Recent results from the CMS SMP-V group

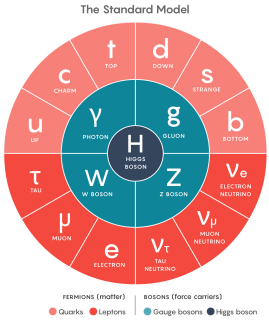
Markus Seidel

October 10, 2023

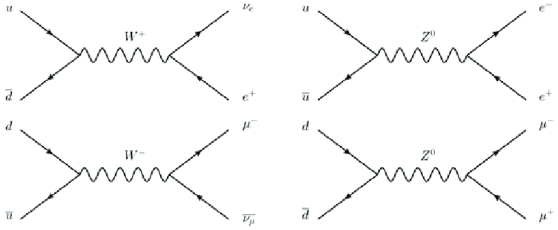
Introduction

- CMS SMP-V (vector boson) group studies production and decay of W and Z bosons, mediator particles of the weak nuclear force
- Very massive: 80.4 and 91.2 GeV (proton mass is 0.938 GeV)
- Production mostly via quark anti-quark annihilation,
  Z interferes with photon in $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$ ("Drell-Yan" process)
- Precision measurements in weak sector may give hints to BSM

Talk by Vytautas

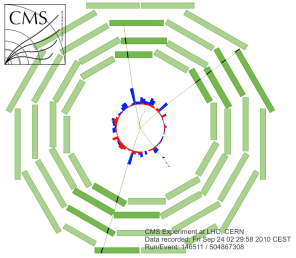


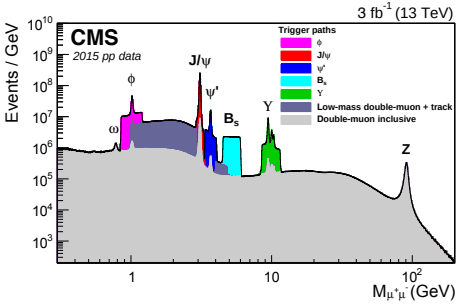
- W decays
  - 32.6% $W^\pm \to \ell^\pm + \nu_\ell$
  - 67.4% $W^\pm \to q\bar{q}'$ (different flavor)
- Z decays
  - 10.1% $Z \to \ell^+\ell^-$
  - 20% $Z \to \nu\nu$
  - 69.9% $Z \to q\bar{q}$ (same flavor)

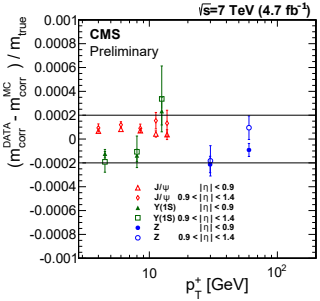


Muon reconstruction

CMS MUO-16-001







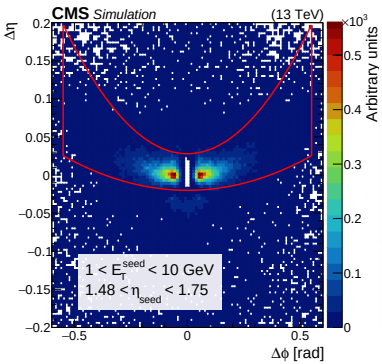
- Muons reconstructed from both inner tracker and muon system
- Identification criteria using track quality, need to be compatible with primary vertex
- Trigger paths targeting specific resonances, excellent resolution
- Calibration from J/Ψ, Y, and $Z \to \mu\mu$ events, precision $\ll 0.1\%$

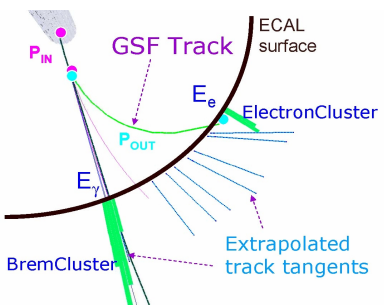
CMS PAS-SMP-14-007

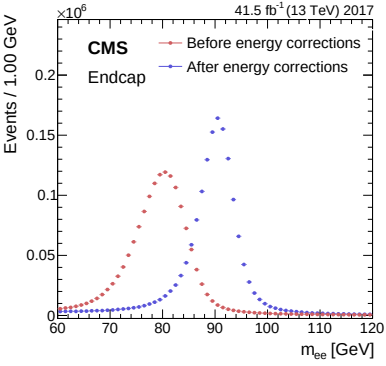
- Efficiencies from tag&probe method $\to$ Poster by Normunds

