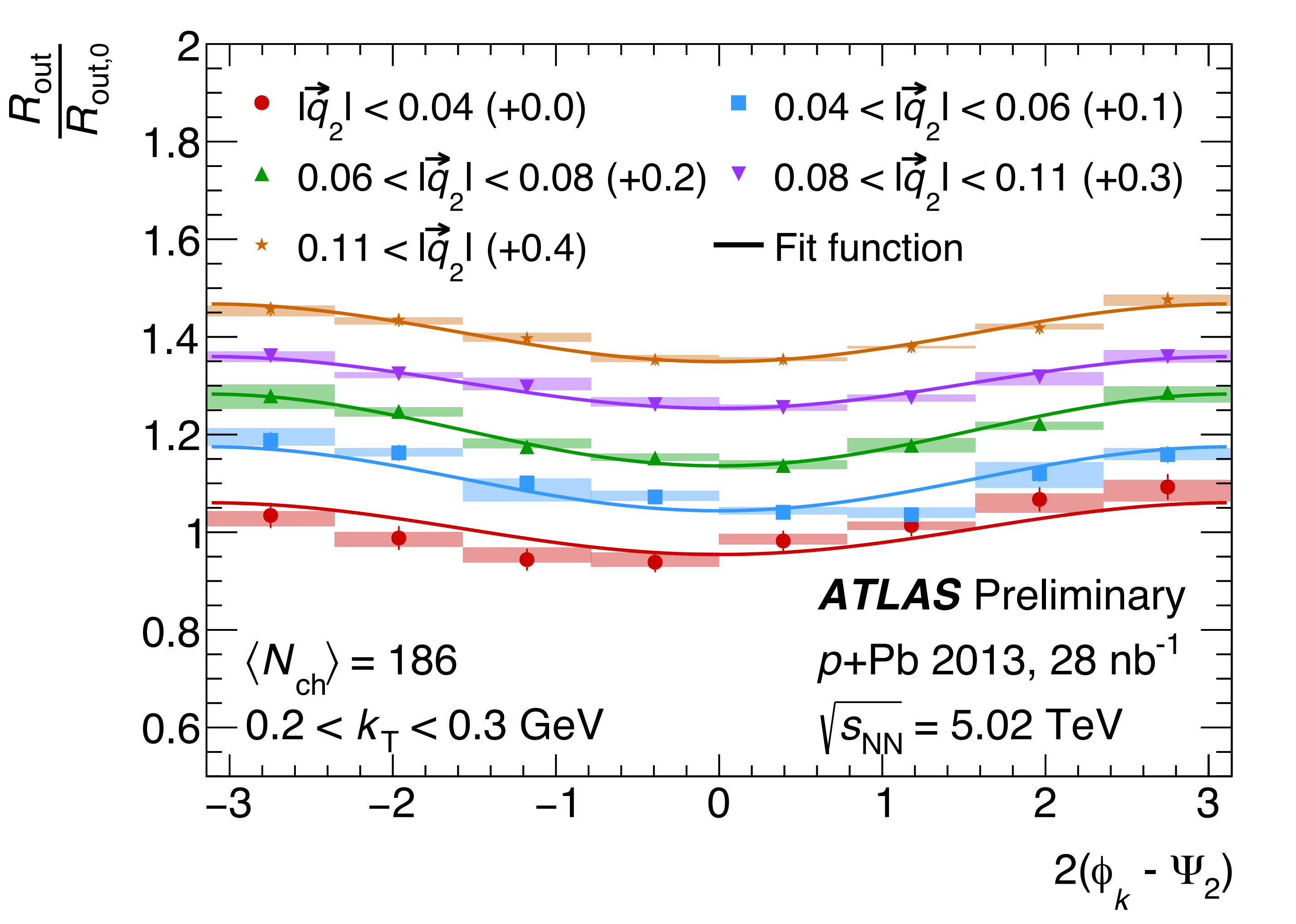
point - data

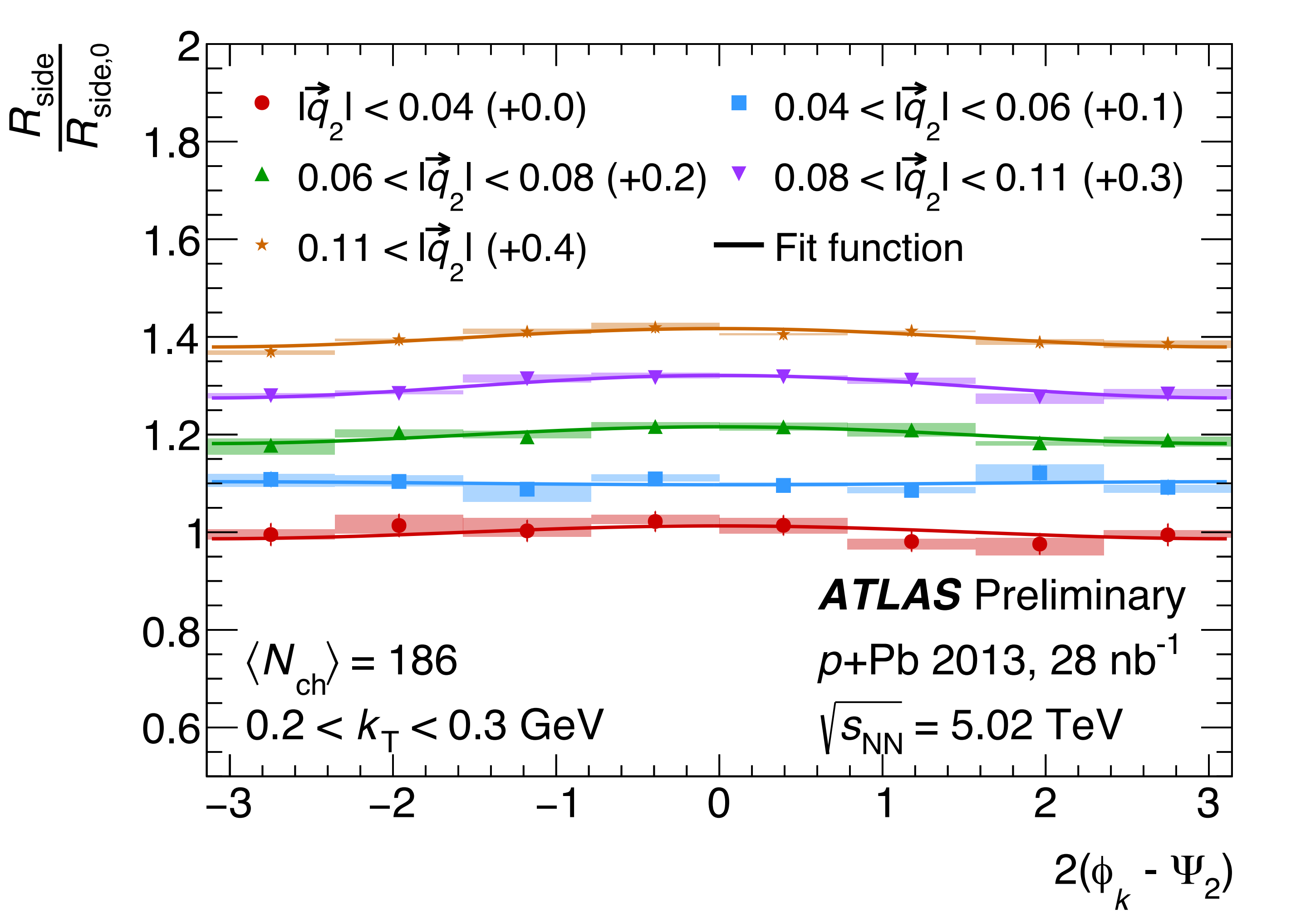
lines - cos/sin fits

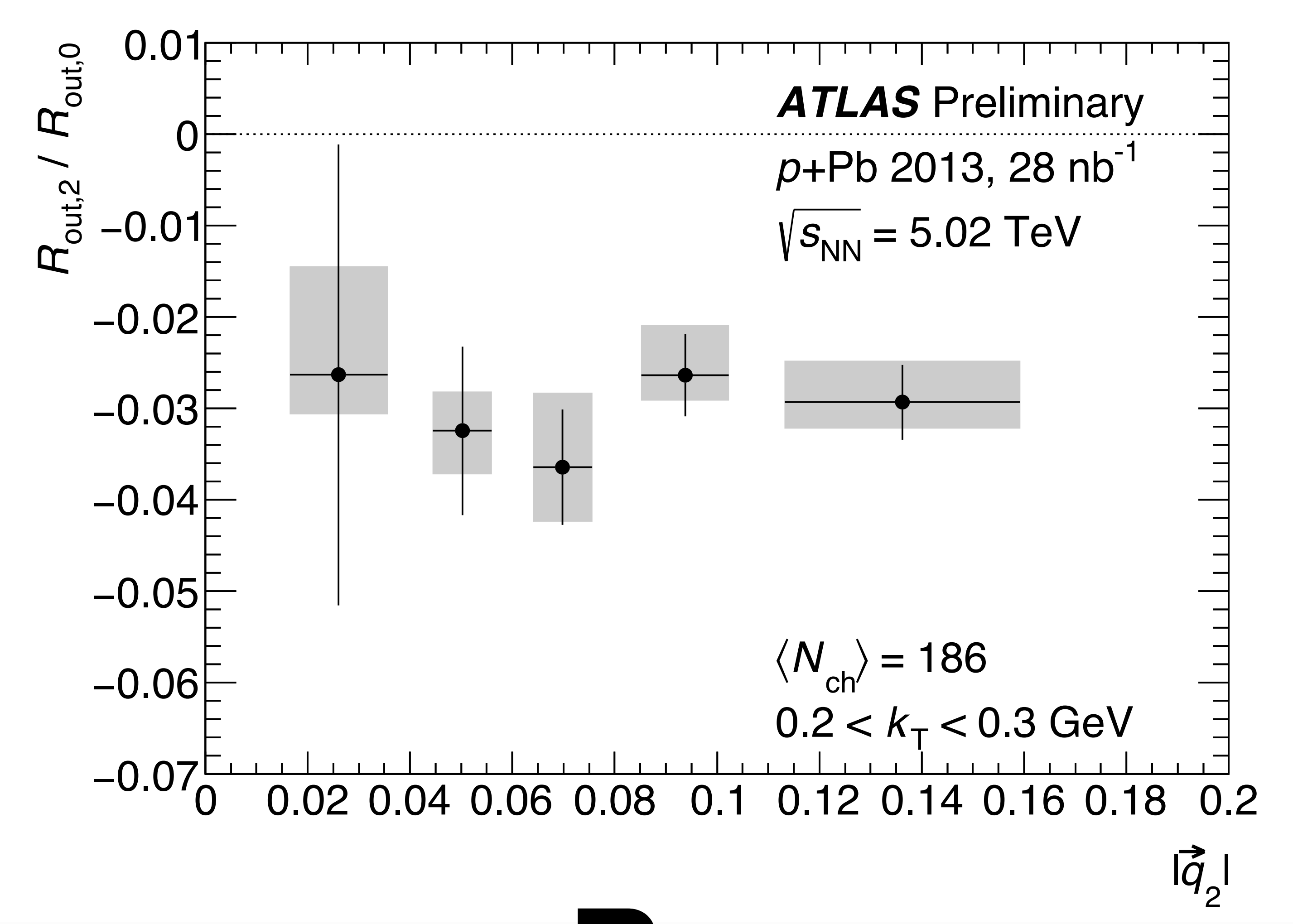


