Measurement of dilepton production from photon fusion processes in UPC in Pb+Pb collisions with the ATLAS detector

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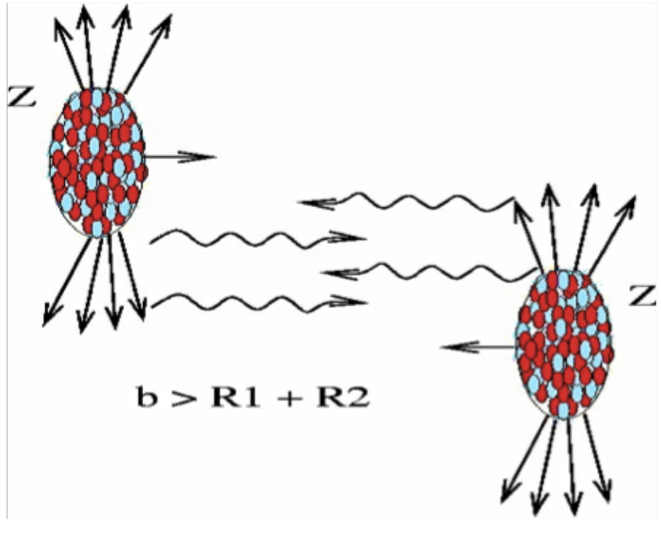
AGH | RESEARCH UNIVERSITY EXCELLENCE INITIATIVE | ATLAS EXPERIMENT

INTRODUCTION



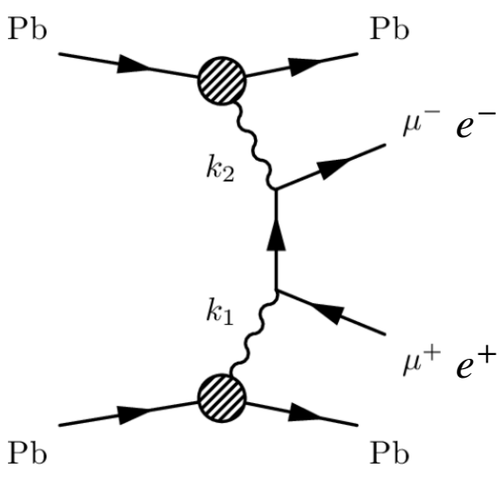
- **Ultra-peripheral collisions** (**UPC**) of lead-lead (Pb+Pb) have attracted a lot of attention in the heavy-ion community
  - Very clean environment to study **quantum electrodynamics** (QED) and **photon fluxes** within the Equivalent Photon Approximation (EPA) framework
  - $Z^4 (\approx 4.5 \times 10^7)$ **enhancement** of cross sections in Pb+Pb wrt proton-proton (pp) collisions
  - **Zero Degree Calorimeters** (ZDC) offer control over backgrounds and impact-parameter dependence
  - $\gamma\gamma$ collisions prove to be a competitive tool for **searches** for **beyond Standard Model** (BSM) physics
  - **Non-UPC** $\gamma\gamma \to \mu^+\mu^-$ events as a **new probe** of the **QGP** or **strong QED** fields

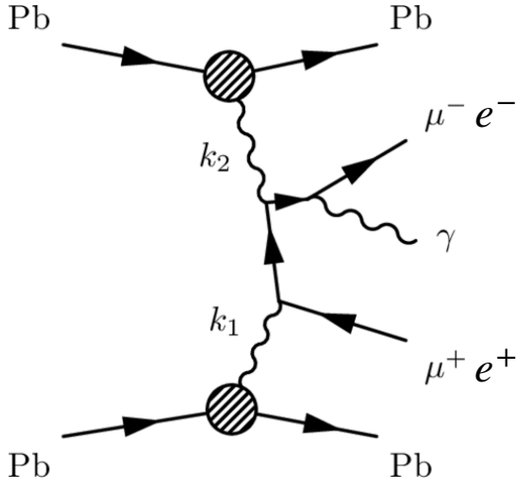
- The following results from 5.02 TeV UPC Pb+Pb collisions from **ATLAS** are discussed:
  - **Final** $\gamma\gamma \to \mu^+\mu^-$ [PRC 104 (2021) 024906]
  - **Final** $\gamma\gamma \to e^+e^-$ [JHEP 06 (2023) 182]
  - **Final** $\gamma\gamma \to \tau^+\tau^-$ [PRL 131 (2023) 151802]
  - **Final** non-UPC $\gamma\gamma \to \mu^+\mu^-$ [PRC 107 (2023) 054907]

EXCLUSIVE DIMUONS AND DIELECTRONS

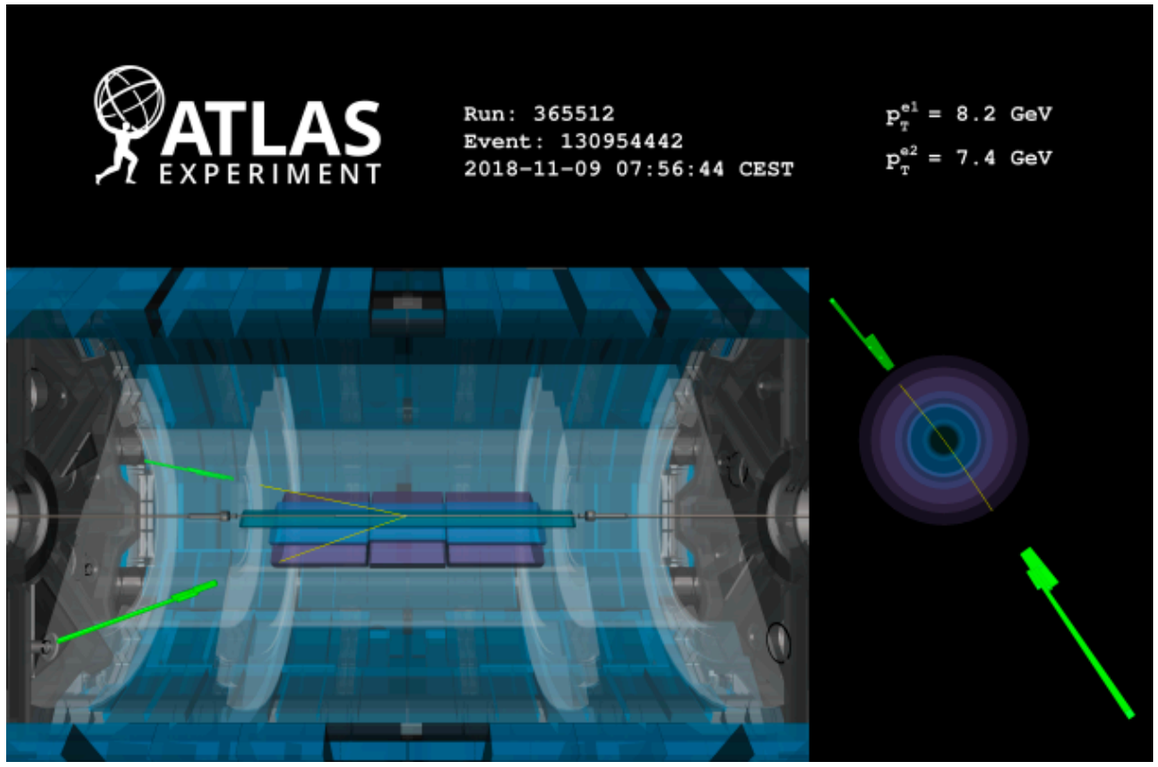
	$\gamma\gamma \to \mu^+\mu^-$	$\gamma\gamma \to e^+e^-$
Data	**2015**	**2018**
Int lumi	0.48 nb^{-1}	1.72 nb^{-1}
Fiducial	$p_{\mathrm{T}}^{\mu} > 4$ GeV $p_{\mathrm{T}}^{\ell\ell} < 2$ GeV $\lvert\eta^{\mu}\rvert < 2.4$ $m_{\mu\mu} > 10$ GeV	$p_{\mathrm{T}}^{e} > 2.5$ GeV $\lvert\eta^{e}\rvert < 2.5$ $m_{ee} > 5$ GeV
Event candidates	12k	30k

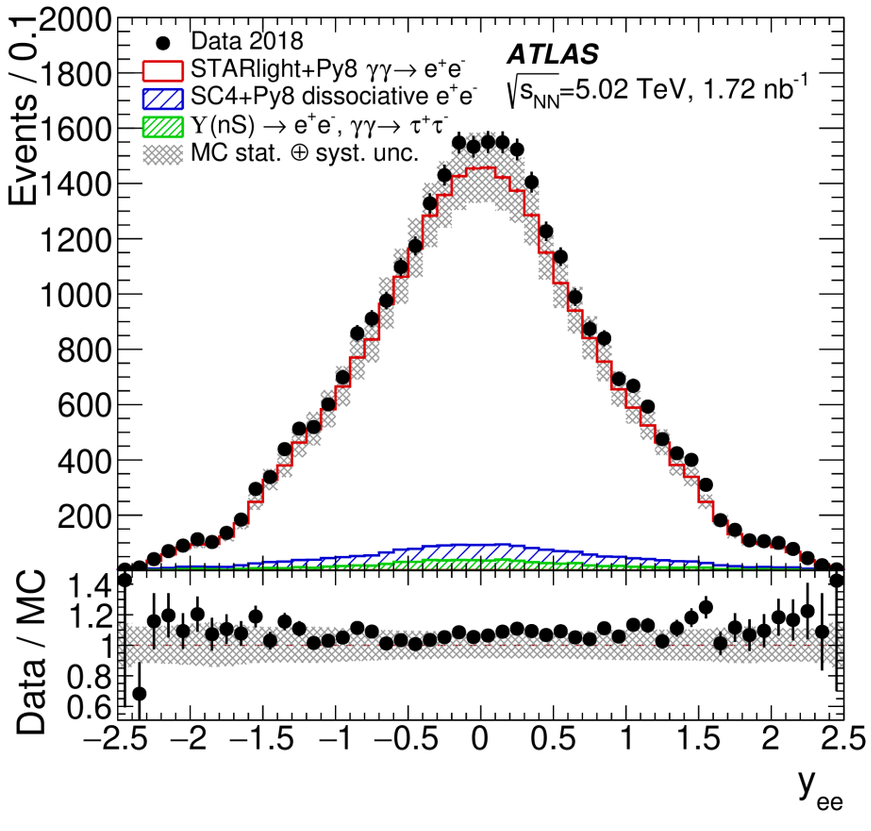
Signal





$\gamma\gamma \to e^+e^-$ event candidate

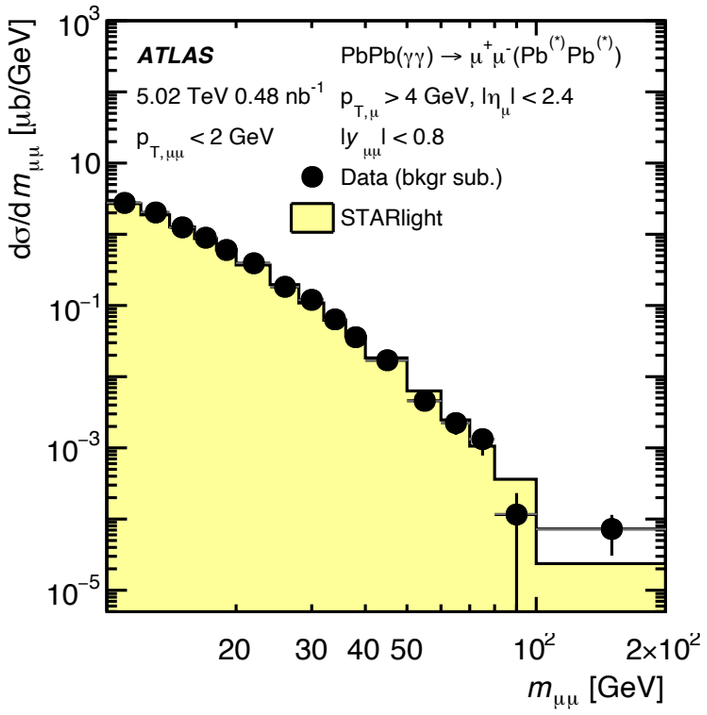


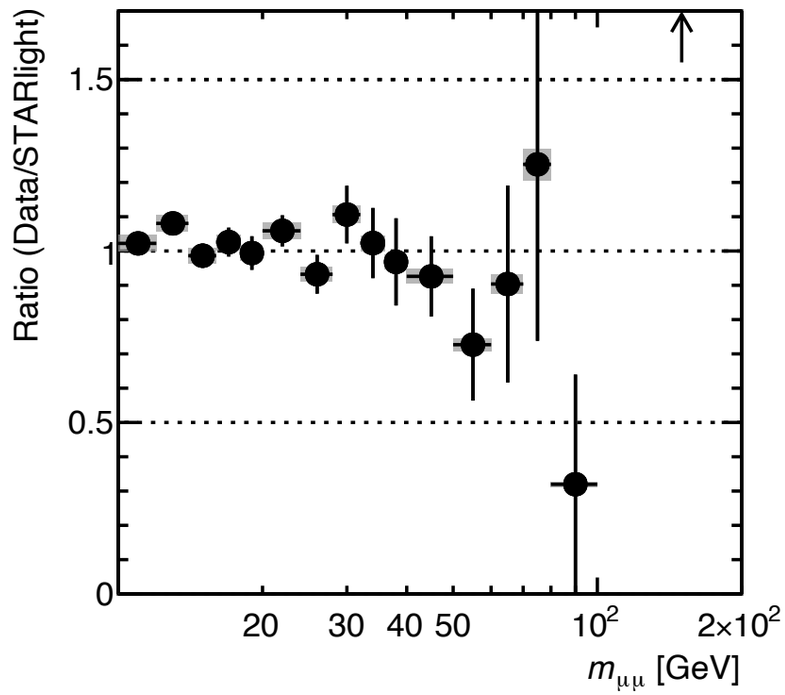


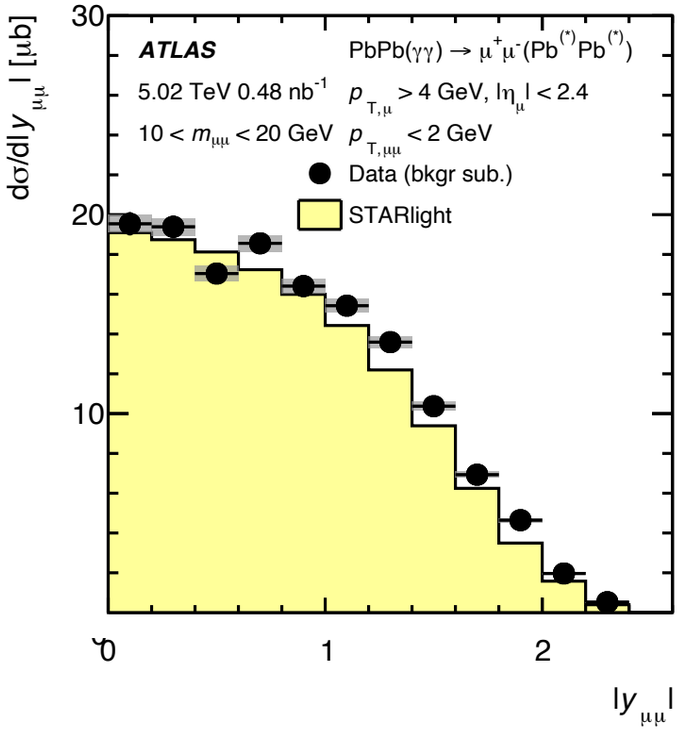
[JHEP 06 (2023) 182]

