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

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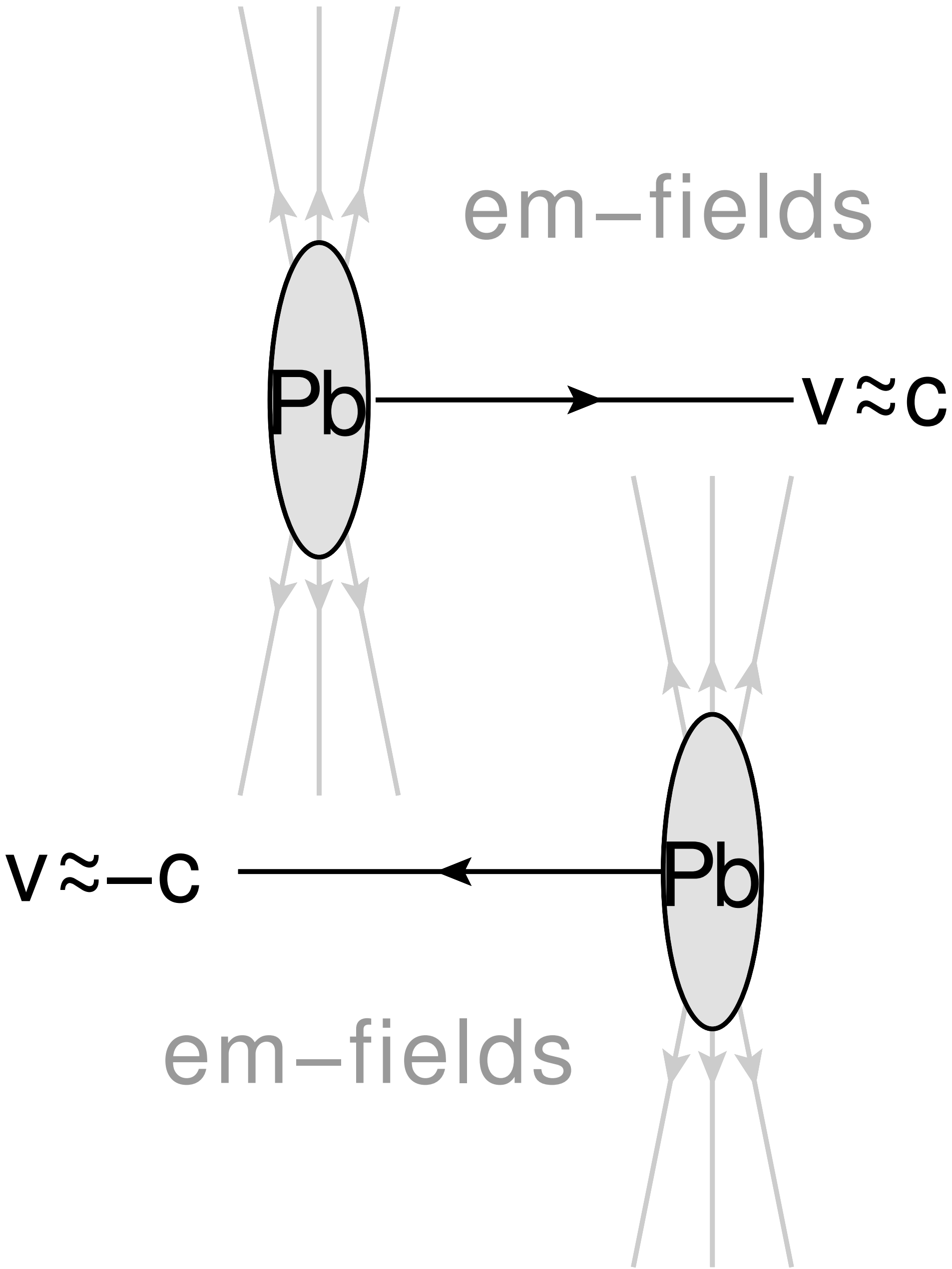
ISMD2022, 01.08.2022

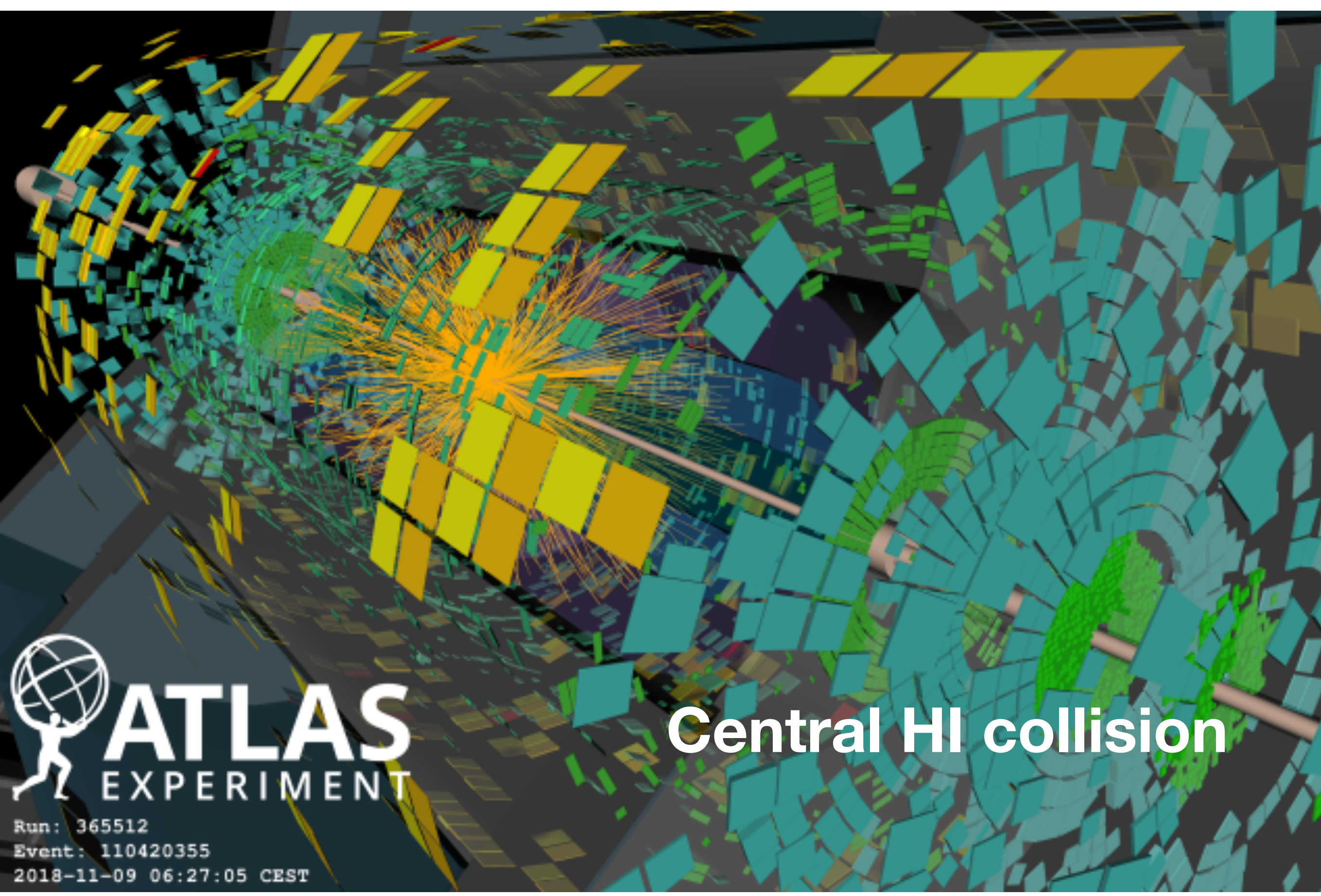
Ultra-peripheral collisions

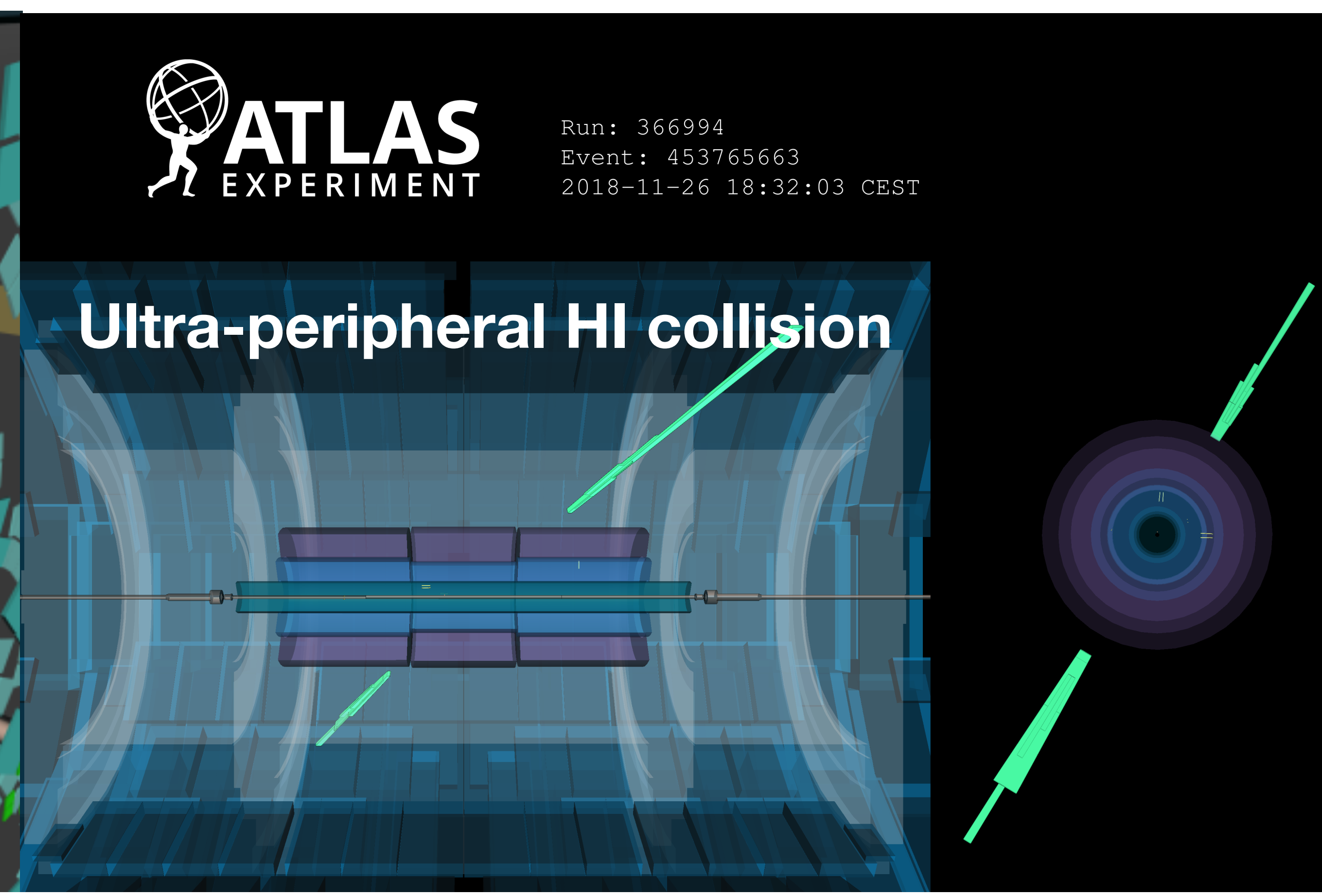
- In **ultra-peripheral heavy-ion collisions (UPC)** we observe photon-photon interactions
  - **New research opportunities**
- Electromagnetic (EM) fields of relativistic ions considered as **fluxes of photons** (they scale with ~ Z^2)
- Described in a **Equivalent Photon Approximation** (EPA) formalism
- Reaction cross-section calculated by **convolving** the respective **photon flux** with the **elementary cross-section** for the process



Ultra-peripheral collisions

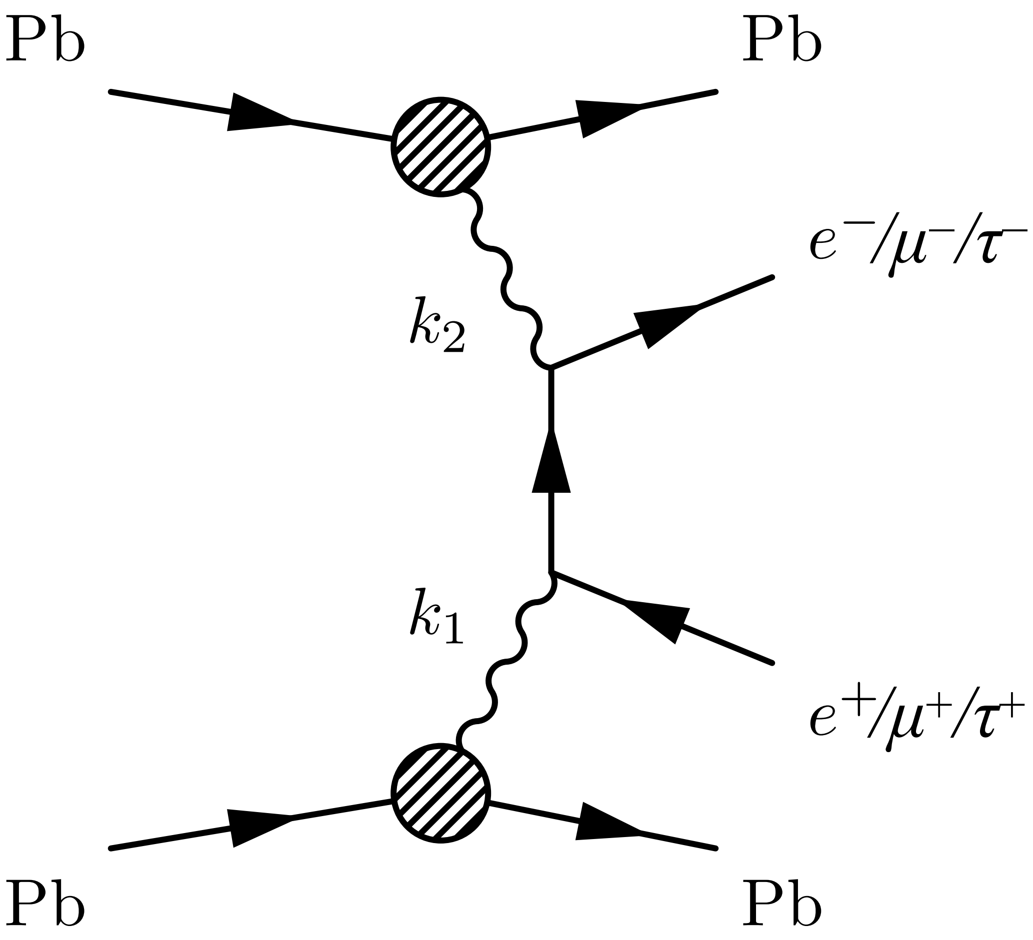
- Advantages of UPC heavy-ion collisions:
  - Increased cross-sections wrt to pp system (Z^4 scaling)
  - Very low hadronic pileup - exclusive selections possible
  - Low p_T particles can be triggered and reconstructed





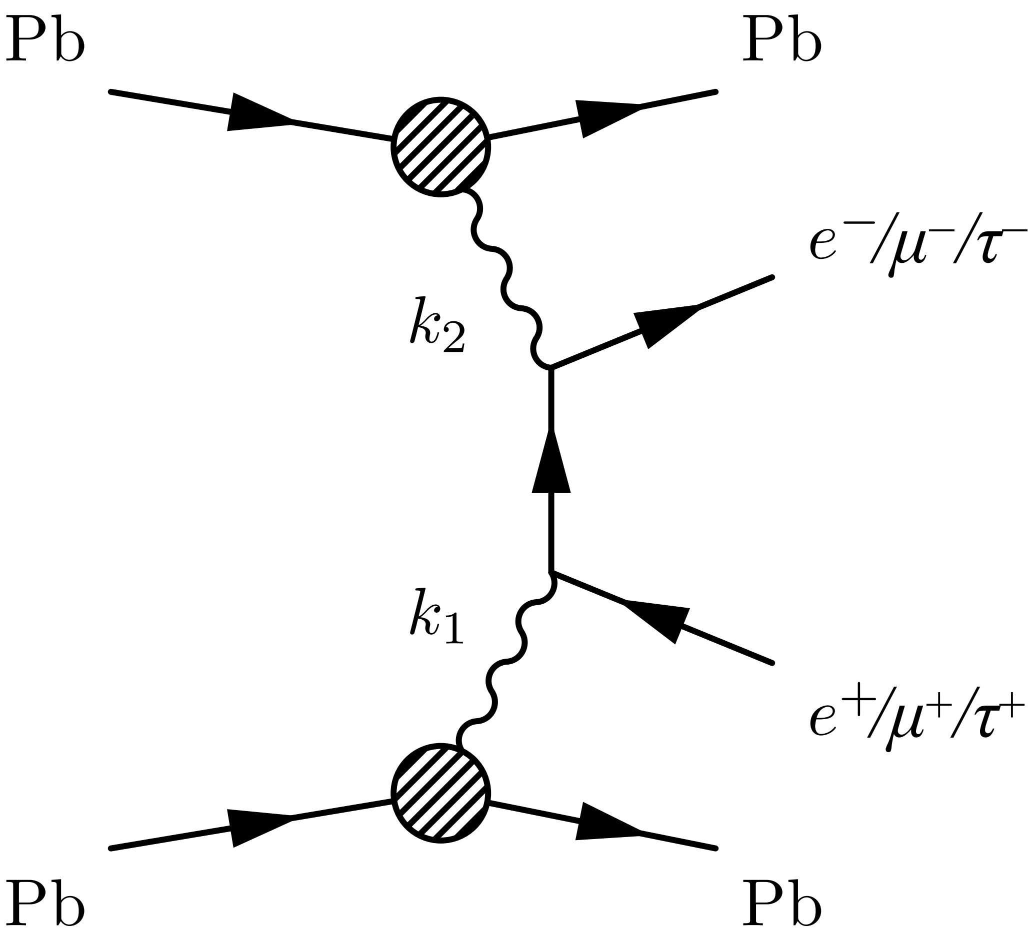
Motivation

- This talk discusses several new measurements of dilepton production performed by ATLAS Collaboration in UPC PbPb at 5.02 TeV:
  - **Exclusive dimuon production:** Phys. Rev. C 104 (2021) 024906
  - **Exclusive dielectron production:** arXiv:2207.12781, submitted to JHEP
  - **Exclusive ditau production and measurement of the τ-lepton anomalous magnetic moment:** arXiv:2204.13478, accepted by PRL



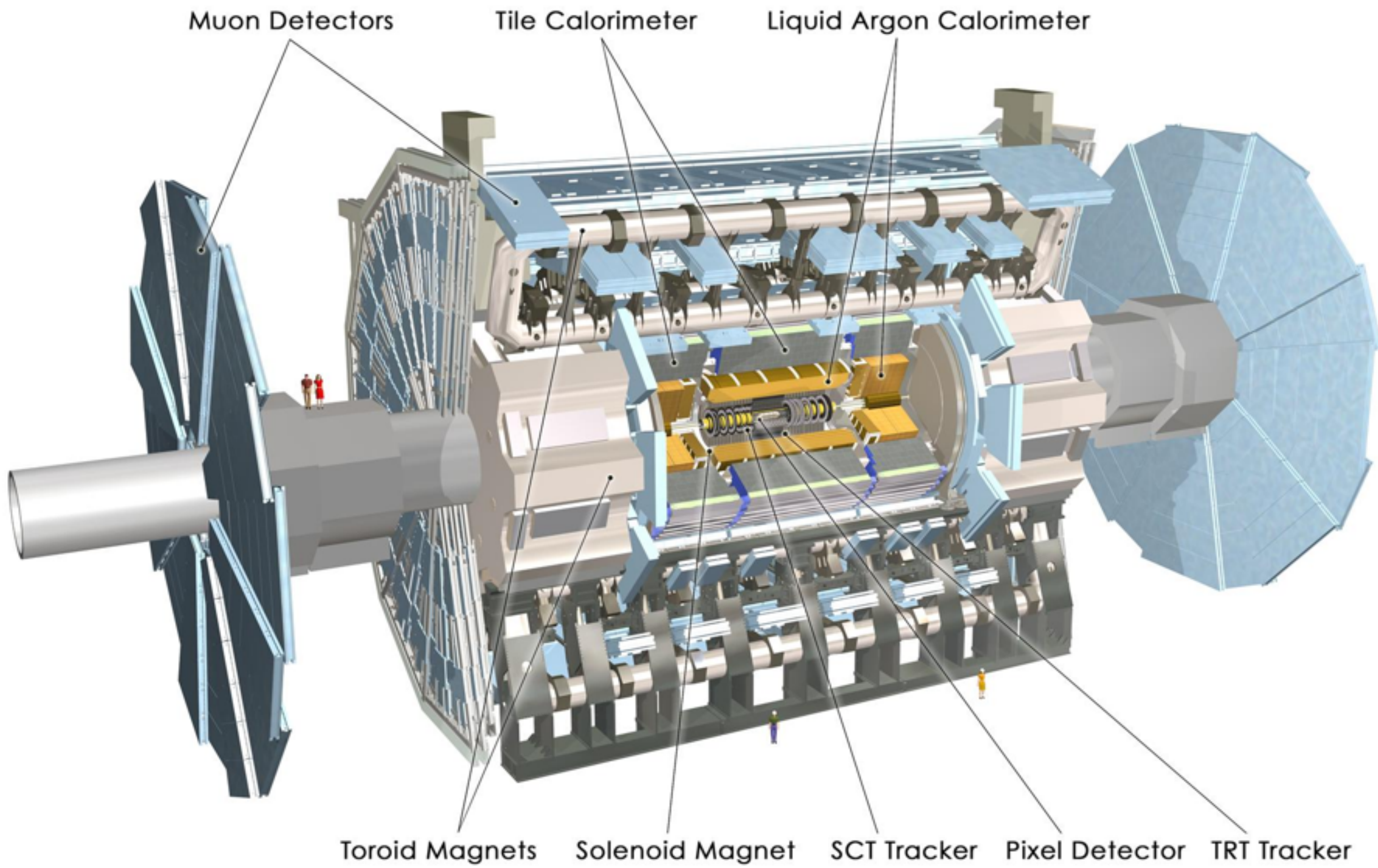
Motivation

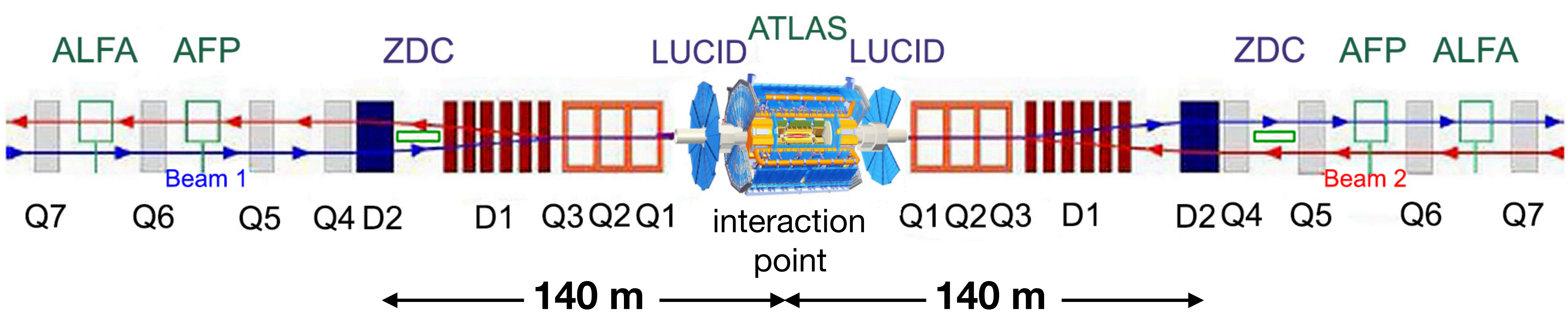
- **Exclusive dilepton production** is one of the fundamental processes in photon-photon interactions
- Dielectron/dimuon production are **benchmark processes** for other photon-induced processes
  - Reduction of systematic uncertainties
    - measurement of the τ-lepton anomalous magnetic moment
  - Important background
    - dielectron production in light-by-light scattering
  - Performance studies
    - tag-and-probe technique



