Recent ATLAS results on exclusive dielectron and dimuon production in Pb+Pb UPC collisions

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for the ATLAS experiment

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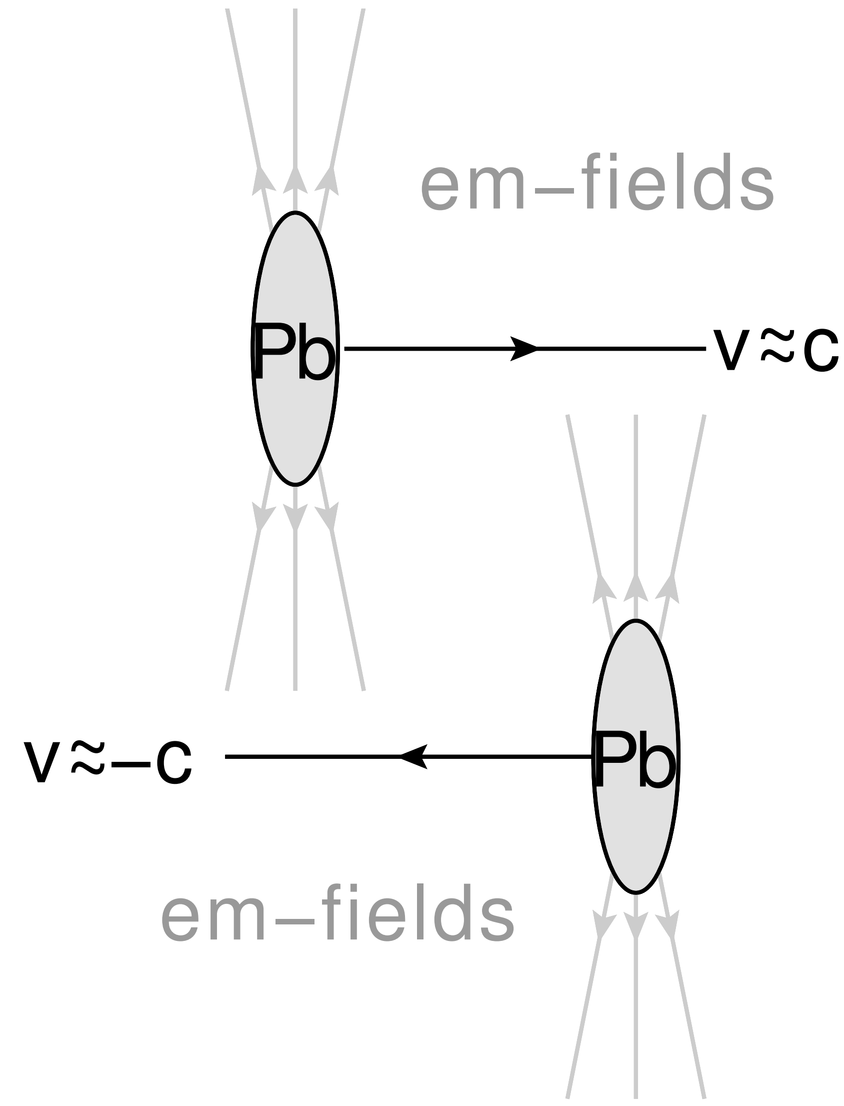
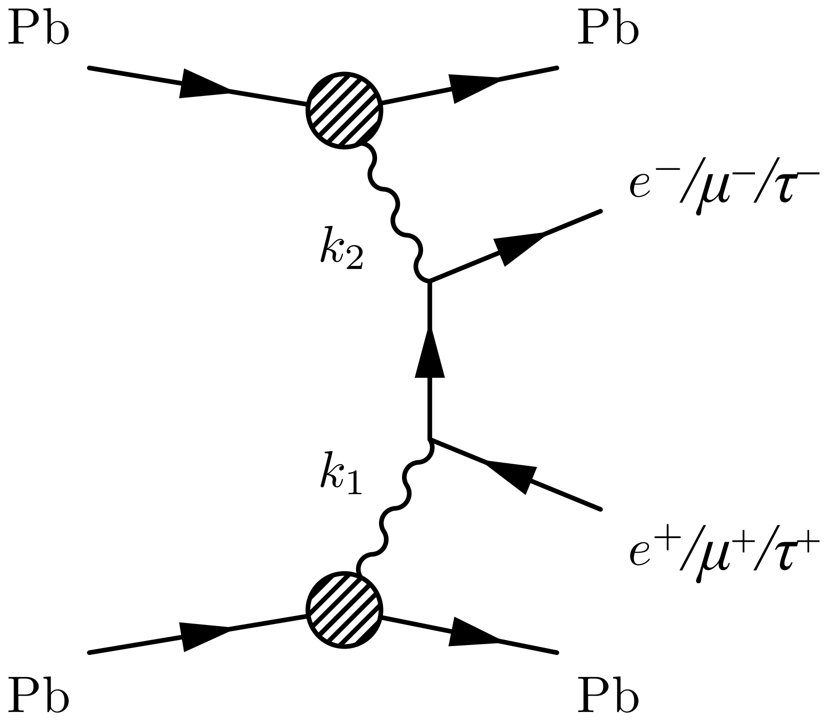
Ultra-peripheral collisions

- 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
- **See Jakub Kremer's talk for overview of ATLAS results**



Motivation

- **Exclusive dilepton production** is one of the fundamental processes in photon-photon interactions
- It is a **benchmark process** for other photon-induced processes
  - Possible reduction of systematic uncertainties
    see Lydia Beresford's talk on τ-lepton *g*-2
  - Important background (e.g. dielectrons in light-by-light)
  - Performance studies with a tag-and-probe technique
- 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



Models - two different implementations

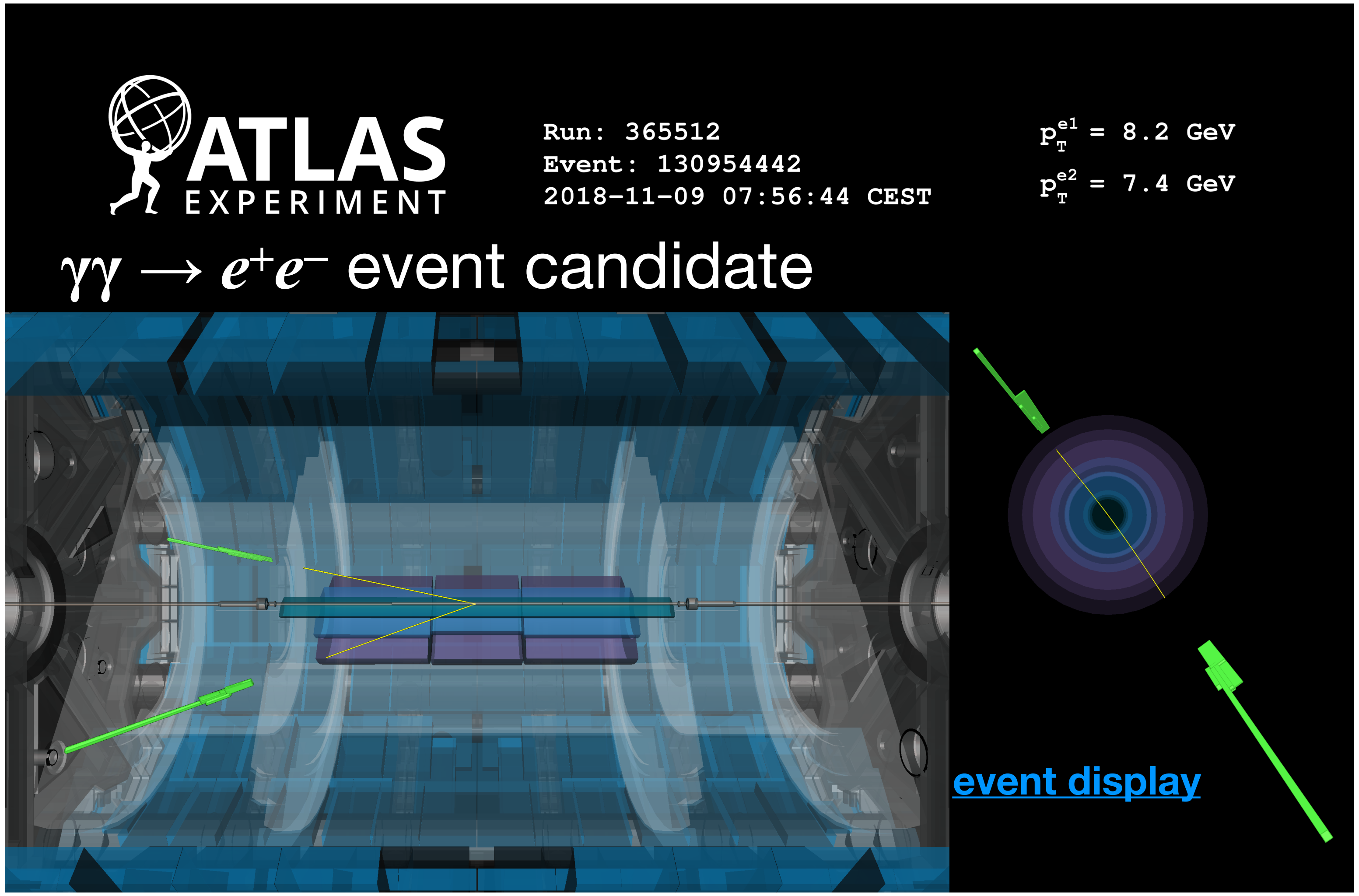
- Two generators commonly used to simulate exclusive dilepton production: **STARlight** and **SuperChic**
- Both based on EPA approach, but with **some differences** in cross-sections calculation
- None of them simulates a FSR contribution

STARlight Comput.Phys.Commun. 212 (2017) 258-268	**SuperChic** Eur.Phys.J.C 80 (2020) 10, 925
Photon flux calculated in impact parameter space for $b_{1,2} > R$	Photon flux calculation without restriction on $b_{1,2}$
Production forbidden at $b_{1,2} < R$	Production allowed at $b_{1,2} < R$
Includes process-independent survival factor and probability of forward neutron topology	Includes process-dependent survival factor and polarization effects at amplitude level, but not forward neutrons

See also Lucian's talk on MC generators for UPC

Event characteristics & selection

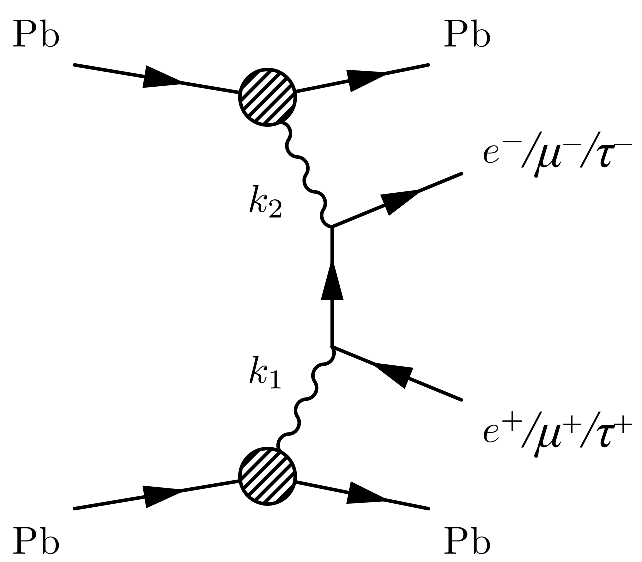
- Exclusive dilepton events are characterized by :
  - **Two low-p_T opposite sign leptons** (of the order of a few GeV) and otherwise empty detector
  - Leptons are produced **back-to-back** in azimuthal angle (described by low dilepton transverse momentum, $p_{T,ll}$)
- ATLAS optimized to detect high-energy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



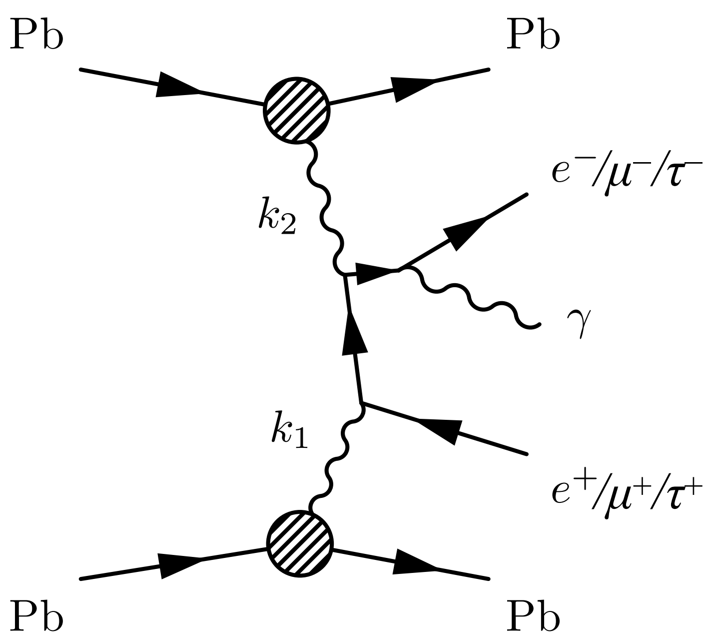
	muons	electrons
Int. Lumi [nb^{-1}]	0.48	1.72
p_T^{ℓ} >	4 GeV	2.5 GeV
$\lvert\eta_{\ell}\rvert$ <	2.4	2.5
$m_{\ell\ell}$ >	10 GeV	5 GeV
$p_T^{\ell\ell}$ <	2 GeV	2 GeV

Background sources for $\mu\mu/ee$

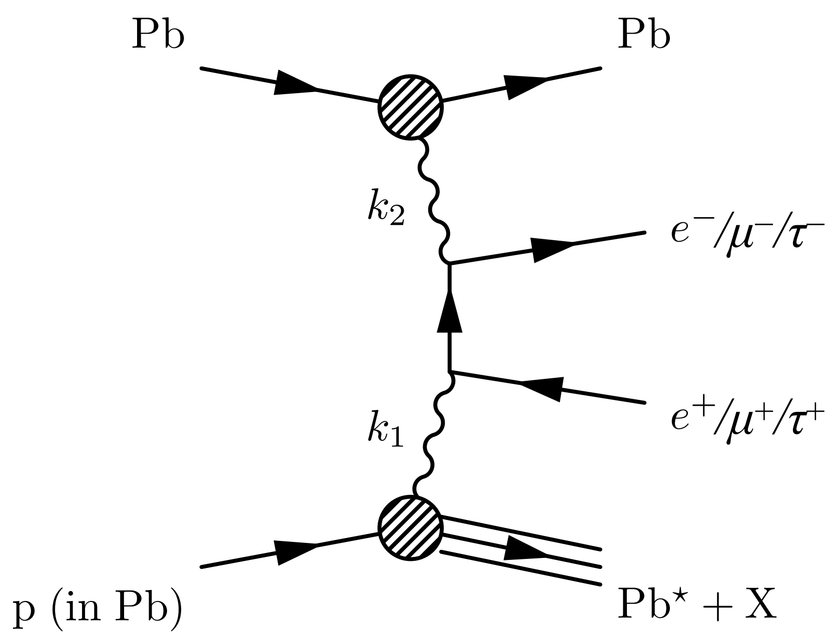
- Several background sources are considered:
  - **dissociative** production of $\ell^+\ell^-$ pairs - estimated with data-driven method (template taken from LPair/SuperChic4+Pythia8 in *pp* collisions)
  - **Upsilon(nS)** production - estimated with STARlight+Pythia8 MC samples (only in dielectron measurement)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



Signal (LO)



