Photon-photon fusion and tau g-2 measurement in ATLAS

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On behalf of the ATLAS Collaboration

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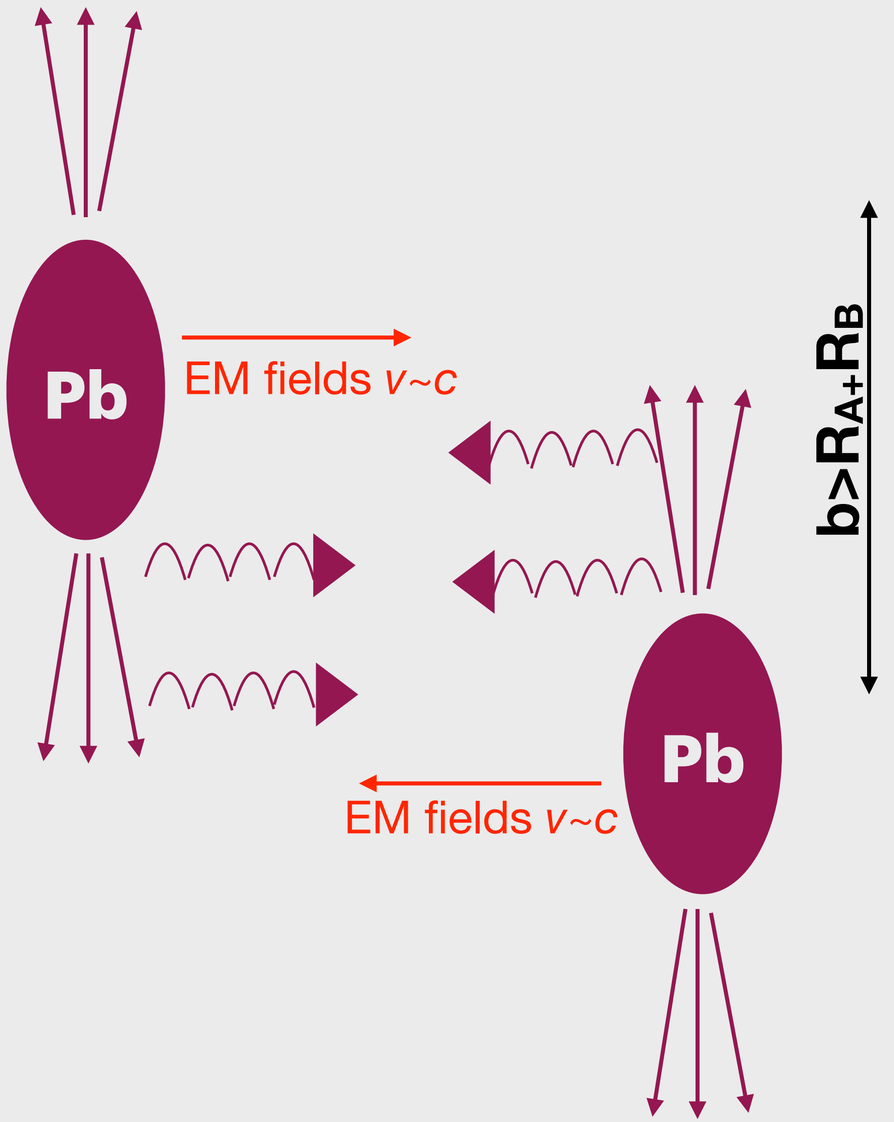
Ultra-peripheral collisions

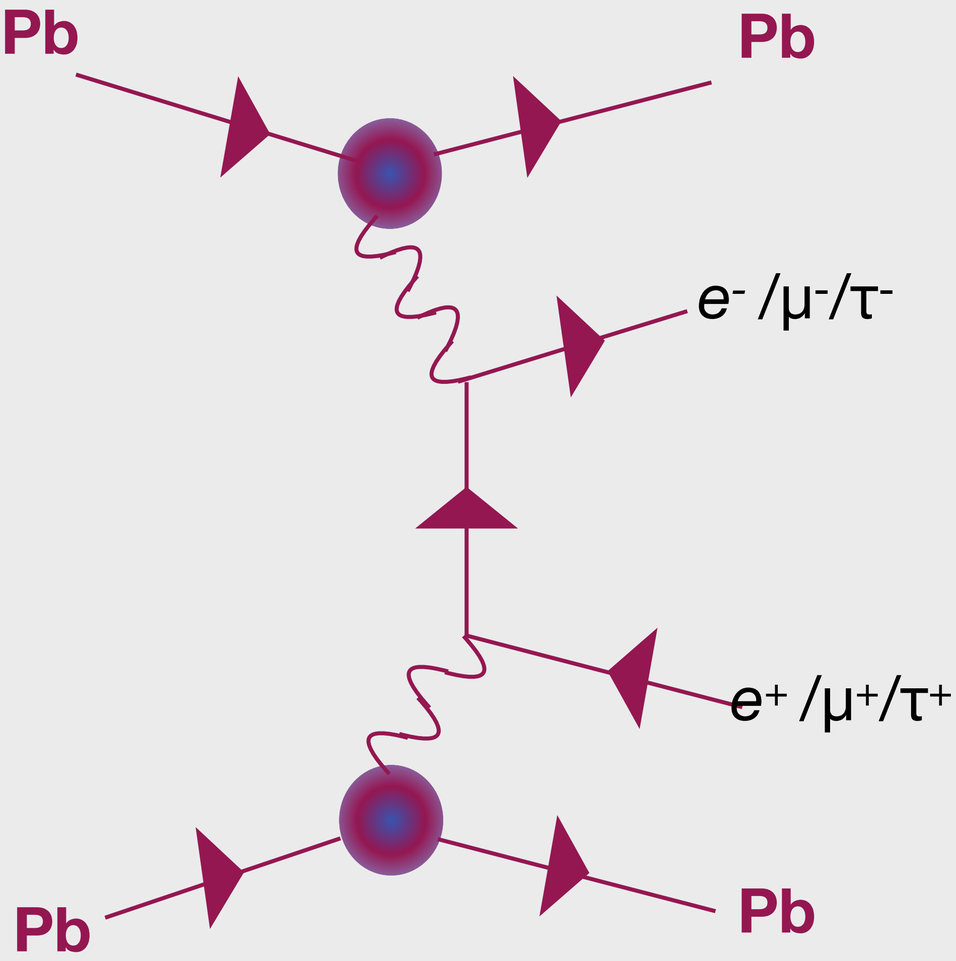
- Electromagnetic (EM) interactions become dominant at large impact parameters, $b>2R_A$, where R_A is the ion radius. Such collisions are usually referred to as **ultra-peripheral collisions (UPC) .**
- EM fields of relativistic ions considered as fluxes of photons (they scale with~ Z^2).
- Described in a Equivalent Photon Approximation (EPA) formalism.
- Cross-section is calculated by convolving the respective photon flux with the elementary cross-section for the process.



Motivation

This talk will cover these new measurements of dilepton production performed by ATLAS Collaboration **in UPC PbPb at 5.02 TeV** :

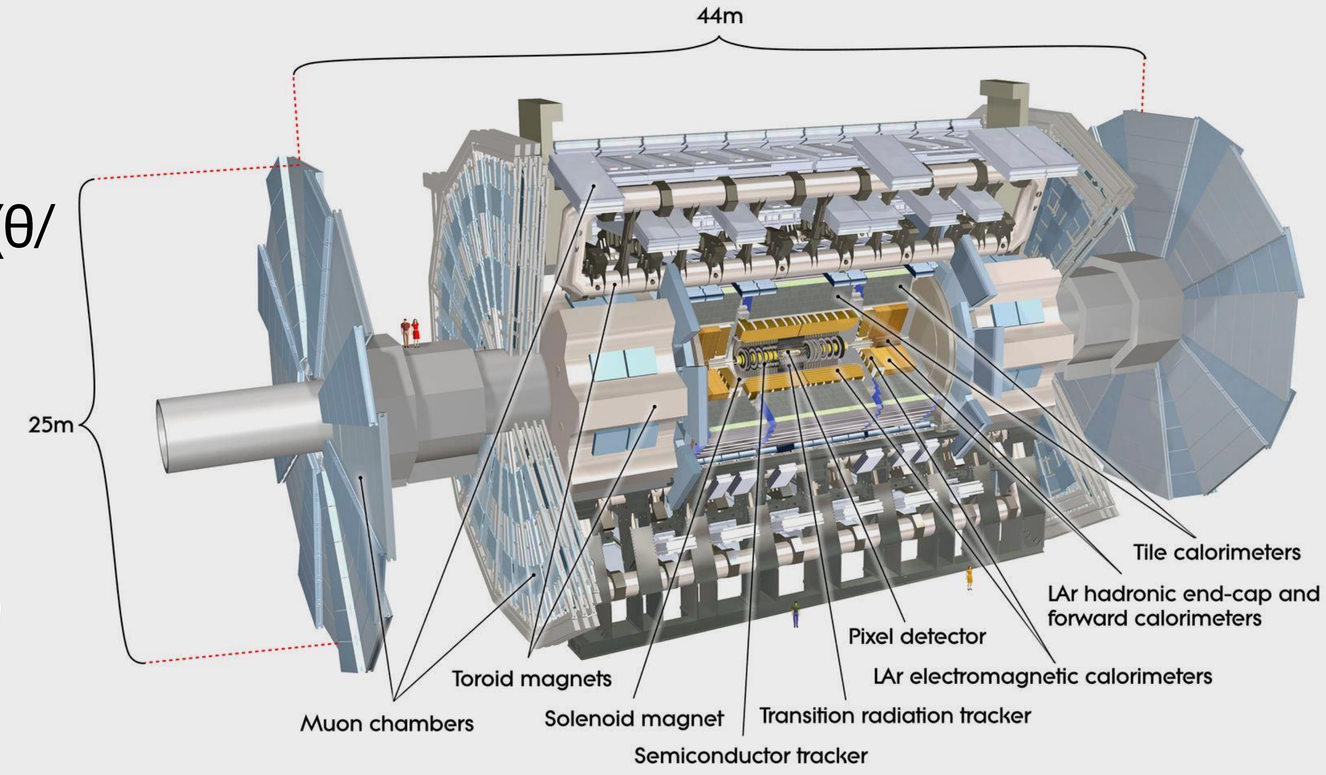
- **Exclusive dielectron production:** arXiv:2207.12781 (2022), submitted to JHEP
- **Exclusive dimuon production:** Phys. Rev. C 104 (2021) 024906
- **Exclusive ditau production and measurement of the τ-lepton anomalous magnetic moment:** arXiv:2204.13478, accepted by PRL

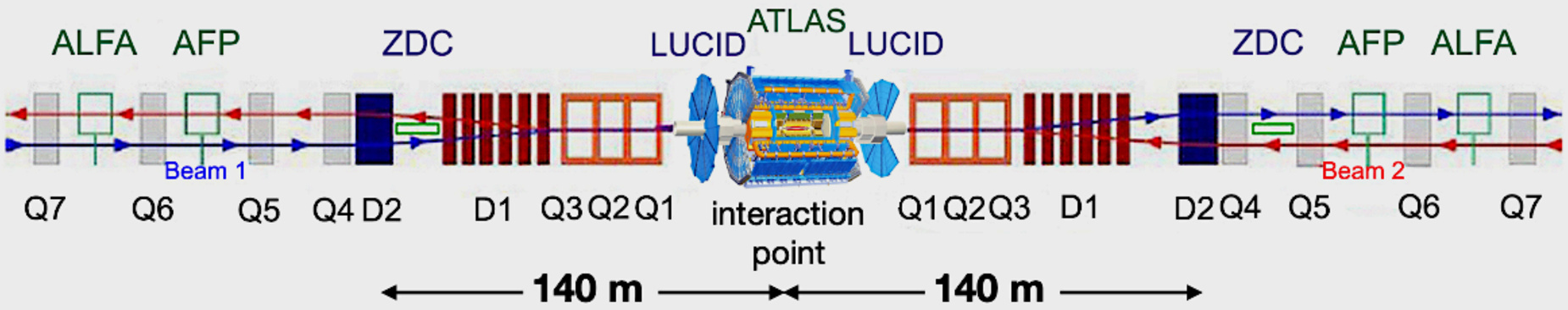


ATLAS detector

Large general-purpose detector with almost 4π coverage :

- Inner detector $|\eta|<2.5$ ($\eta = -\ln(\tan(\theta/2))$)
- Muon system $|\eta|<2.7$ (trig. 2.4)
- Calorimetry out to $|\eta|<4.9$
- **Zero-Degree-Calorimeters (ZDC)** capture neutral particles with $|\eta|>8.3$

