UPC physics in ATLAS

Agnieszka Ogrodnik (CU Prague)

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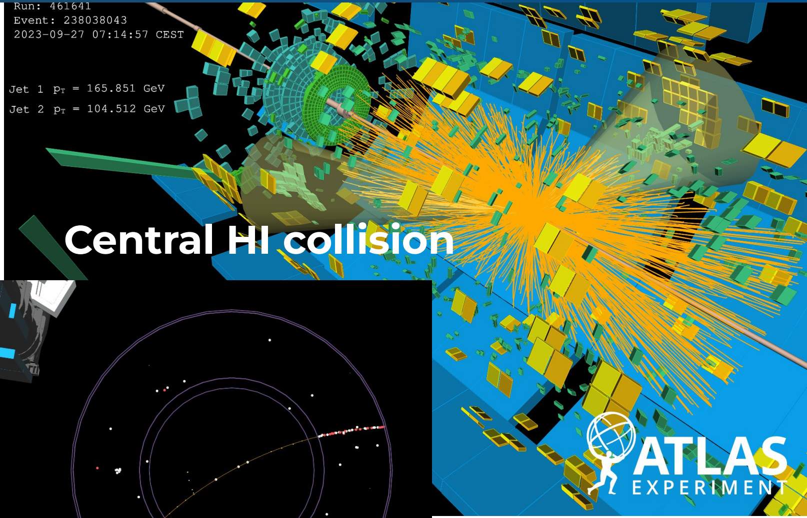
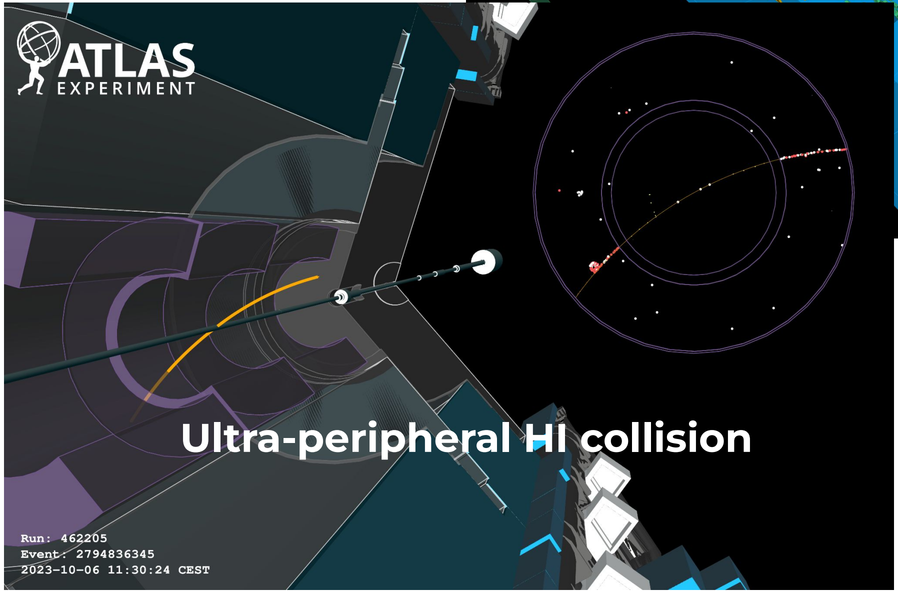
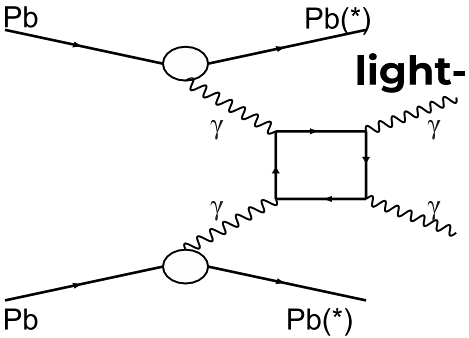
Ultra-peripheral collisions

- Advantages of UPC heavy-ion collisions:
  - Increased cross-sections wrt to pp collisions (cross-sections scale by Z^4 what is ~4.5x10^7)
  - Very low hadronic pileup - exclusive selections possible
  - Low p_T particles can be triggered and reconstructed

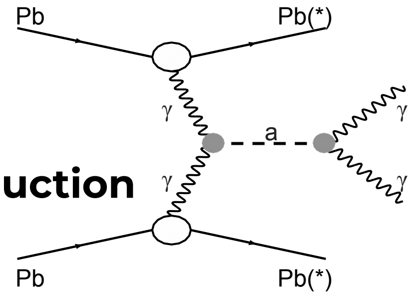




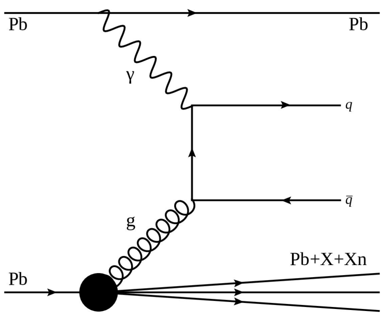
What processes can we measure/search for?



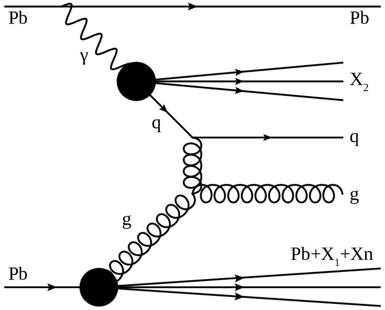
light-by-light scattering

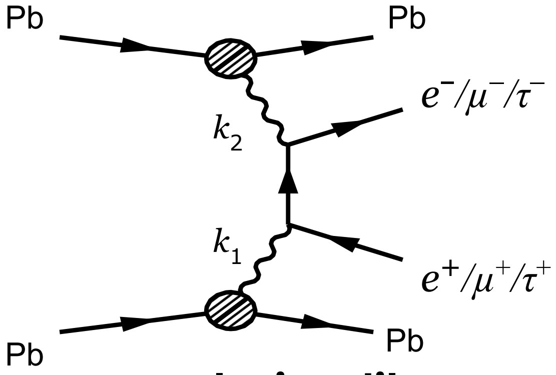


ALP production

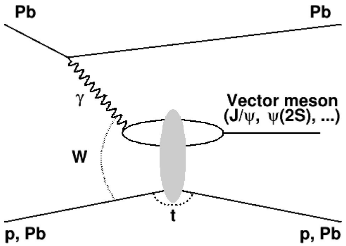


photonuclear jet production





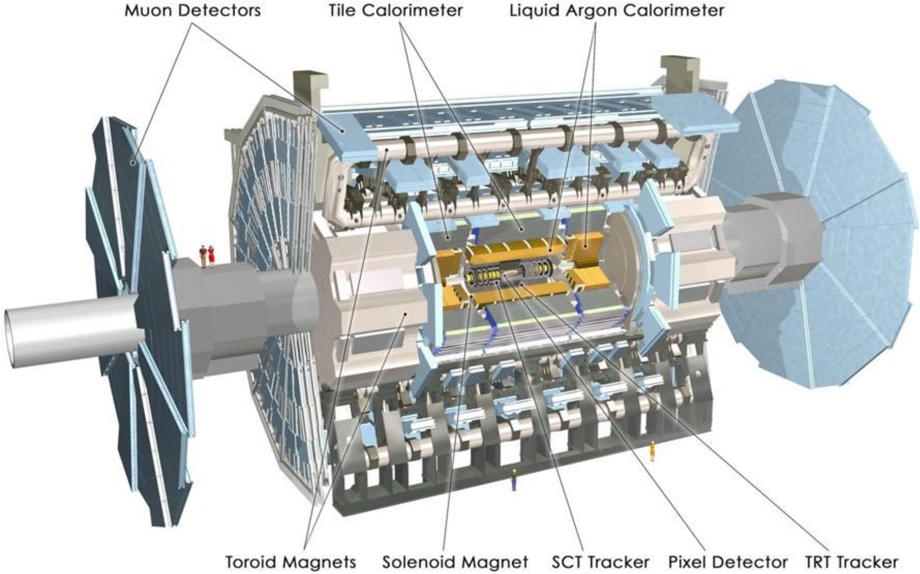
Vector meson production

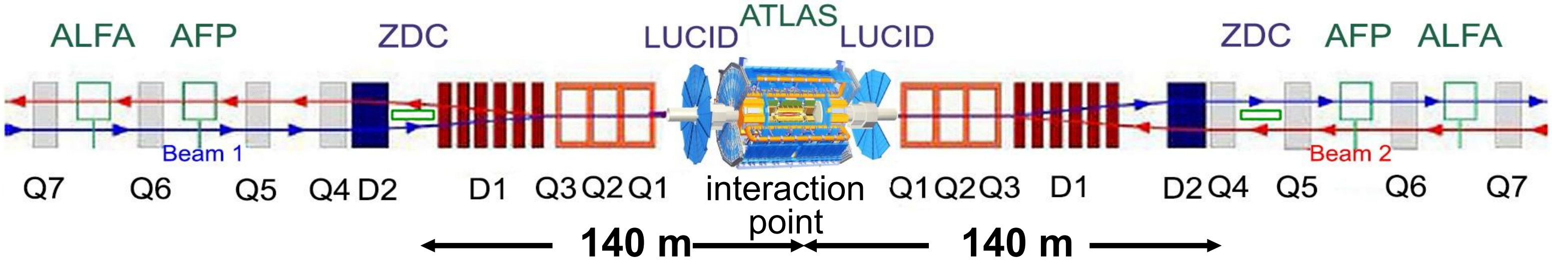


exclusive dilepton production

ATLAS detector

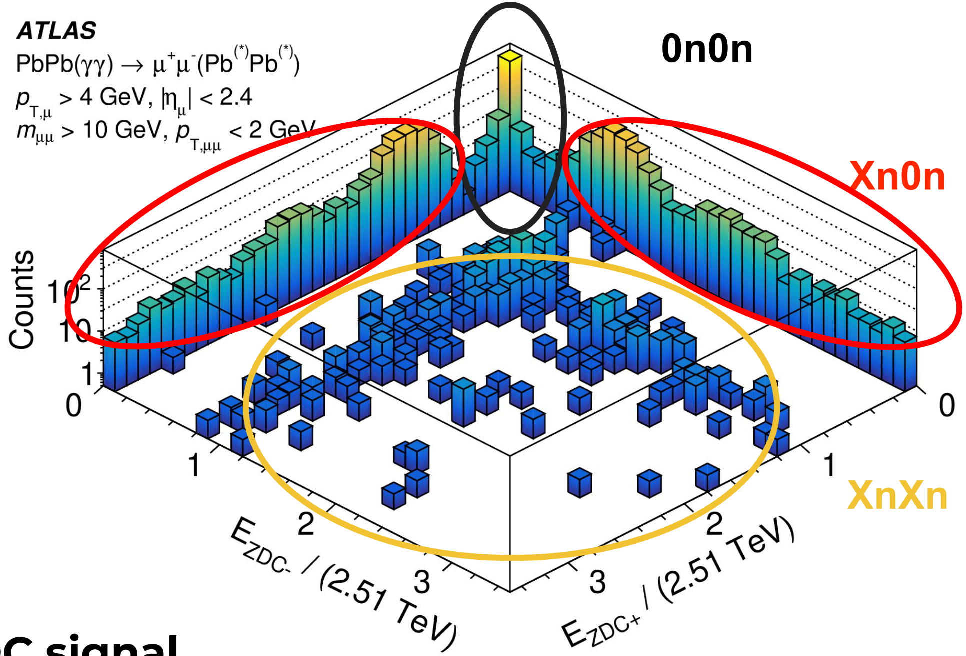
- Large general-purpose detector with almost 4π coverage
- $\eta = -\log(\tan(\theta/2))$
- Inner detector $|\eta| < 2.5$
- Muon system $|\eta| < 2.7$ (trig. 2.4)
- Calorimetry out to $|\eta| < 4.9$
- Zero-Degree-Calorimeters capture neutral particles with $|\eta| > 8.3$





