https://arxiv.org/abs/2509.04135
https://arxiv.org/abs/2504.07795

Measurement of J/ψ and impact of coincident photon-induced processes in ultra-peripheral Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.36 TeV with the ATLAS detector

Peter Steinberg, BNL / 9 Sept 2025 / Initial stages 2025

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

Coincident UPC processes

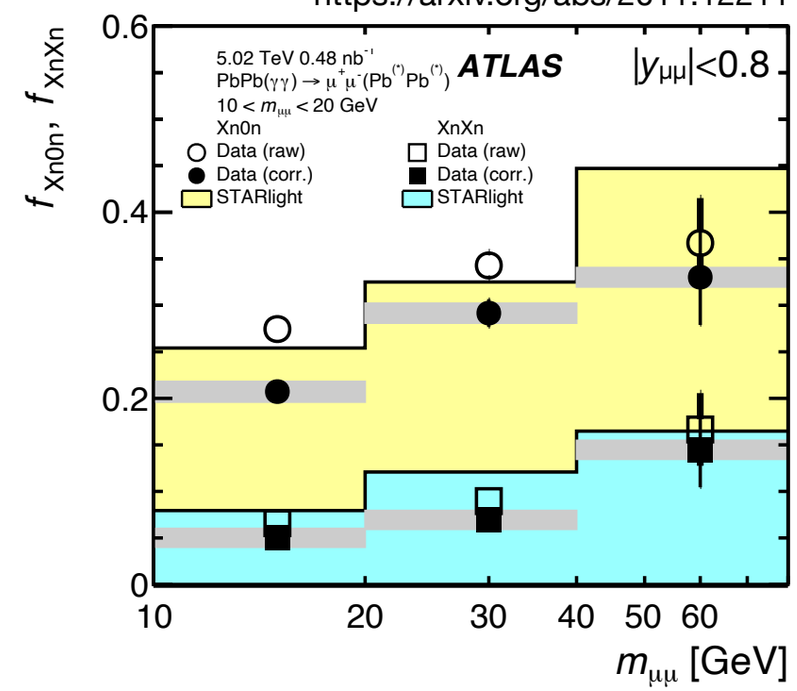
- **ATLAS has measured a range of UPC final states**
  - Exclusive dileptons (e,μ,τ)
  - Inelastic photonuclear
  - Photonuclear dijet

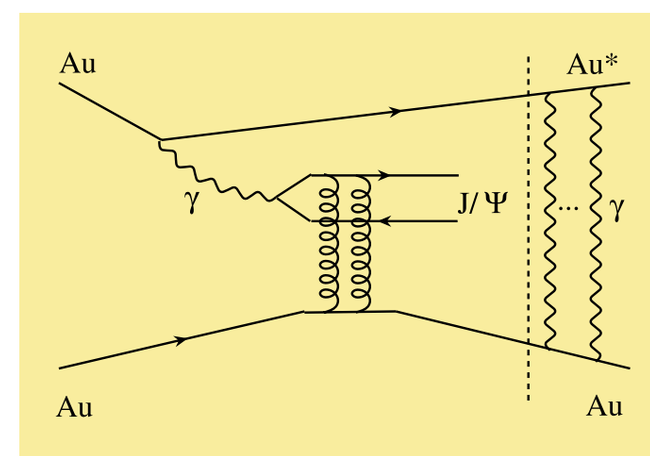
- **"Exclusivity" has been a topic of recent debate**

- **While it has a simple experimental definition it is problematic conceptually:**
  - Photon fluxes in Pb+Pb are quite high, especially for soft photons
  - At large enough production rates, we expect <u>multiple UPC processes</u> to occur simultaneously in a single Pb+Pb interaction
  - Realized since 1999 (and trivially true for coincident forward neutrons!) but not explored systematically for central production.

- **Are some of our exclusive processes "lost" to this?**
  - A question posted by Harland-Lang (SciPost Phys. 11, 064 (2021)) to understand data-theory discrepancies
  - The answer requires measuring coincident UPC processes
  - Concern for analysis and trigger strategies

https://arxiv.org/abs/2011.12211



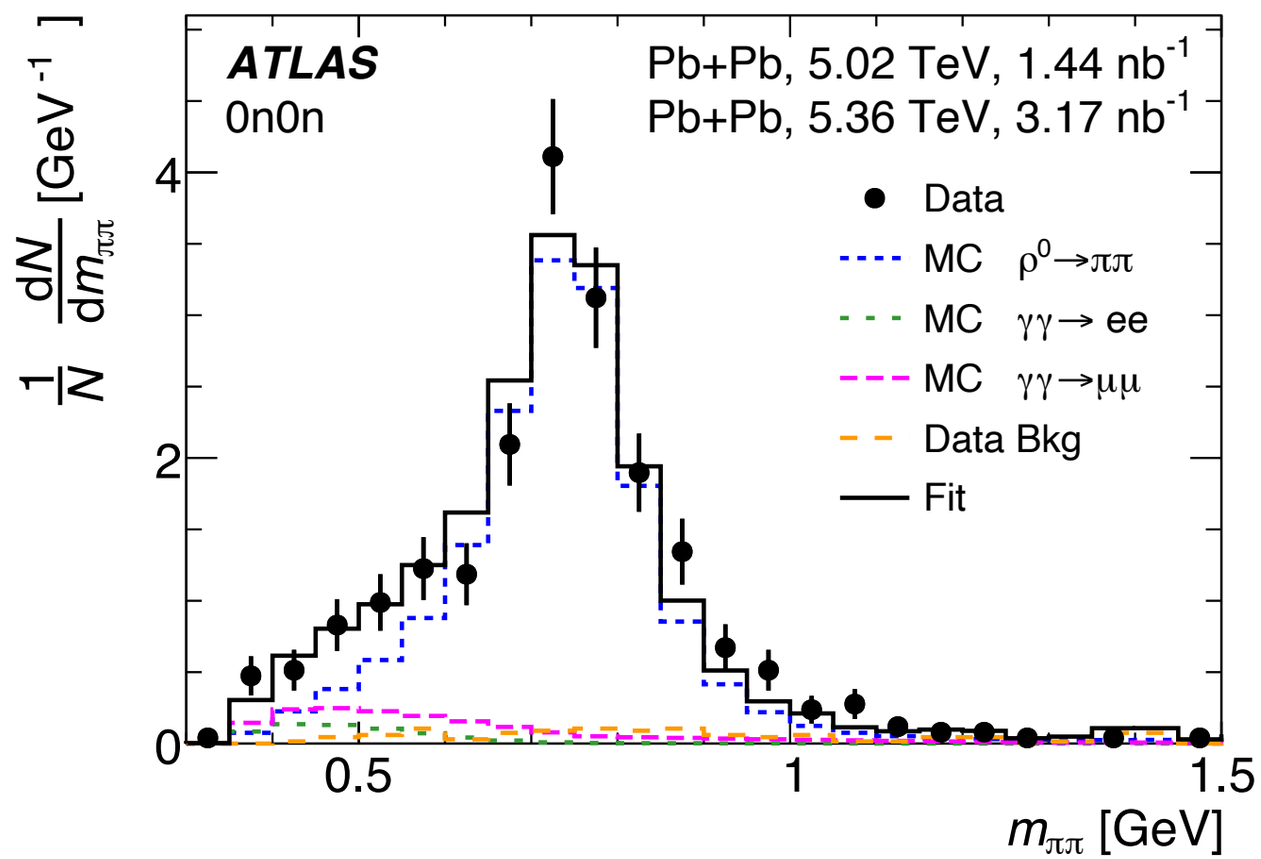


Coincident UPC processes in ATLAS

- **Measurement of two coincident processes**
  - $\gamma+\gamma\rightarrow\mu+\mu-$ and $\gamma+IP\rightarrow\rho^0$

- **Trigger and event selection**
  - μ with p_T>4 GeV at L1
  - Events selected with two opposite sign muons with p_T > 4 GeV
    - $|d_0|$ and $|z_{0,PV}\sin(\theta)|$ < 1 mm
  - Muons satisfy requirements on pair acoplanarity (α<0.15) and momentum asymmetry (A<0.2), to suppress dissociative production
  - An additional two tracks with p_T>100 MeV and $|\eta|$<2.5
    - $|d_0|$ and $|z_{0,PV}\sin(\theta)|$ < 1.5 mm

- **Most of the "additional" track pairs are clearly from ρ^0**
  - Template fit accounts for residual contributions from $\gamma\gamma$ and inelastic collisions



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Coincident UPC events in ATLAS

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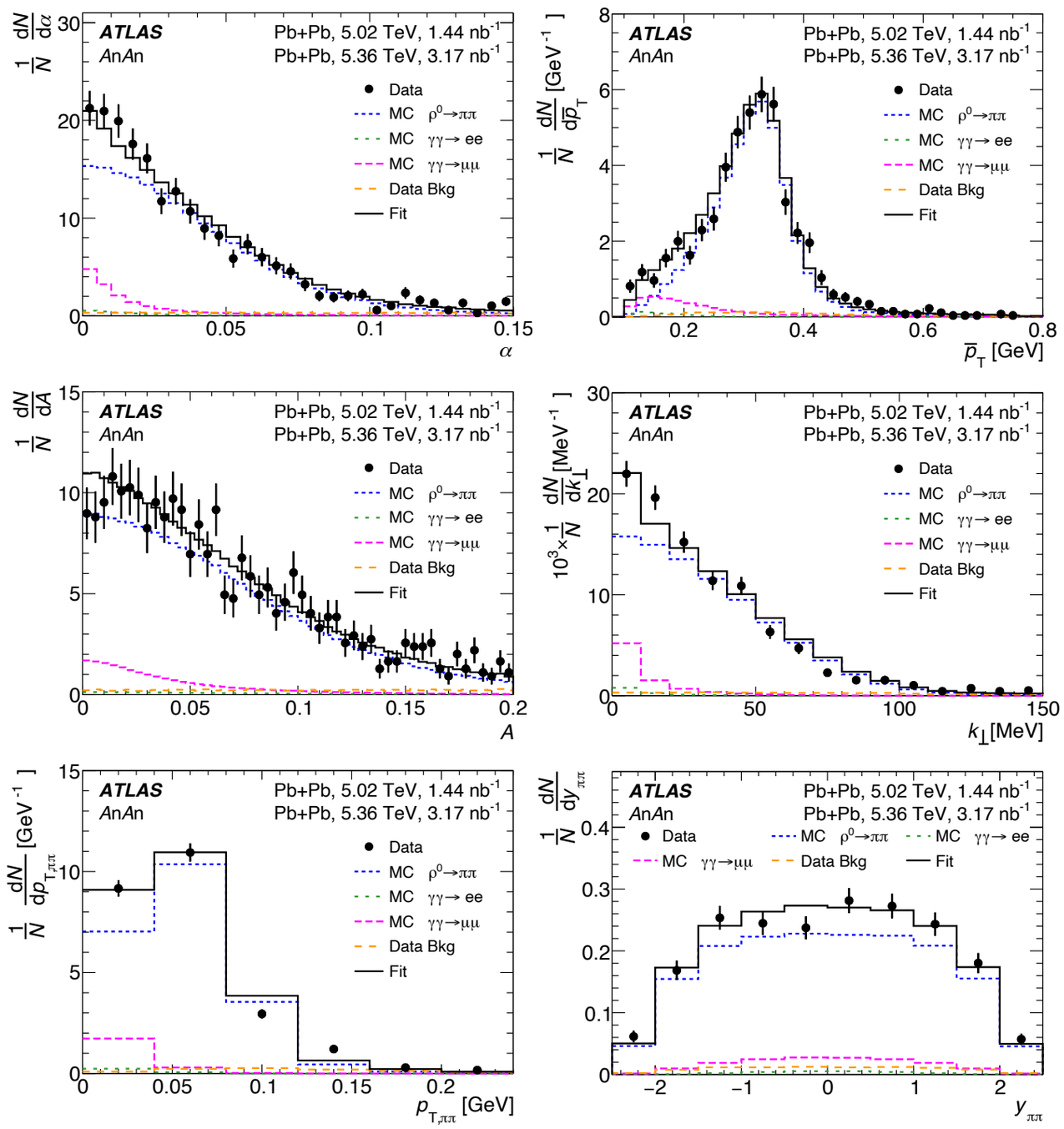

