Rare Decays of EW bosons

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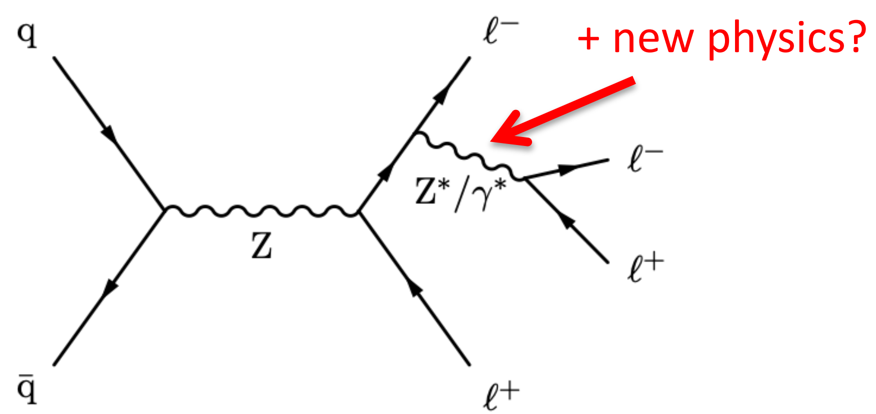
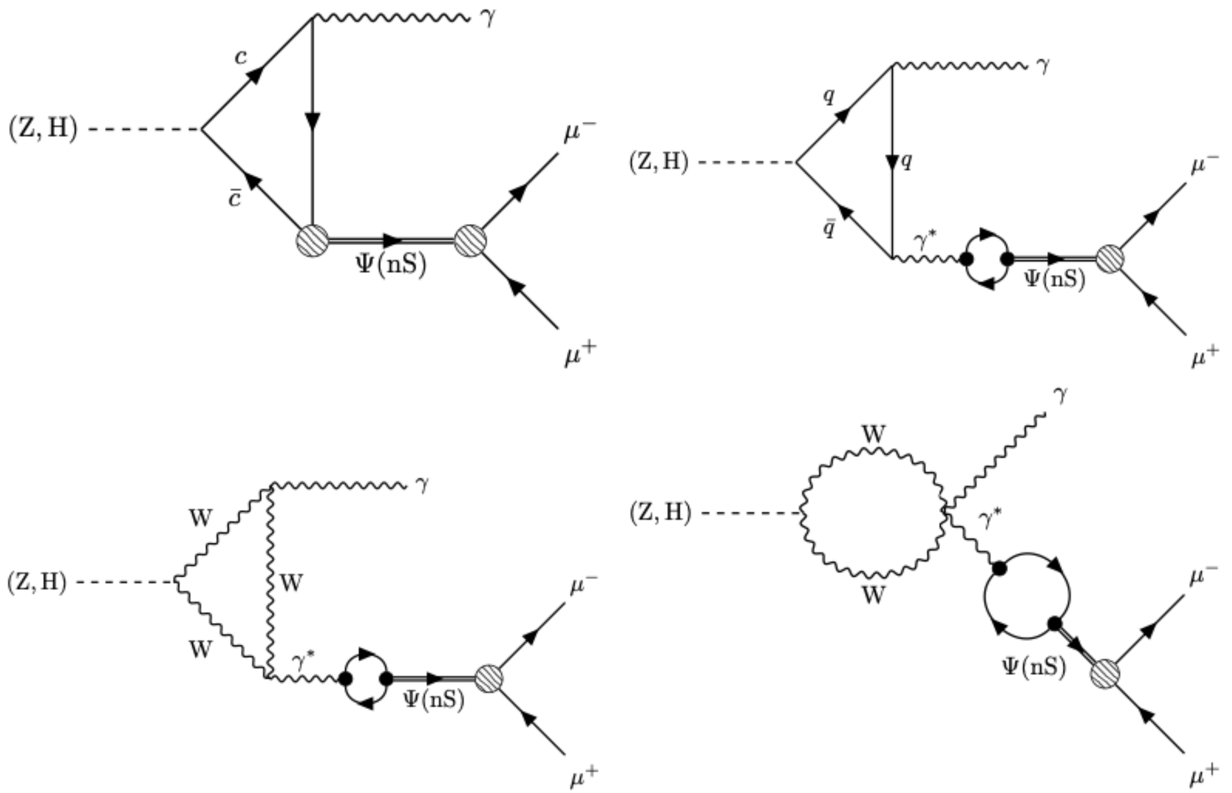
Introduction

- Rare W and Z boson decays offer unique insights into standard model calculations and potential new physics contributions
- Cover three final state groups here from the CMS and ATLAS experiments
  - Z or H → J/Ψ γ
  - W → $\pi\gamma$, Kγ, or $\rho\gamma$
  - Z → 4 leptons



Z/H → J/$\Psi\gamma$ and $\Psi(2S)\gamma$

- As cc resonances, J/Ψ and Ψ‘, offer a chance to probe the Higgs coupling to charm
- Rare SM processes with H branching fractions predicted ~10^{-6}, and Z BFs ~10^{-8}



