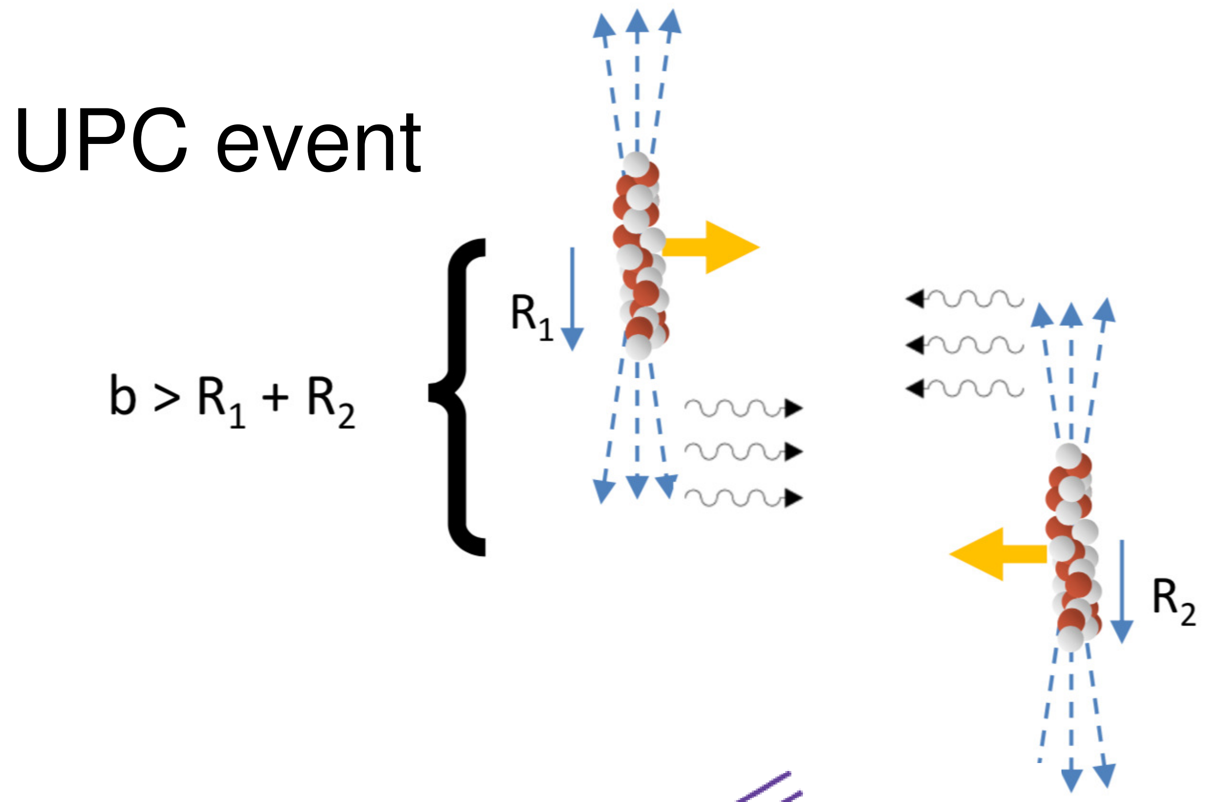
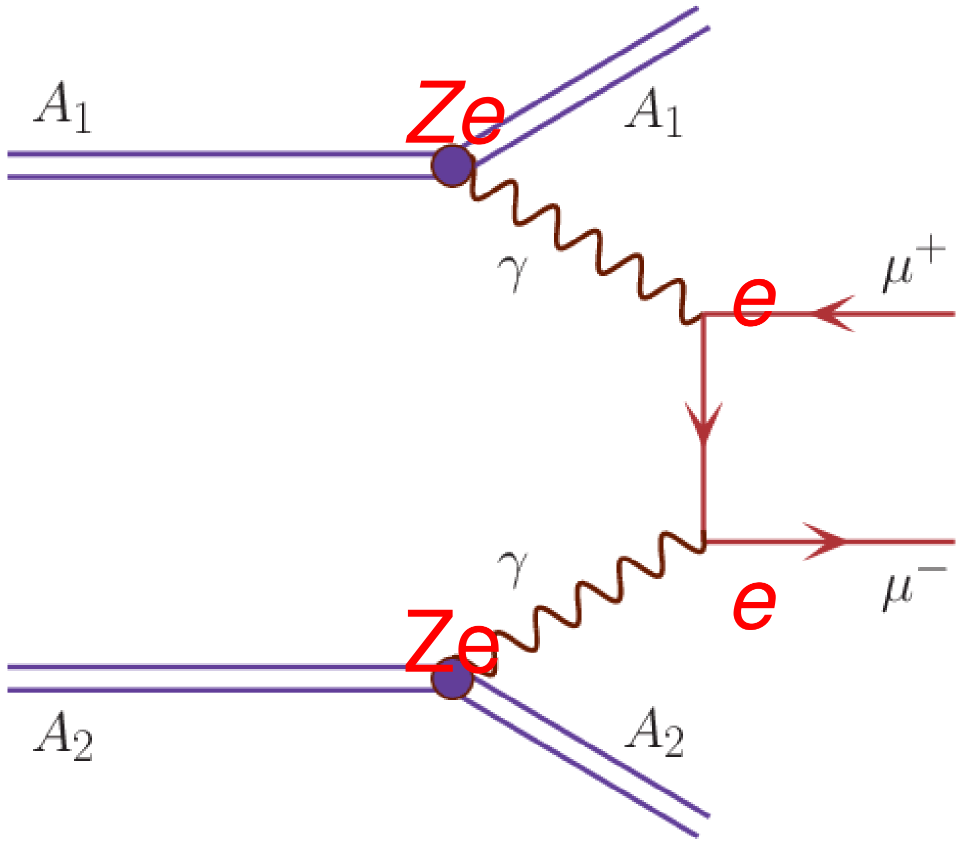
Production of muon-pairs from $\gamma\gamma$ scattering in Non-UltraPeripheral Pb+Pb collisions

Soumya Mohapatra
(Columbia University)

ATLAS-CONF-2019-051
arXiv:2011.12211 (Submitted to PRC)
Phys. Rev. Lett. 121 (2018) 212301

Dilepton production in Ultra-Peripheral Collisions (UPC)





Phys.Rev.C82:014904,2010

In Pb+Pb collisions, the electromagnetic fields of the charged nuclei are enhanced by factors of Z^2.

Modelled as quasi-real photon fields, this provides an enhancement of Z^4 for the $\gamma\gamma\rightarrow\mu^+\mu^-$ processes. For Pb ions Z^4 ~5x10^7

Max p_z of photons in rest frame of nucleus: ~1/(2R) ~1/15fm ~ O(10 MeV)

In Lab frame $|p_z|$ increased by boost: at LHC the $|p_z|$ in lab frame is ~2500*10MeV~25 GeV

Maximum p_T of incoming photons ~same as rest-frame p_T~ O(10 MeV).

Outgoing muons will be nearly back-to back in ϕ and have nearly identical p_T

Observables: Asymmetry (A), Acoplanarity (α), $k_\perp$

$$\mathrm{A} \equiv (p_{\mathrm{T}1} - p_{\mathrm{T}2}) / (p_{\mathrm{T}1} + p_{\mathrm{T}2})$$

Mismatch in transverse momentum of the two muons

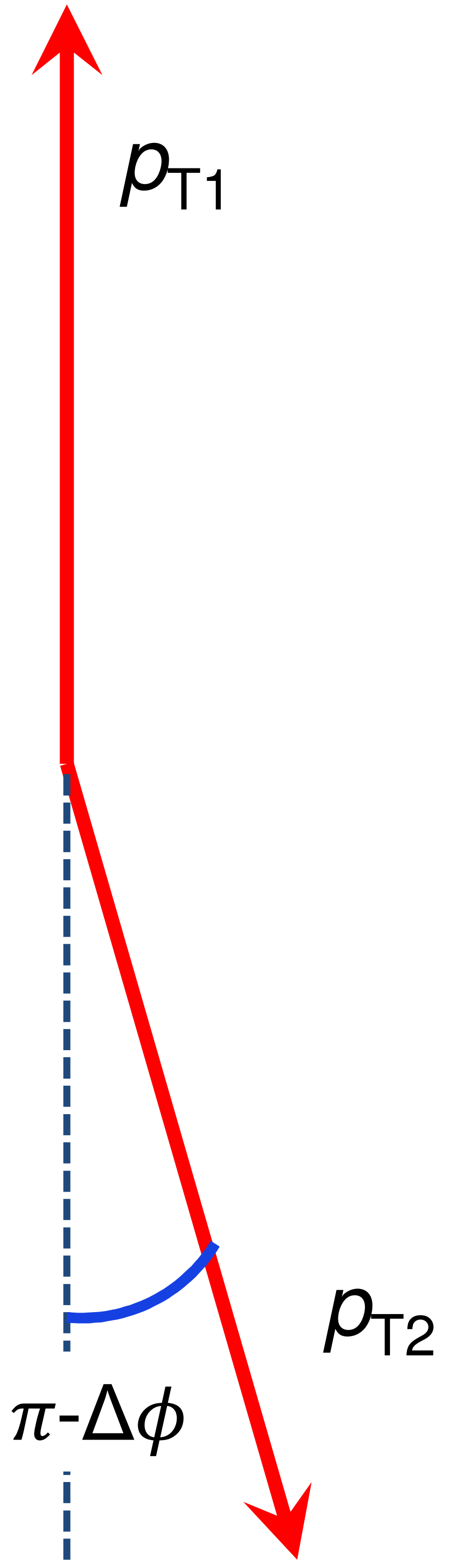
Observables: Asymmetry (A), Acoplanarity (α), $k_\perp$

$$A \equiv (p_{T1} - p_{T2}) / (p_{T1} + p_{T2})$$

Mismatch in transverse momentum of the two muons

$$\alpha \equiv 1 - |\Delta\phi| / \pi$$

Deviation from being perfectly back-to-back



Observables: Asymmetry (A), Acoplanarity (α), $k_\perp$

$$\mathrm{A} \equiv (p_{\mathrm{T}1} - p_{\mathrm{T}2})/(p_{\mathrm{T}1} + p_{\mathrm{T}2})$$

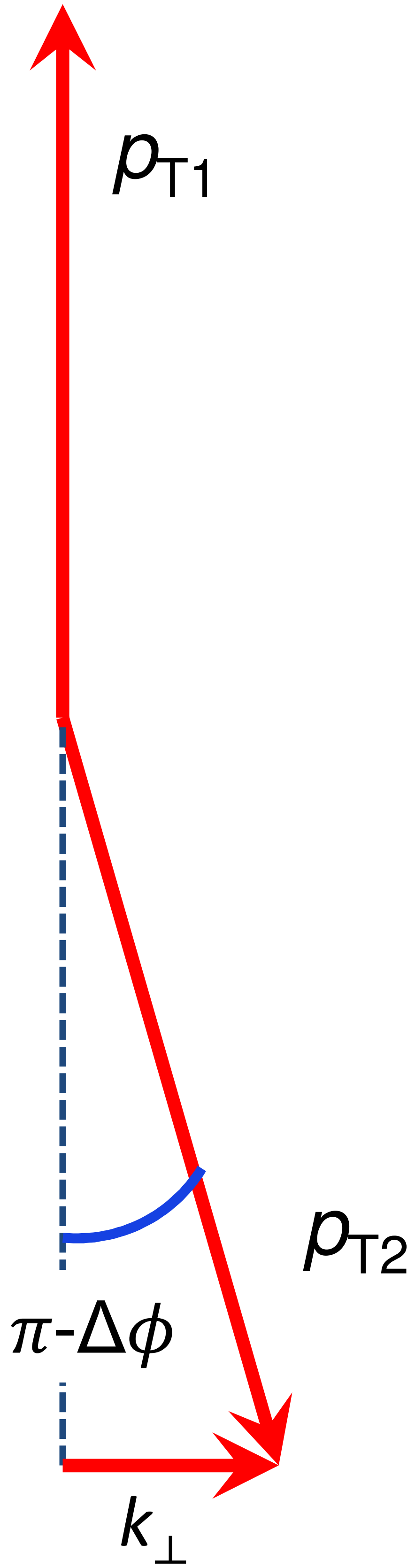
Mismatch in transverse momentum of the two muons

