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

arXiv:2408.11035

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Białasówka Seminar
29 November 2024

Maxwell's equations
In vacuum

Gauss's Law for E:

$$\nabla \cdot \mathbf{E} = 0$$

Gauss's Law for B:

$$\nabla \cdot \mathbf{B} = 0$$

Faraday's Law:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Ampere's Law:

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t}$$

Symmetry between **E** and **B** in vacuum

Maxwell's equations

Adding electric charge and current

Gauss's Law for E:

$$\nabla \cdot \mathbf{E} = \rho_e$$

Gauss's Law for B:

$$\nabla \cdot \mathbf{B} = 0$$

Faraday's Law:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Ampere's Law:

$$\nabla \times \mathbf{B} = \mathbf{J_e} + \frac{\partial \mathbf{E}}{\partial t}$$

Symmetry **broken** by electric charge and current

Maxwell's equations

Adding magnetic charge and current

Gauss's Law for E:

$$\nabla \cdot \mathbf{E} = \rho_e$$

Gauss's Law for B:

$$\nabla \cdot \mathbf{B} = \rho_m$$

Faraday's Law:

$$\nabla \times \mathbf{E} = -\mathbf{J_m} - \frac{\partial \mathbf{B}}{\partial t}$$

Ampere's Law:

$$\nabla \times \mathbf{B} = \mathbf{J_e} + \frac{\partial \mathbf{E}}{\partial t}$$

- Symmetry could be restored by magnetic charges and currents
- Dirac (1931): the existence of magnetic monopole would explain charge quantisation

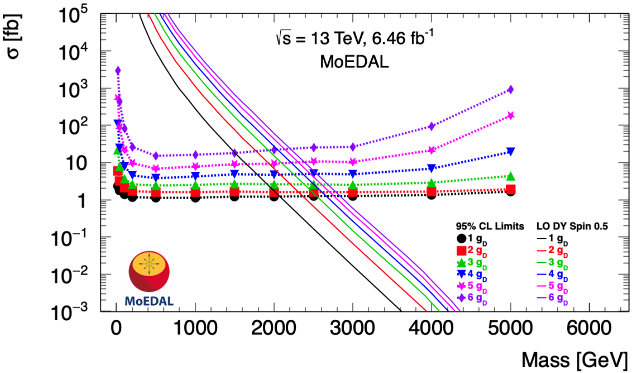
$$\frac{ge}{\hbar c} = \frac{n}{2}; \qquad n = 1, 2, ...$$

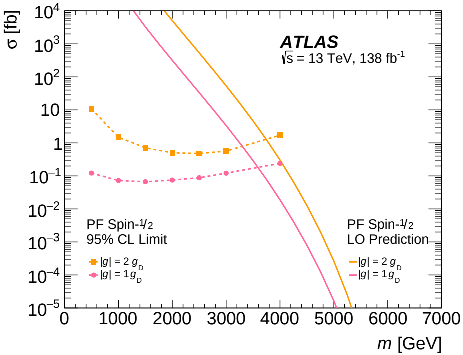
$$g = n g_D \Rightarrow g_D = \frac{\hbar c}{2e} = \frac{e}{2\alpha} \approx 68.5e$$

Recent monpole searches at the LHC (*pp*)

MoEDAL Collaboration, arXiv:2311.06509

ATLAS Collaboration, JHEP 11 (2023) 112

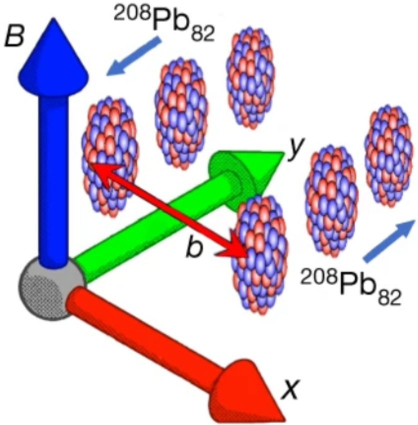




- Complementary detection techniques
- Both searches use production modelled by Drell-Yan or photon fusion (PF)
  - Derived from e^+e^- scattering using naive substitution $\alpha_{EM} \rightarrow \alpha_{MM}$
  - Large γ-MM coupling constant $\alpha_{MM} \sim \frac{1}{4\alpha_{EM}} \approx 34 \rightarrow$ perturbative calculations cannot reliably predict cross-section

Magnetic monopoles in heavy-ion collisions

- LHC Pb+Pb collisions @ 5.02 TeV $\rightarrow$ peak **B** $\sim$ $\mathbf{10^{16}}$ **T**
- Occurs at **distances of twice the nuclear radius**: $b \sim 2R$
- $\sim\mathbf{10^4}$ **greater than the strongest known astrophysical magnetic fields**



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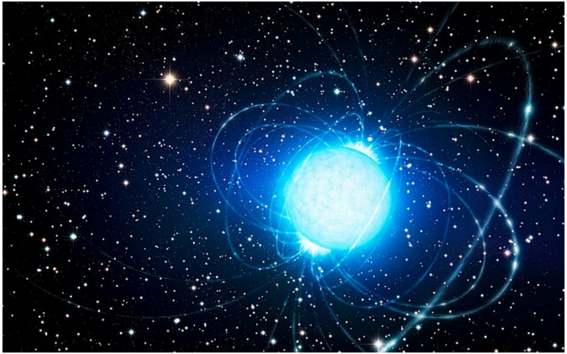
Artist's conception of a **magnetar**

