Exclusive dilepton production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{NN}}$=5.02 TeV with ATLAS

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ATLAS EXPERIMENT

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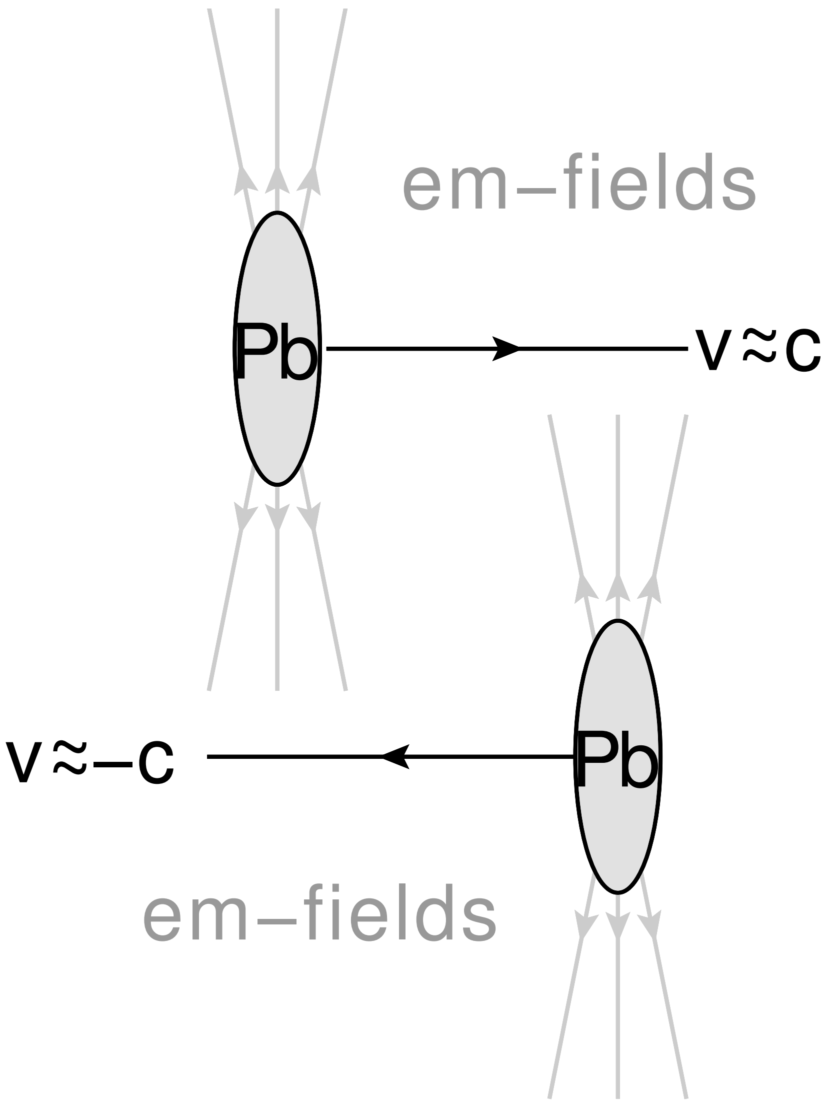
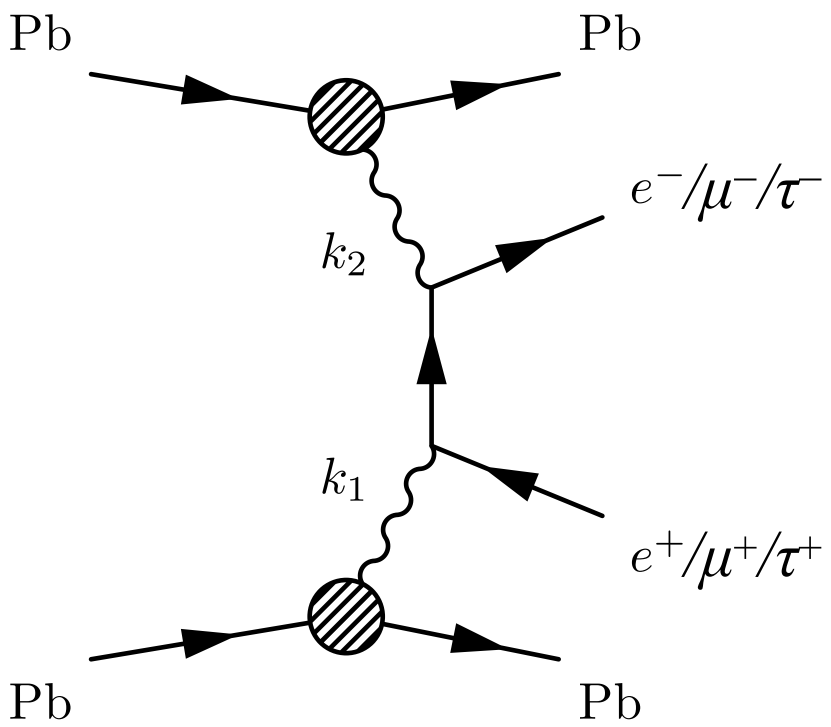
Ultra-peripheral collisions

- In **ultra-peripheral heavy-ion collisions (UPC)** photon-photon interactions can be observed what opens completely **new research opportunities**
- Large electromagnetic (EM) fields associated with relativistic ions can be considered as **fluxes of photons** (they scale with ~ Z^2)
- This is described in a **Equivalent Photon Approximation** (EPA) formalism
- Using EPA, the cross-sections for the reaction are calculated by **convolving** the respective **photon flux** with the **elementary cross-section** for the process



Motivation

- **Exclusive dilepton production** is one of the fundamental processes in photon-photon interactions
  - Precision measurements expected with 12k-30k events
- It is a **benchmark process** for other photon-induced processes
  - Possible reduction of systematic uncertainties (e.g. in measurement of the τ-lepton anomalous magnetic moment)
  - Important background (e.g. dielectron production in light-by-light scattering)
  - Also important for performance studies with a tag-and-probe technique
- 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:** ATLAS-CONF-2022-025
  - Exclusive ditau production: arXiv:2204.13478



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)

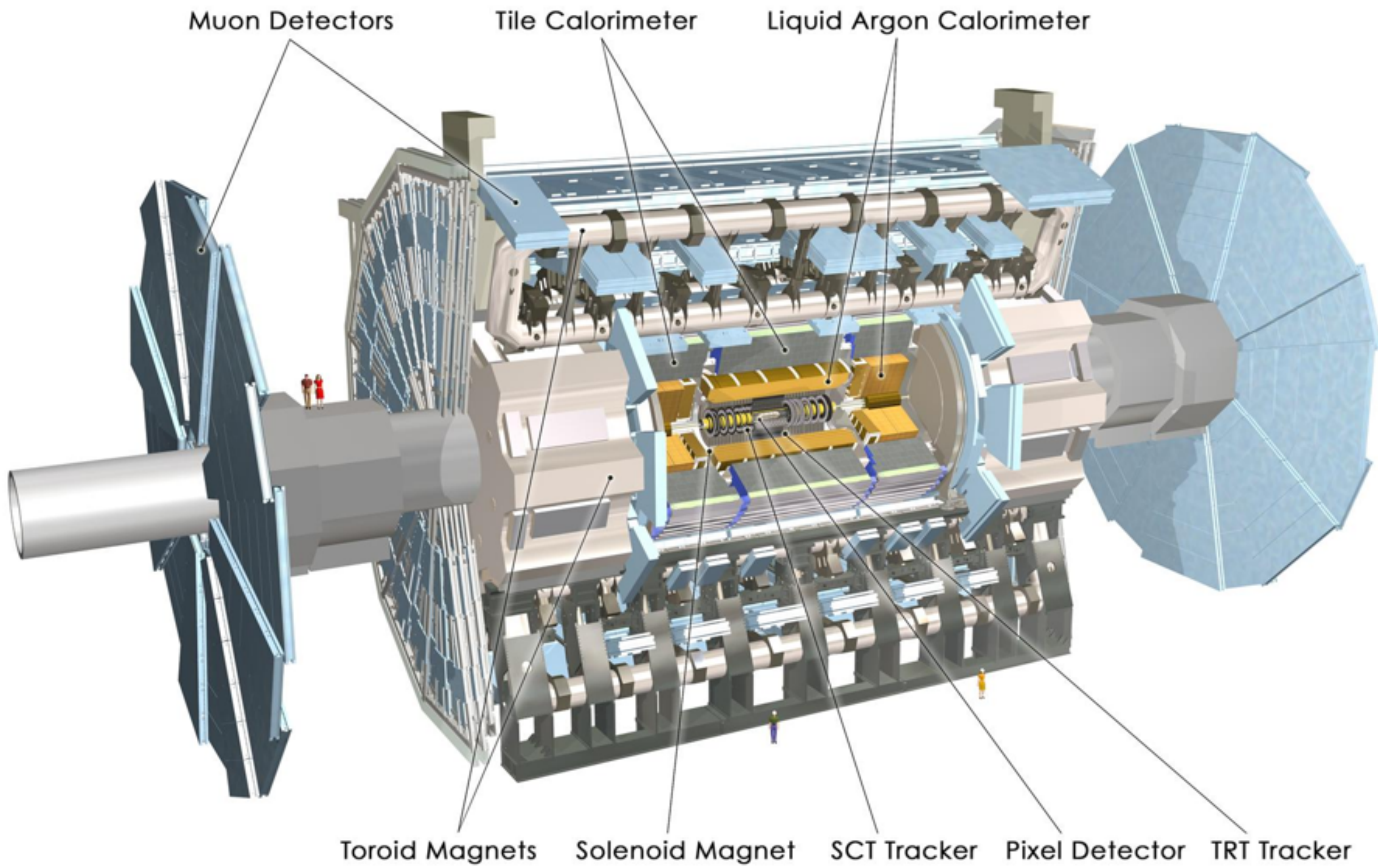
$$\sigma_{N_1N_2\to N_1XN_2} = \int \mathrm{d}x_1\mathrm{d}x_2\, n(x_1)n(x_2)\hat{\sigma}_{\gamma\gamma\to X}$$

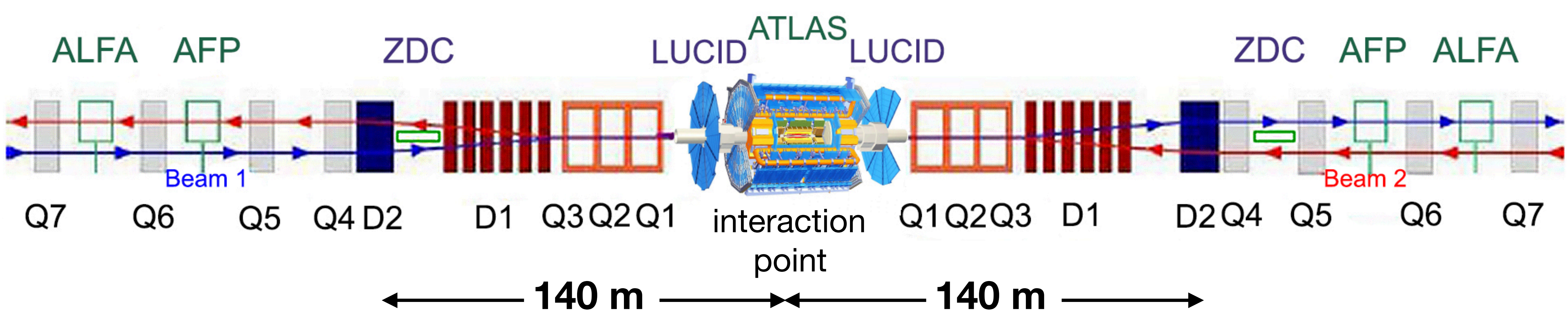
$$n(x_i) = \frac{\alpha}{\pi^2 x_i}\int \frac{\mathrm{d}^2 q_{i_\perp}}{q_{i_\perp}^2 + x_i^2 m_{N_i}^2}\left(\frac{q_{i_\perp}^2}{q_{i_\perp}^2 + x_i^2 m_{N_i}^2}(1-x_i)F_E(Q_i^2) + \frac{x_i^2}{2}F_M(Q_i^2)\right)$$

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

ATLAS detector

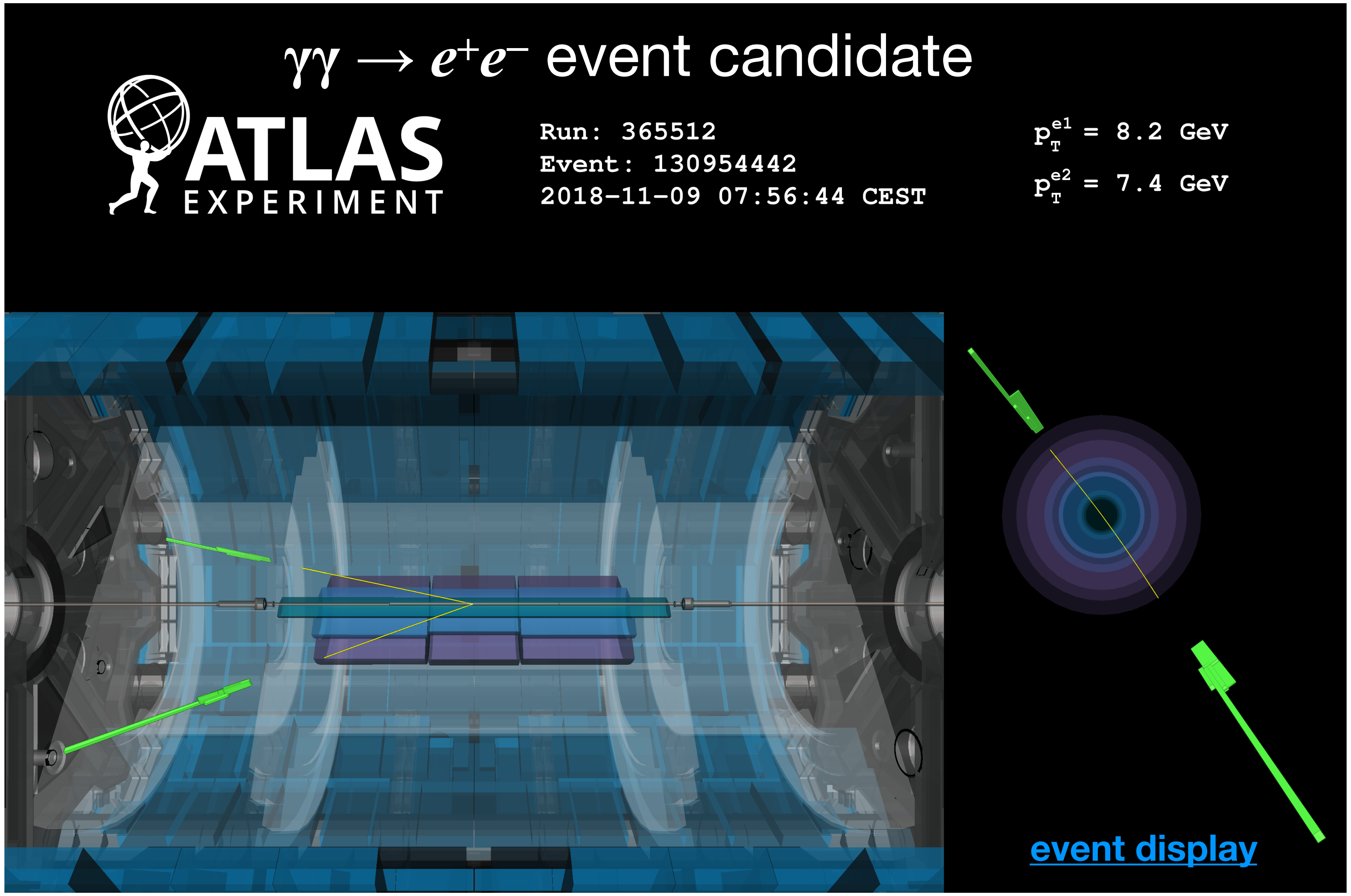
- Large general-purpose detector with almost 4π coverage
- $\eta = -\log(\tan(\theta/2))$
- Inner detector $|\eta|<2.5$
- Muon system $|\eta|<2.7$ (trig. 2.4)
- Calorimetry out to $|\eta|<4.9$
- Zero-Degree-Calorimeters capture neutral particles with $|\eta|>8.3$





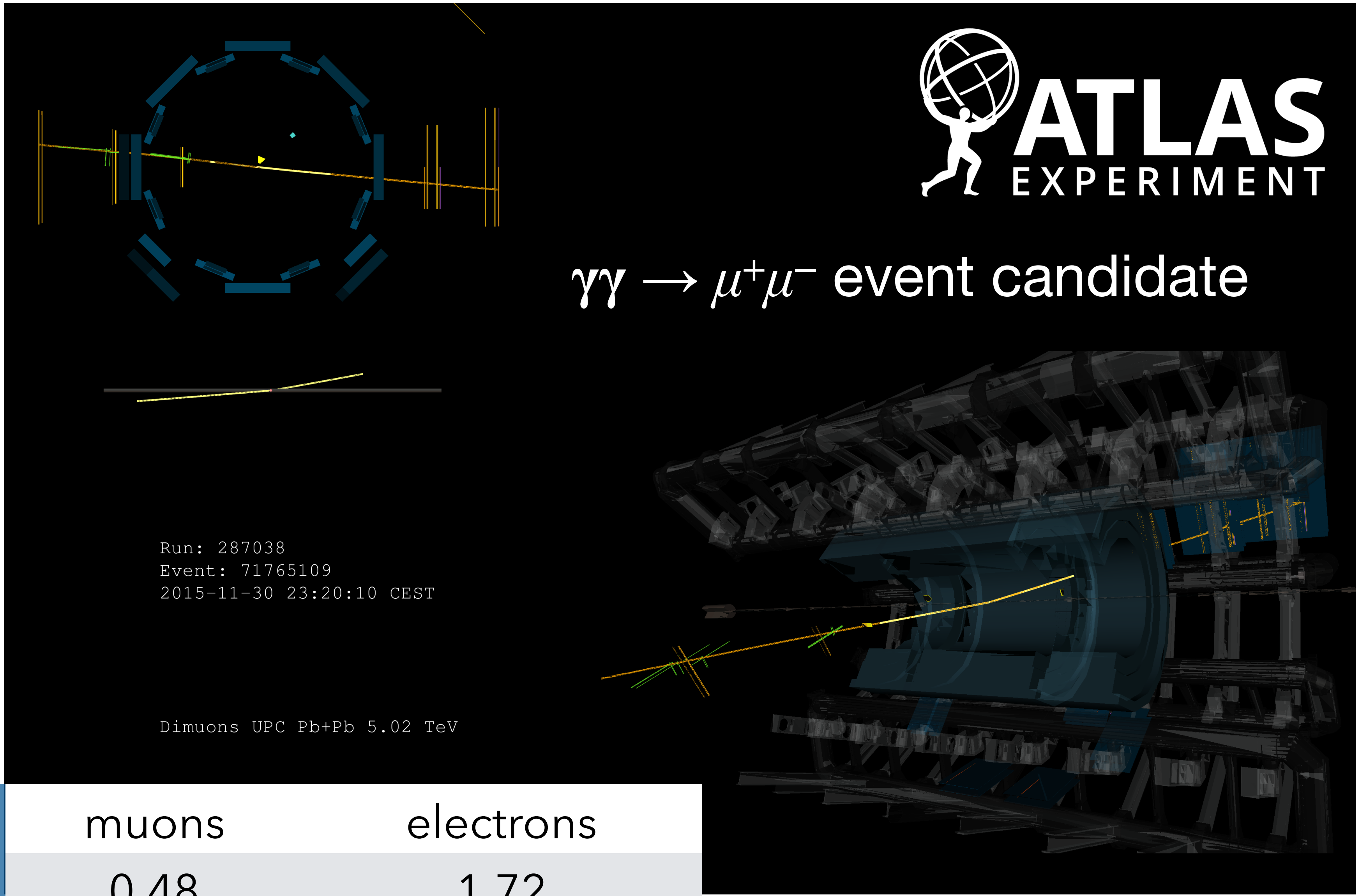
Event characteristics

- 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 was optimized to detect high-energy particles - low kinematic requirements necessitate careful estimation of trigger and particle reconstruction efficiency



