Overview of ATLAS results from ultraperipheral heavy-ion collisions

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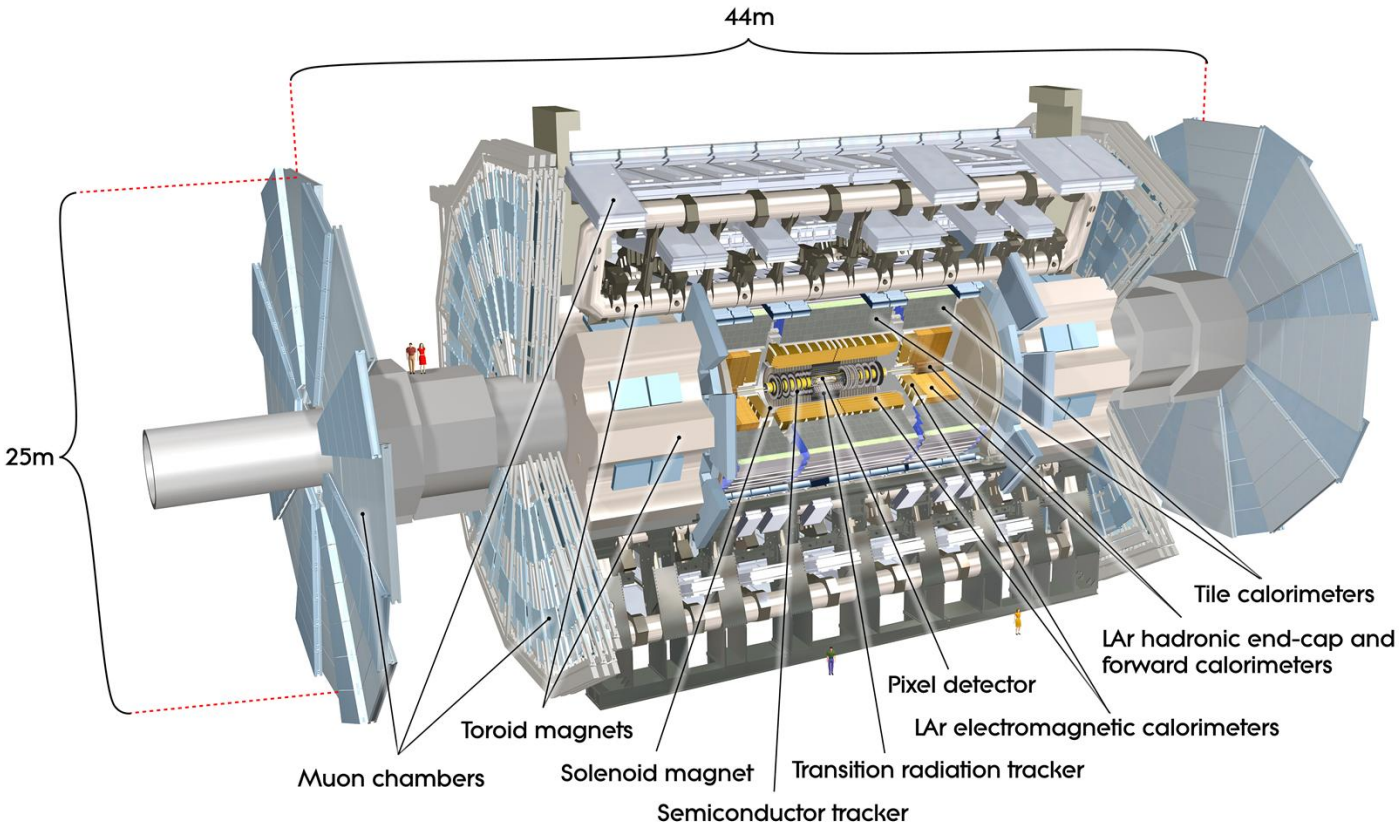
JG|U

ATLAS EXPERIMENT

Alexander von Humboldt Stiftung/Foundation

ATLAS detector / Datasets

- **Charged particle tracking** in $|\eta| < 2.5 \rightarrow$ electrons, muons, charged hadrons
- **Calorimeter system** in $|\eta| < 4.9 \rightarrow$ electrons, photons, jets
- **Muon reconstruction** in $|\eta| < 2.4$ (muon spectrometer + inner detector)
- All components used in UPC measurements

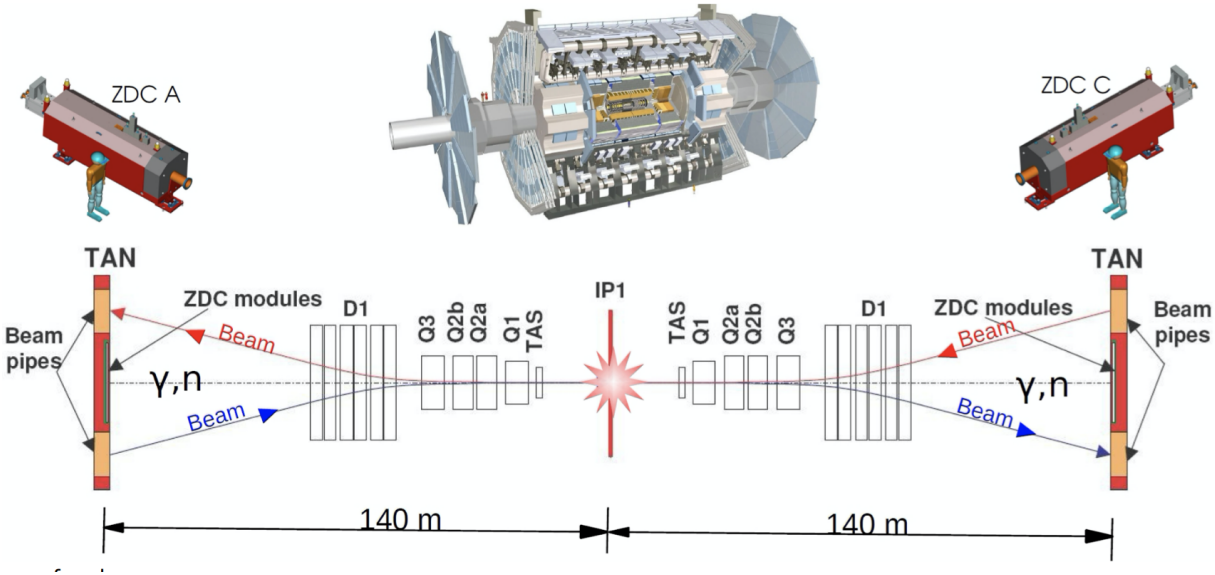


UPC datasets from Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV:

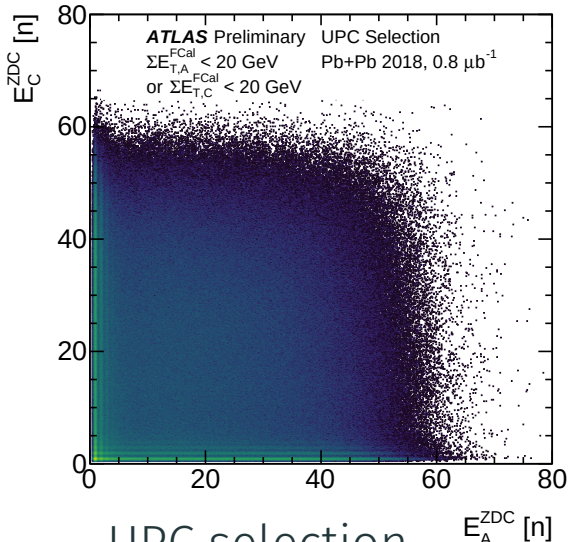
- 0.49 nb^{-1} (2015)
- 1.44-1.72 nb^{-1} (2018)

Zero Degree Calorimeters (ZDC)

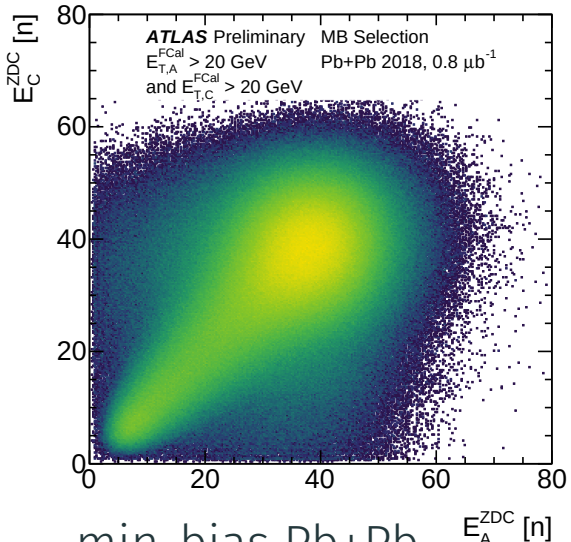
- Two ZDC arms: measure energies of forward neutrons
- Separate UPCs from inelastic Pb+Pb collisions
- Categorise events into 0n0n / 0nXn / XnXn



- Exclusive $\gamma\gamma$ processes: mostly 0n0n
- Neutron emissions if nuclei excited through secondary photon exchanges
- Photonuclear processes: typically 0nXn



UPC selection

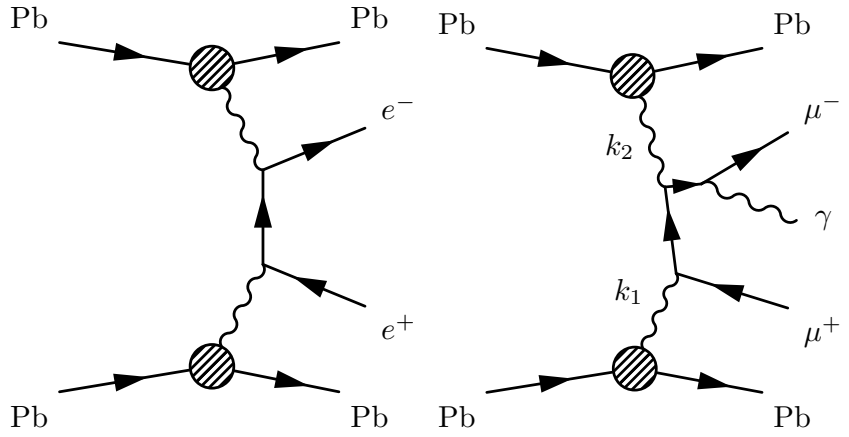


min-bias Pb+Pb selection

$\gamma\gamma \to ee$ / $\gamma\gamma \to \mu\mu$ / $\gamma\gamma \to \tau\tau$

- $\gamma\gamma \to ee$ / $\gamma\gamma \to \mu\mu$:
  - ”standard candles” to calibrate modelling of photon flux
  - importance of modelling final-state QED emissions
  - study correlation with forward neutron emissions

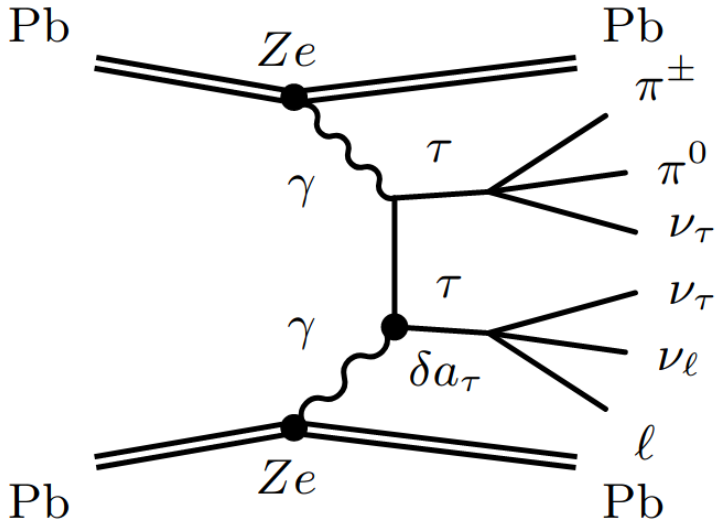
see also talk by Agnieszka



- $\gamma\gamma \to \tau\tau$:
  - not observed at the LHC before
  - τ-leptons never directly targeted in analyses using nucleus-nucleus data
  - cross-section sensitive to τ-lepton anomalous magnetic moment: $a_\tau = \frac{(g-2)_\tau}{2}$

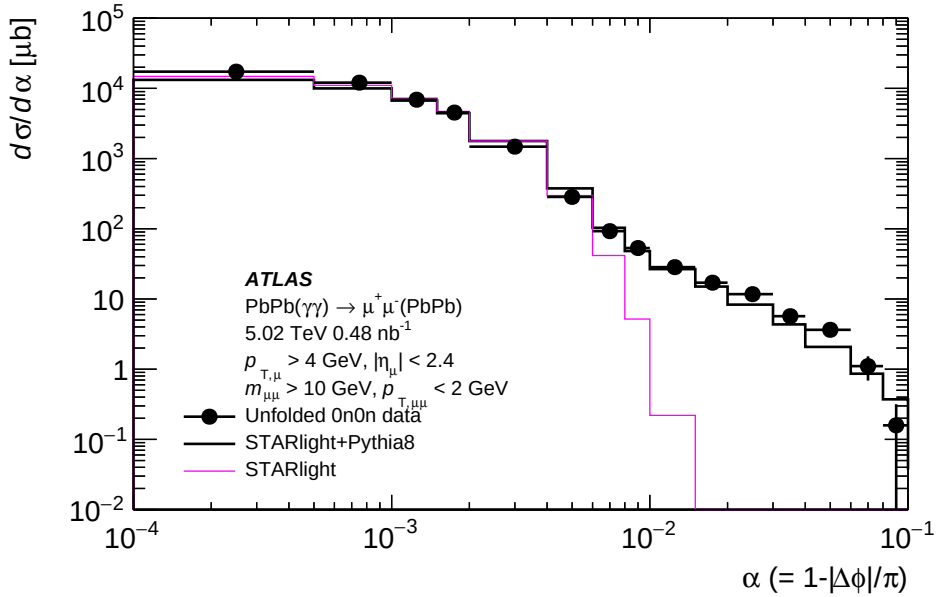
see also talks by Lydia

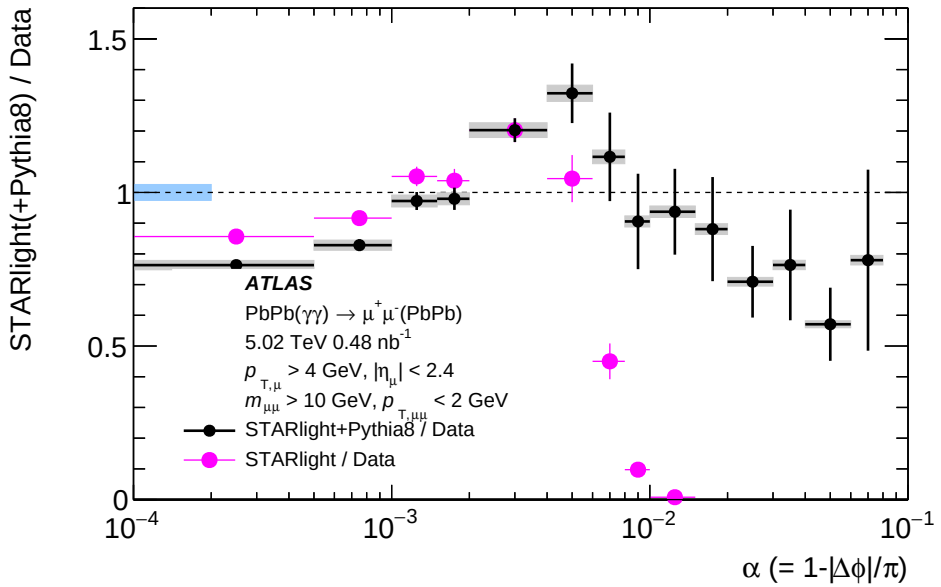
and Georgios (on CMS result)



