Diboson and polarization measurements in CMS

Giulia Sorrentino
On behalf of the CMS Collaboration

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U.S. DEPARTMENT OF ENERGY

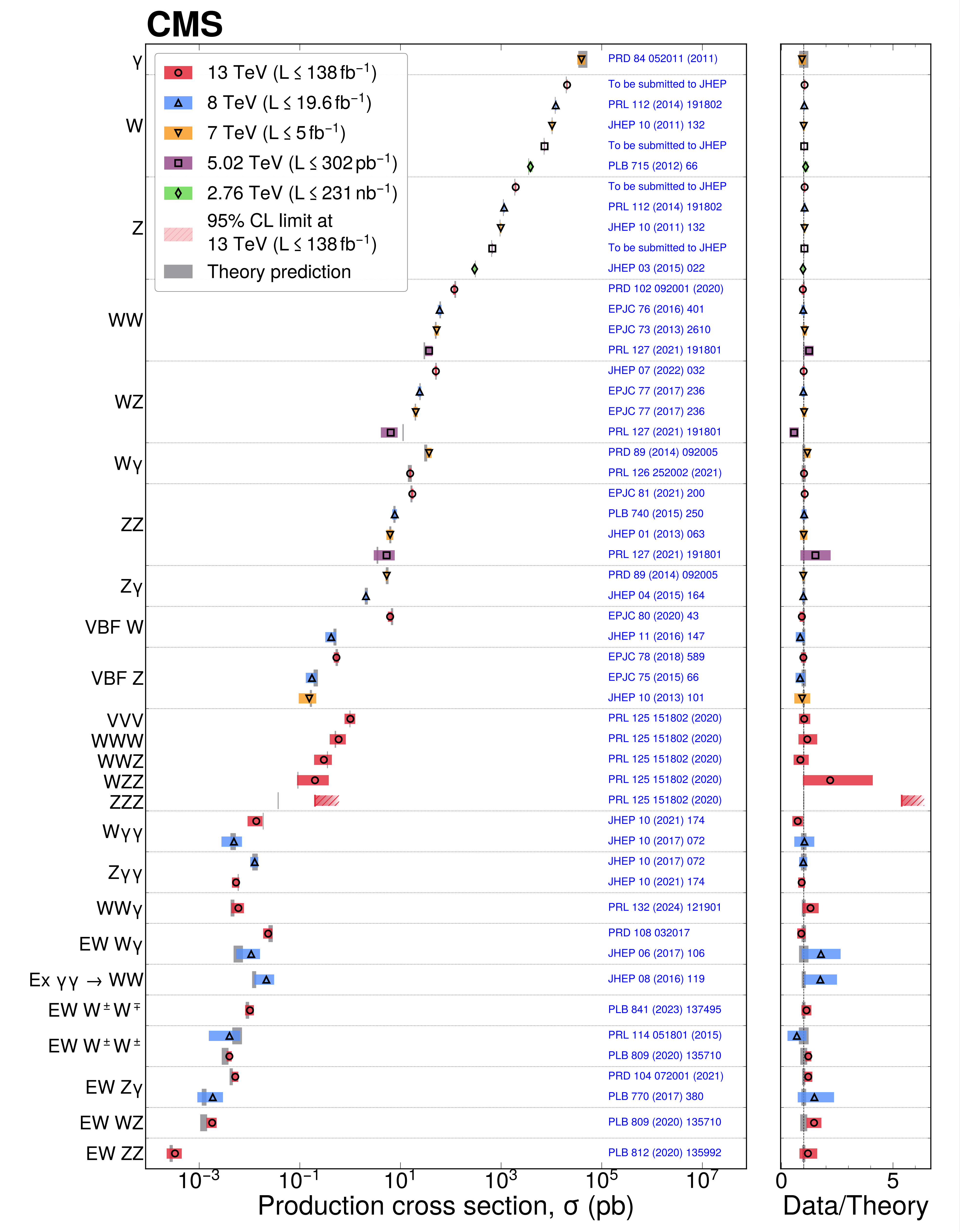
Powerful tests of the Standard Model

- Analysis of boson properties can provide precise measurements of fundamental SM parameters

- Diboson measurements can probe the EWK sector of the SM at TeV scale

    - Background for Higgs analysis and for New Physics (mono-photon searches)

    - Indirect search for New Physics through anomalous gauge boson couplings



Outlook

- **Polarization**
  - **Tau polarization in Z decays** *Published on JHEP*
- **Diboson**
  - **ZZ+jets** *Submitted to JHEP*
  - **$\gamma\gamma \rightarrow \tau\tau$** *Submitted to ROPP* Today!
  - **$Z(\rightarrow \nu\nu)\gamma$** *CMS-PAS-SMP-22-009*
  - **WW@13.6 TeV** *CMS-PAS-SMP-24-001*

In preparation to be submitted

VBS VV results discussed in a dedicated talk

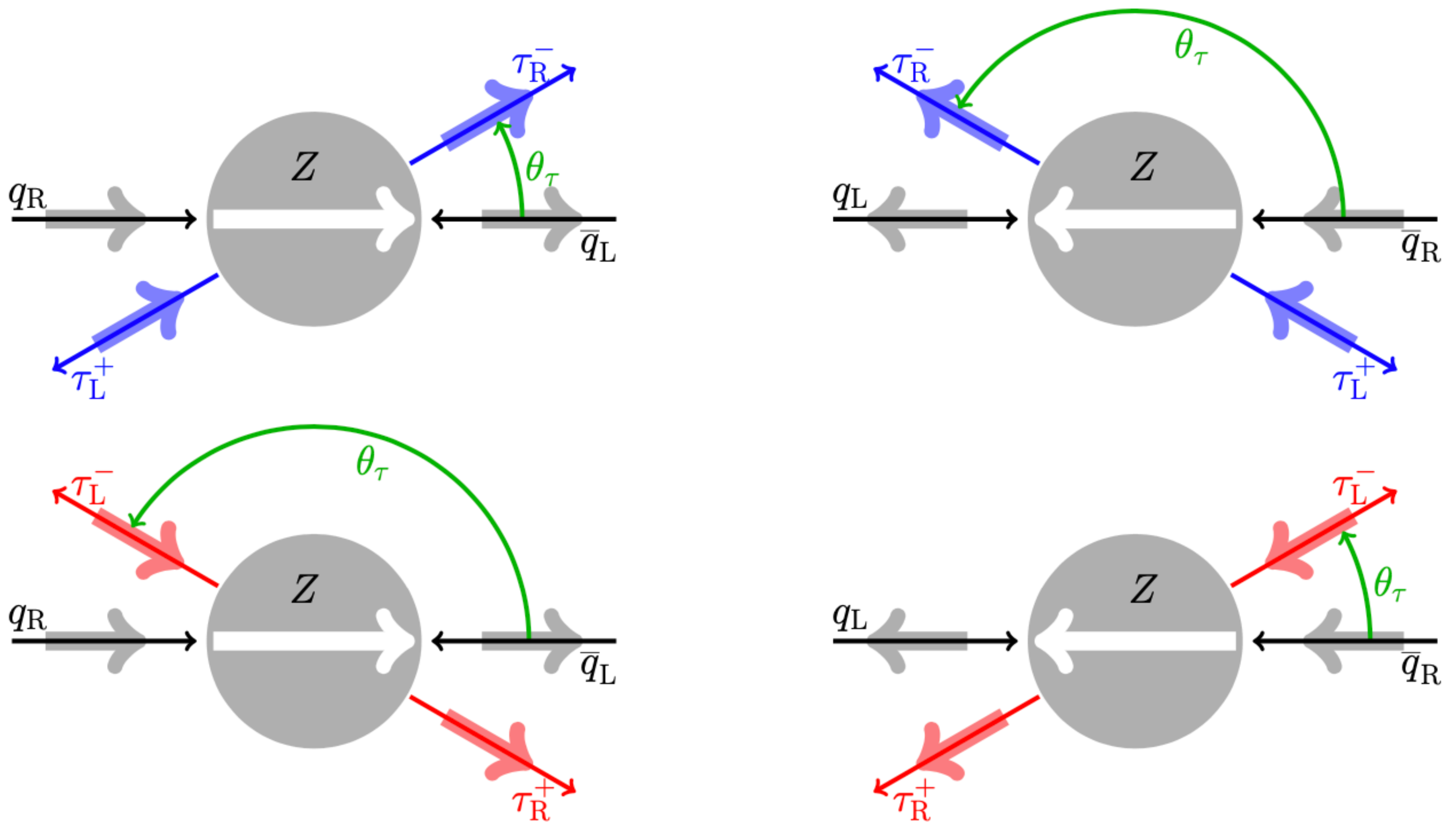
Tau polarization in Z →ττ decays

Published on JHEP

- pp collisions@13 TeV, 2016 data (35.9 fb^{-1})
- Measurement of the average τ polarization
- Convert polarization into $sin^2\theta^{eff}_W$

$$\langle \mathcal{P}_\tau \rangle = \frac{N(Z \to \tau_R^- \tau_L^+) - N(Z \to \tau_L^- \tau_R^+)}{N(Z \to \tau_R^- \tau_L^+) + N(Z \to \tau_L^- \tau_R^+)},$$

- **Helicity** information extracted **from angular kinematics of tau decay products**



4 decay channels
11 categories

Discriminator choice
based on likelihood scans

Channel	Category	Discriminator	
$\tau_e\tau_\mu$	$e+\mu$	$m_{vis}(e,\mu)$	visible mass
$\tau_e\tau_h$	$e+a_1$	$\omega(a_1)$	optimal observable with SVFIT
	$e+\rho$	$\omega_{vis}(\rho)$	visible optimal observable
	$e+\pi$	$\omega(\pi)$	optimal observable with SVFIT
$\tau_\mu\tau_h$	$\mu+a_1$	$\omega(a_1)$	optimal observable with SVFIT
	$\mu+\rho$	$\omega_{vis}(\rho)$	visible optimal observable
	$\mu+\pi$	$\omega(\pi)$	optimal observable with SVFIT
$\tau_h\tau_h$	a_1+a_1	$m_{vis}(a_1,a_1)$	visible mass
	$a_1+\pi$	$\Omega(a_1,\pi)$	combined optimal observable with SVFIT
	$\rho+\tau_h$	$\omega_{vis}(\rho)$	visible optimal observable (for leading ρ)
	$\pi+\pi$	$m_{vis}(\pi,\pi)$	visible mass

- For spin-1 intermediate resonances, θ is not sensitive enough → 3 more angles α, β and γ
- 1D fit to a unique optimal variable ***ω(θ, α, β, γ)***

2τ combination

$$\Omega = \frac{\omega_1 + \omega_2}{1 + \omega_1\omega_2}$$

- Modified SVFIT for τ decay reconstruction
- BDT MVA algorithm applied in addition to the HPS algorithm

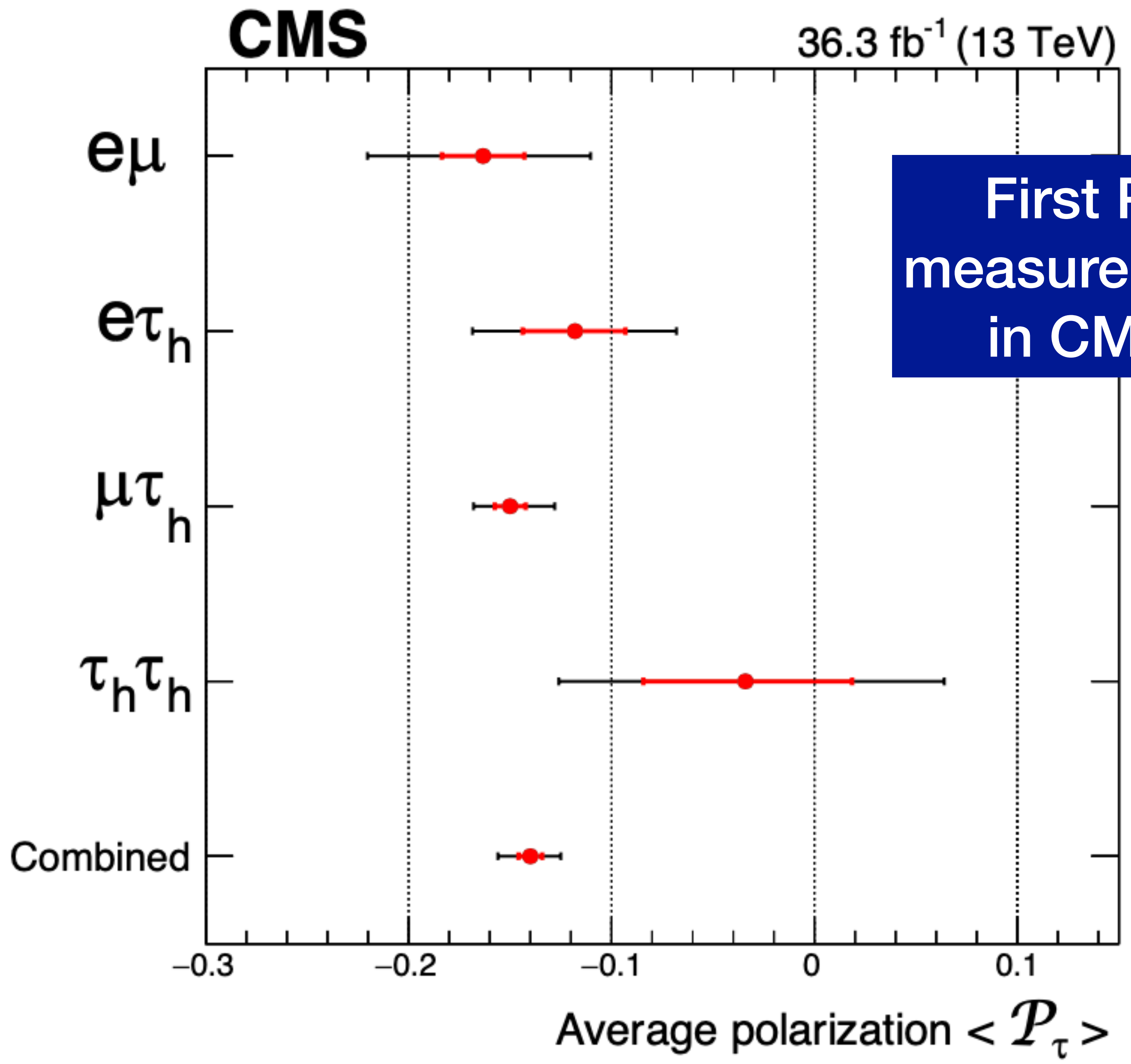
Tau polarization in Z →ττ decays

Published on JHEP

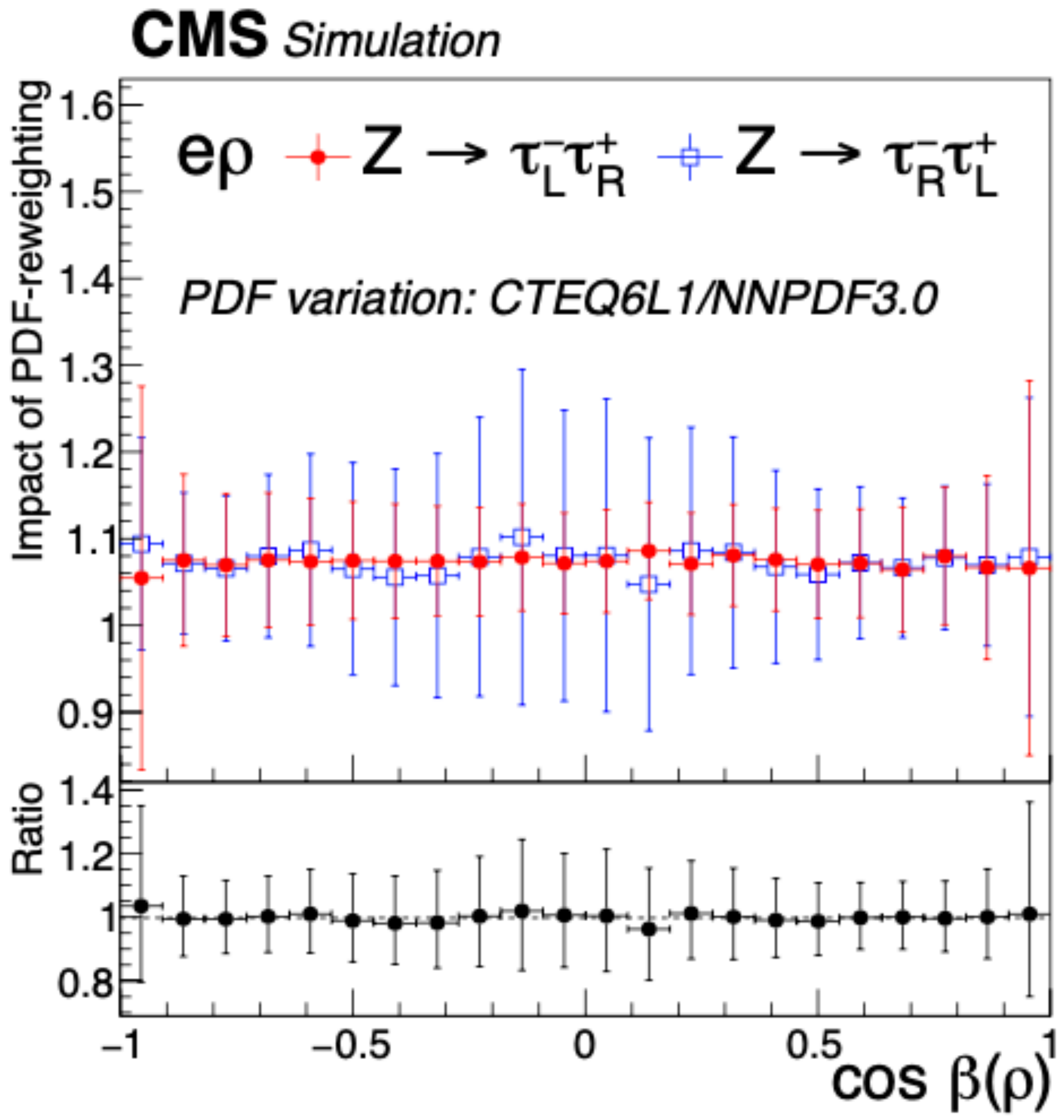
- Extraction of polarization with template fits: $\mathcal{T}(data) \overset{fit}{=} \mathcal{T}(sig, \langle \mathcal{P}_\tau \rangle, r) + \mathcal{T}(bkg)$