R_{out}

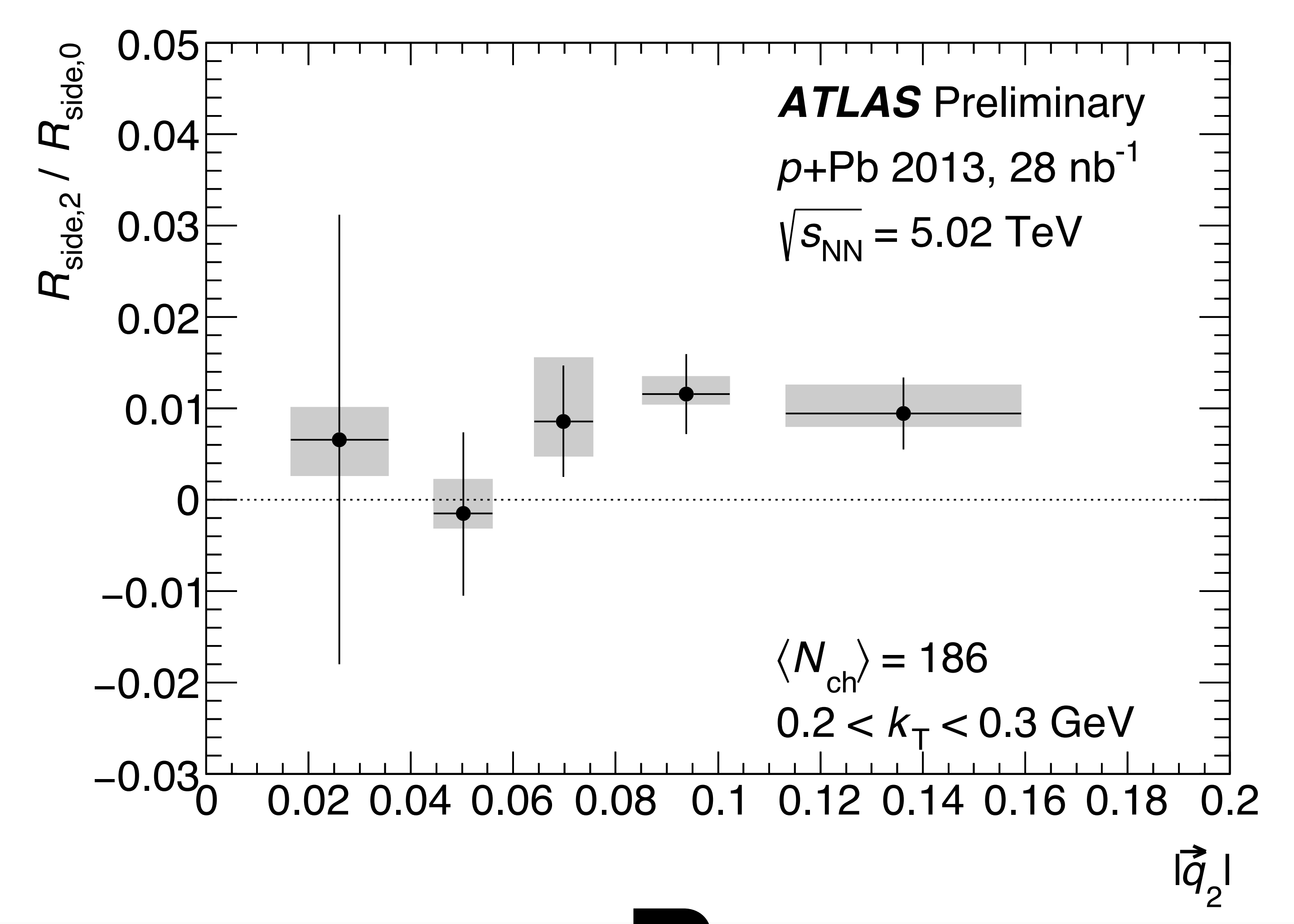
Extracted radii





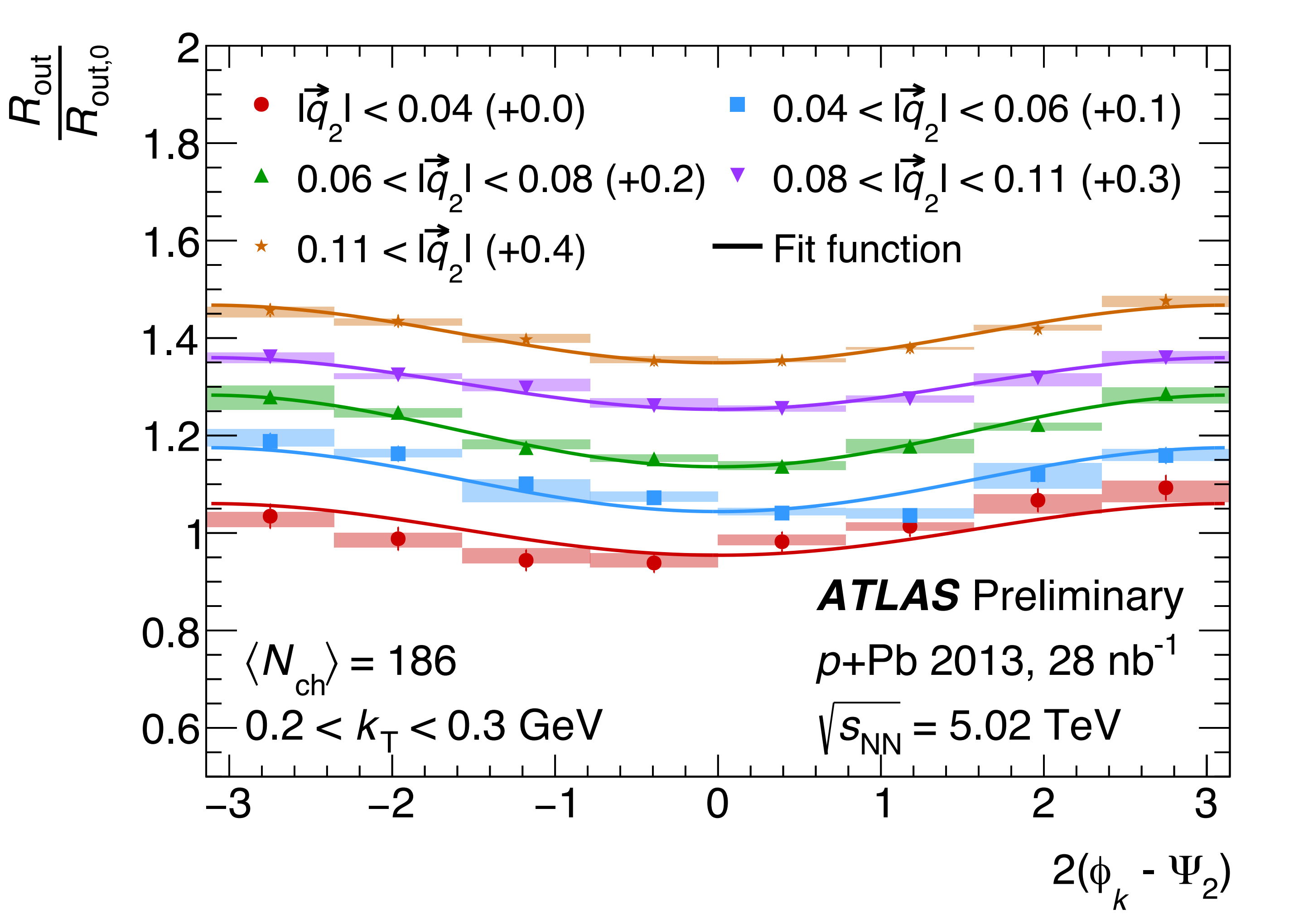