$\gamma\gamma \to \ell\ell$: QED FSR emission modelling

- Modelling studied using acoplanarity distribution in 0n0n $\gamma\gamma \to \mu\mu$ events
- Starlight distribution does not extend beyond 0.01 due to absence of QED FSR emissions
- Adding Pythia8 QED showering improves agreement in the tail

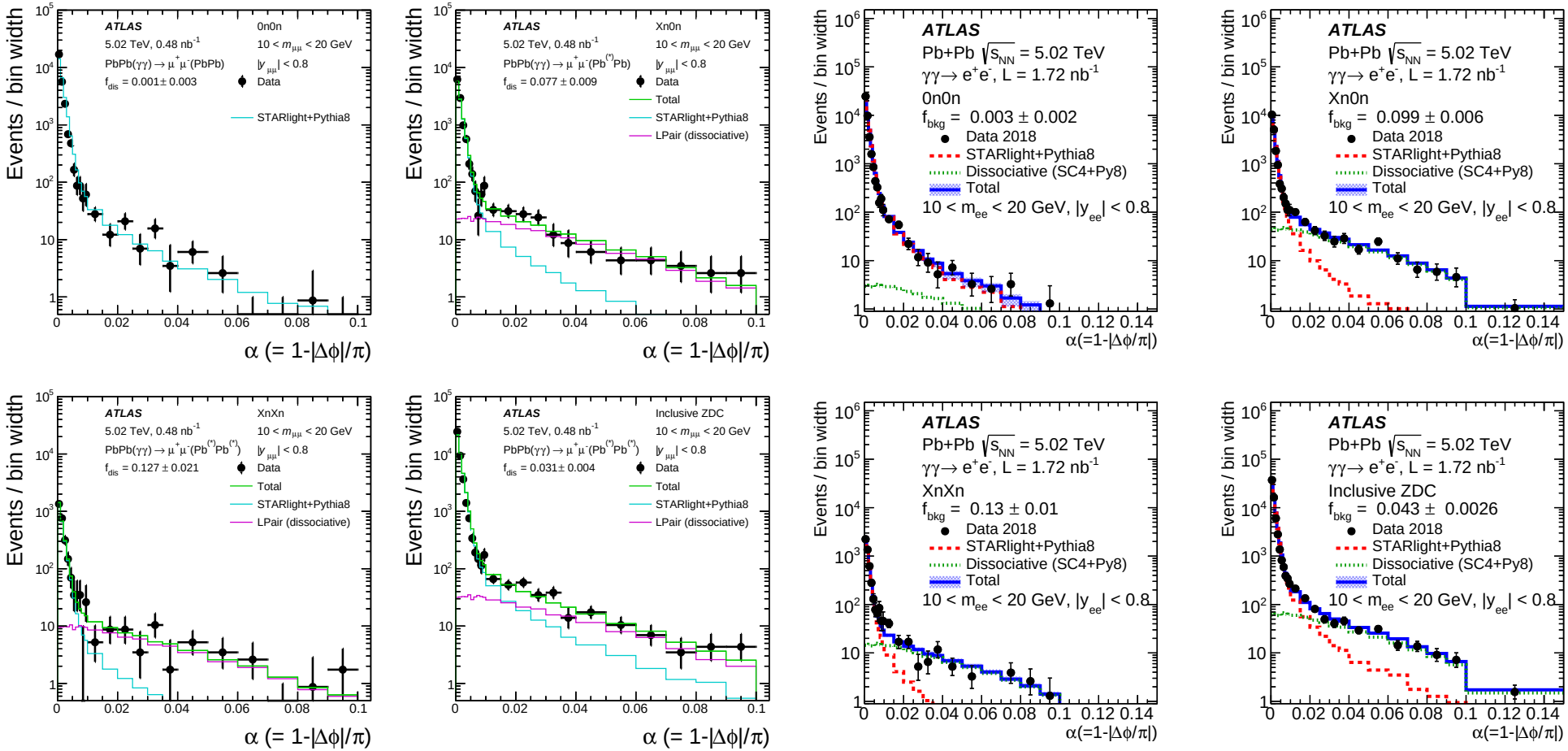




PRC 104 (2021) 024906

$\gamma\gamma \to \ell\ell$: dissociative backgrounds

$\gamma\gamma \to \mu\mu$ $\gamma\gamma \to ee$

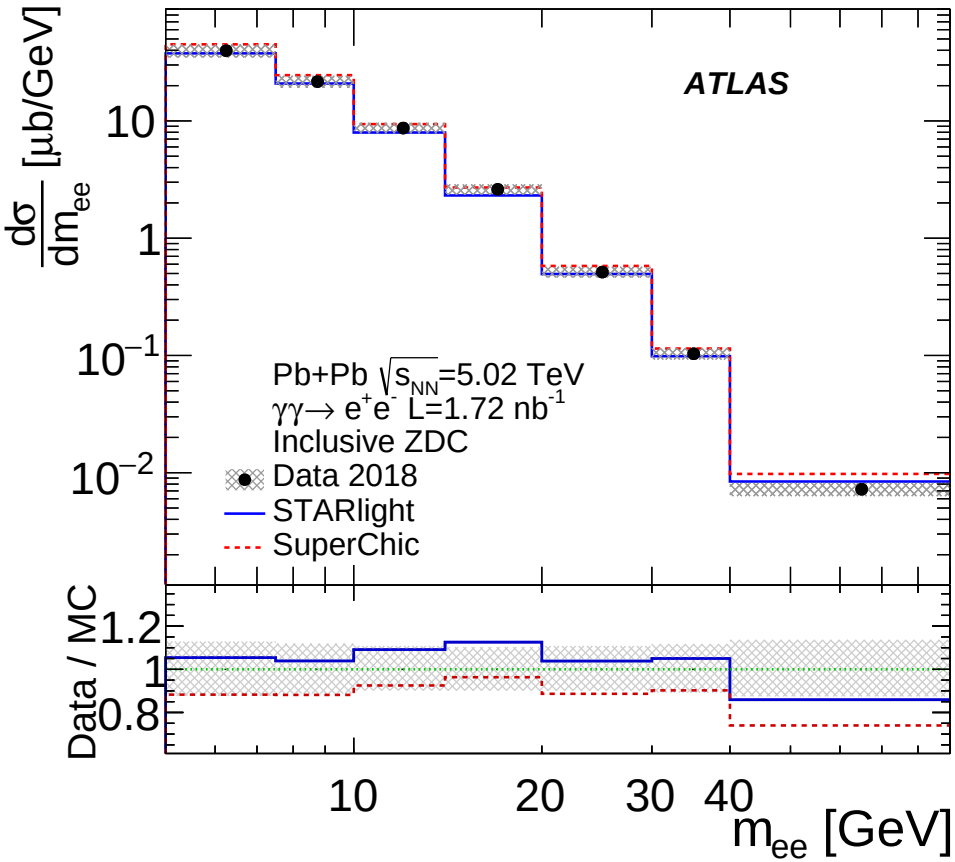


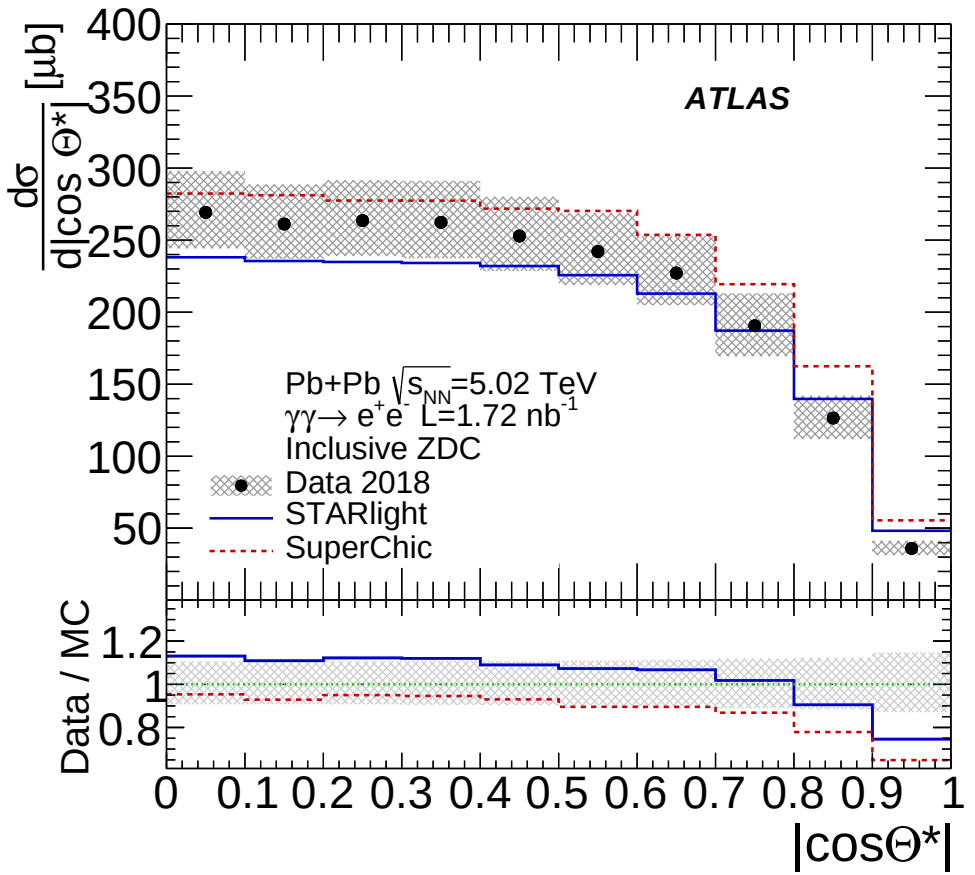
- Dissociative background contribution from fit to acoplanarity distributions
- Contribution increases from 0n0n (negligible) to XnXn ($\sim$ 13%) events

PRC 104 (2021) 024906, arXiv:2207.12781

$\gamma\gamma \to \ell\ell$: differential cross-sections

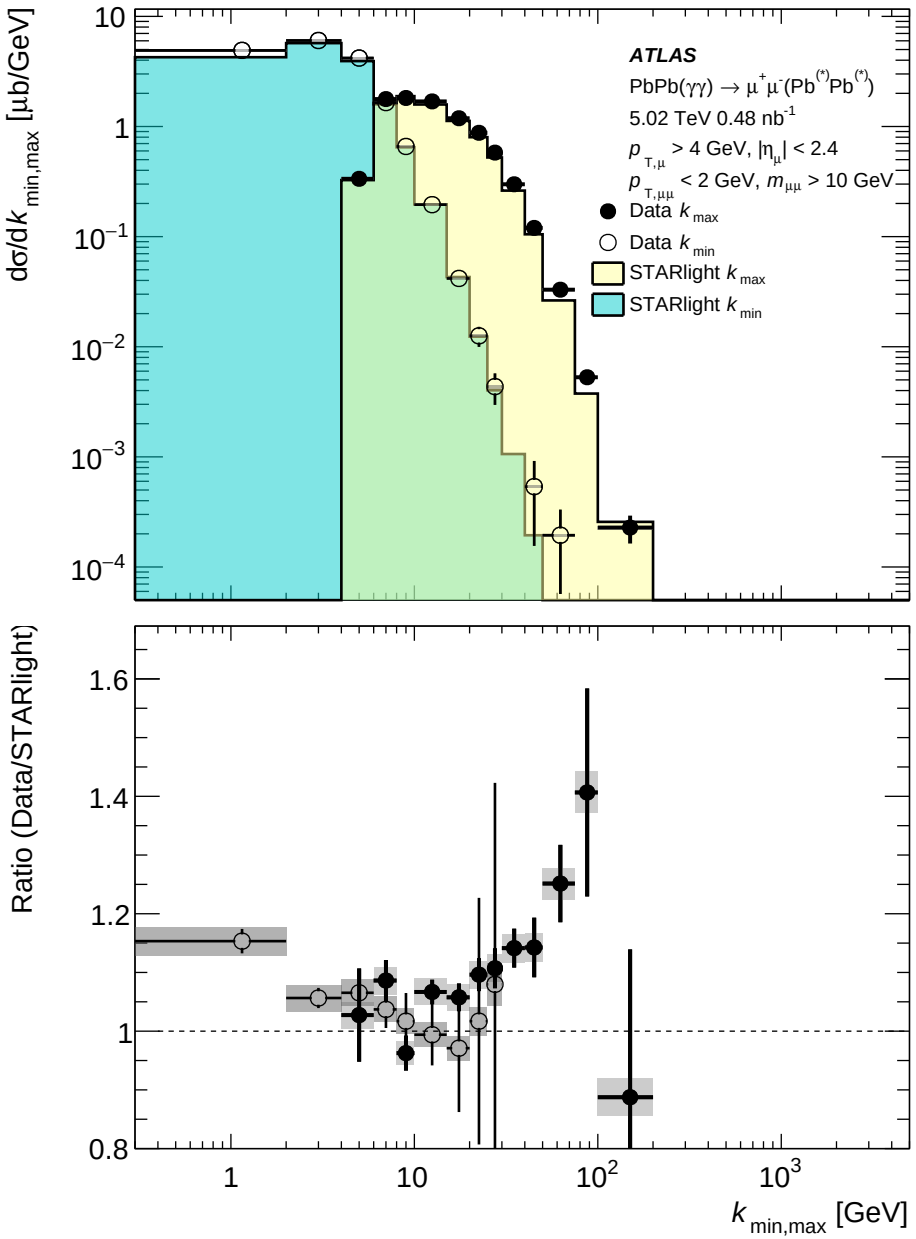
arXiv:2207.12781





- $\gamma\gamma \to ee$ data compared to predictions from Starlight and SuperChic 3
- Generally good shape agreement (except at high $|\cos\theta^*|$)
- 10-20% differences in normalisation (photon flux) between predictions - data typically bracketed by the theory curves

$\gamma\gamma \to \ell\ell$: initial-state photon energies



- Estimate **initial-state photon** energies from **final-state muon** kinematics:

$$k_{\text{max, min}} = \frac{1}{2} m_{\mu\mu} e^{\pm y_{\mu\mu}}$$

- Soft FSR photons not accounted for, but impact is small
- Comparison of data and Starlight predictions shows limitations of Starlight photon flux implementation:
  - agreement for both k_{max} and k_{min} around 5-20 GeV
  - data exceeds prediction at higher and lower energies

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$\gamma\gamma \to \ell\ell$: forward neutron emissions

