Combination of ATLAS+CMS measurements on $\gamma\gamma \to \tau^+\tau^-$ production in Pb+Pb UPC

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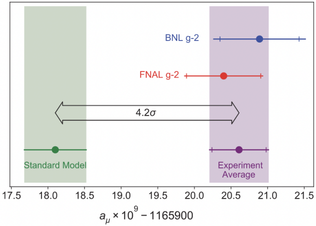
Outline

1. Introduction
2. Measuring a_τ in Pb+Pb UPC
3. Combining ATLAS+CMS measurements
4. Summary & Outlook

Motivation

- Measurements of anomalous magnetic moments of leptons $a_l = \frac{(g-2)l}{2}$ are sensitive to new 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)

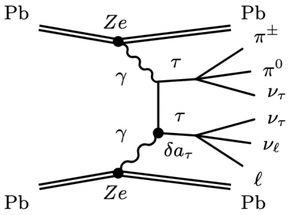


Muon g-2 Collaboration, PRL 126 (2021) 141801

$\gamma\gamma \to \tau^+\tau^-$ production in Pb+Pb UPC

Pb+Pb UPC studies have some advantages over pp collisions:

- $\sim Z^4$ ($Z = 82, Z \approx 4.5 \cdot 10^7$) enhancement of cross sections
- $\approx$ no hadronic pileup $\to$ 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



PRD 102 (2020) 113008

Constraints on a_τ anomalous magnetic moment

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 submitted to PRL, arXiv:2204.13478
- Final results from 5.02 TeV Pb+Pb UPC from CMS
  available at the link
  - CMS Collaboration submitted to PRL, arXiv:2206.05192

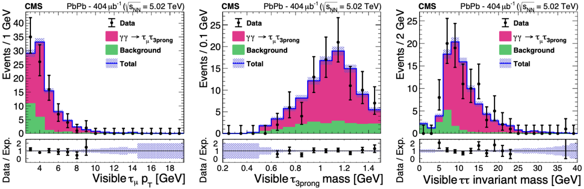
CMS measurement overview

- Measurement uses 0.4 nb^{-1} of 2015 UPC data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV
- Monte Carlo simulations:
  - signal modeled with: `MADGRAPH5 aMC@NLO(v2.6.5)`
    $\gamma\gamma \to \tau^+\tau^-$, $\gamma\gamma \to c\bar{c}$, and $\gamma\gamma \to b\bar{b}$
    `PYTHIA8 (v2.1.2)` is used for the hadronization and decay
- Event selection categorised with semileptonic decay mode (μ3T-SR):

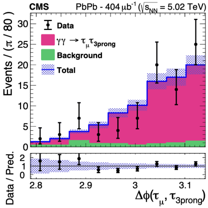
Event selection	Fiducial phase-space region
μ	$p_T^\mu > 3.5$ GeV for $\|\eta\| < 1.2$ $p_T^e > 2.5$ GeV for $1.2 < \|\eta\| < 2.4$
$\pi^\pm$	$p_T > 0.5$ GeV for leading $\pi^\pm$ $p_T > 0.3$ GeV for (sub-)sub-leading $\pi^\pm$ $\|\eta\| < 2.5$
$\tau_{3\text{prong}}$	$p_T^{\text{vis}} > 0.2$ GeV 0.2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

CMS measurement overview

- Control plots in the signal region
  - signal MC is scaled to the integrated luminosity
  - good agreement between the measured distributions and the sum of the signal simulation and background estimation



- Signal yield estimation
- Binned likelihood fit to a discriminating variable
- The best fit value of the signal strength is $0.99^{+0.16}_{-0.14}$ with $N_{\mathrm{sig}} = 77 \pm 12$ of signal events
- Observed significance is more than 5σ
-
  - systematic uncertainties affecting the rate with log-normal priors and the shape with Gaussian prior



Overview of uncertainties (CMS)

- **Statistical** uncertainty is 13%
- The total **systematical** error is 9.7%. The **dominant sources**:
  - muon trigger efficiency
  - pion efficiency
  - integrated luminosity
- Total uncertainty comparable to the current theory uncertainty:
  - difficult to discriminate between existing models
  - model-dependent limits on anomalous moments can be set