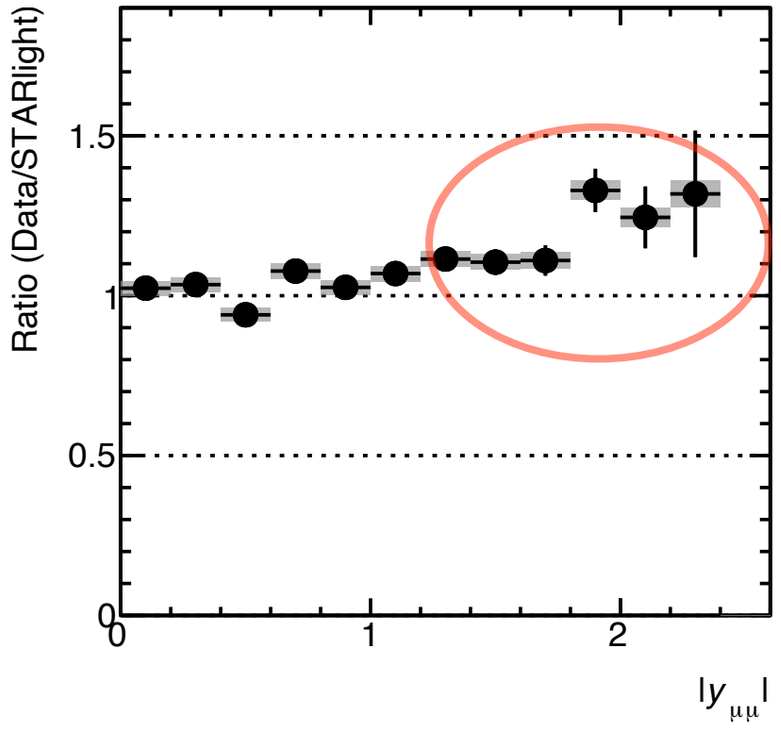
EXCLUSIVE DIMUONS: DIFFERENTIAL CROSS SECTIONS

[Phys. Rev. C 104 (2021) 024906]



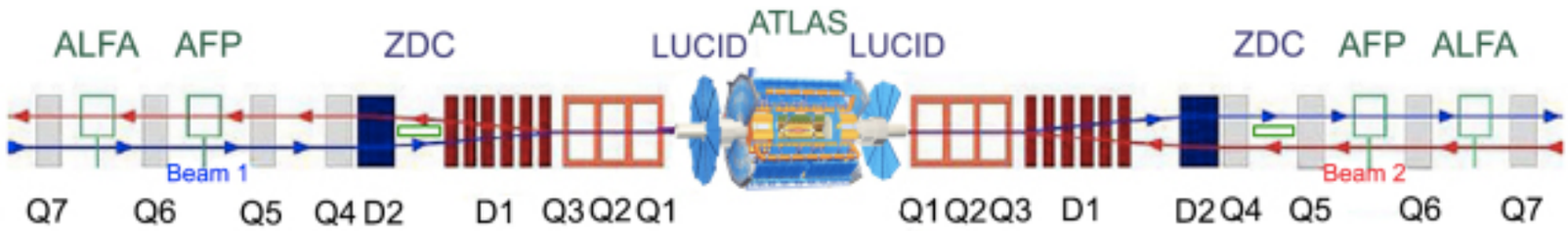


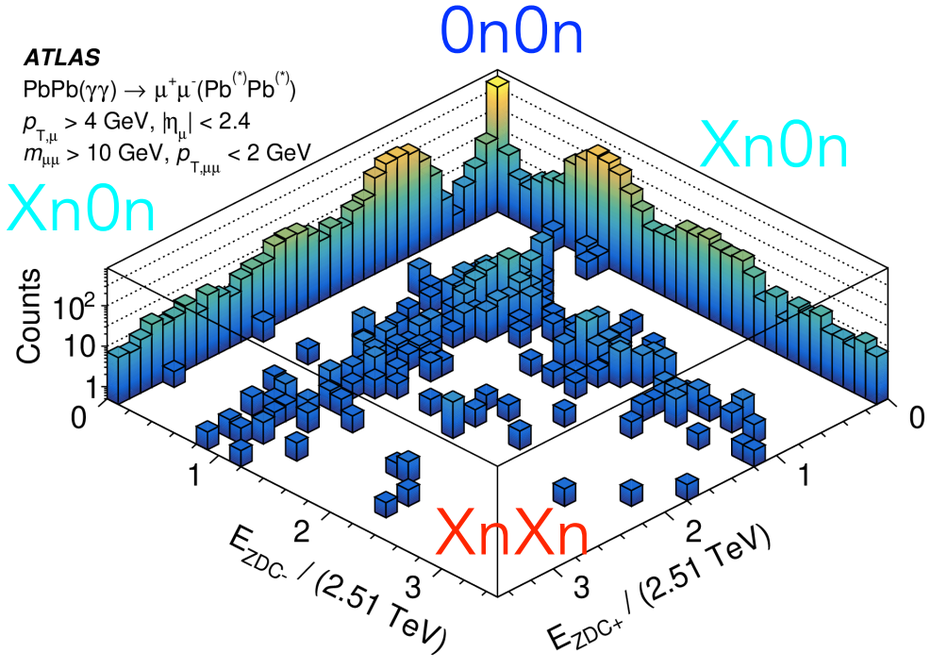




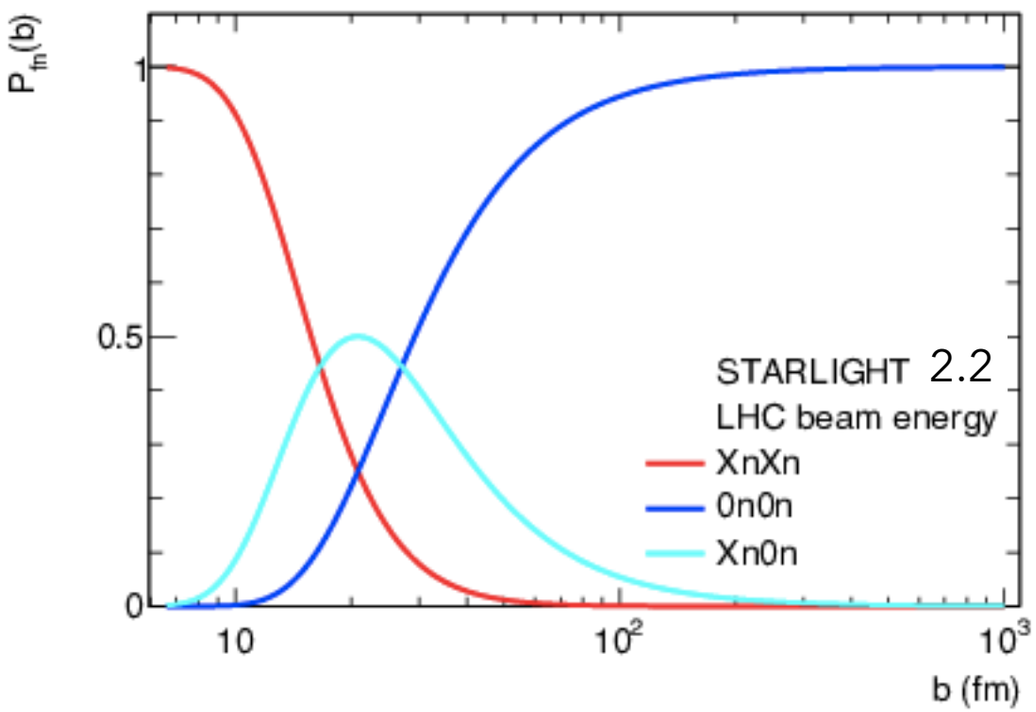
- Differential cross sections studied in $m_{\mu\mu}$, $|y_{\mu\mu}|$, dilepton scattering angle ($|\cos\theta^*|$), photon energy ($k_{\min}$, $k_{\max}$) and acoplanarity (α)
- $m_{\mu\mu}$ measured up to 200 GeV
- **Good agreement** with STARlight 2.0
- … but **systematic excess** of the data at higher $|y_{\mu\mu}|$

EXCLUSIVE DILEPTONS: ACTIVITY IN ZDC





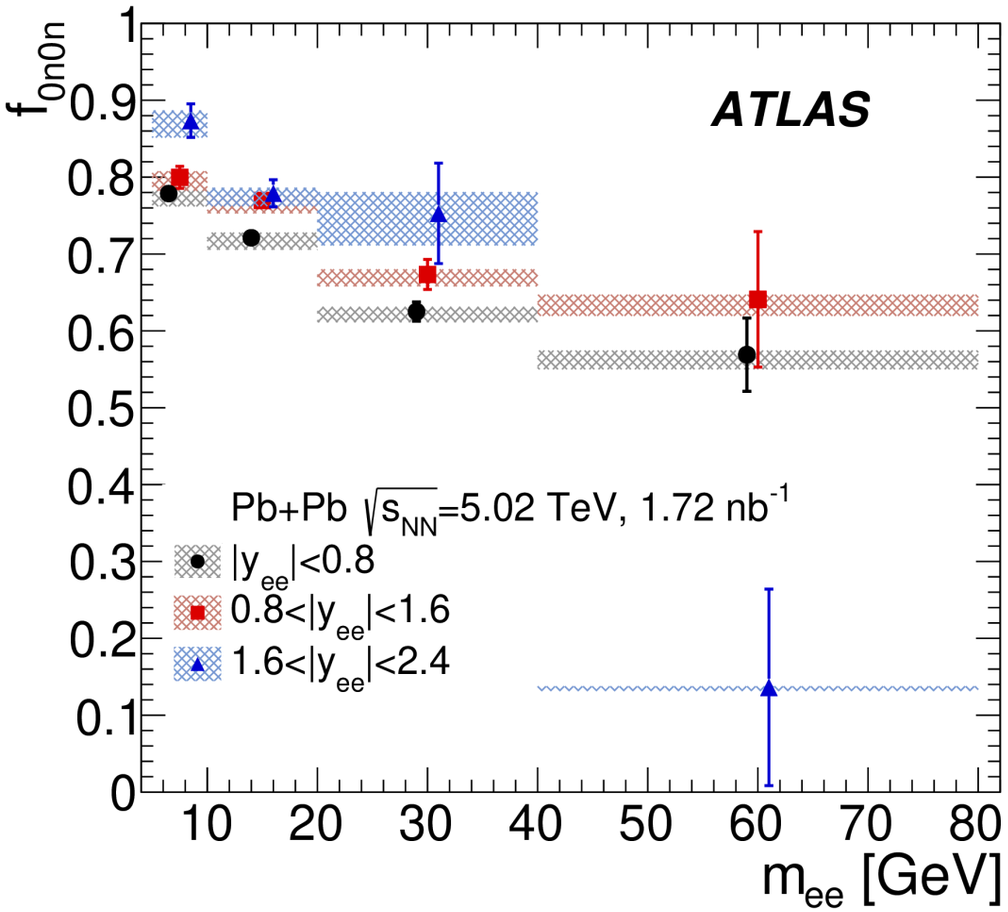
[Ann.Rev.Nucl.Part.Sci. 70 (2020) 323-354]



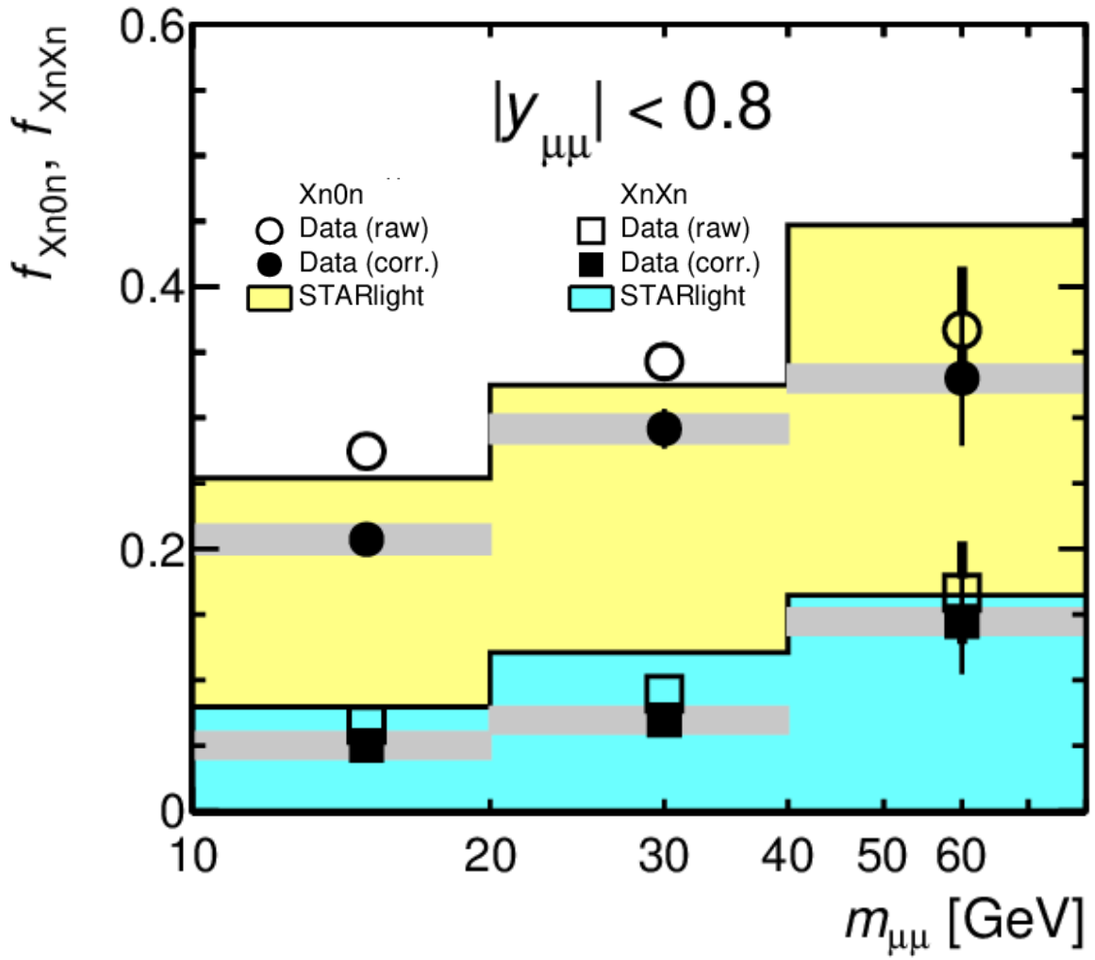
- **ZDC** are 140 m away from the IP ($|\eta| > 8.3$)
  - Detect neutral particles (e.g. neutrons, photons)
- Inclusive sample of $\gamma\gamma \to \ell^+\ell^-$ is divided into three categories
  - **0n0n**: no activity in neither ZDC arm
  - **Xn0n**: activity in one ZDC arm
  - **XnXn**: activity in both ZDC arms
- Fractions of events falling to each category f_{0n0n}, f_{Xn0n}, f_{XnXn} are measured
  - After subtracting backgrounds and accounting for electromagnetic pileup
- **Each category** probes different **impact parameters** (b)

EXCLUSIVE DILEPTONS: FORWARD ACTIVITY

Dielectrons [JHEP 06 (2023) 182]



