Observation of $\gamma\gamma \rightarrow \tau\tau$ in pp collisions and probing tau g-2 at CMS

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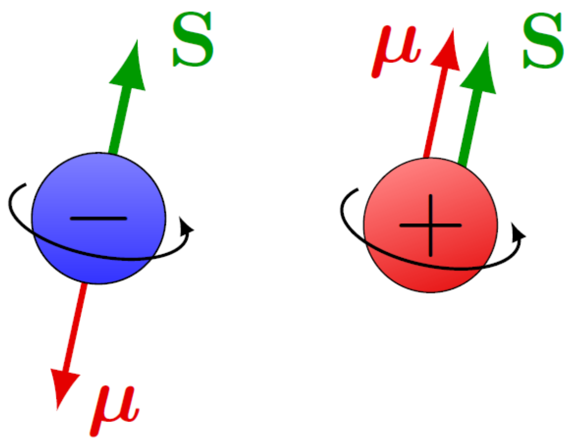
Lepton anomalous magnetic moment



$$\mu = g\frac{e}{2m}\mathbf{S}$$

- Spin and magnetic moment of lepton related via gyromagnetic factor g
- Dirac equation predicts g=2
- In QED, quantum effects modify the value of g, giving rise to an anomalous magnetic moment:

$$a_l = (g-2)/2$$

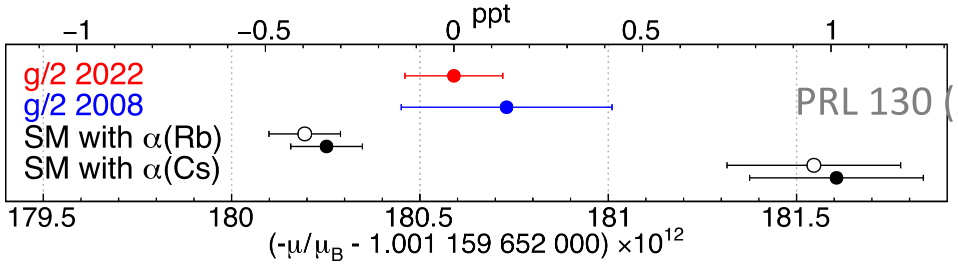
- NLO prediction (Schwinger, 1948):

$$a_l = \frac{\alpha}{2\pi} \cong 0.00116$$

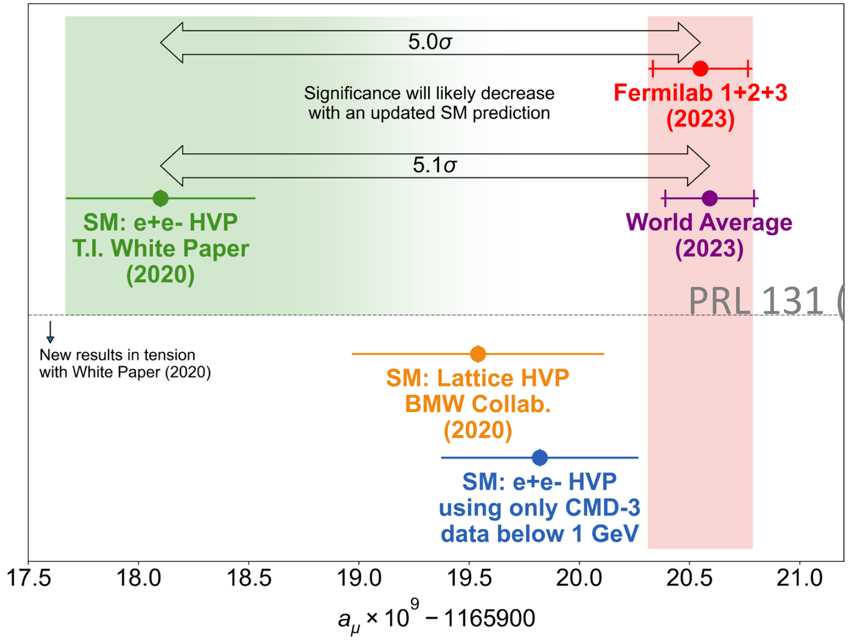
- Further corrections calculated

Measurements of a_l

- 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
- constraints on a_τ in e$^+$e$^-$ or PbPb collisions:
  - $-0.052 < a_\tau < 0.013$, 95% CL (DELPHI@LEP)
  - $-0.088 < a_\tau < 0.056$, 68% CL (CMS HIN)
  - $-0.057 < a_\tau < 0.024$, 95% CL (ATLAS HIN)
- If BSM effects scale with the m_l^2, deviations from SM could be 280 times larger than for a_μ



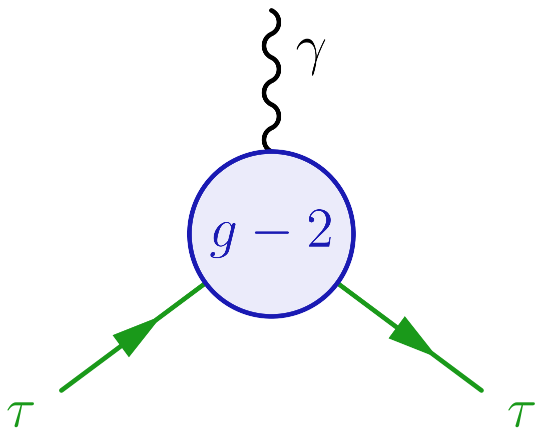
PRL 130 (2023) 071801



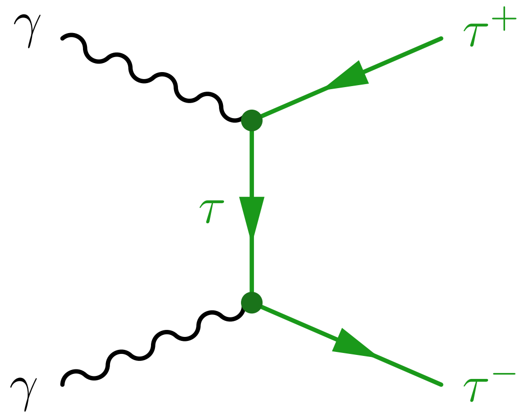
PRL 131 (2023) 161802

Constraint on tau electromagnetic moments a_τ & d_τ

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



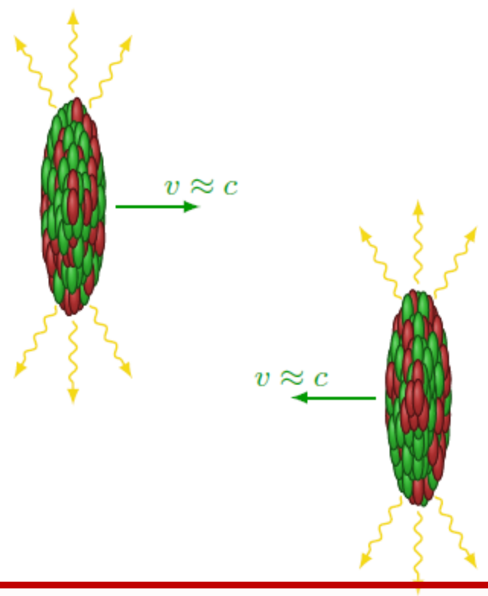
- $\gamma\gamma \to \tau\tau$ process contains 2 $\gamma\tau\tau$ vertices



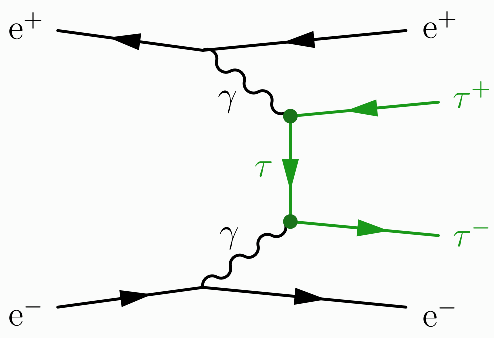
- contraints on electromagnetic moments a_τ & d_τ from *form factors* or *SMEFT*
- in the SM: $d_\tau \sim 10^{-37}$ ecm via CP violation in CKM, but could be much larger in BSMs

Photon-induced processes

- 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
- Cross section proportional to Z^4 → huge enhancement in Pb-Pb runs compared to pp runs
- ATLAS and CMS has observed $\gamma\gamma \rightarrow \tau\tau$ process in Pb-Pb collisions and constrain tau g-2 → but still worse than LEP measurements



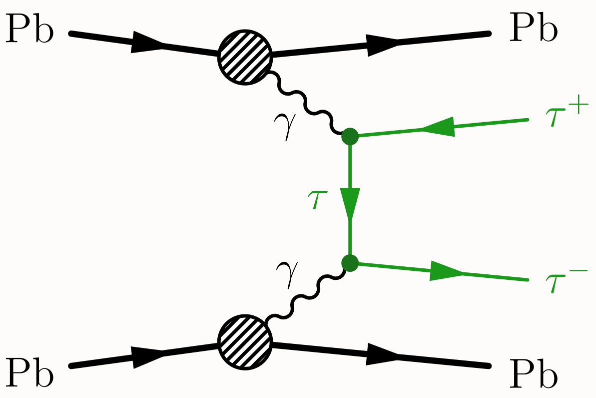
LEP: DELPHI, L3, …



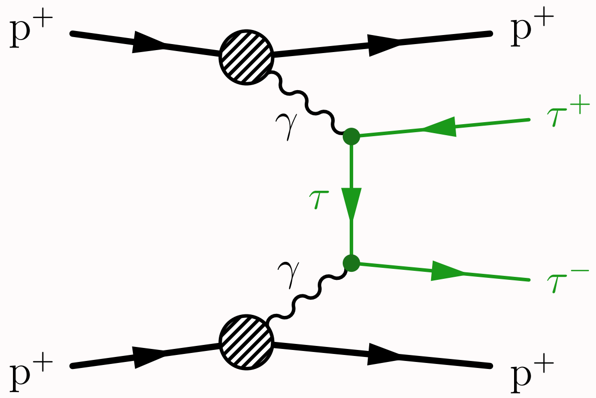
$e^+e^- \rightarrow e^+e^- \tau^+\tau^-$

