Tau anomalous magnetic moment measurements at ATLAS and CMS

Yuriy Volkotrub

on behalf of the ATLAS and CMS collaborations

Jagiellonian University

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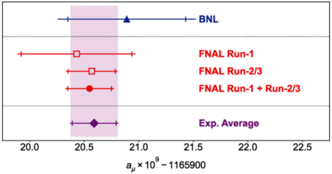
ATLAS EXPERIMENT

JAGIELLONIAN UNIVERSITY IN KRAKÓW

Outline

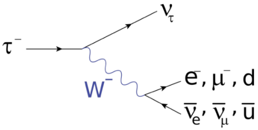
- Magnetic moment of the particle and its spin are related by g-factor: $\vec{\mu} = \frac{gq}{2m}\vec{S}$
- Anomalous magnetic moments $a_l = \frac{(g-2)l}{2}$ are sensitive to BSM physics
  - Dirac equation predicts $g = 2$, but higher-order corrections (QED, weak, hadronic loops, ...) lead to $\neq 2$
- a_τ is poorly constrained experimentally: $-0.52 < a_\tau < 0.013$ (95% CL) DELPHI, EPJC 35 35 (2004) 159
  Due to it can be sensitive to BSM effects
- For example, measurements of a_e and a_μ are the most accurate.
  Difference with SM predictions observed for a_e (2.5σ) and a_μ (up to 4.2σ)
- Sensitivity to supersymmetry effects depends on lepton mass $\delta a_l \sim m_l^2/M_S^2$
  - a_τ is up to ~ 280 more sensitive to new physics than a_μ



Muon g-2 Collaboration, PRL 131 (2023) 161802 represents a factor of 2 improvement in precision compared to the 2021 result

- 1-prong: tau decays into 1 charged particle with BR$\sim$ 80%:

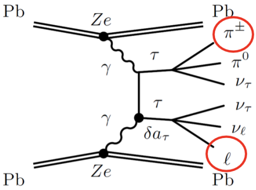
$$\mathrm{BR}(\tau^{\pm} \to e^{\pm} + \nu_e + \nu_\tau) = 17.8\%$$
$$\mathrm{BR}(\tau^{\pm} \to \mu^{\pm} + \nu_\mu + \nu_\tau) = 17.4\%$$
$$\mathrm{BR}(\tau^{\pm} \to \pi^{\pm} + n\pi^{0} + \nu_\tau) = 45.6\%$$



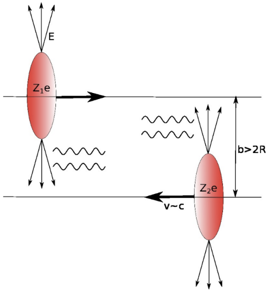
- 3-prong:

$$\mathrm{BR}(\tau^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm} + \text{neutral pions}) = 19.4\%$$

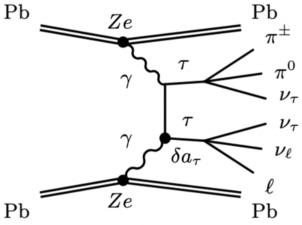
- Selection in UPCs:
  1 lepton + 1 charged particle
  1 lepton + 3 charged particles



- UPC of heavy ions
  - impact parameter $>$ 2x nucleus radius
  - electromagnetic (EM) fields of relativistic ions considered as fluxes of photons (scale $\sim Z^2$)
- Advantages of UPCs of heavy-ions:
  - no hadronic interaction between nuclei
  - very low hadronic pileup (little activity in the detector) - exclusive selections possible
  - high charge = large photon flux
  - increased cross-sections wrt to pp system (Z^4 scaling)
  - ion emitting photon does not break up
  - low-p_T particles can be triggered and reconstructed
  - as a probe can be used to study very rare processes (exclusive dielectrons, light-by-light, ALP searches, etc)



- Well described in Weizsäcker-Williams approximation
- Hadronic interactions strongly suppressed $\to$ exclusivity selections
- Low p_T thresholds in trigger and offline reconstruction
- **Zero Degree Calorimeters** (ZDC) and a **Forward Calorimeter** (FCal) @ATLAS and **Forward Hadron** (HF) @CMS calorimeter allow to control event activity above the noise threshold in the forward region
- Exploit $\gamma\gamma \to \tau\tau$ cross section to set limits on a_τ
- $\gamma\gamma \to \tau\tau$ production observed for the first time in hadron collisions at the LHC in 2022

