Cross section measurement and EFT interpretation of $\gamma\gamma \rightarrow W^{+}W^{-}$ in pp collisions at CMS

Dayong Wang

Peking University, on behalf of CMS Collaboration

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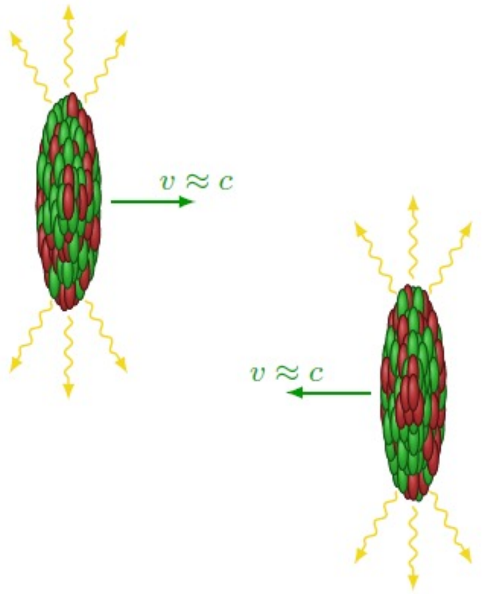
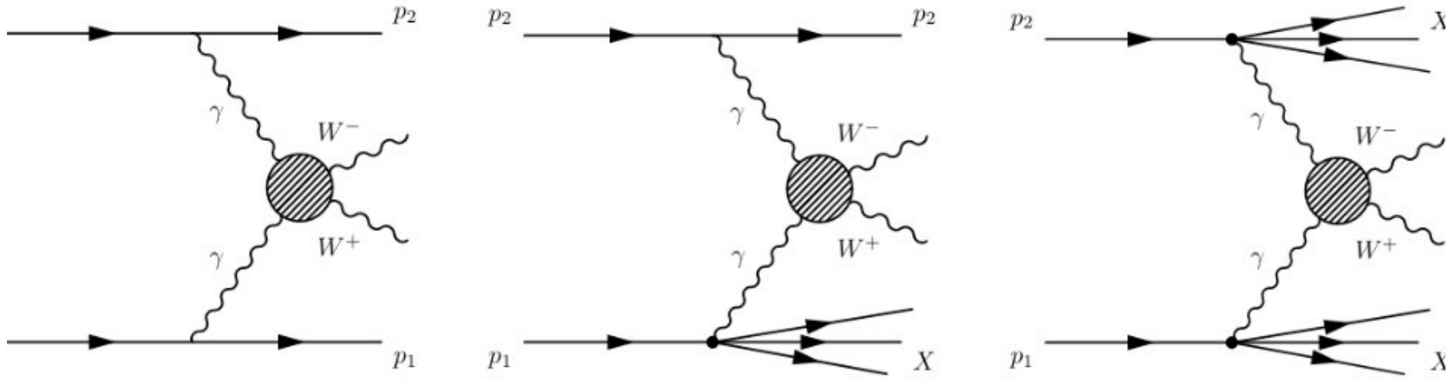
Photon-induced W^+W^- production

Photon-induced process is a clean electroweak lab in pp

- Probes a $\gamma\gamma$ **initial state**, complementary to the usual $qq/qg/gg$ production.
- Exclusive or quasi-exclusive topologies require **no extra tracks** at the production vertex, strongly suppressing inclusive backgrounds.





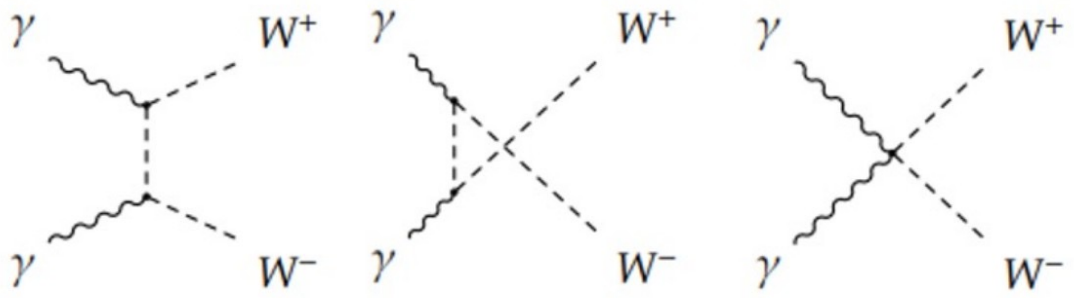
elastic　　semi-elastic　　inelastic

- $\sigma(\gamma\gamma) \propto \log^3(\sqrt{S})$
- **Quasi-real photon**, $q^2 \approx 0$
- Max(longitudinal) γ energy: $\boldsymbol{E_\gamma \approx 2.5}$**TeV(pp,13TeV)**

$\gamma\gamma \to W^+W^-$ EFT interpretation

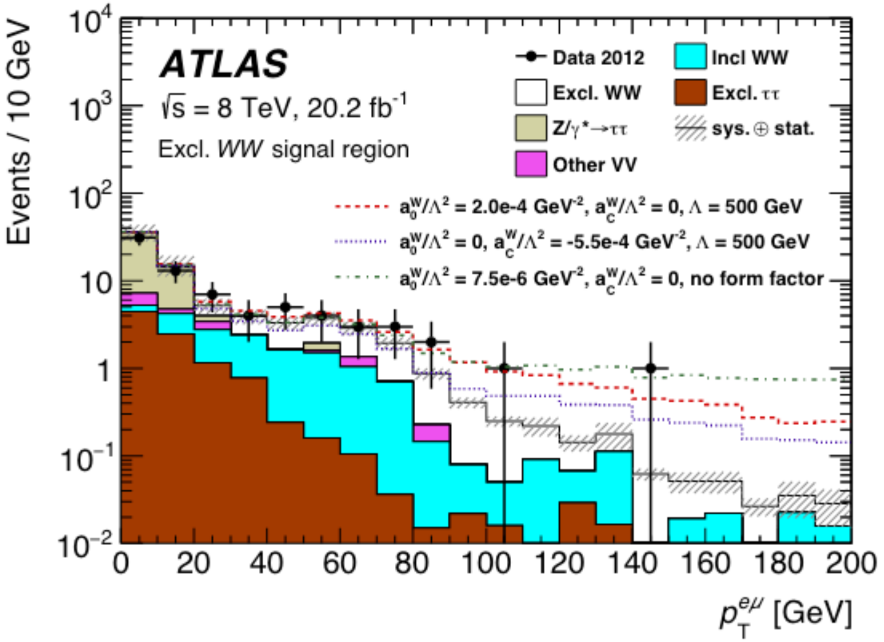
- This channel is a direct probe of the quartic gauge structure, so it is naturally sensitive to dimension-8 EFT operators.
- **Clean interpretation:** once the SM rate is measured in a clean photon-induced topology, any tail distortion can be translated efficiently into EFT constraints.

$$\mathcal{L}_{WW\gamma} = -ie\{(\partial^\mu W^\nu - \partial^\nu W^\mu)W_\mu^\dagger A_\nu - (\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger})W_\mu A_\nu + W_\mu W_\nu^\dagger(\partial^\mu A^\nu - \partial^\nu A^\mu)\}$$
$$\mathcal{L}_{WW\gamma\gamma} = -e^2(W_\mu^\dagger W^\mu A_\nu A^\nu - W_\mu^\dagger A^\mu W_\nu A^\nu)$$



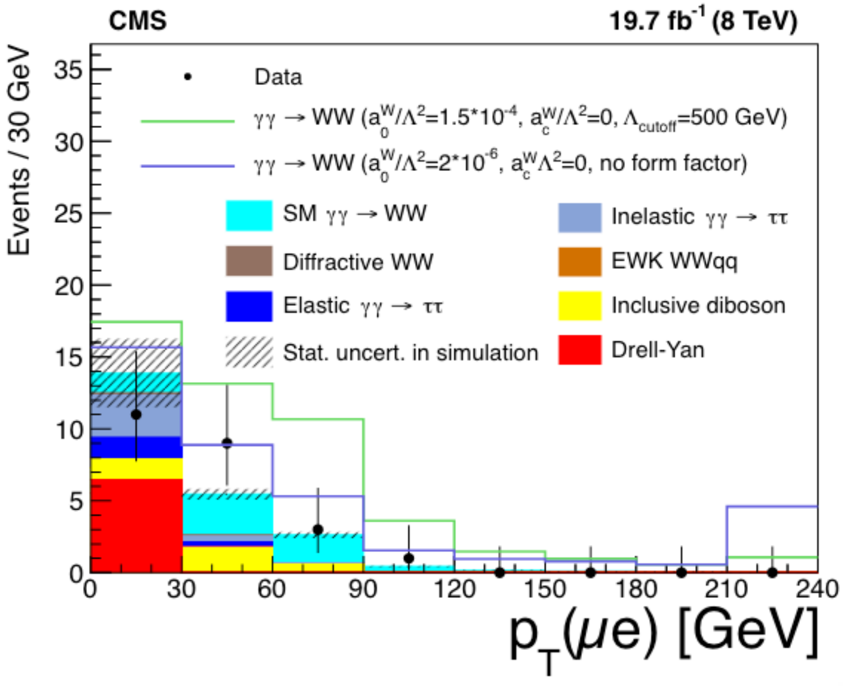
$\gamma\gamma \to WW$ produced via trilinear and quartic gauge couplings.

Previous $\gamma\gamma \to WW$ results



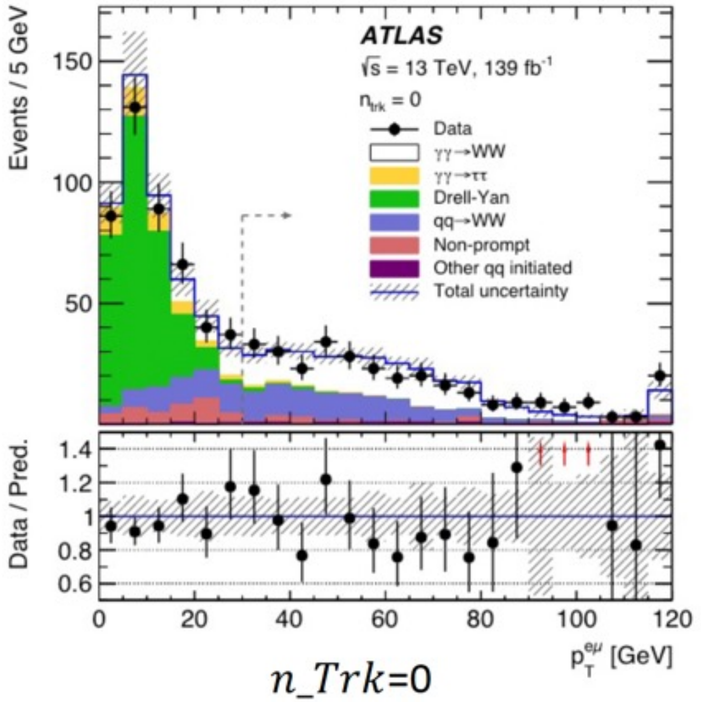
Evidence of $\gamma\gamma \to WW$ by ATLAS with Run-1 data, limited EFT interpretation

PRD 94 (2016) 3, 032011



Evidence of $\gamma\gamma \to WW$ at CMS with Run-1data, limited EFT interpretation

JHEP 2016, 119 (2016).



