

Observation of coherent J/ψ production in ultraperipheral Pb+Pb collisions at ATLAS

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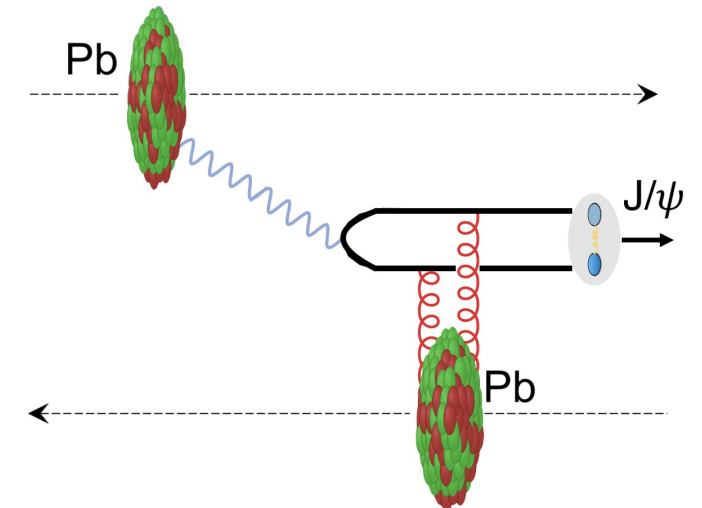
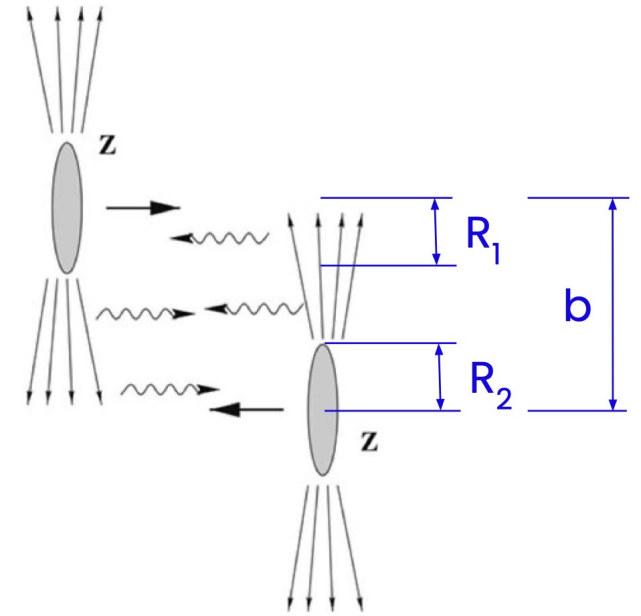
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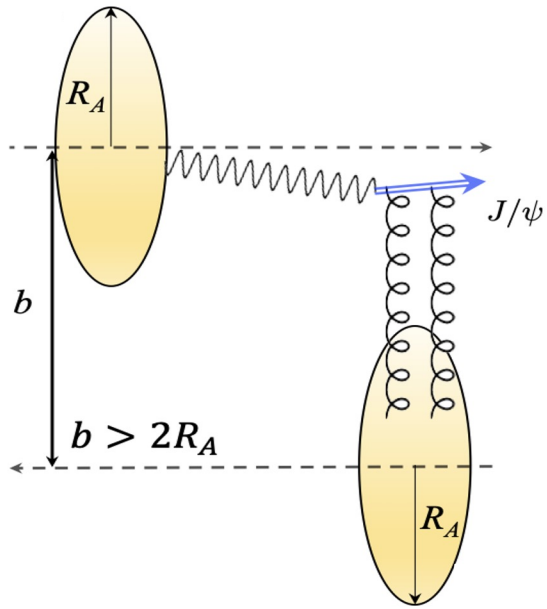
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Introduction

- LHC can act as a "photon collider" under specific conditions
- Ultraperipheral collisions (**UPC**):
 - Impact parameter: $\mathbf{b} > 2R$
 - Dominated by photon-photon and photonuclear interactions
- Quasi-real photons exchanged in relativistic heavy ion interactions are powerful probes of the gluonic structure of nucleon and nucleus
- Coherent J/ψ meson photoproduction in Pb+Pb UPC:
 - Interaction of $c\bar{c}$ fluctuation from emitted **quasi-real** photon with a two-gluon color-neutral state ("pomeron")
 - Process sensitive to nuclear gluon dynamics at **low-x**



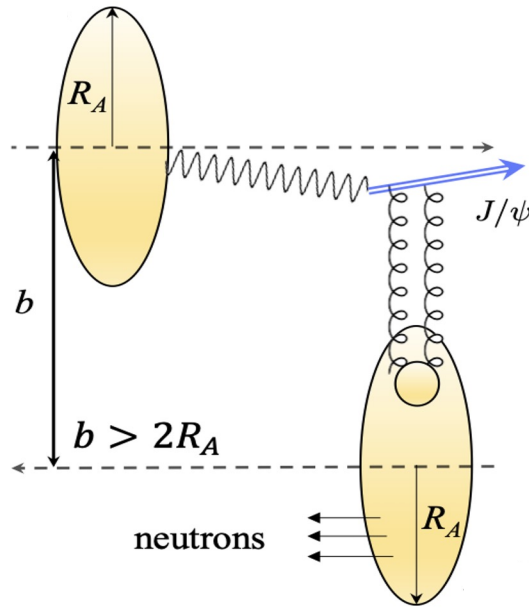
Process of interest



(a) Coherent, nucleus stays intact

- Photon interacts coherently with entire nucleus
- Low p_T^2 ($\lesssim 0.02 \text{ GeV}^2$)

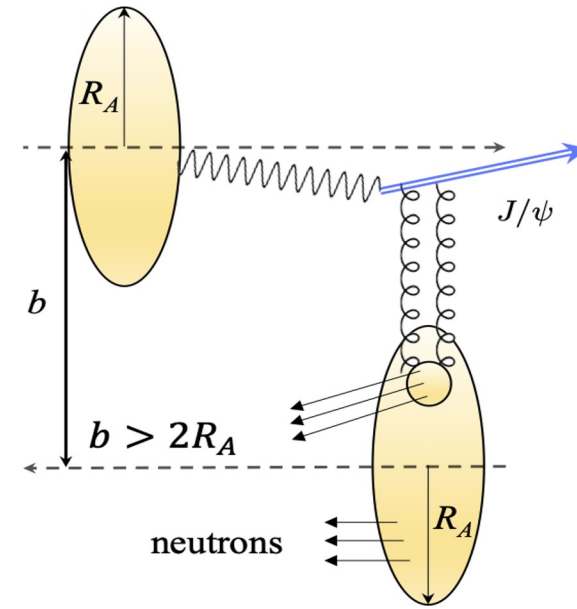
Our signal process



(b) Incoherent with elastic nucleon

- Emitted from a single nucleon
- Higher p_T^2 ($\approx 0.02 - 0.5 \text{ GeV}^2$)

Background process

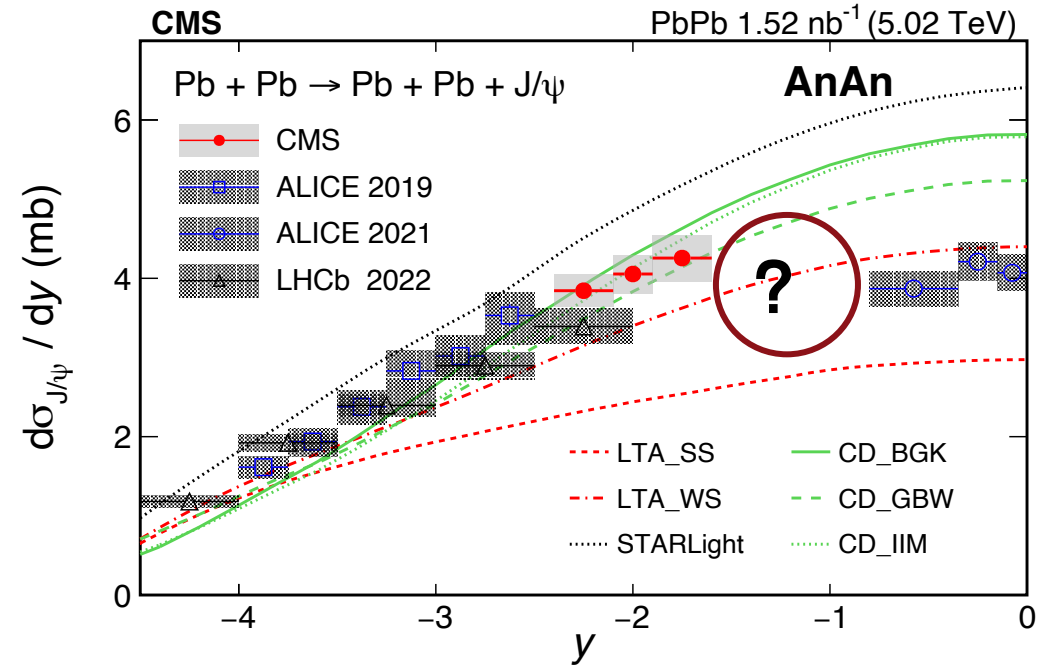


(c) Incoherent with nucleon dissociation

- The nucleon breaks up
- Higher p_T^2 ($\gtrsim 0.5 \text{ GeV}^2$)