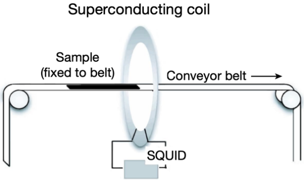


Magnetic monopoles in heavy-ion collisions

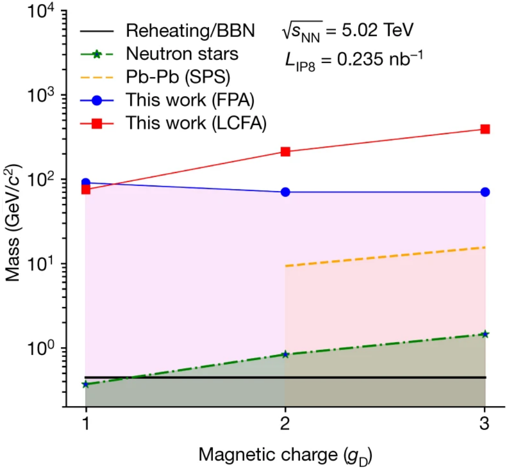
- Production via the **Schwinger mechanism** in strong magnetic fields
  Gould, Ho, Rajantie, PRD 100, 015041 (2019), PRD 104, 015033 (2021)
  - Analogy to originally described spontaneous creation of e^+e^- pairs in presence of ultra-strong electric field
- Advantages over *pp* searches:
  - Cross-section calculated using **semiclassical techniques** $\rightarrow$ do not suffer from non-perturbative nature of coupling
  - Composite monopoles enhance the cross-section
  - No exponential suppression ($e^{-4/\alpha} \sim 10^{-236}$) for composite monopole models

    Drukier & Nussinov, Phys. Rev. Lett. 49 (1982) 102

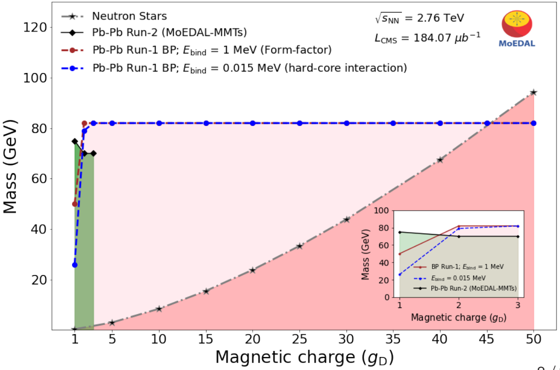
Monopole searches in LHC heavy-ion collisions



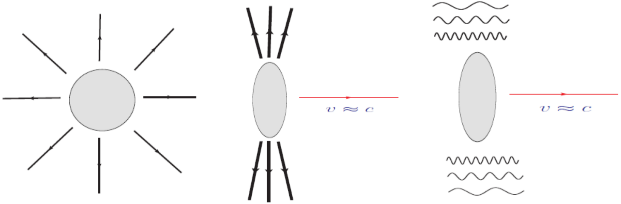
MoEDAL MMT detectors exposed to
0.235 nb^{-1} of Run-2 Pb+Pb (IP8) data
MoEDAL Collaboration, Nature, 602 (2022) 63



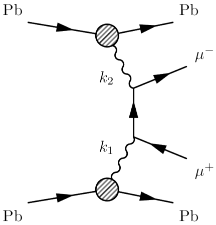
MoEDAL probes CMS Run-1 beam pipe
MoEDAL Collaboration, arXiv:2402.15682



Heavy-ion ultraperipheral collisions



- Ultraperipheral (UPC) heavy-ion collisions are **intense source of quasi-real photons**, with each photon flux scaling with $\mathbf{Z^2}$ (in Pb+Pb: $Z^4 = 82^4 \sim 45$ million times enhancement w.r.t. *pp*)
- Photon-induced processes characterised by a **very clean signature** and almost **no background**
- Various types of interactions possible (including BSM):



SM photon-photon

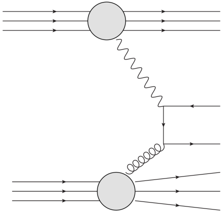
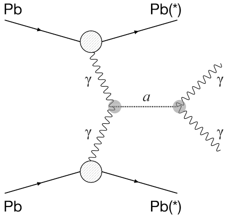
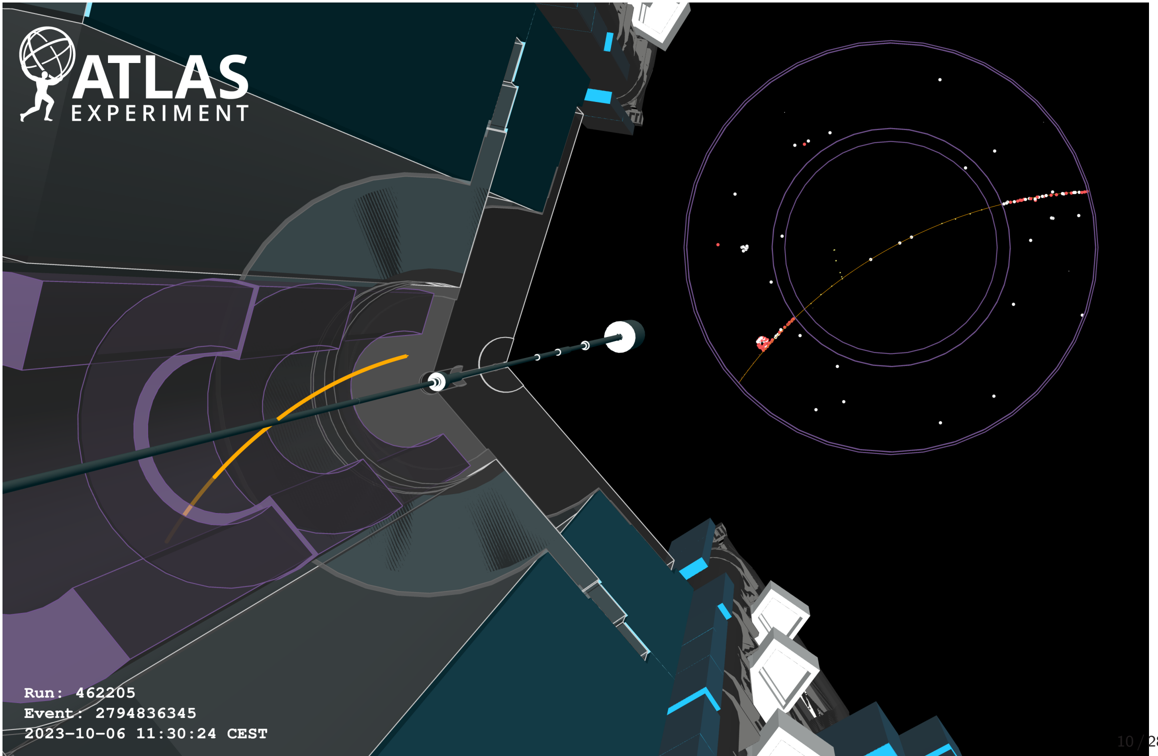