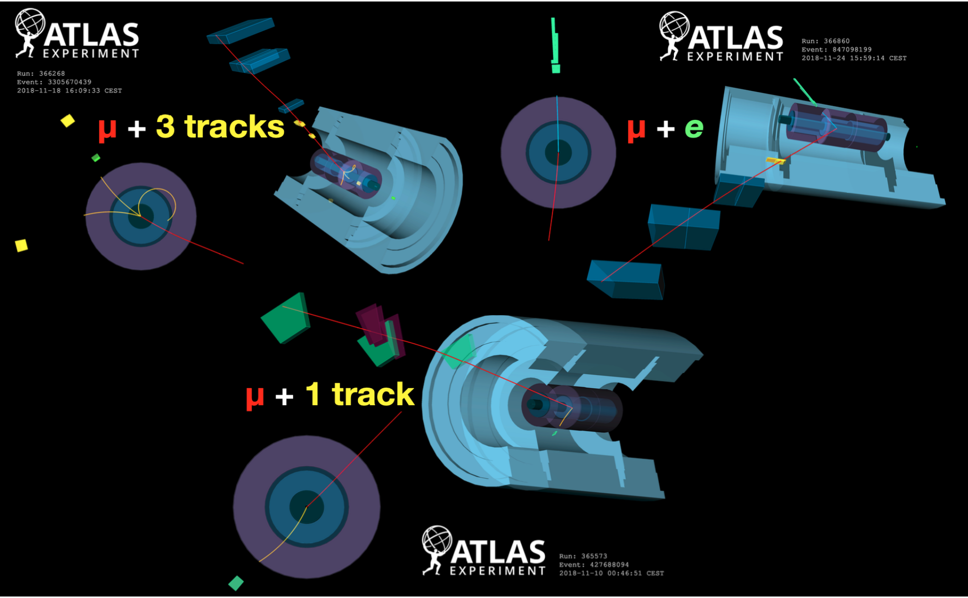


L. Beresford, J. Liu,
PRD 102 (2020) 113008
M. Dyndal et al.,
PLB 809 (2020) 135682

- This talk discusses new measurements performed by the ATLAS and CMS Collaborations in UPC Pb+Pb at 5.02 TeV. The articles were highlighted as an Editor's Suggestion in the journal Physical Review Letters.

ATLAS measurement overview

Ditau events

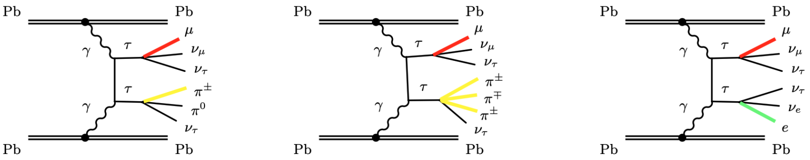


- **First observation** of $\gamma\gamma \to \tau^+\tau^-$ process in HI UPC using 1.44 nb^{-1} of 2018 UPC data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV recorded by ATLAS
- **Signal** τ-leptons are **low-energetic**, typically with $p_T < 10$ GeV
- Events classified based on the charged τ-lepton decay products
- **Three signal regions:**

µ1T-SR: muon + 1 track

µ3T-SR: muon + 3 tracks

µe-SR: muon + electron

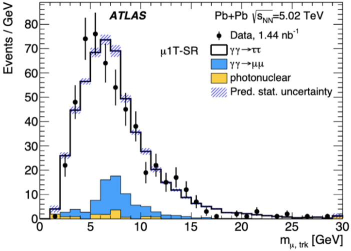


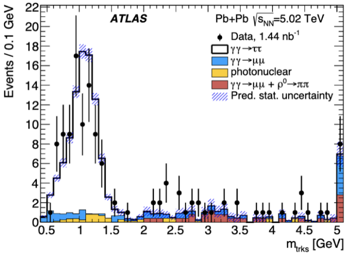
  - requiring 0n0n and cluster veto to suppress dissociative and hadronic backgrounds