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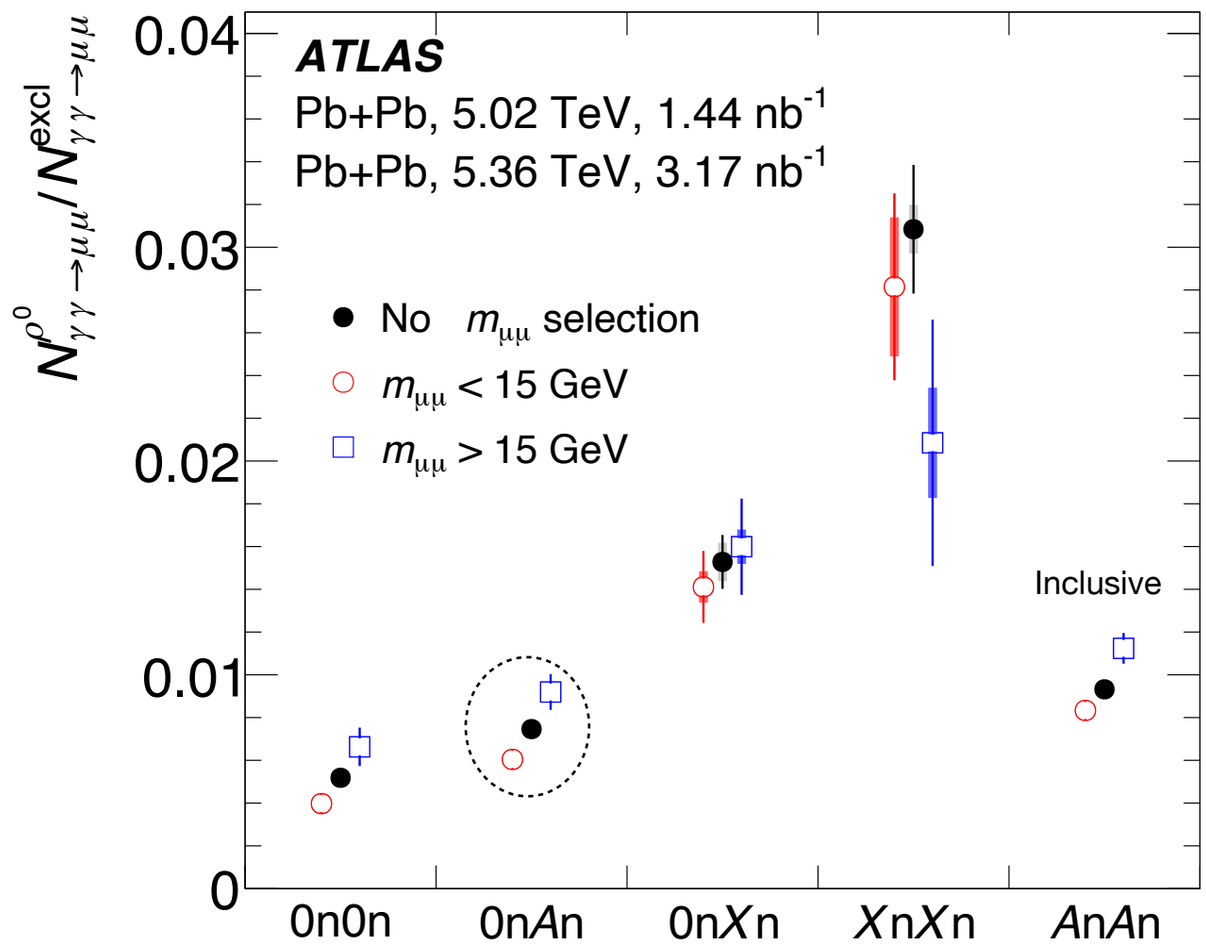
Coincident UPC events in ATLAS

- **Ratio of (ρ^0+μμ)/μμ ("coincidence ratio") shown for 5 ZDC classes**
  - An is inclusive, Xn is one or more neutrons
  - NB that this involves 3 or 4 coincident UPC processes (γγ, ρ, neutrons)
- **Ratio is 1% inclusive in the selected kinematic region**
  - Not a huge overall effect
  - But large enough to not be ignored
- **ZDC selects impact parameter ranges which affect secondary UPC production**
  - Strongest for XnXn
- **Even within a ZDC class, the μμ (γγ) kinematics have an effect on coincidence rate**
  - Selecting different dimuon mass changes momentum of incoming photons, selecting different impact parameter ranges
  - Small, but significant effects within each ZDC class (even inclusive)



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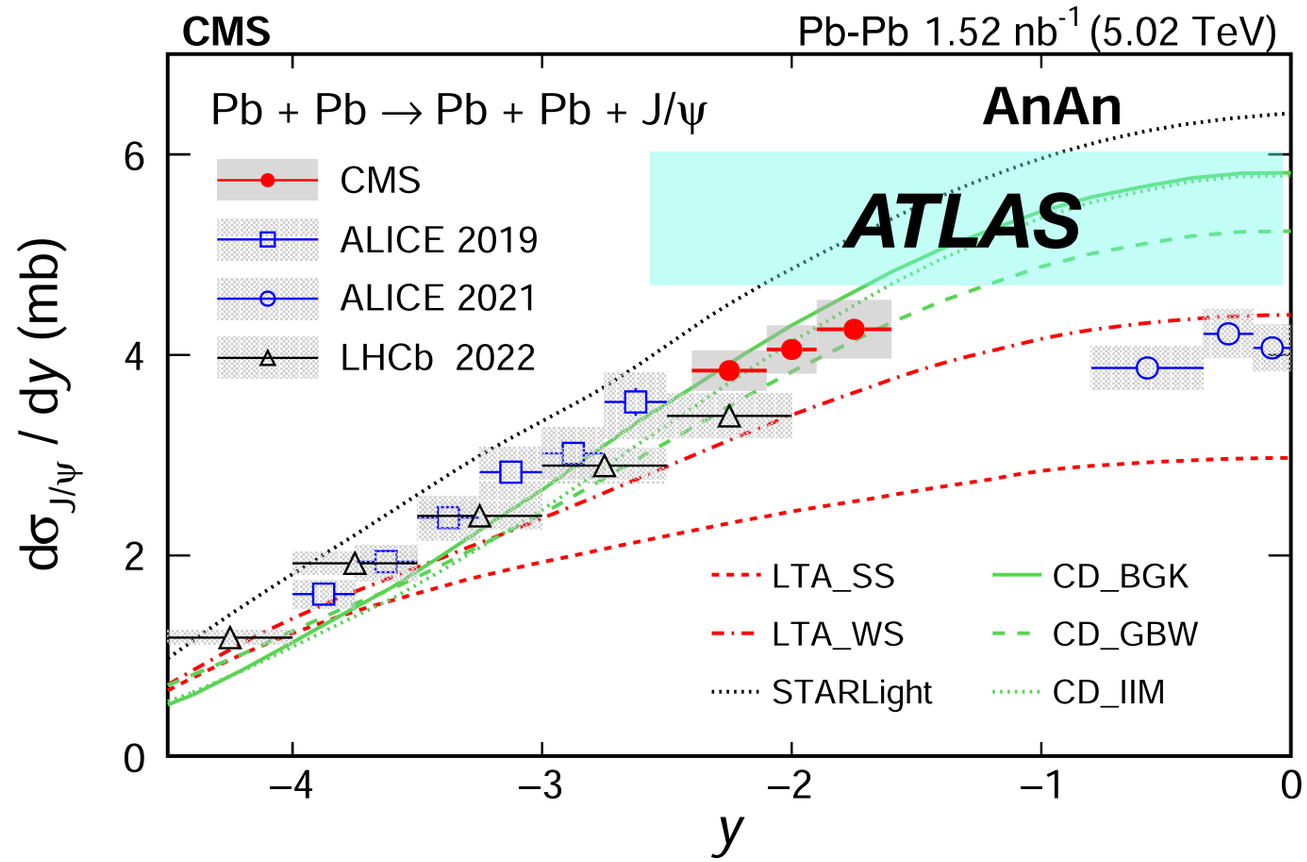
J/Ψ as probe of saturation & shadowing

- **Large mass of J/ψ provides a hard scale that allows perturbative calculations: $Q^2 = m_V^2/4$**
- **Exclusive process implies that the properties of the produced vector meson can be related simply to the kinematics of the Bjorken x of the scattering process**
  - $x = (m_V/\sqrt{s_{NN}})exp(\pm y)$
  - The sign choices reflect the fact that either nucleus can act as the photon emitter

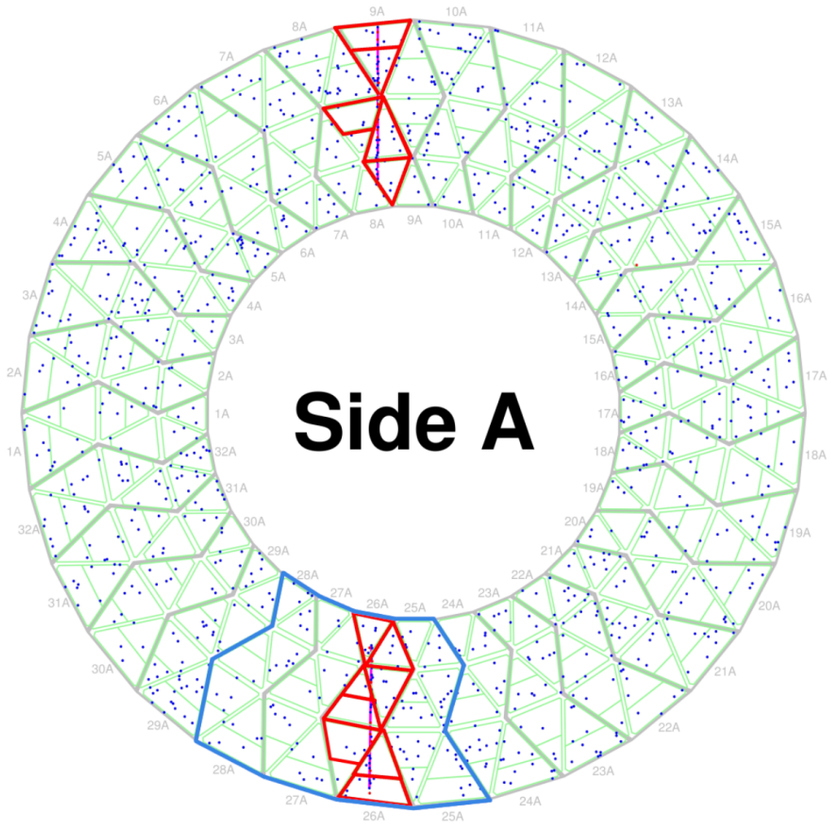
$$\frac{\mathrm{d}\sigma_{\mathrm{PbPb}}}{\mathrm{d}y} = n_\gamma(y,\{b\})\sigma_{\gamma\,\mathrm{Pb}}(y) + n_\gamma(-y,\{b\})\sigma_{\gamma\,\mathrm{Pb}}(-y)$$