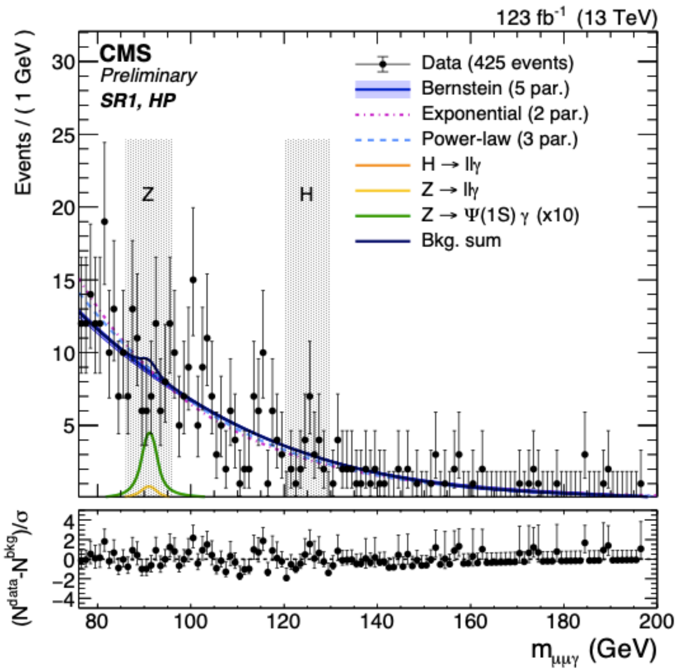
CMS-PAS-SMP-22-012

Event selection

- Dedicated Trigger: 1 photon $p_T > 30$ and 1 muon $p_T > 17$ GeV
- Selection requirements
  - 2 isolated muons with $p_T > 18$ and 5 GeV
  - 1 isolated photon with $p_T > 32$ GeV
  - $m(\mu\mu)$ 3.0-3.2 GeV for J/Ψ; 3.60-3.75 GeV for Ψ'
- Higgs production divided into three channels:
  - VBF, heavy flavor, and gluon-gluon fusion
- Z spin correlations among Z, J/Ψ, and γ are used to build a multivariate likelihood discriminator to classify into high and low purity categories

Background estimation

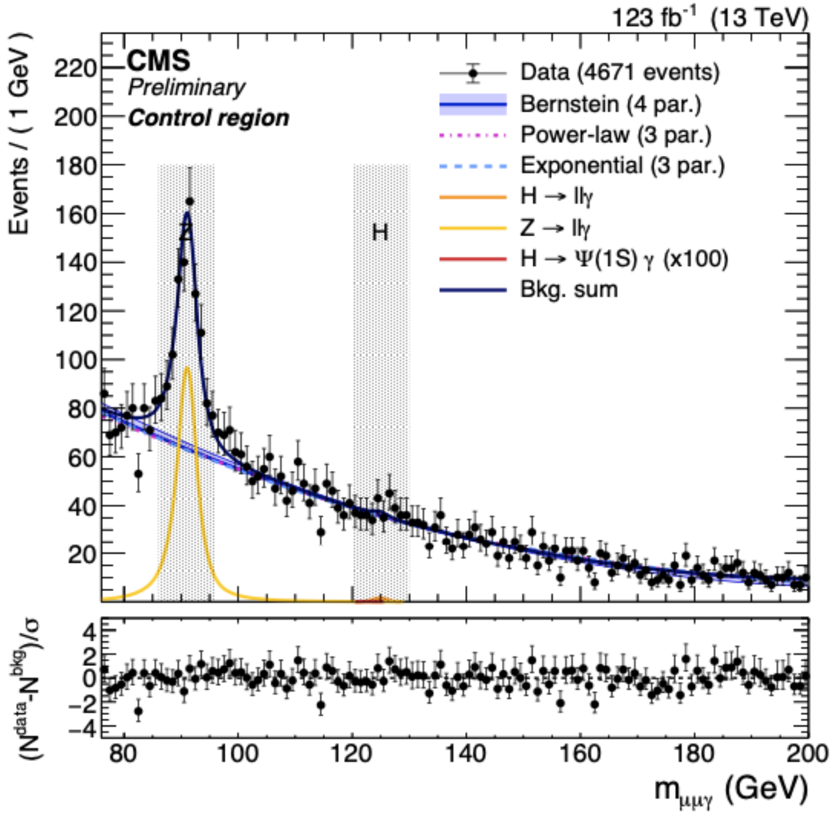
- Extract signal yield from fit to $\mu\mu\gamma$ mass distribution
- EW backgrounds (non-resonant Z/H → $\mu\mu$ decays and Z→ $\mu\mu$ + FSR photon) Modeled from MC
- QCD multi-jet background
  - Estimated directly from data with smoothly falling spectrum in sidebands
  - Different families of fit functions used for systematic variations
- Signal shapes from MC
- Separate fits for J/Ψ and Ψ' and each Z and H category