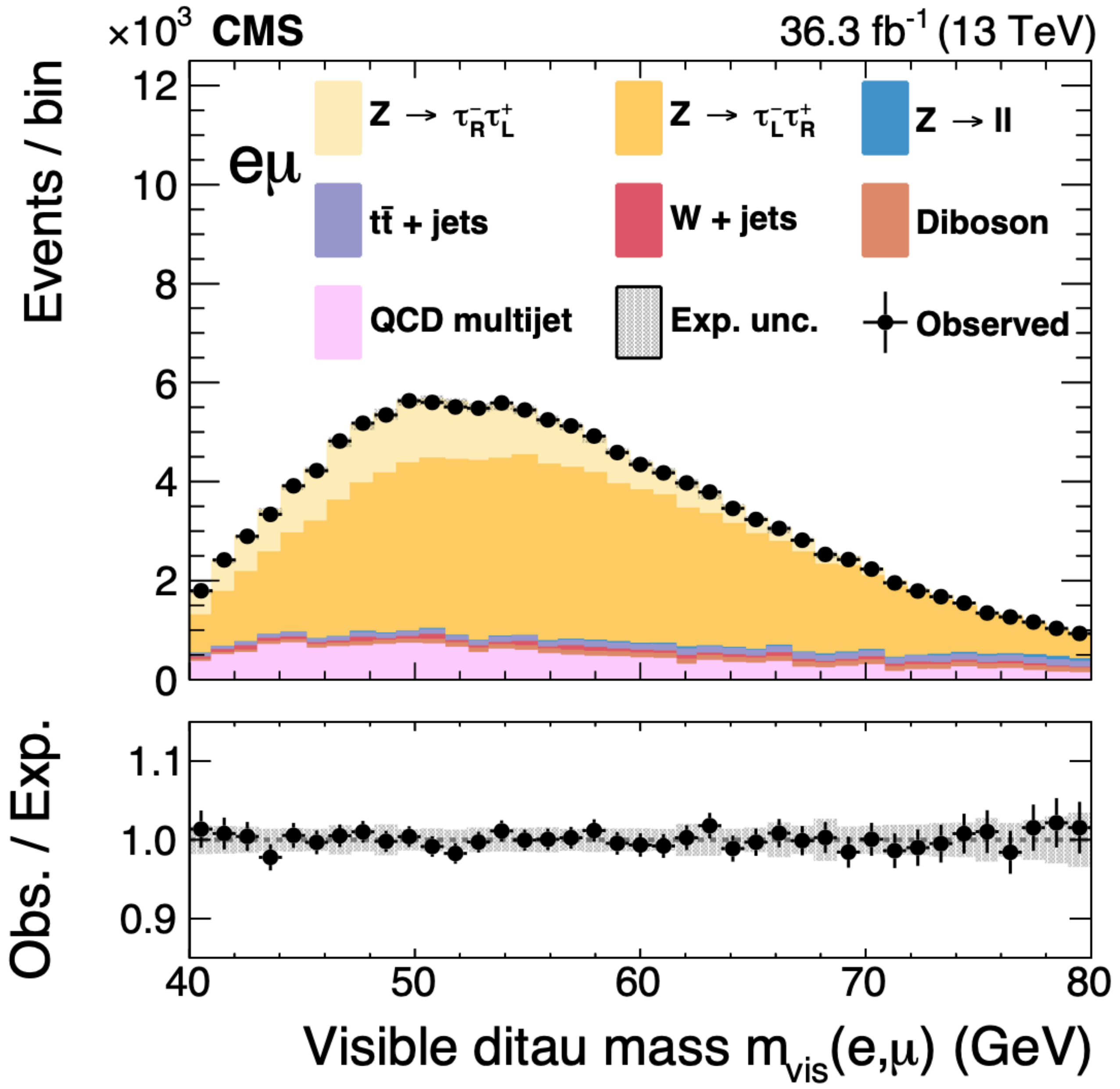
  2 P.O.I.

- Templates for right- and left-handed τ



First Pτ measurement in CMS





$\langle \mathrm{P}\tau \rangle_{75-120\ \mathrm{GeV}}$ = **−0.140 ± 0.006(*stat*) ± 0.014(*syst*)**

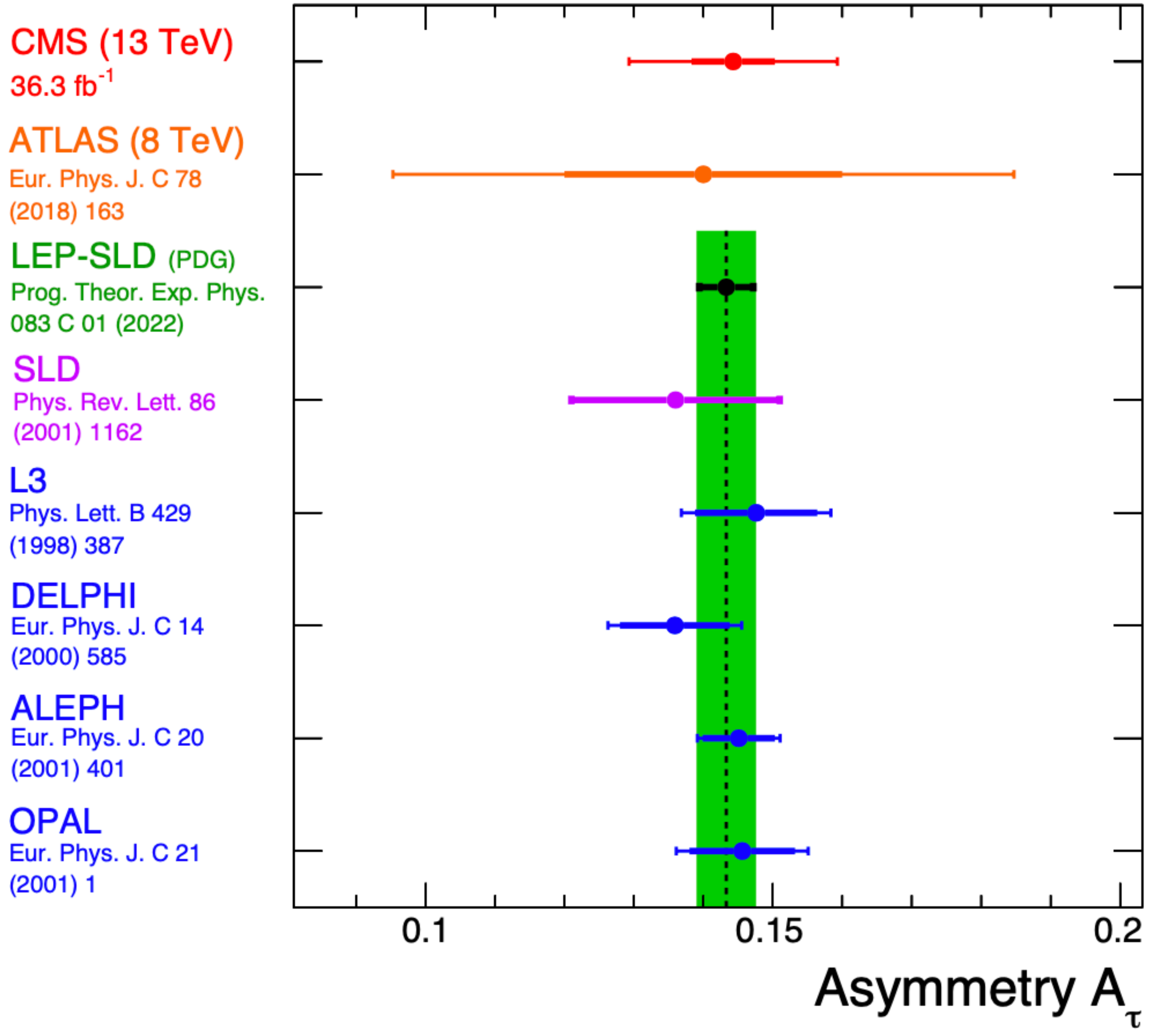
- **Stability** of extracted polarisation **wrt eta**

- Possible **PDF effects are negligible**
- Signal reweighted to test different PDF sets (nominal PDF set is NNPDF30_lo_as_0130)

Tau polarization in Z →ττ decays

Published on JHEP

- Correct ⟨P_τ⟩ to the polarization value at the Z pole → **$P_\tau(Z)=-A_\tau$**



- **Most precise measurement of A_τ at the LHC**
- Precision comparable to the SLD experiment

Extracting $sin^2\theta^{eff}_W$ as $P_\tau(Z)=-A_\tau = -2(1-4\ sin^2\theta^{eff}_W)$

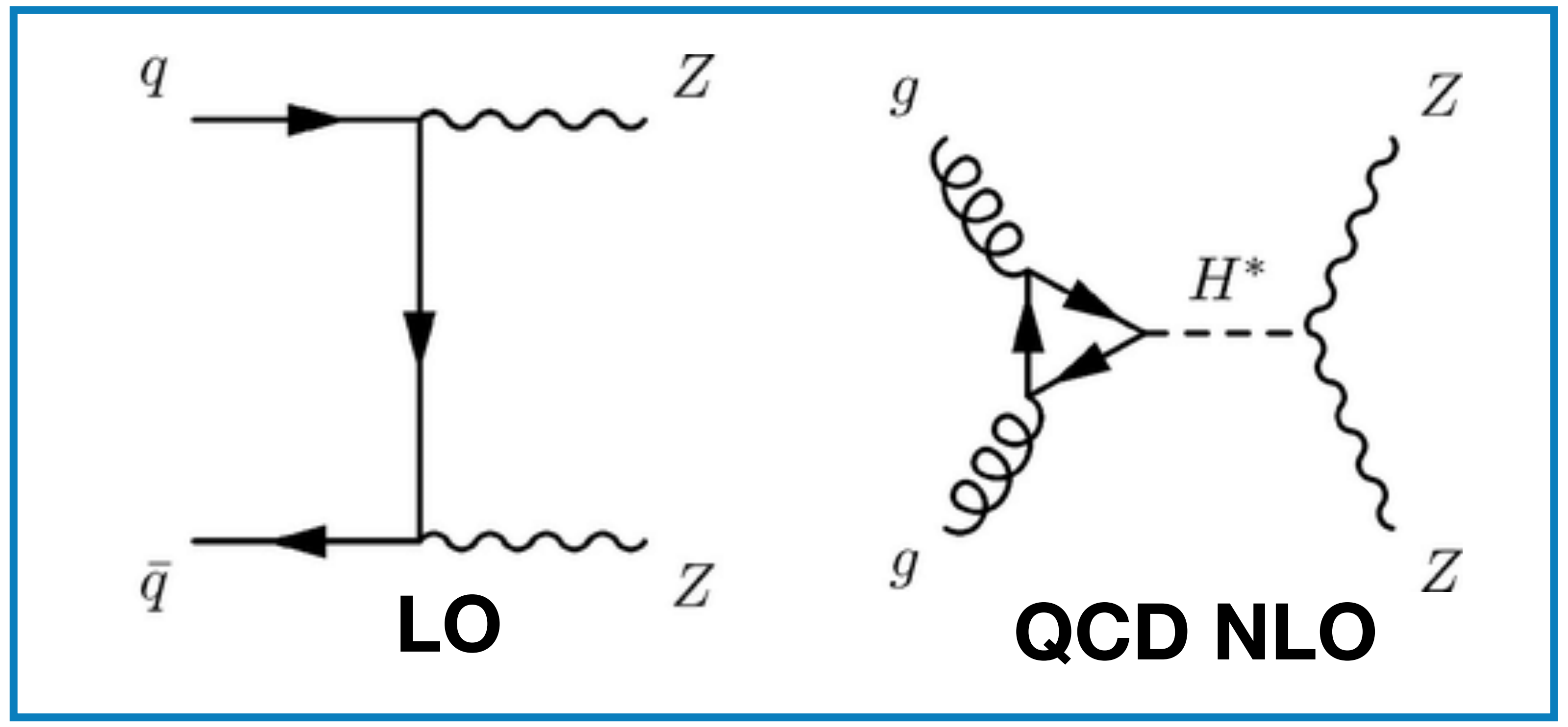
$$\boldsymbol{sin^2\theta^{eff}_W = 0.2319 \pm 0.0008(stat) \pm 0.0018(syst)}$$
$$\boldsymbol{= 0.2319 \pm 0.0019}$$