ATLAS detector

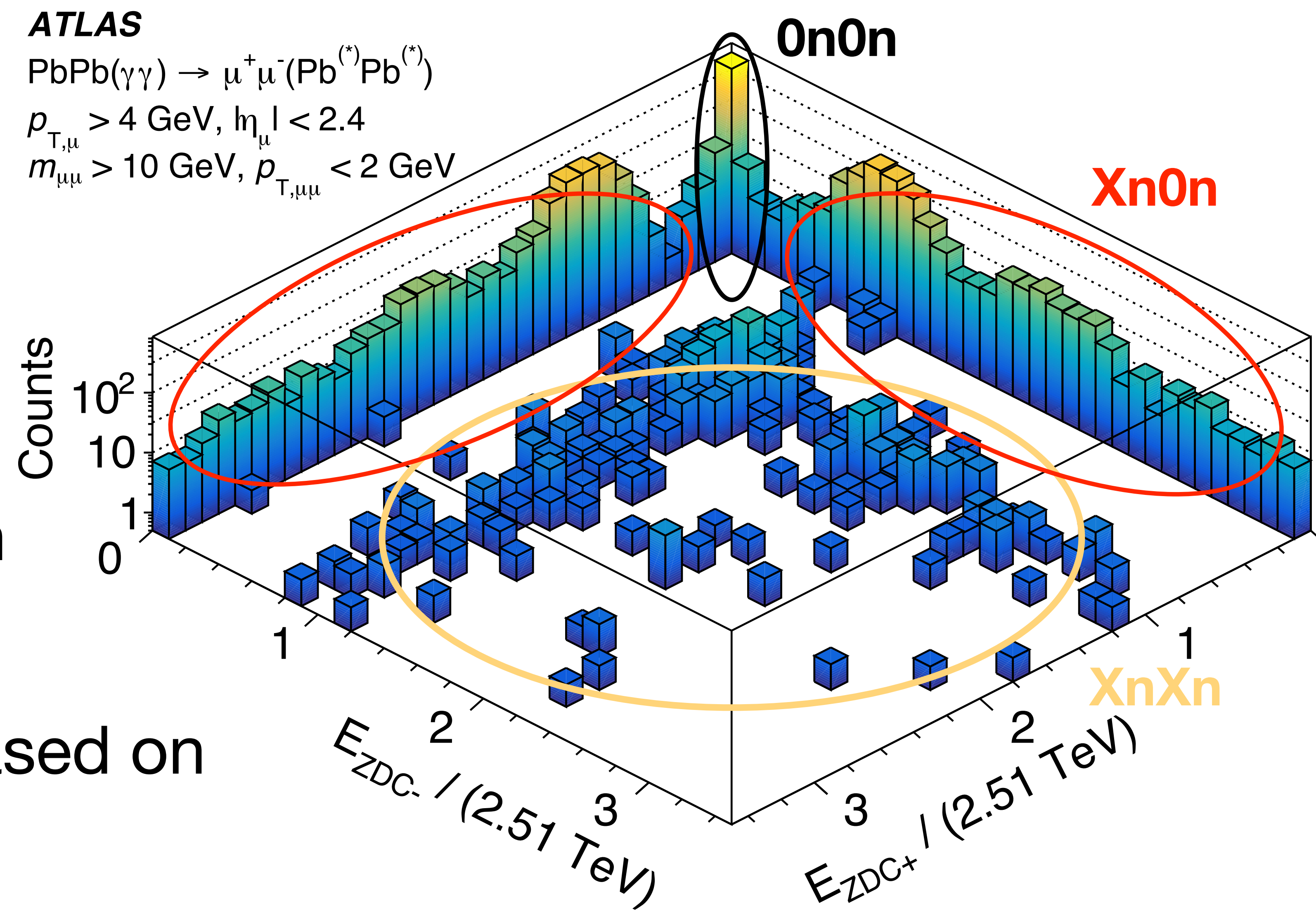
- Large general-purpose detector with almost 4π coverage
- $\eta = -\ln(\tan(\theta/2))$
- Inner detector $|\eta|<2.5$
- Muon system $|\eta|<2.7$ (trig. 2.4)
- Calorimetry out to $|\eta|<4.9$
- Zero-Degree-Calorimeters capture neutral particles with $|\eta|>8.3$





Signal categories - ZDC selection

- Different processes present **different activity in the forward region**:
  - Exclusive dilepton production - ions stay intact
  - Background events with nuclear breakup

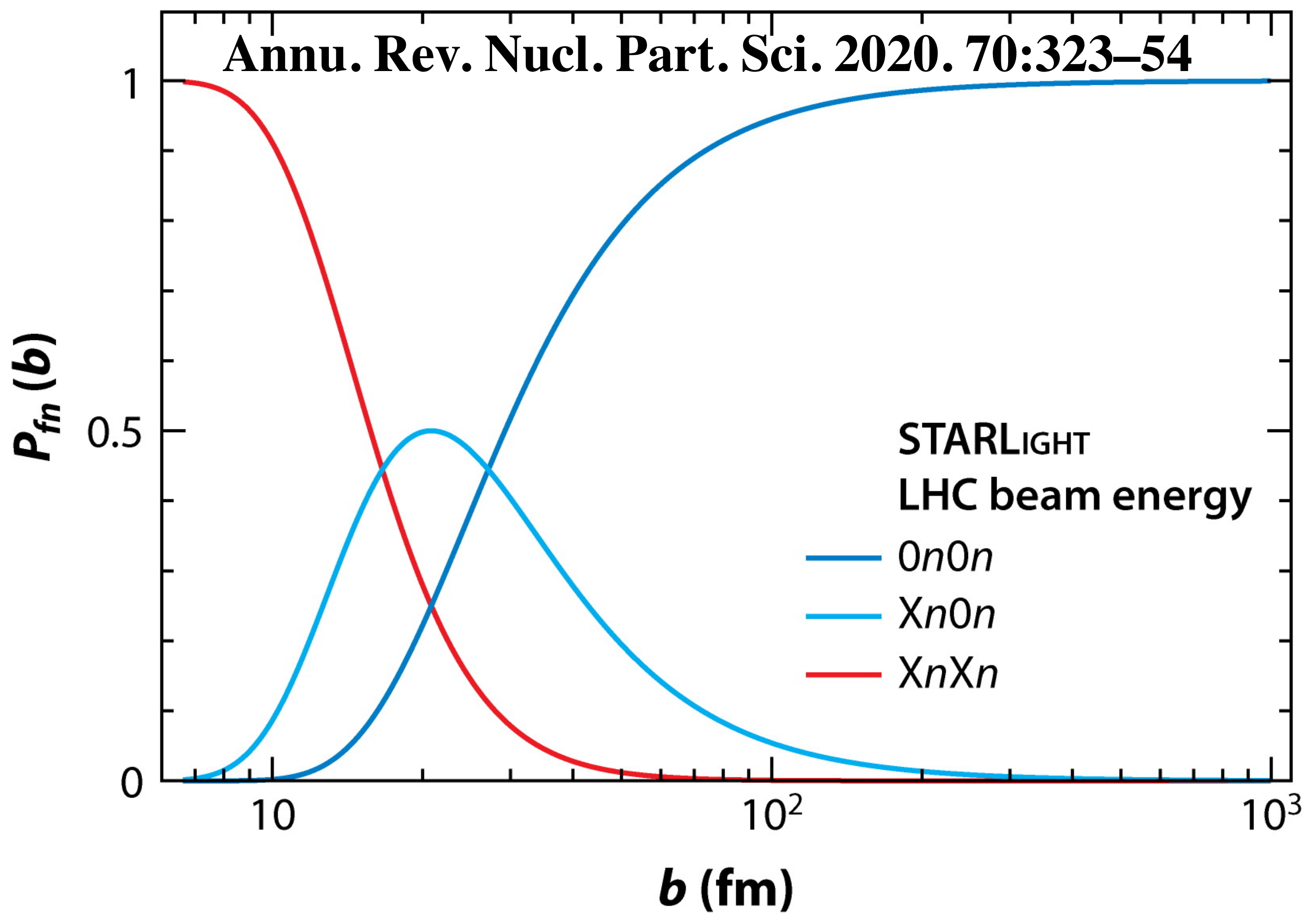


- **Three classes** defined, based on the signal in the ZDC
- The **association between** given **ZDC signal** and given **process** is **nontrivial**
  - Migrations due to ion excitation and presence of EM pile-up

ZDC fractions - *b* dependence

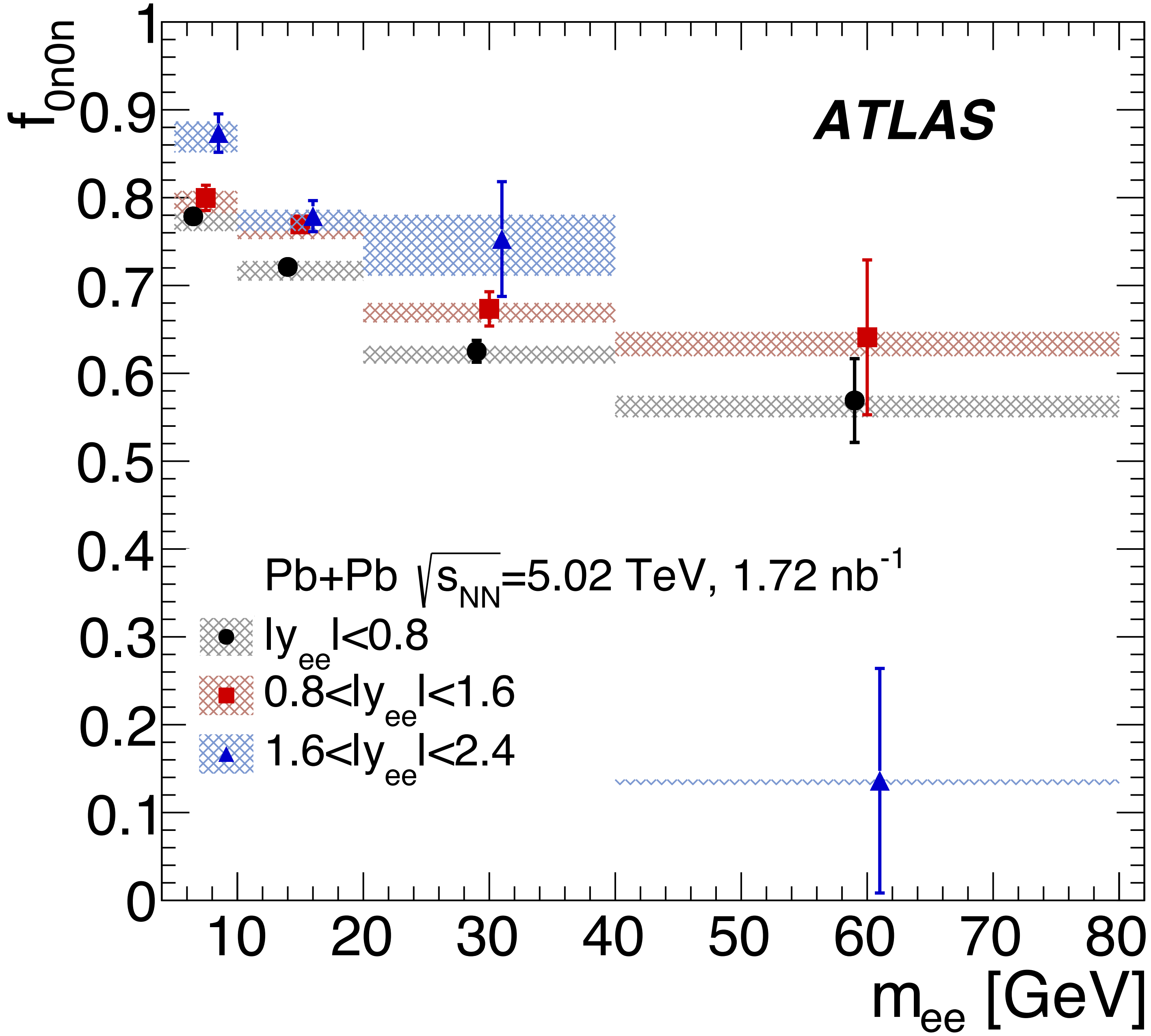
- The probability of producing a given **ZDC category depends on** the value of the **impact parameter**, *b* (based on the Coulomb excitation probabilities ~ $1/b^2$)

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



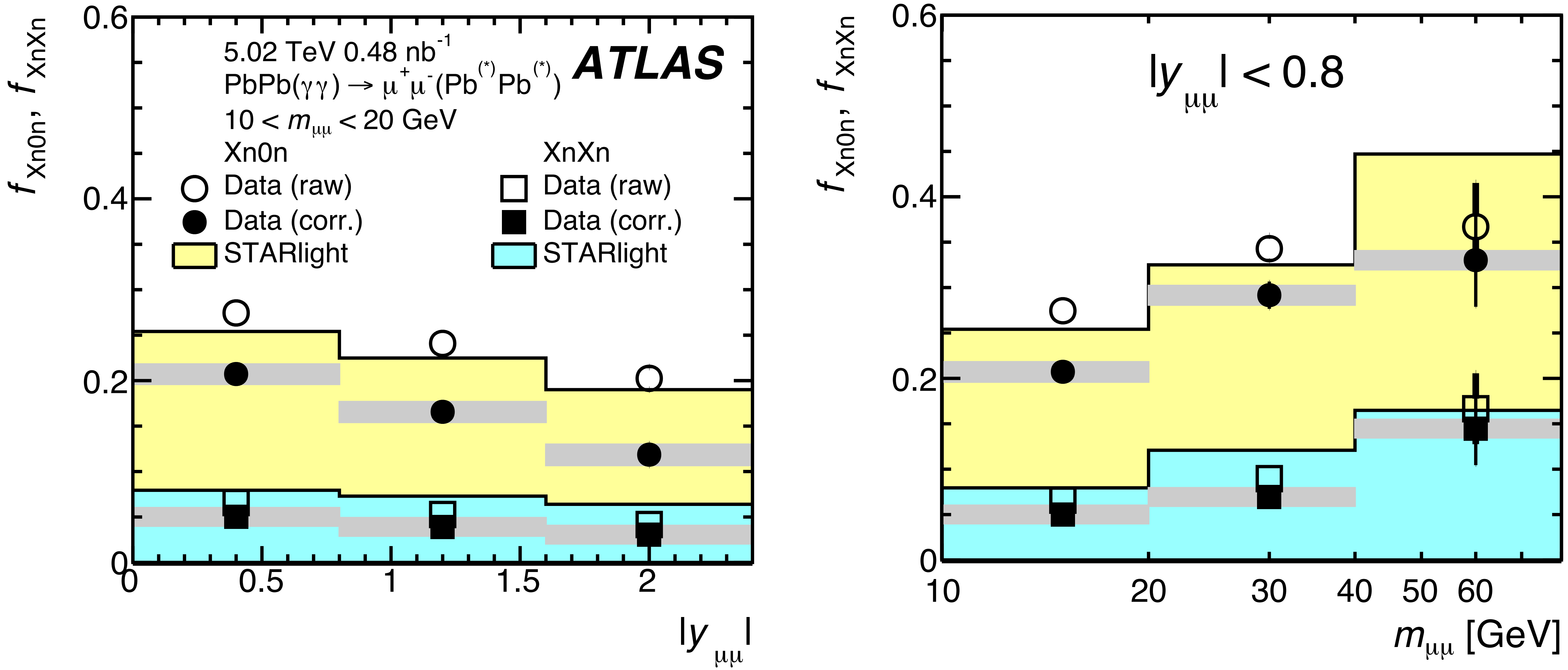
f0n0n fractions - dielectrons

- The **0n0n category** should in principle be very **pure**, at least in terms of dissociative background
- To select 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



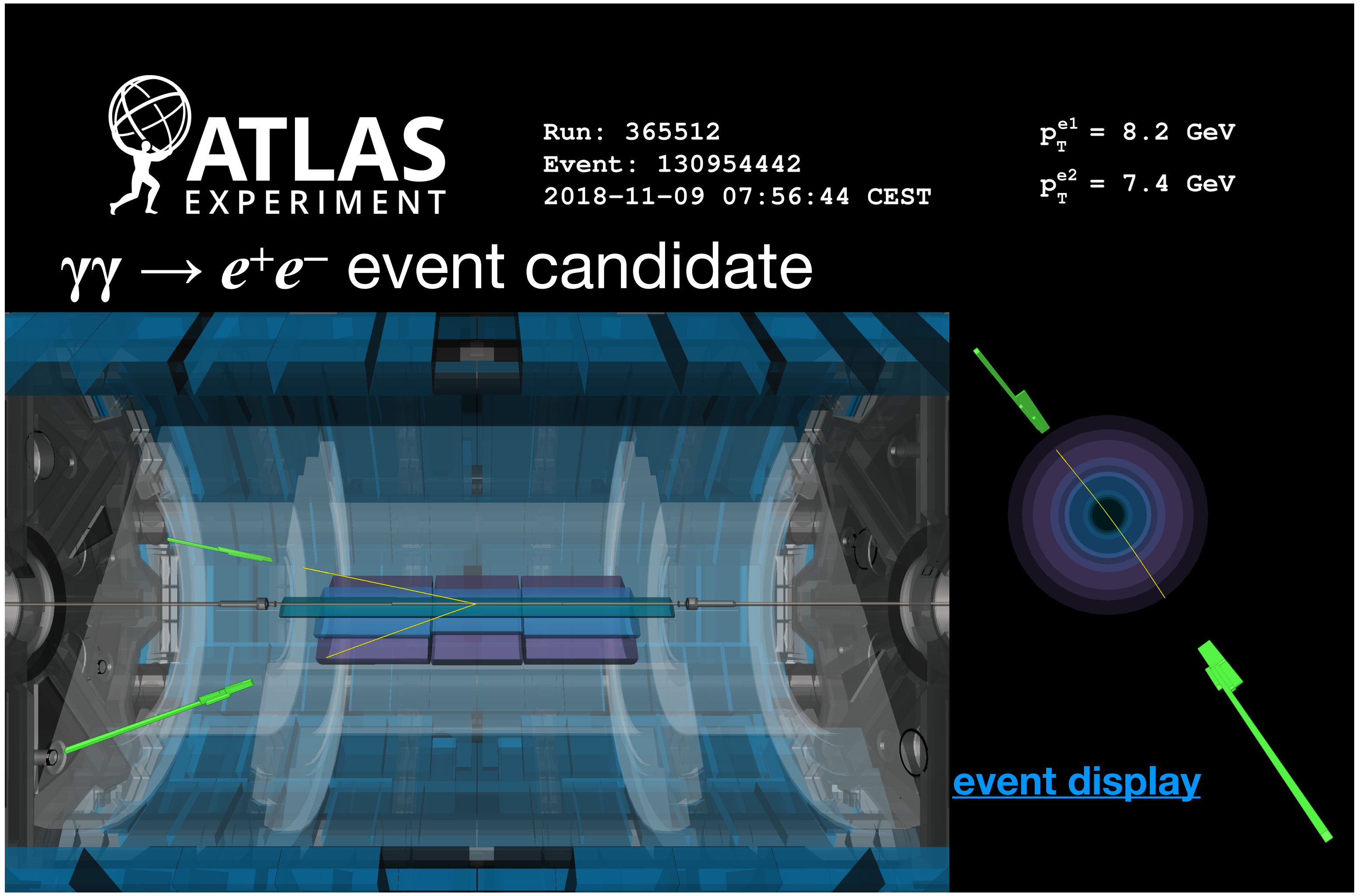
fXn0n and fXnXn fractions - dimuons

- The raw (open points) fractions higher than corrected (full markers)
- The corrected f_{Xn0n} and f_{XnXn} fractions are compared with the **STARlight predictions** — the latter are systematically **higher** for f_{Xn0n} and f_{XnXn} fractions



Event characteristics & selection

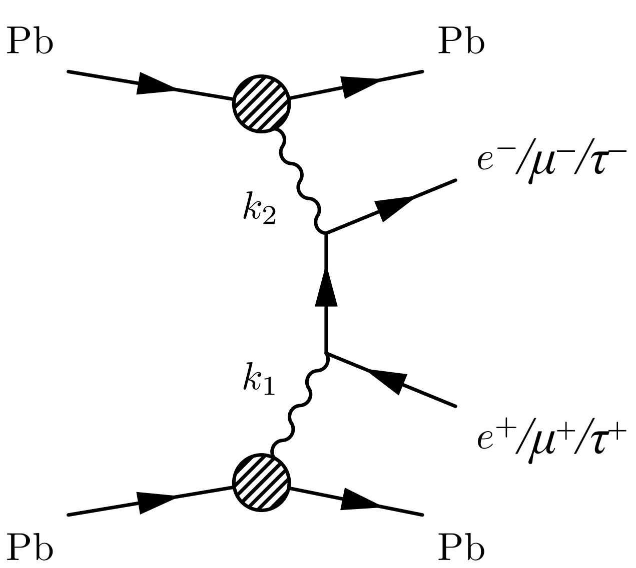
- Exclusive dilepton events are characterized by :
  - **Two low-p_T opposite sign leptons** (of the order of a few GeV) and otherwise empty detector
  - Leptons are produced **back-to-back** in azimuthal angle (described by low dilepton transverse momentum, $p_{T,ll}$)
- ATLAS optimized to detect high-energy particles
  - careful estimation of trigger and particle reconstruction efficiency in low energy region



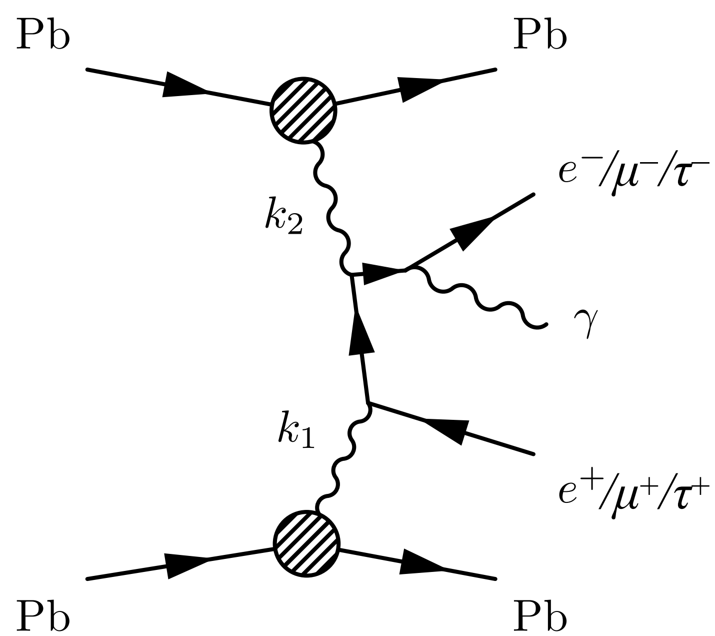
	muons	electrons
Int. Lumi [nb^{-1}]	0.48	1.72
p_T^{ℓ} >	4 GeV	2.5 GeV
$\|\eta_{\ell}\|$ <	2.4	2.5
$m_{\ell\ell}$ >	10 GeV	5 GeV
$p_T^{\ell\ell}$ <	2 GeV	2 GeV

Background sources for $\mu\mu/ee$

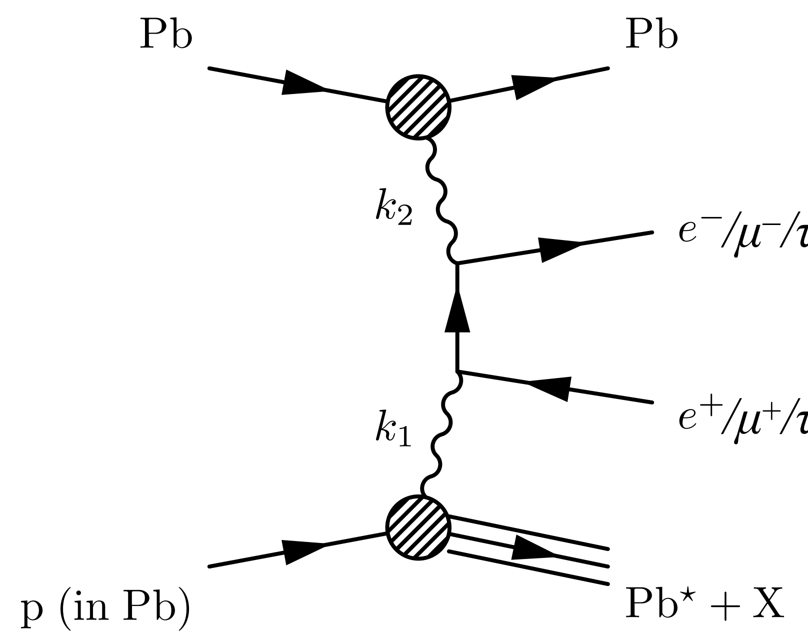
- Several background sources are considered:
  - **dissociative** production of $\ell^+\ell^-$ pairs - estimated with data-driven method (template taken from LPair/SuperChic4+Pythia8 in *pp* collisions)
  - **Upsilon(nS)** production - estimated with STARlight+Pythia8 MC samples (only in dielectron measurement)
  - exclusive **ditau** production - estimated with STARlight+Pythia8 MC samples (only in dielectron measurement)



Signal (LO)



