ZZ Production in Proton-Proton Collisions at $\sqrt{s}$ =13 TeV in Four-Lepton Events Using the CMS Detector at the LHC

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Doctoral Thesis Defense

The Standard Model and ZZ Physics

The Standard Model

- **Description of fundamental particles and their interactions**
- **Matter: fermions in 3 generations**
  - Quarks form hadron bound states
  - Leptons in (charged, neutral) pairs
- **Forces: exchange of gauge bosons**
  - Gluon (strong force)
  - Photon (electromagnetism)
  - $W^{\pm}$, Z (weak force)
    - Massive due to scalar Higgs boson
- **Not covered: gravity, dark matter, dark energy, neutrino mass**

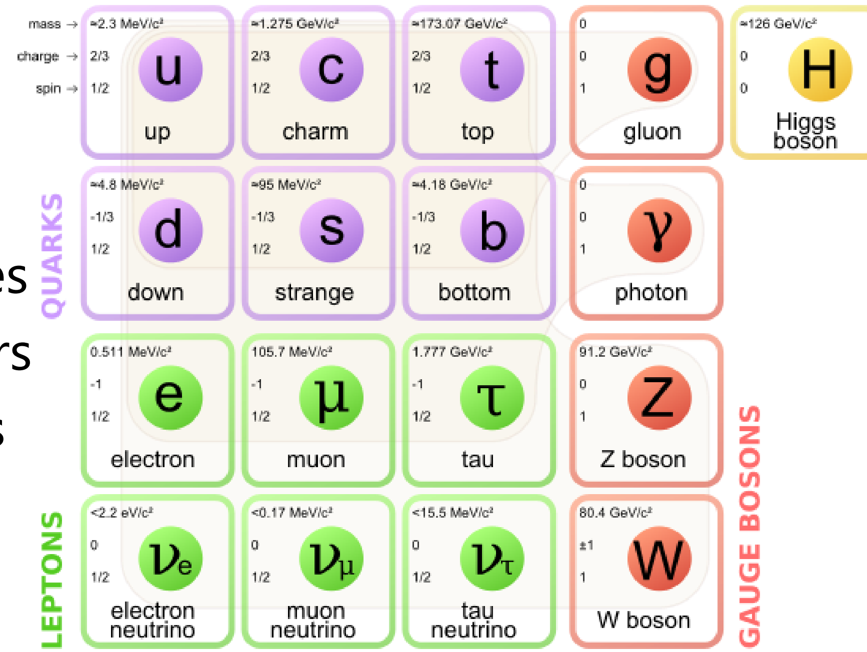
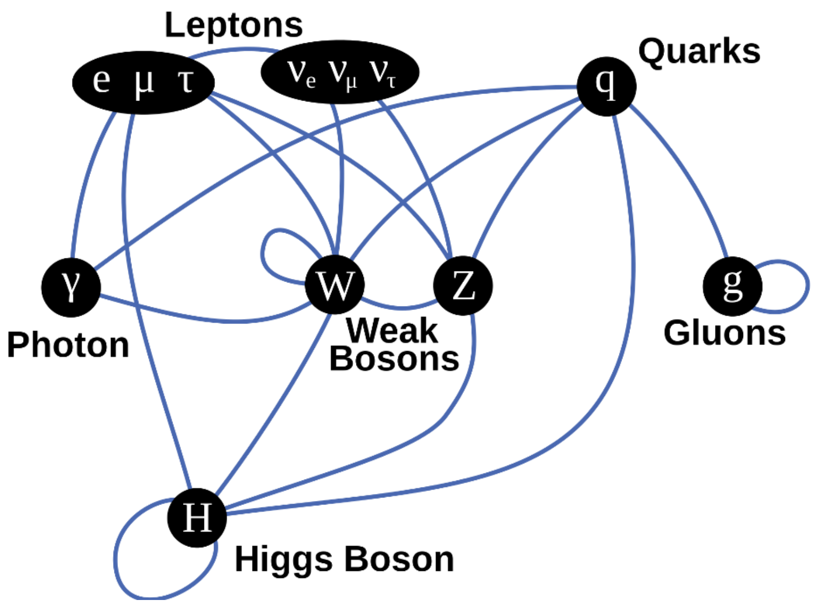


Image: Wikimedia Commons

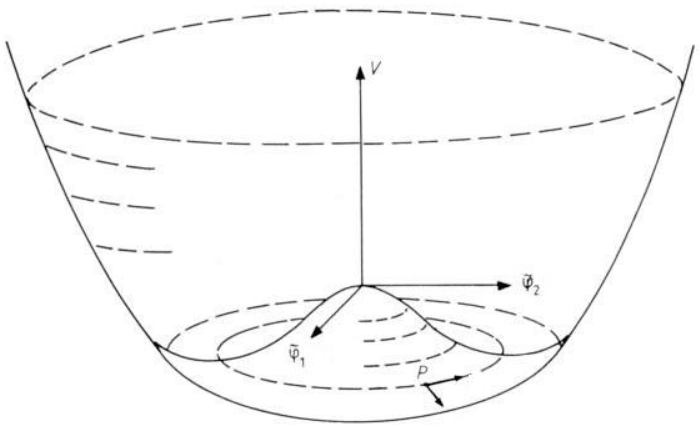
Particle Interactions

- **Strong force (g)**
  - 3-component color charge carried by quarks and gluons
  - Gluon self-interaction causes anti-screening: interaction strength grows with distance
    - Confinement: no free color charge
- **Electromagnetic force (γ)**
  - Charge carried by quarks, charged leptons, $W^{\pm}$ bosons
- **Weak force ($W^{\pm}$, Z)**
  - Interact with all except gluon and (Z only) γ
  - Massive mediators → short range



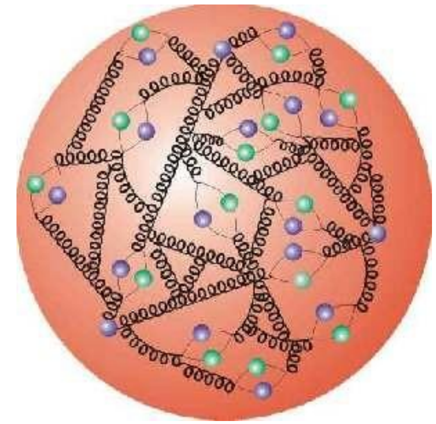
Electroweak Symmetry Breaking

- Glashow-Weinberg-Salam (GWS) model yields a unified electroweak force but with massless mediators
- Higgs mechanism: introduce doublet of complex scalar fields with nonzero vacuum expectation value

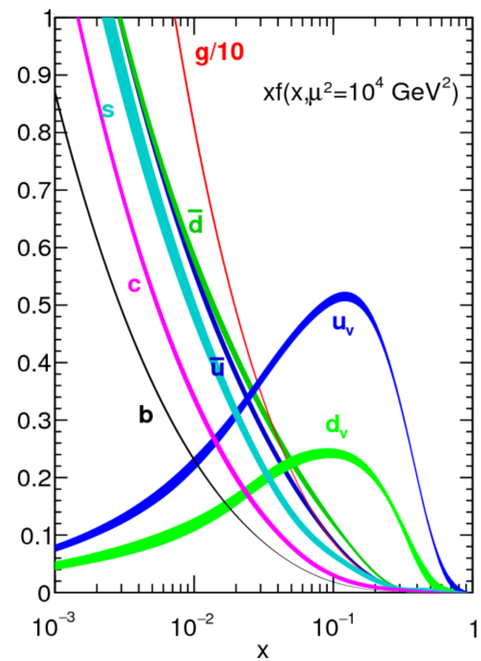


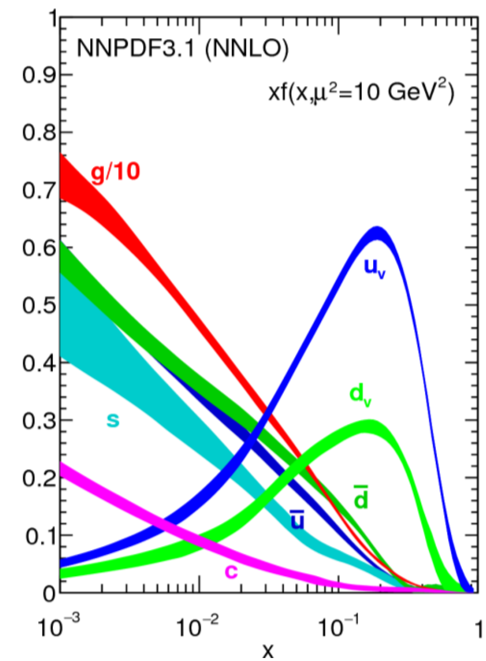
- Gauge symmetry is spontaneously broken, leaving massive $W^{\pm}$ and Z bosons (massless γ remains)
- Higgs field's 4 degrees of freedom become longitudinal $W^{\pm}$ and Z polarizations and a new scalar, the Higgs boson (H)
- Mixing causes new interactions between bosons
- Fermions acquire mass through H-induced Yukawa couplings

Proton Structure and Collisions



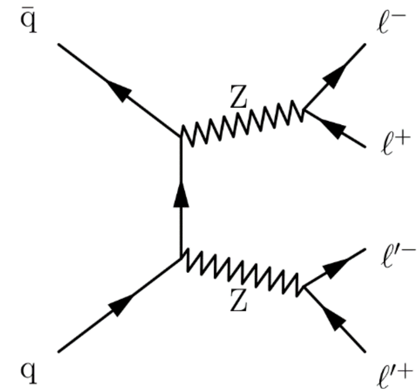
- **A proton is a bound state of 3 valence quarks (uud) exchanging virtual gluons**
  - Also contains “sea” quarks, including heavy quarks
  - Valence quarks, sea quarks, or gluons can collide
- **Parton distribution functions (PDF) give probability of each parton type as functions of momentum transfer μ and the fraction x of proton momentum they carry**
- **Hadron collisions allow discoveries at many masses with many initial states**

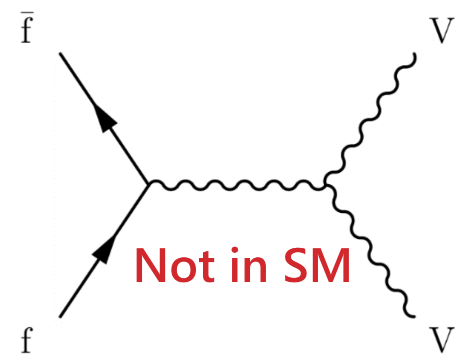


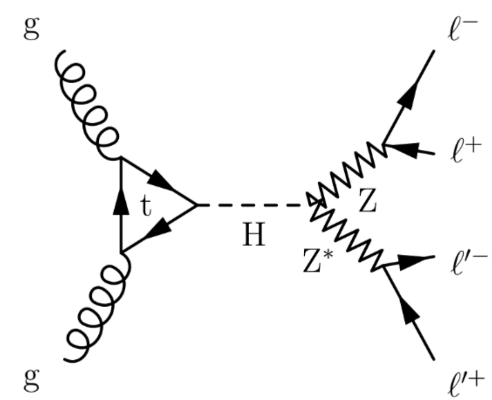


Diboson and 4ℓ Production

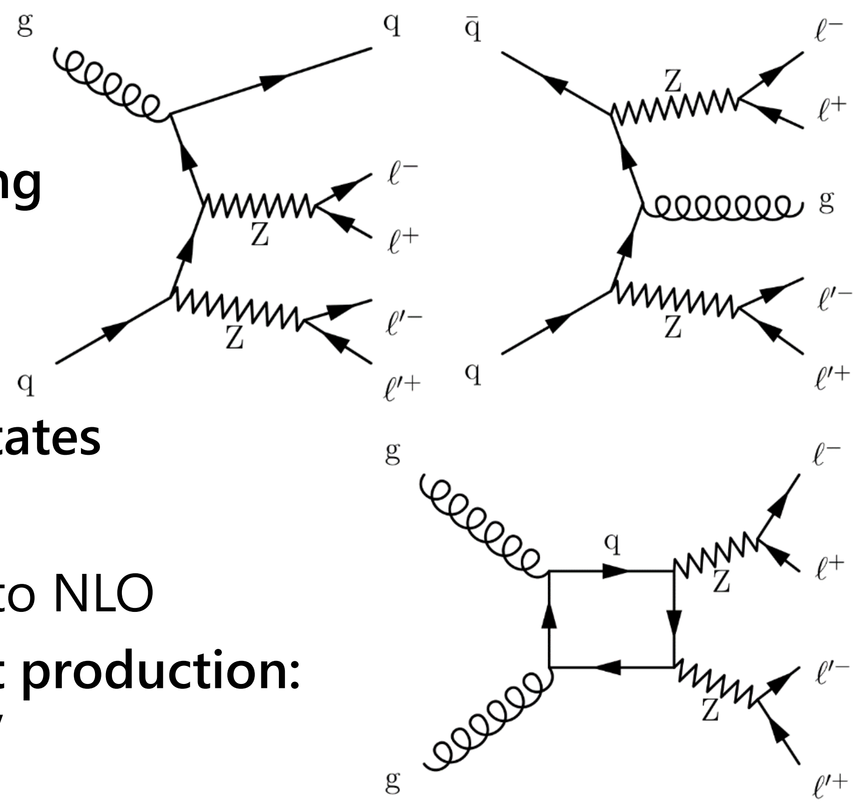
- **Details of gauge boson interactions are important predictions of the SM**
  - No fully neutral gauge couplings
- **Anomalous triple or quartic couplings (aTGC, aQGC) would change diboson production rates**
- **ZZ cross section is small but 4ℓ final state is clean and can be reconstructed well**
- **ZZ^* is a primary Higgs boson discovery and measurement channel**
- **Branching fraction to 4ℓ only ~1%**
  - High efficiency and low background compensate







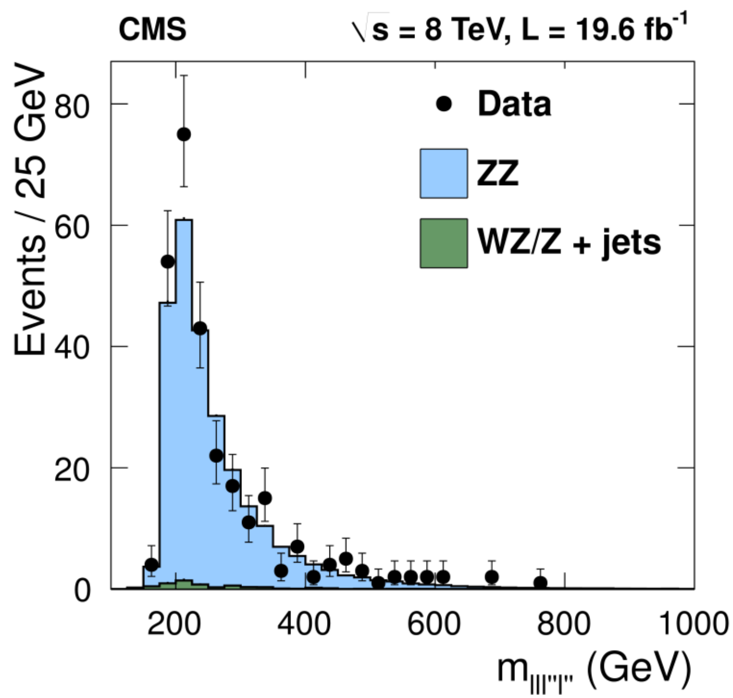
Nonresonant ZZ

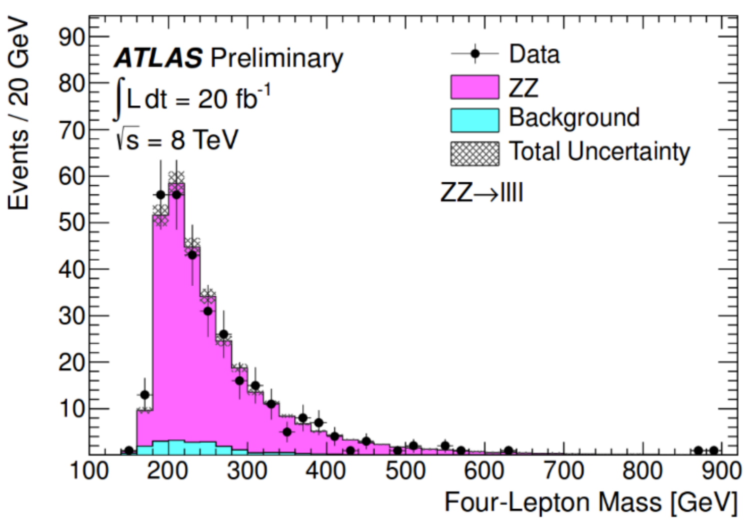


- **Large corrections at next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) in QCD perturbative calculation from introduction of qg and gg initial states**
  - "NLO+gg" often used, with gg fusion box diagrams in addition to NLO
- **Our definition for doubly resonant production: both Zs have mass in 60 – 120 GeV**
- **Sharp turn-on around $m_{4\ell} = 2m_Z \approx$ 182 GeV, followed by exponential decay**
- **Looser Z mass requirements allow Z/γ* admixture at lower $m_{4\ell}$**
  - 4ℓ continuum ~flat for $m_Z < m_{4\ell} < 2m_Z$

Nonresonant ZZ: Previous Results

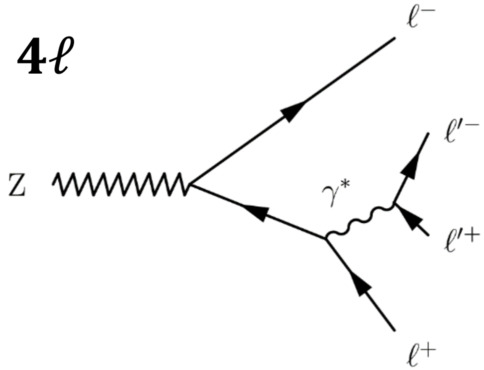
- CMS and ATLAS measured ZZ at 7 and 8 (shown) TeV
- CMS (top plot)
  - $60 < m_{Z_{1,2}} < 120$ GeV
  - $ZZ \to \ell\ell\ell'\ell';\ \ell = (e,\mu), \ell' = (e,\mu,\tau)$
  - $\sigma_{pp\to ZZ} = 7.7 \pm 0.5(\text{stat.})^{+0.5}_{-0.4}(\text{syst.}) \pm 0.4(\text{theo.}) \pm 0.3(\text{lum.})\text{ pb}$
- ATLAS (bottom plot)
  - $66 < m_{Z_{1,2}} < 116$ GeV
  - $ZZ \to \ell\ell\ell'\ell';\ \ell,\ \ell' = (e,\mu)$
  - $\sigma_{pp\to ZZ} = 7.1^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.2(\text{lumi.})\text{ pb}$



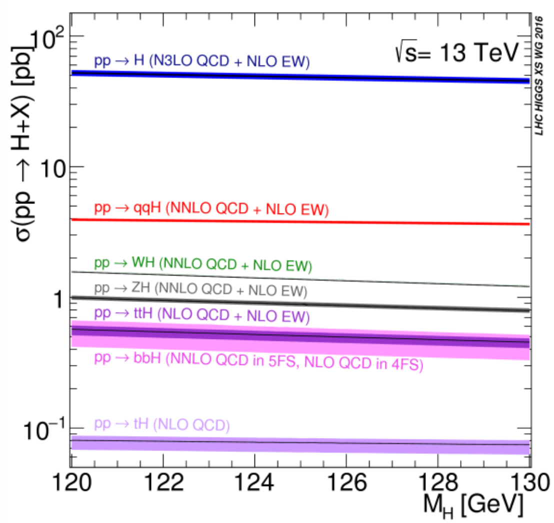


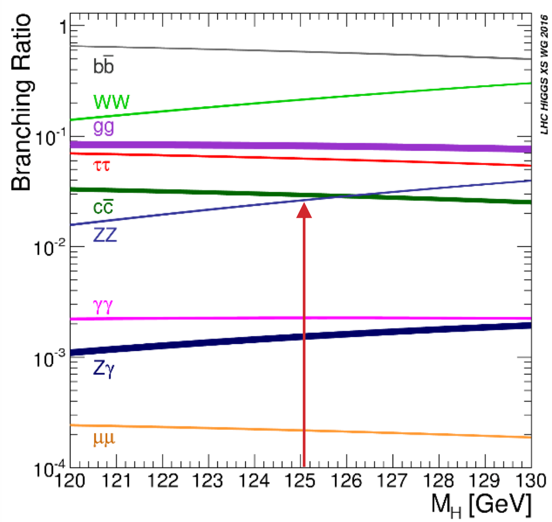
Resonant Production: Single-Z and Higgs Boson

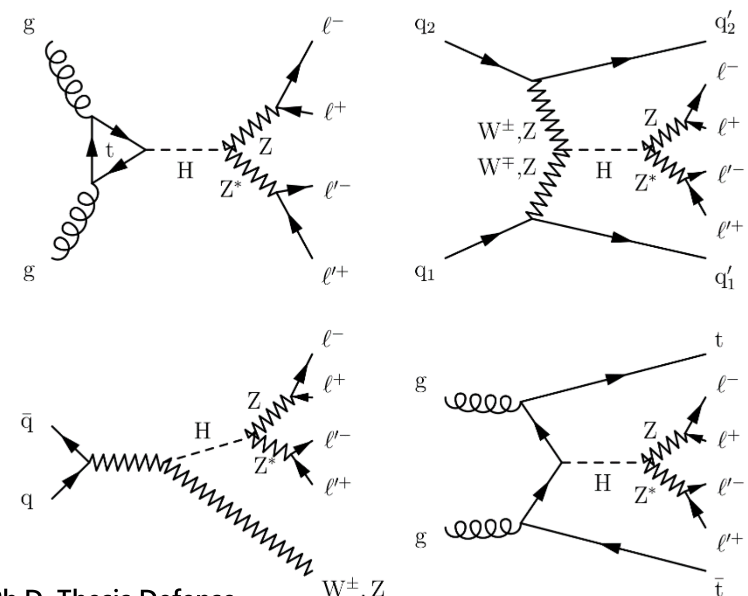
- Expanding "Z" mass window admits $Z \to \ell\ell\gamma^* \to 4\ell$ and $H \to ZZ^* \to 4\ell$ resonances
- ZZ^* a primary channel for Higgs discovery and measurement of its properties
  - Angular distributions sensitive to spin/parity



arXiv:1610.07922

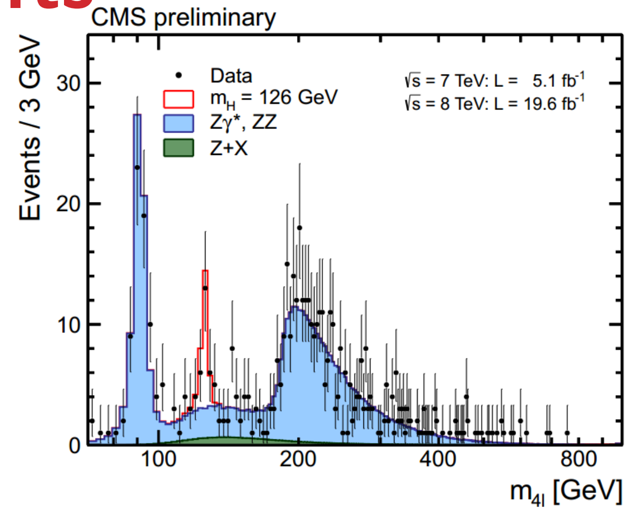


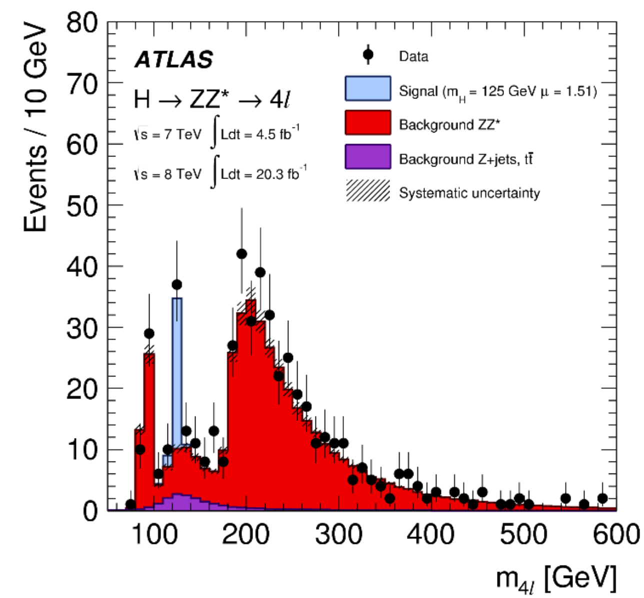




Higgs Boson: Previous Results

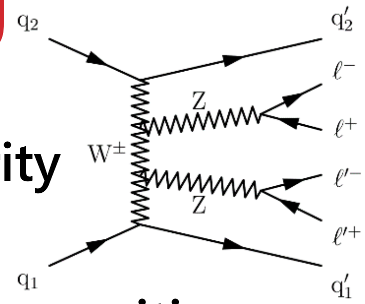
- **CMS and ATLAS both discovered particle consistent with Standard Model Higgs near 125 GeV in 2012**
  - $H \rightarrow ZZ^* \rightarrow 4\ell$ was a primary channel
- **8 TeV measurements in this channel:**
  - CMS (top plot)
    - $\sigma/\sigma_{SM} = 0.93^{+0.26}_{-0.23}(\text{stat.})^{+0.13}_{-0.09}(\text{syst.})$
  - ATLAS
    - $\sigma/\sigma_{SM} = 1.50^{+0.35}_{-0.31}(\text{stat.})^{+0.19}_{-0.13}(\text{syst.})$
- **Combined mass measurement (both experiments, ZZ and γγ channels):**
  - $m_{\text{H}} = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})$

