UPC 2023 First international workshop on the physics of Ultra Peripheral Collisions

Recent results from ultra-peripheral lead-lead collisions with ATLAS

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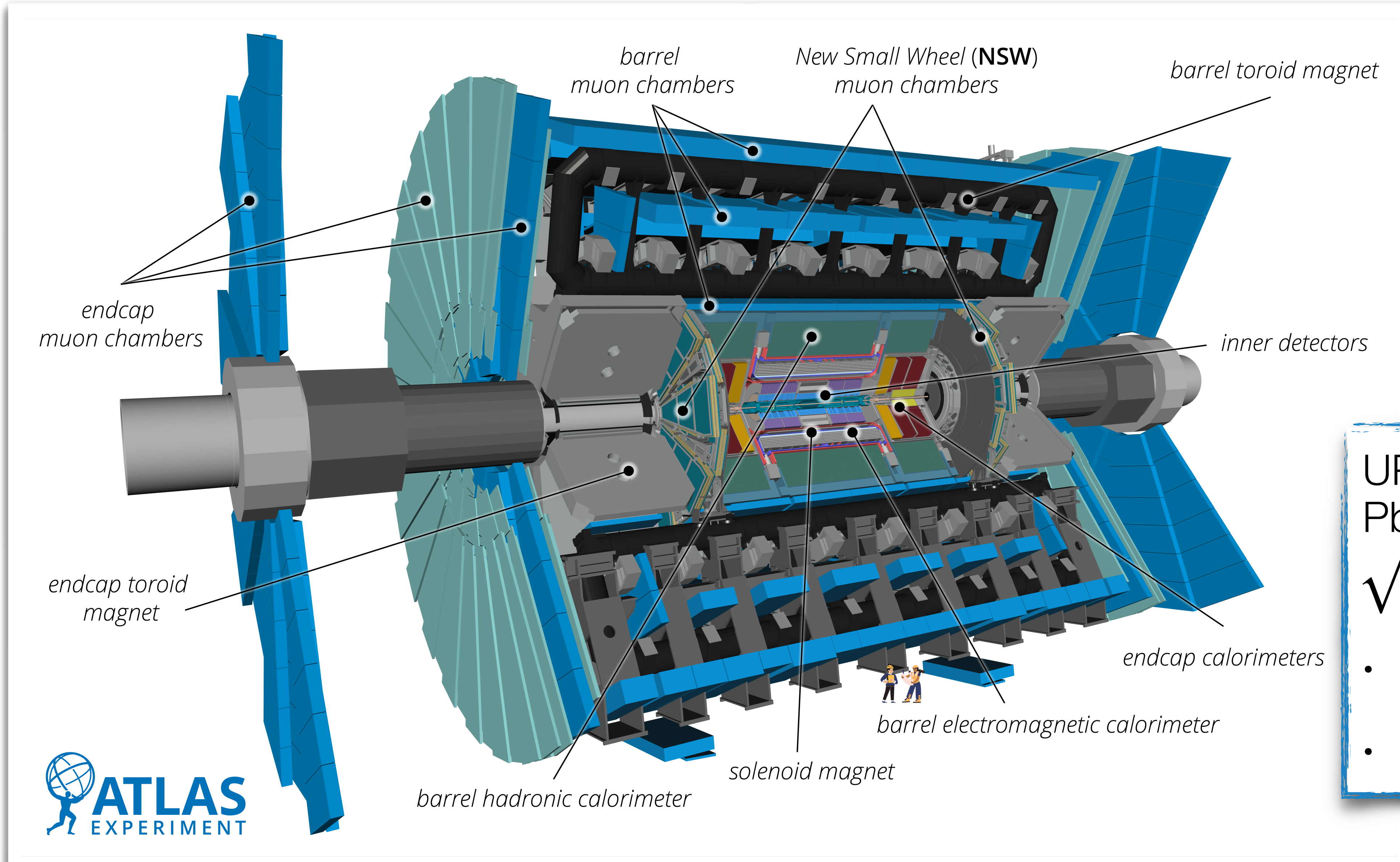
for ATLAS Collaboration
Playa del Carmen, 11 Dec 2023

ATLAS detector



44m long
22m tall

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

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)

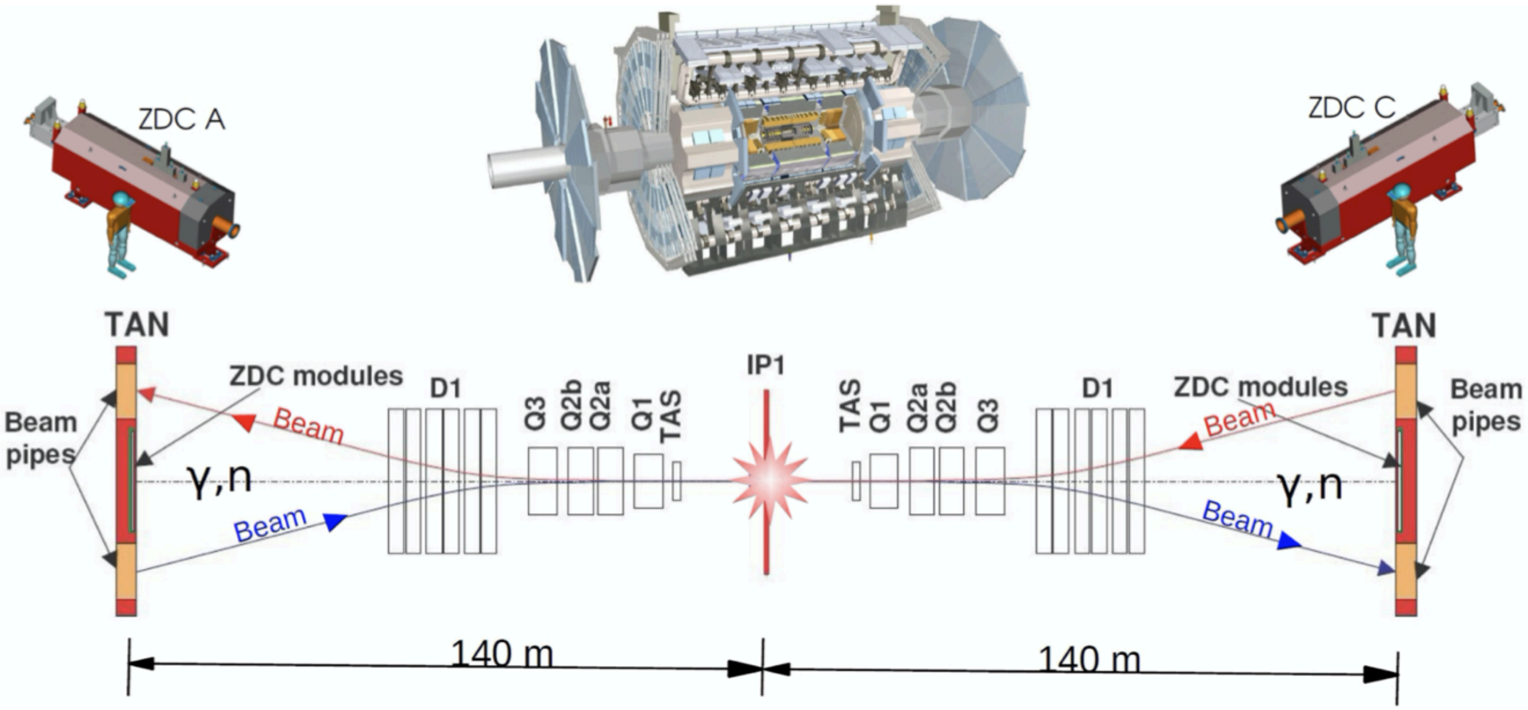
Charged particle tracking in $|\eta| < 2.5$ → electrons, muons, charged hadrons

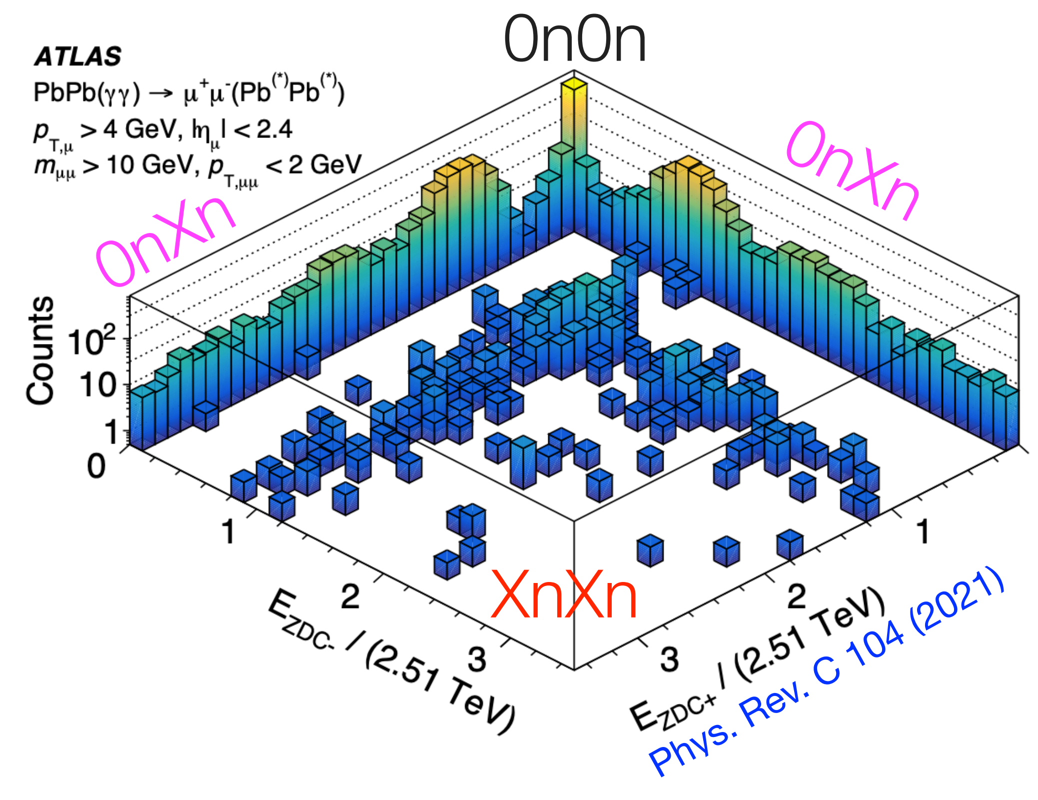
Calorimeter system in $|\eta| < 4.9$ → electrons, photons, jets

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

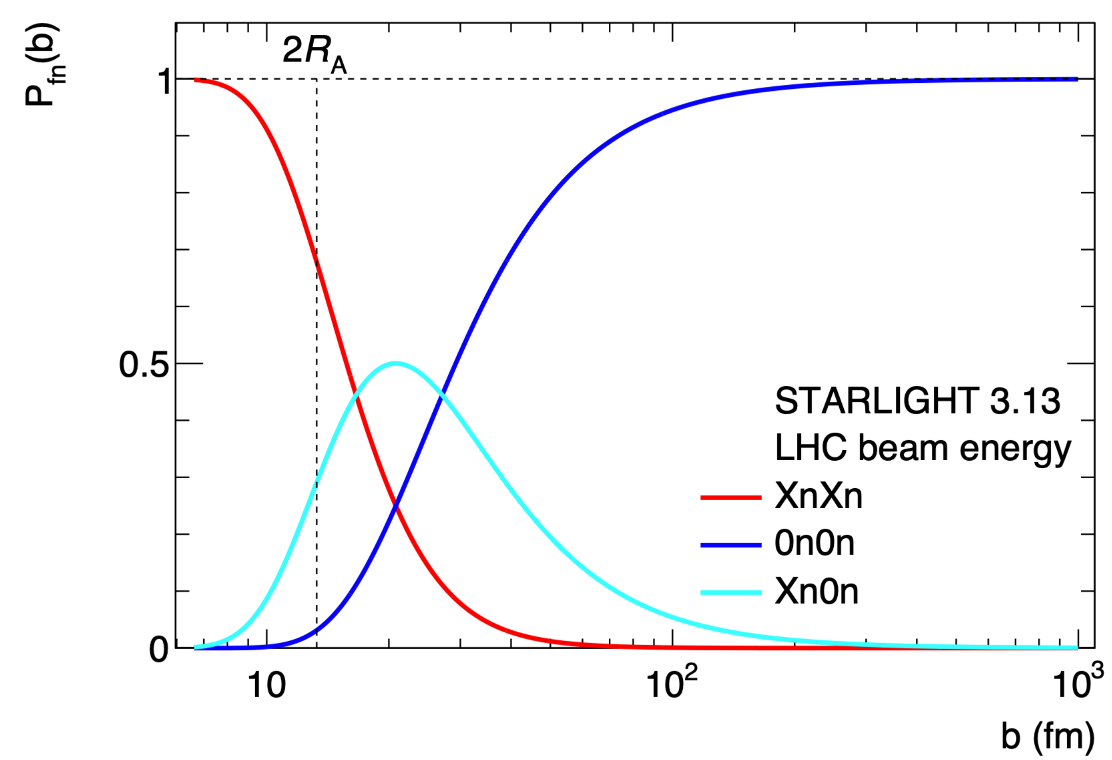
All components used in UPC measurements

Zero Degree Calorimeters (ZDC)





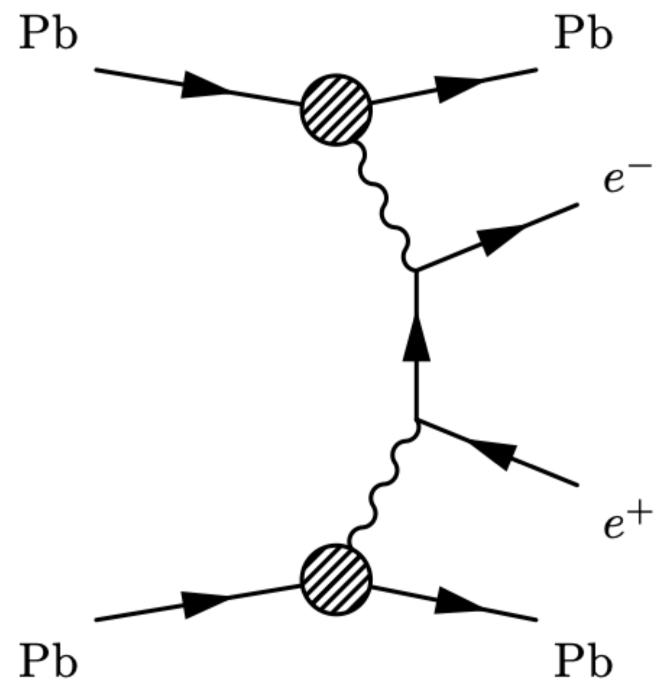
- ZDC are 140 m away from the IP (|η|> 8.3)
  - Detect neutral particles: e.g. neutrons, photons
- Separate UPCs from inelastic Pb+Pb collisions
- Events are categorised into: 0n0n / 0nXn / XnXn
- Exclusive $\gamma\gamma$ processes: mostly 0n0n
- Photonuclear processes: typically 0nXn
- Each category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

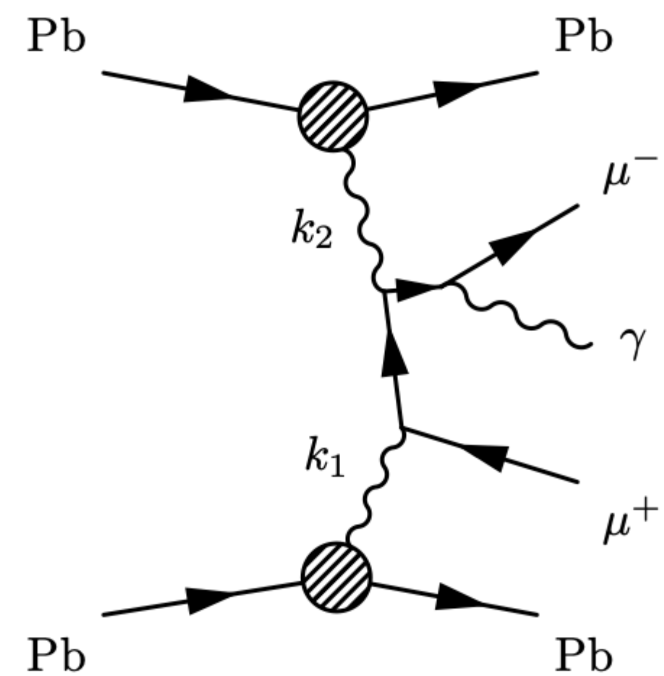


Ann.Rev.Nucl.Part.Sci. 70 (2020) 323-354

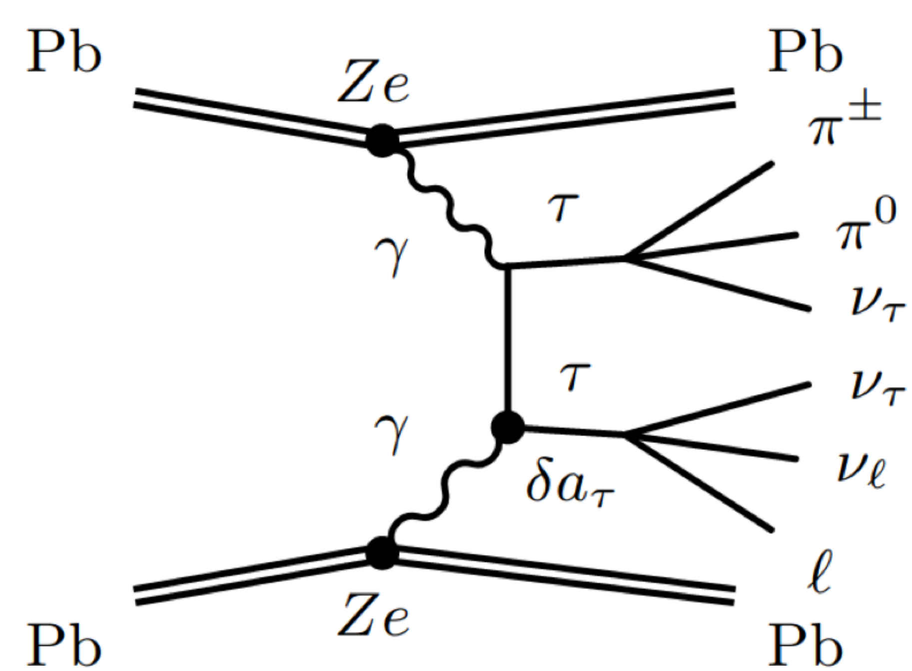
$\gamma\gamma \to ee$ / $\gamma\gamma \to \mu\mu$ / $\gamma\gamma \to \tau\tau$

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



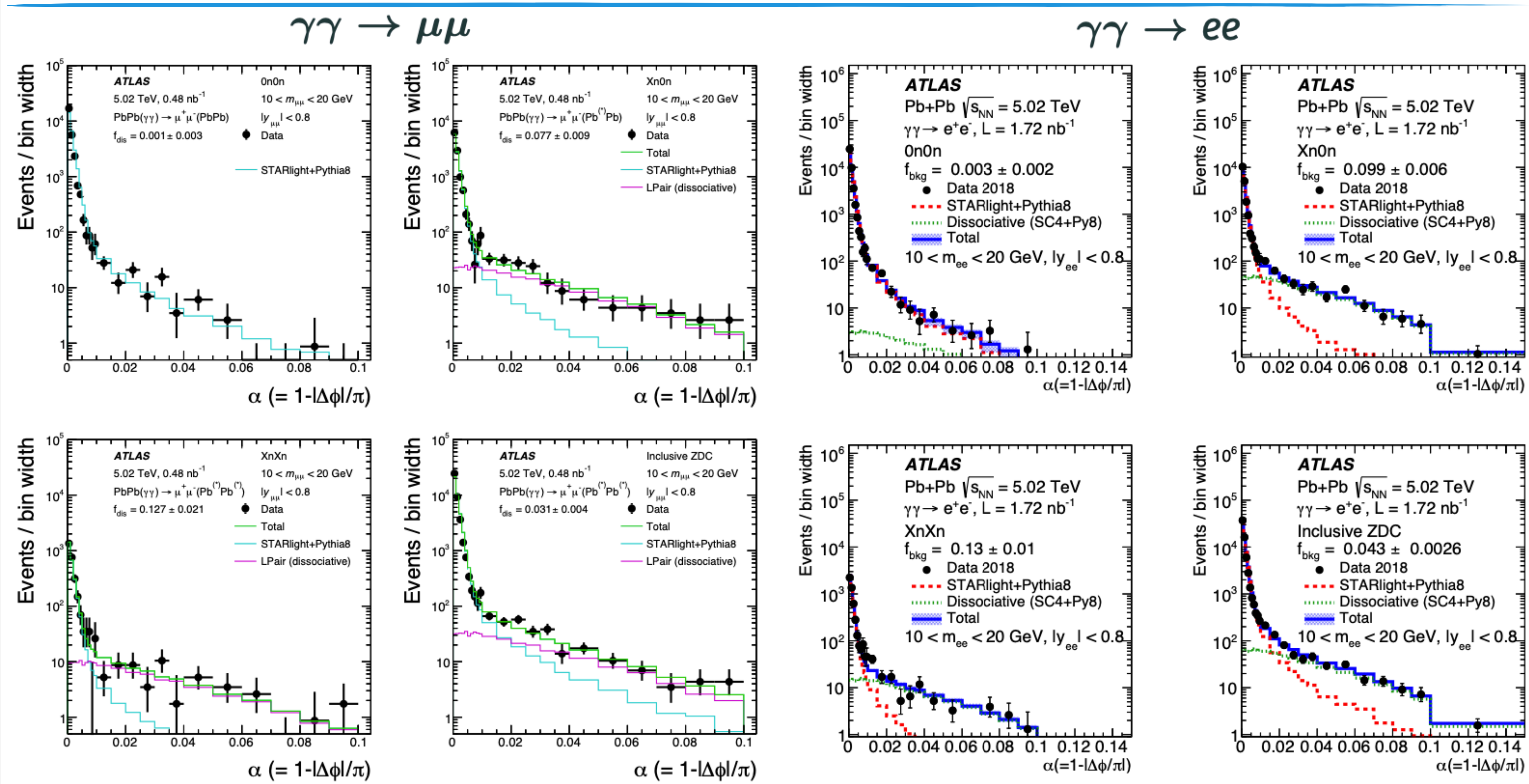


- $\gamma\gamma \to \tau\tau$:
  - not observed at the LHC before
  - τ-leptons never directly targeted in analyses using nucleus-nucleus data
  - constraints on τ-lepton anomalous magnetic moment: $a_\tau = \frac{(g-2)_\tau}{2}$
  - its value is sensitive to many BSM models (lepton compositeness, supersymmetry $\delta a_\tau \sim m_\tau^2/M^2$, TeV-scale leptoquarks, ...)