Sample fit from Z→J/$\Psi\gamma$ high purity category

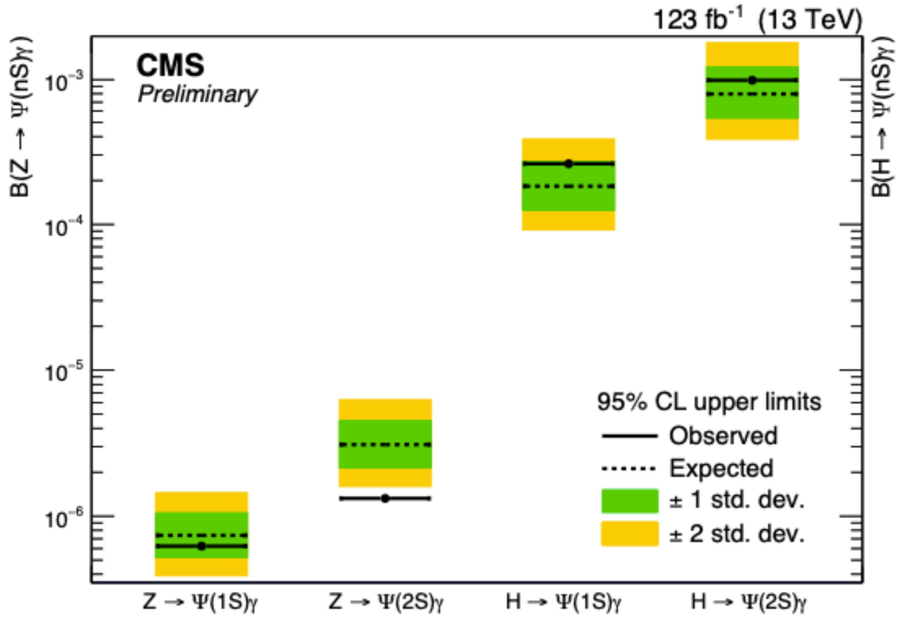
Signal extraction

- Systematic uncertainties applied for modeling of multi-jet background, limited knowledge of detector simulation, and theoretical uncertainties
  - Total uncertainty dominated by limited statistical precision in the data
- The non-resonant Z→$\mu\mu$ backgrounds constrained in final fit with simultaneous fit to m(mu,mu) sideband.



Results

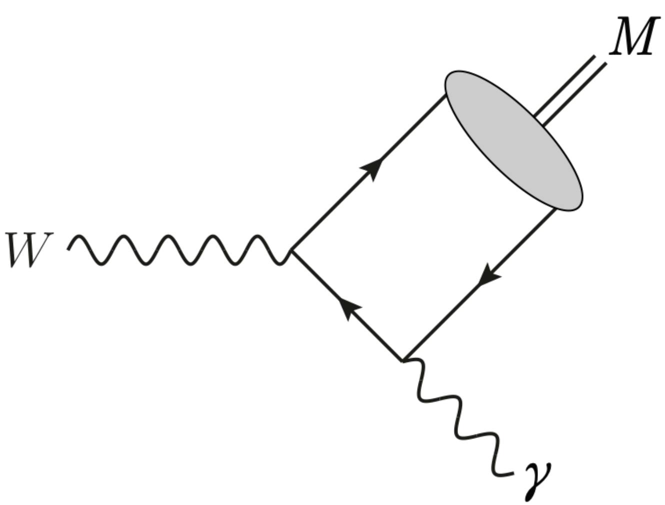
- Significant improvement in 95% CL upper limits over previous results
- Around 2 orders of magnitude above the SM values

