STUDY OF ZZ→4 LEPTONS AT $\sqrt{s} = 13$ TeV WITH THE CMS DETECTOR

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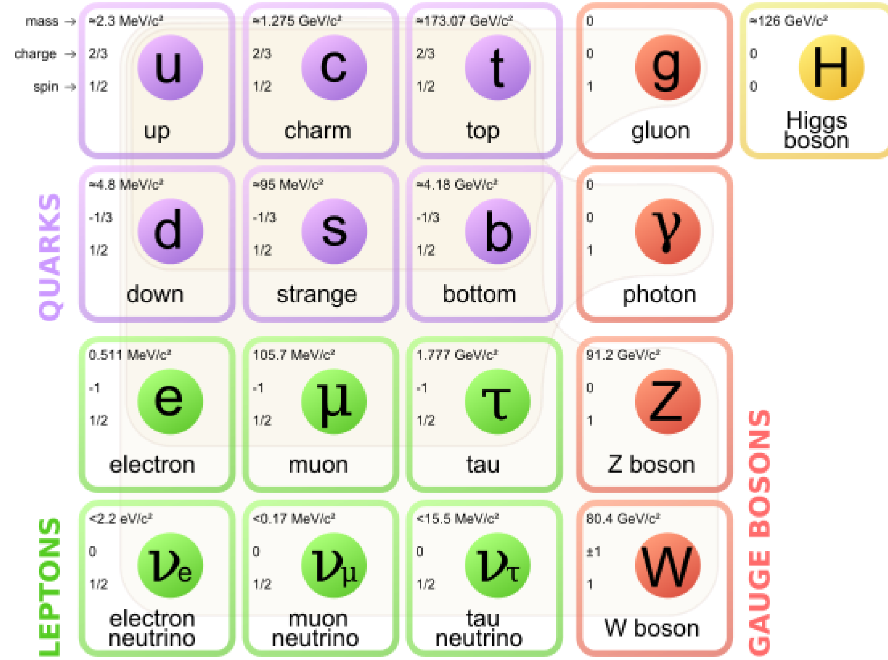
PRELIMINARY EXAMINATION

OUTLINE

- **Physics background**
  - The Standard Model
  - Electroweak symmetry breaking
- **The Large Hadron Collider**
- **The Compact Muon Solenoid**
- **Physics object reconstruction**
- **Analysis strategy**
- **Results**
- **Conclusions and future work**

THE STANDARD MODEL

- **Explains fundamental particle interactions**
  - Fermions constitute matter
    - Quarks form hadron bound states
  - Gauge bosons mediate forces
    - Gluon: Strong force
    - W±, Z: Weak force
    - Photon: Electromagnetic force
  - Scalar Higgs boson imparts mass to other particles
- **Not included: gravity, dark matter, dark energy**



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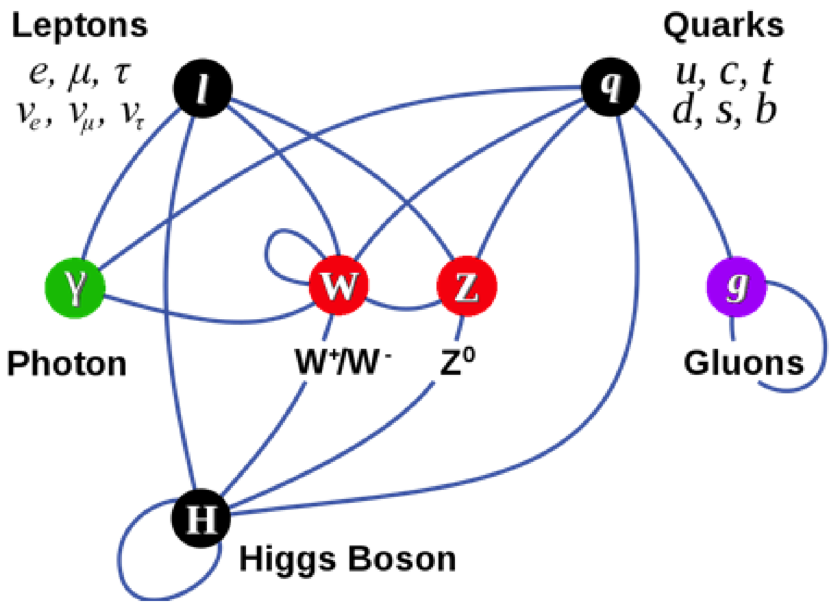
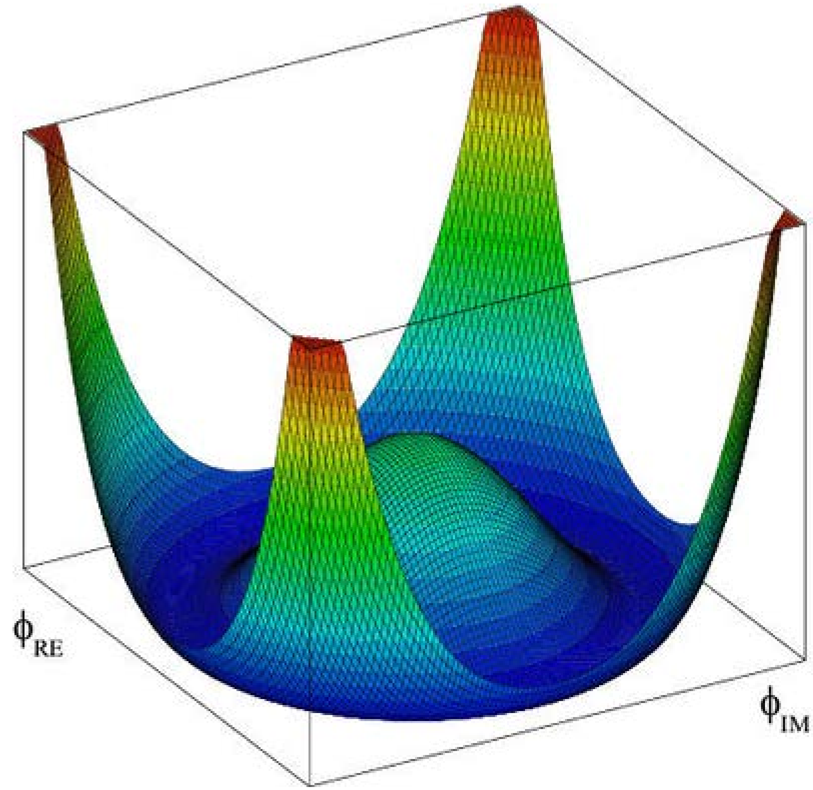
PARTICLE INTERACTIONS

- **Strong force**
  - Holds quarks in meson and baryon bound states
  - Confinement: interaction strength grows with distance, preventing free color charge
- **Weak force**
  - Causes some nuclear decays
- **Electromagnetic force**
  - Holds electrons in atomic orbitals



ELECTROWEAK SYMMETRY BREAKING

- **Electroweak $SU(2)_L \times U(1)_Y$ gauge symmetry spontaneously broken in vacuum state by nonzero expectation value of complex scalar Higgs field**
- **$W^{\pm}$ and Z bosons arise as massive pseudo-Nambu-Goldstone bosons**
- **$U(1)_{EM}$ symmetry remains, leaving massless photon**



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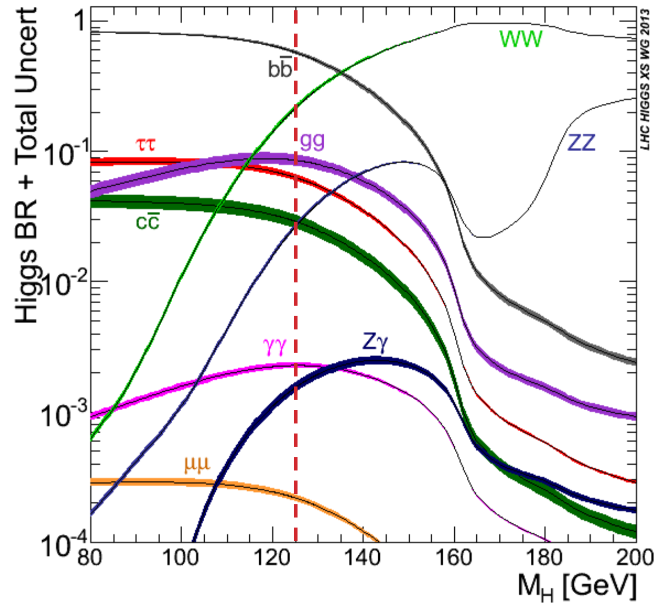
ZZ→4ℓ STUDY MOTIVATION

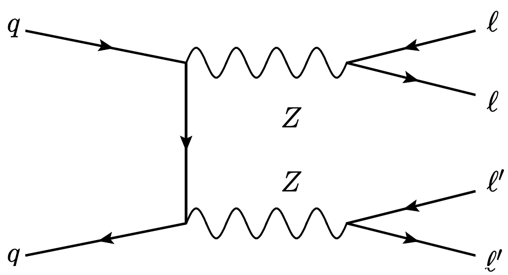
- $e^{\pm}$ and $\mu^{\pm}$ can be accurately reconstructed and 4ℓ $(\ell = e, \mu)$ backgrounds are very low
- $H \rightarrow ZZ^{*} \rightarrow 4\ell$ is a primary Higgs discovery mode and allows precision measurement of Higgs properties despite low branching ratio
- Electroweak $ZZ \rightarrow 4\ell$ is the primary $H \rightarrow ZZ^{*} \rightarrow 4\ell$ background, and allows measurement of electroweak gauge couplings



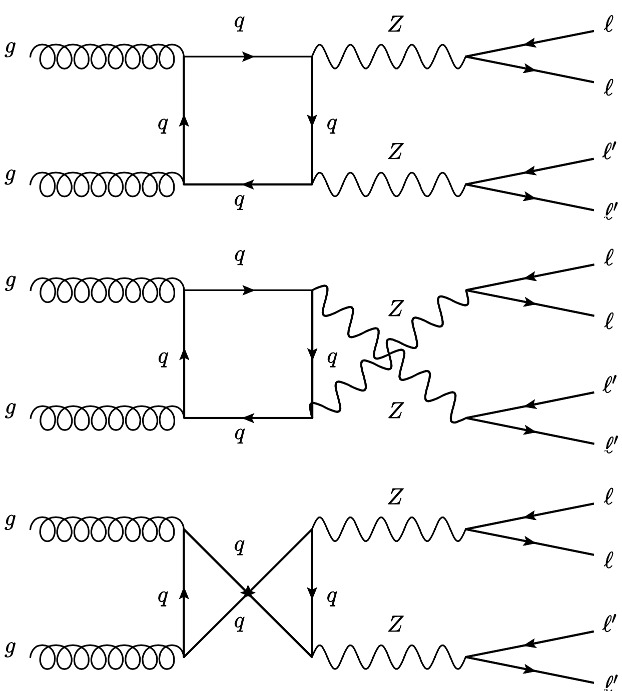
Decay Mode	ZZ Branching Ratio
$\ell^{+}\ell^{-}\ell'^{+}\ell'^{-}$	1%
$\ell^{+}\ell^{-}\nu\bar{\nu}$	4%
$\ell^{+}\ell^{-}$ + hadrons	15%
$\nu\bar{\nu}$ + hadrons	28%
$\nu\bar{\nu}\nu'\bar{\nu}'$	4%
All hadrons	49%

ZZ PRODUCTION IN PP COLLISIONS

SM Leading Order



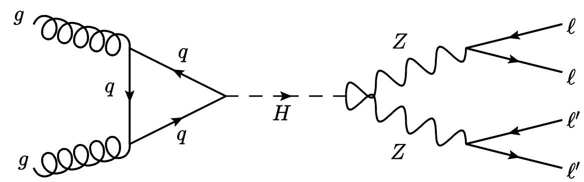
SM Next-to-Next-to-Leading Order



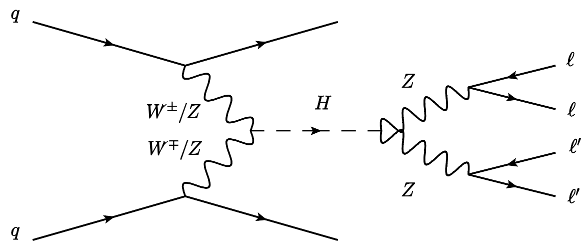
+ more at NLO in α_{EWK}

Higgs Production

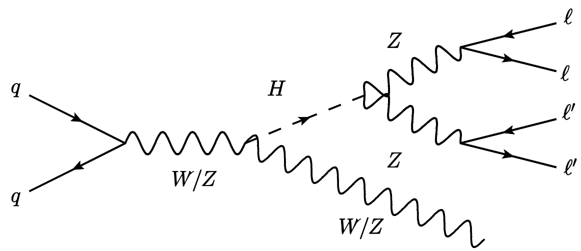
Gluon-Gluon Fusion



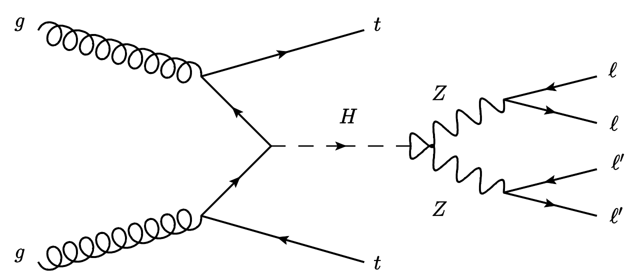
Vector Boson Fusion



Vector Boson Associated



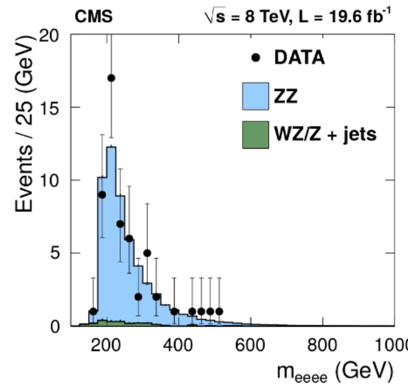
$t\bar{t}$ Associated

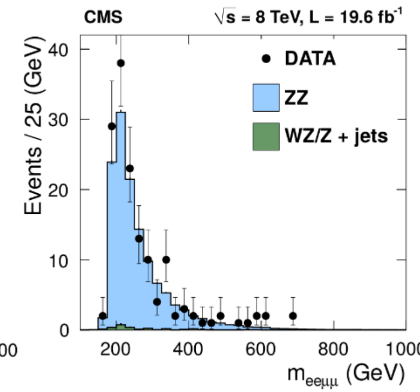


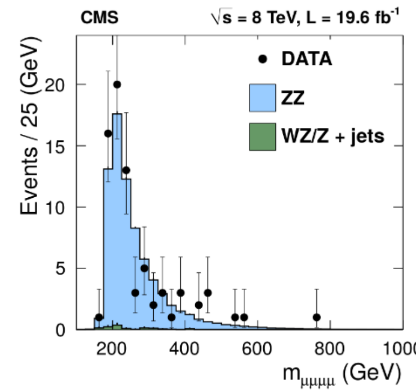
	13TeV Cross Section × BR (NNLO) [pb]
SM ZZ	15.4
gg→H→ZZ	1.2
VBF H→ZZjj	0.1
VH→VZZ	0.06
$t\bar{t}$H→ZZ$t\bar{t}$	0.01

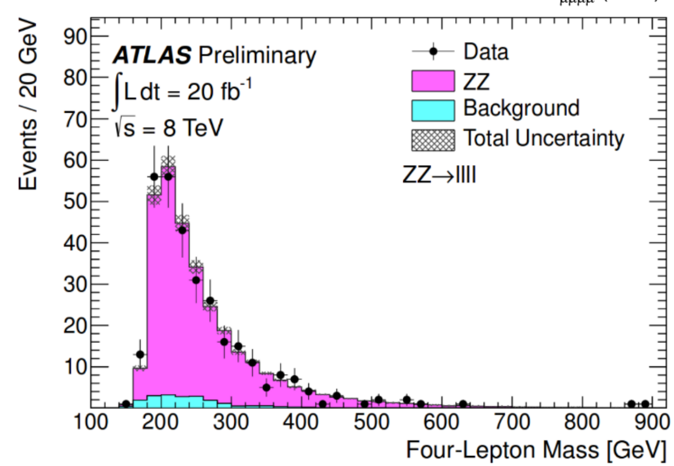
8 TeV RESULTS: ON-SHELL ZZ

- **CMS (top 3 plots)**
  - $60\ \text{GeV} < m_{Z_{1,2}} < 120\ \text{GeV}$
  - $ZZ \to \ell\ell\ell'\ell';\ \ell = (e,\mu), \ell' = (e,\mu,\tau)$
  - $\sigma_{pp\to ZZ} = 7.7 \pm 0.5(\text{stat.})^{+0.5}_{-0.4}(\text{syst.}) \pm 0.4(\text{theo.}) \pm 0.3(\text{lum.})$ pb at $\sqrt{s} = 8$ TeV
- **ATLAS (bottom plot)**
  - $66\ \text{GeV} < m_{Z_{1,2}} < 116\ \text{GeV}$
  - $ZZ \to \ell\ell\ell'\ell';\ \ell,\ \ell' = (e,\mu)$
  - $\sigma_{pp\to ZZ} = 7.1^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.2(\text{lumi.})$ pb