Electrons

CMS EGM-17-001



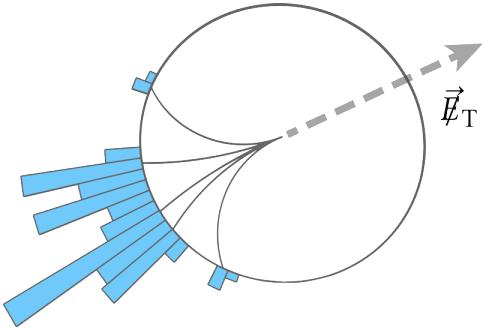


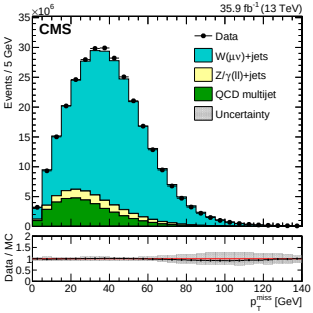


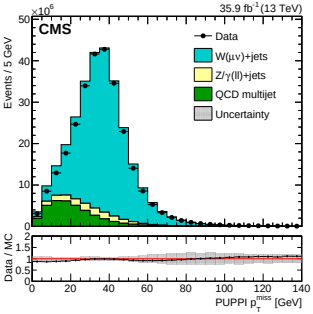
- Electrons are light and lose energy through photon radiation
- Recover bremsstrahlung: "mustache" supercluster, "GSF" tracking algorithm, supercluster refinement (additional conversion and bremsstrahlung clusters)
- ID criteria include SC-to-track matching, HCAL/ECAL energy, isolation
- Energy regression using BDT based on shower shape and PU density (up to $\sim 8\%$)
- Efficiencies and calibration from $Z \to ee$ events, precision 0.1% (0.3%) in barrel (endcap)

Missing transverse momentum

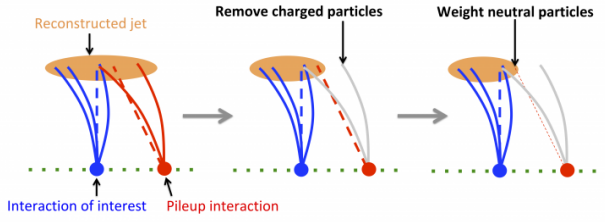
CMS JME-17-001 CMS JME-18-001







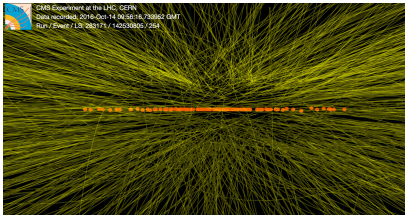
- $p_{\mathrm{T}}^{\mathrm{miss}}$ = negative vector $\vec{p}_{\mathrm{T}}$ sum of all visible final-state particles $\rightsquigarrow \sum p_{\mathrm{T}}^{\nu}$
- PUPPI algorithm tries to remove PF candidates that are likely from PU $\rightarrow$ improved resolution

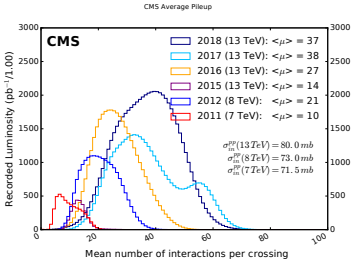


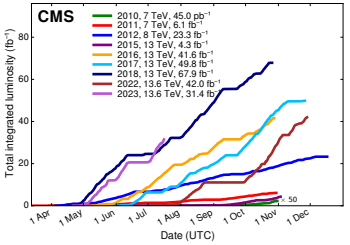
Luminosity and "pileup"

CMS LumiPublicResults CMS LUM-17-003

- Luminosity (event rate) key parameter of collider
- High instantaneous luminosity → multiple pp interactions per bunch crossing ("pileup")





