

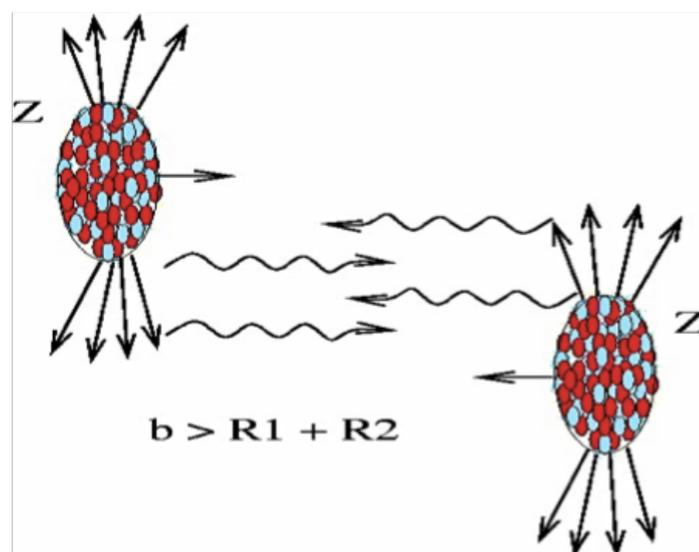


Recent measurements of photon-induced processes in ultra-peripheral collisions of Pb+Pb with the ATLAS detector

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(AGH University of Kraków)*

*XVI Polish Workshop on Relativistic Heavy-Ion Collisions
Kielce, December 2nd, 2023*





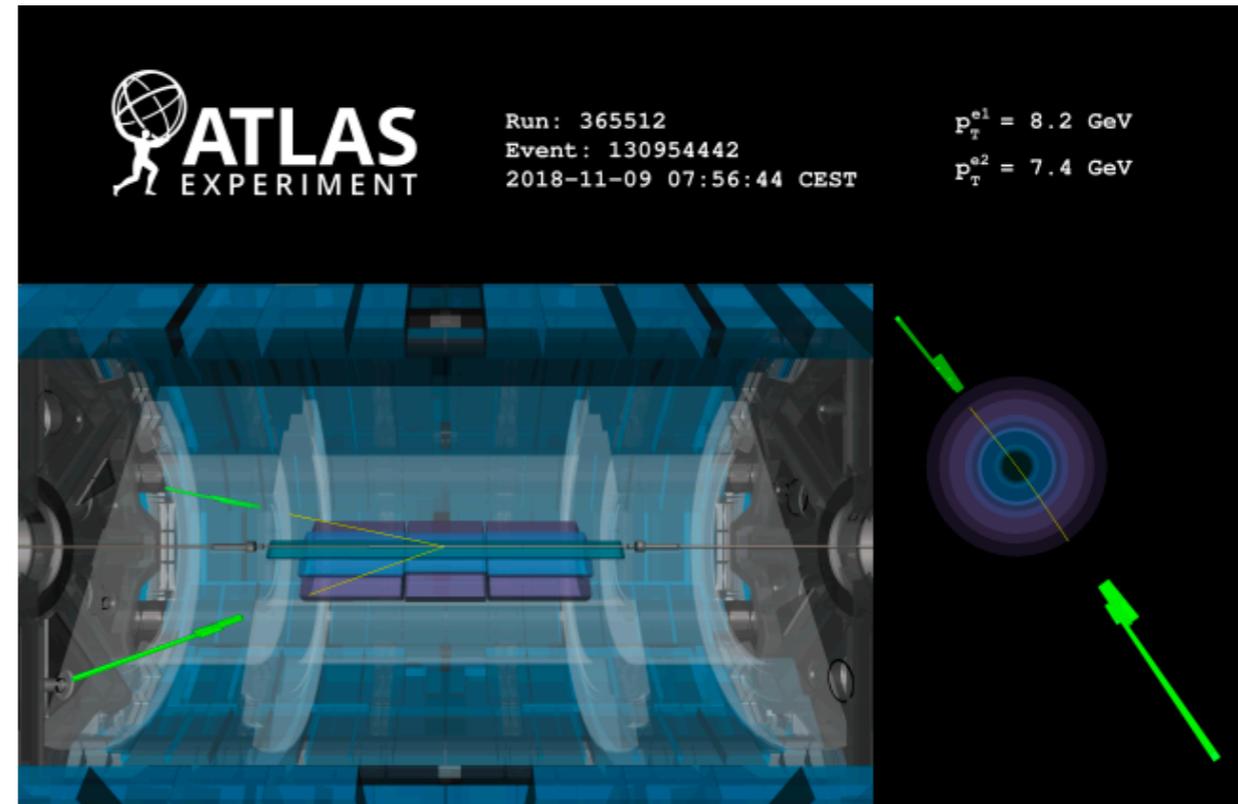
- **Ultra-peripheral collisions (UPC)** of lead-lead (Pb+Pb) have attracted a lot of attention in the heavy-ion community
 - Very clean environment to study **quantum electrodynamics (QED)** and **photon fluxes** within the Equivalent Photon Approximation (EPA) framework
 - $Z^4 (\approx 4.5 \times 10^7)$ **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** $\gamma\gamma \rightarrow \mu^+\mu^-$ events seem to be a **new probe** of the QGP
- The following results from 5.02 TeV UPC Pb+Pb collisions from **ATLAS** are discussed:
 - **Final** $\gamma\gamma \rightarrow \mu^+\mu^-$ [[PRC 104 \(2021\) 024906](#)]
 - **Final** $\gamma\gamma \rightarrow e^+e^-$ [[JHEP 06 \(2023\) 182](#)]
 - **Final** $\gamma\gamma \rightarrow \tau^+\tau^-$ [[PRL 131 \(2023\) 151802](#)]
 - **Final** non-UPC $\gamma\gamma \rightarrow \mu^+\mu^-$ [[PRC 107 \(2023\) 054907](#)]

EXCLUSIVE DIMUONS AND DIELECTRONS

$$\gamma\gamma \rightarrow \mu^+\mu^- \quad \gamma\gamma \rightarrow e^+e^-$$

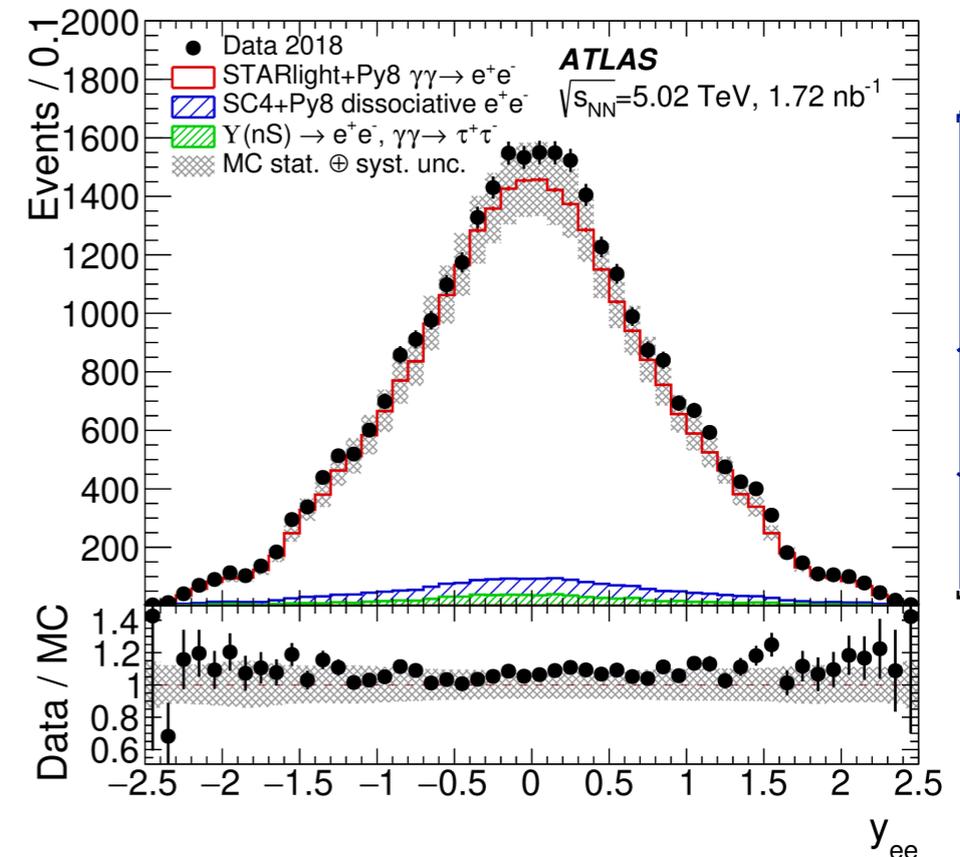
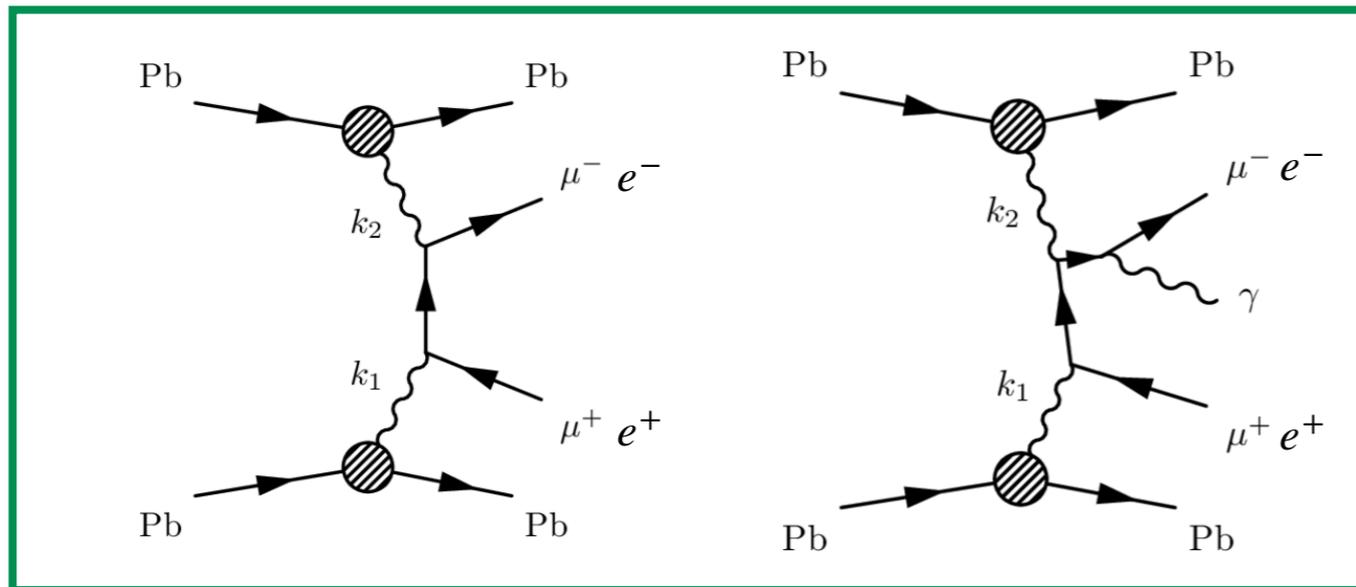
Data	2015	2018
Int lumi	0.48 nb ⁻¹	1.72 nb ⁻¹
Fiducial	$p_T^\mu > 4 \text{ GeV}$ $ \eta^\mu < 2.4$ $m_{\mu\mu} > 10 \text{ GeV}$ $p_T^{\ell\ell} < 2 \text{ GeV}$	$p_T^e > 2.5 \text{ GeV}$ $ \eta^e < 2.5$ $m_{ee} > 5 \text{ GeV}$
Event candidates	12k	30k

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



Background Dissociative LPair (3%) Dissociative SuperChic v4.0 (4%)

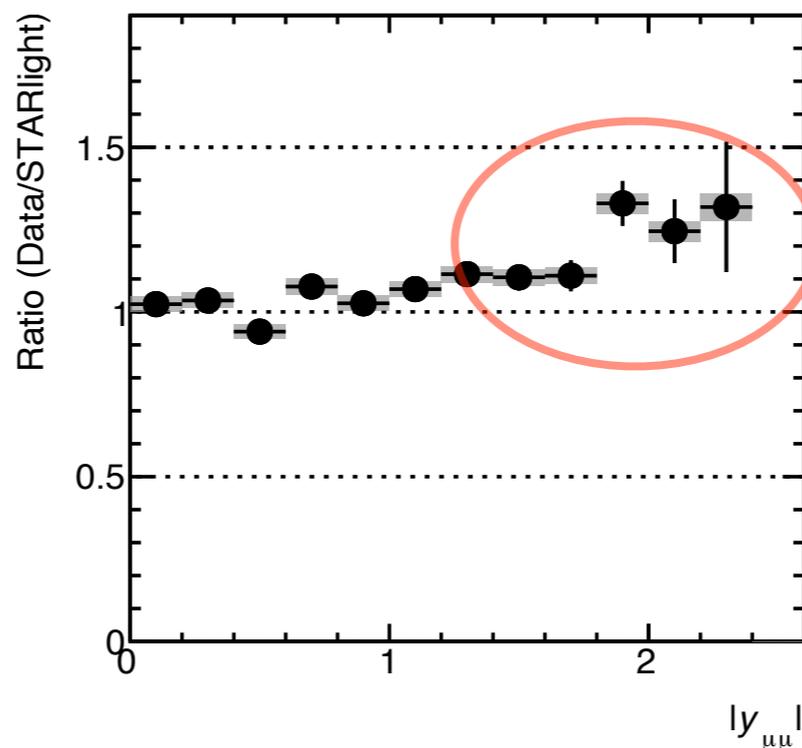
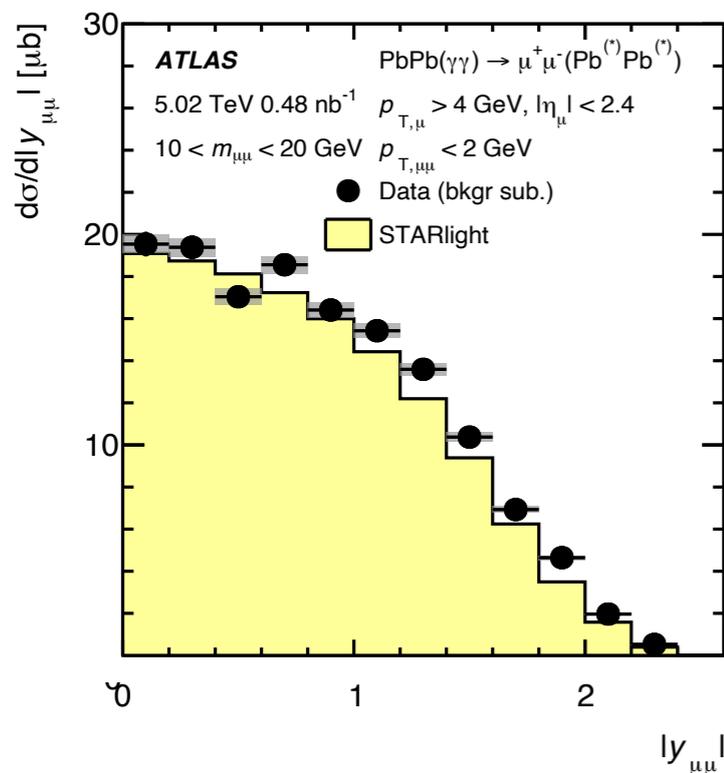
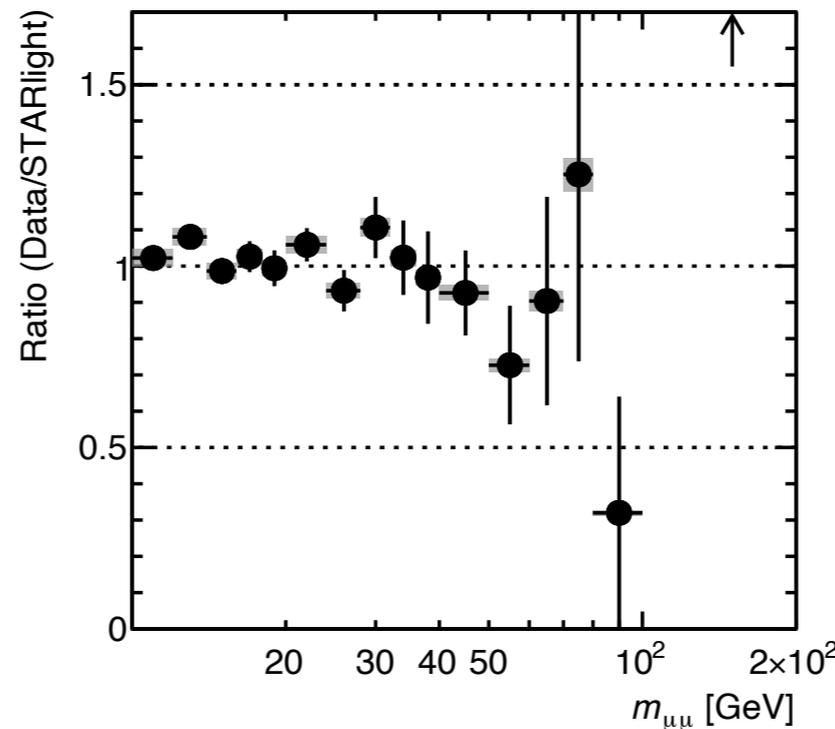
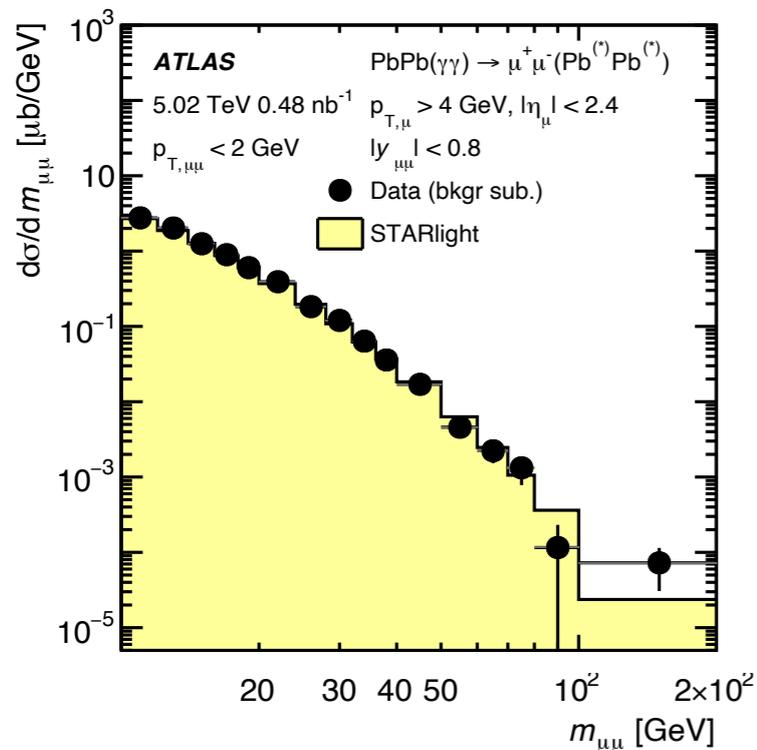
Signal



