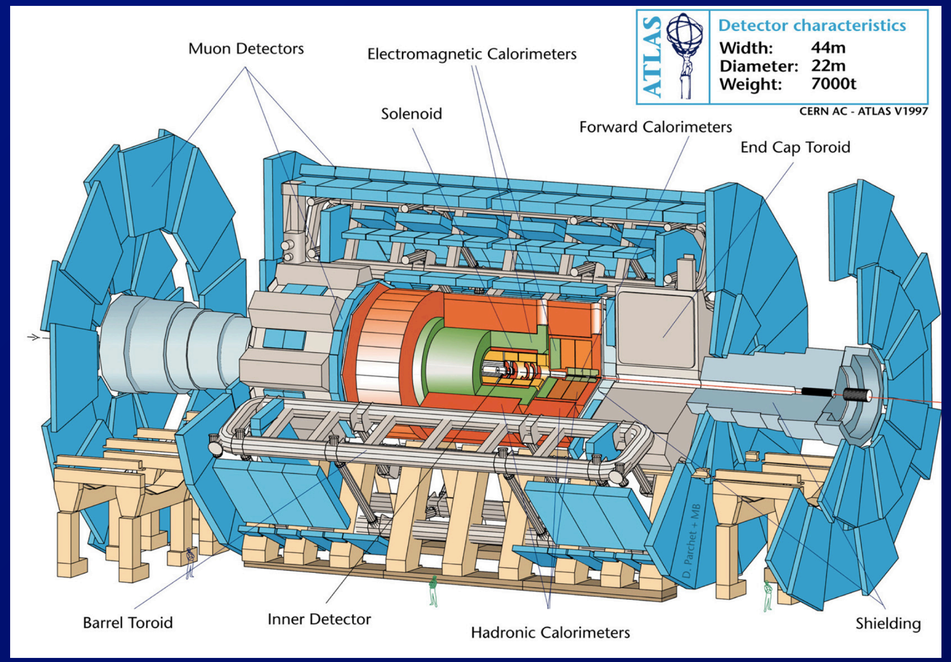
Dimuon production from two-photon scattering in Pb+Pb collisions with the ATLAS detector

Prof. Brian Cole
Columbia University and ATLAS collaboration

July 29, 2021

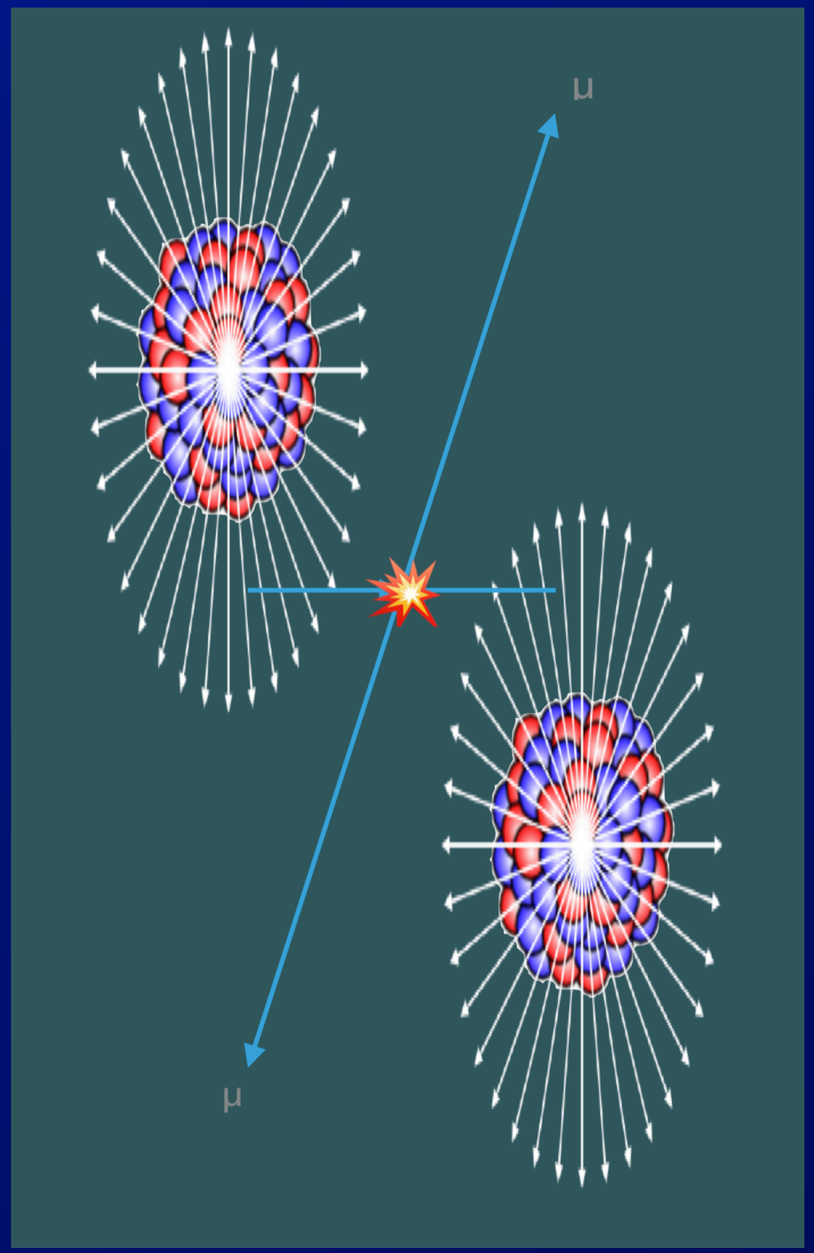


Dimuon production in γ+γ collisions

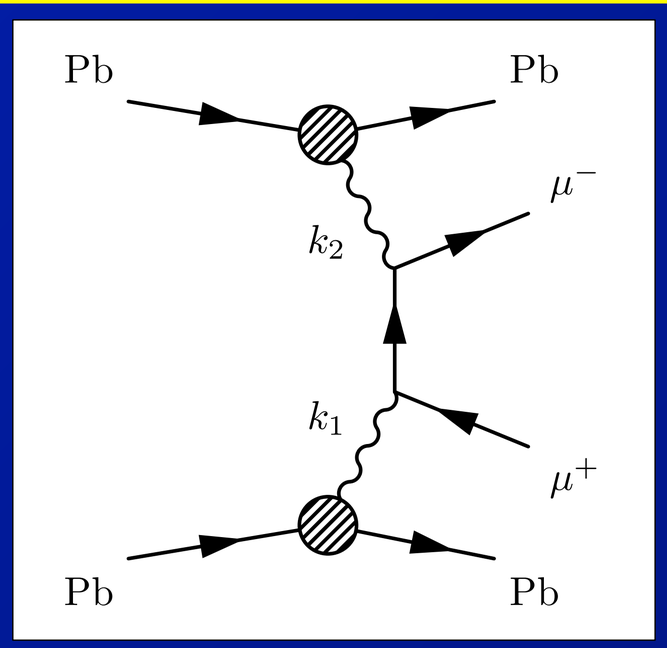
why study γ+γ → μ+μ- in Pb+Pb?

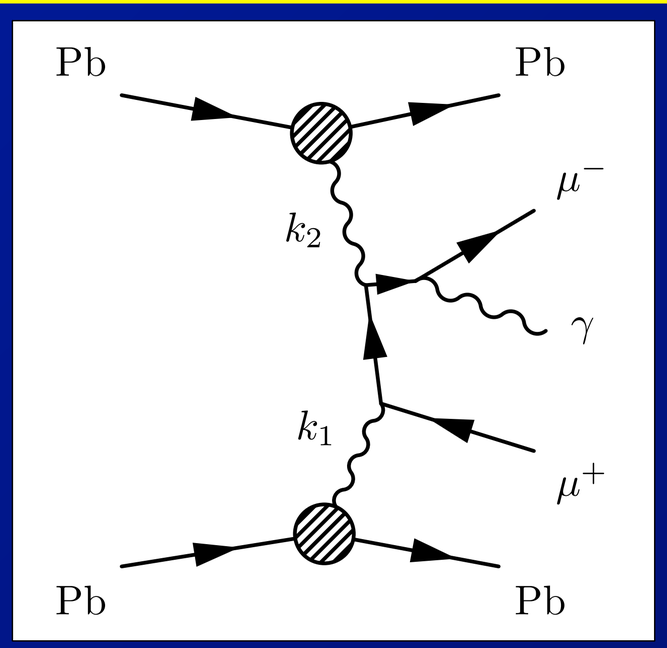
- **Ultra-peripheral collisions:**
  - fundamental physics process at large Z
  - ⇒ interesting in its own right
  - important calibration of photon flux
  - also calibrate nuclear breakup in UPC

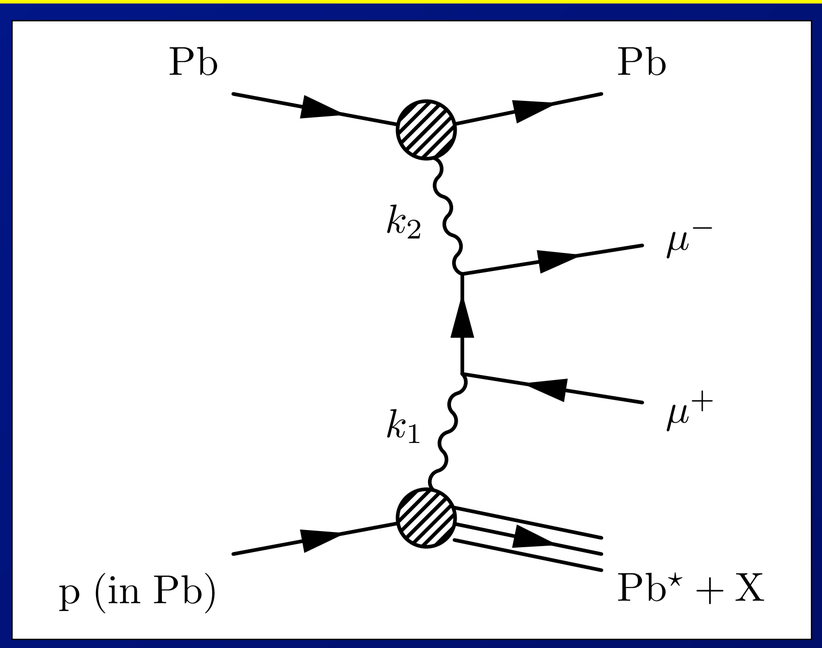
- **Hadronic Pb+Pb collisions**
  - precise angular alignment of muons from γ+γ processes makes it possible to use as an electromagnetic probe of QGP
  - ⇒first measurement by ATLAS showed centrality-dependent broadening



Dimuon production in γ+γ collisions





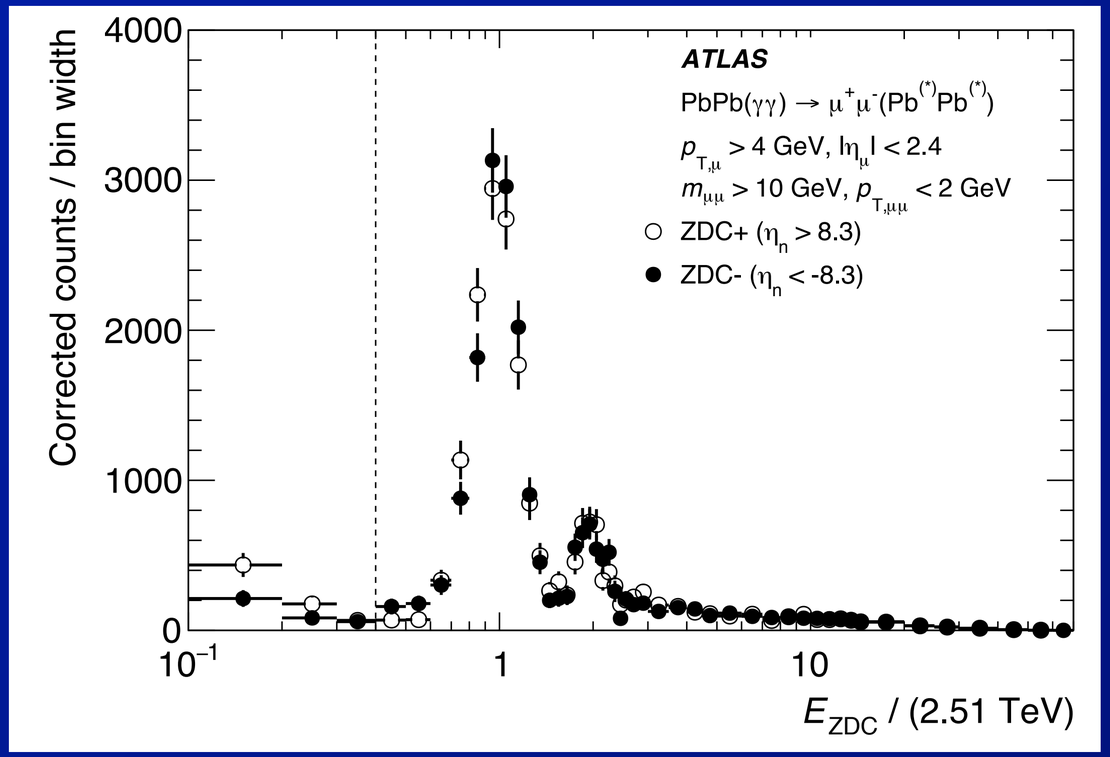


- **Three contributions to γ+γ → μ⁺μ⁻ processes:**
  - Breit-Wheeler (LO QED)
  - Radiative (NLO QED)