Signal with FSR



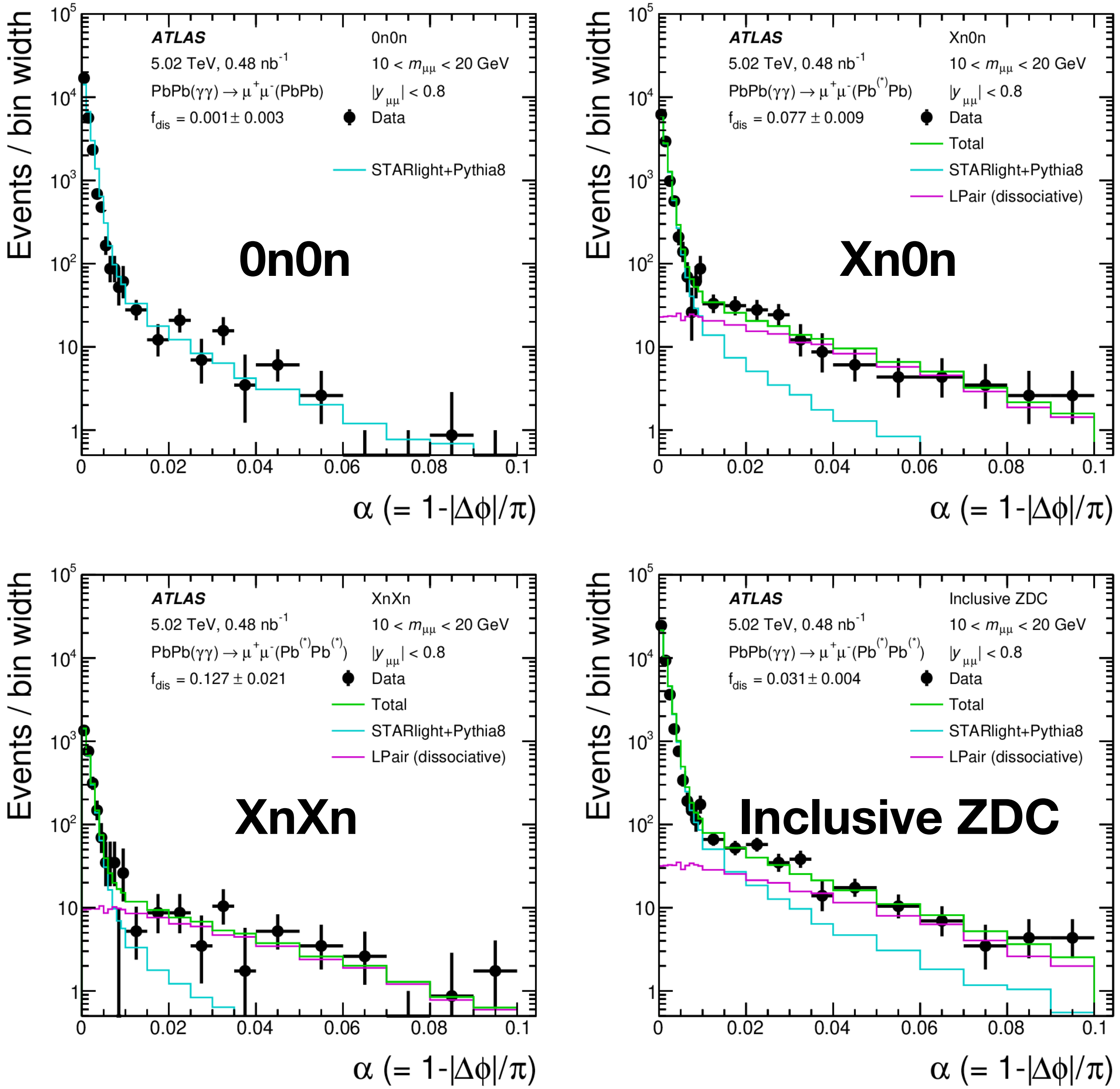
dissociative background

Dimuons

Dimuons - background

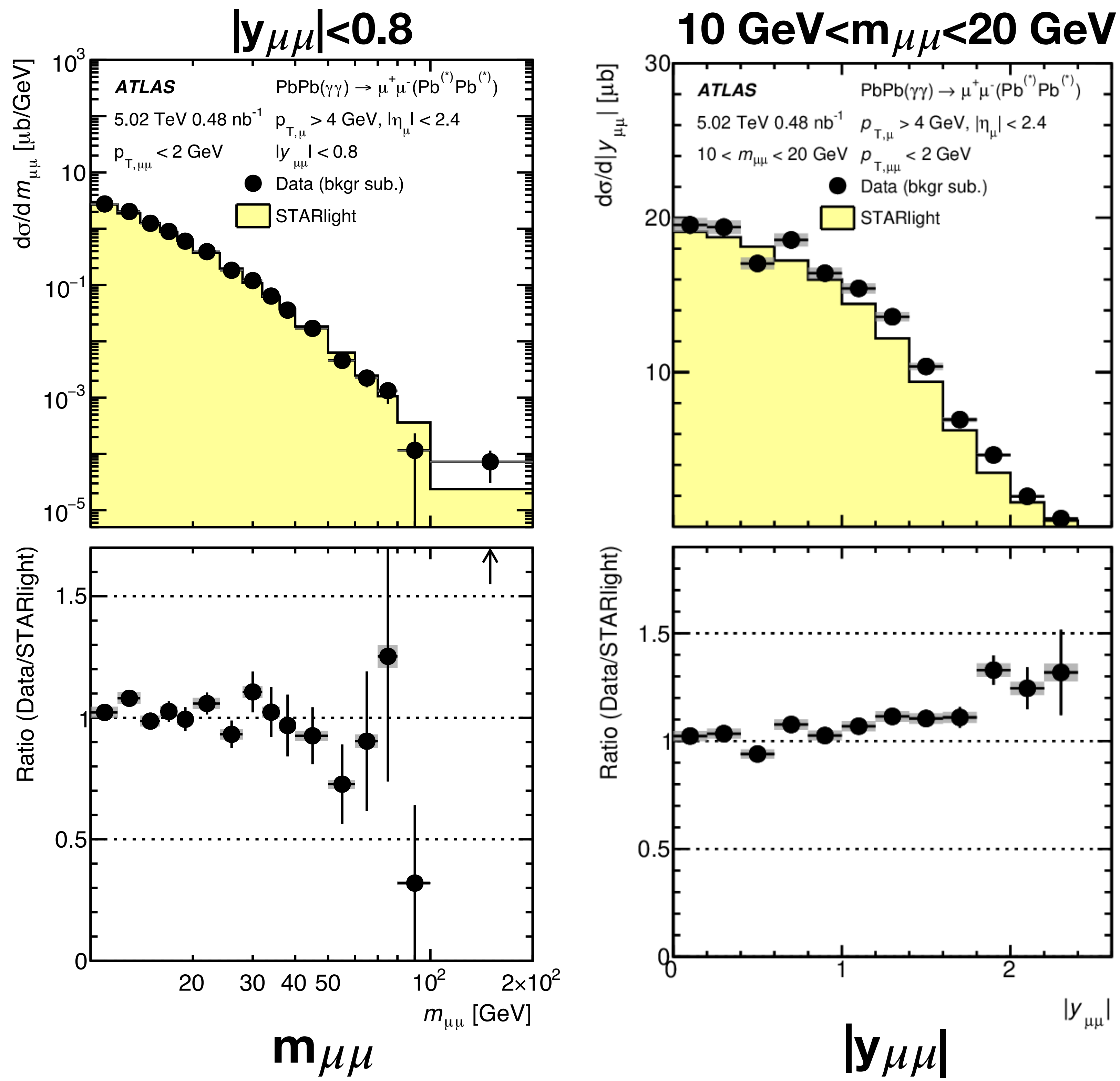
$$P(\alpha, m_{\mu\mu}, y_{\mu\mu}) = (1 - f_{dis}) P_{EPA}(\alpha, m_{\mu\mu}, y_{\mu\mu}) + f_{dis} P_{dis}(\alpha, m_{\mu\mu}, y_{\mu\mu})$$

- Based on number of neutrons detected in ZDC, **events** are **categorized** in 0n0n, Xn0n and XnXn classes
- The differences between these classes are strongly pronounced in acoplanarity distribution
- The data is compared with STARlight+Pythia8 **simulation** for $\gamma\gamma \rightarrow \mu^+\mu^-$ process with FSR and LPair **for dissociative events** (for pp collisions)
- The **simultaneous fit** is performed in all ZDC topology classes to estimate fraction of dissociative events



Dimuons - results

- 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 $m_{\mu\mu}$)
- Data is **compared with STARlight** MC simulation of $\gamma\gamma \to \mu^+\mu^-$ process w/o FSR
- The overall shape of the spectra is **well described** out to the highest masses
- Some hints of decreasing ratio for larger $m_{\mu\mu}$
- **Good agreement** is found in central region of rapidity distribution (small $|y_{\mu\mu}|$), but data to simulation ratio increases with $|y_{\mu\mu}|$

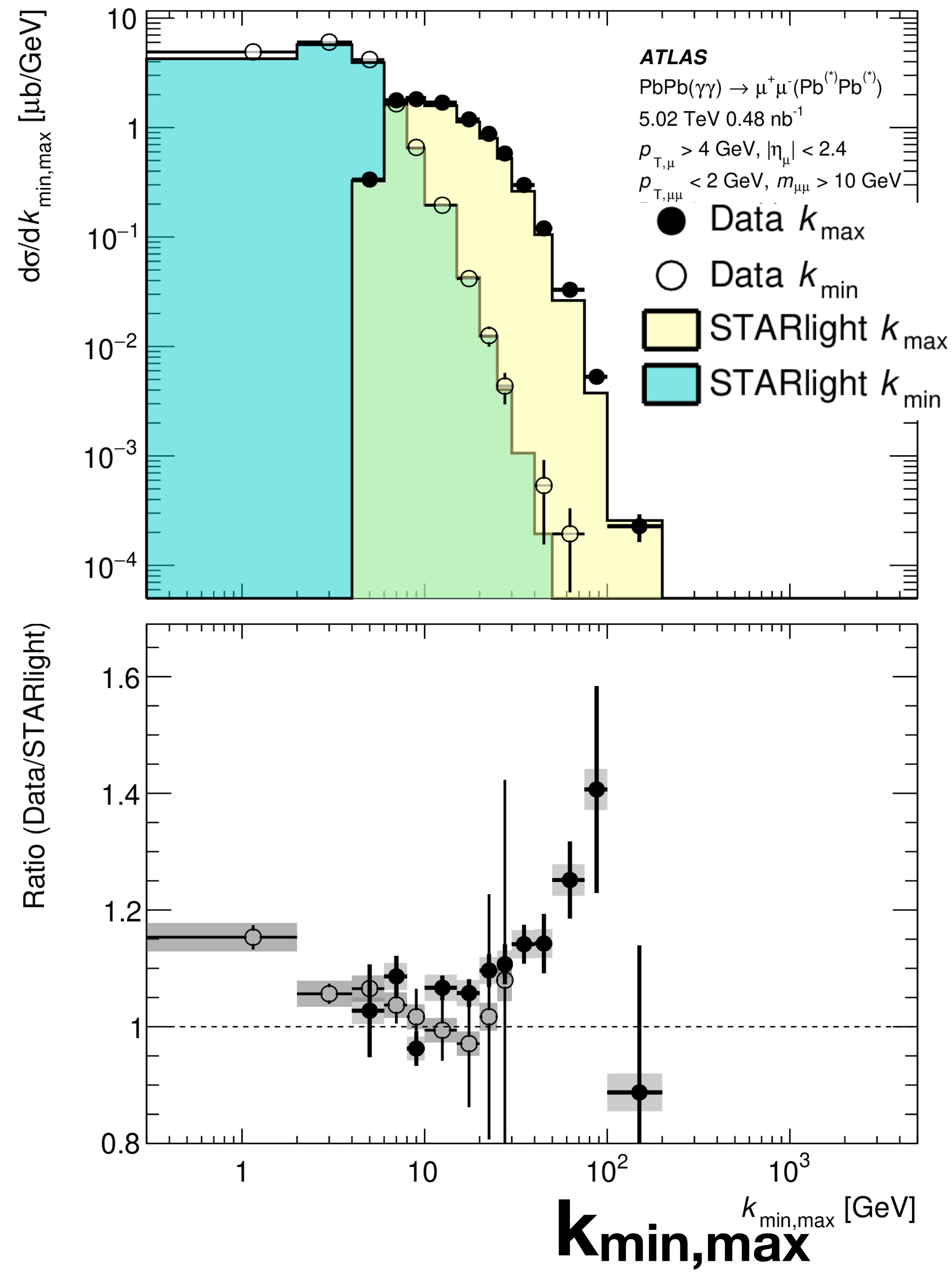


What can we learn about initial photon fluxes?

- The muon kinematics can be used to estimate **initial photon energies**

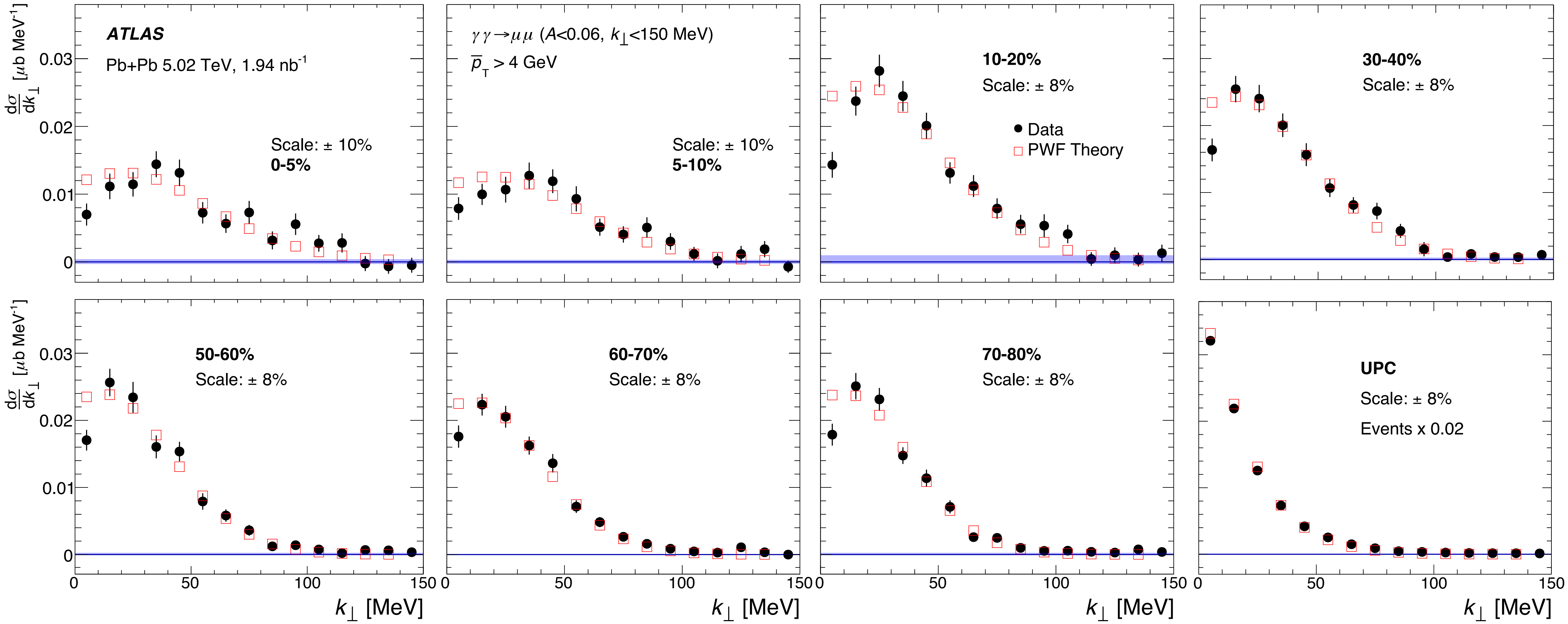
$$k_{\mathrm{min,\,max}} = (1/2)m_{\mu\mu}\exp(\pm y_{\mu\mu})$$

- The **cross section** is presented as a function of maximum and minimum photon energies
- The STARlight predictions are correct in intermediate region 5-20 GeV
- Disagreement between the data and MC for lower k_{min} and higher k_{max}
- Further developments needed to better model photon fluxes



Non-UPC dimuons

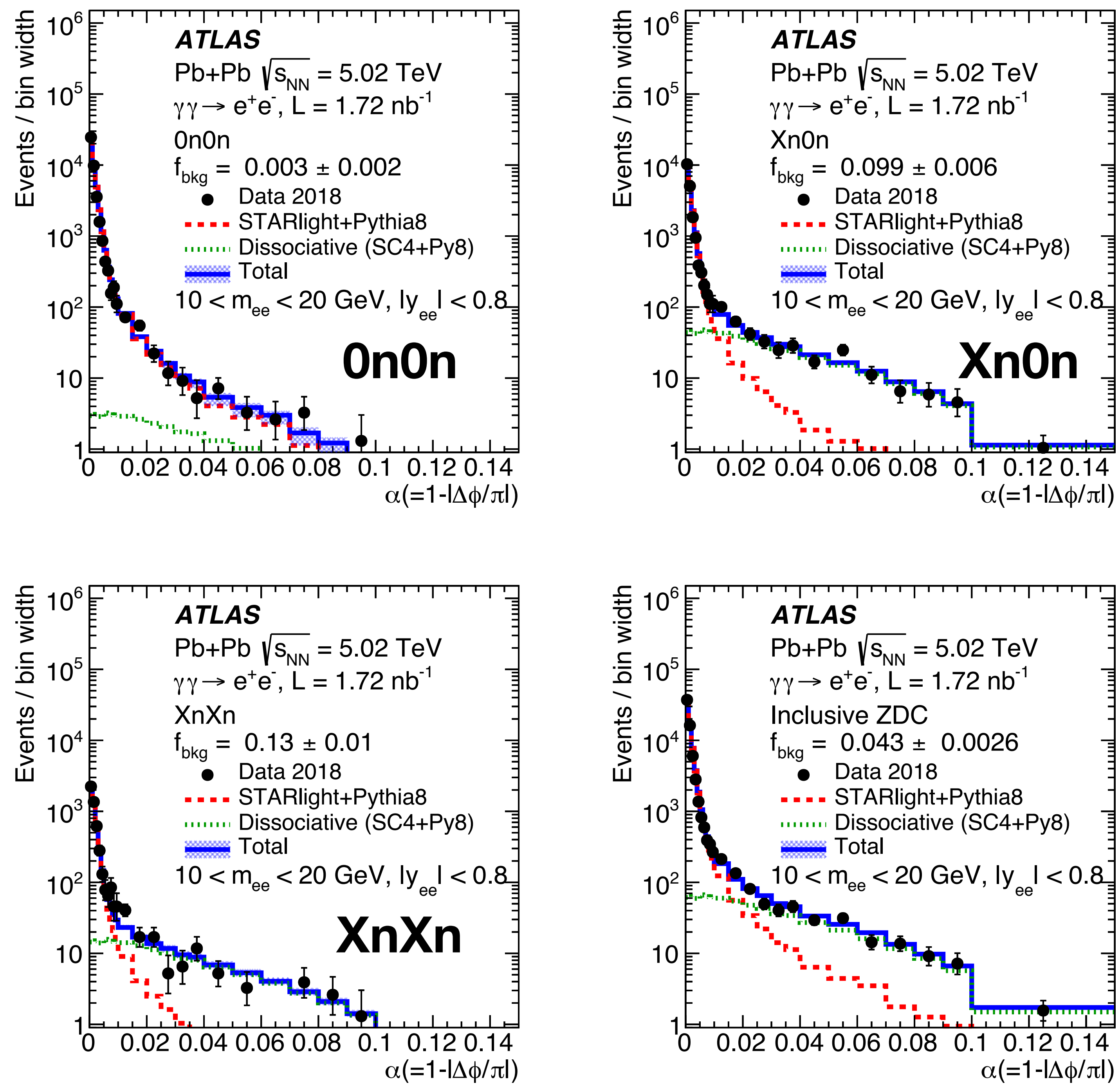
- The dimuons originating from photon-photon interactions were also observed in non-UPC events by ATLAS arXiv:2206.12594
- Studied α and k_T ($=\alpha\pi(p_{T,1}+p_{T,2})/2$) distributions as a function of event centrality
- Observed depletion in cross-section in the region of low-k_T, not predicted by models



Dielectrons

$$P(\alpha, m_{ee}, y_{ee}) = (1 - f_{dis}) P_{EPA}(\alpha, m_{ee}, y_{ee}) + f_{dis} P_{dis}(\alpha, m_{ee}, y_{ee})$$

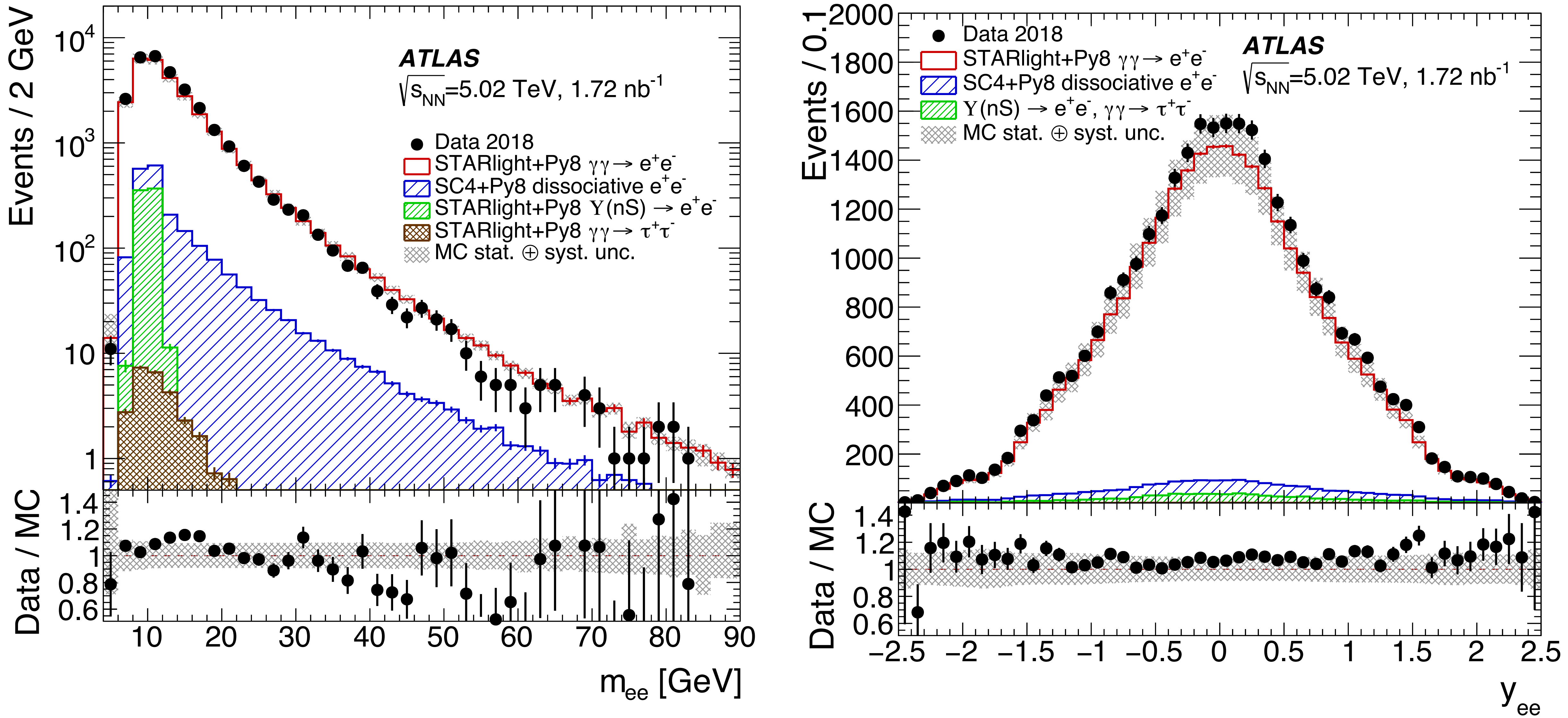
- The background samples for **single dissociation** from SuperChic4+Pythia8 are used instead of LPair
- Fitting procedure similar to the one used in dimuon measurement
- Small background contributions from **ditau** and **Upsilon(nS)** production also estimated