Data & event selection

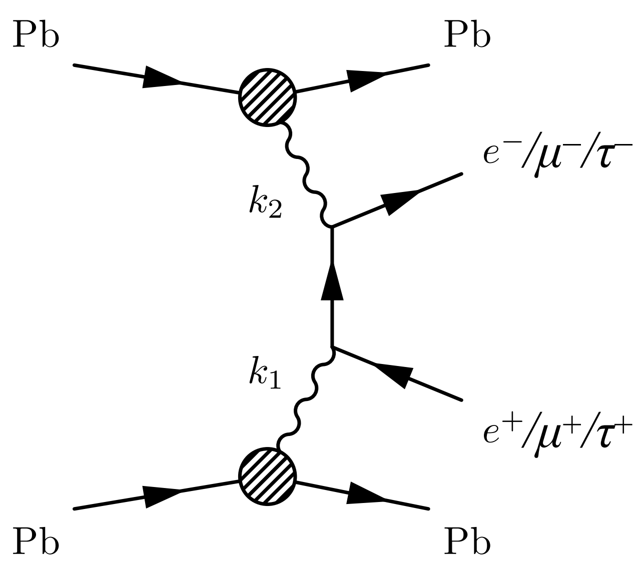
- Dimuon analysis is based on 2015 Pb+Pb data
- Dielectron analysis is based on 2018 Pb+Pb data
- Slightly different fiducial selections



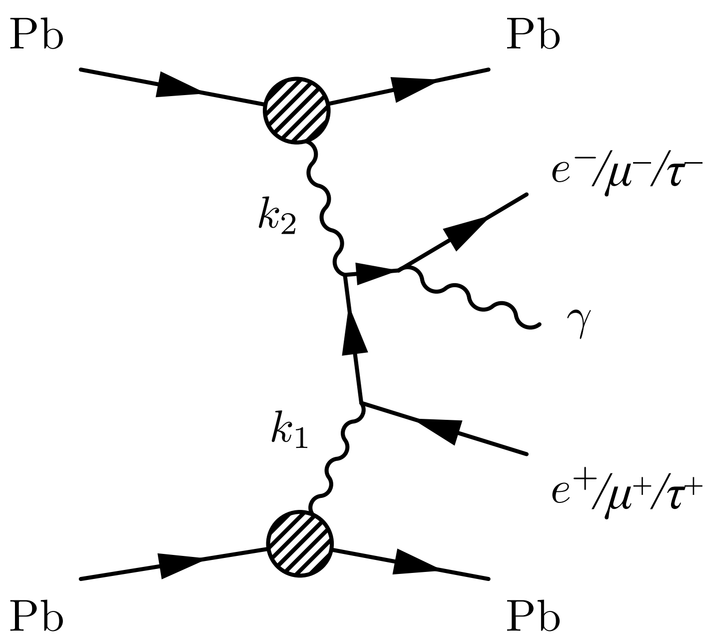
	muons	electrons
Int. Lumi [nb^{-1}]	0.48	1.72
$p_T^\ell >$	4 GeV	2.5 GeV
$\lvert\eta_\ell\rvert <$	2.4	2.5
$m_{\ell\ell} >$	10 GeV	5 GeV
$p_T^{\ell\ell} <$	2 GeV	2 GeV
N of events	12k	30k

Background sources

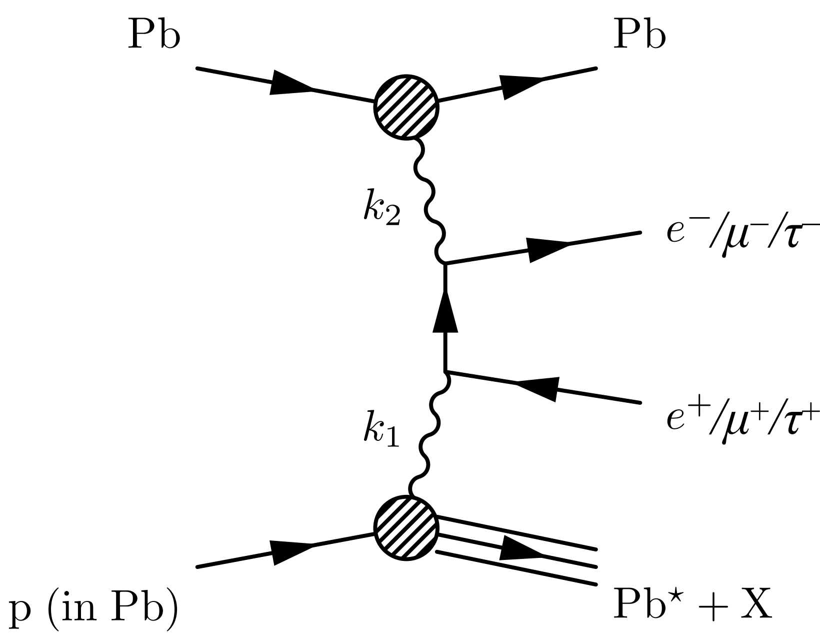
- Several background sources are considered:
  - **dissociative** production of $\ell^+\ell^-$ pairs - estimated with data-driven method (template taken from LPair/SuperChic4+Pythia8 in *pp* collisions)
  - **Upsilon(nS)** production - estimated with STARlight+Pythia8 MC samples (only in dielectron measurement)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



Signal (LO)



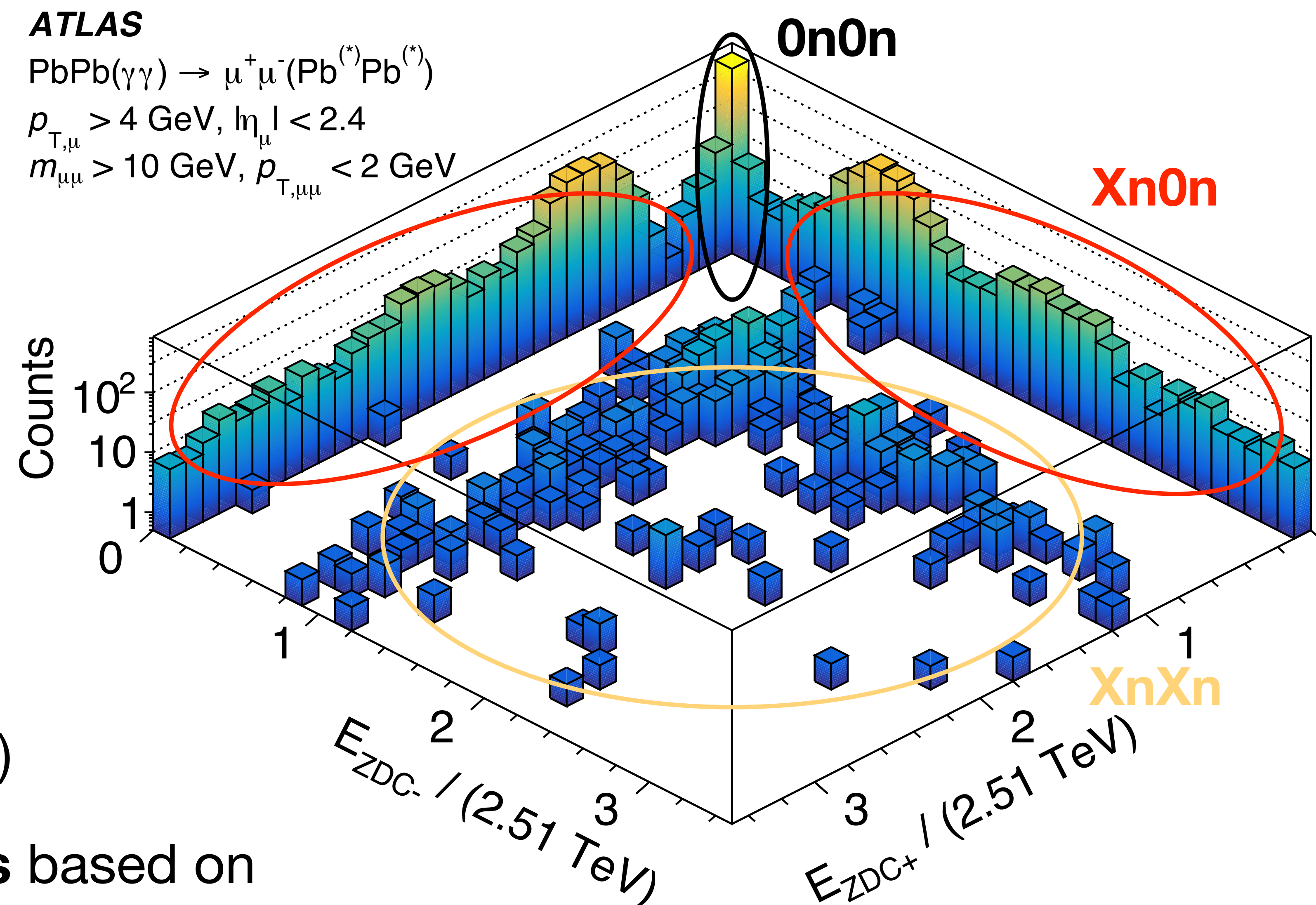
Signal with FSR



dissociative background

Signal categories - ZDC selection

- In selected events one can identify several processes that should present **different activity in the forward region**:
    - Signal events: for both LO and NLO process ions stay intact
    - Background events with ion dissociation: photon is emitted from substructure of one nucleus (or both nuclei)



- Events are divided into **3 classes** based on the signal in the Zero-Degree Calorimeter (ZDC), which describes forward neutron activity
- The **association between** given **ZDC signal** and given **process** is **nontrivial** due to possible ion excitation and presence of EM pile-up

ZDC fractions

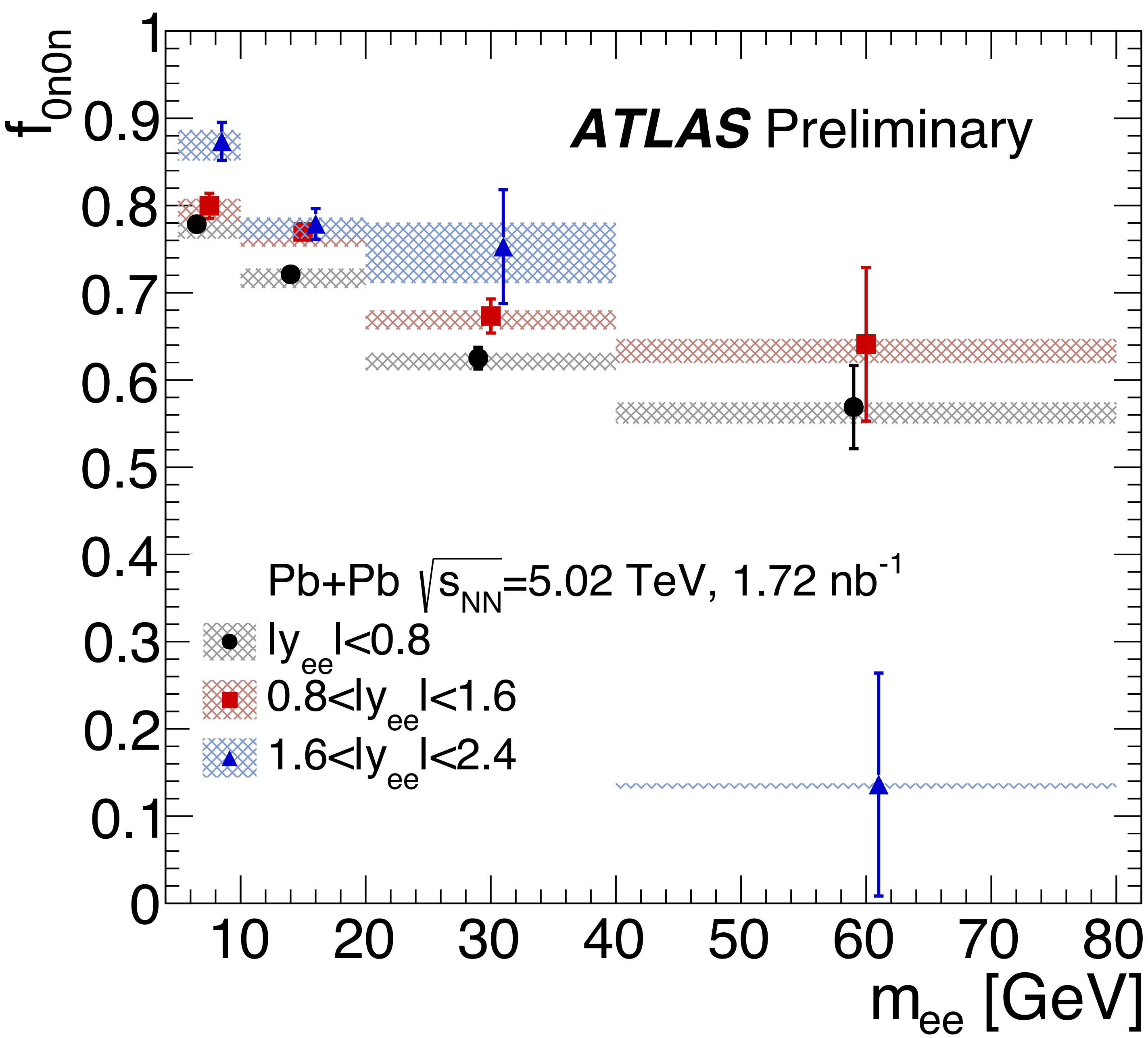
- The fractions of events in each ZDC class are affected by the presence of EM pile-up
- The probabilities of single and mutual dissociation (p_s, p_m) are determined using the same method both in dimuon and dielectron measurement, with p_s, p_m values calculated for given data taking period
- The fractions 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**

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

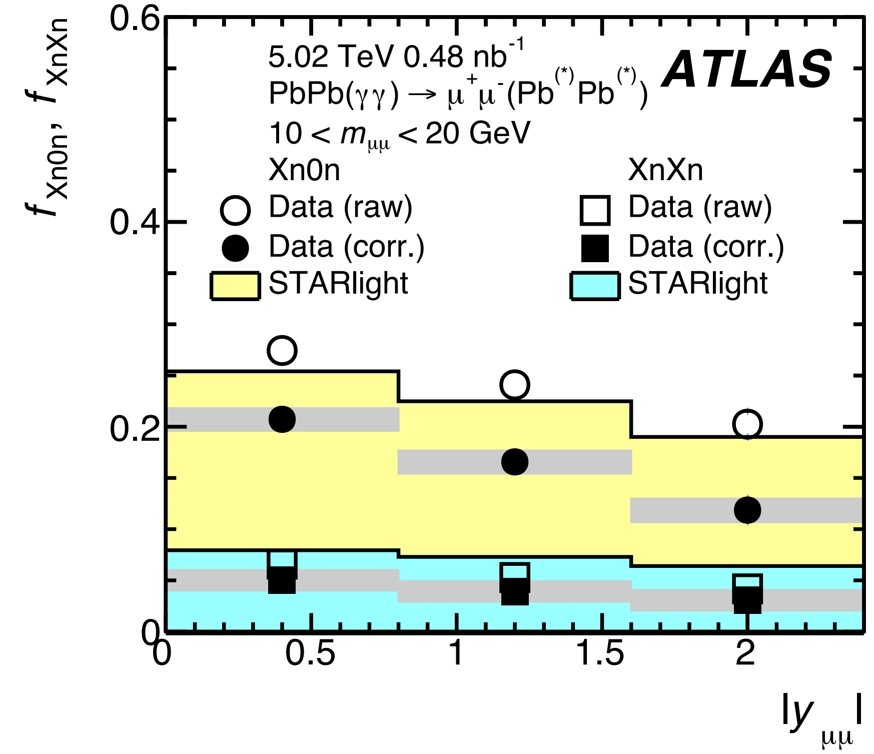
f0n0n fractions - dielectrons

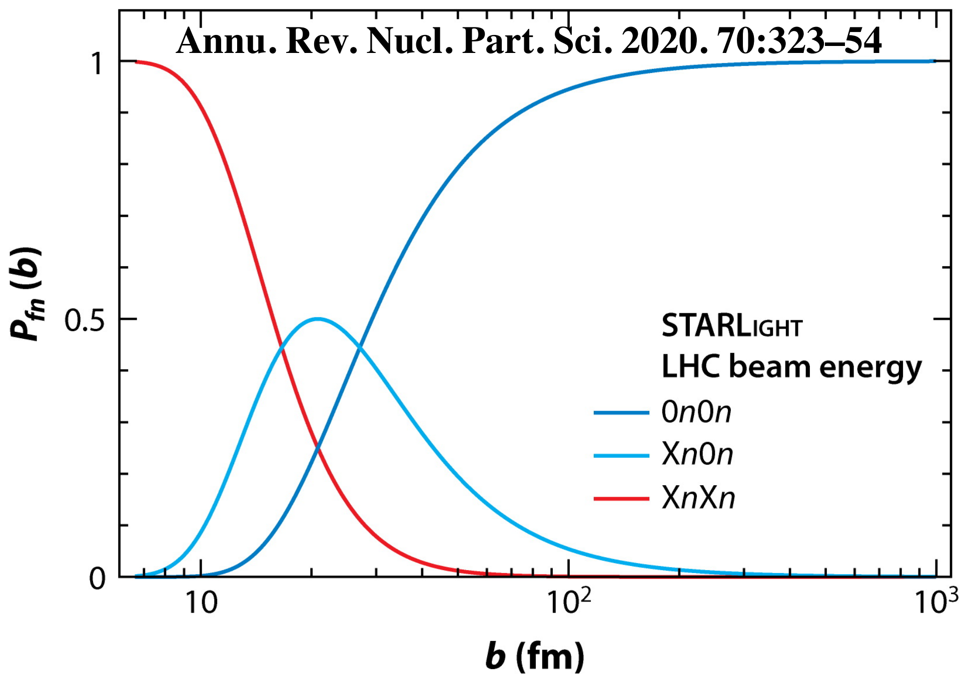
- The 0n0n category should in principle be very pure, at least in terms of dissociative background
- To select 0n0n sample, events are required to have low energy deposits in the ZDC (below 1 TeV on each side)
- There is no ZDC simulation in the MC samples, so a dedicated approach, correcting also for EM pile-up 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