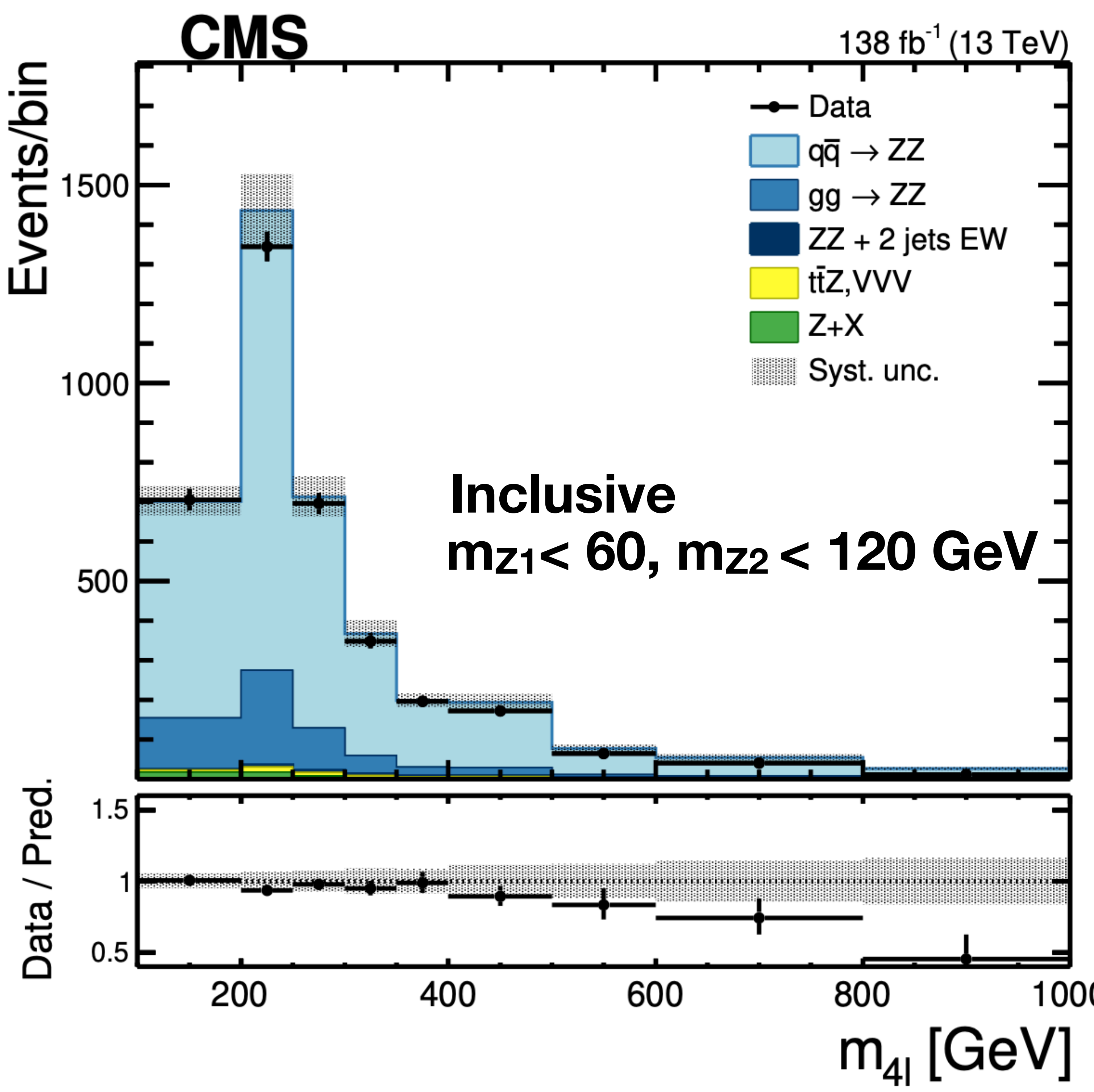
In agreement with SM

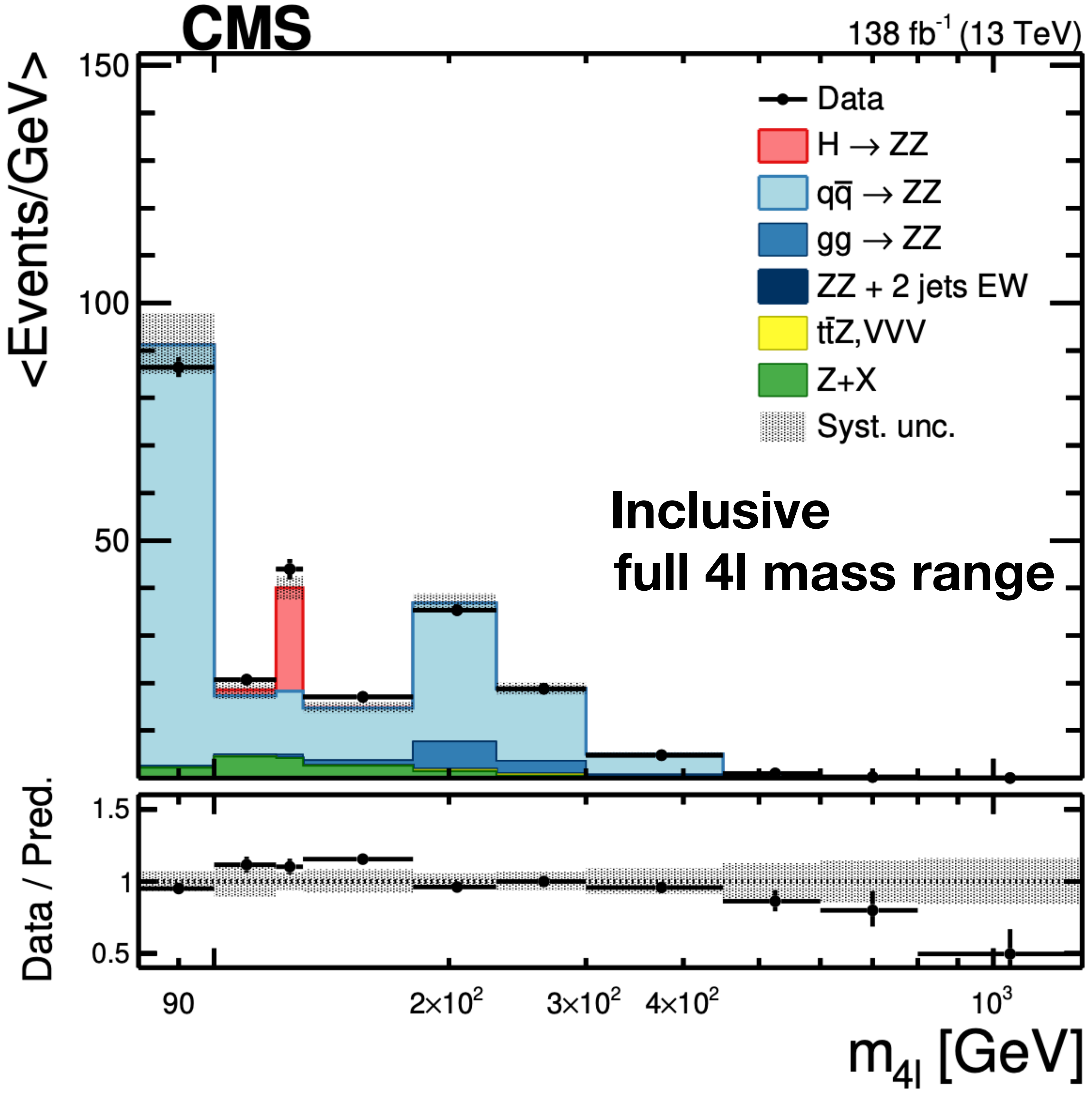
ZZ+jets production

Submitted to JHEP

- pp collisions@13 TeV and Full Run2 statistics (138 fb^{-1})
- Differential xsec







- Four isolated leptons from PV + contribution from FSR photon with ΔR(l,γ) < 0.5
- 2 on-shell Z candidates built from OS, same flavor leptons
- $40 < m_{Z1} < 120$ GeV, $4 < m_{Z2} < 120$ GeV
- $p_T^{jets} > 30$ GeV and ΔR(jet,l/γ) > 0.4

Very low background

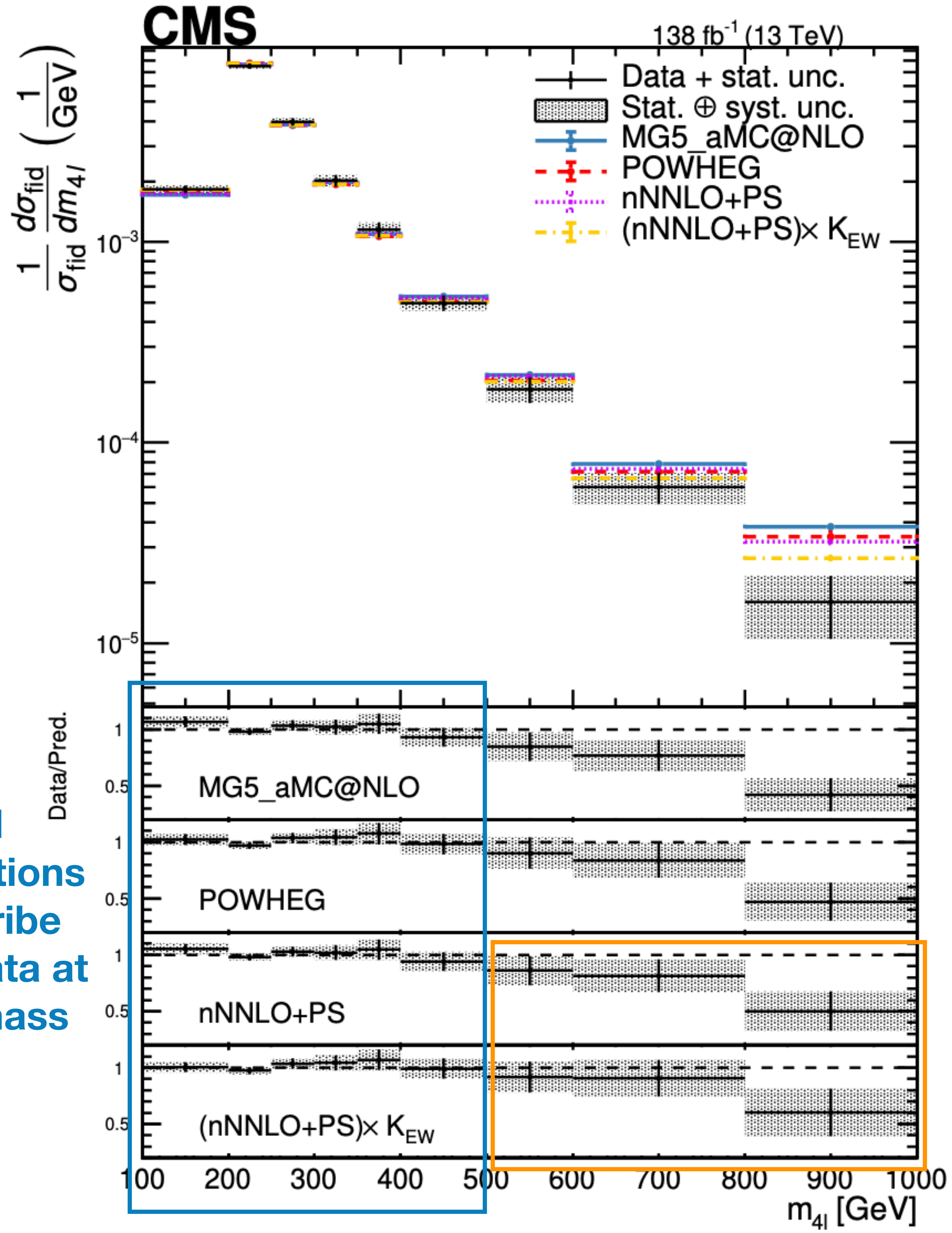
- Z and WZ production + jets estimated using control regions (1/2%)
- ttZ and VVV from simulation (1–1.5%)

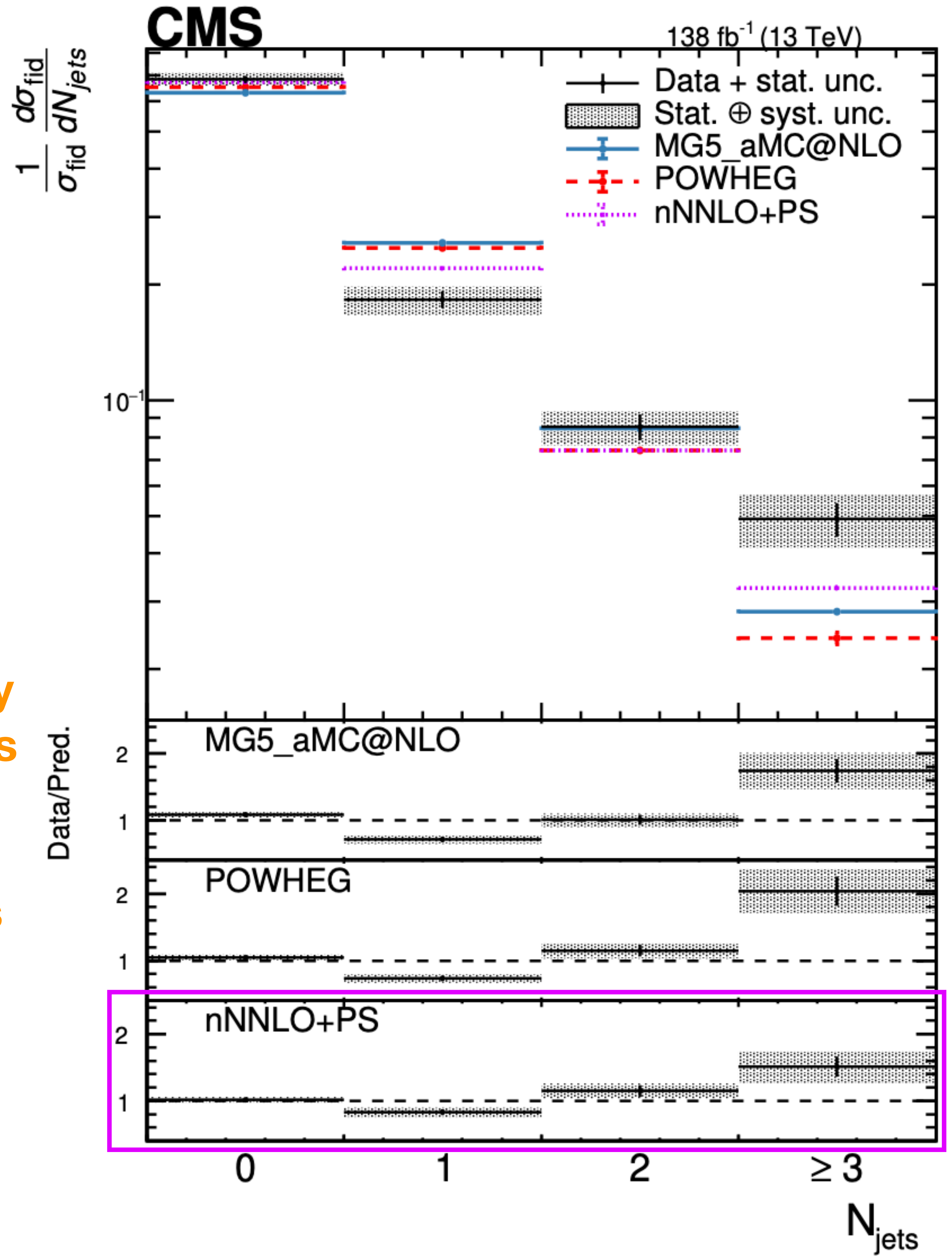
- **qq → ZZ:** MadGraph5 aMC@NLO+POWHEG 2.0+NNLO K-factor
- **gg → ZZ:** LO with MCFM+QCD NLO K-factor
- **EWK ZZ + 2 jets:** MadGraph at LO
- **HZZ:** POWHEG at NLO

ZZ+jets production

Submitted to JHEP

- Data unfolded using the iterative D'Agostini's method





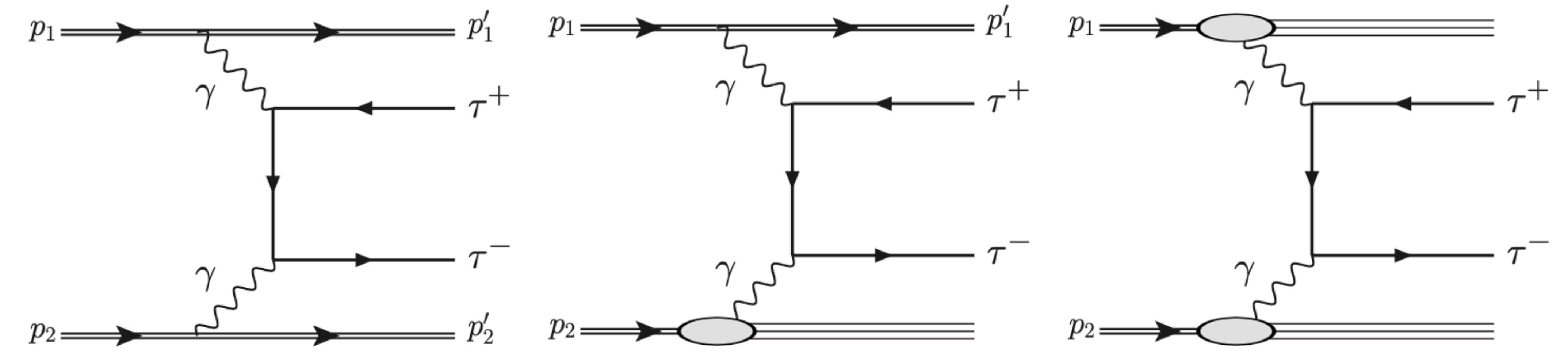
All predictions describe well data at low mass

