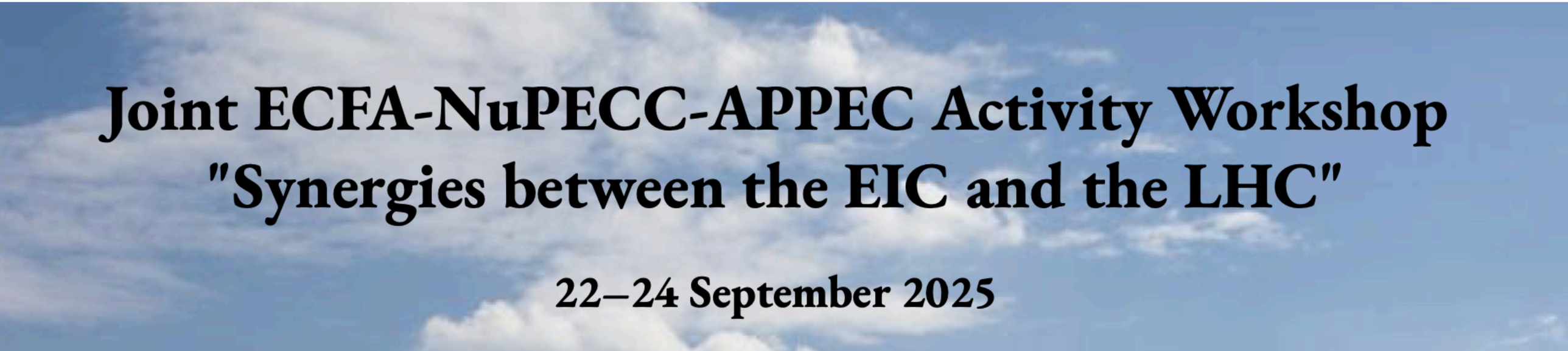
Recent ATLAS results on ultra-peripheral collisions

Klaudia Maj (AGH University of Krakow)
for ATLAS Collaboration



LHC as a photon collider

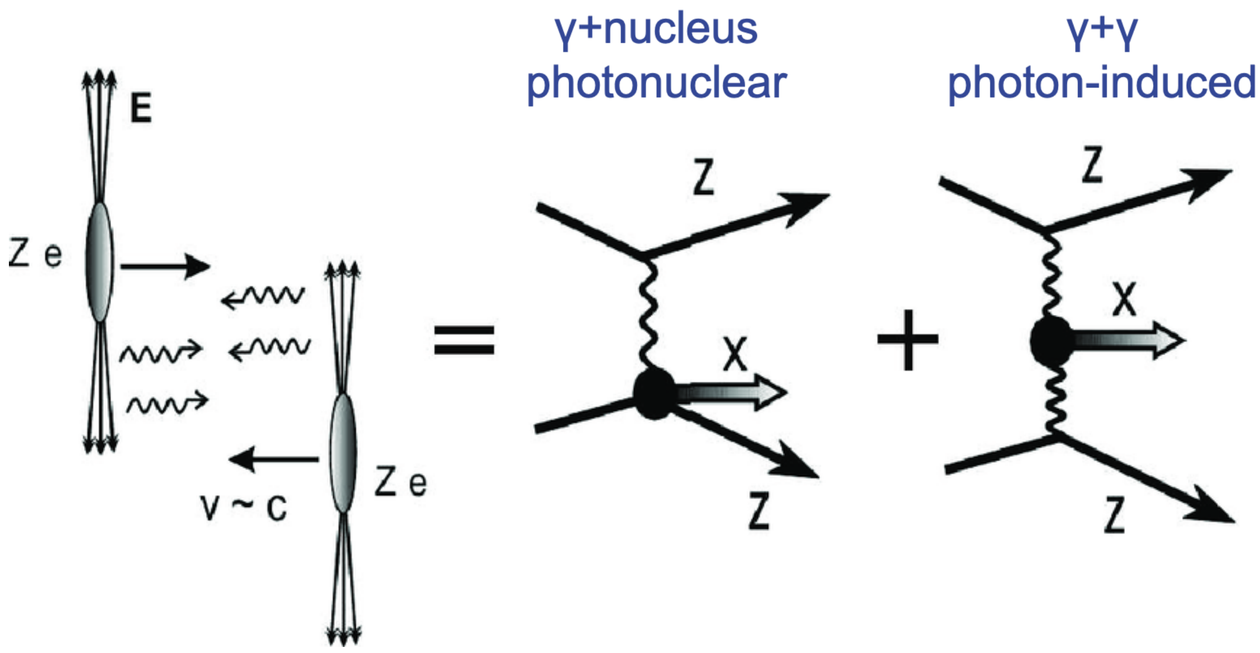
Colliding charged particles at LHC: p, Pb → Feature electromagnetic (EM) fields

- Can be described as cloud of quasi-real photons (γ) ➡️ Colliding photons at LHC

  ➡️ Focus on γ from Pb

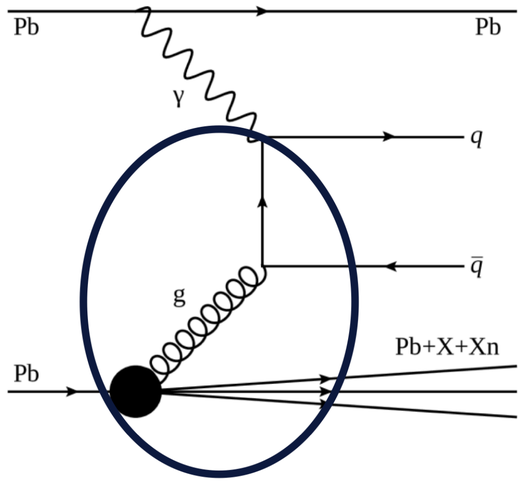
  - For coherent γ emission from entire Pb nucleus, cross section enhanced by Z^2 per emitting nucleus (Z=82)
  - Dominant reaction if impact parameter > 2*Pb nuclear radius → Ultraperipheral collisions (UPC)

Possible reactions:



A closer look at the possible interactions

Photonuclear interactions



- Direct γ interaction with a quark/gluon in nucleus

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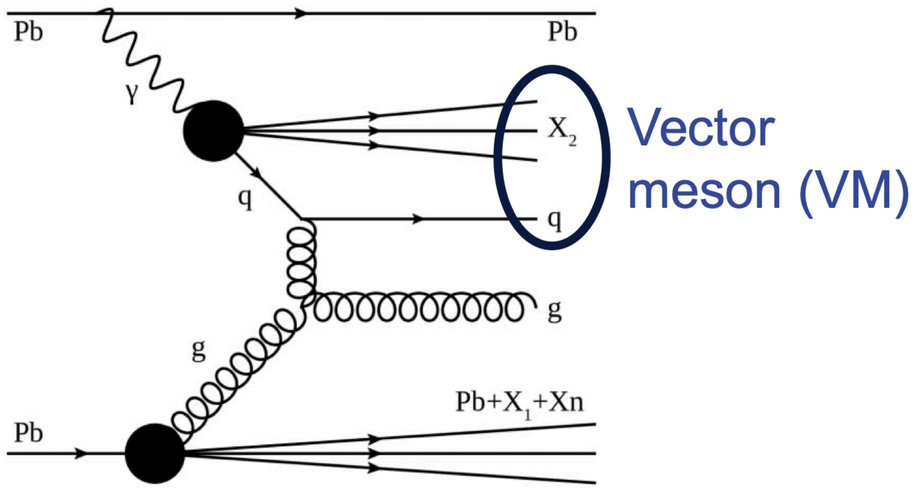

Vector meson (VM)

- Direct γ interaction with a quark/gluon in nucleus
- Resolved γ interaction, i.e. fluctuation into a vector meson and hard-scattering with nucleus

A closer look at the possible interactions

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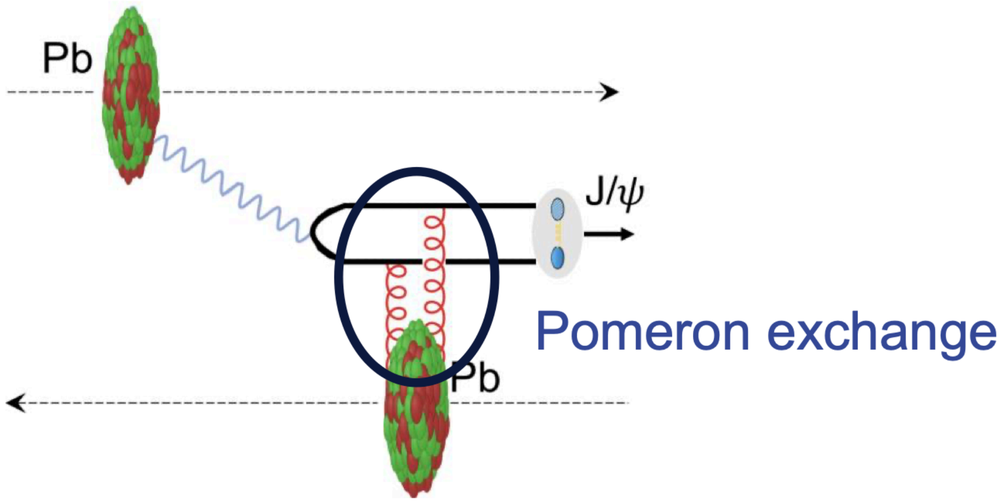
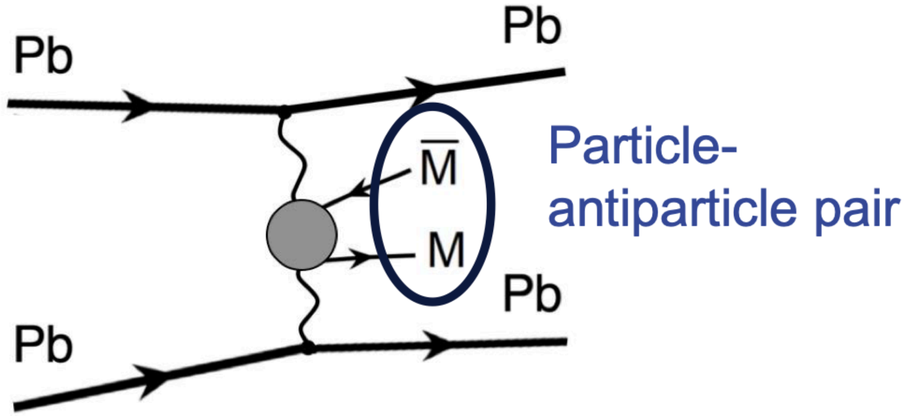