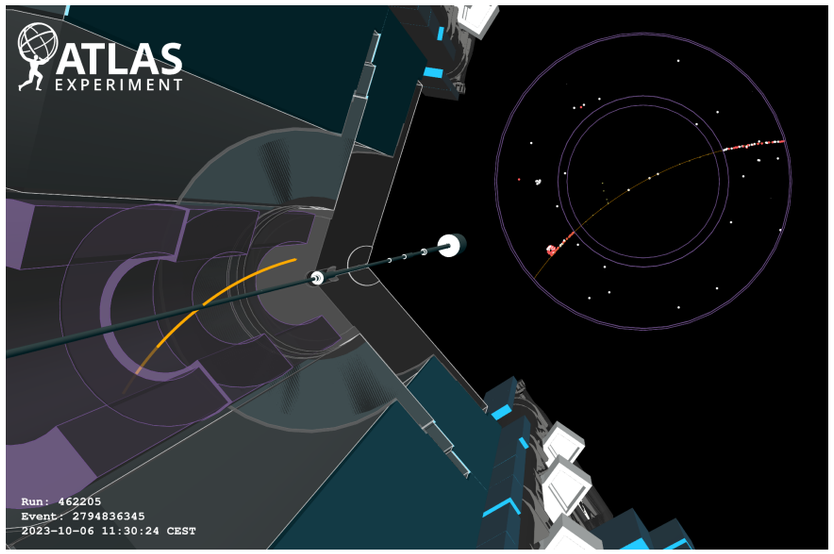
- **In recent measurements from ALICE & CMS, use the ZDC to break the degeneracy and extract the fundamental photonuclear cross section**



Dataset and primary trigger

- **This analysis is a measurement of coherent J/ψ photoproduction in the μ+μ- decay channel**
  - Data from 2023 with $\sqrt{s_{NN}}$ = 5.36 TeV
- **No ZDC selections in this first result, e.g. as used by ALICE & CMS**
  - Expected to be part of next round of ATLAS results
- **Primary event trigger requires**
  - TRT FastOR
  - Total E_T<20 GeV
  - Trigger level E_T in FCal regions below 5 GeV
  - HLT track selections requiring 1-5 tracks with p_T>1 GeV
  - Maximum of 15 tracks with p_T>200 MeV
  - Integrated luminosity of 78 μb^{-1} for Pb+Pb
- **TRT FastOR efficiency measured in data, and "scale factors" used to correct for MC trigger efficiency**





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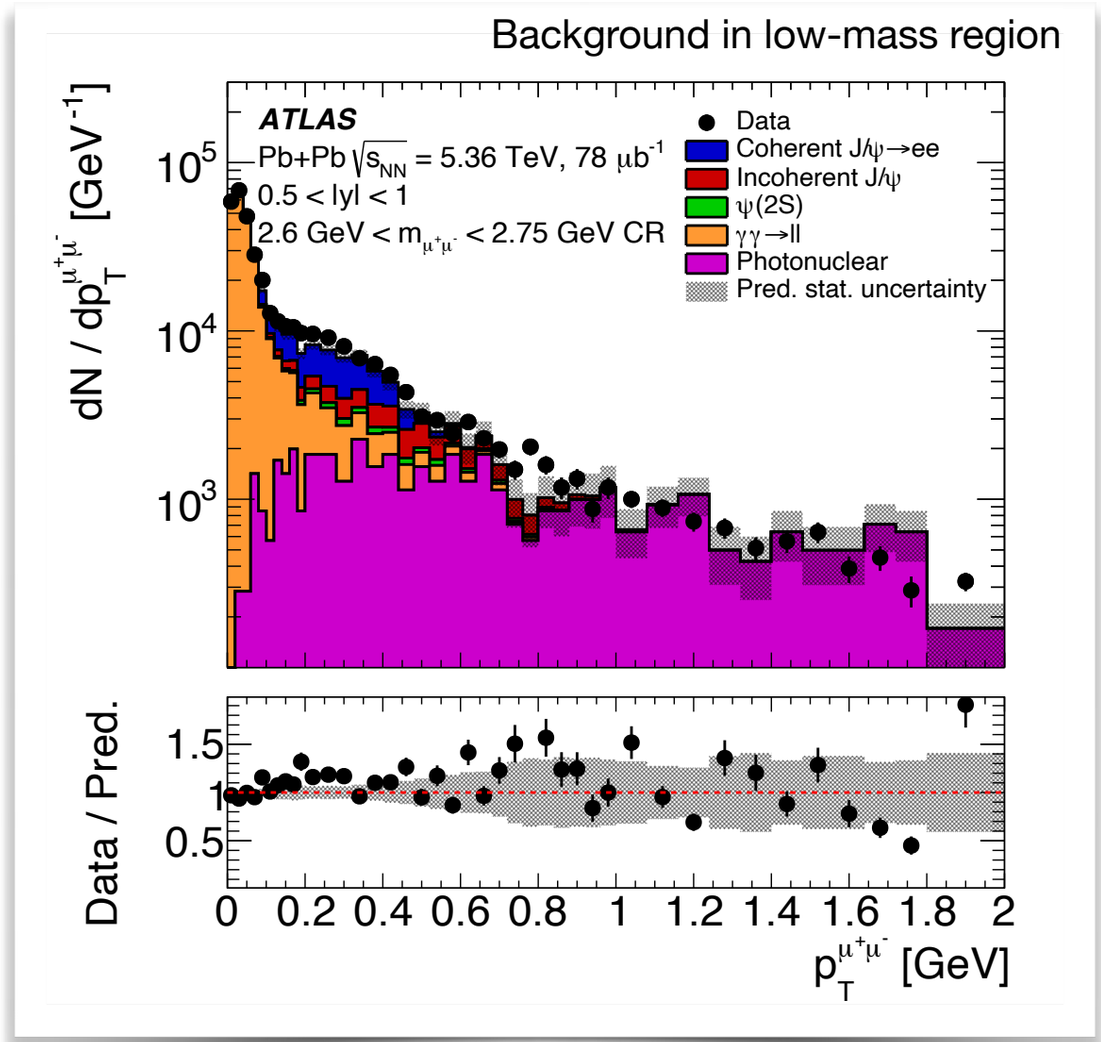
Event selection and signal extraction

- **Charged particle tracks pre-selected with**
  - pT > 100 MeV, $|\eta| < 2.5$, $|d_0| < 2$ mm, Loose primary working point
- **Events selected with exactly two opposite-charged tracks, each with p_T > 1 GeV (to match trigger conditions)**
  - In subsequent analysis, tracks are assigned the muon mass
- **Fiducial signal region**
  - $2.9 < m_{\mu\mu} < 3.2$ GeV
  - $p_T^{\mu\mu} < 0.2$ GeV
  - Final result extrapolated to full phase space
- **Signal extraction of the coherent J/ψ yield requires a systematic subtraction of several sources of background**
  - $J/\psi \to e^+e^-$
  - **Incoherent** J/ψ

    } Floating
  - $\psi(2S)$ feeddown to J/ψ (coherent & incoherent)
  - Non-resonant background from $\gamma\gamma \to \ell^+\ell^-$
  - Charged hadrons from inelastic photonuclear production

    } Fixed in data



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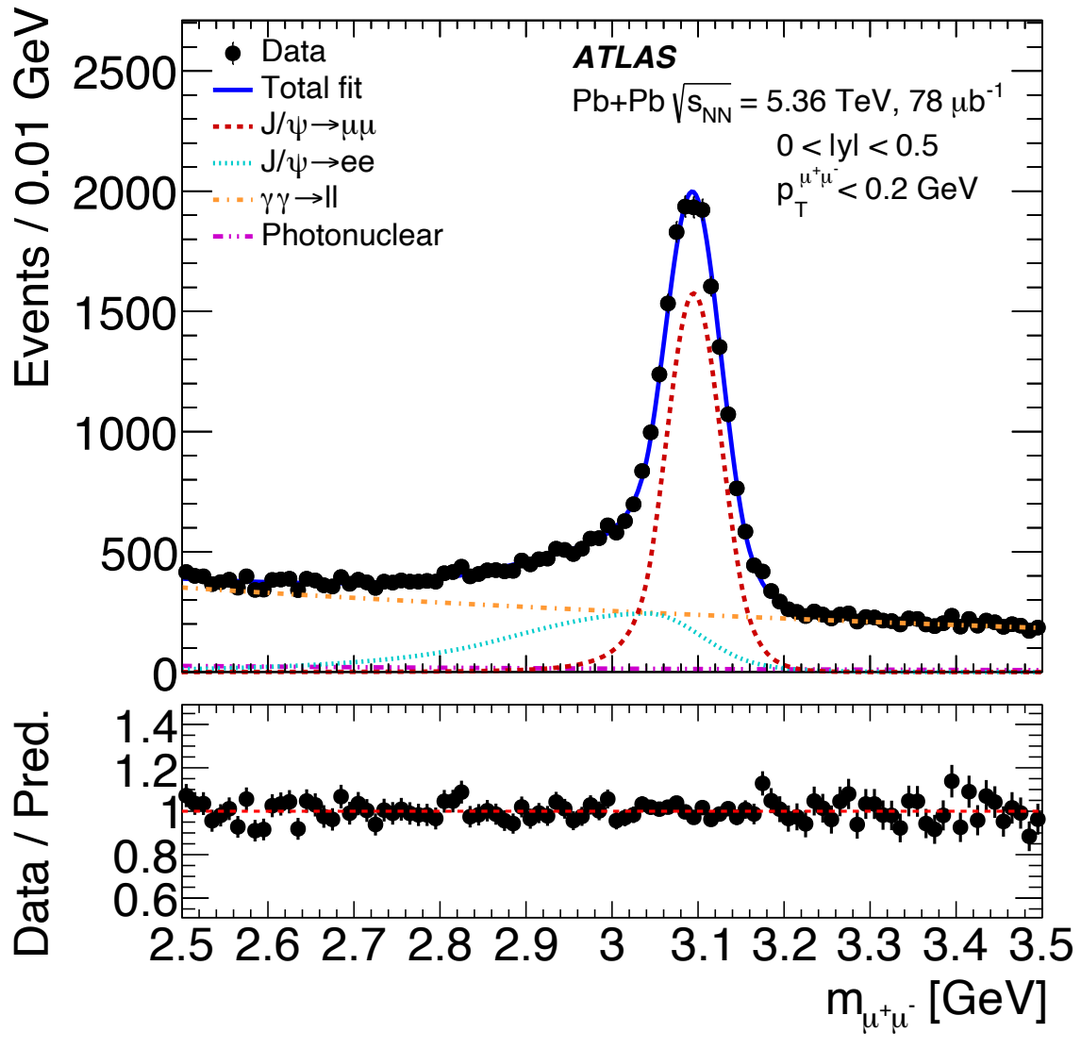
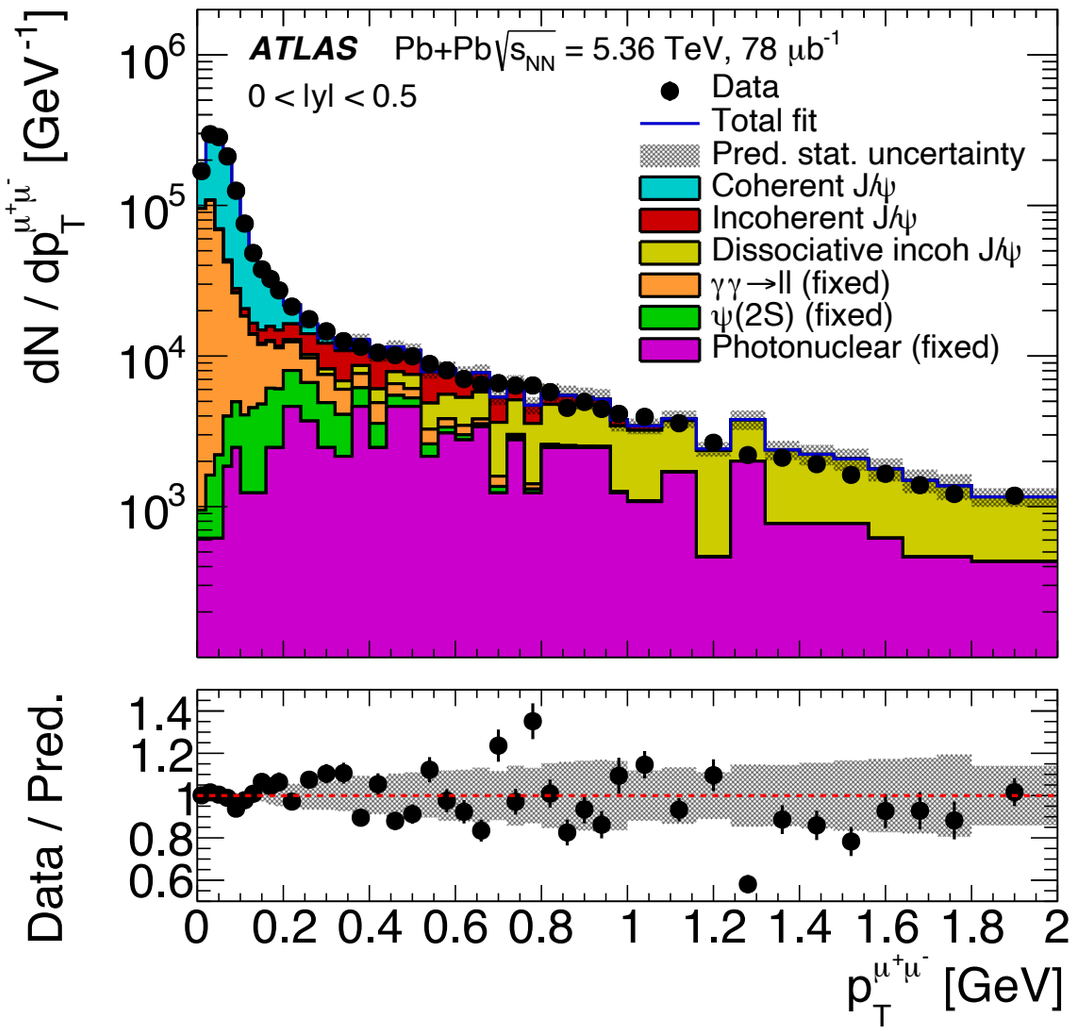
Example yield extraction: |y|<0.5