  ⇒ No nuclear breakup except for Coulomb Excitation processes
  - Dissociative - photon emitted from nucleon constituent

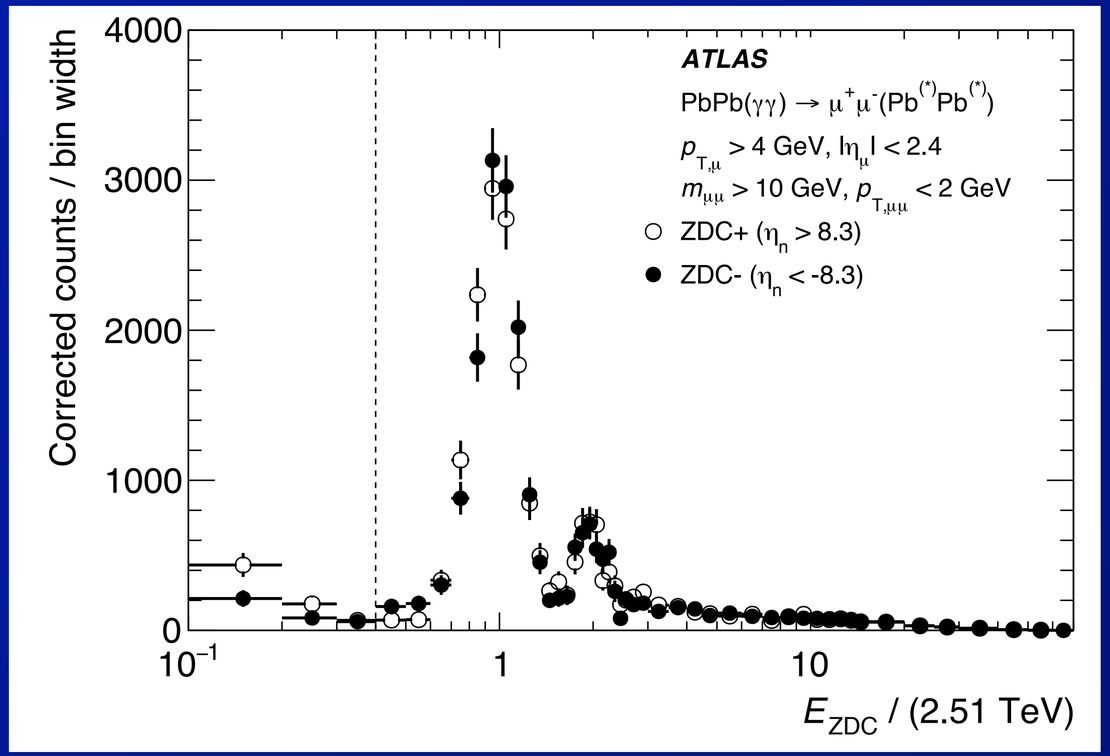
  ⇒ Nuclear breakup

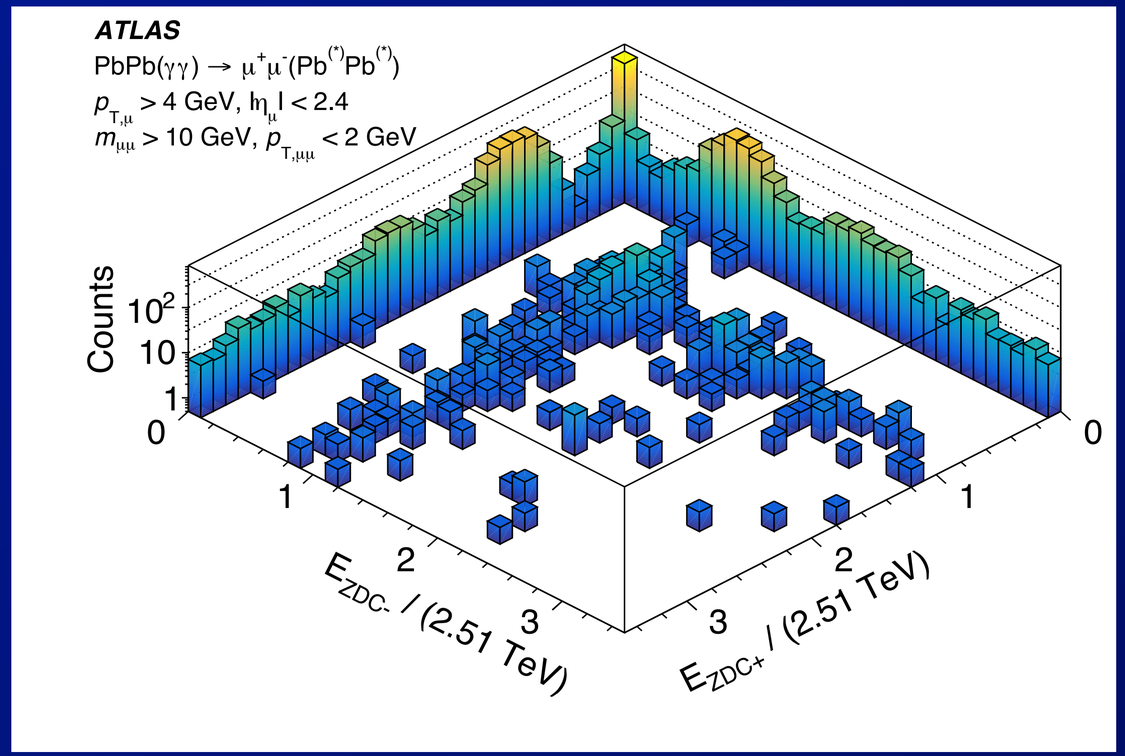
Dimuon production in UPC γ+γ, nuclear breakup



- The zero degree calorimeters detect neutrons emitted when the incident nuclei break up.

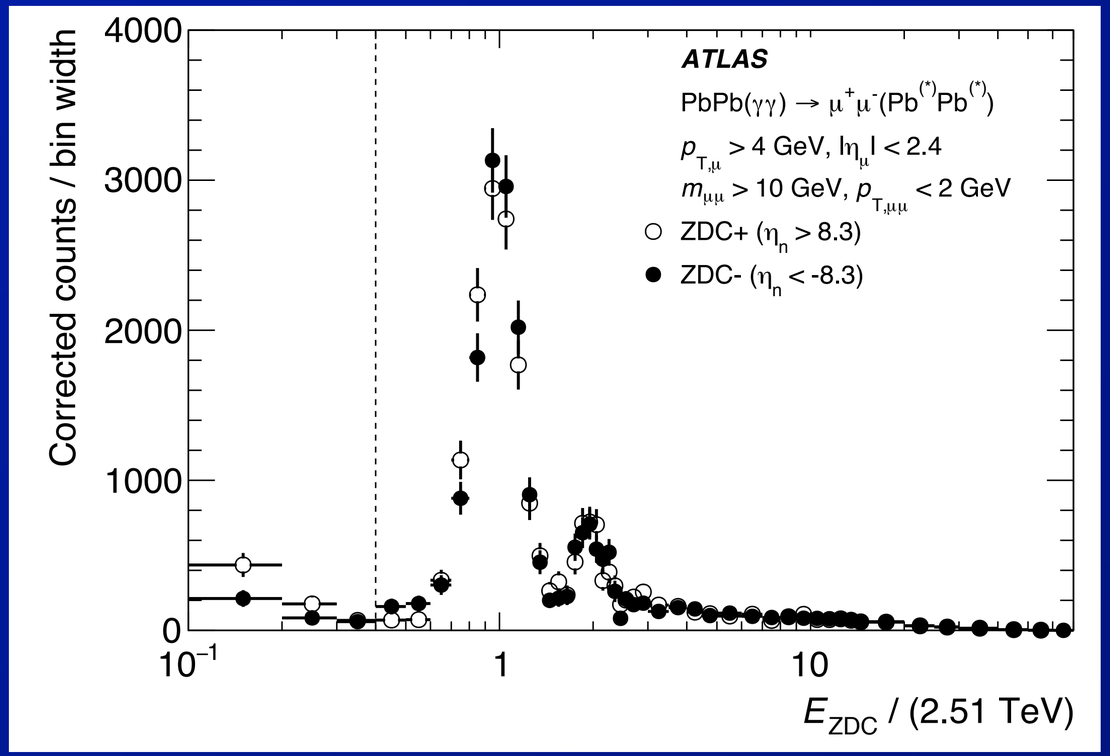
Dimuon production in UPC γ+γ, nuclear breakup

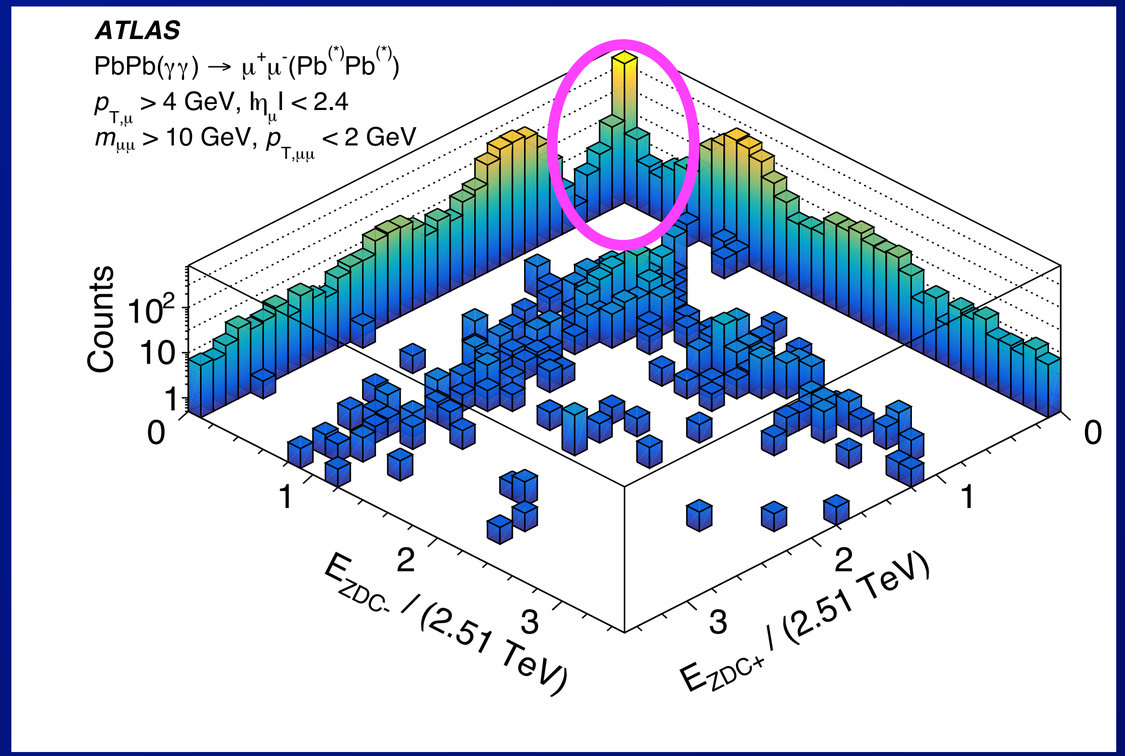




- Event "topology" as seen in the two ZDCs

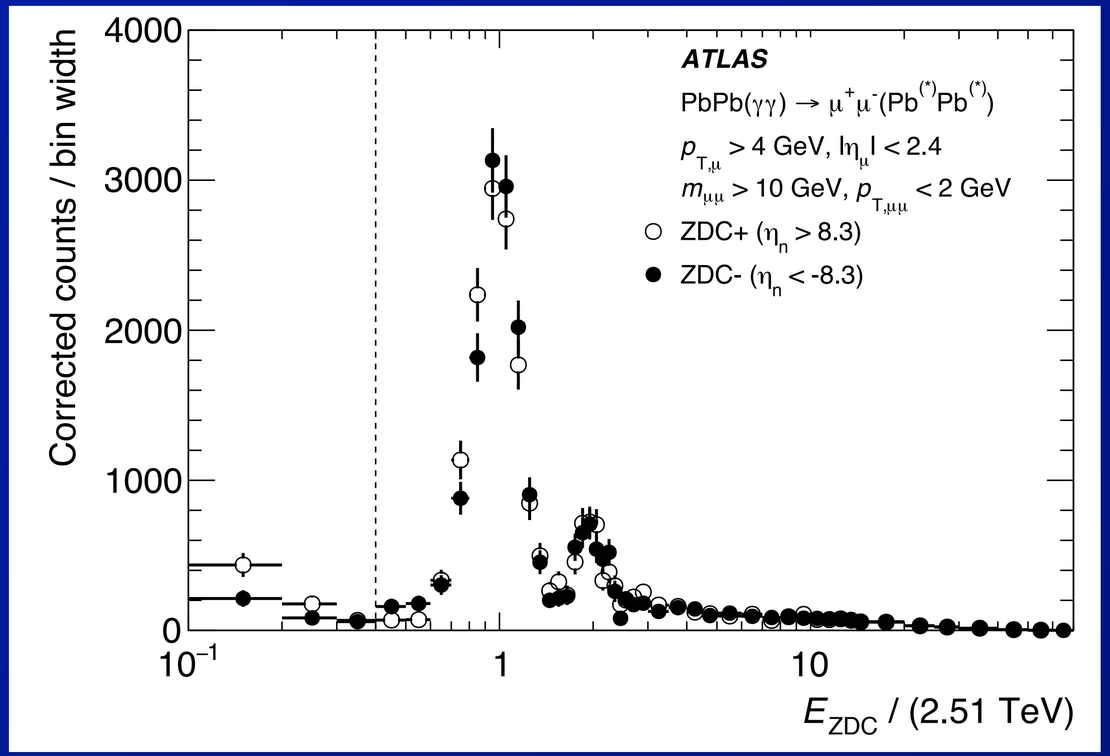
Dimuon production in UPC γ+γ, nuclear breakup

