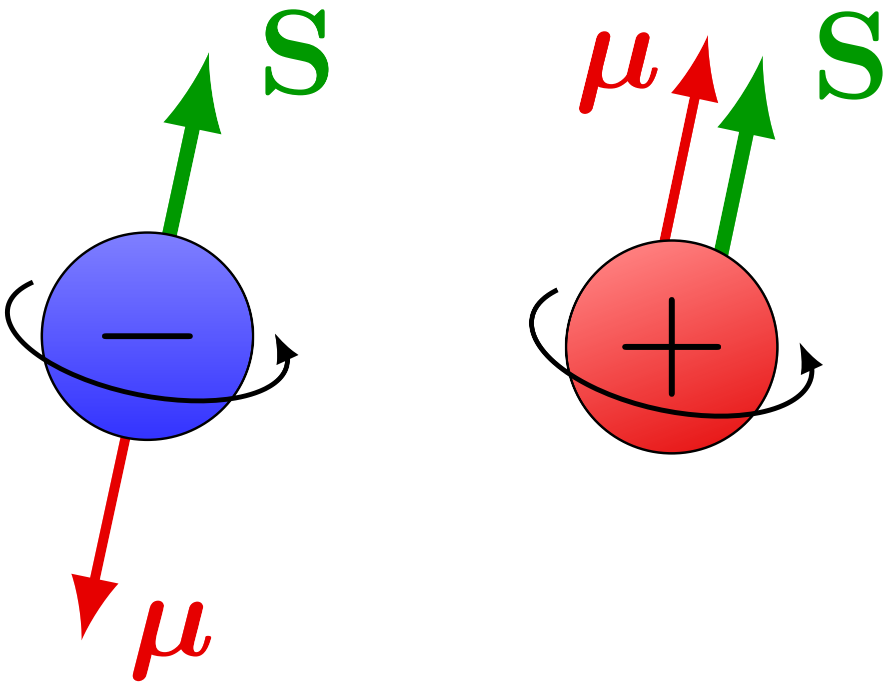
First observation of $\gamma\gamma \rightarrow \tau\tau$ in pp collisions

Constraints on τ electromagnetic moments

Cécile Caillol, CERN

LPCC seminar, March the 12th 2024

Lepton magnetic moment



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

- Spin and magnetic moment of lepton related via gyromagnetic factor g
- Dirac equation predicts g = 2

Lepton anomalous magnetic moment

- In QED, quantum effects modify the value of g, giving rise to an anomalous magnetic moment:

$$a_\ell = (g - 2)/2$$

- NLO prediction (Schwinger, 1948):

$$a_\ell = \alpha / 2\pi \cong 0.00116$$

- Further corrections calculated

a_ℓ measurements

Electron

- One of the most precisely measured quantities in physics
- Measurement aligns with QED predictions, with an extraordinary precision of up to 12 decimal places

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- Persistent discrepancy between experimental measurements and theoretical predictions

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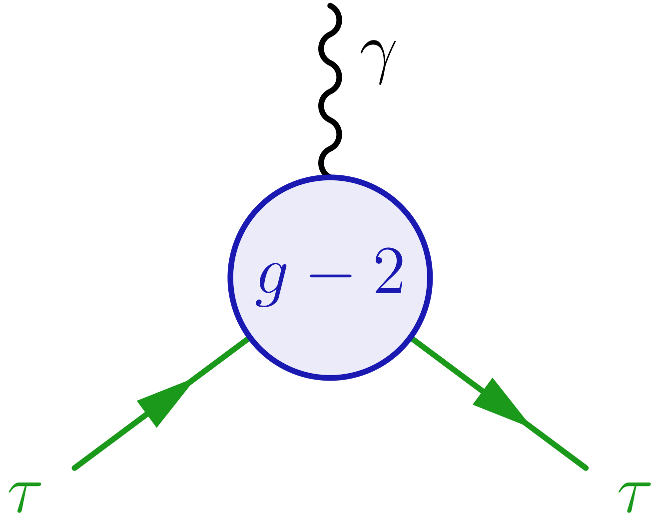
Tau

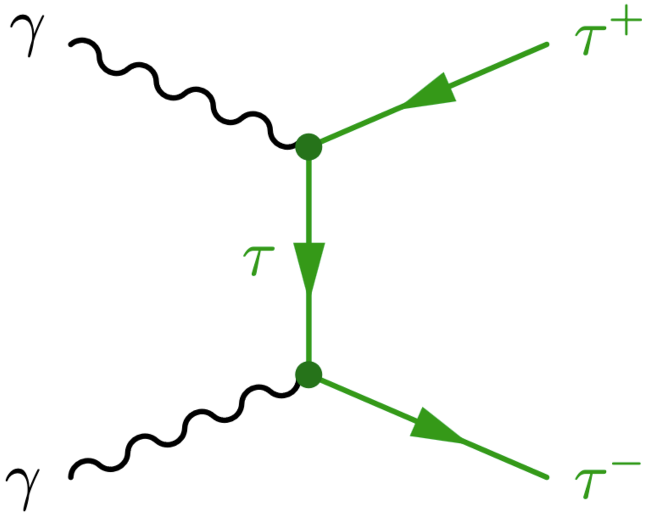
- Poorly measured because of short lifetime
- Limit from PDG dates back 20 years (LEP) and is about 20 times the Schwinger term
- If BSM effects scale with the m_ℓ^2, deviations from SM could be 280 times larger than for a_μ

τ electromagnetic moments from $\gamma\gamma \rightarrow \tau\tau$ events

- τ g-2 (a_τ) and electric dipole moment (EDM, d_τ) can be probed from $\gamma\tau\tau$ vertex



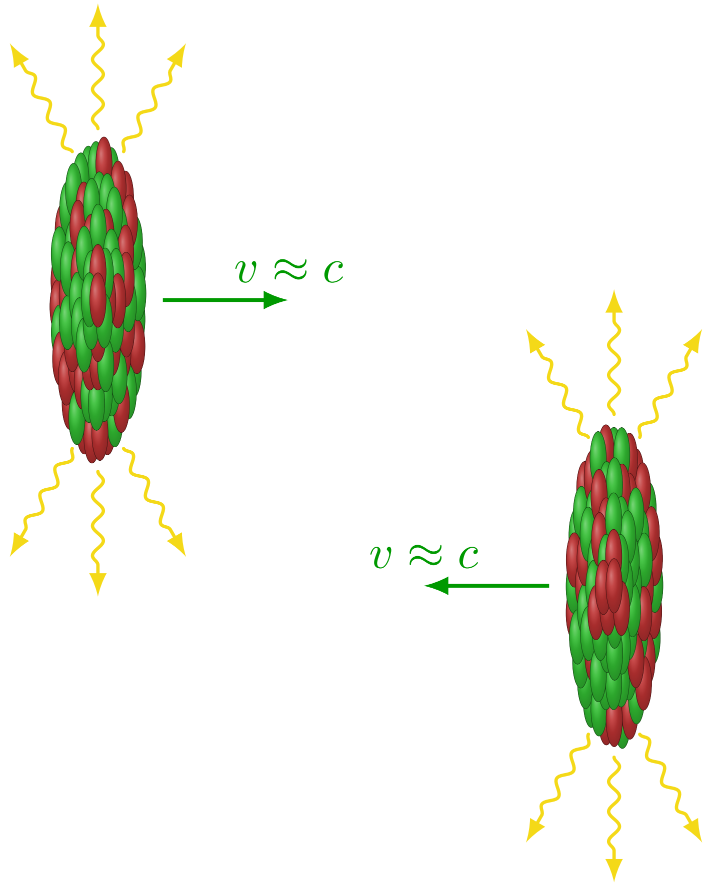
- The $\gamma\gamma \rightarrow \tau\tau$ process includes 2 $\gamma\tau\tau$ vertices



- Constraints on τ electromagnetic moments from form factor formalism or SMEFT approach
- In the SM, d_τ is extremely small (no appreciable CP violation) but it could be increased in BSM models

Photon-induced processes

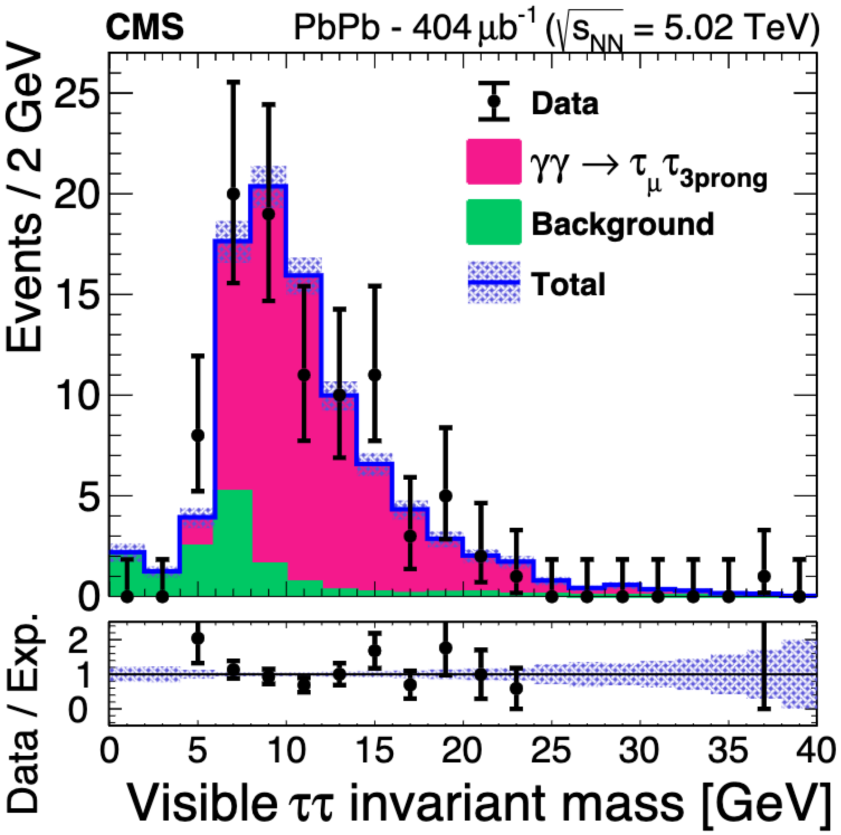
- As two charged particles (e.g. protons or ions) pass each other at relativistic velocities, they generate intense electromagnetic fields → **photon-photon collisions** can happen



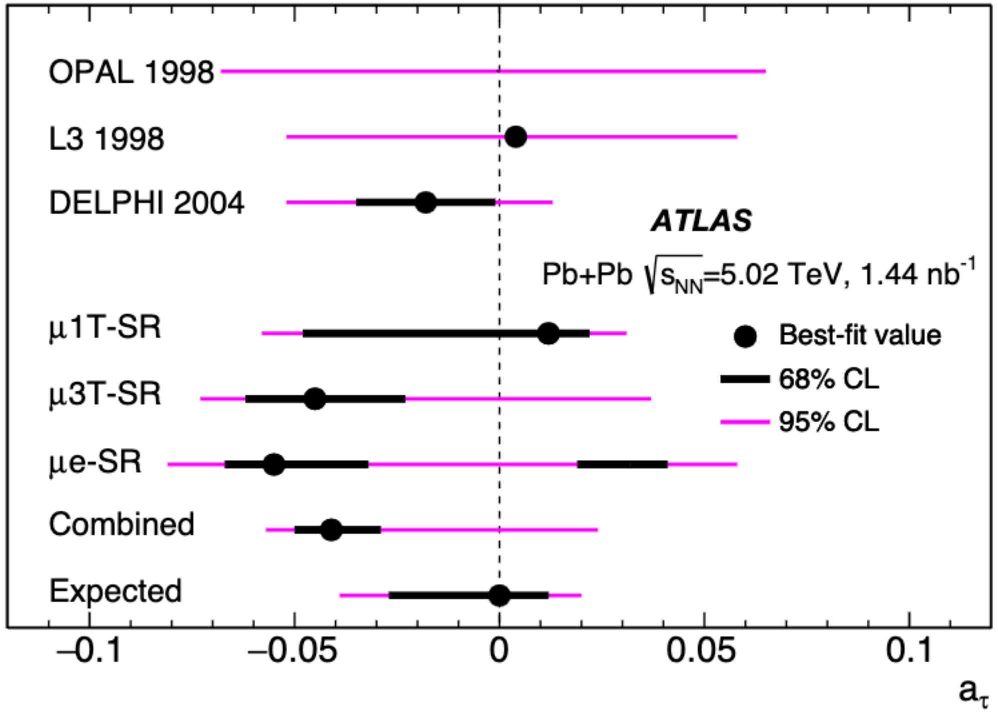
- **Cross section proportional to Z^4** → huge enhancement in Pb-Pb runs compared to pp runs

$\gamma\gamma \rightarrow \tau\tau$ in Pb-Pb ultraperipheral collisions

- $\gamma\gamma \rightarrow \tau\tau$ observed recently in Pb-Pb collisions by both [CMS]() and [ATLAS]()



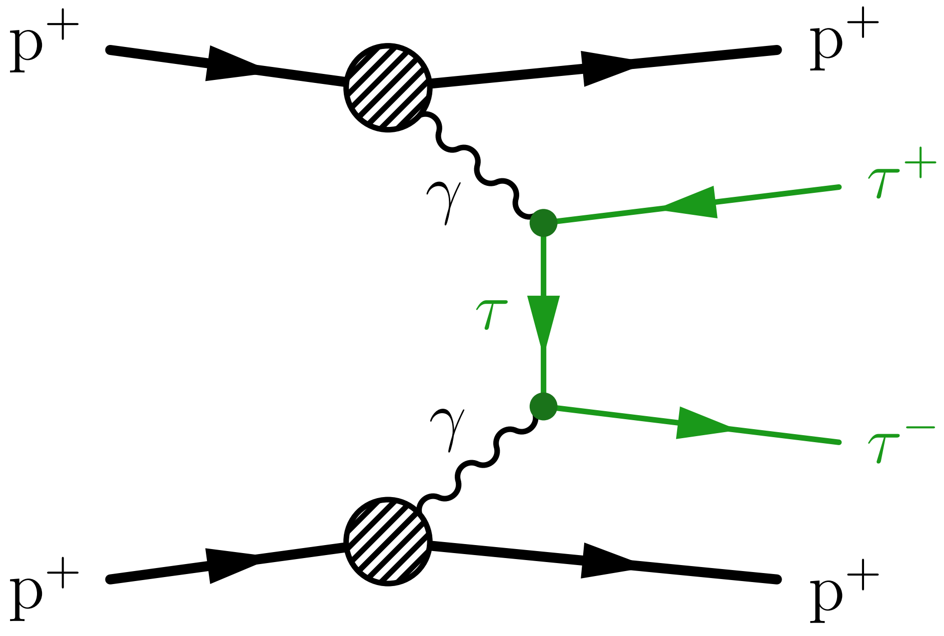
- Clean channel with small background contributions
- Accessing phase space with $m_{\tau\tau} \lesssim 25$ GeV



Used to set constraints on a_τ, close to best result from DELPHI

Can we see $\gamma\gamma \rightarrow \tau\tau$ in ultraperipheral pp collisions?