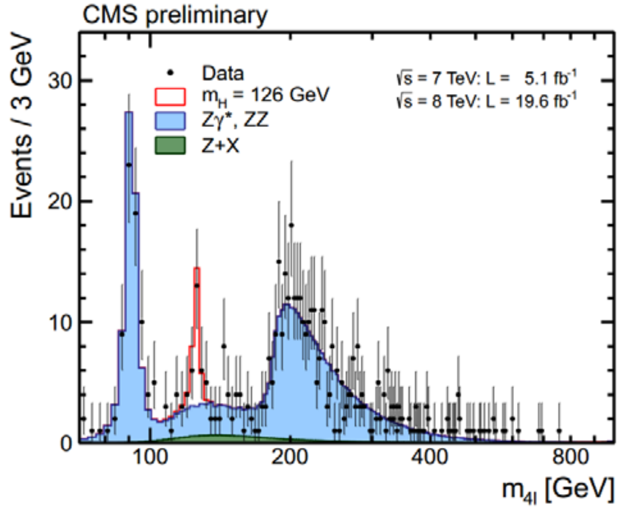


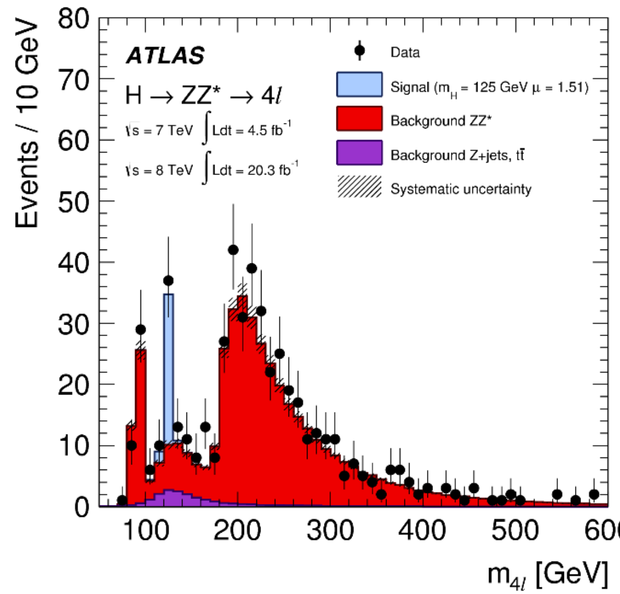




8 TeV RESULTS: H→ZZ*→4ℓ

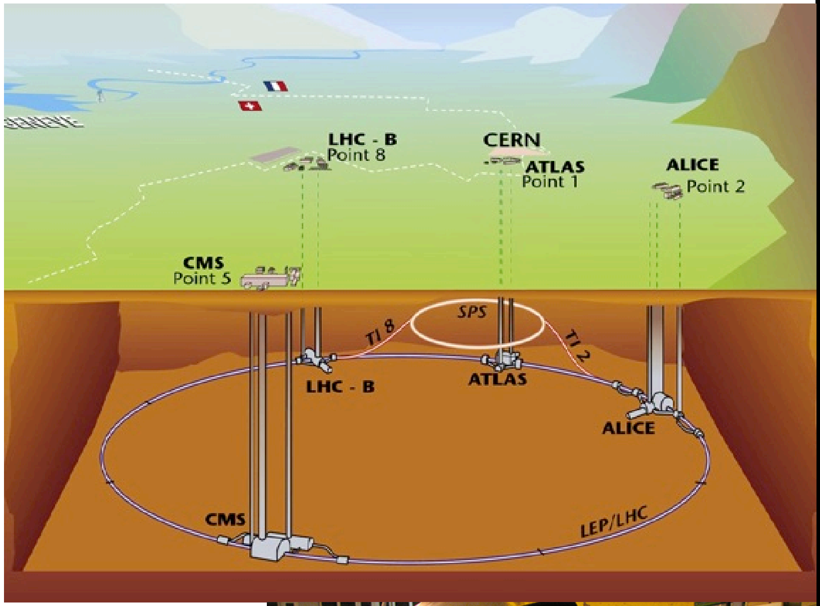
- **CMS and ATLAS both discovered particle consistent with Standard Model Higgs near 125 GeV**
- **Most recent measurements in this channel:**
  - CMS (top plot)
    - $m_H = 125.6 \pm 0.4(\text{stat.}) \pm 0.2(\text{syst.})\ \text{GeV}$
    - $\sigma/\sigma_{SM} = 0.93^{+0.26}_{-0.23}(\text{stat.})^{+0.13}_{-0.09}(\text{syst.})$
  - ATLAS
    - $m_H = 124.51 \pm 0.52(\text{stat.}) \pm \pm 0.06\ (\text{syst.})\ \text{GeV}$
    - $\sigma/\sigma_{SM} = 1.50^{+0.35}_{-0.31}(\text{stat.})^{+0.19}_{-0.13}(\text{syst.})$



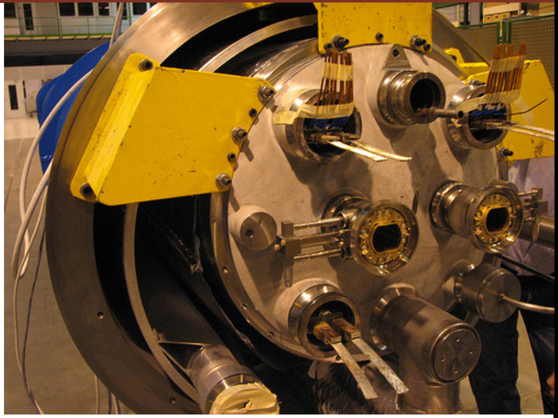


THE LARGE HADRON COLLIDER

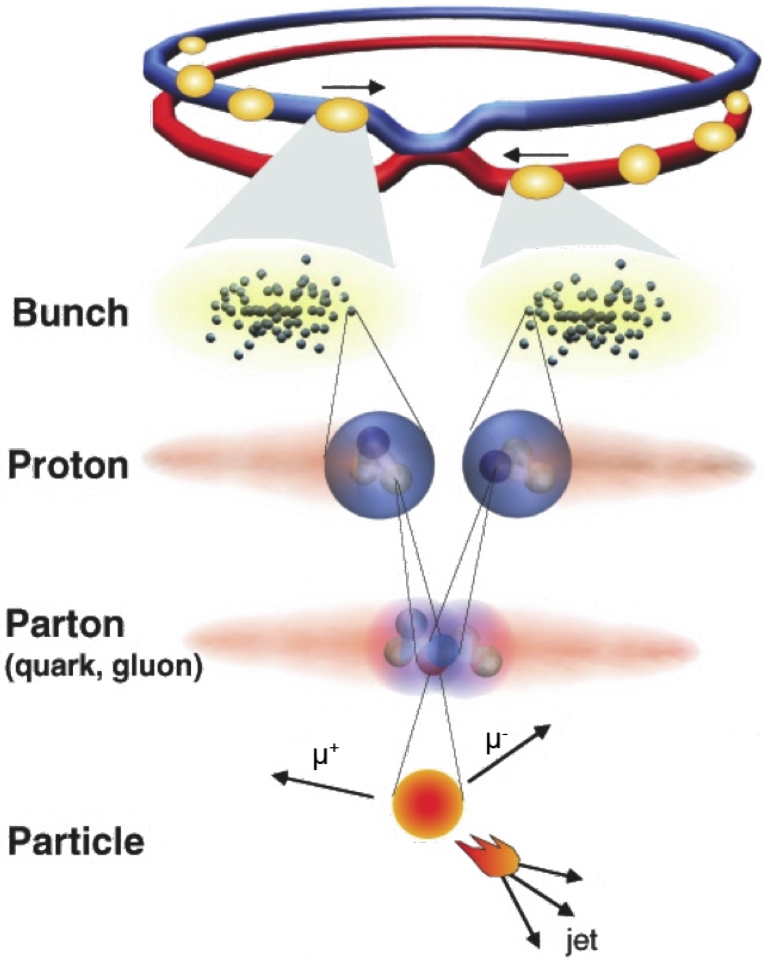
- **27 km circumference collider at CERN near Geneva, CH, capable of colliding protons and heavy ions**
- **Serves four primary experiments**
  - CMS and ATLAS: general purpose
  - LHCb: forward hadronic physics
  - ALICE: heavy ion collisions
- **Designed for 14TeV center of mass energy**
  - Achieved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



LHC dipole

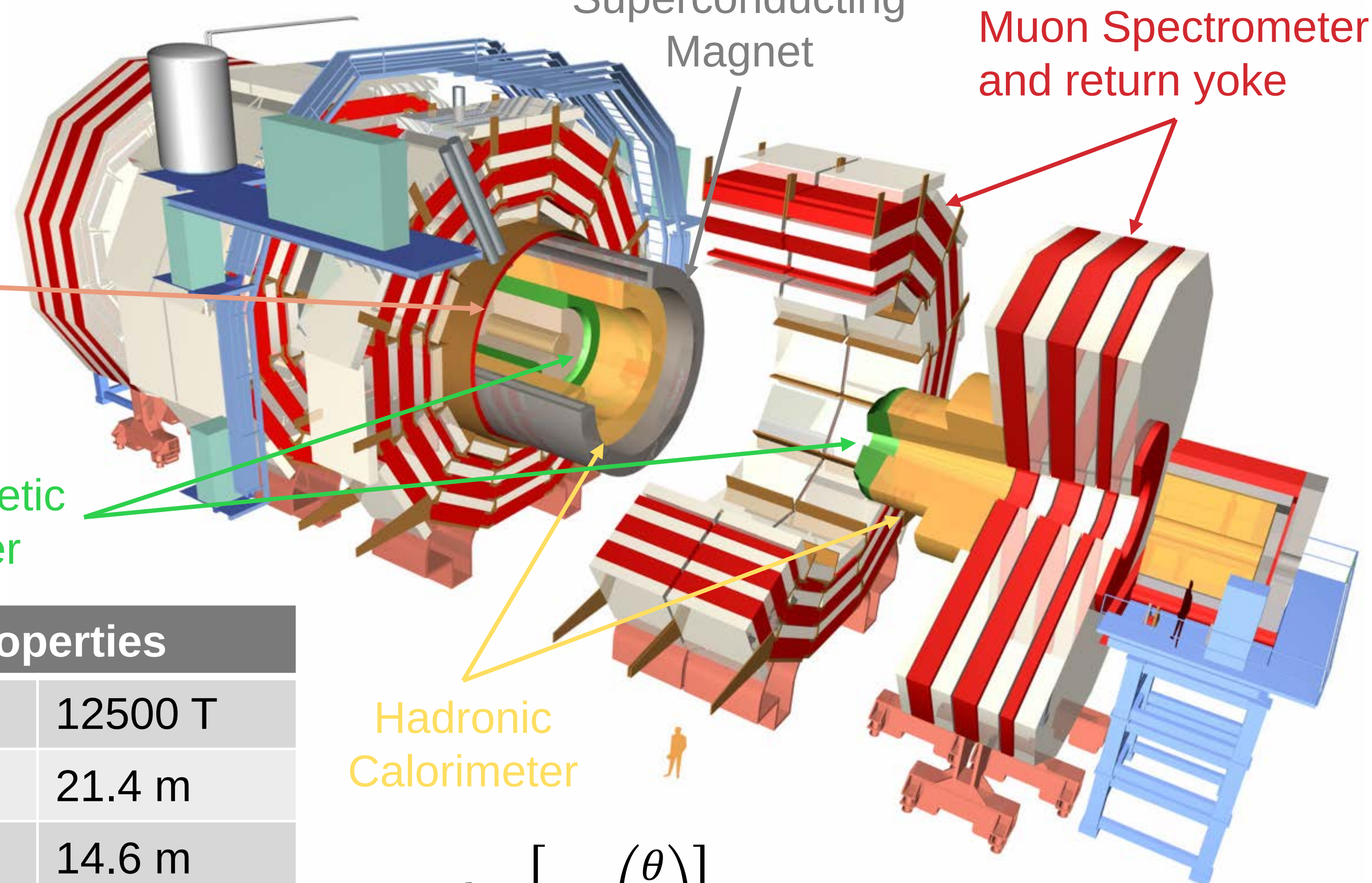


PROTON-PROTON COLLISIONS AT LHC



	Design	2011	2012	2015-2016 (expected)
Beam Energy [TeV]	7	3.5	4	6.5
Bunches/beam	2808	1380	1380	2748/2508
Protons/bunch [10^{11}p]	1.15	1.45	1.7	1.2
Peak instantaneous luminosity $[10^{33}\ \frac{\mathrm{Hz}}{\mathrm{cm}^2}]$	10	3.7	7.7	8.5/12.9
Integrated Luminosity $[\mathrm{fb}^{-1}]$		6.1	23.3	~70
Avg. collisions per bunch crossing	23	8	21	22/36

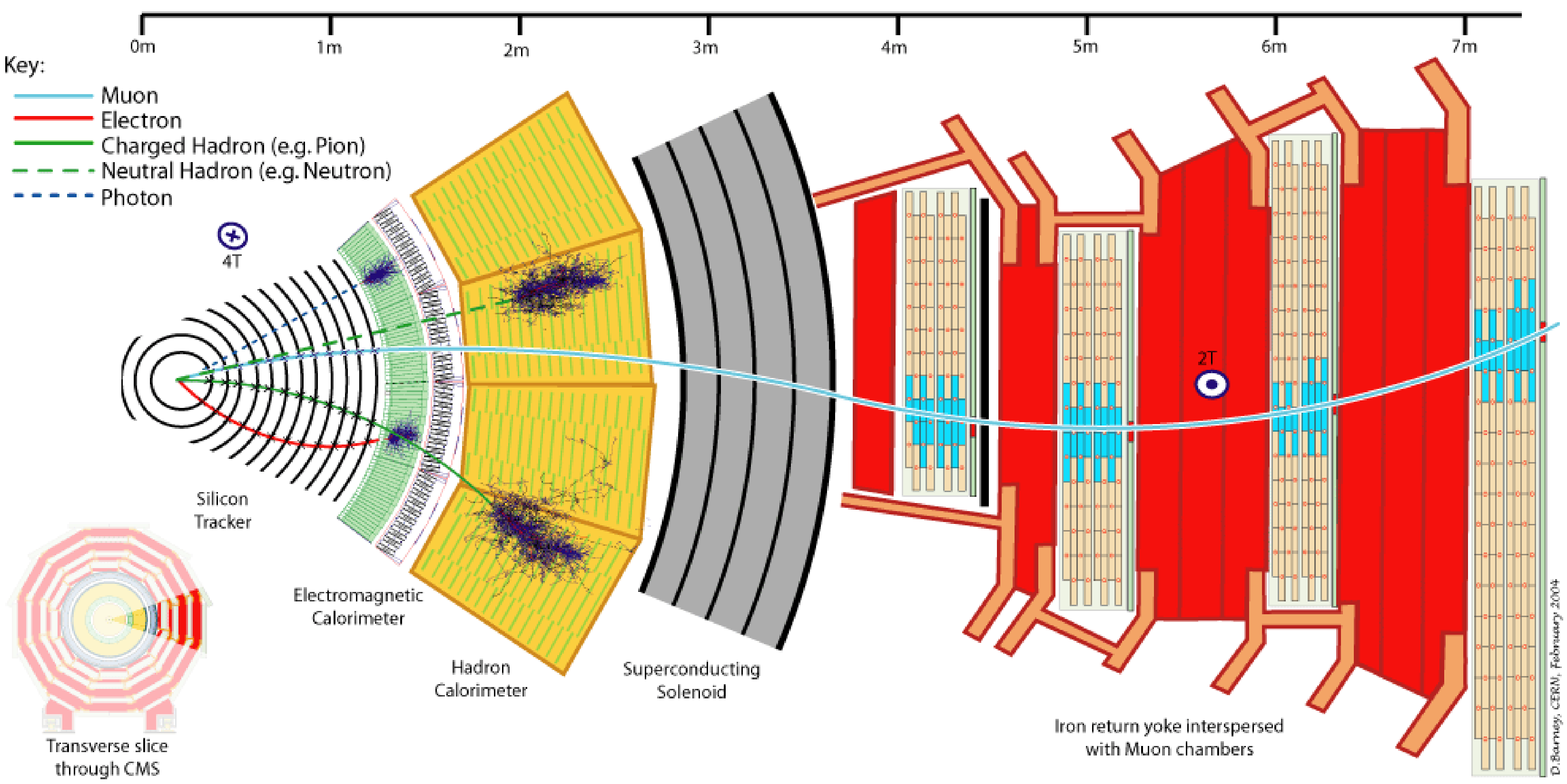
THE COMPACT MUON SOLENOID



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

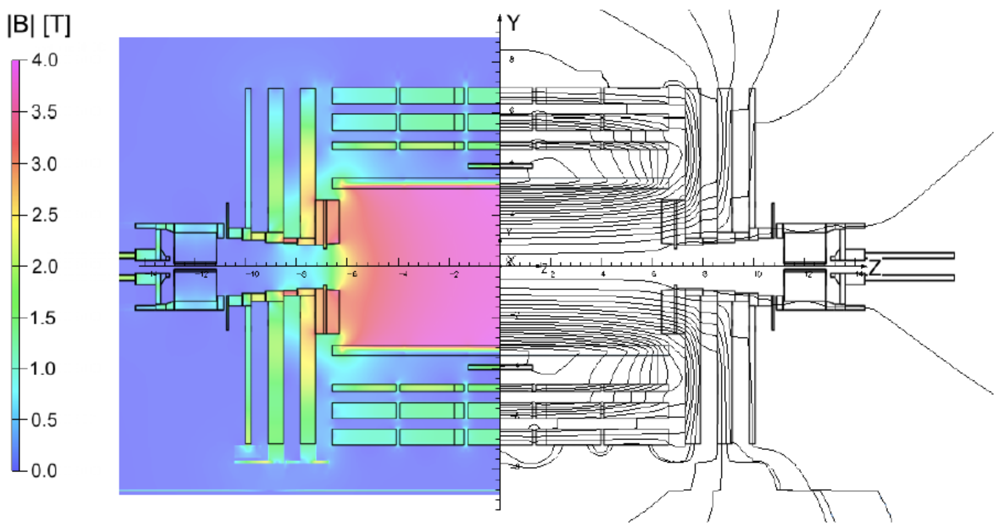
$$\eta = -\log\left[\tan\left(\frac{\theta}{2}\right)\right]$$

PARTICLE DETECTION IN CMS

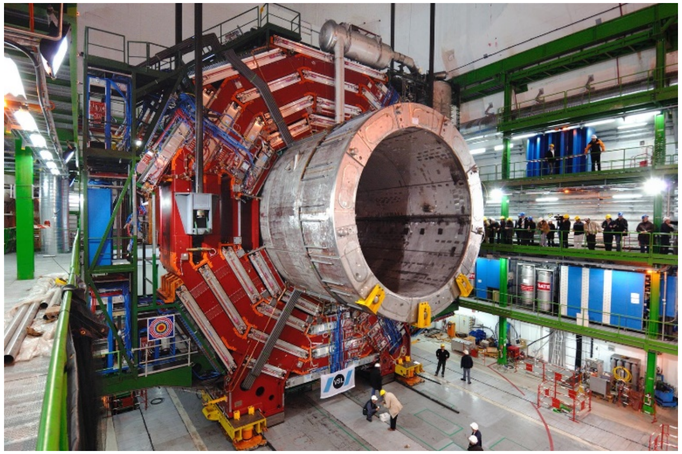


MAGNET

- **Charged particle momentum and vertex found 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**