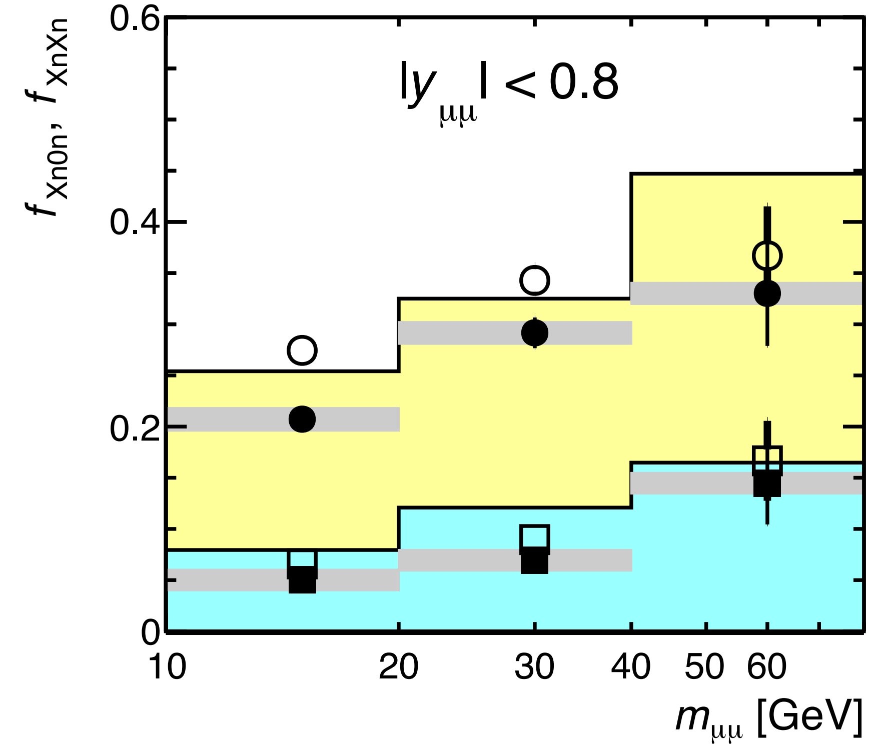


fXn0n and fXnXn fractions - dimuons

- The f_{Xn0n} and f_{XnXn} fractions are compared with the STARlight predictions
- STARlight predicts systematically higher f_{Xn0n} and f_{XnXn} 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*



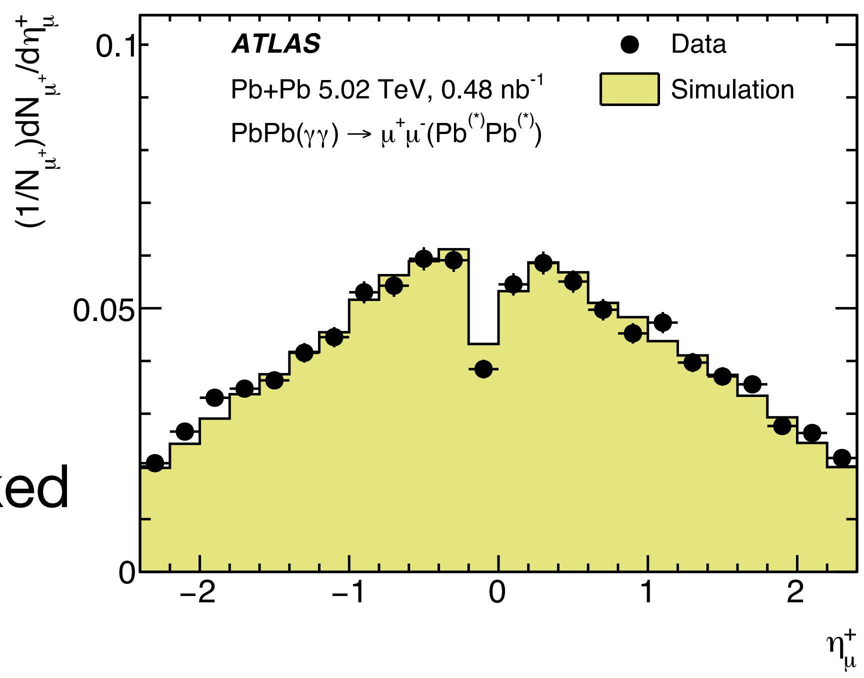


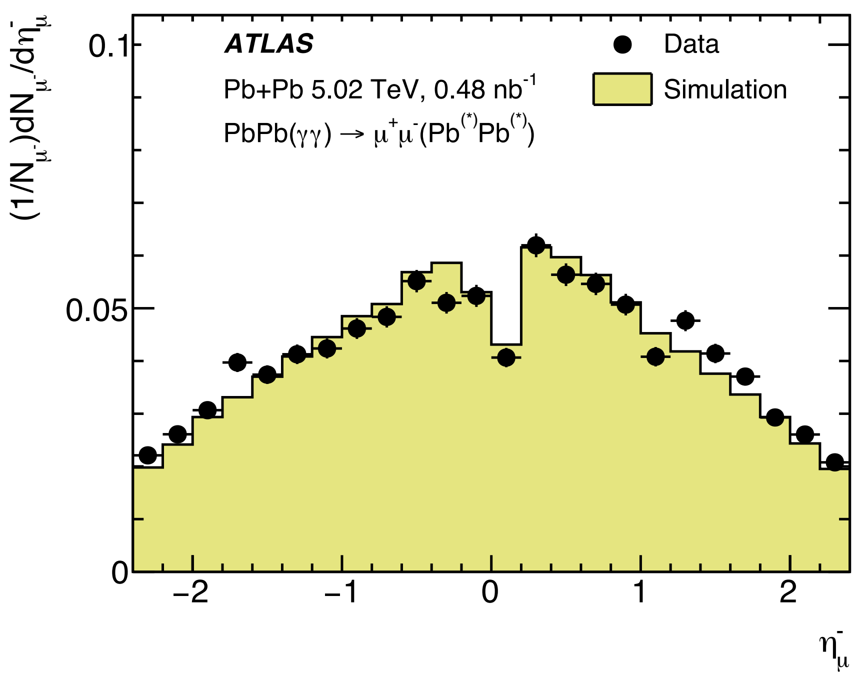


Dimuons

Dimuons - efficicency corrections

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



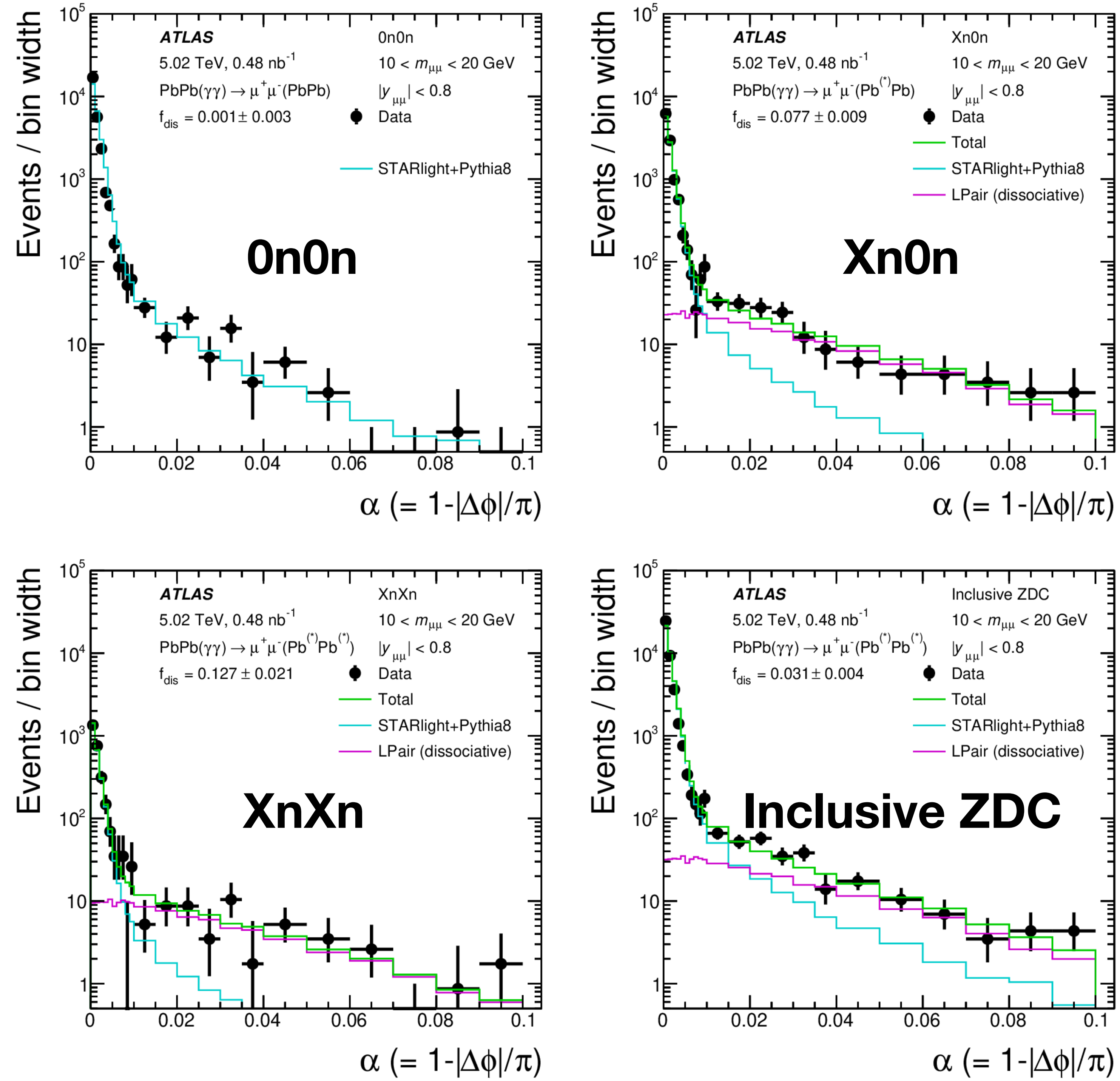


- The total trigger efficiency is derived as: $\varepsilon_{T\mu\mu} = 1 - (1 - \varepsilon_T(\eta^+))(1 - \varepsilon_T(-\eta^-))$
- The typical trigger efficiency is 93% at $m_{\mu\mu} < 20$ GeV and $|y_{\mu\mu}| < 1$, and increases to 97% at $m_{\mu\mu} > 40$ GeV and $|y_{\mu\mu}| > 1.5$
- Good data 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 - background

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

- 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 γγ → $\mu^+\mu^-$ 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 several kinematic variables as:

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

Bin migration

Background from dissociative events

Muon kinematic variable

Reconstruction and trigger efficiencies

- Measured fiducial cross section is:

