



# DIS2022

**XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects**

Santiago de Compostela, 2-6 May 2022

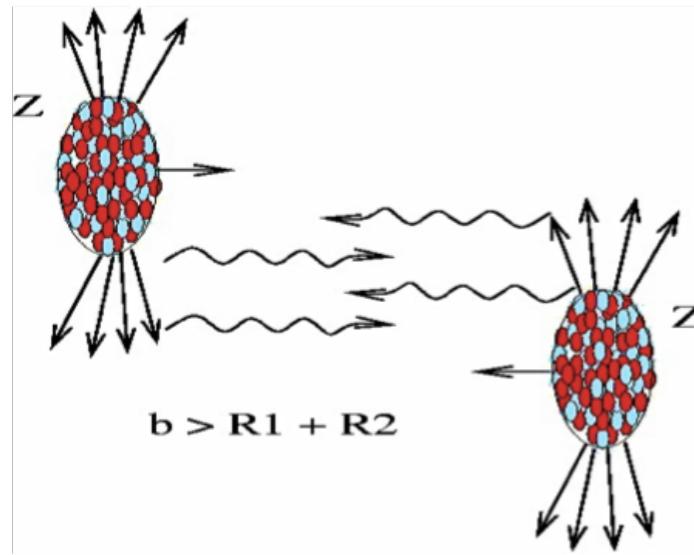
*ATLAS measurements of photon-photon  
fusion processes in Pb+Pb collisions*

Iwona Grabowska-Bold (AGH UST, Kraków)  
for the ATLAS Collaboration

May 4th, 2022



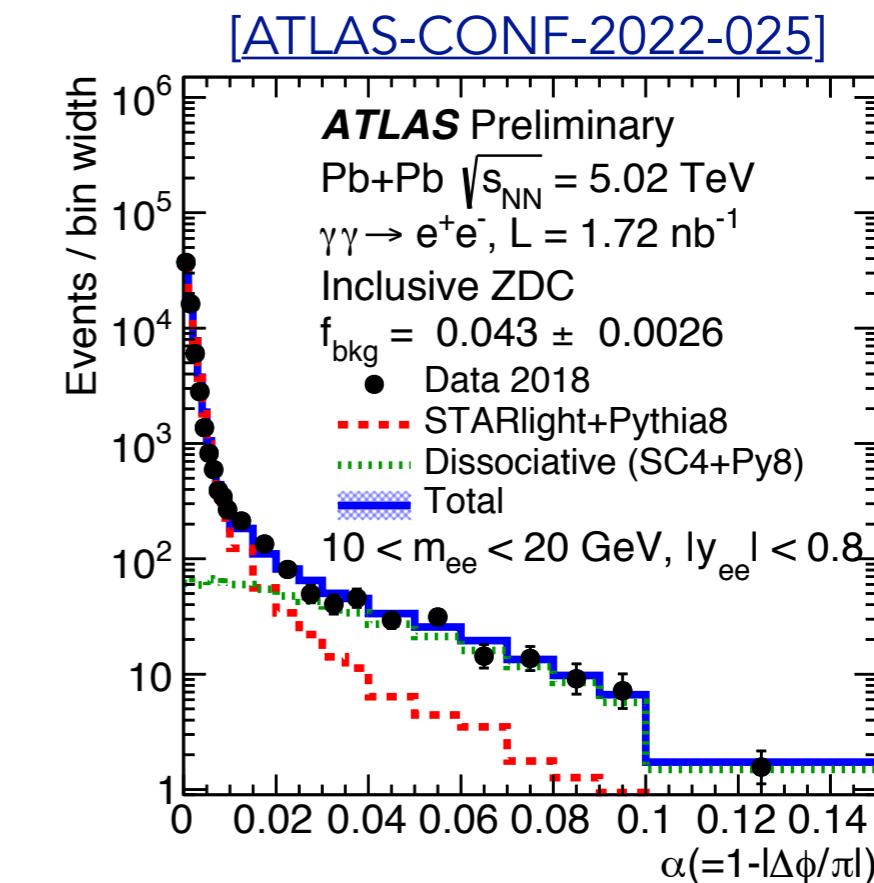
# INTRODUCTION



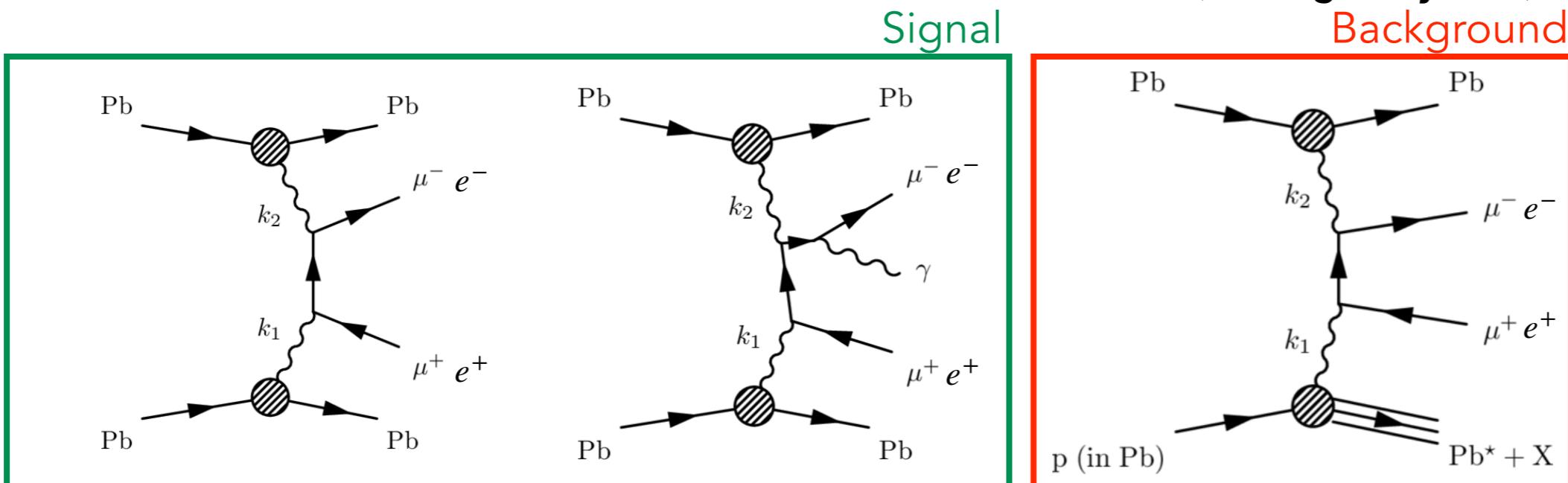
- Ultra-peripheral collisions (UPC) of lead-lead (Pb+Pb) are gaining more and more interest in the heavy-ion community
  - Very clean environment to study quantum electrodynamics (QED)
  - Precision tool to study photon fluxes within the EPA framework
  - $Z^4 (\approx 4.5 \times 10^7)$  enhancement 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 are considered a tool to search for beyond Standard Model (BSM) physics
- 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](#)]
  - Preliminary  $\gamma\gamma \rightarrow e^+e^-$  [[ATLAS-CONF-2022-025](#)]
  - Final  $\gamma\gamma \rightarrow \tau^+\tau^-$  [[arXiv:2204.13478](#)] NEW
  - Final light-by-light scattering and ALP search [[JHEP 03 \(2021\) 243](#)]
- Not covered:
  - Non-UPC  $\gamma\gamma \rightarrow \mu^+\mu^-$  [[ATLAS-CONF-2019-051](#)] - major update coming soon

# EXCLUSIVE DIMUONS AND DIELECTRONS

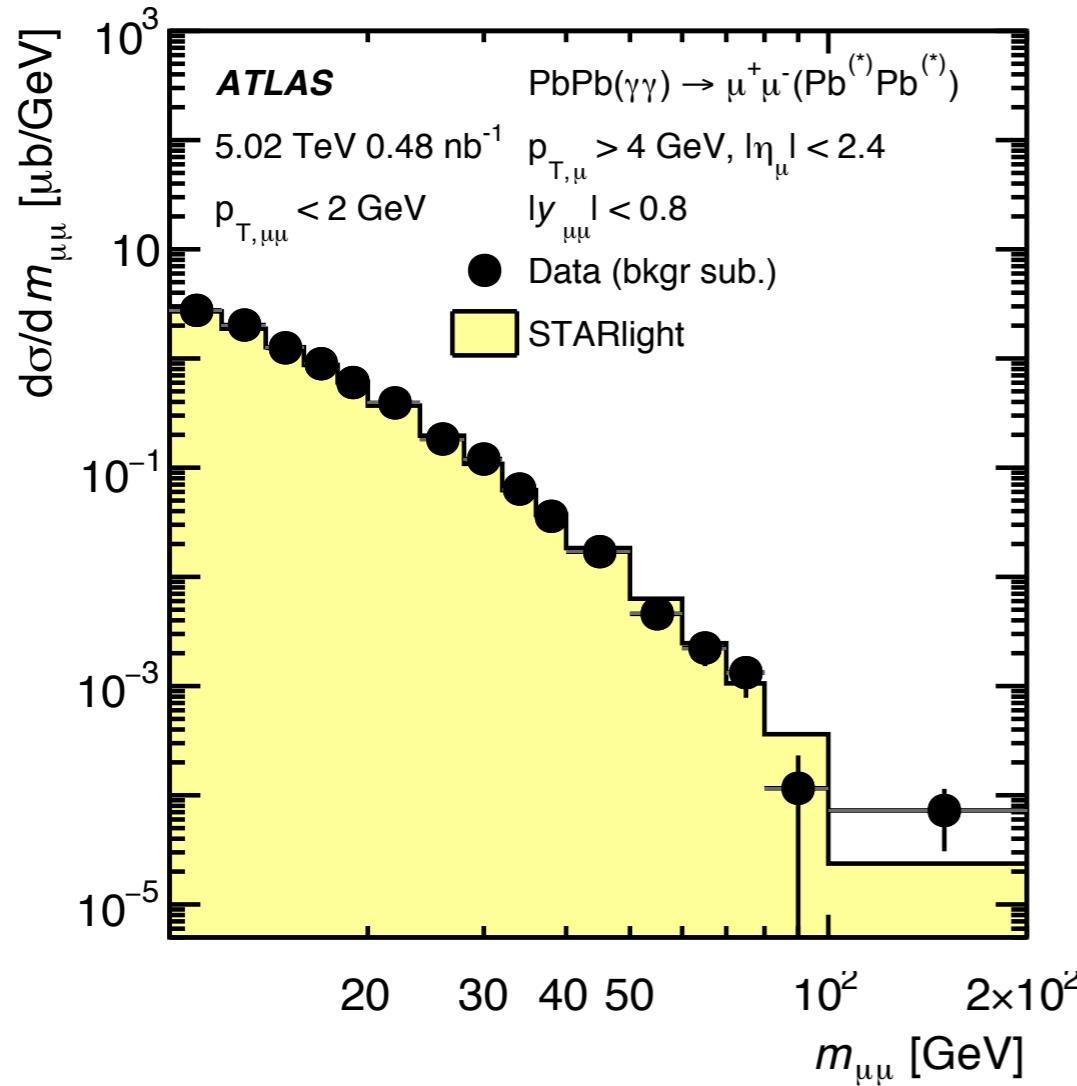
	$\gamma\gamma \rightarrow \mu^+\mu^-$	$\gamma\gamma \rightarrow e^+e^-$
Data	2015	2018
Int lumi	0.48 nb <sup>-1</sup>	1.72 nb <sup>-1</sup>
Fiducial	$p_T^\mu > 4 \text{ GeV}$ $  \eta^\mu   < 2.4$ $m_{\mu\mu} > 10 \text{ GeV}$ $p_T^{\ell\ell} < 2 \text{ GeV}$	$p_T^e > 2.5 \text{ GeV}$ $  \eta^e   < 2.5$ $m_{ee} > 5 \text{ GeV}$
Event candidates	12k	30k
Background	Dissociative LPair (3%)	Dissociative SuperChic v4.0 (4%)



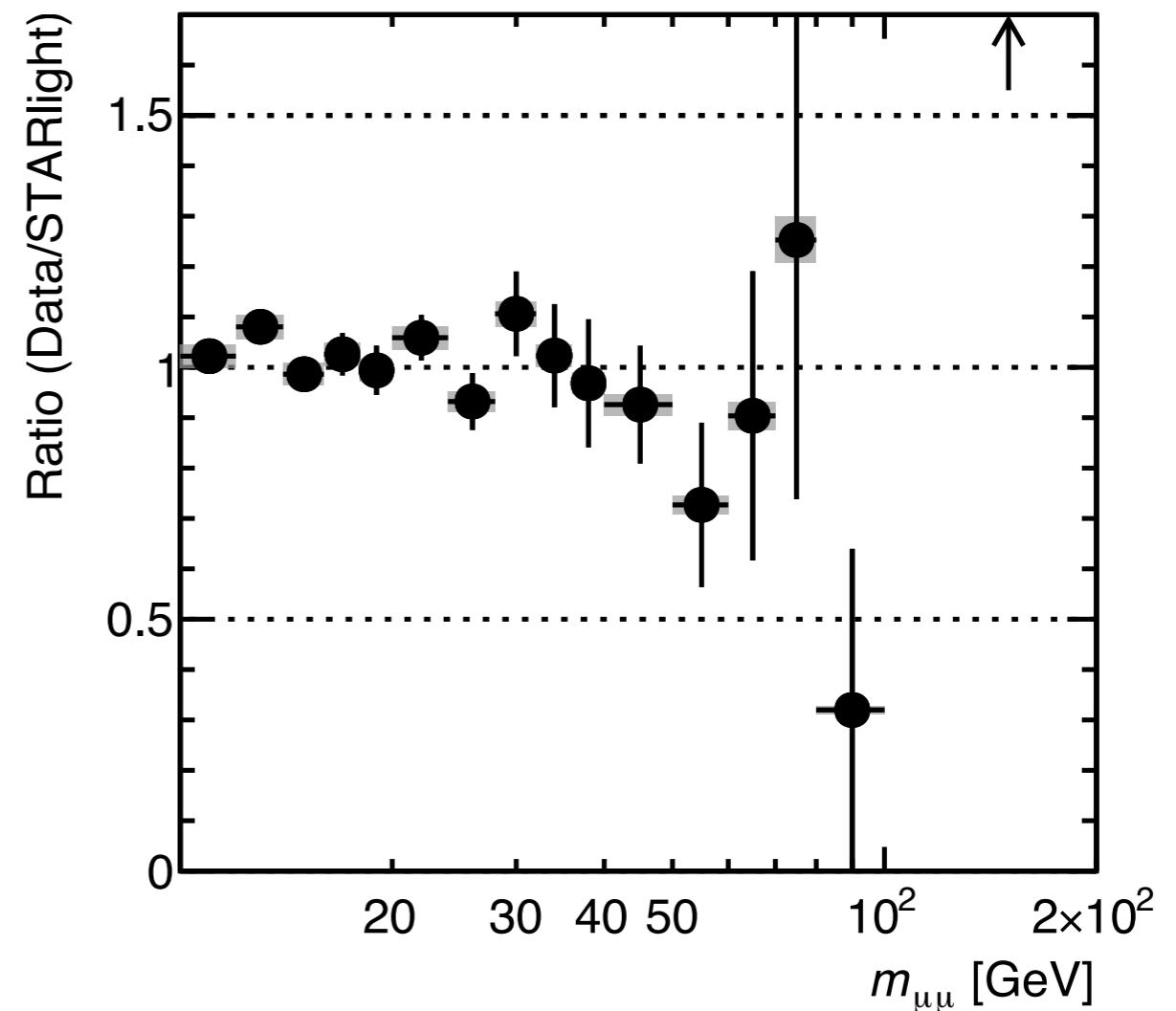
- Dissociative background uses **template fitting** to  $\alpha$ 
  - Contribution from **FSR** important to have a good description of  $\alpha$  distribution (**STARlight+Pythia8**)



