Probe the anomalous electromagnetic moments of the tau lepton at LHC

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The 29th LHC mini-workshop， 福州

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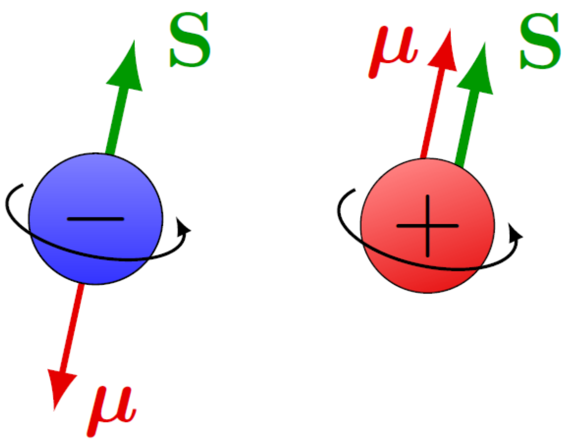
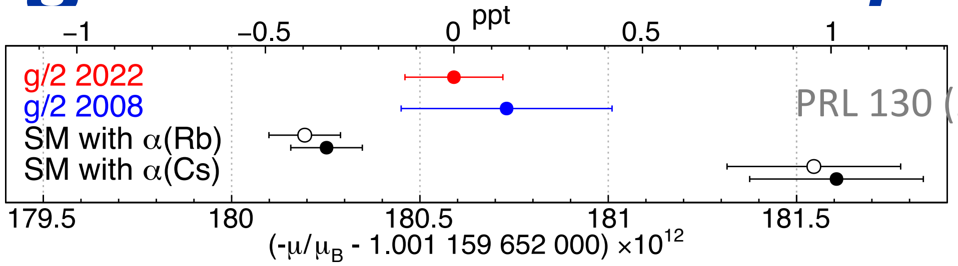
Outline

- Introduction
- Photon-induced $\tau\tau$ production
- ATLAS/CMS heavy ion measurements
- CMS pp measurement
- Beyond ATLAS/CMS
- Summary

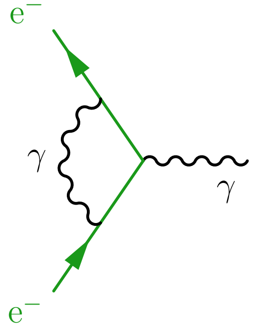
Lepton anomalous magnetic moment a_l

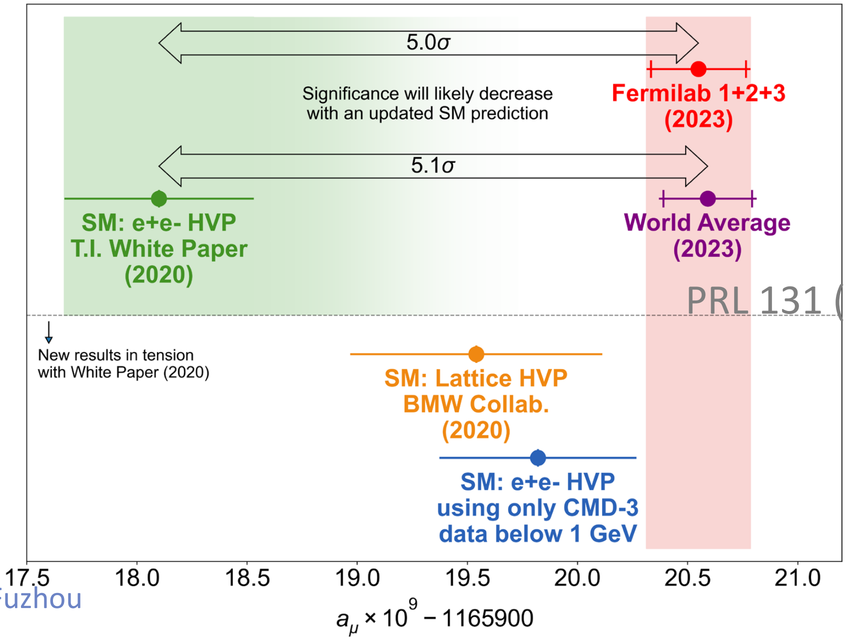


$$\mu = g\frac{e}{2m}\mathbf{S} \qquad a_l = (g-2)/2$$



PRL 130 (2023) 071801





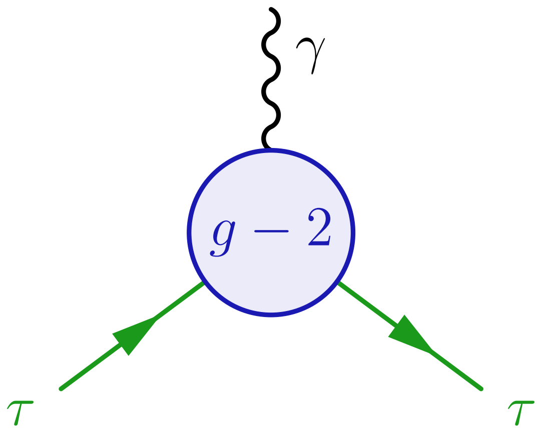
PRL 131 (2023) 161802

- measurements of a_e in Penning traps are the "most precise in physics"
- measurements of a_μ in storage rings are in longstanding tension with theoretical computations

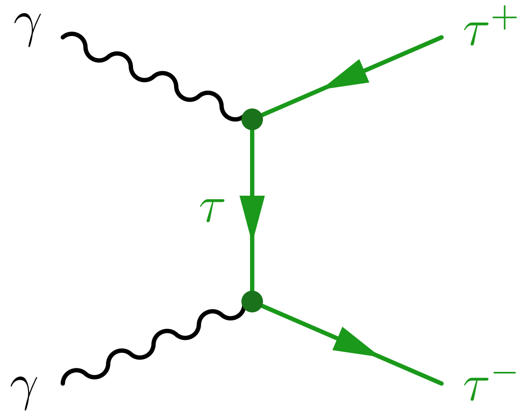
Constrain tau EM moments a_τ & d_τ

If BSM effects scale with the m_l^2, deviations from SM could be 280 times larger than for a_μ

- a_τ & electric dipole moment d_τ can be probed from **$\gamma\tau\tau$ vertex**



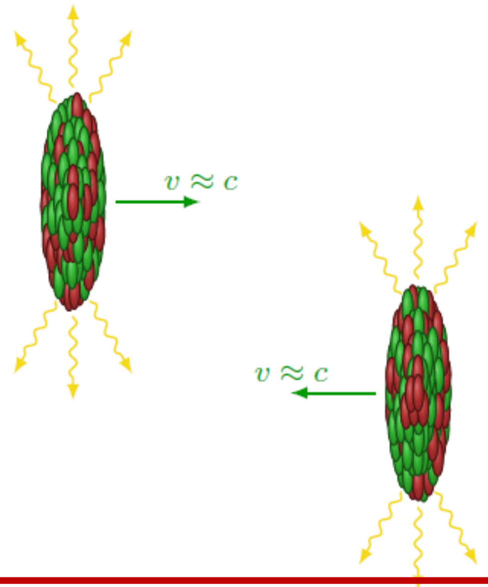
- $\gamma\gamma \rightarrow \tau\tau$ process contains 2 $\gamma\tau\tau$ vertices



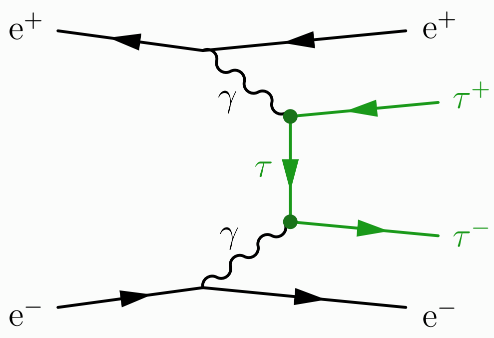
- contraints on electromagnetic moments a_τ & d_τ from *form factors* or *SMEFT*
- in the SM: $d_\tau \sim 10^{-37}$ ecm via CP/T violation in CKM, but could be much larger in BSMs
- Best constraints on a_τ and d_τ are both from e^+e^- collisions:
  - $-0.052 < a_\tau < 0.013$, 95% CL (DELPHI@LEP)
  - $-1.85 < d_\tau < 0.61$ x 10–17 ecm, 95% CL (Belle)

Photon-induced $\tau\tau$ production

Photon-induced process: two charged particles (e.g. protons or ions) pass each other at relativistic velocities, they generate intense electromagnetic fields → **photon-photon collisions** can happen