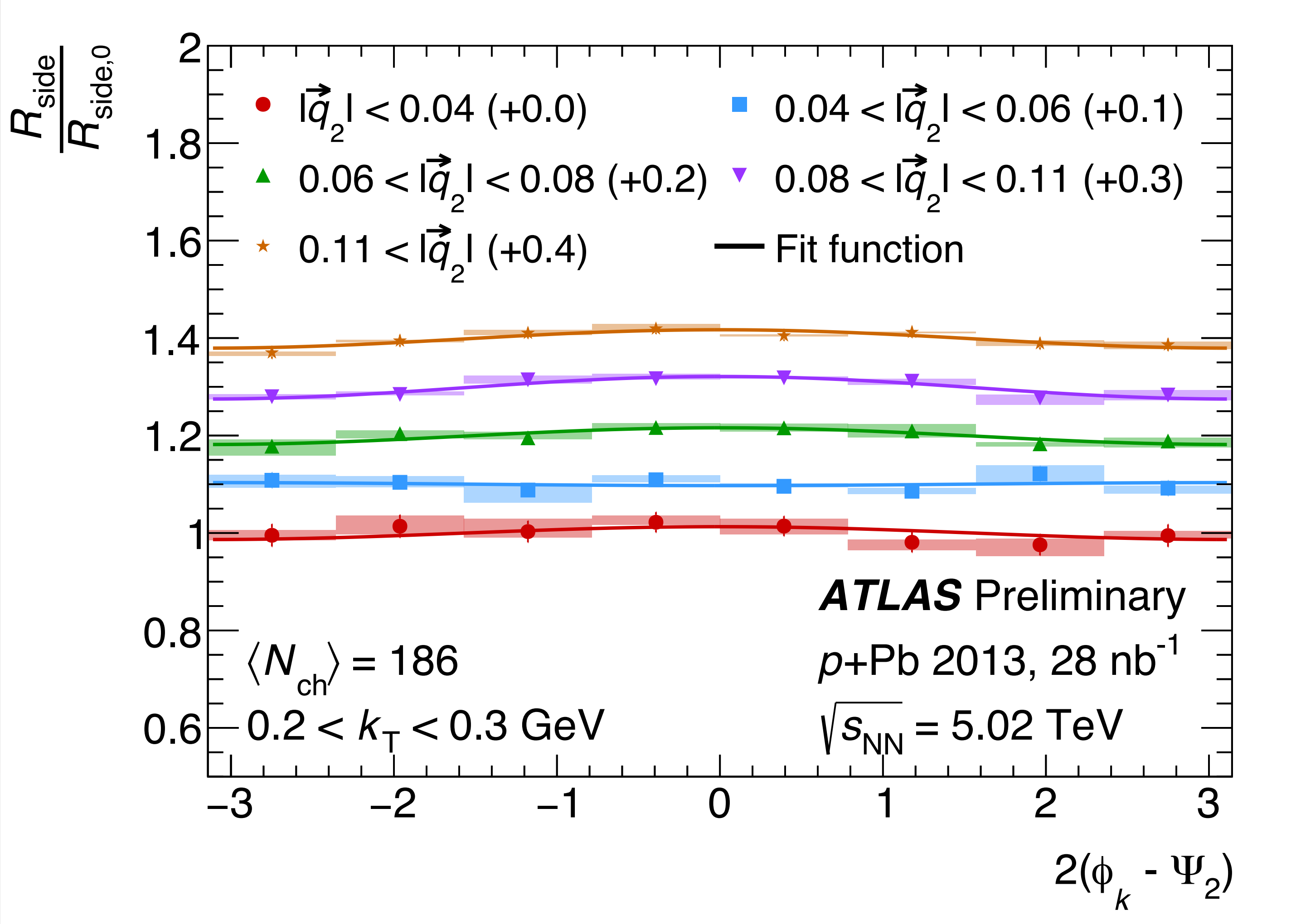
Rout

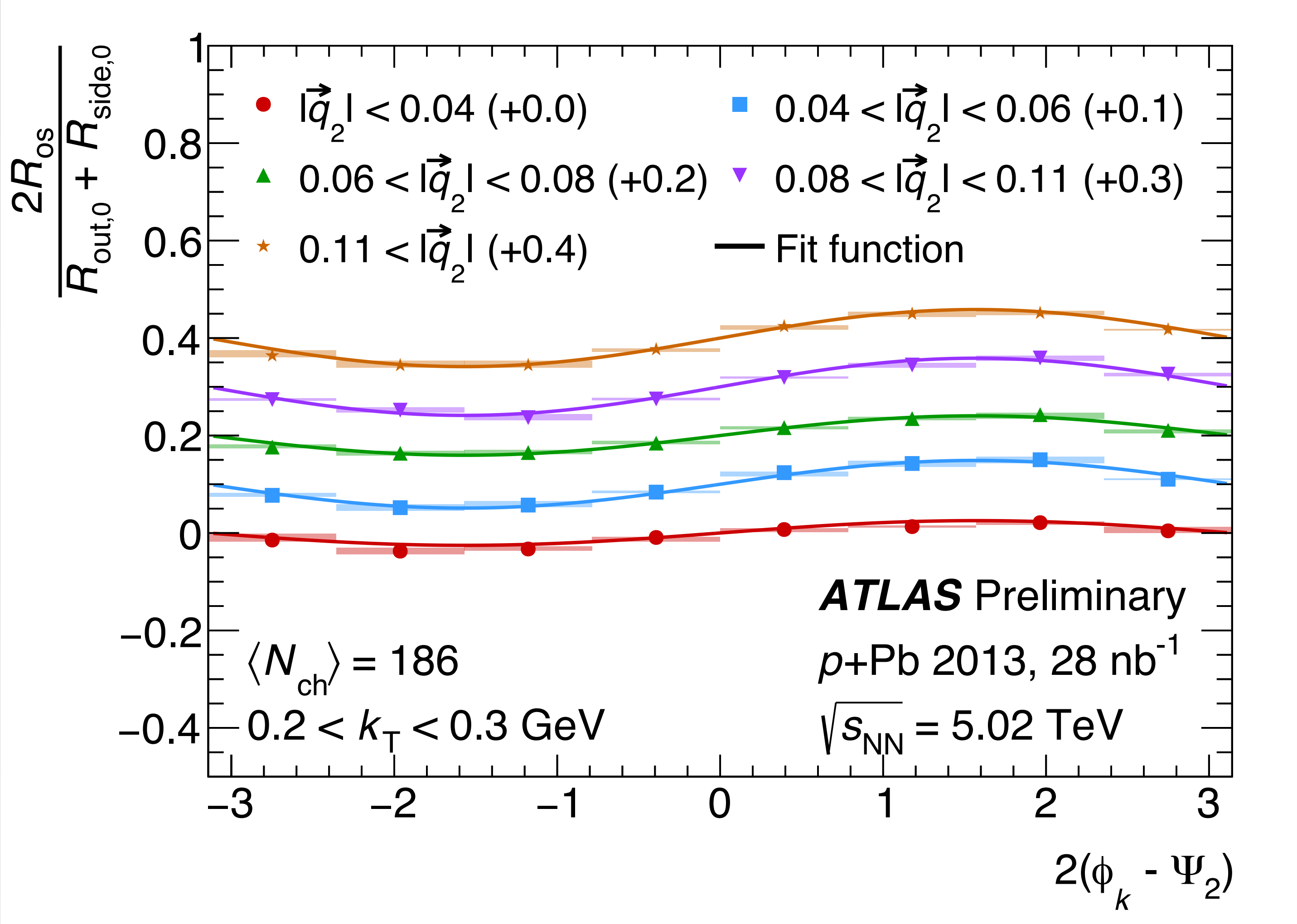


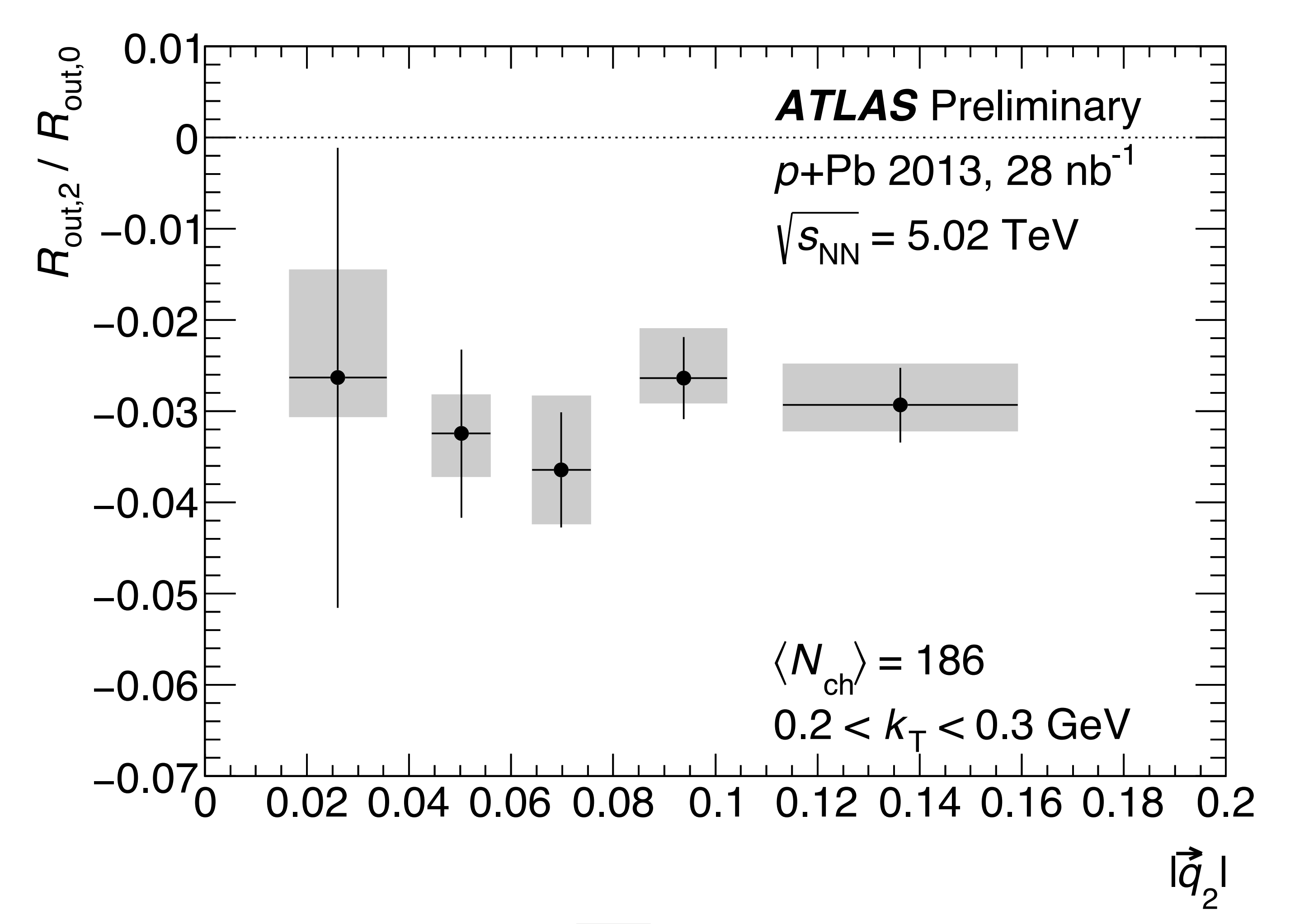
Rside