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

LHC: CMS, ATLAS, …



PbPb → PbPb $\tau^+\tau^-$

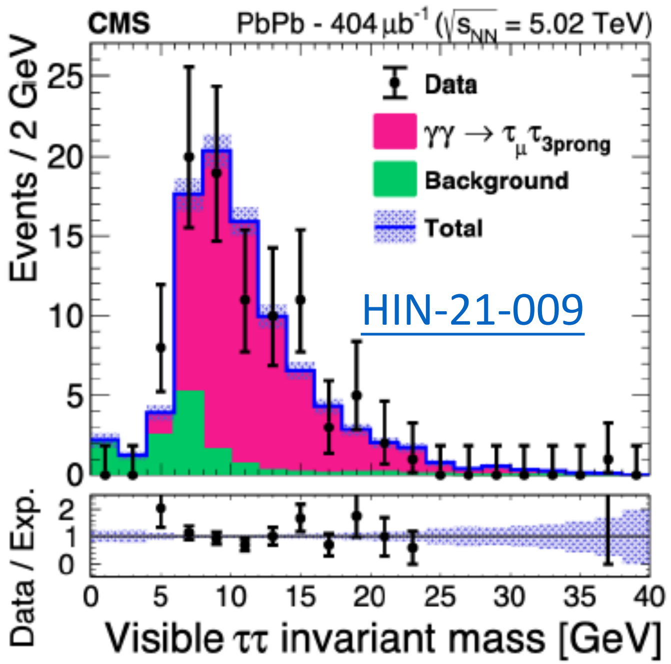


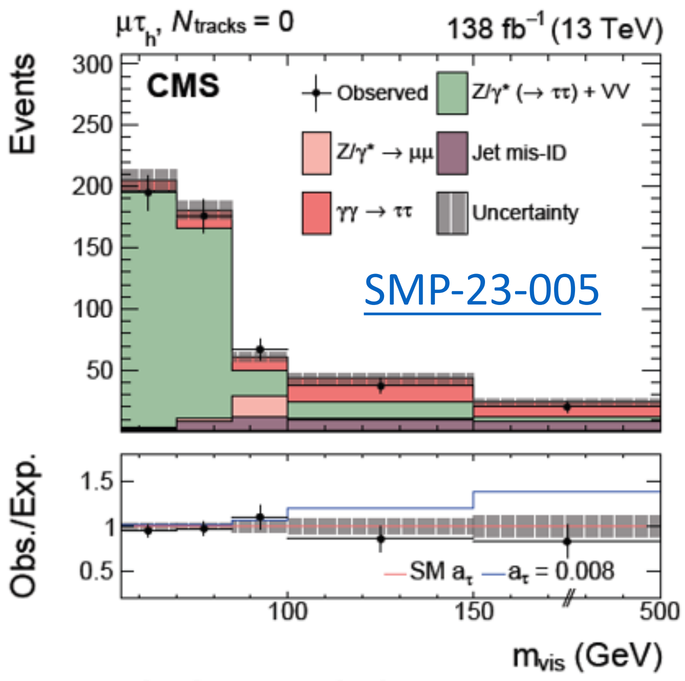
pp → pp $\tau^+\tau^-$

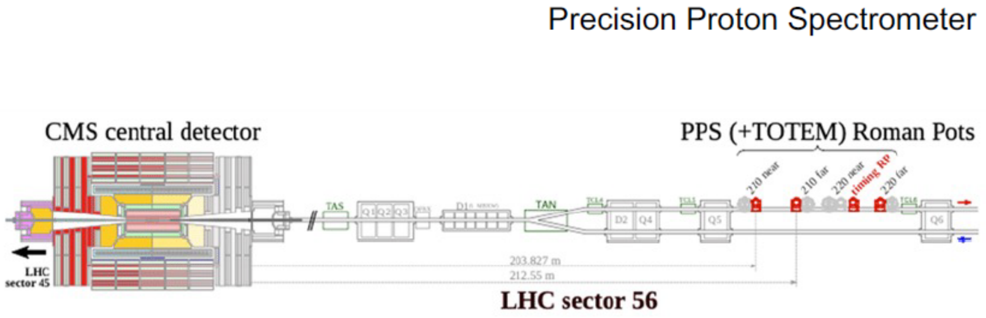
ATLAS: PRL 131 (2023) 151802
CMS: PRL 131 (2023) 151803

Focus of this talk

$\gamma\gamma \rightarrow \tau\tau$ study at CMS





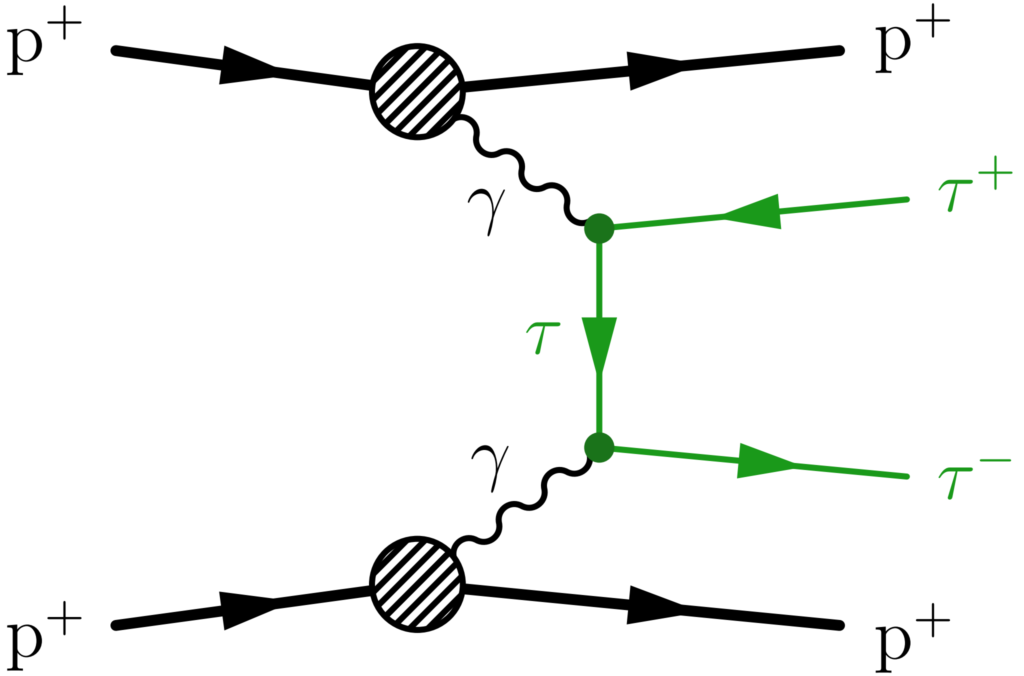


ultra-peripheral PbPb | pp with track counting | pp with forward proton tagging

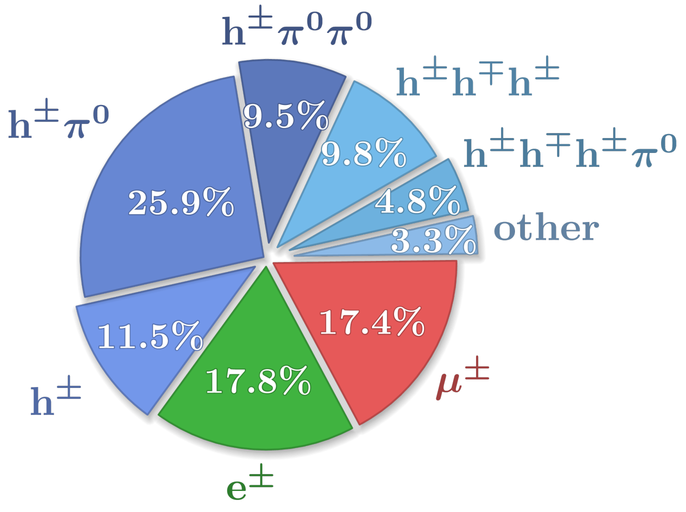
0 GeV — 50 GeV — 350 GeV — 2 TeV

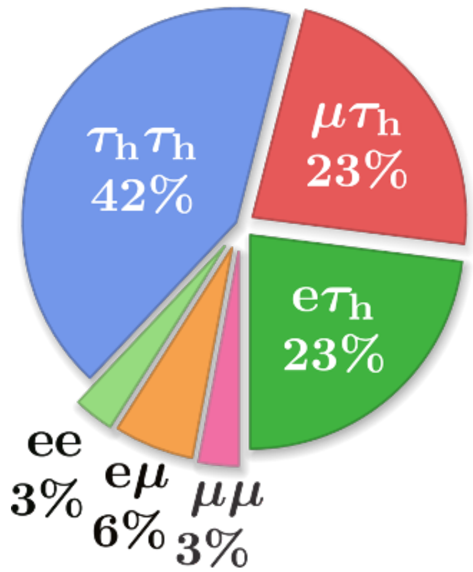
Focus of this talk

$\gamma\gamma \to \tau\tau$ signature



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

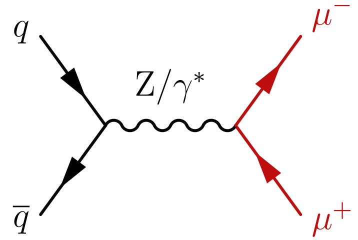


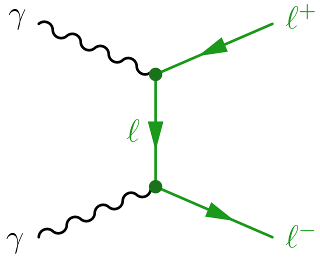


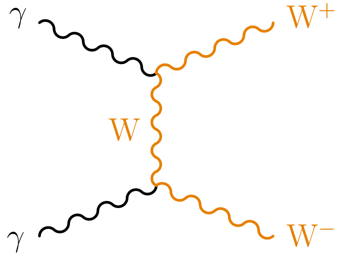
- **2 diffracted protons**
  - no hadronic activity close to $\tau\tau$ vertex