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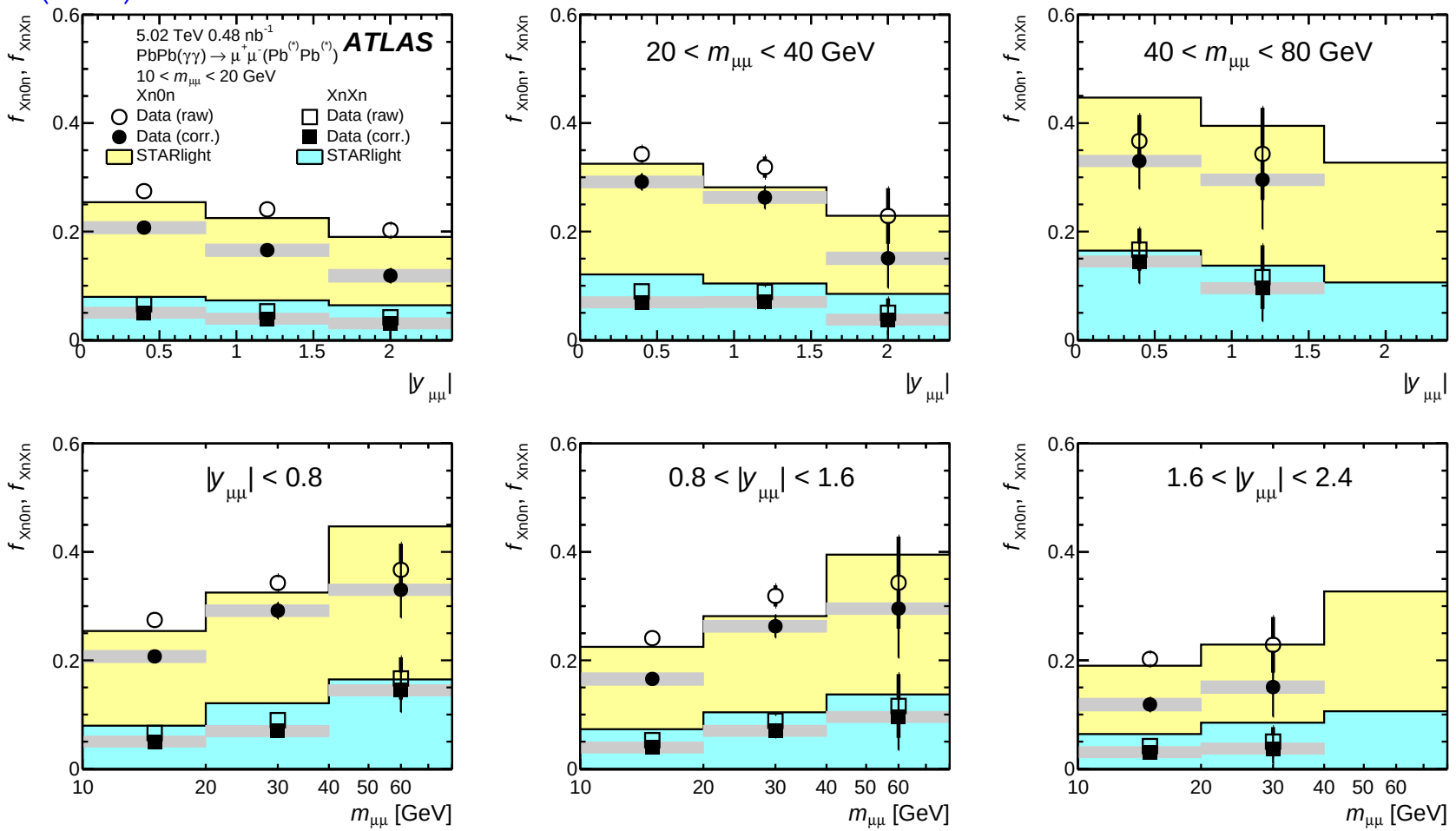
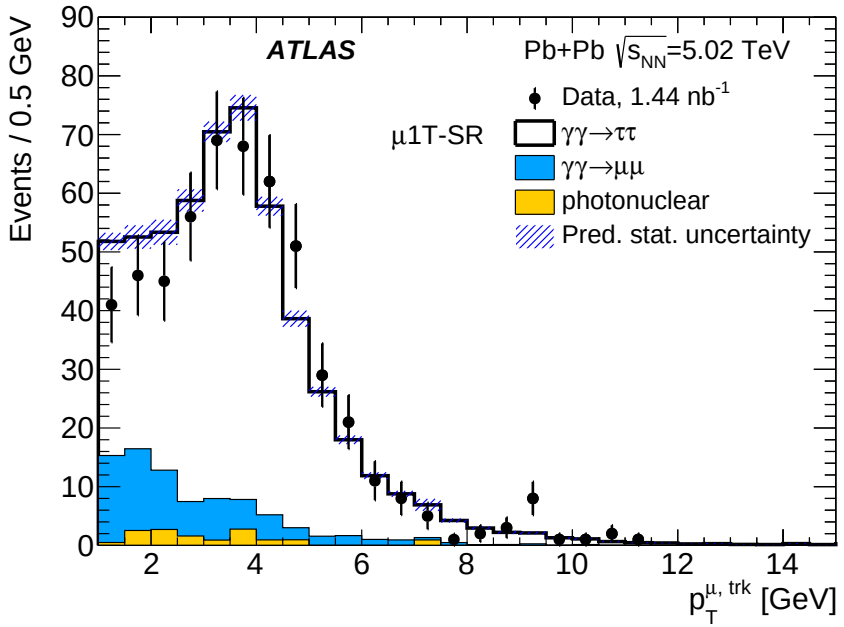
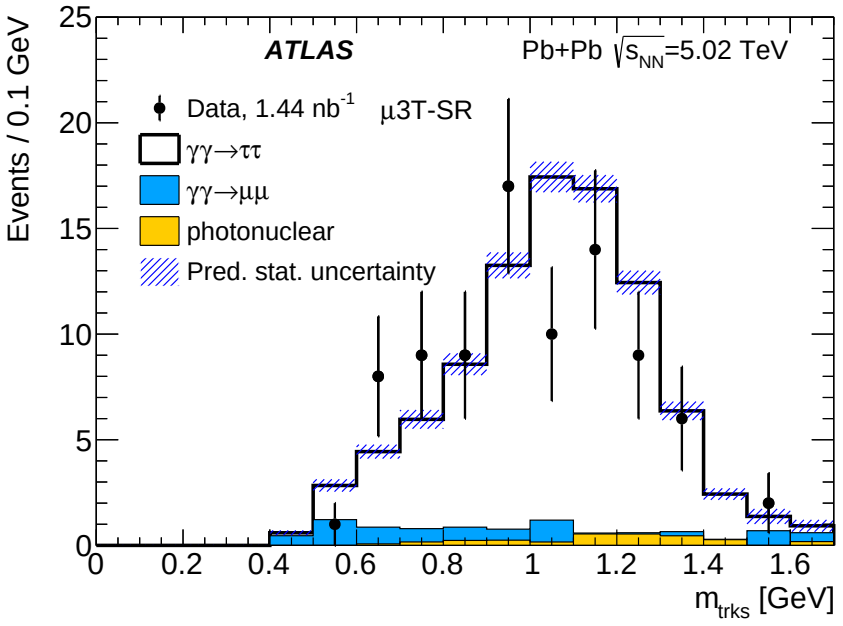
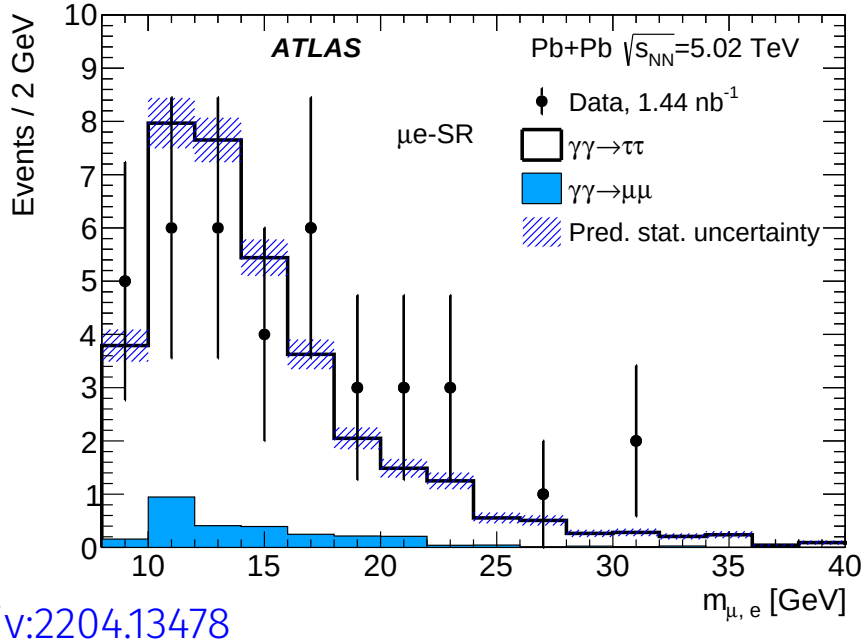


- Fractions of $\gamma\gamma \to \mu\mu$ events in 0nXn/XnXn categories (corrected for EM pileup)
- Forward neutron emissions correlated with muon kinematics
  (more central rapidities, higher masses $\Leftrightarrow$ larger 0nXn and XnXn fractions)
- Starlight predicts larger fractions of events with forward neutron emissions

$\gamma\gamma \to \tau\tau$: signal regions



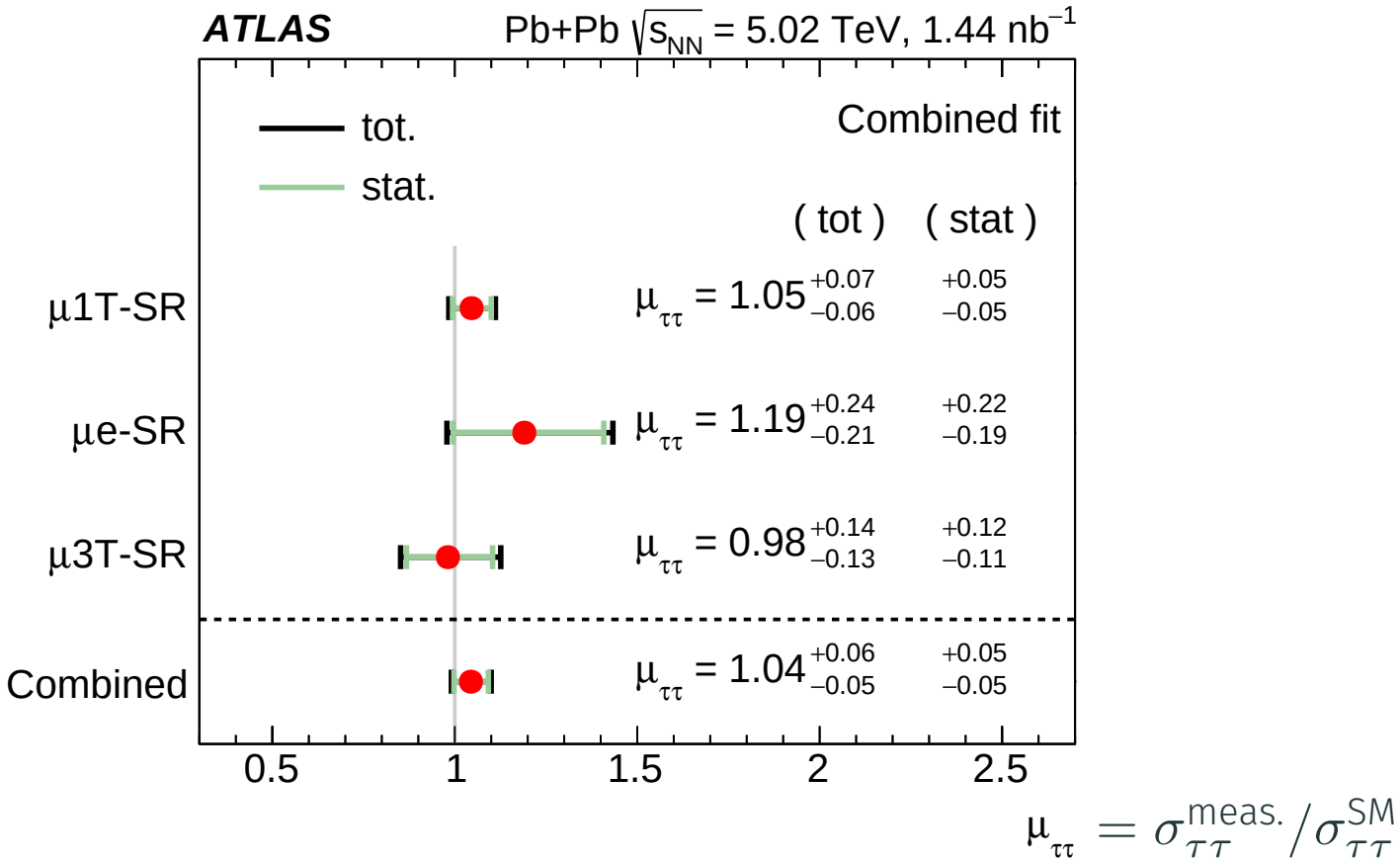




- Three signal regions defined:
  - μ1T-SR: muon + 1 track (e/μ/hadron)
  - μ3T-SR: muon + 3 tracks (3 hadrons)
  - μe-SR: muon + electron
- Total of $\sim$ 650 events across all SRs
- Clear observation of $\gamma\gamma \to \tau\tau$ process
- Various distributions in good agreement with predictions

arXiv:2204.13478

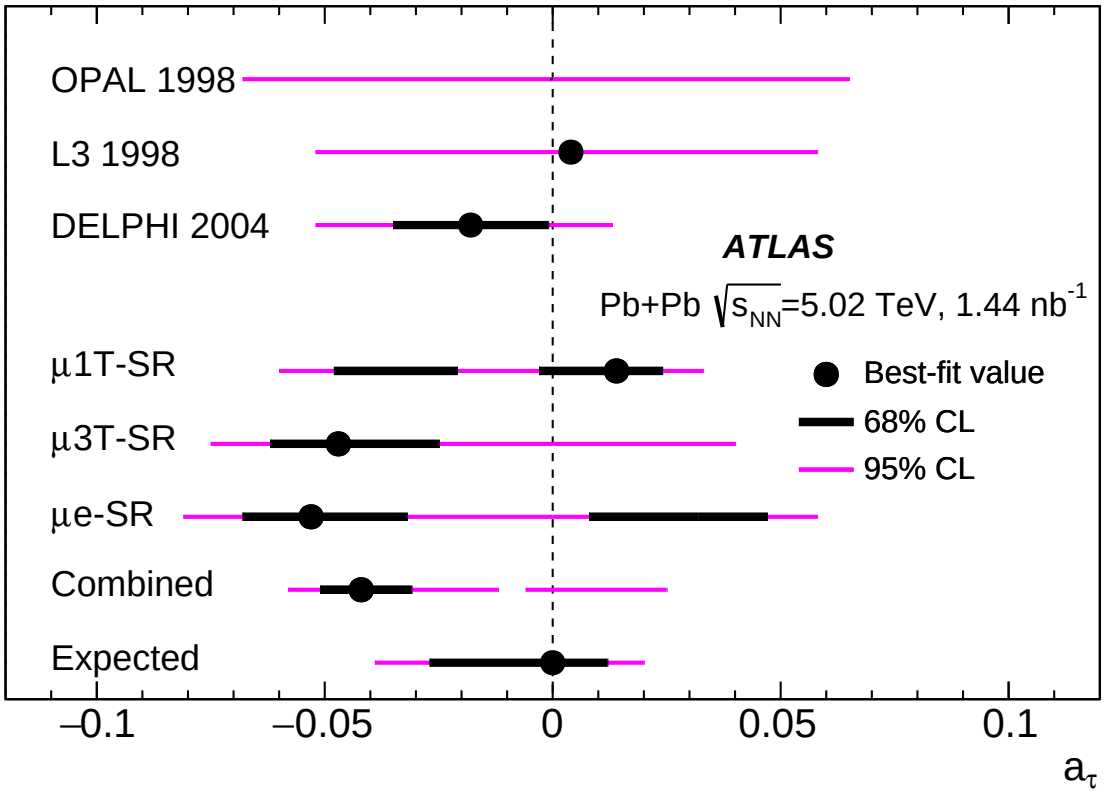
$\gamma\gamma \to \tau\tau$: signal strength