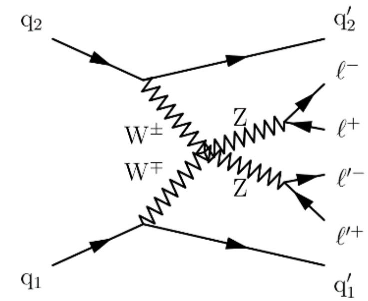


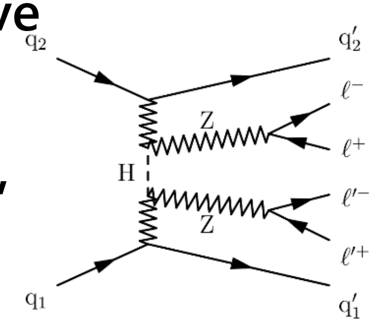


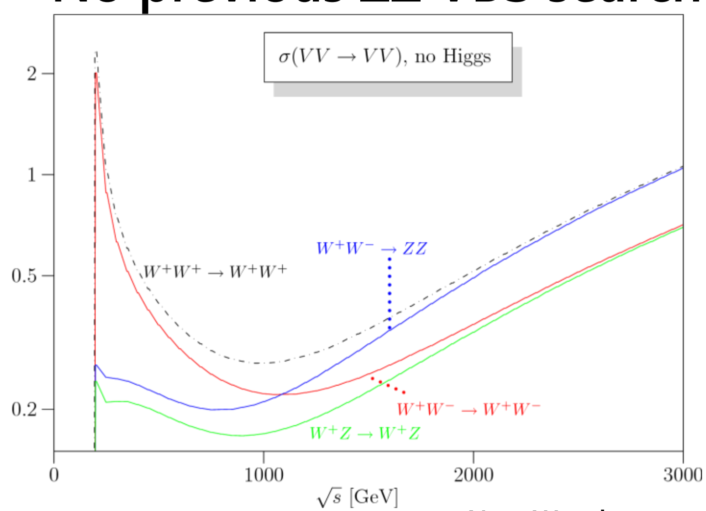
Vector Boson Scattering

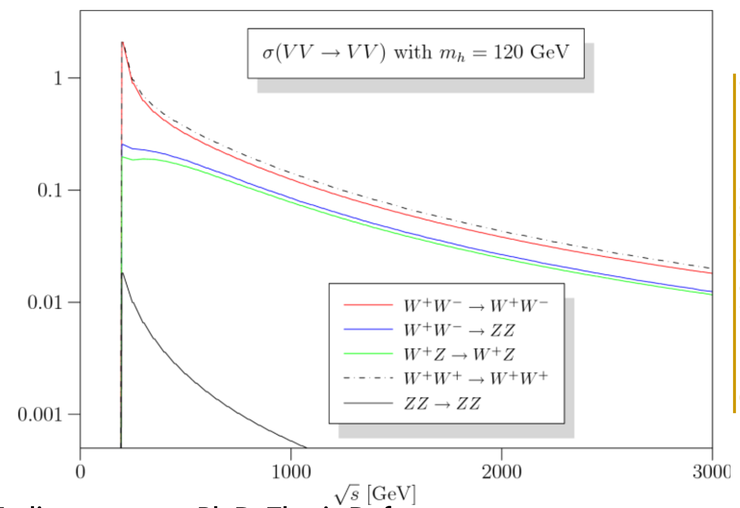
- VV→VV scattering (VBS) violates unitarity in SM without Higgs diagrams
- Pure electroweak ZZ + 2jets production sensitive to gauge boson interactions and Higgs sector
- Experimental signature: 2 jets with high energy, high rapidity separation
- No previous ZZ VBS searches











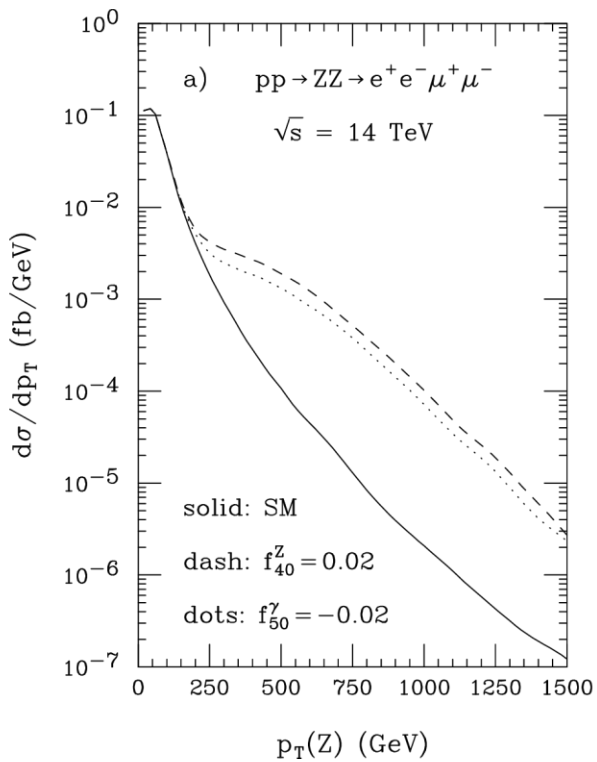
arXiv:0806.4145

Anomalous Triple Gauge Couplings

- ZZZ and ZZγ couplings forbidden in SM
- New physics, e.g. a new gauge boson at very high mass, could appear as an effective modification to the couplings
- Can be described by an effective Lagrangian parameterized by coefficients f_4^Z, f_4^γ (CP-odd) and f_5^Z, f_5^γ (CP-even)
- Nonzero aTGCs would increase the ZZ cross section at high $m_{4\ell}$
- Previous best limits (from CMS):

$$-0.0022 < f_4^Z < 0.0026, \quad -0.0023 < f_5^Z < 0.0023$$

$$-0.0029 < f_4^\gamma < 0.0026, \quad -0.0026 < f_5^\gamma < 0.0027$$



arXiv:0008063

Anomalous Quartic Gauge Couplings

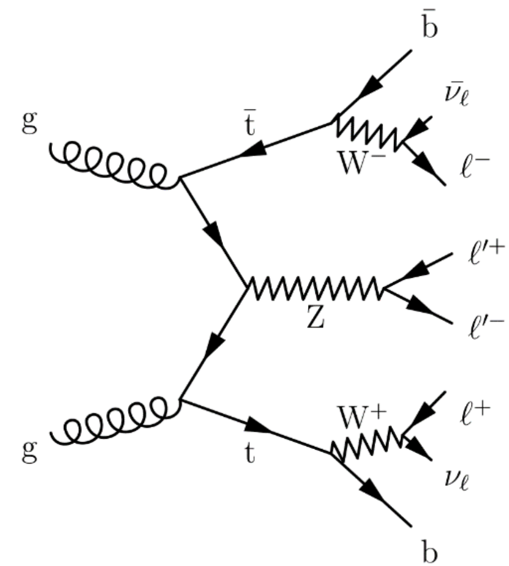
- Fully neutral VVVV vertices also forbidden in SM
- Nonzero aQGCs increase ZZ VBS cross section at high m_{ZZ}
- Parameterize with dimension-8 effective field theory operators

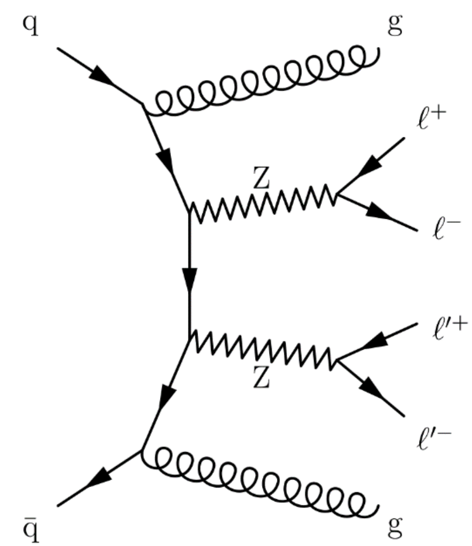
$$\mathcal{L}_{T0} = \frac{f_{T0}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\right] \times \mathrm{Tr}\left[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}\right]$$
$$\mathcal{L}_{T1} = \frac{f_{T1}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\alpha\nu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\mu\beta}\hat{W}^{\alpha\nu}\right]$$
$$\mathcal{L}_{T2} = \frac{f_{T2}}{\Lambda^4} \mathrm{Tr}\left[\hat{W}_{\alpha\mu}\hat{W}^{\mu\beta}\right] \times \mathrm{Tr}\left[\hat{W}_{\beta\nu}\hat{W}^{\nu\alpha}\right]$$
$$\mathcal{L}_{T8} = \frac{f_{T8}}{\Lambda^4} B_{\mu\nu}B^{\mu\nu}B_{\alpha\beta}B^{\alpha\beta}$$
$$\mathcal{L}_{T9} = \frac{f_{T9}}{\Lambda^4} B_{\alpha\mu}B^{\mu\beta}B_{\beta\nu}B^{\nu\alpha},$$

- T8 and T9 affect only the fully neutral couplings
- No previous limits from ZZ searches

Background Processes

- **Small contribution from processes with 4 prompt leptons**
  - $WWZ \to 4\ell 2\nu$, $t\bar{t}Z \to 4\ell 2\nu 2b$
  - Processes are "real physics" that can be modeled
- **More often, 2 or 3 prompt leptons plus 2 or 1 jet fragments**
  - $WZ + X \to 3\ell\nu + X'$
  - $t\bar{t} \to 2\ell 2\nu 2b$
  - $Z/\gamma^* + 2X \to 2\ell + 2X'$
  - Fake objects are complicated and hard to model, must be estimated from data
- **Continuum ZZ with QCD jets is background for VBS search**

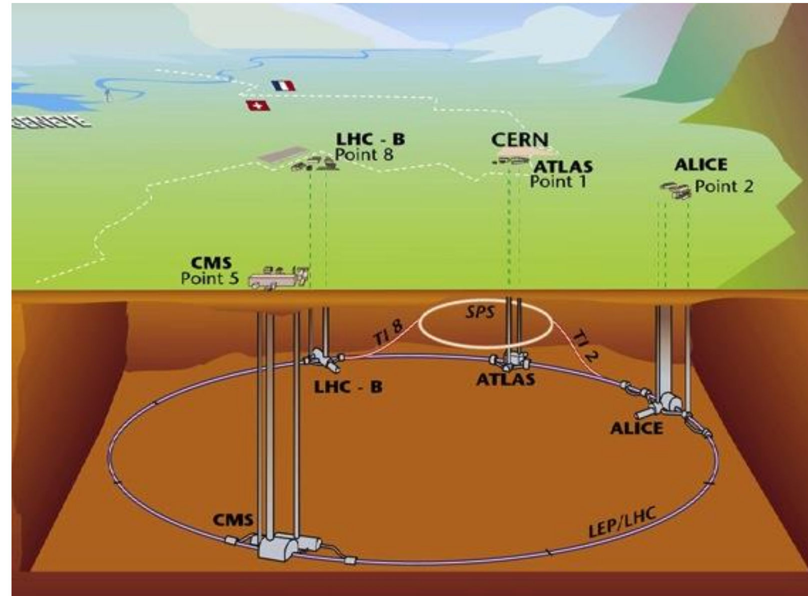


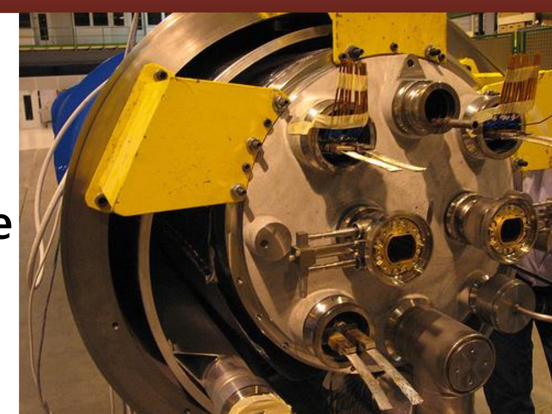


The LHC and CMS

The Large Hadron Collider

- **27 km circumference collider at CERN near Geneva, CH, capable of colliding protons and heavy ions**
- **Serves four primary experiments**
  - CMS and ATLAS: general purpose
  - LHCb: forward hadronic physics
  - ALICE: heavy ion physics
- **Designed for 14 TeV center of mass energy**
  - Achieved 8 TeV in 2012
  - 13 TeV since 2015





LHC dipole

LHC Operating Conditions

- **Superb machine performance**
- **Instantaneous luminosity:**

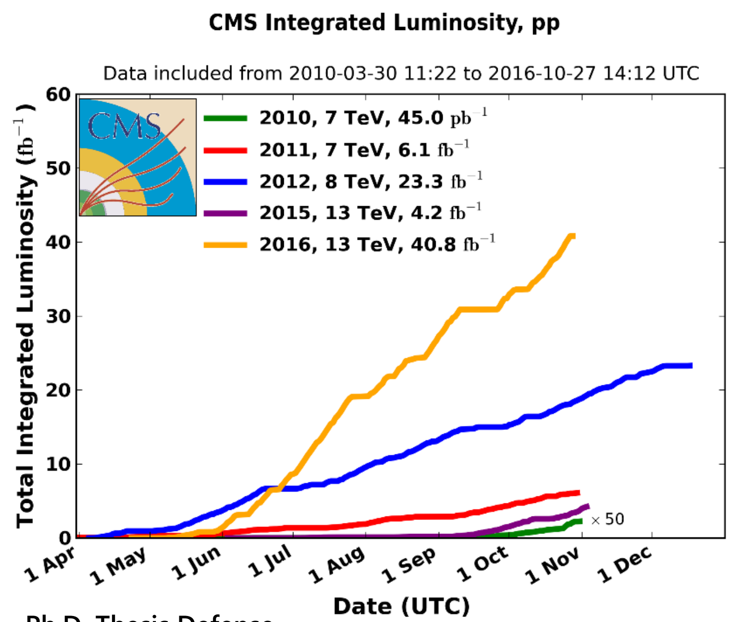
$$\mathscr{L} = f_{\text{rev}} \frac{n_b N_b^2 \gamma}{4\pi\beta^* \epsilon_N} R$$

- **Event yield (cross section σ):**

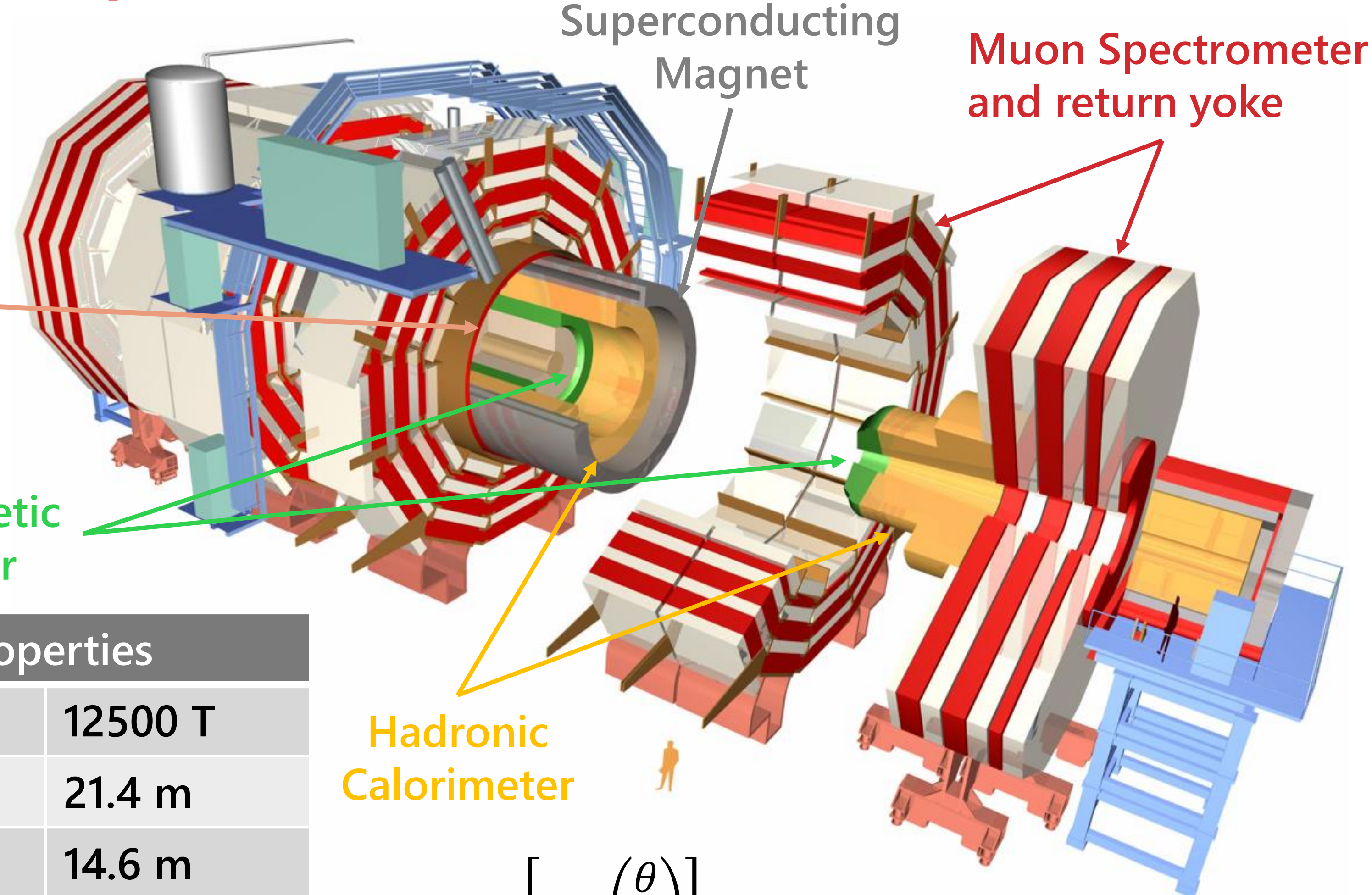
$$N = \sigma \int \mathscr{L}\, \mathrm{d}t$$

- **Maximize luminosity with high bunch occupancy, compact bunches**
  - High pileup (collisions per bunch crossing) a major experimental challenge
- **Very high $\mathscr{L}$ in 2016, 2017 even higher**
- **Results shown today: 35.9 fb^{-1} (2016)**

	Design	Run I			Run II	
Year		2010	2011	2012	2015	2016
Energy per beam (TeV)	7	3.5	3.5	4	6.5	6.5
Bunch spacing (ns)	25	150	50	50	25	25
n_b	2808	348	1331	1368	2232	2208
N_b (10^{11})	1.15	1.2	1.5	1.7	1.15	1.25
β^* (m)	0.55	3.5	1.0	0.6	0.8	0.4
ϵ_N (mm mrad)	3.75	2.2	2.3	2.5	3.5	3.0
Peak pileup		4	17	37	22	49
Peak $\mathscr{L}$ ($10^{34}\text{cm}^{-2}\text{s}^{-1}$)	1	0.02	0.35	0.77	0.52	1.53
$\mathscr{L}_{int}$ (fb^{-1})		0.04	6.1	23.3	4.2	41.1



The Compact Muon Solenoid

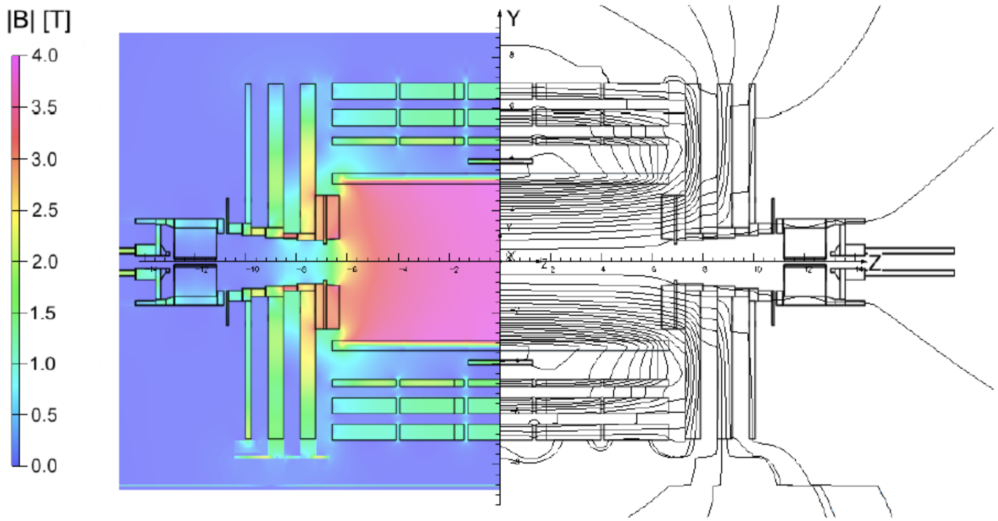


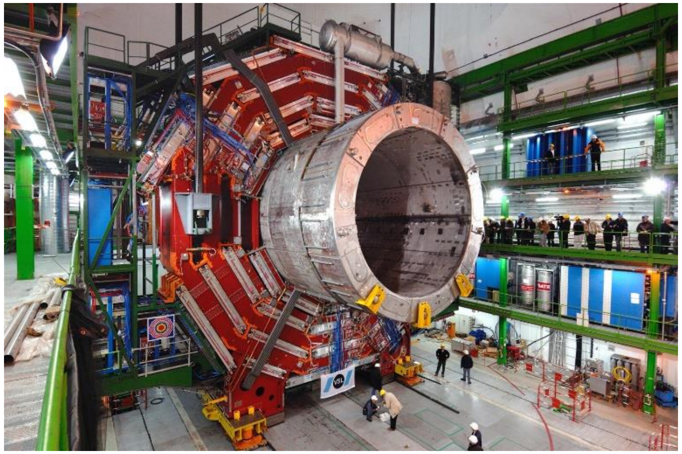
CMS Properties	
Mass	12500 T
Length	21.4 m
Diameter	14.6 m
Magnetic Field	3.8 T

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

Magnet

- Charged particle momentum measured by finding curvature of trajectory in magnetic field
- Superconducting solenoid provides 3.8 T field in central barrel of detector
- Iron return yokes provide ~2T field in outer muon system

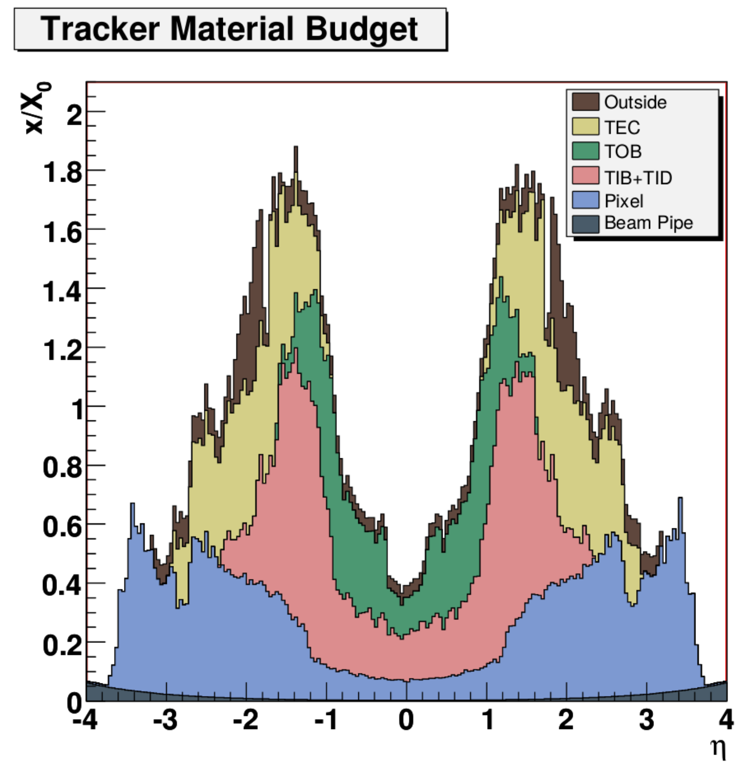


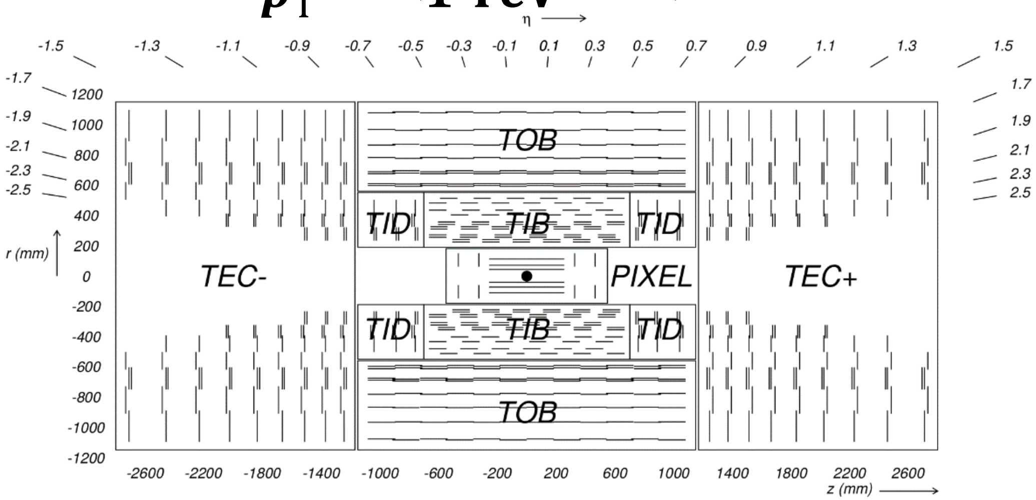


Silicon Tracker

- 66M channel Si pixel system close to interaction point finds primary vertices and seeds tracks
- 9.6M channel Si strip detector iteratively fits tracks from these seeds in $|\eta| < 2.5$
- Resolution (barrel):

$$\frac{\delta p_T}{p_T} = \left(\frac{p_T}{1\ \mathrm{TeV}} 15\%\right) \oplus 0.5\%$$

