Electromagnetic moments of the τ lepton with CMS

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NuFact, September 2024

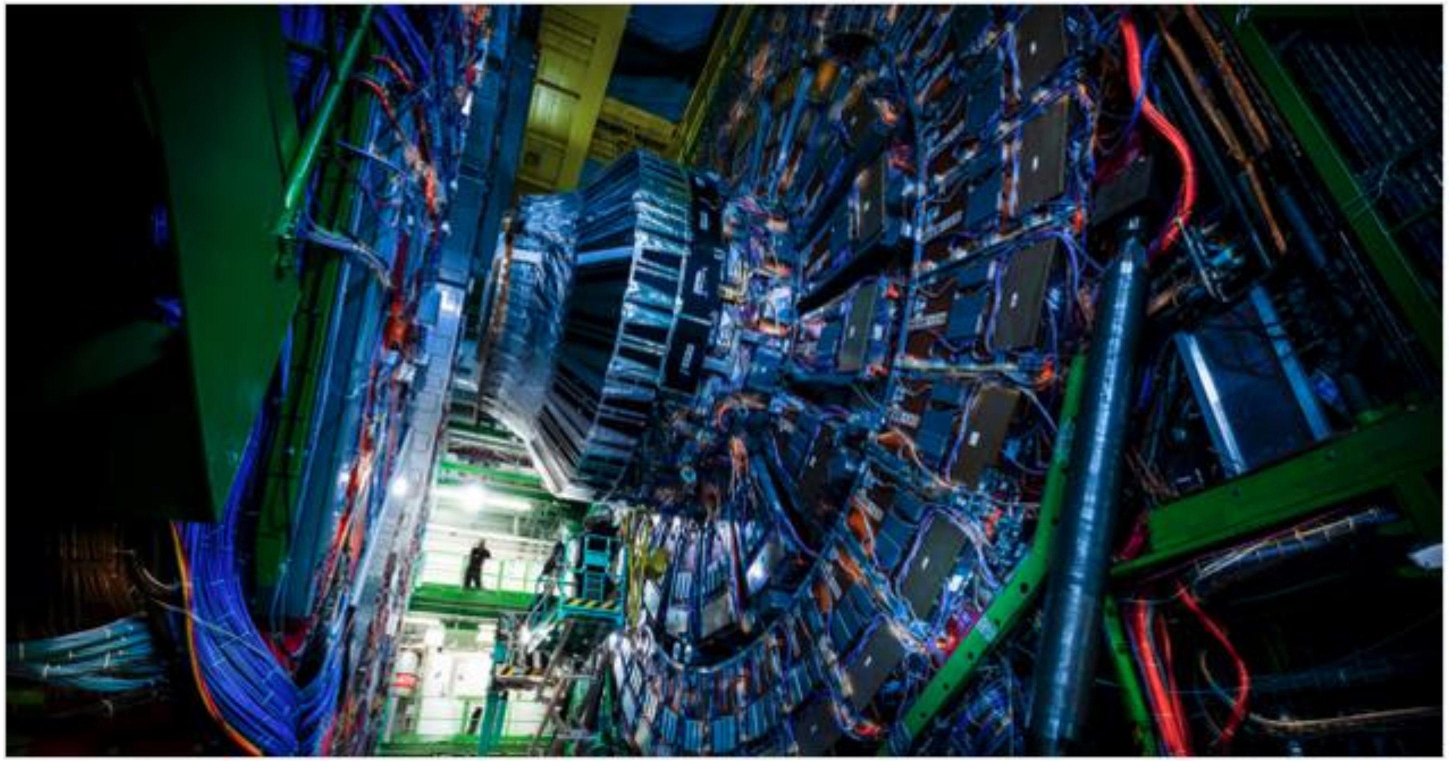
HIGGS AND ELECTROWEAK | NEWS

CMS closes in on tau g–2

19 March 2024

CERN Courier

A report from the CMS experiment



The CMS experiment. Credit: J Hosan / OPEN-PHO-LIFE-2019-022-5

The CMS collaboration has reported the first observation of $\gamma\gamma \rightarrow \tau\tau$ in pp collisions. The results set a new benchmark for the tau lepton's magnetic moment, surpassing previous constraints and paving the way for studies probing new physics.

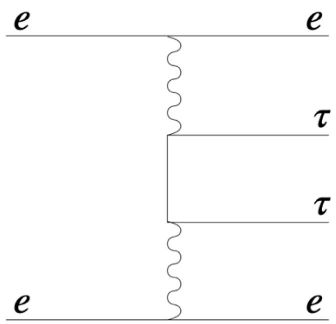
τ g-2 less well known than e and μ g-2…

- Tau leptons have a **very short lifetime** and cannot be stored in storage rings

$\mu_\tau/(e\hbar/2m_\tau)-1 = (g_\tau-2)/2$

For a theoretical calculation $[(g_\tau-2)/2 = 117\,721(5) \times 10^{-8}]$, see EIDELMAN 07.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
> -0.052 and < 0.013 (CL = 95%) OUR LIMIT					
> -0.052 and < 0.013	95	[1] ABDALLAH	04K	DLPH	$e^+e^- \to e^+e^-\tau^+\tau^-$ at LEP2

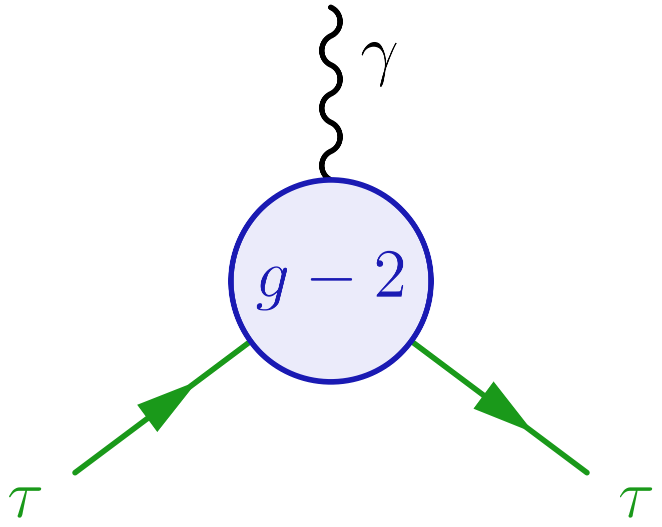


- Limit from PDG dates back 20 years (LEP) and is about 20 times the Schwinger term
- Many **orders of magnitude less precise** than e and μ g-2 measurements!

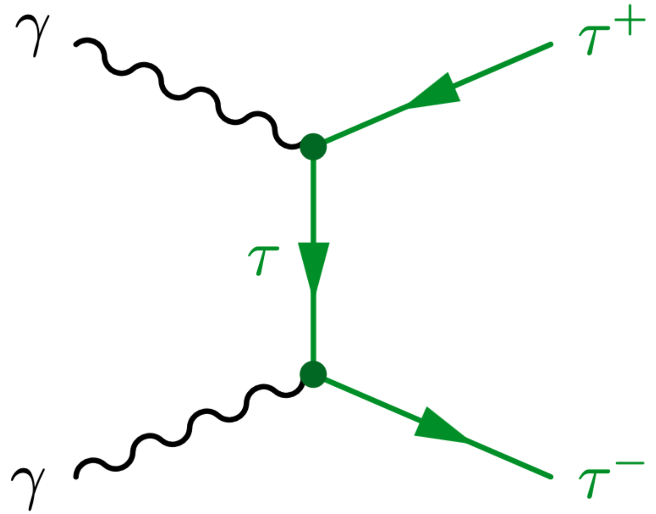
- If BSM effects scale with the squared lepton mass (m_ℓ^2), deviations from the SM could be 280 times larger than for a_μ

At the LHC: τ moments from $\gamma\gamma \rightarrow \tau\tau$ events

- τ g-2 can be indirectly probed from $\gamma\tau\tau$ vertex

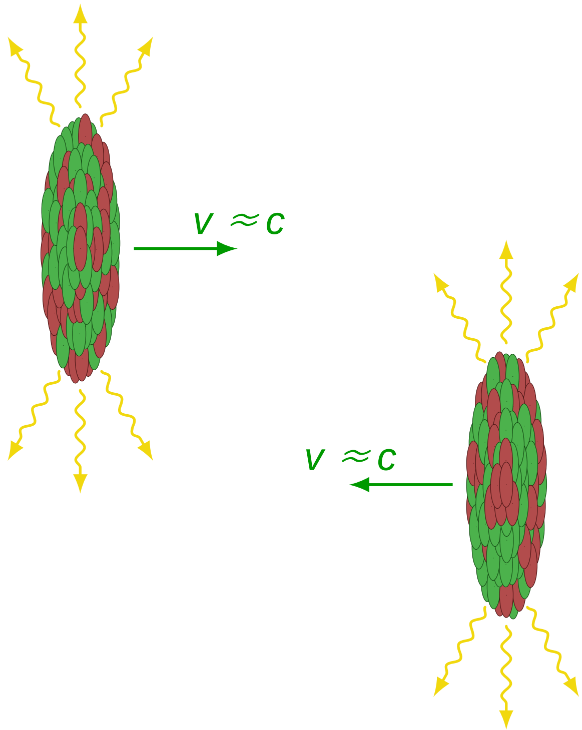


- Photon-induced processes: $\gamma\gamma \rightarrow \tau\tau$ includes 2 $\gamma\tau\tau$ vertices



- Constraints on τ electromagnetic moments from effective field theory approach (SMEFT) based on (differential) cross section measurement of $\gamma\gamma \rightarrow \tau\tau$

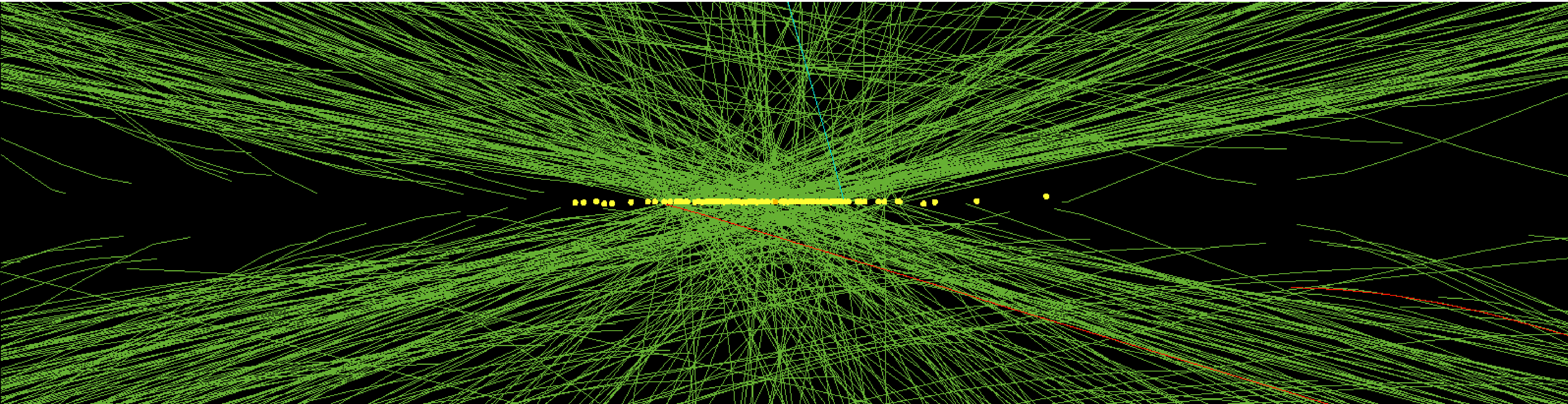
Photon-induced processes at the LHC



- Two charged particles (e.g. protons or ions) passing each other at relativistic velocities generate intense electromagnetic fields → **photon-photon collisions** can happen
- Typically study "head-on" collisions but rare photon-induced processes can be studied in ultraperipheral collisions
- Protons losing some of their energy to the photons are slightly deflected
- **Cross section proportional to Z^4** → huge enhancement of photon-induced processes in Pb-Pb (Z = 82) runs compared to pp runs

pp collisions with track counting

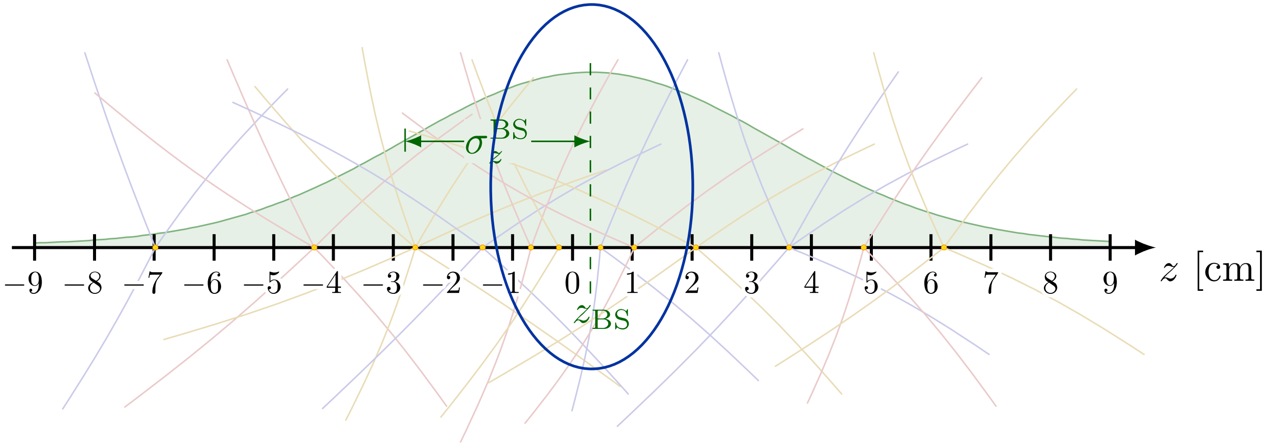
- If energy too low for protons to be in PPS acceptance, the only way to identify photon-induced processes is through a **vertex with very little track activity**
- Photon-induced processes are exceptionally clean but proton-proton collisions are incredibly busy → challenging to identify a vertex among all pileup interactions



