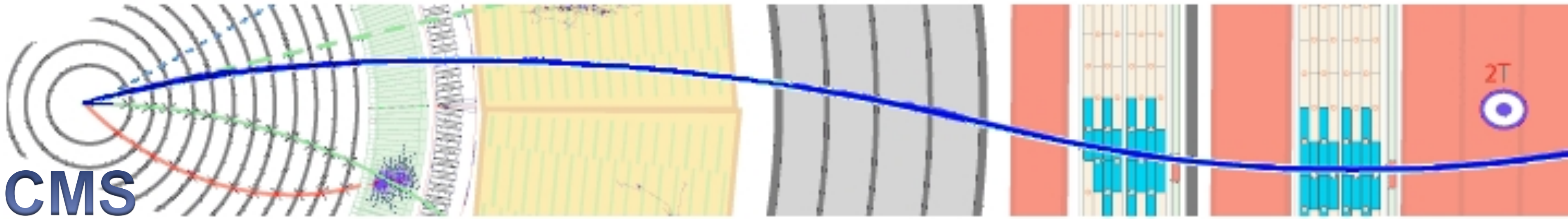


Diboson production at CMS

Isobel Ojalvo

November 22nd 2011

THE UNIVERSITY of WISCONSIN MADISON

CMS

Contents

The Standard Model

CMS

Fundamental Particles:

Quarks, Leptons

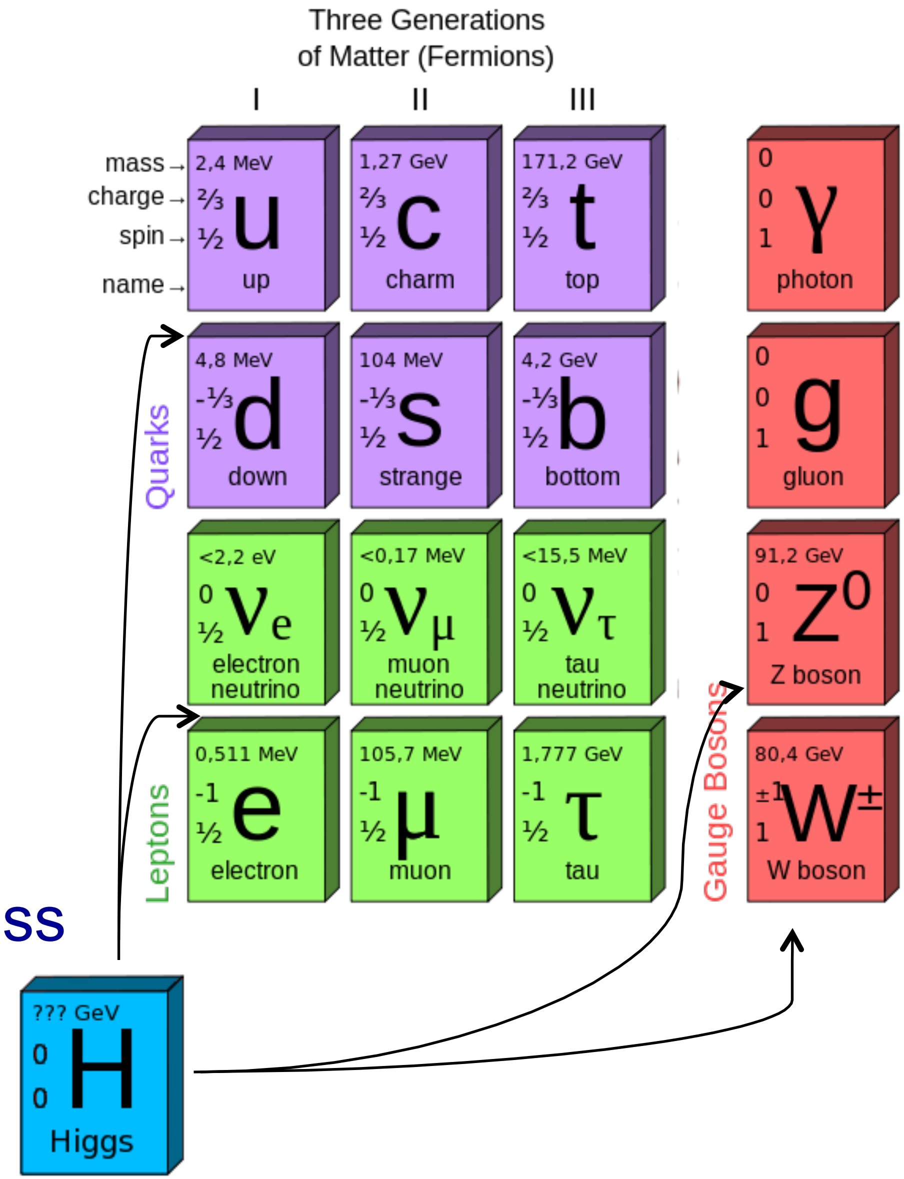
- ✧ 3 Generations
- ✧ Quarks form Hadrons

Gauge Bosons

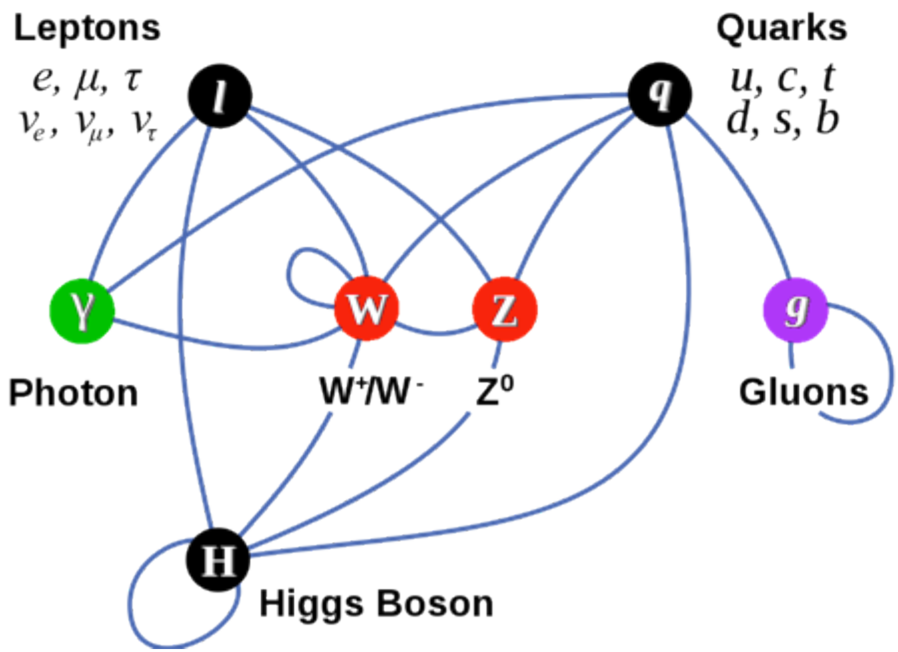
- ✧ Mediate Forces

Scalar Higgs Boson

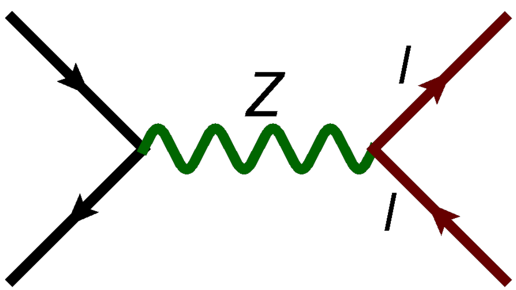
- ✧ Theoretical Particle
- ✧ Higgs mechanism gives mass to the W and Z Bosons and the fermions

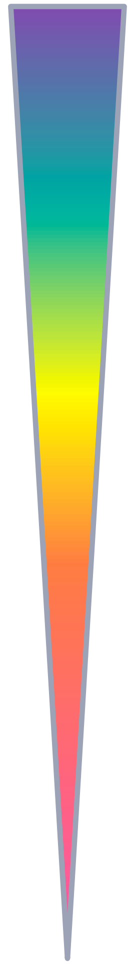


Particle Interactions



During **High Energy** collisions Z Bosons are produced via the Weak Force





Relative force strength

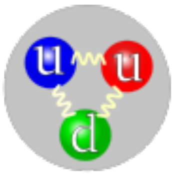
Low Energy

The Strong Interaction binds quarks in hadrons

- Baryons
  - 3-quark states
    - Protons, neutrons
- Mesons
  - quark-antiquark states
    - pions, kaons

Electromagnetic interaction binds atoms together

Weak force responsible for radioactive decay



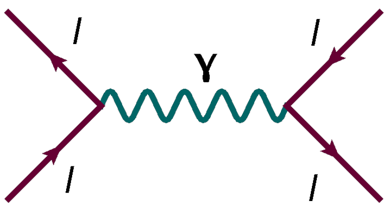
Proton

Pion

High Energy Interactions

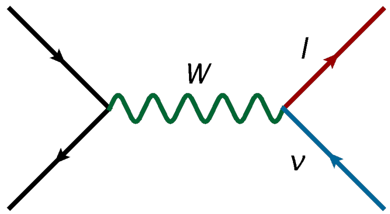
✧ Examples of Processes observed at High Energies:

Electromagnetic

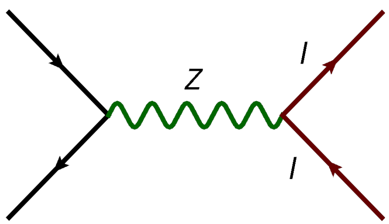


Scattering

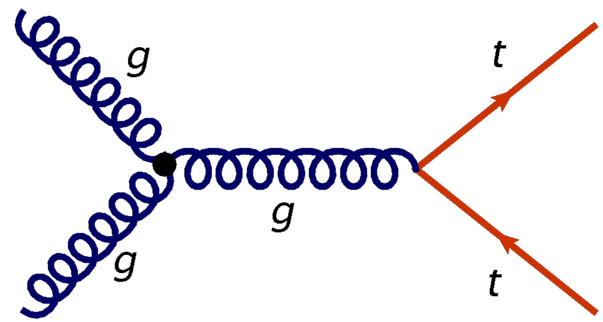
Weak



W/Z Boson Decay



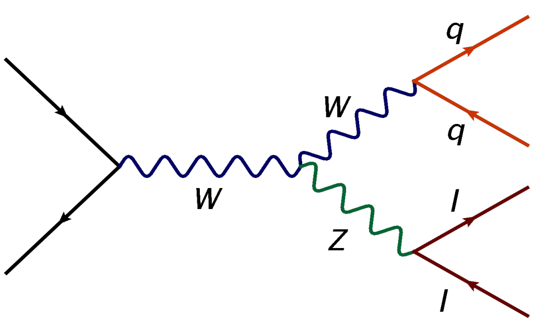
Strong



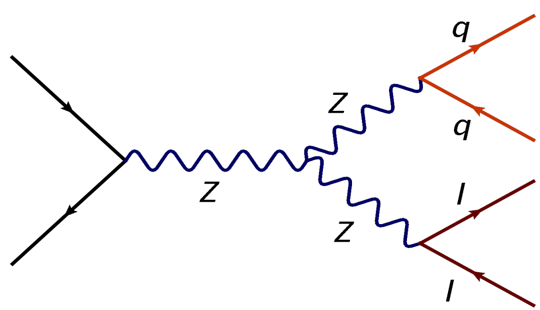
$t\bar{t}$ production

✧ Weak Processes at High Energies (not well tested):

Triple Gauge Couplings

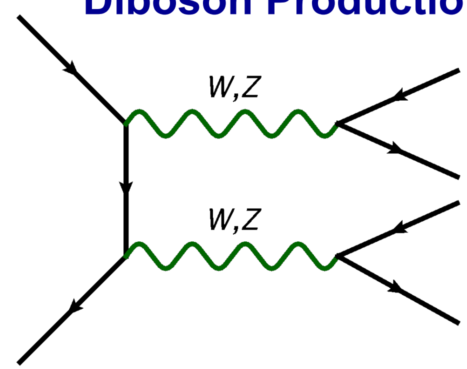


WWZ Coupling



ZZZ Coupling
(Not Allowed)