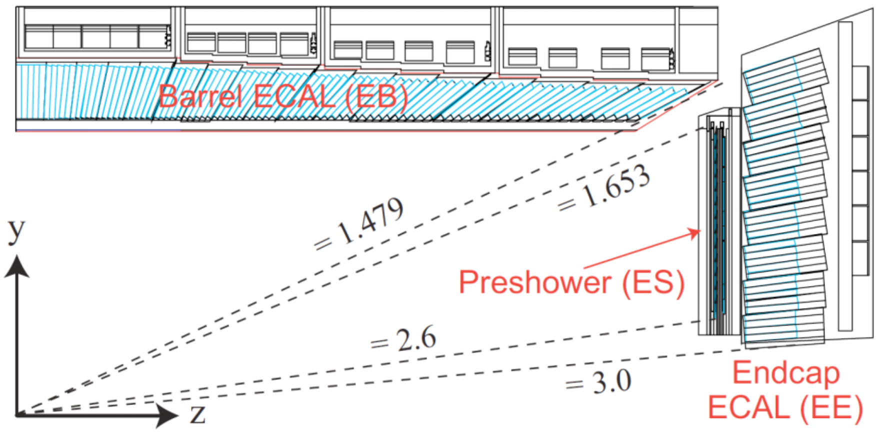


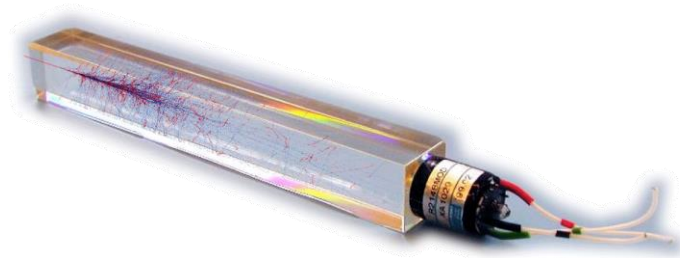


Electromagnetic Calorimeter

- Electron and photon energy and position measured by high granularity electromagnetic calorimeter (ECAL)
- 61200 $PbWO_4$ crystal scintillators in barrel region (EB, $|\eta| < 1.48$) and 14648 in endcap (EE, $|\eta| < 3.0$) read out by amplifying photodetectors
- In addition to energy measurement, provides triggering for electrons and photons
- Resolution (stochastic+noise+const.):

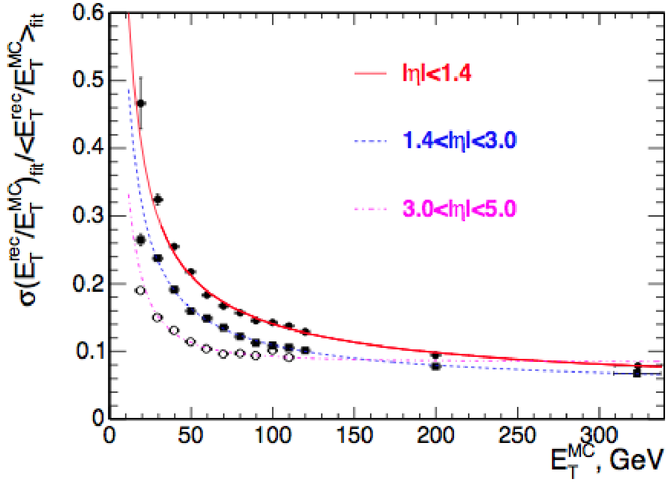
$$\frac{\sigma}{E} = \frac{2.8\%}{\sqrt{E/\mathrm{GeV}}} \oplus \frac{.128}{E/\mathrm{GeV}} \oplus 0.3\%$$





ECAL crystal with photodetector and cartoon of an electron shower

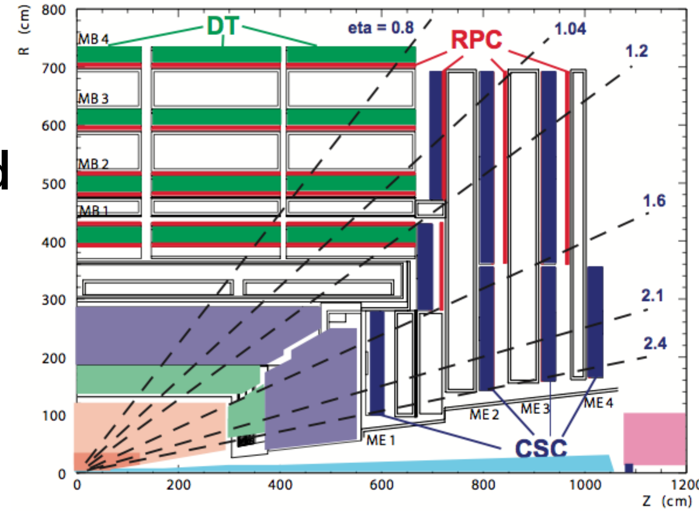
Hadronic Calorimeter

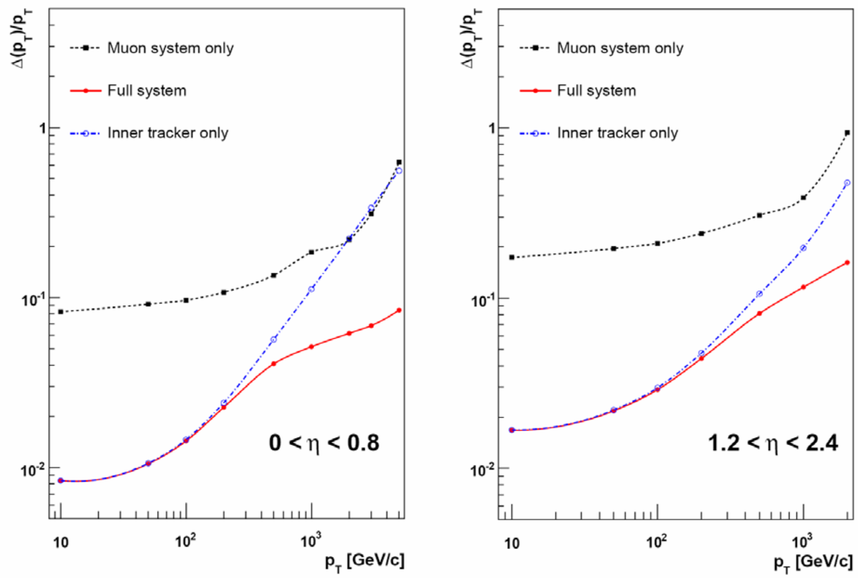


- **Long-lived neutral hadrons measured and triggered by compact (inside solenoid), hermetic ($|\eta| < 5$) sampling hadronic calorimeter (HCAL)**
- **Barrel and endcap (HB and HE, $|\eta| < 3.0$)**
  - Plastic scintillator tiles embedded with wavelength shifting fibers interleaved with brass absorber
  - $\frac{\sigma}{E} \approx \frac{85\%}{\sqrt{E/\mathrm{GeV}}} \oplus 7\%$ (HB), $\frac{\sigma}{E} \approx \frac{113\%}{\sqrt{E/\mathrm{GeV}}} \oplus 3\%$ (HE)
- **Forward (HF, $3 < |\eta| < 5$)**
  - Steel with embedded quartz fibers
  - Also measures EM rich jets outside ECAL acceptance
  - $\frac{\sigma}{E} \approx \frac{280\%}{\sqrt{E/\mathrm{GeV}}} \oplus 11\%$, $\frac{\sigma}{E} \approx \frac{198\%}{\sqrt{E/\mathrm{GeV}}} \oplus 9\%$ (EM)

Muon System

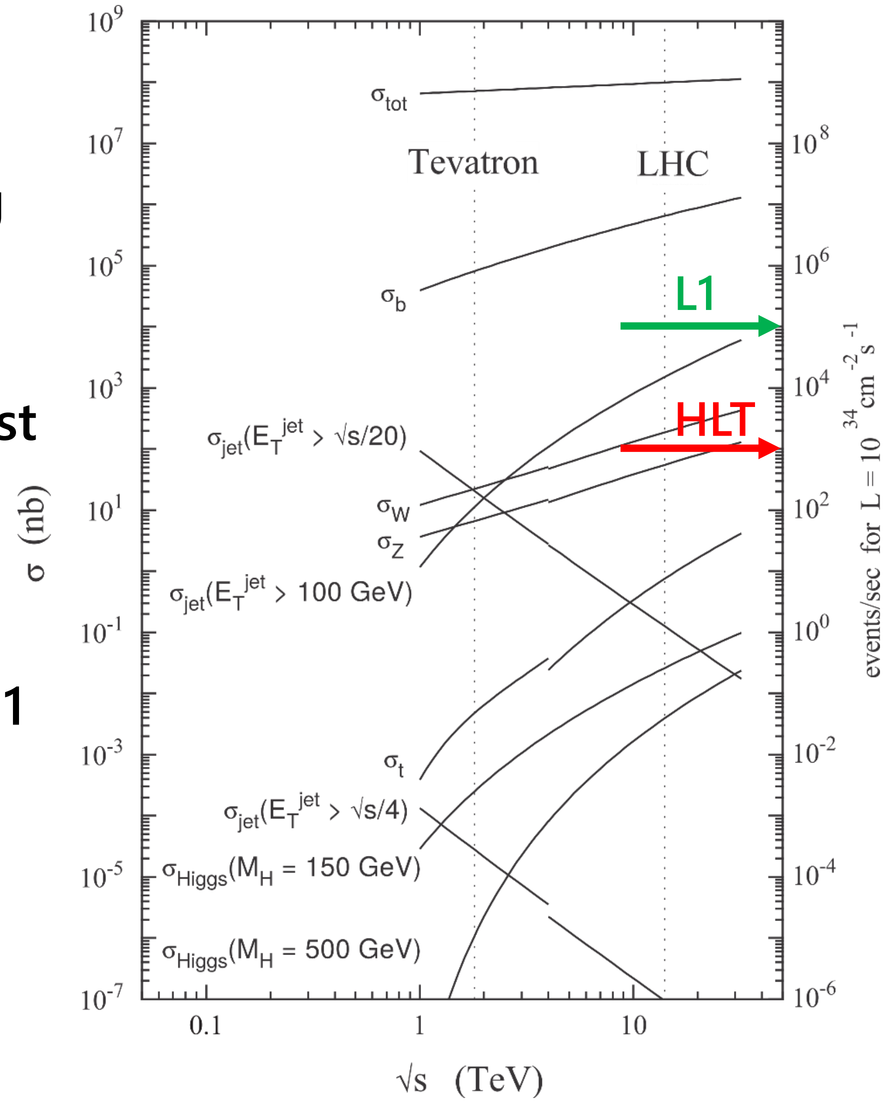
- **Several gas ionization systems interleaved with iron return yoke outside solenoid**
- **Muon triggering and identification**
- **Improved high-p_T muon measurements**
- **Drift Tubes (DT) in barrel ($|\eta| < 1.2$)**
  - Resolution: 80-120 μm, ~3 ns
- **Cathode Strip Chambers (CSC) in endcap ($0.9 < |\eta| < 2.4$)**
  - Resolution: 40-150 μm, ~3 ns
- **Resistive Plate Chambers (RPC, $|\eta| < 1.6$)**
  - 1 ns timing, redundant triggering





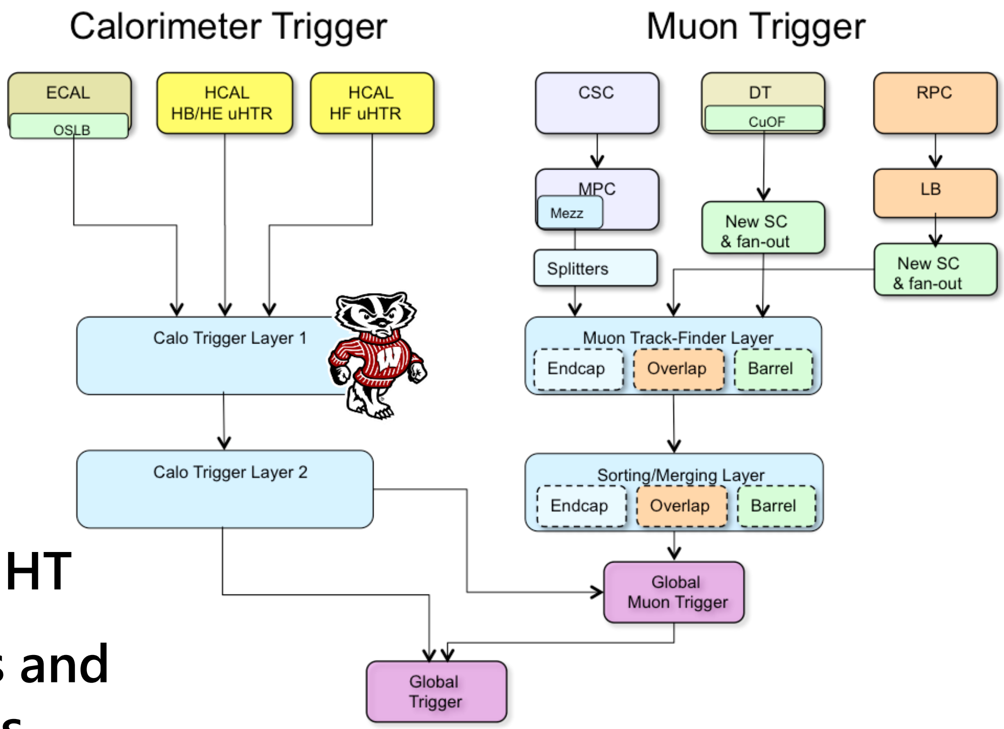
Trigger

- LHC 40 MHz bunch crossing rate with ~40 interactions per crossing gives potential ~40 TB/s data rate
- CMS produces far too much raw data to store and analyze, but most is uninteresting soft QCD
- 2-tier trigger system reduces 40 MHz bunch crossing rate to ~100 kHz in dedicated hardware (Level-1 Trigger), then to ~1 kHz appropriate for storage and analysis with software (High Level Trigger)



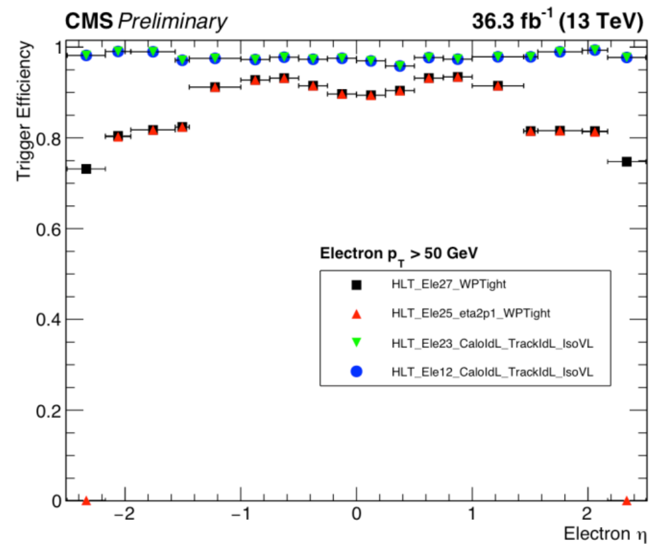
Level-1 Trigger

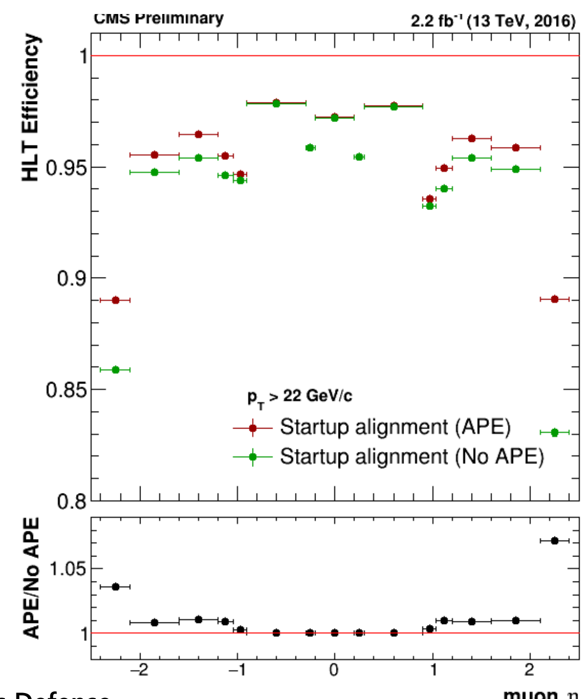
- **Low granularity detector information is processed in dedicated hardware**
- **L1 Calorimeter Trigger finds (possibly isolated) electrons, photons, taus, jets, total E_{T}, MET, hadronic E_{T} (HT) and MHT**
- **L1 Muon Trigger builds tracks and reconstructs muon candidates**
- **Global Trigger combines calo and muon objects and makes final decision based on configurable menu**
  - Topological selections possible
- **<~4 µs latency, ~100 kHz max readout**



High Level Trigger

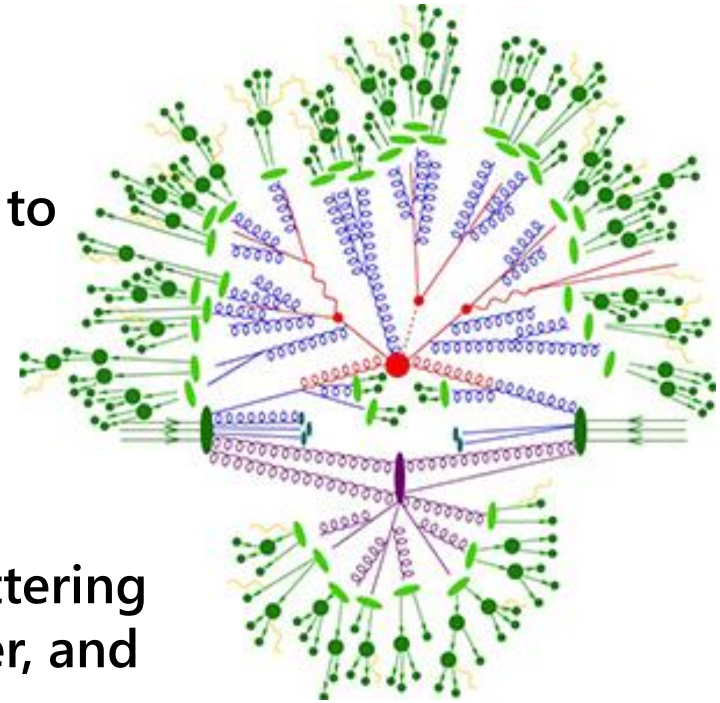
- **Modified version of offline reconstruction software run on commercial processor farm**
- **Uses full detector information, including tracker**
- **Can perform complex analysis-specific algorithms such as vertex tagging, tau reconstruction, etc.**
- **Optimized for speed**
  - Check detector only in region of L1 objects
  - Reconstruct fast objects first to allow early rejection





Simulation and Reconstruction

Simulation



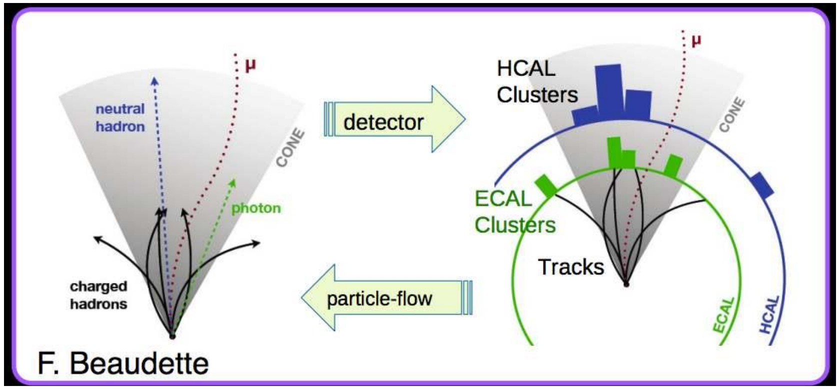
- Simulation of physics observables is vital to experiment design and validation, and data-theory comparison
- Use Monte Carlo methods to generate individual events
- Matrix element generation: calculate scattering amplitudes at a chosen perturbative order, and generate a hard process-level spectrum
- Parton showering and hadronization performed by shower MC
- Pileup simulated with overlaid minimum bias events
- Particle-matter interactions and detector response simulated with GEANT4
- Reconstruction and analysis with same software as data

Generators

- **Matrix element generators**
  - POWHEG (NLO, scaled to NNLO yields)
    - $gg \to H \to ZZ^*$, $q\bar{q}/qg \to ZZ$, $q\bar{q} \to Z \to 4\ell$
  - MadGraph5_aMC@NLO
    - $q\bar{q}/qg \to ZZ$ (NLO)
    - ZZ + 2jets (QCD and EWK), aQGC signal (LO)
  - MCFM
    - $gg \to ZZ$ (LO, scaled to NLO yield)
  - SHERPA
    - aTGC signal (LO)
- **Parton shower and hadronization with Pythia 8 (except SHERPA samples)**

Particle Flow Reconstruction

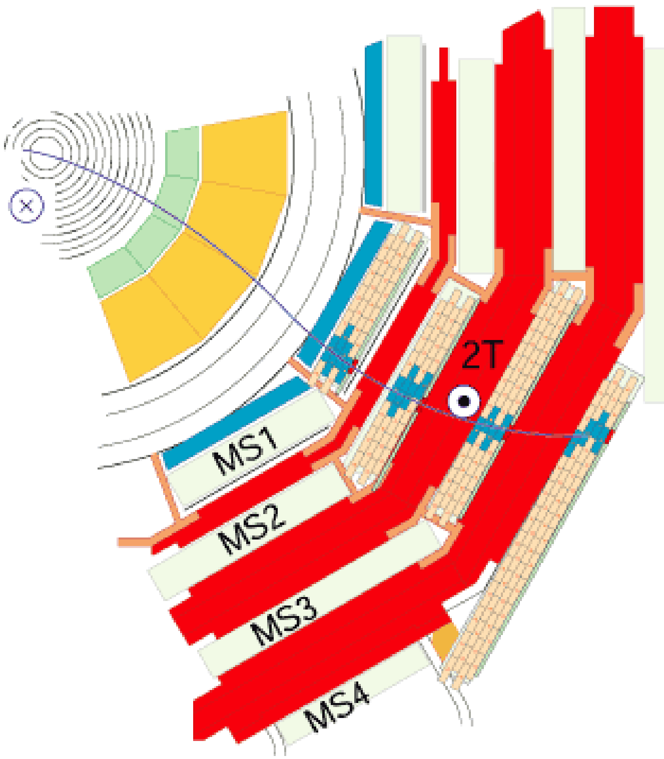
- **CMS design is optimized to allow signals to be combined across detector subsystems**
- **Correlations improve identification and resolution**



- **Tracks and calorimeter clusters are matched and combined to reconstruct particle flow (PF) candidates**
  - Tracker tracks matched to muon system hits are muons
  - Remaining tracks are associated to ECAL clusters to make electrons or HCAL clusters to make charged hadrons
  - Remaining ECAL clusters are photons, remaining HCAL clusters are neutral hadrons
- **PF candidates can be clustered into higher-level objects (jets, taus, missing energy) or further selected for analysis use**

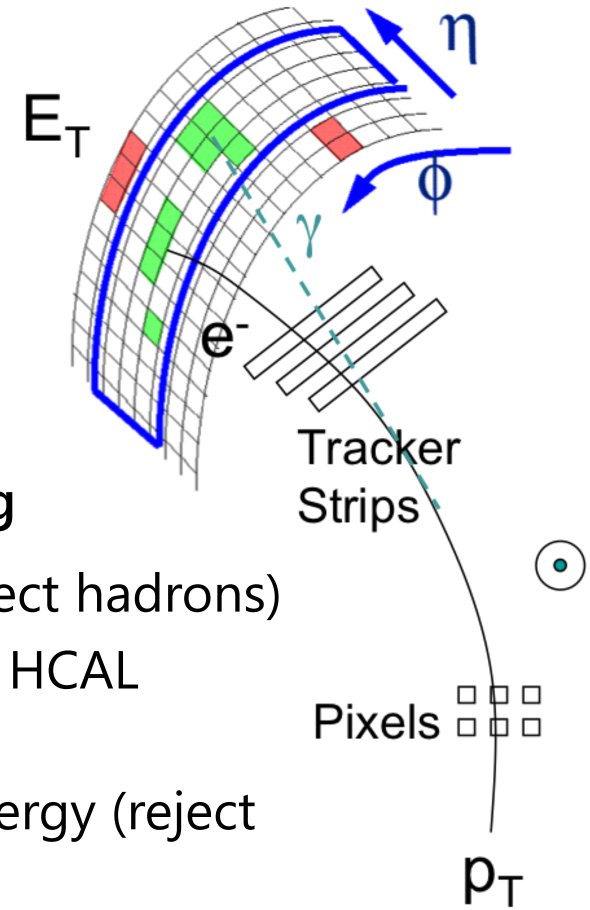
Muon Reconstruction and Selection

- **Three types of muon reconstruction**
  - Tracker muon, found by silicon tracker
  - Standalone muon, found by muon system
  - Global muon, matched tracks in both
- **This study requires**
  - Global or tracker
  - Close to primary interaction vertex
  - Several more cuts (e.g. small χ^2 of track fit) to eliminate hadrons that "punch through" to the muon system