Counting tracks

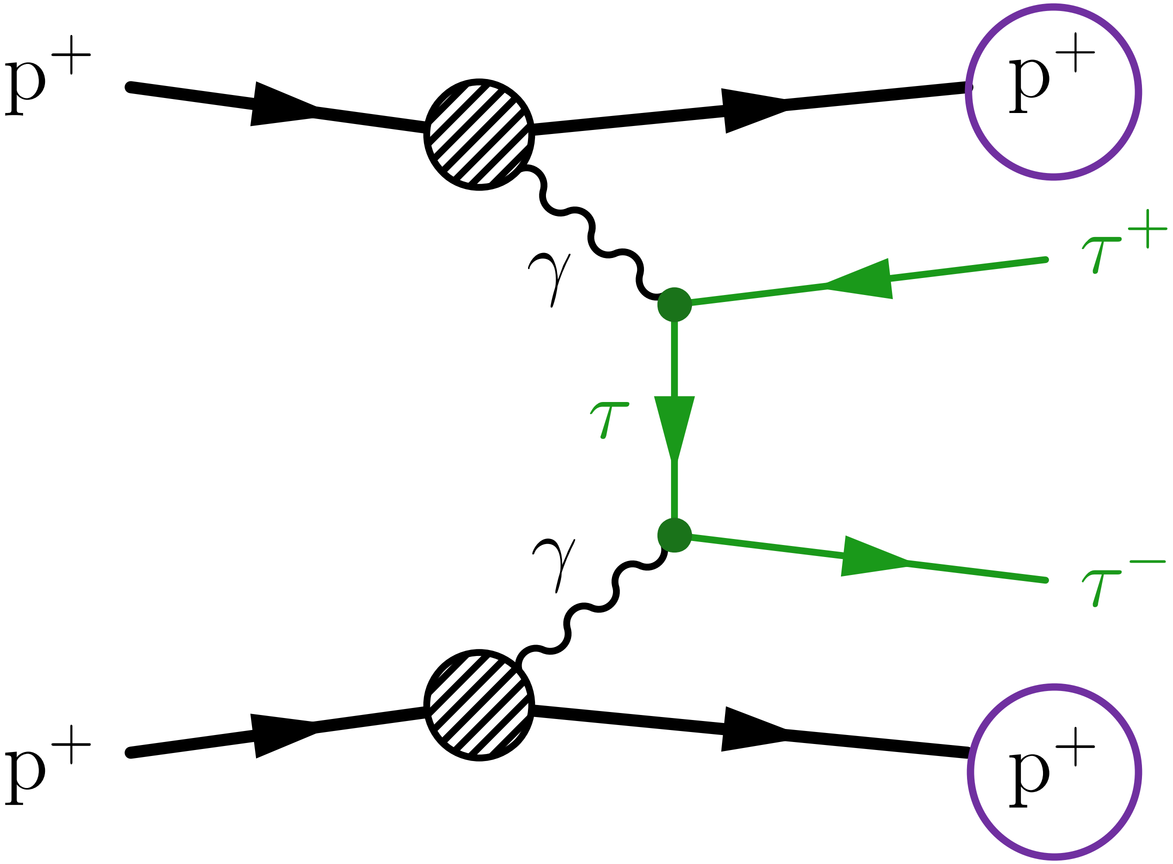
- Define **z position of di-tau vertex** as average z position of selected tau leptons
- Define $\mathbf{N_{tracks}}$ as the number of tracks
  - with $p_T > 0.5$ GeV and $|\eta| < 2.5$
  - within a window of **0.1 cm** around the di-tau vertex
  - Excluding tracks from tau leptons

Simulations cannot model track multiplicity accurately → correct them using data



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

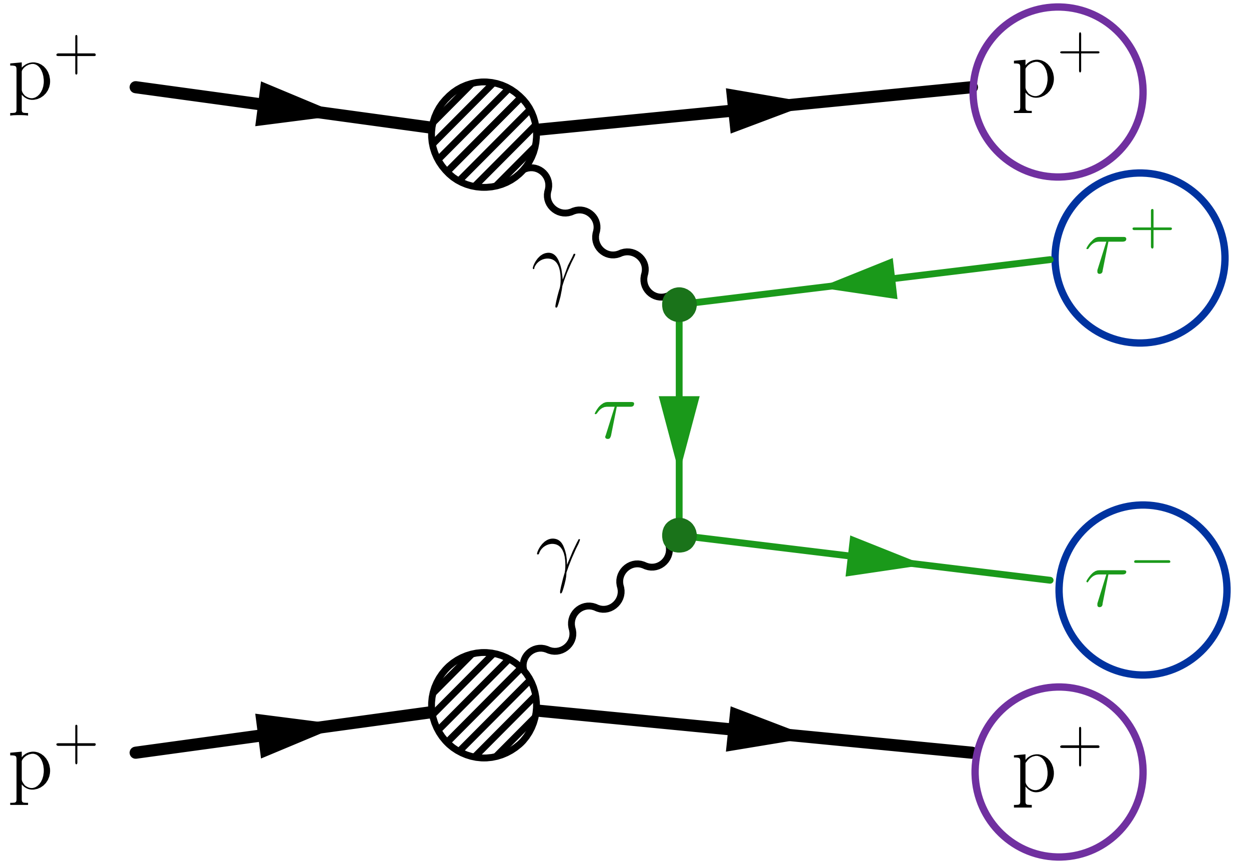
Signature



- 2 diffracted protons
  - Could be reconstructed in PPS 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

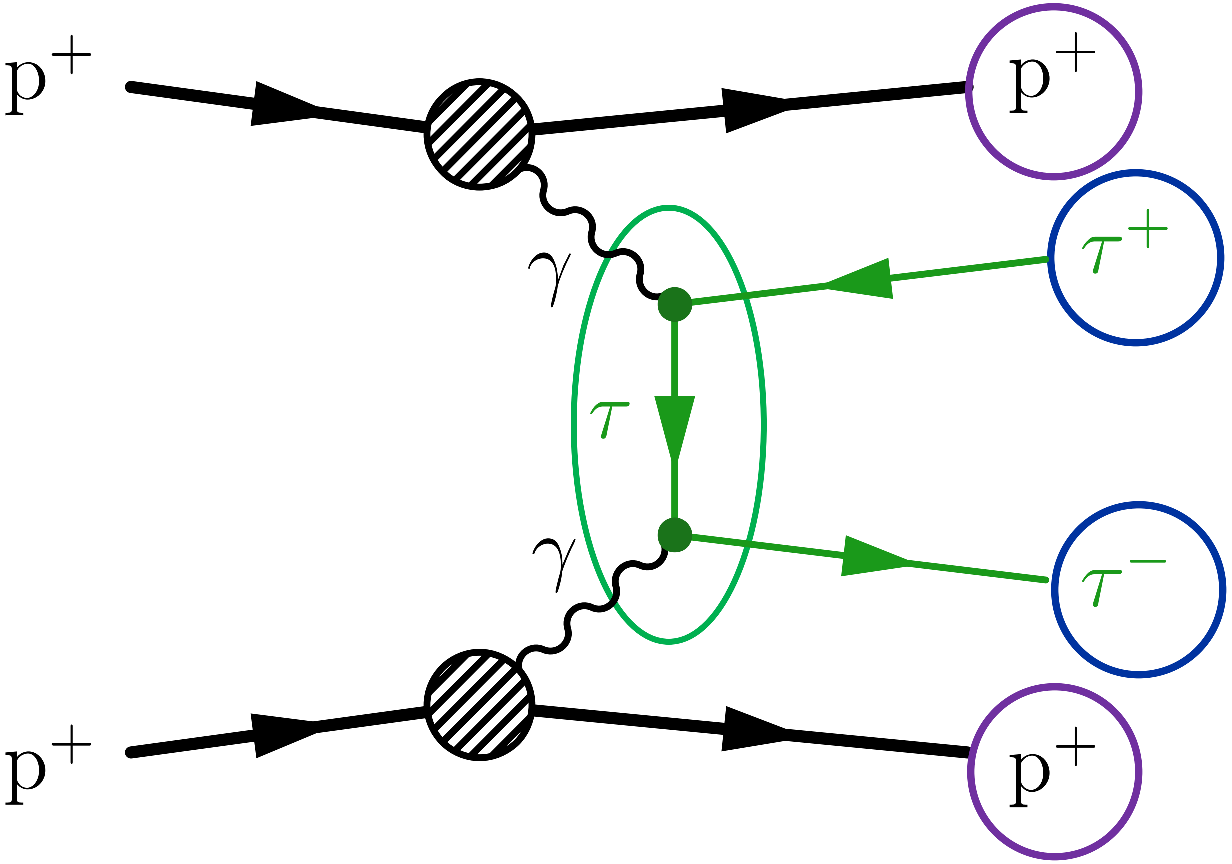
Signature



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

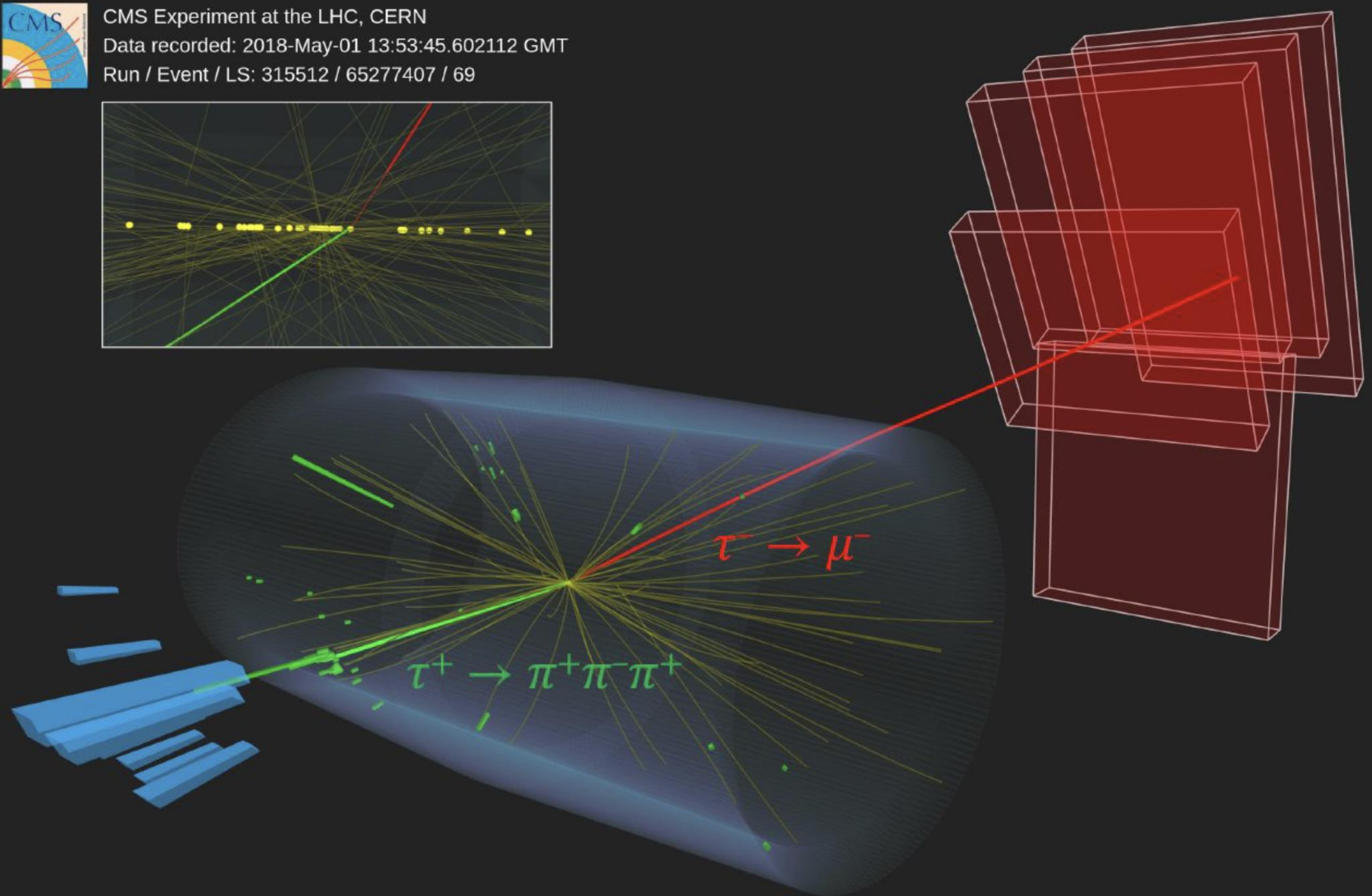
Elastic process, protons do not dissociate