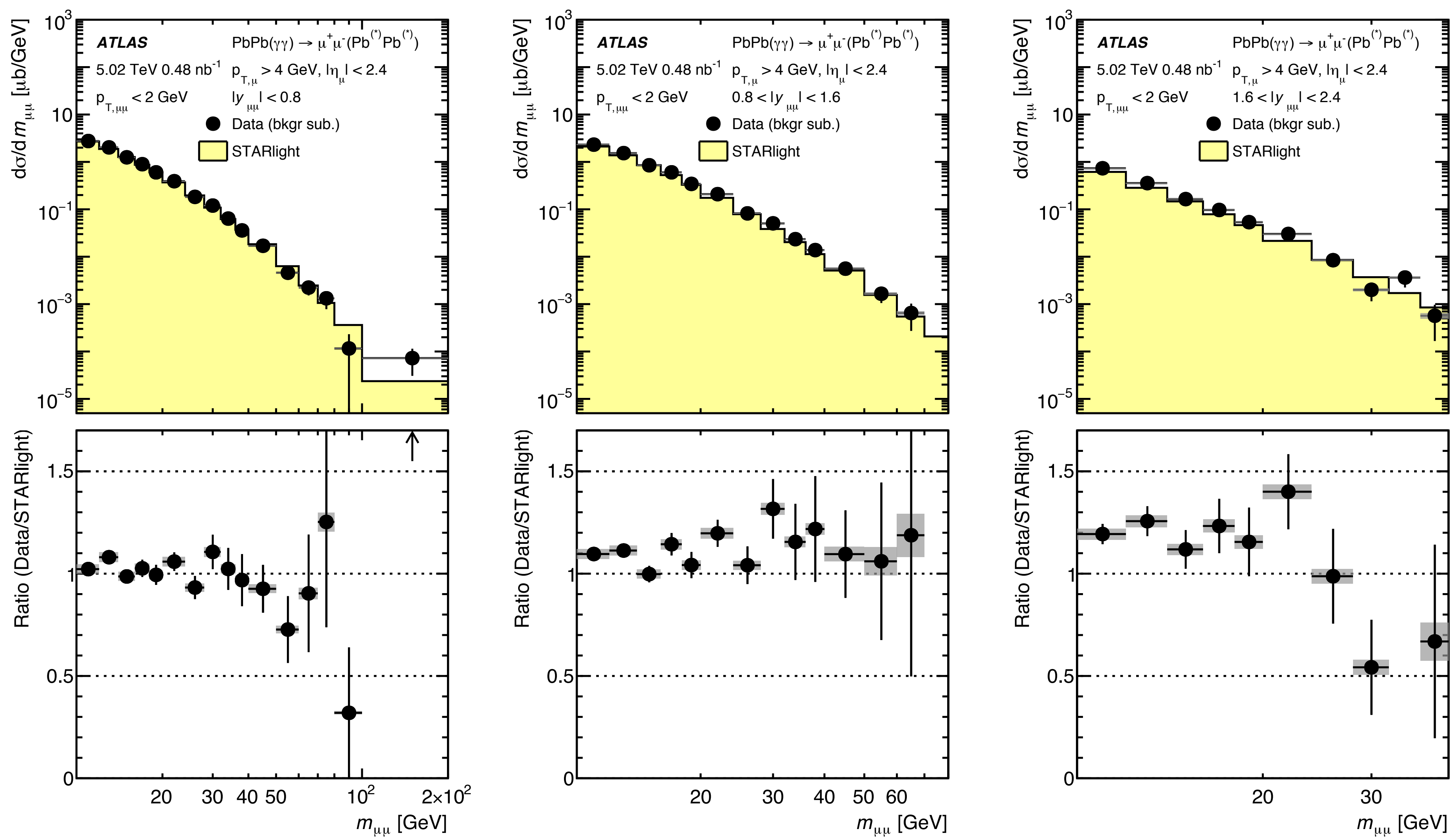
σ = 34.1±0.3(stat.)±0.7(syst.) μb,

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

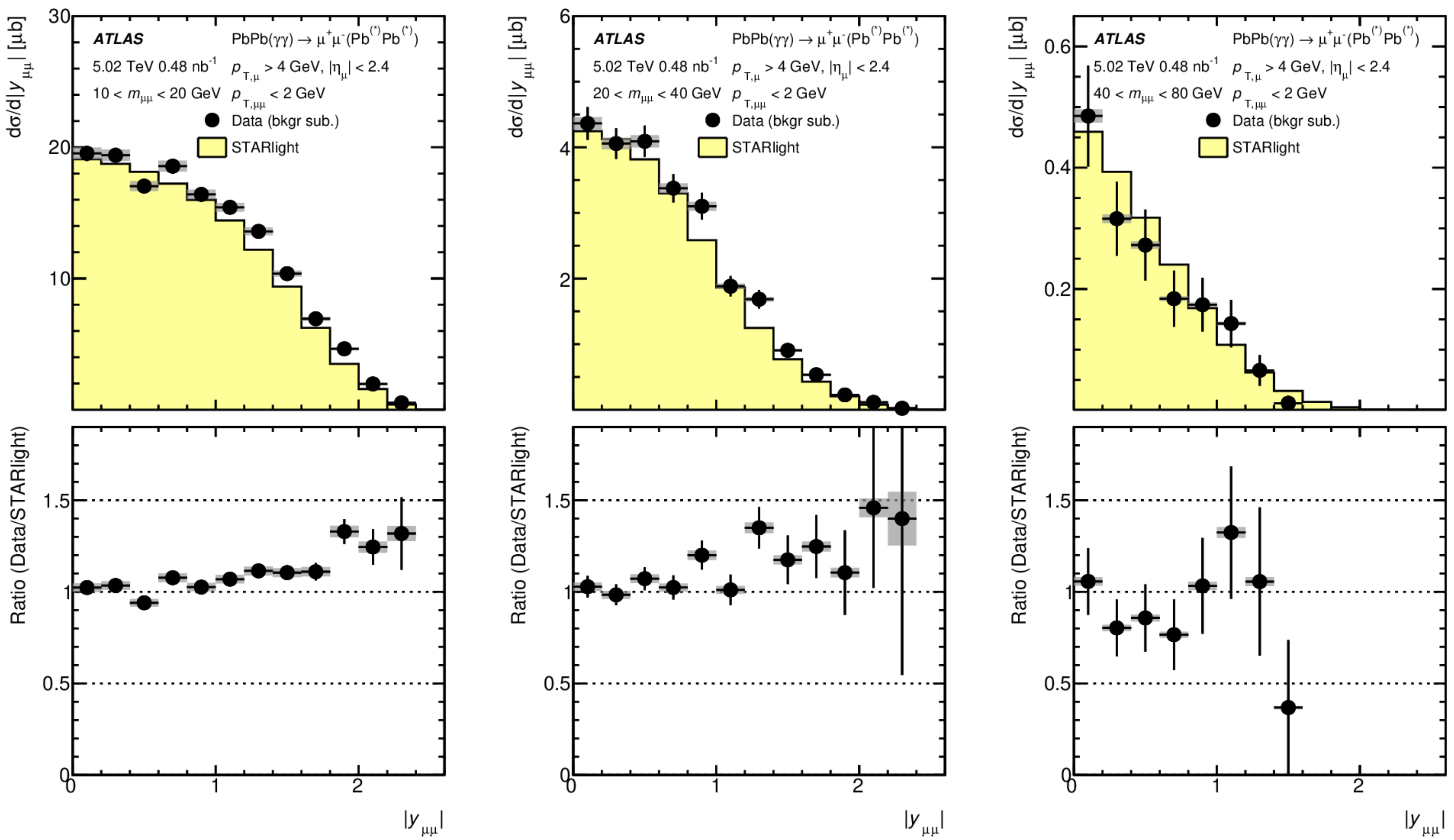
Dimuons - results

- 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

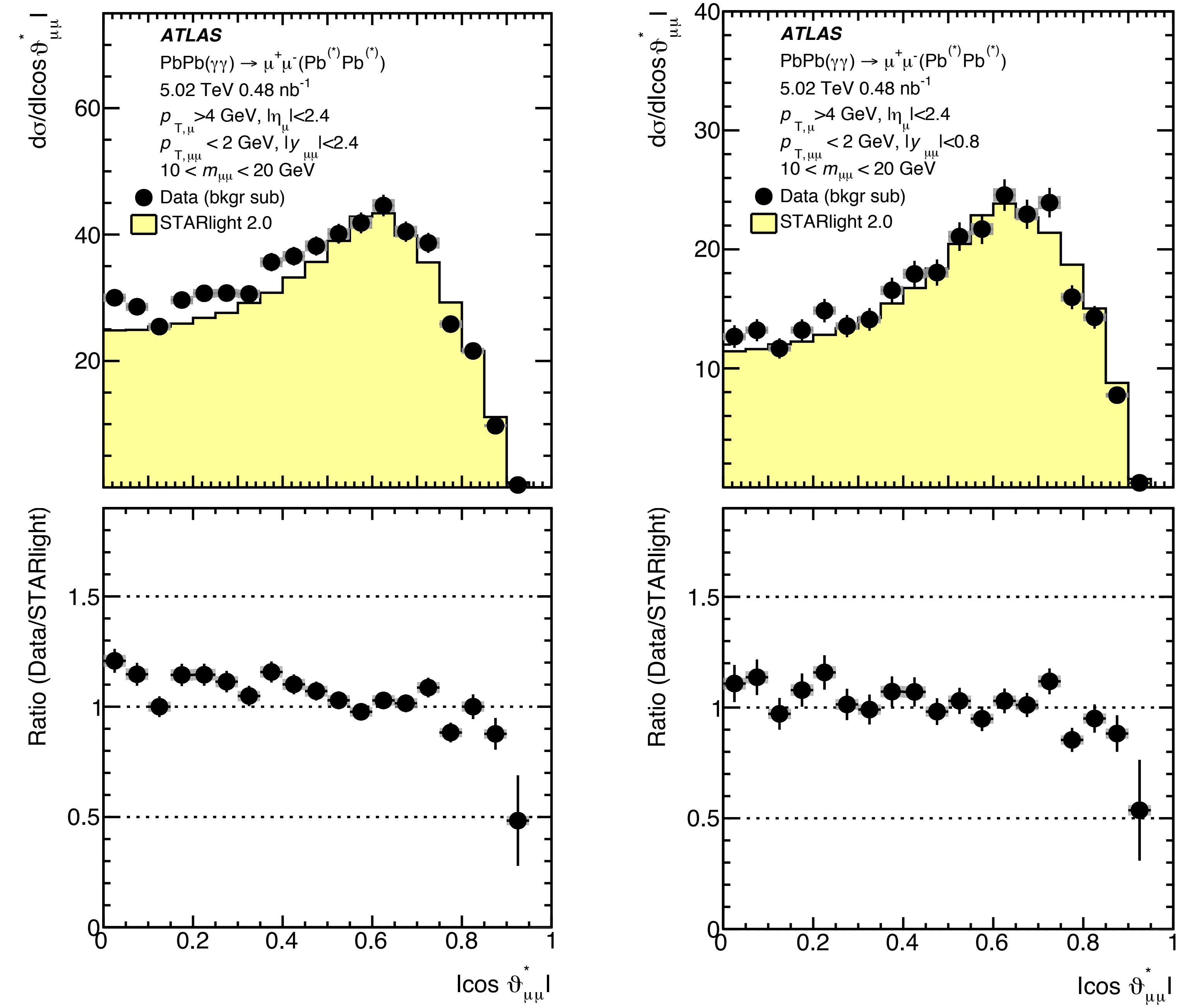
- The cross-sections are presented as a function of absolute dimuon rapidity in 3 mass slices
- Data is compared with STARlight MC simulation of $\gamma\gamma \rightarrow \mu^+\mu^-$ process w/o FSR
- Good agreement is found in central region of rapidity distribution (small $|y_{\mu\mu}|$),but data to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



Dimuons - results

- The shape of the $|\cos\theta^*|$ ($= |\tanh(\Delta\eta_{\ell\ell})/2|$) is affected by the fiducial requirement of $|\eta_\mu| < 2.4$
- 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 $|\cos\theta^*|$

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

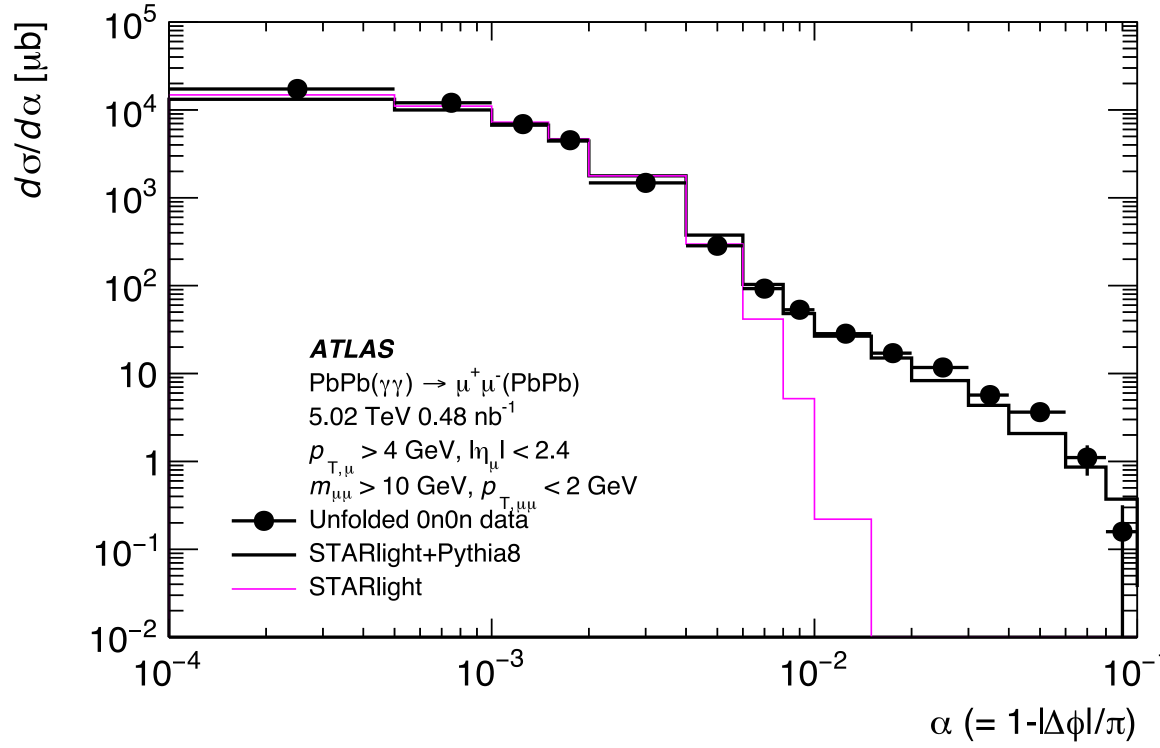


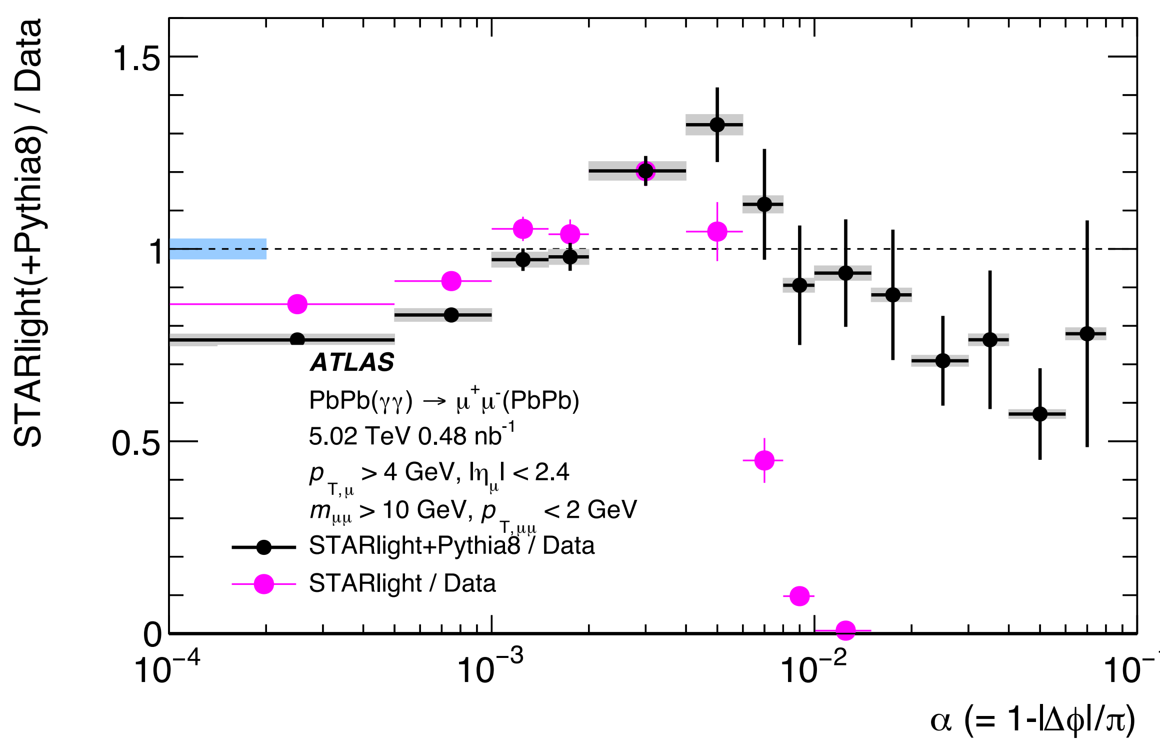
Dimuons - results

- 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





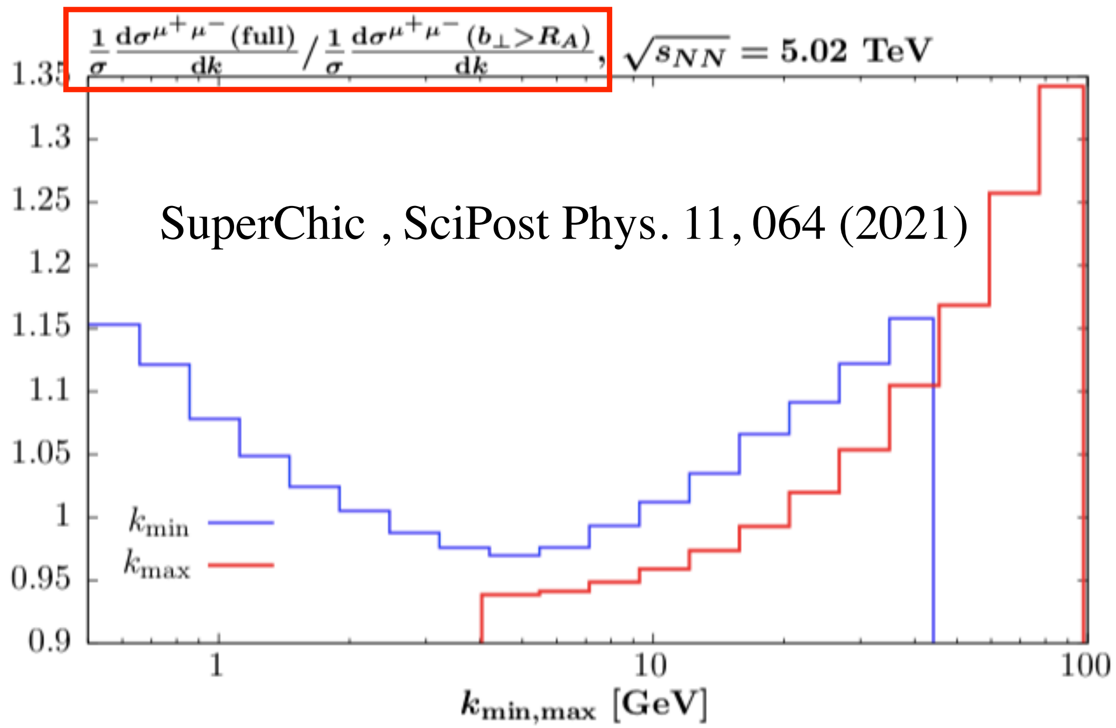
What can we learn about initial photon fluxes?

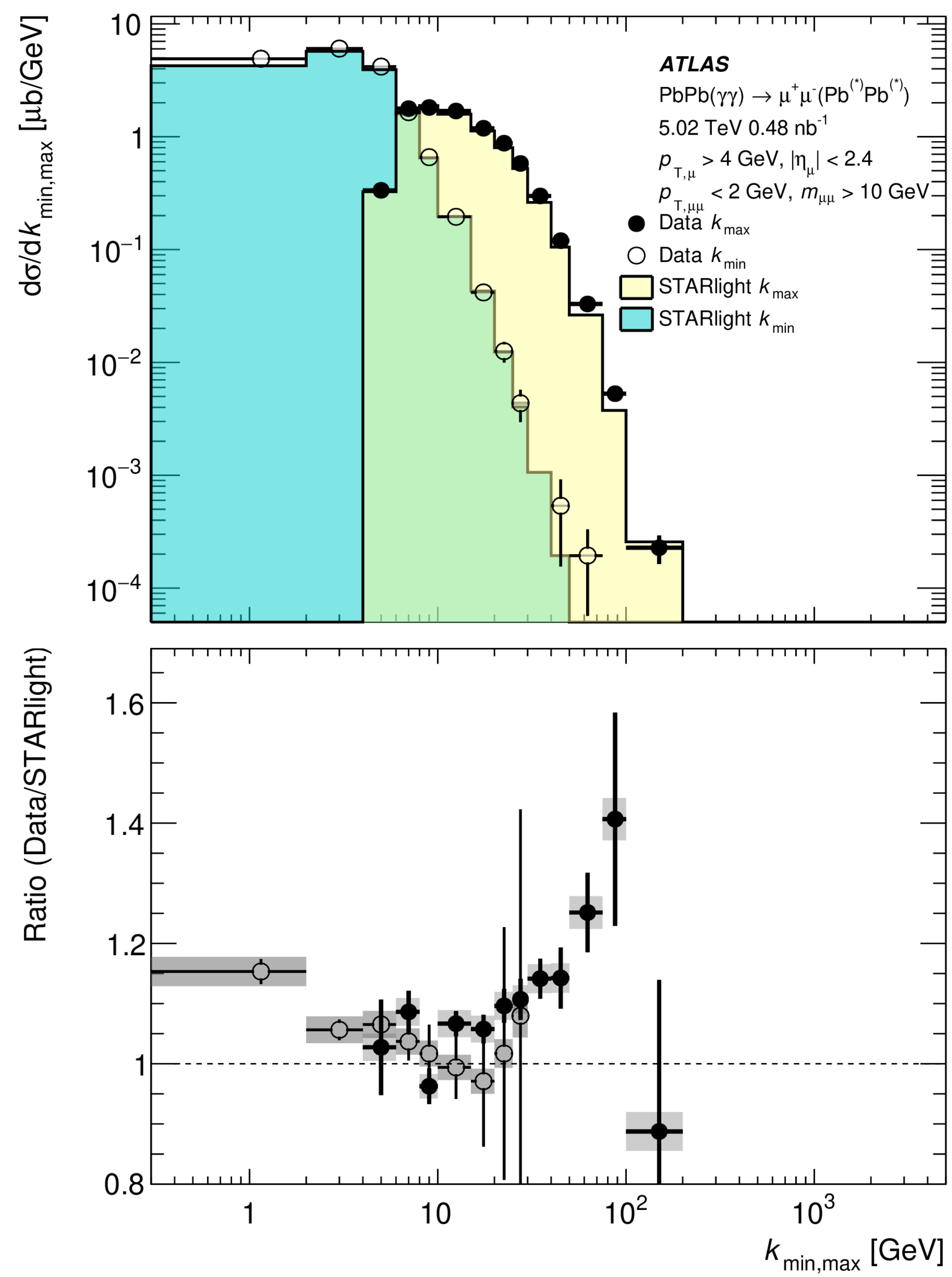
- The muon kinematics can be used to estimate initial photon energies