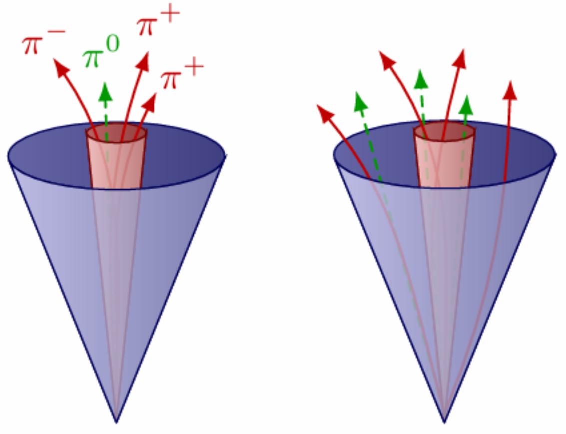
Background in signal region

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





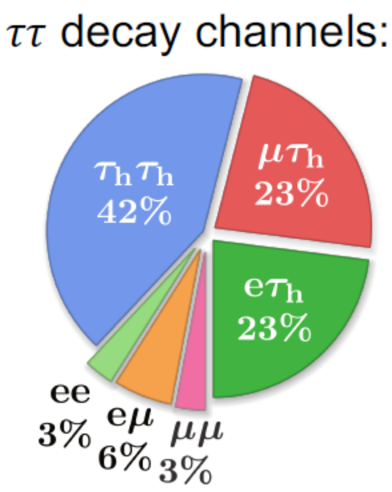


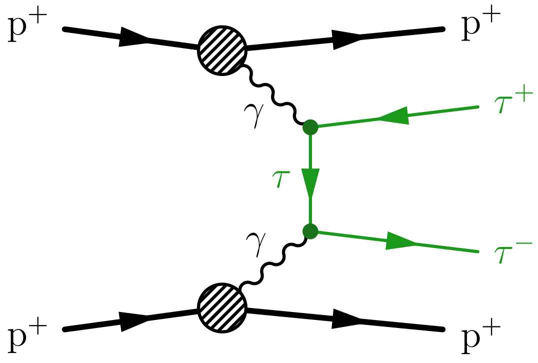


hadronic τ_h jet

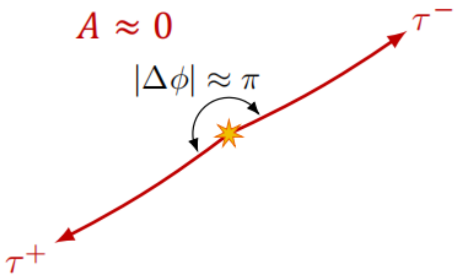
hadronic quark/gluon jet

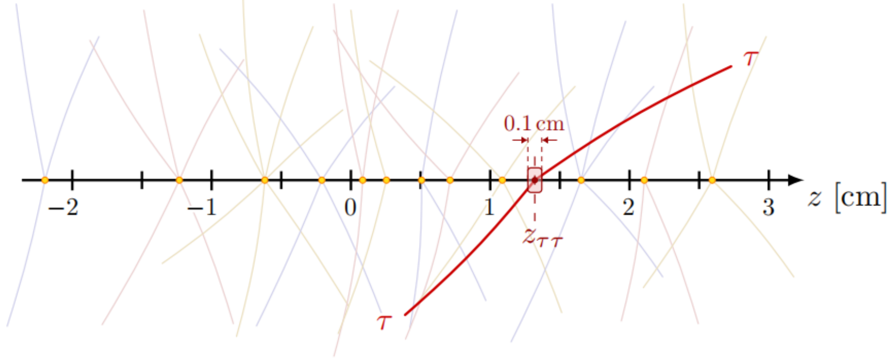
Strategy for $\gamma\gamma \rightarrow \tau\tau$ in pp





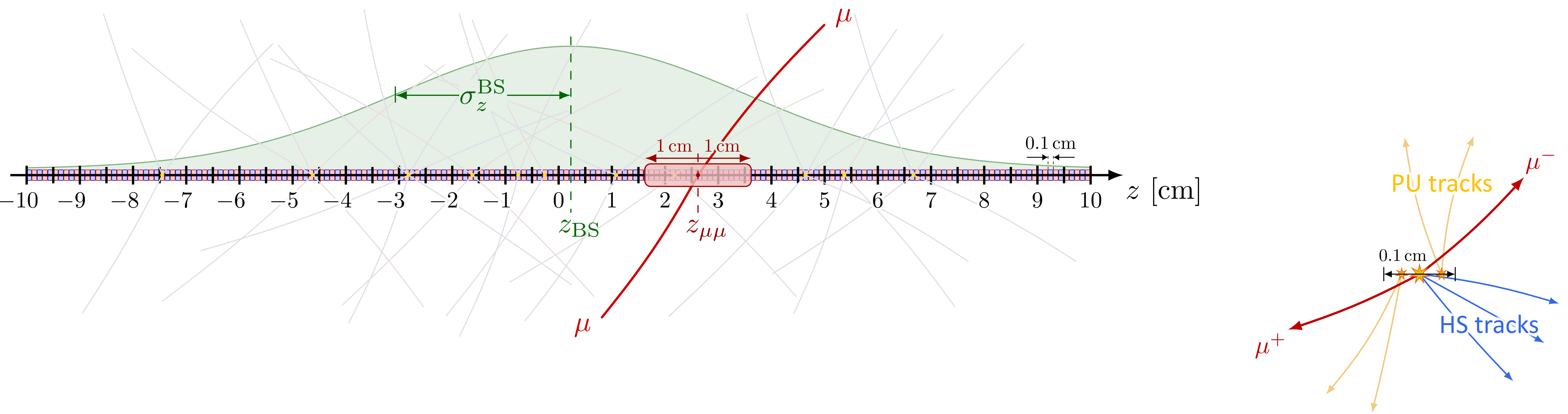
- select events with opposite sign $\tau^+\tau^-$
  - ➢ combine 4 $\boldsymbol{\tau\tau}$ final states: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$
  - ➢ **exclusivity cuts**:
    - back-to-back: $\boldsymbol{A = 1 - \frac{|\Delta\phi|}{\pi} < 0.015}$
    - low activity around $\tau\tau$ vertex: $\mathbf{N_{tracks}}$**=0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





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

N_{tracks} corrections



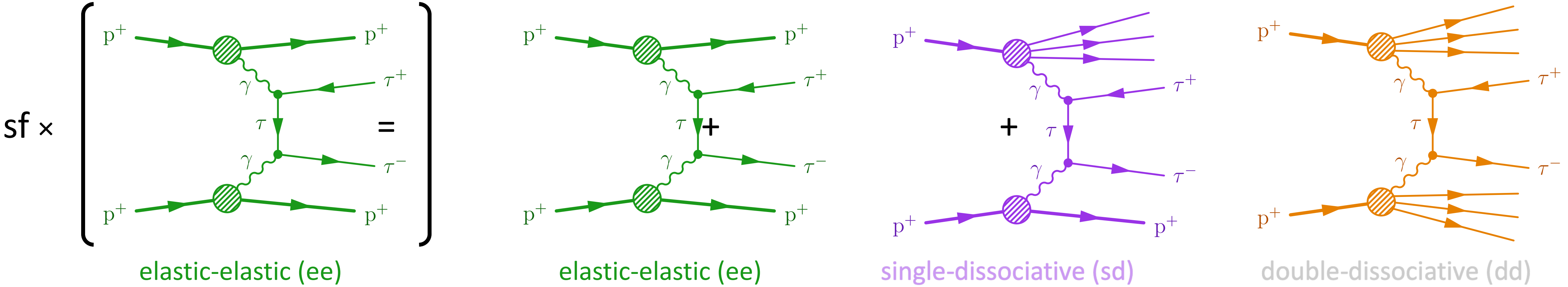
derive obs. / sim. corrections in Z → $\mu\mu$ events at Z peak, $|m_{\mu\mu} - m_Z| < 15$ GeV:

- **pileup tracks**: compare N_{tracks}^{PU} distributions in 0.1 cm *z* windows (far away from $\mu\mu$ vertex) → applied to all simulations
- **hard scattering tracks**: compare N_{tracks}^{HS} distributions in 0.1 cm *z* window around $\mu\mu$ vertex → applied to Drell-Yan process

Elastic rescaling

- signal samples: only **elastic-elastic (ee)** process generated by gammaUPC (Shao&d'Enterria 2207.03012, JHEP 09 (2022) 248)
- **single-dissociative (sd)** and **double-dissociative (dd)** processes not included
  - have larger cross section
  - can have an exclusive signature
- estimate dissociative contributions (incl. higher-order corrections) by rescaling elastic-elastic $\gamma\gamma \to \mu\mu$ signal in $\mu\mu$ data

$$\Rightarrow \text{measure rescaling factor} = \frac{(\mathbf{ee}+\mathbf{sd}+\mathbf{dd})_{\text{obs}}}{(\mathbf{ee})_{\text{sim}}}$$

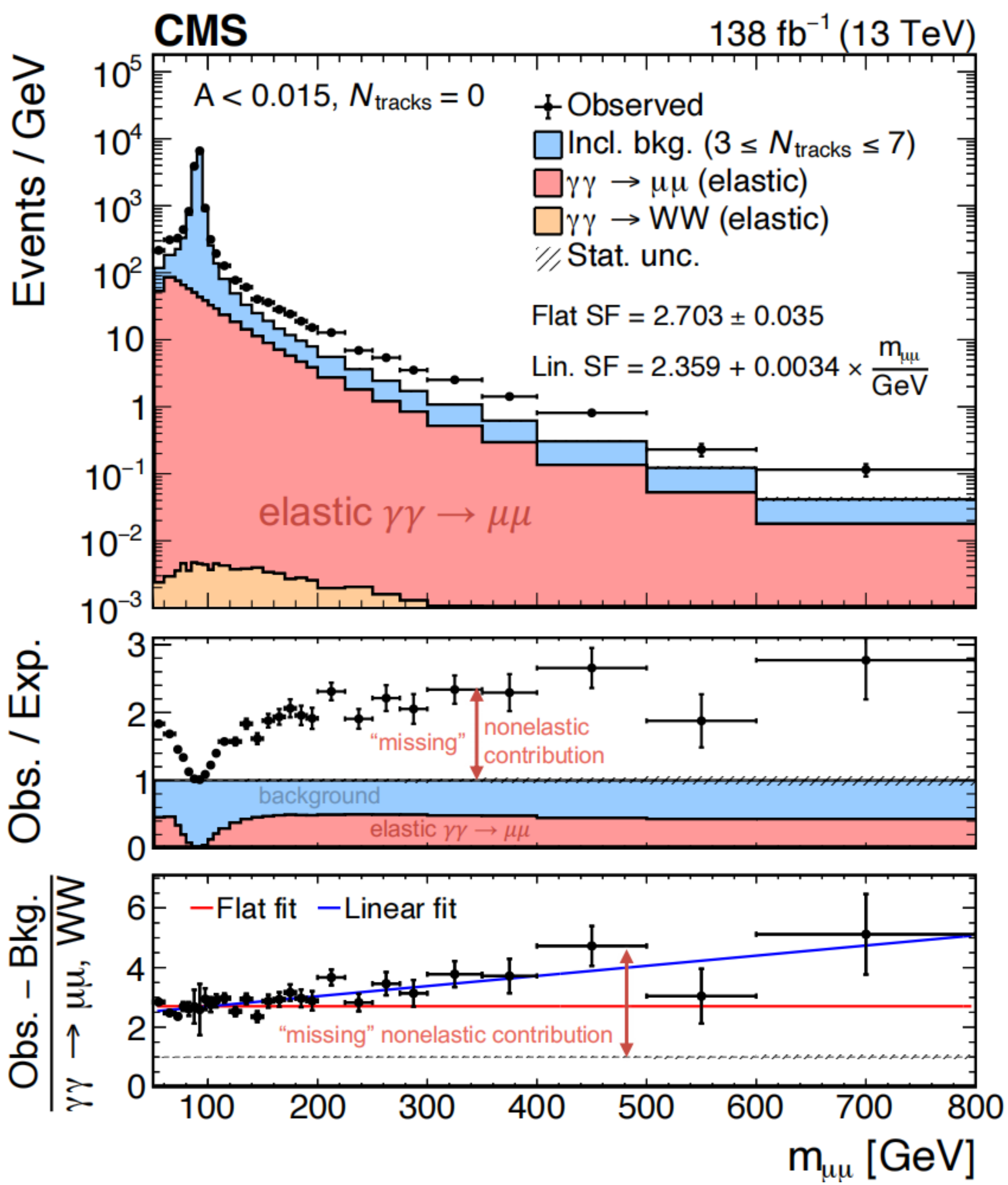


Elastic rescaling

applied to photon-induced simulation ($\gamma\gamma \rightarrow \ell\ell$, WW)

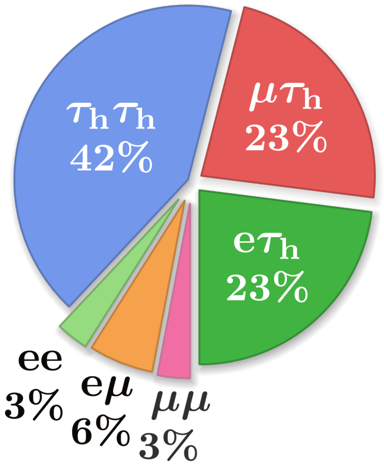
- rescaling factor measured in $m_{\mu\mu}$ distribution in dimuon events with A < 0.015 and N_{tracks} = 0 or 1
- inclusive background (mostly Drell–Yan)
  - estimated from data in $3 \leq N_{tracks} \leq 7$ region
  - normalized to Z peak
- **elastic $\gamma\gamma \rightarrow \mu\mu$/WW "signal"**
  - contributes significantly $m_{\mu\mu}$ > 150 GeV
  - rescale to data to estimate nonelastic contribution
- fits:
  - **linear fit** applied as nominal corrections to all elastic simulation ($\gamma\gamma \rightarrow$ ee, $\mu\mu$, $\tau\tau$, WW)
  - **flat fit (~2.7)** used to obtain uncertainty (conservative)

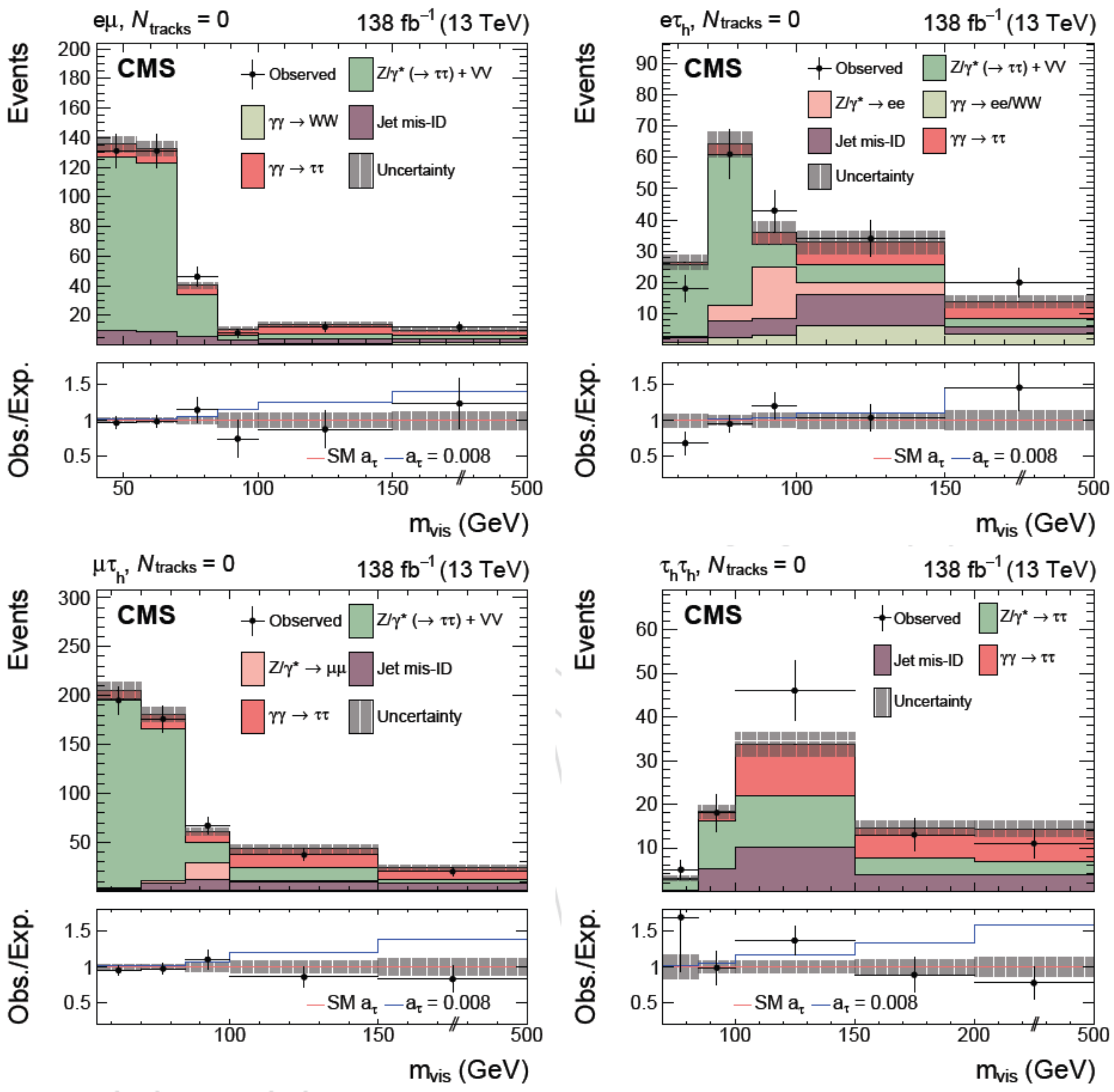
$$\text{rescaling factor} = \frac{(\text{ee}+\text{sd}+\text{dd})_{\text{obs}}}{(\text{ee})_{\text{sim}}} = \frac{\text{Obs.} - \text{Bkg.}}{\gamma\gamma \longrightarrow \mu\mu, \text{WW}}$$