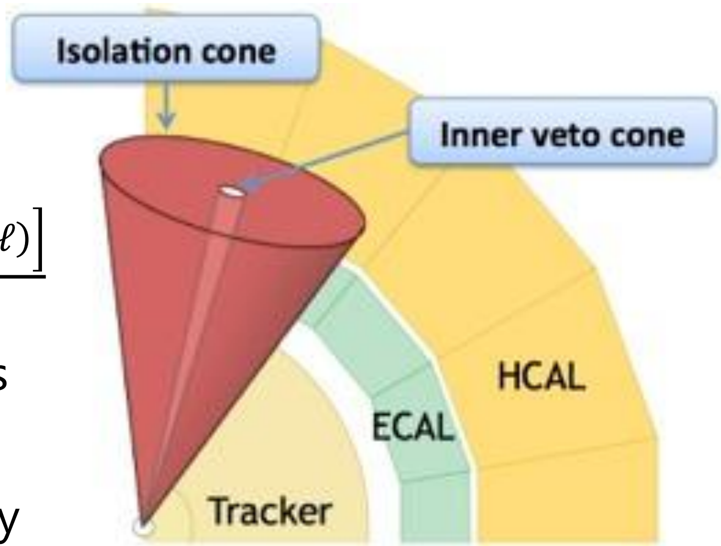
Electron Reconstruction and Selection

- **Electrons lose substantial energy to material interactions**
  - Tracks re-reconstructed with Gaussian sum filter algorithm due to stochastic energy loss
  - ECAL clusters extended in ϕ to collect bremsstrahlung photons
- **Track must originate from primary vertex**
- **Identification uses boosted decision tree (BDT) multivariate discriminator with inputs including**
  - Track quality and energy loss observables (reject hadrons)
  - Calorimeter cluster shape and properties, e.g. HCAL activity (reject EM-rich jets)
  - Track-cluster compatibility by position and energy (reject photons)

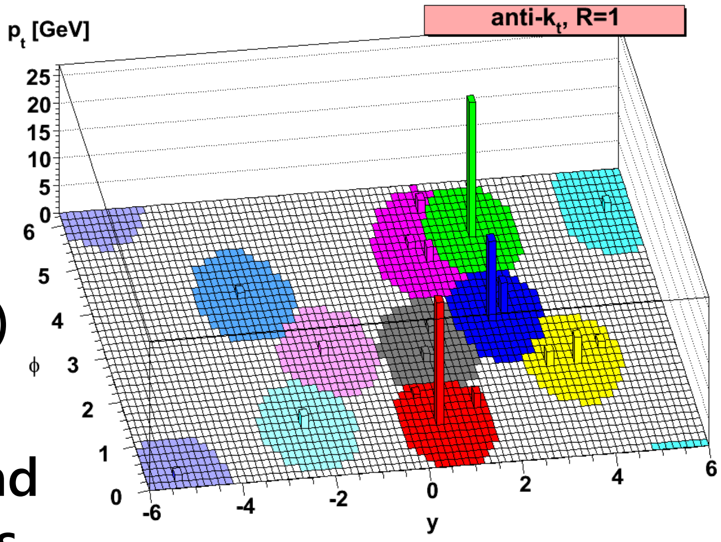


Lepton Isolation

- **QCD backgrounds produce lepton candidates inside jets that may be strongly rejected by limiting the energy in cones around them**
- **Particle Flow Relative Isolation:**
  - $R_{\mathrm{Iso}}^{\ell} \equiv \frac{\sum p_{\mathrm{T}}^{\mathrm{charged}} + \max\left[0, \sum p_{\mathrm{T}}^{\mathrm{neutral}} + \sum p_{\mathrm{T}}^{\gamma} - p_{\mathrm{T}}^{\mathrm{PU}}(\ell)\right]}{p_{\mathrm{T}}^{\ell}}$
    - Charged and neutral refer to PF hadrons
    - $p_{\mathrm{T}}^{\mathrm{PU}}(\mathrm{e}) \equiv \rho \times A_{\mathrm{eff}}$
      - ρ: median jet neutral particle energy
      - A_{eff}: cone area scaled for N_{vtx}
    - $p_{\mathrm{T}}^{\mathrm{PU}}(\mu) \equiv 0.5 \times \sum_i p_{\mathrm{T}}^{\mathrm{PU},i}$, i runs over charged hadrons from other vertices



Jet Reconstruction

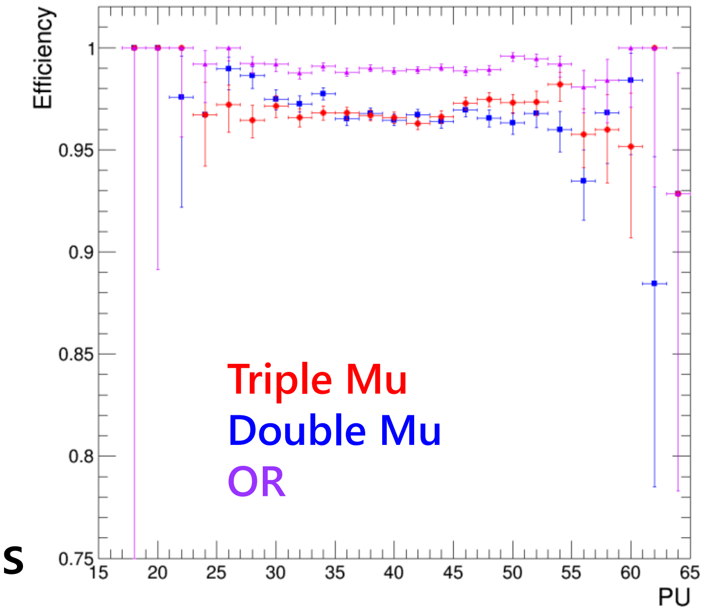


- Jets are made from clusters of charged hadrons (~65%), neutral hadrons (~25%) and photons (10%)
- Clustering algorithm must be infrared and collinear safe, i.e. insensitive to processes that surround a hadron with soft radiation or split one hadron into two nearly collinear ones
- Here: anti-k$_T$ algorithm with $\boldsymbol{R = 0.4}$
  - Iteratively merge particle pairs with smallest d_{ij}
    - $d_{ij} = \min(p_{Ti}^{-2}, p_{Tj}^{-2})\frac{\Delta_{ij}}{R}, \qquad \Delta_{ij}^2 \equiv (y_i - y_j)^2 + (\phi_i - \phi_j)^2$
- MC jet energies corrected to remove pileup and smeared to match data
- Reject jets within $\boldsymbol{\Delta R < 0.4}$ of leptons and FSR photons

Event Selection

Triggers

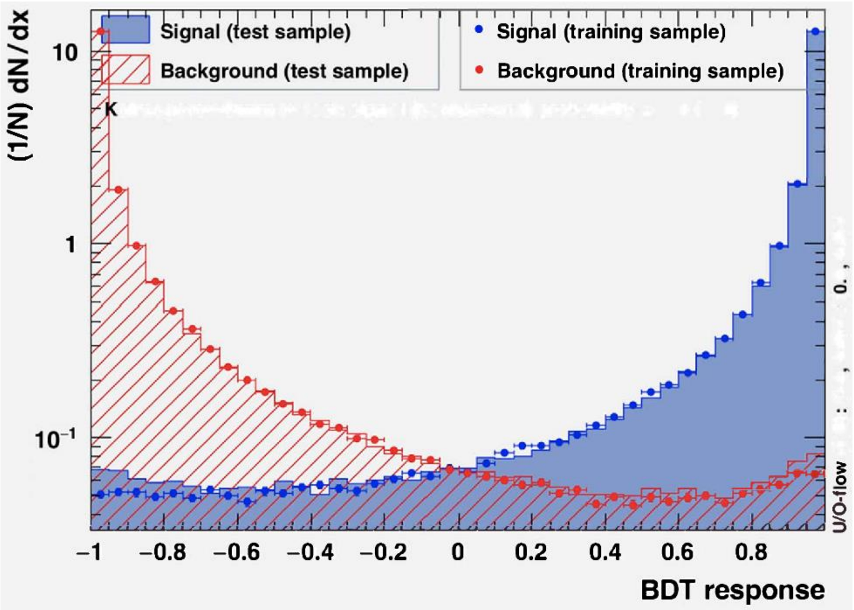
- Trigger on pairs of isolated leptons
- Additional triggers with a single very high p_T or isolated lepton, or three leptons, to bring efficiency close to 1
- p_T thresholds increased with instantaneous luminosity, full list in backup slides



- Most important: 23 GeV electron/17 GeV muon + 12 GeV electron/8 GeV muon (both particles isolated)
- 2- and 3-lepton triggers may be same flavor or cross trigger (e.g. ee, eμ, μe, μμ all used)
- Use simple OR of all paths

Lepton Selection Details

- Leptons must pass minimal "loose" ID cuts to be used in control regions, plus an additional "tight" requirement for signal leptons
- $p_{\mathrm{T}}^{\mathrm{e}(\mu)} > 7\ (5)$ GeV, $|\eta^{\mathrm{e}(\mu)}| < 2.5\ (2.4)$
- $\mathbf{SIP} \equiv \frac{|\mathrm{IP_{3D}}|}{\sigma_{\mathrm{IP_{3D}}}} < 10$ for all leptons
- Electrons: $\Delta R(\mathrm{e}, \text{any } \mu) > 0.05$
  - Tight requirement: Pass BDT discriminator
- Muons: $|\eta| < 2.4$, global or tracker muon
  - Tight requirement: PF muon
- $R_{\mathrm{Iso}}^{\ell} < 0.35$



Electron BDT ID performance

Event Selection

- **Consider all possible lepton pairings that give 2 opposite sign, same flavor Z/γ* candidates ($\ell^+\ell^-\ell'^+\ell'^-, \ell \in \mathrm{e}, \mu$)**
  - One with $40 < m_{\ell\ell} < 120$ GeV, other with $m_{\ell\ell} < 120$ GeV
  - All opposite-sign pairs must have $m_{\ell\ell'} > 4$ GeV
- **Z_1: lepton pair with $m_{\ell\ell}$ closest to nominal m_{Z}**
- **$p_{\mathrm{T}}^{\ell_1} > 20$ GeV, $p_{\mathrm{T}}^{e(\mu)_2} > 12(10)$ GeV**
- **In case of more than one possible ZZ system, the one with smallest $\left|m_{\mathrm{Z}_1} - m_{\mathrm{Z}}\right|$ is chosen, then $\sum_i p_{\mathrm{T}}^{\ell_i}$ is maximized**
- **Further requirements for specific measurements:**
  - On-shell: $60 < m_{\mathrm{Z}_{1,2}} < 120$ GeV
    - ZZjj (VBS): Two jets with $m_{\mathrm{jj}} > 100$ GeV
  - $\mathrm{Z} \to 4\ell$: $80 < m_{4\ell} < 100$ GeV, $\mathrm{H} \to 4\ell$: $118 < m_{4\ell} < 130$ GeV

Cut Flow

- **Number of $2\ell 2\ell'$ events passing each cut**
- **$ZZ \to 4\ell$, $Z \to 4\ell$, and $H \to 4\ell$ selections applied on top of full spectrum selection**
- **Best candidate in each event chosen in full spectrum selection**
  - Measurement-specific samples are strict subsets
  - At earlier steps, events may appear in multiple channels

Selection	4e	$2e2\mu$	4μ	Total
Trigger	580633	645640	399212	1598705
Lepton ID	2195	6760	11614	20563
Lepton Isolation	597	1189	1548	3334
Full Spectrum	440	1111	838	2389
$Z \to 4\ell$	78	206	225	509
$H \to 4\ell$	19	41	34	94
$ZZ \to 4\ell$	220	543	335	1098

Signal Efficiency (%)			
	4e	2e2μ	4μ
$Z \to 4\ell$	24	36	73
$ZZ \to 4\ell$	54	65	78

Background Estimation Overview

Process	Approx. fraction of ZZ background
$t\bar{t}Z$	10%
Z+X	70%
WZ	10%
$t\bar{t}$	10%

- Backgrounds are small (~6% of ZZ yield)
- WWZ and $t\bar{t}Z$ from MC; data driven $Z + X$ and $t\bar{t}$
- Strategy: weight events in control regions with 1 or 2 non-prompt lepton candidates by the rate at which such non-prompt leptons are misidentified as prompt
- Lepton fake rate $f^{\ell}(p_{\mathrm{T}}^{\ell}, \eta^{\ell})$ found with Z+ℓ_{loose} sample
- 4ℓ control regions:
  - 3P1F (3 prompt, 1 fake): one lepton fails tight ID or isolation
  - 2P2F (2 prompt, 2 fake): both leptons in one Z fail
- 2P2F is already counted (twice) in 3P1F, so it is subtracted out
- $N_{SR} = \sum_{3P1F_i} \frac{f^{\ell}i}{1-f^{\ell}i} - \sum_{2P2F_{i,j}} \frac{f^{\ell}i f^{\ell}j}{(1-f^{\ell}i)(1-f^{\ell}j)}$

Lepton Fake Rate Estimation

- **Z+ℓ_{loose}**
  - Z selected as in signal region but with $|m_{\ell\ell} - m_Z| < 10\text{ GeV}$
  - 3rd lepton passes loose ID, no isolation cut
  - MET < 20 GeV and $m_T\left(\vec{p}_T^{\,\ell_3}, \vec{p}_T^{\,\text{miss}}\right)$ < 30 GeV to remove WZ
  - 4th lepton veto
  - Dielectron and dimuon triggers only
- **Any remaining WZ and ZZ contamination estimated from MC and removed**
- **Fake rate: $\boldsymbol{f} = \dfrac{\textbf{\# also passing tight ID+isolation}}{\textbf{total}}$**

Systematic Uncertainties

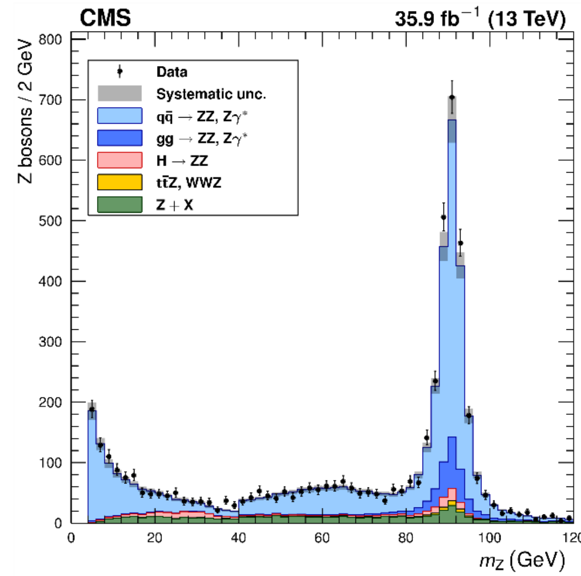
- Lepton ID and isolation efficiency systematics found by varying scale factors by fit uncertainties
- Pileup uncertainty found by varying estimated minbias cross section by 4.6%
- 40% uncertainty on fake rate

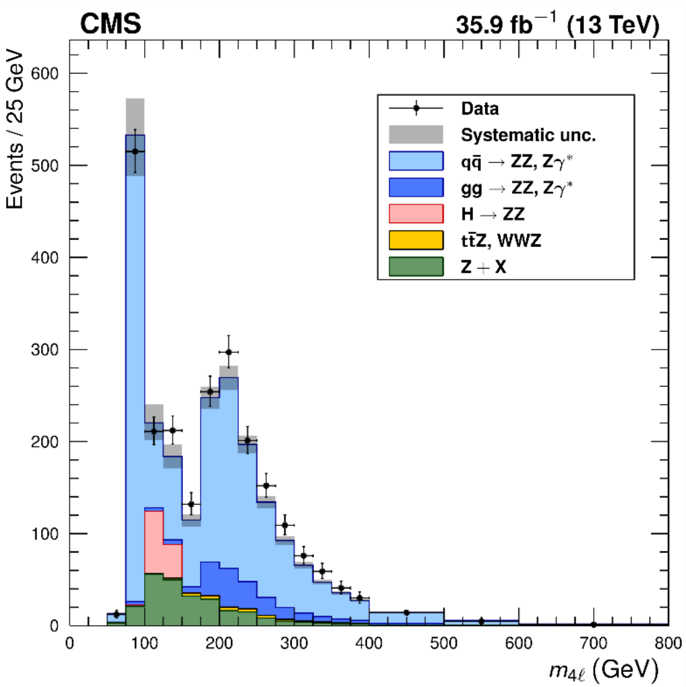
Uncertainty	$Z \to 4\ell$	$ZZ \to 4\ell$
Lepton efficiency	6–10%	2–6%
Trigger efficiency	2–4%	2%
MC statistics	1–2%	0.5%
Background	0.6–1.3%	0.5–1%
Pileup	1–2%	1%
PDF	1%	1%
QCD Scales	1%	1%
Integrated luminosity	2.5%	2.5%

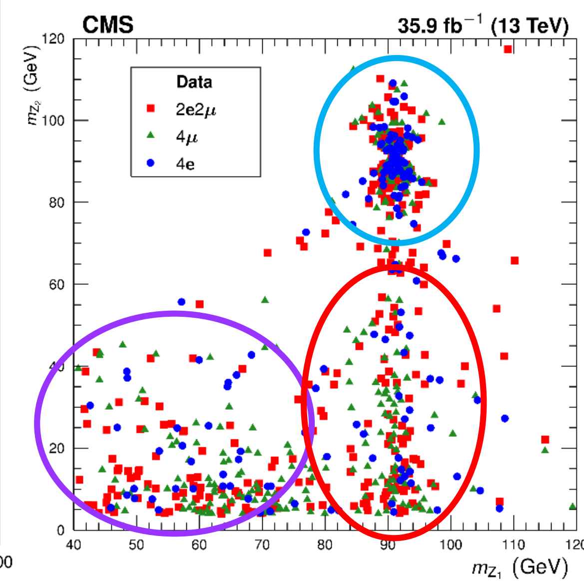
Yields and Inclusive Cross Sections

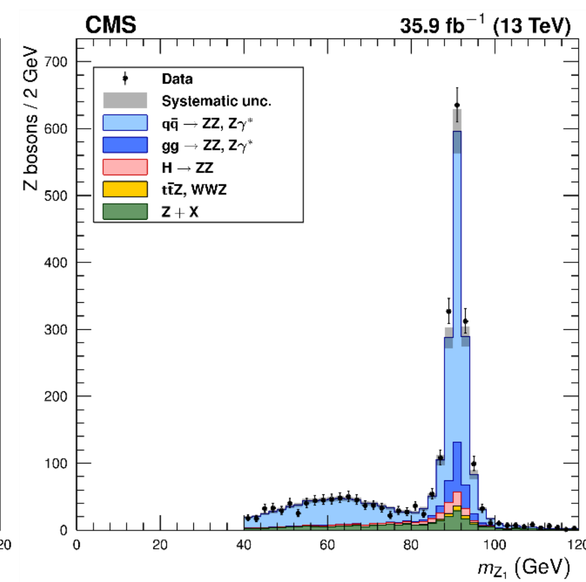
Full Spectrum

- Various production modes ($Z \rightarrow 4\ell$, $\gamma^*\gamma^*$, $H \rightarrow 4\ell$, $Z\gamma^*$, ZZ) clearly visible
- Not used for cross section measurements



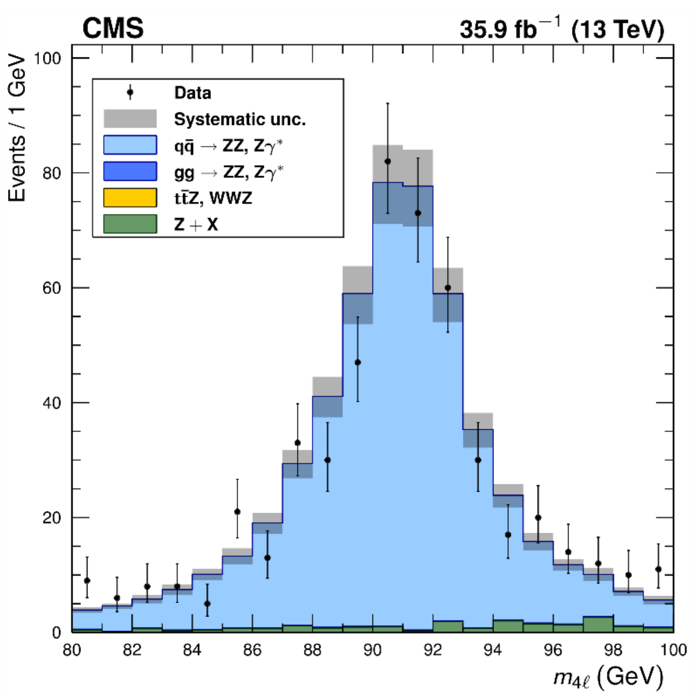


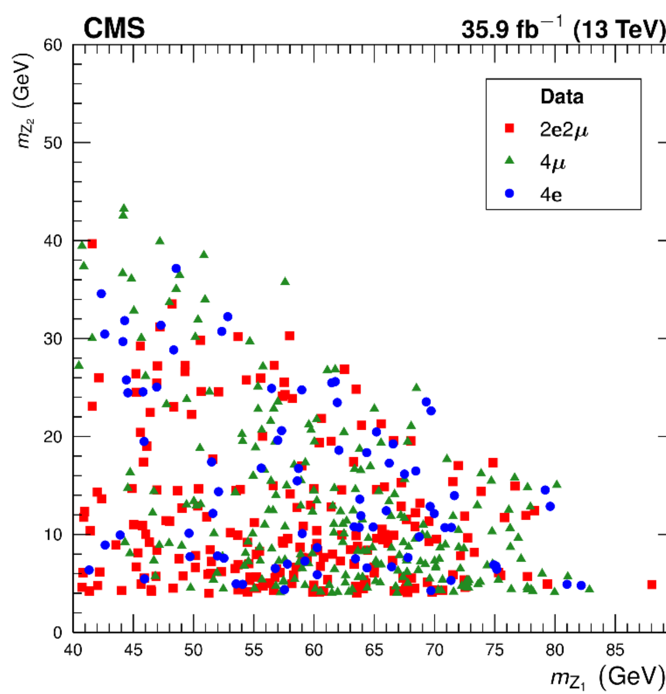




$Z \to 4\ell$ Yield

Final state	Expected $N_{4\ell}$	Background	Total expected	Observed
4μ	$224 \pm 1 \pm 16$	$7 \pm 1 \pm 2$	$231 \pm 2 \pm 17$	225
$2e2\mu$	$207 \pm 1 \pm 14$	$9 \pm 1 \pm 2$	$216 \pm 2 \pm 14$	206
4e	$68 \pm 1 \pm 8$	$4 \pm 1 \pm 2$	$72 \pm 1 \pm 8$	78
Total	$499 \pm 2 \pm 32$	$19 \pm 2 \pm 5$	$518 \pm 3 \pm 33$	509





$Z \to 4\ell$ Cross Section

- **Total inclusive signal strength found with maximum likelihood fit of yields, treating each channel as an independent bin**

$$\mu = 0.980^{+0.046}_{-0.044}\,(\text{stat})^{+0.065}_{-0.059}\,(\text{syst}) \pm 0.025\,(\text{lumi})$$

- $\boldsymbol{\sigma_{\text{fid}} = \mu \times \sigma_{\text{fid}}^{\text{theo}}}$

$$\sigma_{\text{fid}}\,(\text{pp} \to \text{Z} \to 4\ell) = 31.2^{+1.5}_{-1.4}\,(\text{stat})^{+2.1}_{-1.9}\,(\text{syst}) \pm 0.8\,(\text{lumi})\,\text{fb}$$

- $\boldsymbol{\sigma_{\text{fid}}}$ **scaled to total** $\boldsymbol{\sigma \times \mathcal{B}}$ **by** $\boldsymbol{\mathcal{A} = 0.125 \pm 0.002}$
  - Removes all but $80 < m_{4\ell} < 100$ GeV and $m_{\ell\ell} > 4$ GeV requirements
  - Includes correction for nonresonant contribution

$$\sigma(\text{pp} \to \text{Z}) \times \mathcal{B}(\text{Z} \to 4\ell) = 249 \pm 8\,(\text{stat})^{+9}_{-8}\,(\text{syst}) \pm 4\,(\text{theo}) \pm 6\,(\text{lumi})\,\text{fb}$$

$\pm 5.5\%$

- **But we already know the Z cross section with higher precision**
  - More interesting to interpret as branching fraction

$Z \longrightarrow 4\ell$ Branching Fraction

$$\mathcal{B}(Z \to \ell\ell\ell'\ell') = \frac{\sigma(pp \to Z) \times \mathcal{B}(Z \to \ell\ell\ell'\ell')}{\sigma(pp \to Z) \times \mathcal{B}(Z \to \ell\ell) / \mathcal{B}(Z \to \ell\ell) \cdot \mathcal{C}^{60-120}_{80-100}}$$