Signal categories - ZDC selection

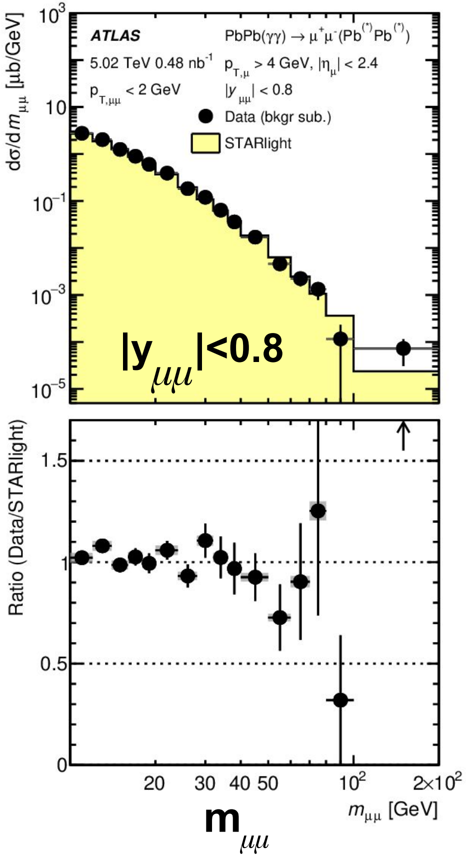
- Different processes present **different activity in the forward region**:
  - photon-photon interaction - ions stay intact
  - Background events with nuclear breakup
- **Three classes** defined, based on the signal in the ZDC

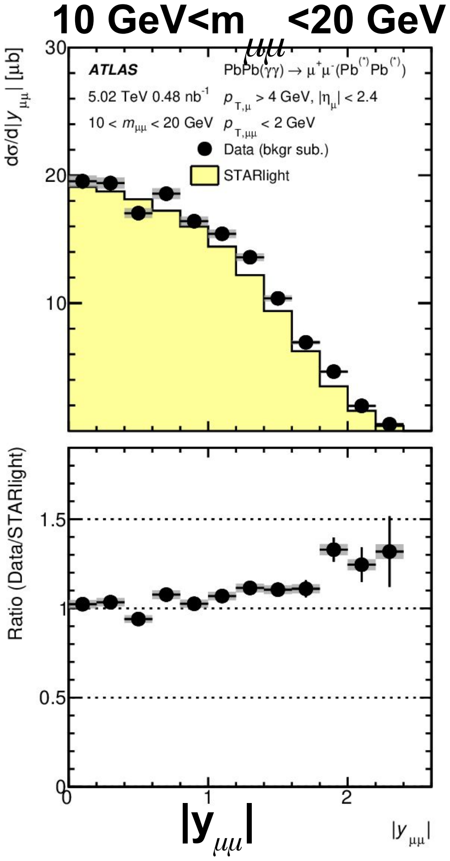


- The **association between** given **ZDC signal** and given **process** is **nontrivial**
  - Migrations due to ion excitation and presence of EM pile-up

Dimuons - results

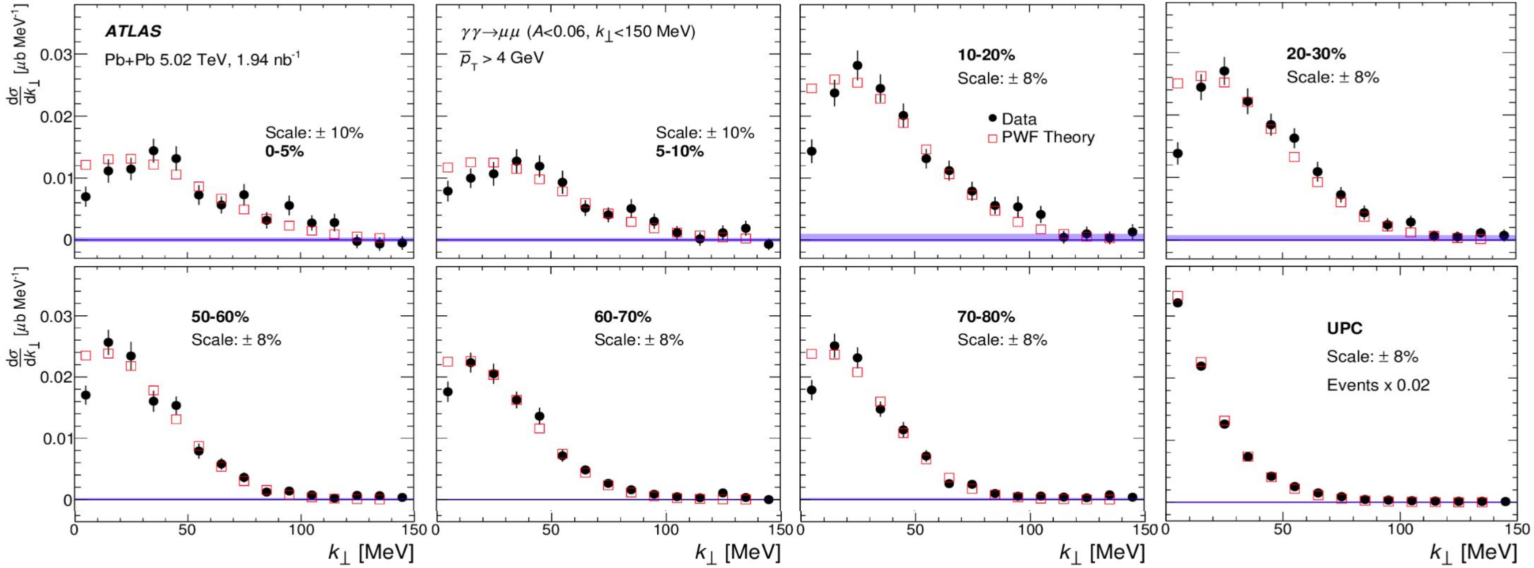
- The **cross-sections** are **measured** as a function of $m_{\mu\mu}$ (in 3 slices of $|y_{\mu\mu}|$) and $|y_{\mu\mu}|$ (in 3 slices of $m_{\mu\mu}$)
- Data is **compared with STARlight** MC simulation of $\gamma\gamma \rightarrow \mu^+\mu^-$ process w/o FSR
- The overall shape of the spectra is **well described** out to the highest masses
- Some hints of decreasing ratio for larger $m_{\mu\mu}$
- **Good agreemen**t is found in central region of rapidity distribution (small $|y_{\mu\mu}|$), but data to simulation ratio increases with $|y_{\mu\mu}|$





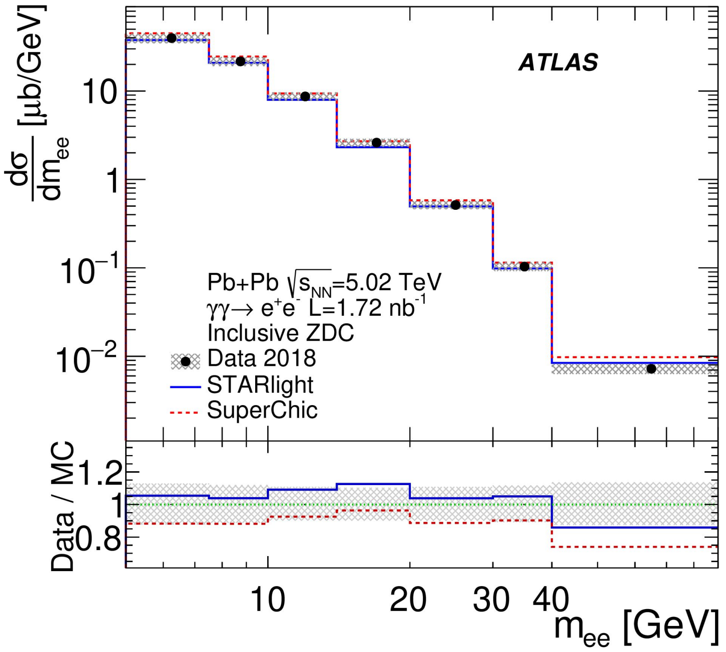
Non-UPC dimuons

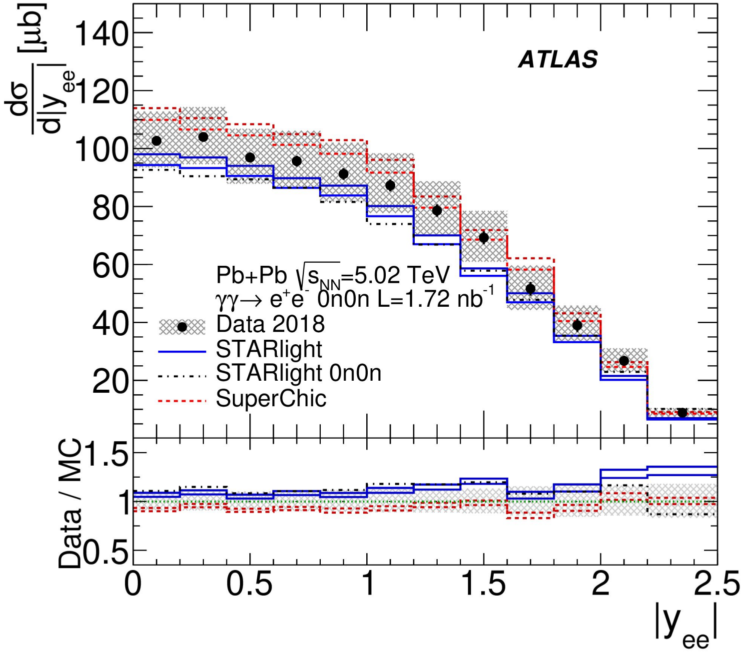
- The dimuons originating from photon-photon interactions were also observed in non-UPC events by ATLAS Phys. Rev. C 107 (2023) 054907
- Studied α and $k_\perp$ (=$\alpha\pi(p_{T,1}+p_{T,2})/2$) distributions as a function of event centrality
- Observed depletion in cross-section in the region of low-$k_\perp$, not predicted by models