Signature

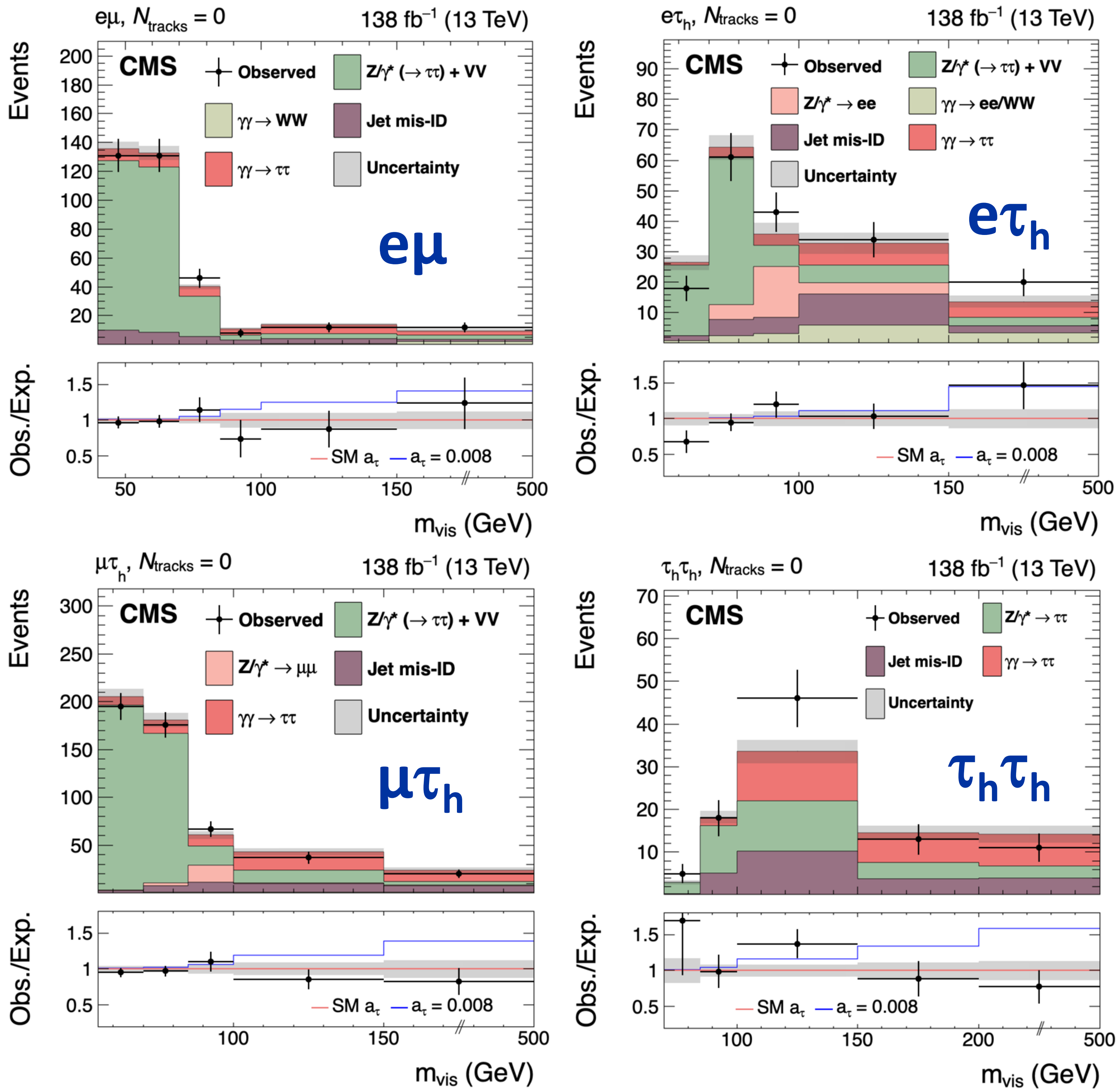


- 2 diffracted protons
- 2 back-to-back OS τ leptons
- No hadronic activity close to the di-τ vertex
  - $N_{tracks} = 0$

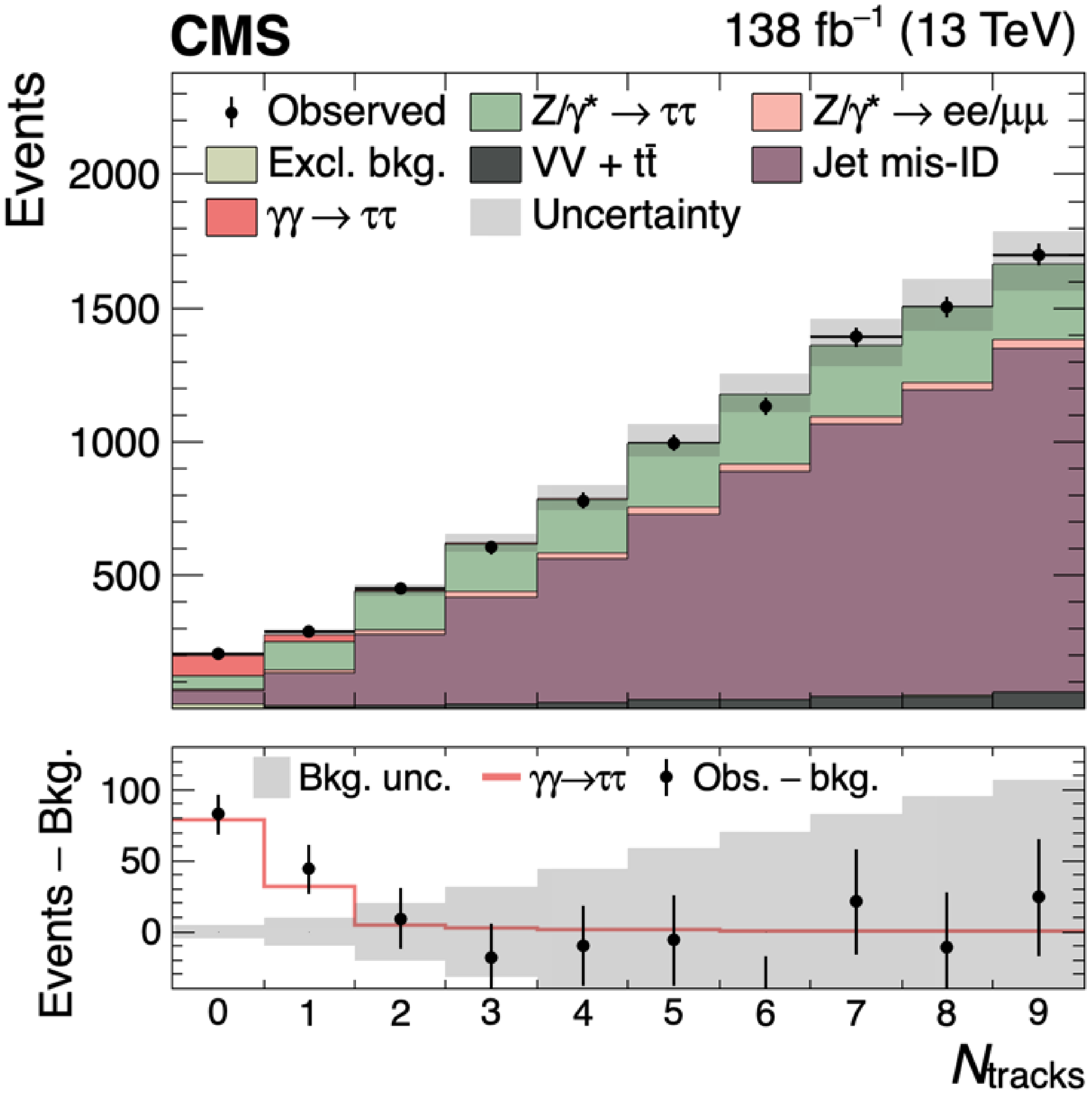
Elastic process, protons do not dissociate


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

$N_{tracks} = 0$



- 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**
  - **5.3 σ observed, 6.5 σ expected**
- **First observation of γγ→ττ in pp collisions**



- N_{tracks} distribution for events with 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}**

Constraining τ g-2 with an effective field theory

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

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

- BSM contributions to a_τ:

SMEFT-sim_general alphaScheme_UFO

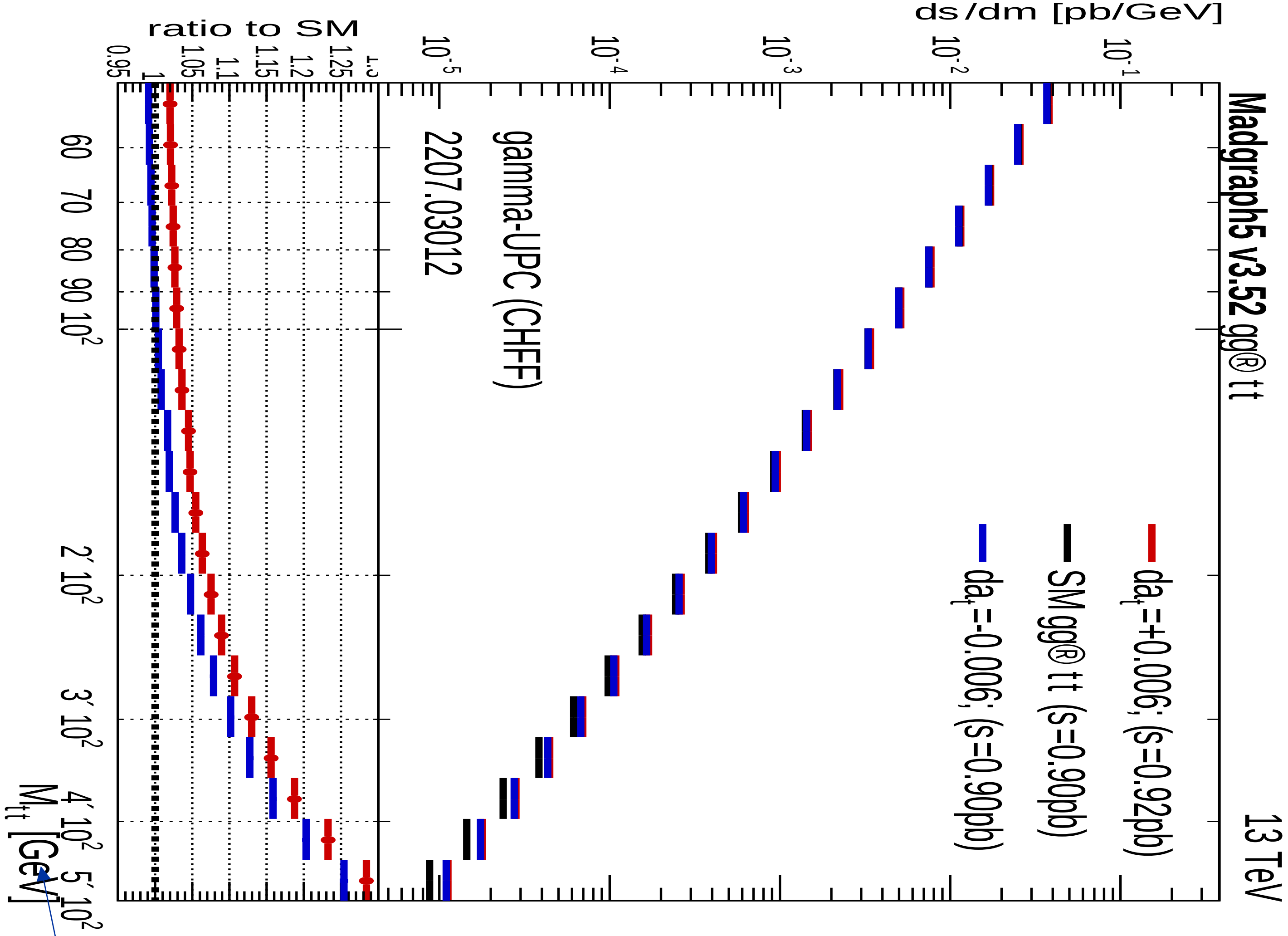
$$\delta a_\tau = \frac{2m_\tau}{e} \frac{\sqrt{2}v}{\Lambda^2} \text{Re}\left[C_{\tau\gamma}\right]$$

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

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

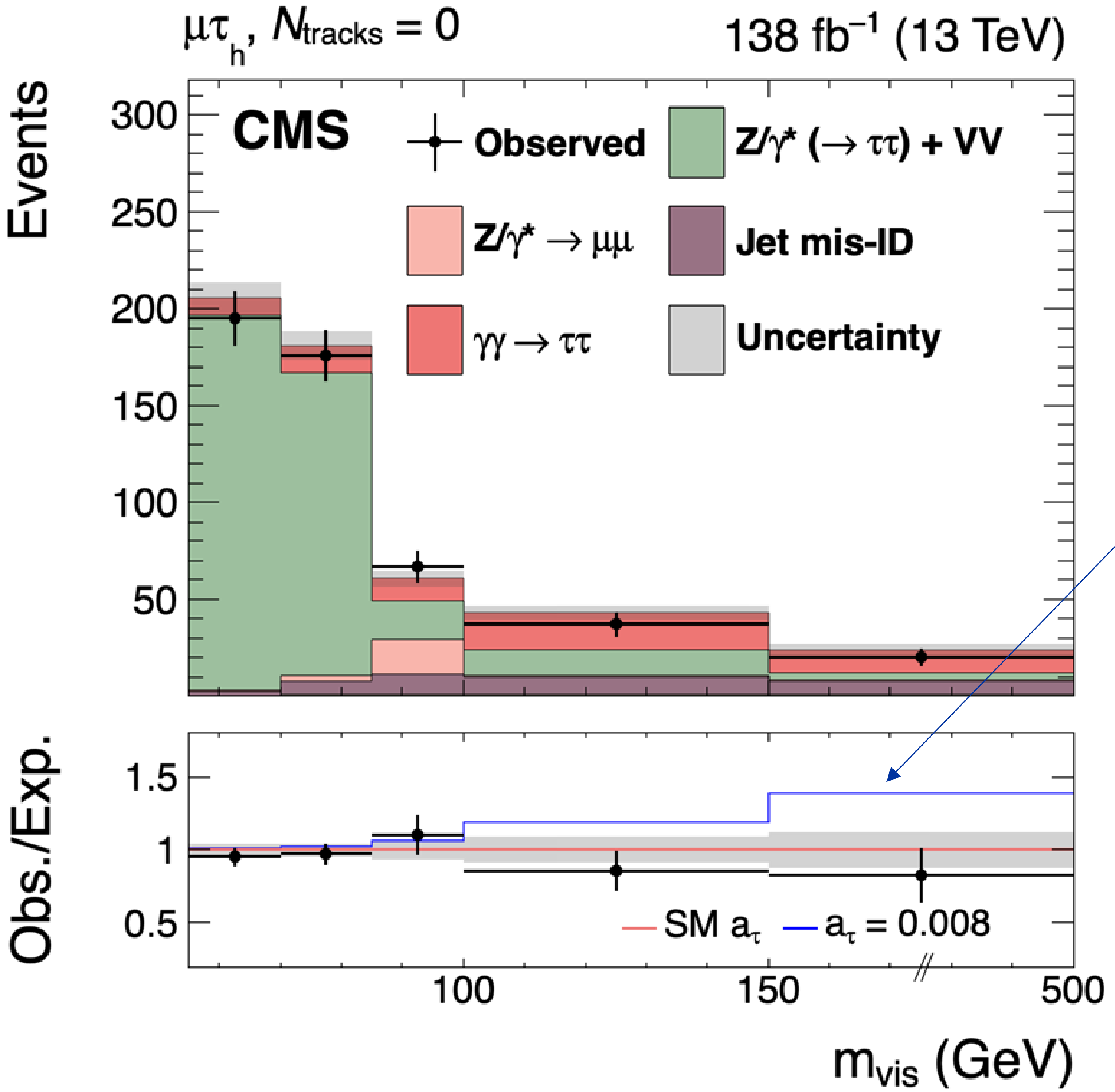
- At large $m_{\tau\tau}$, $\gamma\gamma \rightarrow \tau\tau$ cross section increases with both positive and negative variations to a_τ
- The effect grows with $m_{\tau\tau}$