CMS Magnetic Field

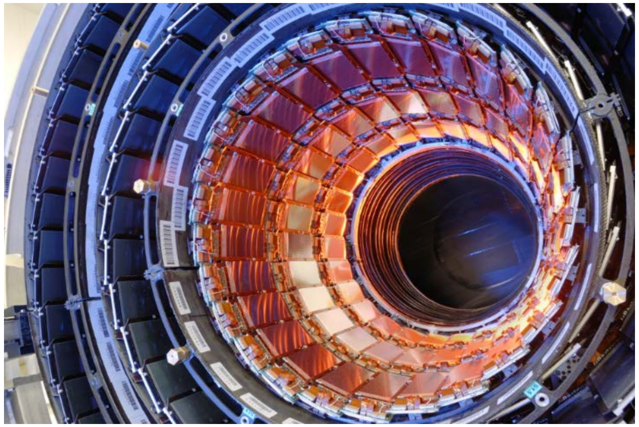


Magnet Installation

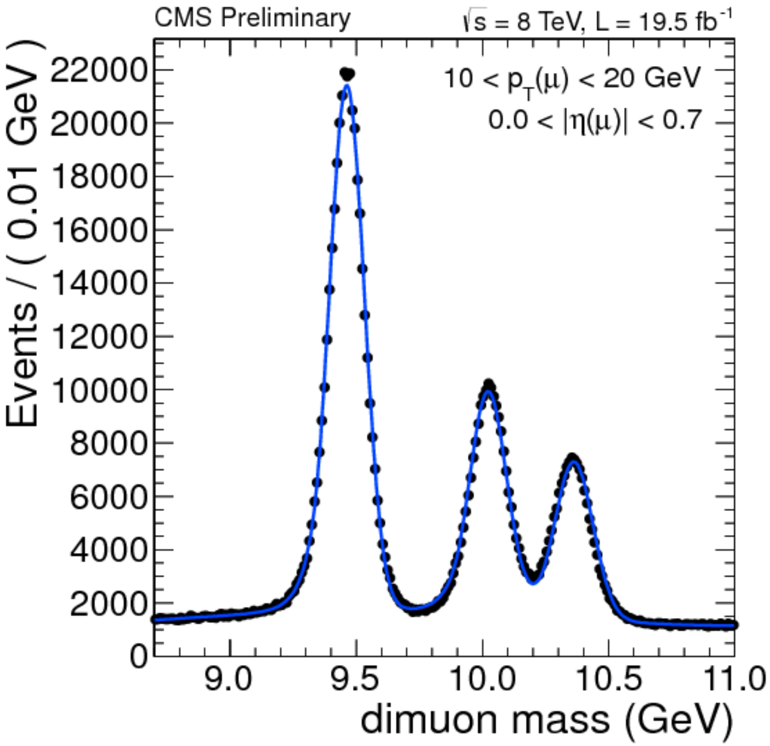
SILICON TRACKER

- **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:**

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



Si Strip Tracker Barrel

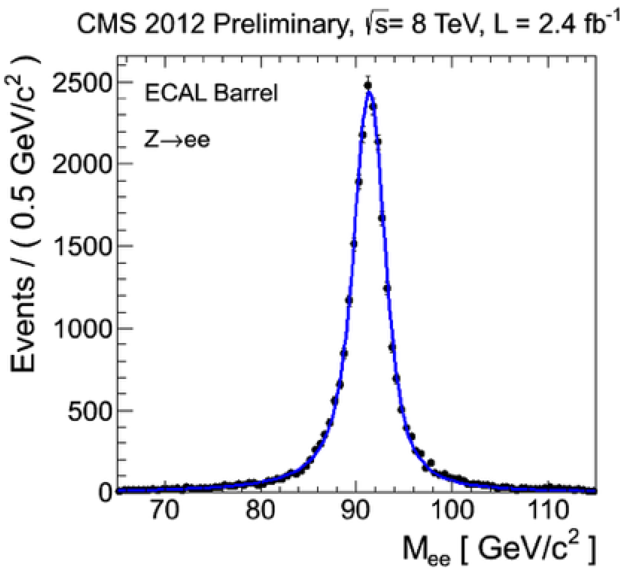


Tracker resolution demonstrated in $\Upsilon \to \mu\mu$ events ($\Gamma_{\Upsilon(j)\to\mu\mu} = 1.4,\ 0.6,\ 0.4\ \mathrm{keV}$)

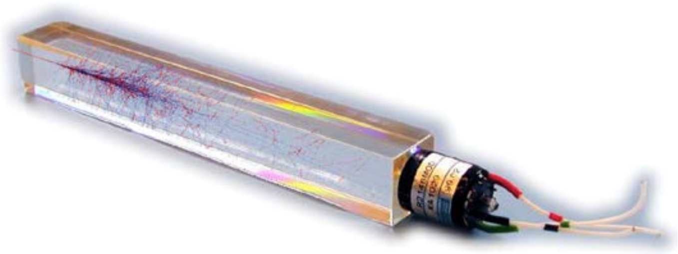
ELECTROMAGNETIC CALORIMETER

- **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.):**

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



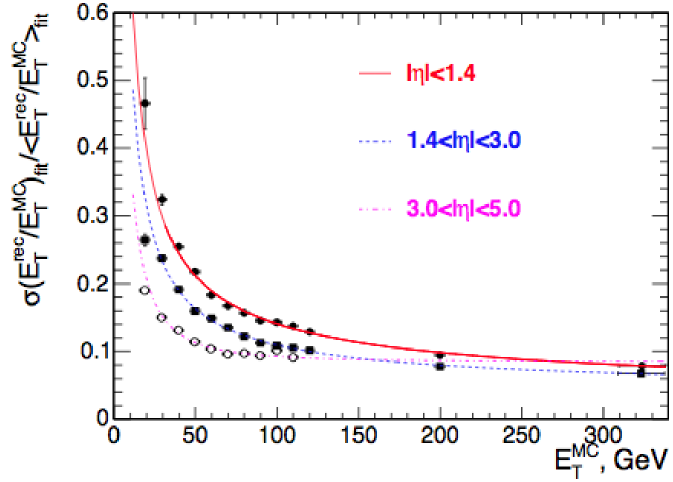
ECAL resolution demonstrated in $Z \to ee$ events ($\Gamma_{Z\to ee} = 84$ MeV)



ECAL crystal with photodetector and cartoon of an electron shower

HADRONIC CALORIMETER

- **Long-lived hadrons interact very little with tracker and ECAL, so jets and missing E_T (ME_T) measured and triggered by compact (inside solenoid), hermetic ($|\eta| < 5$) sampling hadronic calorimeter (HCAL)**
- **In barrel (HB, $|\eta| < 1.2$) and endcap (HE, $1.3 < |\eta| < 3.0$), plastic scintillator tiles embedded with wavelength shifting fibers are 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 calorimeter (HF, $3 < |\eta| < 5$) made of steel with embedded quartz fibers for radiation hardness. Also measures EM rich jets outside of 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)

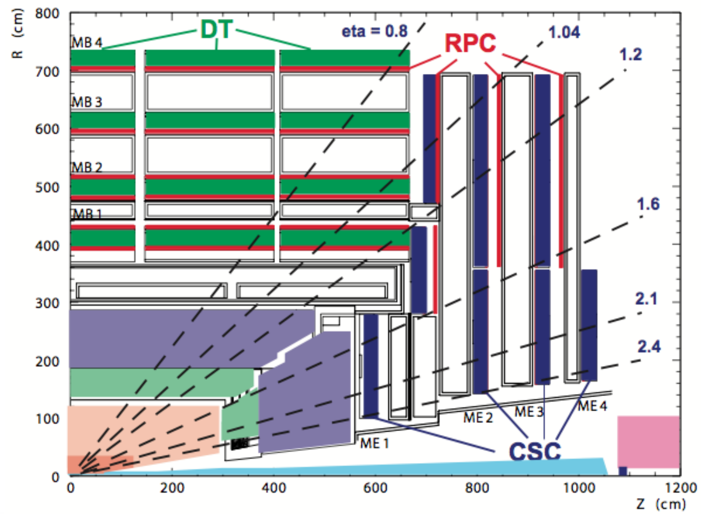


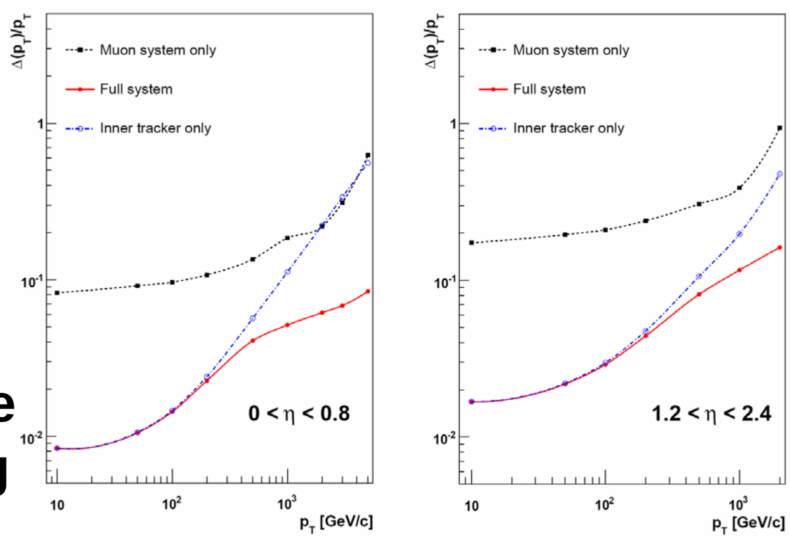
HCAL E_T Resolution
(Simulated Hadrons)

HE mounted on endcap disc

MUON SYSTEM

- **Several systems interleaved with iron return yoke outside solenoid allow muon triggering and provide long "lever arm" for 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) give 1 ns timing and redundant triggering ($|\eta| < 1.6$)**

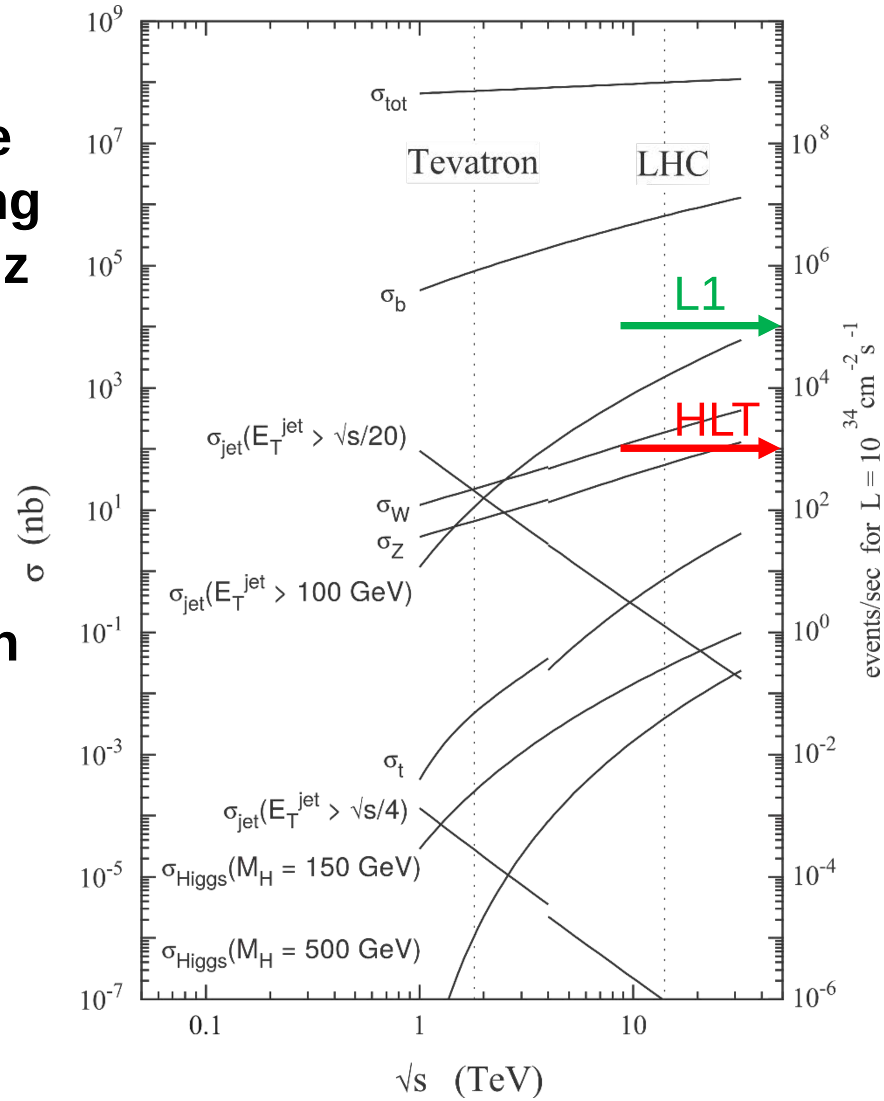




Design Muon p_T Resolution

TRIGGER

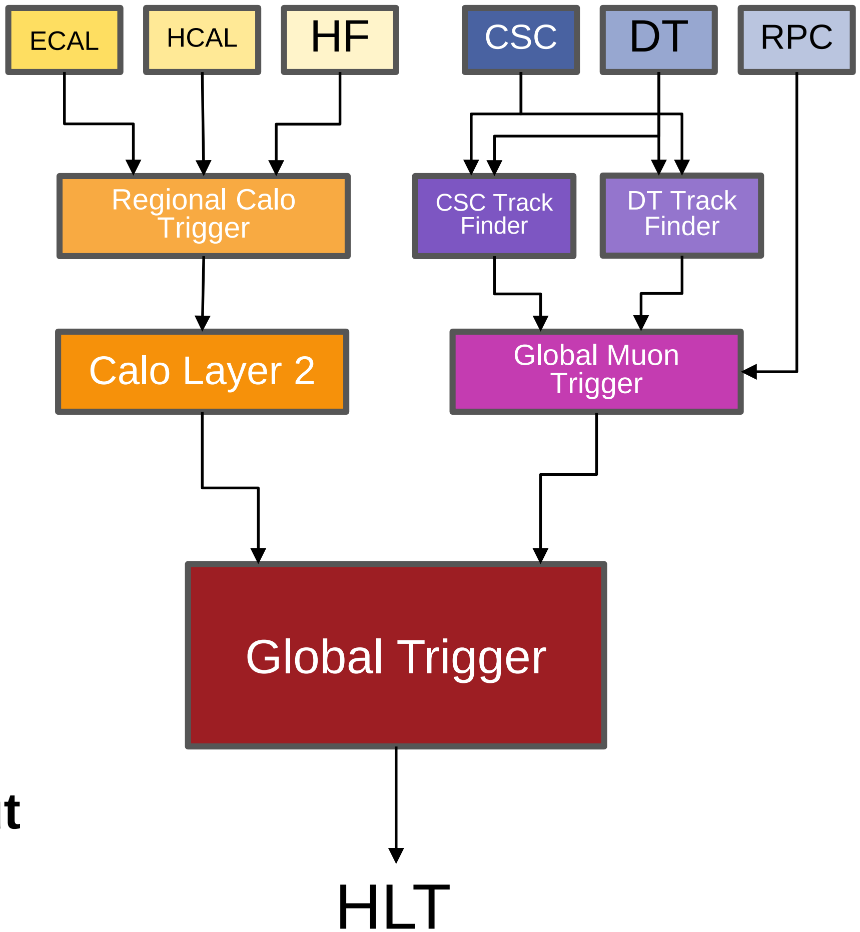
- **LHC 40 MHz bunch crossing rate with ~40 interactions per crossing gives potential event rate > 1 GHz**
- **CMS produces far too much raw data to store and analyze, but most is uninteresting soft QCD**
- **2-tier trigger system reduces 40 MHz collision rate to <~100kHz in dedicated hardware (Level-1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



LEVEL-1 TRIGGER

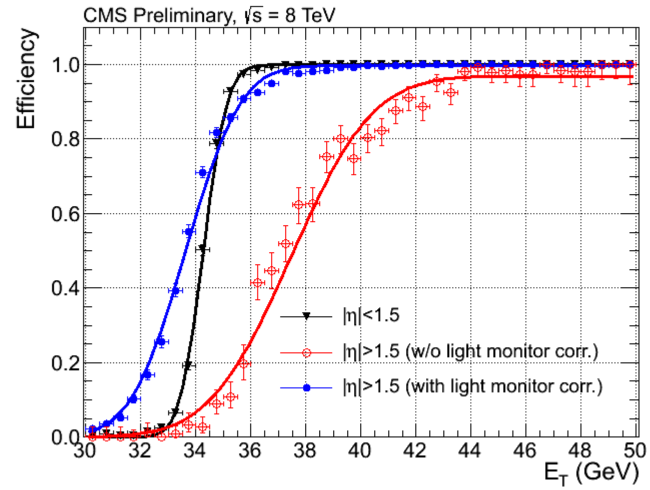
- **Low granularity raw detector information is processed in dedicated hardware**
- **L1 Calorimeter Trigger finds (possibly isolated) electrons and photons, jets, total E_T, MET, hadronic E_T (HT) and MHT**
  - 2015 phase 1 upgrade: pileup subtraction, dedicated tau objects, improved isolation
- **L1 Muon Trigger builds tracks and reconstructs muon candidates**
- **<~4 μs latency, 100 kHz max readout**

