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Precision Measurements and the Search for New Physics

in WZ⟶3ℓν Events with the CMS Detector

Kenneth Long
University of Wisconsin - Madison

Outline

1. Physics Overview
2. WZ Production at the LHC
3. Predictions for Precision Measurements
4. The Large Hadron Collider
5. The Compact Muon Solenoid
6. Physics Objects and Event Reconstruction
7. Analysis Overview
8. Results
9. Moving Forward

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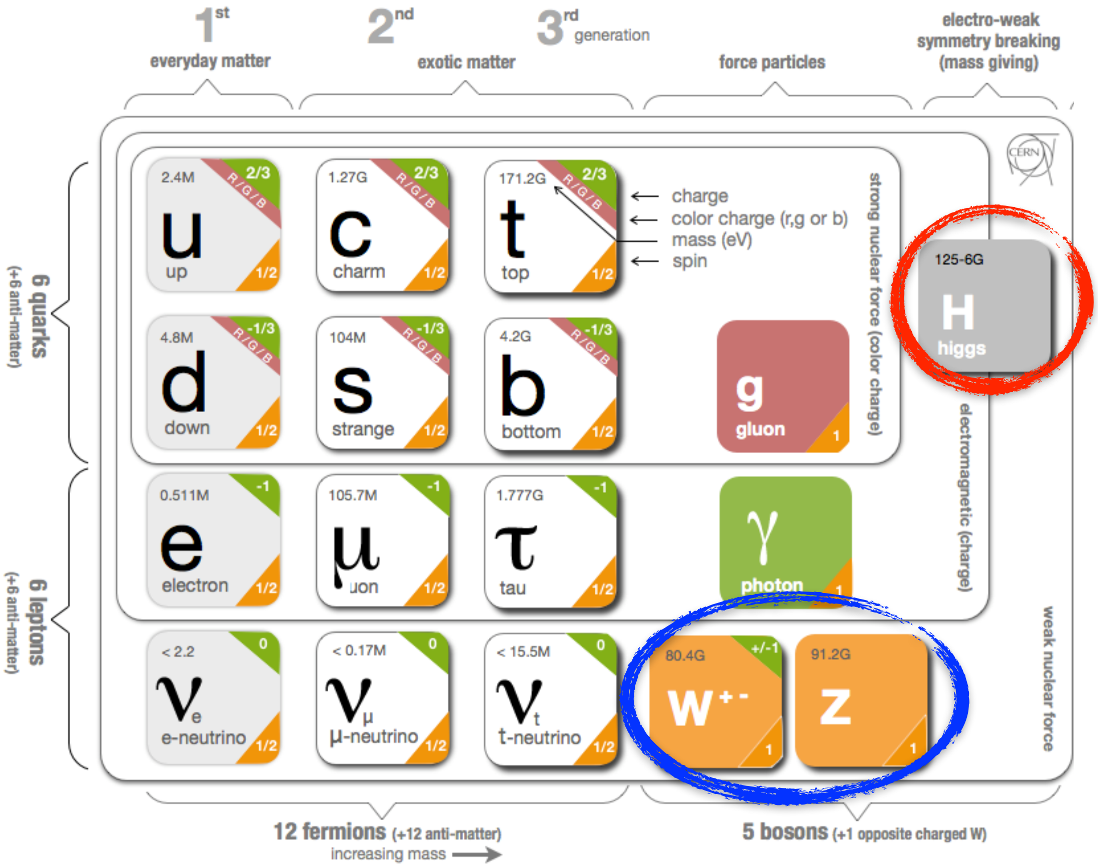
The Standard Model

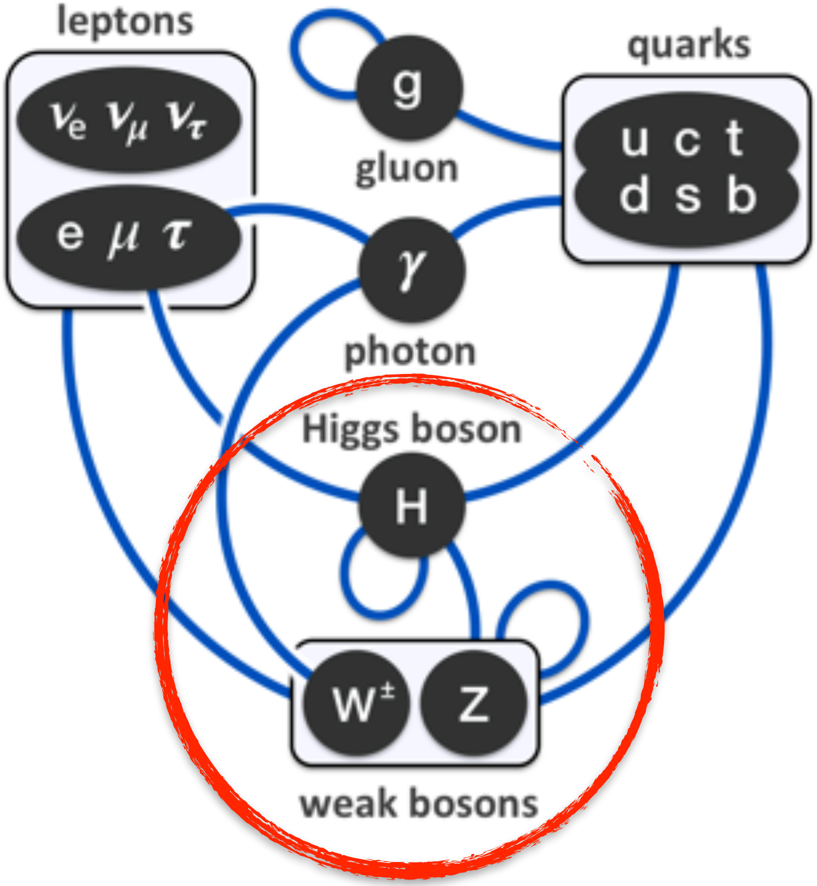
- Concise, elegant theory of the fundamental particles and their interactions
- Particles and interactions described by the standard model Lagrangian in the language of Quantum Field Theory
  - Matter composed of spin 1/2 fermions
  - Interactions mediated by spin 1 vector bosons
  - Mass arises from interactions with scalar Higgs field



- Spectacularly precise and successful theory
- Does not include **gravity**, **dark matter**, or **dark energy**

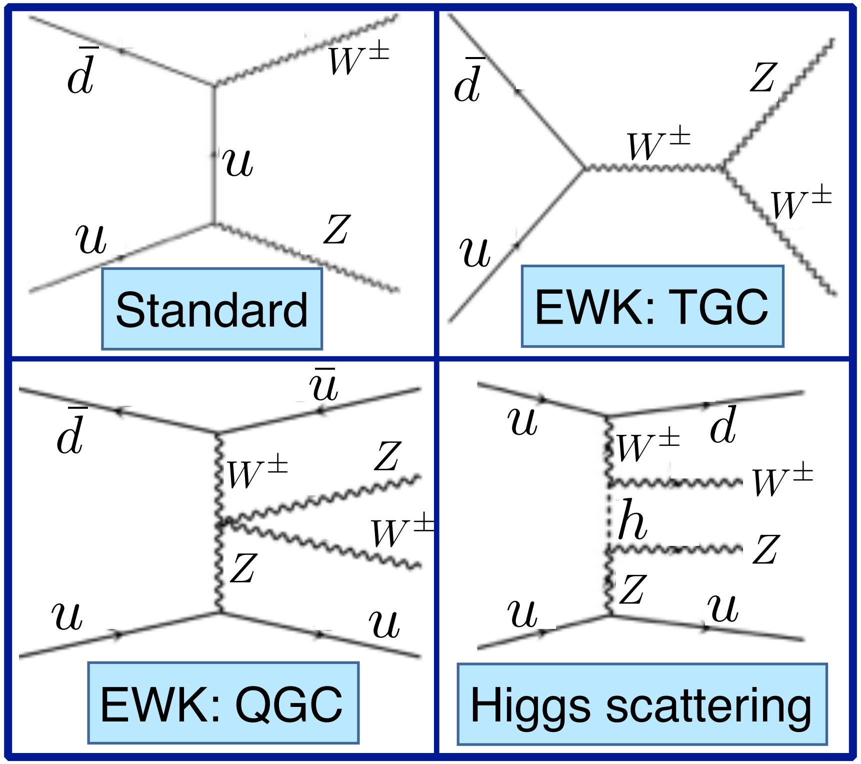
Interactions in the Standard Model

- Interactions of quarks and leptons are mediated by vector bosons
  - Act as force carriers
- Electromagnetic Force
  - Mediated by photons
  - Long range
  - Responsible for familiar electromagnetic processes
- Weak Force
  - Mediated by massive W and Z bosons
  - Short range
  - Responsible for some nuclear decays
- Strong Force
  - Mediated by gluons
  - Short range
  - Forms bound states of quarks
- Interactions with the Higgs
  - Leads to particles acquiring mass



Motivation for Diboson Studies

- Standard Model (SM) predicts direct interactions of electroweak bosons
  - Couplings predicted precisely
  - Deviations from SM predictions sign of New Physics (NP)
- Production of pairs of electroweak vector bosons (dibosons) at the Large Hadron Collider (LHC)
  - Standard production: Bosons radiated from the quarks
  - Electroweak (EWK) production
    - Triple gauge couplings (TGC)
    - Quartic gauge coupling (QGC) in vector boson scattering (VBS)
    - Higgs scattering (in VBS)
  - QGC and Higgs scattering of massive vector bosons not yet observed

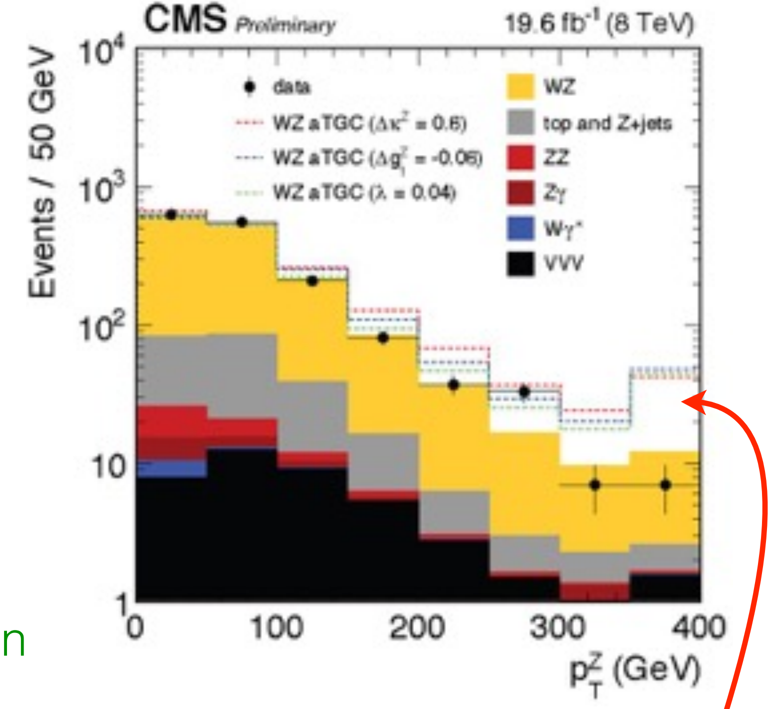


$\sigma(pp\rightarrow WZ\rightarrow 3\ell\nu)$ at 13 TeV (in fb)

Fiducial Selection	$\sigma_{\text{Std+TGC}}$	σ_{VBS}
Inclusive WZ	280	3.5
VBS (with 2 jets)	0.96	0.67

New Physics in Diboson Production

- Can probe fundamental aspects of (new) physics
  - New scalar particles
    Example: Additional Higgs bosons in extended Higgs sectors (SUSY)
  - New gauge bosons
    Example: Unification models predict extended gauge sectors with additional gauge bosons
- Direct production of new particles with resonant decay to dibosons
- Indirect indications of new physics
  - Observable as deviations from SM prediction
    - Total cross section
    - Differential cross sections
      - Example: transverse momentum (p_T) of Z
  - Observable even when new particles are very massive (possibly above LHC energy scale)
    - Produced in s-channel but off-shell
    - Present only in t-channel or loops



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Thesis Physics Goals

- ✓ Observe WZ production at 13 TeV
- Precision measurement of WZ production cross section
- Differential measurements of WZ production
  - Focussing on distributions with NP potential
  - Z p_T and WZ (transverse) mass
    - WZ mass set by the scattering interaction in VBS
    - for anomalous TGC (aTGC) or QGC (aQGC) NP contribution
  - Jet kinematics (experimental observations of final state partons)
    - Understand two jet events in vector boson scattering
    - Observe EWK vector boson scattering including QGC and Higgs scattering
- Searches for new physics
  - Resonant searches
    - Some 700 GeV diphoton resonance models predict WZ signals
  - Non resonant contributions causing anomalous TGCs and QGCs

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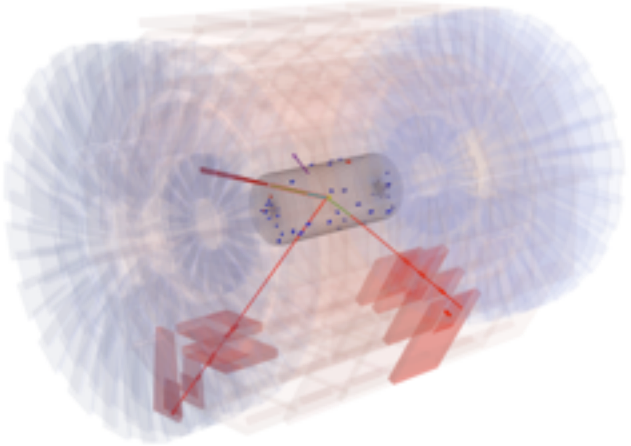
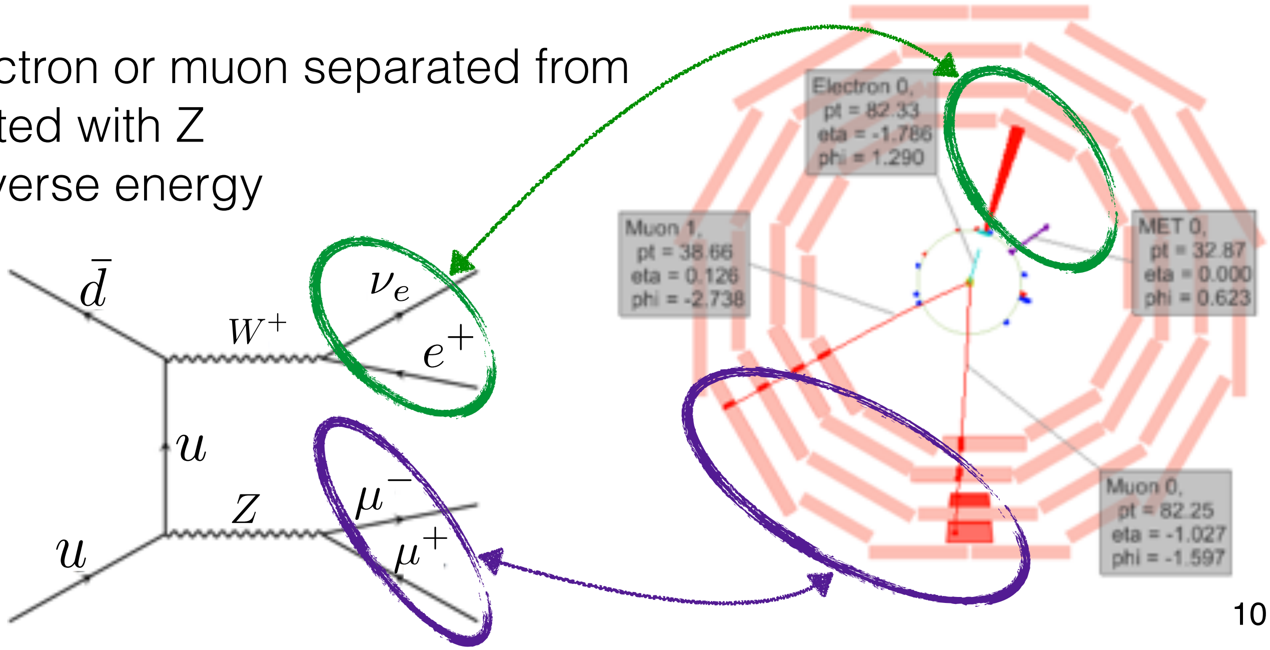
Observing WZ⟶3ℓν at CMS