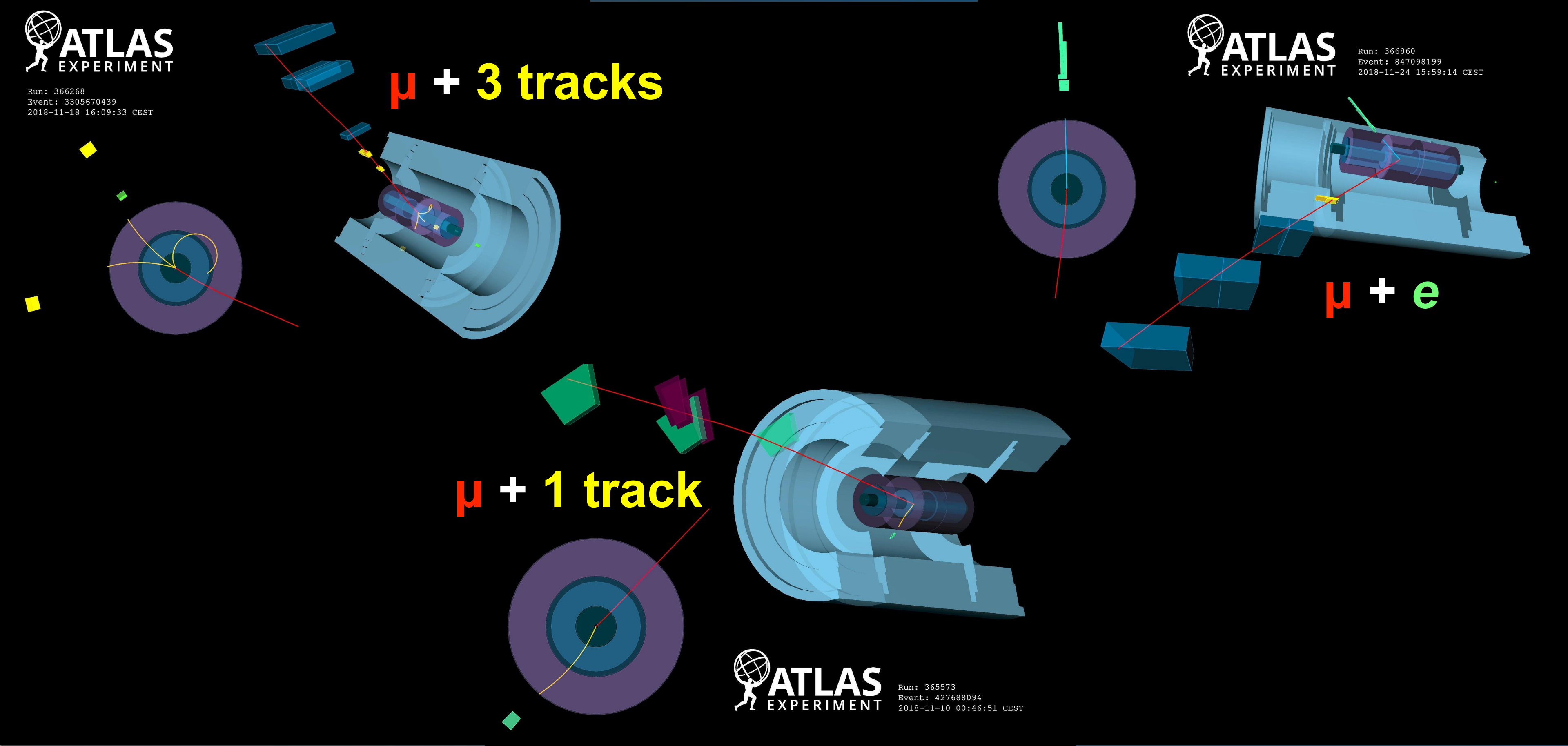
Dielectrons - results

- **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





Ditau events

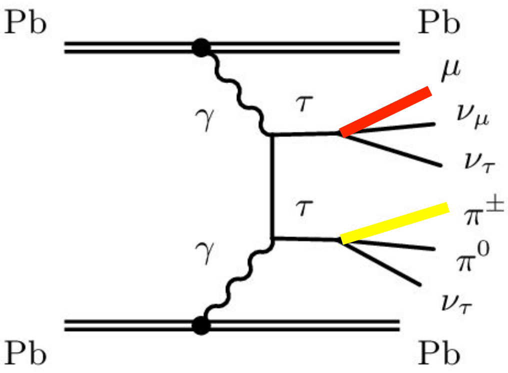


Signal categories

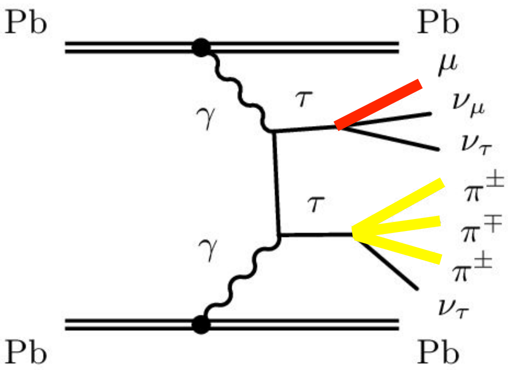
Phys. Rev. Lett. 131 (2023) 151802

- **First observation** of $\gamma\gamma \to \tau\tau$ process in HI UPC using 1.44 nb^{-1} of Pb+Pb data recorded by ATLAS in 2018
- **Signal** τ-leptons are **low-energetic**, typically with $p_T < 10$ GeV
  - No standard ATLAS identification of τ-leptons is used
- Events classified based on the charged τ-lepton decay products
- **Three signal categories:**

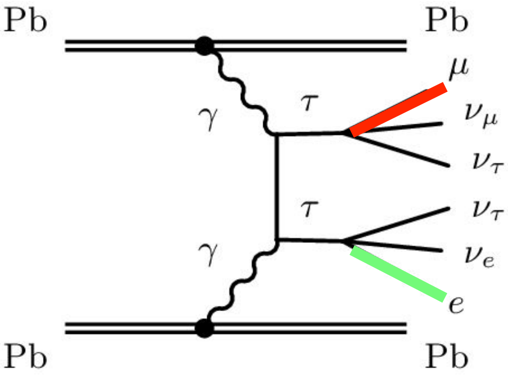
μ1T-SR: muon + 1 track



μ3T-SR: muon + 3 tracks

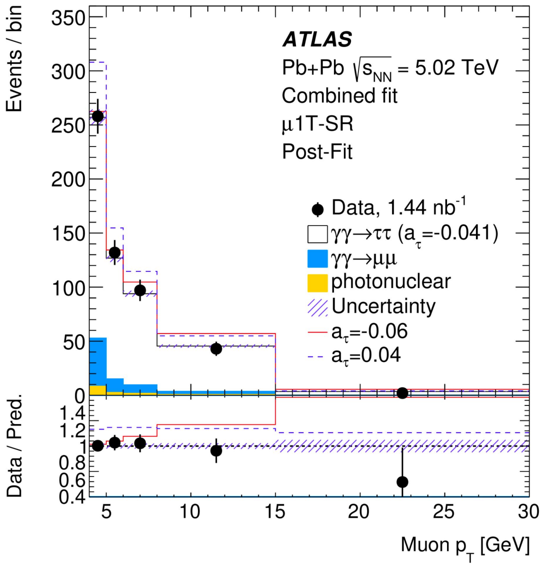


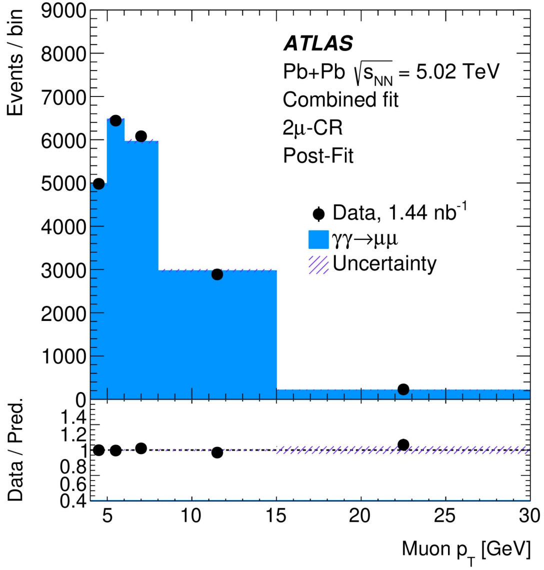
μe-SR: muon + electron



Observation of exclusive ditau production

- 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 (> 5σ) of $\gamma\gamma \to \tau\tau$ process

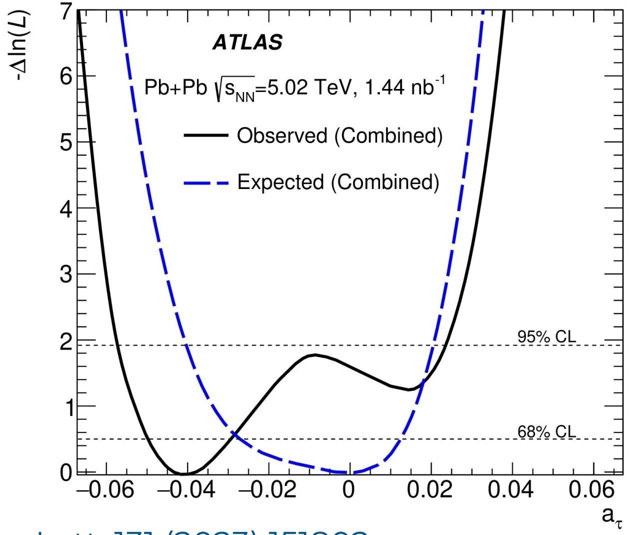


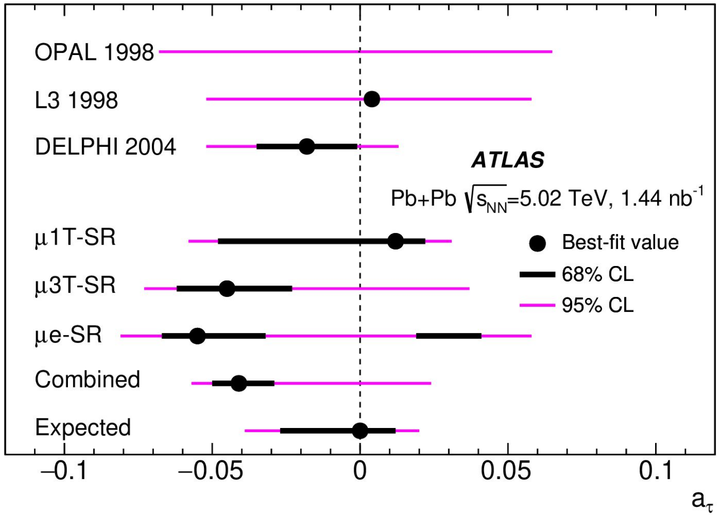


Phys. Rev. Lett. 131 (2023) 151802

τ-lepton g–2

- Constraints similar to DELPHI (EPJ C 35 (2004) 159)
- Expected 95% CL limits from combined fit: $-0.039 < a_\tau < 0.020$
- The **best fit value** is $a_\tau = -0.041$, with the corresponding **95% CL interval** being **(−0.057, 0.024)**
- The result is largely limited by statistics, what will improve with Run-3 data





