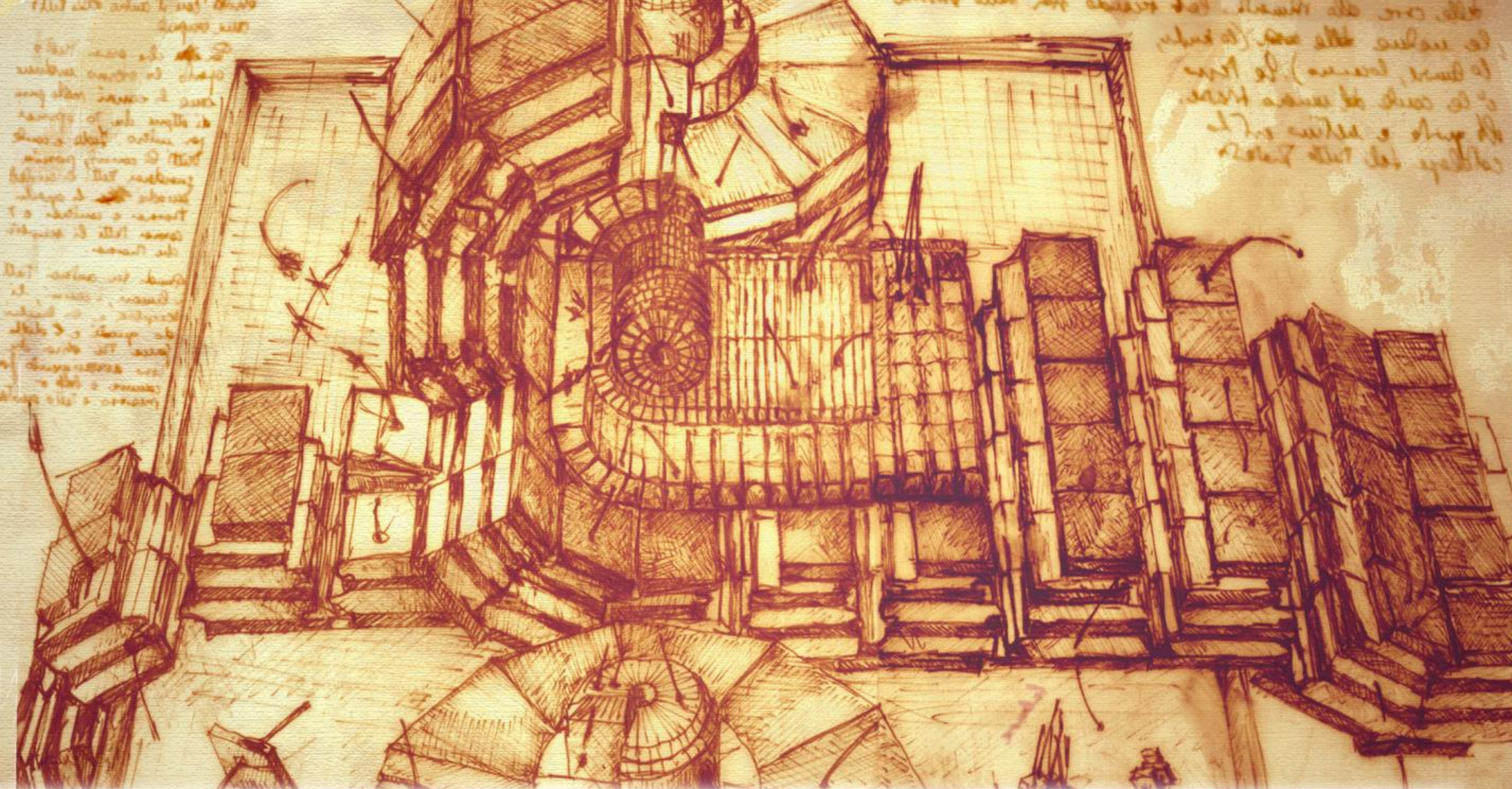


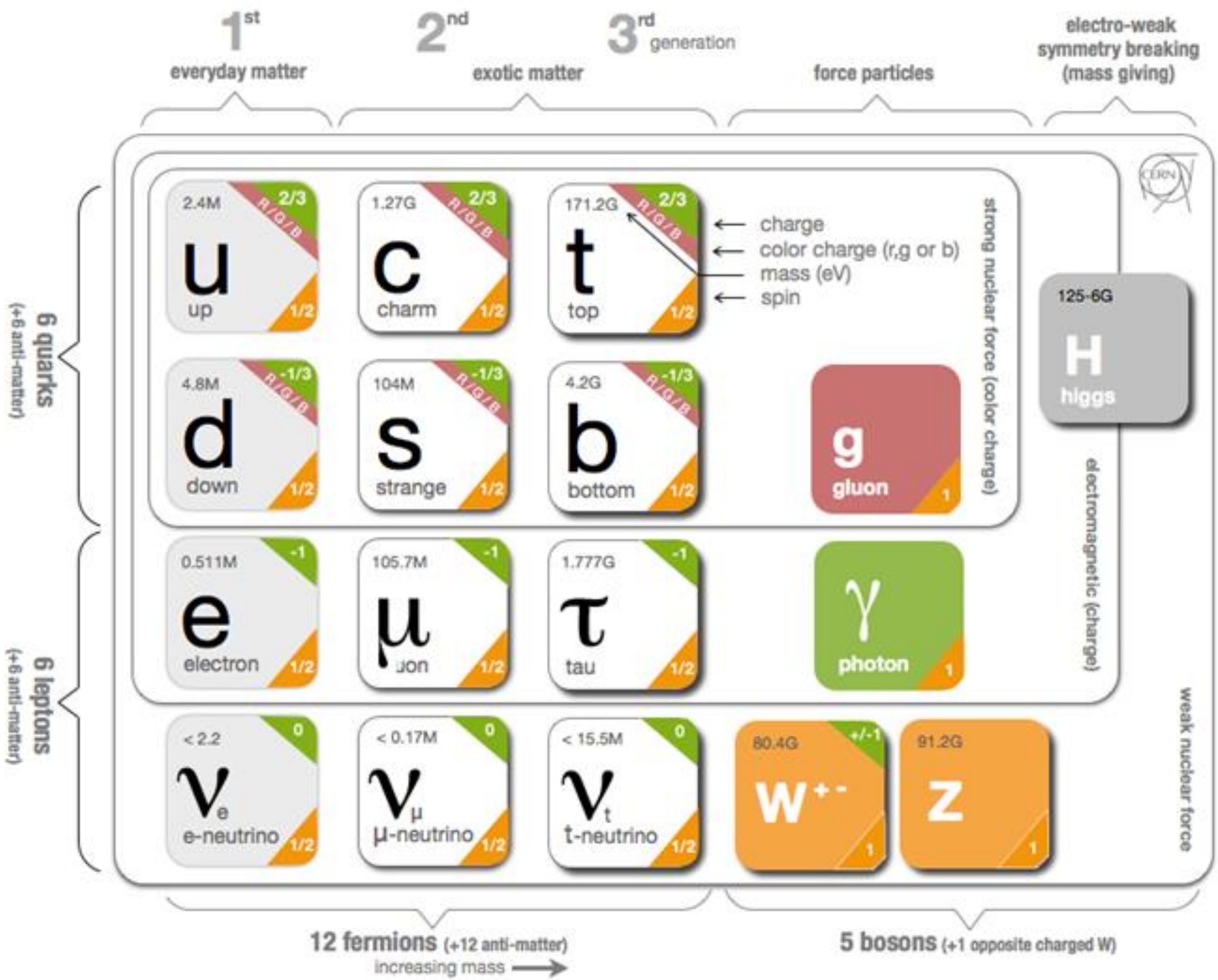
A Search for Doubly Charged Higgs Production at 8 TeV Using the CMS Detector at the LHC

Devin Taylor – UW-Madison – Preliminary Examination

Outline

- The Standard Model
- Doubly Charged Higgs
  - Motivation
  - Type II Seesaw Mechanism
- The Large Hadron Collider
- CMS Detector
- CMS Cathode Strip Chamber System
- Analysis
  - Monte Carlo Production
  - Reconstruction of Data
  - Event Selection
  - Expected Limits
- 13 TeV Outlook
- Conclusions and Going Forward

The Standard Model



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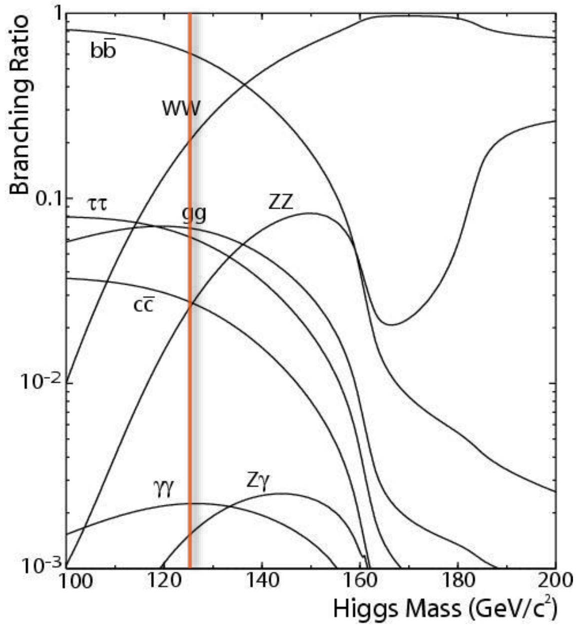
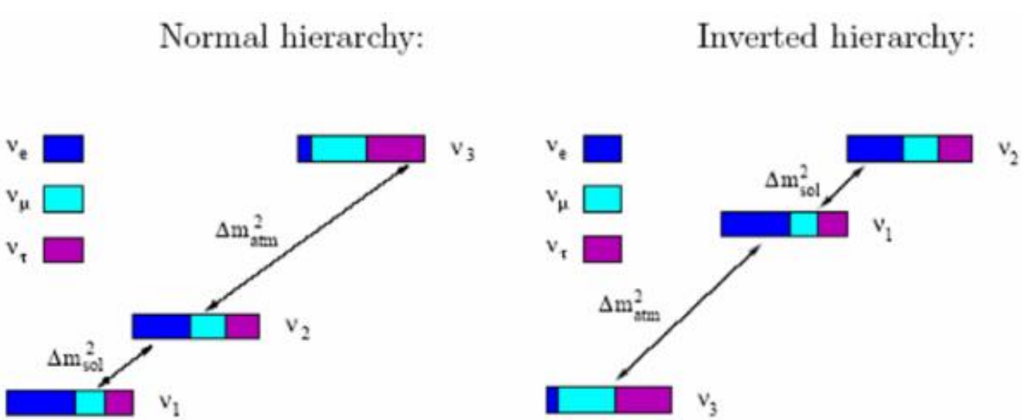
The Standard Model Higgs

- The standard model Higgs gives mass to the gauge bosons via symmetry breaking
  - Without this mechanism, they would be massless
  - Acquires a vacuum expectation value (vev) of 246 GeV
- The standard model Higgs could be part of a larger non-standard model Higgs multiplet
- Announcement of the discovery of a particle matching the Higgs boson at ~125 GeV on July 4, 2012 by CMS and ATLAS GeV



Neutrino Mixing

- Atmospheric and solar neutrino oscillation experiments have shown neutrinos do have mass
  - Three mixing angles θ_{12}, θ_{13}, and θ_{23} and one CP violating phase δ
  - Three masses m_1, m_2, and m_3
- Atmospheric oscillation experiments cannot measure sign of the splitting
  - Gives rise to two possible orderings, normal and inverted hierarchy
- The mixing angles have also been measured



Neutrino Parameter	Value
Δm_{sol}^2	(7.53 ± 0.18)e-5 eV^2
Δm_{atm}^2	± 2.4e-3 eV^2
$\sin^2(2\theta_{13})$	0.093 ± 0.008
$\sin^2(2\theta_{23})$	~1
$\sin^2(2\theta_{12})$	0.846 ± 0.021

Doubly Charged Higgs Motivation

- Experimental evidence of non-zero neutrino masses
  - Observation of neutrino oscillations provide evidence of non-zero neutrino masses
  - Cosmological observations give most stringent upper bounds of neutrino masses
    - Sum of neutrino masses < 0.32 eV
  - Many parameters not measurable in oscillation experiments
    - Mass hierarchy
    - Lightest neutrino mass
    - Majorana phases
  - Yukawa coupling to standard model Higgs would not naturally result in such small masses
- Light standard model Higgs boson
  - Such a small mass relative to the Planck scale
- Type II seesaw mechanism possible explanation (next slide)
  - Can result in small masses for left-handed neutrinos
  - Gives rise to a Higgs triplet

Type II Seesaw Mechanism

- Includes a Higgs triplet, Φ

$$SU(2)_L \times U(1)_Y, \Phi\ (3,2)$$

- Gives rise to a new interaction term that allows lepton flavor violation

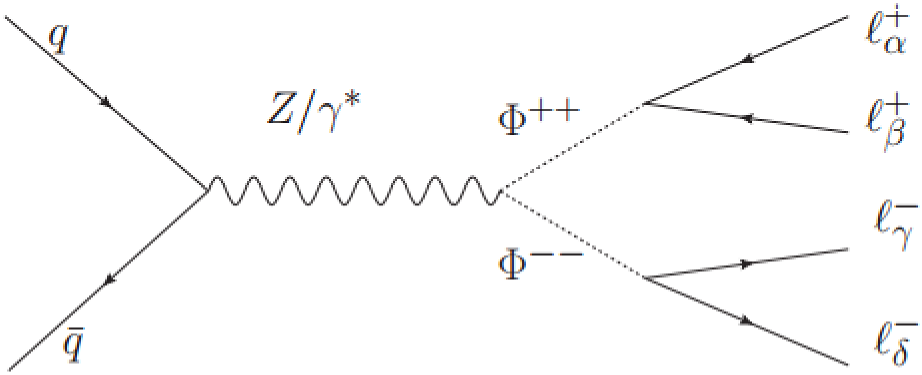
$$L = i\overline{\ell^c_{Li}}\tau_2 Y^{ij}_{\Phi}(\tau \cdot \Phi)\ell_{Lj} + h.c.$$

$$\Phi = \begin{pmatrix} \frac{\Phi^+}{\sqrt{2}} & \Phi^{++} \\ \Phi^0 & \frac{-\Phi^+}{\sqrt{2}} \end{pmatrix}$$

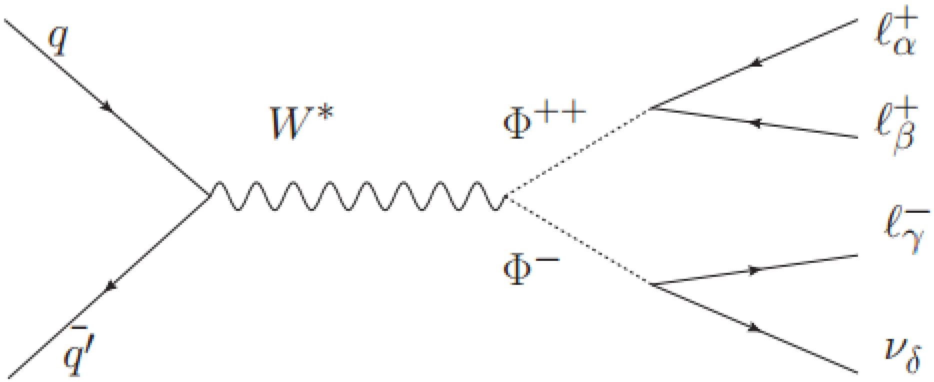
- Φ vacuum expectation value arises from the neutral component coupling to the standard model Higgs doublet (not symmetry breaking)
- The decay to W^+W^+ is suppressed with the assumption that the VEV is small
  - Natural assumption from non-observation in precision data and small neutrino masses
- Neutrino masses (in flavor basis) would then be extracted from the mass of the Φ^{++} and Yukawa coupling strengths (and thus the branching fractions to various lepton final states)

Pair and Associated Production

- Pair production
  - 4 lepton final states



- Associated production
  - 3 lepton final states
  - The focus of this talk



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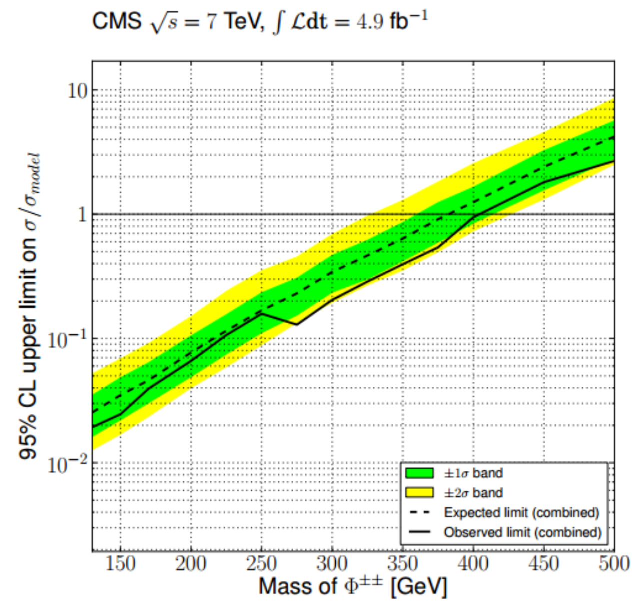
Current Experimental Limits

- Limits at LHC
  - CMS
    - e, μ, τ with 4.9 fb^{-1} (7 TeV)
    - 3 and 4 lepton final states
  - Atlas
    - e, μ with 4.7 fb^{-1} (7 TeV) and 20.3 fb^{-1} (8 TeV)
    - 2 lepton final state

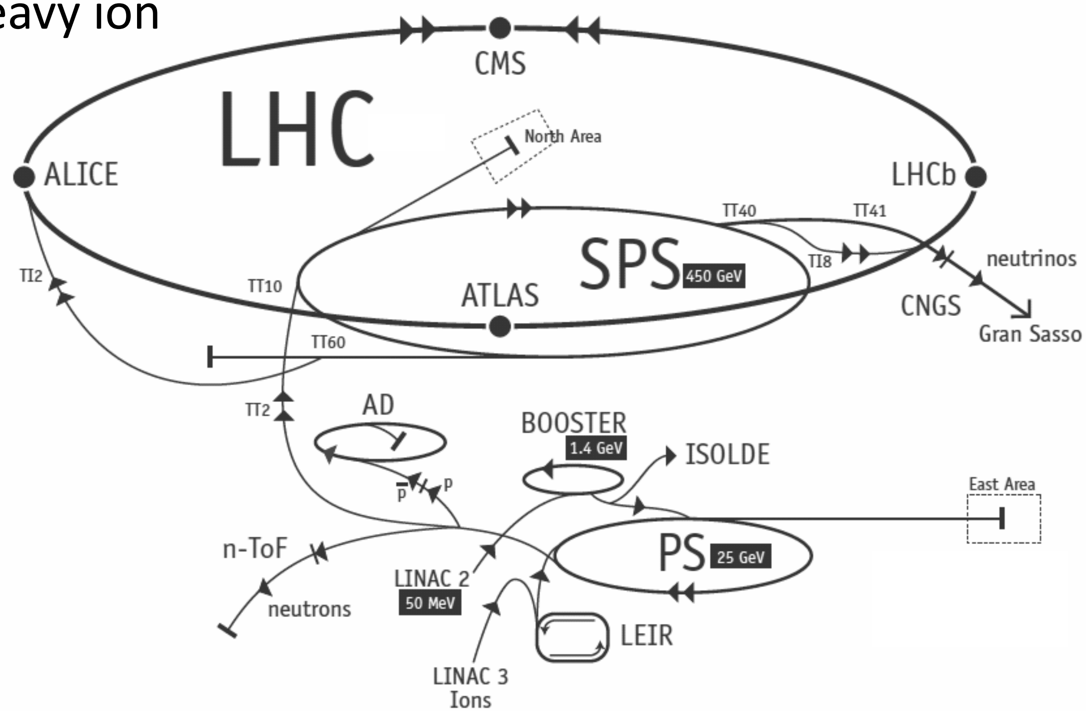


Scenario	CMS 7 TeV	CMS 8 TeV	ATLAS 7 TeV	ATLAS 8 TeV
$BR(\Phi^{\pm\pm} \to e^{\pm}e^{\pm}) = 100\%$	445 GeV		409 GeV	551 GeV
$BR(\Phi^{\pm\pm} \to e^{\pm}\mu^{\pm}) = 100\%$	455 GeV		375 GeV	468 GeV
$BR(\Phi^{\pm\pm} \to e^{\pm}\tau^{\pm}) = 100\%$	410 GeV	This Analysis ($19.7\ fb^{-1}$)	–	–
$BR(\Phi^{\pm\pm} \to \mu^{\pm}\mu^{\pm}) = 100\%$	459 GeV		398 GeV	516 GeV
$BR(\Phi^{\pm\pm} \to \mu^{\pm}\tau^{\pm}) = 100\%$	396 GeV		–	–
$BR(\Phi^{\pm\pm} \to \tau^{\pm}\tau^{\pm}) = 100\%$	228 GeV		–	–
Equal Branching Fractions	441 GeV		–	–