- **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



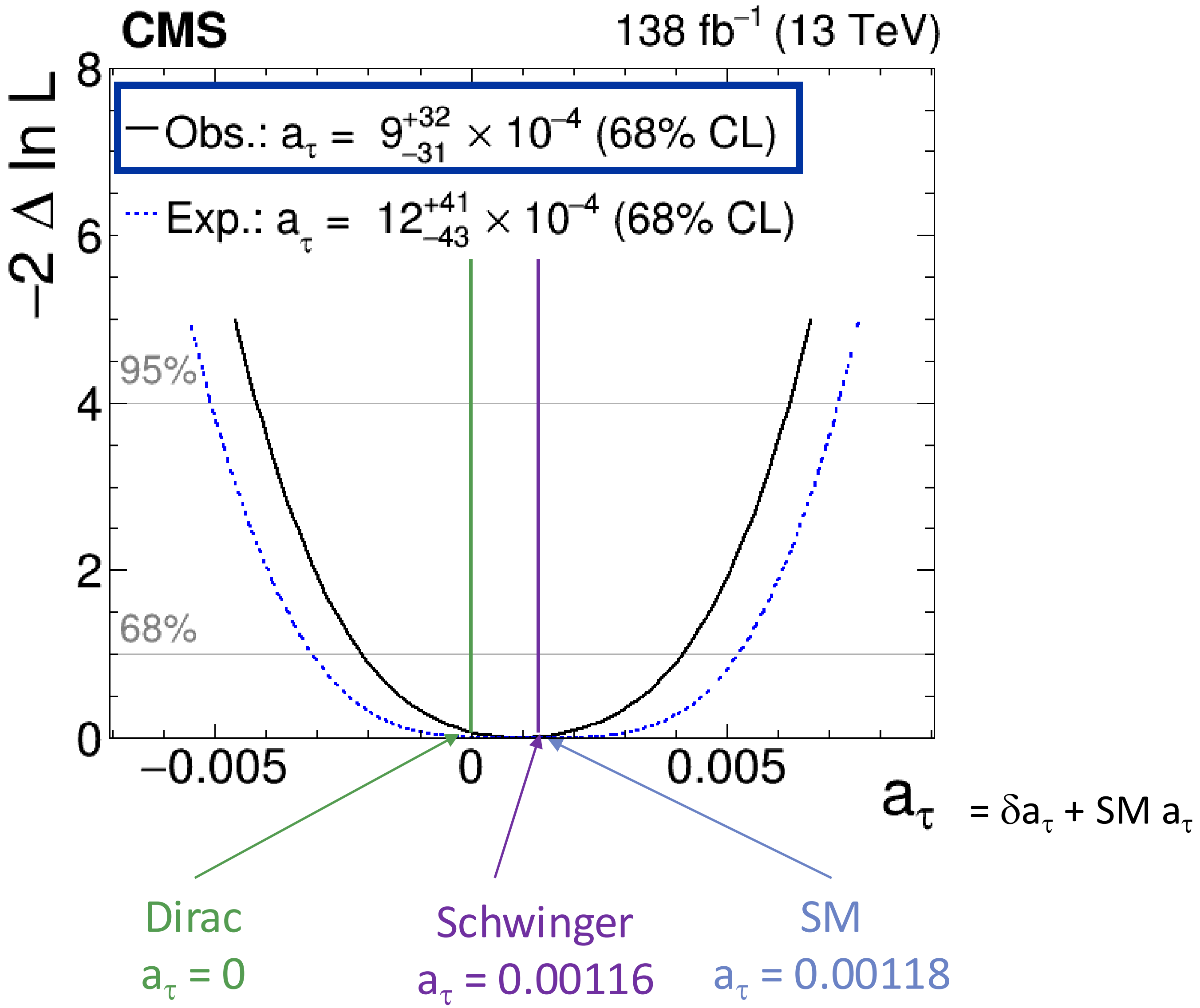
PbPb analyses sensitive to low $m_{\tau\tau}$ range

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 $\gamma\gamma \rightarrow \tau\tau$

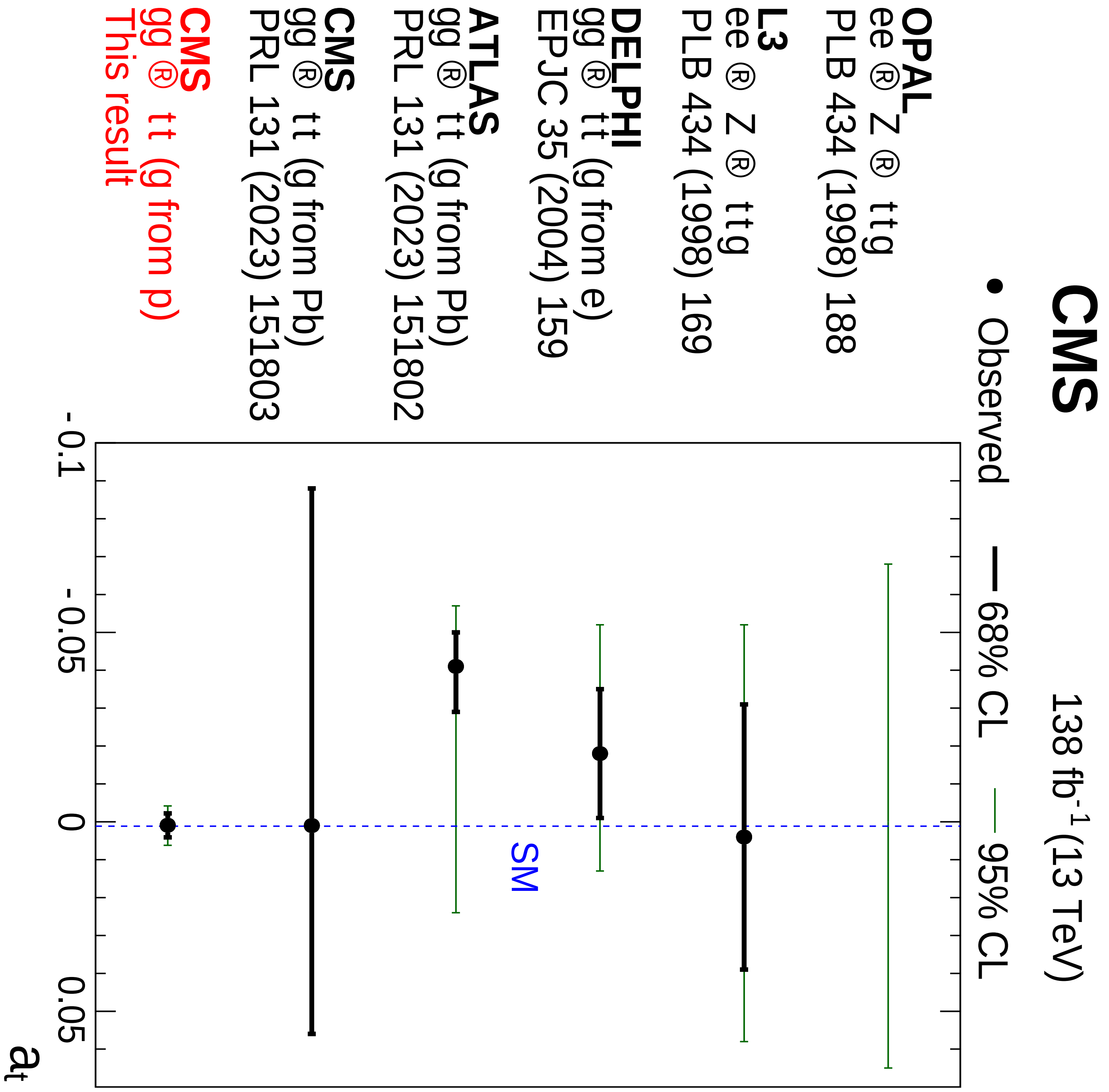
Extracting a_τ



1σ uncertainty of 0.003

Only 3 times the Schwinger term!

Comparing to previous results



Large improvement over LEP and LHC Pb-Pb

Conclusion

- **The LHC is also a high energy photon collider**
- The CMS experiment can indirectly probe the τ g-2 in photon-induced collisions ($\gamma\gamma \rightarrow \tau\tau$) both in PbPb and pp runs

- **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 g-2: $-0.0042 < a_\tau < 0.0062$ at 95% CL, **improving previous constraints on tau g-2 by almost an order of magnitude**

More info in arXiv:2406.03975 (Rep. Prog. Phys. **87** 107801)

Backup

The precision journey has just started…

DELPHI

OPAL

Pb-Pb LHC

CMS pp

Approaching the

Schwinger term!

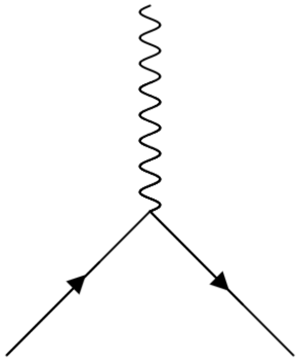
More precision needed to

probe BSM effects scaling

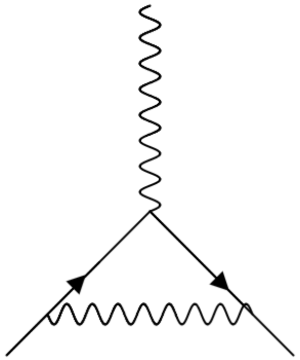
with m_ℓ^2…

τ g-2 precision

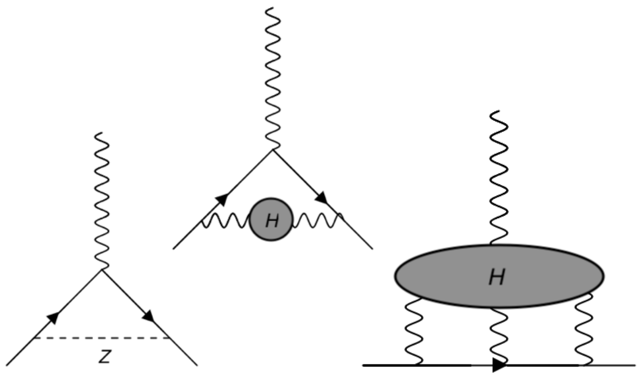
Dirac



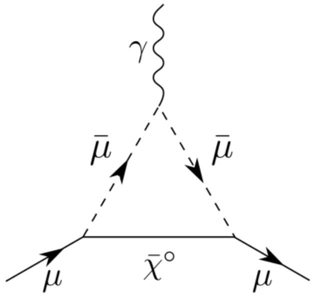
Schwinger term



Higher-order corrections

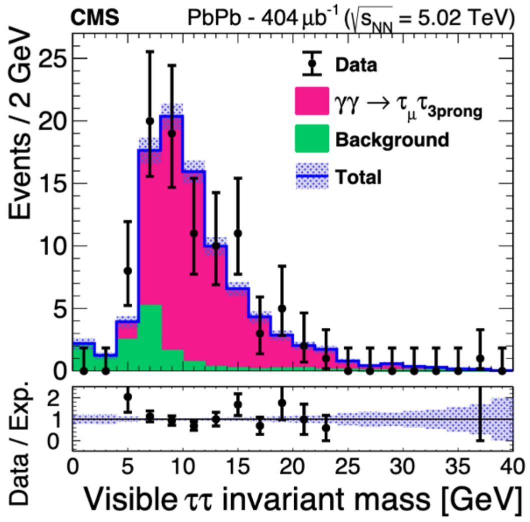


BSM effects?

