Search for monopole production in ultraperipheral Pb+Pb collisions with the ATLAS detector

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on behalf of the ATLAS collaboration

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Heavy-ion ultraperipheral collisions

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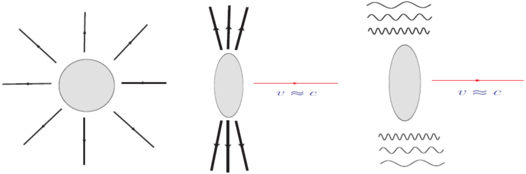
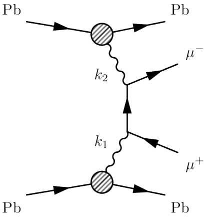


- Ultraperipheral (UPC) Pb+Pb collisions are **intense source of quasi-real photons**, with each photon flux scaling with $\mathbf{Z^2}$
- Photon-induced processes characterised by a **very clean signature** and almost **no background**
- Various types of interactions possible:



SM photon-photon

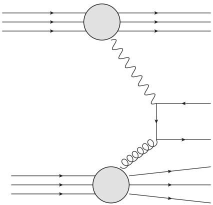
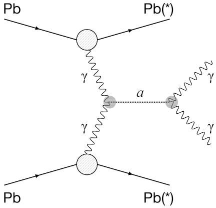


Photo-nuclear



BSM photon-photon

- UPC collisions are a very attractive place to look for BSM processes

Magnetic monopoles

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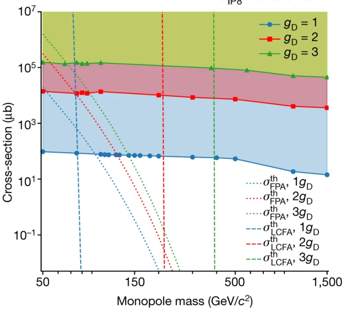
- Pb+Pb UPC can be used to search for magnetic monopole pair production
- Occurs in strong magnetic fields, primarily via the Schwinger mechanism
- First search in Pb+Pb from MoEDAL released in 2022 (Nature 602, 63–67 (2022))
- Large coupling of $M\bar{M}$s to photons → perturbation theory could not be used → affects pp searches interpretations
- $M\bar{M}$ cross-section in HI UPC can be computed nonperturbatively using semiclassical models, e.g. **free-particle approximation** (FPA, arXiv:1902.04388):

Nature 602, 63–67 (2022)



$$\sigma_{FPA} = \frac{\omega}{m}\frac{2(q_m B)^4 R_{Pb}^4}{9\pi^2 m^4 \omega^2}\ exp(-4m/\omega)$$

- Breaks down for light monopoles (m < 20 GeV)
- Back-to-back monopole pair production with isotropic angular distribution

$$\frac{d\sigma_{FPA}(|p|)}{d\sigma_{FPA}(0)} = exp\left[-4/\omega\left(\sqrt{m^2+|p|^2}-m\right)\right]$$

Low-energy monopole interaction in ATLAS

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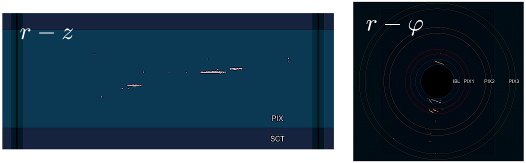
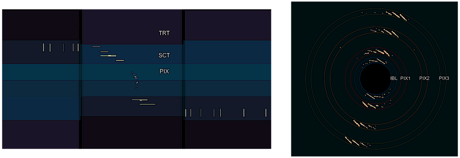
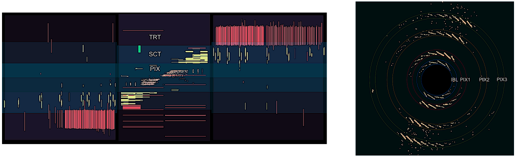
- An example: simulated magnetic monopoles pair with m = 20 GeV and varying p_T
- Parabolic trajectory in r-z
- No bending in r-φ
- Energy loss via δ-electrons: always bend anti-clockwise in B-field
- Monopoles with $\mathrm{p_T} < 300$ GeV – never reach calorimeter
- Monopoles with $\mathrm{p_T} < 30$ GeV – typically do not reach SCT
- Main focus: **Pixel detector activity**!