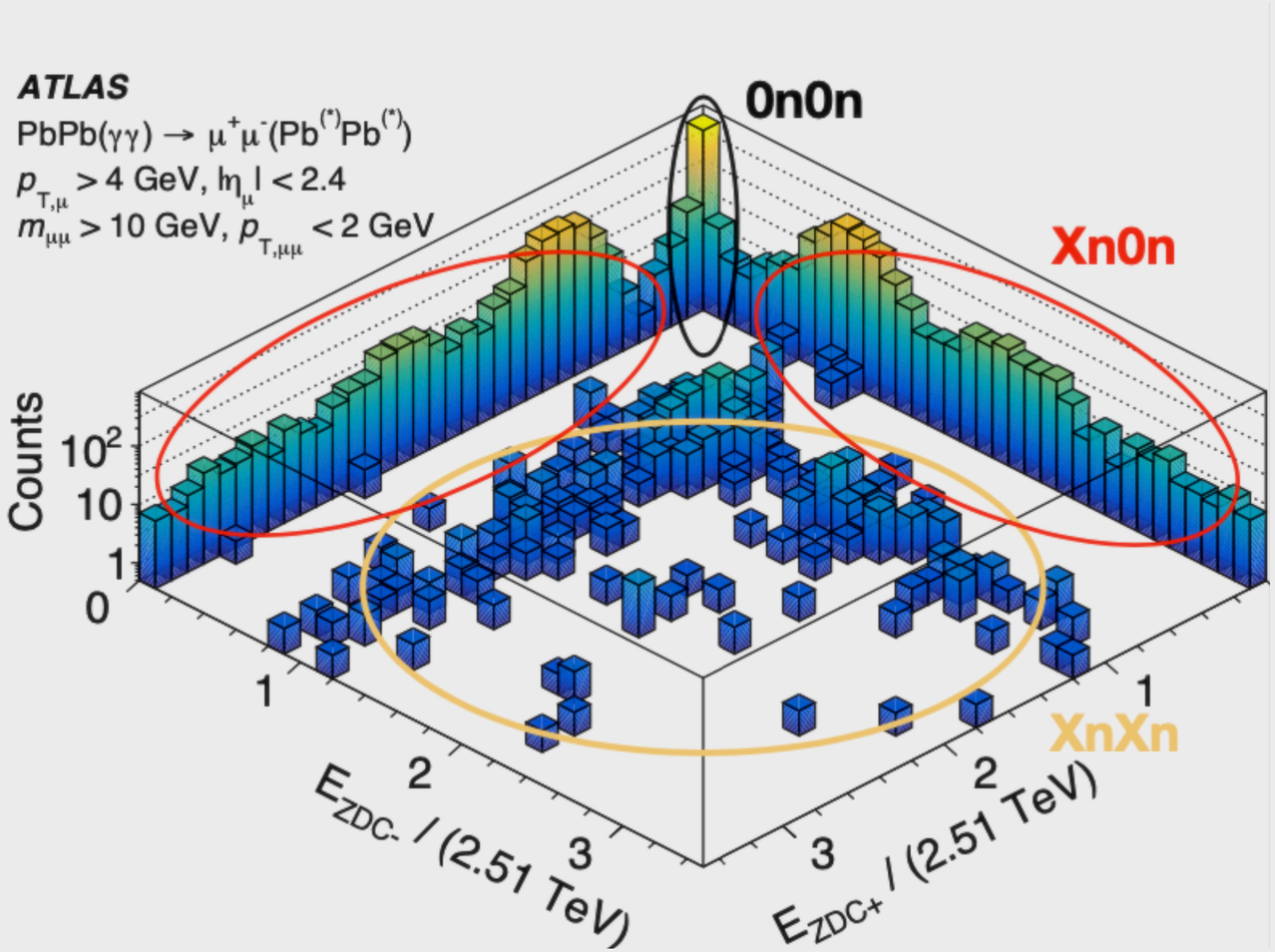




ZDC selection

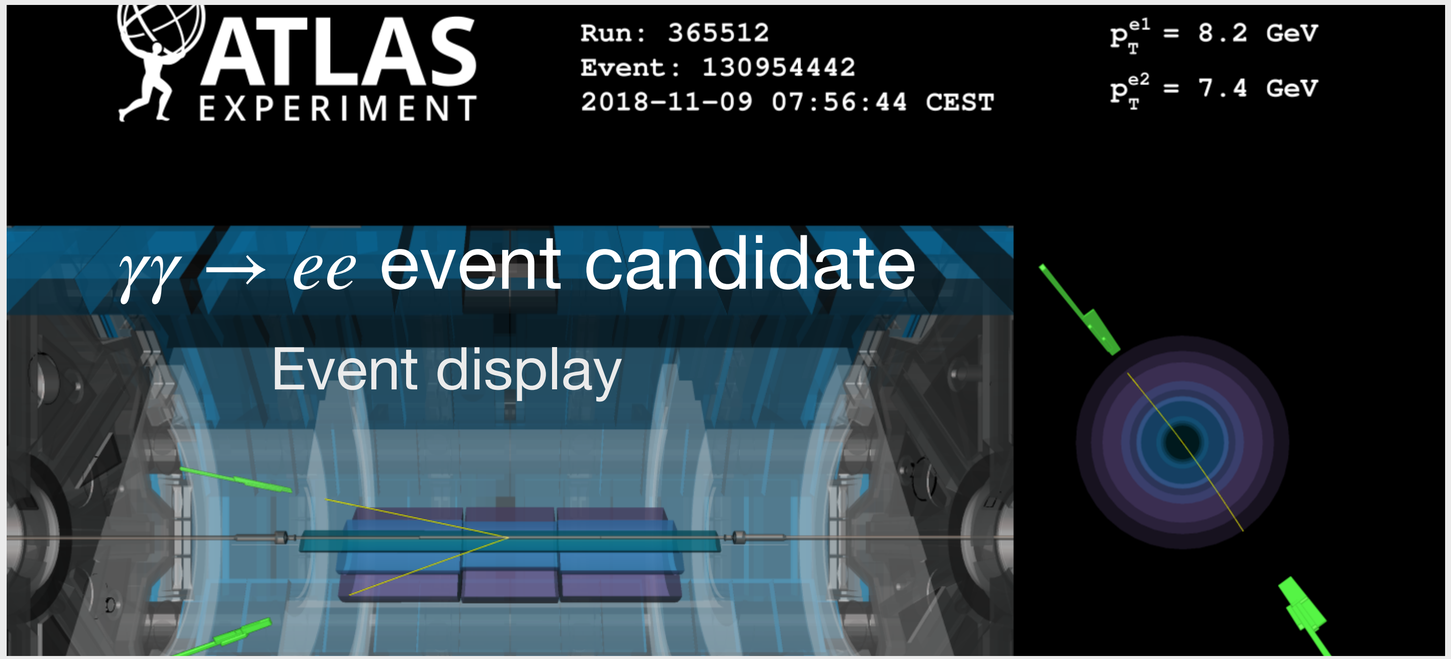
PRC 104, 024906 (2021)

- Different processes present **different activity in the forward region**:
  - Exclusive dilepton production - ions **remain intact**
  - Background events with nuclear breakup
- **Three different classes** are defined based on the signal in the ZDC: **0n0n**, **Xn0n** and **XnXn.**
- **The association** between given **ZDC signal** and given process is **nontrivial:**
  - Migrations due to ion excitation and presence of EM pile-up.



Event selection

- Exclusive dilepton events are characterized by :
  - **Two low-pT opposite sign leptons &&** otherwise empty detector.
  - Leptons are produced **back-to-back** in azimuthal angle.
- ATLAS optimized to detect high-energy particles:
  - Particle reconstruction efficiency in low energy region.

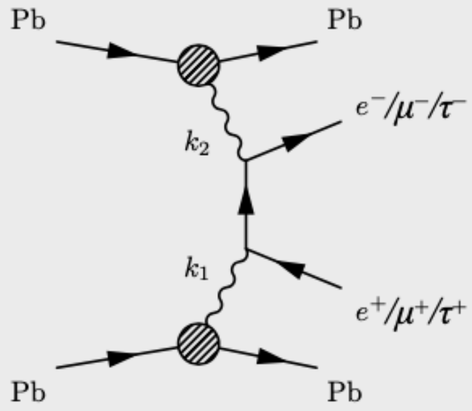


	Muons	Electrons
Int. Lumi [nb^{-1}]	0.48	1.72
p_T^{ℓ} > [GeV]	4	2.5
$\lvert\eta_{\ell}\rvert$ <	2.4	2.5
$m_{\ell\ell}$ > [GeV]	10	5
$p_{T\ell\ell}$ <	2	2

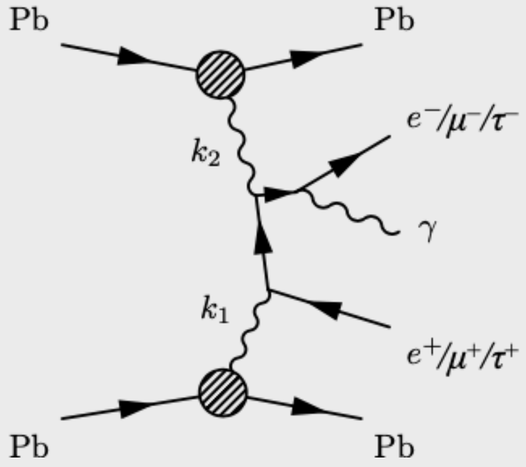
Background sources

Various background sources are considered for $\mu\mu/ee$:

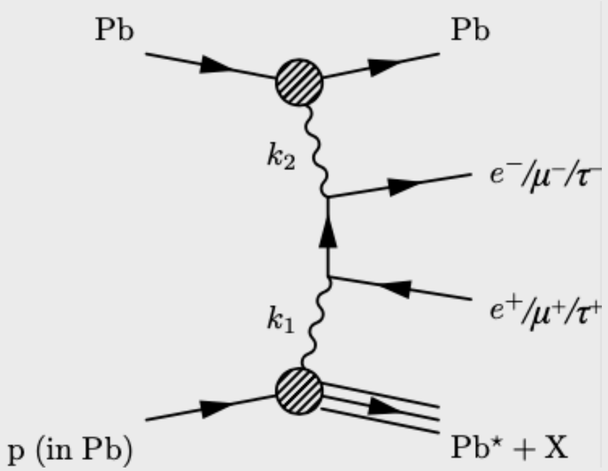
- **Upsilon (nS)** production: STARlight+Pythia8 MC samples (only in dielectron measurement).
- **Exclusive ditau production** : STARlight+Pythia8 MC samples (only in dielectron measurement).
- **Dissociative production of $\ell^+\ell^-$ pairs:** Data-driven method (LPair / SuperChic4 + Pythia8 in pp collisions).



Signal (LO)



Signal (FSR)