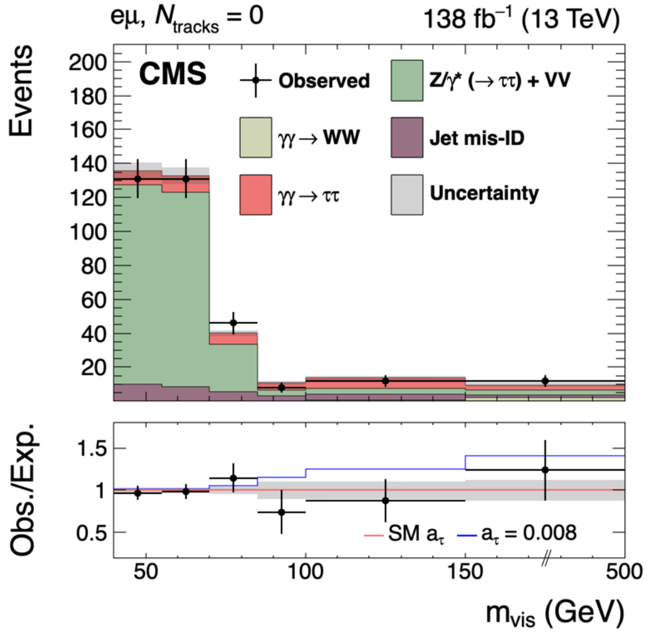


… and CMS will be a part of it

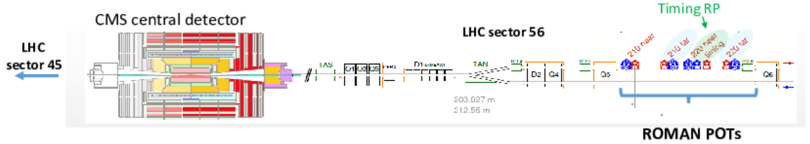
- Heavy ion runs



- pp runs with track counting



- pp runs with proton tagging



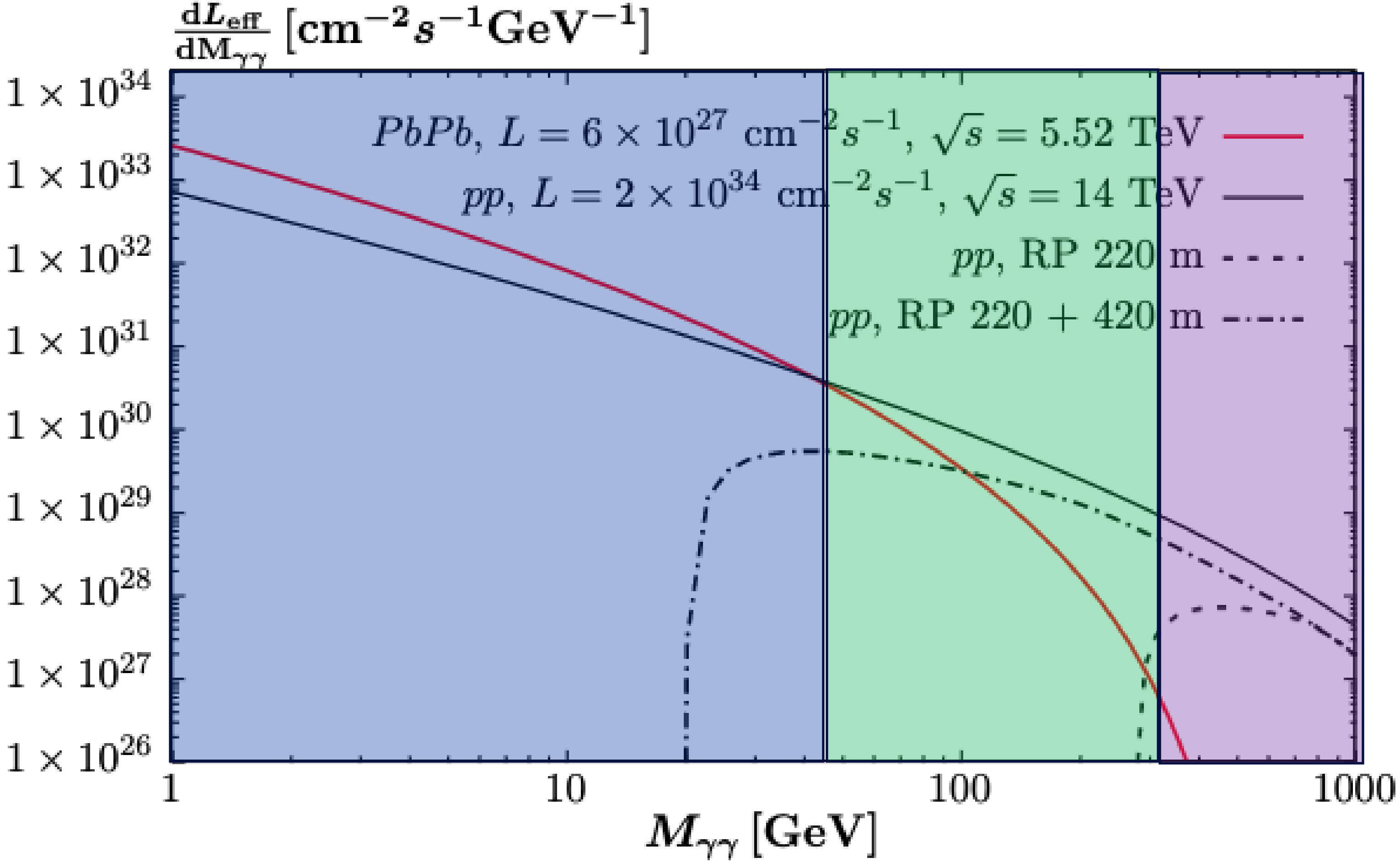
PPS approved for Run-4

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

The LHC is (also) a photon collider

arXiv:1812.07688

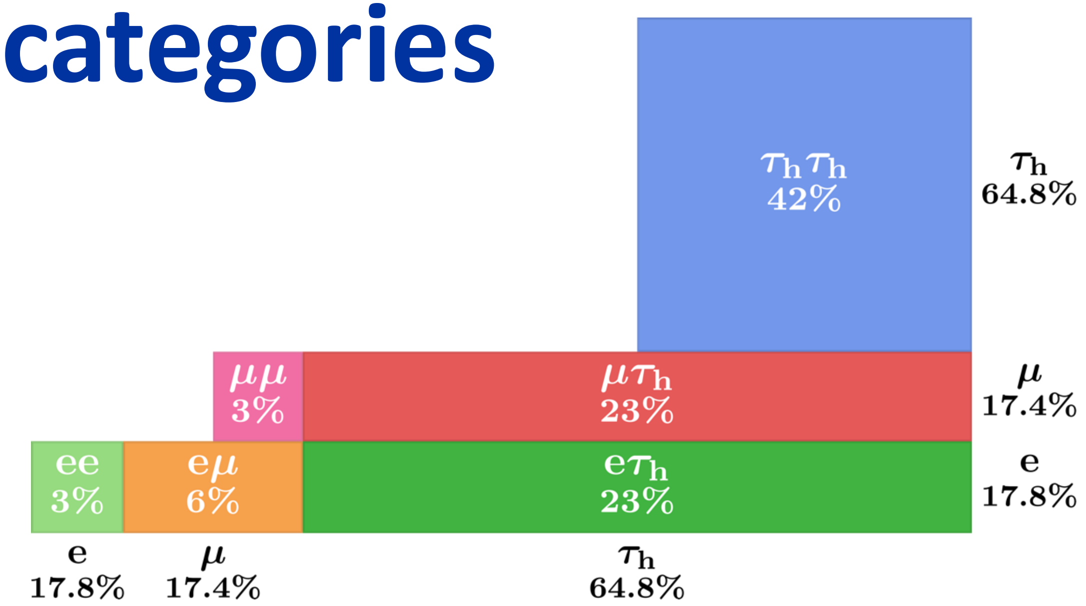
At low masses, PbPb runs have the largest effective $\gamma\gamma$ luminosity



At very high masses, diffracted protons can be tagged by forward detectors

At intermediate masses, pp takes over but need to handle pileup

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

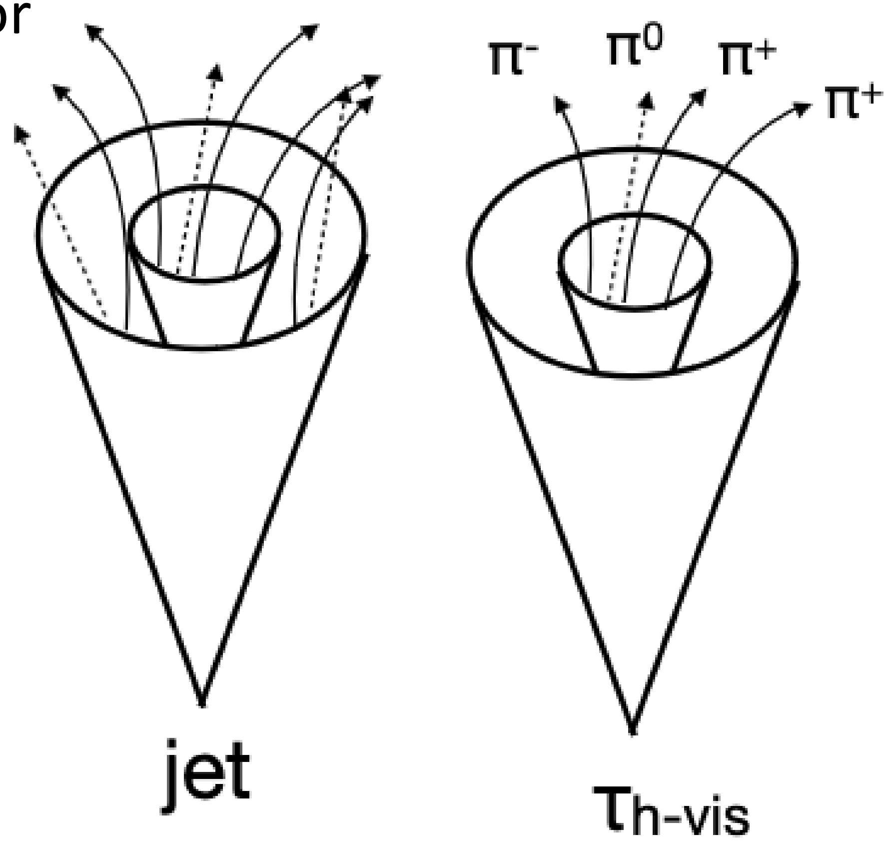
- Dimuon control region to derive corrections to the simulations

Dominant backgrounds

- **$Z/\gamma^* \rightarrow \tau\tau$ (Drell-Yan)**
  - Same final state as the signal but more tracks at the vertex (from hard scattering)
  - Resonant ditau production → ditau mass peaks at Z mass
  - Taus are rather back-to-back (low acoplanarity) but less so than for the signal
  - Estimated from simulation with data-driven corrections
- **Jet mis-ID (QCD, W+jets, …):**
  - When a jet is misreconstructed as a tau
  - Data-driven estimation (no reliable MC prediction)
  - Nonresonant, mass distribution similar to that of the signal

Jets misidentified as τ_h

- Hadronically decaying taus (τ_h) are reconstructed as 1 or 3 tracks with energy deposits in the calorimeters
- Typically look like quark- and gluon-jets
- Main handles to separate τ_h and jets:
  - τ_h are **more isolated** (less activity around)
  - τ_h are **slightly displaced** (from τ lifetime)
- Information used in a neural net



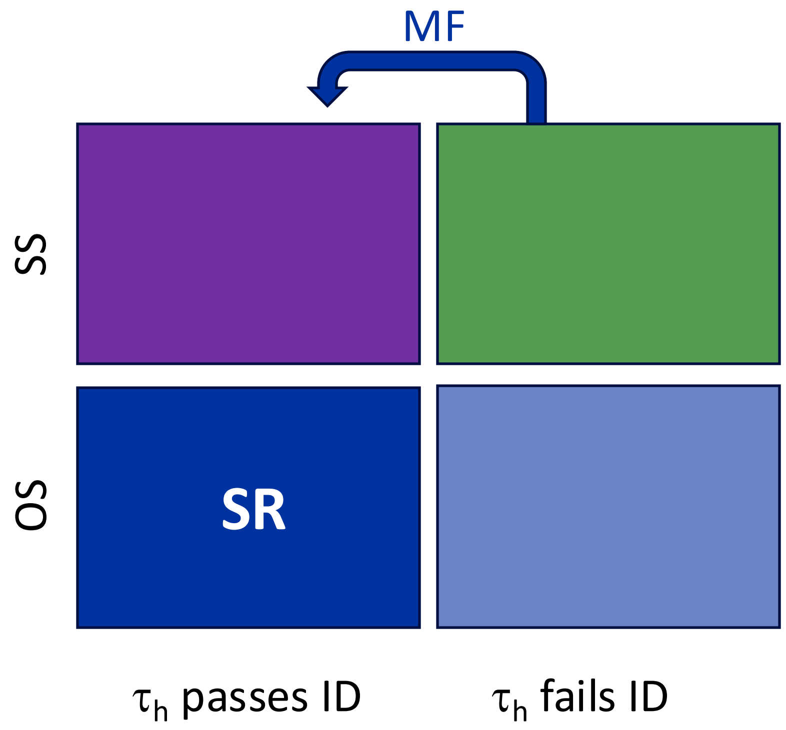
Jet→τ_h mis-ID background (1)

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

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

  - 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



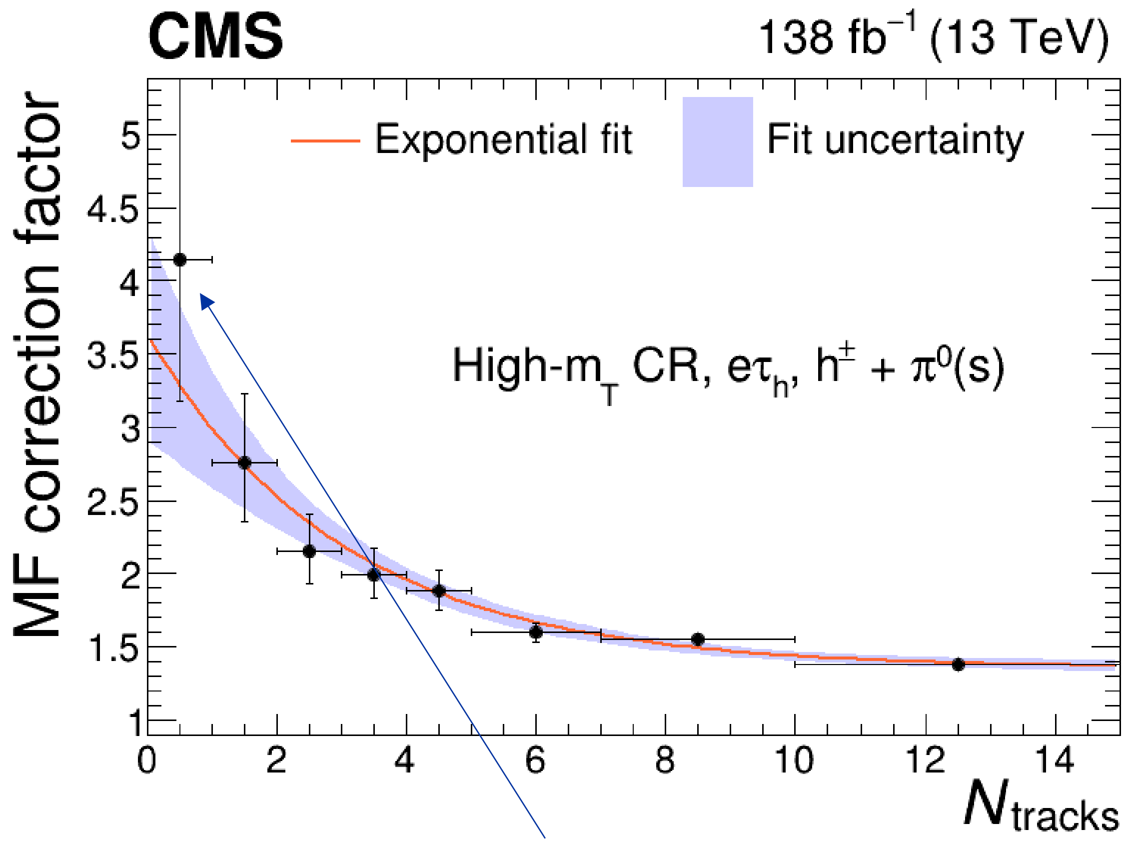
But it is not that simple…

How does N_{tracks} affect MF?

