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

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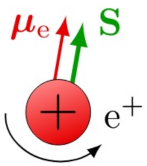
Anomalous Magnetic Moments of Lepton



$$\mu_l = g_l \frac{e}{2m_l} S_l$$

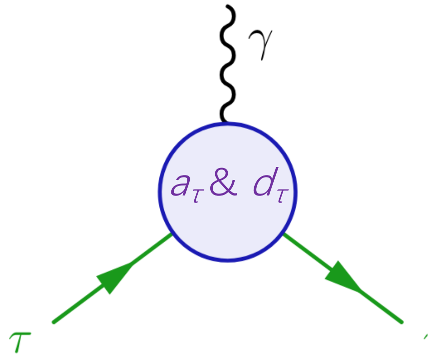
$$a_l = \frac{g_l - 2}{2}$$

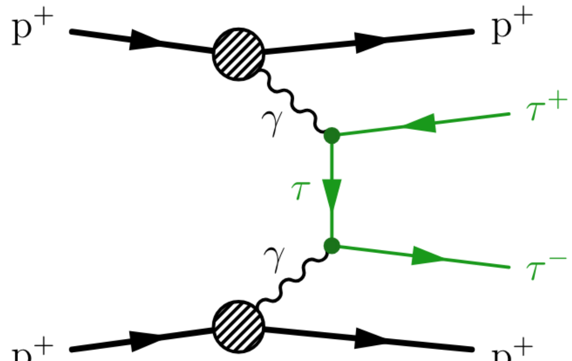
Measurements of $\mathbf{a_e}$ agree with SM with 12 significant digits.
Measurements of $\mathbf{a_\mu}$ appear in longstanding tension with theoretical predictions.
Many BSMs predict the enhancement of τ because of its larger mass $\frac{m_\tau^2}{m_\mu^2} \approx 280$

$$a_\tau^{SM} \approx 0.001\,177$$
$$a_\tau = \frac{g-2}{2} = a_\tau^{SM} + \delta a_\tau$$

CP violation in CKM:
$d_\tau^{SM} \approx 10^{-37}$ ecm

some BSMs predict:
$d_\tau \approx 10^{-19}$ ecm





Constraints on electromagnetic moments a_τ & d_τ with form factors (DELPHI & ATLAS HIN) or **SMEFT** (CMS pp(this study) & CMS HIN)

Analysis Overview

- CMS Run II data (pp collisions, $\sqrt{s}$=13TeV,138 fb^{-1})
- Four final states: $\boldsymbol{e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h}$
- Use **μμ** events($Z \to \mu\mu, \gamma\gamma \to \mu\mu$) to measure corrections to simulations
- simulated backgrounds: Drell-Yan, Di-boson, Top quark
- data-driven methods to estimate QCD and W+jets background

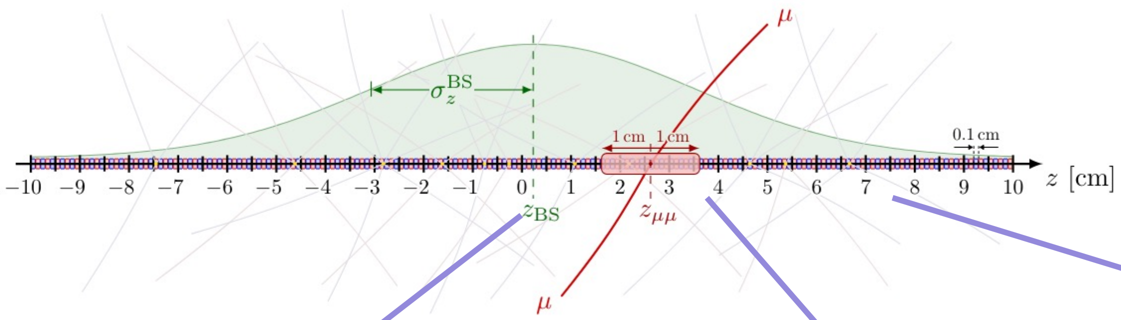
Basic selection

	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	$\mu\mu$
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	—	—

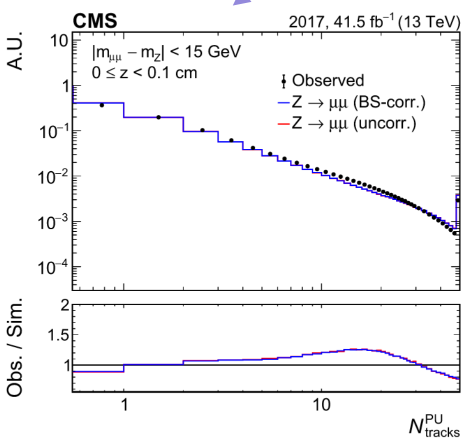
Exclusive selection:

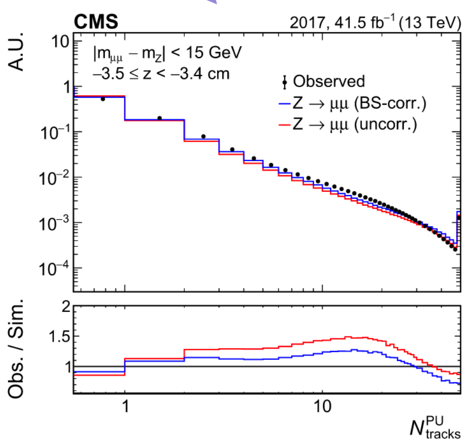
- **Acoplanarity** $\mathbf{A = 1 - \frac{|\Delta\Phi|}{\pi}}$ **,A<0.015**
- $\boldsymbol{N_{tracks} = 0, 1}$ in the 0.1 cm width window of the di-τ vertex (N_{tracks}:number of extra charged tracks)

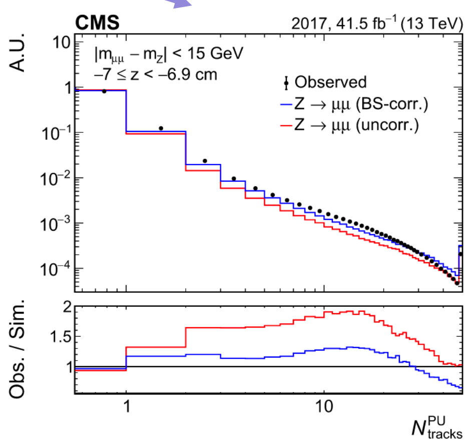
Pileup Track Multiplicity Correction



windows far from the di-μ vertex
discard the tracks from hard scattering interactions

