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

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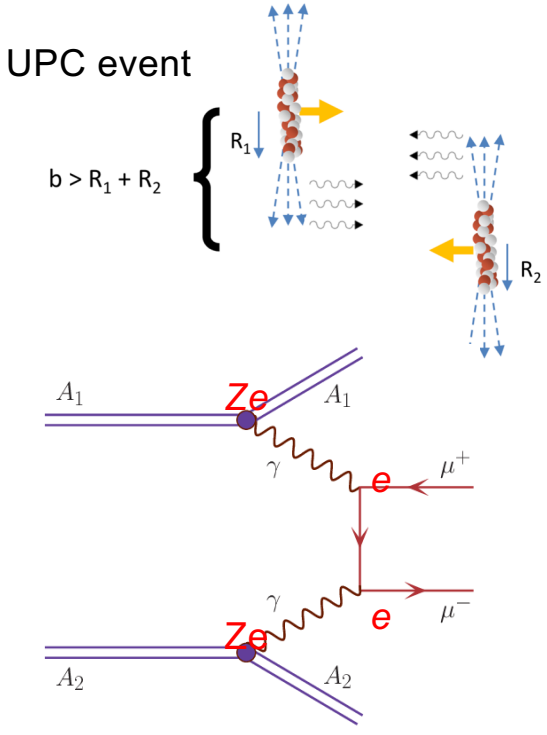
For the ATLAS Collaboration

ATLAS-CONF-2019-051
Phys. Rev. Lett. 121 (2018) 212301
ATLAS-CONF-2016-025

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 ~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

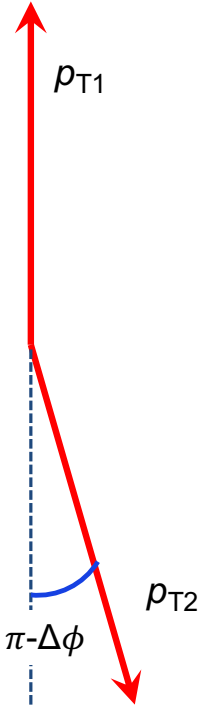
Maximum p_T of incoming photons ~same as rest-frame p_T~ O(10 MeV).

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

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

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

Mismatch in transverse momentum of the two muons



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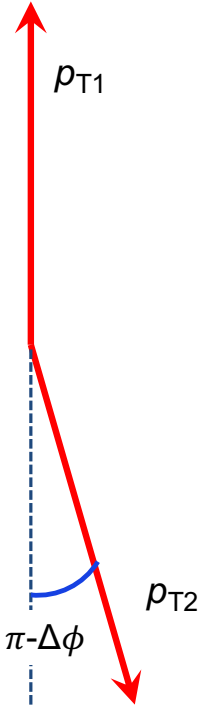
Mismatch in transverse momentum of the two muons

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

Deviation from being perfectly back-to-back



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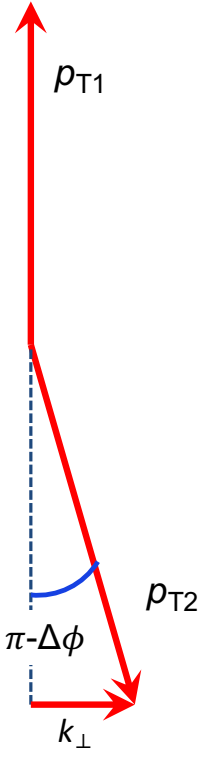
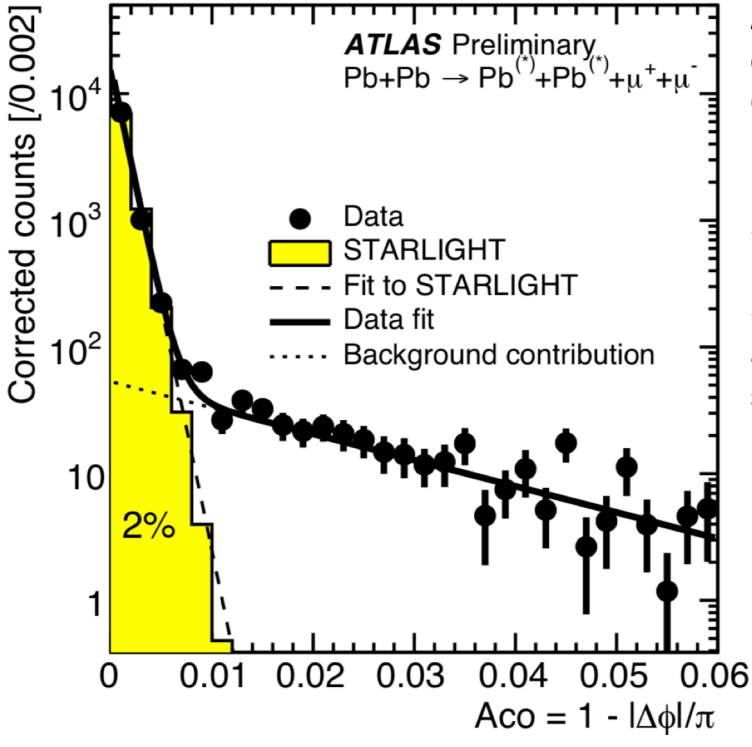
Deviation from being perfectly back-to-back

$$k_\perp \equiv (p_{T1} + p_{T2}) \, |(\pi - \Delta\phi)| / 2 = \pi \alpha \bar{p}_T$$

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

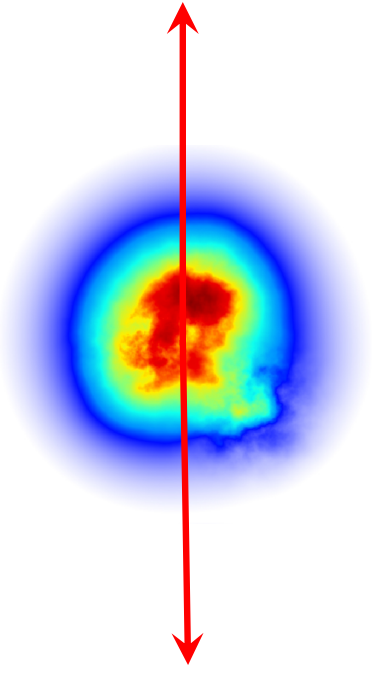
STARLIGHT uses the equivalent photon approximation + leading order QED cross-sections

ATLAS-CONF-2016-025

See also CMS-PAS-HIN-19-014
Talk by Shuai Yang, EW Probes-II

$\gamma\gamma \rightarrow \mu\mu$ 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, which must be removed.