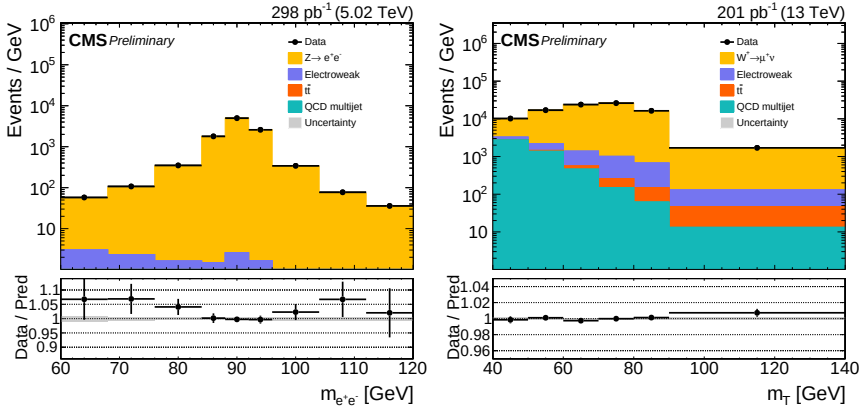


- Tracking copes well: tracks assigned to distinct interaction vertices
- Calorimeters: energy deposits overlap and cannot be distinguished
- Phase-2 upgrade for high-lumi LHC: MIP timing detector → 4D vertexing Talk by Karlis, endcap calorimeters with cluster timing (HGCAL)
- Multiple methods to measure luminosity, calibration using beam-separation (vdM) scans
- Integrated luminosity $\mathcal{L}$ gives total expected events per year, known to $1.2 - 2.5\%$

CMS PAS-LUM-17-004 CMS PAS-LUM-18-002

W and Z production at 5 and 13 TeV

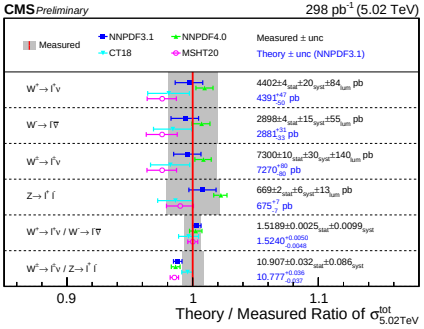
CMS PAS-SMP-20-004

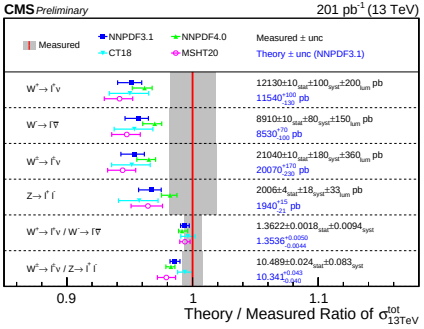


- Production cross section $\sigma = N^{\text{obs}} / (A \cdot \epsilon \cdot \mathcal{L})$
  - N^{obs} = observed events, A = acceptance, ϵ = efficiency, $\mathcal{L}$ = integrated luminosity
- Z boson fully reconstructed from 2 charged leptons, W boson partially from lepton + $p_{\text{T}}^{\text{miss}}$
- Measurement in low-PU data: $\langle N_{PU} \rangle = 3 \rightarrow$ better $p_{\text{T}}^{\text{miss}}$ resolution
- Fitting signal strength of MC predictions to data, backgrounds from MC or data sidebands

W and Z production at 5 and 13 TeV

CMS PAS-SMP-20-004





5 TeV results (left)

- 5 TeV predictions depend strongly on proton PDF
- Prediction with NNPDF3.1 (=CMS default) in good agreement with measurement
- W^+/W^- ratio in good agrement; $W^\pm/Z$ higher than predicted

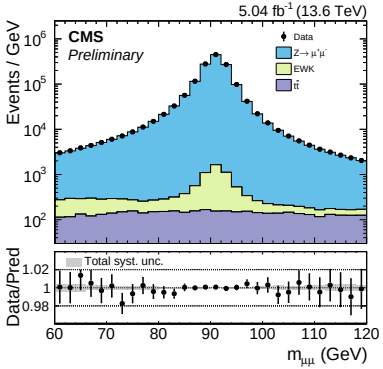
13 TeV results (right)

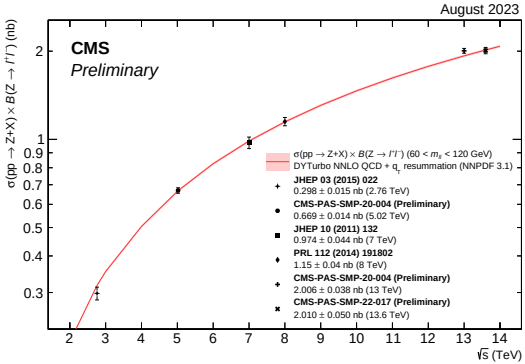
- Measurement 5% above prediction, not covered by uncertainties (mostly lumi)