Mass fit constrains fraction of dilepton yield within signal region (2.9-3.2 GeV), also constrains μμ to ee ratio

p_T fit uses constraints from data on dileptons, feed down and photonuclear contributions: 3 free parameters are coherent and incoherent J/Ψ, and dissociative

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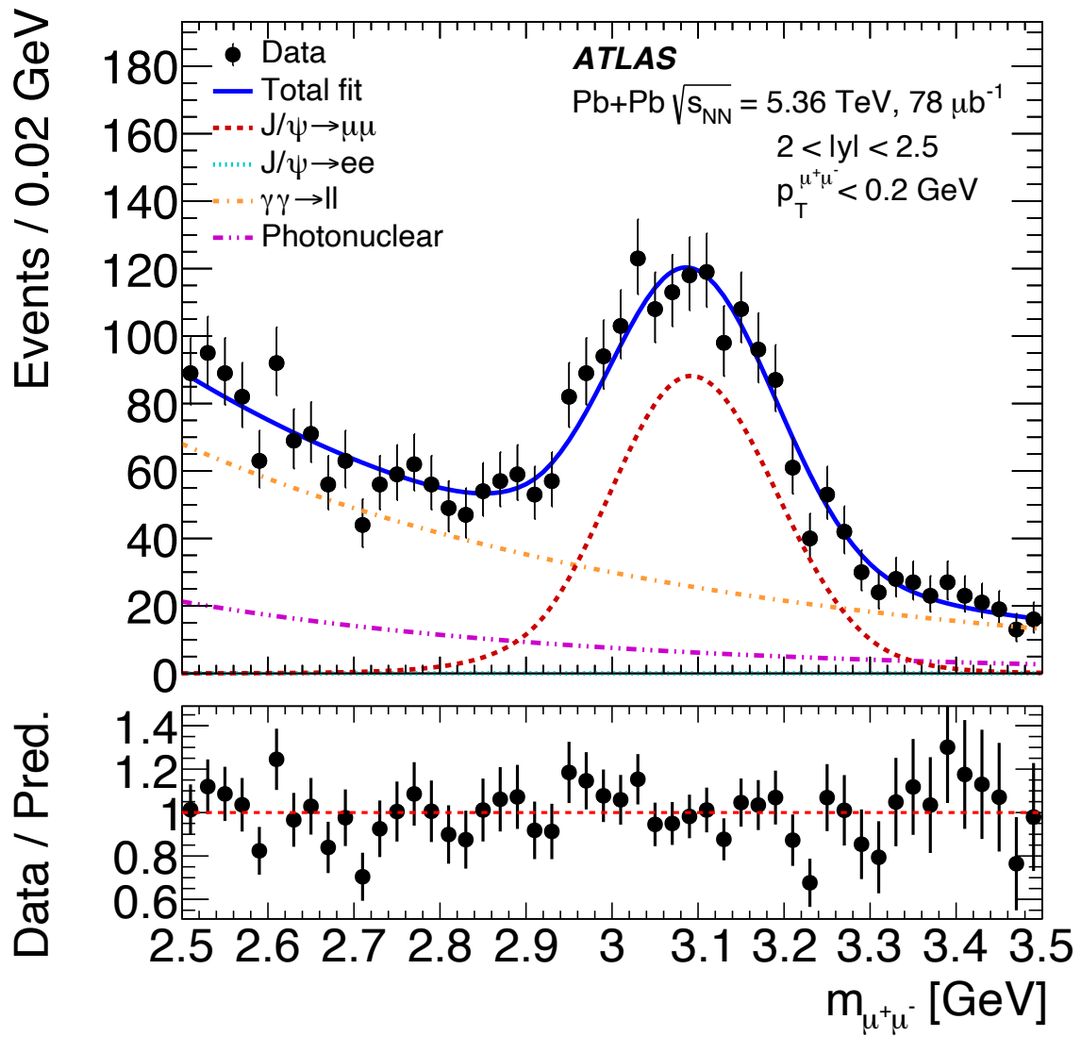
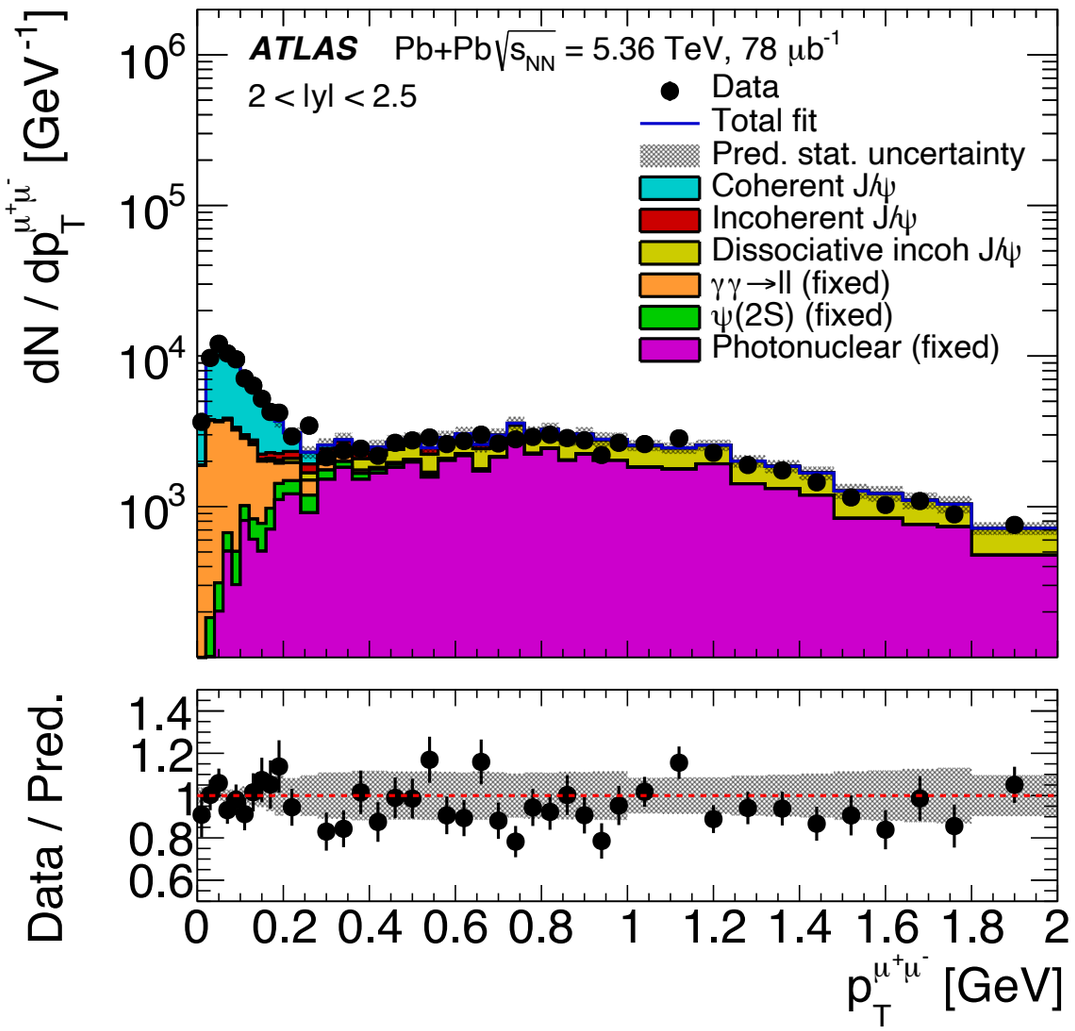
Example yield extraction: 2<|y|<2.5





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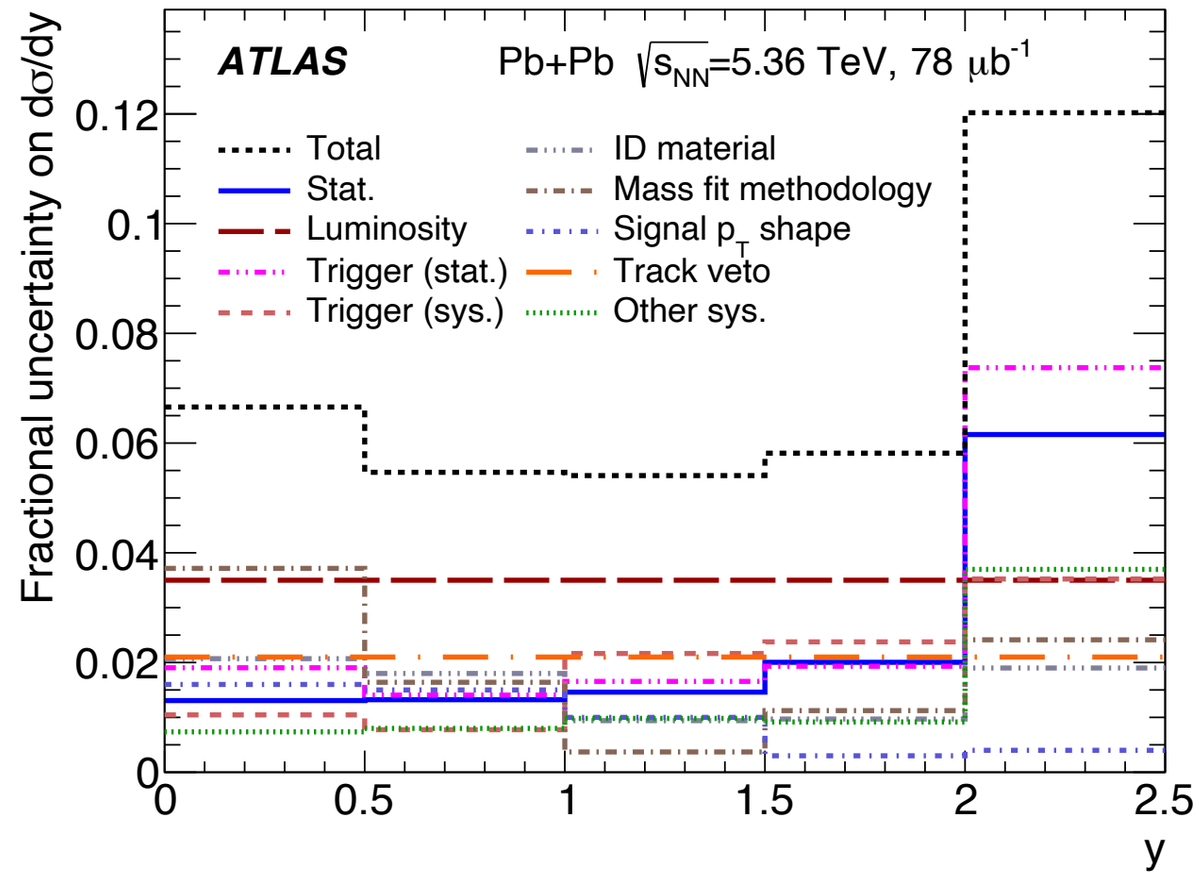
Efficiency and acceptance corrections