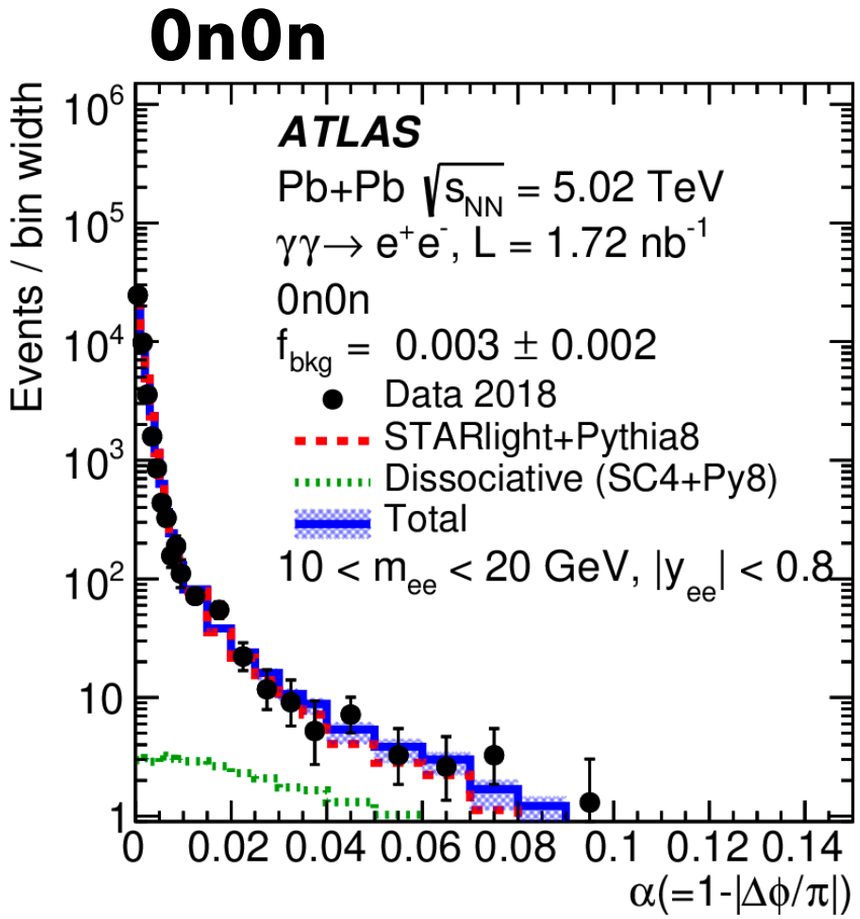
Dimuons [PRC 104 (2021) 024906]

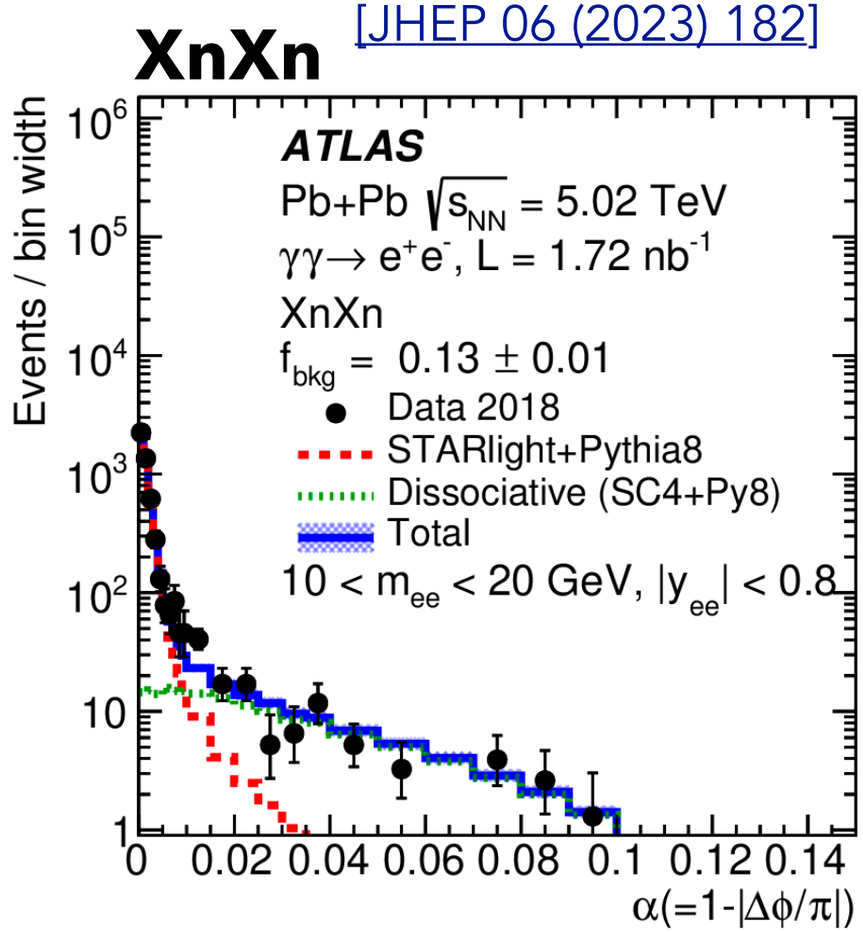


- **Corrected fractions** of events in the **0n0n** (dielectrons) and **Xn0n/XnXn** (dimuons) categories as a function of $m_{\ell\ell}$ in three $|y_{\ell\ell}|$ intervals
  - **f_{0n0n}** (f_{Xn0n}, f_{XnXn}) **decreases** (increases) with $m_{\ell\ell}$ and increases (decrease) with $|y_{\ell\ell}|$
  - Results consistent between dielectron and dimuon channels
  - **STARlight** qualitatively describes the impact-parameter dependence of the fluxes, but some systematic differences are observed

EXCLUSIVE DILEPTONS: BACKGROUNDS

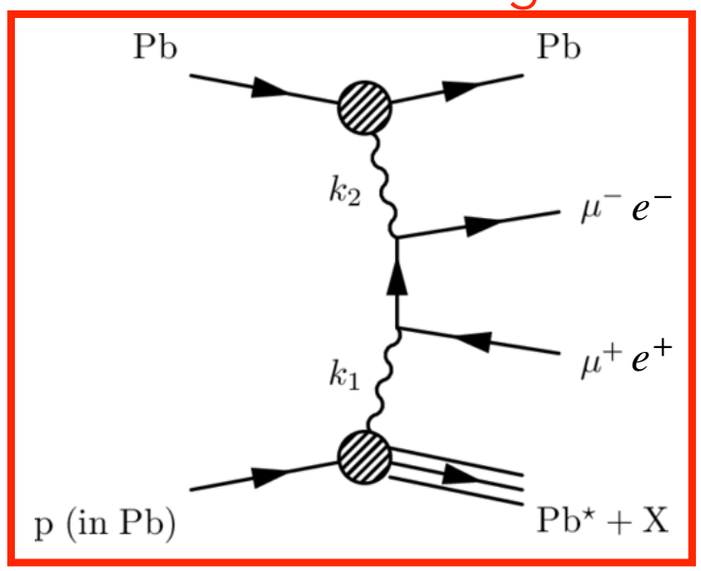
[JHEP 06 (2023) 182]



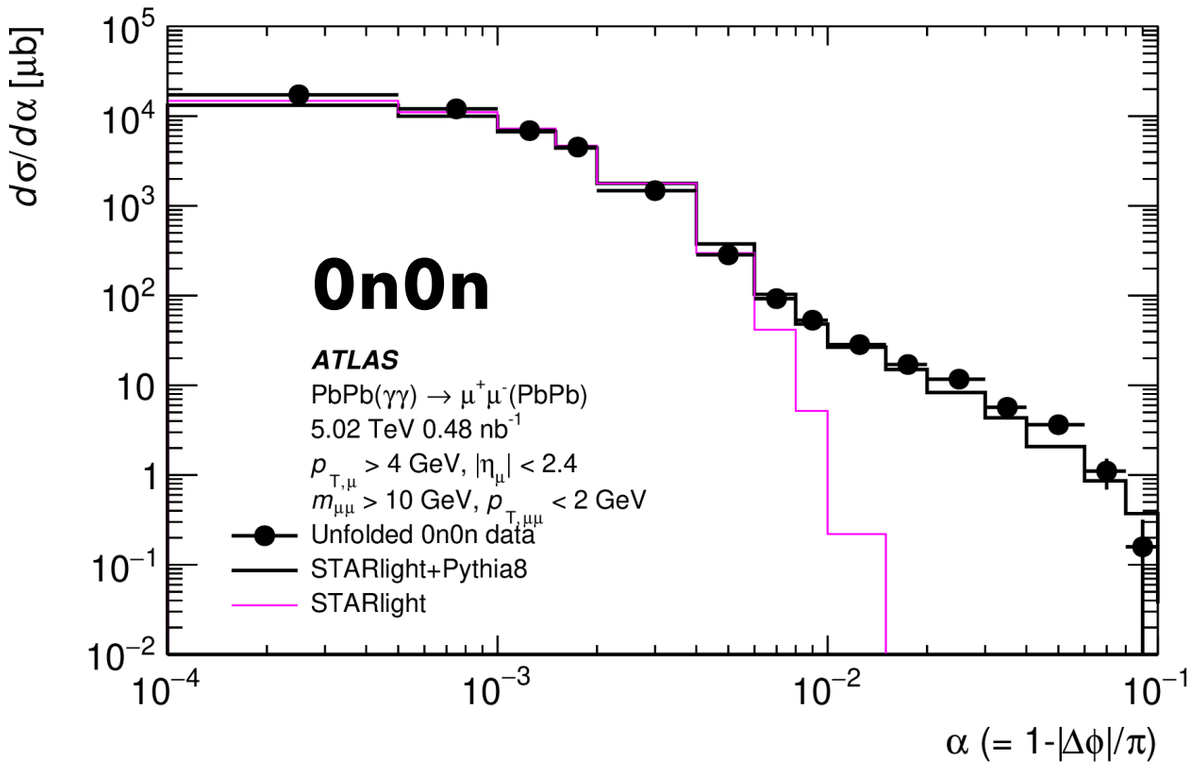


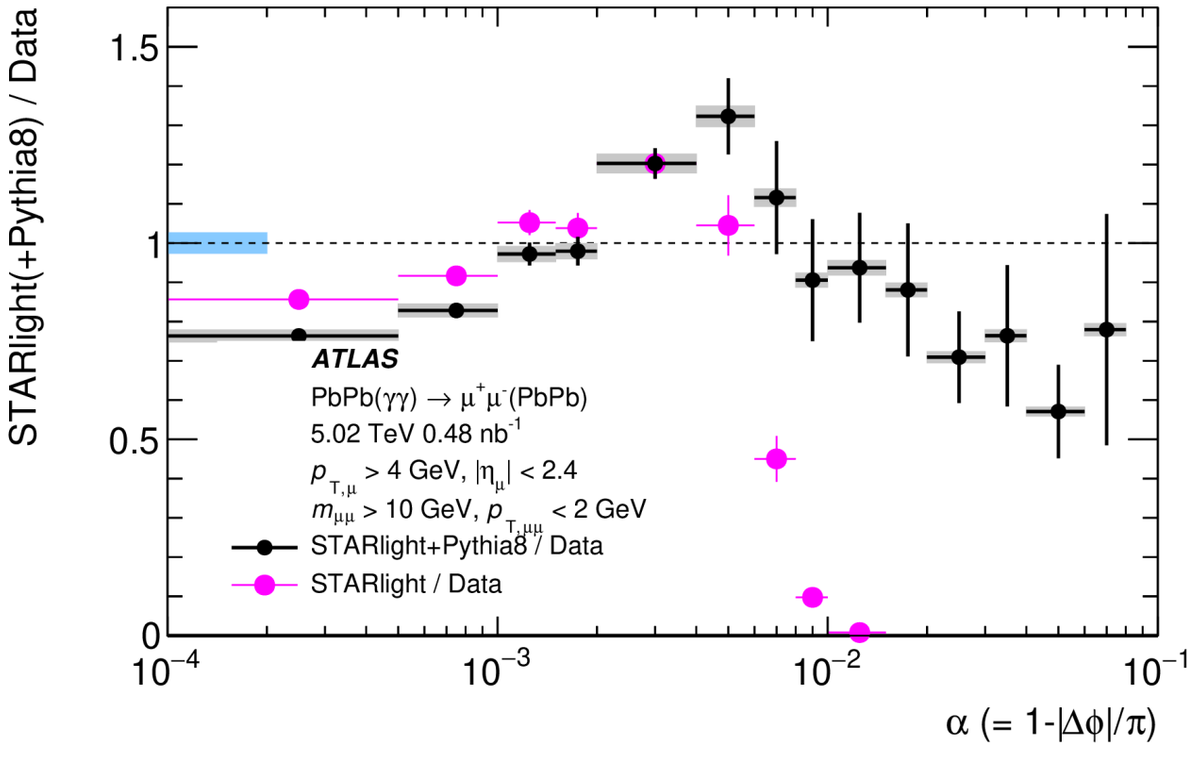
- Use **ZDC categories** to constraint **dissociative background** via template method
- Precise evaluation of dissociative background in **SuperChic v4.0** (**LPair**) in e^+e^- ($\mu^+\mu^-$)
- In inclusive samples: dimuons - 3%, dielectrons - 4.3%