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

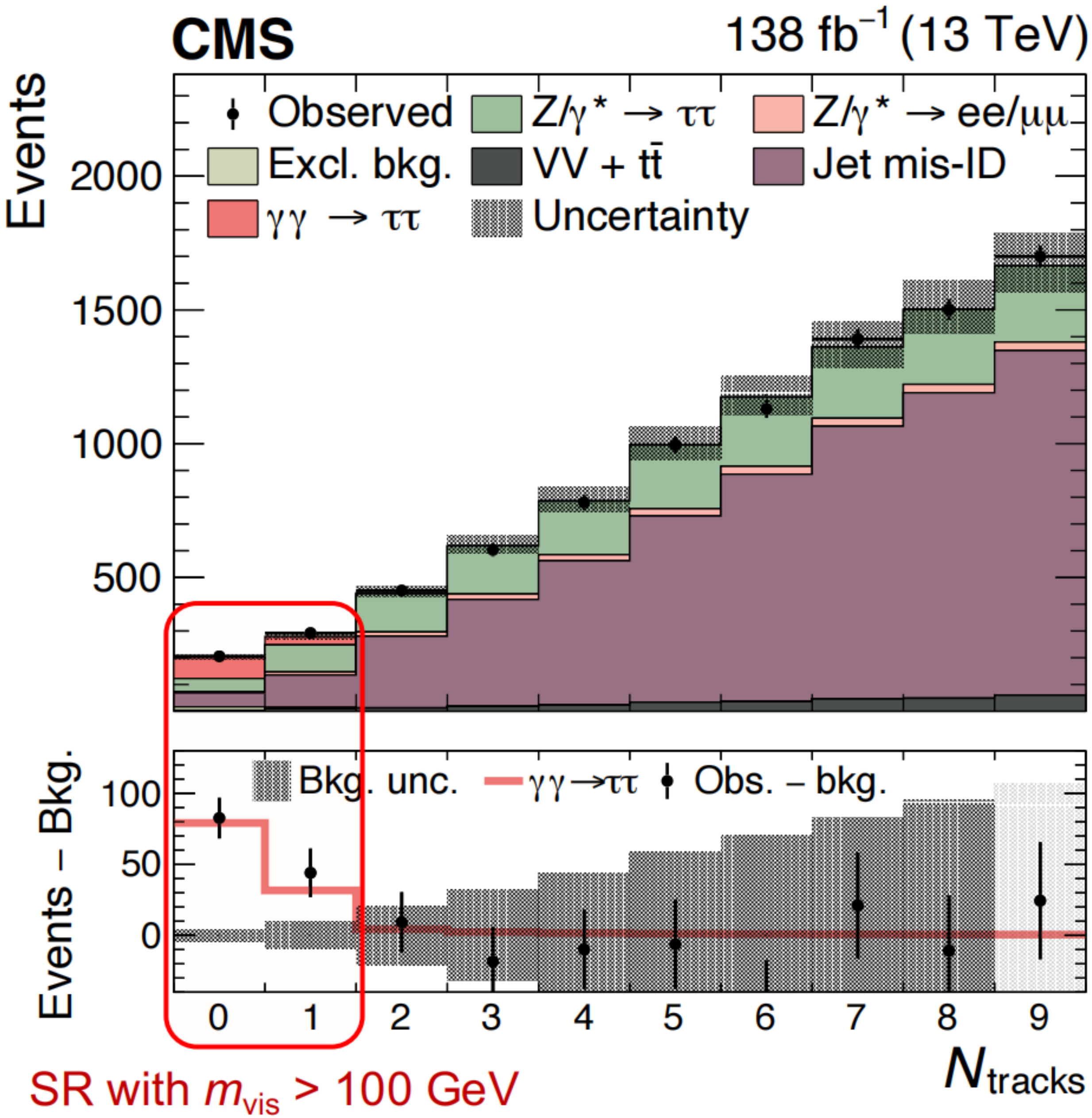
- after maximum-likelihood fit to observed data
- assuming SM a_τ & d_τ
- signal clearly visible in high $m_{\text{vis}}(\tau\tau)$ bins





N_{tracks} distributions

- same selections as SR, but
  - allowing $N_{track} < 10$
  - **m_{vis} > 100 GeV**
- combination of
  - all 4 $\tau\tau$ channels
  - all 3 data-taking years
- very nice modeling of N_{tracks} !
- signal clearly visible



SR with m_{vis} > 100 GeV

First observation of $\gamma\gamma \to \tau\tau$ in pp collisions!

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

  ⇒ *first* observation of $\gamma\gamma \to \tau\tau$ in pp !

- combined **signal strength**

  $r = 0.75 +0.21 -0.18$

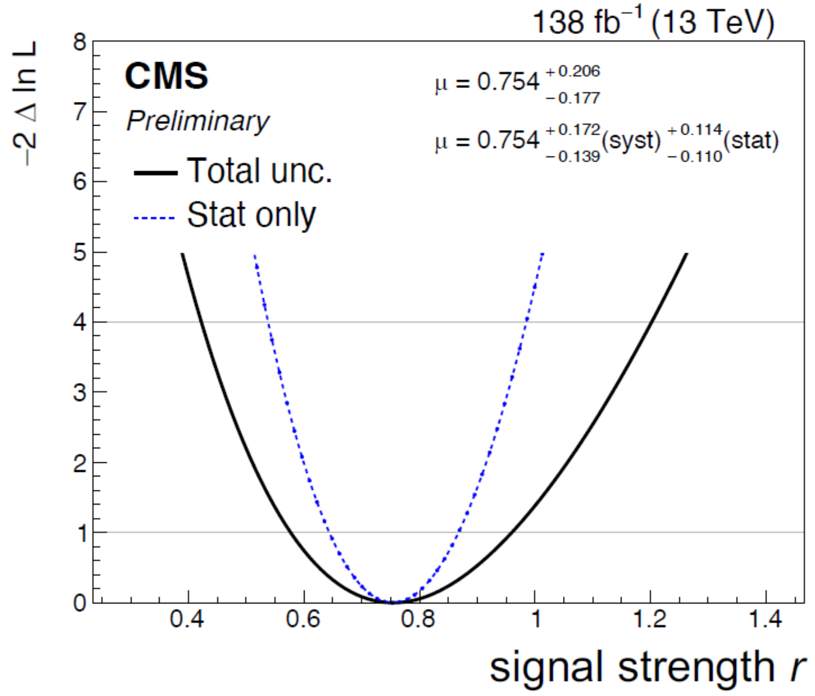
  w.r.t. gammaUPC elastic prediction

  × rescaling measured in $\mu\mu$ data

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

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

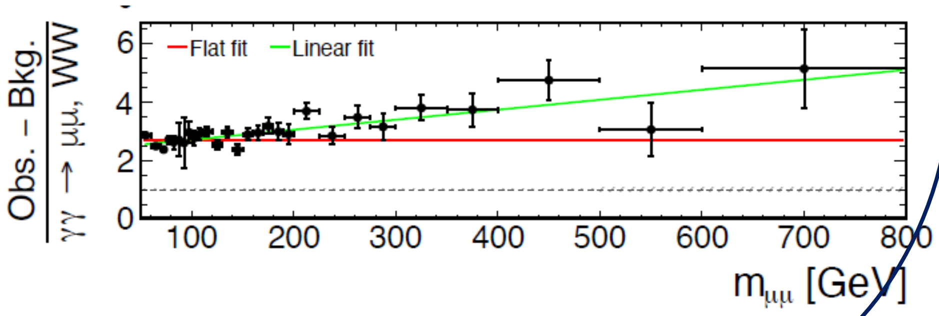
$\tau\tau$ channel	Observed	Expected
$e\mu$	2.3σ	3.2σ
$e\tau_h$	3.0σ	2.1σ
$\mu\tau_h$	2.1σ	3.9σ
$\tau_h\tau_h$	3.4σ	3.9σ
Combined	5.3σ	6.5σ