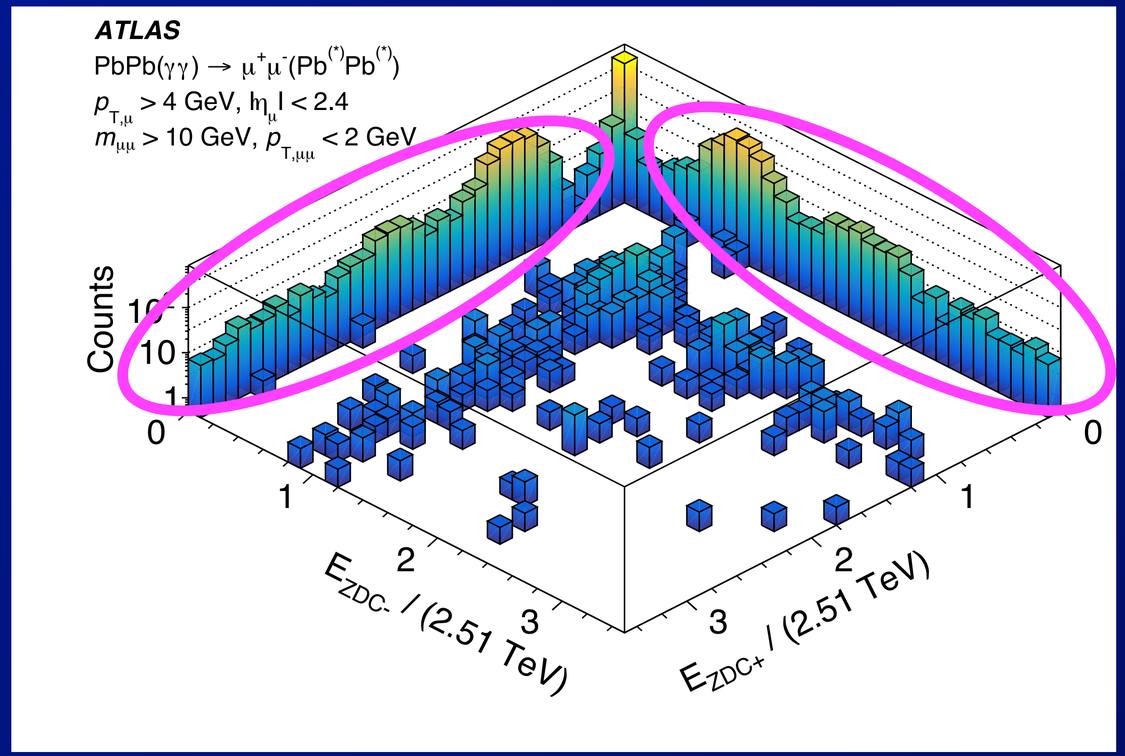




- Event "topology" as seen in the two ZDCs
  - 0n0n - no neutrons in either

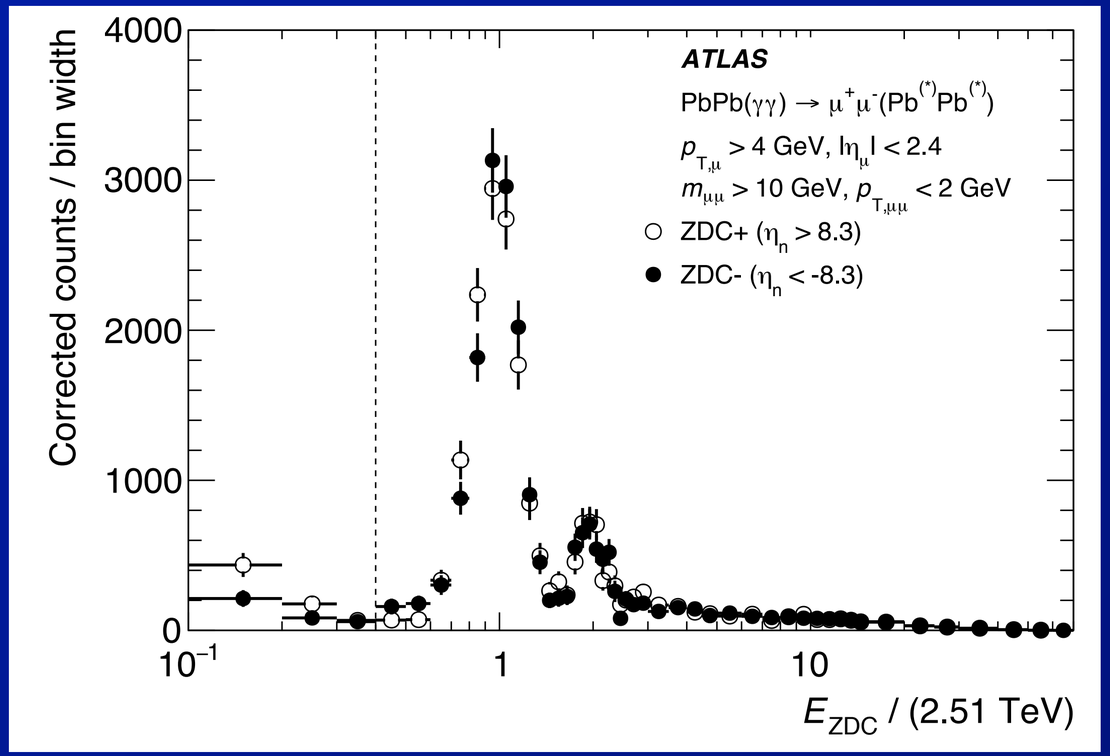
Dimuon production in UPC γ+γ, nuclear breakup

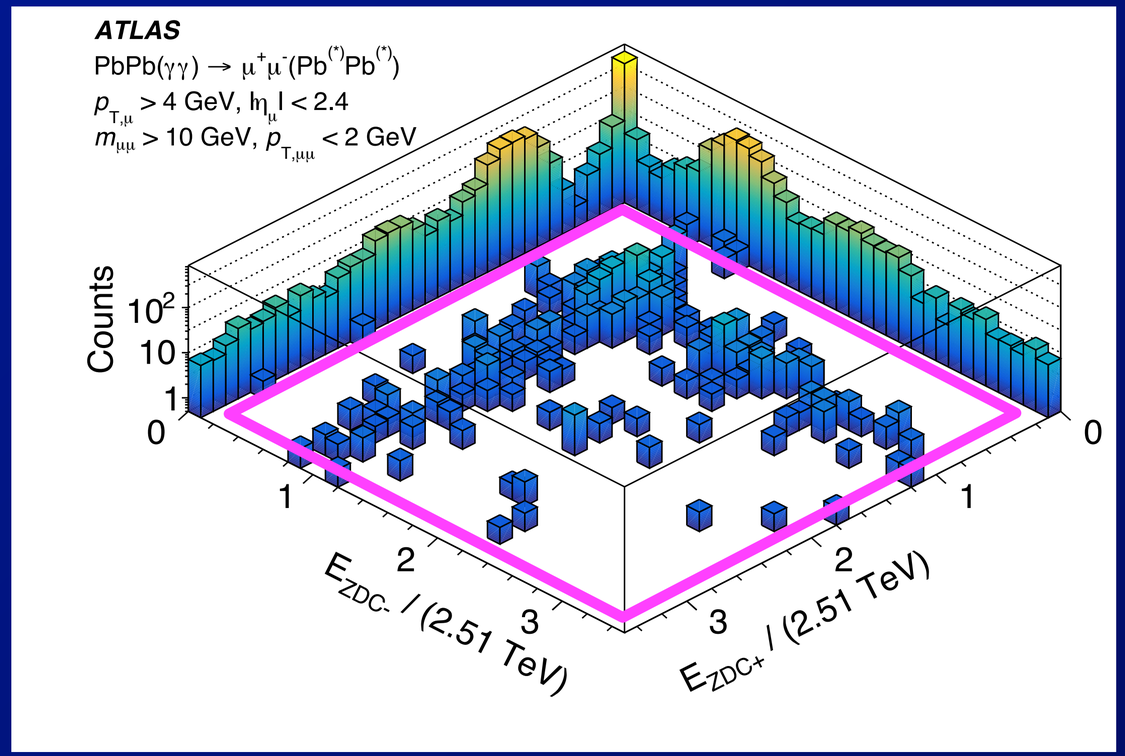




- Event "topology" as seen in the two ZDCs
  - 0nXn
    - ⇒ 0 neutrons in one
    - ⇒ ≥ 1 in the other

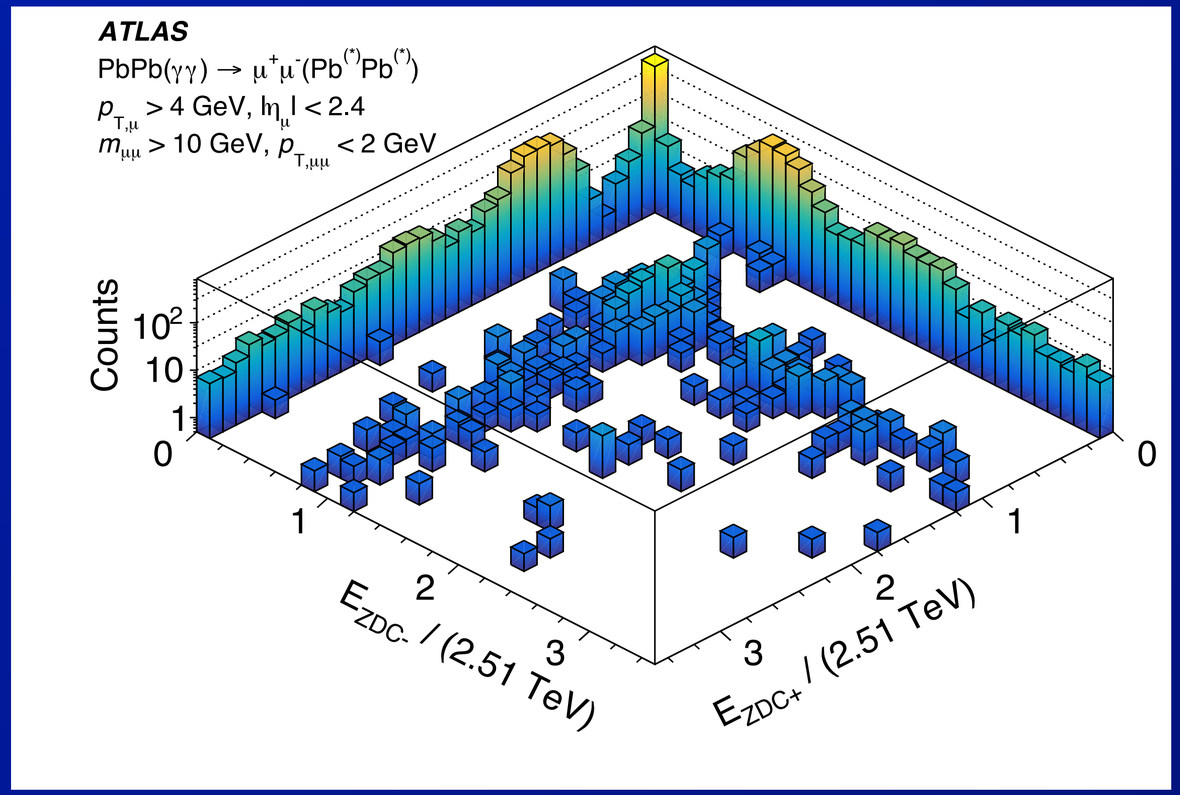
Dimuon production in UPC γ+γ, nuclear breakup