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

- 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}





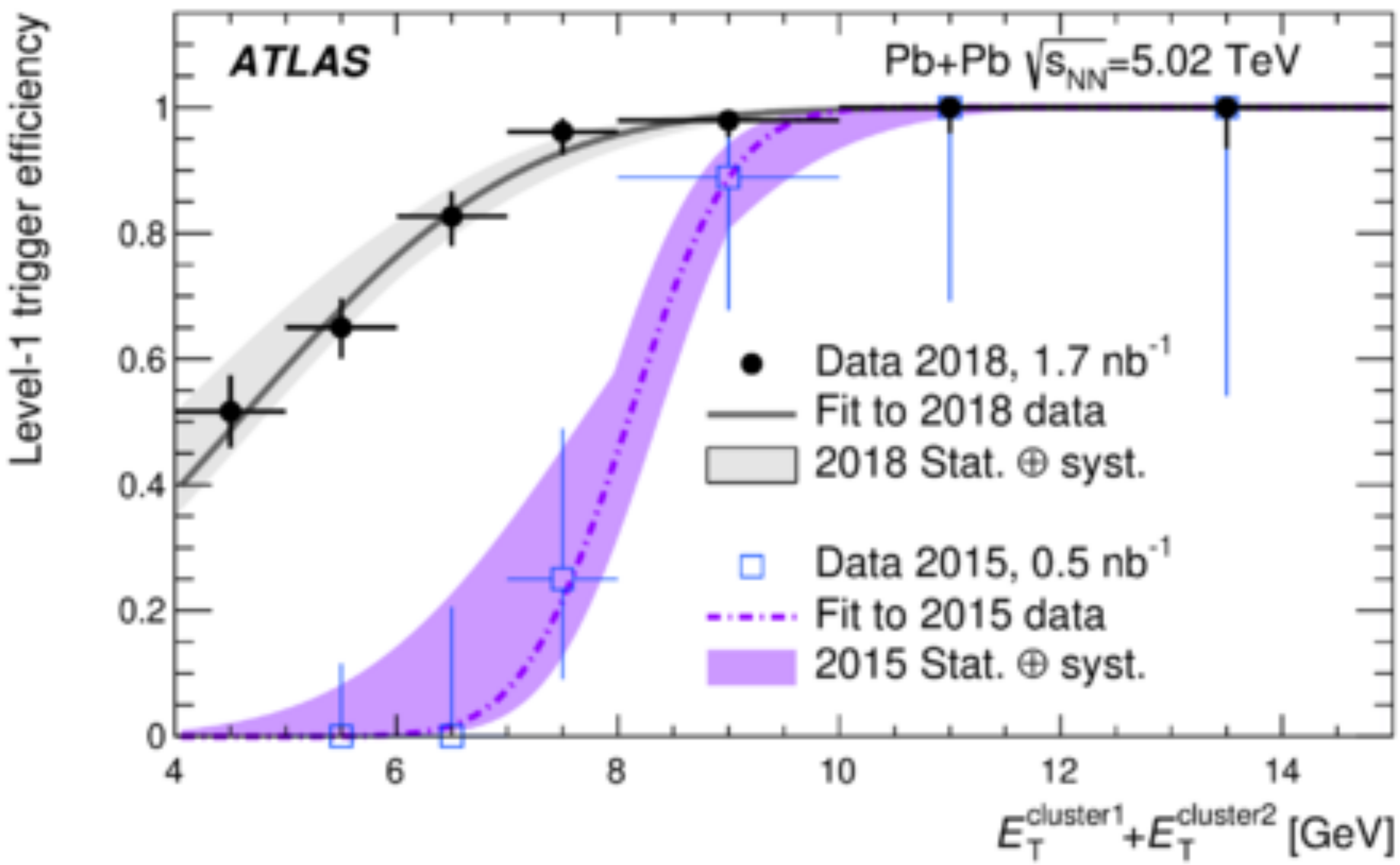
Dielectrons

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 $|y_{ee}| > 2$

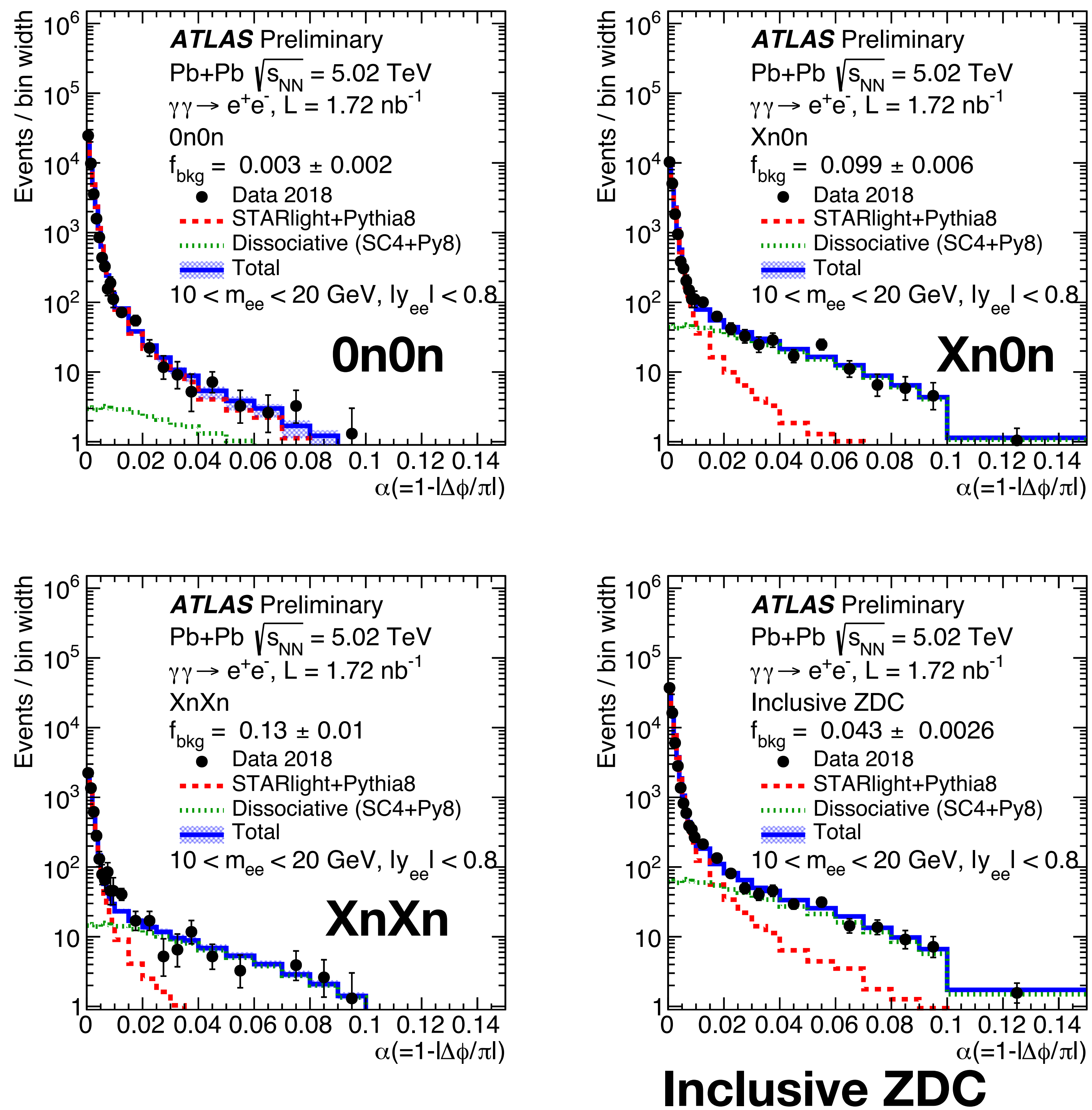


- Tag and probe method used to derive electron efficiency in data and MC simulation
- Electron reconstruction efficiency ranges from about 30% at $p_T = 2.5$ GeV to 95% above 15 GeV, PID efficiency flat in p_T, and vary weakly with η in range between 80 and 90%
- Ratio of the full reconstruction efficiency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

Dissociative background

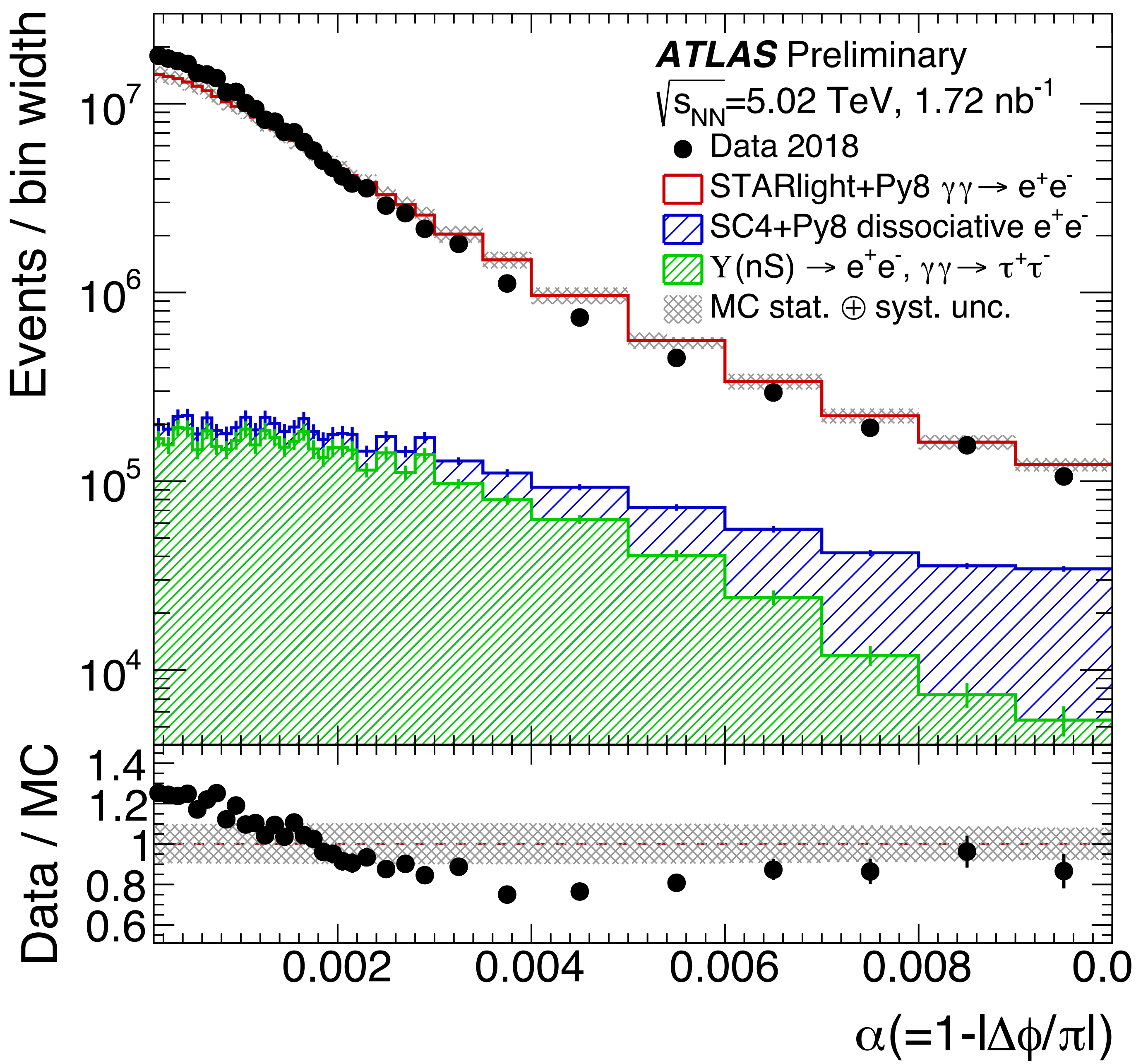
$$P(\alpha, m_{\mu\mu}, y_{\mu\mu}) = (1 - f_{dis}) P_{EPA}(\alpha, m_{\mu\mu}, y_{\mu\mu}) + f_{dis} P_{dis}(\alpha, m_{\mu\mu}, y_{\mu\mu})$$

- 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
- Several sources of systematic uncertainties are considered, most important are:
  - Data 0n0n instead of MC
  - Adding double dissociation



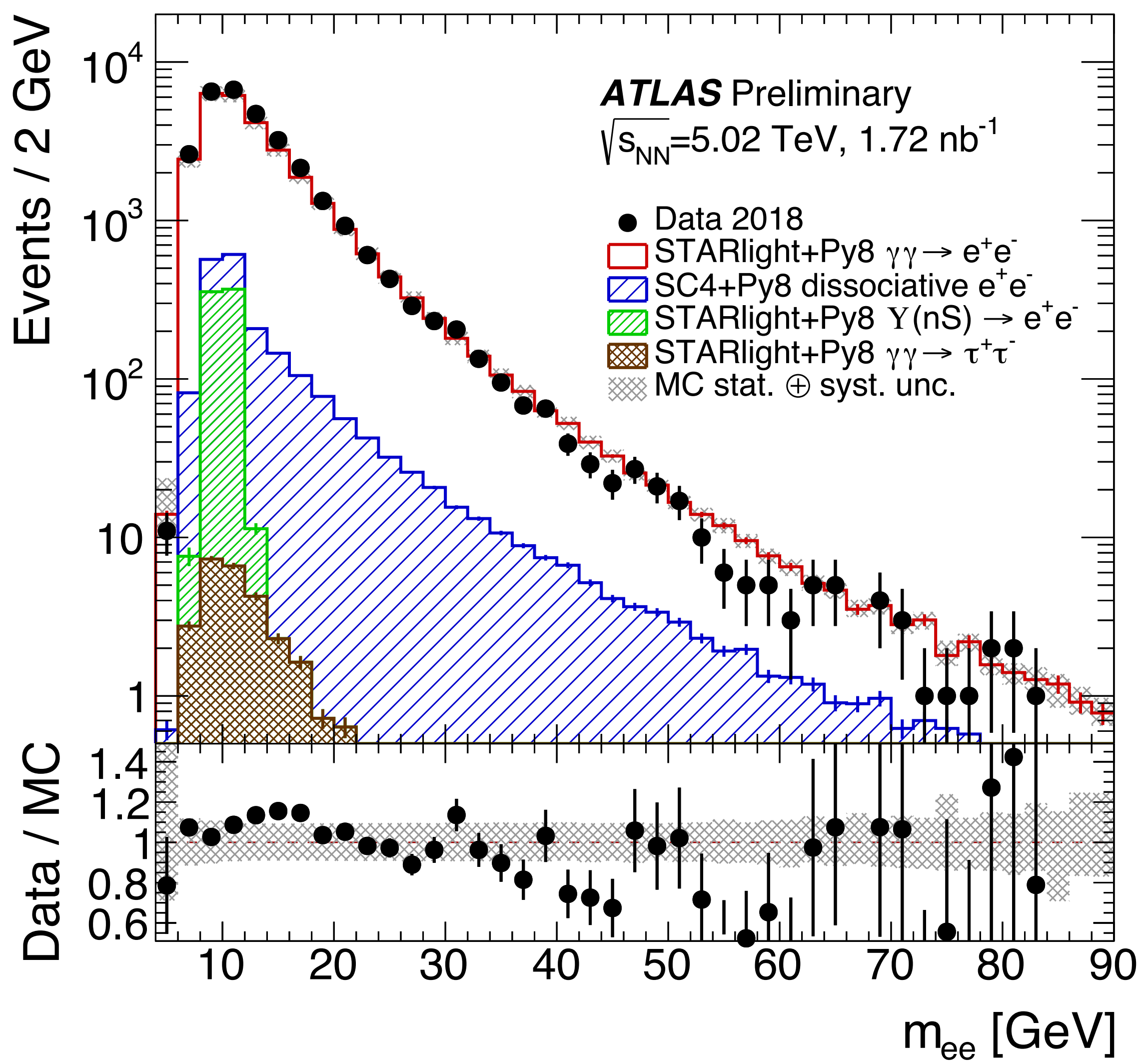
Background - upsilon

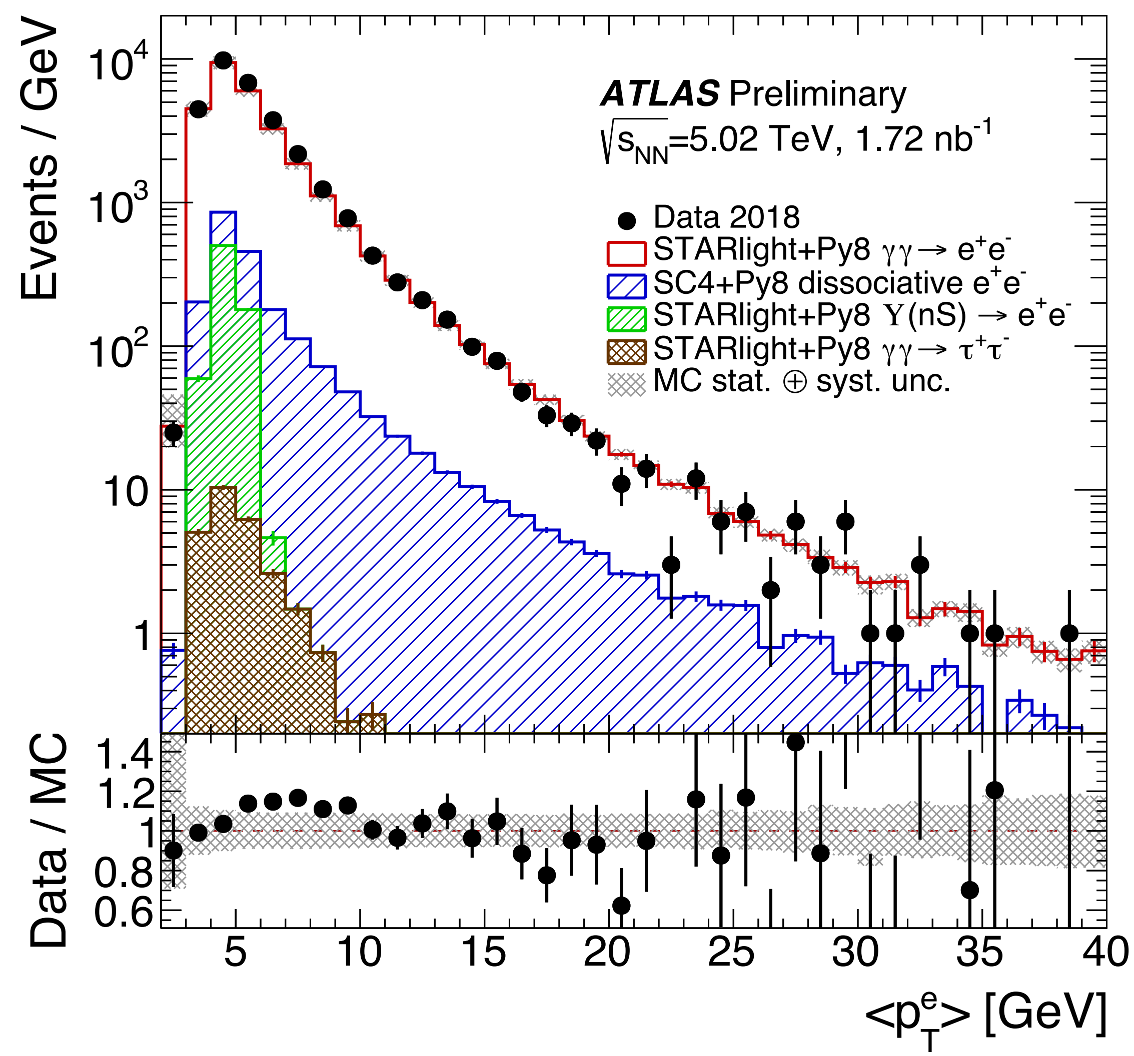
- The background from Upsilon(nS) decays to dielectrons is estimated using STARlight+Pythia8
- Upsilon 1S, 2S and 3S are considered
- The acoplanarity distribution for this background is peaked at 0 and should not influence the background fit for dissociation
- In total Upsilon background is at the level 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