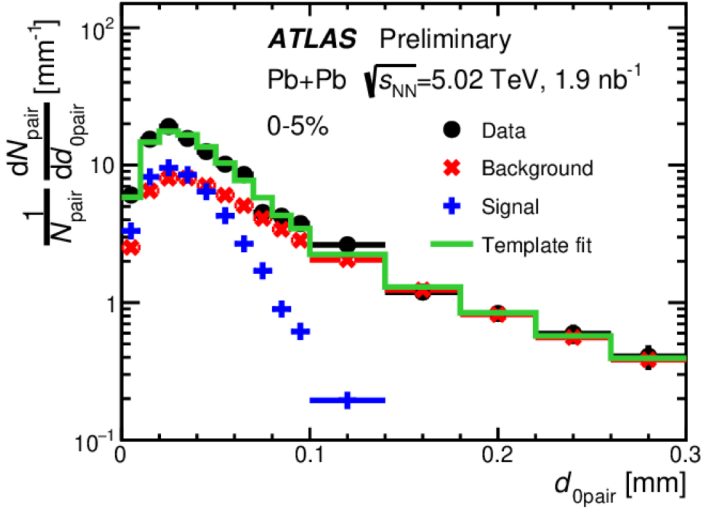
Signal & background pairs

- Reduce the HF contribution by requiring muons to be closely matched in p_T and be 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 or magnitude in central collisions

- HF muons often arise from displaced secondary decay vertices
  - Use impact parameter in the transverse (d_0) plane to remove residual background

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

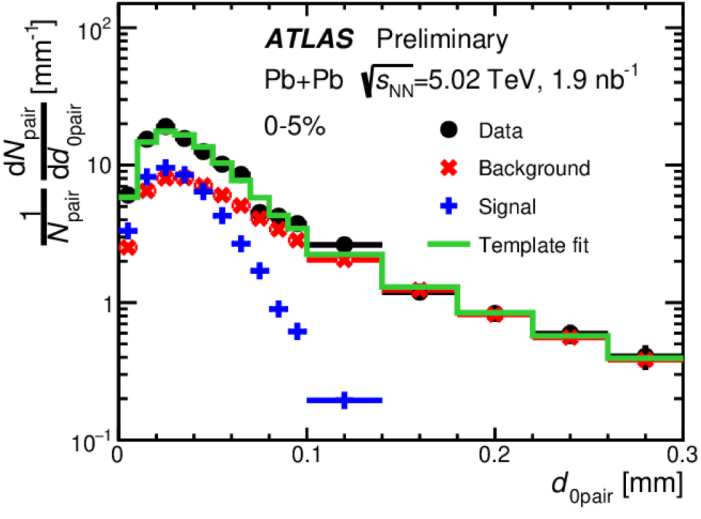
Estimating residual background contribution

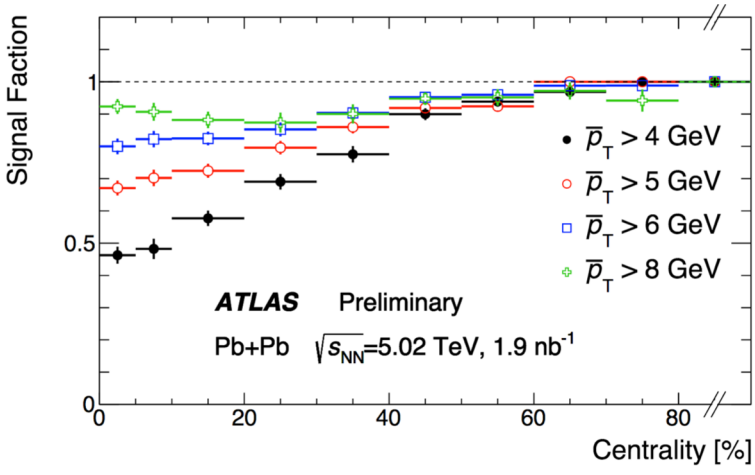


$$d_{0_{pair}} = \sqrt{d_{0_1}^2 + d_{0_2}^2}$$

- To estimate the residual background, fit the d_{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

Estimating residual background contribution





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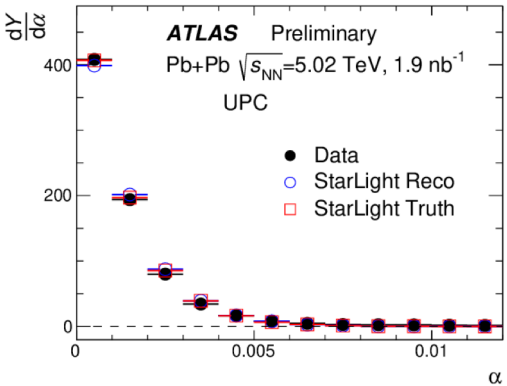
Acoplanarity distributions

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

Data compared to STARLIGHT

For UPC collisions the data matches STARLIGHT.