See also talk by Iwona

$\gamma\gamma \rightarrow ll$: dissociative backgrounds



- Dissociative background contributions precisely evaluated from fit to acoplanarity distributions
- Clear dependence on ZDC topologies:
  - 0n0n - excellent agreement with STARlight+Pythia8
  - 0nXn & XnXn - clear contributions from dissociative backgrounds (modelled with SuperChic4)

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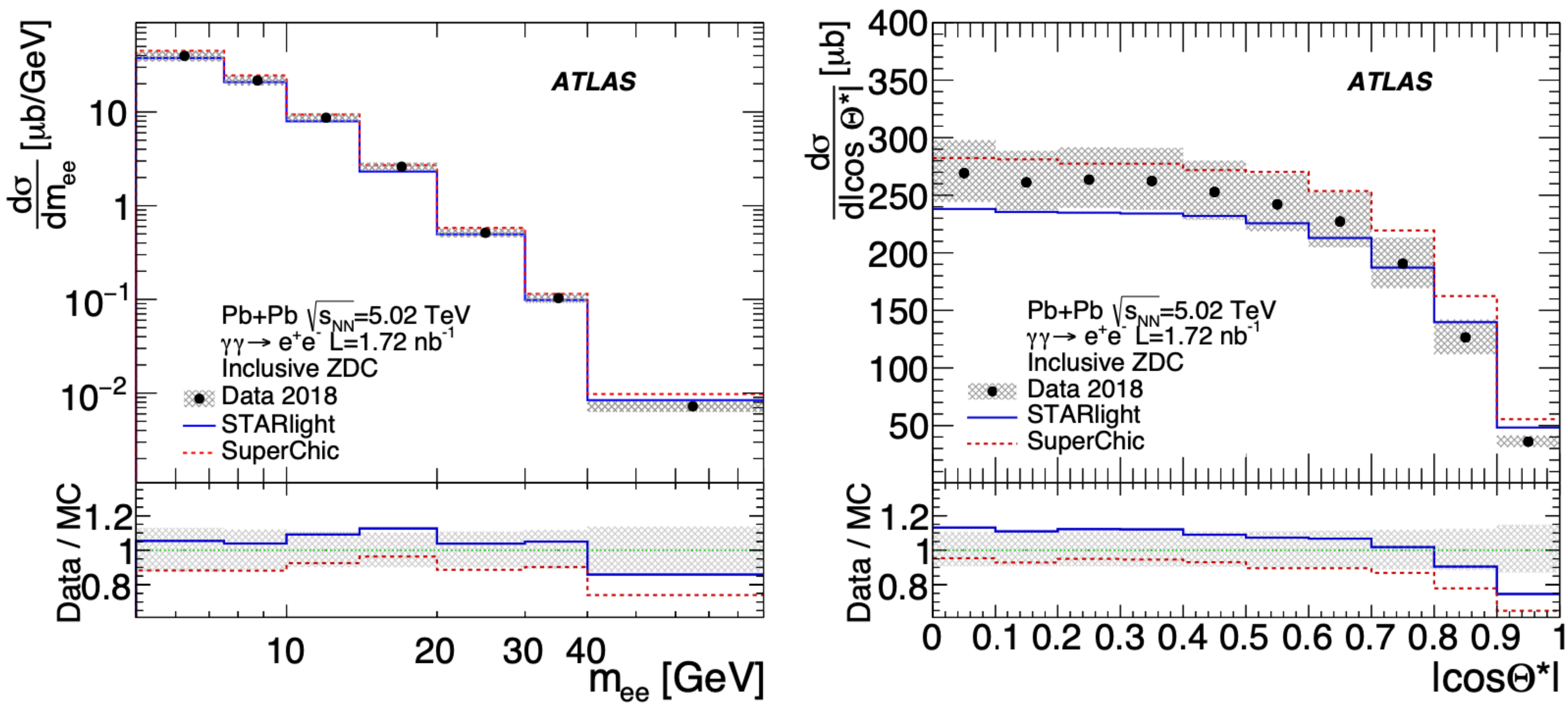
$\gamma\gamma \to ll$: differential cross-sections



- $\gamma\gamma \to ee$ 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

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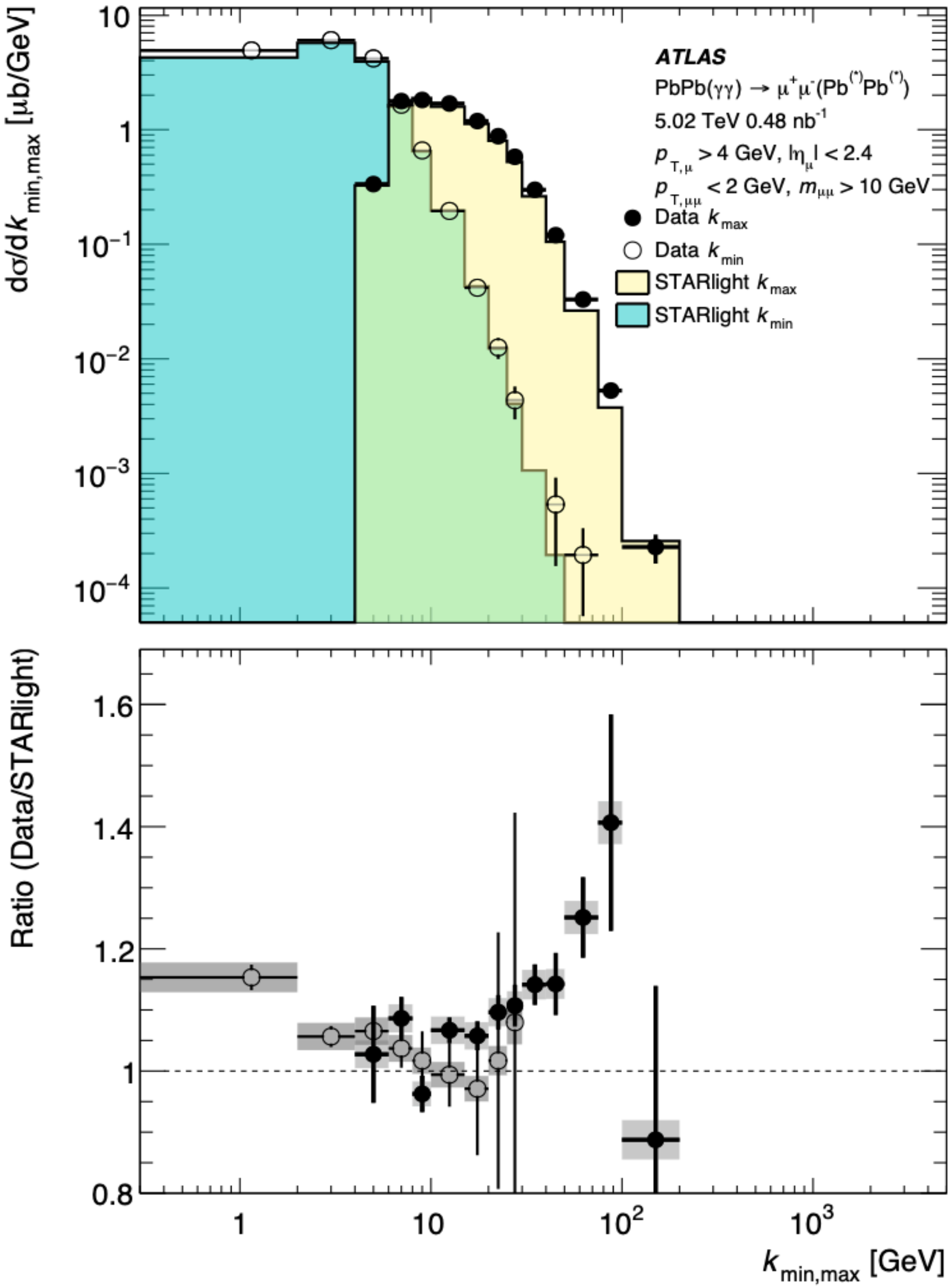
$\gamma\gamma \to ll$: initial-state photon energies



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

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

- 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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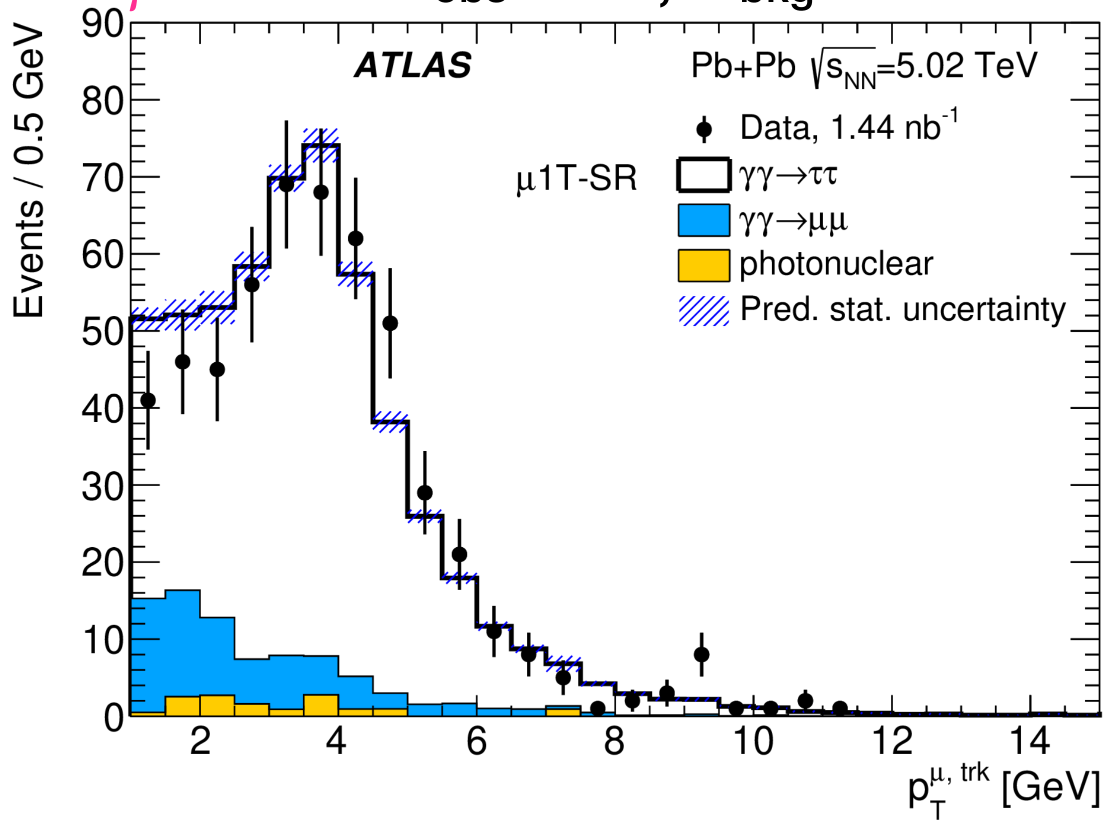
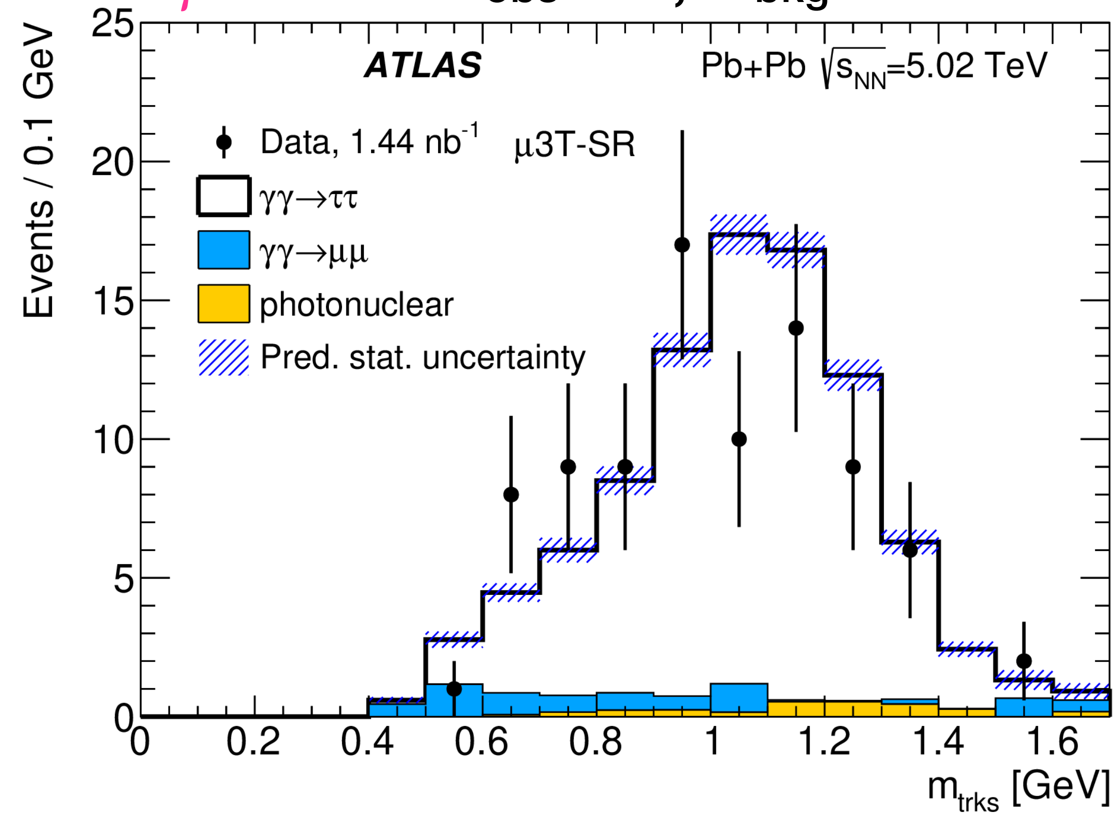
$\gamma\gamma\rightarrow\tau\tau$: signal regions

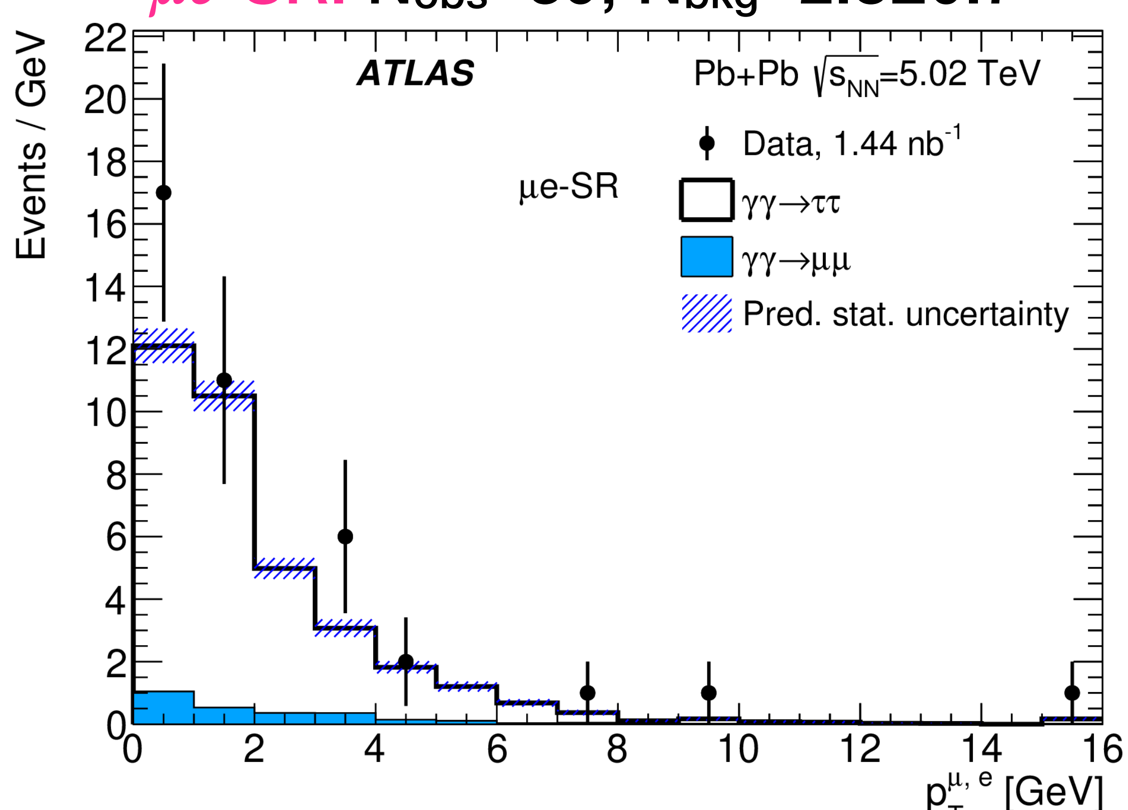
μ1T-SR: N_{obs}=532, N_{bkg}=84±19



μ3T-SR: N_{obs}=85, N_{bkg}=9±3



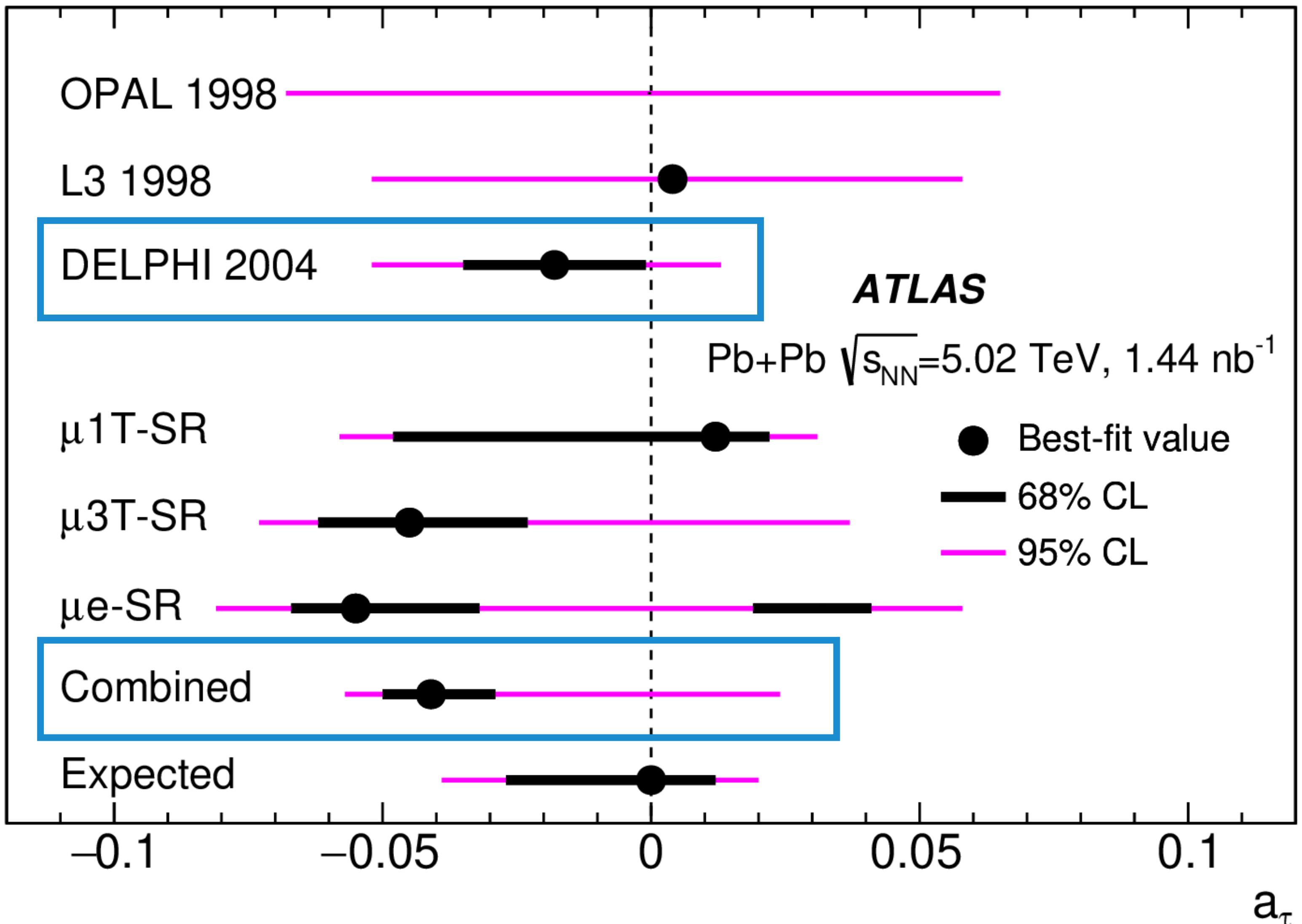
μe-SR: N_{obs}=39, N_{bkg}=2.8±0.7



- 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 ~650 events across all SRs
- Clear observation of $\gamma\gamma\rightarrow\tau\tau$ process
- Various distributions in good agreement with predictions

Phys. Rev. Lett. 131, 151802

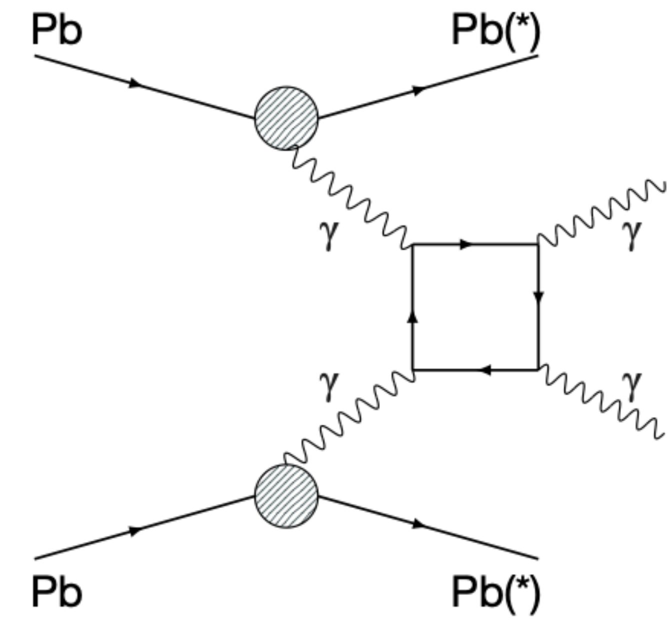
$\gamma\gamma \to \tau\tau$: anomalous magnetic moment a_τ



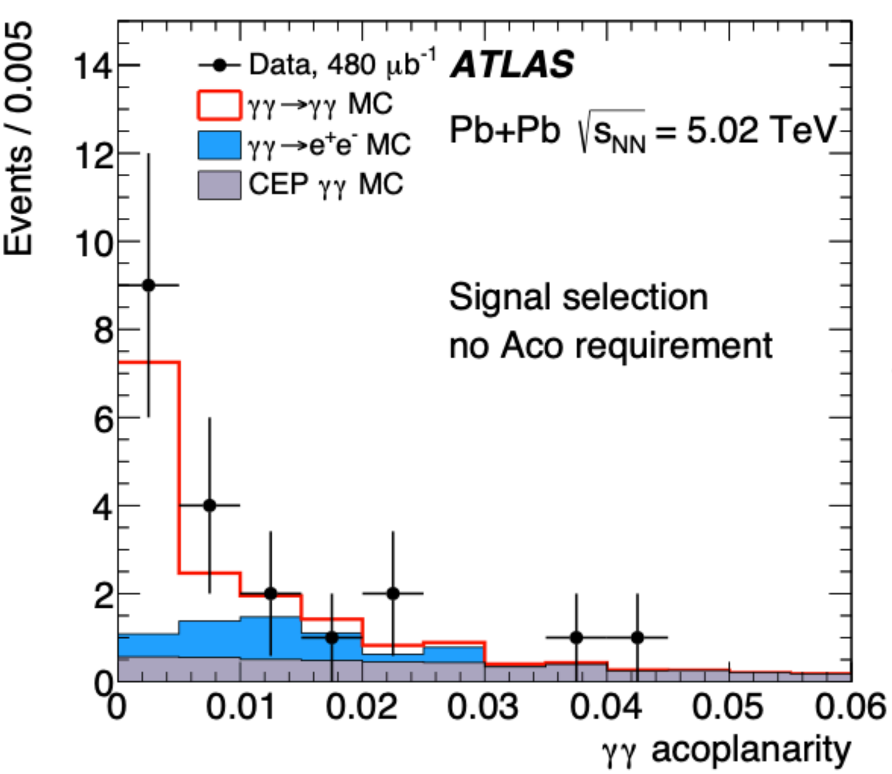
- a_τ from fit to muon p_T distribution in three signal regions — Phys. Rev. Lett. 131, 151802
- Observed 95% CL limits: $a_\tau \in (-0.057, 0.024)$
- First limits on a_τ since LEP era - competitive with DELPHI constraints [EPJC 35 (2004) 159]
- Statistical uncertainties dominant → **expected to improve with Run-3 data**