Leading systematics

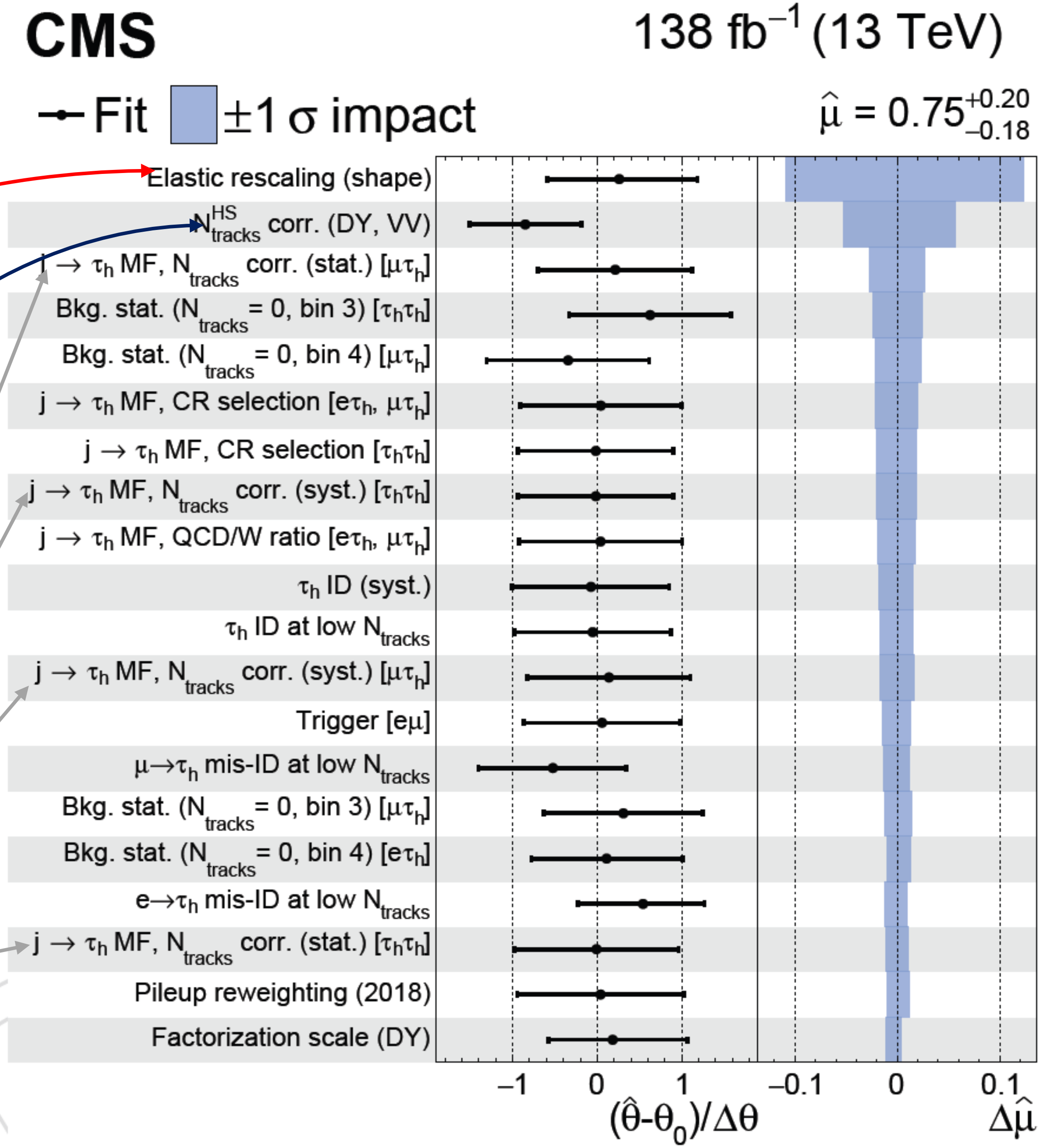
Elastic-elastic rescaling ($\gamma\gamma \to ll/WW$)

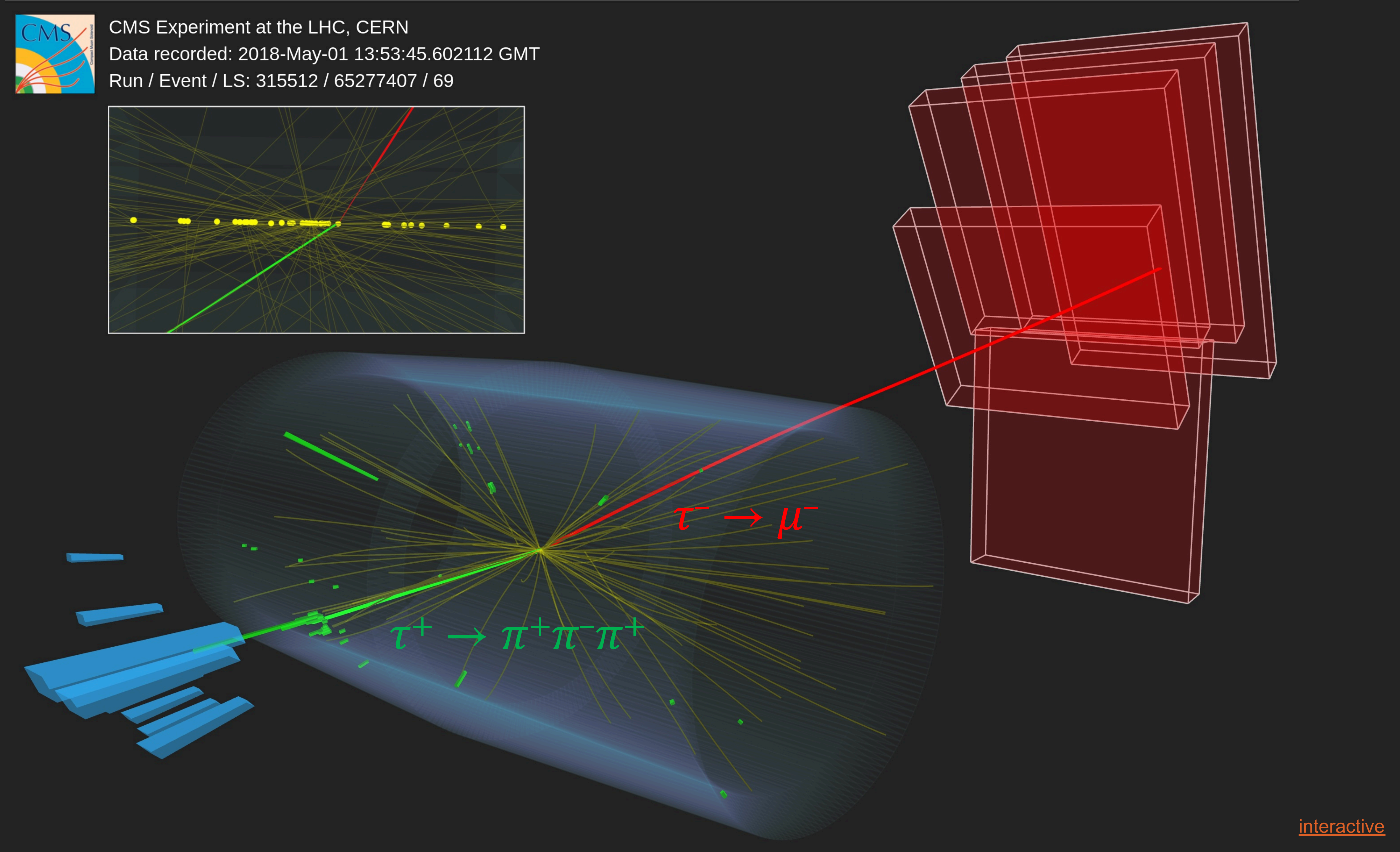
- Flat fit used to obtain systematic uncertainty
- Dominant systematic