Diboson Production

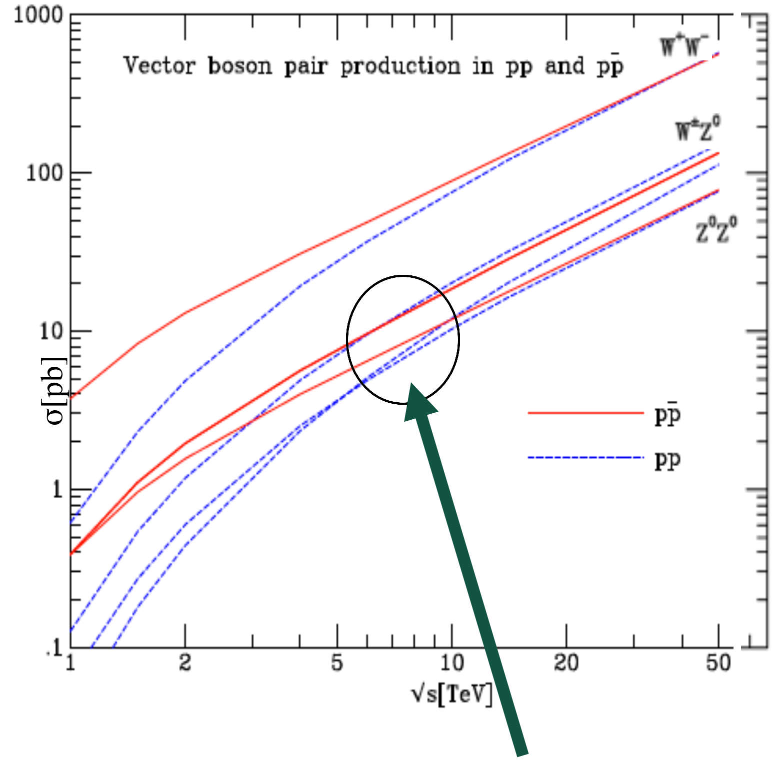


Motivations for Studying Dibosons

CMS

Precision test of the Standard Model

- ✧ Electroweak Symmetry Breaking via the Higgs Mechanism
- ✧ Anomalous Triple Gauge Couplings
- ✧ ZZ decays of New Particles



Opportunity:

- ✧ Increasing rate of proton-proton Collisions at the LHC

→ More Data

Searching for the Higgs Boson

CMS

LHC designed to find the Higgs

→My focus: ZZ Channel

Low mass Higgs

→Search for ZH→μμbb

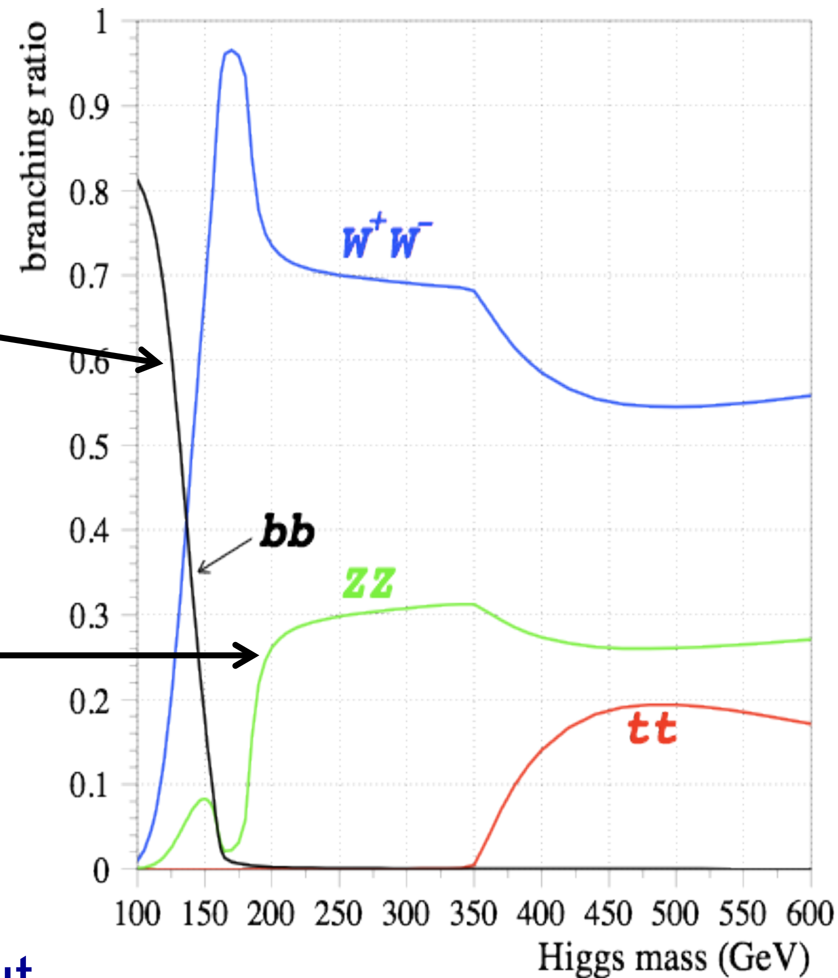
✧ BR high for $M_H < 2M_W$

High mass Higgs

→Search for H→ZZ

✧ BR becomes prominent for $M_H > 2M_Z$

✧ WW branch has higher BR, but more difficult due to weakly interacting neutrinos

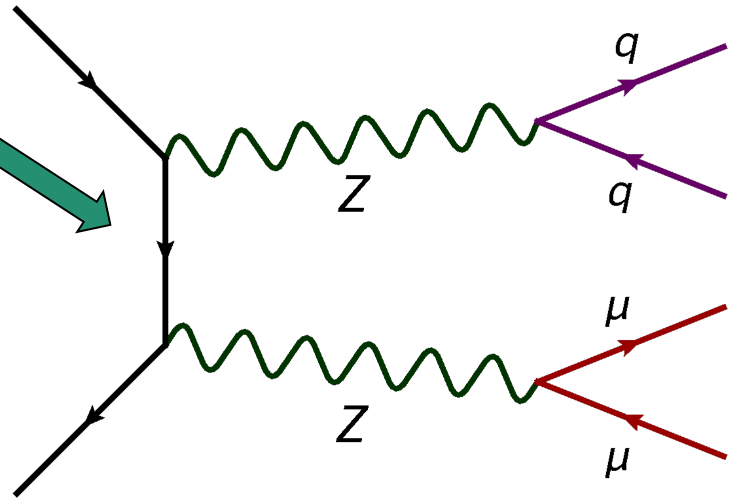


ZZ Final States

LHC collisions are at $\sqrt{S}$ = 7 TeV

Process	Cross Section at LHC
qq →ZZ → μμqq	0.252 pb

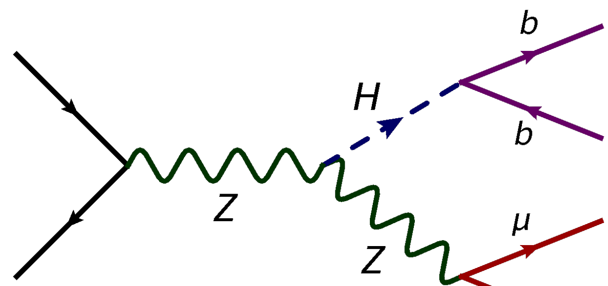
ZZ → Studying decay to
quark anti-quark + muon anti-muon



Decay Mode	Branching Ratio
ZZ → ll+qq	14%
ZZ → qqqq	49%
ZZ → qq+νν	28%
ZZ → νννν	4%
ZZ → ll+νν	4%
ZZ → llll	1%

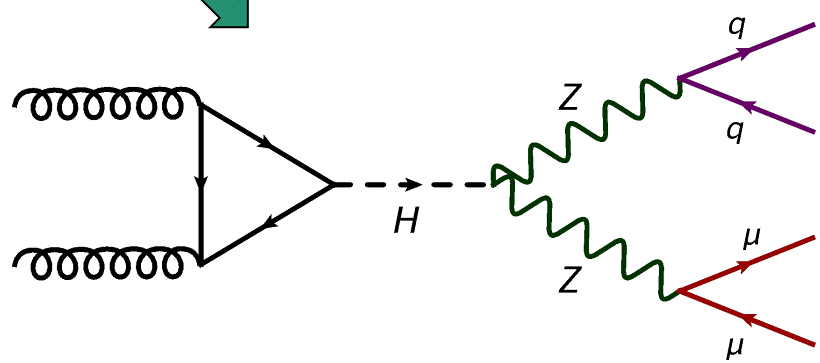
Higgs Production

Process	Cross Section at LHC
qq→ZH m_H = 130GeV	0.277 pb
gg→H→ZZ m_H = 230GeV	1.17 pb



ZH → μμ bb

Look for Higgs in the bb quark Combined Mass



H→ZZ

Look for Higgs in the μμ + qq Combined Mass

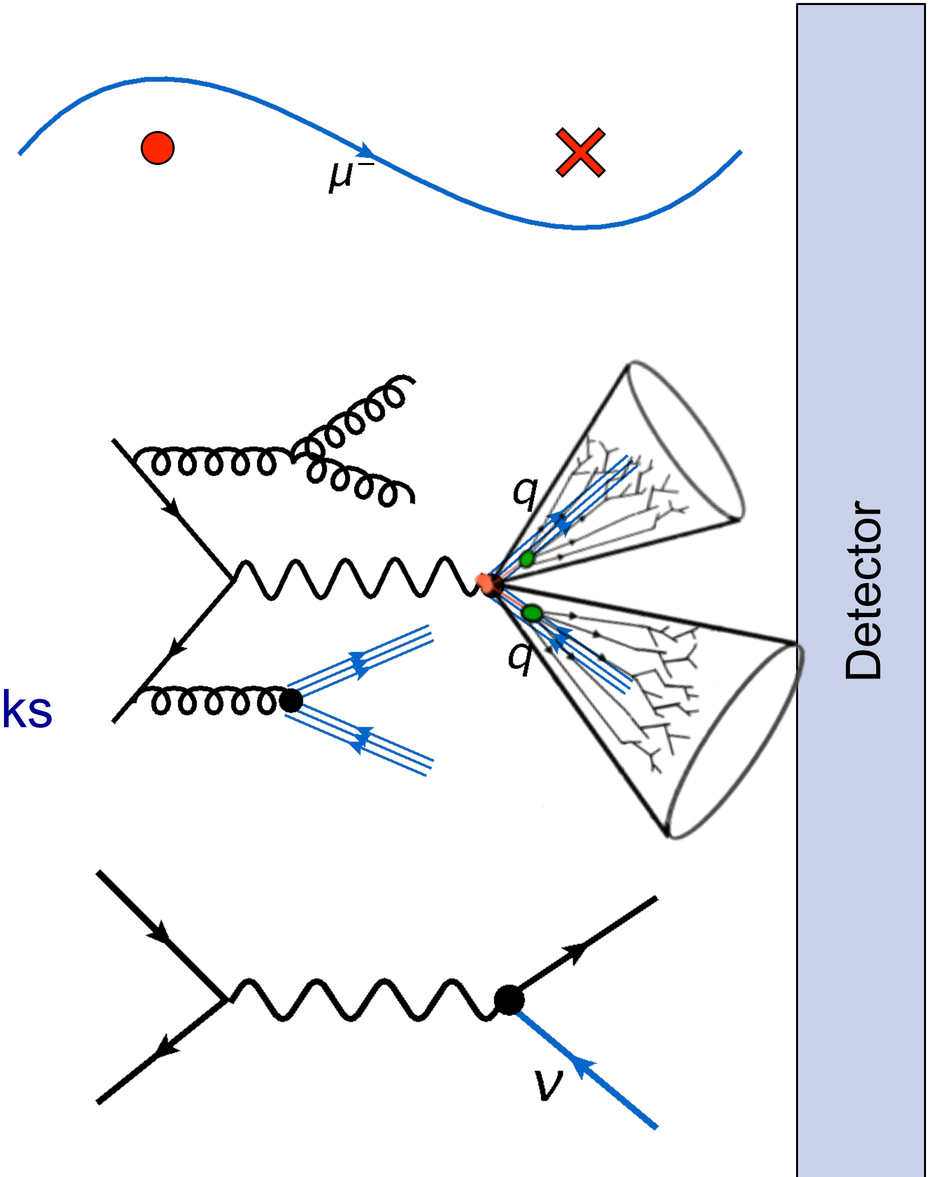
CMS

Particle Detection

Muons
Charged Massive Particle

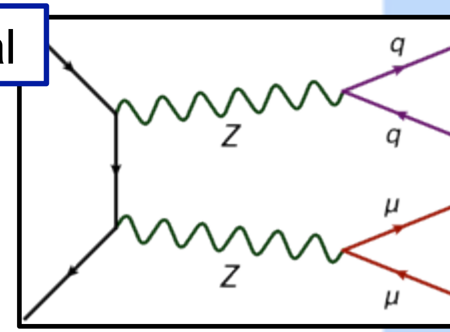
Quarks
No Free Quarks
Hadronization
quarks form **Jets** along the direction of initial particle tracks