$$\alpha \equiv 1 - |\Delta\phi|/\pi$$

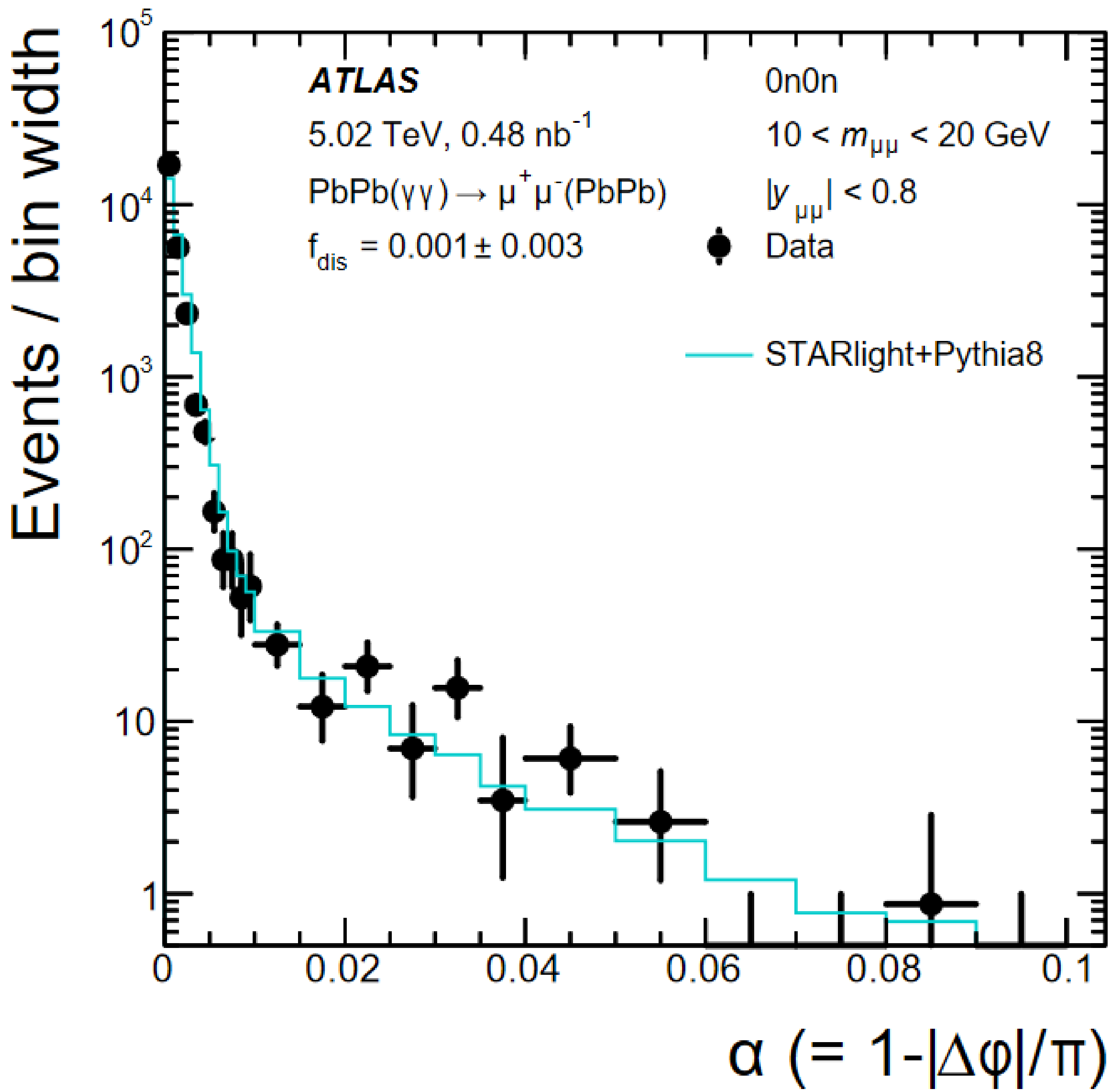
Deviation from being perfectly back-to-back

$$k_\perp \equiv (p_{\mathrm{T}1} + p_{\mathrm{T}2})\,|(\pi - \Delta\phi)|/2 = \pi\alpha\bar{p}_{\mathrm{T}}$$

Momentum scale corresponding to the angular scale α



Acoplanarity distributions in UPC collisions



ATLAS measurements of Acoplanarity distribution of dimuons in UPC Pb+Pb collisions

Measurements well reproduced by STARLIGHT calculations

STARLIGHT uses the equivalent photon approximation + leading order QED cross-sections

arXiv:2011.12211

$\gamma\gamma \rightarrow \mu\mu$ in non-UPC collisions : why study it?

- $\gamma\gamma \rightarrow \mu\mu$ process also present in inelastic heavy ion collisions

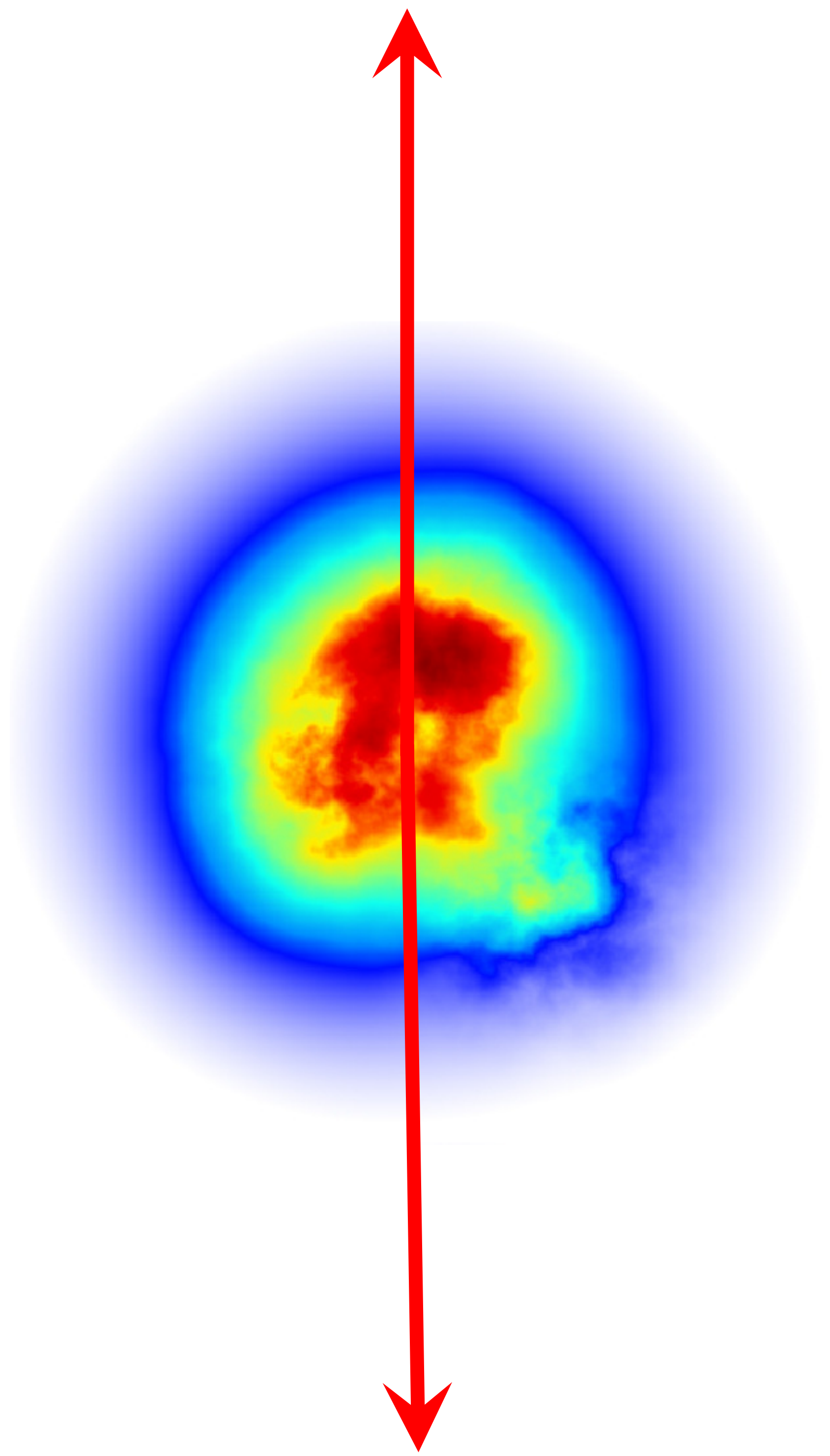
- Muons produced by photon scattering can in principle interact with the QGP produced in heavy-ion collisions.

- Can act as a EM probes of the QGP (Klien *et.al.* Phys. Rev. Lett. 122 (2019) 132301)

- Can also see effects of the magnetic fields of the colliding nuclei (Ye *et. al.* *Phys. Rev. C99 (2019) 044901*)

- Impact parameter dependence of EM Fields (W. Zha *et.al.* *Phys. Lett. B 800 (2020) 135089*)

- Measurement more complicated as there are other sources of muons : Heavy-Flavor decays.

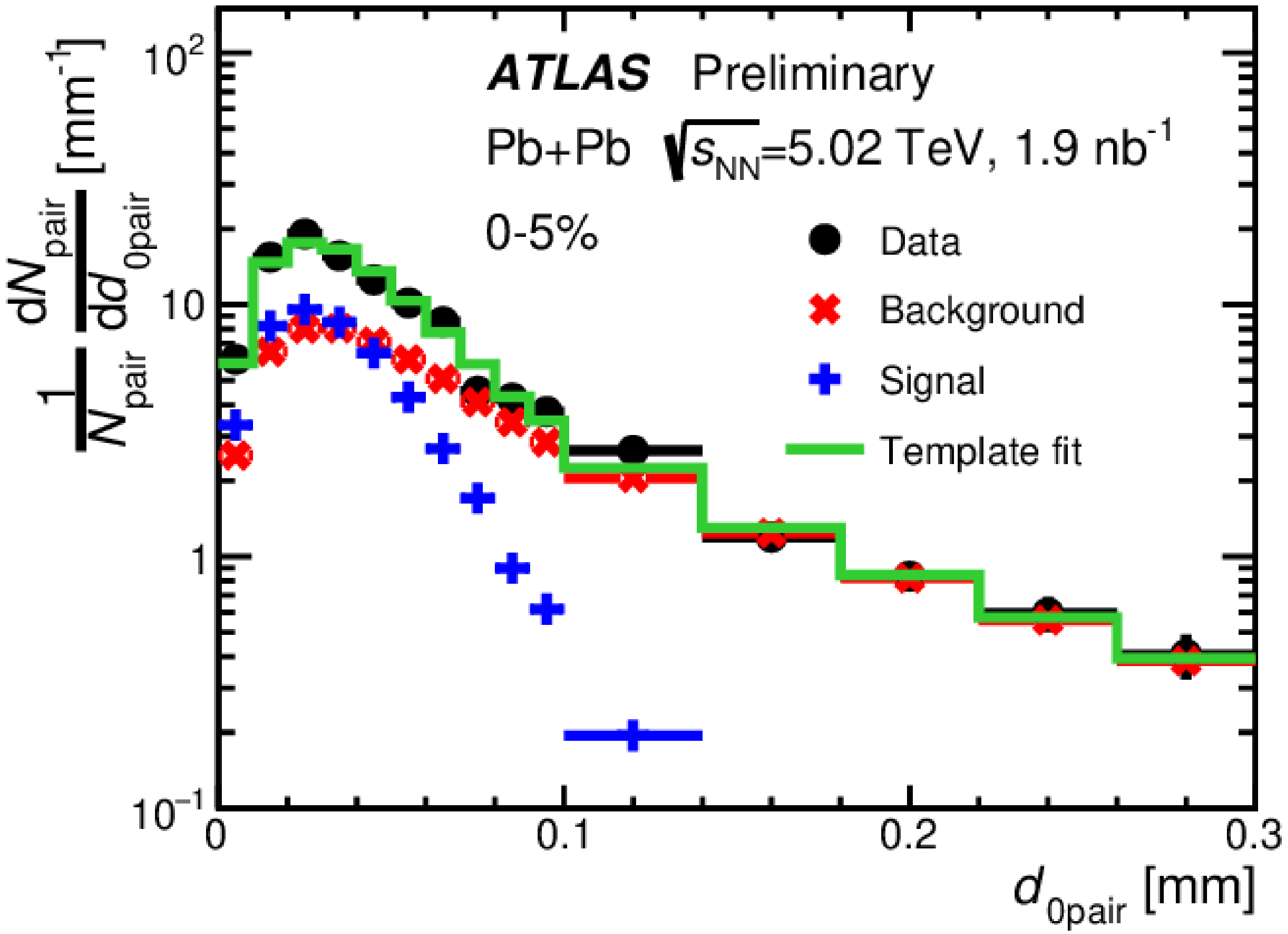


Signal & background pairs

- Reduce the HF contribution by requiring muons to be closely matched in p_{T} and be nearly back to back in ϕ
  - Require Asymmetry<0.06, i.e. the p_{T} of the two muons to be within 6% of the average p_{T}.
  - Require Acoplanarity<0.012
  - Reduces background by ~2 orders of magnitude in central collisions

