Observation of $\gamma\gamma \to \tau\tau$ in Pb+Pb collisions and constraints on the τ-lepton $g-2$ with the ATLAS detector

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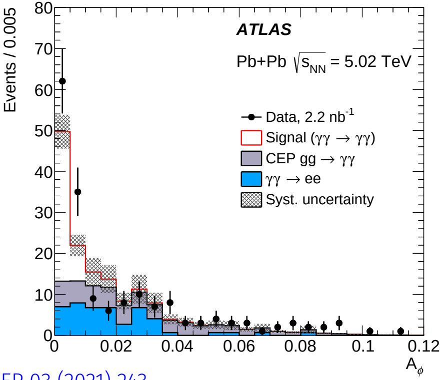
ATLAS EXPERIMENT

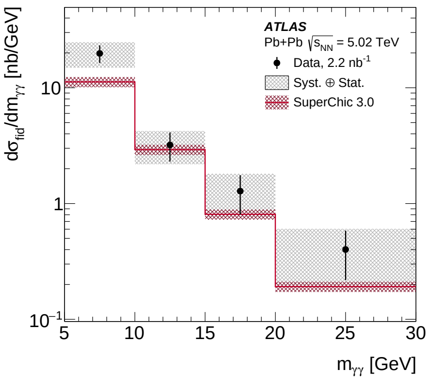
Alexander von Humboldt Stiftung/Foundation

QM QUARK MATTER KRAKÓW 2022

Before going to the τ-leptons, let's look back at the photons...

- Light-by-light scattering: probe rare SM process and search for BSM phenomena
- Event selection: 2 photons with $E_{\mathrm{T}}^{\gamma} > 2.5$ GeV, $A_{\phi}^{\gamma\gamma} < 0.01$, no tracks
- Backgrounds from:
    - CEP $gg \to \gamma\gamma$ (data-driven estimate)
    - $\gamma\gamma \to ee$ with mis-identified electrons (MC estimate)
- Cross-sections measured differentially in $m_{\gamma\gamma}$, $|y_{\gamma\gamma}|$, p_{T}^{γ}, $|\cos\theta^*|$





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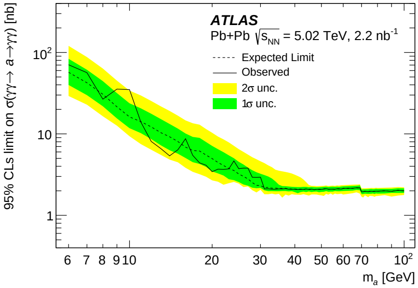
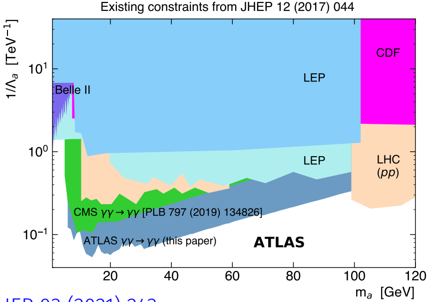
$\gamma\gamma \to \gamma\gamma$: search for axion-like particles





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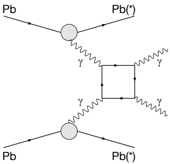
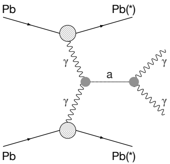
SM: loops



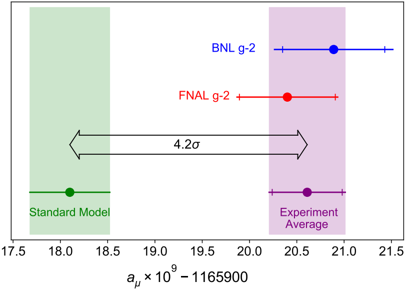
ALPs: s-channel



- 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

Now let's move to the τ-leptons...