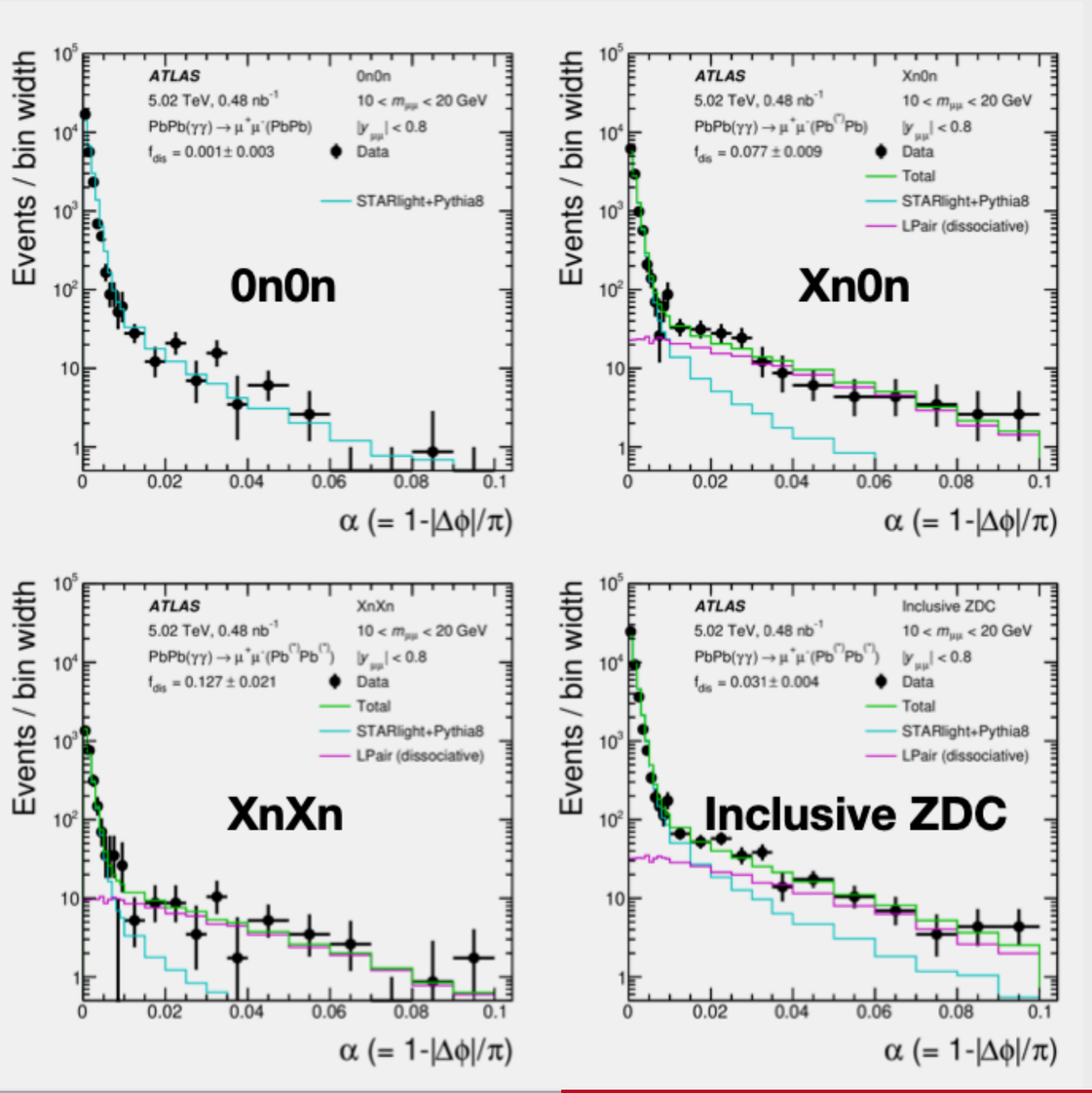
Dissociative background

Dimuons

Dimuons - background

arXiv:2207.12781

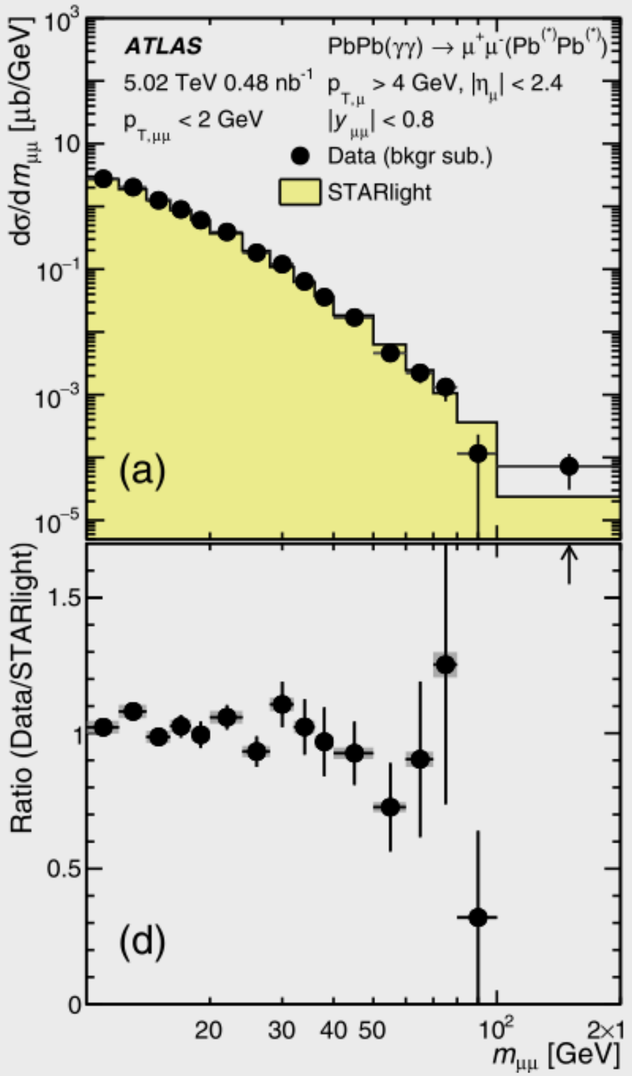
- **Events** are **categorized** in 0n0n, Xn0n and XnXn classes.
- The data is compared with STARlight+Pythia8 **simulation** for $\gamma\gamma \rightarrow \mu^{+}\mu^{-}$ process with FSR and LPair for **dissociative events** (pp collisions).
- The **simultaneous fit** is performed in all ZDC topology classes.

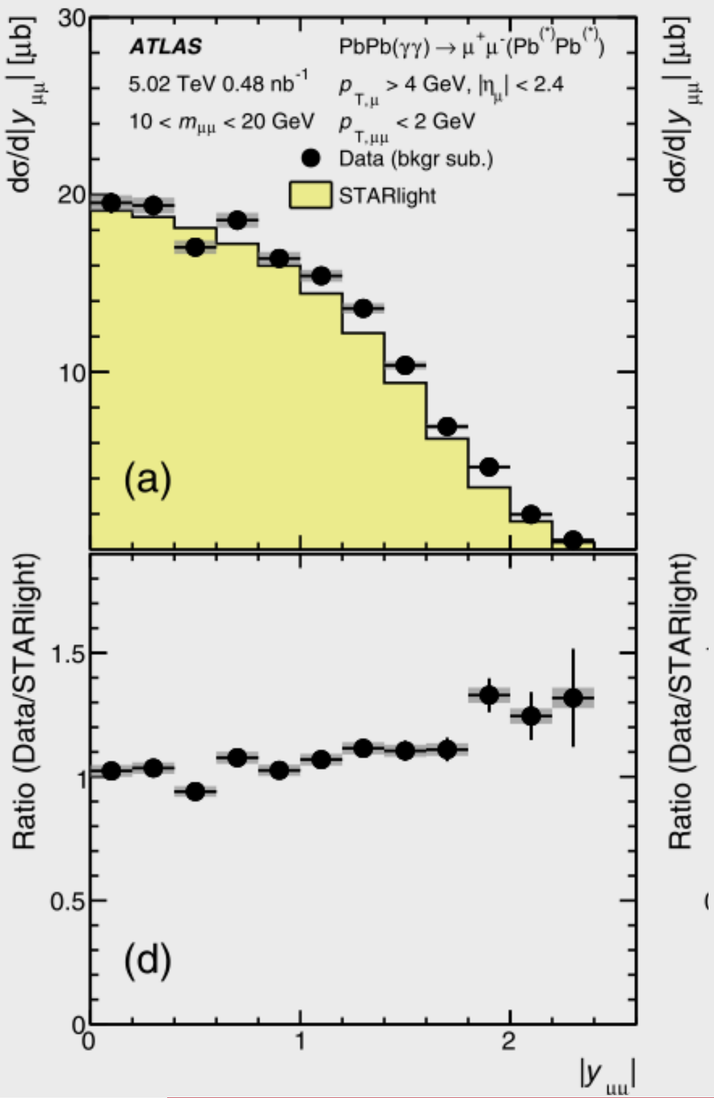


Dimuons - results

arXiv:2207.12781

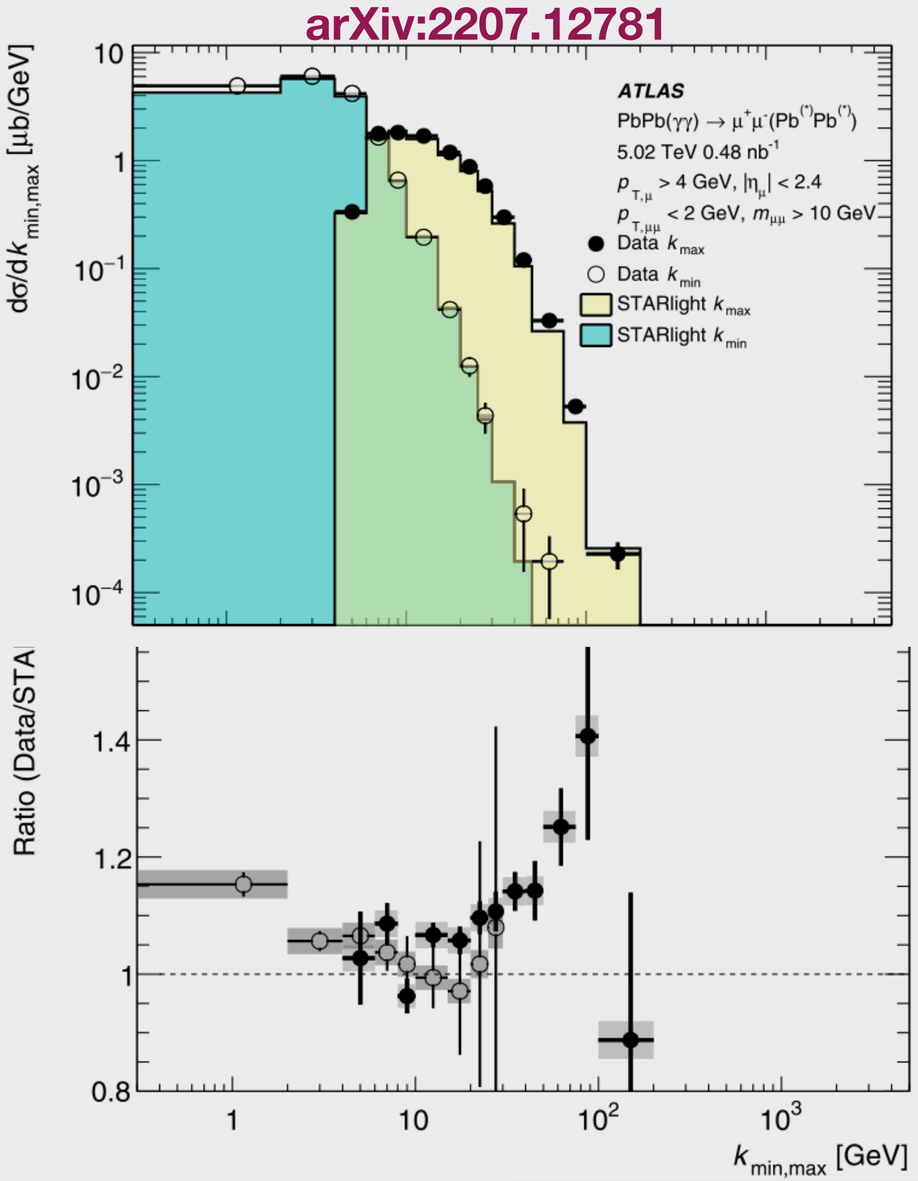
- **The cross-sections are measured** as a function of m$\mu\mu$ (in 3 slices of |y$\mu\mu$|) and |y$\mu\mu$| (in 3 slices of m$\mu\mu$) .
- The data is **compared with STARlight simulation** for $\gamma\gamma \to \mu^+\mu^-$ process with FSR.
- The overall shape of the spectra is well described out to the highest masses
- **Good agreement is found** in central region of rapidity distribution.





Initial photon fluxes

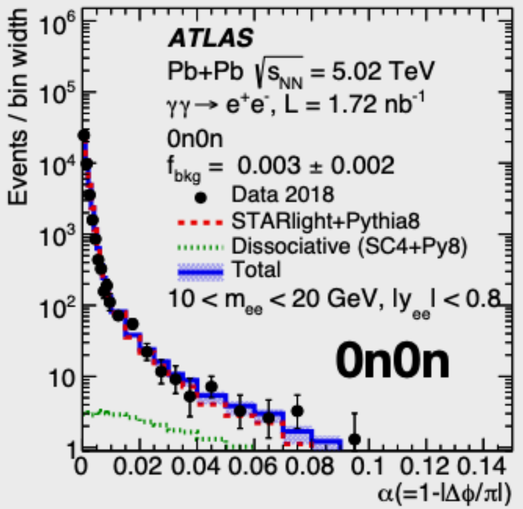
- The muon kinematics can be used to estimate **initial photon energies:**
  $k_{min,max} = (1/2)\, m_{\mu\mu}\, exp(\pm\, y_{\mu\mu})$
- The cross section is presented as a function of maximum and minimum photon energies.
- The data is compared with STARlight.
  - The starlight predictions are corrected in intermediate region **5-20 GeV**.
- Disagreement between the data and MC for lower $\mathbf{k_{min}}$ and higher $\mathbf{k_{max}}$.