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

- $\mathscr{L}_{int}$ **is integrated luminosity of data sample, BR is from PDG**
- **Efficiency factor** ϵ_C **defined relative to fiducial region**
  - $p_T^{\mu} > 1$ GeV, $|\eta_\mu|<2.5$, $2.9 < m_{\mu\mu} < 3.2$ GeV, $p_T^{\mu\mu} < 0.2$ GeV
  - $\epsilon_C = N(rec)/N(gen, fid.)$
  - Varies between 64-78% except for 2<|y|<2.5 where it is 22%, due to limited TRT acceptance
- **Acceptance factor defined relative to all** J/ψ **produced in a particular rapidity region**
  - $A = N(gen, fid.)/N(all)$
  - Corrected to MC born level (before FSR)
  - Varies between 51-63% for |y|<2 and is also about 19% for 2<|y|<2.5
  - Corrects for how acceptance cuts into cos(θ*) distribution

Systematic uncertainties

- **Luminosity uncertainty is 3.5%**
- **Statistical and systematic uncertainties on the trigger corrections**
- **ID material variations**
  - Four standard changes in the ID material, capturing range of data-MC differences
  - Impact both on tracking efficiency, and on mass line shape
- **Alternate fitting procedure using STARlight continuum mass spectrum, and J/ψ templates directly from MC (also fixing μμ/ee ratio) (2-3.7%)**
- **Alternate assumptions for continuum mass shape (2nd order polynomial vs. exponential)**
- **Removing LHCb correction to J/ψ signal p_T shape**
- **Relaxing track veto to allow for events with up to 4 tracks (2.1%)**
- **BR uncertainty is 0.5%**



Material variations

Absolute rapidity interval	0–0.5	0.5–1	1–1.5	1.5–2	2–2.5
$J/\psi \to \mu^+\mu^-$ $m_{\mu^+\mu^-}$ lineshape	1.4%	1.2%	0.7%	0.7%	1.6%
$J/\psi \to e^+e^-$ $m_{\mu^+\mu^-}$ lineshape	0.7%	0.6%	0.3%	0.2%	0.1%
$p_T^{\mu^+\mu^-}$ shape	0.1%	0.1%	0.1%	0.2%	0.3%
Total ID material unc. on signal yield	2.1%	1.8%	0.9%	1.0%	0.8%

Total uncertainty ~6% (12% in 2<|y|<2.5)

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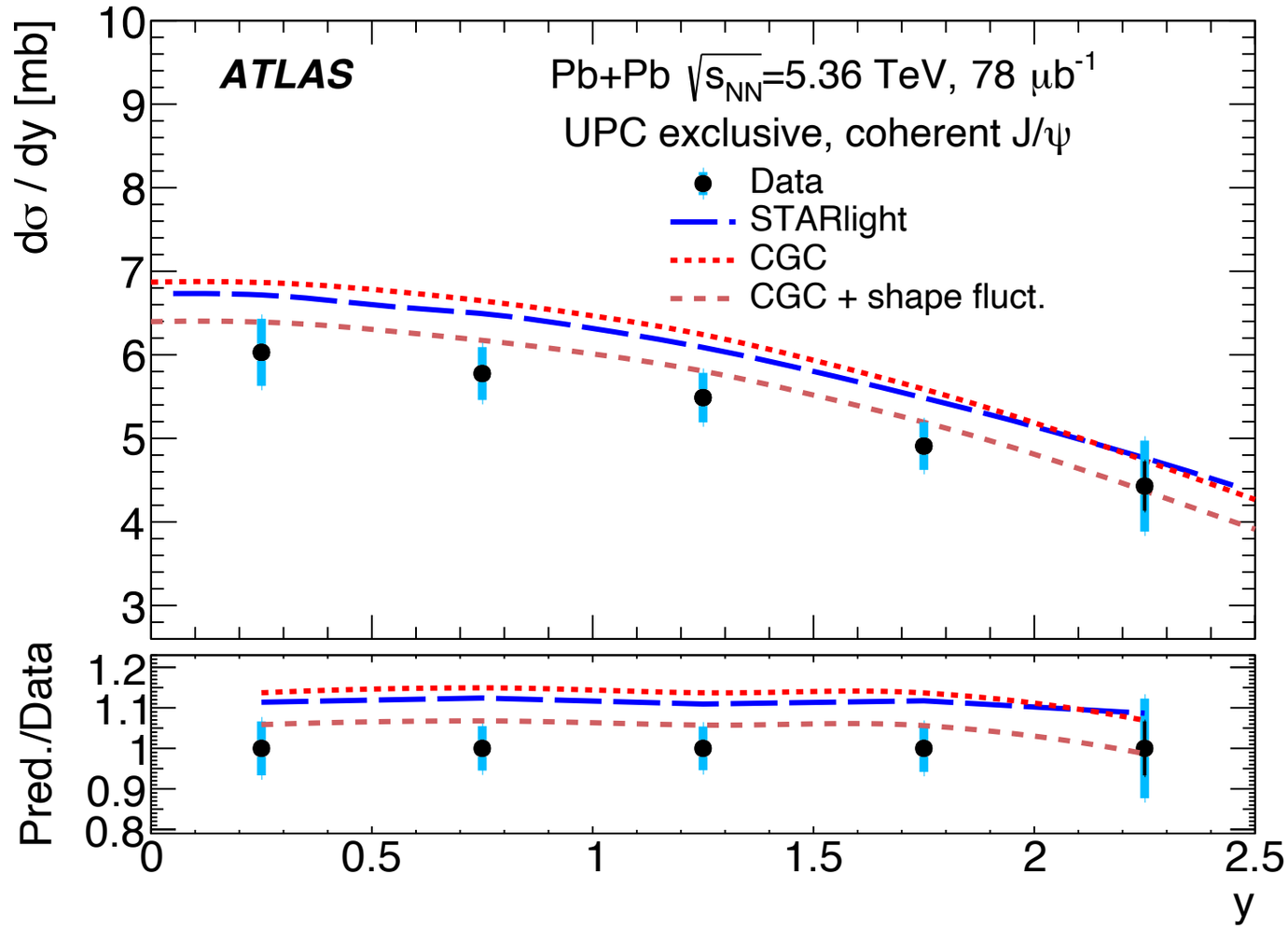
ATLAS results



- **Data presented in 5 bins in J/ψ y (averaged over ±|y|)**
  - Error bars are statistical, while blue bands are total uncertainty
- **Compared to two theoretical approaches**
  - STARlight convolves photon flux with photonuclear cross section parametrization, in a Glauber approach
  - CGC (parton saturation) approach (Mantyasaari, Salazar & Schenke) with and without nucleon shape variations. The version with shape variations gets the best description of this set.

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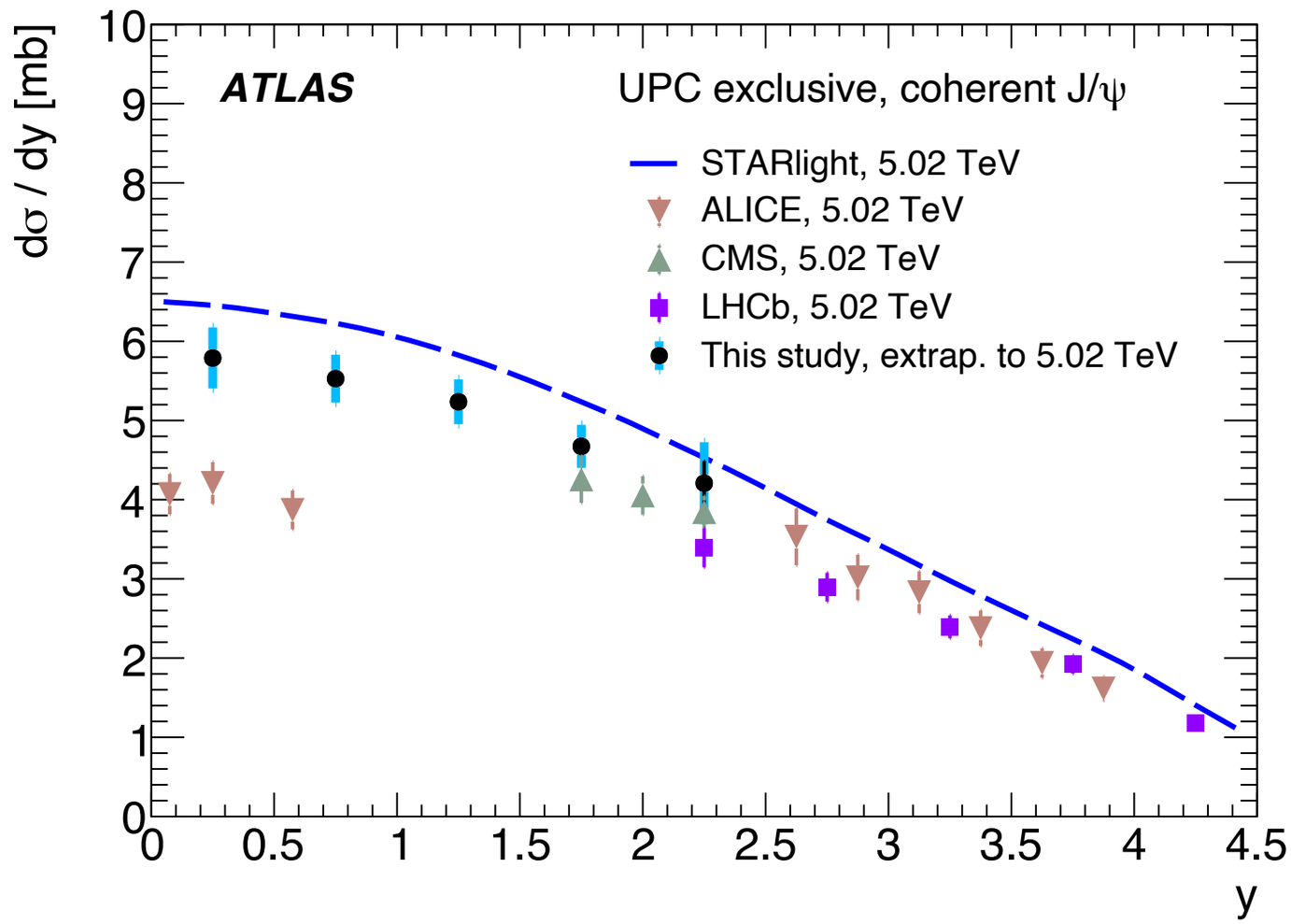
ATLAS results in context



- **ATLAS 5.36 TeV data extrapolated to 5.02 TeV using STARlight**
  - Simple rapidity-dependent ratio to correct each bin, about 5% for all bins
- **Comparison with previous measurements**
  - Reasonable agreement with CMS in the overlap region 1.5<|y|<2.5
  - Slope continuous with the forward ALICE & LHCb data
  - Substantial <u>tension</u> 30-40% with the ALICE data |y|<0.8