- Fit of $\gamma\gamma \to \tau\tau$ signal strength assuming SM value for a_τ
- Result for each signal region compatible with unity
- Combined fit reaches 5% precision, limited by statistical uncertainties

arXiv:2204.13478

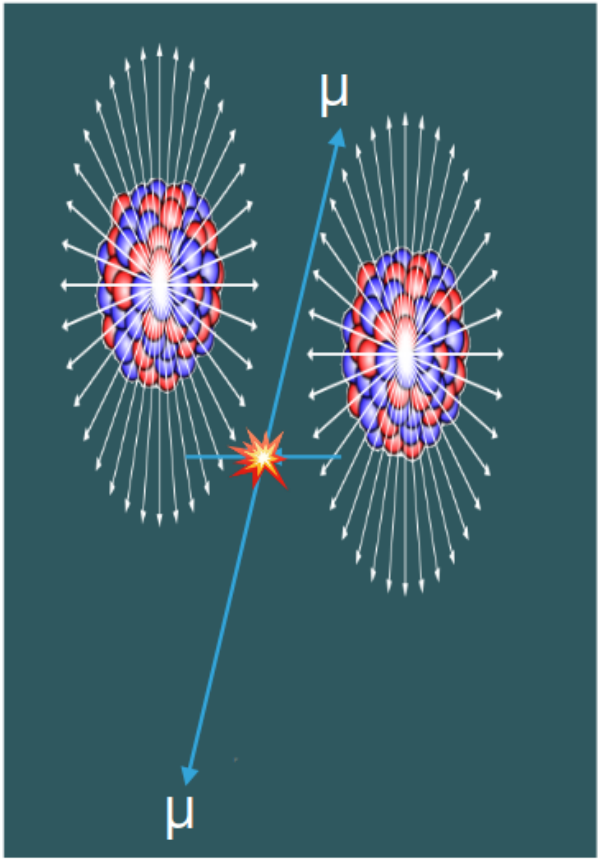
$\gamma\gamma \to \tau\tau$: a_τ

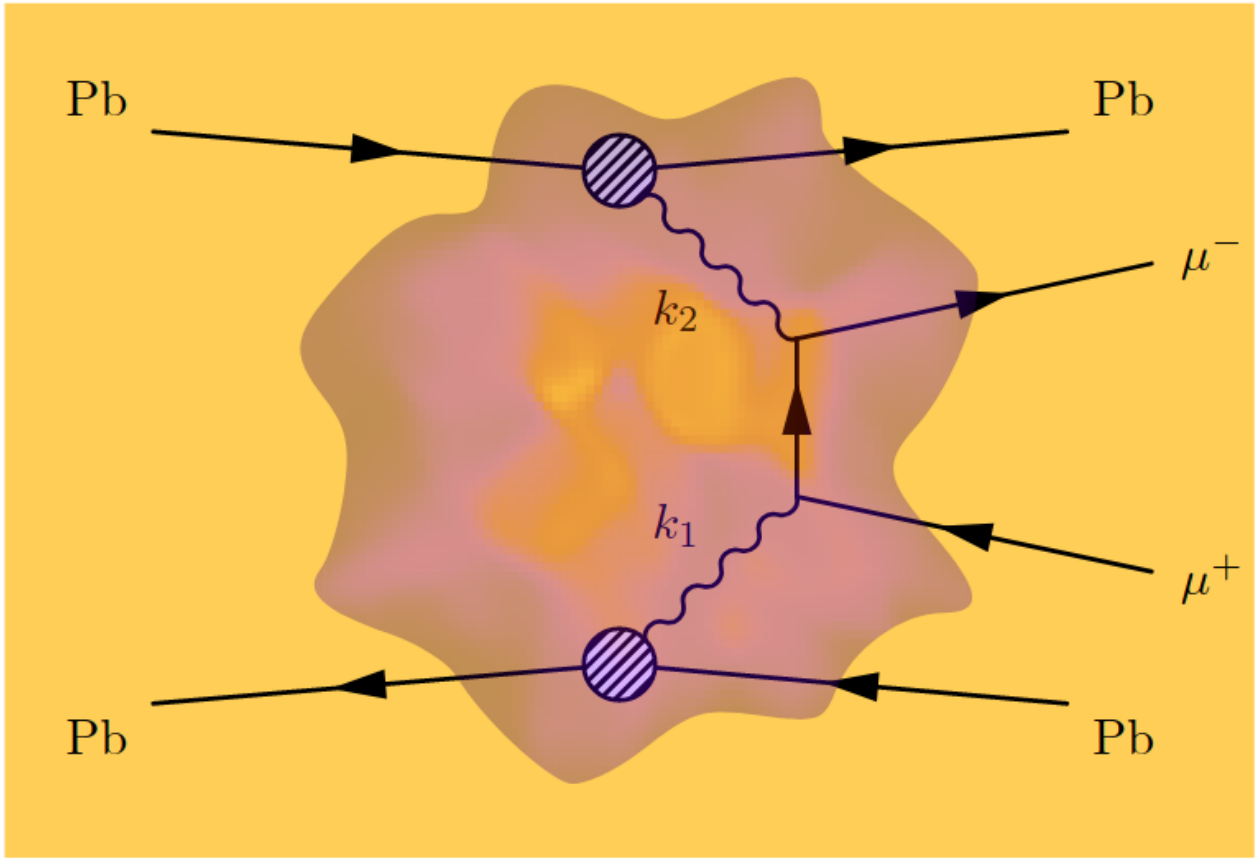


- a_τ from fit to muon p_T distribution in three signal regions
- **Observed 95% CL limits**: $a_\tau \in (-0.058, -0.012) \cup (-0.006, 0.025)$
- First limits on a_τ since LEP era - competitive with DELPHI constraints

arXiv:2204.13478

$\gamma\gamma \to \mu\mu$ in non-UPC collisions





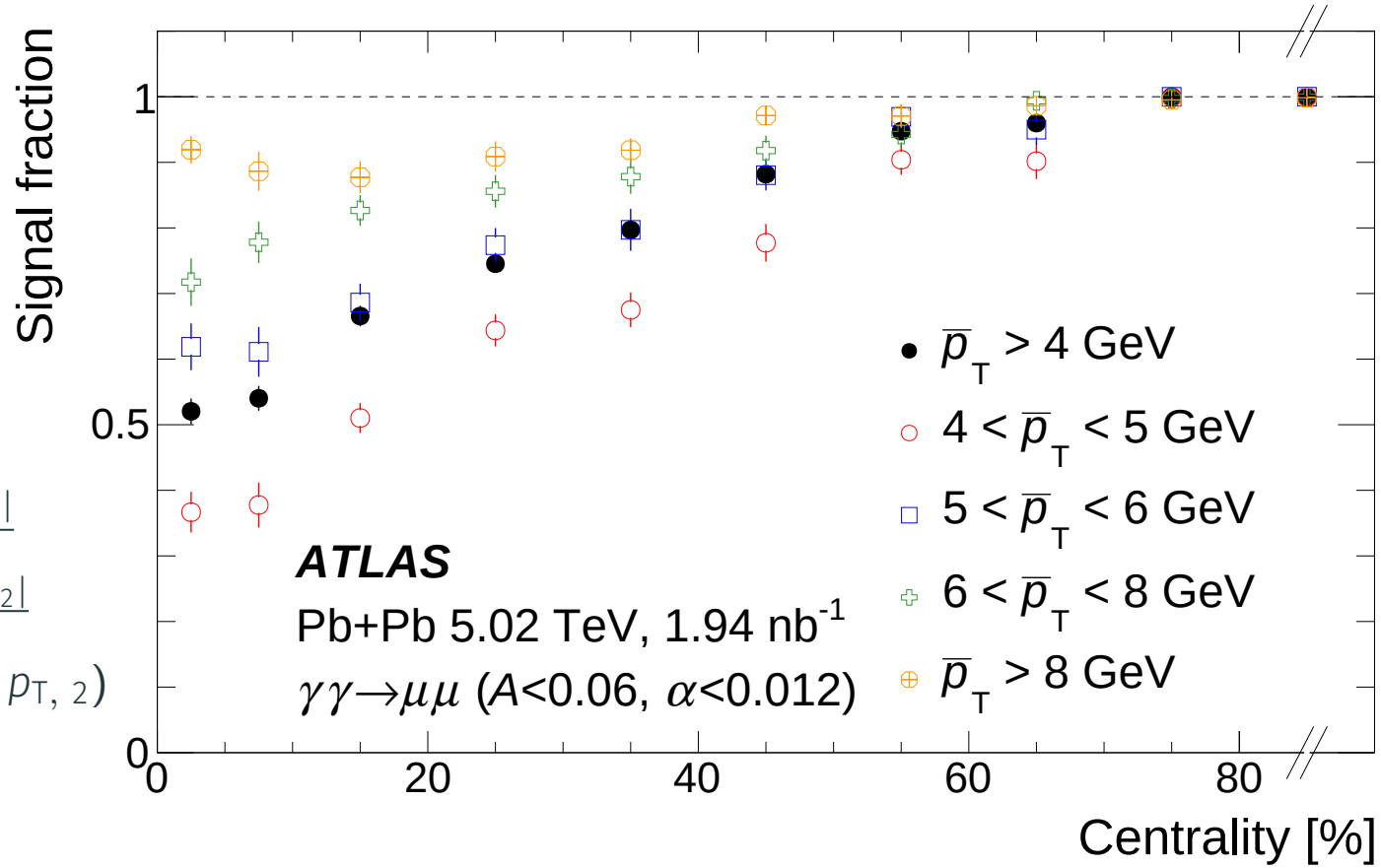
- $\gamma\gamma \to \mu\mu$ process can also be observed in non-UPC collisions
- Are the muons sensitive to initial-state (large B-field) or final-state (QGP) effects?

$\gamma\gamma \to \mu\mu$ in non-UPC collisions: backgrounds

$$A = \frac{|p_{T,1} - p_{T,2}|}{p_{T,1} + p_{T,2}}$$

$$\alpha = 1 - \frac{|\phi_1 - \phi_2|}{\pi}$$

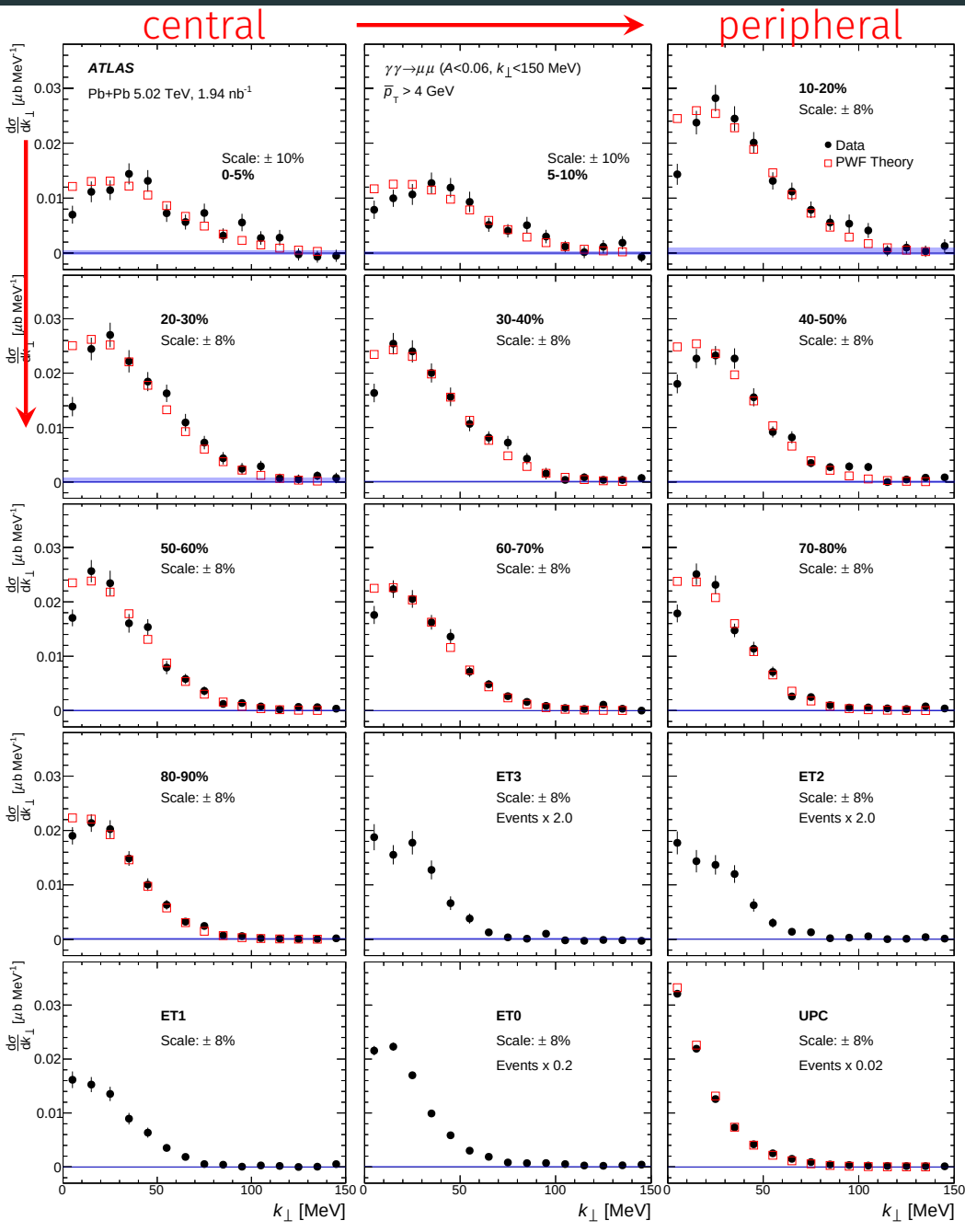
$$\bar{p}_T = \frac{1}{2}(p_{T,1} + p_{T,2})$$