- Single muon trigger recording events having muon with $p_T > 4$ GeV
- Veto on forward neutron activity (based on ZDC signal) $\rightarrow$ MC samples reweighed

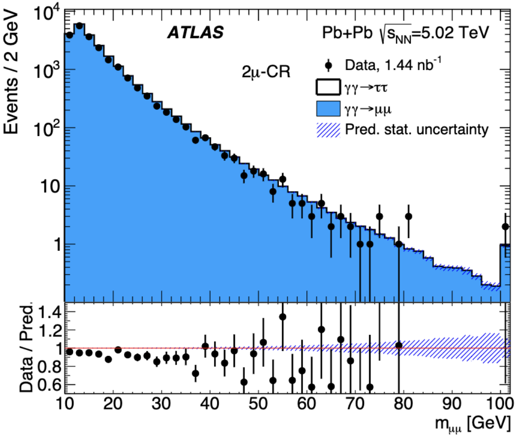
- **Kinematic selection:**
  - muons: $p_T > 4$ GeV, $|\eta| < 2.4$
  - electrons: $p_T > 4$ GeV, $|\eta| < 2.47$
  - tracks: $p_T > 100$ MeV, $|\eta| < 2.5$

- **Other requirements:**
  - veto on additional low-p_T clusters (for μ1T-SR and μ3T-SR) and low-p_T tracks
  - For μ1T-SR: $p_T^{\mu,trk} > 1$ GeV
  - For μ3T-SR: $m_{3trks} < 1.7$ GeV



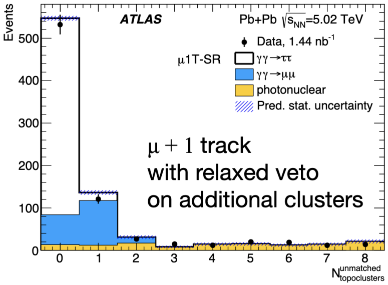


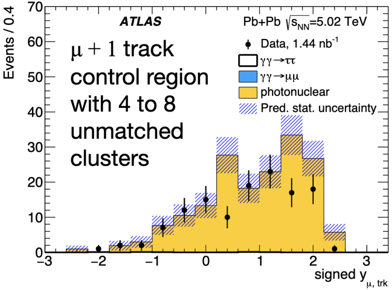
- Main **background contributions** from dimuon production and diffractive photonuclear interactions
- Background from $\gamma\gamma \to \mu\mu(\gamma)$ **production** estimated using **MC simulation**, constrained by a data CR
- Already pre-fit distributions in the two muon CR show good agreement of data and MC



Backgrounds

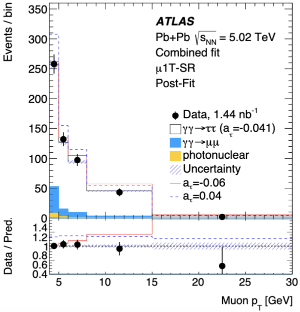
- **Diffractive photonuclear** present in μ1T-SR and μ3T-SR signal regions, estimated with data-driven technique
- Control regions defined with additional track with $p_T < 500$ MeV and allowing events from Xn0n category
- Event yields extrapolated from control to signal region by relaxing the veto on additional (unmatched) clusters from 0 to 8
- Normalisation done to the event yield in the region with 4 to 8 unmatched clusters

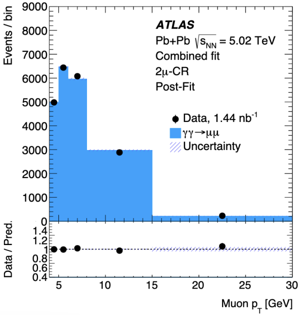




- The $\gamma\gamma \to \tau^+\tau^-$ signal strength and a_τ value are extracted using a **profile likelihood fit** using the muon p_T distribution
- Main background from $\gamma\gamma \to \mu\mu(\gamma)$ **production** estimated using **MC simulation**, constrained by a data CR
- **Simultaneous fit** combining all signal regions and dimuon control region
    - Dimuon **control region** ($\gamma\gamma \to \mu\mu$ events) used to **reduce systematic uncertainty** from the photon flux