[JHEP 06 (2023) 182]

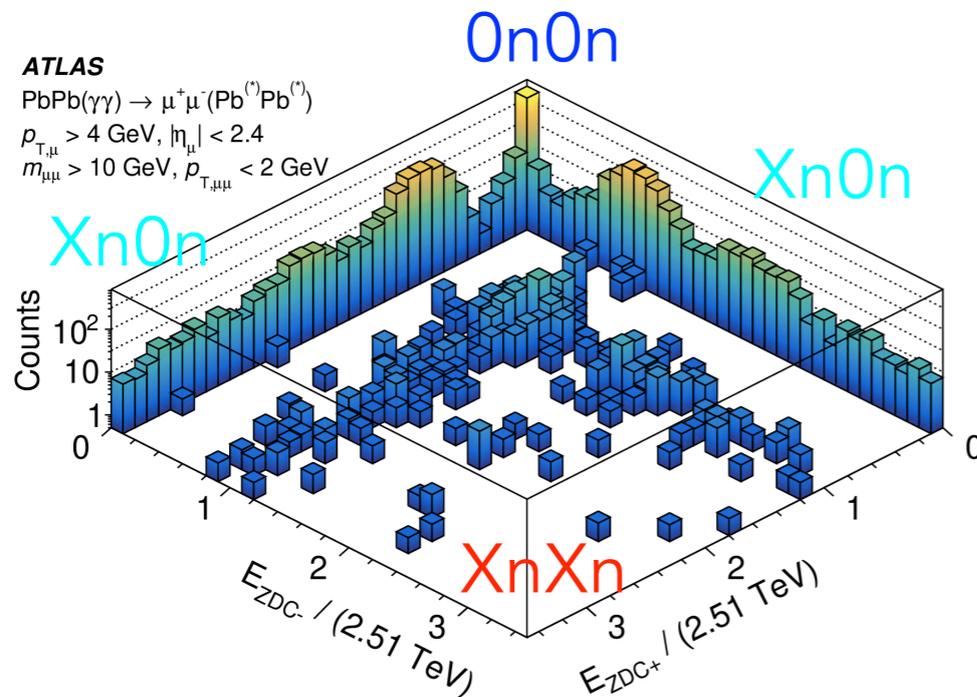
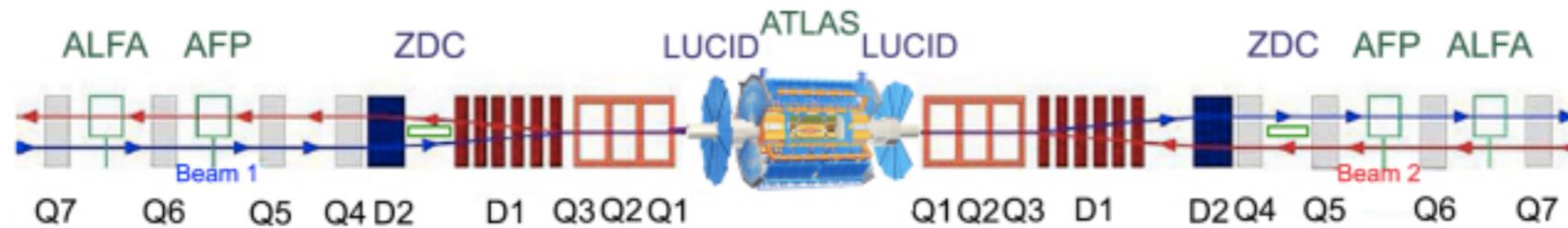
EXCLUSIVE DIMUONS: DIFFERENTIAL CROSS SECTIONS

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

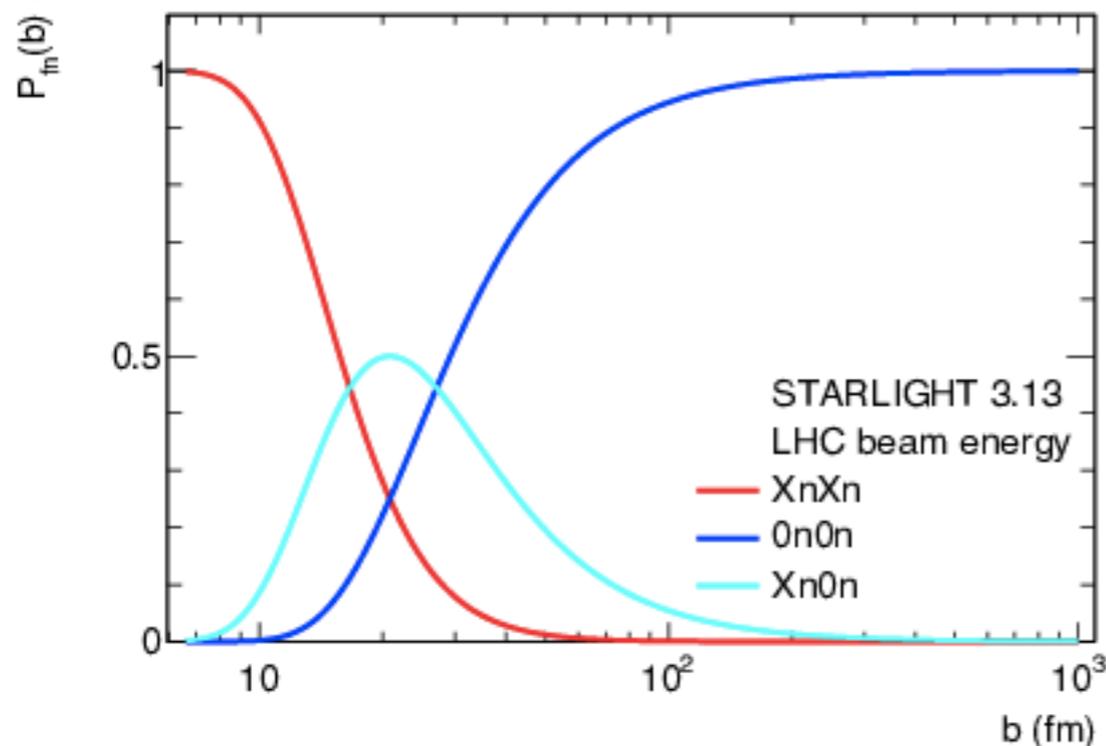


- Differential cross sections studied in $m_{\mu\mu}$, $|y_{\mu\mu}|$, dilepton scattering angle ($|\cos \theta^*|$), photon energy (k_{\min}, k_{\max}) and acoplanarity (α)
- $m_{\mu\mu}$ measured up to 200 GeV
- **Good agreement** with STARlight 2.0
- ... but **systematic excess** of the data at higher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

EXCLUSIVE DILEPTONS: ACTIVITY IN ZDC

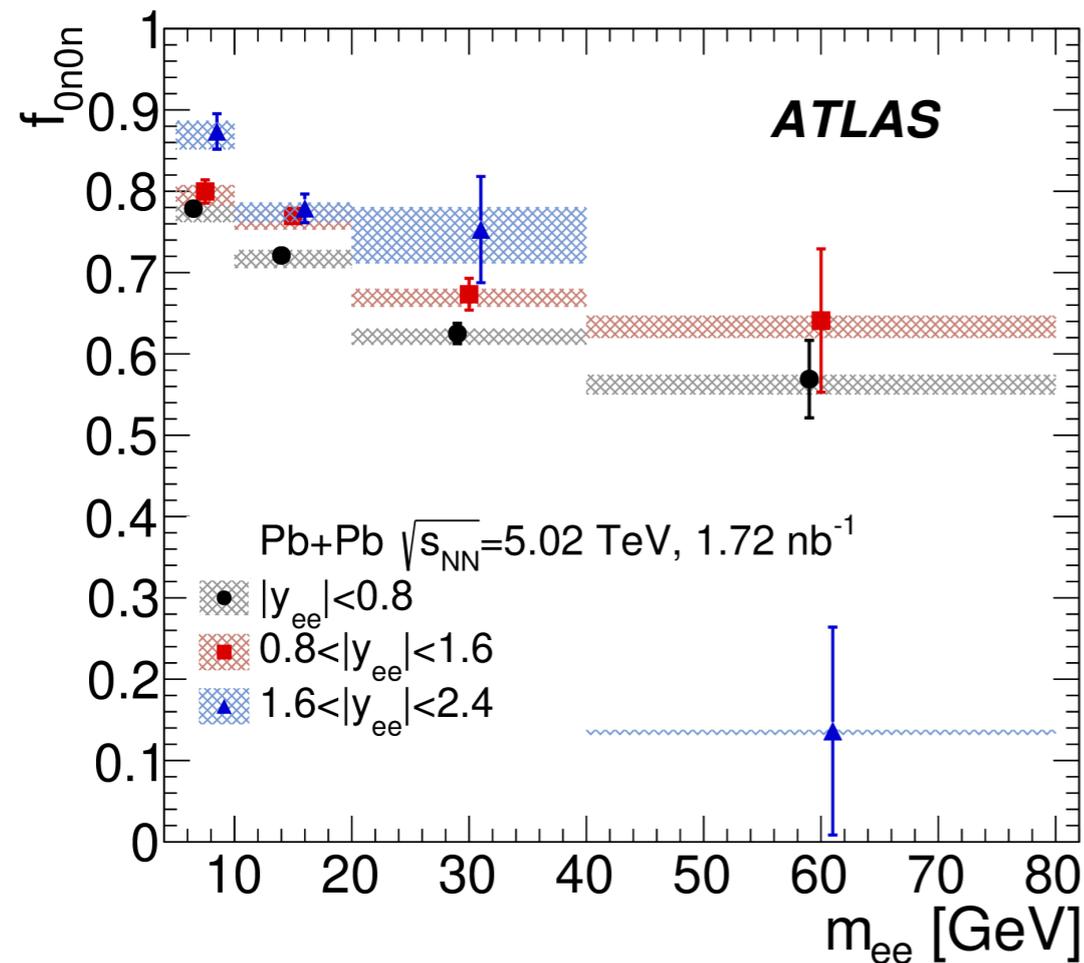


[[Ann.Rev.Nucl.Part.Sci. 70 \(2020\) 323-354](#)]

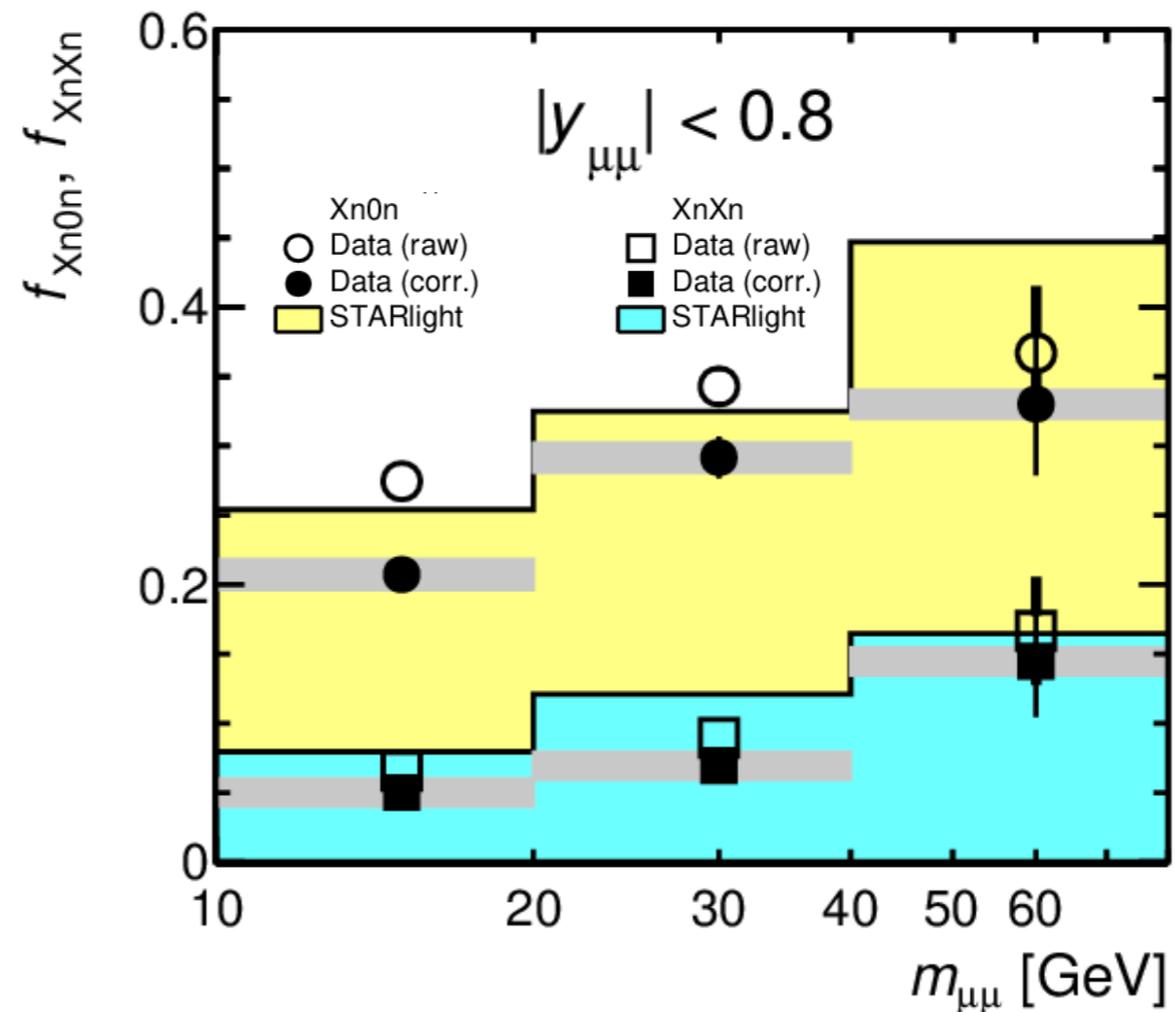


- **ZDC** are 140 m away from the IP ($|\eta| > 8.3$)
 - Detect neutral particles (e.g. neutrons, photons)
- Inclusive sample of $\gamma\gamma \rightarrow \ell^+\ell^-$ is divided into three categories
 - **0n0n**: no activity in neither ZDC arm
 - **Xn0n**: activity in one ZDC arm
 - **XnXn**: activity 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)