Jet→τ_h mis-ID background (2)

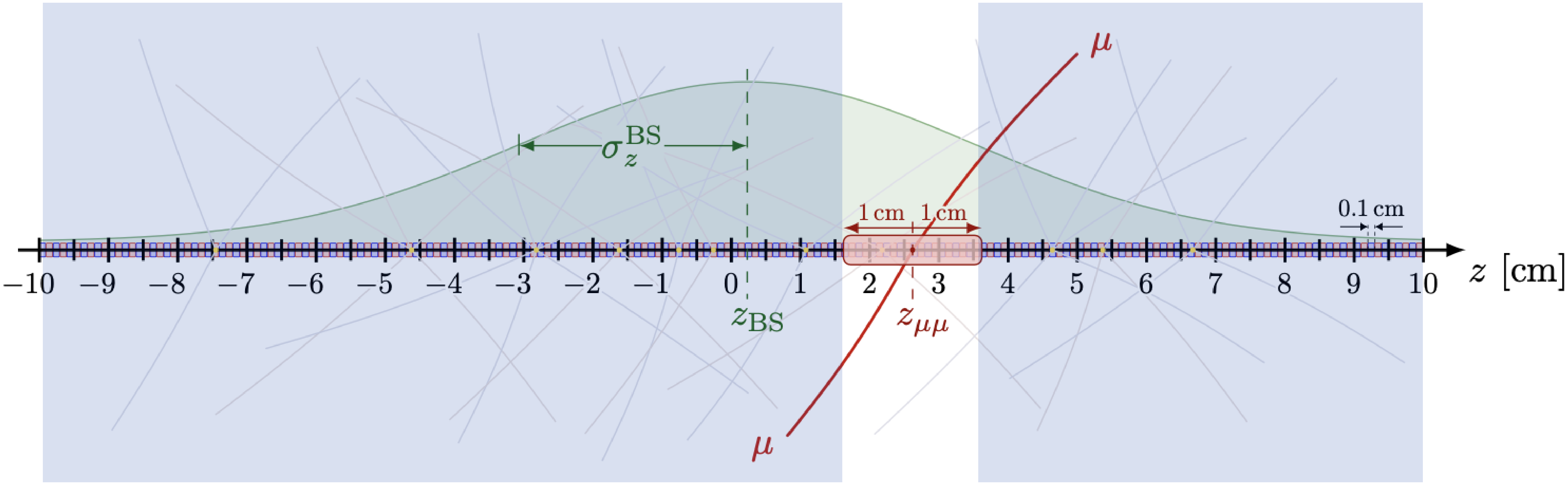
- If there is less track activity around the τ_h candidate:
  - The τ_h candidate is more isolated
  - It is more likely to pass the ID criteria
  - MF is higher

- Model N_{tracks} dependence with a multiplicative correction to the mis-ID rates
  - Parameterized with exponential at low N_{tracks}



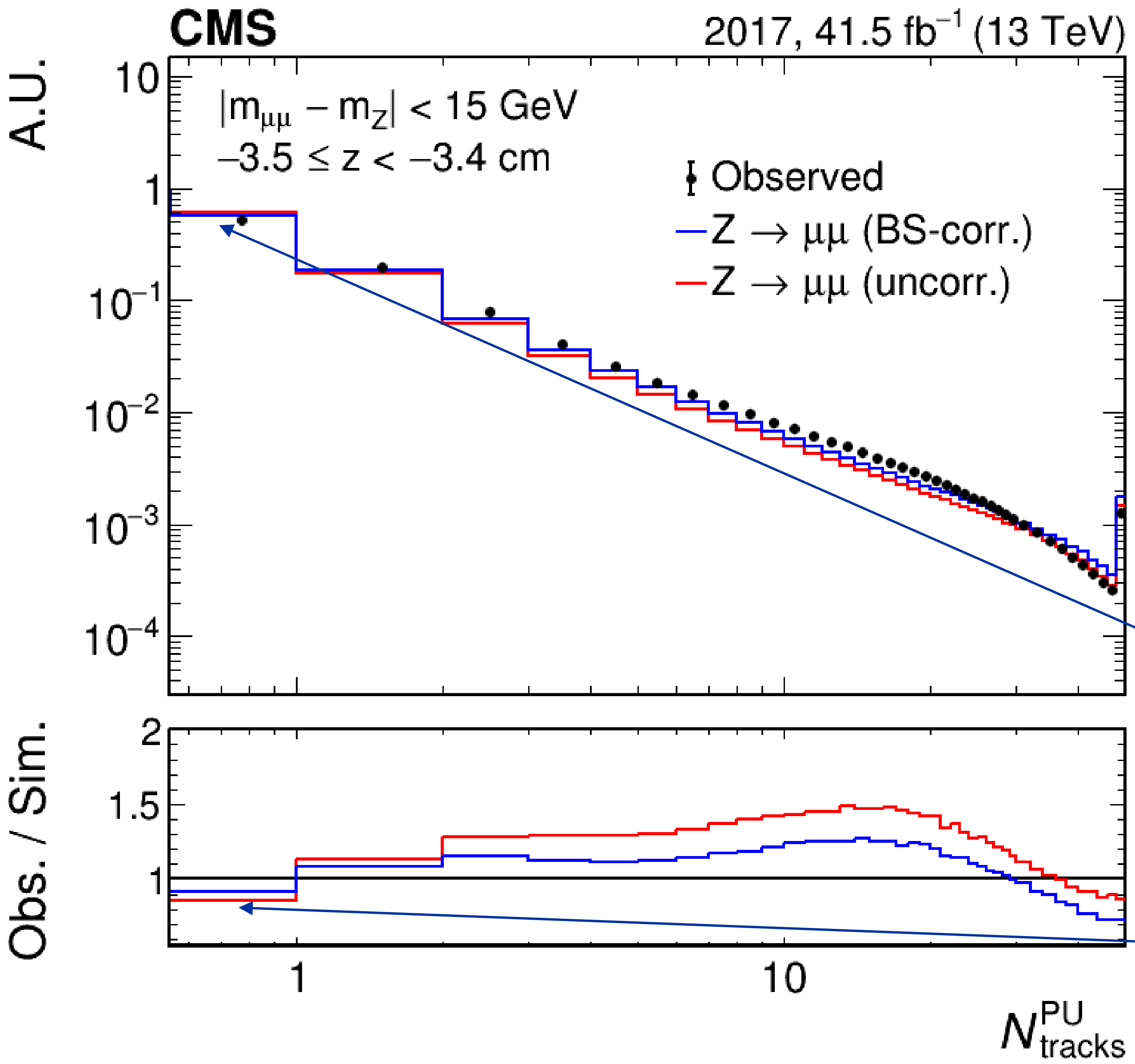
The jet is 4 times more likely to pass the nominal τ_h ID criteria if there is no other track at the vertex

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

Pileup track multiplicity correction

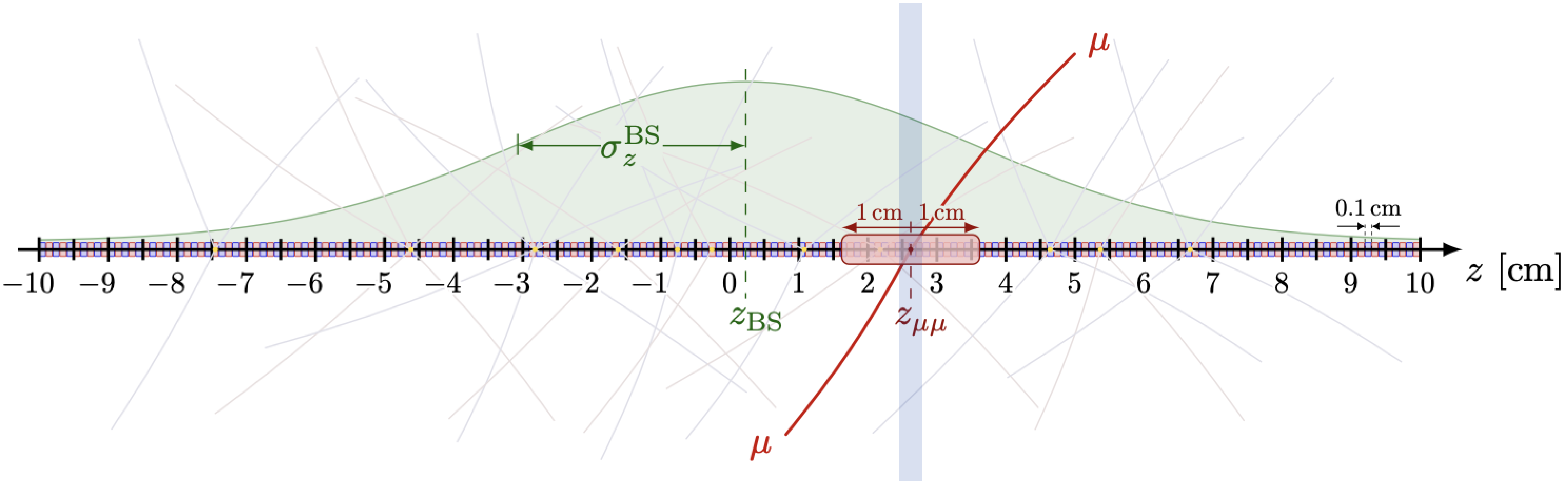


- Correction derived as a function of N_{tracks} and z

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

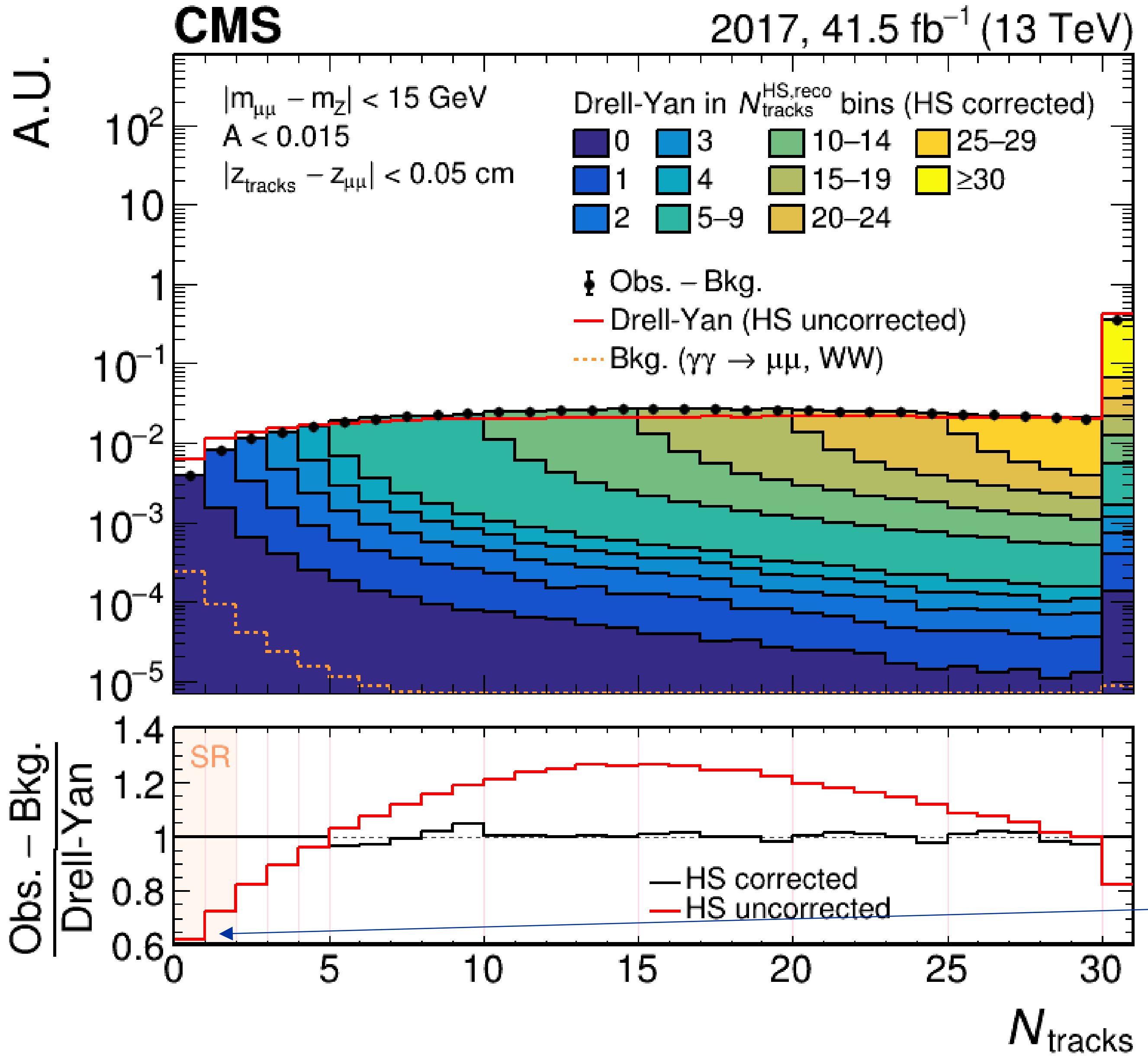
For a window 1 beamspot width away from beamspot center with no PU track inside, the event-weight correction is 0.95

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

Hard scattering track multiplicity correction

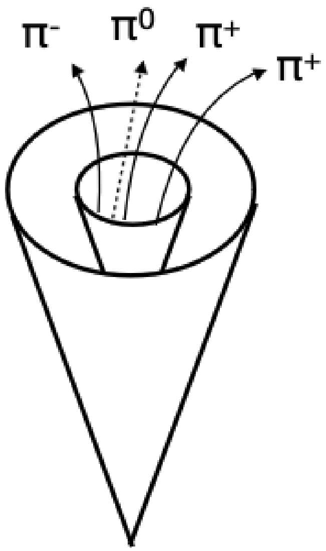


- Compare number of reconstructed tracks in data and in DY simulation at the μμ vertex
- These tracks can come from pileup or from the hard interaction
- Split simulation based on the number of reconstructed tracks associated to the hard interaction, and rescale all components simultaneously to match 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 ˜0.6

Interlude: τ decay and reconstuction

- **Leptonic τ decays (˜35%):** 1 electron or 1 muon + 2 neutrinos
  - Reconstructed as standard electrons and muons
- **Hadronic τ decays (τ_h, ˜65%):** 1 or 3 charged hadrons + sometimes p0s + 1 neutrino
  - Reconstructed as 1 or 3 tracks with energy deposits in the calorimeters
- Always missing energy in the detector from escaping neutrinos