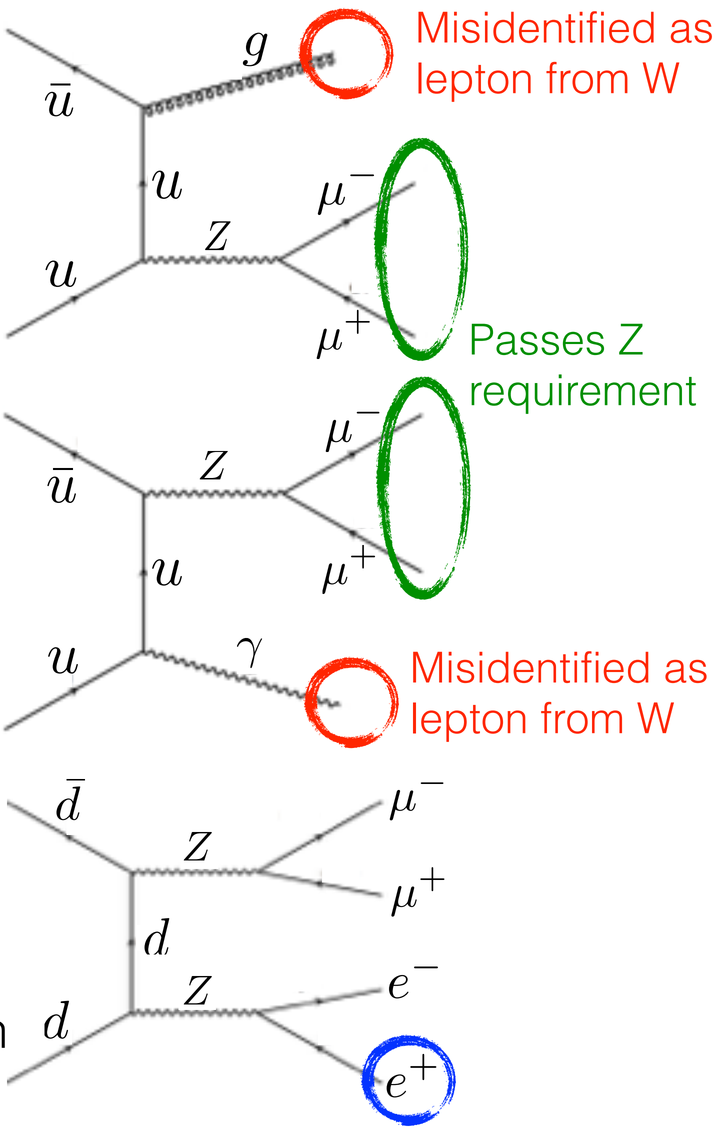
- W and Z bosons too short-lived for direct observation
  - Properties inferred by from decay products
  - Decays to electrons (*e*) and muons (μ) are ideal
    - Very accurately reconstructed by CMS
    - Final state of 3 *e*, *μ* is a unique signature
  - Z boson
    - Identify 2 opposite sign, same flavor (*e* or *μ*), high momentum, isolated leptons
    - Invariant mass consistent with Z
  - W boson
    - Additional electron or muon separated from those associated with Z
    - Missing transverse energy





Major Backgrounds to WZ⟶3ℓν

- Other processes can mimic WZ⟶3ℓν
  - With or without misidentification of final state particles
  - Contribution can be minimized, but cannot be completely removed
  - Critical to understand these “background” contributions
- Z (Drell-Yan) and Zγ production (55% of total background contribution)
  - Produced at very high rate
  - Passes Z candidate requirement
  - Third lepton and missing energy from misidentification
    - Misidentified leptons are not isolated from other detector objects
- ZZ⟶4ℓ production (~20% total background)
  - Passes Z candidate requirement
  - Overlaps WZ⟶3ℓν signal when one lepton escapes detection



Misidentified as lepton from W

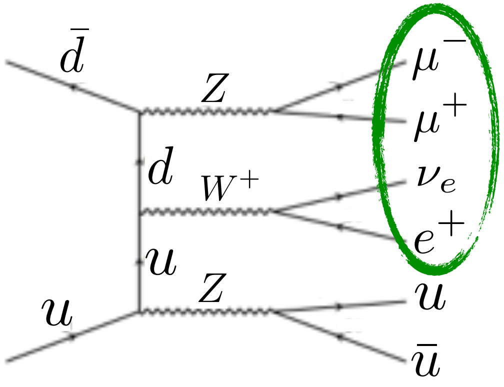
Passes Z requirement

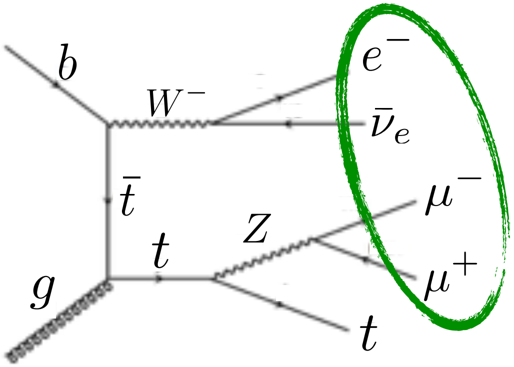
Misidentified as lepton from W

Escapes detector acceptance

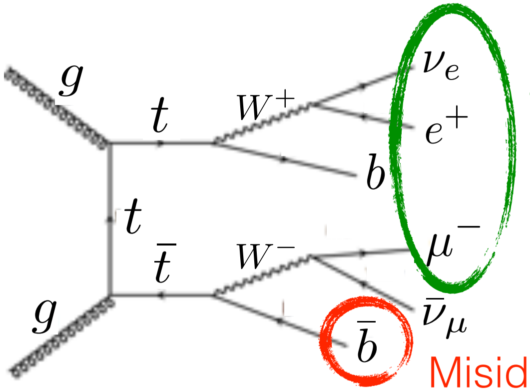
Other Backgrounds to WZ→3ℓν

- VVV, ttV, tV, (V = W, Z) production
  (~10% of background contribution)
  - Small rate of production
  - Can precisely mimic WZ→3ℓν
- tt̄ production
  (~15% of background contribution)
  - Large rate of production
  - True leptons and missing energy from W decays (from top decay)
  - Extra leptons from misidentification
  - No resonant decay of a Z



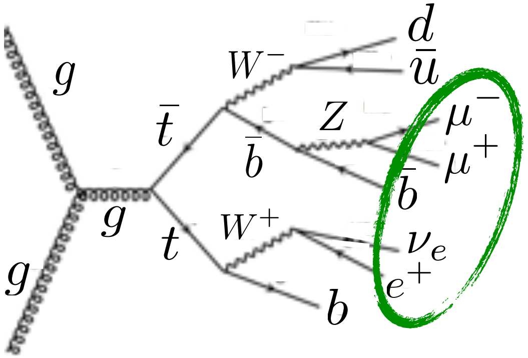


Mimics WZ→3ℓν



True leptons and missing energy from W decays

Misidentified as lepton



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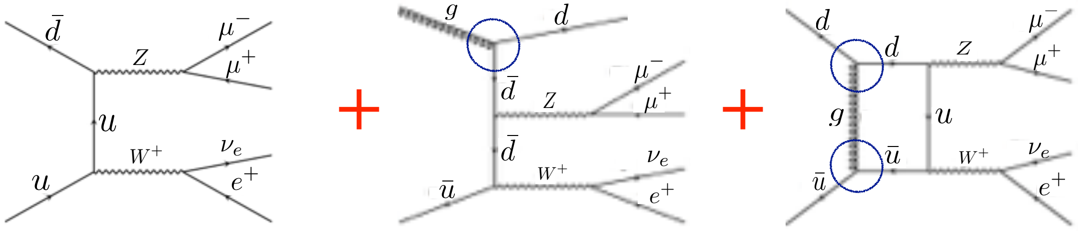
Predictions from the Standard Model

- Extracting predictions for LHC collisions is not trivial!
- For weakly interacting fields, observables from a scattering process can be studied from a perturbative expansion
  - Coupling constants of fundamental forces express strengths of interactions
  - Perturbative expansion in “orders” as a function of coupling constant (α_S, α_{QED})

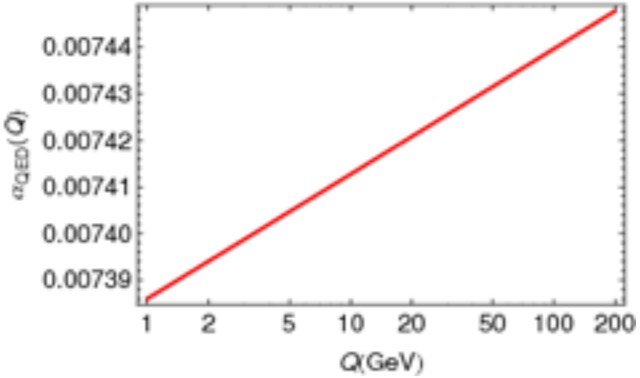
$\mathcal{M} =$

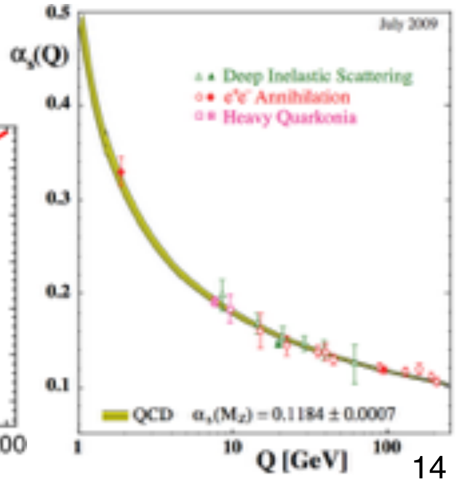


$+ \cdots$

$$\hat{\sigma} = \alpha_S^k \left(\underset{\substack{\uparrow \\ \text{LO}}}{\hat{\sigma}^{(0)}} + \frac{\alpha_S}{\pi} \underset{\substack{\uparrow \\ \text{NLO}}}{\hat{\sigma}^{(1)}} + \left(\frac{\alpha_S}{\pi}\right)^2 \underset{\substack{\uparrow \\ \text{NNLO}}}{\hat{\sigma}^{(2)}} + \ldots \right) \propto |\mathcal{M}|^2$$

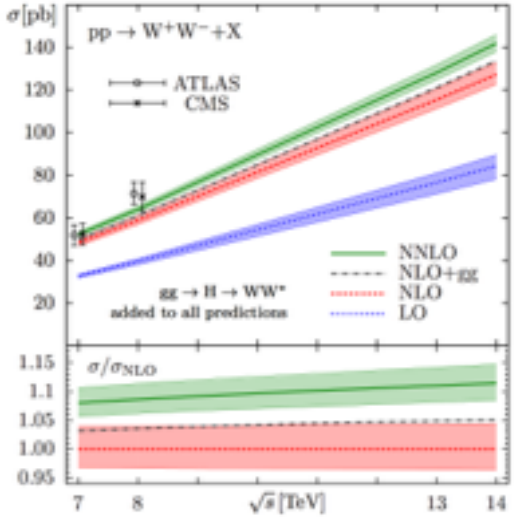
- Perturbative QCD calculation possible at LHC energies
  - Calculation in NLO minimum for accurate cross section prediction. NNLO?

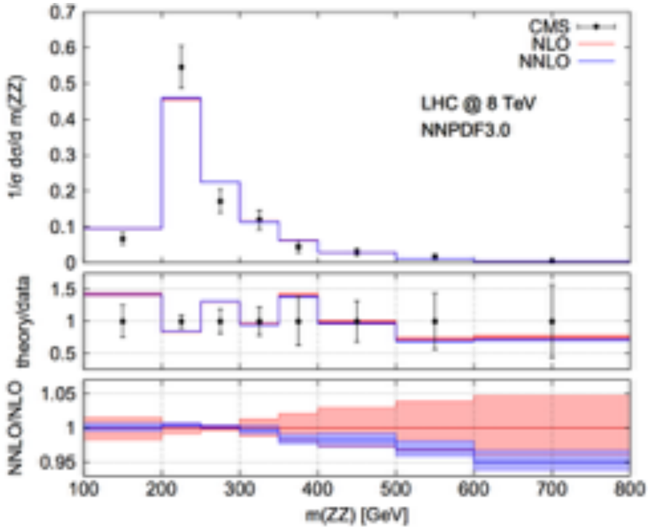




Predictions for WZ⟶3ℓν at the LHC

- Cross sections and distributions for WZ⟶3ℓν known at NLO in QCD
  - Change in cross section from LO to NLO ~100%
  - Significant affect on distributions
- NNLO QCD corrections calculated for ZZ and WW
  - For ZZ, $\boldsymbol{\sigma}_{\mathrm{NLO}}$ to $\boldsymbol{\sigma}_{\mathrm{NNLO}}$ is ~15%, uncertainty ~3%
    - Improves agreement with experiment
  - Work in progress for WZ
- NLO EWK Corrections (Assume EWK/QCD factorize)
  - Affect on total cross section *negative* and ~5%
- NLO with parton shower (NLO+PS)
  - Generate extra partons and jet structure using soft radiation approximation (Crucial for accurate simulation of distributions)
- My work: Determine 13 TeV cross sections for CMS diboson Monte Carlo
  - Liaison with theory community for NNLO diboson cross sections
  - Run and validate NLO and NLO+PS programs for WZ (all decays) and ZZ processes

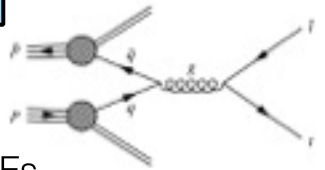




arXiv:1408.5243 and1507.06257

Simulating Events at the LHC

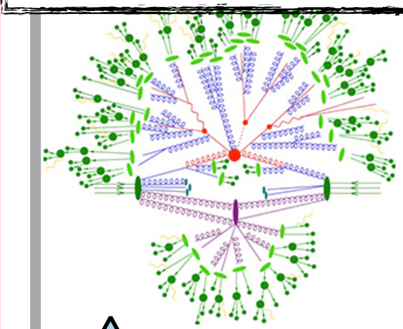
Hard Process



- PDFs
- Perturbative QCD

Programs at CMS
- MadGraph5_aMC@NLO
- POWHEG BOX
- Pythia 8

Soft Processes and Non-perturbative QCD



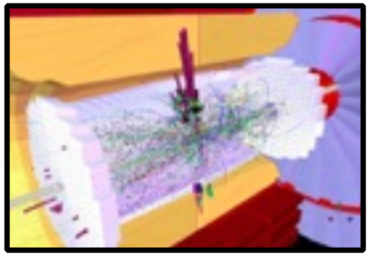
- Initial and final state radiation
- Hadronization
- Soft interactions

Programs at CMS
- Pythia 8
- Herwig++

"Complete" physics simulation
➡Pre-detector studies

Detector Simulation

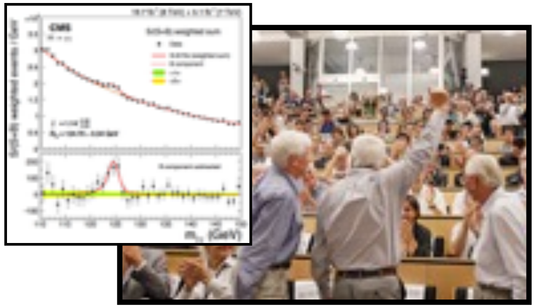
Modeled in Geant4
- Particle interactions with matter
- Detector response



Data Collection

Event Reconstruction

Analysis and Discovery!