p_T = 20 GeV



p_T = 50 GeV



p_T = 280 GeV

ZDC UPC categories

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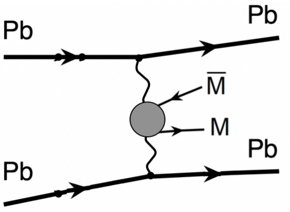
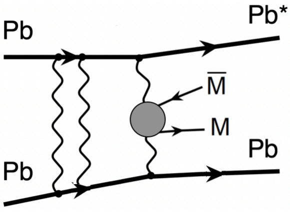
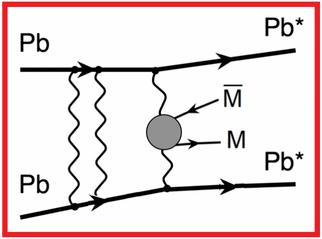
0n0n	Xn0n	XnXn
		Our primary signal category

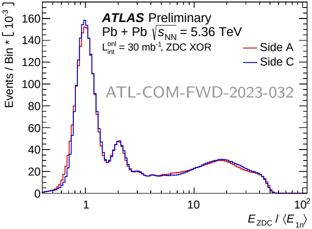






∼60% events @ $m_X = 30$ GeV	∼30% events @ $m_X = 30$ GeV	∼10% events @ $m_X = 30$ GeV

- Different UPC topologies possible due to emission of neutrons
- Crucial role of **Zero Degree Calorimeters**
- Fraction of XnXn events increases with central system mass



Analysis strategy

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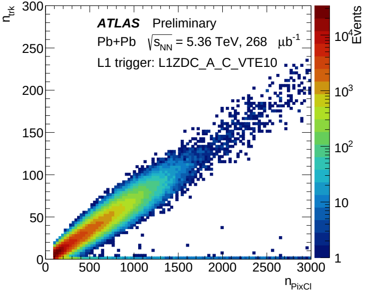
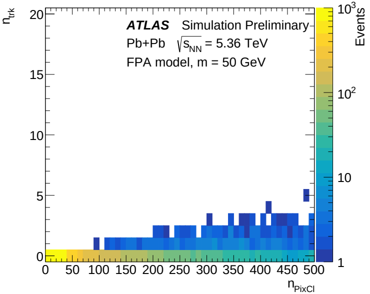
- Using 2023 Pb+Pb data at $\sqrt{s_{\rm NN}} = 5.36$ TeV, 1.6 nb^{-1}
  - First ATLAS result using Run3 Pb+Pb data
- Signal trigger:
  - L1: presence one or more neutrons in both ZDCs, and total $E_T < 10$ GeV in calorimeter
  - HLT: presence of more than 100 Pixel clusters
  - Prescale: about 1/6 of events were saved → **0.262 nb^{-1}**
- Supporting trigger: ZDC activity on either side, same as signal trigger otherwise – background estimation, **9.6 μb^{-1}**





Offline event selection

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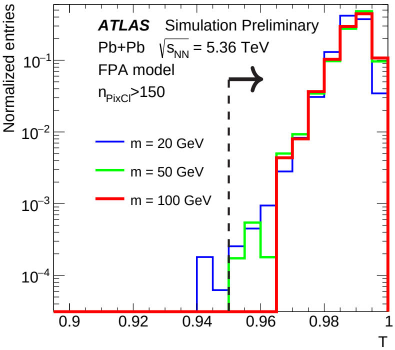
- At least 150 Pixel clusters, including at least 50 IBL clusters
- At most one reconstructed charged-particle track ($p_T > 100$ MeV, $|\eta| < 2.5$, $|d_0| < 1$ mm) to suppress collision backgrounds
- At most one calorimeter cluster ($E_T > 100$ MeV, $|\eta| < 4.9$) to suppress the remaining collision backgrounds
- Additional cuts to suppress Pixel detector noise
- Signal region definition: transverse thrust $\mathbf{T} > \mathbf{0.95}$

$$T = \frac{1}{n_{PixCL}} \sum_{i=i}^{n_{PixCL}} |\hat{r}_i \cdot \hat{n}|$$



Background estimation (I)

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- Background: **Beam-induced-background** (BIB) – characterised by particles almost parallel to the beam line, especially one with small radial range
- **Fully data-driven** background estimation method
- Events in CR2 are used to extrapolate the background contribution from CR1 to SR – cross-checked in VR