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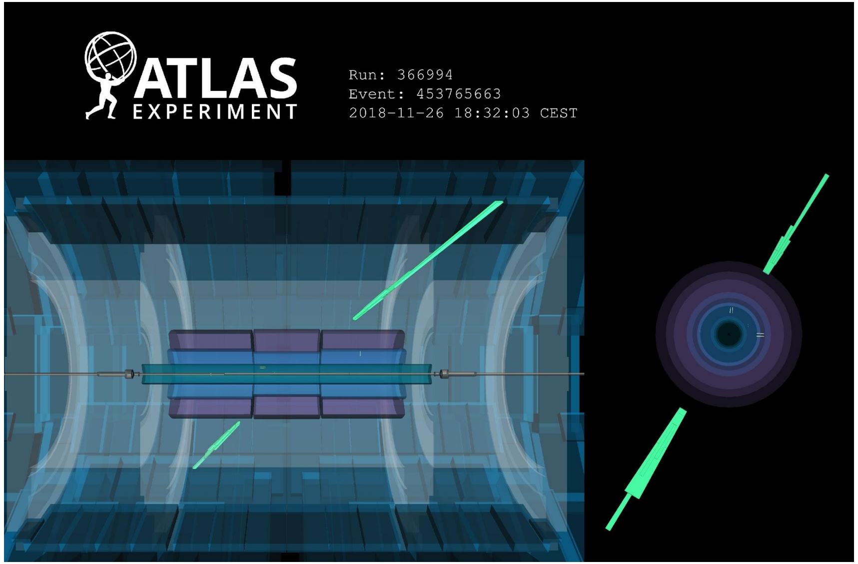
Light-by-light scattering

- **Light-by-light (LbyL) scattering** is a rare Quantum Electrodynamics (QED) process
- Several LbyL measurements done using Pb+Pb collision data at 5.02 TeV, collected by LHC experiments:
  - ATLAS: 2015: Nature Physics 13 (2017) 852,
  - 2018: Phys. Rev. Lett. 123 (2019) 052001
  - **2015+2018: JHEP 03 (2021) 243**
  - CMS: 2015: Phys. Lett. B 797 (2019) 134826
- Signal selection:
  - Two photons with $E_T > 2.5$ GeV, identified with dedicated NN ID algorithm)
  - Diphoton mass above 5 GeV, low diphoton p_T, low diphoton acoplanarity: $1- |\Delta\phi|/\pi < 0.01$
  - Veto on any extra low-p_T tracks

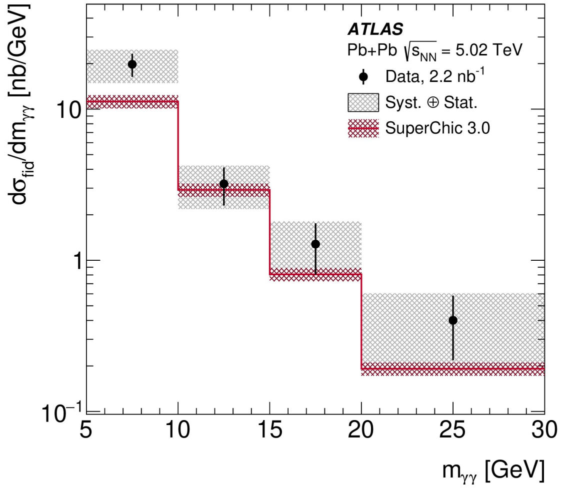


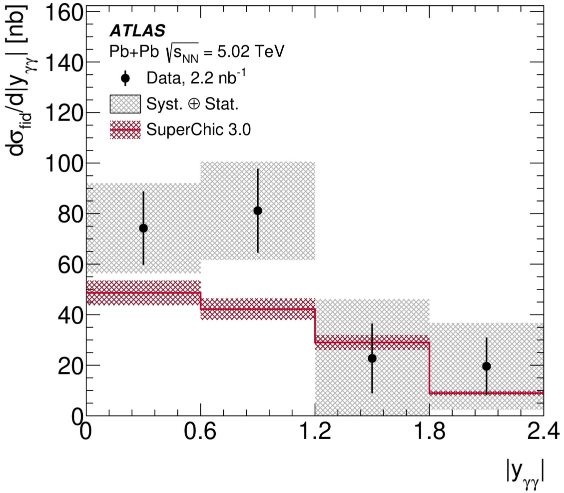
JHEP 03 (2021) 243

Differential cross sections

- Cross-section is measured in a fiducial phase space, defined by the requirements reflecting event selection
- The measured **integrated fiducial cross-section** is **σ_{fid} = 120 ± 17(stat.) ± 13(syst.) ±4 (lumi.) nb**, while the predicted values are 80 ± 8 nb (Szczurek et al.) and 78 ± 8 nb (SuperChic3)
- Differential fiducial cross-sections are **unfolded to particle level** in the fiducial phase space to correct for bin migrations due to detector resolution effects
- The unfolded differential fiducial cross-sections are compared with the predictions from SuperChic v3.0
- **No significant differences** between predictions and data are seen

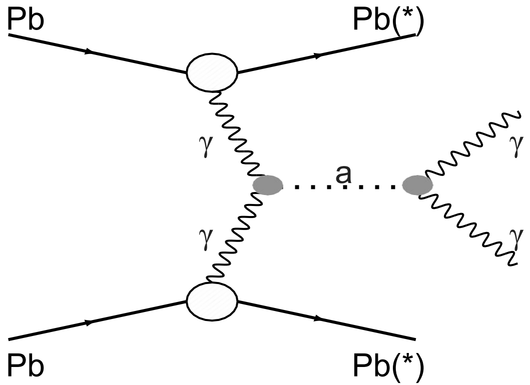
JHEP 03 (2021) 243



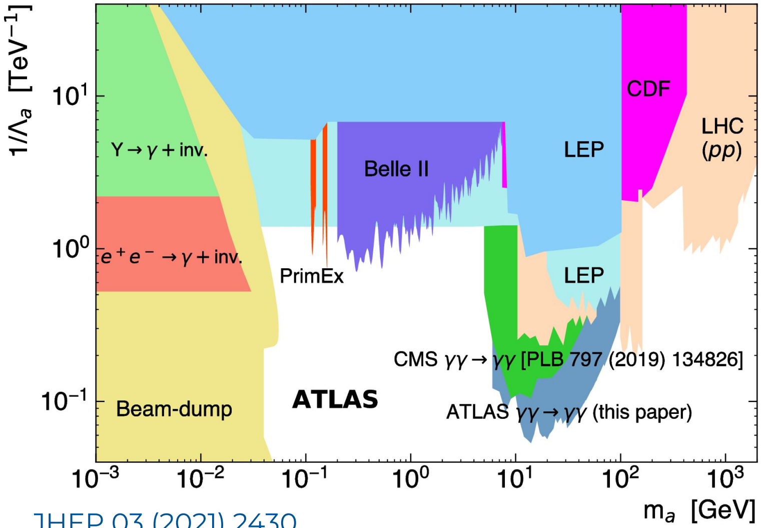


ALP limits

- Axion-like particles (ALP) are **hypothetical particles** that appear in many theories with a spontaneously broken global symmetry
- ALPs may **decay to two photons,** what might be visible as an excess in $m_{\gamma\gamma}$ distribution
- Simulated LbyL events are normalized to the data yield, after subtracting $\gamma\gamma \to e^+e^-$ and CEP $gg \to \gamma\gamma$ contributions and excluding the mass search region
- ALP contribution is fitted individually for every mass bin
- **No significant deviation** from the **background-only hypothesis** is observed
- The result is used to estimate the upper limit on the **ALP cross-section** and **ALP coupling** $1/\Lambda_a$ at 95% confidence level



Existing constraints from JHEP 12 (2017) 044

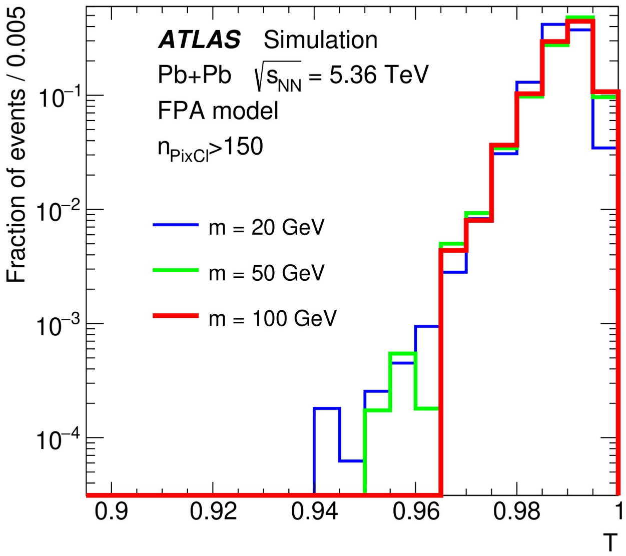


JHEP 03 (2021) 2430

Search for magnetic monopoles

- Magnetic monopoles are hypothetical particles
- Could be produced via Schwinger mechanism in presence of strong magnetic fields
- Data from 2023 Pb+Pb collisions @ 5.36 TeV was used (0.262/nb)
- Events selected with following criteria:
  - $N_{tracks} \leq 1$, $N_{topoclusters} \leq 1$ → removes collision background
  - $N_{PixelClusters}$ >150, including $N_{IBLclusters}$ > 50 → suppress beam-induced background (BIB)
  - additional cut to remove noise Pixel modules
- Signal region definition:
  - transverse thrust T > 0.95

$$T = 1/n_{\mathrm{PixCl}} \sum_{i=1}^{n_{\mathrm{PixCl}}} |\hat{r}_i \cdot \hat{n}|$$

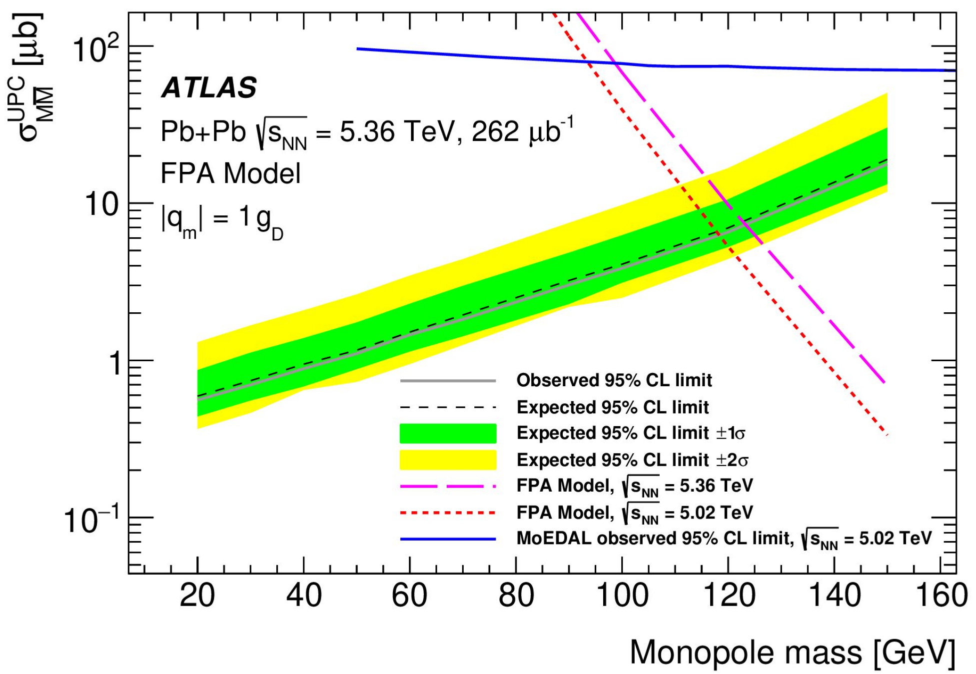


T_{max} = 1 - fully aligned pixel clusters
T_{min} = 2/π - cluster uniformly distributed in transverse plane

arXiv:2408.11035

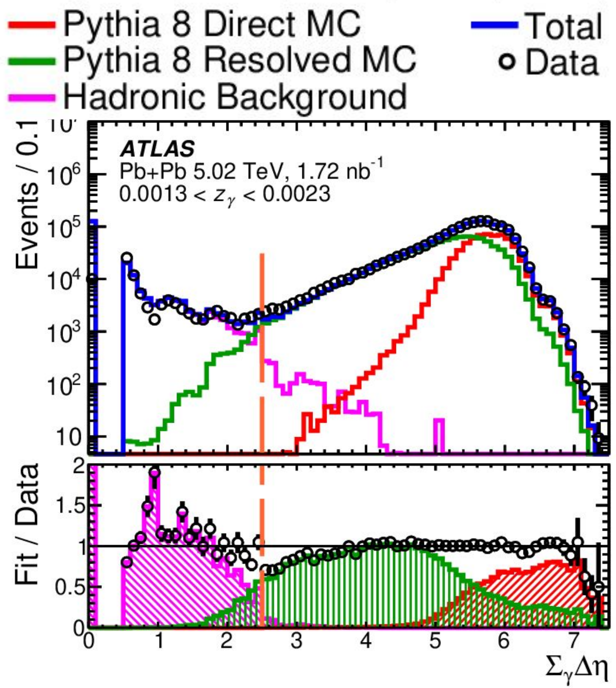
Results

- 3 events in SR, consistent with background estimate
- Cross-section upper limits computed in mass range between 20 and 150 GeV
- Monopoles with a single Dirac magnetic charge and mass below 120 GeV are excluded