Discrepancy at high mass mitigated with EW corrections

Best prediction

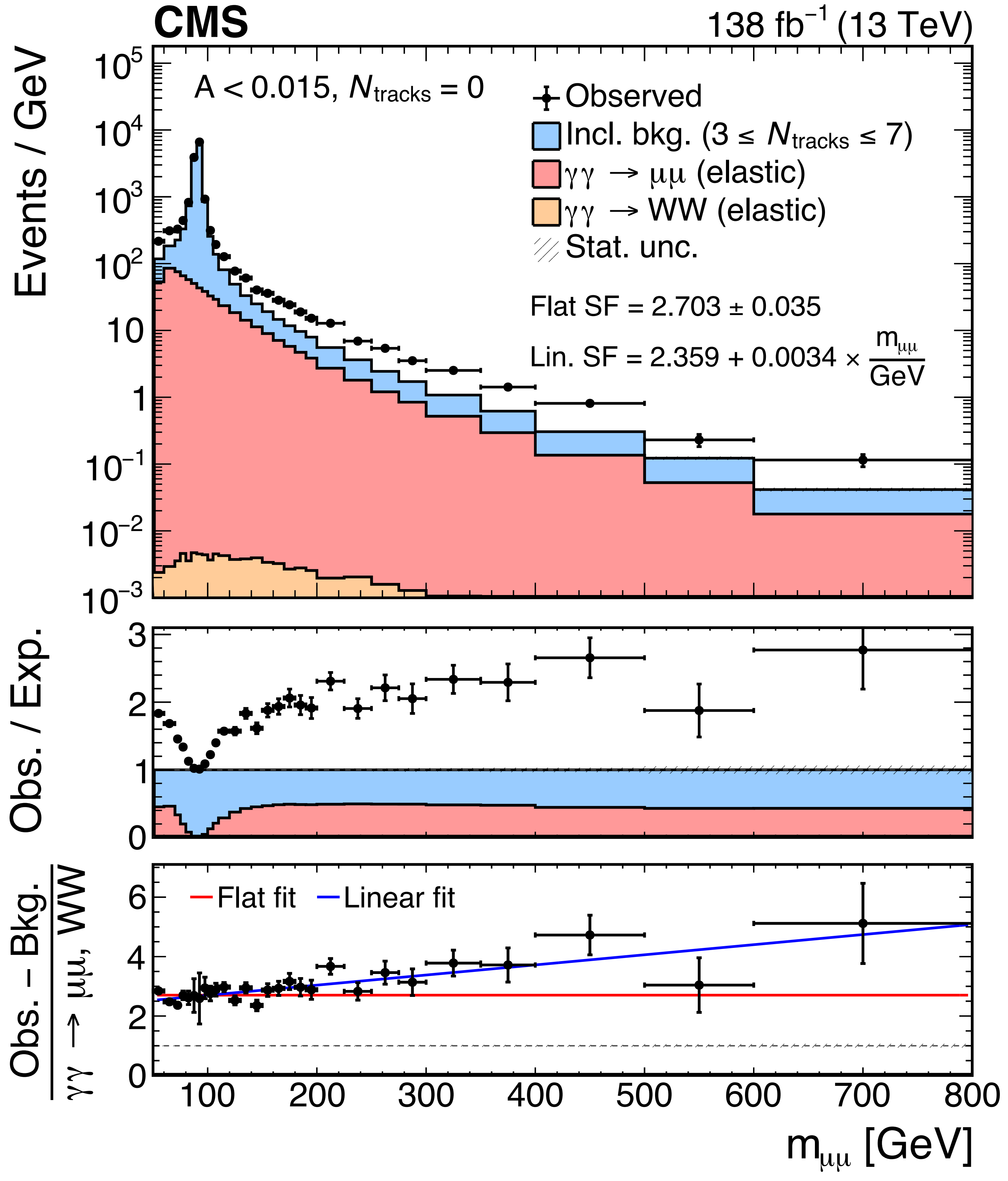
ττ photon-induced production

Submitted to ROPP



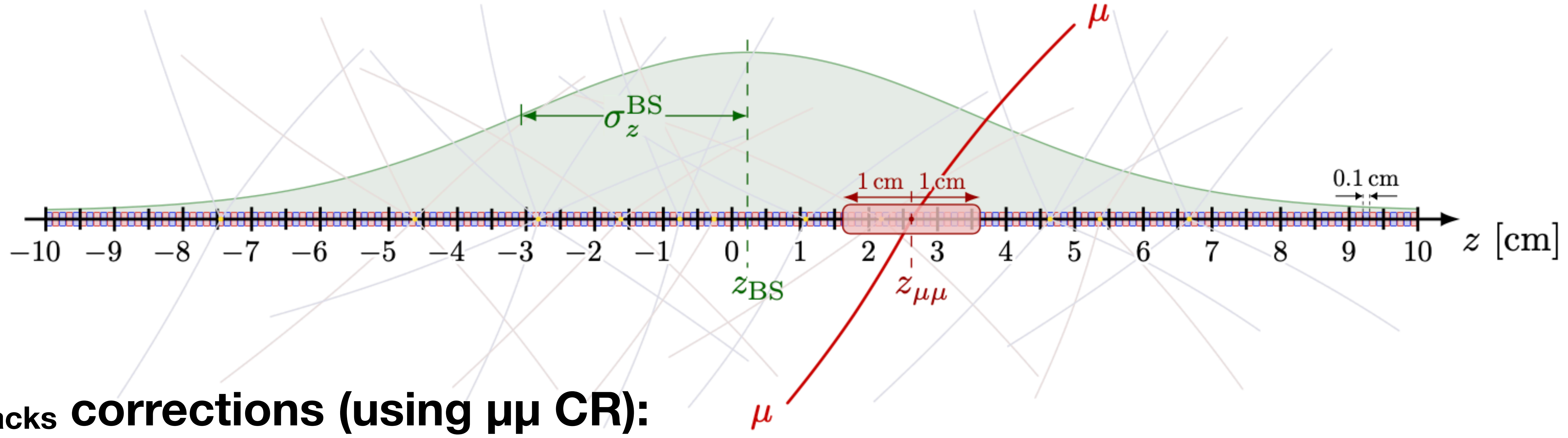
Exclusive/Elastic | Single-dissociative (SD) | Double-dissociative (DD)

- pp collisions@13 TeV and Full Run2 statistics (138 fb^{-1})
- First observation of ττ photon-induced production
- Limits on the τ anomalous electromagnetic momenta



- SD and DD contributions estimated from **μμ CR** in data
- **Inclusive bkg** estimated in sideband region (3 < N_{tracks} < 7 GeV)
- **Elastic γγ→μμ/WW** estimated from GAMMA-UPC and rescaled to match data

- **4 Final States:** eμ, eτ_h, μτ_h, $\tau_h\tau_h$
- **50 < $m^{vis}_{\tau\tau}$ < 500 GeV**
- **Exclusivity cuts**
  - Back-to-back production → acoplanarity A = 1–|ΔΦ|/π < 0.015
  - Low activity around ττ vertex, N_{tracks} = 0,1 (75% signal efficiency)



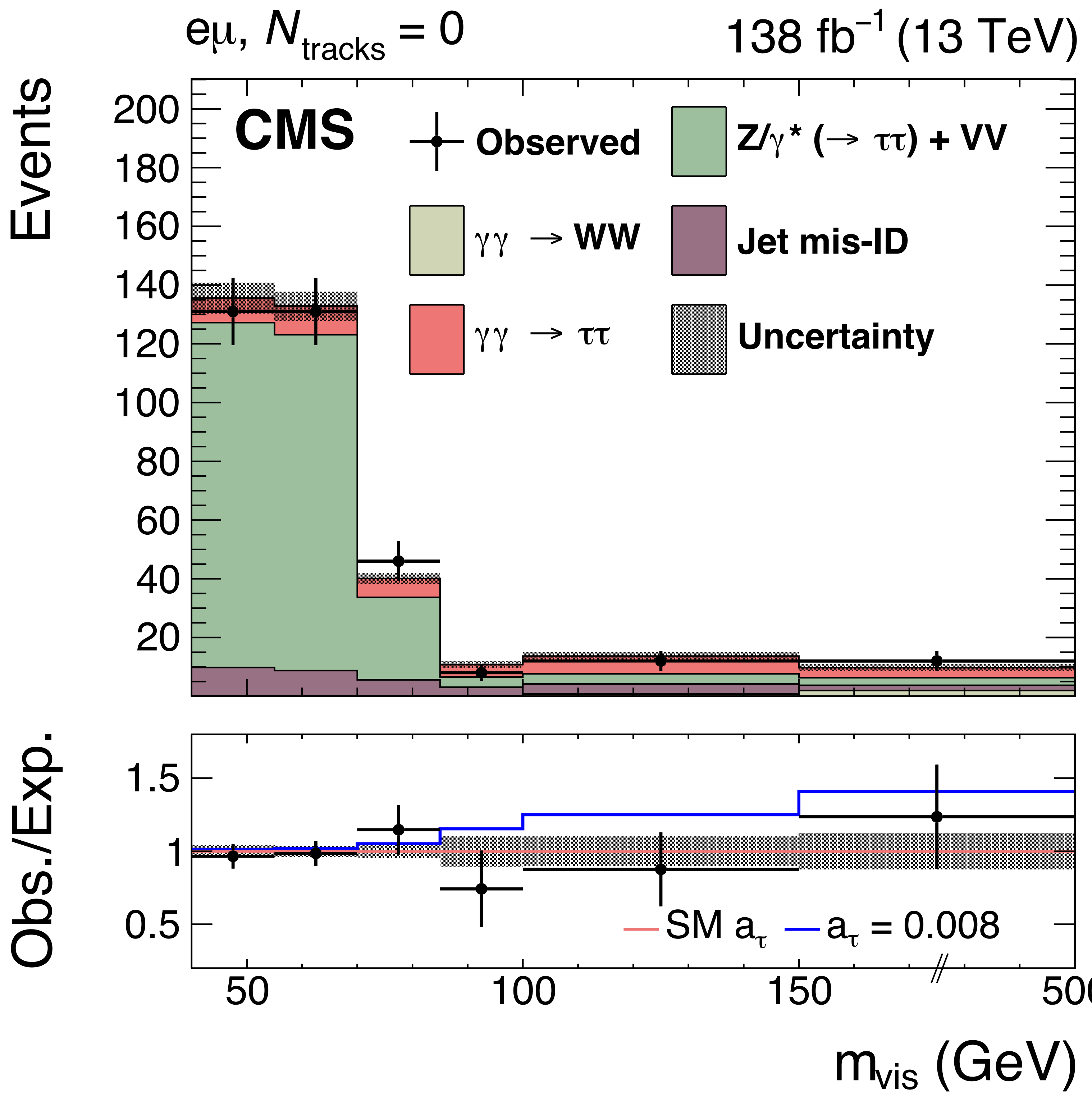
N_{tracks} corrections (using μμ CR):

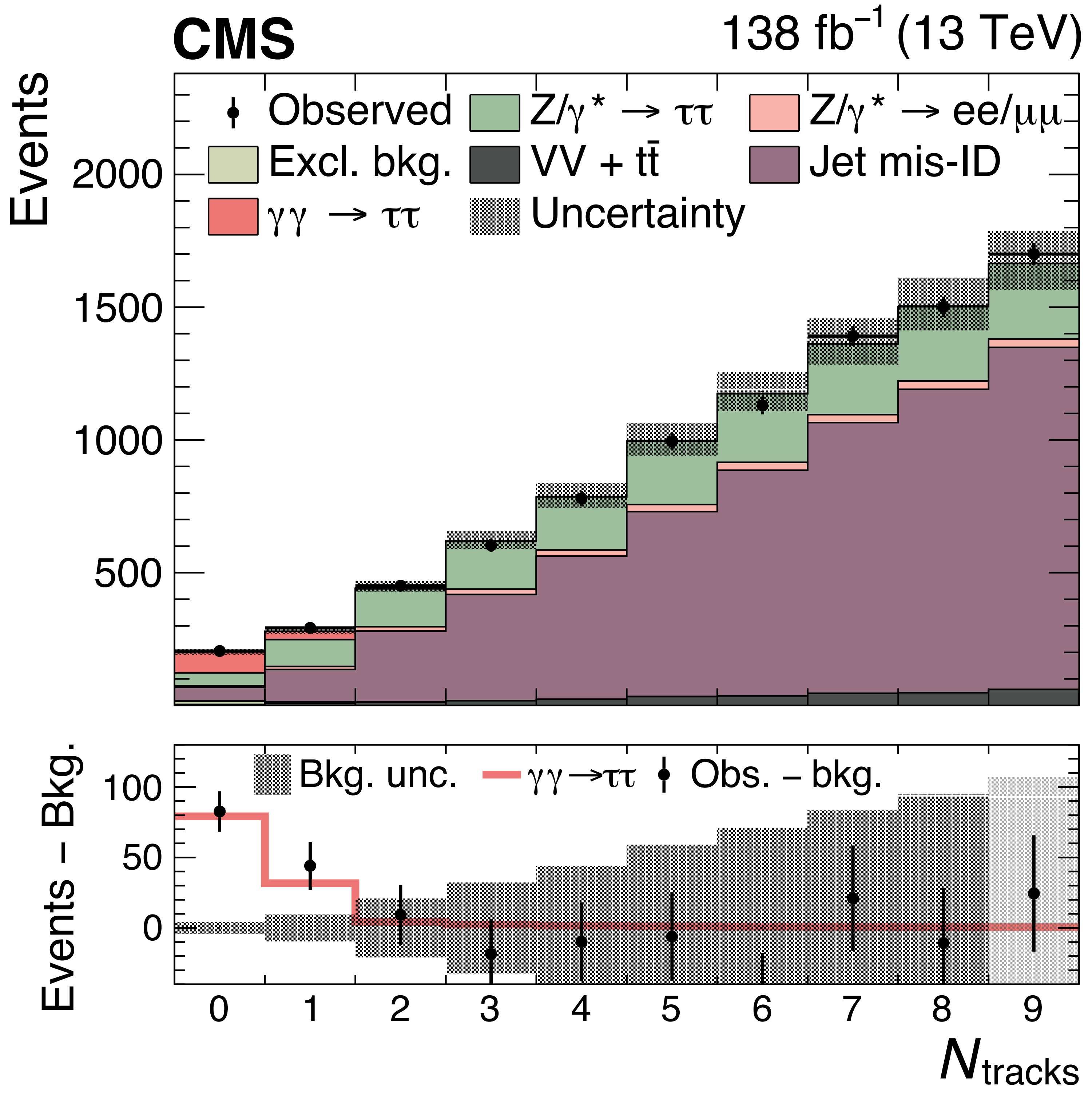
- **PU tracks:** compare N_{tracks} distributions in 0.1 cm **z-windows** far from μμ vertex
- **HS tracks:** compare N_{tracks} around μμ vertex after subtracting PU tracks

$\tau\tau$ photon-induced production

Submitted to ROPP

- m_{vis} and N_{tracks} distributions after ML fit, **assuming SM τ momenta**





Fiducial region

	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
p_T^e (GeV)	$> 15/24$	> 25	—	—
$\lvert\eta^e\rvert$	< 2.5	< 2.5	—	—
p_T^μ (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