- HF muons often arise from displaced secondary decay vertices
  - Use impact parameter w.r.t. collision vertex in the transverse (d_0) plane to remove residual background
  - "Pair impact parameter" defined as: $d_{0_{pair}} = \sqrt{d_{0_1}^2 + d_{0_2}^2}$

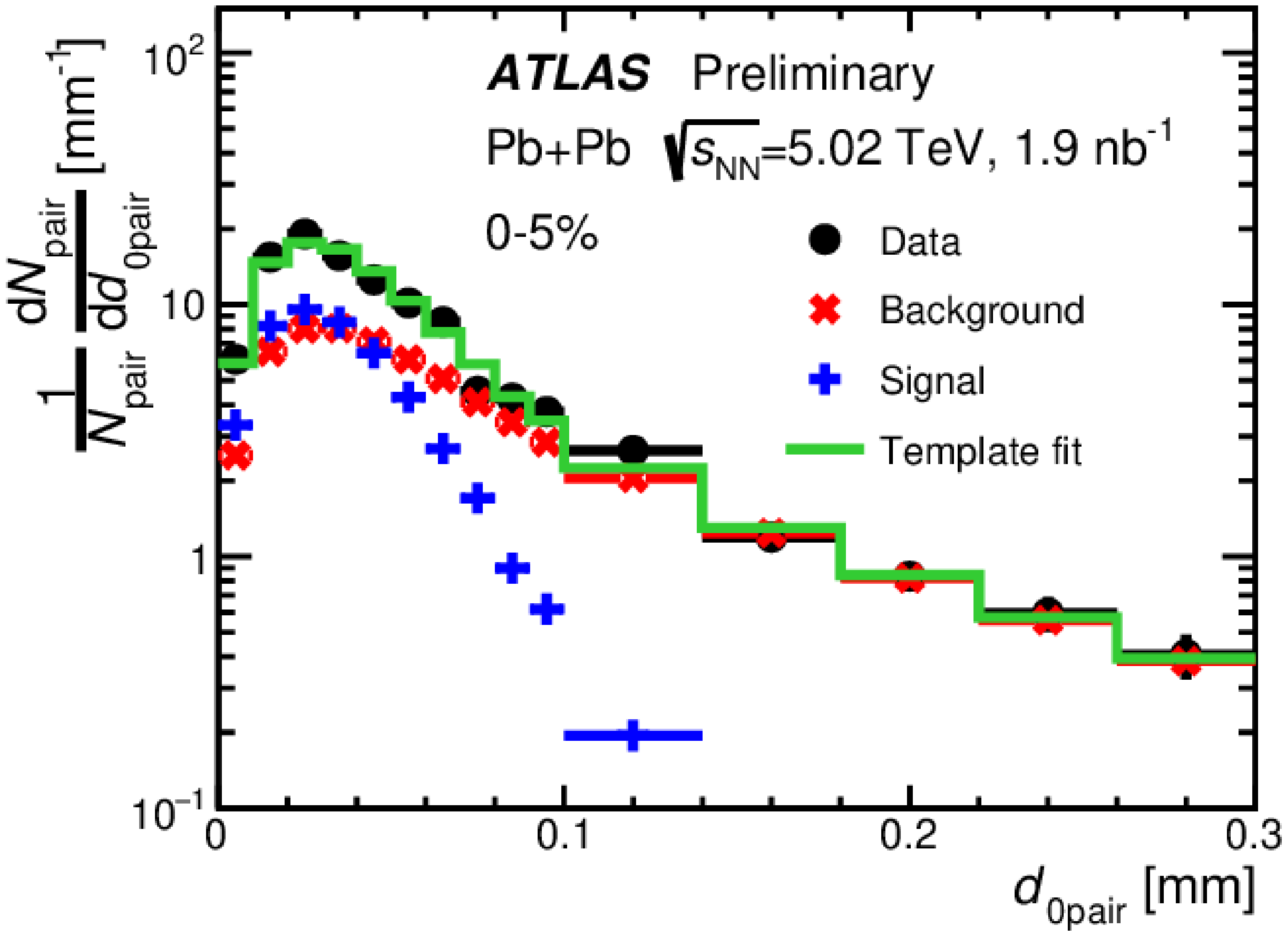
Estimating residual background contribution

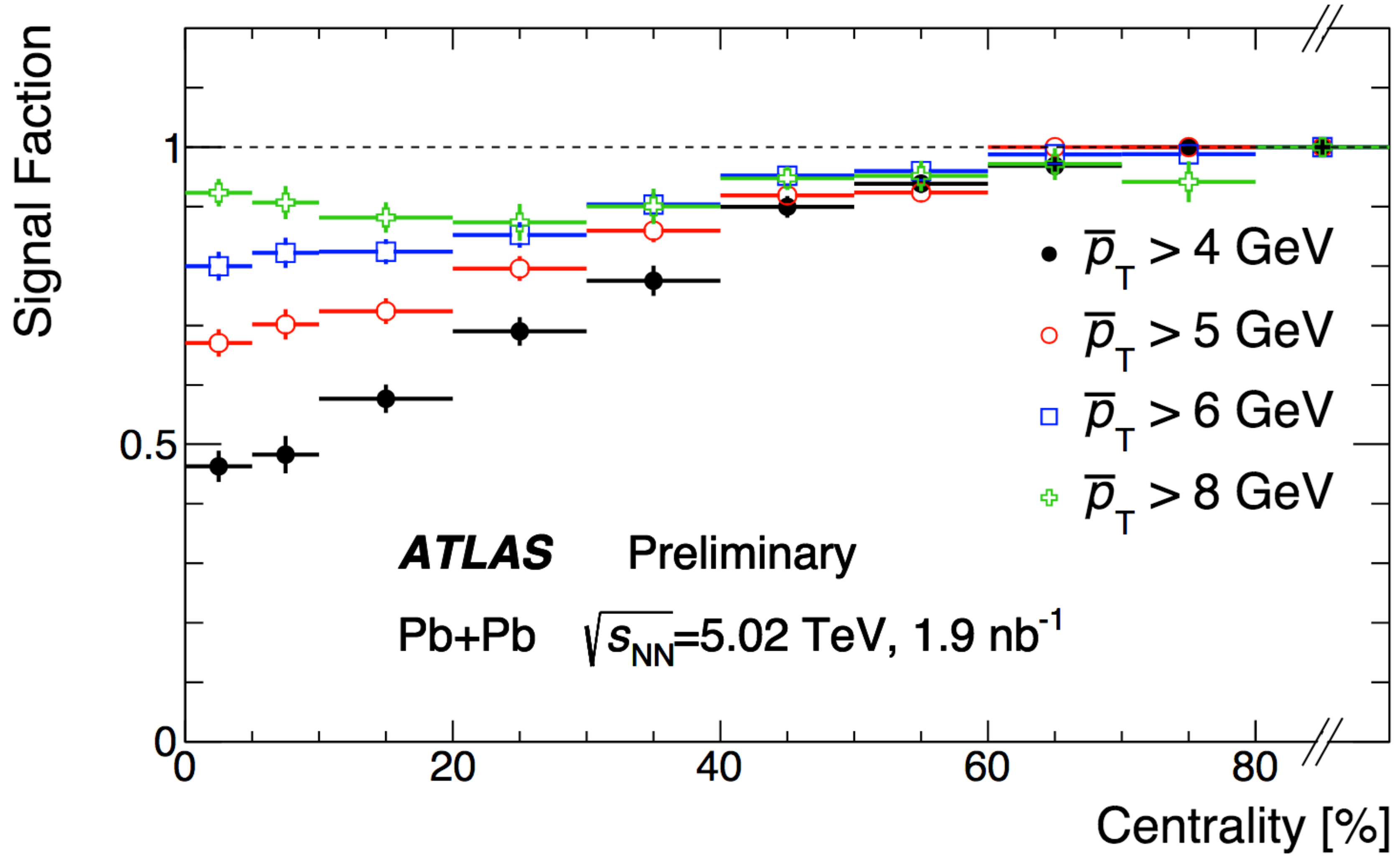


$$d_{0_{pair}} = \sqrt{d_{0_1}^2 + d_{0_2}^2}$$

- To estimate the residual background, fit the $d_{0\text{pair}}$ distribution in the data by linear sum of signal and background $d_{0\text{pair}}$-templates
  - $d_{0\text{pair}}$ template for signal obtained from MC (STARLIGHT)
  - $d_{0\text{pair}}$ template for background obtained from Data:
    - require Acoplanarity>0.015, Asymmetry>0.2

Estimating residual background contribution





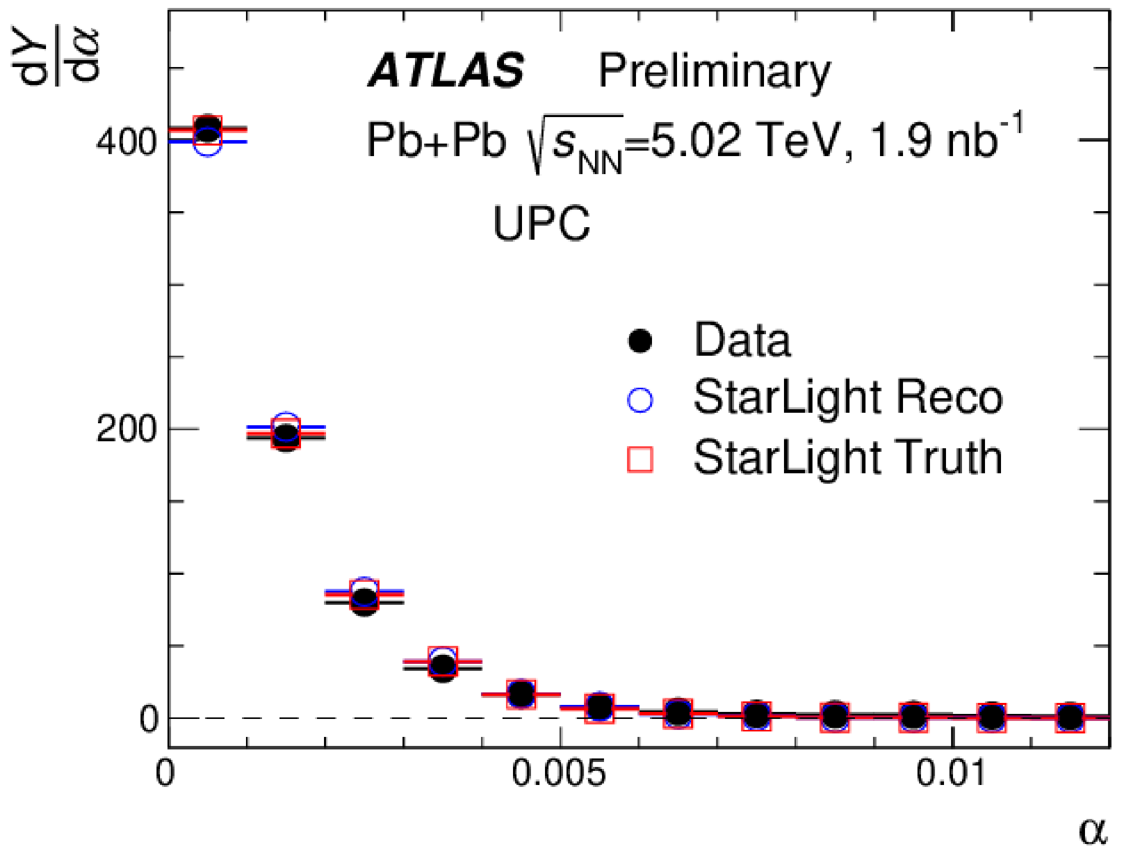
- To estimate the residual background, fit the d_{0pair} distribution in the data by linear sum of signal and background d_{0pair}-templates
  - d_{0pair} template for signal obtained from MC (STARLIGHT)
  - d_{0pair} template for background obtained from Data:
    - require Acoplanarity>0.015, Asymmetry>0.2