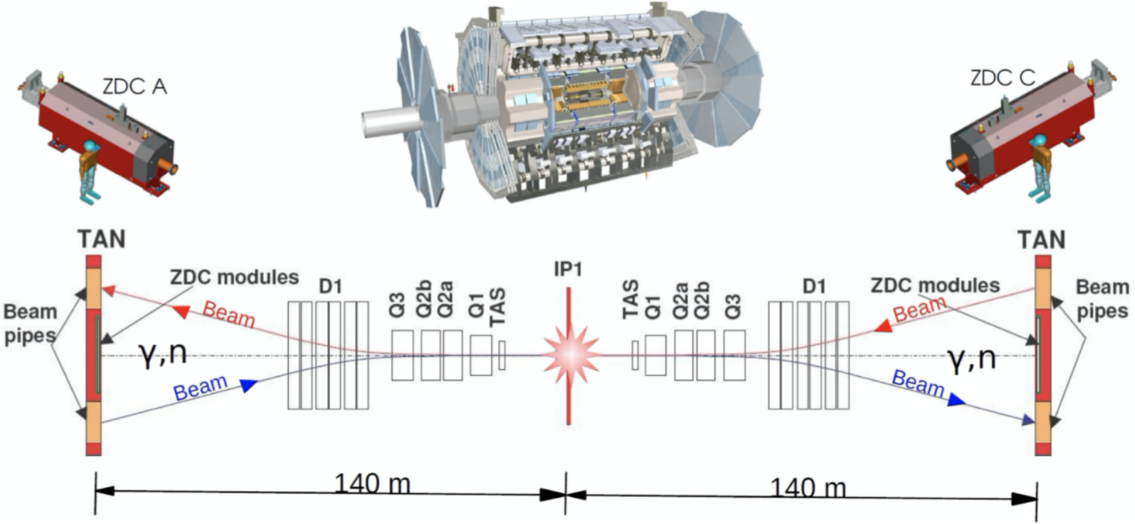
Photo-nuclear



BSM photon-photon


ATLAS
EXPERIMENT
Run: 462205
Event: 2794836345
2023-10-06 11:30:24 CEST

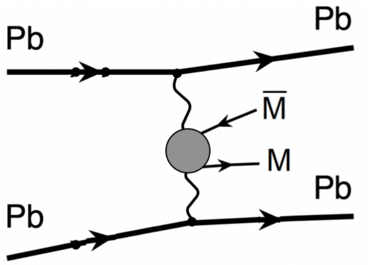
ATLAS & ZDC



- Various types sub-detectors available in ATLAS ($|\eta| < 4.9$)
- Different UPC event topologies measured via **Zero Degree Calorimeters (ZDC)**

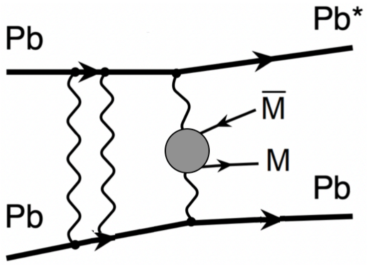
ZDC UPC categories

0n0n



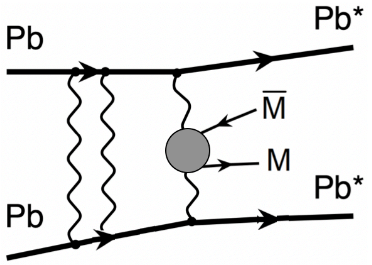
~60% events @ $m_X = 30$ GeV

0nXn



~30% events @ $m_X = 30$ GeV

XnXn

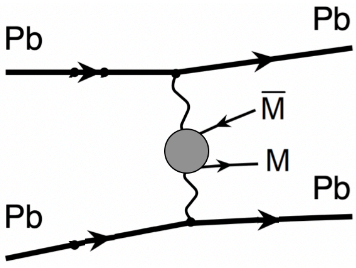


~10% events @ $m_X = 30$ GeV

- Different UPC topologies possible due to emission of neutrons
- **Crucial role** of Zero Degree Calorimeters

ZDC UPC categories

0n0n



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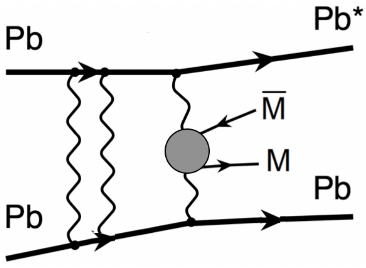
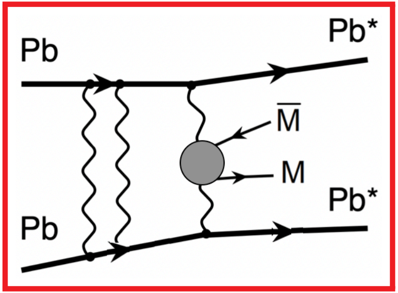