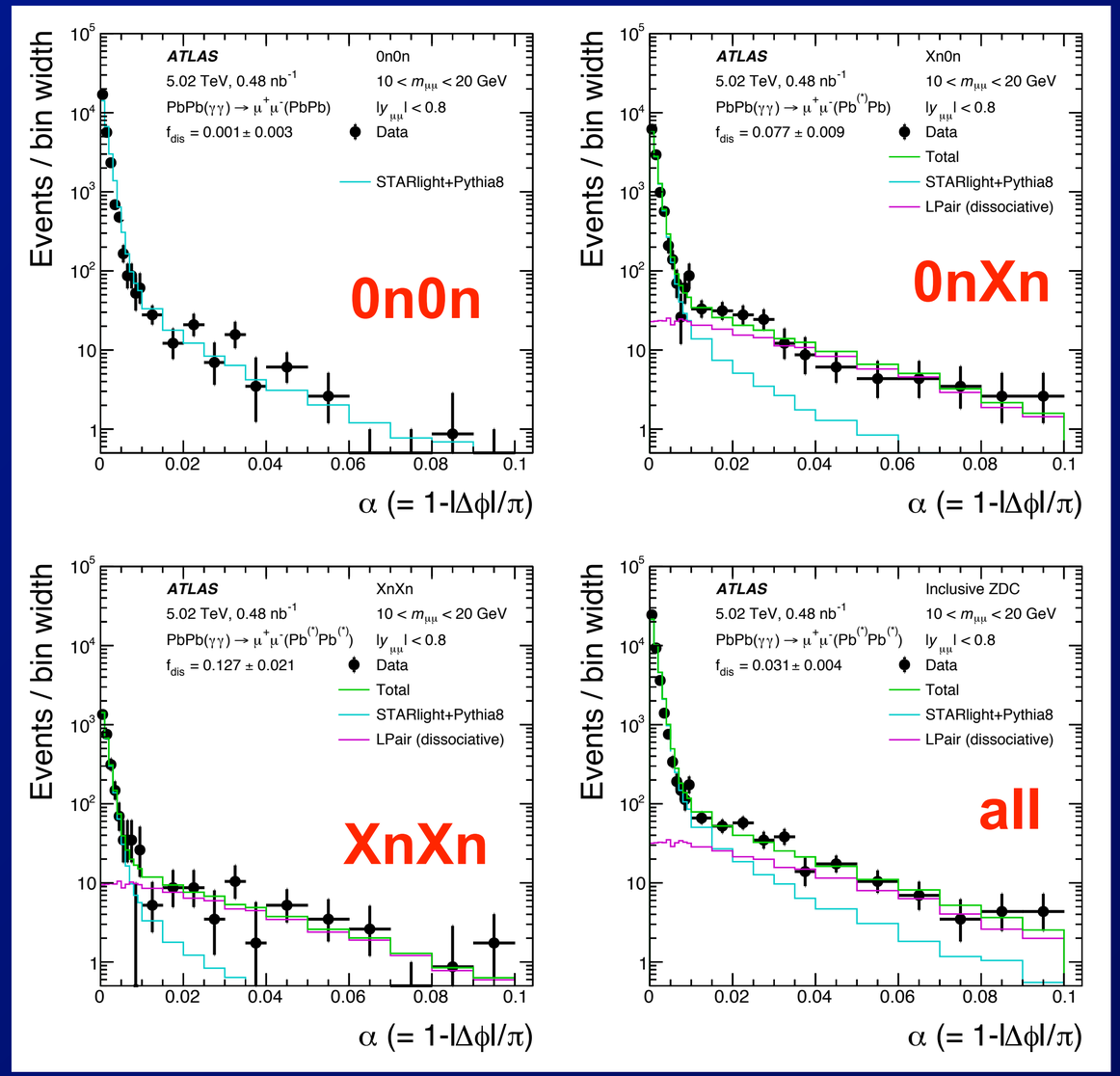




- Event "topology" as seen in the two ZDCs
  - XnXn
  - ⇒≥ 1 neutrons in both

Dimuon production in UPC γ+γ, nuclear breakup





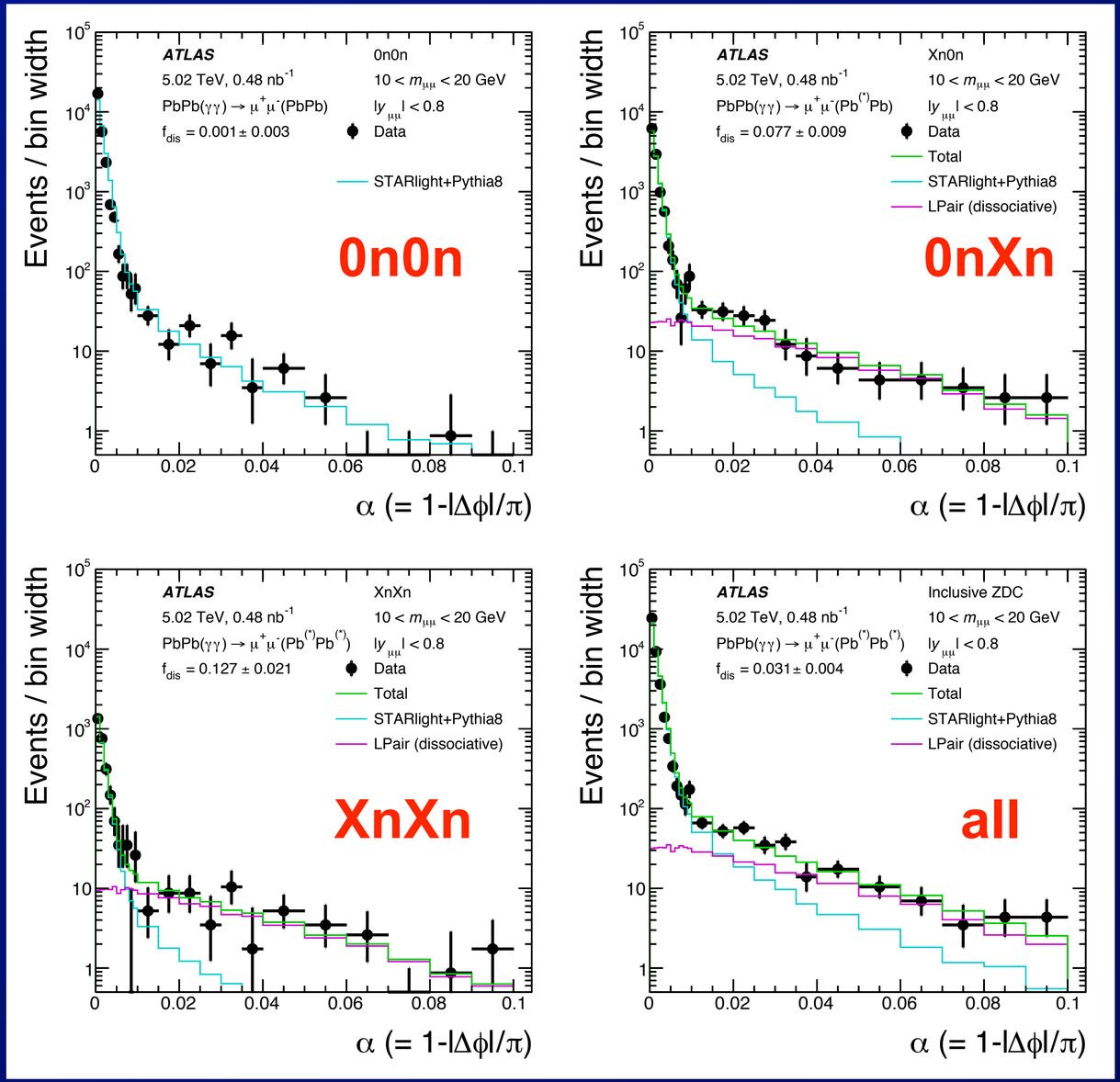
- **Dimuon acopolanarity** $\alpha = 1 - \frac{\Delta\phi}{\pi}$ **distributions**
  - for different neutron topologies

⇒Large-acoplanarity tails change shape for different neutron topologies

Dimuon production in UPC γ+γ, nuclear

- Template fit using
  - STARlight+Pythia8 for BW+QED,
  - LPair for dissociative

ATLAS, 2011.12211 [nucl-ex]



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⇒0n0n well described by STARlight+Pythia8

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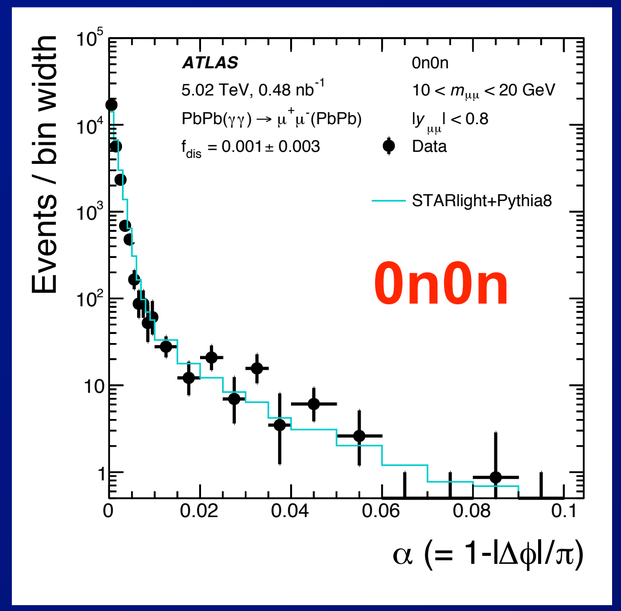

Dimuon production in UPC γ+γ, nuclear

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⇒Tails on 0nXn and XnXn dominated by dissociative