# EXCLUSIVE DIMUONS: DIFFERENTIAL CROSS SECTIONS



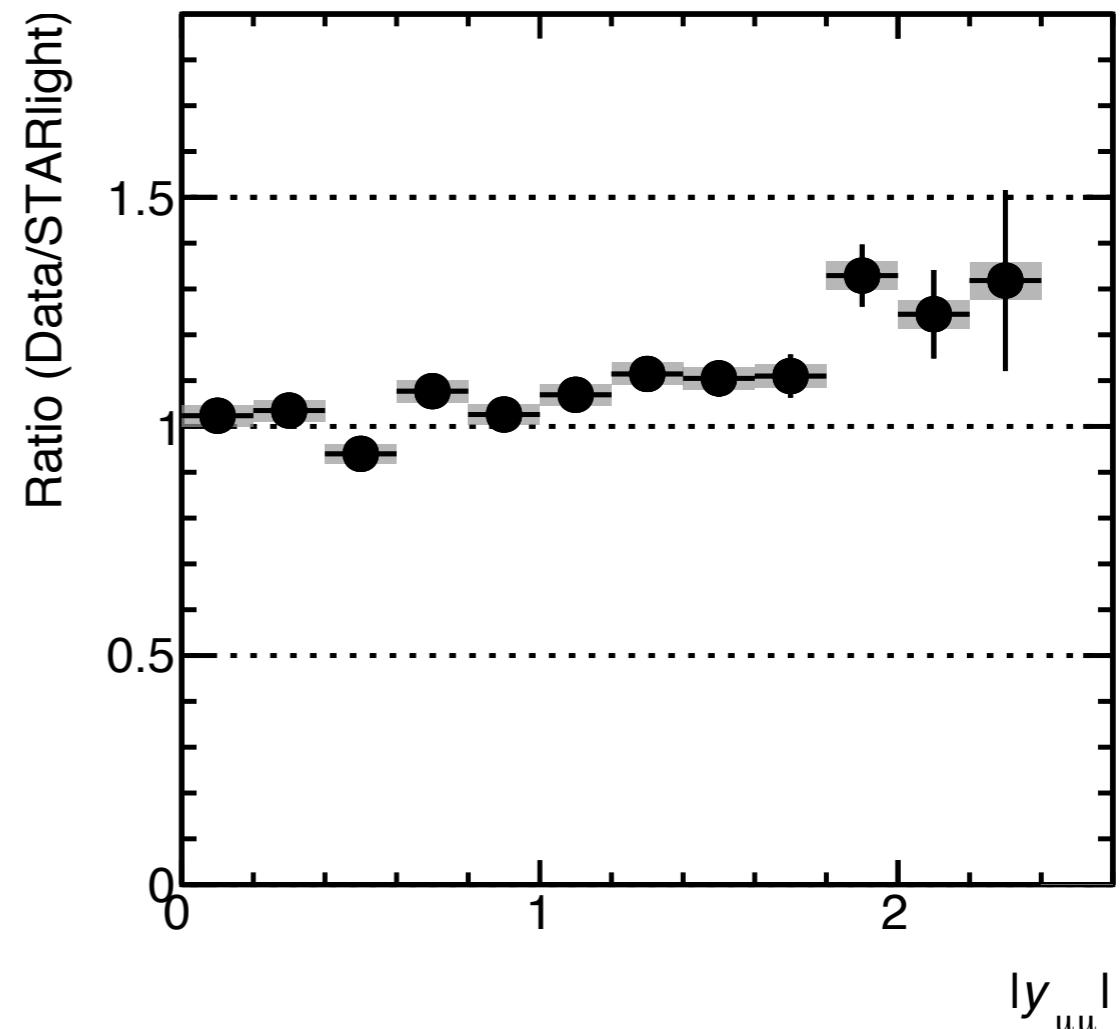
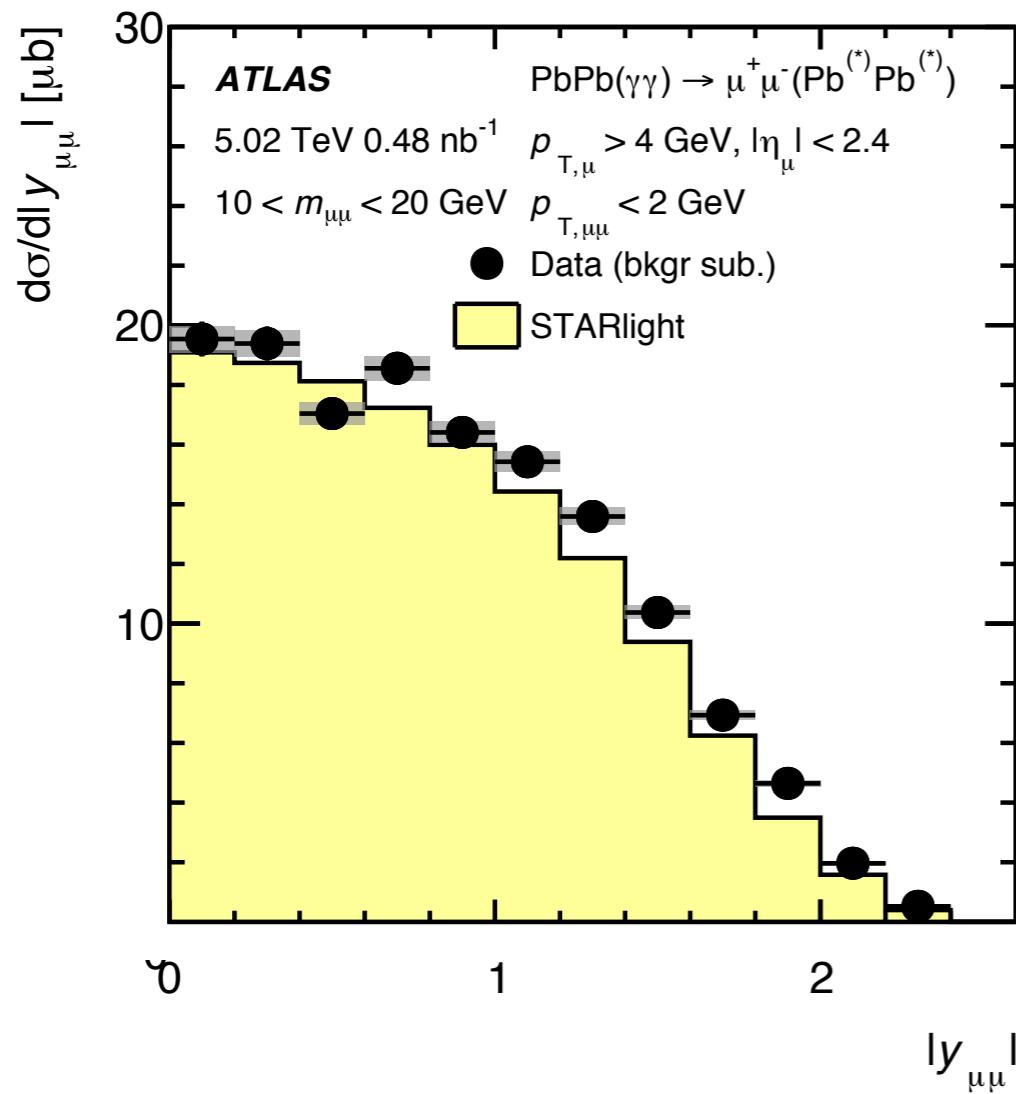
[Phys. Rev. C 104 (2021) 024906]



- Differential cross sections studied in  $m_{\mu\mu}$ ,  $|y_{\mu\mu}|$ ,  $|\cos \theta^*|$ ,  $k_{\min}$ ,  $k_{\max}$ ,  $\alpha$
- $m_{\mu\mu}$  measured up to 200 GeV
- **Good agreement** with STARlight 2.0

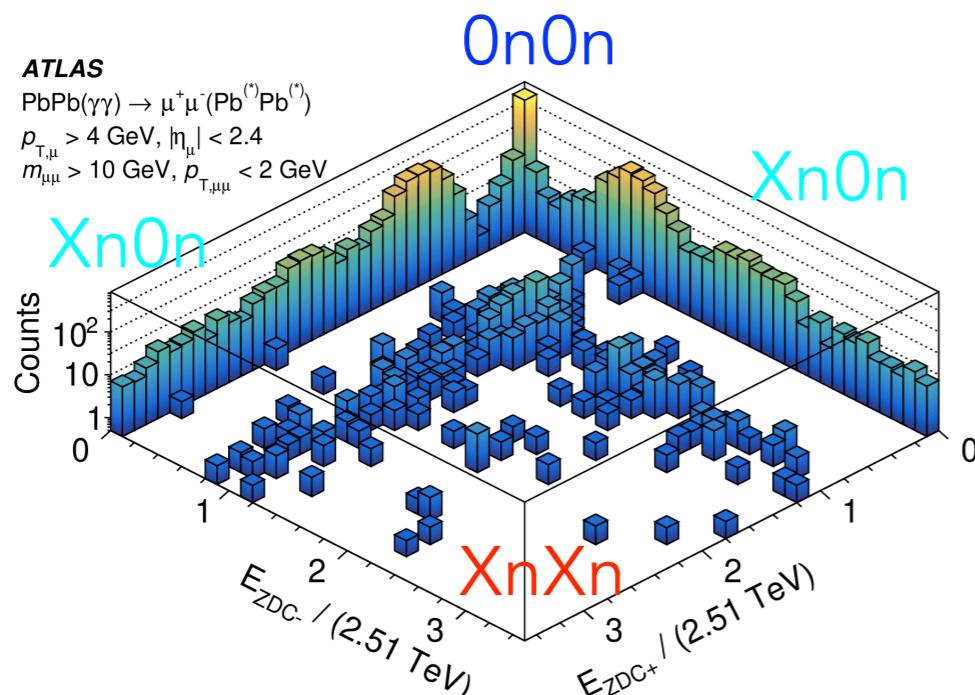
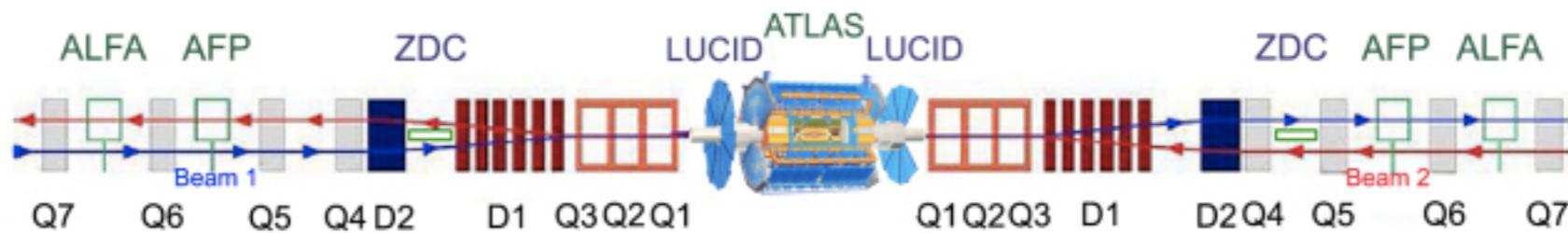
# EXCLUSIVE DIMUONS: DIFFERENTIAL CROSS SECTIONS

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

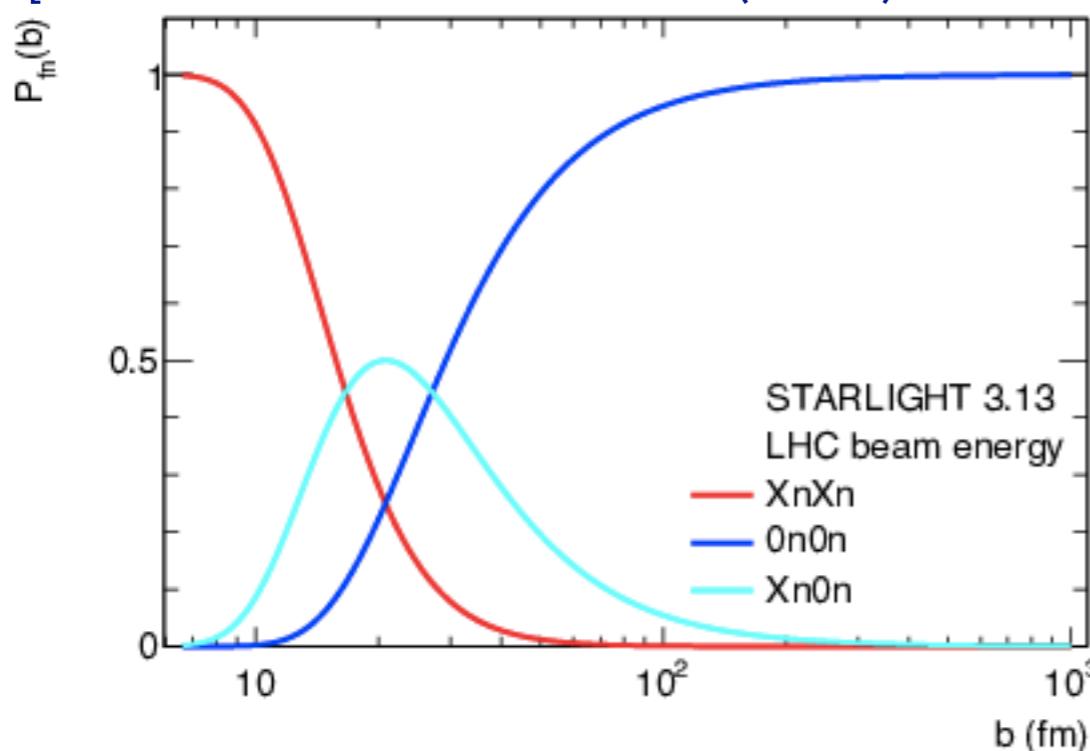


- Differential cross sections studied in  $m_{\mu\mu}$ ,  $|y_{\mu\mu}|$ ,  $|\cos \theta^*|$ ,  $k_{\min}$ ,  $k_{\max}$ ,  $\alpha$
- **Good agreement** with STARlight 2.0
- ... but **systematic excess** of the data at higher  $|y_{\mu\mu}|$

# EXCLUSIVE MUONS: ACTIVITY IN ZDC

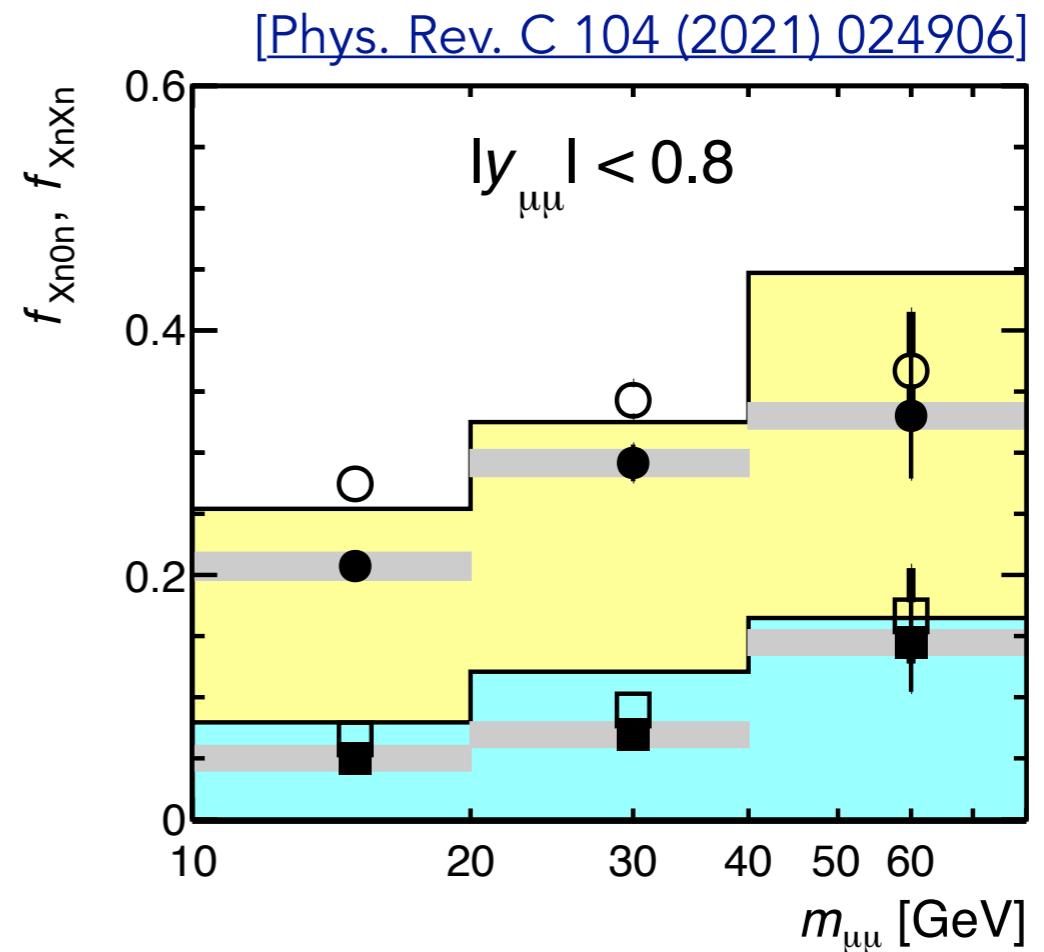
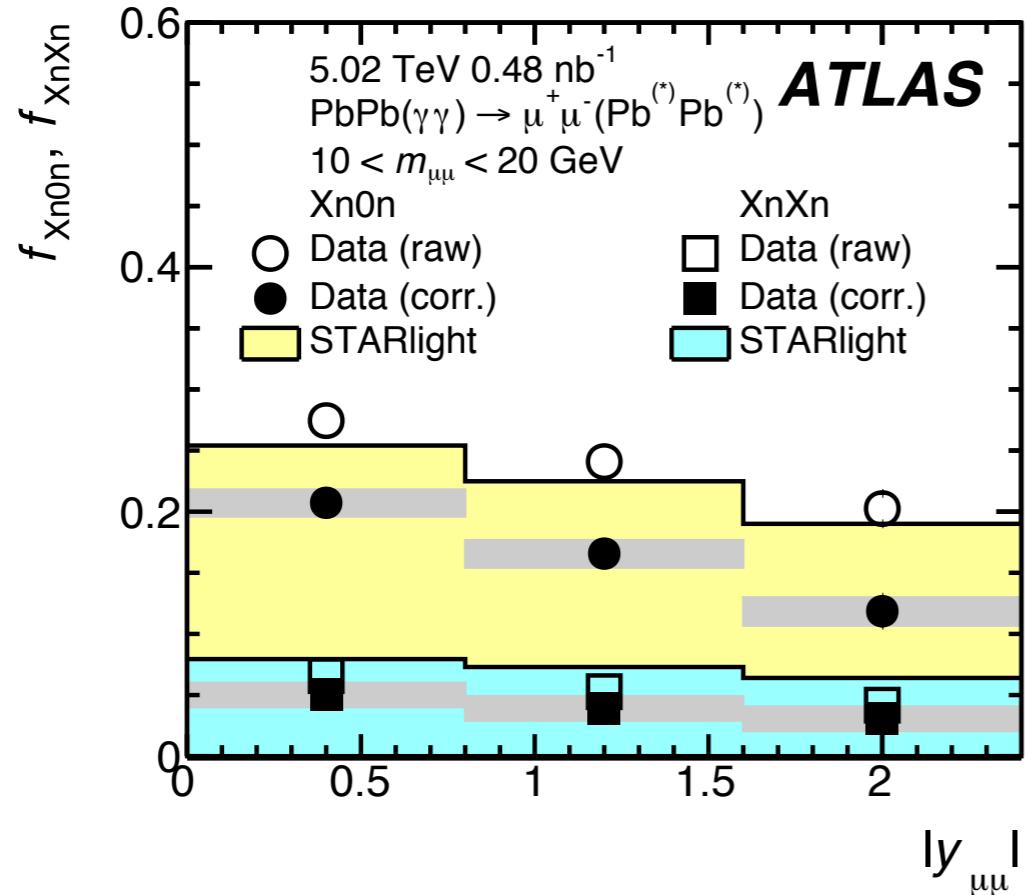