- Direct γ interaction with a quark/gluon in nucleus
- Resolved γ interaction, I.e. fluctuation into a vector meson and hard-scattering with nucleus
- Coherent VM photo production, i.e. pomeron emitted coherently by all nucleons in nucleus

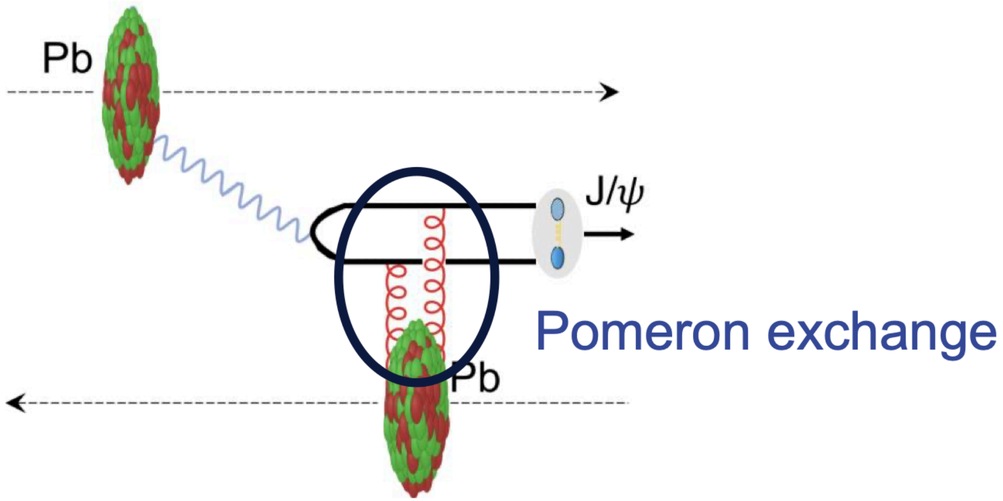
Photon-induced interactions



- Exclusice pair-production of Standard Model (SM) or Beyond SM (BSM) particles

A closer look at the possible interactions

Photonuclear interactions



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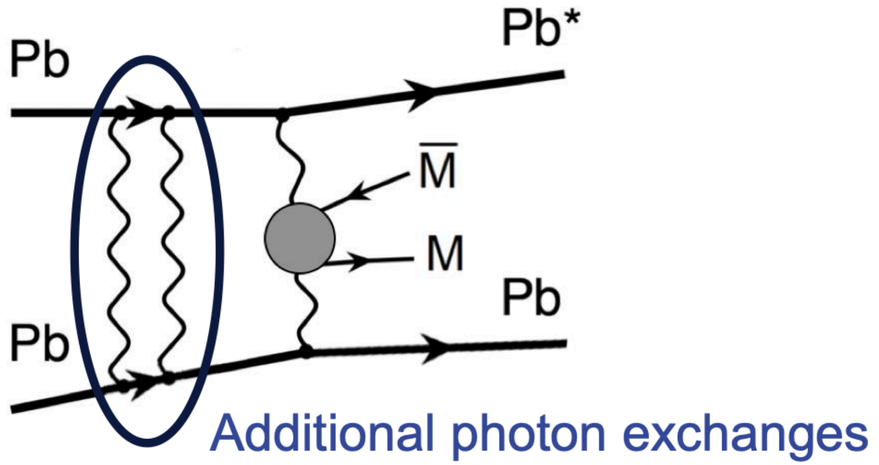

- Exclusice pair-production of Standard Model (SM) or Beyond SM (BSM) particles
- Additional single or mutual ion EM excitation, e.g. via giant dipole resonance → neutron emission

What can we learn?

Photonuclear interactions

- What is the nuclear parton distribution function(nPDF)?
  - Is and how it is different from free proton/ neutron PDFs?

→ Study photonuclear jet and J/ψ production

- Are droplets of quark-gluon-plasma (QGP) produced?

→ Study charged-hardon and identified-hadron distribution modifications similar to pPb

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Photon-induced interactions

- Are there multi photon-induced processes?
  - How do production probabilities and photon energy depend on impact parameter?

→ Study coincident production of γγ→μμ and γPb→ρPb

- What is the production probability and kinematics of τ-leptons?

→ Study γγ→ττ

- Are there magnetic monopoles produced?

→ Search for γγ→MM

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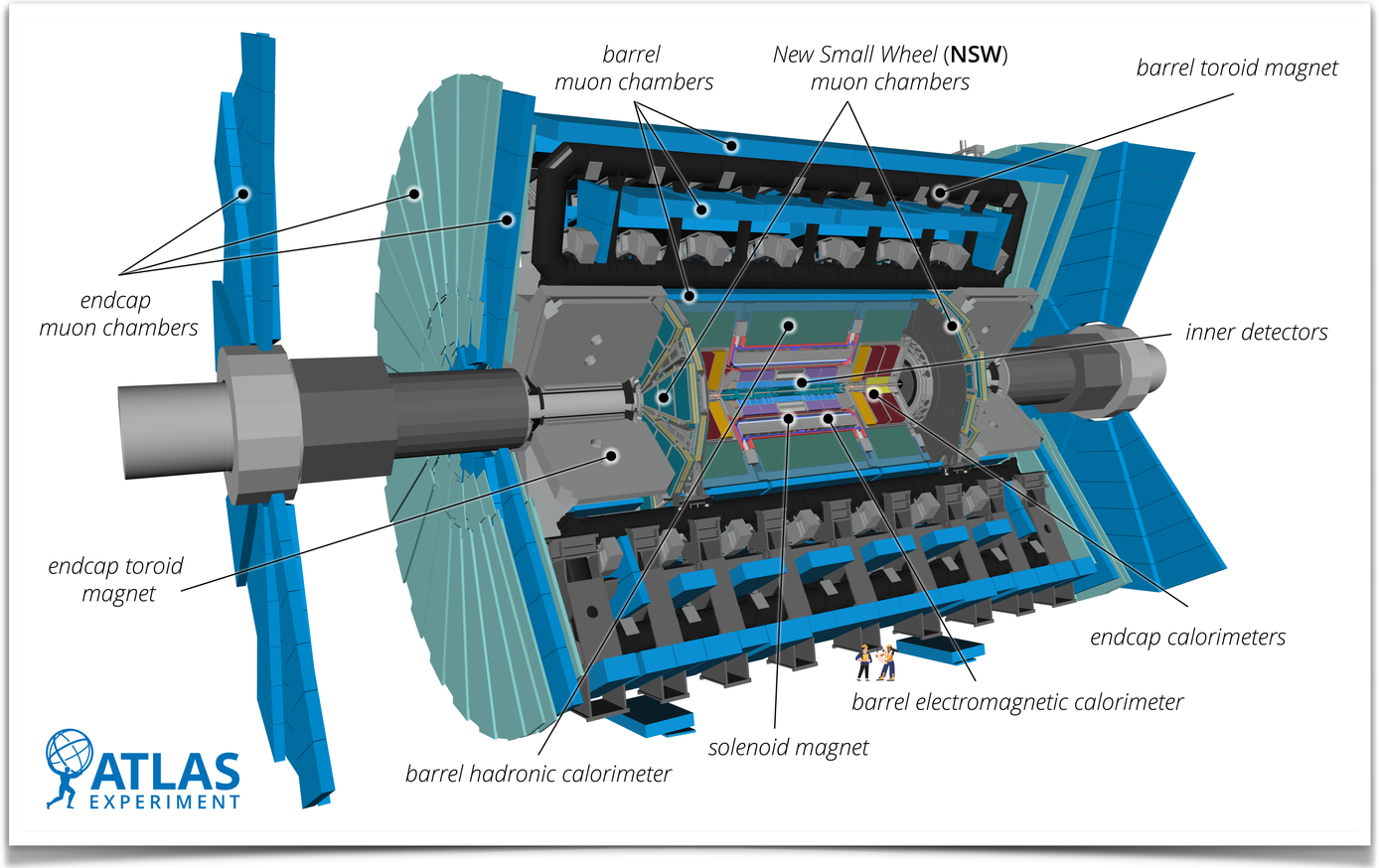
So, we can learn … → Something about the nucleus, something about the photons, something about the generated particles

A quick look at the ATLAS detection system



See more in Riccardo talk at 10:15

44m long
22m tall

$\eta = -\log(\tan(\theta/2))$

UPC datasets from Pb+Pb collisions

at $\sqrt{s_{NN}}$ = 5.02 TeV (Run 2):

- 0.49 nb^{-1} (2015)
- 1.44-1.72 nb^{-1} (2018)

at $\sqrt{s_{NN}}$ = 5.36 TeV (Run 3):

- ~3.4 nb^{-1} (2023&2024)

