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


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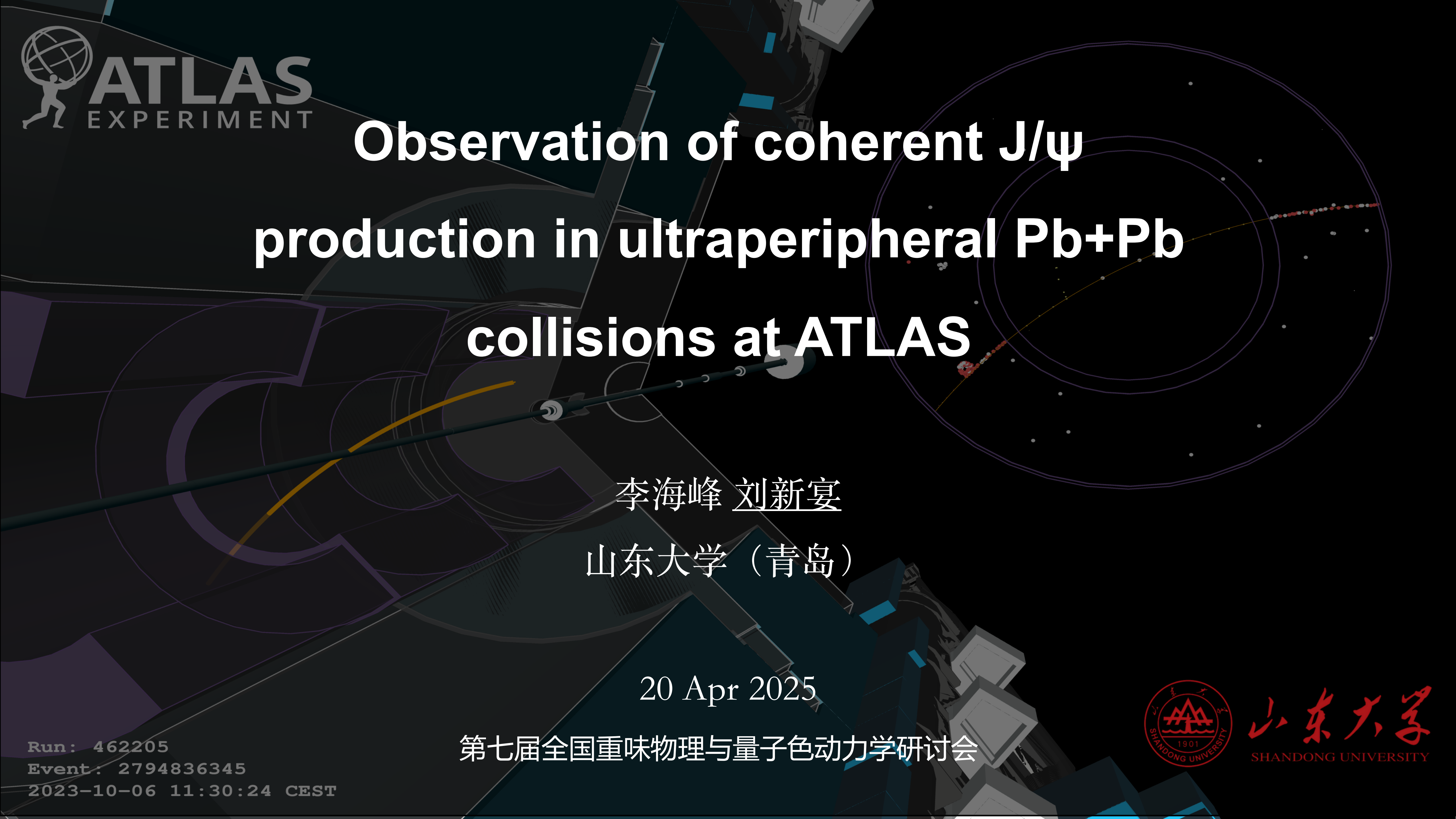
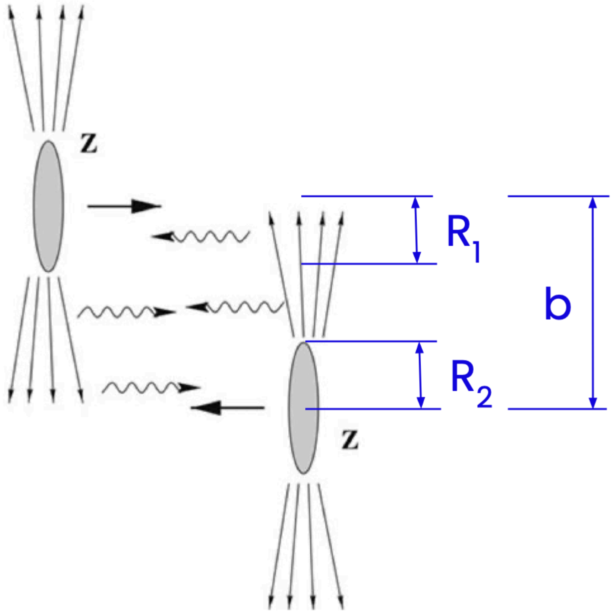


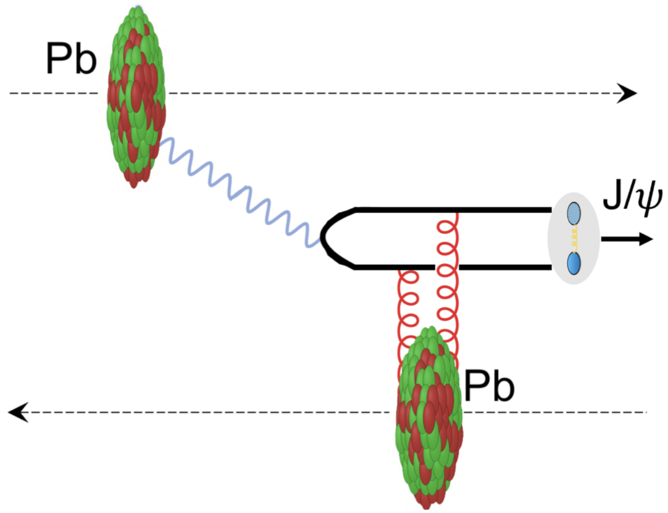
# Introduction

- LHC can act as a "photon collider" under specific conditions
- Ultraperipheral collisions (**UPC**):
  - Impact parameter: **b > 2R**
  - Dominated by photon-photon and photonuclear interactions

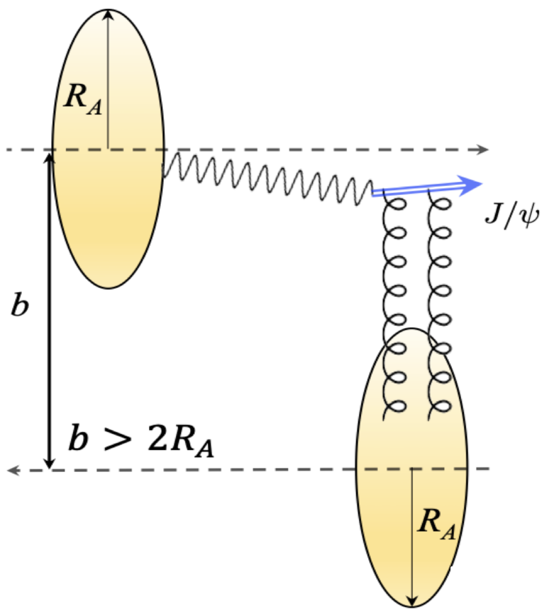
- Quasi-real photons exchanged in relativistic heavy ion interactions are powerful probes of the gluonic structure of nucleon and nucleus