Signal with FSR



dissociative background

Signal categories - ZDC selection

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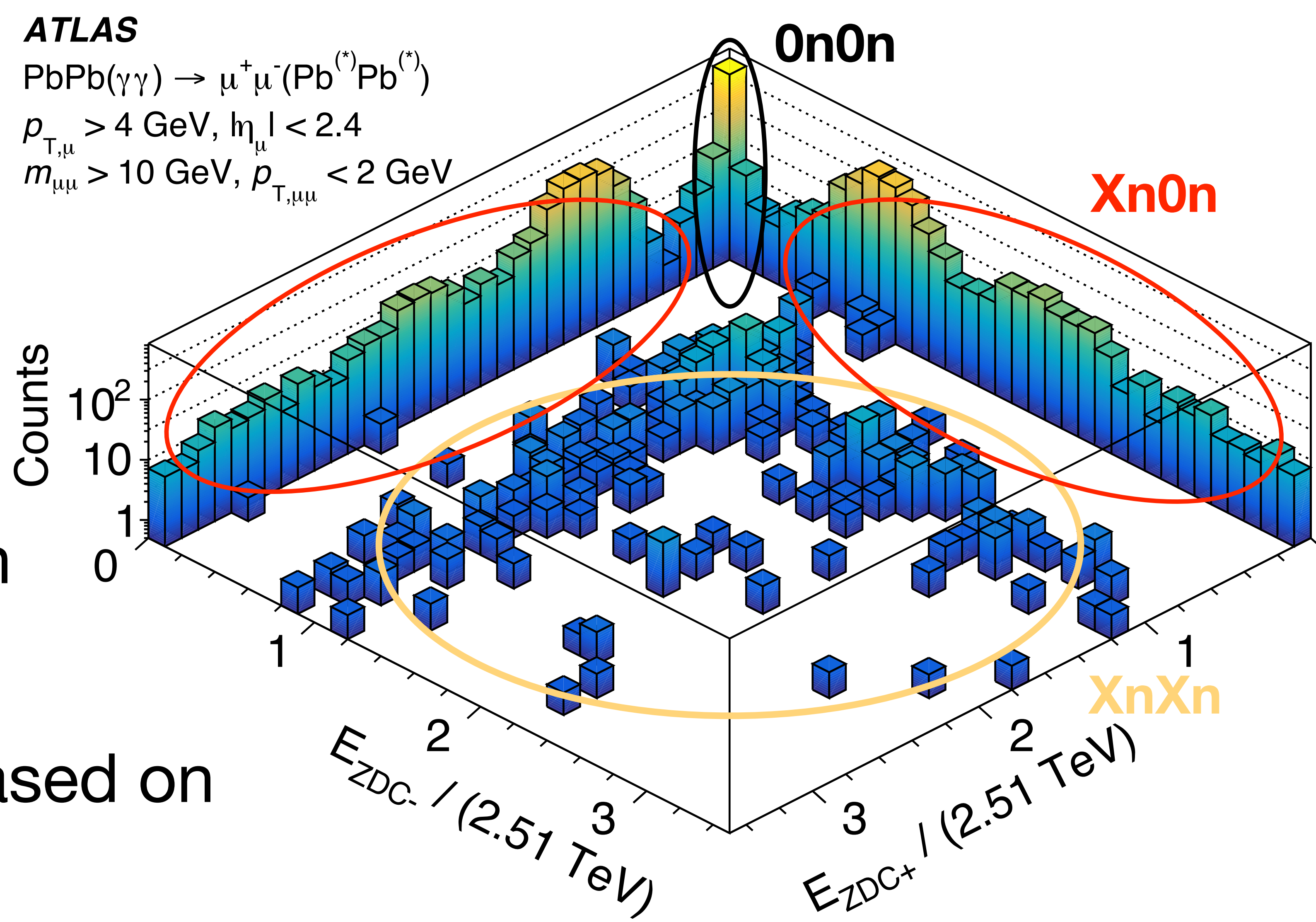
- Different processes present **different activity in the forward region**:
  - Exclusive dilepton production - ions stay intact
  - Background events with nuclear breakup

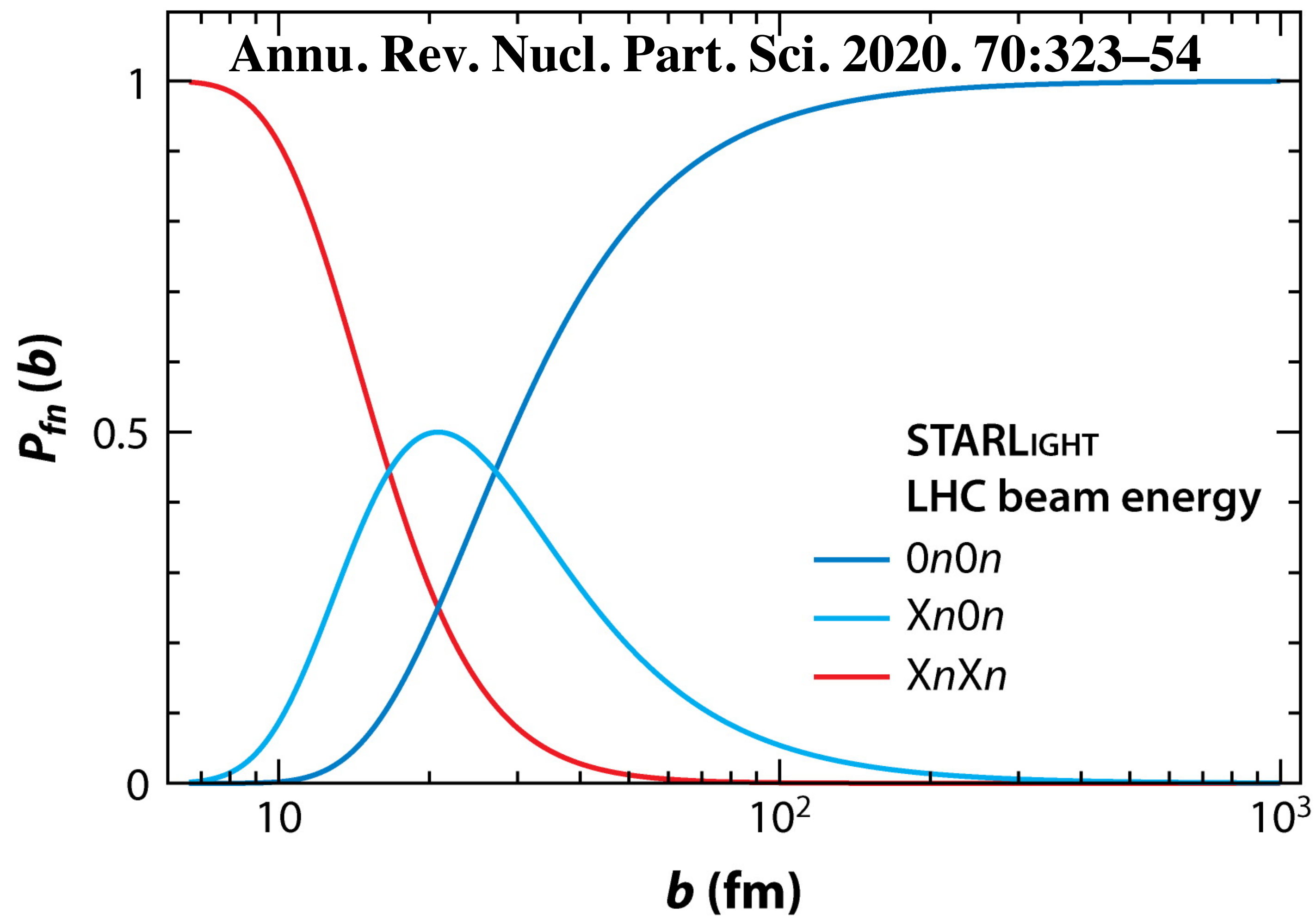


- **Three classes** defined, based on the signal in the ZDC
- The **association between** given **ZDC signal** and given **process** is **nontrivial**
  - Migrations due to ion excitation and presence of EM pile-up

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 ~ $1/b^2$)

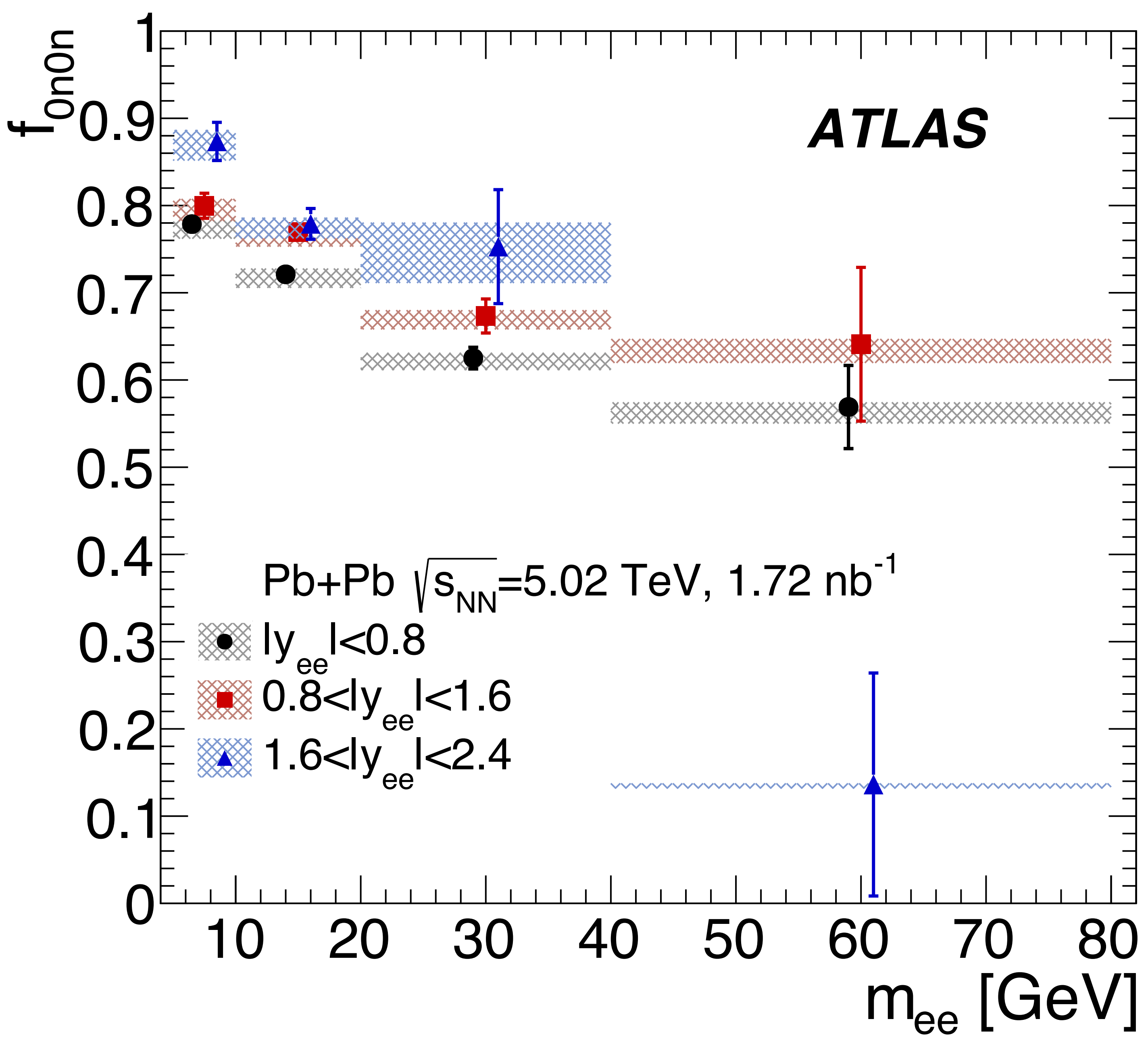
- With different selections on the ZDC topology, we probe different ranges of dilepton mass and impact parameters, as photon fluxes vary with *b*



f0n0n fractions - dielectrons

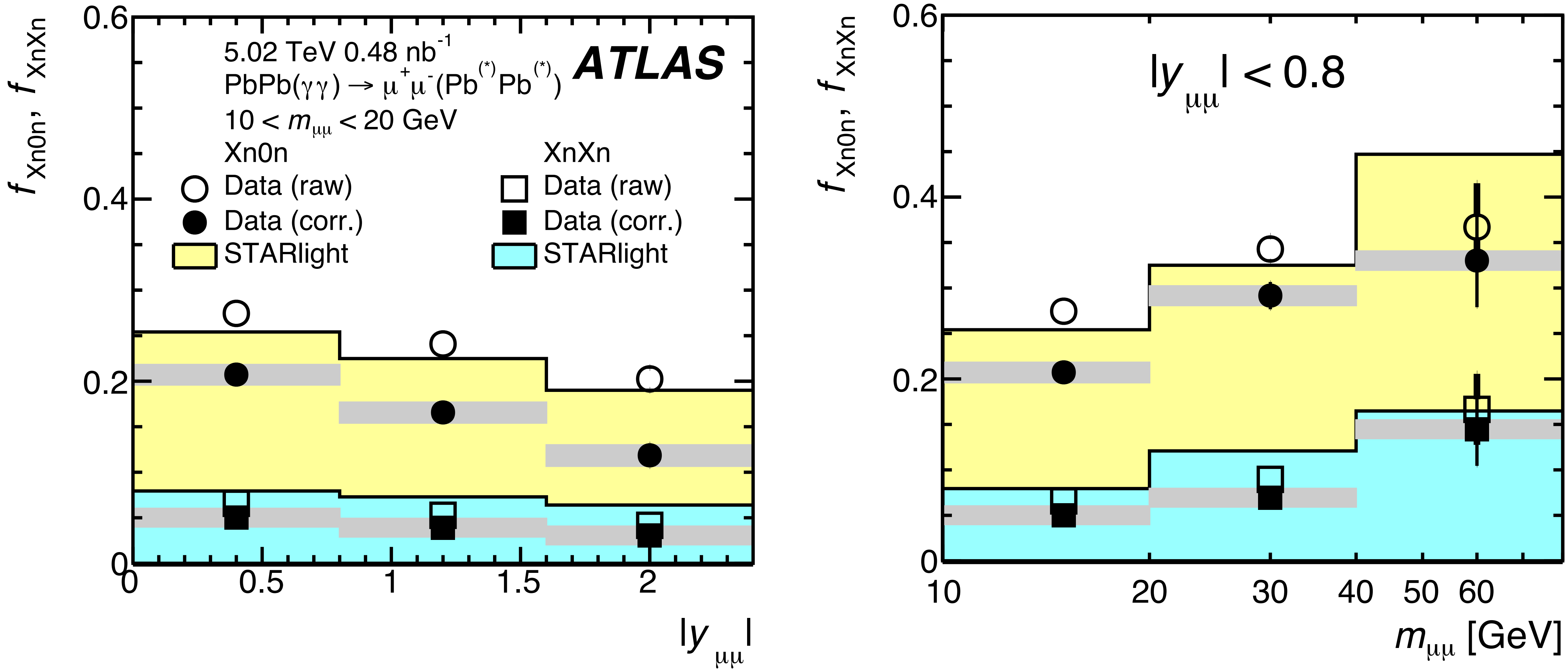
- The **0n0n category** should in principle be very **pure**, at least in terms of dissociative background
- To select 0n0n sample, events are required to have **low energy** deposits in the **ZDC** (below 1 TeV on each side)
- There is no ZDC simulation in the MC samples, so a dedicated approach, correcting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

arXiv:2207.12781



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



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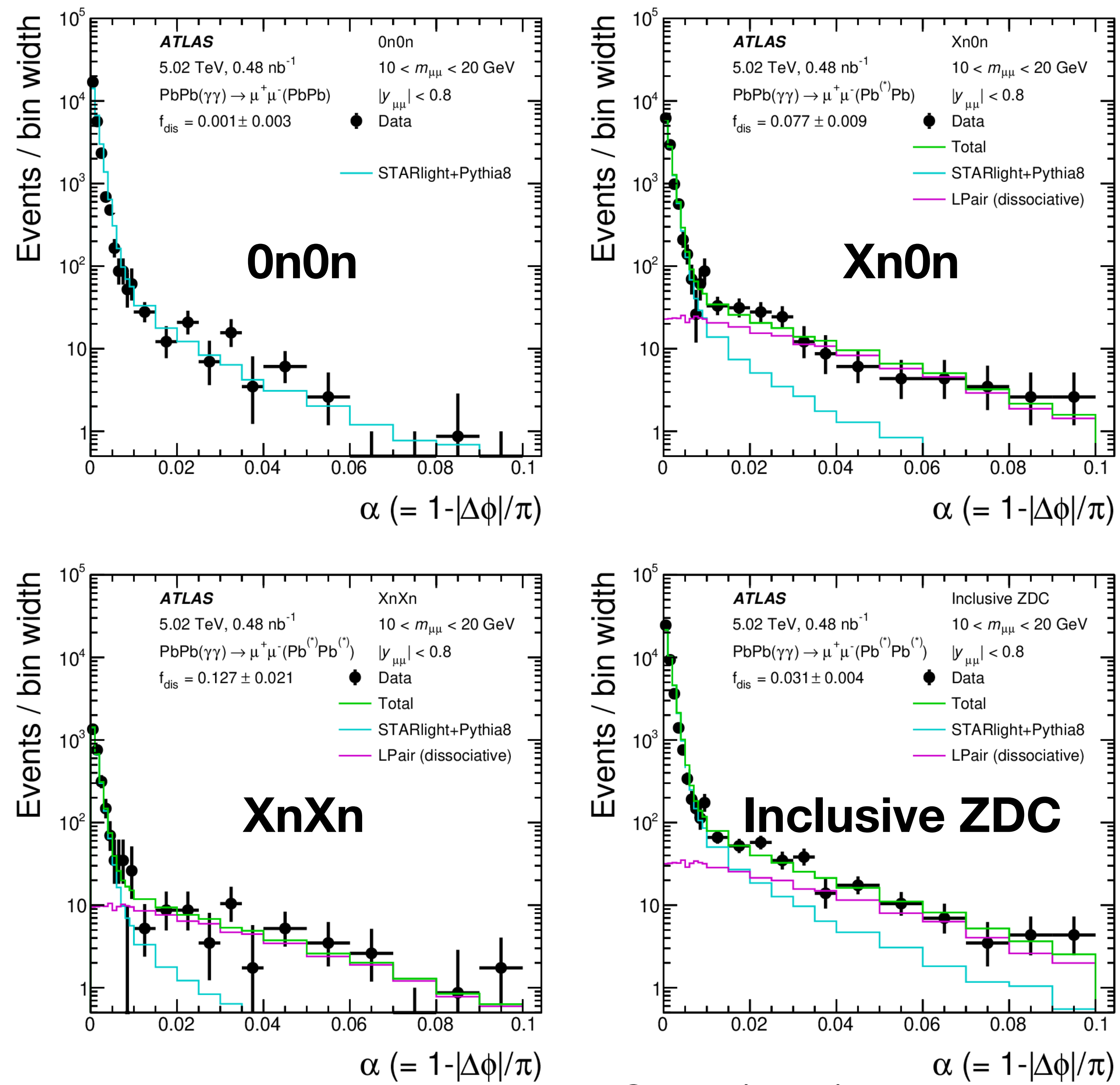
Dimuons