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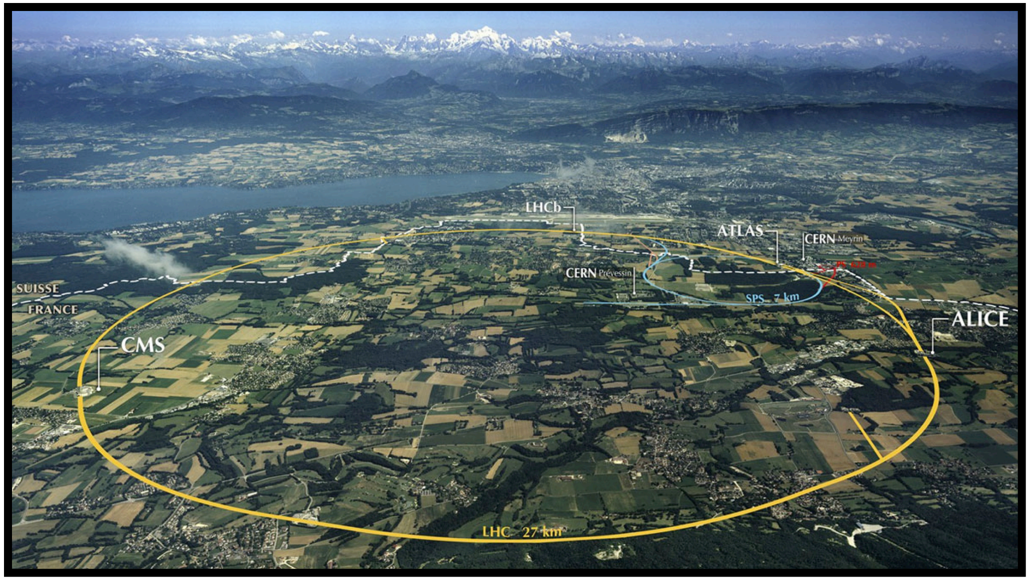
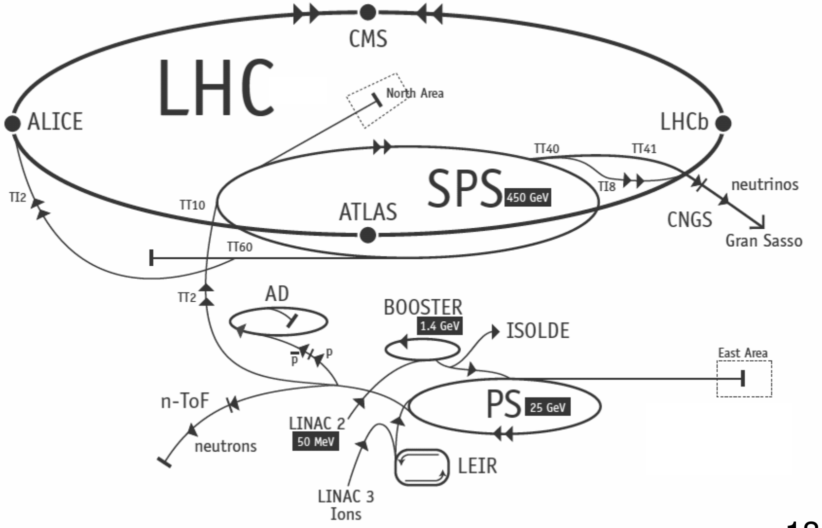
The LHC: Overview

- 27 kilometer circumference collider at CERN outside of Geneva, Switzerland
  - Used for proton-proton and heavy-ion collisions
  - Currently colliding protons at a center of mass energy of 13 TeV
- Supports 4 large experiments
  - Alice
    - Heavy Ion Physics
  - LHCb
    - Forward Hadronic and b-quark physics
  - Atlas and **CMS**
    - Exploration of the Standard Model
    - Characterization of the Higgs Boson
    - Searches for new physics





Luminosity and Beam Parameters

- Beams brought to collision at four detector sites
- Luminosity — quantifies delivered beam
  - Derive number of events for a given process by integrating over time

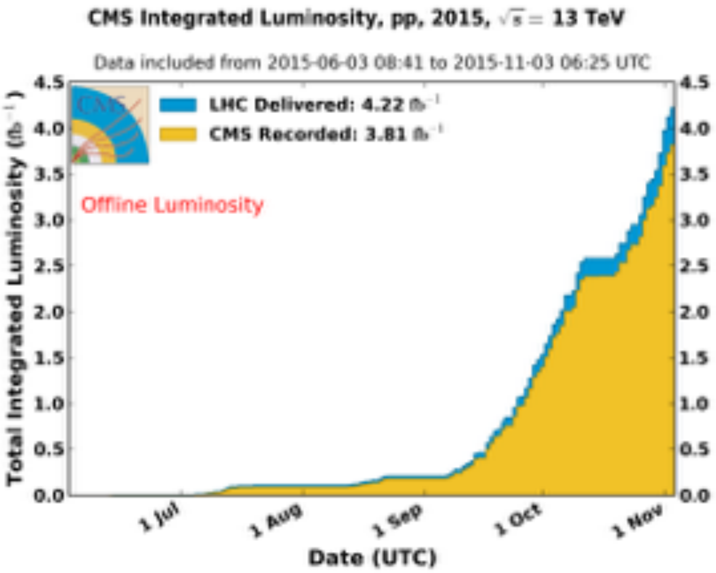
$$N = \sigma \int L \, dt$$

  - L = instantaneous luminosity
  - **σ** = cross section of process

$\boldsymbol{\sigma}_{\mathrm{tot}}(WZ \to 3\ell\nu)$ ~300 fb

$\boldsymbol{\sigma}_{\mathrm{VBS}}(WZ \to 3\ell\nu)$ ~3 fb

13 TeV



	Design	2011	2012	2015	2016-2018 (projected)
Beam Energy (TeV)	7.0	3.5	4.0	6.5	6.5
Bunches/beam	2808	1380	1380	2808	2808
Bunch spacing (ns)	25	75/50	50	50/25	25
Peak luminosity ($cm^{-2}s^{-1}$)	1×10^{34}	3.5×10^{33}	7.6×10^{33}	$\sim 4 \times 10^{33}$	1×10^{34}
Integrated luminosity (fb^{-1})	—	8	21	3.8	100

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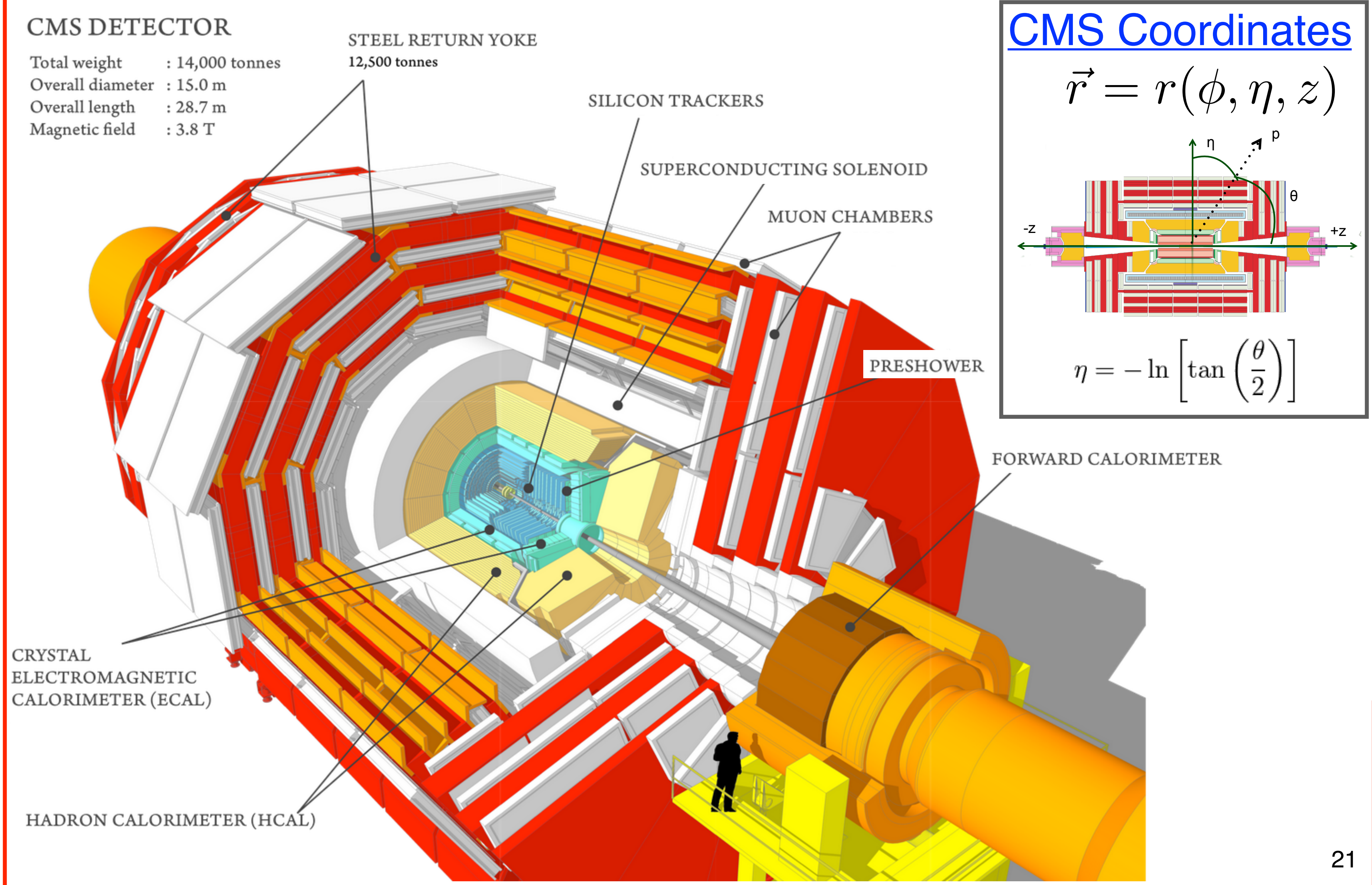
The Compact Muon Solenoid



CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

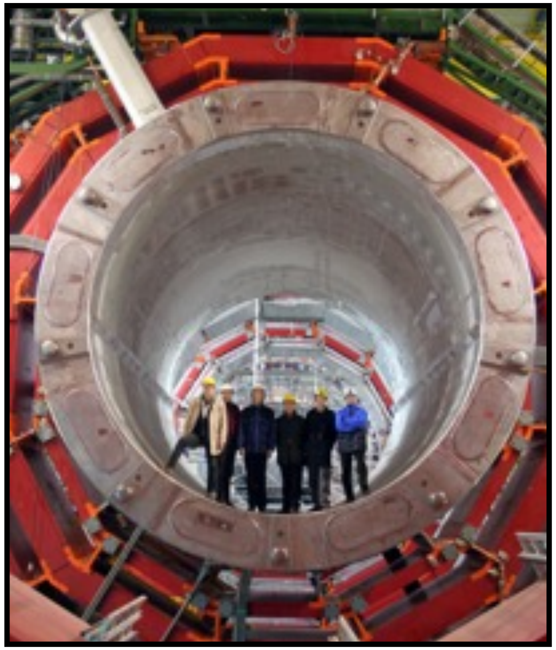
CMS Coordinates

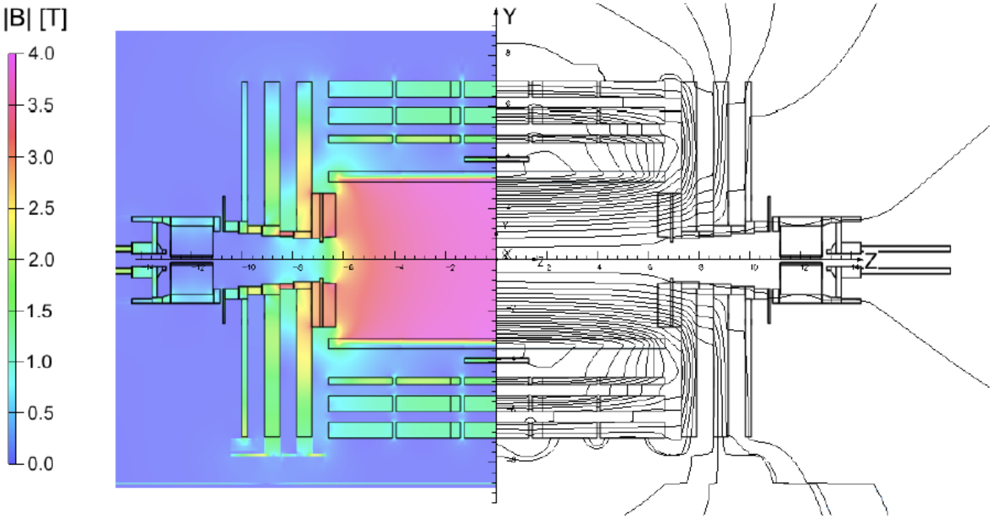
$$\vec{r} = r(\phi, \eta, z)$$

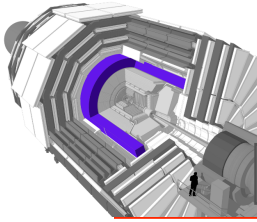
$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

Solenoid

- CMS detector designed around a 3.8 T superconducting solenoid magnet
  - 12.5 m length
  - 6.3 m diameter
  - Cooled to to 4.7 K
  - 2.0 T field in iron return yoke
- Allows precise measurement of transverse momentum (p_T) for charged particles



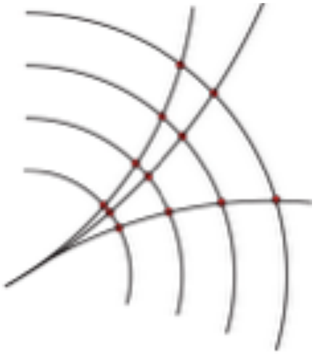


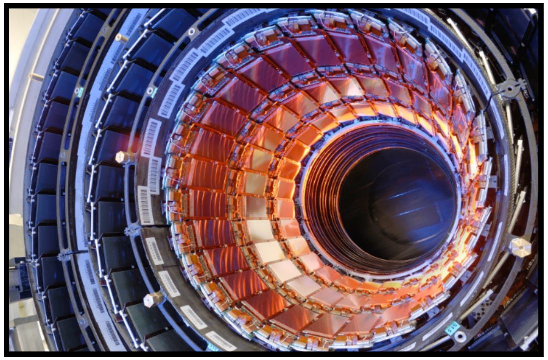


Silicon Tracker

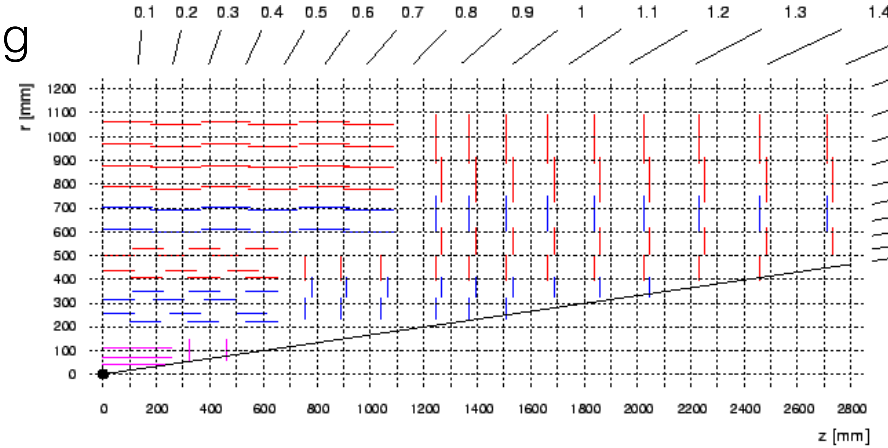
- Interactions of charged particles with silicon detectors used to reconstruct particle tracks
  - Magnetic field allows precise p_T measurement
  - Coverage: $|\eta| < 2.4$
  - Over 200 m^2 of silicon
  - Resolution (in barrel):