- Coherent $J/\psi$ 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**



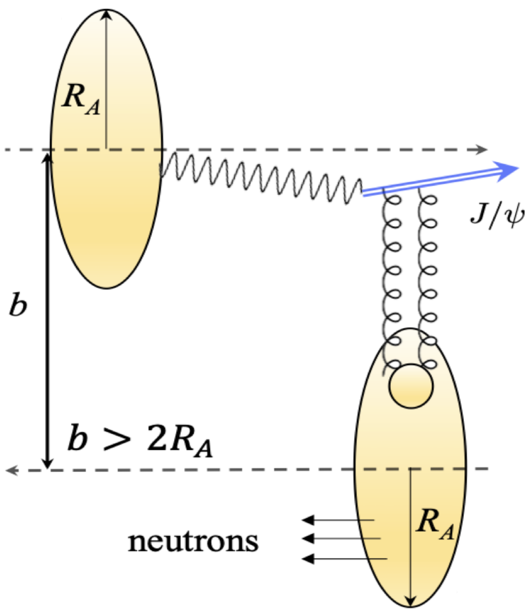
# Process of interest




(a) Coherent, nucleus stays intact

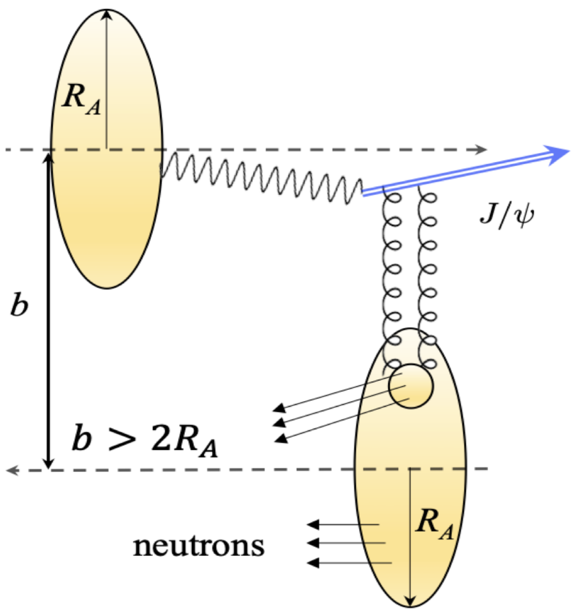
- Photon interacts coherently with entire nucleus
- Low $p_T^2$ ( $\lesssim 0.02\mathrm{GeV}$)

Our signal process




(b) Incoherent with elastic nucleon

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




(c) Incoherent with nucleon dissociation

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

Background process

Adapted from arxiv 2311.13632

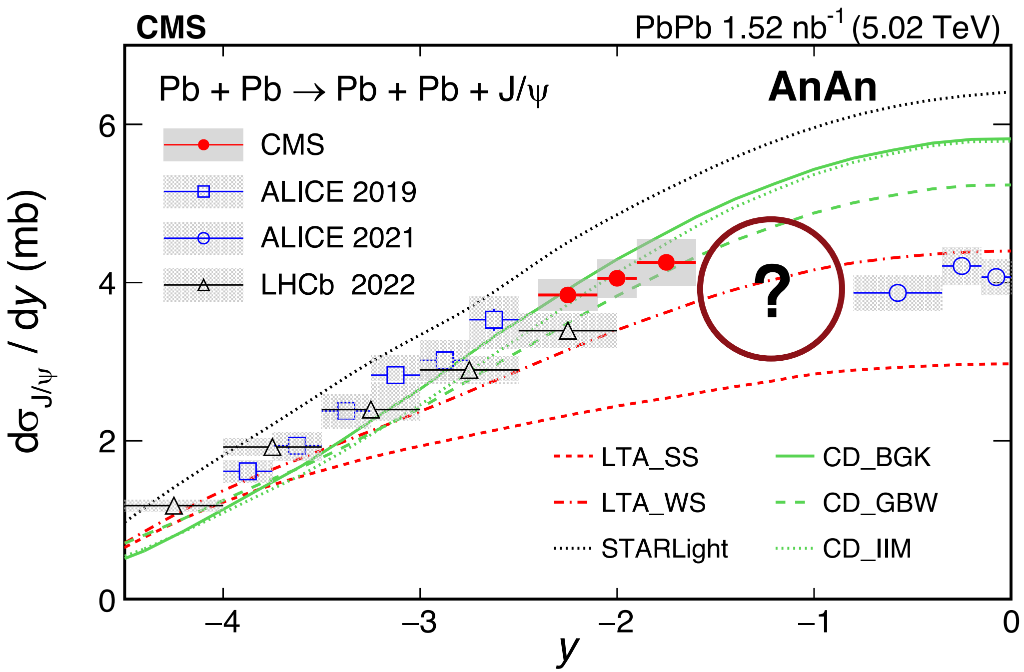
# Motivation

- Measurement of the differential cross-section **dσ/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 ($p_{\mathrm{T}}$~$1.5\,\mathrm{GeV}$) leptons



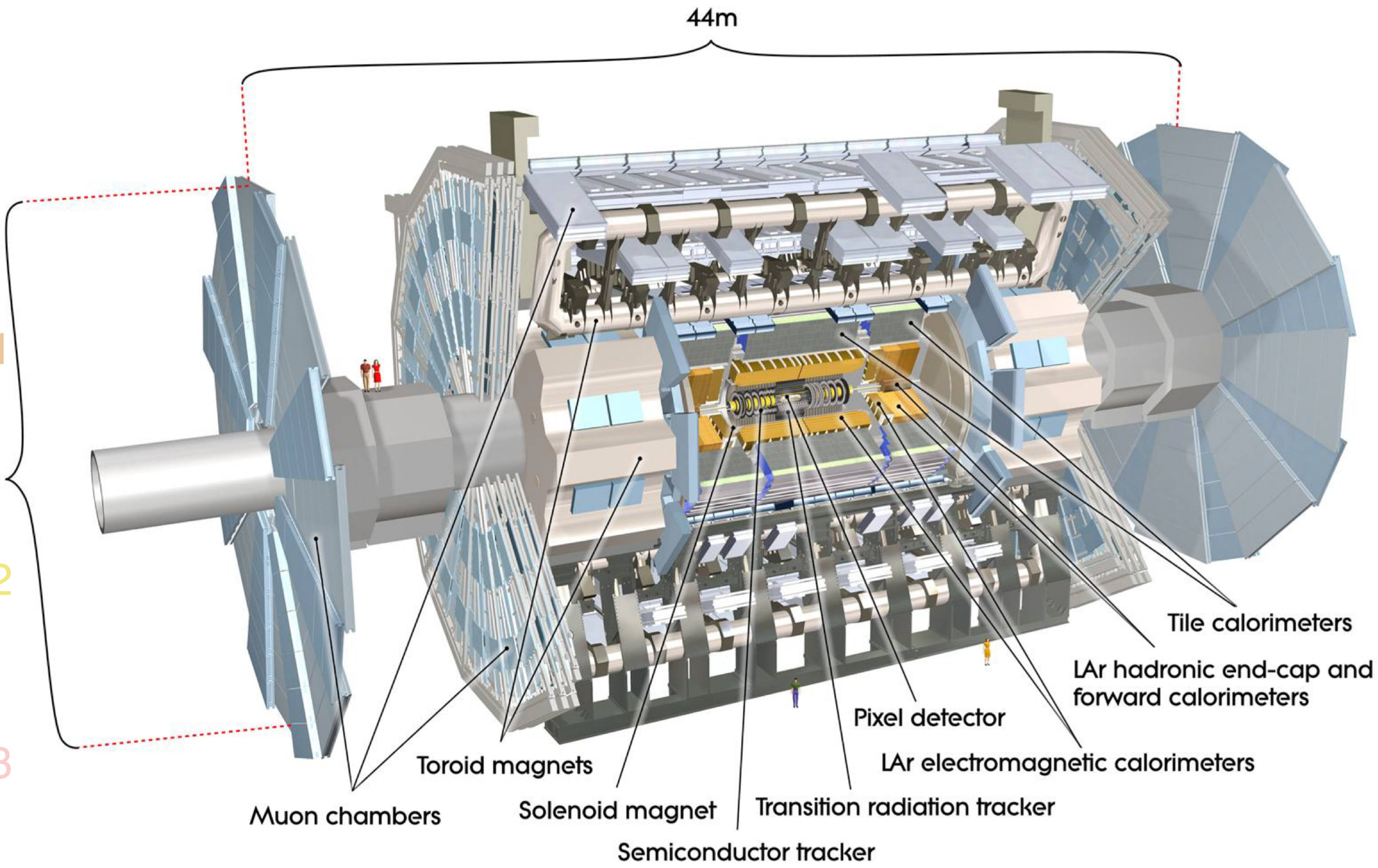
# ATLAS detector and Heavy Ion Data

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

| System | Year | $\sqrt{s_{NN}}$ [TeV] | $\mathcal{L}_{int}$ | |
|---|---|---|---|---|
| Pb+Pb | 2010 | 2.76 | 7 $\mu b^{-1}$ | Run1 |
| Pb+Pb | 2011 | 2.76 | 0.14 $\text{nb}^{-1}$ | |
| pp | 2013 | 2.76 | 4 $\text{pb}^{-1}$ | |
| p+Pb | 2013 | 5.02 | 29 $\text{nb}^{-1}$ | |
| pp | 2015 | 5.02 | 28 $\text{pb}^{-1}$ | Run2 |
| Pb+Pb | 2015 | 5.02 | 0.49 $\text{nb}^{-1}$ | |
| p+Pb | 2016 | 5.02 | 0.5 $\text{nb}^{-1}$ | |
| p+Pb | 2016 | 8.16 | 0.16 $\text{pb}^{-1}$ | |
| Xe+Xe | 2017 | 5.44 | 3 $\mu b^{-1}$ | |
| pp | 2017 | 5.02 | 270 $\text{pb}^{-1}$ | |
| Pb+Pb | 2018 | 5.02 | 1.76 $\text{nb}^{-1}$ | |
| Pb+Pb | 2023 | 5.36 | 1.71 $\text{nb}^{-1}$ | Run3 |
| pp | 2024 | 5.36 | 425 $\text{pb}^{-1}$ | |
| Pb+Pb | 2024 | 5.36 | 1.67 $\text{nb}^{-1}$ | |