Observation of $\gamma\gamma \to WW$ at ATLAS with Run-2 data, no EFT interpretation

PLB 816, 136190(2021).

Analysis Overview

- Full Run-2 data: $\sqrt{s}$=13TeV, L=138fb^{-1}
- Dataset: SingleElectron, SingleMuon, MuonEG
- Final State: eμ
  - ➢ opposite sign $e^{\pm}\mu^{\mp}$
  - ➢ low activity (low $\boldsymbol{N_{tracks}}$) around eμ vertex
  - ➢ Acoplanarity = 1-$\frac{|\Delta\Phi|}{\pi}$
- Use μμ final state as control channel to derive corrections
  - ➢ Acoplanarity correction
  - ➢ Beam spot correction
  - ➢ Pileup N_{tracks}^{PU} correction
  - ➢ Hard scattering N_{tracks}^{HS} correction
- Measure $\gamma\gamma \to WW$ and derive EFT constraintsfrom observed $p_{Te\mu}$ shape & yield

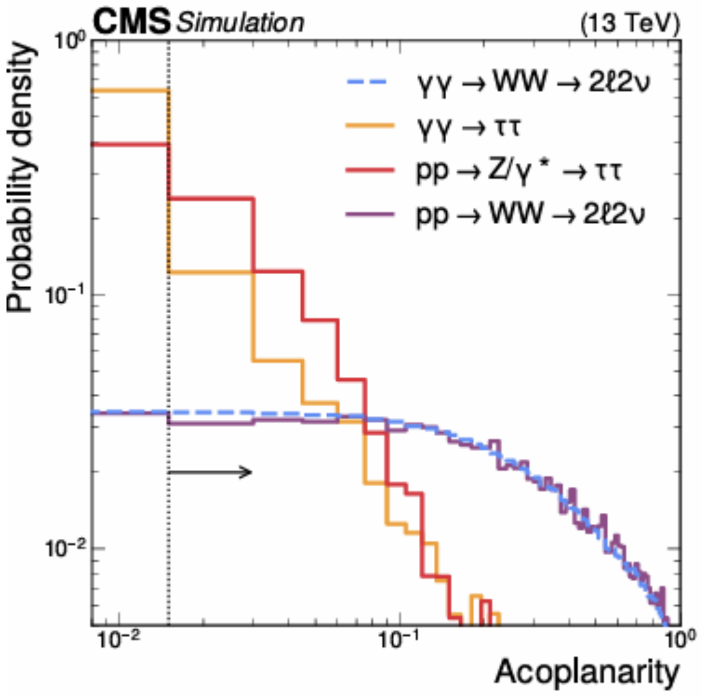
Physics Objects Requirements

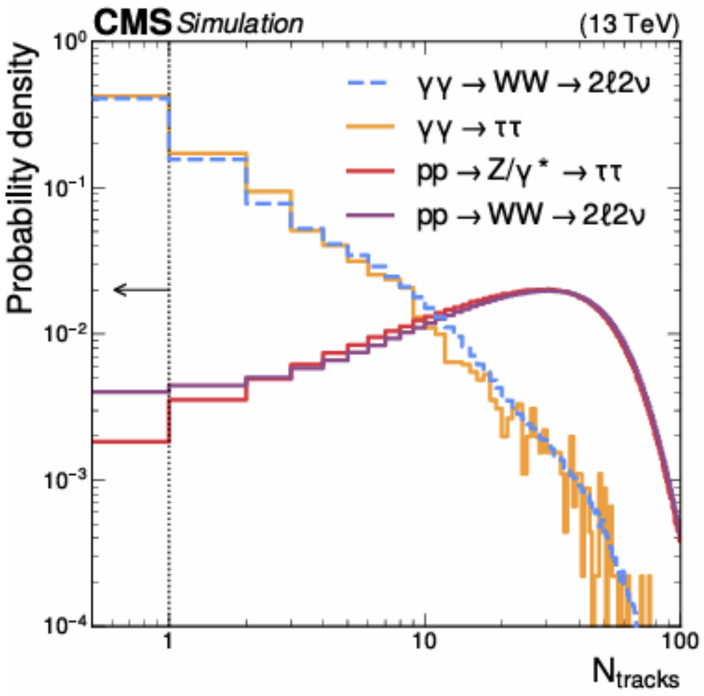
- **μ**: Medium ID, Medium Isolation, p_T>15GeV, |η|<2.4
- **e**: MVAiso WP80 working point, p_T>15GeV, |η|<2.5
- **Tracks**: p_T>0.5GeV, |η|<2.5,

Year	dataset	Trigger path
2016	SingleElectron	HLT_Ele25_eta2p1_WPTight_Gsf
	SingleMuon	HLT_IsoMu24
		HLT_IsoTkMu24
	MuonEG	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL
		HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL
		HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ
		HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ
2017	SingleElectron	HLT_Ele32_WPTight_Gsf_L1DoubleEG
	SingleMuon	HLT_IsoMu27
	MuonEG	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ
		HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ
2018	SingleElectron	HLT_Ele32_WPTight_Gsf
	SingleMuon	HLT_IsoMu24
	MuonEG	HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ
		HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ

Event selection

	$e\mu$ SR (CR)	$\mu\mu$
p_T^e (GeV)	$> 15/24$	—
$\|\eta^e\|$	< 2.5	—
$\|d_{xy}^e\|$ (cm)	< 0.05 (barrel)	—
	< 0.1 (endcap)	
p_T^μ (GeV)	$> 24/15$	$> 26 - 29/10$
$\|\eta^\mu\|$	< 2.4	< 2.4
$\|d_{xy}^\mu\|$ (cm)	< 0.02	< 0.05
$m_{\ell\ell}$ (GeV)	> 20	> 50
OS	Yes	Yes
$\|dz(\ell,\ell)\|$ (cm)	< 0.04	< 0.1
ΔR	> 0.5	> 0.5
A	> 0.015	—
N_{tracks}	0 ([1, 5])	—





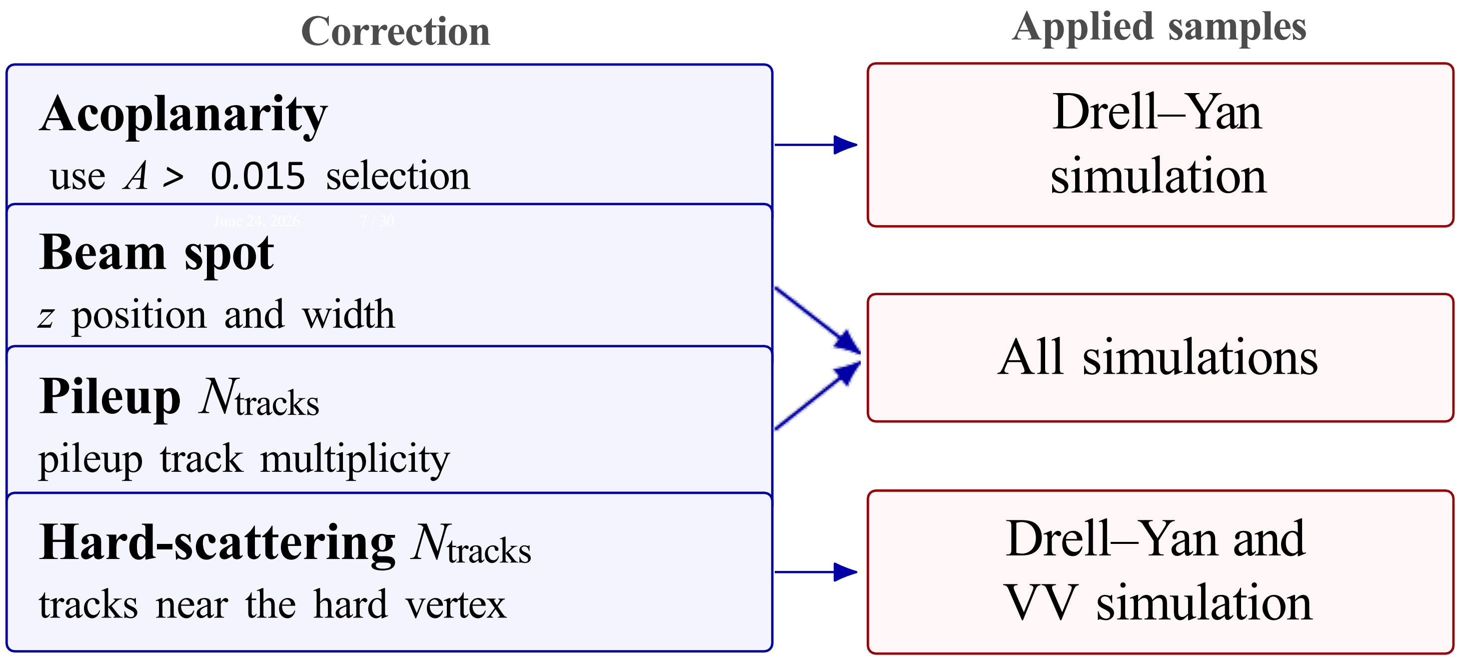
Definition: $A = 1 - |\Delta\phi_{\ell\ell}|/\pi$, where $\Delta\phi_{\ell\ell}$ is the azimuthal angle difference between the selected leptons.

Back-to-back dilepton events have $A \simeq 0$.

The requirement $A > 0.015$ suppresses exclusive $\gamma\gamma \to \tau\tau$ while keeping high signal efficiency.

N_{tracks}: number of tracks with $|dz|<0.05$cm to the di-W vertex, reconstructed as $(z(e)+z(\mu))/2$, removing tracks used to build lepton candidates.