Background



EXCLUSIVE DIMUONS: ACOPLANARITY

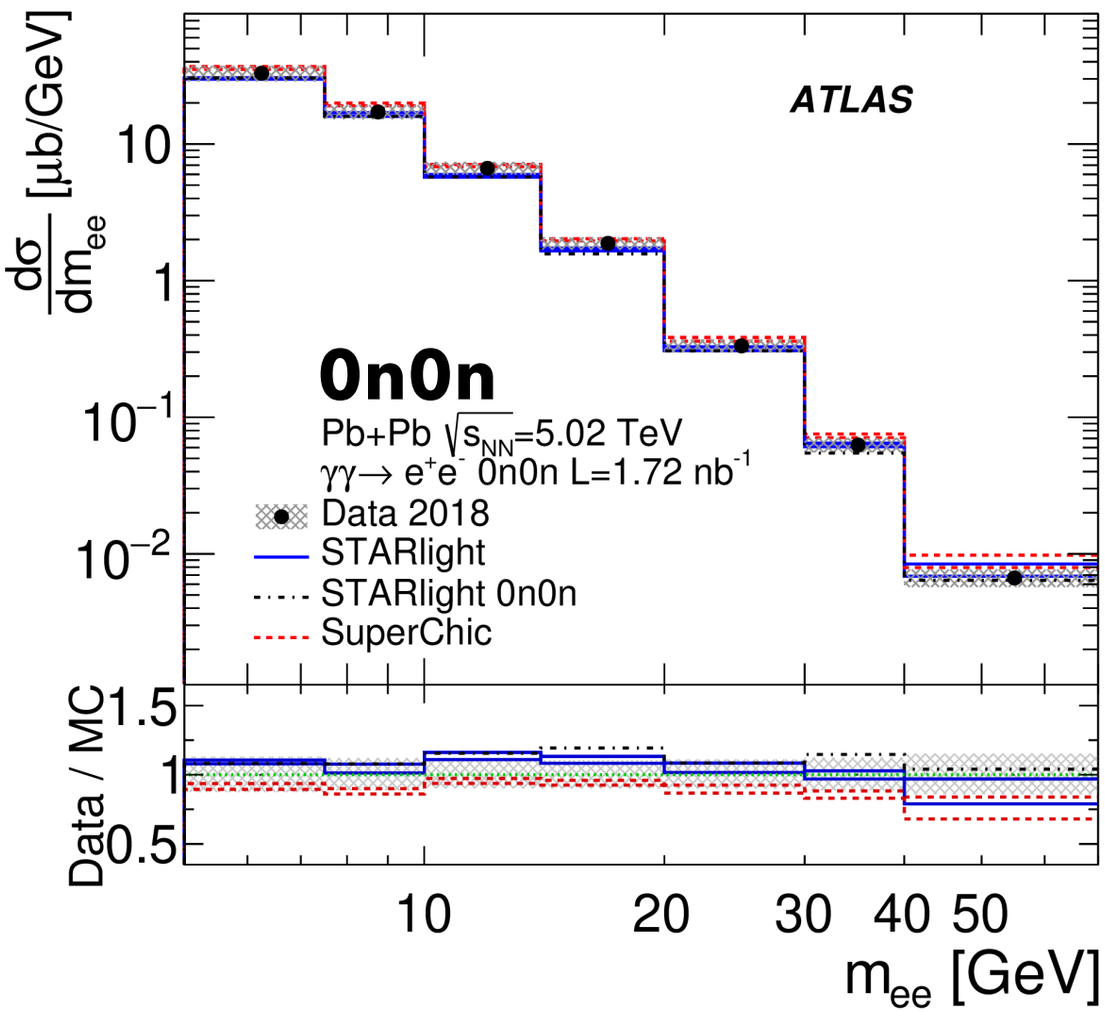


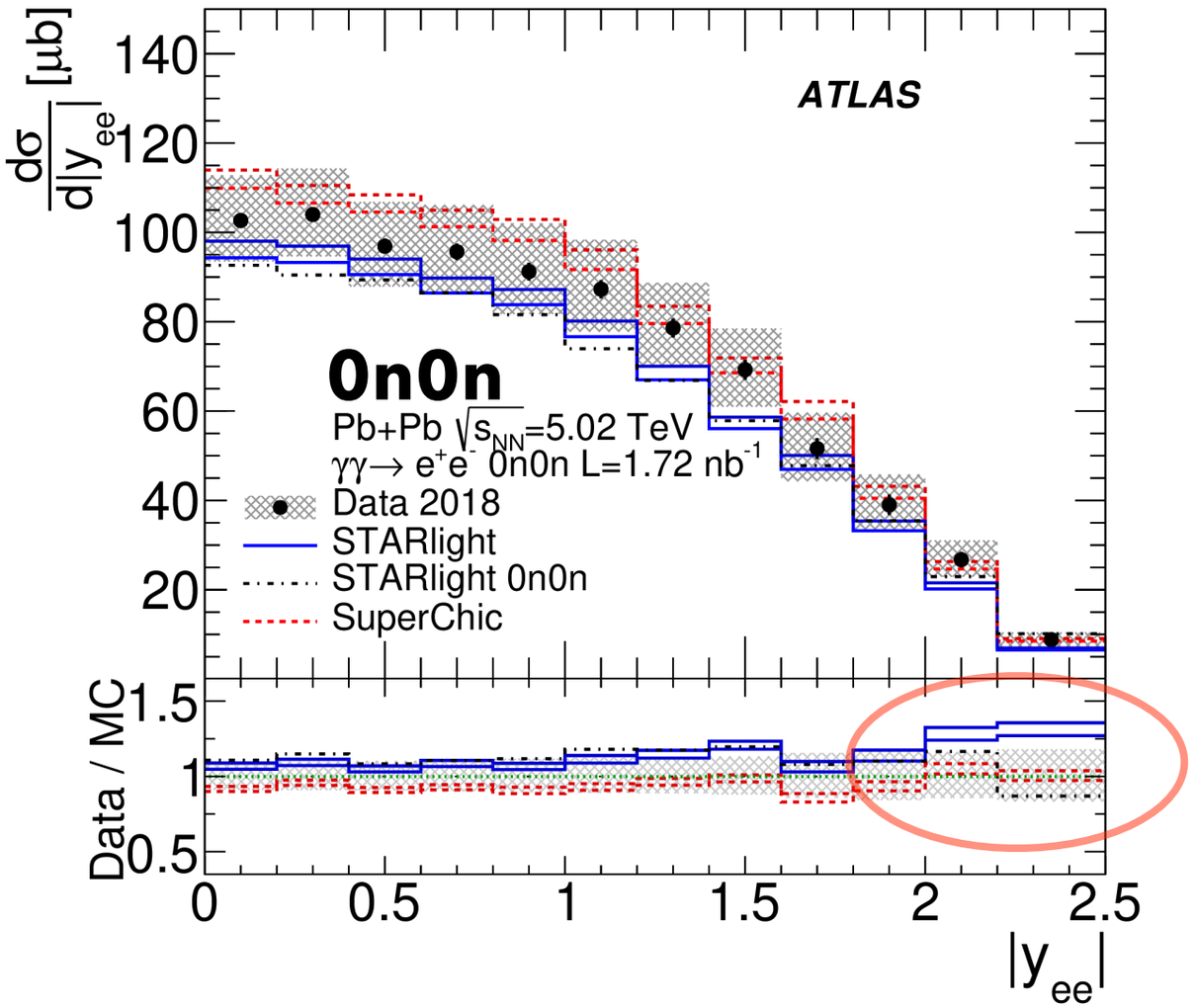


- Differential cross section in acoplanarity for **0n0n**
- Comparison to inclusive STARlight and STARlight+Pythia8 scaled to 0n0n from data
- Pure STARlight fails at high α due to a missing **FSR contribution**
- STARLight+Pythia8 with QED showering describes $\alpha > 0.01$ quite well
- However, for $\alpha < 0.01$ differences in shapes observed which can be attributed to differences in the photon flux of STARlight

EXCLUSIVE DIELECTRONS: CROSS SECTIONS

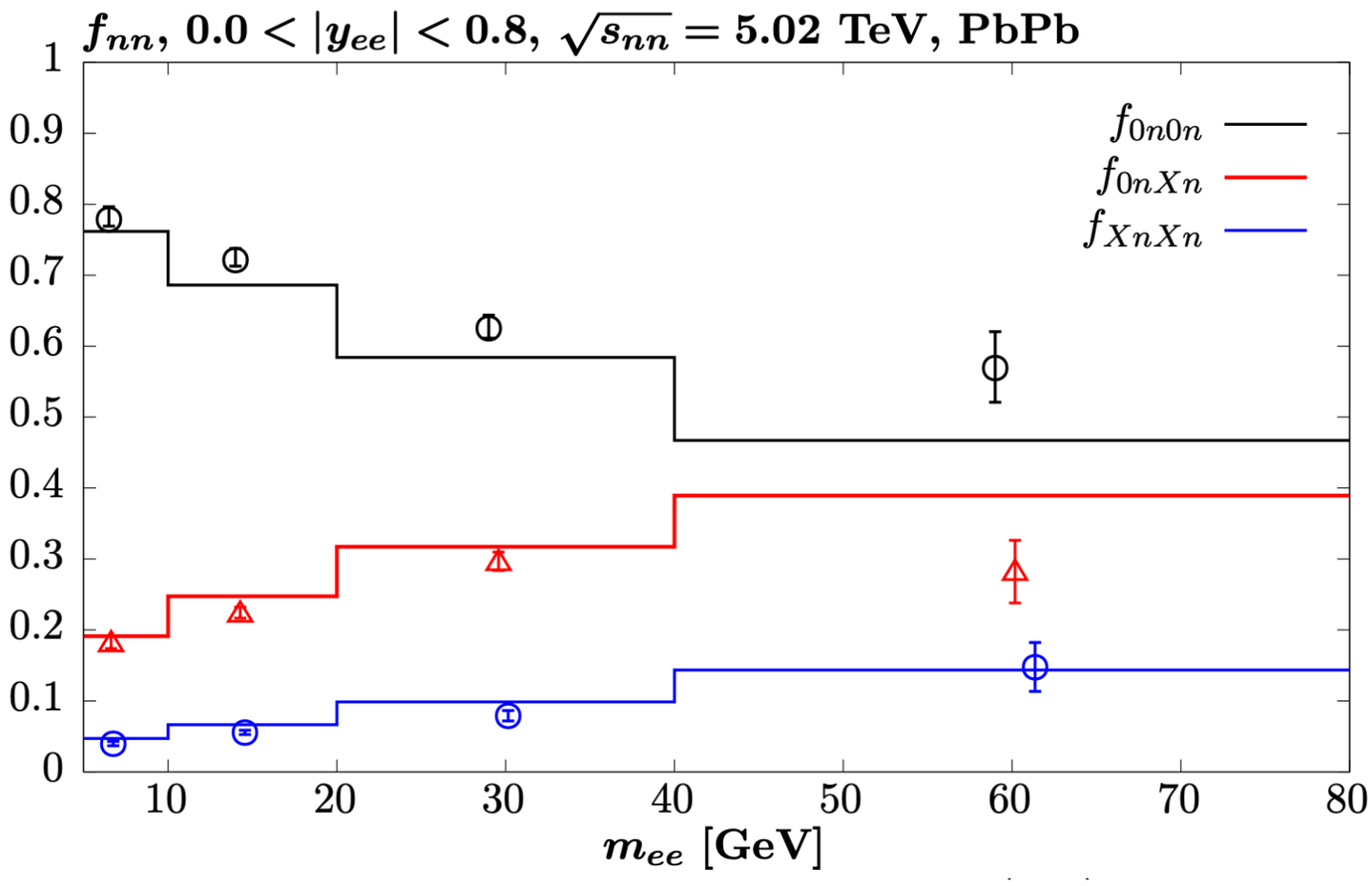
[JHEP 06 (2023) 182]





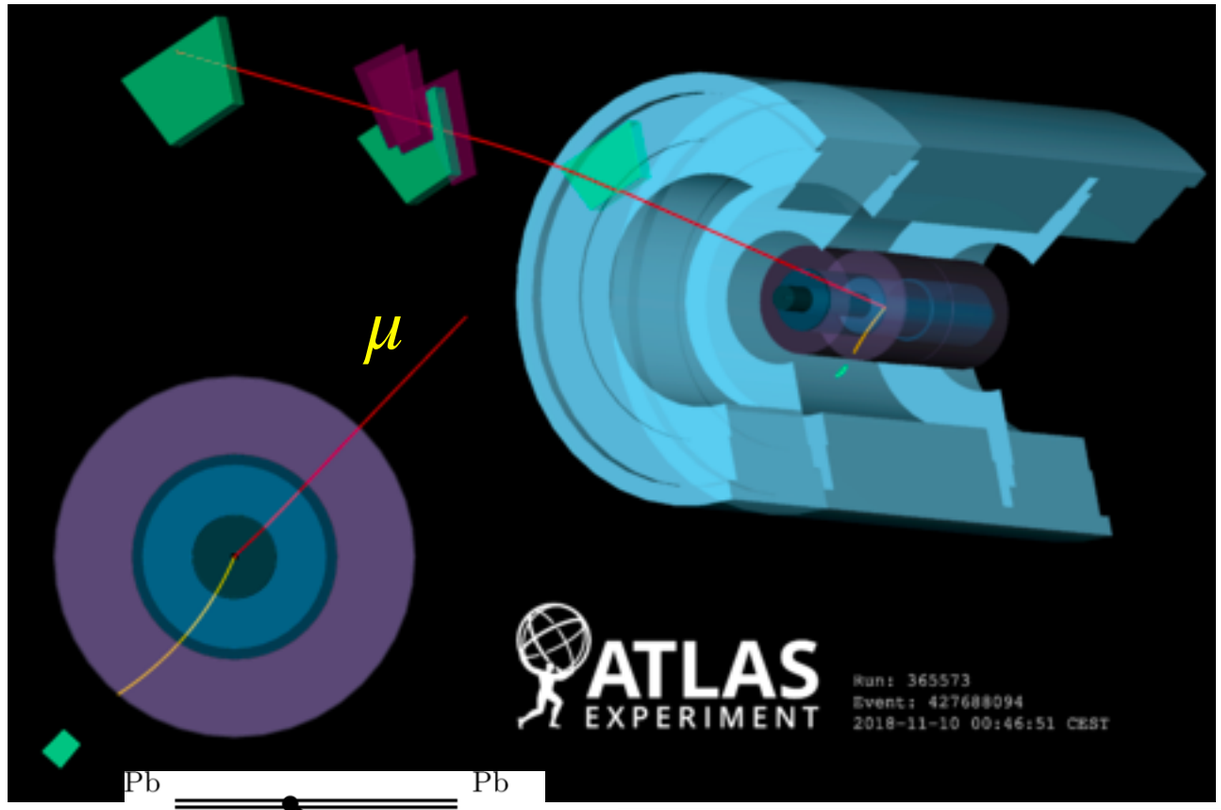
- Differential cross sections measured in m_{ee}, $|y_{ee}|$, $\langle p_{\mathrm{T}}^{e} \rangle$ and $|\cos\theta^*|$ in the **0n0n category**
  - **STARlight 0n0n** provides predictions for **no neutron production** (black dotted line)
  - **SuperChic 3.05** doesn't implement ZDC selections
  - Use **measured 0n0n fractions with uncertainties** to correct both STARlight and SuperChic predictions
- General conclusions similar to the inclusive ZDC case
  - **STARlight 2.2** (**SuperChic 3.05**) systematically lower (higher) than data
  - SuperChic does a better job in the description of shapes