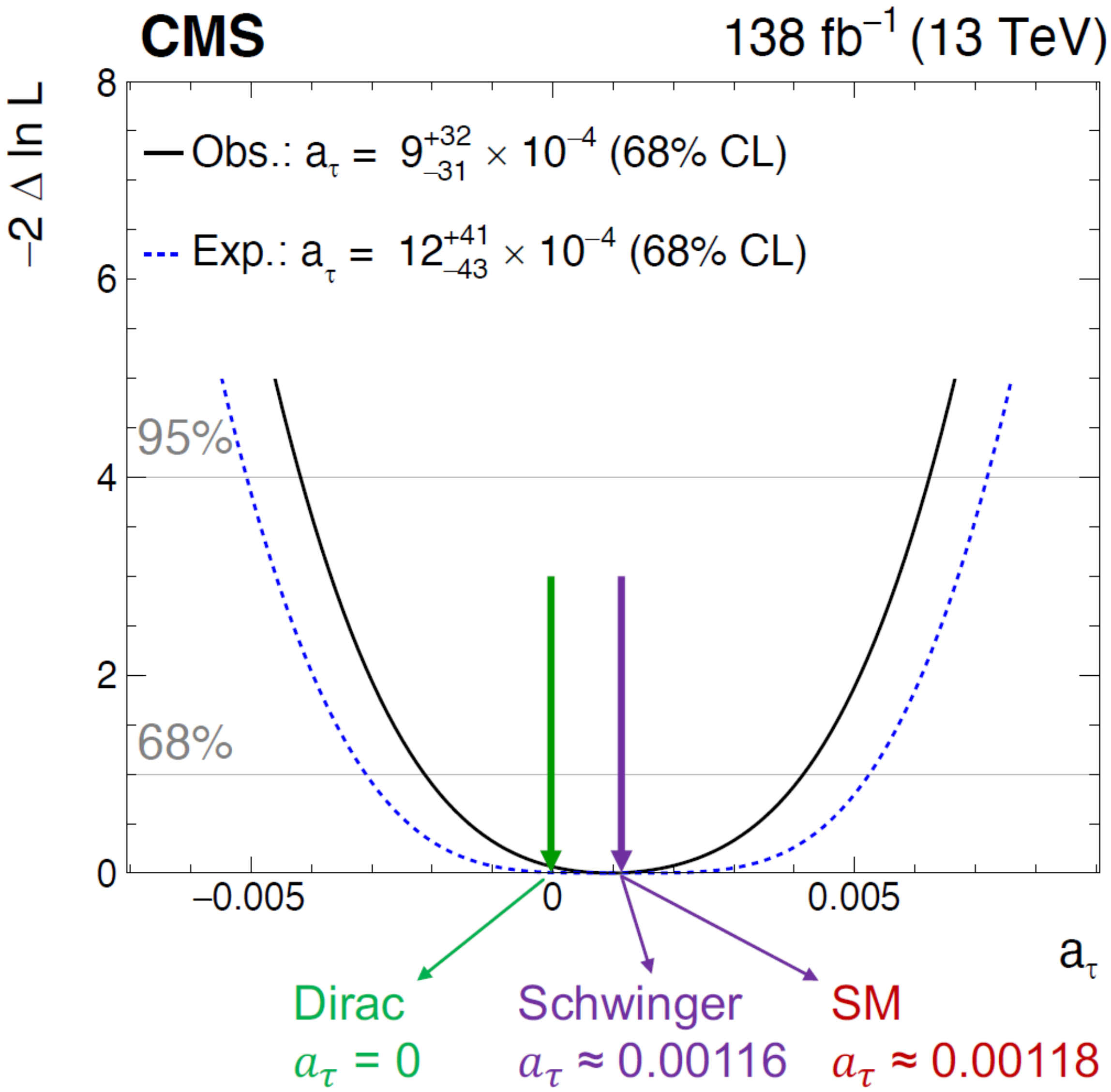
N_{tracks}^{HS} correction in Drell-Yan: including or not $\gamma\gamma \to \mu\mu$ when derive the correction (6.5% for $N_{tracks} = 0$)

N_{tracks} extrapolation to Jet -> τ_h MF




CMS
CMS Experiment at the LHC, CERN
Data recorded: 2018-May-01 13:53:45.602112 GMT
Run / Event / LS: 315512 / 65277407 / 69
$\tau^- \rightarrow \mu^-$
$\tau^+ \rightarrow \pi^+\pi^-\pi^+$
interactive

Constraints on a_τ



- fit all $m_{\tau\tau}$ distributions
- scan likelihood over a_τ
- compatible with the SM

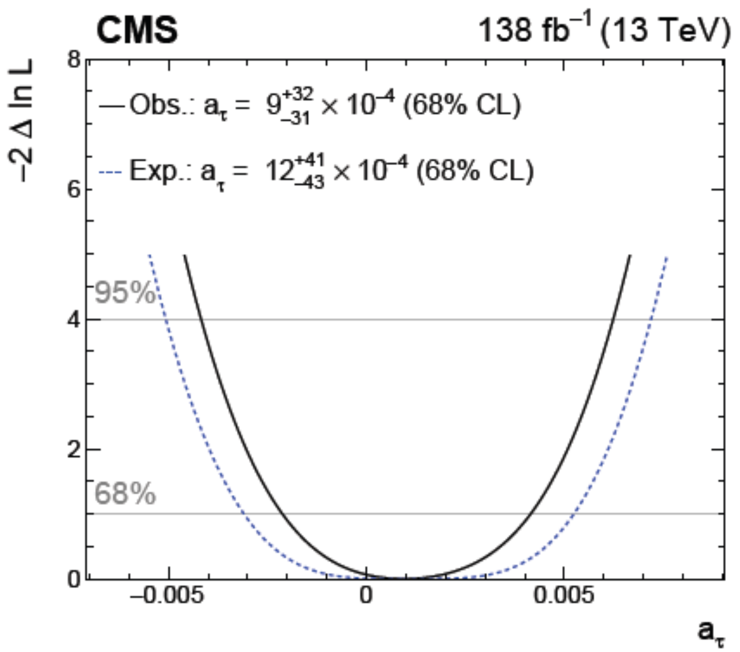
Schwinger: a_τ = 0.001 161 4

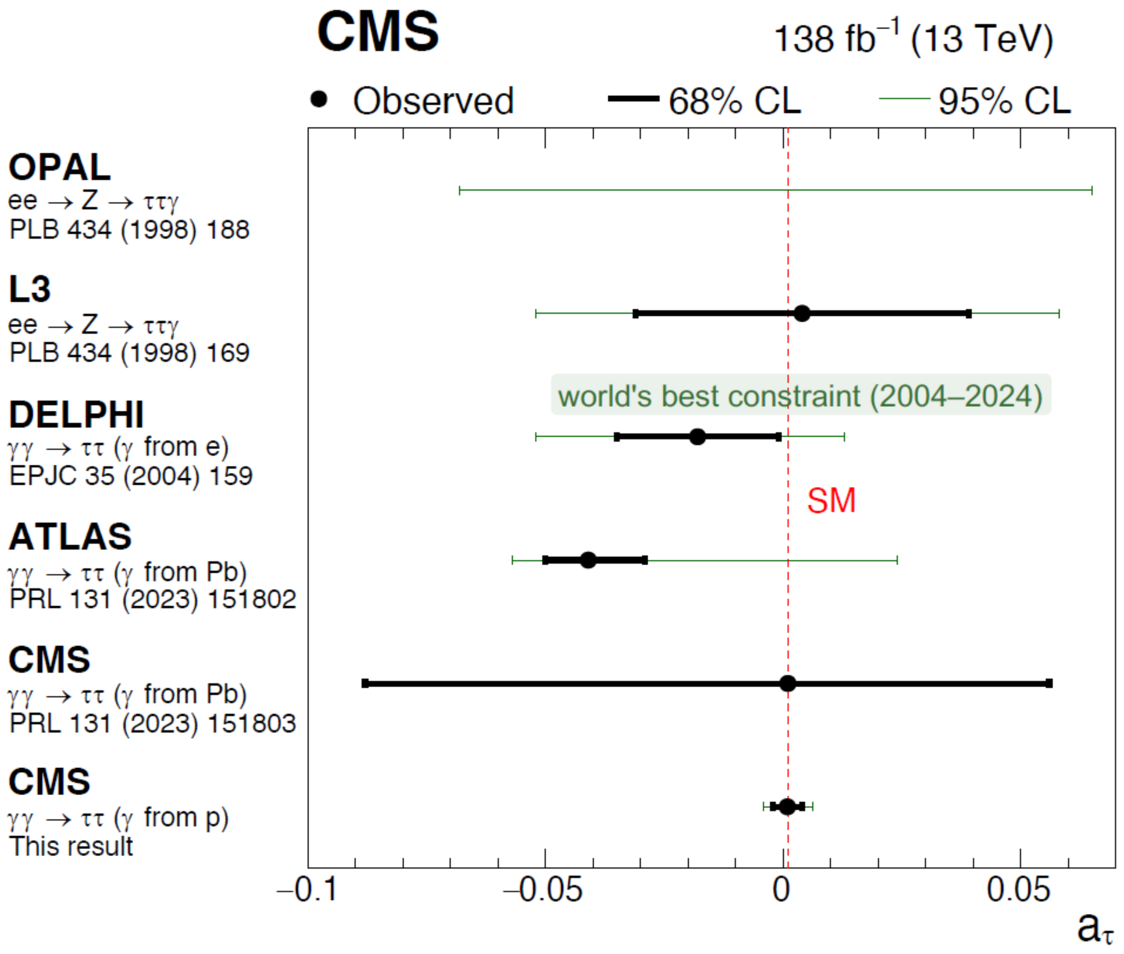
SM: a_τ = 0.001 177 21(5)

our result: a_τ = 0.0009 (32)

⇒ uncertainty ~3×Schwinger !