The Large Hadron Collider

- Proton-proton collider near Geneva, Switzerland
  - 27 km circumference
  - Design center of mass energy of 14 TeV
- 4 Experiments
  - ATLAS, CMS: general purpose
  - LHCb: b-physics
  - Alice: heavy ion

Year	LHC Energy
2010-2011	7 TeV
2012	8 TeV
2015	13 TeV



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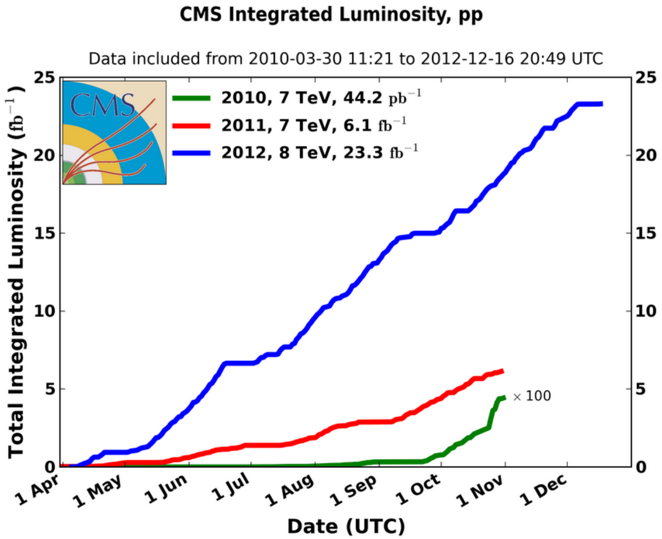
Luminosity and Beam Parameters

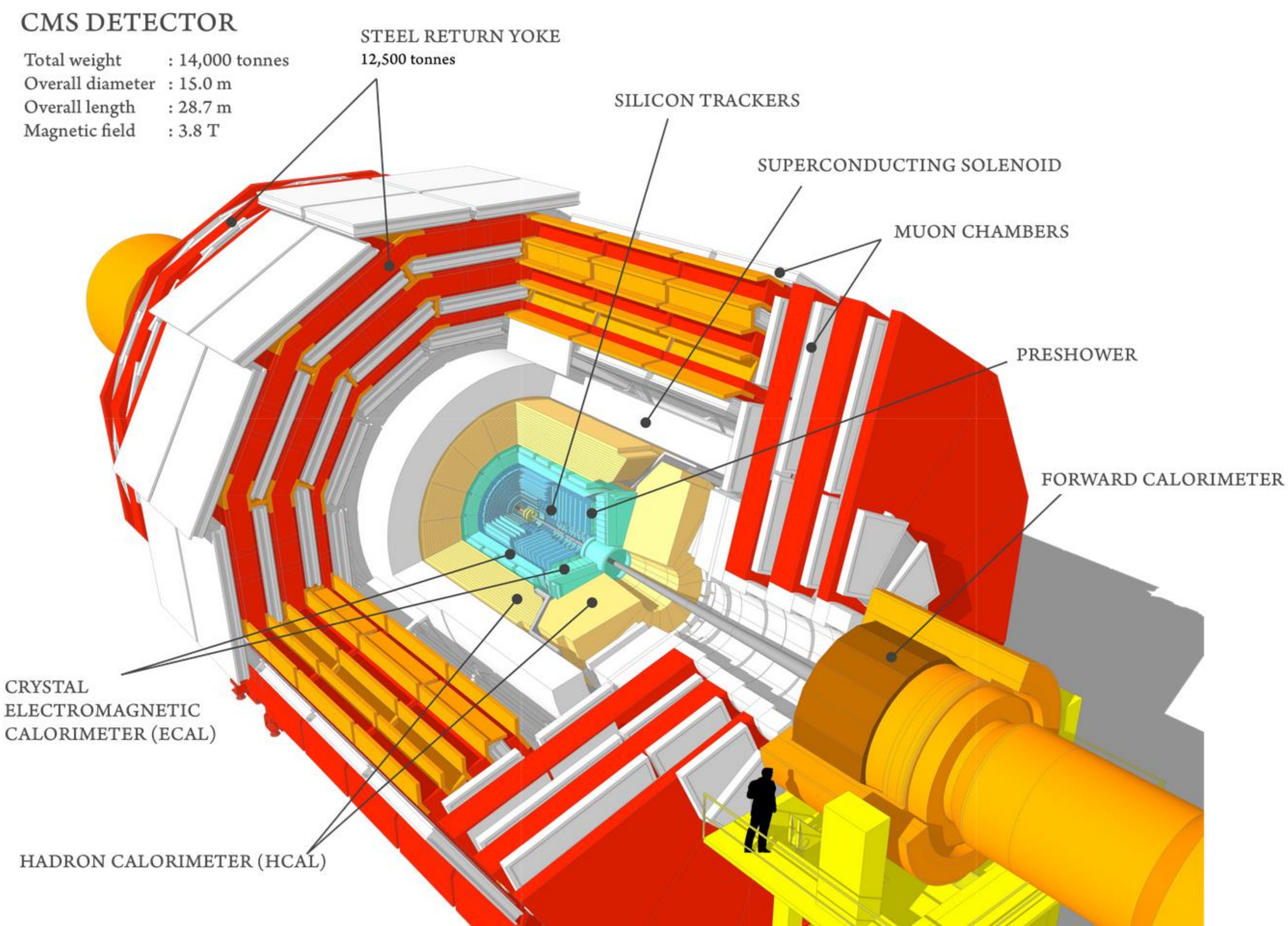


- Recorded luminosity
  - 4.9 fb^{-1} (7 TeV) + 19.7 fb^{-1} (8 TeV)
  - 50 ns bunch spacing
- Expected in 2015
  - 1 fb^{-1} (50 ns) + 10 fb^{-1} (25 ns)
- Expected Run 2
  - 100-120 fb^{-1}
- Doubly charged Higgs production cross section (500 GeV)
  - Associated: ~0.5 fb, Pair: ~0.4 fb

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

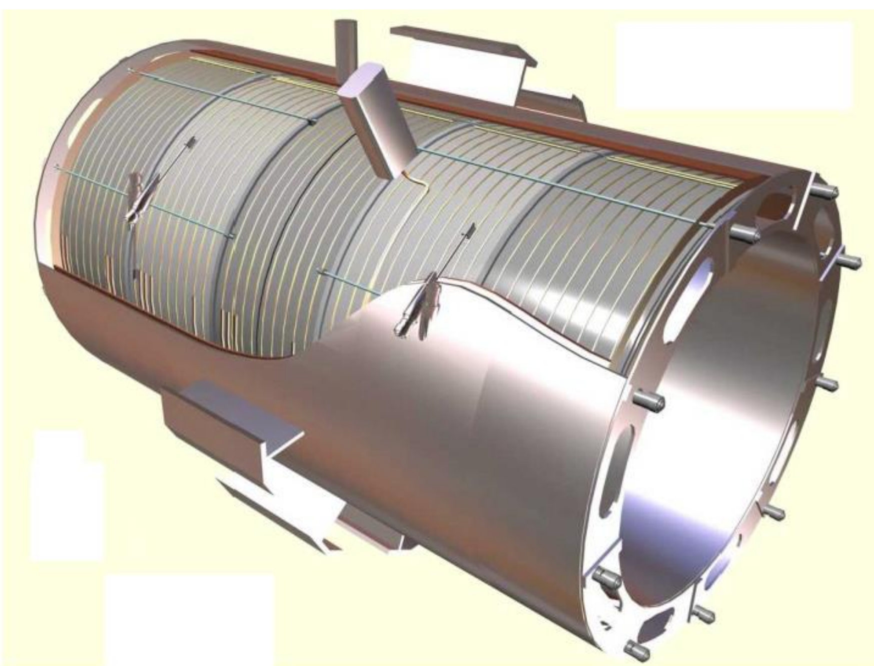
Parameter	2011	2012	2015	Design
Beam energy (TeV)	3.5	4.0	6.5	7.0
Bunch spacing (ns)	75/50	50	50/25	25
Number of bunches	1380	1380	~2800	2808
Peak Luminosity ($1/cm^2s$)	3.5e33	7.6e33	1.2e34	1e34
Peak pile-up	17	38	40/20	26

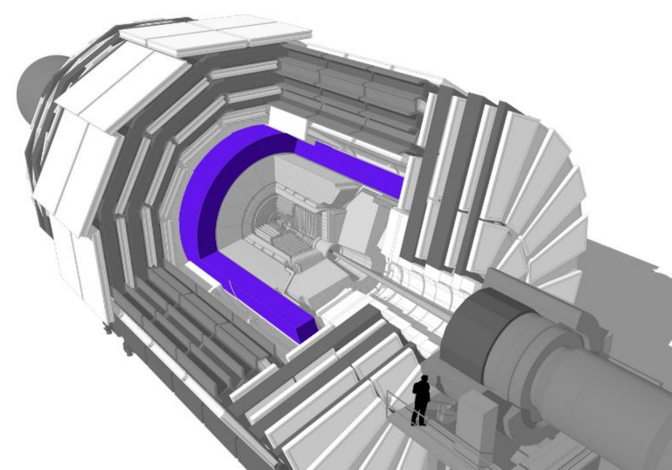
The Compact Muon Solenoid



Solenoid and p_T Measurement

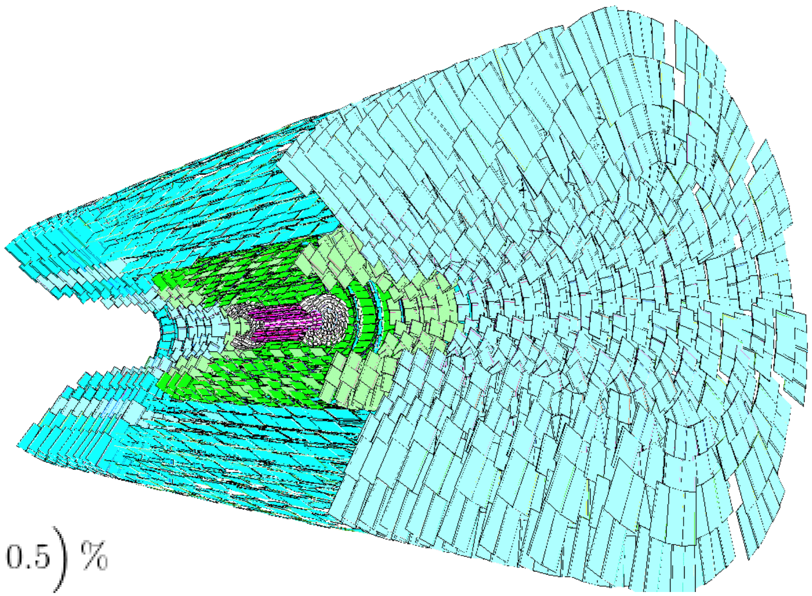
- The central feature of CMS is the large 3.8 T solenoid magnet
  - Length: 12.5 m, diameter: 6.3 M
  - Cooled to 4.7 K
- Drove the design of the rest of the detector systems
  - All calorimetry inside solenoid for good energy resolution
- Good p_T measurement of charged particles due to strong magnetic field

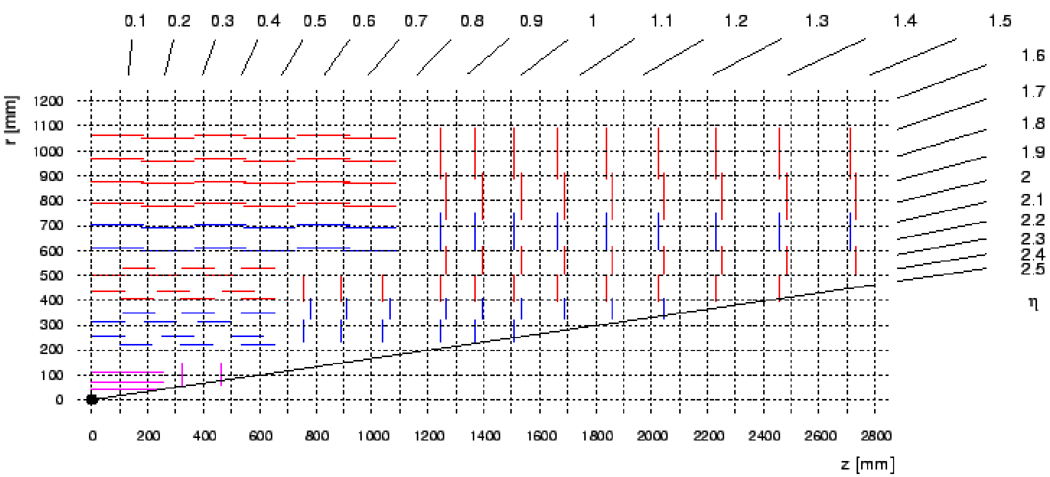


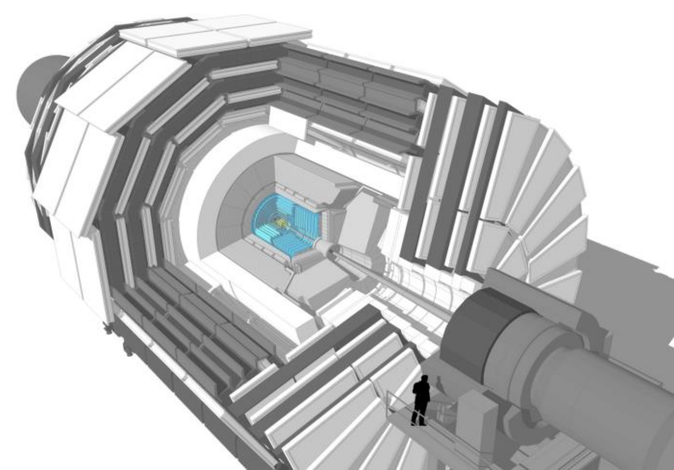


Pixel and Silicon Tracker

- Silicon Pixel Detector
  - 3 barrel layers, 2 disks each endcap
- Silicon Strip Detector
  - Outside pixel detector
  - Inner and outer barrel and endcap
- Coverage: $|\eta| < 2.5$
- Resolution (in barrel): $\frac{\delta p_T}{p_T} = \left(15\frac{p_T}{TeV} \oplus 0.5\right)\%$

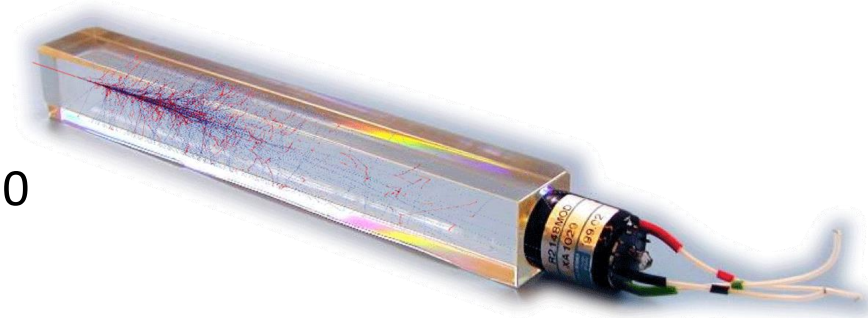


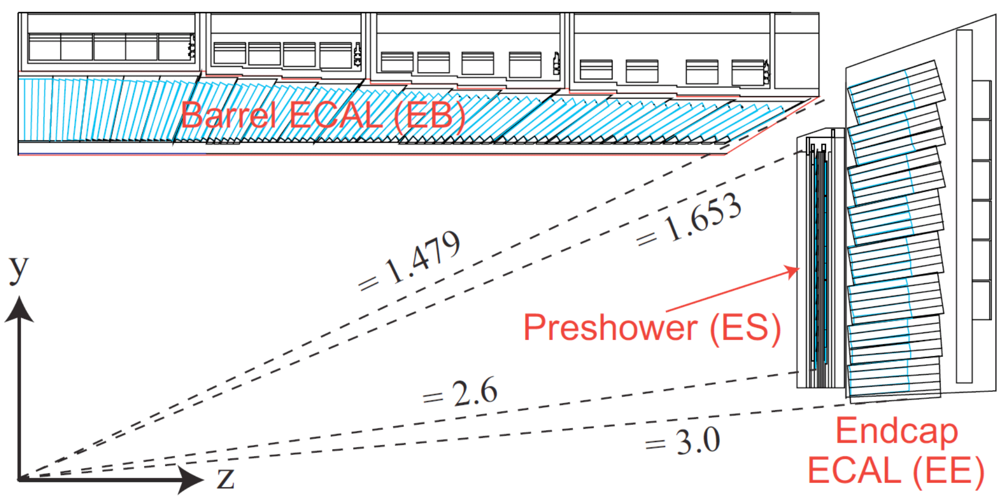


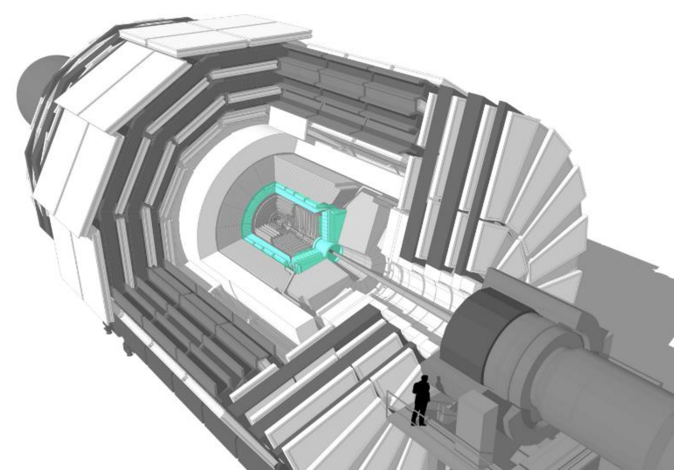


Electromagnetic Calorimeter

- $PbWO_4$ Crystals with photodetectors
  - Barrel Region, $|\eta| < 1.479$
    - Length 230 mm, 25.8 X_0
  - Endcap Region, $1.479 < |\eta| < 3.0$
    - Length 220 mm, 24.7 X_0
- Preshower detector
  - $1.653 < |\eta| < 2.6$
  - Silicon strips
- Resolution: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{0.12}{E}\right)^2 + (0.3\%)^2$