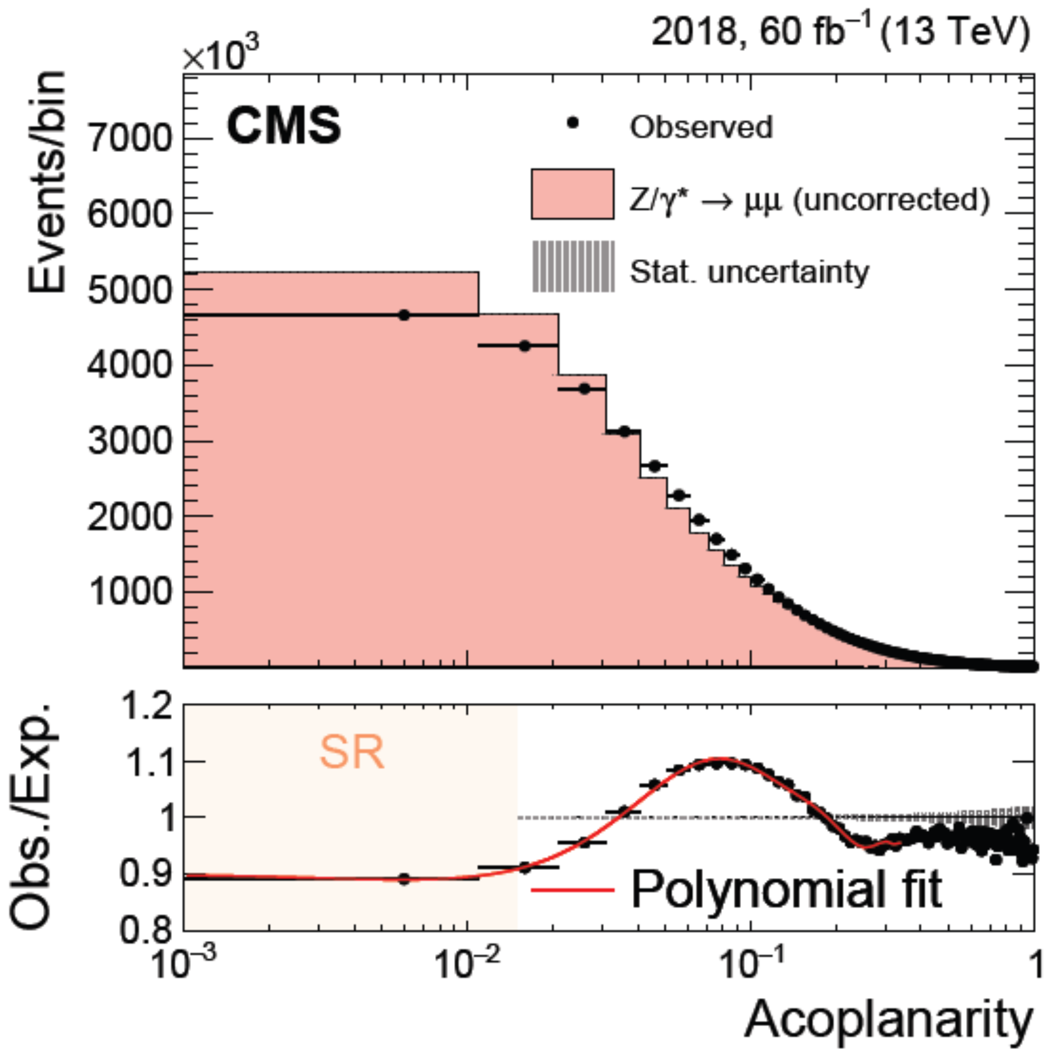
Corrections derived from μμ control samples



- following methods from $\gamma\gamma \to \tau\tau$ analysis: Rep. Prog. Phys. 87 (2024) 107801

Acoplanarity correction (for DY simulation)

- Divide Z->μμ data and MC in different bins of leading and subleading muon p_T
- Derive correction as data/MC ratio in each bin, fitted up to 0.35 then plateau
- Apply correction in the SR as a function of the generated di-tau acoplanarity (SR: A<0.015)



Beam spot correction on pileup tracks

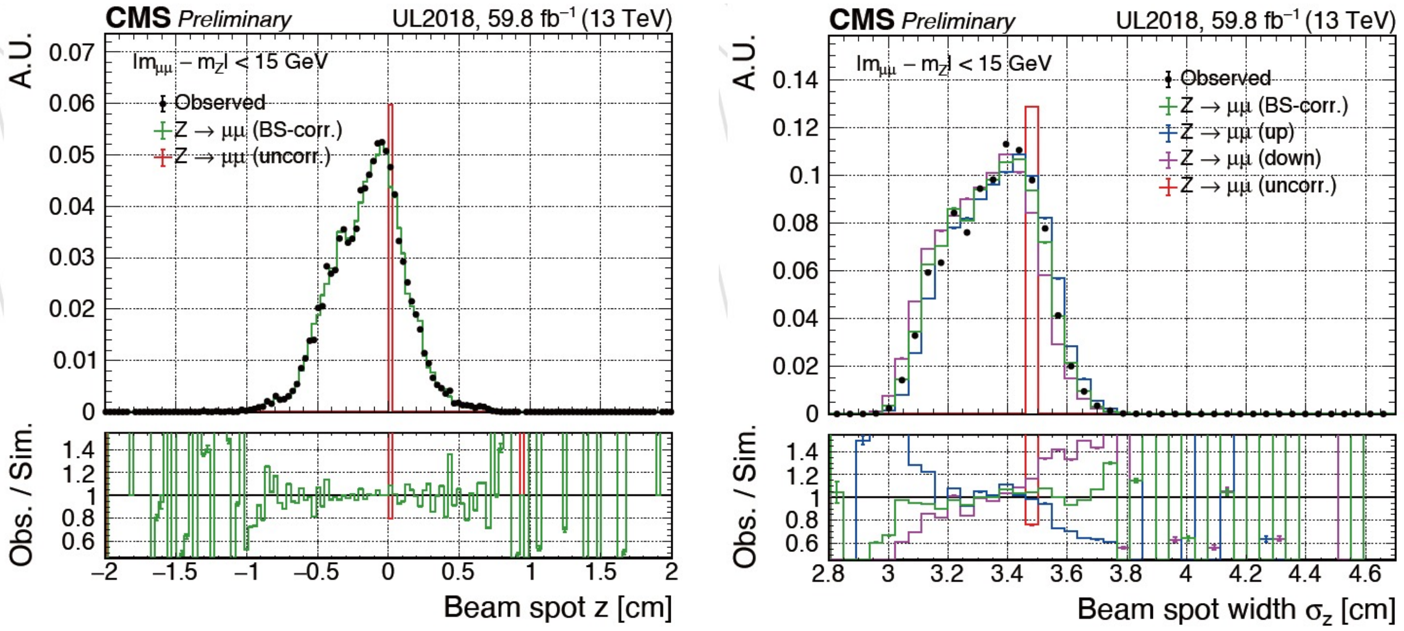
- Simulated events in a given year have a fixed beam spot z position and width

- In data, beam spot z position and width are run-dependent

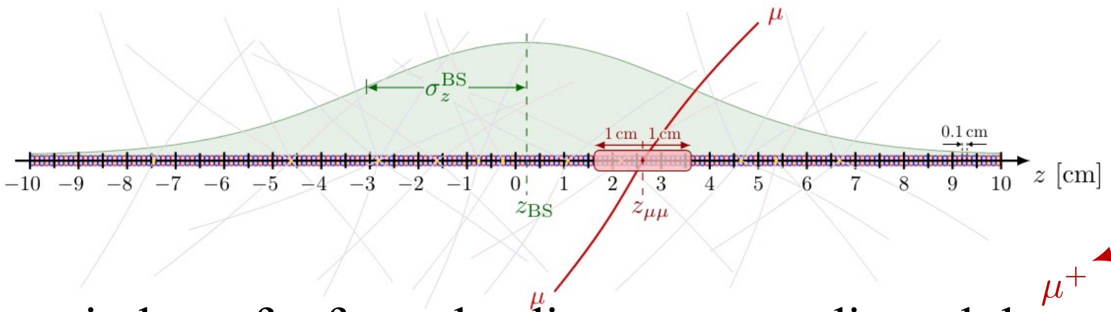
- To each simulated event, randomly assign a BS position z_{Data}^{BS} and a BS width σ_{Data}^{BS} with a probability

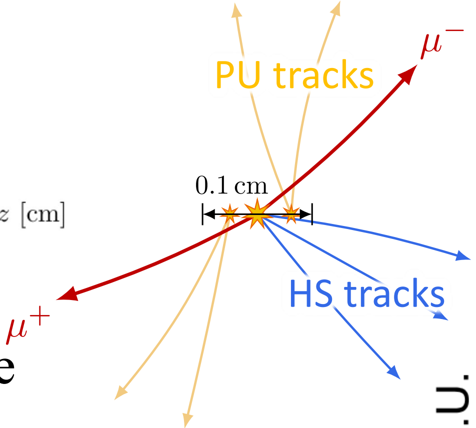
$$z^{\mathrm{corr}} = z_{\mathrm{MC}}^{\mathrm{BS}} + \frac{\sigma_{\mathrm{Data}}^{\mathrm{BS}}}{\sigma_{\mathrm{MC}}^{\mathrm{BS}}}\left(z - z_{\mathrm{MC}}^{\mathrm{BS}}\right)$$

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



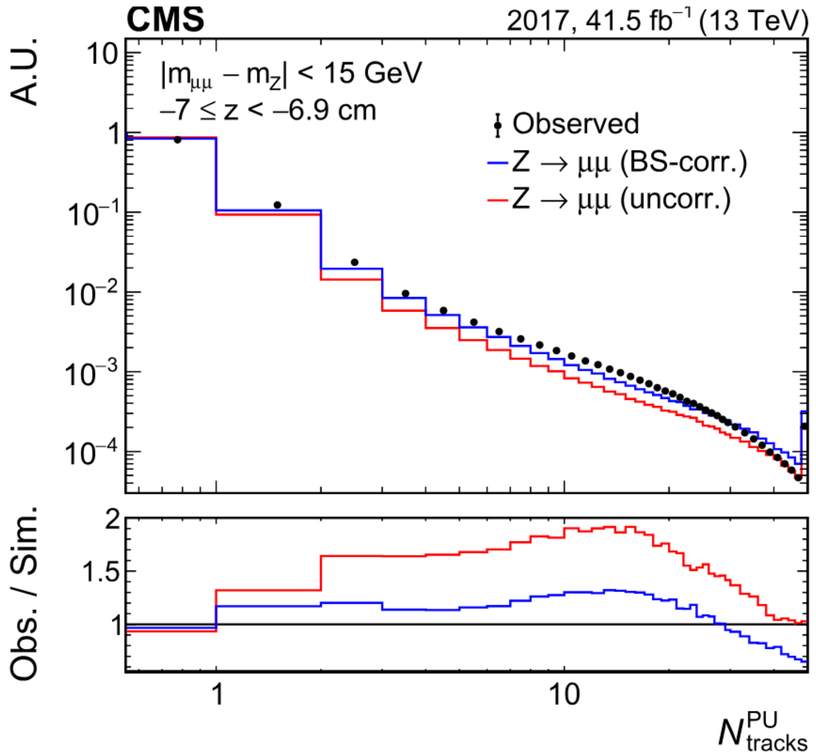
$N_{tracks}^{PU}/N_{tracks}^{HS}$ correction