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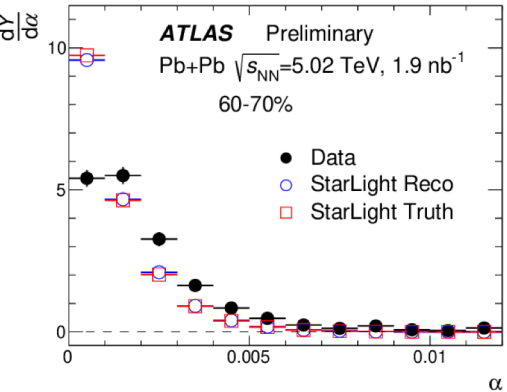
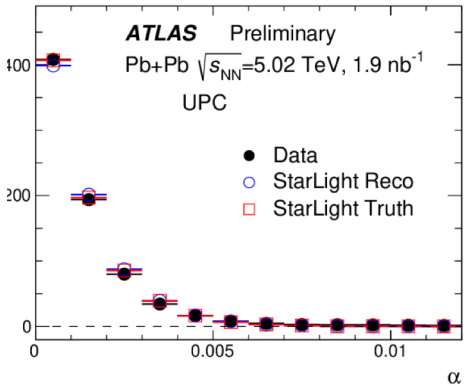
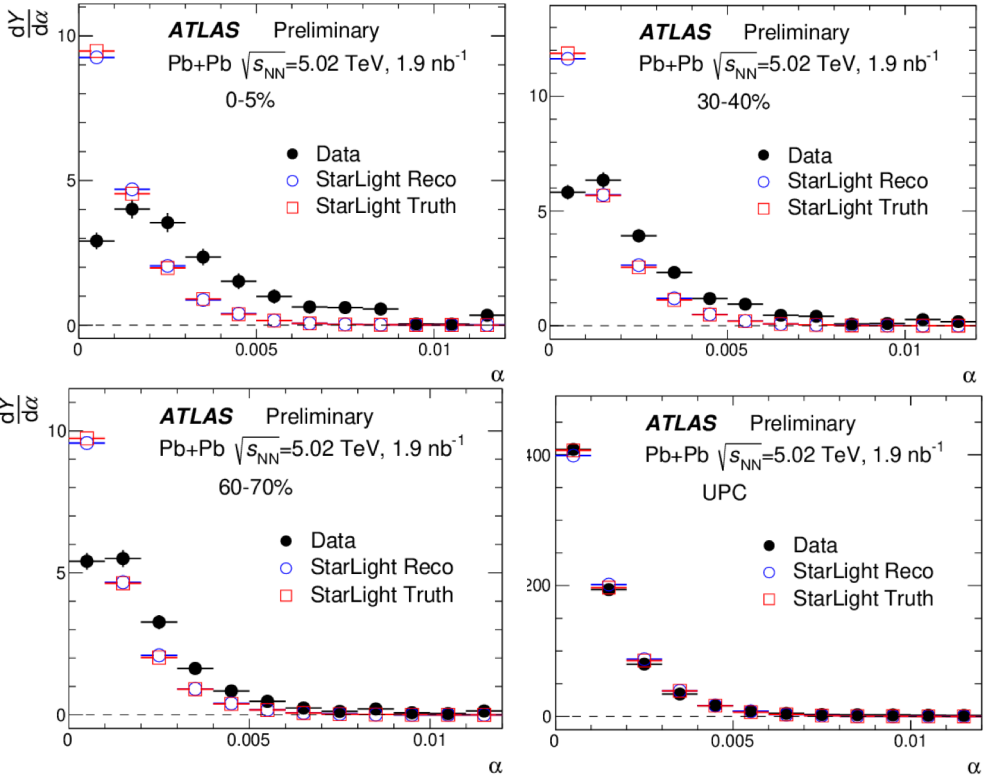
See distinct change in shape of distribution from UPC->mid-central->central collisions





Acoplanarity distributions



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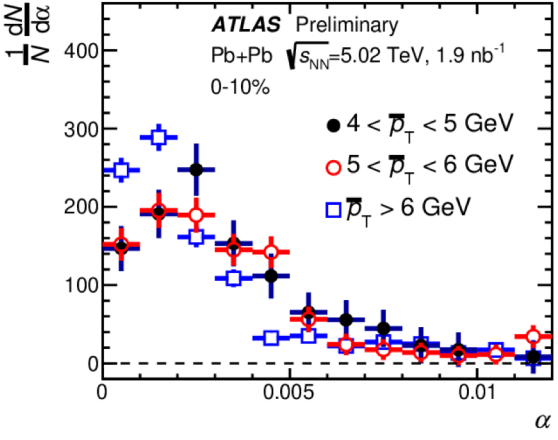
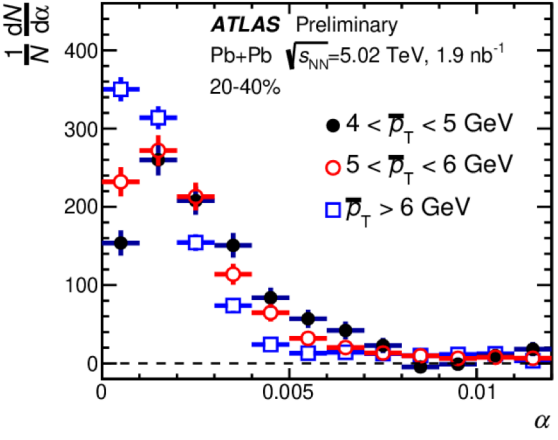
For UPC collisions the data matches STARLIGHT.