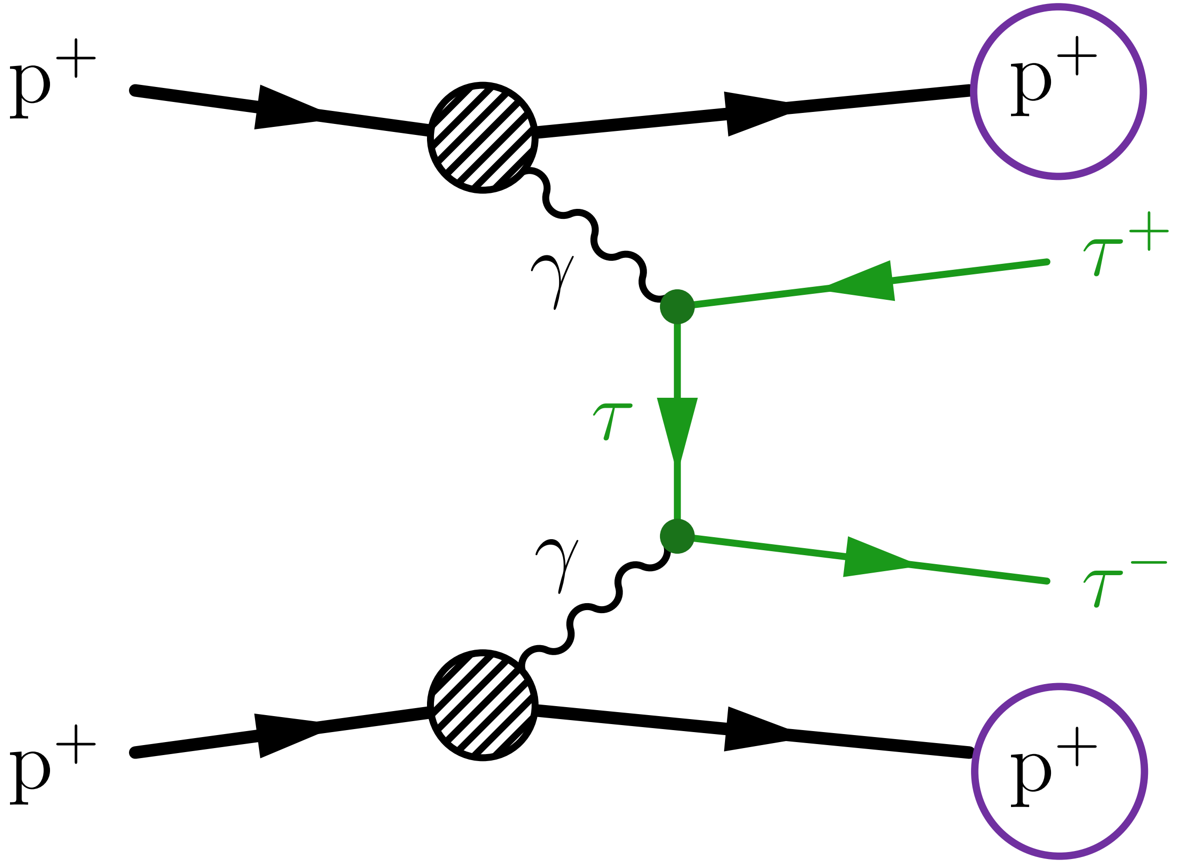
- **Much larger integrated luminosity ($O(10^8)$)**
- But:
  - No gain from Z^4 enhancement
  - Low signal acceptance (soft signal)
  - Large backgrounds
  - High pileup



- If we can see $\gamma\gamma \rightarrow \tau\tau$ in pp runs, tight constraints on τ g-2 could be set because **a_τ modifications from BSM physics are enhanced at large τ p_T and ditau mass**

Signature

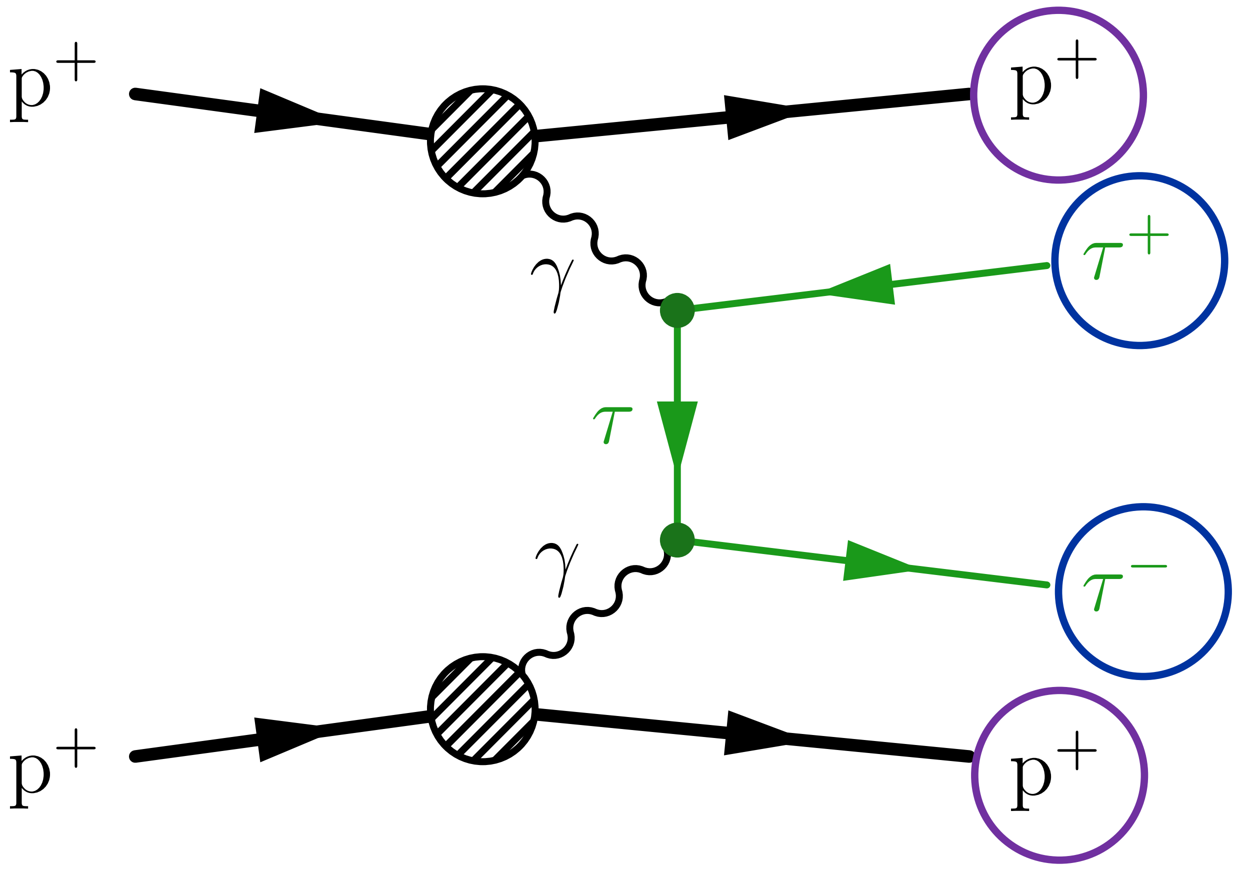
Signature



- 2 diffracted protons
  - Could be reconstructed in PPS (Precision Proton Spectrometer) if $m_{\tau\tau} \gtrapprox 350$ GeV → low signal acceptance
  - Decided not to require diffracted protons in the analysis

Elastic process, protons do not dissociate

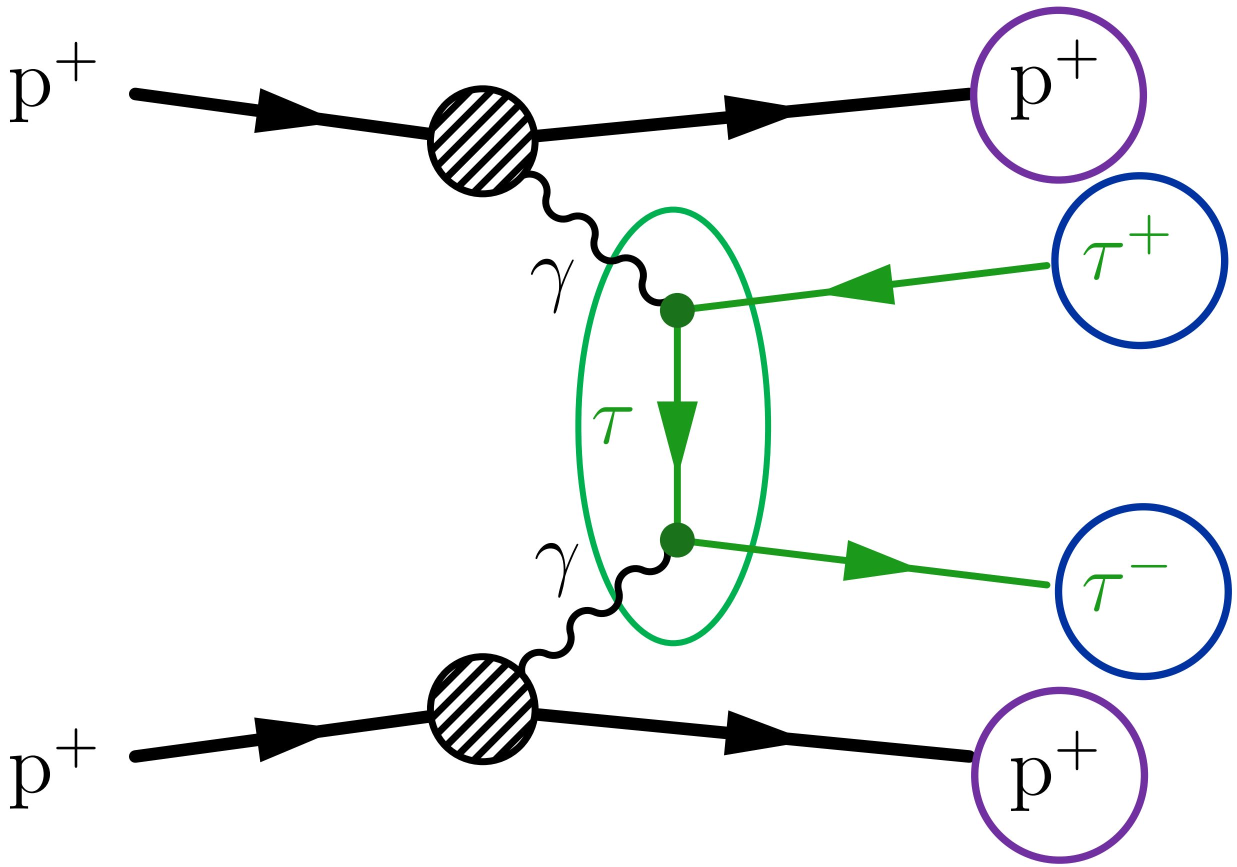
Signature



- 2 diffracted protons
- 2 back-to-back OS τ leptons
  - Acoplanarity $\boldsymbol{A} = 1 - \frac{|\Delta\phi|}{\pi} \approx 0$

Elastic process, protons do not dissociate

Signature

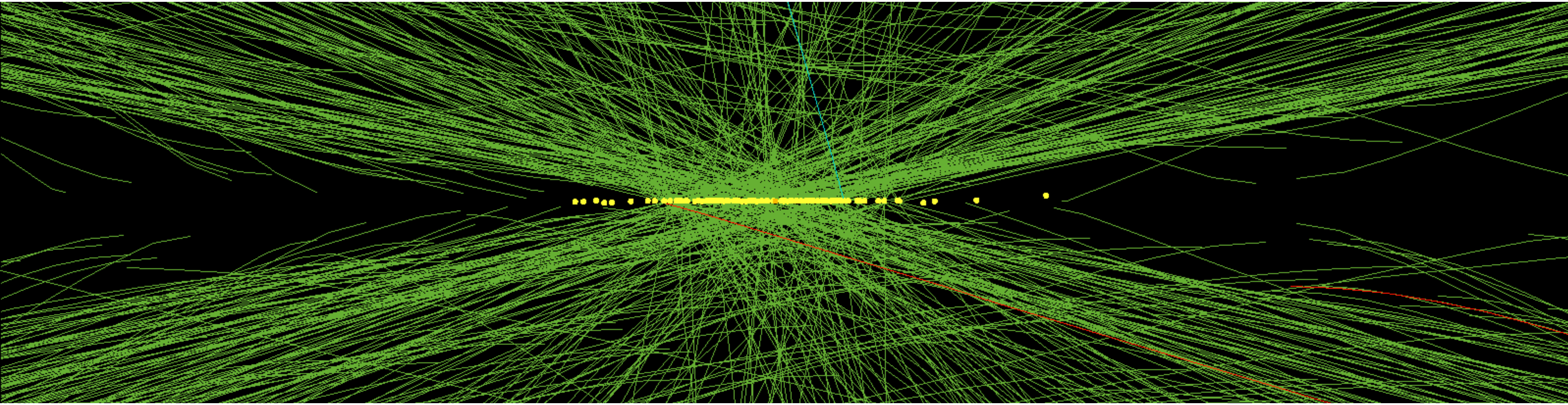


- 2 diffracted protons
- 2 back-to-back OS τ leptons
- No hadronic activity close to the di-τ vertex
  - $N_{tracks} = 0$

Elastic process, protons do not dissociate

Counting tracks

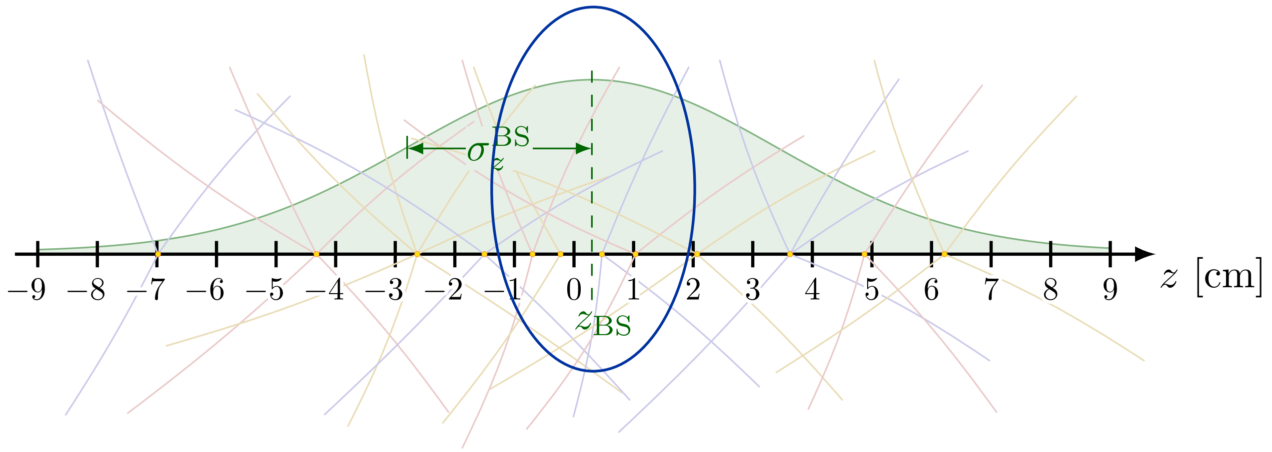
- Photon-induced processes are exceptionally clean…
- … but proton-proton collisions are incredibly busy
  - Average of > 30 pileup interactions in 2018



Counting tracks

- Define **z position of di-tau vertex** as average z position of selected tau leptons
- Define $\mathbf{N_{tracks}}$ as the number of tracks
  - with $p_T > 0.5$ GeV and $|\eta| < 2.5$
  - within a window of **0.1 cm** around the di-tau vertex
  - Excluding tracks from tau leptons

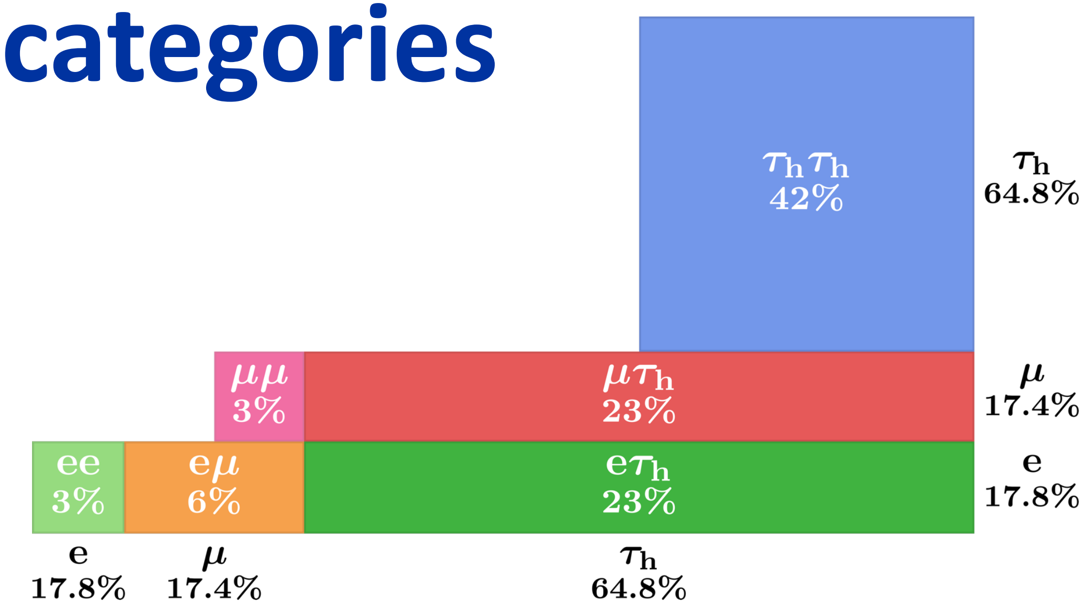
Extraordinary tracking capabilities of the CMS detector!