Dimuons - background

- 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

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



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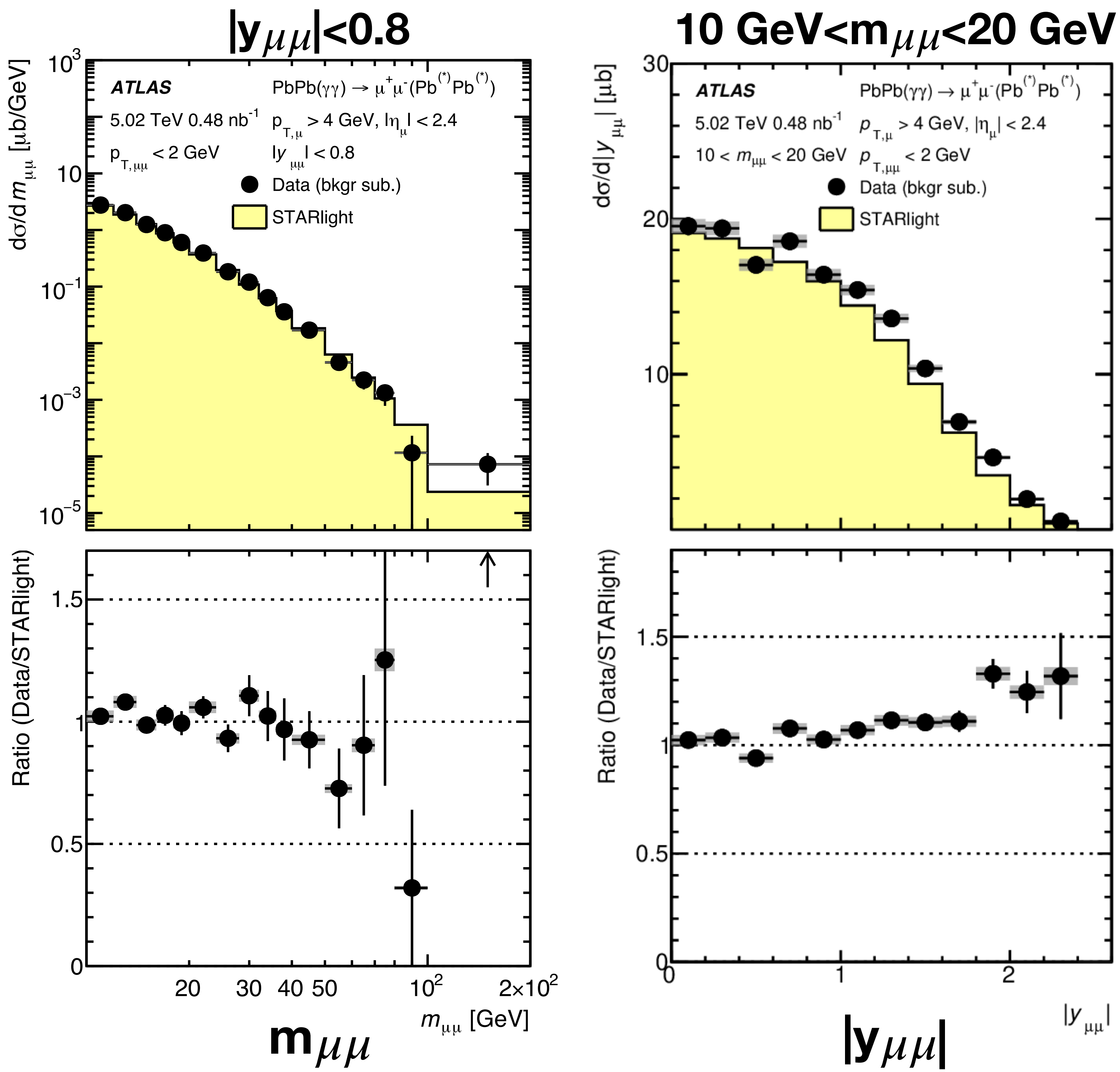
Dimuons - results

- 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 $\gamma\gamma \rightarrow \mu^+\mu^-$ 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 $|y_{\mu\mu}|$



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What can we learn about initial photon fluxes?

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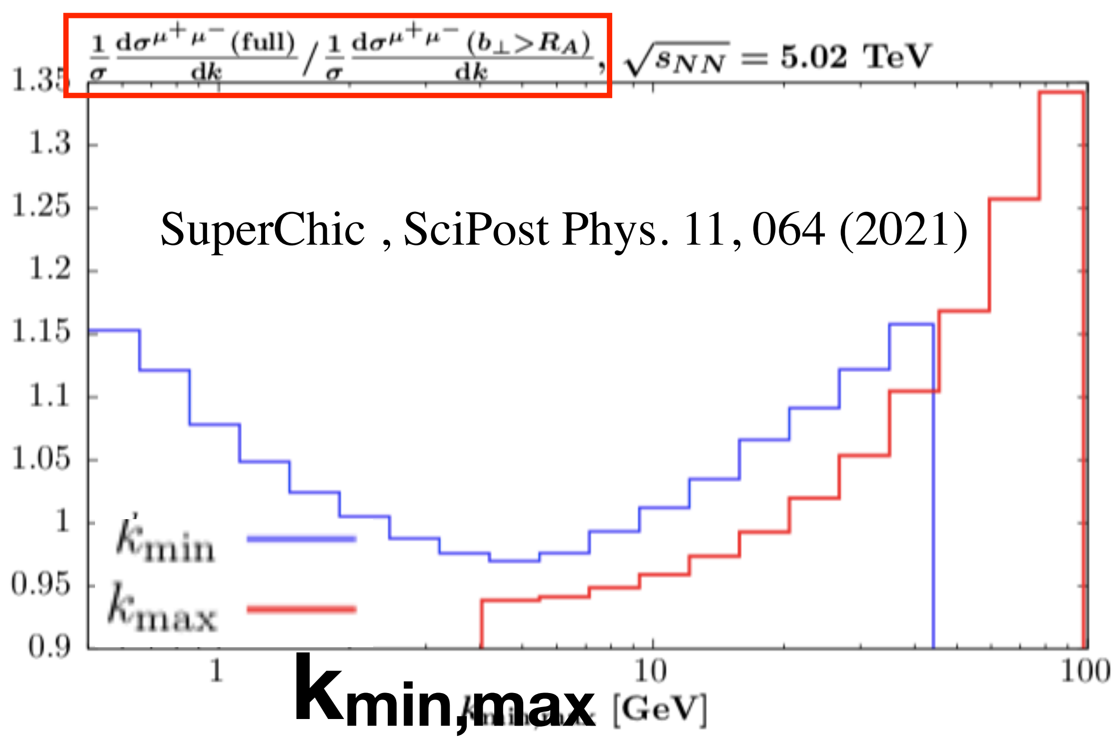
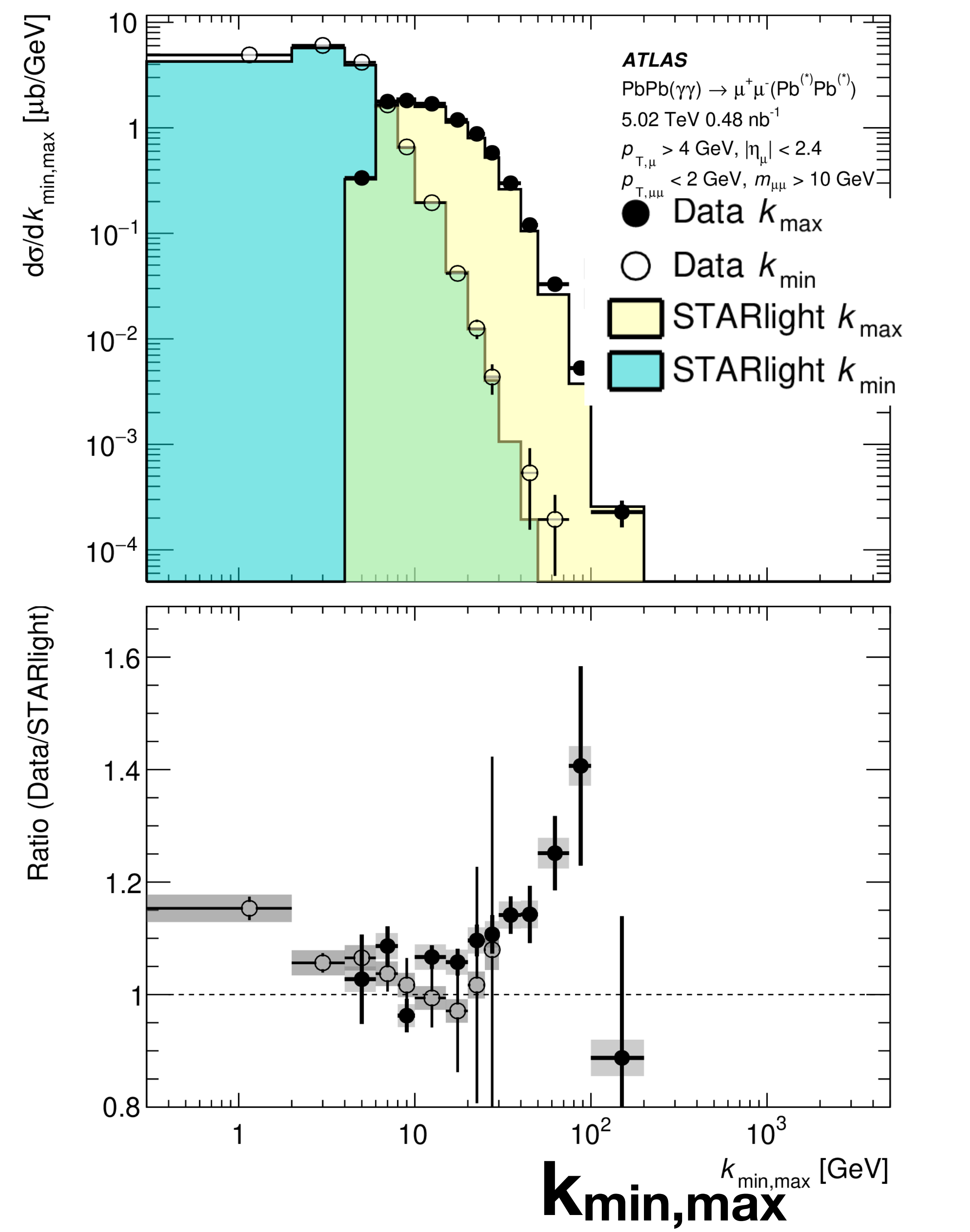
- The muon kinematics can be used to estimate **initial photon energies**

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

- The **cross section** is presented as a function of maximum and minimum photon energies
- The STARlight predictions are correct in intermediate region 5-20 GeV
- Disagreement between the data and MC for lower $k_{\min}$ and higher $k_{\max}$ likely due to restriction of production to b > R



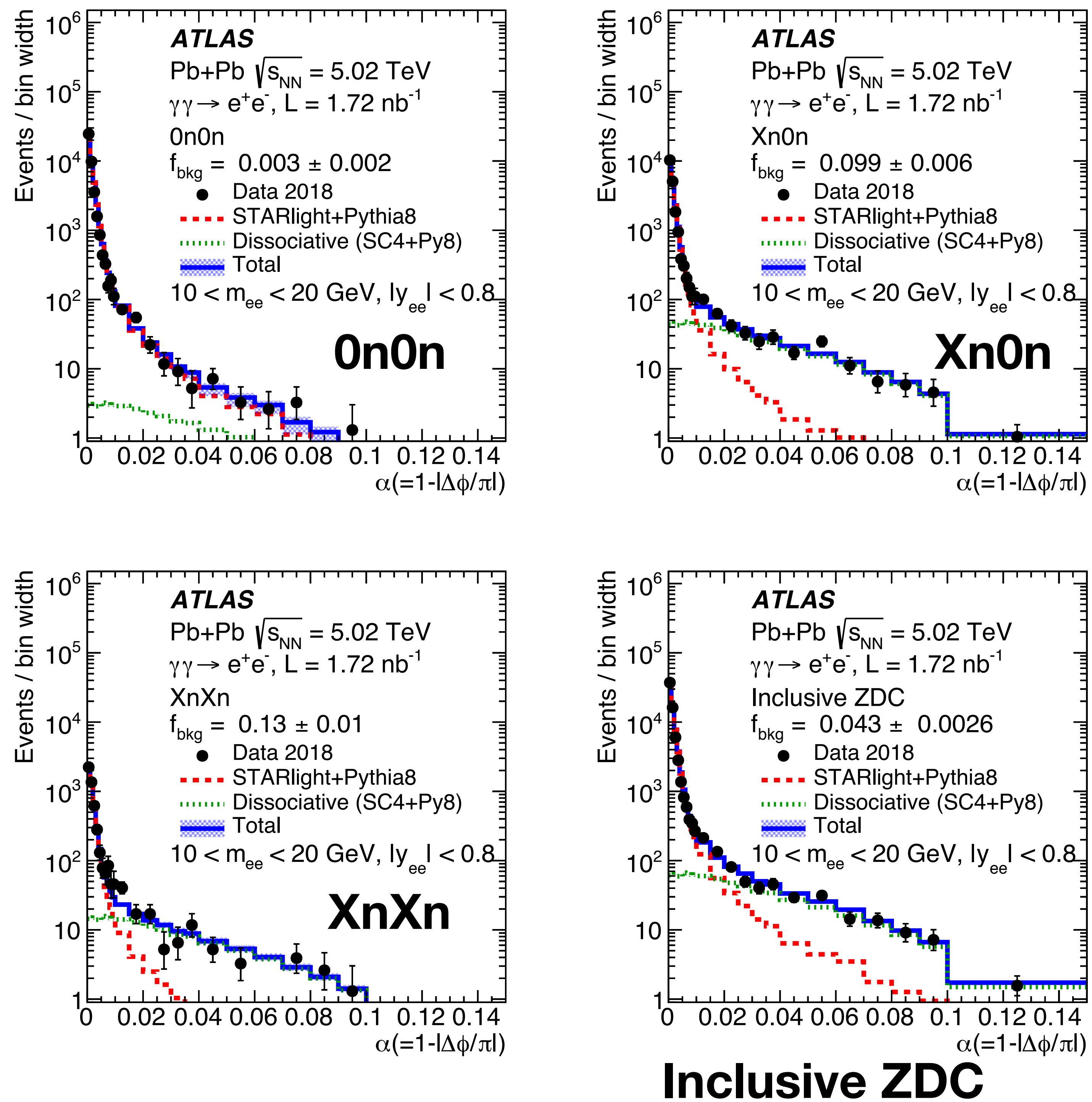


Dielectrons

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
- Fitting procedure similar to the one used in dimuon measurement
- Small background contributions from **Upsilon(nS)** and **ditau** production also estimated