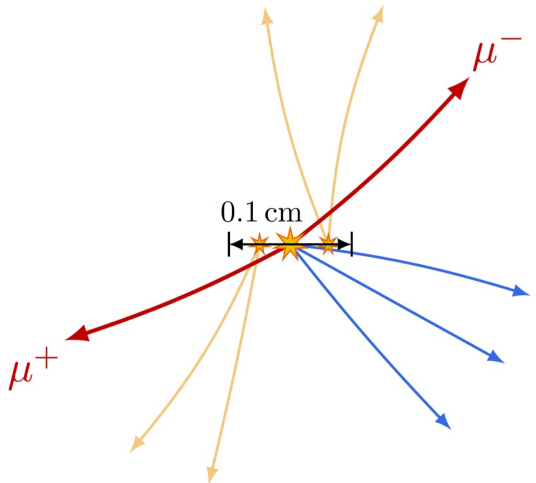




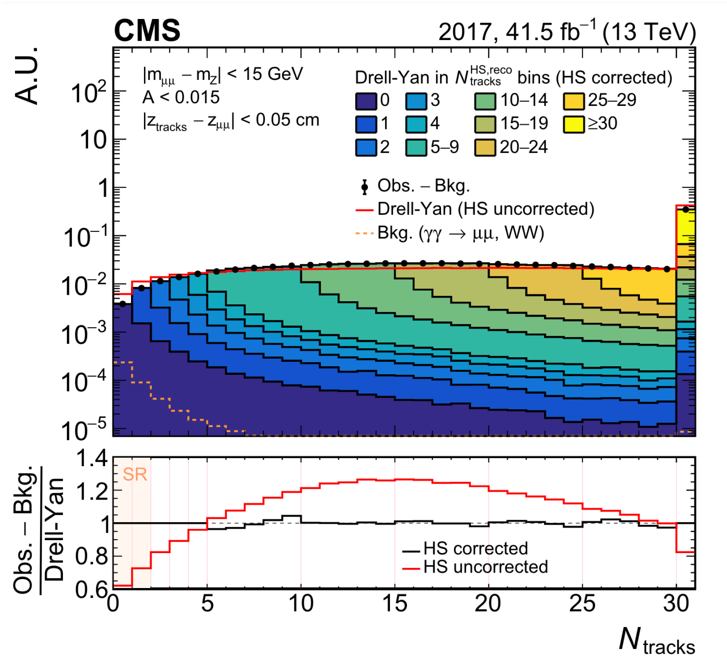


Applied on all simulated processes

Hard Scattering Track Multiplicity Correction



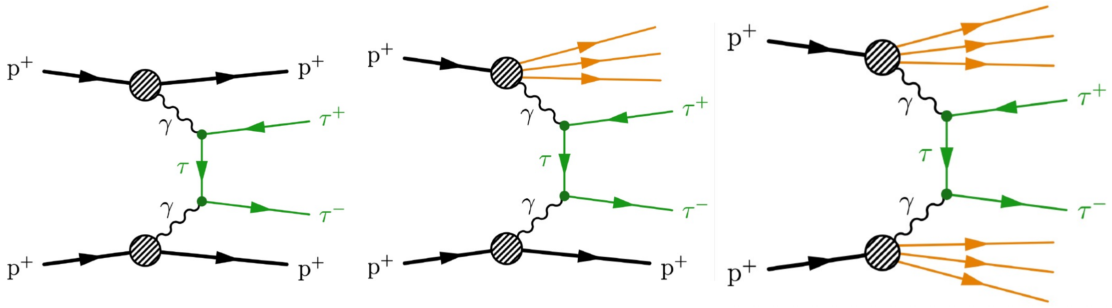
$$N_{tracks} = N_{tracks}^{PU} + N_{tracks}^{HS}$$



The reweighting factors for each DY component with a given number of N_{tracks}^{HS} is determined **iteratively** by matching the simulation to the observed data, starting from events with $N_{tracks} = 0$, to which only the simulated component with $N_{tracks}^{HS} = 0$ contributes.

Applied on all Drell-Yan and di-boson processes

Photon-induced Process Correction

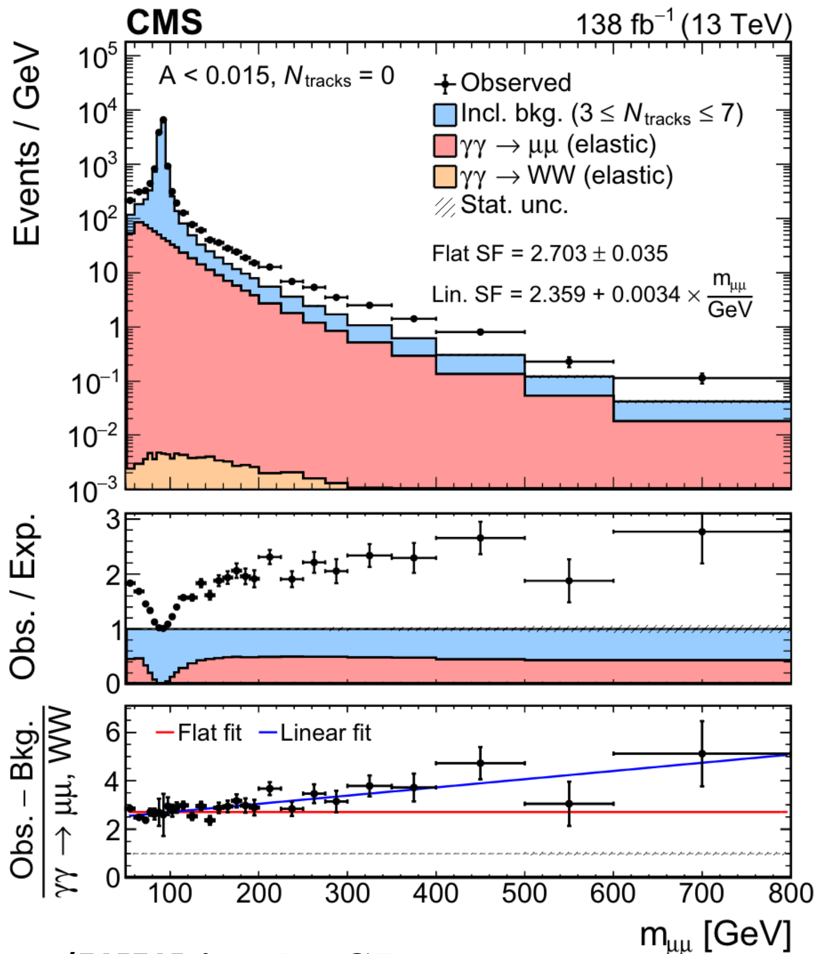


elastic semi-dissociative fully-dissociative

gammaUPC

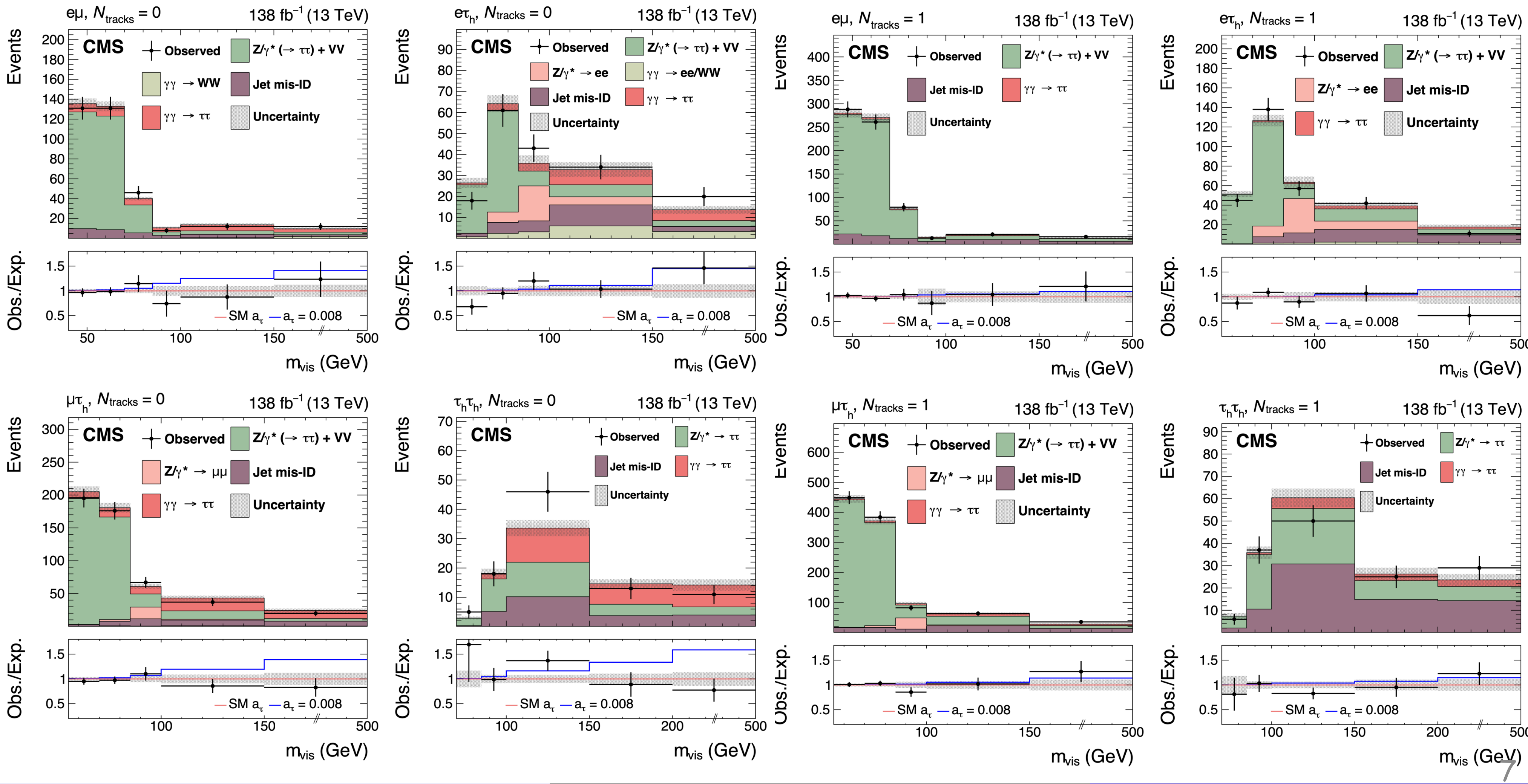
$$\text{scaling factor} = \frac{(N_{elastic}+N_{semi-dissociative}+N_{fully-dissociative})}{[N_{elastic}]}$$

$$\text{scaling factor} = \frac{N(obs)-N(inclusive\ background)}{N(\gamma\gamma\rightarrow\mu\mu)+N(\gamma\gamma\rightarrow WW)}$$