- About 30% of the windows at the center of the beamspot do not contain any pileup track

Analysis overview

Final states and categories



- 4 di-tau final states: $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

- In each di-tau final state, 2 signal regions: N_{tracks} = 0 or 1
  - **N_{tracks} = 0**: ~50% of the signal, inclusive backgrounds reduced by $O(10^3)$
  - **N_{tracks} = 1**: ~25% of the signal, larger background

- Dimuon control region to derive corrections to the simulations

Strategy

- In each of the 8 categories ($e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$) x (N_{tracks} =0, N_{tracks} =1), fit visible invariant mass of tau pair (m_{vis})
  - SM $\gamma\gamma \rightarrow \tau\tau$ measurement: S/B ratio increases with m_{vis} because Drell-Yan background concentrated at lower masses
  - BSM a_τ and d_τ measurements: deviations from SM predictions increase with the mass

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Drell-Yan $Z/\gamma^* \rightarrow \tau\tau/ee/\mu\mu$	**Jet $\rightarrow e/\mu/\tau_h$ mis-ID**	**Exclusive $\gamma\gamma \rightarrow ee/\mu\mu/WW$**	**$\gamma\gamma \rightarrow \tau\tau$**
Resonant	Non-resonant	Small but at low N_{tracks}	Signal, non resonant
From simulation	From data	From elastic simulation	From elastic simulation

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Drell-Yan $Z/\gamma^* \rightarrow \tau\tau/ee/\mu\mu$
Resonant
From simulation

Jet$\rightarrow e/\mu/\tau_h$ mis-ID
Non-resonant
From data

Exclusive $\gamma\gamma \rightarrow ee/\mu\mu/WW$
Small but at low N_{tracks}
From elastic simulation

$\gamma\gamma \rightarrow \tau\tau$
Signal, non resonant
From elastic simulation

Corrections from $Z \rightarrow \mu\mu$ CR:
1. Acoplanarity
2. N_{tracks} from pileup
3. N_{tracks} from hard interaction
4. Dissociative contributions

Selection

Electron + muon triggers

Single lepton or lepton + τ_h triggers

$p_T(\tau_h)$ > 30 GeV to reduce fakes

Di-tau trigger

To reduce W+jets background

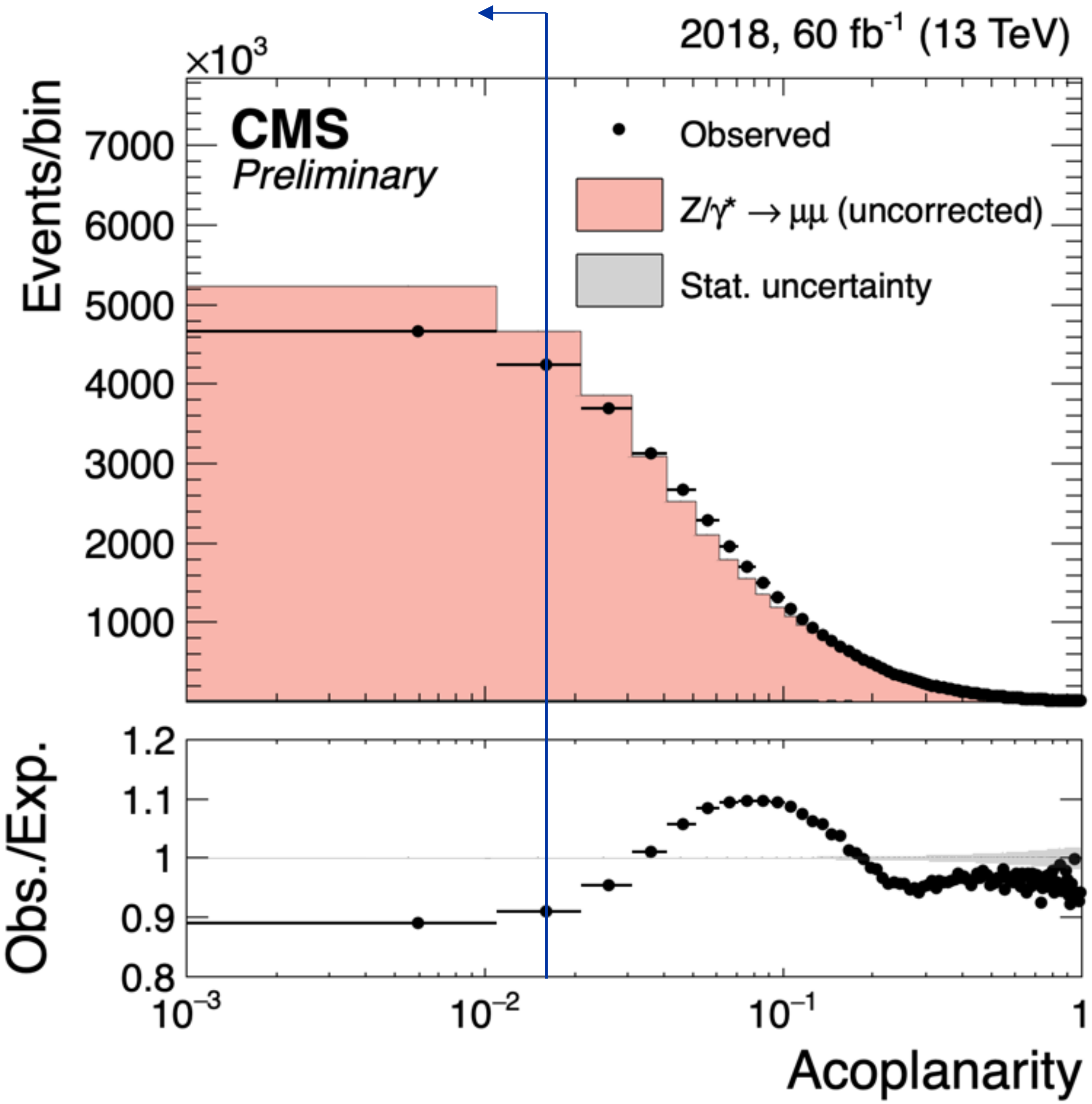
	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	$\mu\mu$
p_T^e (GeV)	$> 15/24$	$> 25-33$	—	—	—
$\lvert\eta^e\rvert$	< 2.5	$< 2.1-2.5$	—	—	—
p_T^μ (GeV)	$> 24/15$	—	$> 21-29$	—	$> 26-29/10$
$\lvert\eta^\mu\rvert$	< 2.4	—	$< 2.1-2.4$	—	
$p_T^{\tau_h}$ (GeV)	—	$> 30-35$	$> 30-32$	> 40	—
$\lvert\eta^{\tau_h}\rvert$	—	$< 2.1-2.3$	$< 2.1-2.3$	< 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
$m_T(e/\mu,\vec{p}_T^{miss})$ (GeV)	—	< 75	< 75	—	—

In the signal regions, also require $A = 1 - \frac{|\Delta\phi|}{\pi} < 0.015$ and N_{tracks} = 0 or 1

μμ control region – deriving corrections to the simulations

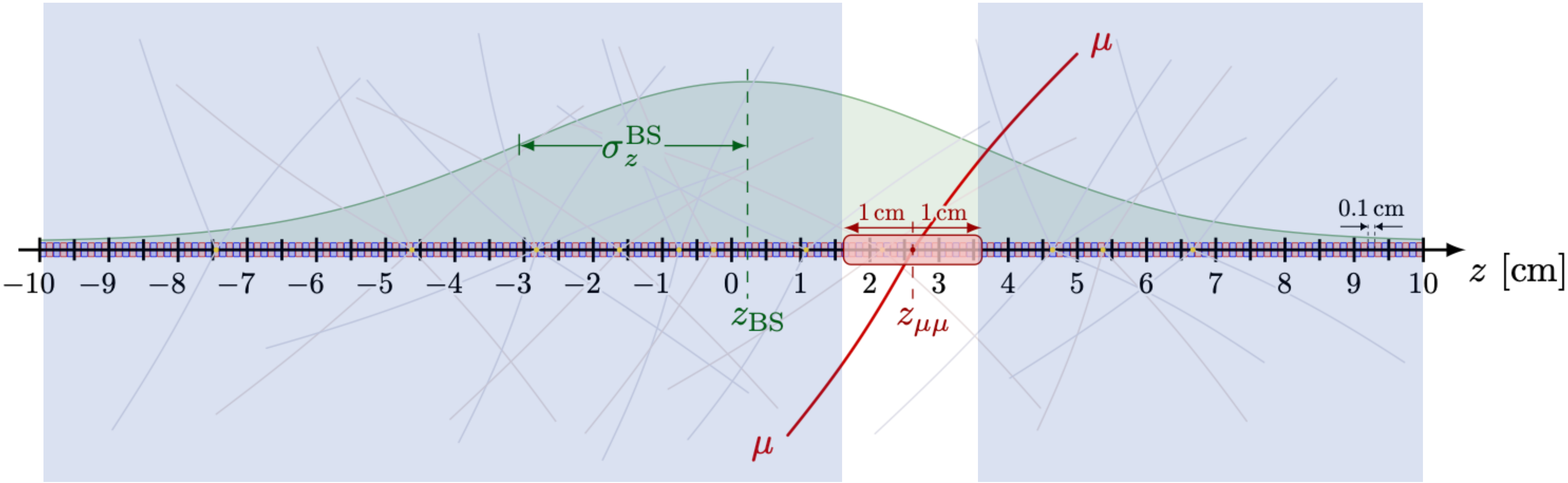
1. Acoplanarity correction

Signal region, A < 0.015



- The Drell-Yan simulation *(aMC@NLO, FxFx merging)* does not model well the acoplanarity distribution in the dimuon control region
- The mismodeling depends on the lepton p_T
- Derive corrections to acoplanarity distribution in 2D bins of leading and subleading lepton p_T
- Corrects Z p_T distribution simultaneously

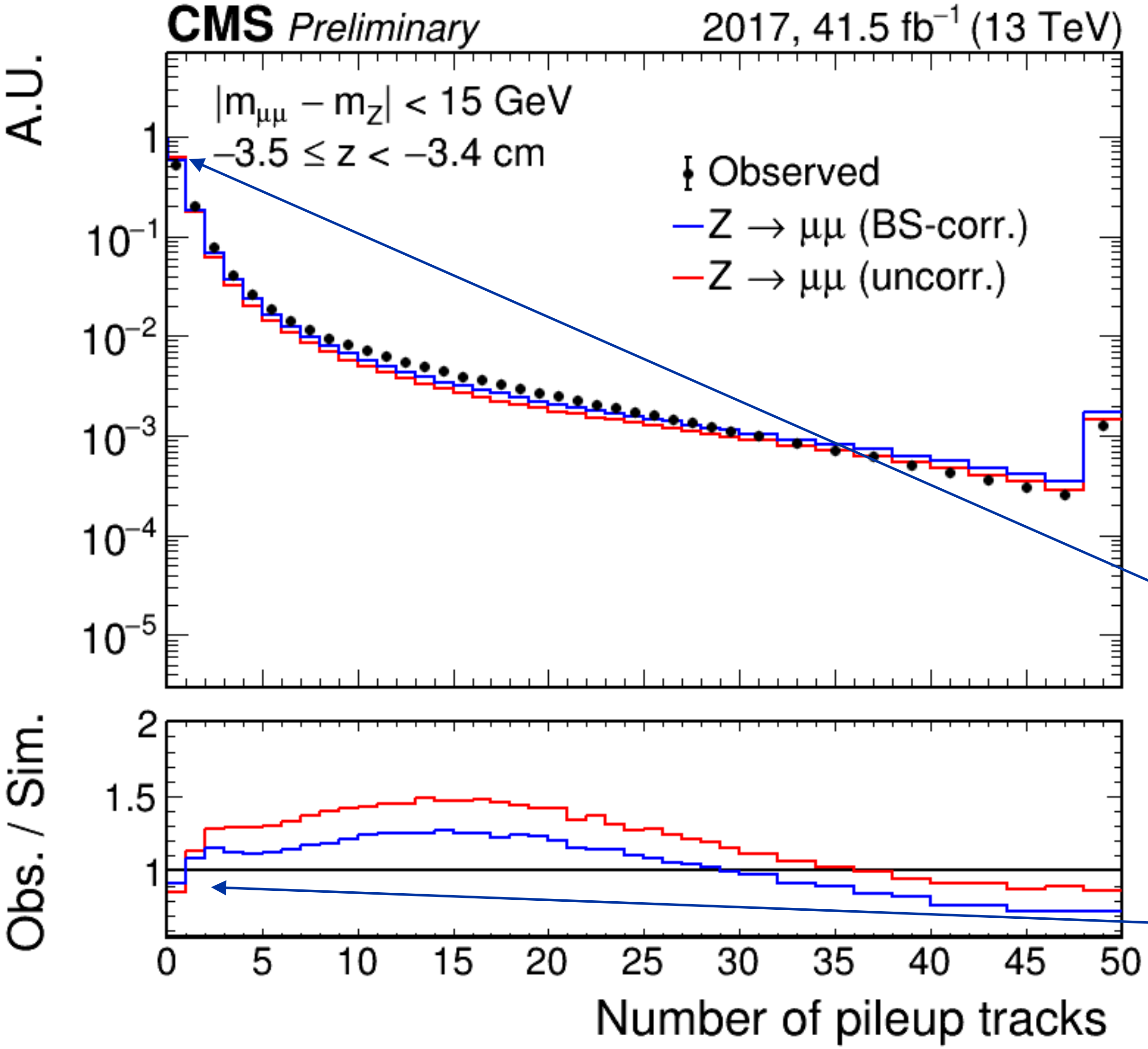
2. Pileup track multiplicity correction



- Can simulations describe accurately the number of pileup tracks within windows of 0.1 cm width all over the z axis?
- Compare N_{tracks} distribution in Z→μμ data and Z→μμ MC, inside windows sampled over the z axis far (> 1cm) from the μμ vertex

Applied to all simulations

2. Pileup track multiplicity correction

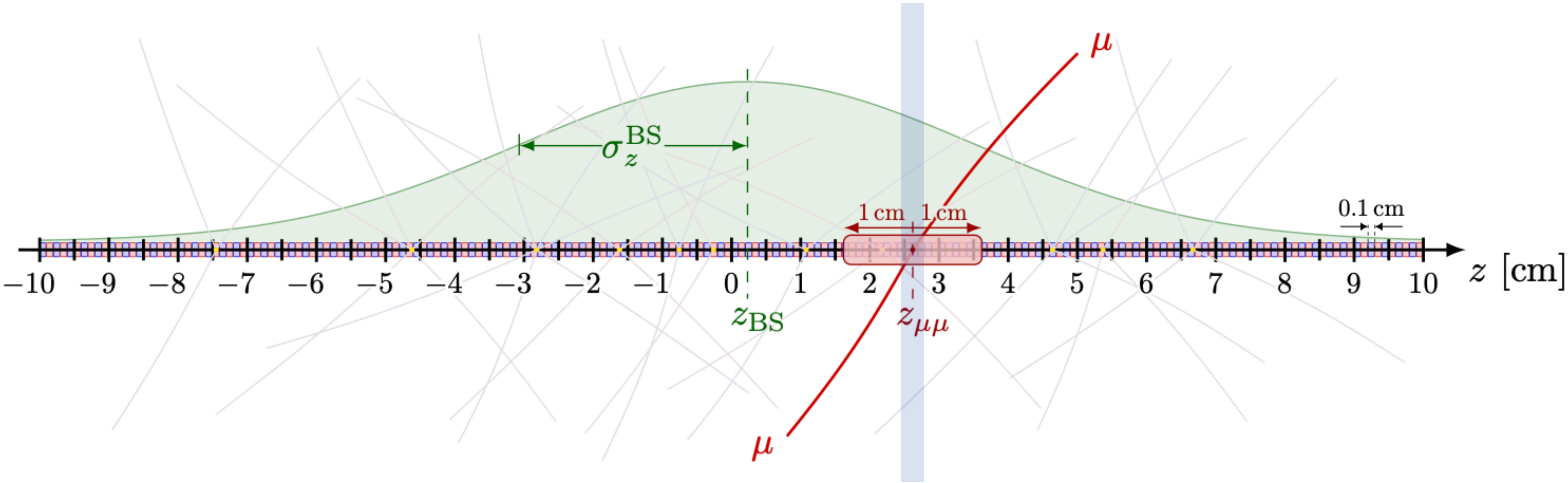


- First, correct simulated z position and width of beamspot (constant values) to match the profiles in data
- Then, derive event-weight correction as a function of N_{tracks} and z