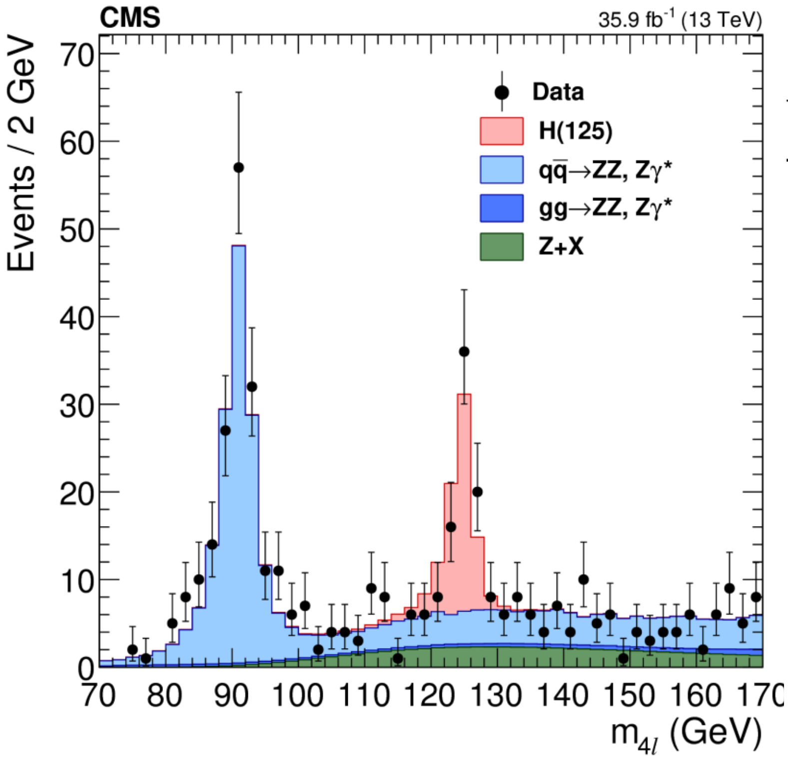
- **Z cross section (FEWZ NNLO):**
  - $\sigma(pp \to Z) \times \mathcal{B}(Z \to \ell\ell) = 1870^{+50}_{-40}$ pb
- **Translation between Z mass windows:**
  - $\mathcal{C}^{60-120}_{80-100} = 0.926 \pm 0.001$
- **Nominal dilepton branching fraction (PDG):**
  - $\mathcal{B}(Z \to \ell\ell) = 0.03366$

$$\mathcal{B}(Z \to 4\ell) = 4.8 \pm 0.2\,(\text{stat}) \pm 0.2\,(\text{syst}) \pm 0.1\,(\text{theo}) \pm 0.1\,(\text{lumi}) \times 10^{-6}$$

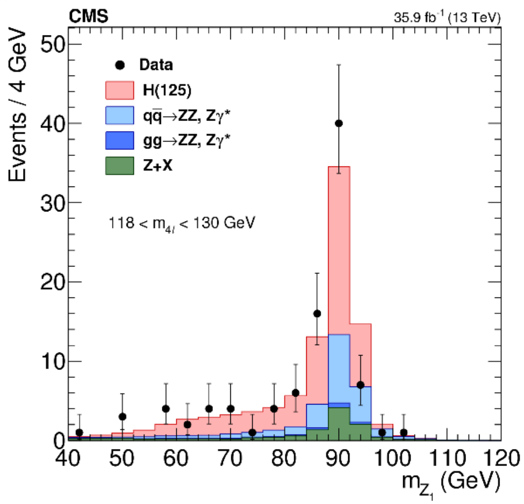
$\pm 6.6\%$

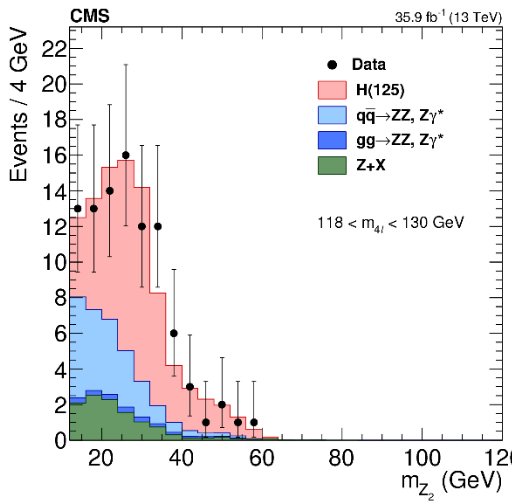
- **Compare to 4.6×10^{-6} (MCFM or MadGraph5_aMC@NLO)**

$H \to 4\ell$ Yield



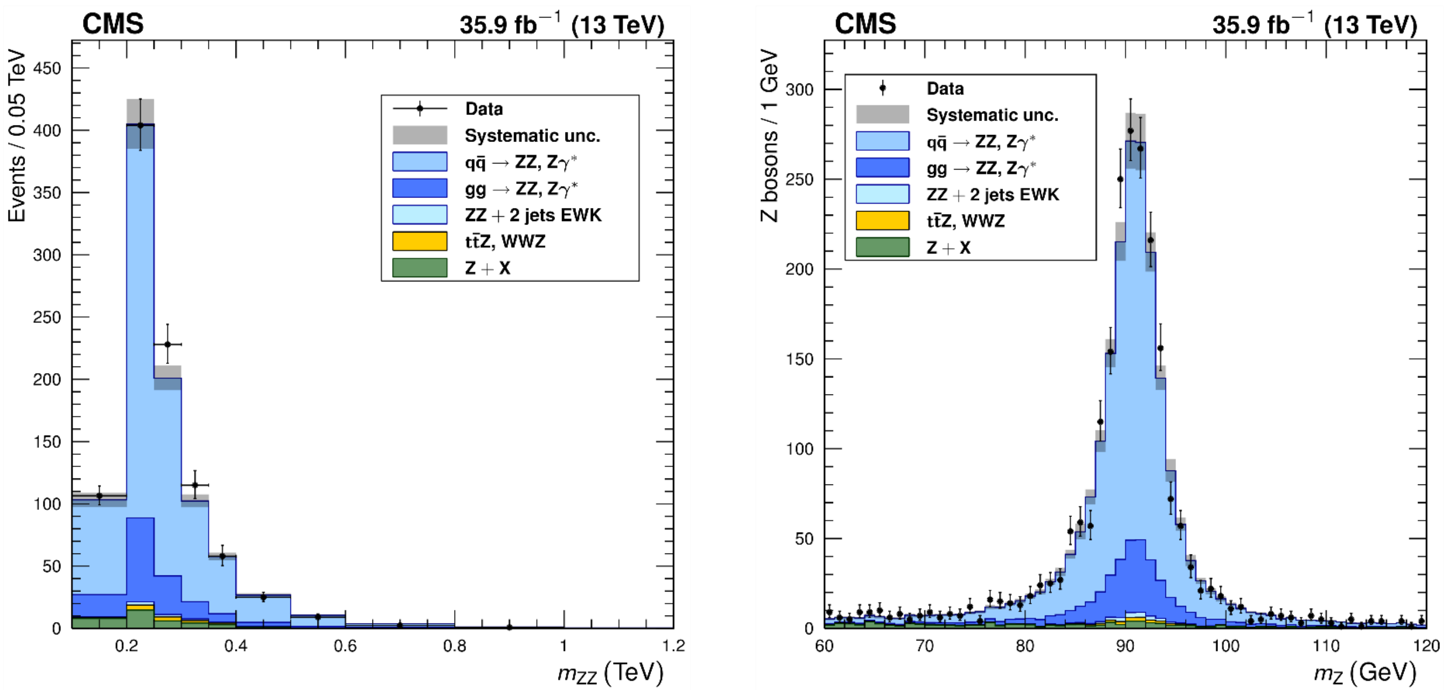
Final state	Expected N_{H}	SM continuum background	Z + X	Total expected	Observed
4μ	21.6 ± 1.9	$9.4^{+0.6}_{-0.7}$	$4.7^{+2.0}_{-1.8}$	35.8 ± 2.9	34
$2e2\mu$	26.5 ± 2.3	$11.0^{+0.7}_{-0.8}$	$6.9^{+3.1}_{-2.9}$	$44.4^{+3.7}_{-3.6}$	41
4e	10.2 ± 1.1	3.6 ± 0.3	$1.9^{+0.8}_{-1.0}$	15.8 ± 1.6	19
Total	58.3 ± 5.0	$24.1^{+1.5}_{-1.6}$	$13.5^{+3.7}_{-3.5}$	96.0 ± 6.7	94





$ZZ \rightarrow 4\ell$ Yield

Final state	Expected N_{ZZ}	Background	Total expected	Observed
4μ	$301 \pm 2 \pm 9$	$10 \pm 1 \pm 2$	$311 \pm 2 \pm 9$	335
$2e2\mu$	$503 \pm 2 \pm 19$	$31 \pm 2 \pm 4$	$534 \pm 3 \pm 20$	543
4e	$205 \pm 1 \pm 12$	$20 \pm 2 \pm 2$	$225 \pm 2 \pm 13$	220
Total	$1009 \pm 3 \pm 36$	$60 \pm 3 \pm 8$	$1070 \pm 4 \pm 37$	1098



$ZZ \rightarrow 4\ell$ Cross Section

- Signal strength

$$\mu = 1.040^{+0.033}_{-0.032}\,(\mathrm{stat})^{+0.037}_{-0.035}\,(\mathrm{syst}) \pm 0.026\,(\mathrm{lumi})$$

$$\sigma_{\mathrm{fid}}(\mathrm{pp} \rightarrow \mathrm{ZZ} \rightarrow 4\ell) = 40.9 \pm 1.3\,(\mathrm{stat}) \pm 1.4\,(\mathrm{syst}) \pm 1.0\,(\mathrm{lumi})\,\mathrm{fb}$$

- Total cross section requires only $60 < m_{Z_{1,2}} < 120$ GeV, $m_{\ell\ell} > 4$ GeV

$$\sigma(\mathrm{pp} \rightarrow \mathrm{ZZ}) = 17.5^{+0.6}_{-0.5}\,(\mathrm{stat}) \pm 0.6\,(\mathrm{syst}) \pm 0.4\,(\mathrm{theo}) \pm 0.4\,(\mathrm{lumi})\,\mathrm{pb}$$

- Measured on 2015 data (2.6 fb^{-1})

$$\sigma(\mathrm{pp} \rightarrow \mathrm{ZZ}) = 14.6^{+1.9}_{-1.8}\,(\mathrm{stat})^{+0.3}_{-0.5}\,(\mathrm{syst}) \pm 0.2\,(\mathrm{theo}) \pm 0.4\,(\mathrm{lumi})\,\mathrm{pb}$$

- Combining 2016 and 2017 data gives

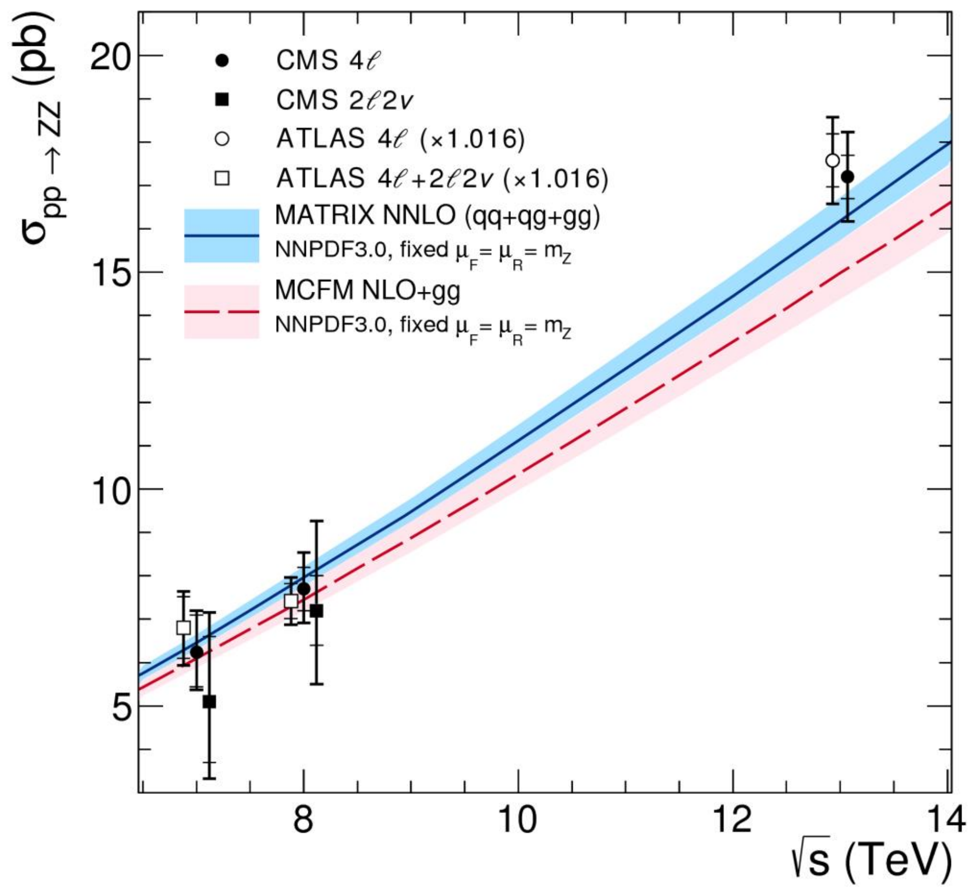
$$\sigma(\mathrm{pp} \rightarrow \mathrm{ZZ}) = 17.2 \pm 0.5\,(\mathrm{stat}) \pm 0.7\,(\mathrm{syst}) \pm 0.4\,(\mathrm{theo}) \pm 0.4\,(\mathrm{lumi})\,\mathrm{pb}$$

$\pm 6.0\%$

- Compare total cross section to $16.5^{+0.5}_{-0.7}$ pb (MATRIX NNLO, NNPDF3) or $15.4^{+0.5}_{-0.4}$ pb (MCFM NLO, MSTW2008)

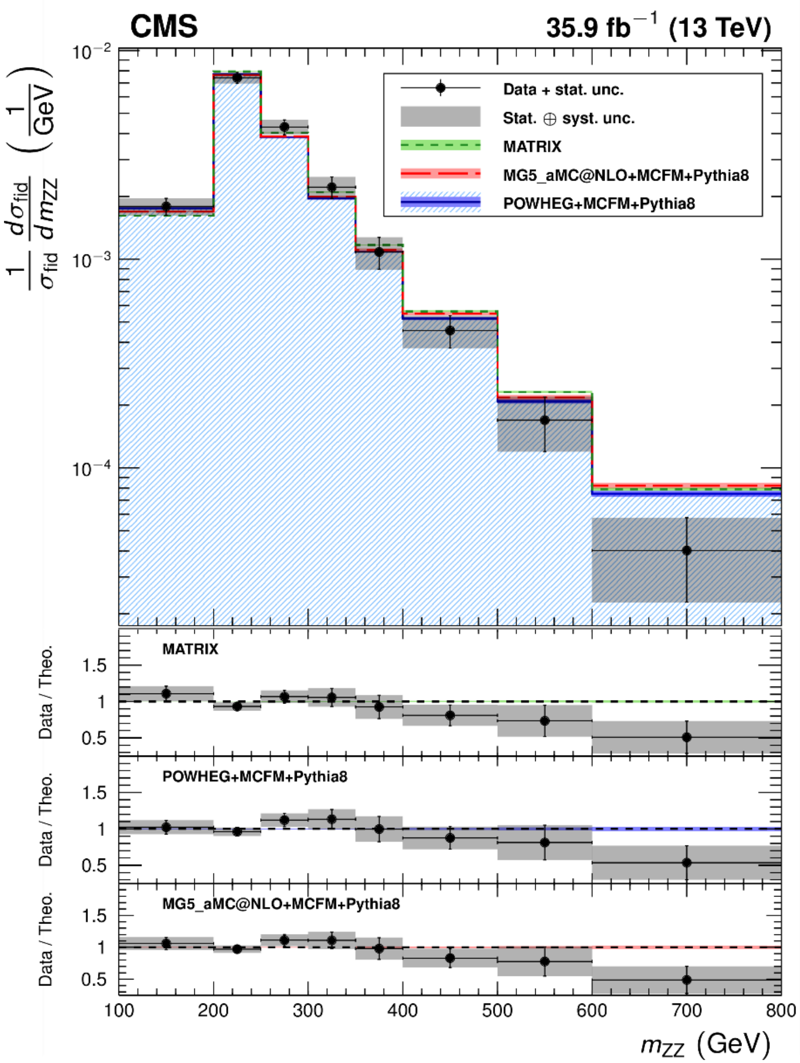
Total Cross Section Vs. $\sqrt{s}$

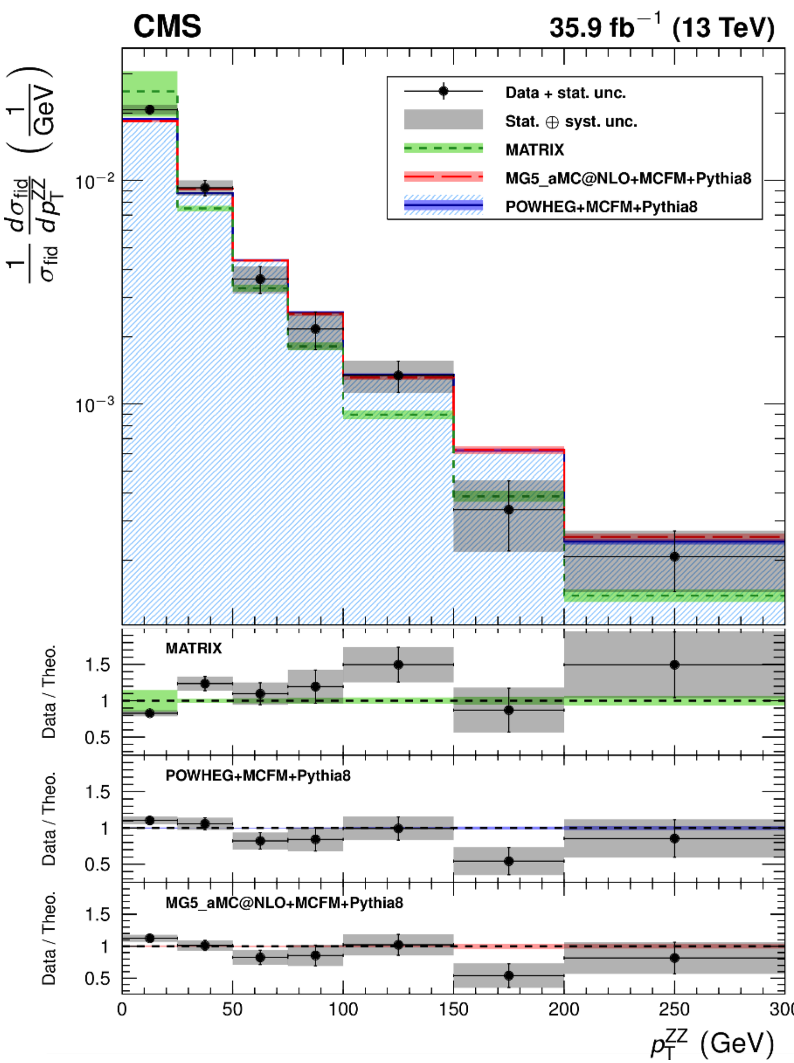
- Cross section very sensitive to NLO and NNLO corrections (outside scale uncertainties of lower orders)
- Comparisons here are to MCFM NLO+gg and MATRIX NNLO
  - Both: $\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = m_{\mathrm{Z}}$
- CMS and ATLAS measurements all agree with NNLO theory over large energy range



Differential Cross Sections

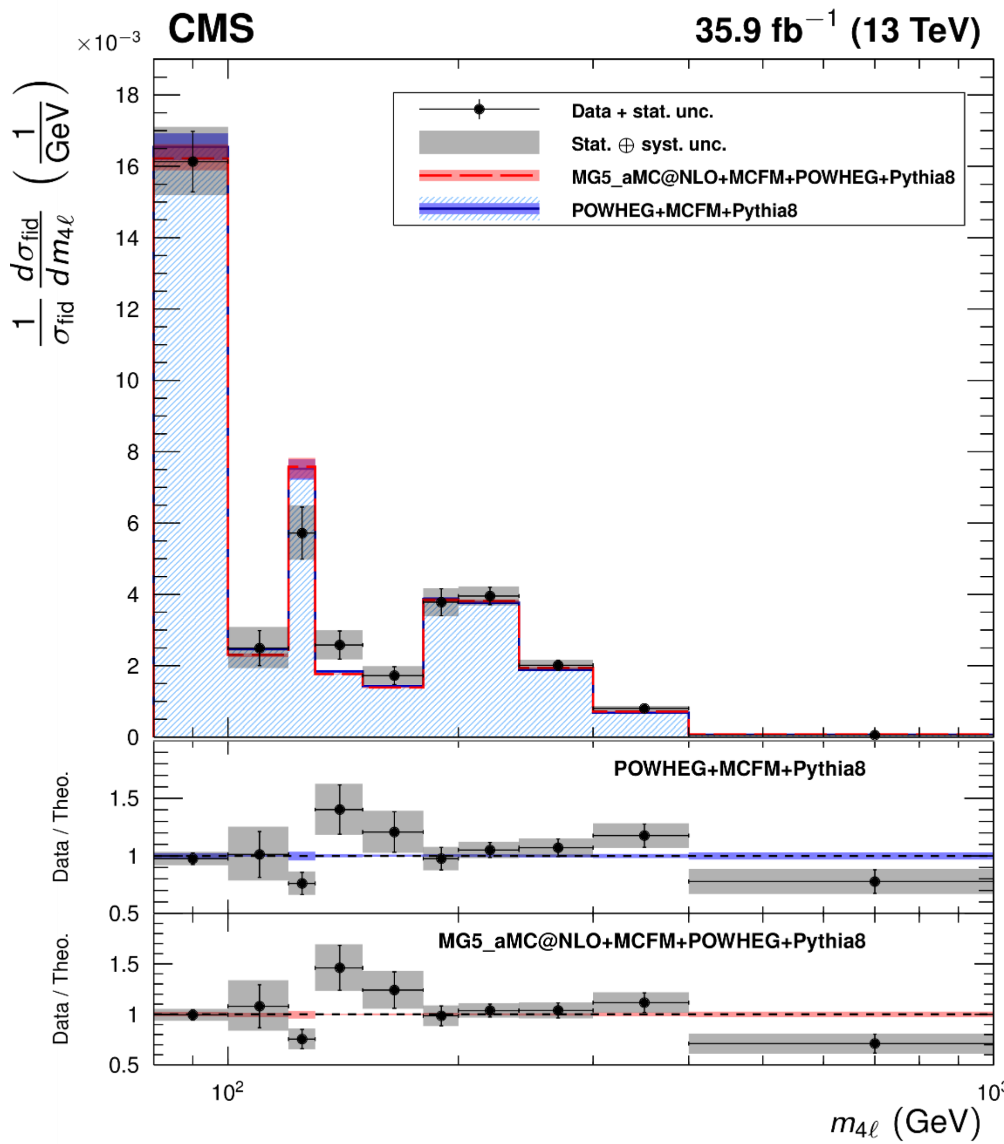
Measured Differential Cross Sections





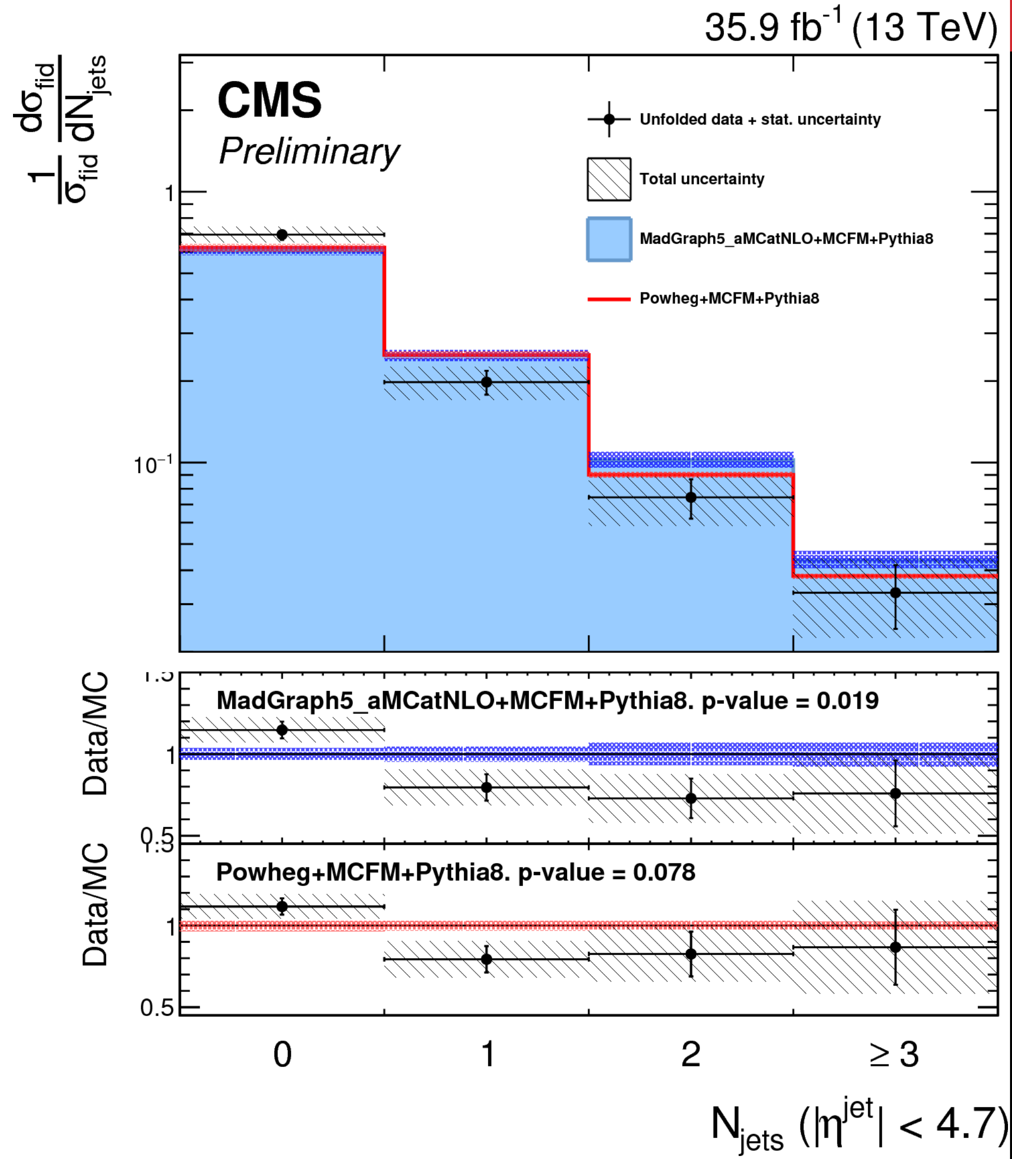
Measured Differential Cross Sections

- Expand to full spectrum selection to include $Z \rightarrow 4\ell$, Higgs resonance, full continuum