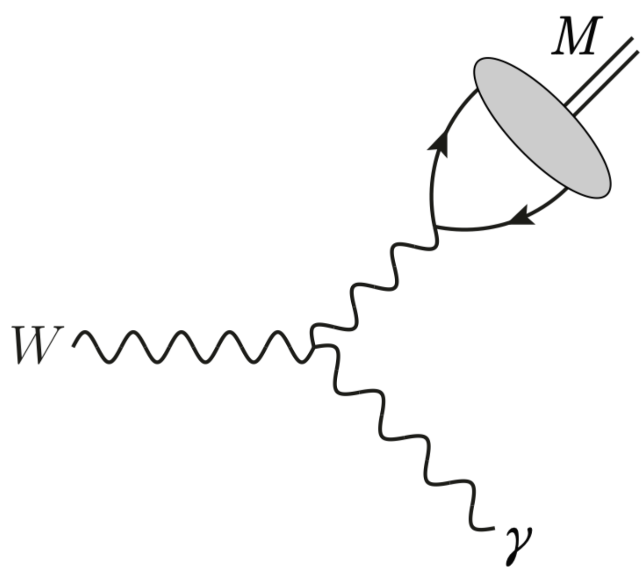


Process	This analysis (123 fb^{-1})			CMS (36 fb^{-1}) [13]	ATLAS (139 fb^{-1}) [15]
	$\mu_{obs}(\mu_{exp})$	$\sigma_{obs}(\sigma_{exp})$ [pb]	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$	$\mathcal{B}_{obs}(\mathcal{B}_{exp})$
$Z \to \Psi(1S)\gamma$	$7.2\ (8.6^{+4.1}_{-2.7})$	$3.8\ (4.4^{+1.9}_{-1.3}) \times 10^{-2}$	$0.6\ (0.7^{+0.3}_{-0.2}) \times 10^{-6}$	$1.5\ (1.7^{+0.7}_{-0.5}) \times 10^{-6}$	$1.2\ (0.6^{+0.3}_{-0.2}) \times 10^{-6}$
$Z \to \Psi(2S)\gamma$	$29\ (68^{+36}_{-22})$	$8\ (19^{+8}_{-6}) \times 10^{-2}$	$1.3\ (3.1^{+1.4}_{-0.9}) \times 10^{-6}$	—	$2.3\ (2.9^{+1.3}_{-0.8}) \times 10^{-6}$
$H \to \Psi(1S)\gamma$	$88\ (62^{+30}_{-19})$	$1.4\ (1.0^{+0.5}_{-0.3}) \times 10^{-2}$	$2.6\ (1.8^{+0.9}_{-0.6}) \times 10^{-4}$	$7.6\ (5.2^{+2.4}_{-1.6}) \times 10^{-4}$	$2.1\ (1.9^{+0.8}_{-0.5}) \times 10^{-4}$
$H \to \Psi(2S)\gamma$	$970\ (781^{+417}_{-259})$	$5.5\ (4.4^{+2.3}_{-1.5}) \times 10^{-2}$	$9.9\ (8.0^{+4.2}_{-2.6}) \times 10^{-4}$	—	$10.9\ (8.5^{+3.8}_{-2.4}) \times 10^{-4}$

W → $\pi\gamma$, Kγ, and $\rho\gamma$

- Study understanding of W couplings
  - Radiative W decays probe QCD factorization framework
- First ever search for Kγ and $\rho\gamma$
- Leading SM diagrams below:





arXiv:2309.15887

Selection cuts

- Two signal regions: track + photon and tau + photon
  - Hadronic tau reconstruction repurposed for $\rho^{+} \rightarrow \pi^{0}\pi^{+}$ reconstruction
- Dedicated track + photon trigger
  - Photon p_T >25 GeV; isolated track p_T >30 GeV; with mass >50 GeV
- Diphoton trigger used for $\rho\gamma$ from $\pi^0 \rightarrow 2\gamma$
- Selection requirements
  - Track + photon channel
    - Isolated photons and tracks
    - $\Delta\varphi(\text{track}, \gamma) > \pi/2$
    - Total efficiency ~5% for π/K γ
  - Tau-photon region:
    - Use only 1 π^{+} and 1 π^{0} modes from τ_h algorithm
    - ρ pT > 30 GeV, log(d0/mm) < -1.2 (short lifetime)
    - Efficiency only 0.3% (also fit this channel in track + photon)

Backgrounds

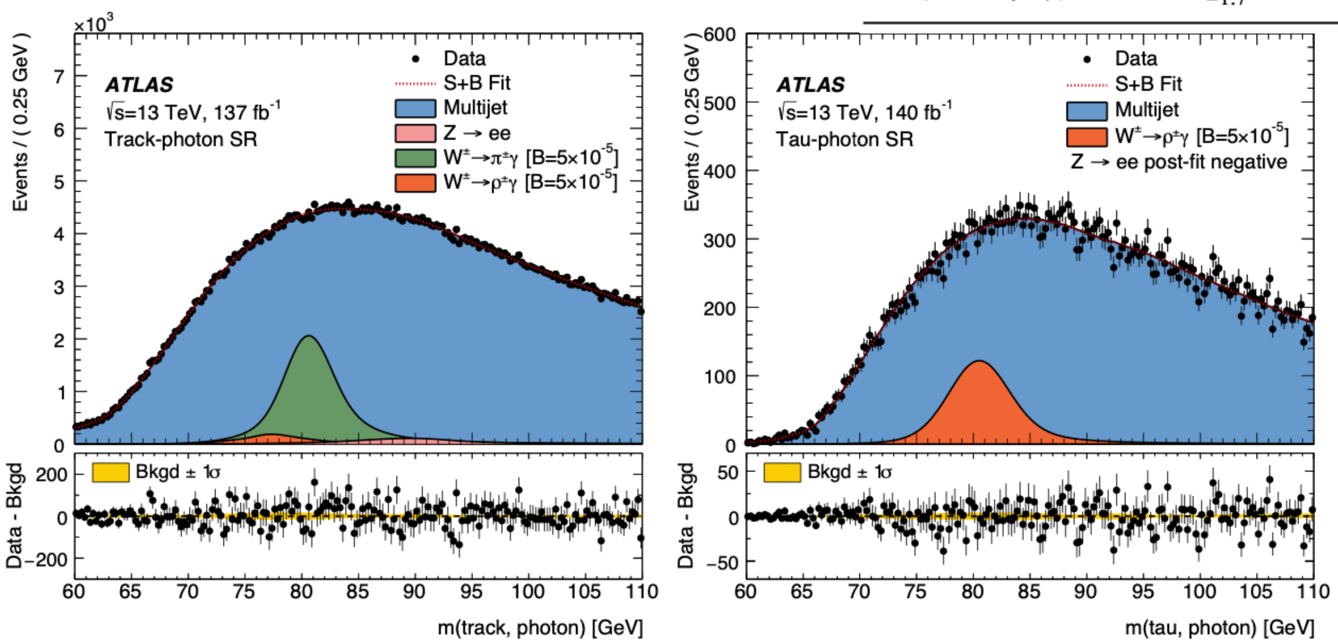
- Multi-jet (QCD)
  - Derive templates from signal region without the isolation cuts. Use up to three dimensions consisting of photon p_T, track p_T, and isolation variables
  - Generate pseudo-events from the templates to model the background
  - Use validation regions to check modeling of pseudo-events compared to data
- $Z \rightarrow e^+e^-$
  - One electron misID as photon
  - One electron misID as track
  - Shape taken from MC