Z production at 13.6 TeV

CMS PAS-SMP-22-017

- First measurement of vector boson cross section at 13.6 TeV! (early 2022 data)





- Preliminary calibrations for muon efficiency, muon momentum scale, and luminosity
- Excellent agreement with NNLO prediction for $Z/\gamma^* \to \ell^+\ell^-$ with $60 < m(\ell\ell) < 120\,\text{GeV}$

$$(\sigma_{\text{tot}}\mathcal{B})_{\text{measured}} = (2.010 \pm 0.001(\text{stat}) \pm 0.018(\text{syst}) \pm 0.046(\text{lumi}) \pm 0.007(\text{theo}))\,\text{nb},$$

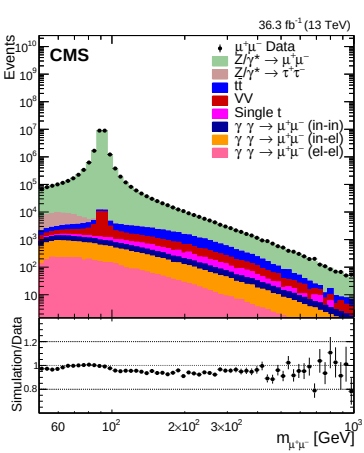
$$(\sigma_{\text{tot}}\mathcal{B})_{\text{predicted}} = (2.018 \pm 0.012(\text{PDF})^{+0.018}_{-0.023}(\text{scale}))\,\text{nb},$$

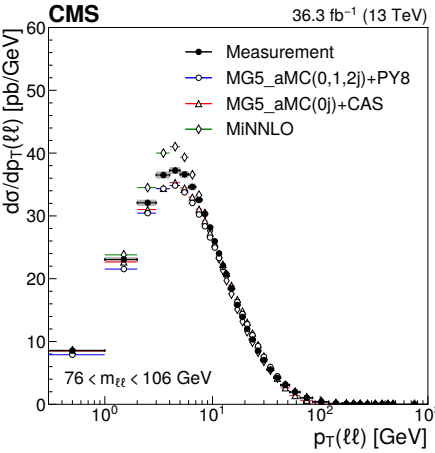
- Suggests that 13 TeV result is an outlier

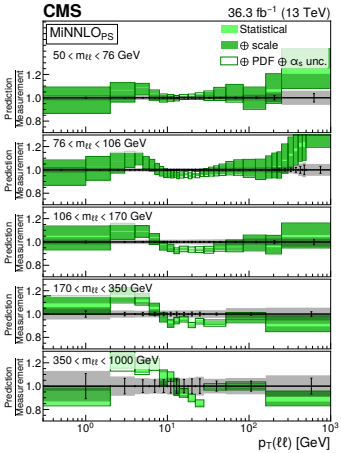
Differential DY cross section

CMS SMP-20-003

- Measurement of Z/γ^* transverse momentum p_T in bins of invariant mass





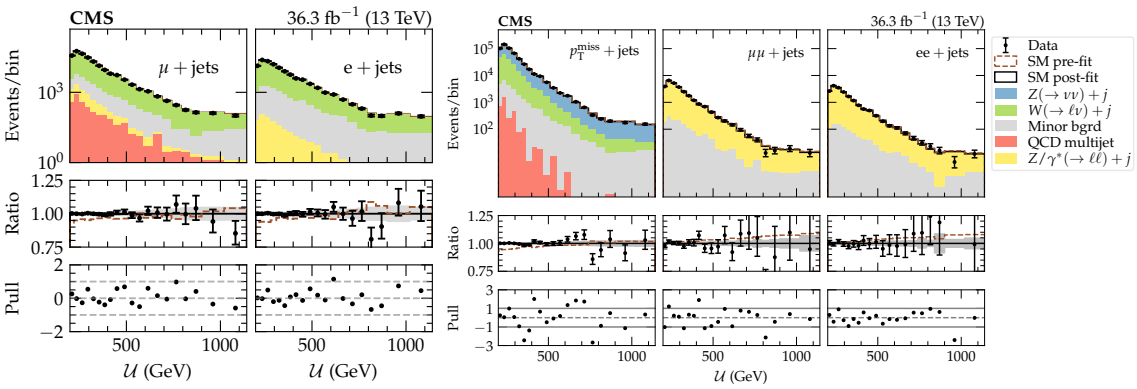


- Measured with extremely good precision ($< 2\%$)
- Shape at low p_T difficult to predict but very important for measurement of m_W