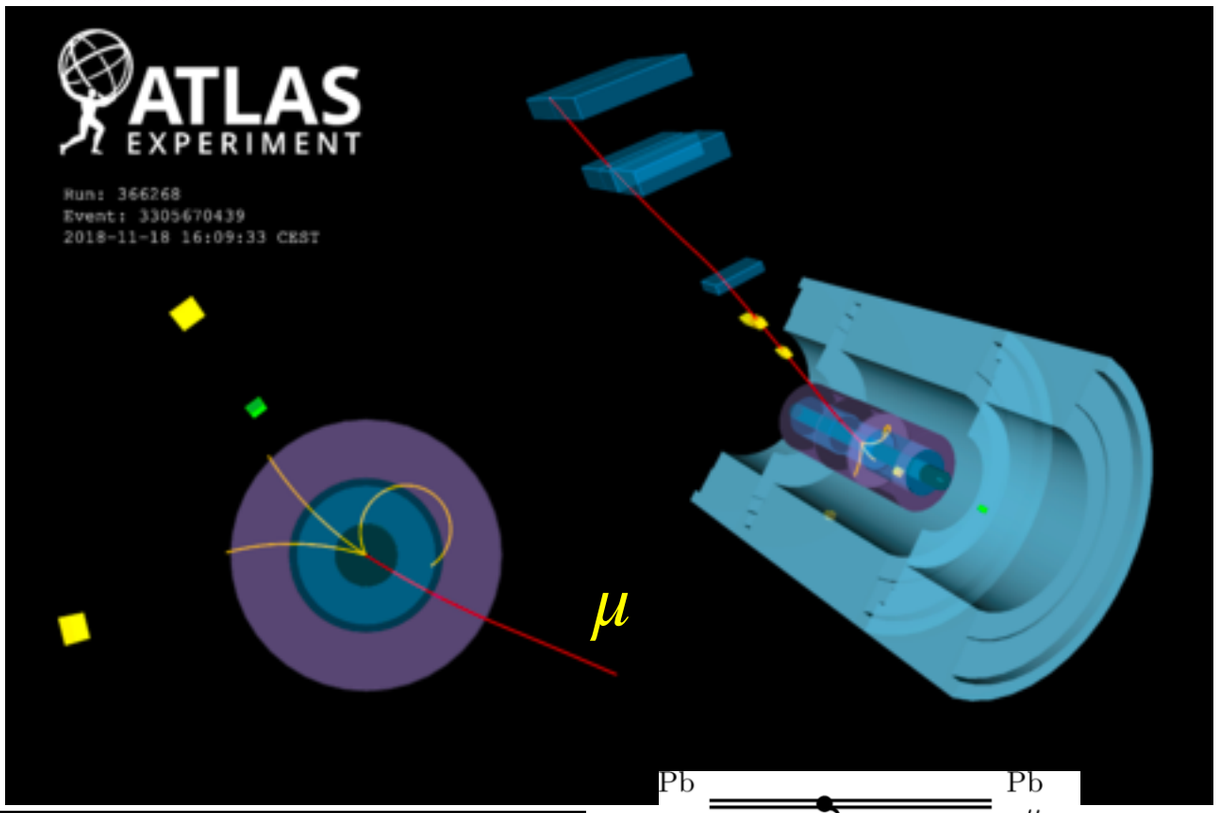
EXCLUSIVE DILEPTONS: MC DEVELOPMENTS

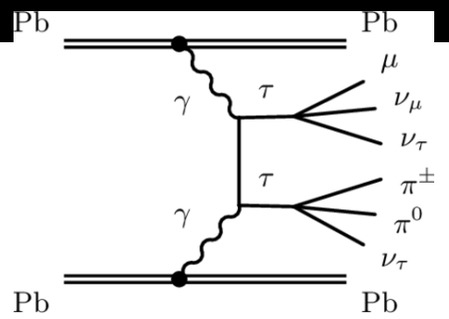


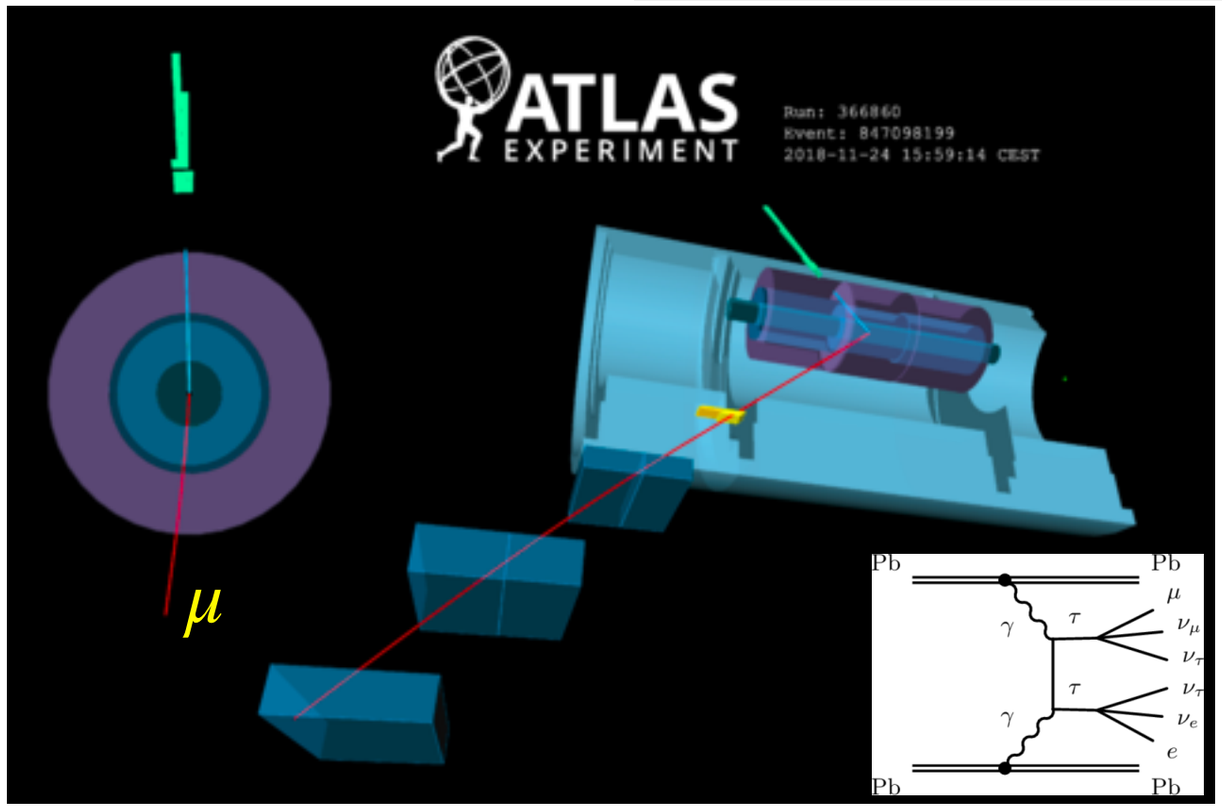
- New data triggered developments in **SuperChic v4.2** which brings modeling of ion excitation/de-excitation and emission of neutrons in the forward direction
  - See L.H. Harland-Lang arXiv:2303.04826 for more details
- **Good description** of dielectron/dimuon data from ATLAS

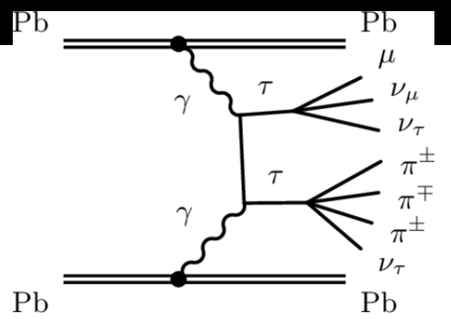
EXCLUSIVE DITAUS







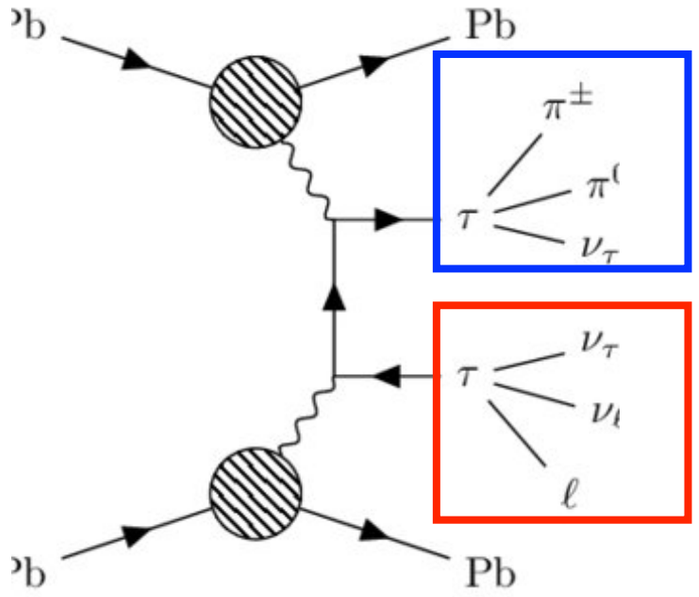




- Event candidates for $\gamma\gamma \to \tau^+\tau^- \to \mu^\pm\nu_\mu\nu_\tau$track(s) or $\gamma\gamma \to \tau^+\tau^- \to \mu^\pm\nu_\mu\nu_\tau e^\pm\nu_e\nu_\tau$

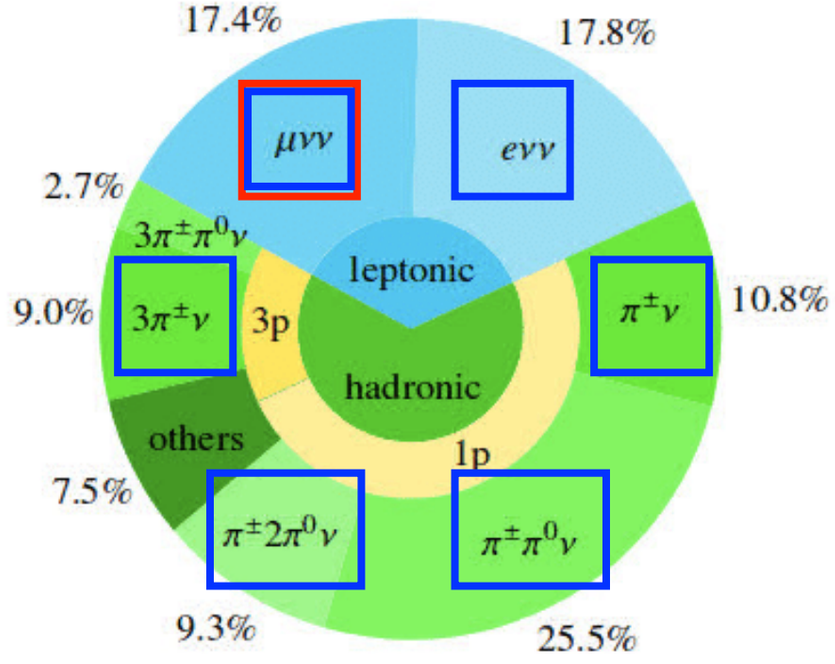
EXCLUSIVE DITAUS

[PRL 131 (2023) 151802]



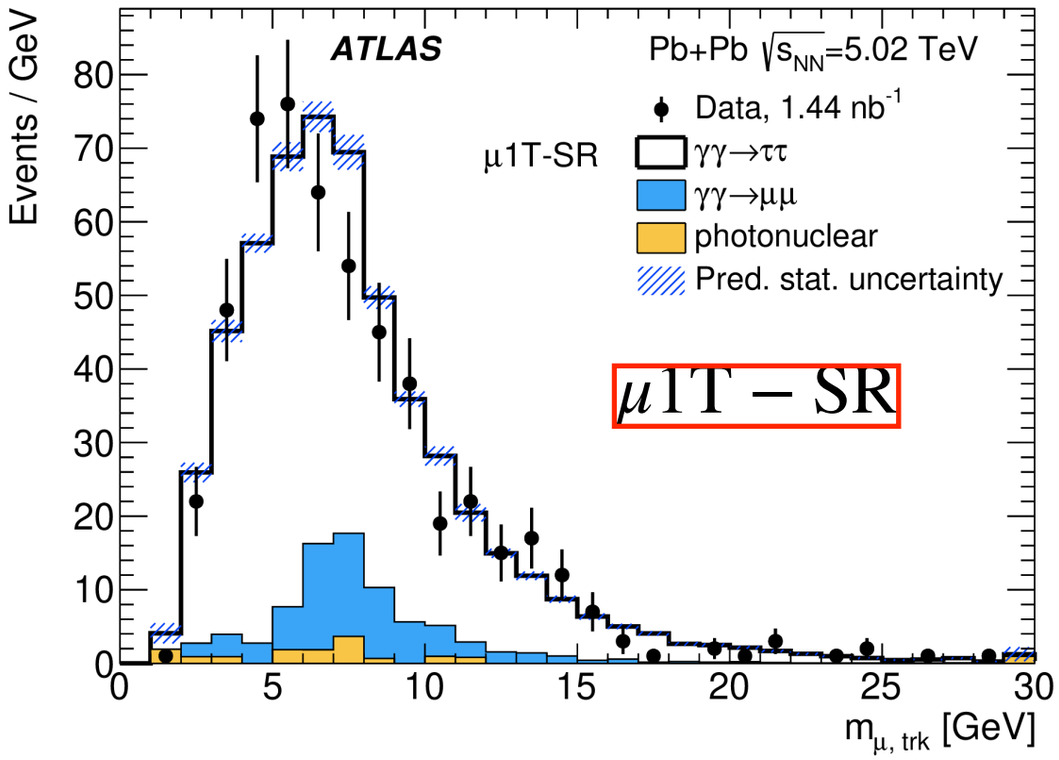
- **First observation** of τ leptons in A+A collisions in **2018** UPC Pb+Pb collisions of 1.44 nb^{-1}
- Exclusive ditau production $\gamma\gamma \to \tau^+\tau^-$ with (**semi)leptonic decay** modes
  - μ1T-SR: muon + 1 track (e/μ/hadron)
  - μ3T-SR: muon + 3 tracks (3 hadrons)
  - μe-SR: muon + electron

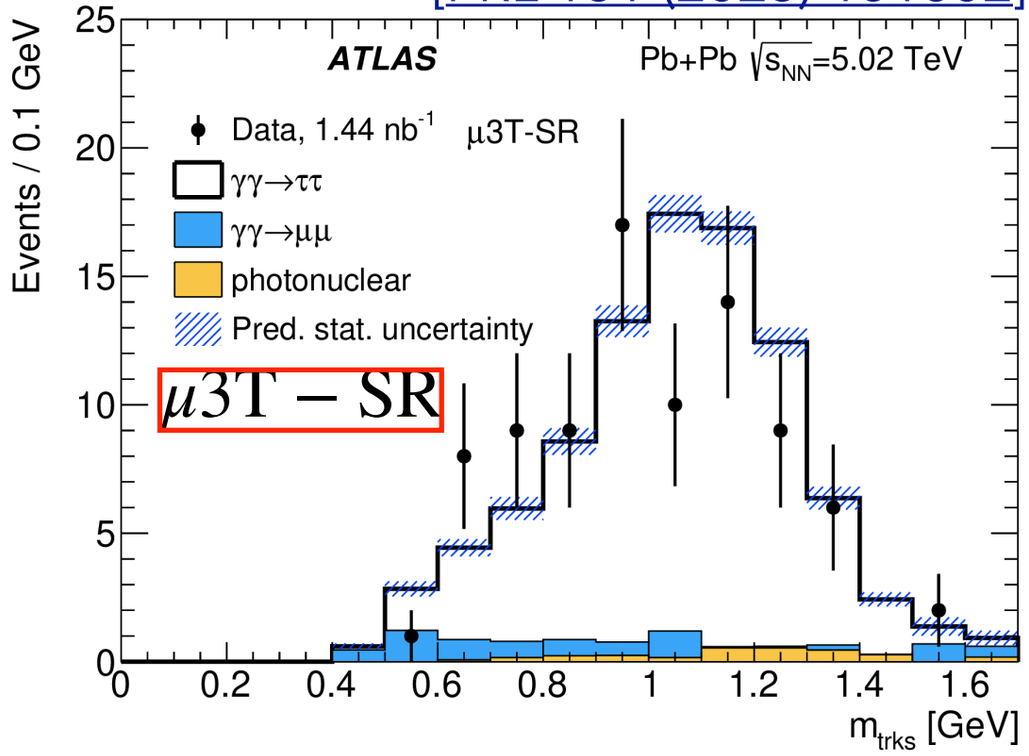
  with $p_{\mathrm{T}}^{\mu} > 4$ GeV, $p_{\mathrm{T}}^{e} > 4$ GeV, $p_{\mathrm{T}}^{\mathrm{trk}} > 100$ MeV
  $p_{\mathrm{T}}^{\mathrm{clus}} > 1$ GeV ($|\eta| < 2.5$)
  $p_{\mathrm{T}}^{\mathrm{clus}} > 100$ MeV ($2.5 < |\eta| < 4.5$)
  - Exclusivity: veto additional clusters (μ1T-SR and μ3T-SR only) and tracks
- Total of ~ **650 events** across all SRs
- Only **data** in the **0n0n category** used to suppress photonuclear/hadronic backgrounds
- Simulation (**STARlight+Tauola**) reweighted to 0n0n with data-driven weights



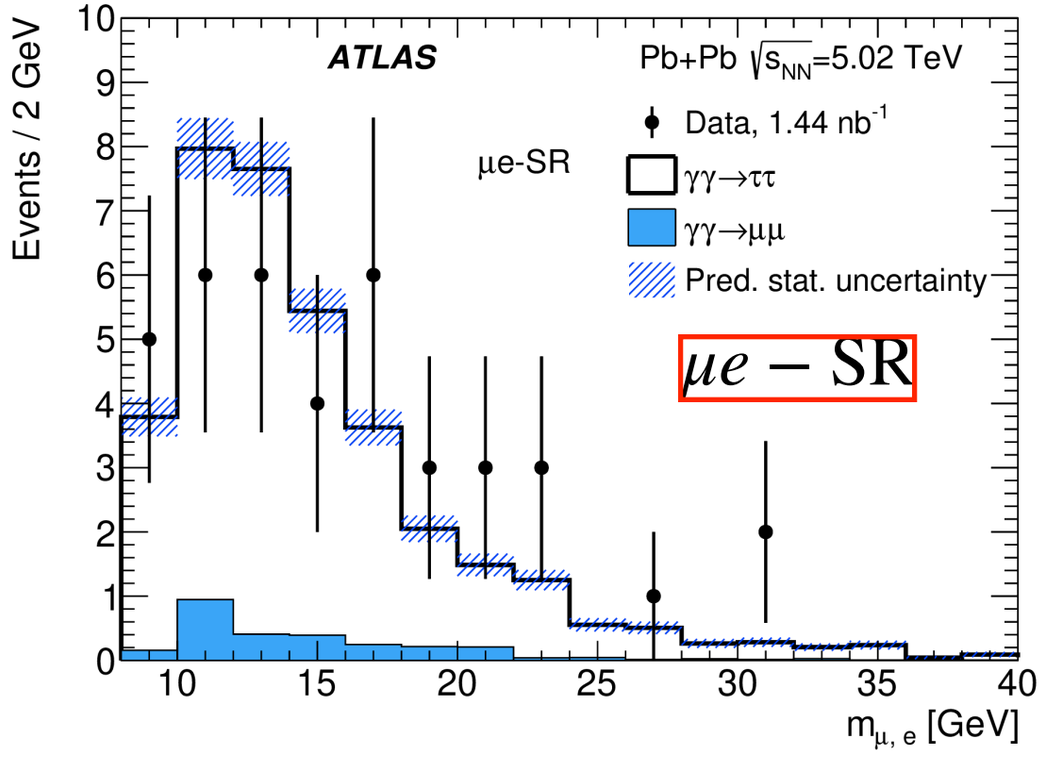
EXCLUSIVE DITAUS: CONTROL PLOTS

[PRL 131 (2023) 151802]