Charged particle tracking in $|\eta| < 2.5$ → electrons, muons, charged hadrons

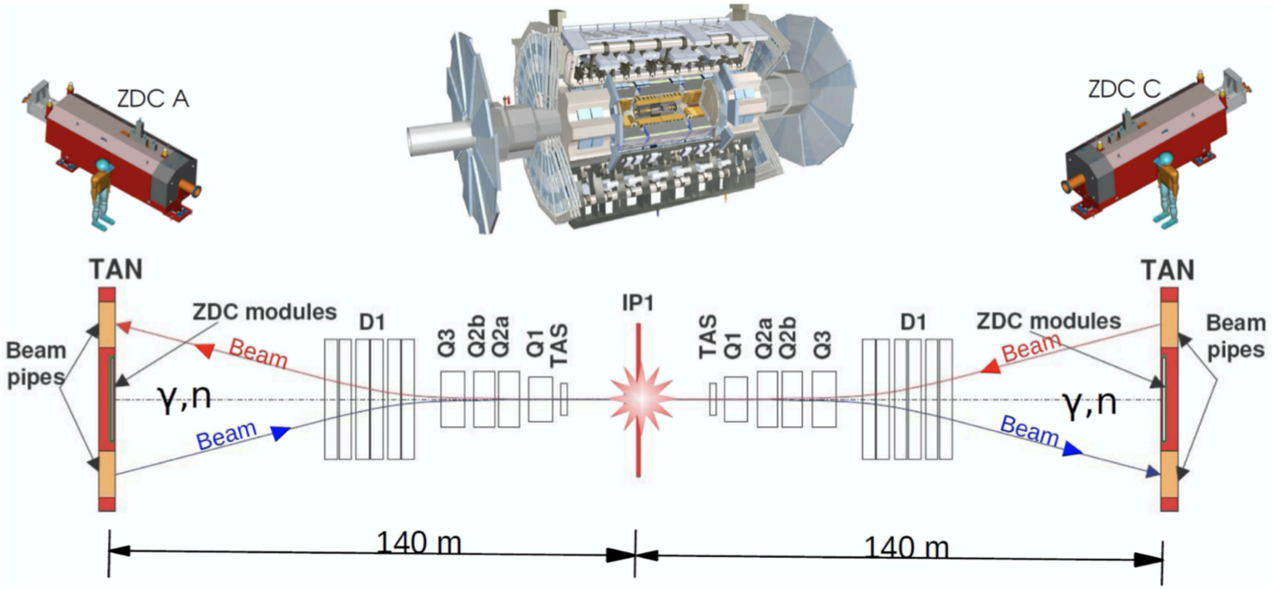
Calorimeter system in $|\eta| < 4.9$ → electrons, photons, jets

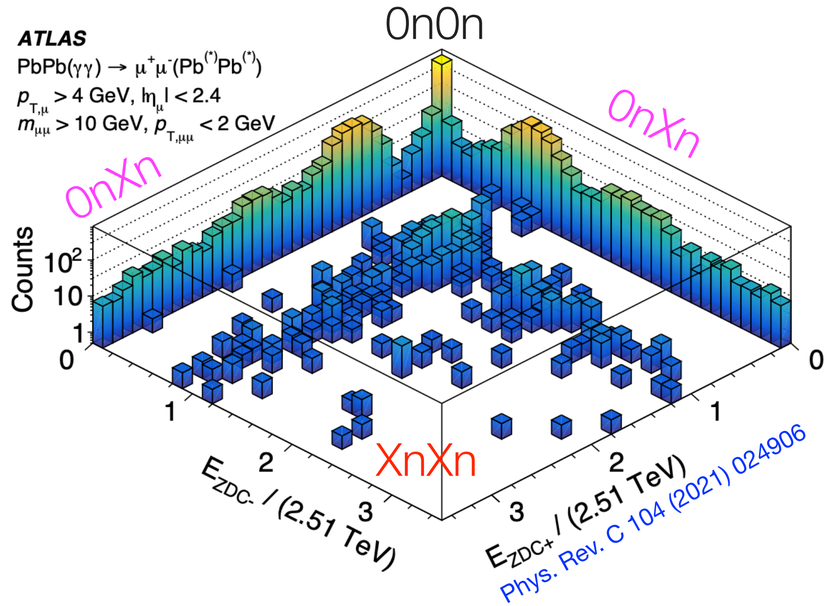
Muon reconstruction in $|\eta| < 2.4$ (muon spectrometer + inner detector)

All components used in UPC measurements

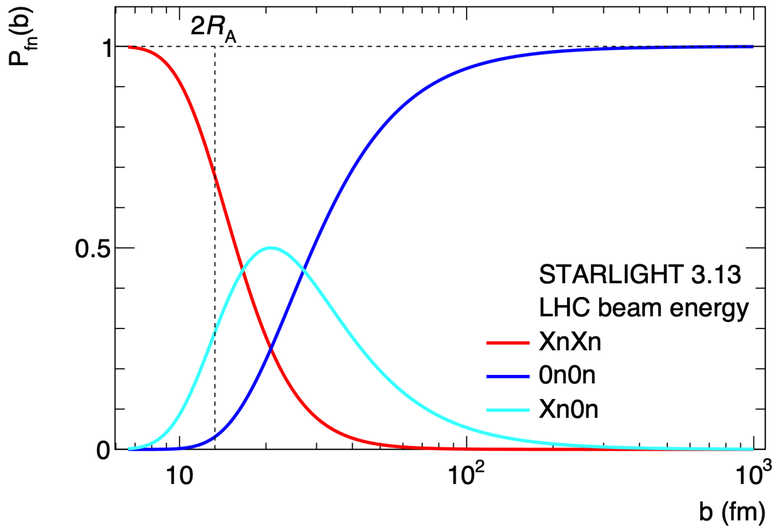
Zero Degree Calorimeter (ZDC)

See more in Riccardo talk at 10:15





- **ZDC are 140 m away from the IP (|η|> 8.3)**
  - Detect neutral particles: e.g. neutrons, photons
- Separate UPCs from inelastic Pb+Pb collisions
- Events are categorised into: 0n0n / 0nXn / XnXn
  - Exclusive $\gamma\gamma$ processes: mostly 0n0n
  - Photonuclear processes: typically 0nXn
- Each category probes different impact parameters (b)



Ann.Rev.Nucl.Part.Sci. 70 (2020) 323-354

Photonuclear jet production

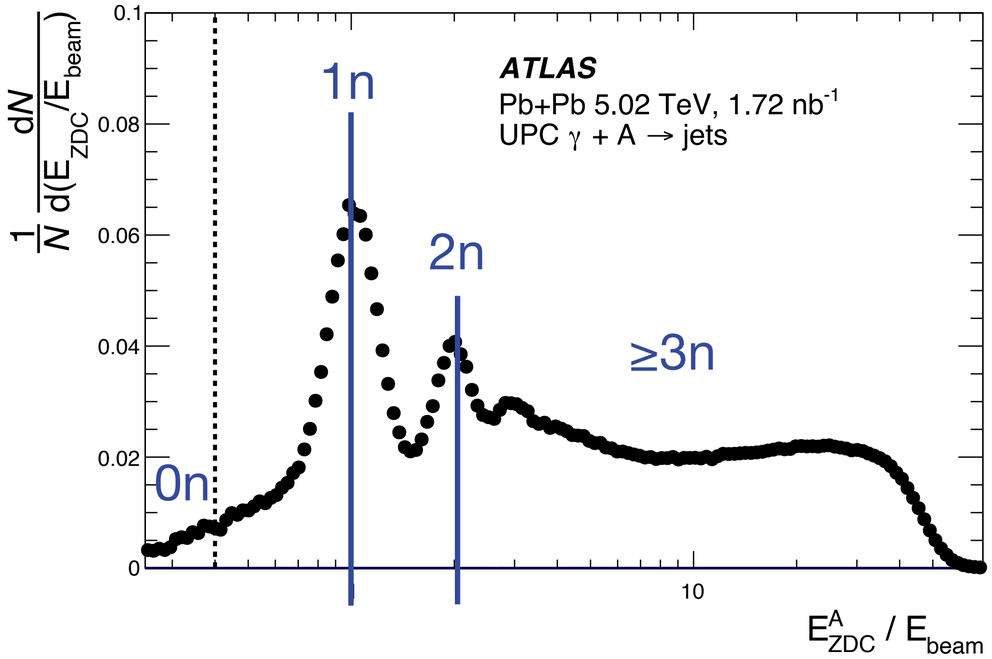
ATLAS 5.02 TeV, 1.72nb^{-1}
PRD 111 (2025) 052006

Probe nPDFs in a region kinematically otherwise not accessible

- Especially cover region in Bjorken-x (< 0.01) where shadowing effects expected
  - Shadowing = Suppression compared to free proton/neutron PDFs
- Cover intermediate momentum transfer Q^2 of 10^2GeV^2-10^4GeV^2, given photon energies up to 80 GeV
  - Lower Q^2 than reachable with pPb

Important: Distinguish UPC photonuclear jets from non-UPC hard scattering

- Require γ-emitting Pb nucleus to remain intact
  - Veto neutron emission in photon-going direction → Use ZDC



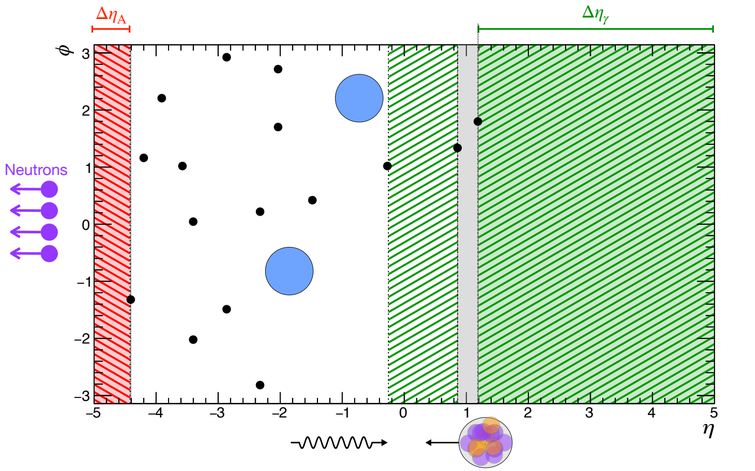
→ Require no neutron on one side, at least one on the other side = 0nXn ZDC topology

Photonuclear jet production (II)