Neutrinos
Weakly Interact
Reconstruct p_T in the Detector
→Calculate Missing E_T



Signal and Important Backgrounds

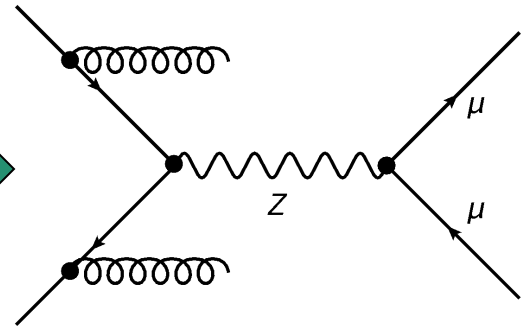
Signal: ZZ→ μμ+ 2 quark jets

Signal


Important Backgrounds

Z+jets → μμjj

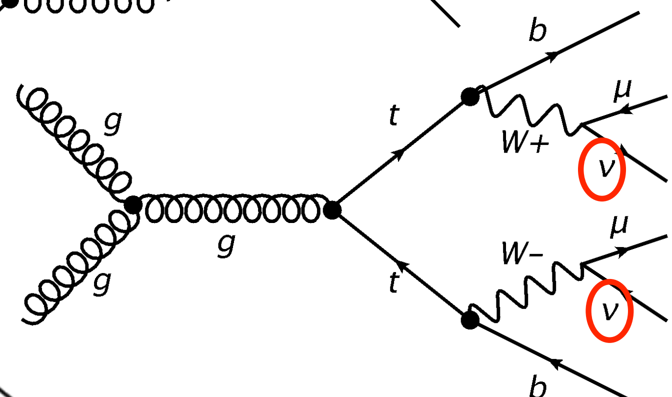
σ = 79 pb



ttbar

σ = 157 pb

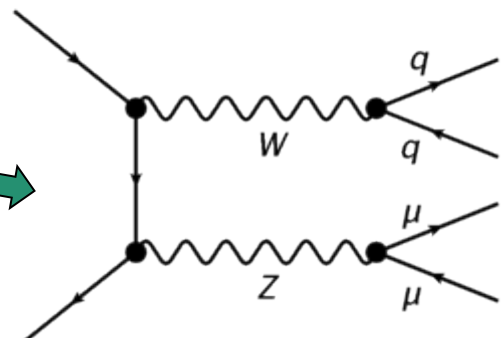
Missing E_T



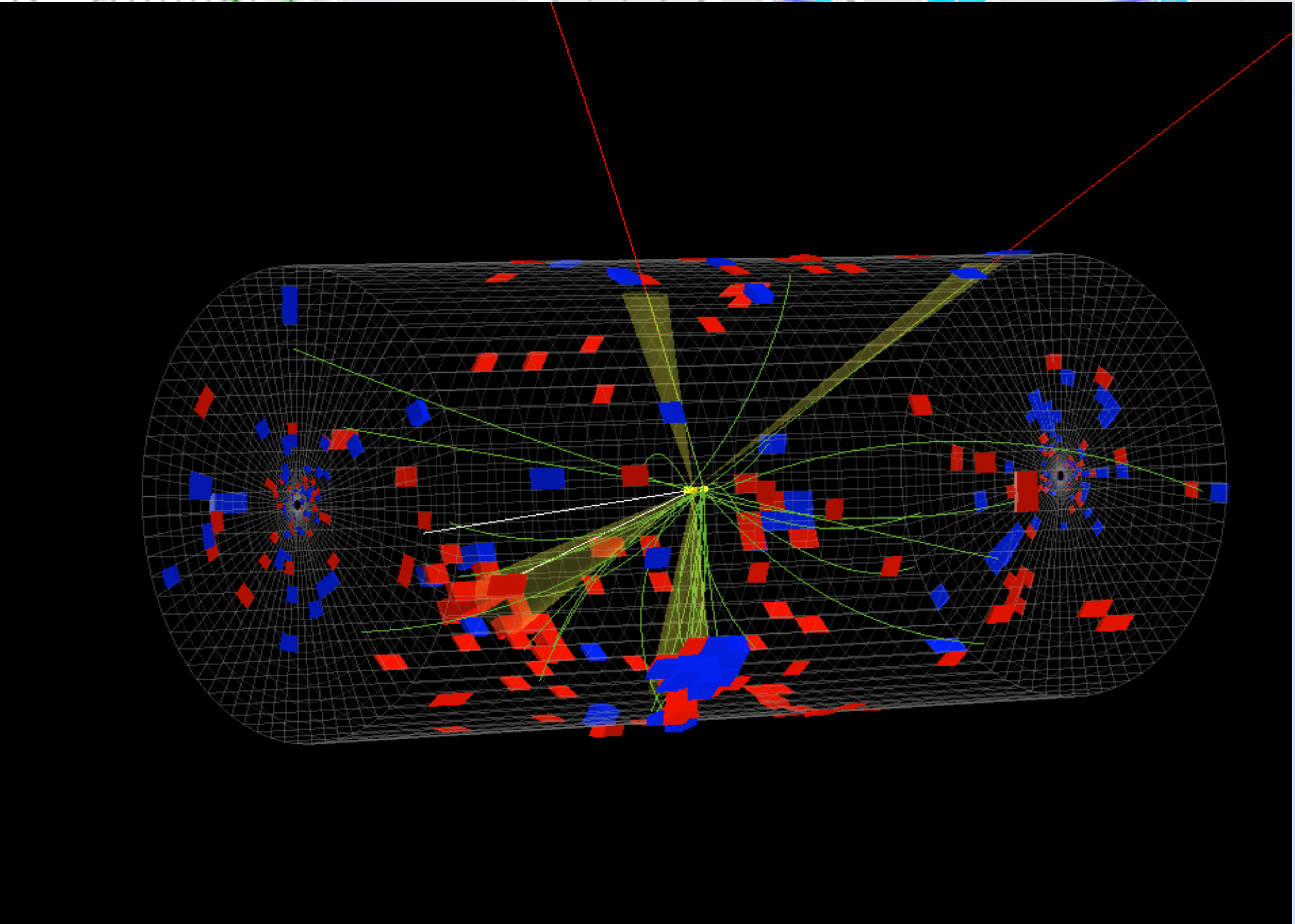
WZ

σ = 18.2 pb

No b-quarks

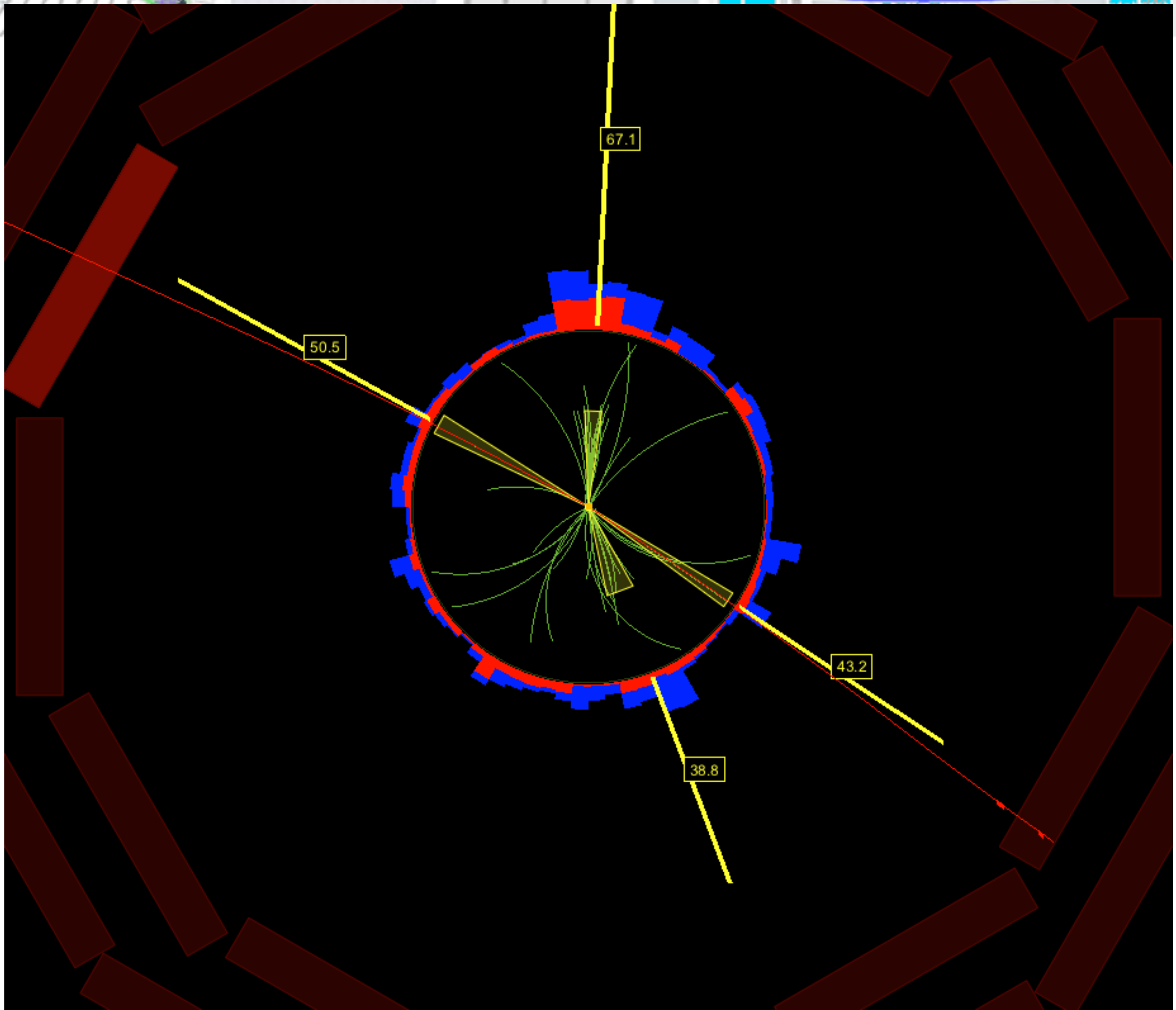


Event Display
Run: 166950 Lumi: 615 Event:725632261



Event Display
Run: 166864 Lumi: 284 Event: 297409470

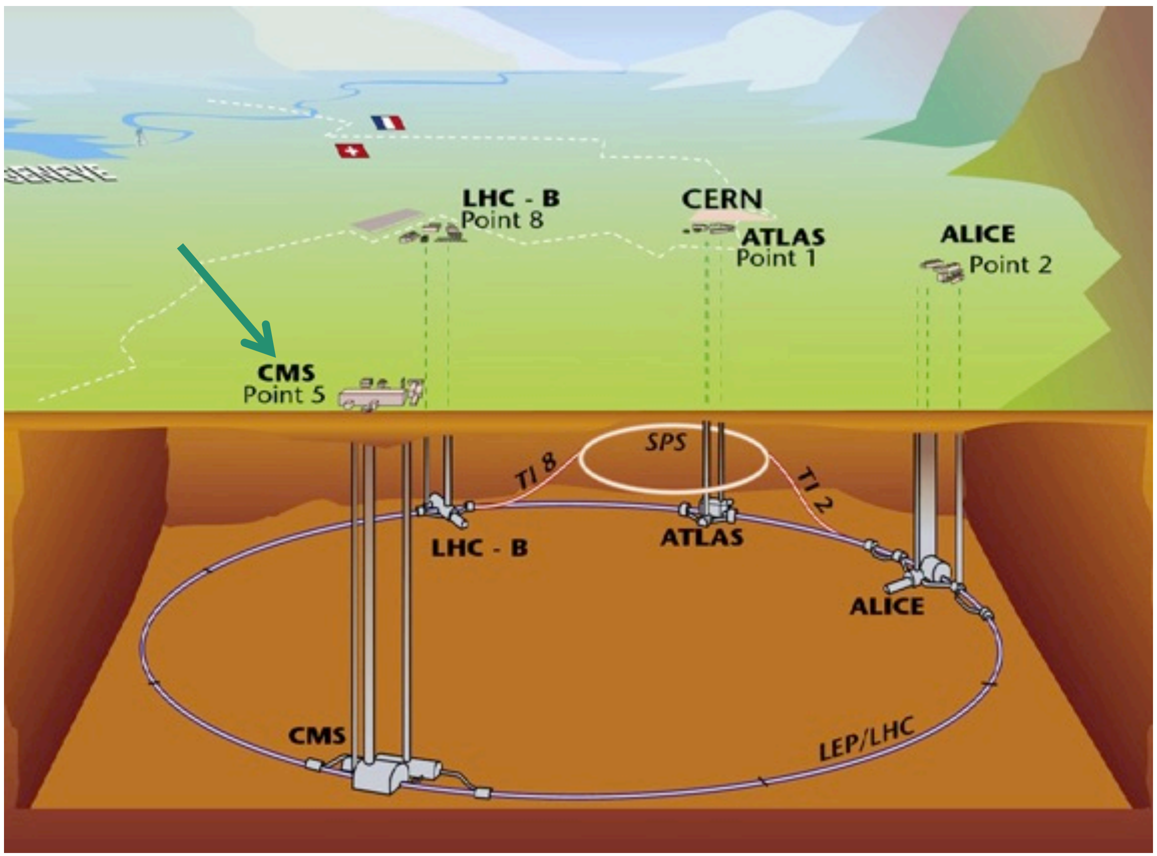
CMS



Large Hadron Collider

Proton-proton Collider 7 TeV Center of Mass Energy (Design is 14TeV)

27km in circumference, 100 m underground



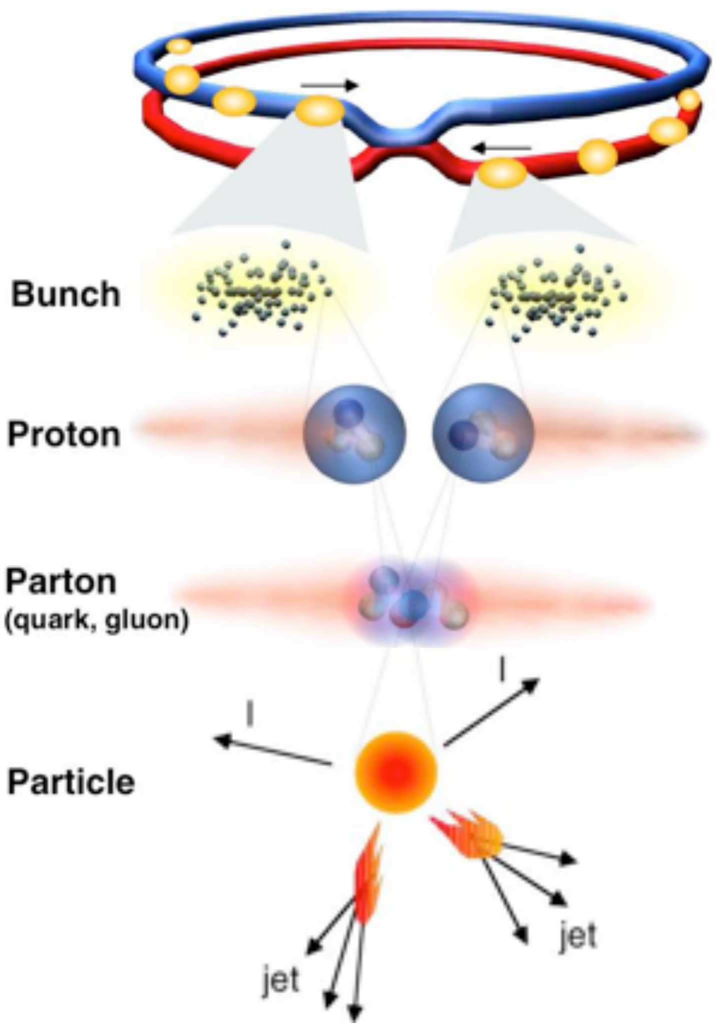
Four Primary Detectors:

CMS, ATLAS - general physics searches

ALICE – Heavy Ion Experiment

LHCb – Forward detector for b-physics

Proton-Proton Collisions at the LHC



	Design	2010	2011
Beam Energy	7 TeV	3.5 TeV	3.5 TeV
Bunches/ Beam	2835	368	1380
Protons/ bunch	1.15×10^{11}	1.3×10^{11}	1.5×10^{11}
Peak Luminosity	$10^{34} cm^{-2}s^{-1}$	$2 \times 10^{32} cm^{-2}s^{-1}$	$3 \times 10^{33} cm^{-2}s^{-1}$
Integrated Luminosity		$36\ pb^{-1}$	$5\ fb^{-1}$
ZZ's Produced		~190	~20,000

Luminosity

$$\mathcal{L} = \frac{\text{Particle Flux}}{\text{Time}}$$

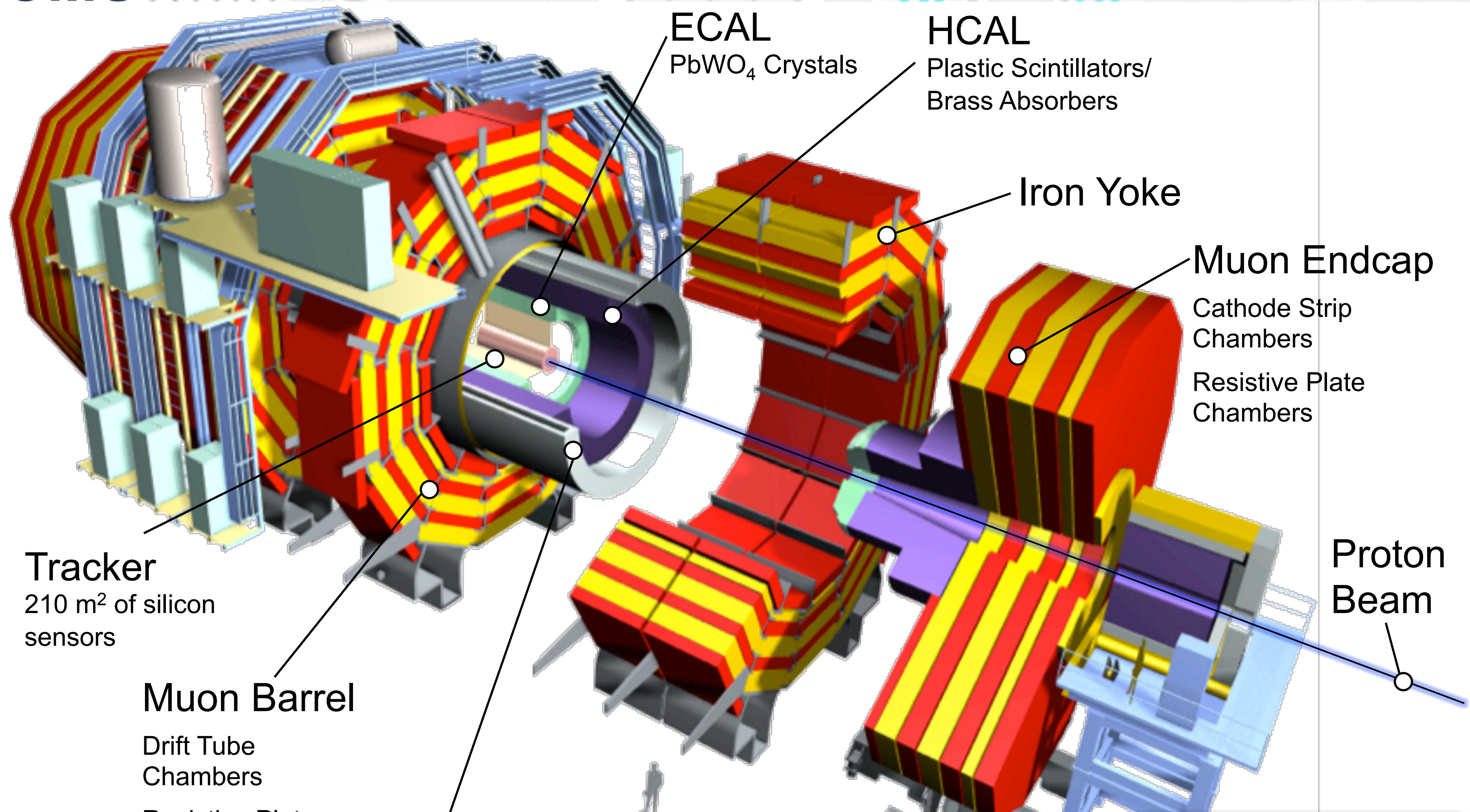
Interaction rate

$$\frac{dN}{dt} = \mathcal{L}\sigma$$ (σ = effective area of interacting particles)

*Expecting 20 fb^{-1} for 2011-2012→ My thesis!

Compact Muon Solenoid

CMS



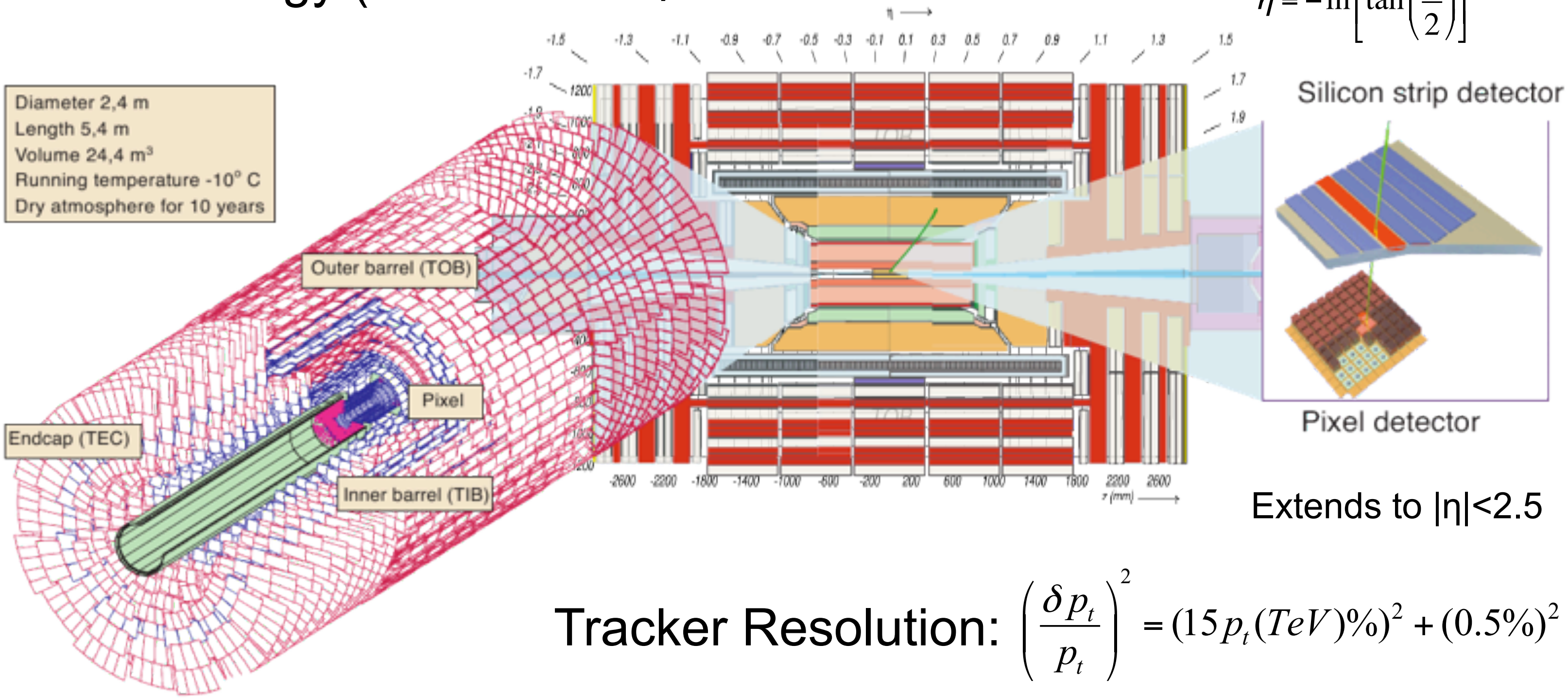
Mass: 12,500T
Diameter: 15.0m
Length: 21.5m