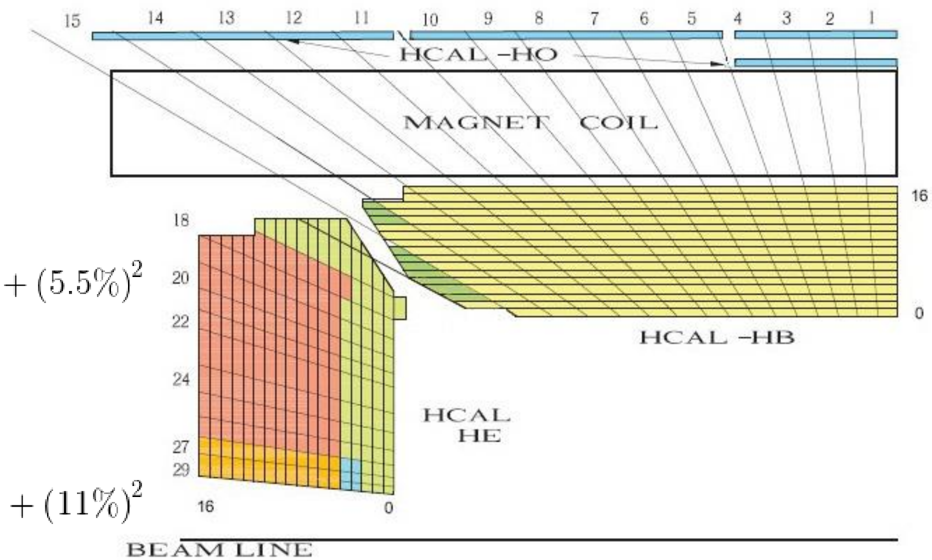


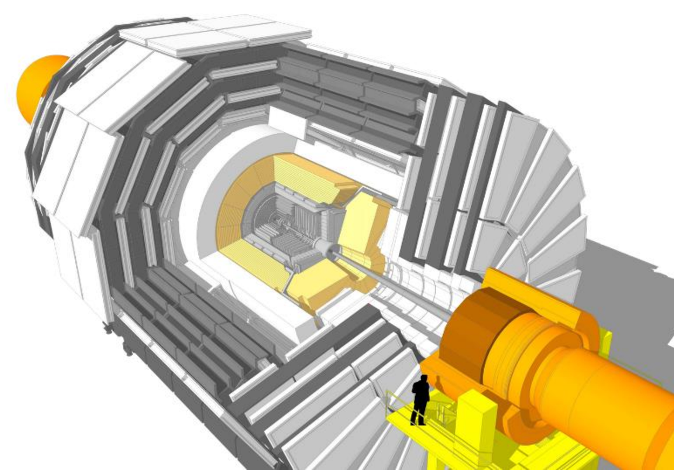




Hadronic Calorimeter

- Brass and steel absorbers
  - Steel outer and inner absorber layers
  - 14 brass absorber layers
- Scintillator
  - Between absorber layers
- HCAL Barrel (HB)
  - |η| < 1.3 $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{115\%}{E}\right)^2 + (5.5\%)^2$
  - 5.8-10.6 λ (+1.1 λ from ECAL)
- HCAL Endcap (HE)
  - 1.3 < |η| < 3.0 $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{280\%}{E}\right)^2 + (11\%)^2$
  - ~10 λ (including ECAL)
- HCAL Outer (HO)
  - 5 rings outside the solenoid (not used)
- HCAL Forward (HF)
  - 3.0 < |η| < 5.2
  - Cherenkov-based detector





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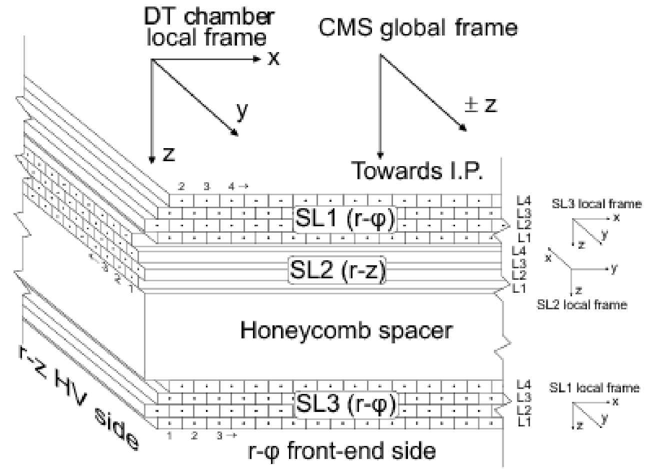
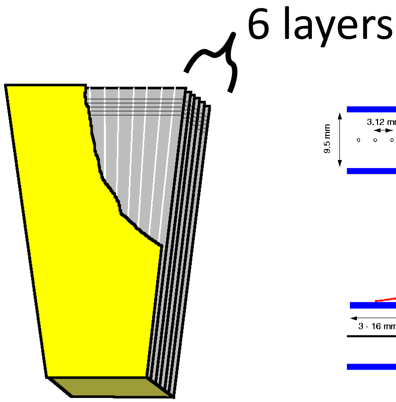
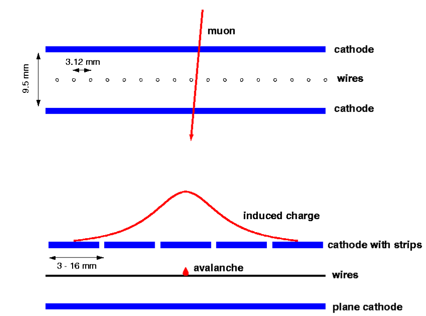
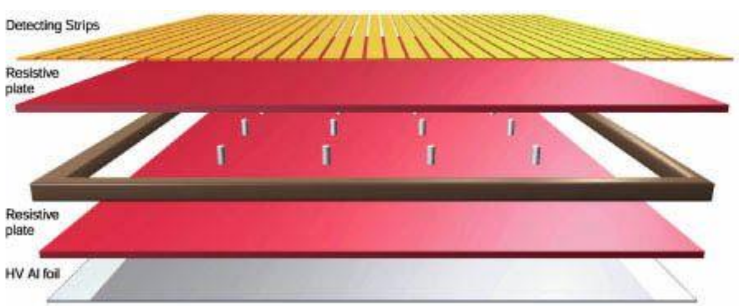
The Muon System

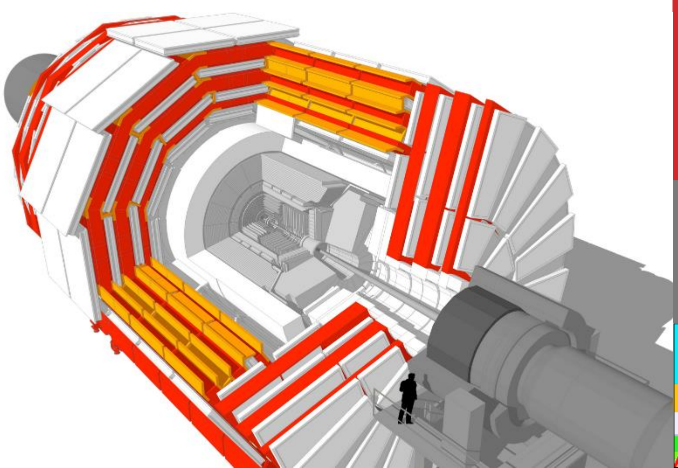
- Embedded in CMS solenoid return yoke
  - 2 T magnetic field
- Drift Tubes
  - Barrel region, |η| < 1.2
- Cathode Strip Chambers
  - Endcap region, 0.9 < |η| < 2.4
- Resistive Plate Chambers
  - Barrel and Endcap, |η| < 1.6
- Relative p_T resolution (with tracker)
  - 2% in barrel
  - 6% in endcap











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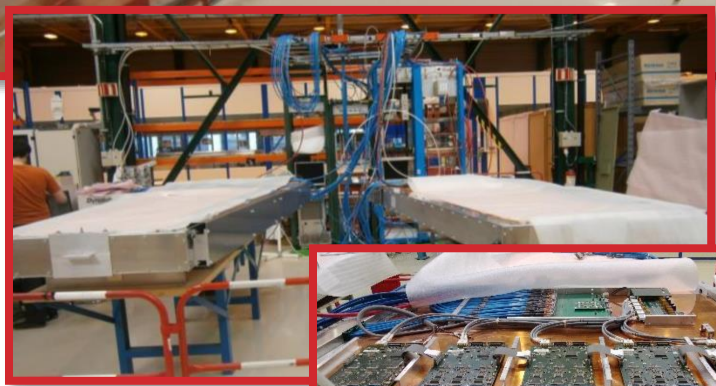
Cathode Strip Chambers Upgrade

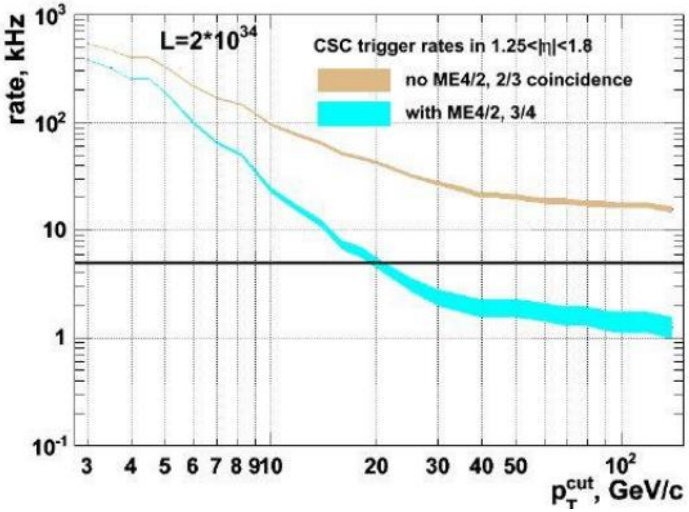
- Addition of descoped ME4/2
  - Add 4 chamber segment coverage for $1.2 < |\eta| < 1.8$
  - Manufacture, assembly, testing, and installation of 67 new chambers + extras
    - My summer 2013 work
- Upgrade of ME1/1 electronics
  - Replace old analog readout electronics
  - Upgraded to faster optical readout
  - Ungang ME1/1a strips (nearest beampipe)
- Additional work
  - Validation of chamber performance
  - Post long shutdown 2 (LS2) studies
  - CSC data visualization
  - Preparation for Run 2 CSC prompt feedback

Cathode Strip Chambers Upgrade



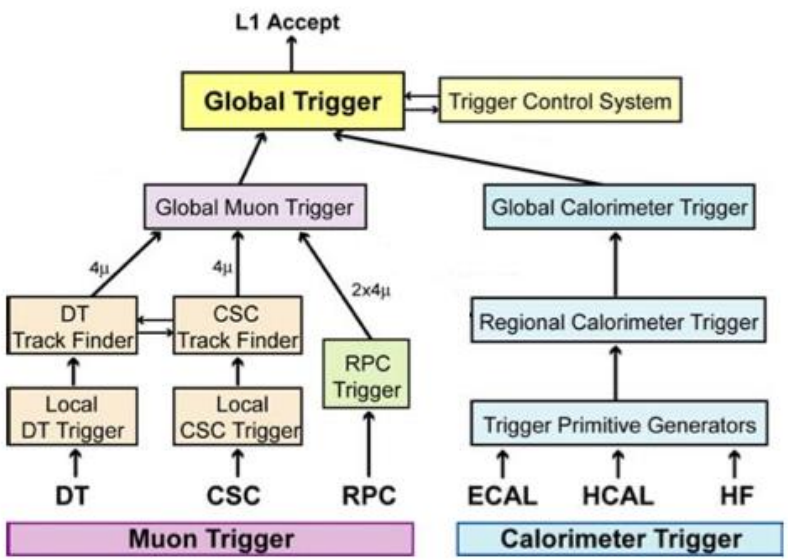
CSC Upgrade Performance

- ME4/2 performance increase
  - Reduced trigger rate
    - CSC track finder required 2/3 chamber coincidence to trigger
    - Can now trigger on 3/4 chamber coincidence
  - Increased muon efficiency in ME 4/2 eta region
    - ~2% at $p_T < 60$ GeV
- ME1/1 performance increase
  - Unganging of strips in ME1/1a
    - Removes ambiguity on triggering
  - New electronics
    - Able to handle higher rates (even SLHC)
- Further upgrades in LS2 and beyond
  - Currently under study
    - Replacement of inner ring (or all) electronics (as done with ME1/1)
    - New muon chambers in high eta region

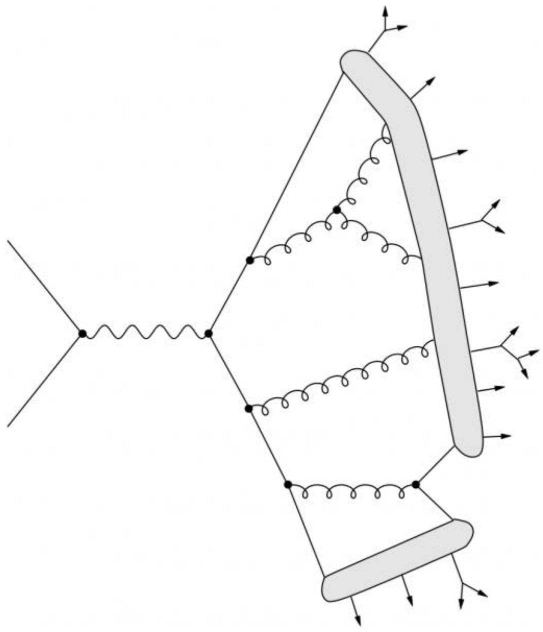


CMS Trigger System

- Level 1 Trigger
  - Separate calorimeter and muon trigger paths
  - Dedicated on detector and peripheral electronics
  - At 25 ns, must reduce 40 MHz event rate to 100 kHz
- High Level Trigger (HLT)
  - Large, dedicated computer farm
  - Combine information from all detector systems
  - Allows easily programmable trigger paths similar to offline reconstruction
  - Further reduce rate to 500 Hz



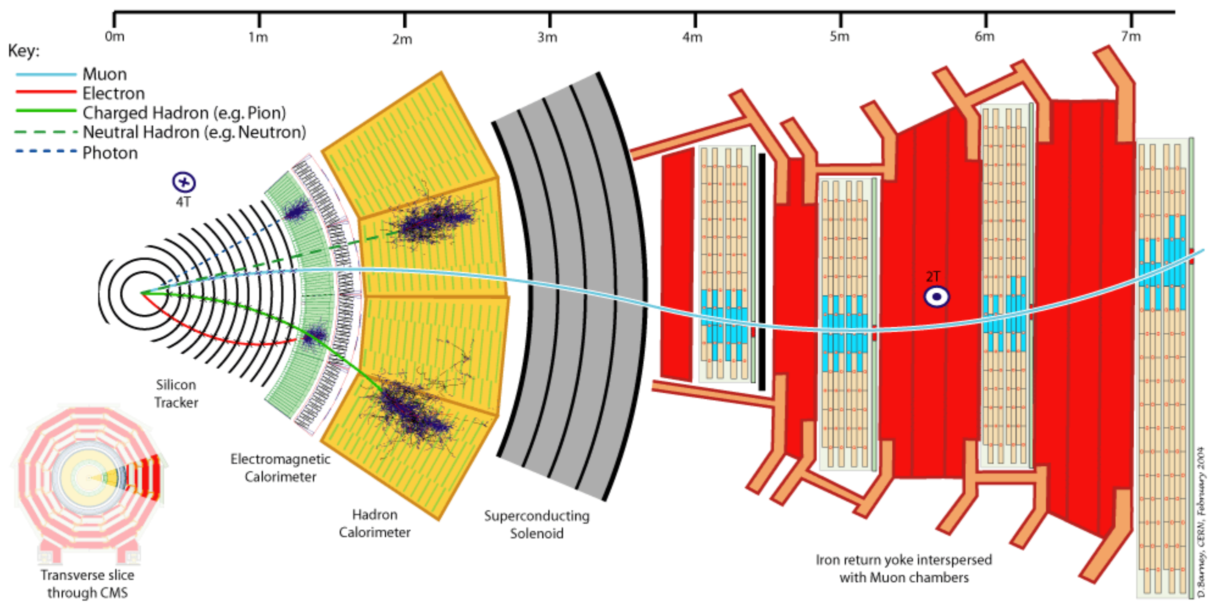
Monte Carlo Generation



- Events are simulated using the MC method
- Underlying vertex first generated in
  - Madgraph (most processes)
  - POWHEG (some diboson, single top)
  - Pythia (pair production signal)
  - Calchep (associated production signal)
- The underlying event is then passed to Pythia
  (or Tauola) for hadronization and decays
- The event is combined with minimum bias data to simulate pile-up effects
- Finally, the event is passed to a detailed GEANT4 simulation of the CMS detector to simulate the particle interaction
- Simulated events are then digitized and follow the rest of the event reconstruction chain the same as data

Event Reconstruction

- CMS uses Particle Flow (PF) to combine information from each detector and select physics objects
  - Improves resolution and identification
  - Charged and neutral hadrons, photons, electrons, and muons
- Algorithm
  - First muon detector tracks are matched to tracks in the inner tracker
  - Remaining tracks are then associated with energy deposits in ECAL (electrons) and HCAL (charged hadrons)
  - Remaining energy deposits are called photons (ECAL) or neutral hadrons (HCAL)



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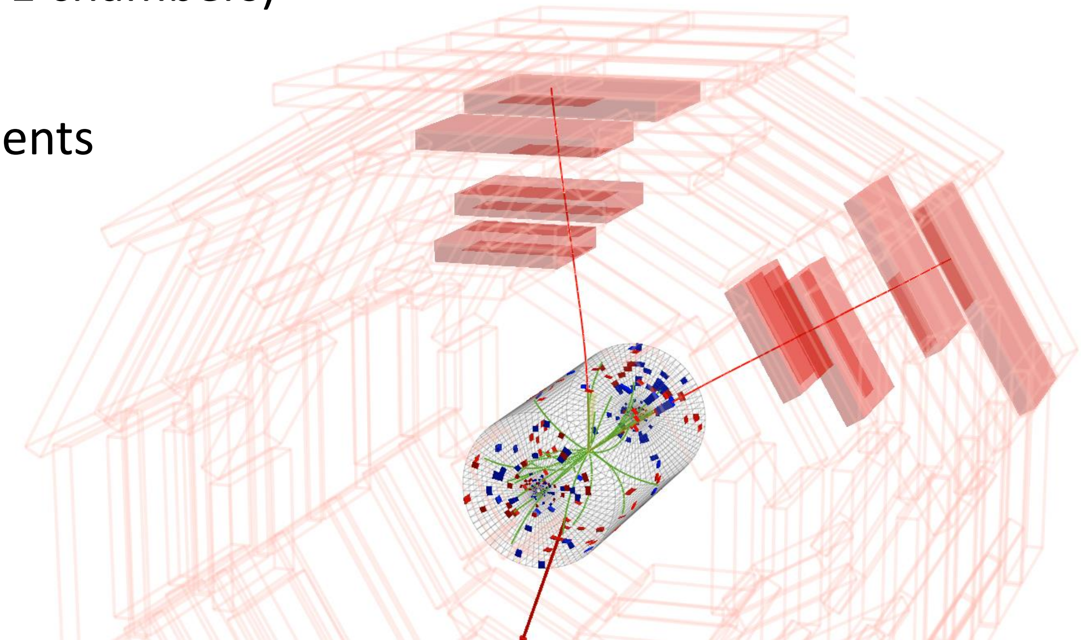
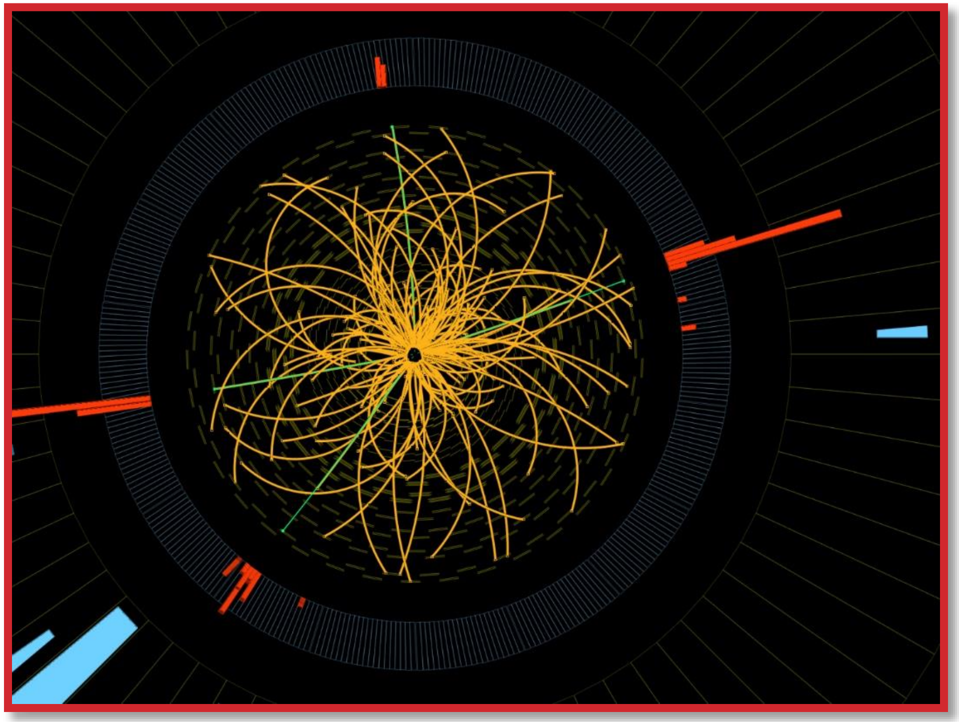
Muon Reconstruction