- $\gamma\gamma \to \mu\mu$ events in UPC are almost background-free
- In non-UPC collisions, heavy-flavour and Drell-Yan muons have some contribution, increasing with the collision centrality

arXiv:2206.12594

$\gamma\gamma \to \mu\mu$ in non-UPC collisions: cross-sections



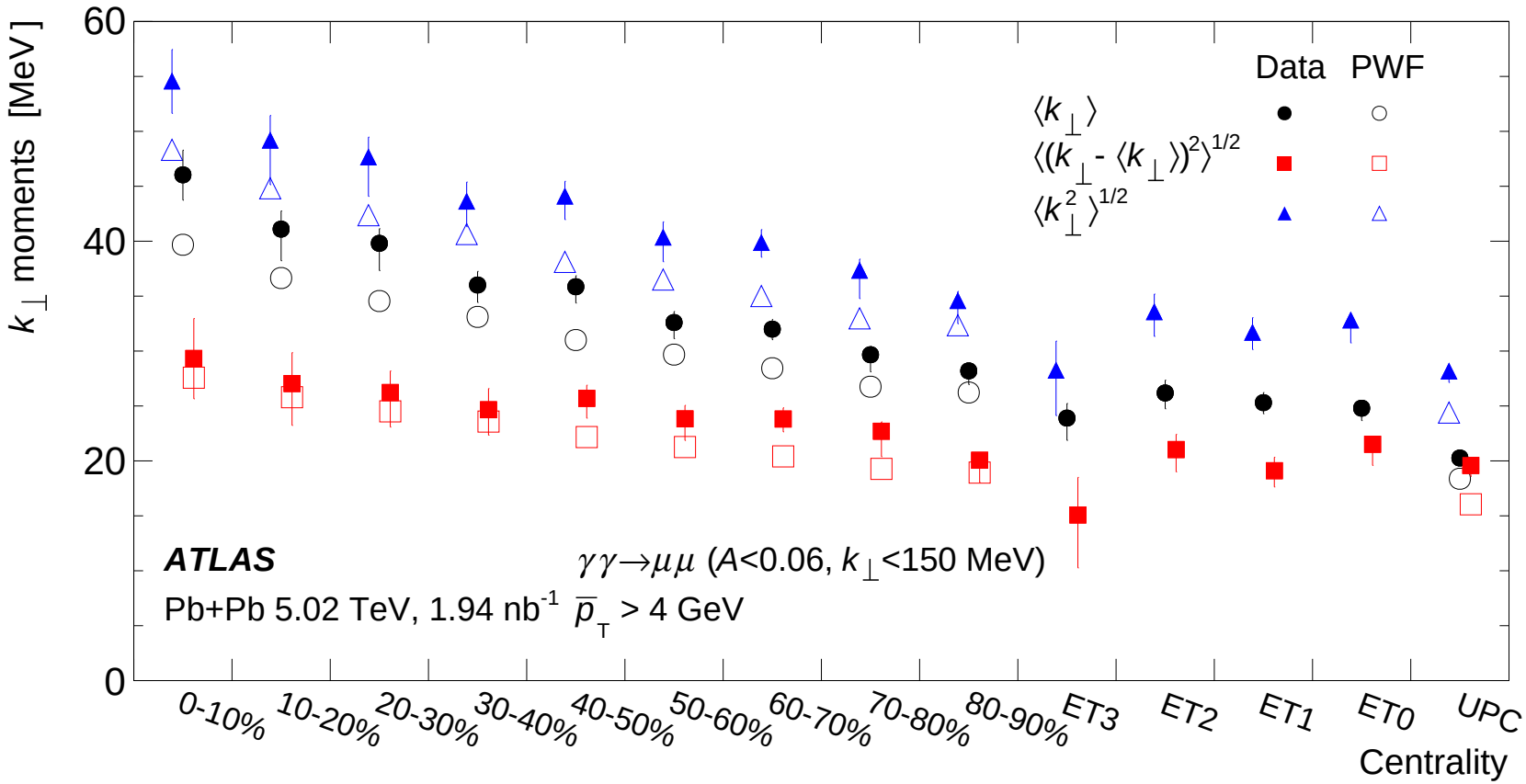
- Centrality-dependent cross-sections differential in:

$$k_\perp = \frac{1}{2}(p_{\mathrm{T},\,1} + p_{\mathrm{T},\,2})(\pi - |\phi_1 - \phi_2|)$$

- Significant broadening and shift of peak position from UPC to central collisions
- Broadening already present in most peripheral events
- Comparison to theoretical calculations using photon Wigner distribution (S. Klein et al.):
  - broadening well reproduced
  - drop at small $k_\perp$ values smaller than in data

arXiv:2206.12594

$\gamma\gamma \to \mu\mu$ in non-UPC collisions: distribution moments

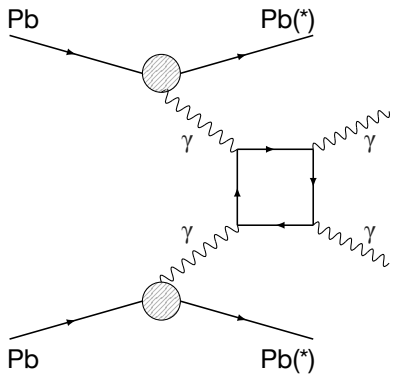


- Steady increase of mean and RMS from UPC to central collisions
- Trends reproduced by theoretical calculations, but with systematic shifts compared to data

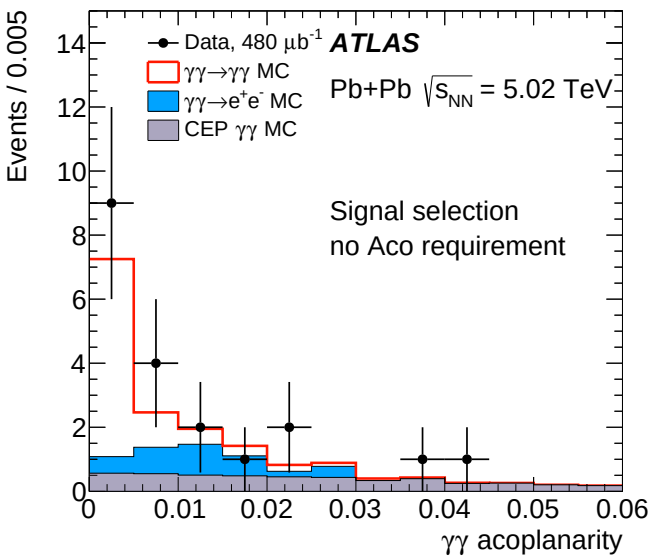
arXiv:2206.12594

$\gamma\gamma \to \gamma\gamma$

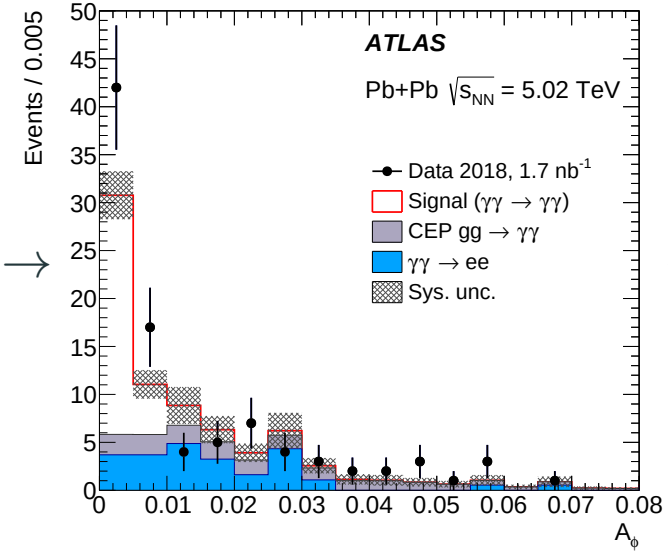
- Light-by-light scattering: key example of rare SM process probed in UPC
- Not allowed clasically, but possible in QED at $O(\alpha^4)$
- Evolving level of understanding of the process:
  - 2015 data $\to$ evidence at 4.4σ (also CMS result: 4.1σ)
  - 2018 data $\to$ first observation at 8.2σ
  - **2015+18 data $\to$ differential cross-sections**



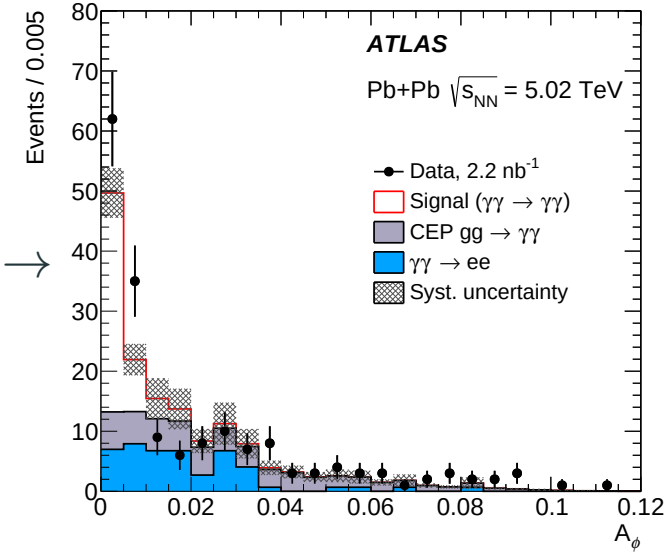
2015 data



2018 data



2015+18 data



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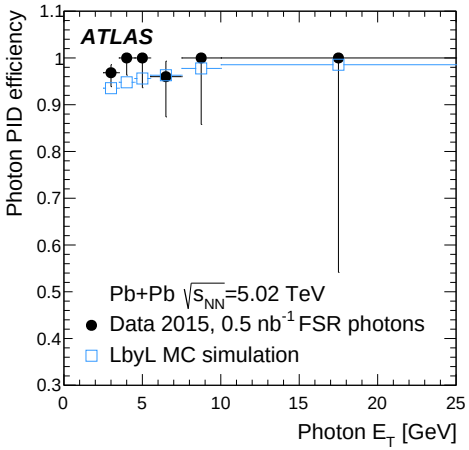
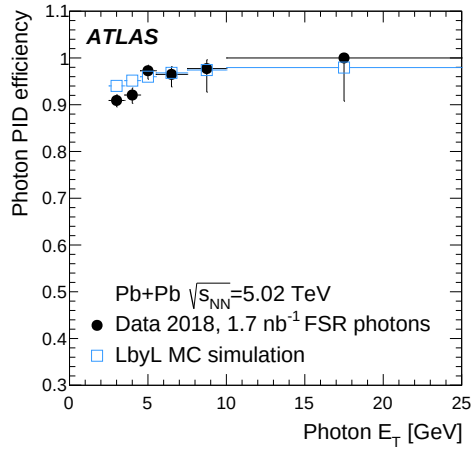
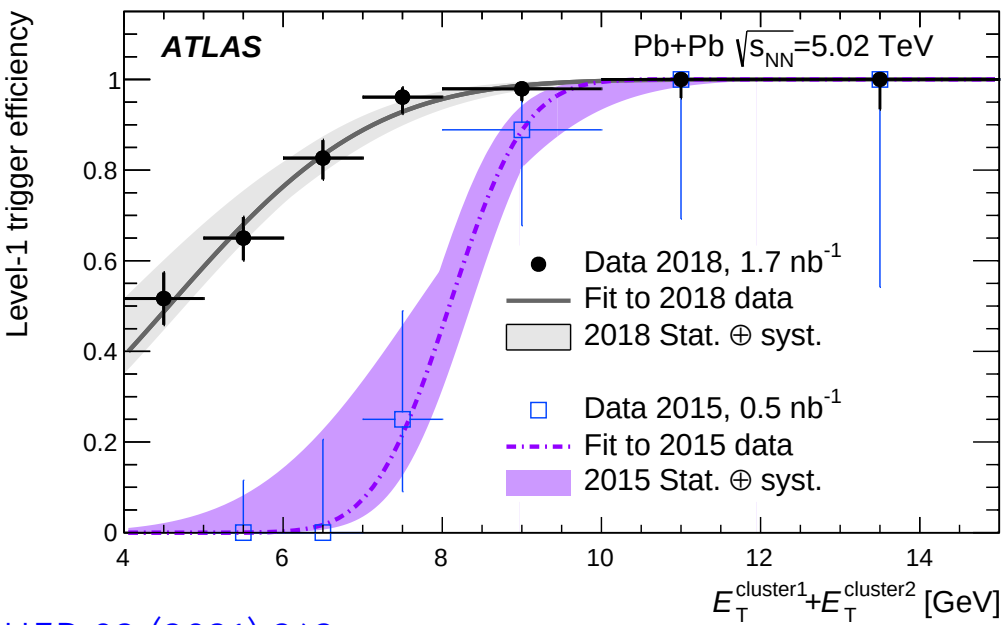
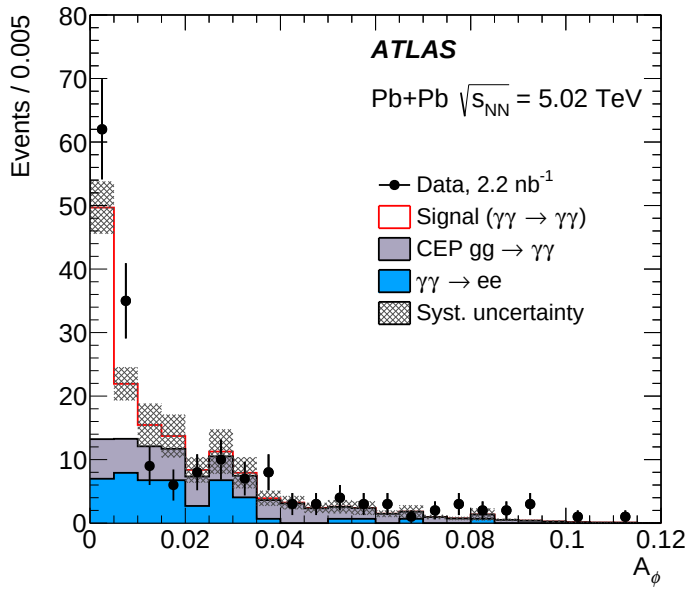
$\gamma\gamma \to \gamma\gamma$: analysis

- Event selection: 2 photons with $E_{\mathrm{T}}^{\gamma} > 2.5$ GeV, $A_{\phi}^{\gamma\gamma} < 0.01$, no tracks
- Dedicated triggers (with large improvements for 2018 data-taking)
- NN PID optimised for low-p_{T} photons
- Background estimates:
  - CEP $gg \to \gamma\gamma$ (data-driven)
  - $\gamma\gamma \to ee$ with mis-identified electrons (MC)









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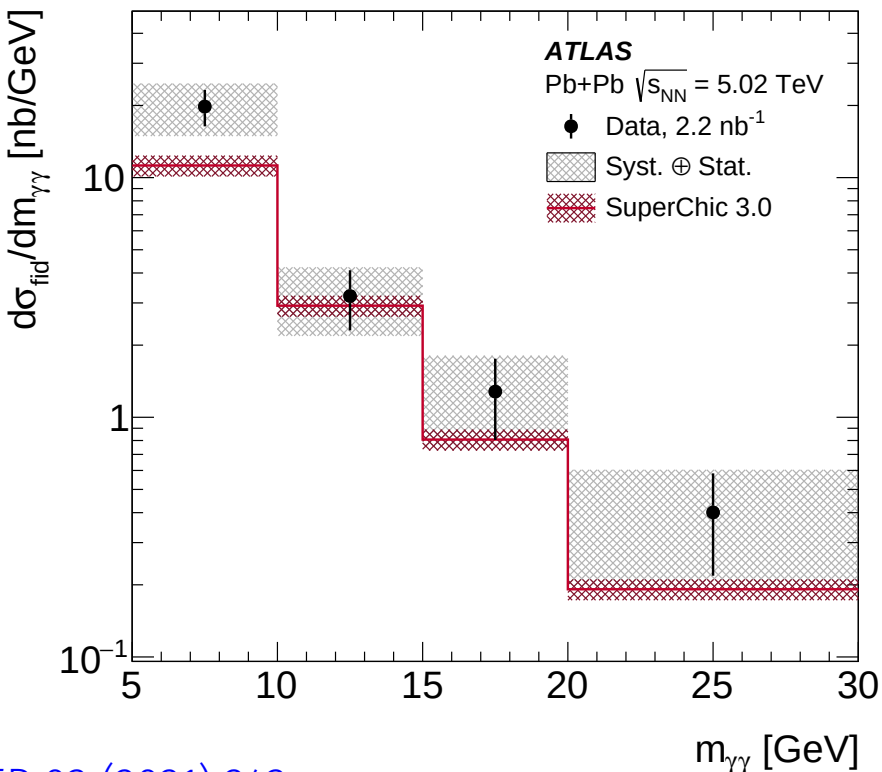
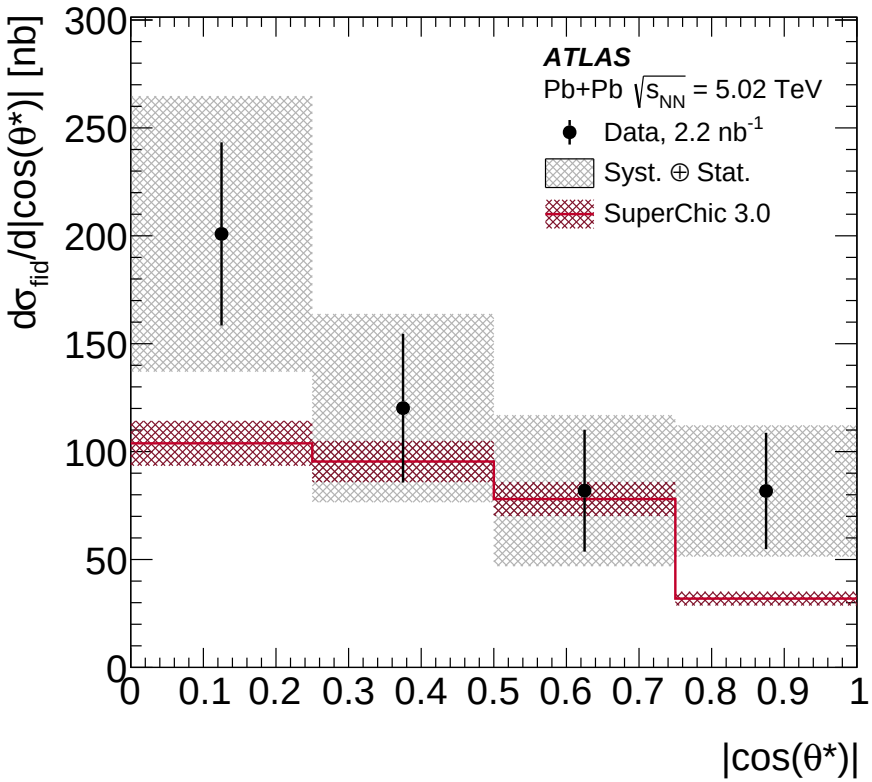
$\gamma\gamma \to \gamma\gamma$: cross-sections