1 beamspot width away from beamspot center, 50% of windows do not contain any PU track

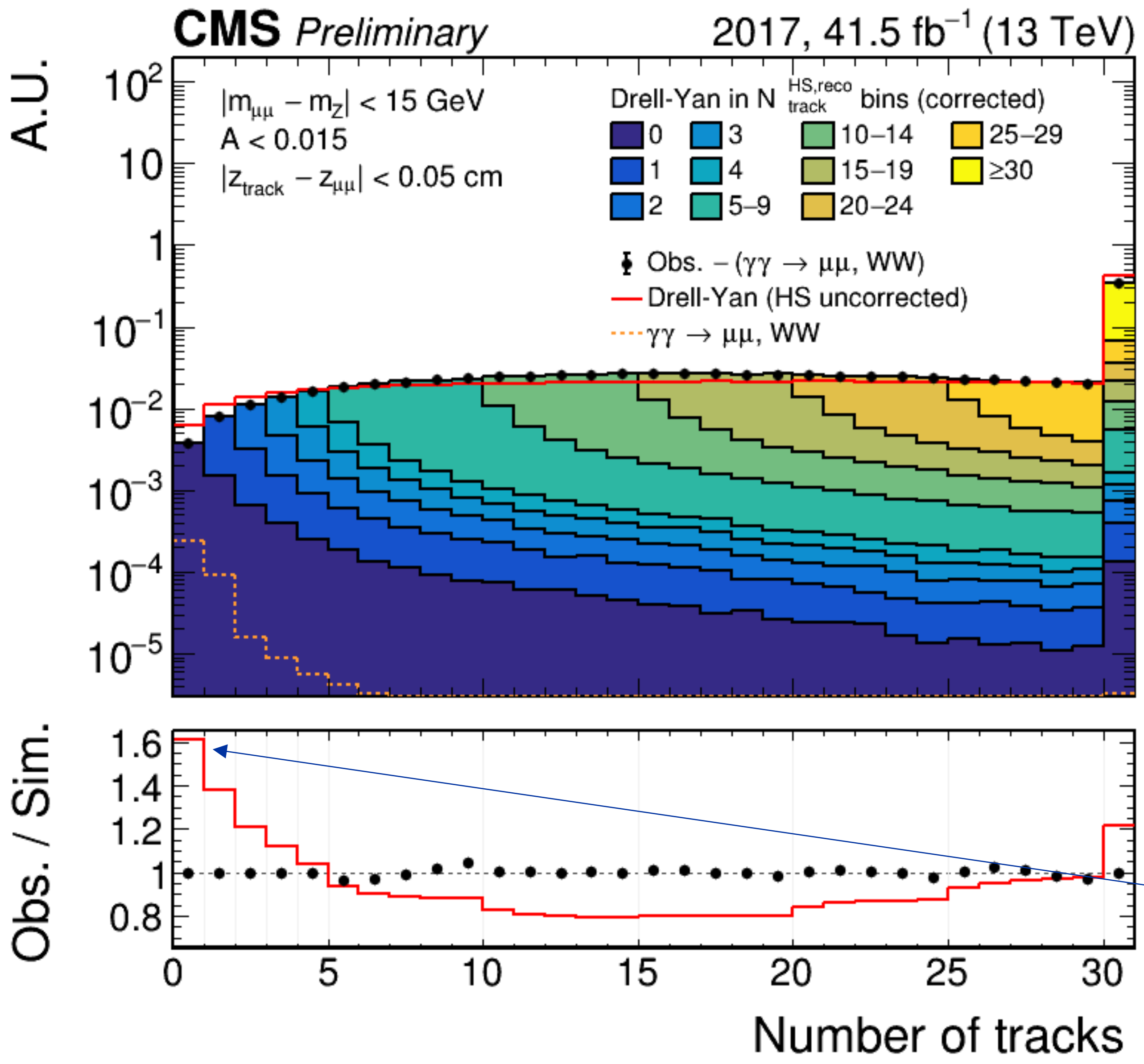
For a window 1 beamspot width away from beamspot center with no PU track inside, the event-weight correction is 0.95

3. Hard scattering track multiplicity correction



- Can the Drell-Yan simulation describe accurately the number of tracks from the hard interaction in windows of 0.1 cm width?
- Compare N_{tracks} distribution in Z→μμ data and Z→μμ MC (subtracting elastic processes), inside window centered at the μμ vertex

3. Hard scattering track multiplicity correction

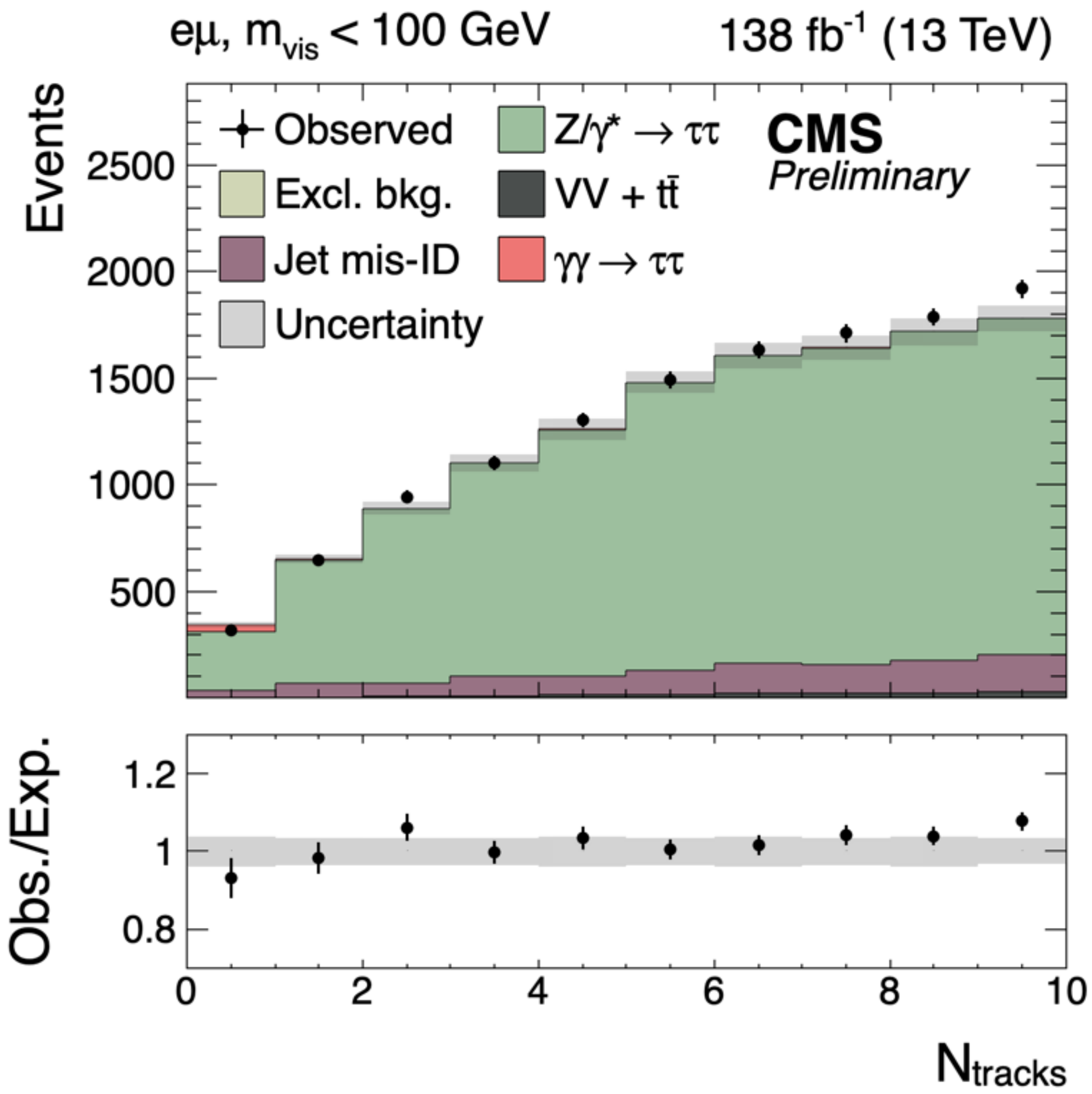


- Compare number of reconstructed tracks in data and in DY simulation at the μμ vertex
- These tracks can come from pileup or from the hard interaction
- Split simulation based on the number of reconstructed tracks associated to the hard interaction, and rescale all components simultaneously to match the data

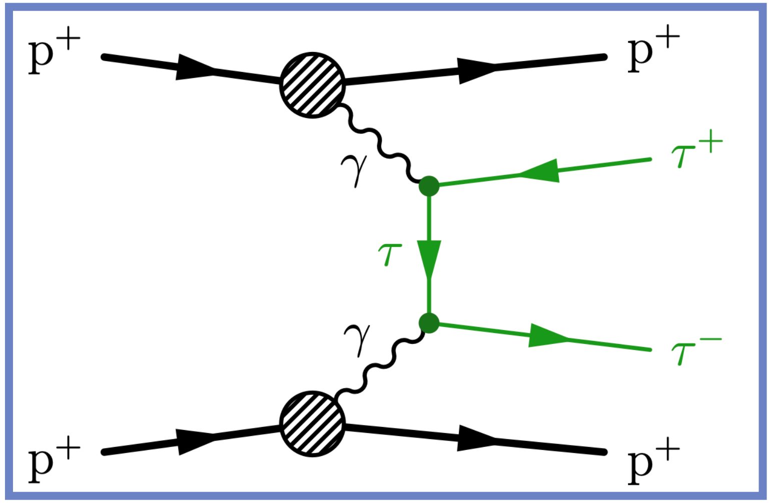
Simulated Drell-Yan events with no reconstucted track associated to the hard interaction in the μμ window should be assigned a weight of 1/1.6 = 0.625

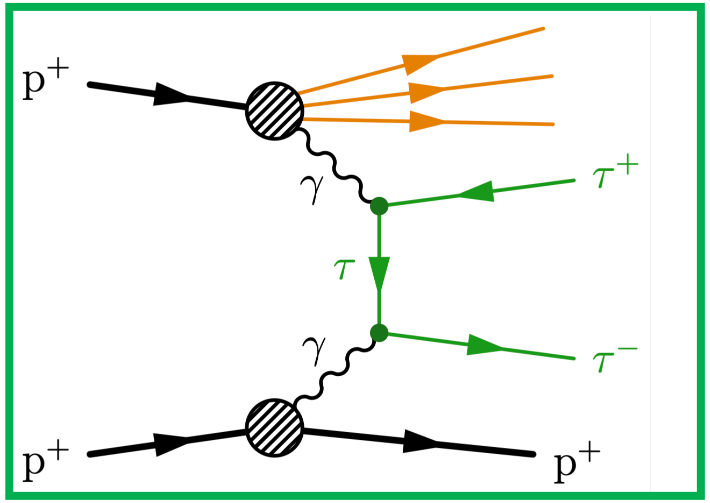
Applying these corrections to $Z/\gamma^* \rightarrow \tau\tau$ simulation

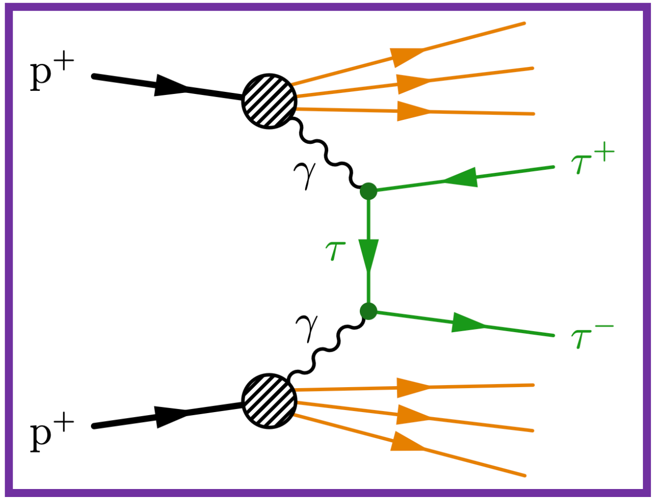
- Good data/MC agreement in N_{tracks} distribution in all di-tau final states for the DY-enriched region with m_{vis} $(\tau, \tau) < 100$ GeV



4. Including (semi-)dissociative contributions





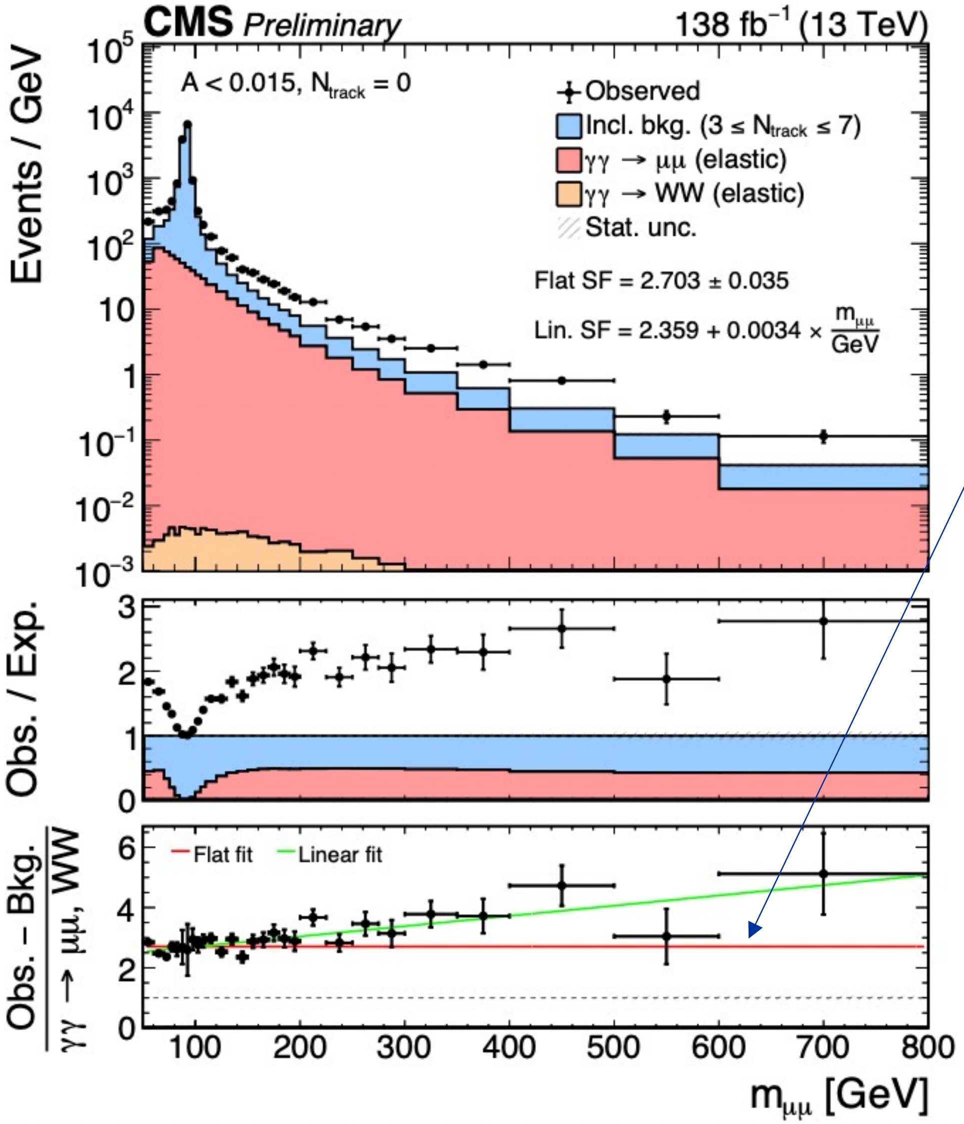


- **Elastic-elastic (ee)** signal process modeled with gammaUPC
- **Single-dissociative (sd)** and **double-dissociative (dd)** processes have larger cross section and may end up with an exclusive signature → rescale elastic signal to include these contributions
- Scaling factor = $(ee + sd + dd)_{obs}$ / ee_{sim} can be measured with $\gamma\gamma \rightarrow \mu\mu$ in the μμ CR and applied to $\gamma\gamma \rightarrow ee/\mu\mu/\tau\tau/WW$ in the signal region