Inclusive ZDC

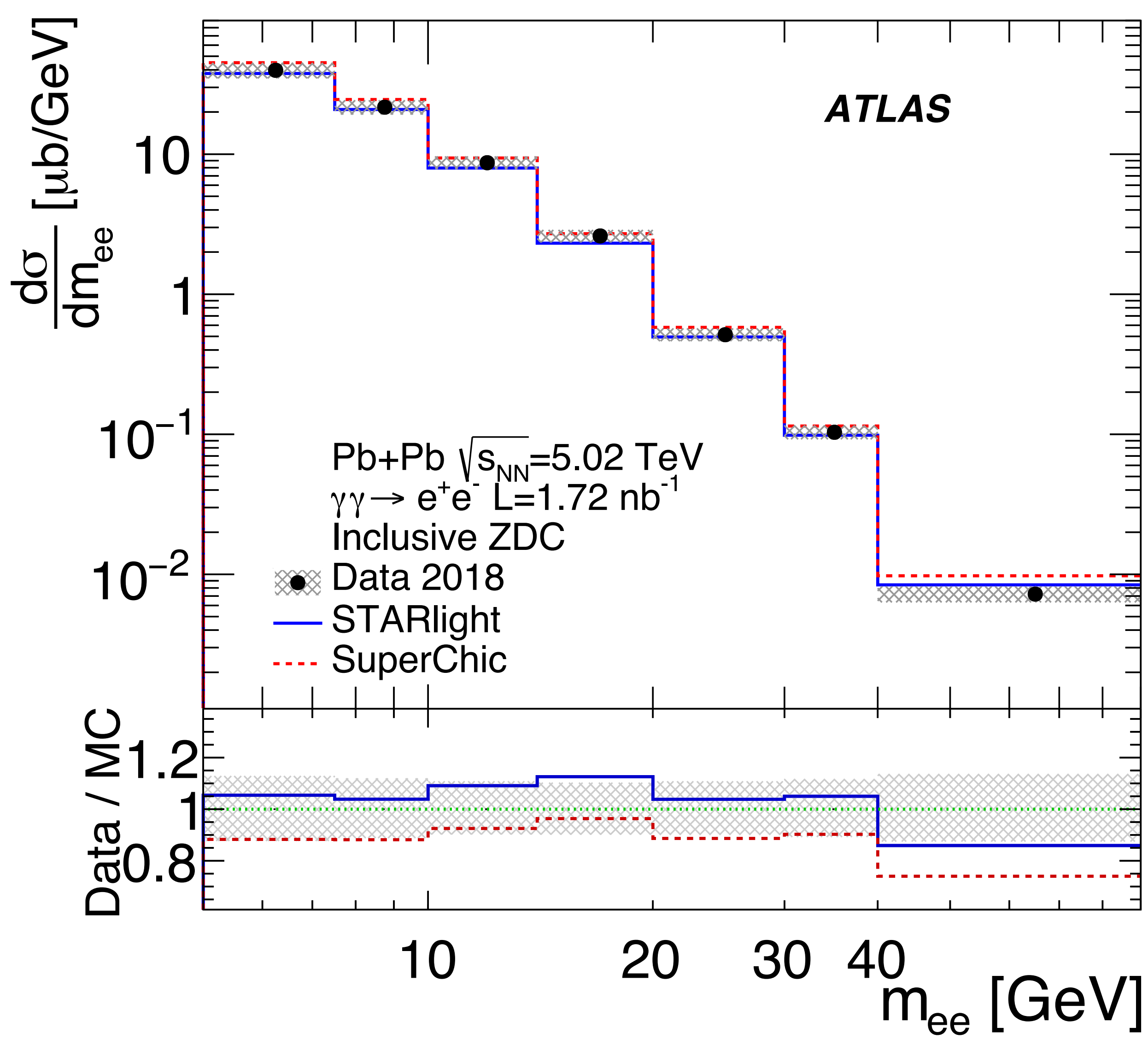
Detector-level control plots

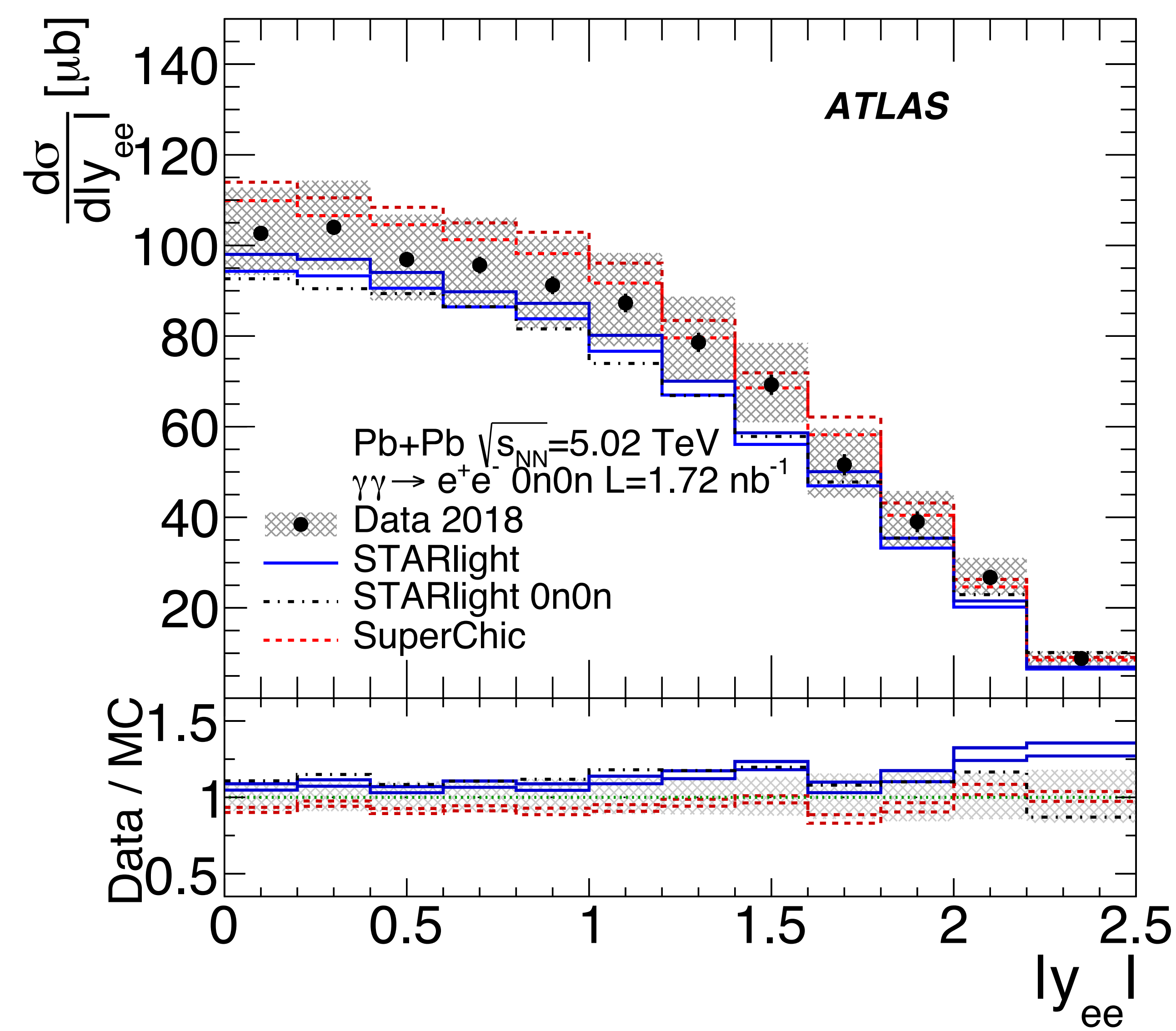
- The data sample is ~93% pure, with about 10% more counts in data than in the MC prediction



Dielectrons - results

- **Good agreement** with STARlight and SuperChic is observed, differences in the same regions as in detector-level plots
- Results for mass compatible with dimuon measurement
- Two lines for predictions in 0n0n category show the predicted cross-section with f_{0n0n} varied up and down

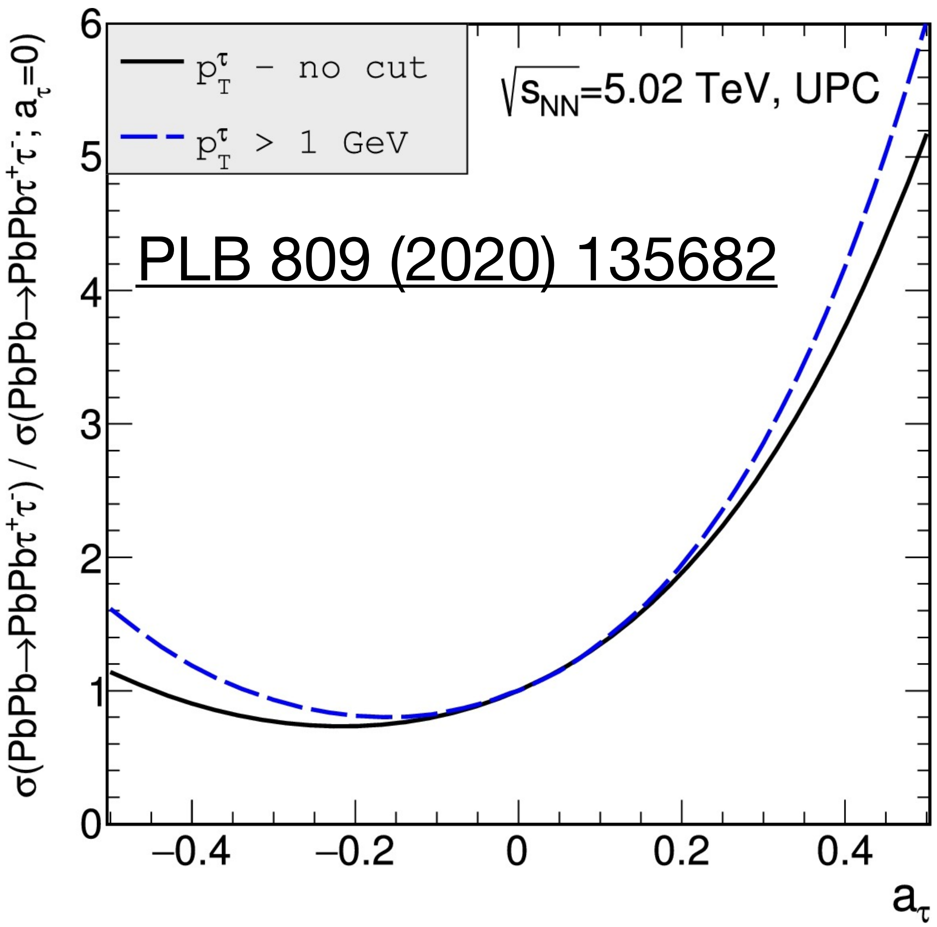




Ditaus

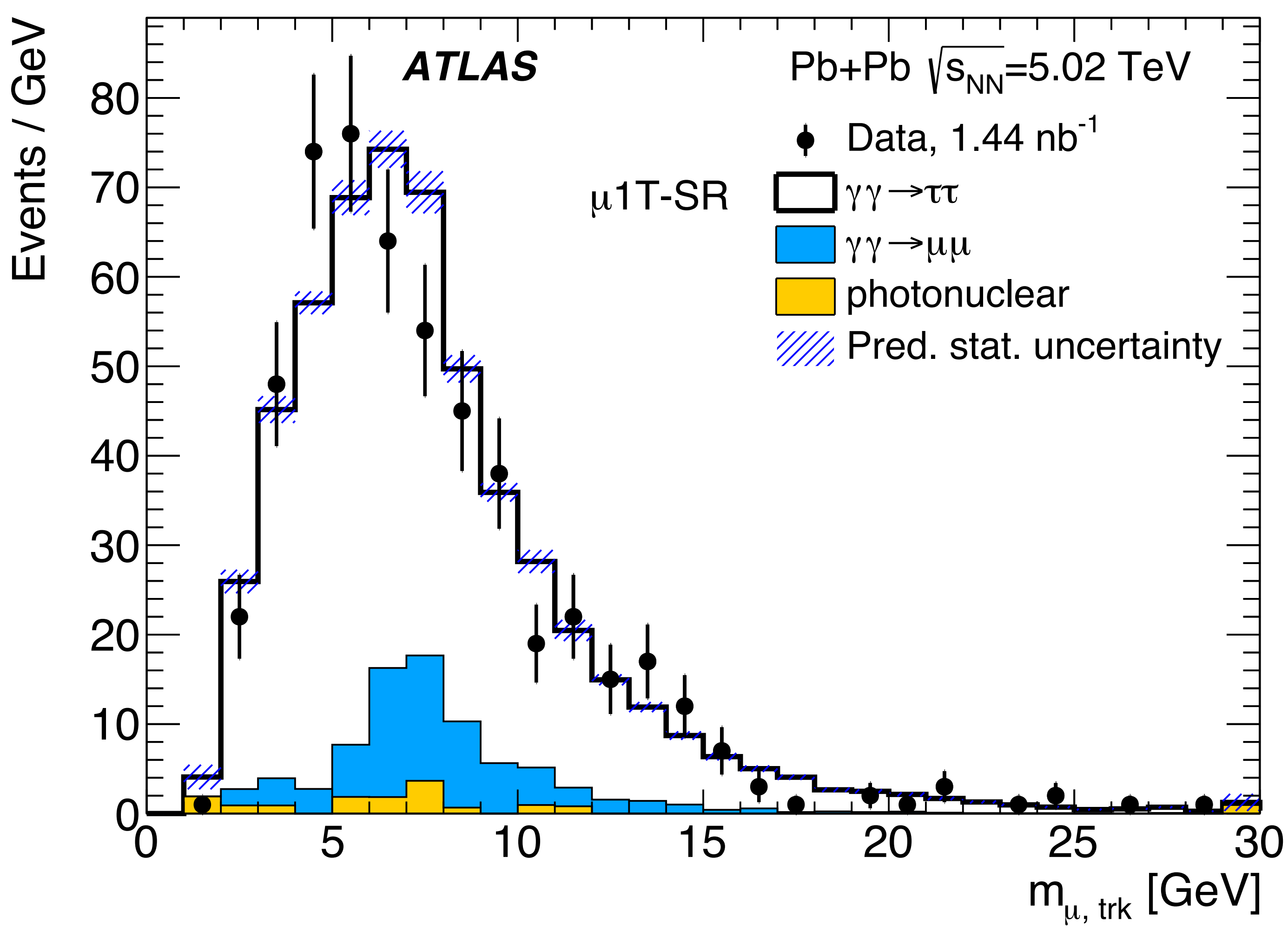
a_τ - measurement strategy

- Magnetic moment of the particle and its spin are related by *g*-factor: $\boldsymbol{\mu} = g\, q/2m\, \mathbf{S}$
- Dirac's equation predicts $g=2$ for charged leptons, higher-order corrections result in $g \neq 2$,
- These discrepancies are measured with lepton **anomalous magnetic moments** $a_\ell = (g-2)_\ell/2$
- The value of a_ℓ can be modified by various **BSM phenomena** (leptoquarks, lepton compositeness, SUSY, …)
- Currently the **best constraints** for a_τ are from DELPHI experiment: $-0.052 < a_\tau < 0.013$ (95% CL), EPJC 35 (2004) 159
- Measurement of **a_τ 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

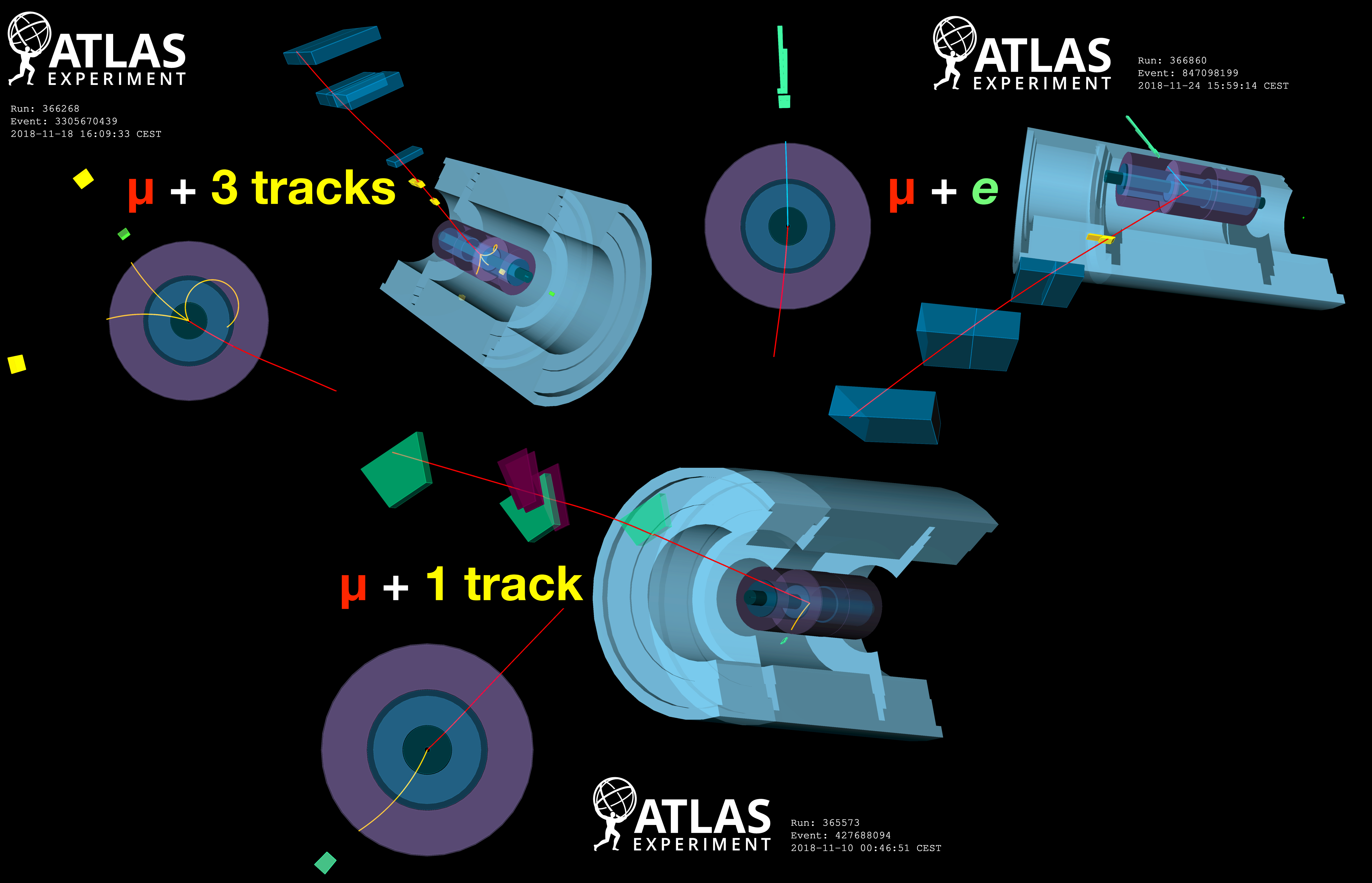


Ditau event selection

- **Signal** τ-leptons are **low-energetic**, typically with $p_T < 10$ GeV
- No standard ATLAS identification of τ-leptons is used,
  - Instead events classified based on the charged τ-lepton decay products
- **Three signal categories:**
- $\mu + 1$ track, $\mu + 3$ tracks, $\mu + e$
- Single muon trigger used to record signal events with muon $p_T > 4$ GeV
- **Exclusivity requirements:**
  - veto on forward neutron activity (using 0n0n configuration based on ZDC signal)
  - for $\mu + 1$ track and $\mu + 3$ tracks signal regions: veto on additional low-p_T tracks and low-p_T clusters

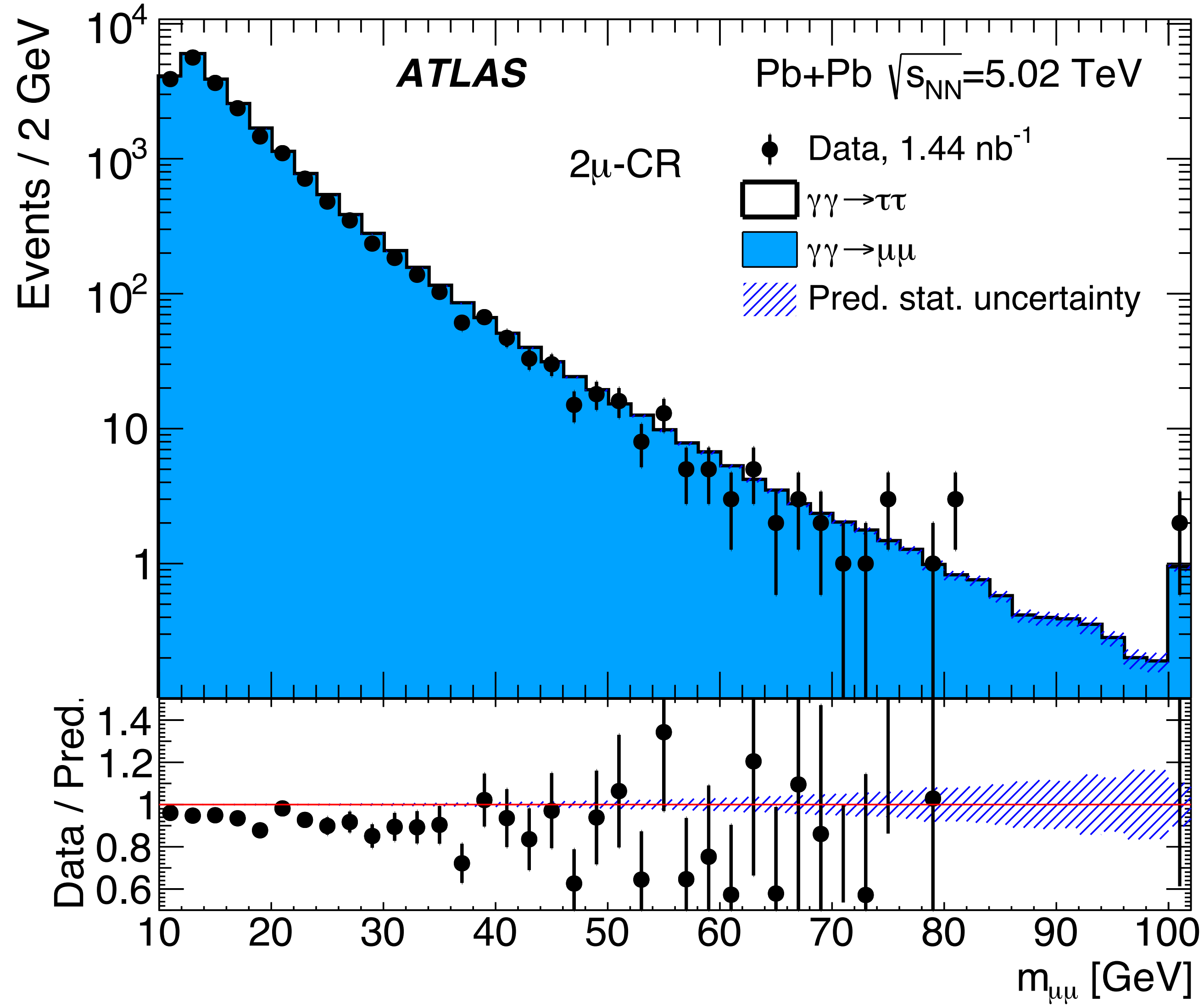


Ditau events



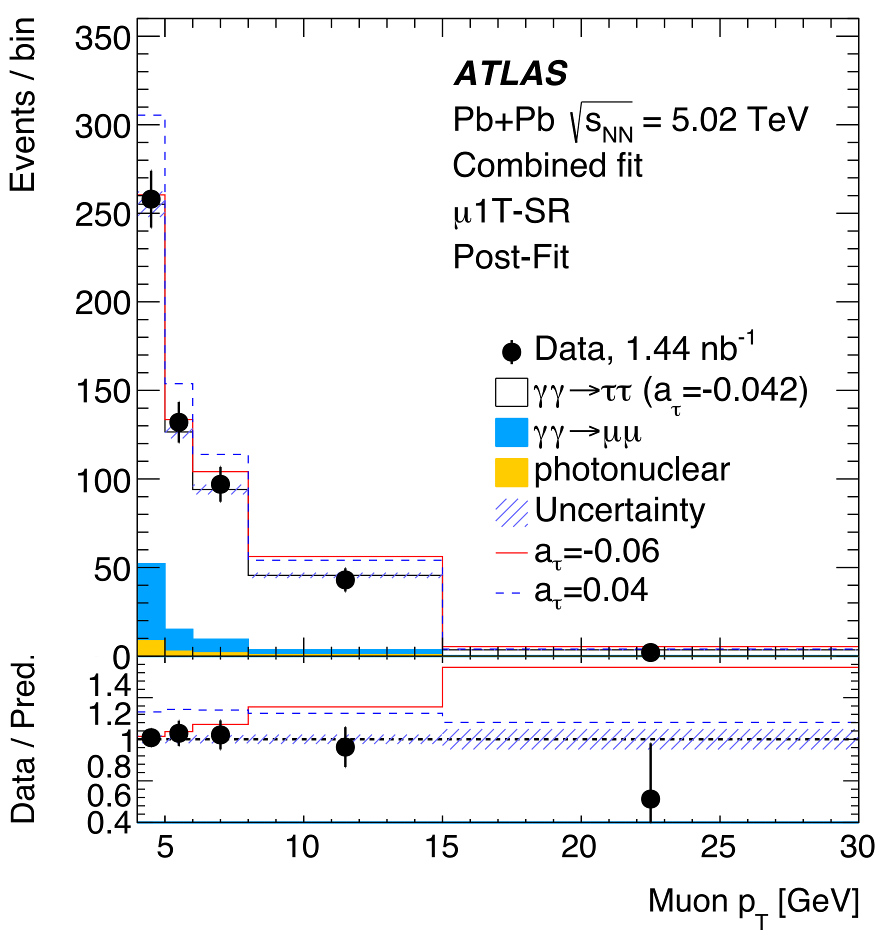
Backgrounds

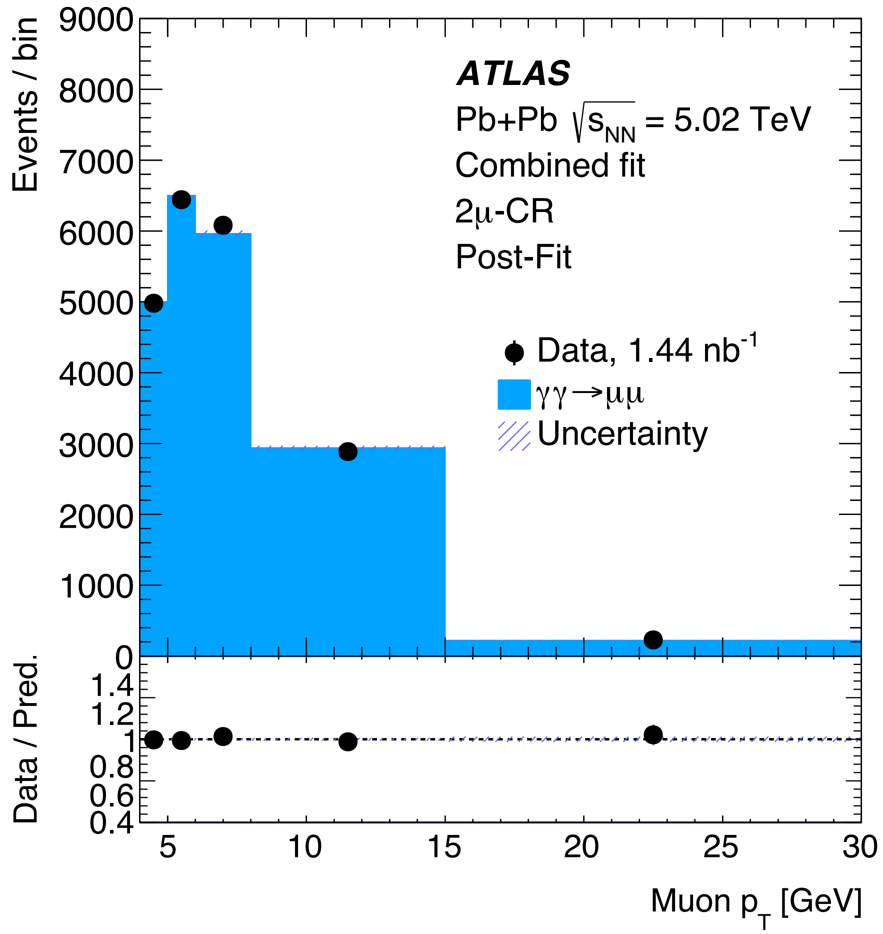
- Main **background contributions** from dimuon production and diffractive photonuclear interactions
- Background from $\gamma\gamma \rightarrow \mu\mu(\gamma)$ **production** estimated using **MC simulation,** constrained by a data CR
- Already pre-fit distributions in the two muon CR show good agreement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