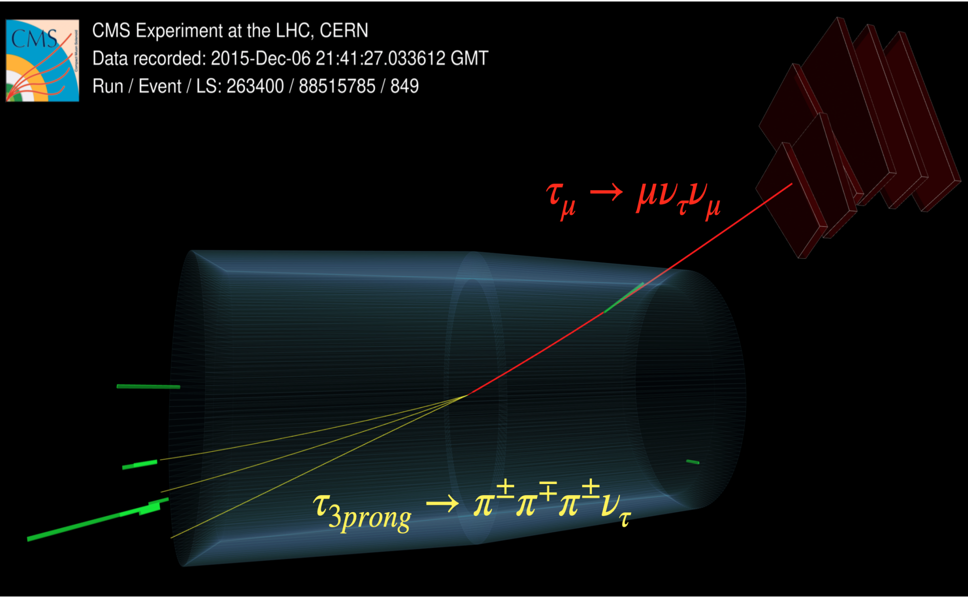
- Calculations are based on the same parameterization as was used in previous LEP measurements
- Clear observation ($\gg 5\sigma$) of $\gamma\gamma \to \tau\tau$ process





CMS measurement overview

Ditau events

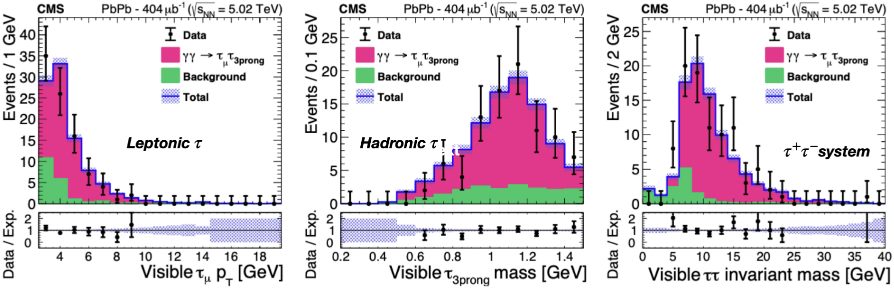


- Measurement uses 0.4 nb^{-1} of 2015 UPC Pb+Pb data recorded at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with a trigger requiring 1 muon, at least 1 track in the pixel detector and no HF activity in at least one side
- The signal region consists of 1 muon and 3 charged hadrons (semileptonic decay mode, τ_{3prong}):

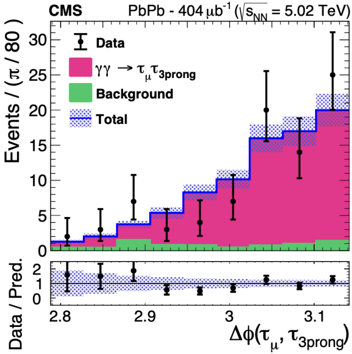
Event selection	**Fiducial phase-space region**
μ	$p_T^{\mu} > 3.5$ GeV for $\lvert\eta\rvert < 1.2$ $p_T^{e} > 2.5$ GeV for $1.2 < \lvert\eta\rvert < 2.4$
$\pi^{\pm}$	$p_T > 0.5$ GeV for leading $\pi^{\pm}$ $p_T > 0.3$ GeV for (sub-)sub-leading $\pi^{\pm}$ $\lvert\eta\rvert < 2.5$
τ_{3prong}	$p_T^{\text{vis}} > 0.2$ GeV 0.2 GeV $< m_{\pi\pi\pi} <$ 1.5 GeV