Measured Differential Cross Sections

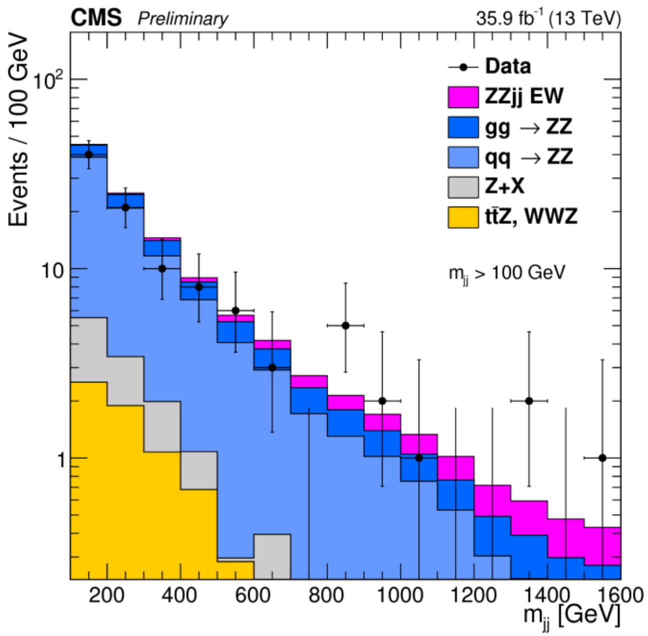
- Include jets with $p_T > 30$ GeV, $|\eta| < 4.7$

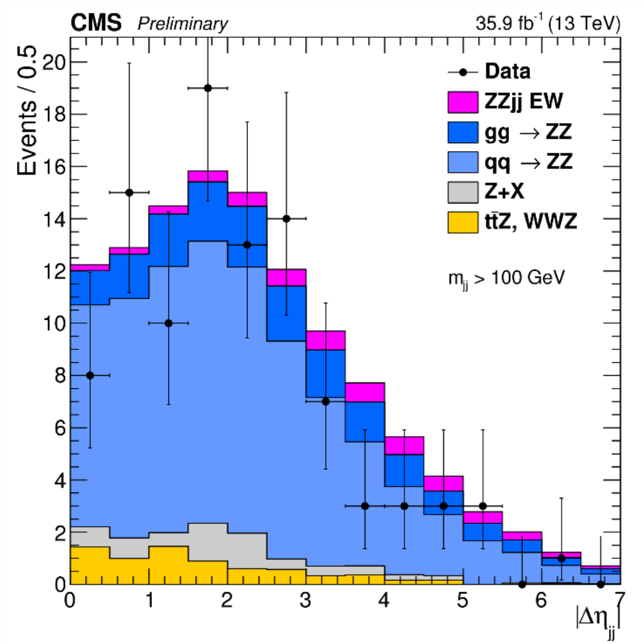


VBS and Anomalous Couplings

VBS Search

- **VBS signal is too small compared to QCD ZZ + 2jets for a cut-and-count analysis to be sensitive**
- **Instead, extract signal with BDT**
  - Observables considered include dijet and 4ℓ kinematics, hadronic activity levels, and whole-event topology
  - Poorly modeled observables (e.g. $p_T^{j_3}$) not used
  - Seven observables with highest discrimination power retained
- **Use whole ZZjj sample, extract signal and background yields with shape fits to BDT output**



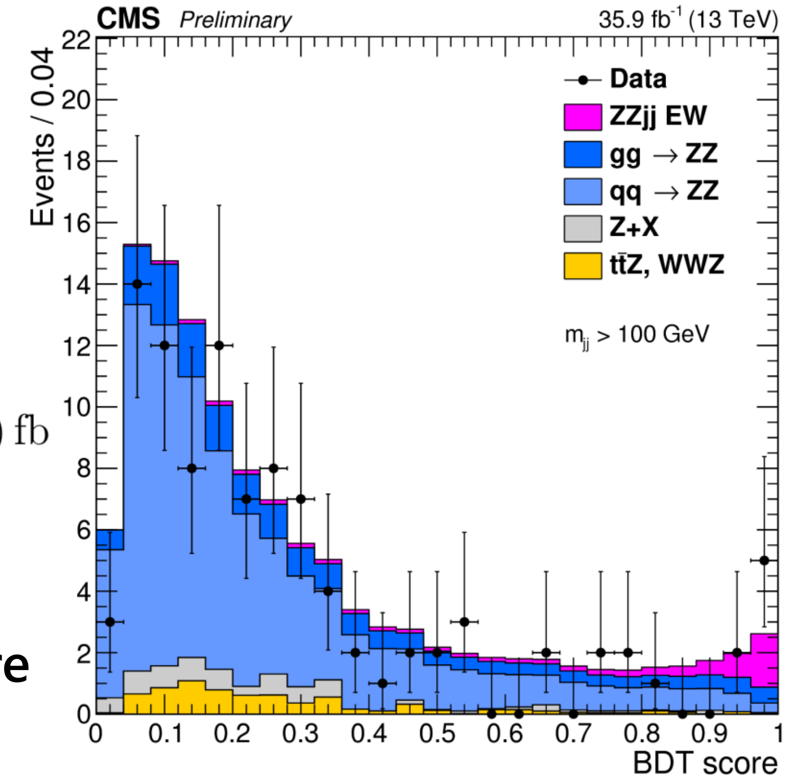


VBS Search Results

- **Excess of events consistent with VBS observed at the level of 2.7σ**
  - 1.6σ expected
- **Measured VBS fiducial cross section**

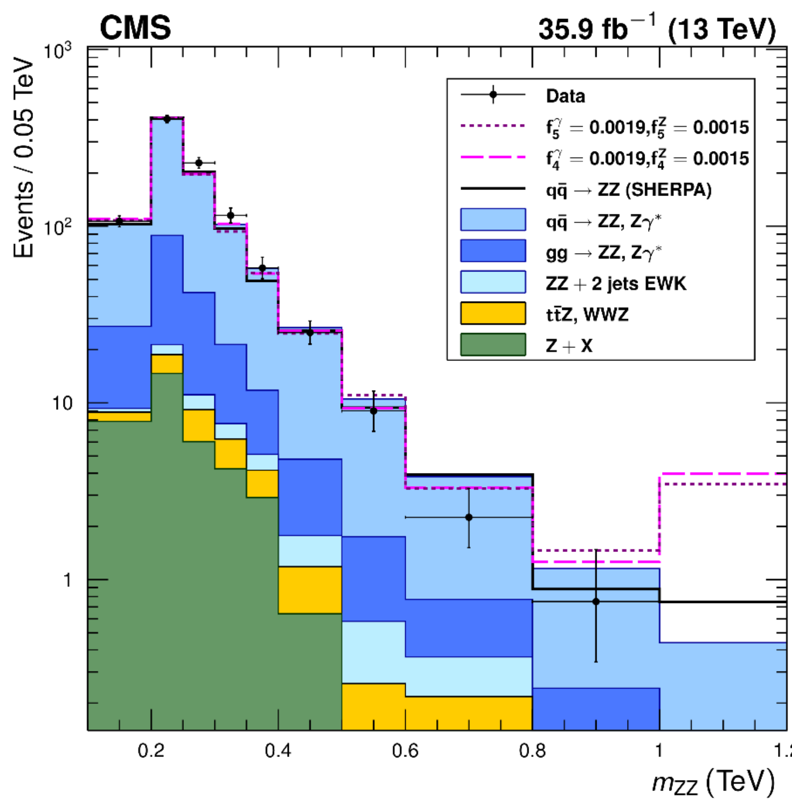
$$\sigma_{\text{fid}}(\text{pp} \to \text{ZZjj(EWK)} \to 4\ell\text{jj}) = 0.40^{+0.21}_{-0.16}\,(\text{stat})^{+0.13}_{-0.09}\,(\text{syst})\,\text{fb}$$

  - Consistent with SM prediction of $0.29^{+0.02}_{-0.03}$ fb
- **This is the first ZZ VBS search; there are no previous results to compare to**



aTGC Search

- Nonzero ZZZ and ZZγ couplings would increase ZZ cross section at high mass
- Strategy to obtain continuous limits: generate samples at several aTGC working points, fit yields in each $m_{4\ell}$ bin to a polynomial of 2nd order in both $f_{4(5)}^{\gamma}$ and $f_{4(5)}^{Z}$
- Set limits at 95% CL

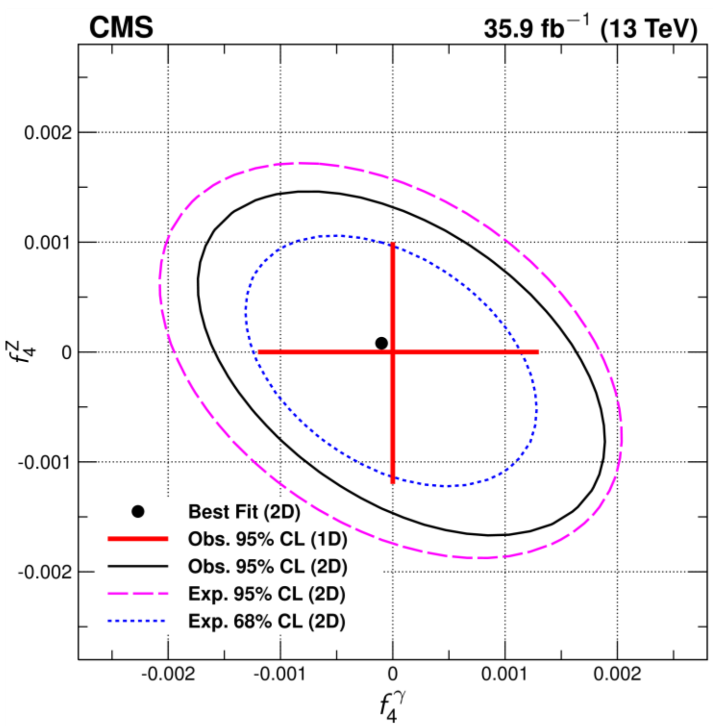


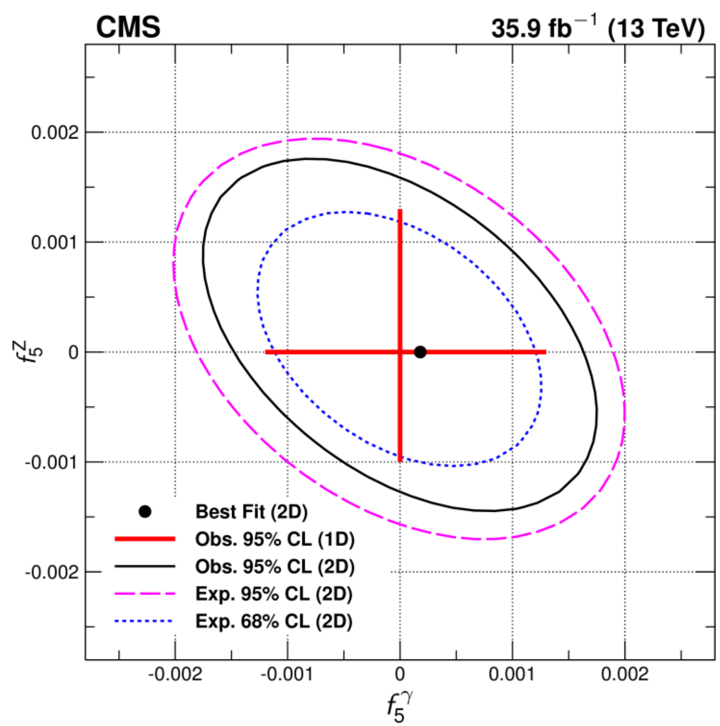
aTGC Limits

- ~2x better than previous best (also from CMS)

$$-0.0012 < f_4^Z < 0.0010, \quad -0.0010 < f_5^Z < 0.0013$$

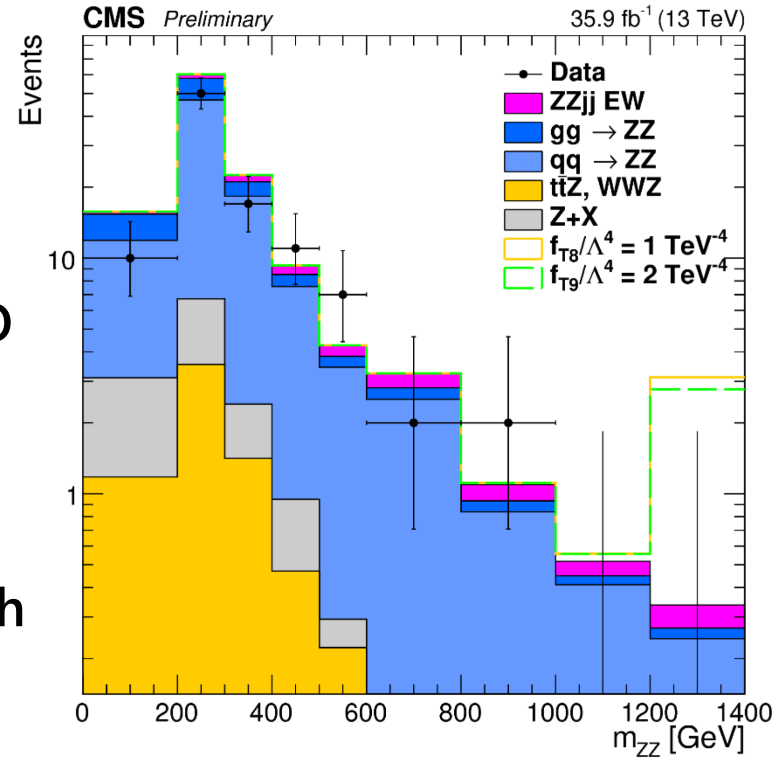
$$-0.0012 < f_4^\gamma < 0.0013, \quad -0.0012 < f_5^\gamma < 0.0013$$





aQGC Search

- Sensitivity in ZZjj phase space
- Signal samples at several working points obtained with matrix element reweighting of MadGraph5_aMC@NLO signal samples
- Unitarization: set cutoff scale Λ as the energy at which the observed 95% CL limit violates unitarity (determined with VBFNLO generator)
  - Report limits on f/Λ^4
- Yield parameterization and limit setting done with same methods as aTGCs
  - 1D only



aQGC Limits

- **Most sensitive limits on all parameters when published**

$-0.46 < f_{T0}/\Lambda^4 < 0.44 \ \mathrm{TeV}^{-4}$	**Previous: [-3.4, 2.9] (ATLAS Zγ)**
$-0.61 < f_{T1}/\Lambda^4 < 0.61 \ \mathrm{TeV}^{-4}$	**Previous: [-2.1, 2.4] (CMS $W^{\pm}W^{\pm}$)**
$-1.2 < f_{T2}/\Lambda^4 < 1.2 \ \mathrm{TeV}^{-4}$	**Previous: [-5.9, 7.1] (CMS $W^{\pm}W^{\pm}$)**
$-0.84 < f_{T8}/\Lambda^4 < 0.84 \ \mathrm{TeV}^{-4}$	**Previous: [-1.8, 1.8] (CMS/ATLAS Zγ)**
$-1.8 < f_{T9}/\Lambda^4 < 1.8 \ \mathrm{TeV}^{-4}$	**Previous: [-3.9, 3.9] (ATLAS Zγ)**

- **First limits set with ZZ search**
- **Limits on f_{T0}, f_{T1}, and f_{T2} have been superseded by tighter limits set by CMS $W^{\pm}W^{\pm}$ analysis**

Summary and Outlook

Summary

- **Several studies of four-lepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV have been performed on data collected by the CMS experiment at the LHC**
  - Inclusive and differential ZZ cross section measurements
  - Measurement of the Z $\rightarrow 4\ell$ branching fraction
  - A search for ZZ vector boson scattering
  - Searches for anomalous triple and quartic gauge couplings
- **All results are consistent with the standard model**
  - Excess consistent with VBS at 2.7σ level
  - World best limits on many anomalous couplings parameters

Outlook

- **LHC may run at 14 TeV soon, but no further energy increases are expected in the near future**
  - Progress must come from more precise measurements of quantities we have access to now
- **Rough estimate: as much data in 2017 as 2016, as much in 2018 as 2016+2017**
- **Inclusive cross section uncertainties will improve only marginally; they will be systematics dominated after 2017**
- **Most bins in differential cross sections are statistically dominated and should improve by ~2x after 2018**
- **VBS and aGC searches driven by low-occupancy tails, should improve by more than 2x**

Backup

Anomalous Quartic Gauge Coupling Details

- **Treat SM as a low-energy effective theory and add terms with new dimension-8 operators to represent new physics**
  - Lowest dimension that gives aQGC without aTGC
- **Parameterize search in coefficients of these new terms**
- **Non-unitary without model-dependent form factor or cutoff**

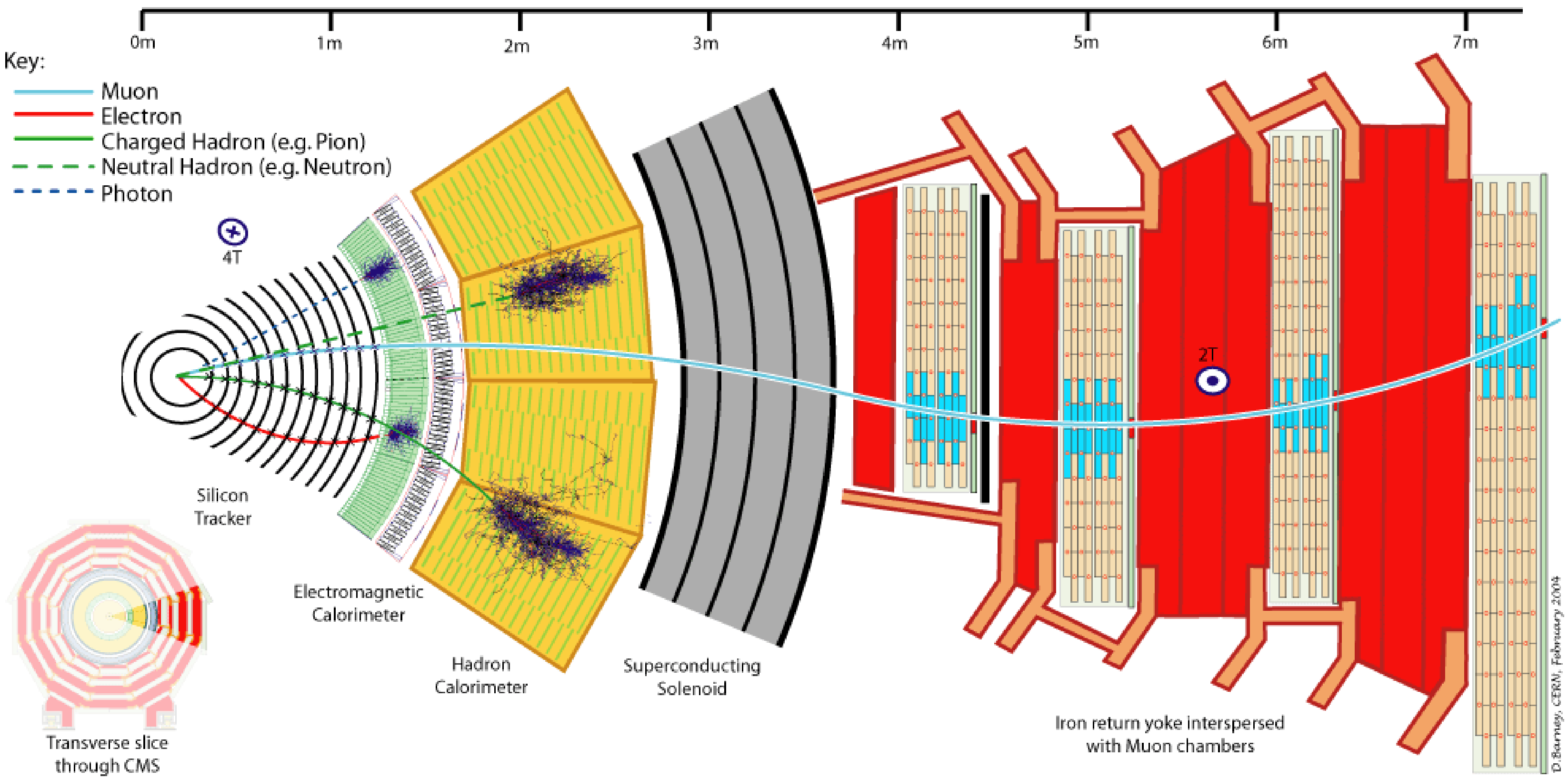
		Couplings modified								
	Terms	WWWW	WWZZ	ZZZZ	WWZγ	WWγγ	ZZZγ	ZZγγ	Zγγγ	γγγγ
Longitudinal + transverse	$f_{M0}, f_{M1}, f_{M6}, f_{M7}$	✓	✓	✓	✓	✓	✓	✓		
	$f_{M2}, f_{M3}, f_{M4}, f_{M5}$		✓	✓	✓	✓	✓	✓		
Transverse	f_{T0}, f_{T1}, f_{T2}	✓	✓	✓	✓	✓	✓	✓	✓	✓
	f_{T5}, f_{T6}, f_{T7}		✓	✓	✓	✓	✓	✓	✓	✓
	f_{T8}, f_{T9}			✓			✓	✓	✓	✓

Table modified from here

All Trigger Paths

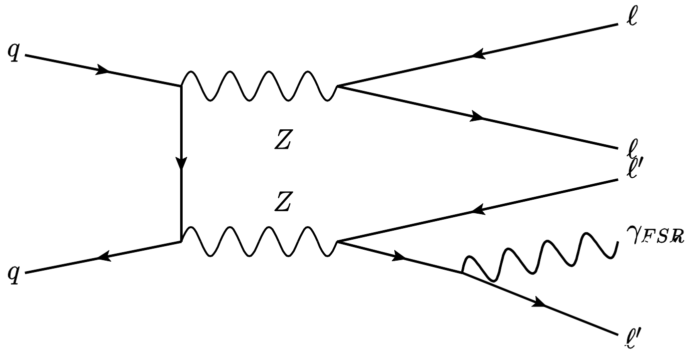
Muon triggers
HLT_IsoMu20_v⋆
HLT_IsoTkMu20_v⋆
HLT_IsoMu22_v⋆
HLT_IsoTkMu22_v⋆
HLT_IsoMu24_v⋆ †‡
HLT_IsoTkMu24_v⋆ †‡
HLT_Mu50_v⋆
HLT_Mu45_eta2p1_v⋆
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v⋆
HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v⋆
HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_DZ_v⋆
HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_DZ_v⋆
HLT_TripleMu_12_10_5_v⋆
Electron triggers
HLT_Ele25_eta2p1_WPTight_Gsf_v⋆
HLT_Ele27_WPTight_Gsf_v⋆
HLT_Ele27_eta2p1_WPLoose_Gsf_v⋆
HLT_Ele32_eta2p1_WPTight_Gsf_v⋆ †‡
HLT_Ele17_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v⋆
HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v⋆
HLT_DoubleEle33_CaloIdL_GsfTrkIdVL_v⋆ * †
HLT_DoubleEle33_CaloIdL_GsfTrkIdVL_MW_v⋆ ‡
HLT_DoubleEle33_CaloIdL_MW_v⋆ ‡
HLT_Ele16_Ele12_Ele8_CaloIdL_TrackIdL_v⋆
Cross triggers
HLT_Mu8_TrkIsoVVL_Ele17_CaloIdL_TrackIdL_IsoVL_v⋆ * †
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v⋆ * †
HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_DZ_v⋆ †‡
HLT_Mu17_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v⋆ * †
HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v⋆ * †
HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v⋆ †‡
HLT_DiMu9_Ele9_CaloIdL_TrackIdL_v⋆
HLT_Mu8_DiEle12_CaloIdL_TrackIdL_v⋆
Integrated luminosity
35.9 fb^{-1}
* 2016B–F †2016G ‡2016H