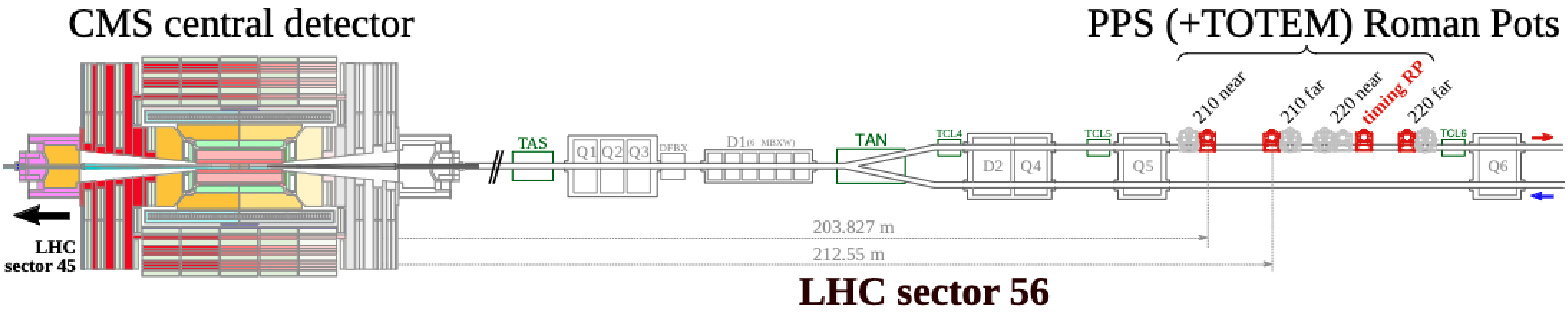
Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other modes with hadrons		3.2
All modes containing hadrons		64.8

1 prong ~47%

3 prongs ~15%

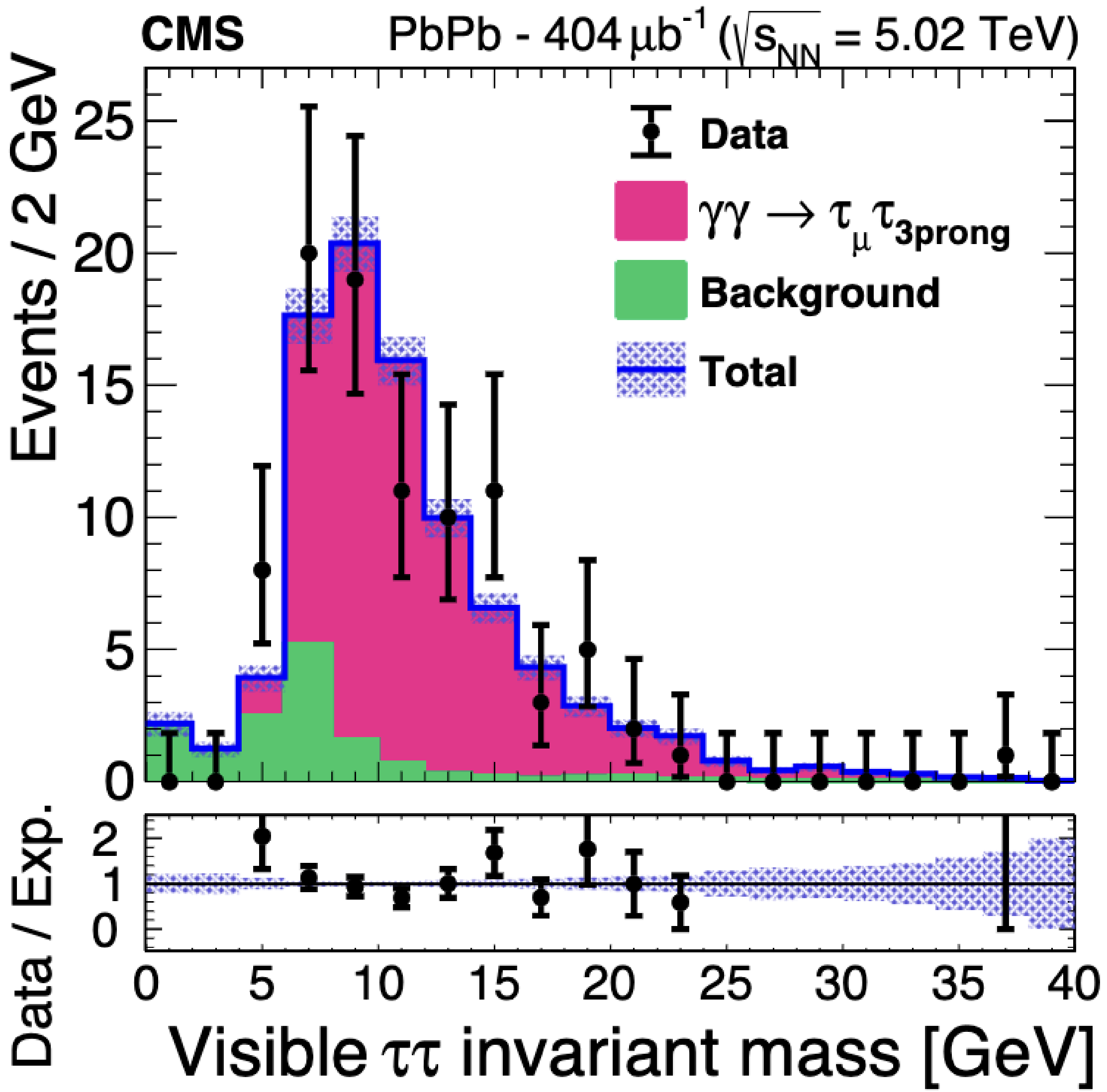
Analyses with τ leptons are difficult because of variety of possible decays, and large backgrounds mimicking τ signature

The high energy regime – pp collisions with proton tagging



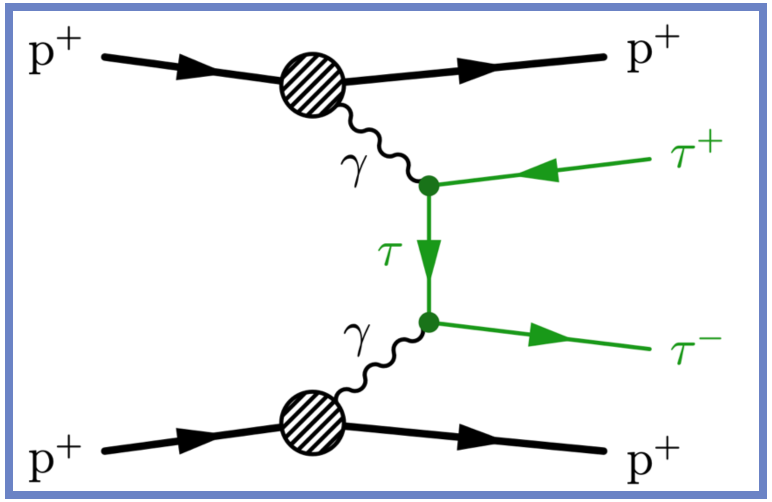
- PPS is a forward detector situated ~200 meters away from CMS (1 PPS arm on each side)
- Can tag diffracted protons that have lost a small fraction of their energy
- Proton kinematics (from PPS) correlated to kinematics of central system (from CMS) → powerful handle to reduce backgrounds

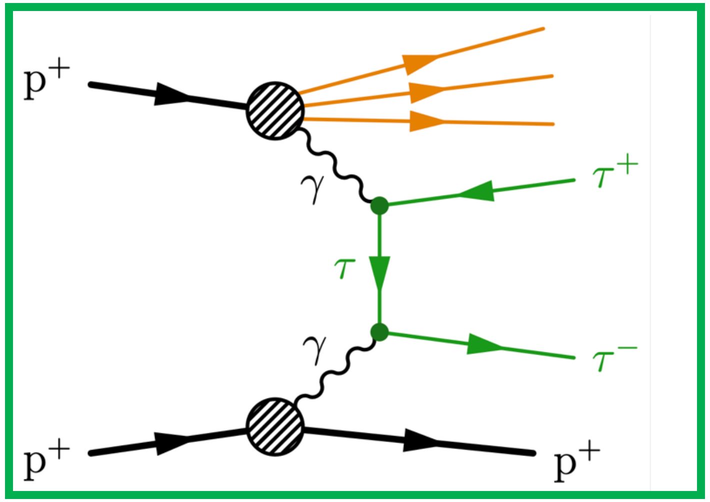
$\gamma\gamma \rightarrow \tau\tau$ in PbPb ultraperipheral collisions

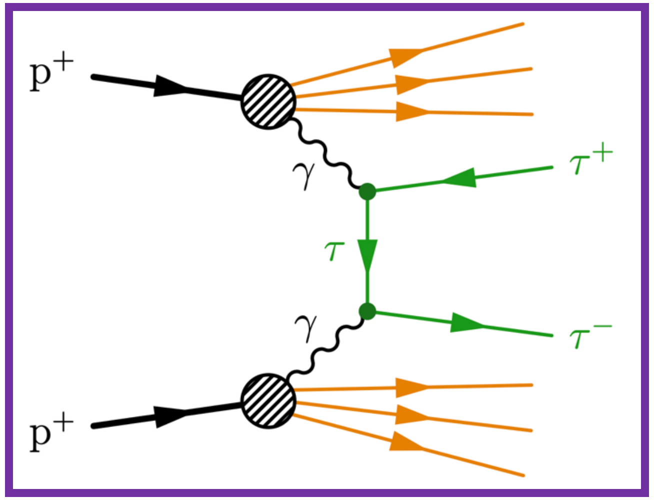


- $\gamma\gamma \rightarrow \tau\tau$ observed recently in Pb-Pb collisions by both CMS and ATLAS
- Clean channel with small background contributions
- Accessing phase space with $m_{\tau\tau} \lessapprox 25$ GeV

Including (semi-)dissociative contributions



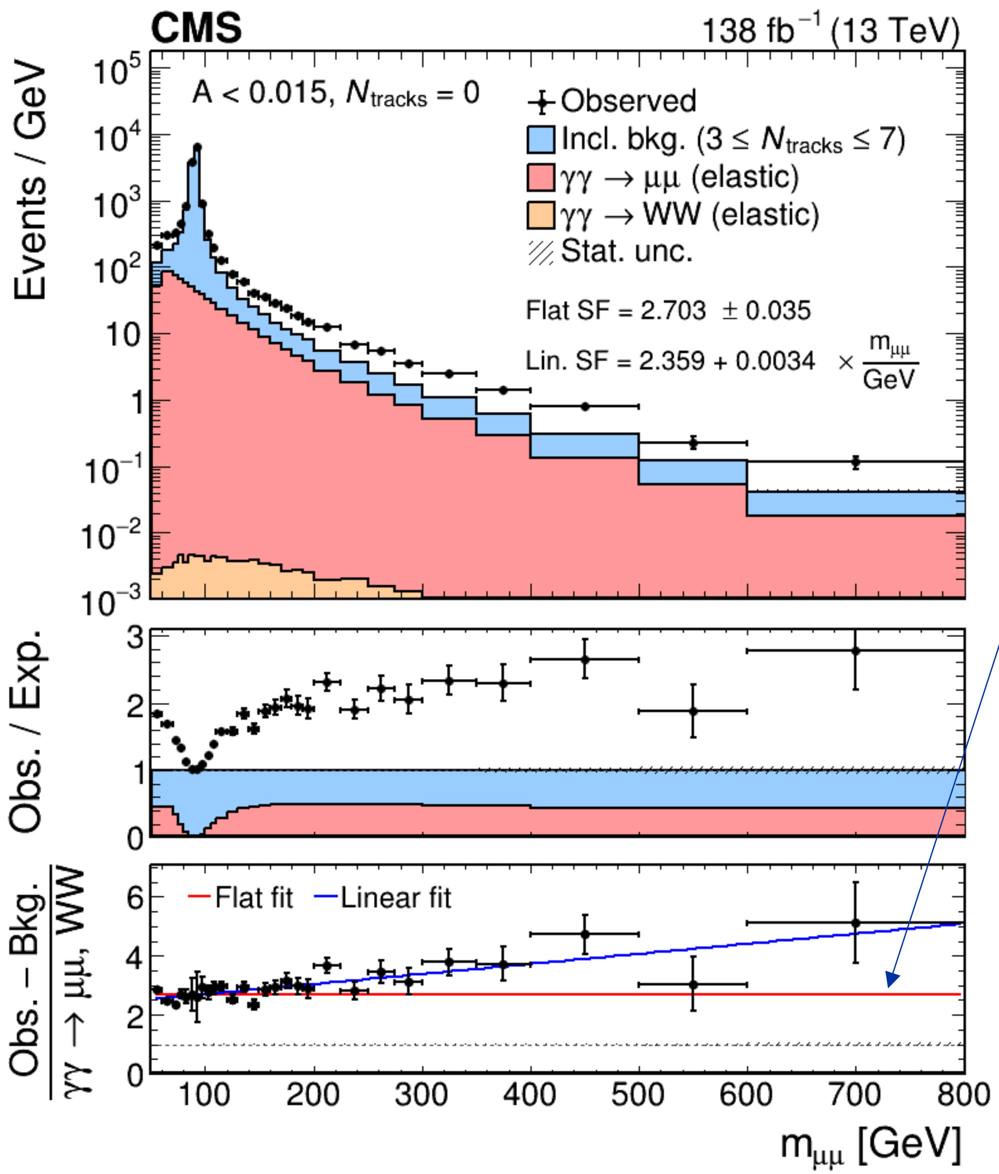




- **Elastic-elastic (ee)** signal process modeled with gammaUPC
- **Single-dissociative (sd)** and **double-dissociative (dd)** processes have larger cross section and may end up with an exclusive signature → rescale elastic signal to include these contributions
- Scaling factor = $(ee + sd + dd)_{obs}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

Including (semi-)dissociative contributions

- **Elastic $\gamma\gamma \rightarrow \mu\mu$/WW:**
  - Estimated with 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