Motivation

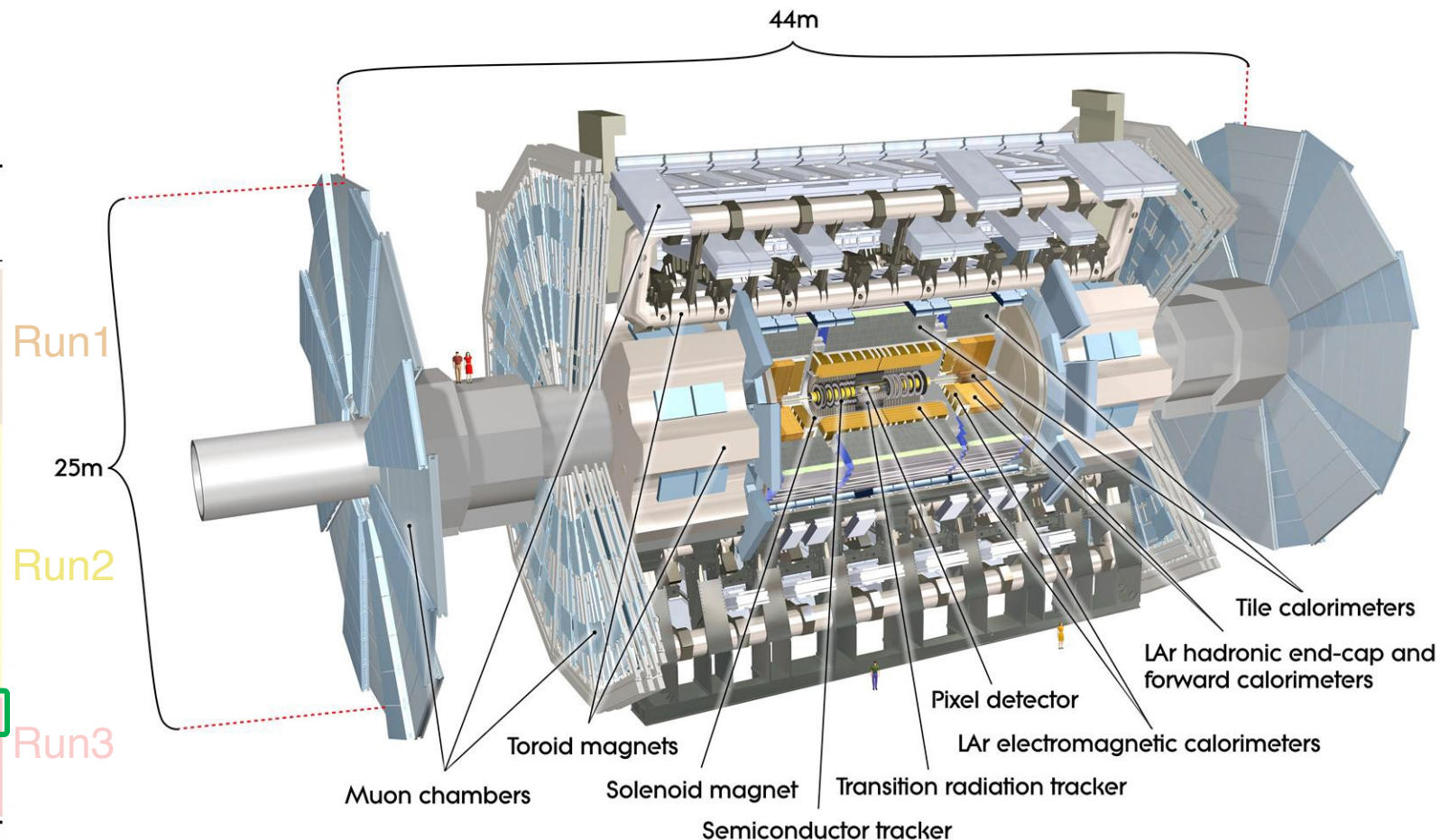
- Measurement of the differential cross-section $d\sigma/dy$ **for coherent J/ψ production** and comparison with theoretical predictions and with the previous LHC Run-2 measurements from other experiments
- **Filling the gap in the J/ψ rapidity acceptance of $0.8 < |y| < 1.6$** (completing previous LHC Run-2 measurement)
- Focusing on **dimuon** decay channel (electrons have too large momentum distortions due to ID material)
- Key experimental challenge in ATLAS:
 - Trigger on soft ($p_T \sim 1.5\text{GeV}$) leptons



ATLAS detector and Heavy Ion Data

- Summary of heavy-ion collision data collected by ATLAS:

System	Year	$\sqrt{s_{NN}}$ [TeV]	$\mathcal{L}_{int}$
Pb+Pb	2010	2.76	$7 \mu b^{-1}$
Pb+Pb	2011	2.76	0.14 nb^{-1}
pp	2013	2.76	4 pb^{-1}
p+Pb	2013	5.02	29 nb^{-1}
pp	2015	5.02	28 pb^{-1}
Pb+Pb	2015	5.02	0.49 nb^{-1}
p+Pb	2016	5.02	0.5 nb^{-1}
p+Pb	2016	8.16	0.16 pb^{-1}
Xe+Xe	2017	5.44	$3 \mu b^{-1}$
pp	2017	5.02	270 pb^{-1}
Pb+Pb	2018	5.02	1.76 nb^{-1}
Pb+Pb	2023	5.36	1.71 nb^{-1}
pp	2024	5.36	425 pb^{-1}
Pb+Pb	2024	5.36	1.67 nb^{-1}



This study is based on 2023 Pb+Pb runs

- Next run3 heavy-ion collision data will be collected at the end of 2025

- Tracker: $|\eta| < 2.5$
- EM and hadronic calorimeters: $|\eta| < 3.2$
- Forward calorimeters: $3.1 < |\eta| < 4.9$ used for centrality
- Muon spectrometers: $|\eta| < 2.7$
- ZDC: $|\eta| > 8.3$