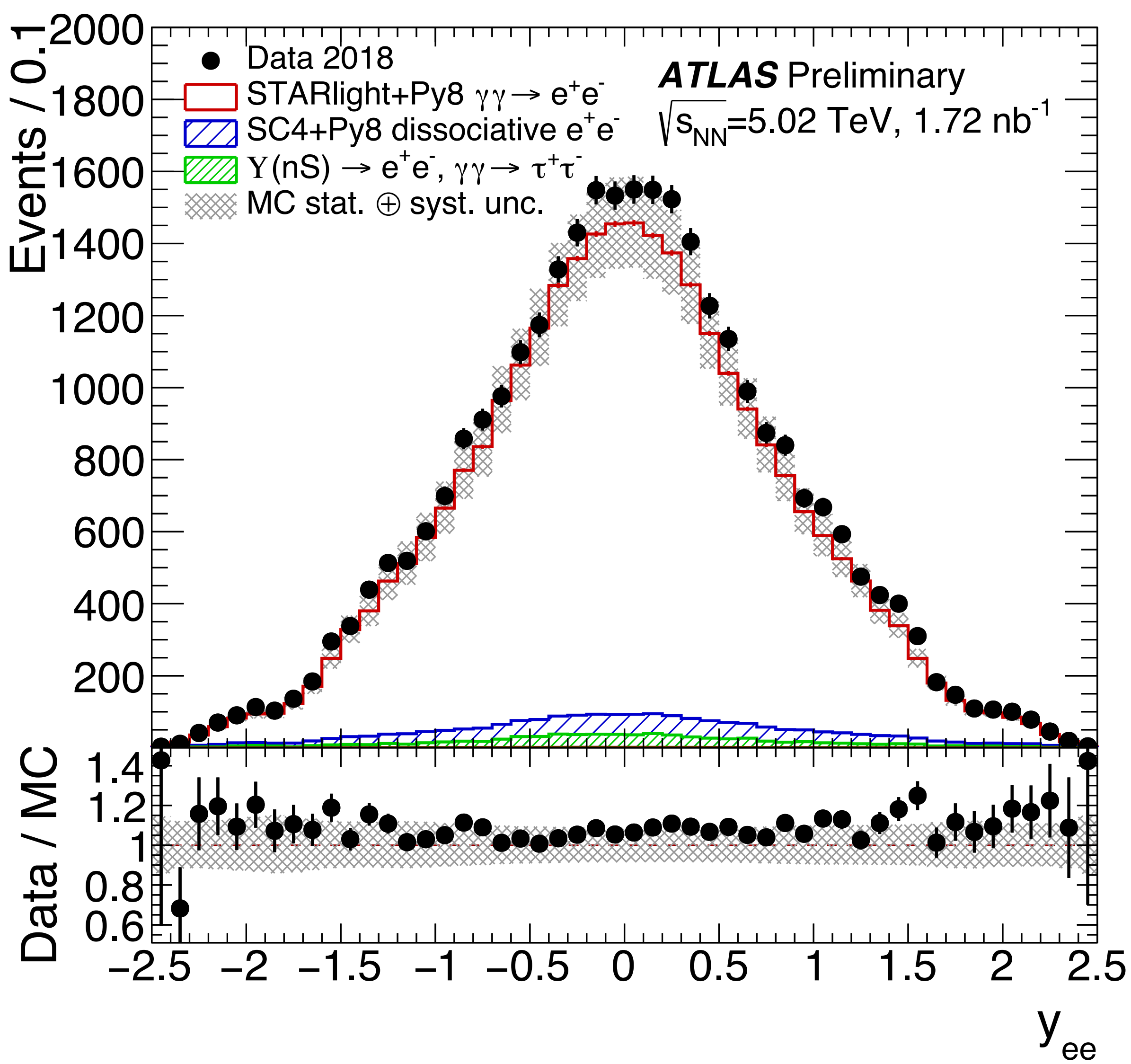
- The data sample is ~93% pure, with about 10% more counts in data than in the MC prediction
- The difference is higher for masses in range 10-20 GeV and p_T in range 5-10 GeV
- The dissociative background is plotted using shape from the MC and using integrated background fraction

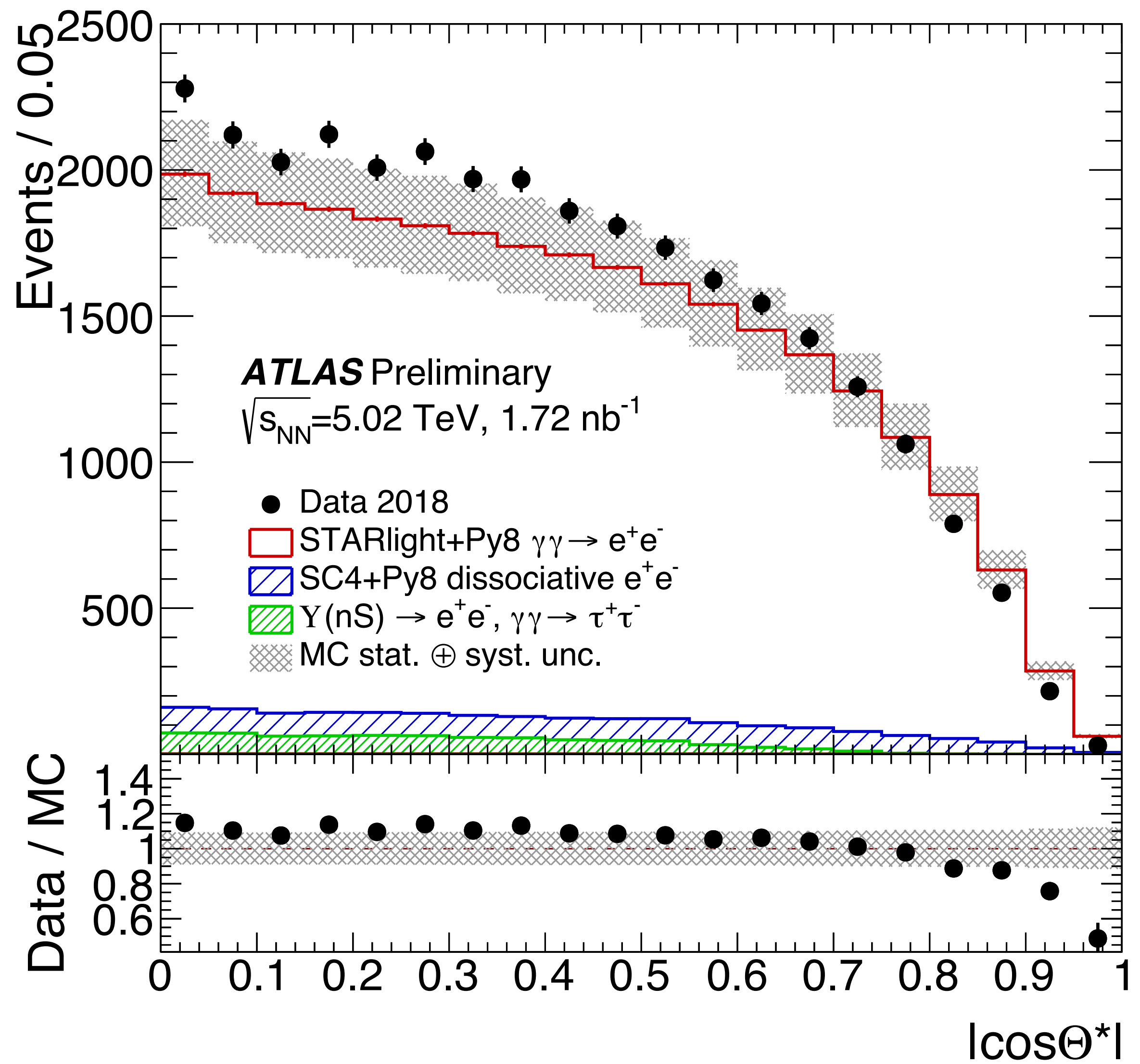




Detector-level control plots

- The data sample is ~93% pure, with about 10% more counts in data than in the MC prediction
- The difference rises slightly for larger absolute rapidities, 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

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 $|\eta_e| < 2.5$)

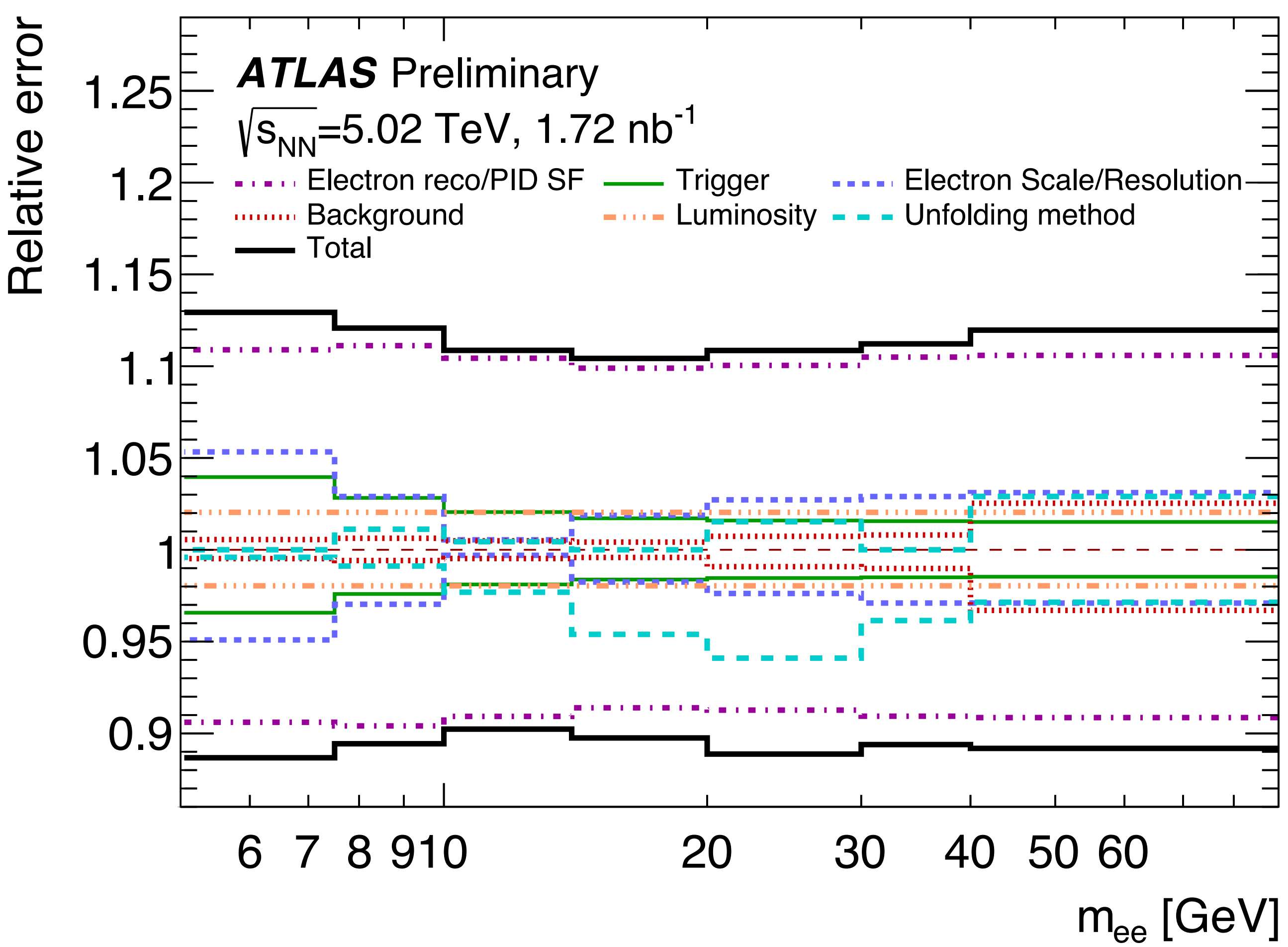
$p_T^e >$	2.5 GeV
$\|\eta_e\| <$	2.5
$m_{ee} >$	5 GeV
$p_T^{ee} <$	2 GeV

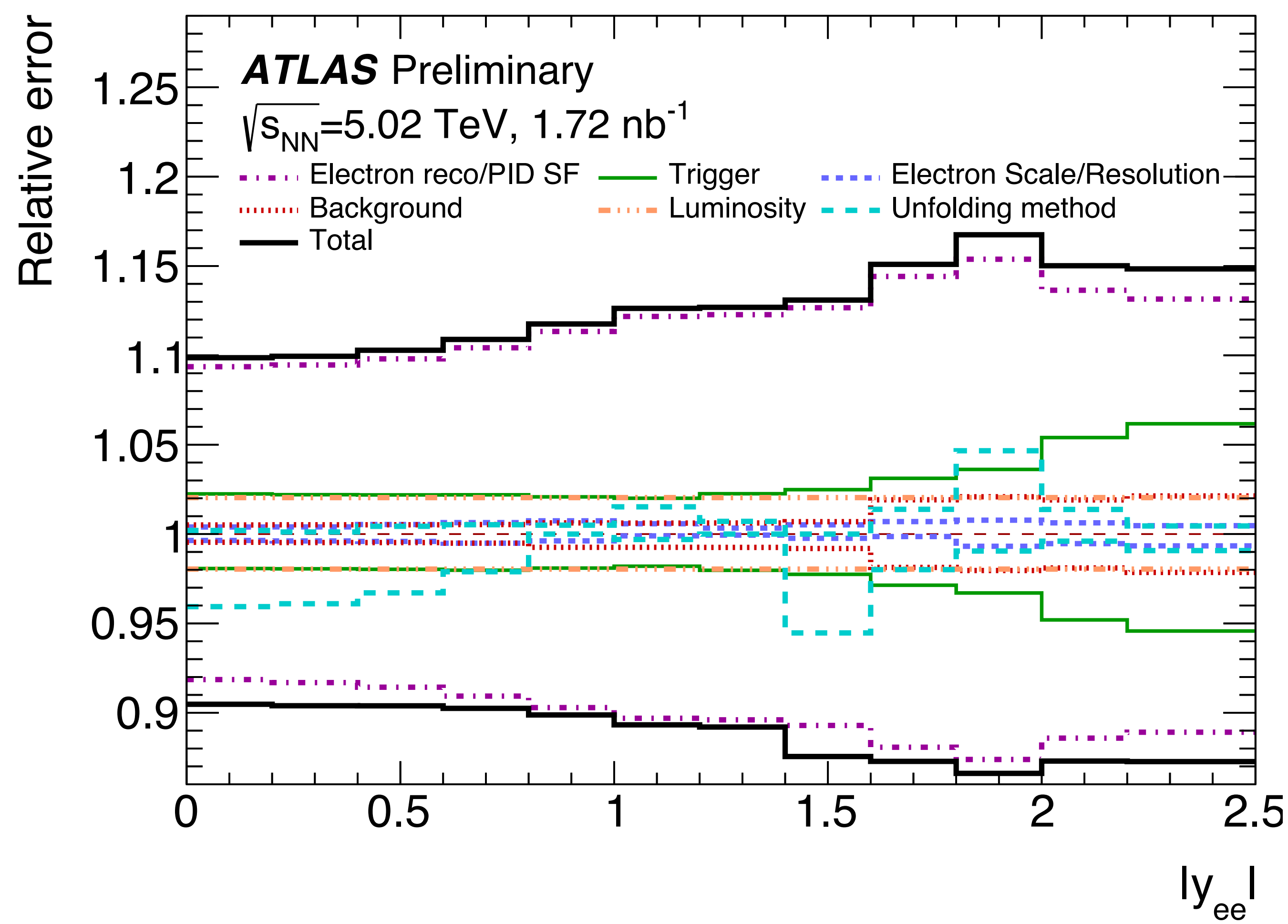
- The integrated cross-section is calculated in fiducial region determined by the event selection
- Besides mentioned reported below stat+syst uncertainties, there is 4 μb lumi uncertainty

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

Breakdown of systematics

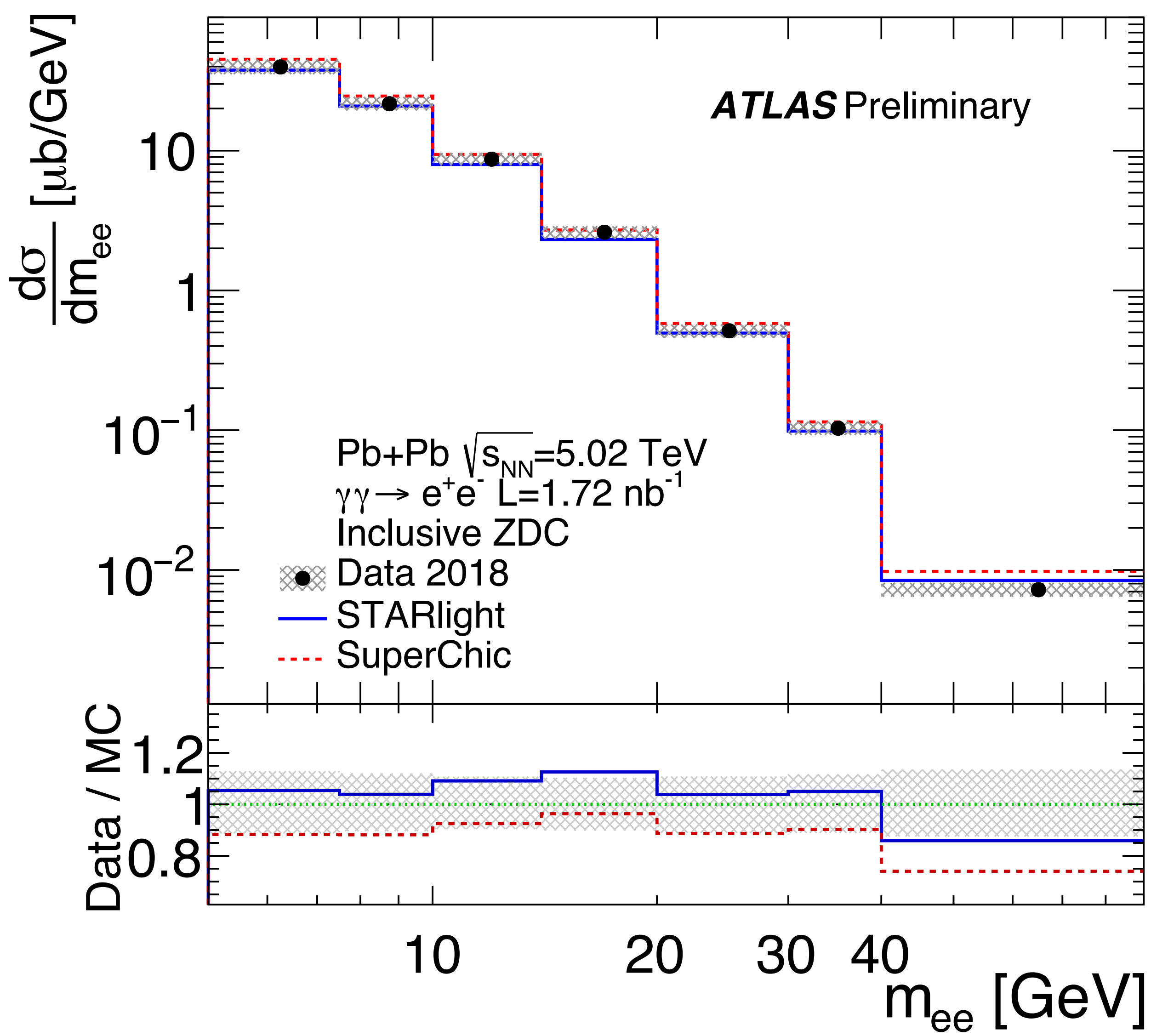
- For small masses the dominant systematics come from electron reconstruction and identification efficiency (about 10%), other systematics mostly below 5%
- For $|y_{ee}|$ dominant systematics come from electron reconstruction and identification efficiency (from 9% up to 15% in some bins), other systematics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