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: $|\eta| > 8.3$

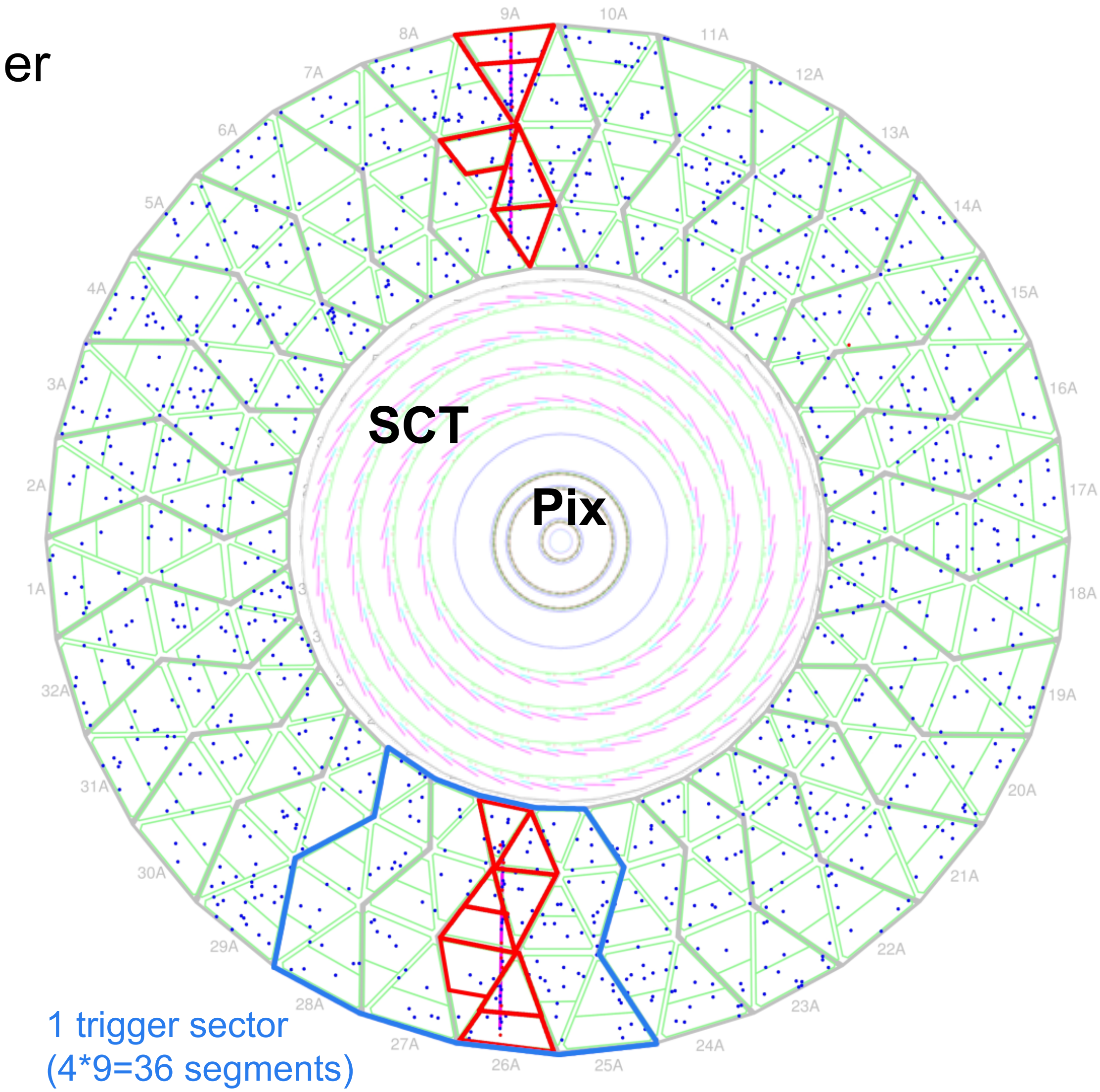
# Object and event selection

## Dataset

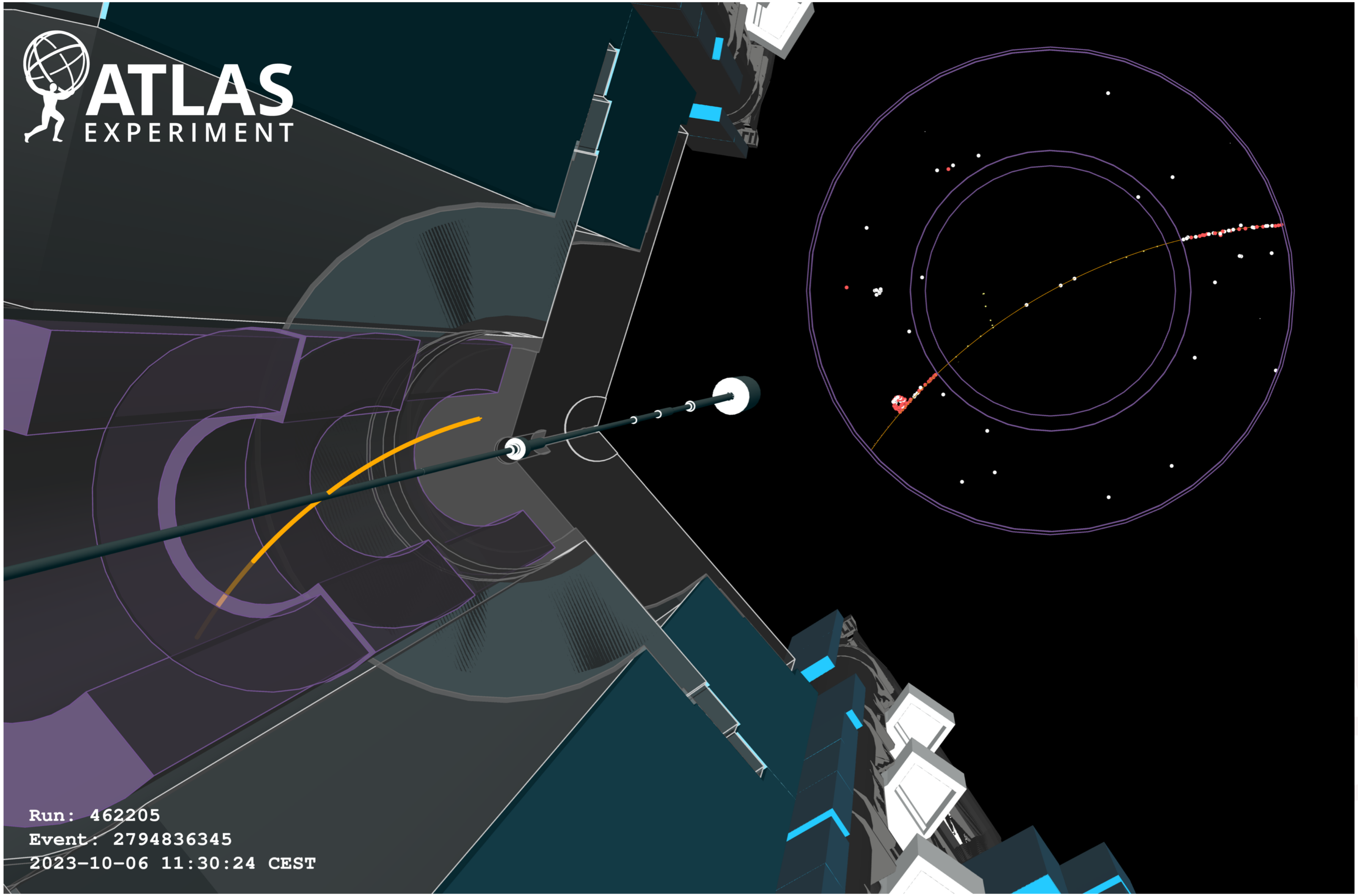
- 2023 data effective luminosity: 76.5 $\mu b^{-1}$ for signal trigger
- MC samples: STARlight (+ Pythia8/EvtGen+Photos)

## Trigger

- Previous ATLAS HI runs were unable to trigger on J/$\psi$
- L1TRT "FastOR" trigger utilized in 2023
  - Take the advantage of TRT high threshold (HT) hits to catch low $p_{\mathrm{T}}$ 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, $p_{\mathrm{T}} > 100\mathrm{MeV}$, $|d_0| < 2\mathrm{mm}$
- Loose Primary working point