L1 Trigger 2015

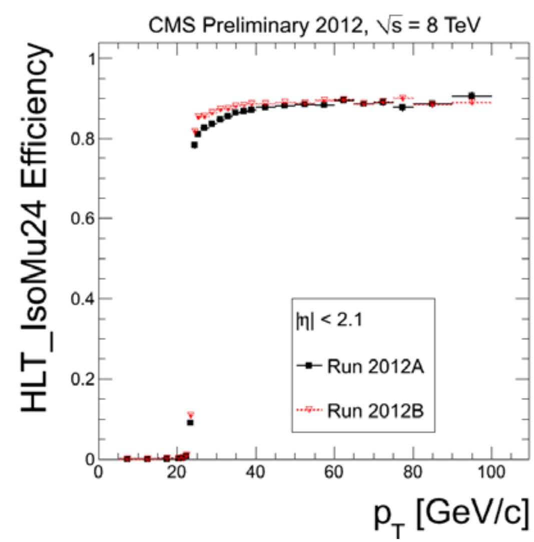


HIGH LEVEL TRIGGER

- **Modified ($\mathcal{O}$(100) times faster) 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



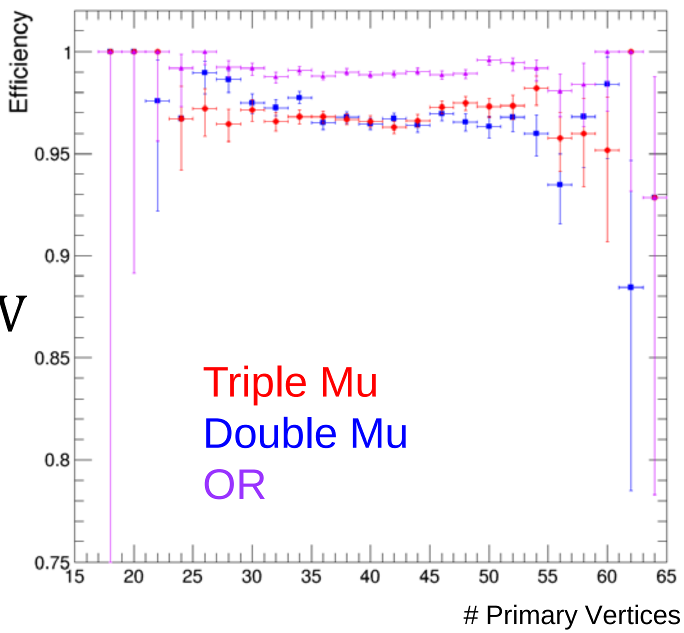
33 GeV Electron HLT Efficiciency



ZZ TRIGGERS

Expected total rate: 87 Hz

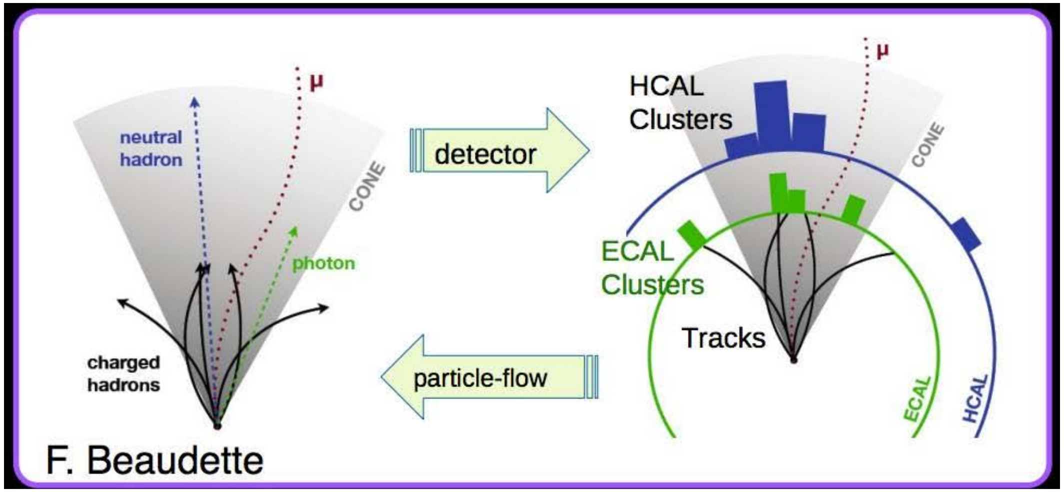
- **Dilepton and trilepton triggers used to efficiently identify 4-lepton events**
- **Dilepton (using loose track isolation)**
  - Dimuon: $p_{T_{\mu 1,2}} > 17{,}8\ \mathrm{GeV}, |\eta| < 2.4$
  - Dielectron: $E_{T_{e1,2}} > 23{,}12\ \mathrm{GeV}, |\eta| < 2.5$
  - Cross triggers: $p_{T_\mu} > 23\ \mathrm{GeV}, E_{T_e} > 12\ \mathrm{GeV}$
    $E_{T_e} > 23\ \mathrm{GeV}, p_{T_\mu} > 8\ \mathrm{GeV}$
- **Trilepton (no isolation cut)**
  - Trimuon: $p_{T_{\mu 1,2,3}} > 12{,}10{,}5\ \mathrm{GeV}$
  - Trielectron: $E_{T_{e1,2,3}} > 16{,}12{,}8\ \mathrm{GeV}$
  - Cross triggers: $E_{T_{e1,2}} > 12\ \mathrm{GeV}, p_{T_\mu} > 8\ \mathrm{GeV}$
    $p_{T_{\mu 1,2}} > 9\ \mathrm{GeV}, E_{T_e} > 9\ \mathrm{GeV}$



Efficiency of gg→H→ZZ →4l events that pass analysis cuts at generator level, for the trimuon path, the dimuon path, and a logical OR of the two, as a function of the number of primary vertices in the event.

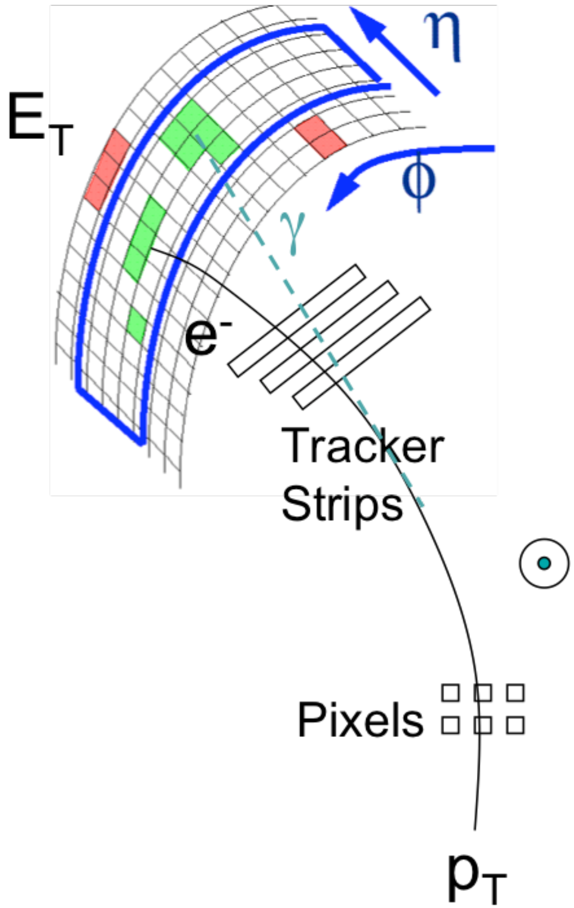
PARTICLE FLOW RECONSTRUCTION

- **Multiple detector systems working in concert yield more information than the sum of their parts**
- **Tracks and calorimeter clusters are matched and combined to reconstruct Particle Flow (PF) Candidates**
  - Electrons, muons, photons, charged and neutral hadrons
- **PF Candidates can be clustered into higher level objects**
  - Jets, taus, ME_T
- **PF objects are used to reconstruct particles such as Z and W bosons that decay too quickly for direct observation**



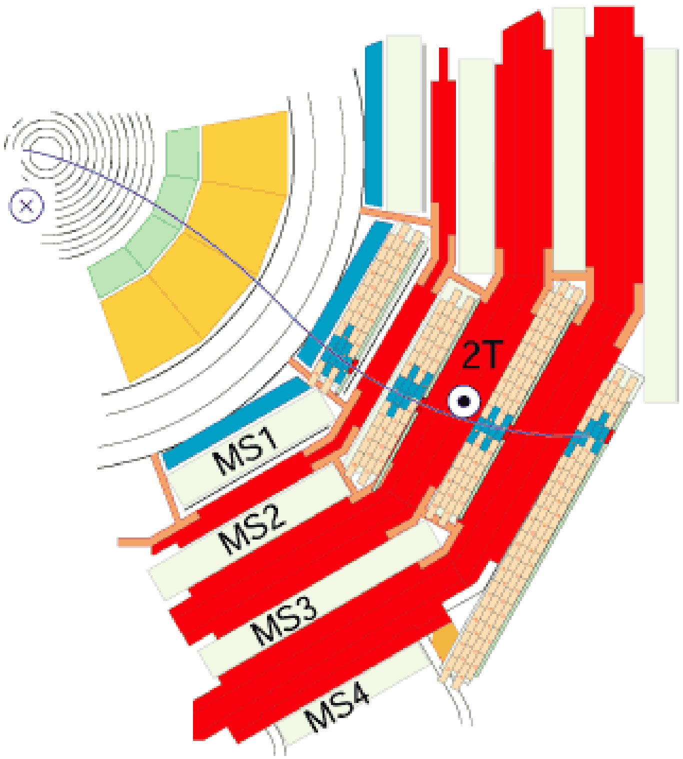
ELECTRON RECONSTRUCTION

- Clusters of deposits in ECAL are matched to nearby tracks to identify charged, electromagnetically interacting electron
- ECAL supercluster includes extended area in ϕ direction to contain bremsstrahlung photons radiated from electron
- Track must be close to primary interaction vertex
- For this study, electrons were identified based on the output of a Boosted Decision Tree algorithm trained on simulated data



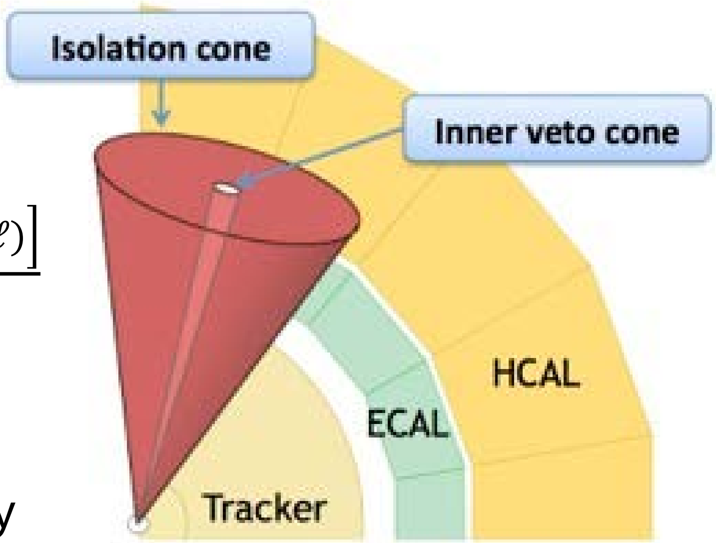
MUON RECONSTRUCTION

- **Three types of muon reconstruction**
  - Tracker muon, found by silicon tracker
  - Standalone muon, found by muon spectrometer
  - 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) to eliminate hadrons that “punch through” to the muon system



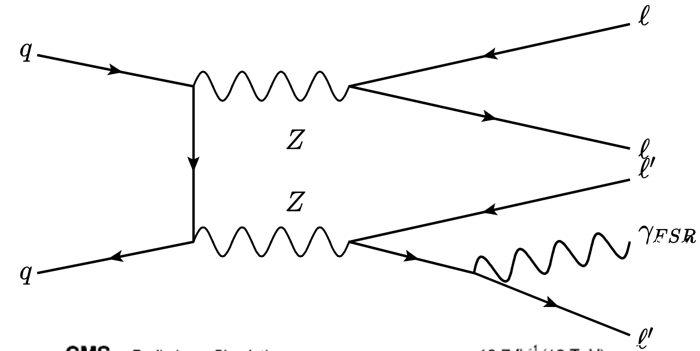
LEPTON ISOLATION

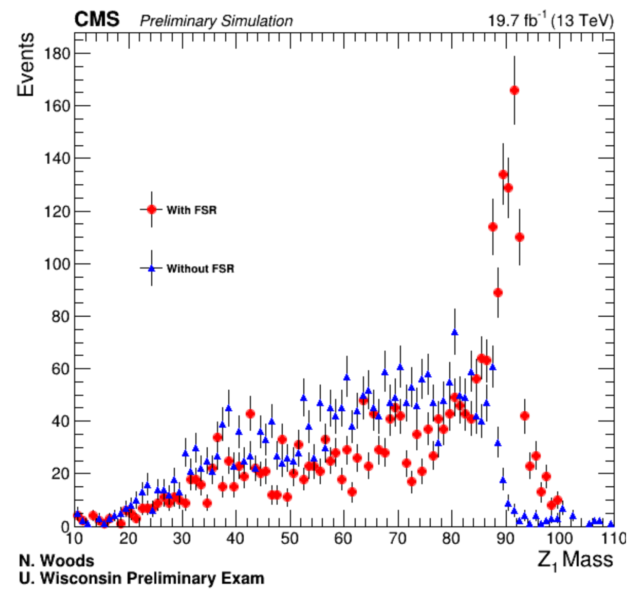
- **QCD backgrounds produce leptons inside jets and may be strongly rejected by limiting the energy in a cone around each leptons**
- **Particle Flow Relative Isolation:**
  - $R^{\ell}_{\mathrm{Iso}} \equiv \frac{\sum p_T^{\mathrm{charged}} + \max\left[0, \sum p_T^{\mathrm{neutral}} + \sum p_T^{\gamma}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



FINAL STATE RADIATION

- **Leptons can radiate a photon while in flight, leading to a mismeasured Z**
- **A photon is counted as FSR if:**
  - $\Delta R_{\ell\gamma} < 0.07$ and $p_{T_\gamma} > 2$ GeV, or $\Delta R_{\ell\gamma} < 0.5$, $p_{T_\gamma} > 4$ GeV, and the photon is loosely isolated
  - The photon is not part of another electron supercluster
  - $m_{\ell\ell\gamma} < 100$ GeV
  - $|m_{\ell\ell\gamma} - m_Z| < |m_{\ell\ell} - m_Z|$
  - Only one photon per Z candidate
    - Prefer highest $p_{T_\gamma} > 4$ GeV, then smallest ΔR if all $p_{T_\gamma} < 4$ GeV



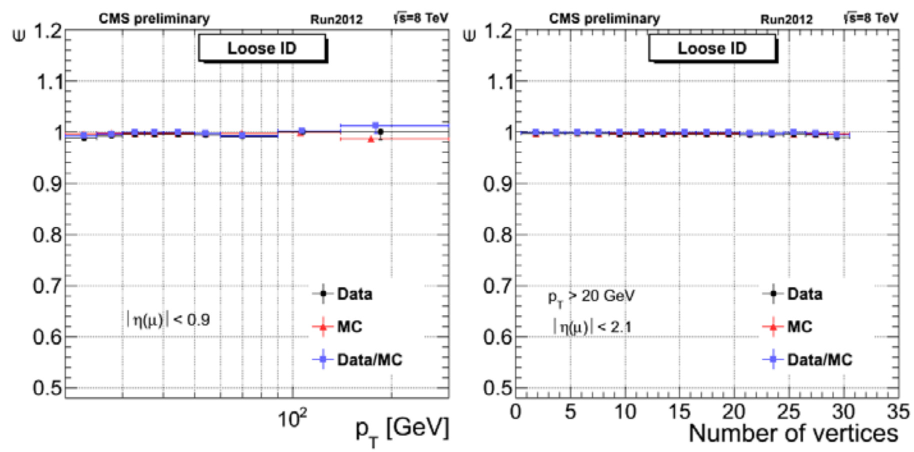


H→ZZ→4l events with found FSR, before and after

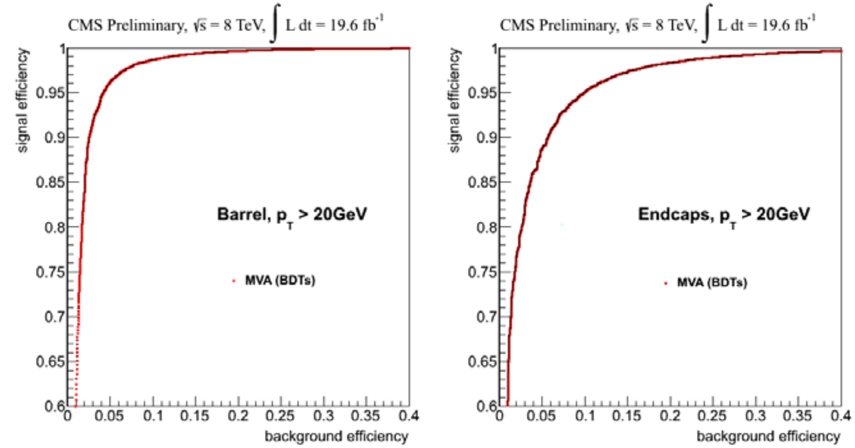
$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

PREVIOUS DETECTOR PERFORMANCE

- **Goal of ID algorithms is to correctly identify nearly all leptons (high efficiency) without incorrectly tagging other objects (fakes) as leptons**
- **ID definitions may be tuned to yield signal-to-background ratio appropriate to a specific analysis**
- **In previous runs, lepton efficiencies were close to 1 while maintaining low fake rates for most analyses**