arXiv:2207.12781

Detector-level control plots

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

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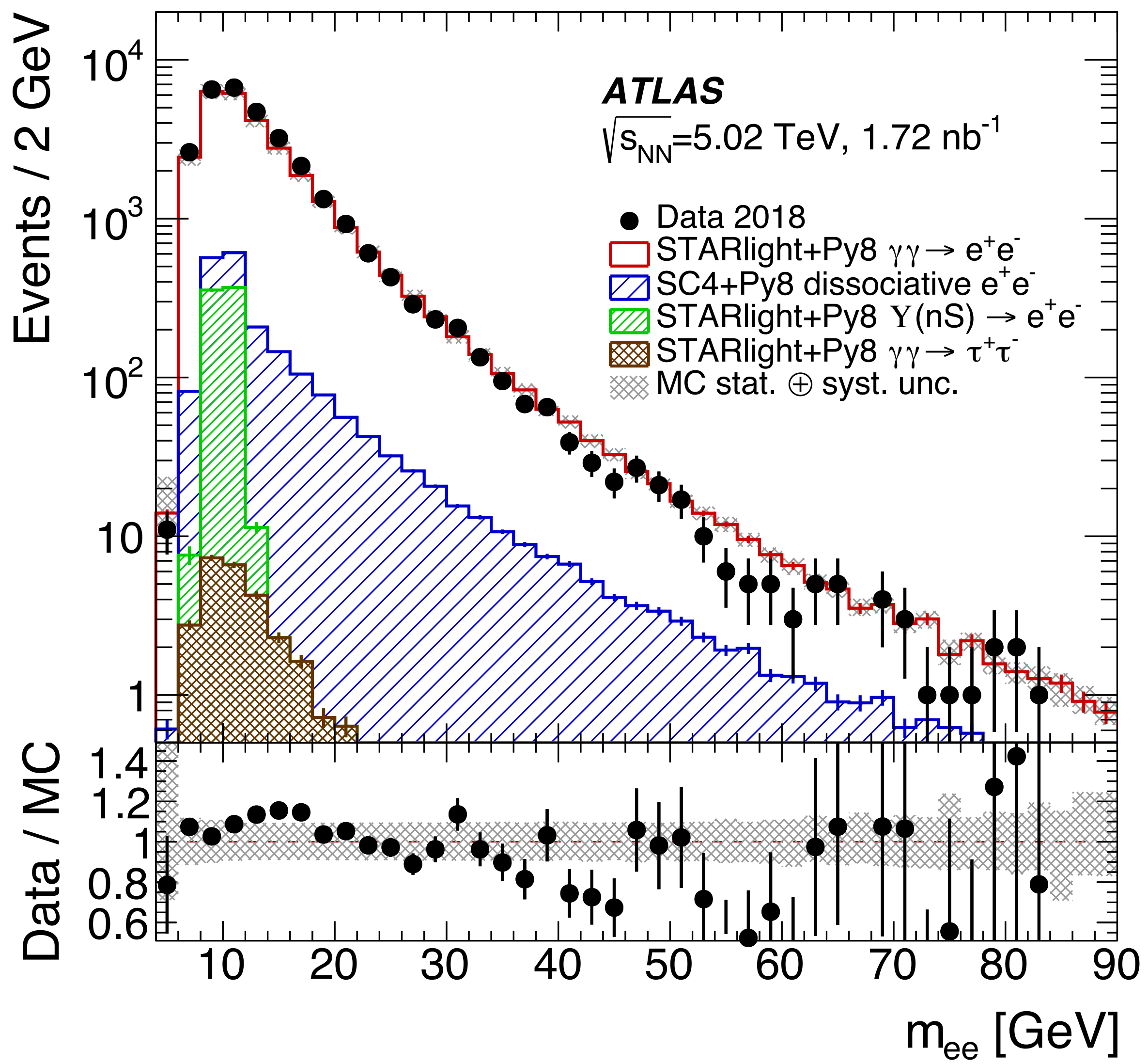
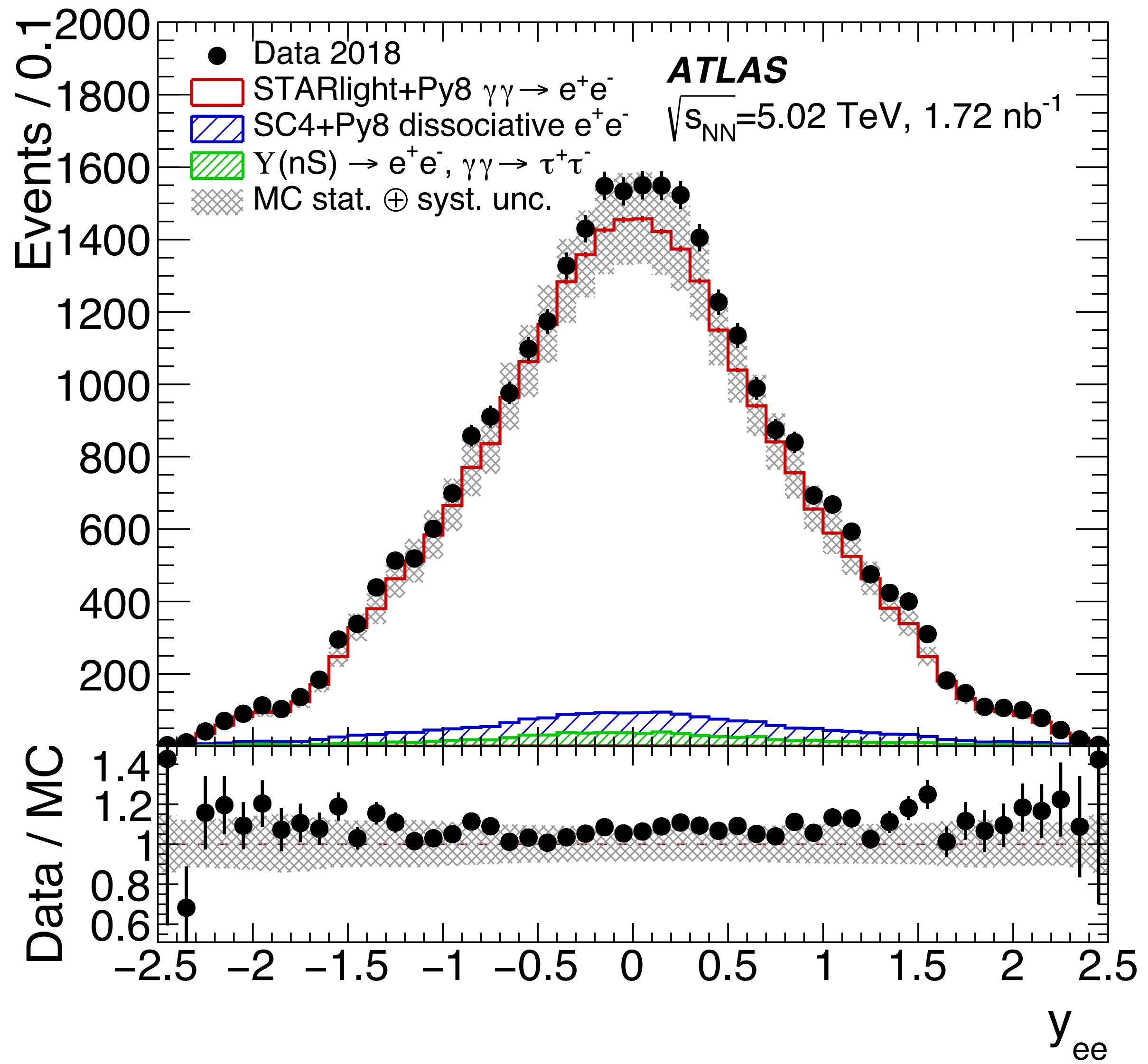
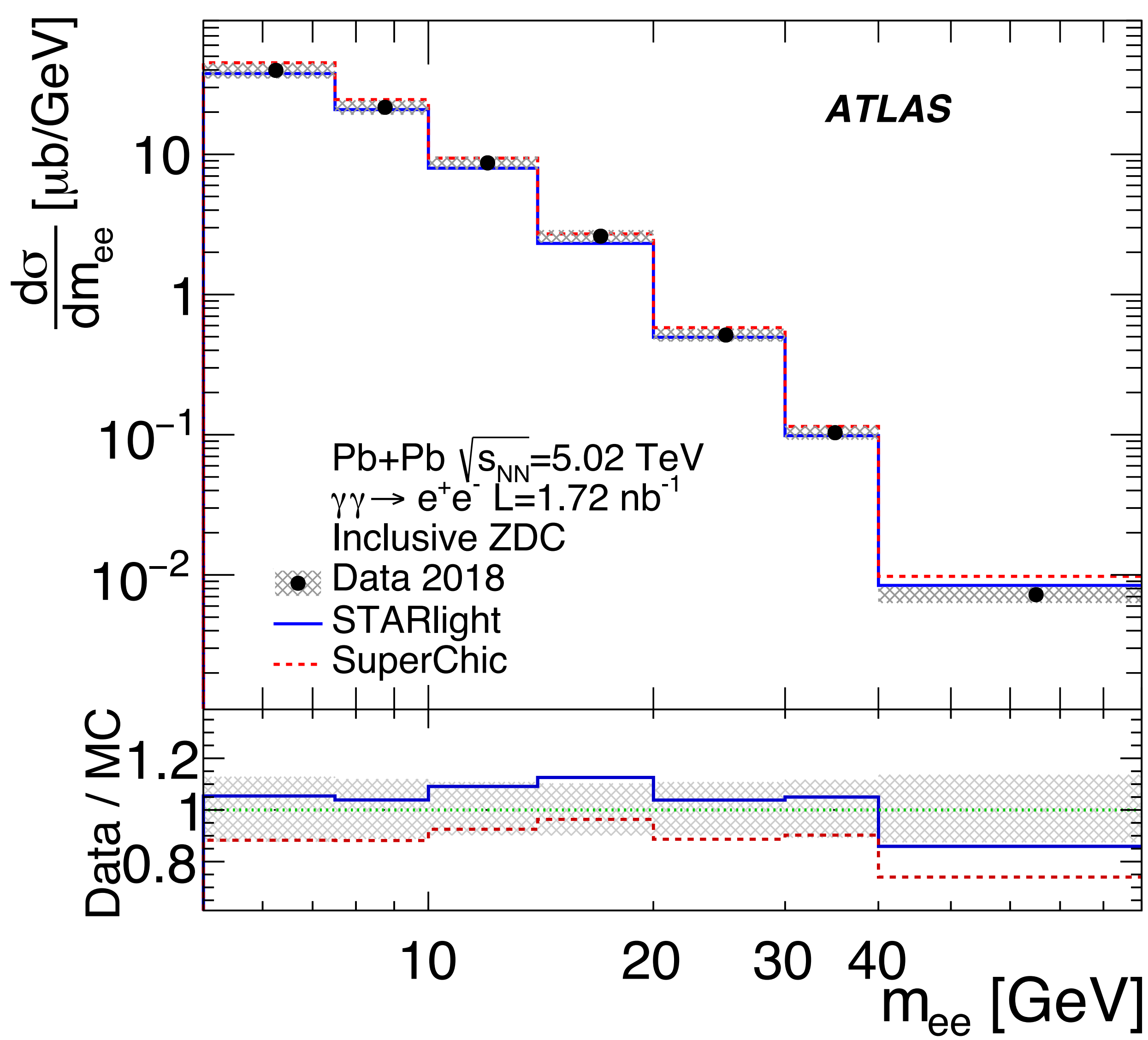


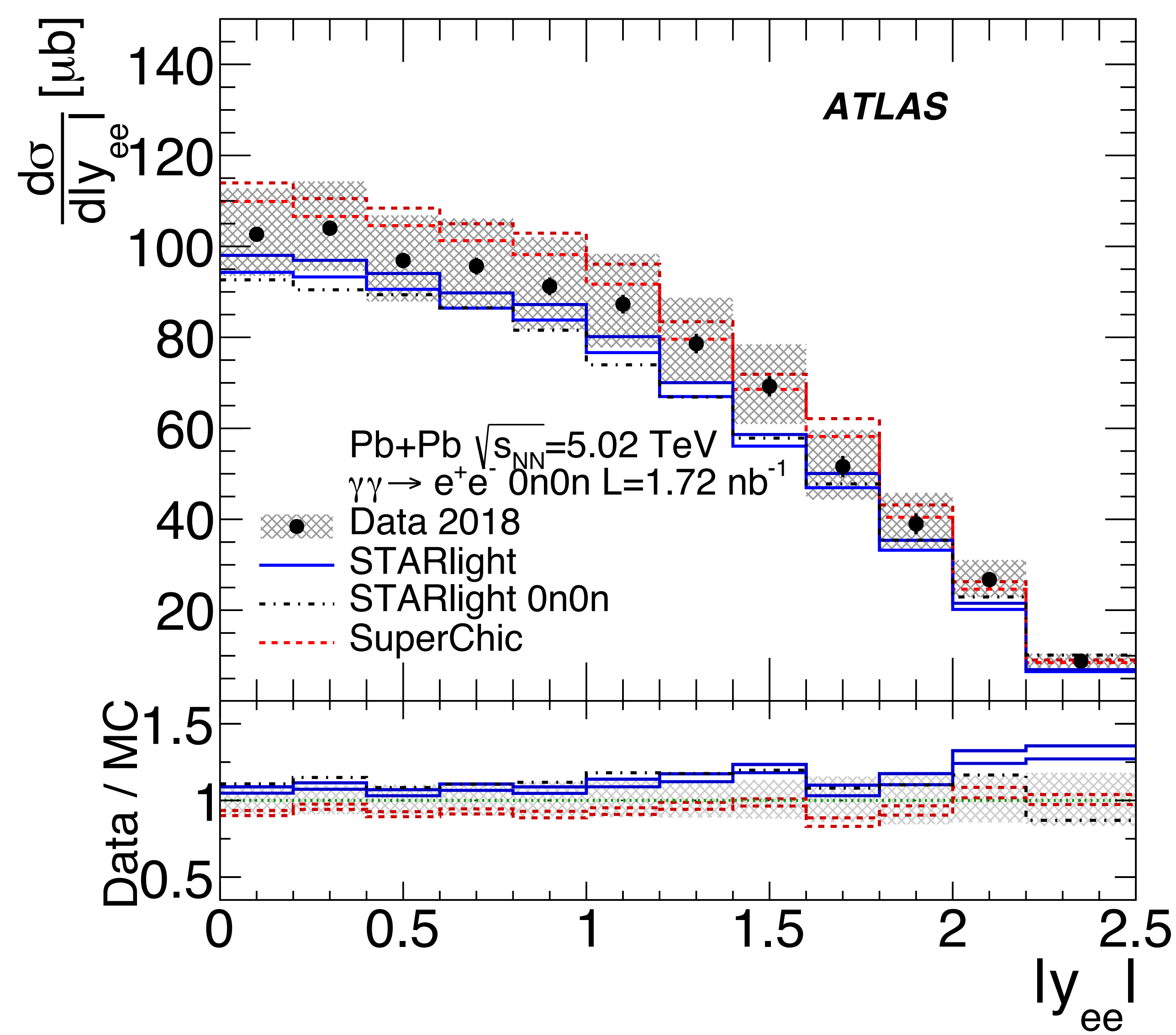


Dielectrons - results

- **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

arXiv:2207.12781





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

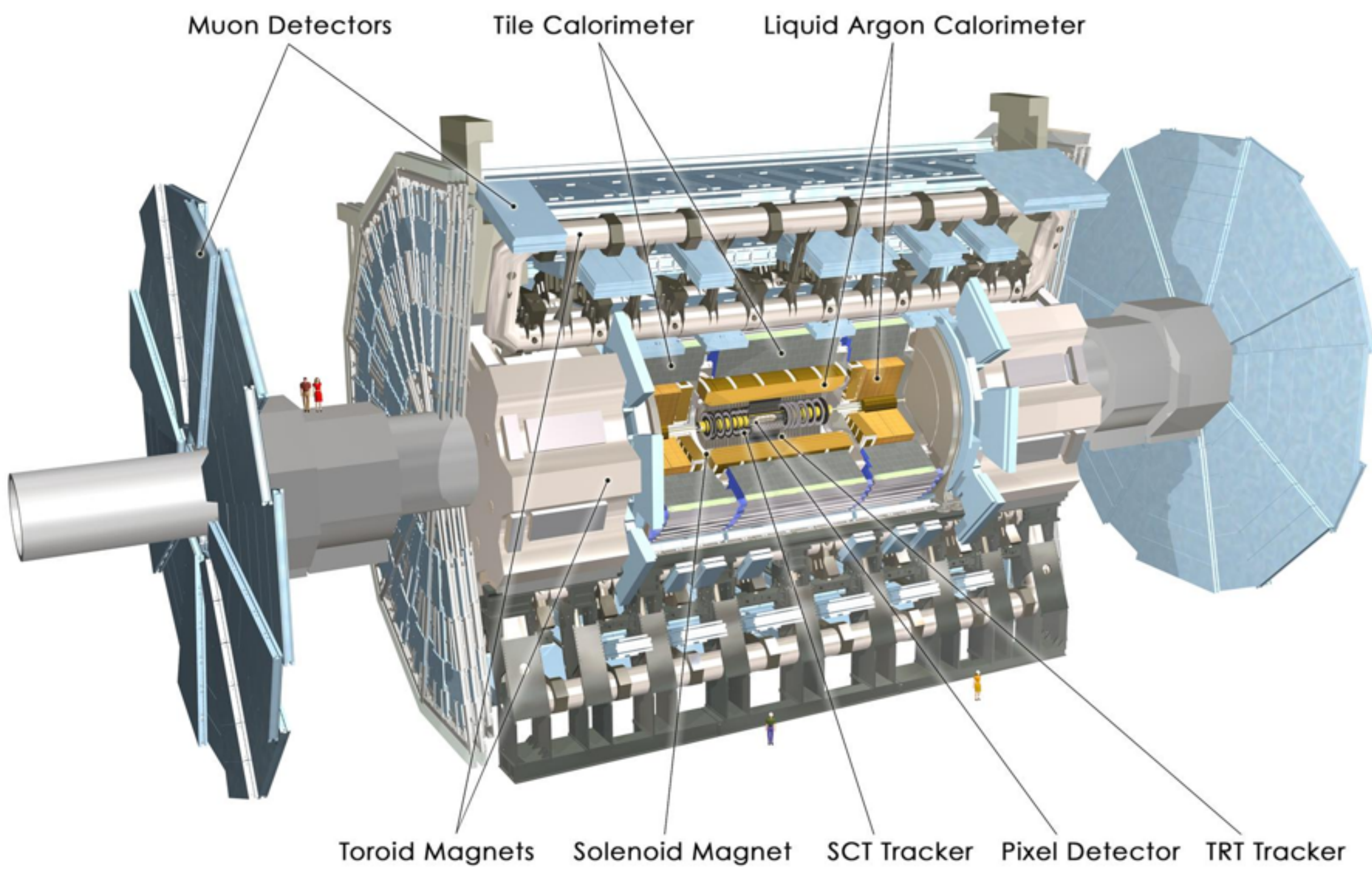
    - This should provide constraints for **impact-parameter dependence** of dilepton production