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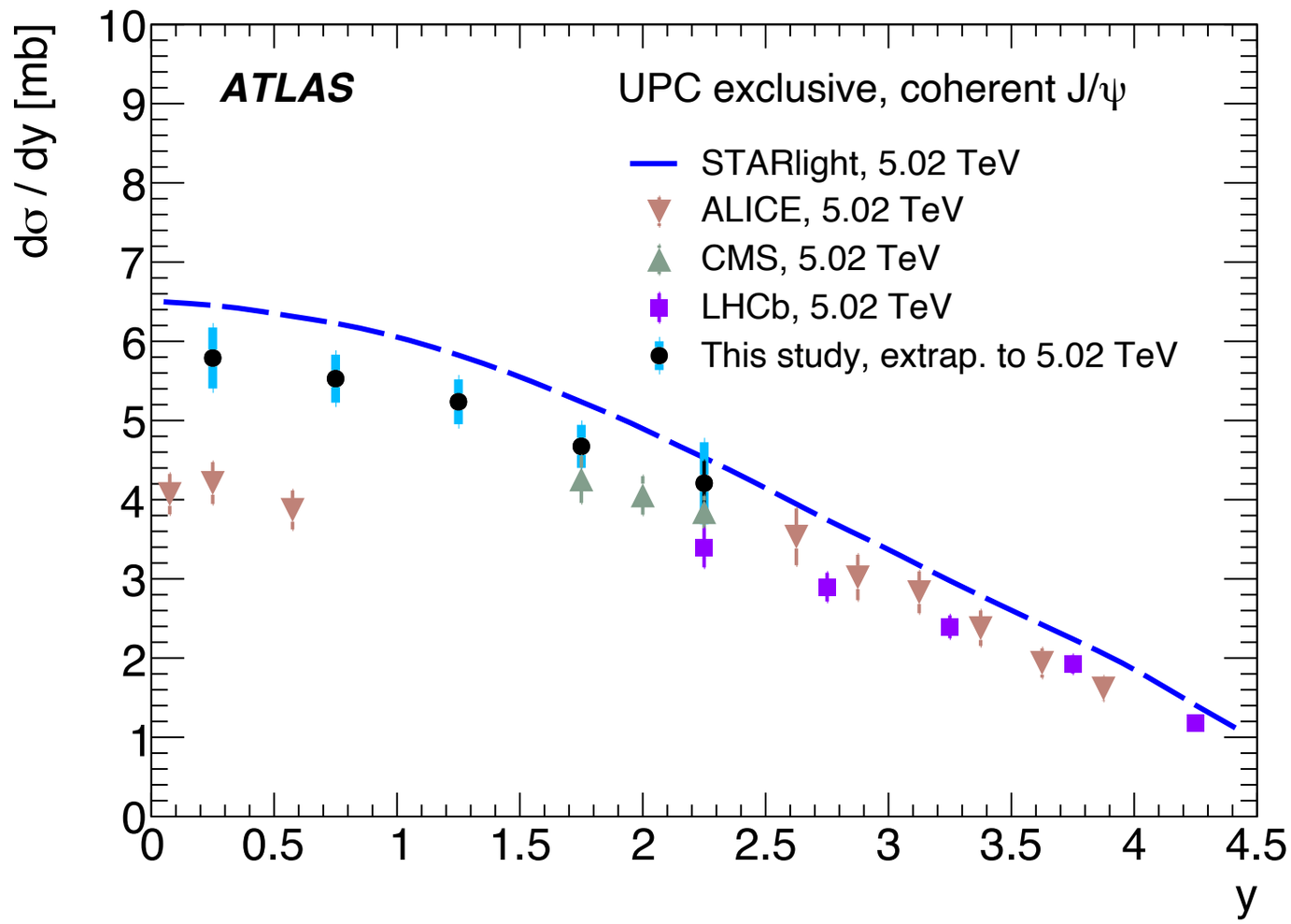
ATLAS results in context



- **ALICE mid-rapidity data requires veto on forward counters (V0 and AD, both in regions well beyond ATLAS acceptance)**
  - ALICE publications raise concern that simultaneous forward e+e- pairs (assumed to be pileup) could lead to self-veto
  - Correct for pileup using veto rate measured in an <u>unbiased</u> beam-crossing trigger

- **ALICE forward results do not apply this selection**

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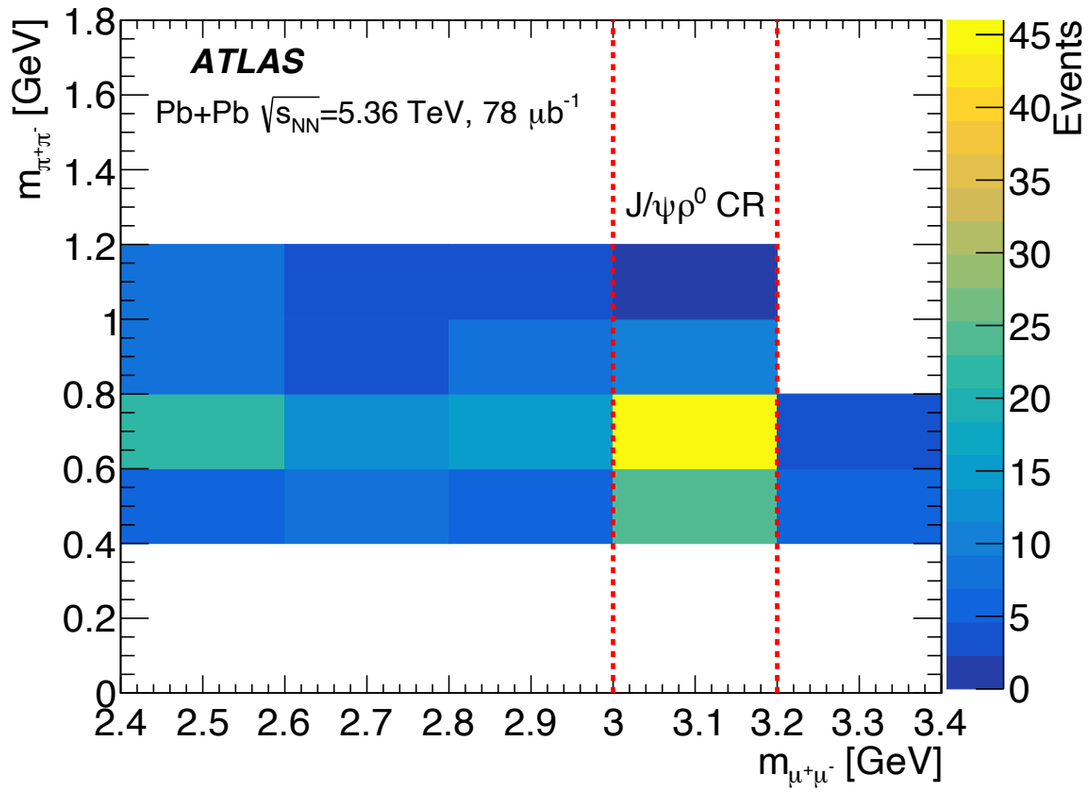
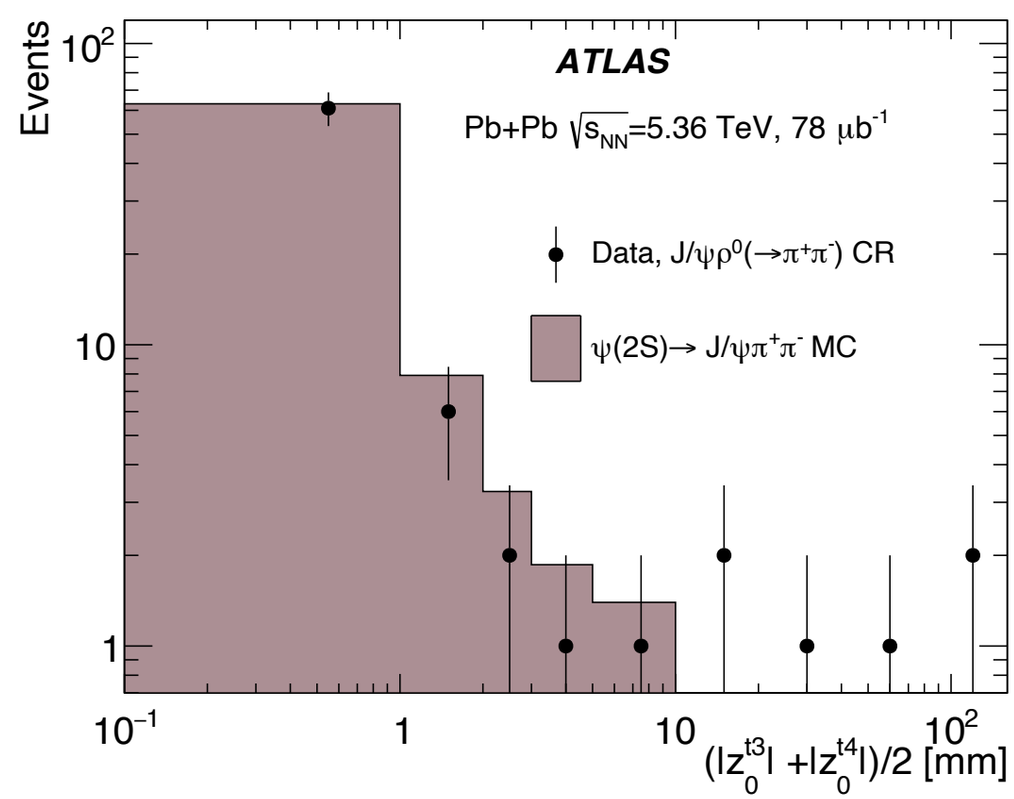
Discussion - coincident UPC events





- **Similar to previous result, ATLAS have looked for events with 4-tracks in which both J/ψ and ρ^0 are produced**
  - Require back-to-back track pairs for each decay
  - Require large acoplanarity of J/Ψ and ρ candidates

- **Average distance of ρ^0 decay pion z_0 from J/ψ vertex is consistent with both particles emitted from the same vertex**

Double VM production is "same event", and not pileup

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Conclusions

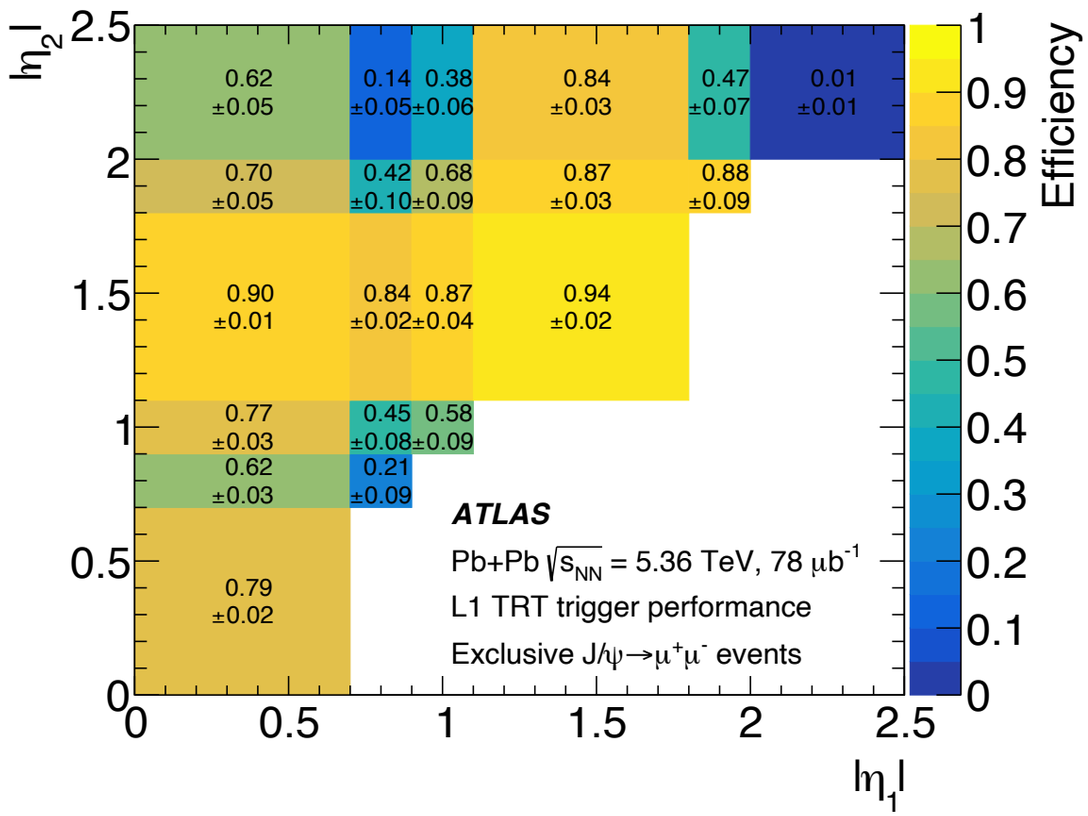
- **First ATLAS measurements of J/ψ and coincident UPC processes in 5.36 TeV Pb+Pb data**