[Ann. Rev. Nucl. Part. Sci. 70 (2020) 323-354]



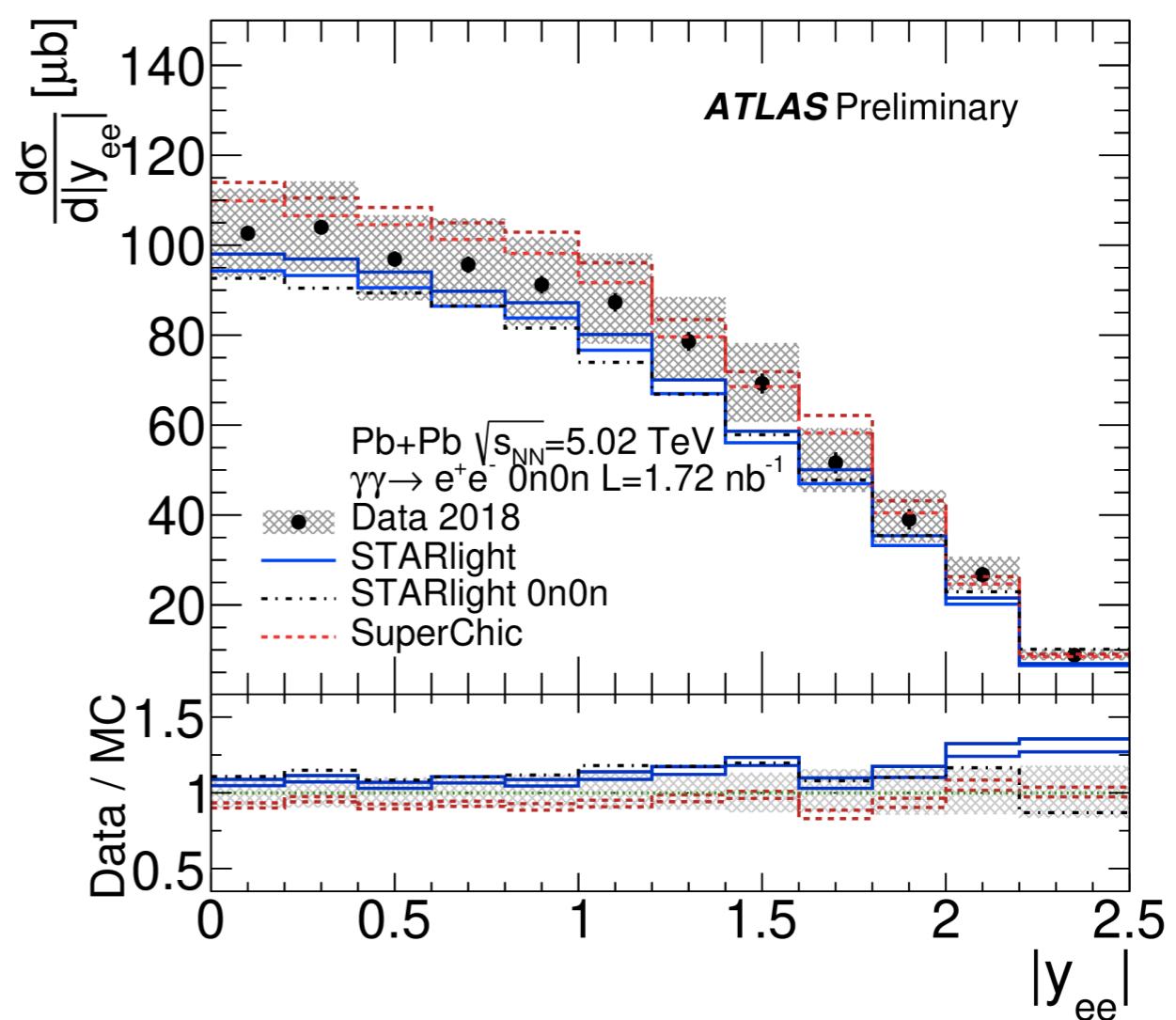
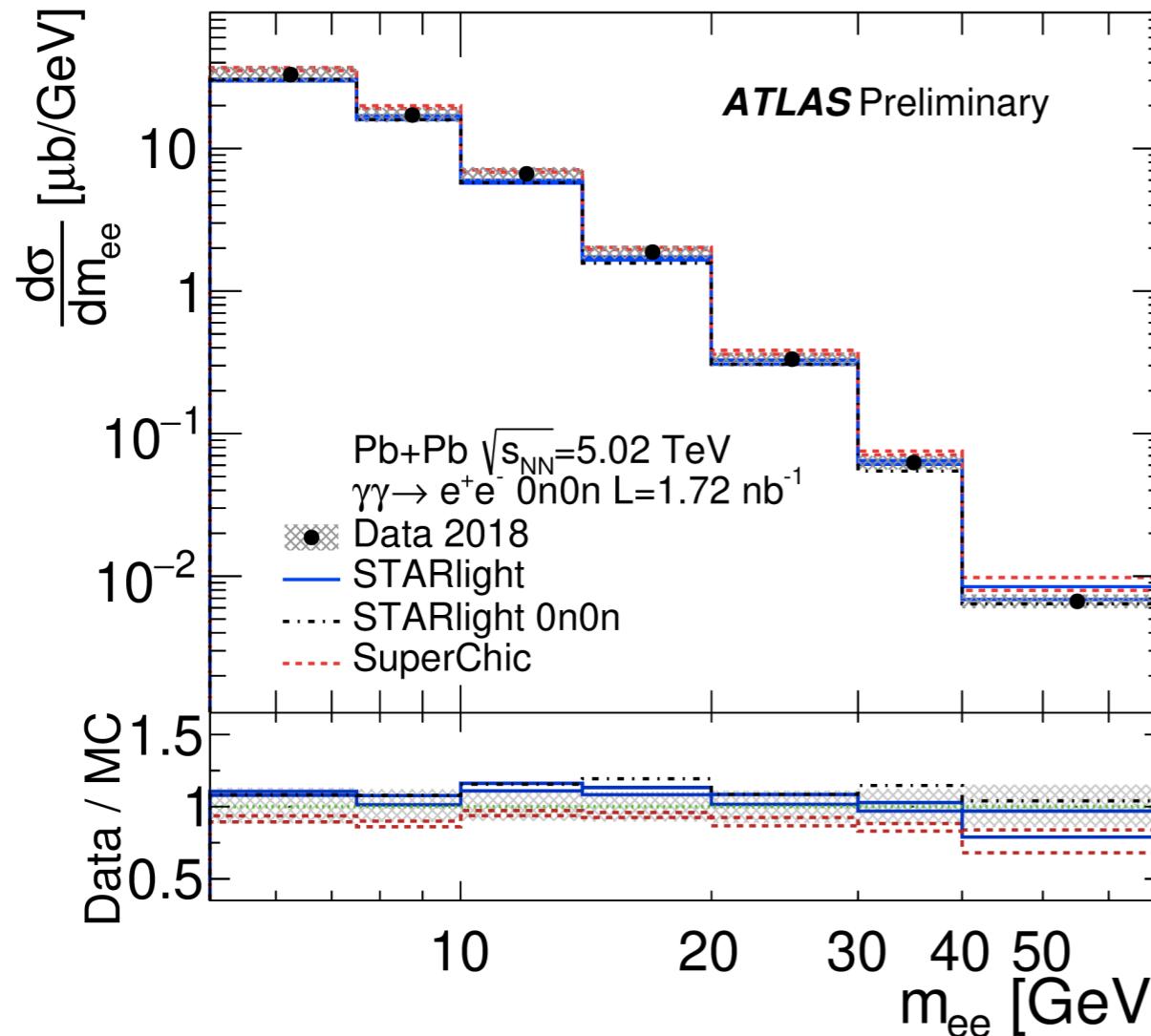
- **ZDC** are 140 m away from the IP ( $|\eta| > 8.3$ )
  - Detect neutral particles (e.g. neutrons, photons)
- Inclusive sample of  $\gamma\gamma \rightarrow \ell^+\ell^-$  can be divided into three categories
  - **On0n**: no activity in either ZDC arm
  - **Xn0n**: activity in one ZDC arm
  - **XnXn**: activity in both ZDC arms
- Fractions of events falling to each category  $f_{\text{On0n}}, f_{\text{Xn0n}}, f_{\text{XnXn}}$  are measured
  - After subtracting backgrounds and accounting for electromagnetic pileup
- **Each category** probes different **impact parameters (b)**

# EXCLUSIVE DIMUONS: FORWARD ACTIVITY



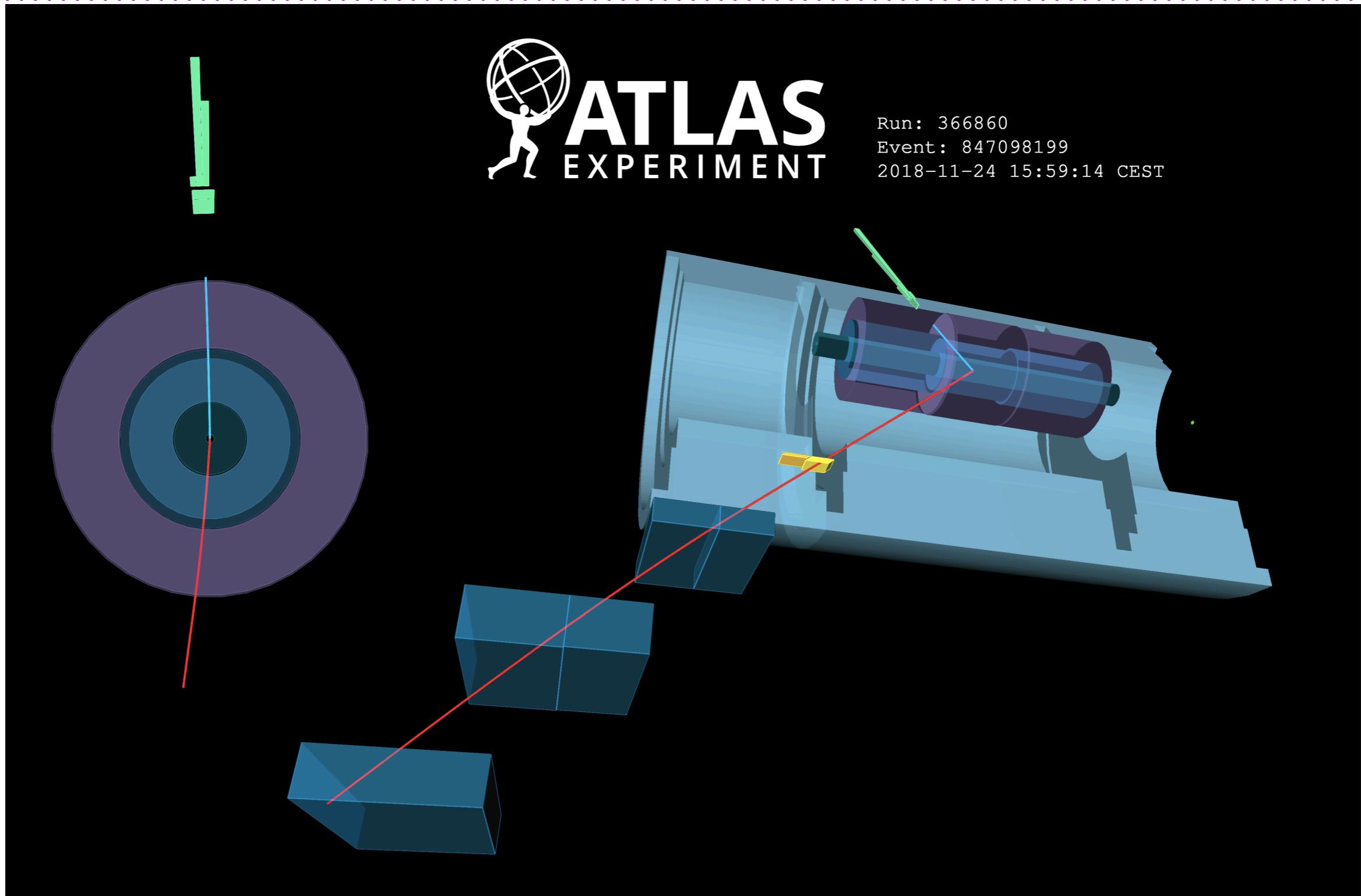
- Raw and **corrected fractions** of events in **Xn0n** and **XnXn** categories as a function of  $|y_{\mu\mu}|$  (left) and  $m_{\mu\mu}$  (right)
  - Corrected fractions are lower after accounting for electromagnetic pileup
  - $f_{Xn0n}, f_{XnXn}$  decrease with  $|y_{\mu\mu}|$  and increase with  $m_{\mu\mu}$
  - STARlight describes the shapes well but overestimates the value

# EXCLUSIVE DIELECTRONS: ONON CROSS SECTIONS



- Differential cross sections measured in  $m_{ee}$ ,  $|y_{ee}|$ ,  $\langle p_T^e \rangle$  and  $|\cos \theta^*|$  in the **0n0n category**
  - **STARlight** provides predictions for **neutron production** (black dotted line)
  - Use **measured 0n0n fractions with uncertainties** to correct both STARlight and SuperChic predictions
- General conclusions similar to the inclusive ZDC case
  - **STARlight 3.13 (SuperChic 3.05)** systematically lower (higher) than data
  - SuperChic does a better job in description of shapes

# EXCLUSIVE DITAUS



- Event candidate for  $\gamma\gamma \rightarrow \tau^+\tau^- \rightarrow e^+\nu_e\nu_\tau\mu^-\nu_\mu\nu_\tau$