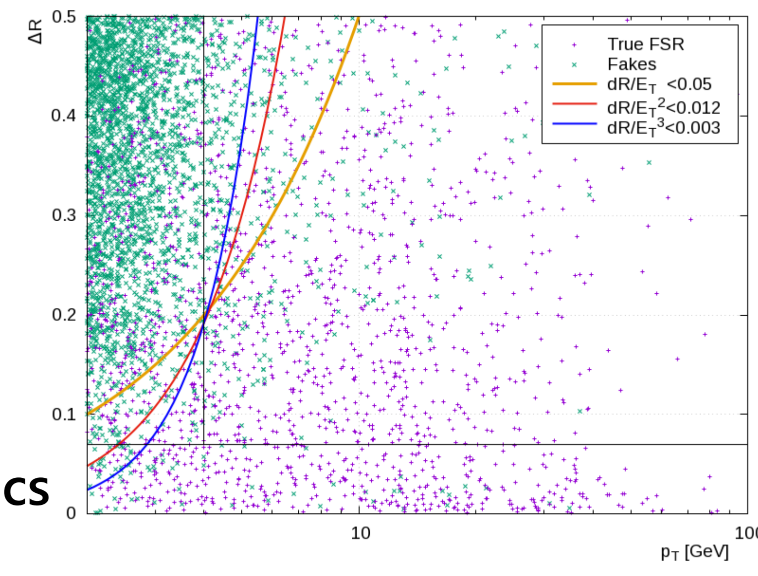
Particle Detection in CMS



Final State Radiation Recovery

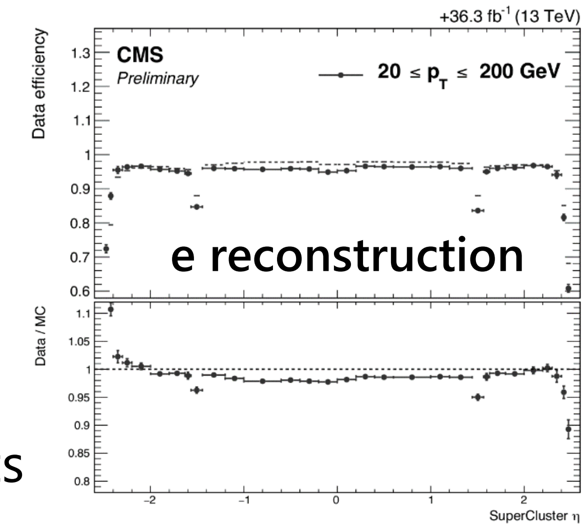
- **Leptons may radiate photons, leading to mismeasurement of isolation and Z mass**
  - FSR photons harder, closer than π^0 etc.
- **We associate a photon with the nearest lepton if**
  - $E_{\mathrm{T}}^{\gamma} > 2$ GeV, $|\eta_{\gamma}| < 2.4$
  - $R_{\mathrm{Iso}}^{\gamma} < 1.8$ (no PU correction)
  - $\Delta R(\ell, \gamma) < 0.5$
  - $\frac{\Delta R}{E_{\mathrm{T}}^{\gamma}} < 0.012$
- **Include accepted photon in 4ℓ kinematics**
- **Exclude them from lepton isolation calculations**

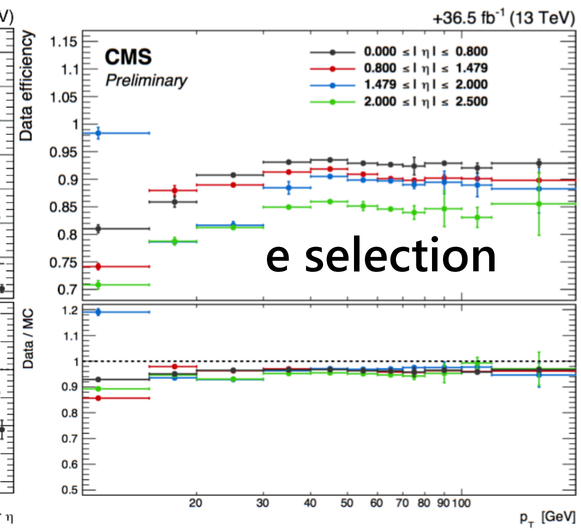


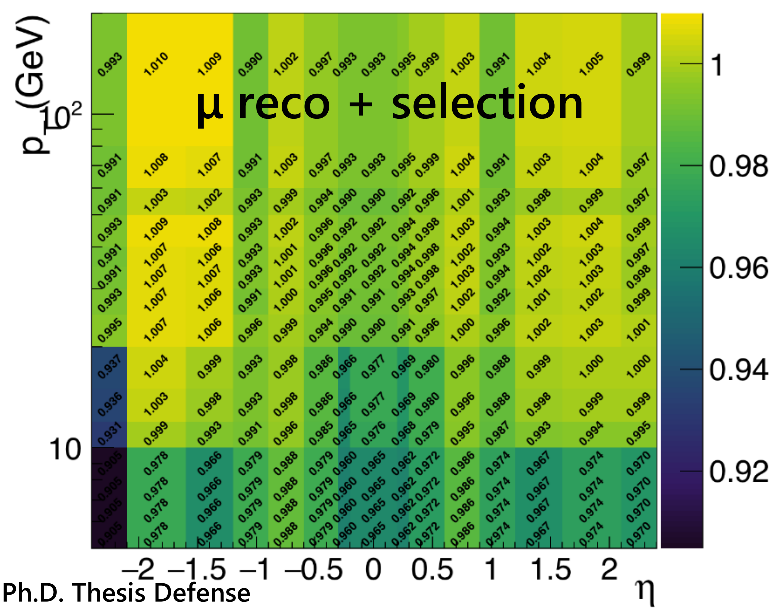


Tag and Probe Scale Factors

- **To improve data-MC agreement, efficiency scale factors are found with a tag-and-probe method**
  - Use Z mass constraints to identify leptons
  - Check what fraction pass each cut in data and MC
  - Shape fits to find nonprompt contamination
- **Scale factors calculated and applied to Monte Carlo in bins of p_T^ℓ and η_ℓ**

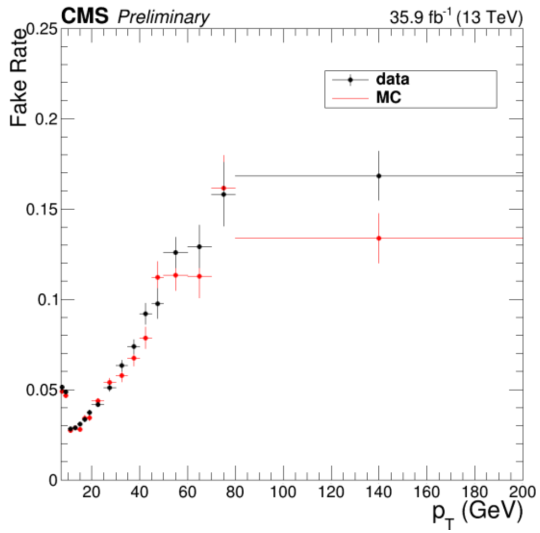




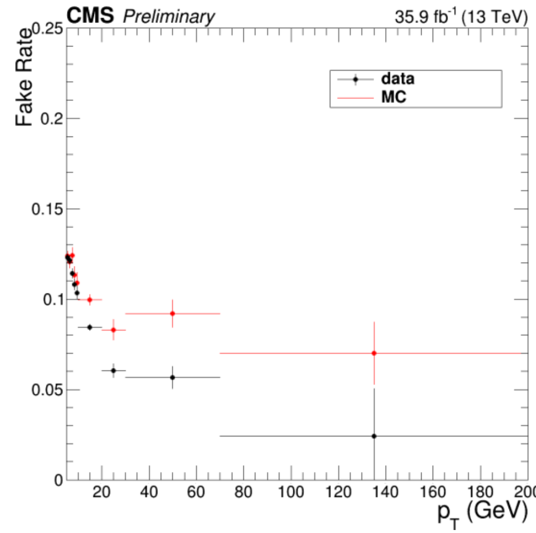


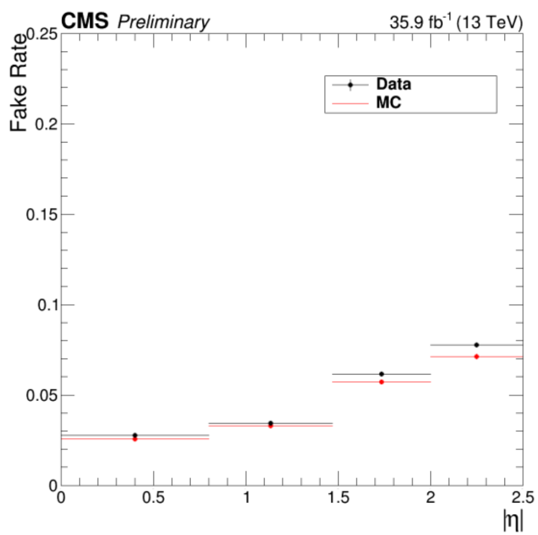
Fake Rates

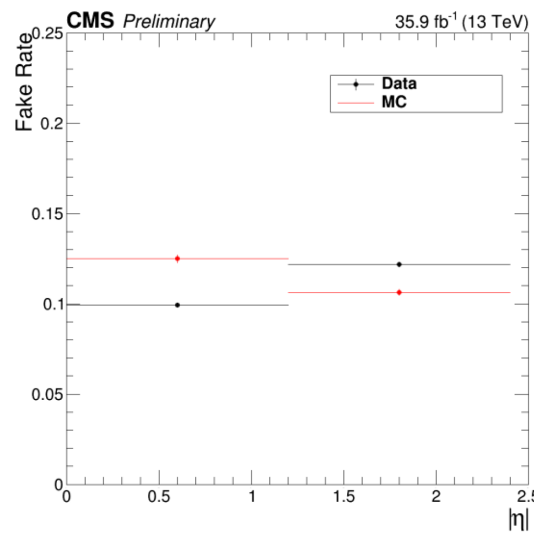
Electrons



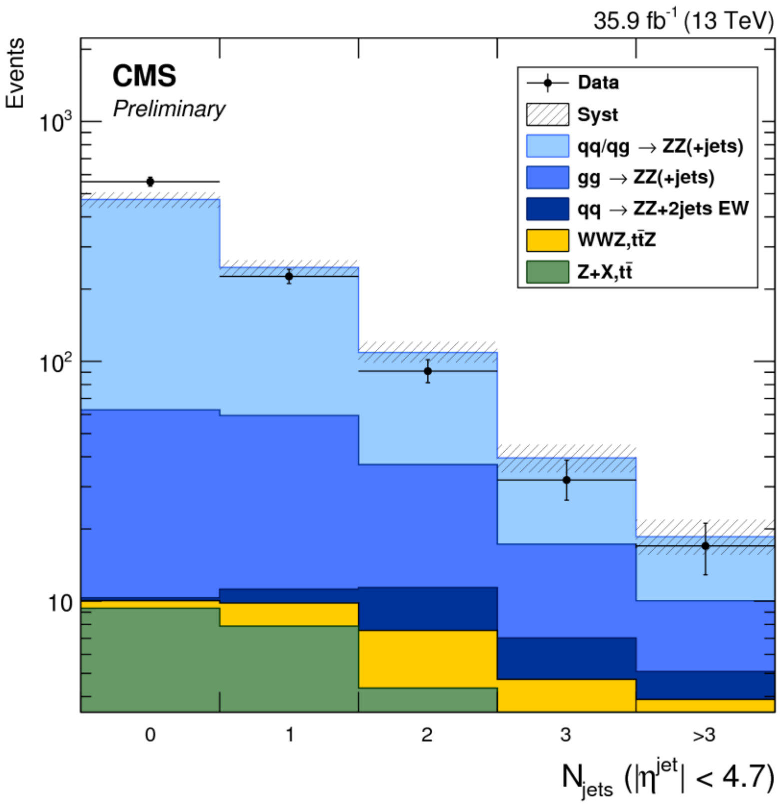
Muons

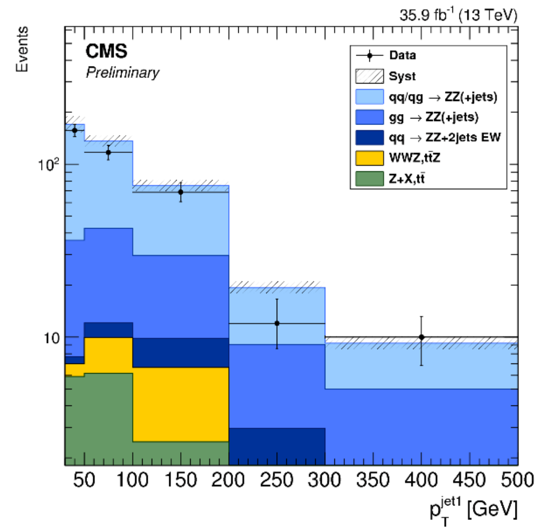


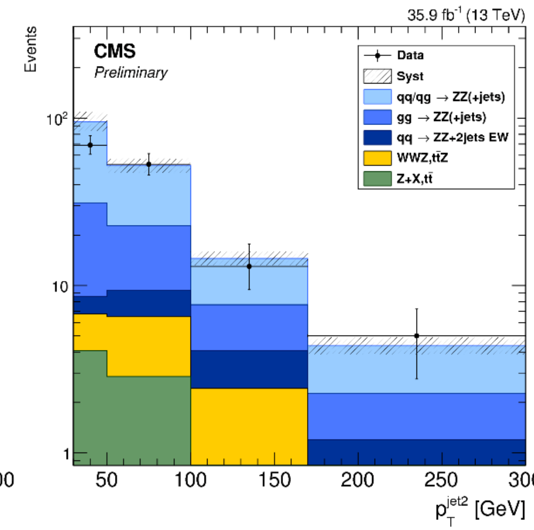


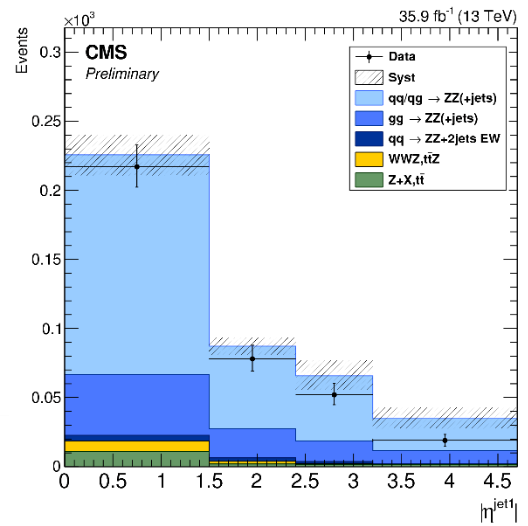


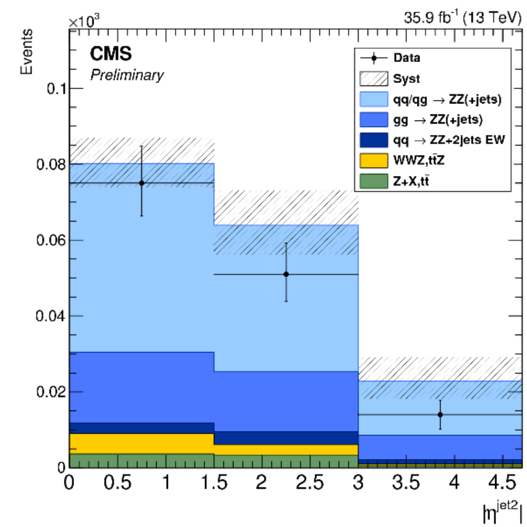
ZZ + Jets


35.9 fb^{-1} (13 TeV)
CMS
Preliminary
Events
Data
Syst
qq/qg → ZZ(+jets)
gg → ZZ(+jets)
qq → ZZ+2jets EW
WWZ,tt̄Z
Z+X,tt̄
0
1
2
3
>3
N_{jets} ($|\eta^{jet}|$ < 4.7)


35.9 fb^{-1} (13 TeV)
CMS
Preliminary
Events
Data
Syst
qq/qg → ZZ(+jets)
gg → ZZ(+jets)
qq → ZZ+2jets EW
WWZ,tt̄Z
Z+X,tt̄
p_T^{jet1} [GeV]


35.9 fb^{-1} (13 TeV)
CMS
Preliminary
Events
Data
Syst
qq/qg → ZZ(+jets)
gg → ZZ(+jets)
qq → ZZ+2jets EW
WWZ,tt̄Z
Z+X,tt̄
p_T^{jet2} [GeV]

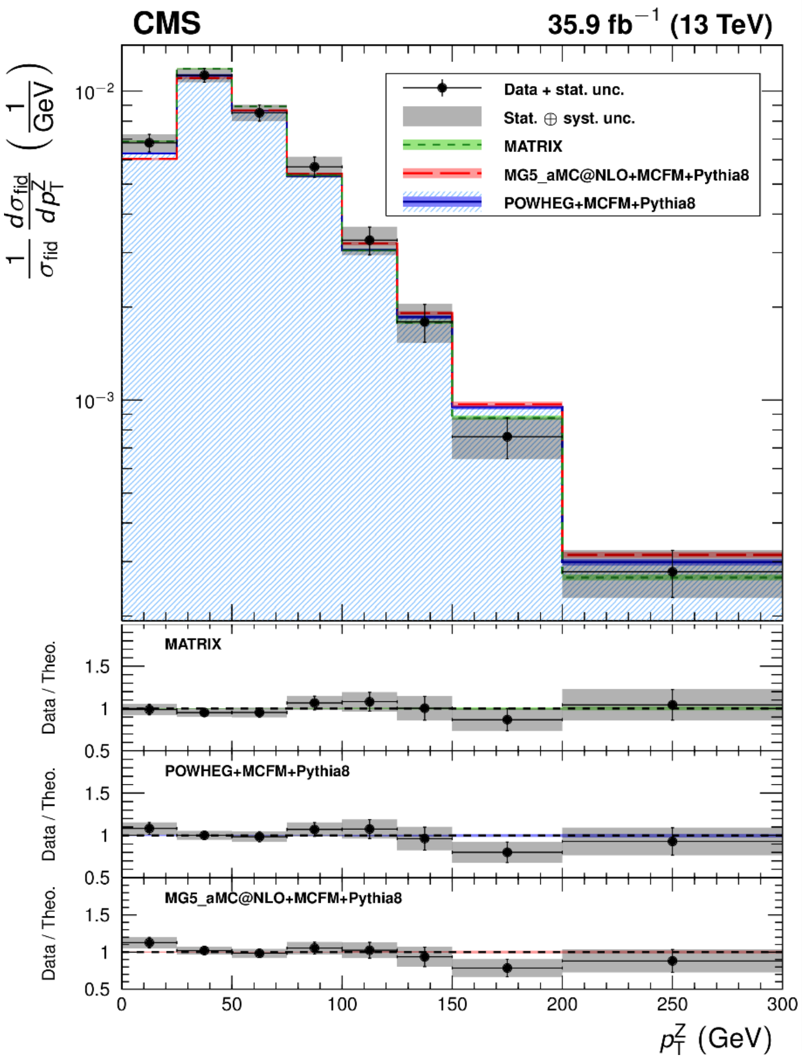

35.9 fb^{-1} (13 TeV)
CMS
Preliminary
Events
×10^3
Data
Syst
qq/qg → ZZ(+jets)
gg → ZZ(+jets)
qq → ZZ+2jets EW
WWZ,tt̄Z
Z+X,tt̄
$|\eta^{jet1}|$

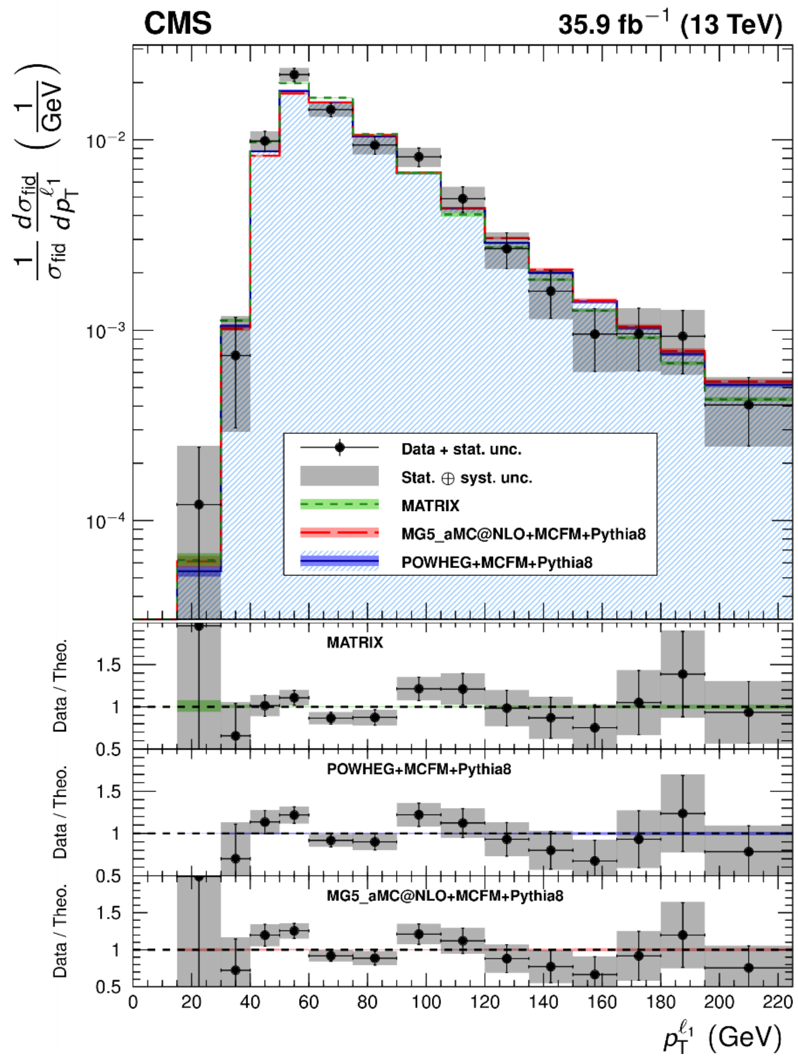

35.9 fb^{-1} (13 TeV)
CMS
Preliminary
Events
×10^3
Data
Syst
qq/qg → ZZ(+jets)
gg → ZZ(+jets)
qq → ZZ+2jets EW
WWZ,tt̄Z
Z+X,tt̄
$|\eta^{jet2}|$

Unfolding

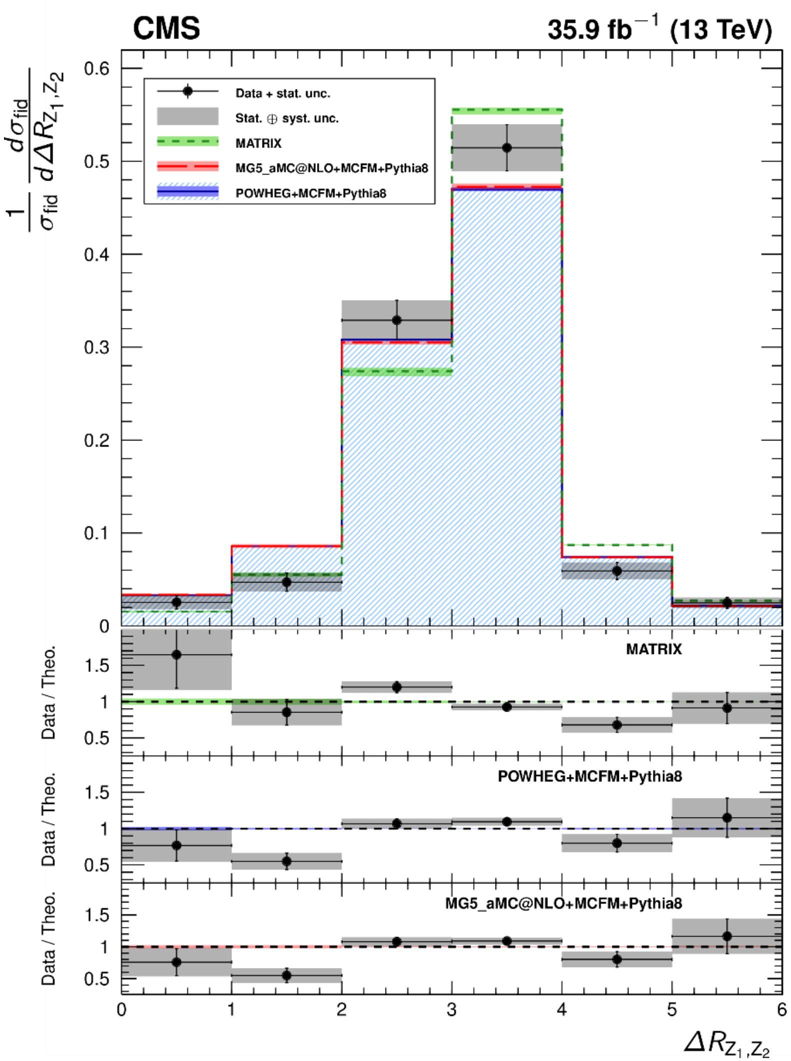
- We want to compare our results to theory at generator level, and obtain differential cross sections
- Our acceptance and efficiency aren't 100%, and experimental effects smear observables
- Solving the "unfolding"/deconvolution problem of working backwards to the true underlying distribution is difficult and often ill-posed even when the smearing function is known
- D'Agostini (et al) method: iteratively undo the expected (by Bayes' theorem) smearing into each bin, weighted by the observed data in the bin, starting from a flat prior or MC prediction
- Regularization: prevent overfitting by stopping after n iterations (we use 4)