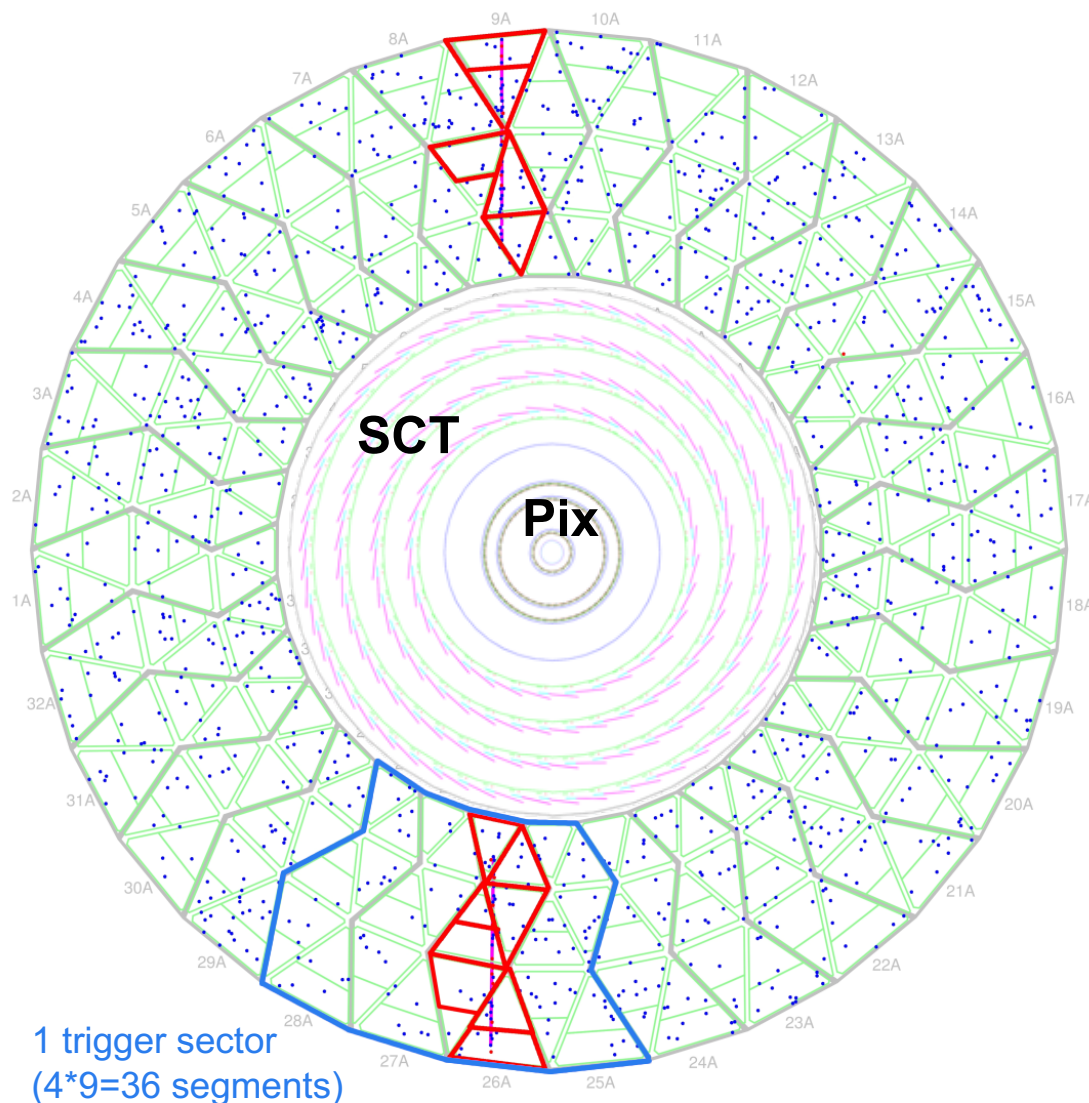
Object and event selection

Dataset

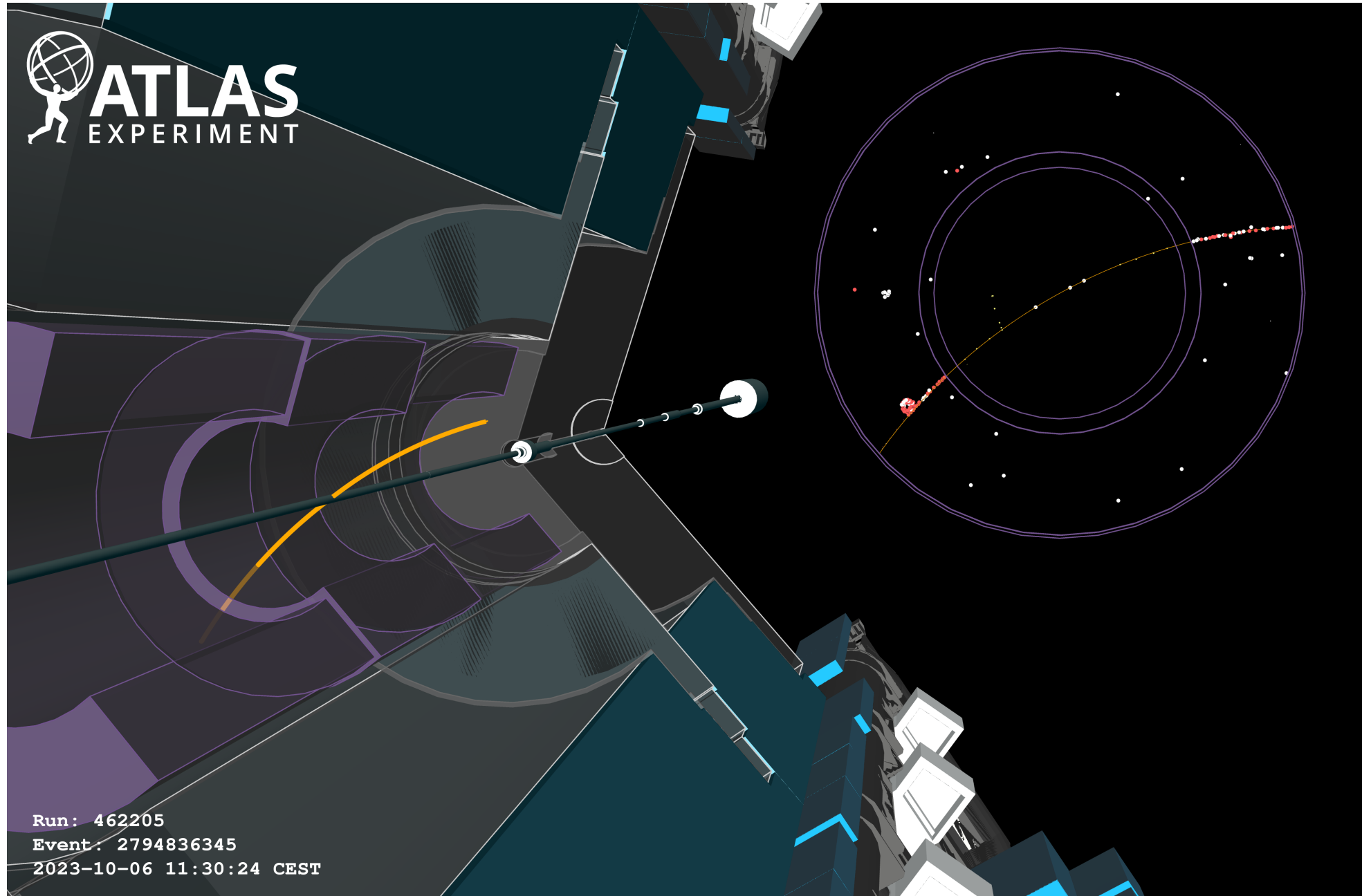
- 2023 data effective luminosity: $78 \mu b^{-1}$ for signal trigger
- MC samples: STARlight (+ Pythia8/EvtGen+Photos)

Trigger

- Previous ATLAS HI runs were unable to trigger on J/ψ
- L1TRT “FastOR” trigger utilized in 2023
 - Take the advantage of TRT high threshold (HT) hits to **catch low p_T events** that don't have particles reaching calorimeters
 - Requires at least 4 sectors, and then each TRT region (Barrel A and C, Endcap A and C) are OR'd to make a final decision per event
 - Not selective against high multiplicity events, but very efficient for low multiplicities



Event Display



Object and event selection

Charged particle tracks pre-selected

- $|\eta| < 2.5$, $p_T > 100 \text{ MeV}$, $|d_0| < 2 \text{ mm}$
- Loose Primary working point

Exactly two opposite-charged tracks

- Each with $p_T > 1 \text{ GeV}$ (to match trigger conditions)
- In subsequent analysis, tracks are assigned the muon mass

Signal region definition

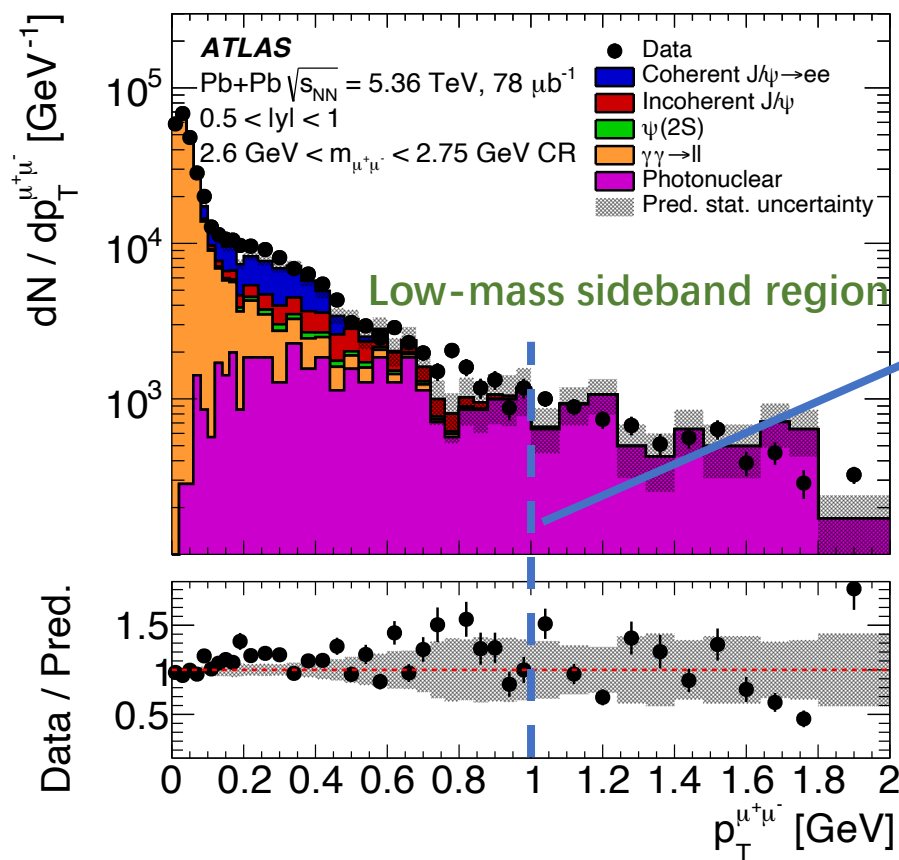
- $2.9 \text{ GeV} < m^{\mu\mu} < 3.2 \text{ GeV}$ (assuming μ mass per track)
- $p_T^{\mu\mu} < 0.2 \text{ GeV}$ to suppress incoherent production

No further selections for μ/e identification

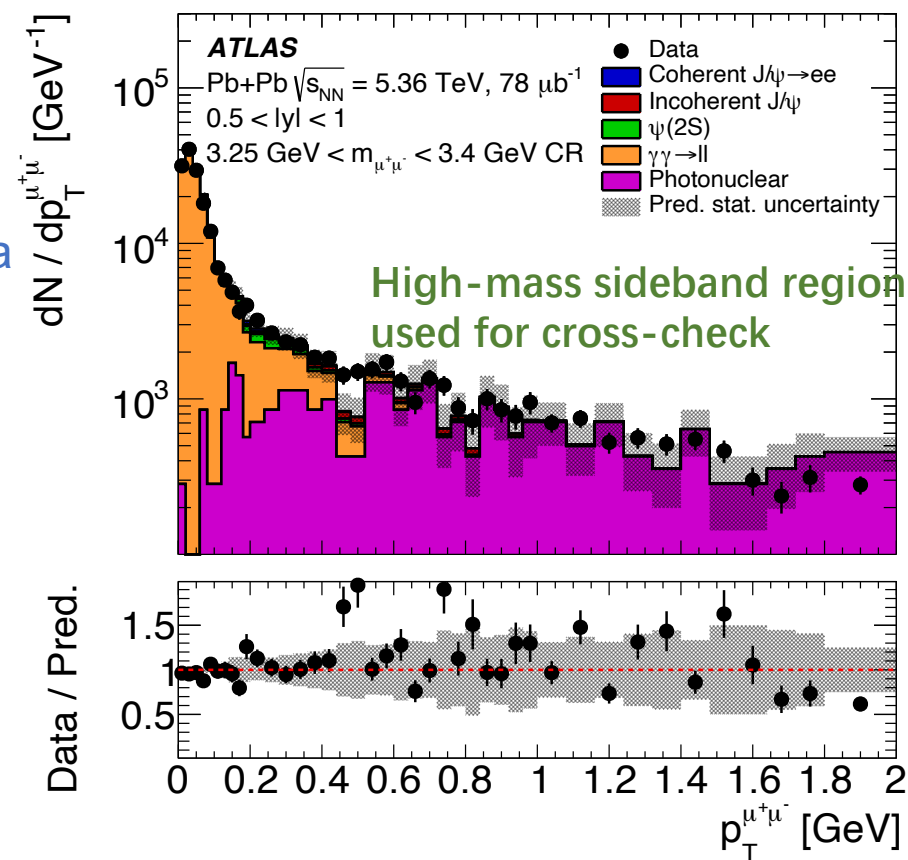
- Tracks are insufficiently energetic to be observed in the ATLAS muon spectrometer
- Electron channel decay products tend to lose even more energy in the ID material - treated as background

Background estimation - photonuclear contributions

Charged hadrons from inelastic photonuclear production



Normalised to data
at $p_T^{\mu\mu} > 1\text{GeV}$,
where other
contributions are
negligible



- Estimated using same selection as SR but with **same-sign pairs** in data
- Good description of sideband regions with our background processes (& some signal leakage to low mass region)