$\gamma\gamma \rightarrow \gamma\gamma$

- Light-by-light (LbyL) scattering: key example of rare SM process probed in UPC
- Not allowed classically, but possible in QED at $O(\alpha^4)$
- Several LbyL measurements performed with the LHC Pb+Pb UPC data:
  - 2015 data → evidence at 4.4σ (also CMS result: 4.1σ)
  - 2018 data → first observation at 8.2σ
  - **2015+18 → differential cross-sections**

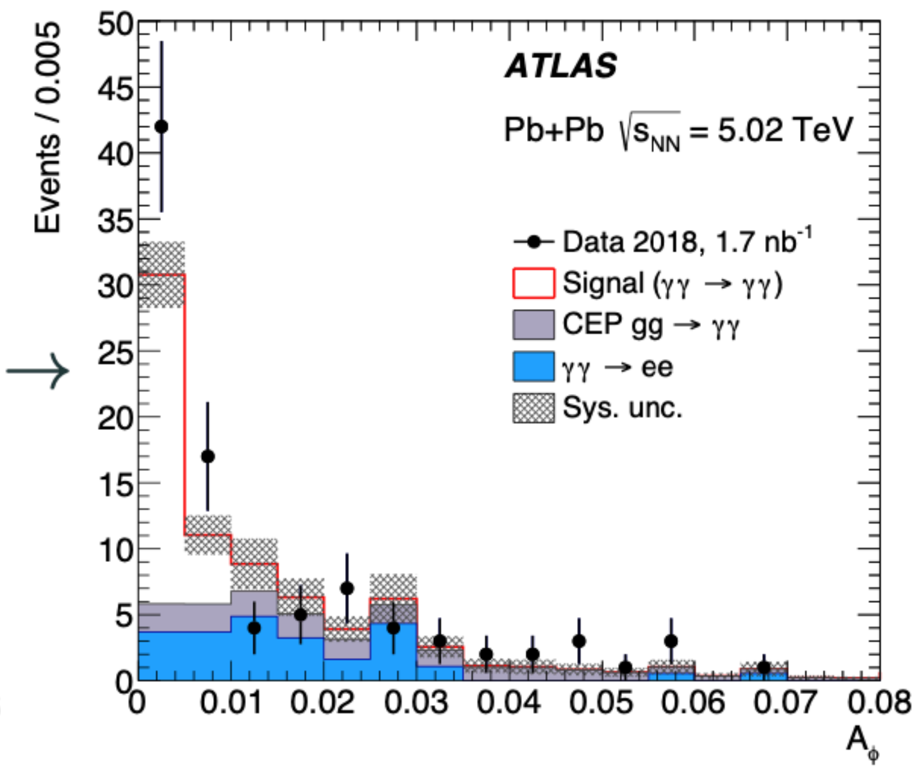


2015 data



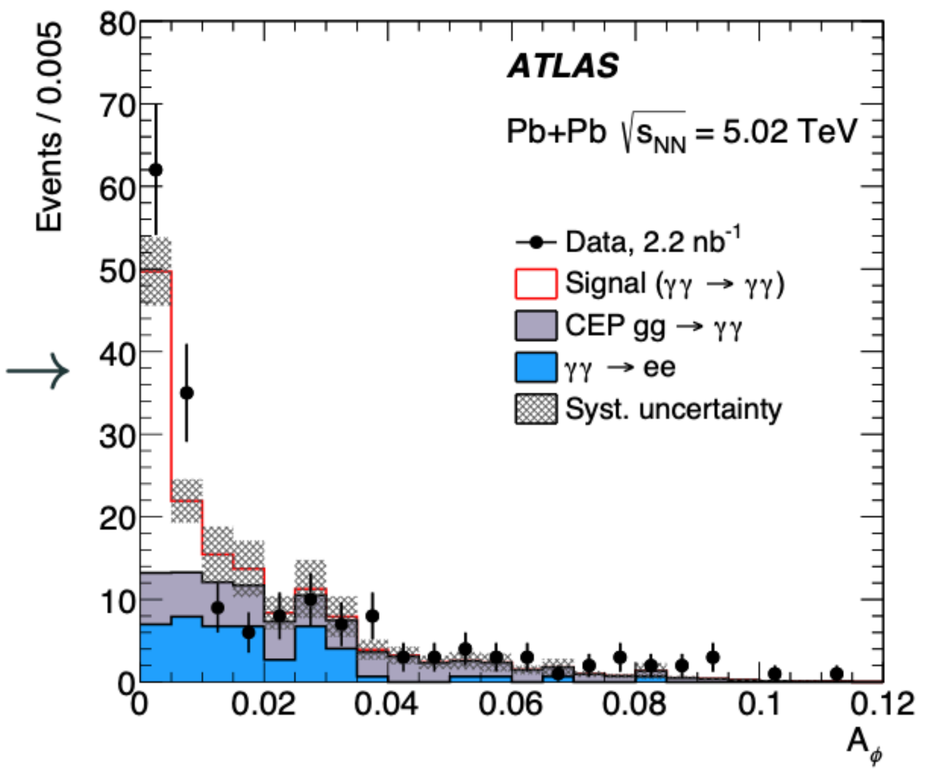
Nature Phys. 13 (2017) 852

2018 data



PRL 123 (2019) 052001

2015+18 data



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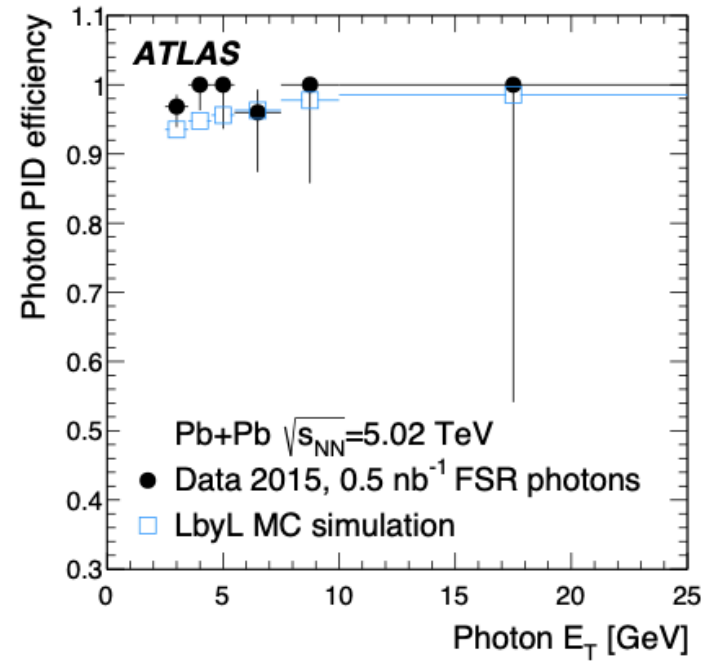
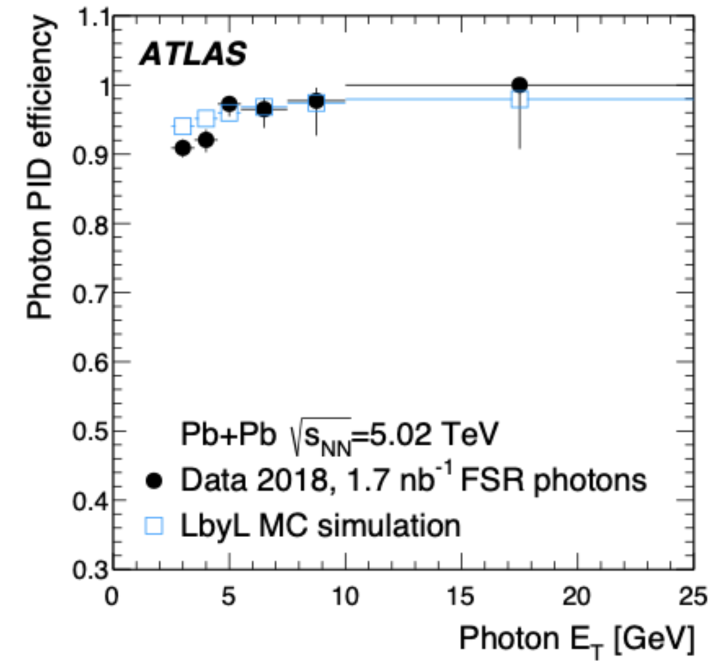
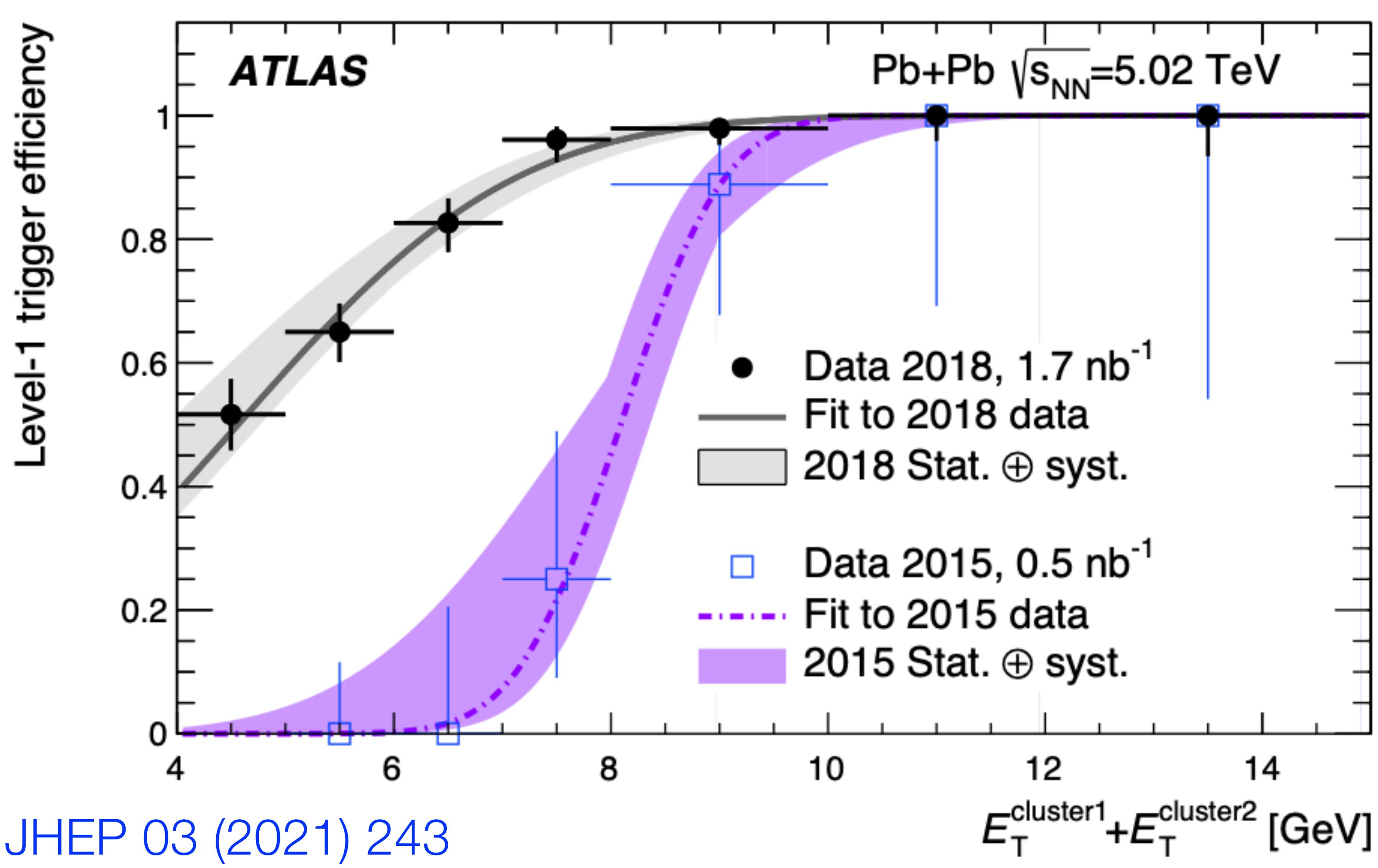
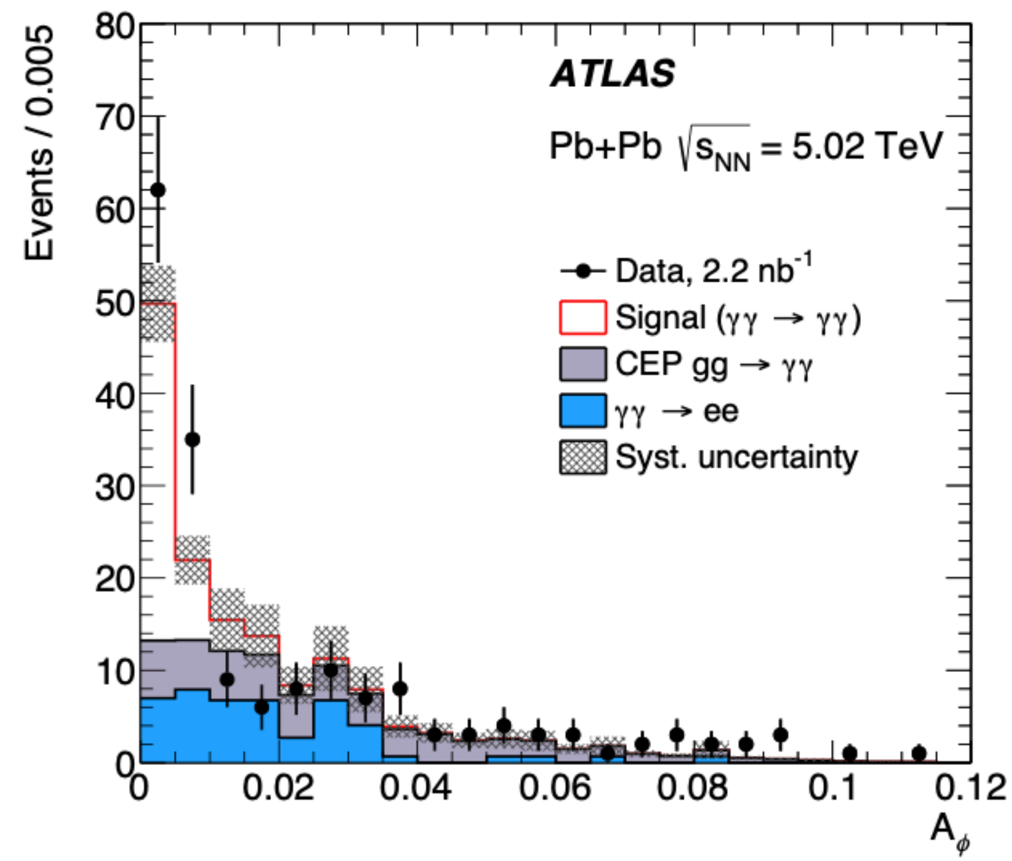
$\gamma\gamma\rightarrow\gamma\gamma$: analysis

- Event selection: 2 photons with $E_T^{\gamma} > 2.5$ 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 → $\gamma\gamma$ (data-driven)
  - $\gamma\gamma\rightarrow ee$ with mis-identified electrons (data-driven)









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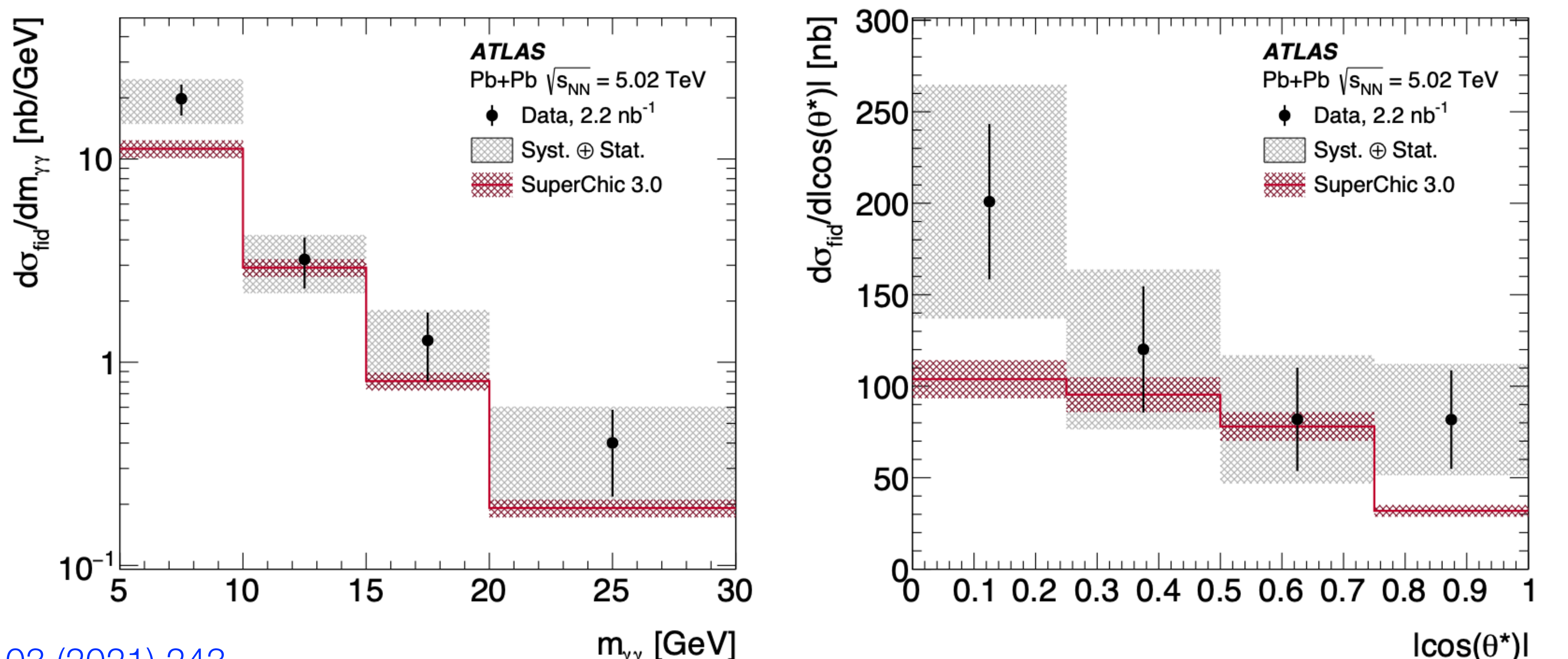
$\gamma\gamma\rightarrow\gamma\gamma$: cross-sections

- 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 $m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, $p_T{}^{\gamma}$, $|\cos\theta^*|$
  - Reasonably good agreement of distribution shapes with SuperChic 3 predictions