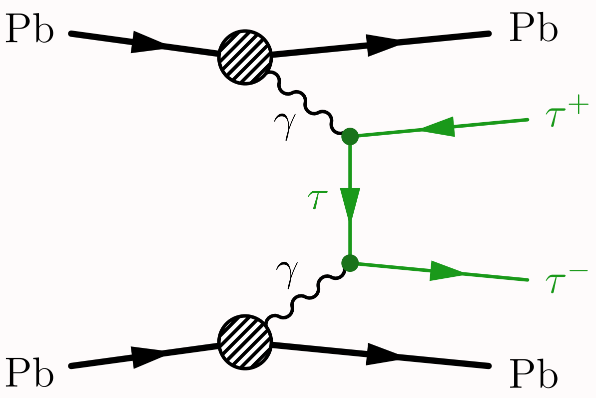


LEP: DELPHI, L3, …

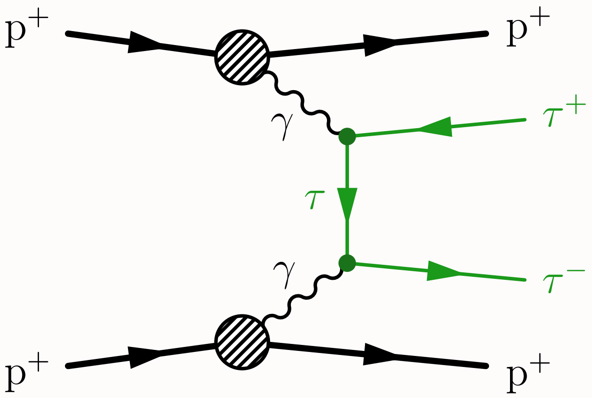


$e^+e^- \rightarrow e^+e^- \tau^+\tau^-$

LHC: CMS, ATLAS, …



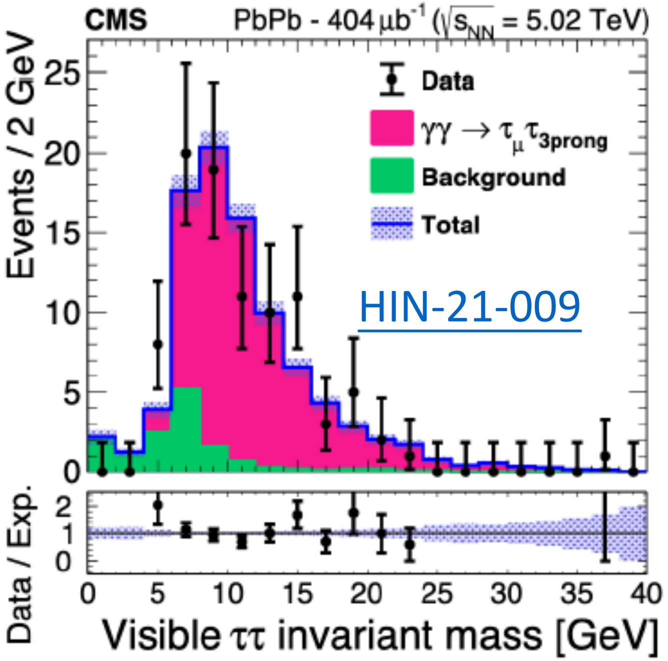
PbPb → PbPb $\tau^+\tau^-$

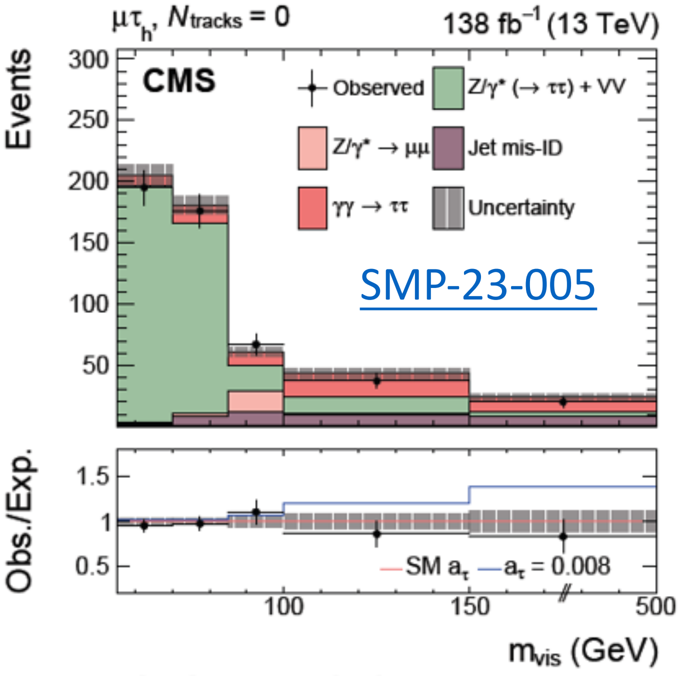


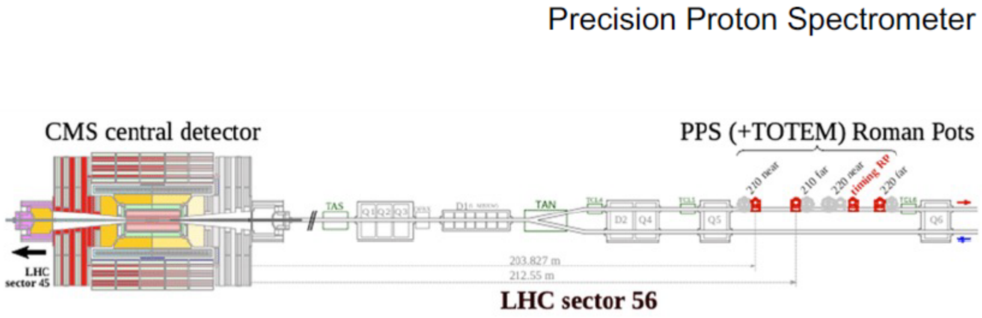
pp → pp $\tau^+\tau^-$

EPJC 35 (2004) 159
PLB 407 (1997) 341

$\gamma\gamma \to \tau\tau$ study at ATLAS/CMS







ultra-peripheral PbPb | pp with track counting | pp with forward proton tagging

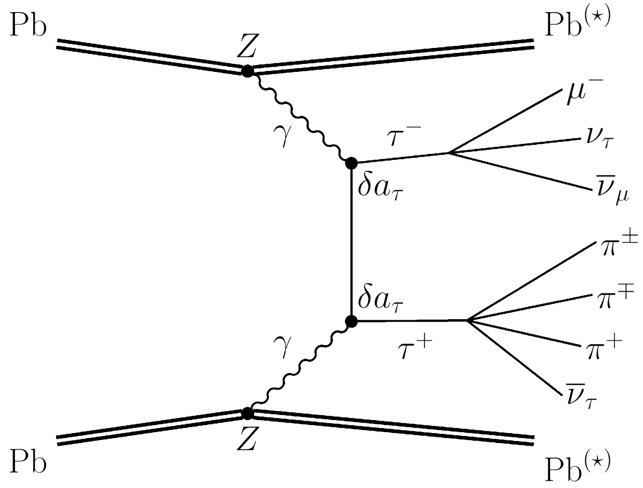
0 GeV | 50 GeV | 350 GeV | 2 TeV

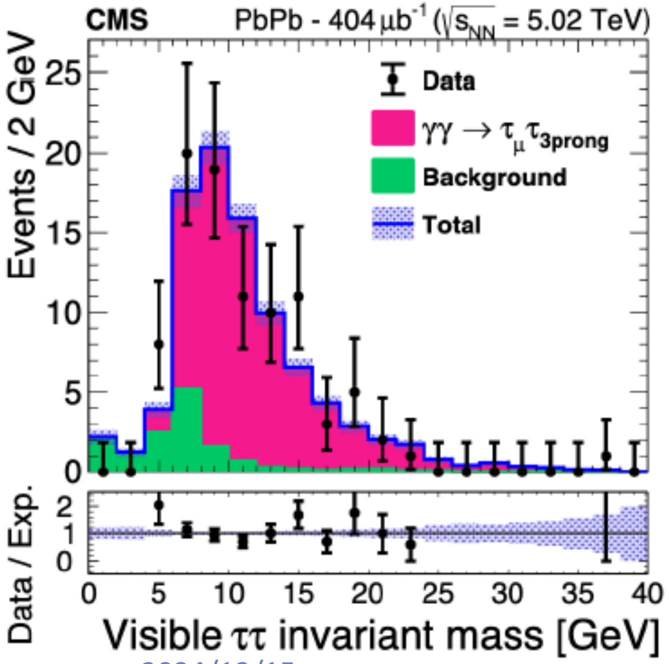
Not covered by this talk due to no public result

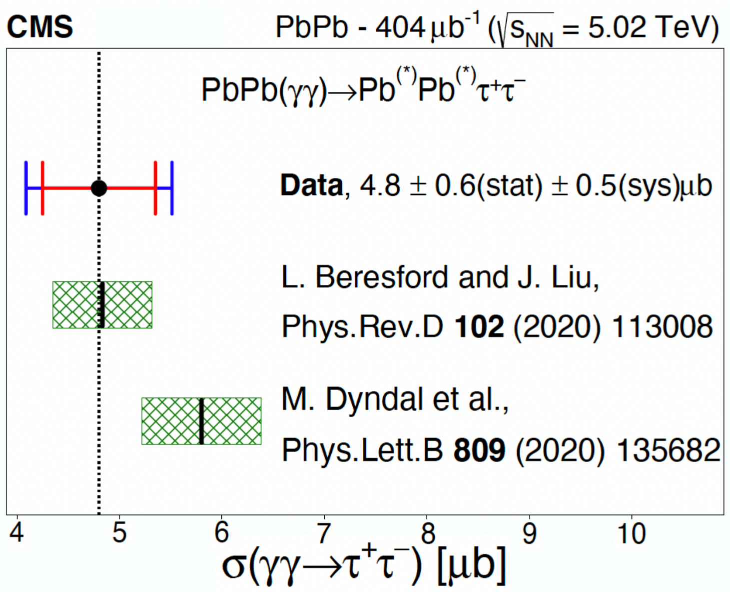
$\gamma\gamma \to \tau\tau$ measurements in PbPb collisions:CMS22