## Exactly two opposite-charged tracks

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

## Signal region definition

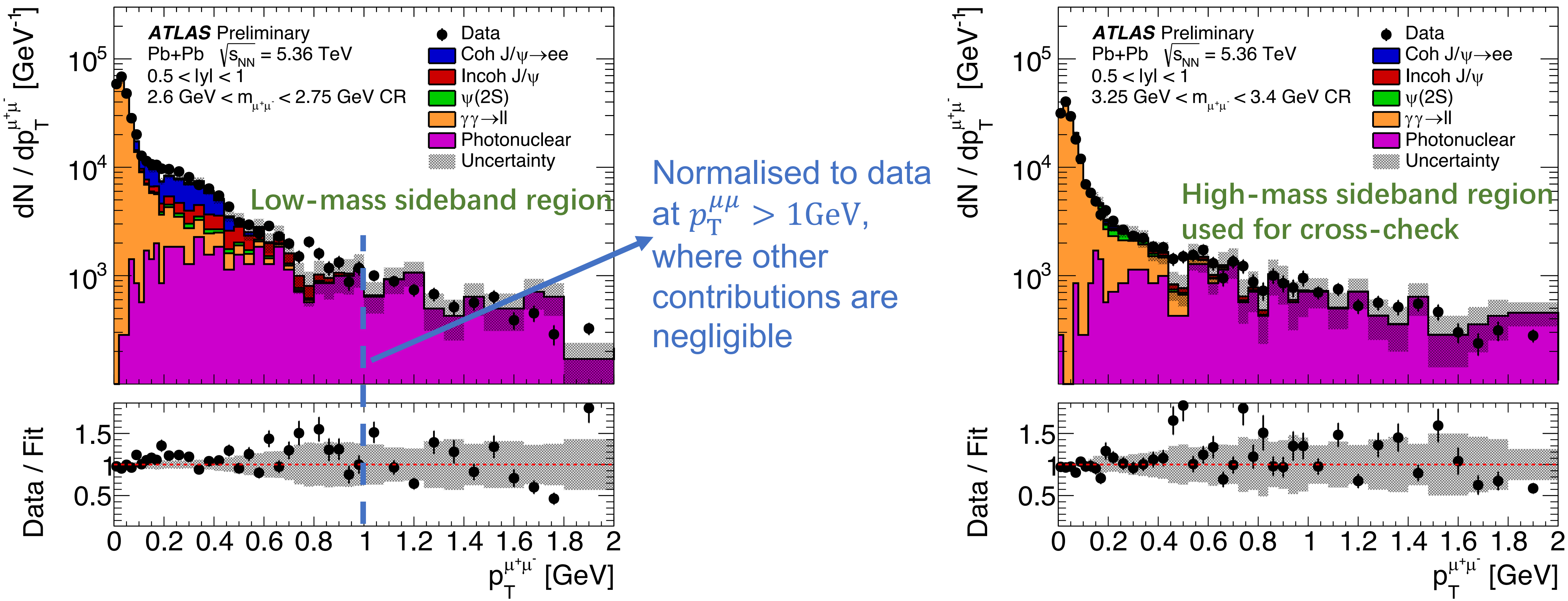
- $2.9\mathrm{GeV} < m^{\mu\mu} < 3.2\mathrm{GeV}$ (assuming μ mass per track)
- $p_{\mathrm{T}}^{\mu\mu} < 0.2\mathrm{GeV}$ to suppress incoherent production

## 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 $p_T^{\mu\mu} > 1\mathrm{GeV}$, where other contributions are negligible

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

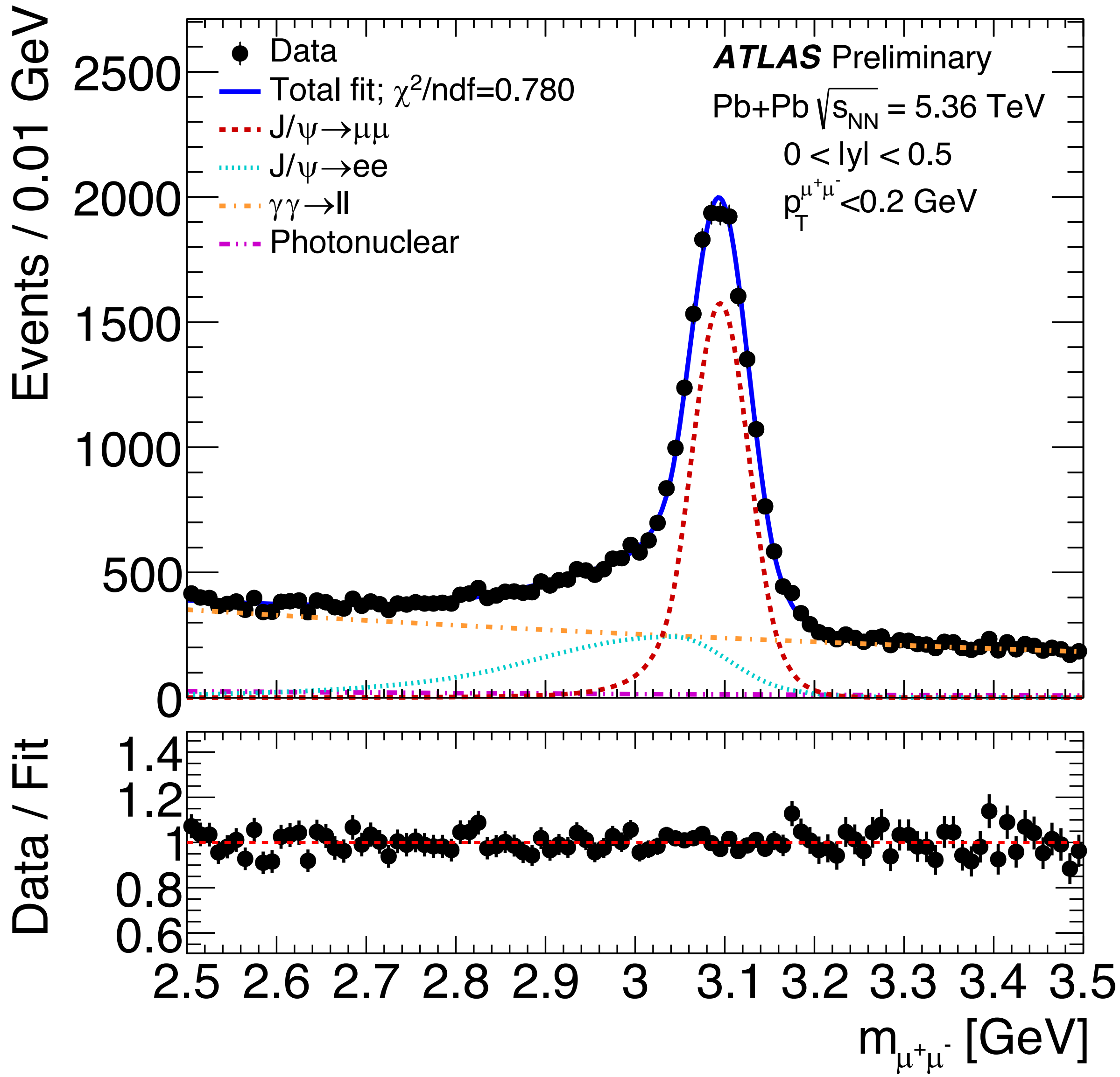
# Background estimation - ψ(2S) - dilepton

## ψ(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/ψ+ρ0** production

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

- **Fit to 2 tracks system invariant mass distribution in** $p_T^{\mu\mu} < 0.2GeV$
  - 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 $2.9GeV < m^{\mu\mu} < 3.2GeV$, also constrains μμ and ee ratio