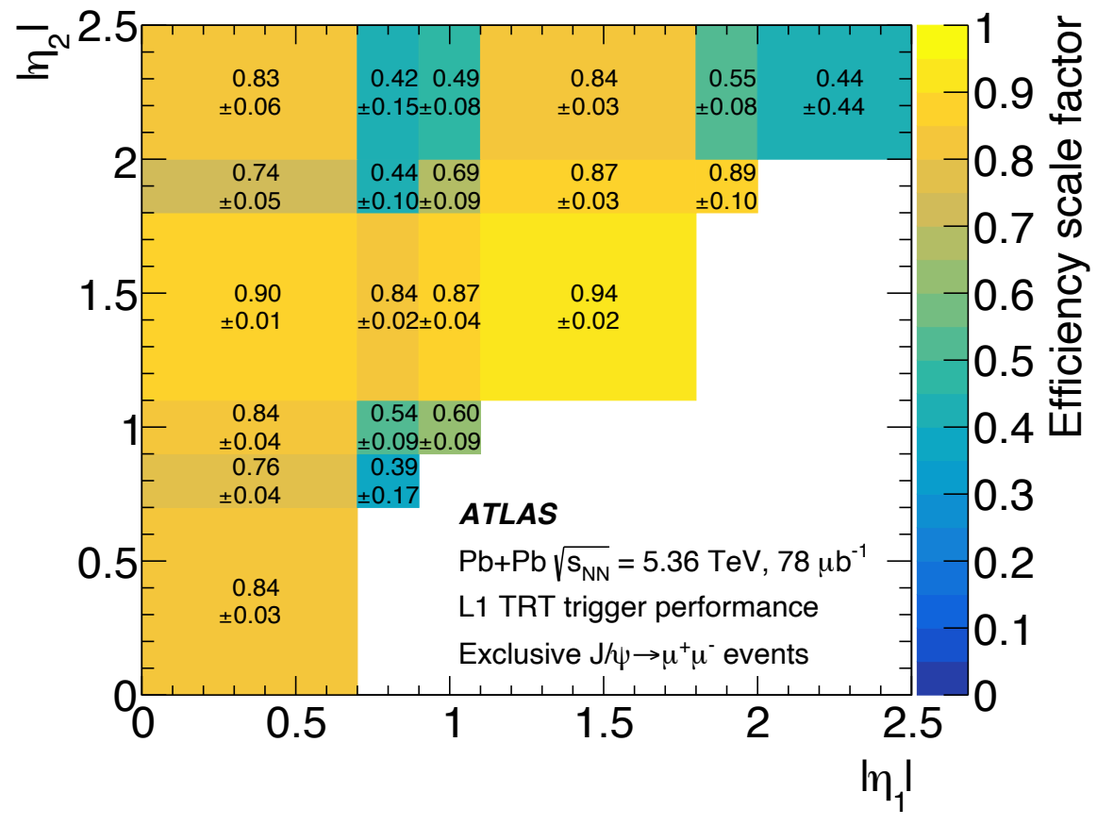
- **Coincident UPC production of $\mu^+\mu^-$ and ρ^0**
  - Small overall effect (1% inclusive, 3% for XnXn), but crucial to account for in future measurements
  - Large impact from changing ZDC categories
  - Small but significant impact of changing μμ kinematics

- **Coherent J/ψ production from ultraperipheral collisions**
  - Measured in the $\mu^+\mu^-$ channel
    - *Removing contributions from e+e-, incoherent production, photonuclear backgrounds, and continuum dileptons*
  - Cross section measured differentially in $0 < |y| < 2.5$
  - Good agreement with model trends, and magnitude is best described by CGC models with nucleonic shape variations
  - Good agreement at large |y|, but tension with ALICE data at $|y| < 0.8$
    - *Tension may be related to prevalence of multiple UPC processes*

- **Clear indications that our field has work to do to improve our understanding and modeling of multiple UPC processes**
  - We can't wait: the EIC is coming and needs input from RHIC/LHC

Trigger scale factors

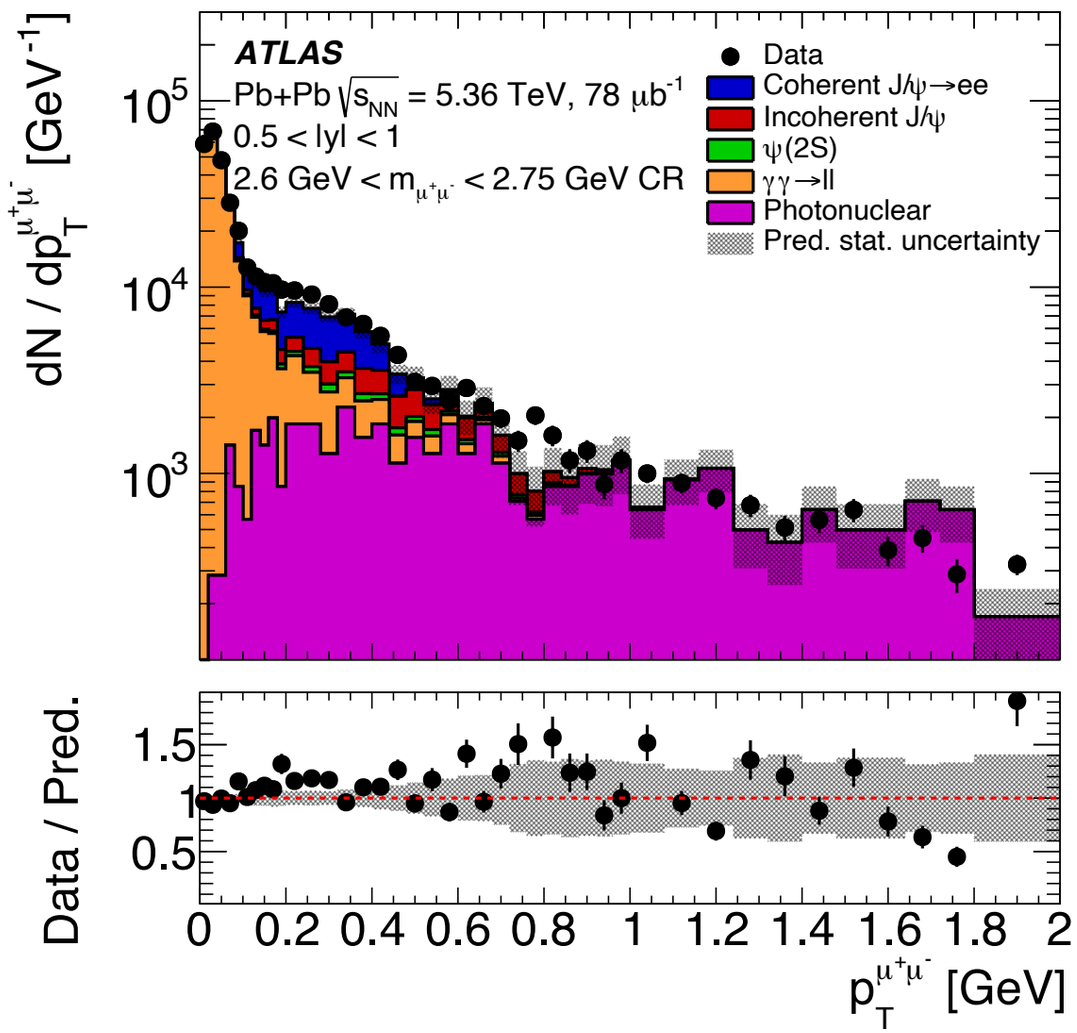




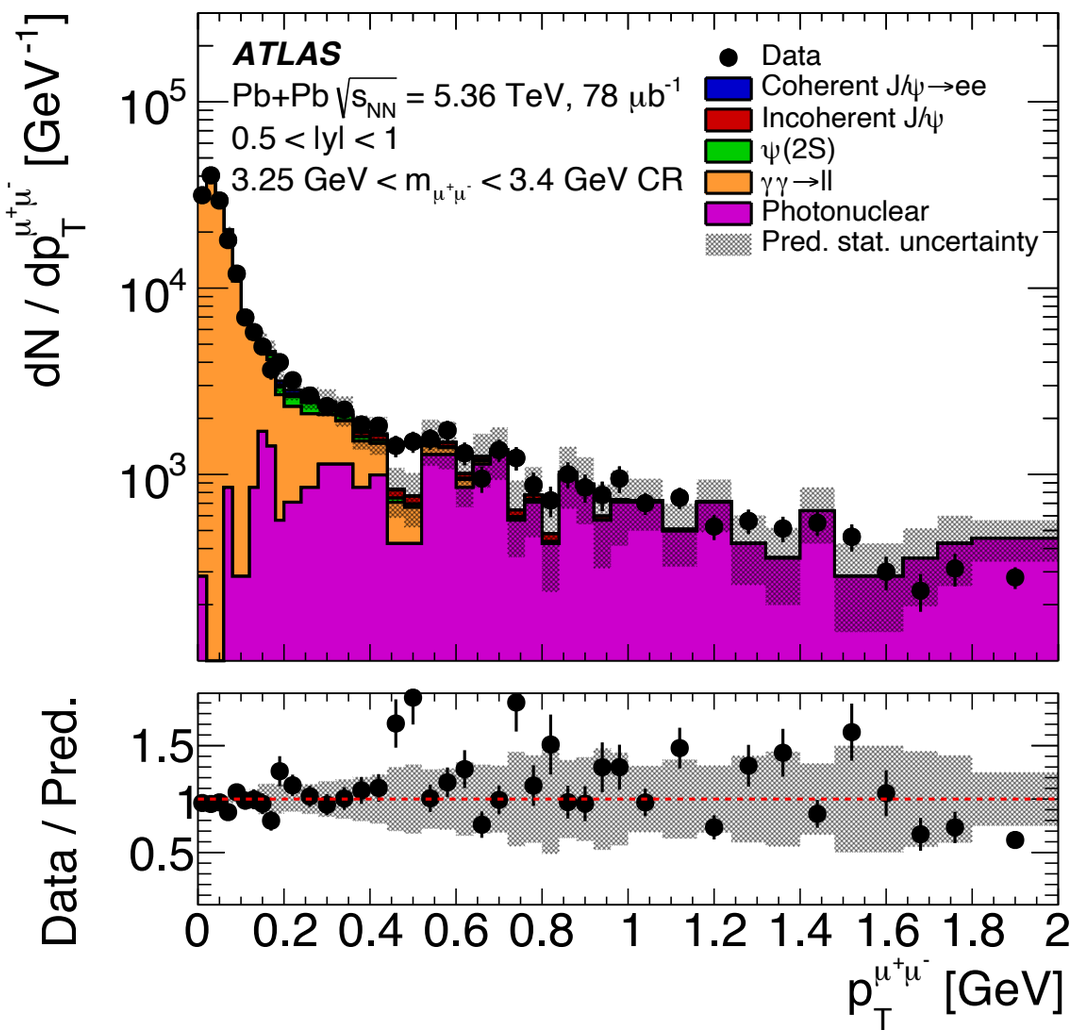
- **Trigger efficiency is parametrized as a function of $|\eta|_1$ and $|\eta|_2$**
  - The minimum $|\eta|_1$ and maximum $|\eta|_2$ pseudorapidity in a track pair
  - Binning reflects structure of TRT (Barrel <0.7, Transition 0.7-0.9 / 0.9-1.1, Endcap 1.1-1.8, Edge 1.8-2.5)
- **Derived in data and MC using mass fits, similar to yield extraction, but binned in $|\eta|_1$ and $|\eta|_2$**
  - Accounts for continuum backgrounds and separately yields ee and μμ
  - Data/MC scale factors allow correction of MC efficiency to data (applied to every MC event)
  - No dependence on muon p_T