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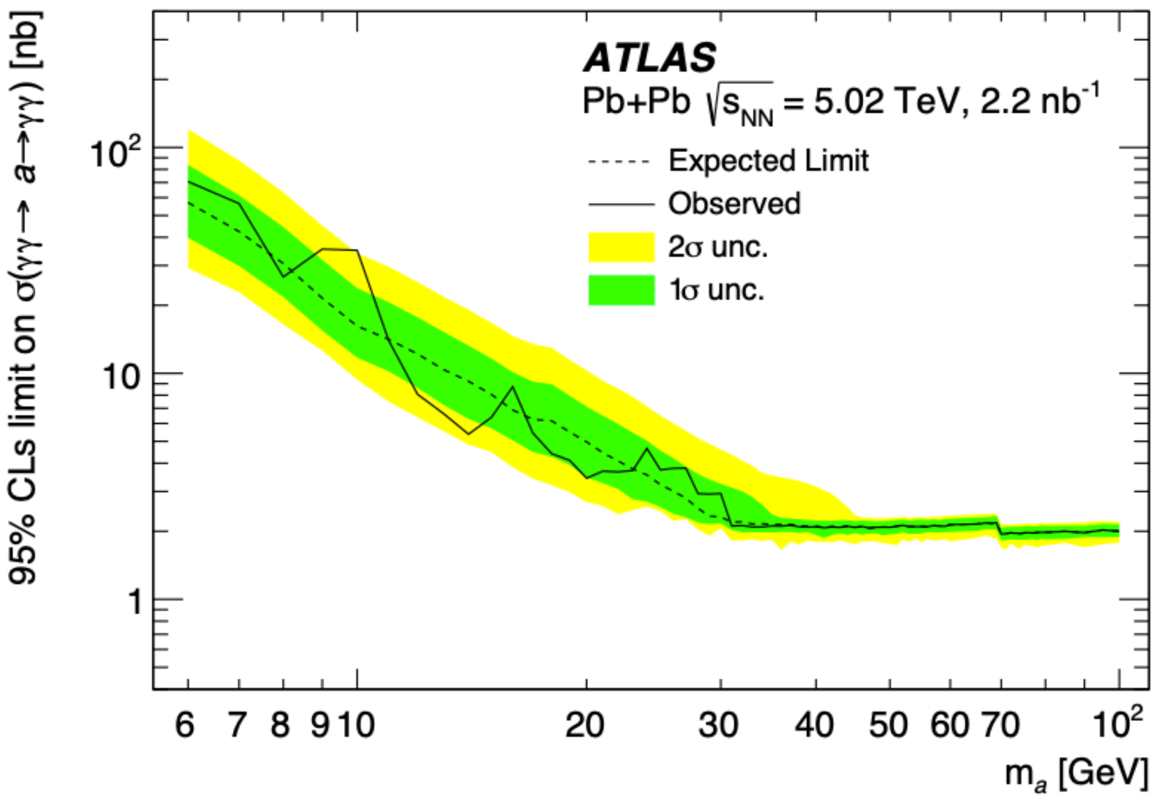
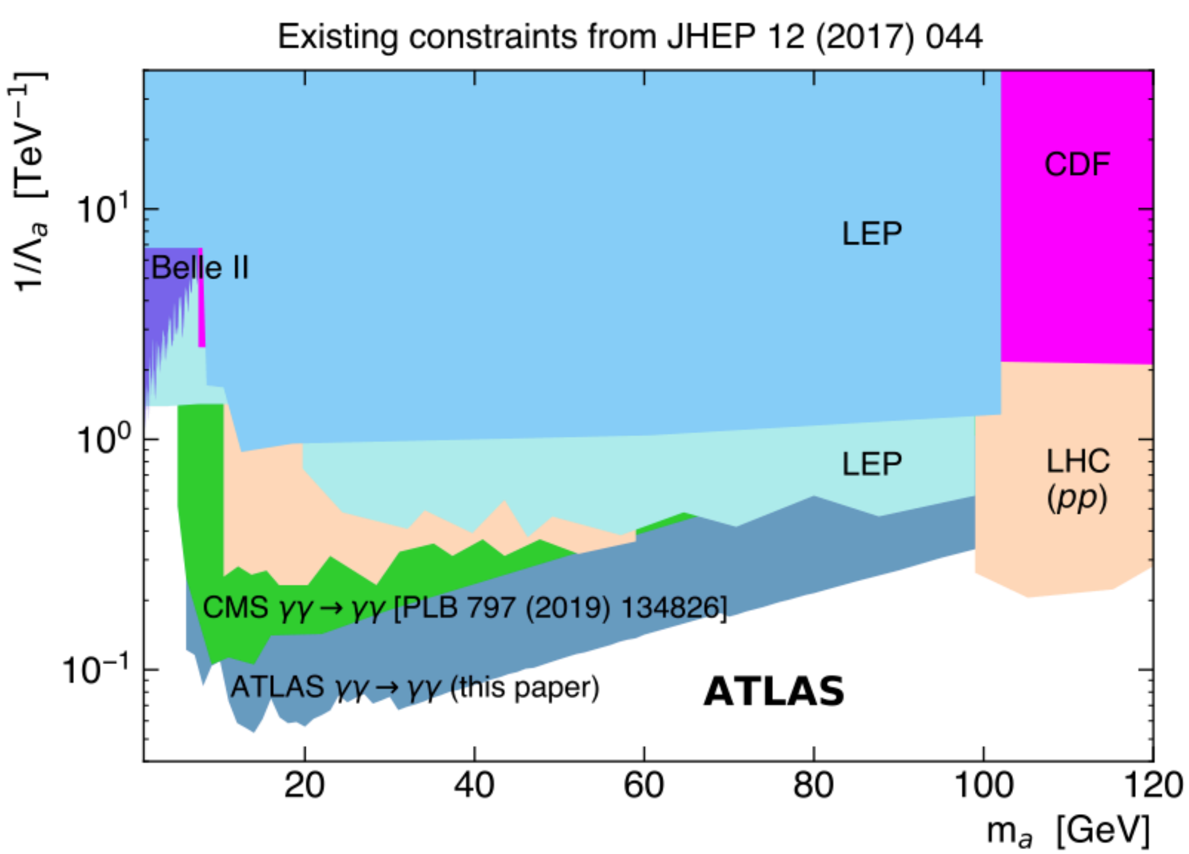
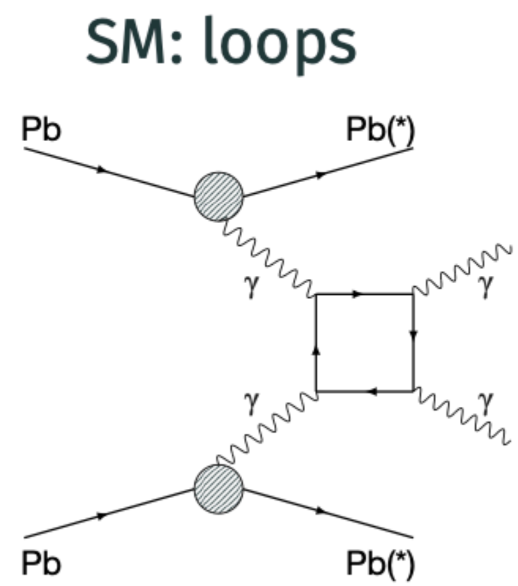
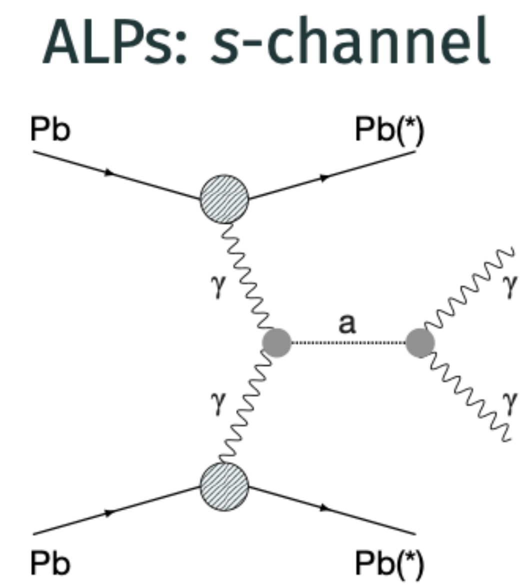
$\gamma\gamma\rightarrow\gamma\gamma$: search for axion-like particles









- Axion-like particles can couple to photons in initial- and final-state of $\gamma\gamma\rightarrow\gamma\gamma$
- 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

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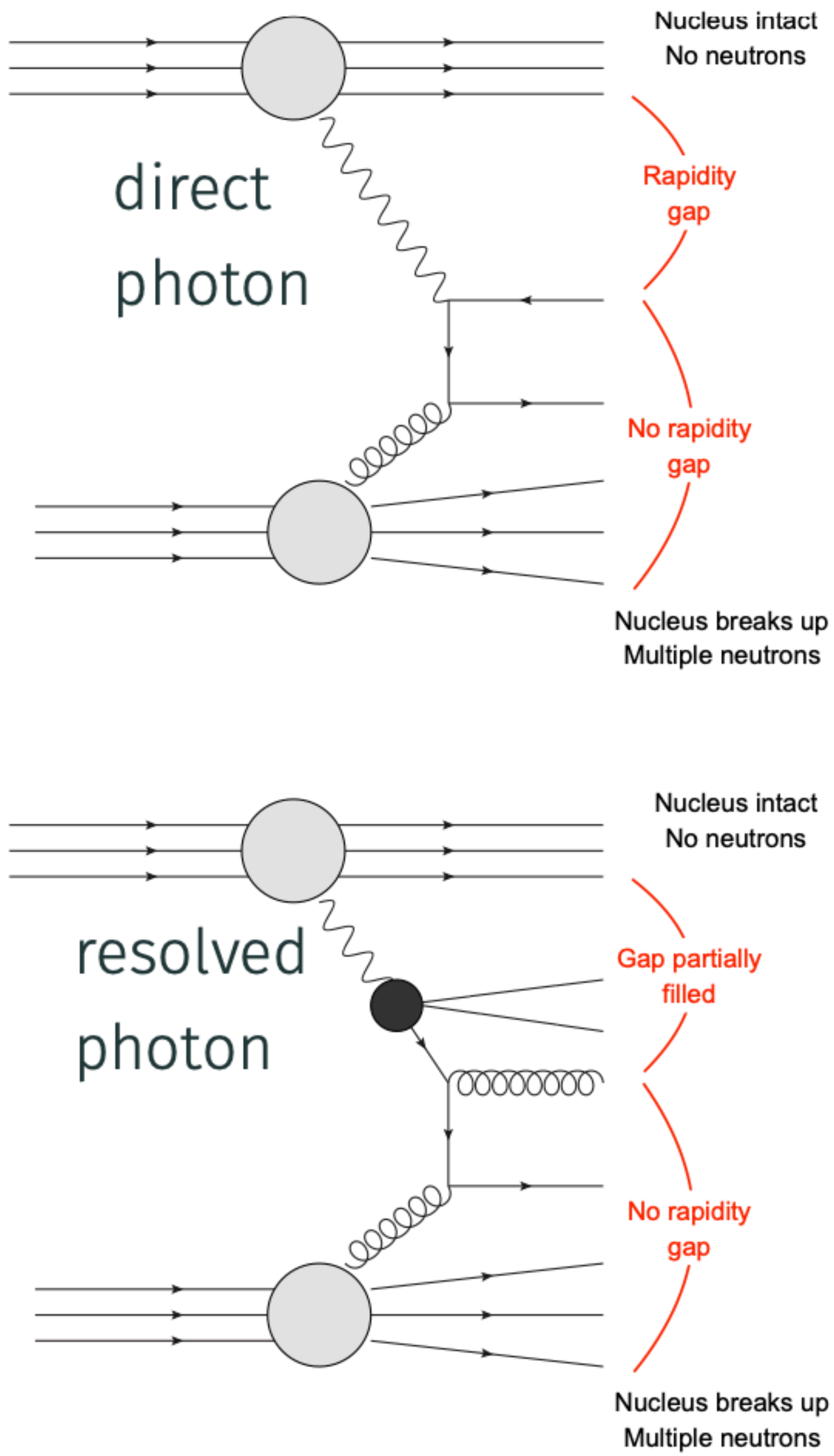
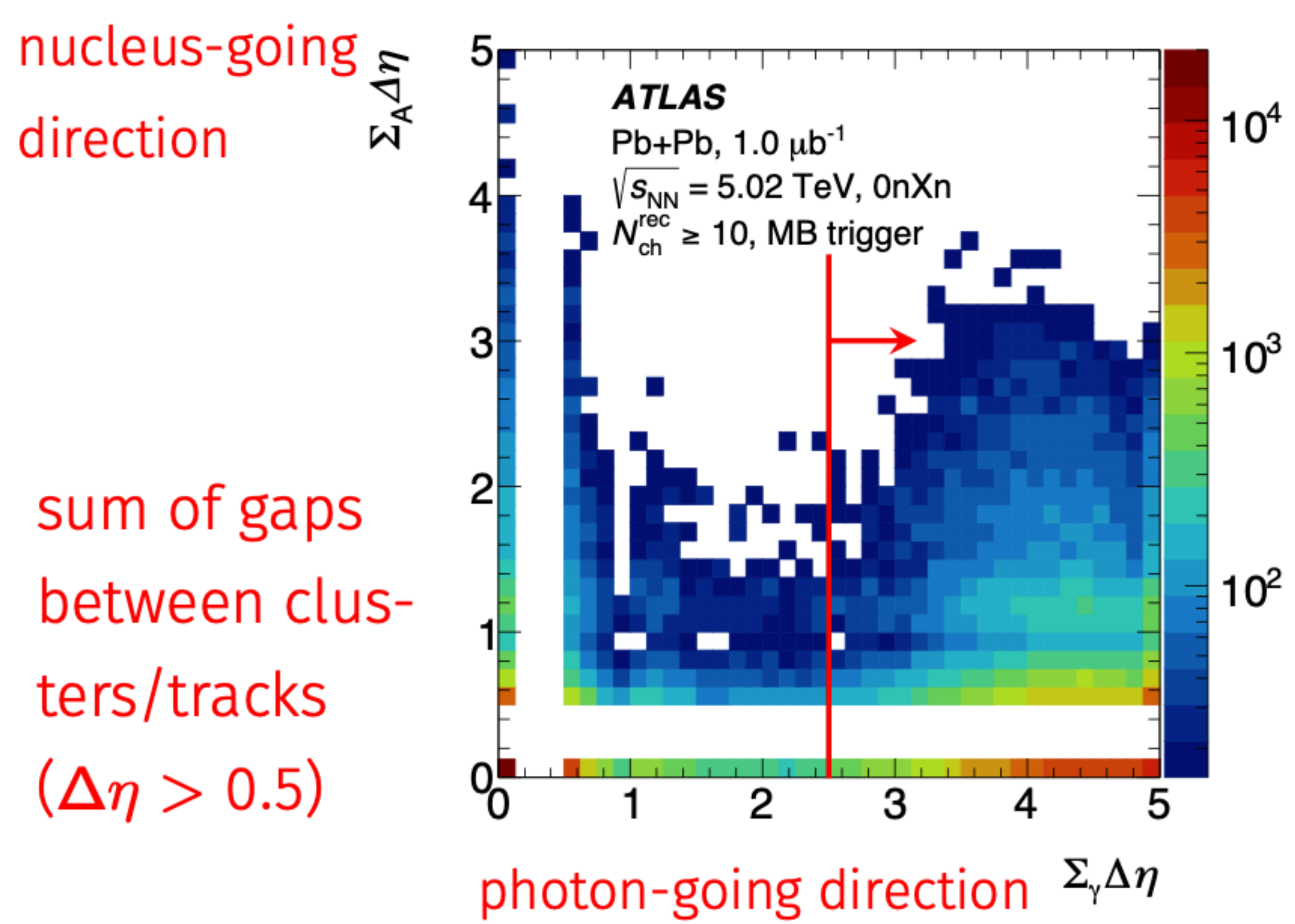
γ+Pb: global properties

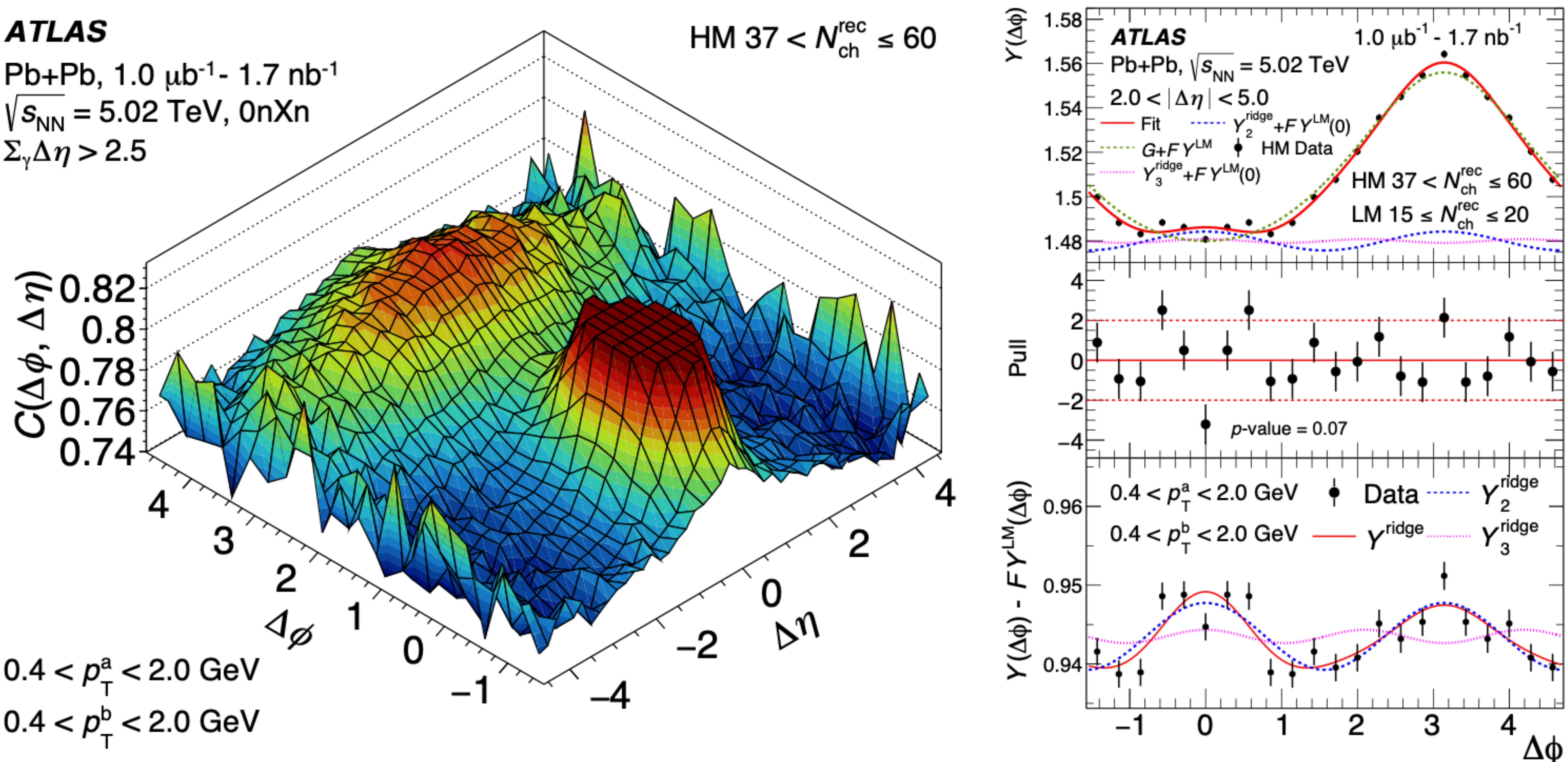


- Photon expected to fluctuate into quark-antiquark pair, and interacts hadronically
- Small systems like p+Pb and pp exhibit signals of collectivity - what about γ+Pb processes?
- Expect forward neutron emissions from break-up of struck nucleus → 0nXn ZDC events



Phys. Rev. C 104 (2021) 014903

γ+Pb: looking for collectivity

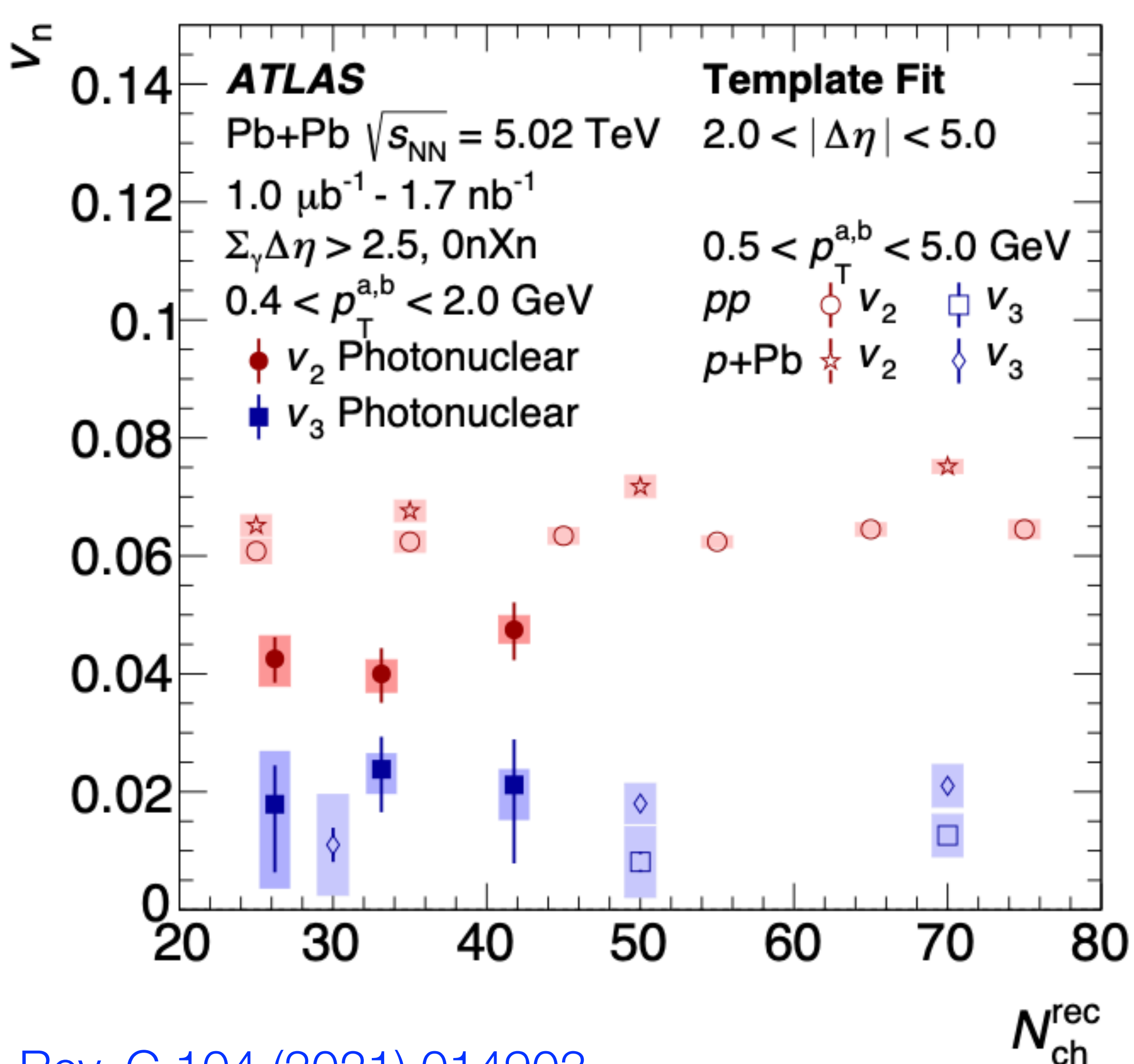


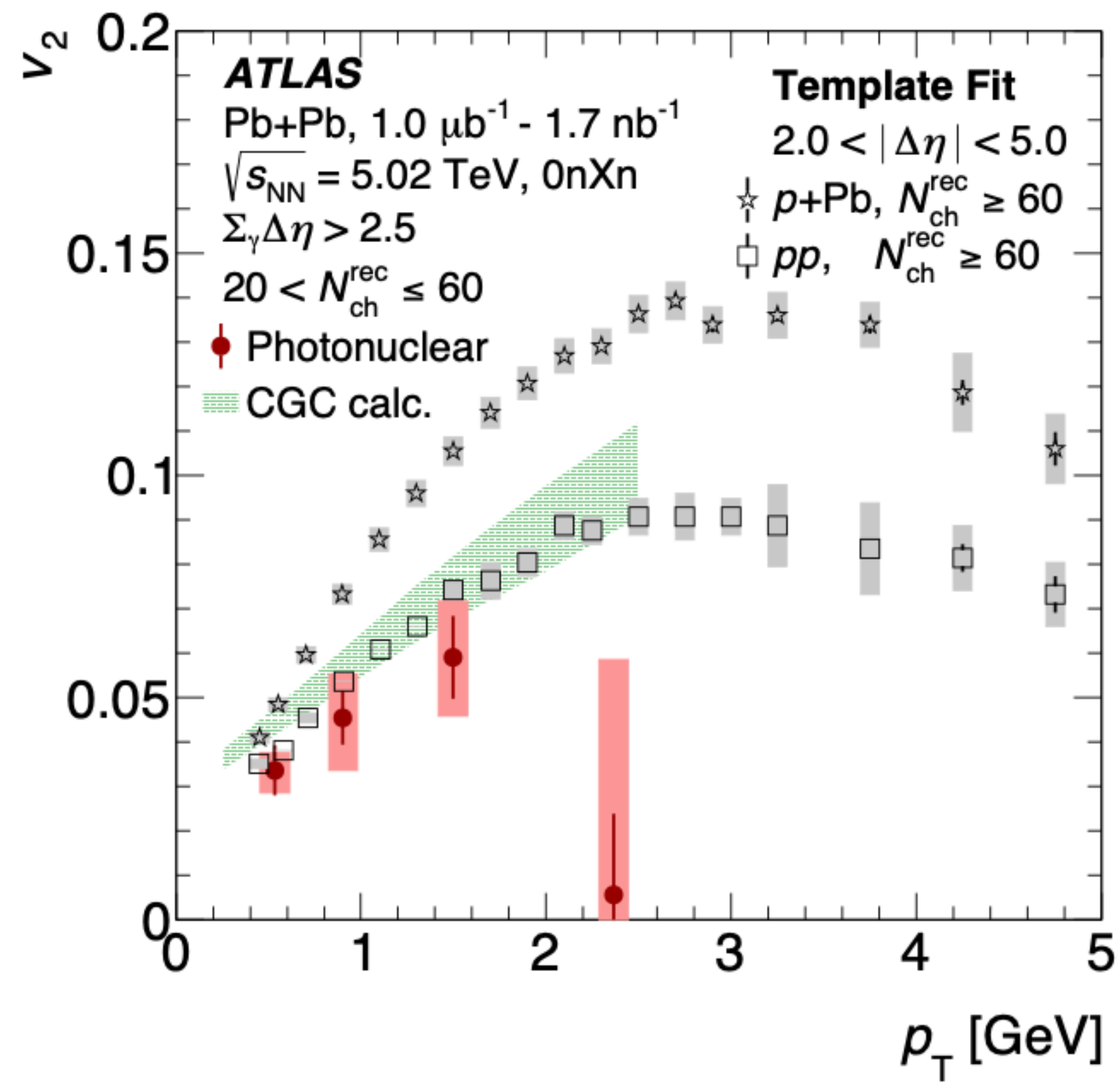
- Correlations between charged particles studied as a function of Δη and Δφ
- Template method used to extract flow coefficients, with non-flow contributions subtracted using low-multiplicity events