~30% events @ $m_X = 30$ GeV

XnXn

Our primary signal category

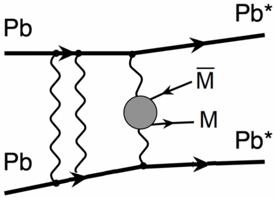


~10% events @ $m_X = 30$ GeV

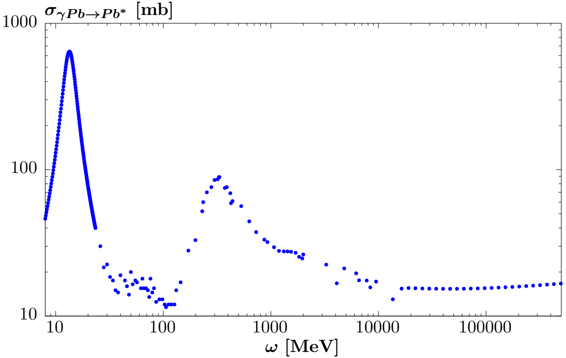
- Different UPC topologies possible due to emission of neutrons
- **Crucial role** of Zero Degree Calorimeters
- Mainly due to trigger limitations – **empty events at L1**
- Fraction of XnXn events **increases with central system mass**

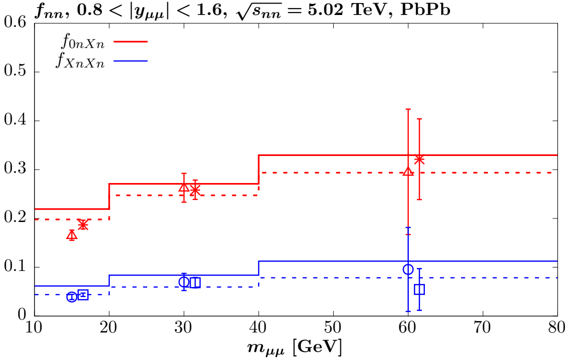
EM breakup modelling

- Models of EM breakup fractions use parametrisations based on low-energy photonuclear scattering data
  - Significant contribution from Giant Dipole Resonance
  - Models can describe the LHC data at ∼20% level



SuperChic 4.2 MC (Harland-Lang et al.) PRD 107 (2023) 9, 093004





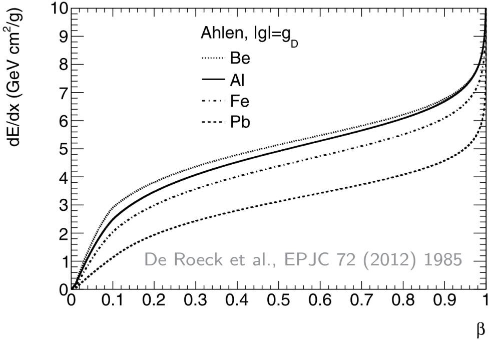
Monopole interactions in the detector

- Energy loss:
  - Ionisation dominates

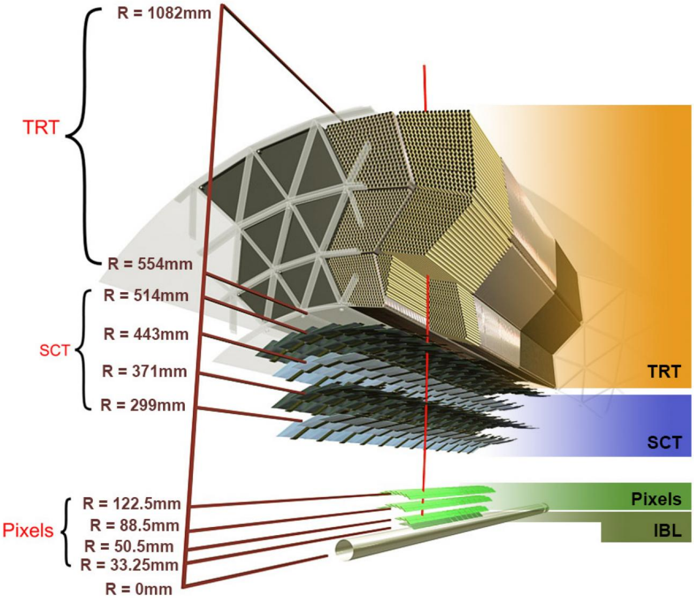
    Ahlen, Phys. Rev. D 17 (1978) 229

$$-\frac{dE}{dx} = K\frac{Z}{A}g^2\left[\ln\frac{2m_e c^2\beta^2\gamma^2}{I_m} + \frac{K(|g|)}{2} - \frac{1}{2} - B(|g|)\right]$$

  - For $g = 1g_D$ $(= 68.5e)$ and $\beta \sim 1$: $(dE/dx)_{MM} \approx 5000(dE/dx)_{MIP}$
  - Highly ionising particle (HIP) $\rightarrow$ lots of **δ-electrons** near trajectory
  - Slow monopoles $\rightarrow$ less ionisation
- Equations of motion:
  - Monopoles accelerated by magnetic field
  - Trajectory **bends in $r - z$** plane, **straight-line in $r - \varphi$** plane



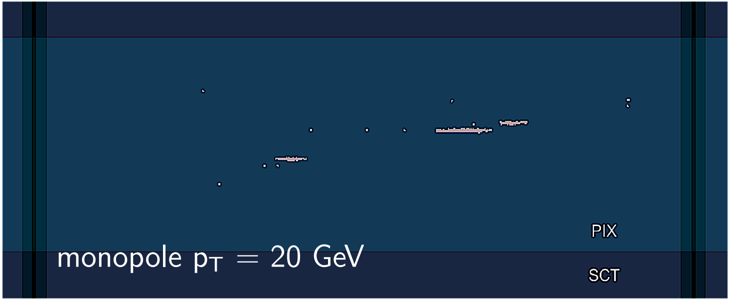
The ATLAS Inner Detector



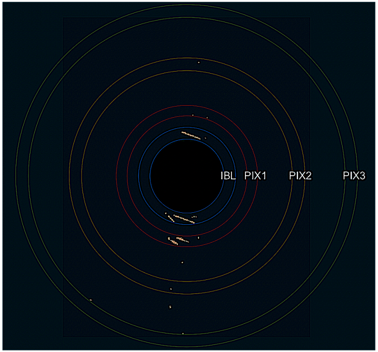
Low-energy monopole interaction in ATLAS

- Simulated pairs of monopoles in UPC (each with $m_M = 20$ GeV)
  - Large activity in the **Pixel detector**
  - Monopoles with $p_T < 30$ GeV typically do not reach SCT