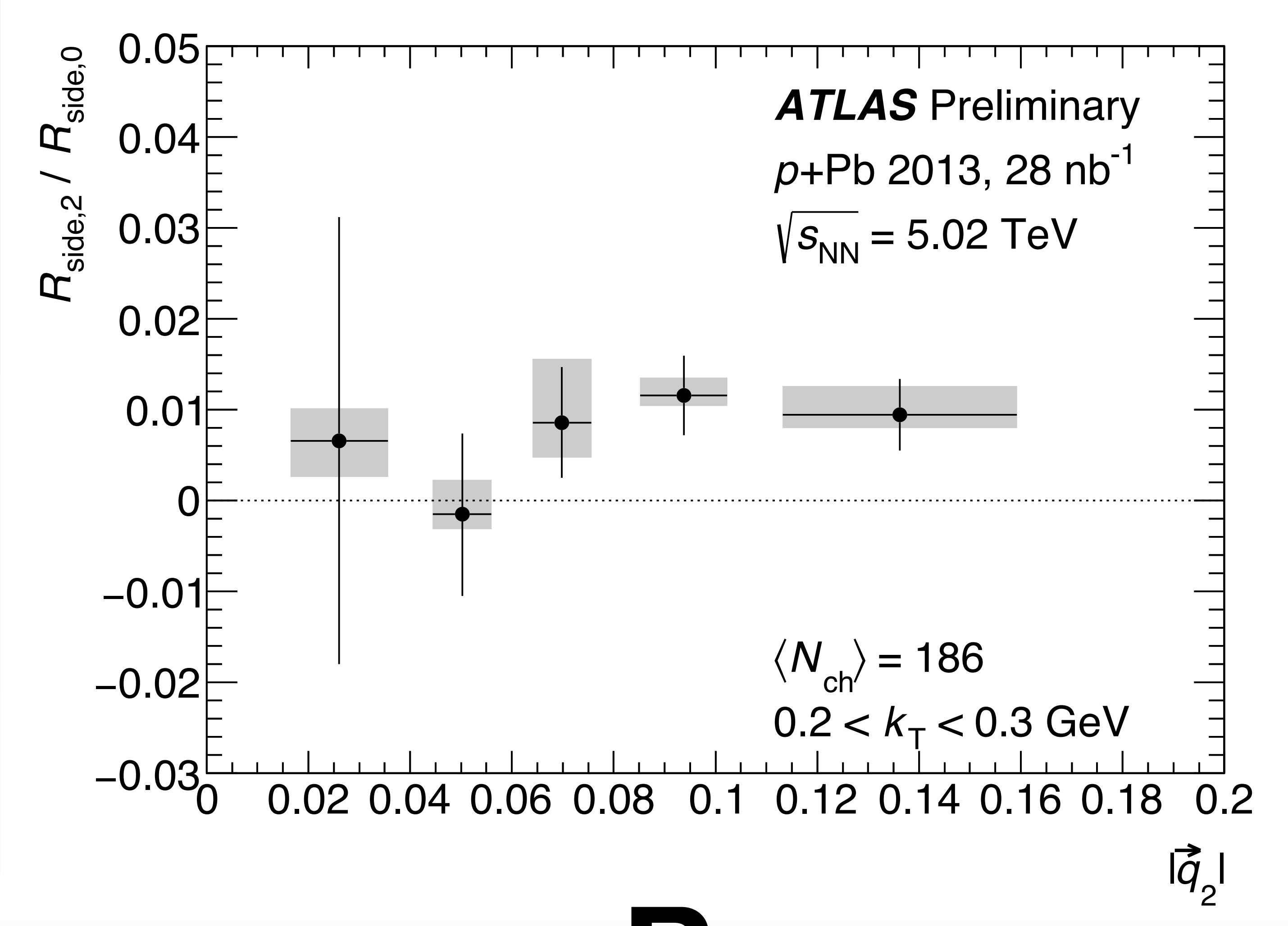
Extracted radii

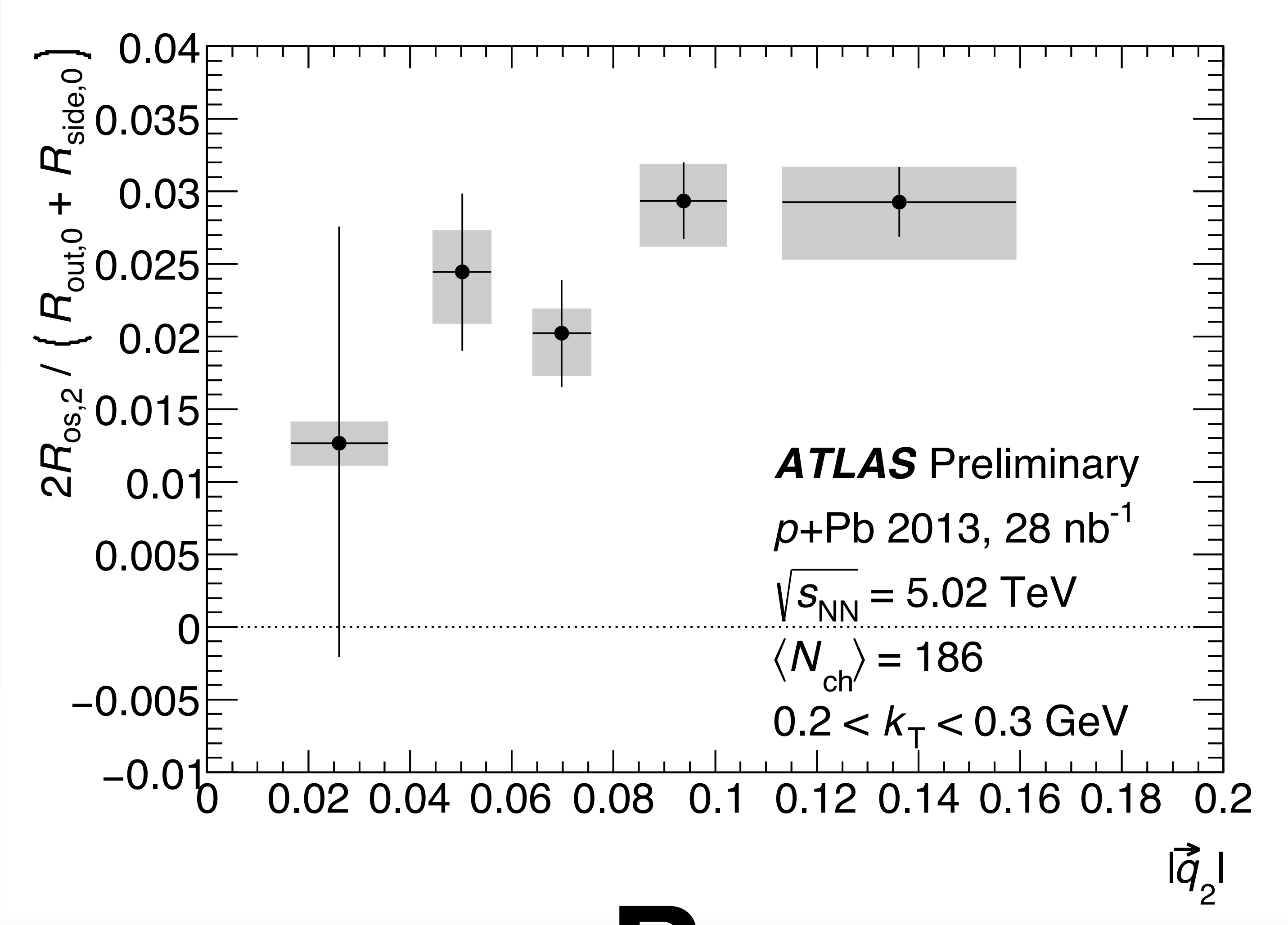






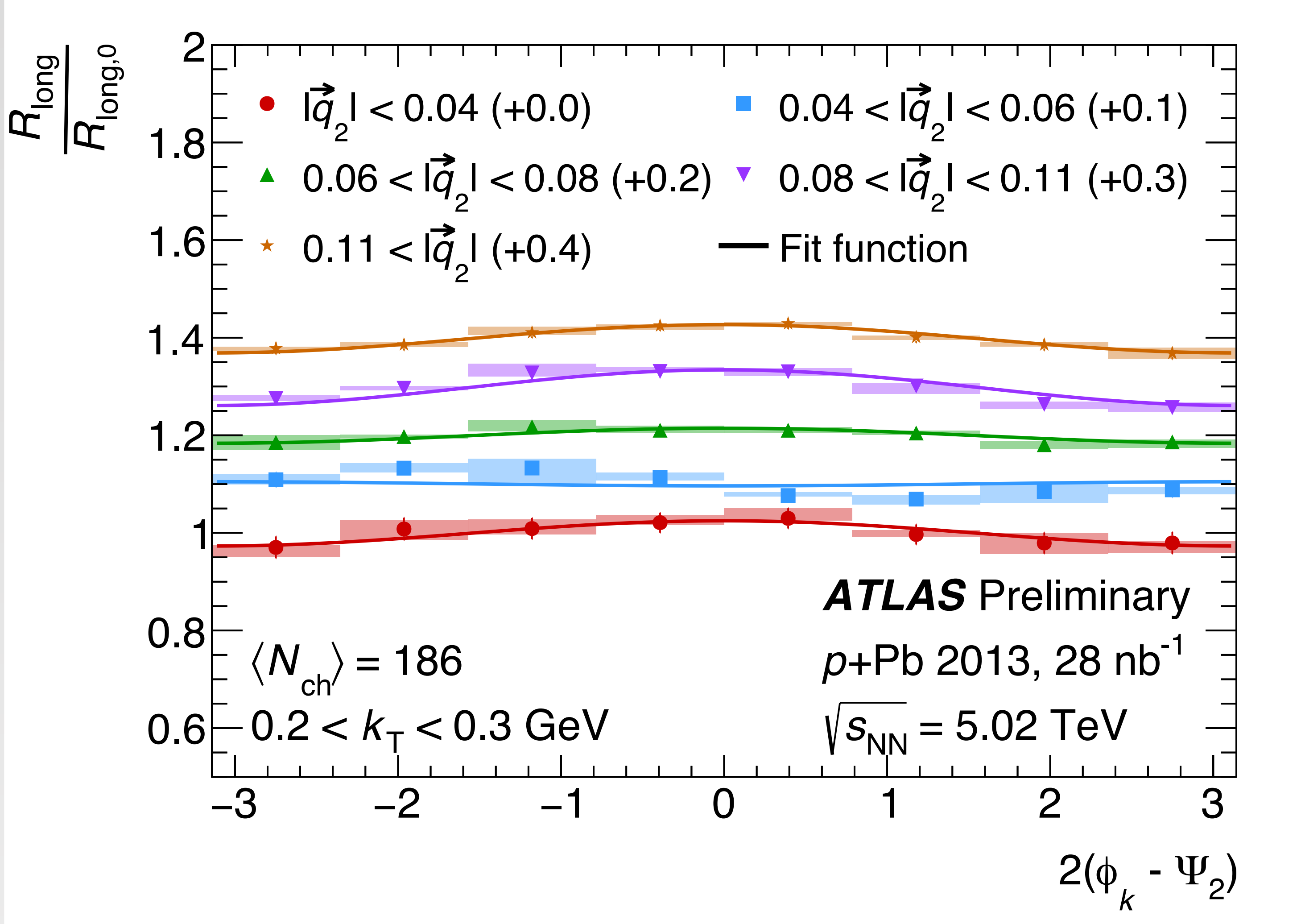