- The background was estimated with the ABCD method with background regions with more charged hadrons and higher HF activity (HF tower $>$ 4 GeV)

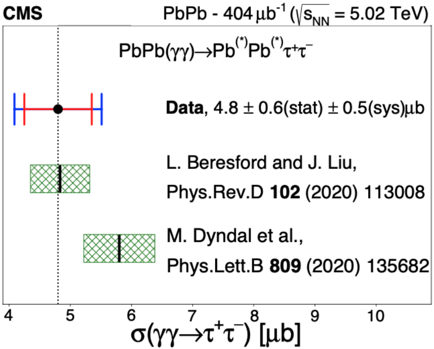
- Figures below show the control plots for the leptonic τ, hadronic τ and $\tau^+\tau^-$ system
- Control plots show great agreement between expectations (MC) and data
  - signal MC is scaled to the **integrated luminosity**
  - an almost bkg-free phase space region
  - **unambiguous reconstruction** of the $\tau^+\tau^-$ system



- Binned maximum likelihood fit on the distribution of $\Delta\phi(\tau_\mu, \tau_{3prong})$
  - ABCD background + MC signal (free scale) $\rightarrow$ data
  - MC signal (peaky) and bkg template (flat) from data
- Postfit signal events: 77 ± 12; the best-fit of the signal strength is $0.99^{+0.16}_{-0.14}$
- Observation significance well above 5 σ
  - **taking into account** systematic uncertainties

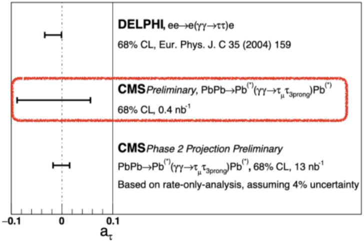


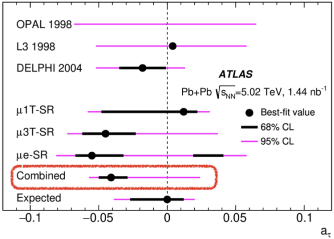
- efficiency (ϵ) from MC $= \frac{\text{reconstructed events}}{\text{gen events within acceptance phase space}}$
- $\epsilon = 78.5\%$
- $\text{BR}_{\mu-3\text{prong}} = 5.06\ \%$
- $L = 404.3\mu b^{-1}$
- $N_{\text{signal}} = 77$
- $\sigma_{\text{fiducial}} = \frac{N_{\text{signal}}}{L \times BR \times \epsilon}$



- $\sigma_{\text{fiducial}} = 4.8 \pm 0.6\ \text{stat} \pm 0.5\ \text{syst}\ \mu\text{b}$

- **ATLAS**:
  - $a_\tau = -0.041$ at: 68% CL $(-0.050, -0.029)$ and
    95% CL $(-0.057, 0.024)$
    from combined fit
- **CMS**:
  - $a_\tau = 0.001$ at: 68% CL $(-0.088, 0.056)$





- Both ATLAS and CMS provide their first constraints on a_τ
- ATLAS precision (stat.-dominated) competitive with DELPHI@LEP (PDG) limits

Summary & Outlook

- The $\gamma\gamma \to \tau^+\tau^-$ production was clearly observed by ATLAS and CMS in UPC Pb+Pb collisions.
  - Both experiments provide their first constraints on a_τ with above 5σ.
- ATLAS precision is comparable to the DELPHI@LEP (PDG) results.
- Statistical uncertainties are dominated in both experiments.
- The result is largely limited by statistics, what will improve with Run-3 data.
- Combining ATLAS and CMS $\gamma\gamma \to \tau^+\tau^-$ results is in progress.

Thank you for your attention!