Applied to all photon-induced processes

4. Including (semi-)dissociative contributions

- **Inclusive backgrounds:**
  - Shape from data with $2 < N_{tracks} < 8$
    → Negligible exclusive contributions
  - Normalized to Z peak in events with $N_{tracks} = 0$ or 1
- **Elastic $\gamma\gamma \rightarrow \mu\mu/WW$:**
  - Estimated from gammaUPC
  - Rescaled with linear $m_{\mu\mu}$ function to match data



Elastic simulation should be scaled by ~2.7 to describe all photon-induced contributions

Compatible with SuperChic predictions

Jet mis-ID background modeling

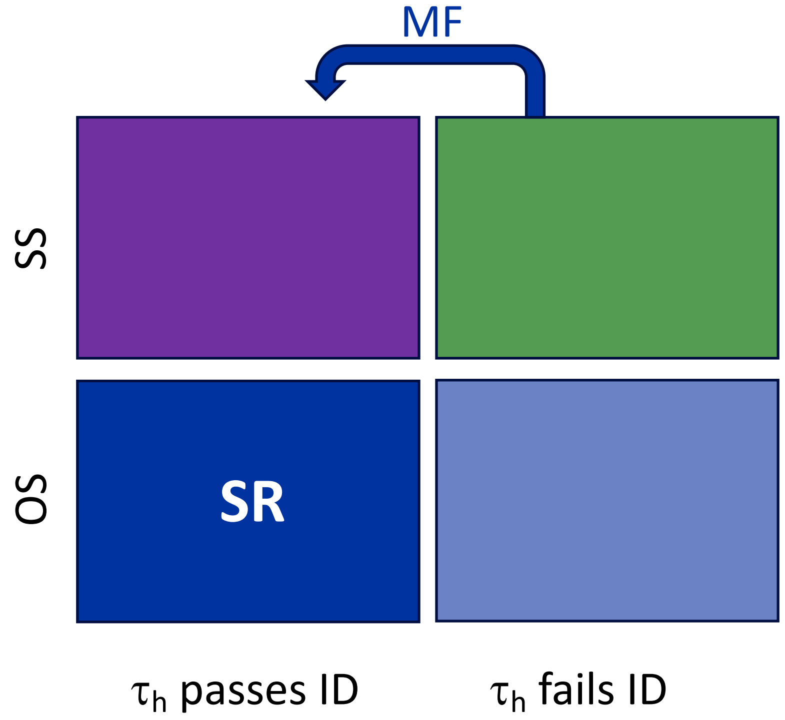
Jet→τ_h mis-ID background (1)

- Measure ”mis-ID factor”, MF, for jets as

$$MF = \frac{N(\text{jets passing nominal } \tau_h \text{ ID})}{N(\text{jets failing nominal } \tau_h \text{ ID but passing very loose } \tau_h \text{ ID})}$$

  - As a function of the τ_h p_T and decay mode
  - In data control regions (e.g. require SS leptons/τ_h to enrich in QCD multijet events)

- To estimate background in the SR, select events passing the SR selection except the τ_h fails the nominal τ_h ID and reweigh them with MF

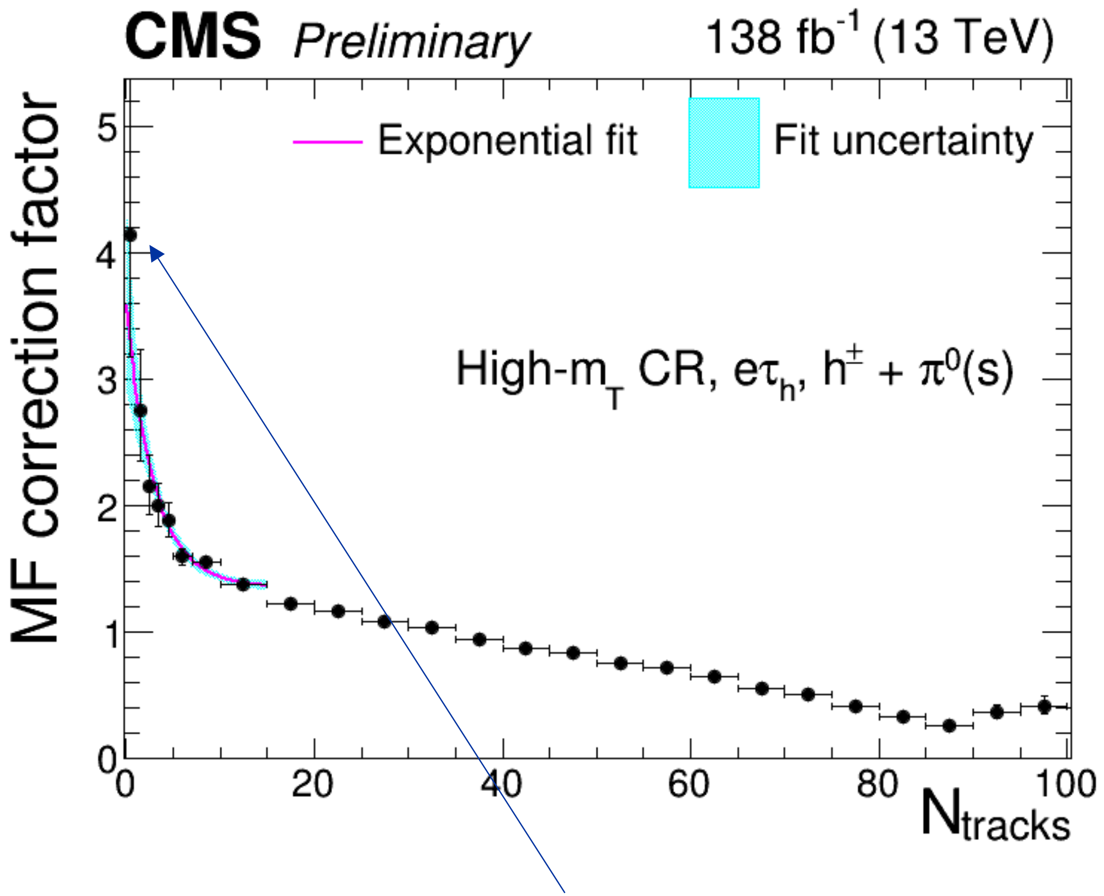


But it is not that simple…

How does N_{tracks} affect MF?

Jet→τ_h mis-ID background (2)

- If there is less track activity around the τ_h candidate:
  - The τ_h candidate is more isolated
  - It is more likely to pass the ID criteria
  - MF is higher
- Model N_{tracks} dependence with a multiplicative correction to the mis-ID rates
  - Parameterized with exponential at low N_{tracks}

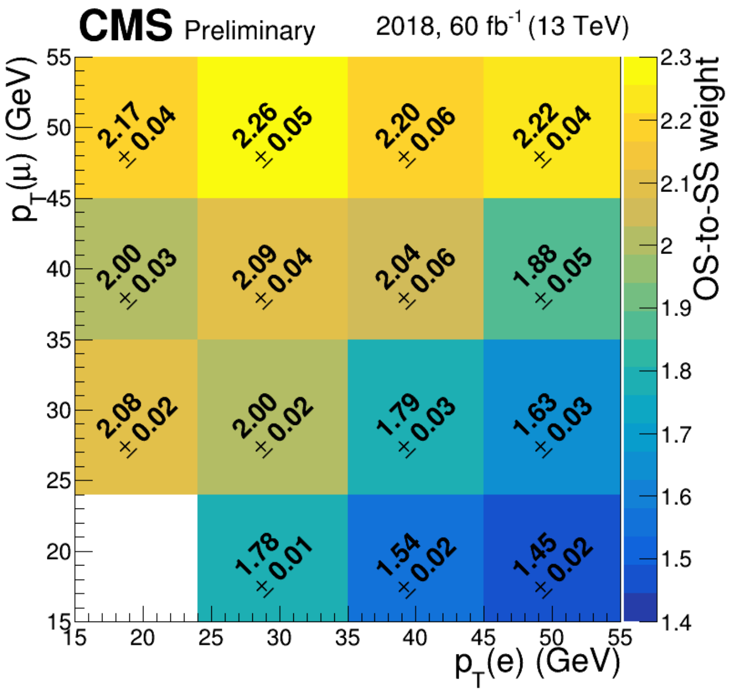


The jet is 4 times more likely to pass the nominal τ_h ID criteria if there is no other track at the vertex *eμ final state*

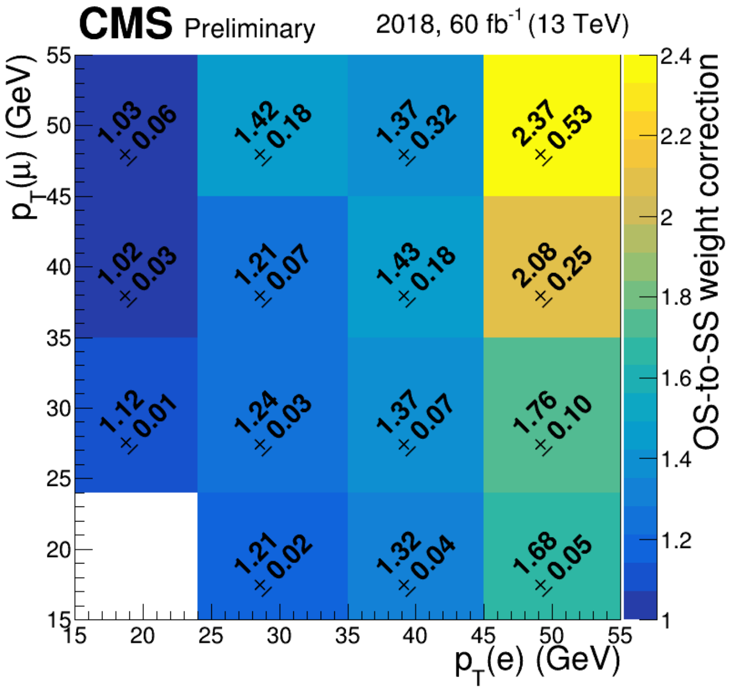
Jet→e/μ background

- Normalization: reweigh SS events with SF made of 3 multiplicative terms
- Shape: SS events with N_{tracks} < 10 to improve statistical precision

1. OS/SS SF measured in events with anti-isolated muon
2. Correction for muon inverted isolation
3. *N_{tracks}* corrections



1.



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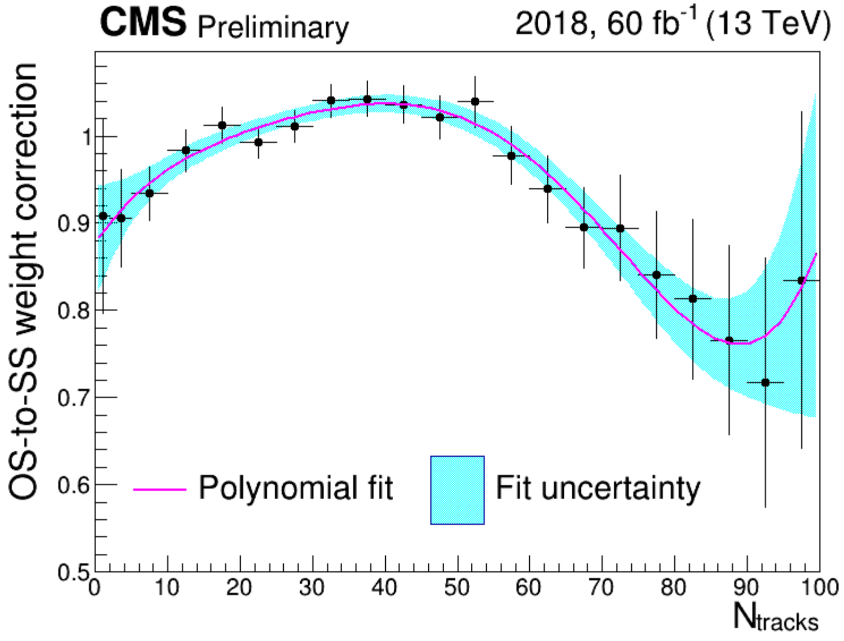
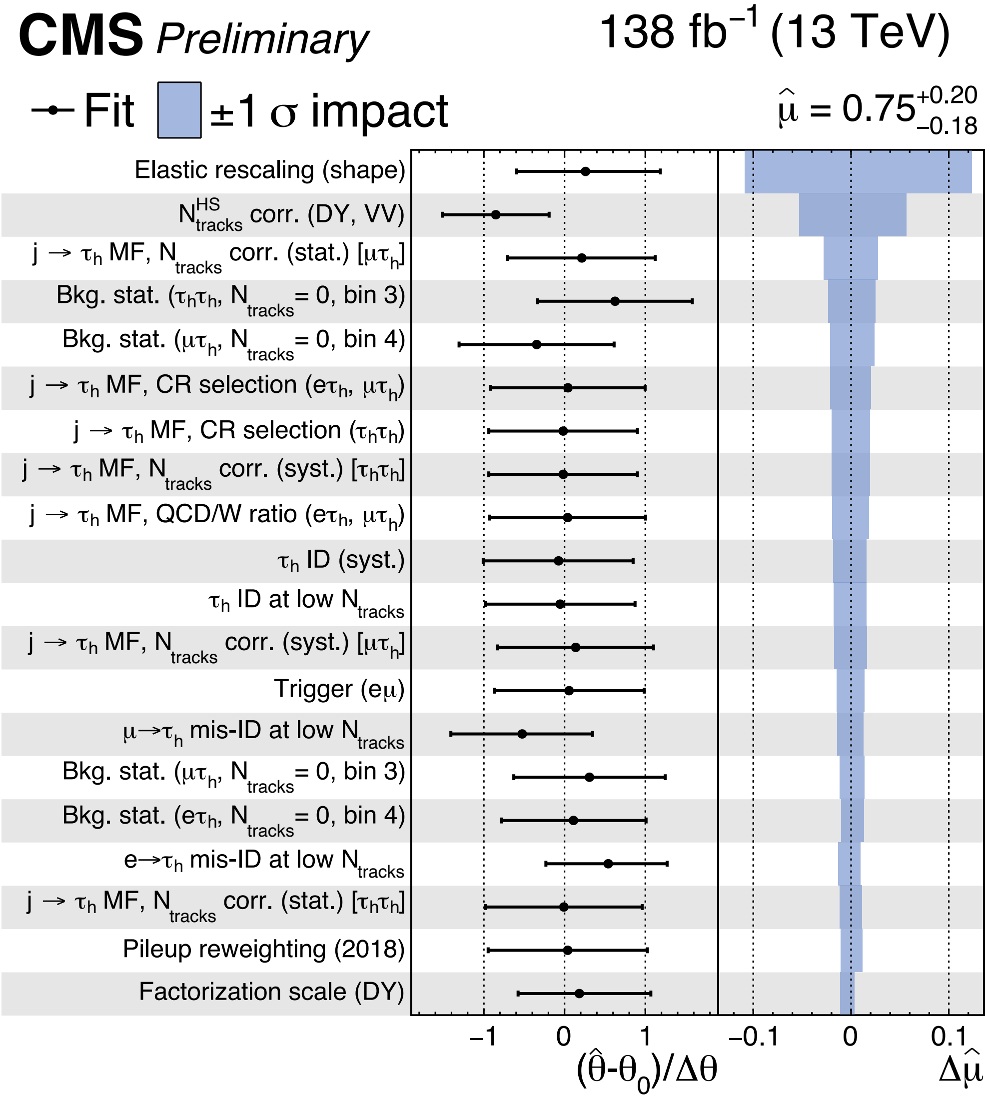


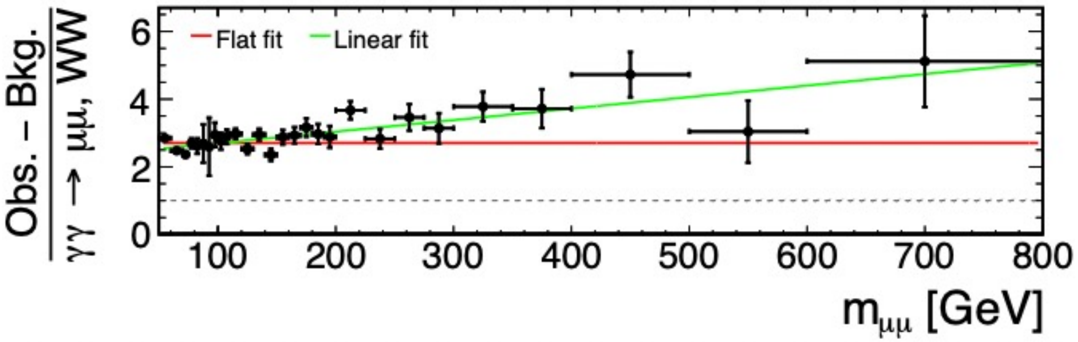
3.