Phys. Rev. C 104 (2021) 014903

γ+Pb: flow coefficients

- Significant v_2 observed, lower than in pp or p+Pb collisions
- non-zero v_3 values, compatible with pp and p+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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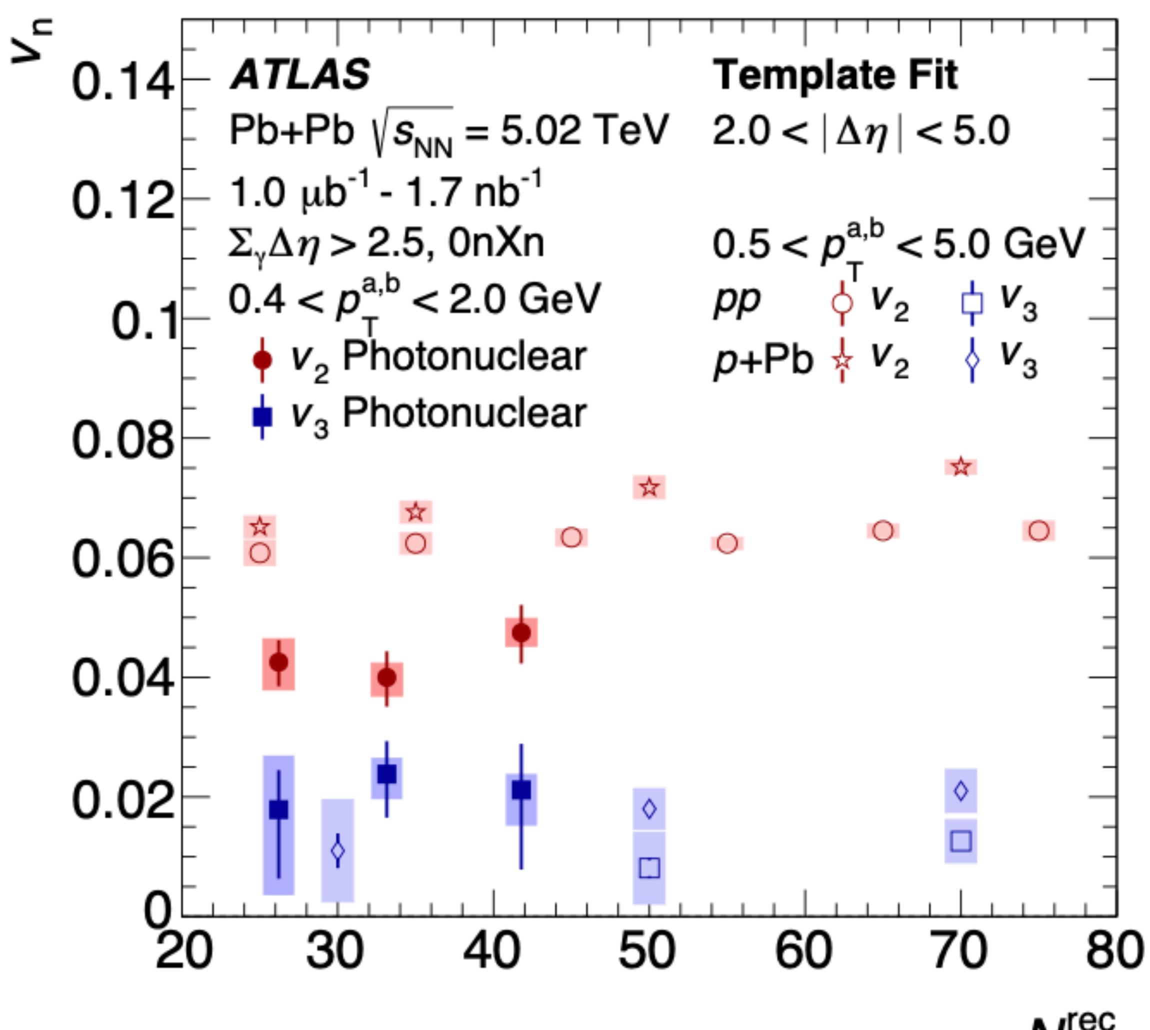
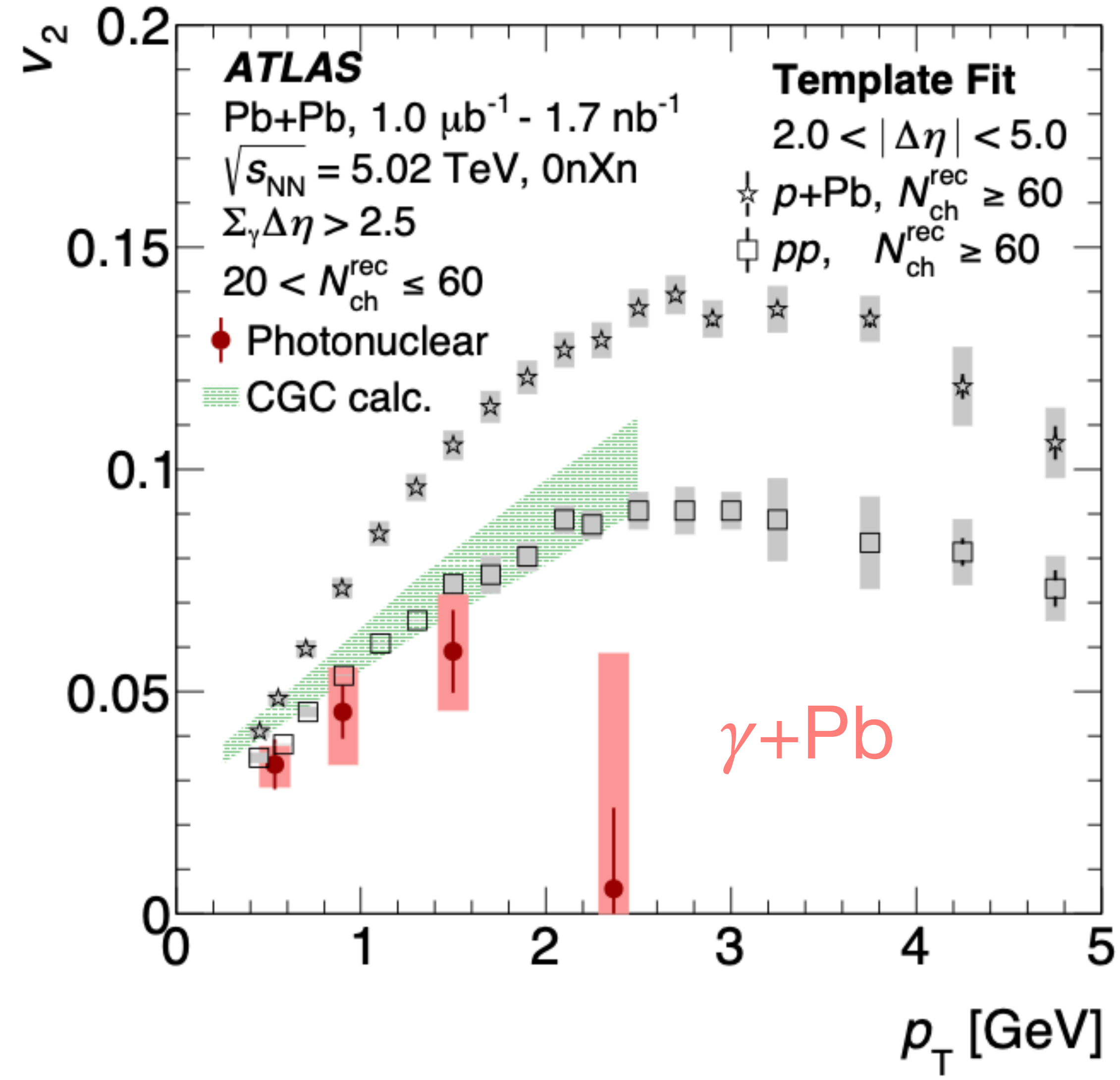
γ+Pb: flow coefficients

- Significant v_2 observed, lower than in pp or p+Pb collisions
- non-zero v_3 values, compatible with pp and p+Pb collisions
- Both v_2 and v_3 show no significant multiplicity dependence
- **Motivation to look for more QGP-like signals!**





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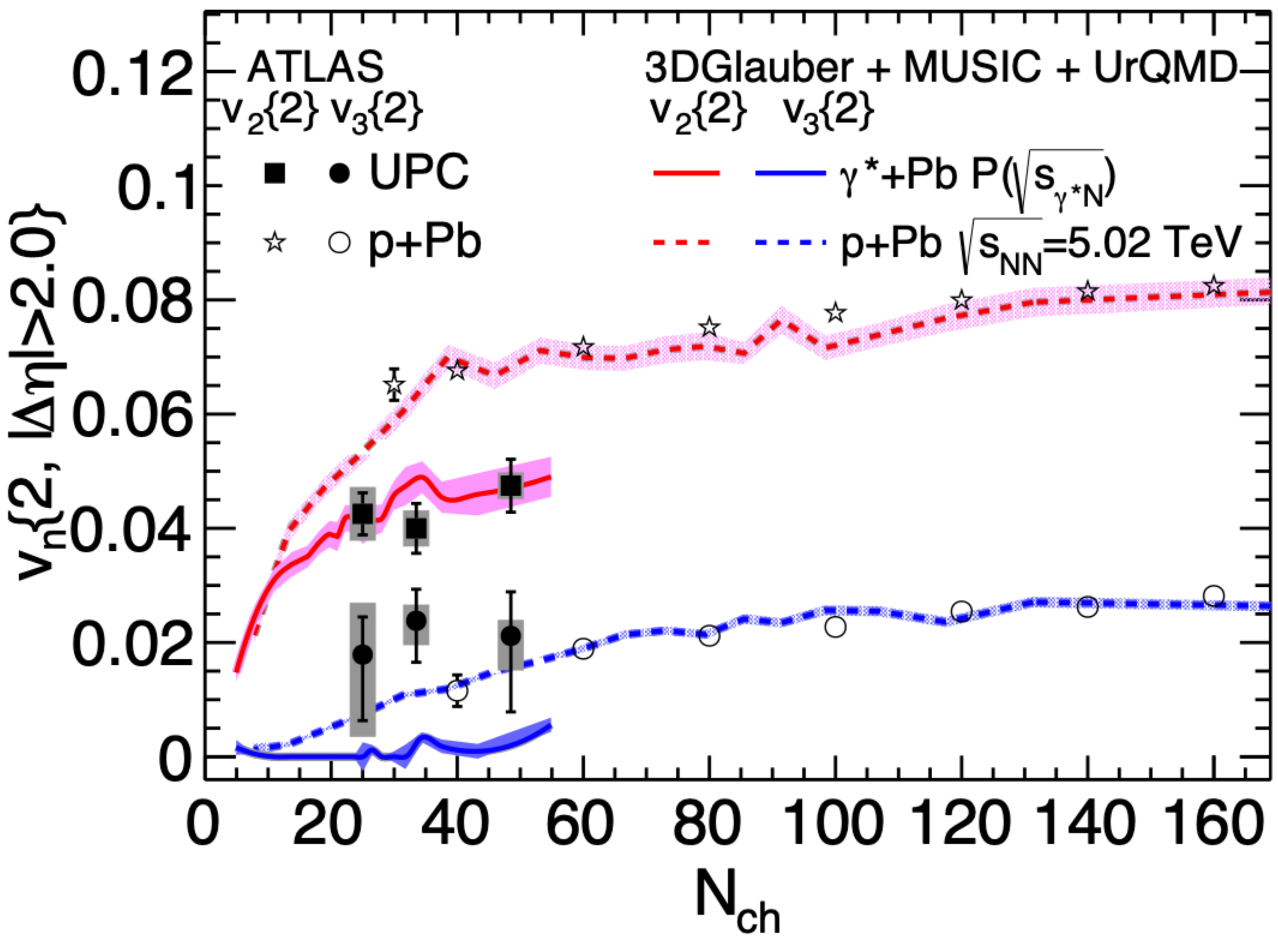
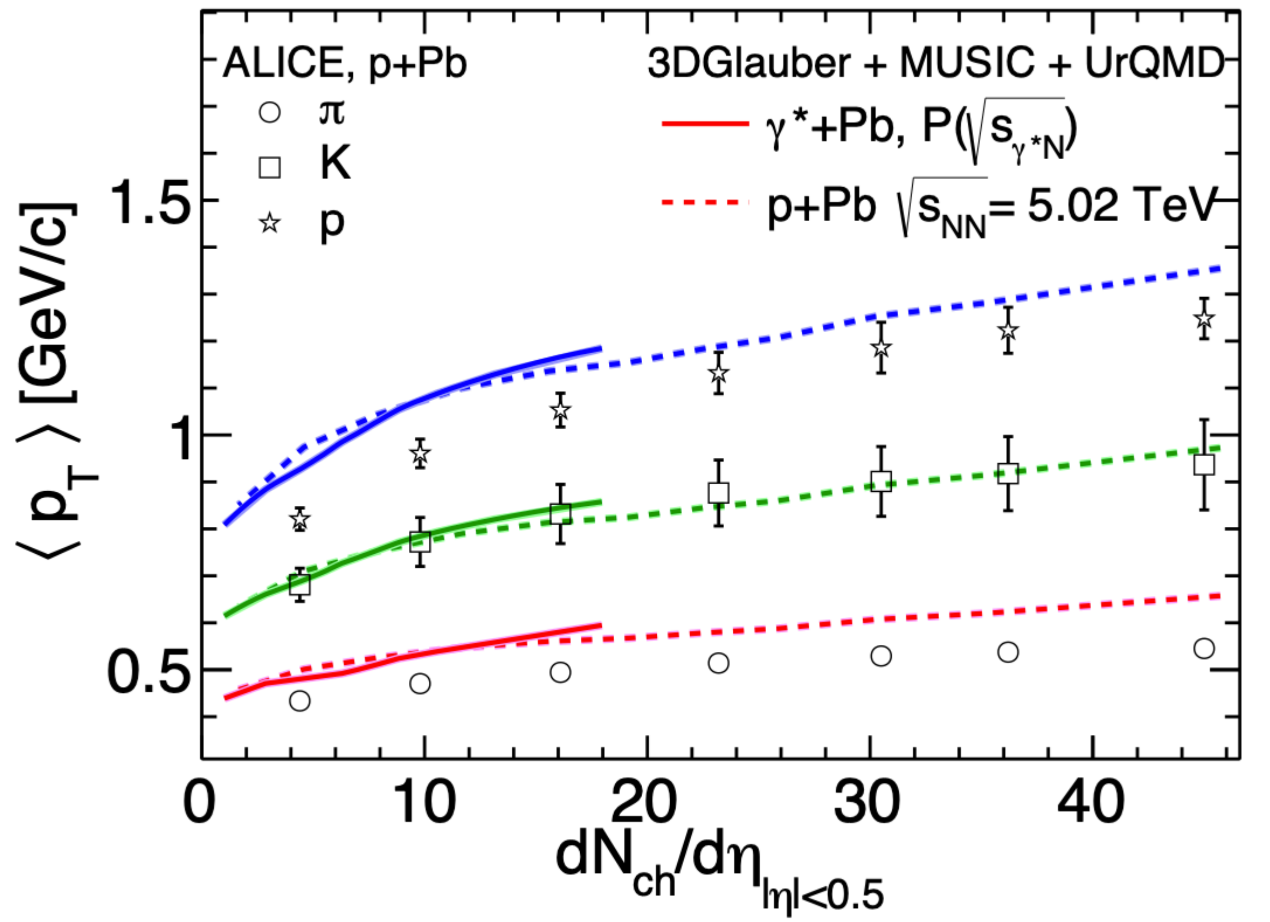
γ+Pb vs. p+Pb: theory predictions



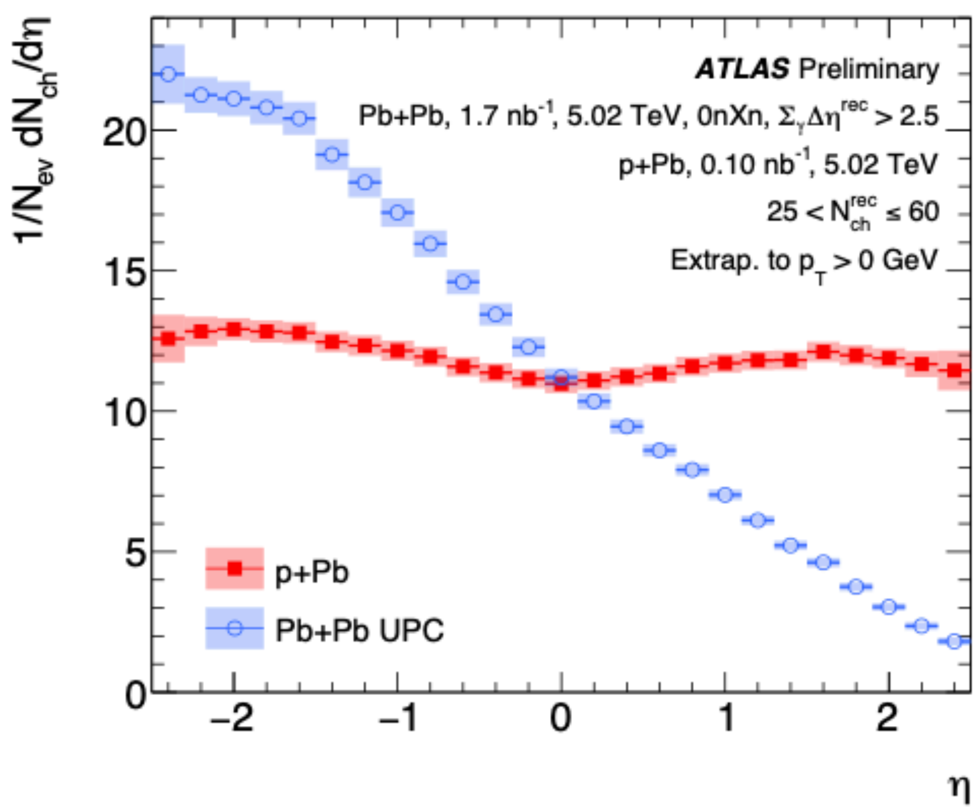


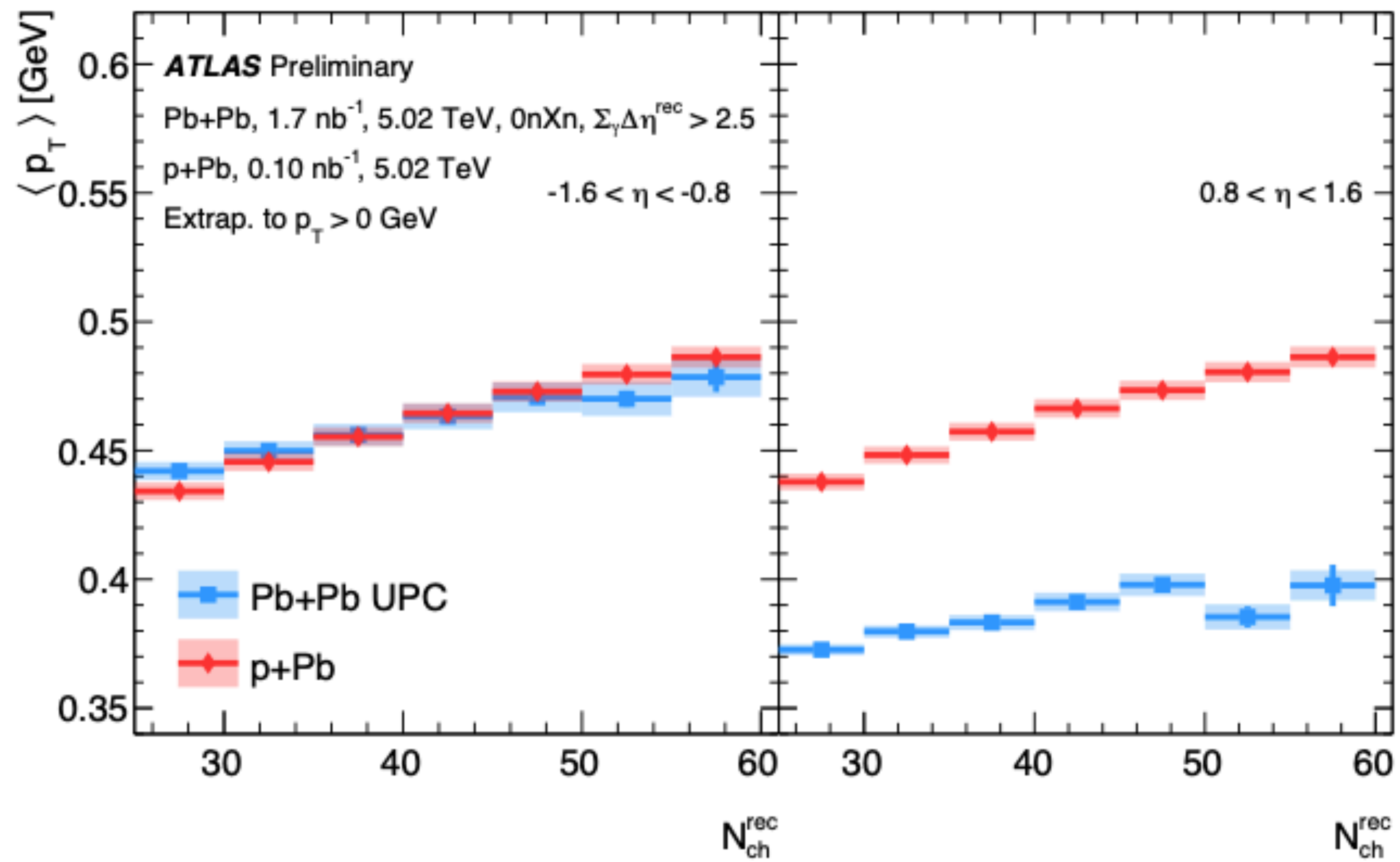
- Theory (3+1D hydrodynamics) suggests elliptic flow hierarchy between γ+Pb and p+Pb is dominated by longitudinal flow decorrelations
- Prediction is that both systems should have same radial flow, therefore the same $\langle p_T \rangle$
- Relevant observables: $\langle p_T \rangle$ of charged hadrons