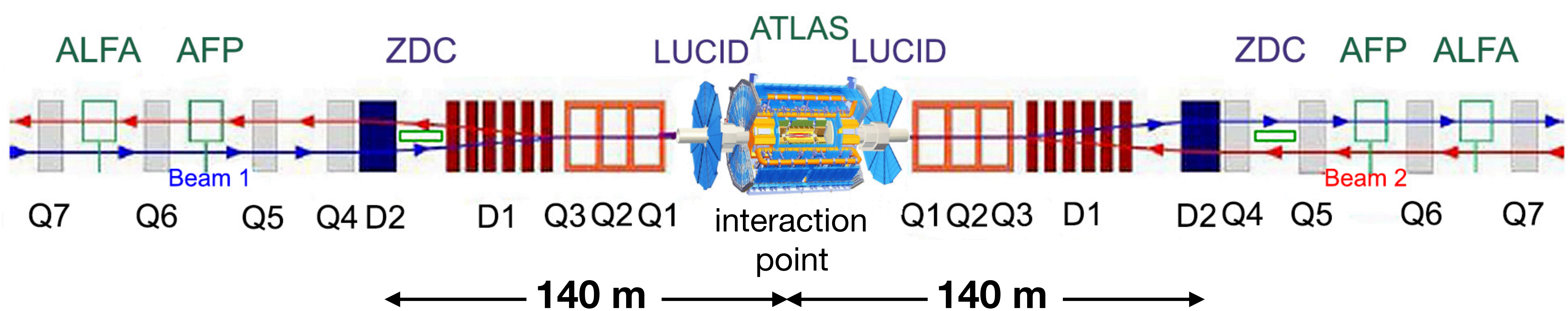
- Results from dielectrons and dimuons provide valuable constrains for **theoretical approaches** in the modeling of the **initial photon flux**

Backup

ATLAS detector

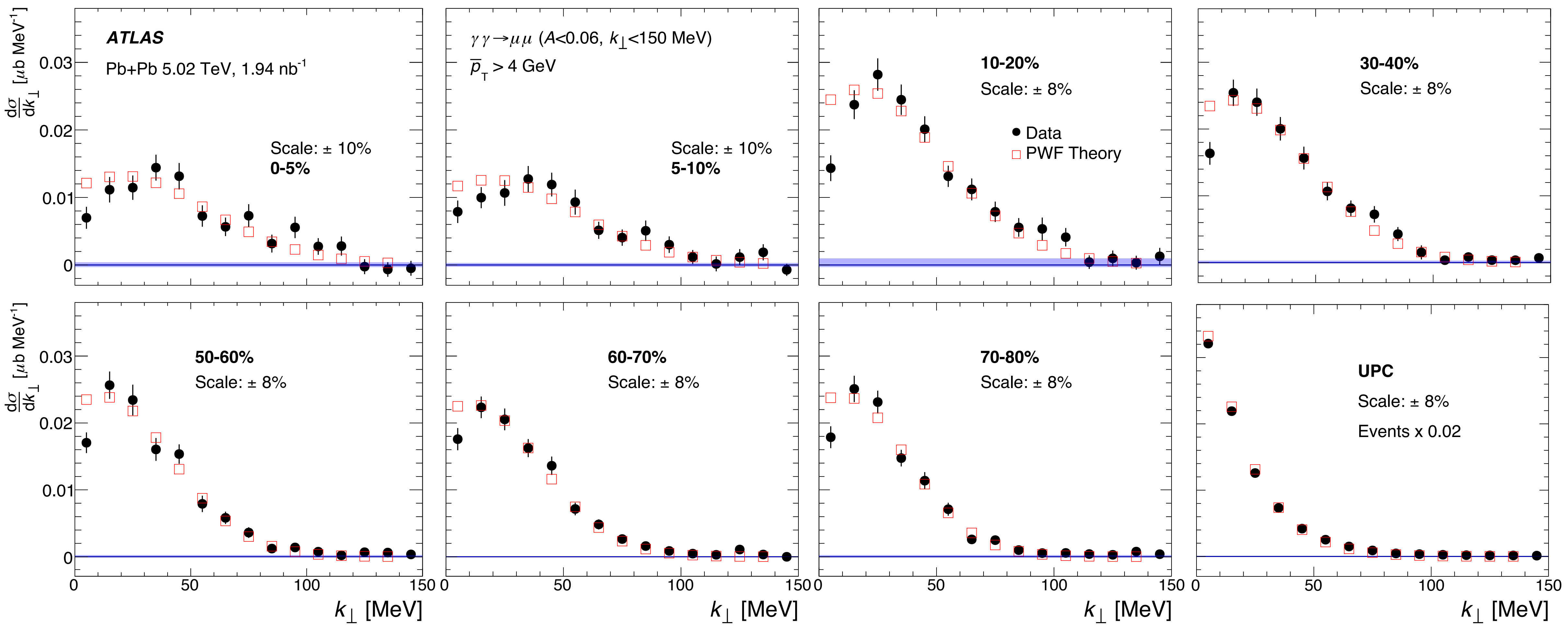
- Large general-purpose detector with almost 4π coverage
- $\eta = -\log(\tan(\theta/2))$
- Inner detector $|\eta|<2.5$
- Muon system $|\eta|<2.7$ (trig. 2.4)
- Calorimetry out to $|\eta|<4.9$
- Zero-Degree-Calorimeters capture neutral particles with $|\eta|>8.3$





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



ZDC fractions

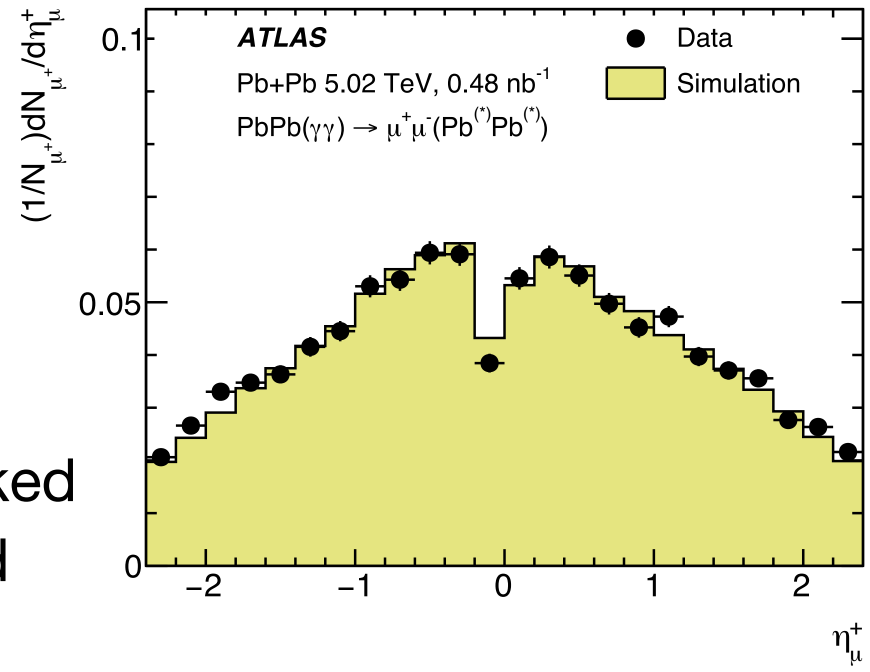
- The fractions of events in each ZDC class are affected by the presence of EM pile-up
- The probabilities of single and mutual dissociation (p_s, p_m) are determined using the same method both in dimuon and dielectron measurement, with p_s, p_m values calculated for given data taking period
- The fractions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

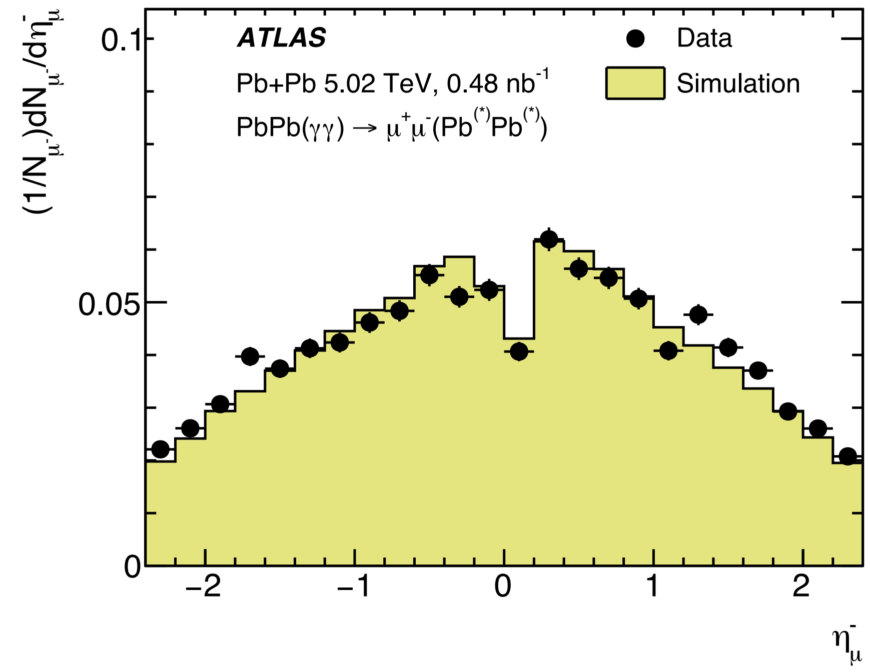
Observed fractions **Corrected fractions**

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

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; Muon kinematic variable; Reconstruction and trigger efficiencies

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

- Measured fiducial cross section is:

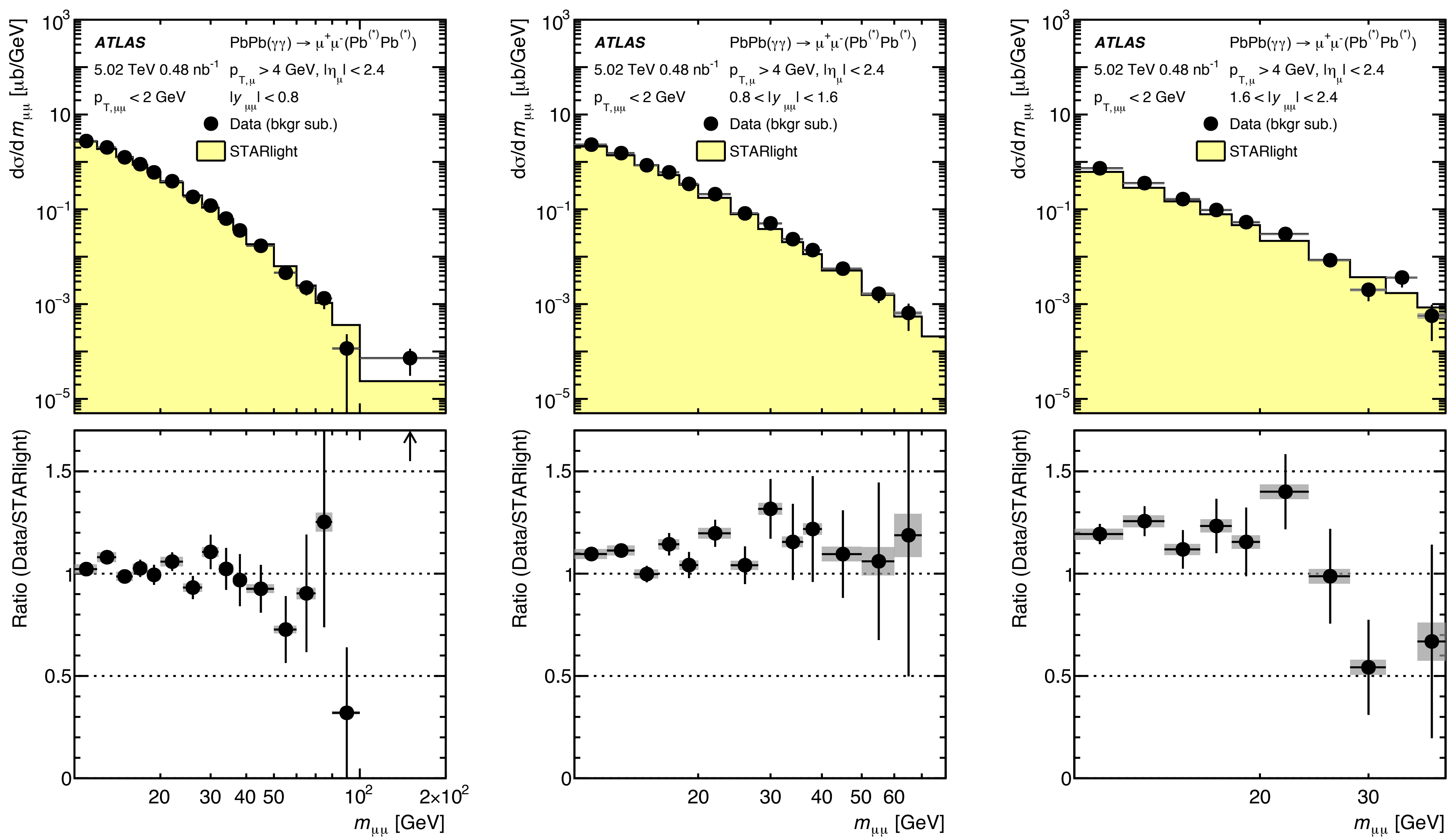
σ = 34.1±0.3(stat.)±0.7(syst.) μb,

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

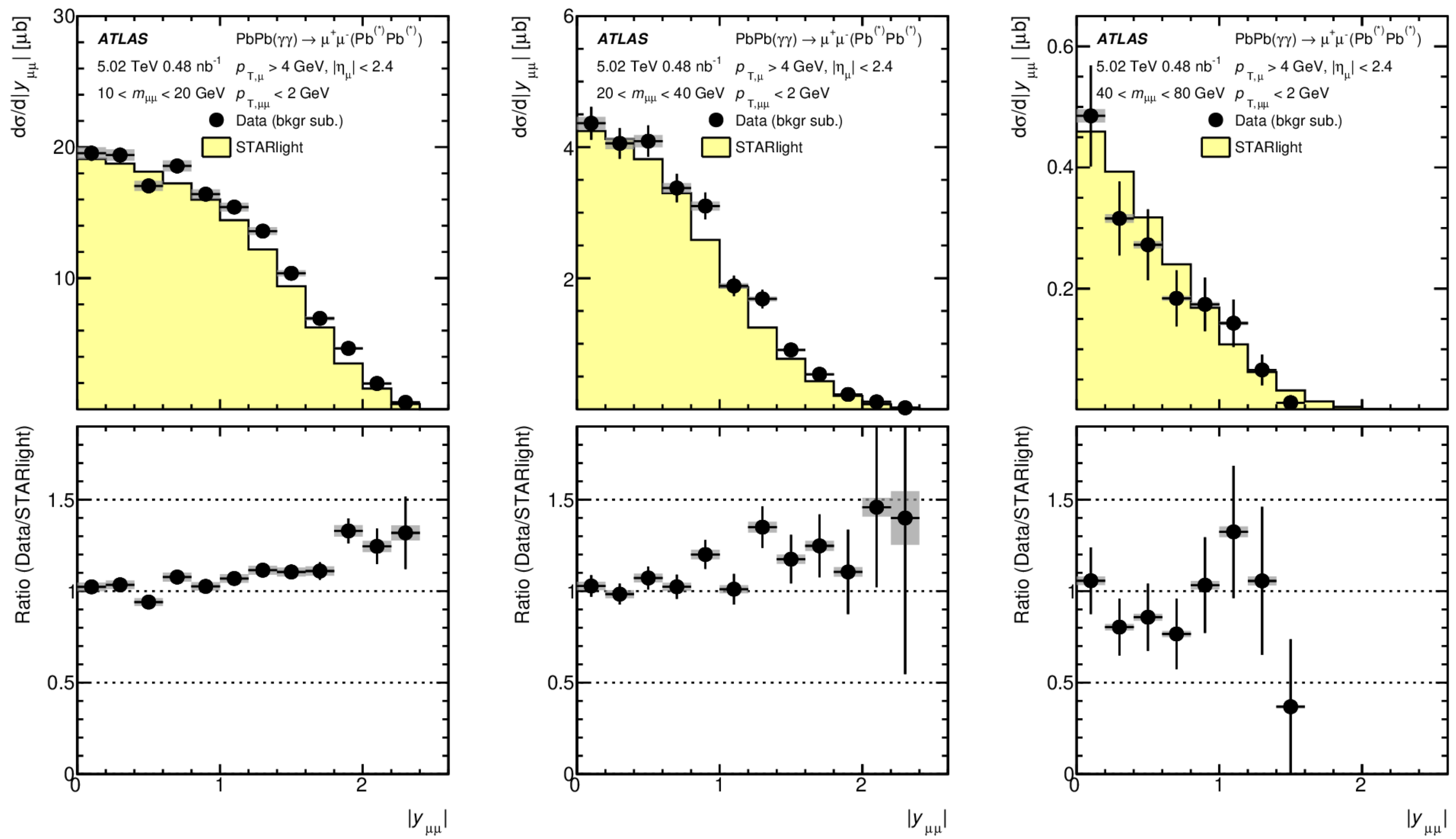
Dimuons - results

- The cross-sections are presented as a function of absolute dimuon mass in 3 rapidity slices
- Data is compared with STARlight MC simulation of $\gamma\gamma \rightarrow \mu^+\mu^-$ 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