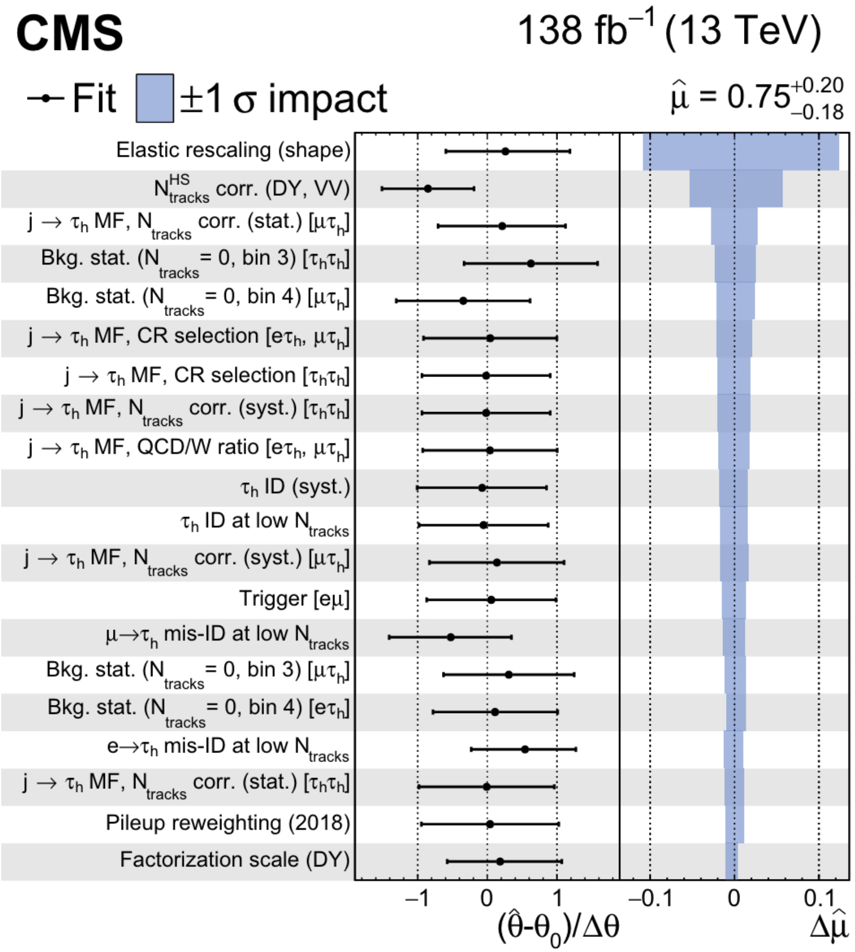


Applied on all $\gamma\gamma \rightarrow ee/\mu\mu/\tau\tau/WW$ in the SR

m_{vis} distribution



Systematic Uncertainties

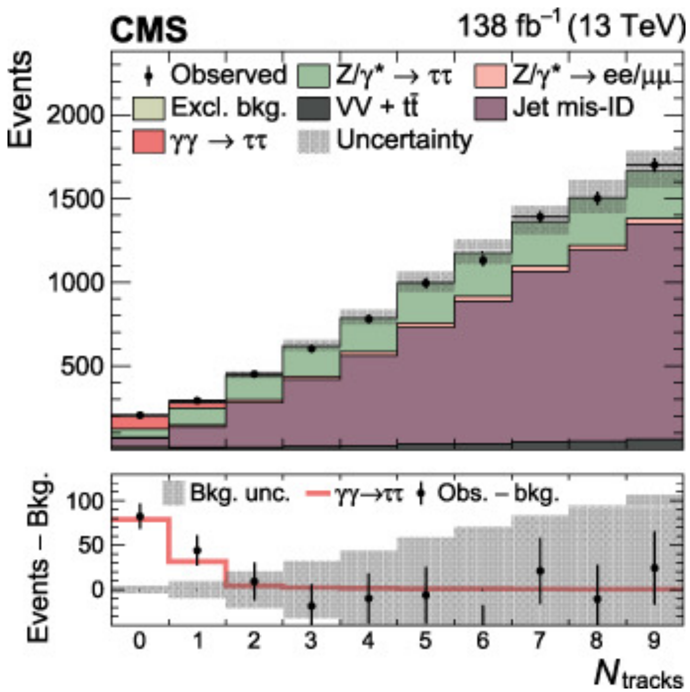


shape uncertainty of the elastic rescaling: the difference between the flat factor and the linear factor
16%

uncertainty of the N_{tracks}^{HS} correction is taken to have the same magnitude as the relative fraction of $\gamma\gamma \to \mu\mu/WW$ in the correction derived region
7%

6.5σ expected, 5.3σ observed

Based on m_{vis} distribution for 4 final states with nTrk=0,1 concerning the gammaUPC elastic prediction rescaling factor.



Measured fiducial cross section: $\sigma_{obs}^{fid} = 12.4^{+3.8}_{-3.1}$ fb

	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$p_T{}^e$ (GeV)	>15/24	>25	—	—
$\lvert\eta^e\rvert$	<2.5	<2.5	—	—
$p_T{}^{\mu}$ (GeV)	>24/15	—	>21	—
$\lvert\eta^{\mu}\rvert$	<2.4	—	<2.4	—
$p_T^{\tau_h}$ (GeV)	—	>30	>30	>40
$\lvert\eta^{\tau_h}\rvert$	—	<2.3	<2.3	<2.3
$\Delta R(\ell, \ell')$	>0.5	>0.5	>0.5	>0.5
$m_T(e/\mu, \vec{p}_T^{\text{miss}})$ (GeV)	—	<75	<75	—
A	<0.015	<0.015	<0.015	<0.015
m_{vis} (GeV)	<500	<500	<500	<500
N_{tracks}	0	0	0	0

EFT Interpretation

- Deviations of a_τ & d_τ from the SM can be parameterized in terms of a BSM lagrangian with dim-6 operators with new physics scale Λ:

$$\mathcal{L}_{BSM} = \frac{C_{\tau B}}{\Lambda^2}\bar{L}_L\sigma^{\mu\nu}\tau_R H B_{\mu\nu} + \frac{C_{\tau W}}{\Lambda^2}\bar{L}_L\sigma^{\mu\nu}\tau_R\sigma^i H W^i_{\mu\nu} + h.c.$$

- δa_τ and δd_τ are linearly dependent on the complex Wilson coefficients:

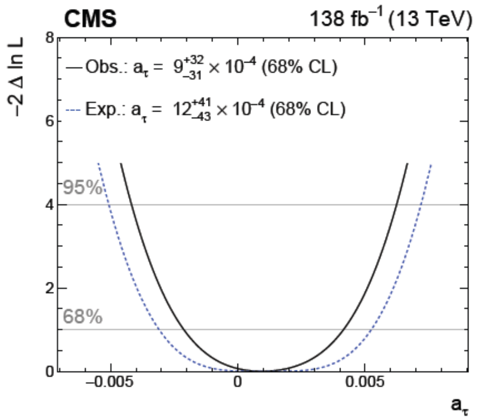
$$\delta a_\tau = \frac{2m_\tau}{e}\frac{\sqrt{2}v}{\Lambda^2} Re[cos\theta_W C_{\tau B} - sin\theta_W C_{\tau W}]$$

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

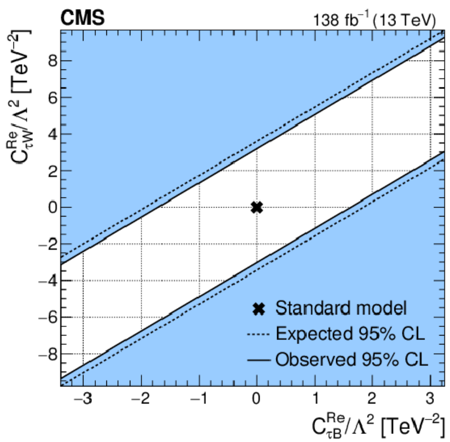
- Simplify by setting $C_{\tau\gamma} = cos\theta_W C_{\tau B} - sin\theta_W C_{\tau W}$