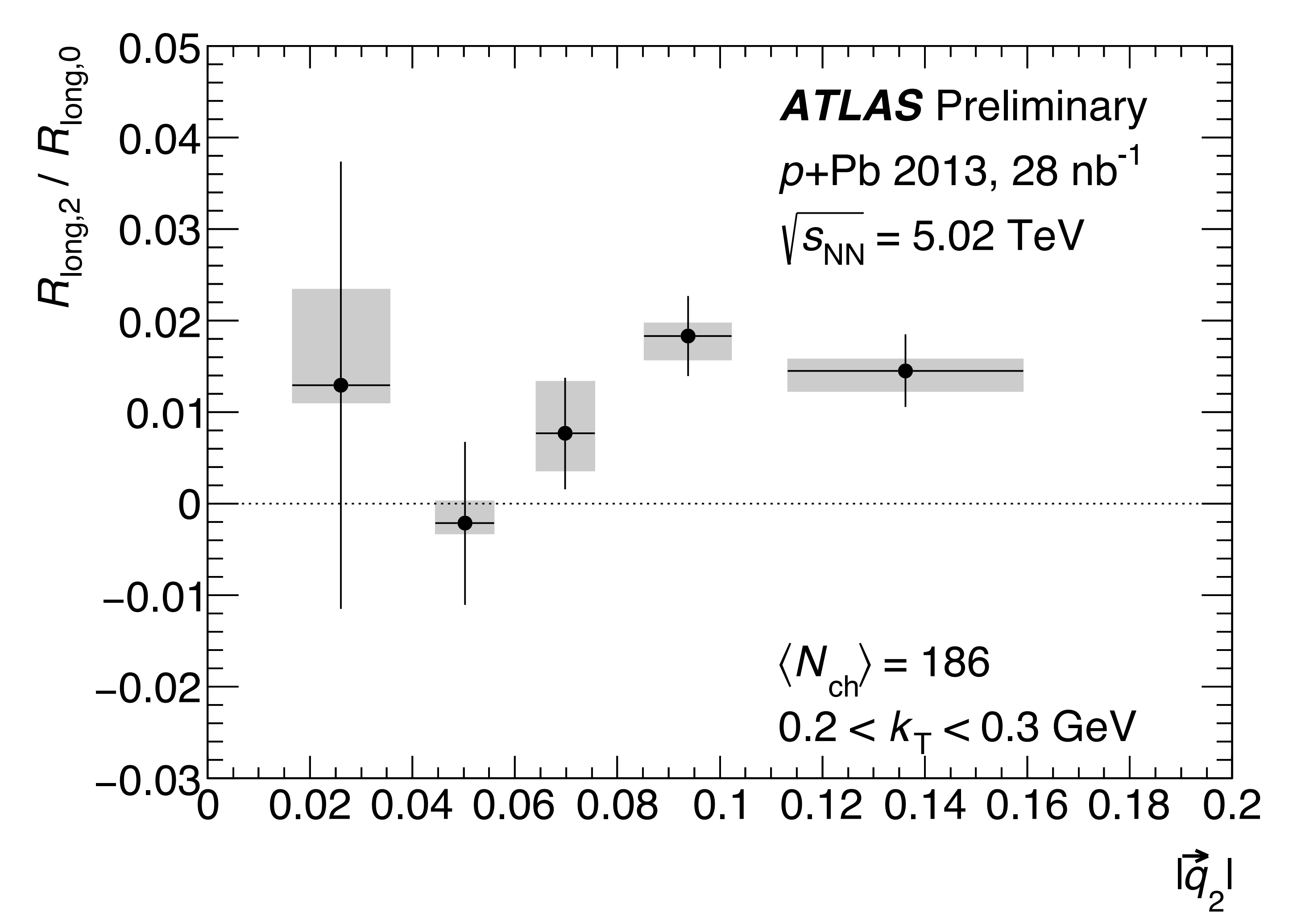




Rout **Rside** **Ros**

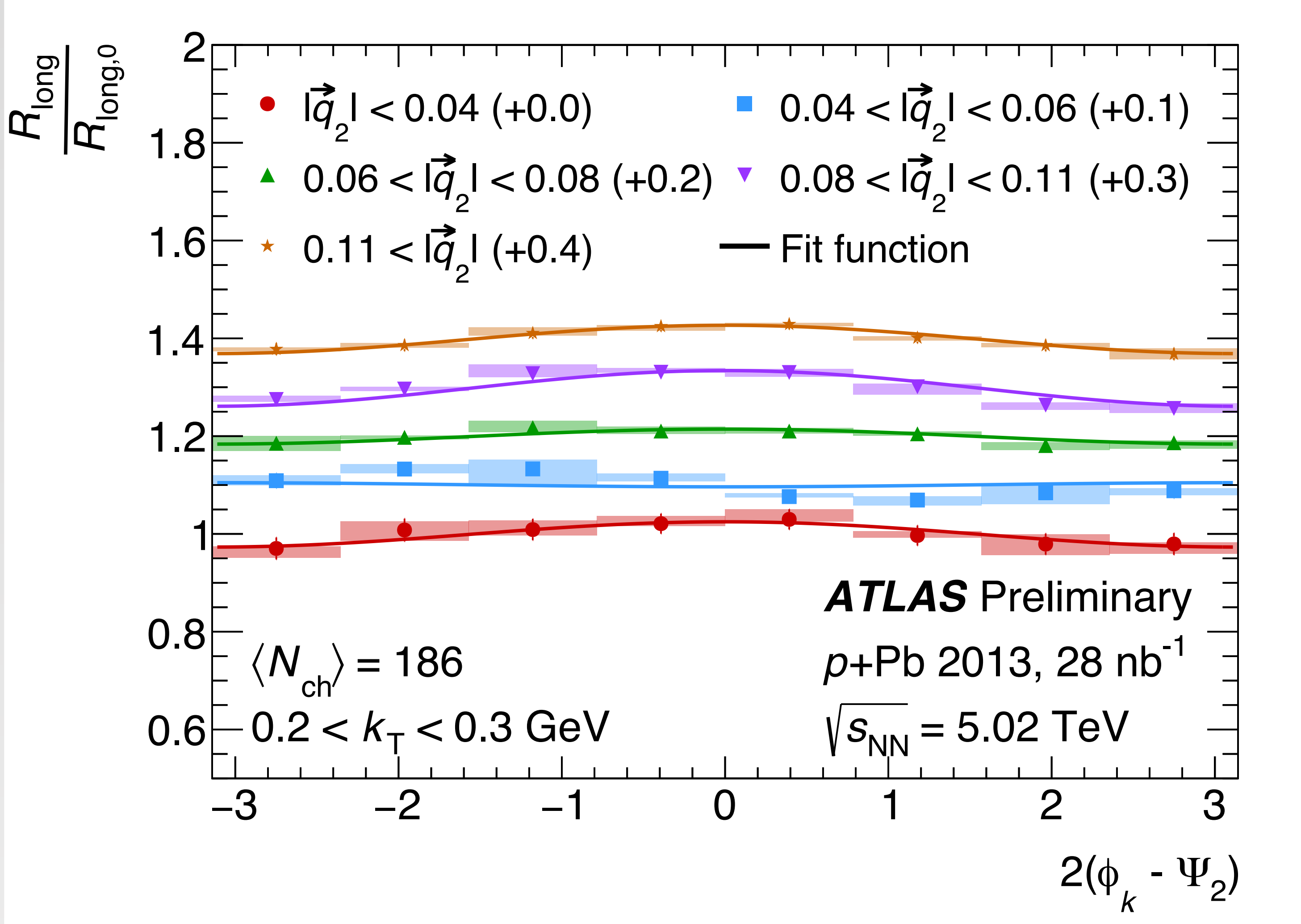
Extracted radii (cont)