Dielectrons [JHEP 06 (2023) 182]



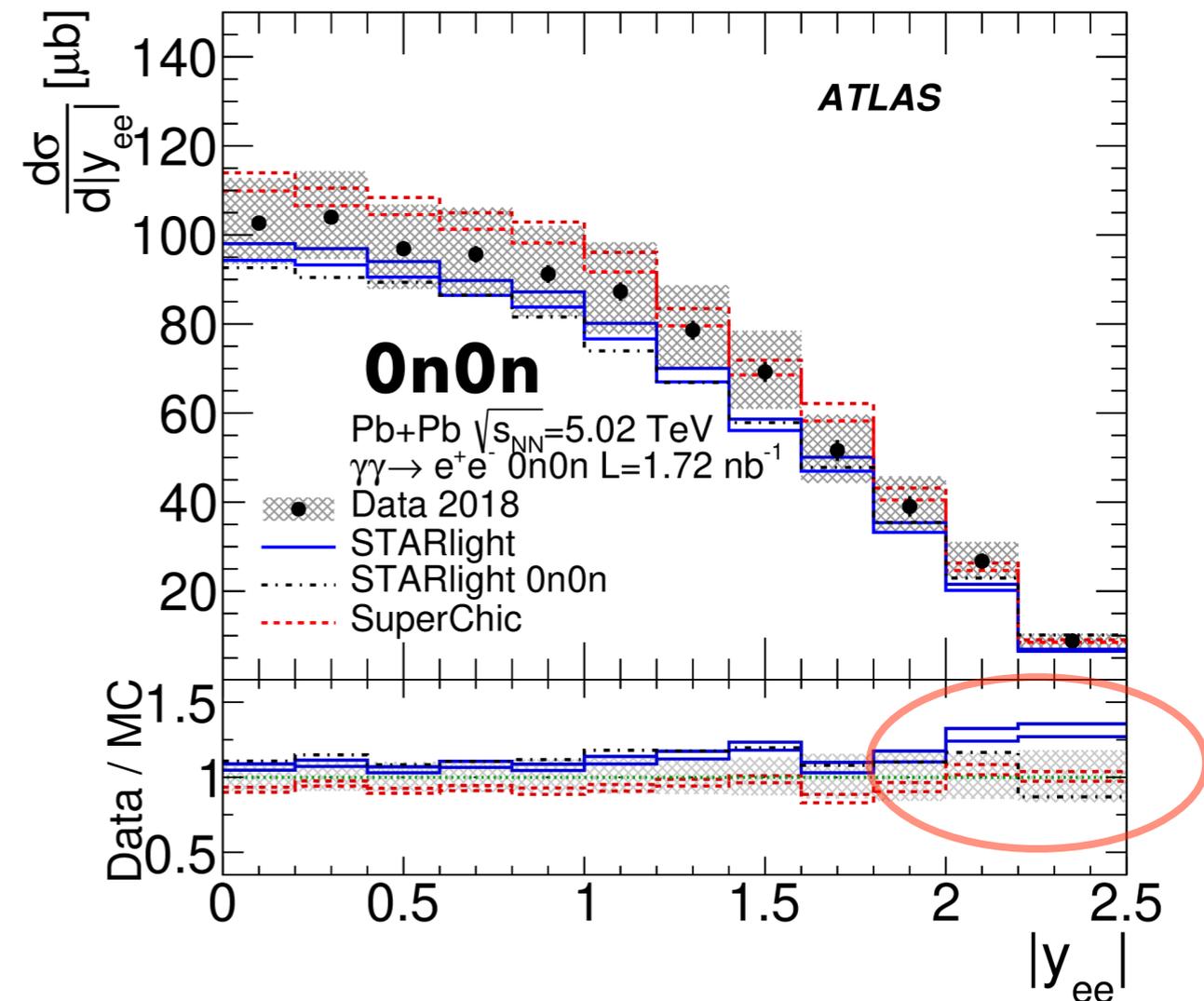
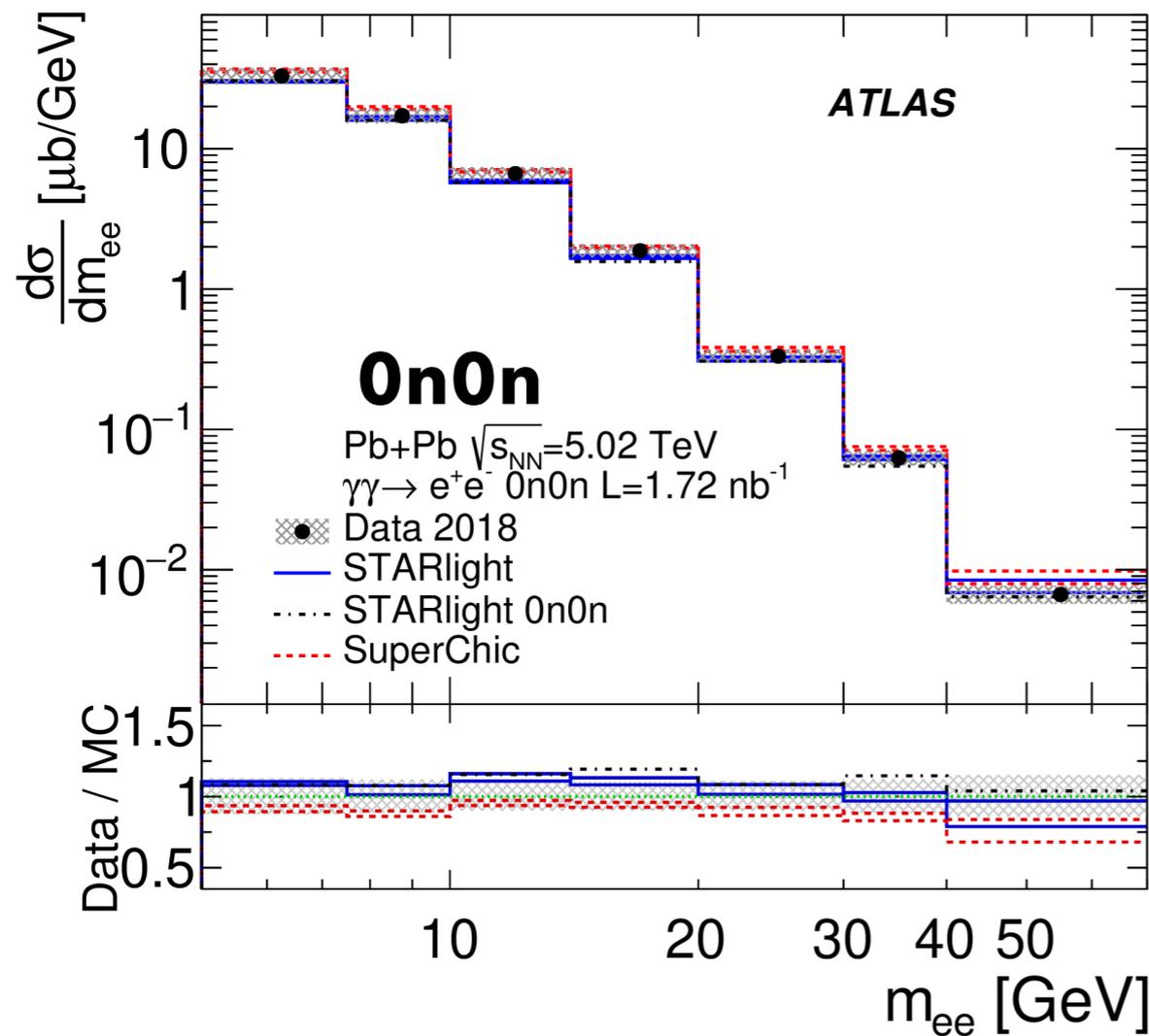
Dimuons [PRC 104 (2021) 024906]



- **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

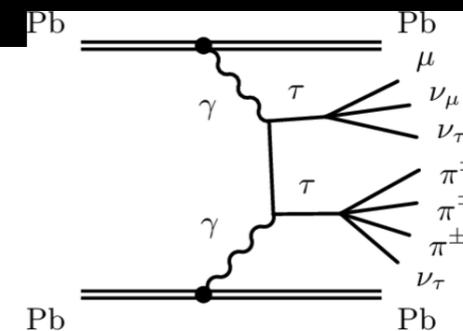
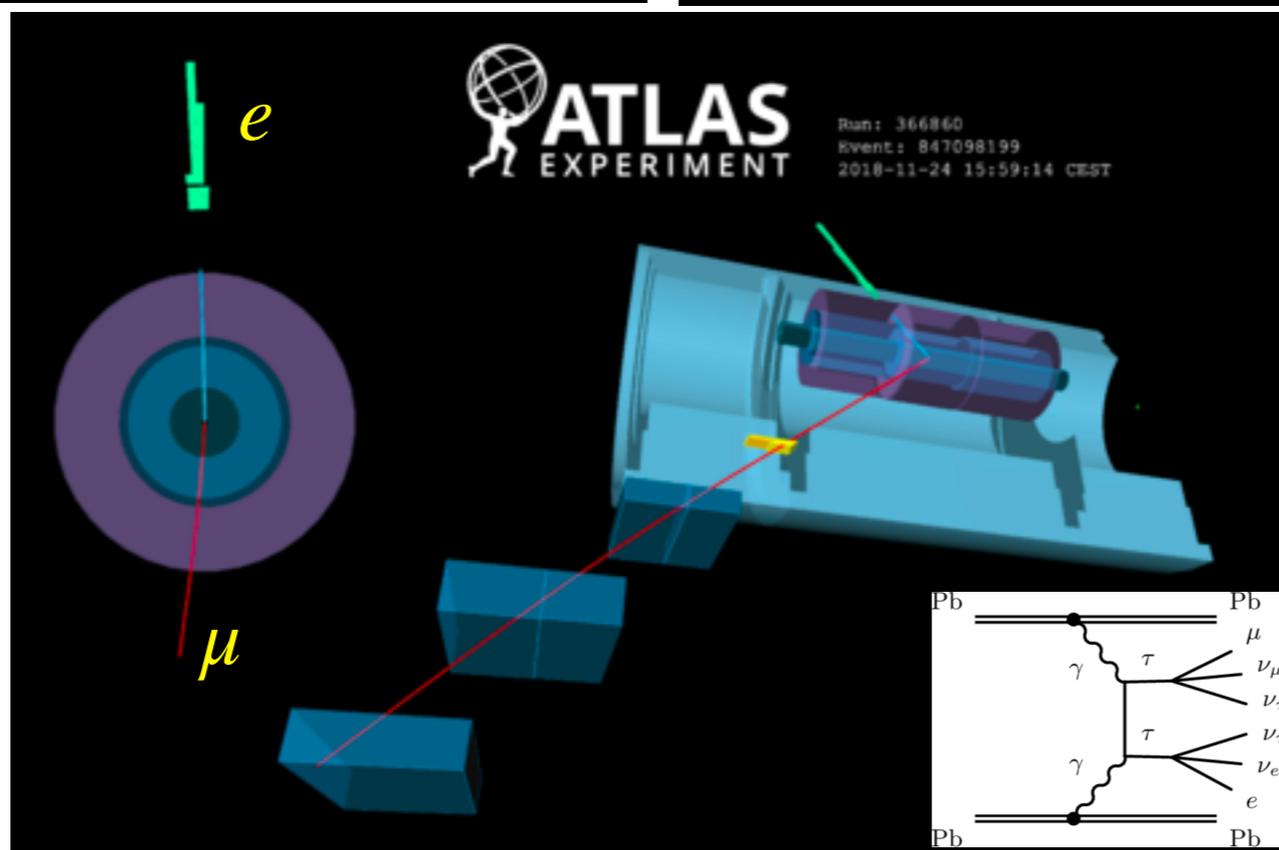
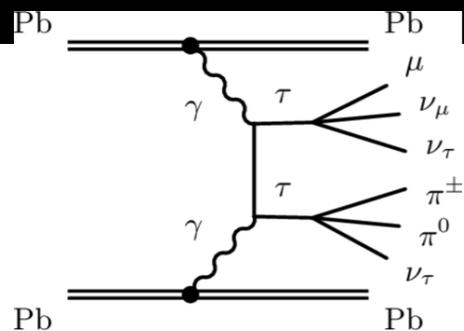
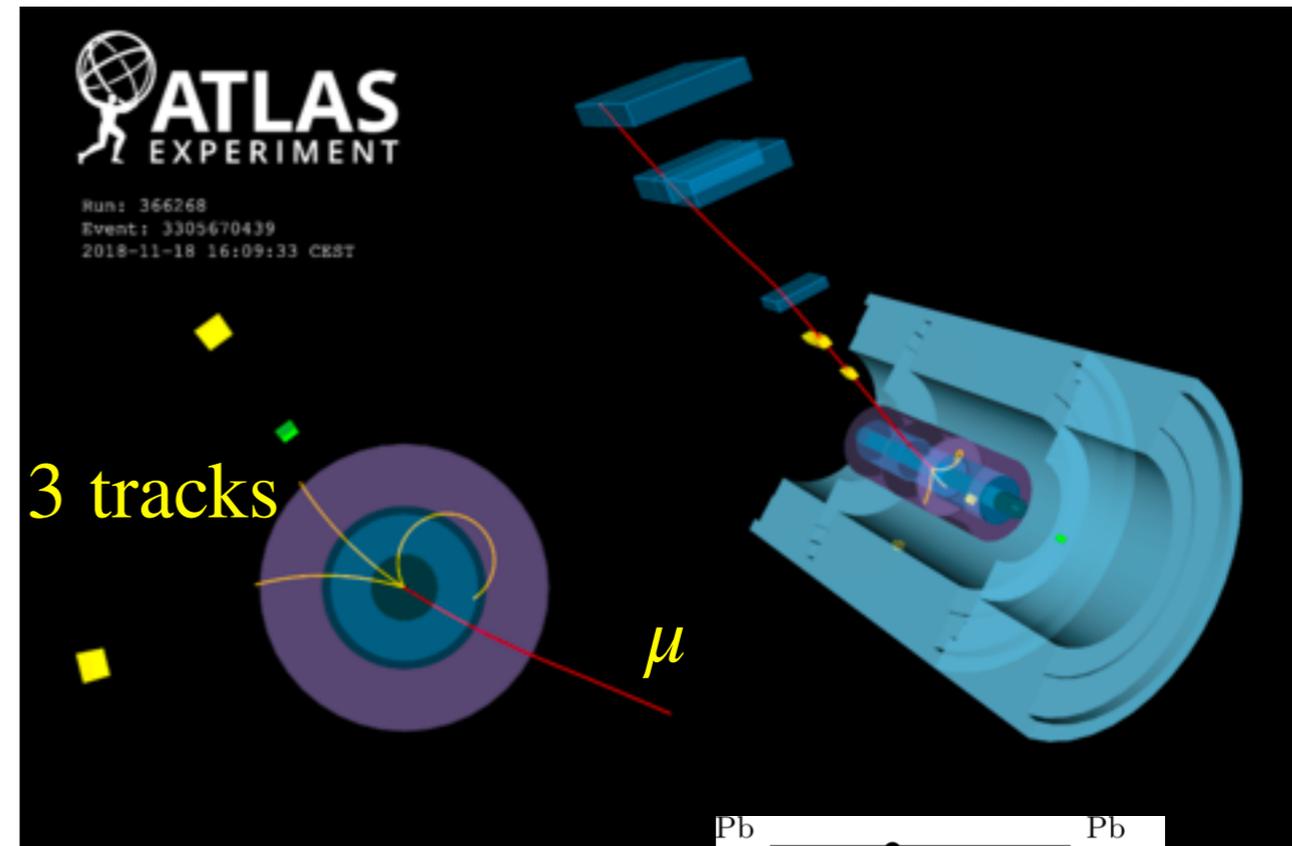
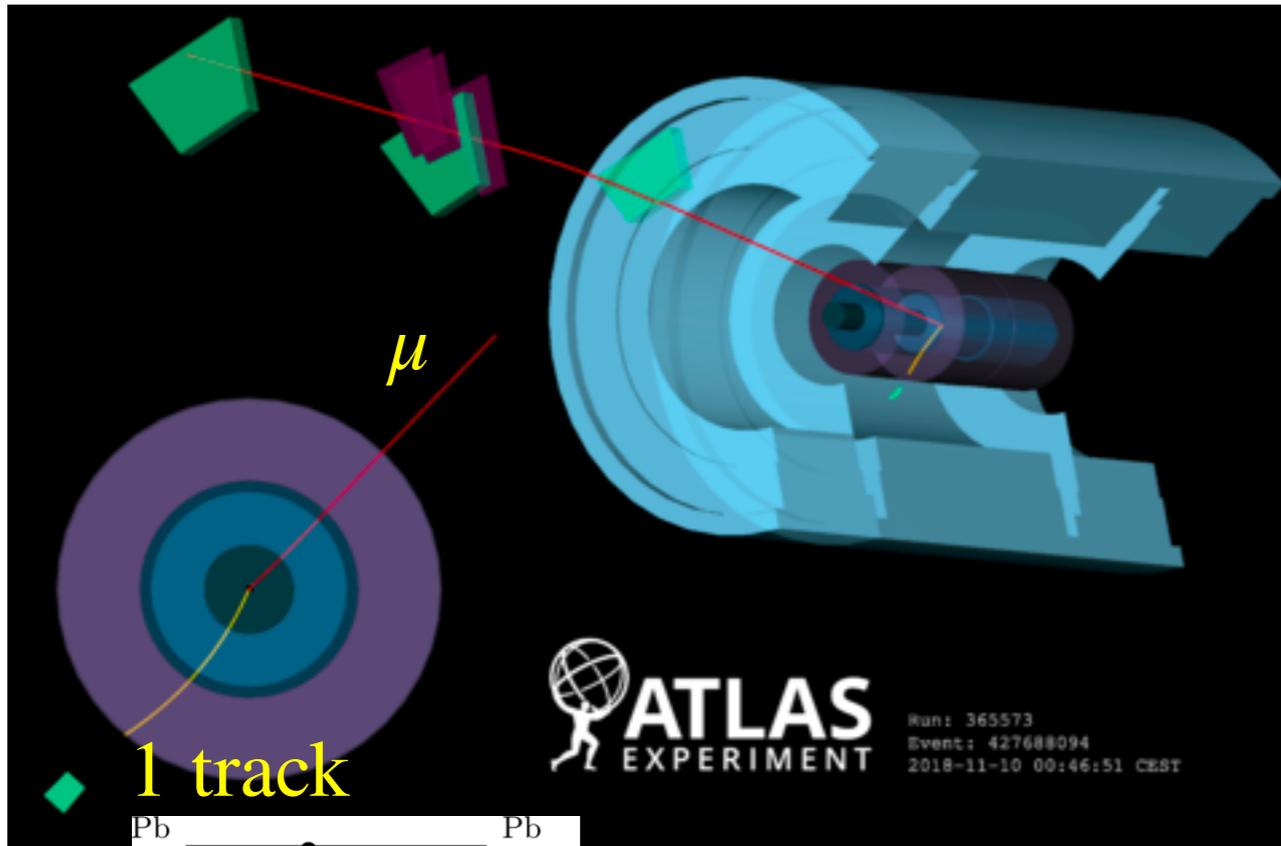
EXCLUSIVE DIELECTRONS: CROSS SECTIONS