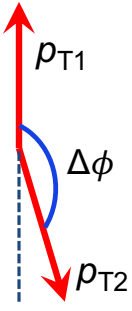
See distinct change in shape of distribution from UPC->mid-central->central collisions

In particular development of a "dip" at α=0

Acoplanarity distributions : p_T Dependence



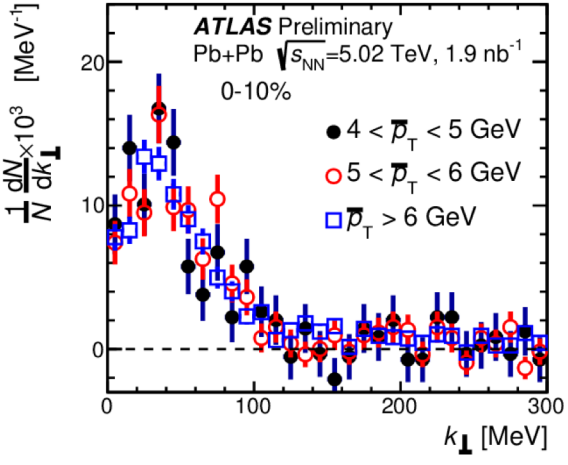


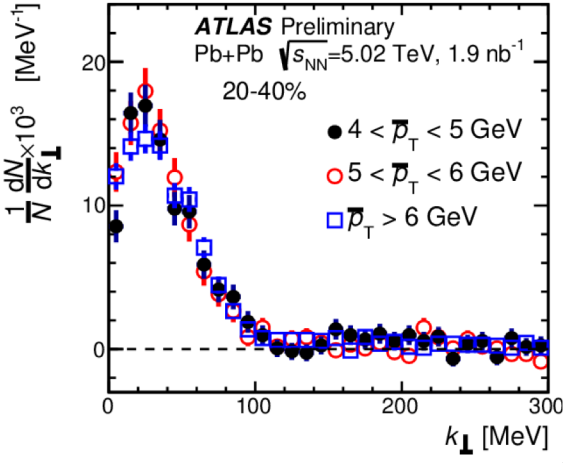


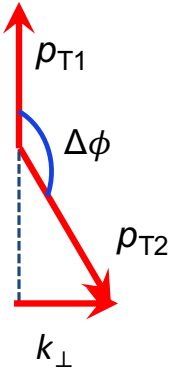
$$\alpha \equiv 1 - |\Delta\phi|/\pi$$

- 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

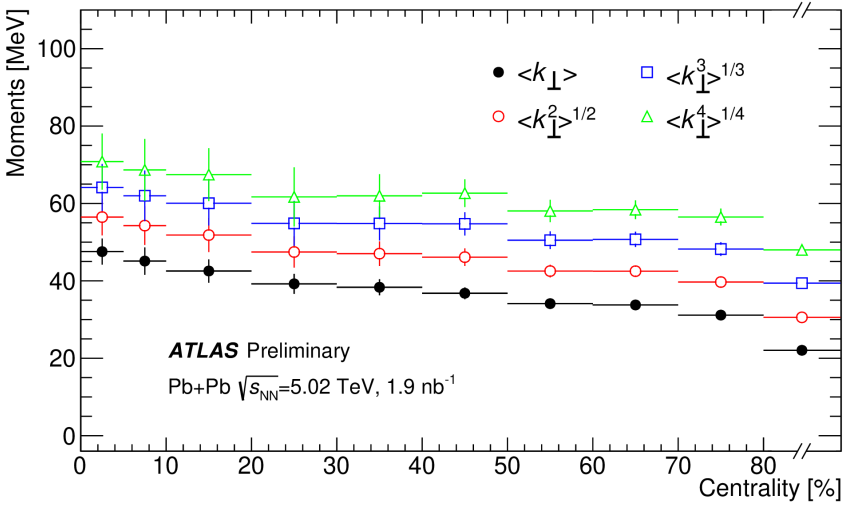


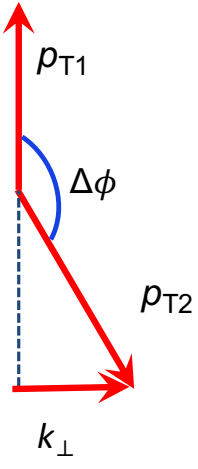




- Much weaker p_T dependence observed for $k_\perp$ distributions.
- Indicates similar momentum kick at different p_T
  - Thus higher p_T particles deflected less.

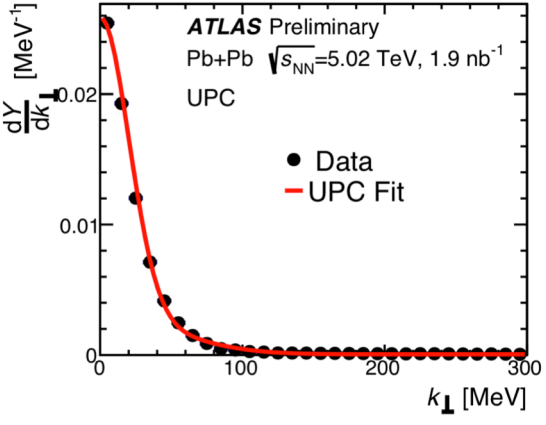
$k_\perp$ distributions





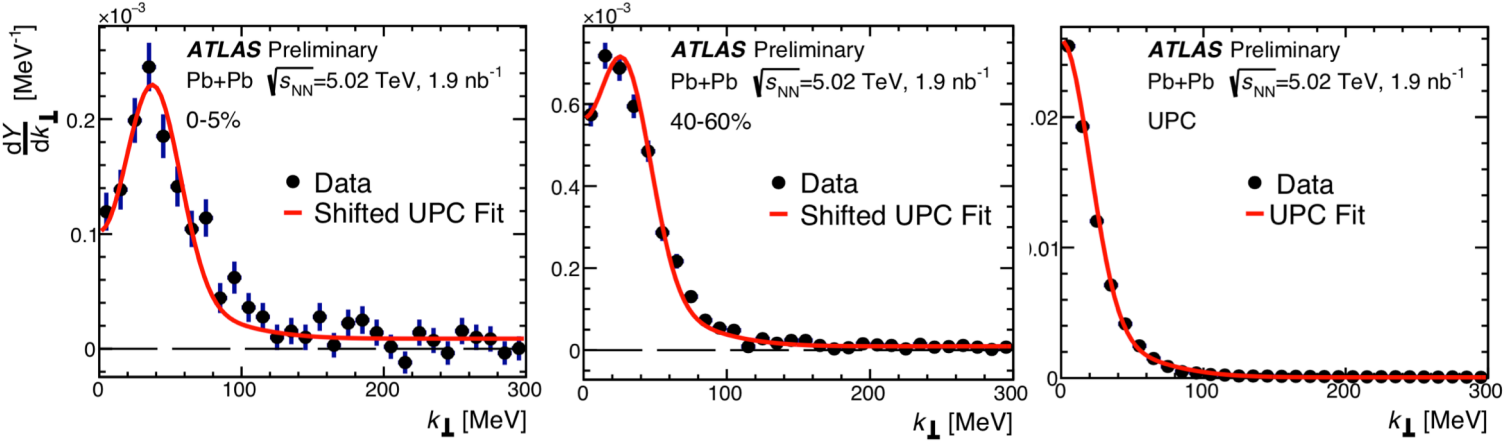
- Can quantify change in shape with moments $k_\perp$ distributions.
- Generally moments increase by 20-25 MeV from UPC to central collisions
  - Indicating a broadening of the $k_\perp$ distributions from UPC to central collisions