Constraints on a_τ and d_τ

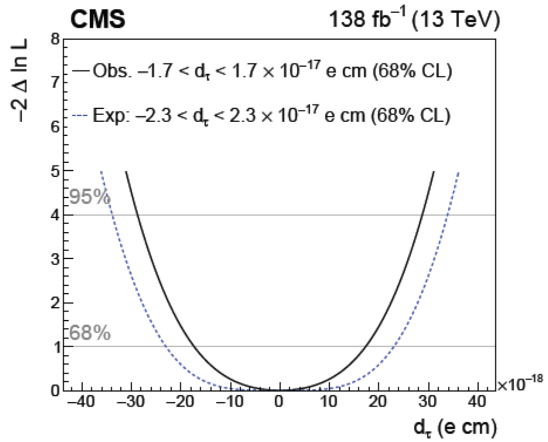
$$\delta a_\tau = \frac{2m_\tau}{e}\frac{\sqrt{2}v}{\Lambda^2}\,\mathrm{Re}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}]$$



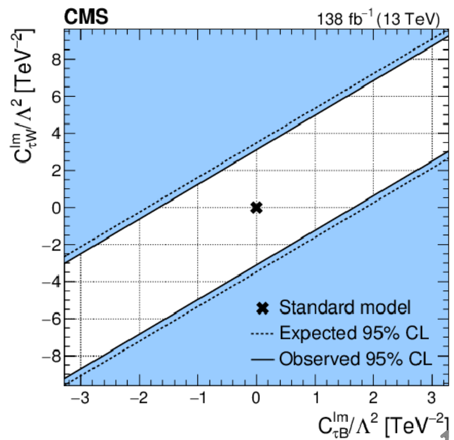
real part:



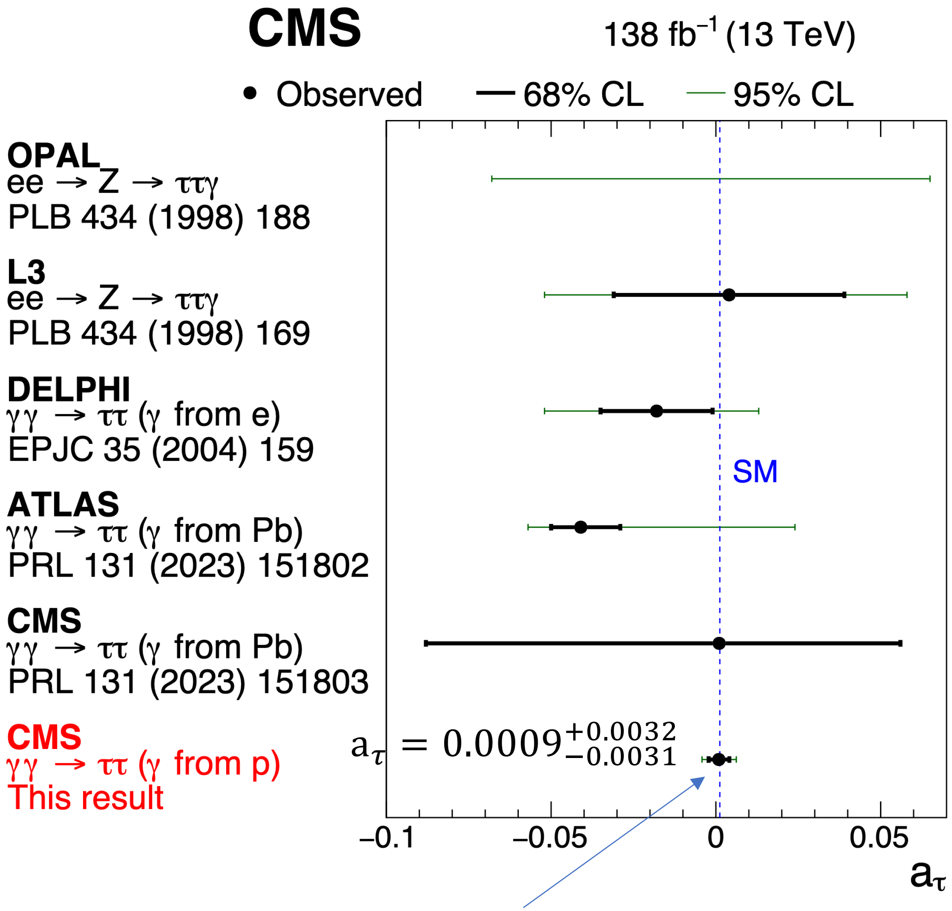
$$\delta d_\tau = \frac{\sqrt{2}v}{\Lambda^2}\,\mathrm{Im}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}]$$

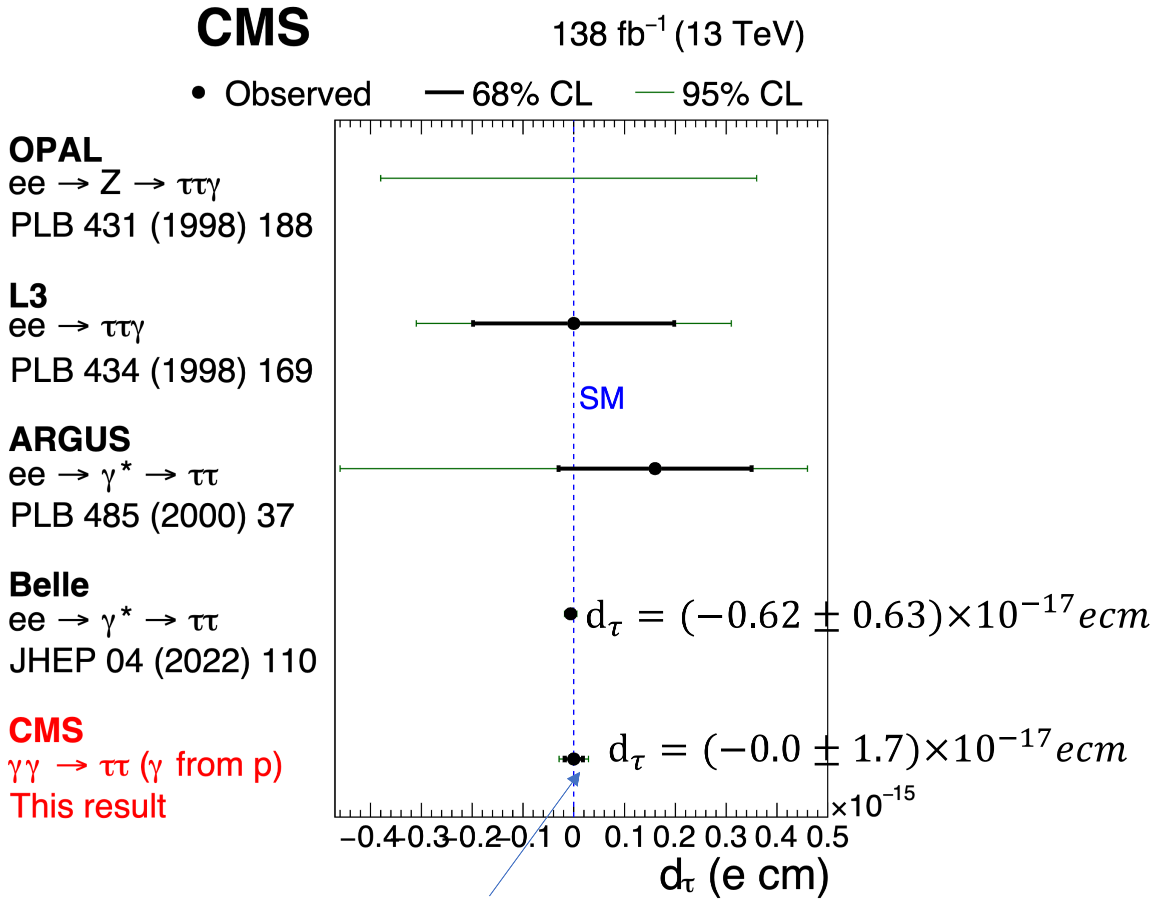


imaginary part:



Comparison to Previous Results





Large improvement over LEP and LHC HIN, 3 times larger than the Schweiger term

Approaching Belle precision(extrapolated from $q^2>0$), at $q^2 \approx 0$

Summary

The CMS Collaboration has **first observed $\gamma\gamma \rightarrow \tau\tau$ process in pp collisions with 5.3σ**