σ^{obs} = 12.4 +3.8 -3.1 fb

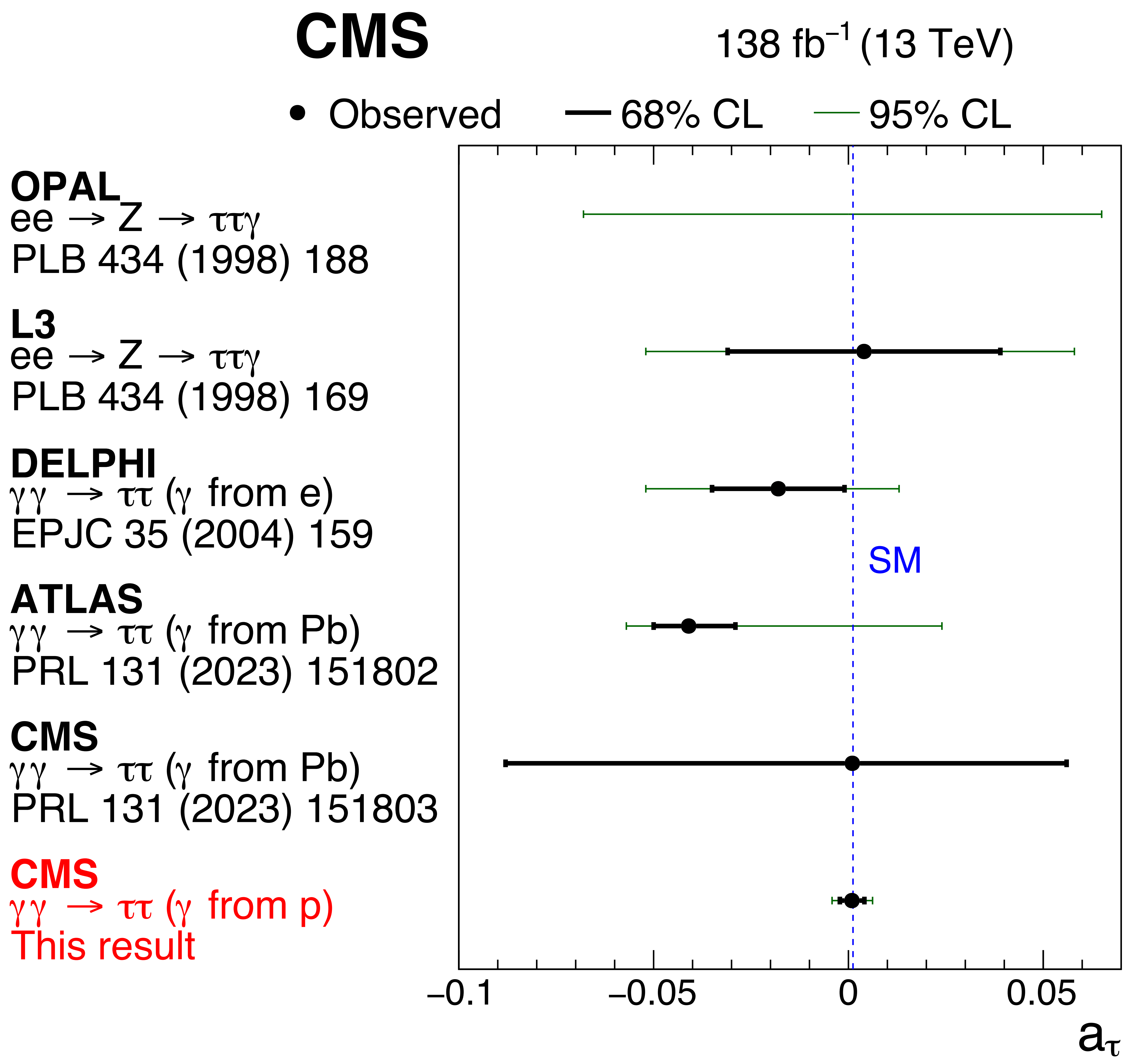
Compatible with predictions:
σ^{exp} = 16.5 ± 1.5 fb (GAMMA-UPC)

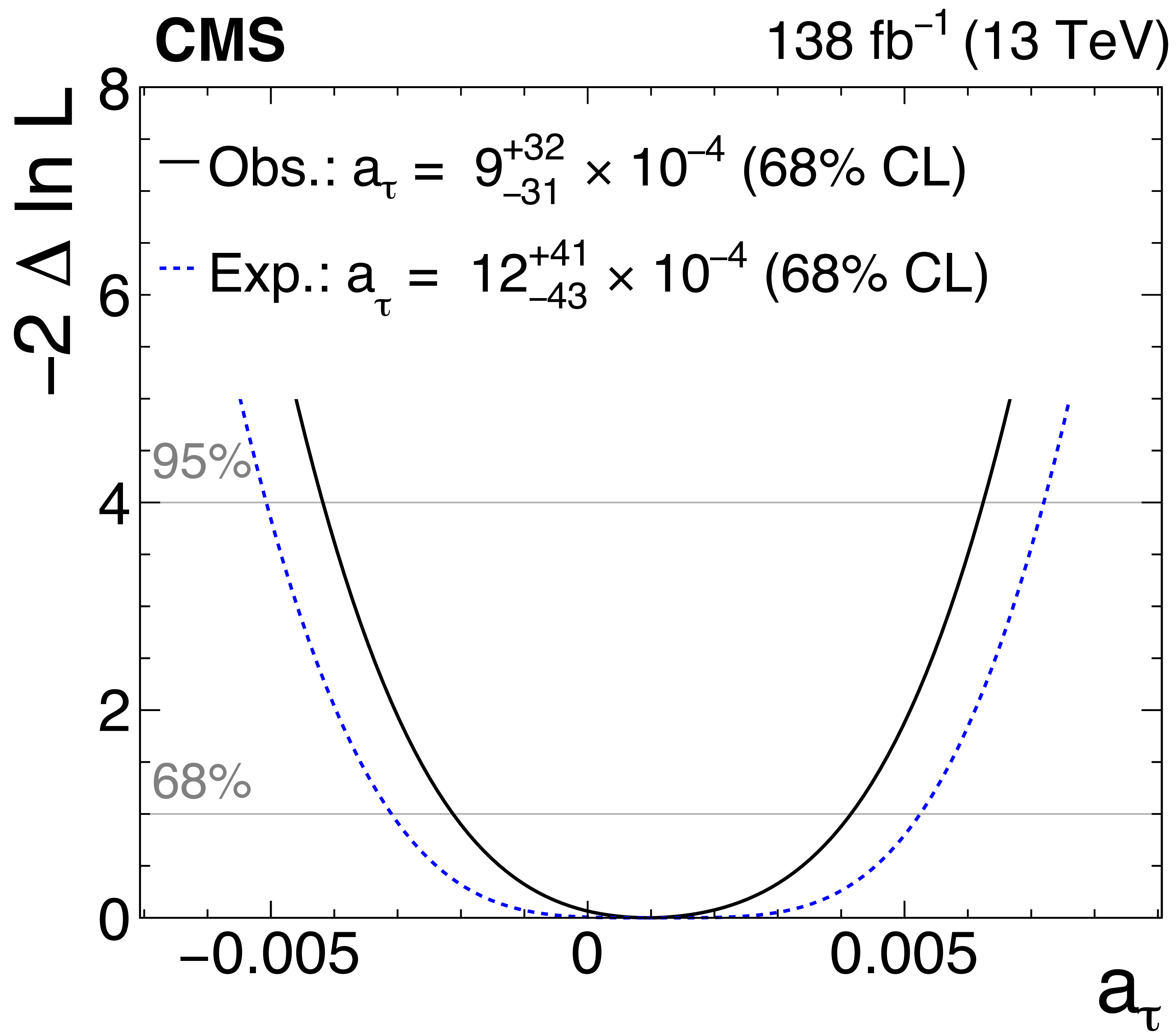
5.3 σ observed (6.5 σ expected)

First γγ→ττ observation in pp runs

ττ photon-induced production

- a_τ and d_τ parameterized within SMEFT framework

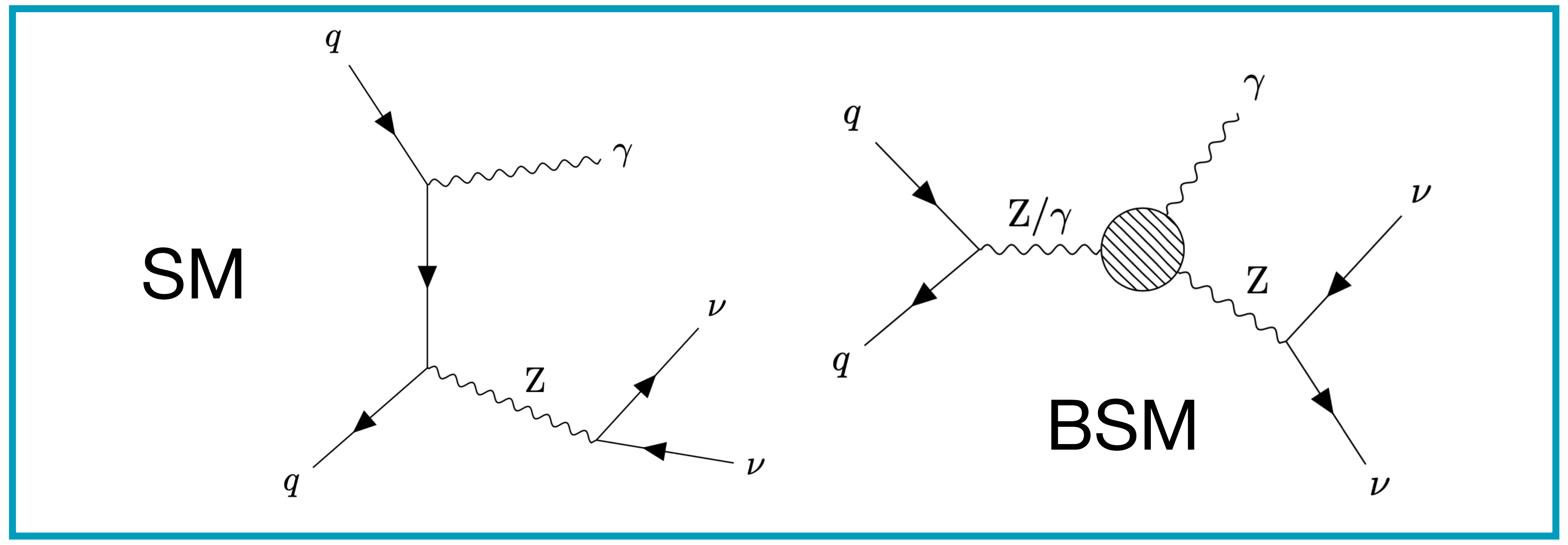




- SM a_τ=0.00117721(5)
- DELPHI: a_τ=-0.018±0.017
- This result: a_τ=-0.0009+0.0032/-0.0031

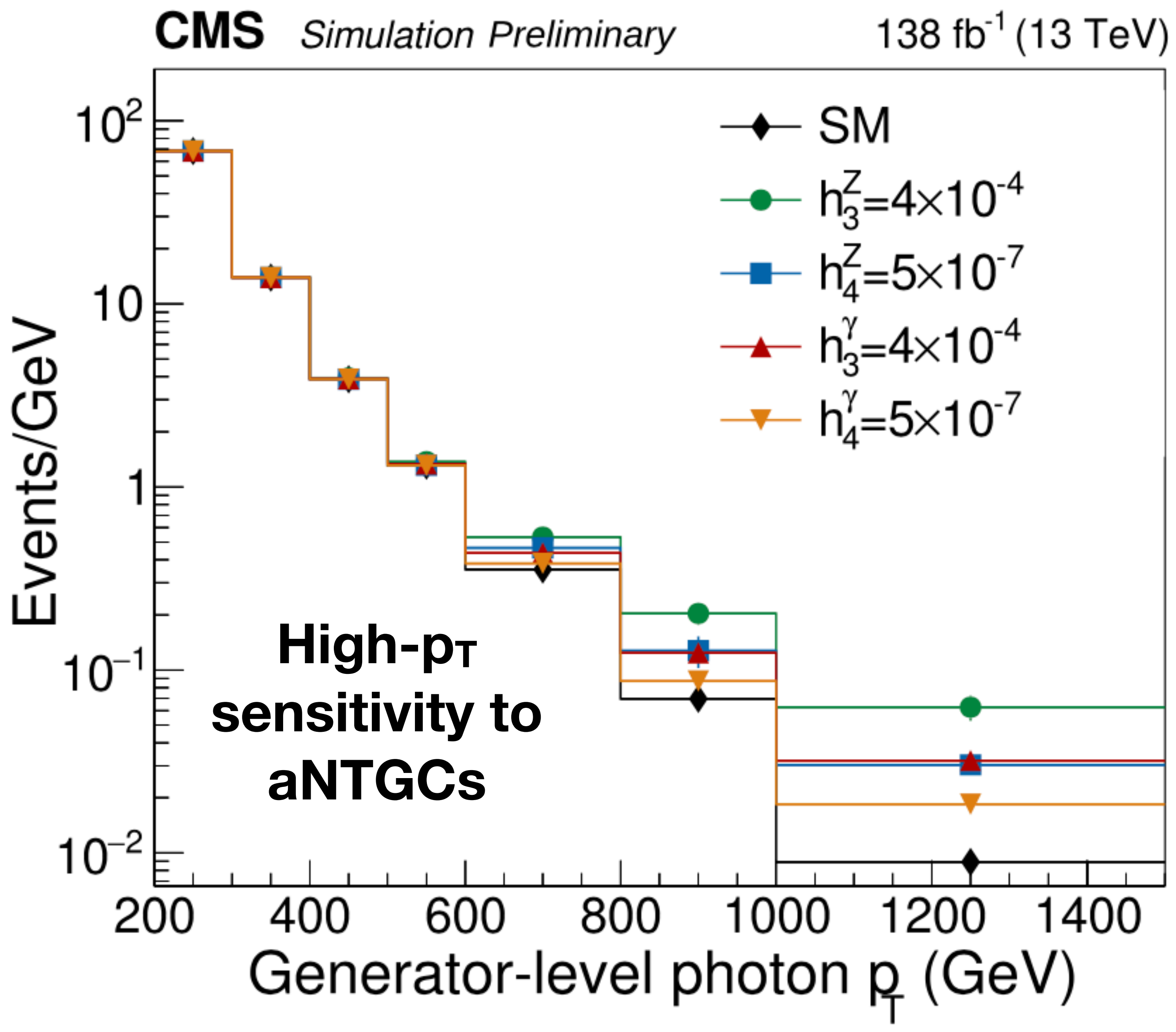
>5X better than LEP

Z(→νν)γ production

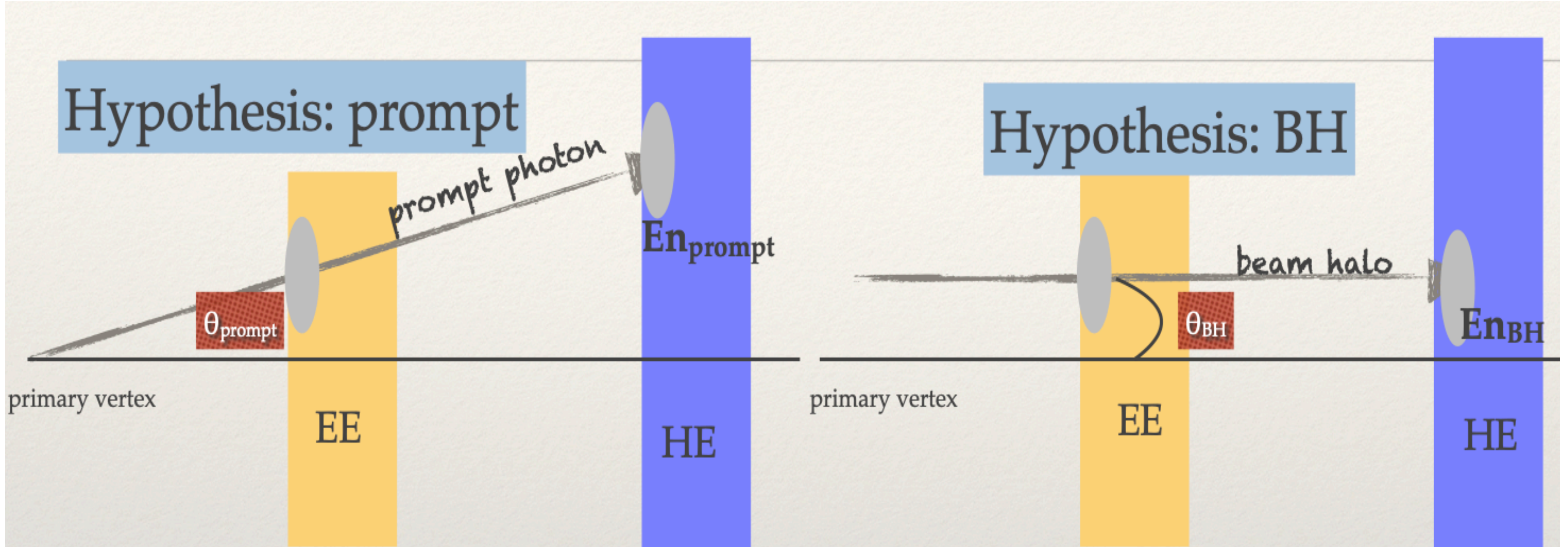


- pp collisions@13 TeV, Full Run2 statistics (138 fb^{-1})
- Fiducial and differential xsec measurement
- Limits on aNTGCs $h_3^{Z,\gamma}$ and $h_4^{Z,\gamma}$

- Exactly **1 high-p_T (>225 GeV) photon + MET**
- BDT algorithm to identify high-p_T photons (92% efficiency)