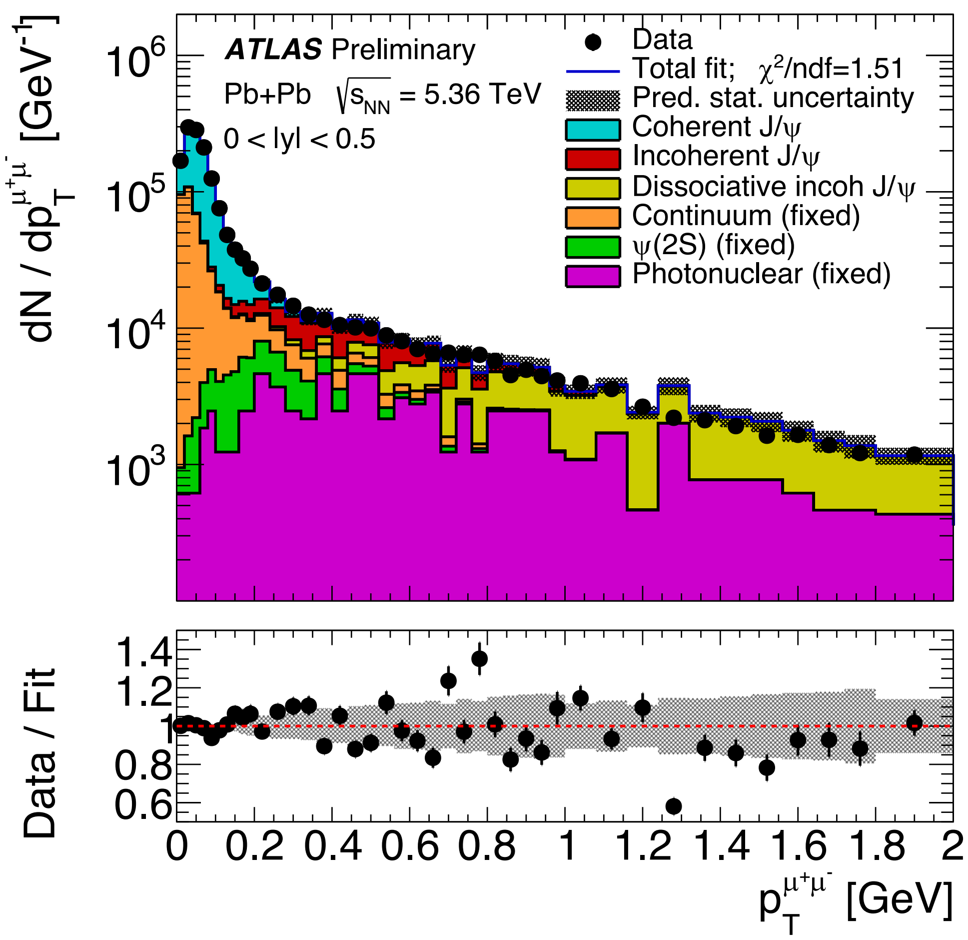


# Extraction of coherent J/ψ→μμ signal yield: $|y| < 0.5$

- **Fit to the $p_T$ distribution** (in $2.9\text{GeV} < m^{\mu\mu} < 3.2\text{GeV}$)
  - Using constraints from photonuclear contributions, $\boldsymbol{\psi(2S)}$ feed down and $\gamma\gamma \to \boldsymbol{l^+ l^-}$
  - J/ψ → $e^+e^-$
    - 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

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

  - Binned likelihood performed incorporating all of these contributions



# Acceptance&efficiency corrections, uncertainties

## Differential cross section measurement

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

Raw coherent yield from $p_T$ fits

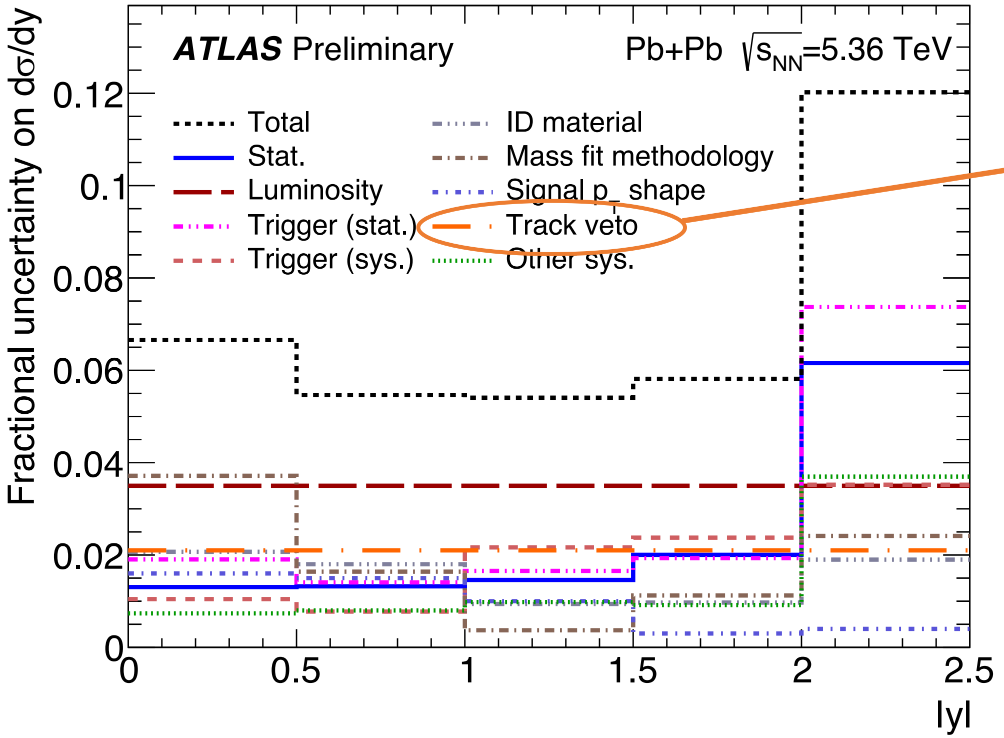
Acceptance correction (from MC)

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

J/ψ →μμ BR from PDG

Integrated luminosity of data

## Uncertainties

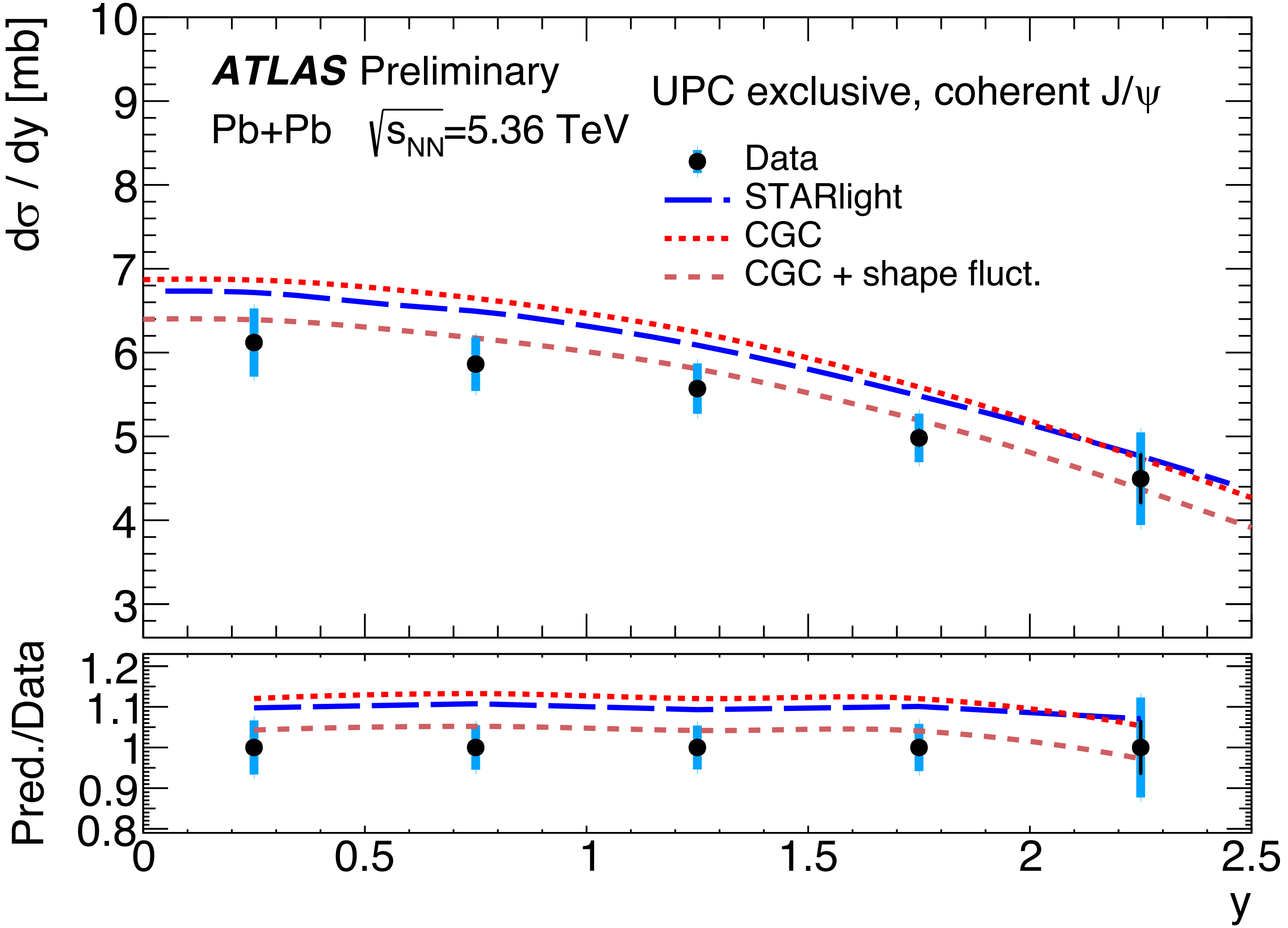



≈1.9% - coincident pair production (mainly $\rho0\to\pi\pi$) on exclusivity requirement
≈0.2% - pile-up pairs
total effect: **2.1%**