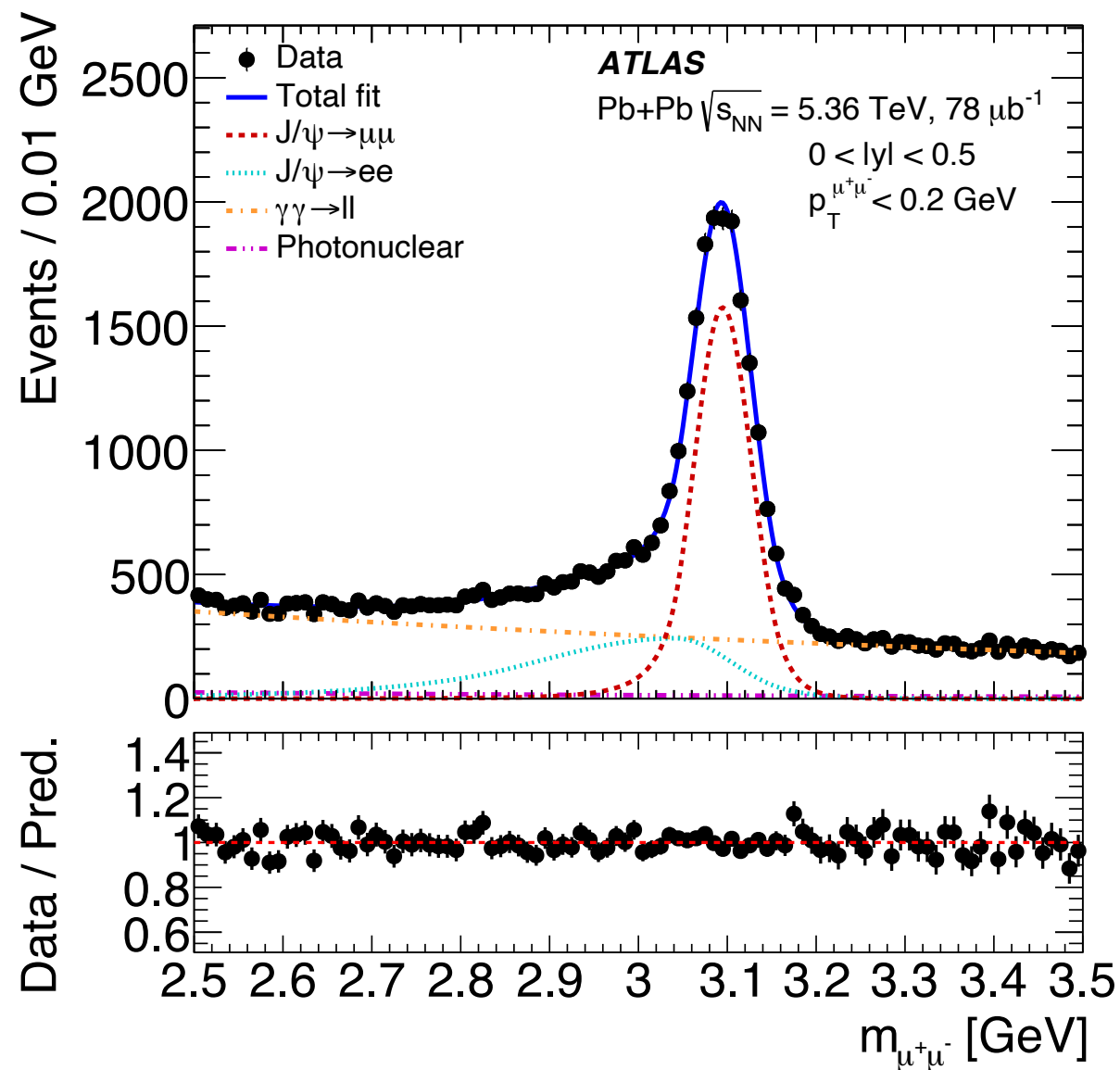
Background estimation - $\psi(2S)$ - dilepton

$\psi(2S)$ feed down to J/ψ : $\psi' \rightarrow J/\psi (\rightarrow l^+ l^-) \pi^+ \pi^-$

- **Fit to p_T in $\psi(2S)$ control region** using events with 4 tracks or 3 tracks + 1 pixel track
 - Including backgrounds from **inelastic photonuclear**, **$J/\psi + \rho^0$** production

Non-resonant background from $\gamma\gamma \rightarrow l^+ l^-$

- **Fit to 2 tracks system invariant mass distribution in $p_T^{\mu\mu} < 0.2 \text{ GeV}$**
 - Dilepton continuum modeled with **exponential function**
 - J/ψ shapes modeled with **Crystal Ball functions** using MC simulated samples
 - Constrains fraction of $\gamma\gamma \rightarrow l^+ l^-$ within $2.9 \text{ GeV} < m^{\mu\mu} < 3.2 \text{ GeV}$, also constrains $\mu\mu$ and ee ratio



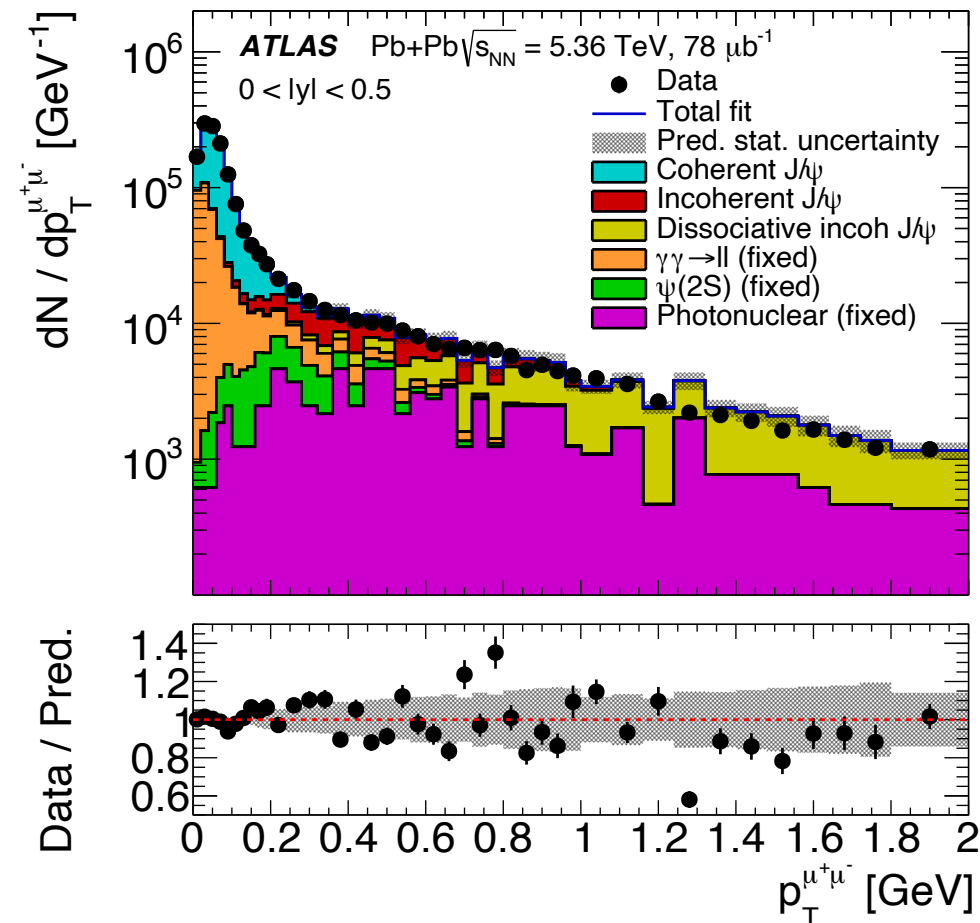
Extraction of coherent $J/\psi \rightarrow \mu\mu$ signal yield: $|y| < 0.5$

- **Fit to the p_T distribution** (in $2.9\text{GeV} < m^{\mu\mu} < 3.2\text{GeV}$)

- Using constraints from photonuclear contributions, $\psi(2S)$ feed down and $\gamma\gamma \rightarrow l^+l^-$
- $J/\psi \rightarrow e^+e^-$
 - Strongly distorted by ID material, so estimated as a background not corrected-for
- **Incoherent J/ψ**
 - Exclusive incoherent production p_T distributions from simulated STARlight events
 - Contributions from nucleon dissociation (which overlap photonuclear production at high p_T) modeled with functional form from [HERA](#)

$$\frac{dN}{dp_T} = 4 \cdot bpd \cdot p_T^2 \cdot \left(1 + \left(\frac{b_{pd}}{n_n}\right) \cdot p_T^2\right)^{-nn-1}$$

- Binned likelihood performed incorporating all of these contributions



Acceptance & efficiency corrections, uncertainties

Differential cross section measurement

$$\frac{d\sigma}{dy} = \frac{N_{J/\psi \rightarrow \mu\mu}^{\text{coh}}}{A \times \epsilon_C \times BR \times \mathcal{L}_{\text{int}} \times \Delta y}$$