Invisible Z width

CMS SMP-18-014

- Measure $Z \to \nu\bar{\nu}$ in events with large missing p_T and jets
- Using observable $\mathcal{U} = p_T^{miss}$ or hadronic recoil (in dilepton events), $\mathcal{U} > 200$ GeV



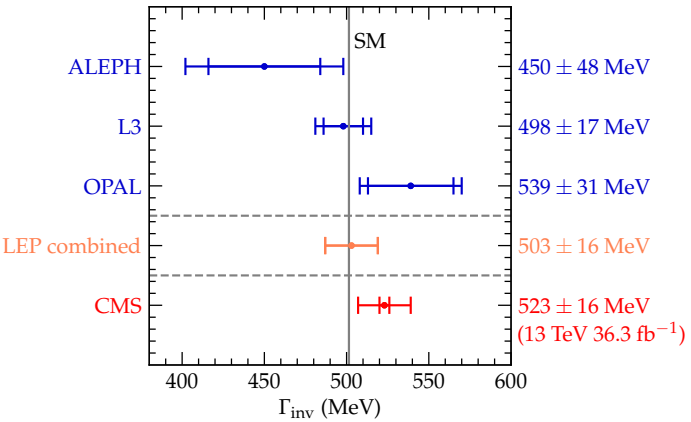
ℓ+jets region | signal region | $\ell^+\ell^-$+jets region

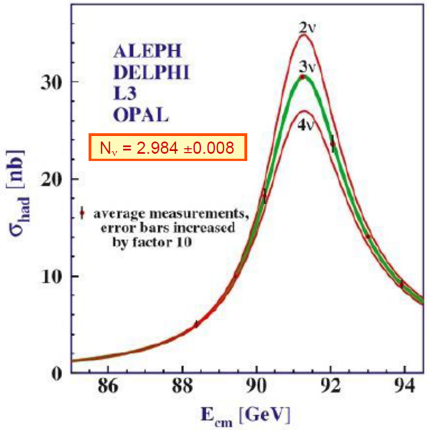
- ℓ+jets control region → W+jets background prediction
- Signal shape from $(Z \to \ell^+\ell^-)$ +jets region
- QCD multijet from events where missing p_T in direction of a jet

Invisible Z width

CMS SMP-18-014

- Determine invisible width as $\Gamma(Z \to \nu\bar{\nu}) = \mathcal{B}(Z \to \nu\bar{\nu}) / \mathcal{B}(Z \to \ell^+\ell^-) \times \Gamma(Z \to \ell^+\ell^-)$



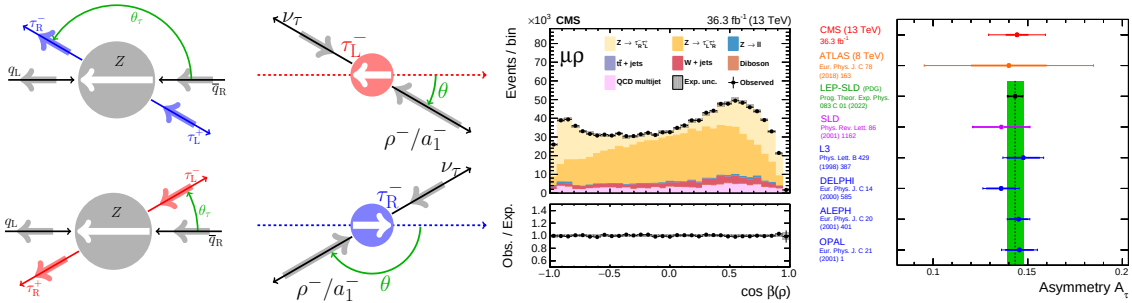


- Uncertainties mainly from lepton identification and jet energy scale
- Single most precise measurement of $\Gamma(Z \to \nu\bar{\nu})$, competitive with LEP combination
- Compatible with Standard Model, no sign of Z decays to unknown light fermions