# EXCLUSIVE DITAU

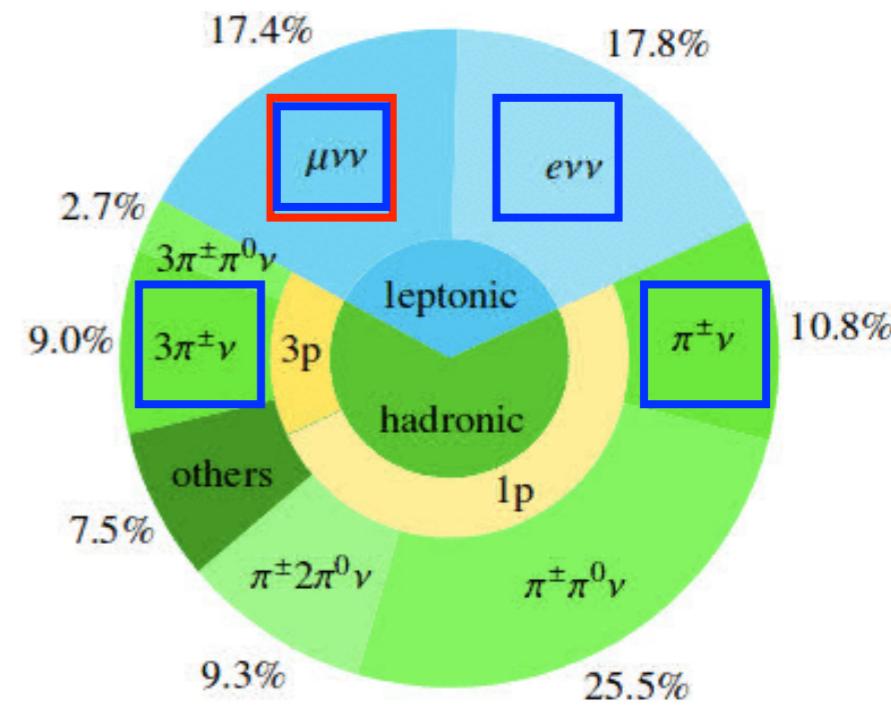
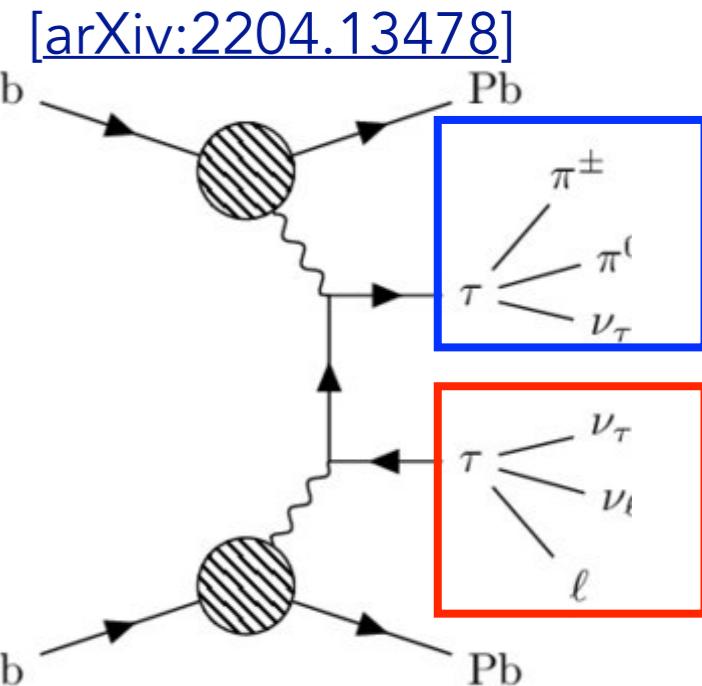
- **NEW First observation** of  $\tau$  leptons in A+A collisions in 2018 UPC Pb+Pb collisions of  $1.44 \text{ nb}^{-1}$
- Exclusive ditau production  $\gamma\gamma \rightarrow \tau^+\tau^-$  with **semileptonic decay** modes
  - $\mu 1T\text{-SR}$ : muon + 1 track (e/ $\mu$ /hadron)
  - $\mu 3T\text{-SR}$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

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

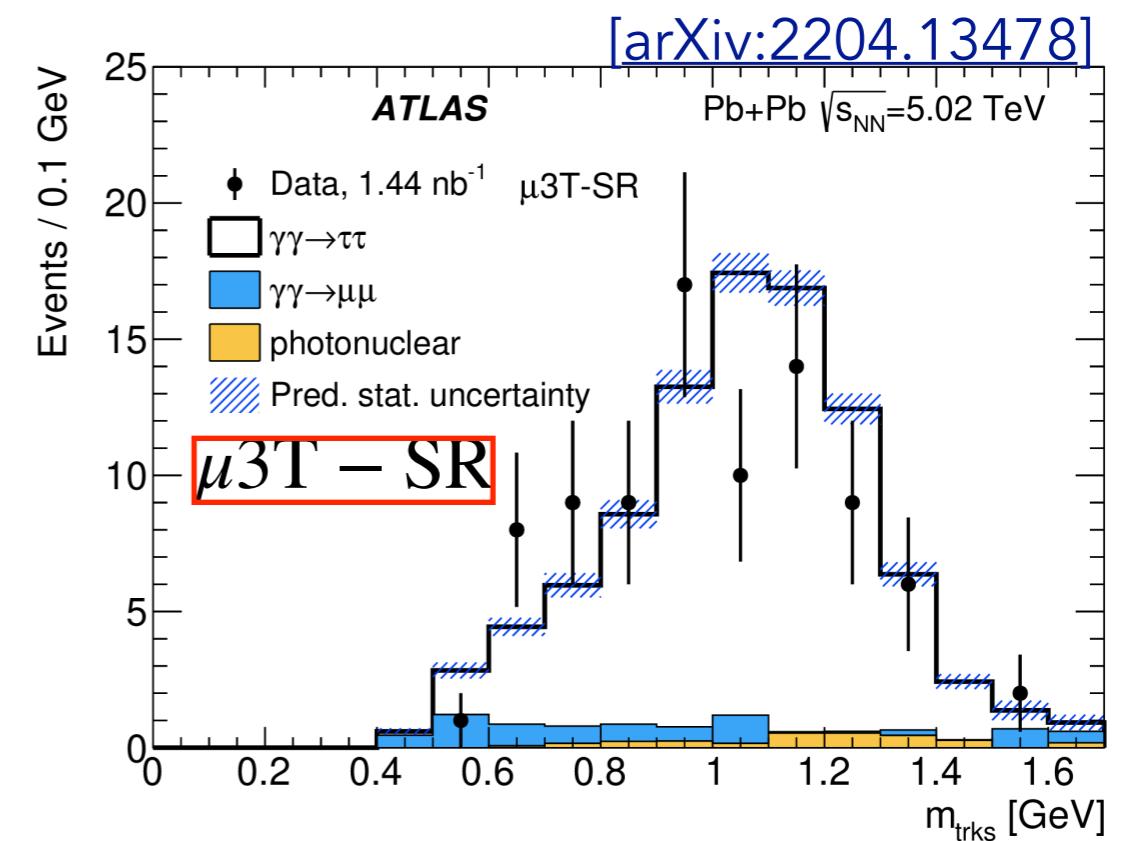
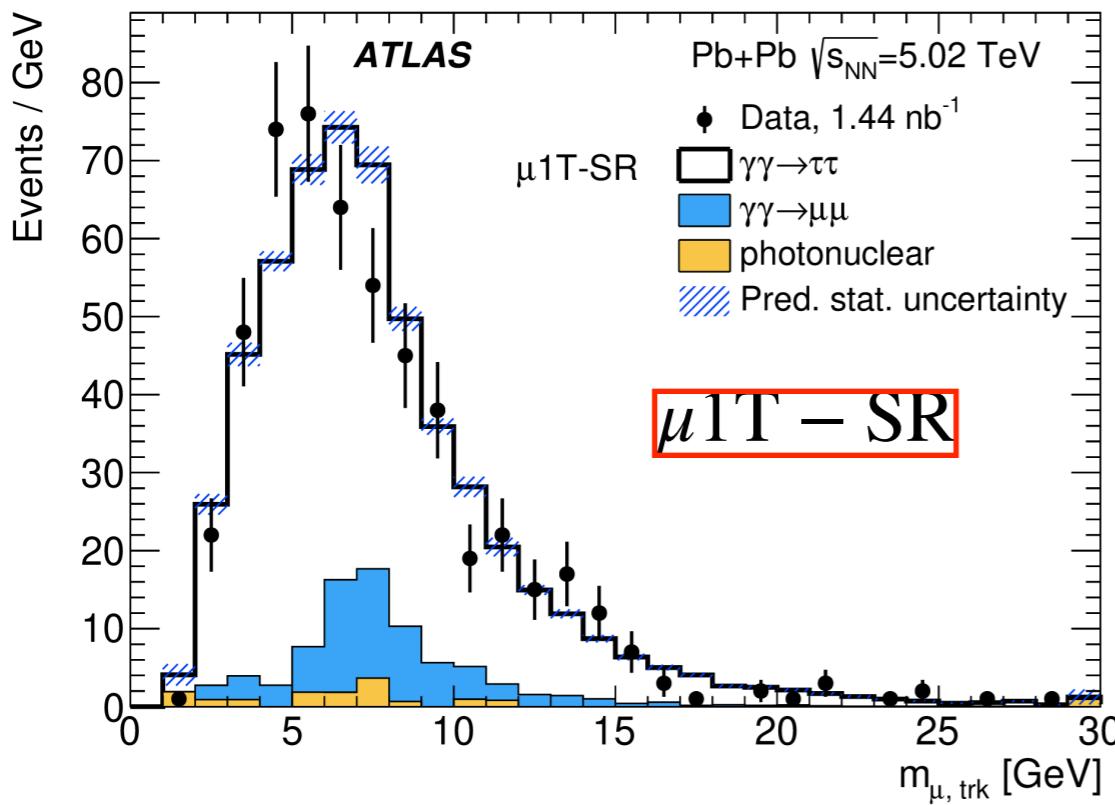
$p_T^{\text{clus}} > 1 \text{ GeV}$  ( $|\eta| < 2.5$ )

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

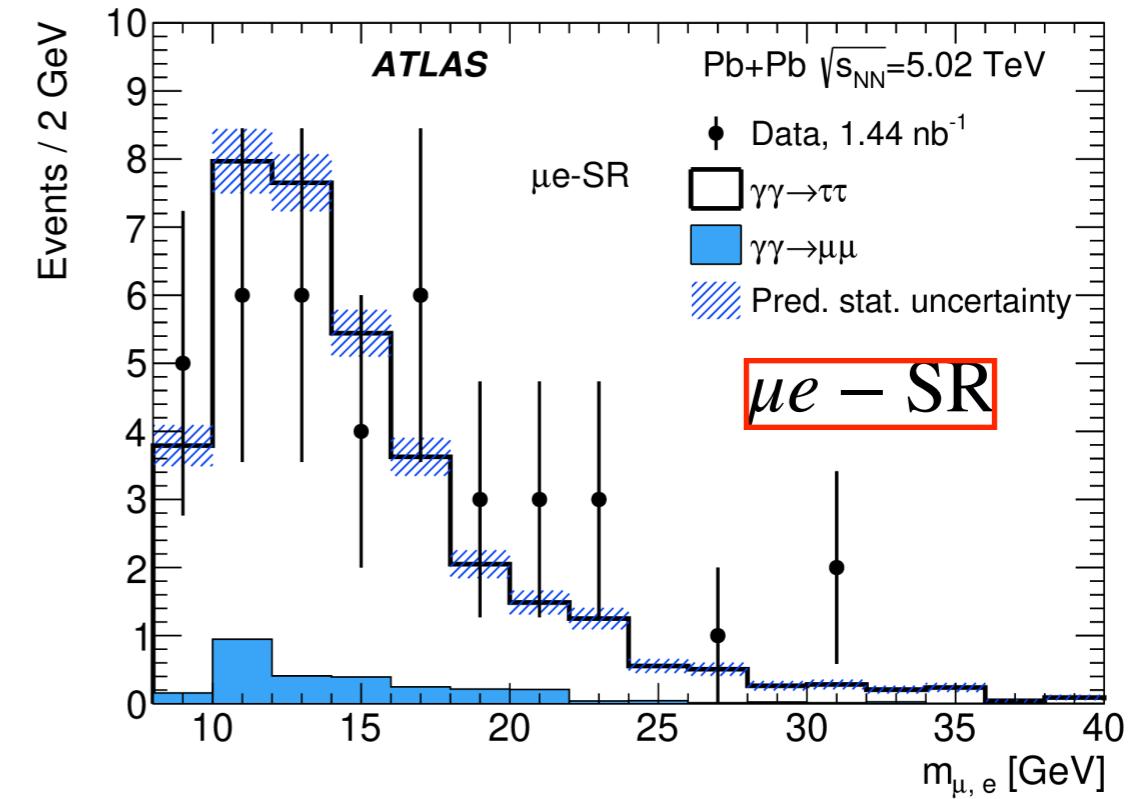
- Exclusivity: veto additional clusters ( $\mu 1T\text{-SR}$  and  $\mu 3T\text{-SR}$  only) and tracks
- Total of  $\sim 650$  events across all SRs
- Only **data** in the **OnOn category** used to suppress photonuclear/hadronic backgrounds
- Simulation (**STARlight+Tauola**) reweighted to OnOn with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



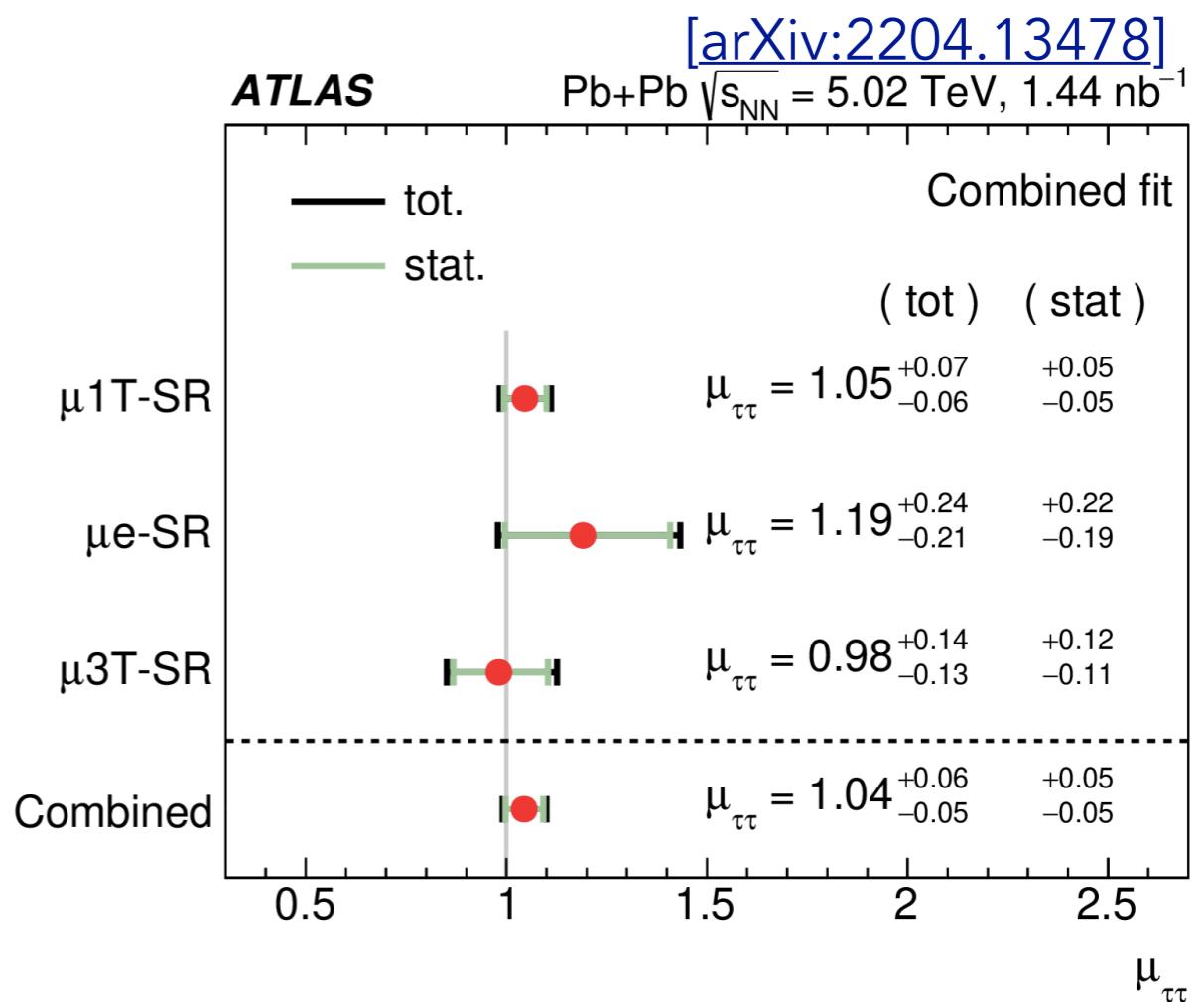
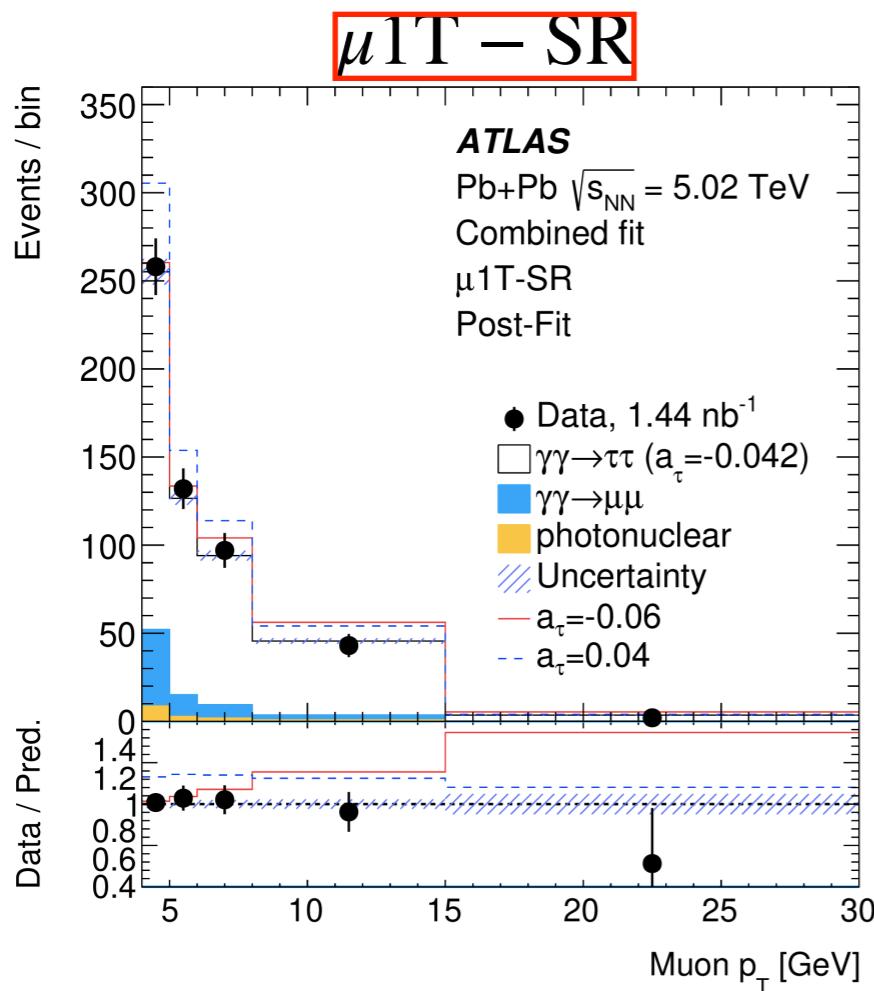
# EXCLUSIVE DITAU: CONTROL PLOTS