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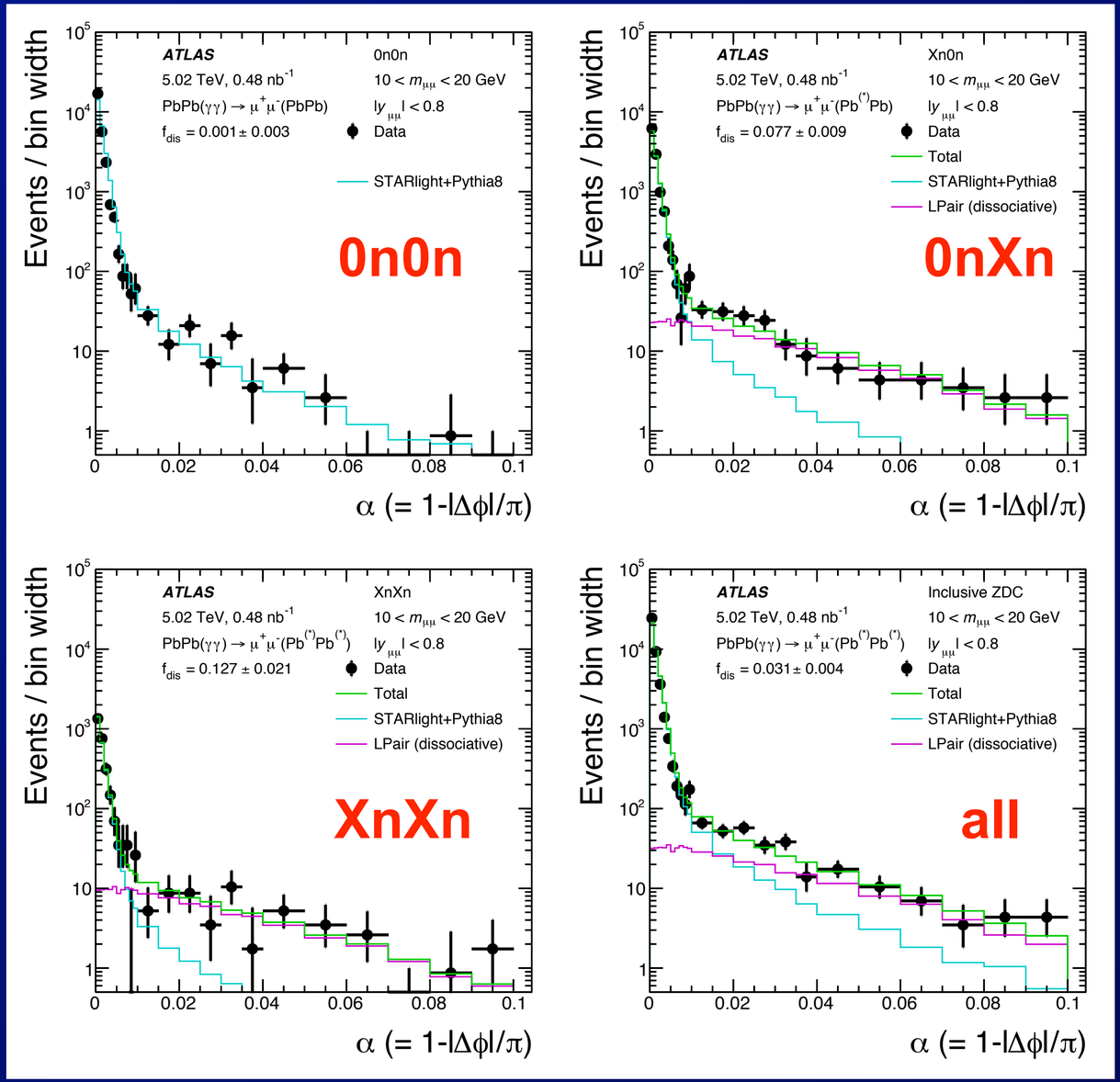
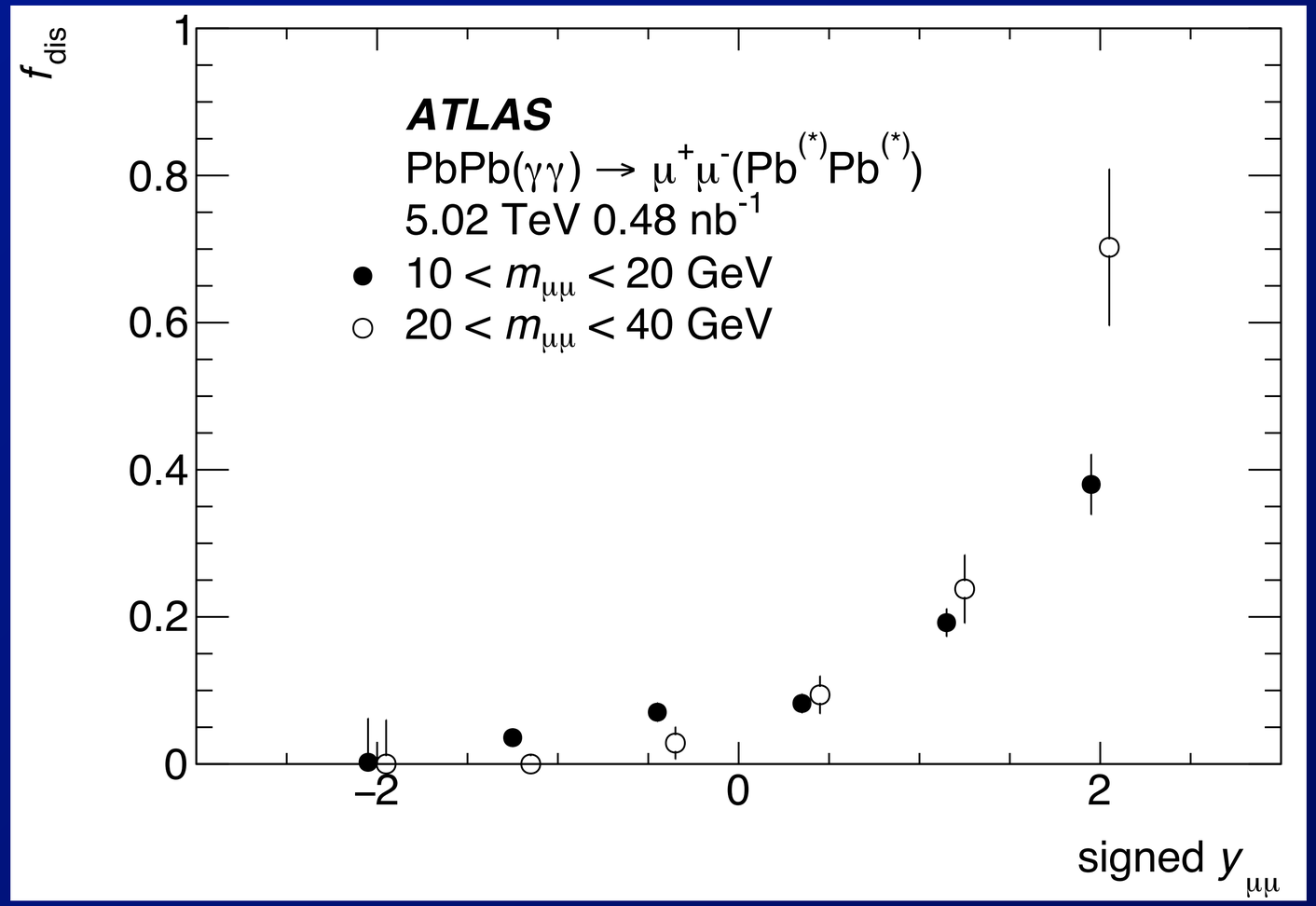


Dimuon production in dissociative UPC γ+γ,

- Select 0nXn and use the asymmetric topology to study:
  breakup ⟺ dissociation
- use signed $y_{\mu\mu}$ relative to Xn direction
  - larger $y_{\mu\mu}$ means more energetic photon emitted by nucleus that breaks up
- See *large* breakup fractions for large $y_{\mu\mu}$



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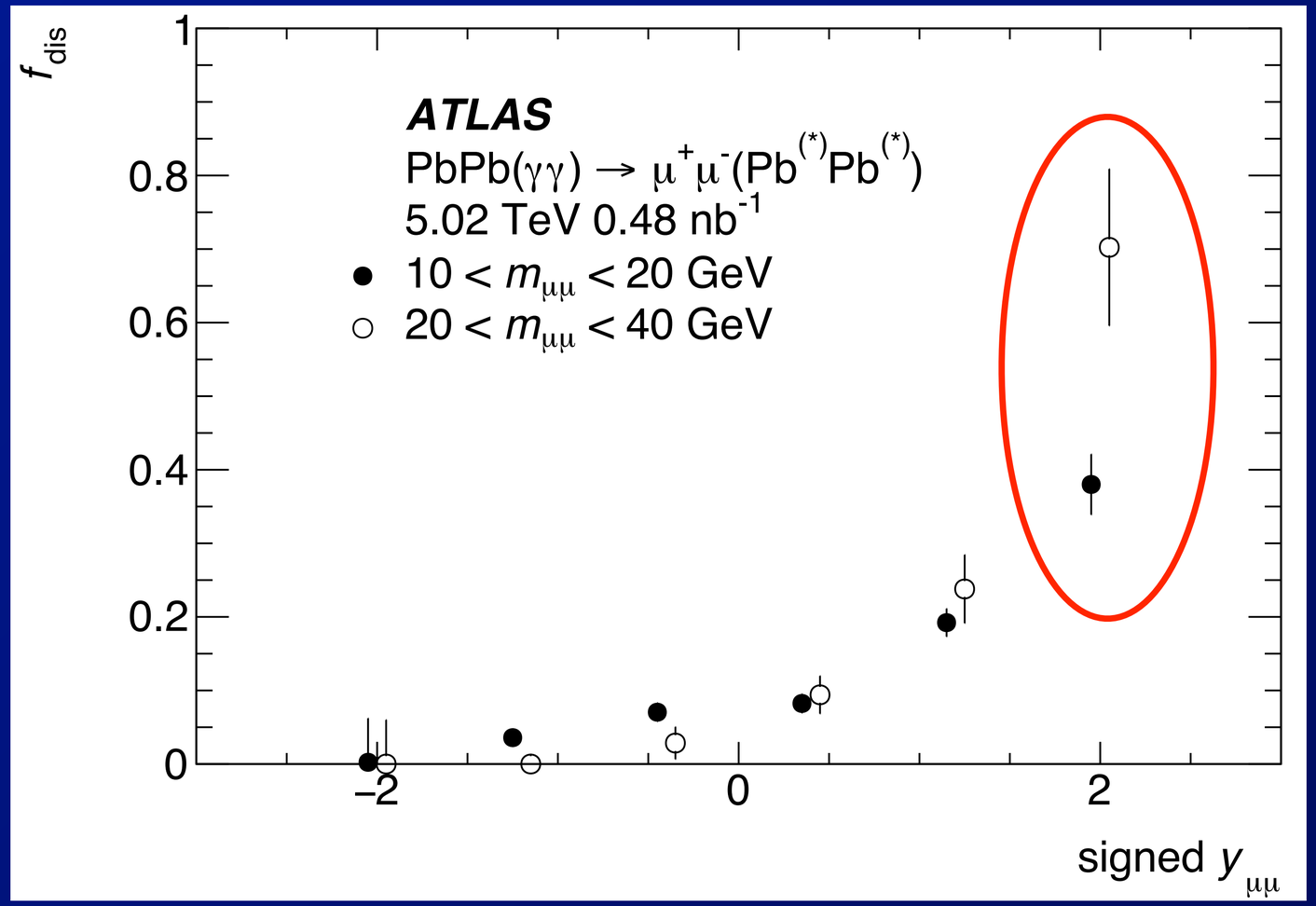
New ATLAS exclusive $\mu^+\mu^-$ results

- Select 0nXn and use the asymmetric topology to study:
  breakup $\Longleftrightarrow$ dissociation
- use signed $y_{\mu\mu}$ relative to Xn direction
  - larger $y_{\mu\mu}$ means more energetic photon emitted by nucleus that breaks up
- See *large* breakup fractions for large $y_{\mu\mu}$

⇒As expected, larger dissociative contributions for photon energies

⇒~ all yield to nuclear breakup



ATLAS, 2011.12211 [nucl-ex]

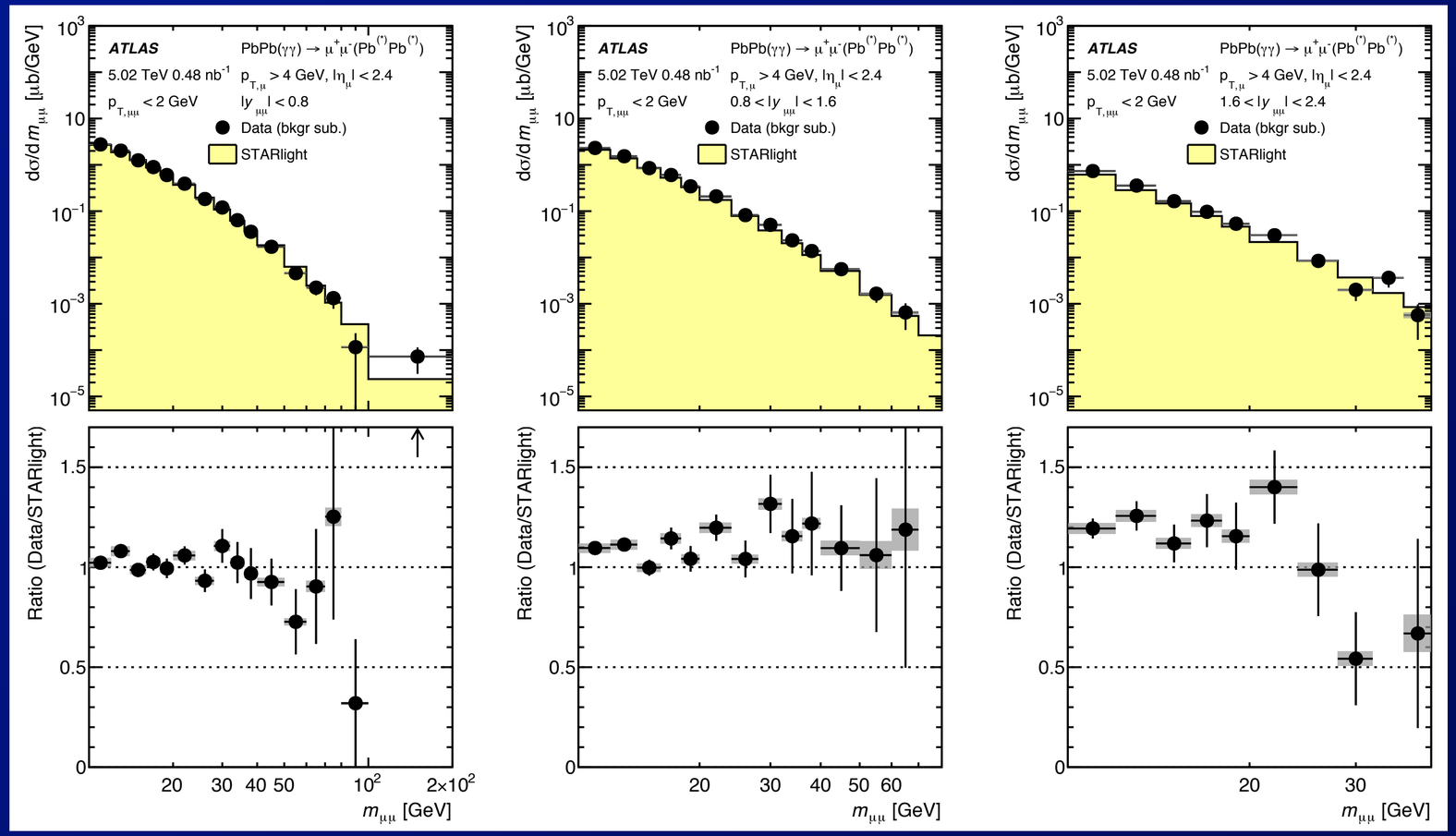
Dimuon production in UPC γ+γ

- **Mass distributions in three $y_{\mu\mu}$ intervals:**
  - Compared to predictions from STARlight