Region	SR	VR	CR1	CR2
Trigger		signal		ZDC XOR
n_{trk}		≤ 1		≤ 1
n_{TC}		≤ 1		1–3 (incl. at least 1 OOT)
n_{PixCl}		> 150		> 150
n_{IBLCl}		> 50		> 50
$f_{\text{leading-module}}$		< 0.9		< 0.9
T	> 0.95	0.87–0.95	≤ 0.87	—

Background estimation (II)

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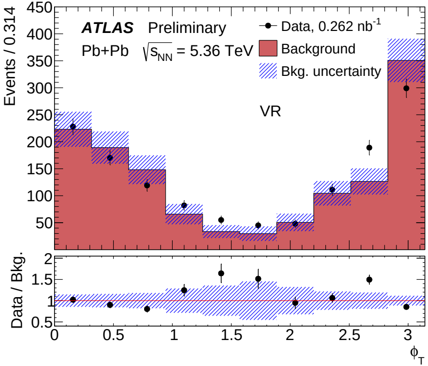
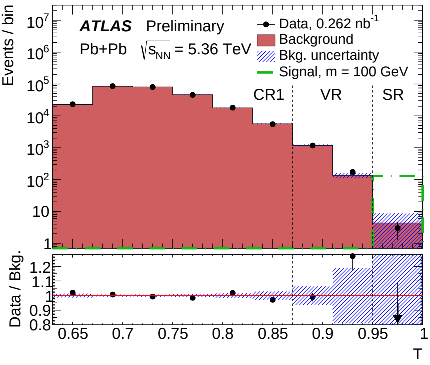
- CR2-based background estimate adequately describes the data
- Enhanced event activity at $\phi_T \approx 0$ and $\phi_T \approx \pi$ characteristic for BIB
- Background estimate in SR: **4 $\pm$ 4 events**





XnXn correction

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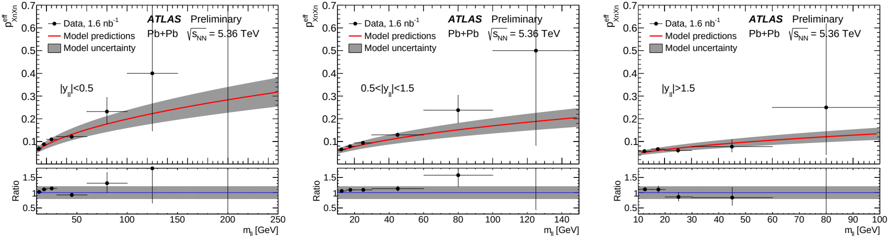
- Need to correct signal Monte Carlo (0n0n) for XnXn requirement in the data:

$$p^{eff}_{XnXn} = (2 \cdot f_{0nXn} \cdot p_{EMPU} + f_{XnXn}) \cdot (1 + f_{diss})$$

- f_{0nXn} and f_{XnXn} derived from SuperChic 4.2
- $f_{diss} = 0.13$ derived from $\gamma\gamma \to l^+l^-$ events Phys. Rev. C 104 (2021) 024906 JHEP 06 (2023) 182
- p_{EMPU} estimated to be 0.038 for signal trigger
- Cross-checked with dilepton events in three rapidity bins



Systematic uncertainties

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- **Detector material modelling**: alternative geometries with increased detector material: $<$1% $\rightarrow$ 20% effect
- **δ-electrons propagation range**: low energy δ-electrons evolution simulated only down to some kinetic energy threshold: $<$3% effect
- **δ-electrons production modelling**: dE/dx formulas for ionisation by monopoles have $\pm$3% uncertainty in analysis kinematic region $\rightarrow$ reducing δ-electrons production rate by 3%: 2-5% effect
- **Luminosity** (3.5%, preliminary)
- **Pixel noise modelling**: mismodelling observed while comparing "empty" events with neutrino-gun MC $\rightarrow$ pixel cluster overlay applied: $<$1% effect
- **Calorimeter noise modelling**: procedure similar to pixel noise modelling: $\sim$ 1% effect
- **XnXn weight modelling** (20%): covers data/MC differences observed for $\gamma\gamma \rightarrow l^+l^-$ production and differences between nominal (SuperChic) and alternative models for f_{0nXn} and f_{XnXn} (STARlight MC, Gamma-UPC MC)