- Fiducial cross-section: 120 ± 17 (stat) ± 13 (syst) ± 4 (lumi) nb
- Compare to theoretical predictions:
  - 80 ± 8 nb (M. Kłusek-Gawenda et al.)
  - 78 ± 8 nb (SuperChic 3)
- Cross-sections measured differentially in $m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, p_{T}^{γ}, $|\cos\theta^*|$
  - reasonably good agreement of distribution shapes with SuperChic 3 predictions





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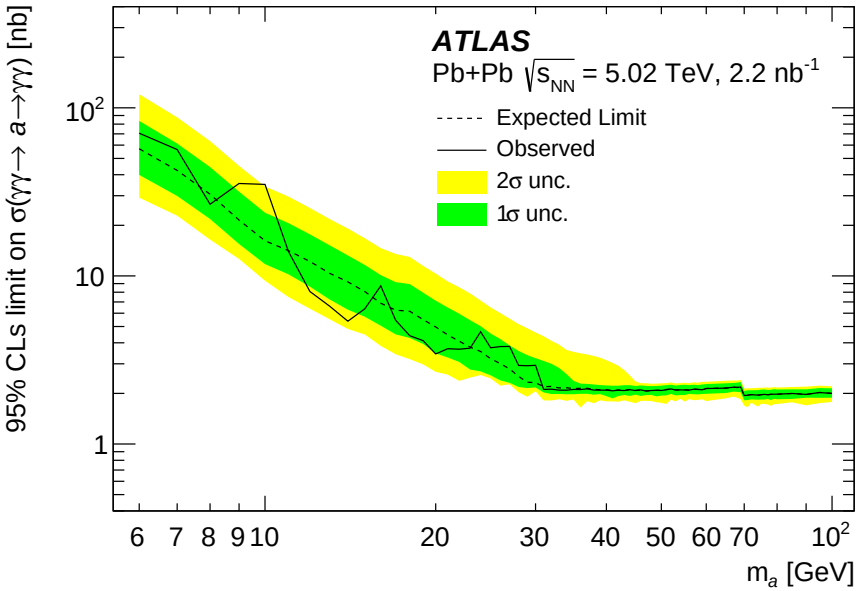
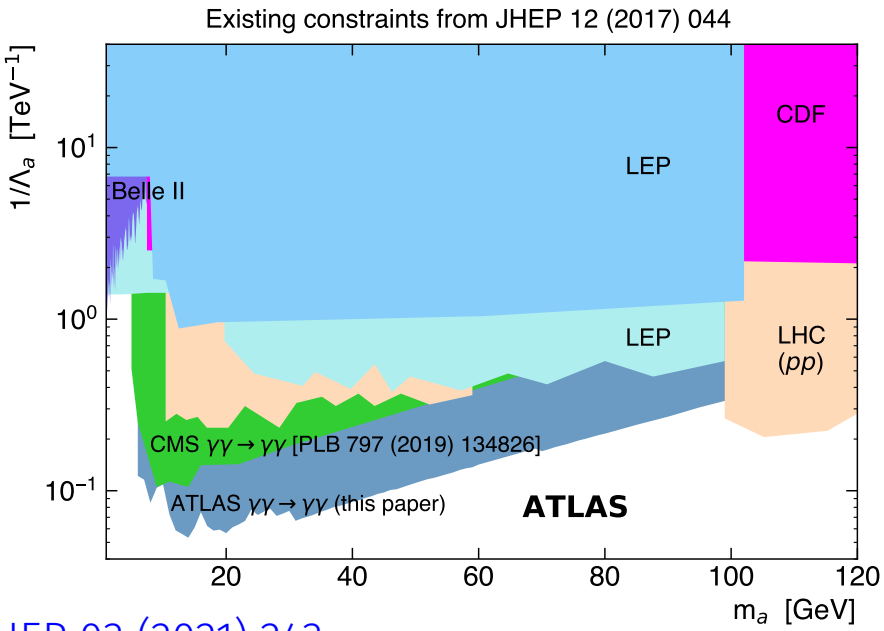
$\gamma\gamma \to \gamma\gamma$: search for axion-like particles





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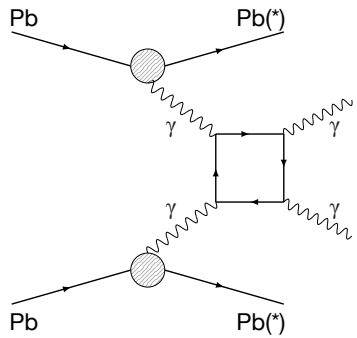
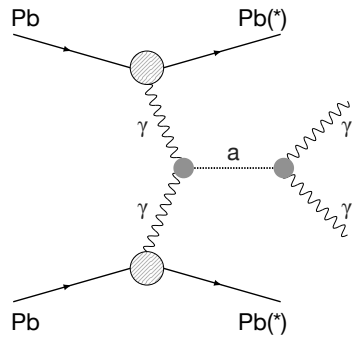
SM: loops

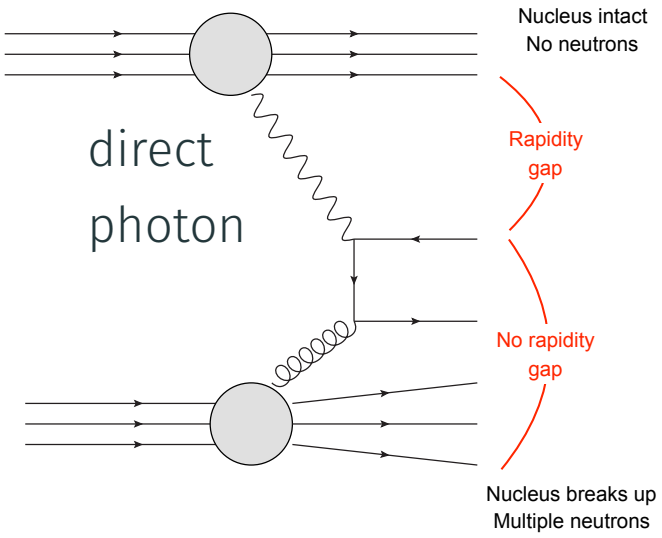


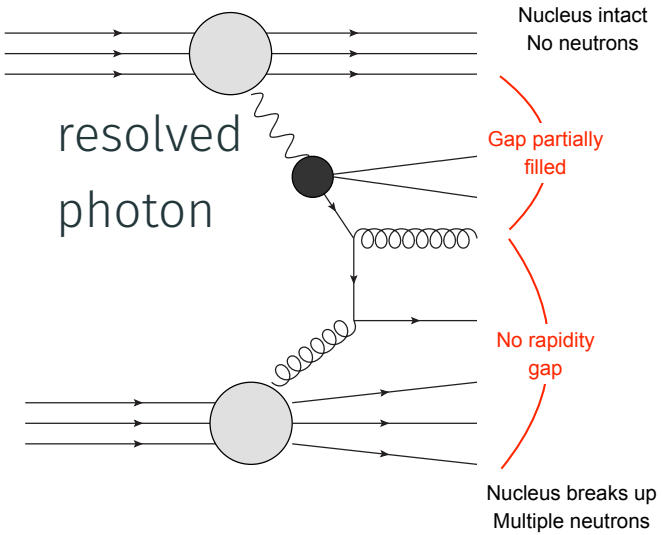
ALPs: s-channel



- Axion-like particles can couple to photons in initial- and final-state of $\gamma\gamma \to \gamma\gamma$
- No significant deviation from SM
- Setting 95% CL limits on:
  - cross-section σ
  - coupling $1/\Lambda_a$
- Most stringent limits in the mass range $6 < m_a < 100$ GeV

$\gamma + A$: global properties

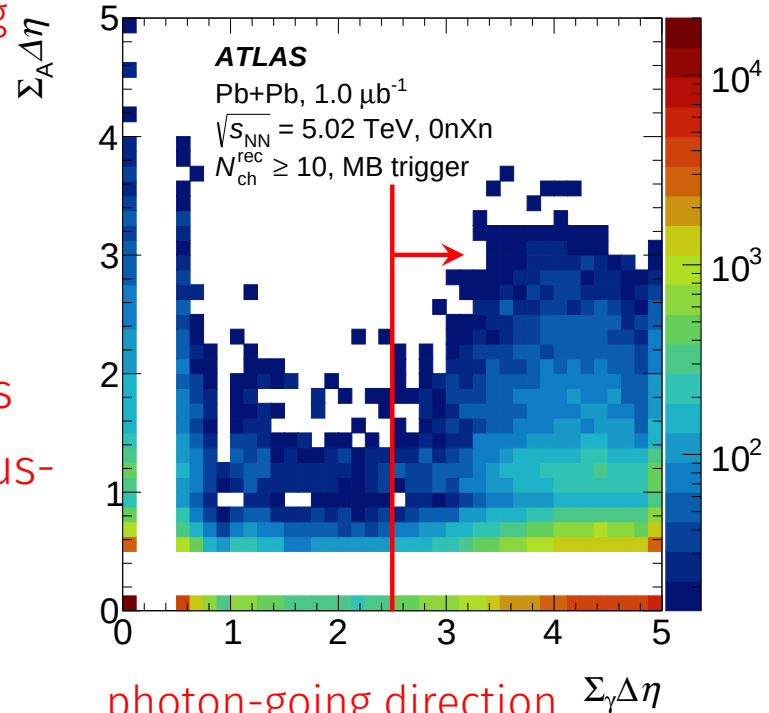




- Photon expected to fluctuate into quark-antiquark pair
- Small systems like $p + \mathrm{Pb}$ and pp exhibit signals of collectivity - what about $\gamma + \mathrm{A}$ processes?
- Expect forward neutron emissions from break-up of struck nucleus $\rightarrow$ 0nXn ZDC events

nucleus-going direction

sum of gaps between clusters/tracks ($\Delta\eta > 0.5$)



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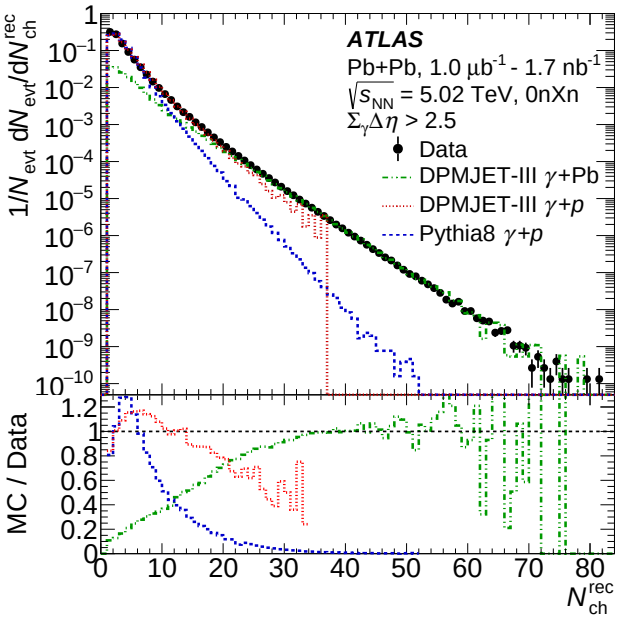
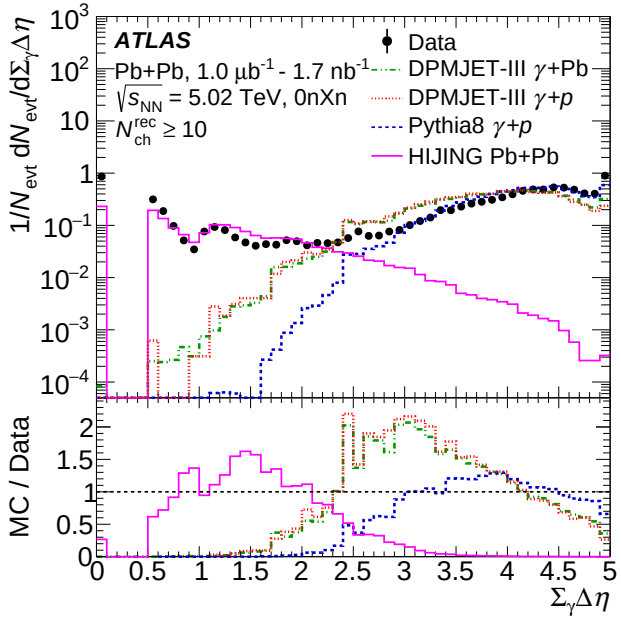
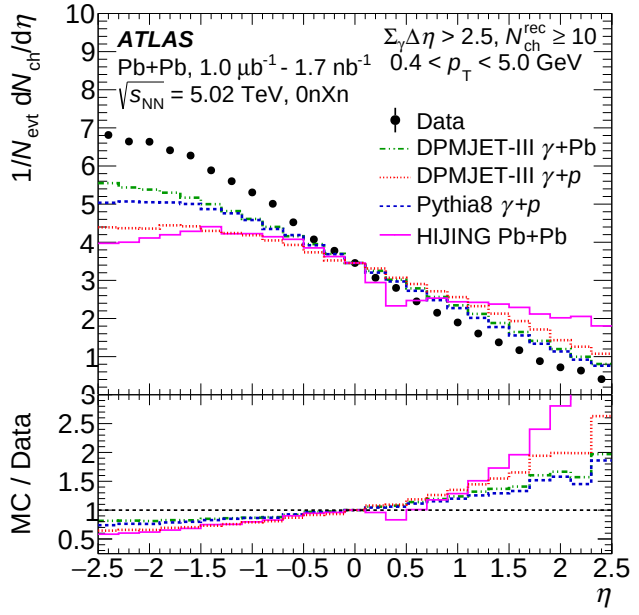
$\gamma + A$: event characteristics







- Event characteristics of min-bias $\gamma + A$ events not studied much previously
- **Track multiplicity**: fairly good description at low values by DPMJET-III and Pythia8 $\gamma + p$, tail better described by DPMJET-III $\gamma +$ Pb
- **Photon-direction sum of gaps**: reasonable agreement with sum of peripheral HIJING Pb+Pb and DPMJET-III $\gamma +$ Pb
- **Track signed rapidity**: distribution strongly skewed towards nucleus-going direction (negative η), all generator setups fail to reproduce steep slope