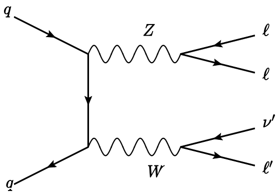
Muon ID efficiency



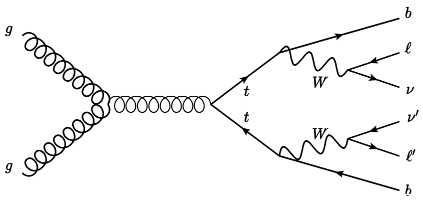
Electron ID efficiency vs. fake rate

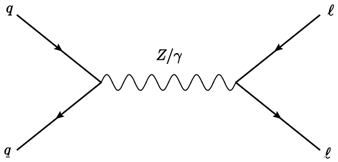
BACKGROUNDS

- **Few physics processes have a signature of 4 isolated leptons, so backgrounds are quite small, but some objects can fake leptons, and real leptons can come from other vertices in the same event**
- $\boldsymbol{W^{\pm} + Z + X \to 3\ell + \nu + X'}$
  - Small cross section but only requires 1 fake/unrelated lepton
- $\boldsymbol{t\bar{t}}$
  - Large cross section and can yield 4 leptons from 2 W decays and 2 b decays, but well rejected by isolation requirement
- $\boldsymbol{Z/\gamma + X \to 2\ell + X'}$ **(Drell-Yan)**
  - Large cross section and requires only 2 fake/unrelated leptons



+ 1 fake

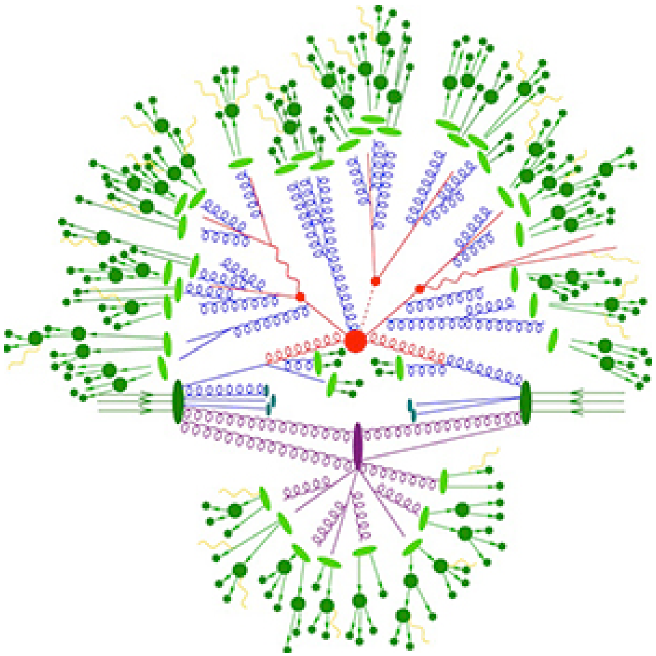




+ 2 fakes

MONTE CARLO SIMULATION

- **MadGraph, POWHEG**
  - Calculate matrix elements and generate hard scattering spectrum
- **Pythia, TAUOLA**
  - Parton showering and hadronization
  - Underlying event, initial/final state radiation
- **GEANT**
  - Particle interactions with matter
  - Simulated detector response
- **Simulated detector output reconstructed and analyzed with same software as data**



Sample	Generator
$gg \to H \to ZZ \to 4\ell$	POWHEG
$ZZ \to 4\ell$	POWHEG
Drell-Yan$\to 4\ell$	MadGraph
WZ+jets$\to 3\ell+\nu$	MadGraph
$t\bar{t}$+jets	MadGraph

ANALYSIS STRATEGY

- **Use events that pass multilepton triggers and have at least 2 opposite-sign, same-flavor pairs of electrons and muons**
- **Require all leptons to be well-identified and isolated, and to come from the same vertex**
- **Require both pairs to have a Z-like invariant mass**
  - For Higgs analysis, m_{Z_2} requirement relaxed to allow Z^*
- **Require leptons to be in a p_T range where trigger efficiencies are well understood**
- **Eliminate leptons from QCD and coincidence by placing an invariant mass requirement on all opposite-sign lepton pairs**
- **Cuts shown here are extremely loose, to show the "full" ZZ^* spectrum, and are expected to be tuned for specific analyses**

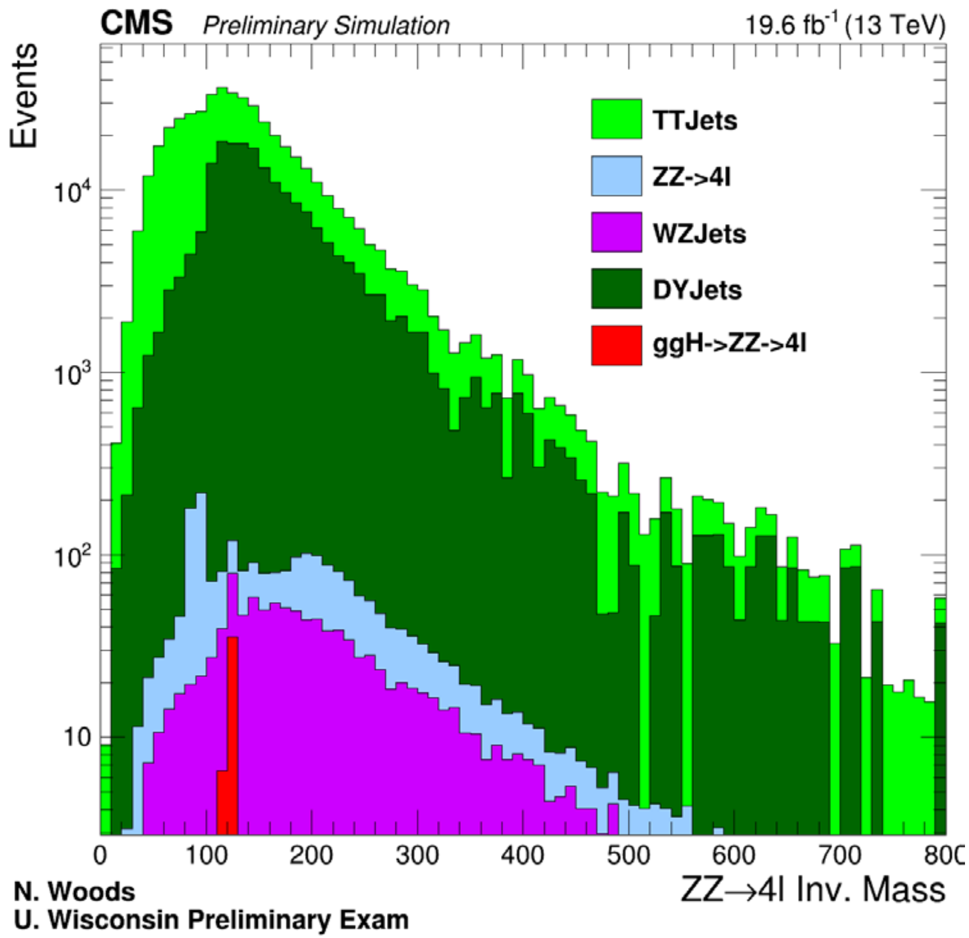
IDENTIFICATION, SELECTION, ISOLATION

- **Electrons identified by boosted decision tree algorithm**
  - May not have more than 1 missed hit in the tracker
  - $p_T > 7\text{ GeV},\ |\eta| < 2.5$
- **Muons must be from tracker or tracker + muon system**
  - $p_T > 5\text{ GeV},\ |\eta| < 2.4$
- **Vertex compatibility (Significance of Impact Parameter)**
  - $\text{SIP}_{3D} \equiv \frac{\text{IP}_{3D}}{\sigma_{\text{IP}_{3D}}} < 4$
    - IP_{3D}: 3-D impact parameter of track with vertex
    - $\sigma_{\text{IP}_{3D}}$: Uncertainty of IP_{3D}
- **Isolation**
  - $R^{\ell}_{\text{Iso}} < 0.4$ in cone of $\Delta R < 0.4$

UNSELECTED SPECTRUM

- **Fewest possible selections**
  - Events tagged with four possible lepton candidates, regardless of quality
  - Many fakes included
  - Minimal skimming done in creation of data files to reduce size
- **Trigger will bias spectrum from data more than spectrum from Monte Carlo, match not yet expected**

Sample	Expected in 19.6 fb^{-1}
WZ+jets	1042 ± 12
$t\bar{t}$+jets	275100 ± 300
DY+jets	201100 ± 2900
$ZZ\to4\ell$	1313.6 ± 4.0
$gg\to H\to ZZ^*\to4\ell$	80.6 ± 0.3
Total Signal	1365.6 ± 4.0
Total Background	477300 ± 2900
Total	478600 ± 2900

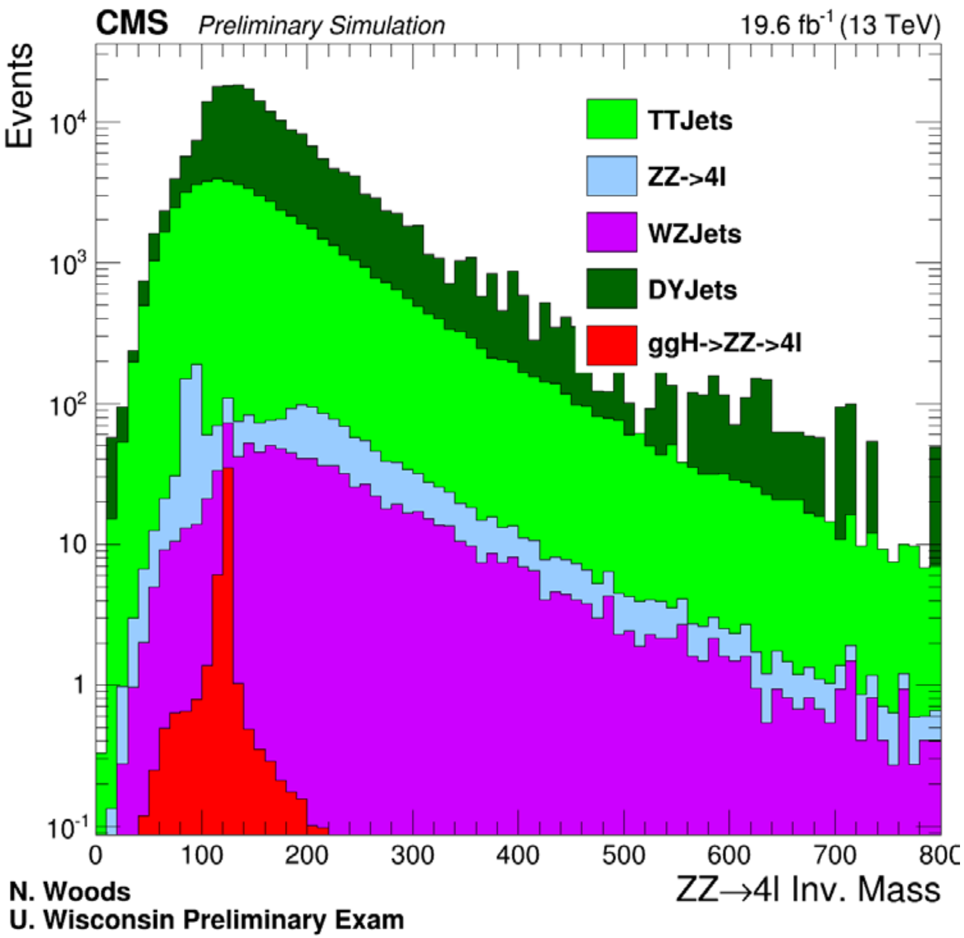


Stat. uncertainty only

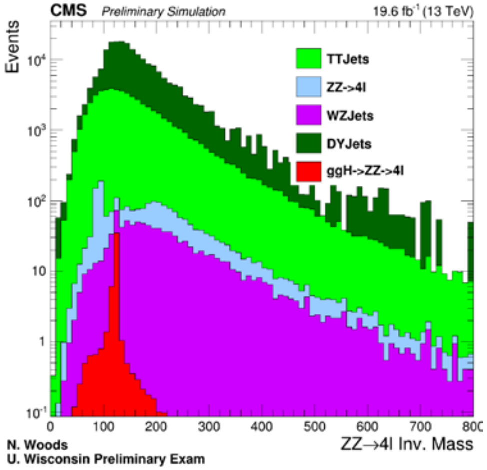
ZZ TRIGGERS

- **Trigger strategy: multilepton HLT**
  - Dilepton triggers with tracker isolation
  - Non-isolated Trilepton triggers

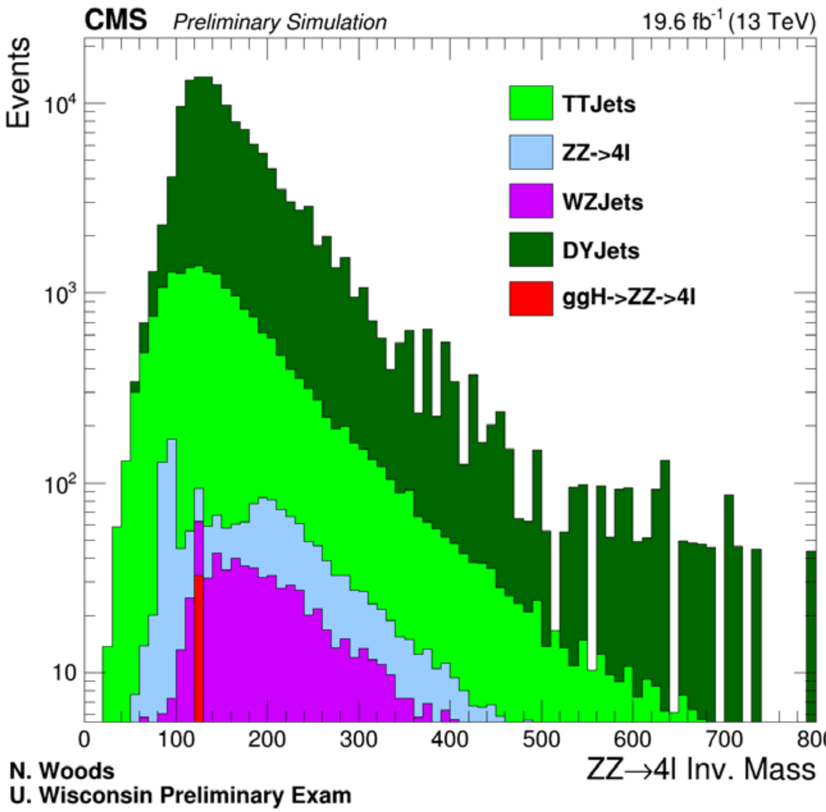
Sample	Before	After
WZ+jets	1042 ± 12	928 ± 11
$t\bar{t}$+jets	275100 ± 300	56420 ± 140
DY+jets	201100 ± 2900	155100 ± 2500
ZZ→4ℓ	1313.6 ± 4.0	1194.4 ± 3.8
gg→H→ZZ*→4ℓ	80.6 ± 0.3	48.8 ± 0.2
Total Signal	1365.6 ± 4.0	1243.2 ± 3.8
Total Background	477300 ± 2900	212500 ± 2500
Total	478600 ± 2900	213700 ± 2500



Z_1 LEPTON ID AND SELECTION



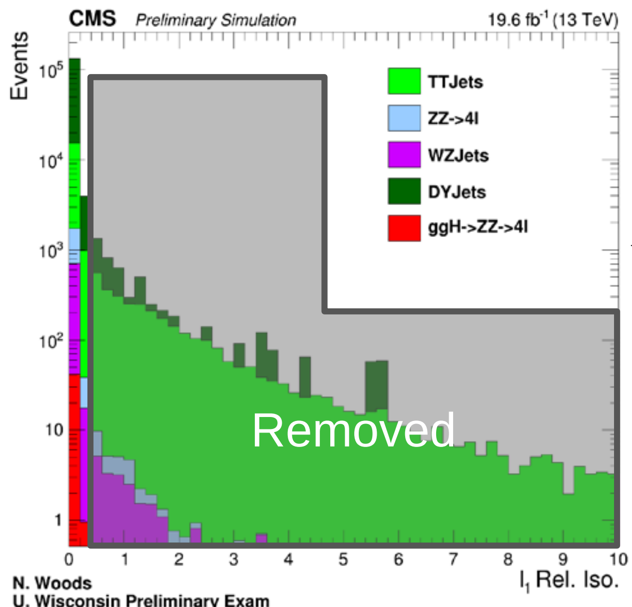
Z_1: Opposite sign, same flavor lepton pair with invariant mass closest to nominal m_Z

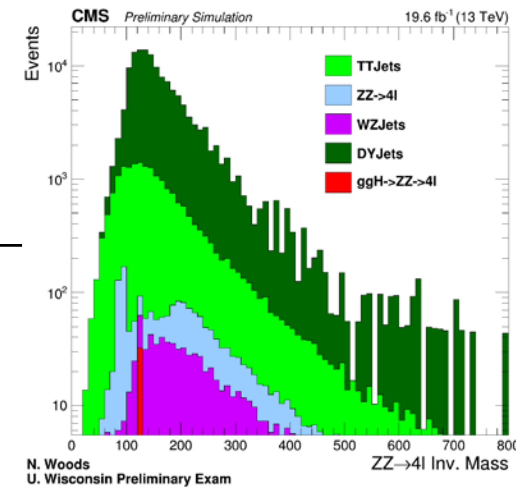


Sample	Before	After
WZ+jets	928 ± 11	704.6 ± 9.7
$t\bar{t}$+jets	56420 ± 140	17740 ± 76
DY+jets	155100 ± 2500	122400 ± 2300
ZZ→4ℓ	1194.4 ± 3.8	1055.2 ± 3.6
gg→H→ZZ*→4ℓ	48.8 ± 0.2	43.5 ± 0.2
Total Signal	1243.2 ± 3.8	1098.7 ± 3.6
Total Background	212500 ± 2500	140800 ± 2300
Total	213700 ± 2500	142900 ± 2300