- Combine muon system for identification and tracker for better p_T assignment
  - Muon subdetectors able to function as a standalone system
  - Reconstruction requires a standalone muon track to match with a tracker track to produce a “global” muon
- “Tight” muon selections
  - Good vertex
  - Hits in muon system (>1 chambers)
  - Pixel and tracker hits
  - Track quality requirements



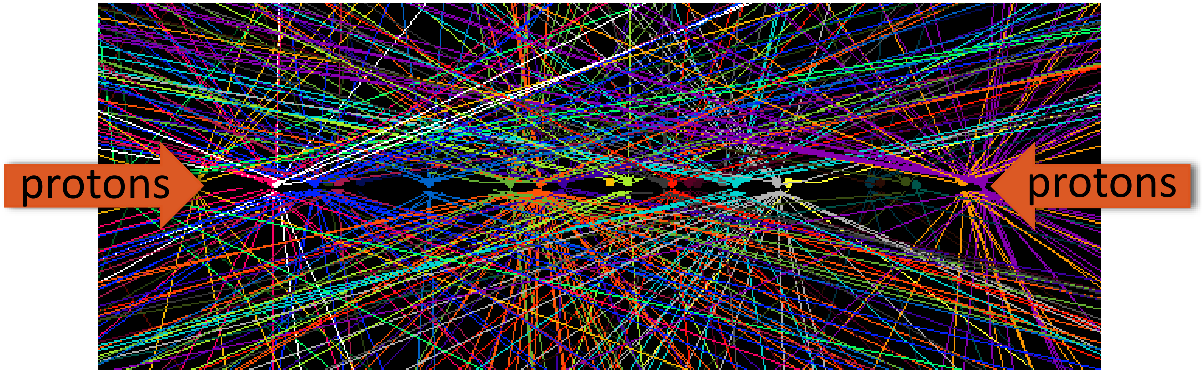
Electron Reconstruction

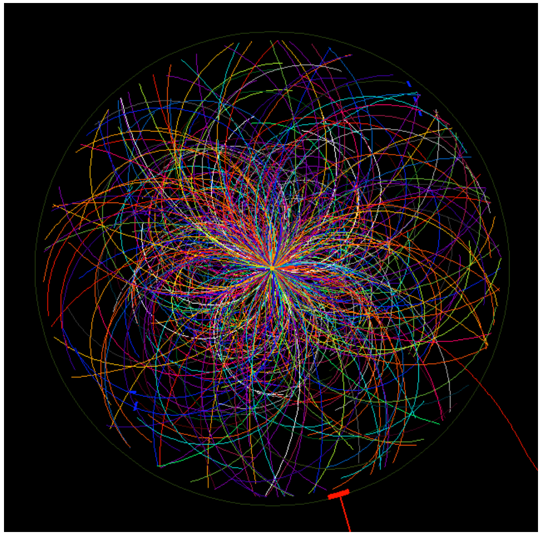
- Use energy deposits in ECAL and tracker for p_T assignment
- Cut based and multivariate analysis selections
  - Optimized for high purity
  - Good vertex selections
  - Reject photon conversions (missing hits)



Pile-up

- To achieve large integrated luminosity, many collisions occur at each bunch crossing
  - This leads to pile-up, many uninteresting QCD events that act as a background to the event that was triggered
  - Particle flow (via the excellent pixel detector) can mitigate some of the tracks associated with these pile-up events
  - Energy deposits not associated with a pile-up track are more difficult
  - At the analysis level, require objects from primary vertex to reduce pile-up effects





Lepton Isolation

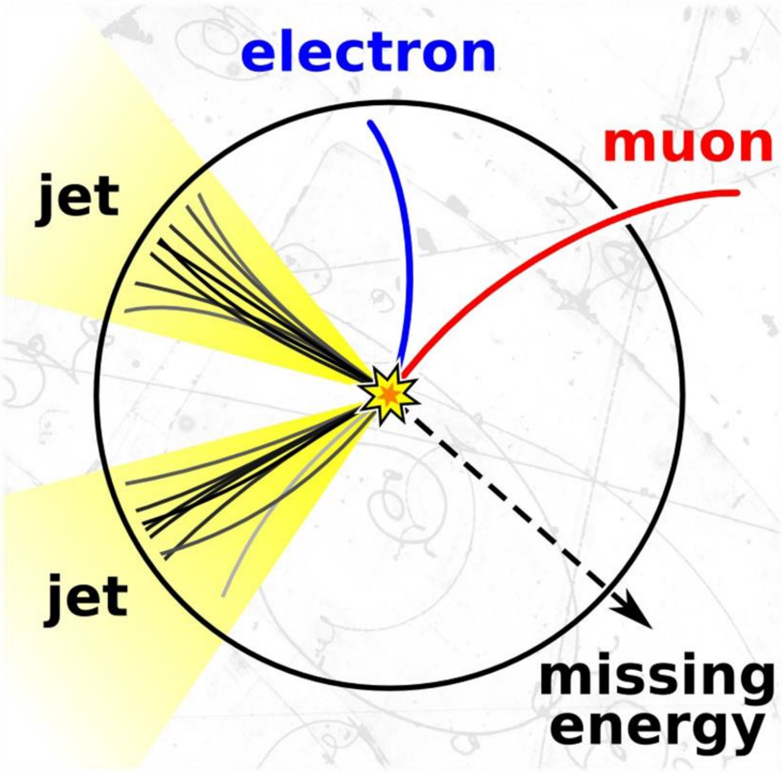
- Leptons must be well isolated
  - Sum energy deposited within ΔR = 0.3 of the lepton
  - Relative isolation < 0.12 (0.15) for muons (electrons)
    - Corrections are applied to account for pile-up
    - Charged hadron pile-up already removed with vertex cuts
    - To reduce neutral hadron pile-up, subtract 0.5 * charged hadron pile-up
      - Known composition of jet: 2/3 charged hadrons, 1/3 neutral hadrons

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

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

Missing Energy

- Neutrinos and potentially other beyond the standard model particles will not deposit energy in the CMS detector
  - Leads to missing energy (MET)
  - Sum energy from all detectors
    - Use sum of particle flow objects
    - Missing energy can only be resolved in ϕ
- Pile-up also contributes to errors in the MET measurement

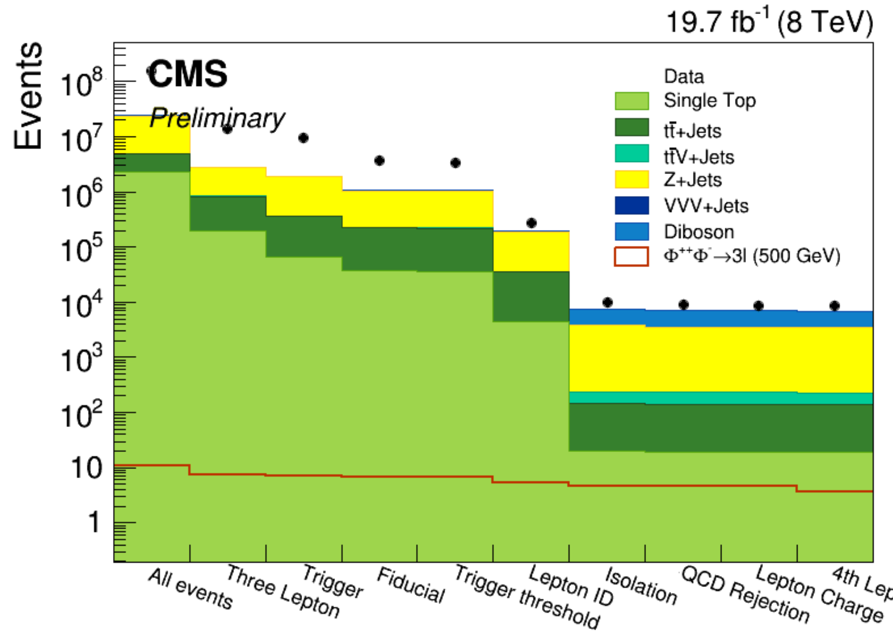


Signal and Backgrounds

- Backgrounds simulated with Madgraph and hadronized with Pythia, Tau decays simulated with Tauola
- Backgrounds
  - Single top production: t_s, t_t, t_tW
  - ttbar+Jets
  - Z+Jets
  - ttbarV
  - VVV
  - VV+Jets
- Largest backgrounds come from VV and ttV where we have 3 real leptons, especially ttW where we cannot reduce the contribution via a Z mass veto
- Signal generated in Pythia for pair production (4 lepton) and in Calchep for associated production (3 lepton)

Event Preselection

- Multi-lepton trigger
  - 2 muons, 2 electrons, 3 electrons, or muon and electron
- Leptons in detector fiducial
  - $|\eta_e| < 2.5$, $|\eta_\mu| < 2.4$
- Lepton p_T
  - $p_T^{leading} > 10$ GeV
- Lepton ID
  - Electrons and muons must pass tight cut-based selections
  - Electrons must additionally pass a multivariate analysis trained tight selection
- Lepton isolation
  - Relative isolation < 0.12 (0.15) for muons (electrons)
- QCD suppression
  - $M_{ll} > 12$ GeV
- Require ++- or --+ charge triplets
- Veto on 4th lepton
  - Event would be included in 4l analysis
- 3570 events after preselection

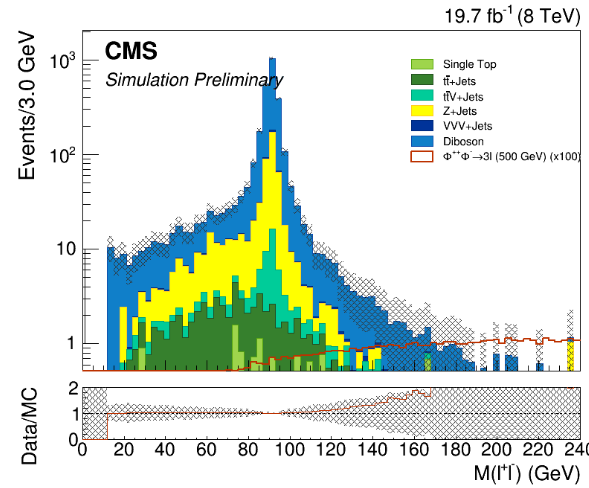


$$I^{\mu}_{rel} = \frac{\sum p_T^{charged} + max[\sum E_T^{neutral} + \sum E_T^{photon} - 0.5 \cdot \sum p_T^{charged,PU}, 0.0]}{p_T}$$

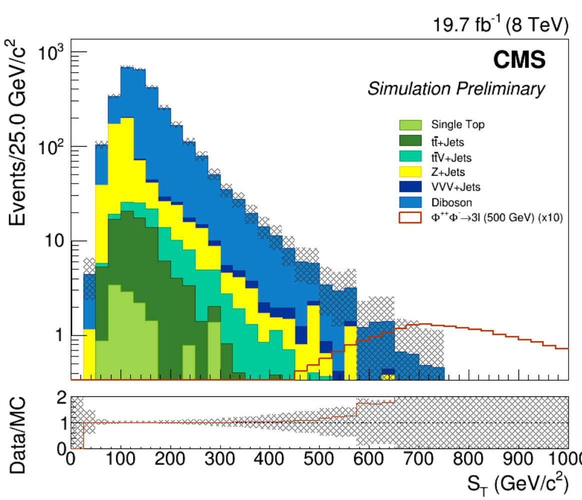
$$I^{e}_{rel} = \frac{\sum p_T^{charged} + max[\sum E_T^{neutral} + \sum E_T^{photon} - \Delta\rho \cdot E.A., 0.0]}{p_T}$$

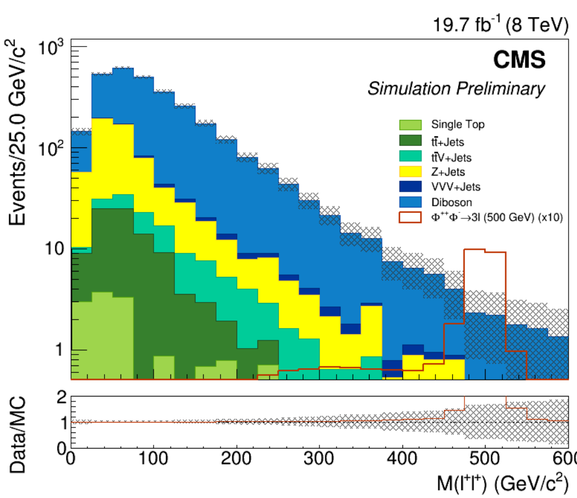
Analysis Selections

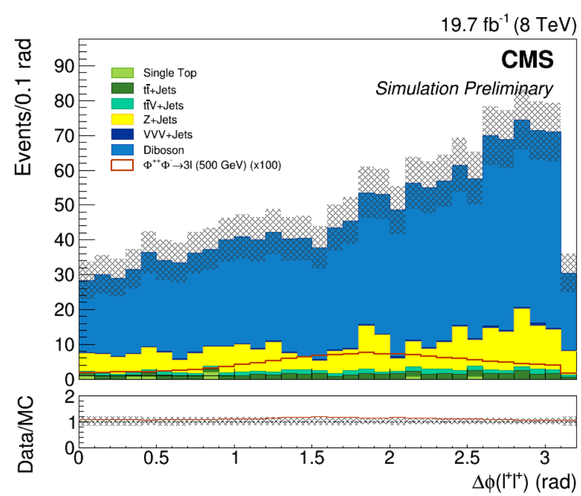
- Optimization of signal region
  - Maximize $\frac{S}{\sqrt{B}}$
- Variables of interest
  - $M_{\ell^\pm\ell^\pm}$ ($\Phi^{\pm\pm}$ mass)
  - $M_{\ell^\pm\ell^\mp}$ (Z mass)
  - $\Delta\phi(\ell^\pm, \ell^\pm)$
  - $S_T = \Sigma p_T^{lepton}$



Cut	ee, eμ, μμ
S_T	$> 1.1\ m_\phi + 60$
$\|m(l^+l^-) - m_Z\|$	> 80
$\Delta\phi$	$< m_\phi/600 + 1.95$
Mass Window	$[0.9\ m_\phi, 1.1\ m_\phi]$







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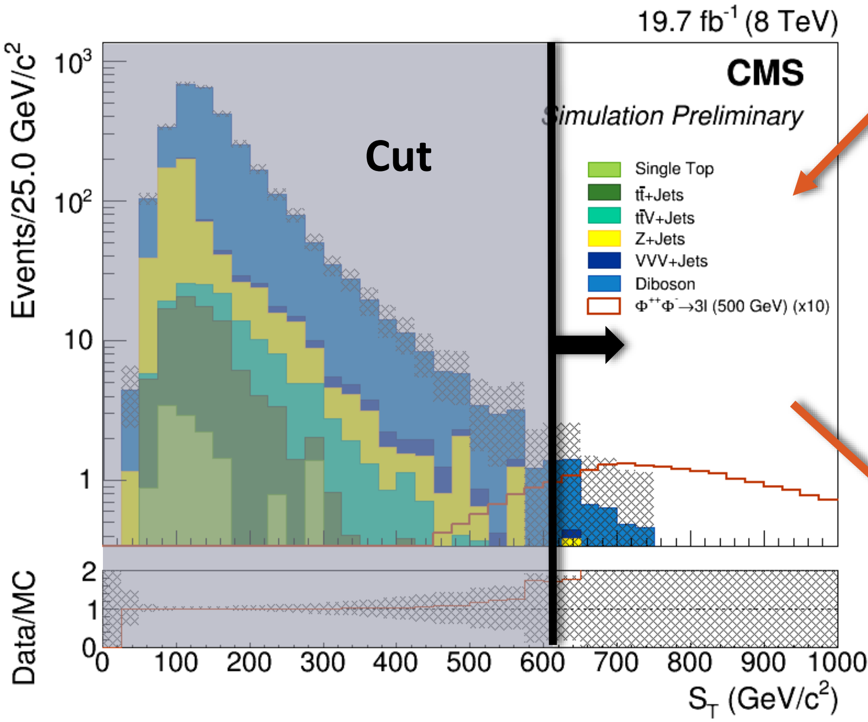
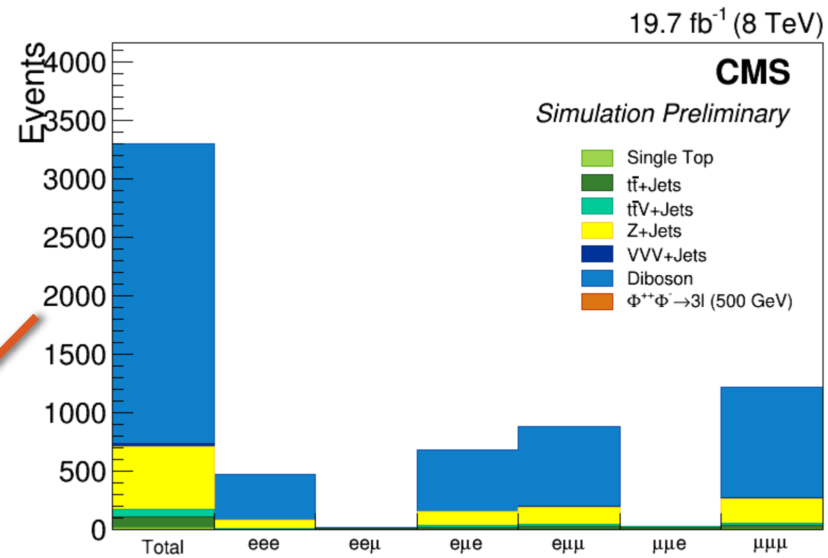
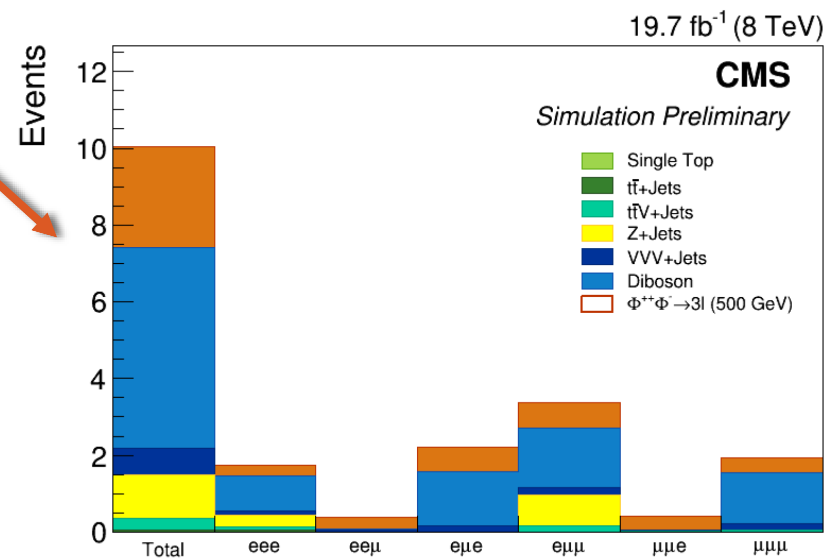
Lepton p_T Sum Selection

- Leptons expected to be high p_T
- Significantly reduces many Standard Model processes



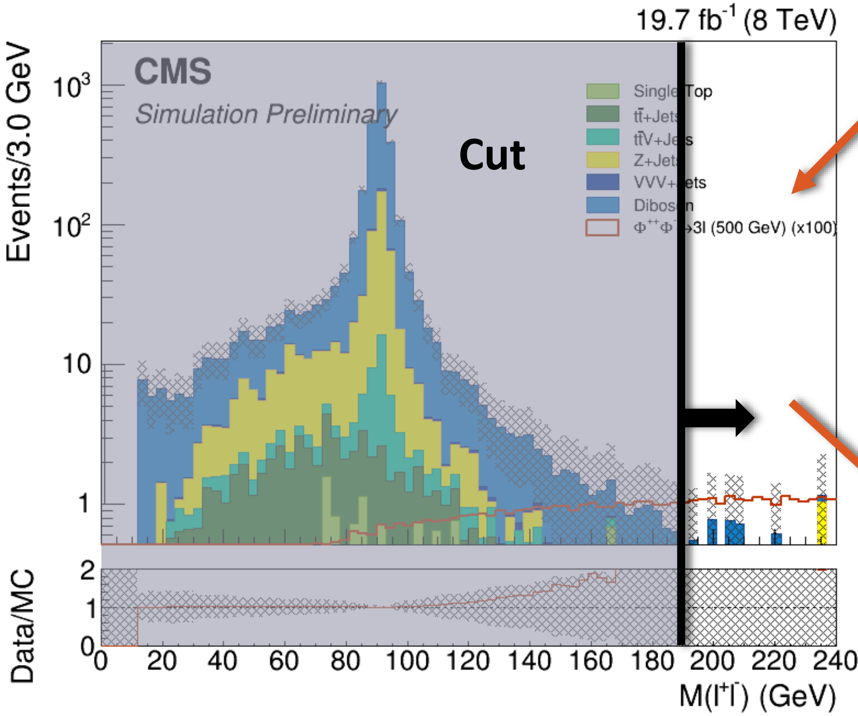
$\frac{S}{\sqrt{B}}$ Before	$\frac{S}{\sqrt{B}}$ After
0.056	1.015