⇒Very good agreement on shape of $m_{\mu\mu}$ distributions

⇒But STARlight under-predicts the yield at larger rapidities

$0 < |y_{\mu\mu}| < 0.8$ $\quad$ $0.8 < |y_{\mu\mu}| < 1.6$ $\quad$ $1.6 < |y_{\mu\mu}| < 2.4$



ATLAS, 2011.12211 [nucl-ex]

New ATLAS $\mu^+\mu^-$ results

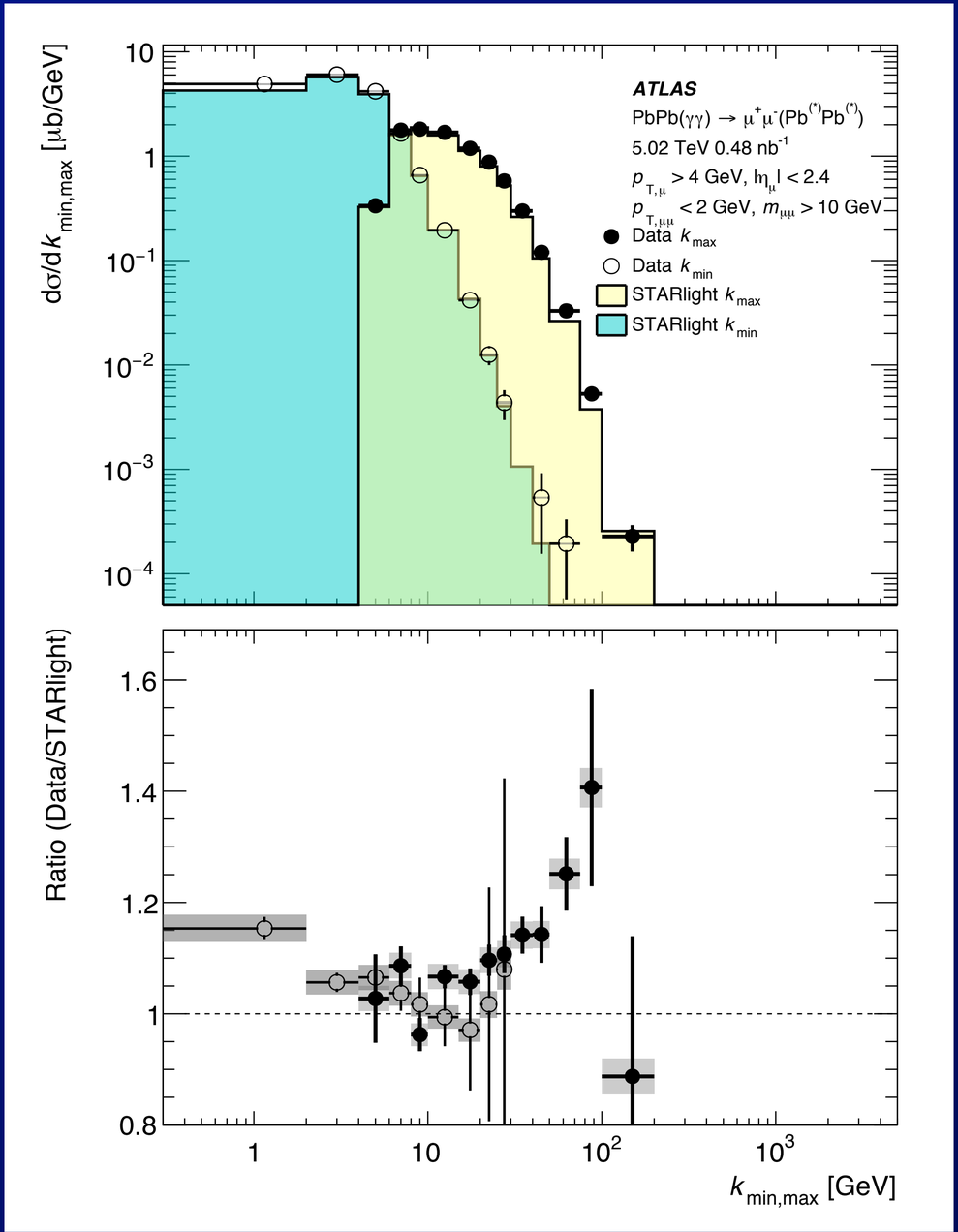
- **Determine the photon energies using the μμ pair kinematics:**
  - $$k_{\mathrm{max,min}} = \frac{m_{\mu\mu}}{2} e^{\pm y_{\mu\mu}}$$
  - first direct measurement of the nuclear photon flux

    ⇒but not only the coherent component

- **Compare to STARlight**
  - Excess observed in the data at higher photon energies

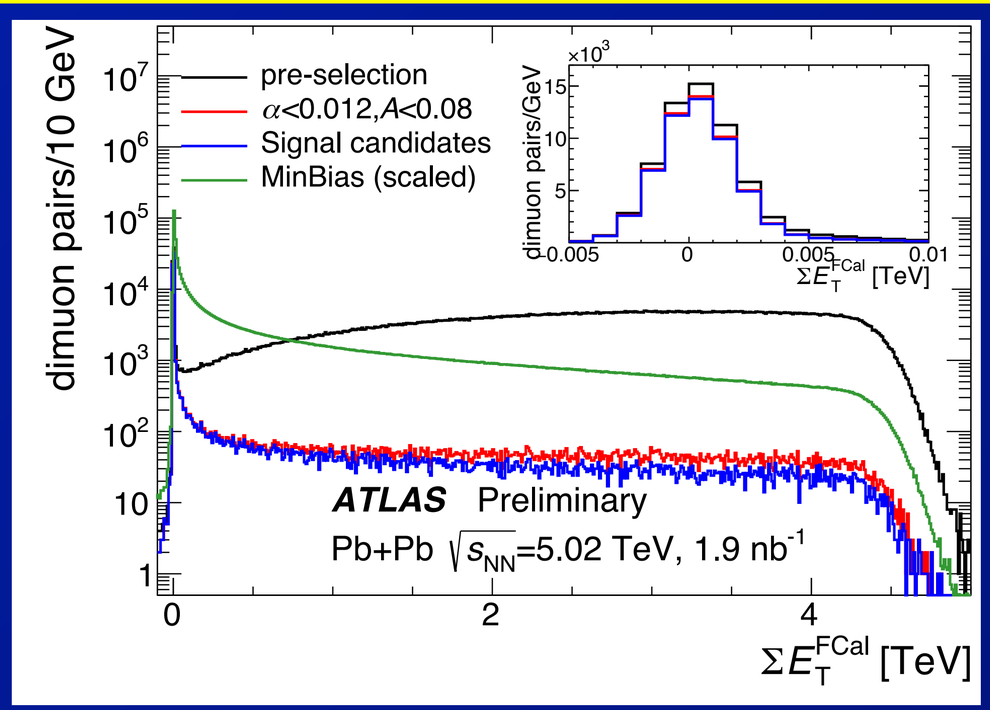
    ⇒ >~ 30-40 GeV

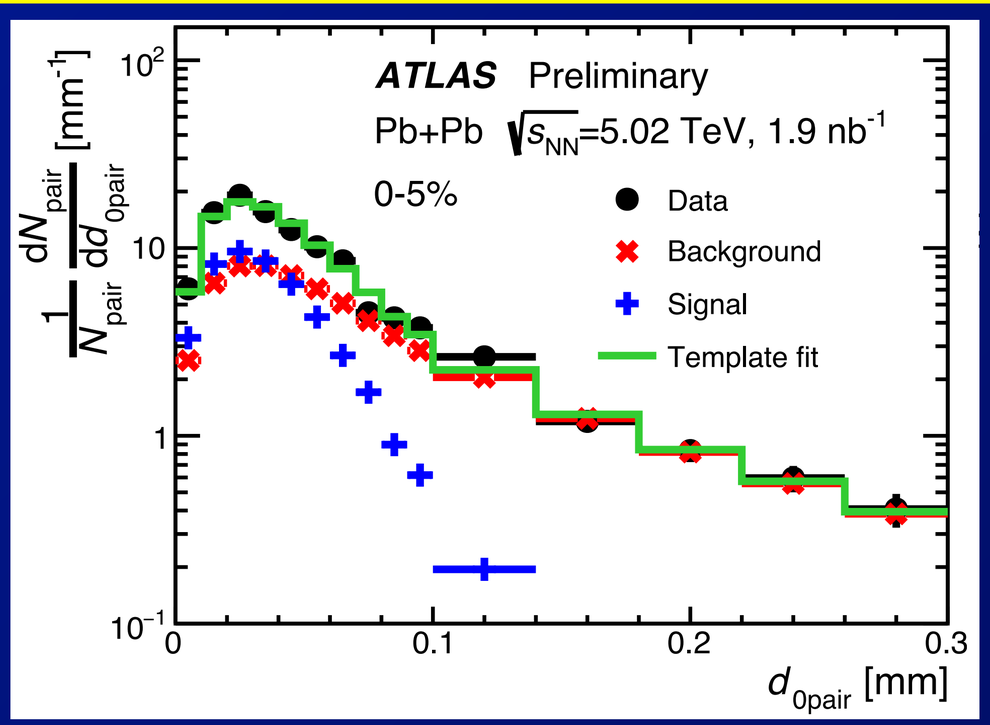
    ⇒consistent with observations above



Non-UPC photo-induced processes

ATLAS non-UPC $\mu^+\mu^-$ production



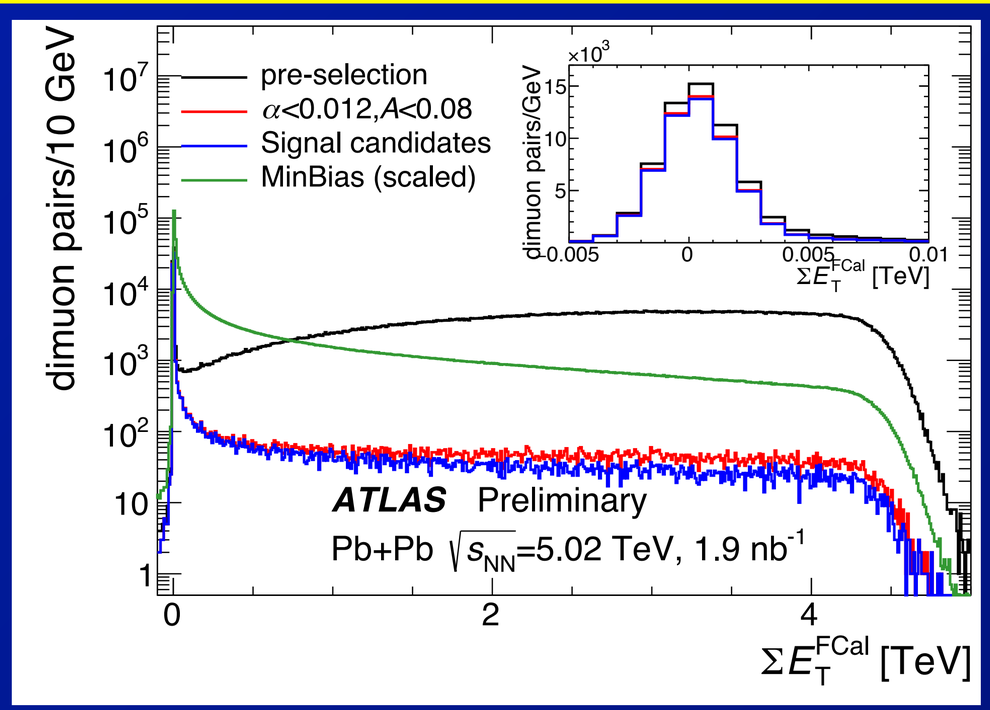


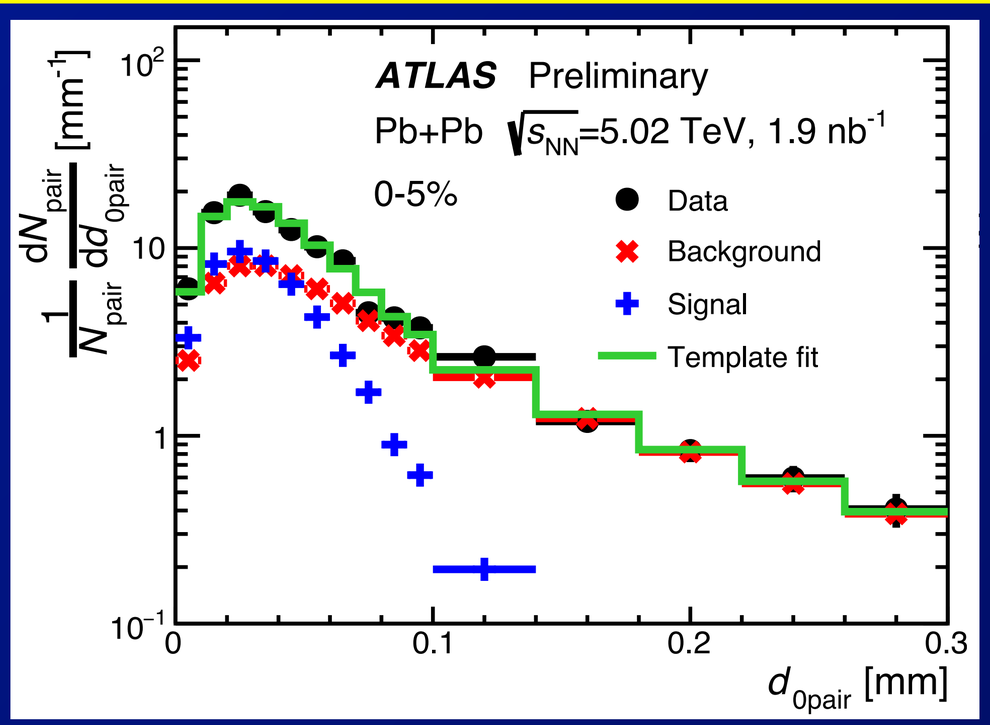
- ATLAS previously published observation of $\gamma+\gamma \rightarrow \mu^+\mu^-$ pairs in non-UPC collisions using 2015 data.