Acoplanarity distributions

$$\alpha \equiv 1 - |\Delta\phi|/\pi$$

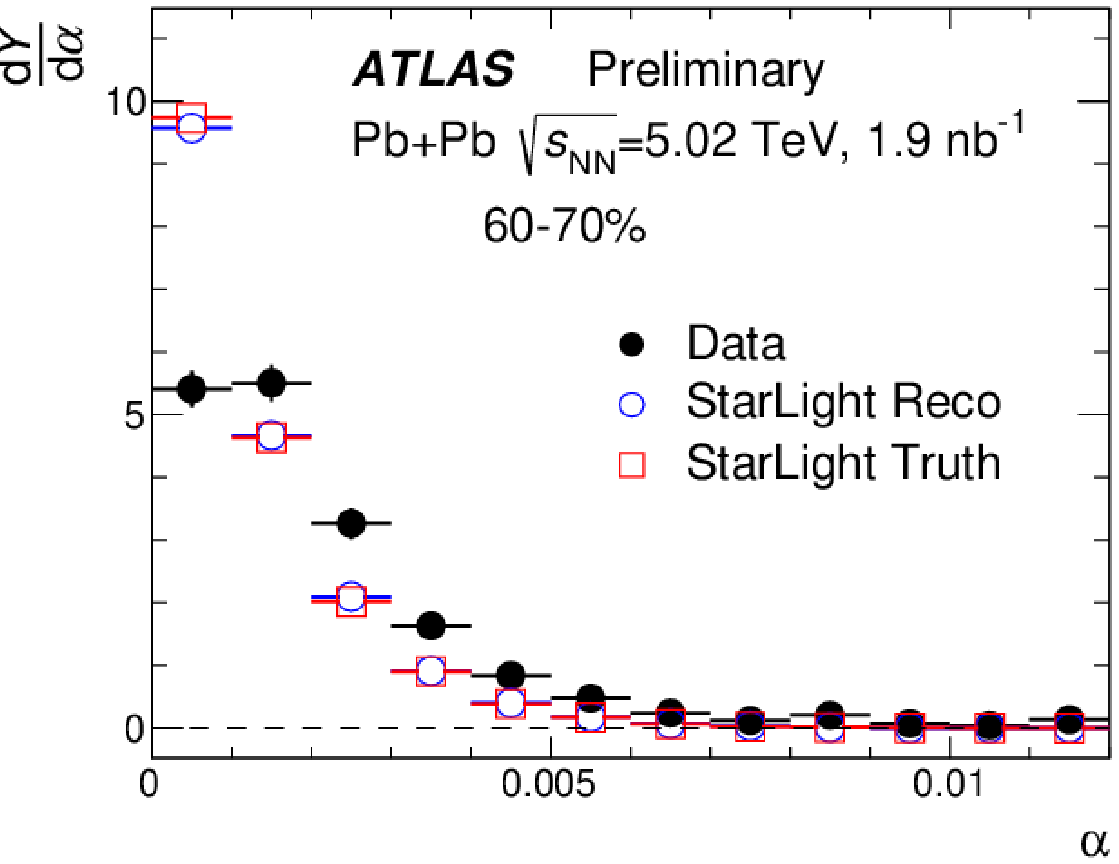
Data compared to STARLIGHT

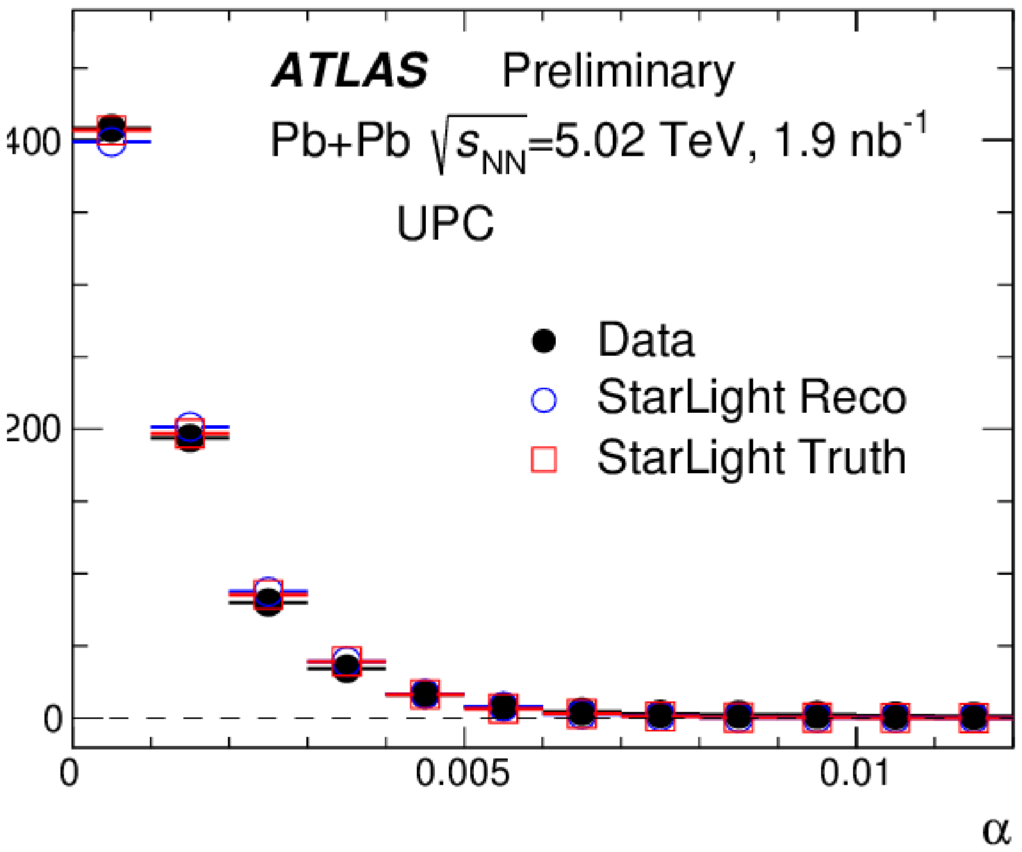
For UPC collisions the data matches STARLIGHT.



Acoplanarity distributions

$$\alpha \equiv 1 - |\Delta\phi|/\pi$$





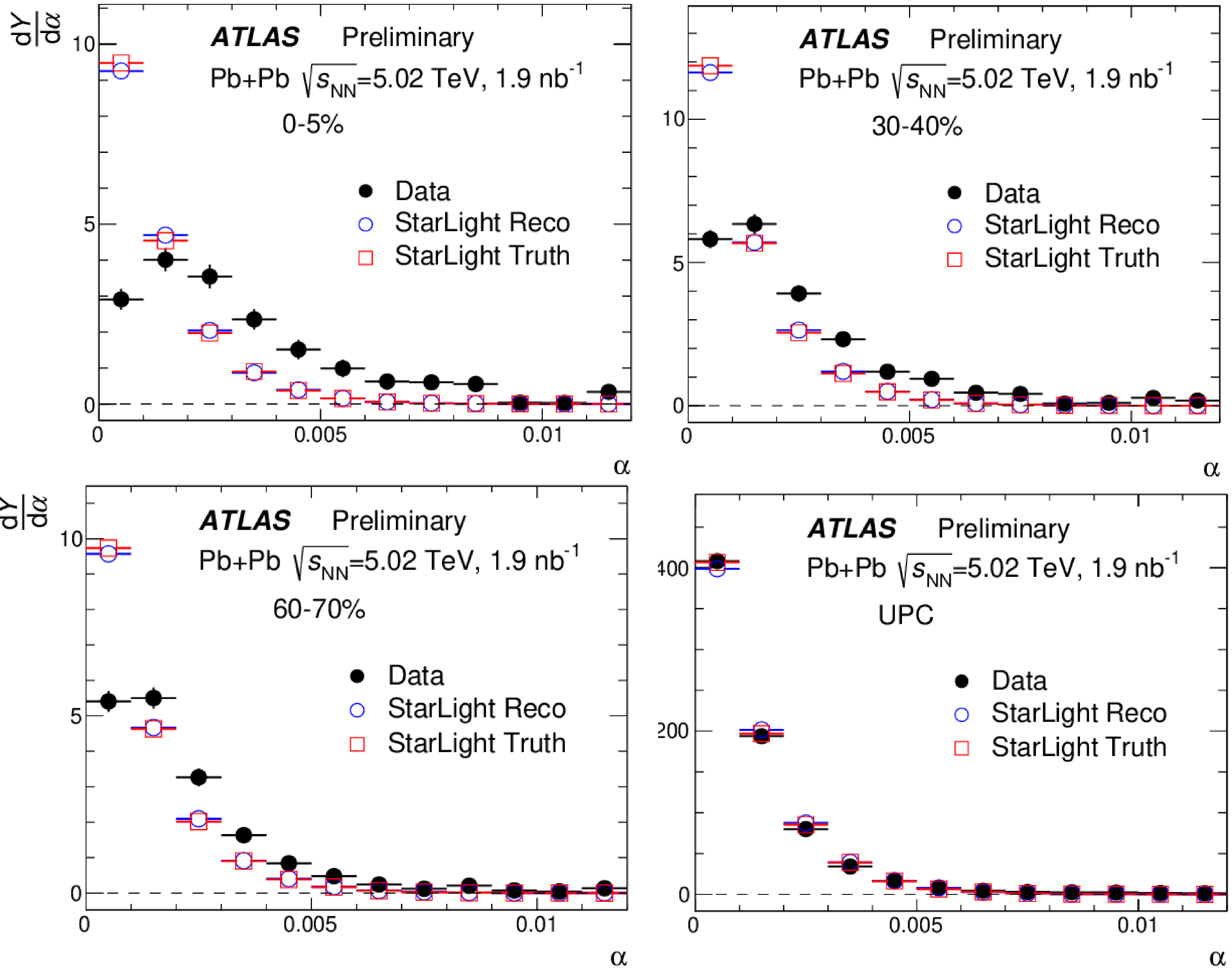
Data compared to STARLIGHT

For UPC collisions the data matches STARLIGHT.