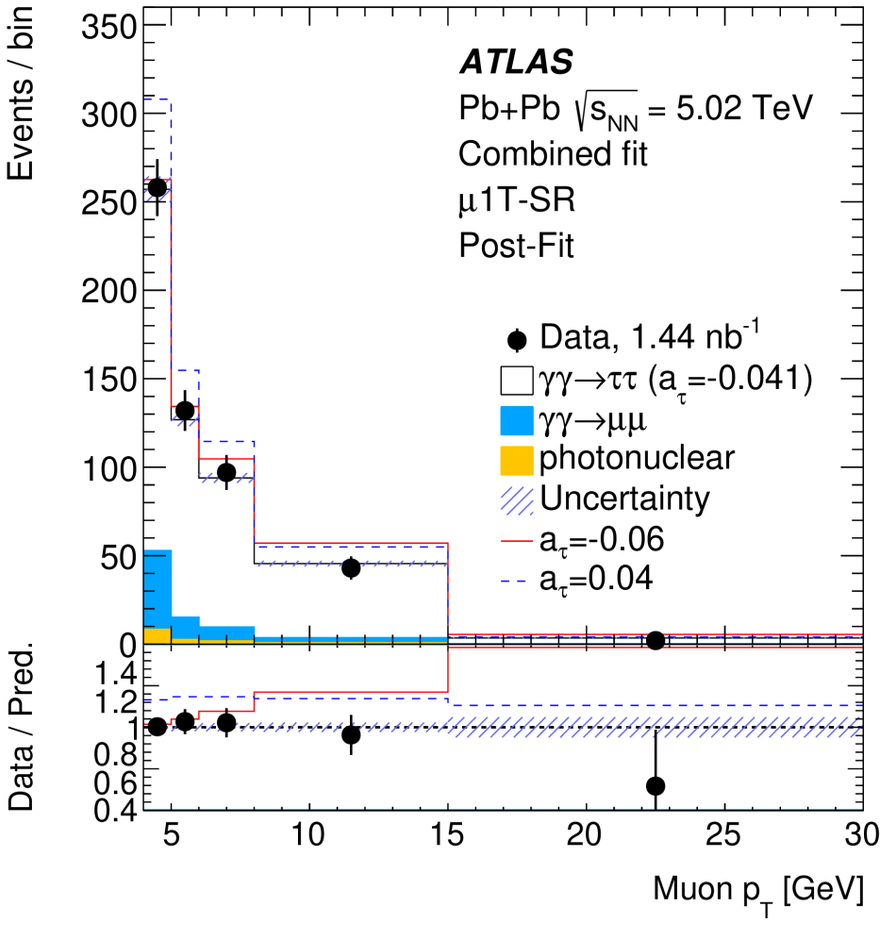


- $\gamma\gamma \to \tau^+\tau^-$ measured in **three channels**:
  - μ1T-SR: muon + 1 track (e/μ/hadron)
  - μ3T-SR: muon + 3 tracks (3 hadrons)
  - μe-SR: muon + electron
- Main backgrounds:
  - $\gamma\gamma \to \mu^+\mu^-(\gamma)$ and photonuclear
  - In general little background contributions in all three SR (15%)
- **Good agreement** of SM predictions with data

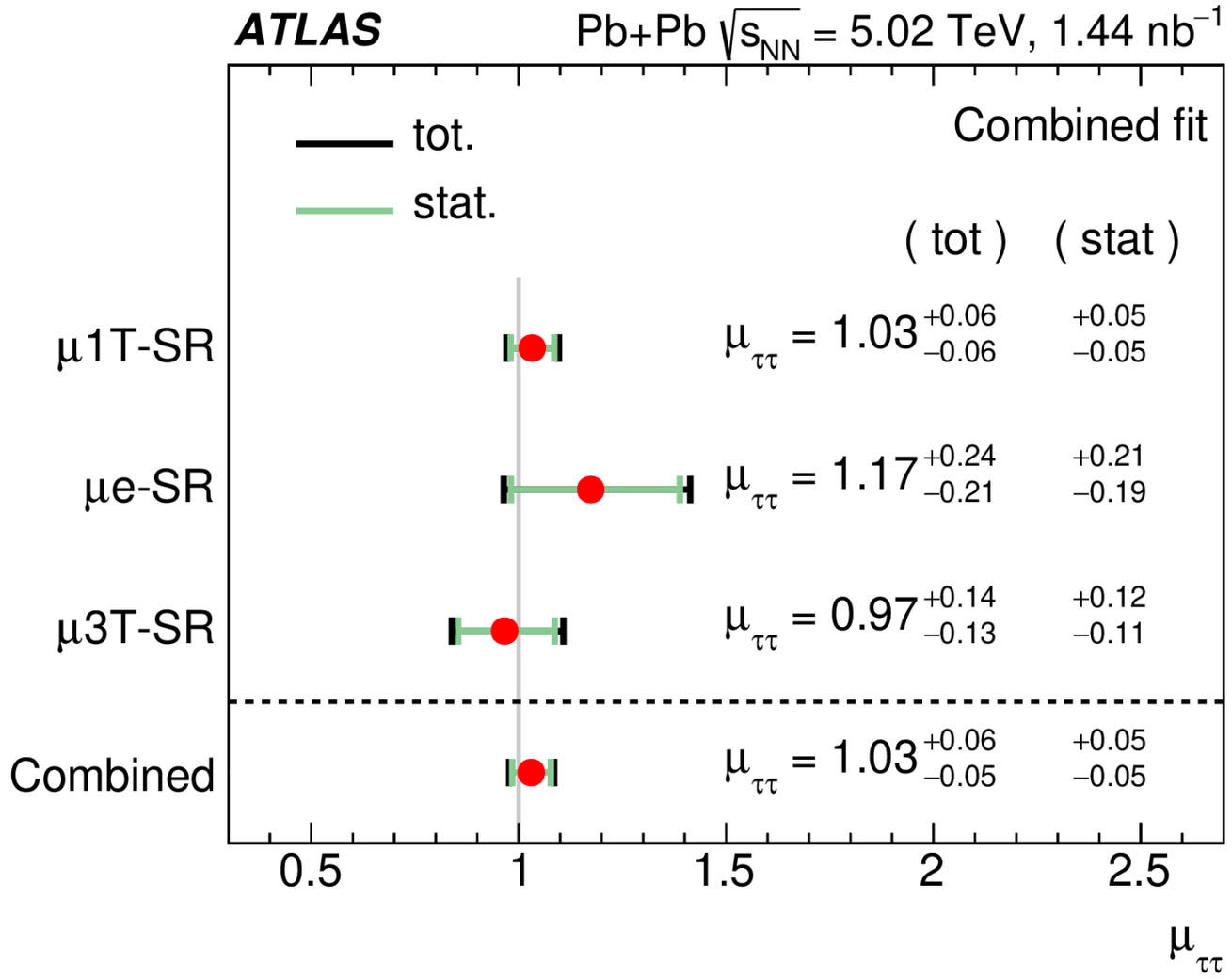


EXCLUSIVE DITAUS: SIGNAL STRENGTH

$\mu 1\mathrm{T} - \mathrm{SR}$



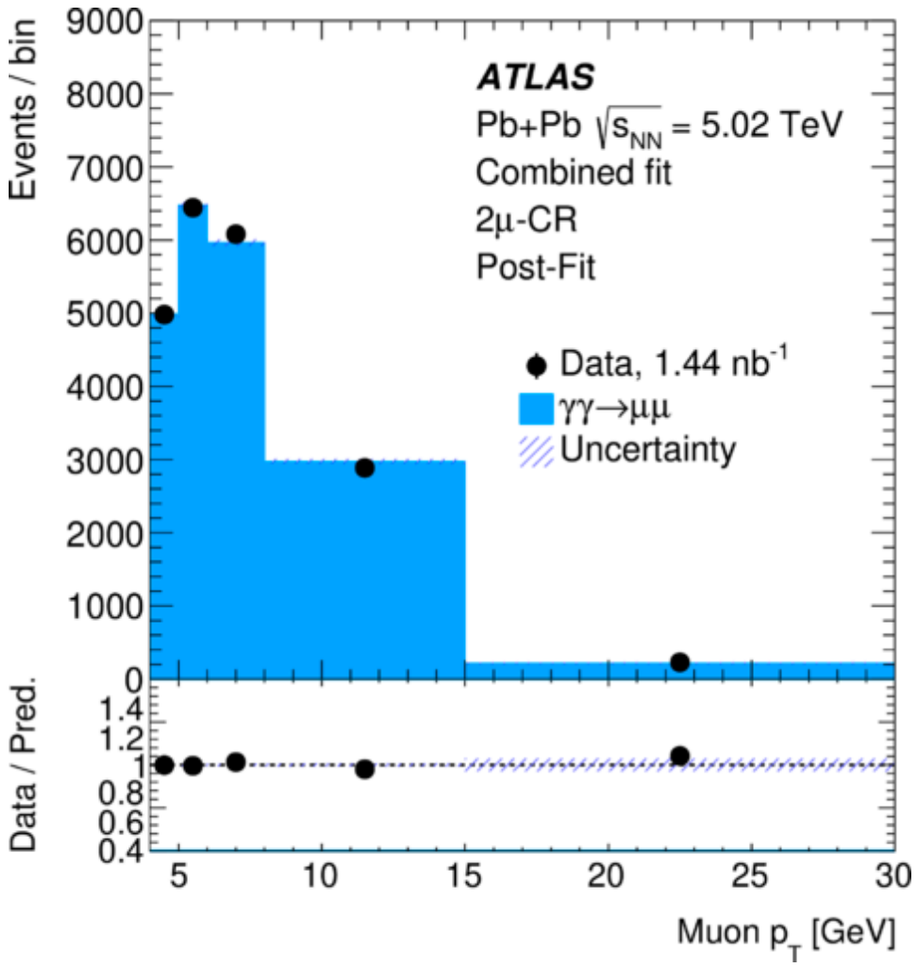
[PRL 131 (2023) 151802]

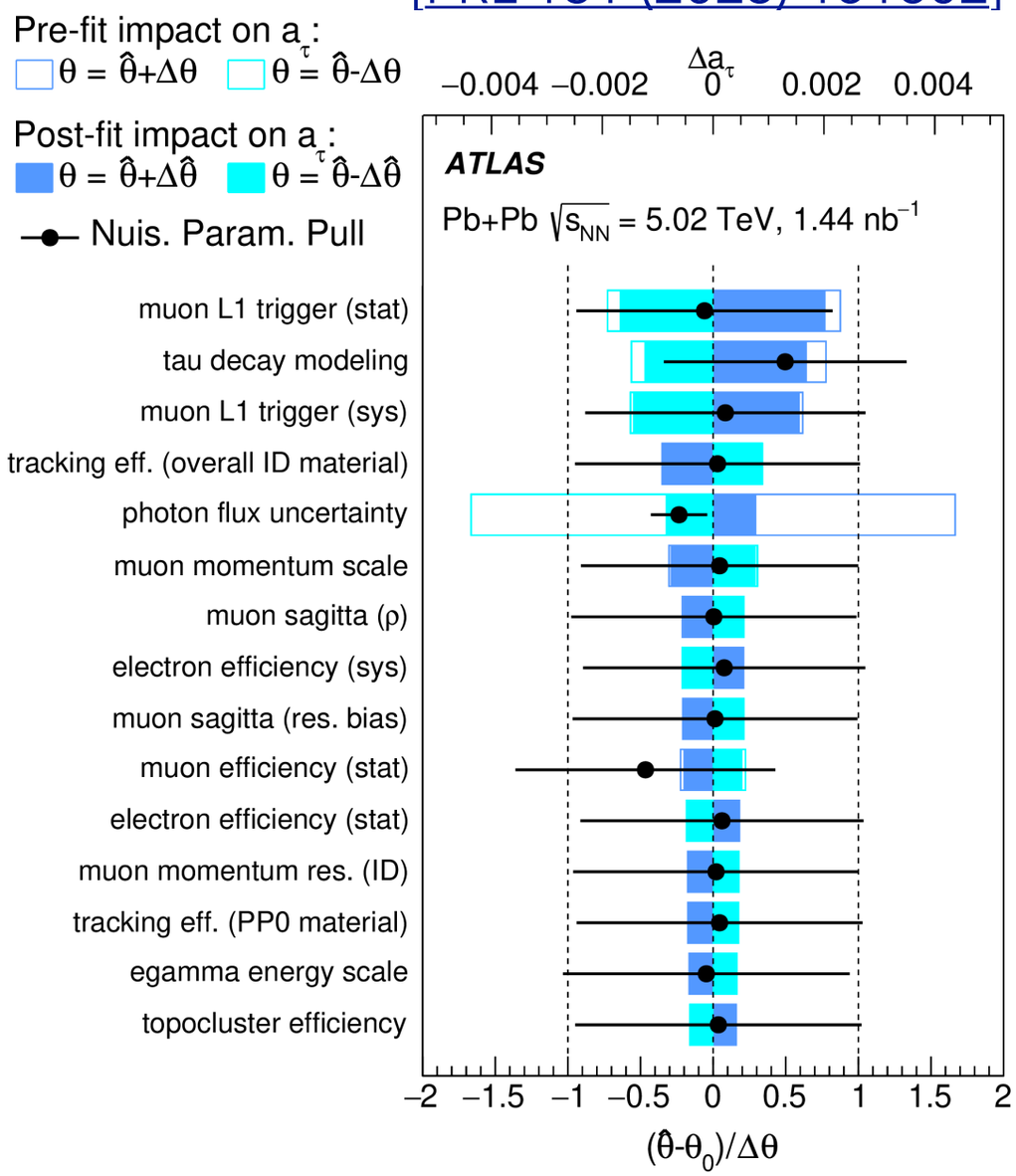


- **Signal strength** $\mu_{\tau\tau} = N^{\mathrm{meas}}_{\gamma\gamma\to\tau\tau} / N^{\mathrm{SM,pred}}_{\gamma\gamma\to\tau\tau}$ measured using a profile-likelihood fit to the p^{μ}_{T} **distribution** in the three SRs and $\mu\mu$ control region (2μ-CR)
- **First observation** of **tau leptons** and $\gamma\gamma \to \tau^+\tau^-$ process with more than 5σ significance in HI collisions at the LHC
- Result of $\mu_{\tau\tau}$ for each SR assuming a_τ anomalous magnetic moment from SM are **compatible with unity**

EXCLUSIVE DITAUS: UNCERTAINTIES

[PRL 131 (2023) 151802]