Investigation of dip



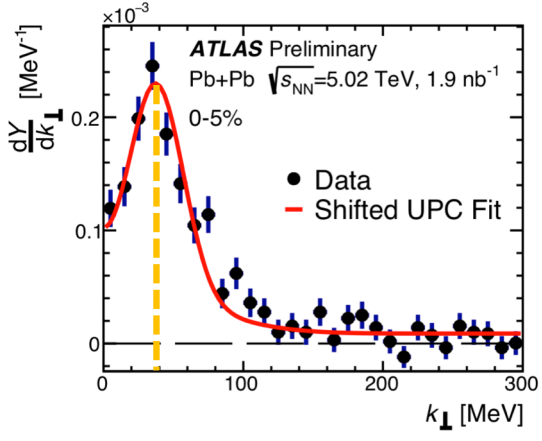
- See if any systematic modification of the UPC distribution can reproduce centrality dependence.
- Parameterize UPC distribution as sum of two gaussians
- Refit the distributions in other centralities as a smeared+shifted version of the UPC distribution

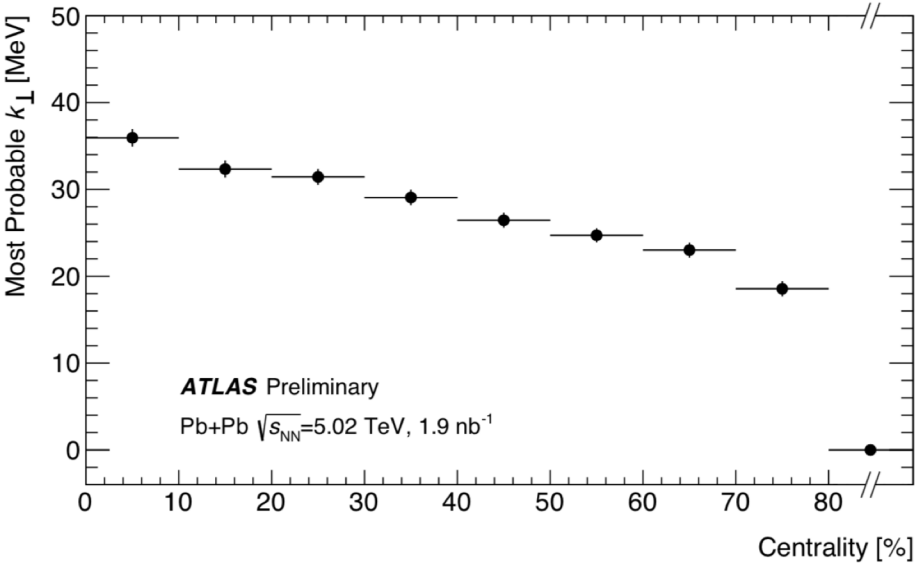
Investigation of dip



- 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 resonably well!

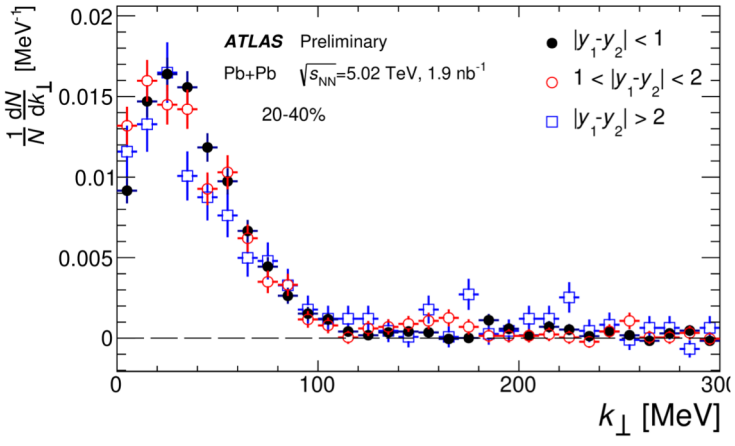
Quantifying the shift

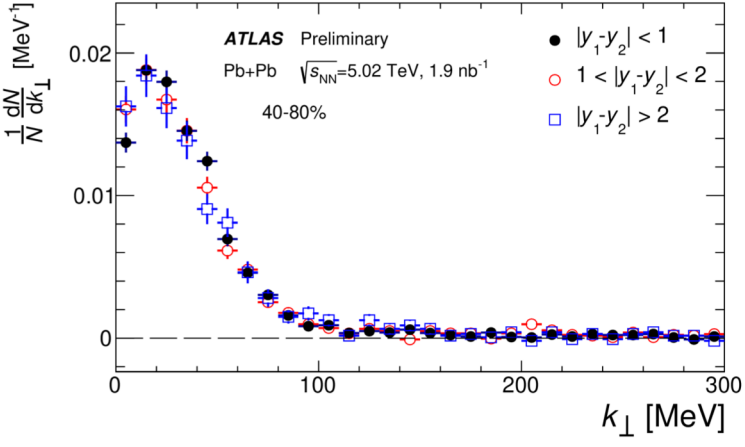




- Left plot: Locate most-probable value of $k_\perp$ distributions.
- Right plot : Most probable value as function of centrality