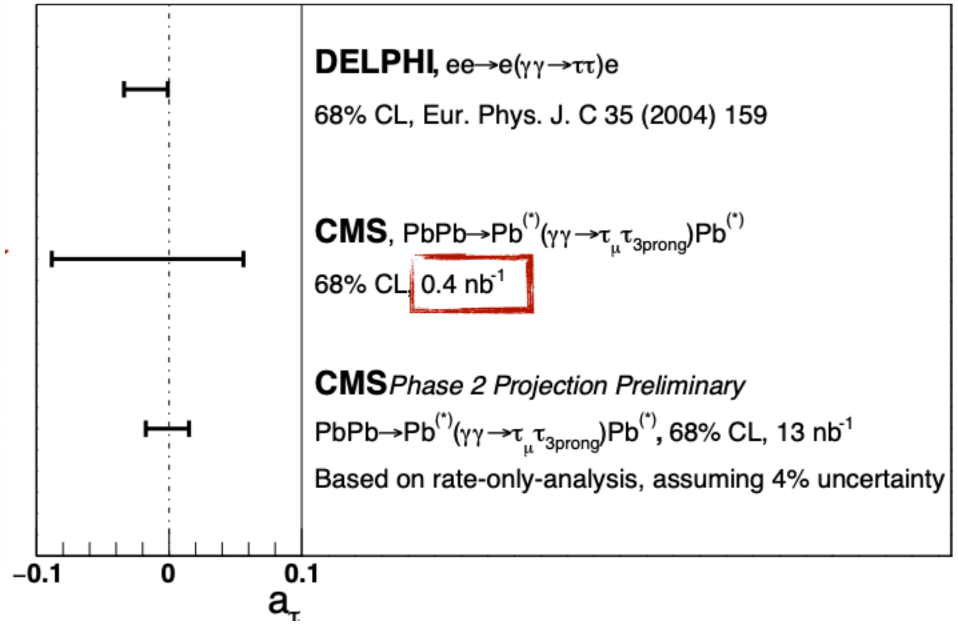
- first observed of $\gamma\gamma \to \tau\tau$ in PbPb by CMS & ATLAS in 2022
- $\sigma \propto Z^4$ enhancement
- clean channel: small backgrounds
- phase space $m_{\tau\tau} < 40$ GeV