Longitudinal detector view



Transverse view (Pixel only)



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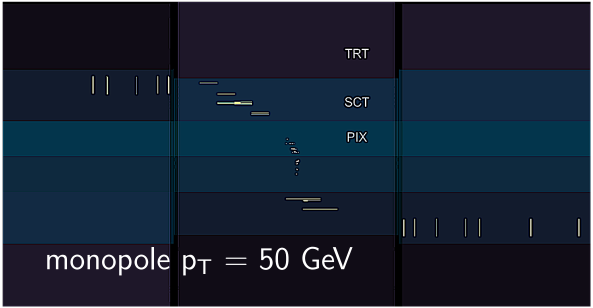
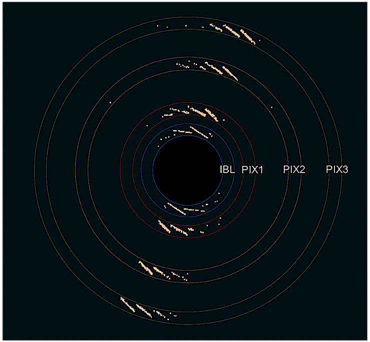


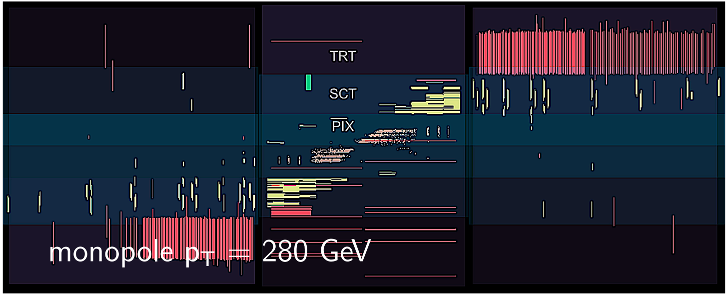
Transverse view (Pixel only)



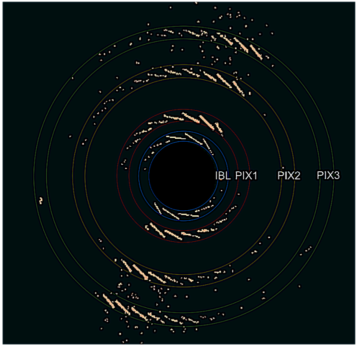
Low-energy monopole interaction in ATLAS

- Simulated pairs of monopoles in UPC (each with $m_M = 20$ GeV)
  - Large activity in the **Pixel detector** ← **primary focus**
  - Monopoles with $p_T < 30$ GeV typically do not reach SCT
  - Monopoles with $p_T < 300$ GeV do not reach calorimeter

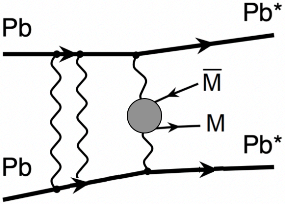
Longitudinal detector view



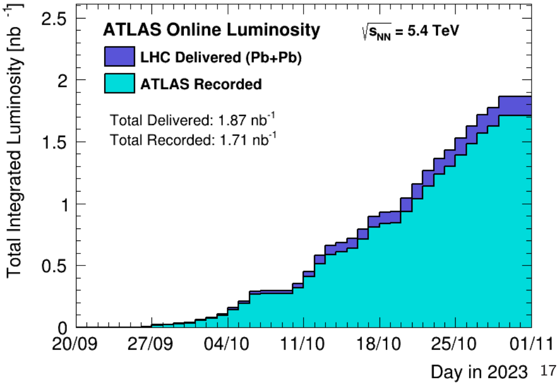
Transverse view (Pixel only)



Analysis strategy



- Using 2023 Pb+Pb data at $\sqrt{s_{NN}} = 5.36$ TeV, 1.7 nb^{-1}
- First ATLAS result using Run3 Pb+Pb data
- **Signal trigger**:
  - **L1**: presence one or more neutrons in both ZDCs, and veto on total energy in calorimeter ($E_T < 10$ GeV)
  - **HLT**: presence of more than 100 Pixel clusters
  - **Prescale**: about 1/6 of total events were saved $\rightarrow$ **0.262 nb^{-1}**
- **Supporting trigger**: ZDC activity on either side, same as signal trigger otherwise – background estimation, **9.6 μb^{-1}**



Signal simulation

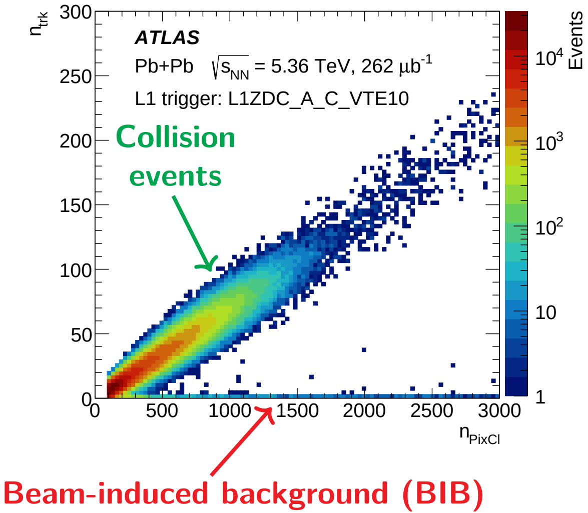
- Use predictions based on the semiclassical model
  - **Free Particle Approximation (FPA)**
    Gould, Ho, Rajantie, PRD 100, 015041 (2019), PRD 104, 015033 (2021)
  - Monopole coupling with initial magnetic fields treated exactly (up to all orders), with self-interactions neglected
  - Monopole kinematics based on simplified model with **back-to-back monopole production** and **sampled momentum**:

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

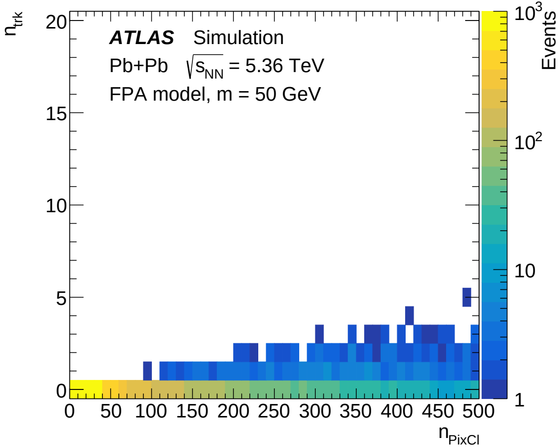
  - Same model as used by MoEDAL
  - Exploring **only** $\boldsymbol{g = 1g_D}$
- Detector simulation
  - Benefits from previous ATLAS *pp* searches
  - Includes descriptions of **monopole acceleration** in the detector magnetic field, **ionisation energy losses** in matter and **δ-electron production** along the monopole trajectory

Event properties

Events in data after trigger selection

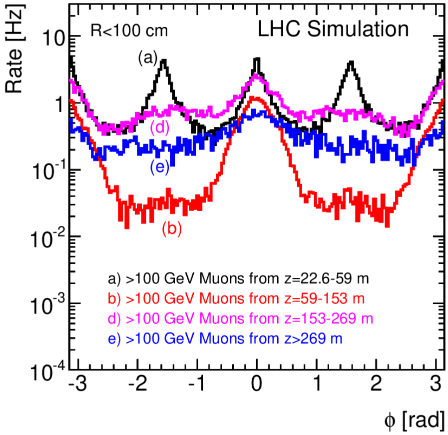


Simulated signal events

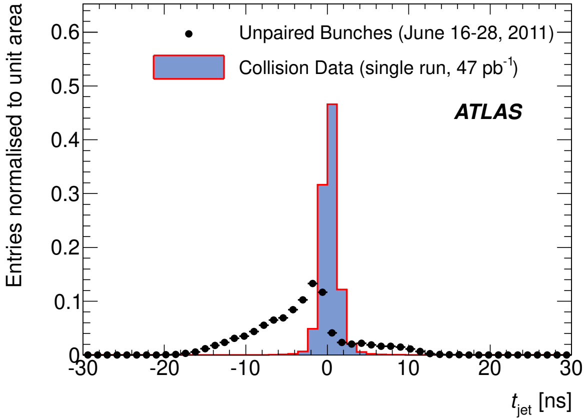


Beam-induced background characteristics

ATLAS, JINST 8 (2013) P07004



BIB particles largely deflected in the horizontal plane by the LHC magnets



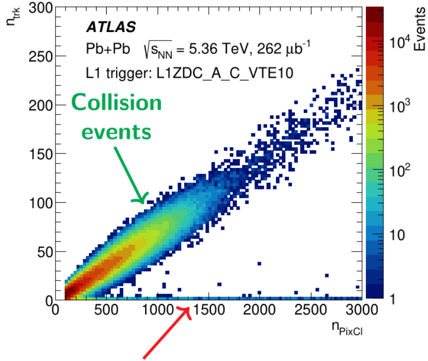
Fake jets from OOT energy deposits

Offline event selection

- $N_{\mathrm{tracks}} \leq 1$
- $N_{\mathrm{topo\text{-}clusters}} \leq 1$

} Remove **collision background**

- $N_{\mathrm{PixelCl}} > 150$ and $N_{\mathrm{IBLCl}} > 50$
  $\rightarrow$ suppress **beam-induced background**
- Fraction of Pixel clusters from a single module $f_{\mathrm{leading\text{-}module}} < 0.9$ $\rightarrow$ suppress events from **noisy Pixel modules**

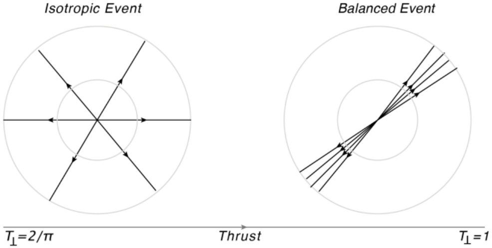


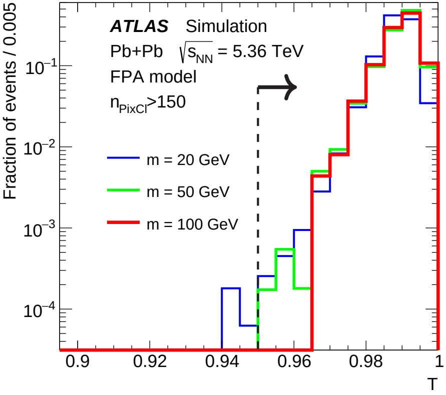
Offline event selection

- Final background-discriminating variable based on azimuthal correlations between Pixel clusters
- Calculate "transverse thrust" using Pixel clusters:

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

  - $\hat{\boldsymbol{r}}_{\boldsymbol{i}}$ – unit vector of cluster orientation in the lab frame
  - $\hat{\boldsymbol{n}}$ – direction which maximizes thrust
- **Require T $>$ 0.95**