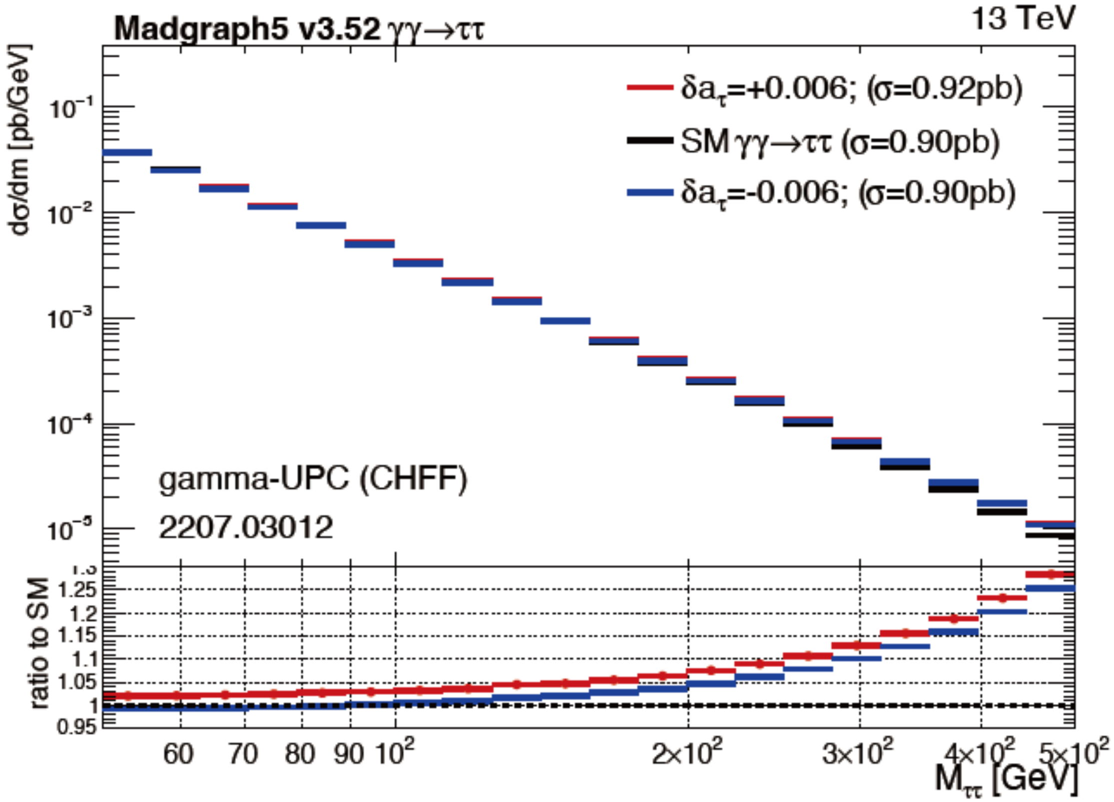
- These events were used to constrain the τ electromagnetic moments with an EFT approach

$$-0.0042 < a_\tau < 0.0062 \quad \text{at 95\% CL}$$
$$-1.7\times10^{-17}\,e\text{cm} < d_\tau < 1.7\times10^{-17}\,e\text{cm}$$

- Improving previous constraints on a_τ by a factor of ~5 (PDG:-0.052<a_τ<0.013 at 95% CL) and approaching the precision of the Schwinger term(0.00116)
- The constraints on d_τ is approaching to Belle

Thanks for listening!

backup BSM effect



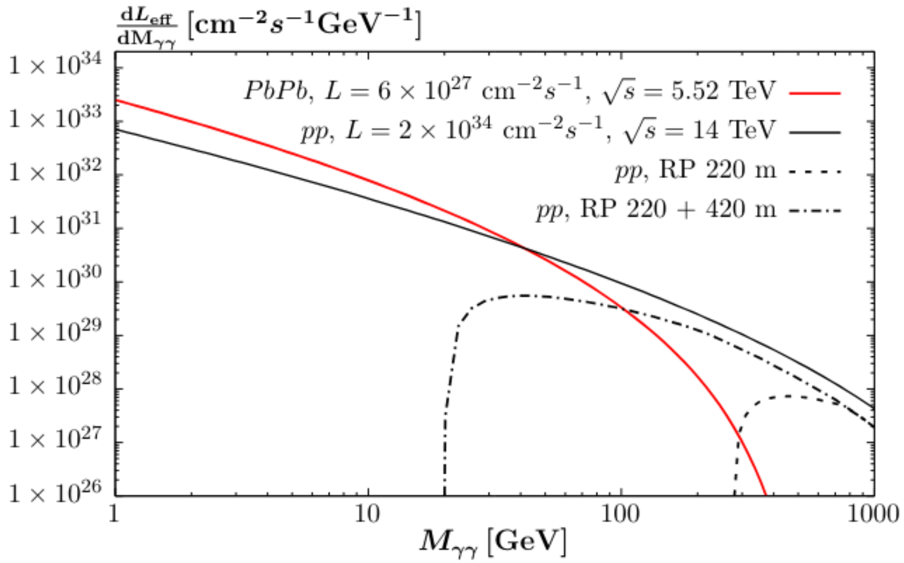
backup Electromagnetic ultra-peripheral collisions(UPC)

- provide a pure QED(electrodynamics) environment
- $\sigma(\gamma\gamma) \propto Z^4, \sigma(\gamma\gamma) \propto \log^3(\sqrt{S})$, much larger luminosities of pp collisions than PbPb collisions
- quasi-real photon, $q^2 \approx 0$
- max(longitudinal) γ energies $E_\gamma \approx$ 80GeV(PbPb), 2.5TeV(pp)
- much larger BSM effect on larger $m_{\tau\tau}$
- process signature:

  -opposite sign(OS) $\tau^\pm\tau^\mp$

  -back-to-back in azimuthal plane: $|\Delta\Phi| \approx \pi$

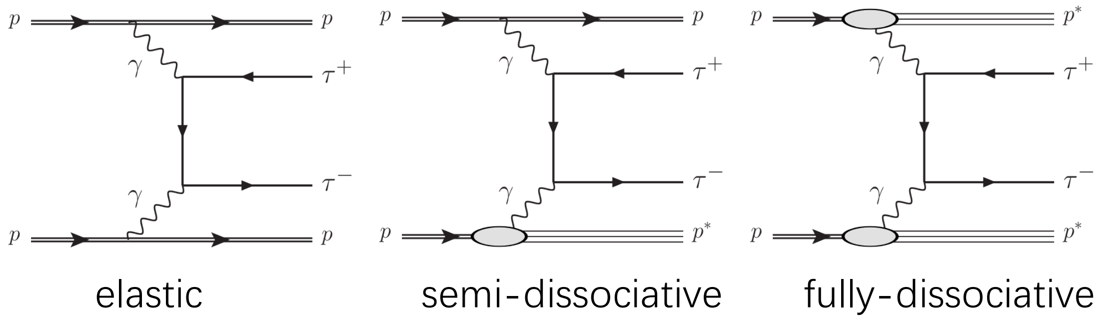
  -low activity around ττ vertex

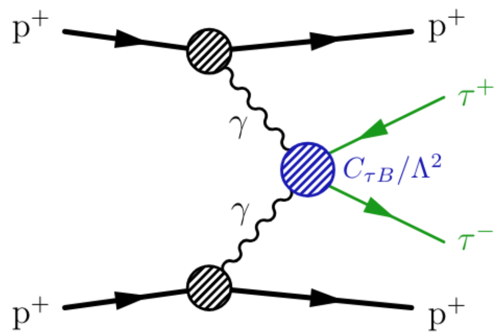


backup Signal Simulation pp

- **only** **elastic events** are generated using gammaUPC, data-driven method to include the dissociative component and SUPERCHIC for cross-check
- a_τ & d_τ interpretation using the **EFT approach** with the SMEFTsim package, simplifying with $C_{\tau W}$=0 since the linear combination of $C_{\tau B}$ and $C_{\tau W}$:

$$\delta a_\tau \propto \frac{Re[C_{\tau B}]}{\Lambda^2}, \delta d_\tau \propto \frac{Im[C_{\tau B}]}{\Lambda^2}$$





backup Acoplanarity Correction pp

$$A = 1 - |\frac{\phi}{\pi}|$$

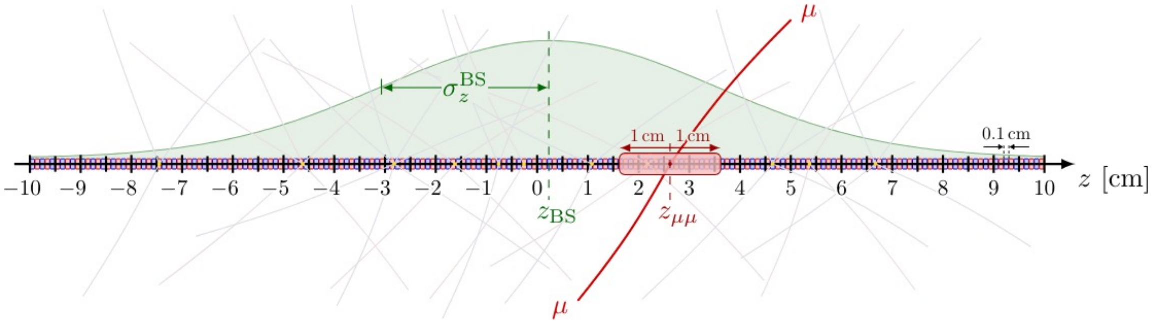
The correction is derived as a function of acoplanarity by fitting the data/MC ratio.
It is kept constant above 0.35.
It modifies the Drell-Yan normalizations in various p_T ranges (the corrections are different in different p_T ranges), but keeps the overall Drell-Yan normalization constant.