- 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

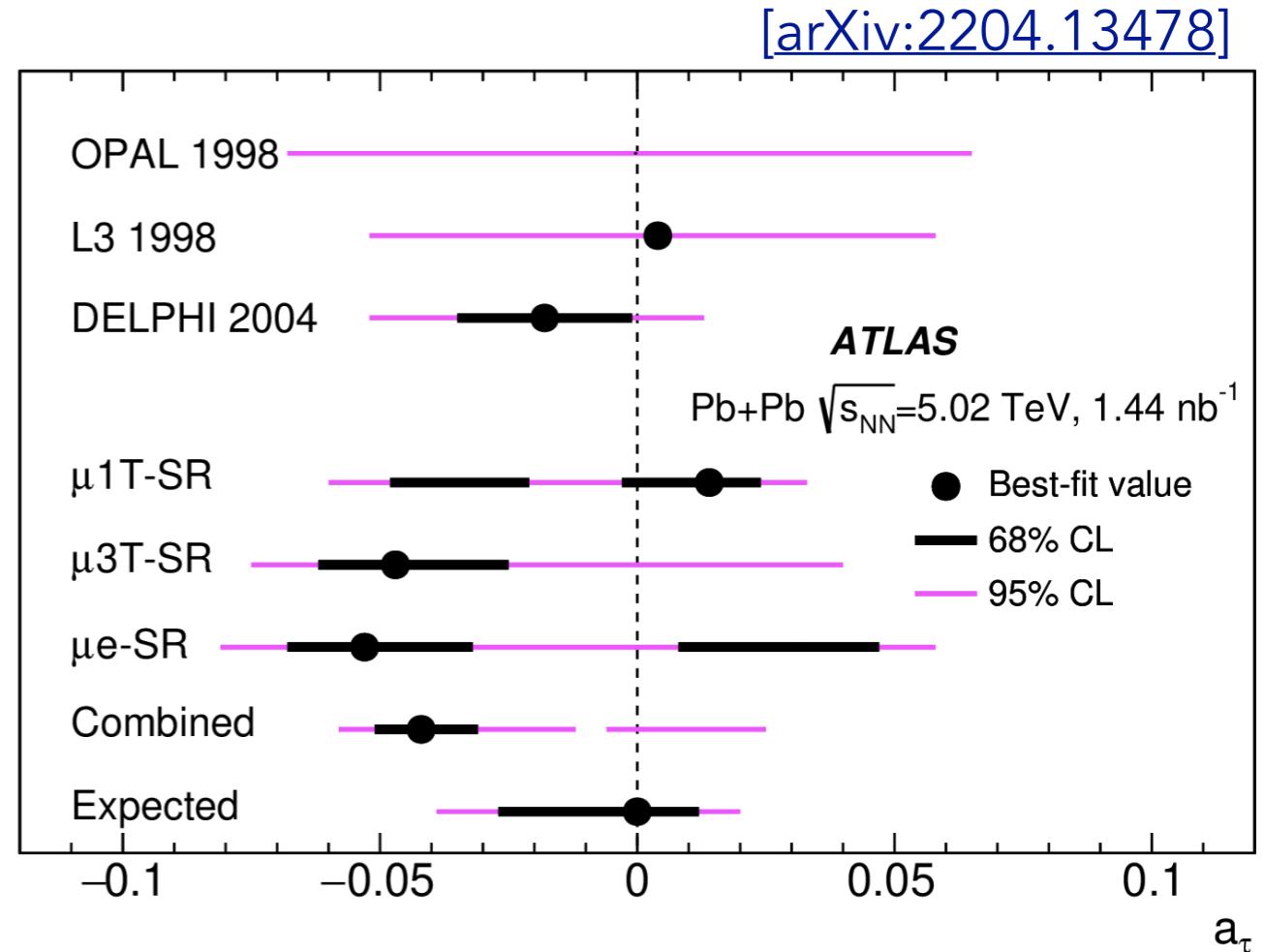
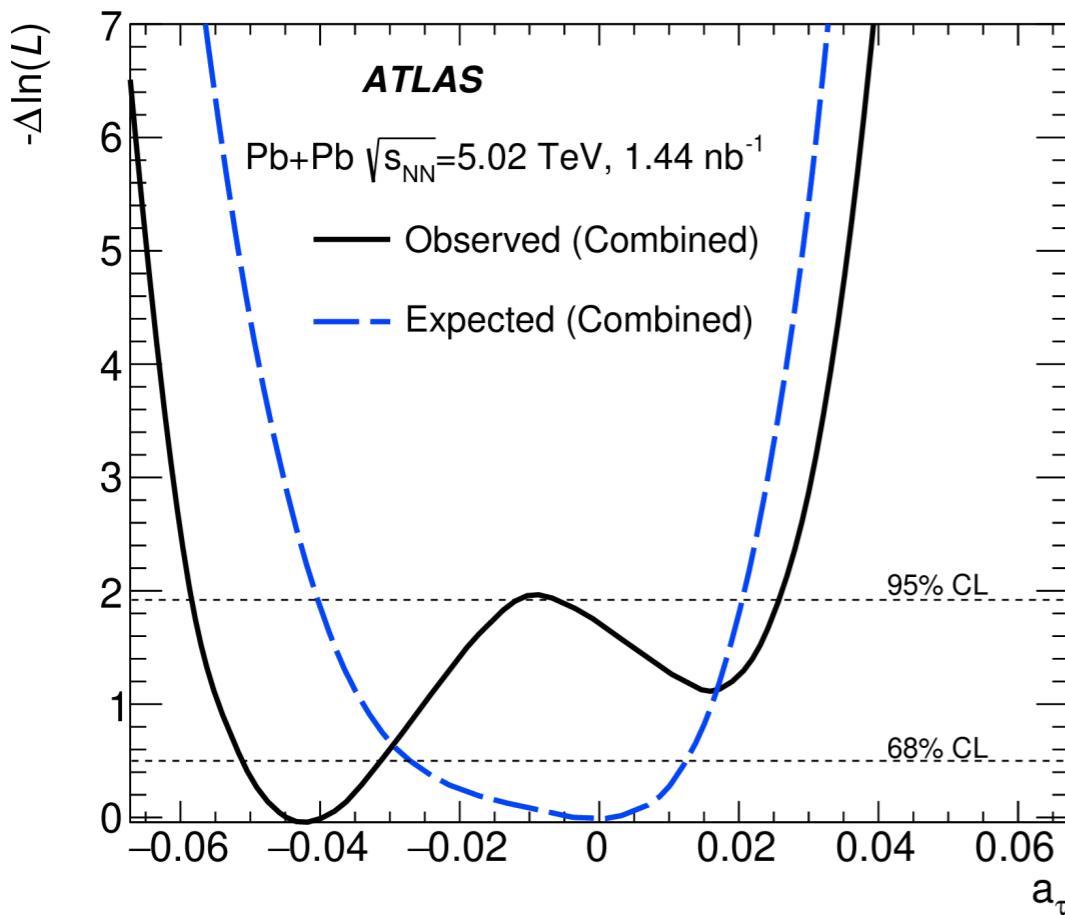


# EXCLUSIVE DITAUS: SIGNAL STRENGTH



- Measure  $\gamma\gamma \rightarrow \tau^+\tau^-$  signal strength  $\mu_{\tau\tau} = N_{\gamma\gamma \rightarrow \tau\tau}^{\text{meas}} / N_{\gamma\gamma \rightarrow \tau\tau}^{\text{SM,pred}}$  and  $a_\tau$  using profile likelihood fit to the  $p_T^\mu$  **distribution** in the three SRs and 2 $\mu$ -CR
- Result of  $\mu_{\tau\tau}$  for each SR assuming  $a_\tau$  from SM **compatible with unity**

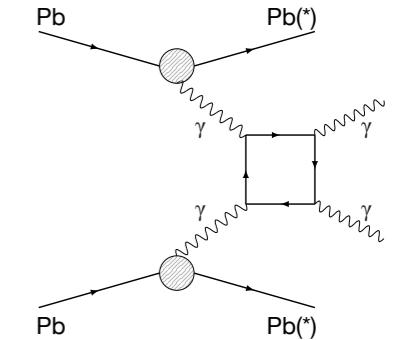
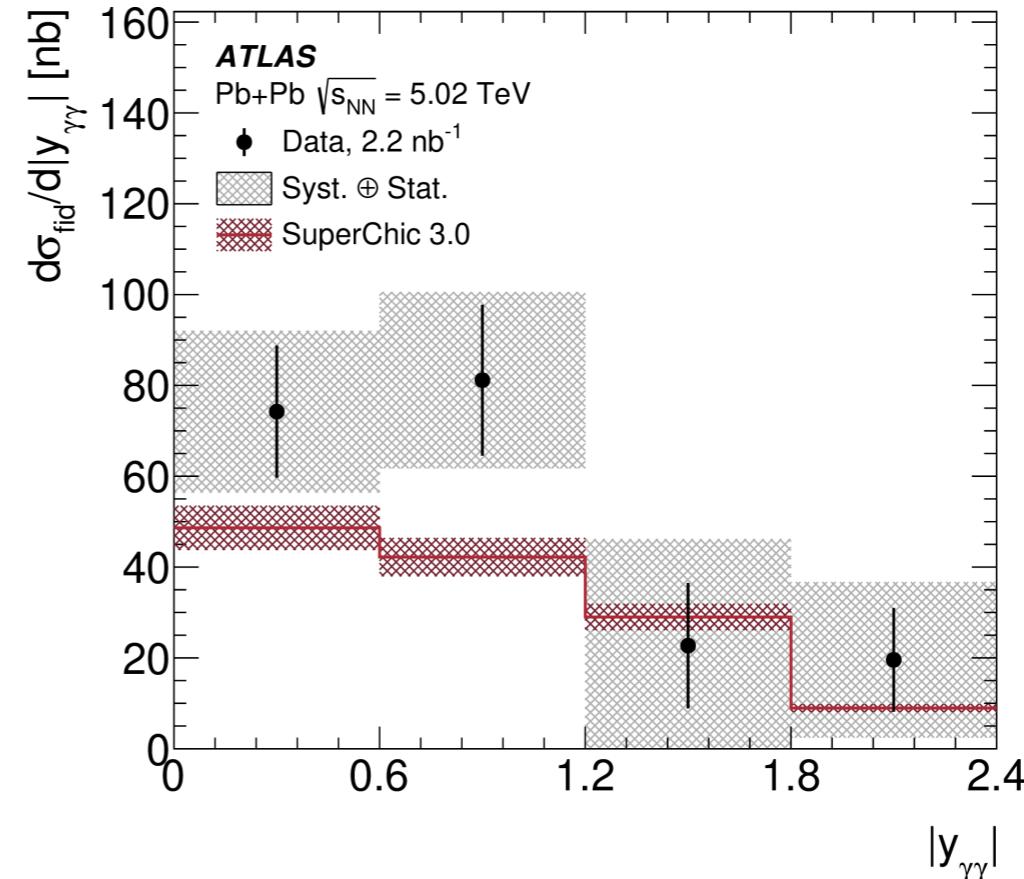
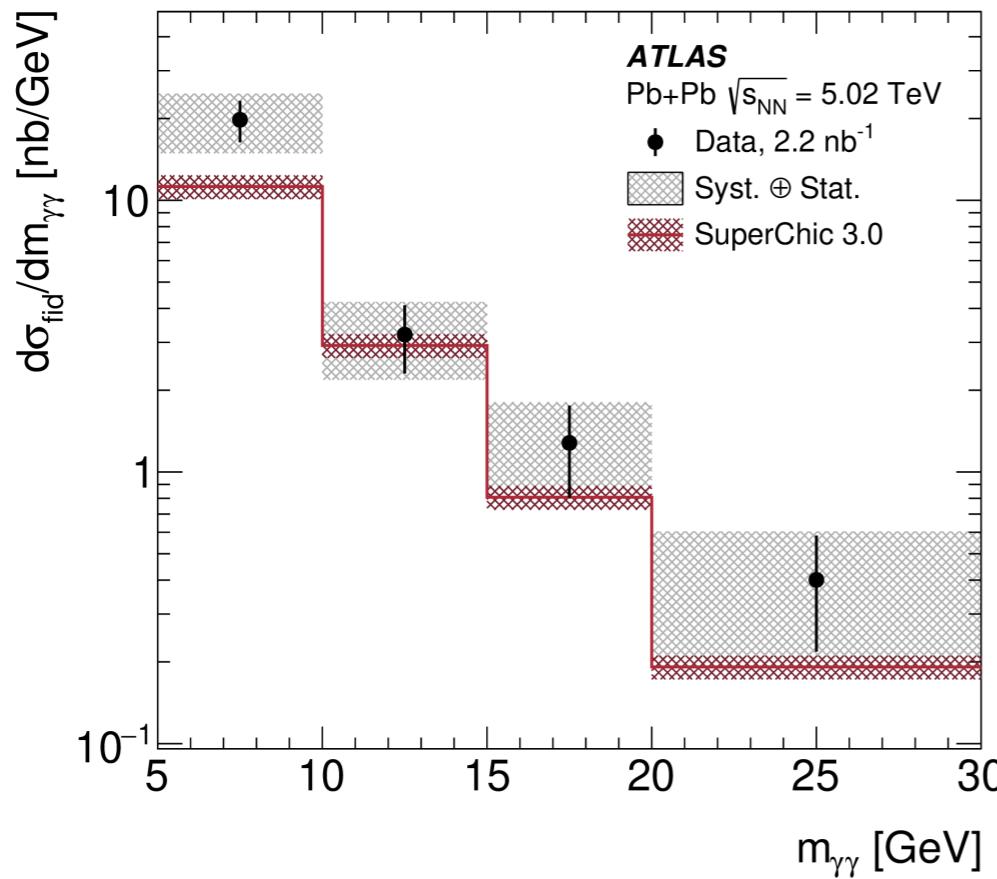
# EXCLUSIVE DITAUS: TAU MAGNETIC MOMENT



- Measure  $a_\tau = \frac{g-2}{2}$  using profile likelihood fit to the  $p_T^\mu$  **distribution** in the three SRs and 2 $\mu$ -CR
- Templates built for different  $a_\tau$  values by reweighting signal MC using weights from [\[PLB 809 \(2020\) 135682\]](#)
- Expected 95% CL limits from the combined fit:  $-0.039 < a_\tau < 0.020$
- Observed 95% CL limits:  $a_\tau \in (-0.058, -0.012) \cup (-0.006, 0.025)$ 
  - Double-interval structure due to interference of SM and BSM amplitudes
- **Constraints on  $a_\tau$  similar** to those observed by **DELPHI**