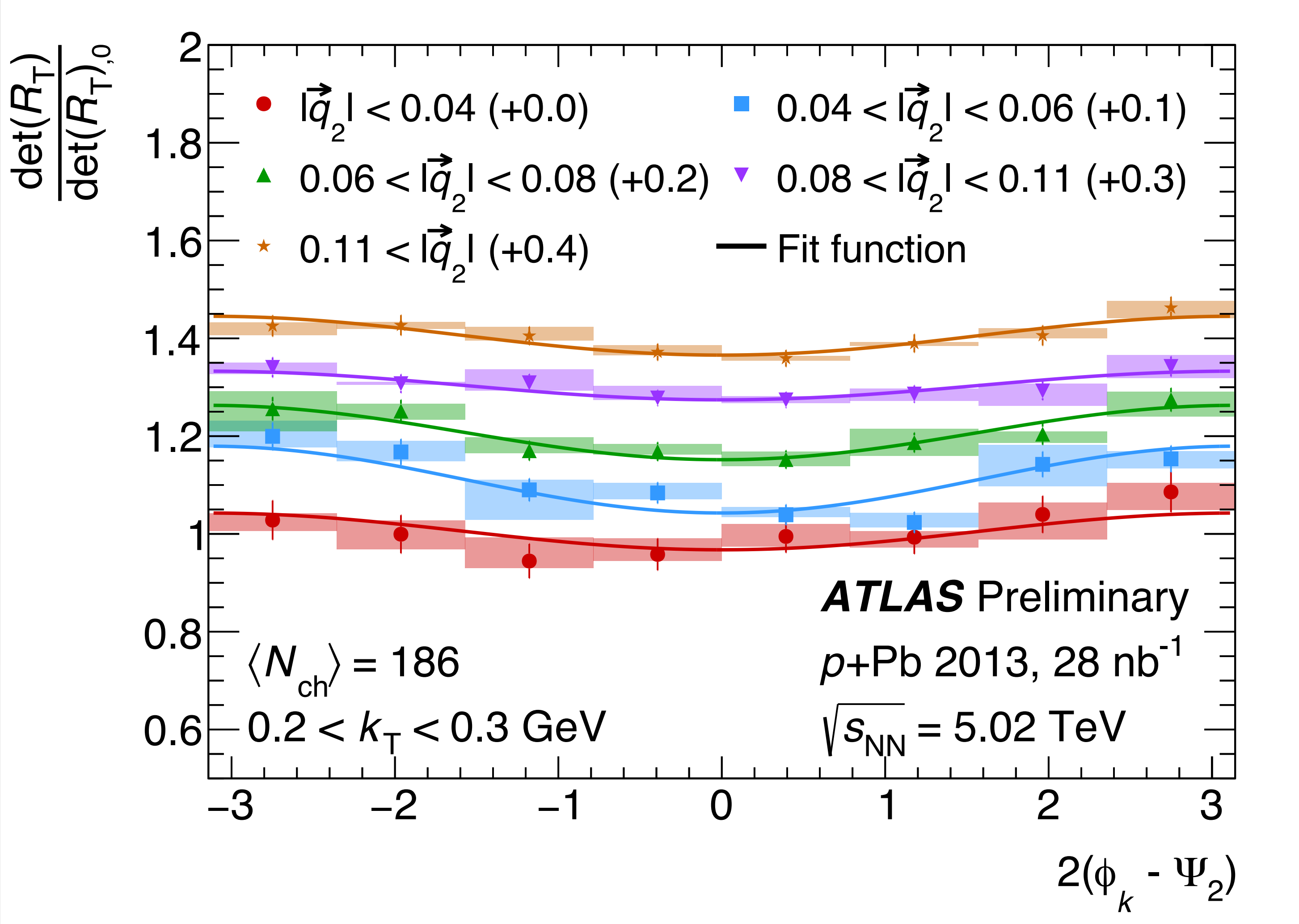


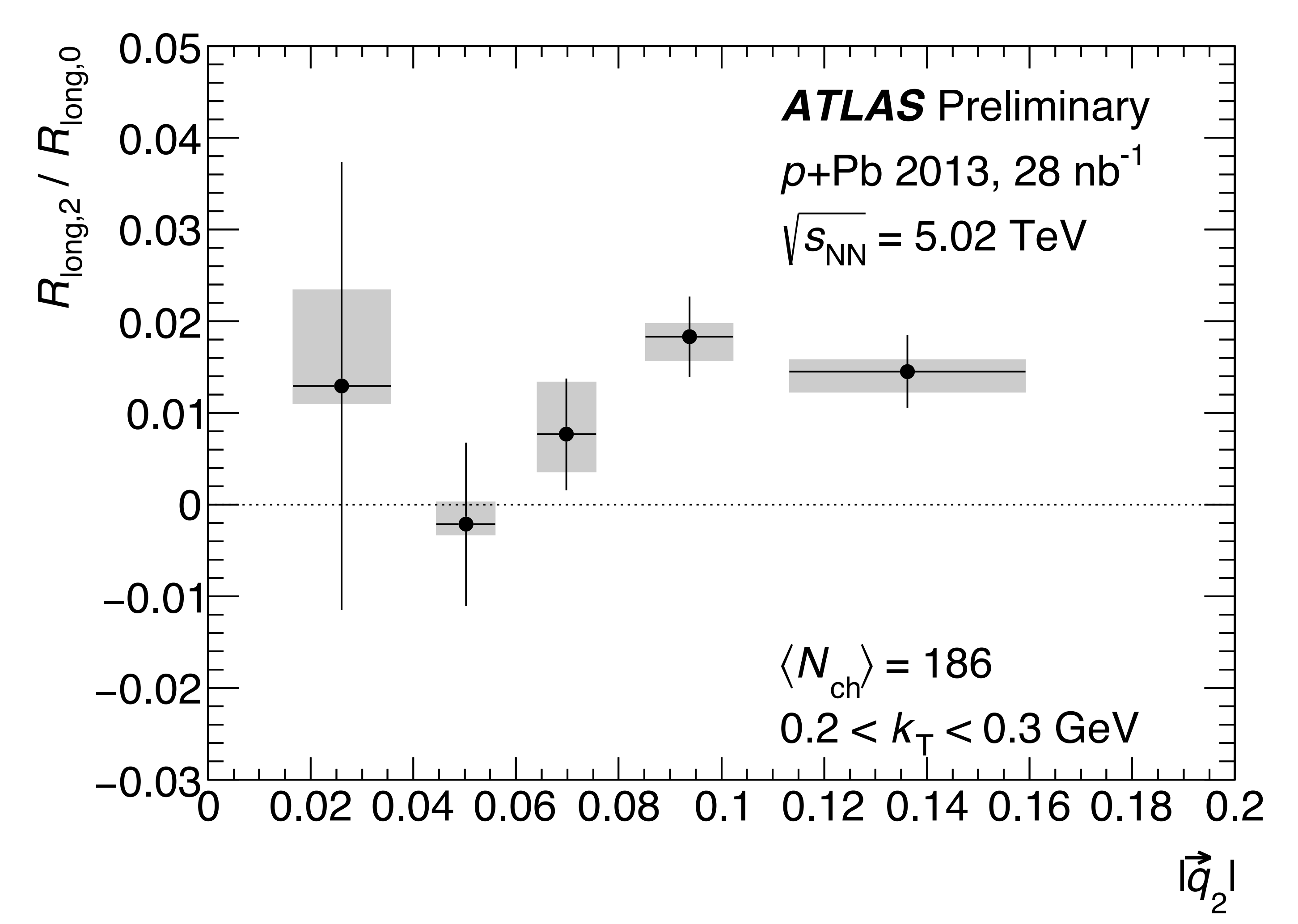


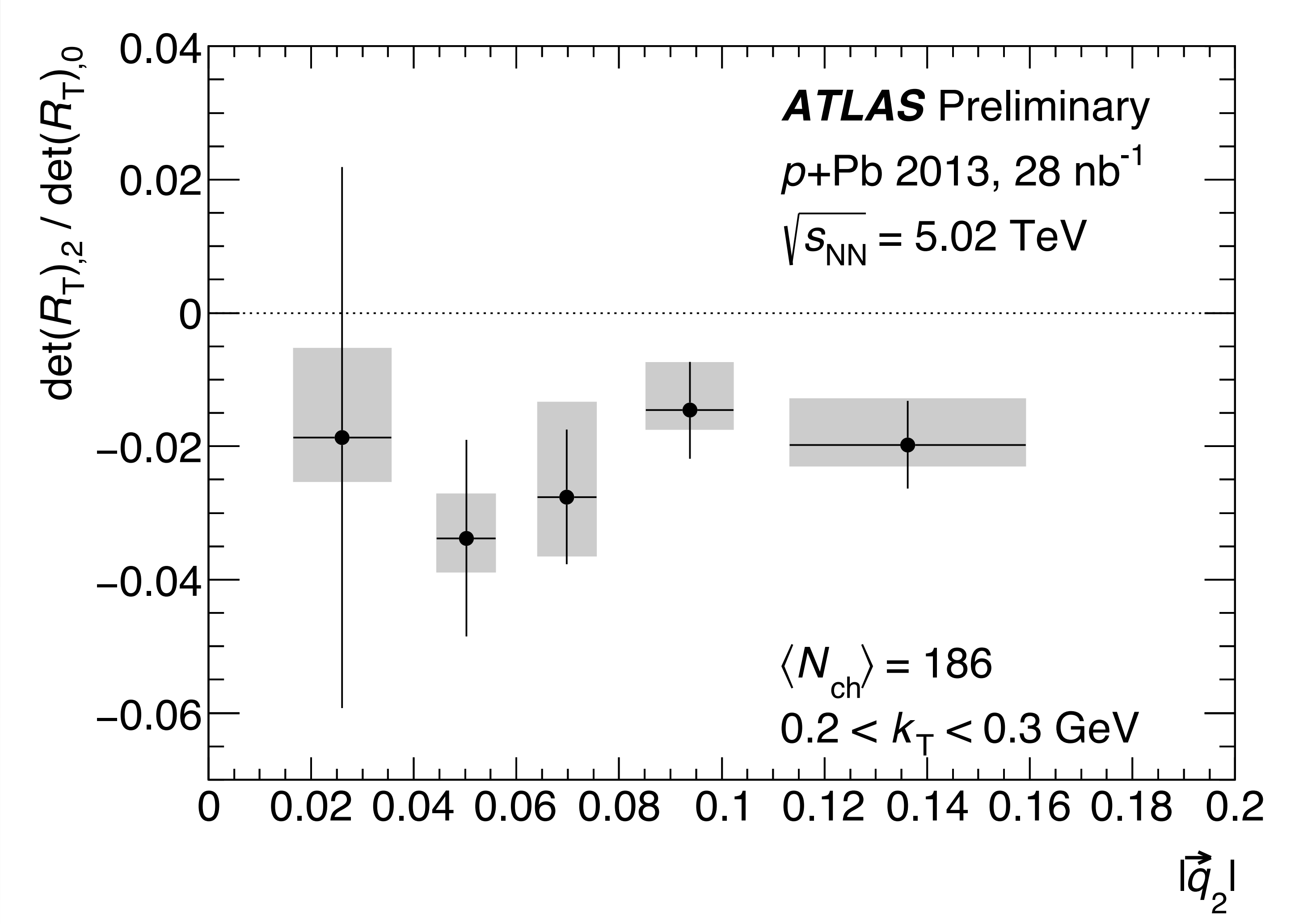
R_{long}

Extracted radii (cont)