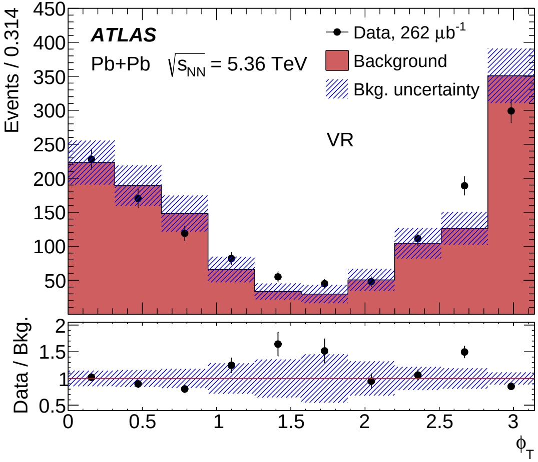
Background estimation

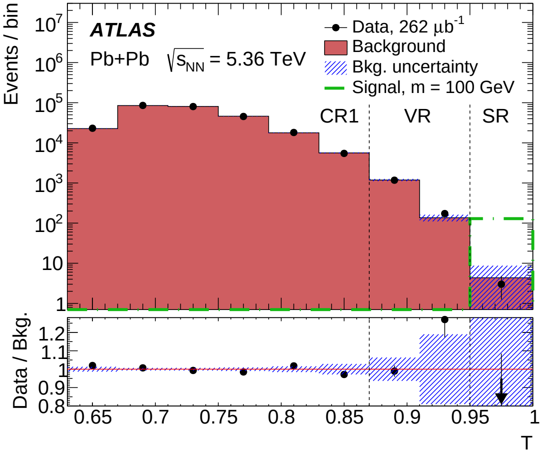
- Background: **Beam-induced-background** (BIB) – characterised by particles almost parallel to the beam line, especially one with small radial range
- **Fully data-driven** background estimation method
- Events in CR2 are used to extrapolate the background contribution from CR1 to SR – cross-checked 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
$f_{\mathrm{leading\text{-}module}}$		< 0.9		< 0.9
T	> 0.95	0.87–0.95	≤ 0.87	—

Background estimation

- 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

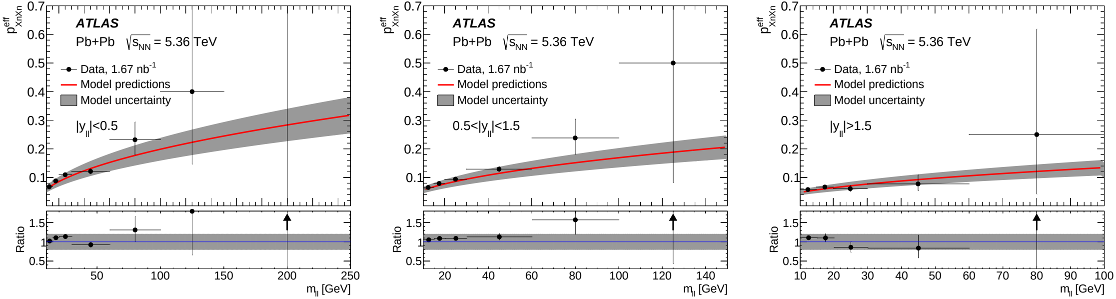
- Need to correct signal Monte Carlo (0n0n) for XnXn requirement in the data:

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

- f_{0nXn} and f_{XnXn} derived from SuperChic 4.2
- $f_{diss} = 0.13$ derived from $\gamma\gamma \to l^+l^-$ events
- p_{EMPU} estimated to be 0.038 for signal trigger
- Cross-checked with dilepton events in three rapidity bins

Phys. Rev. C 104 (2021) 024906

JHEP 06 (2023) 182



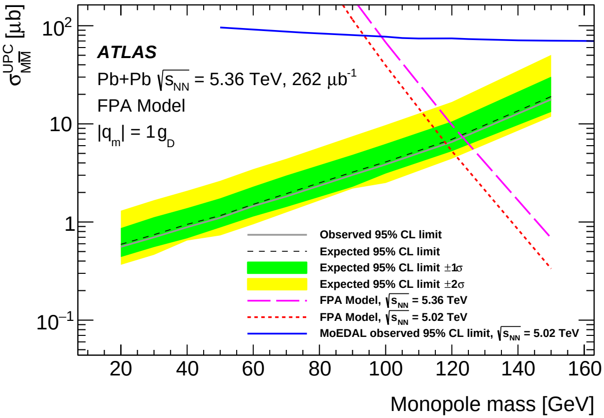
Systematic uncertainties

- **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

Results

- **3 events in SR**, consistent with background estimate of 4 ± 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

- 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 $q_m = 1 g_D$
- Main focus on the Pixel detector activity, „transverse thrust" as primary background-discriminating variable
- 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
- Data-driven background estimate of 4 $\pm$ 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**
- Future directions: trigger improvements, higher magnetic charges, MVA methods, unconventional tracking
- This new approach **can be further explored** for other similar searches (HIPs)

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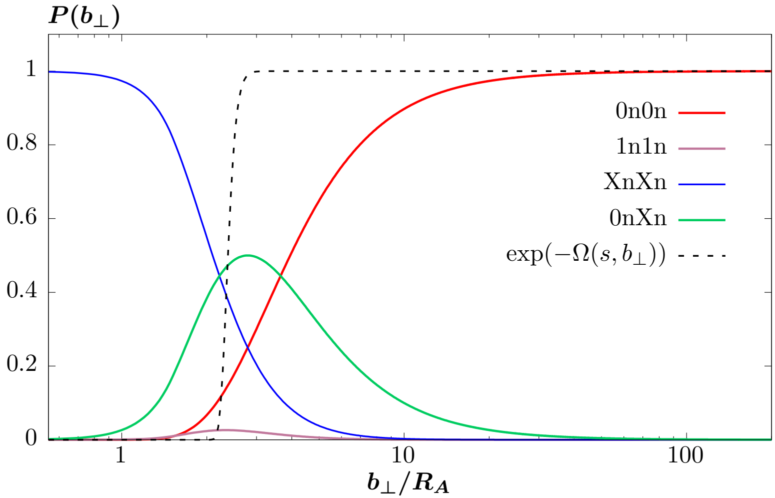
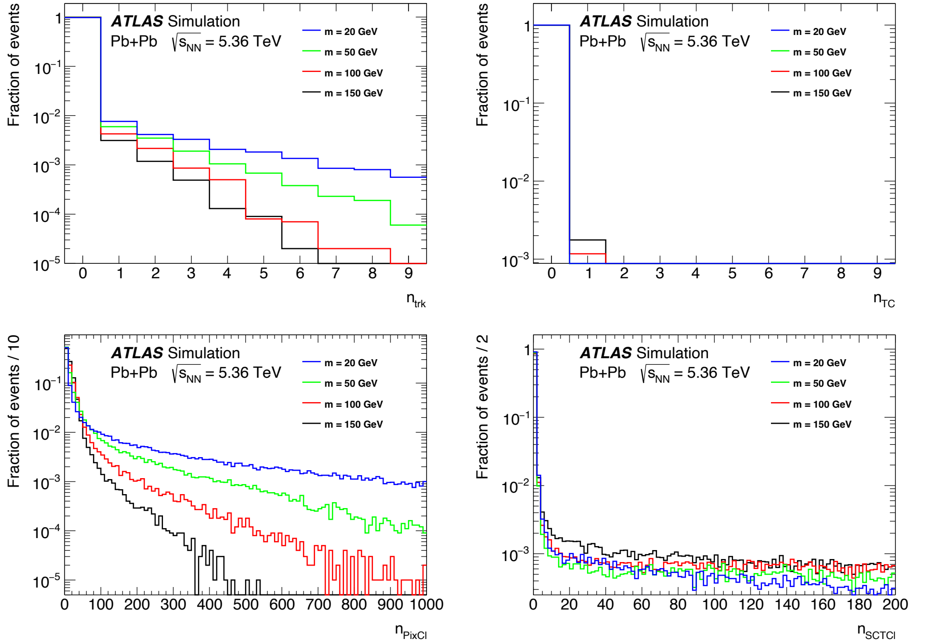
Backup