Phys. Rev. Lett. 129 (2022) 252302

γ+Pb vs. p+Pb: measurements

$p + \mathrm{Pb}$ comapred with $\gamma + \mathrm{Pb}$





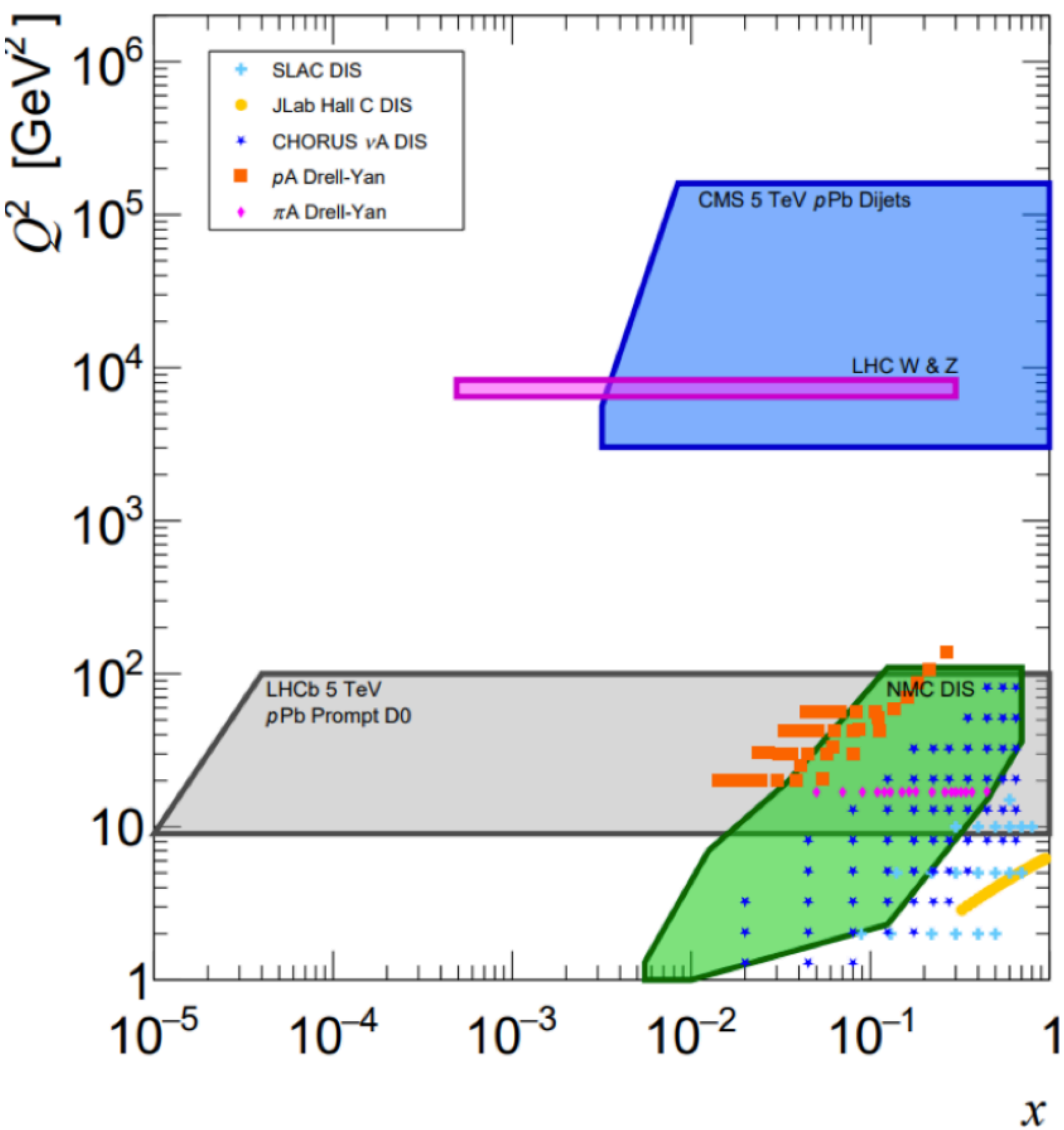
- γ+Pb distribution is highly asymmetric - photon energy lower compared to energy per nucleon in Pb
- p+Pb distribution is nearly symmetric for selected low multiplicity events
- Important to study γ+Pb properties in different η regions separately

- Negative η: $\langle p_T \rangle$ similar for both p+Pb and γ+Pb
- Positive η: $\langle p_T \rangle$ γ+Pb lower than for p+Pb

See also talk by Sruthy!

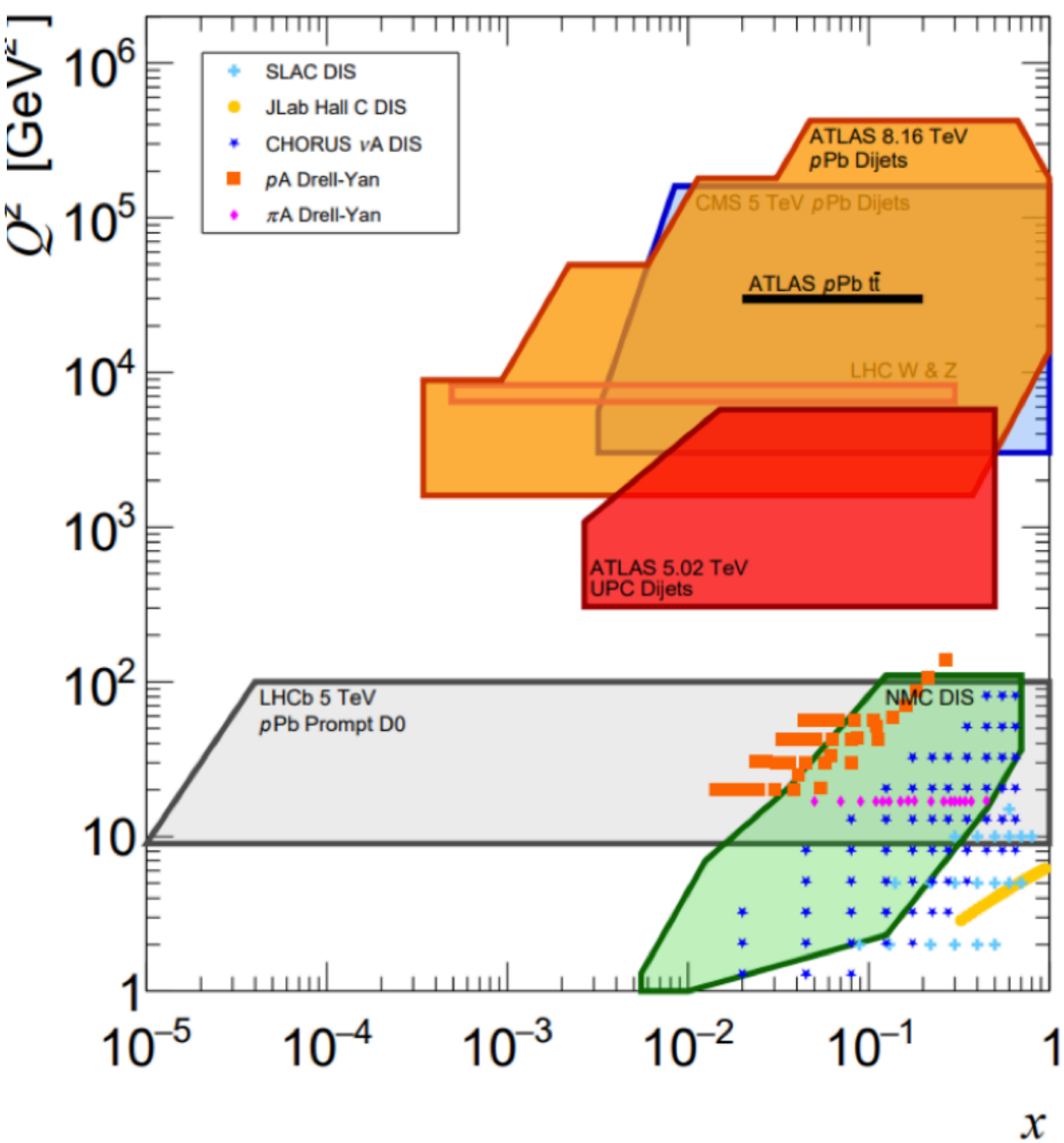
ATLAS-CONF-2023-059

γ+Pb: dijet production and nPDFs



- Precise measurements of various processes in nuclear interactions require good understanding of nuclear parton distribution functions (nPDFs)
- Poor nPDF constraints at low x and intermediate Q^2 ($100 < Q^2 < 1000$ GeV)

γ+Pb: dijet production and nPDFs



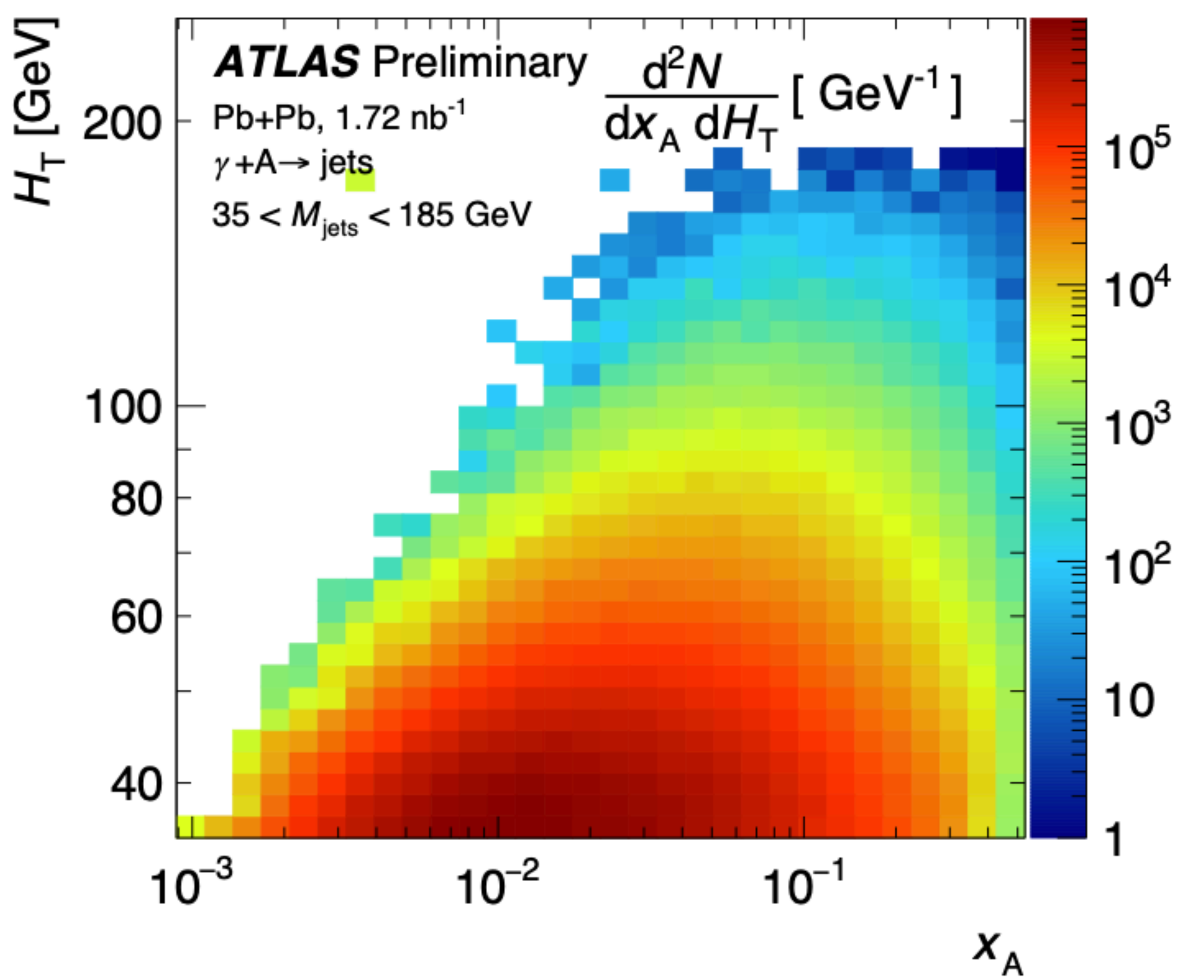
- Precise measurements of various processes in nuclear interactions require good understanding of nuclear parton distribution functions (nPDFs)
- Poor nPDF constraints at low x and intermediate Q^2 ($100 < Q^2 < 1000$ GeV)
- γ+Pb dijet production → clean, DIS-like probe of this kinematic region
- Measurement of triple-differential cross-sections:

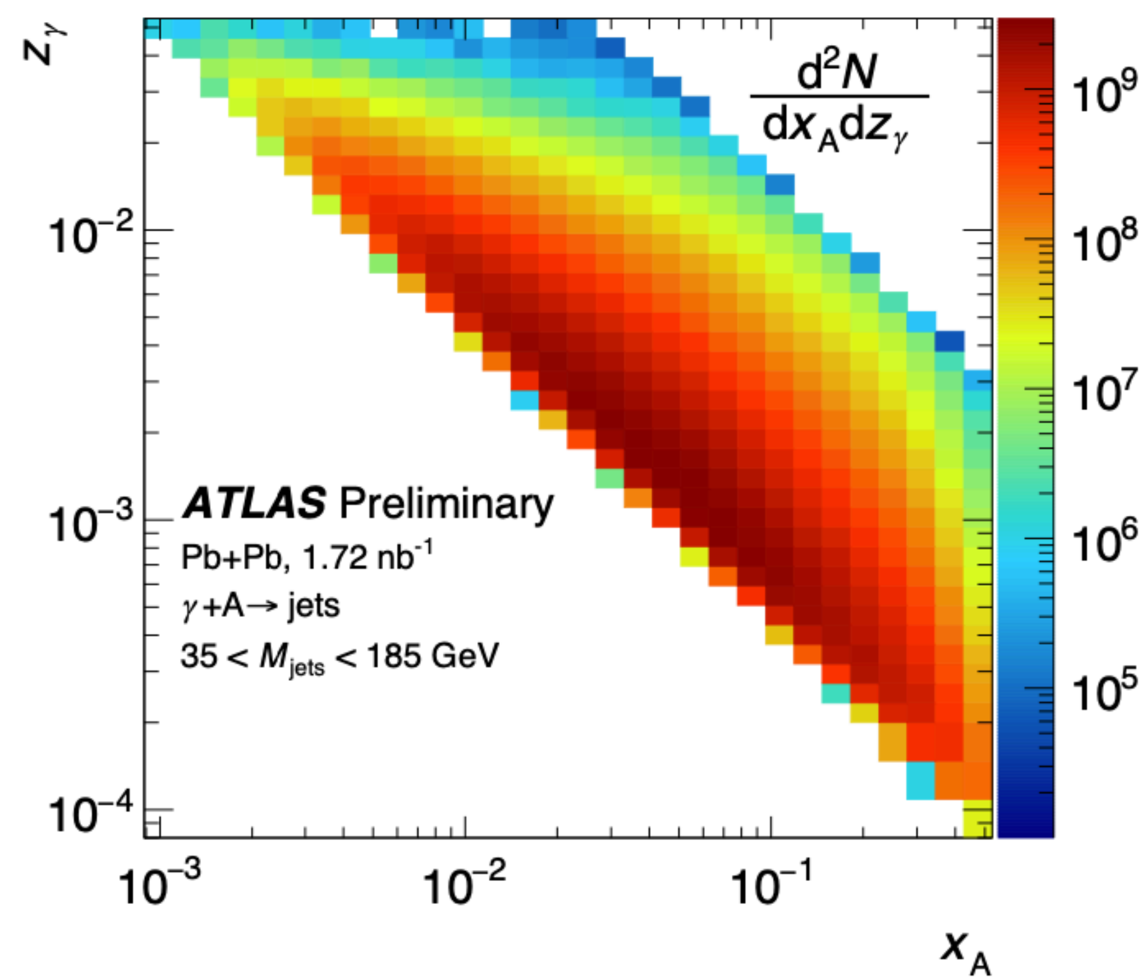
$H_T = \Sigma p_T^{jet}$ (proxy for Q),

$$x_A = \frac{m_{jets} e^{-y_{jets}}}{\sqrt{s_{NN}}}, \qquad z_\gamma = \frac{m_{jets} e^{+y_{jets}}}{\sqrt{s_{NN}}}$$

γ+Pb: dijet kinematic coverage

- Requiring $\Delta R = 0.4$ particle-flow jets with $p_T > 15$ GeV, $|\eta| < 4.4$
- Selecting events with 0nXn ZDC, $\sum_\gamma \Delta\eta > 2.5$, $35 < m_{jets} < 185$ GeV
- H_T does not depend significantly on x_A or z_γ
- x_A and z_γ highly correlated → acceptance effects