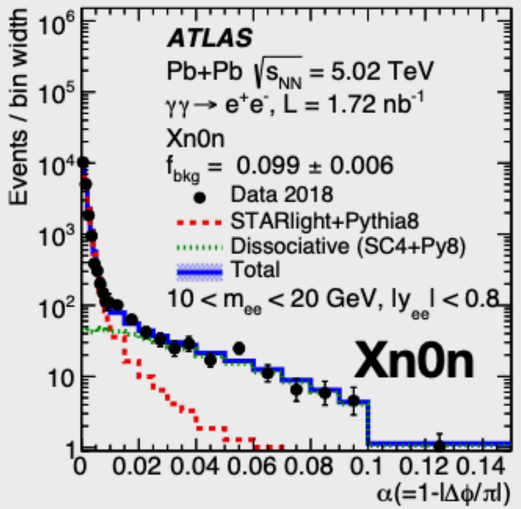


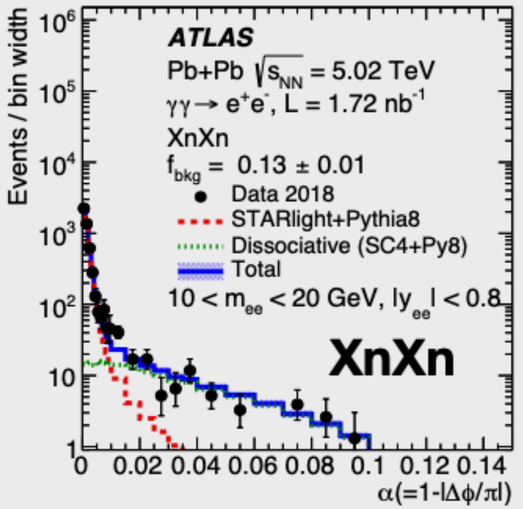
Dielectrons

Dielectrons- background

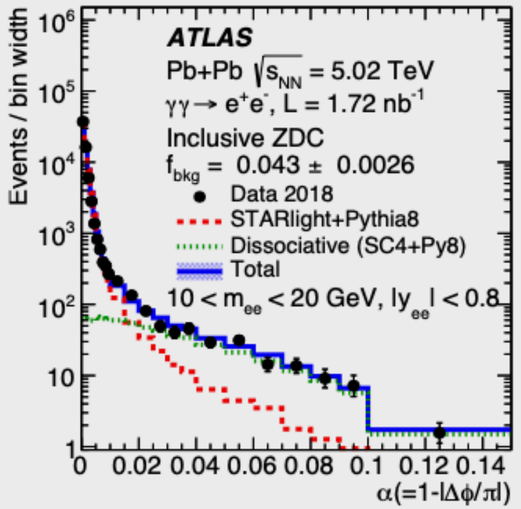
- The background samples for single dissociation from SuperChic4+Pythia8 are used instead of LPair .
- Fitting procedure similar to the one used in dimuon measurement.
- Small background contributions from ditau and Upsilon production also estimated.







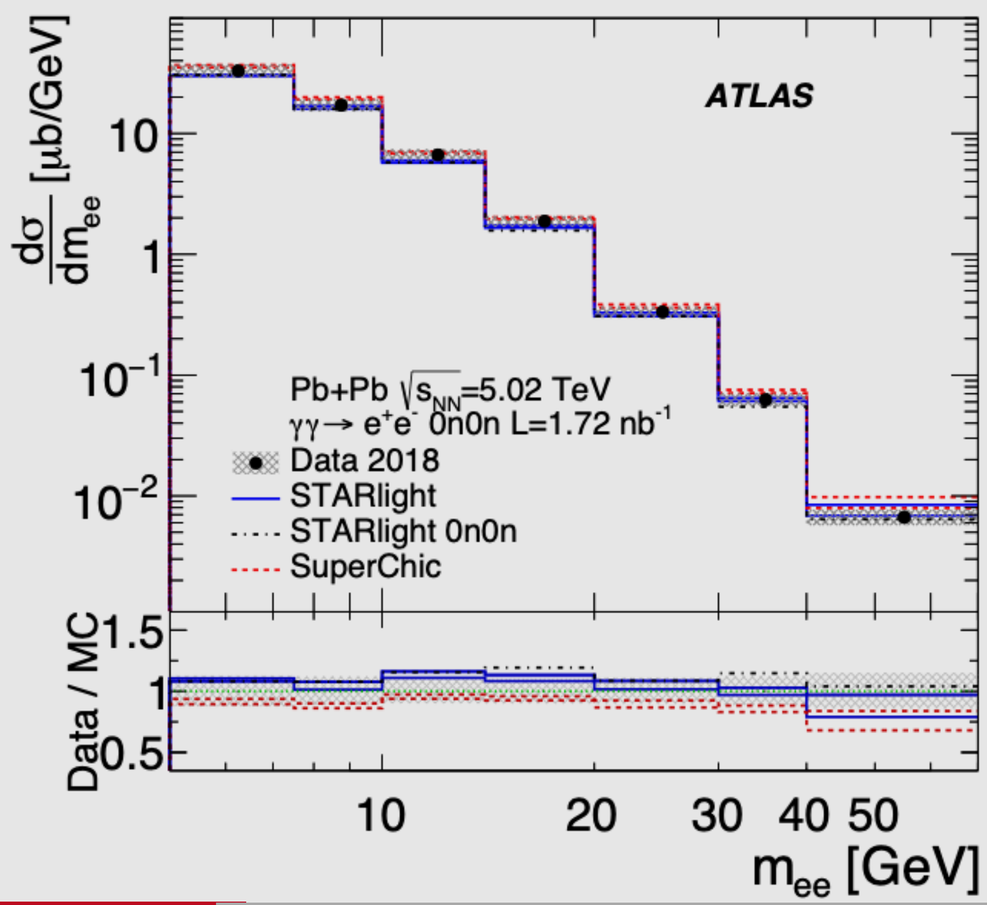
arXiv:2207.12781

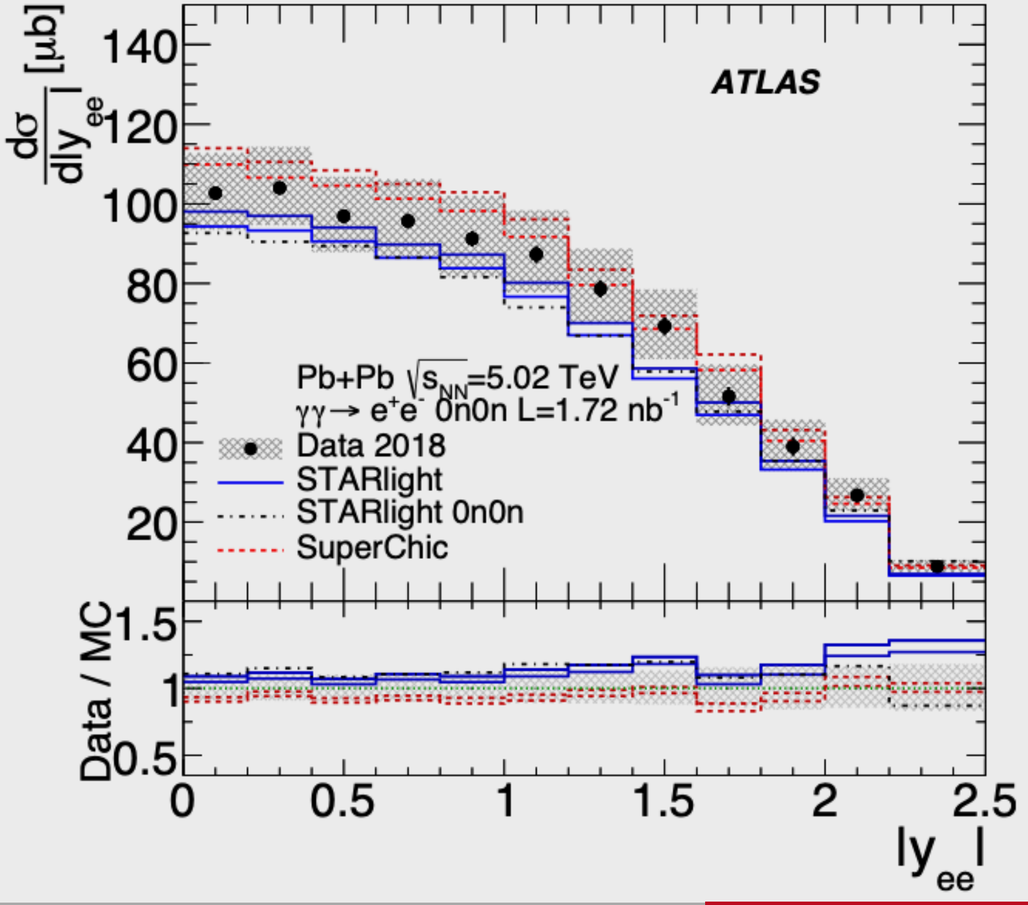


Inclusive ZDC

Dielectrons - results

- **Good agreement** with STARlight and SuperChic is observed, differences in the same regions as in detector-level plots.





Ditaus

a_τ - measurement strategy

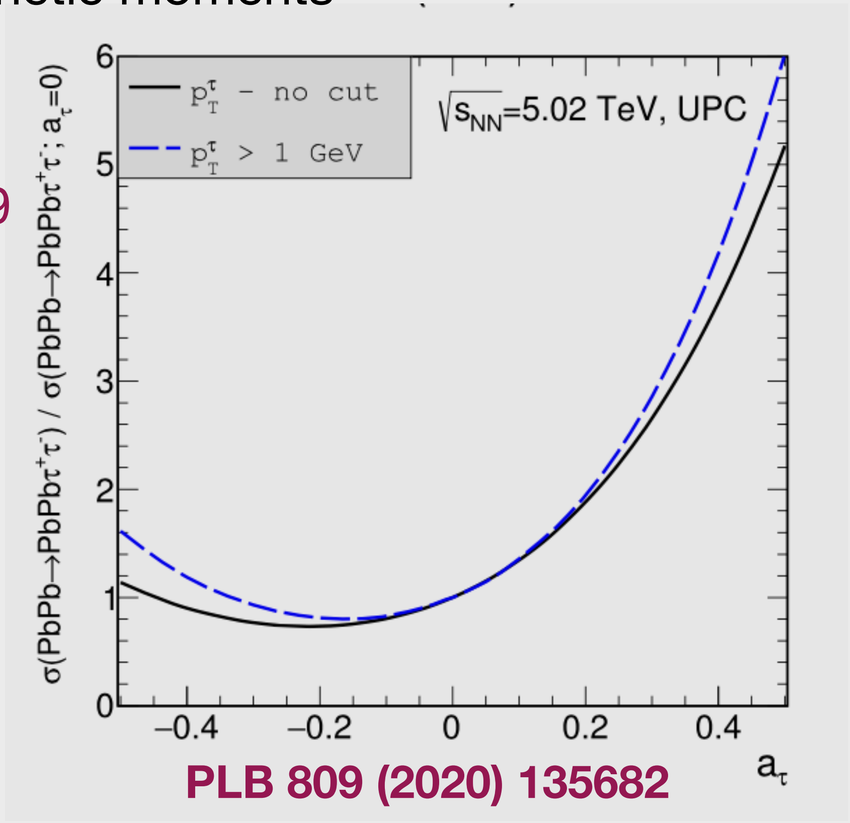
- Magnetic moment of the particle and its spin are related by g-factor: **μ**=g q/2m **S**.
- Dirac's equation predicts **g=2** for charged leptons, higher-order corrections result in **g≠2**.
- These discrepancies are measured with lepton anomalous magnetic moments $a_\ell = (g-2)_\ell / 2$.
- Currently the best constraints for aτ are from **DELPHI** experiment: $-0.052 < a_\tau < 0.013$ (95% CL), EPJC 35 (2004) 159
- Measurement of aτ in HI UPC collisions proposed

in several publications:

- *F. del Águila, F. Cornet, J.I. Illana,*

  PLB 271 (1991) 256 L. Beresford, J. Liu, PRD 102 (2020) 113008
- *M. Dyndal, M. Schott, M. Klusek-Gawenda,*