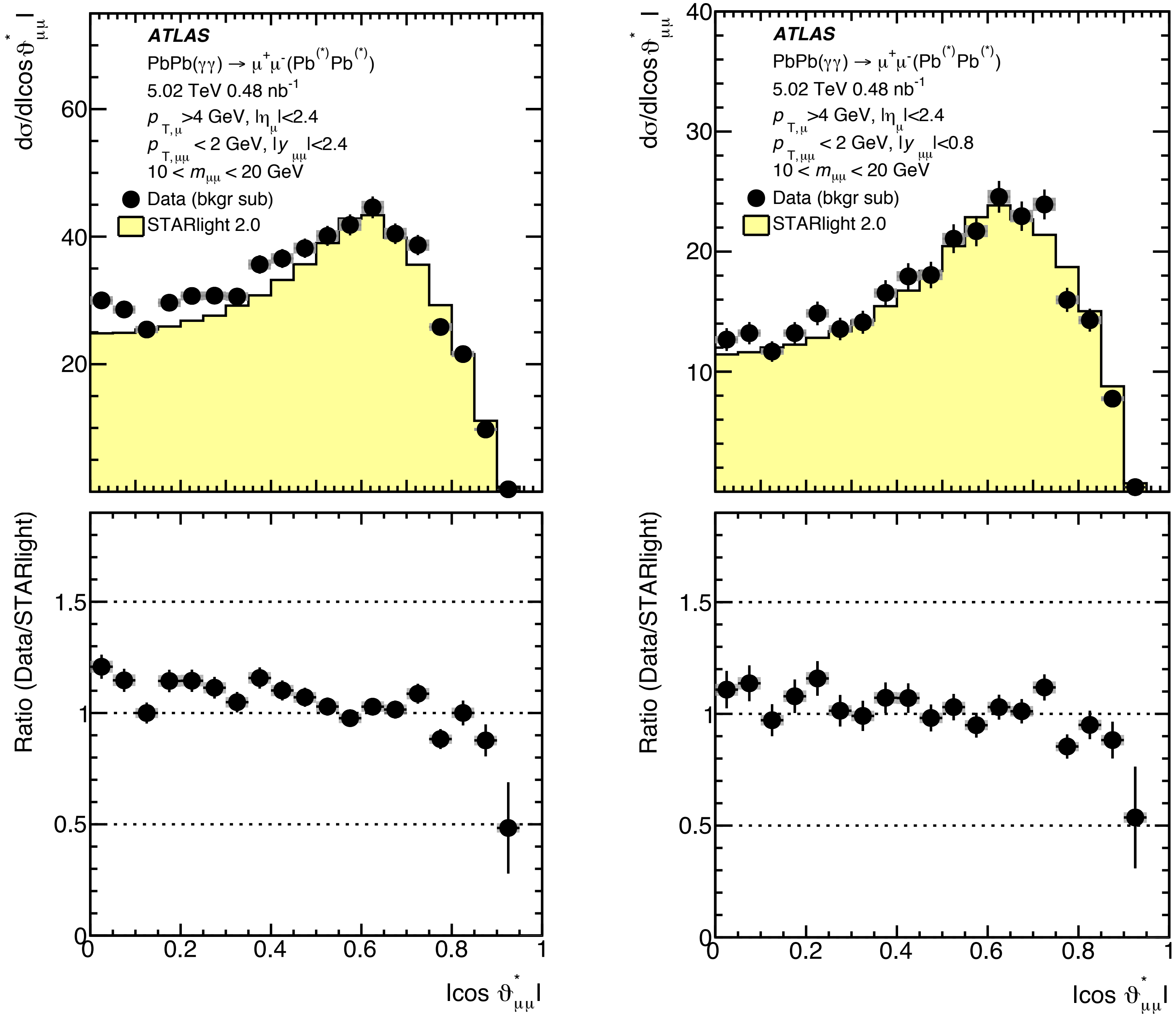
- The cross-sections are presented as a function of absolute dimuon rapidity in 3 mass slices
- Data is compared with STARlight MC simulation of γγ → $\mu^+\mu^-$ process w/o FSR
- Good agreement is found in central region of rapidity distribution (small $|y_{\mu\mu}|$),but data to simulation ratio increases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



Dimuons - results

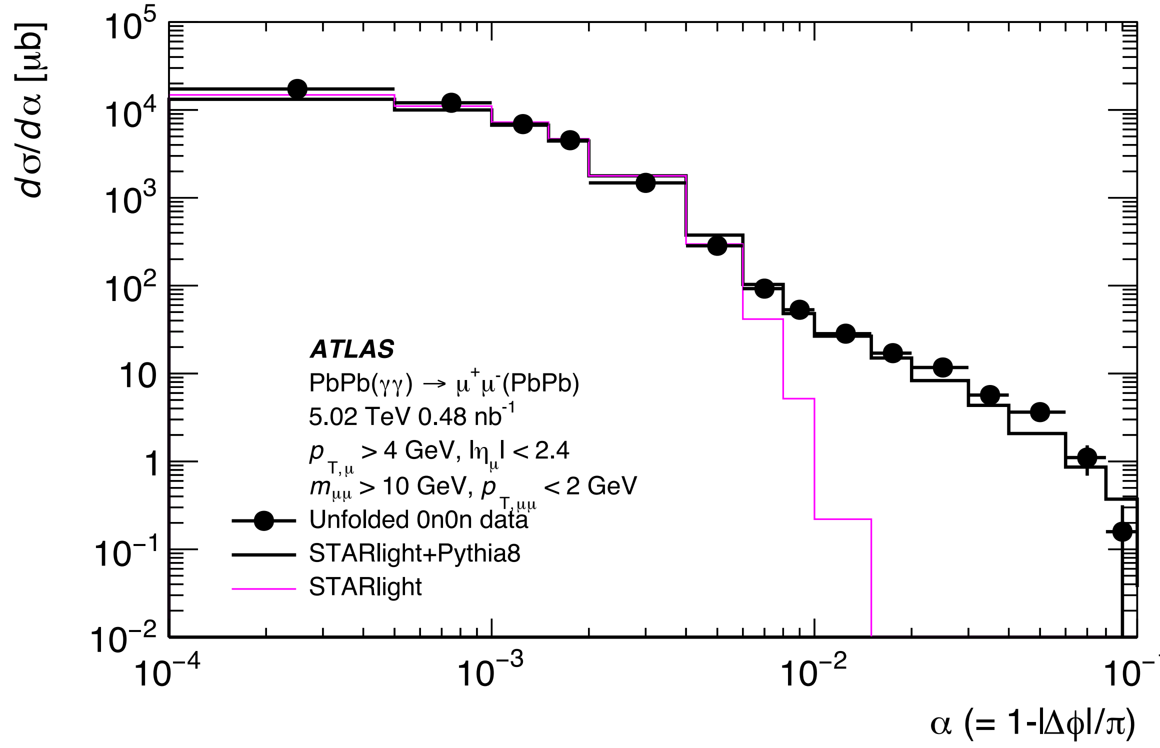
- The shape of the |cos θ*| (= |tanh(Δη$_{\ell\ell}$)/2|) is affected by the fiducial requirement of $|\eta_\mu| < 2.4$
- Thus, this distribution may be affected by the mismodelling observed at large $|y_{\mu\mu}|$
- Limiting the data with $|y_{\mu\mu}| < 0.8$ improves data to simulation agreement in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

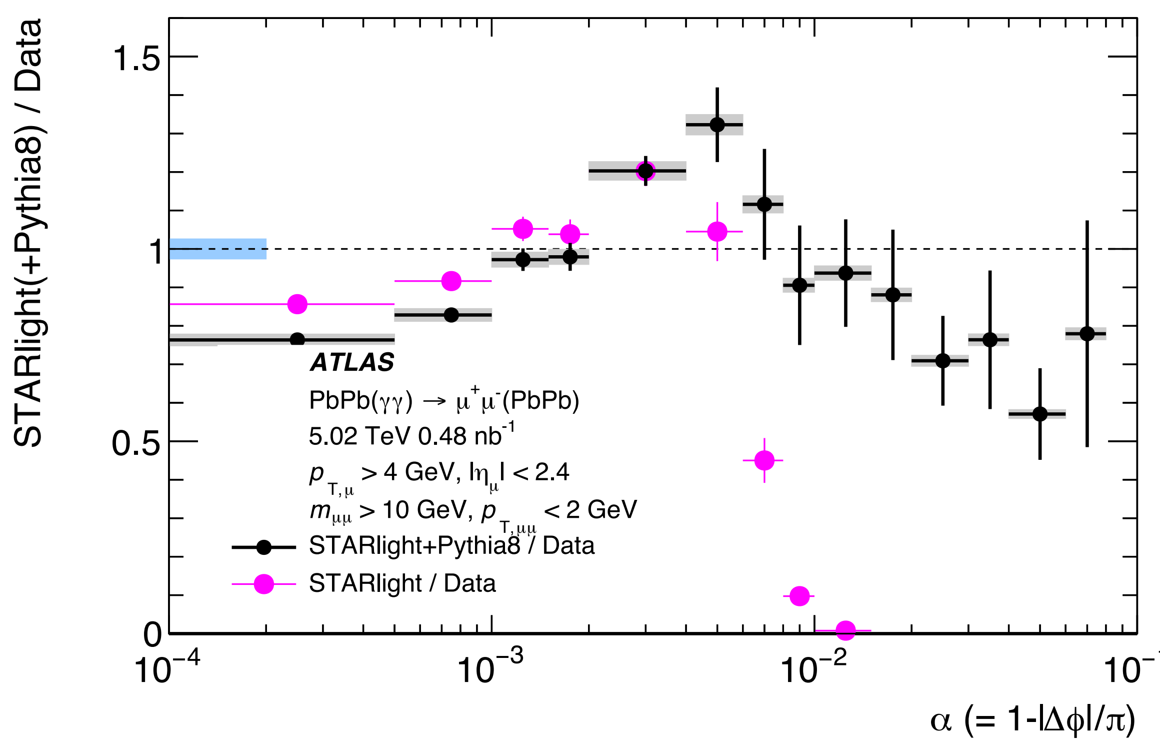
$|y_{\mu\mu}| < 2.4$ $|y_{\mu\mu}| < 0.8$



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



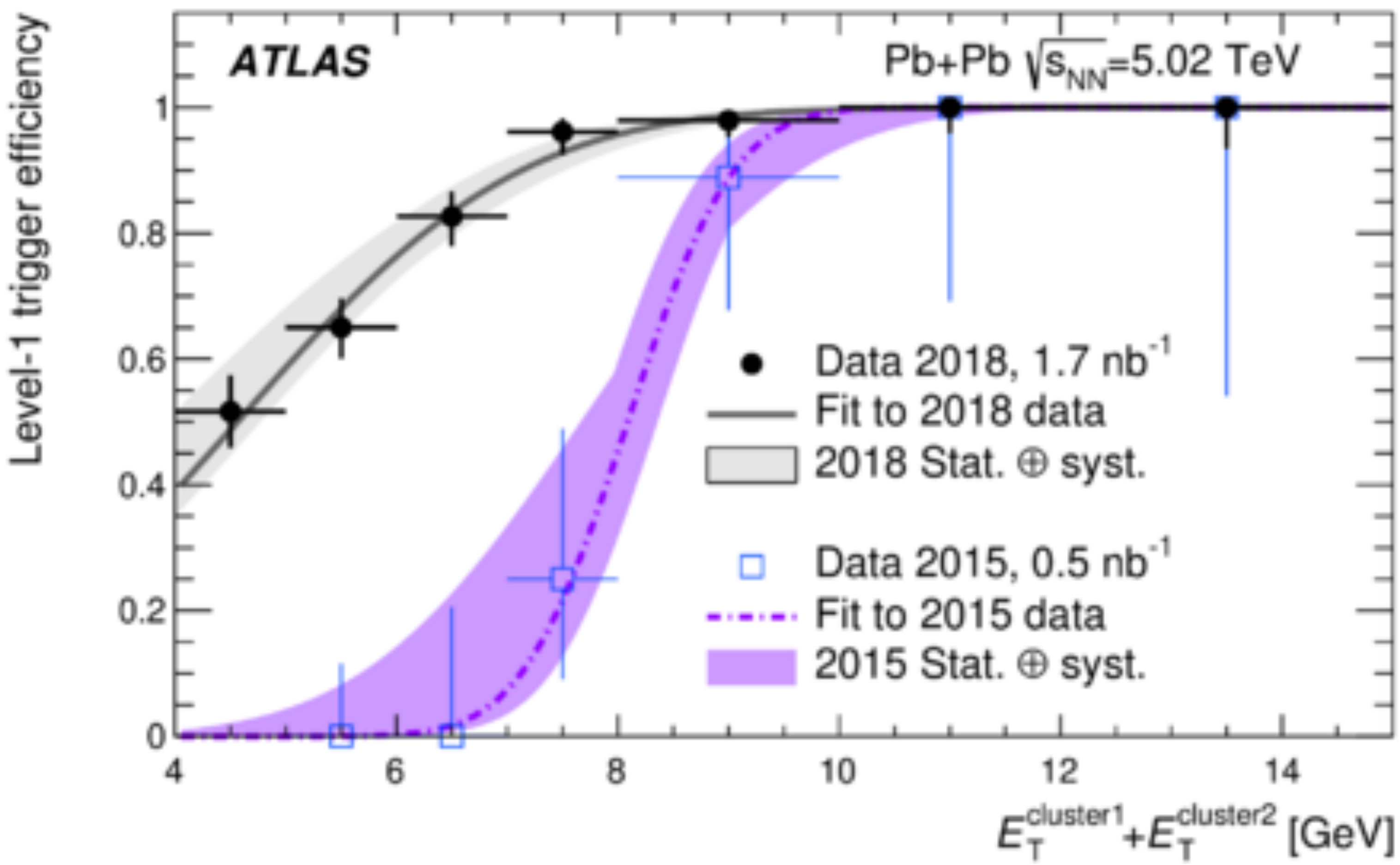


Dielectrons - efficiency corrections

- 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

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

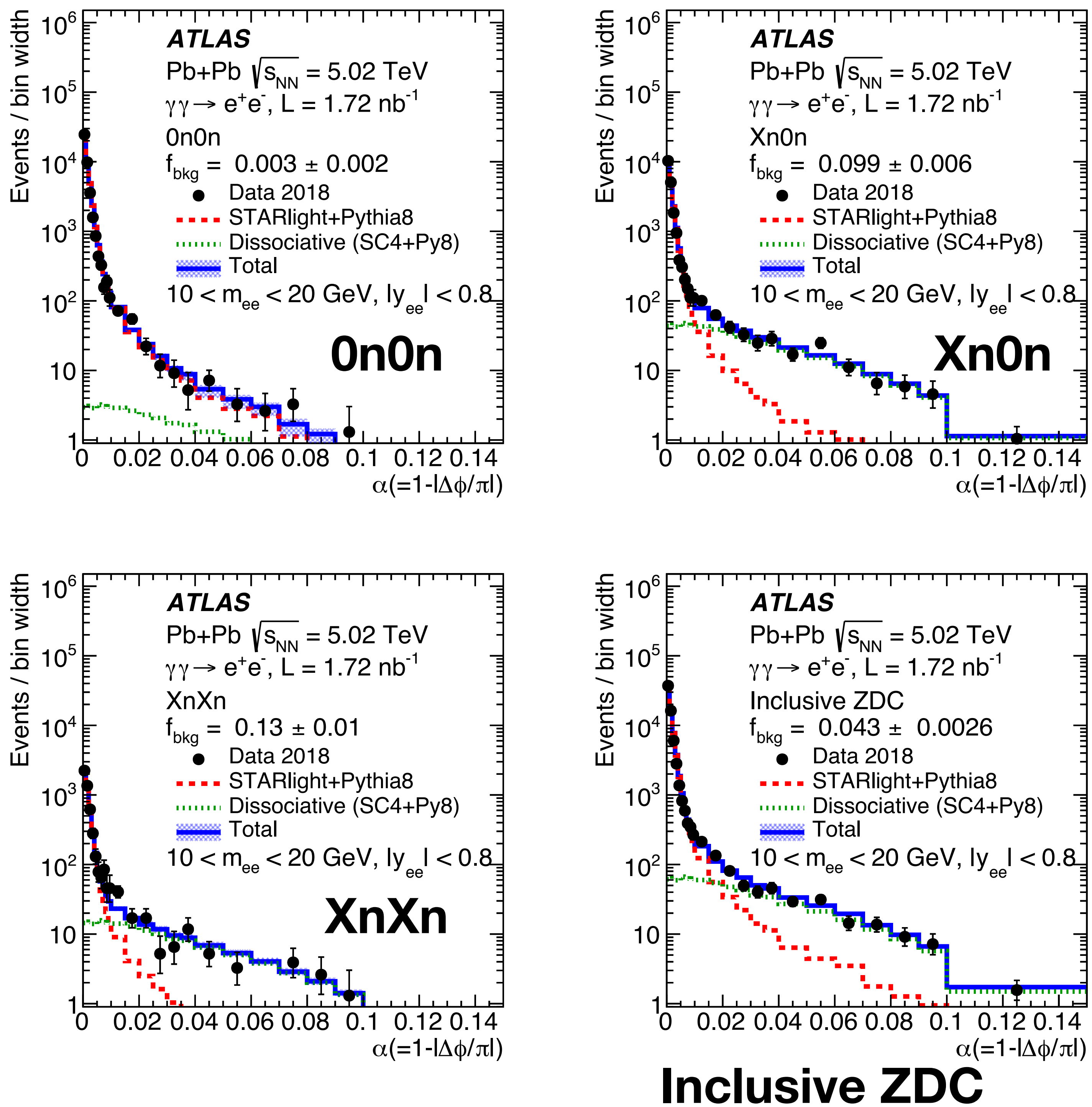
- The background samples for **single dissociation** from SuperChic4+Pythia8 are used instead of LPair