Raw coherent yield from p_T fits

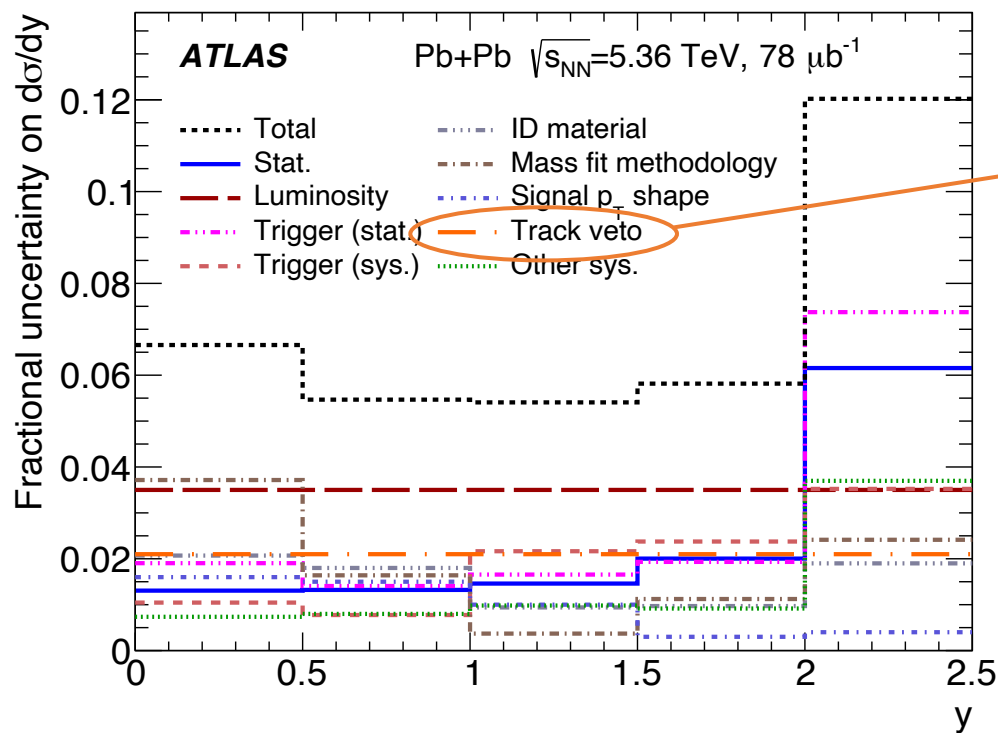
Acceptance correction (from MC)

Efficiency correction (from MC with data-driven corr. factors)

$J/\psi \rightarrow \mu\mu$ BR from PDG

Integrated luminosity of data

Uncertainties

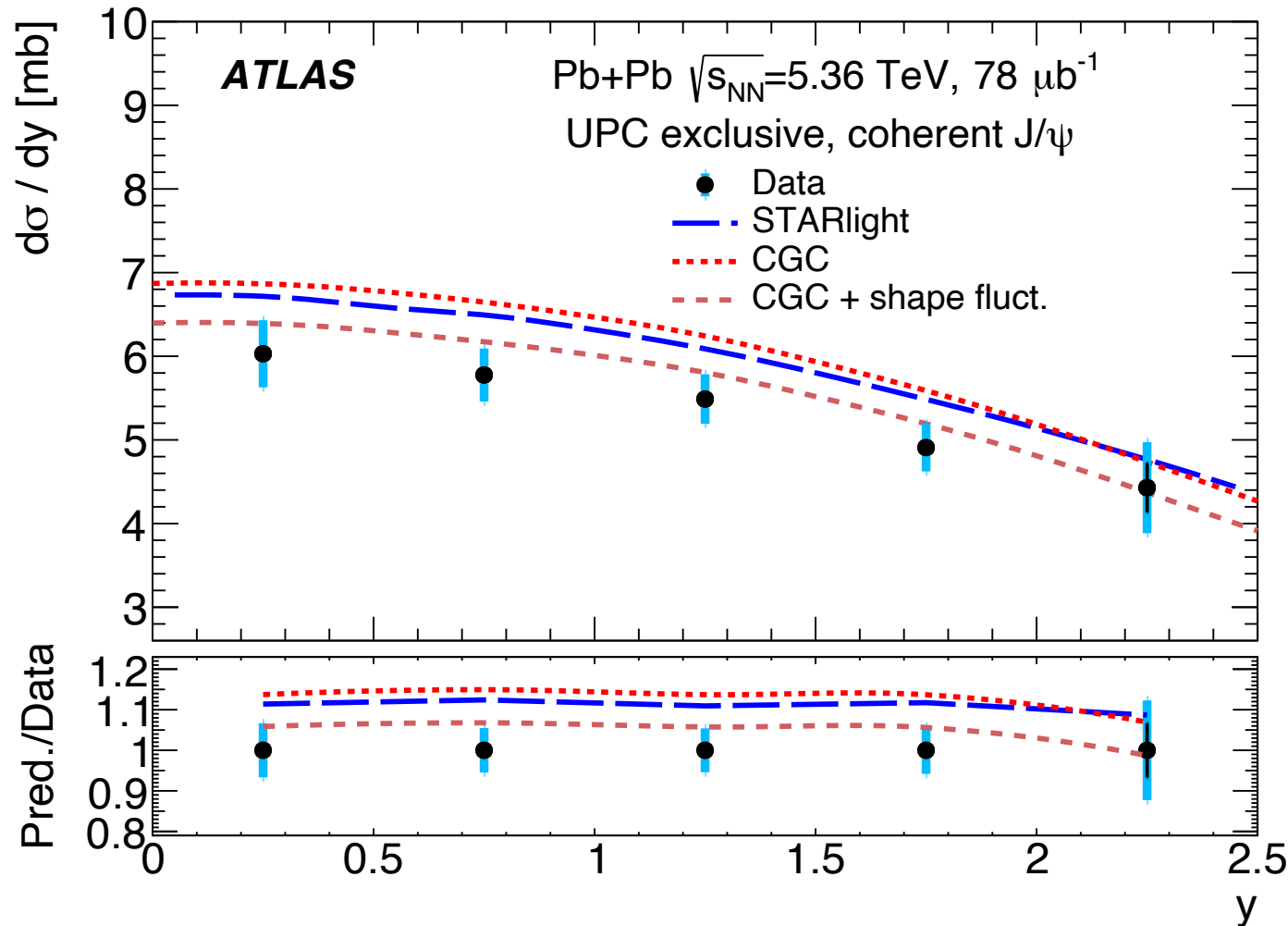


$\approx 1.9\%$ - coincident pair production (mainly $\rho^0 \rightarrow \pi\pi$) on exclusivity requirement
 $\approx 0.2\%$ - pile-up pairs
total effect: **2.1%**

Dominated by systematics (lumi-3.5%, fit methodology, ...)

Results

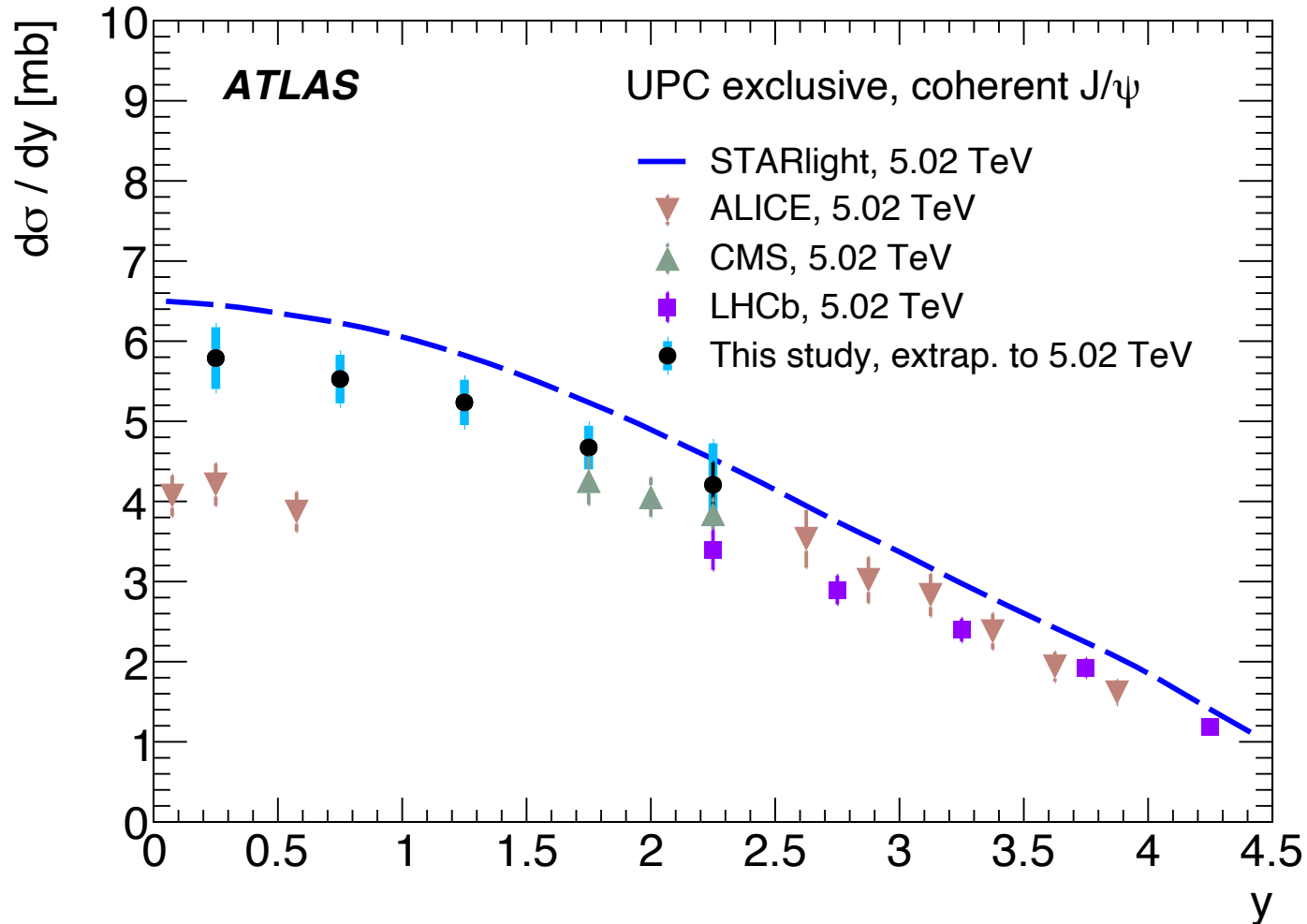
Measured cross-sections



- **Data presented in 5 bins in J/ ψ full $-2.5 < y < 2.5$ range**
 - Error bars = statistical uncertainty,
blue vertical bars = total uncertainty
- **Compared with two theoretical approaches**
 - CGC (parton saturation) approach ([Phys. Rev.D106 \(2022\)074019](#)) with nucleon shape fluctuations gets the best description of this set