[JHEP 06 (2023) 182]



- Differential cross sections measured in m_{ee} , $|y_{ee}|$, $\langle p_T^e \rangle$ and $|\cos \theta^*|$ inclusive and in the **0n0n category**
 - **STARlight 0n0n** provides predictions for **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 2.4 (SuperChic 3.05)** systematically lower (higher) than data
 - SuperChic does a better job in the description of shapes

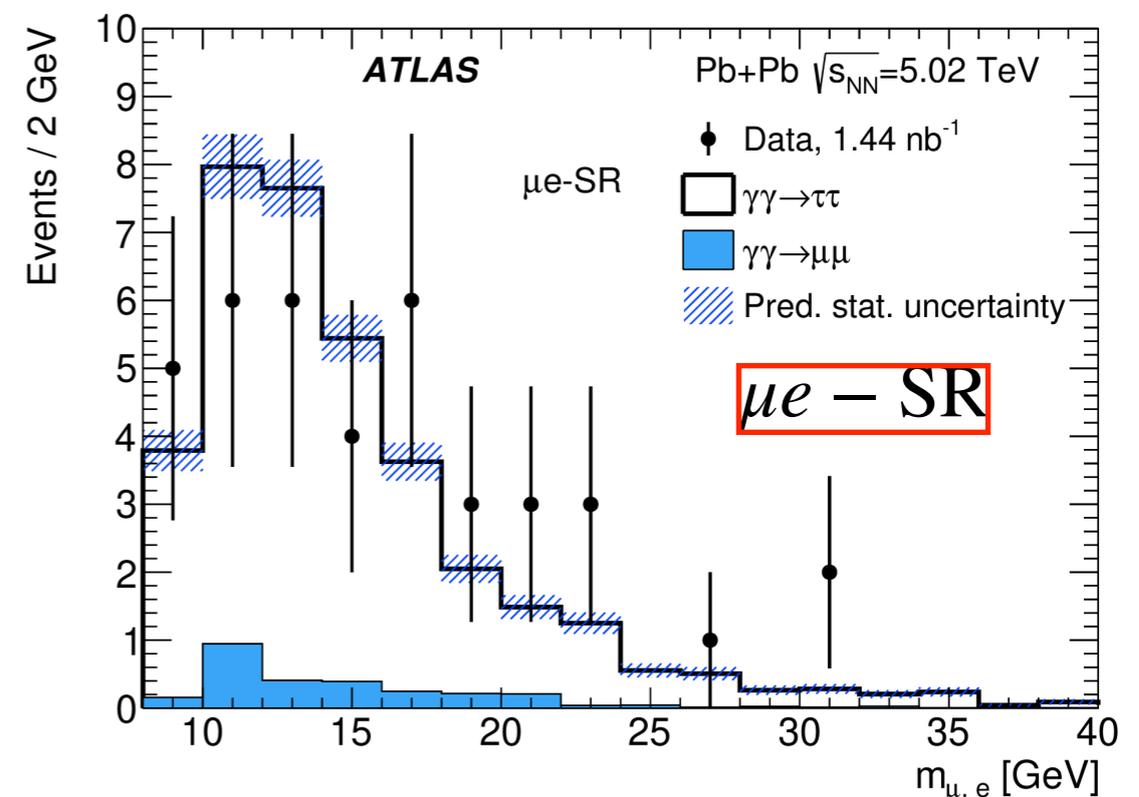
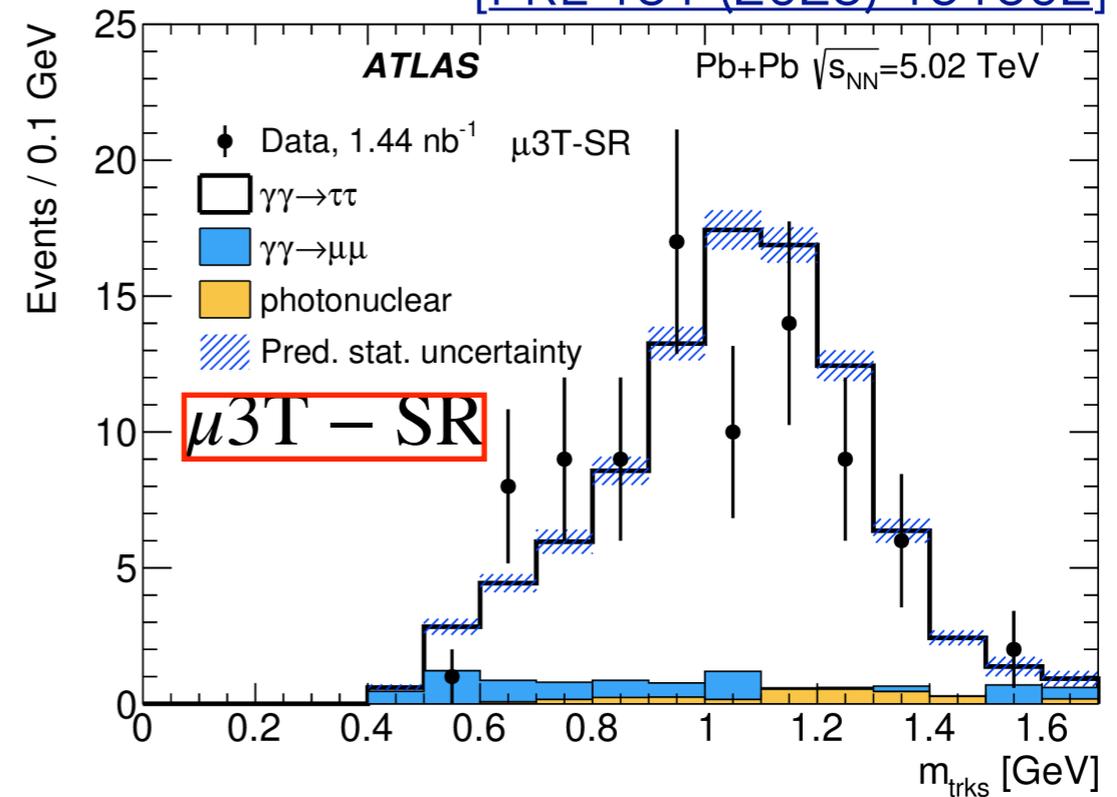
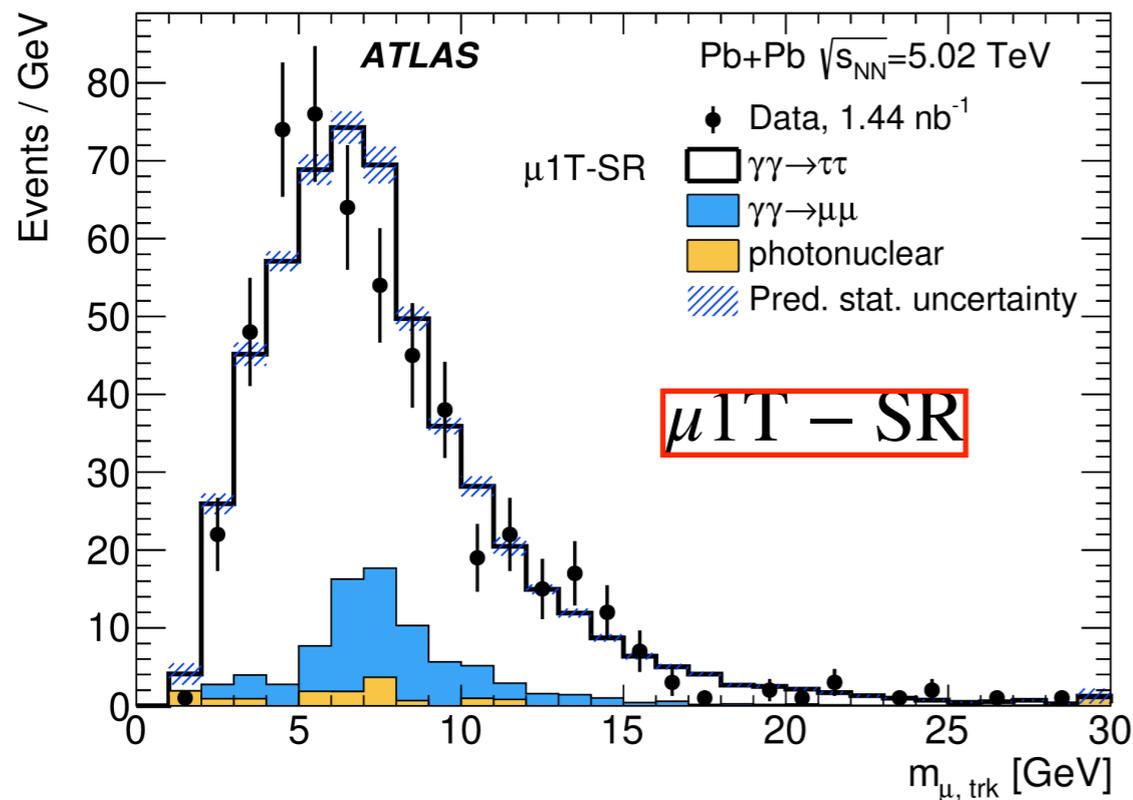
EXCLUSIVE DITAU



➤ Event candidates for $\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow \mu^\pm\nu_\mu\nu_\tau$ hadronic or $\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow \mu^\pm\nu_\mu\nu_\tau e^\pm\nu_e\nu_\tau$

EXCLUSIVE DITAU: CONTROL PLOTS

[PRL 131 (2023) 151802]

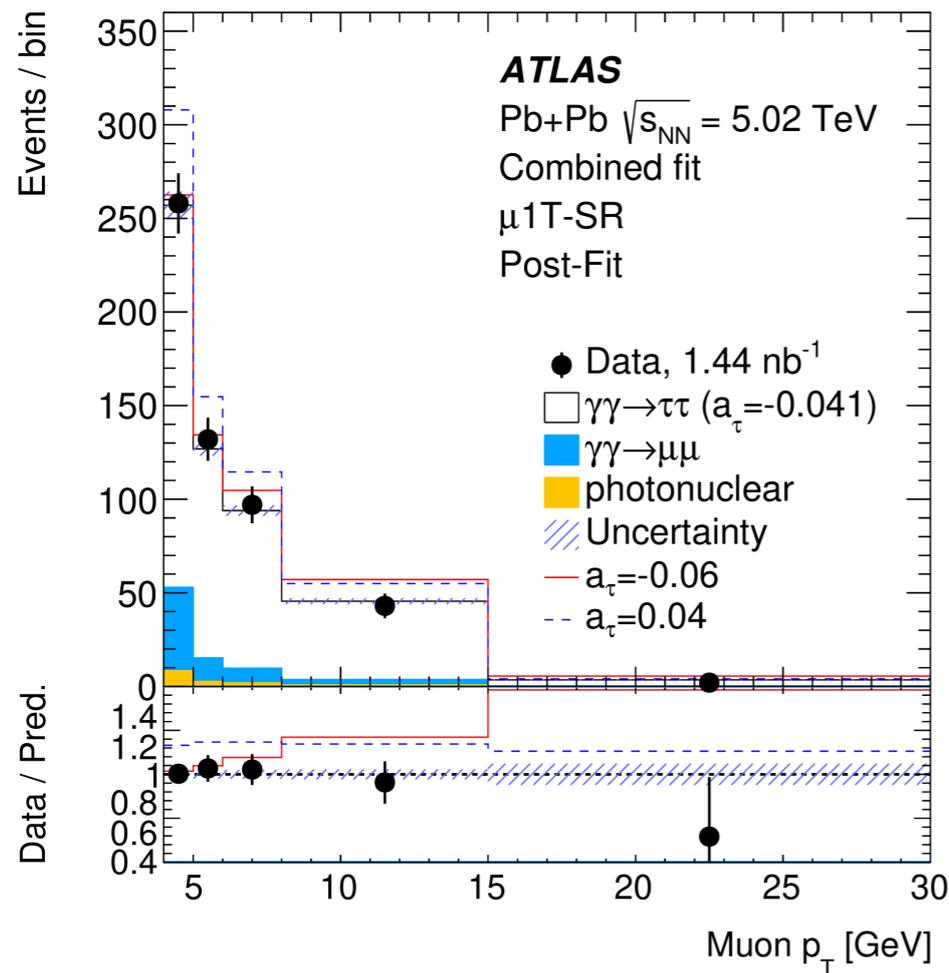


- $\gamma\gamma \rightarrow \tau^+\tau^-$ measured in **three channels**:
 - $\mu 1T-SR$: muon + 1 track (e/ μ /hadron)
 - $\mu 3T-SR$: muon + 3 tracks (3 hadrons)
 - $\mu e-SR$: muon + electron
- About **650 event** candidates
- Main backgrounds:
 - $\gamma\gamma \rightarrow \mu^+\mu^-(\gamma)$ and photonuclear
 - In general little background contributions in all three SR (15%)
- **Good agreement** of SM predictions with data