  ⇒Much improved statistics from 2018.

- Use tight kinematic constraints on acoplanarity and asymmetry
  - and muon pair d_0 template fits to constrain heavy-flavor background

ATLAS non-UPC $\mu^+\mu^-$ production





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- Use tight kinematic constraints on acoplanarity and asymmetry
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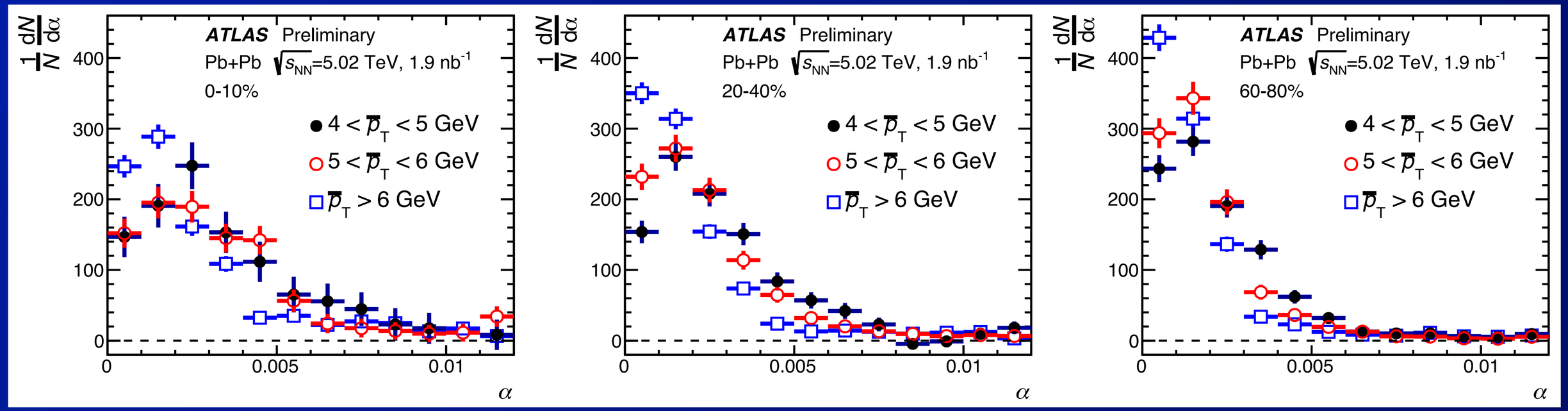
  ⇒ $\gamma+\gamma \rightarrow \mu^+\mu^-$ contribution seen over entire centrality range

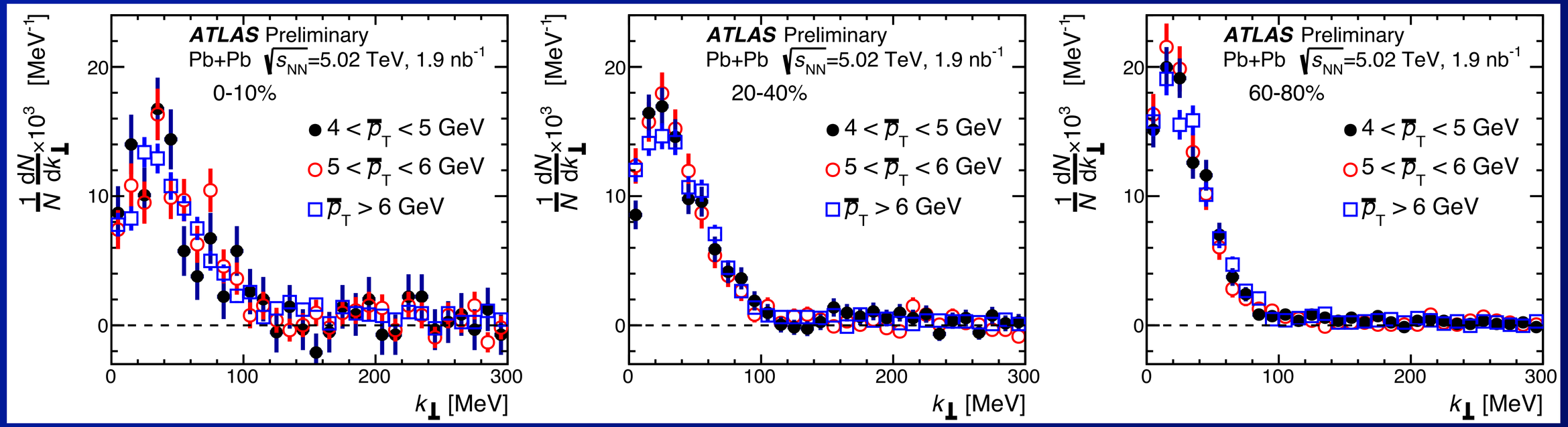
Broadening, α vs k_T



- **Observe significant centrality-dependent broadening between peripheral and central collisions**
  - When expressed in terms of pair acoplanarity, the broadening depends on the muon momenta

$$\bar{p}_T = \frac{1}{2}\left(p_T^+ + p_T^-\right)$$

Broadening, α vs k_T



- **Observe significant centrality-dependent broadening between peripheral and central collisions**
  - But when expressed in terms of k_T, the momentum of one muon perpendicular to the other

$$k_\perp \equiv \pi\alpha\bar{p}_T = \bar{p}_T\left(\Delta\phi - \pi\right)$$

⇒the distributions and broadening are independent of muon momentum

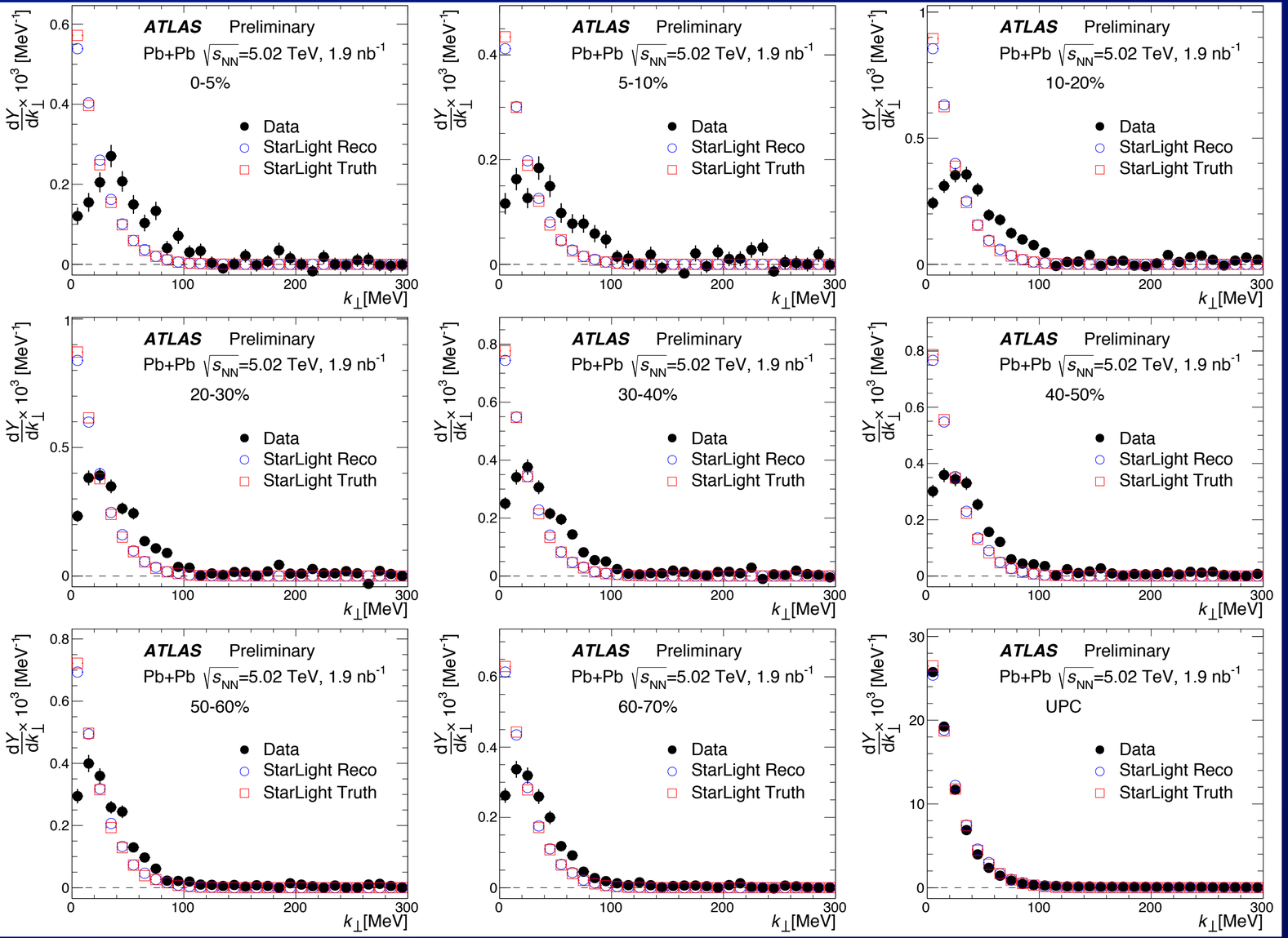
⇒k_T is a better quantity for exploring dimuon alignment

ATLAS non-UPC $\mu^+\mu^-$ production

- $\mu^+\mu^-$ k_T distributions in different Pb+Pb centrality bins
  - UPC to 0-5%
    - ⇒see γ+γ dimuon pairs over entire centrality range
    - ⇒systematic broadening and depletion near k_T = 0 w/ centrality

$$k_\perp \equiv \pi\alpha\bar{p}_T = \bar{p}_T\,(\Delta\phi - \pi)$$

ATLAS-CONF-2019-051



Non-UPC $\mu^+\mu^-$ production, initial state photon k_T

- Multiple calculations (now) predict significant initial-state effects due to b-dependent photon k_T
  - Zha et al, Phys. Lett. B 800 (2020) 135089
  - Klein et al, Phys. Rev. D 102 (2020) 9, 094013
  - Klusek-Gawenda et al, Phys.Lett. B 814 (2021) 136114
- Differences in physics
  - "QED" versus photon Wigner distribution