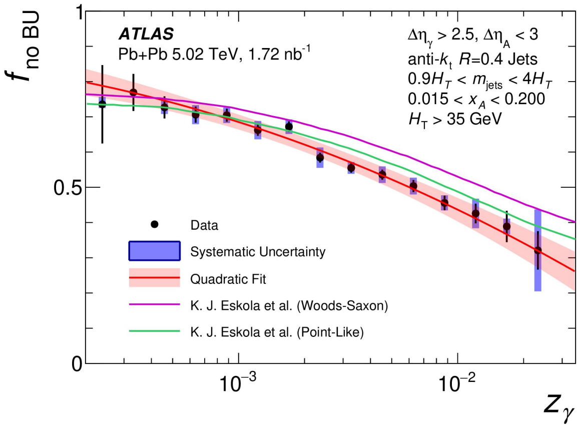


arXiv:2408.11035

Dijet production in UPC



- Photonuclear jet production was studied
  - direct photons or hadronic excitations of photons (resolved photons) striking the nucleus
- Requirement of rapidity gaps in the photon direction - one of ions intact
  - detailed analysis of gaps gave relative proportion between direct and resolved photon events

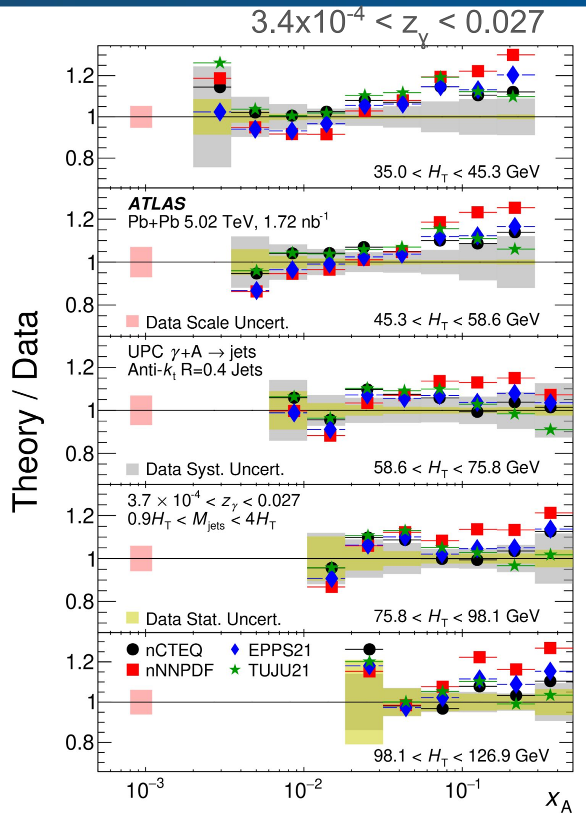


- measured fraction of events with no nuclear breakup
  - needed to compare to correctly compare to predictions

arXiv:2409.11060

Dijet production in UPC

- Measured triple differential cross-sections
- Ratios wrt to various nPDF fits
- Typically the best agreement with nCTEQ
- TUJU agrees better at higher H_T
- nNNPDF overpredicts cross-sections at high H_T and x_A
- Conclusions may change when NLO predictions available, and photon flux modelling uncertainties taken into account



proxy for momentum transfer

$$H_T \equiv \sum_i p_{T\,i}$$

nuclear parton momentum fraction

$$x_A \equiv \frac{m_{\text{jets}}}{\sqrt{s_{\text{NN}}}} e^{-y_{\text{jets}}}$$

parton momentum fraction in photon direction

$$z_\gamma \equiv \frac{m_{\text{jets}}}{\sqrt{s_{\text{NN}}}} e^{+y_{\text{jets}}}$$

arXiv:2409.11060

Summary

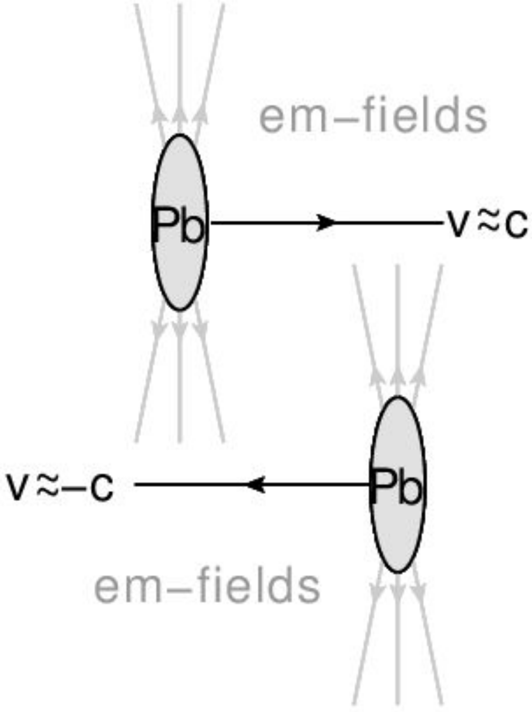
- The UPC physics covers a broad range of processes
- Results from dielectrons and dimuons provide valuable constraints for **theoretical approaches** in the modeling of the **initial photon flux**
  - Very important to make correct predictions for more rare processes
- The **light-by-light scattering** was observed by ATLAS and provided constraints on the ALP production
- The measurement of the **τ-lepton anomalous magnetic moment** using exclusive ditau events **is competitive** with previous measurements
  - Improvement in precision expected with **more data**
- **Improvemed constraints** on magnetic monopole production cross-section
- Measurement of jets in photonuclear collisions provide **unique constraints on nuclear parton distributions**

This work was supported by UNCE24/SCI/016 grant

Backup

Ultra-peripheral collisions

- Heavy-ion collisions - primarily for studies of quark-gluon plasma
- But… 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



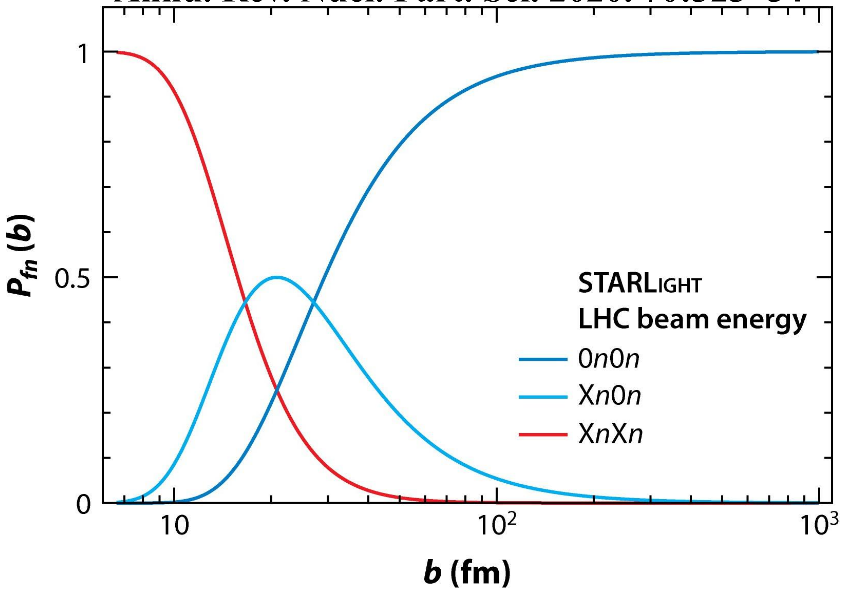
Trigger system

- The LHC provides pp collisions at the rate of 40 MHz and ion collisions up to about 10 MHz
- Only some events are interesting for further analysis and others has to be filtered out online - this is done by the trigger system
- For every process there is a need for a dedicated trigger
- In ATLAS experiment trigger system consist of hardware (Level-1) and software (High Level Trigger, HLT) component
- At first step event rate is reduced to 100 kHz, in the next step down to few kHz
- Ideal trigger provides high **efficiency** and high **purity**
- One of the methods to measure the trigger efficiency is to use signal events selected by other, independent trigger
- Then, efficiency = $\frac{\text{Events selected by both triggers}}{\text{Events selected by independent trigger}}$

ZDC fractions - *b* dependence

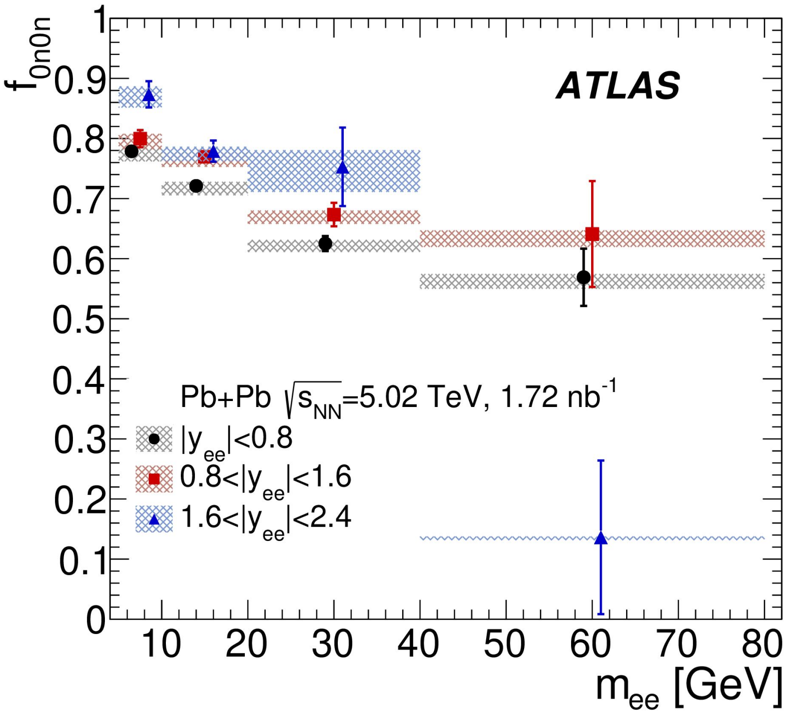
- The probability of producing a given **ZDC category depends on** the value of the **impact parameter**, *b* (based on the Coulomb excitation probabilities ~ $1/b^2$)
- With different selections on the ZDC topology, we probe different ranges of dilepton mass and impact parameters, as photon fluxes vary with *b*