CMS(2022)
PRL 131(2023) 151803

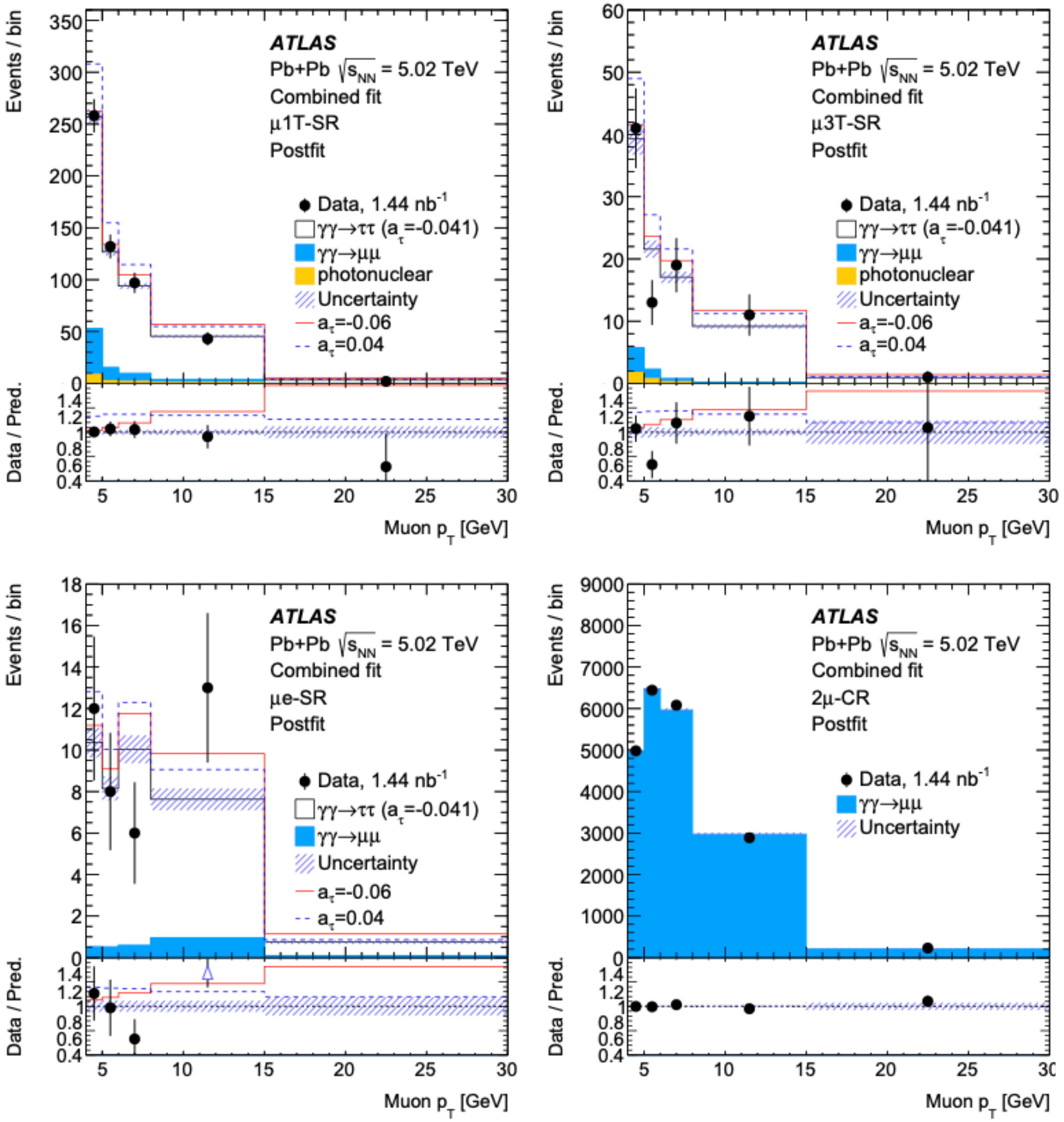


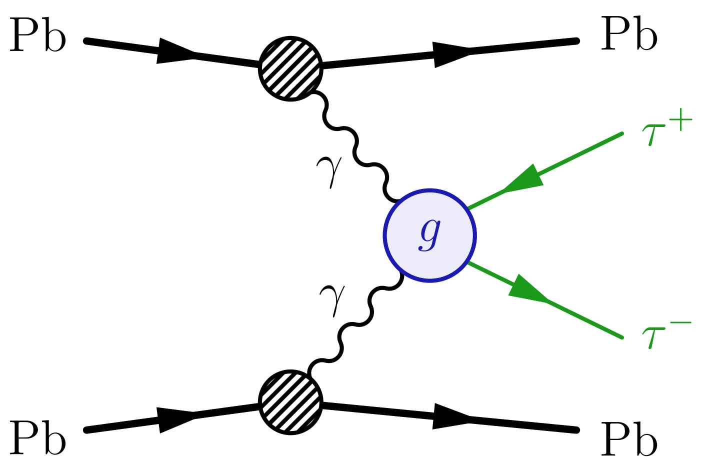


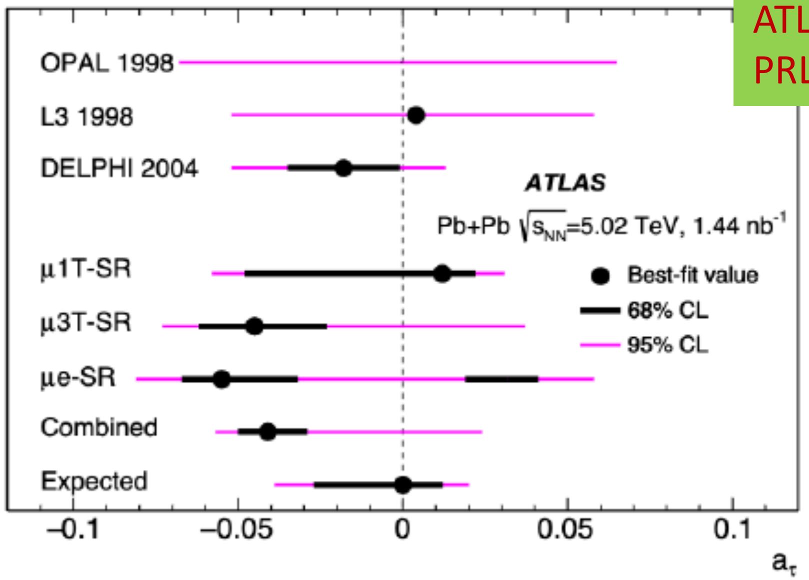




$\gamma\gamma \rightarrow \tau\tau$ measurements in PbPb collisions: ATLAS



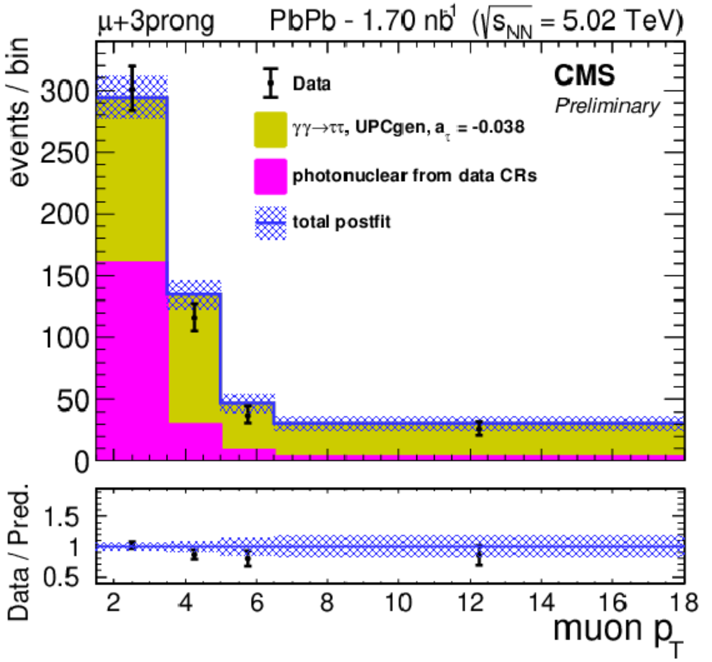


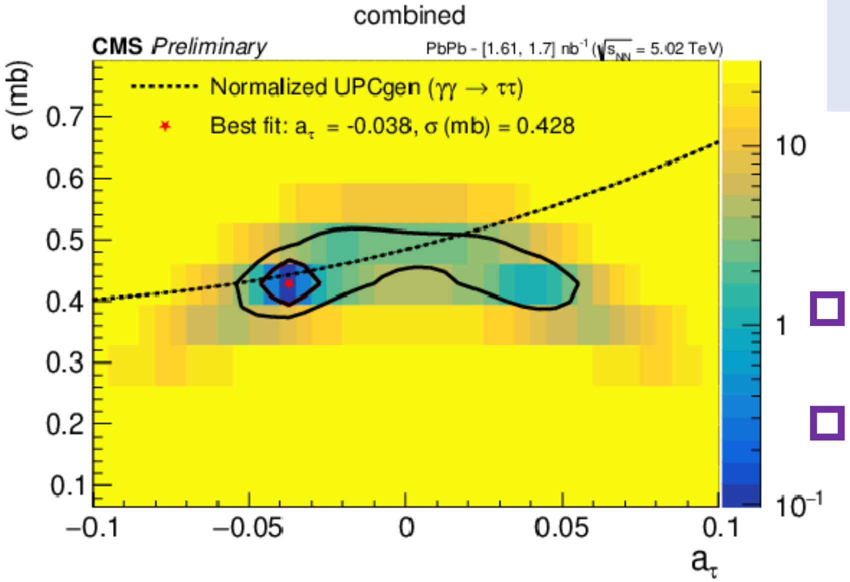


ATLAS(2022)
PRL 131(2023) 151802

Set constraints on a_τ close to best result from DELPHI

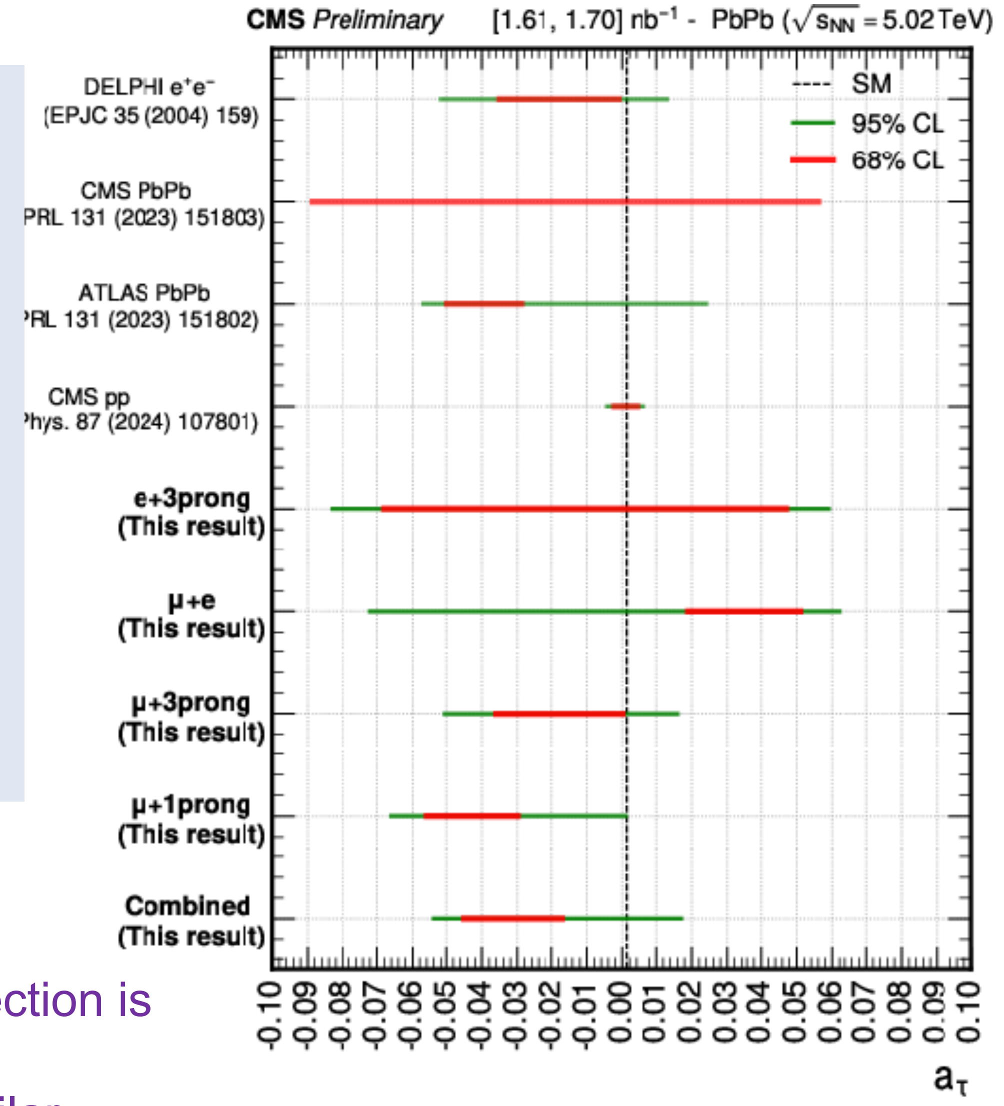
$\gamma\gamma \rightarrow \tau\tau$ measurements in PbPb collisions:CMS(new)





Major updates

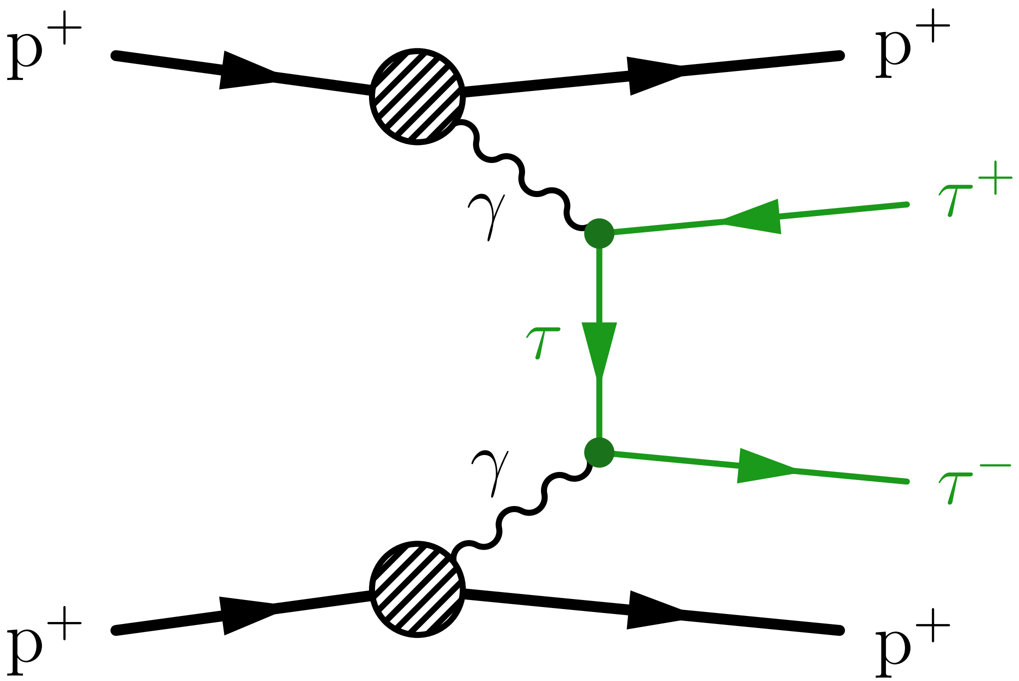
- ✓ With 2018 data, integrated lumi up to 1.70 nb^{-1} (x4)
- ✓ addition of three tau pair decay modes
- ✓ incorporation of both cross section and kinematic distributions



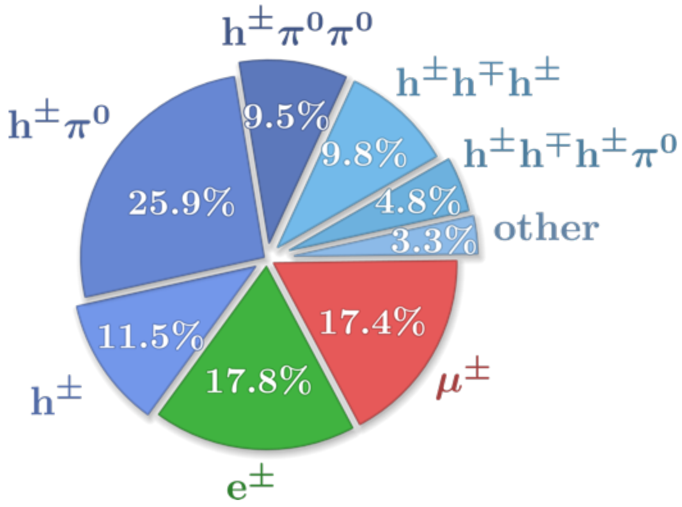
- ❑ The measured fiducial cross section is the most precise to date
- ❑ the g−2 measurement is of similar sensitivity to DELPHI and ATLAS