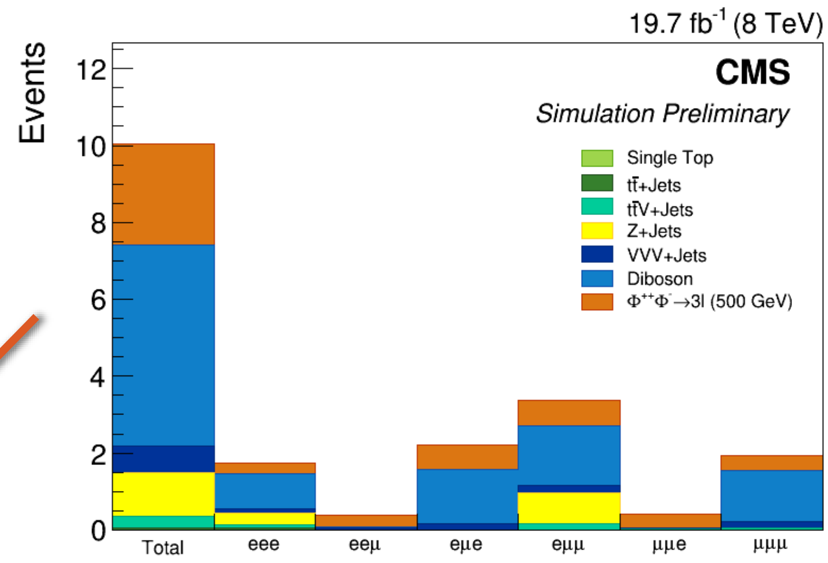


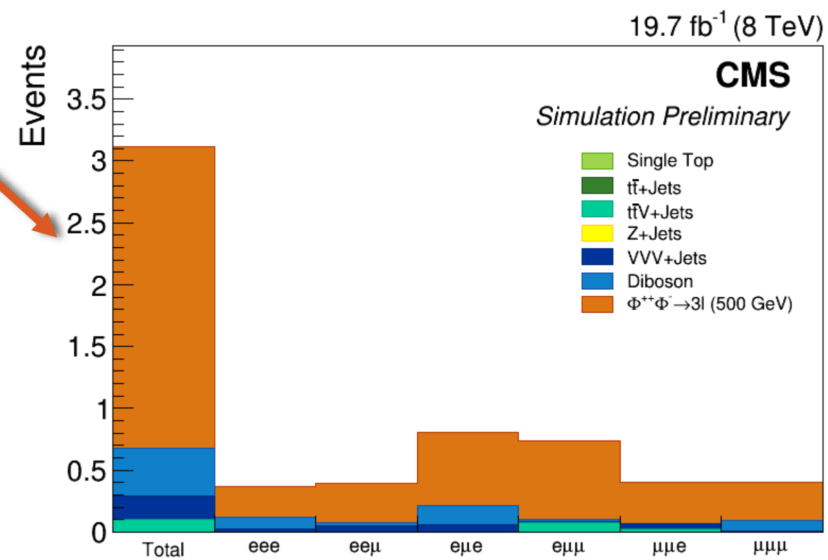
Z Mass Veto

- Veto on Z mass windows removes contributions for Drell-Yan and diboson production



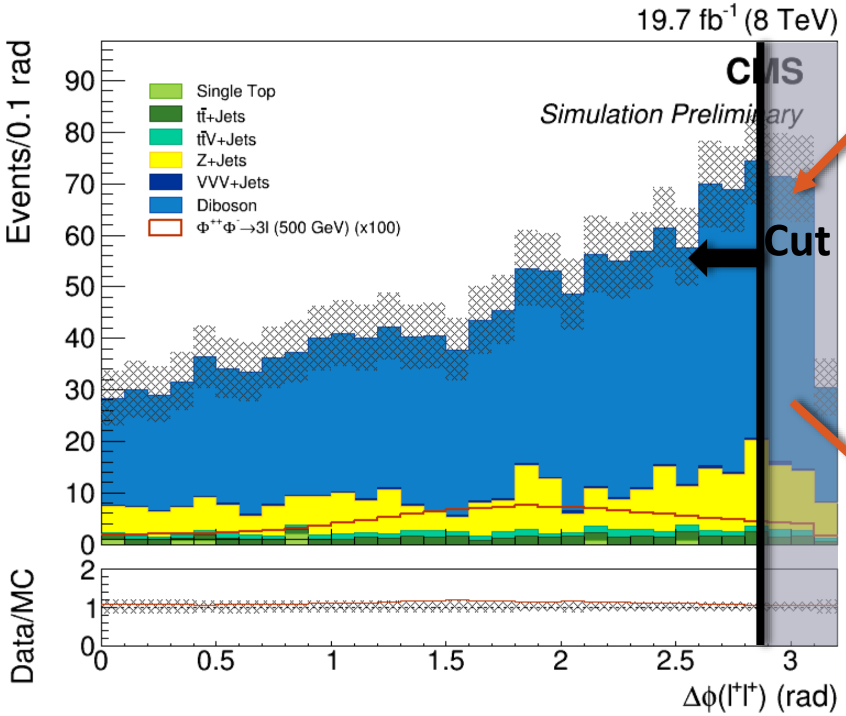
$\frac{S}{\sqrt{B}}$ Before	$\frac{S}{\sqrt{B}}$ After
1.015	2.872

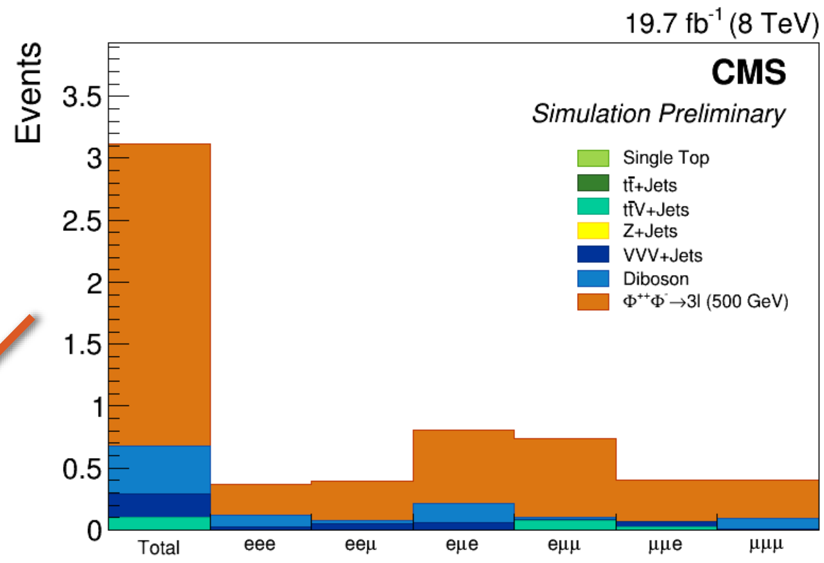


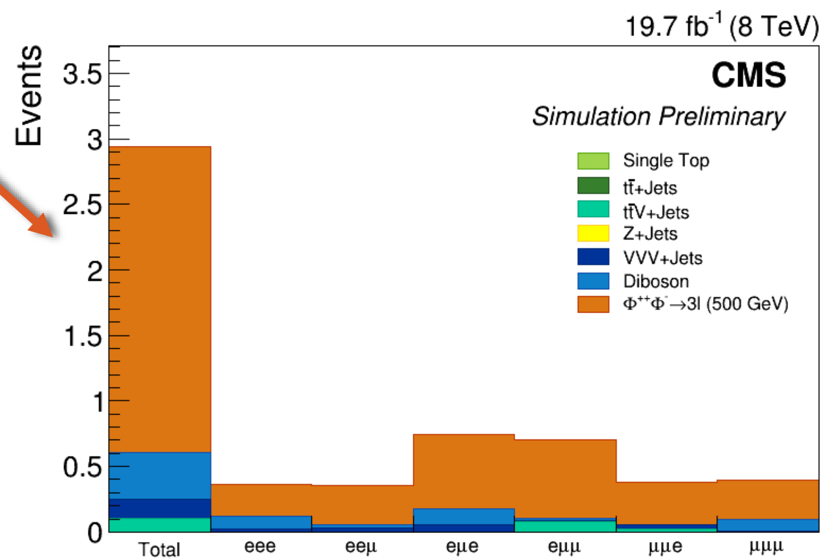


Same Sign Lepton Separation

- Same sign leptons expected to be near each other
- Reduces diboson contribution



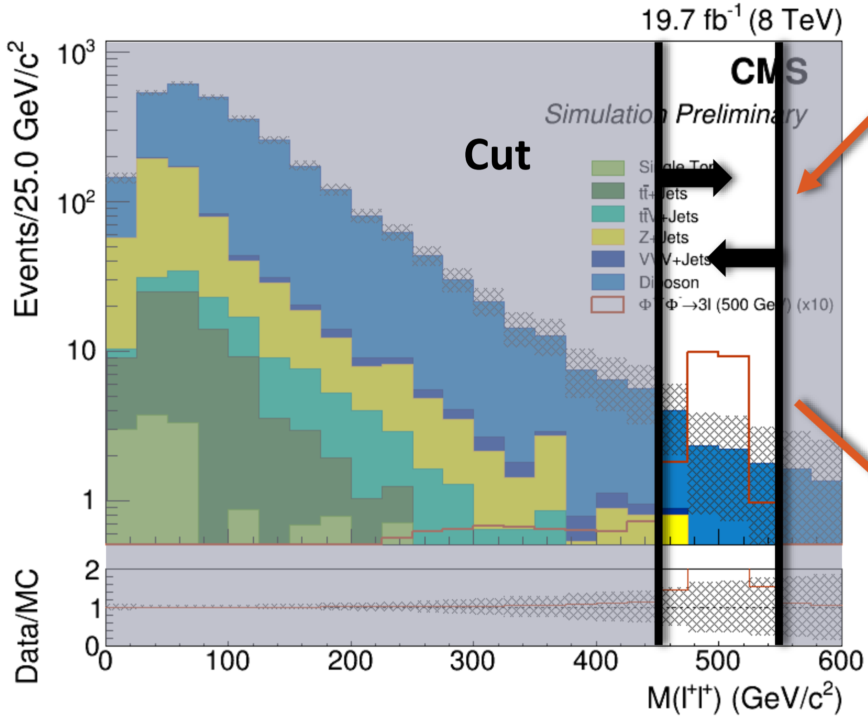




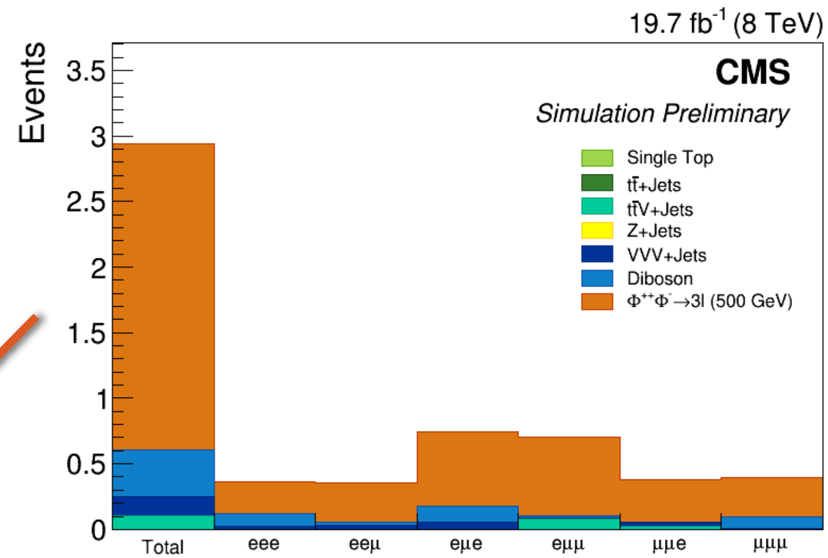
$\frac{S}{\sqrt{B}}$ Before	$\frac{S}{\sqrt{B}}$ After
2.872	2.925

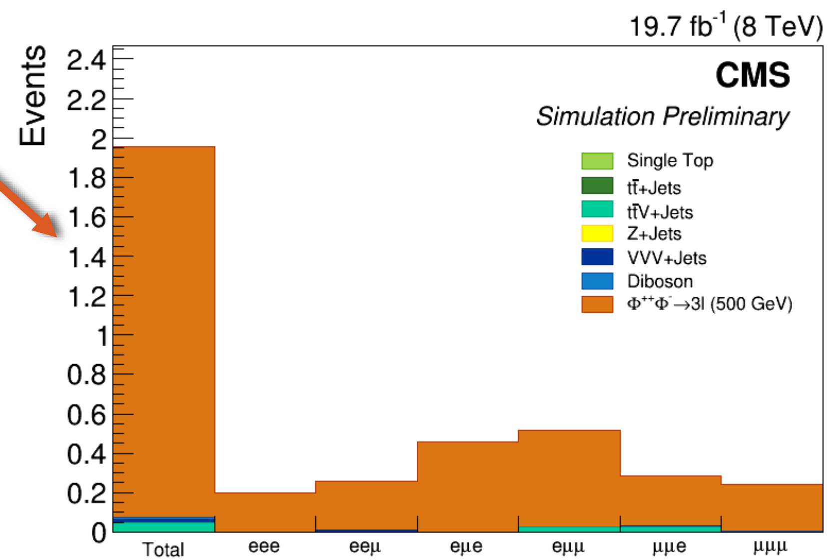
Mass Window Selection

- Finally, we select a same-sign dilepton mass window based on our mass hypothesis



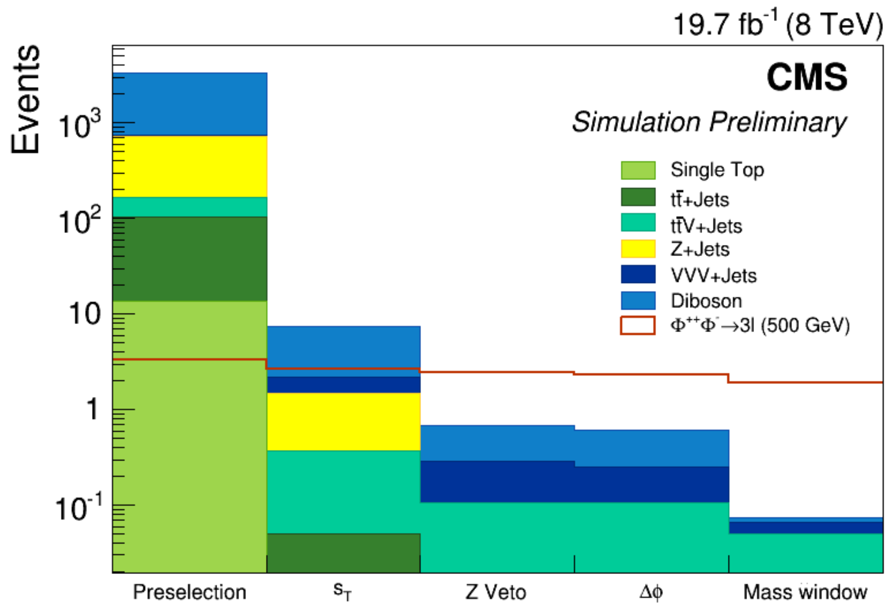
$\frac{S}{\sqrt{B}}$ Before	$\frac{S}{\sqrt{B}}$ After
2.925	6.469





Analysis Selection Event Numbers

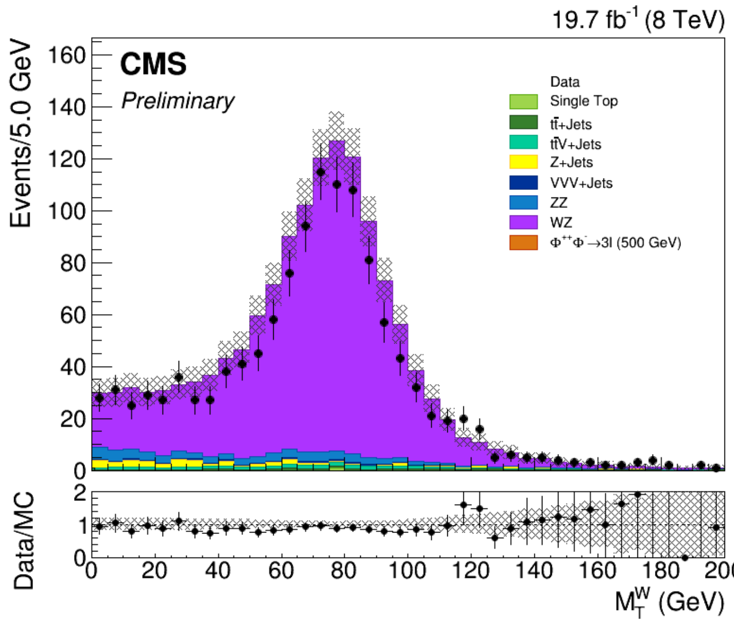
- Associated Production channel
- Event selections assuming $m_{\Phi^{++}} = 500\ GeV/c^2$
- Full selection: $\frac{S}{\sqrt{B}} = 6.47$

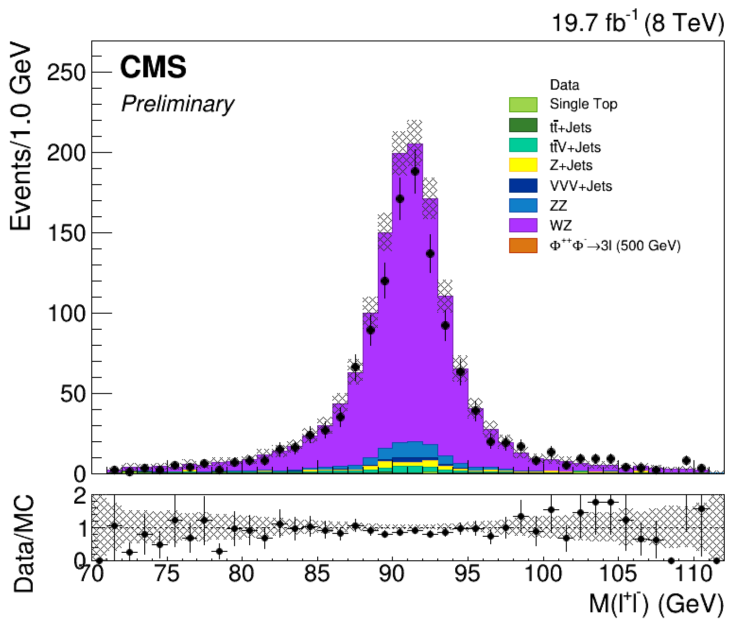


Monte Carlo Sample	Preselection	S_T	Z Veto	$\Delta\phi$	Mass Window
Single Top	13.75	0.00	0.00	0.00	0.00
TT+Jets	90.90	0.05	0.00	0.00	0.00
Z+Jets	544.46	1.11	0.00	0.00	0.00
VVV	27.10	0.71	0.19	0.15	0.02
TTV+Jets	62.94	0.32	0.11	0.11	0.05
Diboson	2561.81	5.22	0.39	0.35	0.01
Signal (500 GeV/c^2)	3.27	2.64	2.44	2.34	1.88