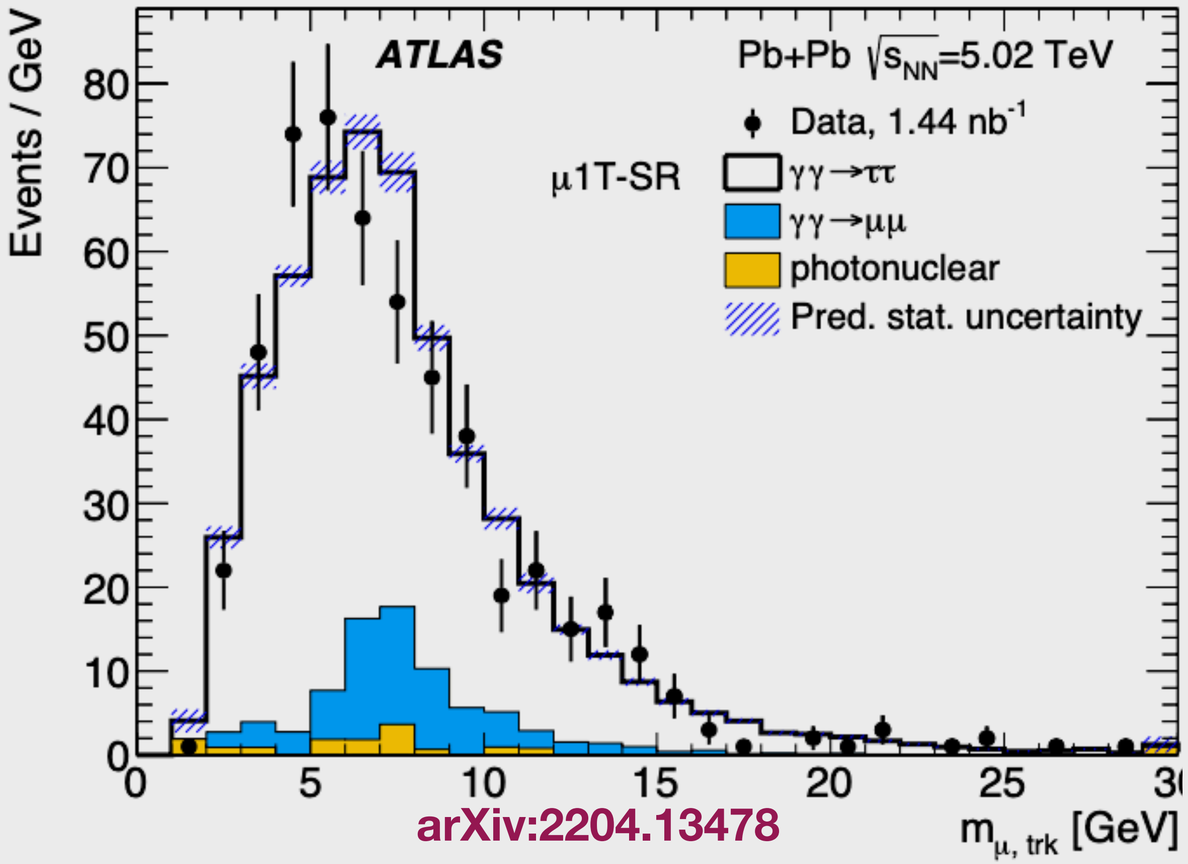
  A. Szczurek, PLB 809 (2020) 135682



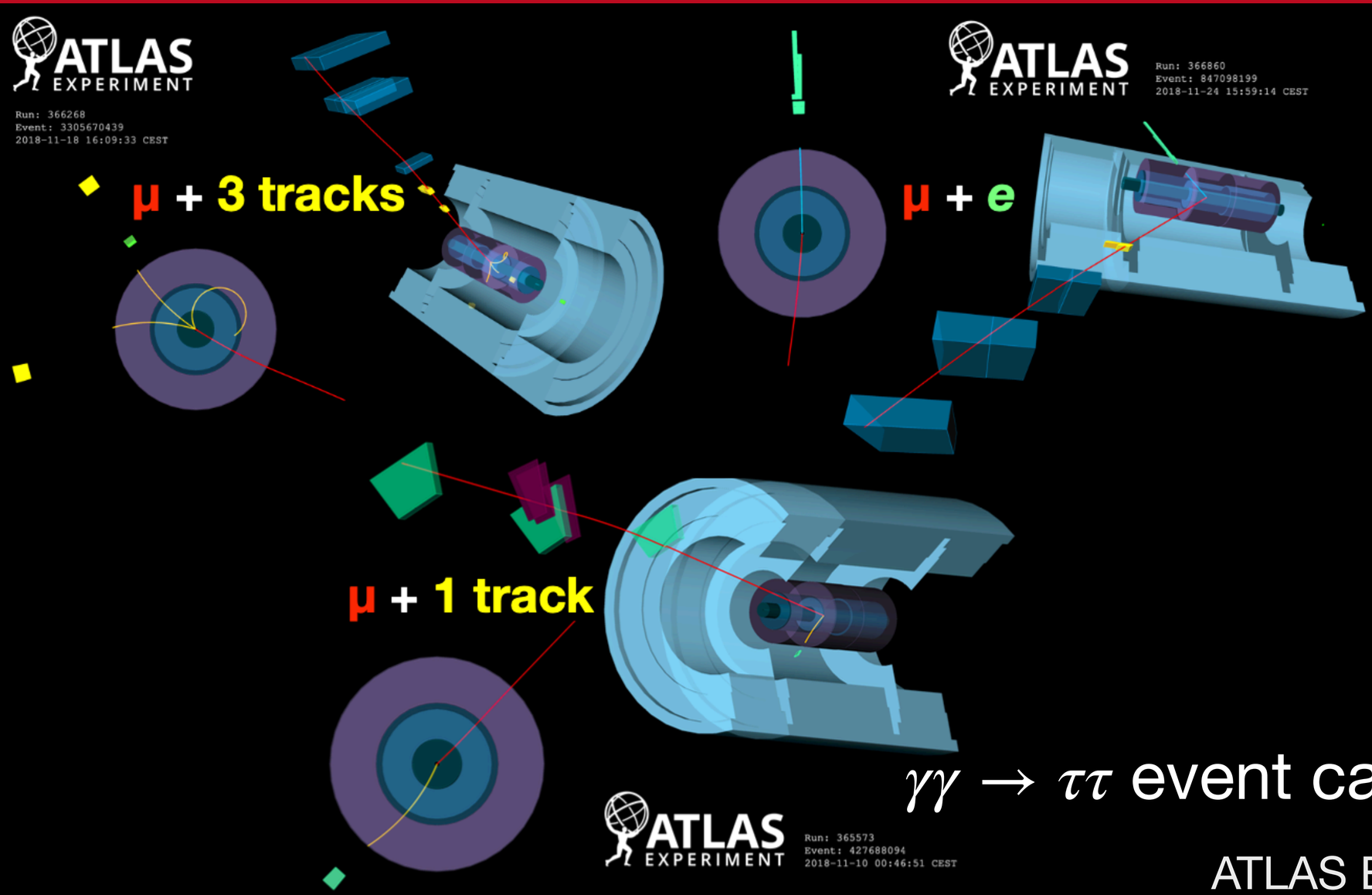
PLB 809 (2020) 135682

Ditau event selection

- **Signal τ-leptons** are **low-energetic**, typically with **p_T < 10 GeV**.
- Events classified based on the charged **τ-lepton decay products**.
- **Three signal categories:** μ + 1 track, μ + 3 tracks, and μ + e.
- **Single muon trigger** used to record signal events with muon **pT > 4 GeV.**
- **Exclusivity requirements**:
  - Veto on forward neutron activity (using 0n0n configuration based on ZDC signal).
  - For μ + 1 track and μ + 3 tracks signal regions: veto on additional low-pT tracks and low-pT clusters.