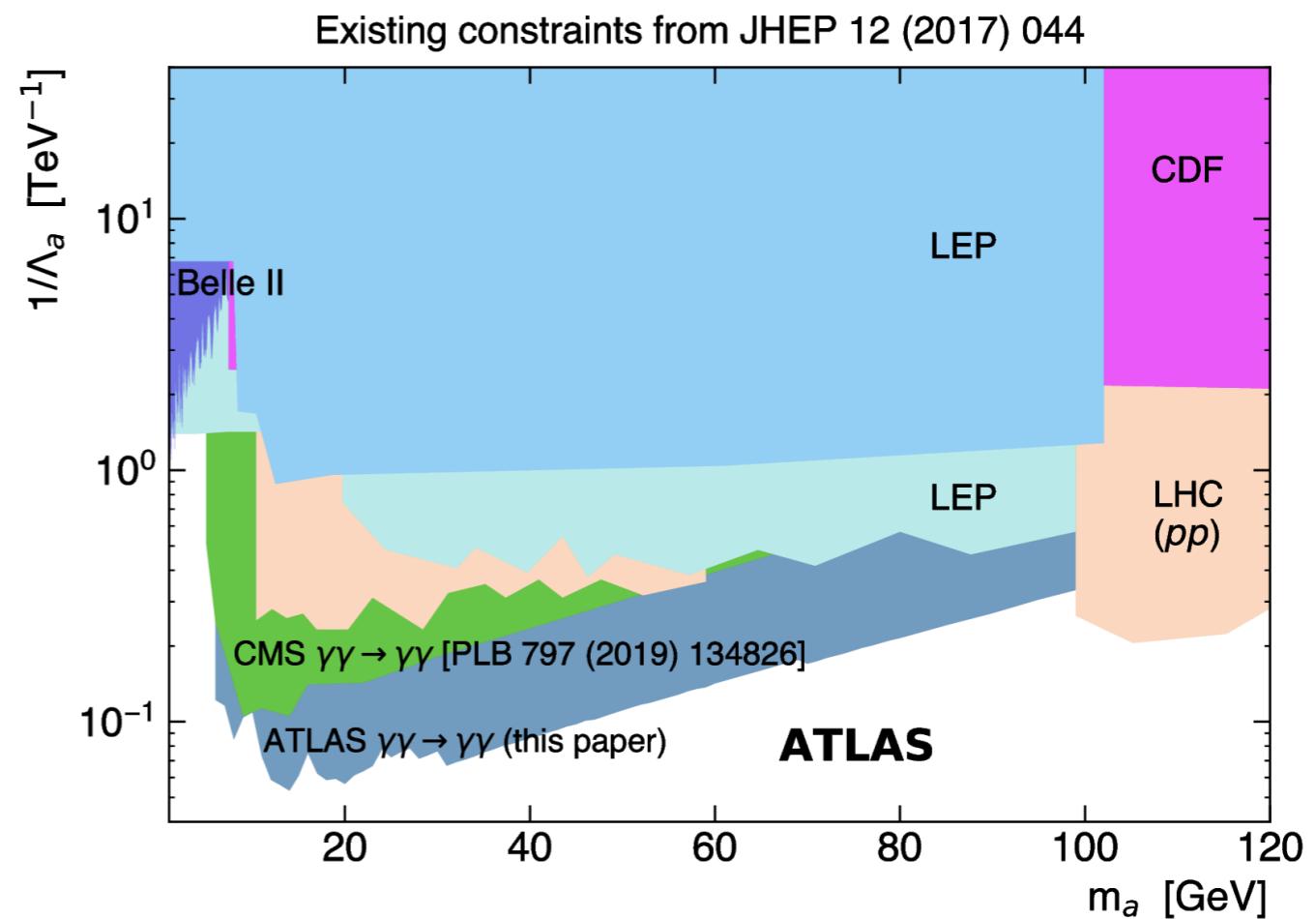
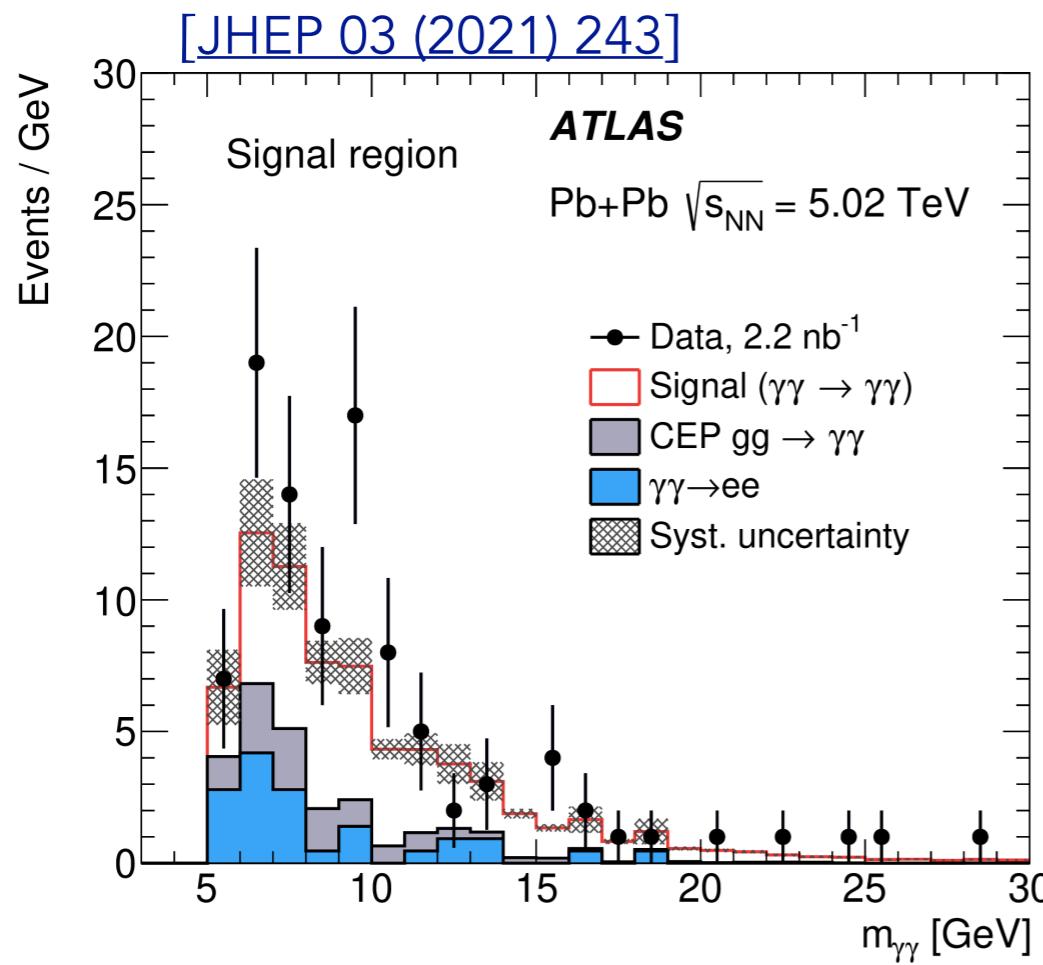
# LIGHT-BY-LIGHT SCATTERING: CROSS SECTIONS

[JHEP 03 (2021) 243]

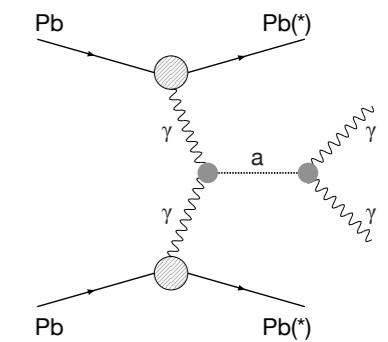


- Light-by-light scattering is a **rare fundamental** QED process
  - Observed in a direct way at the LHC for the first time [[PRL 123 \(2019\) 052001](#)]
  - About **100 event** candidates in combined **2015+2018** (full Run 2) UPC Pb+Pb data
- Cross sections measured in the fiducial region  $E_T^\gamma > 2.5 \text{ GeV}$ ,  $m_{\gamma\gamma} > 5 \text{ GeV}$ ,  $|\eta^\gamma| < 2.4$ ,  $p_T^{\gamma\gamma} < 1 \text{ GeV}$ 
  - Differential in  $m_{\gamma\gamma}$ ,  $|y_{\gamma\gamma}|$ ,  $|\cos \theta^*|$ ,  $(p_T^{\gamma 1} + p_T^{\gamma 2})/2$
  - **Good agreement in shape**, differences in the normalisation
  - **Theory predictions** from [[PRC 93 \(2016\) 044907](#)] and [[EPJ C 79 \(2019\) 39](#)] about **50% below** data

# SEARCH FOR ALP



- Distribution of  $m_{\gamma\gamma}$  used to **search for ALP** in  $6 < m_{\gamma\gamma} < 100$  GeV range using a cut-and-count method
  - Signal:  $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ ,  $\text{BR}(a \rightarrow \gamma\gamma) = 100\%$
  - Background: LbyL,  $\gamma\gamma \rightarrow e^+e^-$ , central exclusive production of  $gg \rightarrow \gamma\gamma$
- 95% CL limits on  $\sigma$  and coupling  $1/\Lambda_a$ 
  - Largest deviation of  $2.1\sigma$  at  $m_{\gamma\gamma} \sim 10$  GeV
  - **The most stringent limit** established for ALP masses between 6-100 GeV

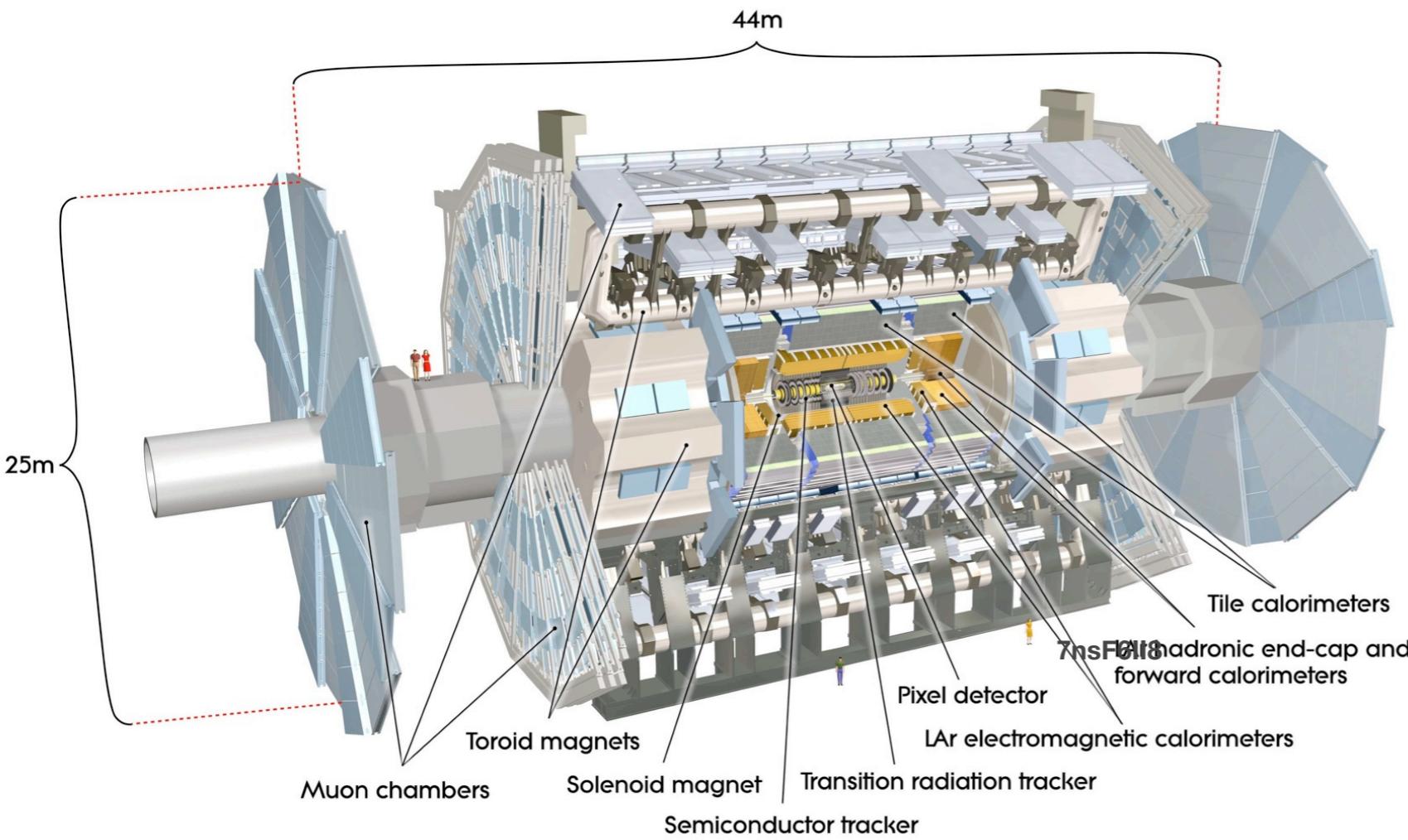


# SUMMARY AND OUTLOOK

- 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
    - **SuperChic** gets the spectral shape right but generally over predicts, suggesting recent discussions on higher order Coulomb effects [[JHEP 2021 \(2021\) 83](#)]
  - Dimuon and dielectron channels limited by **systematic uncertainties**
  - **ZDC** provides constraints for **background** and **impact-parameter dependence**
  - **FSR** needs to be accounted for to get a good description of data
- ATLAS shows a **first final measurement** of exclusive **ditaunu** production in UPC Pb+Pb collisions at the LHC with above  $5\sigma$  **significance**
  - Data is used to **constrain**  $a_\tau$  at the LHC
  - **Precision is comparable** to the DELPHI best limit from the LEP era
- Final light-by-light measurement from ATLAS available from the full Run 2 Pb+Pb data
  - Input to the **first combination** of ATLAS+CMS data at the LHC [[arXiv:2204.02845](#)] **NEW**
- UPC Pb+Pb proves to provide **constraints for BSM physics**
  - **Most stringent** limits on ALP production for  $6 < m_a < 100$  GeV established
- Data taking is about to start in LHC Run 3
  - Expect to **double integrated luminosity** at the end of 2022, a factor of **3.5** more after Run 3
- All results from ATLAS available at  
<https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults>

# BACK-UP SLIDES

# ATLAS DETECTOR



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

**Electrons:** inner tracker, EM calo

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

**Muons:** inner tracker, muon system

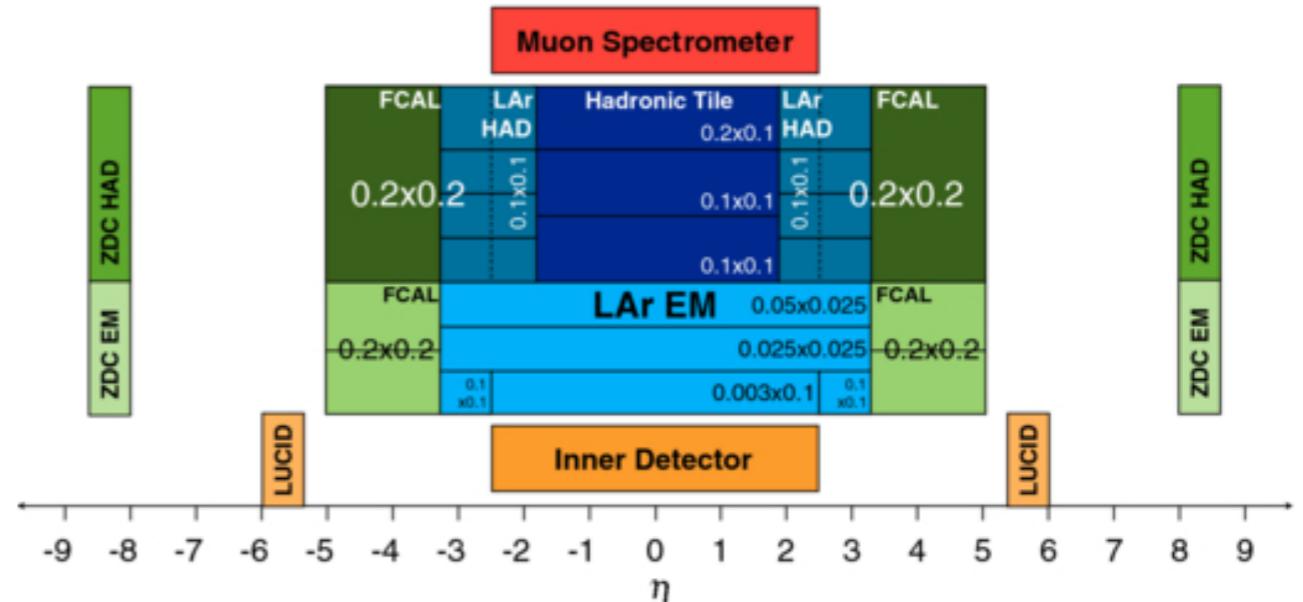
$$p_T^\mu > 20 \text{ (25) GeV for } Z (W^\pm)$$