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

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

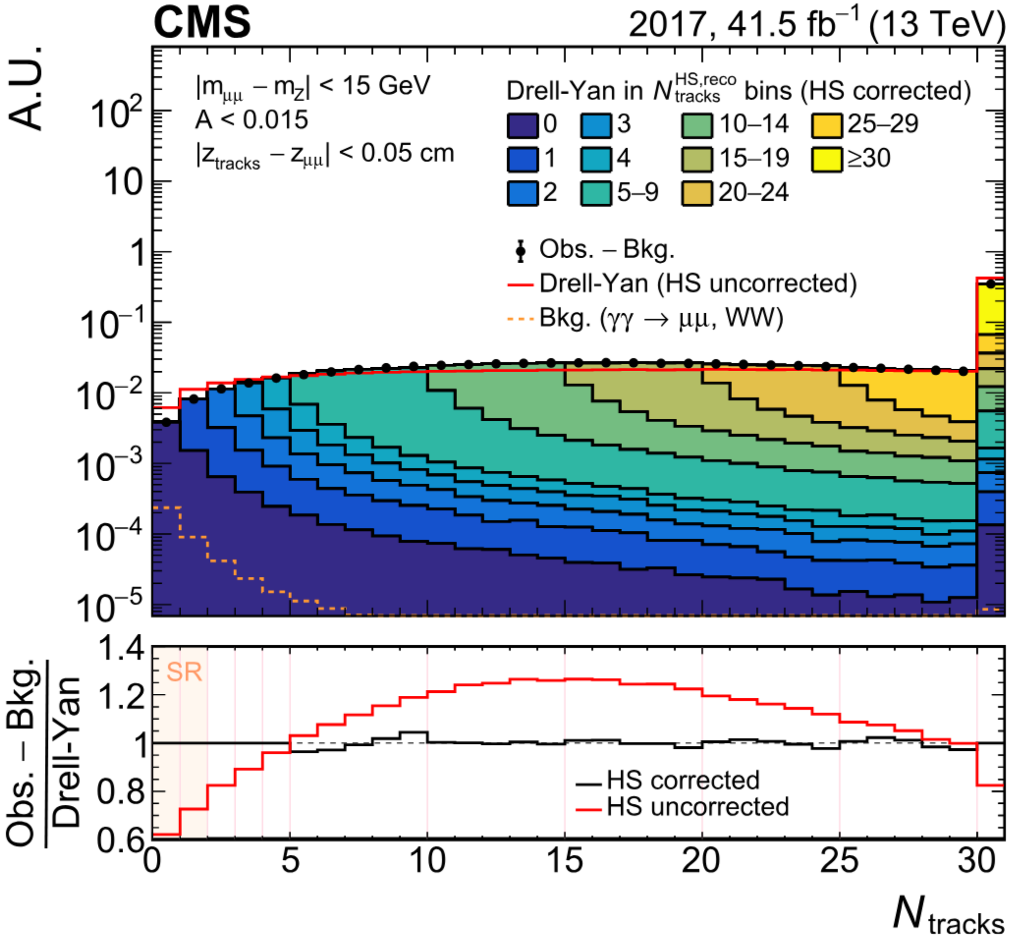


Correct events with N_{tracks}^{HS}=0 at N_{tracks} =0

Correct events with N_{tracks}^{HS}=1 at N_{tracks} =1

⋮

Final corrections



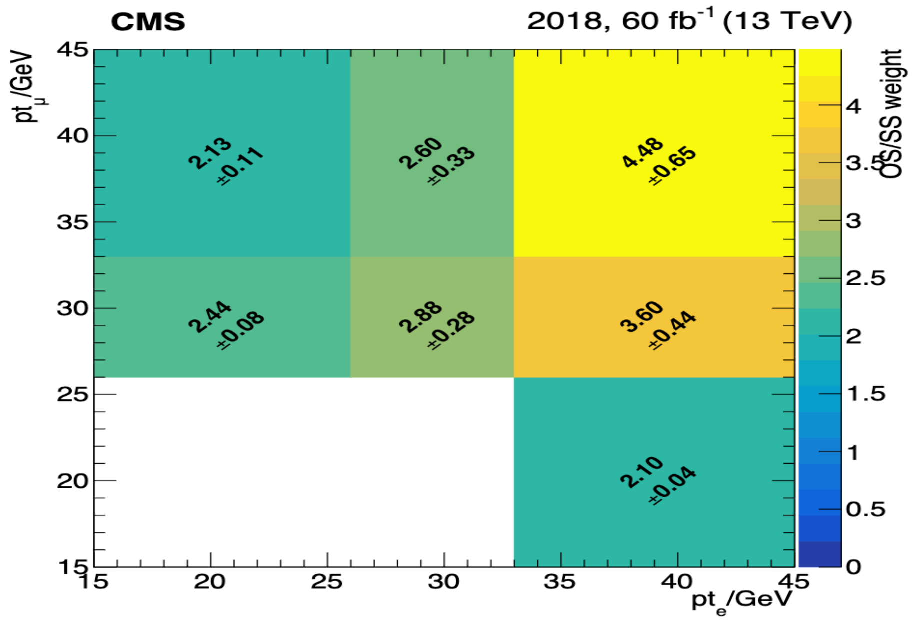
Background composition in SR

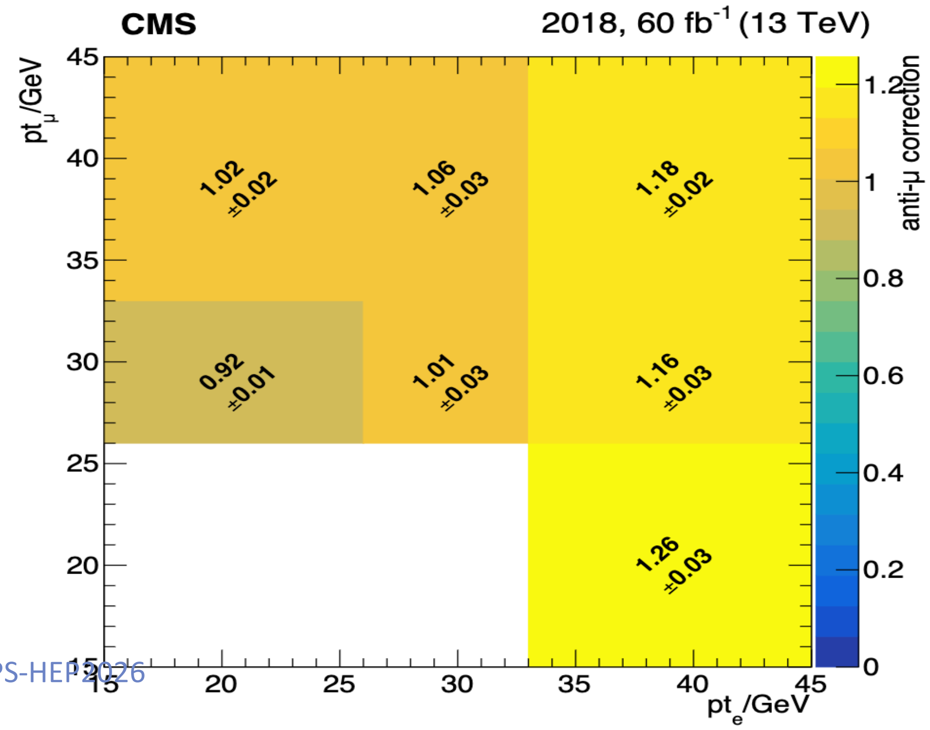
- Drell-Yan(DY) process (dominant in the low p_T region, 50%)
- Di-boson(VV) process (largest background in the high p_T region, 23%)
- Exclusive ττ production (7% fraction)
- Top production (2% fraction)
- jet →e/μ (QCD, W+jets) background (18% fraction)
- DY and VV normalizations are both left floating in the maximum likelihood fit

- Control Region ($1 \leq N_{tracks} \leq 5$)
  - enriched in Drell-Yan and VV
  - The uncertainty of HS track multiplicity of Drell-Yan and VV in CR are left floating

Non-prompt lepton background estimation

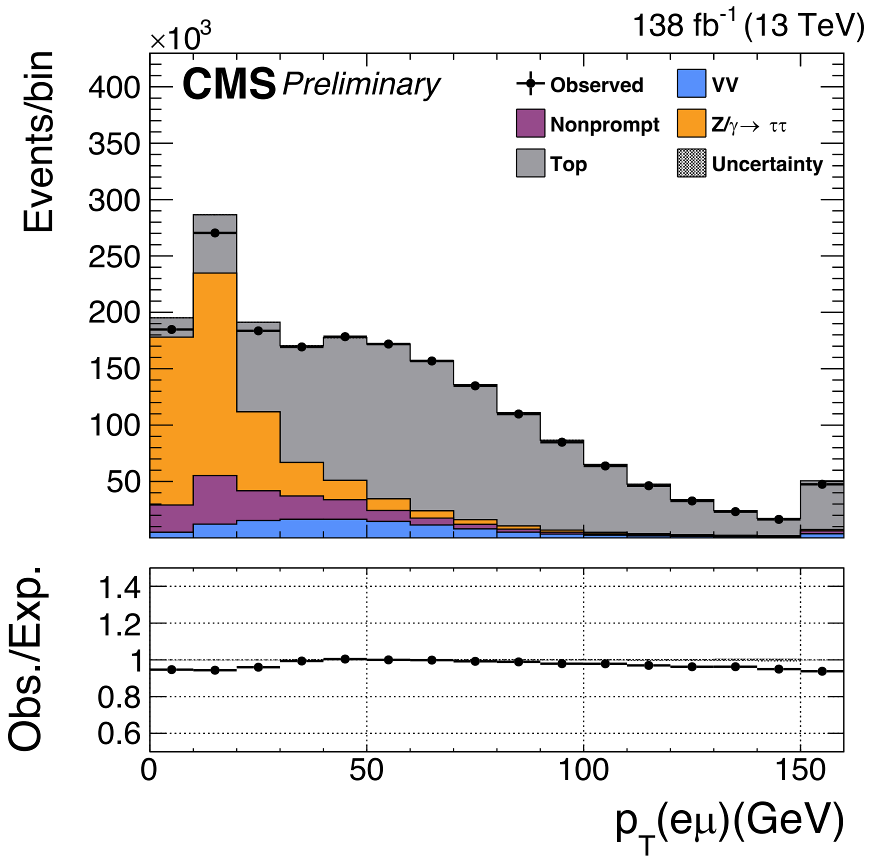
C SS $0.2<\mu_{Iso}<0.5$	D OS $0.2<\mu_{Iso}<0.5$
B SS $\mu_{Iso}<0.2$	A Signal Region OS $\mu_{Iso}<0.2$