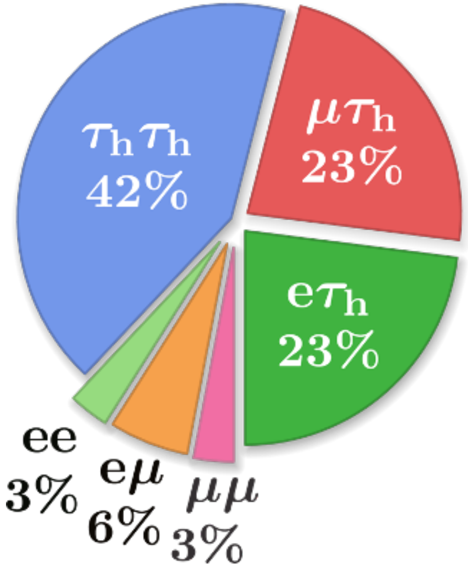
CMS-HIN-24-011

$\gamma\gamma \to \tau\tau$ signature in pp collisions



- **2 τ leptons**
  - opposite charge sign
  - back-to-back: $|\Delta\phi| \approx \pi$
  - τ decays: $\tau\tau$ decays:

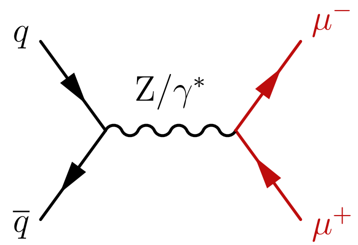


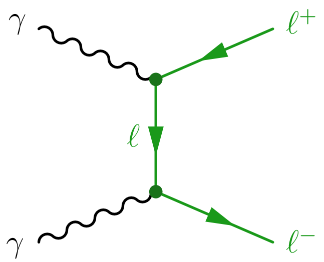


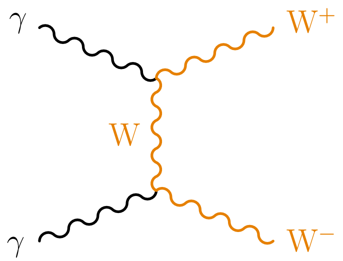
- **2 diffracted protons**
  - no hadronic activity close to $\tau\tau$ vertex

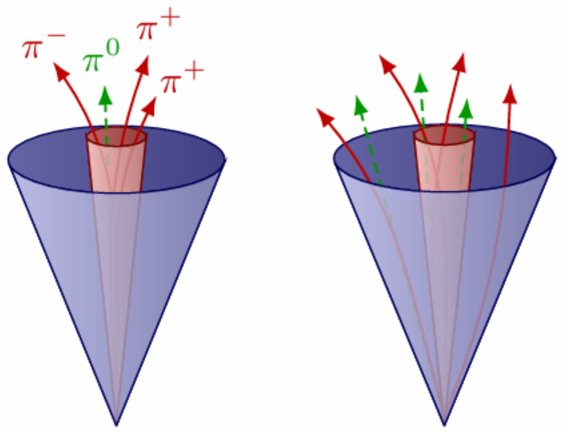
Background in signal region

- **MC simulation**
  - Drell–Yan ($Z/\gamma^* \to \ell\ell$): dominant at low mass
  - exclusive $\gamma\gamma \to$ ee, $\mu\mu$, WW production
  - inclusive WW production (small)
- **data-driven**: misidentified hadronic jets
  - $j \to \tau_h$: $e\tau_h$, $\mu\tau_h$ & $\tau_h\tau_h$ channels
  - $j \to e/\mu$: $e\mu$ channels









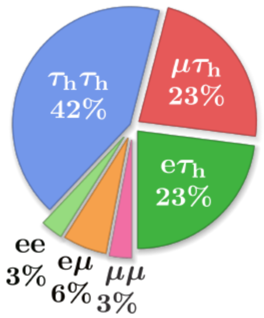
hadronic τ_h jet

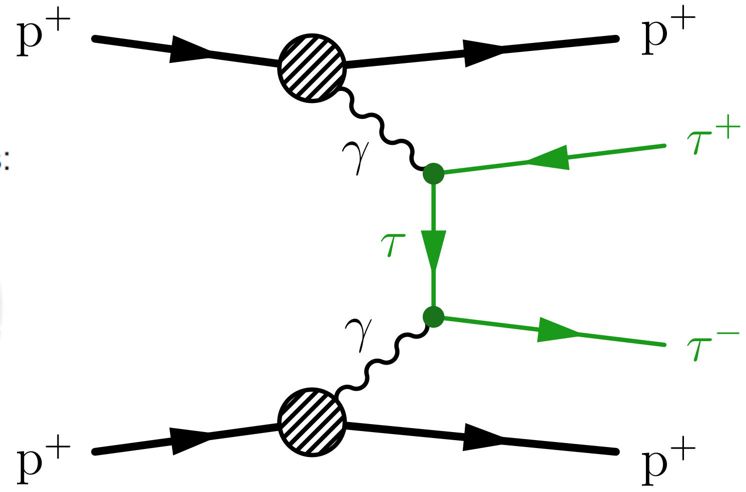
hadronic quark/gluon jet

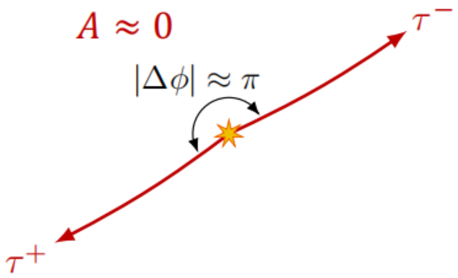
CMS $\gamma\gamma \to \tau\tau$ in pp: Strategy

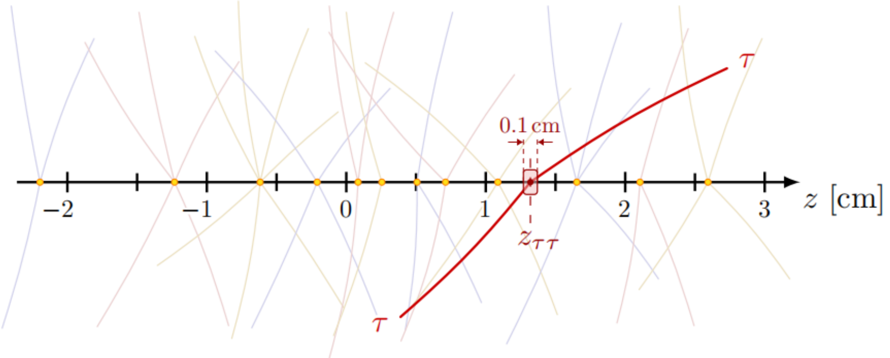
- select events with opposite sign $\tau^{+}\tau^{-}$
  - ➢ combine 4 $\boldsymbol{\tau\tau}$ final states: eμ, eτ_h, $\mu\tau_\mathrm{h}$, $\tau_\mathrm{h}\tau_\mathrm{h}$
  - ➢ **exclusivity cuts**:
    - back-to-back: $A = 1 - \frac{|\Delta\phi|}{\pi} < 0.015$
    - low activity around $\tau\tau$ vertex: $\mathrm{N_{tracks}}$=0 or 1 in 0.1 cm window

ττ decay channels:





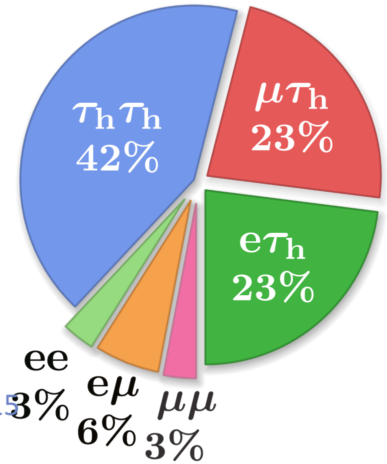


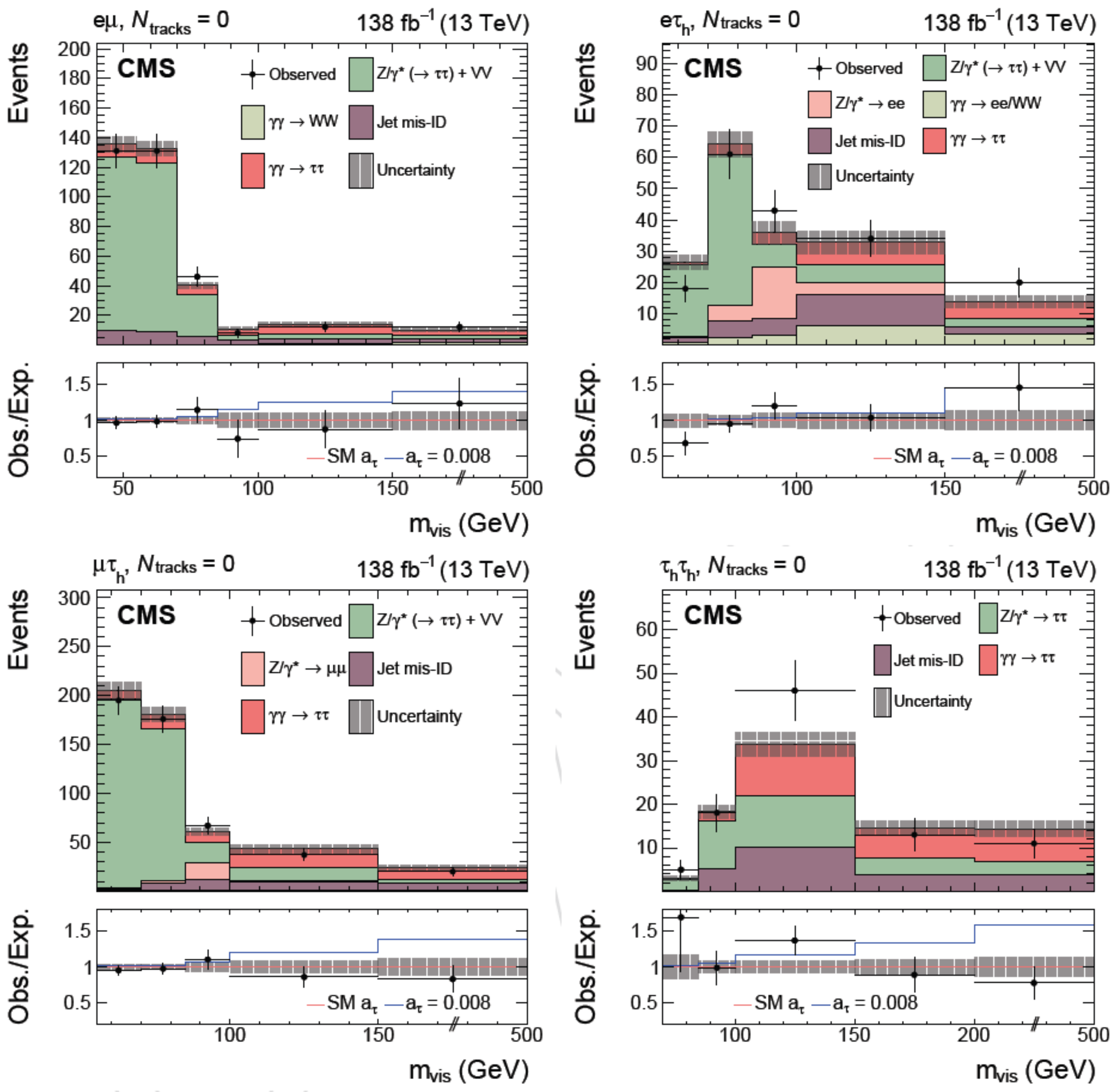


- use $\mu\mu$ events (Z → $\mu\mu$, $\gamma\gamma \to \mu\mu$) to measure corrections to simulation
- measure $\gamma\gamma \to \tau\tau$ from observed $m_{\tau\tau}$ shape & yield in **50 < $m_{\tau\tau}^{\mathrm{vis}}$ < 500 GeV**:
  - above e+e− & PbPb ($m_{\tau\tau} \lesssim$ 50 GeV)
  - $m_{\tau\tau}^{\mathrm{vis}} \lesssim$ 500 GeV to ensure unitarity in signal samples

SR with $N_{\text{tracks}} = 0$

- after maximum-likelihood fit to observed data
- assuming SM a_τ & d_τ
- signal clearly visible in high $m_{\text{vis}}(\tau\tau)$ bins





First observation of $\gamma\gamma \rightarrow \tau\tau$ in pp collisions

- combined **observed significance of 5.3σ (6.5σ expected)** assuming SM a_τ

  $\Rightarrow$ **first observation of $\gamma\gamma \rightarrow \tau\tau$ in pp** !

- combined **signal strength**

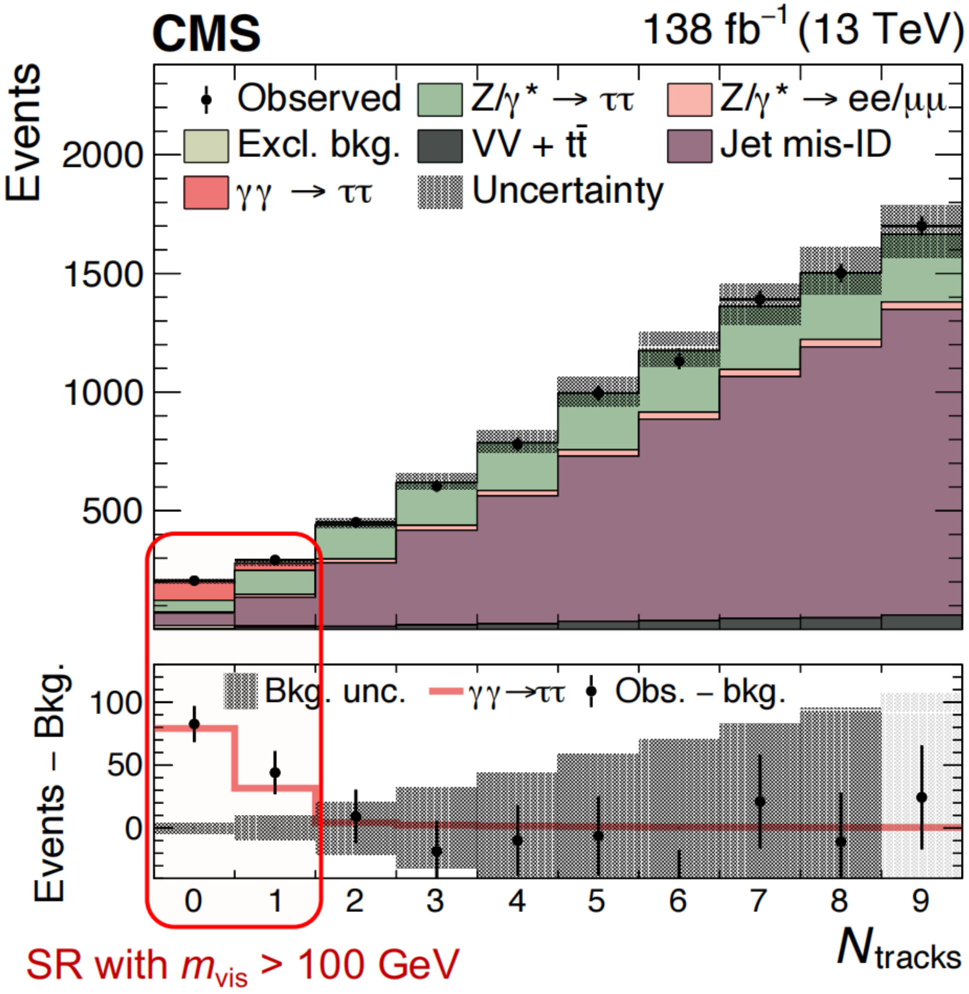
  r = 0.75 +0.21 –0.18

  w.r.t. gammaUPC elastic prediction

  $\times$ rescaling measured in $\mu\mu$ data

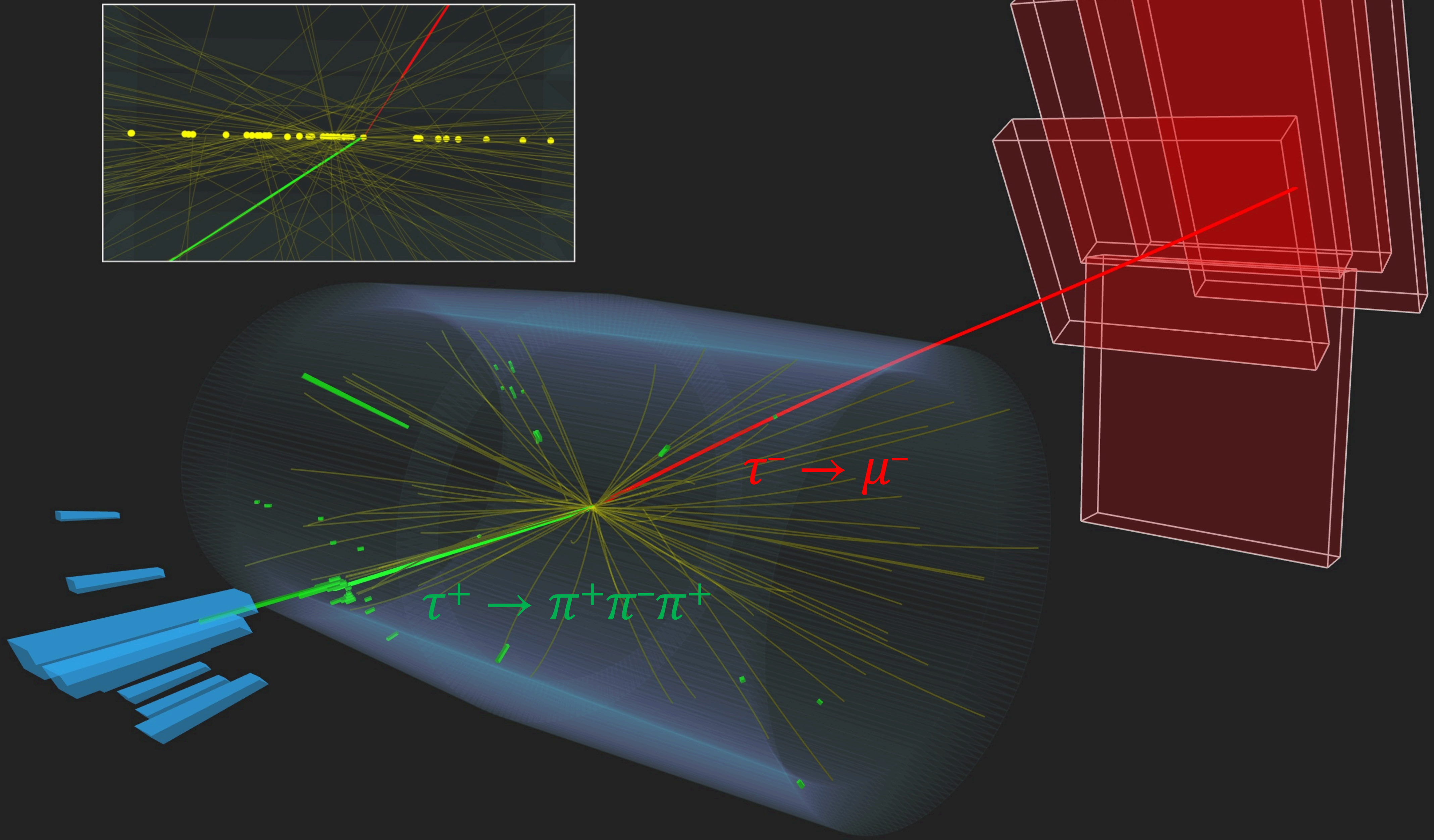
- Fiducial cross section: $12.4^{+3.8}_{-3.1}$ fb