**Charged particles:** inner tracker

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

**Neutrons:** Zero Degree Calorimeter

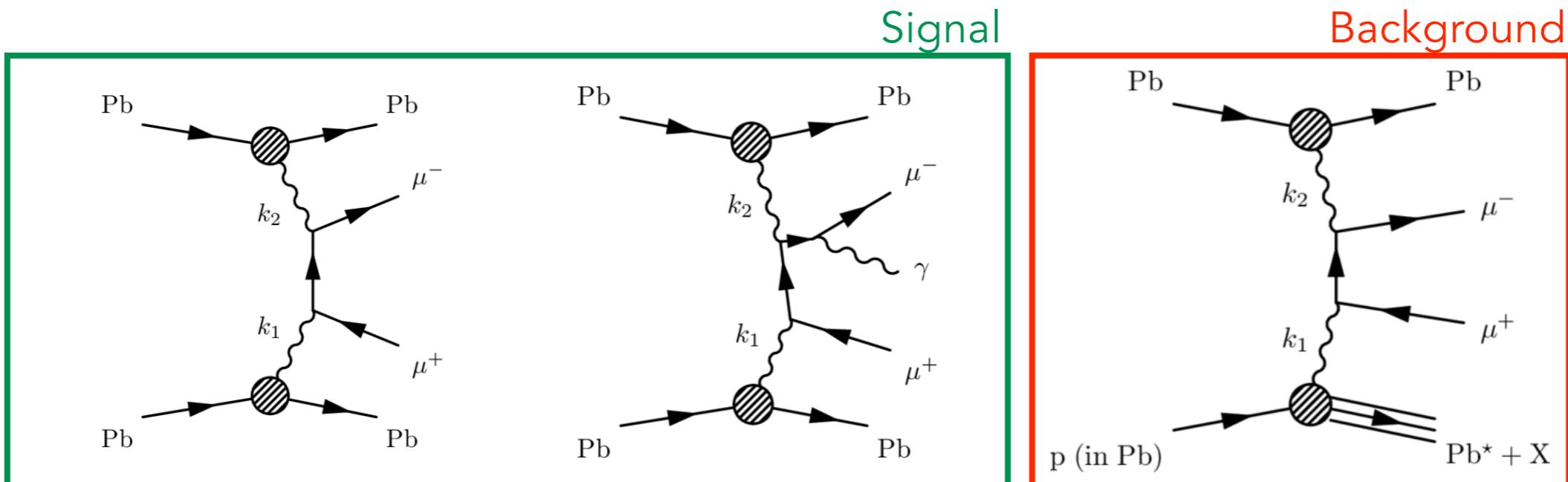
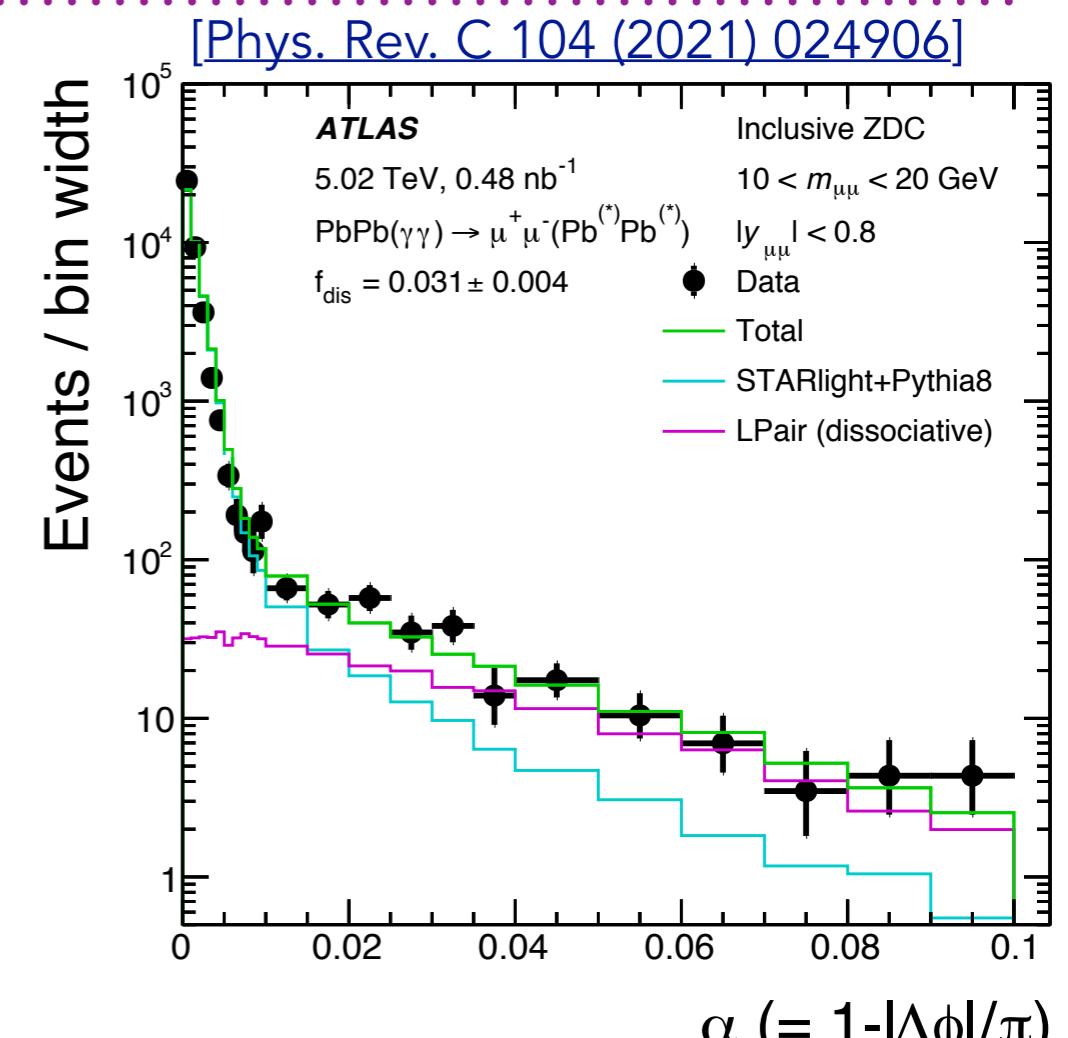
$$|\eta| > 8$$



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

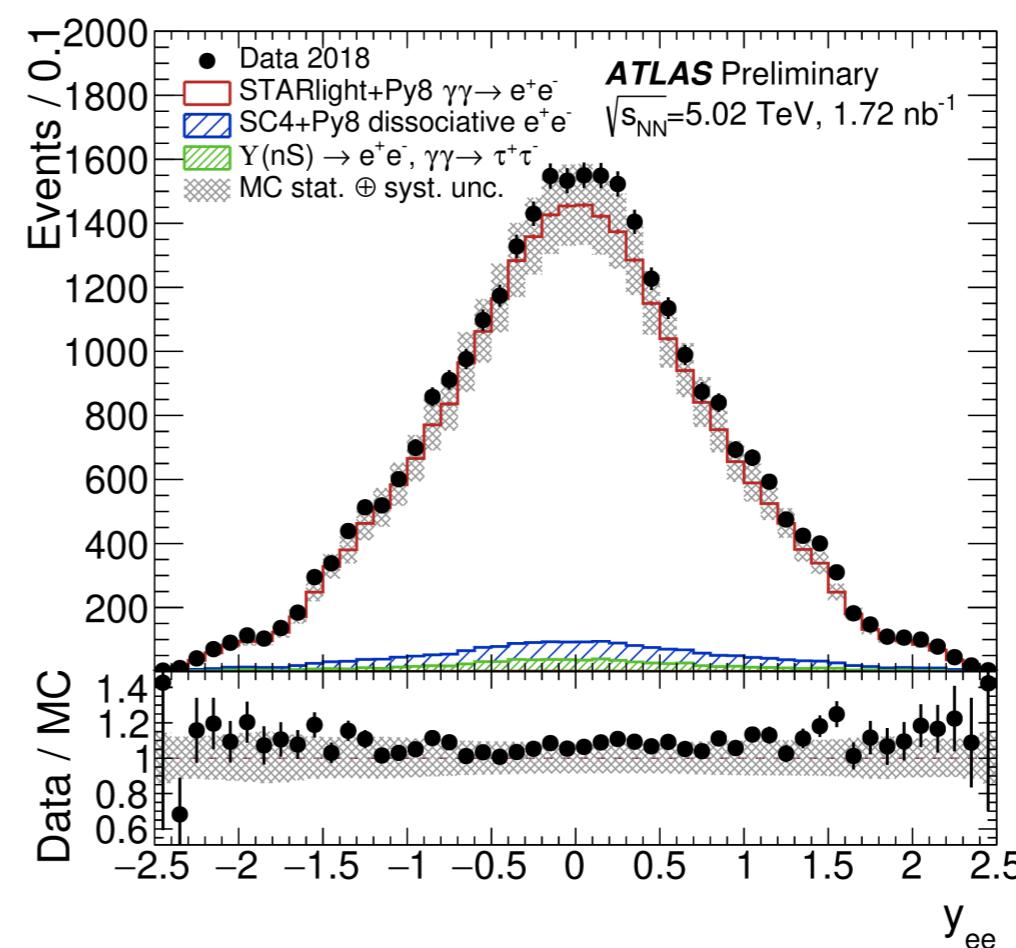
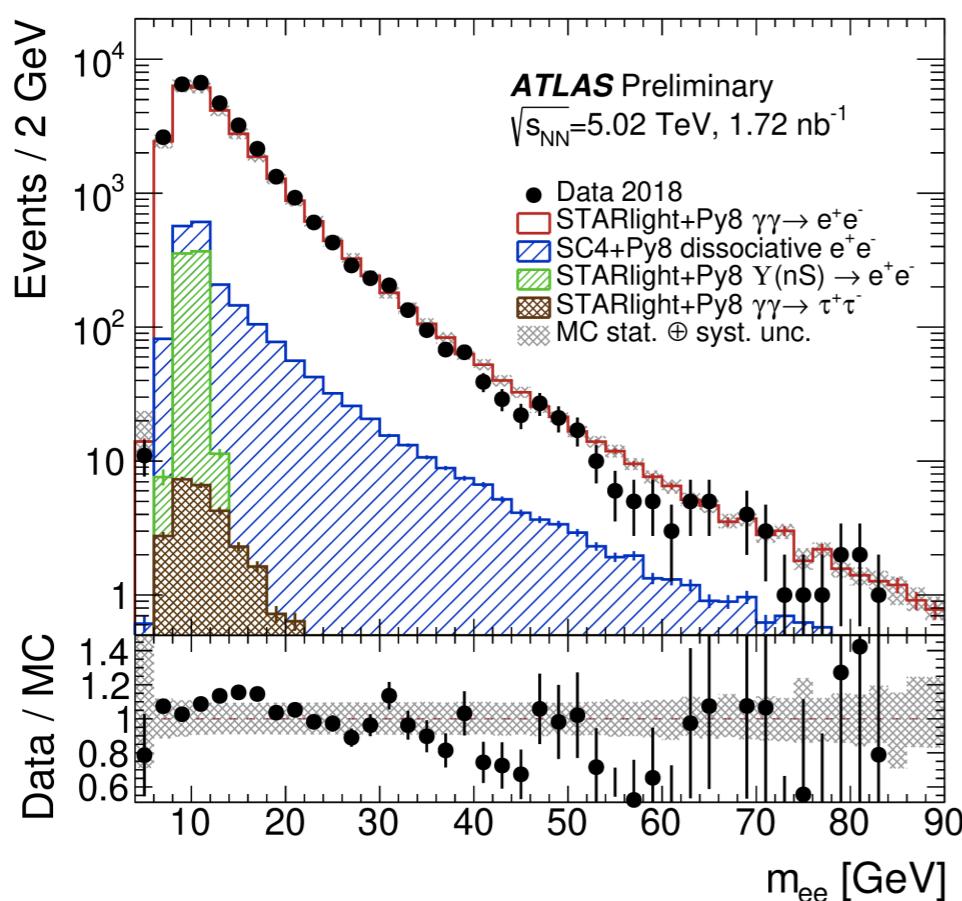
# EXCLUSIVE DIMUONS

- Data set from **2015 Pb+Pb** collisions of  $0.49 \text{ nb}^{-1}$
- Production measured in the fiducial region defined by:  
 $p_T^\mu > 4 \text{ GeV}$ ,  $|\eta^\mu| < 2.4$ ,  $m_{\mu\mu} > 10 \text{ GeV}$  and  
 $p_T^{\mu\mu} < 2 \text{ GeV}$
- About **12k event** candidates
- Background from **single-dissociative** processes (3%) subtracted using a template fitting to the acoplanarity  $\alpha$  distribution
  - Contribution from FSR important to have a good description of  $\alpha$  distribution  
**(STARlight+Pythia8)**