Constraints on a_τ

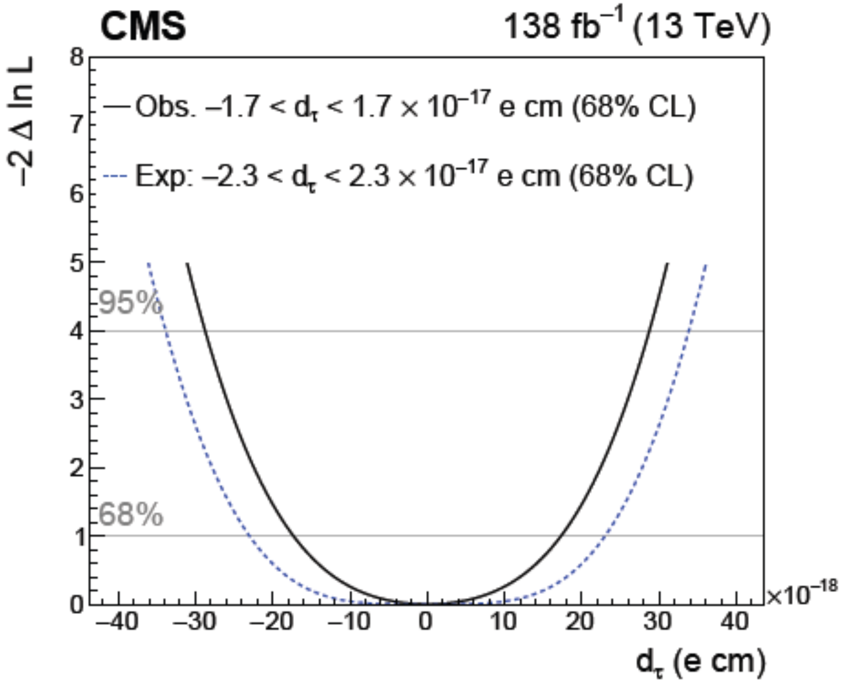


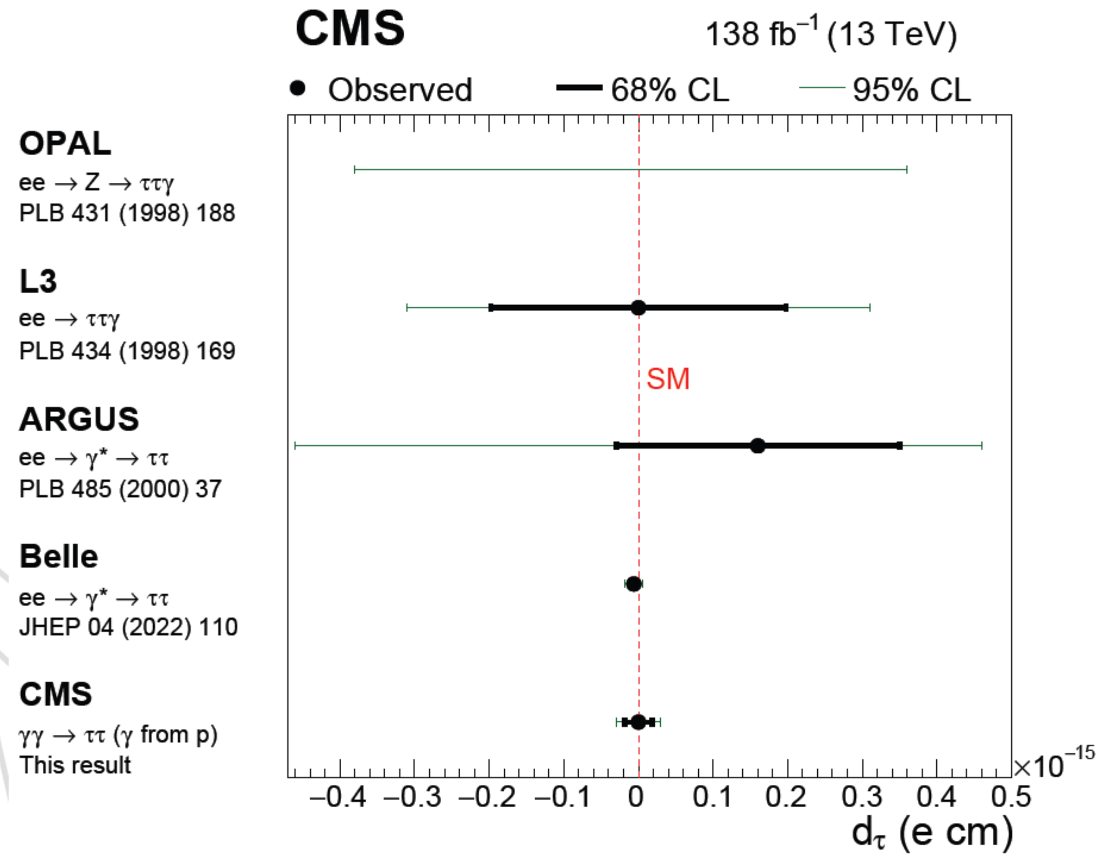


- SM: a_τ = 0.001 177 21(5)
- DELPHI: a_τ = –0.018 ± 0.017
- ATLAS: a_τ = −0.041 +0.012 –0.009
- CMS HIN: a_τ = 0.001 +0.055 –0.089
- this result: a_τ = 0.0009 +0.0032 –0.0031

>5x better than LEP !

Constraints on d_τ





- SM: $d_\tau \sim 10^{-37}$ ecm (due to CPV in CKM)
- Belle: $-1.85 < d_\tau < 0.61 \times 10^{-17}$ ecm (95%)
- this result: $-1.70 < d_\tau < 1.70 \times 10^{-17}$ ecm (68%)

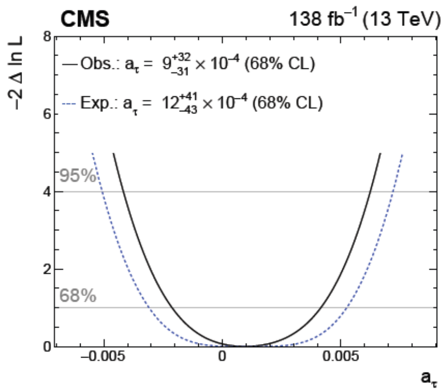
approaching Belle !

Constraints on Wilson coefficients

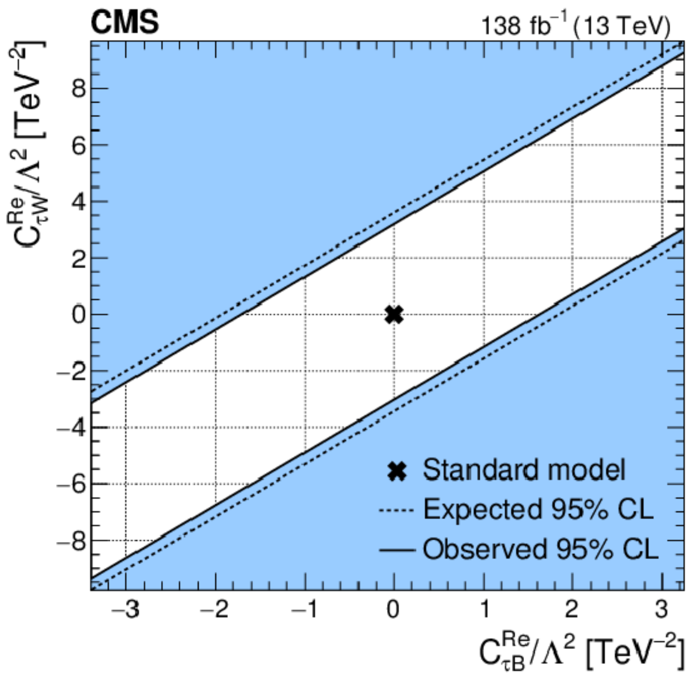
recast results to make exclusion of $C_{\tau B}/\Lambda^2$ vs. $C_{\tau W}/\Lambda^2$:

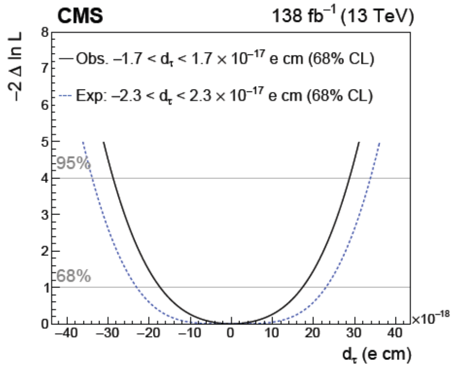
$$\delta a_\tau = \frac{2m_\tau}{e}\frac{\sqrt{2}v}{\Lambda^2}\mathrm{Re}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}]$$

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

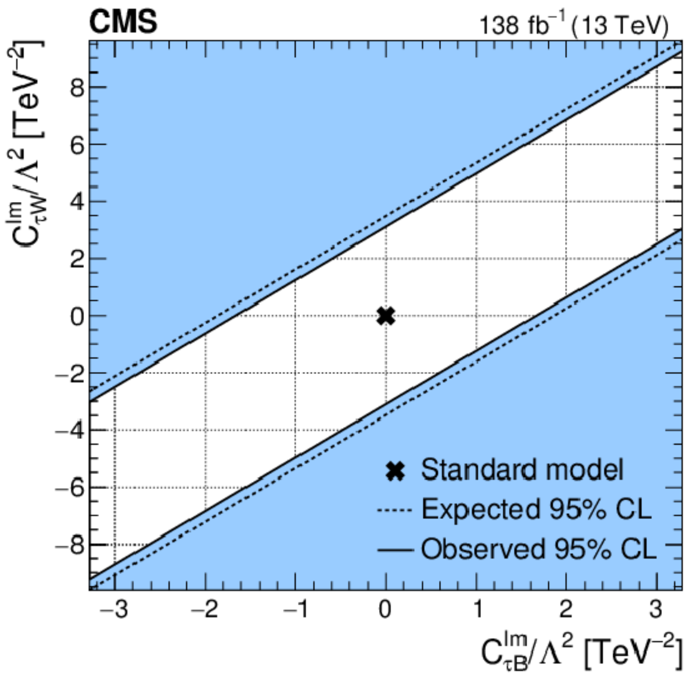


real part:





imaginary part:



Summary

- Tau g-2 and EDM has a strong potential to probe new physics
- CMS made the first observation of $\gamma\gamma \rightarrow \tau\tau$ in pp collisions(5.3σ)
  - Full Run-2 data analyzed in 4 $\tau\tau$ final states
  - Published at Reports on Progress in Physics 87 (2024) 107801
- The measurement is used to constrain the tau electromagnetic moments with an EFT approach
  - Large improvement on tau g-2
  - Tau EDM result is at the same order as the best measurement