- dominant systematic uncertainties:
  - elastic rescaling to $\gamma\gamma \rightarrow \tau\tau$
  - $\mathrm{N}^{\mathrm{HS}}_{\mathrm{tracks}}$ corrections to Drell–Yan



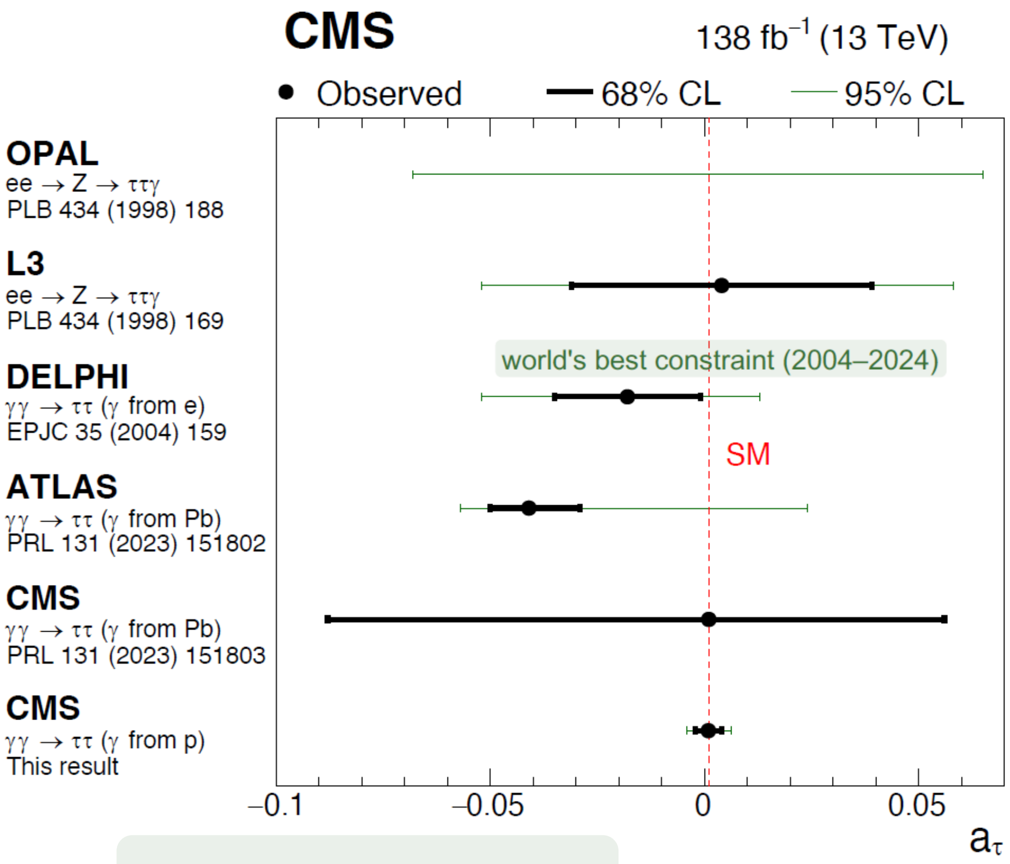
ROPP 87 (2024) 107801

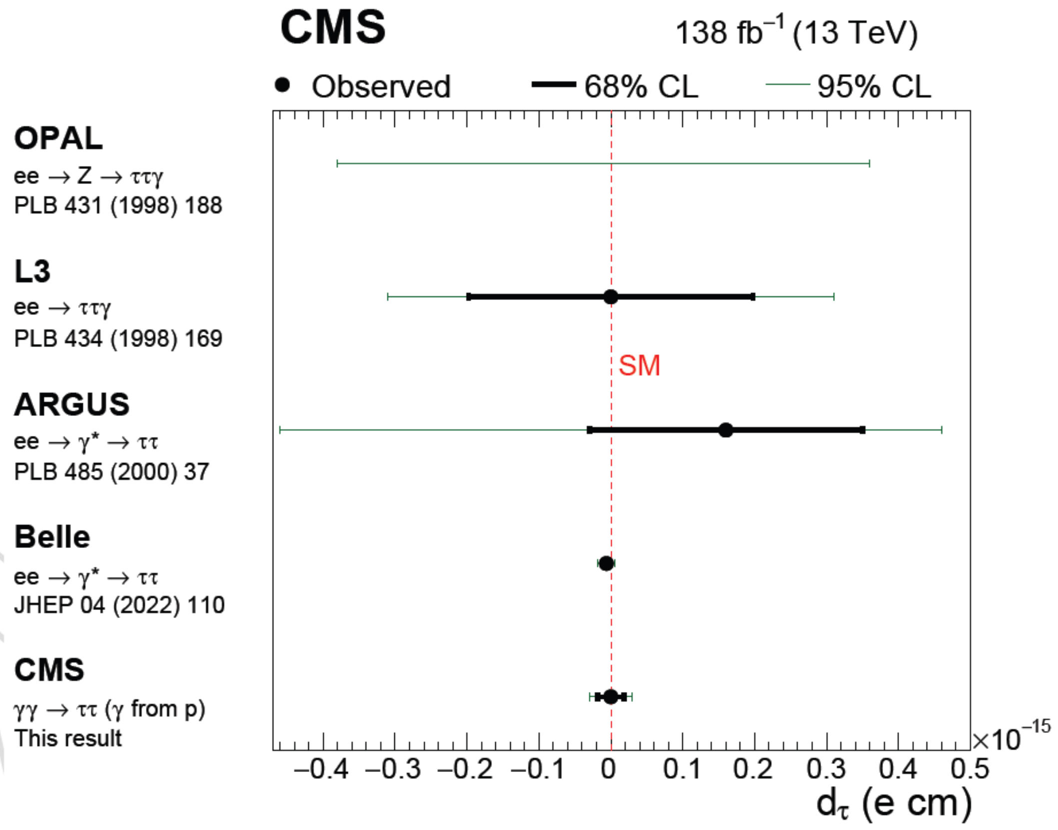
CMS Experiment at the LHC, CERN
Data recorded: 2018-May-01 13:53:45.602112 GMT
Run / Event / LS: 315512 / 65277407 / 69



interactive

Constraints on a_τ and d_τ





>5x better than LEP !

approaching Belle !

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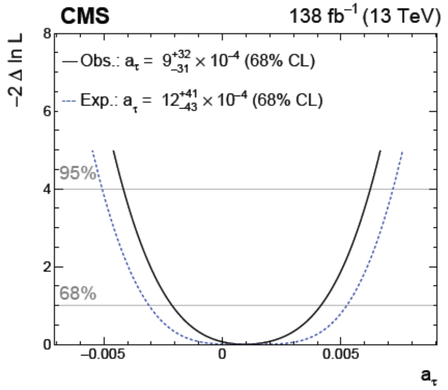
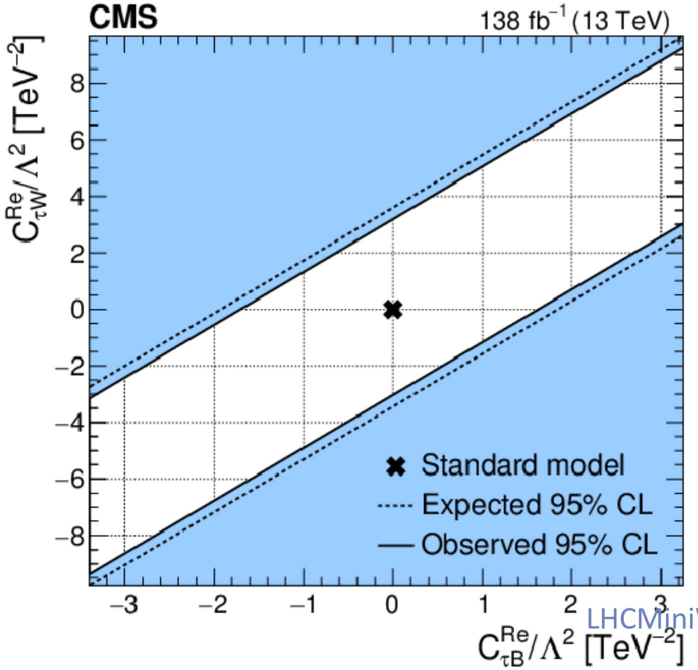
Constraints on Wilson coefficients

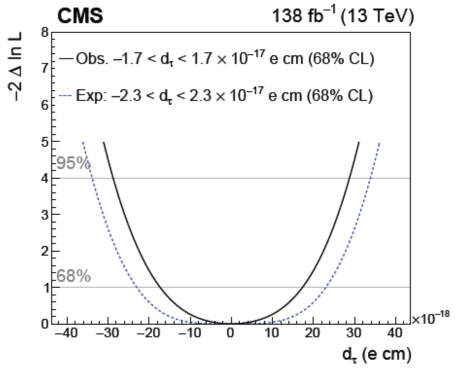
recast results to make exclusion of $C_{\tau B}/\Lambda^2$ vs. $C_{\tau W}/\Lambda^2$:

$$\delta a_\tau = \frac{2m_\tau}{e}\frac{\sqrt{2}v}{\Lambda^2}\mathrm{Re}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}] \qquad \delta d_\tau = \frac{\sqrt{2}v}{\Lambda^2}\mathrm{Im}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}]$$