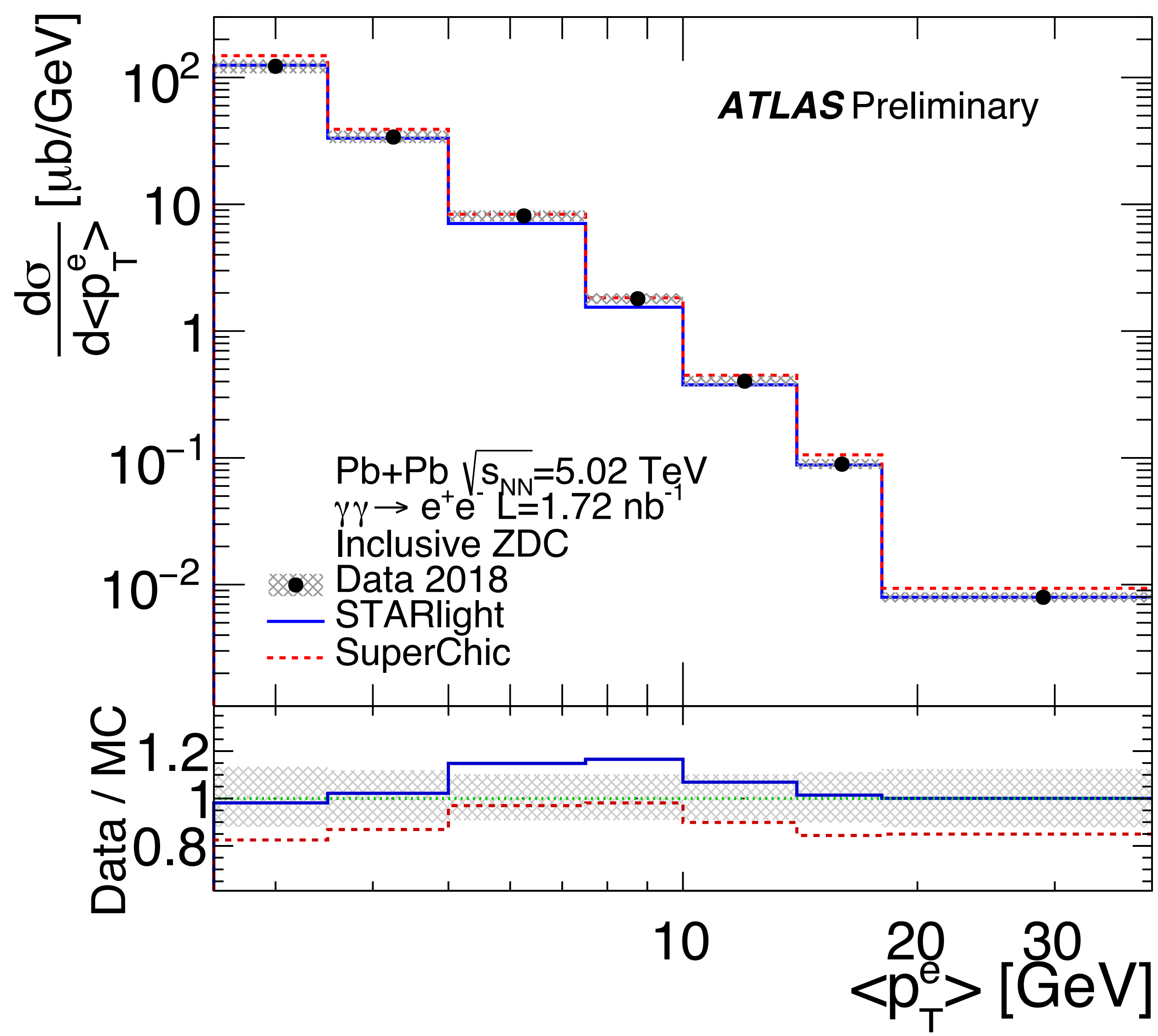




Dielectrons - results

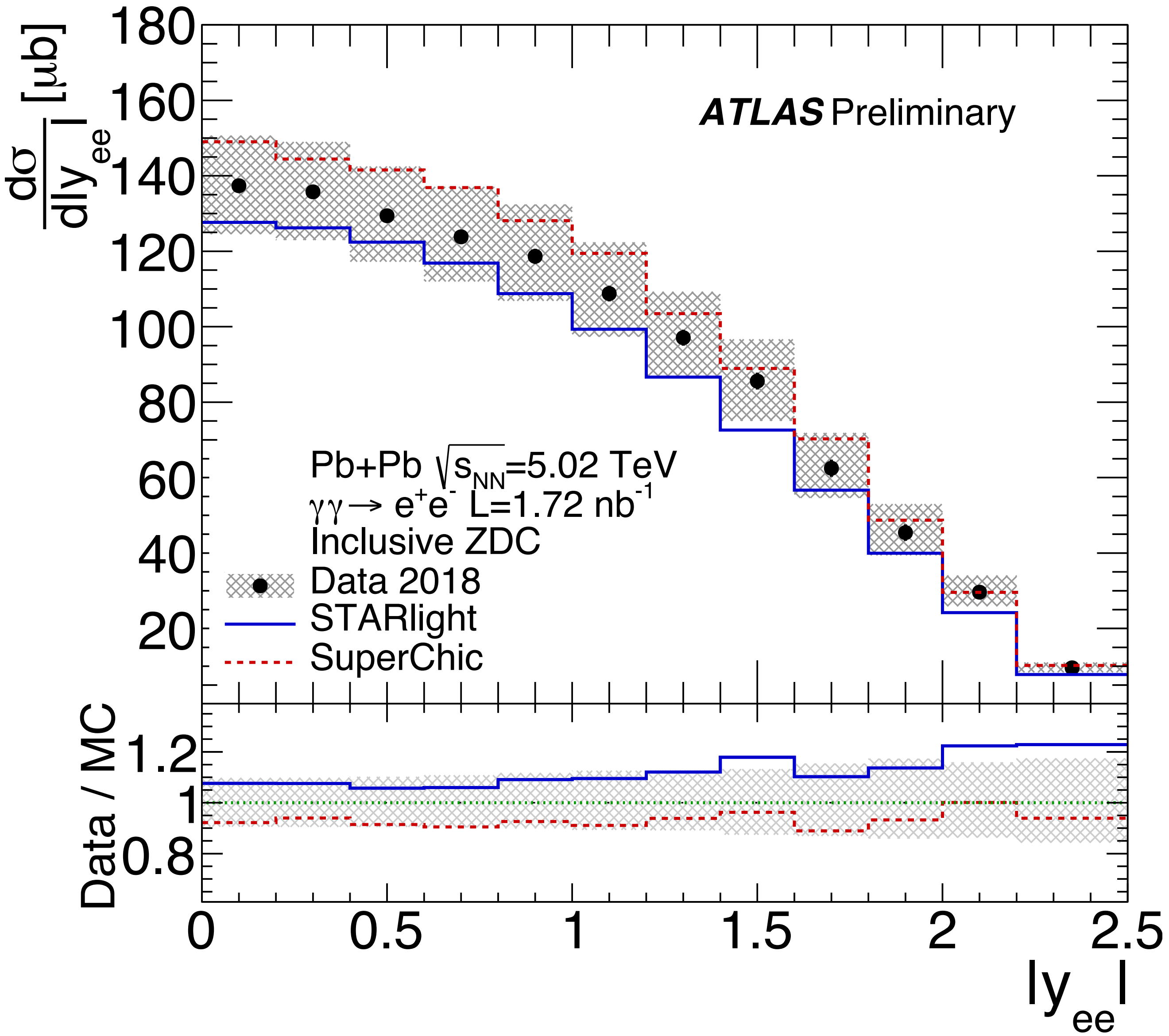
- Good agreement with STARlight and SuperChic is observed, differences in the same regions as in detector-level plots
- Results for mass compatible with dimuon measurement

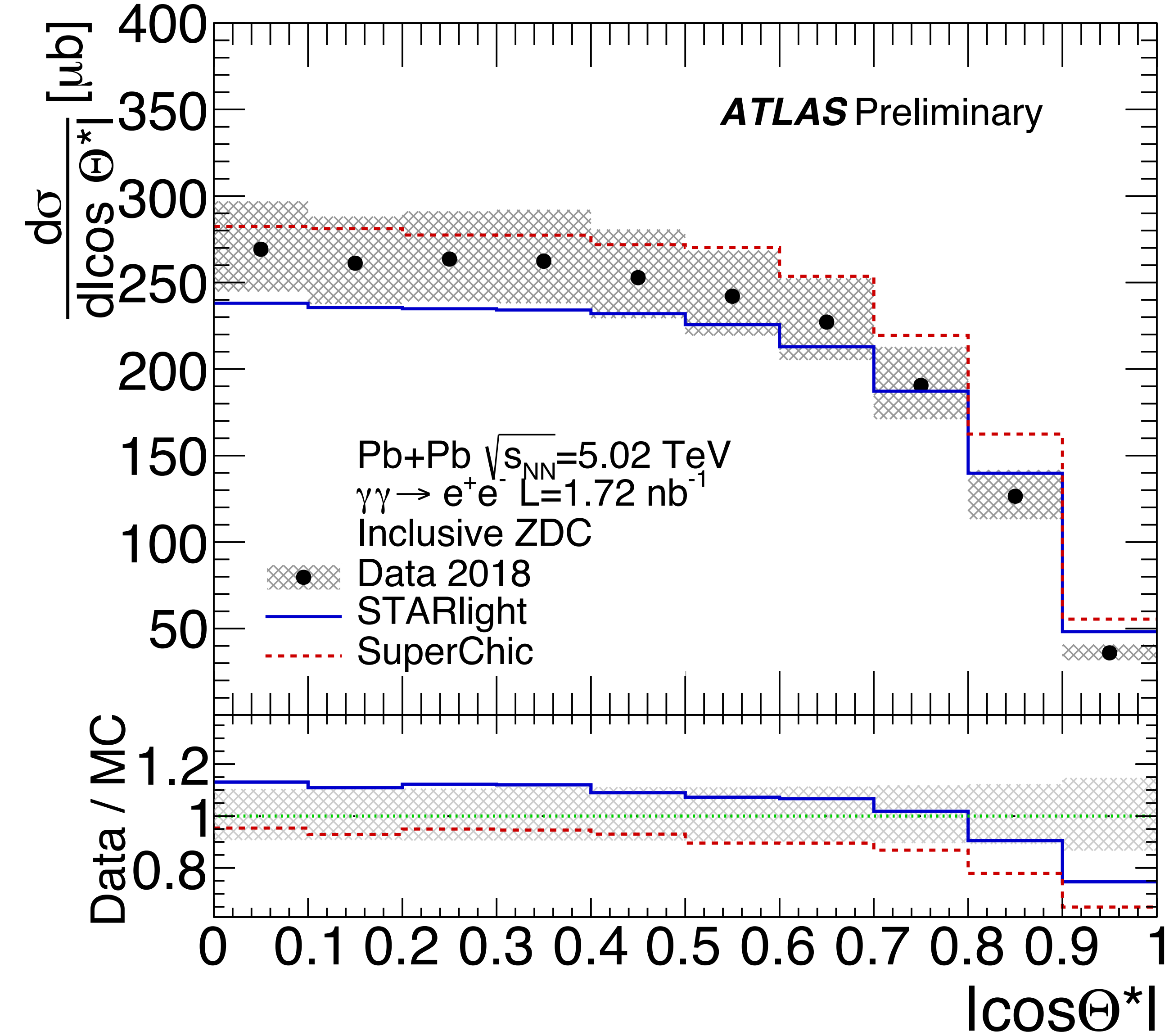




Dielectrons - results

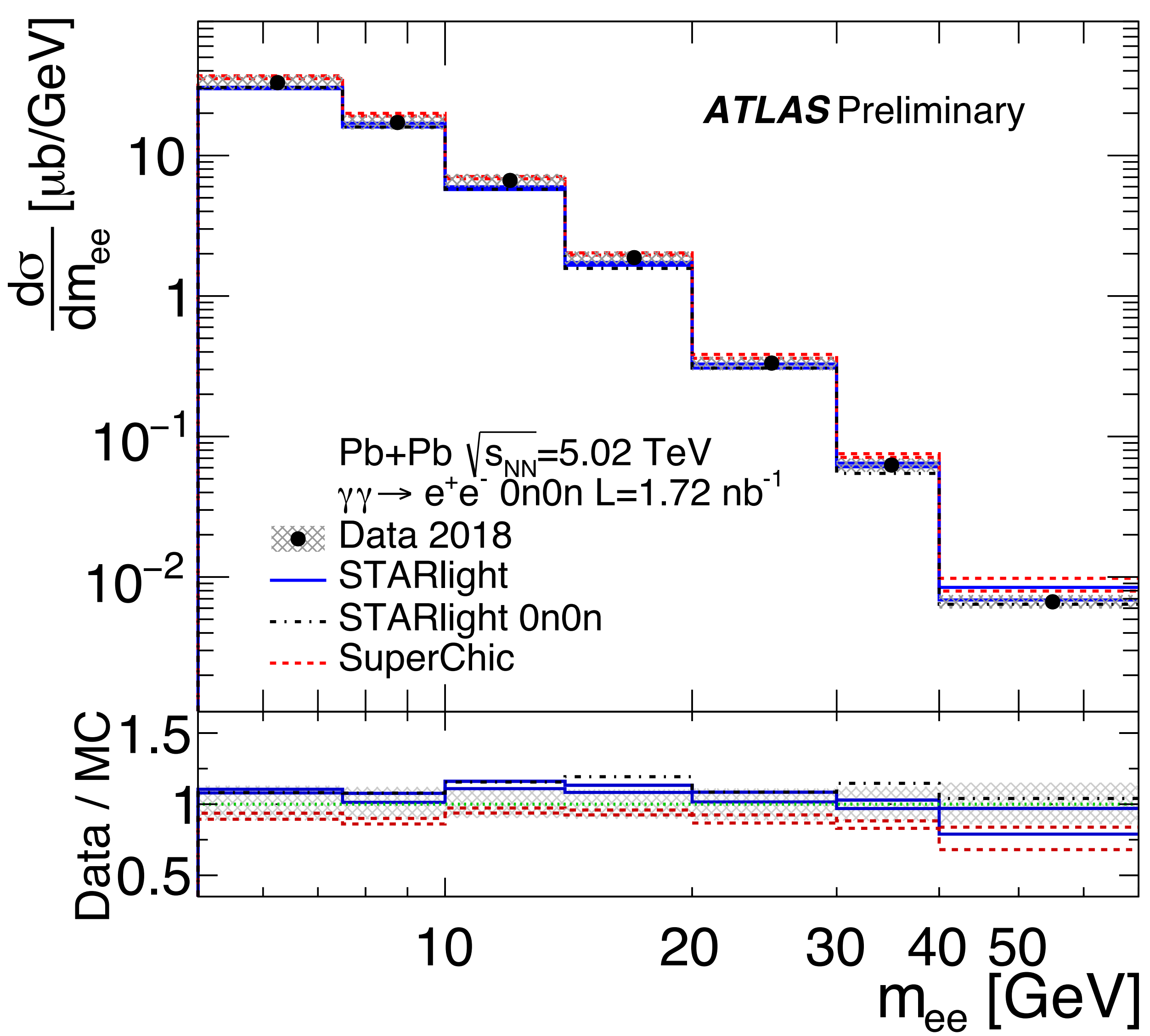
- Good agreement with STARlight is observed, differences in the same regions as in detector-level plots
- Agreement with SuperChic is better than with STARlight in $|y_{ee}|$