Annu. Rev. Nucl. Part. Sci. 2020. 70:323–54



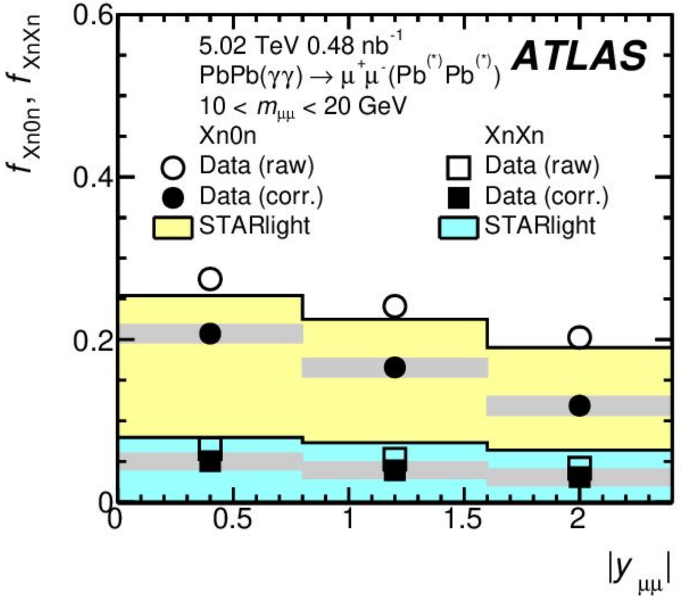
f0n0n fractions - dielectrons

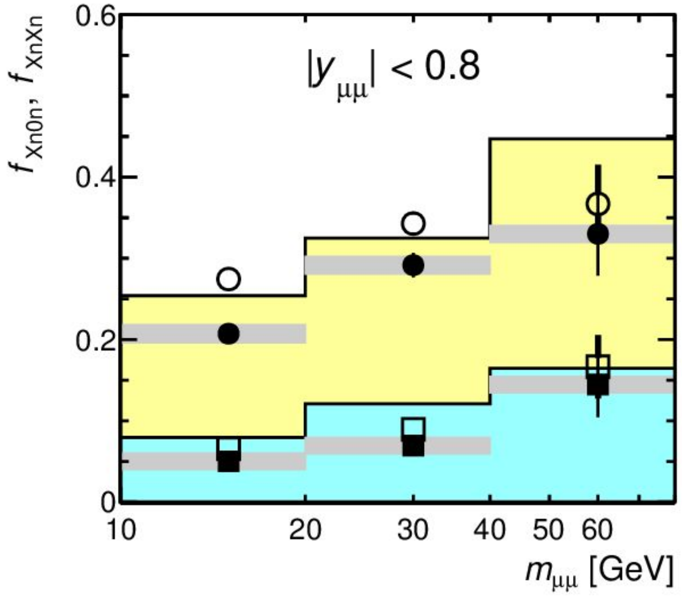
- The **0n0n category** should in principle be very **pure**, at least in terms of dissociative background
- To select 0n0n sample, events are required to have **low energy** deposits in the **ZDC** (below 1 TeV on each side)
- There is no ZDC simulation in the MC samples, so a dedicated approach, correcting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

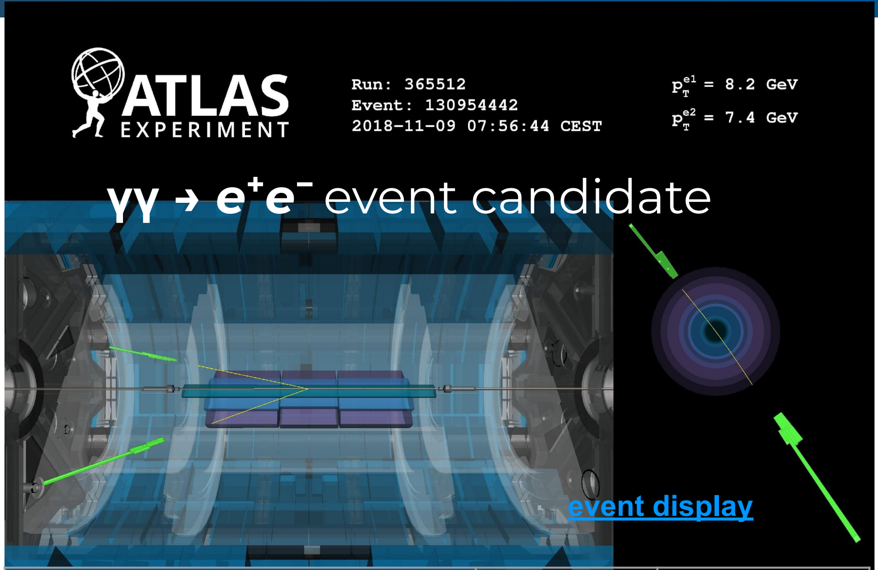
- The raw (open points) fractions higher than corrected (full markers)
- The corrected f_{Xn0n} and f_{XnXn} fractions are compared with the **STARlight predictions** — the latter are systematically **higher** for f_{Xn0n} and f_{XnXn} fractions





Event characteristics & selection

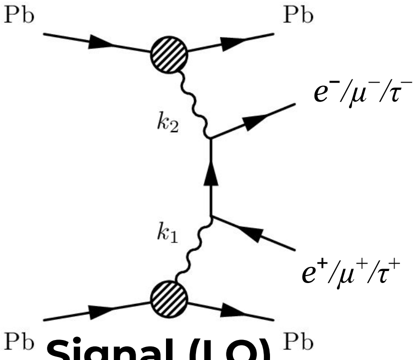
- Exclusive dilepton events are characterized by :
  - **Two low-p_T opposite sign leptons** (of the order of a few GeV) and otherwise empty detector
  - Leptons are produced **back-to-back** in azimuthal angle (described by low dilepton transverse momentum, $p_{T,ll}$)
- ATLAS optimized to detect high-energy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



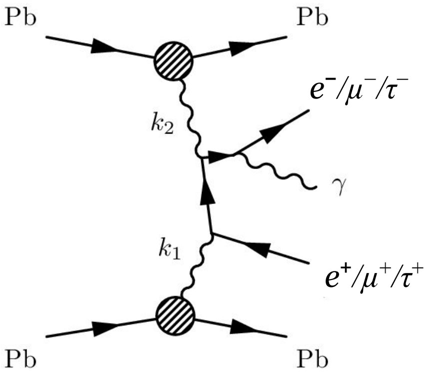
	muons	electrons
Int. Lumi [nb^{-1}]	0.48	1.72
p_T^l >	4 GeV	2.5 GeV
$\|\eta_l\|$ <	2.4	2.5
m_{ll} >	10 GeV	5 GeV
p_{Tll} <	2 GeV	2 GeV

Background sources for $\mu\mu$/ee

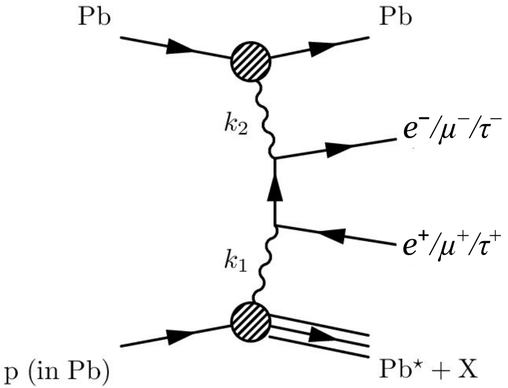
- Several background sources are considered:
  - **dissociative** production of l^+l^- pairs - estimated with data-driven method (template taken from LPair/SuperChic4+Pythia8 in *pp* collisions)
  - **Upsilon(nS)** production - estimated with STARlight+Pythia8 MC samples (only in dielectron measurement)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



Signal (LO)



Signal with FSR



dissociative background

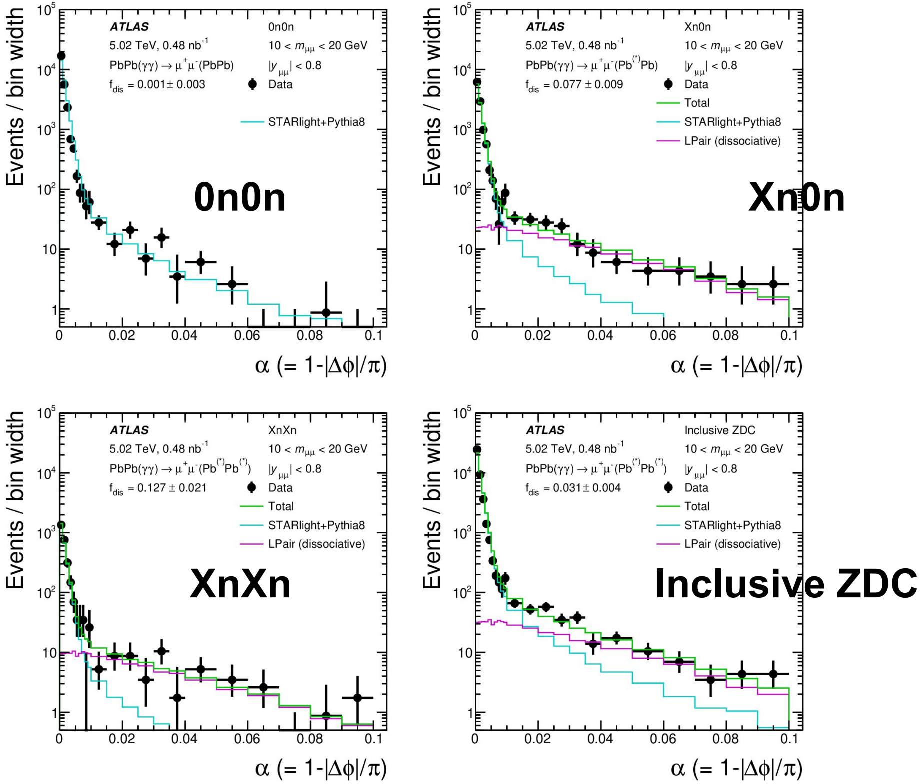
Dimuons

Phys. Rev. C 104 (2021) 024906

Dimuons - background

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

- 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

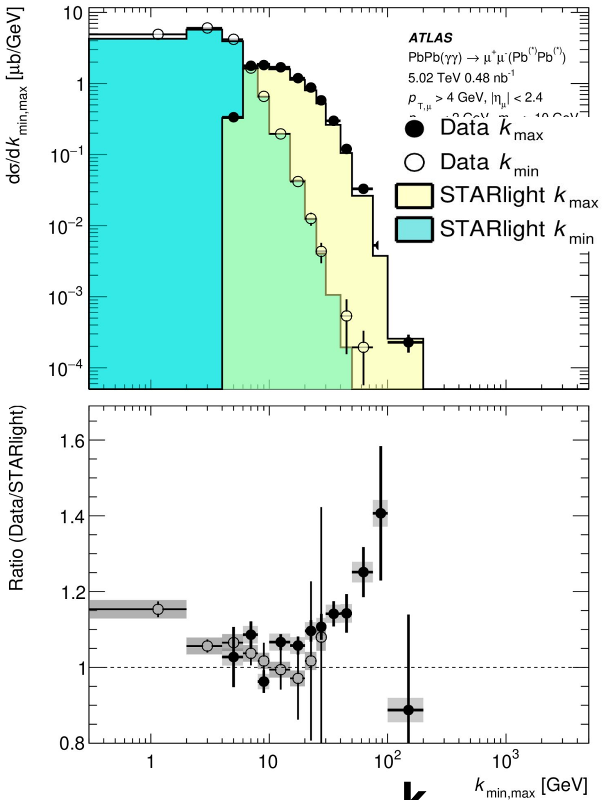


What can we learn about initial photon fluxes?