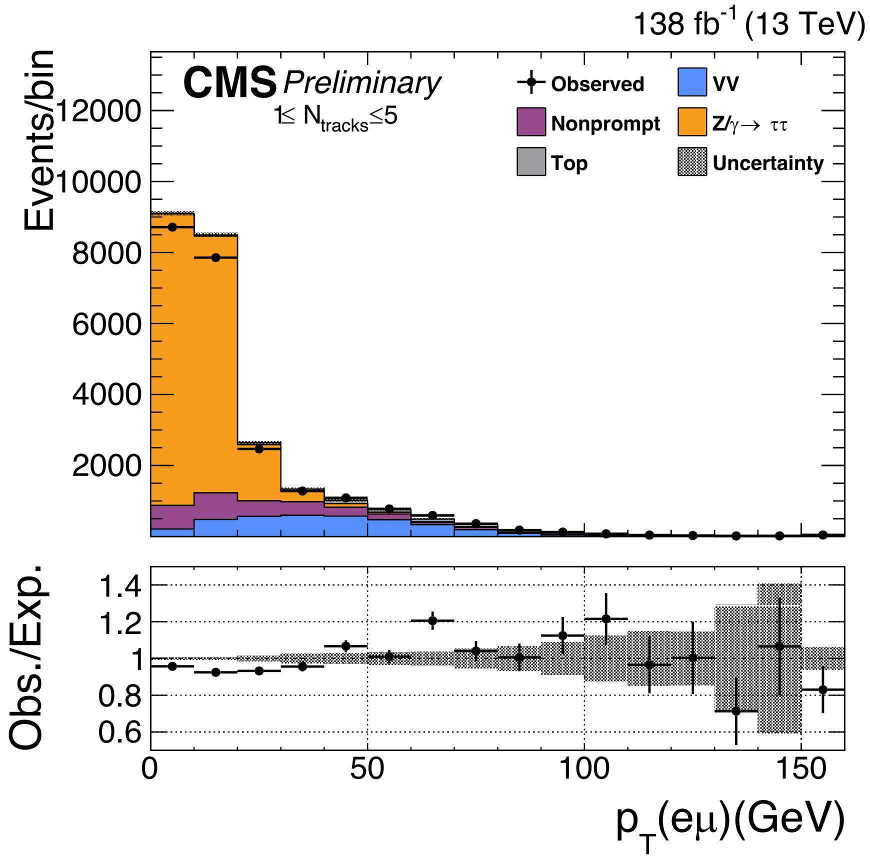




$p_{Te\mu}$ distributions: inclusive and CR

- Data/MC agree well, validating the background modeling and corrections.
- DY is the dominant background in the control region.





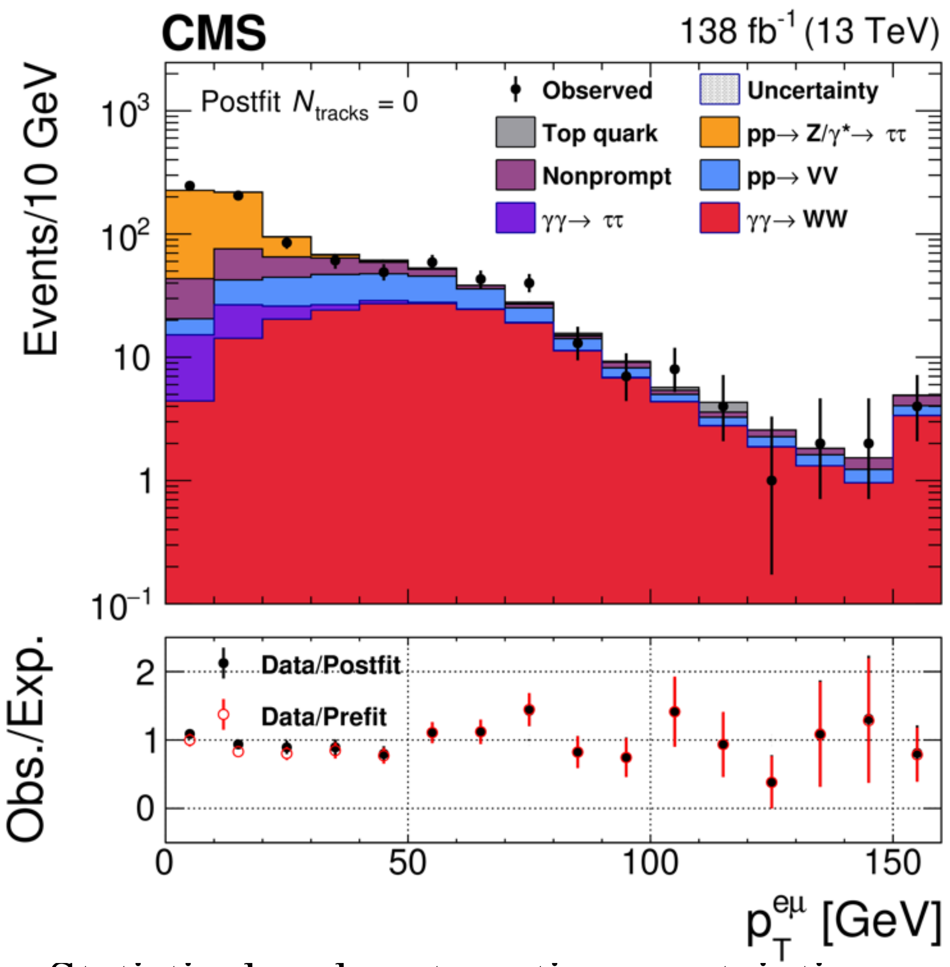
Only statistical uncertainty shown, prefit

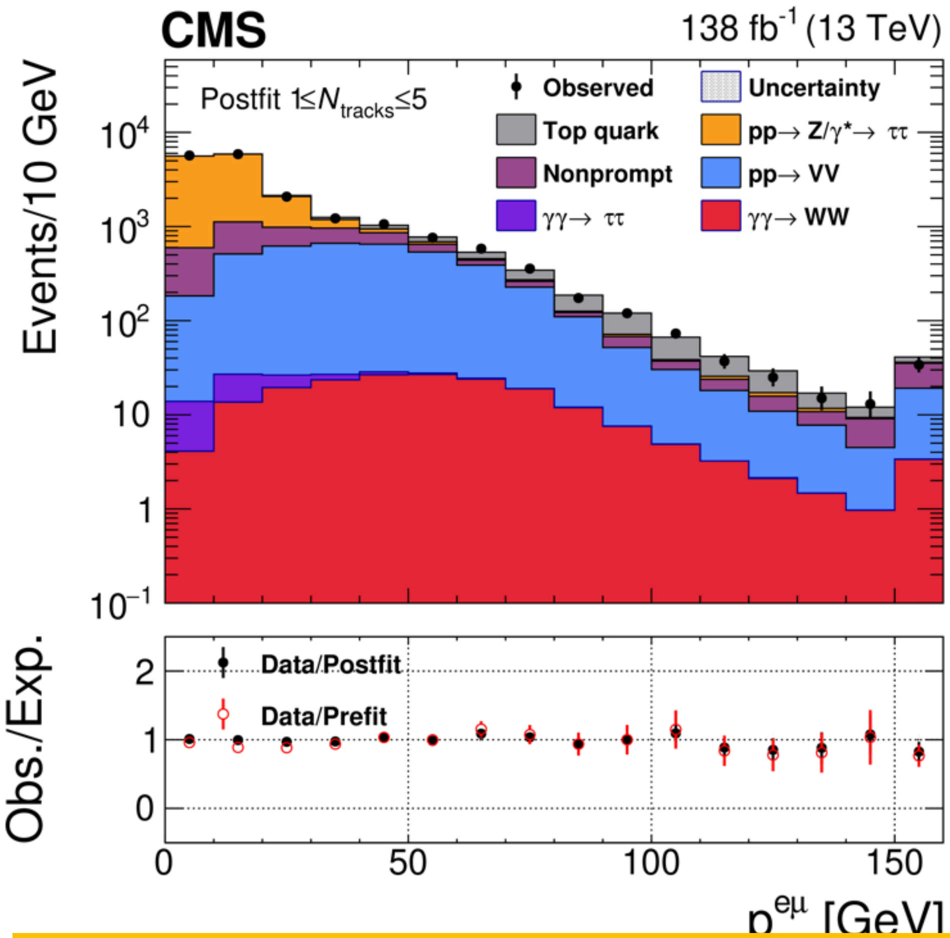
Systematic uncertainties

Leading impacts: $N^{\mathrm{HS/PU}}$ correction and DY normalization.

Sources of uncertainties	Cross section uncertainty (%)
$N_{\mathrm{tracks}}^{\mathrm{HS}}$ correction	3.6
DY normalization	3.5
e selection	2.2
$N_{\mathrm{tracks}}^{\mathrm{PU}}$ correction	2.0
Integrated luminosity	1.6
$\mathrm{t\bar{t}}$ normalization	1.2
Pileup modeling	1.2
Inclusive diboson normalization	1.0
μ selection	1.0
Jet mis-ID prediction	< 1
μ_{R}, μ_{F}, PDF	< 1

First observation of $\gamma\gamma \to WW$ at CMS





- Statistical and systematic uncertainties are shown
- Last bin contains overflows
- The observed significance is well above **5σ**