Tau polarization

CMS SMP-18-010

- Z couples preferably to left-handed particles (ℓ_L^-) and right-handed anti-particles (ℓ_R^+)
  $\rightarrow$ Polarization $\mathcal{P}_\tau = \left(\sigma\left(Z \rightarrow \tau_R^- \tau_L^+\right) - \sigma\left(Z \rightarrow \tau_L^- \tau_R^+\right)\right) / \sigma\left(Z \rightarrow \tau^- \tau^+\right)$
- Subsequent tau decay angles depend on τ spin $\rightarrow$ allows for measurement of $\mathcal{P}_\tau$

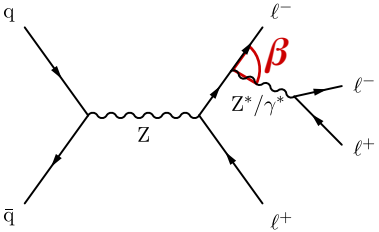


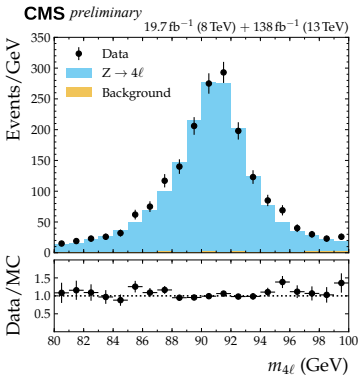
- Extracted asymmetry $A_\tau = -\mathcal{P}_\tau$ agrees well with previous measurements
- Effective weak mixing angle determined as $\sin^2\theta_W^{\text{eff}} = \left(-\mathcal{P}_\tau/2 + 1\right)/4 = 0.2319 \pm 0.0019$
  $\rightarrow$ agrees with world average $\sin^2\theta_W^{\text{eff}} = 0.23153 \pm 0.00016$

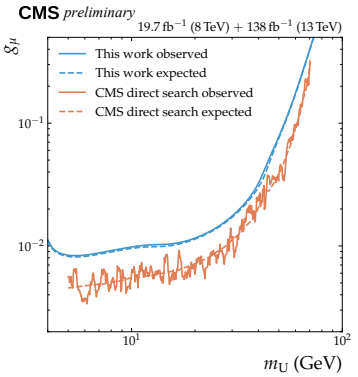
$Z \to 4$ leptons

CMS PAS-SMP-19-007

- Select events with 4 electrons or muons and $80 < m(4\ell) < 100$ GeV





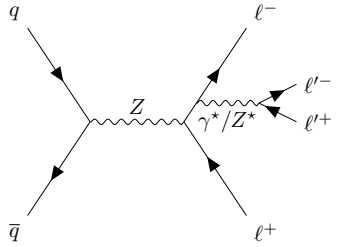


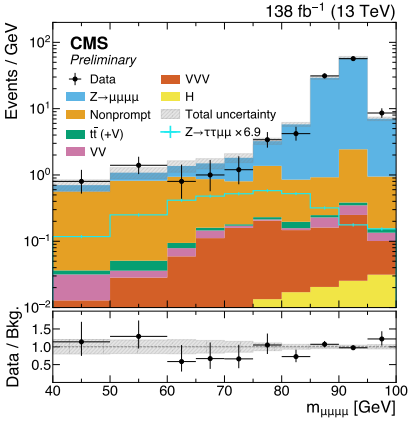
- Minimize uncertainties by normalizing to $Z \to 2\ell$ process
- Measured $\mathcal{B}(Z \to 4\ell) = (4.67 \pm 0.11\ (\text{stat}) \pm 0.10\ (\text{syst})) \times 10^{-6}$, expected $(4.70 \pm 0.02) \times 10^{-6}$
- Translates to competitive limits on couplings and mass of new light gauge boson U
- Decay kinematics (masses and angles) $\to$ in agreement with prediction

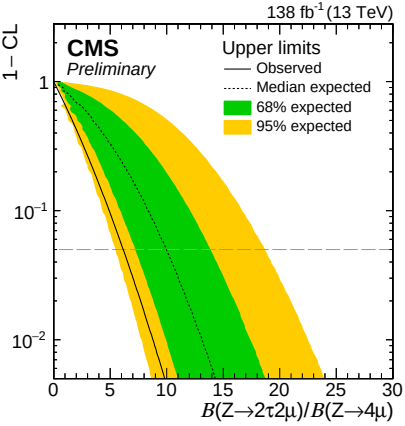
Search for $Z \to \tau^+\tau^-\mu^+\mu^-$