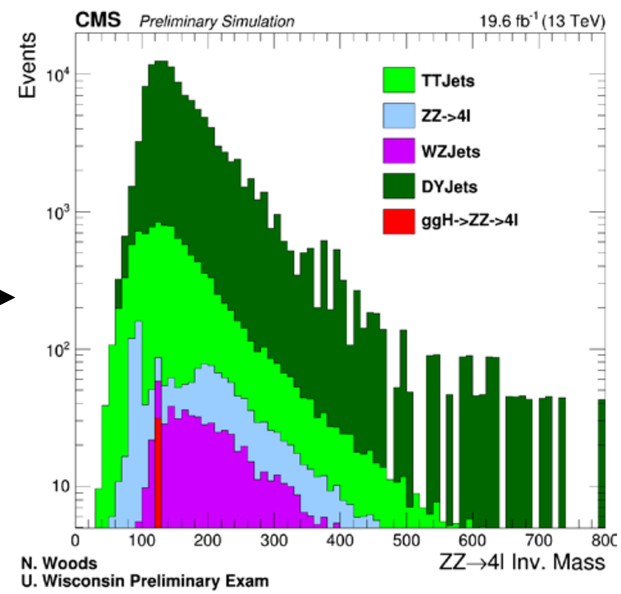
Z_1 LEPTON ISOLATION

Cut chosen to eliminate leptons in or faked by jets, reducing $t\bar{t}$ background



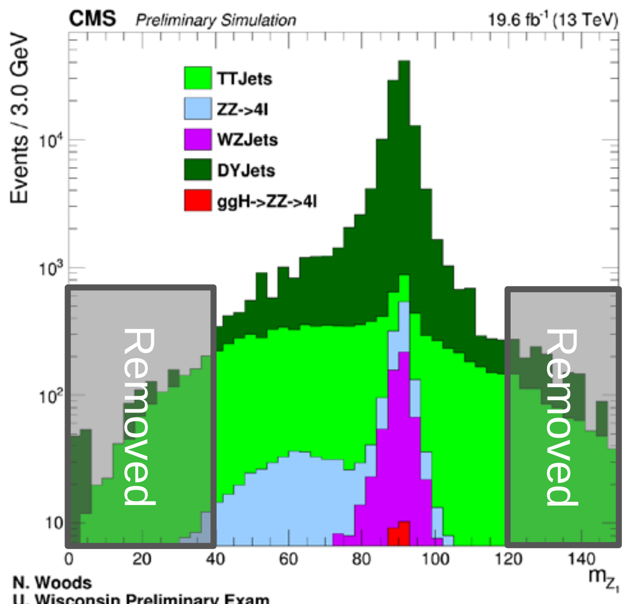


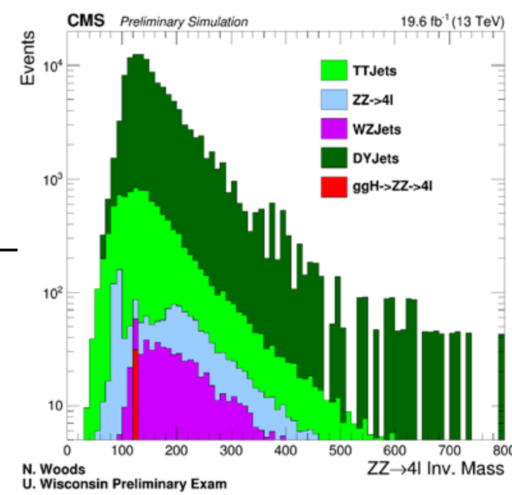
Sample	Before	After
WZ+jets	704.6 ± 9.7	616.6 ± 9.1
$t\bar{t}$+jets	17740 ± 76	9146 ± 55
DY+jets	122400 ± 2300	113400 ± 2200
ZZ→4ℓ	1055.2 ± 3.6	997.0 ± 3.5
gg→H→ZZ*→4ℓ	43.5 ± 0.2	41.0 ± 0.2
Total Signal	1098.7 ± 3.6	1038.0 ± 3.5
Total Background	140800 ± 2300	123100 ± 2200
Total	142900 ± 2300	124200 ± 2200



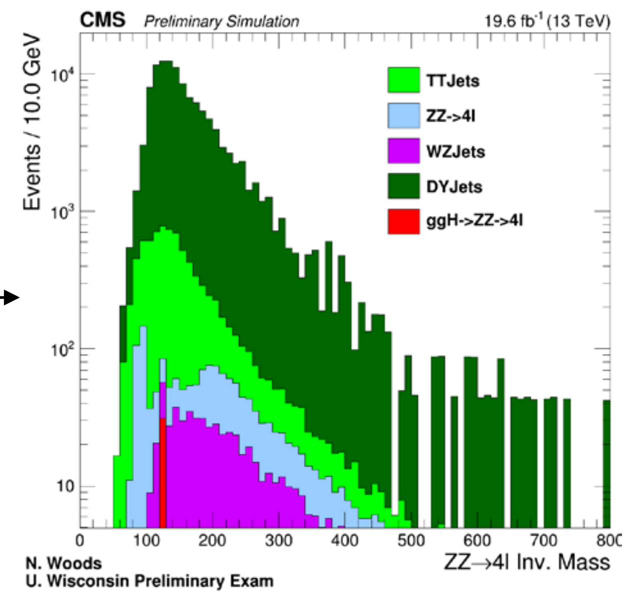
Z_1 MASS

Loose on-shell requirement: $40\ \mathrm{GeV} < m_{Z_1} < 120\ \mathrm{GeV}$
Cut chosen to eliminate events lepton pairs from photons or coincidence

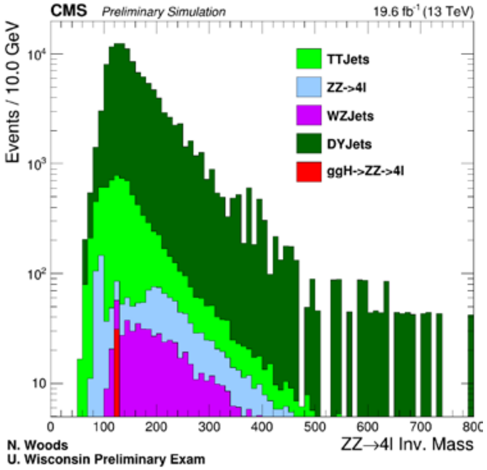




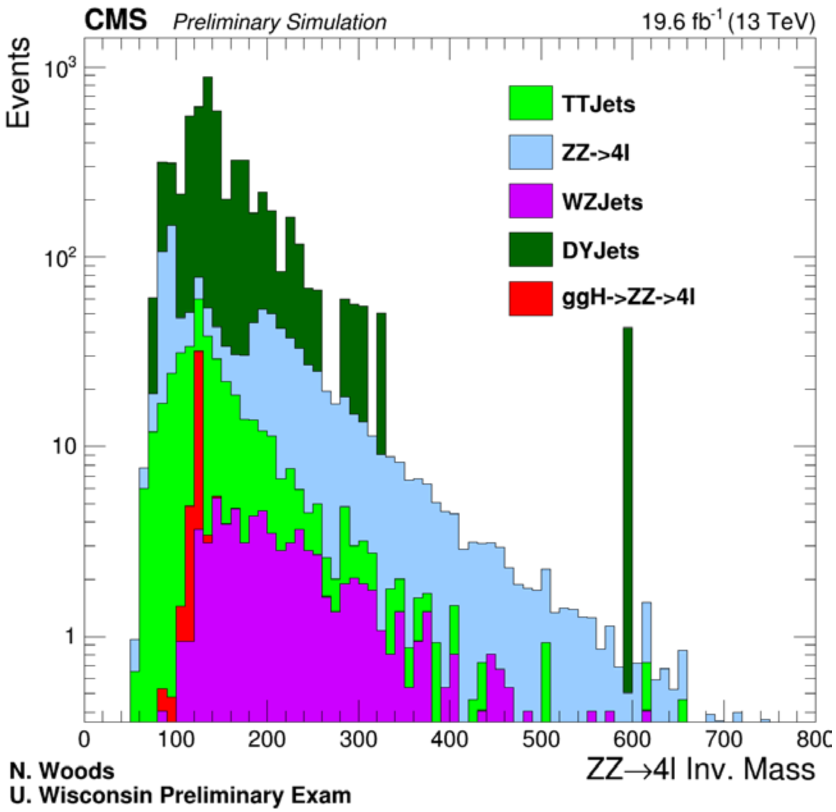
Sample	Before	After
WZ+jets	616.6 ± 9.1	584.5 ± 8.9
$t\bar{t}$+jets	9146 ± 55	6733 ± 47
DY+jets	113400 ± 2200	112100 ± 2200
ZZ→4ℓ	997.0 ± 3.5	948.4 ± 3.4
gg→H→ZZ*→4ℓ	41.0 ± 0.2	39.7 ± 0.2
Total Signal	1038.0 ± 3.5	988.2 ± 3.4
Total Background	123100 ± 2200	119400 ± 2200
Total	124200 ± 2200	120400 ± 2200



Z_2 LEPTON ID AND SELECTION



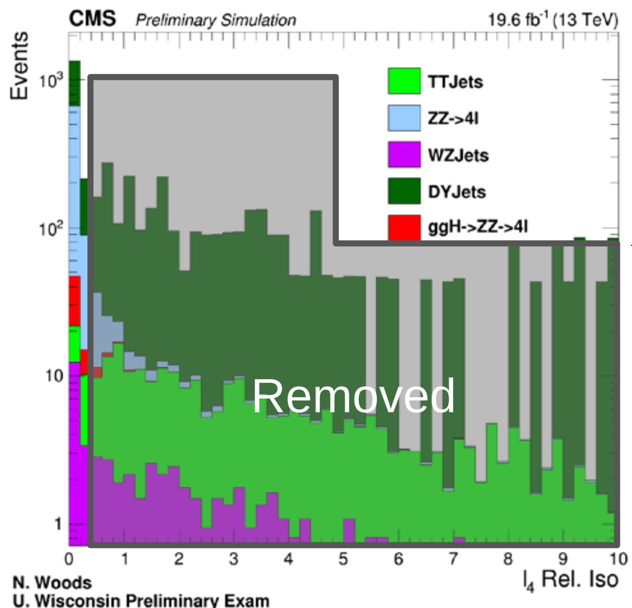
Z_2: Remaining opposite sign, same flavor lepton pair with highest scalar p_T sum

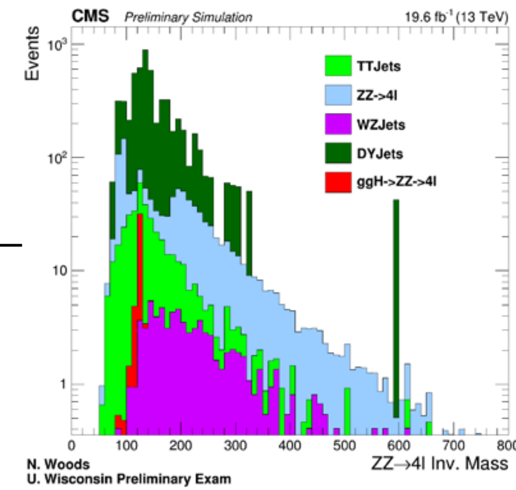


Sample	Before	After
WZ+jets	584.5 ± 8.9	80.4 ± 3.3
$t\bar{t}$+jets	6733 ± 47	300.5 ± 9.9
DY+jets	112100 ± 2200	4720 ± 440
ZZ→4ℓ	948.4 ± 3.4	747.3 ± 3.0
gg→H→ZZ*→4ℓ	39.7 ± 0.2	33.5 ± 0.2
Total Signal	988.2 ± 3.4	780.8 ± 3.0
Total Background	119400 ± 2200	5100 ± 440
Total	120400 ± 2200	5880 ± 440

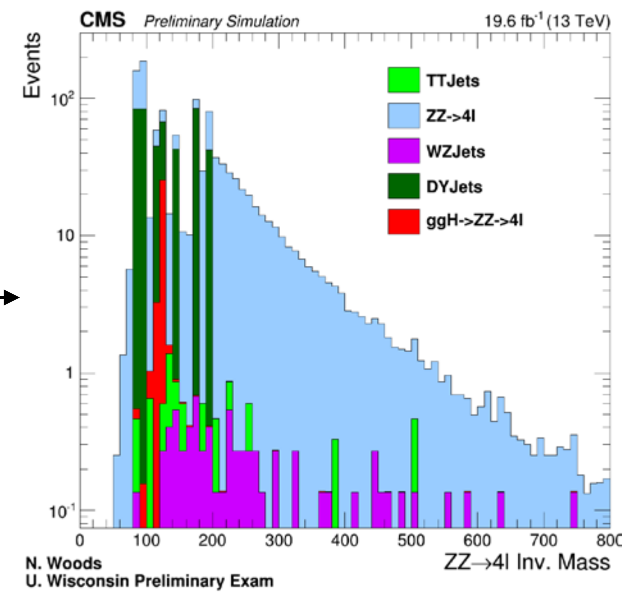
Z_2 LEPTON ISOLATION

Many events have a real Z; many fewer have two.





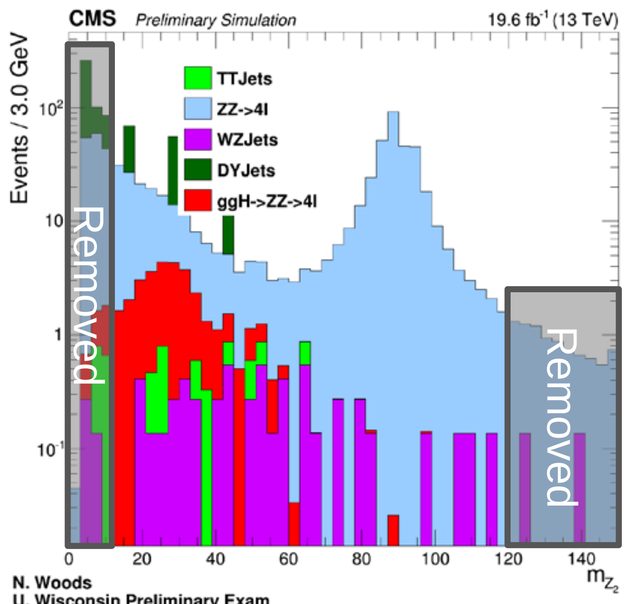
Sample	Before	After
WZ+jets	80.4 ± 3.3	8.0 ± 1.0
$t\bar{t}$+jets	300.5 ± 9.9	4.9 ± 1.3
DY+jets	4720 ± 440	420 ± 130
ZZ→4ℓ	747.3 ± 3.0	668.6 ± 2.8
gg→H→ZZ*→4ℓ	33.5 ± 0.2	33.5 ± 0.2
Total Signal	780.8 ± 2.8	697.6 ± 2.8
Total Background	5100 ± 440	430 ± 130
Total	5880 ± 440	1130 ± 130

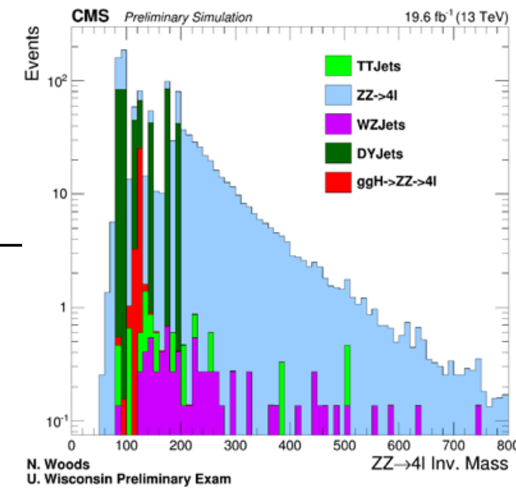


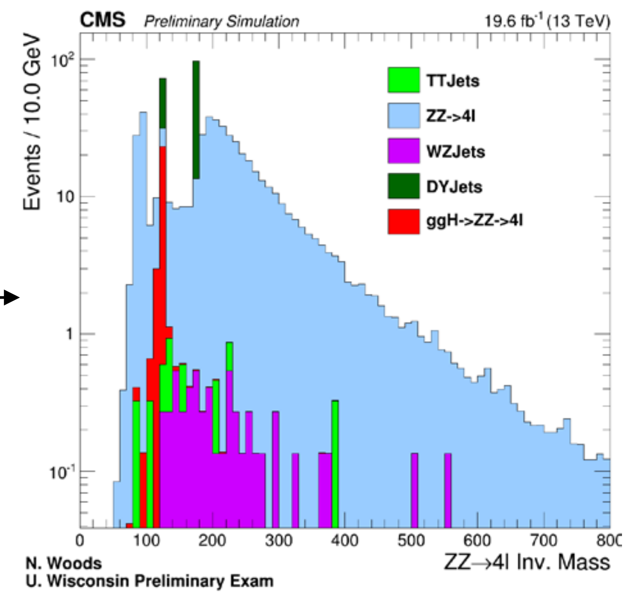
Z_2 MASS

May be off-shell:
$12 \text{ GeV} < m_{Z_2} < 120 \text{ GeV}$

Statistics issue: Drell-Yan contribution comes from only 3 simulated events. This background will eventually be estimated with data driven methods.