- g-factor relates a particle's magnetic moment to its spin: $\vec{\mu} = g\frac{q}{2m}\vec{S}$
- Dirac equation predicts $g = 2$, but higher-order corrections (QED, weak, hadronic loops, ...) lead to $g \neq 2$
- Lepton anomalous magnetic moments $a_\ell = \frac{(g-2)_\ell}{2}$ are sensitive to various BSM models (leptoquarks, lepton compositeness, SUSY, ...)



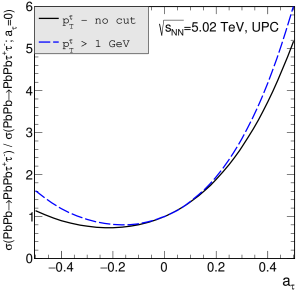
Muon g-2 Coll., PRL 126 (2021) 141801

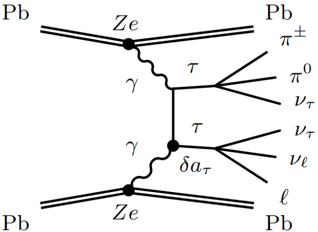
- a_e and a_μ are among the most precisely measured observables in Nature
- Tensions with SM predictions observed for a_e (2.5σ) and a_μ (up to 4.2σ)
- a_τ is much less constrained: $-0.052 < a_\tau < 0.013$ (95% CL)
  DELPHI, EPJC 35 (2004) 159
- a_τ is more sensitive to some BSM effects

Measuring a_τ in ultraperipheral Pb+Pb collisions

- Theoretical framework outlined in:
  - L. Beresford, J. Liu, PRD 102 (2020) 113008
  - M. Dyndal, M. Schott, M. Klusek-Gawenda, A. Szczurek, PLB 809 (2020) 135682
- Exploit $\gamma\gamma \to \tau\tau$ cross-section to set limits on a_τ
- Experimental challenges:
  - hadronic backgrounds
  - neutrinos in the final state
- Advantages of ultraperipheral Pb+Pb collisions (UPC) over *pp* collisions:
  - huge photon fluxes $\to Z^4$ cross-section enhancement
  - $\sim$no hadronic pile-up $\to$ exclusivity selections
  - low p_T thresholds in trigger and offline reconstruction
- τ-leptons never directly targeted in measurements using nucleus-nucleus data

PLB 809 (2020) 135682





$Z = 82$

$Z^4 \approx 4.5 \cdot 10^7$

Measurement overview

New result:
CERN-EP-2022-079

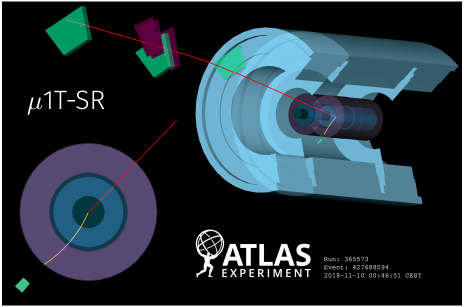
- Measurement uses 1.44 nb^{-1} of 2018 UPC data
- Monte Carlo simulations:
  - $\gamma\gamma \to \tau\tau$ signal: Starlight+Tauola (Pythia8+Photos for QED FSR)
  - $\gamma\gamma \to \mu\mu$ background: Starlight+Pythia8
  - $\gamma\gamma \to \mu\mu\gamma$ background: Madgraph5 (reweighted to Pb+Pb photon flux)
  - all samples reweighted to photon flux from SuperChic3

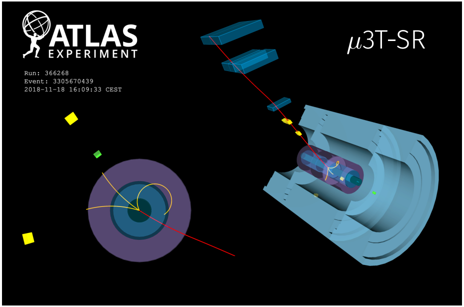
- Standard ATLAS hadronic τ reconstruction not efficient for signal ($p_\mathrm{T}^\mathrm{vis} \lesssim 10$ GeV)
- Trigger signal candidates using muonic τ decays and categorise using electrons or low-p_T tracks for second τ decay:
  - **μ1T-SR**: muon + 1 track (e/μ/hadron)
  - **μ3T-SR**: muon + 3 tracks (3 hadrons)
  - **μe-SR**: muon + electron