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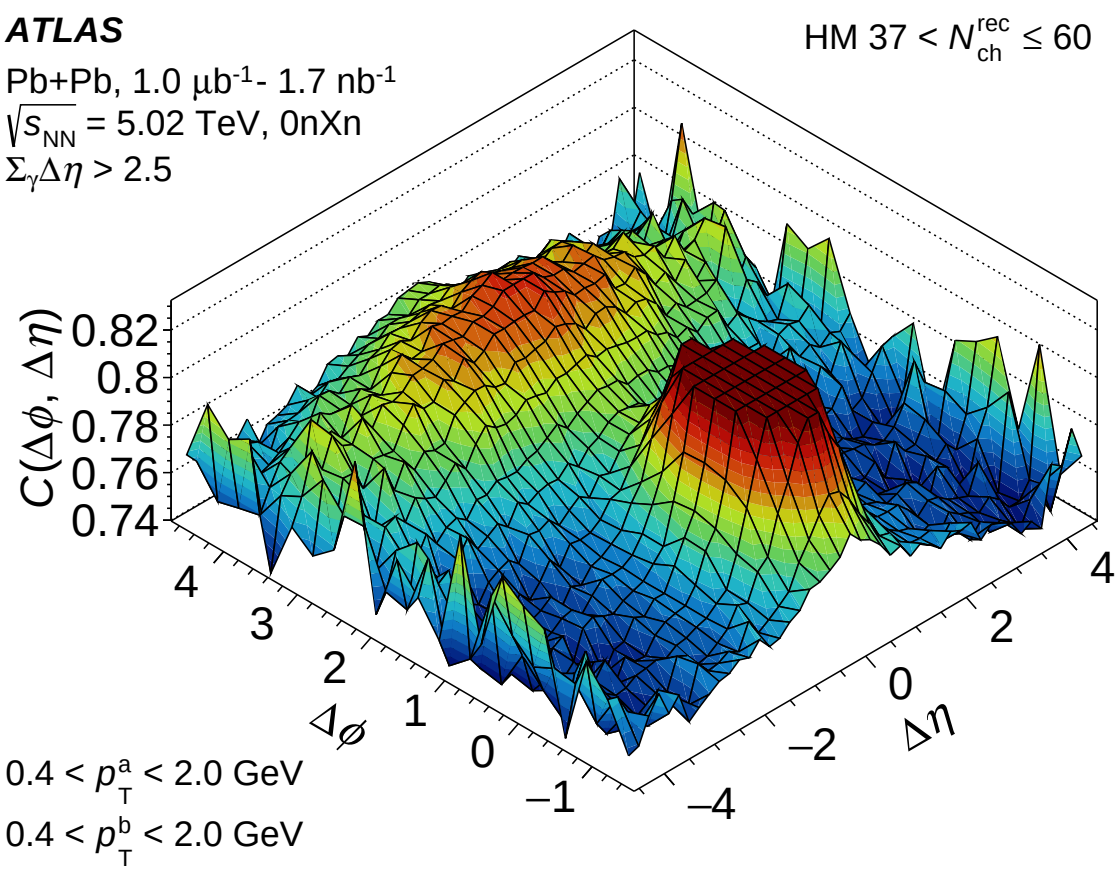
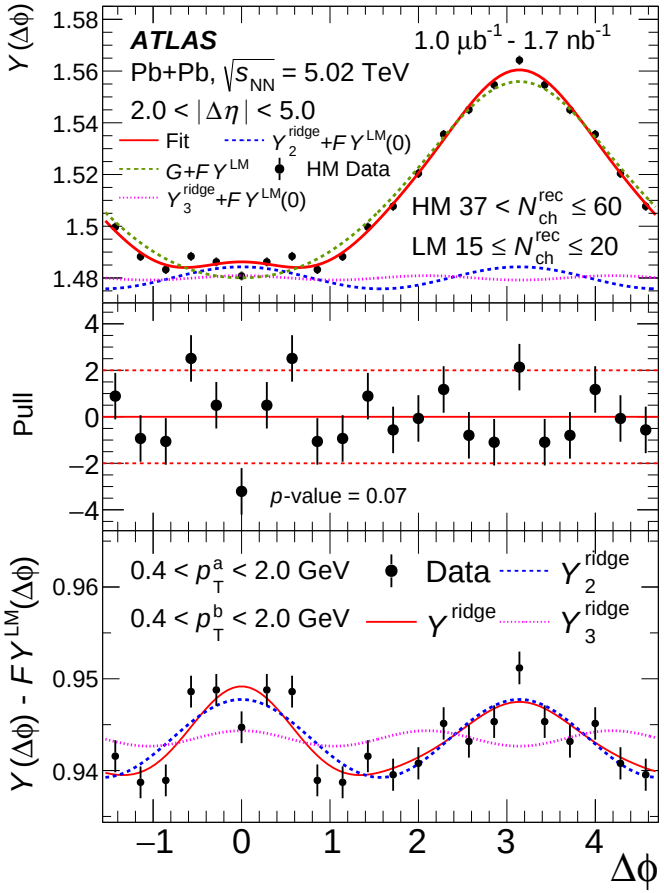
$\gamma + A$: looking for collectivity





- Correlations between charged particles studied as a function of $\Delta\eta$ and $\Delta\phi$
- Template method used to extract flow coefficients, with non-flow contributions subtracted using low-multiplicity events

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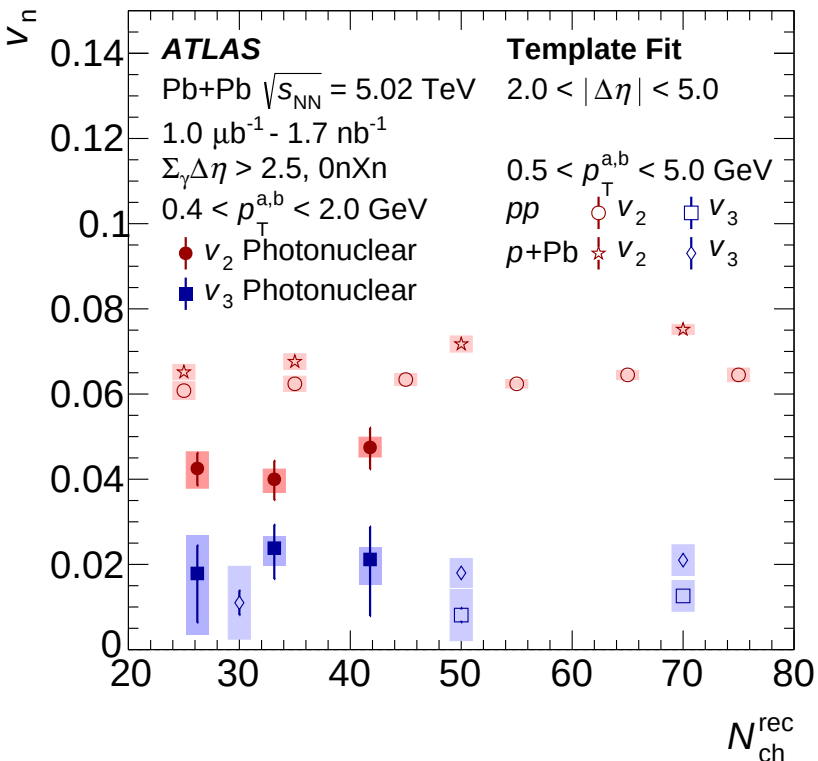
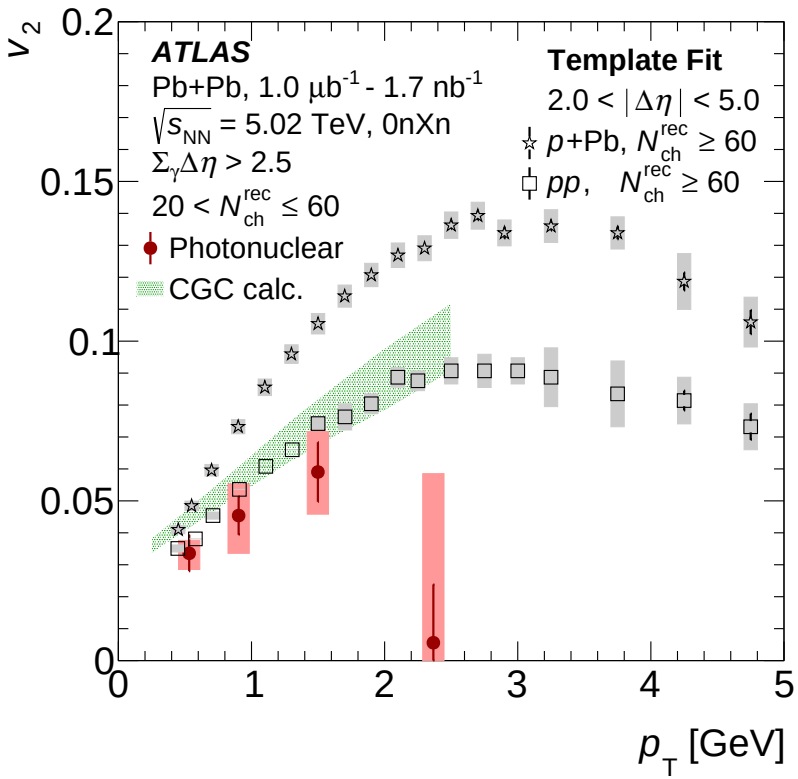
$\gamma + A$: flow coefficients

- Significant v_2 observed, lower than in pp or $p + \text{Pb}$ collisions
- Non-zero v_3 values, compatible with pp and $p + \text{Pb}$ collisions
- Both v_2 and v_3 show no significant multiplicity dependence
- CGC calculation (Y. Shi et al.) of v_2 considering interactions of a color dipole (γ fluctuation) with a Pb nucleus: prediction slightly higher than data





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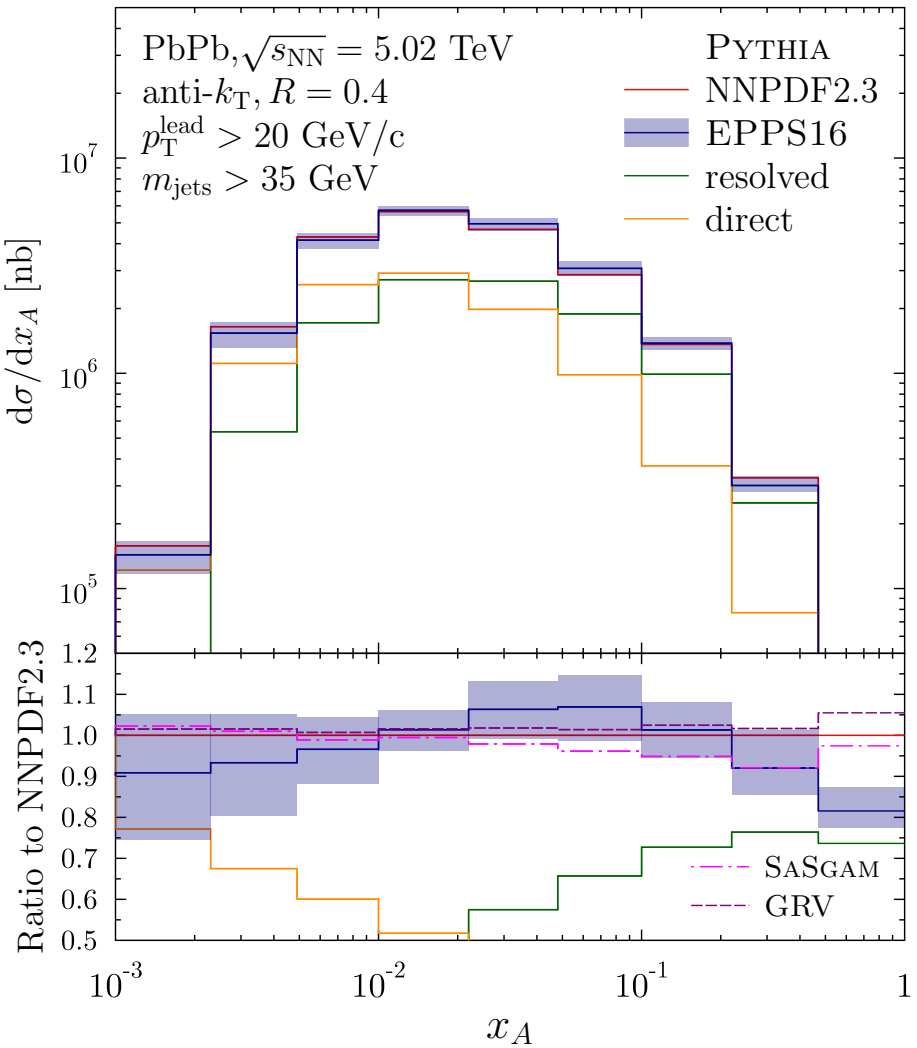
$\gamma + \mathrm{A}$: dijet production and nPDFs