Photonuclear contributions

Low-mass sideband region

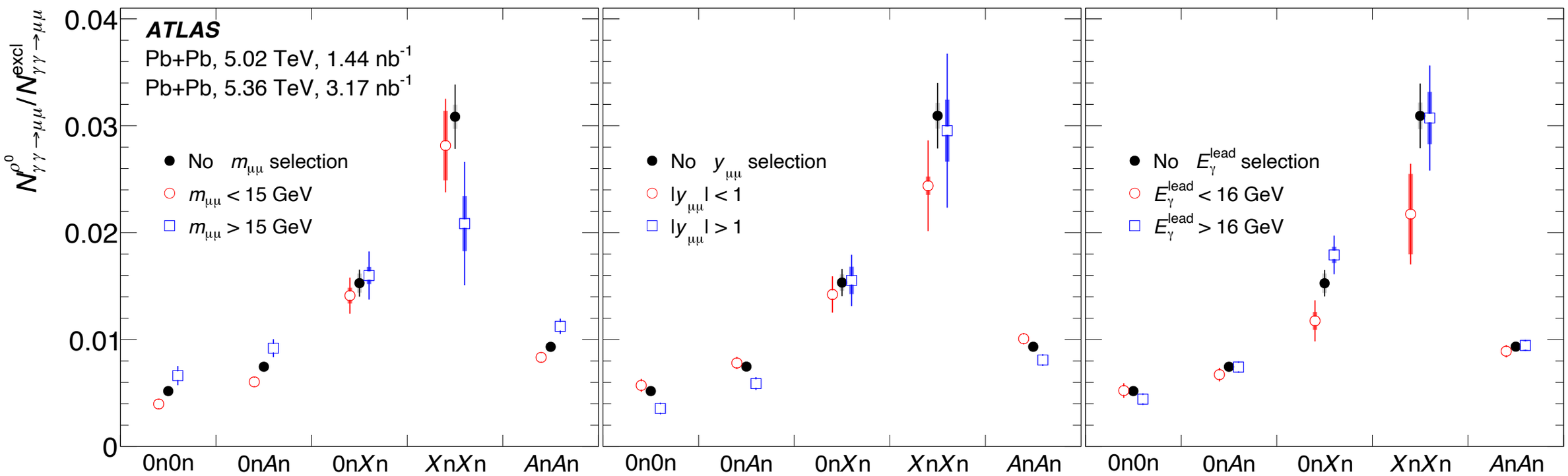


High-mass sideband region



Surprisingly good description of sideband regions with background processes (& some signal leakage to low mass region from e^+e^- channel)

Coincident UPC events in ATLAS



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Monte Carlo samples

- **Signal samples**
  - Using STARlight MC version 2.0 (revision 313)
    - *Interfaced with Pythia 8.312 to model final state radiation (FSR)*
    - *Excellent description of dilepton production (μμ and ee channels, including radiative effects)*
  - STARlight uses a vector meson dominance (VMD) model, with nuclear effects implemented in a Glauber formalism
    - *Multiple interactions in the nucleus, but no explicit PDF shadowing effects*
  - Simulated events each in μμ and ee channels, for both coherent and incoherent processes

- **STARlight also used to model the two primary background processes**
  - Non-resonant two-photon production of dileptons (ee and μμ)
  - Feed down from ψ(2S)

- **Full transverse polarization of the produced J/ψ and ψ(2S)**
  - Imposes a polar angle distribution of $1+\cos^2(\theta)$ on the outgoing leptons
  - Most of the acceptance correction accounts for the events rejected by the ID pseudorapidity acceptance

- **STARlight uses an assumed form of the Pb form factor to provide a p_T distribution to the incoming photons and pomerons**
  - This is found to be shifted from the true distribution
  - LHCb data on J/ψ p_T used to reweigh the MC distributions to better agree with data

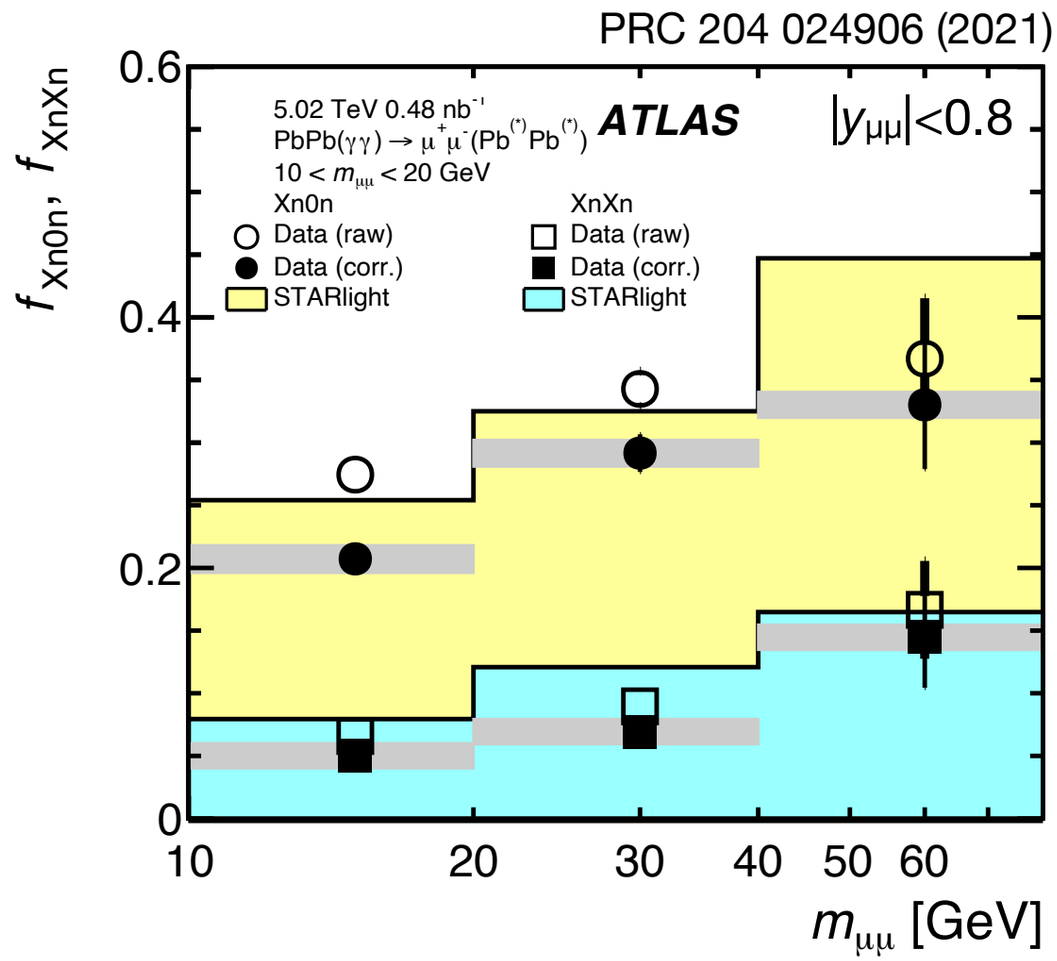
Backgrounds & yield extraction

- **The extraction of the coherent J/ψ yield requires a systematic subtraction of several sources of background**
  - $J/\psi \to e^+e^-$
    - *Nominally a signal sample, but line shape and efficiency strongly distorted by ID material, so its contribution is estimated and accounted for (not presented as a cross section)*
  - **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 a functional form from H1*
  - $\psi(2S)$ feeddown to J/ψ (coherent & incoherent)
    - *Data driven yield constrained from $\psi' \to \psi + \pi^+\pi^-$ using events with 4 tracks or 3 tracks + 1 pixel track*
    - *Used to estimate coherent and incoherent contributions, with backgrounds from inelastic photonuclear (estimated with sidebands), as well as $\psi + \rho$ production (estimated using selection on acoplanarity of the ψ and $\pi\pi$)*
  - Non-resonant background from $\gamma\gamma \to \ell^+\ell^-$
    - *Modeled with an exponential function (and also with STARlight)*
    - *Constrained by fit to invariant mass distribution*
  - Charged hadrons from inelastic photonuclear production
    - *Estimated using same selection as signal region but with same-sign pairs.*
    - *Yield constrained with low and high mass sidebands, normalized at $p_T^{\mu\mu}$>1 GeV, where other contributions are negligible*

- **Binned likelihood performed incorporating all of these contributions**
  - Free parameters indicated in green, others constrained by data
  - Incoherent exclusive and incoherent dissociative normalized separately

- **All MC templates require MC trigger simulation, and corrected by trigger MC scale factors**

ZDC probability in μμ events



If we assumed that μ+μ- should have no ZDC coincidence, then we would interpret the μ+μ- events with any ZDC signals as “backgrounds” - reducing observed σ

If we corrected just for ZDC rates from pileup (e.g. using an unbiased trigger), we’d observe ~5% probability per side, and only correct up by ~10% (far too small)

What about other processes, e.g. double vector mesons?

Calculations of multi-UPC processes

- **Basic formalism is to integrate over the product of impact-parameter dependent probabilities of the processes (e.g. process 1 with selections X and process 2 with selections Y)**

$$\sigma(P_1, P_2) = 2\pi \int P_1(b, X) P_2(b, Y)\ bdb$$

- **This has been discussed since the earliest papers on of UPC at RHIC & LHC, e.g. Klein and Nystrand in 1999, calculating double VM production**

- **Some discussions in the literature following this paper (e.g. Baur et al, NPA 2003) but few measurements!**

- **STARlight can perform calculations in b ranges for dileptons but *not* for coherent J/Ψ (this paper used and unreleased custom version)**

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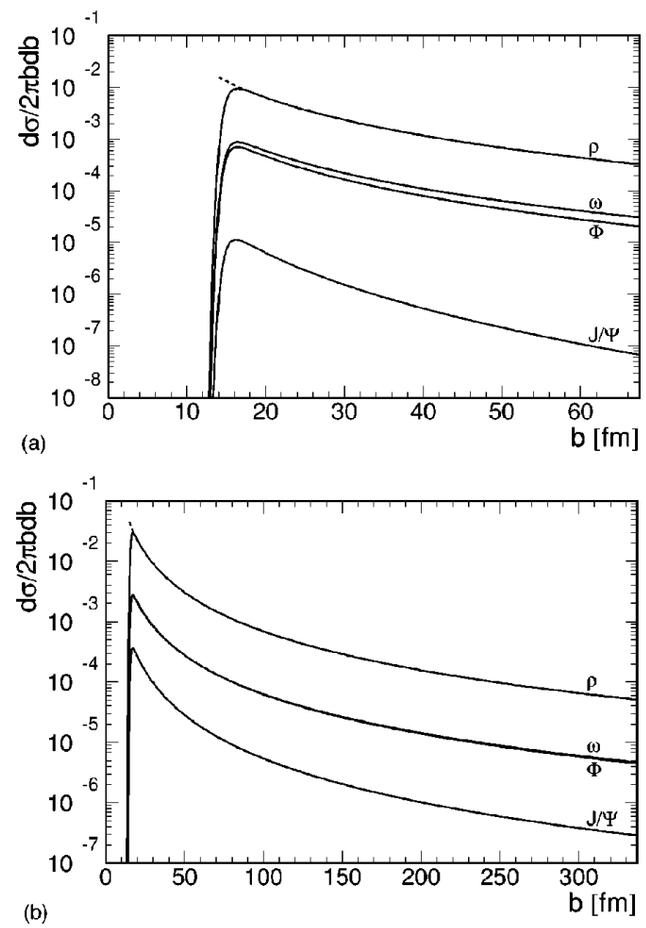

FIG. 7. Probability of vector meson production as a function of collision impact parameter for (a) gold at RHIC and (b) lead at LHC. The solid lines show the Woods-Saxon hadronic interaction probability, while the dashed lines show the result of a hard sphere calculation for the ρ.

Several new results all point at increasing importance of quantitative understanding of multiple UPC processes!