Ditau events

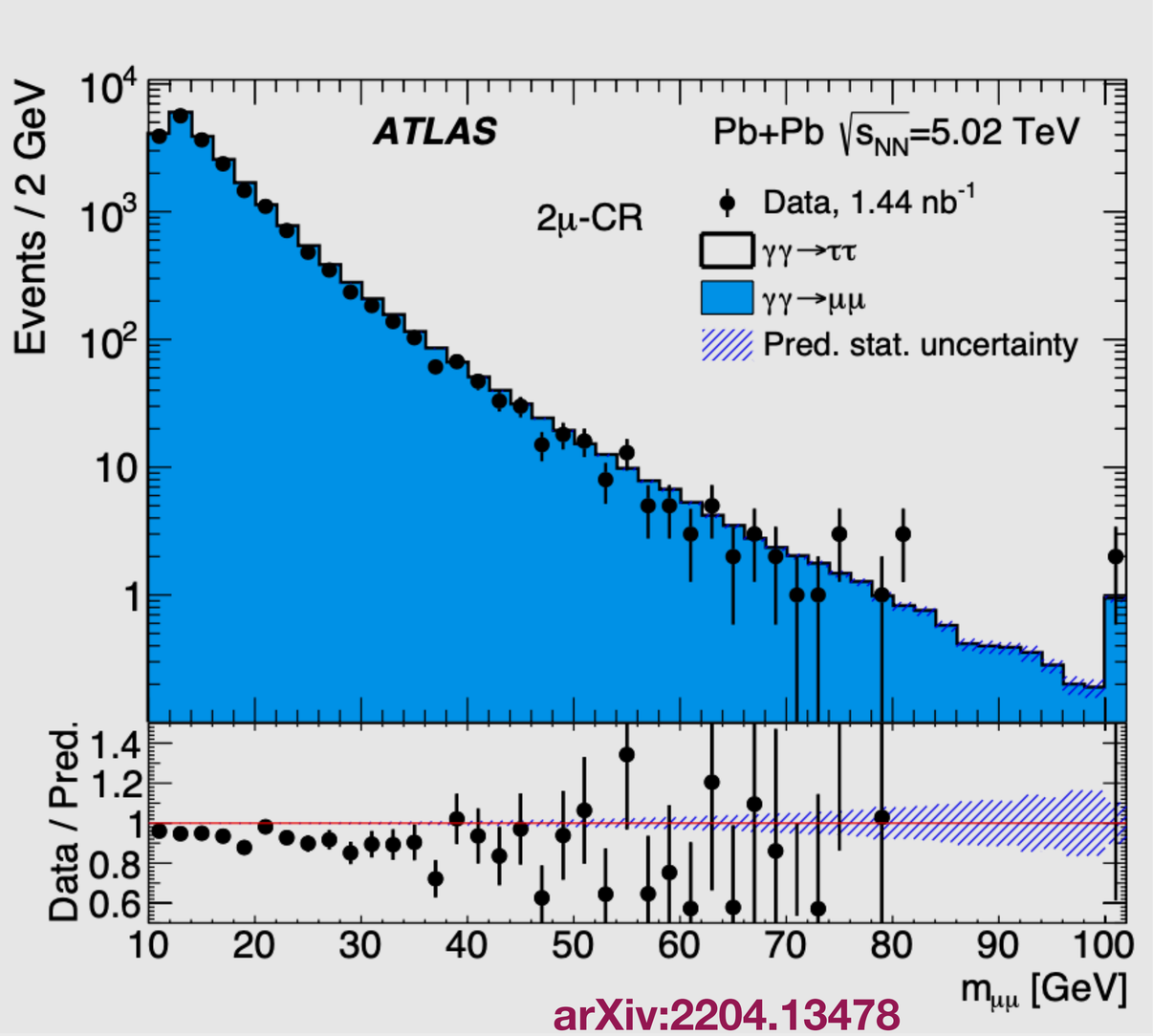


$\gamma\gamma \rightarrow \tau\tau$ event candidate

ATLAS Event display

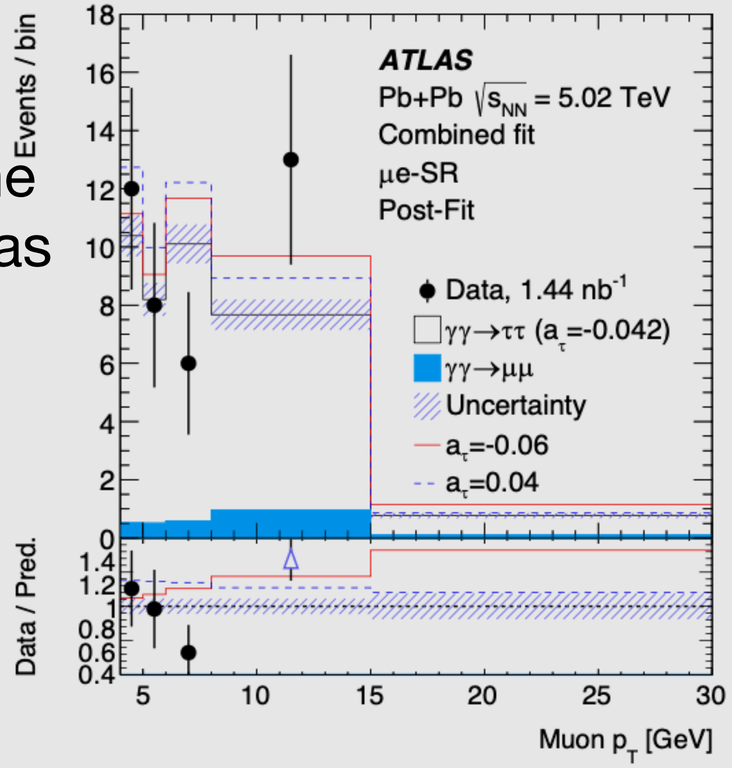
Backgrounds

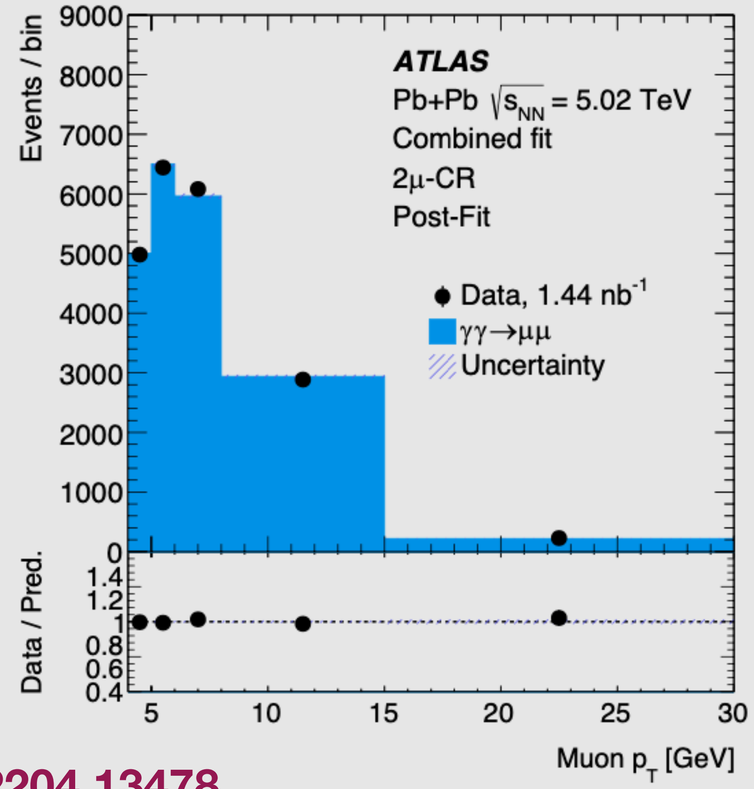
- Main **background contributions** from dimuon production and diffractive photonuclear interactions.
  - Data driven estimation of diffractive photonuclear events
- Background from $\gamma\gamma \rightarrow \mu\mu\ (\gamma)$ production estimated using **MC simulation,** constrained by a data CR.
- Pre-fit distributions in the two muon CR show good agreement of data and MC.



Observation of exclusive ditau production

- **aτ value is extracted**: Using a profile likelihood fit using **the muon p_T** distribution.
- **Simultaneous fit** combining all signal regions and **dimuon control region**:
  - Dimuon **control region** ($\gamma\gamma \to \mu\mu$ events) used to **reduce systematic uncertainty** from the photon flux.
- Calculations are based on the same parameterization as was used in previous LEP measurements.
- Clear observation (» 5σ) of $\gamma\gamma \to \tau\tau$ process.



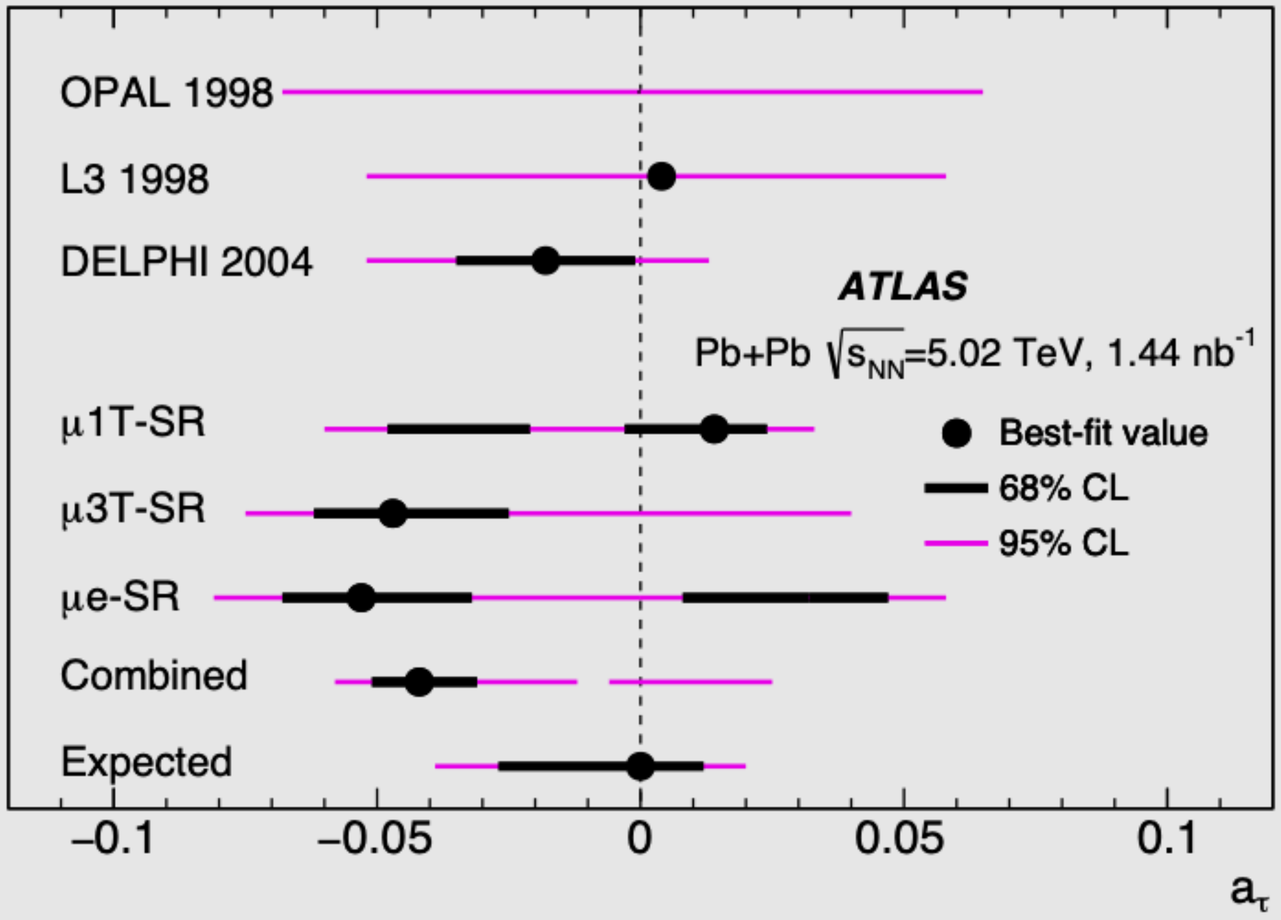


arXiv:2204.13478

τ-lepton g-2

- Expected 95 % CL limits combined fit: $-0.039 < a_\tau < 0.020$.
- The **best fit value** is $a_\tau = -0.042$, with the corresponding 95% CL interval being **(–0.058, –0.012) ∪ (–0.006, 0.025)**.
- Double-interval structure due to interference of SM and BSM amplitude.
- The result is largely limited by statistics.
- Constraints similar to **DELPHI** **(EPJ C 35 (2004) 159)** .

arXiv:2204.13478



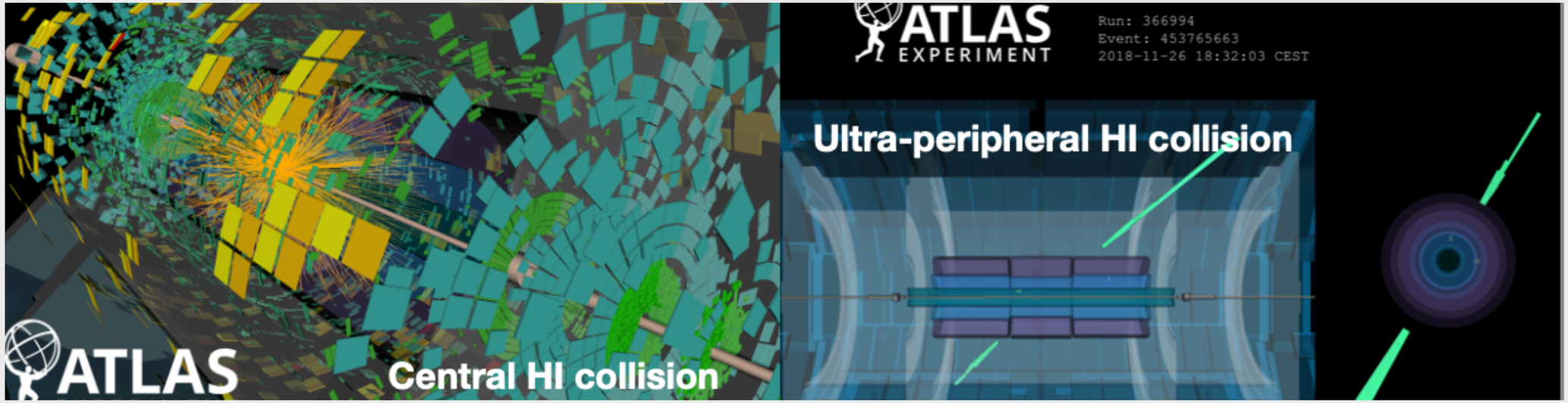
Summary

- The exclusive dilepton production was measured using data collected in 2015 and 2018 with the ATLAS detector.
- The results from the dimuon and dielectron measurements are **consistent**- although they have slightly different definitions of the fiducial region.
- The dielectrons and dimuons measurements provide valuable constrains for theoretical approaches in the modeling of **the initial photon flux.**
- **Activity in the forward region** could be measured by the ZDC .This should provide constraints for impact-parameter dependence of dilepton.
- $\gamma\gamma \rightarrow \tau\tau$ **production** was observed by ATLAS.
- The measurement of the **τ-lepton anomalous magnetic moment is competitive** with previous measurements:
  - improvement in precision expected with more data (Expect to have 7 nb^{-1} for LHC Run 3 for PbPb data)

Backup

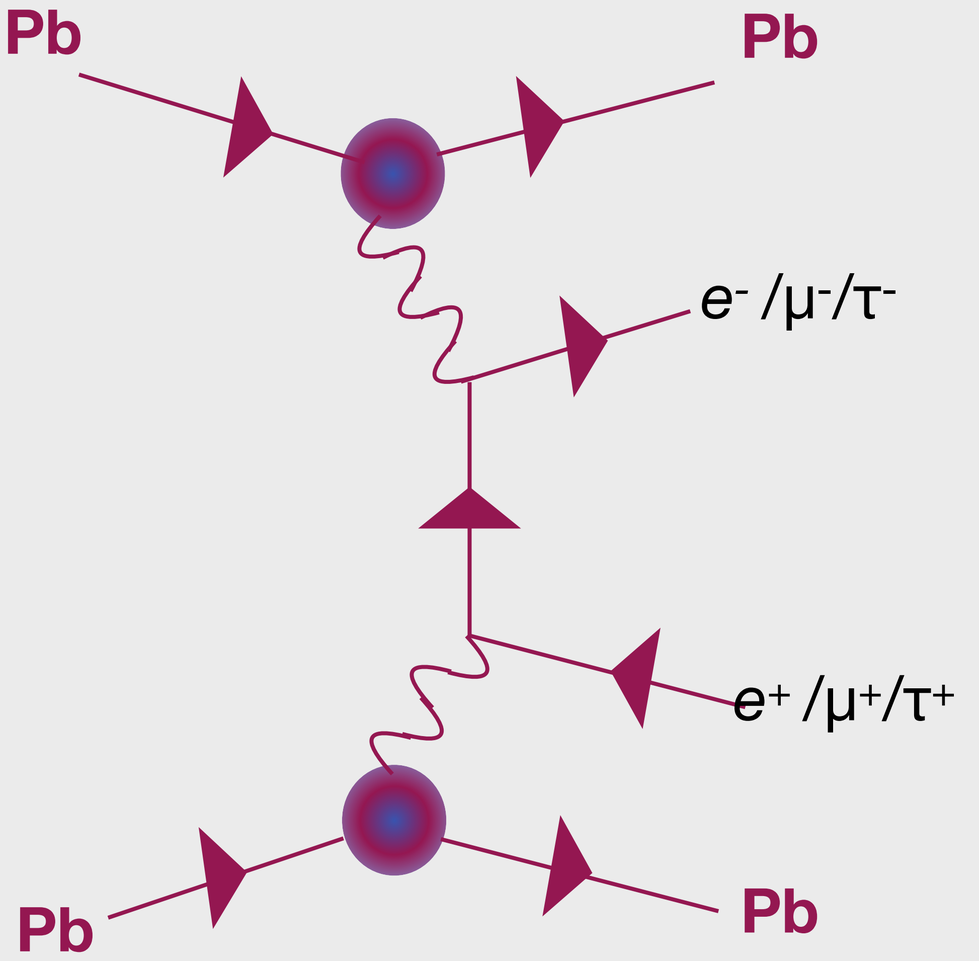
Ultra-peripheral collisions

- **Advantages of UPC heavy-ion collisions:**
  - UPC events are very clean and ideal for precision studies (very low hadronic pileup - exclusive selections possible) - opening physics opportunities for QED studies at hadron collider.
  - Increased cross-sections wrt to pp system (low pT particles can be triggered and reconstructed).