Observation of exclusive ditau production, τ-lepton g–2

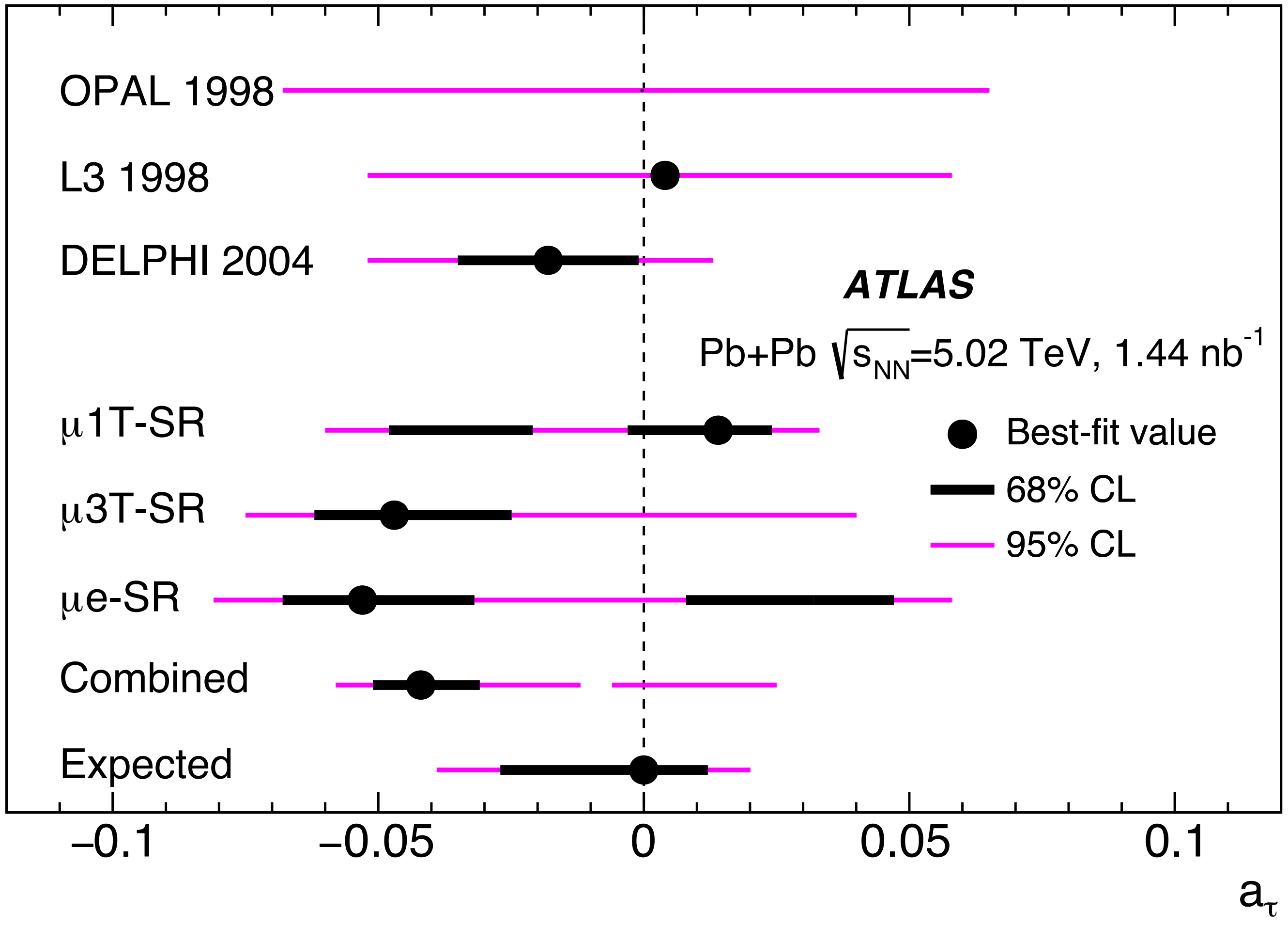
- The $\gamma\gamma \to \tau\tau$ signal strength and a_τ value is extracted using a **profile likelihood fit** using the muon p_T distribution
- **Simultaneous fit** combining all signal regions and dimuon control region
  - Dimuon **control region** ($\gamma\gamma \to \mu\mu$ events) used to **reduce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





τ-lepton g–2

- Expected 95% CL limits from 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)



Summary

- The exclusive dilepton production was measured using data collected in 2015 and 2018 with the ATLAS detector
- Despite slightly different definitions of the fiducial region, the **conclusions** from dimuon and dielectron measurements are **consistent**
- Thanks to the ZDC, **activity in the forward region** could be measured
  - This should provide constraints for **impact-parameter dependence** of dilepton production
- Results from dielectrons and dimuons provide valuable constrains for **theoretical approaches** in the modeling of the **initial photon flux**
- The ditau production was clearly observed by ATLAS
- The measurement of the **τ-lepton anomalous magnetic moment is competitive** with previous measurements
  - Improvement in precision expected with more data

Backup

Models - two different approaches

- There are two generators commonly used to simulate exclusive dilepton production: **STARlight** and **SuperChic**
- They implement **different approaches** in calculation of the cross-sections
- None of them simulates a FSR contribution
- In **STARlight formalism** photon spectrum is calculated in impact parameter space, Comput.Phys.Commun. 212 (2017) 258-268

$$d^2N/dk_1dk_2 = \int_{b_1>R_1} db_1 \int_{b_2>R_2} db_2\, n(k_1, b_1) n(k_2, b_2)\, P_{fn}(b)\, (1 - P_H(b))$$

dilepton pairs are not formed within either nucleus

Probability of forward neutron topology

beam projectiles do not interact hadronically (Glauber calculation)

- In **SuperChic formalism** different implementation of the non-hadronic overlap condition of the Pb ions, SciPost Phys. 11, 064 (2021)

$$\sigma_{N_1N_2\to N_1XN_2} = \int dx_1 dx_2\, n(x_1) n(x_2) \hat{\sigma}_{\gamma\gamma\to X}$$

$$n(x_i) = \frac{\alpha}{\pi^2 x_i} \int \frac{d^2 q_{i_\perp}}{q_{i_\perp}^2 + x_i^2 m_{N_i}^2} \left(\frac{q_{i_\perp}^2}{q_{i_\perp}^2 + x_i^2 m_{N_i}^2} (1 - x_i) F_E(Q_i^2) + \frac{x_i^2}{2} F_M(Q_i^2) \right)$$

- SuperChic includes survival and polarization effects at amplitude level, but not forward neutrons

ZDC fractions

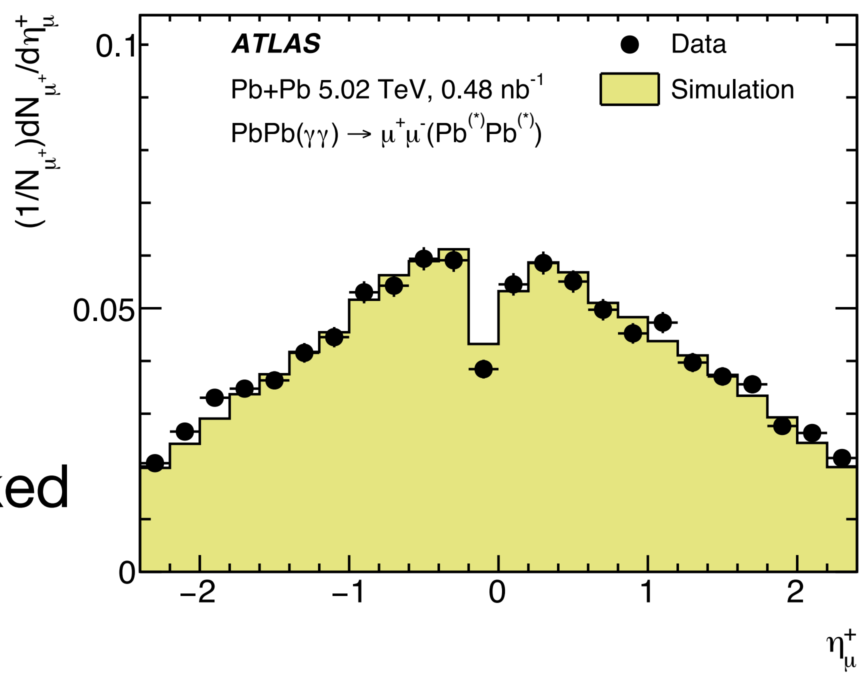
- The fractions of events in each ZDC class are affected by the presence of EM pile-up
- The probabilities of single and mutual dissociation (p_s, p_m) are determined using the same method both in dimuon and dielectron measurement, with p_s, p_m values calculated for given data taking period
- The fractions are determined in 4 bins in m_{ee} and 3 bins in $|y_{ee}|$ and corrected for dissociative background contribution
- Presented results are obtained using data

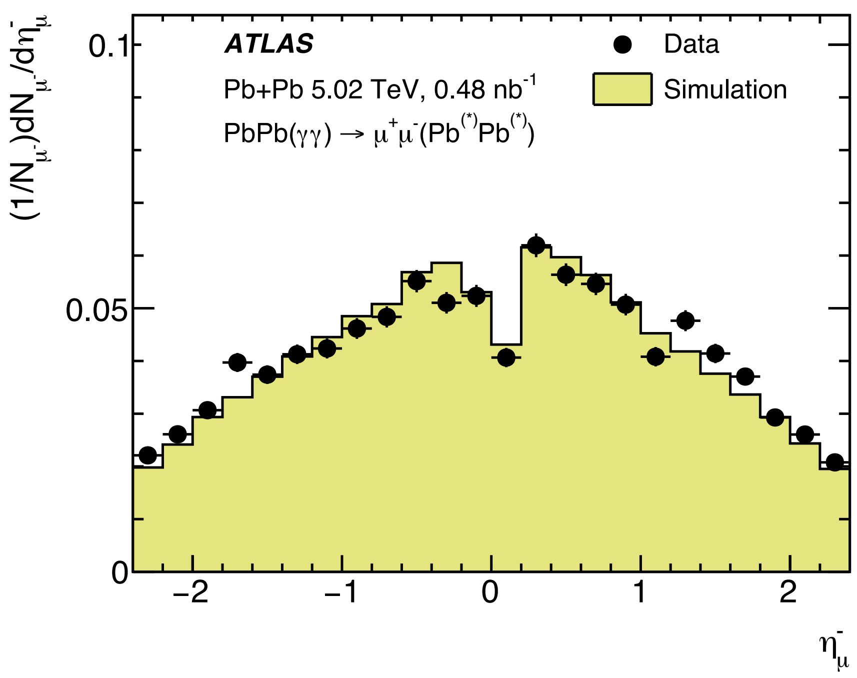
Observed fractions **Corrected fractions**

$$\begin{bmatrix} f'_{0n0n} \\ f'_{Xn0n} \\ f'_{XnXn} \end{bmatrix} = \begin{bmatrix} (1-p_s)(1-p_m) & 0 & 0 \\ 2p_s(1-p_s-p_m+p_m p_s/2) & (1-p_s)(1-p_m) & 0 \\ p_m+p_s^2 & p_m+p_s-p_m p_s & 1 \end{bmatrix} \begin{bmatrix} f_{0n0n} \\ f_{Xn0n} \\ f_{XnXn} \end{bmatrix}$$

Dimuons - efficicency corrections

- Single-muon L1 trigger efficiencies are derived using the minimum-bias data as a function of $q\eta_\mu$, and p_T^μ
- The results are cross-checked with tag-and-probe method using signal muons





- The total trigger efficiency is derived as: $\varepsilon_{T\mu\mu} = 1 - (1 - \varepsilon_T(\eta^+))(1 - \varepsilon_T(-\eta^-))$
- The typical trigger efficiency is 93% at $m_{\mu\mu} < 20$ GeV and $|y_{\mu\mu}| < 1$, and increases to 97% at $m_{\mu\mu} > 40$ GeV and $|y_{\mu\mu}| > 1.5$
- Good data to simulation agreement already after applying trigger correction
- The reconstruction efficiency is based on simulation, corrected with data-driven factor derived using tag-and probe method
- The impact of correcting for the reconstruction efficiency is about 40–50% for $m_{\mu\mu} < 20$ GeV and $|y_{\mu\mu}| < 0.8$, decreasing to 15% at larger values

Dimuons - results

- The cross-sections are measured as a function of several kinematic variables as:

Bin migration — Background from dissociative events

$$\frac{d\sigma_{\mu\mu}}{dX_{\mu\mu}} = \frac{C_{\text{mig}}}{\mathcal{L}_{\text{int}}} \sum_{\text{events}} \frac{(1-f_{\text{dis}})}{\varepsilon_{\text{R}\mu\mu}\,\varepsilon_{\text{T}\mu\mu}}$$

Muon kinematic variable — Reconstruction and trigger efficiencies

- Measured fiducial cross section is:

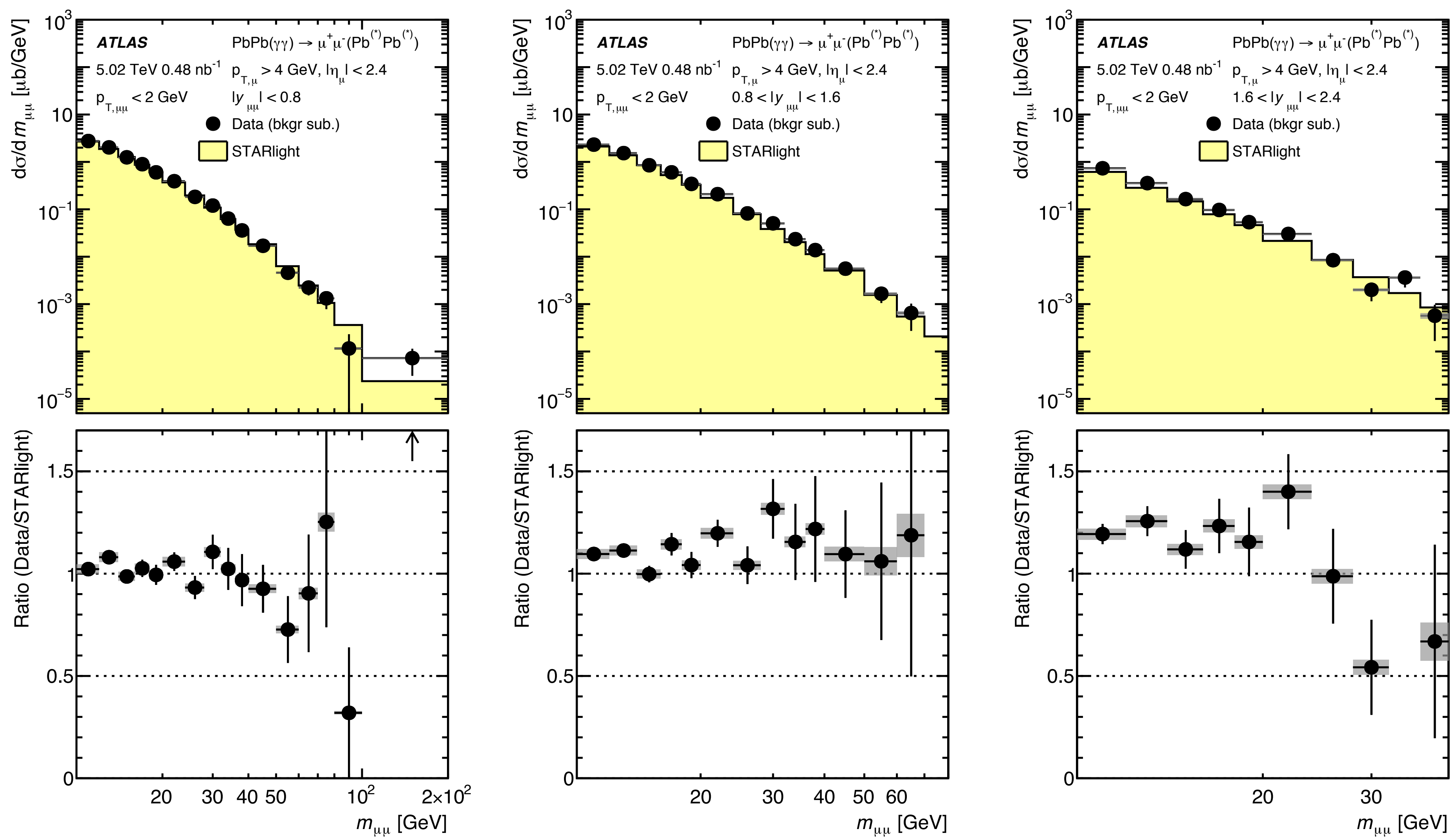
  σ = 34.1±0.3(stat.)±0.7(syst.) μb,

  compared with 32.1 μb from STARlight and 30.8 μb from STARlight+Pythia8

- The systematic uncertainty is dominant
- Differential cross-sections are determined as a function of $|y_{\mu\mu}|$, $m_{\mu\mu}$, $|\cos\theta^*|$, k_{min} and k_{max} in the inclusive sample
- Additionally the acoplanarity distribution is unfolded after selection data from 0n0n category

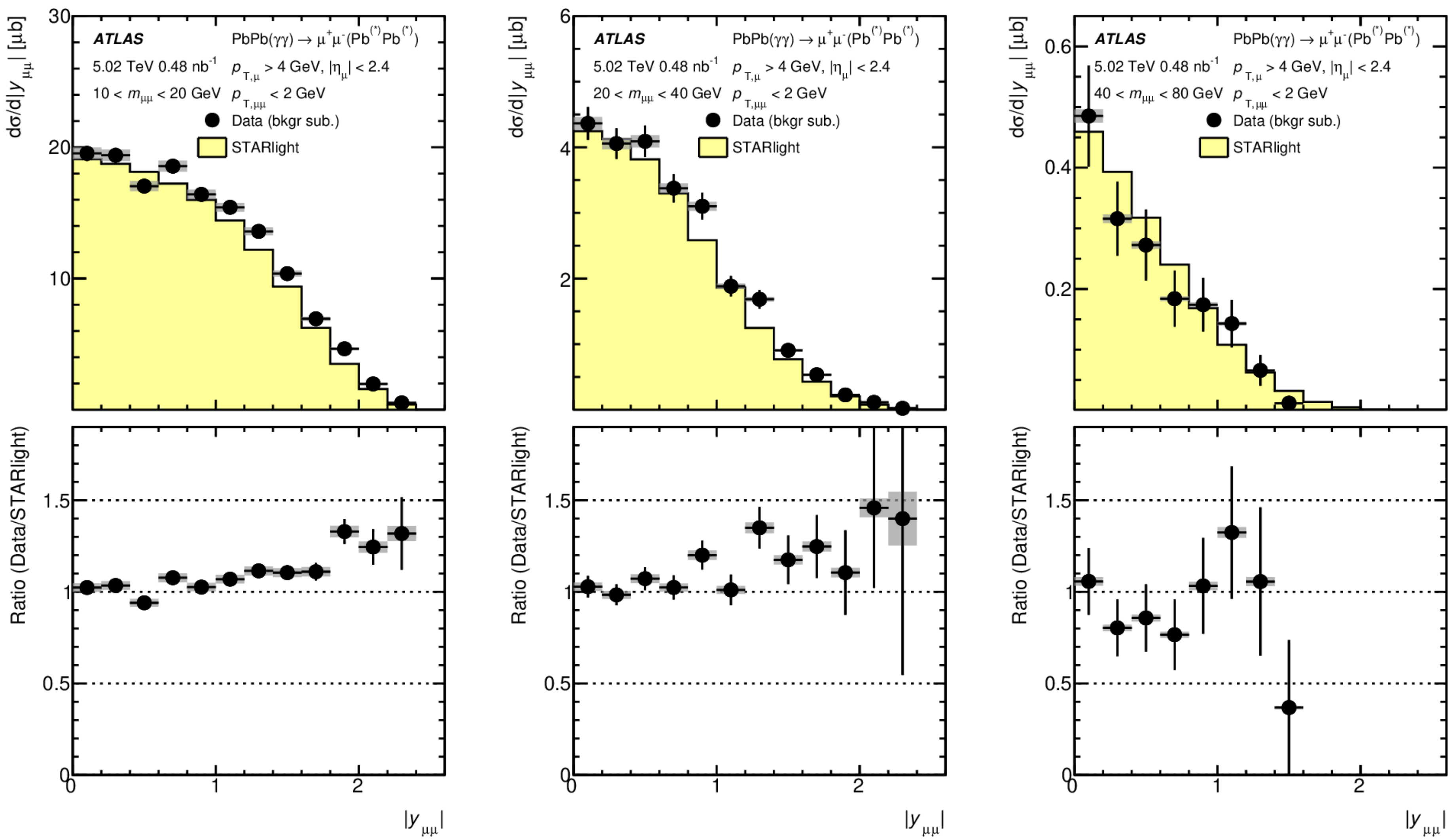
Dimuons - results

- The cross-sections are presented as a function of absolute dimuon mass in 3 rapidity slices
- Data is compared with STARlight MC simulation of γγ → $\mu^{+}\mu^{-}$ process w/o FSR
- The overall shape of the spectra is well described out to the highest masses in the available event sample
- Some hints of decreasing ratio for larger $m_{\mu\mu}$



Dimuons - results

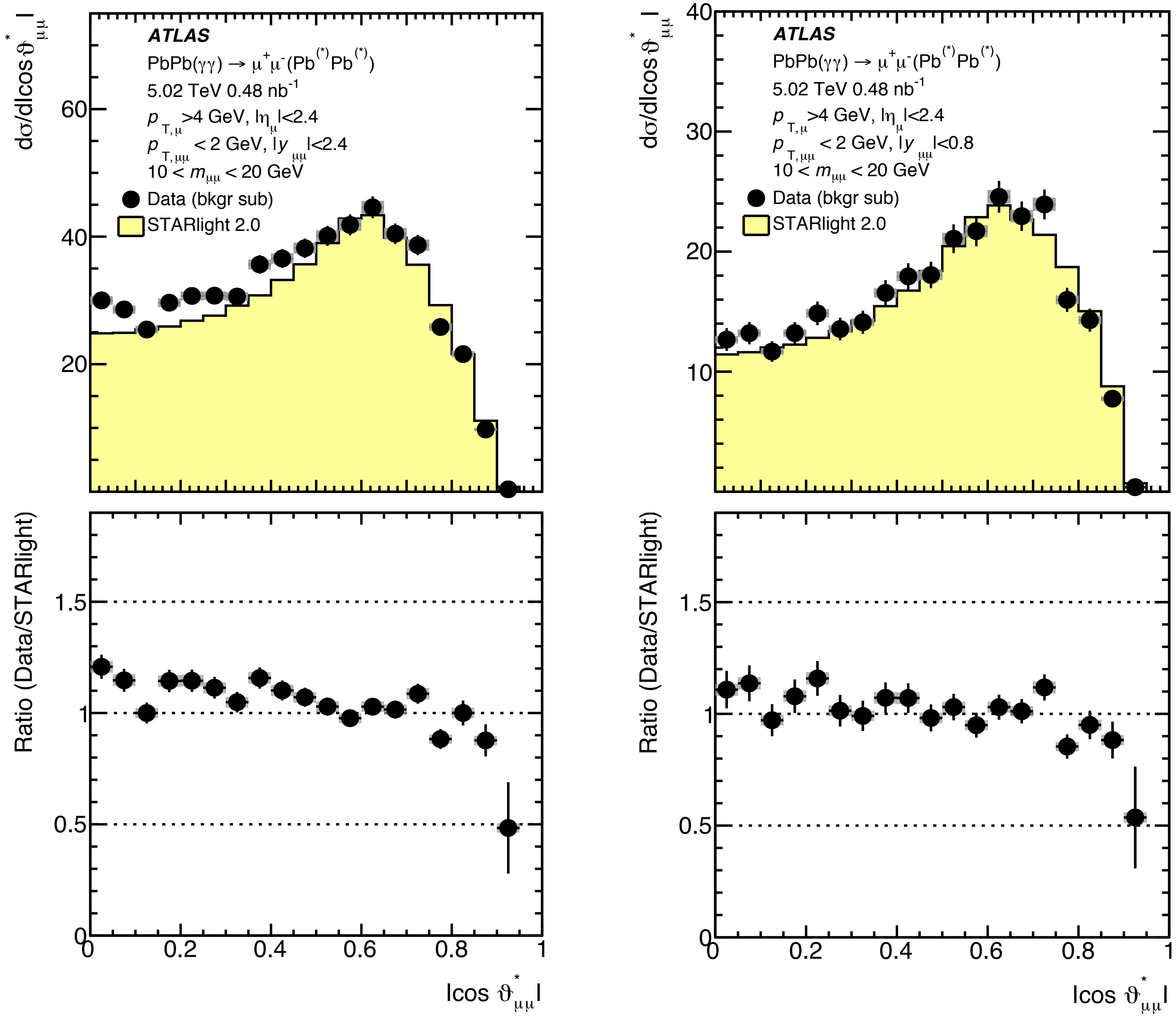
- The cross-sections are presented as a function of absolute dimuon rapidity in 3 mass slices
- Data is compared with STARlight MC simulation of γγ → $\mu^{+}\mu^{-}$ process w/o FSR
- Good agreement is found in central region of rapidity distribution (small $|y_{\mu\mu}|$),but data to simulation ratio increases with $|y_{\mu\mu}|$