backup Beam Spot Correction pp

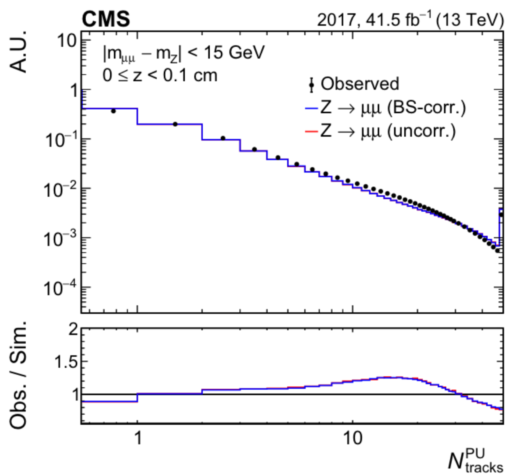
$$z^{\text{corr}} = z_{\text{MC}}^{\text{BS}} + \frac{\sigma_{\text{Data}}^{\text{BS}}}{\sigma_{\text{MC}}^{\text{BS}}}(z - z_{\text{MC}}^{\text{BS}})$$

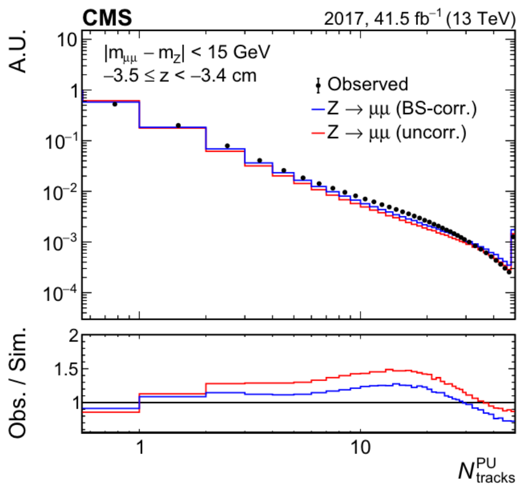
$$z^{\text{corr}} = z + z_{\text{Data}}^{\text{BS}} - z_{\text{MC}}^{\text{BS}}$$

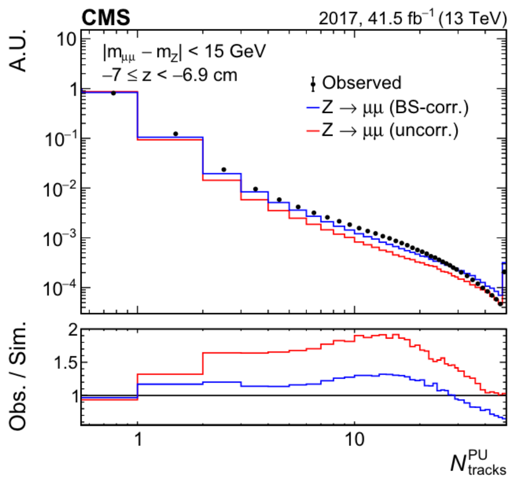
backup Pileup Track Multiplicity Correction



windows far from the di-μ vertex to discard the tracks from the hard scattering interactions in $|m_{\mu\mu} - m_Z|$<15GeV



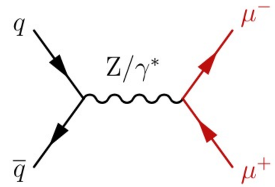


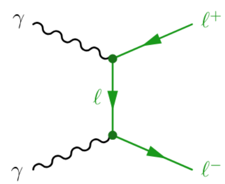


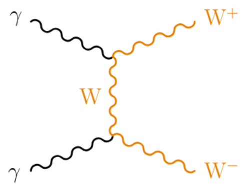
backup Photon-induced Process Correction pp

- scan a_τ & d_τ values through matrix element reweightging in two independent 1D grids of 100 points for $C_{\tau B}$:
  $Re[C_{\tau B}] \in [-40,40], Im[C_{\tau B}] \in [-40,40]$
- result independent from of choice of Λ, $C_{\tau B}$ & $C_{\tau W}$ scale with Λ^2, but we fix Λ=2TeV in event generation

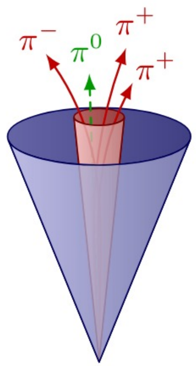
- MC simulation
  - -Drell-Yan($Z/\gamma^* \to ll$):dominant at low mass
  - -exclusive $\gamma\gamma \to ee, \mu\mu, WW$ production
  - -inclusive WW production(small)



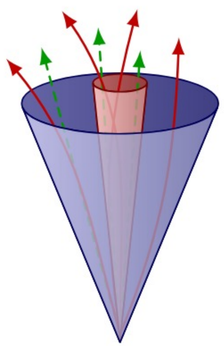




- data-driven: misidentified hadronic jets
  - $-j \to \tau_h$:$e\tau_h$,$\mu\tau_h$,$\tau_h\tau_h$ channels
  - $-j \to e/\mu$:$e\mu$ channels