Motivation

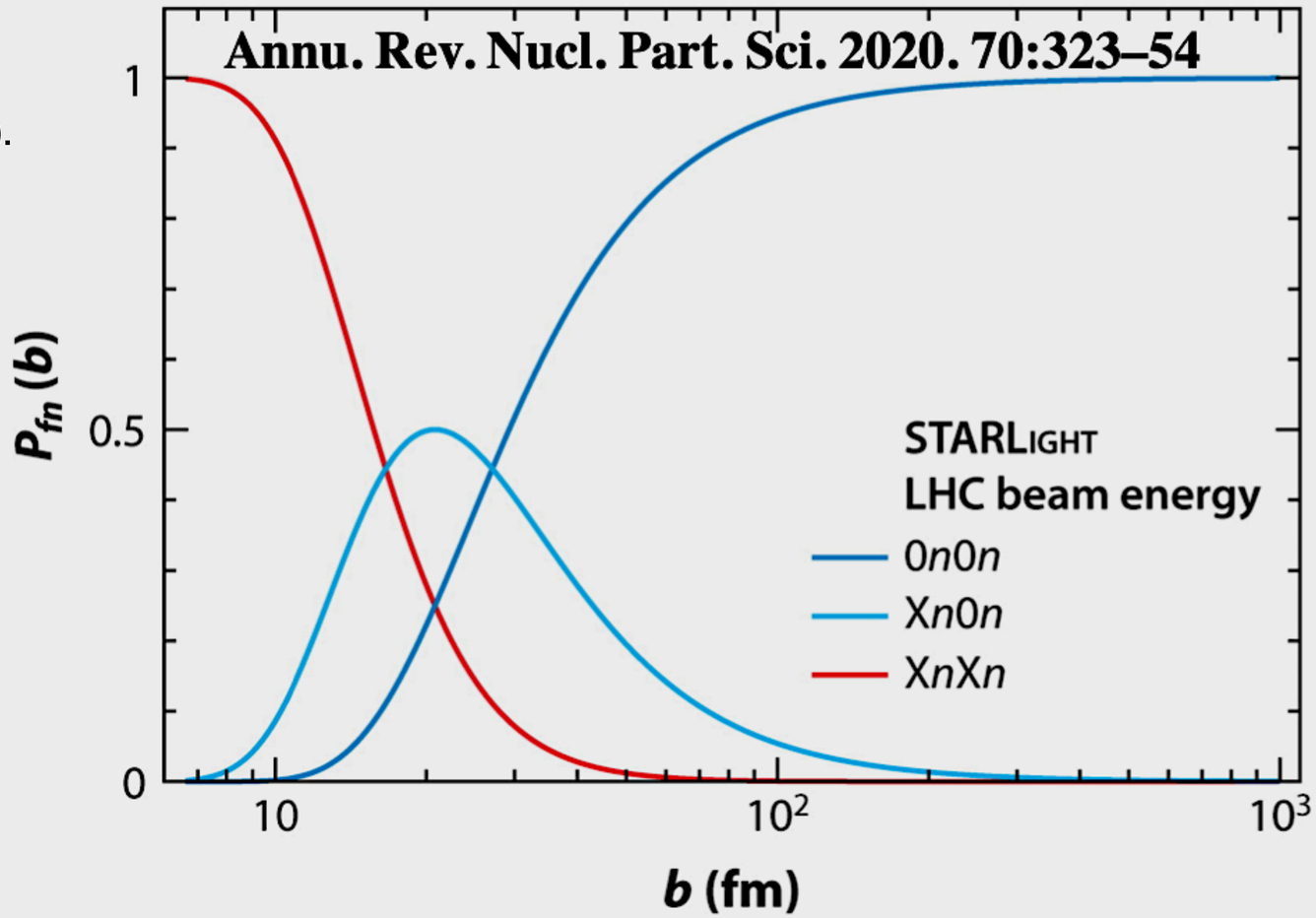
- **Exclusive dilepton production** is one of the fundamental processes in photon-photon interactions.
- **Dileptons** ($\mu\mu/ee$) production are **benchmark processes** for other photon-induced processes.
- **Reduction of systematic uncertainties:** measurement of the τ-lepton anomalous magnetic moment.
- **Important background :** Dielectron production in light-by-light scattering.



ZDC fractions

- The probability of producing a given ZDC category depends on the value of the impact parameter, b (based on the Coulomb excitation probabilities ~ $1/b^{2)}$.

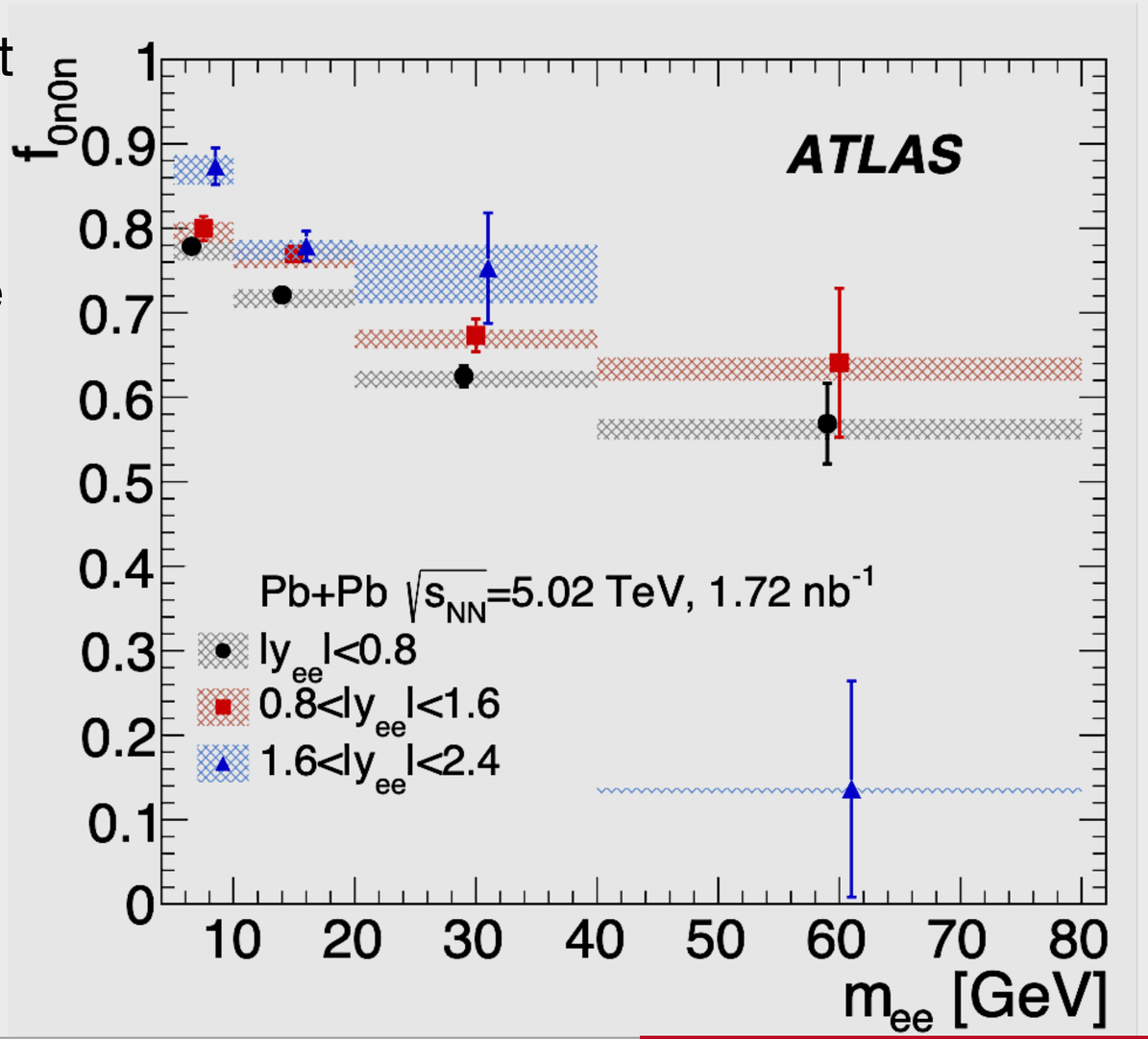
- With different selections on the ZDC topology, we probe different ranges of dilepton mass and impact parameters, as photon fluxes vary with b.



f0n0n fractions - dielectrons

arXiv:2207.12781

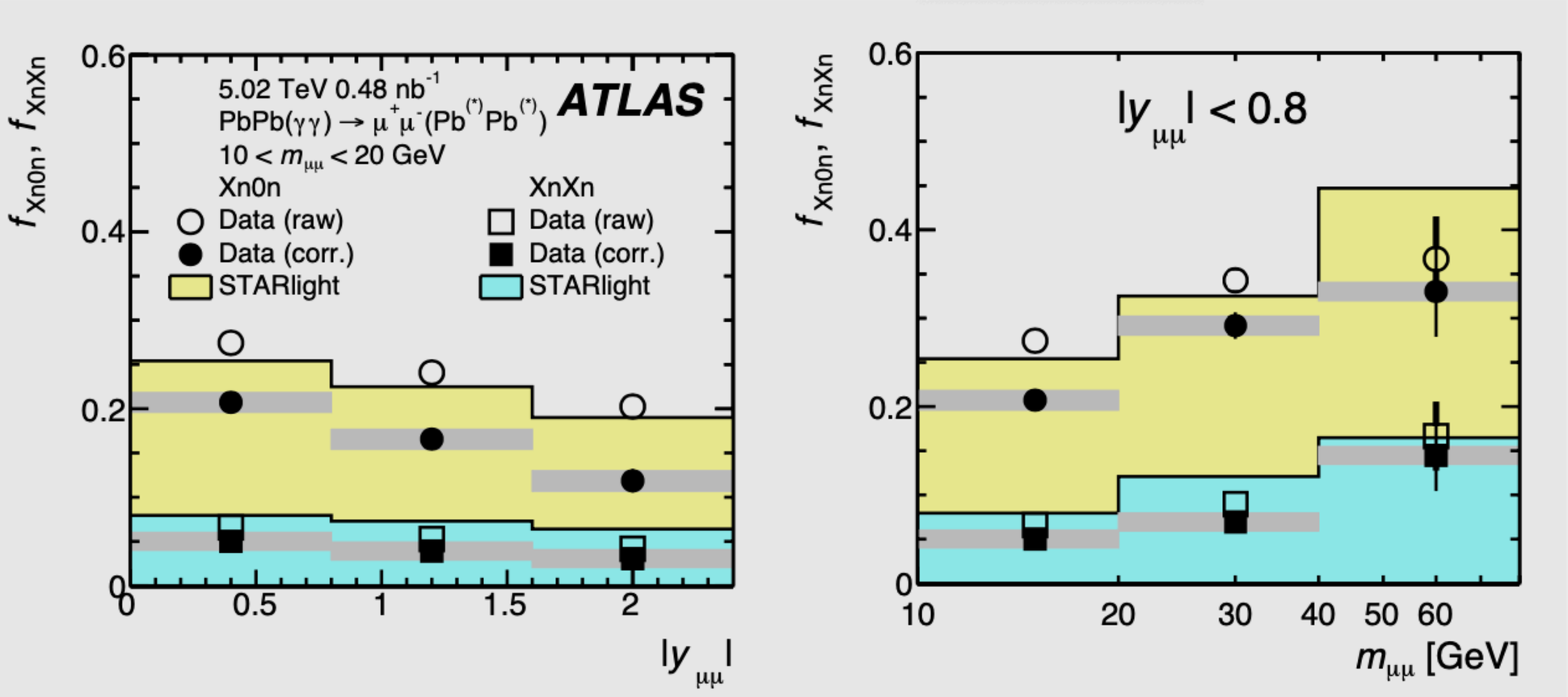
- The 0n0n class expected **very pure** at least in terms of dissociative background.
- **Selection of the 0n0n sample**: Events are required to have low energy deposits in the ZDC (below 1 TeV on each side).
- There is no ZDC simulation in the MC samples, so a dedicated approach, correcting also for EM pileup is used.
- To be able to compare data with the prediction, the weight is applied as a function of truth variables for the MC samples .



fXn0n and fXnXn fractions - dimuons

The corrected f_{Xn0n} and f_{XnXn} fractions are compared with the **STARlight predictions**.