Results

- Fit W candidate mass to extract signal
  - Simultaneous fit to both signal regions
  - Multi-jet background shape from pseudo-events derived from templates
- Largest uncertainties data statistics and multi-jet template modeling (~50%)
- W->$\pi\gamma$ is improvement of factor of 4 over previous result
- First result for Kγ and $\rho\gamma$

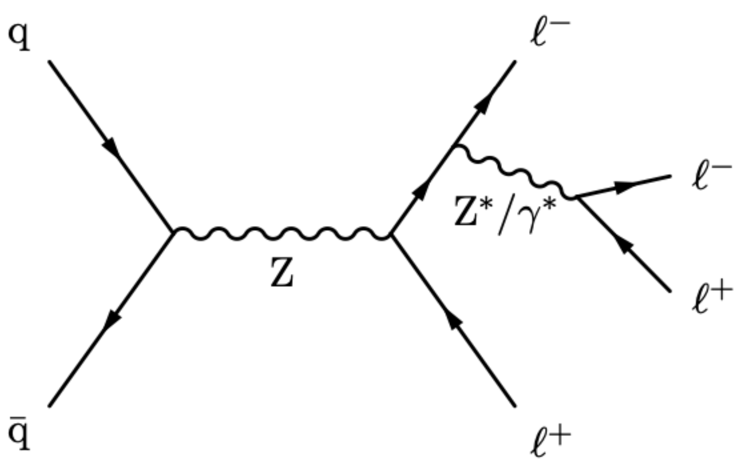
	Number of events	
	Track-photon SR	Tau-photon SR
Multijet	632000 ± 2200	43200 ± 600
$Z \to e^+e^-$	6100 ± 1500	-200 ± 400
$W^\pm \to \pi^\pm/K^\pm\gamma$	1000 ± 800	–
$W^\pm \to \rho^\pm\gamma$	-100 ± 400	-90 ± 240
Data	638962	42918

	95% CL upper limits	
Branching fraction	Expected $\times10^{-6}$	Observed $\times10^{-6}$
$\mathcal{B}(W^\pm \to \pi^\pm\gamma)$	$1.2^{+0.5}_{-0.3}$	1.9
$\mathcal{B}(W^\pm \to K^\pm\gamma)$	$1.1^{+0.4}_{-0.3}$	1.7
$\mathcal{B}(W^\pm \to \rho^\pm\gamma)$	$6.0^{+2.3}_{-1.7}$	5.2

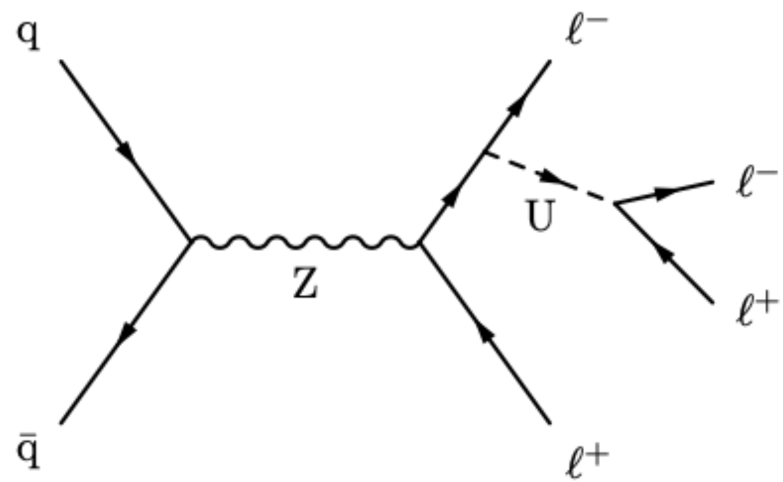


Z → 4 leptons

- Z to 4 lepton decays proceed in the SM through radiative decays with branching fractions ~5*10^{-6}
- New light bosons, such as Z', with couplings to leptons can enhance the branching ratios
  - Some predictions of such new particles can help resolve the flavor anomalies and/or g-2 discrepancy
- Beyond the branching fraction, new physics also sensitive to other observables
  - Differential distributions vs kinematic variables
  - Effective Field Theory interpretation for new operators
- Show results here for
  - 4μ, $2\mu 2e$, 4e (CMS-PAS-SMP-19-007) and $2\mu 2\tau$ (arXiv:2404.18298) final states