Observation of $\gamma\gamma \rightarrow \tau\tau$

Leading systematics



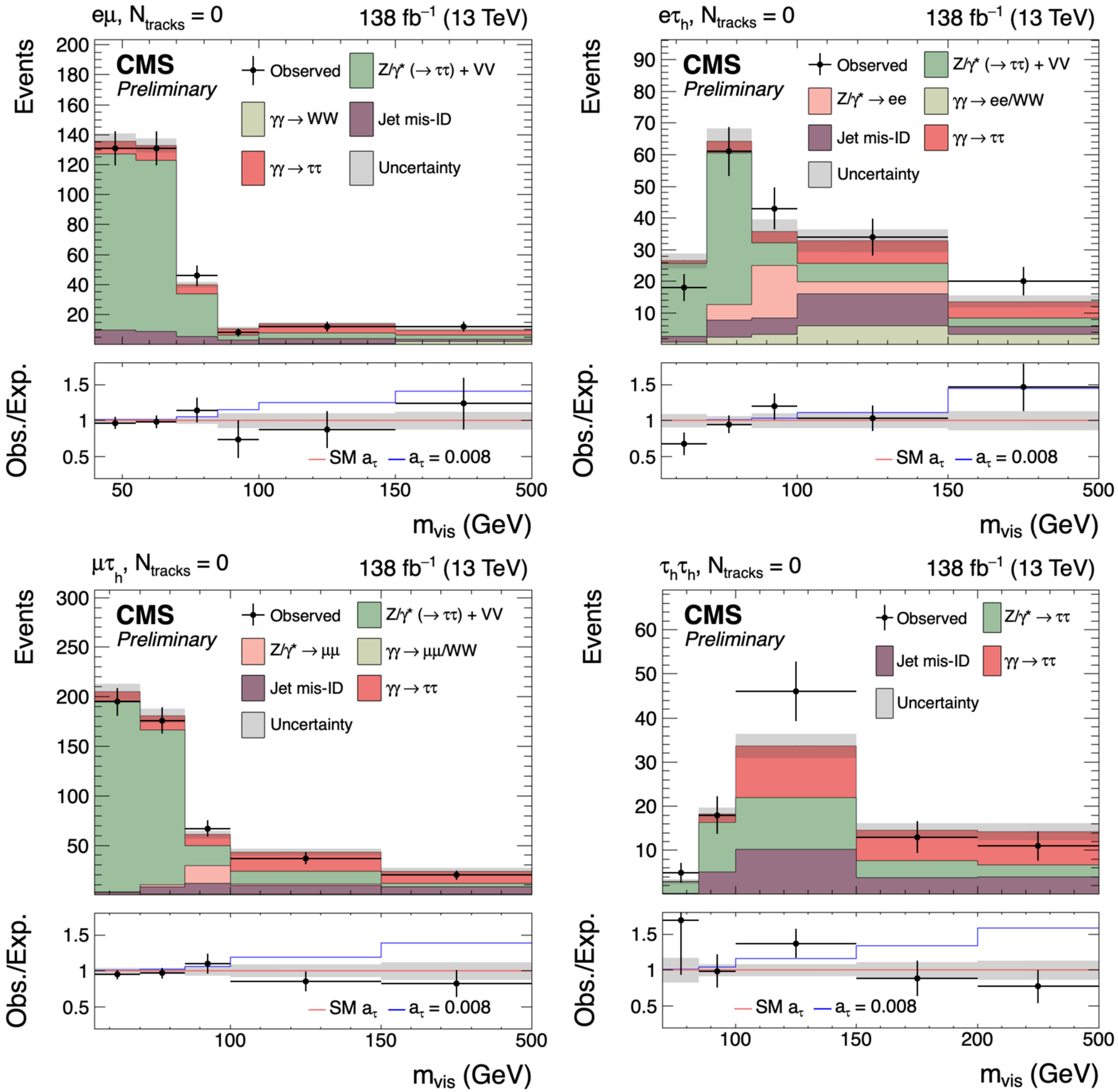
Considering the constant rescaling for the elastic simulations instead of the $m_{\mu\mu}$-dependent one



UE/HS track multiplicity correction to Drell-Yan (6.5% uncertainty for N_{tracks} = 0)

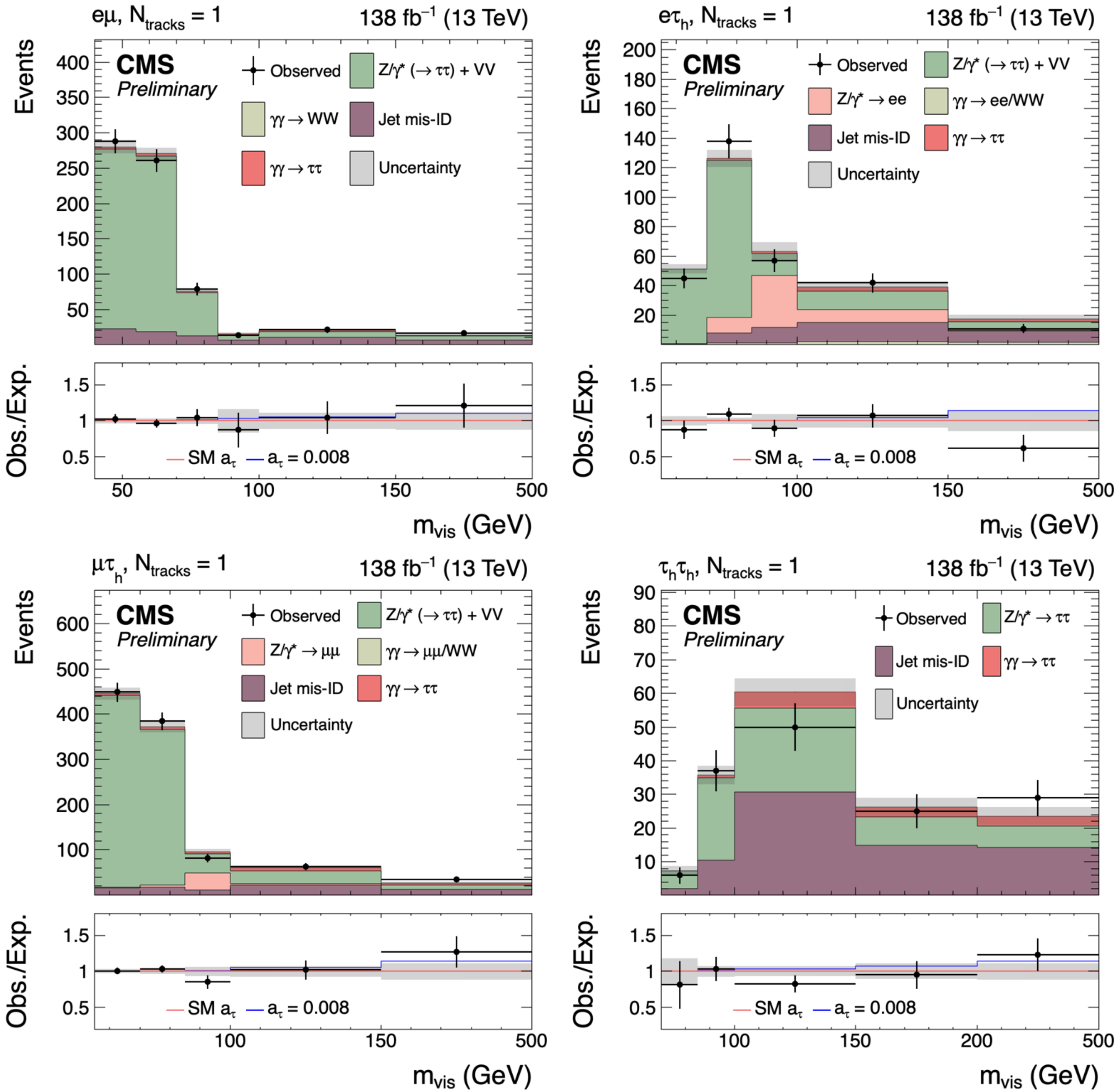
N_{tracks} extrapolation of the jet→τ_h MF to estimate jet mis-ID background (up to ~20%)

Real and fake τ_h identification (at low N_{tracks})



$N_{tracks} = 0$

- m_{vis} distributions in the different final states after the maximum likelihood fit, assuming SM a_τ and d_τ
- **Signal visible in high m_{vis} bins**



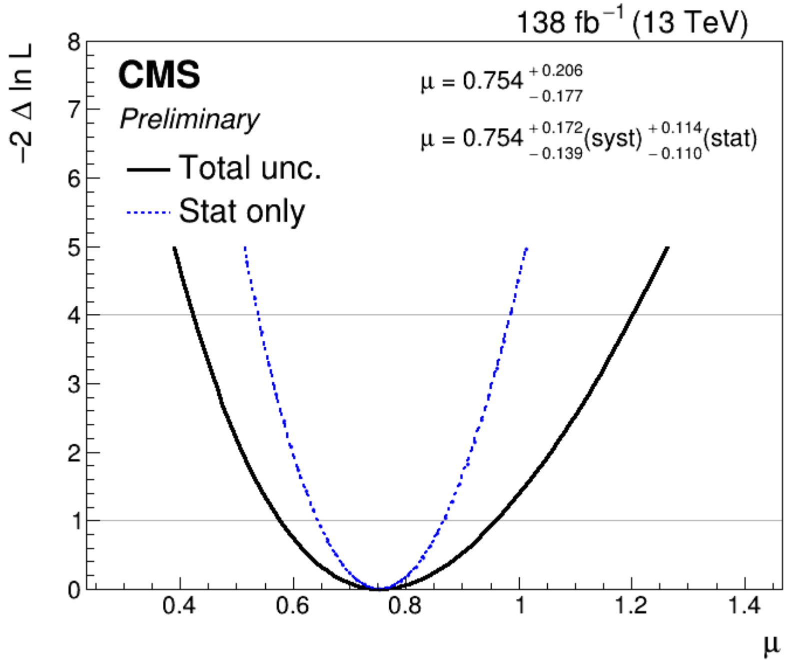
$N_{tracks} = 1$

- m_{vis} distributions in the different final states after the maximum likelihood fit, assuming SM a_τ and d_τ
- Lower signal contributions and larger background → validation of background modeling and adding some sensitivity

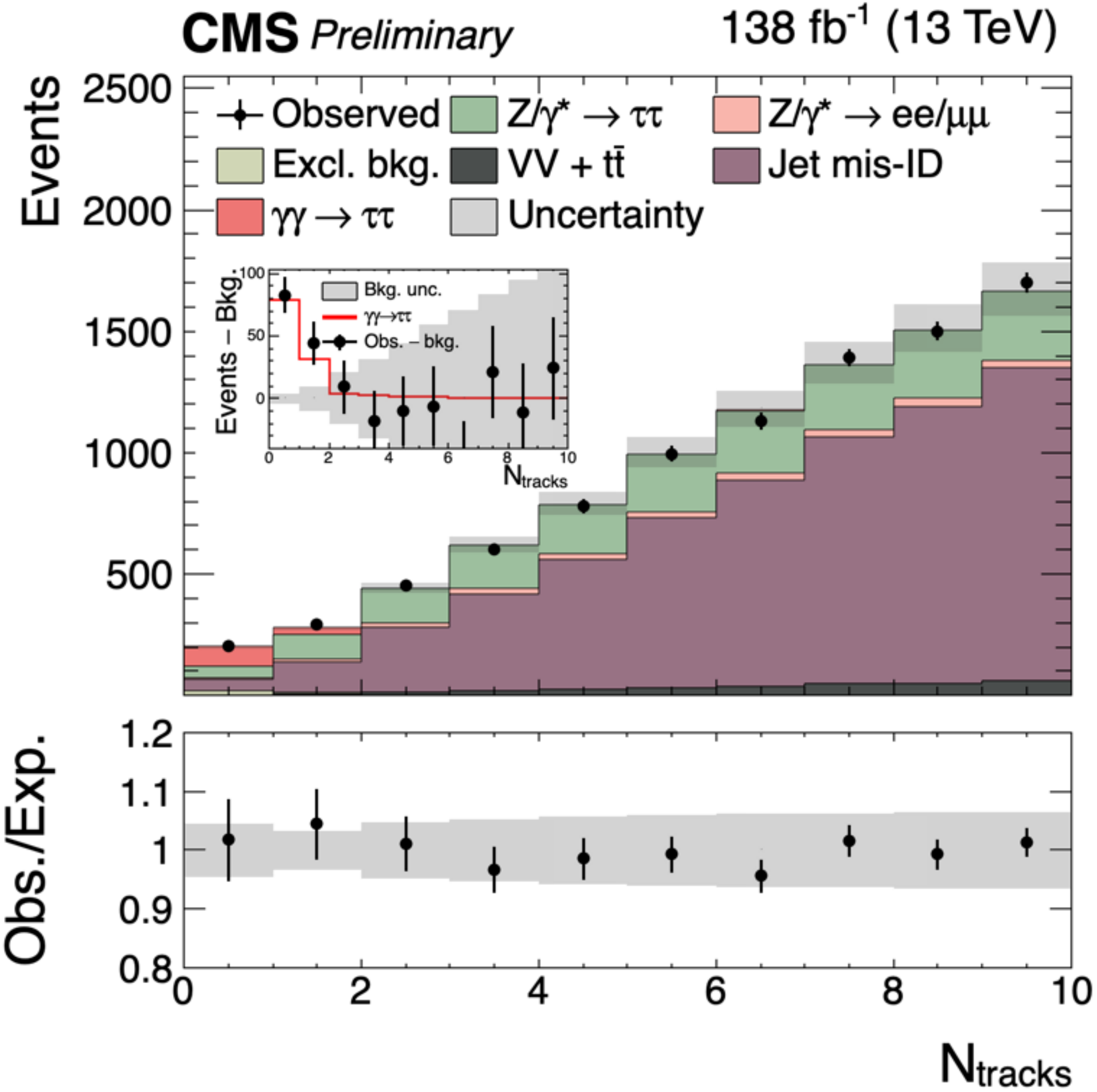
Observation of $\gamma\gamma \rightarrow \tau\tau$

- **5.3 σ observed, 6.5 σ expected**
- **First observation of $\gamma\gamma \rightarrow \tau\tau$ in pp runs**

Signal strength with respect to gammaUPC elastic prediction rescaled by our data-driven correction



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



- Postfit N_{tracks} distribution for m_{vis} > 100 GeV
  - **We can model well the N_{tracks} distribution for backgrounds**
  - **The signal is seen as an excess of events at very low N_{tracks}**

Constraints on tau anomalous electromagnetic moments

Constraining a_τ and d_τ with an EFT

- Two dimension-6 operators modify a_τ and d_τ at tree-level in the SMEFT:

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

- BSM contributions to a_τ and d_τ:

SMEFT-sim_general alphaScheme_UFO

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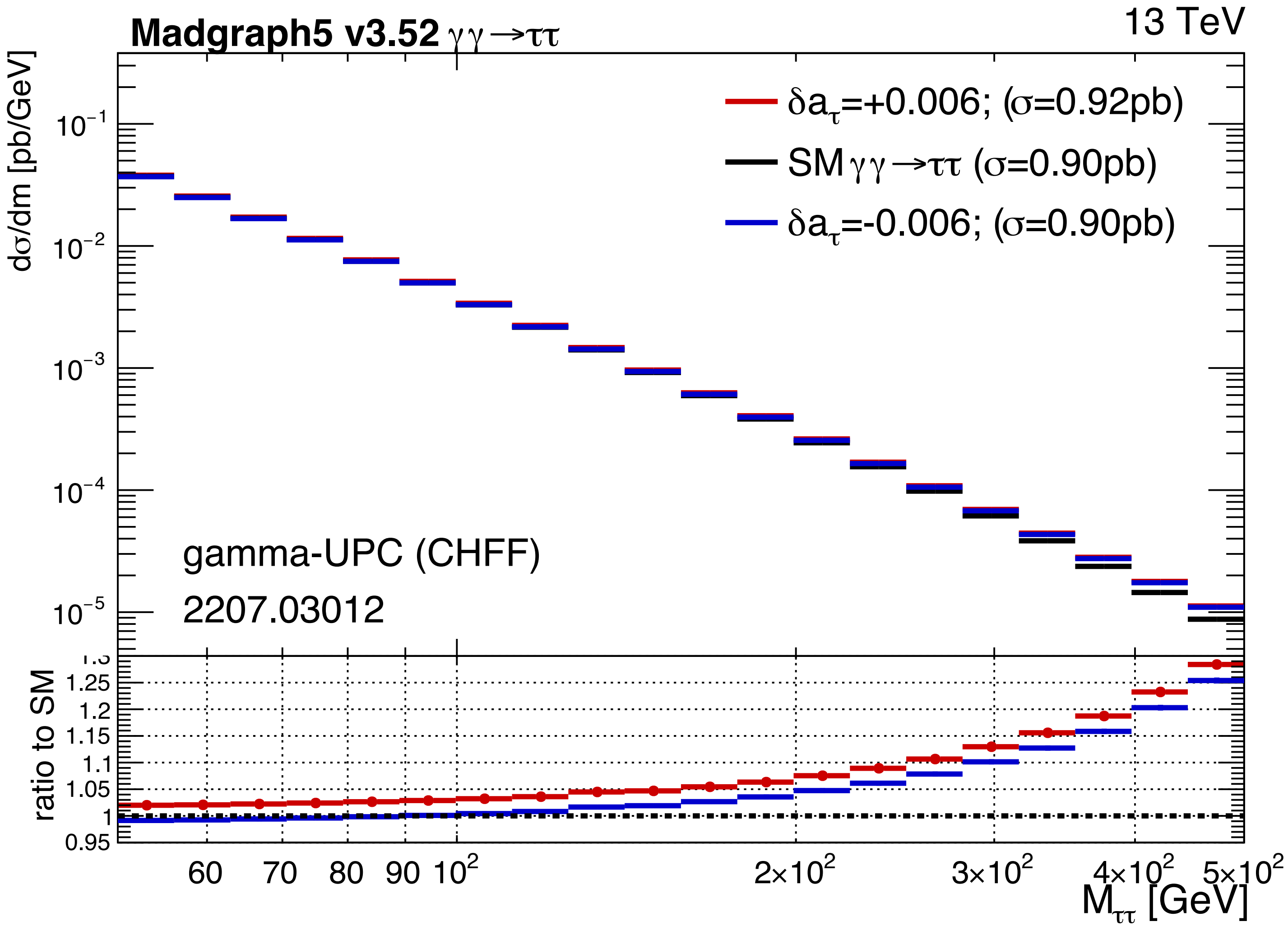
$$\delta a_\tau = \frac{2m_\tau}{e} \frac{\sqrt{2}v}{\Lambda^2} \mathrm{Re}\left[C_{\tau\gamma}\right] \qquad \delta d_\tau = \frac{\sqrt{2}v}{\Lambda^2} \mathrm{Im}\left[C_{\tau\gamma}\right]$$

- where $C_{\tau\gamma} = \left(cos\theta_W C_{\tau B} - \sin\theta_W C_{\tau W}\right)$

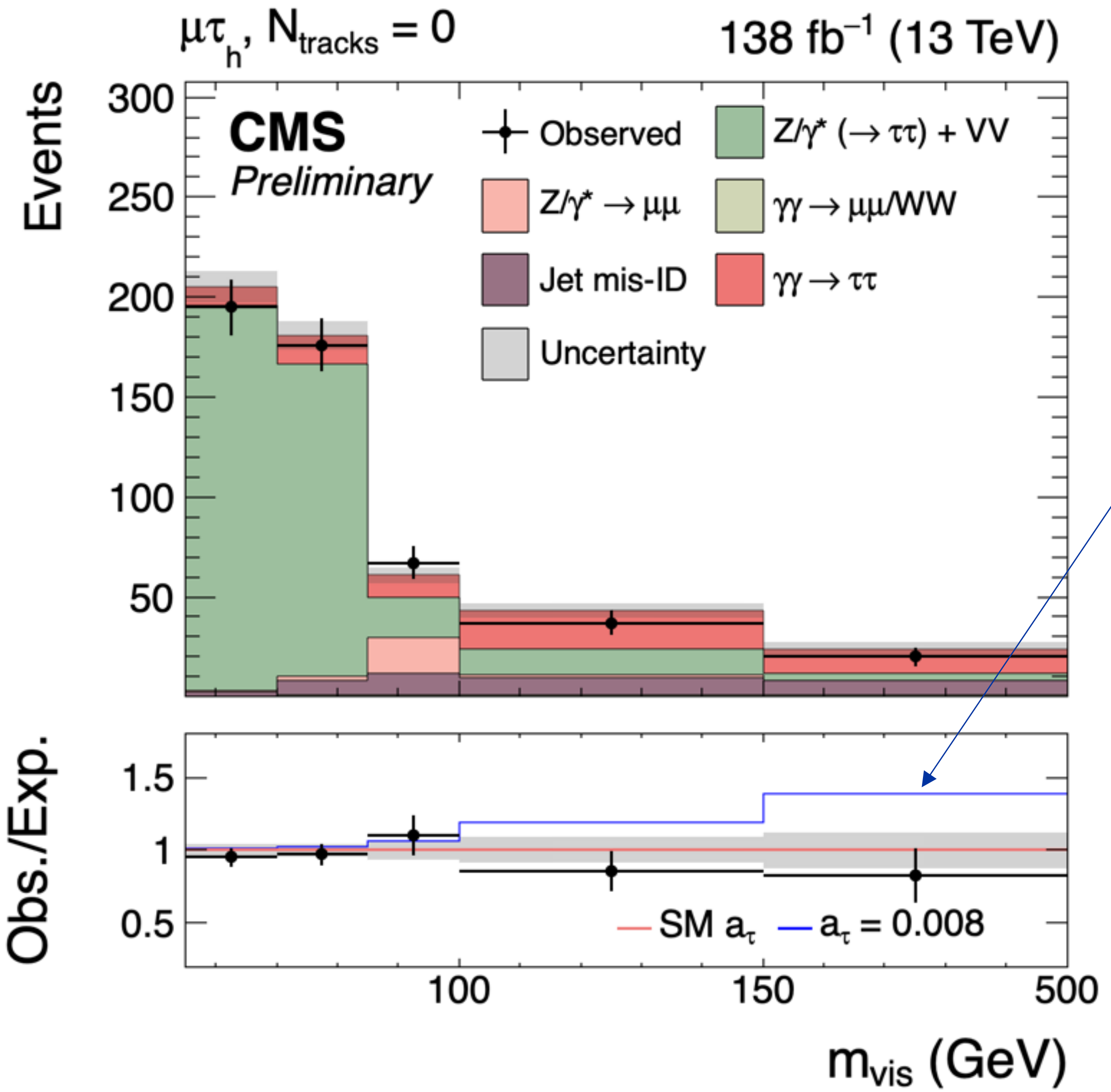
- Matrix element reweighting to model signal for BSM values of a_τ and d_τ, setting $C_{\tau W}$ to 0 and scanning over $C_{\tau B}$ without loss of generality

How BSM physics in a_τ affects $\gamma\gamma \rightarrow \tau\tau$

- At large $m_{\tau\tau}$, $\gamma\gamma \rightarrow \tau\tau$ cross section increases with both positive and negative variations to a_τ
- The effect grows with $m_{\tau\tau}$
- **We can constrain a_τ by looking at the yield and $m_{\tau\tau}$ distribution of the $\gamma\gamma \rightarrow \tau\tau$ process**
- Expect better BSM sensitivity than with Pb-Pb runs because of higher $m_{\tau\tau}$ range probed

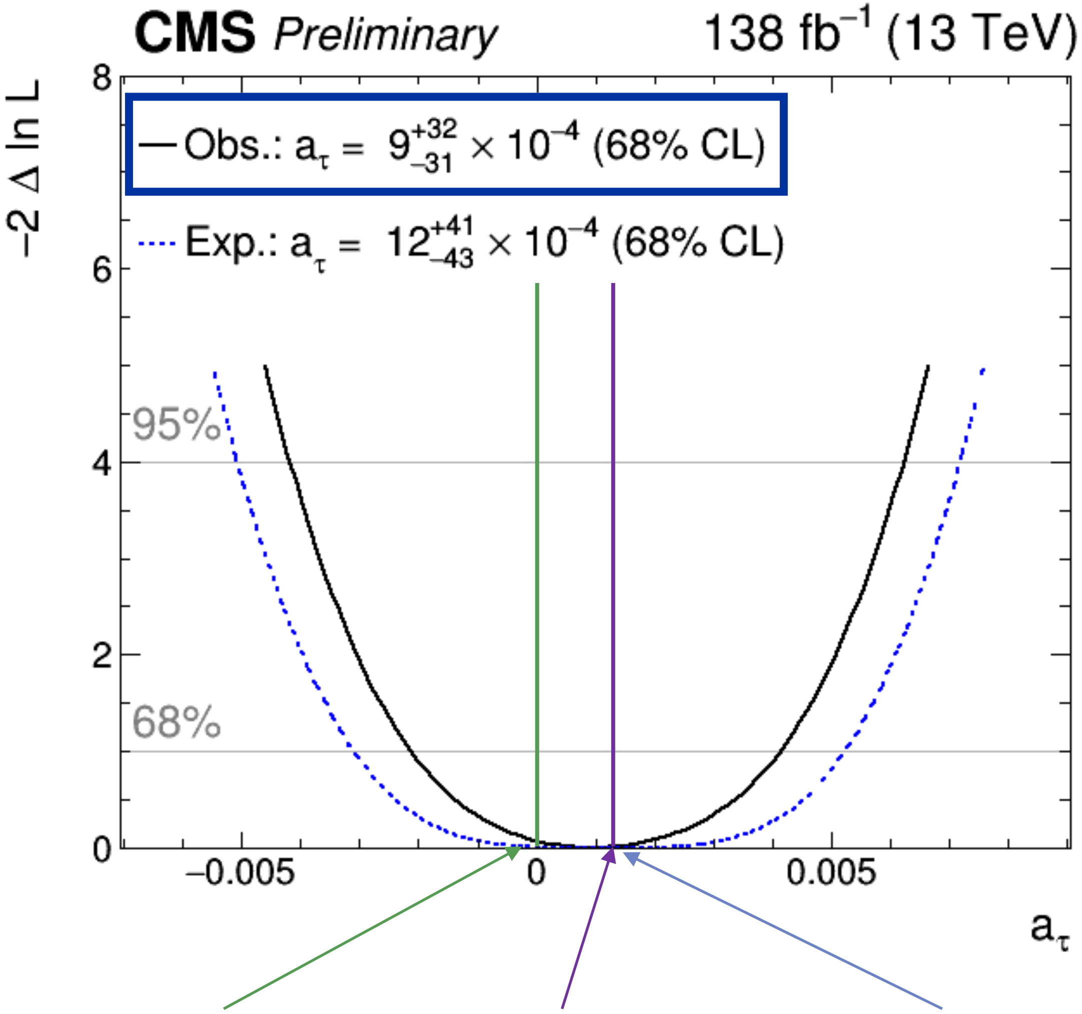


How it translates in this analysis



- Changing a_τ from its SM value modifies the $\gamma\gamma \rightarrow \tau\tau$ prediction
- Differences between SM and BSM a_τ scenarios increase with m_{vis}
- a_τ can be constrained from the same m_{vis} distributions used to observe $\gamma\gamma \rightarrow \tau\tau$
- m_{vis} < 500 GeV to remain far from new physics scale and preserve validity of EFT interpretation

Extracting a_τ



$a_\tau = \delta a_\tau + \text{SM } a_\tau$

Dirac $a_\tau = 0$

Schwinger $a_\tau = 0.00116$

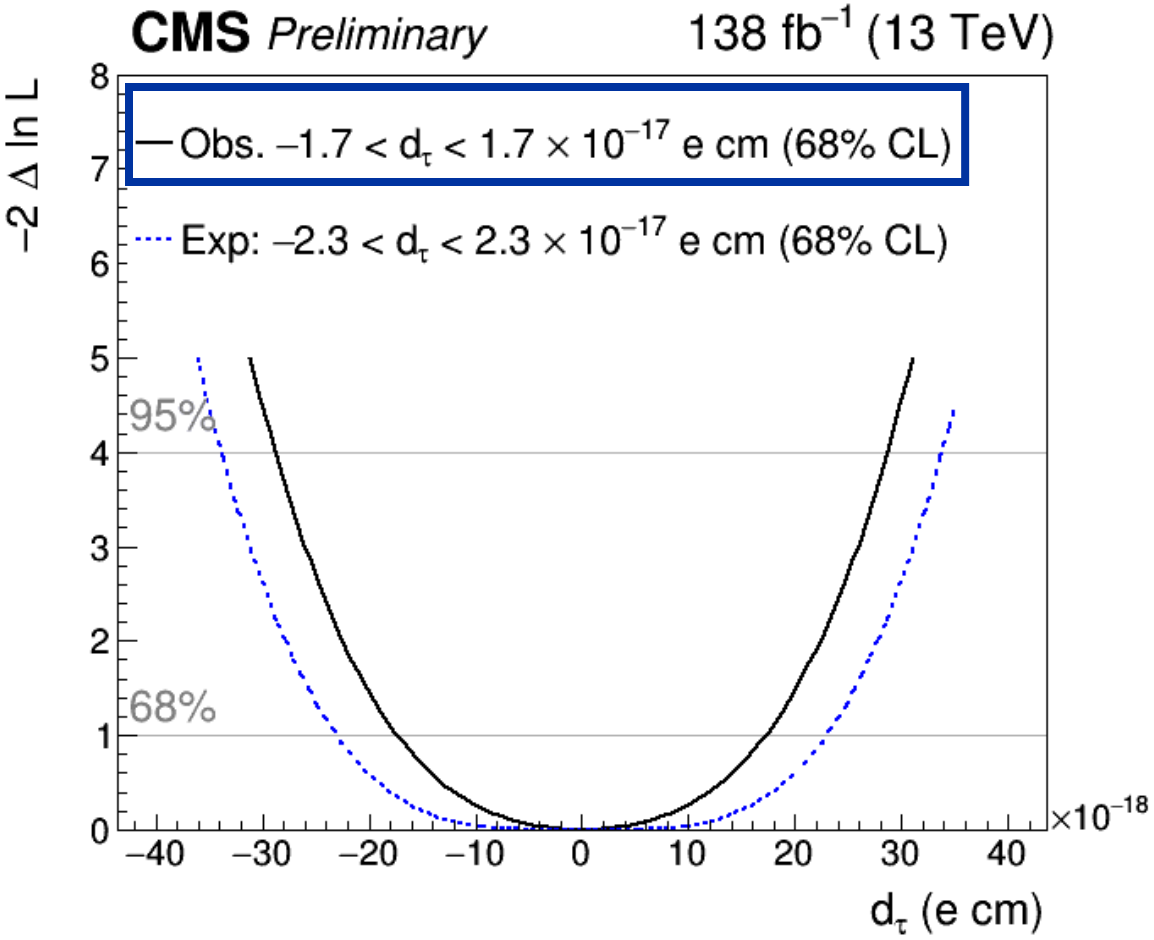
SM $a_\tau = 0.00118$

- Using m_{vis} distributions in the SR, perform negative log likelihood scan over δa_τ, which modifies the signal shape and normalization
- In the $m_{\tau\tau}$ range considered in this analysis, both $\delta a_\tau > 0$ and < 0 increase the signal prediction
- Observed $\gamma\gamma \rightarrow \tau\tau$ deficit: tighter constraints than expected, **compatibility with SM**

1σ uncertainty of 0.003

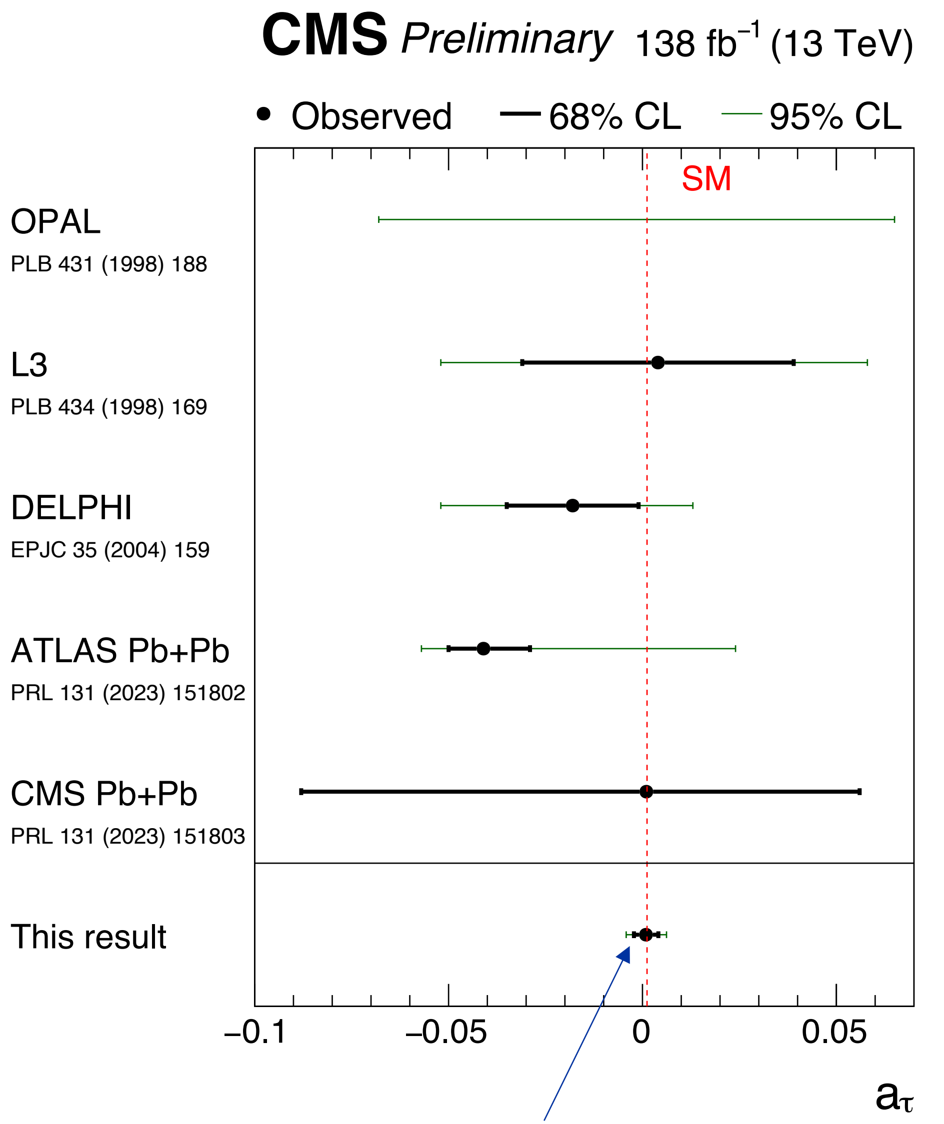
Only 3 times the Schwinger term!