CMS Tracker

Identifies Tracks, Measures Charge and Transverse Momentum

Silicon Technology (5.4m x 2.4m)

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



Extends to |η|<2.5

Tracker Resolution: $\left(\frac{\delta p_t}{p_t}\right)^2 = (15 p_t(TeV)\%)^2 + (0.5\%)^2$

Strong B-fields make the Tracker efficient for a wide range of p_T

Inner Pixel Detector

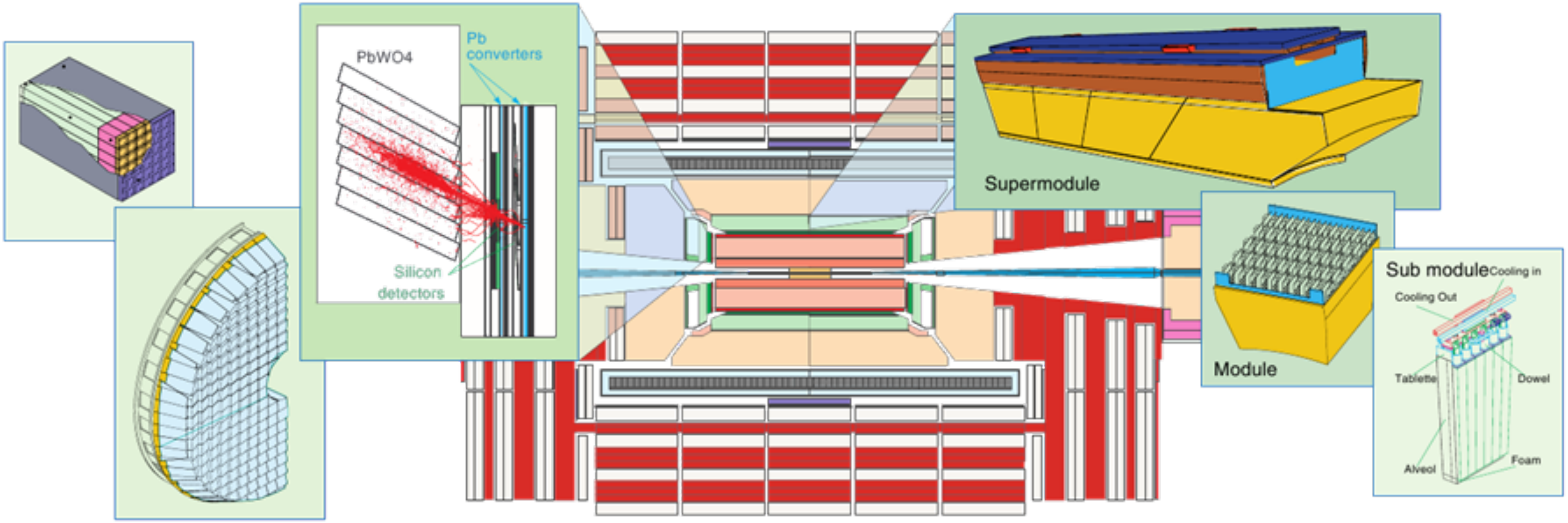
- Close to interaction point
- High Granularity
- Less occupancy per cell

Outer Strip Detectors

- Further from interaction point
- Smaller particle flux

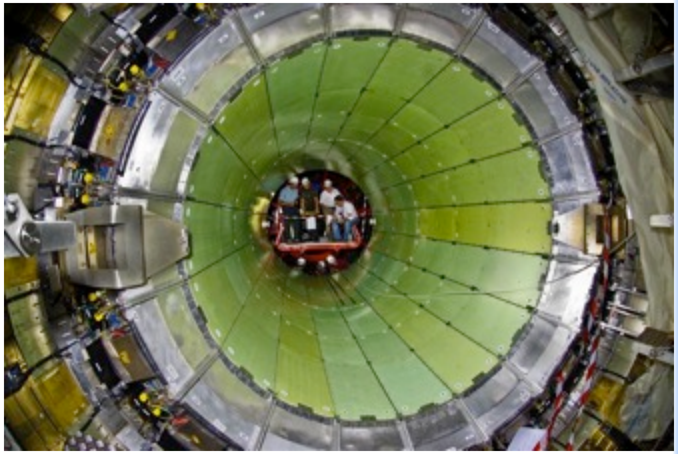
Electromagnetic Calorimeter

The ECAL measures the Energy of Electrons/Photons out to |η|<3



Lead Tungstate Crystals (~75,848)

- High Density (8.2 g/cm^3)
- Short Radiation Length (8.9 mm)
  - Total Crystal Length 230 mm→25.8 X_0
- Small Moliere Radius (22 mm)
- 2 x 2 cm^2 crystal area
- 80% of light is emitted from $PbWO_4$ in 25 ns

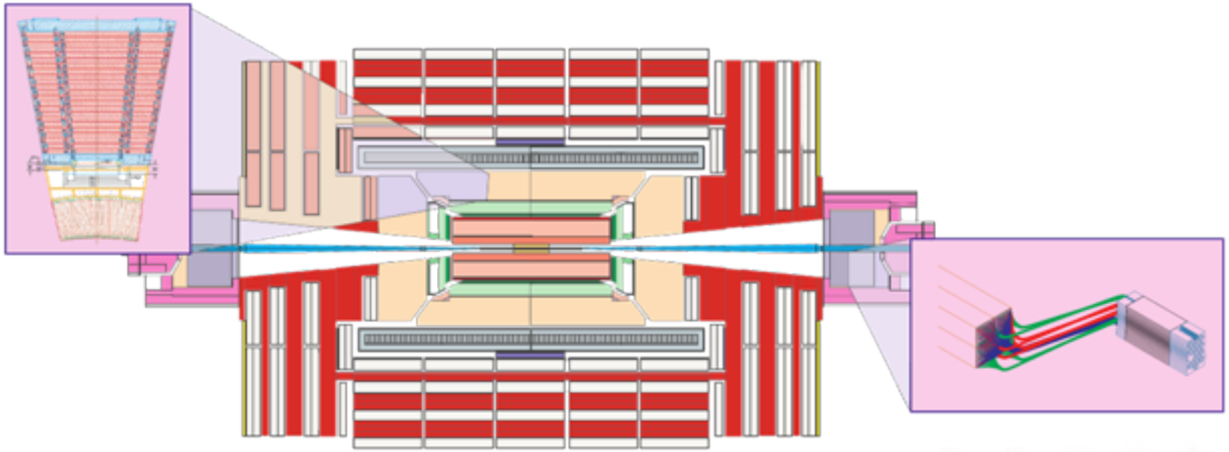


Resolution: $$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.83\%}{\sqrt{E}}\right)^2 + \left(\frac{0.124}{E}\right)^2 + (0.3\%)^2$$

Here, E is in GeV

Hadronic Calorimeter

CMS

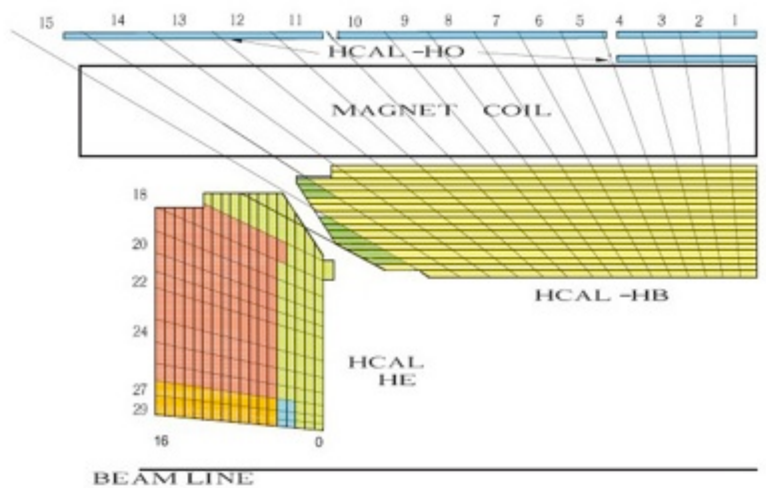


Sampling calorimeter

Layers of Scintillators and Absorbers

Hadron Calorimeter Subsystems located inside the Magnet and in the Forward Region

Covers $|\eta|<5$



Barrel and Endcap Region

Brass and Scintillator

Barrel: $|\eta|<1.4$ Endcap: $1.4<|\eta|<3$

Resolution: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{115\%}{\sqrt{E}}\right)^2 + (5.5\%)^2$

Forward Hadron Calorimeter

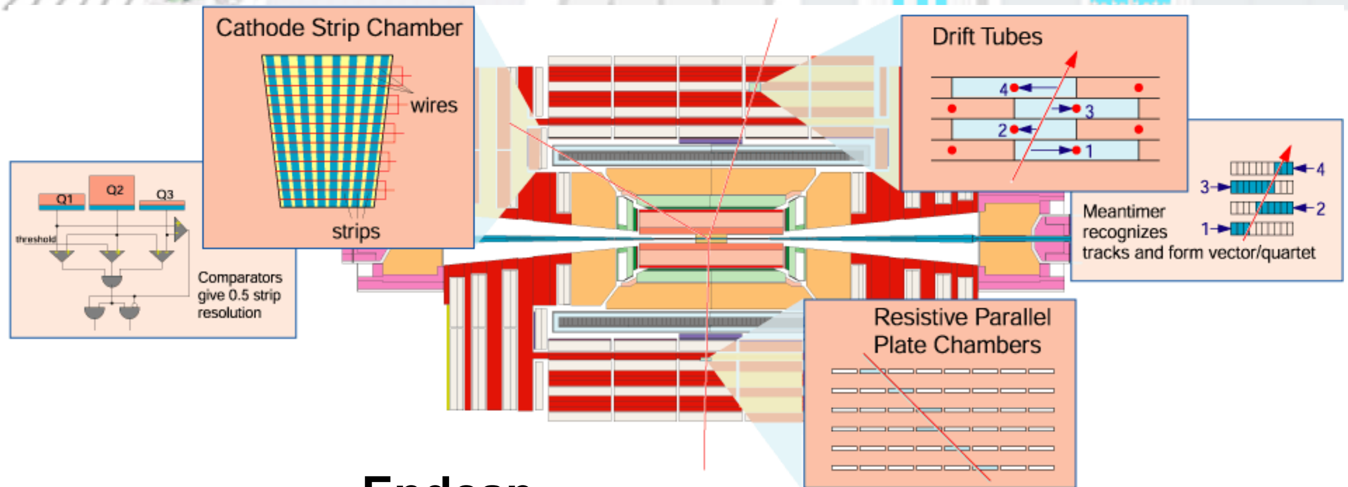
Steel and quartz fiber

$3<|\eta|<5$

Resolution: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{280\%}{\sqrt{E}}\right)^2 + (11\%)^2$