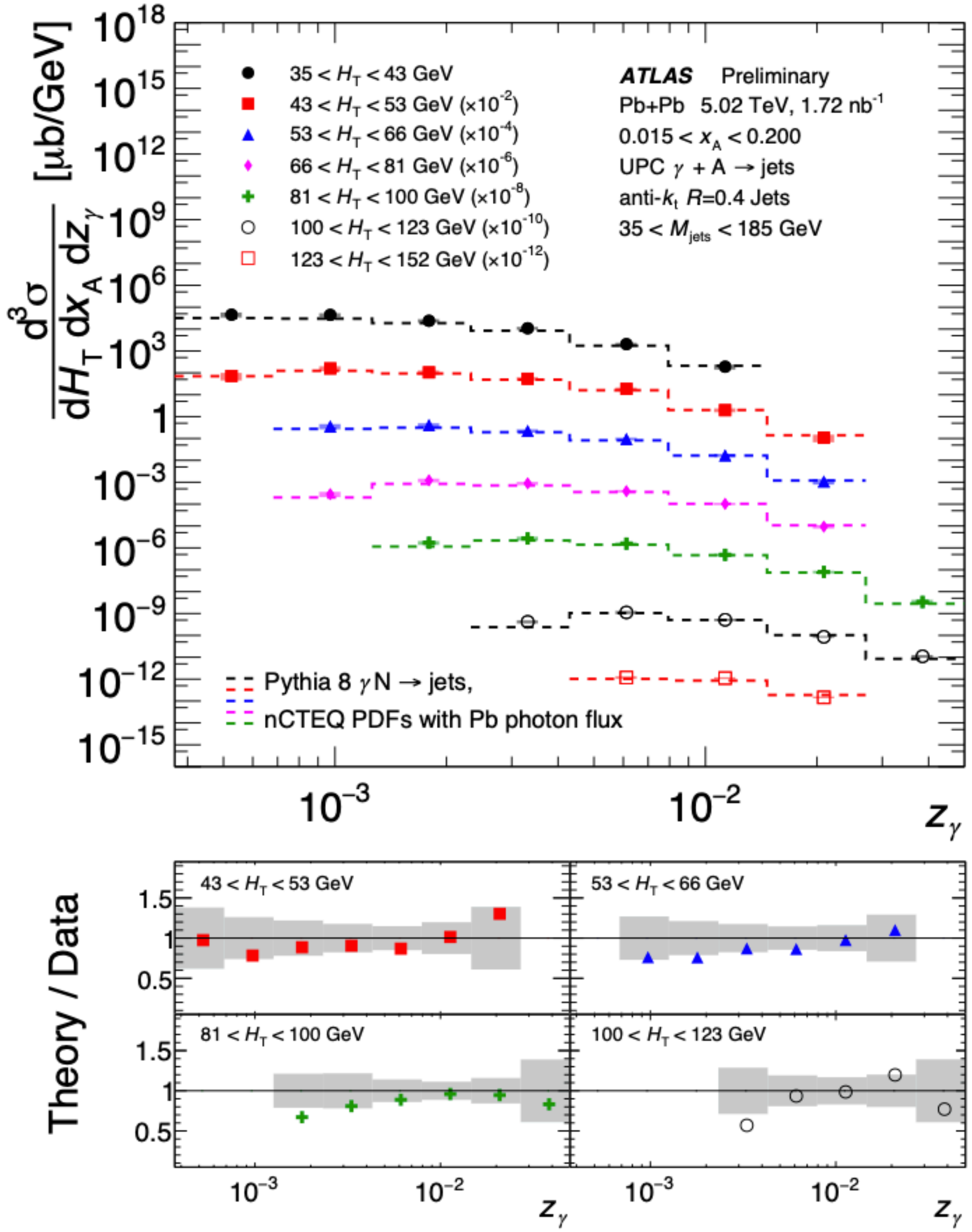




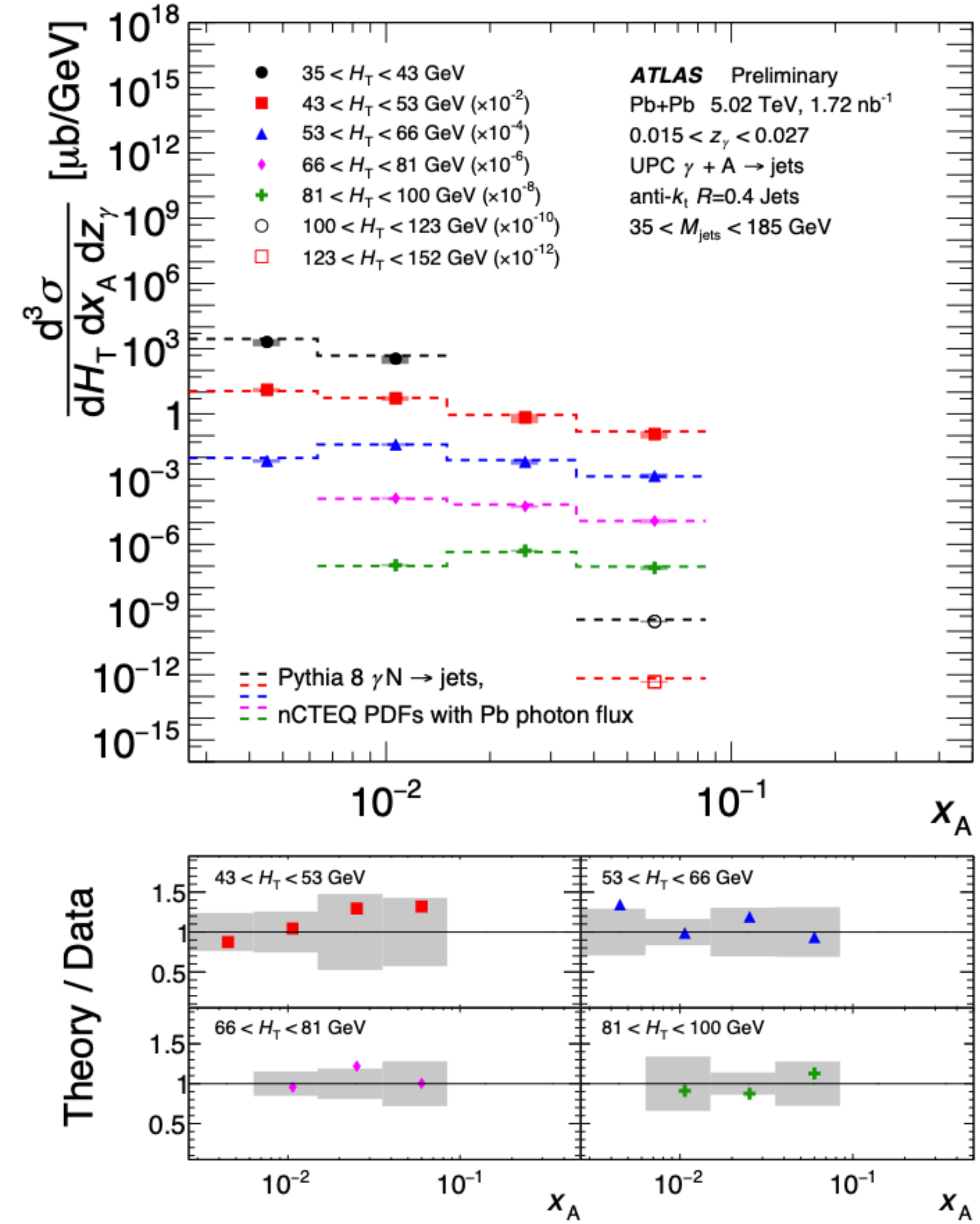
ATLAS-CONF-2022-021

γ+Pb: dijet cross-sections

measured photon flux



access to low x with high z_γ



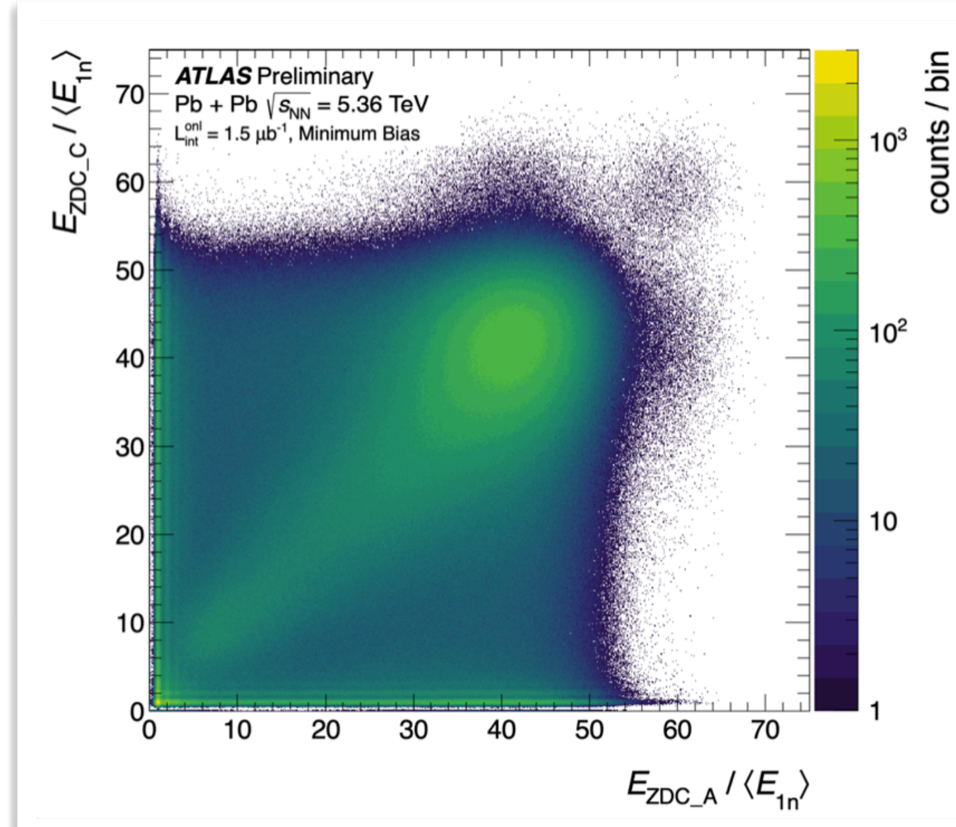
- Good description by Pythia8 with Pb photon flux and nCTEQ PDFs

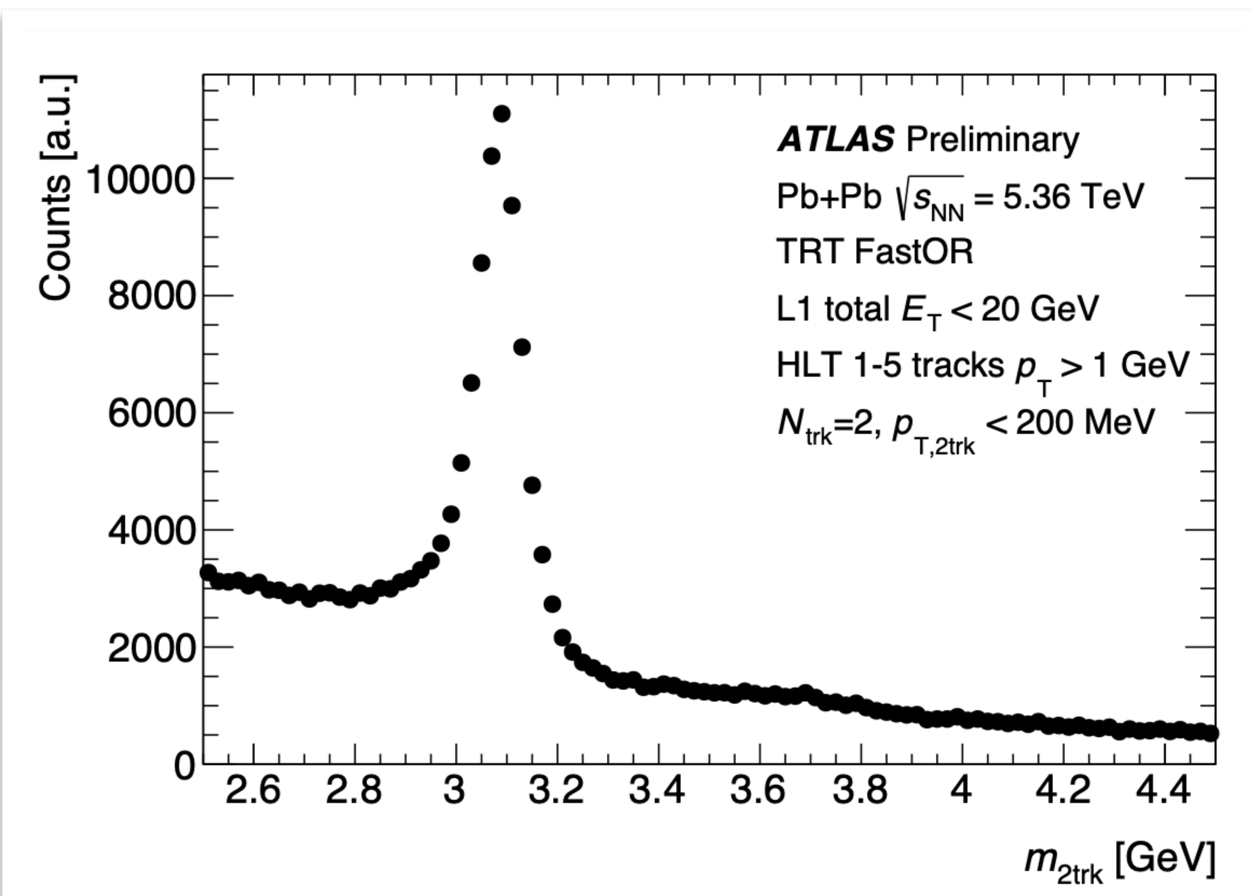
ATLAS-CONF-2022-021

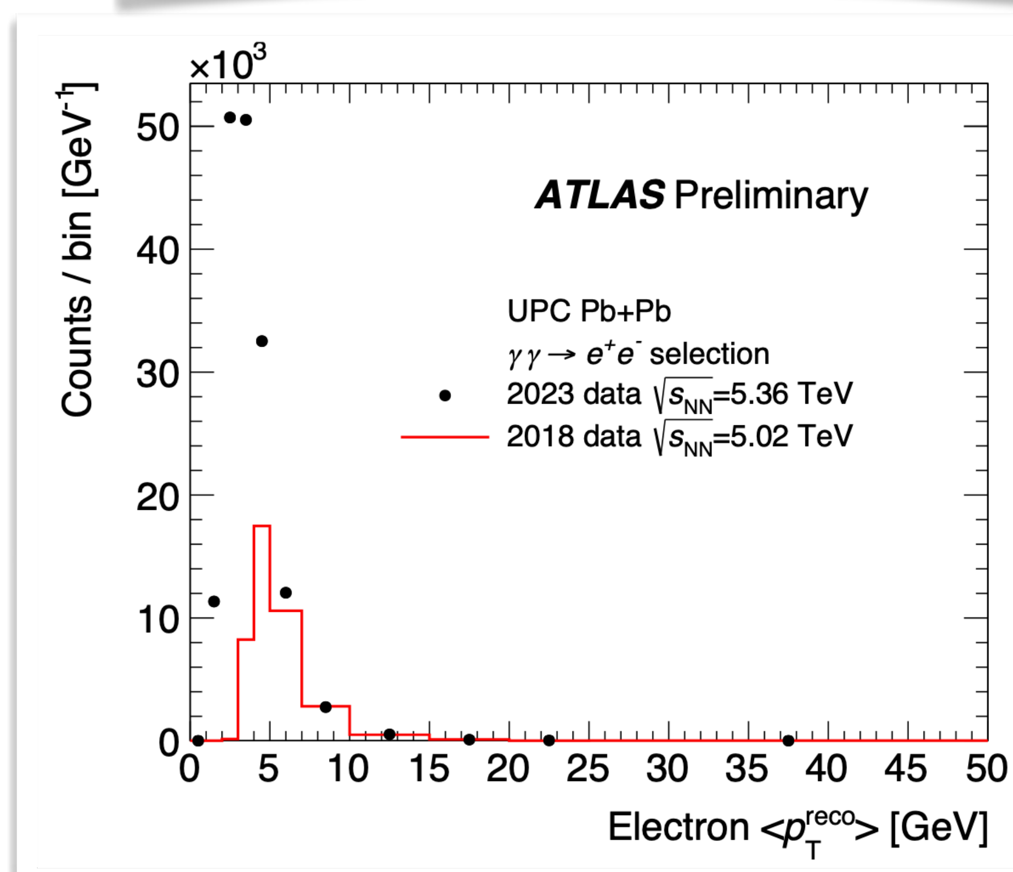
See also talk by Blair!

First Run-3 Pb+Pb data available

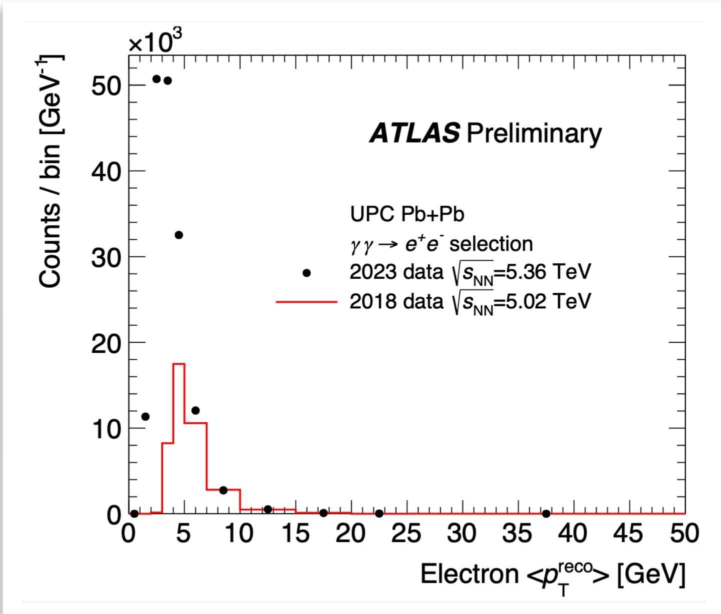
- **New Pb+Pb data collected in October 2023!**
  - 1.7 nb^{-1} at $\sqrt{s_{NN}} = 5.36$ TeV
- Readout and trigger upgrade of ZDC
- Significant improvements in trigger and reconstruction efficiency at low-p_T for leptons
- A lot of J/Ψ from Run-3 Pb+Pb data!

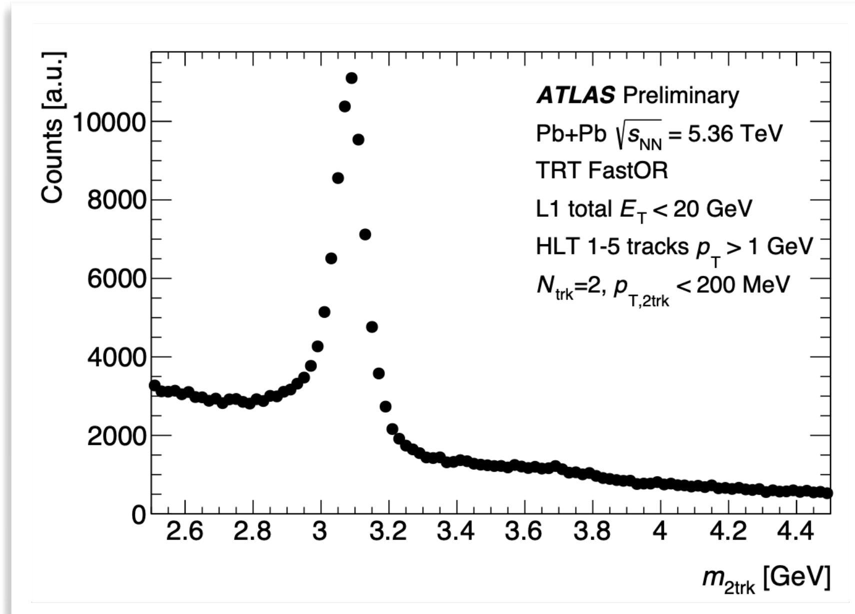


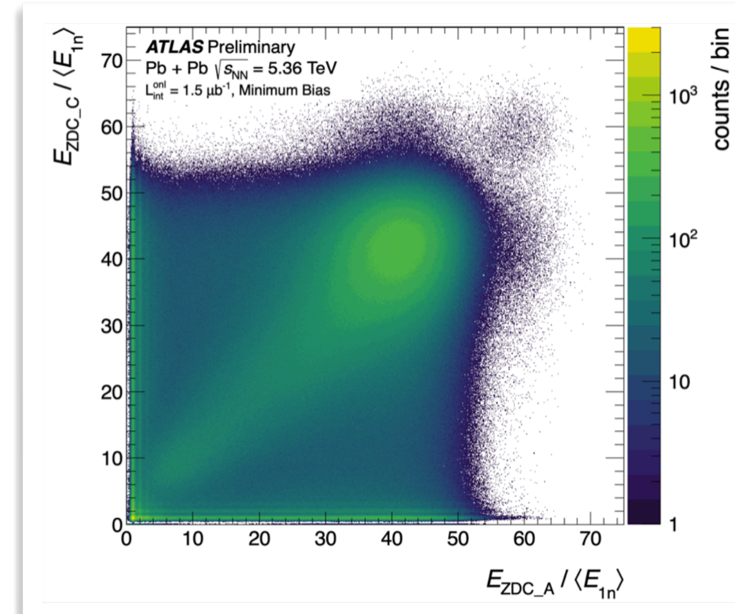




Summary







- UPCs can be used to probe rare SM processes and search for BSM phenomena
- ATLAS has a rich and diverse UPC physics program
- New 2023 Pb+Pb data ready to analyse - stay tuned for new results!

See also talks by Iwona, Sruthy and Blair!

- "Measurement of dilepton production from photon fusion processes in UPC in Pb+Pb collisions with the ATLAS detector"- By **Iwona Grabowska-Bold — Tuesday 2:00 pm**
- "Measurement of dijet production in UPC with the ATLAS detector" - By **Blair Daniel Seidlitz — Thursday 9:30 am**
- „Measurements of the properties of photonuclear events in UPC with the ATLAS detector" - By **Sruthy Jyothi Das - Thursday 6:00 pm**

All results from ATLAS available at:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults

Research project partly supported by the National Science Centre of Poland under grant number UMO-2021/40/C/ST2/00187 and by PL-GRID infrastructure."

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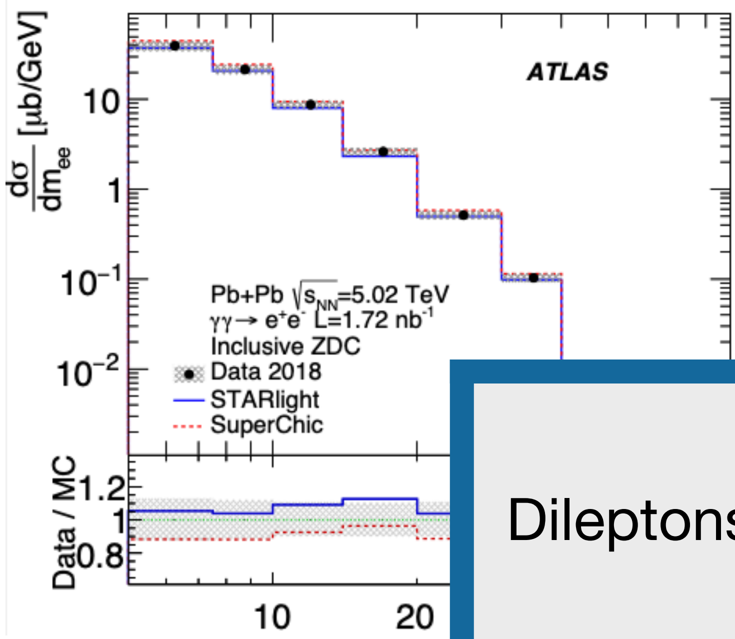
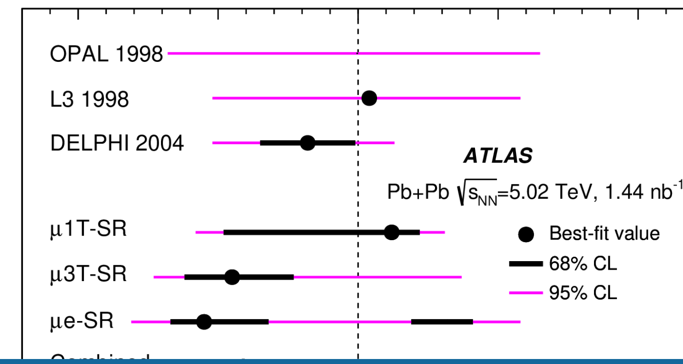
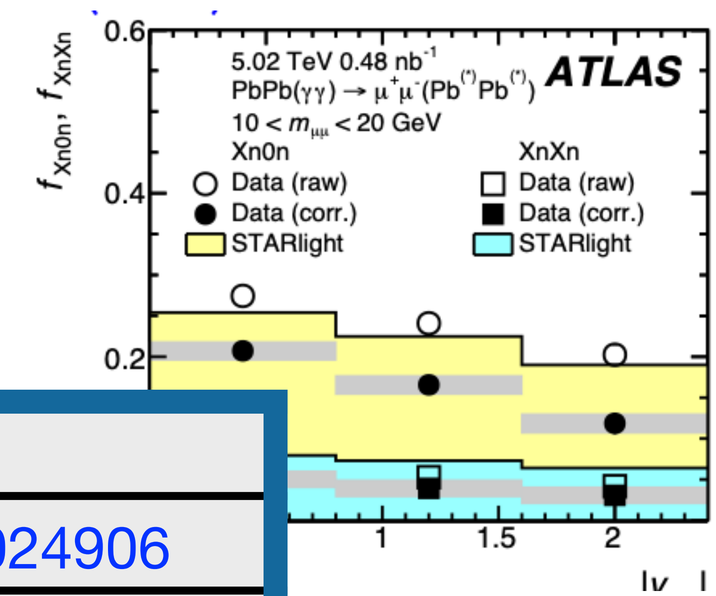
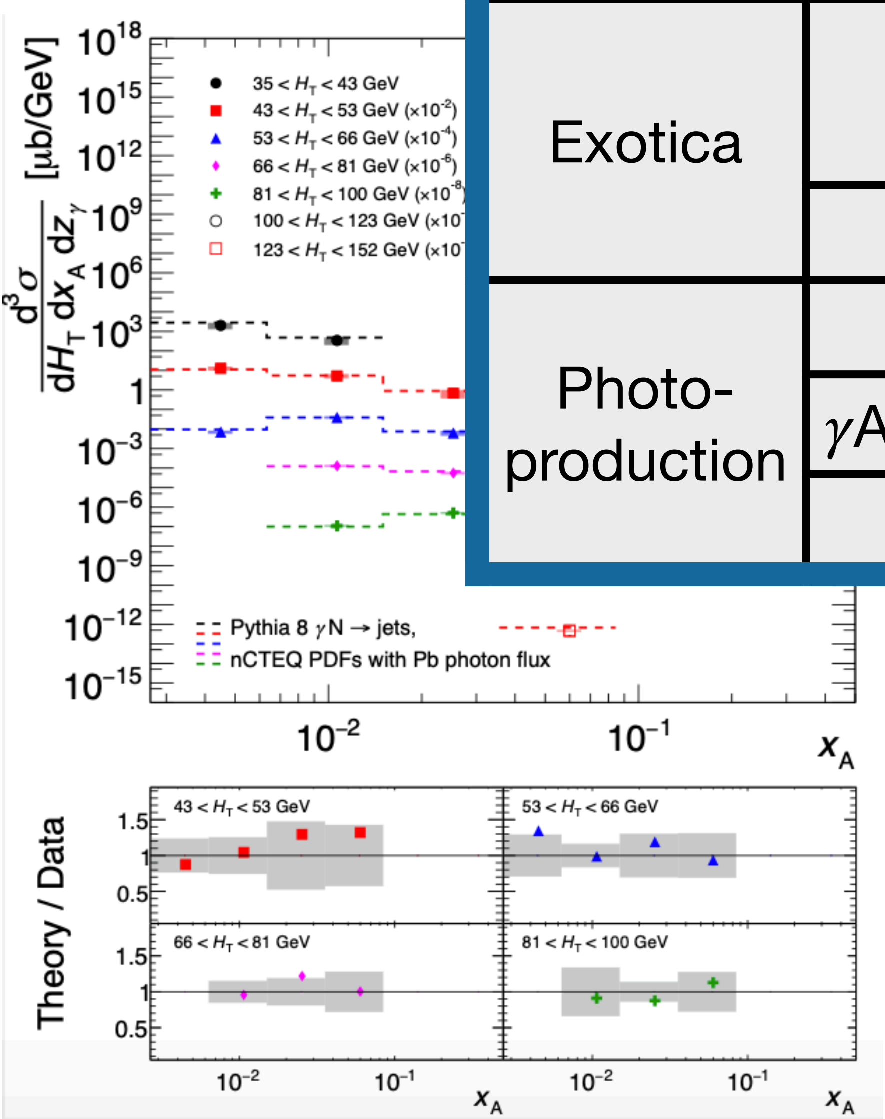
Additional slides