WZ Control Region

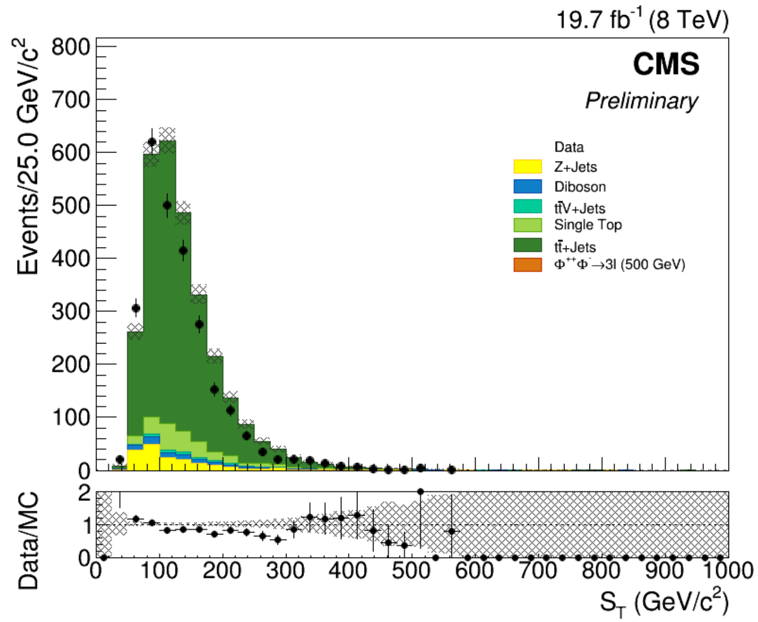
- In addition to the analysis preselections:
  - Z selection
    - $p_T^{leading} > 20$ GeV
    - $|m(l^+l^-) - m_Z| < 20$ GeV
  - W selection
    - $p_T^{W\ lepton} > 20$ GeV
    - $E_T^{miss} > 30$ GeV
    - $\Delta R(Z\ lepton, W\ lepton) > 0.1$
  - $M_{3l} > 100$ GeV
- 1274 events pass selection

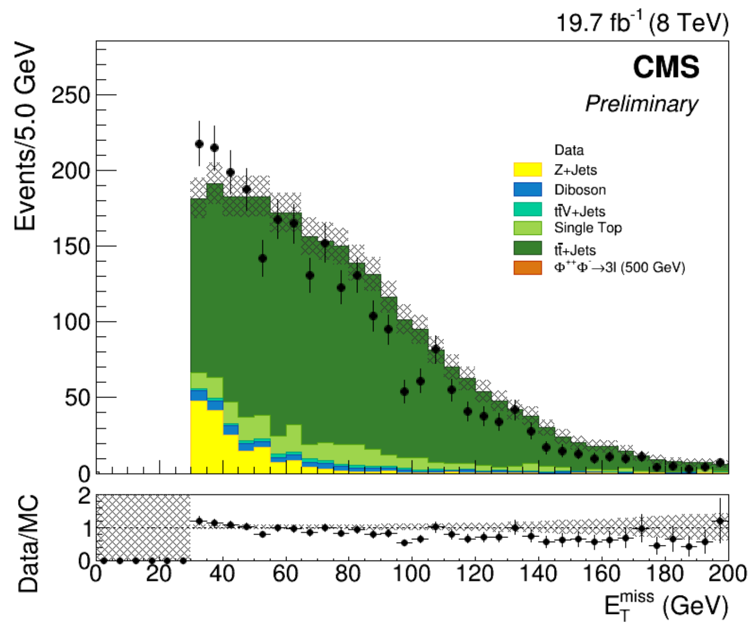




$t\bar{t}$ Control Region

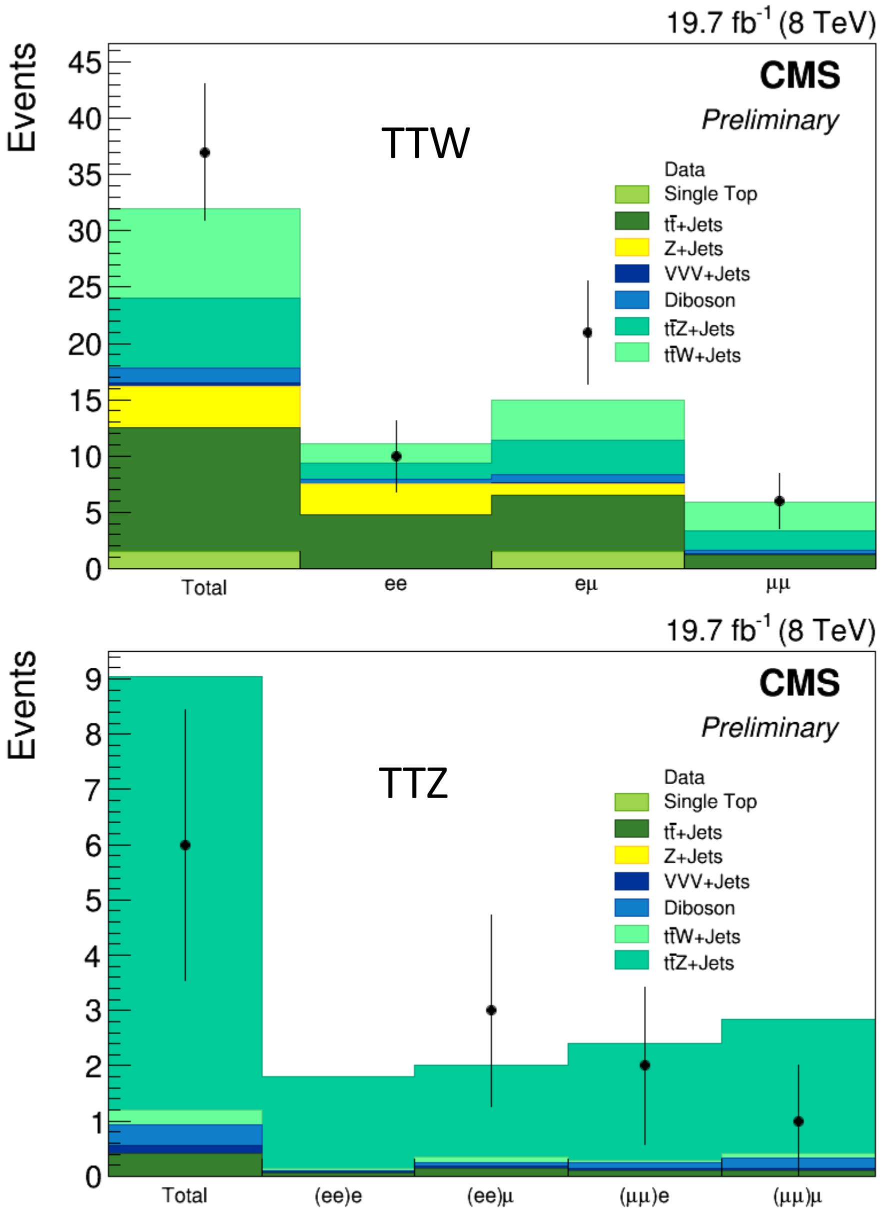
- In addition to the analysis preselections:
  - Require OS leptons
  - Invert 3rd lepton isolation
  - $E_T^{miss} > 30$ GeV
  - $|m(l^+l^-) - m_Z| > 20$ GeV
- 3589 events pass selection





TTV Control Regions

- In addition to the analysis preselections:
- TTW
  - 2 SS leptons
    - $p_T^{leading} > 40$ GeV
  - Jet selection
    - 3 jets, 1 b-tagged
  - 3rd lepton veto if forms Z
    - $|m(l^+l^-) - m_Z| > 20$ GeV
  - 37 events pass selection
- TTZ
  - Jet selection
    - 4 jets, 2 b-tagged
  - Require Z
    - $|m(l^+l^-) - m_Z| < 20$ GeV
  - 6 events pass selection



Sideband Method

- Using the doubly charged Higgs invariant mass, define a sideband away from a given mass hypothesis and a signal region in data with only the preselection applied
  - SB = (12 GeV, 150 GeV) and ($1.1m_{\Phi}$, 800 GeV)
  - SR = ($0.9m_{\Phi}$, $1.1m_{\Phi}$)
- Look at the ratio of the event count in the signal region to the sideband to estimate the background in the signal region after the full selection

Mass (GeV)	MC Estimate	Sideband
170	1.95±0.80	1.51±0.34
200	1.29±0.59	0.90±0.23
250	1.04±0.45	0.41±0.13
300	0.59±0.29	0.10±0.05
350	0.25±0.11	0.05±0.03
400	0.12±0.08	0.02±0.01
450	0.08±0.05	0.01±0.01
500	0.07±0.05	0.00±0.00
600	0.03±0.02	0.00±0.00
700	0.00±0.00	0.00±0.00

$$N_{BGSR} = \alpha \cdot (N_{SB}^{Data} + 1) \quad \alpha = \frac{N_{SR}}{N_{SB}}$$

Systematic Errors

- Systematic errors included
  - Luminosity measurement
  - Lepton ID and isolation
  - Uncertainties in Monte Carlo cross sections
    - Derived from CMS measurements for diboson, ttbar, Drell-Yan
    - All others from uncertainties on the parton distribution functions

Uncertainty Type	Value
Luminosity	2.6%
Muon ID	0.5%
Muon Isolation	0.2%
Electron ID/Isolation	1%

Monte Carlo Sample	Value
Signal	15%
ttbar	2.4%
WW	4.1%
WZ	5.6%
ZZ	10.5%
TTW	28.9%
TTZ	10.5%
ZZZ	2.6%
WZZ	5.1%
WWZ	5.1%
WWW	4.3%

Expected Limits

- Limits are presented for the electron and muon final states
  - 100% branching fractions in the ee, eμ, and μμ
  - 4 benchmark modes, each targeting different physical scenarios
    - BP1: tribimaximal neutrino mixing, no CP violation, normal hierarchy
      - Tribimaximal: $\theta_{13} = 0$, lightest neutrino massless
      - Leads to BR(μμ) ≈ BR(μτ) ≈ BR(ττ) ≈ 1/3
    - BP2: tribimaximal neutrino mixing, no CP violation, inverted hierarchy
      - Electron decays become import
    - BP3: BP1 with assumption of lightest neutrino mass of 0.2 GeV
      - No lepton flavor violation
    - BP4: equal branching fractions
  - Doubly charged Higgs Monte Carlo samples are generated with equal branching fraction to all final states (electron, muon, tau), including flavor violating modes
    - Various benchmarks are achieved with reweighting of final selection channels

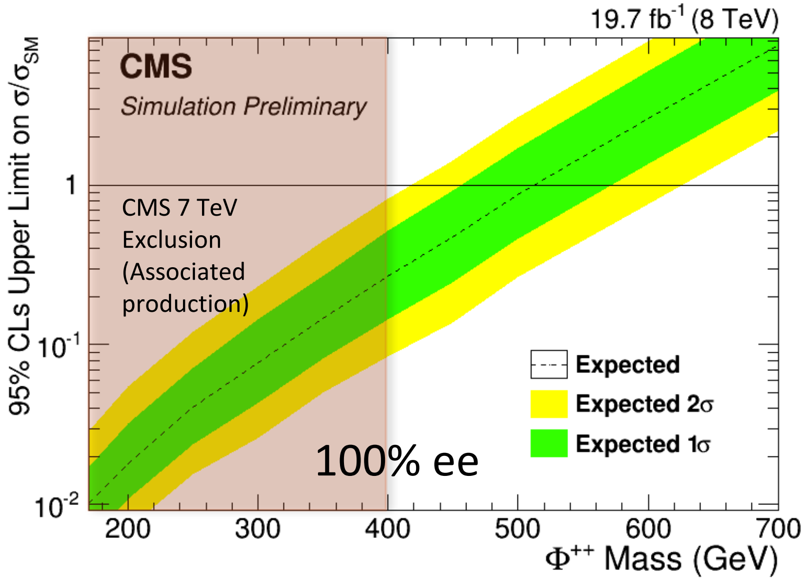
Expected Limits at 8 TeV

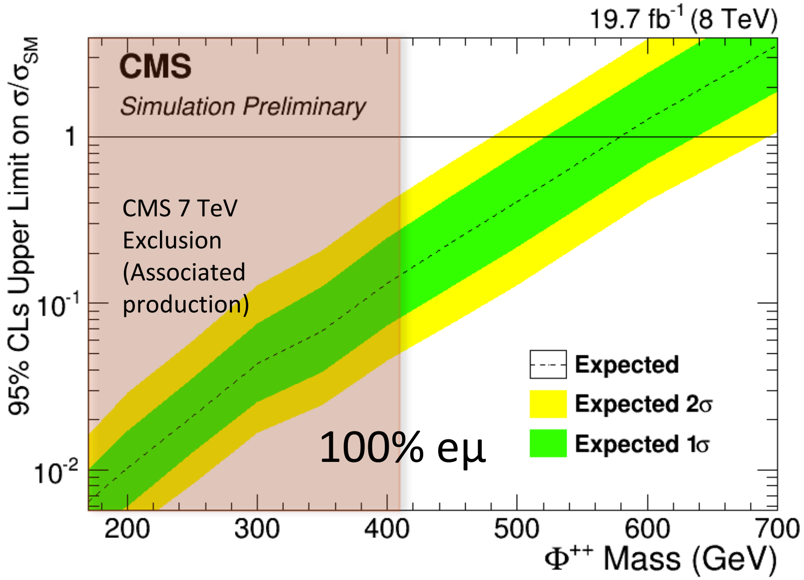
Mode	7 TeV Exp. (3l)	MC BG Exp. (3l)	Data driven BG Exp. (3l)
100% ee	~375 GeV	508 GeV	462 GeV
100% eμ	~390 GeV	568 GeV	523 GeV
100% μμ	~390 GeV	517 GeV	478 GeV
BP1	~360 GeV	457 GeV	418 GeV
BP2	~400 GeV	468 GeV	429 GeV
BP3	~400 GeV	478 GeV	439 GeV
BP4	~390 GeV	474 GeV	439 GeV

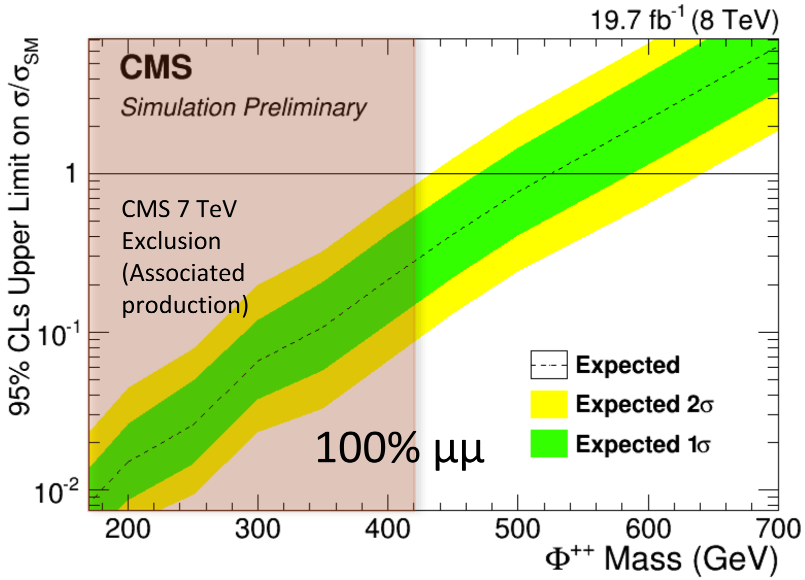
Mode	ee	em	et	mm	mt	tt
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	0.50	0	0	0.125	0.25	0.125
BP3	0.34	0	0	0.33	0	0.33
BP4	1/6	1/6	1/6	1/6	1/6	1/6

- Measurements of these branching fractions would lead to significant insight into neutrino parameters, including a solution to the mass hierarchy problem

100% Branching Fraction
MC Background Estimation Limits

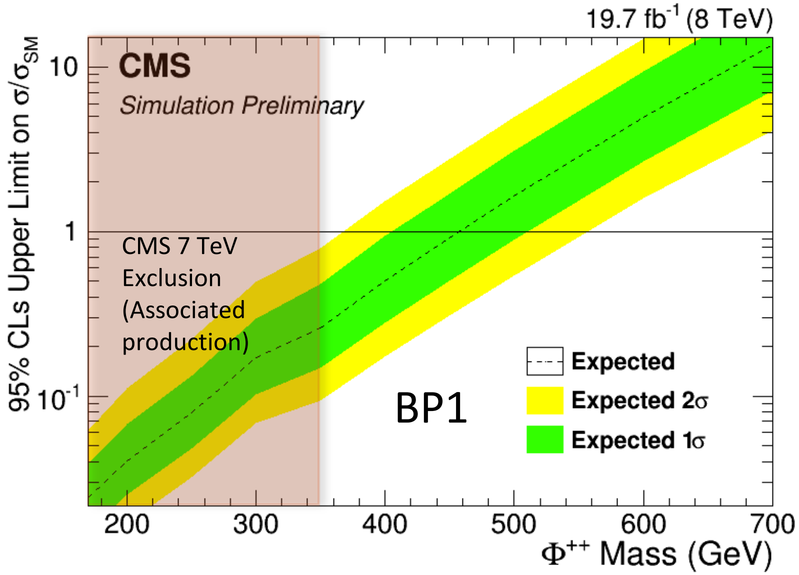


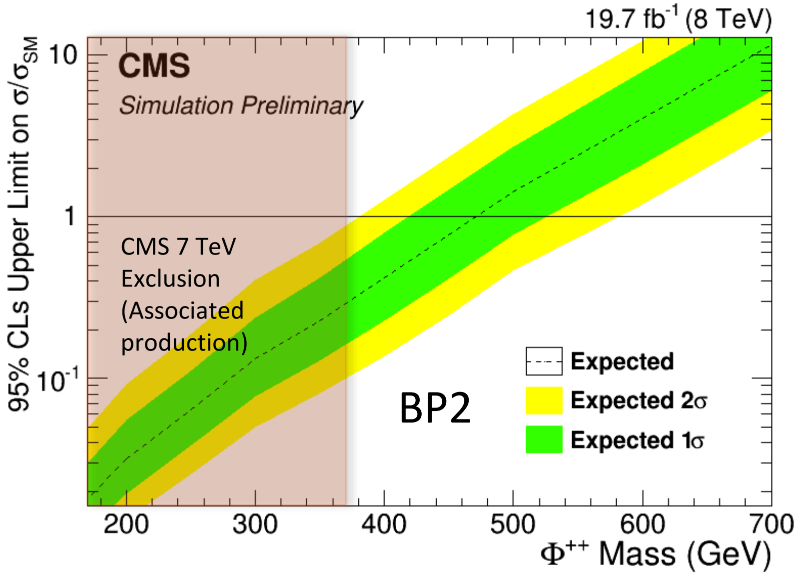


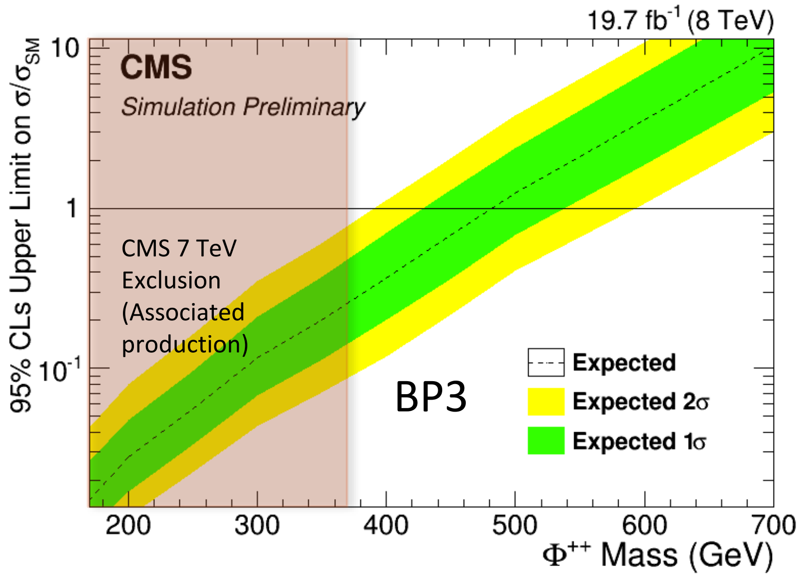


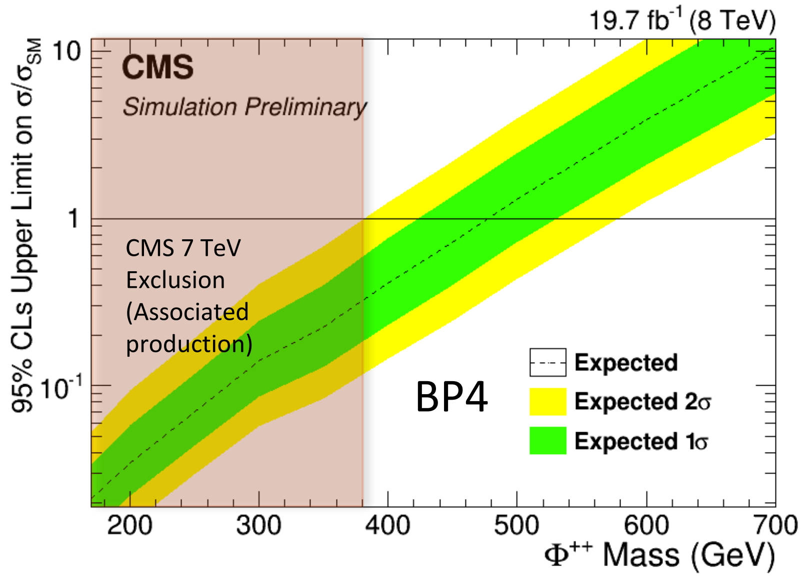
We first note that the 100% branching fraction limits can be extended to >500 GeV with the full 8 TeV dataset with just the associated production channel