EXCLUSIVE DITAU: SIGNAL STRENGTH

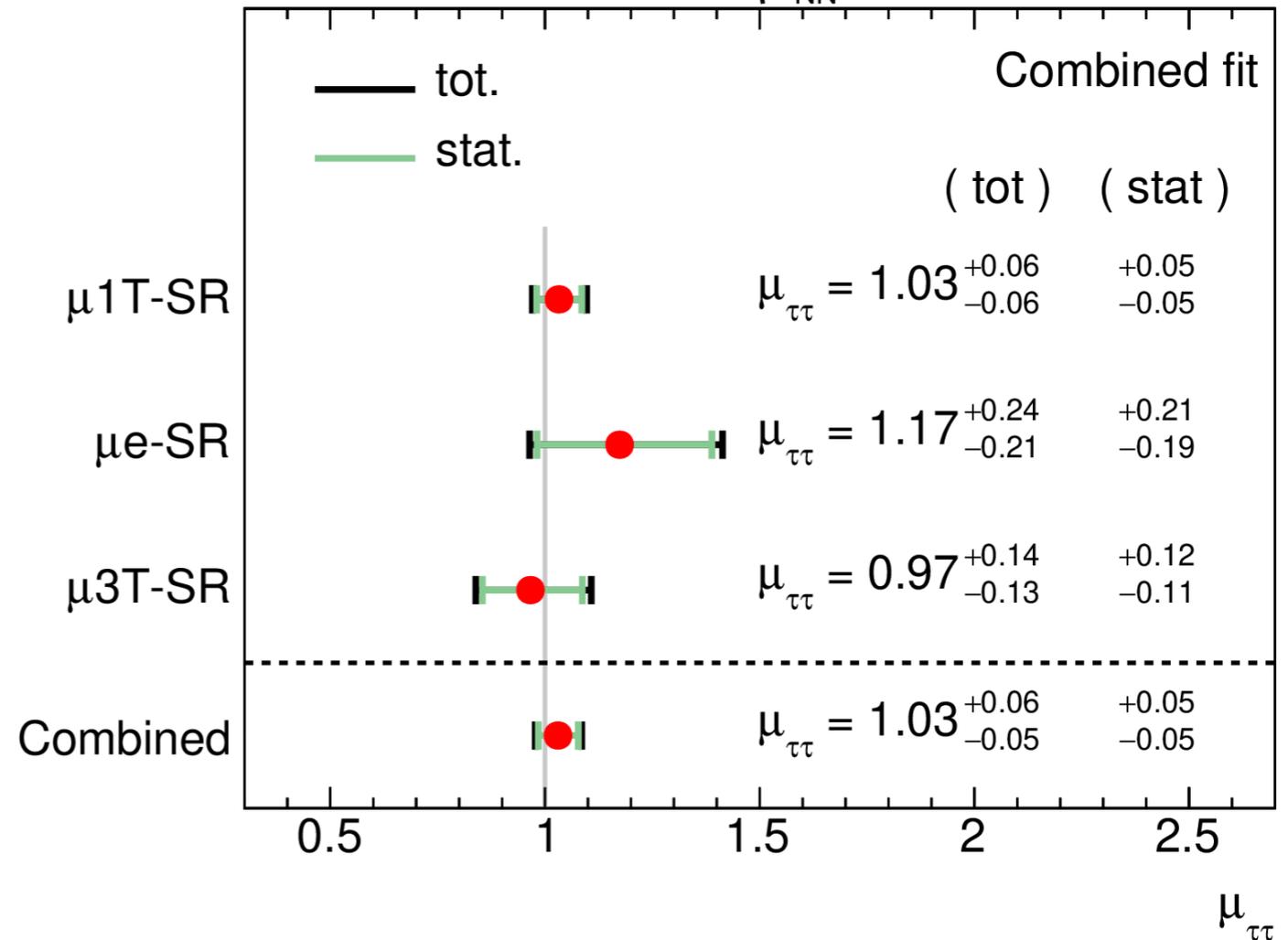
[PRL 131 (2023) 151802]

μ_{1T-SR}



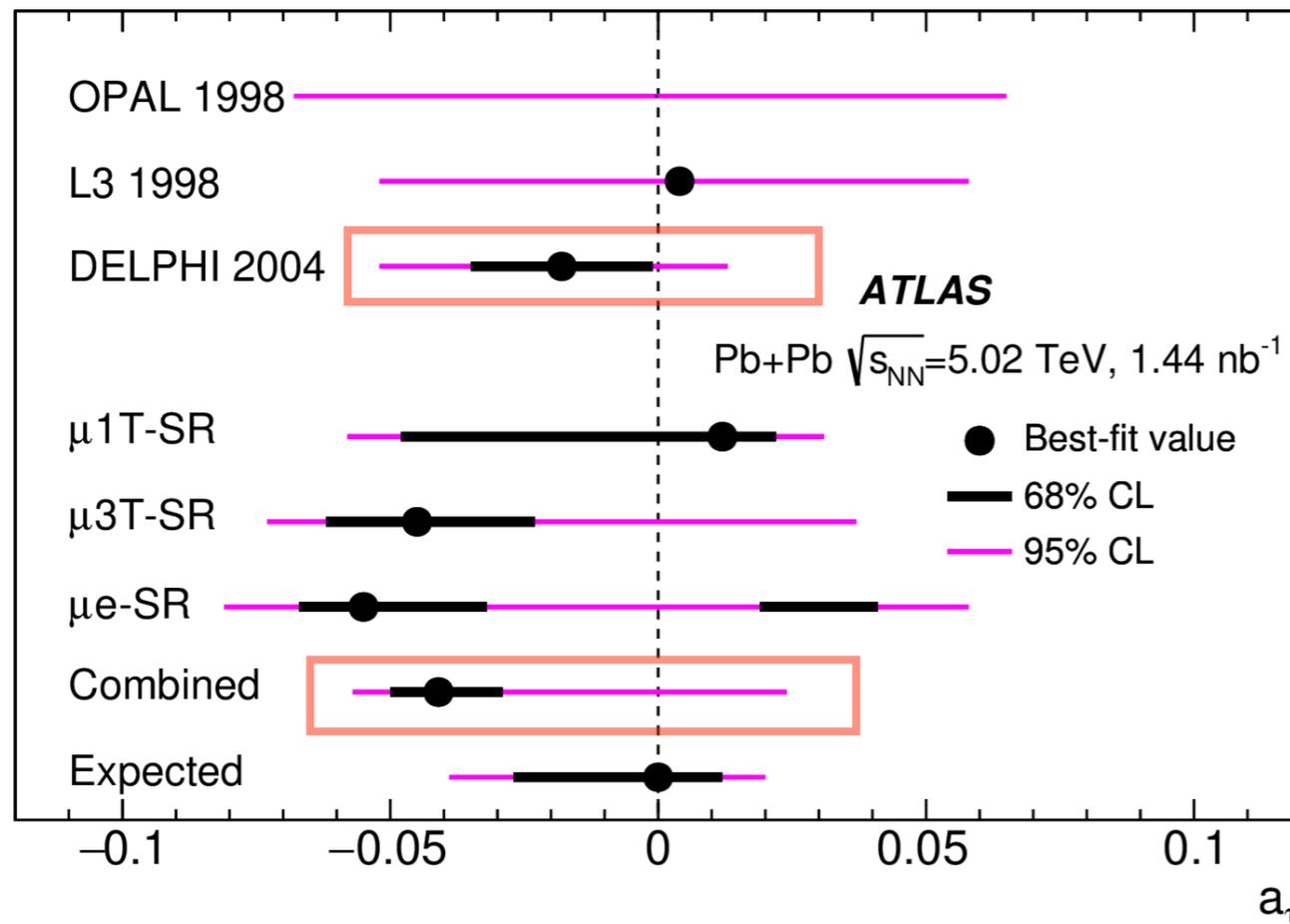
ATLAS

Pb+Pb $\sqrt{s_{NN}} = 5.02$ TeV, 1.44 nb^{-1}



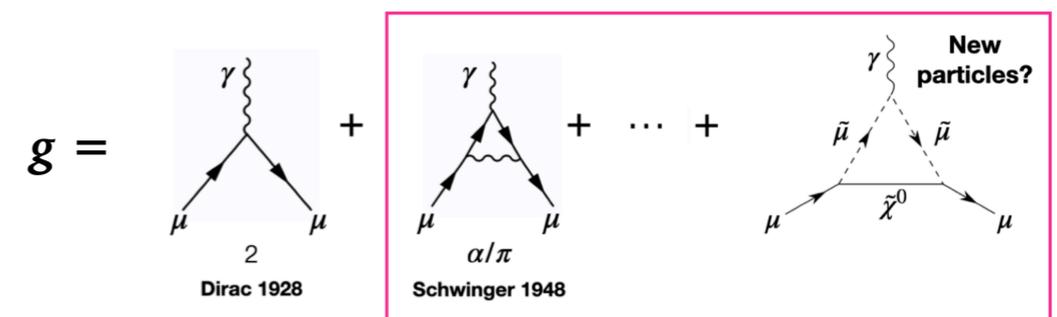
- **Signal strength** $\mu_{\tau\tau} = N_{\gamma\gamma \rightarrow \tau\tau}^{\text{meas}} / N_{\gamma\gamma \rightarrow \tau\tau}^{\text{SM,pred}}$ measured using a profile-likelihood fit to the p_T^μ **distribution** in the three SRs and 2μ -CR
- **First observation** of $\gamma\gamma \rightarrow \tau^+\tau^-$ process and **tau leptons** 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**

[PRL 131 (2023) 151802]



Tau anomalous magnetic

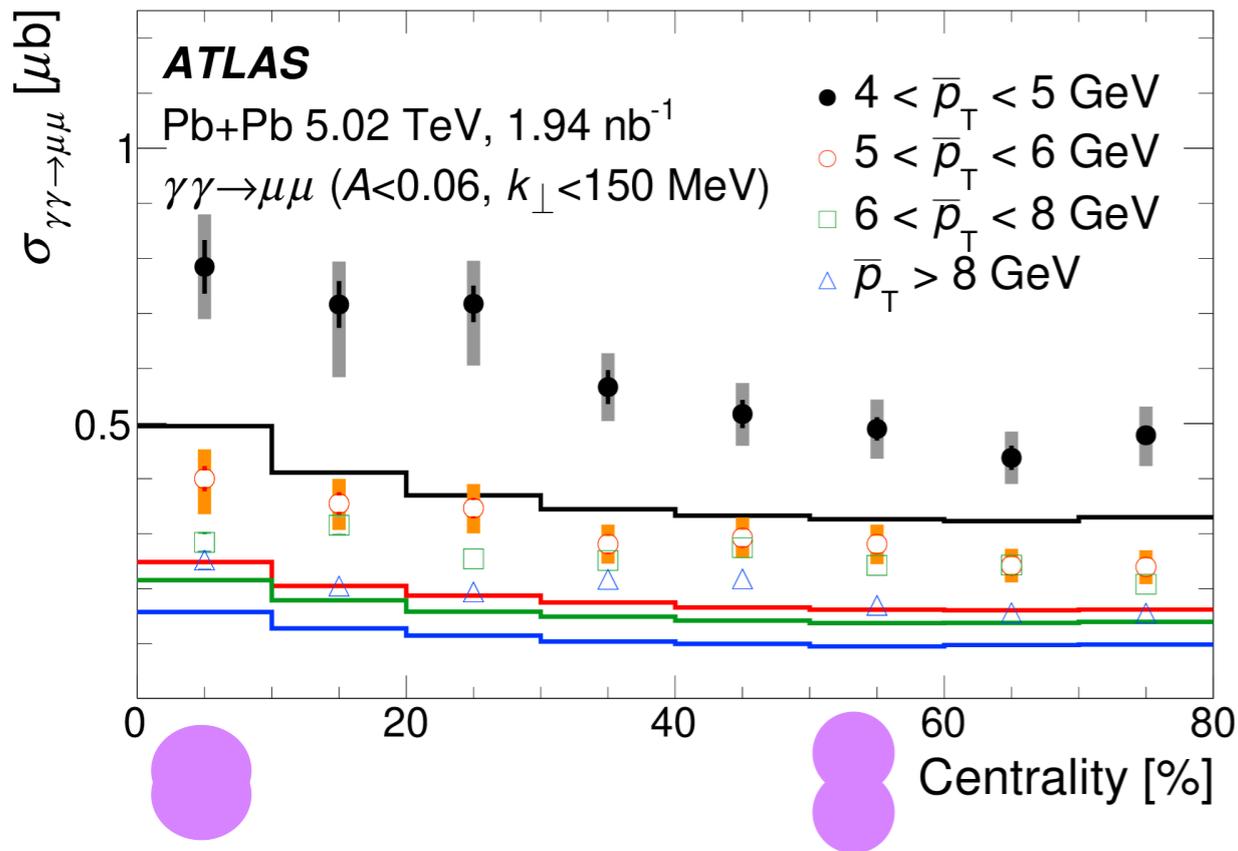
$$\text{moment } a_\tau = \frac{g - 2}{2}$$



- 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]