CMS

Muon Chambers



Barrel

Drift Tube Chambers

$|\eta|<1.3$

Resistive Plate Chambers

$|\eta|<1.3$

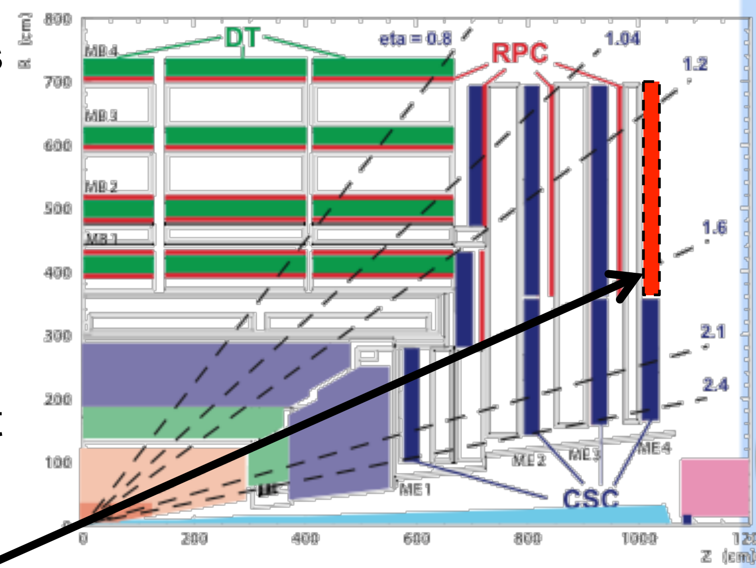
Endcap

Cathode Strip Chambers

$0.9<|\eta|<2.4$

Resistive Plate Chambers

$|\eta|<1.6$



Designed for Efficient Muon Measurement:

Low P_T Muons: the p_T is assigned by the Tracker

High P_T Muons: the Tracker and Muon Chambers contribute to the p_T measurement

New Cathode Strip Chambers will be added to the Endcap during the 2012 Upgrade

CMS Trigger

CMS

Each Bunch at the LHC contains $>10^{11}$ protons

Beams are designed to cross every 25 ns (50 ns)

20 pp interactions per crossing → Pile Up

.5 Billion particles per second grouped in 40 Million beam crossings per second with up to 1 MB data stored/event

→CMS trigger must reduce this to a recordable rate

2-Stage Trigger System:

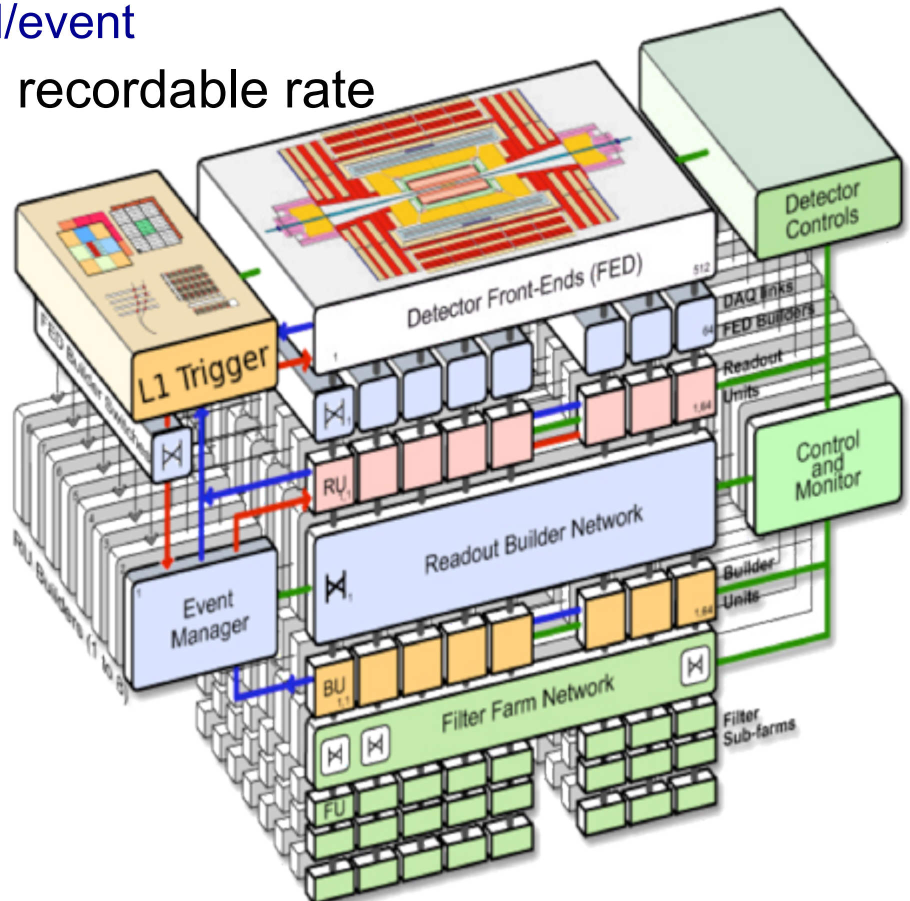
1 GHz

Level 1 Trigger
- High-speed Custom Hardware
- Specialized Algorithms

100 kHz

High Level Trigger
- Software running on Commercial Processor Farm
- Algorithms similar to offline Reco

300 Hz



Level 1 Trigger

CMS

Calorimeter Trigger

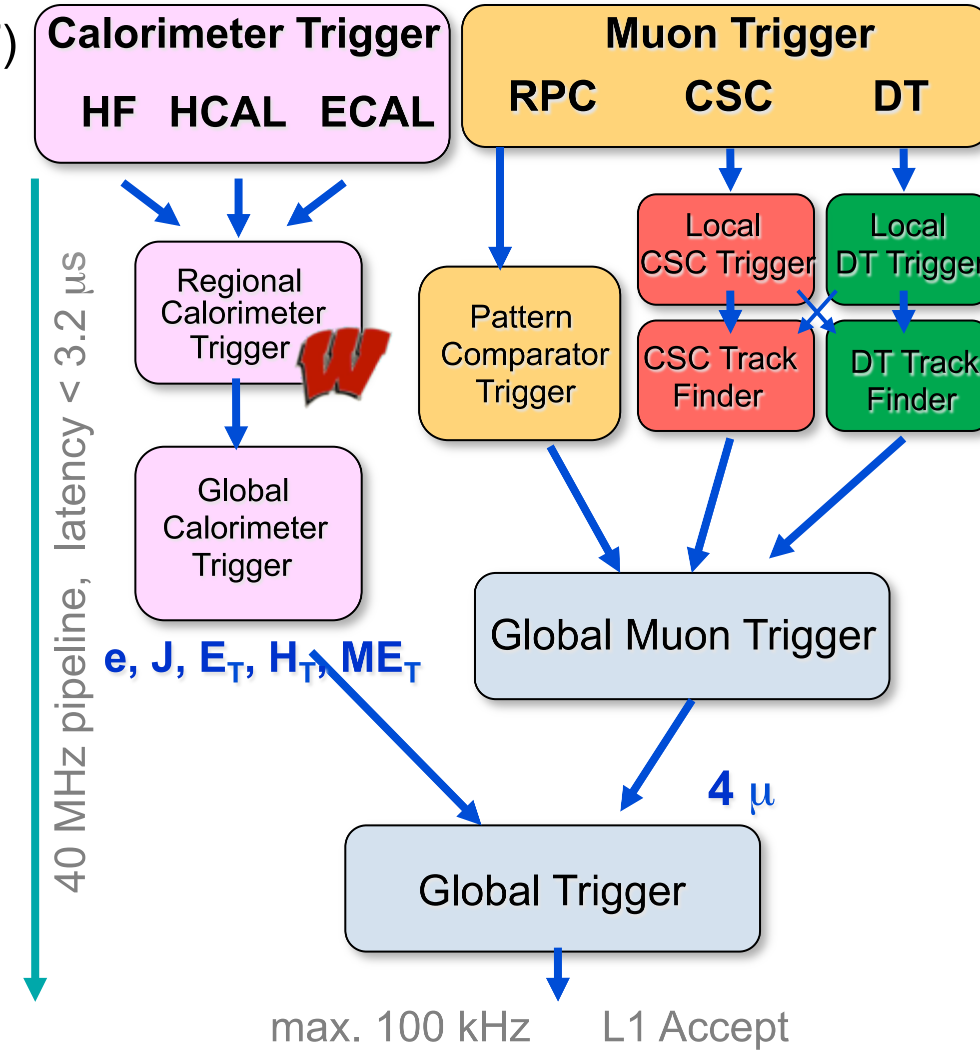
- Regional Calorimeter Trigger (RCT)
  - Finds e/γ energy deposits
  - Finds regional energy deposits
  - Applies τ isolation
  - Forwards RCT objects to GCT
- Global Calorimeter Trigger (GCT)
  - Sorts RCT Objects
  - Calculates Missing E_T
  - Performs Jet Clustering

Muon Trigger

- Regional Triggers
  - CSC DT find tracks
- Global Muon Trigger
  - Sorts Muons

Global Trigger

- Makes Acceptance Decision
- Passes to HLT



High Level Trigger

CMS

Goal: Reduce Event Rate from 100kHz to 300Hz

→Hierarchical Selection of Data

Separate Events into Primary Datasets after Selection

Algorithms Similar to Offline Reconstruction

Tag Events for Analysis

100 KHz

1st: Muon Chambers + Calorimeters used for Reconstruction

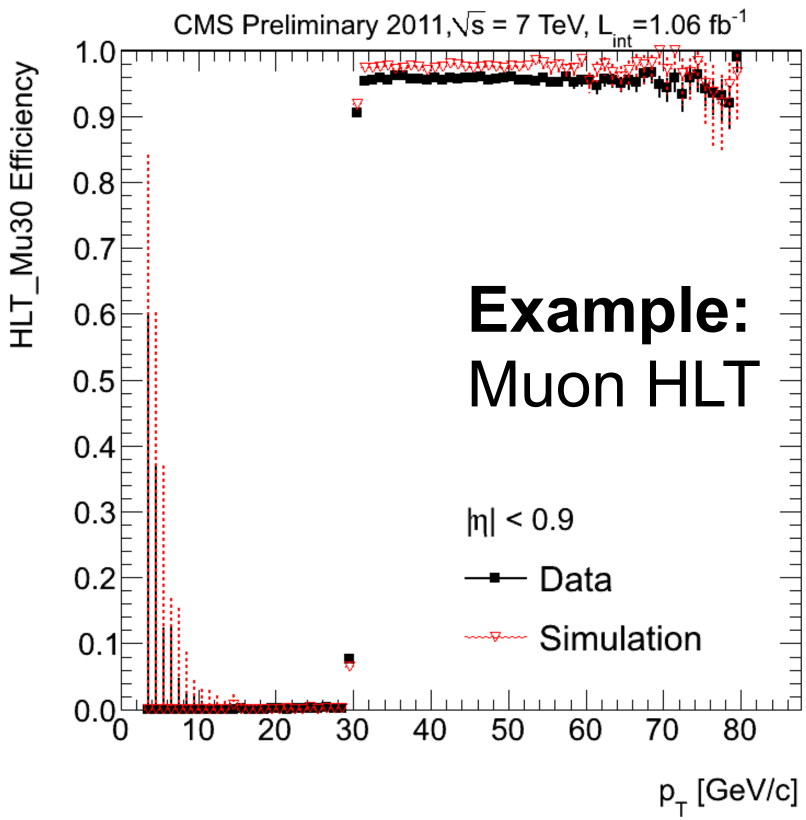
- Reject events based on hits in Chambers/Calorimeters