Neutrino Mass Hypotheses
MC Background Estimation Limits

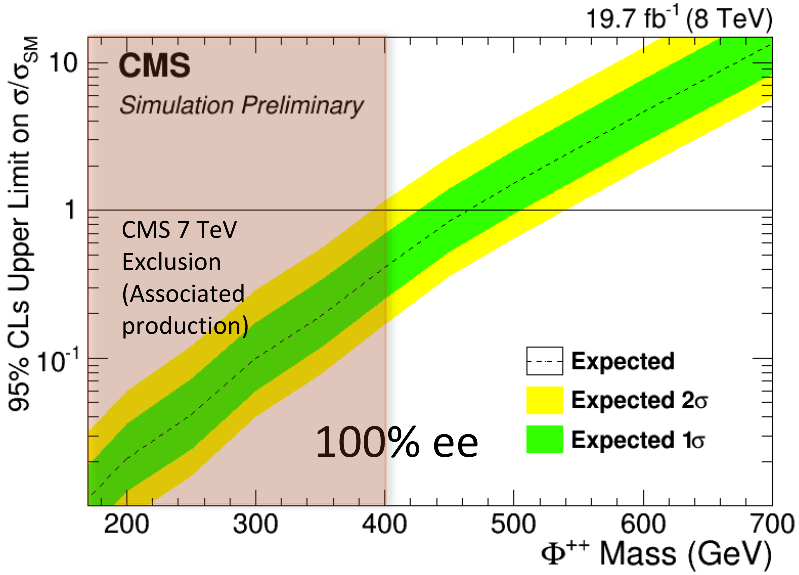


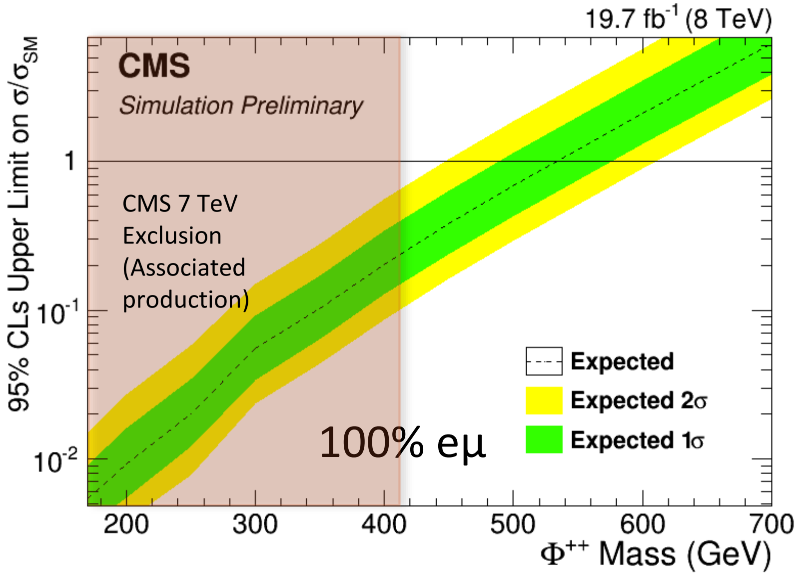


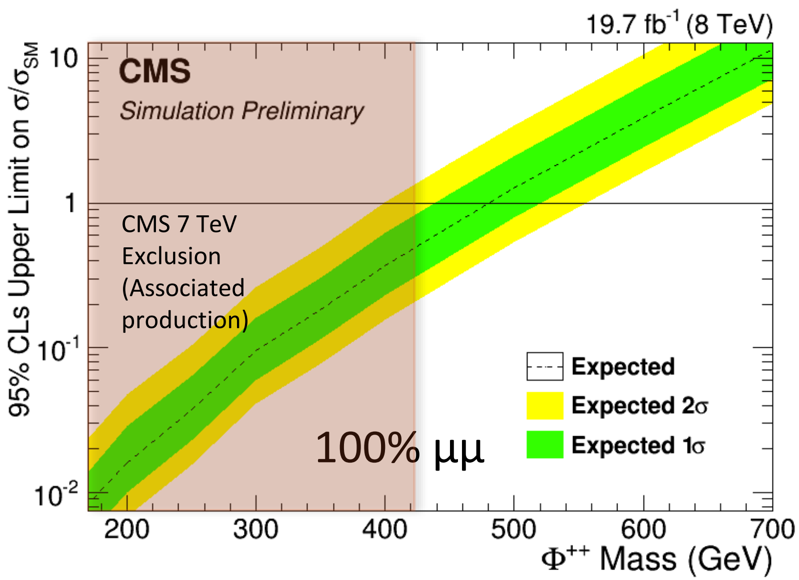




100% Branching Fraction
Data-driven Sideband Estimation Limits

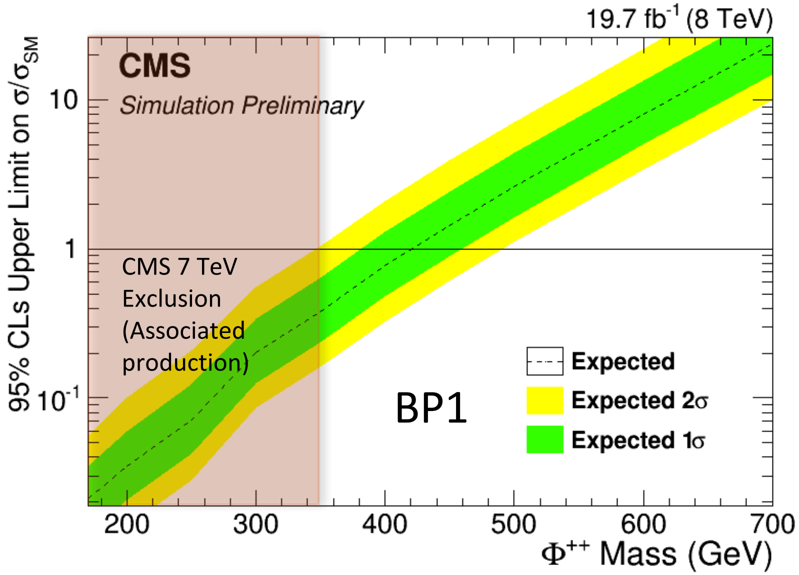


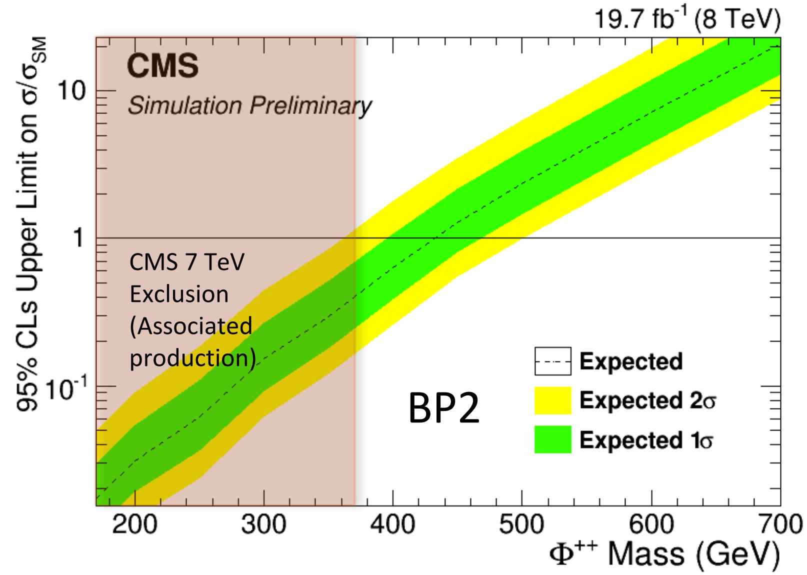


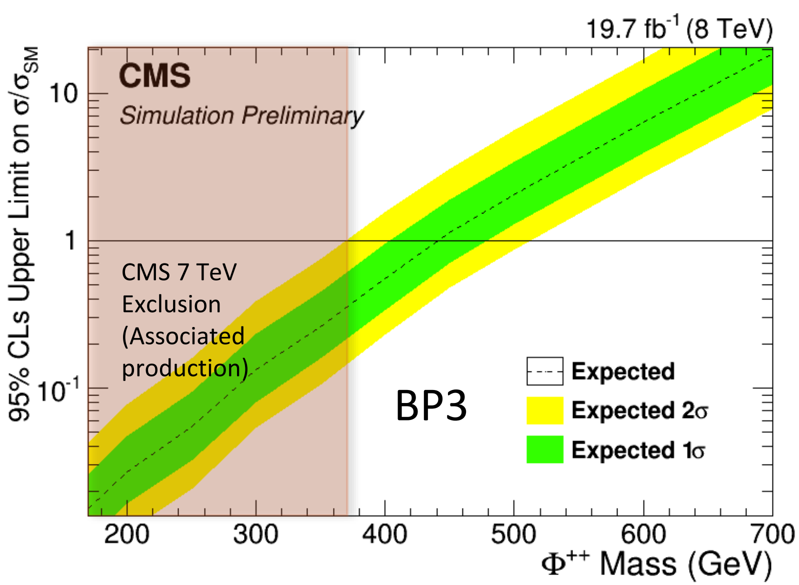


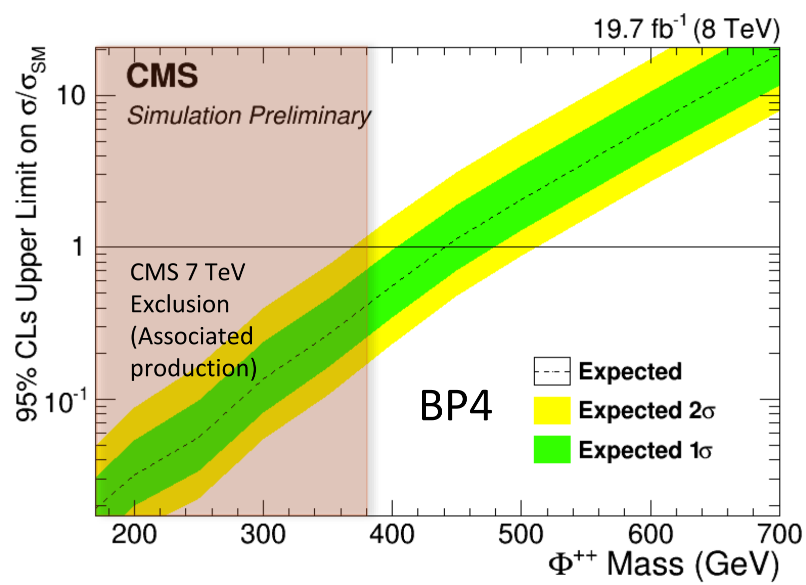
We see similar performance with the sideband estimation method

Neutrino Mass Hypotheses
Data-driven Sideband Estimation Limits









Analysis at 13 TeV

- In June, the LHC will restart with 13 TeV center of mass energy
- Performance changes at 13 TeV
  - Increased pile-up
    - High trigger thresholds
    - Reduced isolation performance
  - Larger cross sections
    - Signal: ~4x increase
    - WZ: ~2x increase
    - ttbar: ~3.3x increase
- Same sensitivity of current (8 TeV) analysis could be reached with about half the data (~6 months of 2015 running)
- With the Run II data will see vast increase in statistics
  - From ~20 fb^{-1} for 8 TeV Run I to ~ 75 fb^{-1} for 13 TeV by the end of 2016
  - Combine with effective quadrupling of signal would expect 10X more statistics, extending our mass range by ~300 GeV beyond 500 GeV 8 TeV expected limits

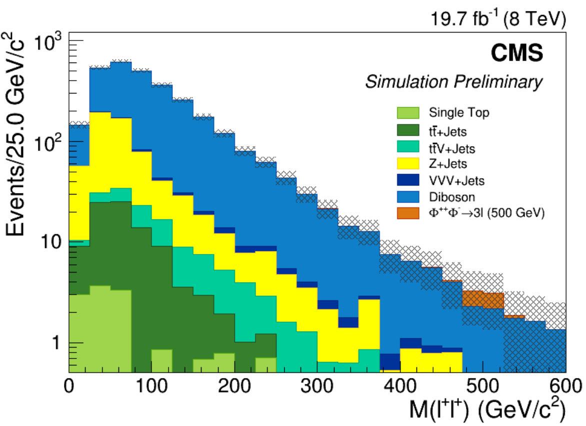
Conclusions and Going Forward

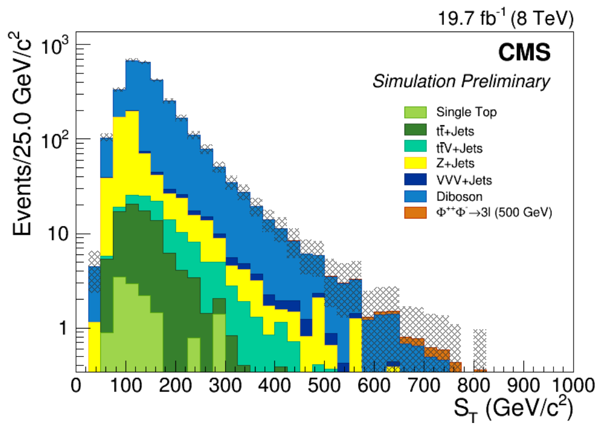
- An in progress search for doubly charged Higgs decay to three and four leptons has been performed
  - We have shown expected limits that outperform the CMS 7 TeV analysis and are comparable to ATLAS 8 TeV limits
  - Expected Physics Analysis Summary approval soon
- Preliminary look at 13 TeV
  - Expect improvements in the analysis, despite larger backgrounds
  - Additionally, analysis to be extended at 13 TeV to include taus
    - Taus were included for CMS 7 TeV analysis
- Exciting prospects for vastly extending the mass range at 13 TeV
  - Potentially 300+ GeV further reach with Run II dataset
  - As much as 100 fb^{-1} of additional data for the next couple years

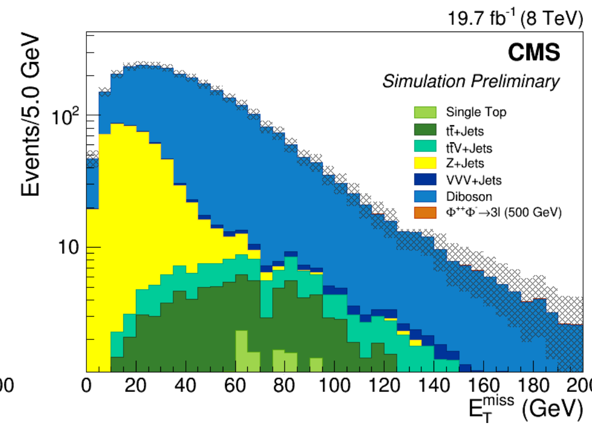
BACKUP

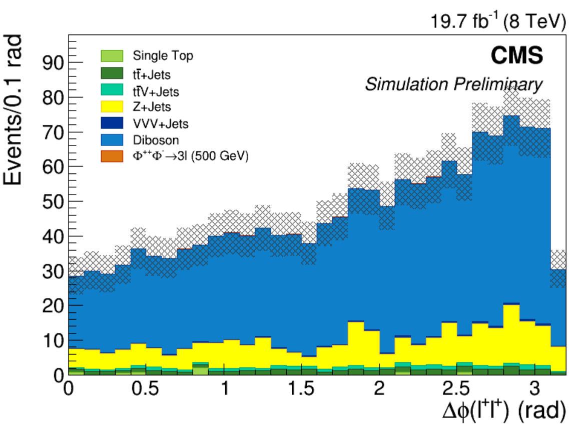
Analysis Preselection Plots

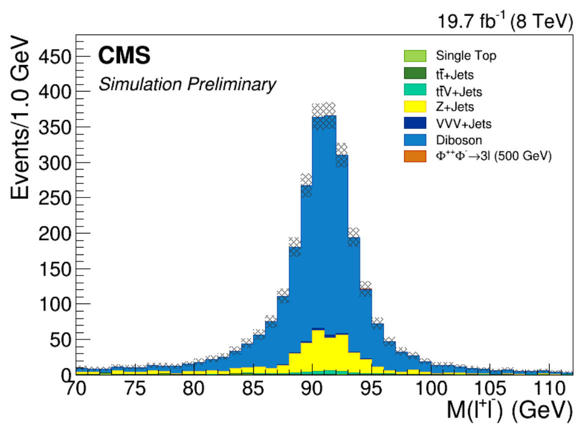
- Preselection only
- All channels

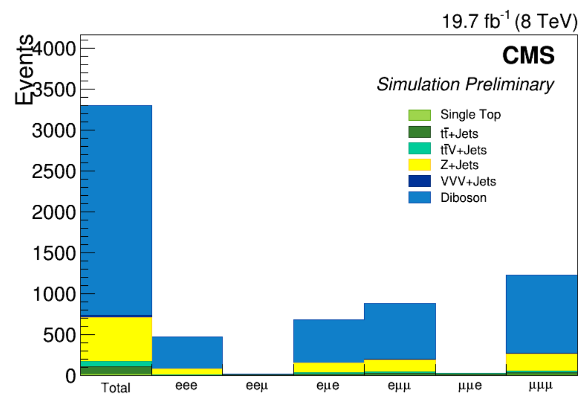












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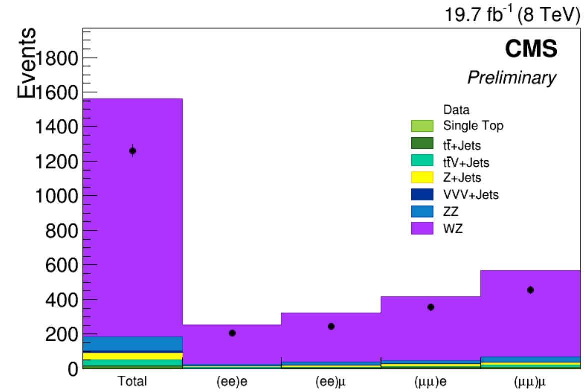
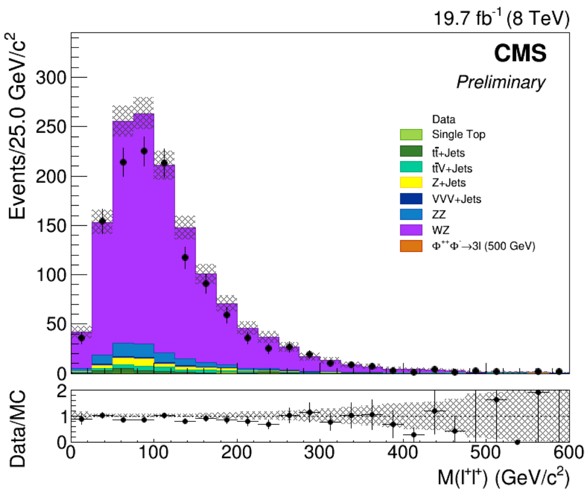
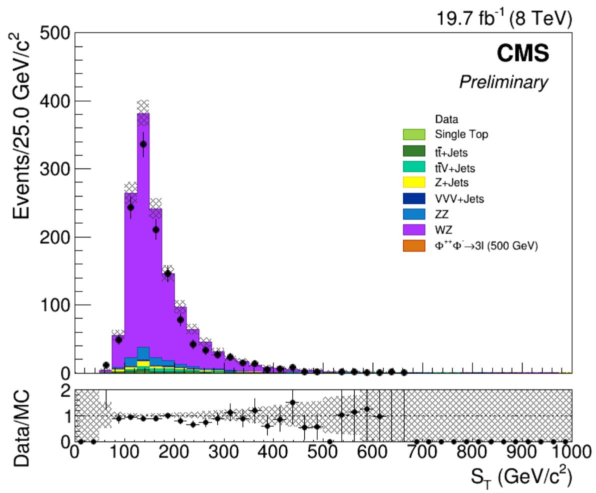
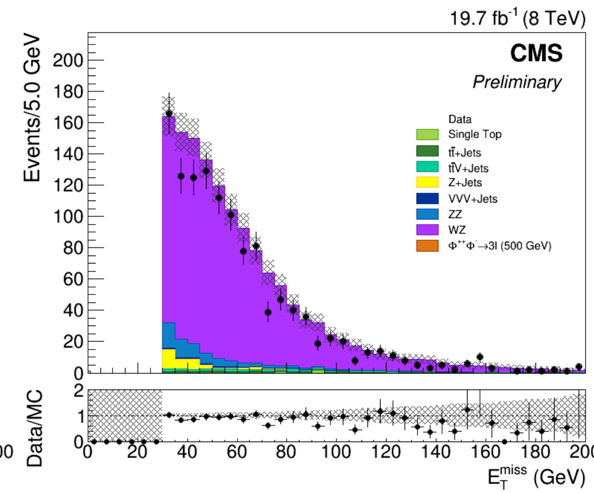
WZ Control Plots