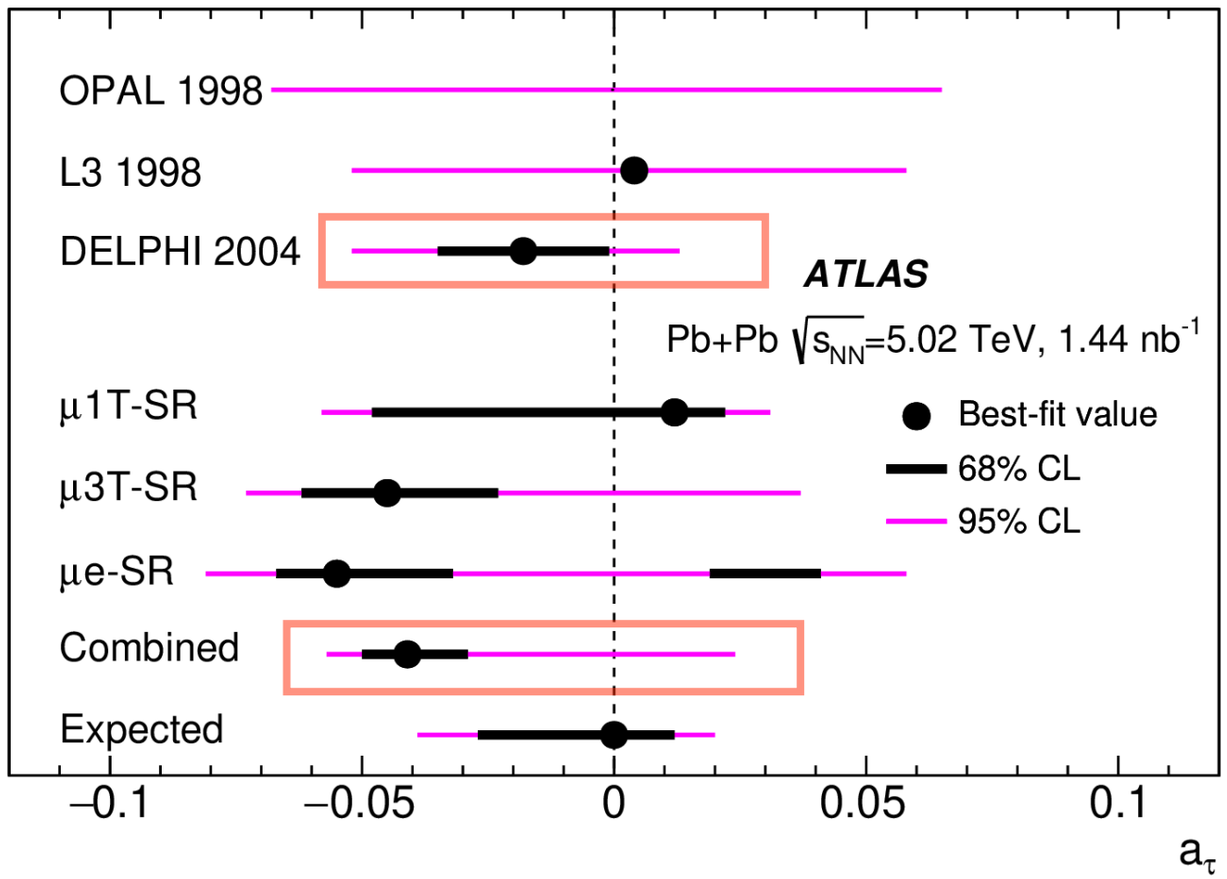




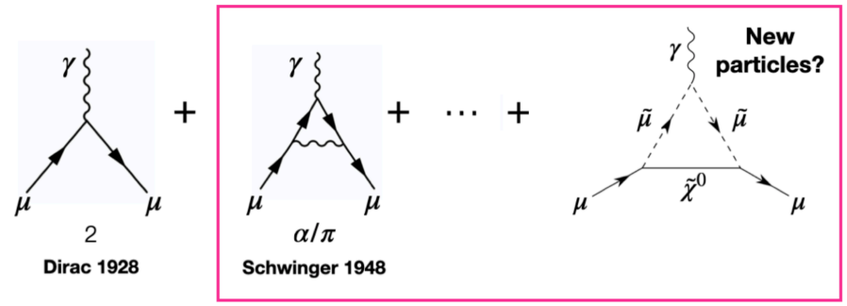
- In addition to 3 SRs , events from 2μ-CR from $\gamma\gamma \rightarrow \mu^{+}\mu^{-}$ used in the fit to **constrain photon fluxes**
- Reach a **total uncertainty** of **5%** for the combined $\mu_{\tau\tau}$ dominated by **statistical precision**

EXCLUSIVE DITAUS: TAU MAGNETIC MOMENT

[PRL 131 (2023) 151802]



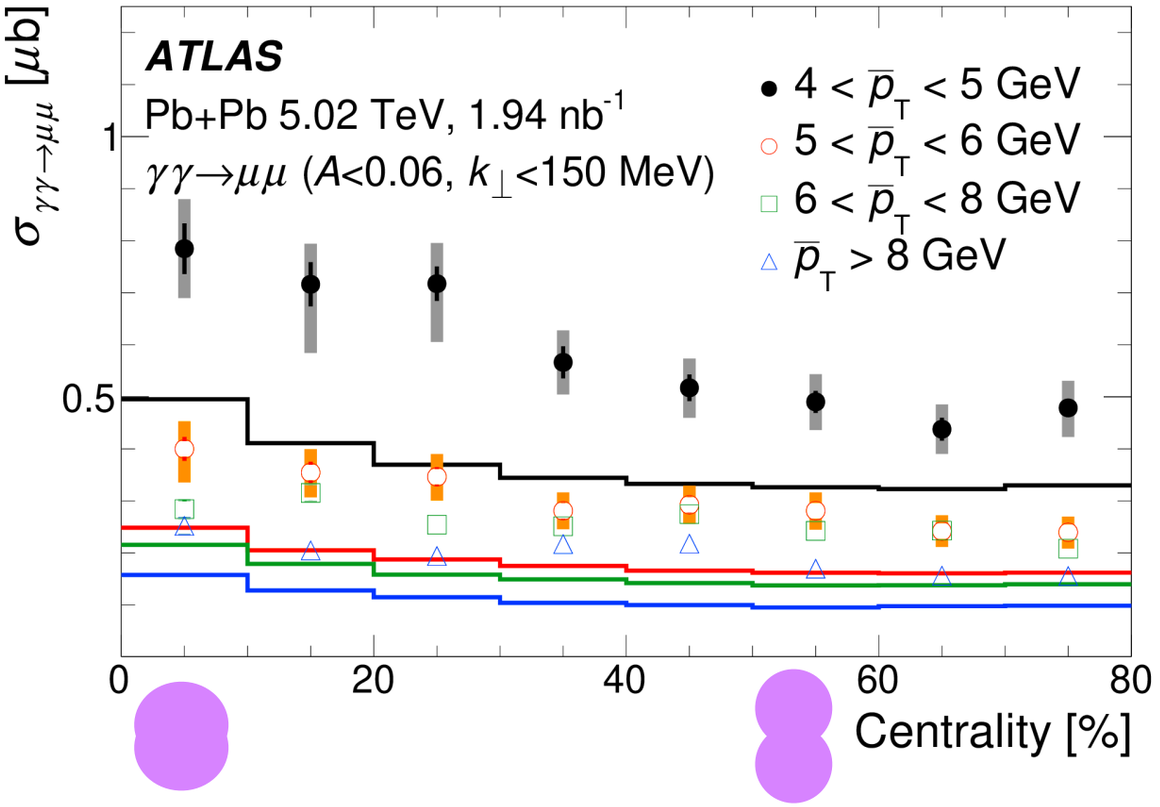
Tau anomalous magnetic moment $a_\tau = \dfrac{g-2}{2}$

$g =$ 

- a_τ extracted in a profile-likelihood fit to the p_{T}^{μ} distribution
  - **HI collisions** at **the LHC** contribute to the hot topic of lepton $g-2$ measurements
  - Templates for different a_τ built by reweighting signal MC using weights from [PLB 809 (2020) 135682]
- **Constraints on a_τ similar** in precision to those observed by **DELPHI at LEP**

NON-UPC DIMUONS: CROSS SECTIONS

[PRC 107 (2023) 054907]



- $\gamma\gamma \to \mu^+\mu^-$ studied in non-UPC events
  - Cross section measured as a function of **centrality**
  - **STARlight predictions** (solid lines) describe the shape but underestimate the normalisation, likely due to the truncation of photon fluxes for $b < R_A$
- Centrality-dependent **broadening** of α and $k_\perp$ is confirmed
  - Described by **QED** [PLB 800 (2020) 135089] and **PWF** [PRD 102 (2020) 094013] calculations
- Also the **depletion** of yields at small α and $k_\perp$ is found to develop with centrality
  - **PWF** does not reproduce the first point

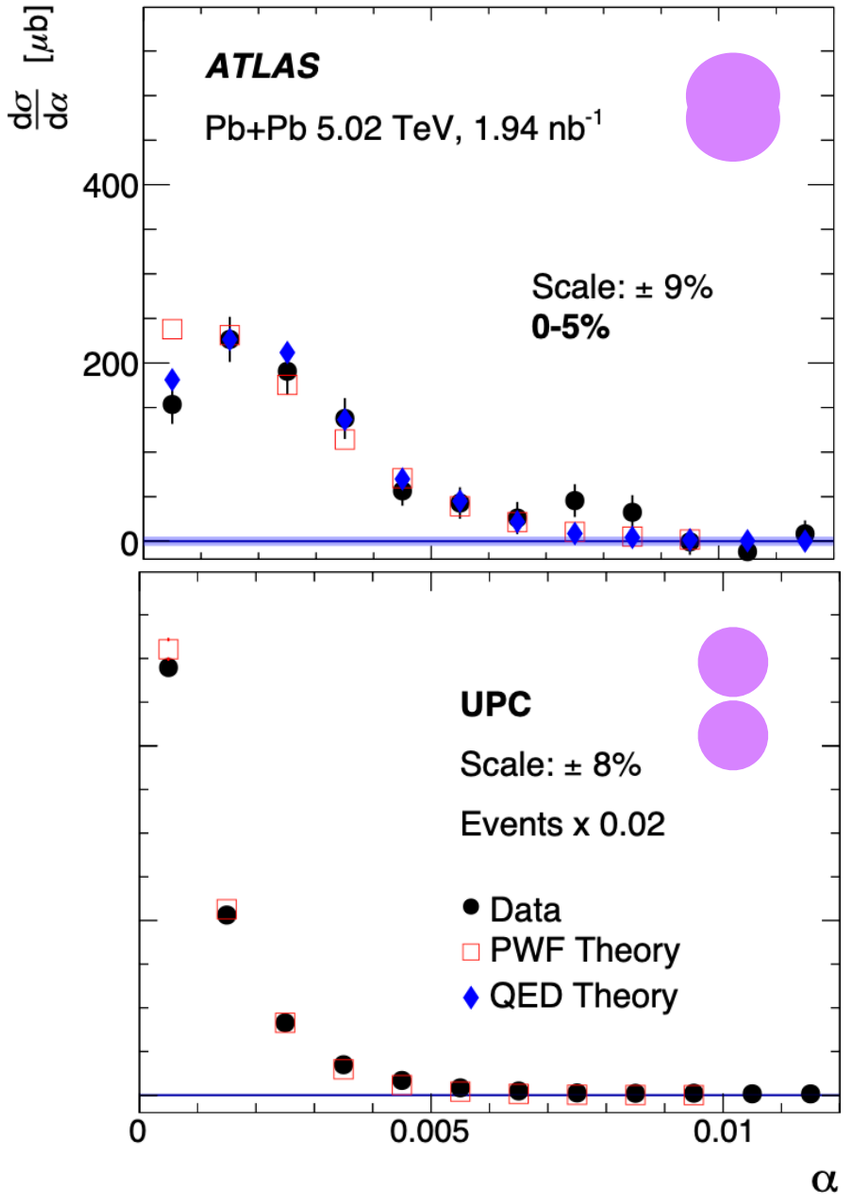
Acoplanarity: $\alpha = 1 - \frac{|\phi_1^\mu - \phi_2^\mu|}{\pi}$

Asymmetry: $A = \frac{|p_{T1}^\mu - p_{T2}^\mu|}{p_{T1}^\mu + p_{T2}^\mu}$

Transverse momentum scale:

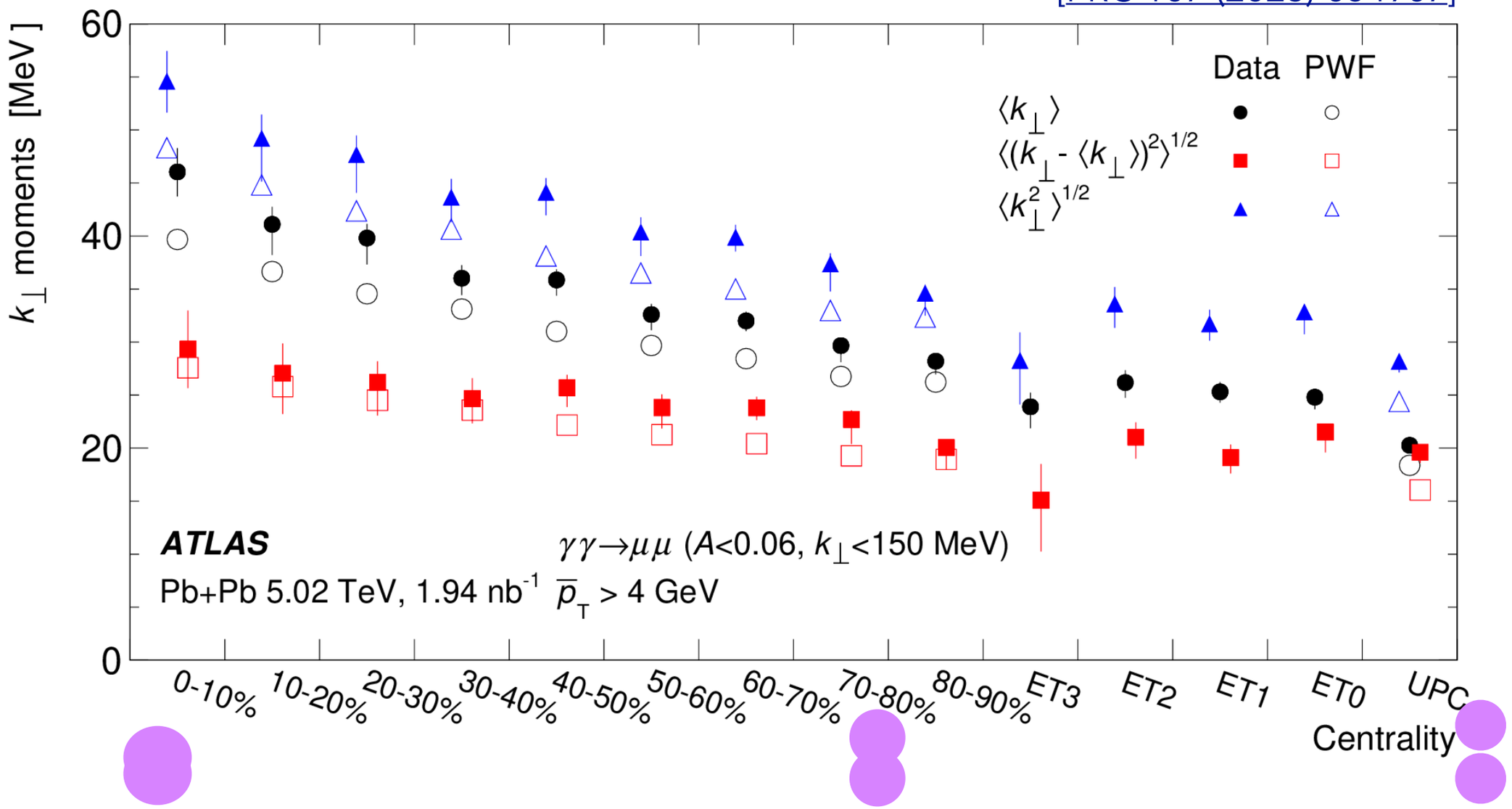
$$k_\perp = \frac{1}{2}(p_{T1}^\mu + p_{T2}^\mu)(\pi - |\phi_1^\mu - \phi_2^\mu|) = \pi\alpha\bar{p}_T$$