Dimuons - results

- The shape of the |cos θ*| (= |tanh(Δ$\eta_{\ell\ell}$)/2|) is affected by the fiducial requirement of |η_μ| < 2.4
- Thus, this distribution may be affected by the mismodelling observed at large |$y_{\mu\mu}$|
- Limiting the data with |$y_{\mu\mu}$| < 0.8 improves data to simulation agreement in |cos θ*|

|$y_{\mu\mu}$| < 2.4 |$y_{\mu\mu}$| < 0.8

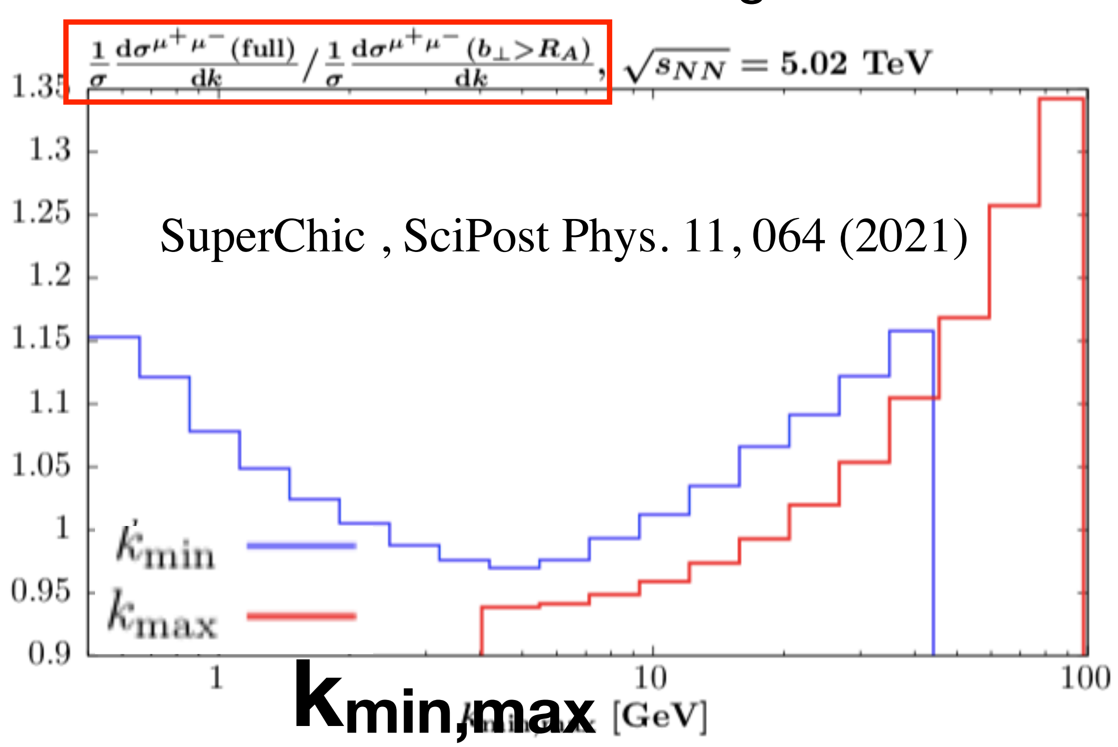


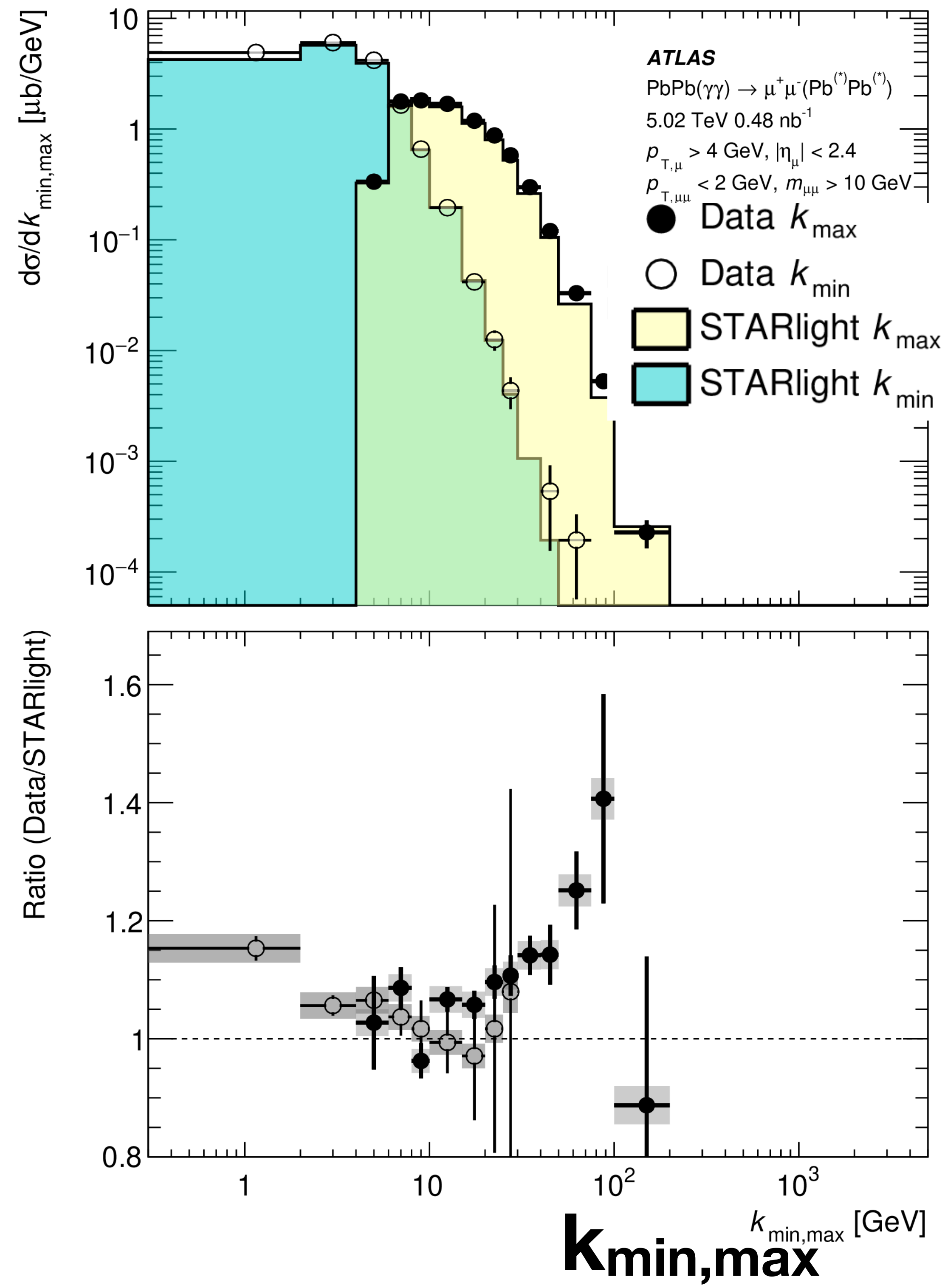
What can we learn about initial photon fluxes?

- The muon kinematics can be used to estimate **initial photon energies**

$$k_{\mathrm{min,\,max}} = (1/2)m_{\mu\mu}\exp(\pm y_{\mu\mu})$$

- The **cross section** is presented as a function of maximum and minimum photon energies
- The comparison with STARlight calculations shows that the predictions are correct in intermediate region 5-20 GeV, but there is a disagreement between the data and MC for lower k_{min} and higher k_{max}



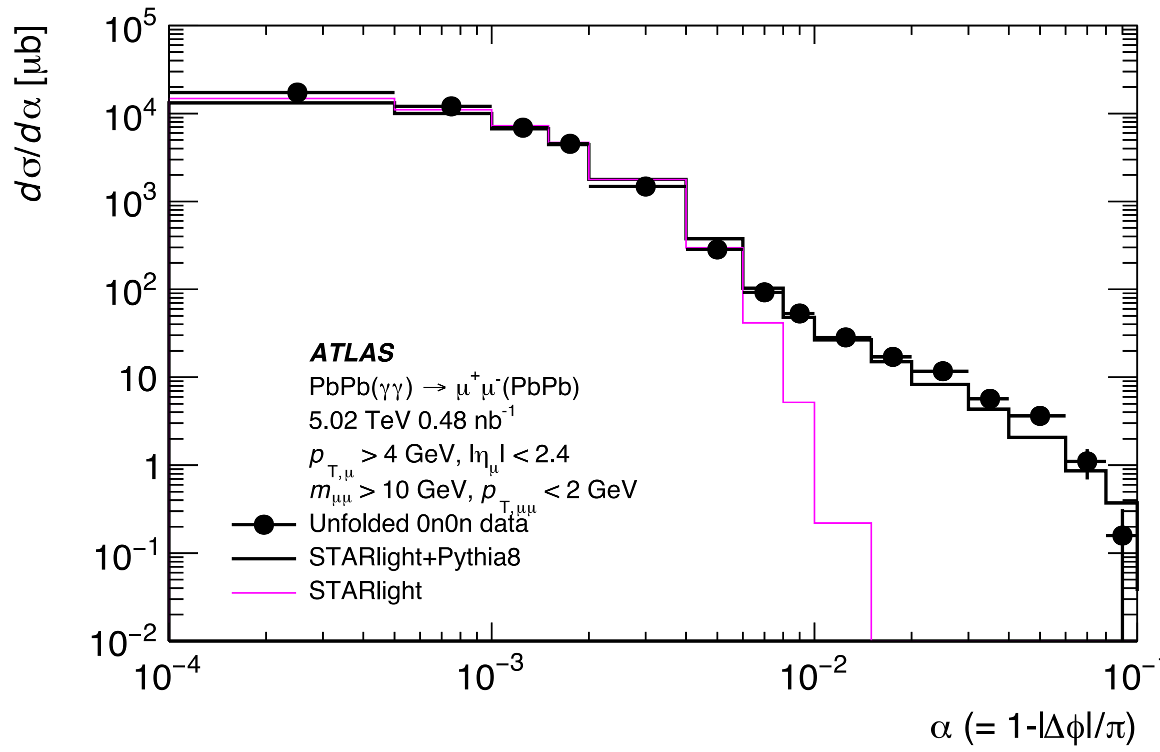


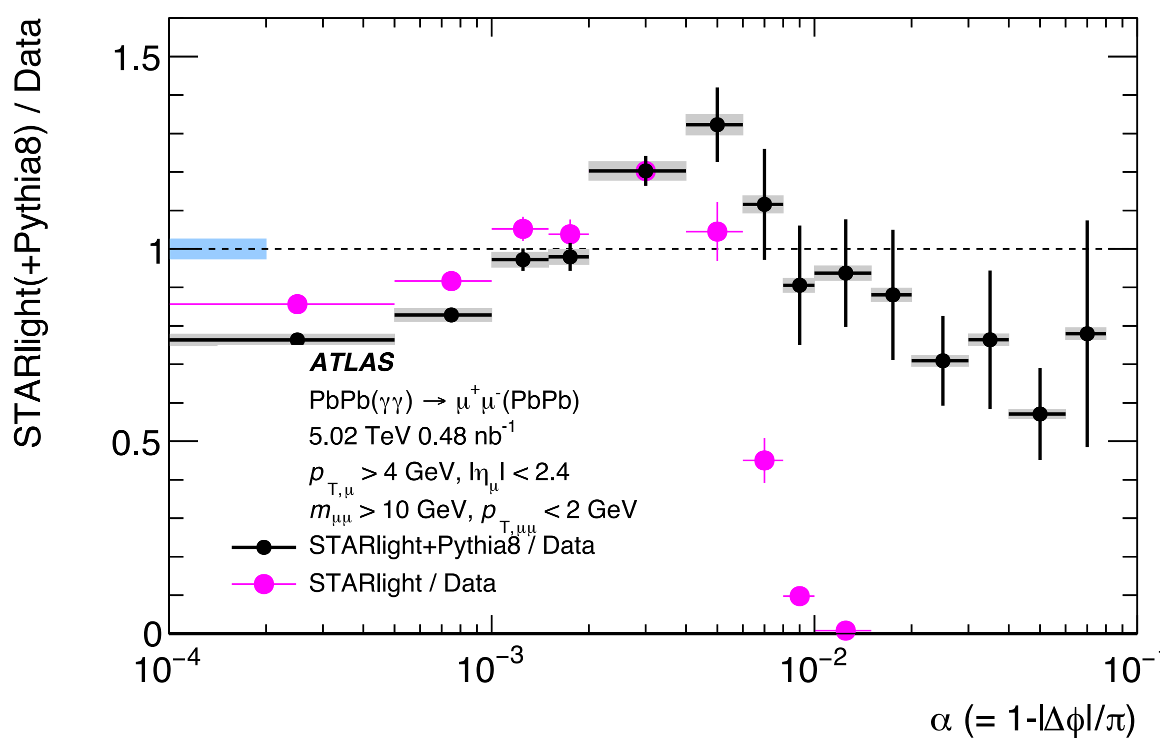
Dimuons - results

- Cross-section as a function of acoplanarity was measured in the 0n0n category, to limit the influence of dissociative background

- The acoplanarity peak is not perfectly described by the STARlight model

- Adding FSR in the modeling improves the description of the tail



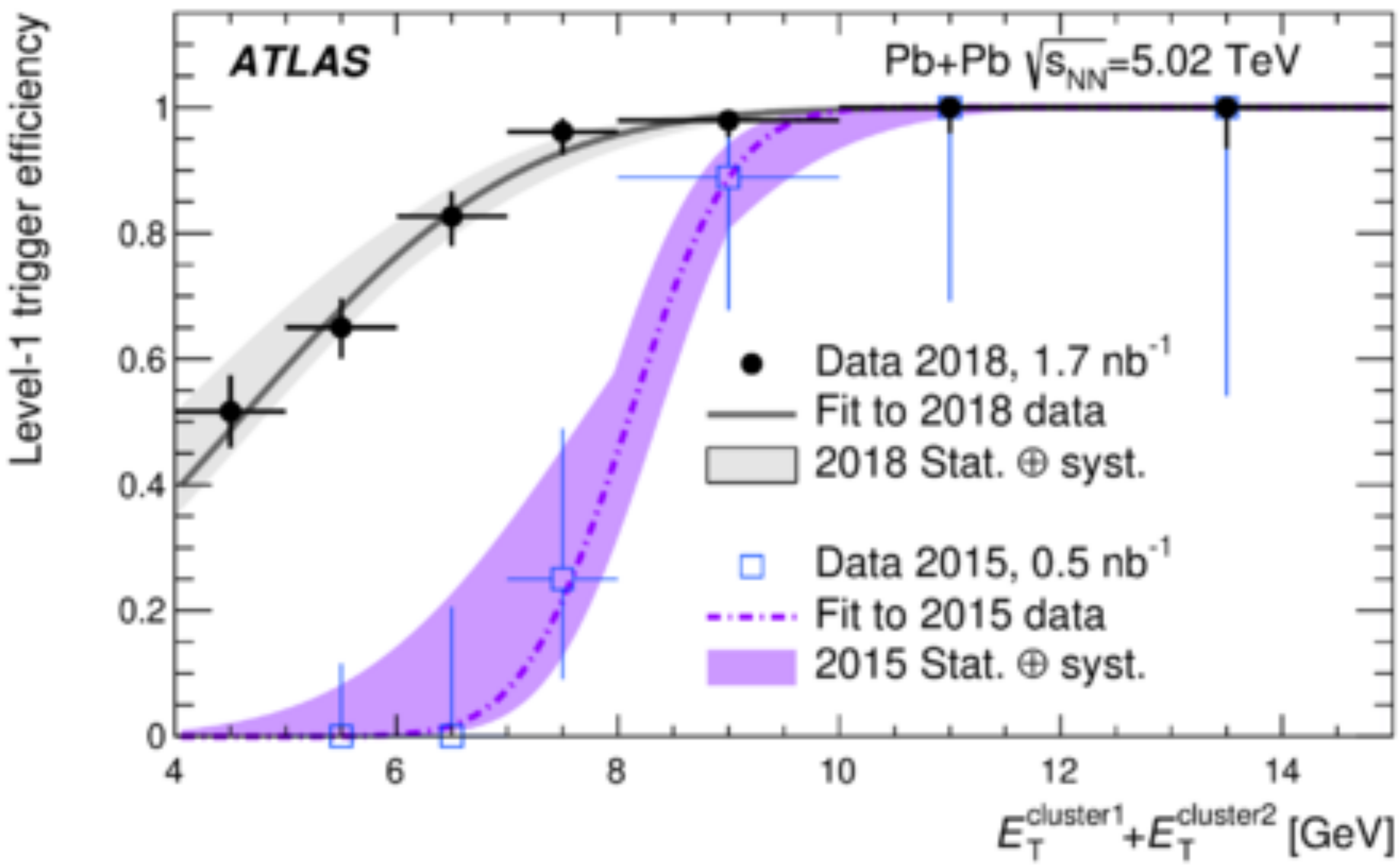


Dielectrons - efficiency corrections

- Trigger has been carefully optimised between 2015 and 2018 data taking campaigns
- Total trigger efficiency is used to reweigh the MC distribution:

  $\varepsilon_T = \varepsilon_{L1} \cdot \varepsilon_{PixVeto} \cdot \varepsilon_{FCalVeto}$

- Pixel-veto efficiency is measured as a function of the dielectron rapidity and is just over 80% for $|y_{ee}| \sim 0$ and falls to about 50% for $|y_{ee}| > 2$

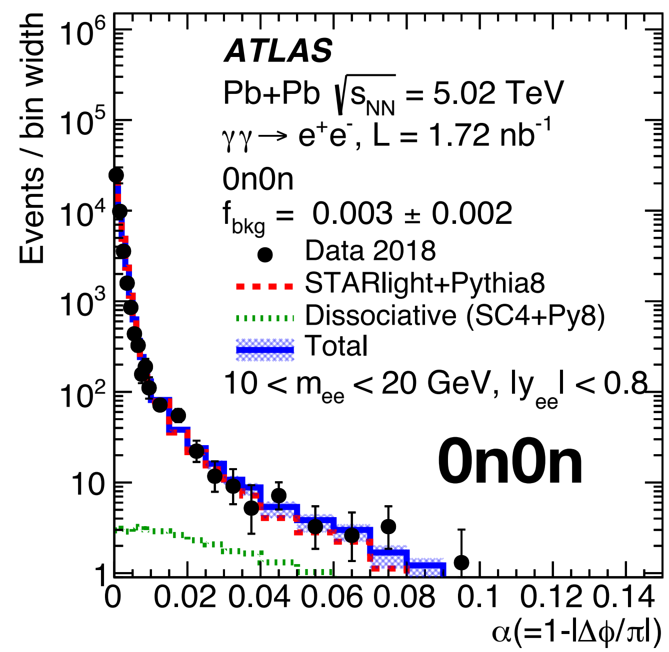


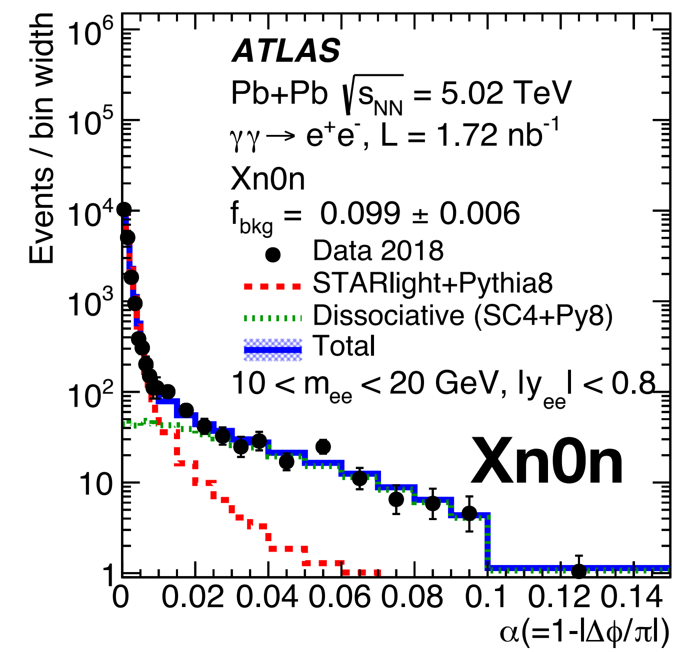
- Tag and probe method used to derive electron efficiency in data and MC simulation
- Electron reconstruction efficiency ranges from about 30% at $p_T = 2.5$ GeV to 95% above 15 GeV, PID efficiency flat in p_T, and vary weakly with η in range between 80 and 90%
- Ratio of the full reconstruction efficiency in data to that in simulation is defined as the SF

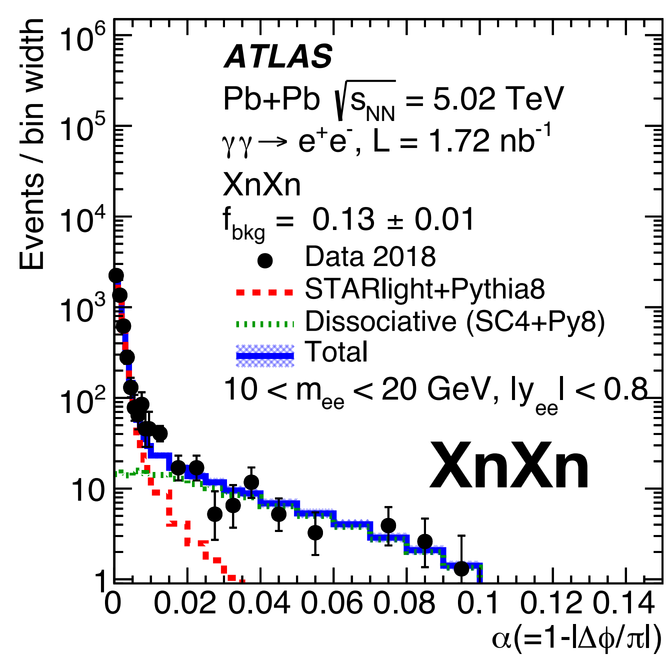
Dielectrons - background

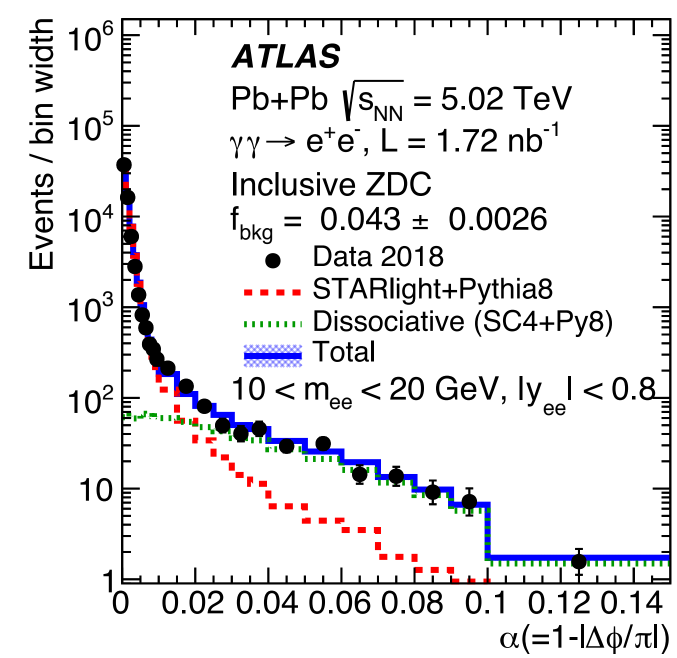
$$P(\alpha, m_{ee}, y_{ee}) = (1 - f_{dis}) P_{EPA}(\alpha, m_{ee}, y_{ee}) + f_{dis} P_{dis}(\alpha, m_{ee}, y_{ee})$$

- The background samples for **single dissociation** from SuperChic4+Pythia8 are used instead of LPair
- The **fits** (binned fits using RooFit) are done in 4 bins in m_{ee} and 3 bins in $|y_{ee}|$, separately for 0n0n, Xn0n and XnXn classes, the inclusive result is their weighted sum
- **Ditau contribution**, at the level of 0.1%, is **included** in the fitted background fraction, due to similar shape of acoplanarity
- Background from **Upsilon(nS)** production estimated with using STARlight+Pythia8 **MC samples**, at the level of 2.4%
- The acoplanarity distribution for Upsilon(nS) is peaked at 0 and should not influence the background fit for dissociation