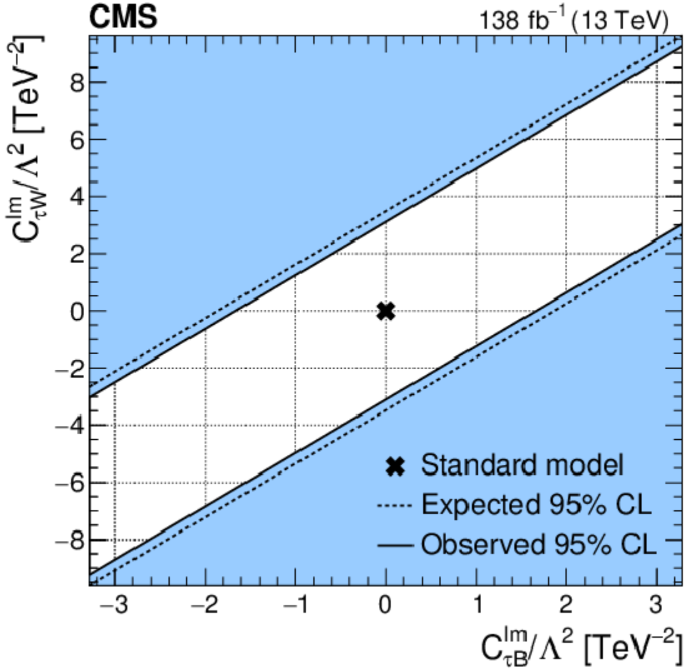


real part:

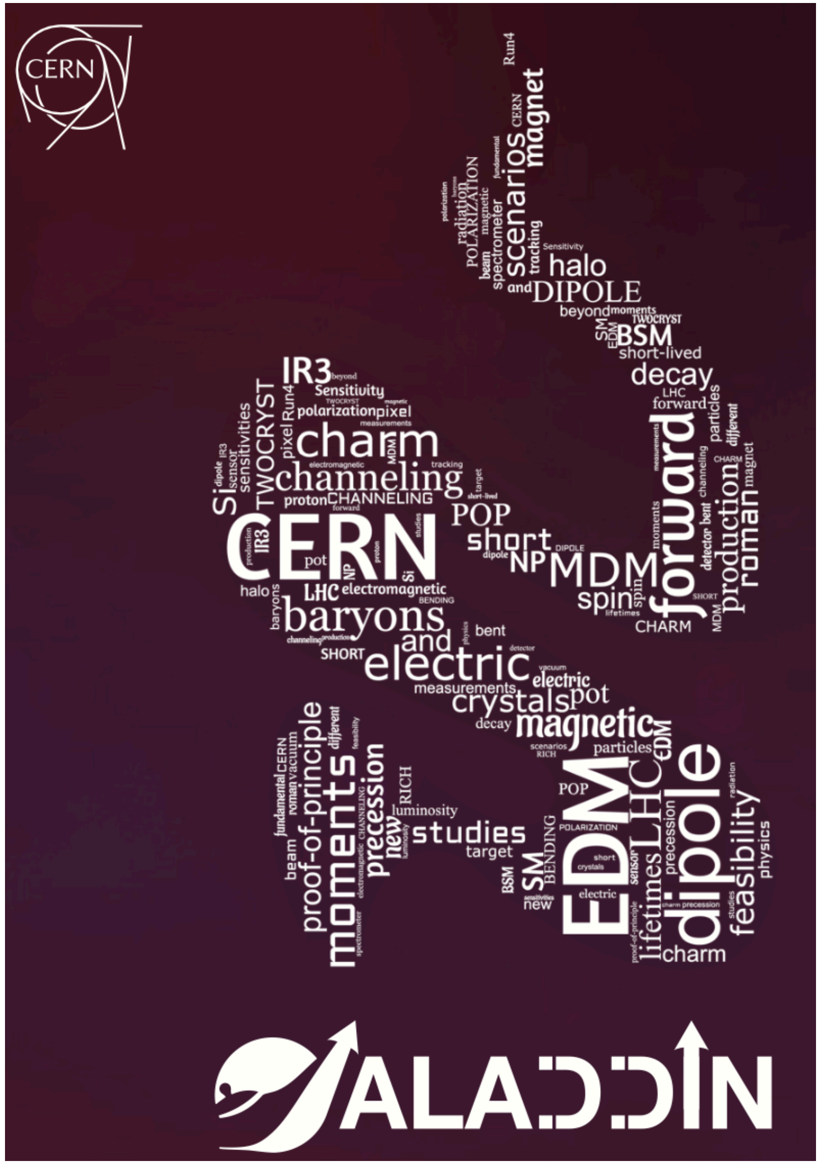




imaginary part:



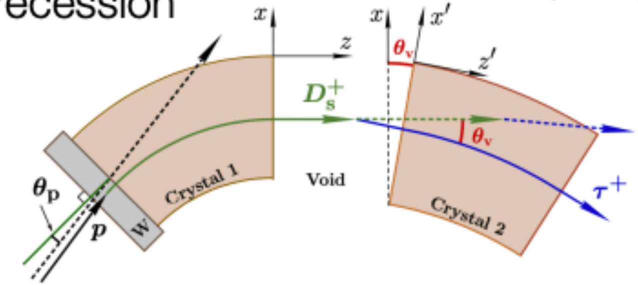
Beyond ATLAS/CMS



Physics Beyond Colliders

Proposed setup for τ precession

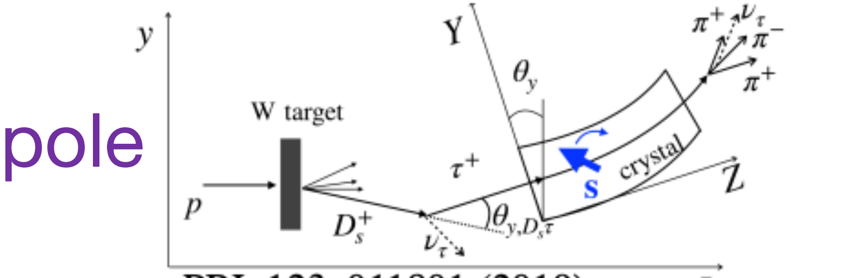
JHEP 03 (2019) 156



SELDOM

ALADDIN: An Lhc Apparatus for Direct Dipole moments Investigation

LoI: CERN-LHCC-2024-011



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Summary

- Tau g-2 and EDM has a strong potential to probe new physics
- ATLAS/CMS observed $\gamma\gamma \to \tau\tau$ in PbPb collisions
  - also used to constrain the tau g-2, with similar precision as LEP
- CMS made the first observation of $\gamma\gamma \to \tau\tau$ in pp collisions(5.3σ)
  - Full Run-2 data, 4 $\tau\tau$ final states, constrain both a_τ & d_τ with an EFT approach
  - Gains large improvement on tau g-2 and also good tau EDM result to zero q2
- These open a new avenue at LHC, even greater potential in future

Back up

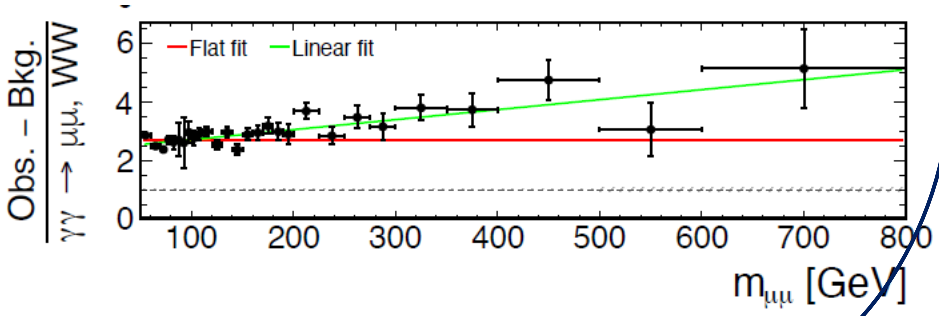
Baseline selection criteria for different final states

	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	$\mu\mu$
p_T^e (GeV)	$> 15/24$	> 25–33	—	—	—
$\lvert\eta^e\rvert$	< 2.5	< 2.1–2.5	—	—	—
p_T^μ (GeV)	$> 24/15$	—	> 21–29	—	> 26–$29/10$
$\lvert\eta^\mu\rvert$	< 2.4	—	< 2.1–2.4	—	< 2.4
$p_T^{\tau_h}$ (GeV)	—	> 30–35	> 30–32	> 40	—
$\lvert\eta^{\tau_h}\rvert$	—	< 2.1–2.3	< 2.1–2.3	< 2.1	—
$m_{\mu\mu}$ (GeV)	—	—	—	—	> 50
OS	yes	yes	yes	yes	yes
$\lvert d_z(\ell,\ell')\rvert$ (cm)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
$\Delta R(\ell,\ell')$	> 0.5	> 0.5	> 0.5	> 0.5	> 0.5
$m_T(e/\mu\, p_T, \vec{p}_T^{\,miss})$ (GeV)	—	< 75	< 75	—	—

Leading systematics

Elastic-elastic rescaling ($\gamma\gamma \to ll/WW$)

- Flat fit used to obtain systematic uncertainty
- Dominant systematic



N_{tracks}^{HS} correction in Drell-Yan: including or not $\gamma\gamma \to \mu\mu$ when derive the correction (6.5% for $N_{tracks} = 0$)

N_{tracks} extrapolation to Jet -> τ_h MF