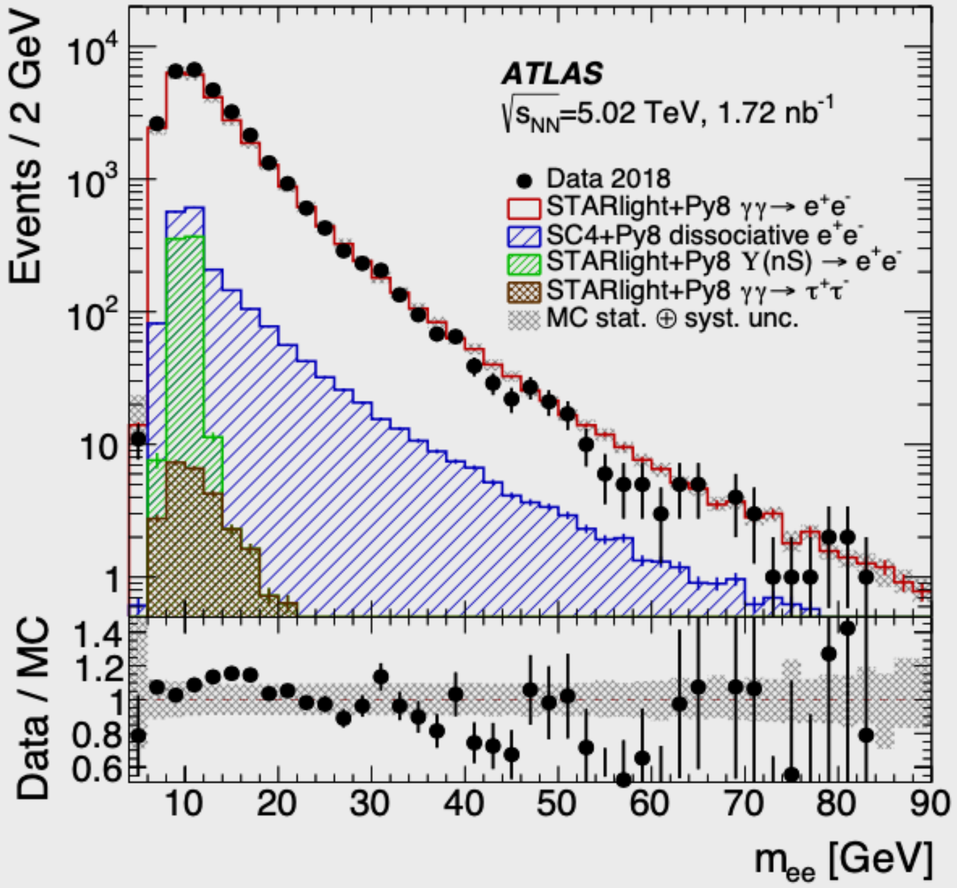
Phys. Rev. C 104 (2021) 024906

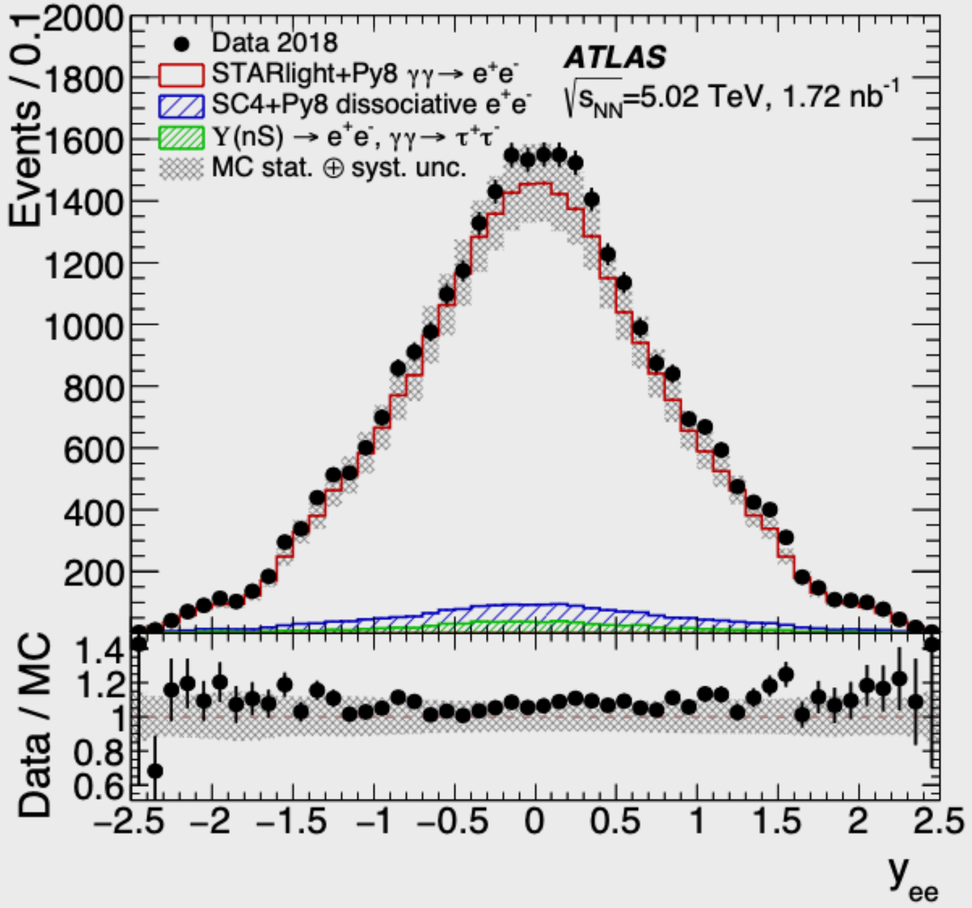


Detector level control plots

The data sample is ~93% pure, with about 10% more counts in data than in the MC prediction.

arXiv:2207.12781





τ-lepton g-2

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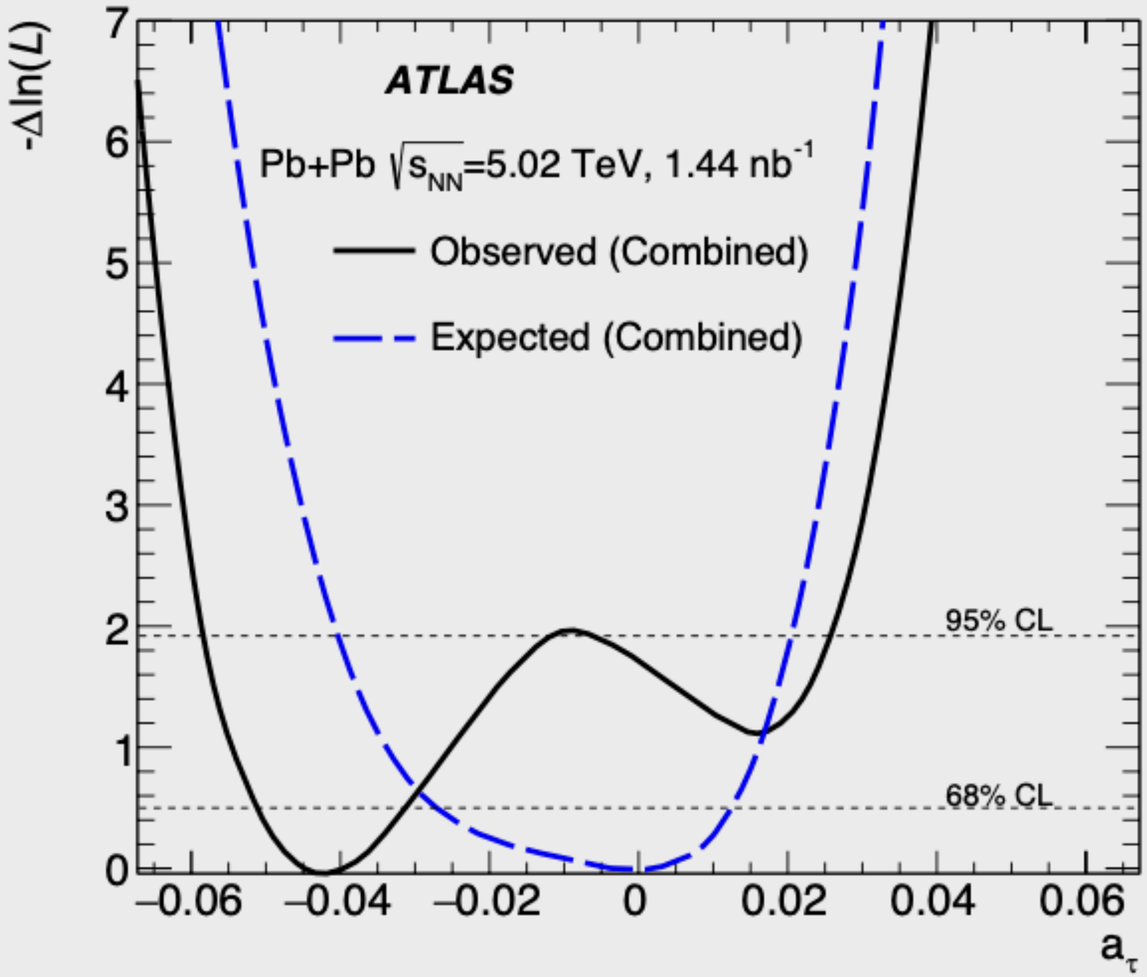

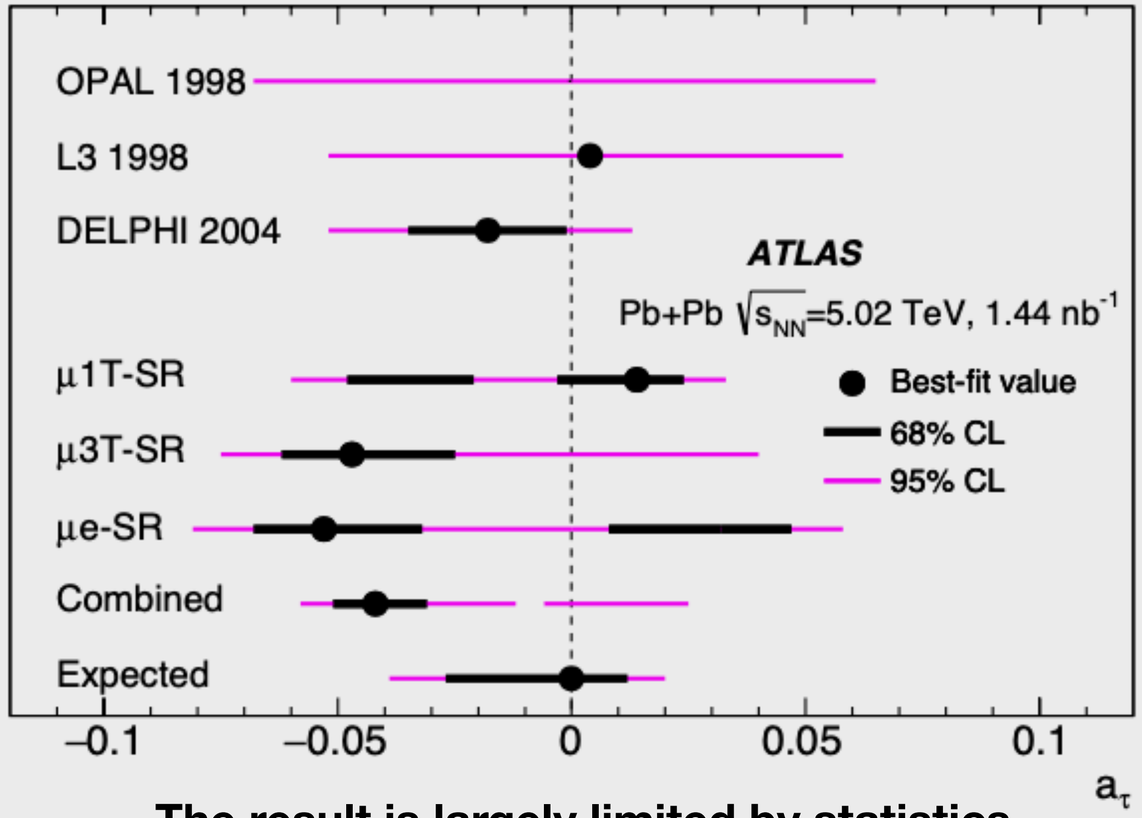

The result is largely limited by statistics.