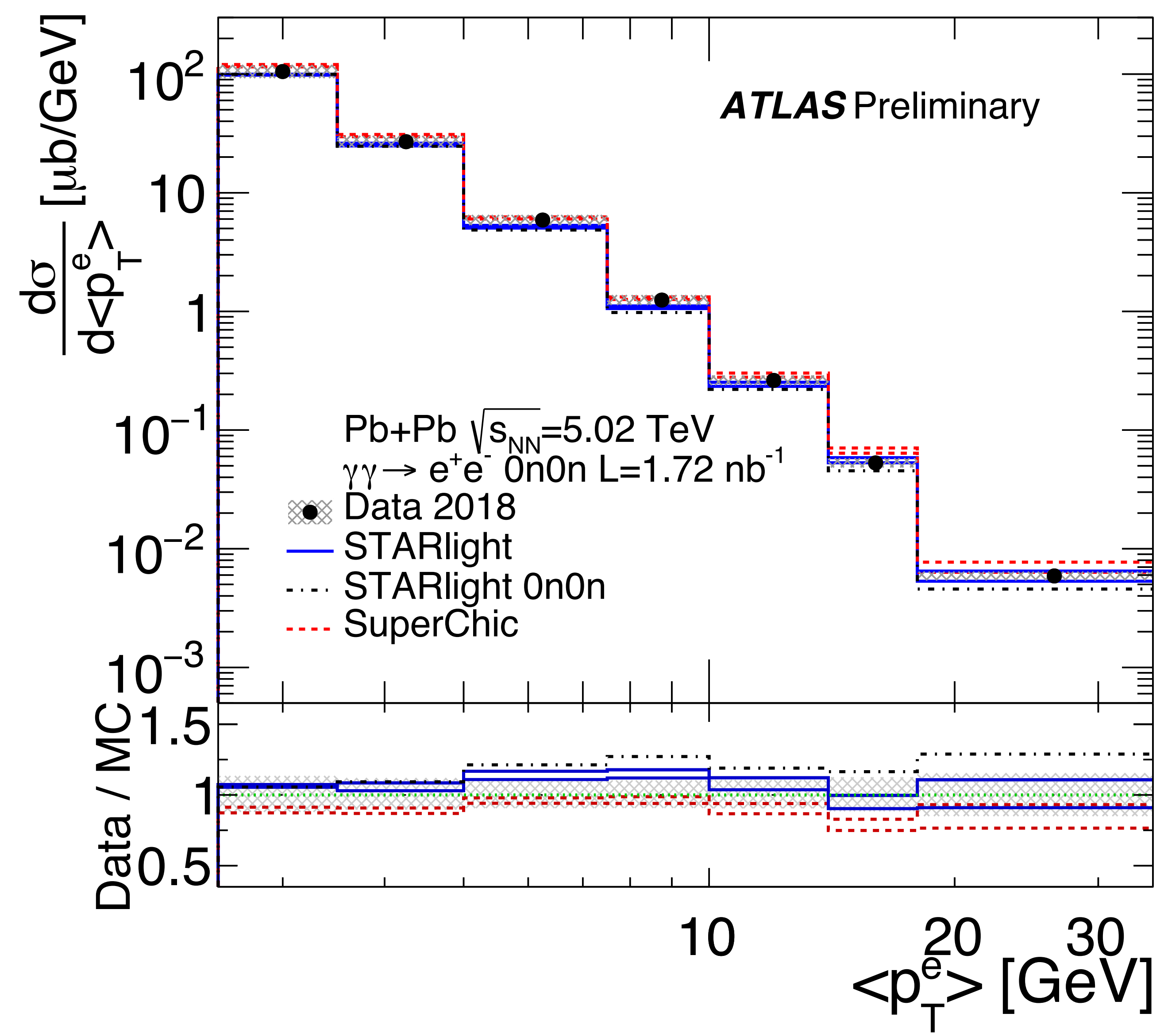




Dielectrons - results 0n0n

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





Dielectrons - results 0n0n

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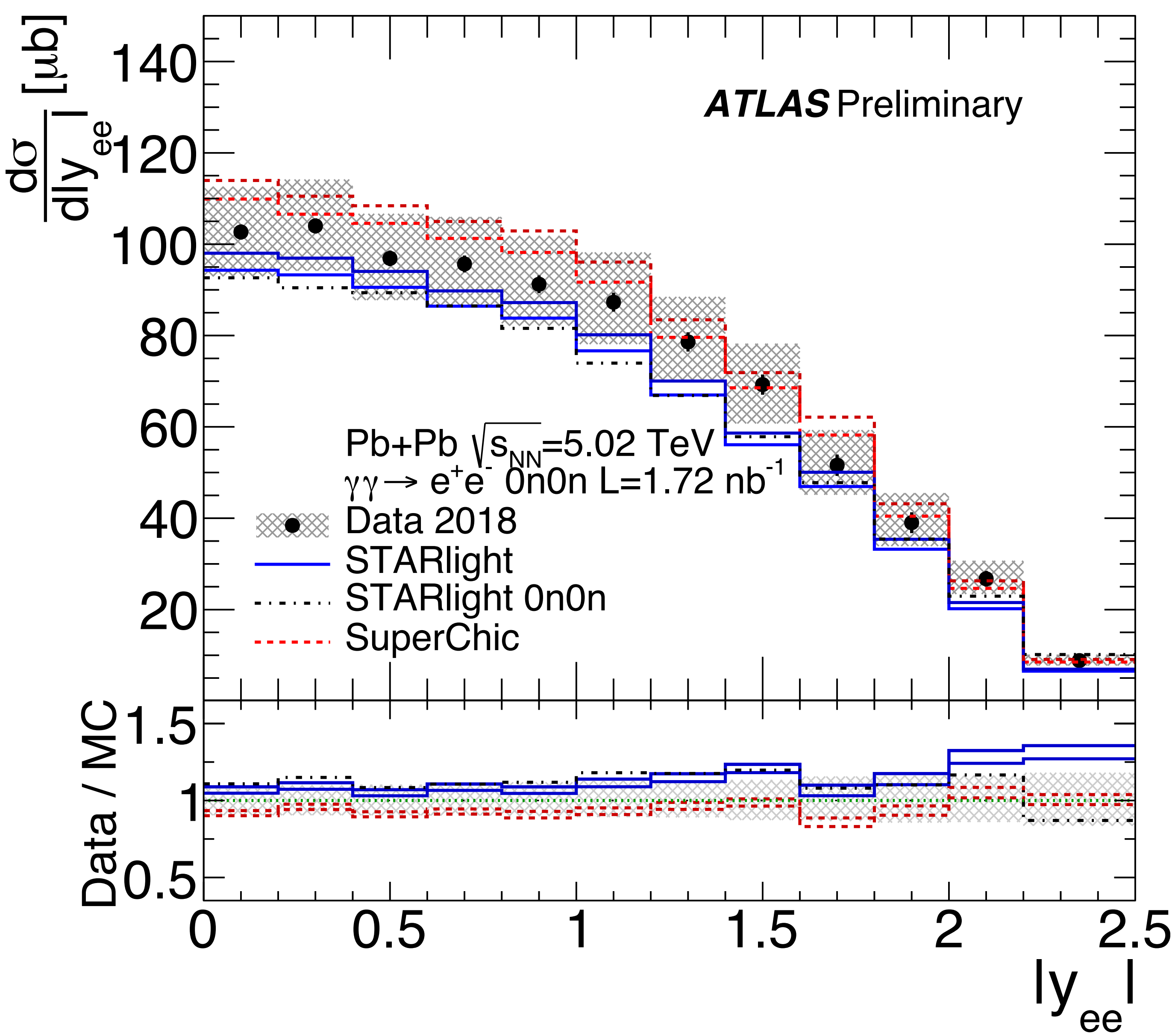
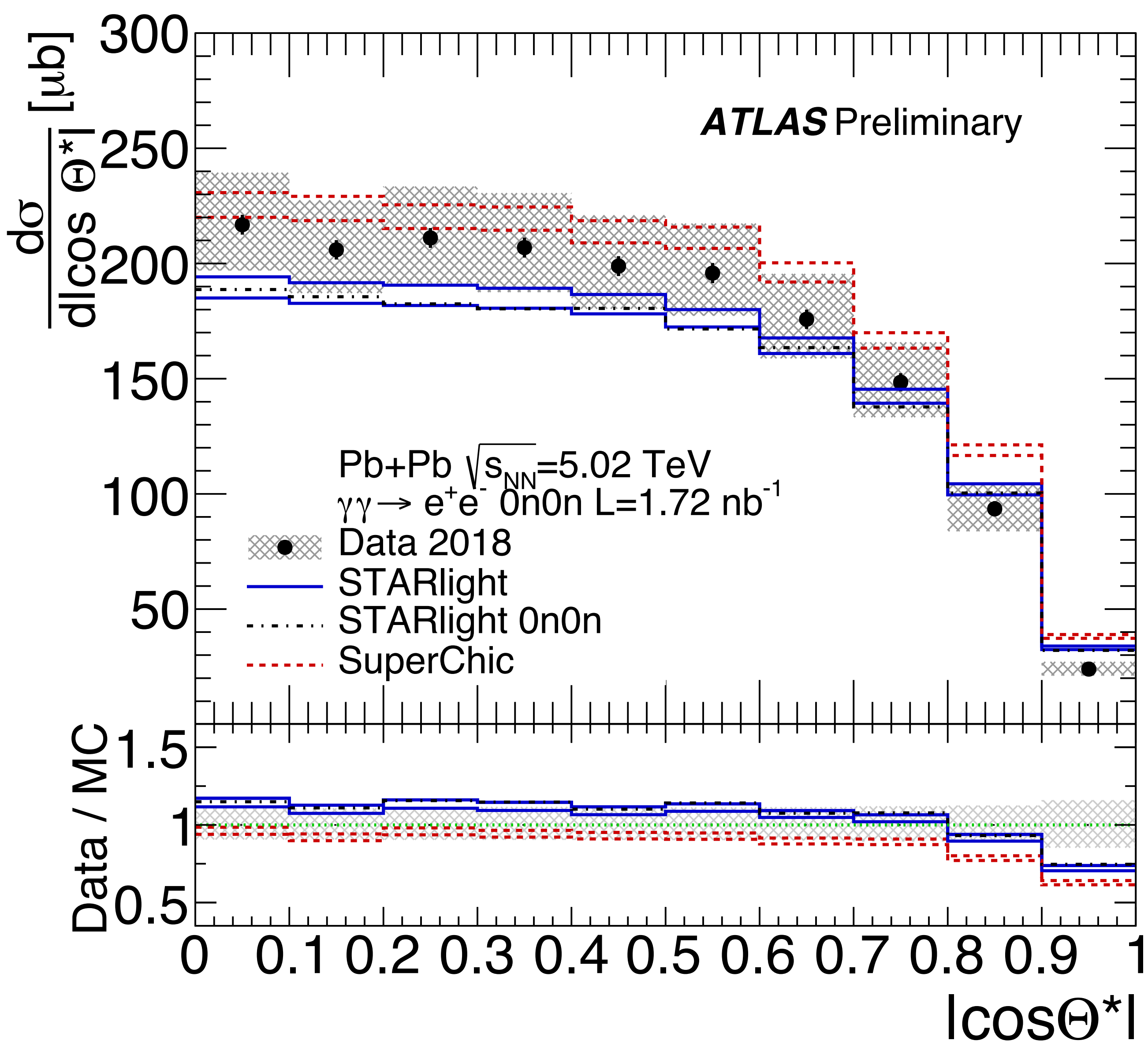
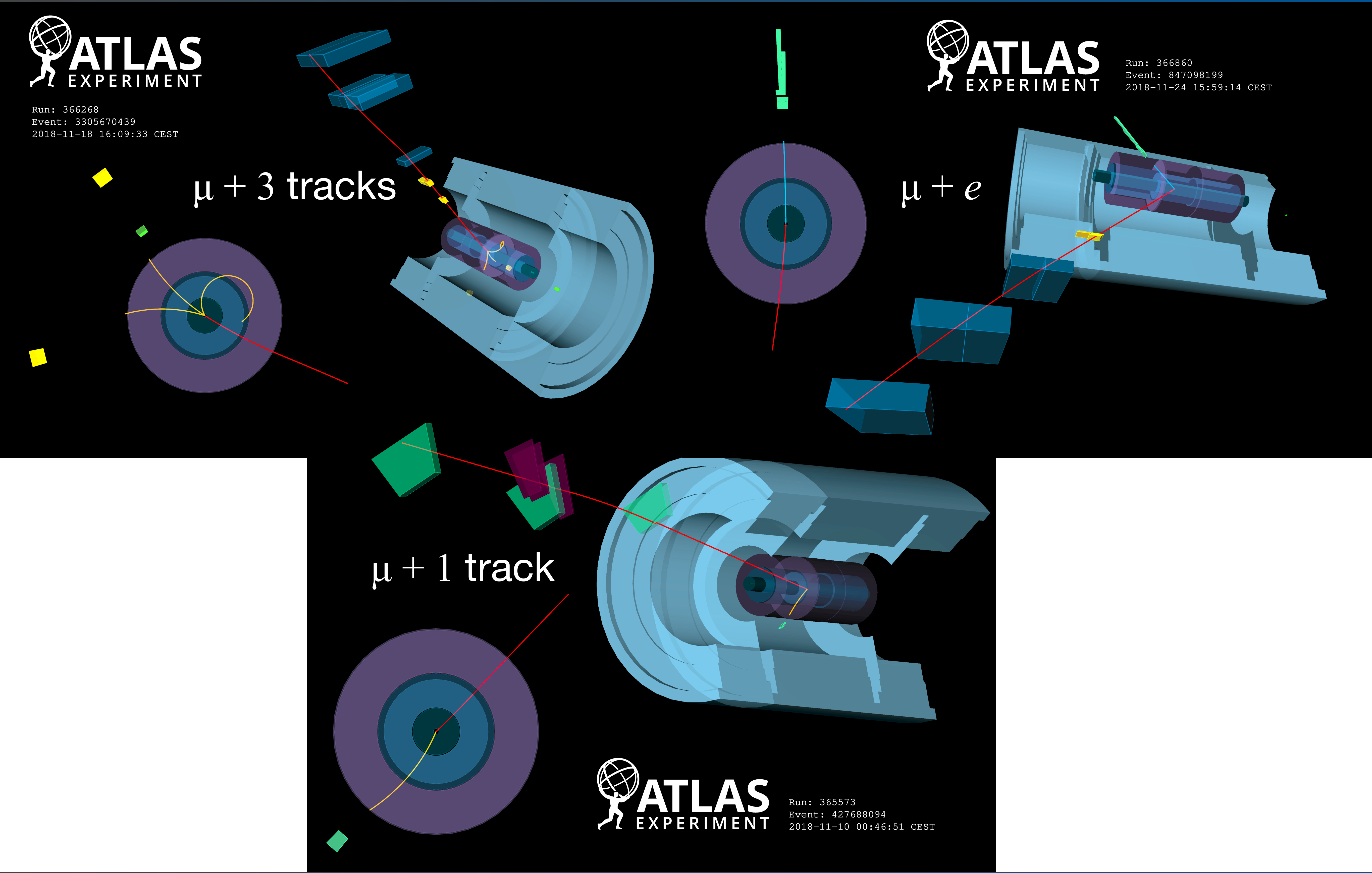




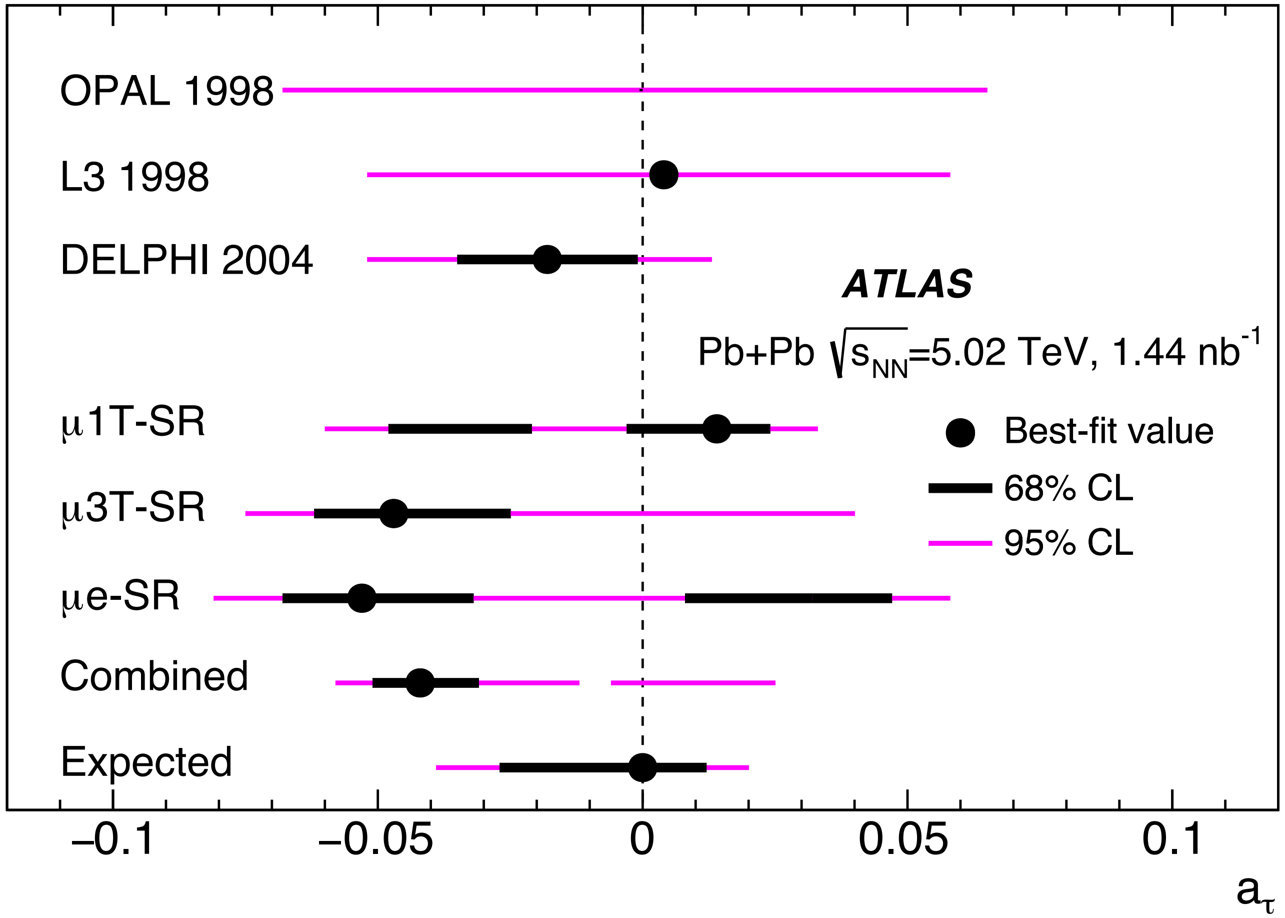
Ditaus

Ditau events



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

- Based on 2018 Pb+Pb data the exclusive ditau production was observed by ATLAS experiment
- Events classified based on the charged τ-lepton decay products
- Events triggered by muon triggers
- Using only 0n0n configuration, based on ZDC
- Dimuon **control region** ($\gamma\gamma \rightarrow \mu\mu$ events) used to **reduce systematic uncertainty** from the photon flux
- The value of τ-lepton anomalous magnetic moment, a_τ is extracted using a **profile likelihood fit** using the muon p_T distribution
- The **best fit value** is $a_\tau = -0.042$, with the corresponding **95% CL interval** being $(-0.058, -0.012) \cup (-0.006, 0.025)$
- 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

- **Dimuon production** was analysed in fiducial region defined by:
  $p_T^{\mu} > 4$ GeV, $|\eta_{\mu}| < 2.4$, $m_{\mu\mu} > 10$ GeV and $p_T^{\mu\mu} < 2.5$ GeV

- **Dielectron production** was analysed in fiducial region defined by:
  $p_T^{e} > 2.5$ GeV, $|\eta_{e}| < 2.5$, $m_{ee} > 5$ GeV and $p_T^{ee} < 2.5$ GeV

- Despite slightly different definitions of the fiducial region, the **conclusions** from dimuon and dielectron measurements are **consistent**

- **Importance** of the **FSR contribution** which is missing in STARlight and SuperChic

- Thanks to the ZDC, **activity in the forward region** could be measured

  - This should provide constraints for **impact-parameter dependence** of dilepton production

- Results provide valuable constrains for **theoretical approaches** in the modeling of the **initial photon flux**