Continuous Event Rejection

2nd: Add in Tracker

- Requirements on hits in Tracker

300 Hz



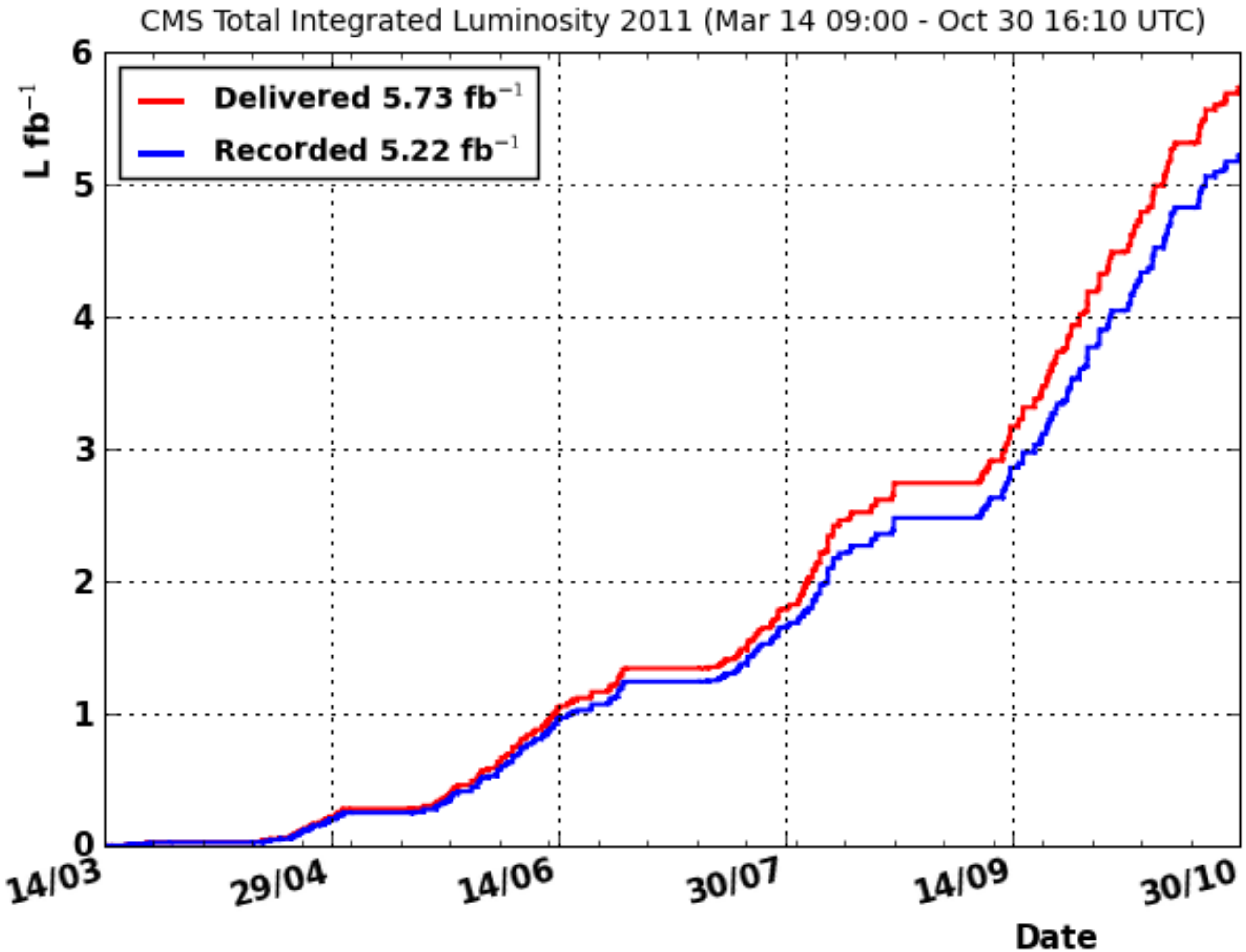
Analysis Overview

- Used CMS 2011 Data (5 fb^{-1} Total Integrated Luminosity)
- Data Reconstruction:
  - Reconstruct and ID Muons
  - Reconstruct and Select Jet
- Simulate data
  - MC Samples used to Simulate Data with GEANT4
- Initial comparison of Data and MC
- Event Selection
  - B-Tagging Jets
- Final Plots
  - Event Table
  - Event Display
- Conclusions/Going Forward

Data Sets Used

CMS

CMS Integrated Luminosity: (analyzed 4.58 fb^{-1})



Monte Carlo Generators

CMS

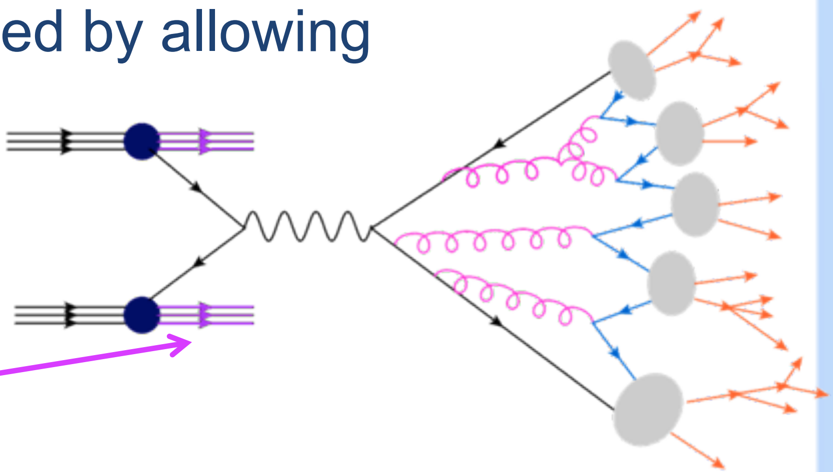
MadGraph

- Used to simulate Standard Model, and Higgs Amplitudes and Events
- Multi-parton processes in hadronic collisions

ZZ, ttbar, Z+Jets, W, WZ Monte Carlo Samples

PYTHIA

- Higher-order order effects estimated by allowing branching of quarks/gluons
- Parton shower
- Hadronization
- Initial/final state radiation
- Underlying event
  - Proton remnants contribute to the total event picture



Showering, hadronization etc. (PYTHIA)

QCD Monte Carlo Sample and Jet Hadronization

Signal and Background

CMS

GEANT4: Detector Simulation

- Toolkit for simulation of the passage of particles through matter

CMSSW: CMS Software Framework

- Detector and Electronics Response
- Event Reconstruction (identical for Data and MC)

Signal

pp$\rightarrow$ZZ$\rightarrow$ μμjj Monte Carlo Sample

- σ = 5.9 pb, MadGraph

Most Important Backgrounds

Z+jets

- σ = 3048 pb, MadGraph

ttbar

- σ = 157 pb, MadGraph

All Simulated Samples normalized to 4.58 fb^{-1}

CMS

Muon Reconstruction

Standalone Reconstruction

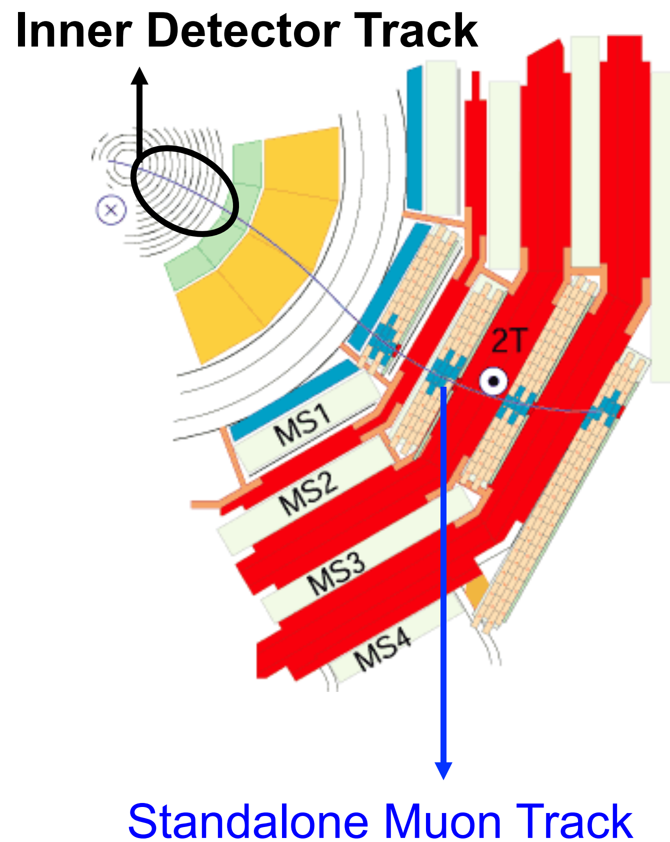
Reconstruct Muons in Muon Chambers only

Tracker Reconstruction

Reconstruct Tracks in the Tracker and match with the Muon Chambers

Global Reconstruction

Match tracks in the tracker to Muon Chamber tracks by minimizing χ^2 value



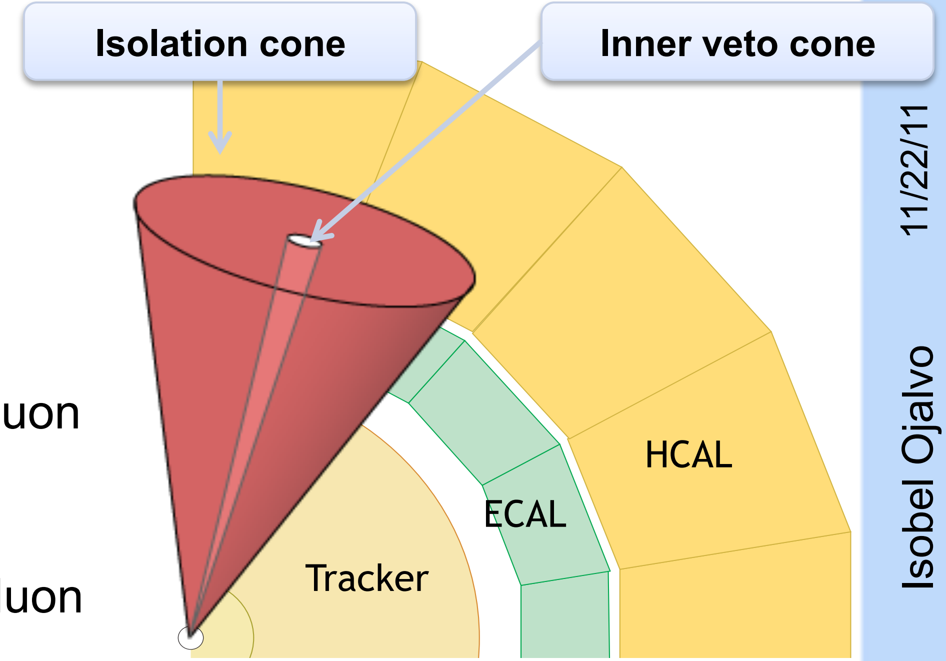
Muon Isolation

Muon Isolation

Muons originating from a Z Boson are expected to be well isolated

Powerful QCD background discriminator

Isolation Variables:



Tracker Isolation

Sum of p_T of the tracks around Muon

ECAL Isolation

Sum of ECAL energy deposit around Muon

HCAL Isolation

Sum of HCAL energy deposit around Muon

Relative Isolation <0.1

$$Rel_{Iso} = \frac{I_{ECAL} + I_{HCAL} + I_{trk}}{P_T}$$

here, p_T = Transverse Momentum of the Muon

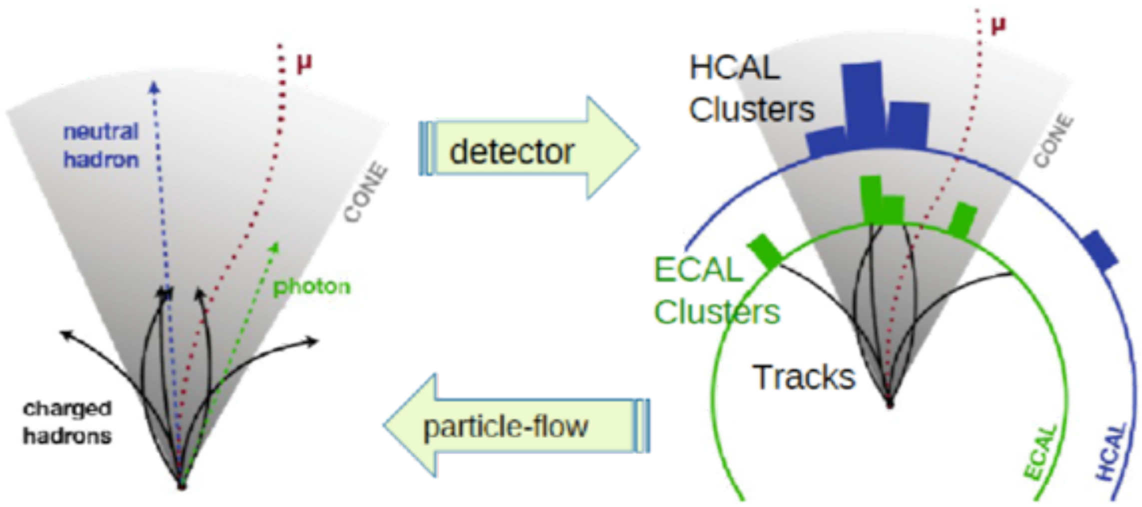
Jet, ME_T Reconstruction

Particle Flow Algorithm:

Combines data from CMS Tracker and Calorimeters

Provides Event description using Particle Candidates:

Electrons, muons, charged & neutral hadrons



Particle candidates are combined to make composite objects:

Taus, Missing E_T and Jets!