See distinct change in shape of distribution from :

UPC → mid-central → central collisions

Acoplanarity distributions



$$\alpha \equiv 1 - |\Delta\phi|/\pi$$

Data compared to STARLIGHT

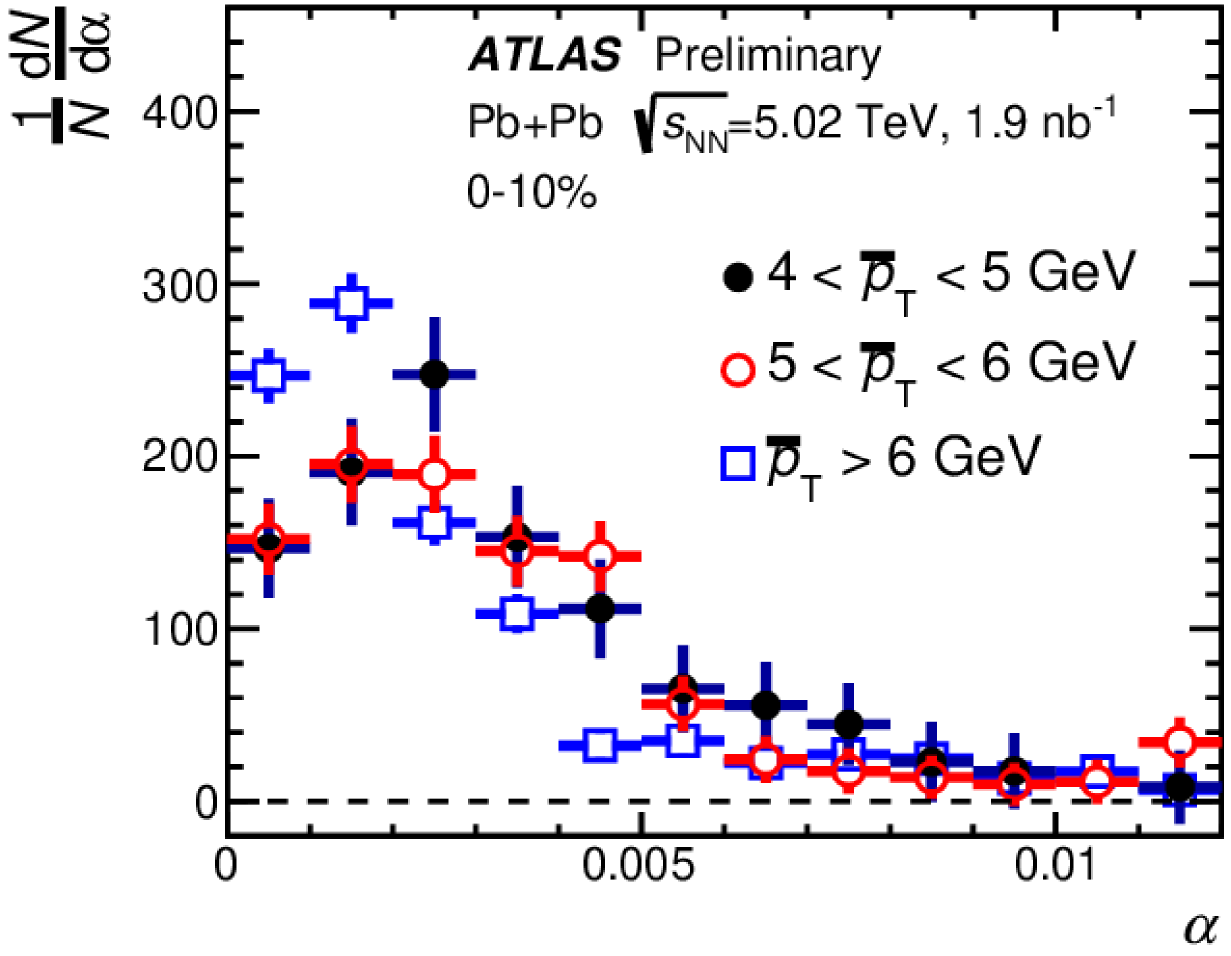
For UPC collisions the data matches STARLIGHT.

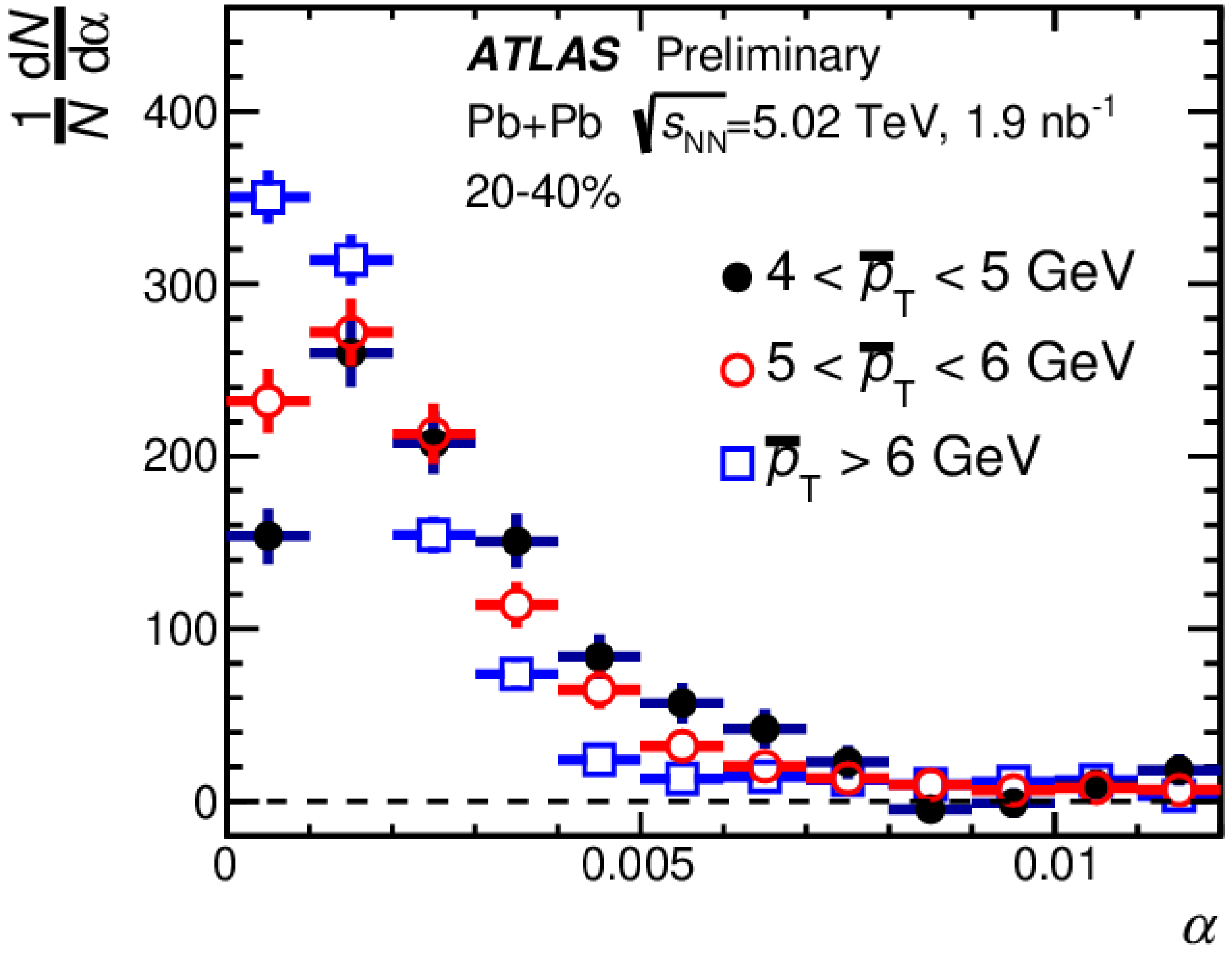
See distinct change in shape of distribution :