- 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

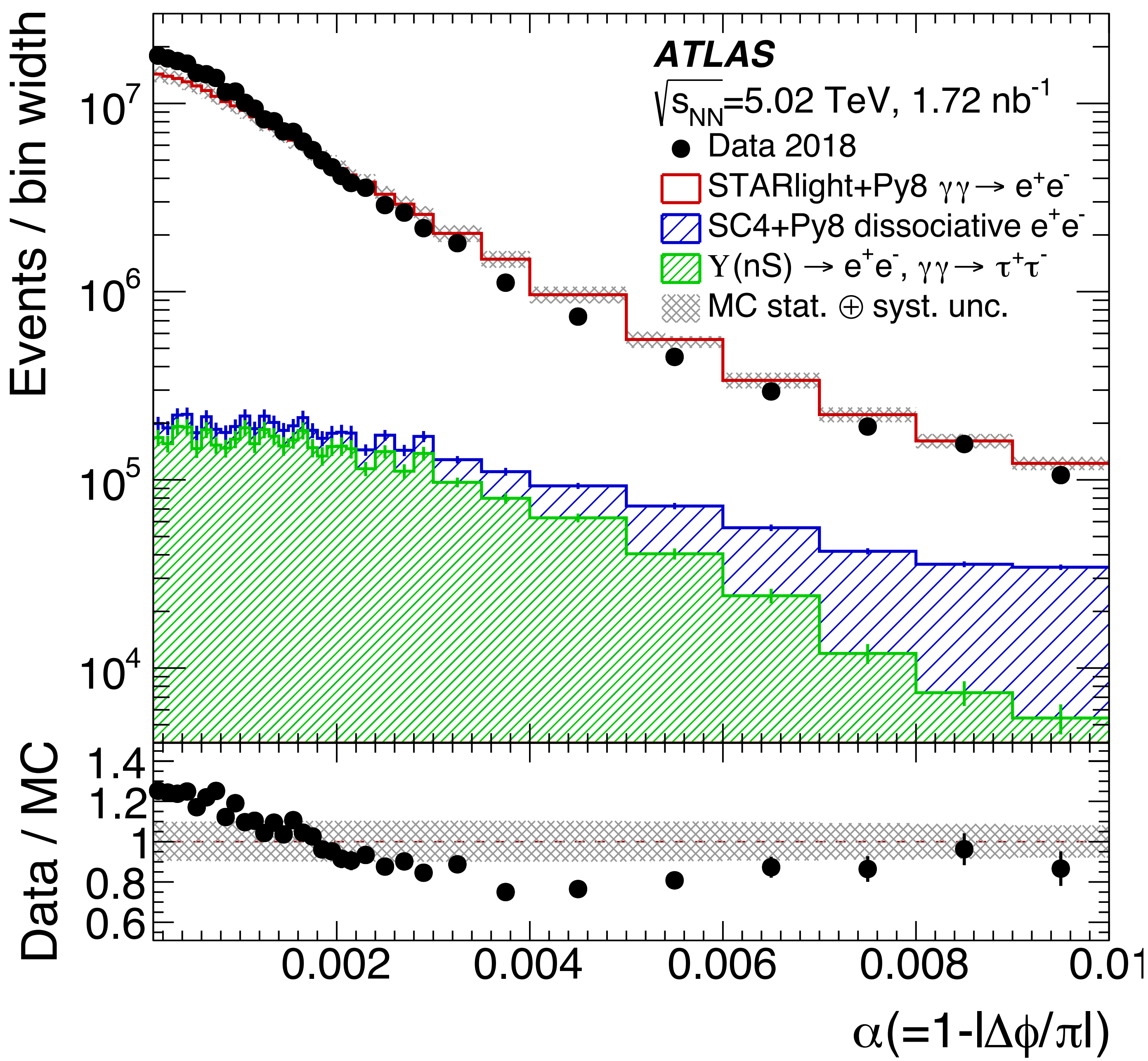
- Background from **Upsilon(nS)** production estimated with using STARlight+Pythia8 **MC samples**, at the level of 2.4%

- The acoplanarity distribution for Upsilon(nS) is peaked at 0 and should not influence the background fit for dissociation



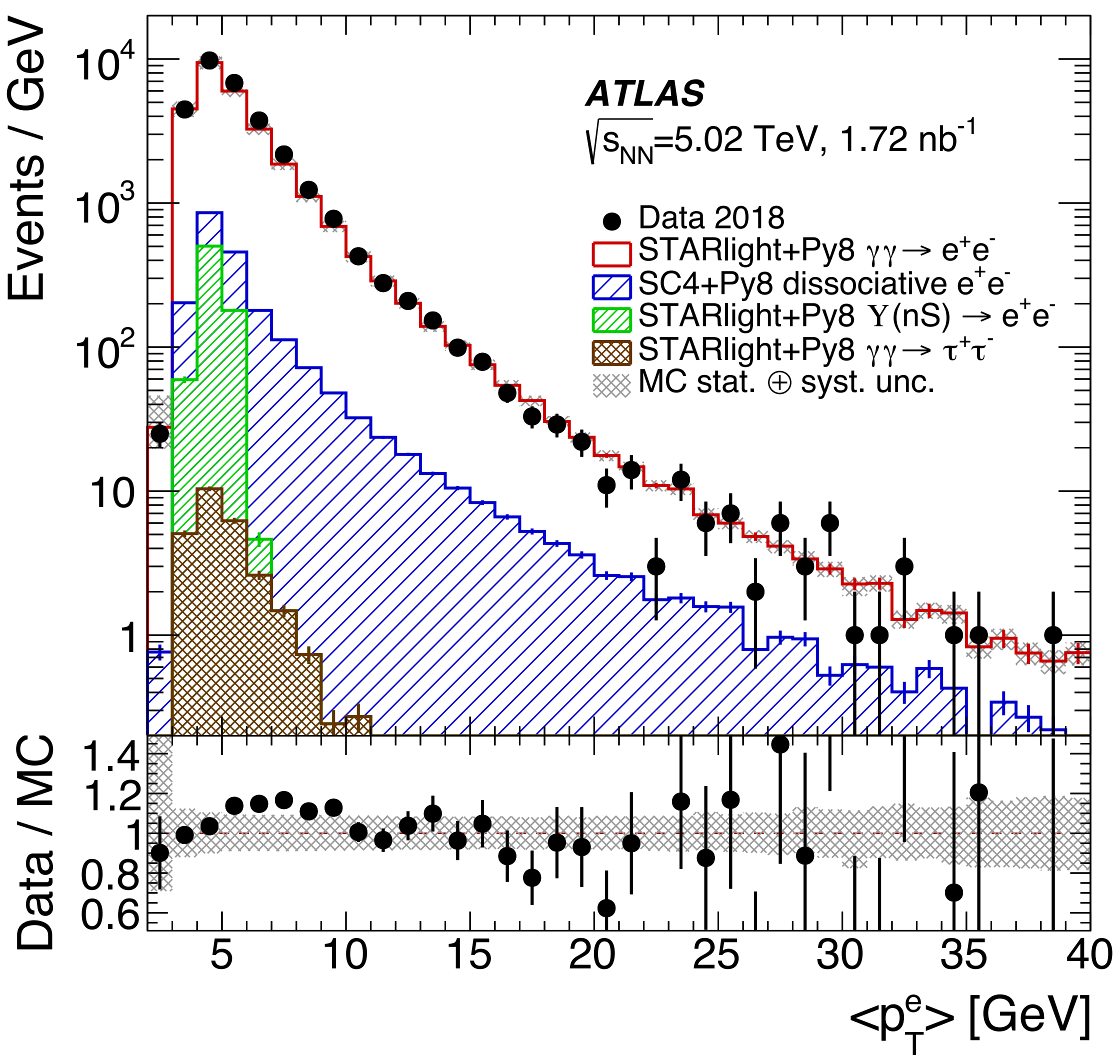
Background - upsilon

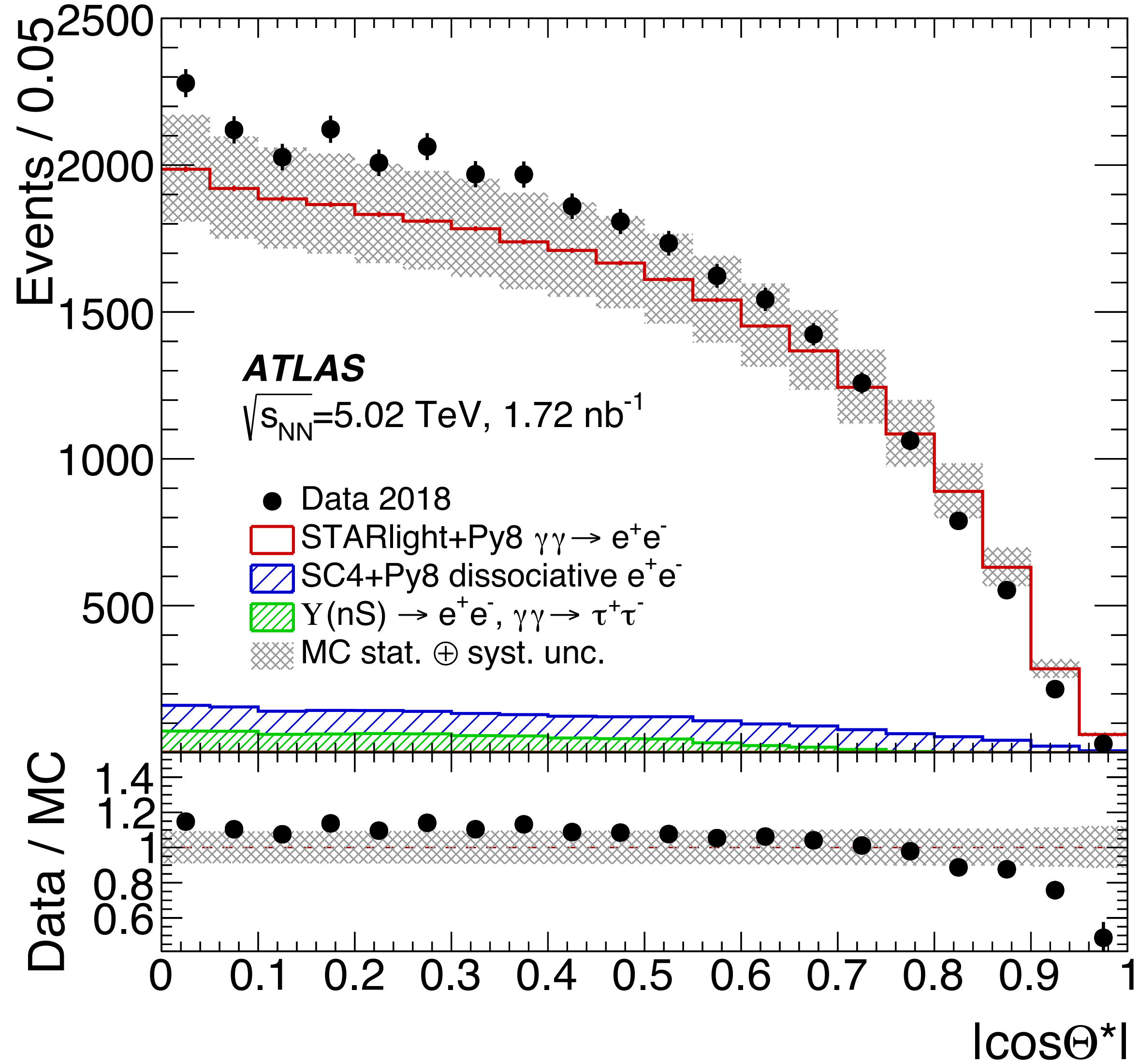
- The background from Upsilon(nS) decays to dielectrons is estimated using STARlight+Pythia8
- Upsilon 1S, 2S and 3S are considered
- The acoplanarity distribution for this background is peaked at 0 and should not influence the background fit for dissociation
- In total Upsilon background is at the level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



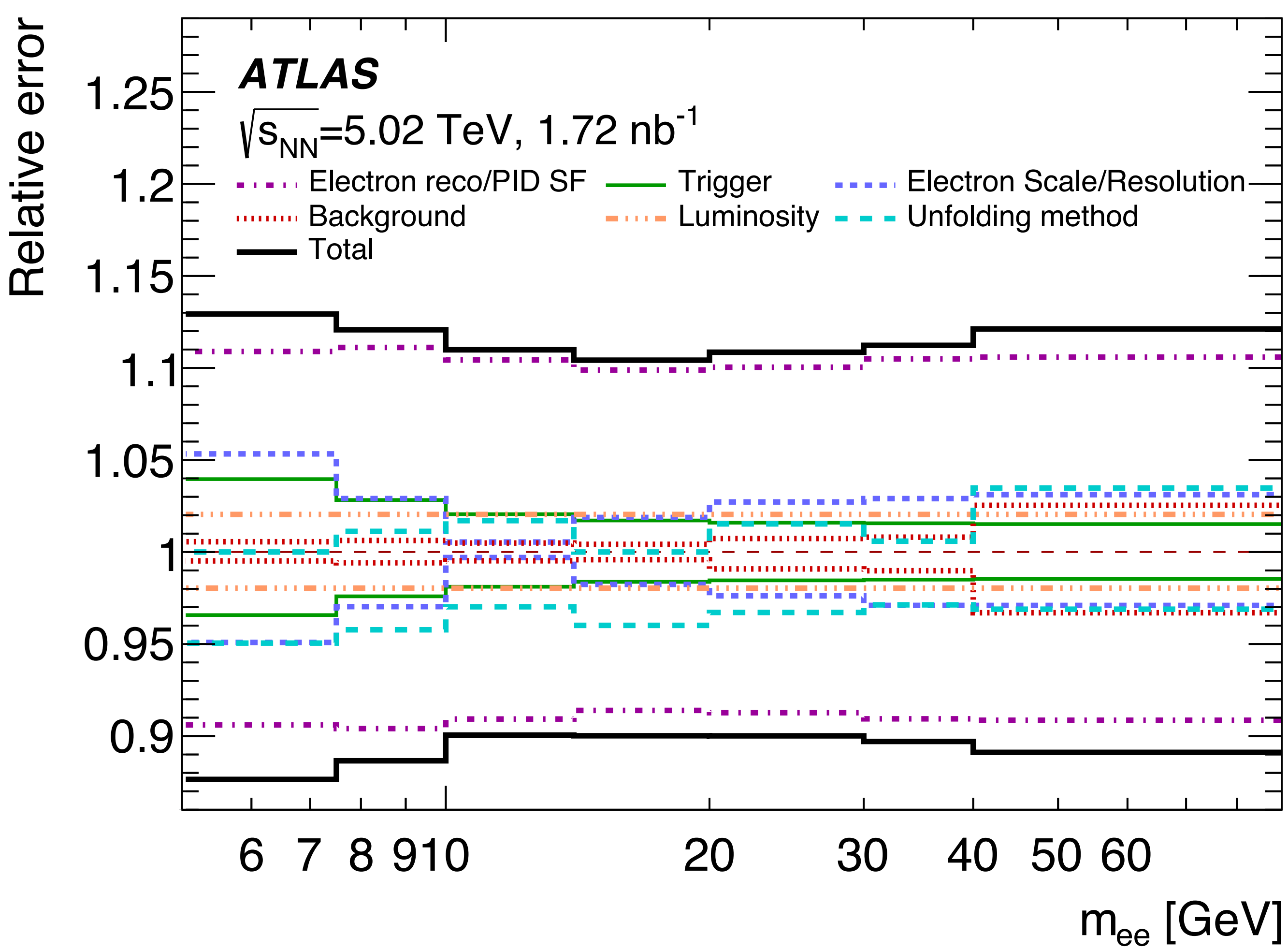


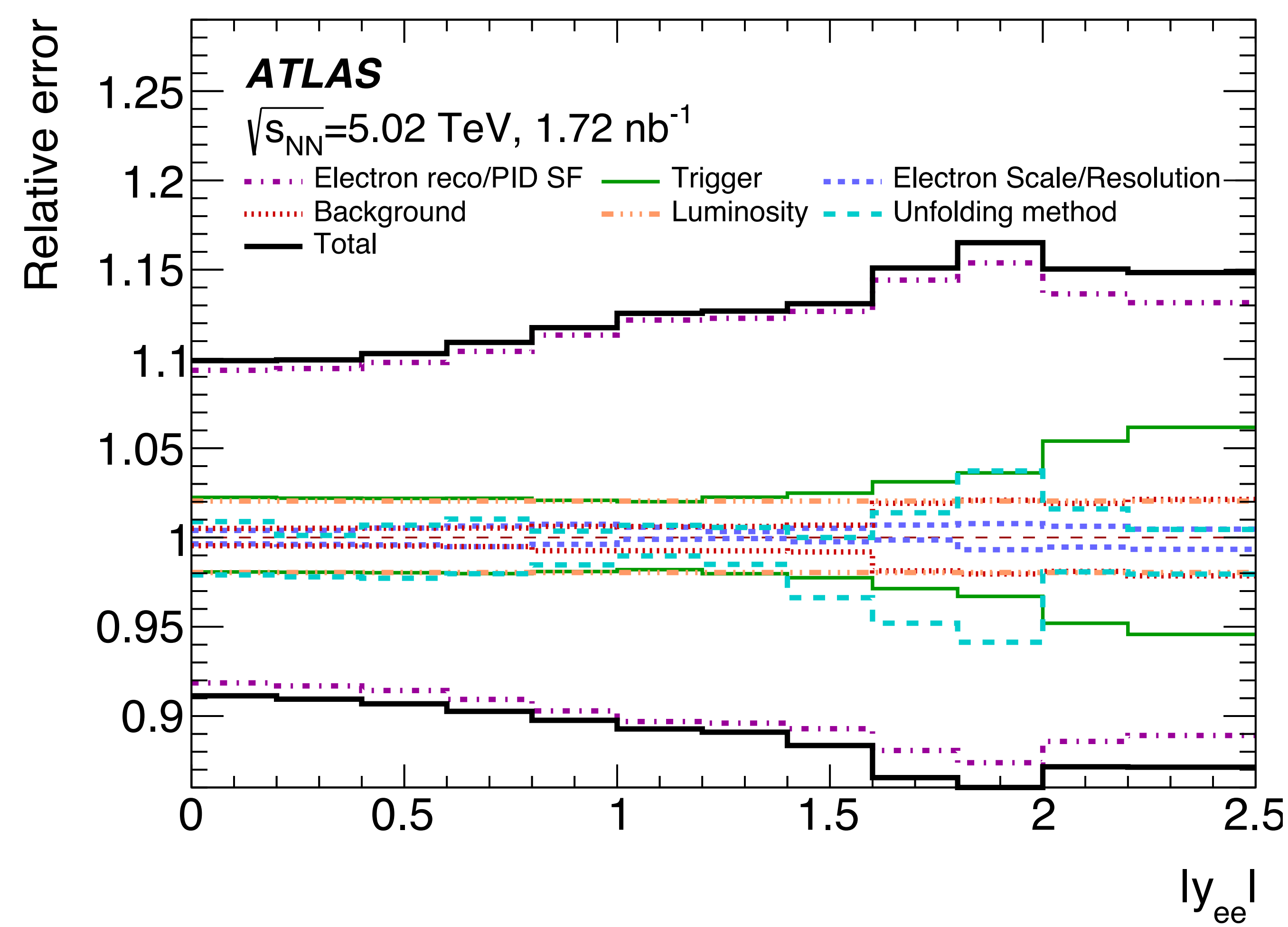
Systematics

- 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 $|\eta_e| < 2.5$)