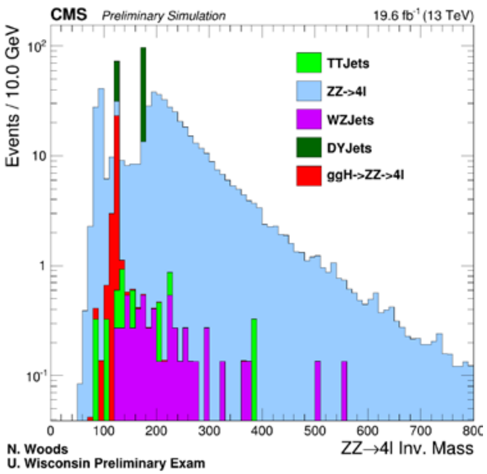




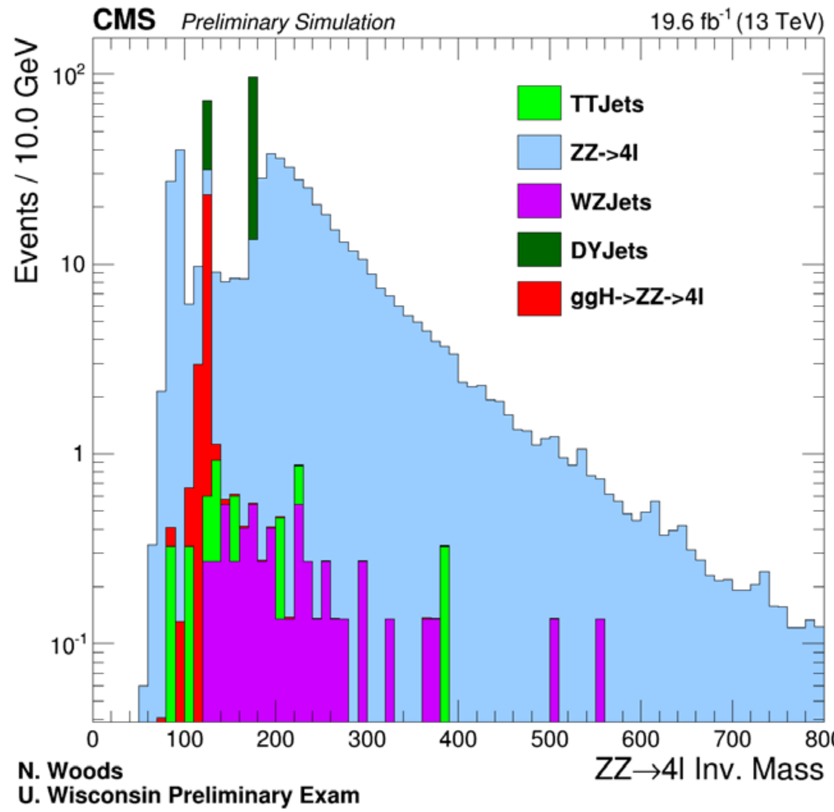


Sample	Before	After
WZ+jets	8.0 ± 1.0	5.7 ± 0.9
$t\bar{t}$+jets	4.9 ± 1.3	2.9 ± 1.0
DY+jets	420 ± 130	125 ± 72
ZZ→4ℓ	668.6 ± 2.8	496.3 ± 2.4
gg→H→ZZ*→4ℓ	33.5 ± 0.2	26.6 ± 0.2
Total Signal	697.6 ± 2.8	522.9 ± 2.4
Total Background	430 ± 130	134 ± 72
Total	1130 ± 130	657 ± 72

LEPTON P_T AND PAIR MASS

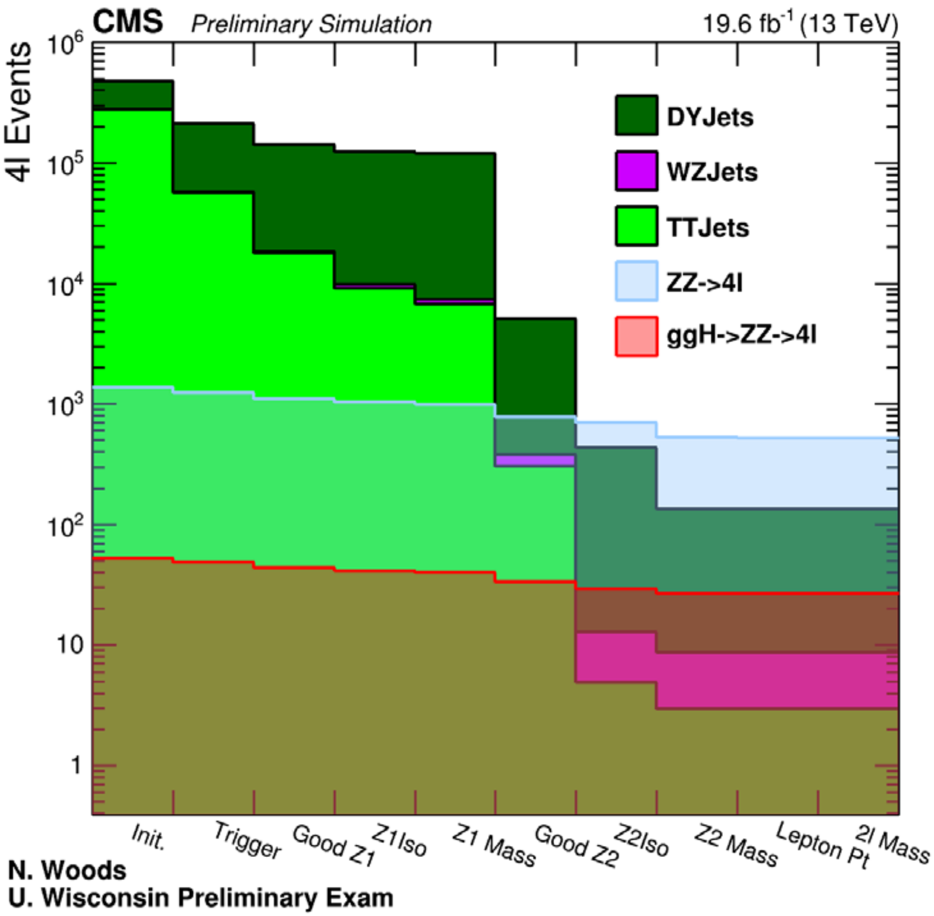


$$p_T^{\ell_1} > 20\text{ GeV},$$
$$p_T^{\ell_2} > 10\text{ GeV}$$
$$m_{\ell^+\ell'^-} > 4\text{ GeV}$$



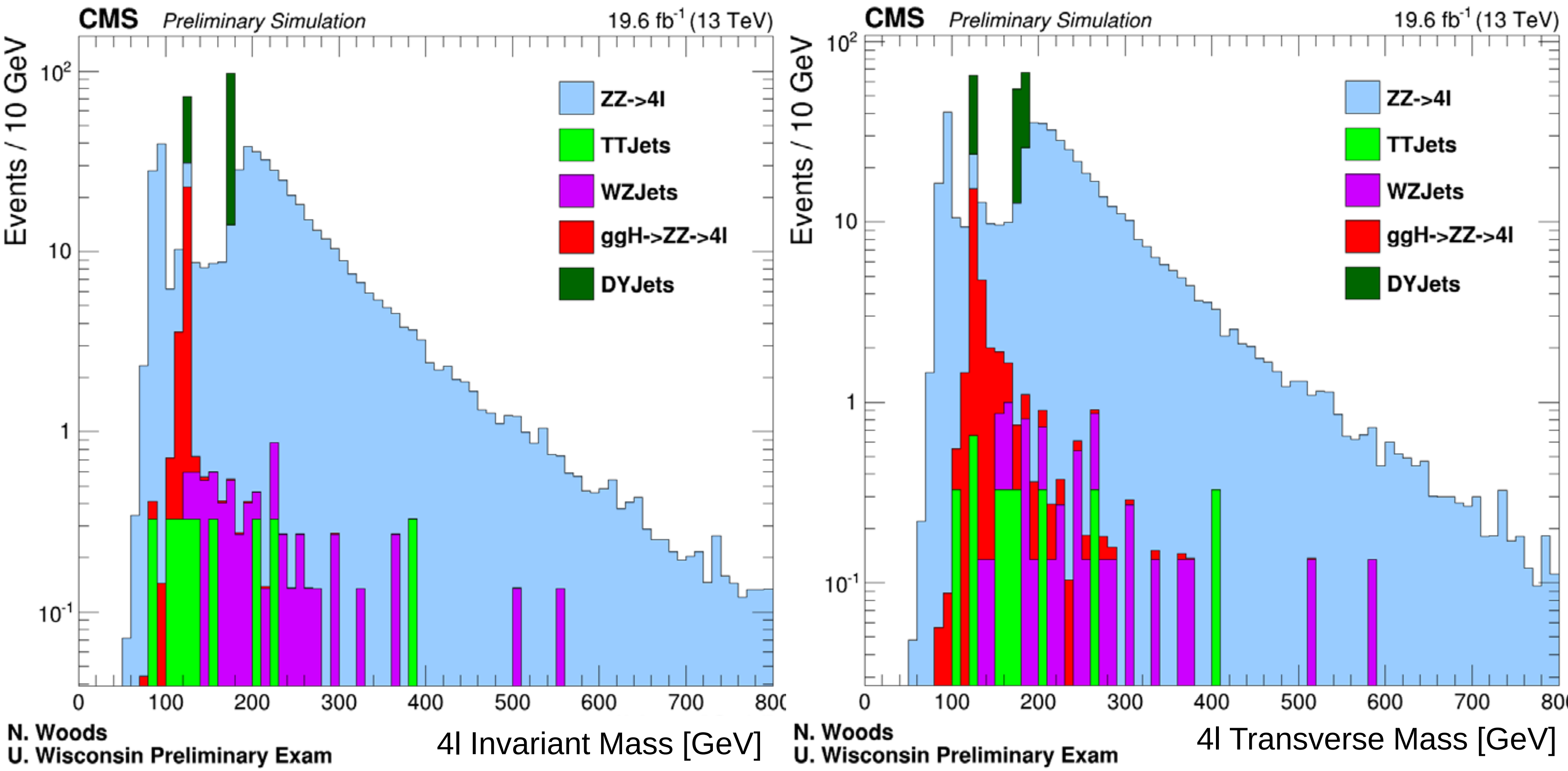
Sample	Before	After
WZ+jets	5.7 ± 0.9	5.7 ± 0.9
$t\bar{t}$+jets	2.9 ± 1.0	2.9 ± 1.0
DY+jets	125 ± 72	125 ± 72
ZZ→4ℓ	496.3 ± 2.4	494.3 ± 2.4
gg→H→ZZ*→4ℓ	26.6 ± 0.2	26.5 ± 0.2
Total Signal	522.9 ± 2.4	520.8 ± 2.4
Total Background	134 ± 72	134 ± 72
Total	657 ± 72	655 ± 72

CUT FLOW



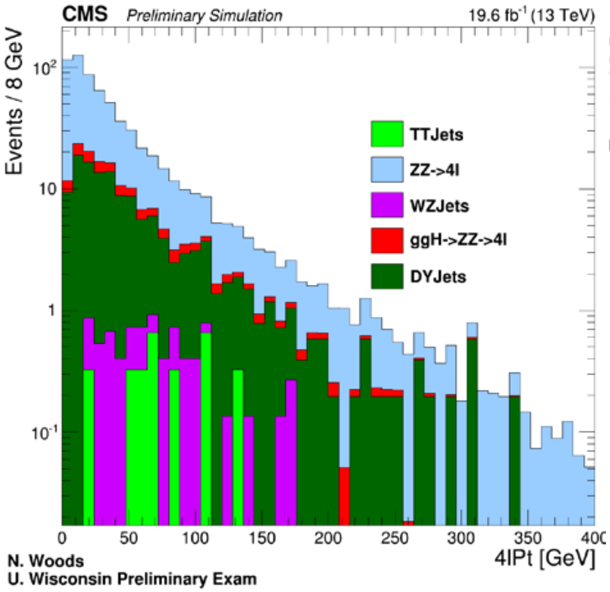
Cut	Signal	Background
Initial	1365.6 ± 4.0	477300 ± 2900
Trigger	1243.2 ± 3.8	212500 ± 2500
Z_1 Leptons	1098.7 ± 3.6	140800 ± 2300
Z_1 Isolation	1038.0 ± 3.5	1231 ± 2200
Z_1 Mass	988.2 ± 3.4	119400 ± 2200
Z_2 Leptons	780.8 ± 3.0	5100 ± 440
Z_2 Isolation	697.6 ± 2.8	430 ± 130
Z_2 Mass	522.9 ± 2.4	130 ± 72
Final	520.8 ± 2.4	130 ± 72

SIMULATED 4L MASS SPECTRUM

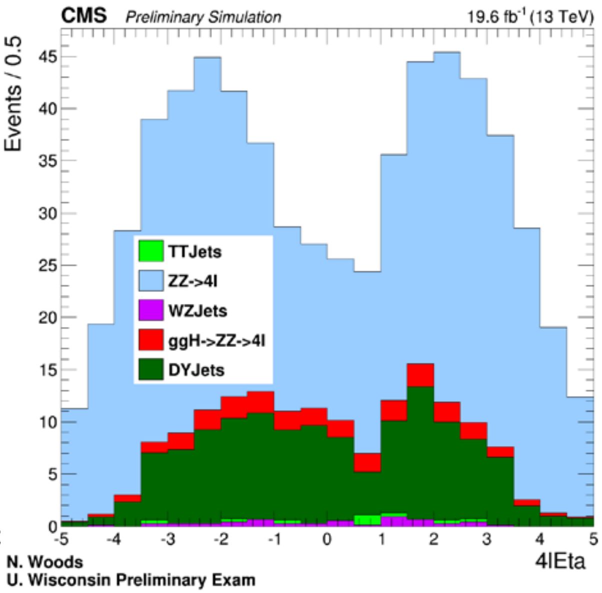


~650 events expected at $19.6\ \mathrm{fb}^{-1}$ (~520 signal)

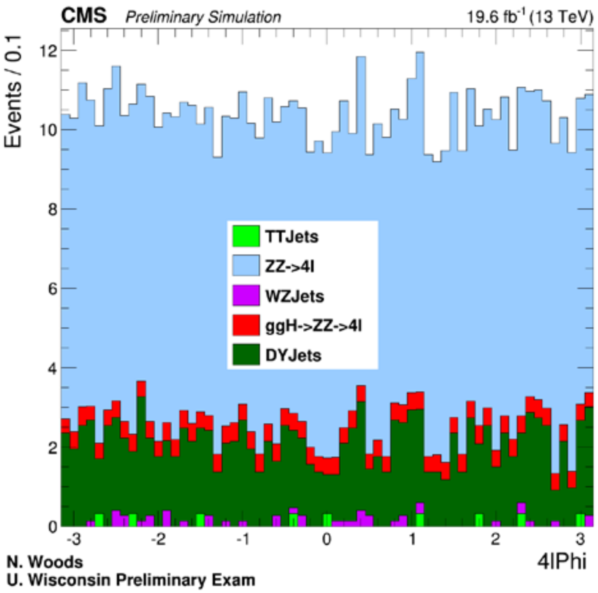
SIMULATED 4L KINEMATICS



4l p_T [GeV]



4l η

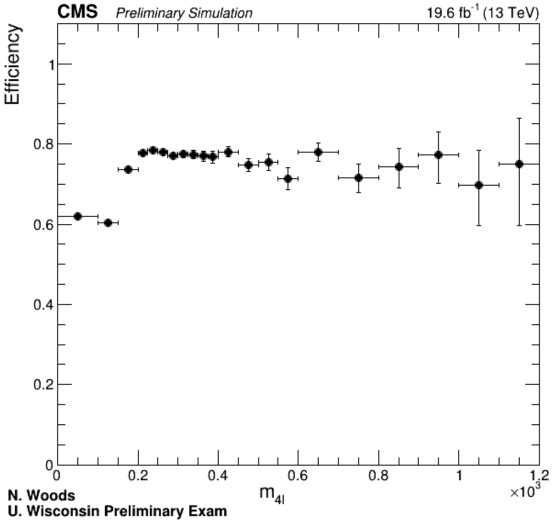


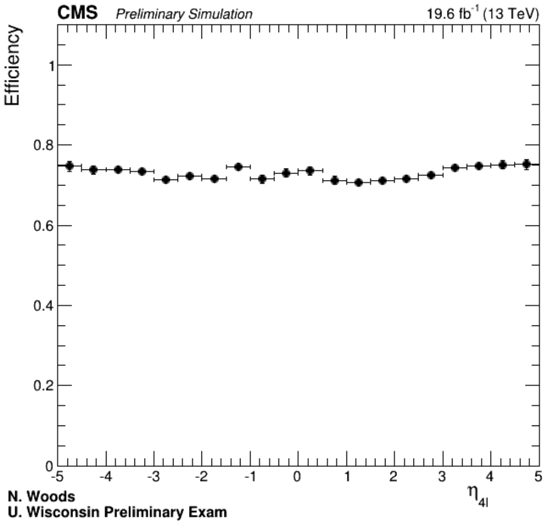
4l ϕ

Drell-Yan spectrum shape is extrapolated and normalized to the same number of total events, due to the statistics issue mentioned previously.