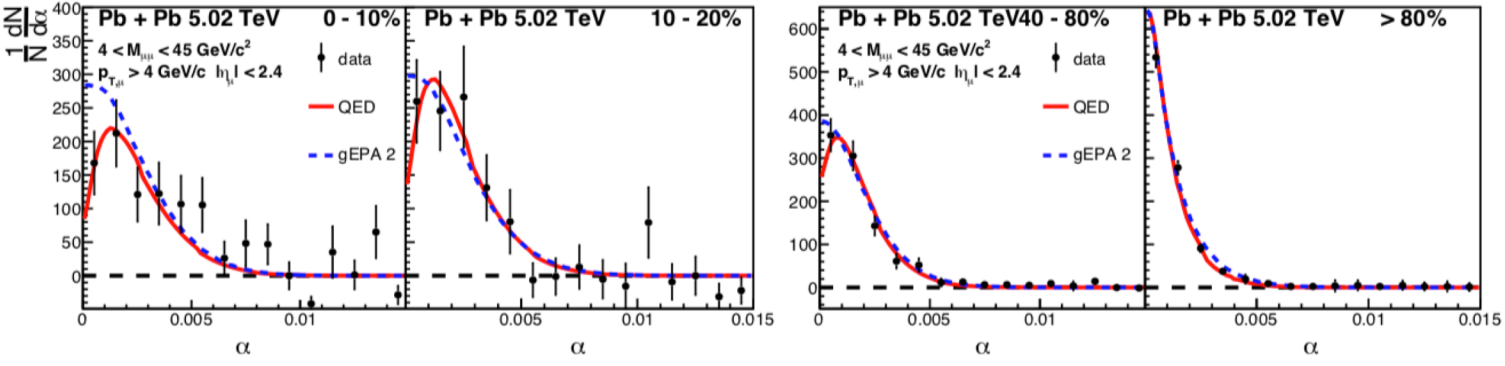
Rapidity separation vs shape for $k_\perp$





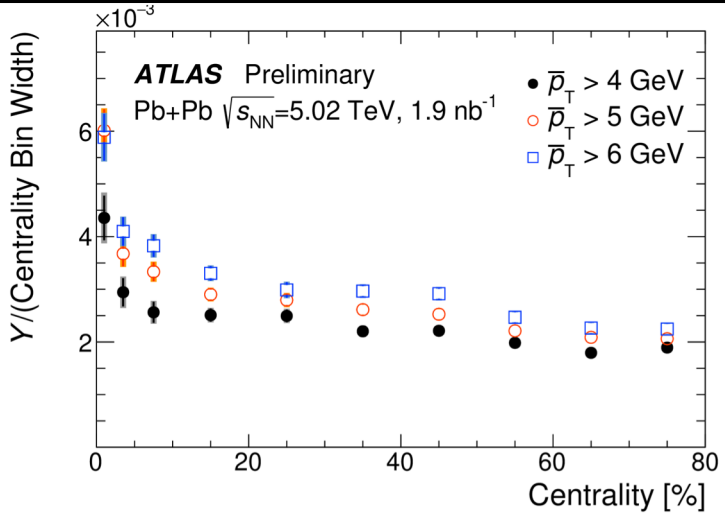
- Prediction from Klein and collaborators (Phys. Rev. Lett. 122, 132301)
  - If broadening was caused by deflection from magnetic field, it should increase with rapidity separation between muons
- No clear dependence of shape on rapidity separation between muons observed

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

Yields of dimuon pairs



$$Y^{\mathrm{cent},\bar{p}_{\mathrm{T}}} \equiv \frac{N_{\mathrm{sig}}^{\mathrm{cent},\bar{p}_{\mathrm{T}}}}{N_{\mathrm{sig}}^{\mathrm{all},\bar{p}_{\mathrm{T}}}} = \frac{\text{Yield in given centrality}(p_{\mathrm{T}})}{\text{Total yield}(p_{\mathrm{T}})}$$

- Centrality dependence of Yield fractions
- Increase from peripheral mid-central collisions
- p_{T} spectra becomes harder with increasing centrality

Summary

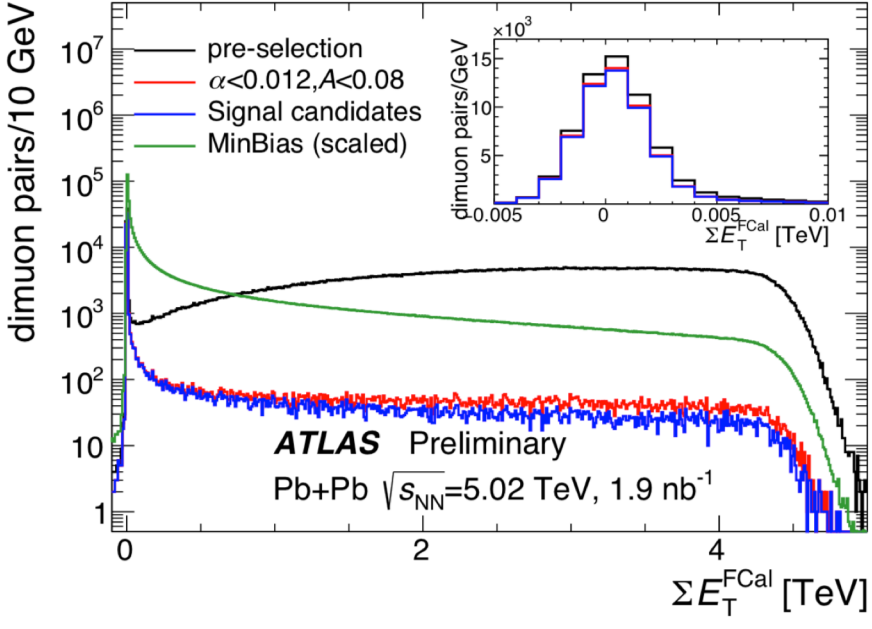
- Measured yields and distributions of dimuons from $\gamma\gamma \rightarrow \mu^+\mu^-$ processes in Pb+Pb collisions
  - In UPC and non-UPC collisions
- Removed background contributions in non-UPC events via a template-fitting method