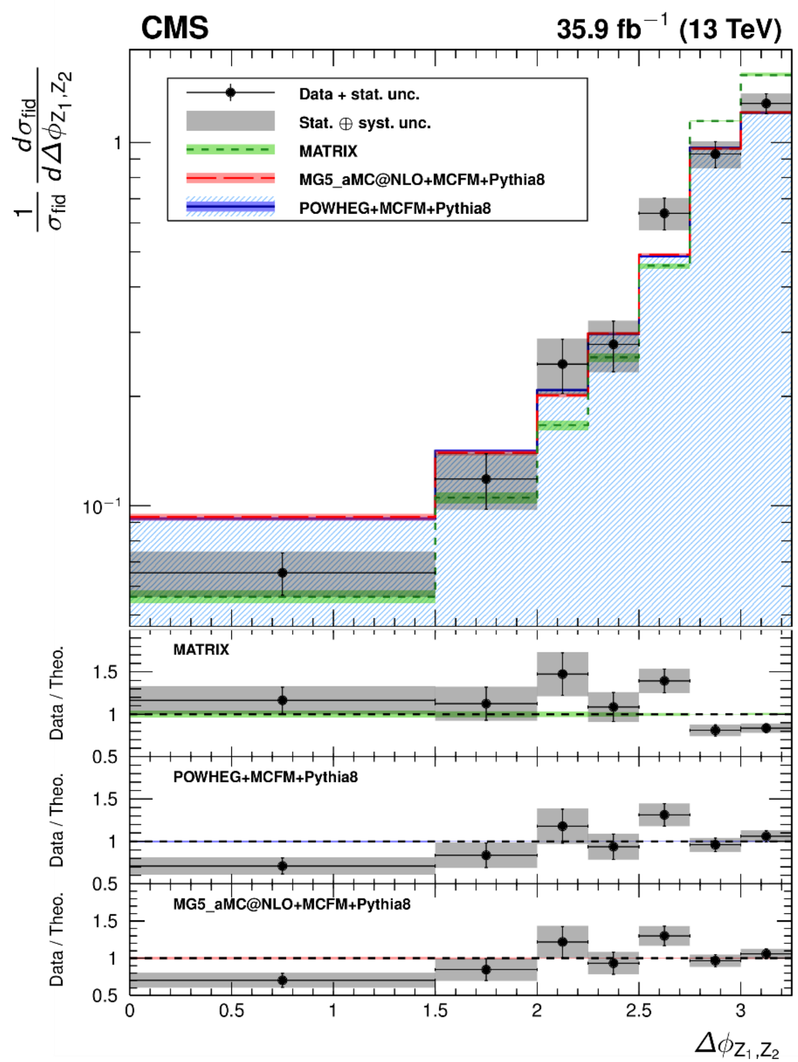
Measured Differential Cross Sections



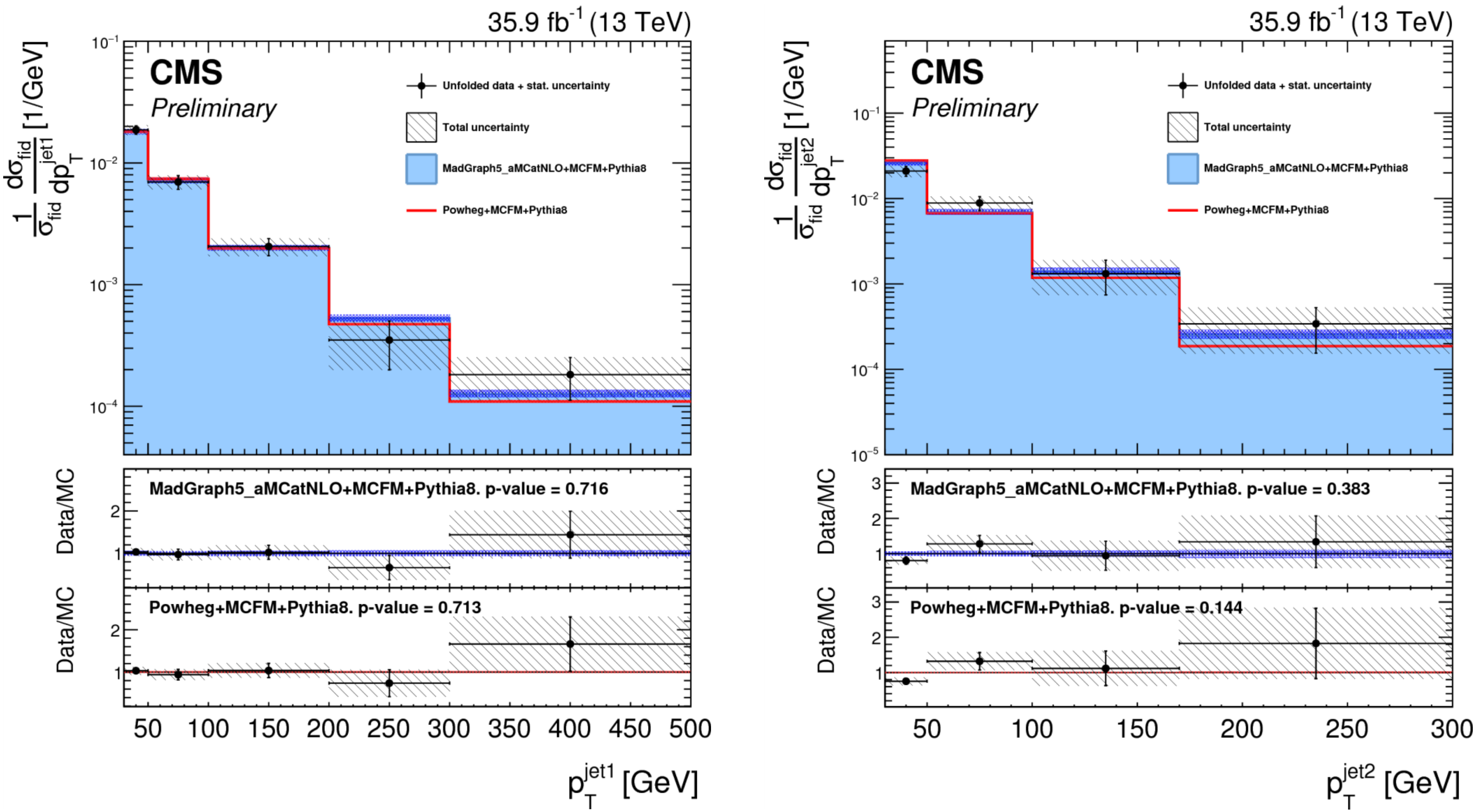


Measured Differential Cross Sections

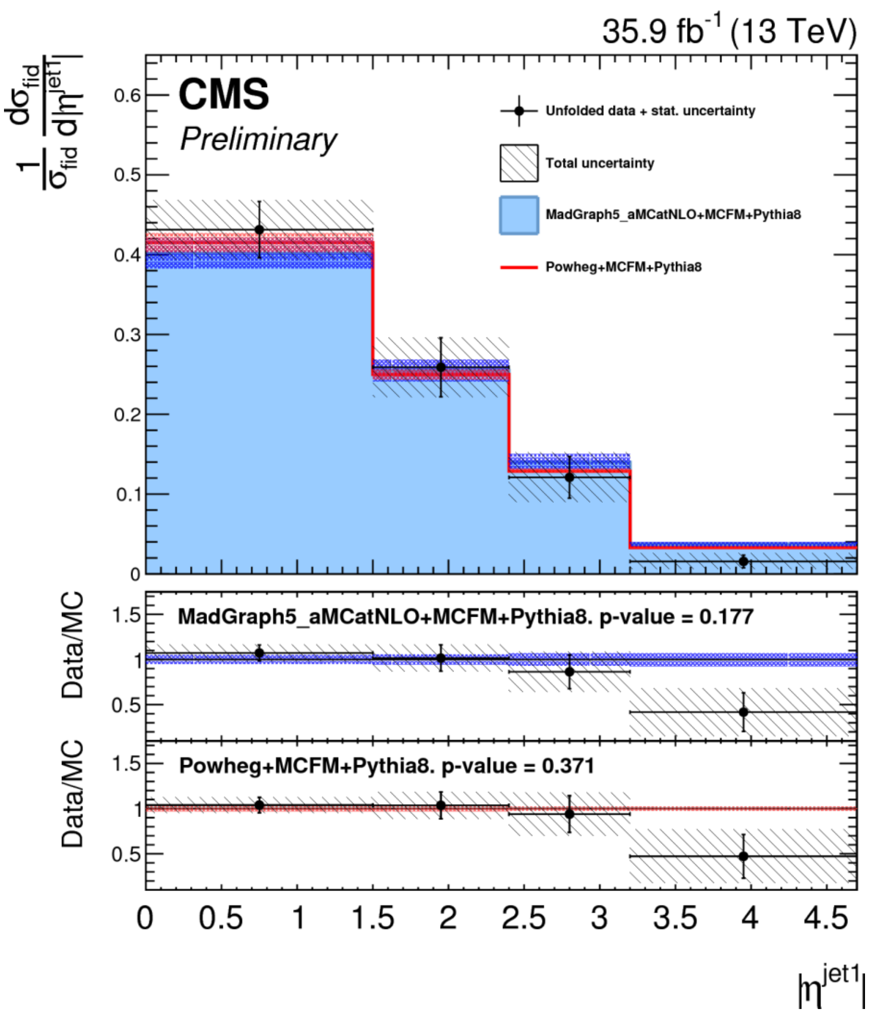


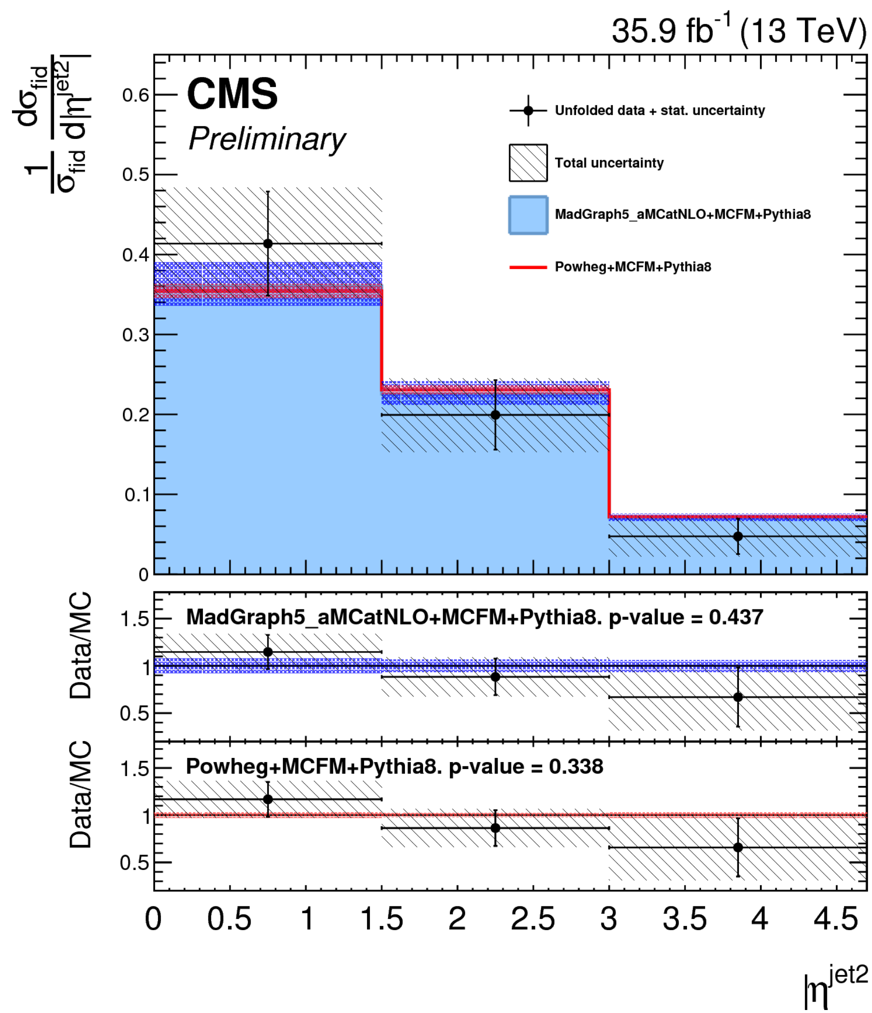


Measured Differential Cross Sections

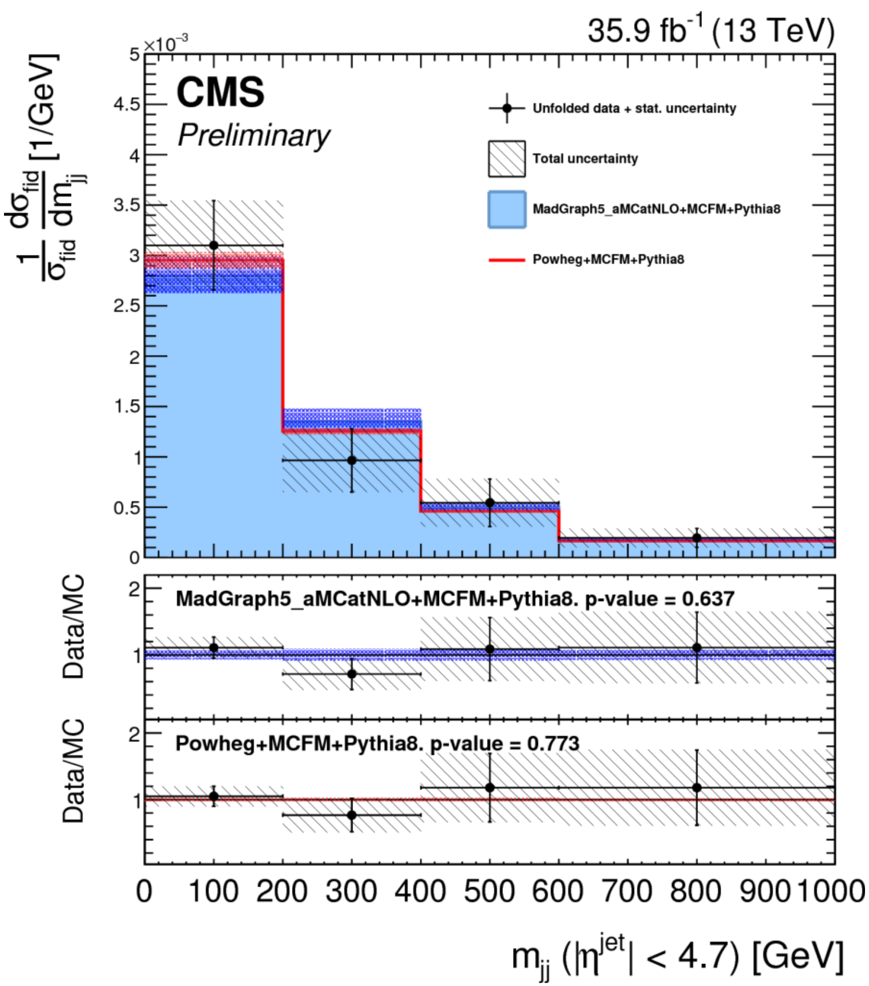


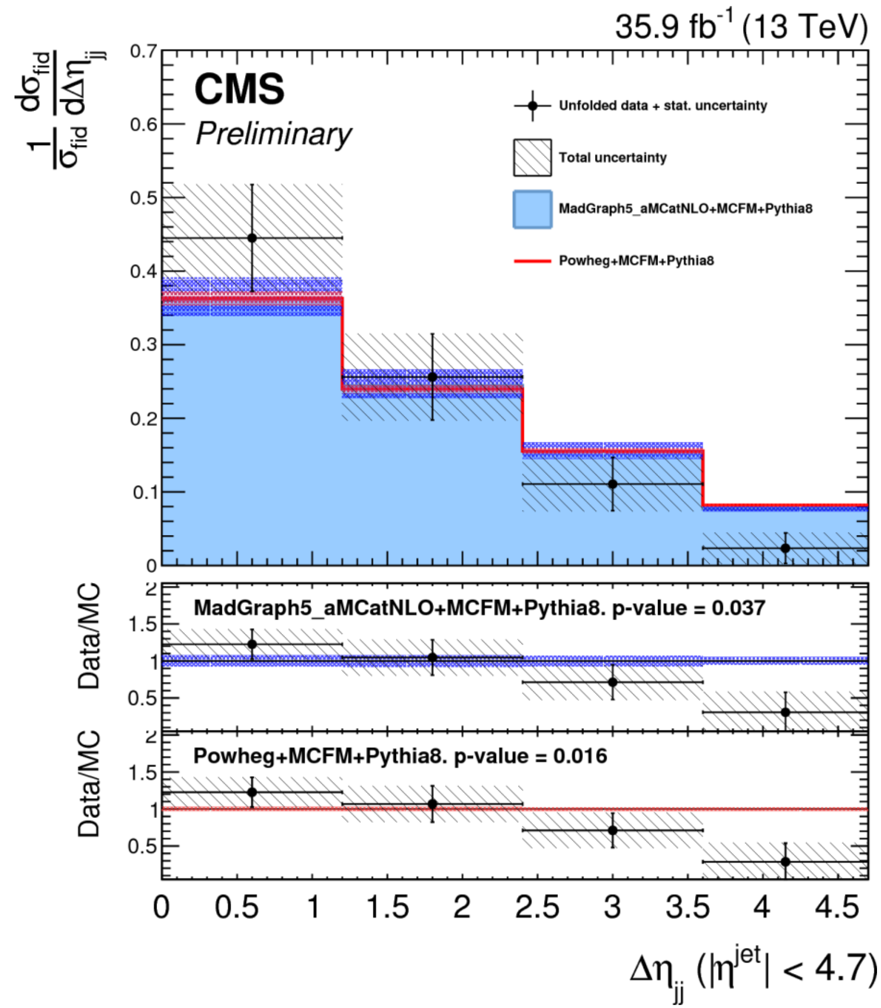
Measured Differential Cross Sections



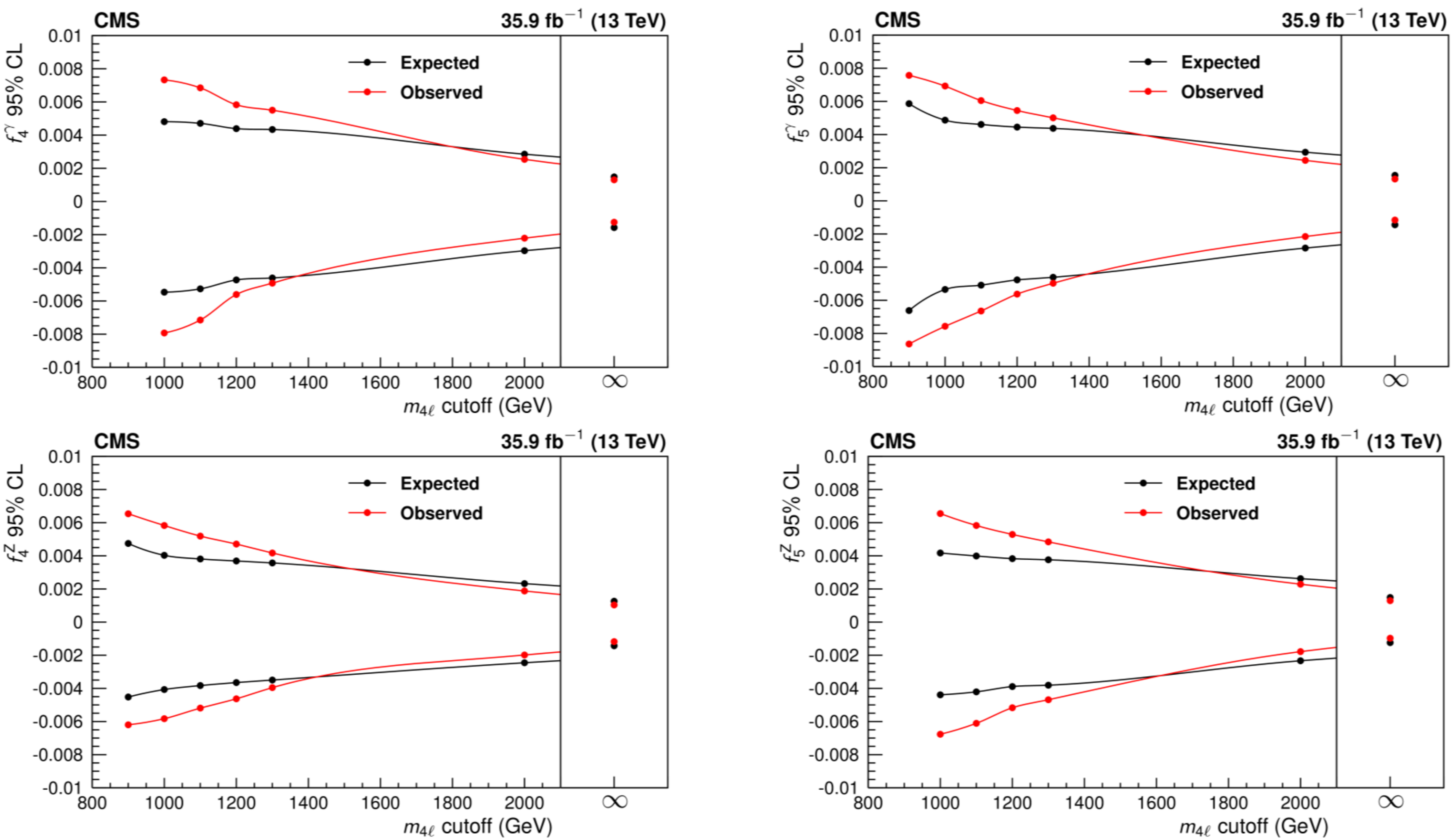


Measured Differential Cross Sections

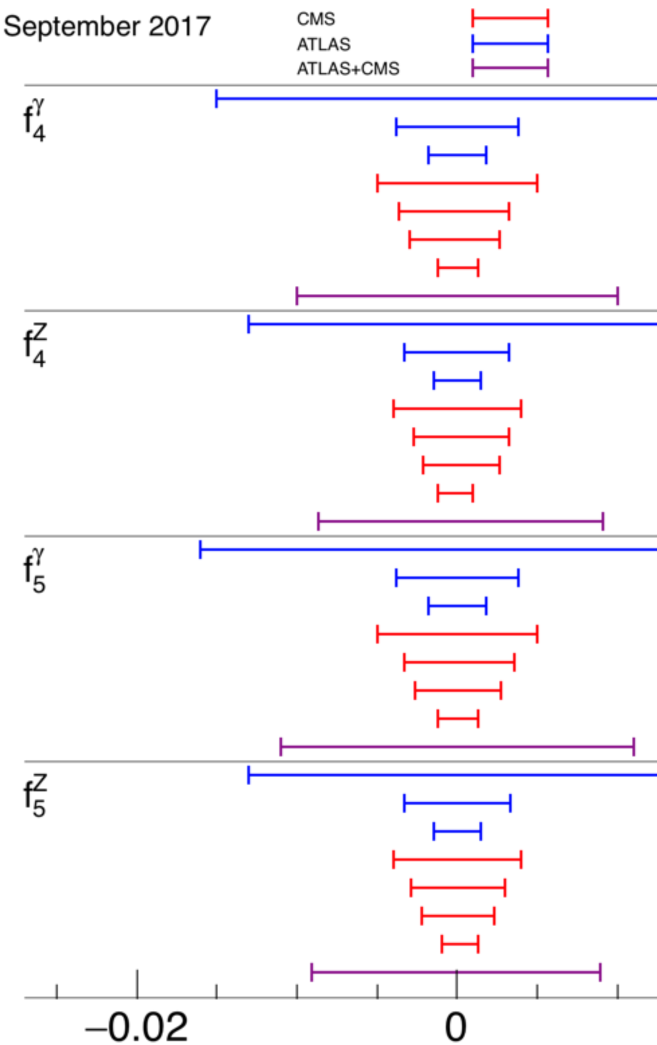




aTGC Limits as a Function of $m_{4\ell}$ Cutoff



All Neutral aTGC Limits



	Channel	Limits	$\int L dt$	$\sqrt{s}$
f_4^γ	ZZ (4l,2l2ν)	[-1.5e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.8e-03, 3.8e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.8e-03, 1.8e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-3.6e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-3.0e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.2e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-1.0e-02, 1.0e-02]	9.6 fb^{-1}	7 TeV
f_4^Z	ZZ (4l,2l2ν)	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.3e-03, 3.2e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.5e-03, 1.5e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-2.7e-03, 3.2e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-2.1e-03, 2.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.2e-03, 1.0e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-8.7e-03, 9.1e-03]	9.6 fb^{-1}	7 TeV
f_5^γ	ZZ (4l,2l2ν)	[-1.6e-02, 1.5e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.8e-03, 3.8e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.8e-03, 1.8e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-5.0e-03, 5.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ(2l2ν)	[-3.3e-03, 3.6e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ(4l,2l2ν)	[-2.6e-03, 2.7e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.2e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-1.1e-02, 1.1e-02]	9.6 fb^{-1}	7 TeV
f_5^Z	ZZ (4l,2l2ν)	[-1.3e-02, 1.3e-02]	4.6 fb^{-1}	7 TeV
	ZZ (4l,2l2ν)	[-3.3e-03, 3.3e-03]	20.3 fb^{-1}	8 TeV
	ZZ (4l)	[-1.5e-03, 1.5e-03]	36.1 fb^{-1}	13 TeV
	ZZ (4l)	[-4.0e-03, 4.0e-03]	19.6 fb^{-1}	8 TeV
	ZZ (2l2ν)	[-2.9e-03, 3.0e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l,2l2ν)	[-2.2e-03, 2.3e-03]	24.7 fb^{-1}	7,8 TeV
	ZZ (4l)	[-1.0e-03, 1.3e-03]	35.9 fb^{-1}	13 TeV
	ZZ (4l,2l2ν)	[-9.1e-03, 8.9e-03]	9.6 fb^{-1}	7 TeV

All Relevant aQGC Limits