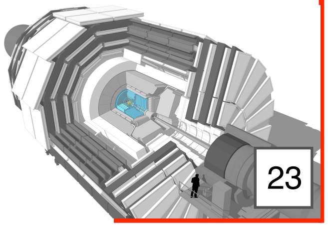
$$\frac{\delta p_T}{p_T} = \left(15\frac{p_T}{TeV} \oplus 0.5\right)\%$$





- Silicon pixel detector
  - 66M channels, fine grain resolution
  - 100 μm x 150 μm pixels
  - Important for identifying track vertex
- Silicon strip detector
  - 9.6M channels
  - 80 μm -180 μm x 4.3 cm -10 cm strips



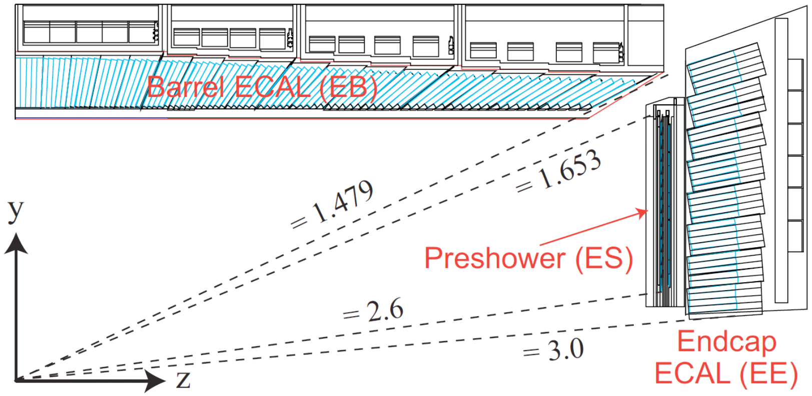


Electromagnetic Calorimeter

- Measures energy of electromagnetic particles
  - Crucial for electron and photon energy measurement and ID
  - High granularity provides position measurement
  - Coverage: $|\eta| < 3.0$
  - Resolution (in barrel):

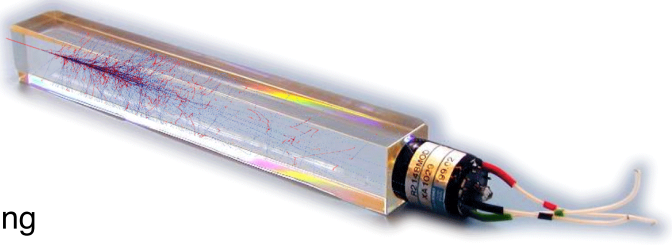
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E} \oplus 0.3\%$$

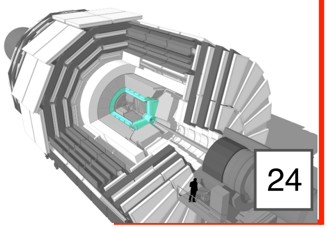
- Lead tungstate ($PbWO_4$) crystal scintillators read out by photodetectors
  - Dimensions: 2.2 cm x 2.2 cm x 23 cm
  - 61,200 crystals in barrel
  - 7,324 crystals in each endcap



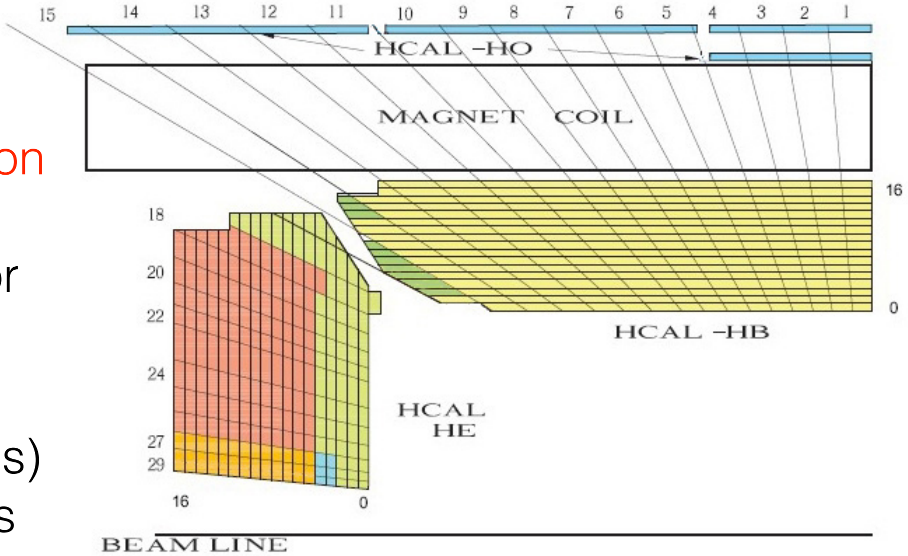
Properties of $PbWO_4$

Density	$8.3\ g/cm^2$
X_0	0.89 cm
Molière radius	2.19 cm
Peak Emission	430 nm
Light yield	~50 γ / MeV

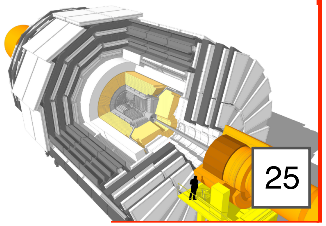




Hadronic Calorimeter

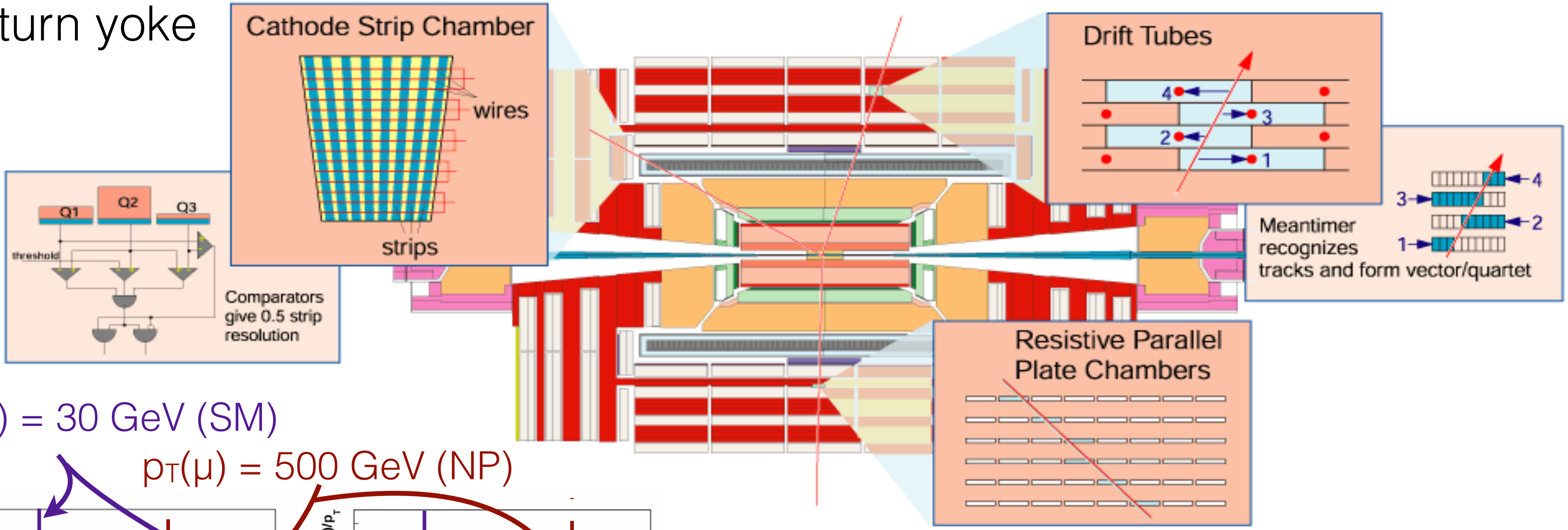


- Measures energy of charged and uncharged hadrons
  - Crucial for charged and neutral hadron energy measurement and ID
  - Hermeticity (up to |η| < 5.0) crucial for calculation of missing energy
- Sampling calorimeter
  - alternating layers of “absorber” (brass) and fluorescent “scintillator” materials
- HCAL Barrel (HB)
  - $|\eta| < 1.3$
- HCAL Endcap (HE)
  - $1.3 < |\eta| < 3.0$
- HCAL Forward (HF)
  - $3.0 < |\eta| < 5.2$
  - Cherenkov detector
  - Steel absorber
- Resolution
  - HB/HE: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{115\%}{\sqrt{E}}\right)^2 + (5.5\%)^2$
  - HF: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{280\%}{\sqrt{E}}\right)^2 + (11\%)^2$



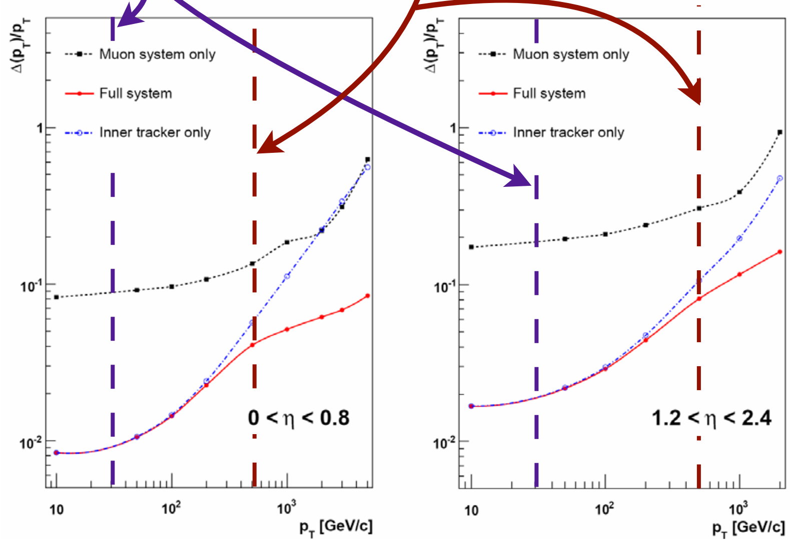
Muon System

- Combination of several detector technologies embedded within iron return yoke

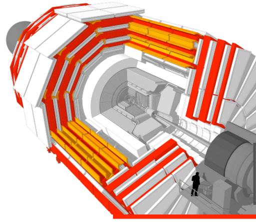


$p_T(\mu)$ = 30 GeV (SM)

$p_T(\mu)$ = 500 GeV (NP)



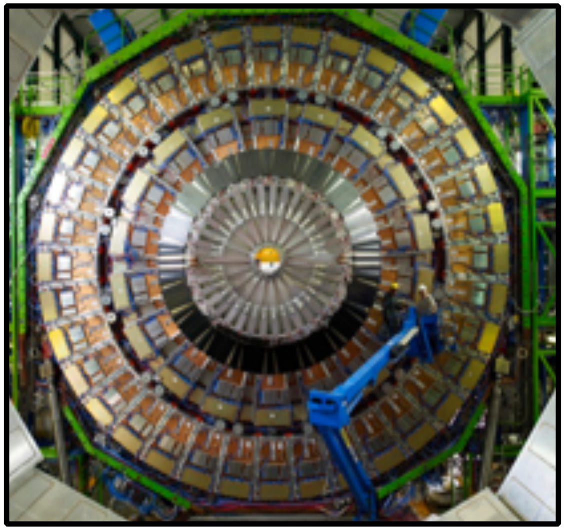
- Cathode Strip Chambers (CSC)
  - Endcap region, 0.9 < |η| < 2.4
  - 40 - 150 μm, ~2 ns
- Resistive Plate Chambers (RPC)
  - Barrel and endcap region, |η| < 1.6
  - ~2 ns
- Drift tubes (DT)
  - Barrel region, |η| < 1.2
  - 80 - 120 μm, ~3 ns

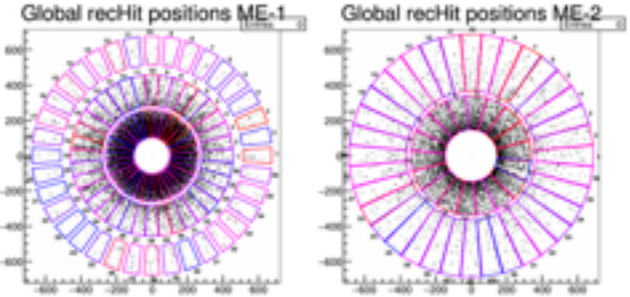


Kenneth Long

My Work on the CSC System

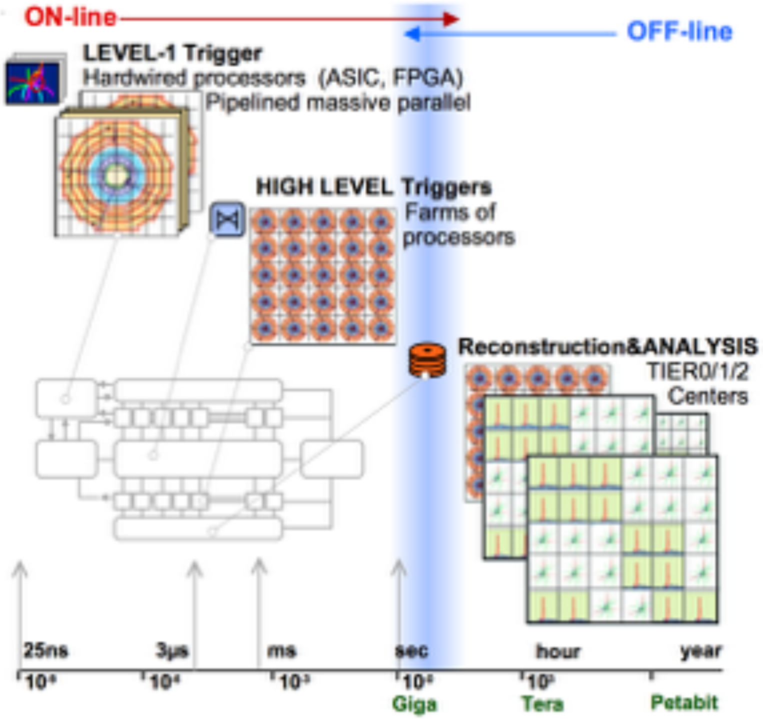
- Each detector system at CMS is carefully monitored.
  - Problematic system can make data unusable
  - As CSC certification expert, I approve/flag CSC performance
    - Data Acquisition (DAQ) information used to monitor many aspects of CSC performance
      - Timing, reconstructed x-y positions (recHits), gas gain, timing…
- LHC upgrade performance and longevity studies
  - Luminosity upgrade to LHC will increase particles per event and luminosity by ~7 times
  - Study affects on CSC performance and aging at Gamma Irradiation Facility (GIF++) at CERN
    - 14 TBq 137Cs source (662 keV gammas)
    - 100 GeV muon beam
    - Secondary particle flux approximates HL-LHC environment
  - System commissioned and filters calibrated to simulate range of HL-LHC radiation conditions





Trigger System

- LHC delivers collisions proton bunches at 40 MHz
  - ~1 Mb of storage required for each collision event
    - ➡ Cannot store every event!
  - Trigger system makes first decision on interesting vs. uninteresting events



- Level-1 Trigger
  - Custom hardware
  - Constructs simple physics objects with information from muon detectors and calorimeters
  - Reduces data rate to 100 kHz
- High Level Trigger (HLT)
  - Compute farm of ~16,000 commercial CPU cores
  - Subset of same software used offline run in an optimized way
  - Reduces data rate to ~1kHz
  - Datasets dived by HLT “paths”