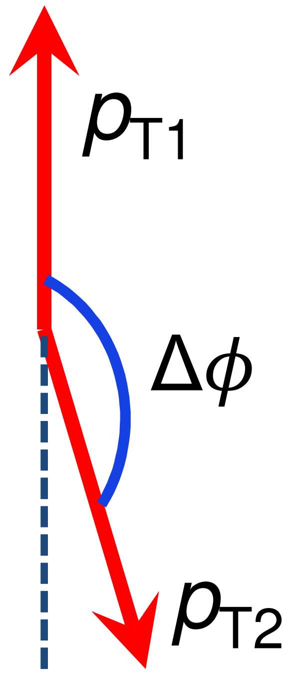
UPC → mid-central → central collisions

In particular development of a “dip” at α=0

Acoplanarity distributions : p_T Dependence



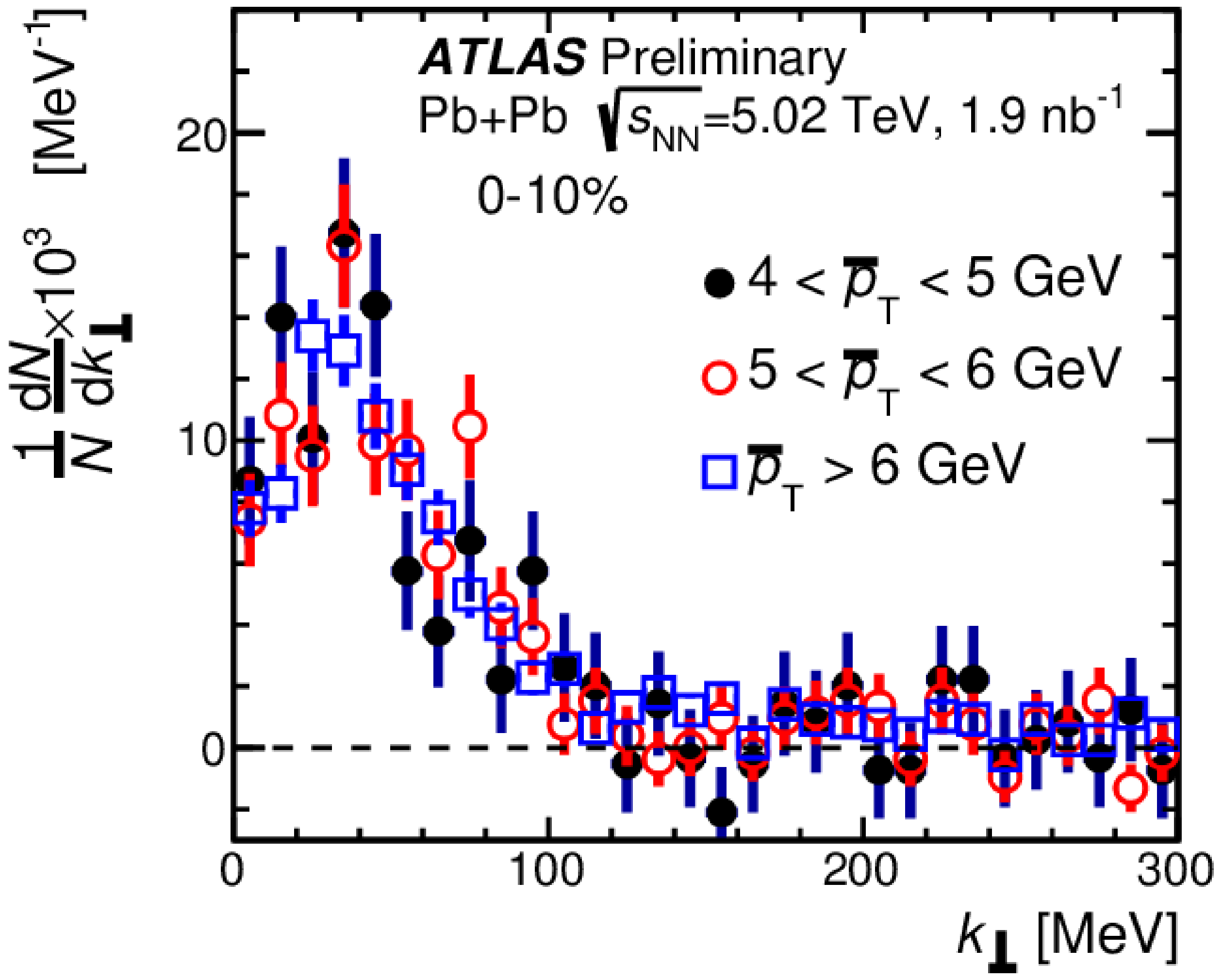


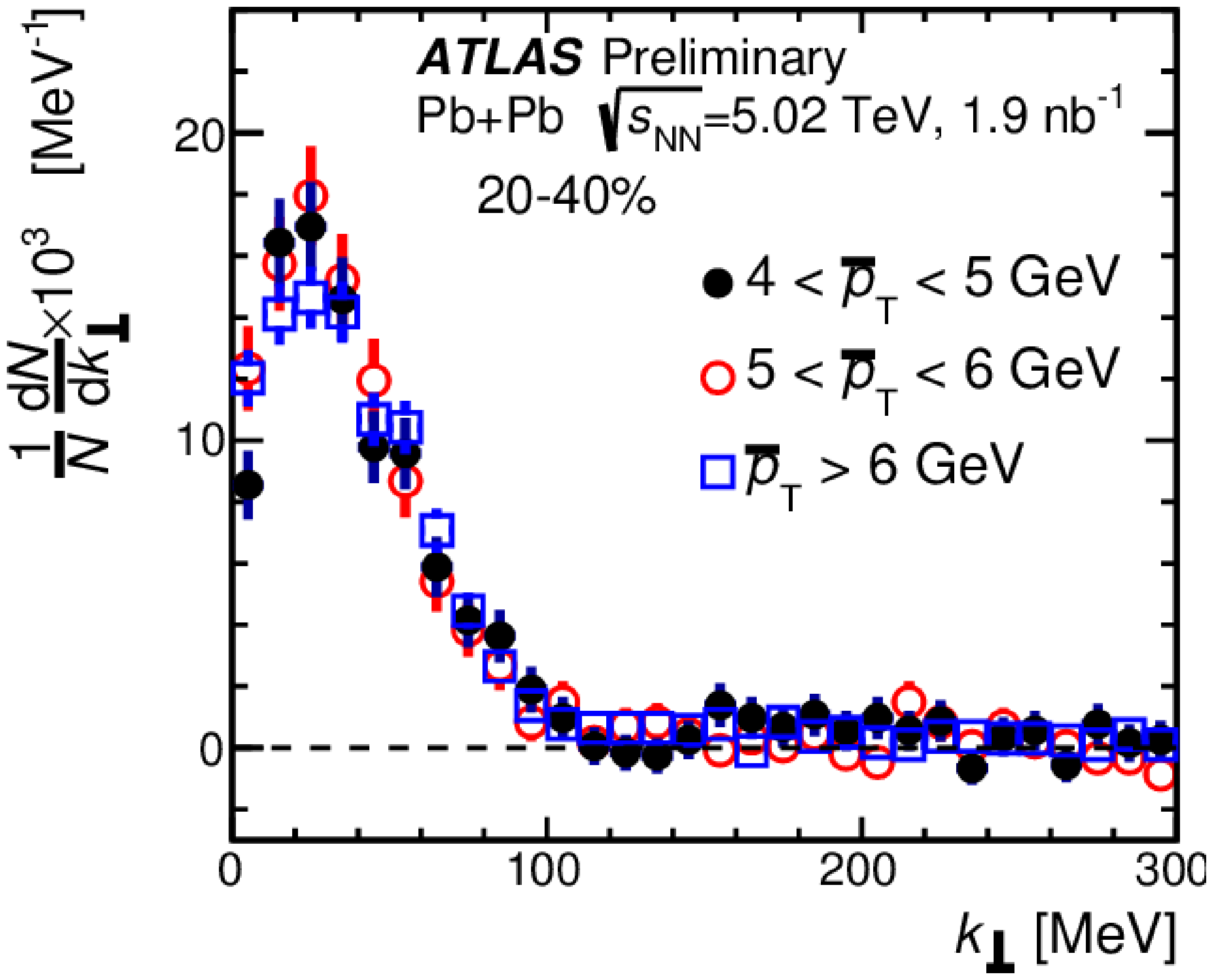


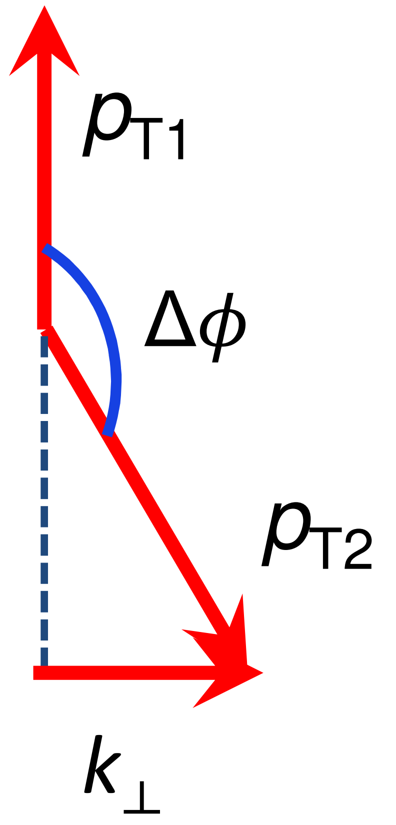
$$\alpha \equiv 1 - |\Delta\phi|/\pi$$

- Strong p_T dependence observed in the shape of the acoplanarity distribution
- Distribution becomes sharper and depletion becomes weaker at higher p_T
- Are higher p_T particles affected less?

$k_\perp$ distributions : p_T Dependence

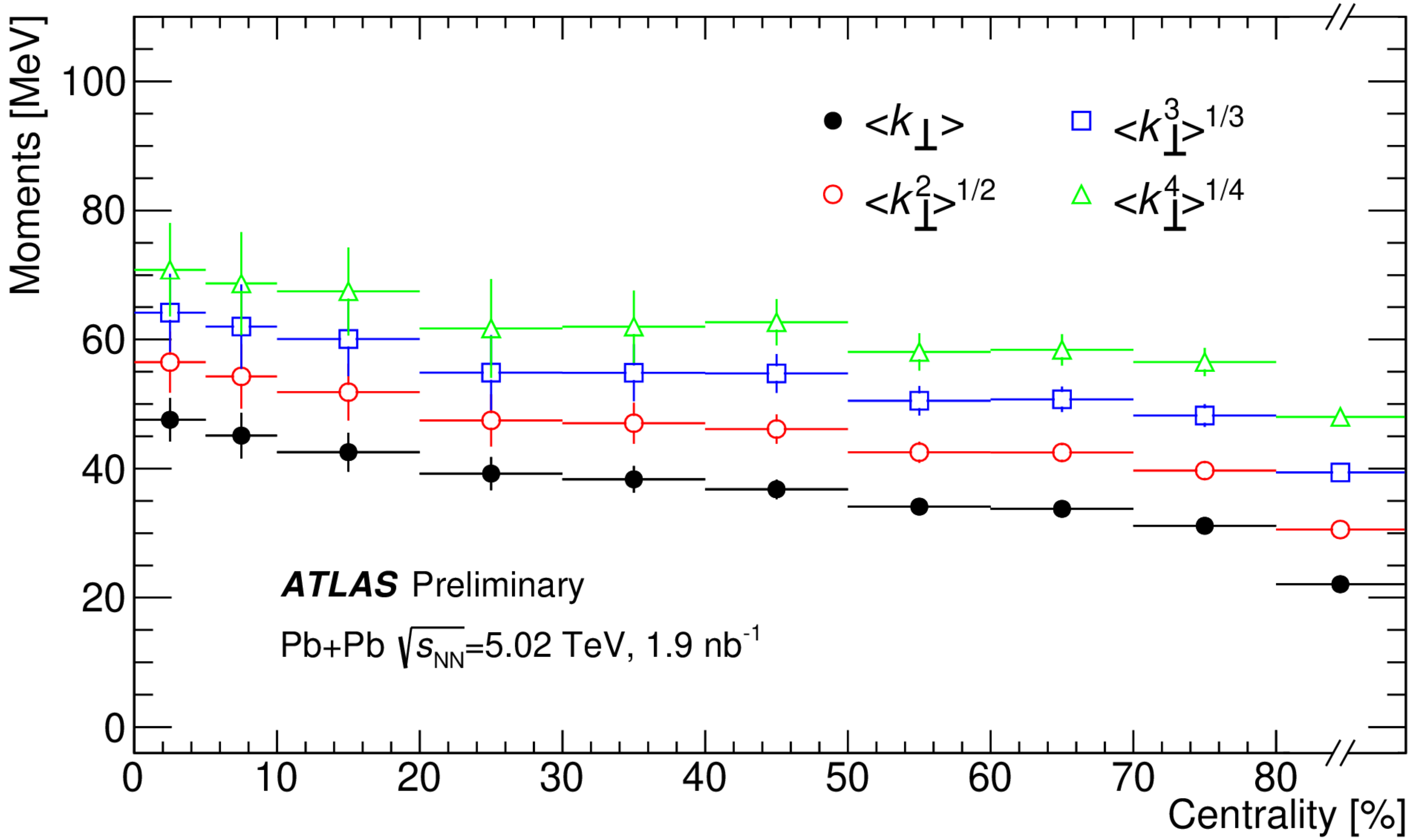


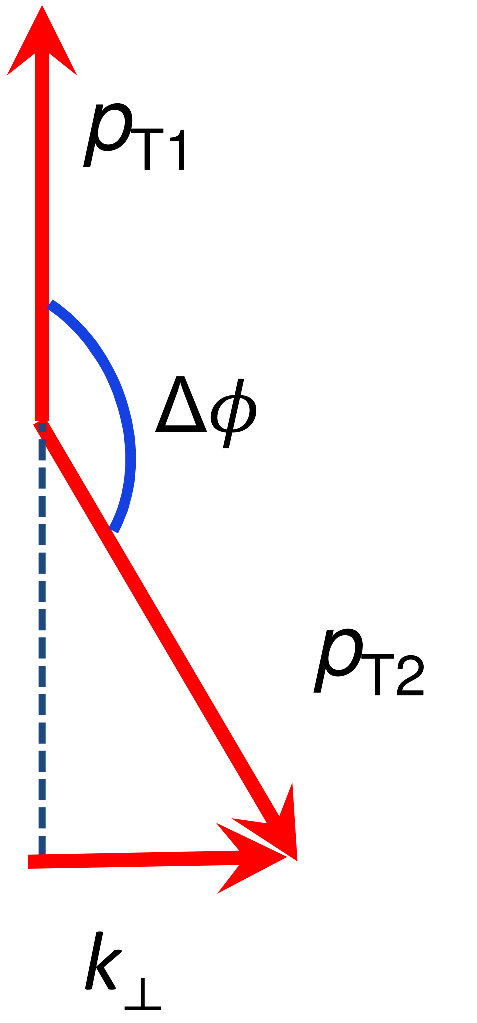




- Much weaker p_T dependence observed for $k_\perp$ distributions.
- Indicates similar momentum kick at different p_T
  - Thus higher p_T particles deflected less.
- $k_\perp$ is “better” observable for studying centrality dependence.