SELECTION EFFICIENCY

- **Efficiency: fraction of generated events inside the fiducial volume passing analysis cuts after reconstruction**
- **Required to find cross section from measurement**
- **“Clean” 4l signal allows good background rejection even with very loose cuts, allowing high signal efficiency**





IMMEDIATE 13TeV OUTLOOK

- **ZZ and Higgs cross sections both expected to be ~2x higher at 13 TeV than at 8 TeV, but conditions will require some analysis changes**
  - High pileup requires isolation definition changes
  - Cuts shown here must be tuned in light of data
  - Higher p_T thresholds and isolation cuts at trigger level
- **Z + X background can be estimated from data**
- **Expected inclusive cross sections are large enough to be measured with first ~1fb^{-1}**

RUN II OUTLOOK

- **CMS with 19.6 fb^{-1} at $\sqrt{s} = 8$ TeV:**

$$\sigma_{pp\to ZZ} = 7.7\ \text{pb} \pm 6\%(\text{stat.})^{+6\%}_{-5\%}(\text{syst.}) \pm 5\%(\text{theo.}) \pm 4\%(\text{lum.})$$

$$\sigma_{H\to ZZ^*}/\sigma_{SM} = 0.93^{+28\%}_{-25\%}(\text{stat.})^{+14\%}_{-10\%}(\text{syst.})$$

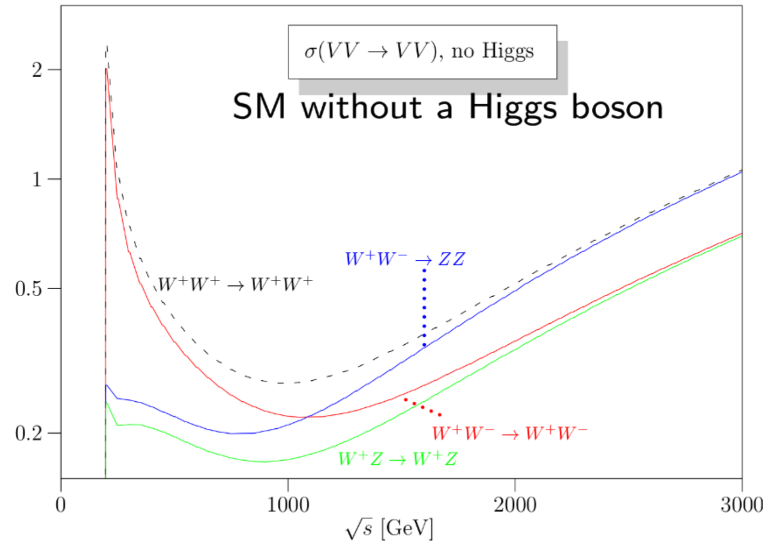
$$m_H = 125.6 \pm 0.4(\text{stat.}) \pm 0.2(\text{syst.})\ \text{GeV}$$

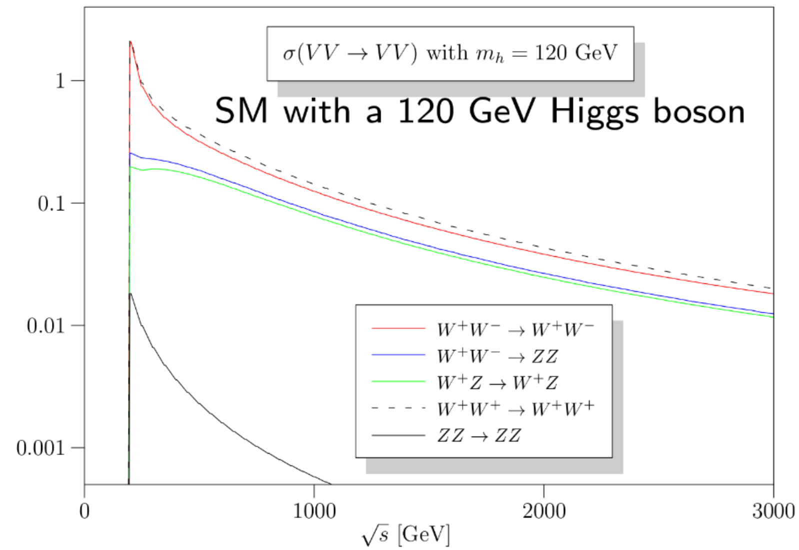
- **With more data, differential cross sections can be measured and electroweak couplings probed. With 70 fb^{-1}:**
  - We expect statistical uncertainty on $\sigma_{pp\to ZZ}$ around 3%, on $\sigma_{H\to ZZ^*}/\sigma_{SM}$ around 11%, on m_H around 0.2 GeV
  - With better reduction of background systematics and smaller PDF and α_s uncertainties, total uncertainty might be reduced
  - With statistical uncertainty on inclusive measurements comparable to or smaller than systematic uncertainty, we can
    - Measure differential cross sections
    - Measure production modes separately
    - Set limits on deviations from Standard Model couplings

BACKUP

VV SCATTERING

- **Higgs boson required by SM to maintain unitarity for vector boson scattering at $\sqrt{s} \gtrsim 1.2$ TeV**





NLO/NNLO CONTRIBUTION TO $\sigma_{pp \to ZZ}$

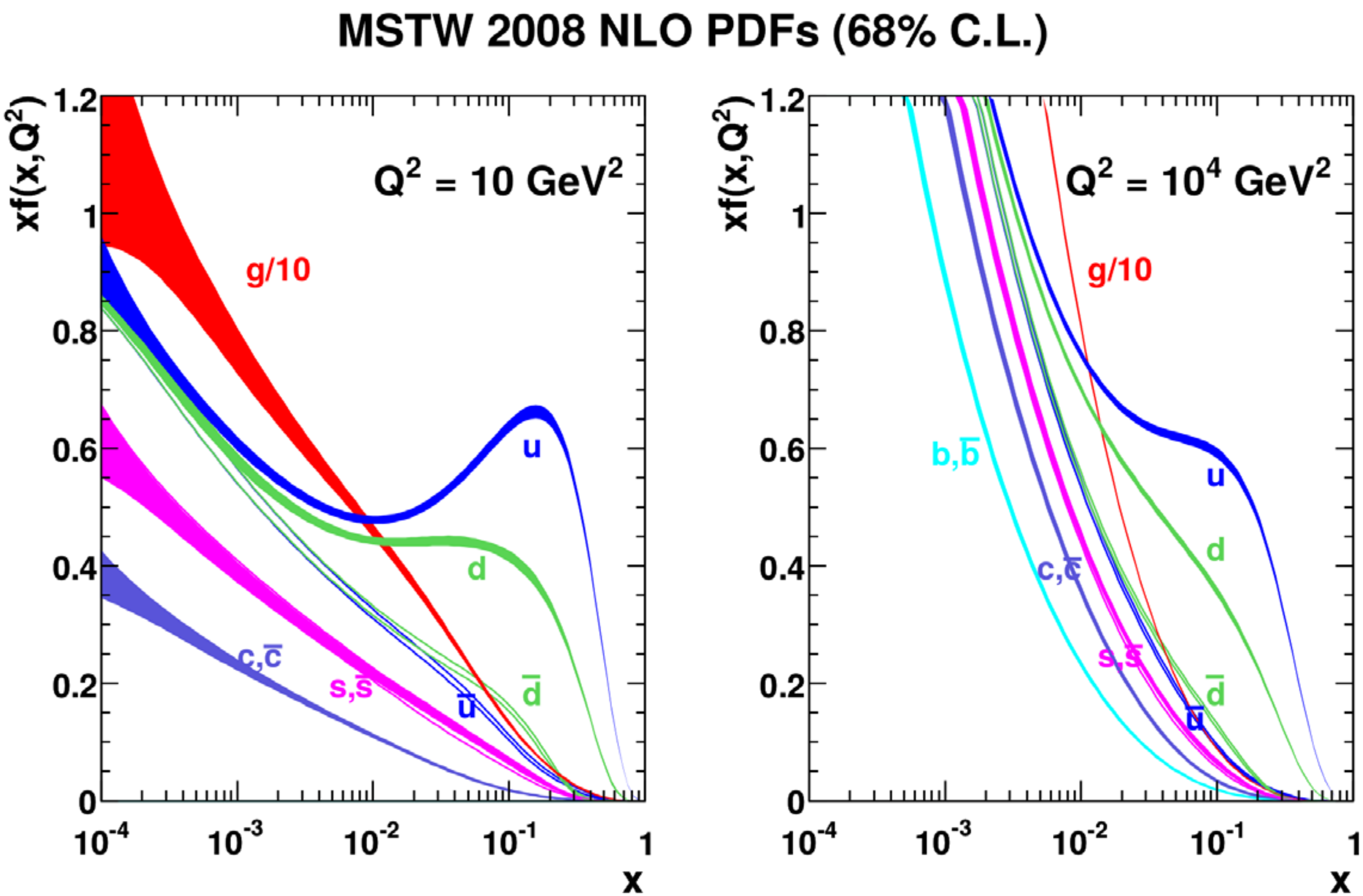
$\sqrt{s}$ [TeV]	$\sigma^{LO}(ZZ)$ [pb]	$\sigma^{NLO}(ZZ)$ [pb]
7	4.17(0)	$6.46(0)^{+4.7\%}_{-3.3\%}$
8	5.06(0)	$7.92(0)^{+4.7\%}_{-3.0\%}$
9	5.98(0)	$9.46(0)^{+4.3\%}_{-3.0\%}$
10	6.93(0)	$11.03(0)^{+4.1\%}_{-2.9\%}$
11	7.90(0)	$12.65(1)^{+3.9\%}_{-2.8\%}$
12	8.89(1)	$14.31(1)^{+3.6\%}_{-2.7\%}$
13	9.89(1)	$15.99(1)^{+3.7\%}_{-2.6\%}$
14	10.92(1)	$17.72(1)^{+3.5\%}_{-2.5\%}$

gg diagrams included (NNLO)

Table 9: Total cross sections for ZZ production as a function of energy. The renormalisation scale and factorisation scales are $\mu_R = \mu_F = M_Z$. Vector bosons are produced exactly on-shell and no decays are included.

arXiv:1105.0020v1 [hep-ph]

EXAMPLE PDFS



INTERACTION LENGTHS TO REACH DETECTOR

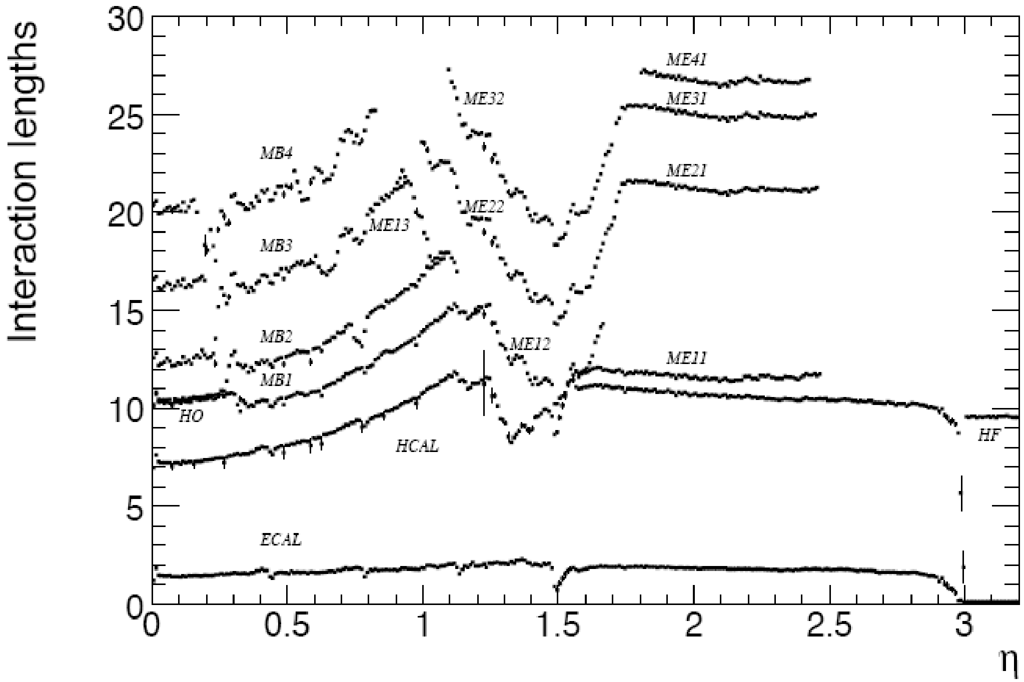
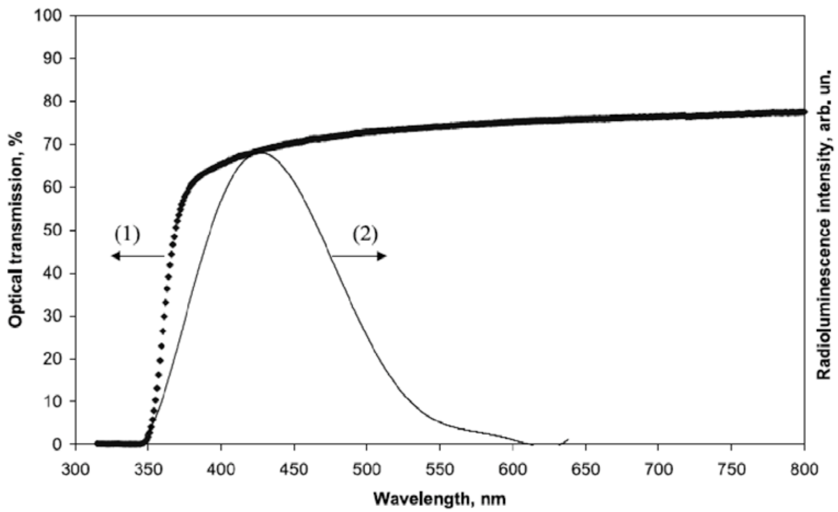


Figure 1.4: Material thickness in interaction lengths after the ECAL, HCAL, and at the depth of each muon station as a function of pseudorapidity. The thickness of the forward calorimeter (HF) remains approximately constant over the range $3 < |\eta| < 5$ (not shown).

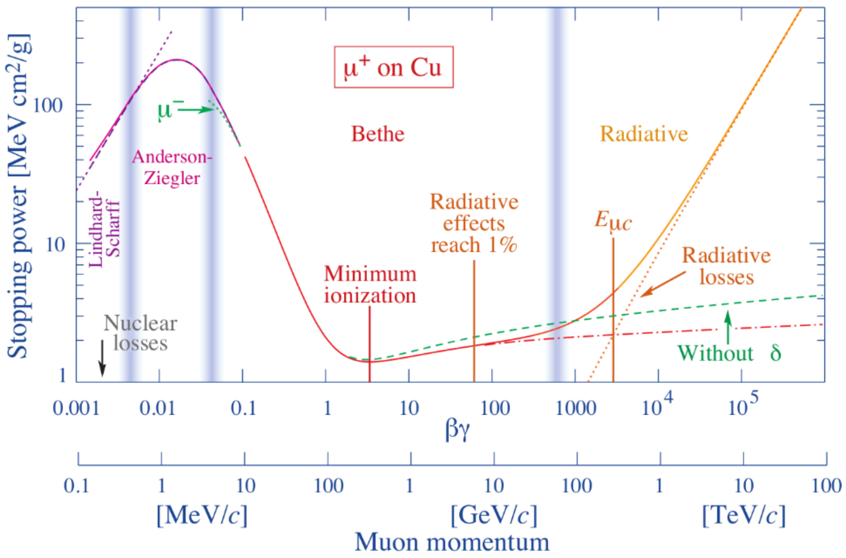
$PbWO_4$ PROPERTIES

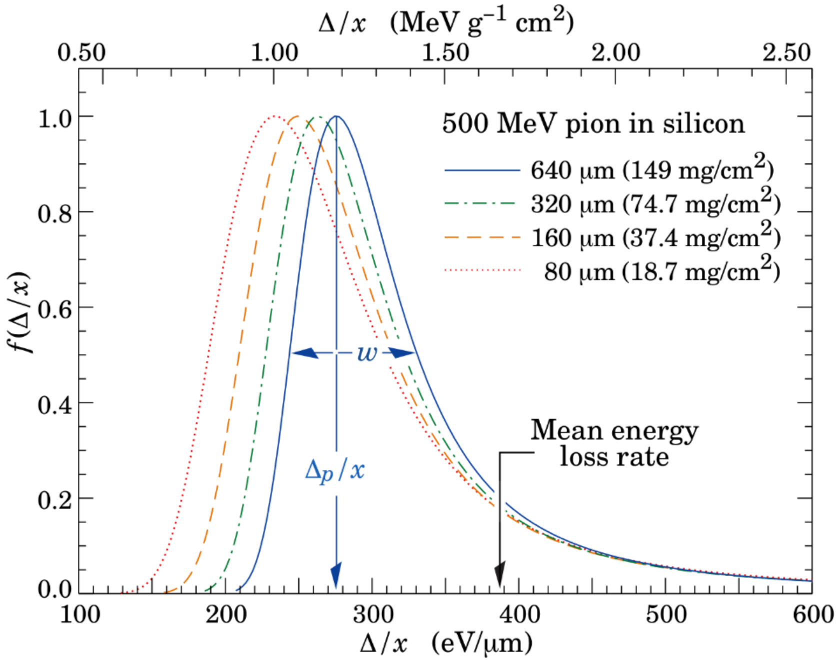
$PbWO_4$	
Density [g/cm^3]	8.28
Molière Radius [cm]	2.19
Radiation Length [cm]	0.85
80% emission time [ns]	25
Emission spectrum peak [nm]	~430
Light yield [photons / MeV of particle]	100



CHARGED PARTICLES IN MATTER

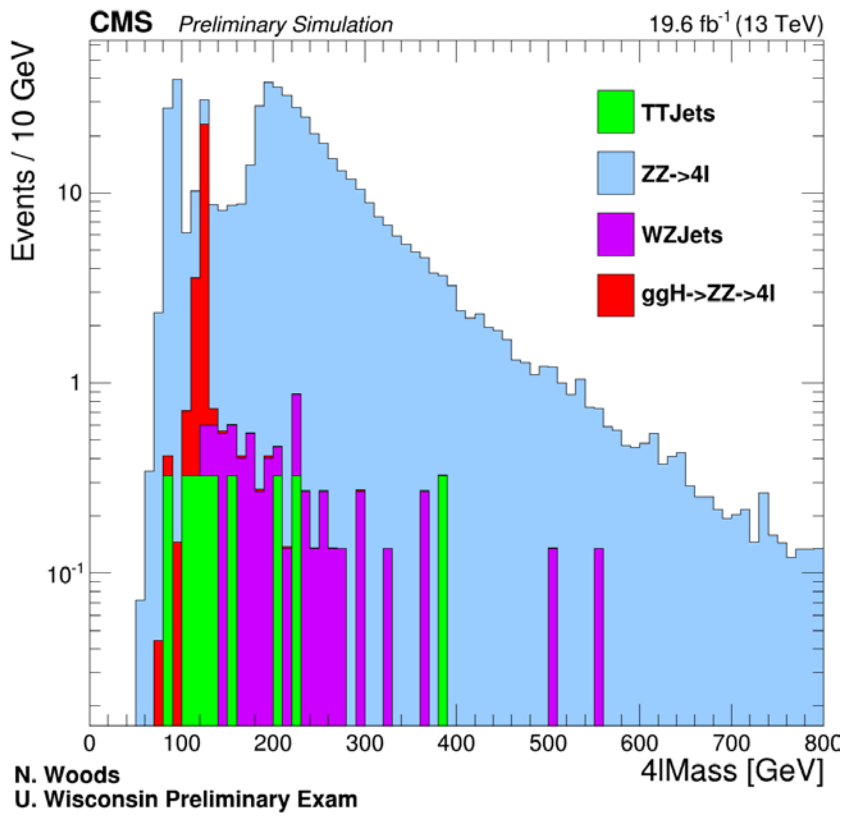
- **Rules of thumb:**
  - 1.5 MeV/(g/cm^2) for Z/A=1
  - 1.2 GeV/m for muon in thick absorber like return yoke





SPECTRUM WITHOUT DRELL YAN

- **Overall Drell Yan contribution expected to be small, results above likely a statistical fluke**
- **Spectrum without it is more similar to what we expect from data**
- **Plots with extrapolated shape created by cutting only on lepton pt and eta and Z candidate mass, and scaling the resulting spectrum to the same integrated number of events**
- **Note: all 3 passing events are in 4μ channel**



SPECTRUM WITH UNMODIFIED DRELL YAN