Results in context

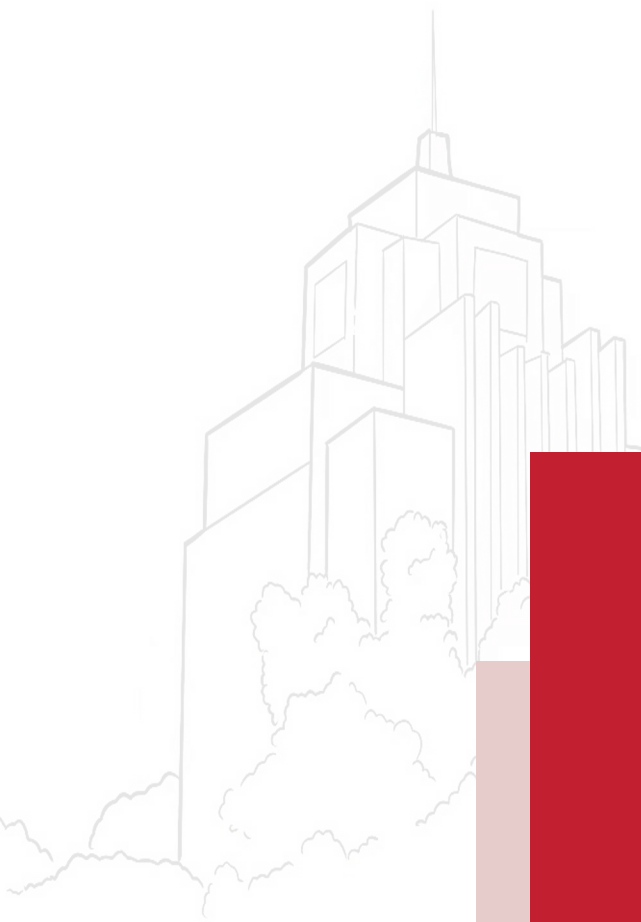
Extrapolation to 5.02 TeV using STARlight to compare with previous measurements



- Reasonable agreement with CMS in the overlap region $1.5 < |y| < 2.5$
- Slope continuous with **forward** ALICE & LHCb data
- Substantial tension 30-40% with ALICE data in $|y| < 0.8$

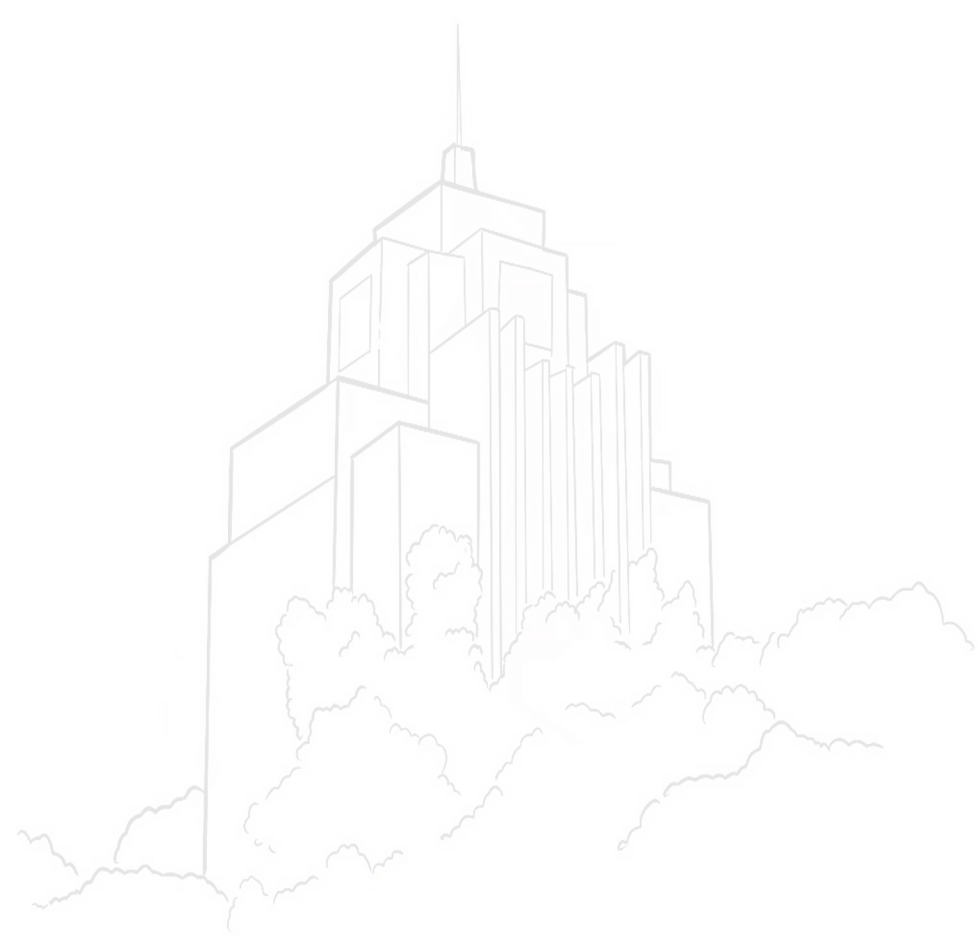
- **First observation of coherent J/ψ production** in ultraperipheral Pb+Pb collisions at ATLAS
- Cross section measured differentially in rapidity intervals from $0 < |y| < 2.5$, covering a **previously-unmeasured region $0.8 < |y| < 1.6$**
- Good agreement with model trends, and magnitude is best described by CGC models with nucleonic shape variations
- Good agreement with large $|y|$ data, but tension with ALICE data at $|y| < 0.8$
- The observation provides a key probe of the gluon structure at low Bjorken- x , serving as a basis for studying saturation and non-linear QCD phenomena
- Submitted to JHEP, available at [arXiv: 2509.04135](https://arxiv.org/abs/2509.04135)





**THANKS FOR YOUR
ATTENTION**

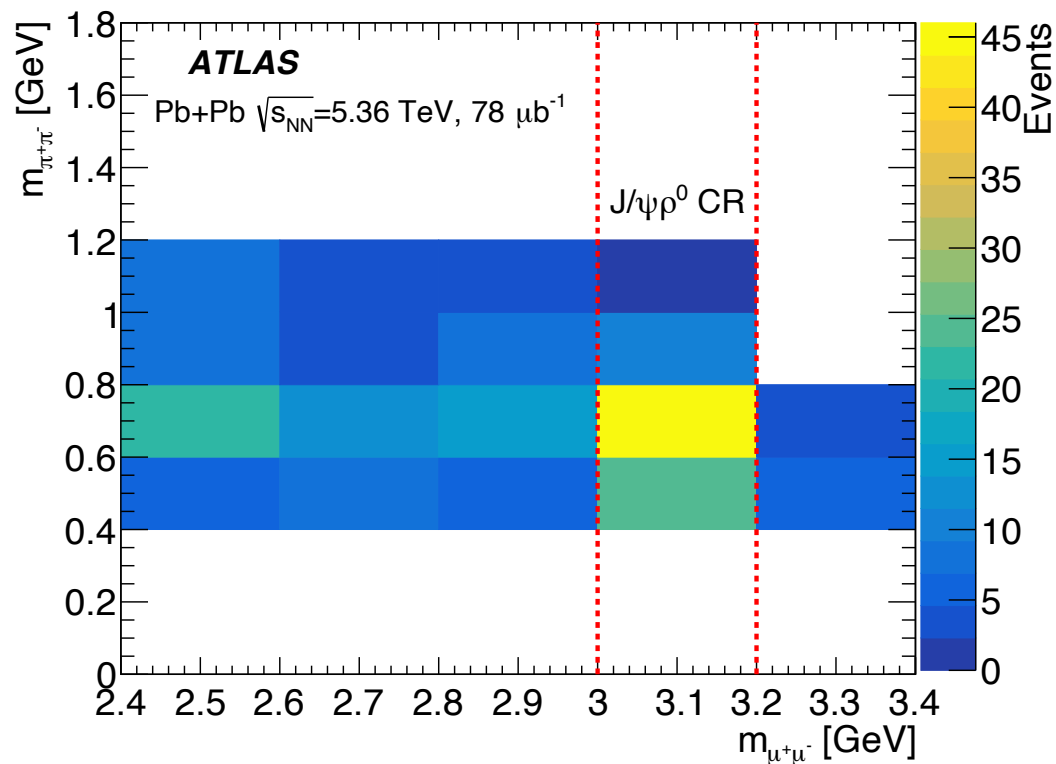




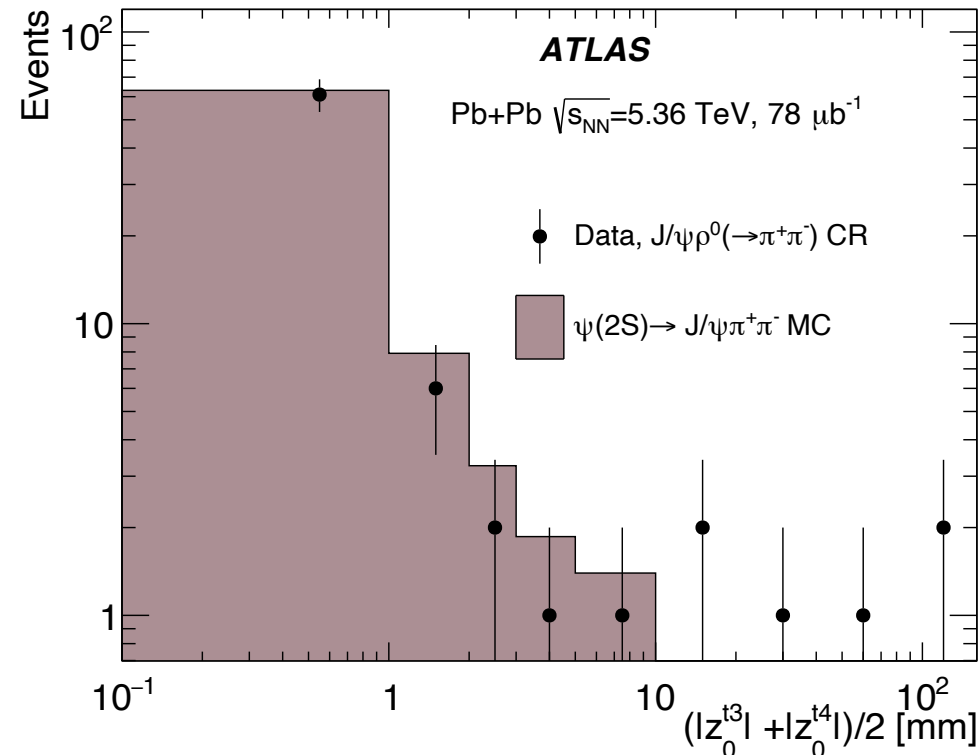
Backup



Coincident pair production ($\rho^0 \rightarrow \pi^+ \pi^-$)