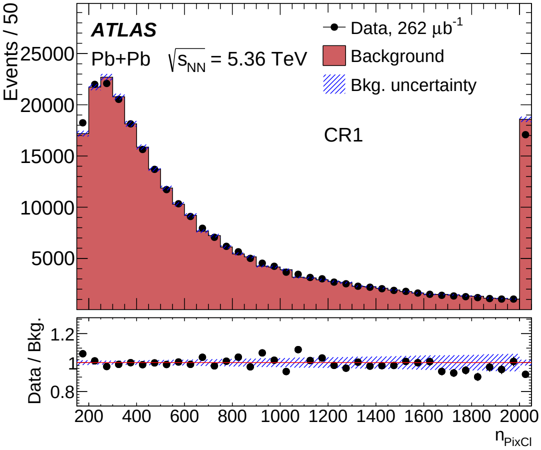
EM breakup fractions

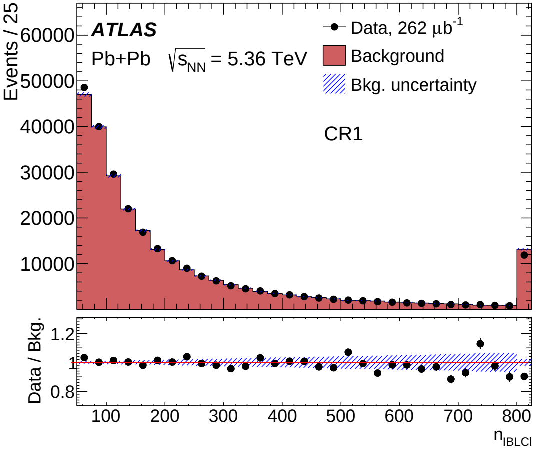


Signal MC control plots

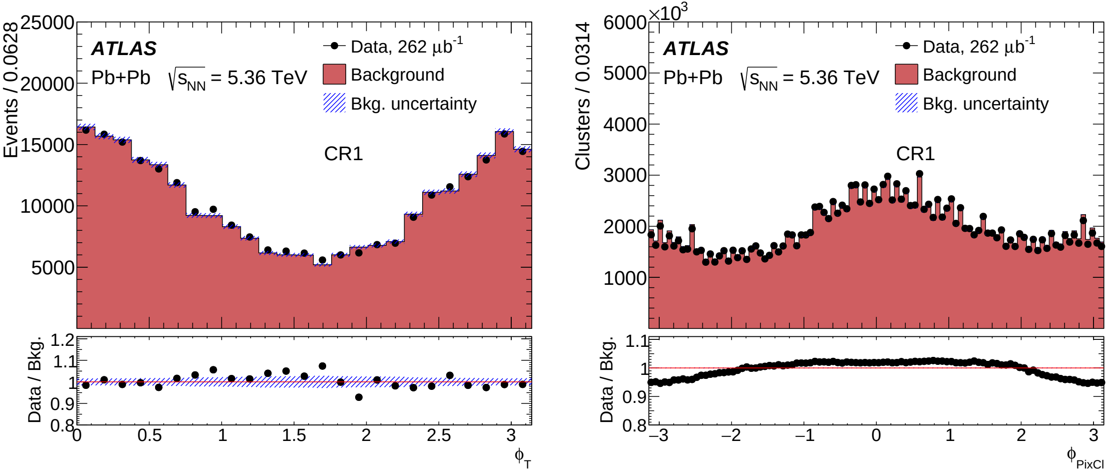


CR control plots

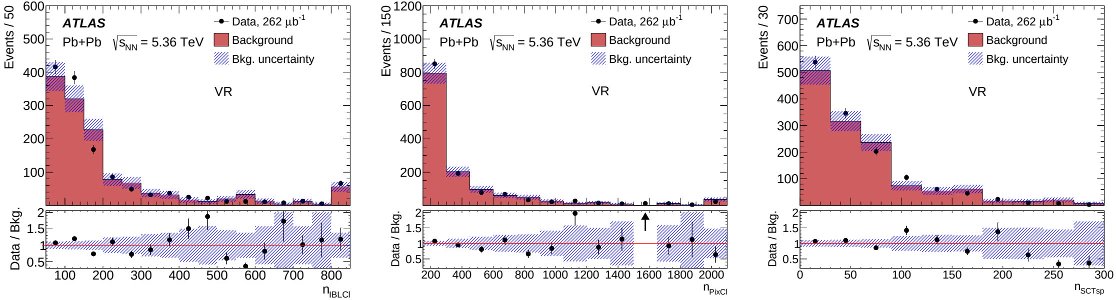




CR control plots



VR control plots



FPA monopoles average p_T