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

# Results

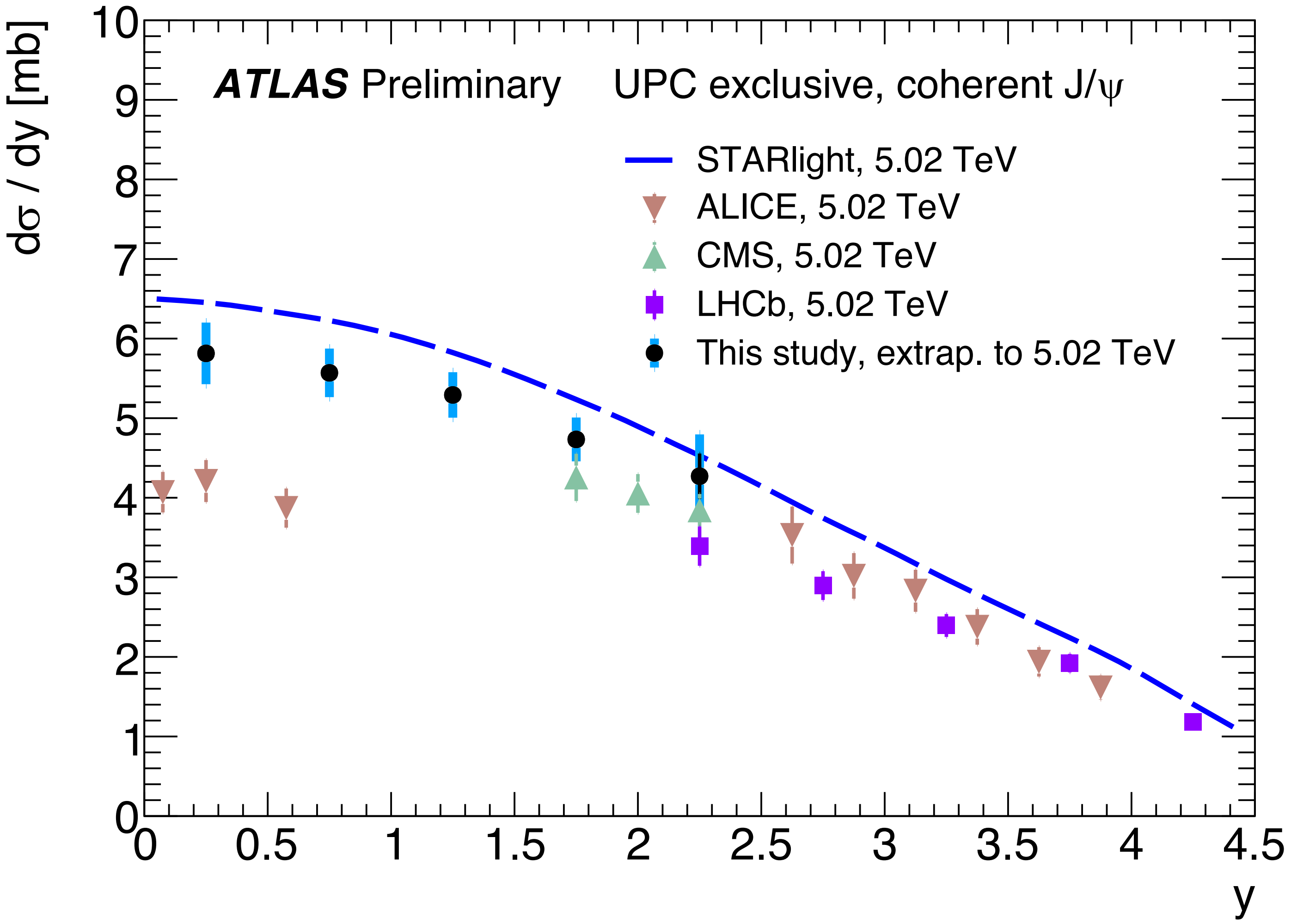
## Measured cross-sections




- **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](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 $\mathbf{1.5} < |y| < \mathbf{2.5}$
- Slope continuous with **forward** ALICE & LHCb data
- Substantial tension 30-40% with ALICE data in $|y| < \mathbf{0.8}$

# Summary

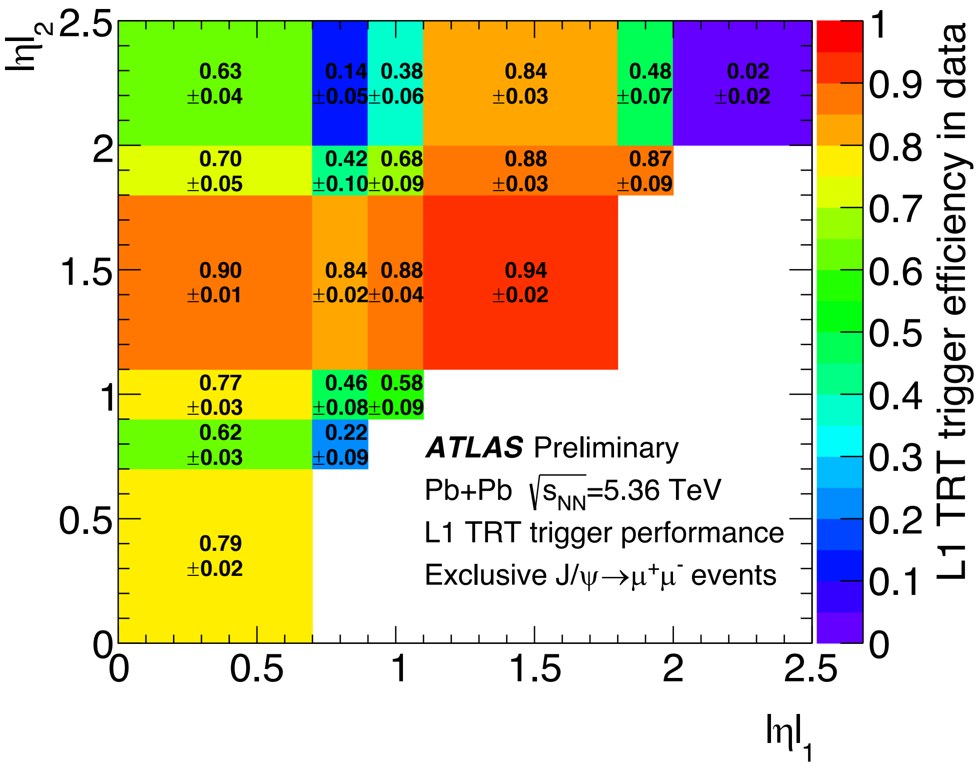
- **First observation of coherent J/ψ production** in ultraperipheral Pb+Pb collisions at ATLAS
- Cross section measured differentially in rapidity intervals from $0<|y|<2.5$, covering a **previously-unmeasured region $0.8 < |y| < 1.6$**
- Good agreement with model trends, and magnitude is best described 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

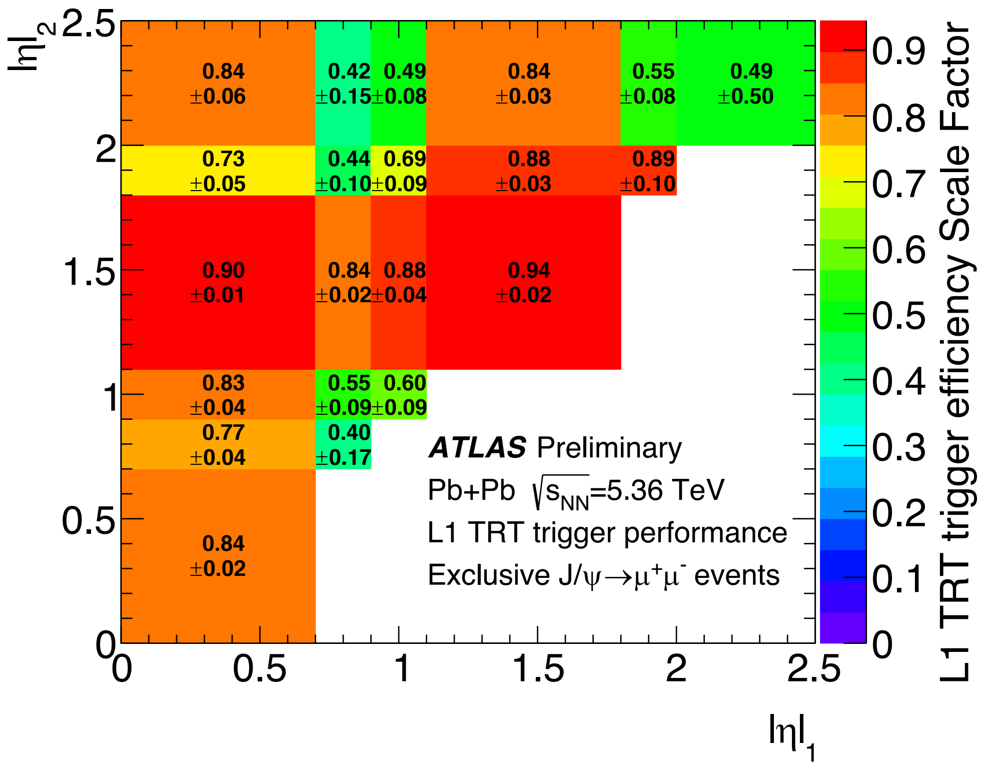
- Results available at ATLAS-CONF-2025-003