Events simultaneously appearing at
 $m_{\mu\mu} \sim 3.1$ GeV and $m_{\pi\pi} \sim 0.8$ GeV (the ρ^0 region)
→ indicating that such simultaneous UPC
events do exist



The vertex positions of J/ψ+ρ⁰ events in data
align closely with the J/ψ vertex
→ indicating that they originate from the same
collision vertex, not from pile-up.

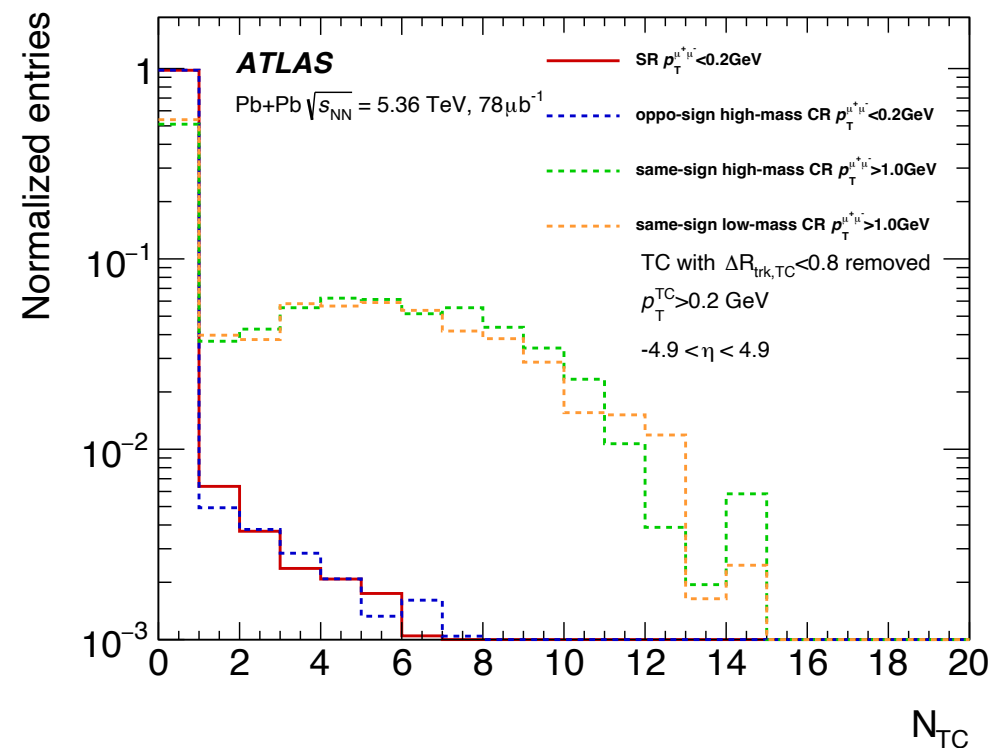
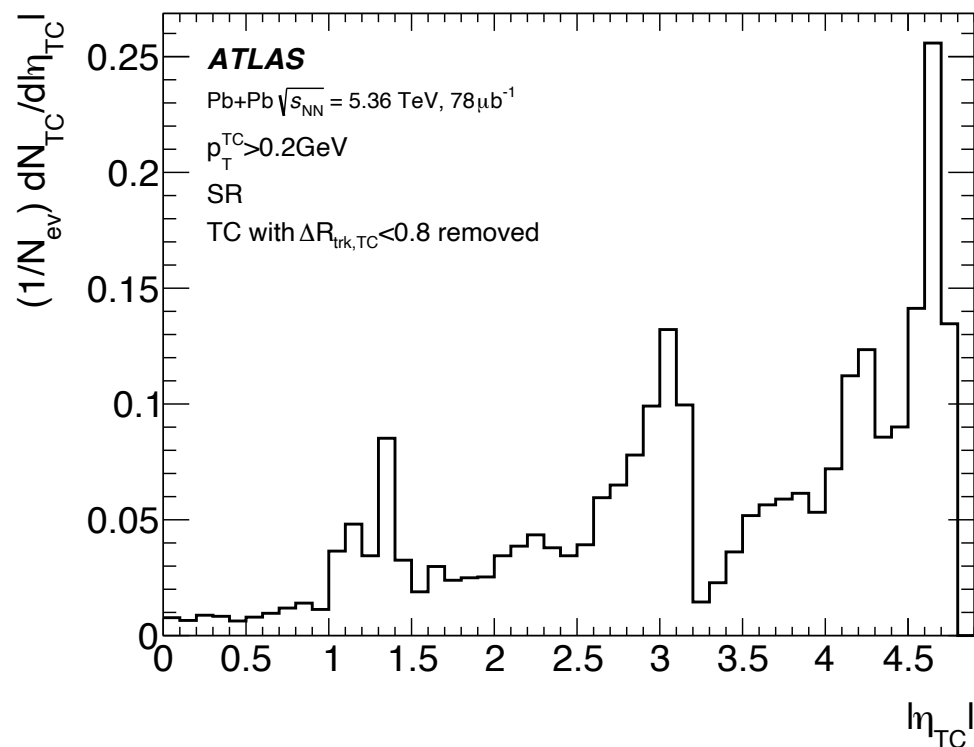
Topological clusters of calorimeter-cell energy deposits

To cross-check event activity in SR beyond ID acceptance ($|\eta| < 2.5$)

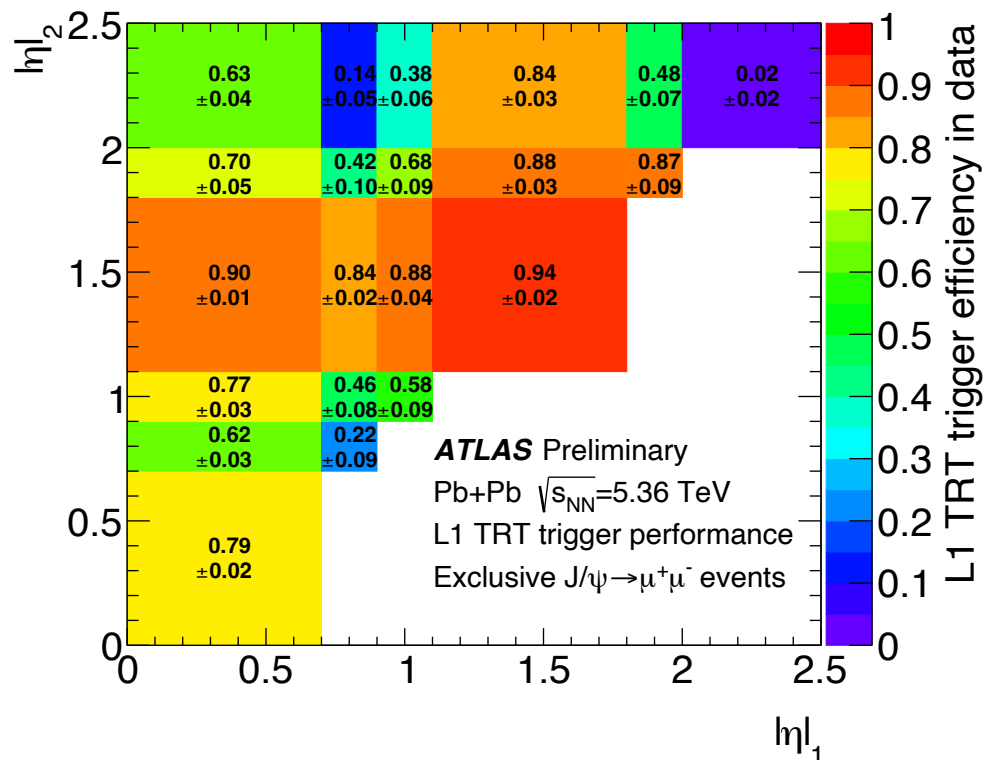
- All topoclusters $E_T > 0.2 \text{ GeV}$
- TC with $\Delta R_{l,TC} < 0.8$ removed (To exclude TC induced by leptons from the J/ψ decay)

~4% of events in SR contain at least one additional TC, consistent with expectations from incoherent backgrounds and the production of extra particle pairs in forward region for signal.