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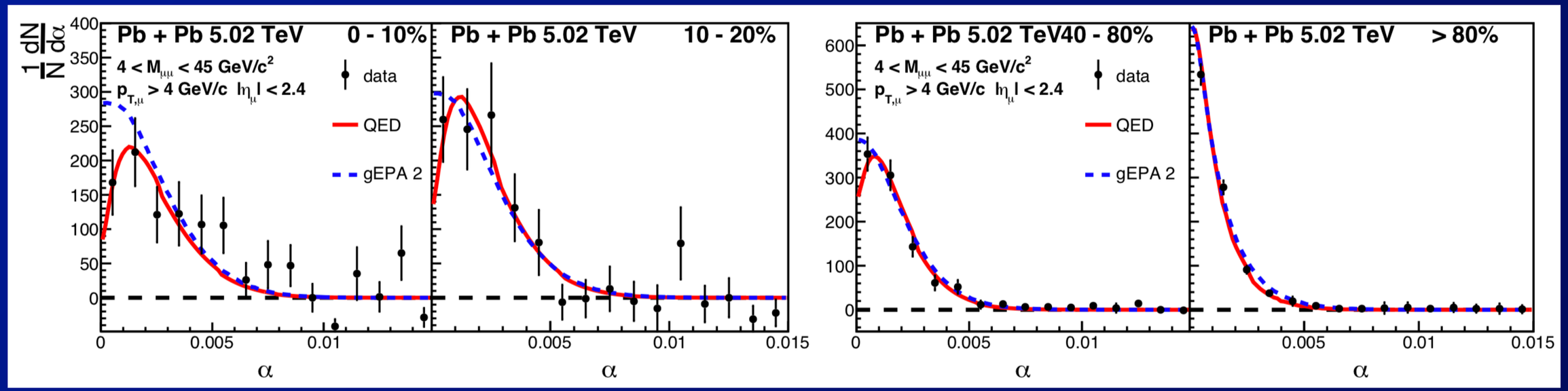
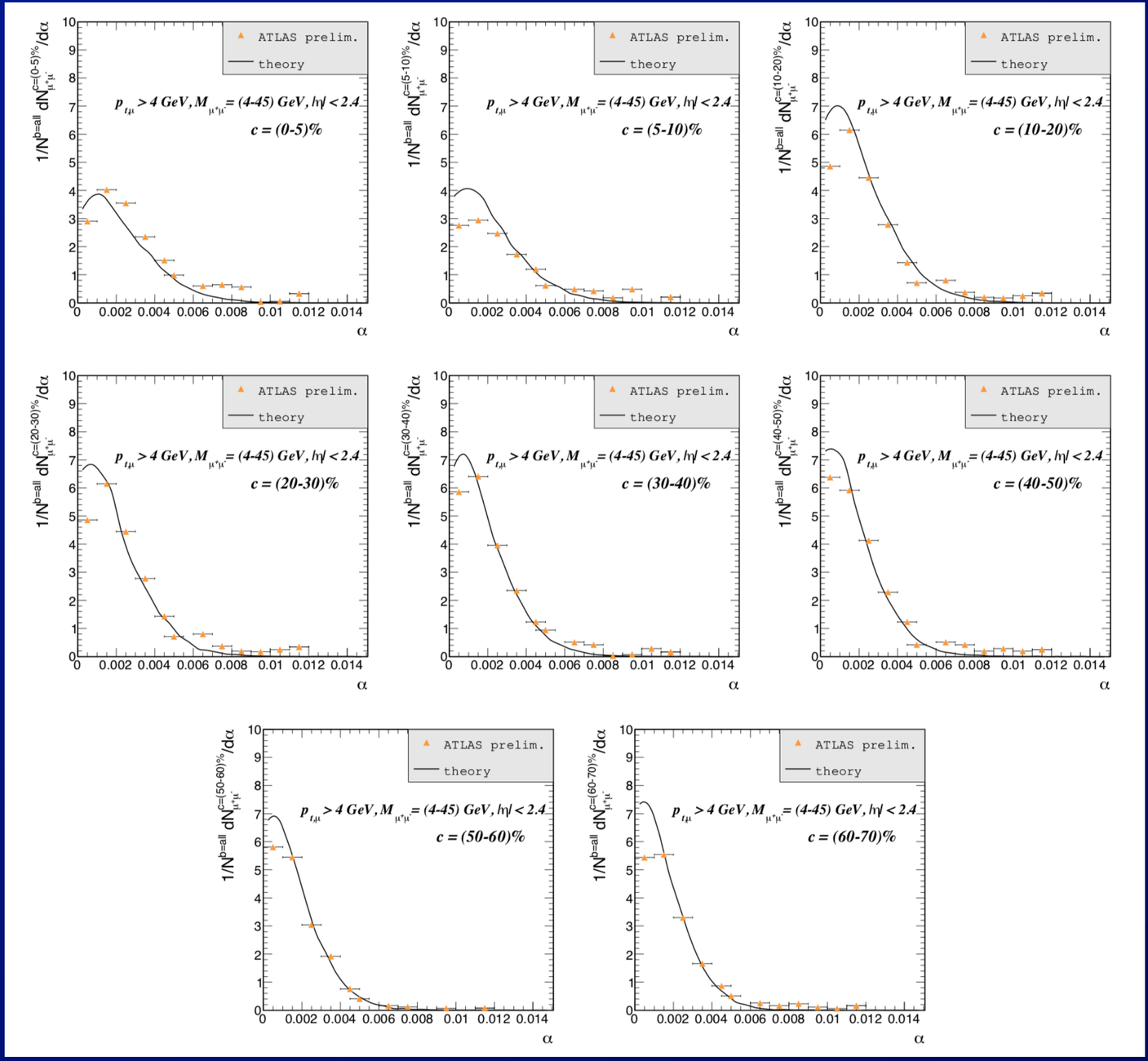


Non-UPC $\mu^+\mu^-$ production, initial state photon k_T

- Comparison of ATLAS 2018 preliminary data with calculation by Klusek-Gawenda *et al.*
  - also based on photon Wigner distribution

⇒ Reproduces the broadening but not the depletion at small acoplanarity



Summary,Conclusions

- **Measurement of UPC $\gamma+\gamma \rightarrow \mu^+\mu^-$ using 2015 data**
  - Clear evidence for both QED and dissociative contributions
    - ⇒elucidated using neutron topology requirements
  - Detailed test of photon fluxes in (e.g.) STARlight
    - ⇒excess observed at large photon energies
    - ⇒likely due to restriction on b range included in STARlight
- **Measurement of hadronic $\gamma+\gamma \rightarrow \mu^+\mu^-$ using 2018 data**
  - confirms broadening reported in ATLAS PRL
    - ⇒ but with improved statistics observe significant suppression in dimuon yield at small acoplanarity, k_T
  - k_T is a better variable for measuring dimuon angular broadening
  - theoretical calculations now predict significant b-dependence to photon k_T distributions, but with different physics
    - ⇒QED-based calculation better describes suppression at small k_T/α

Backup

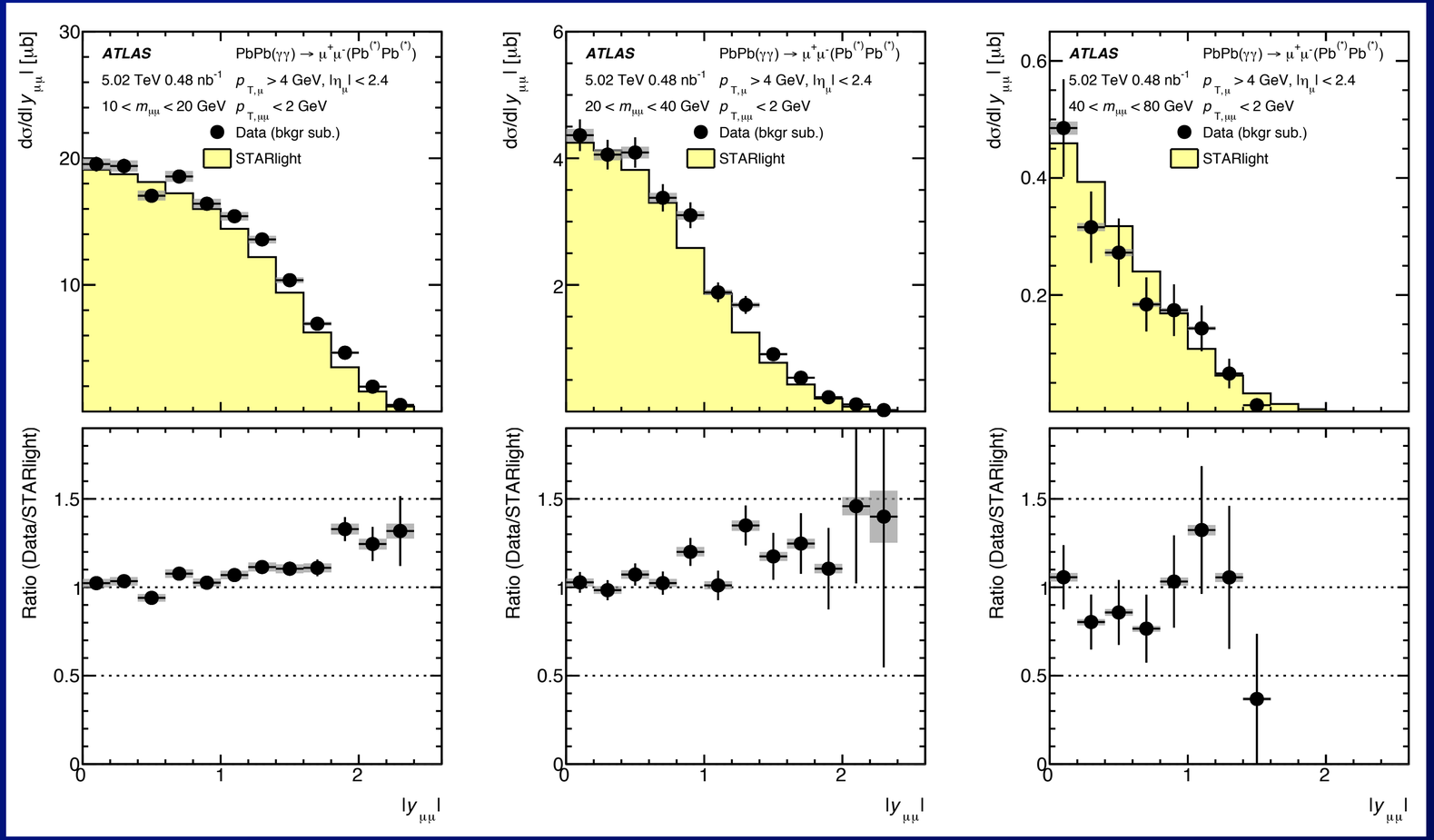
New ATLAS $\mu^+\mu^-$ results

- Pair rapidity distributions in three $m_{\mu\mu}$ intervals:
  - Compared to predictions from STARlight

⇒similar shapes

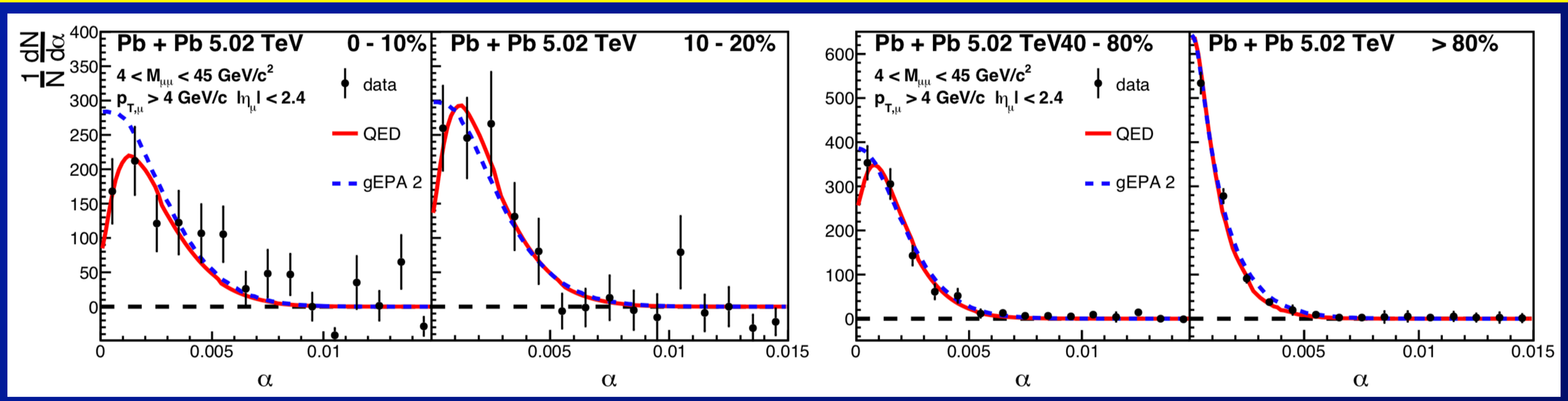
⇒but STARlight is systematically below the data at larger $y_{\mu\mu}$

$10 < m_{\mu\mu} < 20$ GeV $20 < m_{\mu\mu} < 40$ GeV $40 < m_{\mu\mu} < 80$ GeV



ATLAS, 2011.12211 [nucl-ex]

ATLAS non-UPC $\mu^+\mu^-$ production



- Comparison of Zha calculations to ATLAS PRL (2015 data)
  - small α/k_T depletion in data not significant
  - ⇒But it is in the calculation!
- Predictions by Klein *et al* not (yet) compared to data
  - ⇒depletion at small acoplanarity less clear