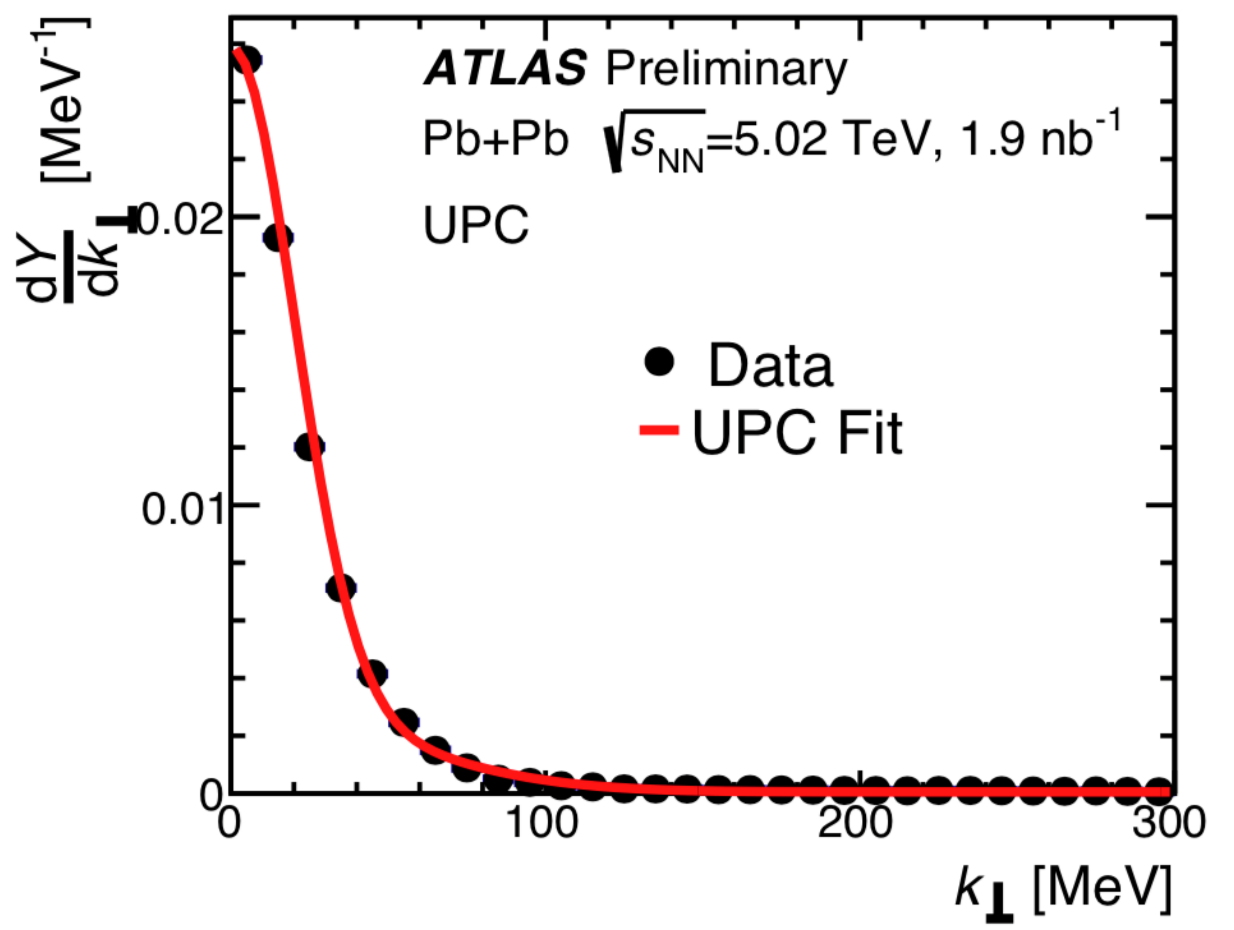
$k_\perp$ distributions





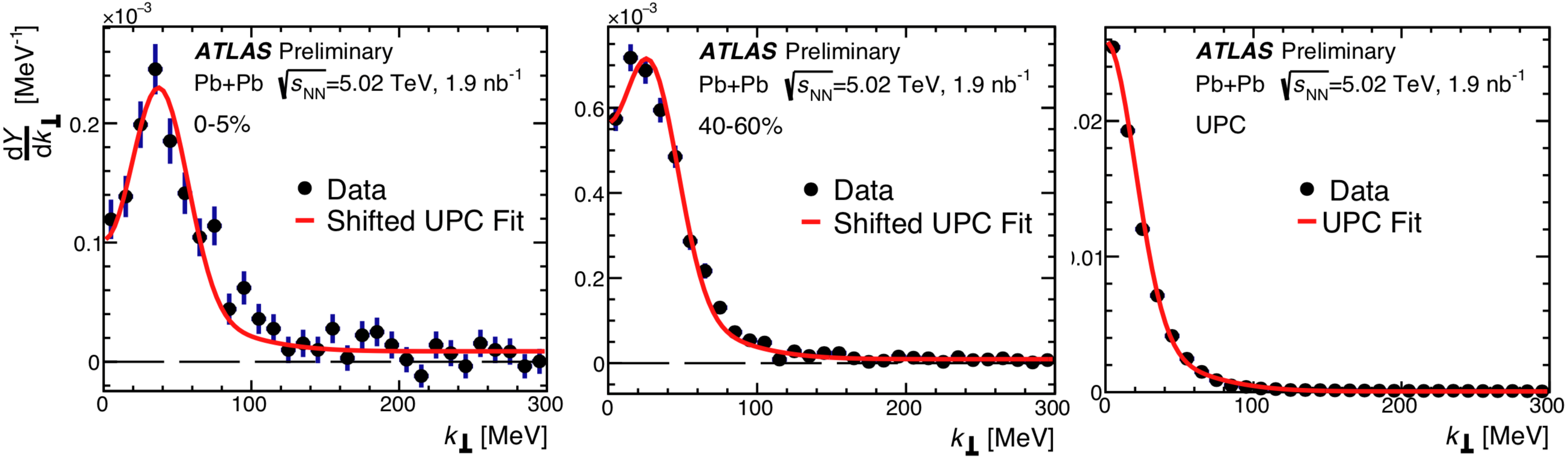
- Can quantify change in shape with moments $k_\perp$ distributions.
- Generally moments increase by 20-25 MeV from UPC to central collisions
  - Indicating a broadening of the $k_\perp$ distributions from UPC to central collisions

Investigation of dip



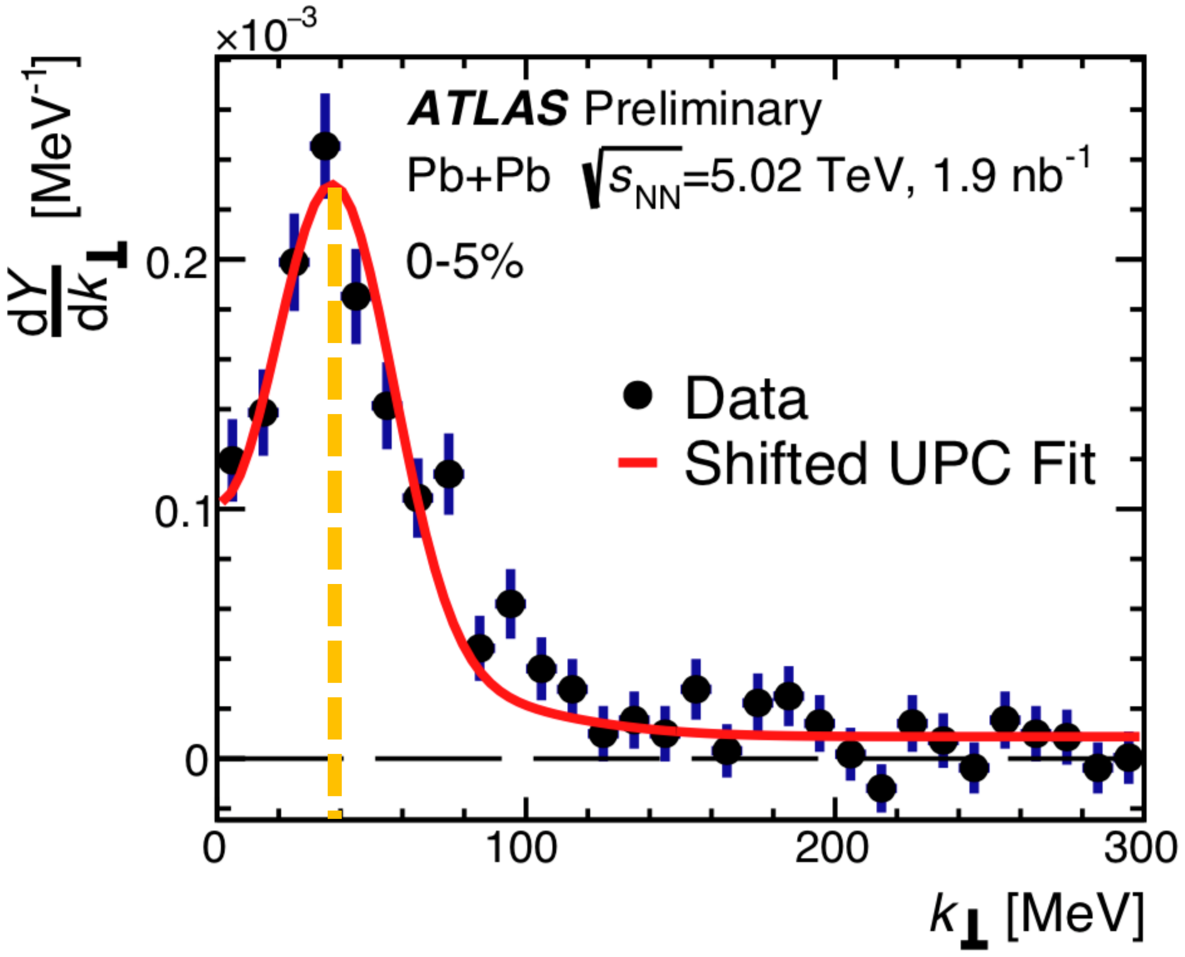
- See if any systematic modification of the UPC distribution can reproduce centrality dependence.
- Parameterize UPC distribution as sum of two gaussians
- Refit the distributions in other centralities as a smeared+shifted version of the UPC distribution

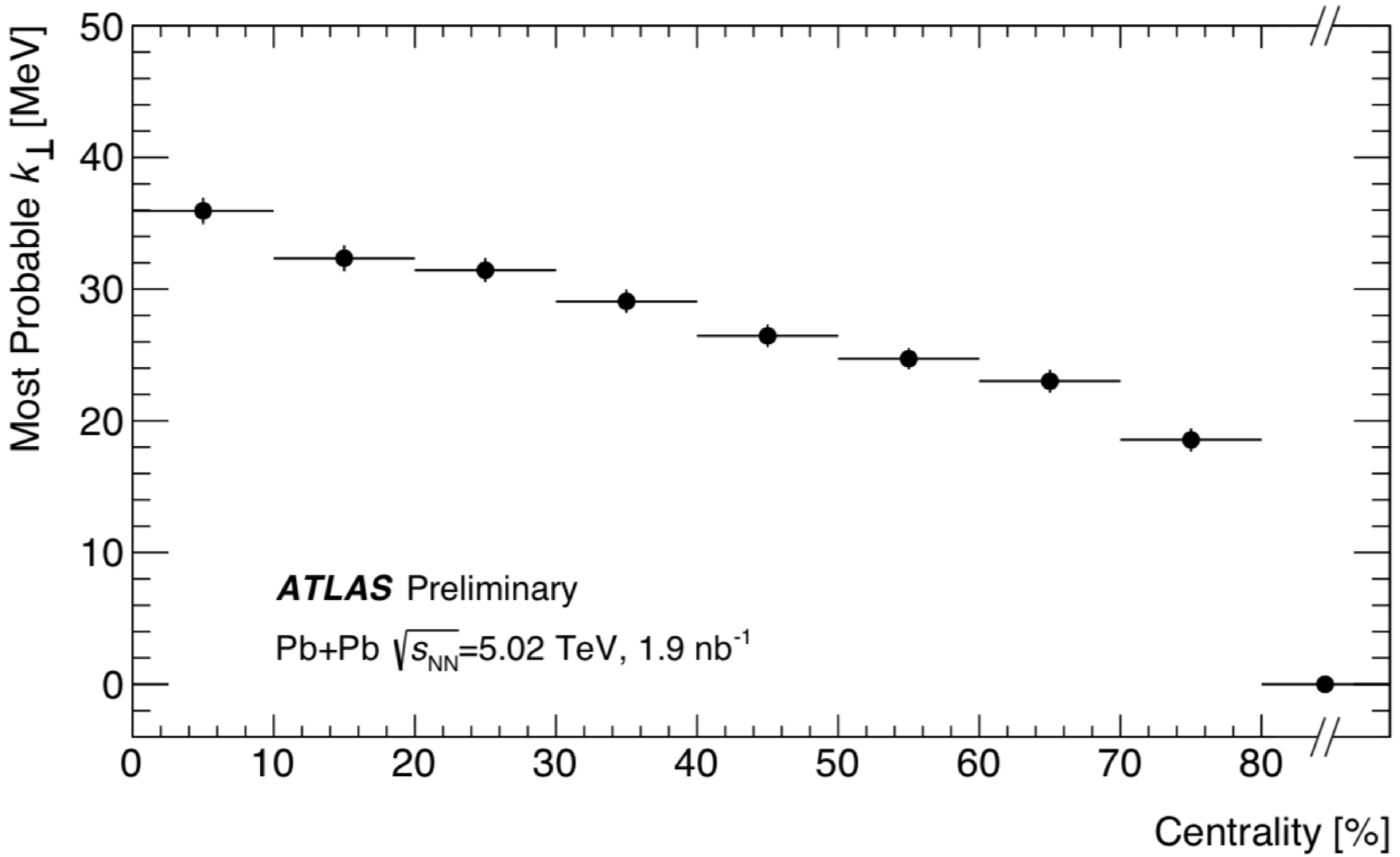
Investigation of dip



- See if any systematic modification of the UPC distribution can reproduce centrality dependence.
- Parameterize UPC distribution as sum of two gaussians
- Refit the distributions in other centralities as a smeared+shifted version of the UPC distribution
- Fits work reasonably well!