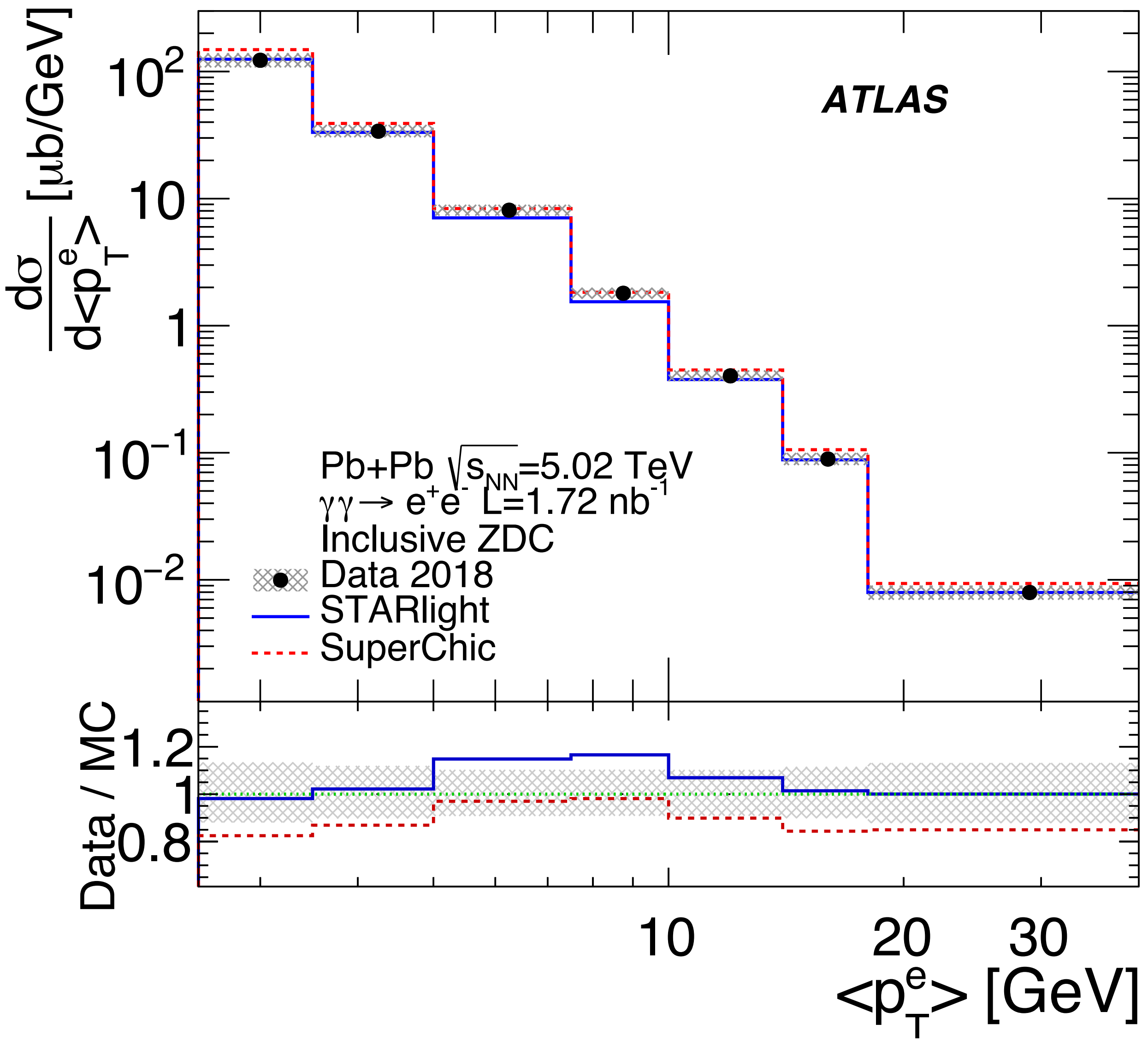
$p_T^e >$	2.5 GeV
$\|\eta_e\| <$	2.5
$m_{ee} >$	5 GeV
$p_T^{ee} <$	2 GeV

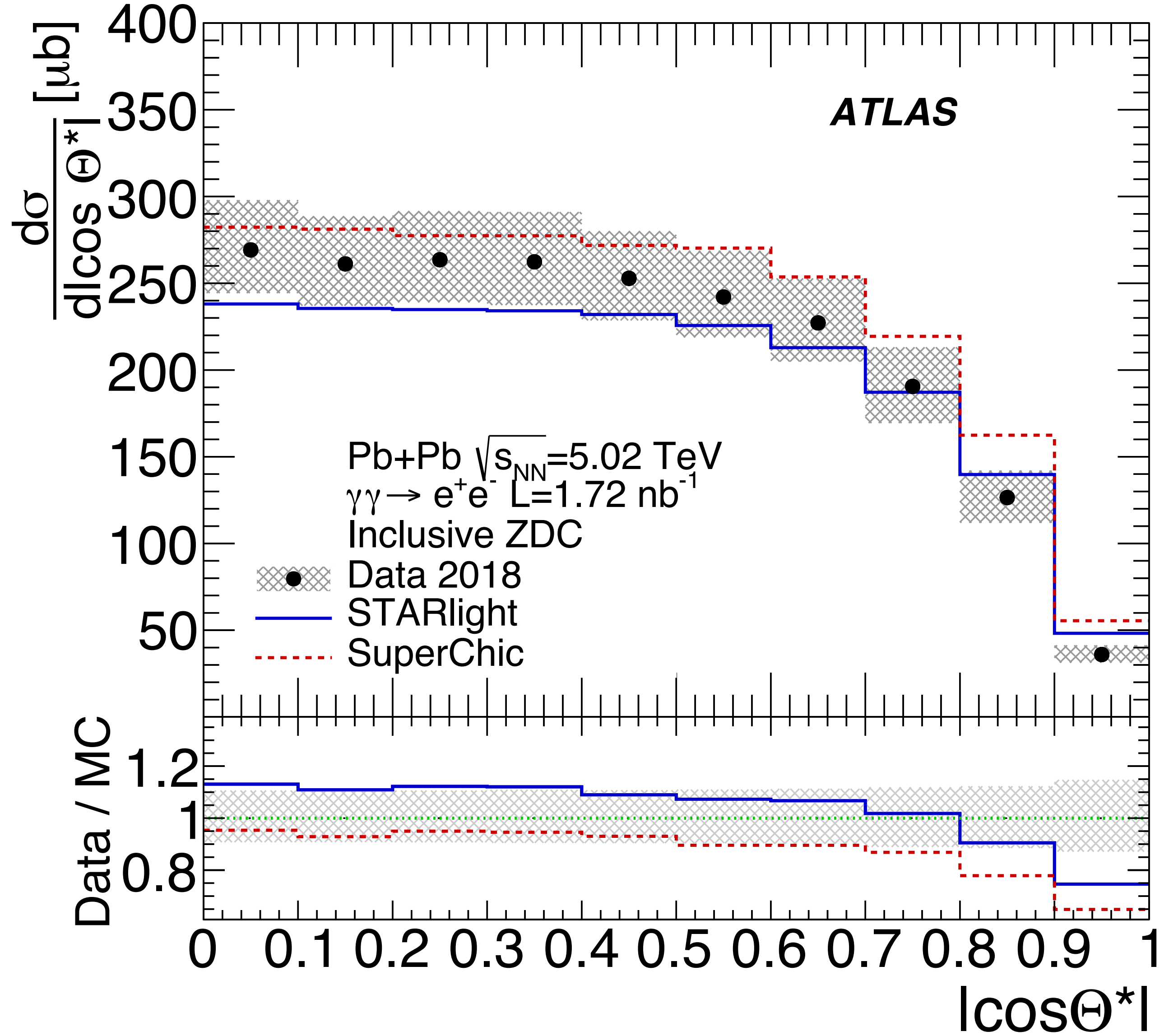
- The integrated cross-section is calculated in fiducial region determined by the event selection
- Besides mentioned reported below stat+syst uncertainties, there is 4 μb lumi uncertainty

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

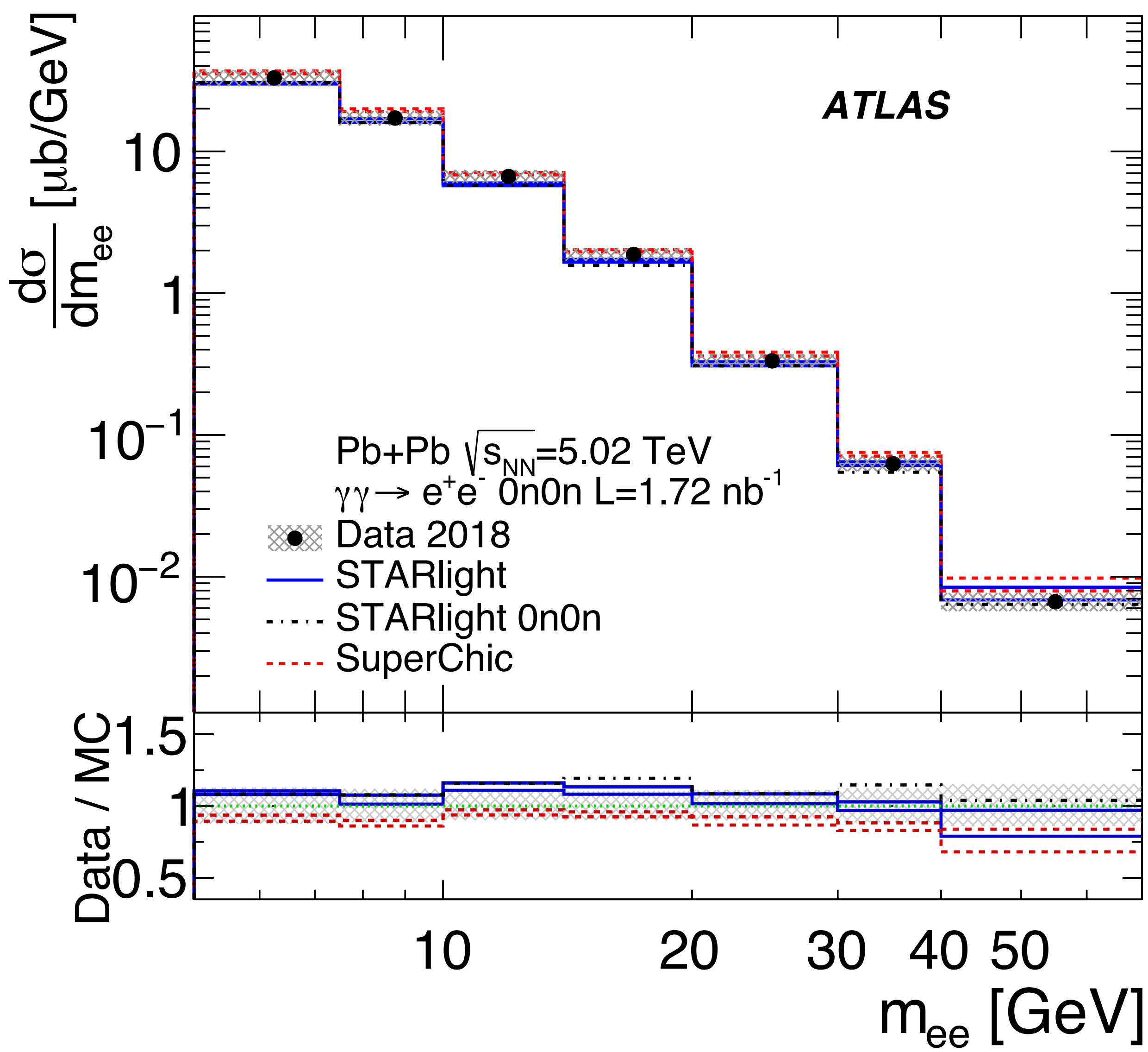
- Good agreement with STARlight is observed, differences in the same regions as in detector-level plots
- Agreement with SuperChic is better than with STARlight in $|y_{ee}|$

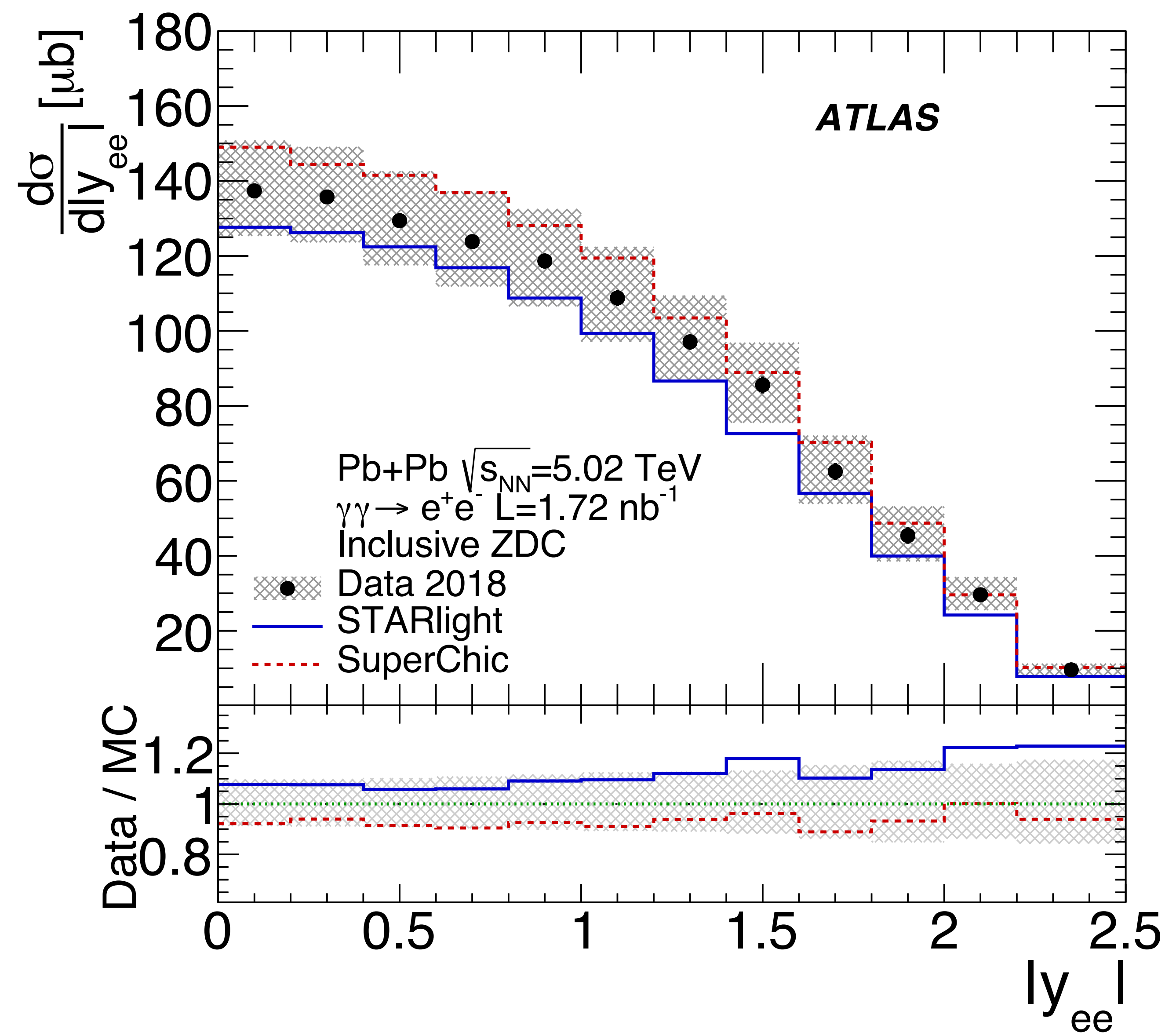




Dielectrons - results 0n0n

- 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