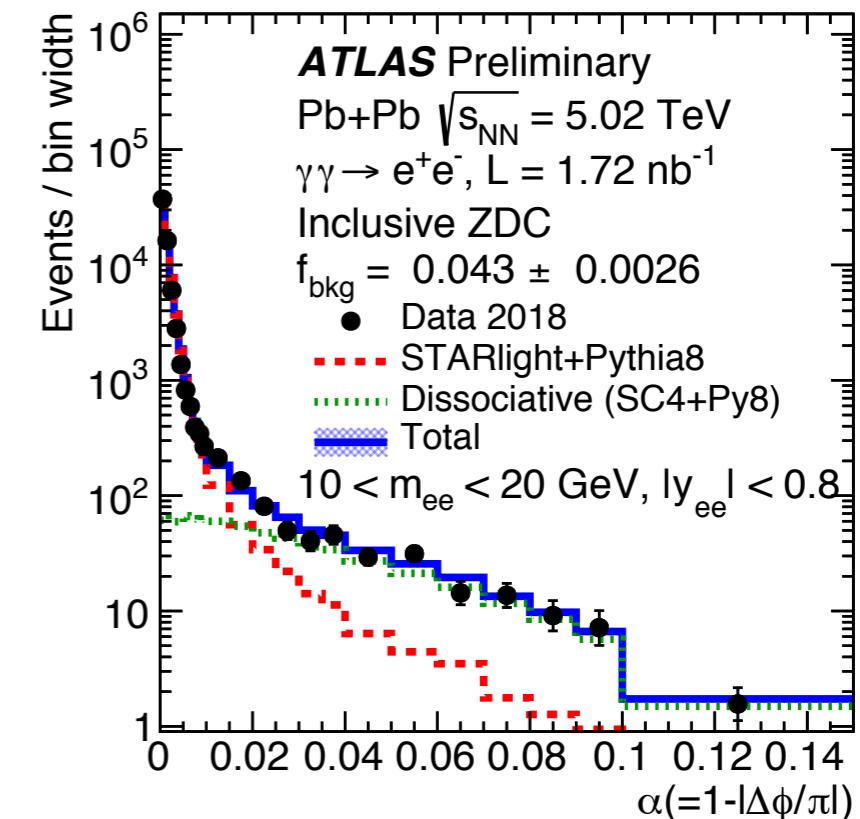


# EXCLUSIVE DIELECTRONS

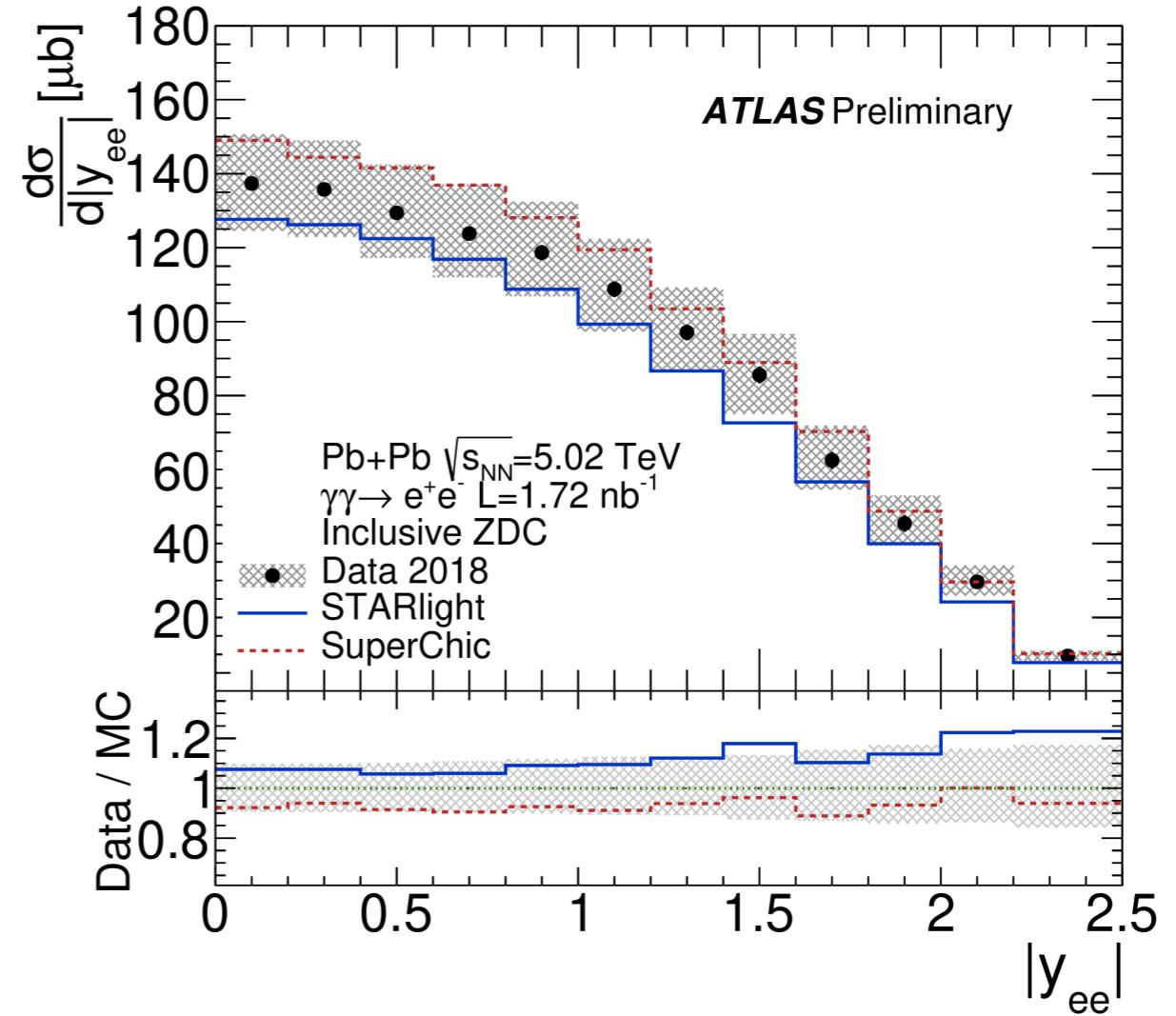
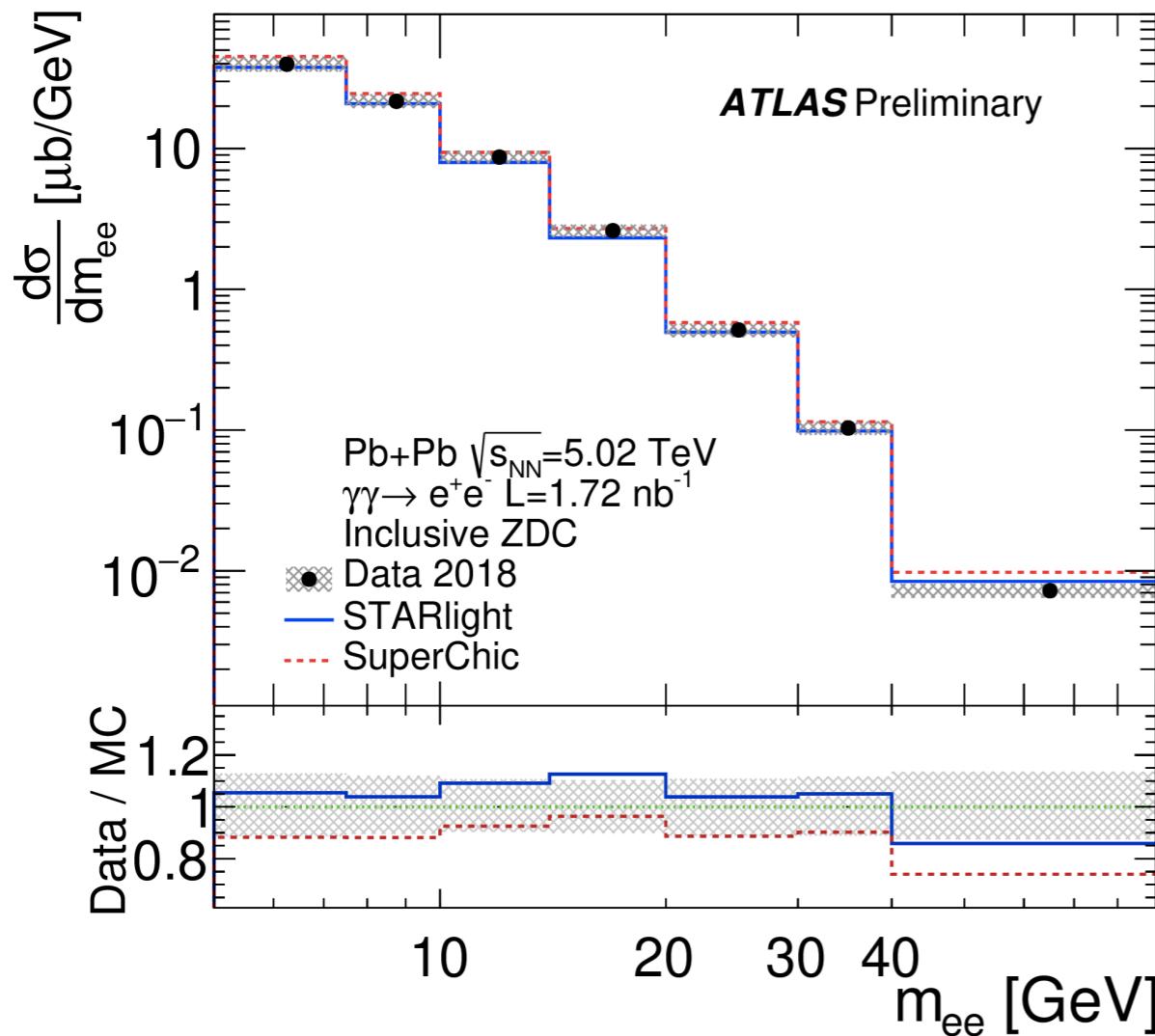
- Data set from **2018** UPC Pb+Pb collisions of  $1.72 \text{ nb}^{-1}$
- Production measured in the **fiducial region** defined by:  
 $p_T^e > 2.5 \text{ GeV}$ ,  $|\eta^e| < 2.5$ ,  $m_{ee} > 5 \text{ GeV}$  and  $p_T^{ee} < 2 \text{ GeV}$
- About **30k event** candidates
- Dissociative background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



[ATLAS-CONF-2022-025]



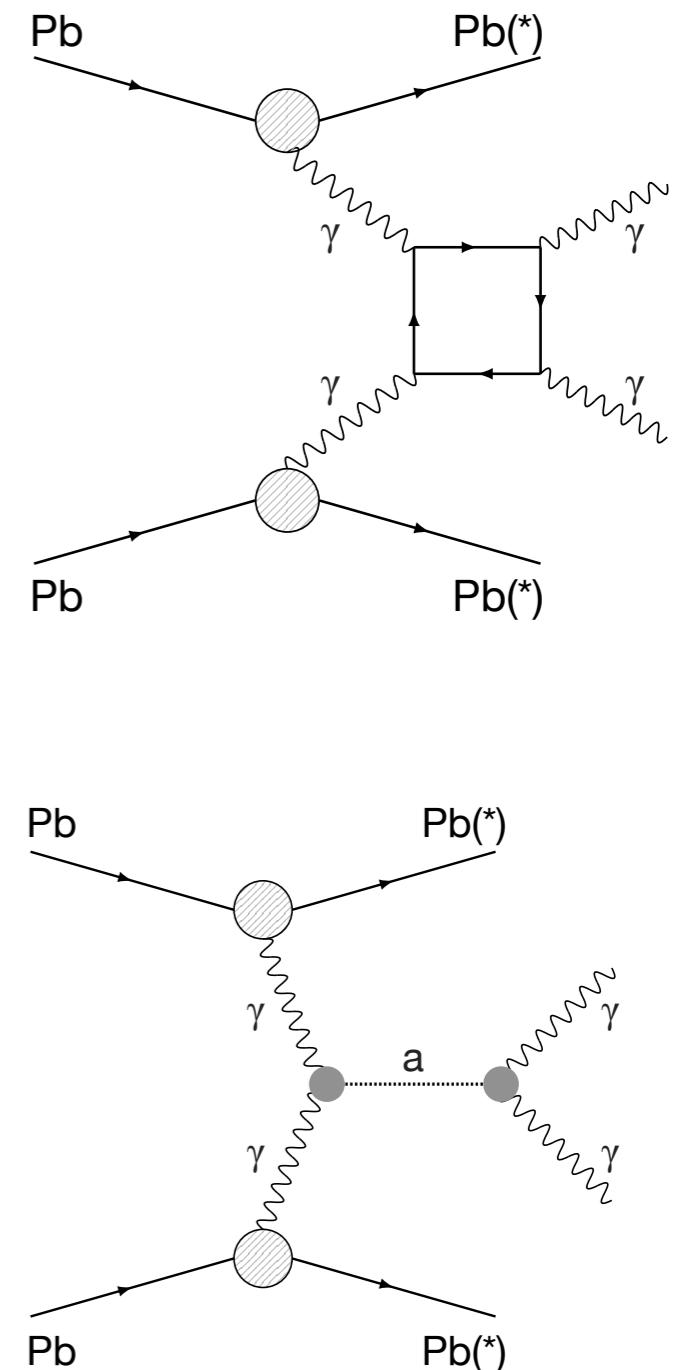
# EXCLUSIVE DIELECTRONS: INCLUSIVE CROSS SECTIONS



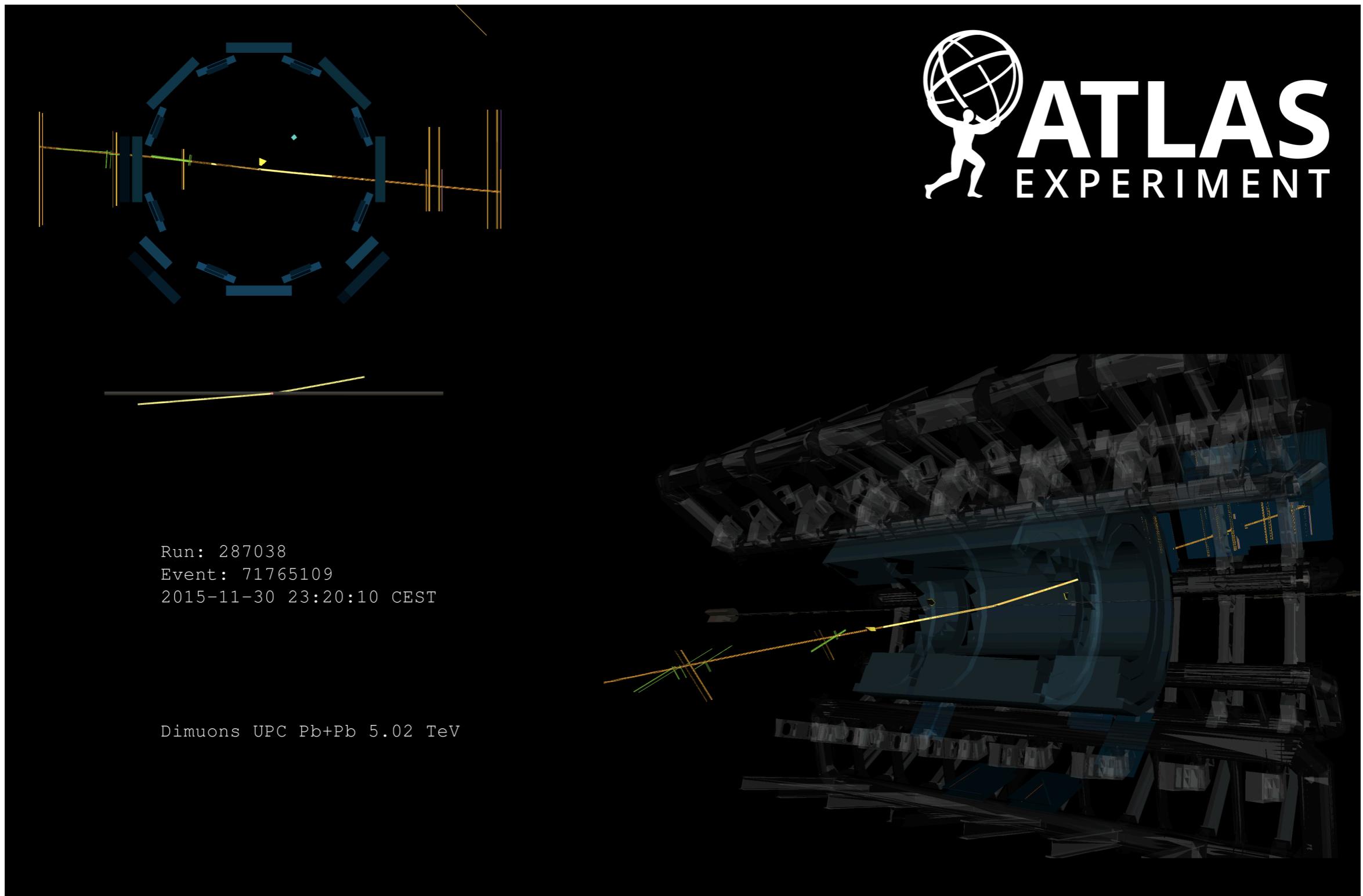
- Differential cross sections measured in  $m_{ee}$ ,  $|y_{ee}|$ ,  $\langle p_T^e \rangle$  and  $|\cos \theta^*|$  for the **inclusive ZDC sample**
  - **STARlight 3.13 (SuperChic 3.05)** systematically lower (higher) than data
  - Fairly good description of shapes

# LIGHT-BY-LIGHT SCATTERING AND AXIONS

- Final result on **LbyL scattering** ( $\gamma\gamma \rightarrow \gamma\gamma$ ) from ATLAS
  - Fundamental QED process with a **tiny cross section**
    - Prior to the LHC, tested indirectly (anomalous magnetic moment of the electron and muon)
  - **Sensitive to new physics**
    - Possible contributions from new particles beyond SM
    - Anomalous gauge couplings
- Earlier results at the LHC:
  - **Evidence with 2015** data: ATLAS and CMS [[Nat. Phys. 13 \(2017\) 852–858](#), [Phys. Lett. B 797 \(2019\) 134826](#)]
  - **Observation with 2018** data: ATLAS [[Phys. Rev. Lett. 123 \(2019\) 052001](#)]
- Several improvements introduced in **the final publication**:
  - All Run-2 Pb+Pb data (2015+2018):  **$2.2 \text{ nb}^{-1}$**
  - **Improved luminosity** calibration: 3.2% uncertainty
  - **Lower photon  $E_T$**  threshold ( $E_T > 2.5 \text{ GeV}$ )
  - **Differential** cross sections
  - **Search for** axion-like particles (ALP)

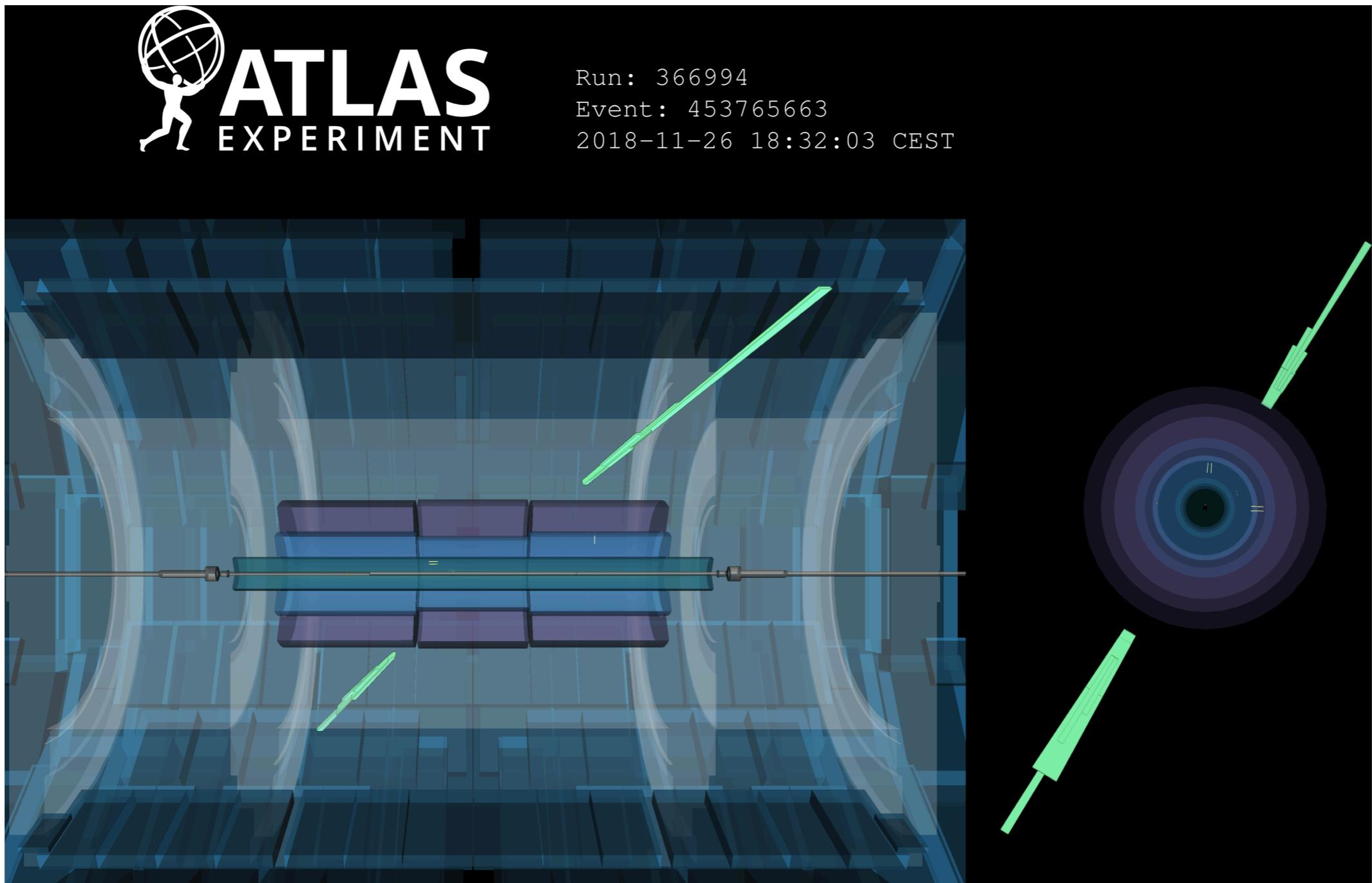


# EXCLUSIVE DIMUONS



- Very clean dimuon event

# LIGHT-BY-LIGHT SCATTERING



- Only two photons in the detector