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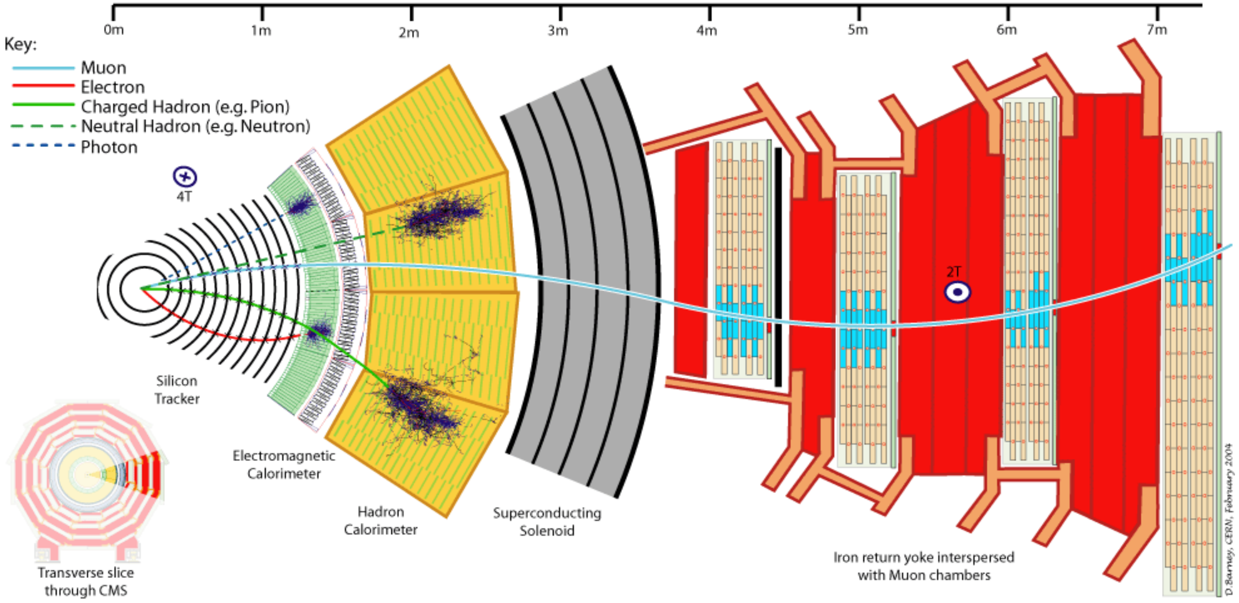
Particle Flow Reconstruction

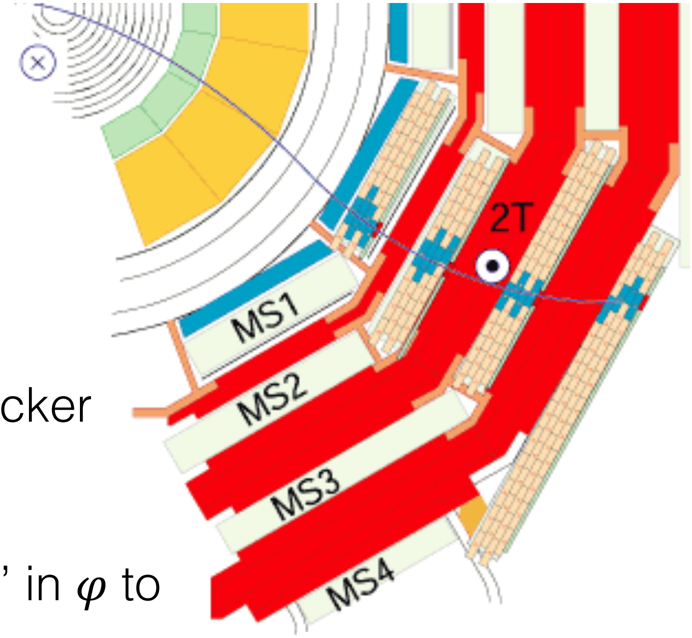
- Provide unique identification and accurate kinematic measurements
  - Combine contributions of different detector systems
- Start with systems essential for basic reconstructed
  1. Muons: Matched tracks in muon system and silicon tracker
  2. Electrons: Match tracks to ECAL energy deposits
  3. Charged Hadrons: Match tracks to ECAL and HCAL energy deposits
  4. Photons: Unmatched ECAL deposits

     Neutral Hadrons: Unmatched ECAL and HCAL deposits

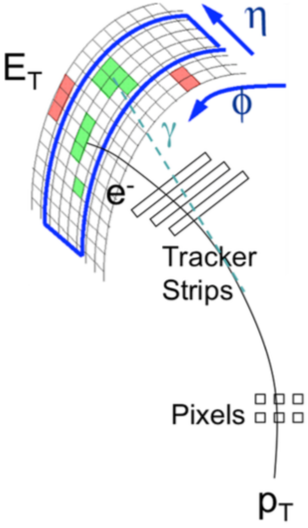
➡ Refine with additional information: Isolation, ratio HCAL/ECAL energy, etc.



Electrons and Muons

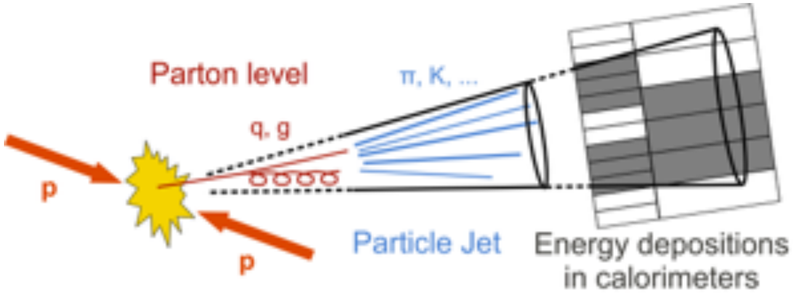


- Electrons and Muons
  - Low χ^2 for track fit quality
  - matched to primary vertex
  - $p_T > 10$ GeV
  - $|\eta(e)| < 2.5$, $|\eta(\mu)| < 2.4$
- Muons for WZ cross section measurement
  - Global — matched track in muon system to tracker
  - Few missing hits in muon system and tracker
- Electrons for WZ cross section measurement
  - Energy in ECAL summed using "superclusters" in φ to capture photons radiated by electron
- "Medium working point" defined by CMS e/γ working group Selections include:
  - $\leq$1 layer with missing hits in pixel tracker barrel ≤ 2 in endcap ($\eta \geq 1.479$)
    - Reject $\gamma \longrightarrow e^+e^-$
  - Ratio of energy in Hadronic calorimeter to electromagnetic energy (H/E) < 0.0876 in barrel (0.0678 in endcap)
    - Reject hadrons



Jets and Lepton Isolation

- Final state quarks and gluons hadronize into bound states
  - Observed as collimated hadrons and decay products called jets
- Clustering algorithms define grouping of objects to form jets
  - Cluster by "distance" until all objects
    - CMS uses anti-k_T distance parameter
  - Form well defined analysis objects
  - Allow consistent comparison with theory



$$d_{ij} = \min\left(\frac{1}{k_{ti}^2}, \frac{1}{k_{tj}^2}\right)\frac{\Delta_{ij}^2}{R^2}$$

$$\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

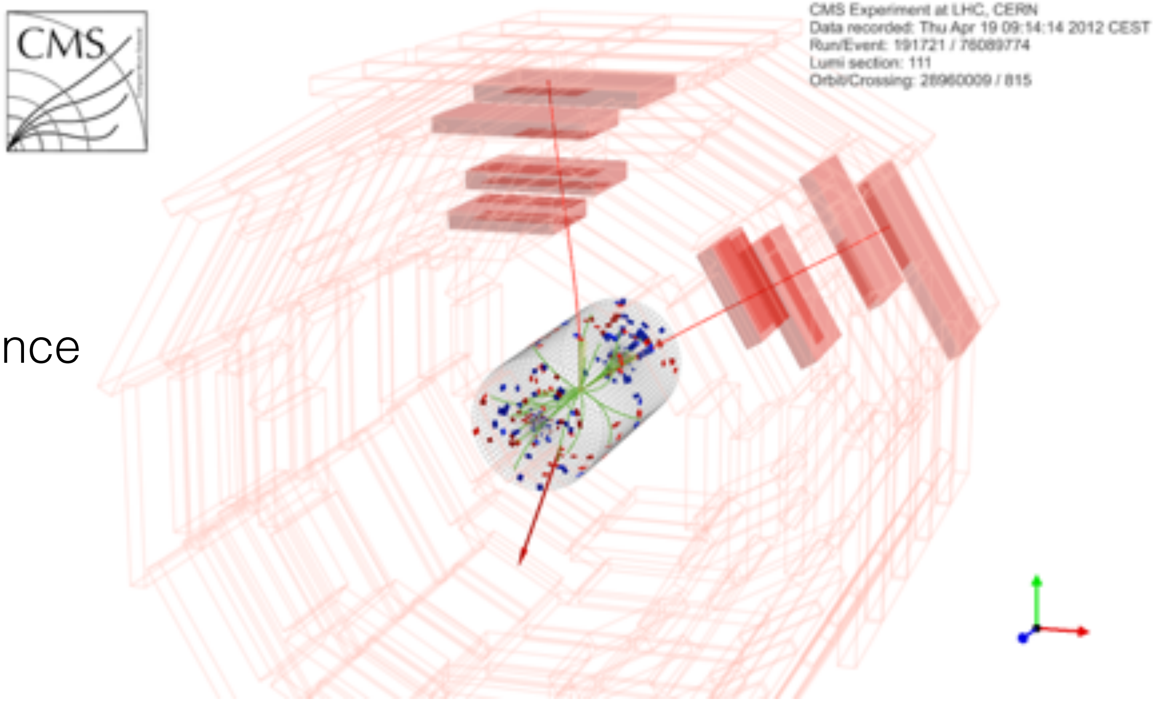
- Hadronic decays often produce leptons as constituents of jets
  - Isolation used to separate from leptons produced in hard interaction
- Isolation in this analysis
  - μ: < 0.12
  - e: < 0.0766 in barrel
    < 0.0678 in endcap

$$I_{rel}^{\mu} = \frac{\sum p_T^{charged} + max[\sum E_T^{neutral} + \sum E_T^{photon} - 0.5 \cdot \sum p_T^{charged,PU}, 0.0]}{p_T}$$

$$I_{rel}^{e} = \frac{\sum p_T^{charged} + max[\sum E_T^{neutral} + \sum E_T^{photon} - \Delta\rho \cdot E.A., 0.0]}{p_T}$$

Missing Transverse Energy

- Neutrinos will not interact with the CMS detector
  - Total transverse energy of the event should sum to zero
  - Infer the presence of neutrinos from an imbalance in transverse momentum
  - known as Missing Transverse Energy (MET, or $\not{E}_T$)



- Particle Flow calculates MET after all particles have been constructed
  - Allows MET to be associated to a single primary vertex

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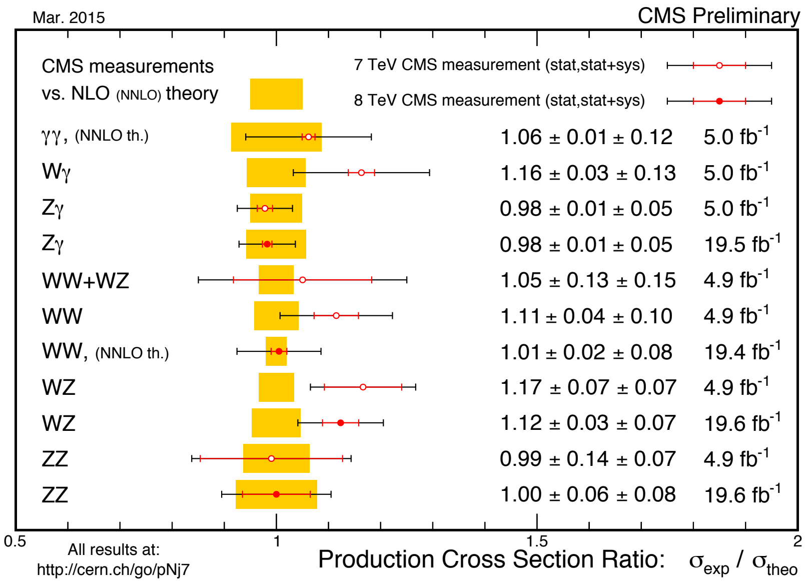
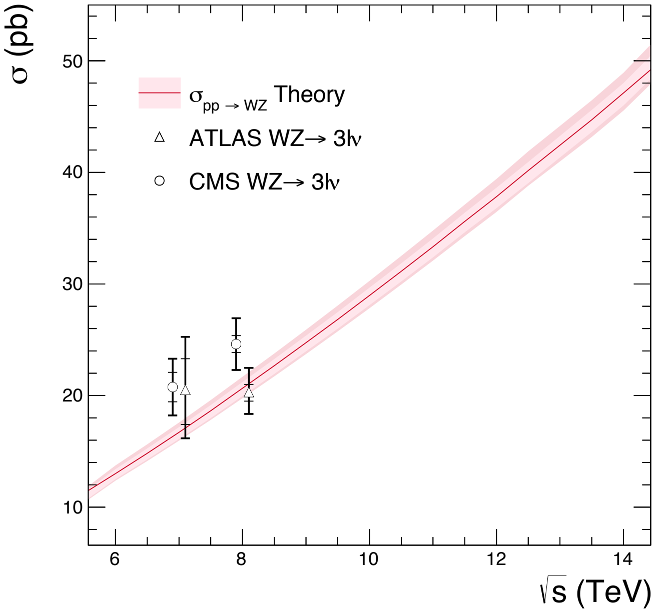
Previous Measurements and Limits

- WZ production first observed at the Tevatron in 2006 at 1.96 TeV with 1.1 fb^{-1}
- Cross section measured at 7 and 8 TeV by CMS and ATLAS
- Constraints on deviations from SM predications from LEP, Tevatron, CMS, and ATLAS

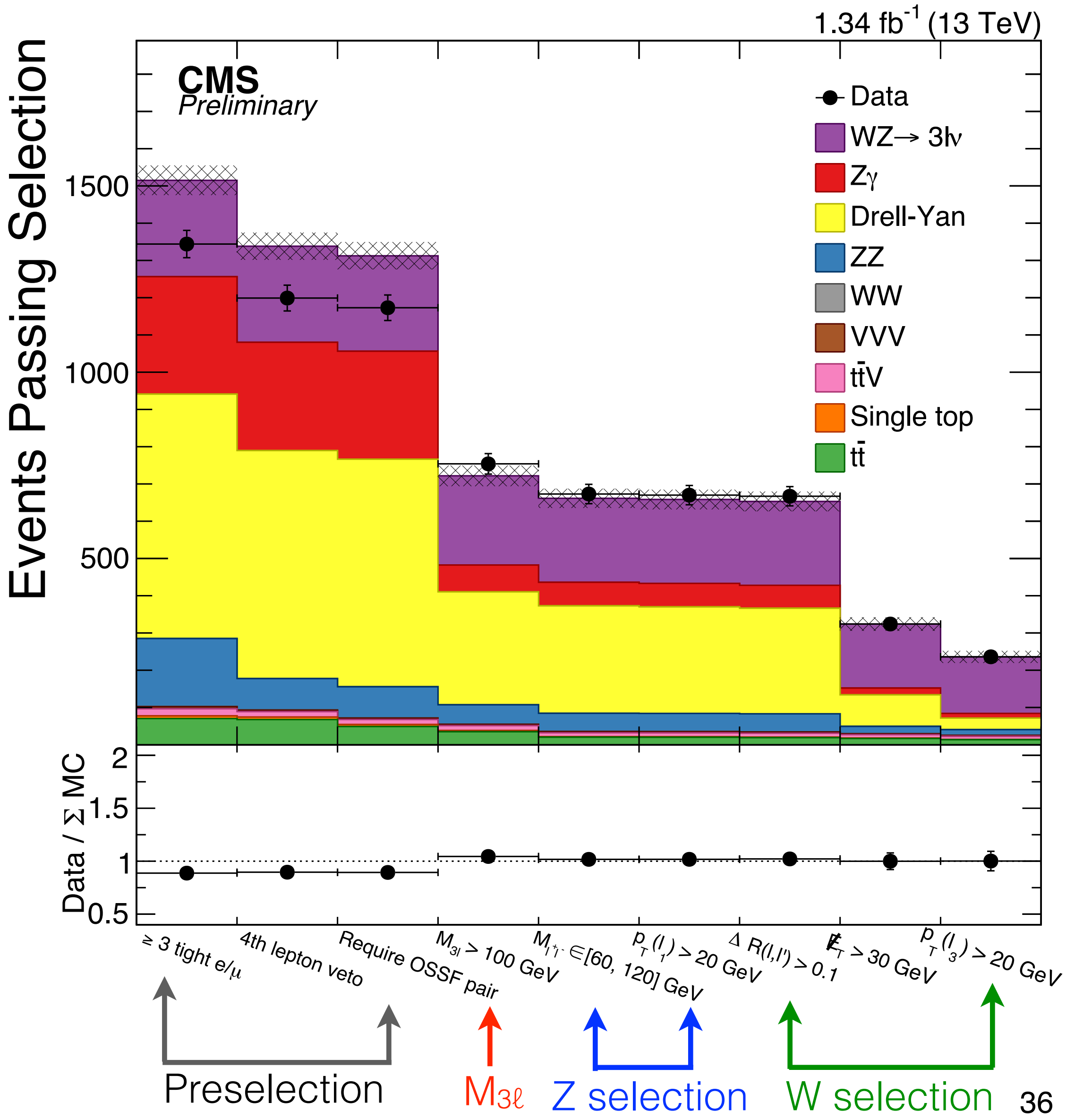




- All previous measurements consistent with SM predictions
  - None preclude new physics at 13 TeV