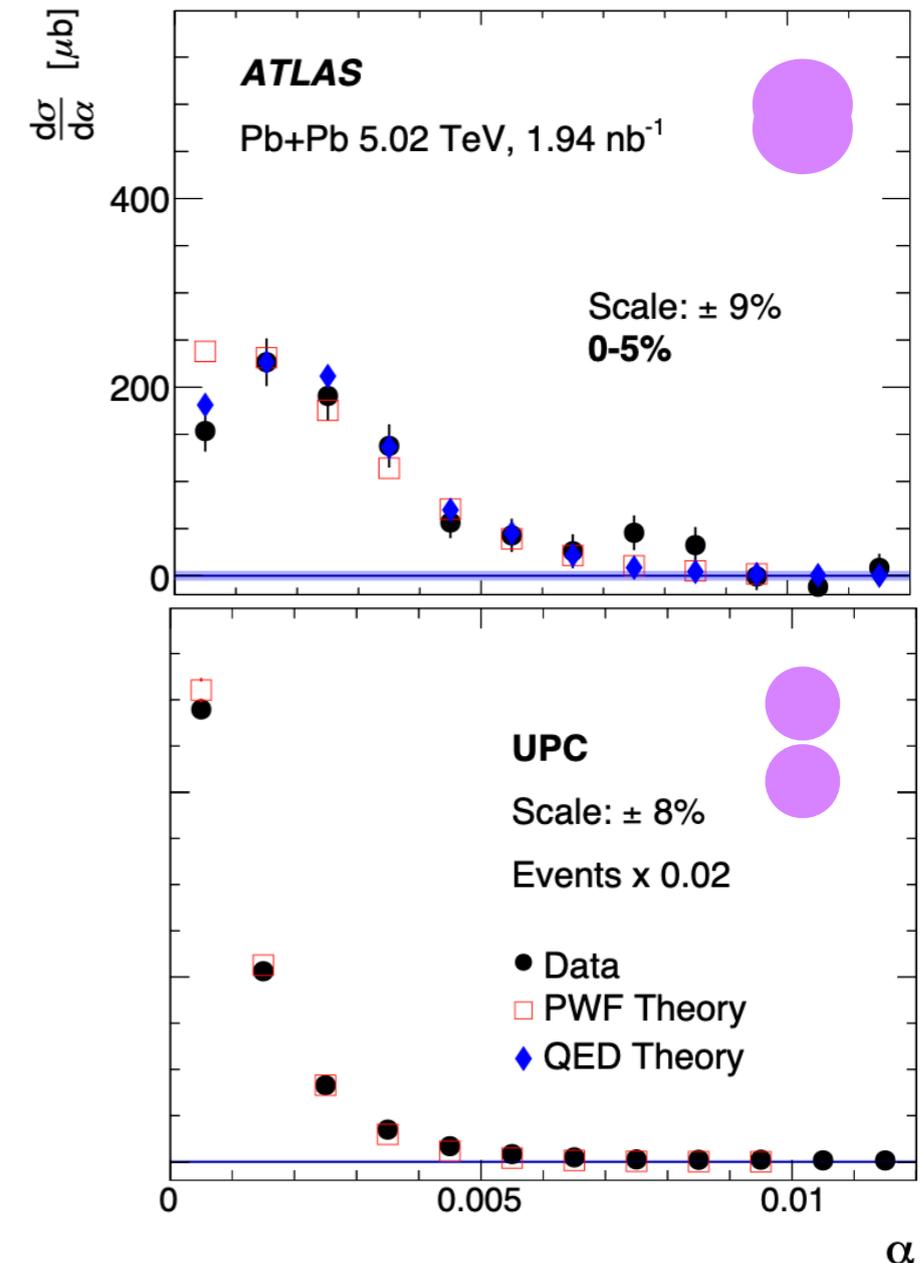


Acoplanarity: $\alpha = 1 - \frac{|\phi_1^\mu - \phi_2^\mu|}{\pi}$

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

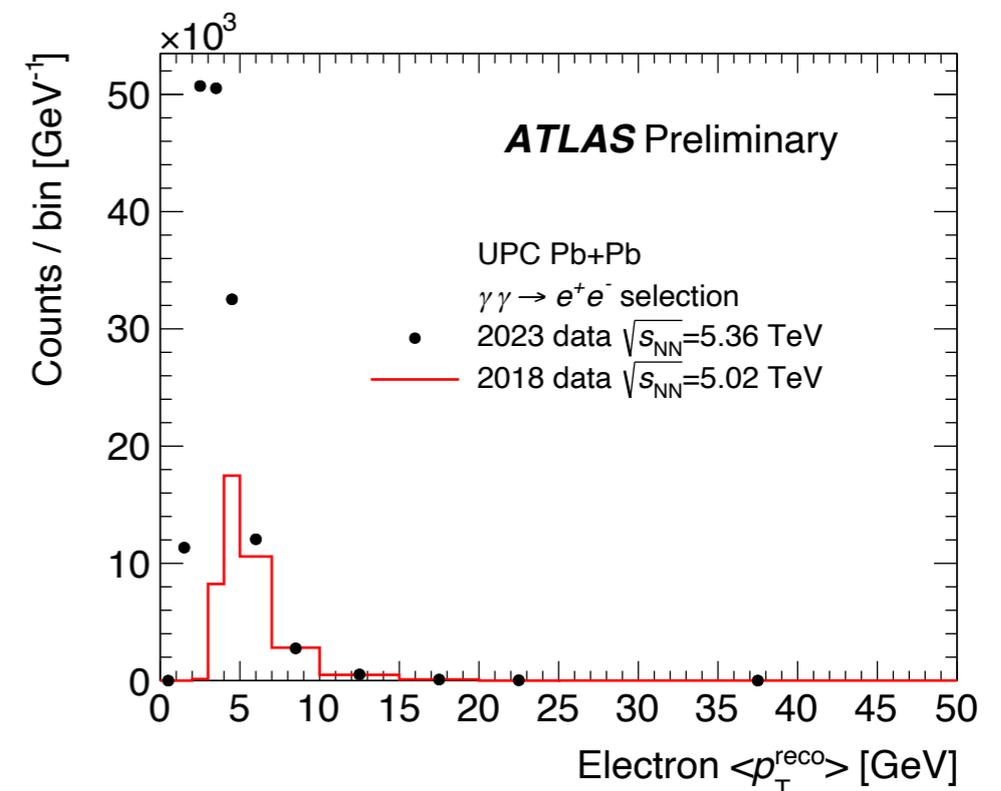
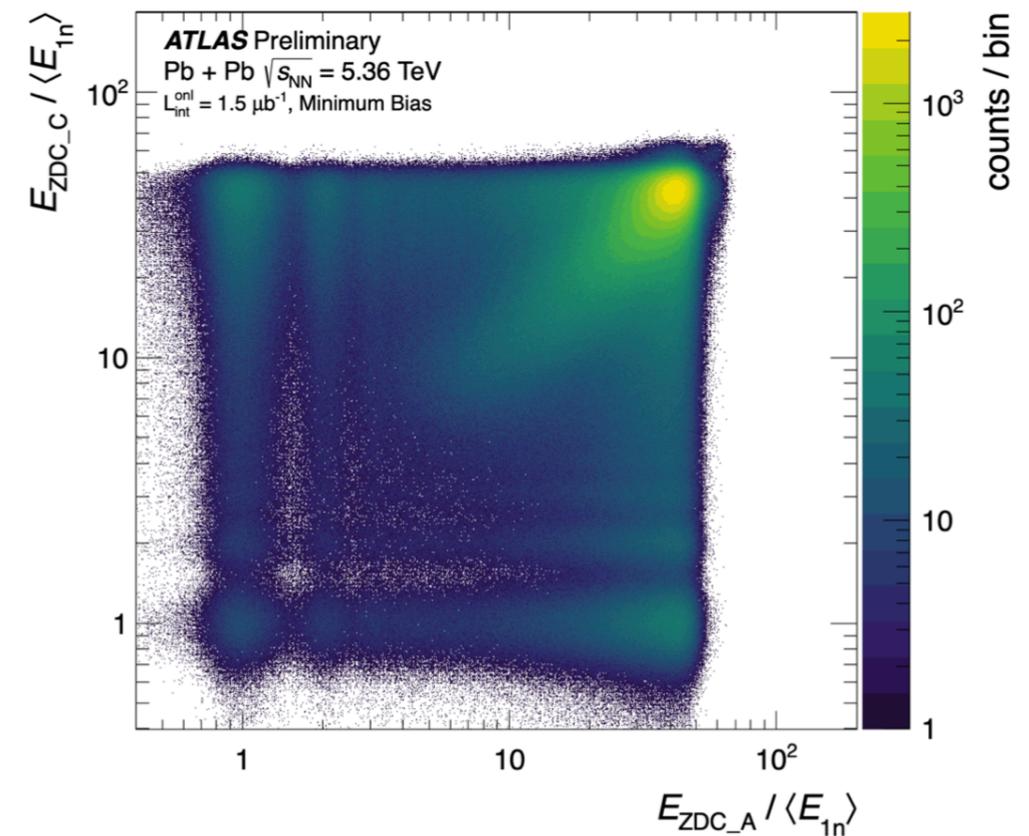
Transverse momentum scale:
 $k_{\perp} = \frac{1}{2}(p_{T1}^\mu + p_{T2}^\mu)(\pi - |\phi_1^\mu - \phi_2^\mu|) = \pi\alpha\bar{p}_T$

- $\gamma\gamma \rightarrow \mu^+\mu^-$ 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



[HION-2023-001]

- ATLAS experiment collected Pb+Pb collisions in October 2023
 - Run 2: 2.2 nb⁻¹ at $\sqrt{s_{NN}} = 5.02$ TeV
 - Run 3: 1.7 nb⁻¹ at $\sqrt{s_{NN}} = 5.36$ TeV
- Brand new **ZDC** which brings more triggering capabilities
- Improved **trigger** strategies for low- p_T particles
- Significant improvements in low- p_T electron efficiency



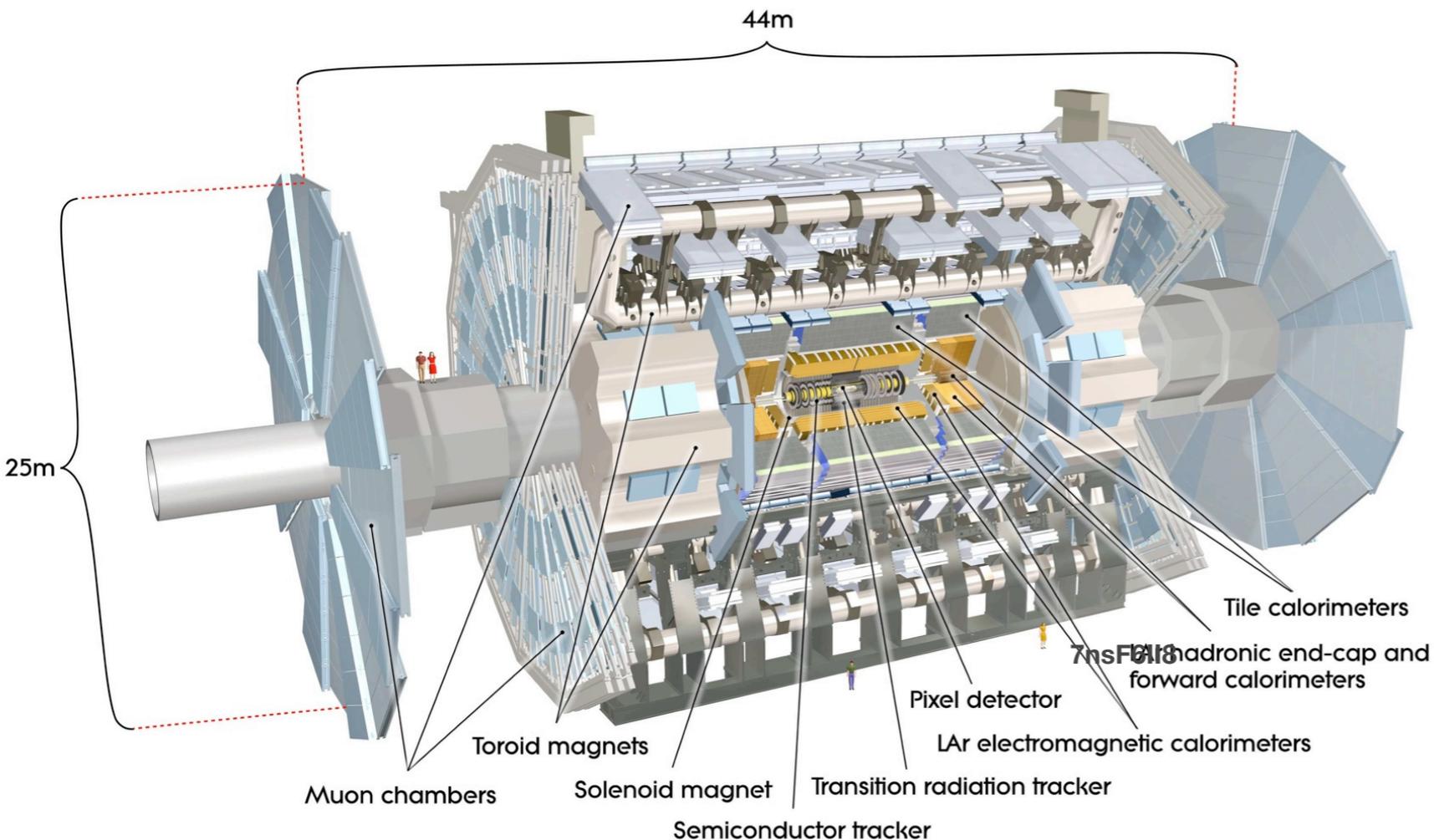
- ATLAS provides **precision results** on $\gamma\gamma \rightarrow \ell^+\ell^-$ with $\ell = e, \mu, \tau$ from UPC Pb+Pb collisions recorded in Run 2
 - **Measured cross sections** reveal systematic differences with **STARlight** and **SuperChic** calculations
 - Perhaps suggesting recent discussions on 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
- 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**
- $\gamma\gamma \rightarrow \mu^+\mu^-$ process is used to probe **non-UPC collisions** with high precision
 - New field of research
 - **Initial-state calculations** quantitatively describe many features but not all of them
- **Run 3** is in progress, new 2023 Pb+Pb data set collected at $\sqrt{s_{NN}} = 5.36$ 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>

Research project partly supported by the National Science Centre of Poland under grant number UMO-2020/37/B/ST2/01043 and by PL-GRID infrastructure."



NATIONAL SCIENCE CENTRE
POLAND

BACK-UP SLIDES



Three main components: **inner tracker**, **electromagnetic (EM)** and **hadronic (HAD)** calorimeters, and **muon system**

Electrons: inner tracker, EM calo

$$p_T^e > 20 \text{ (25) GeV for } Z \text{ (} W^\pm \text{)}$$

Muons: inner tracker, muon system

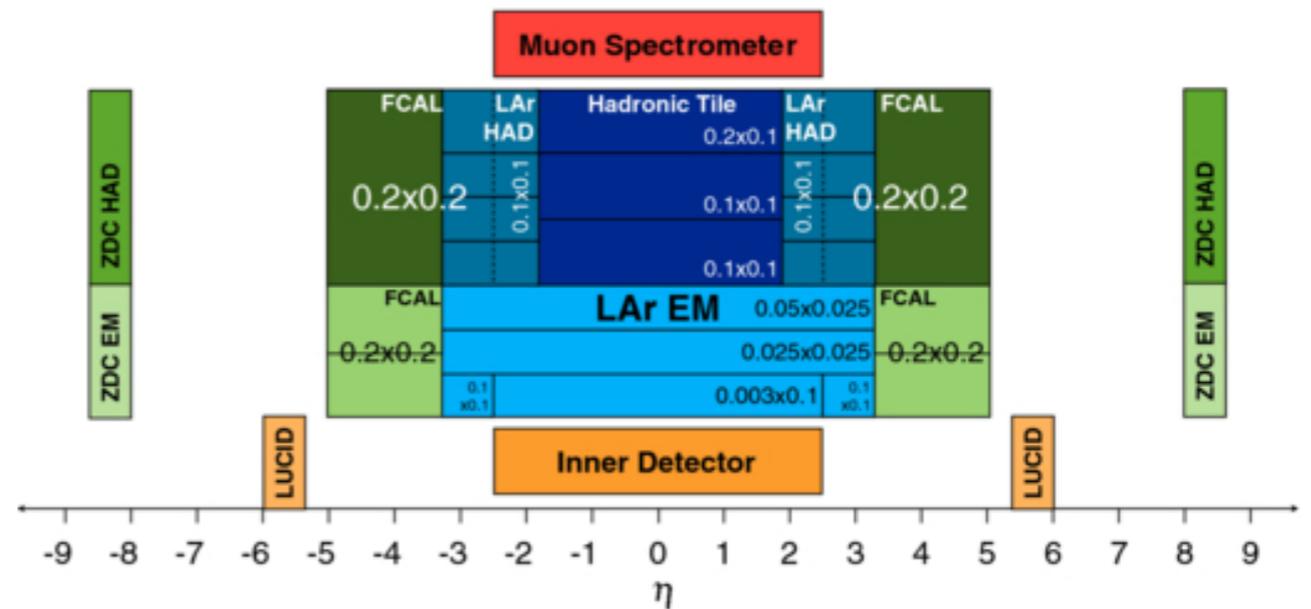
$$p_T^\mu > 20 \text{ (25) GeV for } Z \text{ (} W^\pm \text{)}$$