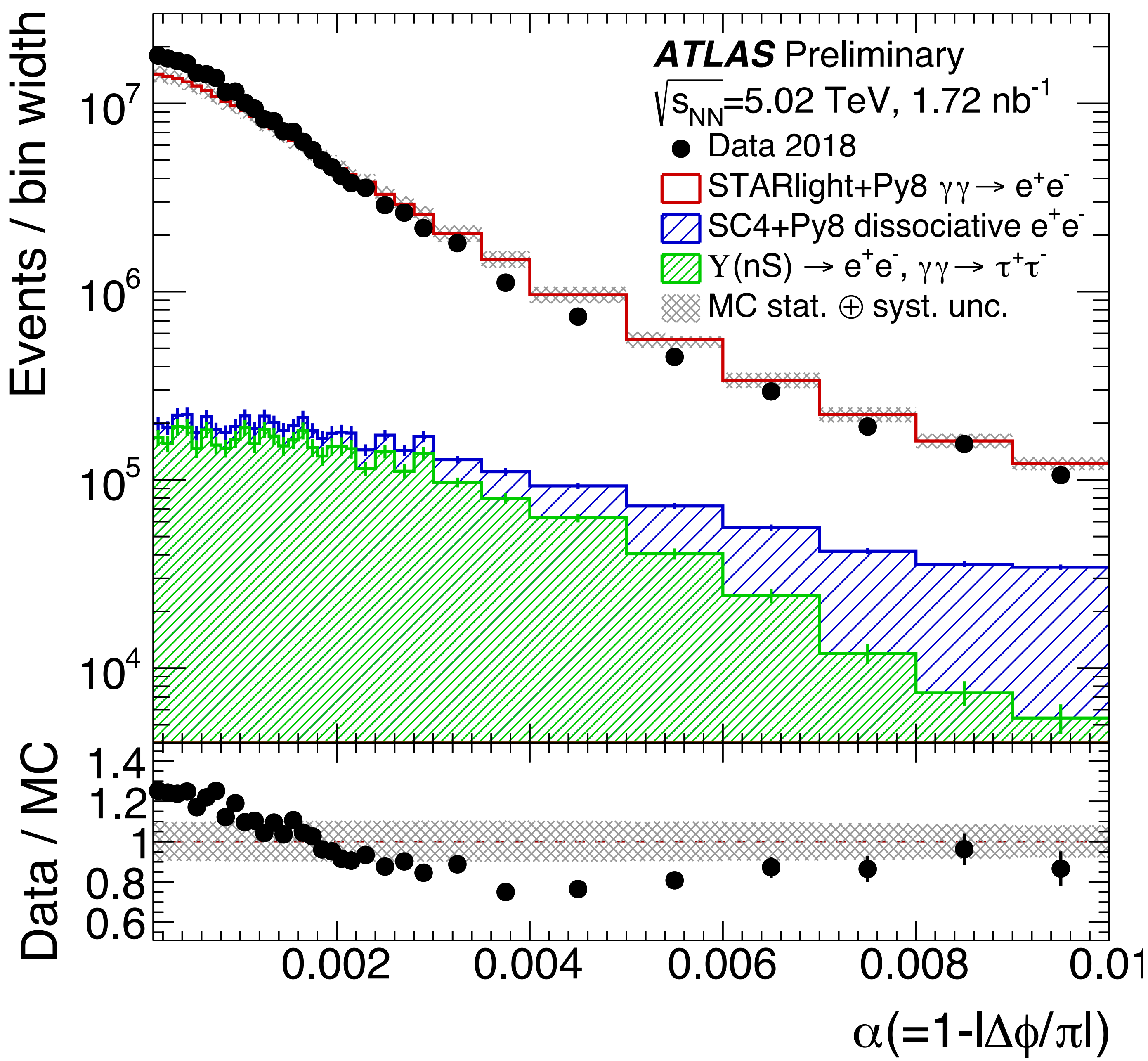




Inclusive ZDC

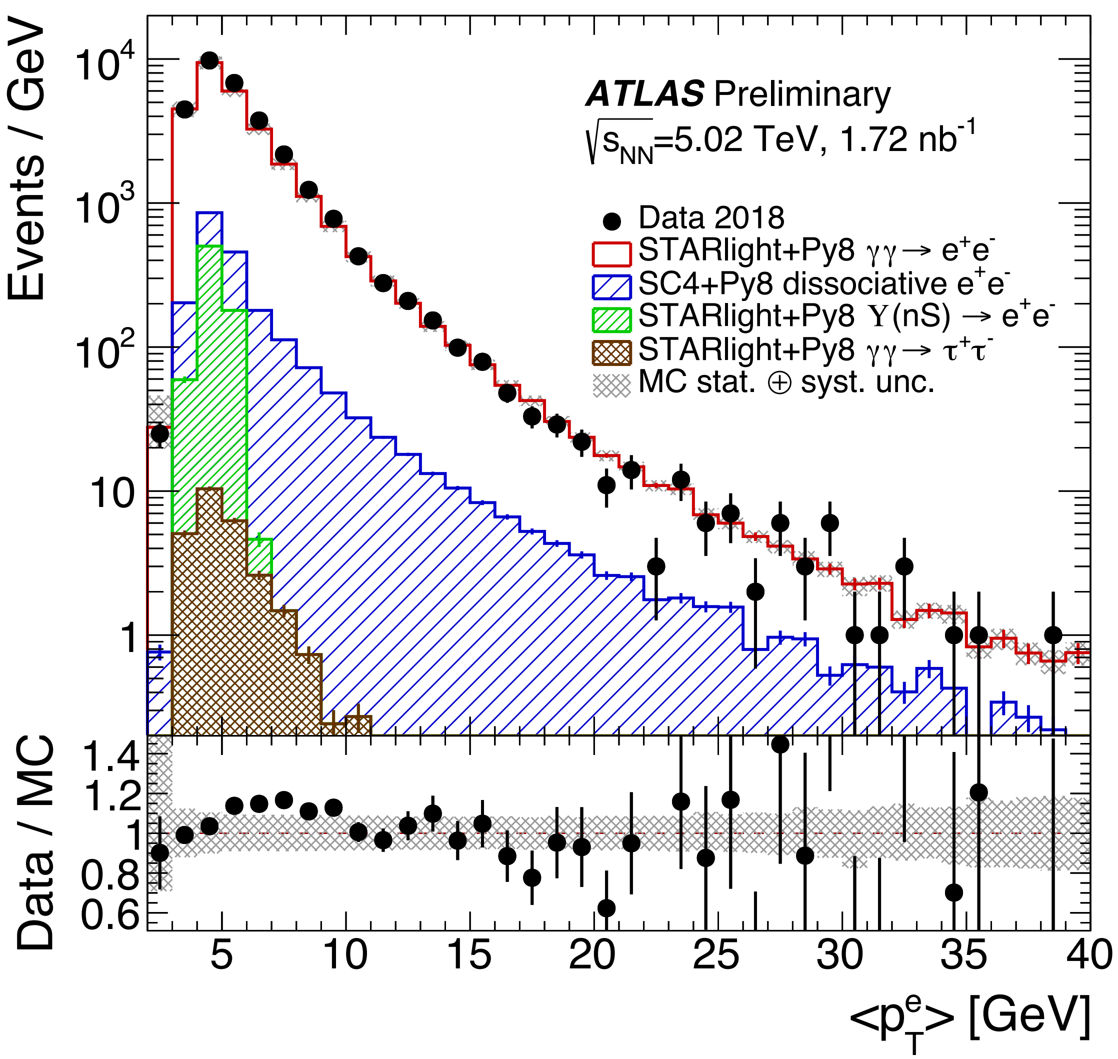
Background - upsilon

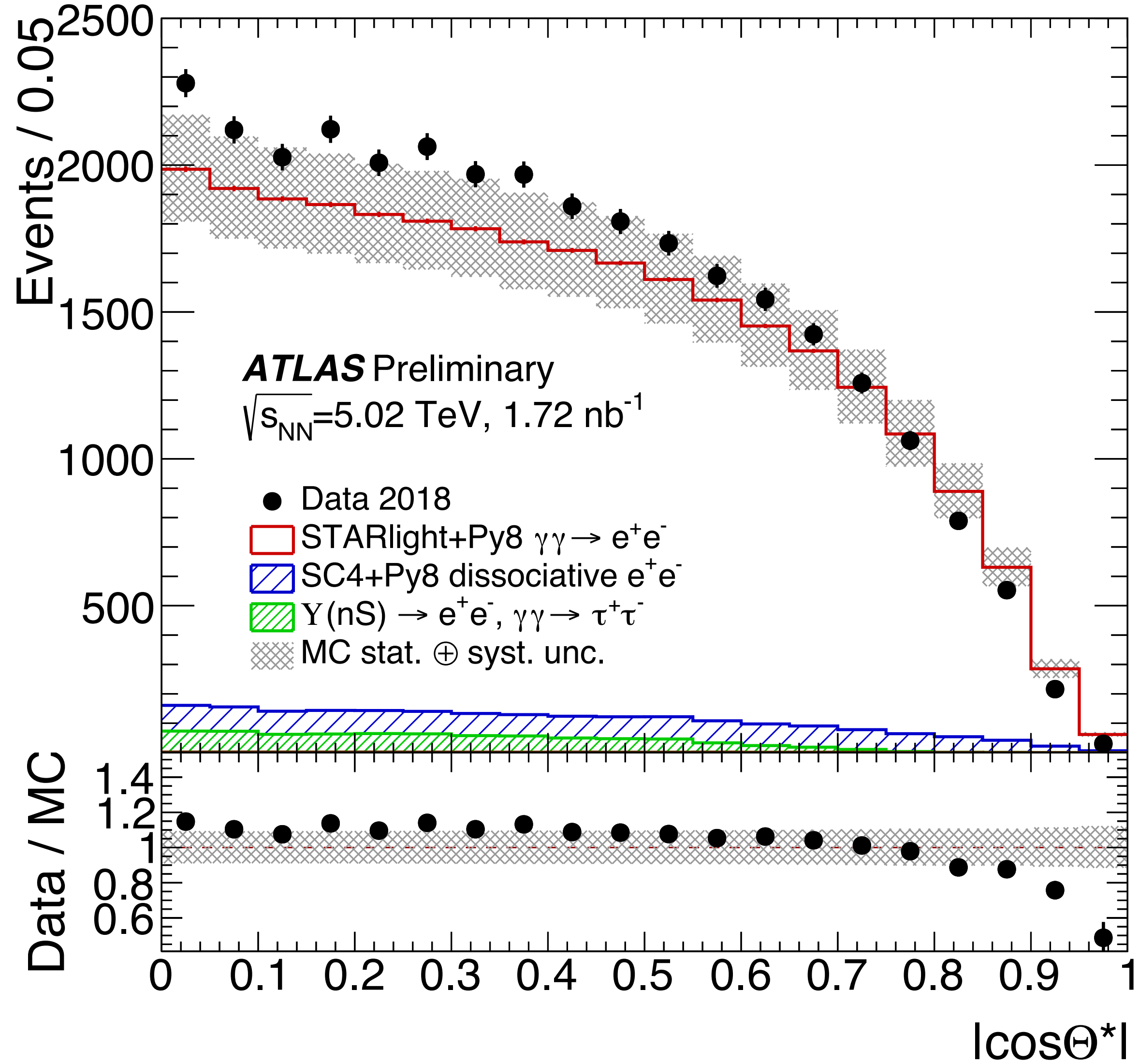
- The background from Upsilon(nS) decays to dielectrons is estimated using STARlight+Pythia8
- Upsilon 1S, 2S and 3S are considered
- The acoplanarity distribution for this background is peaked at 0 and should not influence the background fit for dissociation
- In total Upsilon background is at the level of 2.4% and is important only for small masses (but makes ~5.5% in mass range from 8 to 12 GeV)



Detector-level control plots

- The data sample is ~93% pure, with about 10% more counts in data than in the MC prediction
- The difference is higher for p_T in range 5-10 GeV, the data/MC ratio is almost flat in |cos θ*|, but drops for higher |cos θ*|
- The dissociative background is plotted using shape from the MC and using integrated background fraction



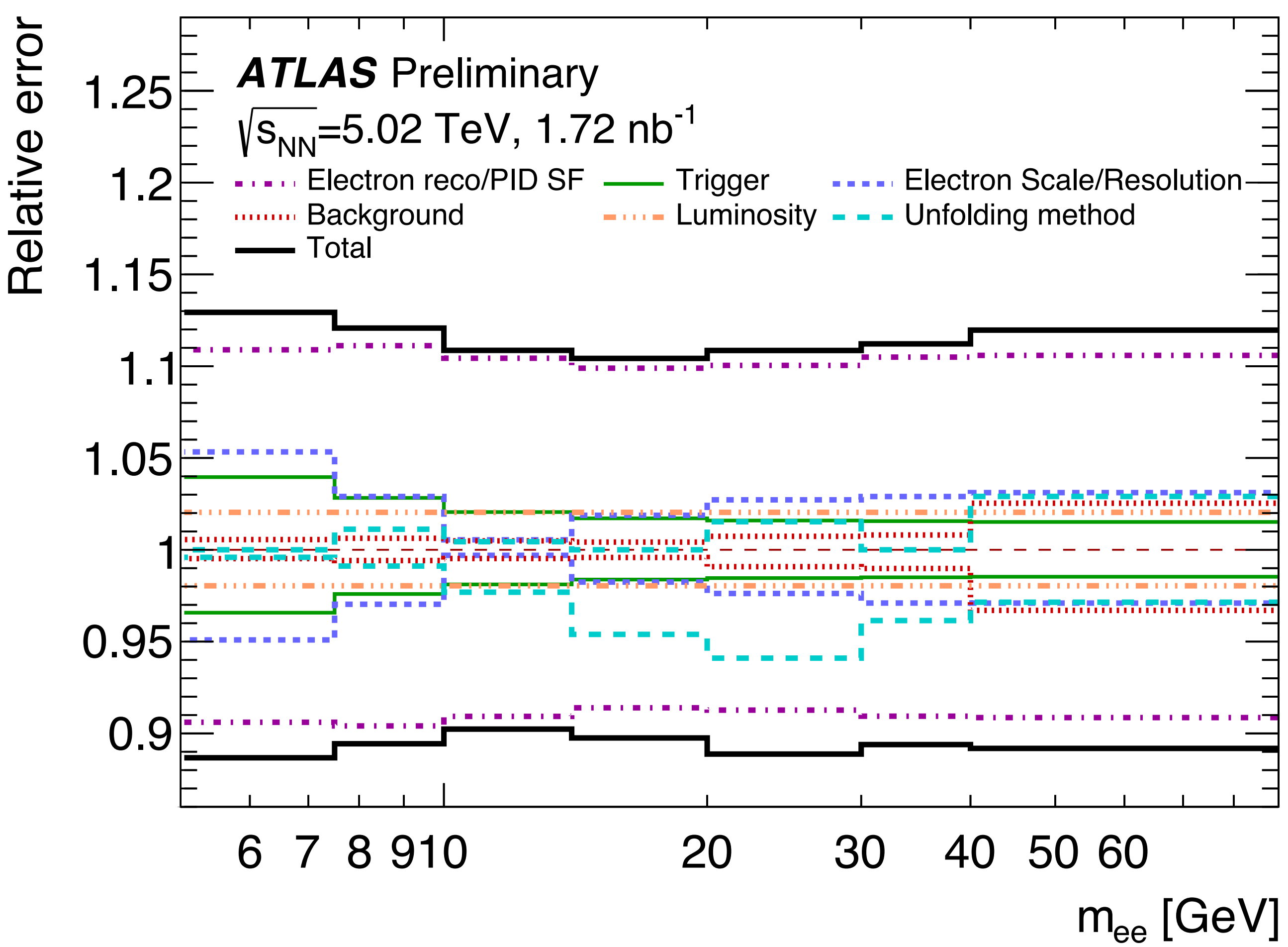


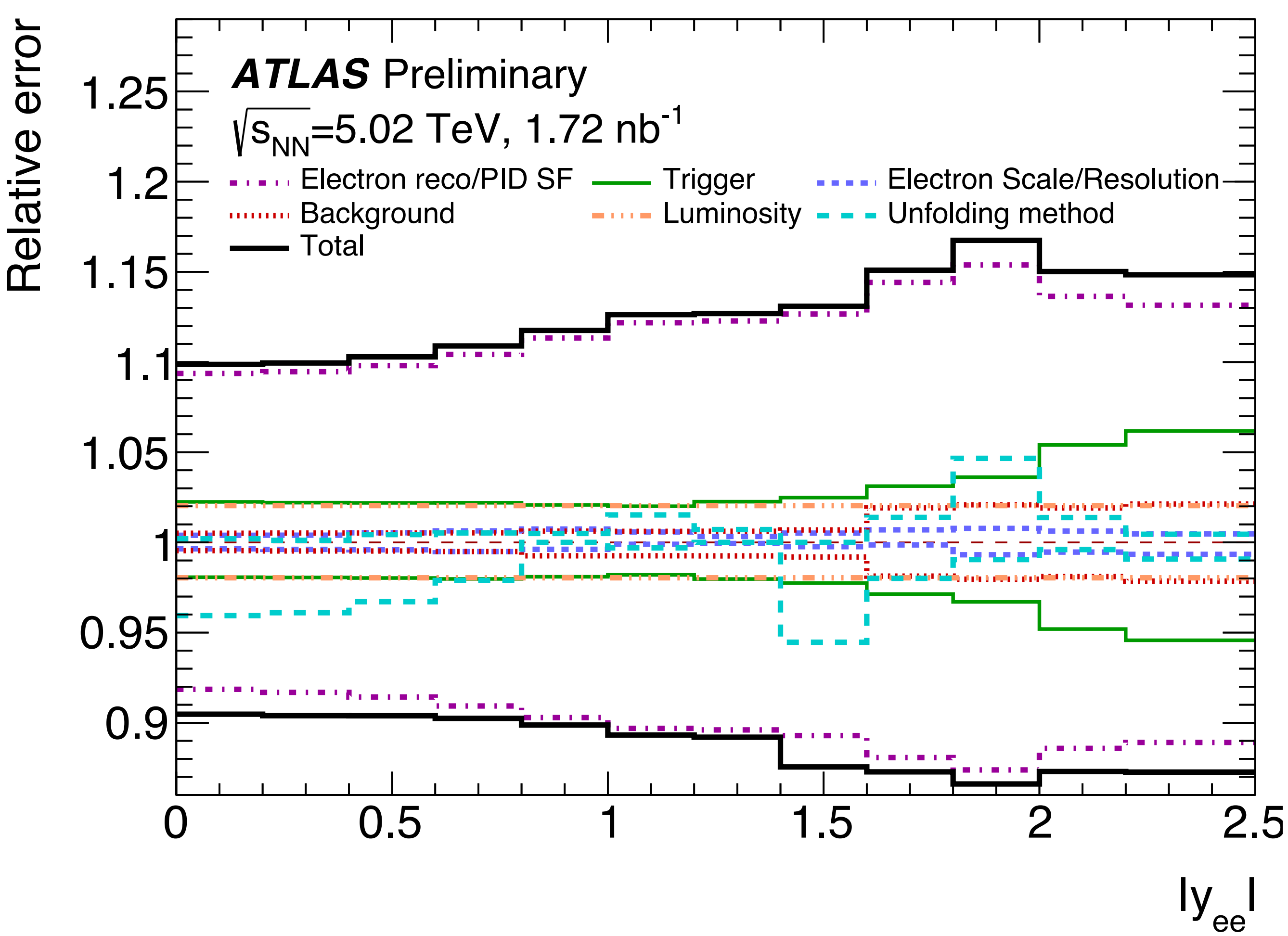
Systematics

- Systematics considered in the cross-section measurement:
  - Variations of electron reconstruction and identification efficiency (on average 9-10%) and trigger efficiency (on average 2-3%)
  - Variations of energy scale and resolution (on average 0.5%)
  - Up and down variations of background contribution (on average 0.5%)
  - Luminosity uncertainty (2.0%)
  - For differential measurement - uncertainties related to unfolding (mostly within the 2-3% range but exceeding this value in some bins, up to 5%)
    - MC non-closure (split sample test, also used to optimize number of iterations)
    - Data-driven non-closure
    - Two-dimensional effects on unfolding

Breakdown of systematics

- For small masses the dominant systematics come from electron reconstruction and identification efficiency (about 10%), other systematics mostly below 5%
- For $|y_{ee}|$ dominant systematics come from electron reconstruction and identification efficiency (from 9% up to 15% in some bins), other systematics mostly below 5%





Integrated fiducial cross-section

- The integrated fiducial cross-section is calculated as: $$\sigma = \frac{N_{data} - N_{bkg}}{C \cdot A \cdot L}$$
- It is measured with respect to the truth particles at the Born level (before the FSR)
- The *C* factor is calculated as $C = \frac{N^{fid}_{MC,reco}}{N^{fid}_{MC,truth}}$
- The *A* factor corrects for the exclusion of the crack region (and extrapolation from $|\eta_e| < 2.47$ to $|\eta_e| < 2.5$)

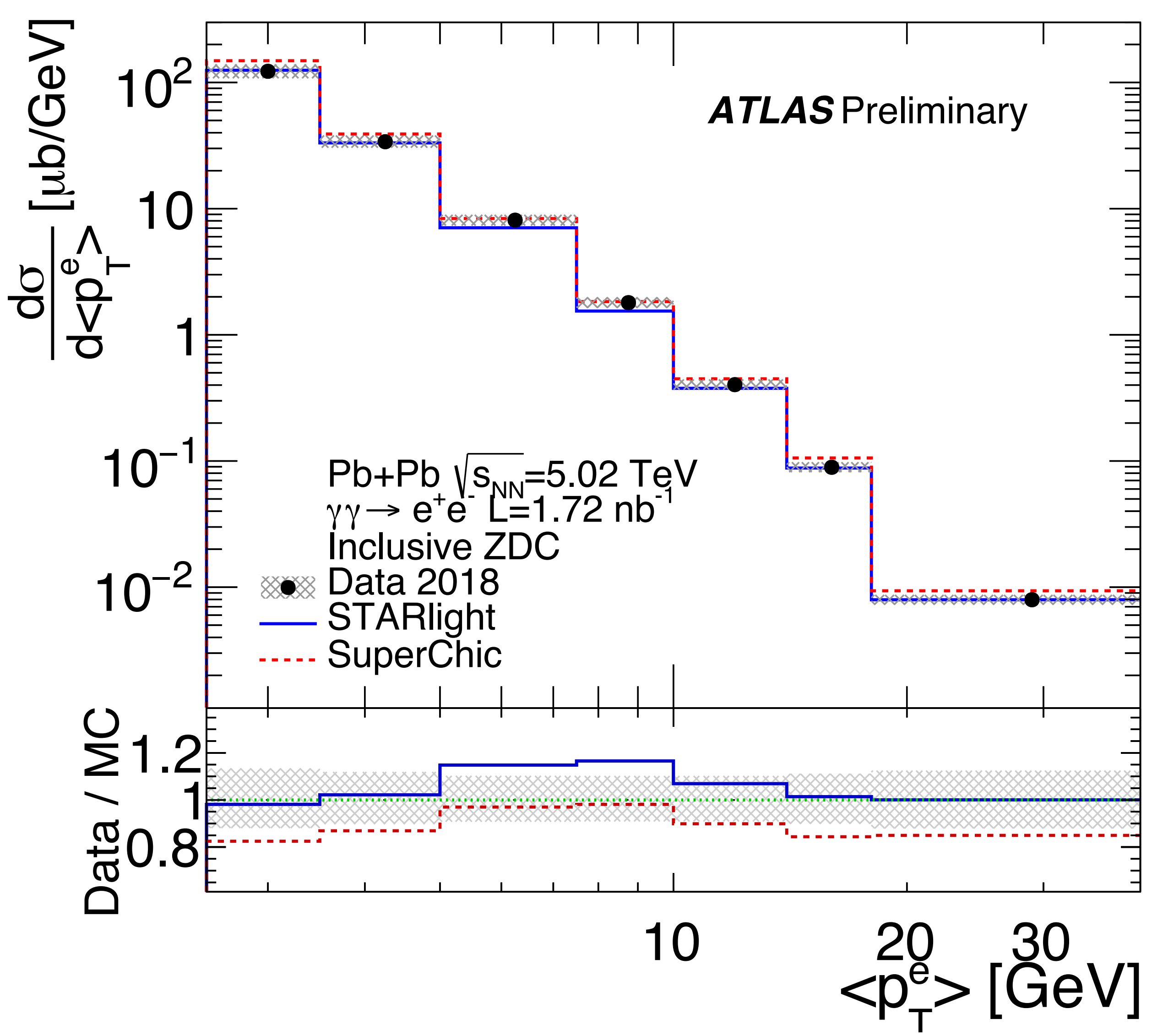
p_T^e >	2.5 GeV
$\|\eta_e\|$ <	2.5
m_{ee} >	5 GeV
p_T^{ee} <	2 GeV