Overview of WZ⟶3ℓν Selections

- This analysis is performed on data collected by CMS from ~100 trillion collisions
  - ~1 billion of these were stored
  - ~100 million fall into the HLT datasets used for this analysis
  - ➡ 236 pass final WZ selections
- Apply selection in stages
  - Target specific backgrounds with each selection
  - Understand modeling of each background



WZ⟶3ℓν: Preselection

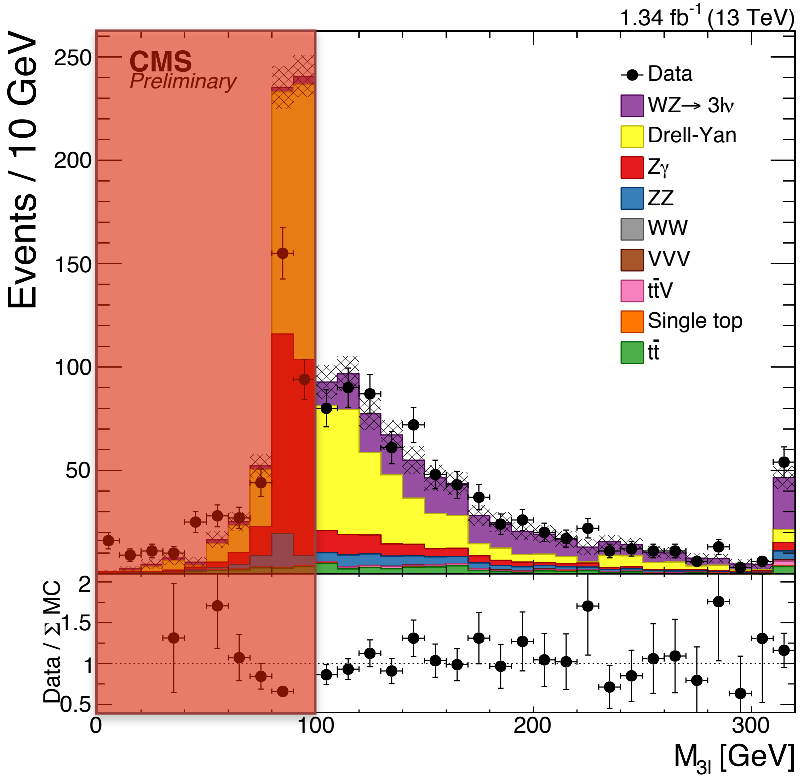
- Study lepton efficiencies and misidentification rates after making only HLT requirements
  - Double *μ*
    - 1 μ candidate with $p_T > 17$ GeV, 1 with $p_T > 8$ GeV
  - Double *e* /*γ*
    - 1 candidate with $p_T > 17$ GeV, 1 with $p_T > 12$ GeV
  - Single *e* /*γ* + Single *μ*
    - *μ* candidate with $p_T > 17$ GeV, *e* /*γ* candidate with $p_T > 12$ GeV
    - *e* /*γ* candidate with $p_T > 8$ GeV, *μ* candidate with pT > 12 GeV
- Preselection: initial selection used to narrow phase space to *WZ-like* region
  - At least one of the of HLT requirements
  - Has exactly 3 muons and electrons
  - At least one pair of opposite sign, same flavor (OSSF) leptons

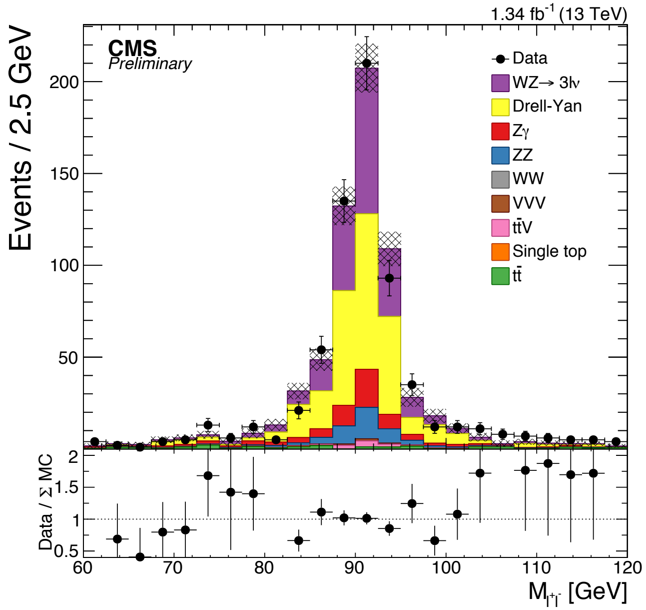
Dataset	Event Counts
WW	0.9
VVV	3.2
Single Top	5.3
$t\bar{t}V$	13.6
$t\bar{t}$	48.8
ZZ	83.8
Zγ	306.1
Drell-Yan	610.8
WZ⟶3ℓν	256.22
Sum MC	**1328.7**
Data	**1173**

WZ⟶3ℓν Selections: $M_{3\ell}$ Cut

- Require $M_{3\ell}$ > 100 GeV
  - Backgrounds with Z boson + fake third lepton have $M_{3\ell} \approx M_Z$
    - e.g. Z⟶ℓℓ' with radiated photon which fakes an electron
  - $M_{3\ell}$ approaches M_{WZ} for true WZ events

➡ Study modeling of Drell-Yan and Zγ background (largest contributions)





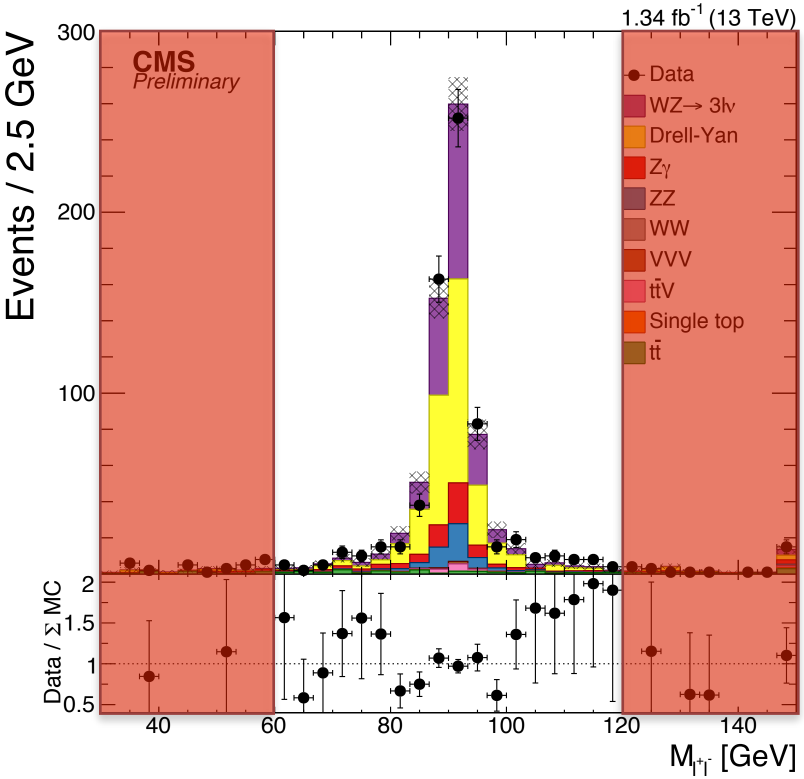
After requiring $M_{3\ell}$ > 100 GeV

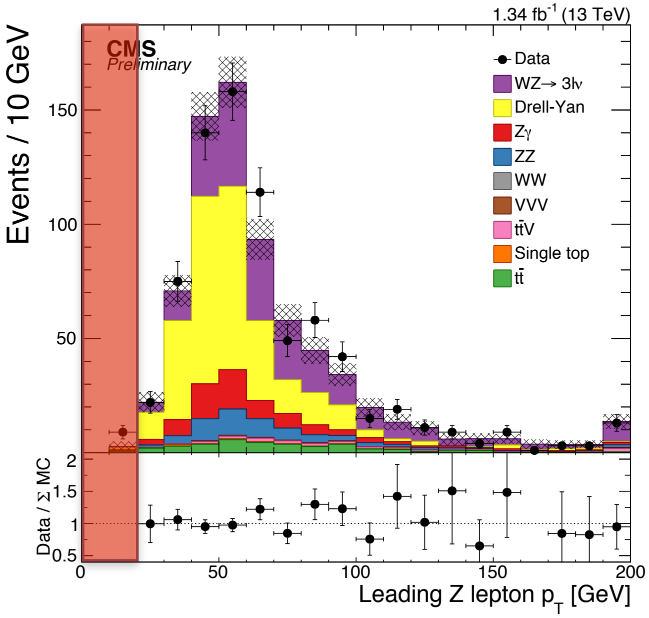
	Before cut	After cut	Ratio
Data	1173	754	0.64
MC	1312	722	0.55
WZ⟶3ℓν	256	240	0.94
WZ / ∑MC	**0.20**	**0.33**	**1.70**

WZ⟶3ℓν Selections: Z Mass Window

- Form Z candidate formed from OSSF lepton pair
  - When ambiguous, choose pair which minimizes $|m_{\ell\ell} - M_Z|$
  - Require $|m_{\ell\ell} - M_Z| \in [60, 120]$ GeV
- At least one lepton associated with Z candidate has $p_T > 20$ GeV

➡ Reduce background without Z resonance
  - Study Drell-Yan modeling



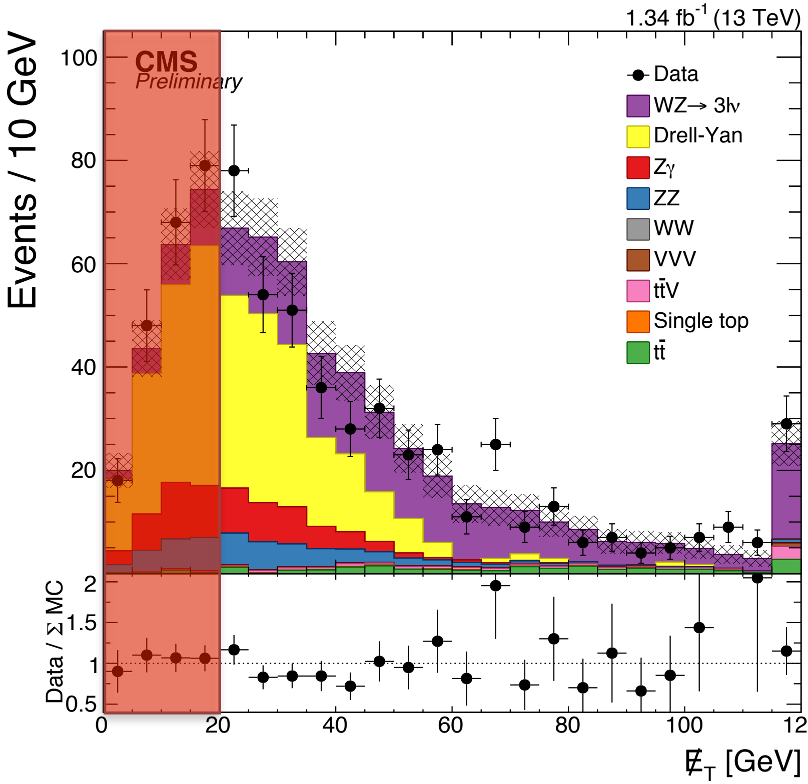


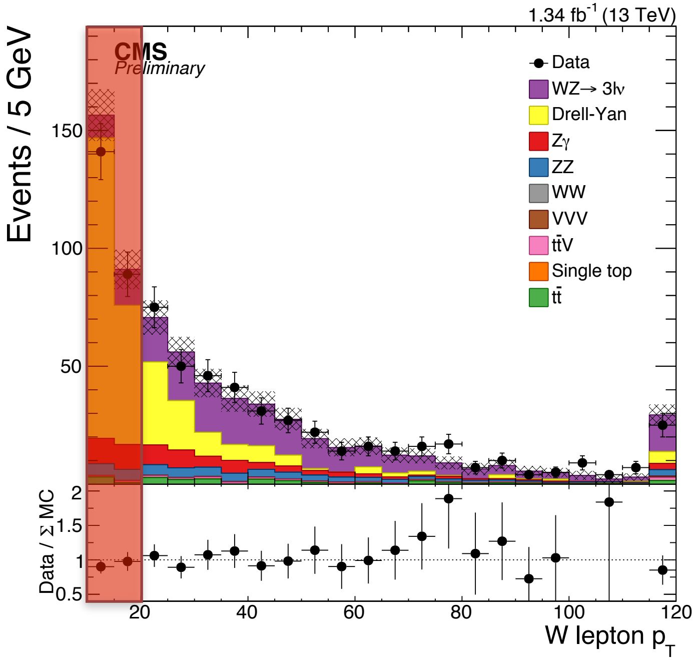
	Before cut	After cut	Ratio
Data	754	670	0.89
∑MC	722	660	0.91
WZ⟶3ℓν	240	225	0.94
WZ / ∑MC	**0.33**	**0.34**	**1.03**

WZ⟶3ℓν Selections: W selection

- W kinematics cannot be fully inferred from decay products
  - Separation between lepton associated with W and leptons associated with Z: $\Delta R(l_{1,2}, l_3) > 0.1$
  - Missing $E_T > 30$ GeV
  - $p_T(\ell_3) > 20$ GeV

➡ Final analysis selection





	Before cut	After cut	Ratio
Data	670	236	0.35
MC	662	234	0.35
WZ⟶3ℓν	225	152	0.68
WZ / ∑MC	**0.34**	**0.65**	**1.91**

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WZ Cross Section Measurement

Dataset	Events
WW	0.1
VVV	2.2
$t\bar{t}V$	8.4
ZZ	15.6
Zγ	13.3

Estimated from data for CMS result

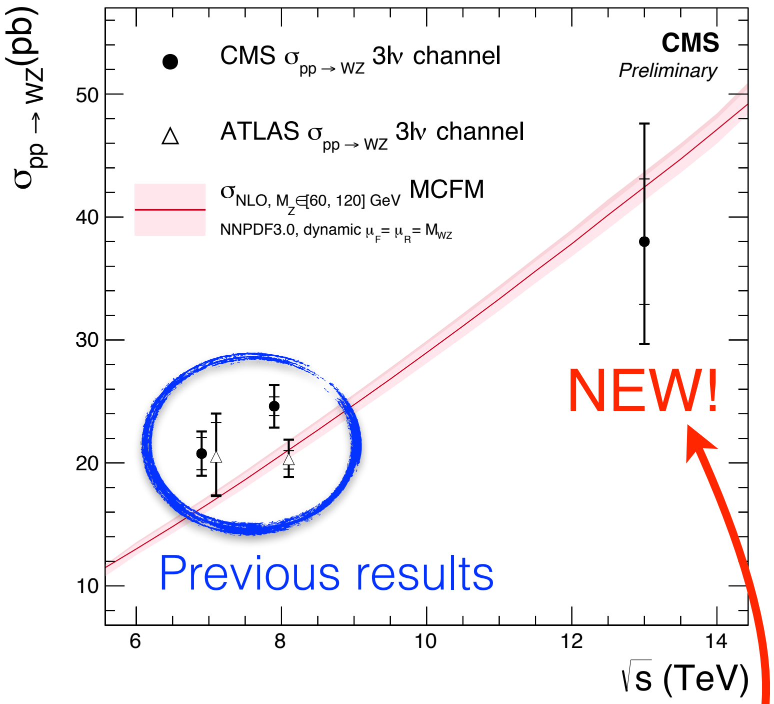
Single top	0.7
$t\bar{t}$	13.5
Drell-Yan	31.0

Expect 152 WZ events

236 Data events - ∑MC Bkgd = 151 events

	Presented	CMS Result
Total Background	85.0	101.6
Signal Strength	0.99	0.86

- CMS released the first 13 TeV WZ cross section measurement in December 2015
  - Agrees with SM NLO prediction
- My work (also for ZZ measurement)
  - Validation of MC signal modeling
  - Use theory tools to produce and understand theoretical predictions



NEW!