Standard Model



Potential New Physics

$Z \rightarrow 4l$ measurement

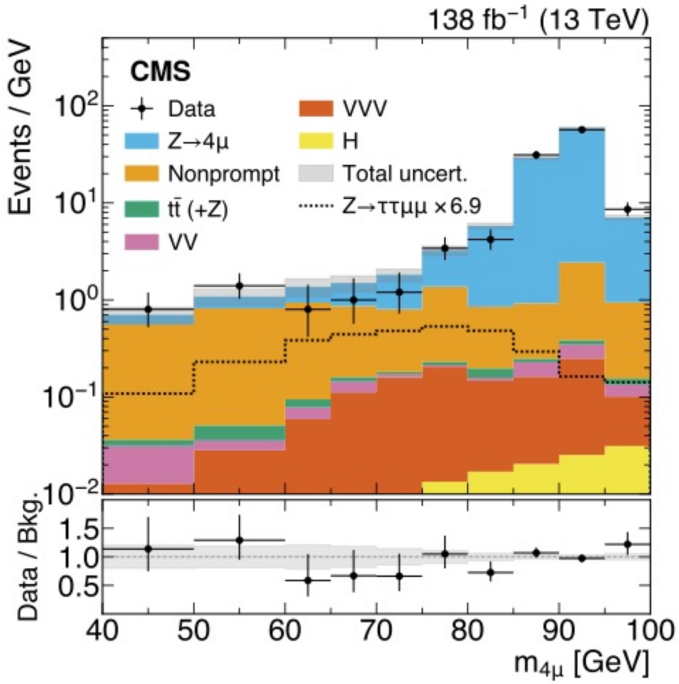
- 4μ, $2\mu 2e$, and 4e channels are measured relative to $Z \rightarrow 2e$ and $Z \rightarrow 2\mu$
  - reduces uncertainties on the Z production cross section and lepton reconstruction efficiencies
- $2\mu 2\tau$ channel measured through $\tau \rightarrow \mu\nu\nu$ decays and relative to 4μ final state
  - Reduce lepton reconstruction uncertainties
- Measure differential $Z \rightarrow 4\mu$, $2\mu 2e$, 4e rates vs many different kinematic quantities
  - Z masses, lepton momenta, kinematic angles, and CP-violating triple product asymmetry (angle between two Z decay planes)

Selection requirements

- Reconstruct 4μ, $2\mu2e$, and 4e as two opposite sign, same flavor pairs with $p_T > 20, 10, 5, 5$ GeV for the four leptons
- Reconstruct $2\mu2\tau$ in 4μ final state with lead μ $p_T > 29$ GeV and remaining μ with $p_T > 3.5$ GeV
- Leptons required to be isolated and have $d_{xy} <$ 0.5 cm to reject candidates from heavy flavor decays
- mass(Z_1) > 12 GeV to reject upsilon backgrounds
- Efficiencies are 37%, 51%, and 70% for 4e, $2e2\mu$, and 4μ, and 1.3% for $2\mu2\tau$

Background estimation

- Main backgrounds from $Z \rightarrow l^+l^-$ and $tt \rightarrow 2l2\nu$ plus two non-prompt leptons
  - Use a same-sign data (4μ, $2\mu 2e$, 4e) and inverted isolation ($2\mu 2\tau$) control regions to estimate non-prompt background from heavy flavor decays
- Other backgrounds (diboson, triboson, Higgs, ttZ) estimated from MC



Uncertainties

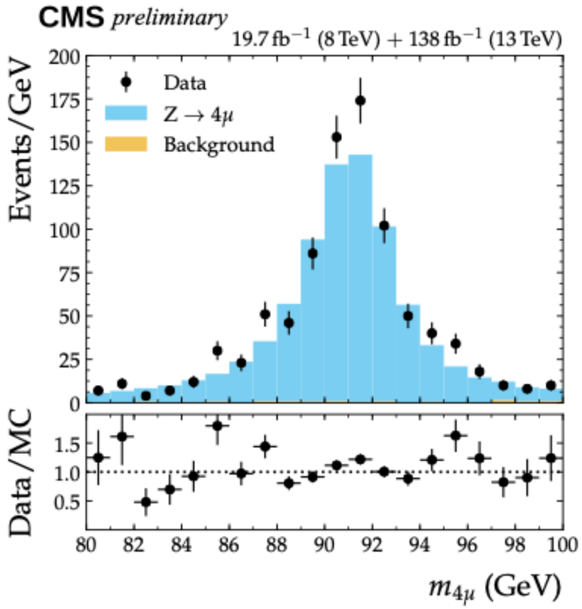
- Many uncertainties such as luminosity, pileup, and Z production cancel in the ratios
- Remaining sources of systematic uncertainty are dominated by the lepton finding efficiency
  - Total uncertainty ~2% for 4mu, ~4% for 2e2mu, and ~7% for 4e
  - For $2\mu 2\tau$ muon finding efficiencies also largely cancel and non-prompt muon background dominates (47%)
- Final statistical and systematic uncertainties are comparable in size