Backup

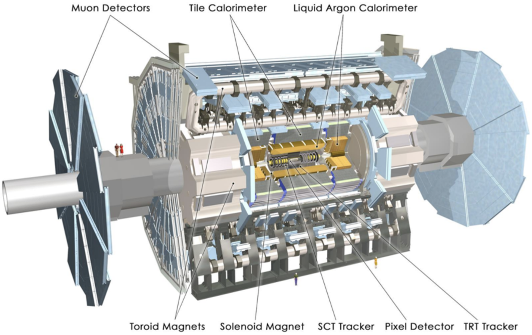
Literature: constraints on a_τ

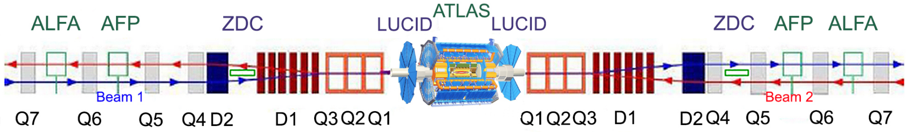
Interest in measuring a_τ at the LHC revisited recently

- Theoretical investigations outlined in:
  - F.del Aguila *et al.*, Phys Lett B, 271, 1–2 (1999)
  - S. Atağ, A. Billur, JHEP11 2010, 060 (2010)
  - L. Beresford, J. Liu, PRD 102 (2020) 113008
  - M. Dyndal, M. Schott, M. Klusek-Gawenda, A. Szczurek, PLB 809 (2020) 135682
    This paper suggested to use datasets from ATLAS experiment to improve the sensitivity on a_τ
    Mateusz had a presentation in the past HonexComb meeting
- Final results from 5.02 TeV Pb+Pb UPC from ATLAS
  - ATLAS Collaboration published in PRL, Phys. Rev. Lett. 131 (2023) 151802
- Final results from 5.02 TeV Pb+Pb UPC from CMS
  - CMS Collaboration published in PRL, Phys. Rev. Lett. 131 (2023) 151803

ATLAS detector

- Large general-purpose detector with almost 4π coverage
- $\eta = -log(tan(\theta/2))$
- Inner detector $|\eta| < 2.5$
- Muon system $|\eta| < 2.7$ (trig. 2.4)
- Calorimetry out to $|\eta| < 4.9$
- Zero-Degree-Calorimeters capture neutral particles with $|\eta| > 8.3$



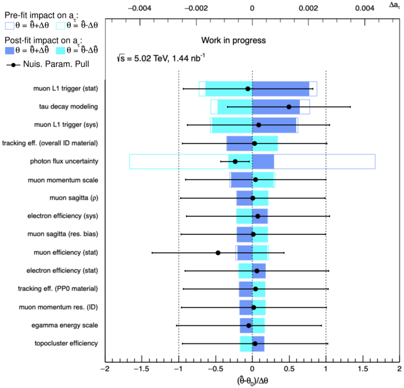


Overview of uncertainties (ATLAS)

- Detector:
  - 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` and `Starlight`)
  - τ decay modelling (`Tauola` and `Pythia8`)
  - `0n0n` ZDC reweighting variation

- The **dominant sources**:
  - muon trigger efficiency (stat/sys)
  - τ-lepton decay
  - track reconstruction efficiency

  dominant ($\approx$ 20%) pre-fit contribution is photon-flux uncertainty, after the post-fit it becomes subdominant



- **Statistical** uncertainty is 13%.
- The total **systematical** error is 9.7%. The **dominant sources**:
    - muon efficiency
    - integrated luminosity
    - pion efficiency
- Total uncertainty comparable to the current theory uncertainty:

CMS

Source	Uncertainty (%)
Muon efficiency	6.7
Integrated luminosity	5.0
Pion efficiency	3.6
Simulation sample size (bin-by-bin)	3.0
Simulation sample size (efficiency)	1.1
HF scale effect on bkg shape	0.9
τ lepton branching fraction	0.6
Effect on n_{ch} on bkg shape	0.2
Total	**9.7**

- Binned profile likelihood based on maximum-likelihood principle, profile-likelihood-ratio test-statistics and asymptotic approximation:
  - fit a_τ using p_T^μ distribution in three SRs and 2μ-CR channels (ATLAS)
- Asymptotic behavior of likelihood for the combined fit (Bayesian inference cannot be used, i.e. BLUE tool)