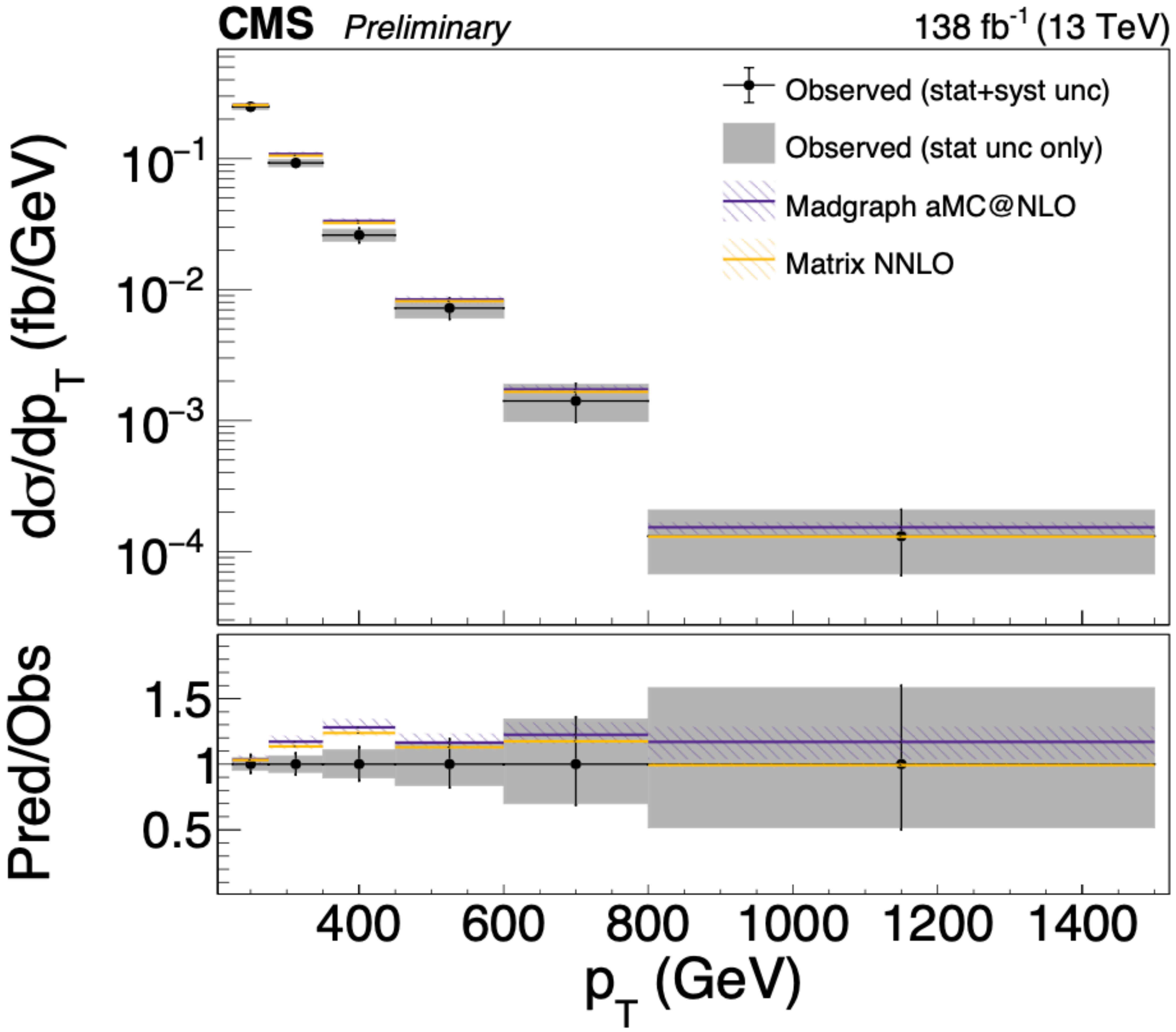
- **True photons bkg**:
  - γ+jets, VV (from MC), W(→lν)γ (from CR in data)
- **Fake photons bkg:**
  - e→γ, jet→γ (data-driven)
  - Particles interacting with ECAL barrel's APDs (data-driven)
  - **Beam Halo in ECAL endcaps** (data-driven)



- **New BH tagger** built using energy deposits
- **Forward** (1.6 < |η| < 2.5) **photons included in the analysis for the first time**

Z(→νν)γ production

- Likelihood-based unfolding technique



Fiducial region

Exactly 1 photon passing

- $p_T > 225$ GeV
- $|\eta| < 1.4442$ (EB) or $1.566<|\eta|<2.5$ (EE)

MET requirements

- $E_T^{miss} > 200$ GeV
- $p_T^{\gamma}/E_T^{miss} < 1.4$
- $\Delta\phi$ (γ, E_T^{miss}) > 2

Fiducial xsec (fb)

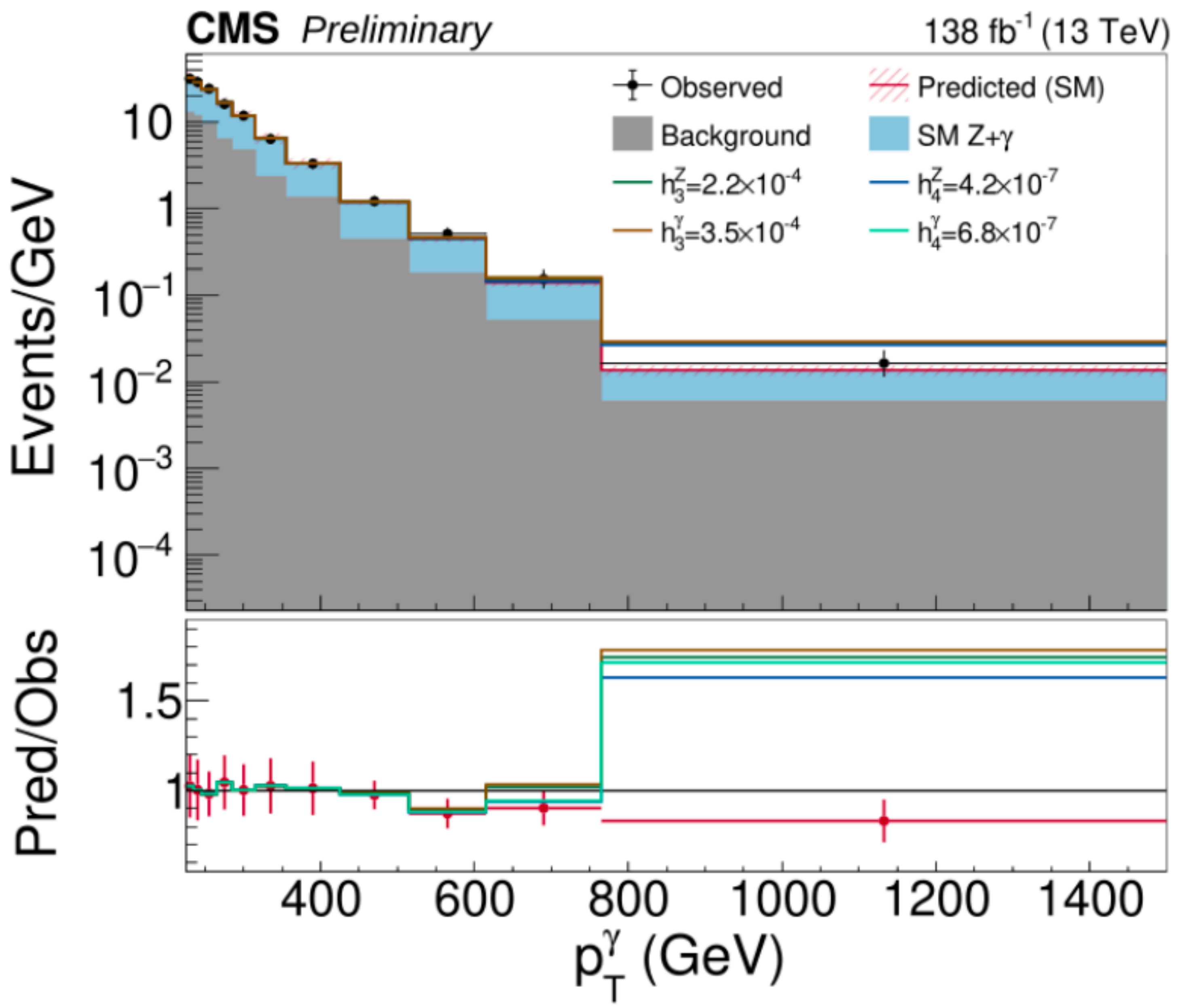
Region	Measured	NLO (Madgraph5)	NNLO (MATRIX)
Barrel $|\eta| < 1.4442$	$16.74^{+1.05}_{-0.99}$	$19.61^{+0.73}_{-0.69}$	$19.33^{+0.27}_{-0.33}$
Endcaps $1.4442 < |\eta| < 2.5$	$7.84^{+0.76}_{-0.70}$	$6.45^{+0.27}_{-0.31}$	$6.21^{+0.07}_{-0.09}$
Combination of barrel and endcaps	$23.32^{+1.40}_{-1.32}$	$26.07^{+0.96}_{-0.97}$	$25.45^{+0.41}_{-0.33}$

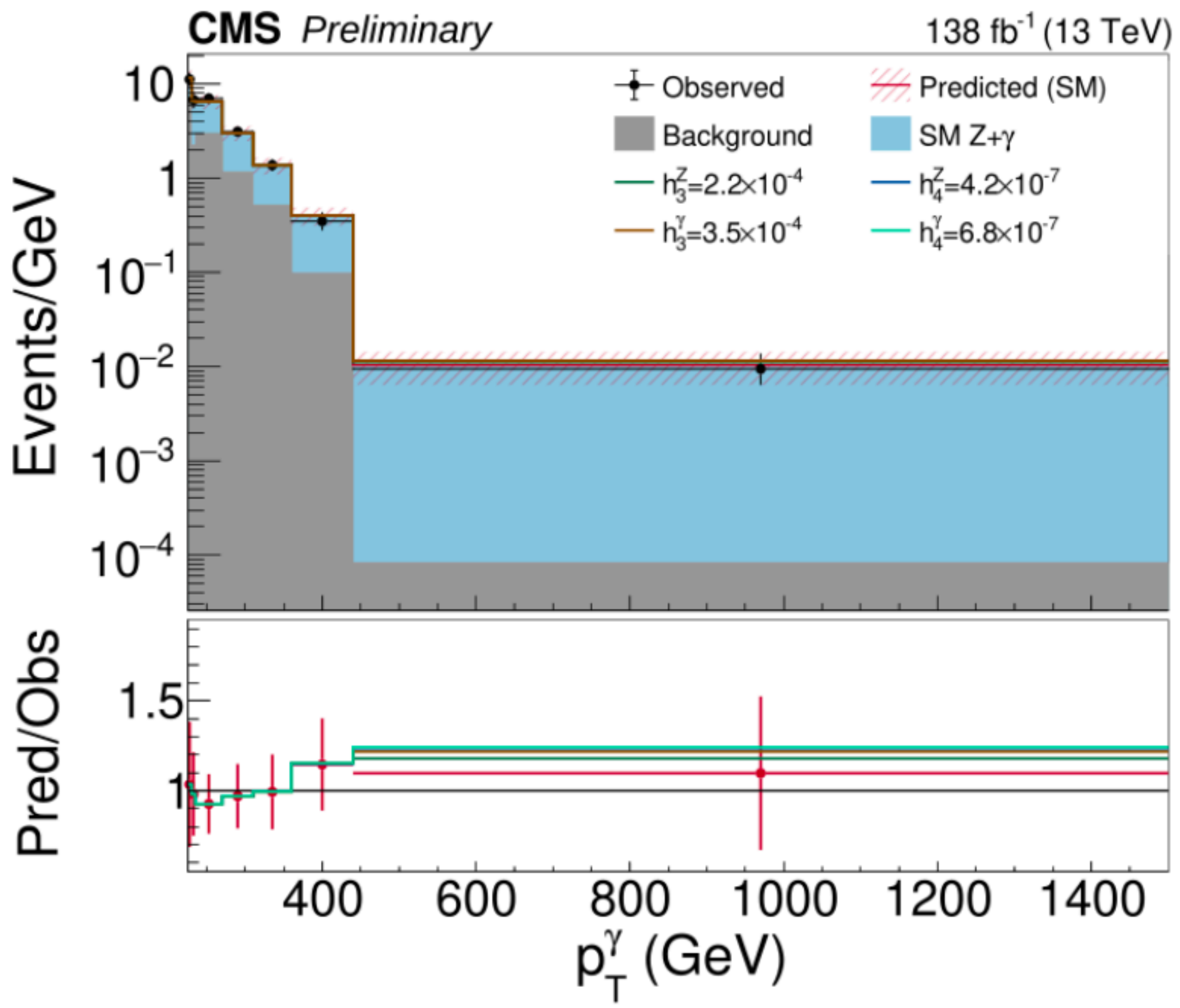
In agreement with SM

Z(→νν)γ production

- Effective vertex approach
- Limits on h_1^V and h_2^V are comparable to those on h_3^V and h_4^V

$$\Gamma^{\alpha\beta\mu}_{Z\gamma V}(q_1,\ q_2,\ p) = \frac{-e(p^2 - m_V^2)}{m_Z^2}\left\{h_1^V\left(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}\right) + \frac{h_2^V}{m_Z^2}p^\alpha\left[(pq_2)g^{\mu\beta} - q_2^\mu p^\beta\right] + h_3^V\epsilon^{\mu\alpha\beta\rho}q_{2\rho} - \frac{h_4^V}{m_Z^2}p^\alpha\epsilon^{\mu\beta\rho\sigma}p_\rho q_{2\sigma}\right\},$$





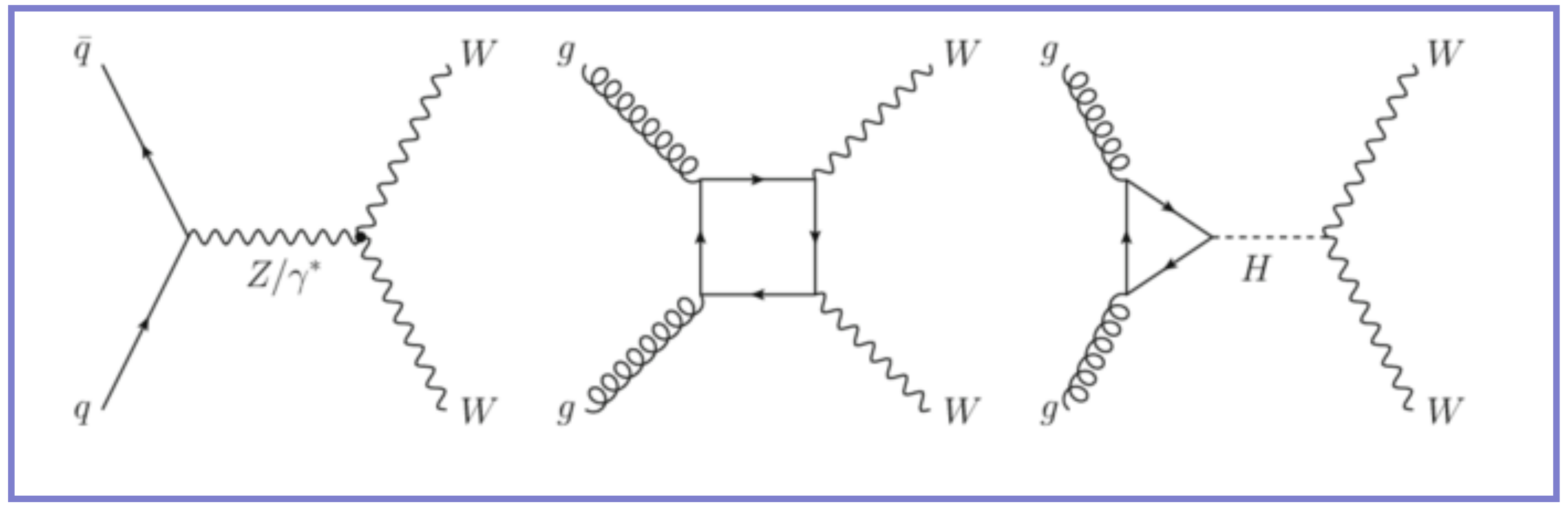
These results

Parameter	Expected	Observed
$h_3^\gamma \times 10^4$	(-2.8, 2.9)	(-3.4, 3.5)
$h_4^\gamma \times 10^7$	(-5.9, 6.0)	(-6.8, 6.8)
$h_3^Z \times 10^4$	(-1.8,1.9)	(-2.2, 2.2)
$h_4^Z \times 10^7$	(-3.7, 3.7)	(-4.1, 4.2)