ATLAS 5.02 TeV, 1.72nb^{-1}
PRD 111 (2025) 052006

Select events with ≥ 2 anti-k_t jets with radius parameter R=0.4 and p_T > 15 GeV

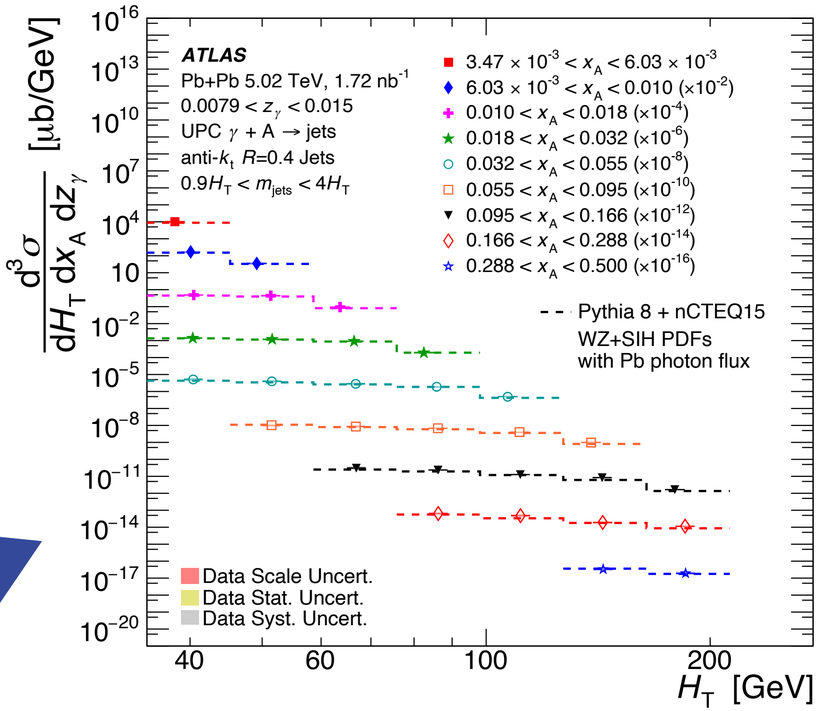
- Use rapidity gaps to suppress hadronic and photon-induced backgrounds

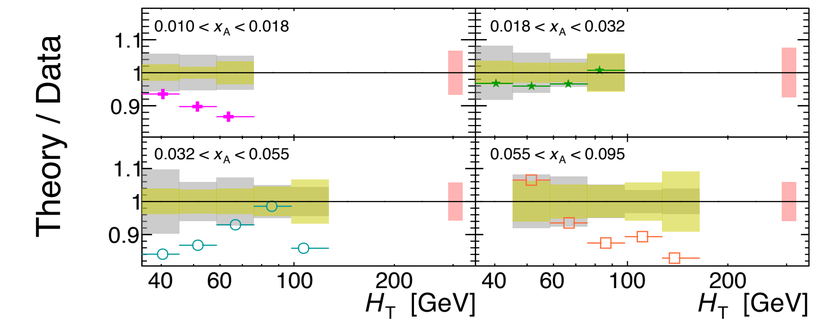


Jet	Event
$p_T^{jet} > 15$ GeV $\lvert\eta^{jet}\rvert < 4.4$	ZDC $0nXn$: $E_{0n} < 1$ TeV and $E_{Xn} > 1$ TeV $N_{jet} \geq 2$ $0.9H_T < m_{jets} < 4H_T$ $\sum_\gamma \Delta\eta > 2.5$, $\Delta\eta_A < 3$, and $\sum \Delta\eta < 9$

➡️ **Leading order (LO) simulation under predicts data in shadowing region**

➡️ **NLO predictions required for proper nPDF extraction**





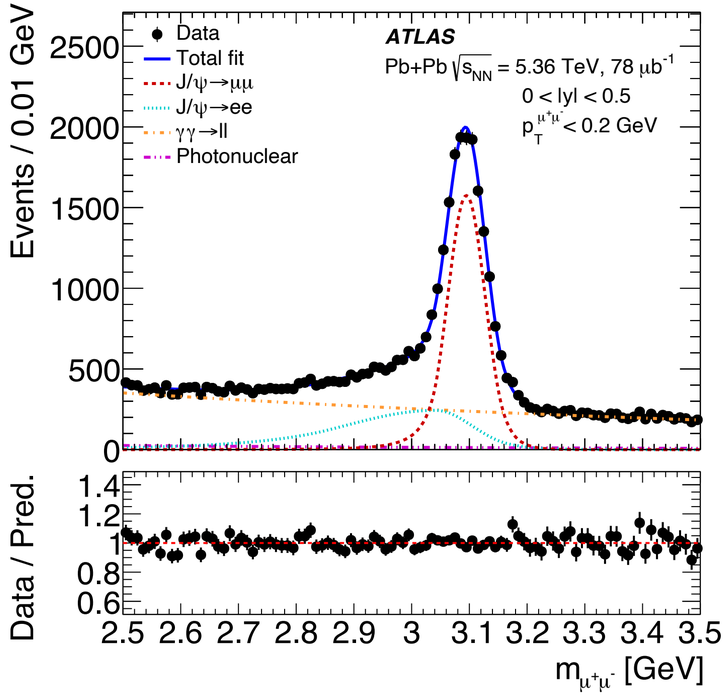
➡️ Study as function of scalar transverse momentum sum H_T (proxy for Q), nuclear parton momentum fraction x_A and parton momentum fraction in photon direction z_γ

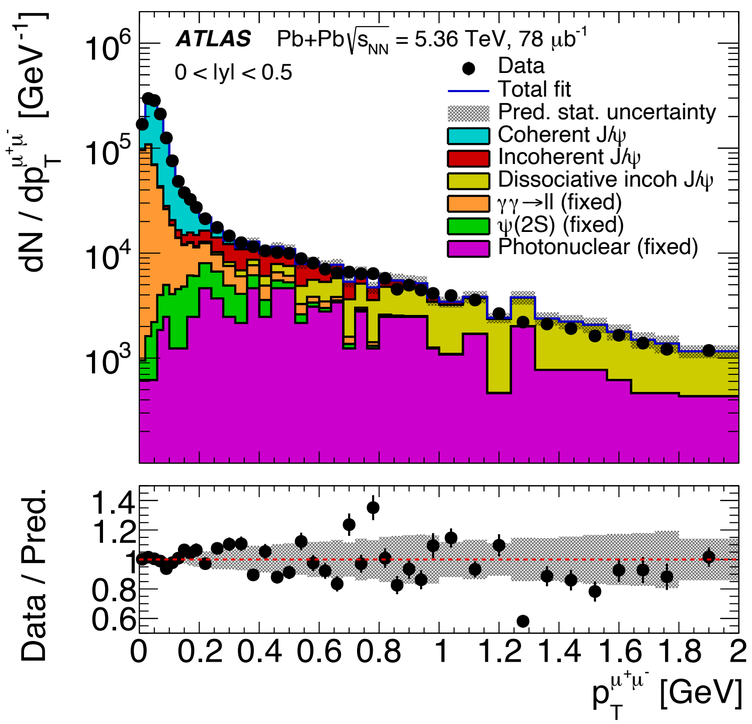
Coherent exclusive J/ψ→μμ production

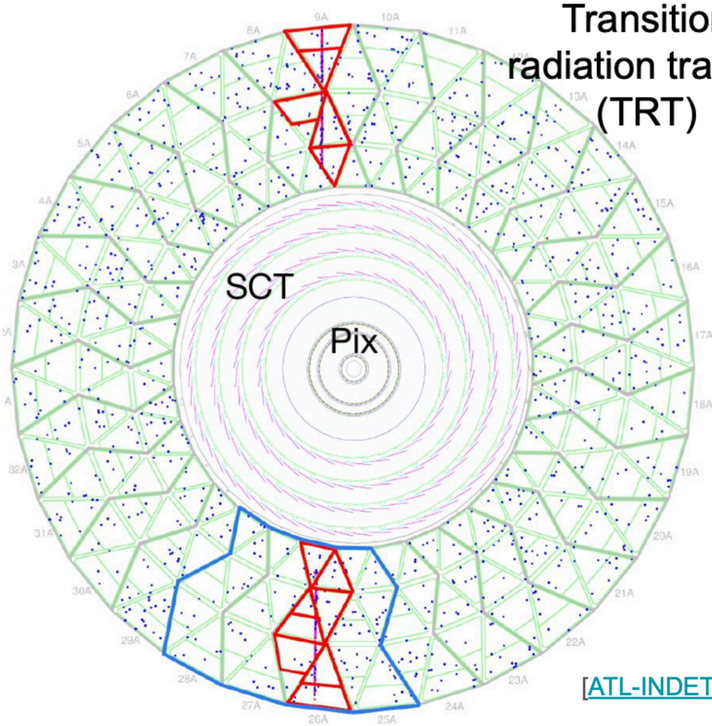
ATLAS 5.36 TeV, 76.5μb^{-1}
arXiv:2509.04135

Study nPDFs - especially gluon PDFs - through coherent exclusive J/ψ production

- Exclusive J/ψ has always been difficult for ATLAS due to minimum muon p_T constraint due to calorimeter material (~ 3.5 GeV)
- However, in Run 3, can use track-based Level-1 TRT trigger
  - In analysis, select exclusive 2 +/- track events







[ATL-INDET-PUB-2009-002]

➡ Identify J/ψ using fits to invariant two-particle mass distribution
➡ Coherent J/ψ yield extracted via pair p_T template fits