Inclusive cross section of $\gamma\gamma \to WW$ with all W decay modes $\sigma^{inclusive} = 643^{+82}_{-78}$ fb

prediction: 631±126 fb

Fiducial Cross Section Measurement

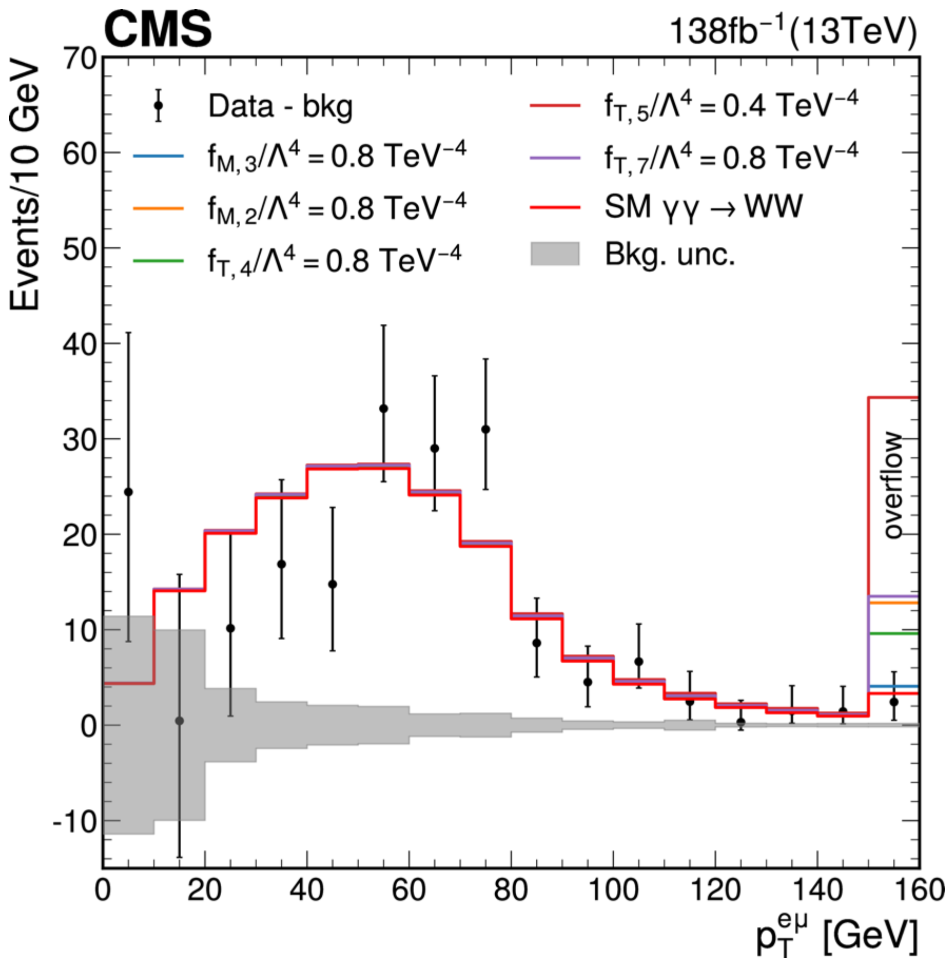
Process	$N_{\text{tracks}} = 0$	$1 \leq N_{\text{tracks}} \leq 5$
$Z/\gamma^* \to \tau\tau$	360 ± 22	11262 ± 166
Jet mis-ID	120 ± 10	2176 ± 186
Inclusive VV	115 ± 10	3734 ± 184
$\gamma\gamma \to \tau\tau$	34.2 ± 1.4	37.3 ± 1.5
Top	7.0 ± 1.5	719 ± 115
Nonfiducial $\gamma\gamma \to WW$	11.5 ± 0.5	70.5 ± 2.4
Total bkg.	648 ± 28	17999 ± 174
Fiducial $\gamma\gamma \to WW$	183.7 ± 22.2	124.0 ± 15.8
Total	835.4 ± 28.8	18122.5 ± 159.6
Observed	829	18112

Meausured result $\sigma^{fid} = 3.96^{+0.53}_{-0.51}$ fb

prediction $= 3.87 \pm 0.77$ fb

- Fiducial region definition:
  - eμ final state from W
  - leading lepton p_T>24GeV
  - subleading lepton p_T>15GeV
  - $|\eta_e|$<2.5
  - $|\eta_\mu|$<2.4
  - 0 extra track
  - A>0.015
  - $\Delta R(e,\mu)$>0.5
  - $m_{e\mu}$>20GeV
- Signal events in the fiducial region: 94%
- Treat signal events outside the fiducial region as background

EFT Constraints on Quartic Coupling



$p_{Te\mu}$ distribution of $\gamma\gamma \to WW$ with nonzero EFT parameters

- EFT parameters extracted from binned likelihood fit
- One dim-8 operator is varied at a time, with the signal yield reweighted bin-by-bin relative to the SM prediction.
- Run1 used an effective Lagrangian with dim-6 operators
- We use the latest recommendation on dim-8 operators from LHC EFT WG
- dim-6 operators can be related to linear dim-8 operators

$$a_0^W = -\frac{M_W^2}{\pi\alpha_{em}}\left[s_w^2\frac{f_{M,0}}{\Lambda^2} + 2c_w^2\frac{f_{M,2}}{\Lambda^2} + s_w c_w\frac{f_{M,4}}{\Lambda^2}\right] ,$$

$$a_c^W = -\frac{M_W^2}{\pi\alpha_{em}}\left[-s_w^2\frac{f_{M,1}}{\Lambda^2} - c_w^2\frac{f_{M,3}}{\Lambda^2} + 2s_w c_w\frac{f_{M,5}}{\Lambda^2} + \frac{s_w^2}{2}\frac{f_{M,7}}{\Lambda^2}\right] ,$$

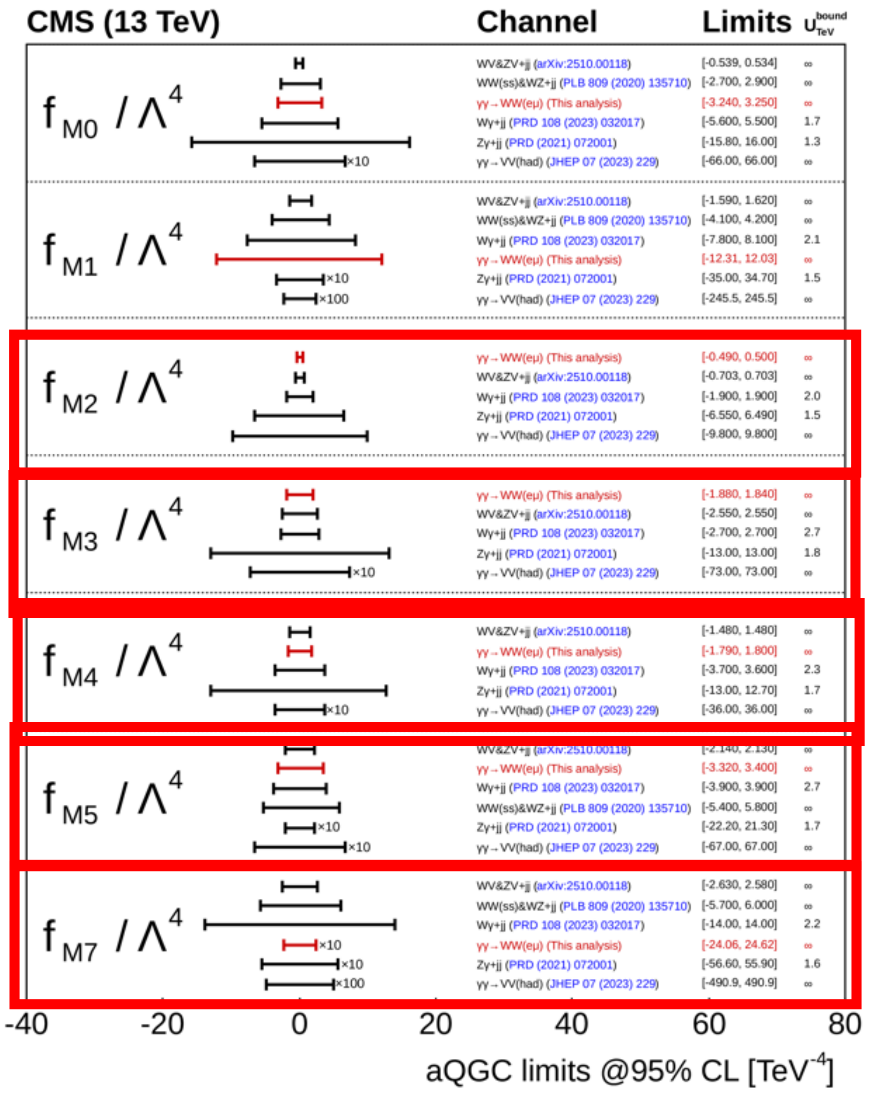
Constraints on EFT parameters

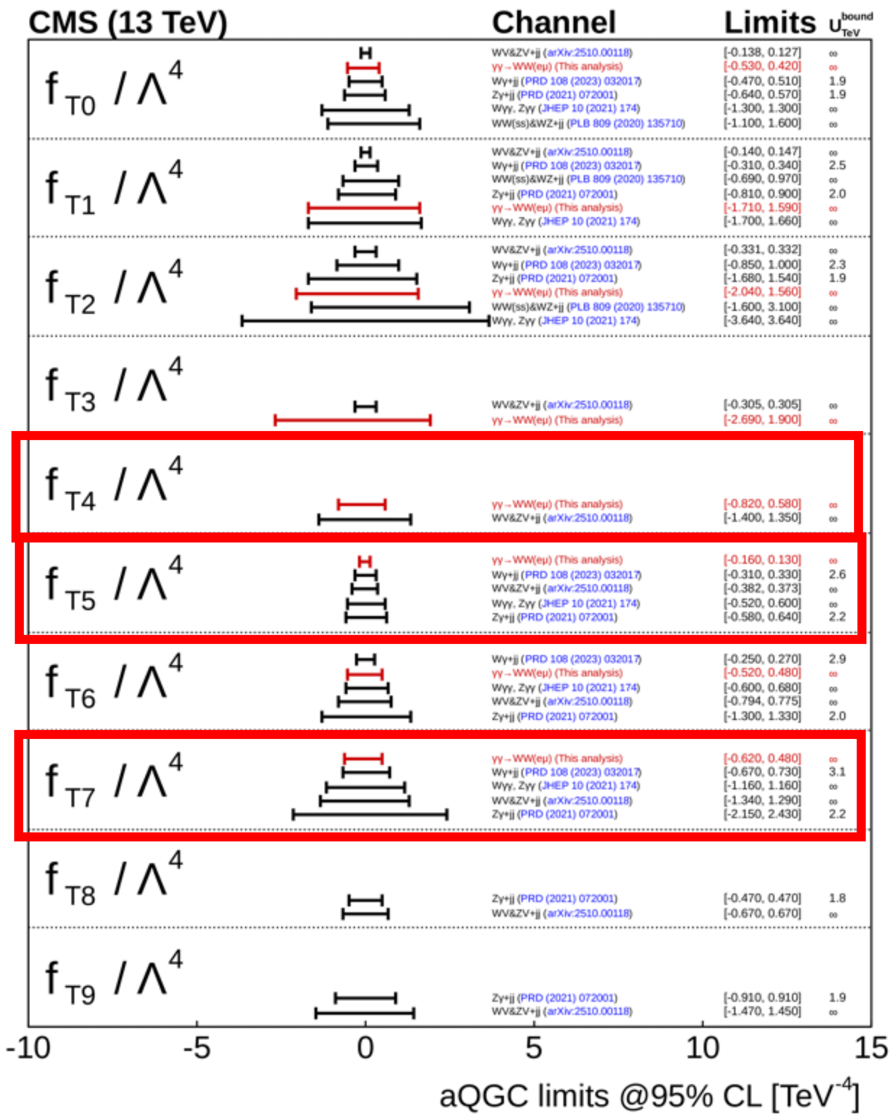
Parameter	Expected 95% CL (TeV^{-4})	Observed 95% CL (TeV^{-4})	Parameter	Expected 95% CL (TeV^{-4})	Observed 95% CL (TeV^{-4})
f_{M0}/Λ^4	$[-4.03,\ 4.10]$	$[-3.24,\ 3.25]$	f_{T1}/Λ^4	$[-2.13,\ 2.00]$	$[-1.71,\ 1.59]$
f_{M1}/Λ^4	$[-15.46,\ 14.93]$	$[-12.31,\ 12.03]$	f_{T2}/Λ^4	$[-2.50,\ 2.01]$	$[-2.04,\ 1.56]$
$\tilde{f}_{M1}/\Lambda^4$	$[-0.62,\ 0.62]$	$[-0.50,\ 0.49]$	$\tilde{f}_{T2}/\Lambda^4$	$[-0.090,\ 0.090]$	$[-0.03,\ 0.03]$
f_{M2}/Λ^4	$[-0.61,\ 0.63]$	$[-0.49,\ 0.50]$	f_{T3}/Λ^4	$[-3.28,\ 2.49]$	$[-2.69,\ 1.90]$
$\tilde{f}_{M2}/\Lambda^4$	$[-2.24,\ 2.24]$	$[-1.80,\ 1.79]$	$\tilde{f}_{T3}/\Lambda^4$	$[-0.089,\ 0.089]$	$[-0.071,\ 0.071]$
f_{M3}/Λ^4	$[-2.36,\ 2.28]$	$[-1.88,\ 1.84]$	f_{T4}/Λ^4	$[-1.00,\ 0.76]$	$[-0.82,\ 0.58]$
f_{M4}/Λ^4	$[-2.22,\ 2.26]$	$[-1.79,\ 1.80]$	$\tilde{f}_{T4}/\Lambda^4$	$[-0.38,\ 0.38]$	$[-0.30,\ 0.30]$
$\tilde{f}_{M4}/\Lambda^4$	$[-4.49,\ 4.49]$	$[-3.59,\ 3.58]$	f_{T5}/Λ^4	$[-0.20,\ 0.16]$	$[-0.16,\ 0.13]$
f_{M5}/Λ^4	$[-4.12,\ 4.27]$	$[-3.32,\ 3.40]$	$\tilde{f}_{T5}/\Lambda^4$	$[-0.21,\ 0.21]$	$[-0.17,\ 0.17]$
$\tilde{f}_{M5}/\Lambda^4$	$[-2.03,\ 2.03]$	$[-1.63,\ 1.62]$	f_{T6}/Λ^4	$[-0.65,\ 0.61]$	$[-0.52,\ 0.48]$
f_{M7}/Λ^4	$[-29.86,\ 30.92]$	$[-24.06,\ 24.62]$	$\tilde{f}_{T6}/\Lambda^4$	$[-0.62,\ 0.62]$	$[-0.50,\ 0.50]$
f_{T0}/Λ^4	$[-0.65,\ 0.53]$	$[-0.53,\ 0.42]$	f_{T7}/Λ^4	$[-0.76,\ 0.61]$	$[-0.62,\ 0.47]$