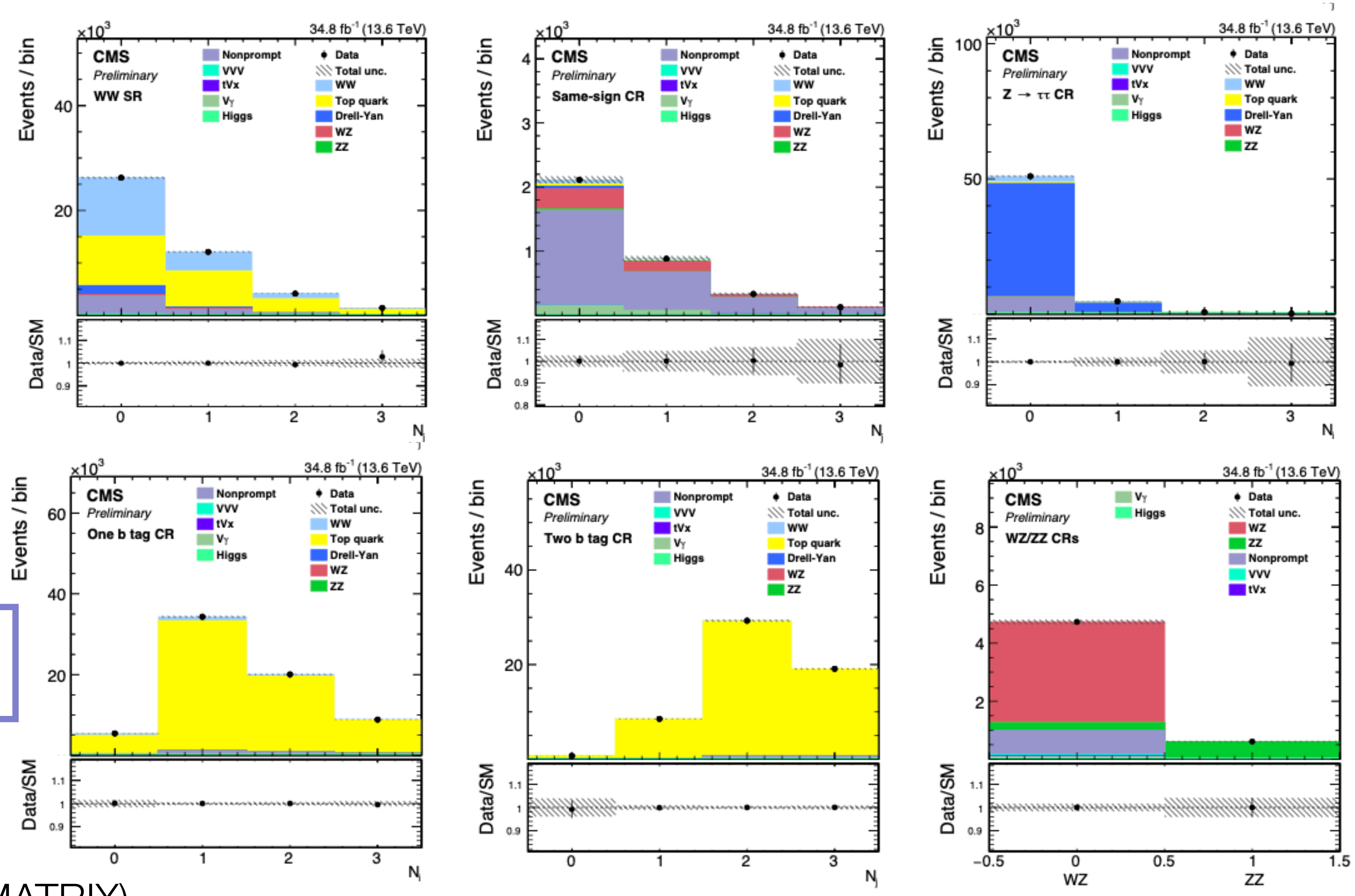
ATLAS@8TeV

Parameter	Limit 95% CL	
	Measured	Expected
h_3^γ	$(-3.7\times10^{-4}, 3.7\times10^{-4})$	$(-4.2\times10^{-4}, 4.3\times10^{-4})$
h_3^Z	$(-3.2\times10^{-4}, 3.3\times10^{-4})$	$(-3.8\times10^{-4}, 3.8\times10^{-4})$
h_4^γ	$(-4.4\times10^{-7}, 4.3\times10^{-7})$	$(-5.1\times10^{-7}, 5.0\times10^{-7})$
h_4^Z	$(-4.5\times10^{-7}, 4.4\times10^{-7})$	$(-5.3\times10^{-7}, 5.1\times10^{-7})$

WW production at 13.6 TeV



- **pp collisions@13.6 TeV, 2022 data (34.8 fb^{-1})**
- **Inclusive and normalized xsec measurement**



- Events selected with **one electron and one muon (OS)** and categorized into **WW SR + 6 CRs**
- xsec extracted from **simultaneous ML fits over SR+CRs**
- 1st fit with one POI (inclusive xsec)

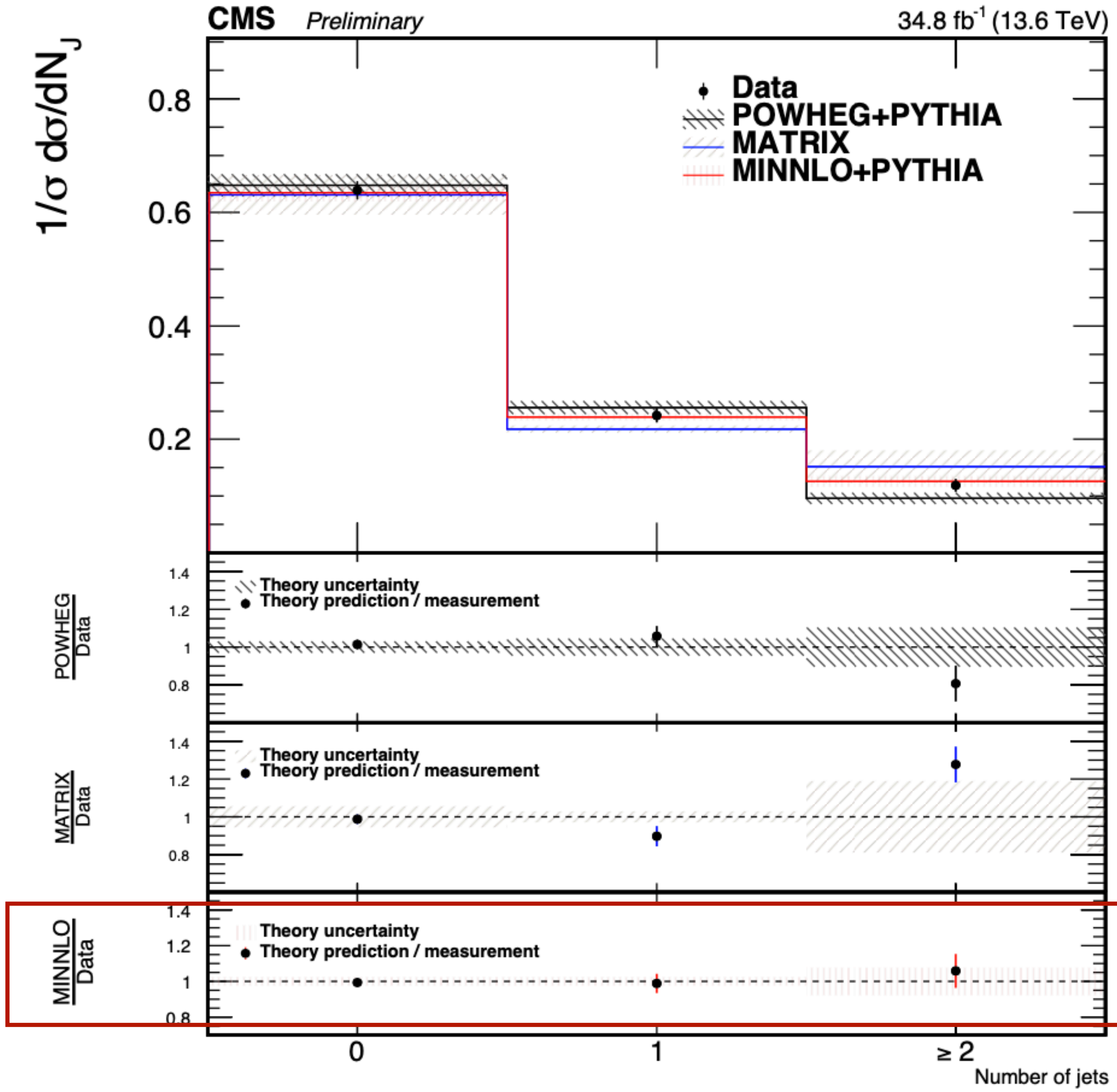
σ^{obs} = 125.7 ± 2.3(*stat*) ± 4.8(*syst*) ± 1.8(*lumi*) pb

Compatible with predictions:
σ^{exp} = 125.8 ± 3.7 pb (QCD NNLO and EW NLO from MATRIX)

WW production at 13.6 TeV

CMS-PAS-SMP-24-001

- 2nd fit with 4 POIs: inclusive fiducial xsec + normalized cross sections (0, 1, ≥ 2 jets)



Best prediction

Fiducial region

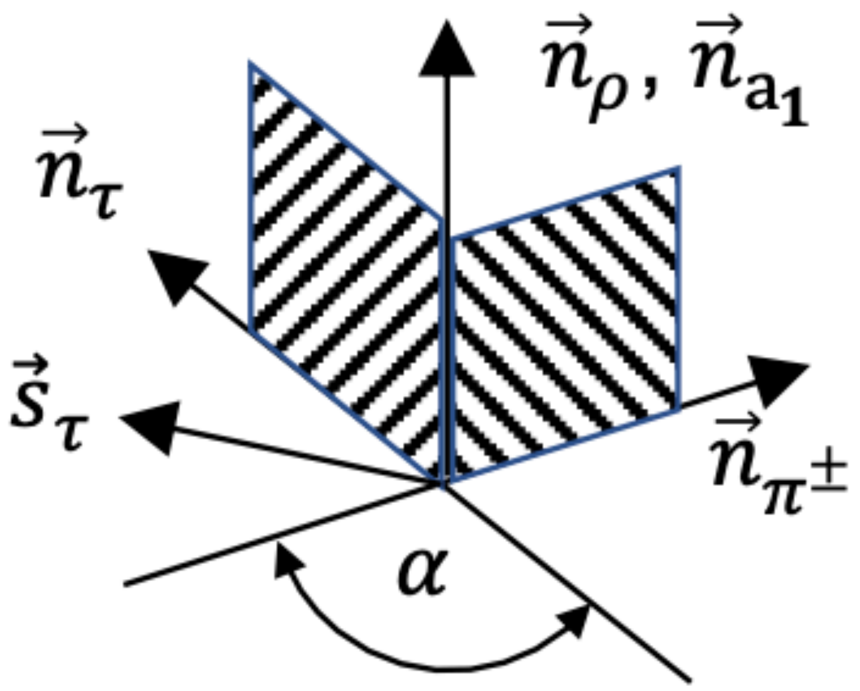
Observable	Requirement
Lepton origin	Direct decay of a W boson
Lepton definition	Dressed-leptons ($e^{\pm}\mu^{\mp}$)
Leading lepton p_T	$p_T^{\ell\,\max} > 25\,\text{GeV}$
Trailing lepton p_T	$p_T^{\ell\,\min} > 20\,\text{GeV}$
$\lvert\eta\rvert$ of leptons	$\lvert\eta\rvert < 2.5$
Dilepton mass	$m_{\ell\ell} > 85\,\text{GeV}$
Jet p_T	$p_T^{j} > 30\,\text{GeV}$
$\lvert\eta\rvert$ of jets	$\lvert\eta^{j}\rvert < 2.5$
Jet-lepton removal	$\Delta R(j, \ell) > 0.4$

Summary

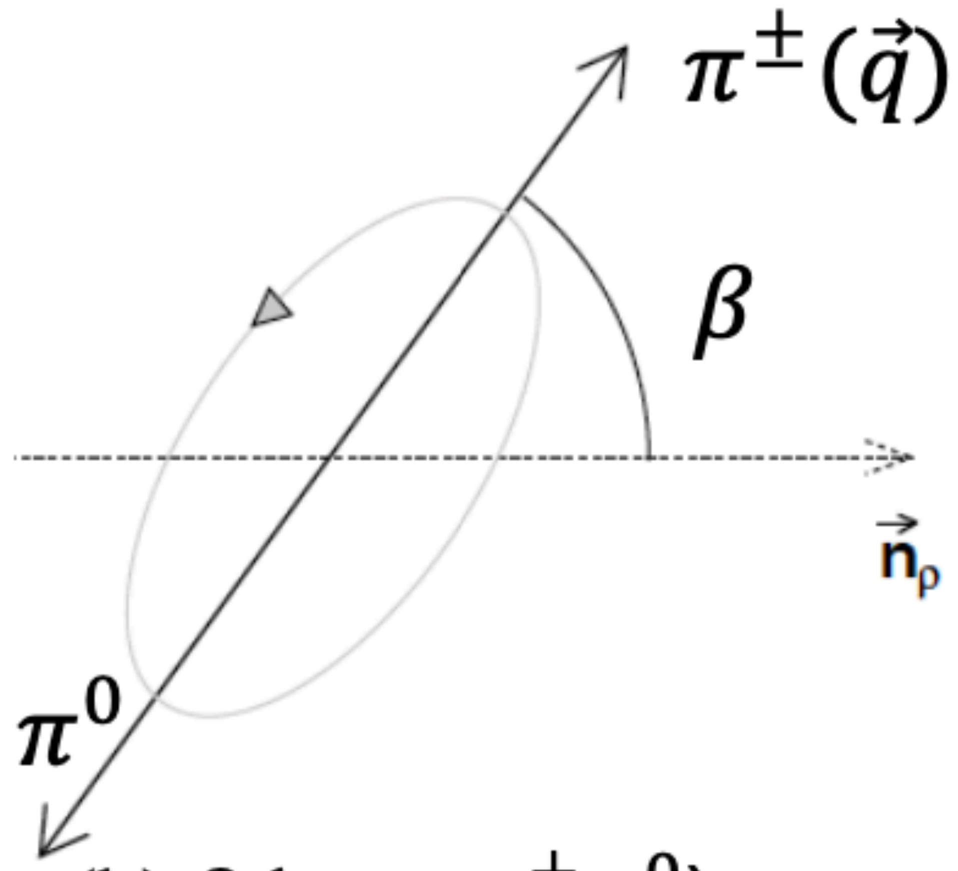
- **CMS has a strong and comprehensive program of SM measurements**
  - Cross section measurements in good agreement with theoretical predictions
  - More stringent constraints on aNTGCs have been provided, exploiting novel approaches and larger datasets
  - First observation of $\gamma\gamma \rightarrow \tau\tau$ in pp collisions
- **Produced several of the most precise results at the LHC**
  - A_τ presented here, but there are many more
  - Limits on anomalous magnetic moment of the τ lepton 5 times better than at LEP