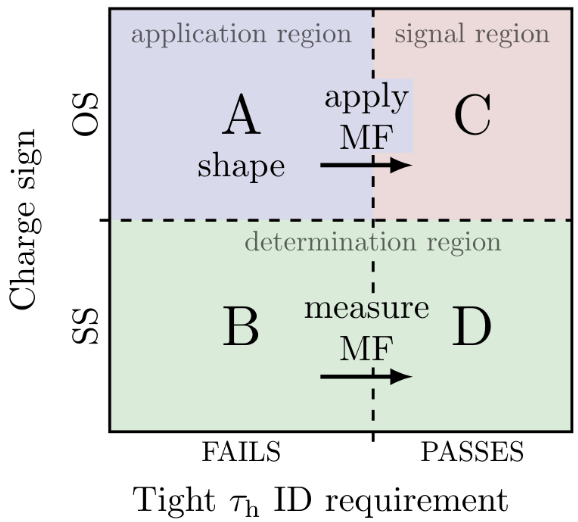


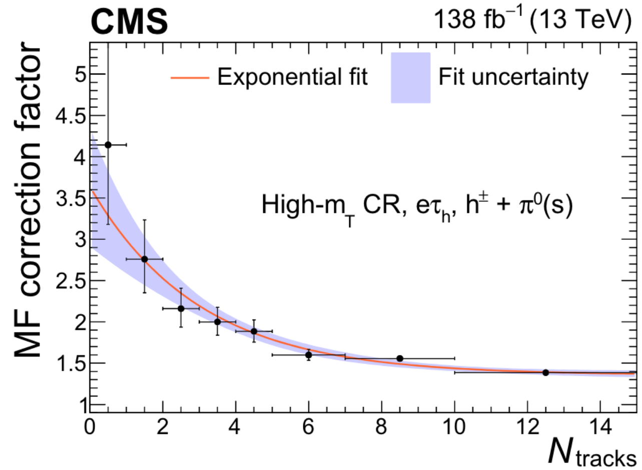
hadronic τ_h jet

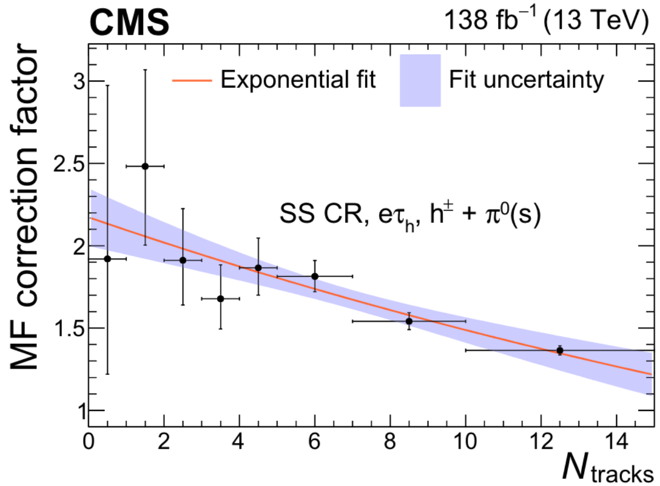


hadronic quark/gluon jet

Misidentified τ_h Background



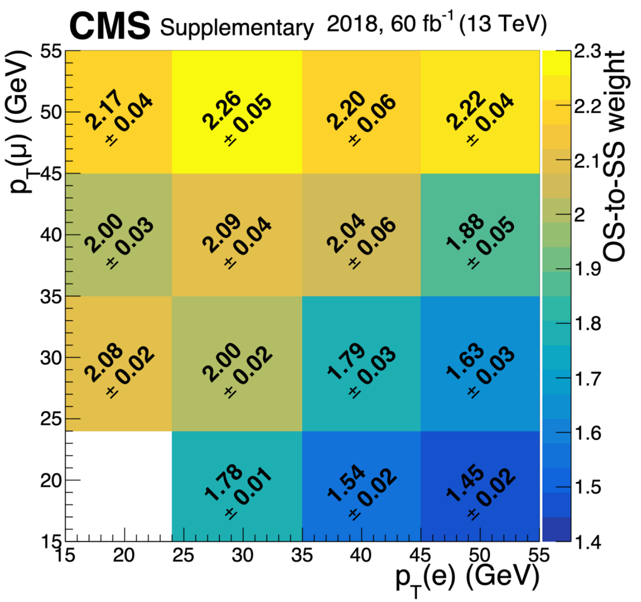




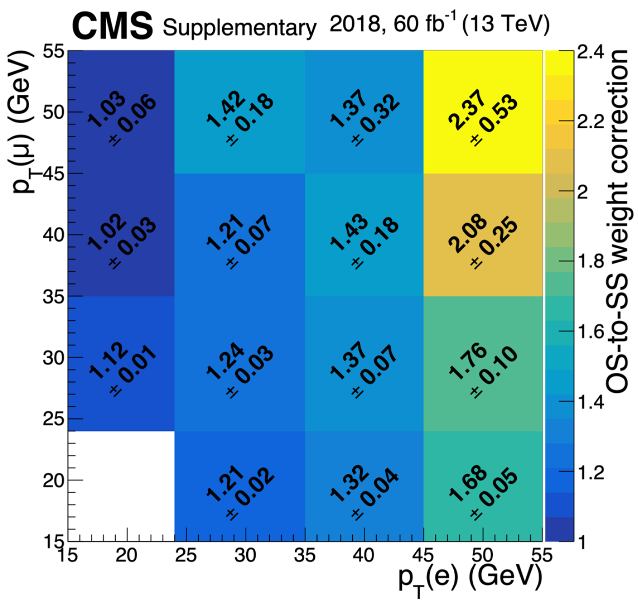
- **MFs measured in separate CRs**
  - -W+jets: m_T>75GeV
  - -QCD:SS, m_T<75GeV

backup jet fake eμ background pp

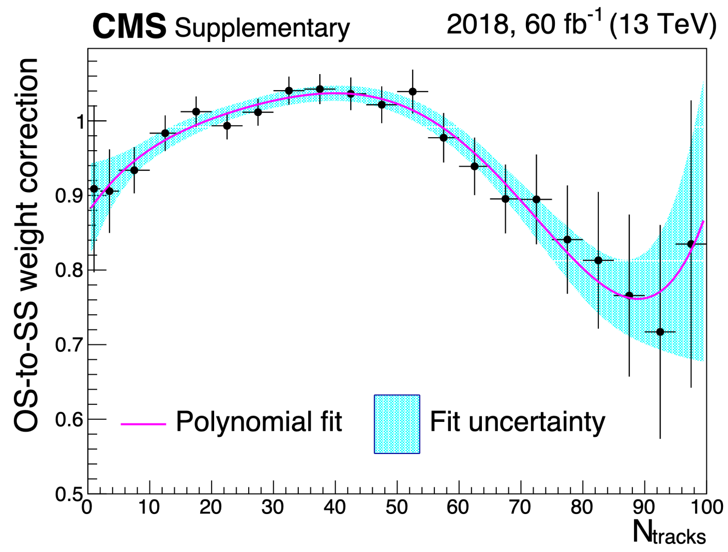
- reweigh SS events with SF made of 3 multiplicative terms
- OS/SS SF measured in events with anti-isolated μ
- correction for μ inverted isolation
- N_{tracks} corretions



Anti-isolated the μ to get the OS-to-SS as fake factors

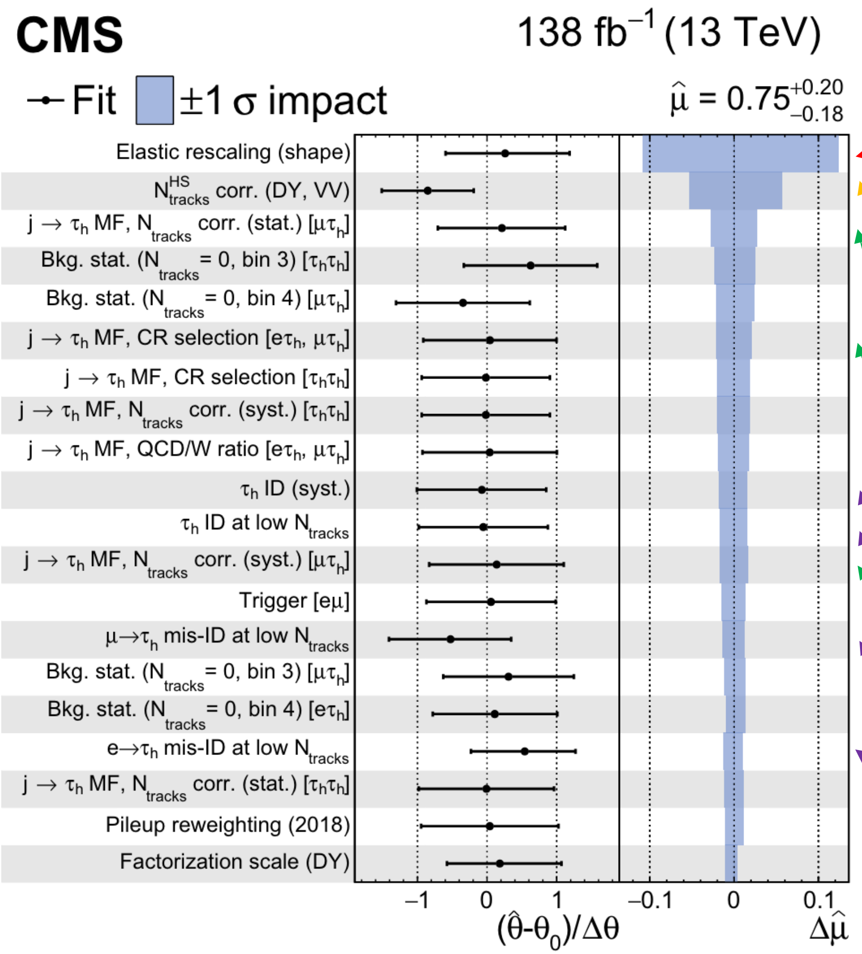


Anti-isolated the e with isolated μ and anti-isolated μ to correct the effect of the shift of the μ isolation

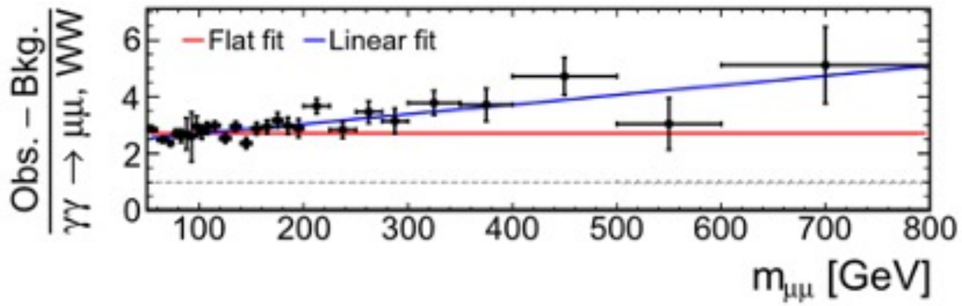


Derive the N_{tracks} dependence of the OS-to-SS

backup Leading Systematics on the signal significance pp



shape uncertainty of the elastic rescaling: the difference between the flat factor and the linear factor