First constraints on CP-odd parameters: $\tilde{f}_{Mi}$ and $\tilde{f}_{Ti}$

Best constraints on f_{M2}, f_{M3}, f_{T4}, f_{T5}, and f_{T7}.

Comparison of Constraints on Quartic Coupling





The constraints are ranked with respect to the sensitivity, on top are the most sensitive constraints.

Tight constraints on f_{m2}, f_{m3}, f_{t4}, f_{t5}, f_{t7}

Only CP-even ones shown

Summary

- **First observation of $\gamma\gamma \rightarrow W^+W^-$ at CMS with 138 fb^{-1} pp data in 13 TeV**, with signal significance well above 5σ.
- **Inclusive and fiducial cross section measured to be**

$$\sigma(\gamma\gamma \rightarrow W\ \ W\ \ ) = 643^{+82}_{-78}\ \text{fb}$$

$$\sigma^{fid} = 3.96^{+0.53}_{-0.51}\ \text{fb}$$

JHEP 06(2026) 187

in agreement with the SM prediction.

- **Stringent EFT constraints on anomalous quartic gauge couplings are set**:
  - First constraints on CP-odd parameters: $\tilde{f}_{Mi}$ and $\tilde{f}_{Ti}$.
  - Best constraints on f_{M2}, f_{M3}, f_{T4}, f_{T5}, and f_{T7}.

Back up

MC simulation

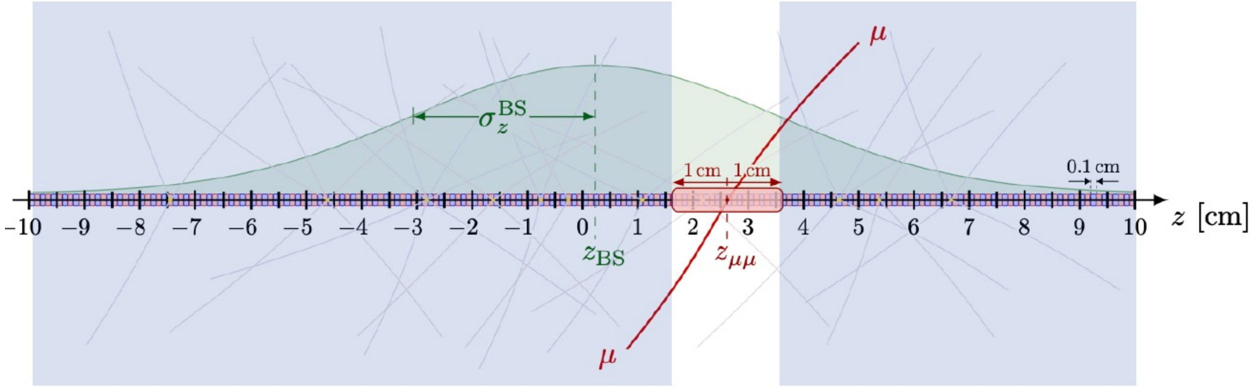
- **Signal samples**
  - Photon-fusion $\gamma\gamma \to W^+W^-$ SM samples are generated with SUPERCHIC4, including elastic, semi-elastic and inelastic events .
  - The contribution from intermediate decays involving τ leptons is also considered
  - EFT signal variations are modeled with MADGRAPH5_AMC@NLO using reweighting for dimension-8 operators, implemented in gammaUPC.
- **Background samples**
  - Drell–Yan: $Z/\gamma^* \to \tau^+\tau^- \to e^\pm\mu^\mp + 4\nu$.
  - Diboson: $WW(\to 2\ell 2\nu)$, $WZ(\to 3\ell\nu)$, $ZZ(\to 2\ell 2\nu)$.
  - Top quark: $\bar{t}t$ ($\bar{t}t_{\text{hadronic}}$, $\bar{t}t_{\text{semi-leptonic}}$, $\bar{t}t_{\text{di-leptonic}}$). Single top: tW (top, antitop), t-channel (top, antitop).

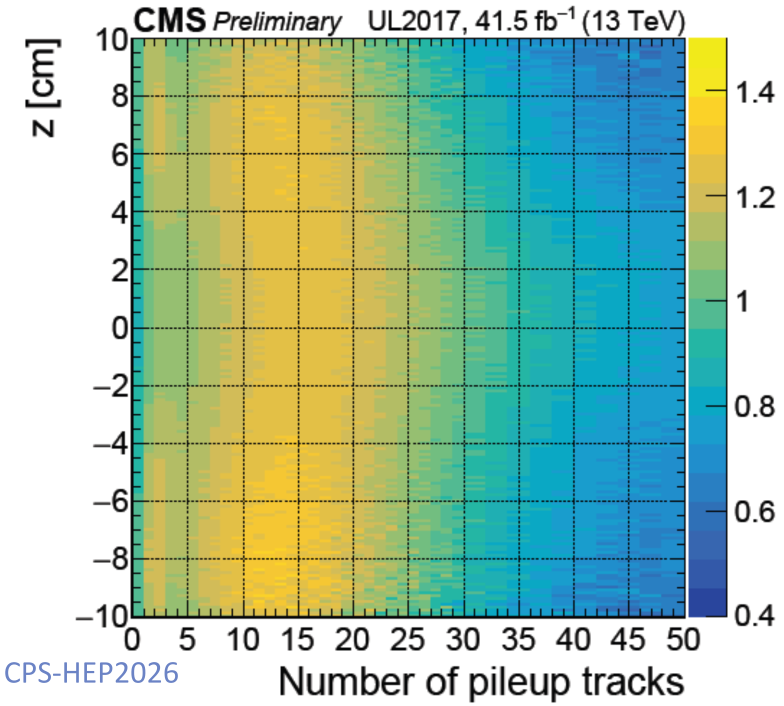
Systematic Uncertainties

Uncertainty	Process	Magnitude
Luminosity	All simulations	$< 3\%$
L1 prefiring	All simulations	negligible
Pileup reweighting	All simulations	Event-dependent
Drell-Yan normalization	Drell-Yan simulation	Rate Parameter
Top cross section	Top simulation	3%
$\gamma\gamma \to$ WW and $\gamma\gamma \to \tau\tau$ normalization	$\gamma\gamma \to$ WW $\gamma\gamma \to \tau\tau$	2%
μ_R, μ_f	Drell-Yan simulation	Shape
PDF	Drell-Yan simulation	Shape
ISR, FSR	Drell-Yan simulation	Shape
Inclusive VV normalization	Inclusive VV simulation	Rate Parameter
e ID, iso, trigger	All simulations	up to 2%
e ID multiplicity correction	All simulation	1%
μ ID, iso, trigger	All simulation	up to 1%
N_{tracks}^{PU} reweighting	All simulations	2%
N_{tracks}^{HS} reweighting	Drell-Yan and inclusive VV	Rate Parameter
OS-to-SS SFs Stat. Unc.	$jet \to e/\mu$ fake background	Shape
Background composition	$jet \to e/\mu$ fake background	10%
Limited statistics	All simulation, fake background	Barlow-Beeston-lite approacl

Pileup track multiplicity correction (for all simulation)