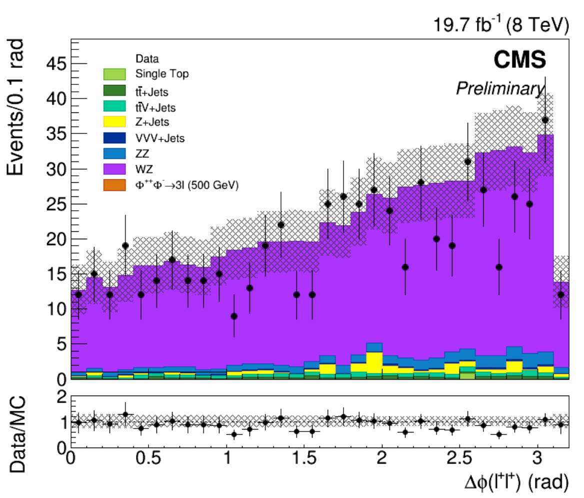
- Full control selection
- All channels

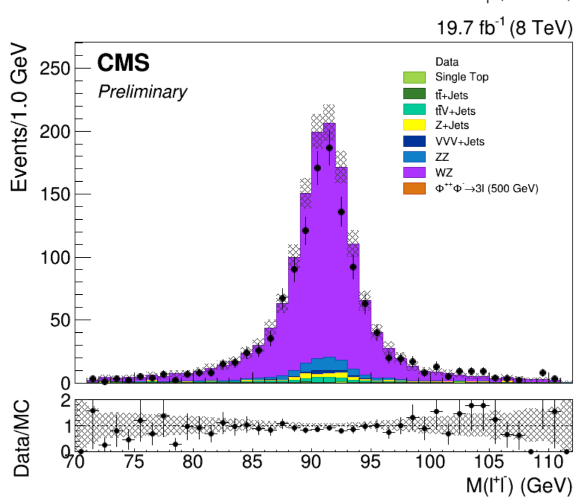


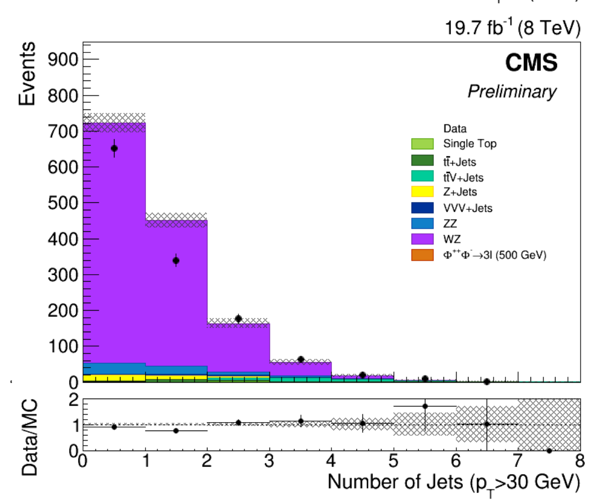












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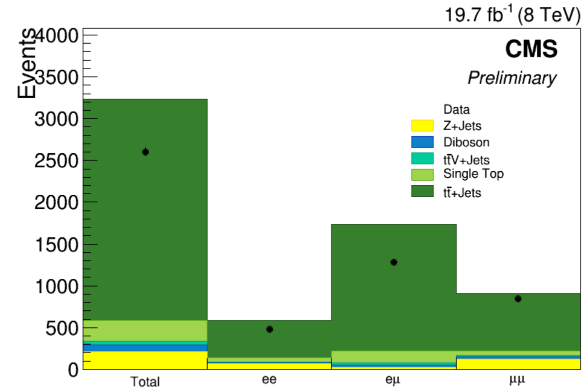
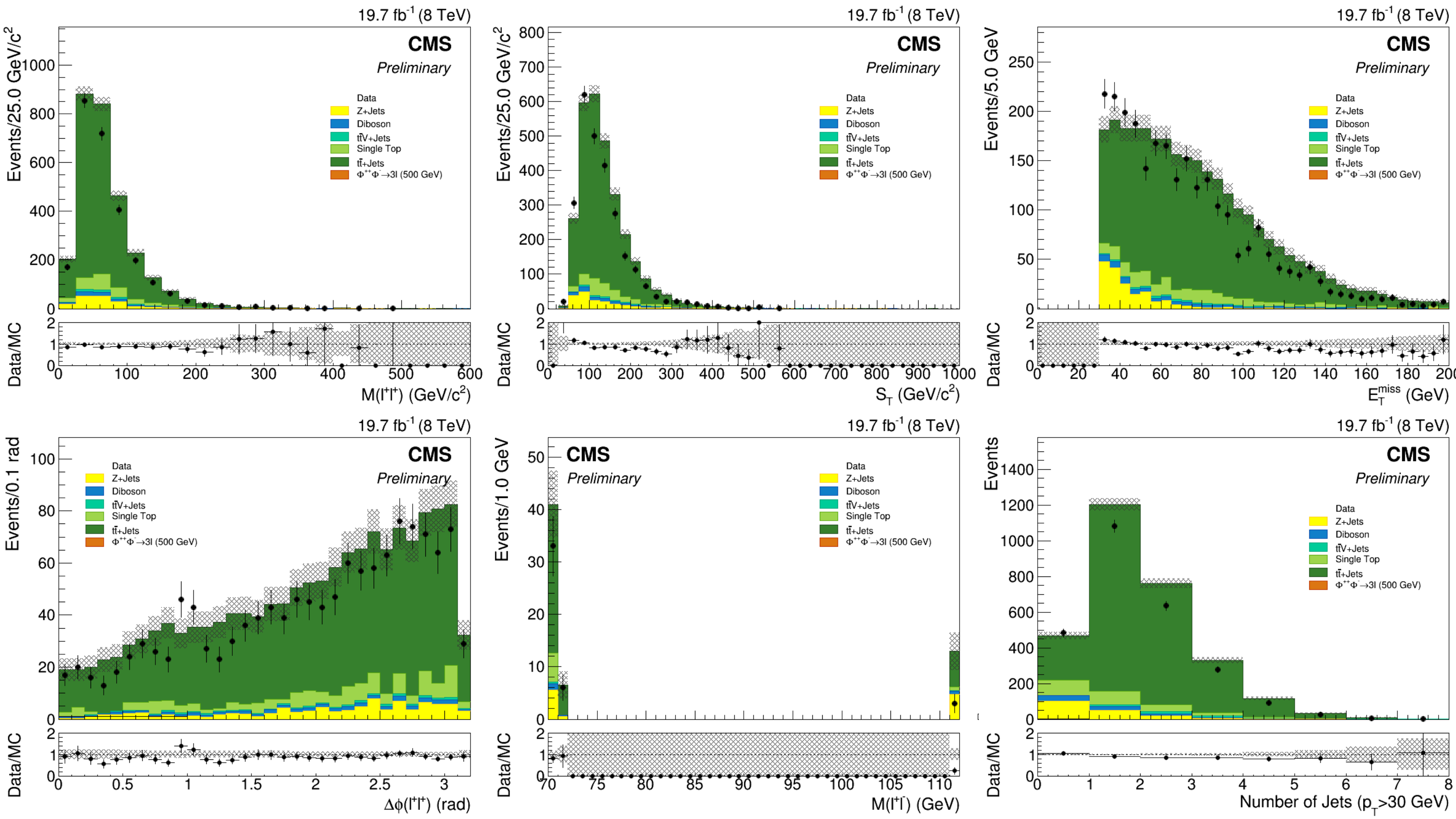
$t\bar{t}$ Control Plots

- Full control selection
- All channels





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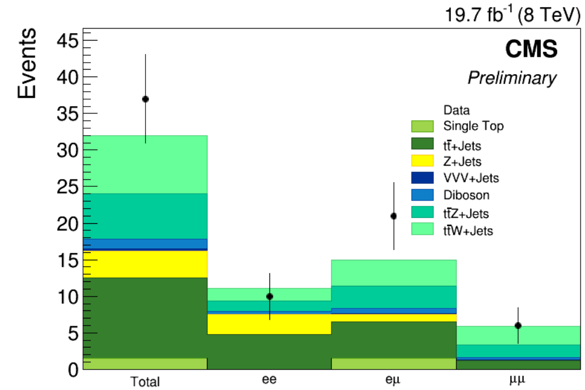
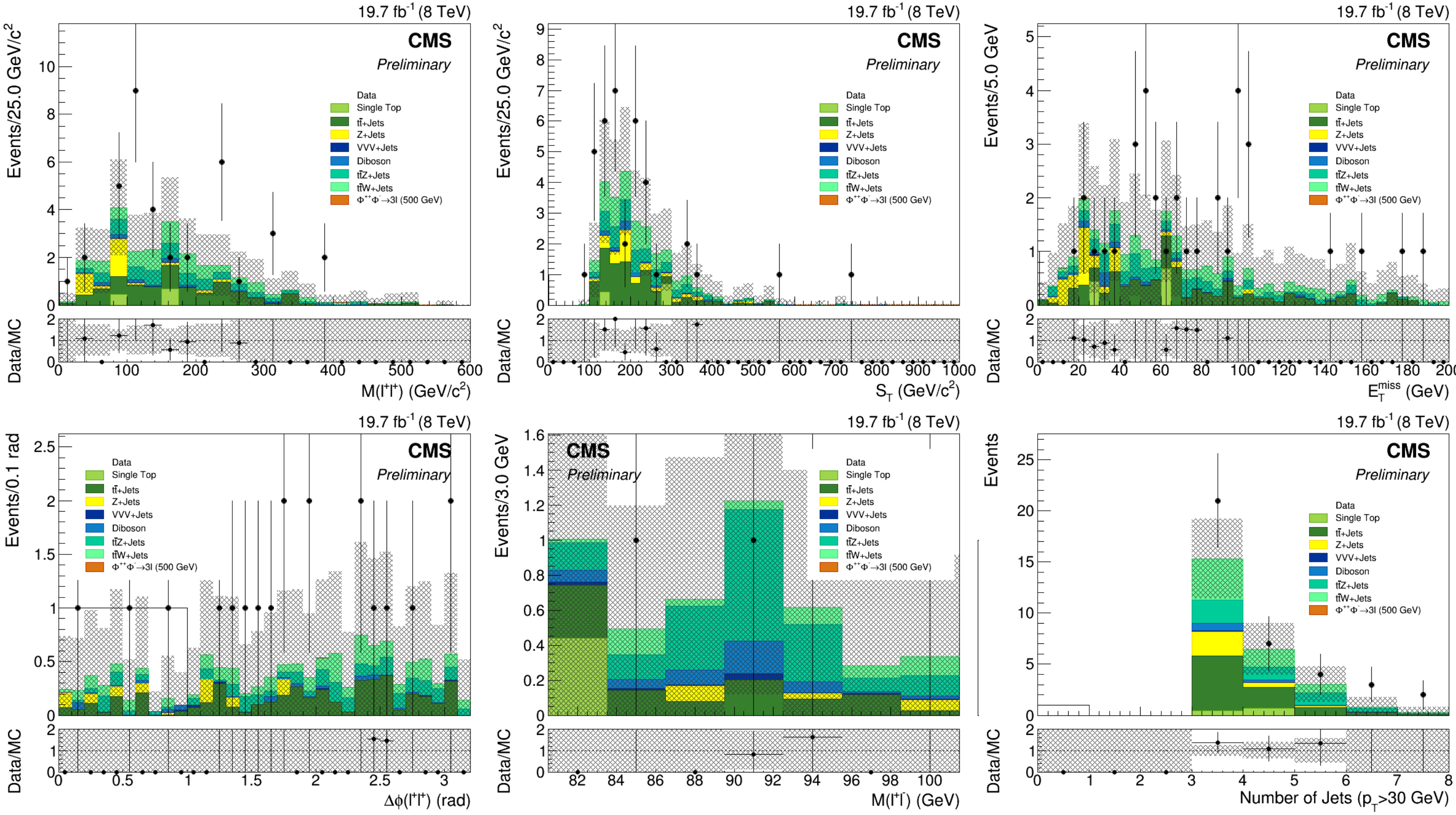
$t\bar{t}W$ Control Plots

- Full control selection
- All channels





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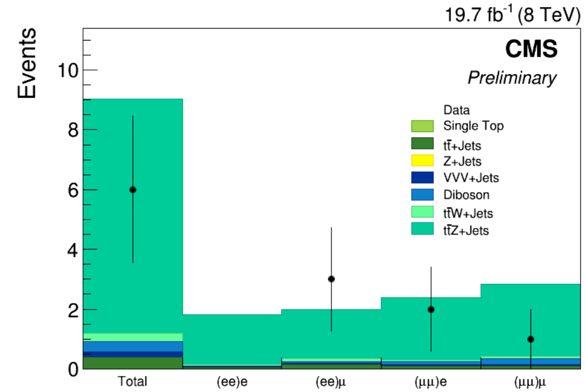
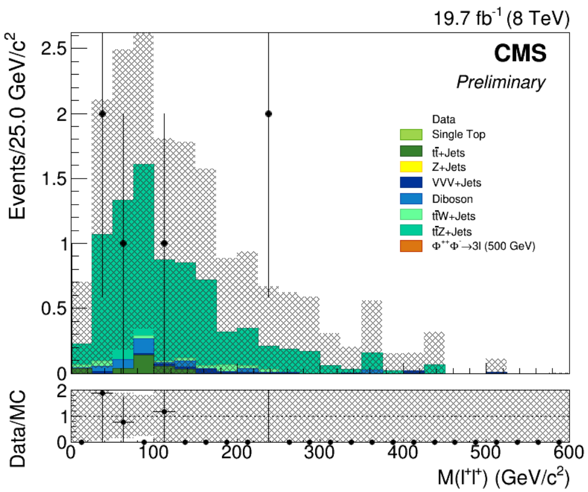
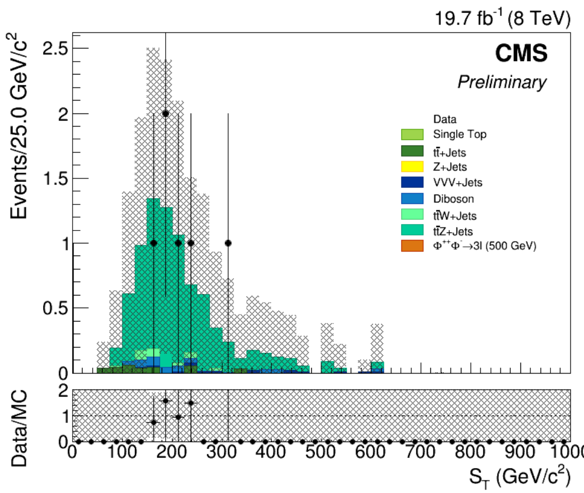
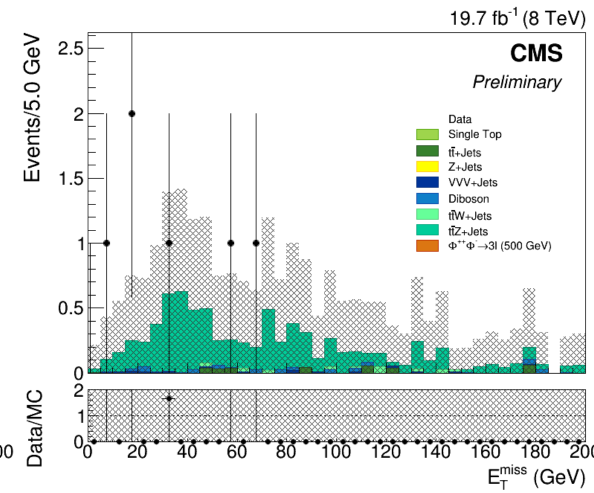
$t\bar{t}Z$ Control Plots

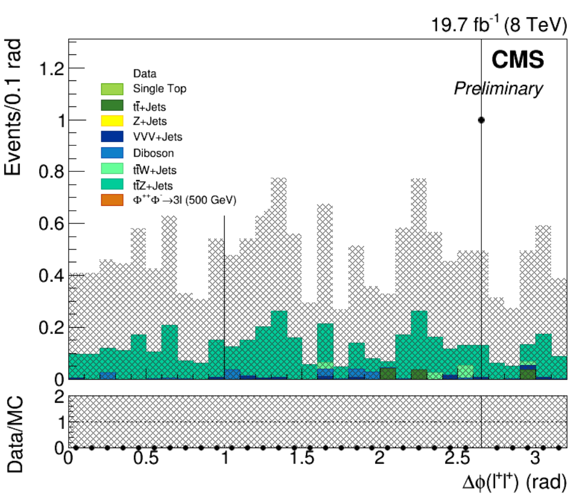
- Full control selection
- All channels

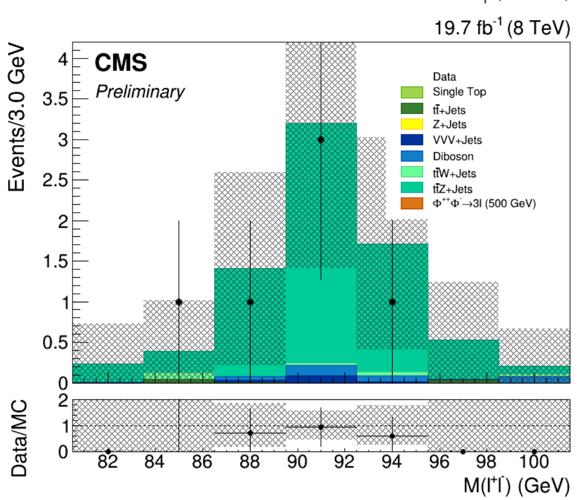


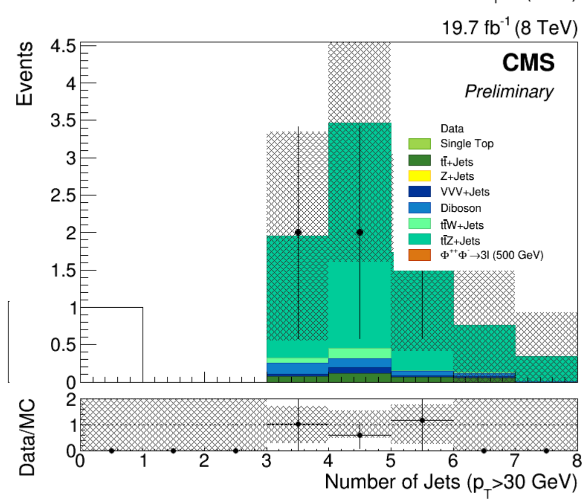












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