- 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 calculations accounting for impact parameter dependence of the EM field qualitatively reproduce the broadening

- Yields increase from peripheral to central events
  - Normalized-yields increase with increasing p_T.
  - Larger fraction of the higher-p_T pairs are produced in central collisions

FCal (i.e. centrality) distribution of candidate pairs



Black: All pairs passing preselections

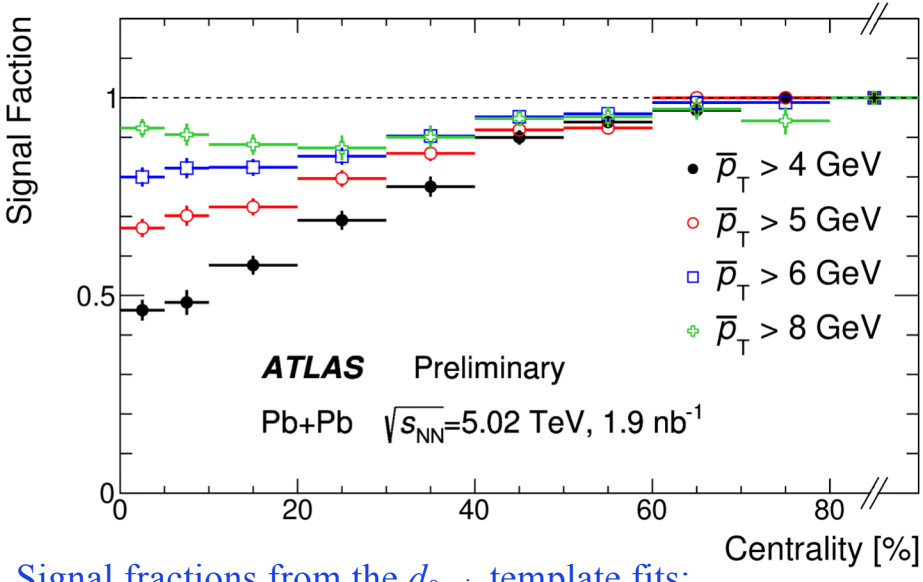
Red: Asymmetry<0.06, Asymmetry<0.012

Blue: Cuts on d_{0pair} and z_{0pair}

Green: min-bias distribution for reference

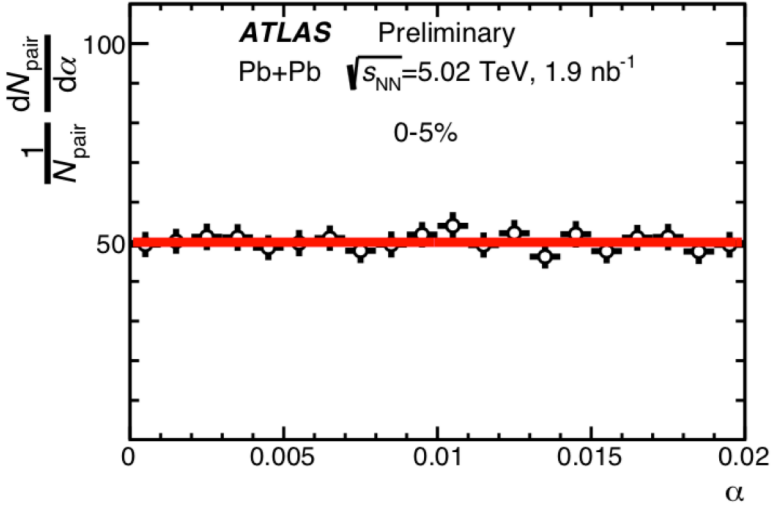
Inset shows the UPC region

Signal fractions



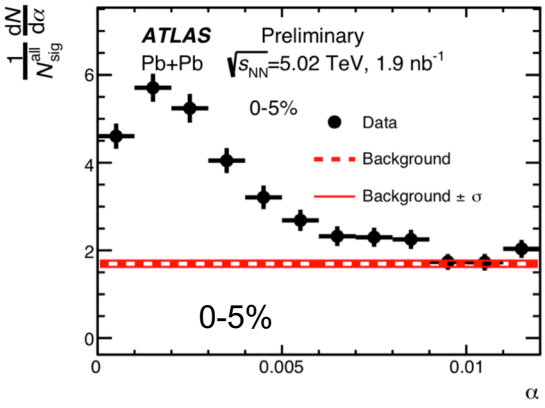
- Signal fractions from the d_{0pair} template fits:
  - For different values of the mean-p_T of the pair.
- Typically fractions decrease from peripheral to central collisions
- At higher p_T signal fractions are larger.

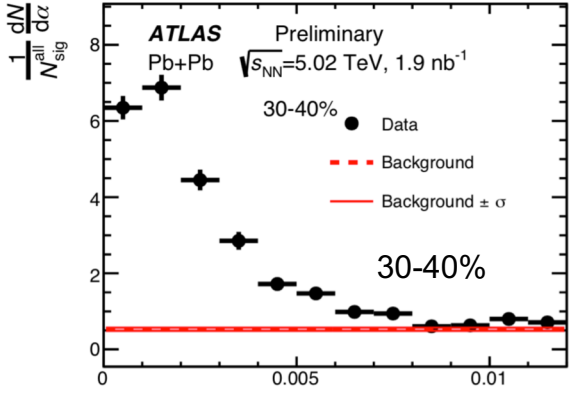
Shape of the background distributions



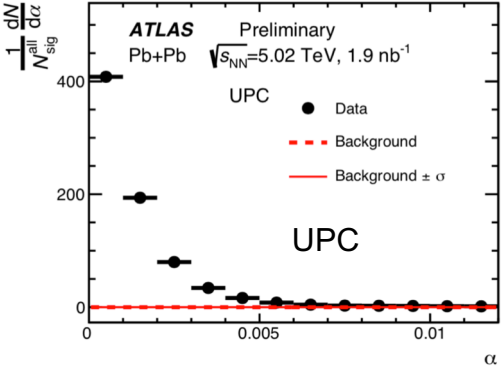
- Also obtained by applying the anti-cuts to the data:
  - Asymmetry>0.08 to obtain background shapes for Acoplanarity (or $k_{\perp}$) distribution