ATLAS 5.36 TeV, 76.5μb^{-1}
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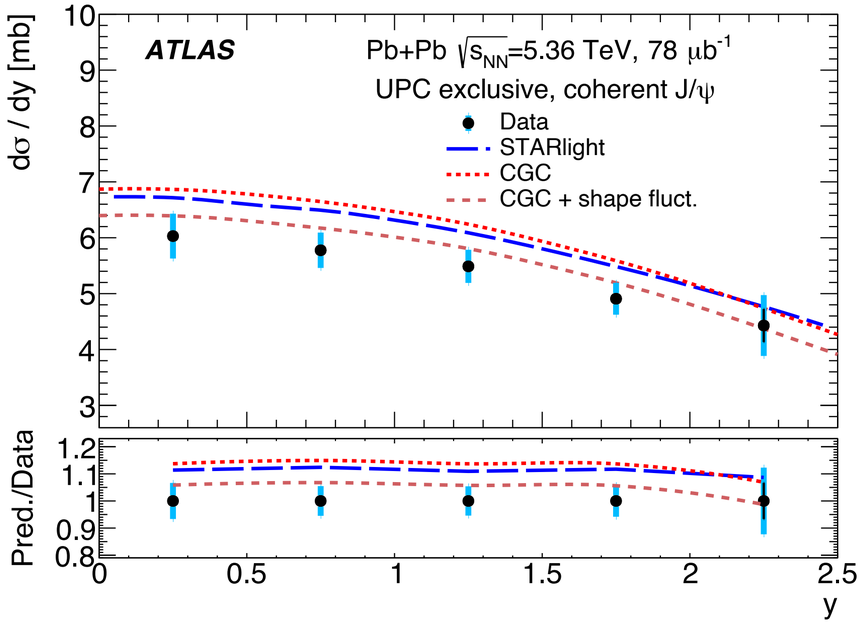
Coherent exclusive J/ψ→μμ production

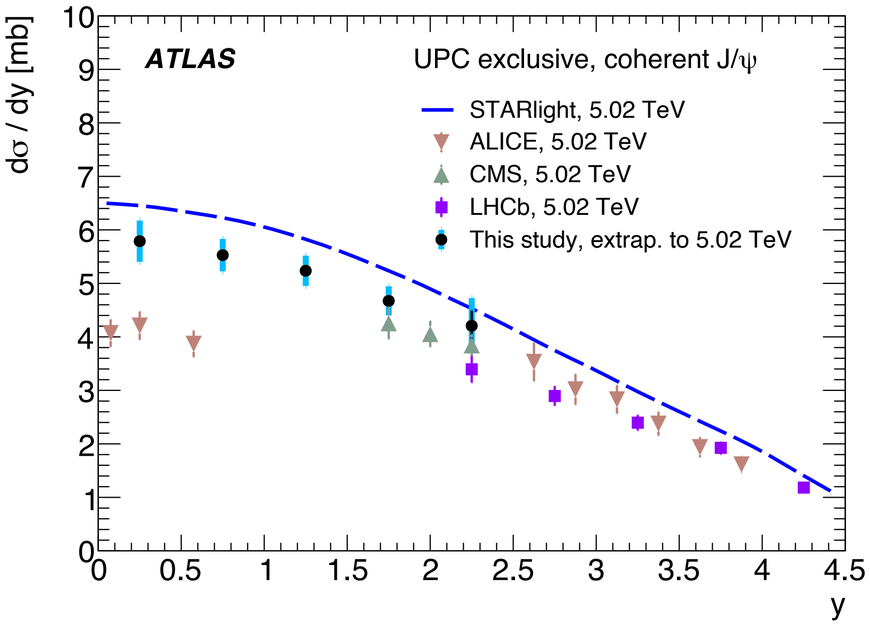
➡ Main physics result:
- Exclusive, coherent J/ψ dσ/dy measured over $|y_{\mu\mu}| < 2.5$

➡ Comparisons to other results
➡ Extrapolate to 5.02 TeV

- ATLAS result in approximate agreement with forward y data from ALICE, CMS, LHCb
  ➡ But not ALICE data at mid-y
  ➡ Why isn't agreement better at forward y?

Could these disagreements result from multi-UPC processes violating exclusivity requirements in trigger or analysis?





Charged and identified-hadron yields

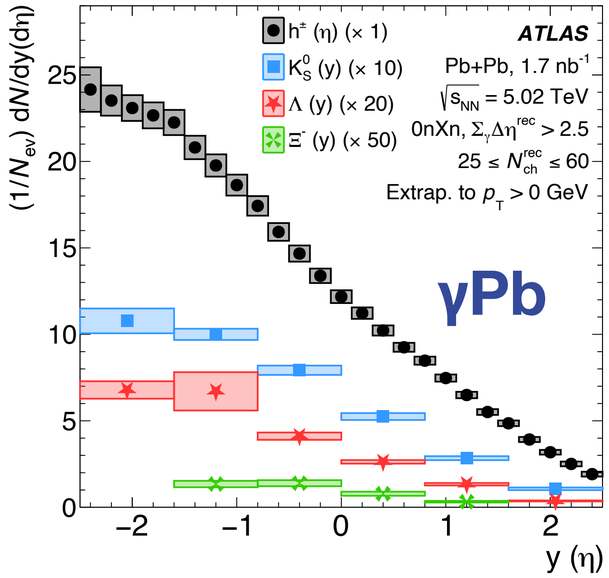
ATLAS 5.02 TeV, 1.7 nb^{-1}
arXiv:2503.08181

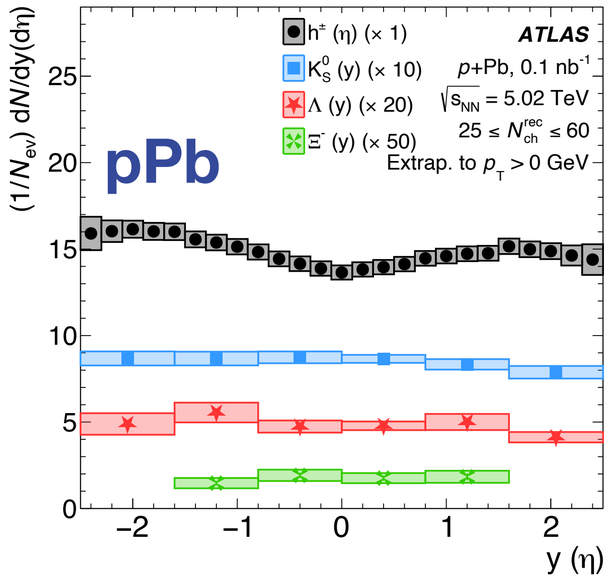
Resolved photonuclear interactions such as ρ-Pb collisions at lower centre-of-mass

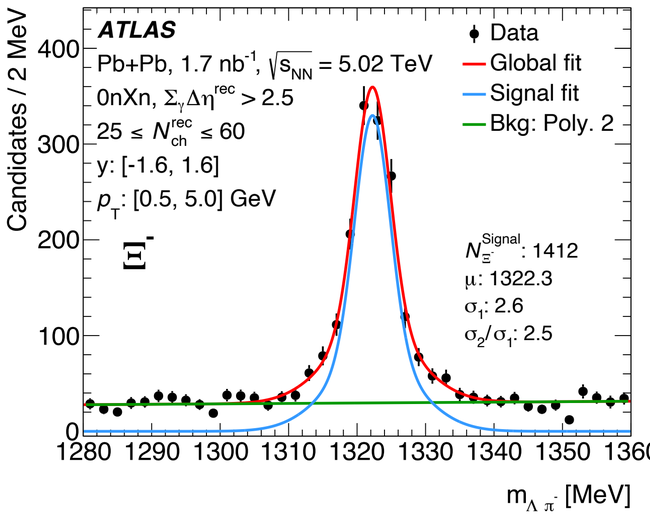
- Droplets of QGP formed? → Look e.g. for baryon/meson or strangeness enhancement

Select tracks as signatures of charged-hadrons → in 0nXn ZDC topology

- Identify K^0_S through $\pi^+\pi^-$, Λ through pπ^- and Ξ^- through $\Lambda\pi^-$ decay







Per event yields as function of (pseudo)rapidity

→ Strong asymmetry in y for γPb – rather symmetric for pPb (more like pp)

→ Only moderate agreement with hybrid model, including QGP formation in γPb and pPb

→ Firm conclusions about QGP formation requires first better data agreement also in pPb

Coincident γγ→μμ and γPb→ρ⁰Pb

ATLAS 5.02 TeV,+5.36 TeV
1.44 nb^{-1} + 3.17 nb^{-1}
arXiv:2504.07795

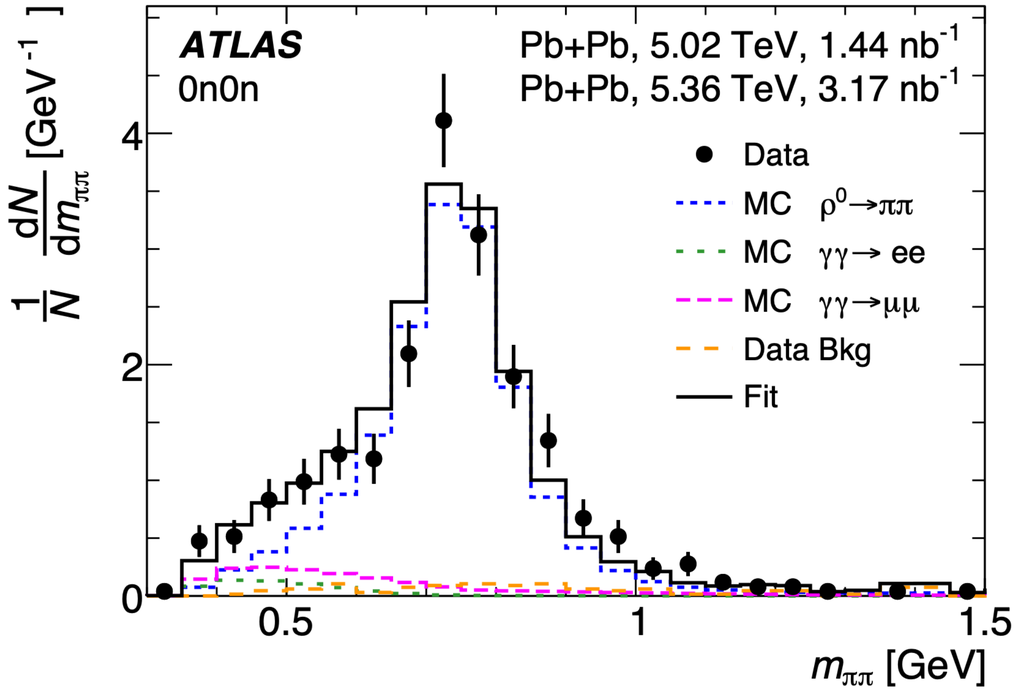
ATLAS has made multiple γγ→l+l- measurements to „calibrate" and test our understanding of UPC processes