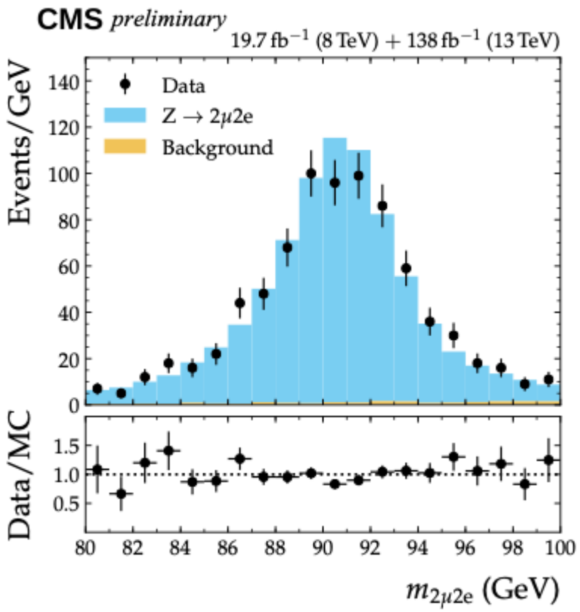
$Z \rightarrow 4\mu$, $2\mu2e$, $4e$ Results

- Observed yields consistent with SM expectations

Type	$N_{4\mu}$	$N_{2\mu2e}$	N_{4e}	$N_{4\ell}$ (total)
Observed	876	800	201	1 877
Expected	806.4 ± 44.0	806.0 ± 43.2	198.1 ± 10.9	1 810.5 ± 62.6
Signal	793.4 ± 43.9	784.6 ± 42.9	195.1 ± 10.7	1 773.1 ± 62.3
Background	12.9 ± 3.4	21.4 ± 4.9	3.0 ± 1.9	37.4 ± 6.3
Nonprompt	8.4 ± 3.4	16.2 ± 4.9	1.3 ± 1.9	25.9 ± 6.3
Other	4.5 ± 0.4	5.2 ± 0.3	1.8 ± 0.3	11.5 ± 0.6
Signal purity (%)	98.4 ± 1.2	97.3 ± 1.1	98.5 ± 2.3	97.9 ± 0.6
N^{obs}/N^{exp} (%)	108.6 ± 3.8	99.3 ± 3.6	101.4 ± 7.4	103.7 ± 2.4

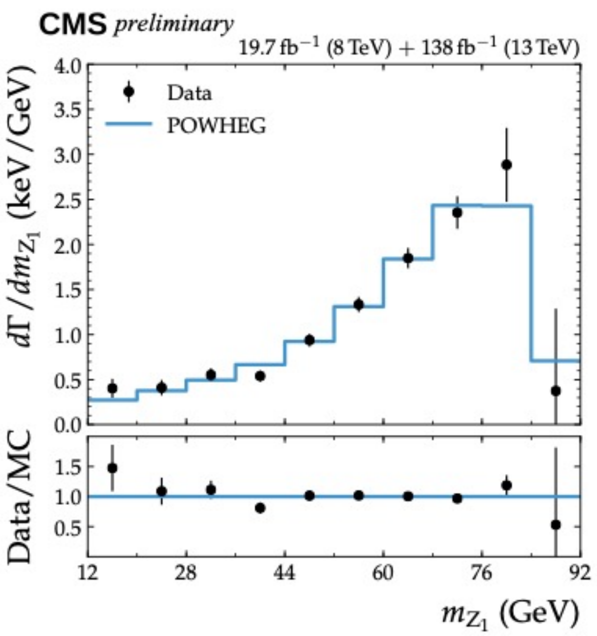
	$\mathcal{B}(Z \rightarrow 4\ell)$ $[\times 10^{-6}]$	
Channel	Expected	Observed
4μ	1.20 ± 0.01	1.25 ± 0.04 (stat) ± 0.03 (syst)
$2\mu2e$	2.31 ± 0.01	2.17 ± 0.08 (stat) ± 0.06 (syst)
$4e$	1.20 ± 0.01	1.16 ± 0.09 (stat) ± 0.06 (syst)
4ℓ	4.70 ± 0.02	4.67 ± 0.11 (stat) ± 0.10 (syst)