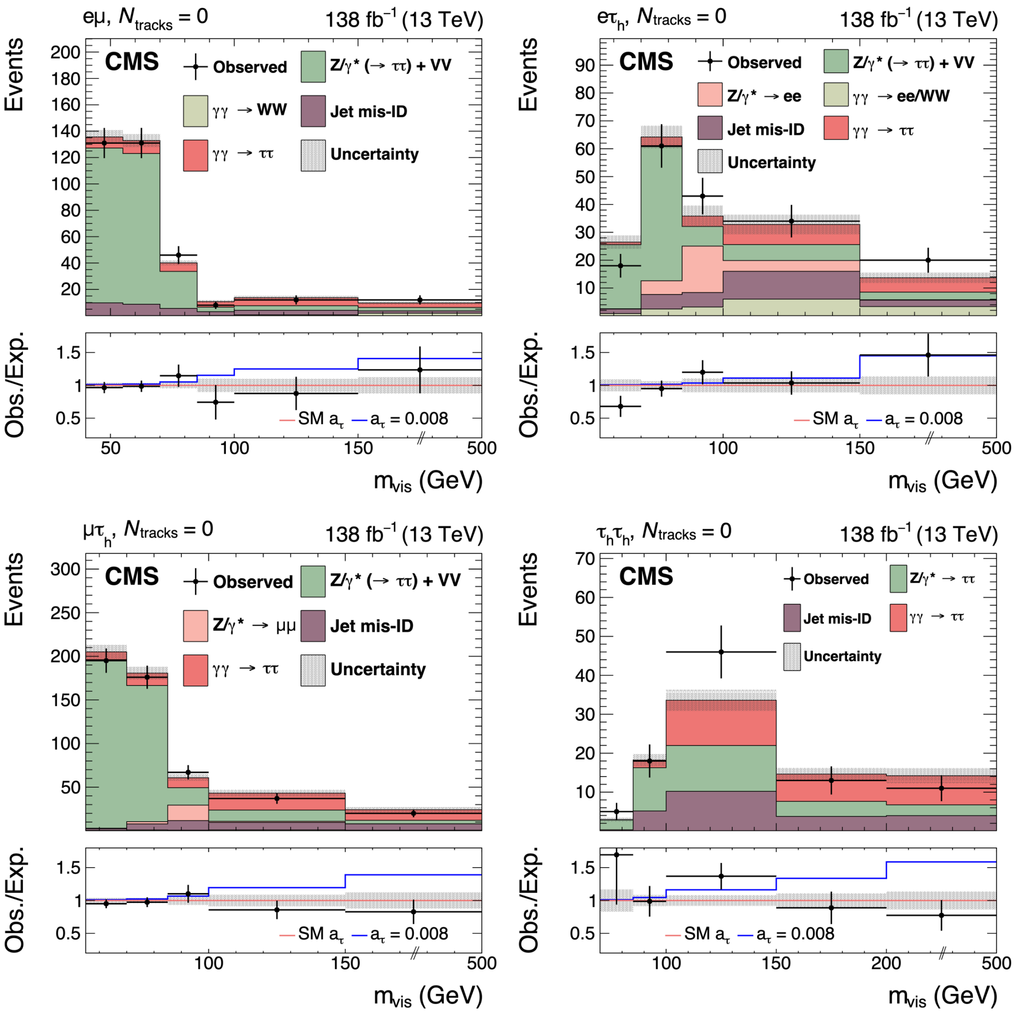


uncertainty of the N^{HS}_{tracks} correction is taken to have the same magnitude as the relative fraction of $\gamma\gamma \to \mu\mu/WW$ in the correction derived region.

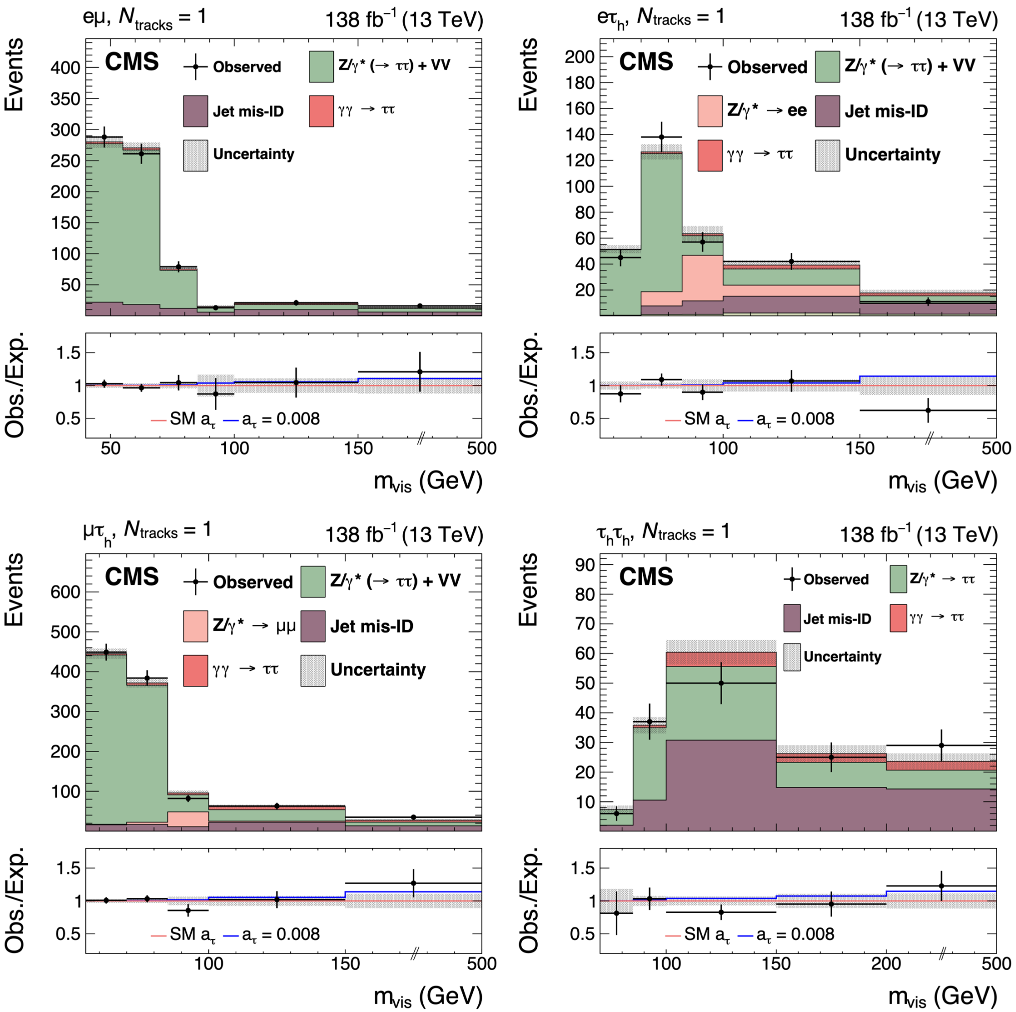
N_{tracks} extrapolation of the jet→ τ_h MF estimate jet mis-ID background(up to ~20%)

Real and fake $\tau_h$idenfication (at low N_{tracks})

backup nTrk=0 pp



backup nTrk=1 pp



backup selection criteria for fiducial cross section

	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$p_T{}^e$ (GeV)	$>15/24$	>25	—	—
$\lvert\eta^e\rvert$	<2.5	<2.5	—	—
$p_T{}^\mu$ (GeV)	$>24/15$	—	>21	—
$\lvert\eta^\mu\rvert$	<2.4	—	<2.4	—
$p_T^{\tau_h}$ (GeV)	—	>30	>30	>40
$\lvert\eta^{\tau_h}\rvert$	—	<2.3	<2.3	<2.3
$\Delta R(\ell,\ell')$	>0.5	>0.5	>0.5	>0.5
$m_T(e/\mu,\vec{p}_T^{miss})$ (GeV)	—	<75	<75	—
A	<0.015	<0.015	<0.015	<0.015
m_{vis} (GeV)	<500	<500	<500	<500
N_{tracks}	0	0	0	0

backup Constraints on a_τ and d_τ