Mass point [GeV]	20	30	40	50	60	70	90	100	120	150
Relative sig. yield var.	0.21	0.22	0.21	0.22	0.22	0.22	0.22	0.24	0.30	0.38

Magnetic monopole production limits

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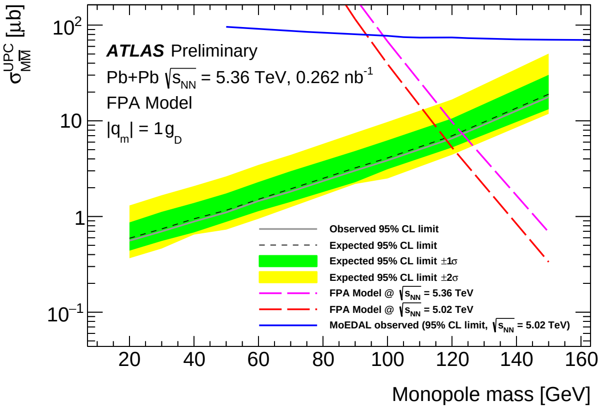
- **3 events in SR**, consistent with background estimate of 4 $\pm$ 4 events
- Cross-section upper limits computed using the CL_s method for $q_m = 1g_D$, in mass range between 20 and 150 GeV and assuming the FPA model
- Better sensitivity compared to MoEDAL by **at least order of magnitude**
- Excluded magnetic monopoles with mass $<$ 120 GeV



Summary

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- The first ATLAS result using 2023 Pb+Pb data and the first ATLAS search for magnetic monopoles in Pb+Pb collisions
- A novel method devised by ATLAS for searches of $M\bar{M}$ in Pb+Pb UPC data presented
- Search relying on semi-classical FPA model with $q_m = 1g_D$
- Main focus on the Pixel detector activity
- Crucial role of ZDC in triggering $\rightarrow$ XnXn correction required to properly describe the data
- Largest systematic uncertainty contribution from alternative detector geometries and XnXn correction
- Background estimate of 4 ± 4 events with 3 events observed
- **The best cross-section upper limits for $M\bar{M}$ in mass range between 20 and 150 GeV are set**
- This new approach **can be further explored** for other similar searches, i.e. heavy ioninsing particles (HIPs)

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Backup

Signal MC control plots

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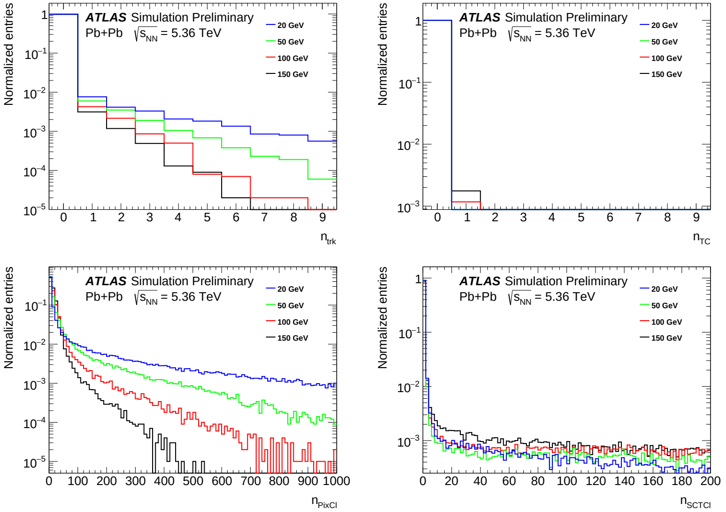

CR control plots

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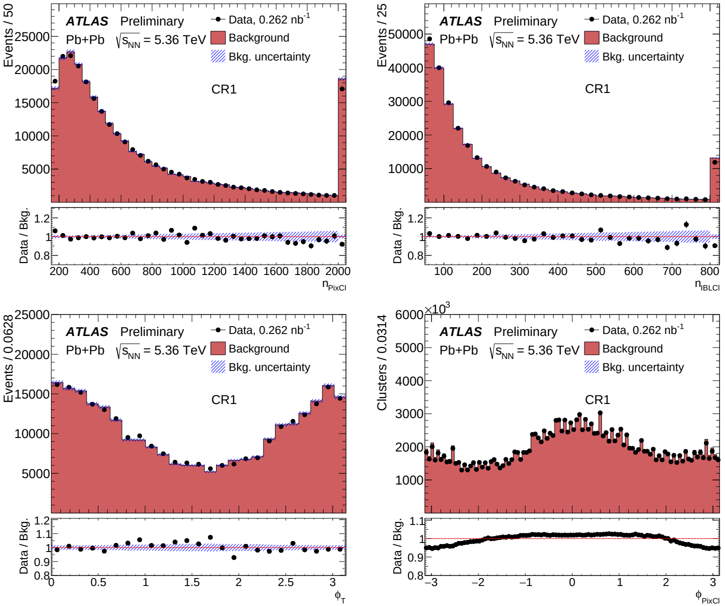