Background subtraction from acoplanarity distributions

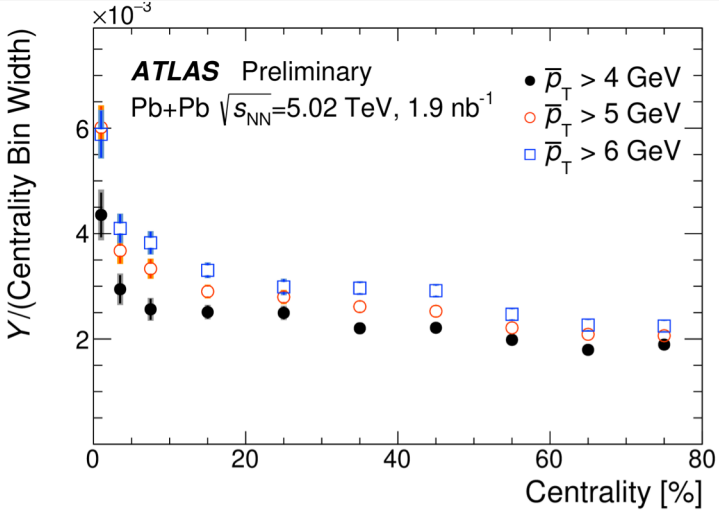




- Knowing the background fractions and shape, the backgrounds can be removed.
- Shown here for the Acoplanarity (or α) distribution for three centrality intervals



Fractional-Yields of dimuon pairs



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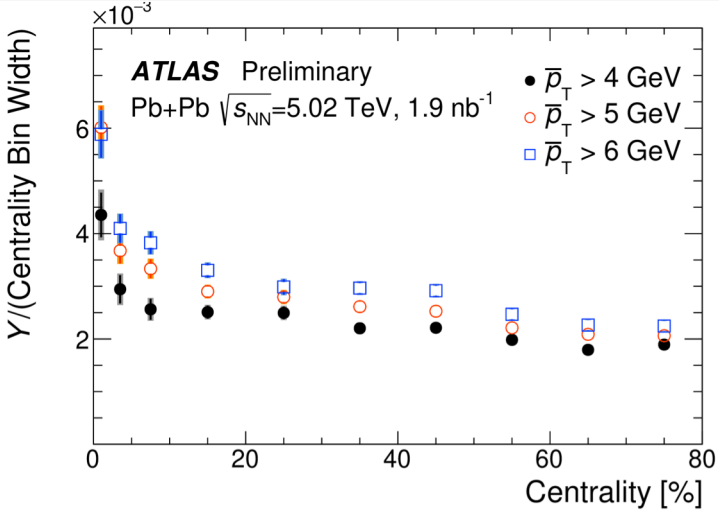
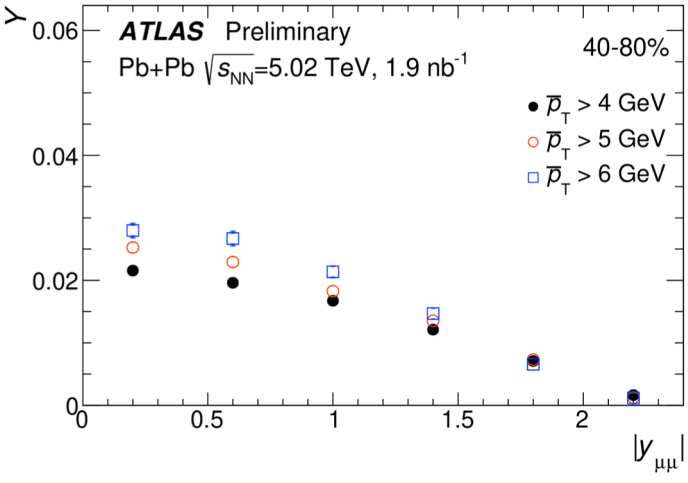
- p_T spectra becomes harder with increasing centrality

Fractional-Yields of dimuon pairs





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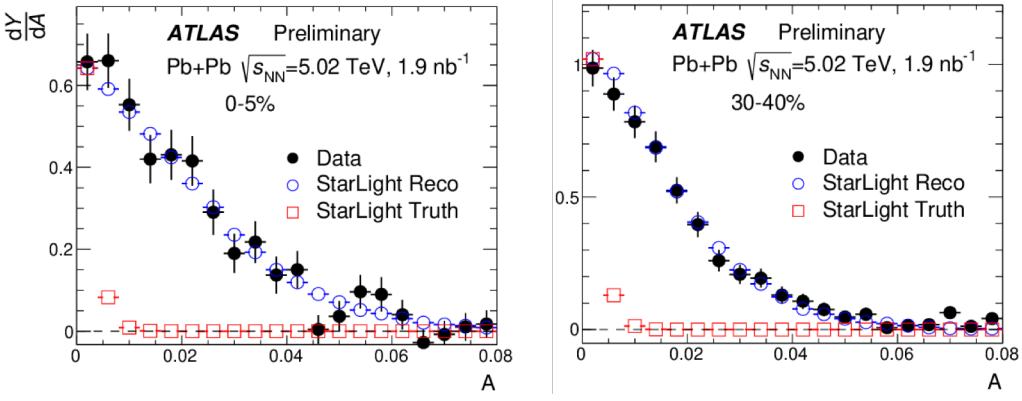
Asymmetry distributions



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

- Compare the Asymmetry distributions in data with the Asymmetry distributions in STARLIGHT MC
- STARLIGHT distributions shown for "Truth" i.e. Generated particles
- As well as for "Reconstructed" particles: after simulation of detector response
- The detector's p_T resolution washes out any possible modifications in the Asymmetry distribution