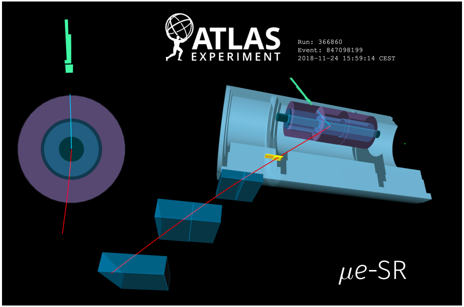
Muons: $p_\mathrm{T}^\mu > 4$ GeV
Electrons: $p_\mathrm{T}^e > 4$ GeV
Tracks: $p_\mathrm{T}^\mathrm{trk} > 100$ MeV
Clusters: $p_\mathrm{T}^\mathrm{clus} > 1$ GeV ($|\eta| < 2.5$),
$p_\mathrm{T}^\mathrm{clus} > 100$ MeV ($2.5 < |\eta| < 4.5$)

- Data only: 0n0n ZDC selection to suppress photonuclear/hadronic backgrounds
- Simulation reweighted from 0n0n+0nXn+XnXn to 0n0n with data-driven weights
- Exclusivity: veto additional clusters (μ1T-SR and μ3T-SR only) and tracks

Signal candidate events

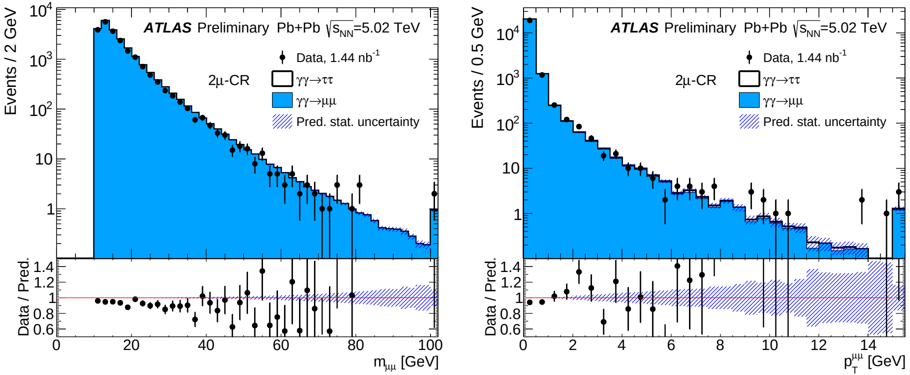




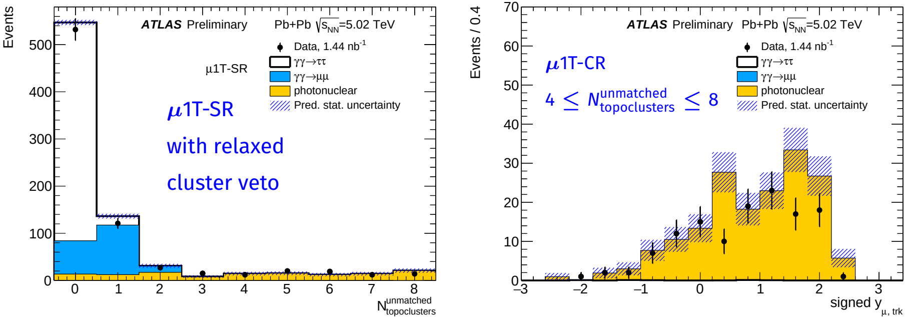


muon
track
electron

Backgrounds: $\gamma\gamma \to \mu\mu(\gamma)$ production

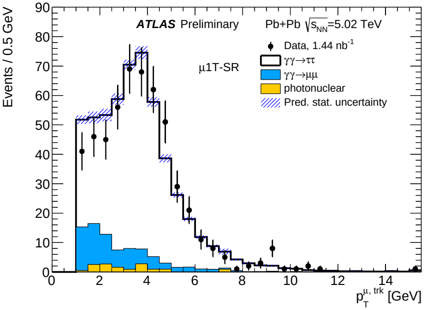


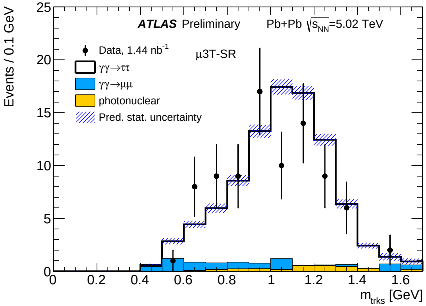
- Background from $\gamma\gamma \to \mu\mu(\gamma)$ production estimated using MC simulation
- Validation of modelling performed in dimuon control region (**2μ-CR**)
- Normalisation off by $+6\%$ with SuperChic3 photon flux (Starlight: -13%)
- Good description of FSR emissions seen in $p_T^{\mu\mu}$ distribution tail

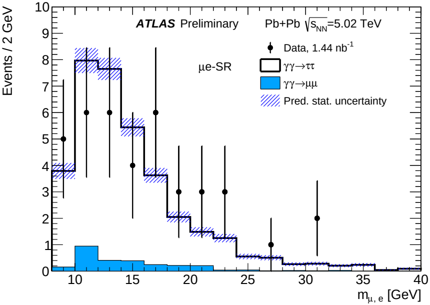