Charged particles: inner tracker

$$p_T^{\text{ch}} > 100 \text{ MeV}$$

Neutrons: Zero Degree Calorimeter

$$|\eta| > 8$$



$$|\eta^{\ell, \text{ch}}| \lesssim 2.5$$

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

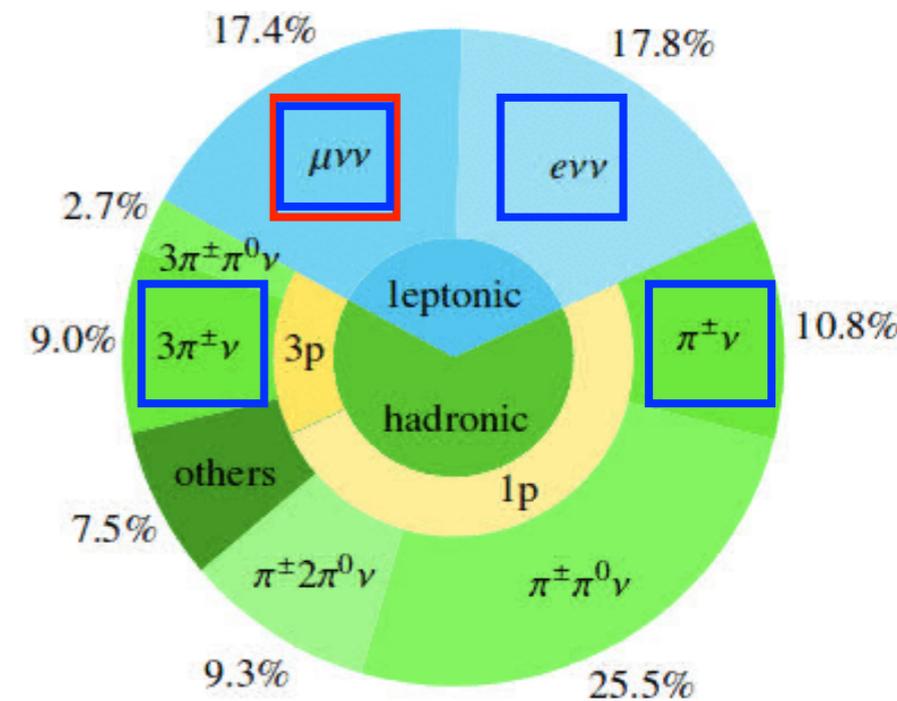
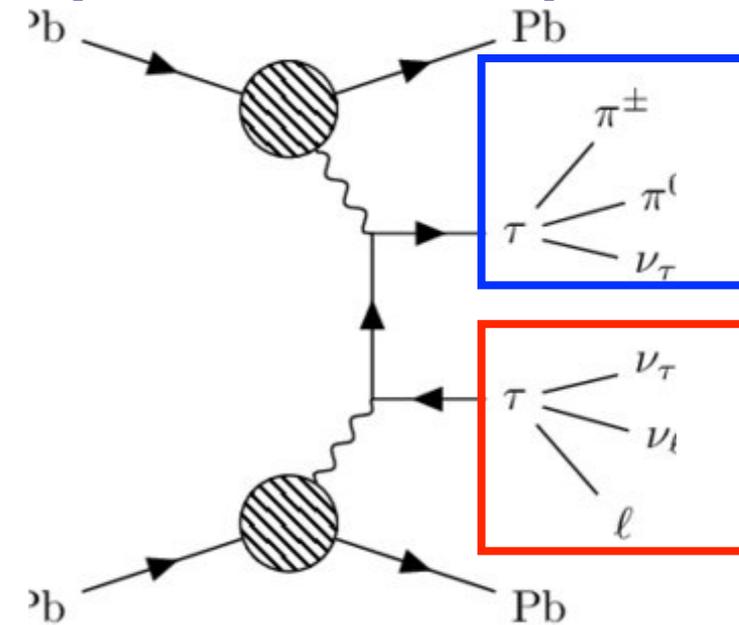
with $p_T^\mu > 4 \text{ GeV}$, $p_T^e > 4 \text{ GeV}$, $p_T^{\text{trk}} > 100 \text{ MeV}$

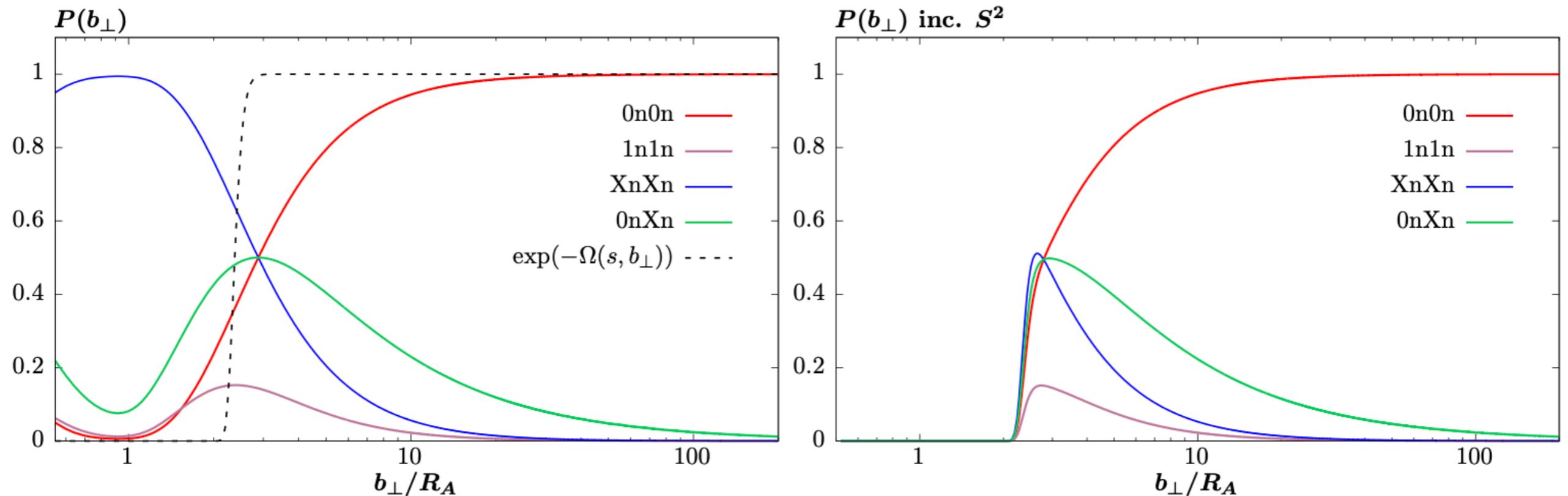
$p_T^{\text{clus}} > 1 \text{ GeV}$ ($|\eta| < 2.5$)

$p_T^{\text{clus}} > 100 \text{ MeV}$ ($2.5 < |\eta| < 4.5$)

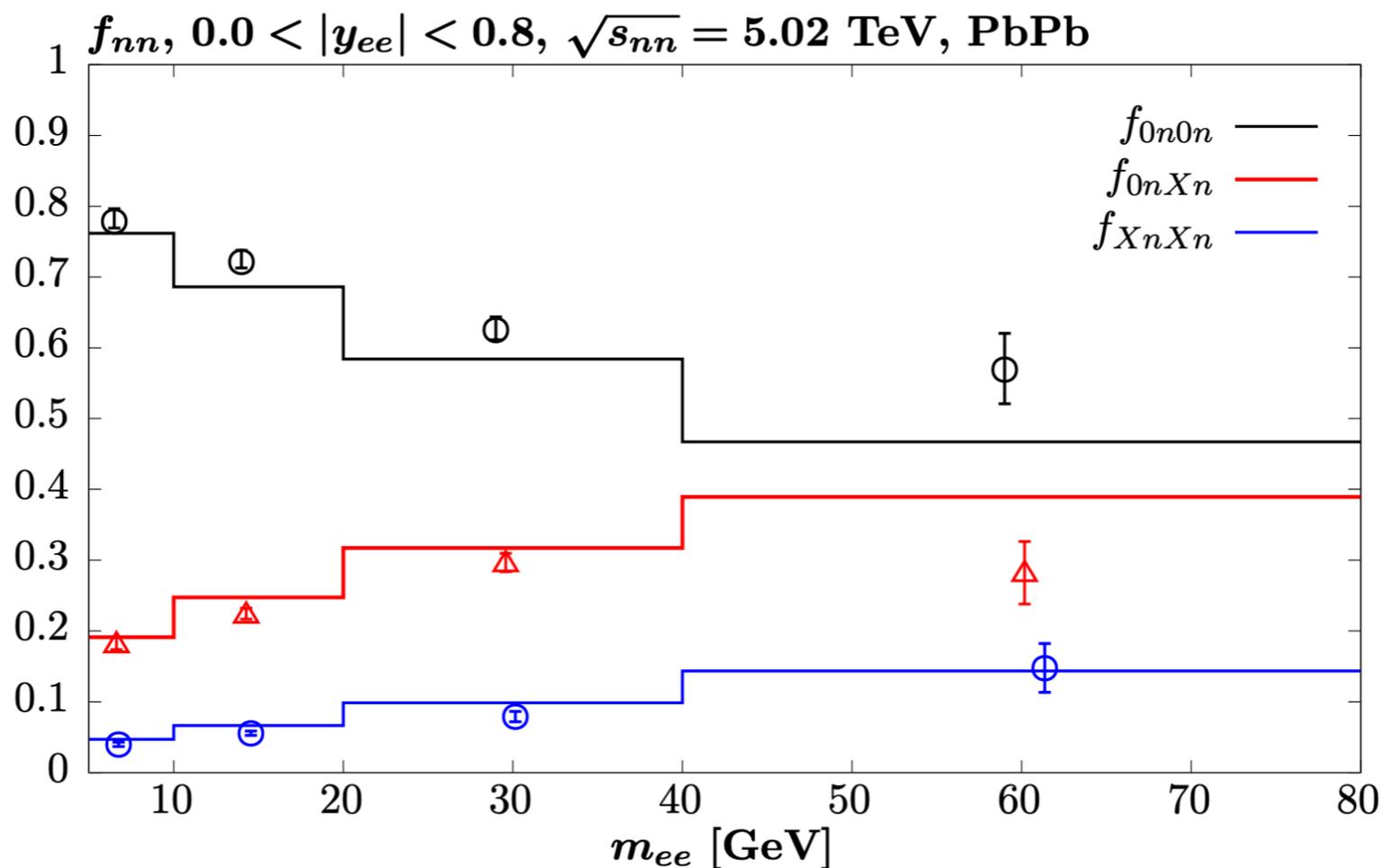
- Exclusivity: veto additional clusters ($\mu 1\text{T-SR}$ and $\mu 3\text{T-SR}$ only) and tracks
- Total of ~ **650 events** across all SRs
- Only **data** in the **0n0n category** used to suppress photonuclear/hadronic backgrounds
- Simulation (**STARlight+Tauola**) reweighted to 0n0n with data-driven weights

[arXiv:2204.13478]



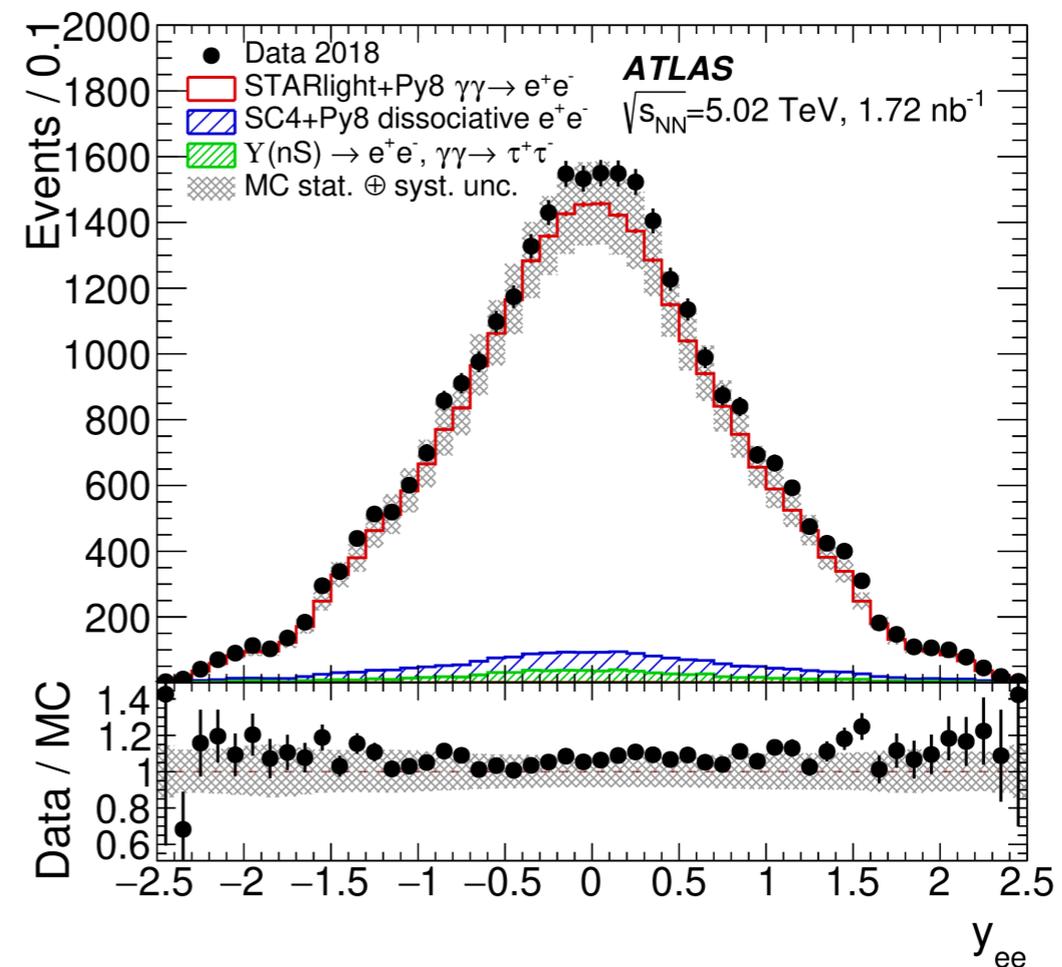
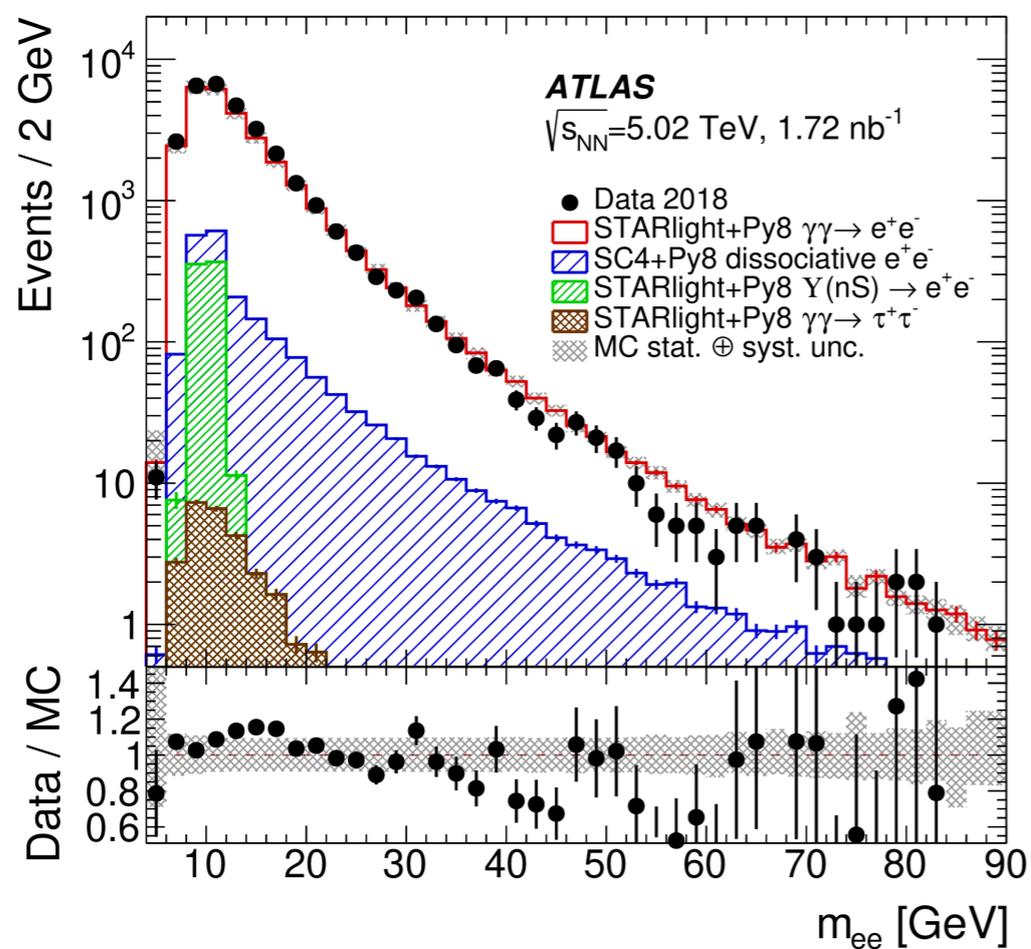