- However, data-theory differences (≳10%) persist

  ➡ Some of disagreement (with Superchic) could arise from multiple γ+γ processes in single Pb+Pb collisions ➡ Lose events to measurement due to exclusivity requirement

Measure rates of γPb→ρ⁰Pb production

- Select events with γγ → μ+μ−, $p_{\mathrm{T}}^{\mu} > 4$ GeV
  - Look for additional opposite-sign track pairs (pions) in same event $p_T > 100$ MeV, $|\eta| < 2.5$
  - Use Run 2 + 3 data
    ➡ **See a clear ρ peak**
- Separate ρ from other contributions
  - Using template fit in $m_{\mu\mu}$
    ➡ ρ(+$\pi^+\pi^-$) ~80% of pairs



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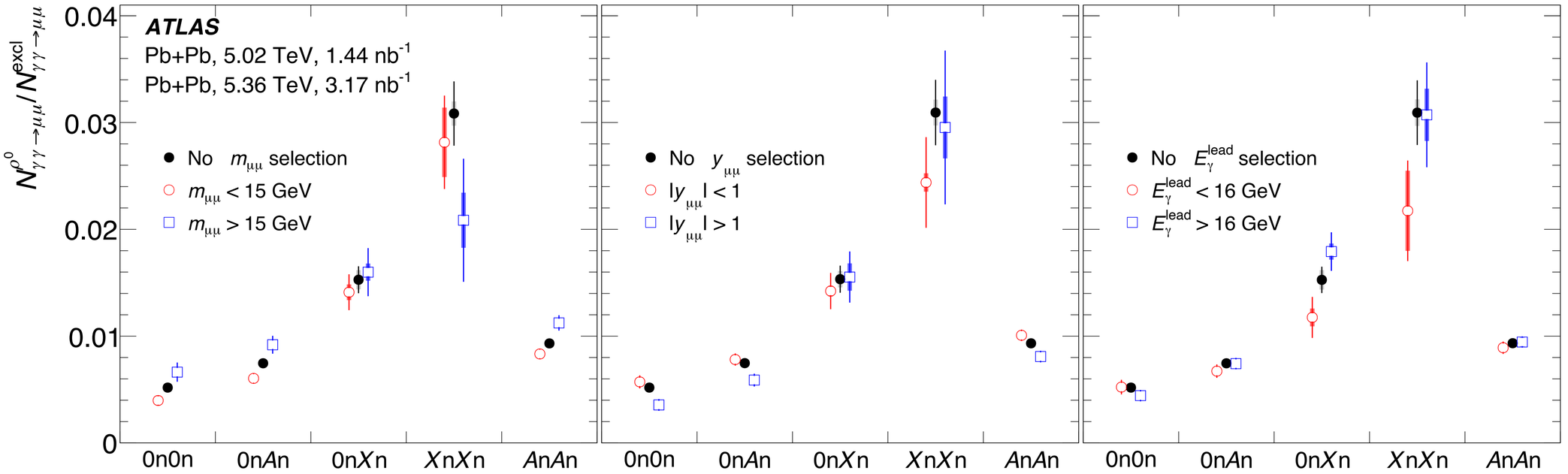


Coincident ρ⁰ vs. exclusive γγ→μμ

- Evaluate fraction of γγ→μμ events w/ additional ρ for different ZDC neutron topologies (A→all, X→n≥1), μμ masses, rapidities and photon energies

➡️ Presence of multi photon-induced processes confirmed!

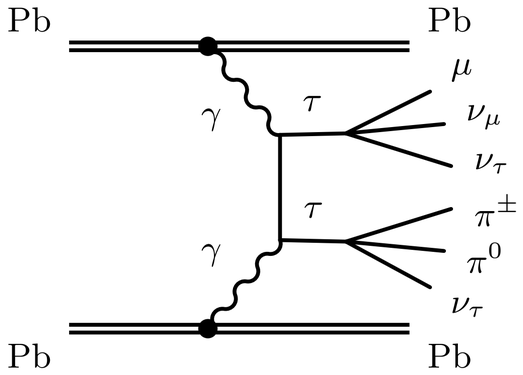
➡️ See dependence of ρ rates on topology ➡ Smaller impact parameter increases probability for coincident ρ⁰ production

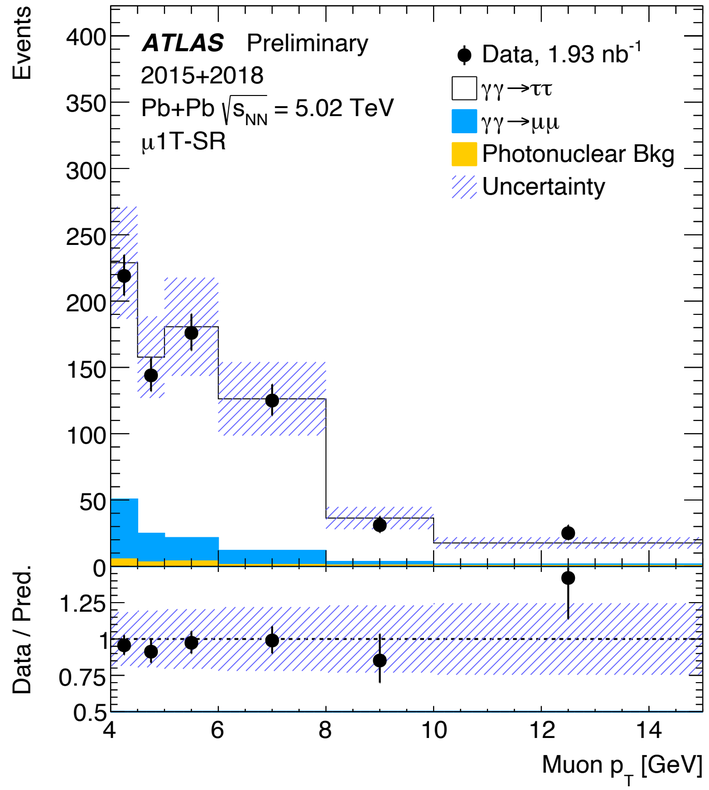
Photon-induced di-τ production

ATLAS 5.02 TeV 1.93 nb^{-1}
ATLAS-CONF-2025-004

Study kinematics of γγ→ττ production

- Veto EM Pb ion excitation, i.e. 0n0n ZDC topology
- Consider 3 τ-lepton decay final states:
  - μ1T: 1 muon, 1 track (=1-prong hadronic or low-pT leptonic decay)
  - μ3T: 1 muon, 3 tracks (=3-prong hadronic decay)
  - μe: 1 muon, 1 electron
- Background estimates
  - γγ→μμ from MC
  - Photonuclear from data-driven estimate < ~15% background contributions



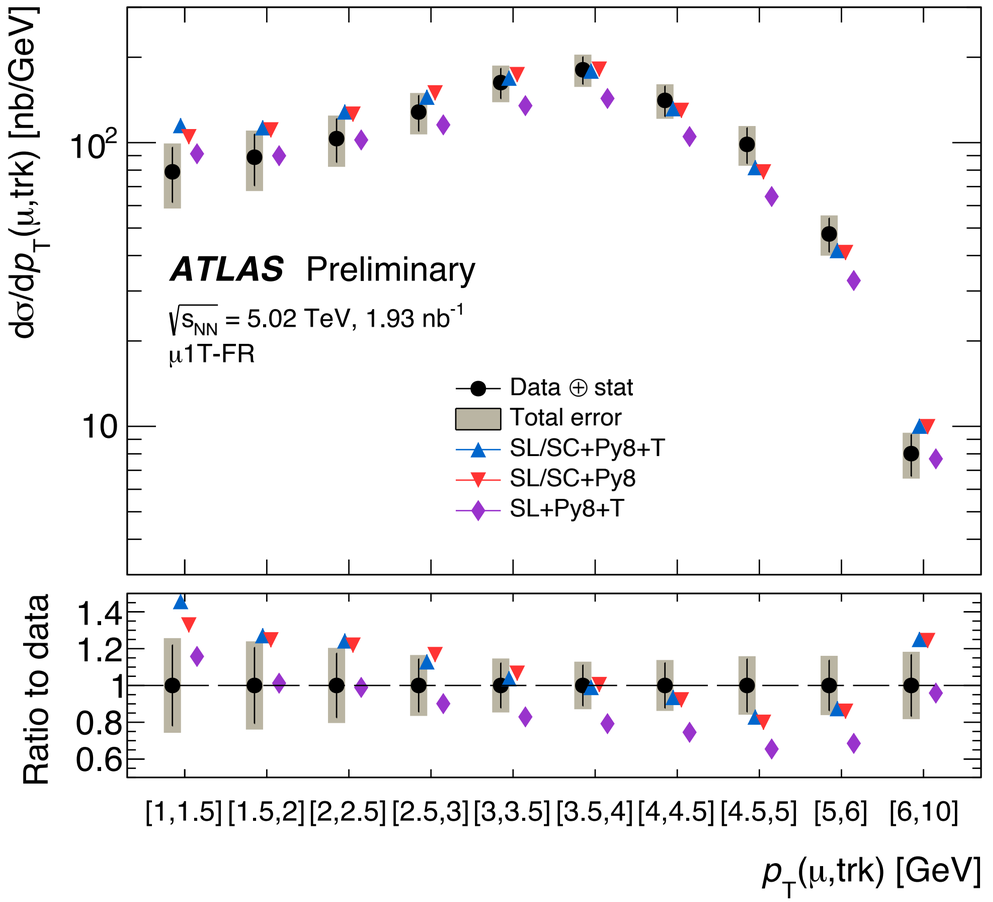


Photon-induced di-τ production

ATLAS 5.02 TeV 1.93 nb^{-1}
ATLAS-CONF-2025-004

Differential cross sections compared to different photon flux predictions

- 7 differential cross sections each for 3 fiducial regions (FRs)