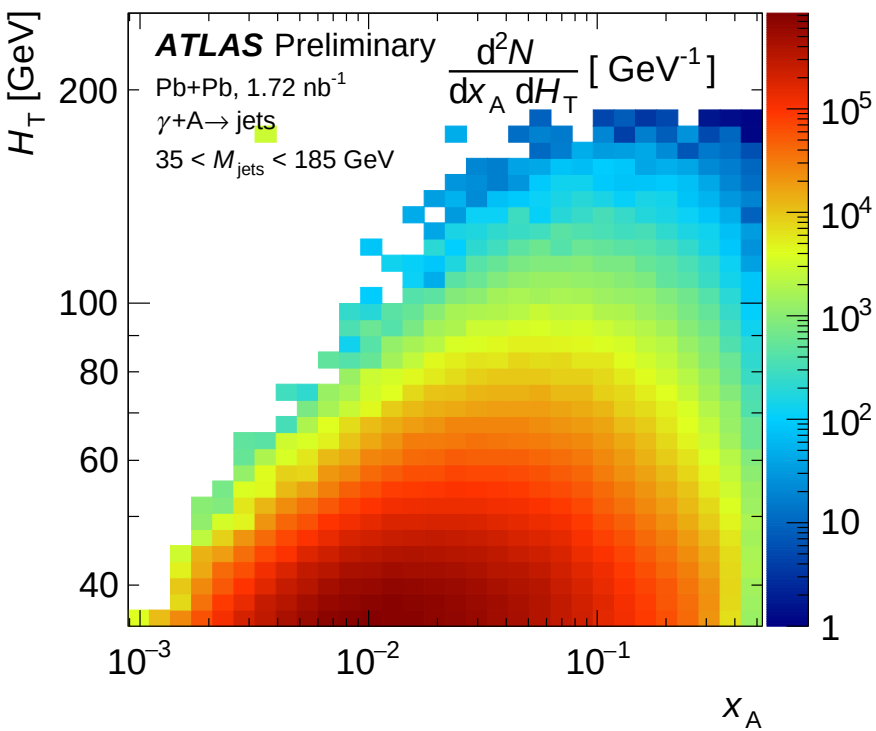


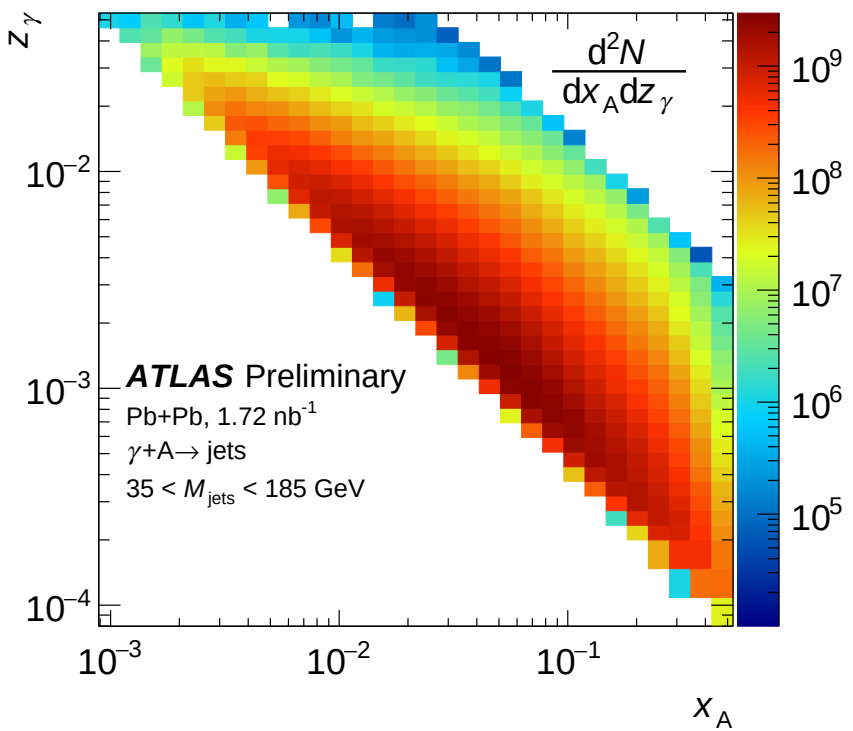
- Precise measurements of various processes in nuclear interactions require good understanding of nuclear parton distribution functions (nPDF)
- Poor nPDF constraints at low x and intermediate Q^2 ($100 < Q^2 < 1000$ GeV)
- $\gamma + \mathrm{A}$ dijet production $\rightarrow$ clean, DIS-like probe of this kinematic region
- Sensitivity studies by I. Helenius (2018): constraints potentially down to $x \sim 10^{-4}$
- Measurement of triple-differential cross-sections:
  - $H_{\mathrm{T}} = \sum p_{\mathrm{T}}^{\mathrm{jet}}$ (proxy for Q)
  - $x_{\mathrm{A}} = \frac{m_{\mathrm{jets}} e^{-y_{\mathrm{jets}}}}{\sqrt{s_{\mathrm{NN}}}}$
  - $z_{\gamma} = \frac{m_{\mathrm{jets}} e^{+y_{\mathrm{jets}}}}{\sqrt{s_{\mathrm{NN}}}}$

I. Helenius, PoS HardProbes2018

$\gamma + \mathrm{A}$: dijet kinematic coverage

- Requiring $R = 0.4$ particle-flow jets with $p_{\mathrm{T}} > 15$ GeV, $|\eta| < 4.4$
- Selecting events with 0nXn ZDC, $\sum_{\gamma} \Delta\eta > 2.5$, $35 < m_{\mathrm{jets}} < 185$ GeV
- H_{T} does not depend significantly on x_{A} or z_{γ}
- x_{A} and z_{γ} highly correlated $\rightarrow$ acceptance effects





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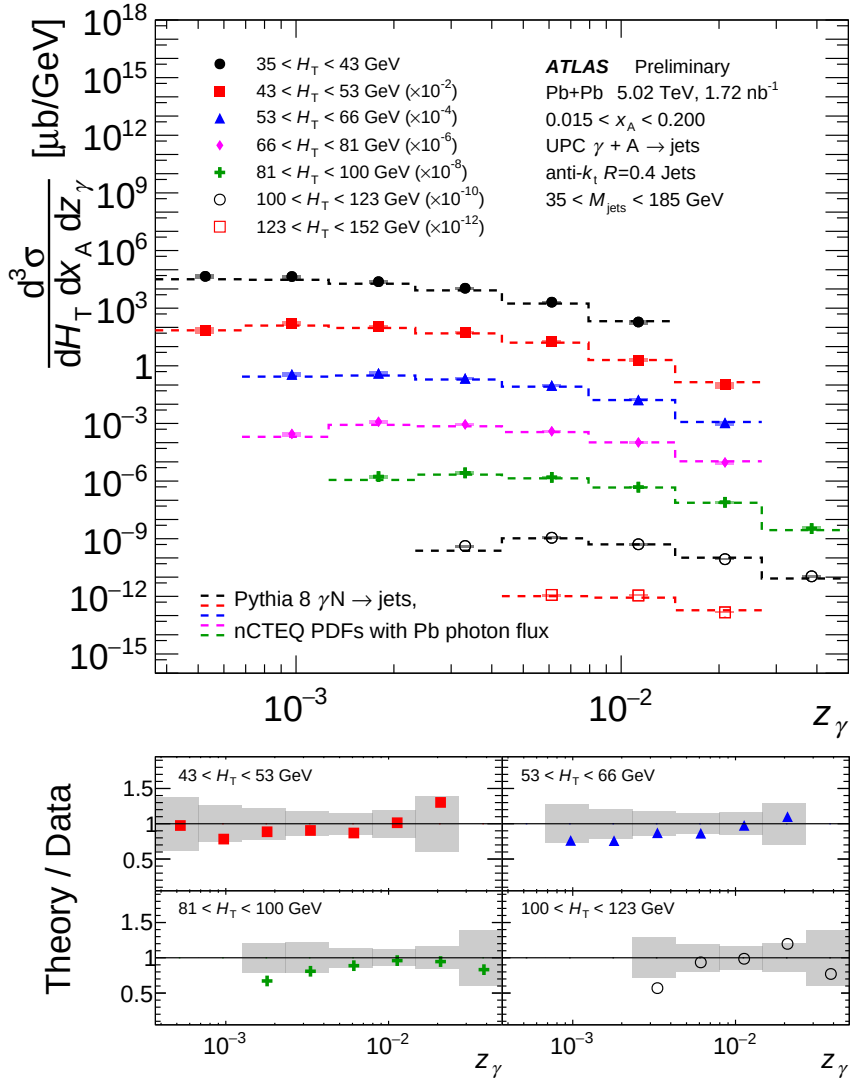
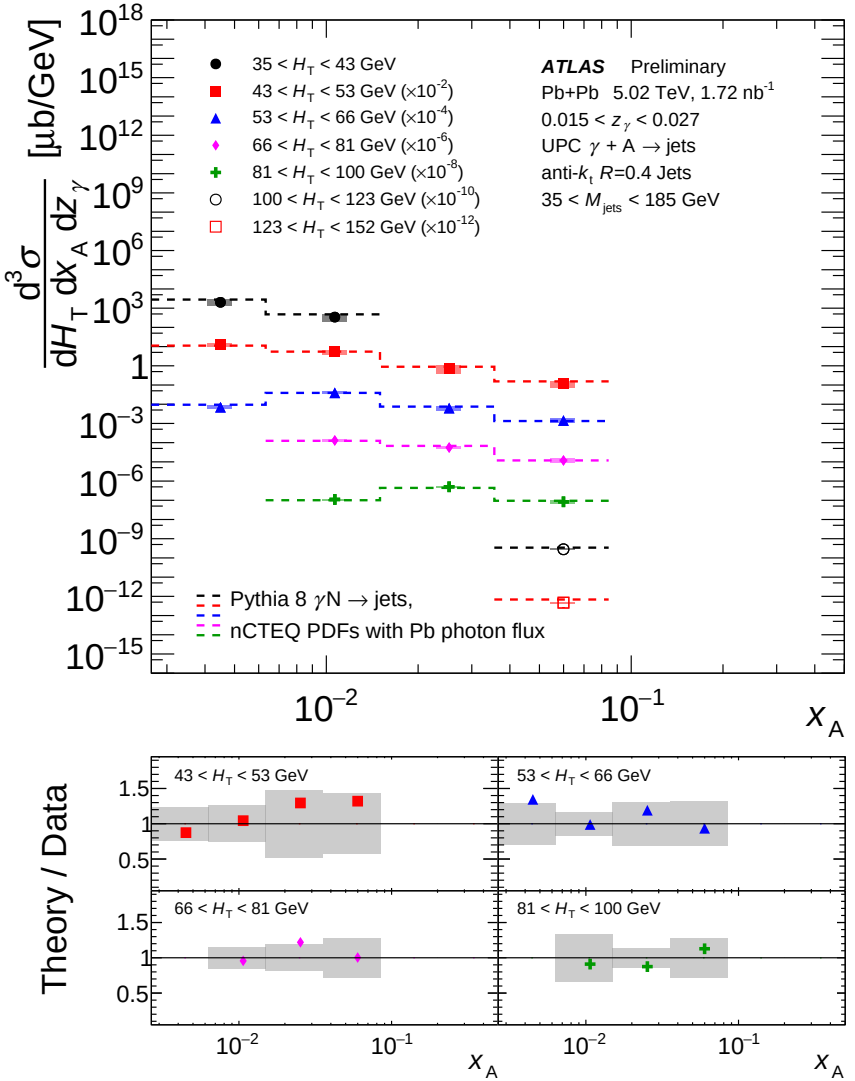
$\gamma + A$: dijet cross-sections

measured photon flux



access to low x with high z_γ



- Good description by Pythia8 with Pb photon flux and nCTEQ PDFs

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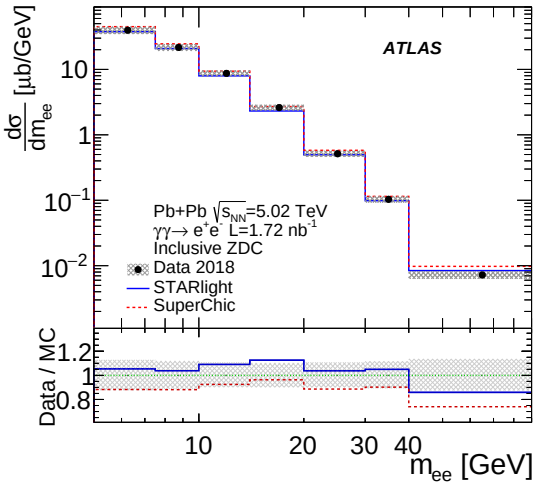
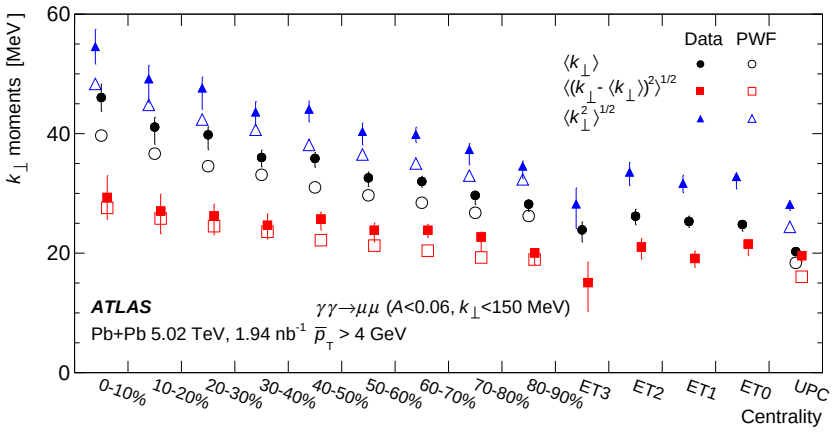
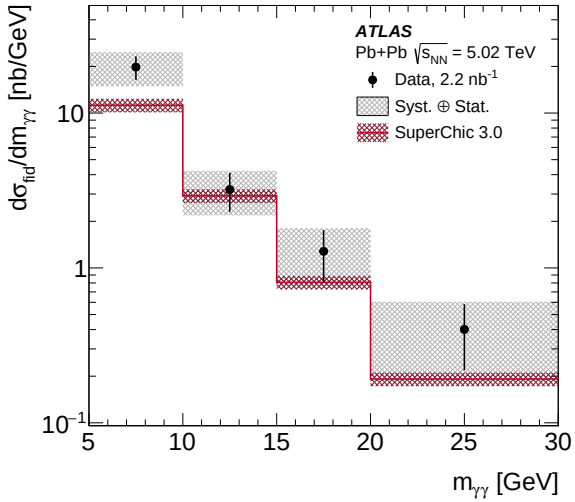
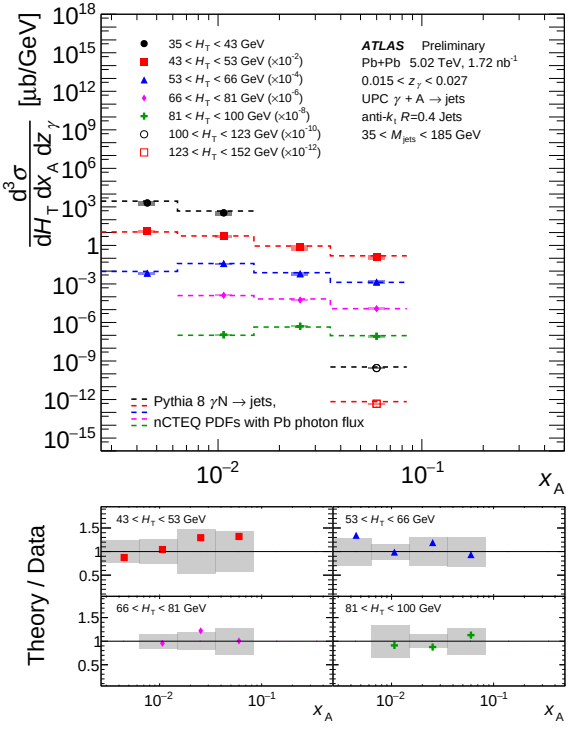
Summary

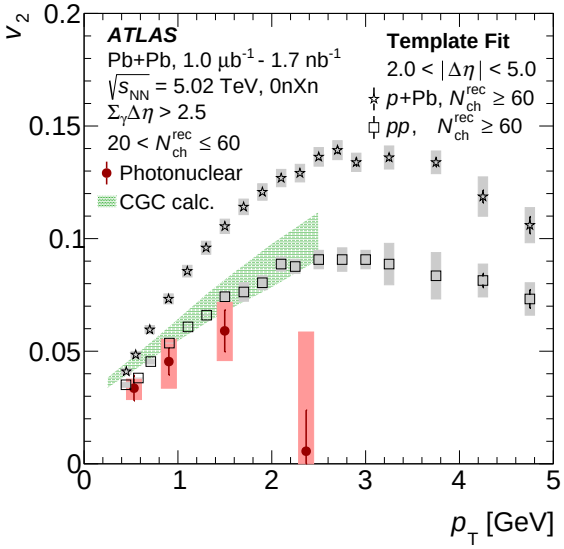
ATLAS has a rich and diverse UPC physics program - stay tuned for new results!

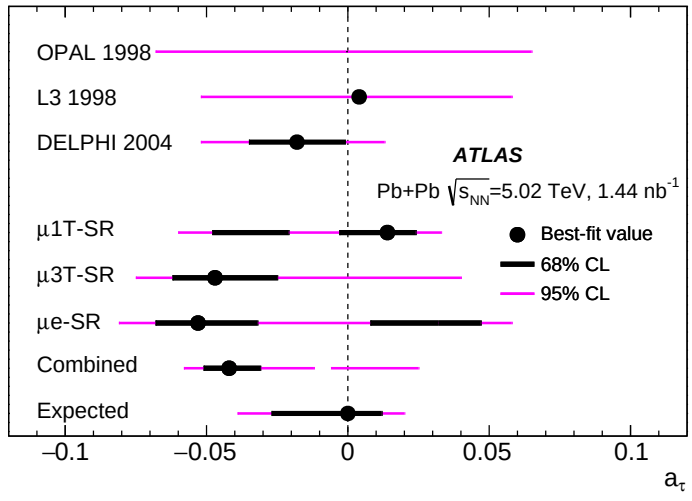












see also talks by Lydia and Agnieszka!