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**

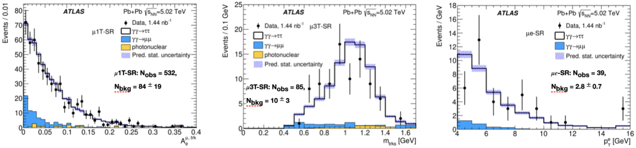
ATLAS measurement overview

- Measurement uses 1.44 nb^{-1} of 2018 UPC data at $\sqrt{s_{\text{NN}}} = 5.02$ TeV
- Monte Carlo simulations:
  - signal modeled with: `Starlight+Tauola` (`Pythia8+Photos` for QED FSR) samples reweighted to photon flux from `SuperChic`
- Event selection categorised with semileptonic decay modes:

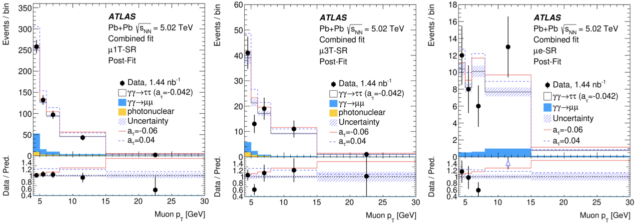
μ1T-SR (46%) muon + 1 track (e/μ/hadron (“prong”))	$p_T^{\mu} > 4$ GeV, $p_T^{e} > 4$ GeV, $p_T^{\text{trk}} > 100$ MeV
μ3T-SR (19%): muon + 3 tracks (3 hadrons (3 prongs))	$p_T^{\text{clus}} > 1$ GeV ($\lvert\eta\rvert < 2.5$), $p_T^{\text{trk}} > 100$ MeV ($2.5 < \lvert\eta\rvert < 4.5$)
μe-SR (35%): muon + 1 track (muon + electron)	

- Only data in `0n0n` ZDC category used to suppress photonuclear/hadronic backgrounds
- Simulation `Starlight+Tauola` reweighted to `0n0n` with data-driven weights

ATLAS measurement overview



- Total of $\sim$ 650 events across all SRs
- Background contributions at the level of 10%
- Measure $\gamma\gamma \to \tau\tau$ signal strength and a_τ using profile likelihood fit to p_T^μ distribution in 3 SRs and 2μ-CR
- Good modelling of pre/post-fit predictions with data

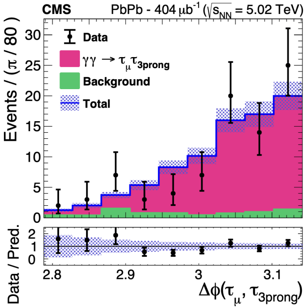


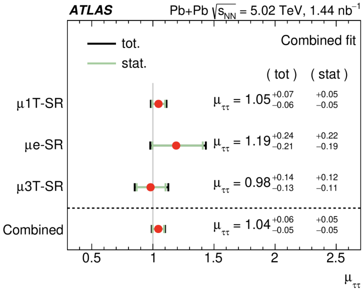
Overview of uncertainties (ATLAS)

- 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

Results from both measurements

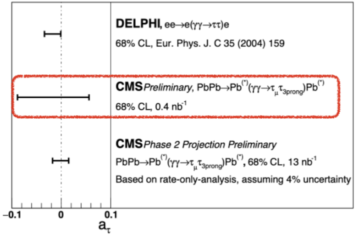
- **CMS**: fiducial cross section measured with 16% relative precision (stat.-dominated) (2015 data)
- **ATLAS**: signal strength measured with 5% relative precision (stat.-dominated) (2018 data)

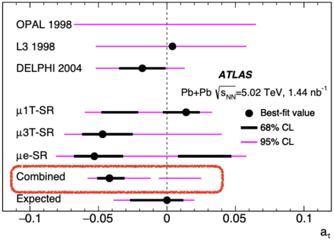




Results for a_τ anomalous magnetic moment

- **ATLAS**:
  - Observed 68% CL from combined fit: $a_\tau \in (-0.051, -0.031)$
  - Observed 95% CL from combined fit: $a_\tau \in (-0.058, -0.012) \cup (-0.06, 0.025)$
  - Result for each signal region compatible with unity
  - Double-interval structure due to interference of SM and BSM amplitude
- **CMS**:
  - $a_\tau = 0.001^{+0.055}_{-0.089}$ at the 68% CL