- 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 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



$k_{min,max}$

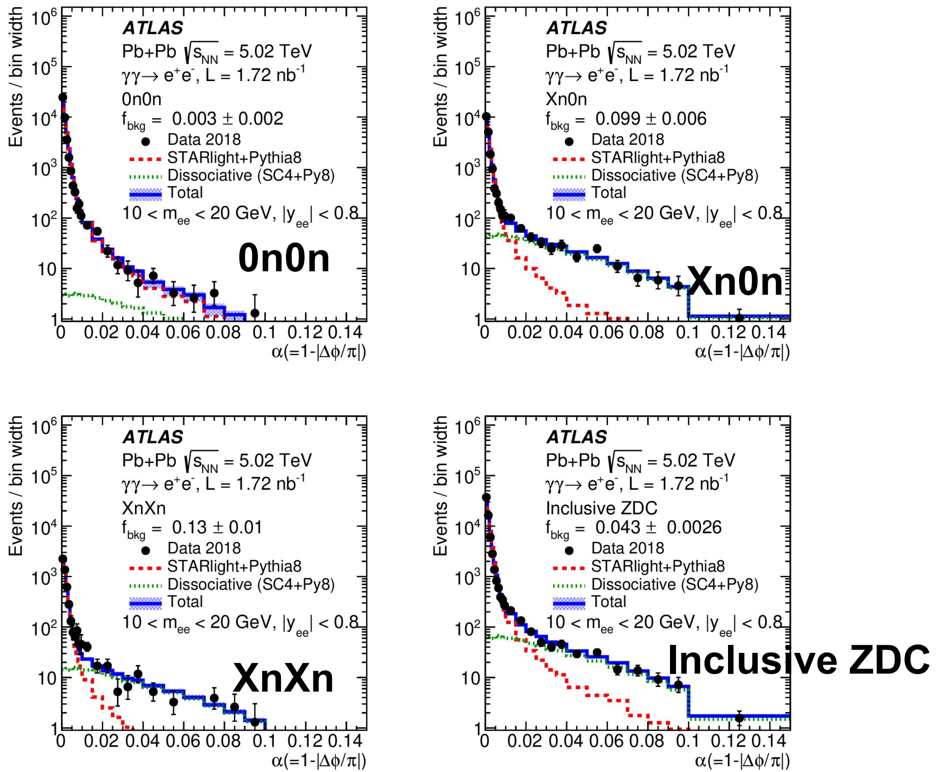
Dielectrons

JHEP 06 (2023) 182

Dielectrons - background

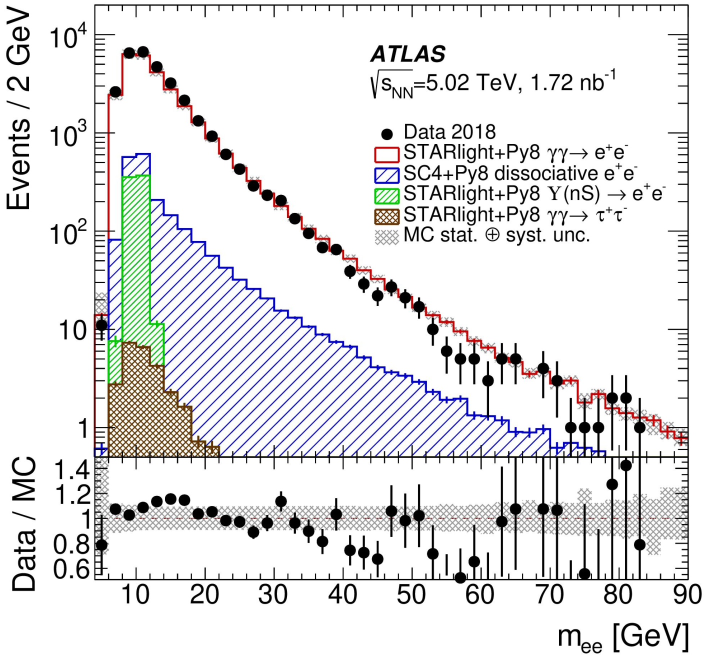
$$P(\alpha, m_{ee}, y_{ee}) = (1 - f_{dis}) P_{EPA}(\alpha, m_{ee}, y_{ee}) + f_{dis} P_{dis}(\alpha, m_{ee}, y_{ee})$$

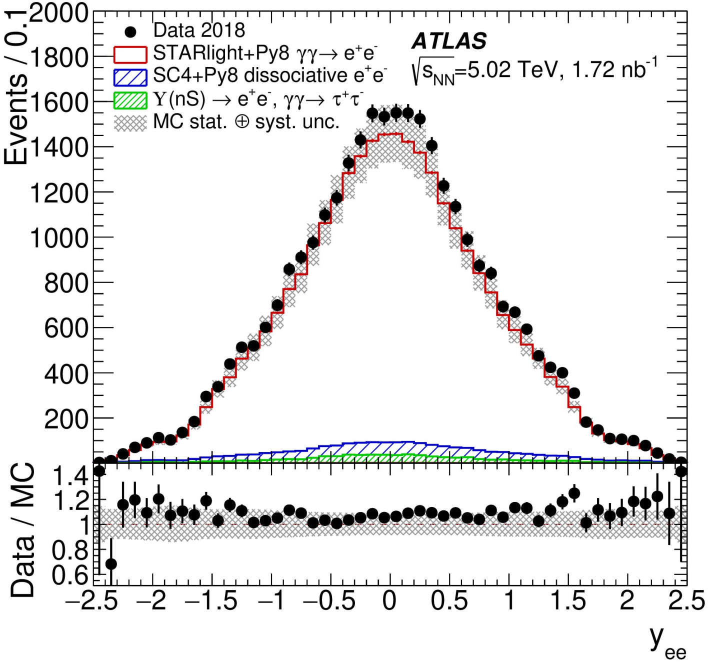
- The background samples for **single dissociation** from SuperChic4+Pythia8 are used instead of LPair
- Fitting procedure similar to the one used in dimuon measurement
- Small background contributions from **ditau** and **Upsilon(nS)** production also estimated



Detector-level control plots

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



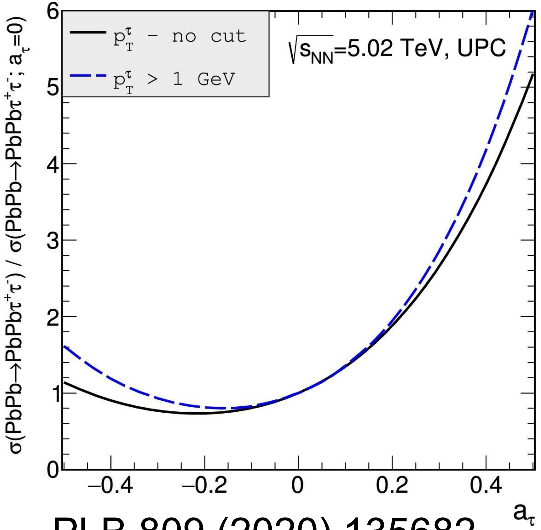


Ditaus

Phys. Rev. Lett. 131 (2023) 151802

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 quantified by the lepton **anomalous magnetic moments** $a_l = (g-2)_l/2$
- 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** using $\gamma\gamma\rightarrow\tau\tau$ events 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



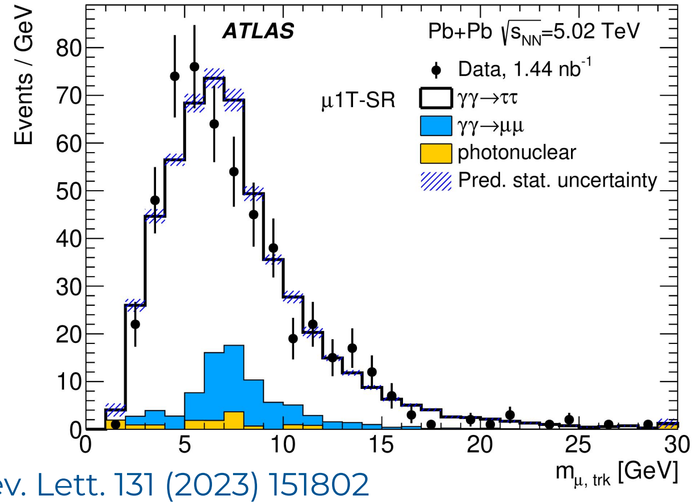
PLB 809 (2020) 135682

Ditau event selection

- Single muon trigger recording events having muon with p_T > 4 GeV
- Veto on forward neutron activity (based on ZDC signal) -> MC samples reweighed

Kinematic selection:

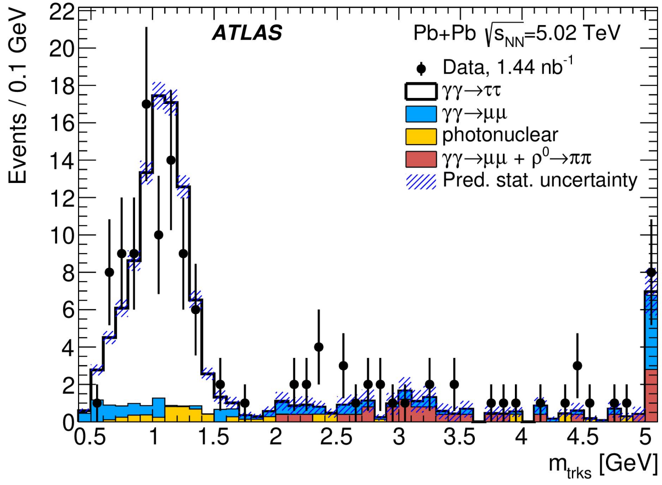
- muons: p_T > 4 GeV, $|\eta|$ < 2.4
- electrons: p_T > 4 GeV, $|\eta|$ < 2.47
- tracks: p_T > 100 MeV, $|\eta|$ < 2.5