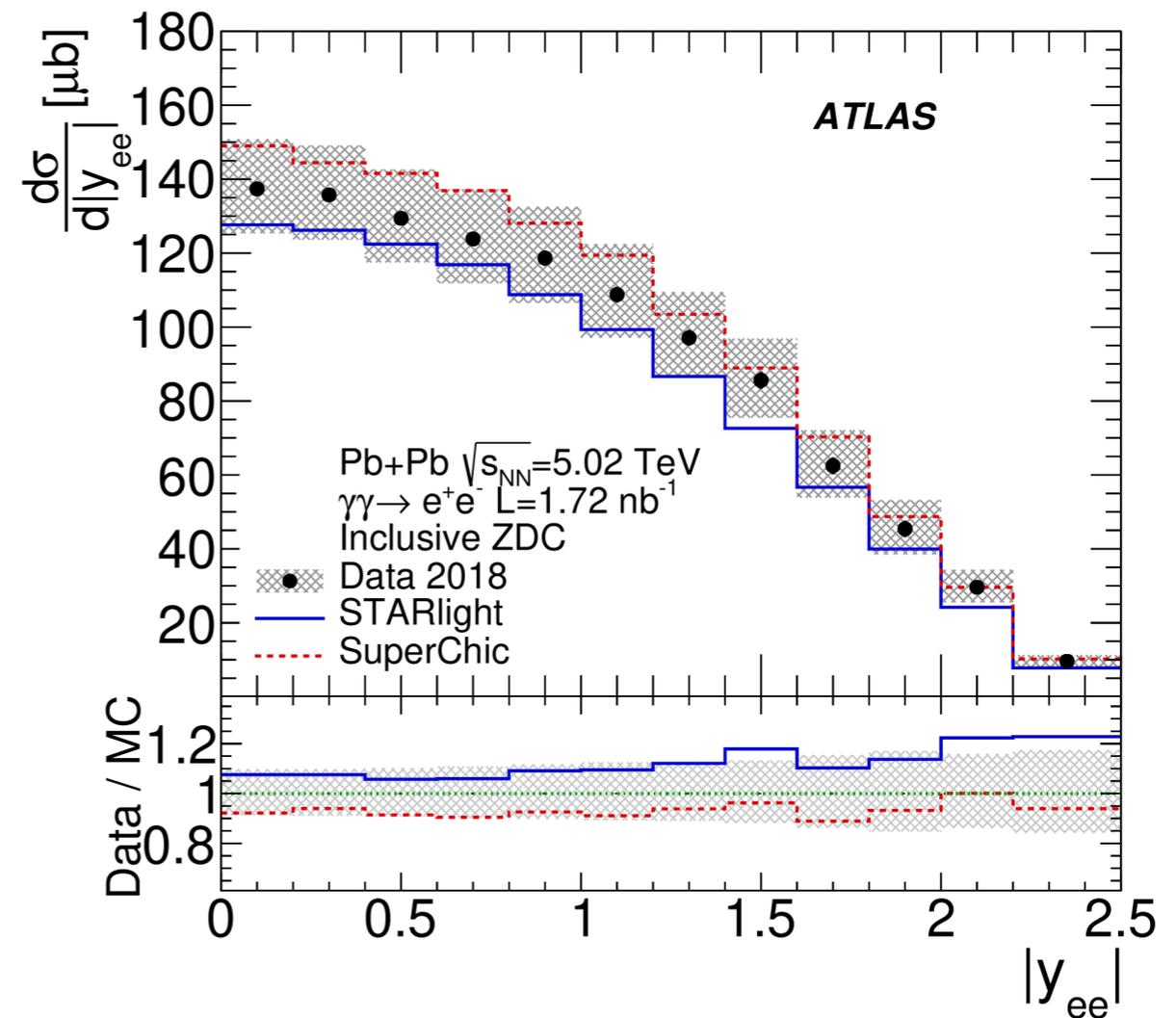
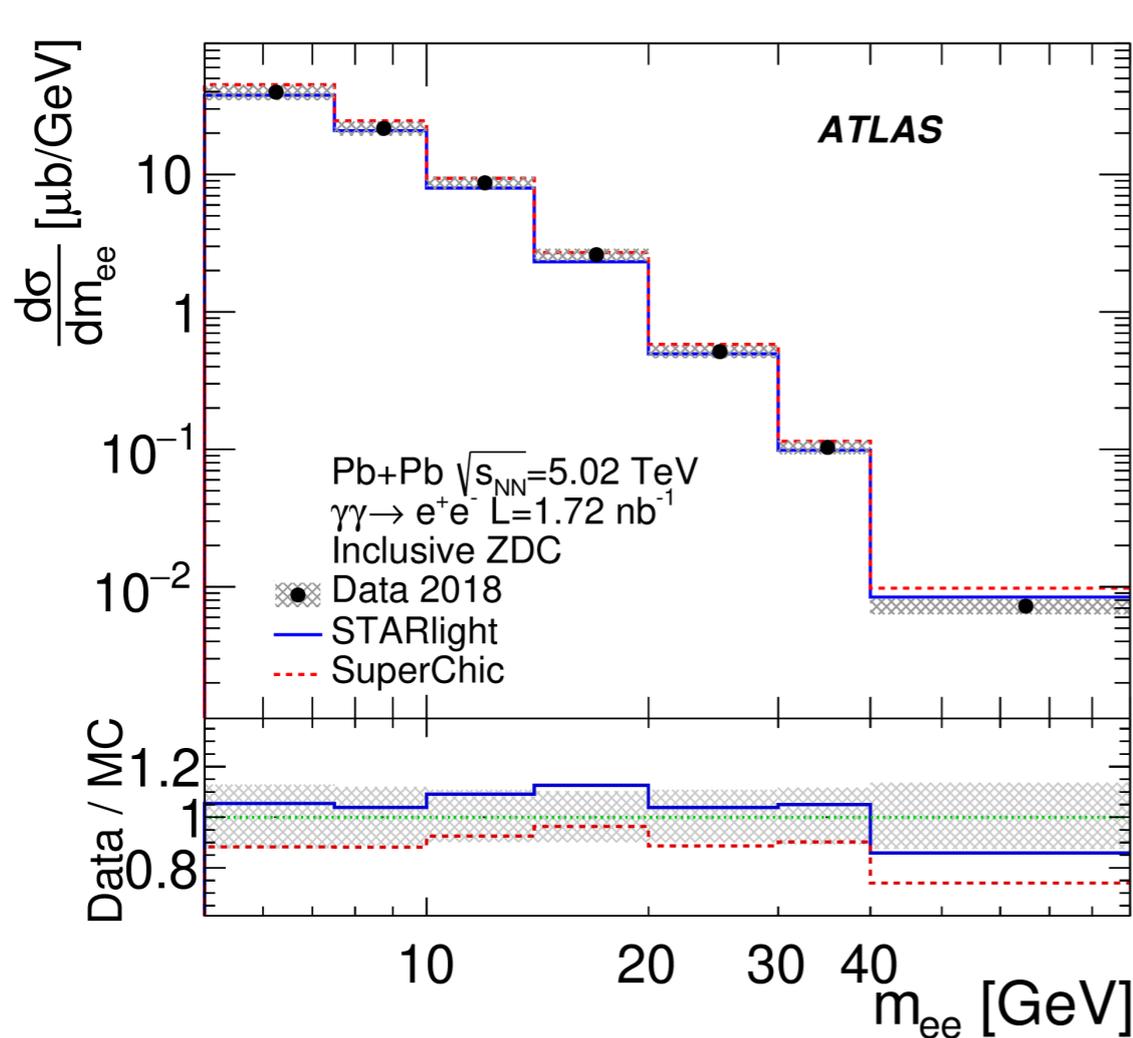
- Recent developments in **SuperChic v4.2** bring modeling of ion excitation/de-excitation and emission of neutrons in the forward direction
 - See L.H. Harland-Lang [arXiv:2303.04826](https://arxiv.org/abs/2303.04826) for more details
- Breakup probabilities for single and multiple neutron emissions



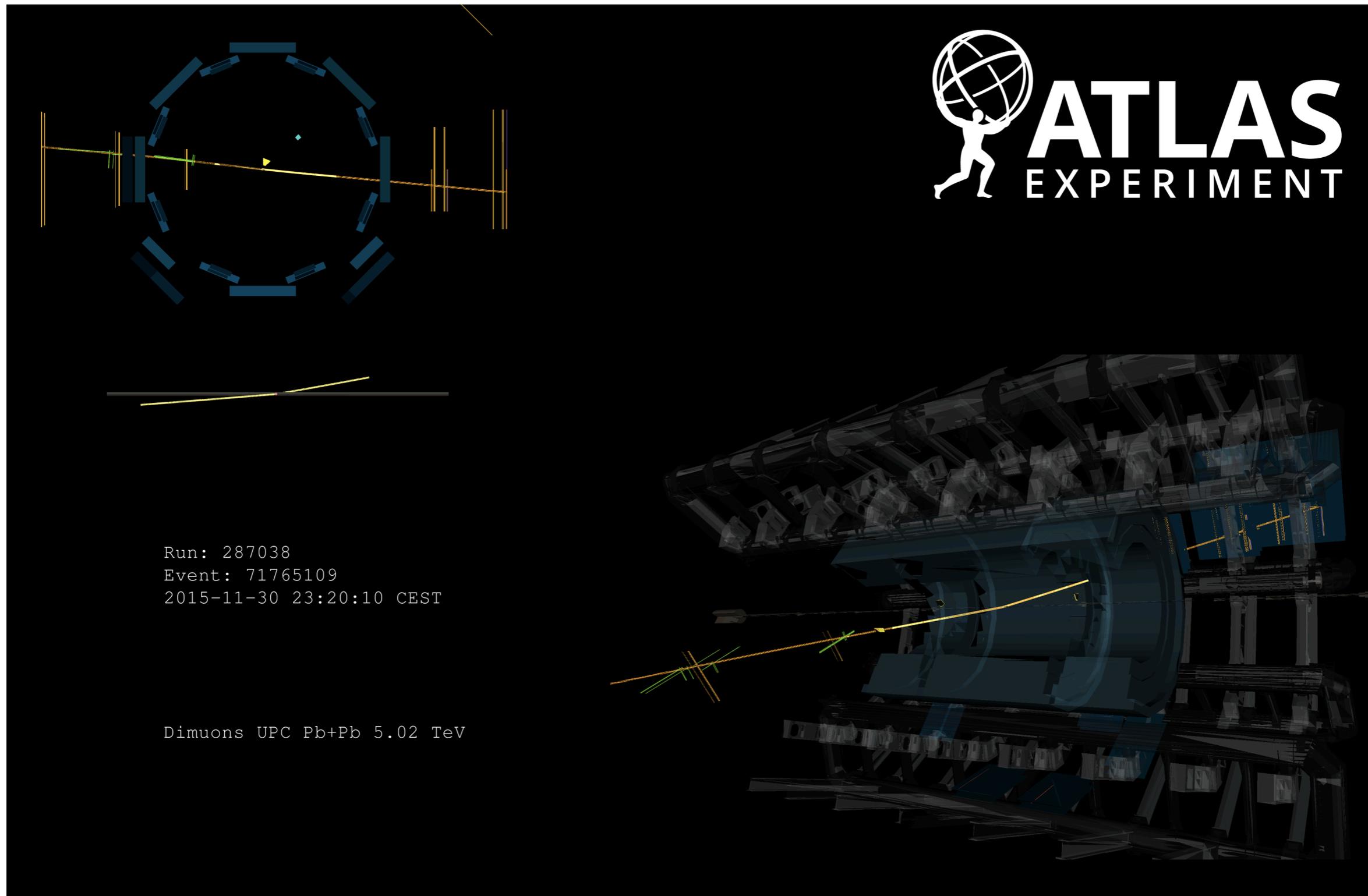
- New data triggered developments in **SuperChic v4.2** which brings modeling of ion excitation/de-excitation and emission of neutrons in the forward direction
 - See L.H. Harland-Lang [arXiv:2303.04826](https://arxiv.org/abs/2303.04826) for more details
- **Good description** of dielectron/dimuon data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

- ▶ Data set from **2018** UPC Pb+Pb collisions of 1.72 nb^{-1}
- ▶ Production measured in the **fiducial region** defined by:
 $p_T^e > 2.5 \text{ GeV}$, $|\eta^e| < 2.5$, $m_{ee} > 5 \text{ GeV}$ and $p_T^{ee} < 2 \text{ GeV}$
- ▶ About **30k event** candidates
- ▶ Dissociative background ($\sim 4\%$) evaluated using **improved template fitting** to the acoplanarity distribution
 - ▶ **SuperChic 4.0** used
 - ▶ Other backgrounds: Υ and $\gamma\gamma \rightarrow \tau^+\tau^-$
- ▶ Systematic uncertainties dominate (10%)

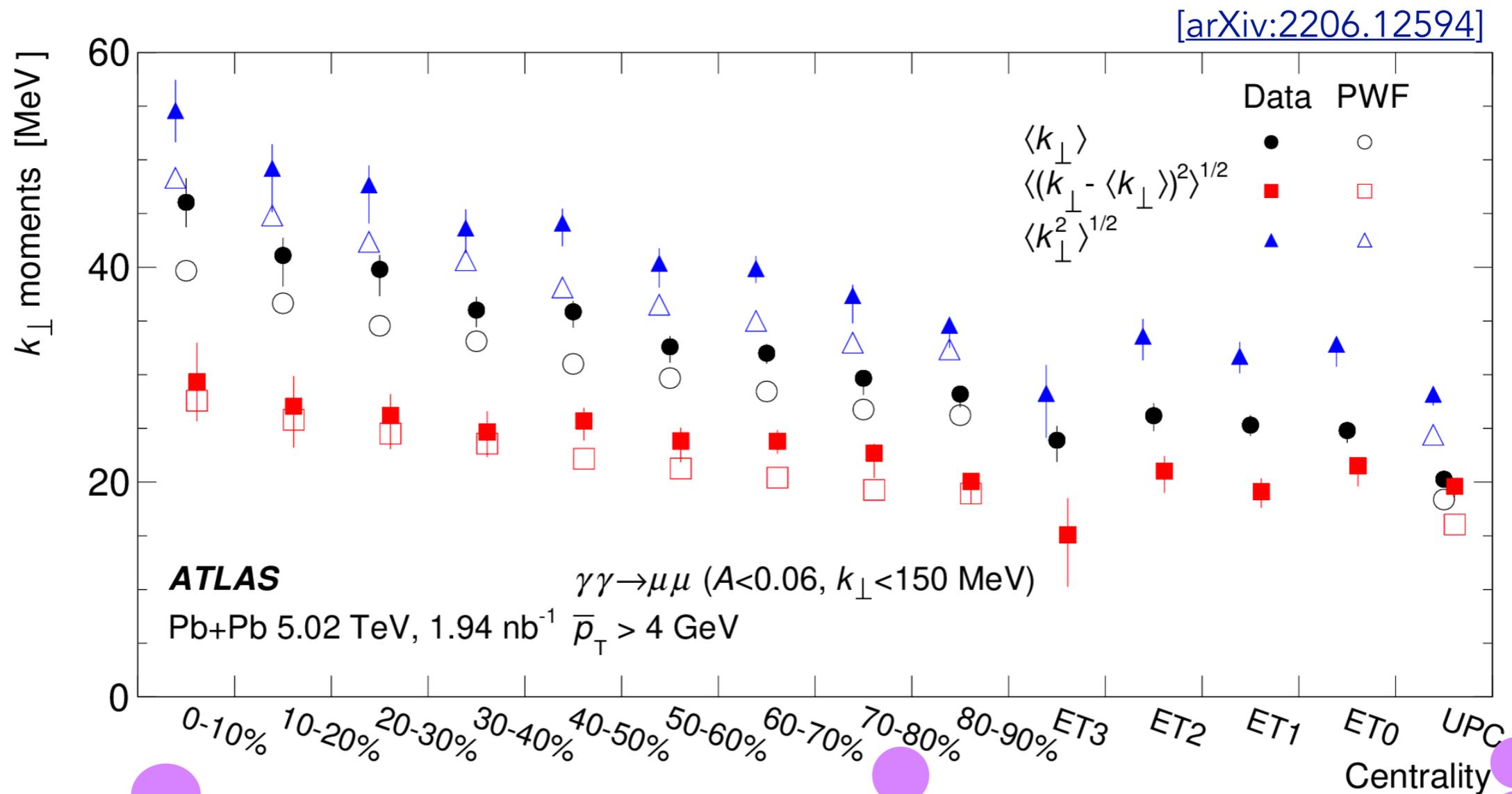




- Differential cross sections measured in m_{ee} , $|y_{ee}|$, $\langle p_T^e \rangle$ and $|\cos \theta^*|$ for the **inclusive ZDC sample**
 - **STARlight 2.4 (SuperChic 3.05)** systematically lower (higher) than data
 - Fairly good description of shapes



- Very clean dimuon event



- 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
- Predicted trends associated with effects of **magnetic fields** on the dimuons are not observed