Additional slides

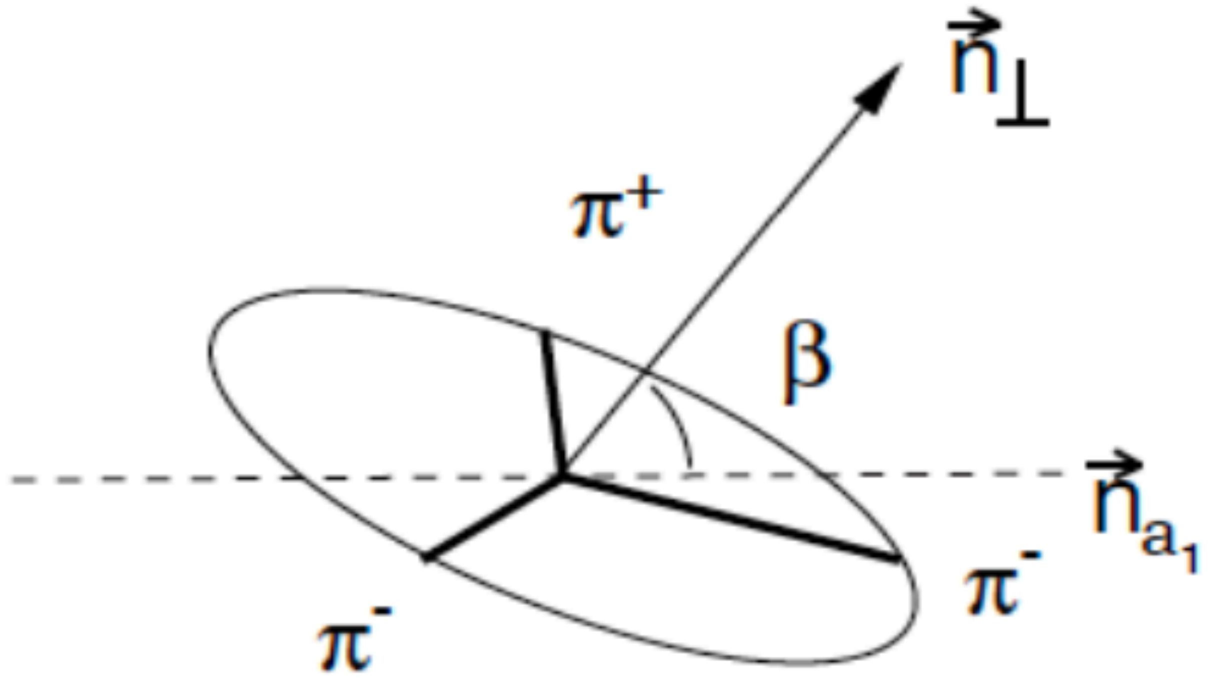
Tau polarization in Z →ττ decays



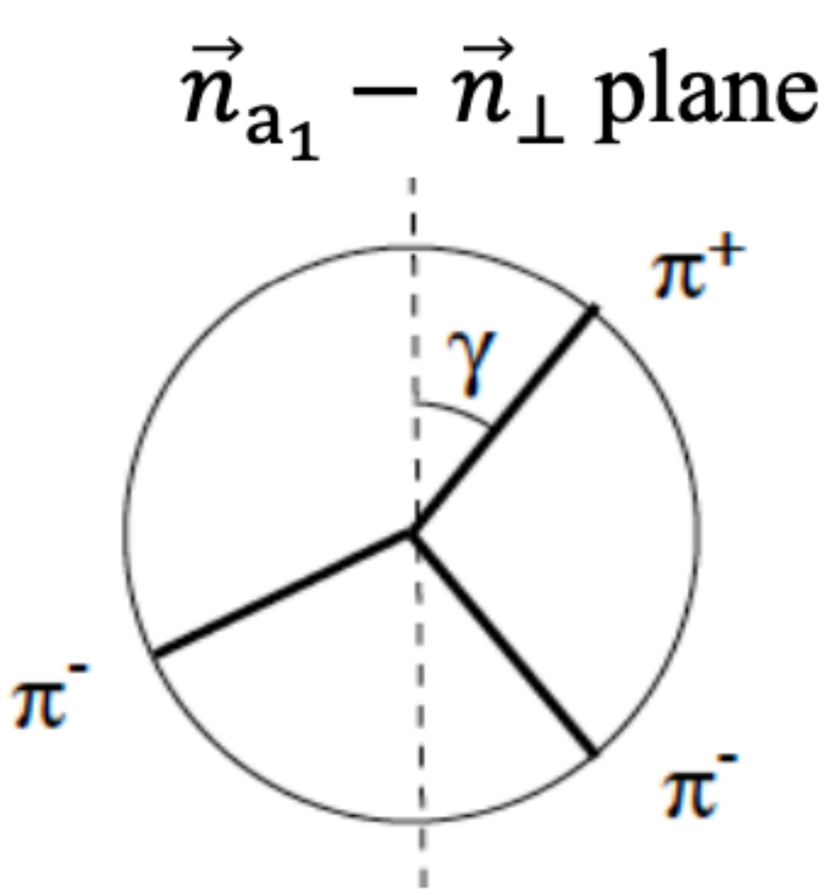
(a) $\alpha(\tau \to \nu_\tau + \rho, a_1)$



(b) $\beta(\rho \to \pi^\pm \pi^0)$



(c) $\beta(a_1 \to \pi^- \pi^+ \pi^-)$



(d) $\gamma(a_1 \to \pi^- \pi^+ \pi^-)$

ττ photon-induced production

- a_τ and d_τ parameterized within SMEFT framework

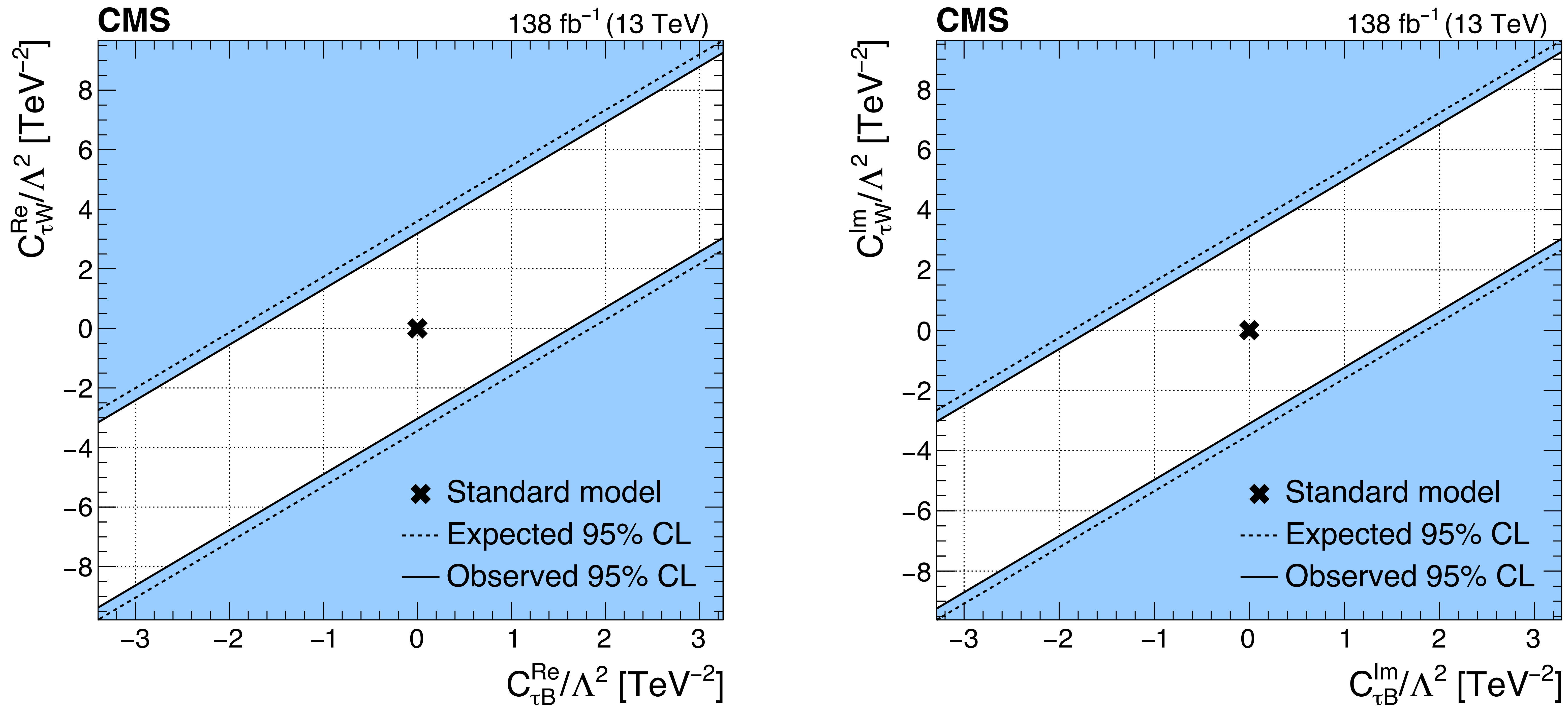
$$a_\tau = a^{SM}_\tau + \delta a_\tau \quad \rightarrow \quad \delta a_\tau = \frac{2m_\tau}{e}\frac{\sqrt{2}v}{\Lambda^2}\mathrm{Re}\left[C_{\tau\gamma}\right]$$

$$d_\tau = d^{SM}_\tau + \delta d_\tau \quad \rightarrow \quad \delta d_\tau = \frac{\sqrt{2}v}{\Lambda^2}\mathrm{Im}\left[C_{\tau\gamma}\right]$$

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

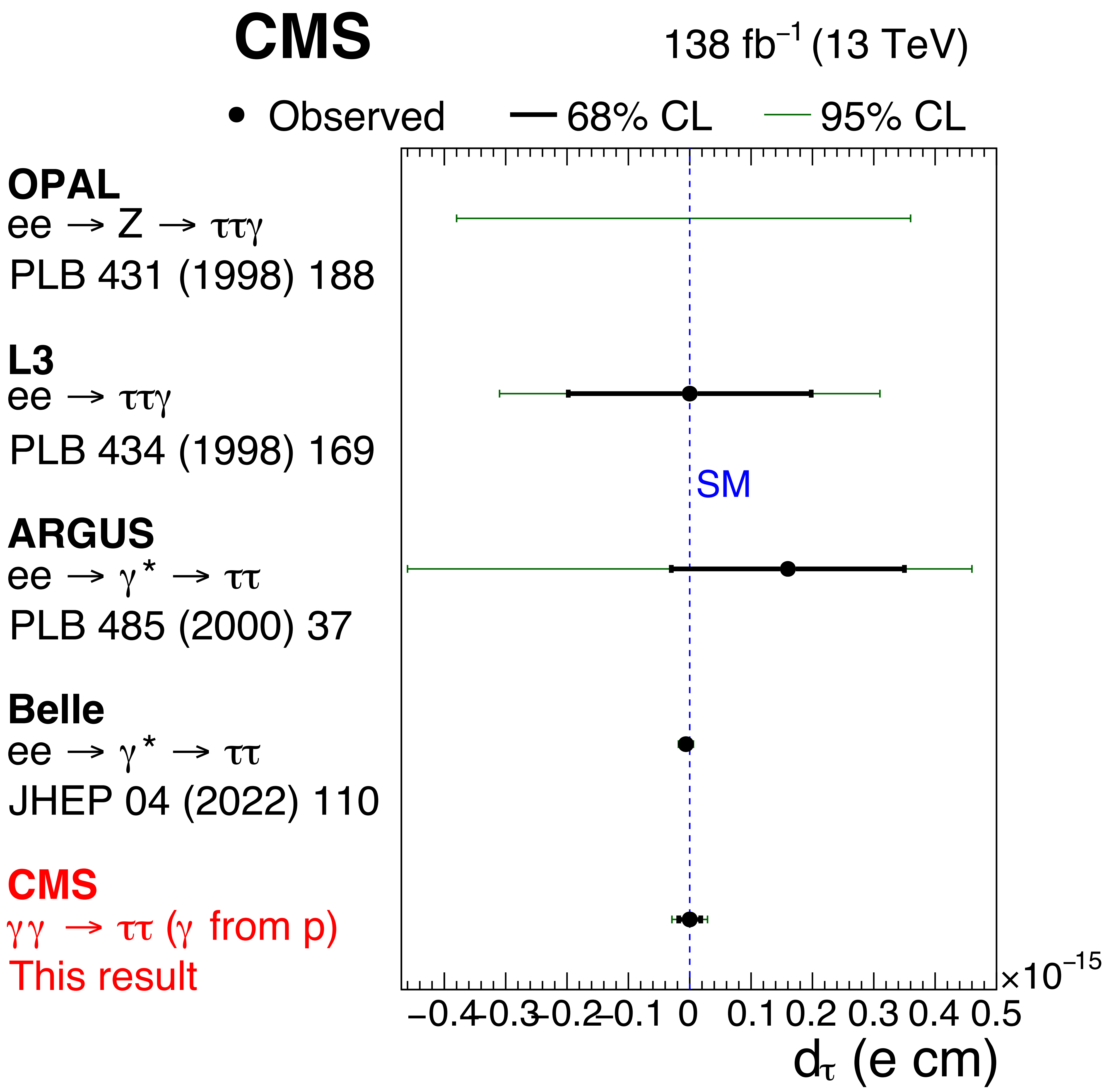
- Recast results to make exclusion plots of Wilson coefficients

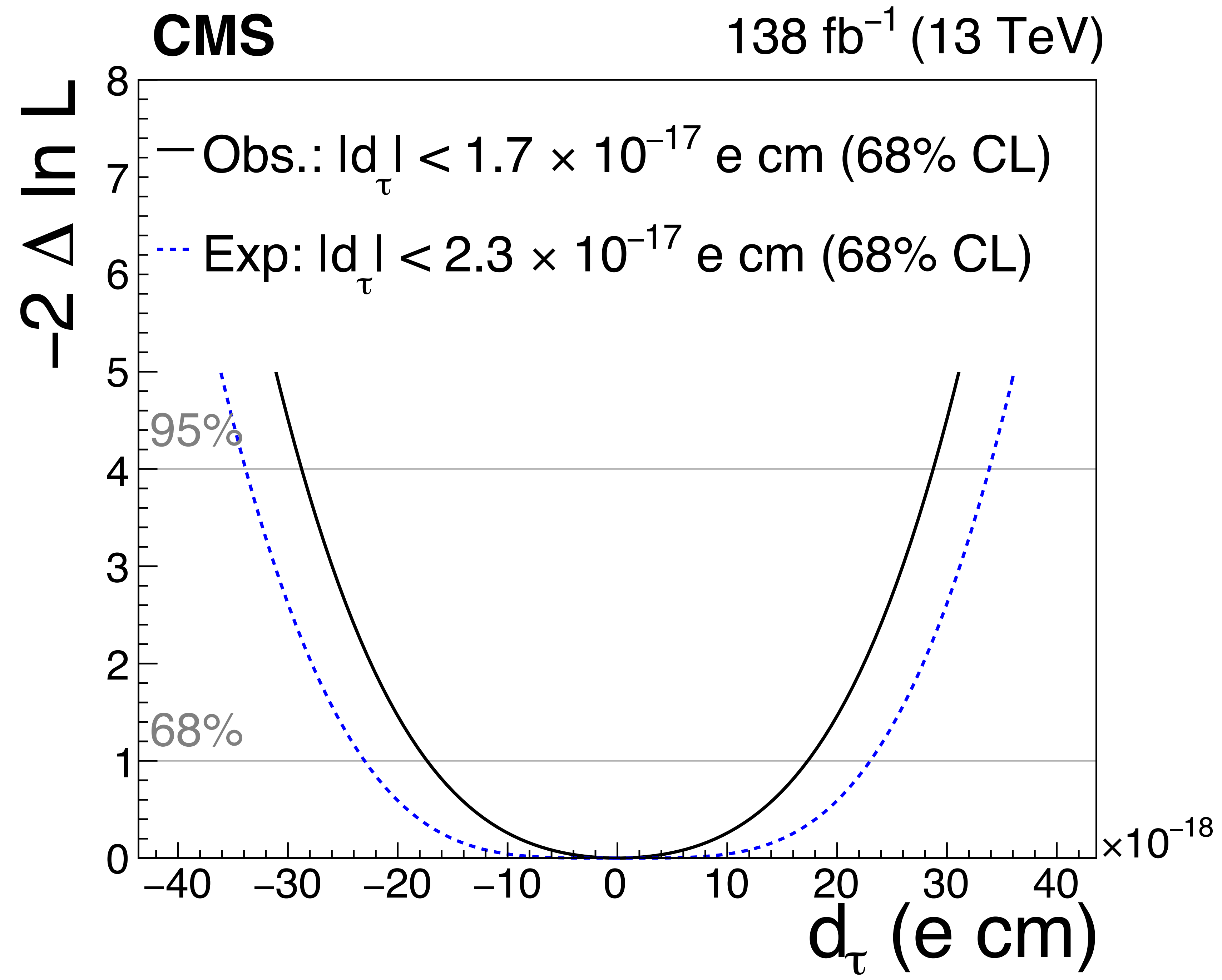
$$\delta a_\tau = \frac{2m_\tau}{e}\frac{\sqrt{2}v}{\Lambda^2}\mathrm{Re}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}] \qquad \delta d_\tau = \frac{\sqrt{2}v}{\Lambda^2}\mathrm{Im}[\cos\theta_W\, C_{\tau B} - \sin\theta_W\, C_{\tau W}]$$



ττ photon-induced production

- a_τ and d_τ parameterized within SMEFT framework





- SM $d_\tau \sim 10^{-17}$
- Belle (CL 95%): $-1.85 < d_\tau < 0.61 \times 10^{-17}$
- This result (CL 68%): $-1.7 < d_\tau < 1.7 \times 10^{-17}$

Same order as Belle

Z(→νν)γ production