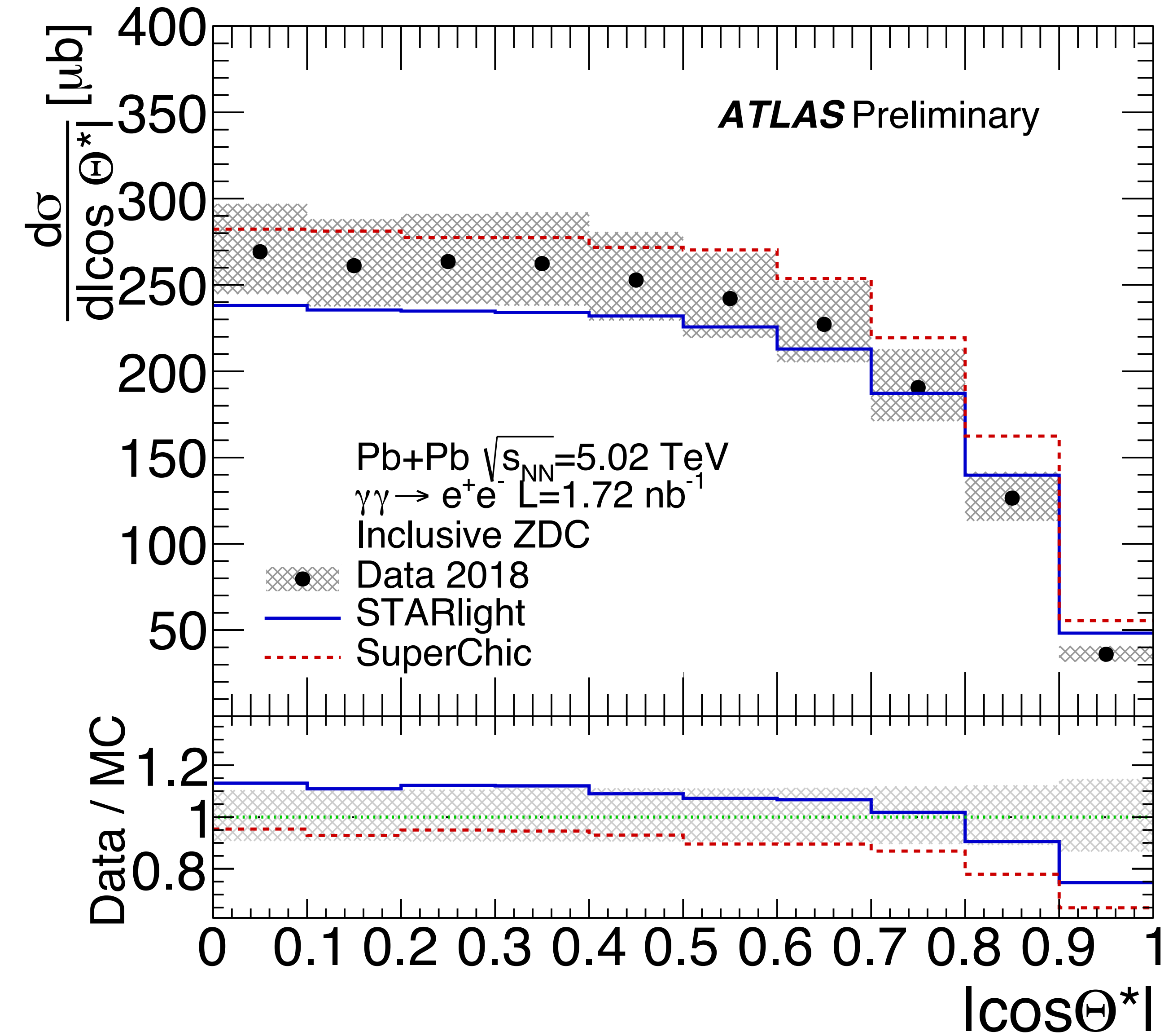
- The integrated cross-section is calculated in fiducial region determined by the event selection
- Besides mentioned reported below stat+syst uncertainties, there is 4 μb lumi uncertainty

C	A	σ (±(stat+syst) unc.) [μb]	STARlight		SuperChic	
			σ_{MC} [μb]	σ/σ_{MC}	σ_{MC} [μb]	σ/σ_{MC}
0.087	0.878	215.0^{+23}_{-20}	196.9	1.09	235.1	0.91

Dielectrons - results

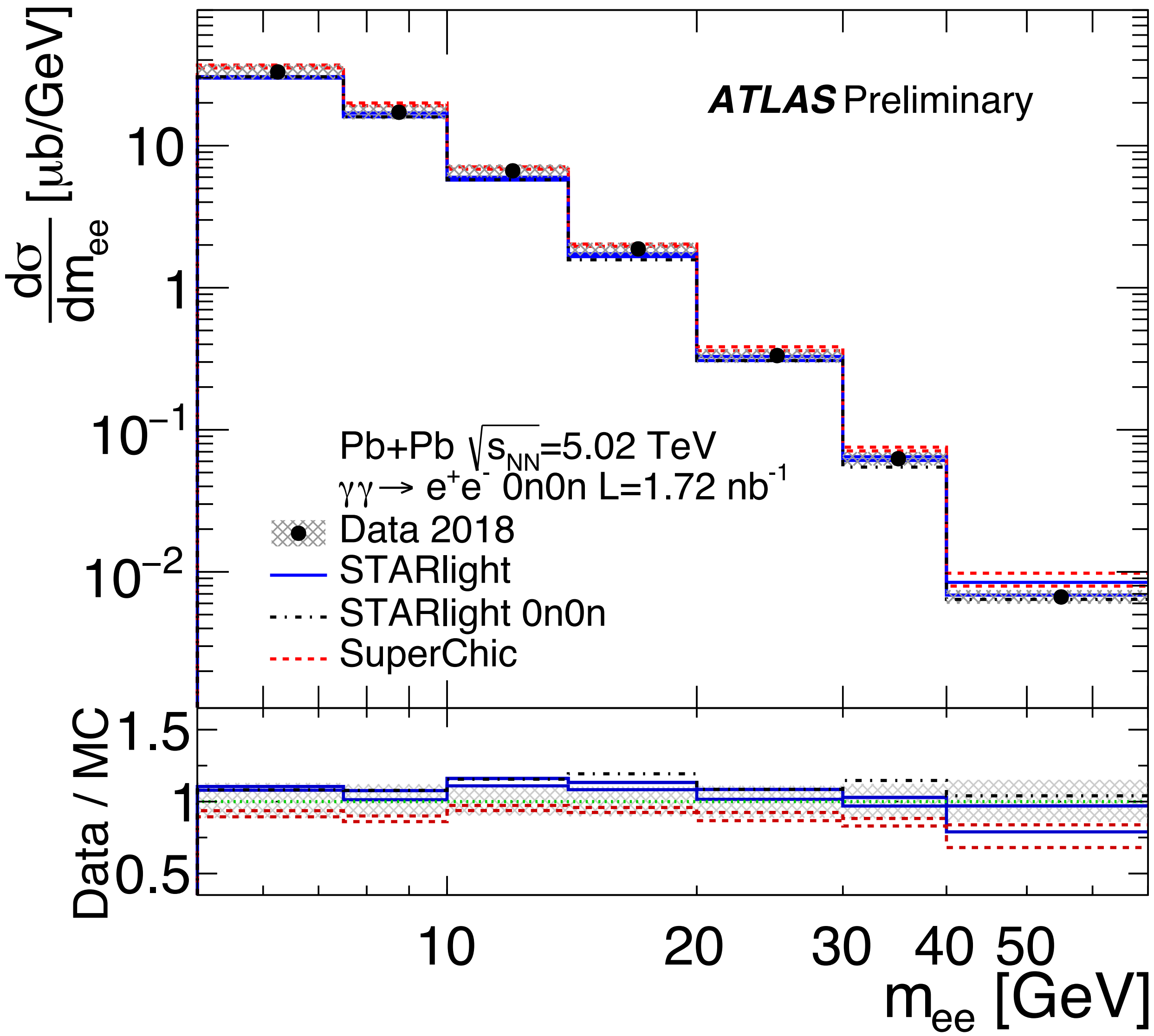
- Good agreement with STARlight is observed, differences in the same regions as in detector-level plots
- Agreement with SuperChic is better than with STARlight in $|y_{ee}|$

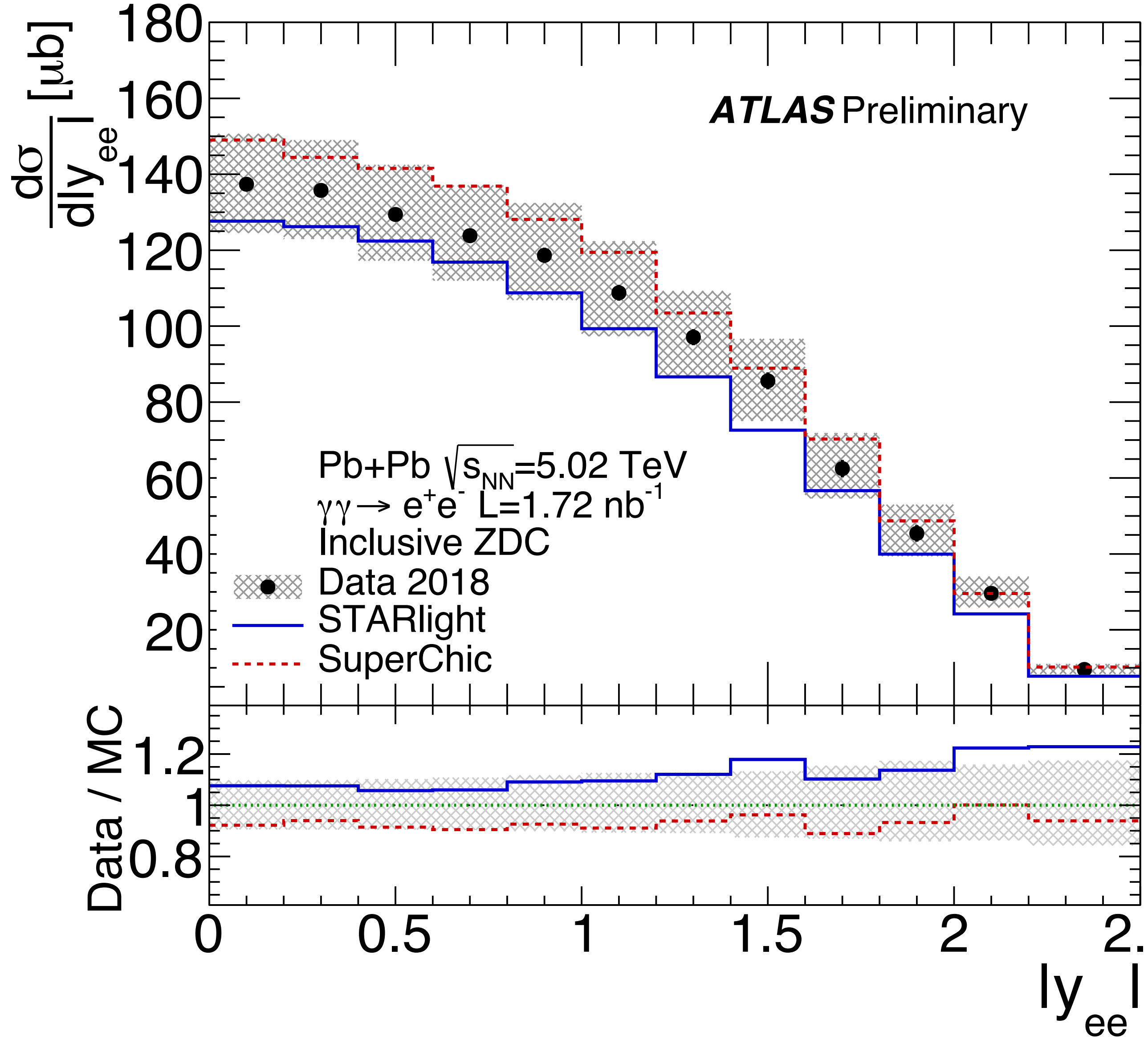




Dielectrons - results 0n0n

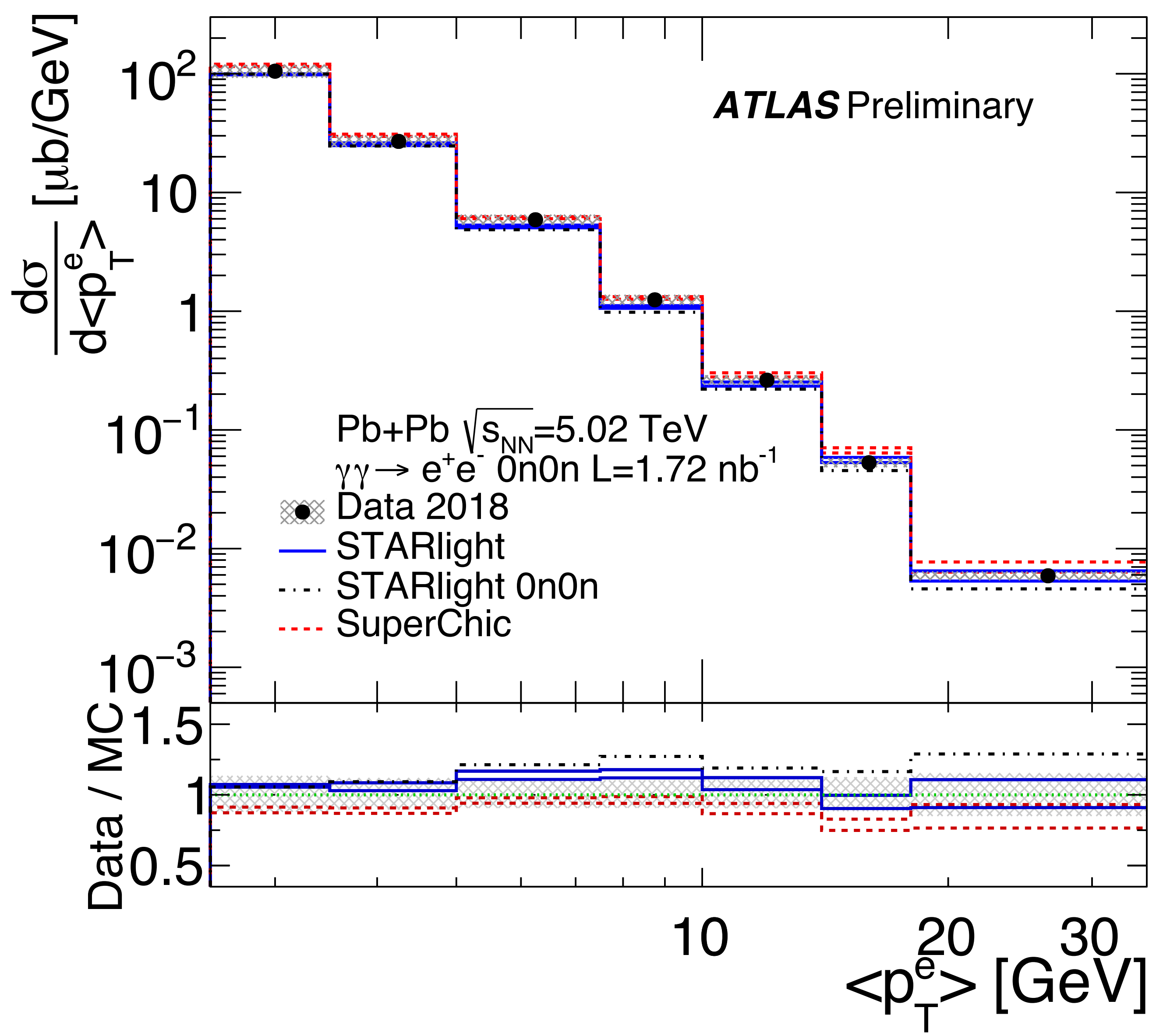
- Two lines for predictions show the predicted cross-section with f_{0n0n} varied up na down

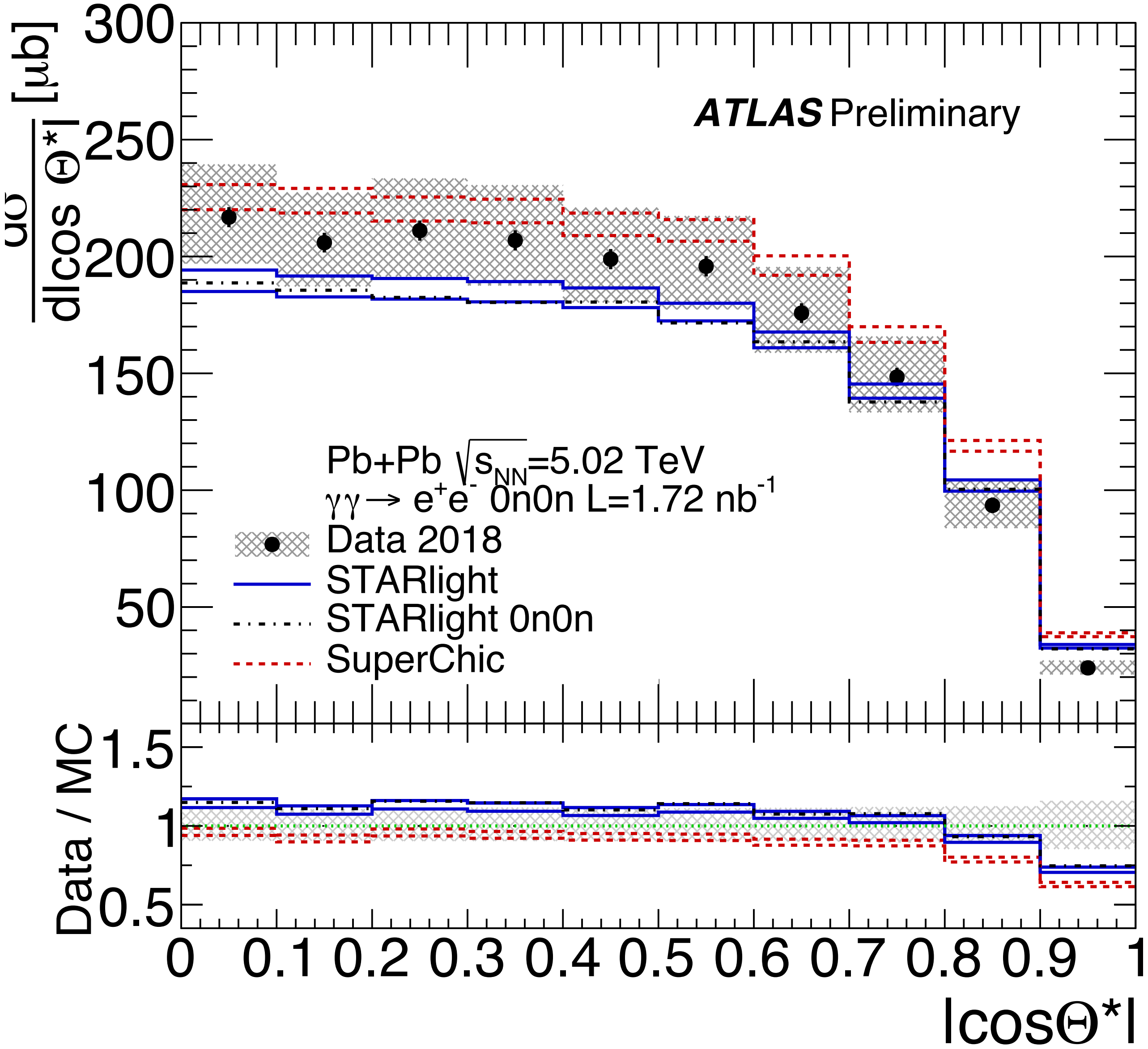




Dielectrons - results 0n0n

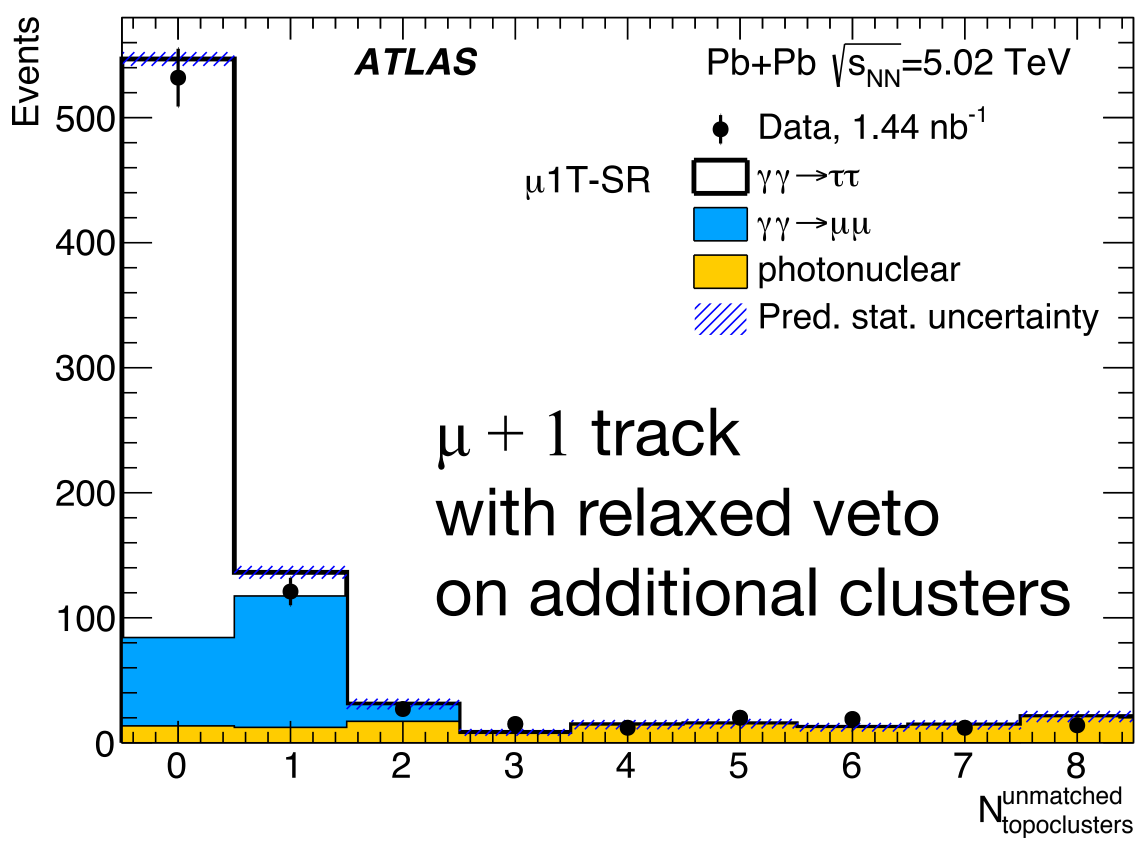
- Two lines for predictions show the predicted cross-section with f_{0n0n} varied up na down

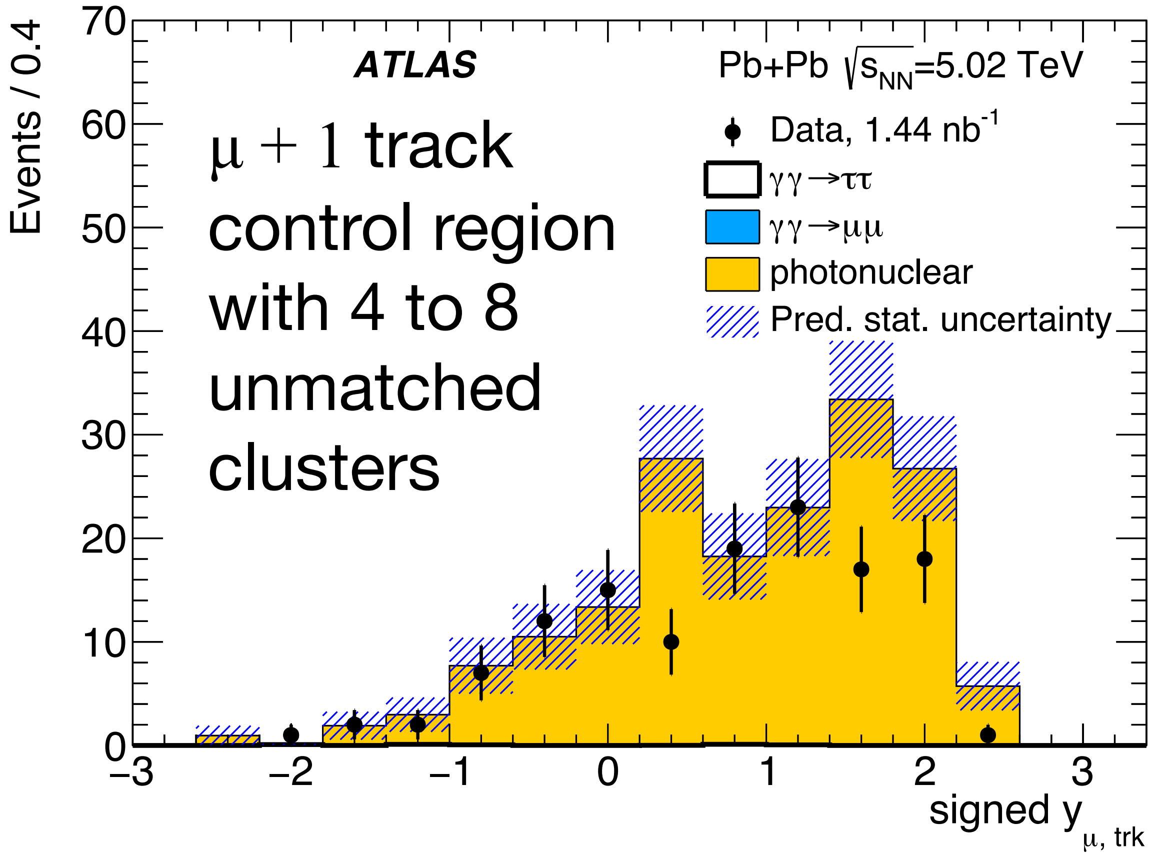




Backgrounds

- **Diffractive photonuclear** present in $\mu + 1$ track and $\mu + 3$ tracks signal regions, estimated with **data-driven** technique
  - Control regions defined with additional track with p_T < 500 MeV and allowing events from Xn0n category
  - Event yields extrapolated from control to signal region by relaxing the veto on additional (unmatched) clusters from 0 to 8
  - Normalisation done to the event yield in the region with 4 to 8 unmatched clusters





τ-lepton g−2 , systematic uncertainties

- Approximately 80 **nuisance parameters** (statistical and systematic uncertainties) are included in the fit
- Many of them correlated between signal and control region
  - Using dimuon **control region** ($\gamma\gamma \rightarrow \mu\mu$ events) significantly **reduced systematic uncertainty** from the photon flux