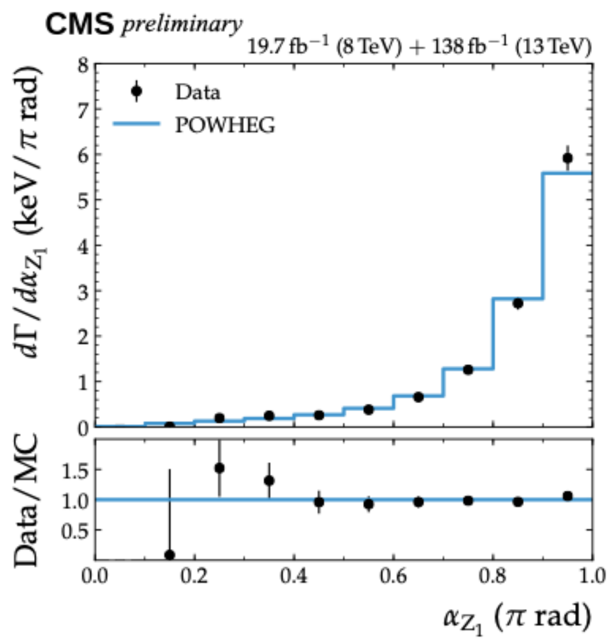


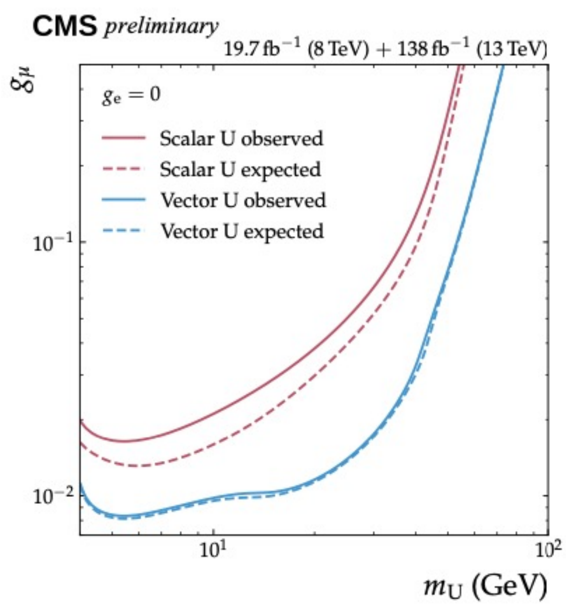


Z→ 4μ, 2μ2e, 4e Results

- Differential distributions in nice agreement with the model
- Also compute upper limits on additional non-SM contributions to rule out phase space for new bosons

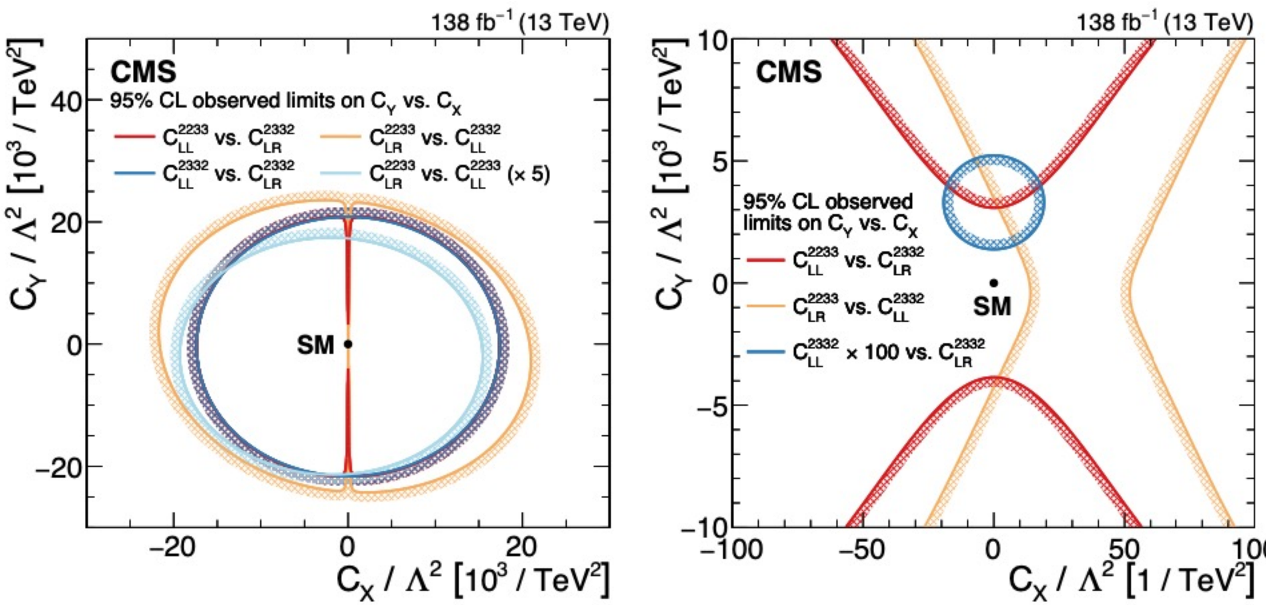






Z→ $2\mu 2\tau$ Results

- 95% CL upper limit on ratio of Z→$2\mu 2\tau$ over Z→4μ of 6.2 observed (10.0 expected)
  - Observed limit corresponds to 6.9x the SM expectation
- Additionally set limits on dim6 Wilson coefficients that conserve lepton flavor and involve 2 muons and 2 taus



Hatched regions excluded at 95% CL

Conclusions

- Rare EW boson decays probe SM couplings and offer unique insights into BSM contributions
  - Potential connections to heavy flavor anomalies and/or g-2 discrepancies
- Reported several results from CMS and ATLAS with many more on the way in the future