# THANKS FOR YOUR ATTENTION

# Backup

# L1 TRT trigger scale factor

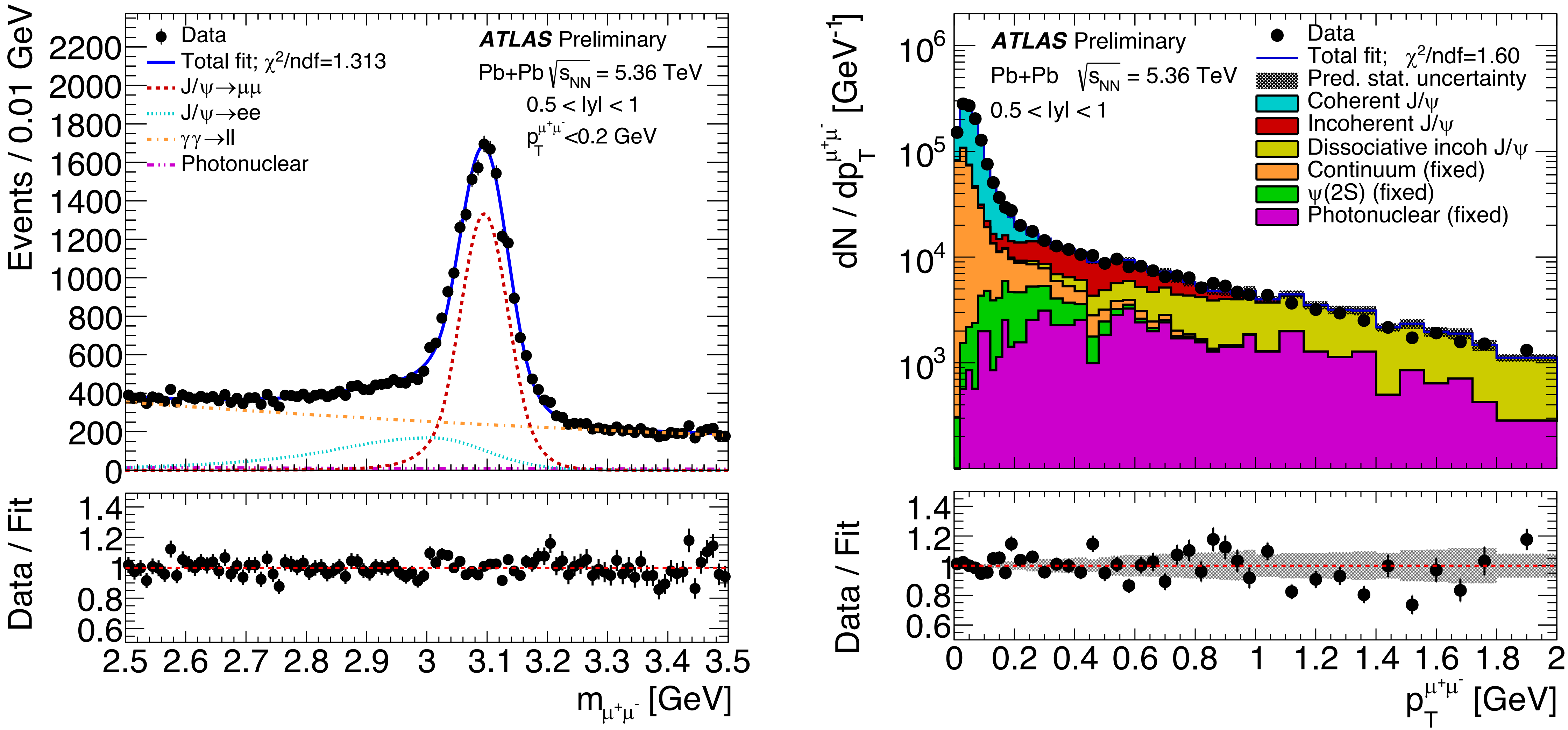


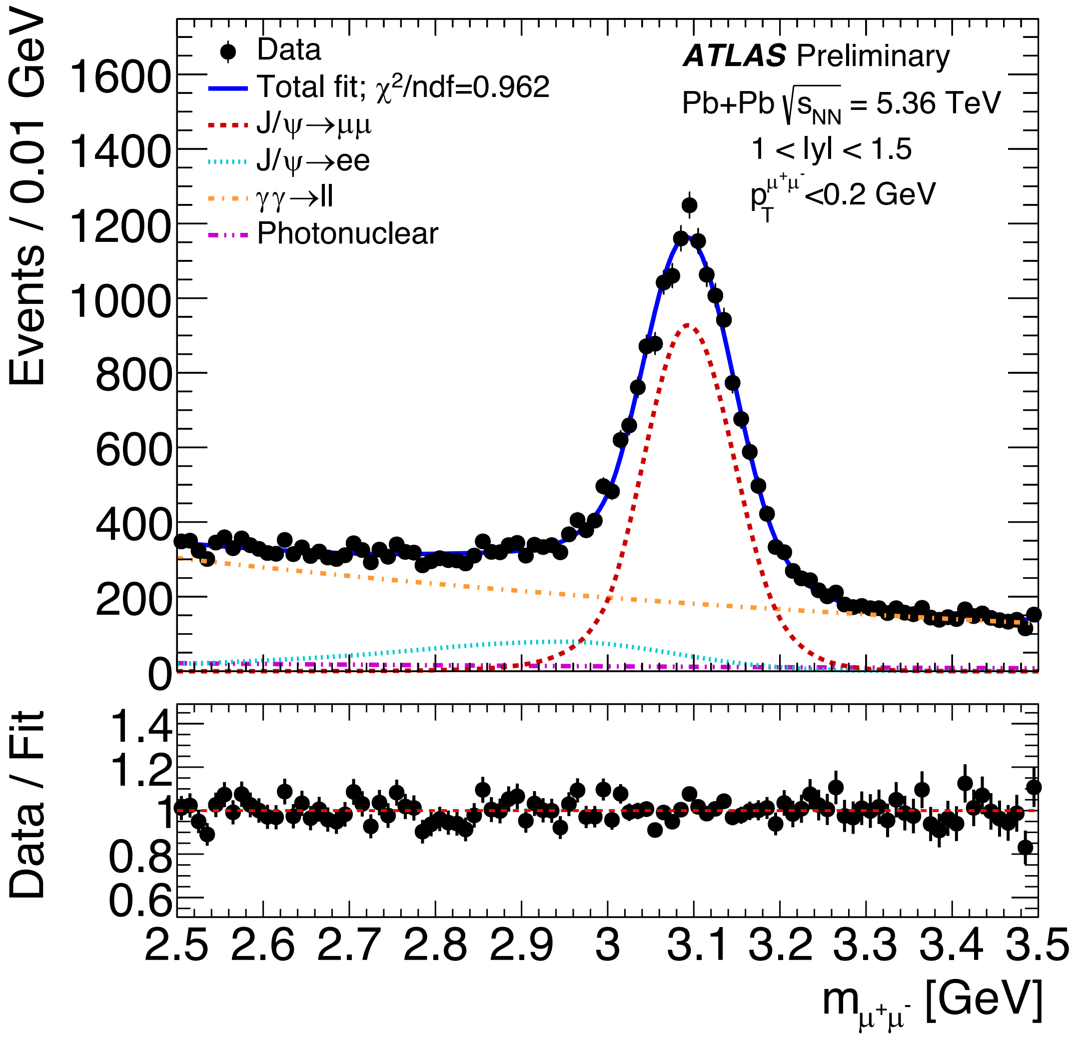

- Trigger efficiency is parametrized as a function of minimum $|\eta|_1$ and maximum $|\eta|_2$ in a track pair
- Binning reflects **structure of TRT** (Barrel<0.7, transition 0.7-0.9, endcap 1-1.8, edge 1.8-2.5)