Phys. Rev. Lett. 131 (2023) 151802

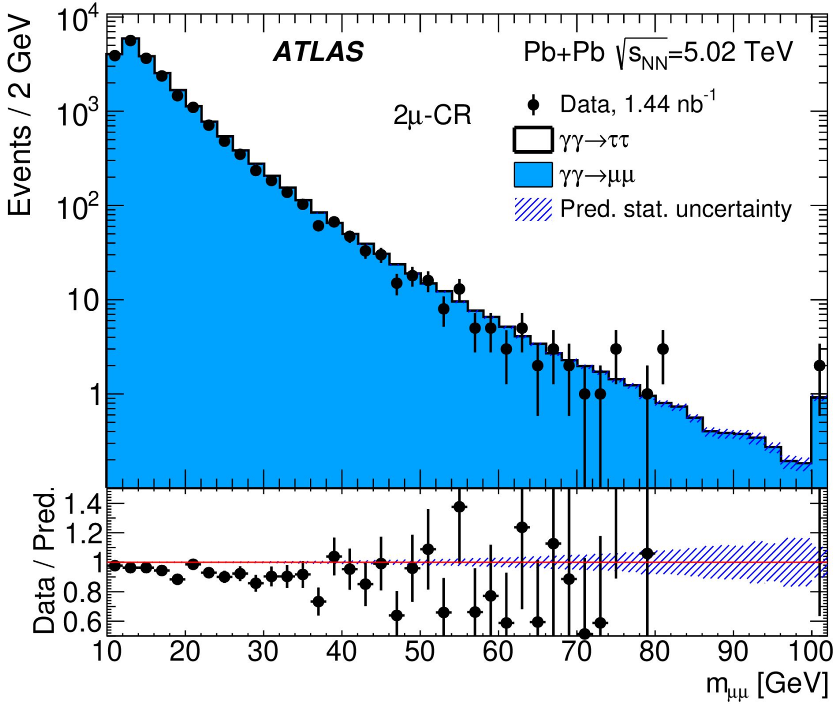
Other requirements:

- veto on additional low-p_T clusters (for μ1T-SR and μ3T-SR) and low-p_T tracks
- For μ1T-SR: $p_T^{\mu,trk}$ > 1 GeV
- For μ3T-SR: m_{3trks} < 1.7 GeV



Backgrounds

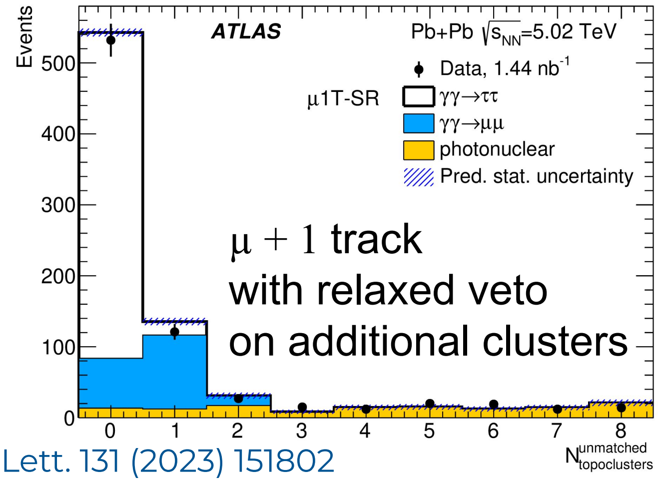
- Main **background contributions** from dimuon production and diffractive photonuclear interactions
- Background from **γγ → μμ(γ) production** estimated using **MC simulation (STARLight+Pythia8, Madgraph5),** constrained by a data CR
- Already pre-fit distributions in the 2μ-CR show good agreement of data and MC

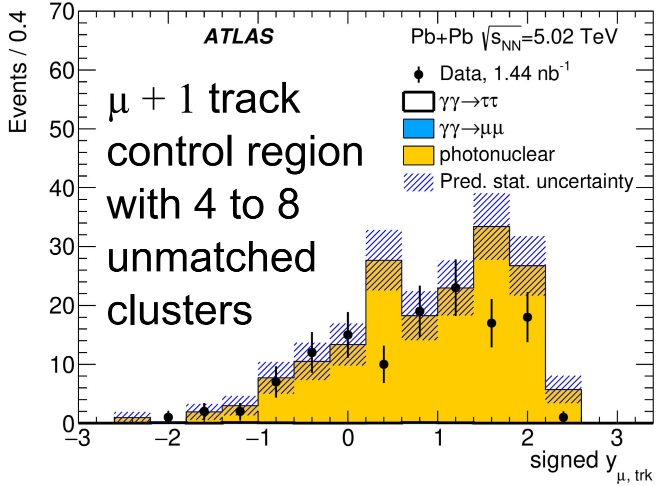


Phys. Rev. Lett. 131 (2023) 151802

Backgrounds

- **Diffractive photonuclear** in μ1T-SR and μ3T-SR 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





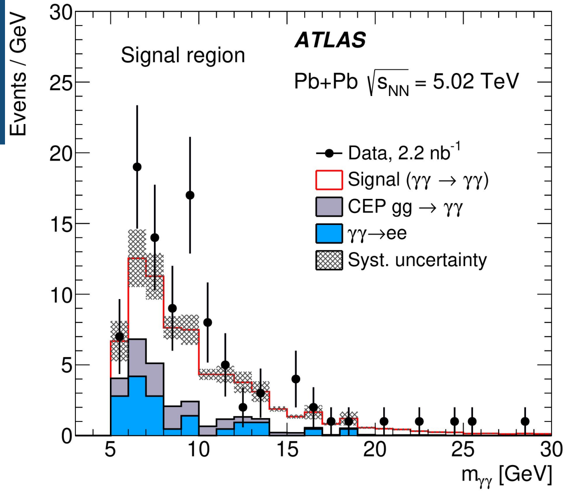
Phys. Rev. Lett. 131 (2023) 151802

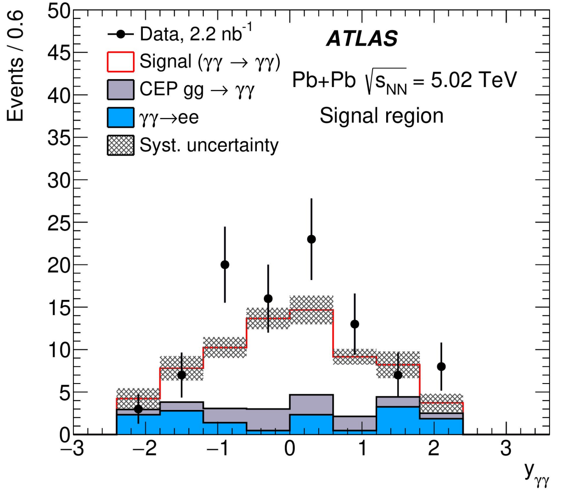
γγ→γγ

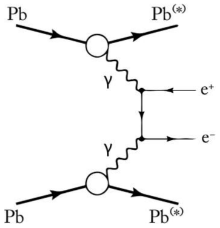
JHEP 03 (2021) 243

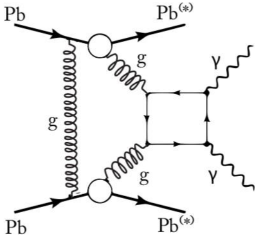
Backgrounds

- Various background sources considered, the largest contributions from:
  - Exclusive dielectron production **$\gamma\gamma \rightarrow e^+e^-$**
  - Central Exclusive Production (CEP) ***gg*** **→ γγ**
- **Main background** sources are estimated using **data-driven** techniques
- **Shapes** of the distributions are **in good agreement** but data excess visible in both distributions









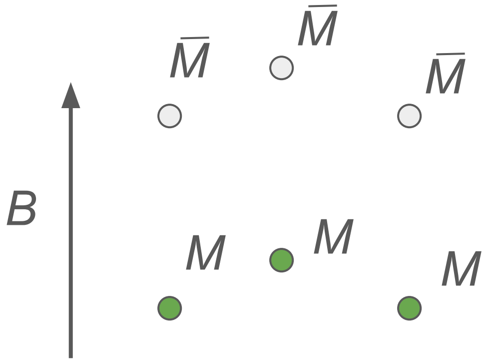
JHEP 03 (2021) 243

magnetic monopoles

arXiv:2408.11035

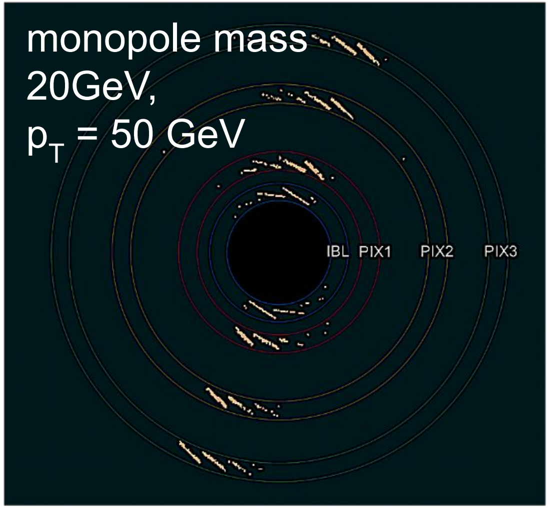
Search for magnetic monopoles

- Magnetic monopoles are hypothetical particles
- Could be produced via Schwinger mechanism in presence of strong magnetic fields
  - Such fields present in UPC - up to B ~ 10^{16} T at LHC Pb+Pb collisions
- Cross-section for magnetic monopoles production in HI UPC can be computed nonperturbatively using semiclassical models
  - not possible for production in pp
  - however models working well only down to monopole mass of 20 GeV



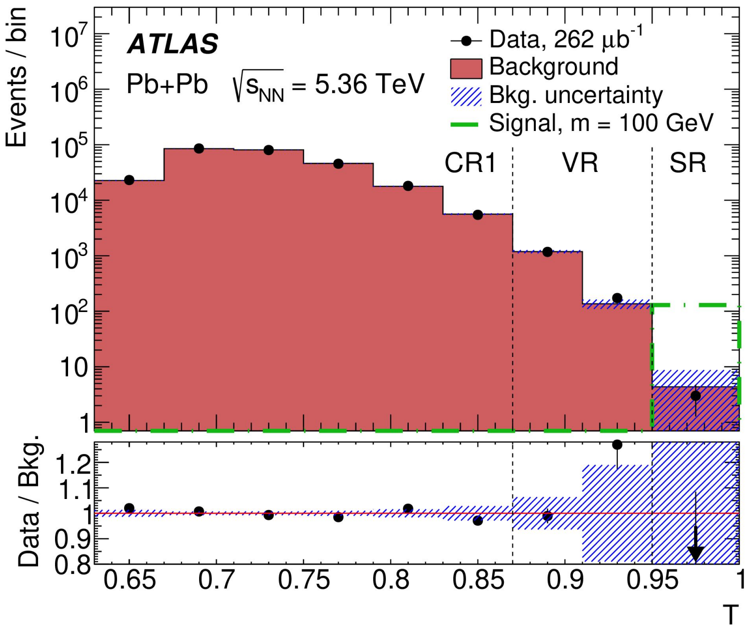
Signal characteristics

- Event signature checked with the MC simulation
- Monopoles with p_T < 300 GeV won't reach calorimeter, below p_T of 30 GeV, they don't reach the SCT
- **Focus on signals in the Pixel detector**
- Only XnXn category (however only fraction of signal there)
- **Dedicated trigger strategy** with
  - ZDC A+C coincidence
  - veto on total transverse energy in calorimeter (< 10 GeV)
  - more than 100 hits in Pixel detector



Background

- Collisional background reduced with event selection
- Residual background originating from beam-induced effects
  - characterised by particles almost parallel to the beam line
- Fully **data-driven** method for **background estimation**
- Background shape from CR2
  - ZDC_XOR-triggered events with 1-3 (soft) calorimeter clusters, incl. at least one out-of time (t<-10 ns), no *T* cut
- Estimated bkg in SR: 4 ± 4 events



$$N_{\mathrm{bkg}}^{\mathrm{SR}} = (N^{\mathrm{CR1}}/N_{T<0.87}^{\mathrm{CR2}})N_{T>0.95}^{\mathrm{CR2}}$$