$= \bar{p}_T$



NON-UPC DIMUONS: MOMENTS

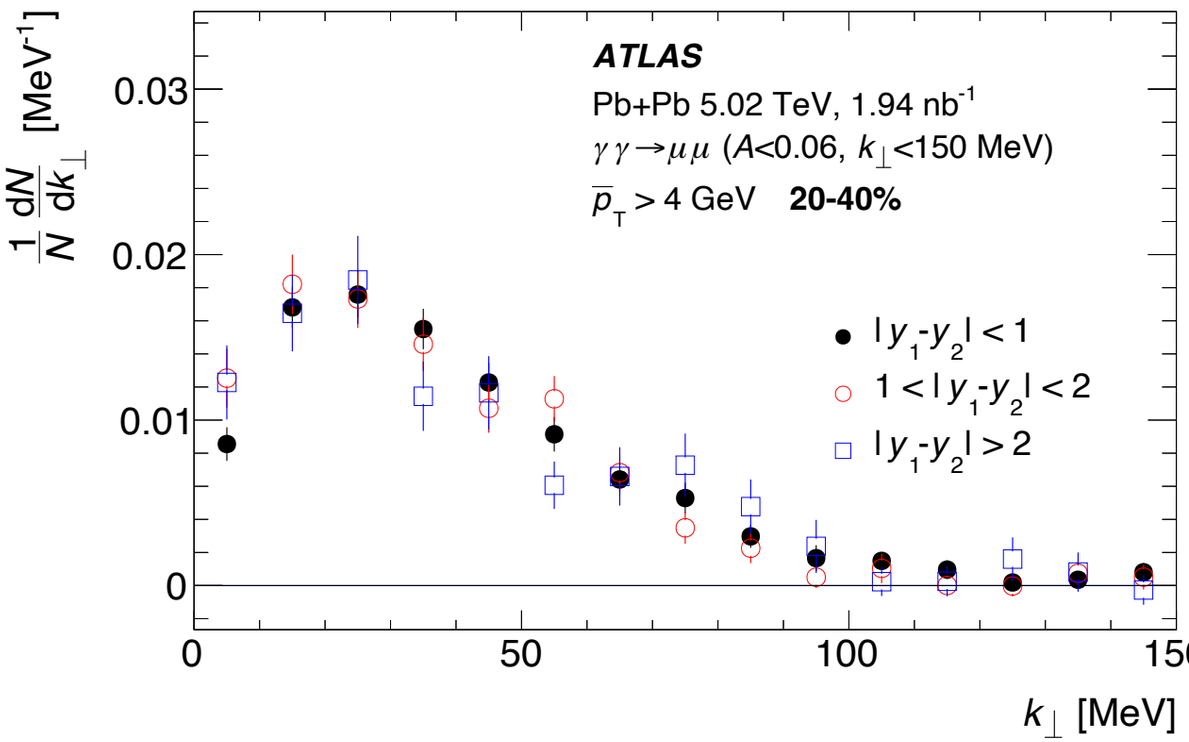
[PRC 107 (2023) 054907]

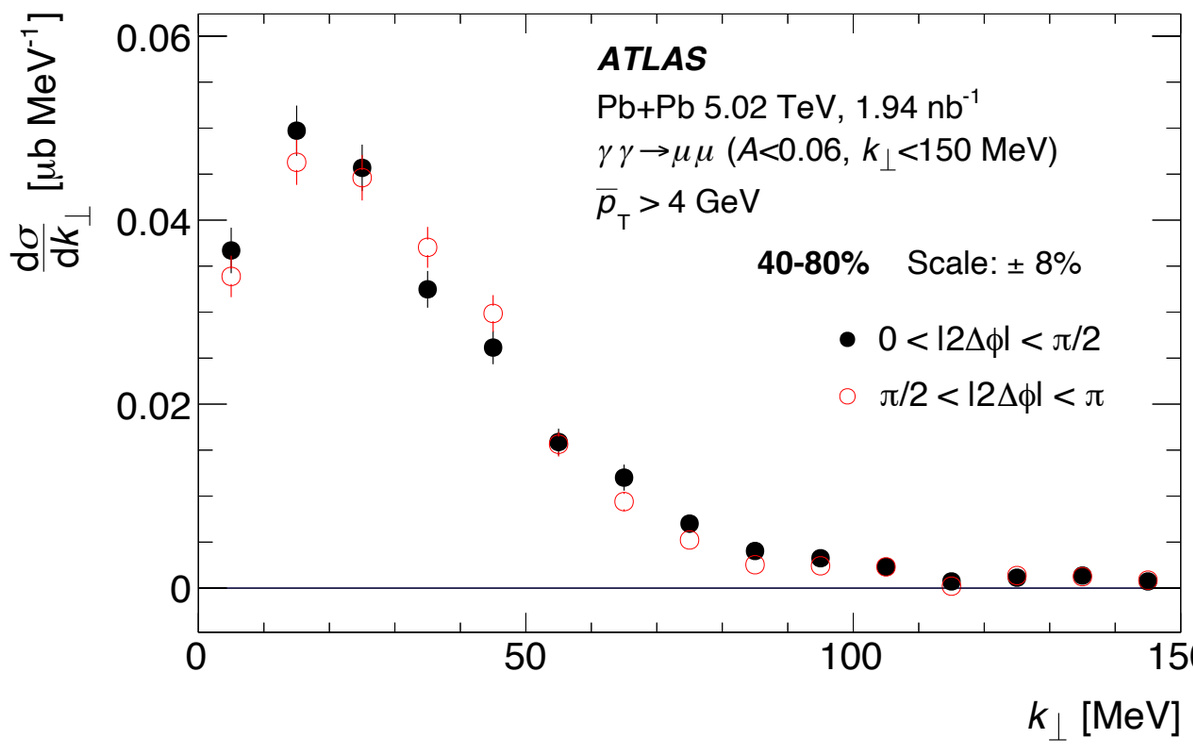


- Significant increase in the **mean** and **RMS** values is observed as one goes from UPC to higher centralities
- **Standard deviation** shows a much slower increase
- **PWF** predictions reproduce many of the trends, but the mean and RMS values systematically lie below the data

NON-UPC DIMUONS: MAGNETIC FIELD

[PRC 107 (2023) 054907]



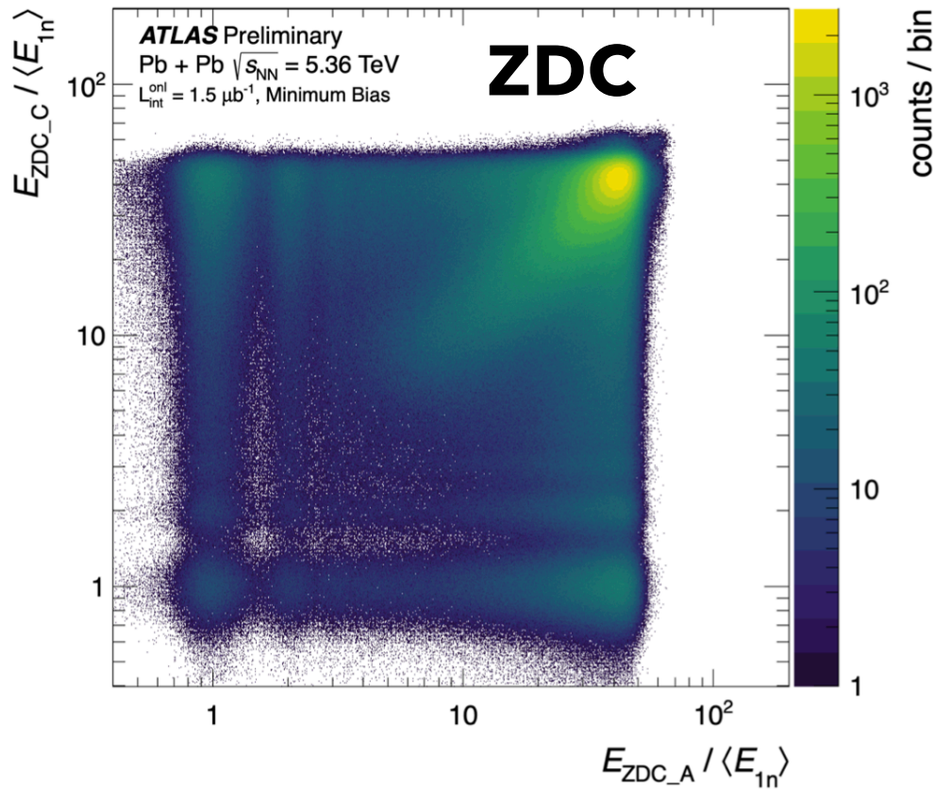


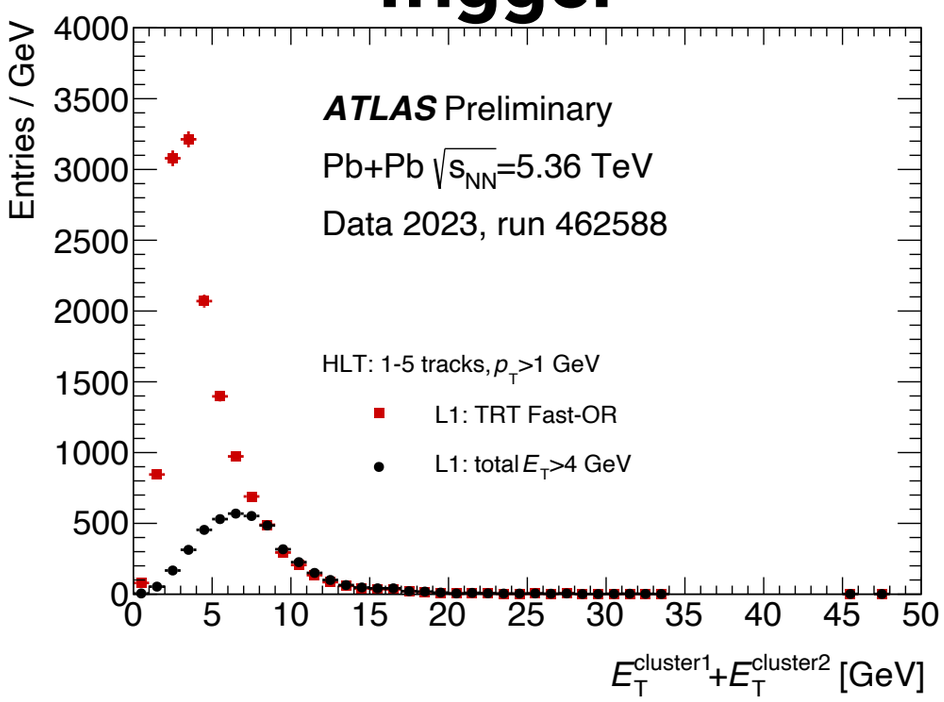
- Hypothesis of centrality-dependent broadening of $k_\perp$ in a **strong magnetic field**
  - Broadening should vary as the hyperbolic tangent of **rapidity difference** of two muons $|\Delta y| = |y_1 - y_2|$
  - $k_\perp$ distribution is supposed to depend on the orientation of muon pairs relative to the direction of the **second-order event plane** $|2\Delta\phi| = |2(\phi_{\mu\mu} - \Psi_2)|$
- Predicted trends associated with effects of **magnetic fields** on dimuons **are not observed**

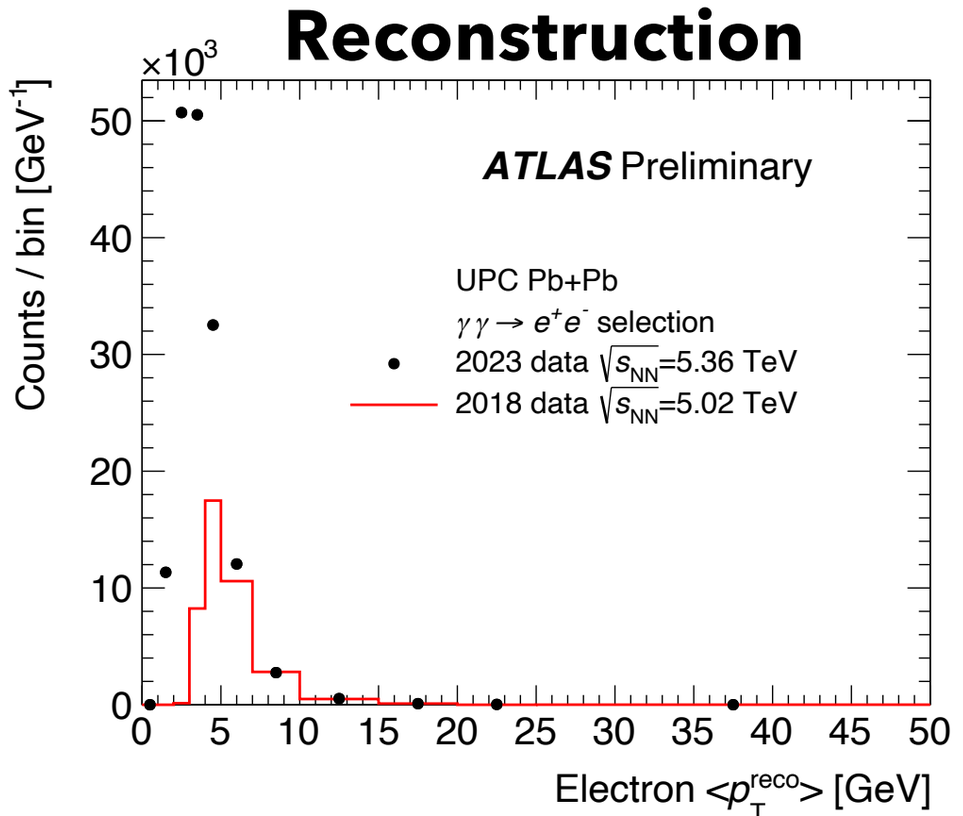
TOWARDS RUN-3 DATA ANALYSIS

- ATLAS experiment collected Pb+Pb collisions in October 2023
  - Run 2: 2.2 nb^{-1} at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
  - Run 3: 1.7 nb^{-1} at $\sqrt{s_{\mathrm{NN}}} = 5.36$ TeV
  - **Readout** and **trigger upgrade** of **ZDC**
  - Improved **trigger** strategies for low-p_{T} particles
  - Significant improvements in low-p_{T} **electron reconstruction**
  - Provide access to electrons with $p_{\mathrm{T}} > 1$ GeV

[HION-2023-001]







SUMMARY AND OUTLOOK

- ATLAS provides **precision results** on $\gamma\gamma \to \ell^+\ell^-$ with $\ell = e, \mu, \tau$ from UPC Pb+Pb collisions recorded in Run 2
  - **Measured cross sections** reveal systematic differences with **STARlight** and **SuperChic** calculations
    - Perhaps suggesting higher order Coulomb effects need to be considered [JHEP 2021 (2021) 83]
  - **ZDC** provides constraints for **background** and **impact-parameter dependence**
  - Establish a **reference** for **non-UPC** studies and rare processes (e.g. light-by-light)
- ATLAS established **observation** of exclusive **ditau** production in UPC Pb+Pb collisions at the LHC with above 5σ **significance**
  - Data is used to **constrain** a_τ at the LHC with a **precision comparable** to the best limit from **DELPHI**
- $\gamma\gamma \to \mu^+\mu^-$ process is used to probe **non-UPC collisions** with high precision
  - **Broadening** of acoplanarity and transverse momentum scale distributions with centrality confirmed
  - Also significant **depletion** at close-to-zero α and $k_\perp$ values with centrality is established
  - **Initial-state calculations** quantitatively describe many features
- **Run 3** is in progress, new 2023 Pb+Pb data set collected at $\sqrt{s_{\mathrm{NN}}} = 5.36\ \mathrm{TeV}$ is on tape
  - **Significant improvements** in instrumentation, trigger and reconstruction efficiency at low-p_T for leptons

- All results from ATLAS available at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

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