➡️ Photon flux modeling by SuperChic (SC) better than by STARlight (SL)

➡️ Few trends in data-MC agreement such as in p_T(μ,trk) in μ1T-FR

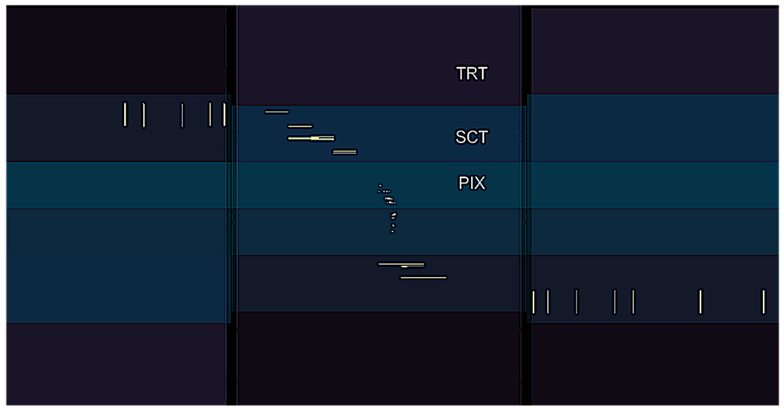
➡️ NLO effect or from missing spin-correlations?

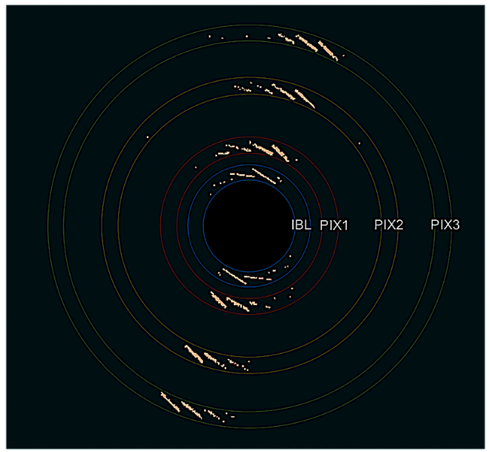
Photon-induced magnetic monopoles

ATLAS 5.36 TeV 262μb^{-1}
PRL 134 (2025) 061803

Existence of magnetic monopoles? → Explain quantization of electric charge

- With magnetic charge $|q_m| = 1g_D$ and $g_D = \frac{e}{2\alpha} = 68.5e$:
  - Highly ionizing in ATLAS inner detector (ID)
  - Unique trajectories in ATLAS solenoid magnetic field: bend in r-z plane, instead of r-ϕ plane as normal tracks

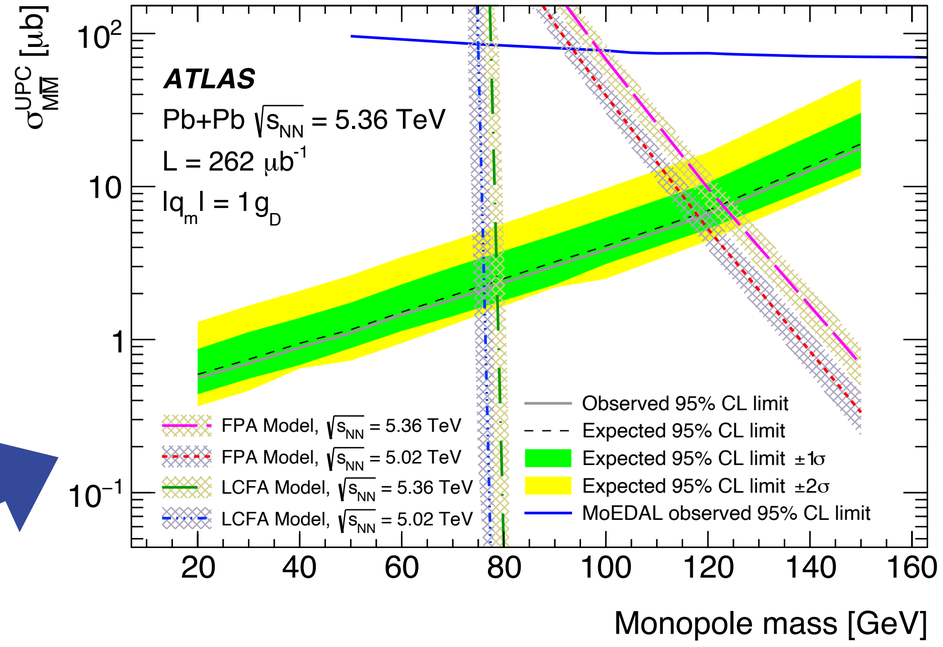




- Identify through large number of Pixel, including IBL clusters
- Collision backgrounds largely suppressed, beam-induced backgrounds estimated with data-driven method

	Events
Background	4 ± 4(stat) ± 1(syst)
Data	3

→ Determined exclusion limits



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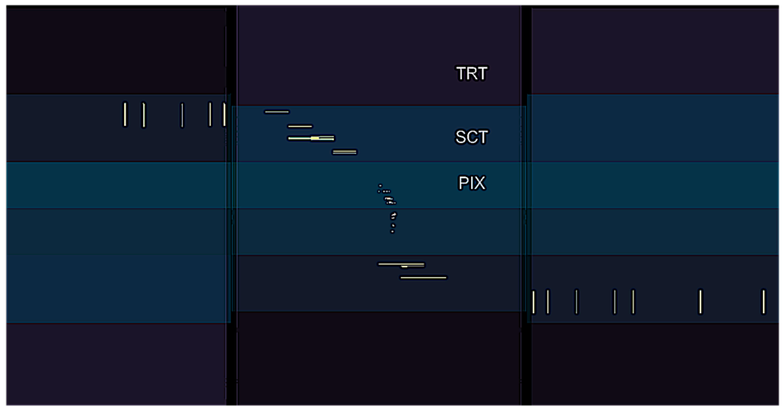

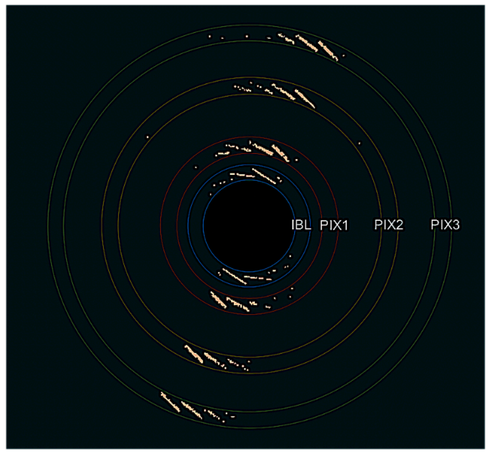

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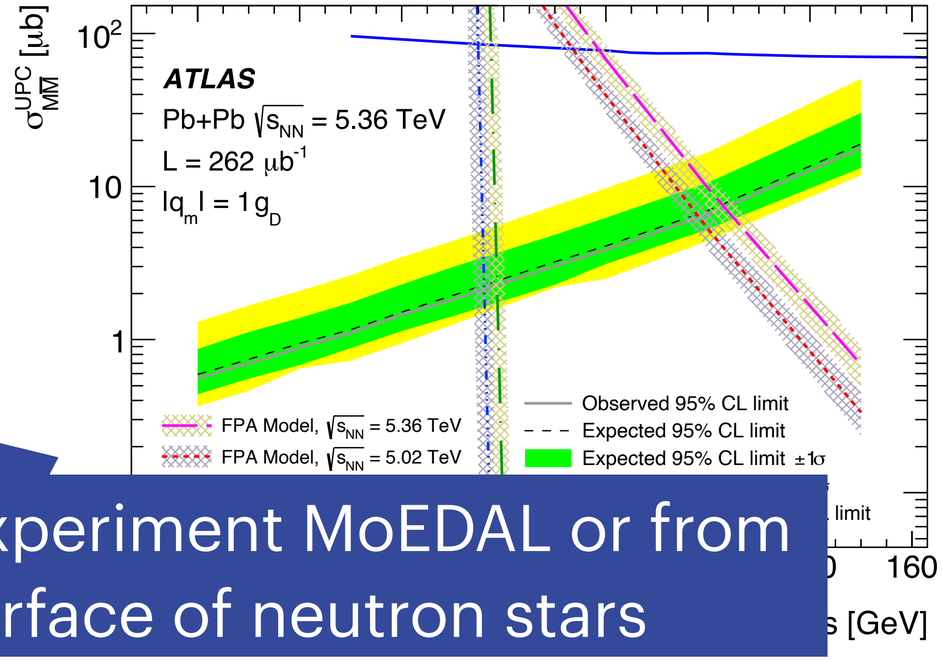
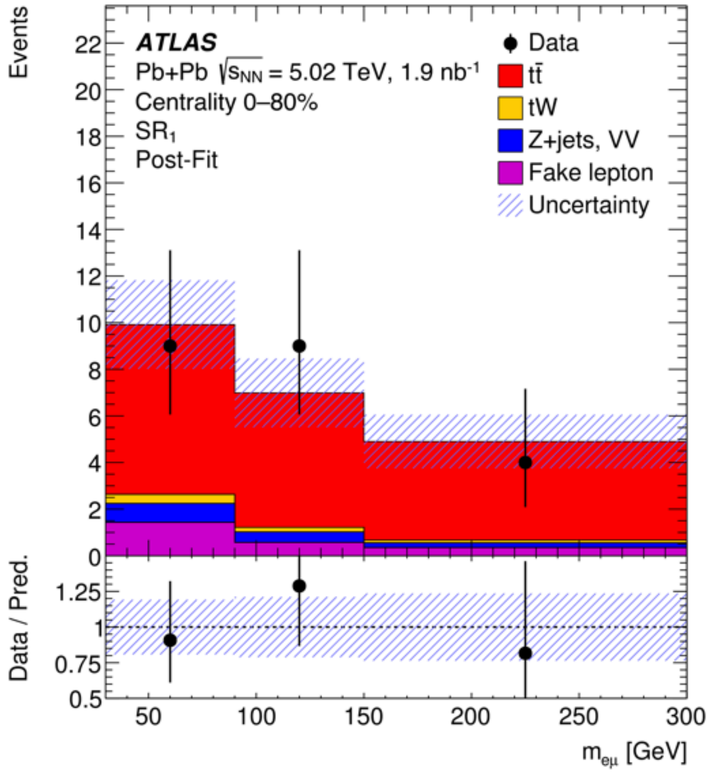