VR control plots

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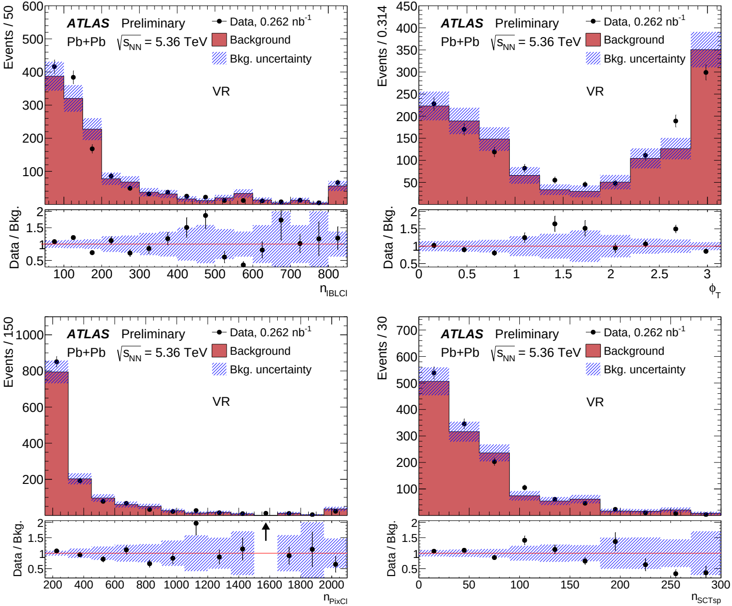

FPA monopoles average p_T

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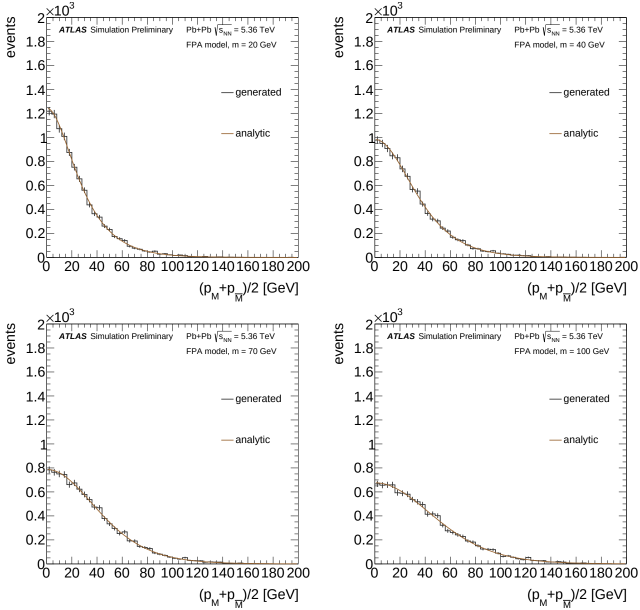

Transverse thrust

- Monopole has straight-line trajectory in r-φ $\rightarrow$ passage through the detector forms highly collimated shower (δ-electrons)
- Calculate "transverse thrust" using Pixel clusters:

$$T = \frac{1}{n_{PixCL}} \sum_{i=1}^{n_{PixCL}} |\hat{r_i} \cdot \hat{n}|$$

- $\hat{\boldsymbol{r}}_{\boldsymbol{i}}$ – unit vector of cluster orientation in the lab frame
- $\hat{\boldsymbol{n}}$ – direction which maximizes thrust

Properties:

- $T \in [{}^{2}/_{\pi}, 1]$
- $T \approx {}^{2}/_{\pi}$ – uniform distribution, roughly the property of our backgrounds
- $T \approx 1$ – perfectly aligned distribution, approximately the property of our signal