Extracting τ EDM (d_τ)

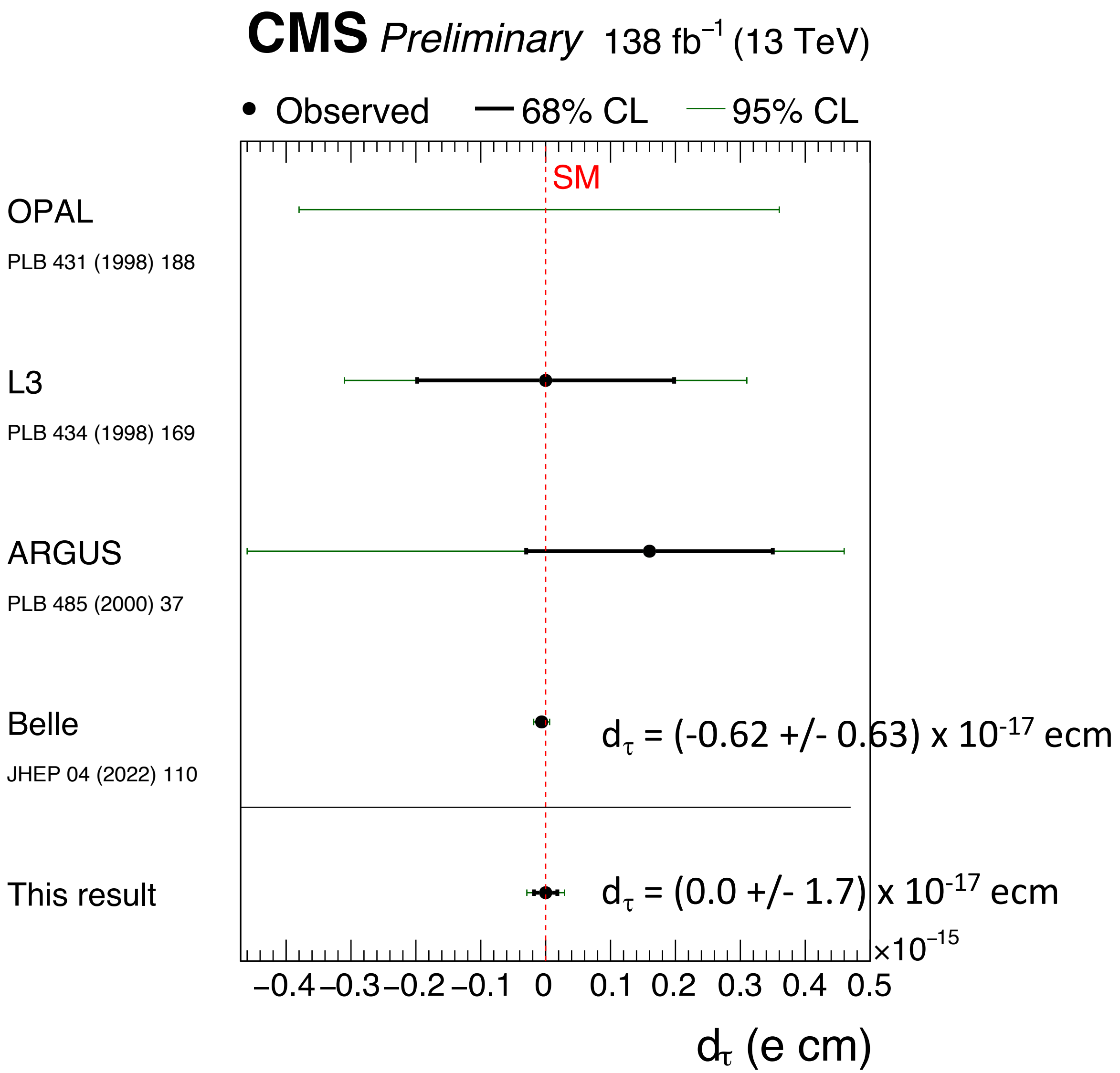


- BSM effects symmetric with sign of δd_τ
- In the $m_{\tau\tau}$ range considered in this analysis, both $\delta d_\tau > 0$ and < 0 increase the signal prediction
- Observed $\gamma\gamma \rightarrow \tau\tau$ deficit: tighter constraints than expected, **compatibility with SM**

Comparing to previous results



Large improvement over LEP and LHC Pb-Pb



Approaching Belle precision

The precision journey has just started…

DELPHI

OPAL

Pb-Pb LHC

CMS pp

Approaching the

Schwinger term!

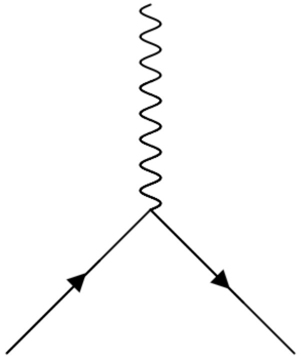
More precision needed to

probe BSM effects scaling

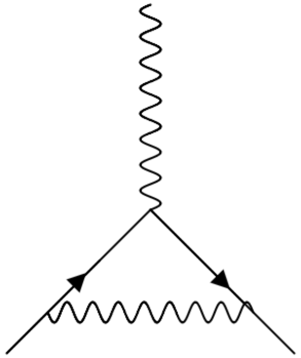
with m_ℓ^2…

a_τ precision

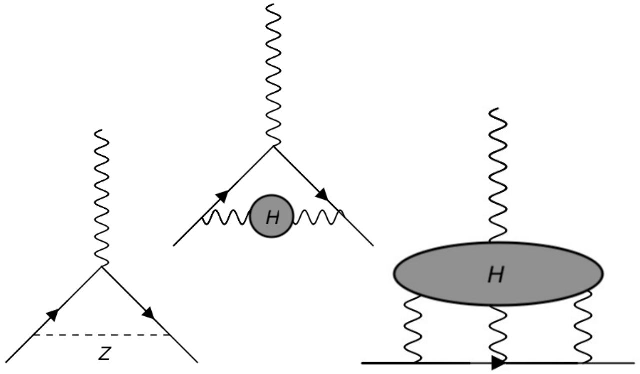
Dirac



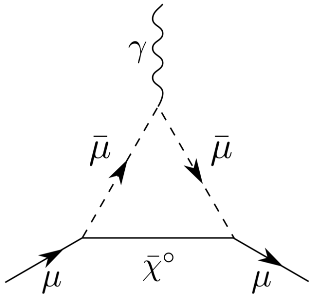
Schwinger term



Higher-order corrections

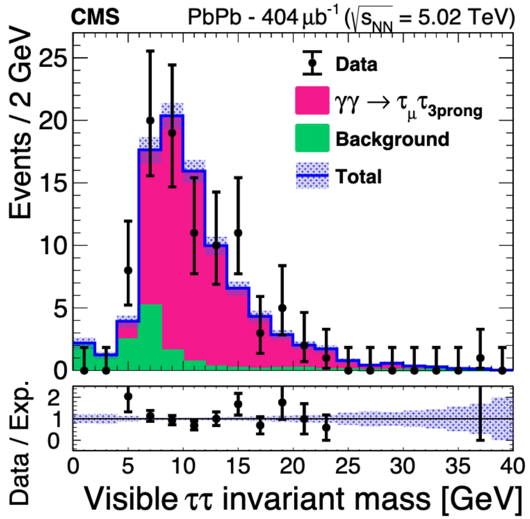


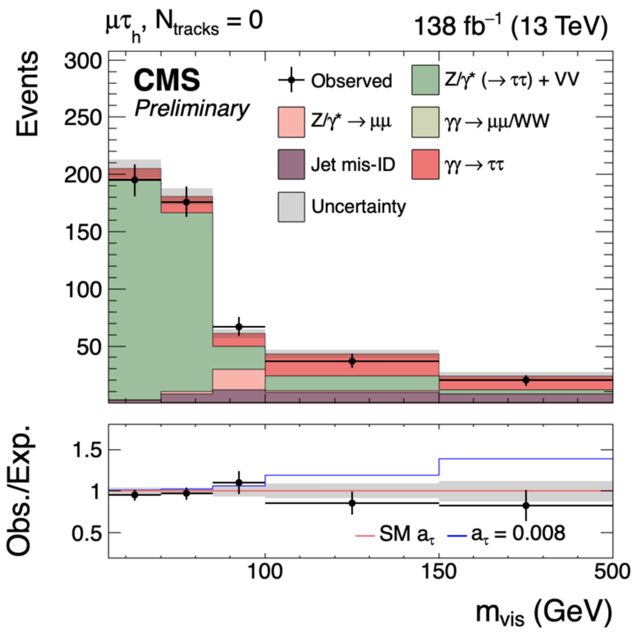
BSM effects?

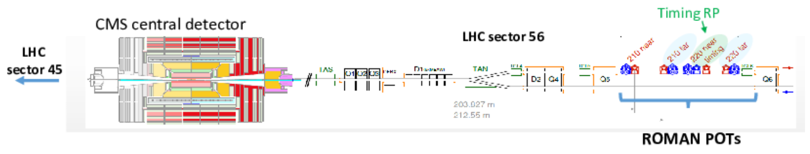


… and CMS will be a part of it

- Heavy ion runs
- pp runs with track counting
- pp runs with proton tagging







PPS approved for Run-4

50 GeV   350 GeV   2 TeV

The majority of CMS data has not been collected yet. Exciting complementary approaches for upcoming Runs!

Conclusion

- Thanks to the excellent tracking performance of the CMS detector, we can isolate photon-induced events in ultraperipheral proton-proton collisions without tagging protons
- **The CMS Collaboration has observed, for the first time, $\gamma\gamma \rightarrow \tau\tau$ events in pp runs**
- These events were used to constrain the tau electromagnetic moments with an EFT approach

$$a_\tau = 0.0009 +0.0032/-0.0031 \text{ at 68\% CL}$$

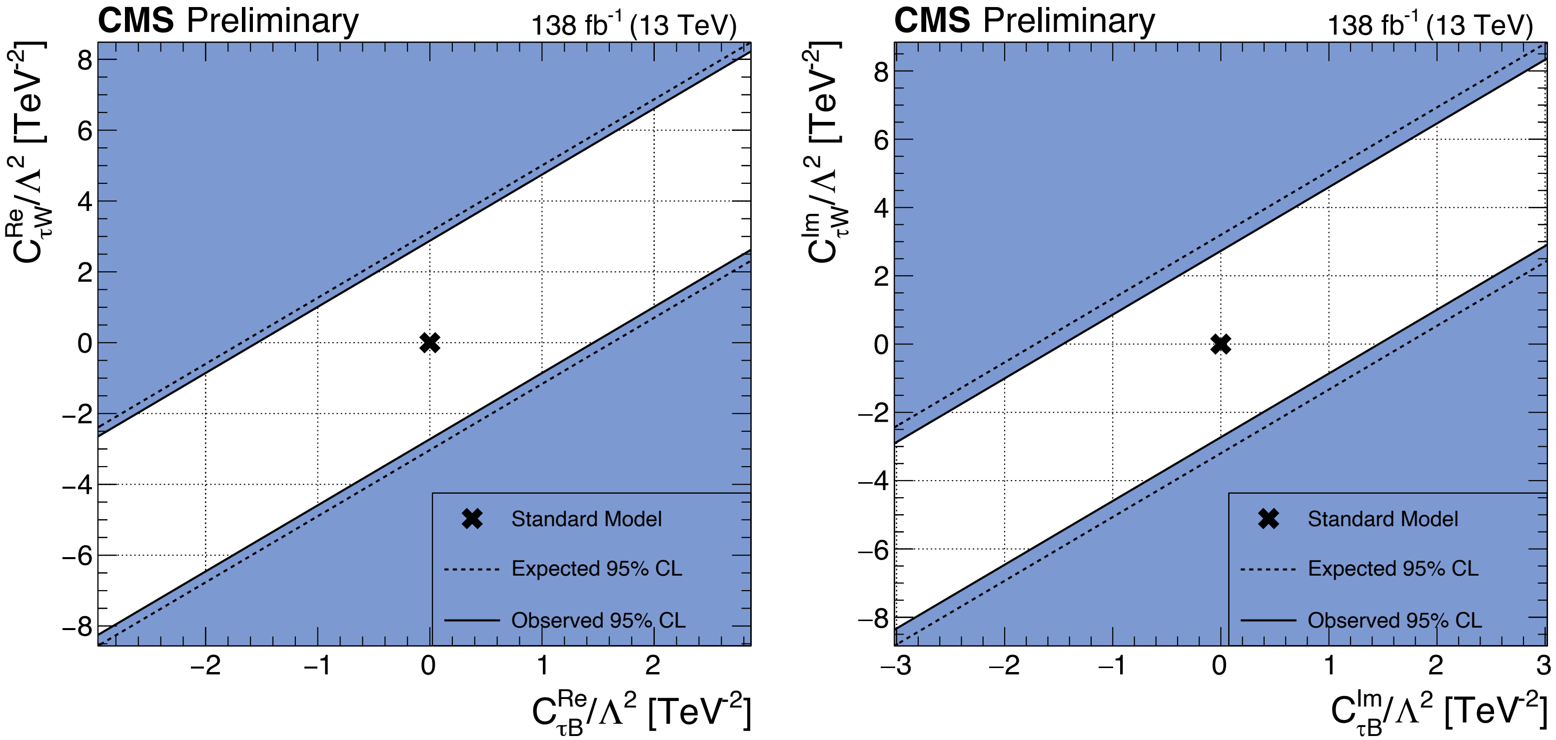
$$-0.0042 < a_\tau < 0.0062 \text{ at 95\% CL}$$

- **Improving previous constraints on tau g-2 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*)

More info in CMS-PAS-SMP-23-005

Backup

Constraints on Wilson coefficients



- $-1.68 < \mathrm{Re}(C_{\tau B})/\Lambda^2 < 1.62$ TeV^{-2}
- $-3.03 < \mathrm{Re}(C_{\tau W})/\Lambda^2 < 3.13$ TeV^{-2}
- $-1.71 < \mathrm{Im}(C_{\tau B})/\Lambda^2 < 1.71$ TeV^{-2}
- $-3.20 < \mathrm{Im}(C_{\tau W})/\Lambda^2 < 3.20$ TeV^{-2}