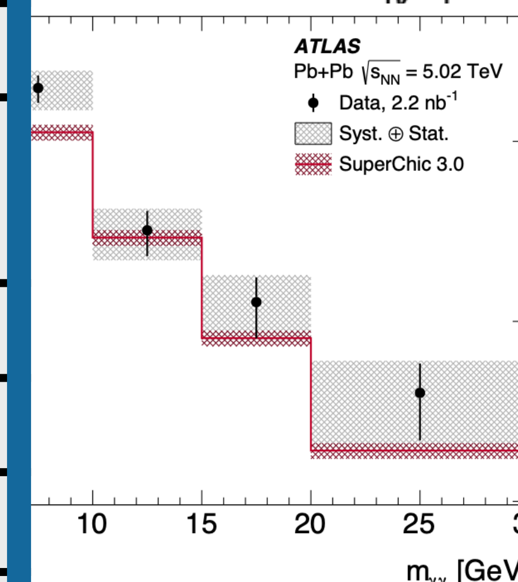
Photon-induced processes: ATLAS results

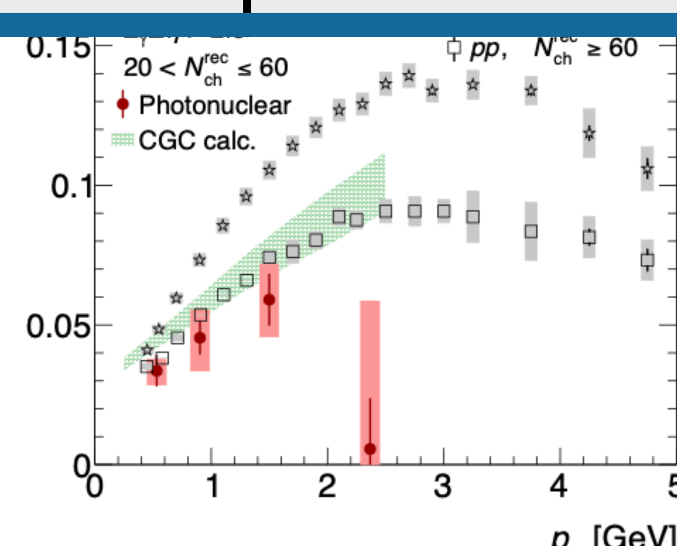


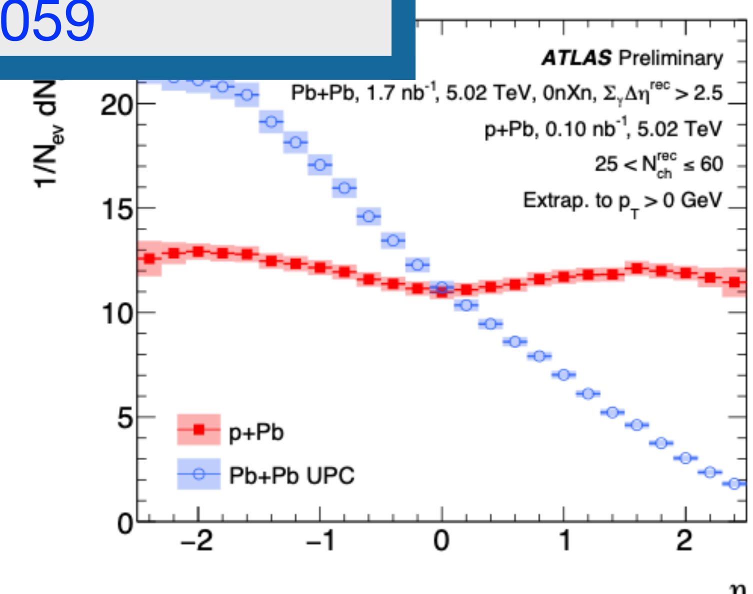










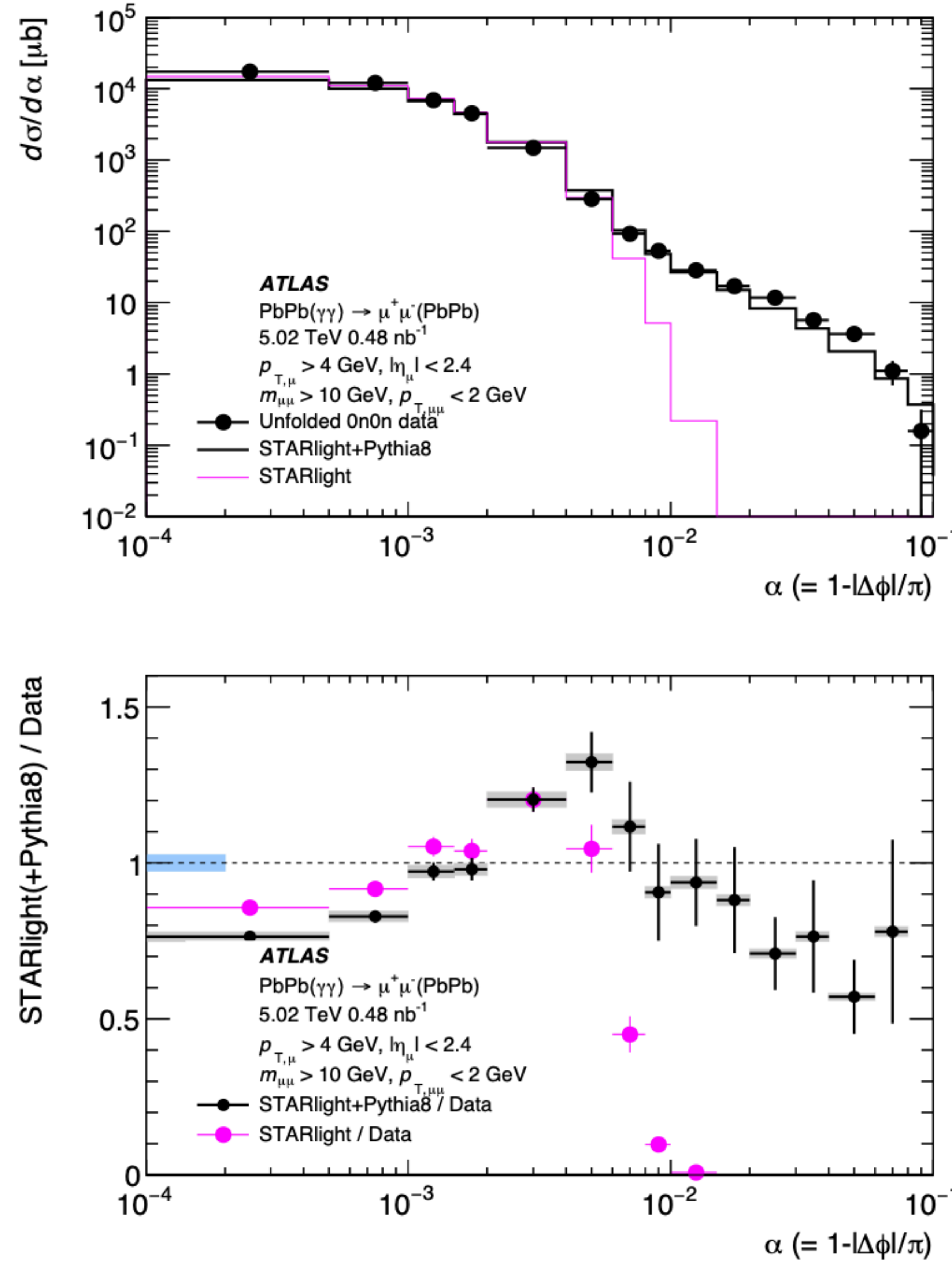


Dileptons	$\gamma\gamma\to ee$	JHEP 06 (2023) 182
	$\gamma\gamma\to\mu\mu$	Phys. Rev. C 104 (2021) 024906
	$\gamma\gamma\to\tau\tau$	Phys. Rev. Lett. 131 (2023) 151802
Exotica	$\gamma\gamma\to\gamma\gamma$	Nature Physics 13 (2017) 852 Phys. Rev. Lett. 123 (2019) 052001
	$\gamma\gamma\to$ALP	JHEP 03 (2021) 243
Photo-production	$\gamma A\to$jets	ATLAS-CONF-2022-021
	$\gamma A\to$h+X, 2PC	Phys. Rev. C 104 (2021) 014903
	$\gamma A\to$h+X	ATLAS-CONF-2023-059

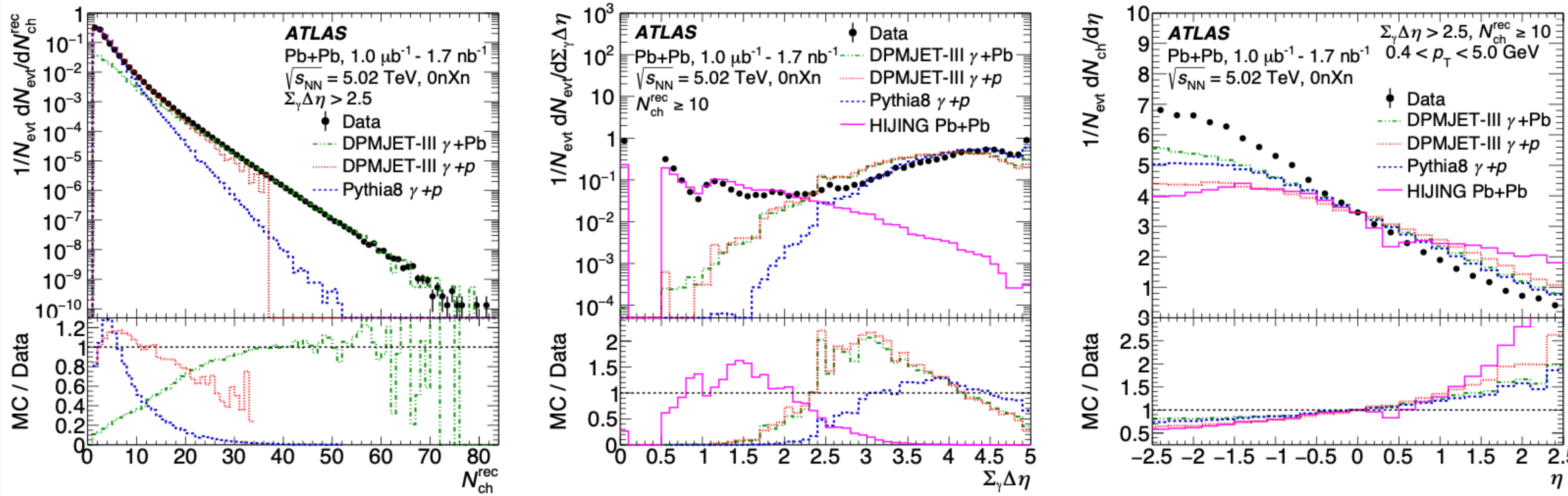
$\gamma\gamma \to ll$: QED FSR emission modelling

- Modelling studied using coplanarity 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

Phys. Rev. C 104 (2021) 024906



γ+A: event characteristics

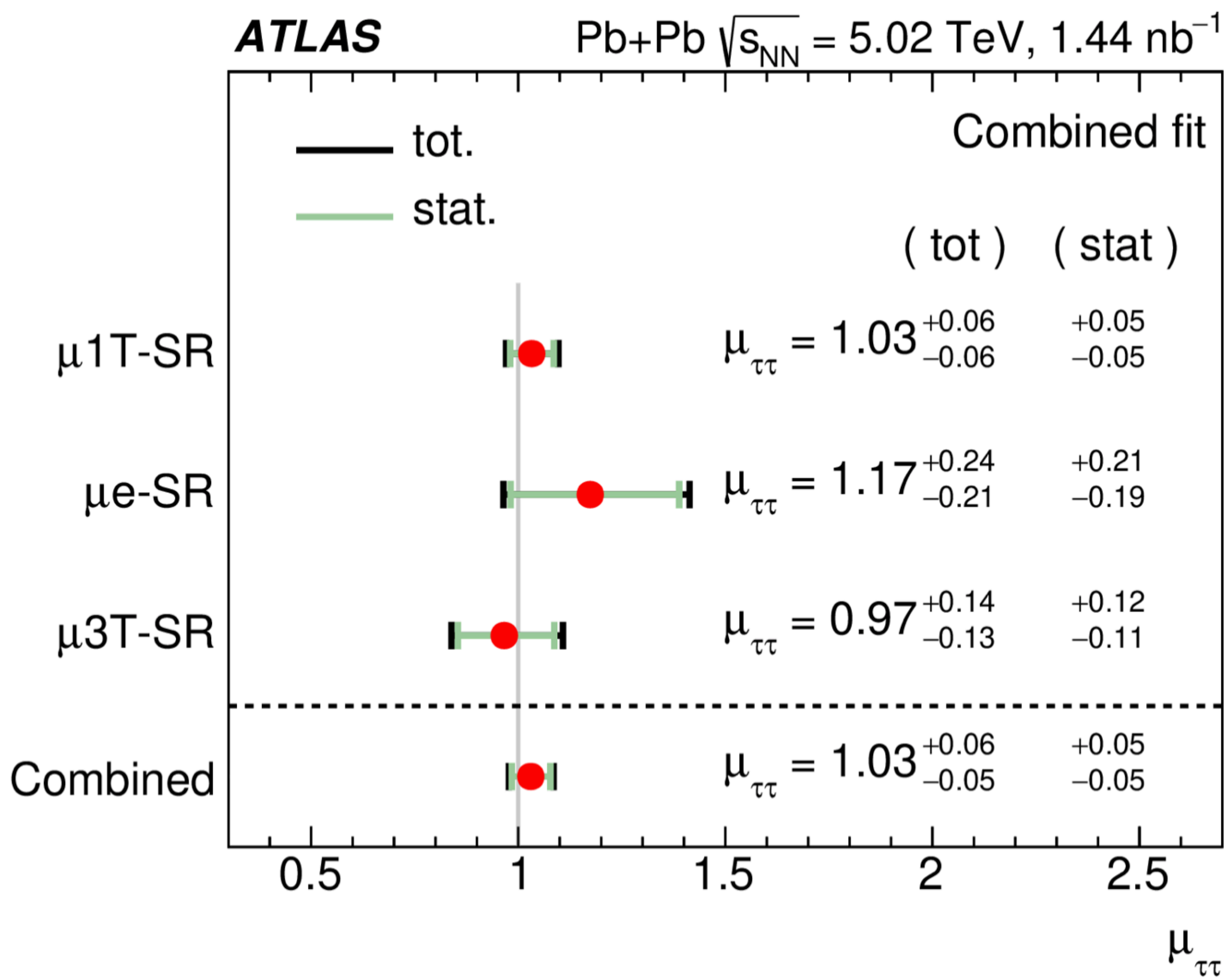


- Few previous studies exist of general characteristics of min-bias γ+A
- Track multiplicity: fairly good description at low values by DPMJET-III and Pythia8 γ+p, tail better described by DPMJET-III γ+Pb
- Photon-direction sum of gaps: reasonable agreement with sum of peripheral HIJING Pb+Pb and DPMJET-III γ+Pb
- Track signed rapidity: distribution strongly skewed towards nucleus-going direction (negative η), all generator setups fail to reproduce steep slope

Phys. Rev. C 104 (2021) 014903

$\gamma\gamma\rightarrow\tau\tau$: signal strength

$\mu_{\tau\tau}$ = observed yield / SM expectation

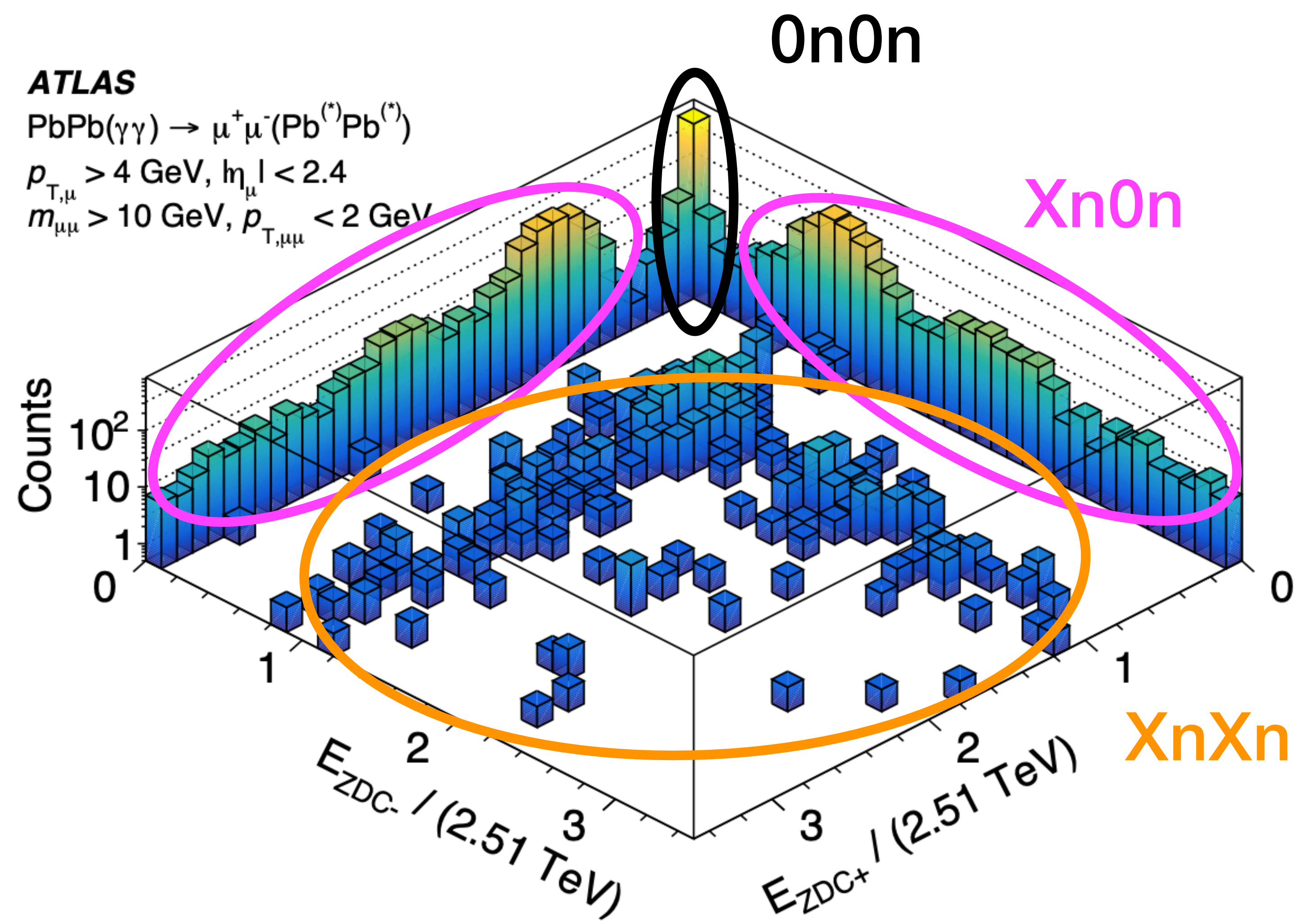


Phys. Rev. Lett. 131, 151802

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

Signal categories - ZDC selection

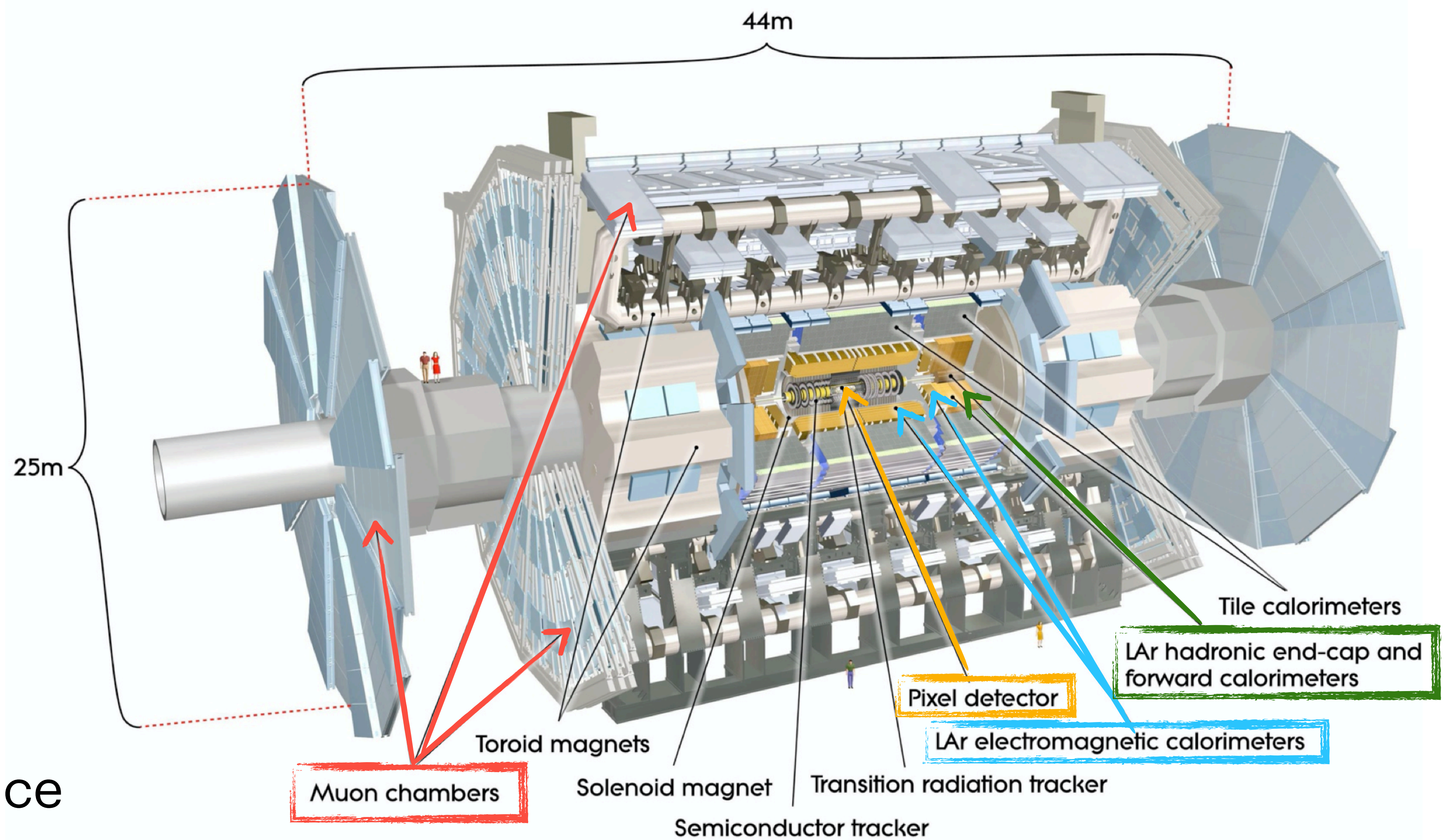
- Different processes present different activity in the forward region:
  - Exclusive dilepton production - ions stay intact
  - Background events with nuclear breakup
- Three classes defined, based on the signal in the ZDC



- The association between given ZDC signal and given process is nontrivial
  - Migrations due to ion excitation and presence of EM pile-up

ATLAS detector

Main components:
inner tracker,
electromagnetic (EM),
and hadronic (HAD)
calorimeters,
and muon system



φ - full azimuth acceptance

η - broad pseudo rapidity coverage

$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

p_T - transverse momentum

$$p_T = \sqrt{p_x^2 + p_y^2}$$