Combination of $\gamma\gamma \to \tau\tau$ a_τ measurements

- Reproduce post-fit distributions of of p_T^μ in the SRs and 2μ-CR (ATLAS) using TRExFitterframework
- Extract "ranking plot" of pre-fit and post-fit impact of individual nuisance parameter (NP) on the determination of a_τ (reproduced)
- Combine a_τ from both experiments:
  1. using BLUE tool at 68% CL interval
  2. using TRExFitter framework
     based on binned profile likelihood, with statistical inference based on maximum-likelihood principle, profile-likelihood-ratio test-statistics and asymptotic approximation
     – add RooFit workspace for CMS results
     – Fit muon p_T distribution targeting μ+3prong decays (CMS) and μ+3prong, μ+1prong, and $\mu + e$ channels (ATLAS)

Validation of BLUE tool on light-by-light (LbyL) scattering measurements

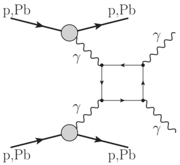
Krintiras et al., arXiv:2204.02845

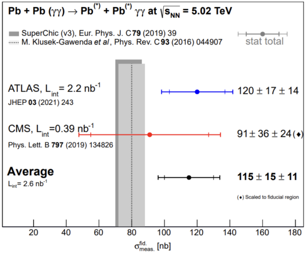
- Available results:
  - ATLAS: 2015 Pb+Pb 0.48 nb^{-1}
  - ATLAS: 2018 Pb+Pb 1.73 nb^{-1}:

    Kinematics: $E_{T,\gamma} > 2.5$ GeV and $m_{\gamma\gamma} > 6$ GeV
  - CMS: 2015 Pb+Pb 0.39 nb^{-1}

    Kinematics: $E_{T,\gamma} > 2$ GeV and $m_{\gamma\gamma} > 5$ GeV
- Best linear unbiased estimator (BLUE) method used for averaging cross section
  - in a "common" fiducial phase-space

$$\sigma^{\text{fid}} = 115 \pm 15(\text{stat.}) \pm 11(\text{syst.}) \pm 3(\text{lumi}) \pm 3(\text{theo.})\ \text{nb}$$

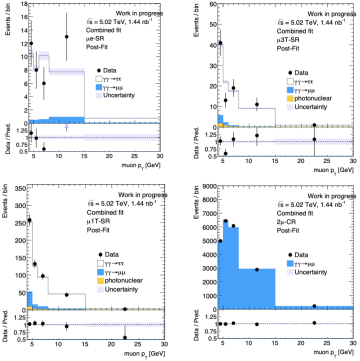




Post-fit distributions

The following results were reproduced after obtaining four workspaces as input to the texttt TRExFitter framework

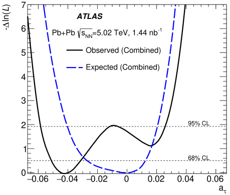
- Results of combined fit using all regions
- Clear observation ($\geq 5\sigma$) of $\gamma\gamma \to \tau\tau$ process
- Post-fit distributions with the signal contribution corresponding to the best-fit $a_\tau = -0.042$ (reproduced)
- Photon flux modelling well constrained with high-precision and high-purity 2μ-CR (in paper)
  In progress: preparing a configuration for the correct fit

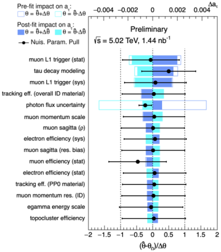


- Post-fit distributions consistent with the ATLAS results

Systematic uncertainties

- **Statistical** uncertainty is about 10%
- The total **systematical** error is 5.6%. 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 sudbominant
- luminosity uncertainty is negligible
- asymptotic behavior of likelihood for the combined fit (Bayesian inference cannot be used, i.e. `BLUE` tool)





ATLAS

Source	Uncertainty (%)
Photon flux uncertainty	3.7
Muon momentum scale	2.3
Integrated luminosity	1.8
Muon sagitta (res. bias)	1.4
Muon sagitta (ρ)	1.4
Muon momentum res. (MS)	1.3
Muon momentum res. (ID)	1.2
Muon L1 trigger (sys)	1
Muon L1 trigger (stat)	0.7
Muon efficiency (stat)	0.3
Muon efficiency (sys)	0.3
Muon HLT trigger (sys)	0.2
0n0n reweighting	0.1
Muon HLT trigger (stat)	0.1
Total	**5.6**

- Work in progress

Summary & Outlook

- HI UPCs are high-quality probes to QED and BSM physics
  - UPC data is used to constrain a_τ at LHC
  - Both experiments provide their first constraints on a_τ with above 5σ at the LHC
  - ATLAS precision is comparable to the DELPHI@LEP (PDG) results
  - Statistical uncertainties are dominated in both experiments
- Finding a way to combine the results of both experiments