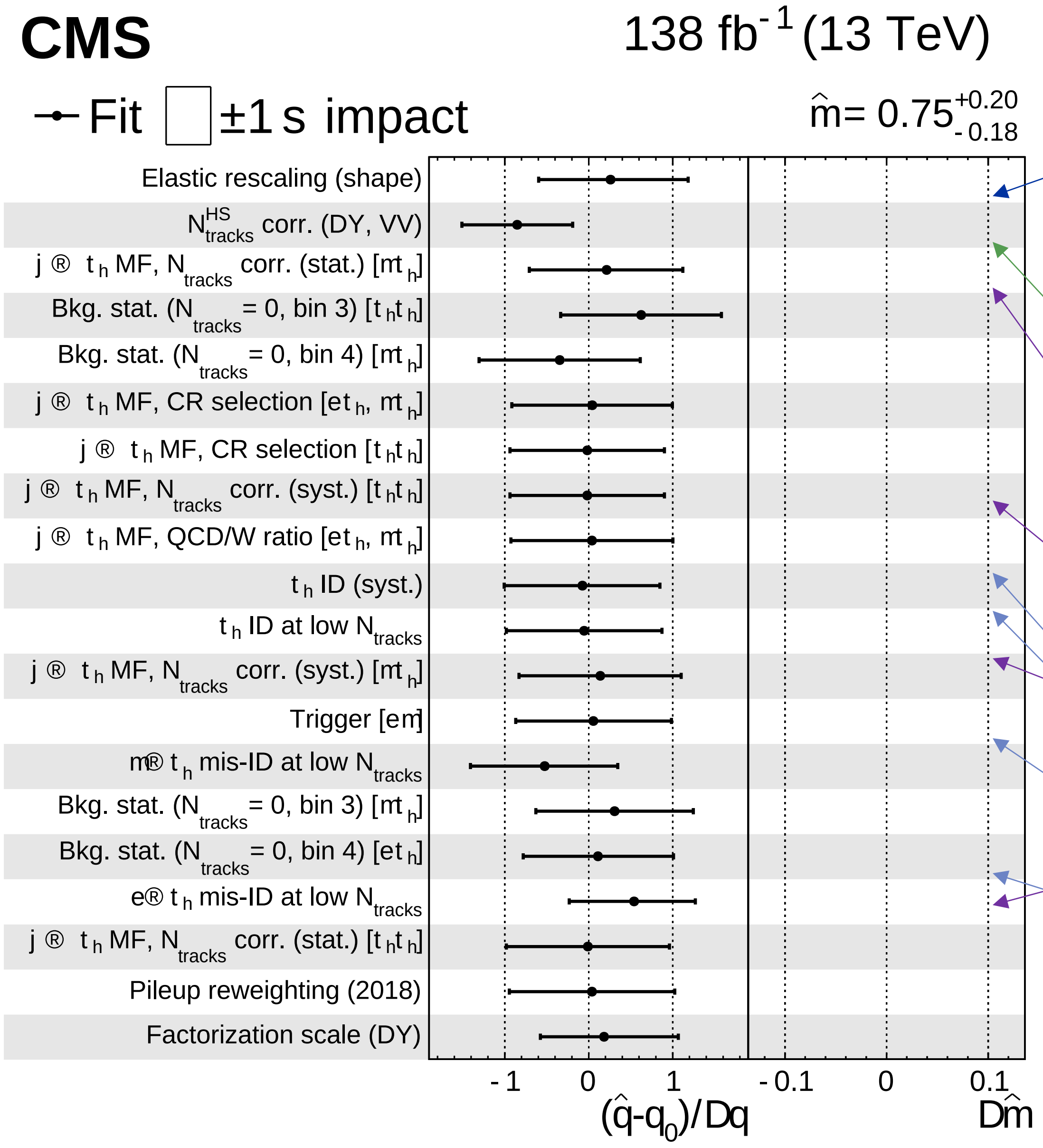
Compatible with SuperChic predictions

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

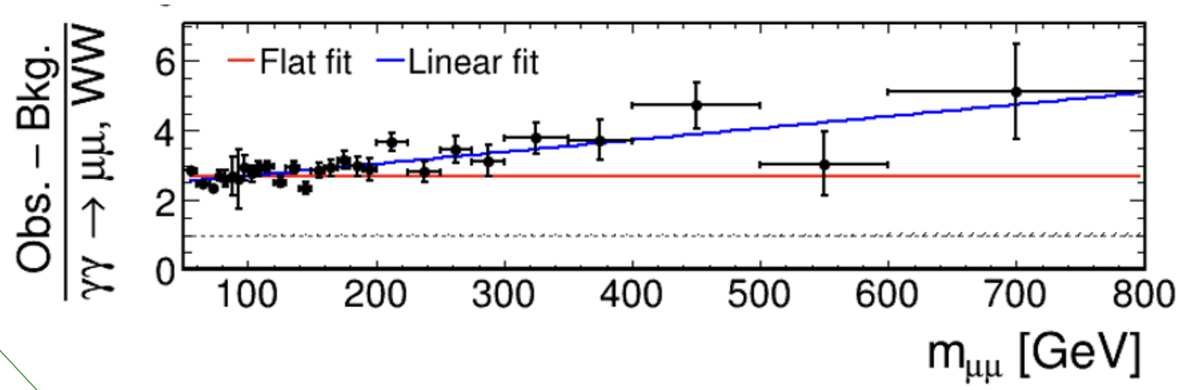
- 5.3 σ observed, 6.5 σ expected
- First observation of $\gamma\gamma \rightarrow \tau\tau$ in pp runs

	Observed	Expected
$e\mu$	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

Leading systematics



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

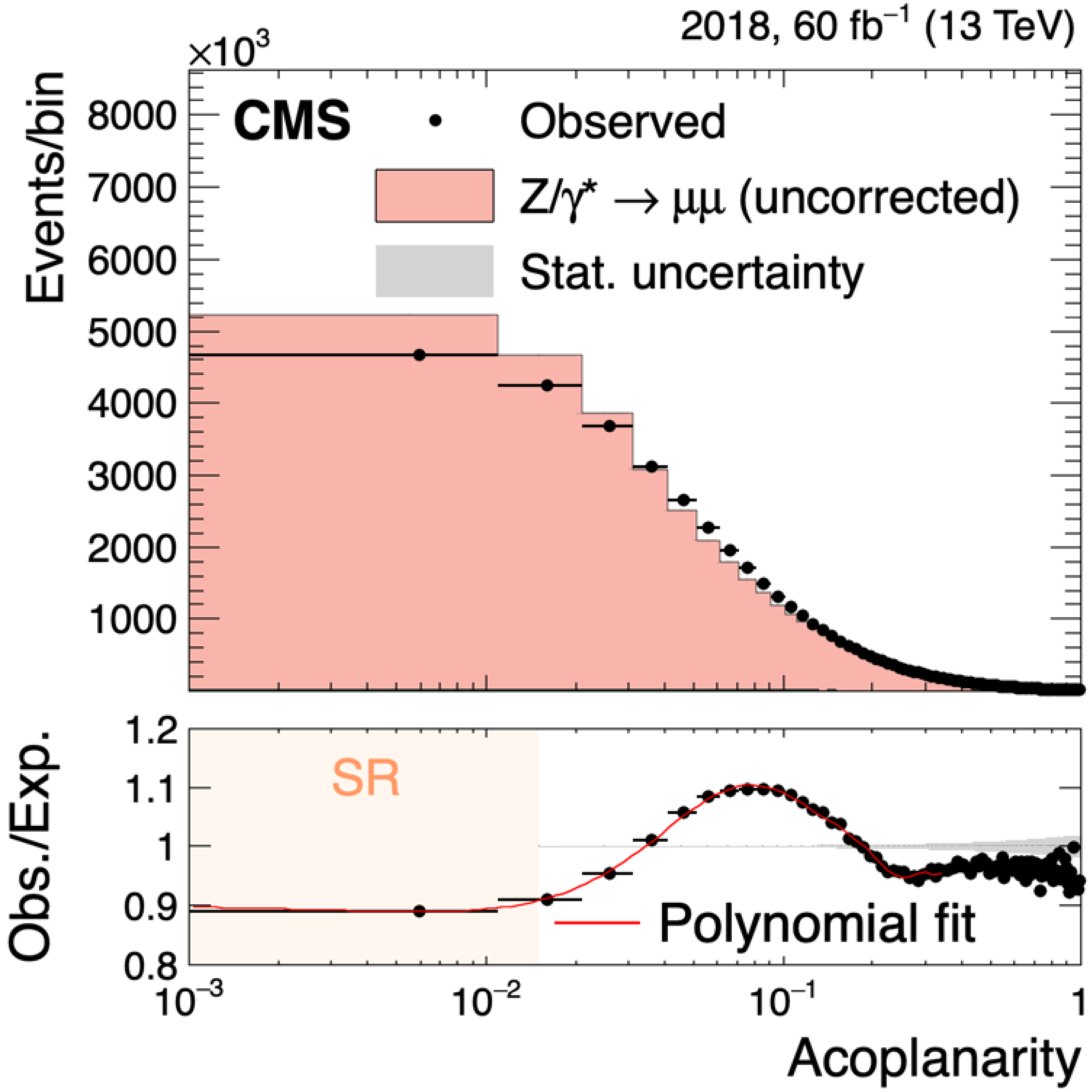


UE/HS track multiplicity correction to Drell-Yan (6.5% uncertainty for N_{tracks} = 0)

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})

Acoplanarity correction



- The Drell-Yan simulation does not model well the acoplanarity distribution in the dimuon control region
- Correction taken as Obs./Exp. Ratio in dimuon control region and applied in ditau signal region

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

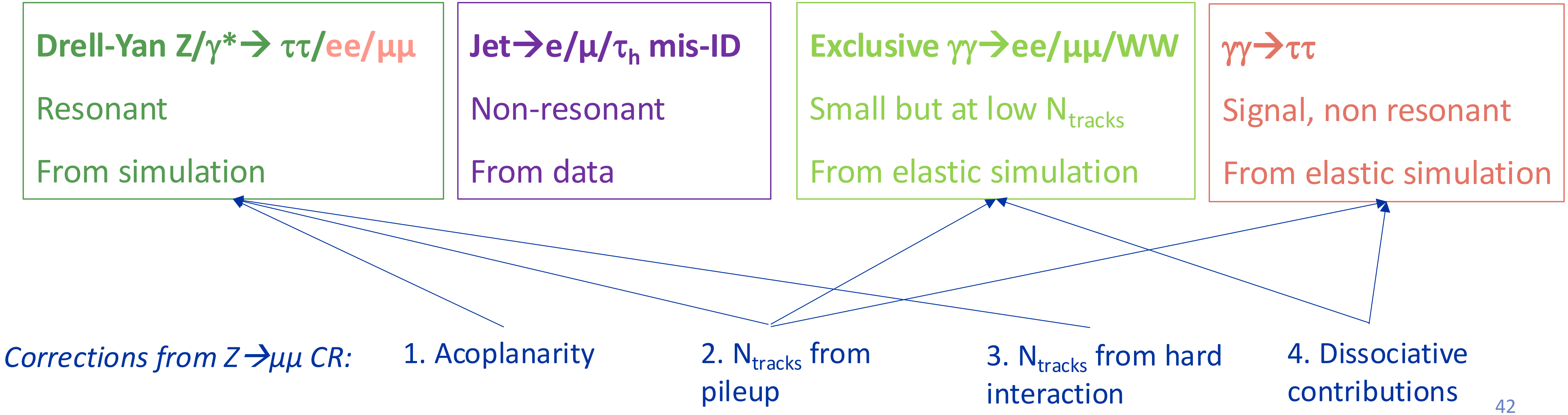
Strategy

- 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})
  - S/B ratio increases with m_{vis} because Drell-Yan background concentrated at lower masses and signal is nonresonant

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

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})
  - S/B ratio increases with m_{vis} because Drell-Yan background concentrated at lower masses and signal is nonresonant



Selection

Electron + muon triggers

Single lepton or lepton + τ_h triggers

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

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

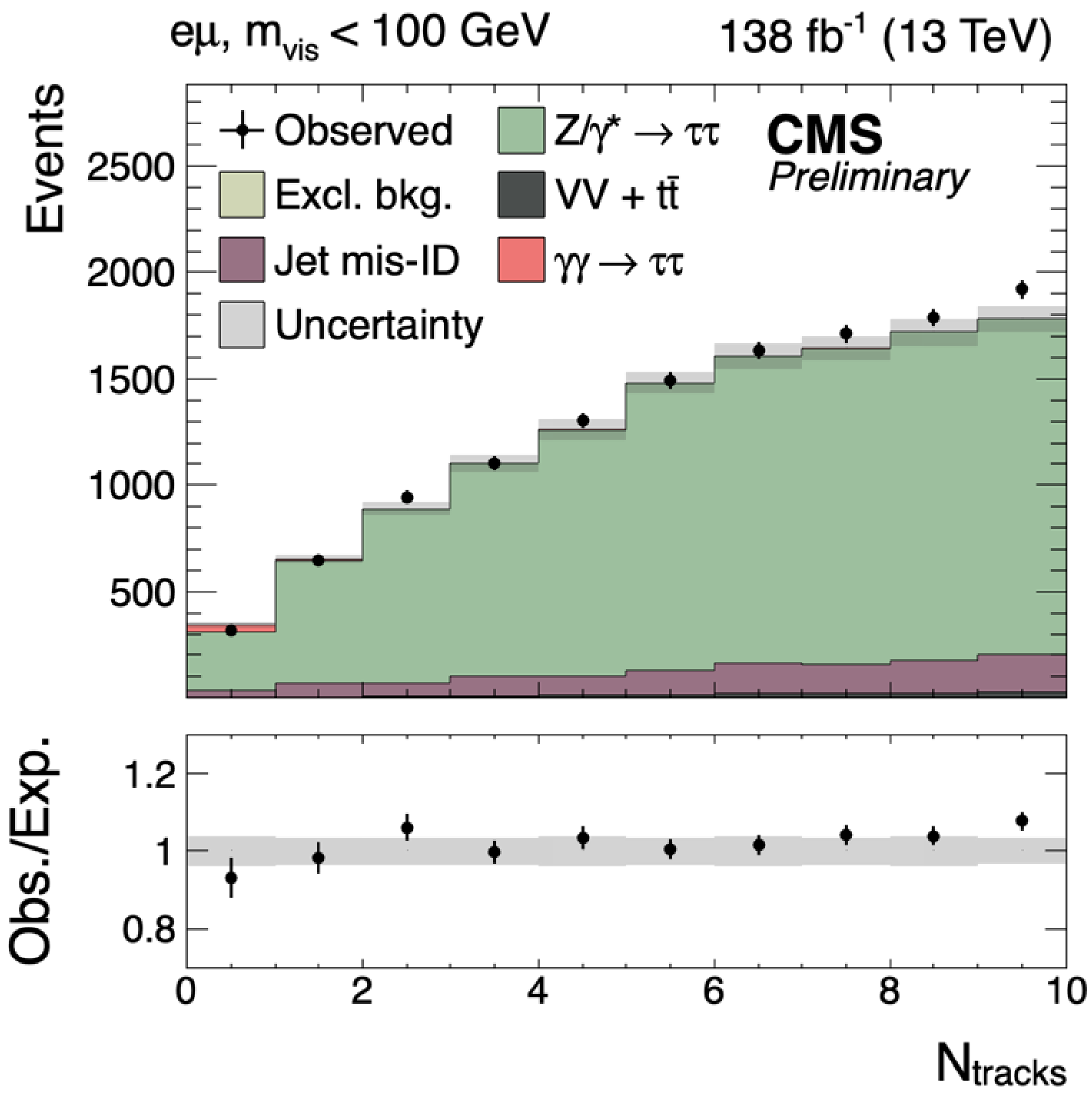
Di-tau trigger

To reduce W+jets background

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

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



Limits on Wilson coefficients