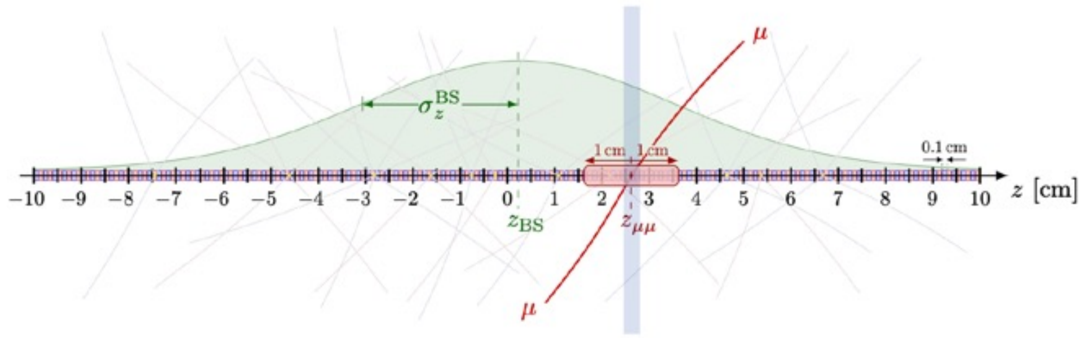
- Use $Z \to \mu\mu$ events at Z peak
- Count number of tracks in small d_z windows away from μμ vertex
- Weight function of window z position and PU track multiplicity

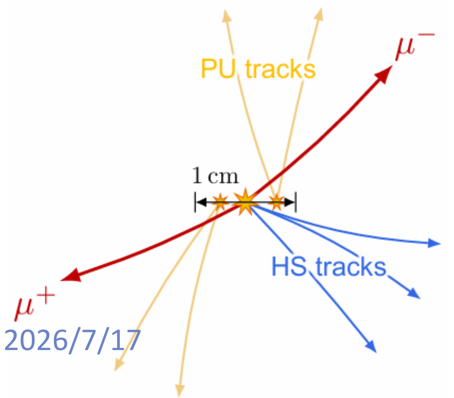


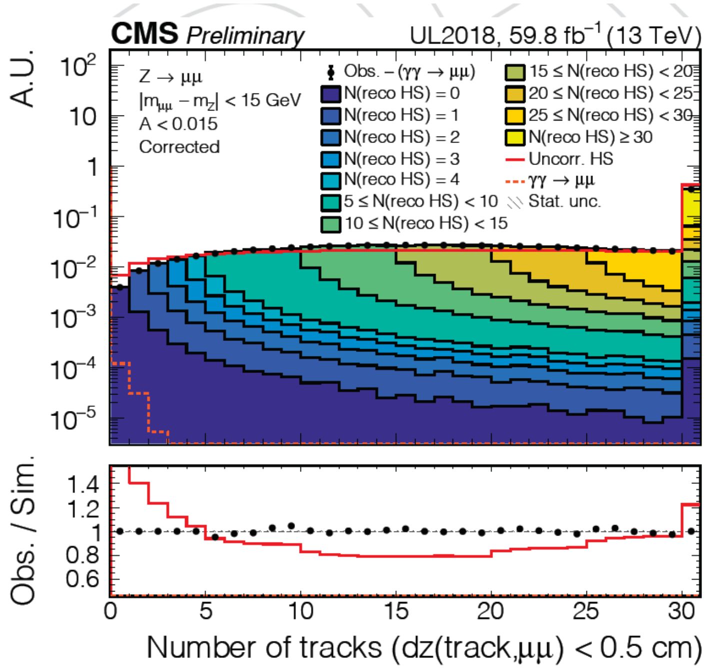


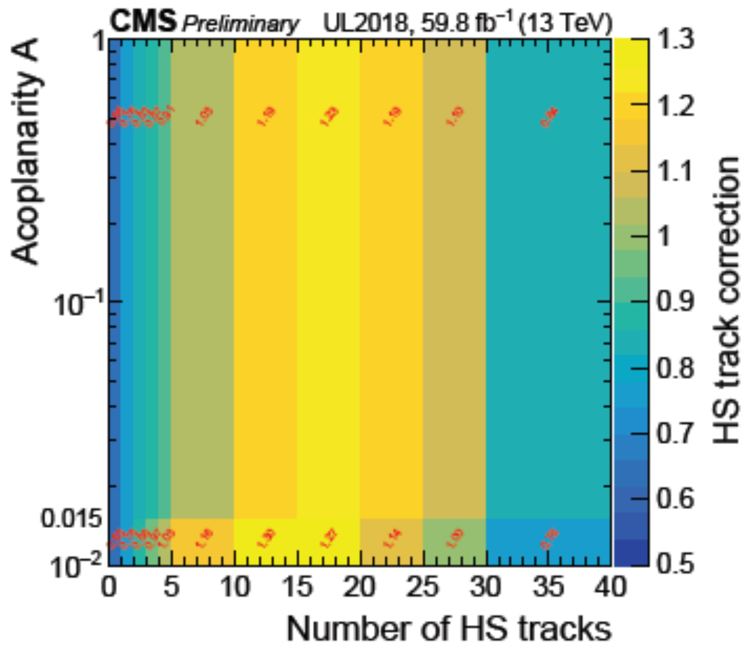
Hard scattering track multiplicity correction (for DY simulation)

- Pileup track multiplicity correction has been applied
- Counting number of tracks ($N_{tracks} = N^{PU}_{tracks} + N^{HS}_{tracks}$) in small dz window around μμ vertex
- Separate Drell-Yan into bins of N^{HS}_{tracks} by gen matching reco tracks
- Corrections are extracted in A<0.015 and A>0.015 separately

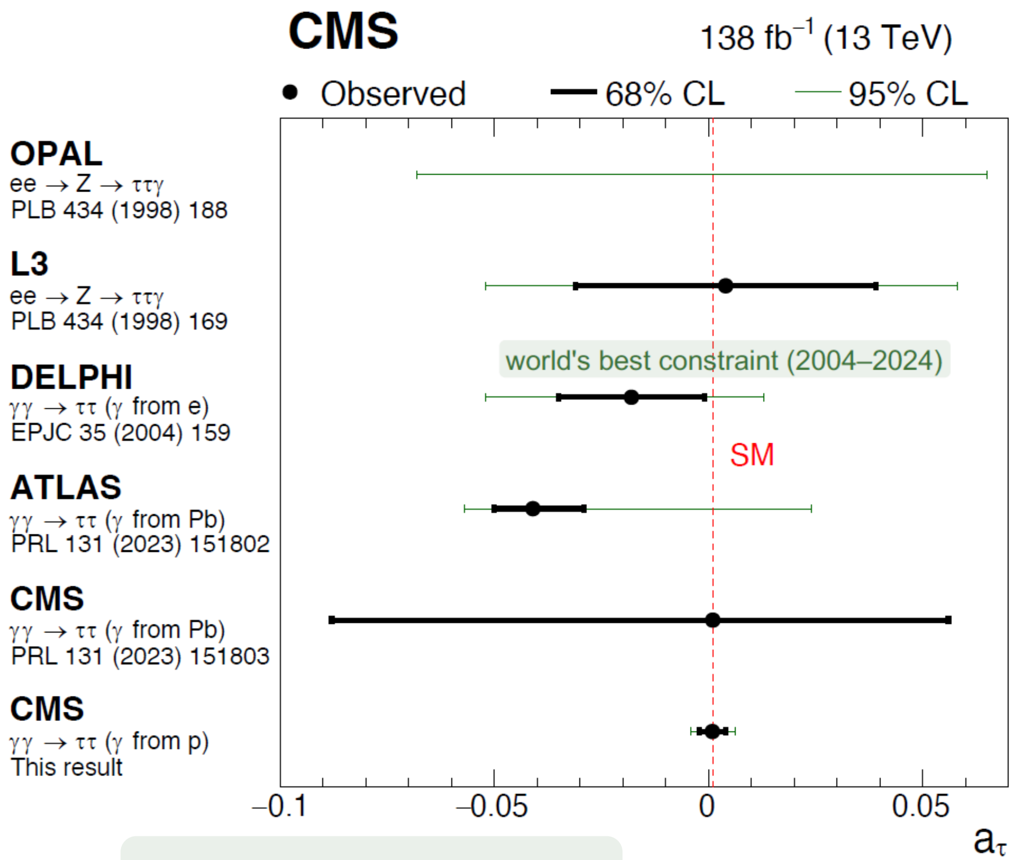




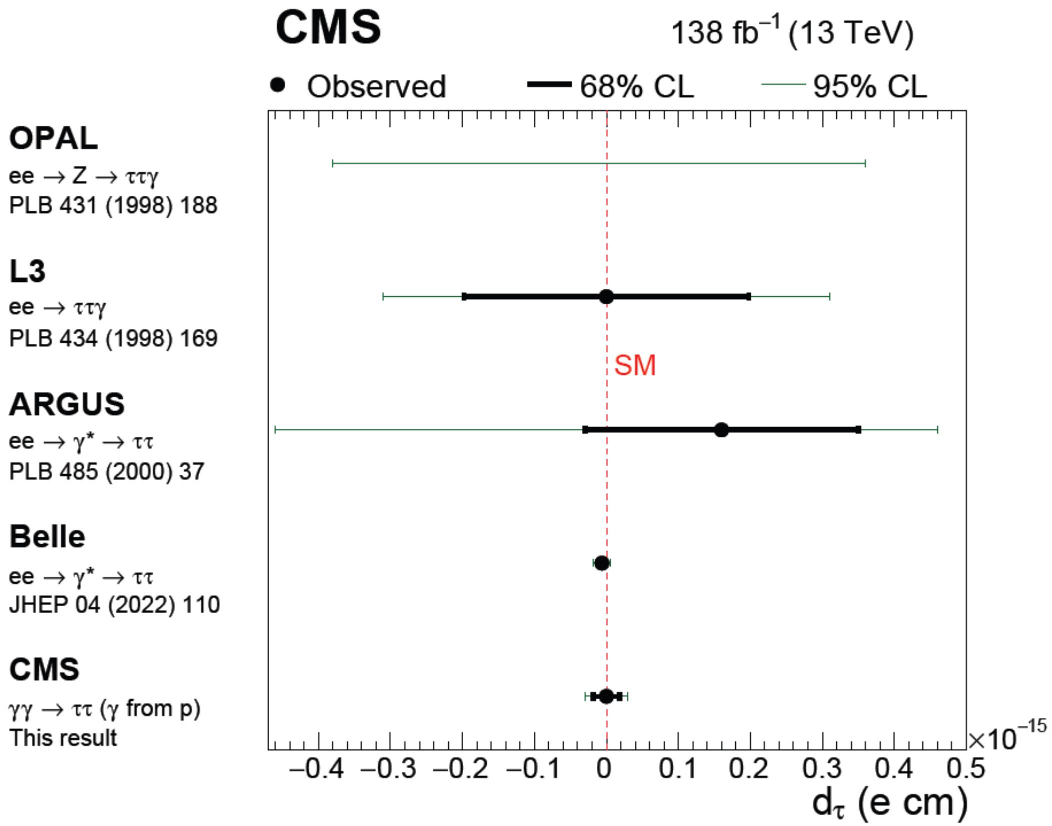




$\gamma\gamma \to \tau\tau$: Constraints on a_τ and d_τ



>5x better than LEP !



approaching Belle !

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