Previous results

CMS Results at 13 TeV

CMS-PAS-SMP-15-006

$$\sigma_{\text{fid}}(\text{pp} \rightarrow \ell\ell'\ell\nu) = 239^{+61}_{-51}\ \text{fb}$$

$$\sigma(\text{pp} \rightarrow \text{WZ}) = 36.8^{+9.5}_{-7.9}\ \text{pb}$$

$$\sigma_{\text{th(NLO)}}(\text{pp} \rightarrow \text{WZ}) = 42.7^{+1.6}_{-0.8}\ \text{pb}$$

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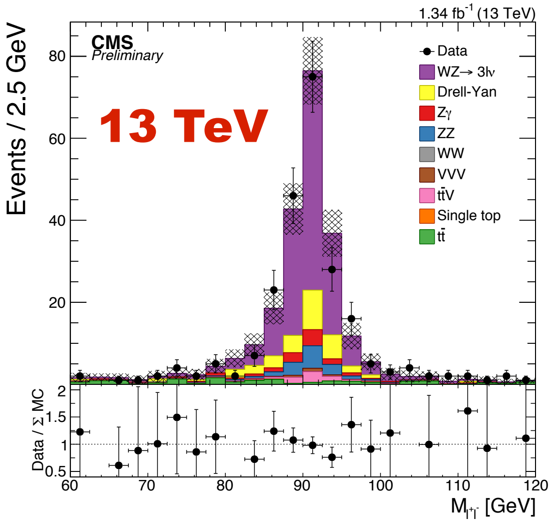
Precision Cross Section Measurement

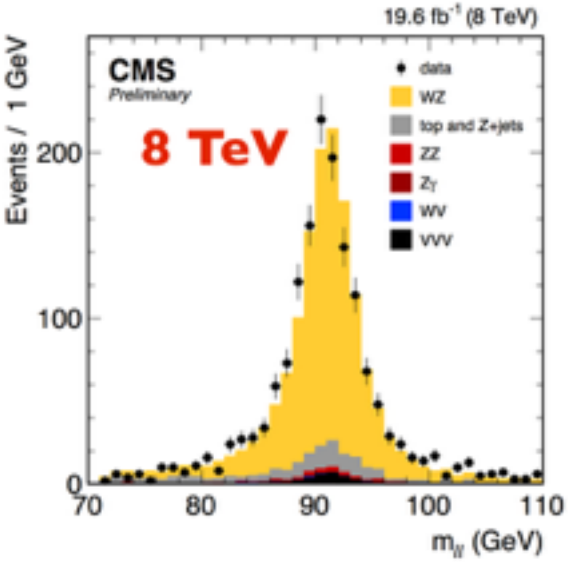
- Goal: reduce uncertainty to level of theory prediction (expect 3-5% at NNLO)
  - Currently 25% for 13 TeV

$$\sigma(pp \to WZ) = 36.8 \pm 4.6\,(\mathrm{stat})^{+8.1}_{-6.2}\,(\mathrm{syst}) \pm 0.6\,(\mathrm{theo.}) \pm 1.7\,(\mathrm{lum.})\,\mathrm{pb}$$

$$\boxed{\begin{aligned}\sigma(pp \to WZ;\ \sqrt{s} = 7\ \mathrm{TeV}) &= 20.76 \pm 1.32\ (\mathrm{stat.}) \pm 1.13\ (\mathrm{syst.}) \pm 0.46\ (\mathrm{lumi.})\ \mathrm{pb}.\\ \sigma(pp \to WZ;\ \sqrt{s} = 8\ \mathrm{TeV}) &= 23.89 \pm 0.81\ (\mathrm{stat.}) \pm 1.34\ (\mathrm{syst.}) \pm 0.62\ (\mathrm{lumi.})\ \mathrm{pb}.\end{aligned}}$$

- What are the sources of uncertainty?
  - Statistical: ~100 times current dataset by end of 2018 will reduce to < 1%
  - Systematic: dominated by 40% error on background estimation (11% of events)
    - Much more background than at 7 and 8 TeV
  - Target: 5-6%
    - Within reach if we achieve systematic and luminosity error from Run I
- How can we reduce the uncertainty?
  - Reduce background estimation error (difficult!)
  - Reduce background with improved selections

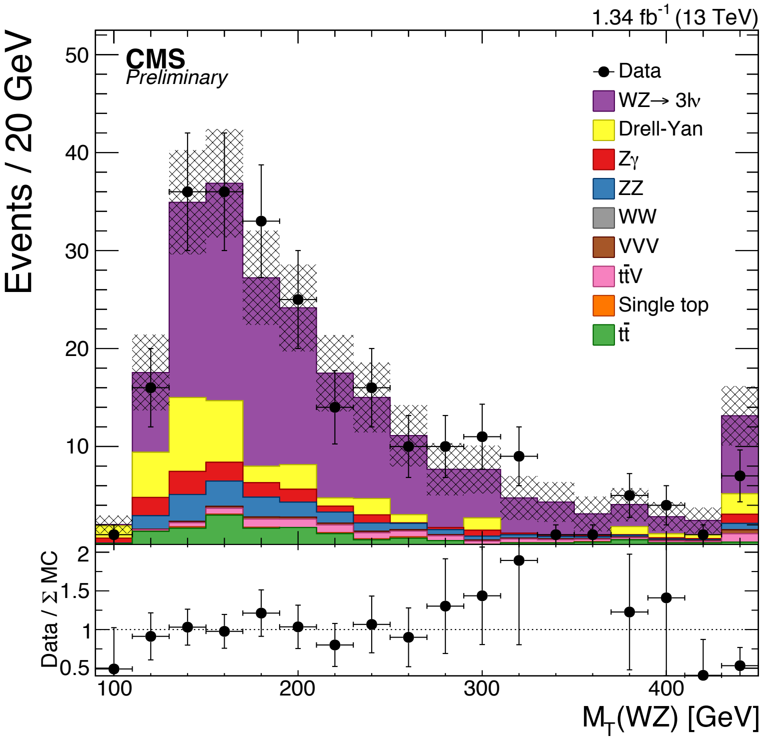


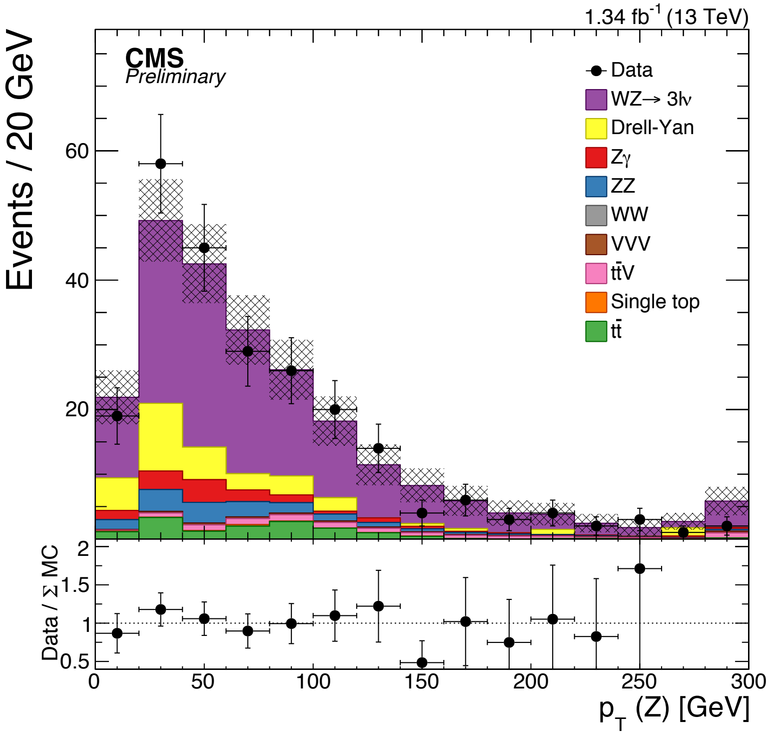


Kenneth Long

Thesis Goals: aQGC Measurement

- Differential measurements of WZ production for anomalous couplings
  - Z p_T (for aTGC NP contribution)
  - WZ (transverse) mass
    - for New Physics via anomalous couplings



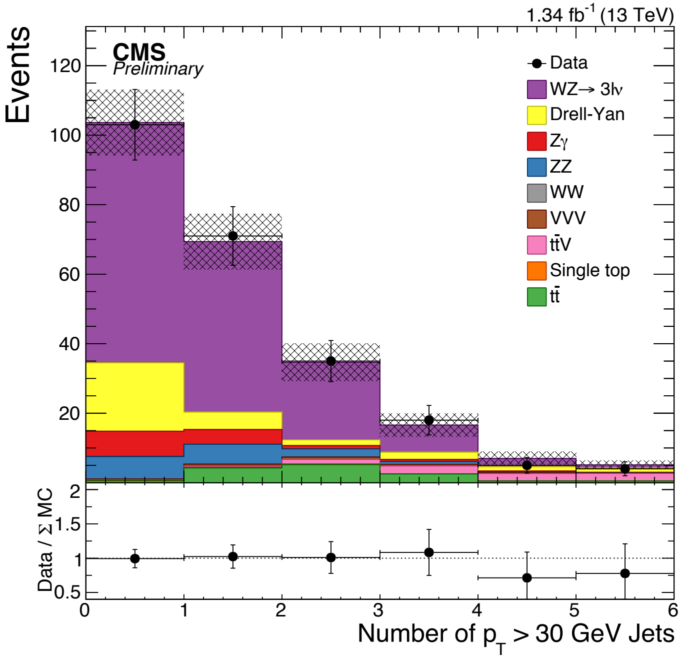


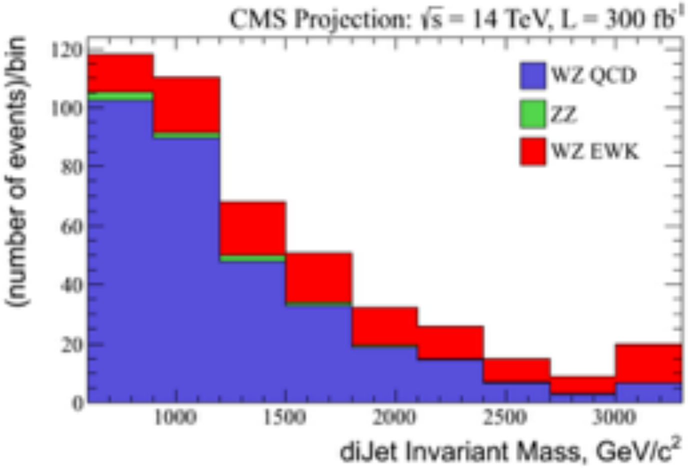
- No visible excess in high $p_T(Z)$ or high $M_T(WZ)$ region
- Expect sensitivity at ~20 fb^{-1}

$$M_T = \sqrt{(E_T^Z + E_T^W)^2 - (p_x^Z + p_x^W)^2 - (p_y^Z + p_y^W)^2}$$

Thesis Goals: EWK Scattering

- Differential measurements of WZ production to observe EWK vector boson scattering
  - Jet kinematics
    - VBS contribution in 2-jet events
  - Additional selections
    - Exactly two high p_T jets (j)
    - $p_T(j) > 50$ GeV
    - $|\eta(j)| < 4.7$
    - $\Delta\eta_{jj} > 4.0$
    - $m_{jj} > 600$ GeV
- Initial studies made in CMS result FTR-13-006
  - Indicate that EWK contribution of WZ production can be observed with Run II luminosity (100 fb^{-1})
    - Observation (3σ confidence) with 75 fb^{-1}
    - Discovery (5σ confidence) with 185 fb^{-1}
  - This study did not investigate optimization of the analysis
    - We can do better!





Conclusions

- Presented WZ→3ℓν analysis with focus on WZ cross section
- Contributed to the first measurement of WZ cross section at 13 TeV
  - Presented CMS results
  - Discussed differences
- Expect 100 fb^{-1} (vs. 1.34 fb^{-1} in this work) by end of 2018
  - Dataset sufficient for precision measurements
- Scope of analysis will be extended
  - Precision cross section measurement
  - Observation of electroweak boson scattering (100 fb^{-1} sufficient)
  - Search for new physics in differential deviations from standard model predictions
- Foundation for this work is in place
  - Understanding theoretical predictions through state of the art calculations and simulations
  - Analysis framework and tools established and understood

Backup

Cross Section Overview

$$\sigma(pp \to WZ + X) \cdot \mathcal{B}(W \to \ell\nu) \cdot \mathcal{B}(Z \to \ell'\ell') = \frac{N_{\text{obs}} - N_{\text{background}}}{A \cdot \epsilon \cdot \mathcal{L}}$$