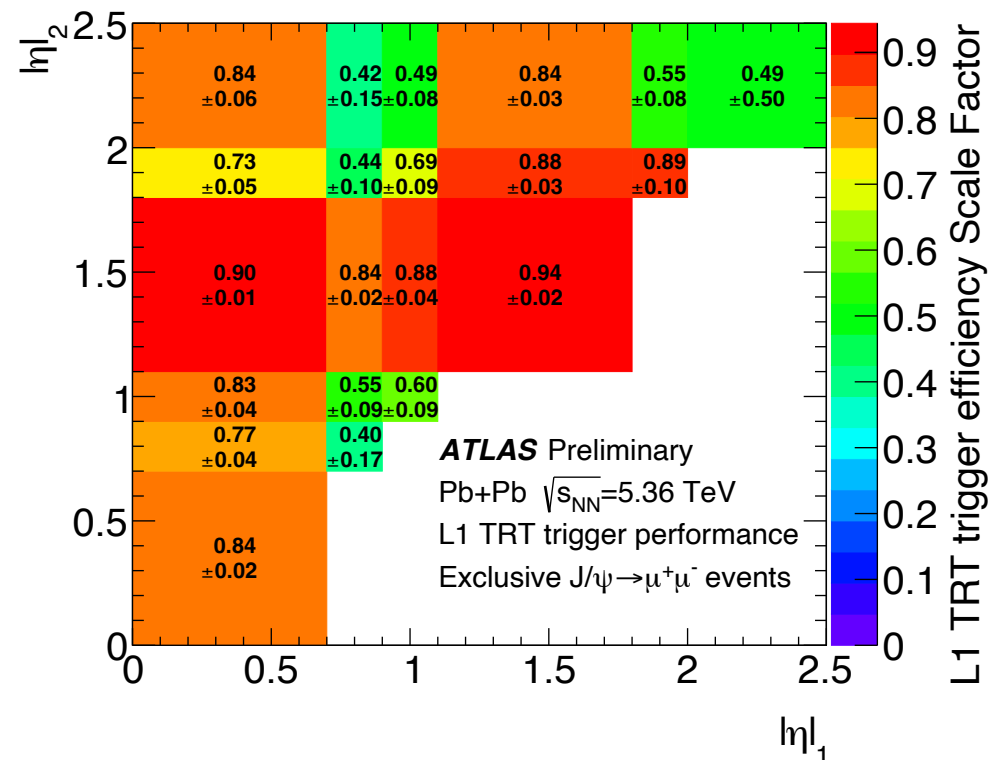
→ no additional systematic uncertainty is assigned.



L1 TRT trigger scale factor

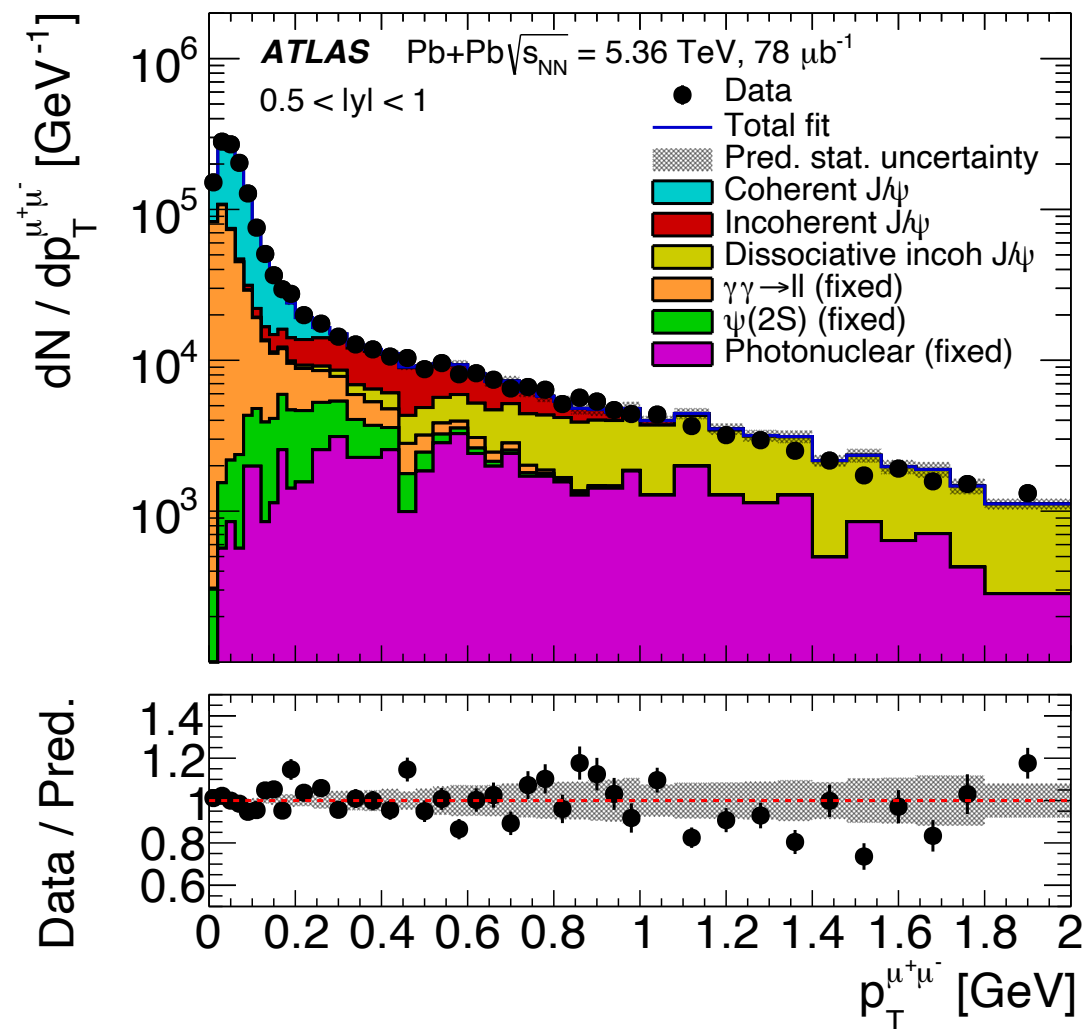
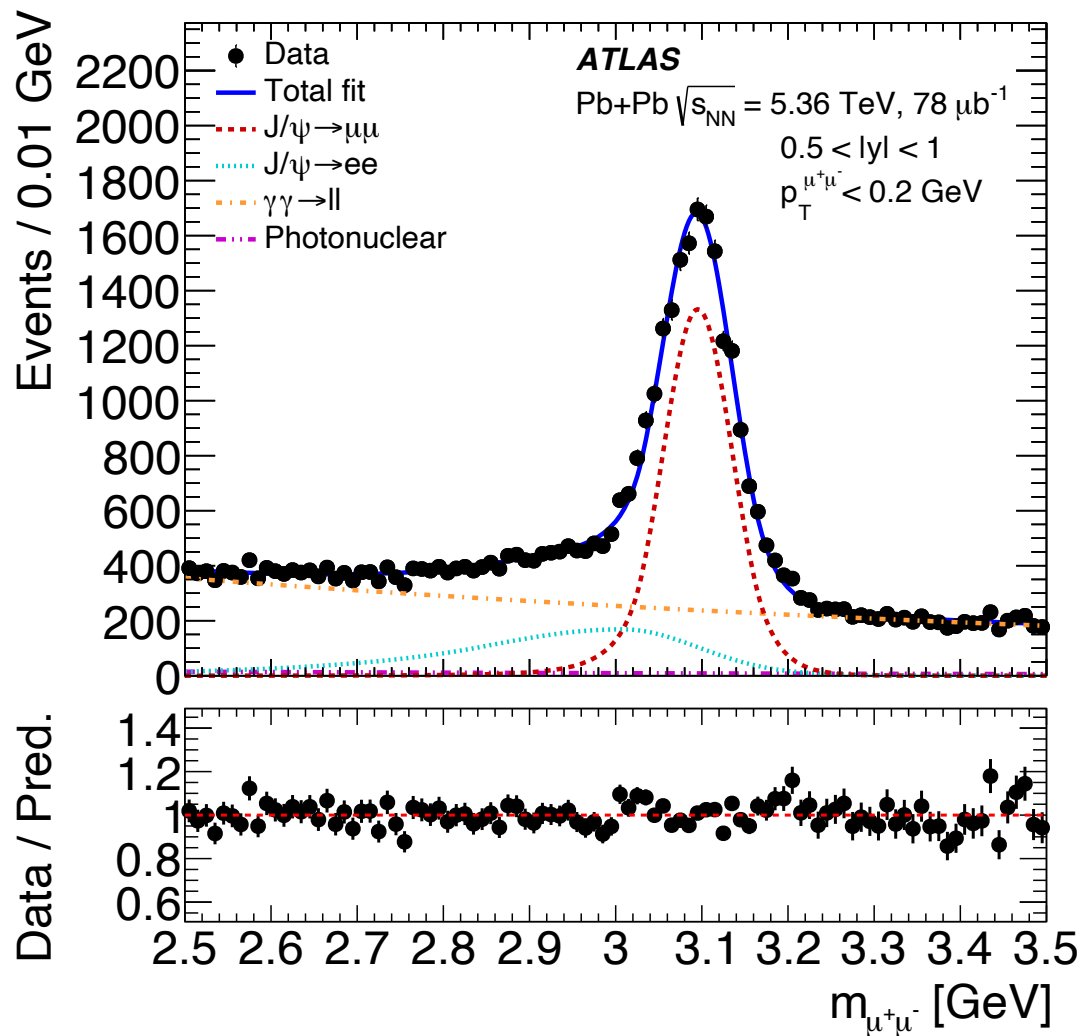


- Trigger efficiency is parametrized as a function of minimum $|\eta|_1$ and maximum $|\eta|_2$ in a track pair
- Binning reflects **structure of TRT** (Barrel <0.7 , transition $0.7-0.9$, endcap $1-1.8$, edge $1.8-2.5$)



- Derived in data and MC using mass fits, binned in $|\eta|_1$ and $|\eta|_2$, No dependence on muon p_T
- Data/MC scale factors allow correction of MC efficiency to data

Extraction of coherent $J/\psi \rightarrow \mu\mu$ signal yield : $0.5 < |y| < 1$



Extraction of coherent $J/\psi \rightarrow \mu\mu$ signal yield : $1 < |y| < 1.5$