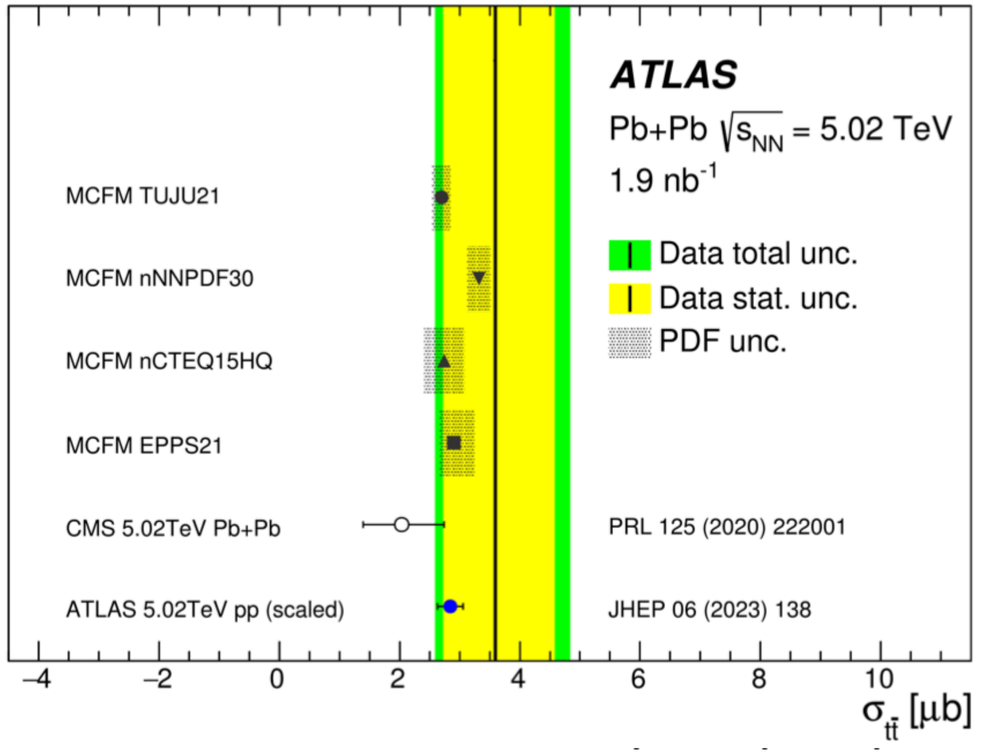
Stronger exclusion limits than from dedicated experiment MoEDAL or from indirect searches for production close to surface of neutron stars

Observation of top-quarks in Pb+Pb

🌟 **First** 🌟 **observation of $t\bar{t}$ in Pb+Pb collisions at the LHC**

[PRL 134 (2025) 142301]





✅ Observed (expected) significance of 5.0 (4.1) standard deviations

✅ $t\bar{t}$ **production cross section** is measured to be

➡️ Consistent with the previous measurements and nPDF predictions

$$\sigma_{t\bar{t}} = 3.6 \pm {}^{1.0}_{0.9}\,(\text{stat.}) \pm {}^{0.8}_{0.5}\,(\text{syst.})\ \mu\text{b}$$

✅ New probe of the QGP established at the LHC 🌟

Observation of top-quarks in p+Pb

Top-quark pair production $t\bar{t}$ in p+Pb collisions

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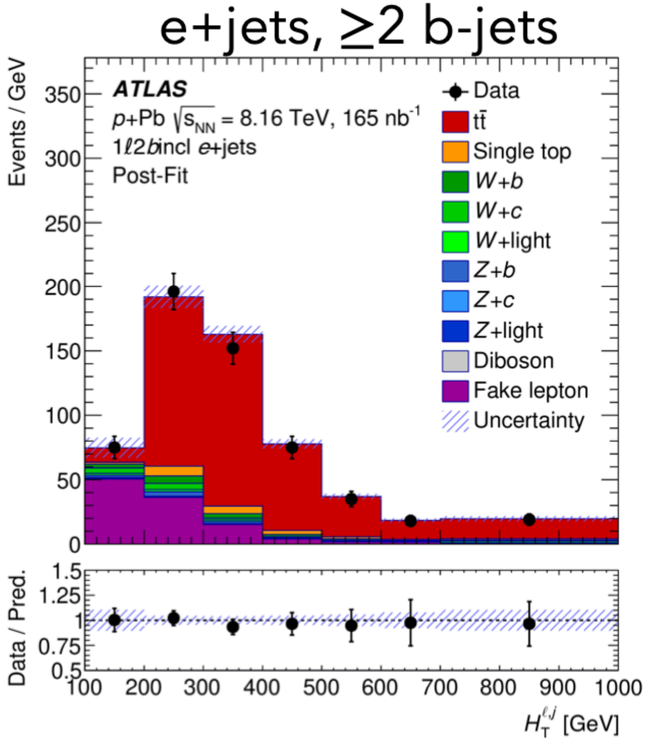
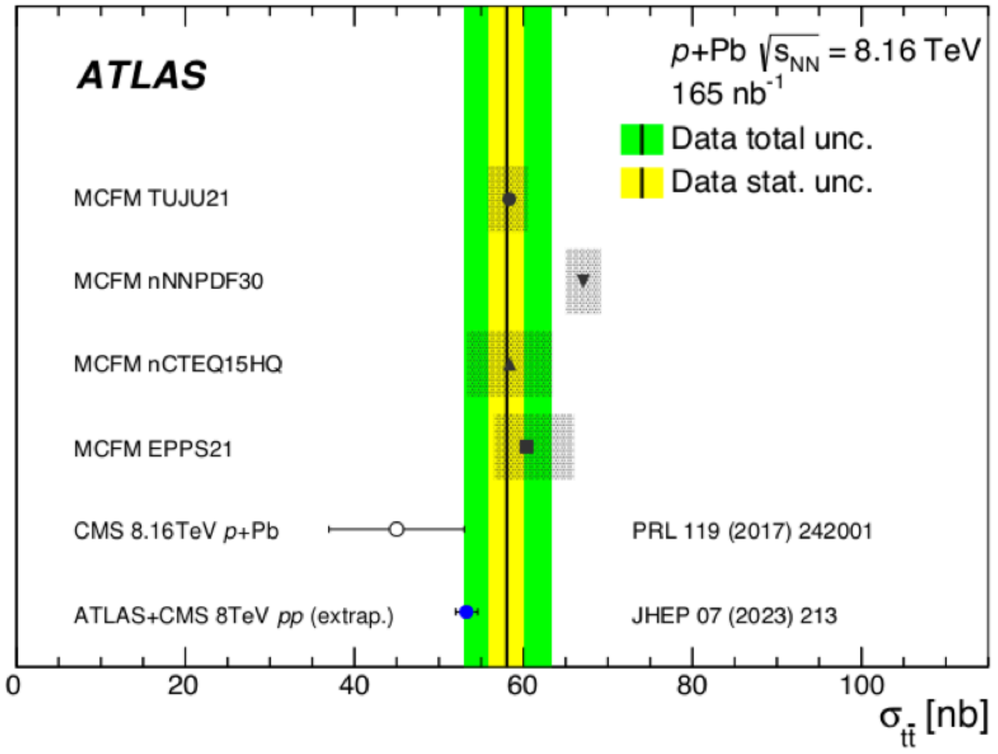
Lepton+jet and **dilepton** channels (BR=~50%)





✅ **Most precise** measurement of $t\bar{t}$ production **cross-section** at the LHC:

➡️ Consistent with the previous measurements and nPDF predictions

$$\sigma_{t\bar{t}} = 58.1 \pm 2.0(\text{stat.}) \pm^{4.8}_{4.4} (\text{syst.})\ \text{nb}$$

✅ **Nuclear modification factor** for $t\bar{t}$ production measured for the **first time**

➡️ Hint of nuclear modifications to PDF

Summary

LHC as a photon collider → Unique access to physics in ultraperipheral collisions

Fascinating physics questions

→ Nuclear parton structure

→ Quark gluon plasma droplets

→ Multi photon-induced production and its impact parameter dependence

→ Photon-induced kinematics

→ Possible BSM contributions

vs.

Amazing ATLAS analyses

→ Photonuclear jet production

→ Coherent exclusive J/ψ production,

→ Charged- and identified hadron production

→ Coincident γγ→μμ and γPb→ρ^{0}Pb production

→ Photon-induced di-τ

→ Magnetic monopole production

➡ Run 3 is in progress ➡ 2023-2024 Pb+Pb data set at $\sqrt{s_{\mathrm{NN}}}$=5.36 TeV collected

➡ Significant improvements in instrumentation, triggers, and reconstruction efficiency

See more in Riccardo talk at 10:15

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Extra slides