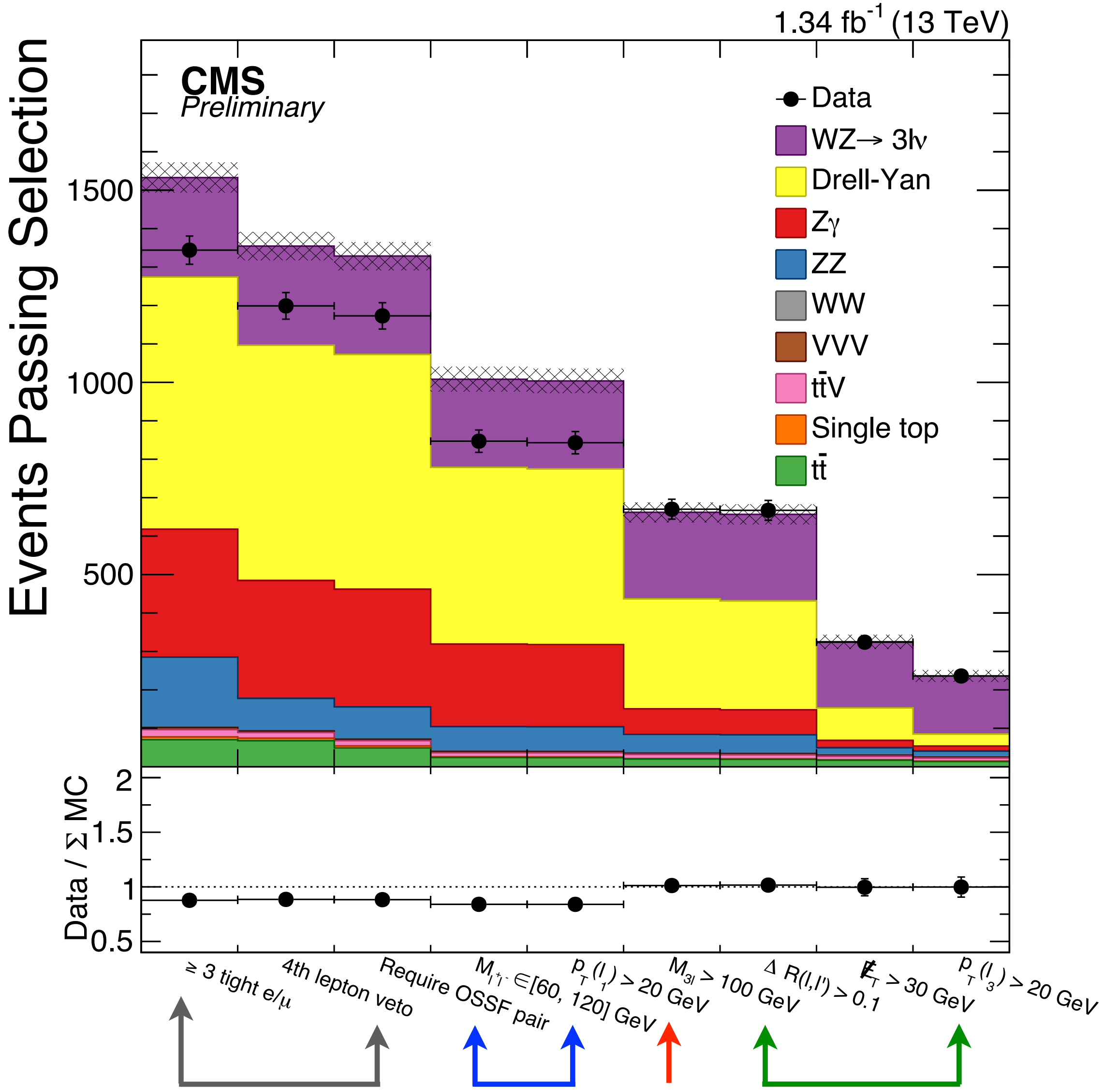
- $\mathscr{L}$ = Luminosity
- A = Acceptance = $\sigma_{\text{fiducial(th.)}}/\sigma_{\text{tot(th.)}}$
  - What percentage of true WZ events fall outside the detector geometry or kinematic cuts? (e.g. μ decaying from Z with $\eta < 2.4$ or $p_T < 20$ GeV)
    - Depends only on theoretical prediction
- ε = *Efficiency*
  - Percentage of true WZ events within acceptance not reconstructed

Equivalently $$\sigma(pp \to WZ + X) \cdot \mathcal{B}(W \to \ell\nu) \cdot \mathcal{B}(Z \to \ell'\ell') = \frac{\mu\sigma_{\text{predicted}}}{A}$$

Where μ is the Signal Strength: $$\mu = \frac{N_{\text{obs}} - N_{\text{background}}}{N_{\text{expect(WZ)}}}$$

- Fiducial cross section (σ_{fid})
  - Defined to minimize theoretical extrapolation
    - $\eta(\ell_1, \ell_2, \ell_3) < 2.5$
    - $p_T(\ell_1, \ell_3) > 20$ GeV, $p_T(\ell_2) > 10$ GeV
    - $|m_{\ell\ell} - M_Z| \in [60, 120]$

Cut Flow: Z after preselection



Preselection

Z selection

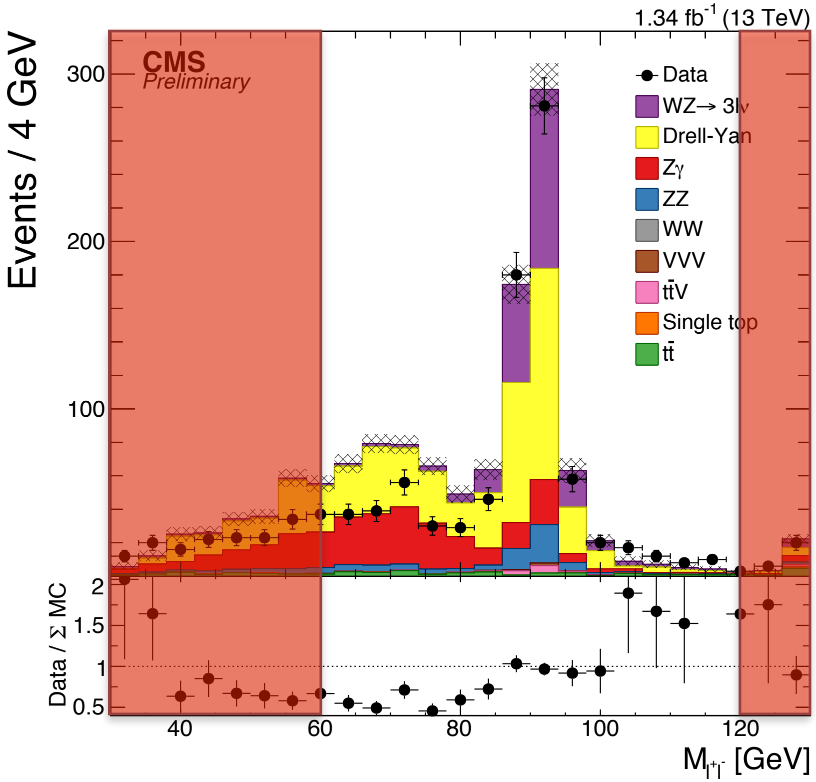
M3ℓ

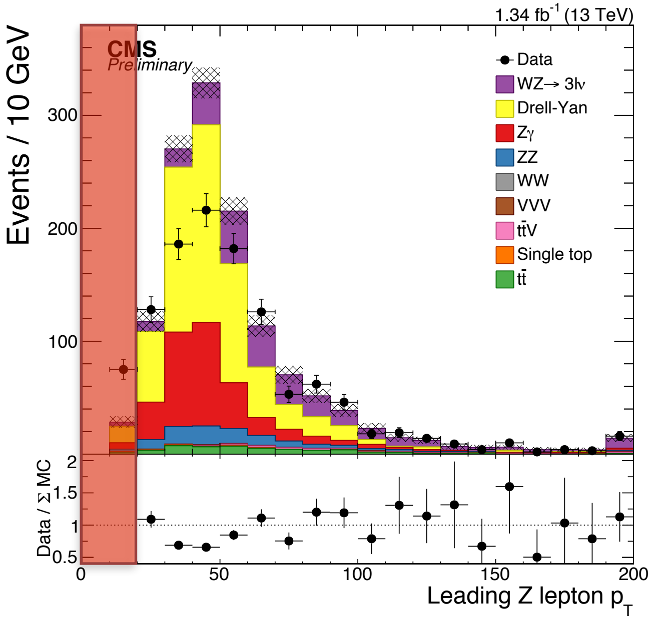
W selection

WZ⟶3ℓν Selections: Z before M_{3l}

- Form Z candidate formed from OSSF lepton pair
  - When ambiguous, choose pair which minimizes $|m_{\ell\ell} - M_Z|$
  - Require $|m_{\ell\ell} - M_Z| \in [60, 120]$ GeV
- At least one lepton associated with Z candidate has $p_T > 20$ GeV

➡ Study modeling of Drell-Yan and Zγ background (largest contributions)

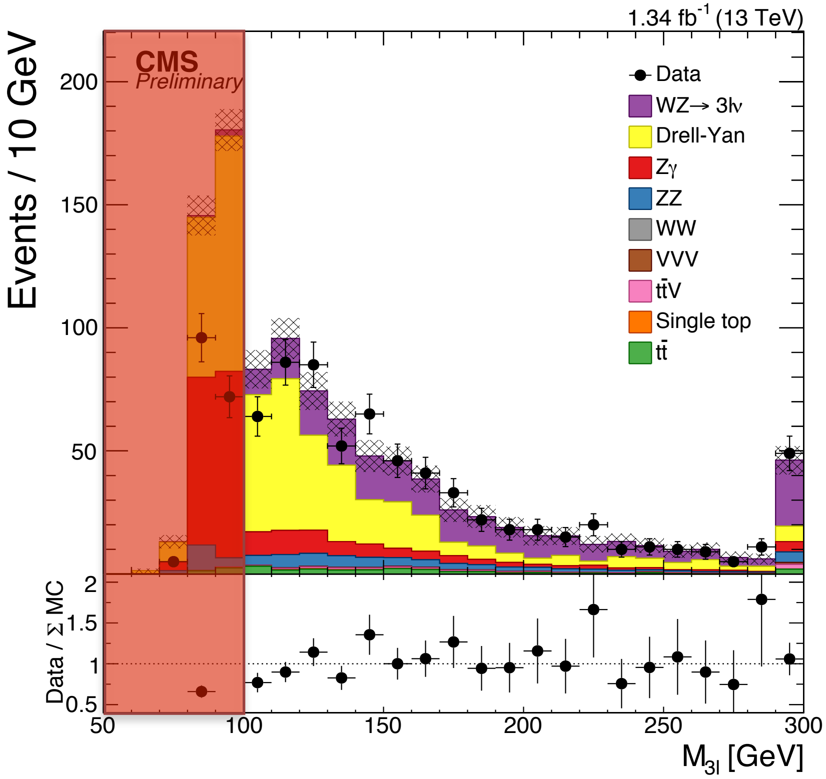


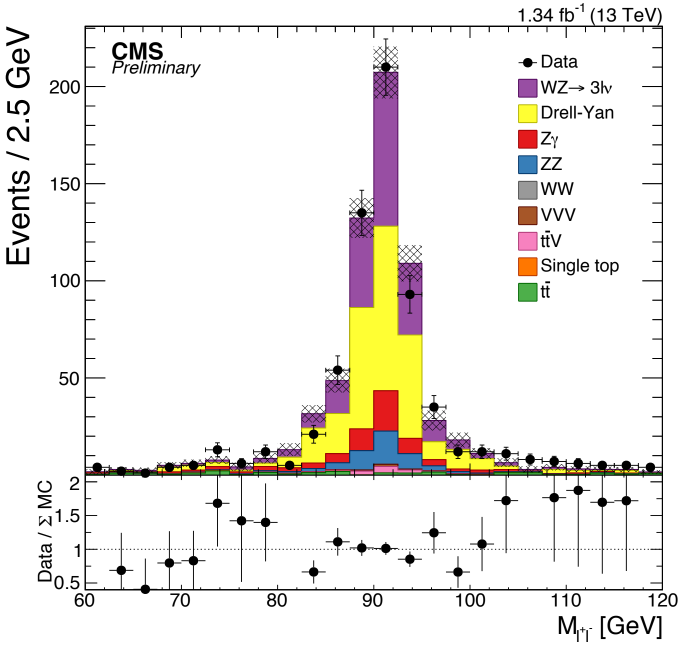


	Before cut	After cut	Ratio
Data	1173	843	0.72
∑MC	1329	1003	0.75
WZ⟶3ℓν	256	229	0.89
WZ / ∑MC	**0.19**	**0.23**	**1.19**

WZ⟶3ℓν Selections: $M_{3\ell}$ After Z

- Require $M_{3\ell}$ > 100 GeV
  - Backgrounds with Z boson + fake third lepton have $M_{3\ell} \approx M_Z$
    - e.g. Z⟶ℓℓ' with radiated photon which fakes and electron
  - $M_{3\ell}$ approaches M_{WZ} for true WZ events



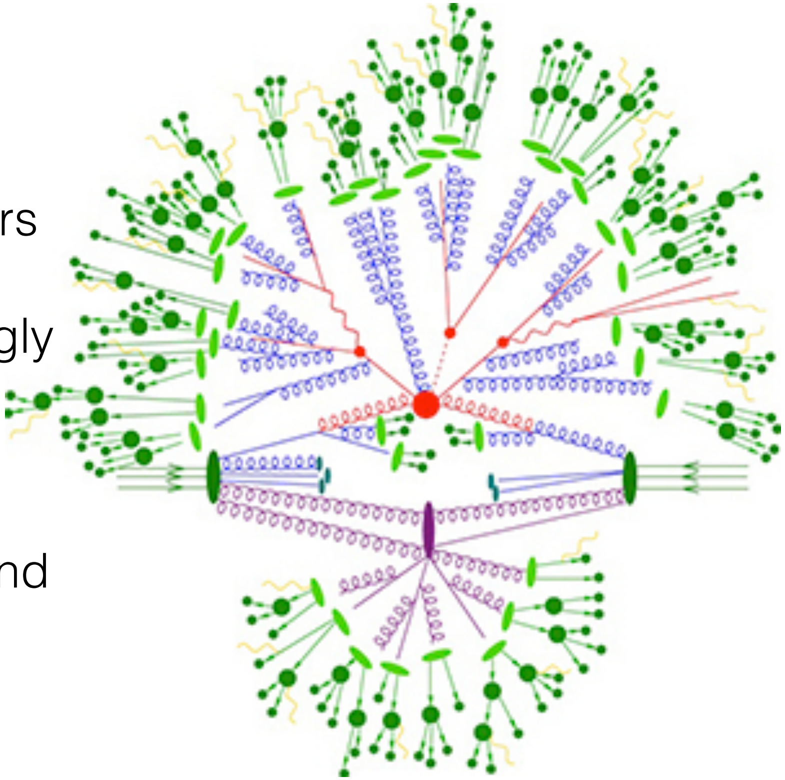


Distribution after requiring $M_{3\ell}$ > 100 GeV

	Before cut	After cut	Ratio
Data	843	670	0.79
MC	1003	662	0.66
WZ⟶3ℓν	229	225	0.98
WZ / ∑MC	**0.23**	**0.34**	**1.49**

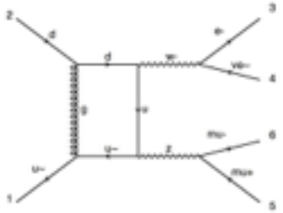
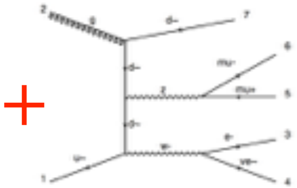
Simulations for Precision Measurements

- Experimental measurements rely on precise theoretical predictions
  - Combine perturbative QFT with phenomenological models
  - Complex integrals calculated with Monte Carlo techniques
- Factorize calculations
  - Hard Processes
    - Matrix element calculations in perturbative QCD and QED
    - Increasingly complex at higher orders in coupling constants
    - Higher QCD orders contribute strongly
  - Soft processes
    - Parton shower model
    - Consider only soft/collinear contributions of higher order QCD and QED
  - Non-perturbative processes
    - Parton Distribution Functions
    - Hadronization
  - Decays

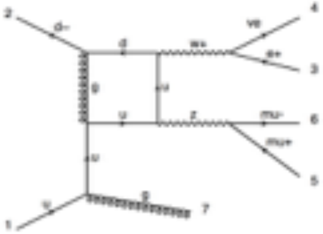
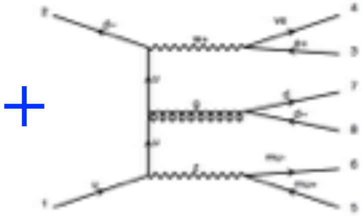


Monte Carlo Generators at CMS

- Event simulations at Next-to-leading order (NLO) in QCD are now the standard
- Two techniques for NLO event generation exist
  - POWHEG
    - Implemented in the POWHEG Box, a toolkit for NLO event generation
  - MC@NLO
    - Fully automated in MadGraph5_aMC@NLO
- Calculations inclusive and exclusive in QCD
  - Inclusive
    - Observables independent of the number of final state partons accurate at NLO
    - NLO calculation of pp ⟶ $3\ell\nu$

$\mathcal{M} =$  $+$  $+$  $+ \cdots$

  - Exclusive
    - Observables dependent on the number of final state partons accurate at NLO
    - Merge calculations of pp ⟶ $3\ell\nu$ and pp ⟶ $3\ell\nu$ + q (q is a light quark or gluon)

$\mathcal{M} = \mathcal{M}_{3\ell\nu} + \cdots +$  $+$  $+ \cdots$