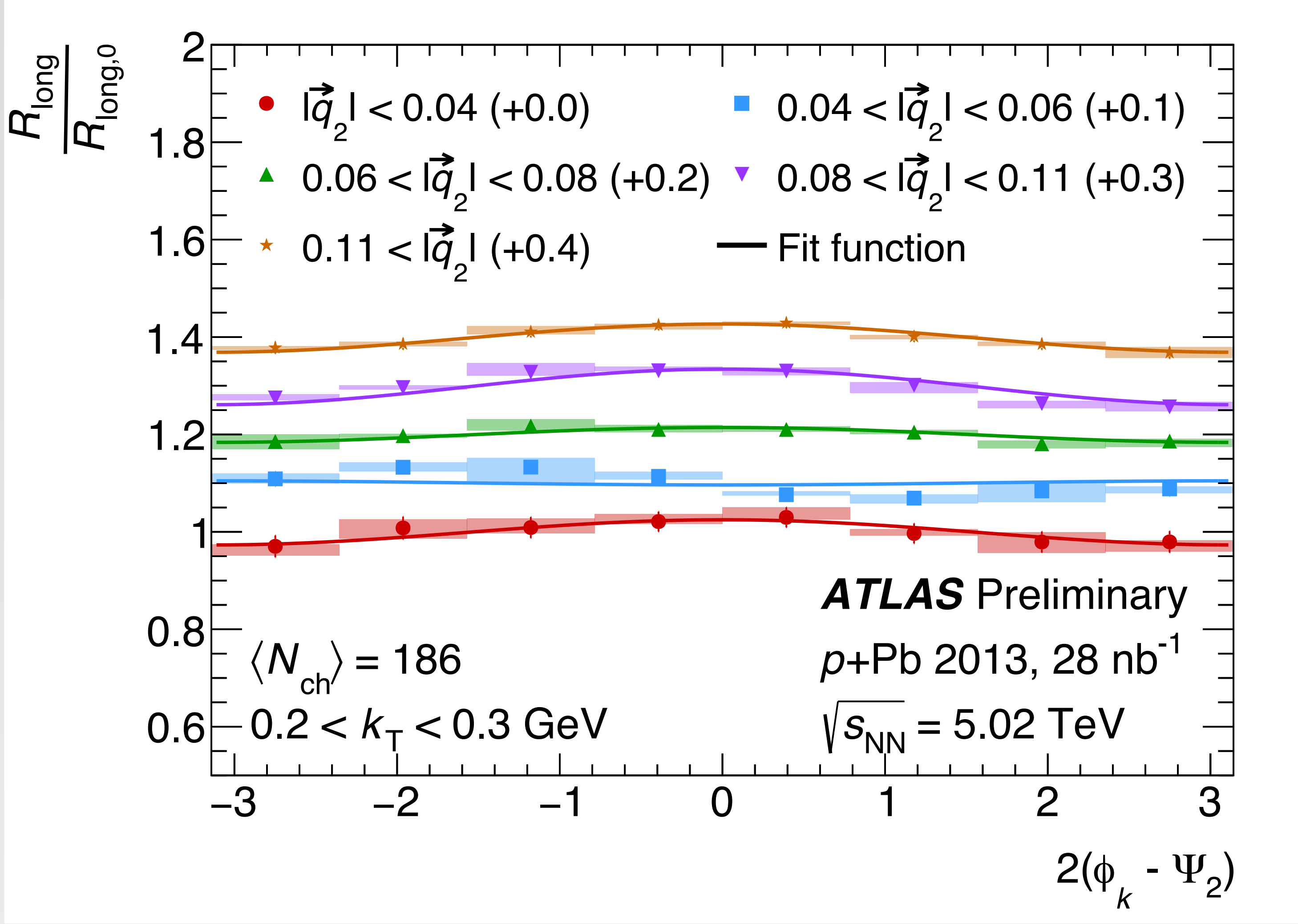


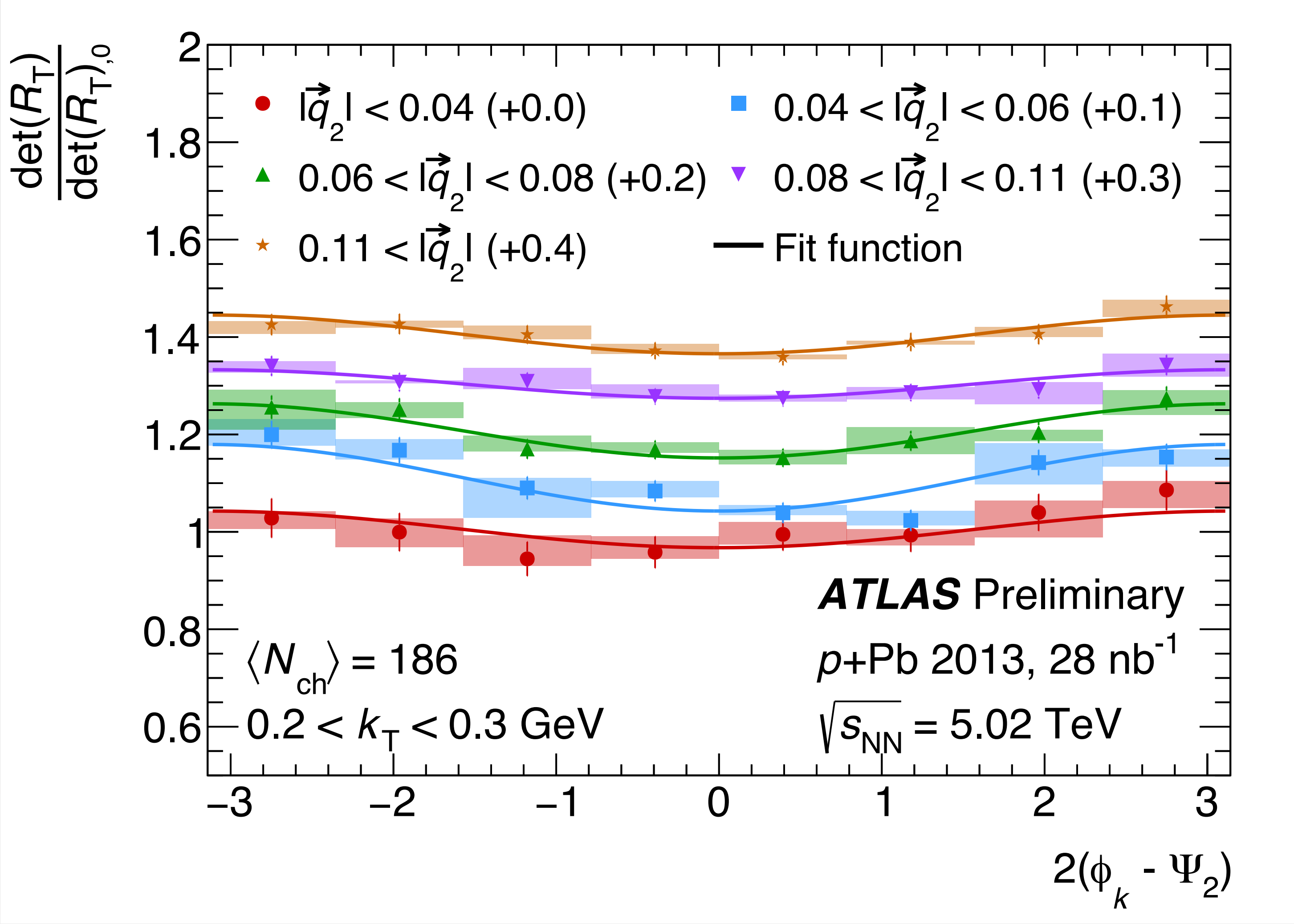


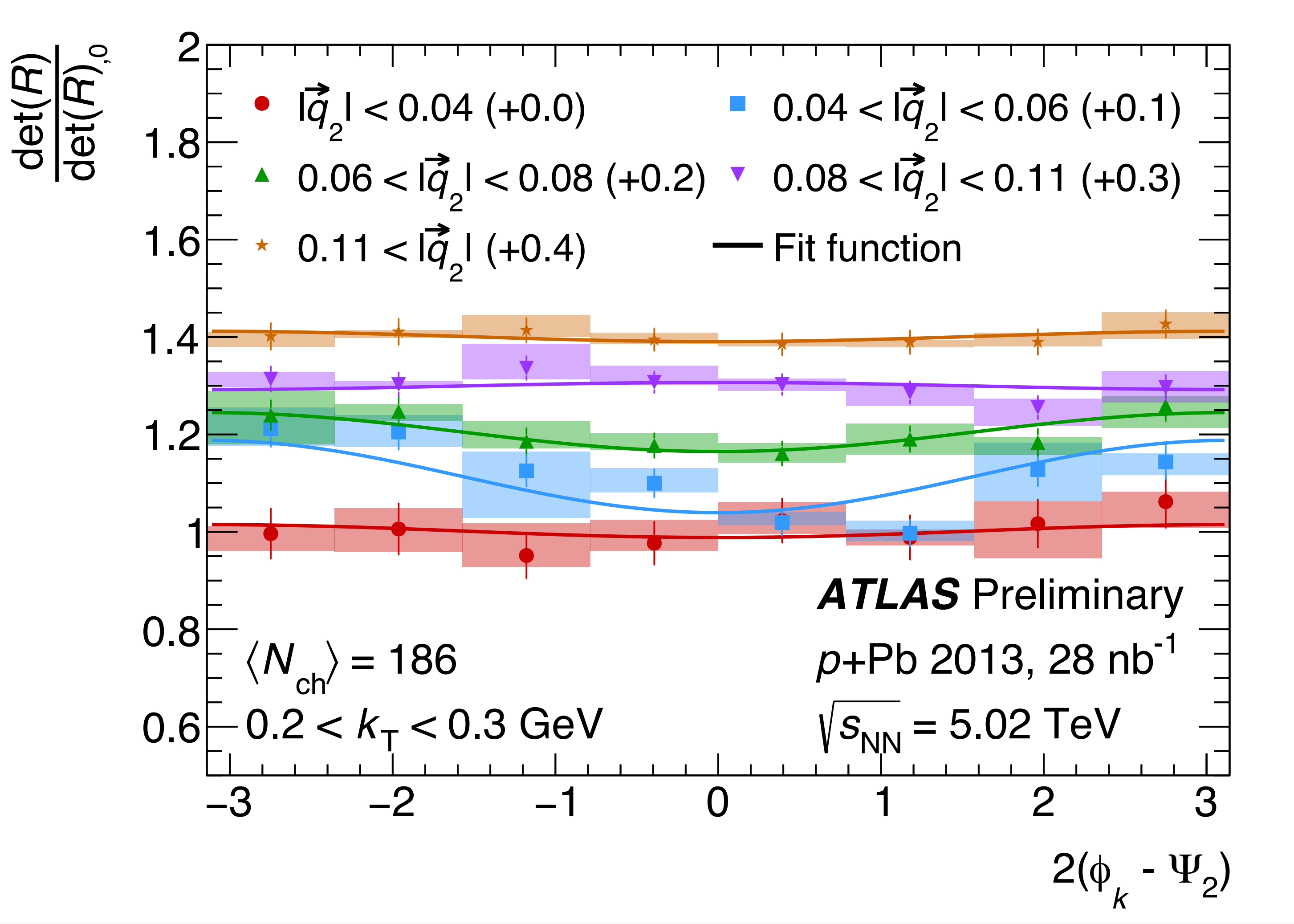
R_{long}

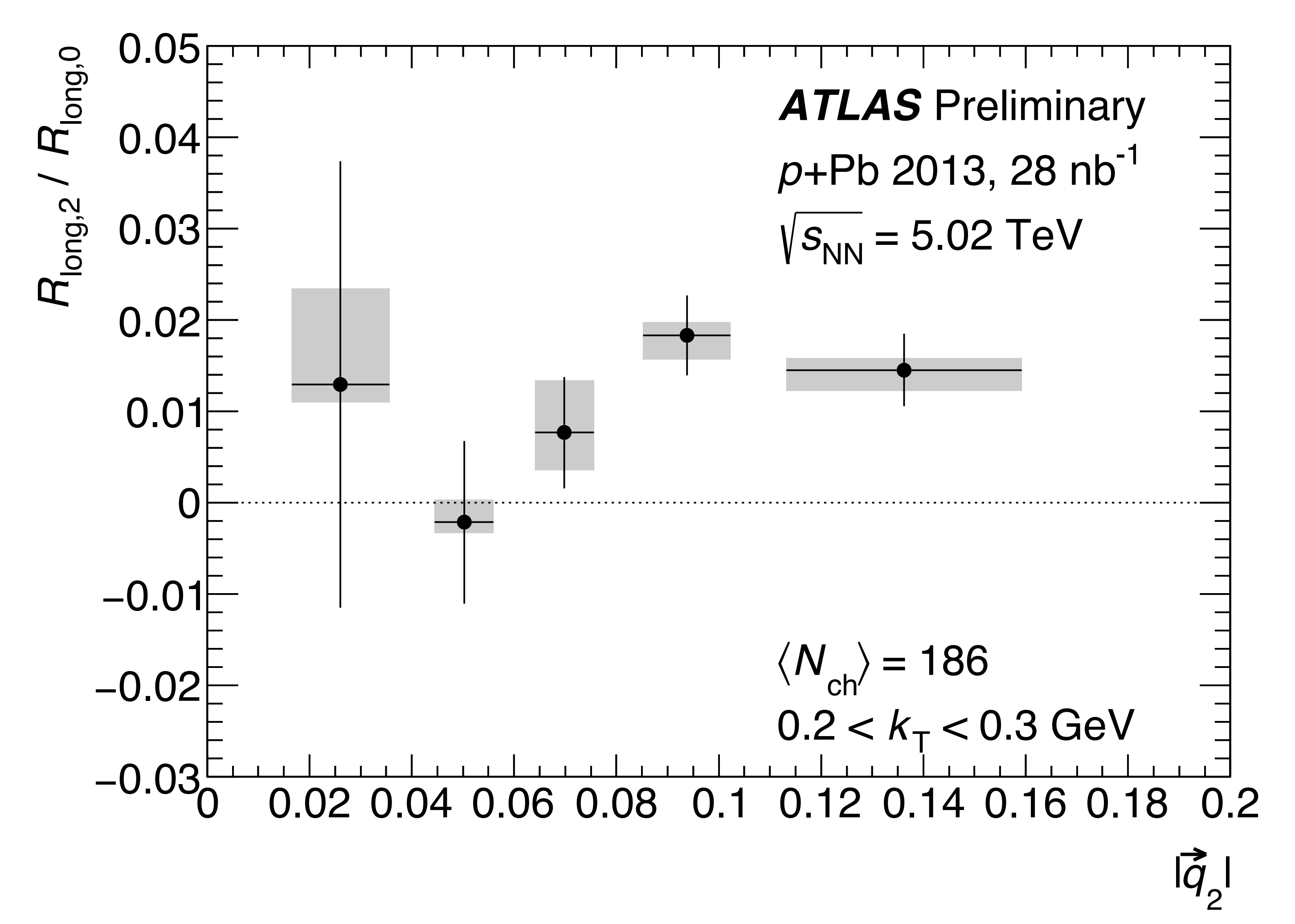
$Det(R_T)$

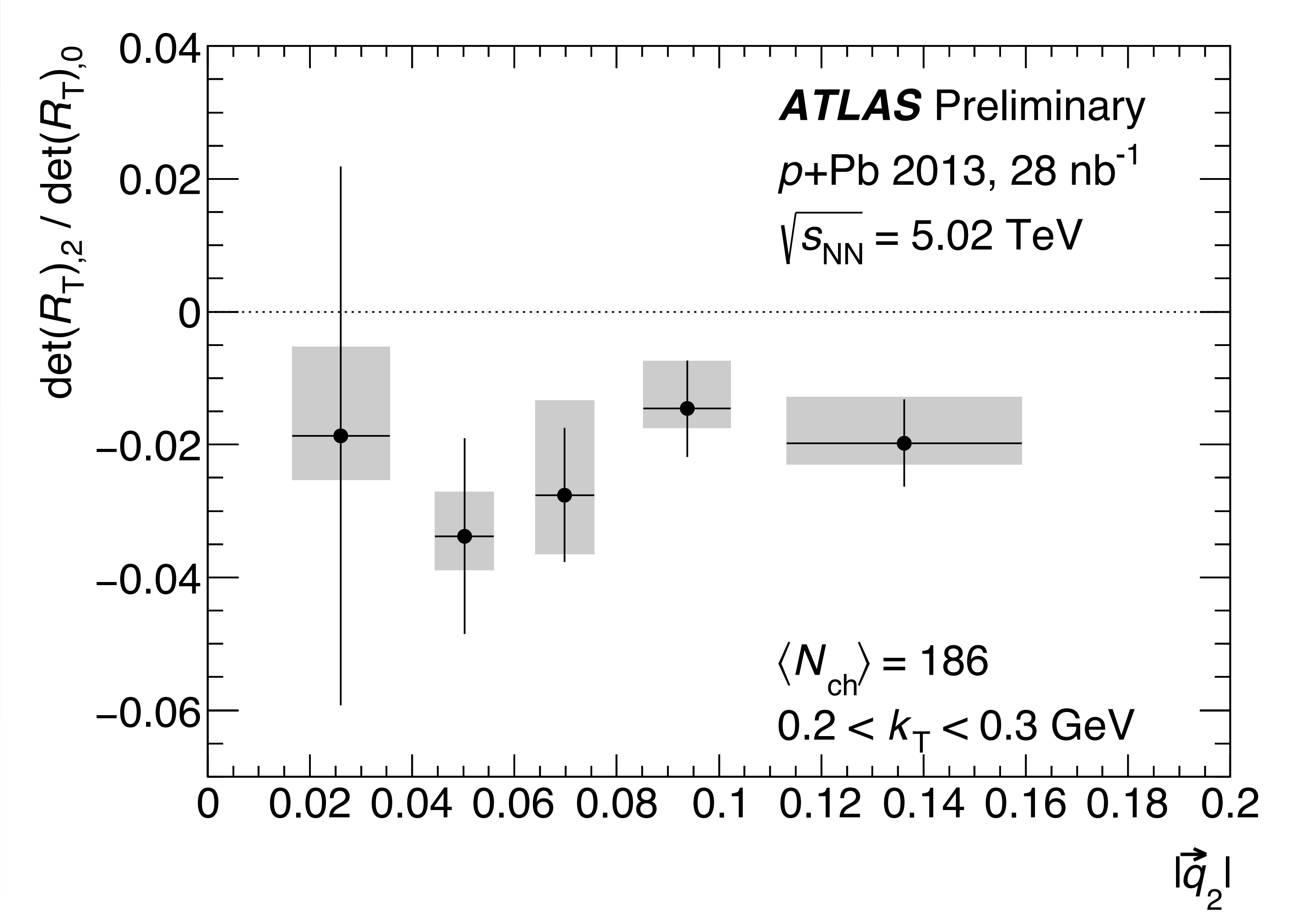
Extracted radii (cont)

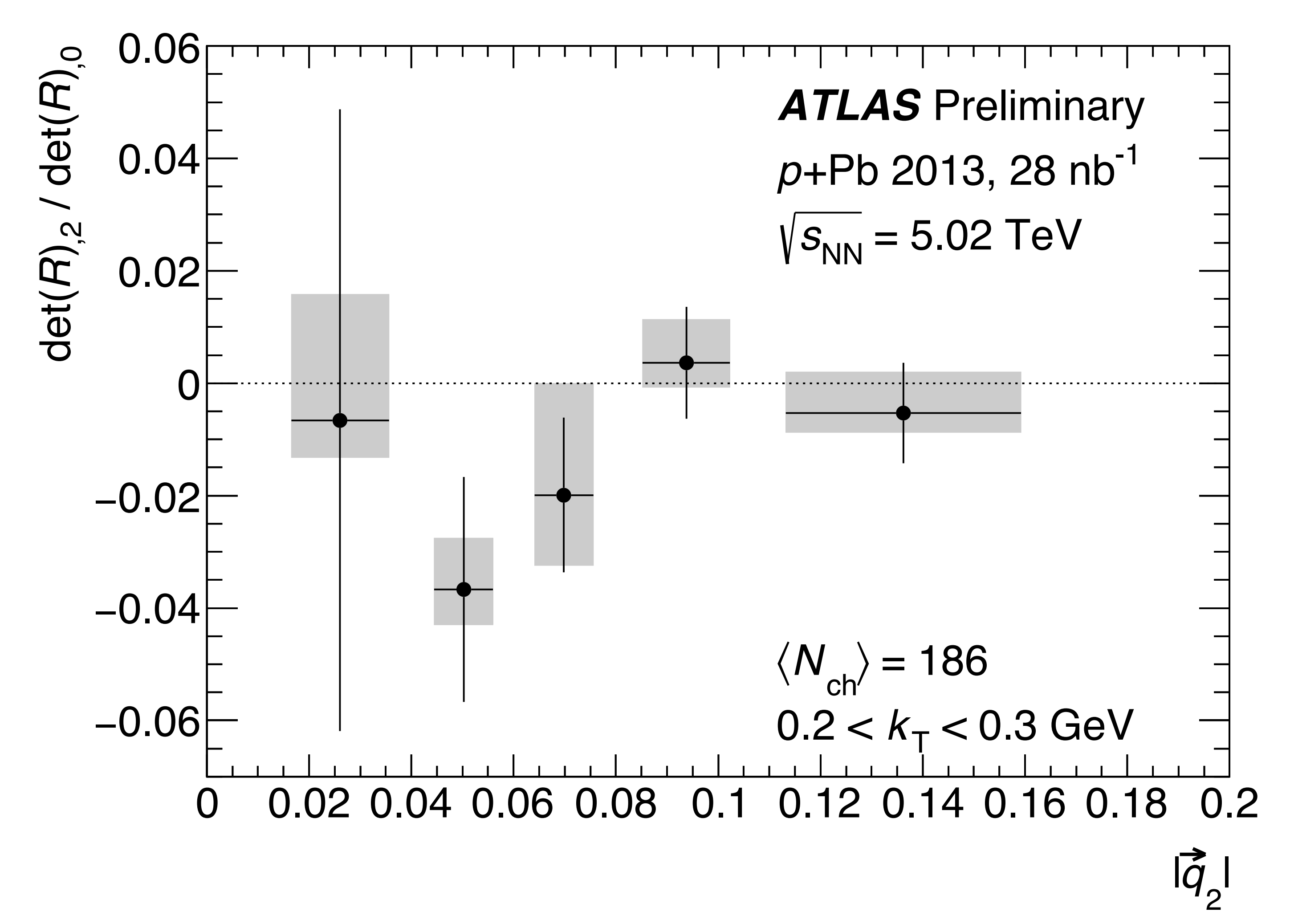












R_{long} **$Det(R_T)$** **Det(R) - volume**

Conclusions

- ATLAS measured correlations of v_n with event mean-p_{T} in *Pb+Pb* and *p+Pb*
  - Significant values for all harmonics in central *Pb+Pb*
    - Very different magnitudes and behaviour with centrality for v_2, v_3 and v_4
  - For peripheral *Pb+Pb* collisions and *p+Pb* the ρ for v_2 correlation is negative and $\sim$ compatible
  - Hydrodynamical simulations predicted such behaviour in *Pb+Pb*, useful insight into initial conditions in *p+Pb*

arXiv:1907.05176

- ATLAS measured azimuthal variation of HBT radii in *p+Pb*
  - Found significant radii modulation
  - Magnitude of $|\vec{q}_2|$ does not affect observed radii, except for very symmetric events
  - Qualitatively reassemble observations in *A+A* systems
  - Naturally explained by hydrodynamics

ATLAS-CONF-2017-008

Thank you