- Data-driven estimation of diffractive photonuclear events in μ1T-SR and μ3T-SR
- Templates built from control regions similar to SRs, but requiring an additional track with $p_T < 500$ MeV and allowing 0nXn ZDC events
- Normalisation: relax cluster veto $\rightarrow$ use region with 4-8 unmatched clusters
- Kinematic distributions in this region well described by the CR templates

Signal region distributions



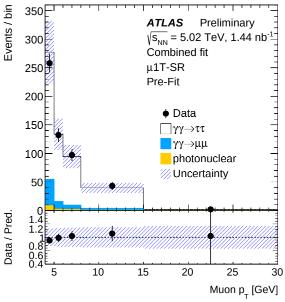


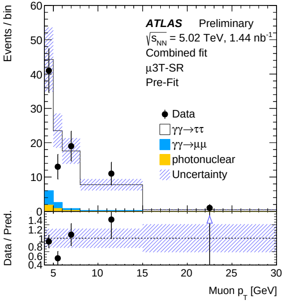


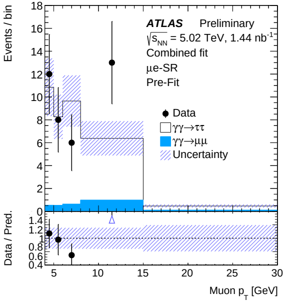
- Good agreement of pre-fit predictions with data
- Total of ∼ 650 events across all SRs
- Small background contributions

Fit setup

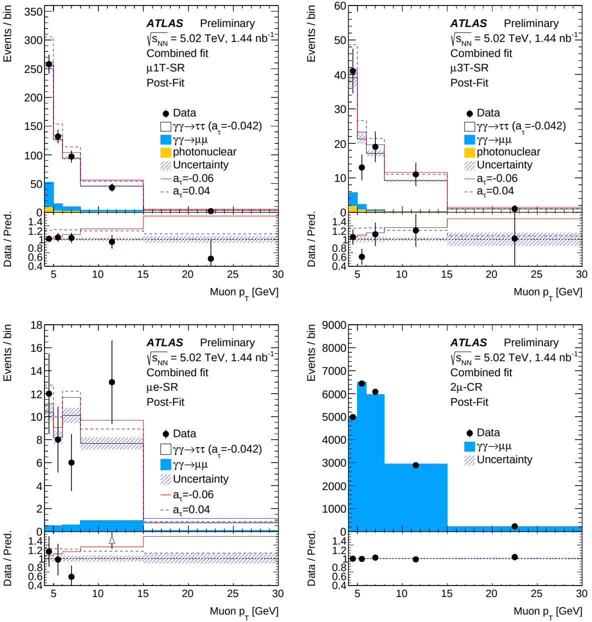
- Measure $\gamma\gamma \to \tau\tau$ signal strength and a_τ using profile likelihood fit to the muon p_T distribution in the three SRs and 2μ-CR
- Build templates for different a_τ values by reweighting signal MC using weights from PLB 809 (2020) 135682:
  - a_τ values: 0, ±0.01, ±0.02, ±0.03, ±0.04, ±0.05, ±0.06, ±0.1
  - 3D weights in $m_{\tau\tau}$, $|y_{\tau\tau}|$, $|\Delta\eta_{\tau\tau}|$
- Pre-fit distributions of p_T^{μ} in the SRs assuming SM value of a_τ:





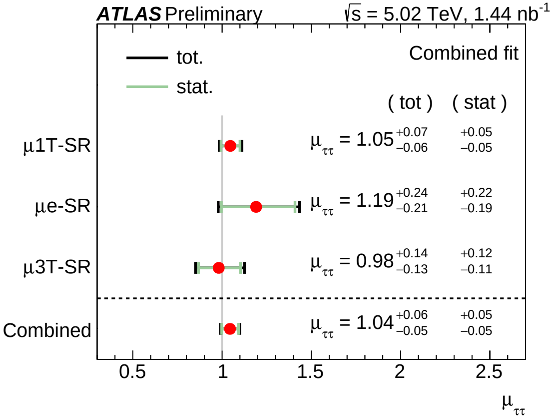


Post-fit p_T^μ distributions

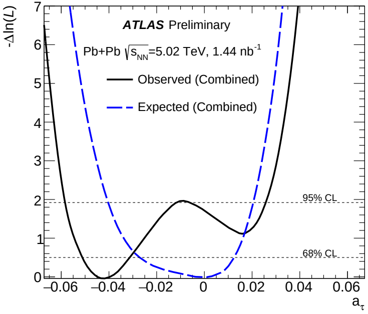


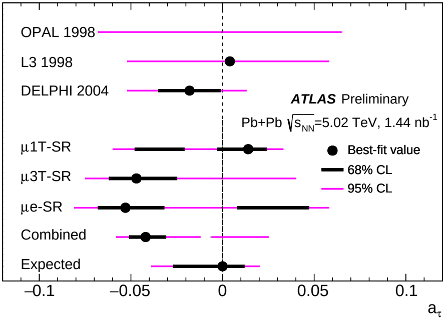
- Post-fit distributions of p_T^μ in the SRs and 2μ-CR
- Results of combined fit using all regions
- Clear observation ($\gg 5\sigma$) of $\gamma\gamma \to \tau\tau$ process
- Photon flux modelling well constrained with high-precision and high-purity 2μ-CR

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



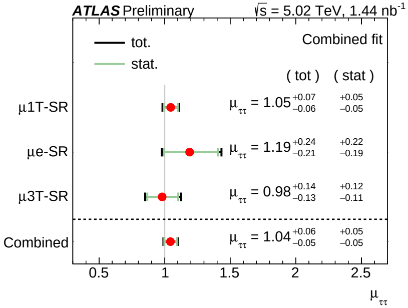
- Fit of $\gamma\gamma \to \tau\tau$ signal strength assuming SM value for a_τ
- Result for each signal region compatible with unity
- Combined fit reaches 5% precision, limited by statistical uncertainties

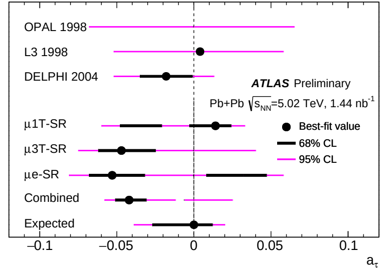




- Expected 95% CL limits from combined fit: $-0.039 < a_\tau < 0.020$
- **Observed 95% CL limits**: $a_\tau \in (-0.058,\ -0.012) \cup (-0.006,\ 0.025)$
- Double-interval structure due to interference of SM and BSM amplitude
- Constraints on a_τ similar to those observed by DELPHI
- Statistical uncertainties dominant, leading systematic uncertainties: trigger efficiency, τ decay modelling