CMS PAS-SMP-22-016

- Target $Z \to \tau^+\tau^-\mu^+\mu^-$ where $\tau \to \mu\bar{\nu}_\mu\nu_\tau \Rightarrow$ 4 muon events
- Energy loss from neutrinos lowers invariant mass $m(4\mu)$







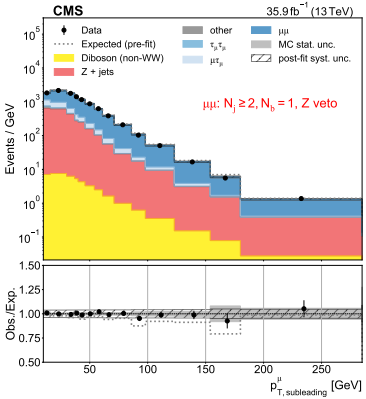
- No signal observed, data in signal region even smaller than prediction
- Branching ratio must be smaller than 6.9 $\times$ prediction [95% CL]

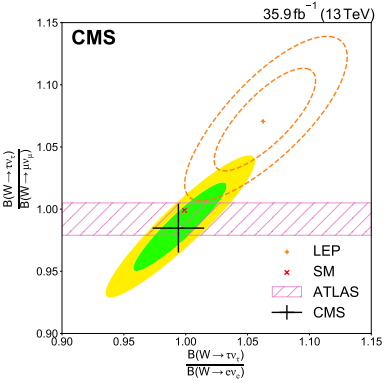
Lepton flavor universality

CMS SMP-18-011

- Measured branching fractions of the W boson to electrons, muons, taus, and quarks
- Fit to (subleading) lepton p_T in 12 signal categories, exploits subtle changes in spectrum

	$N_j = 0$	$N_j = 1$	$N_j = 2$	$N_j = 3$	$N_j \geq 4$
$N_b = 0$	$e\tau_h$, $\mu\tau_h$, $e\mu$	$e\tau_h$, $\mu\tau_h$, $e\mu$	$e\tau_h$, $\mu\tau_h$ $e\mu$		
$N_b = 1$		$e\tau_h$, $\mu\tau_h$, $e\mu$	$e\tau_h$, $\mu\tau_h$	$e\tau_h$, $\mu\tau_h$	
			$ee, \mu\mu, e\mu$		
					eh, μh
$N_b \geq 2$			$e\tau_h$, $\mu\tau_h$	$e\tau_h$, $\mu\tau_h$	
			$ee, \mu\mu, e\mu$		
					eh, μh



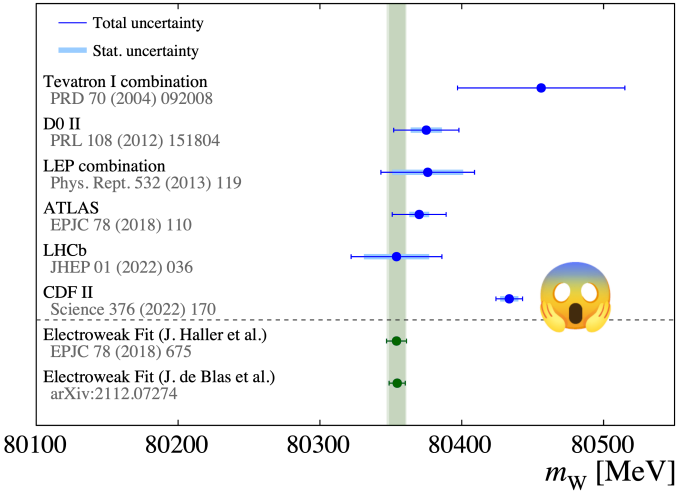


- Consistent with lepton flavor universality for the weak interaction

Summary

- Very active research program in CMS SMP-V group
- W/Z production rates agree (mostly) with the expectations
  CMS PAS-SMP-20-004 CMS PAS-SMP-22-017
- Differential DY cross sections more precise than current predictions
  CMS SMP-20-003
- Measurements of challenging and rare Z decays in agreement with predictions
  CMS SMP-18-014 CMS SMP-18-010 CMS PAS-SMP-19-007 CMS PAS-SMP-22-016
- No sign for violation of lepton flavor universality in W decays
  CMS SMP-18-011

Outlook



- Stay tuned for more precision measurements from CMS!