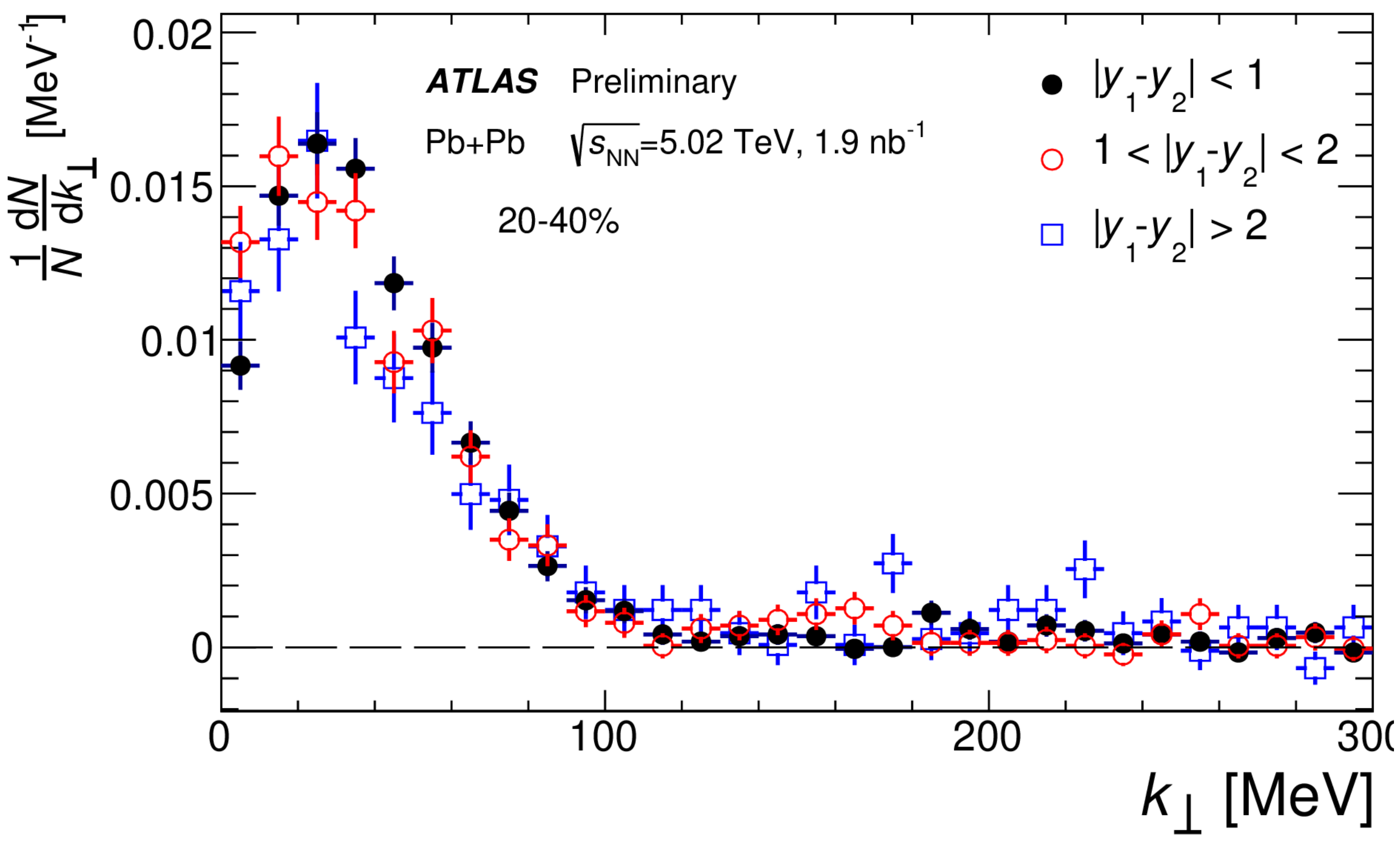
Quantifying the shift

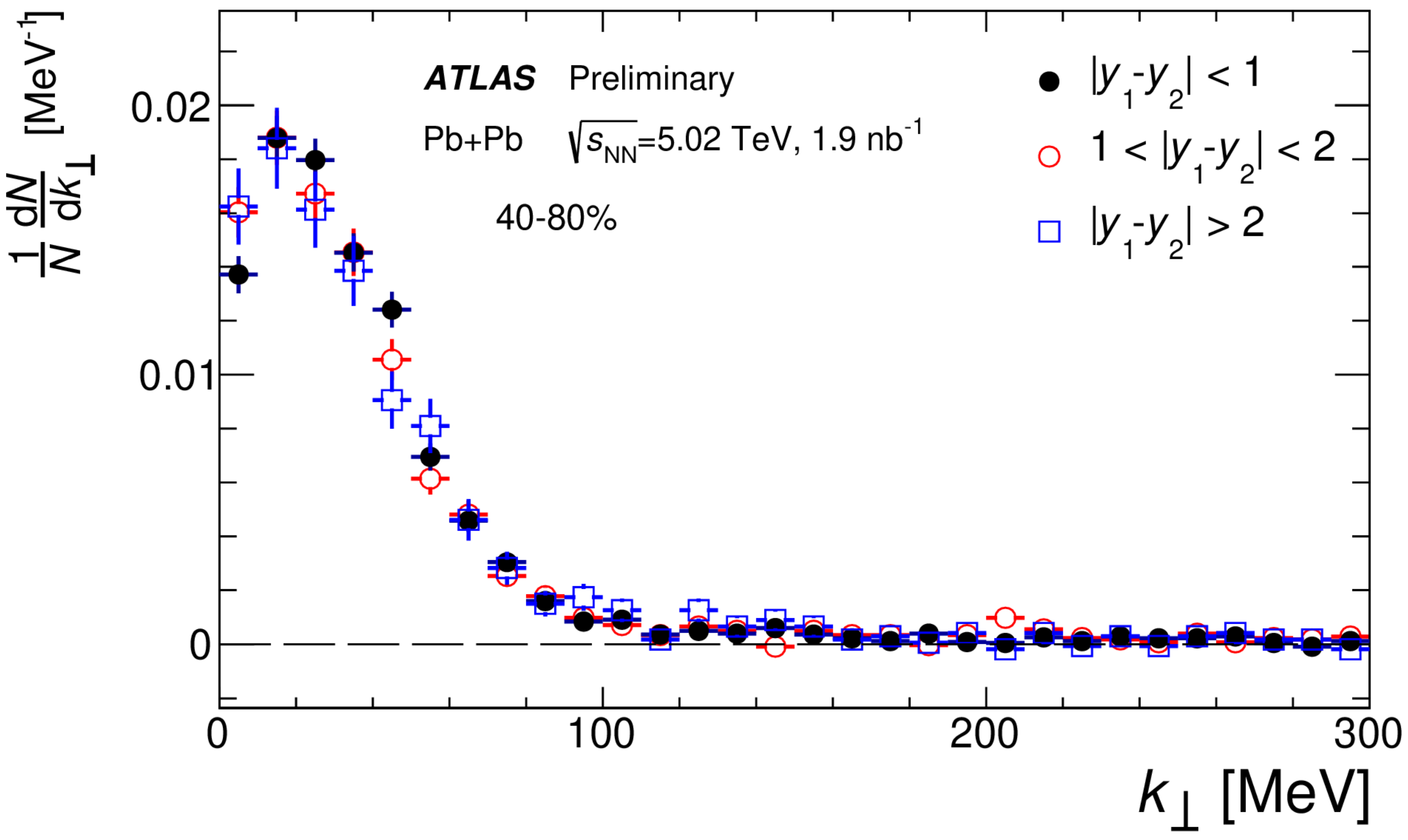




- Left plot: Locate most-probable value of $k_{\perp}$ distributions.
- Right plot : Most probable value as function of centrality.
- Most probable value changes from 0 MeV in UPC to 36 MeV in 0-5% central collisions

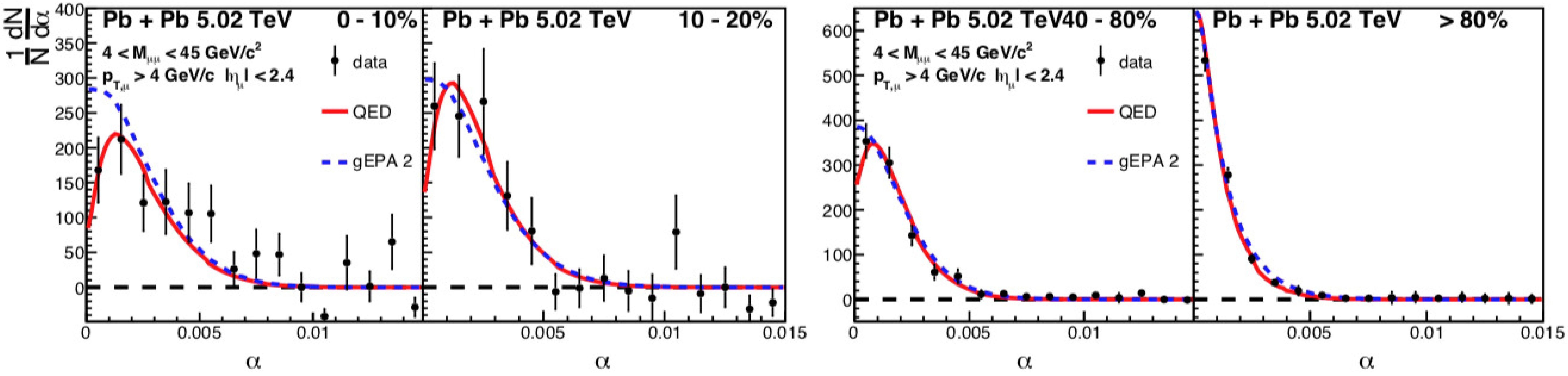
Rapidity separation vs shape for $k_\perp$





- Prediction from Klein and collaborators (Phys. Rev. Lett. 122, 132301)
  - If broadening was caused by deflection from magnetic field, it should increase with rapidity separation between muons
- No clear dependence of shape on rapidity separation between muons observed

Comparison to QED Calculations



- QED Calculation from W. Zha *et.al* (*Phys. Lett. B 800 (2020) 135089*)
  - Qualitatively reproduces dip (compared with prior data from *Phys. Rev. Lett. 121 (2018) 212301*)
- Broadening and depletion entirely reproduced by impact-parameter dependence of EM Fields

Summary

- Measured yields and distributions of dimuons from $\gamma\gamma \rightarrow \mu^+\mu^-$ processes in Pb+Pb collisions
  - In UPC and non-UPC collisions
- Removed background contributions in non-UPC events via a template-fitting method

- Distributions for Acoplanarity and $k_\perp$ show significant centrality dependence
  - Develop a broadening with increasing centrality and a depletion at $k_\perp$=0
  - Most probable value of $k_\perp$ in 0-5% central collisions is at 36 MeV

- Acoplanarity distributions show a p_T dependence while $k_\perp$ distributions do not.
  - Consistent with a process that imparts a momentum kick to the outgoing muons
  - Although QED calculations accounting for impact parameter dependence qualitatively reproduce the broadening