Summary





- UPCs can be used to probe rare SM processes and search for BSM phenomena
- Clear observation of $\gamma\gamma \to \tau\tau$
- Signal strength of $\gamma\gamma \to \tau\tau$ measured with 5% precision
- Opening hadron-collider studies of electromagnetic τ properties
- Constraints on a_τ competitive with electron-collider results
- Results limited by statistical uncertainties $\to$ room for improvement with more data!

see also: poster by A. Ogrodnik

Additional slides

Signal / control regions

μ1T-SR
- exactly 1 muon
- no electrons
- exactly 1 track
- net charge = 0
- $p_T^{\mu+\text{trk}} > 1$ GeV
- $p_T^{\mu+\text{trk}+\gamma} > 1$ GeV
- $p_T^{\mu+\text{trk}+\text{clus}} > 1$ GeV
- $A_\phi^{\mu,\,\text{trk}} < 0.4$

μ3T-SR
- exactly 1 muon
- no electrons
- exactly 3 tracks
- net charge = 0
- $m_{\text{trks}} < 1.7$ GeV
- $A_\phi^{\mu,\,\text{trks}} < 0.2$

μe-SR
- exactly 1 muon
- exactly 1 electron
- net charge = 0

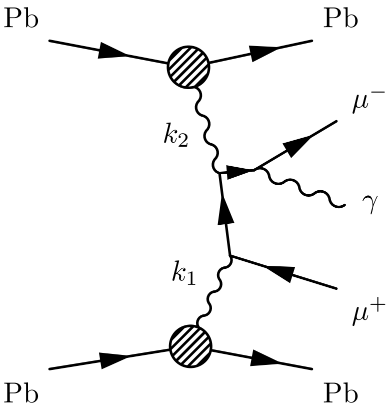
2μ-CR
- exactly 2 muons
- $m_{\mu\mu} > 11$ GeV

Muons: $p_T^\mu > 4$ GeV
Electrons: $p_T^e > 4$ GeV
Tracks: $p_T^{\text{trk}} > 100$ MeV
Clusters: $p_T^{\text{clus}} > 1$ GeV ($|\eta| < 2.5$),
$p_T^{\text{clus}} > 100$ MeV ($2.5 < |\eta| < 4.5$)

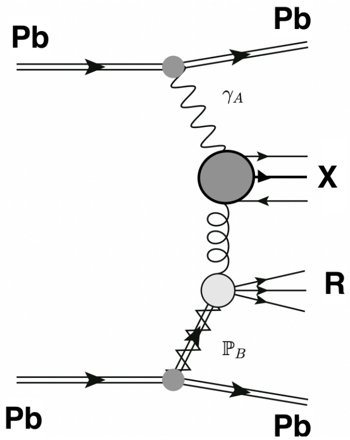
- Trigger requirements:
  - $p_T^\mu > 4$ GeV
  - total E_T in calorimeter below 50 GeV
  - E_T in forward calorimeters below 3 GeV (rapidity gaps)
- Data only: 0n0n ZDC selection (simulation reweighted: 0n0n+0nXn+XnXn $\rightarrow$ 0n0n)
- Exclusivity: veto additional clusters (μ1T-SR and μ3T-SR only) and tracks

Background processes

$\gamma\gamma \to \mu\mu(\gamma)$ production



diffractive photonuclear events



Systematic uncertainties in a_τ

- Detector-related:
  - **muon trigger efficiency**
  - muon/electron reconstruction/identification efficiency and calibration
  - track reconstruction efficiency
  - cluster reconstruction efficiency and calibration
- Background:
  - photonuclear background template variation
- Theory:
  - **photon flux modelling (SuperChic3 vs. Starlight)**
  - **τ decay modelling (Tauola vs. Pythia8)**
  - 0n0n ZDC reweighting variation