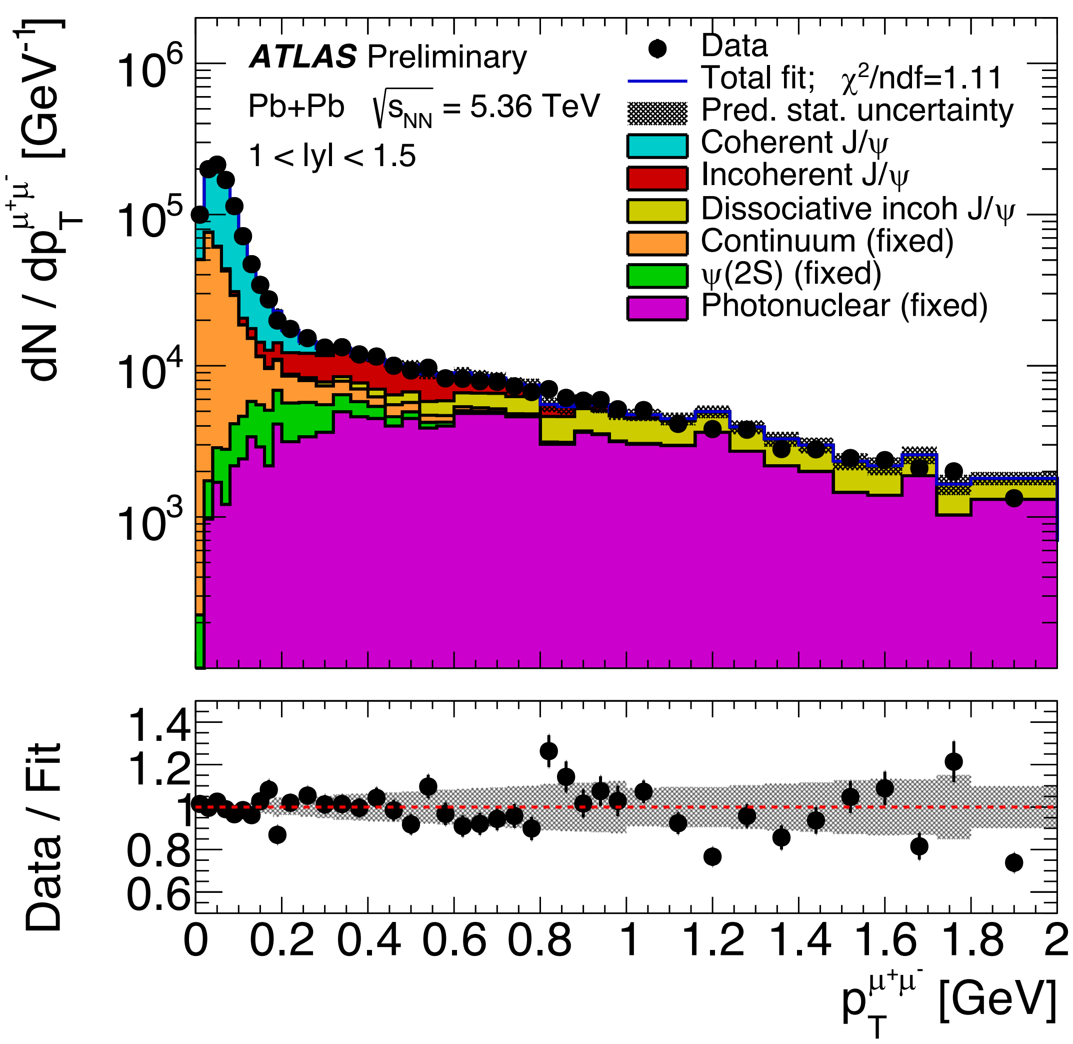
- Derived in data and MC using mass fits, binned in $|\eta|_1$ and $|\eta|_2$, No dependence on muon $p_T$
- Data/MC scale factors allow correction of MC efficiency to data

# Extraction of coherent J/ψ→μμ signal yield : $0.5 < |y| < 1$

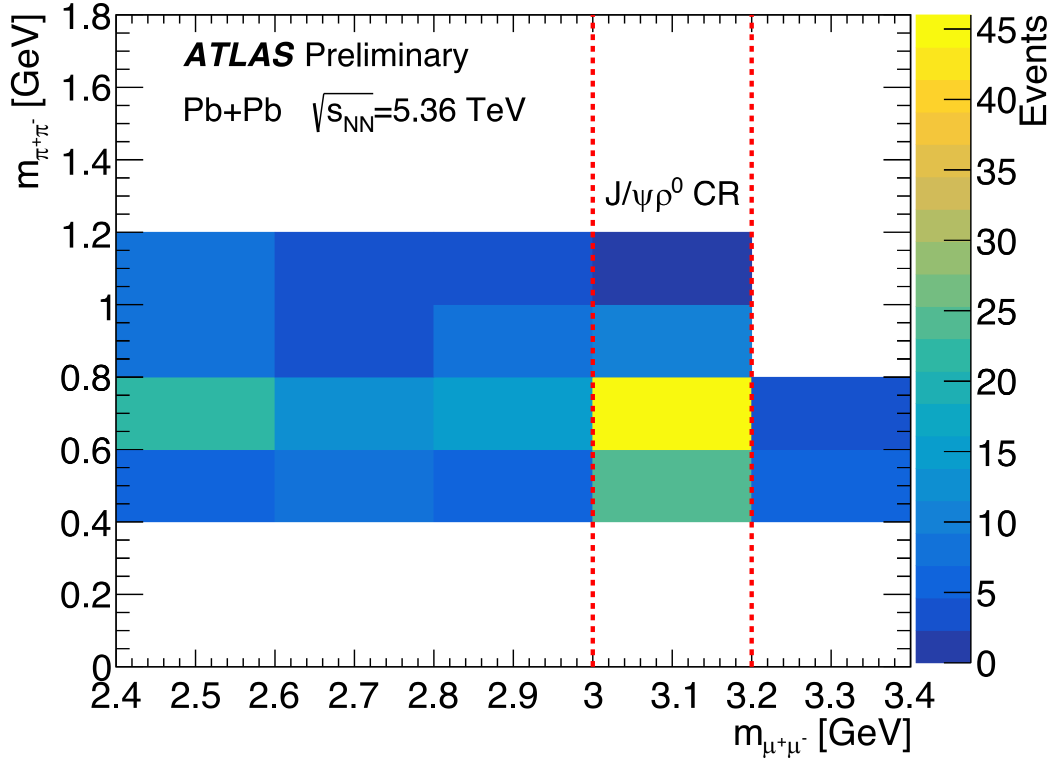


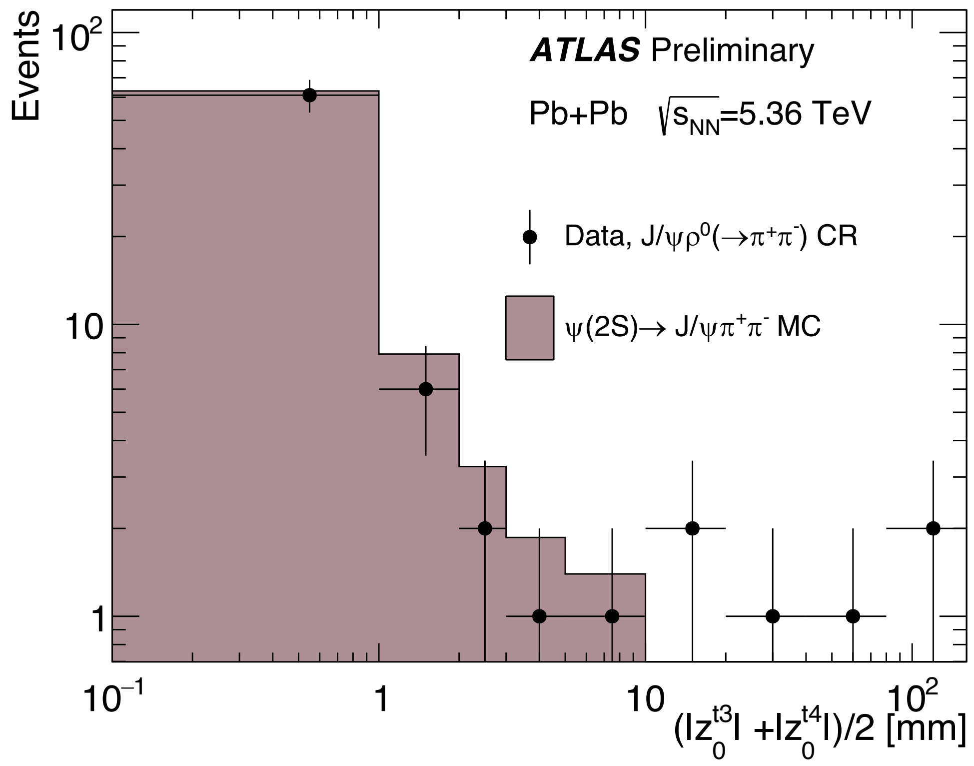
# Extraction of coherent J/ψ→μμ signal yield : $1 < |y| < 1.5$



# Discussion




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

The vertex positions of $J/\psi+\rho^0$ events in data align closely with the $J/\psi$ vertex
→ indicating that they originate from the same collision vertex, not from pile-up.