Jet Algorithms and Jet Selection

Jet Clustering

Anti-kT Algorithm:

- Energy-Weighted Distance Parameter created **iteratively** around all particles
- Particles in a Jet are combined based on **Energy** and **Position**
- Other Particles within the Energy-Weighted Cone are called Proto-Jets
  - These are included in the Jet

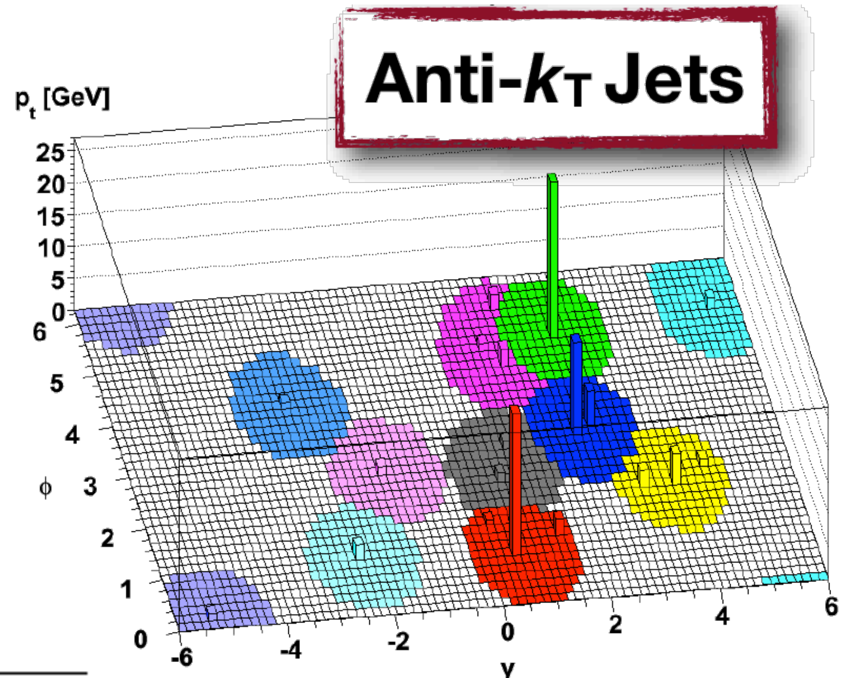
Anti-kT Algorithm is both
Collinear Safe and Infrared Safe

Jet Selection

Particle Flow Jets

- anti-kT, R=0.5, clustering algorithm
- Jet $P_T > 30$ GeV
- Jet $|\eta| < 2.4$

$$\Delta R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



Run 124120, event 6613074

11/22/11

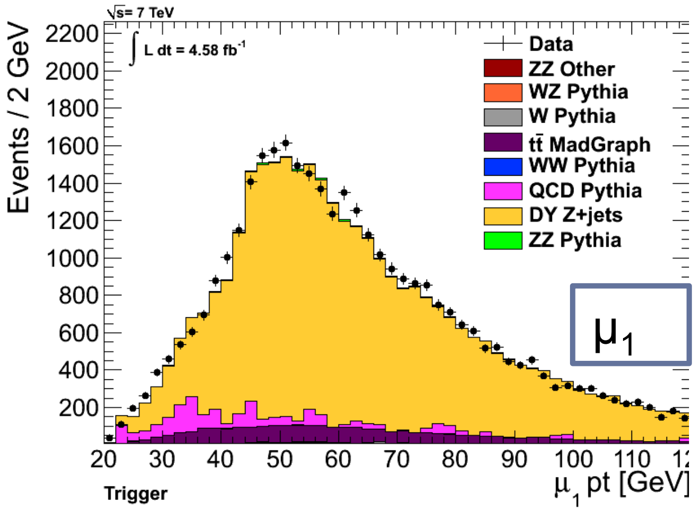
Isobel Ojalvo

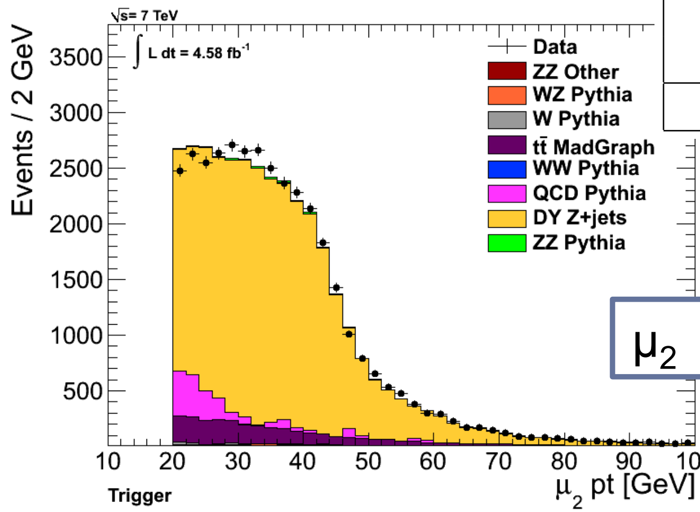
Muon and Jet Spectra at Initial Selection

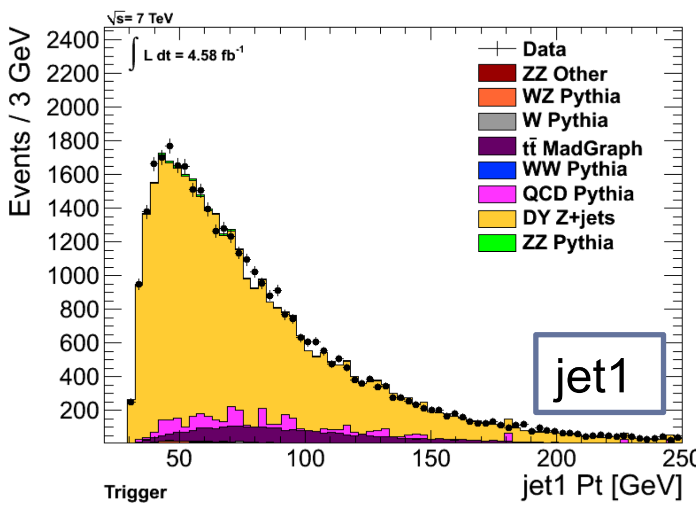
CMS

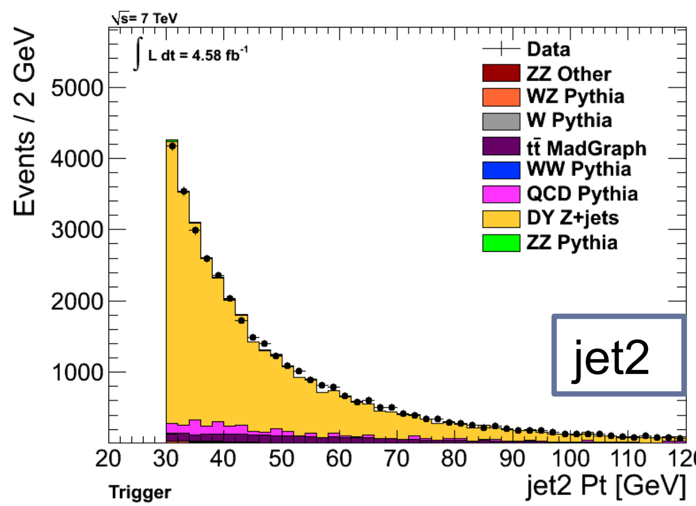
Initial Sample Kinematics

Object	Initial Selection
μ_1	$p_t > 20$GeV, $\eta < \|2.4\|$
μ_2	$p_t > 20$GeV, $\eta < \|2.4\|$
jets	pt>30GeV, $\eta < \|2.4\|$





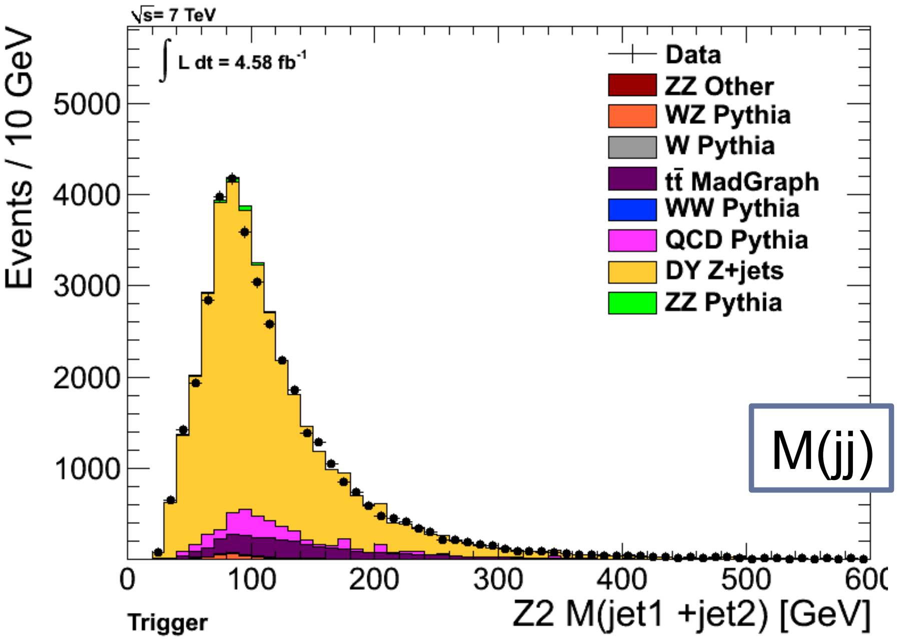


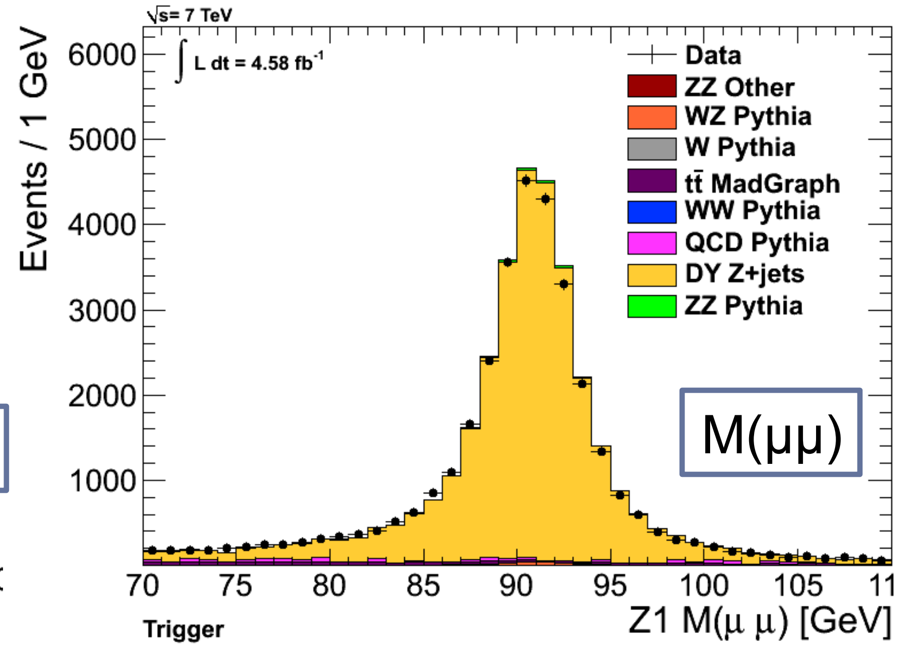


	Number of Events
Signal	186
Bkrd MC	38824
Total MC	39000
Data	38270

Trigger Efficiency Corrections Applied

Invariant Masses at Initial Selection



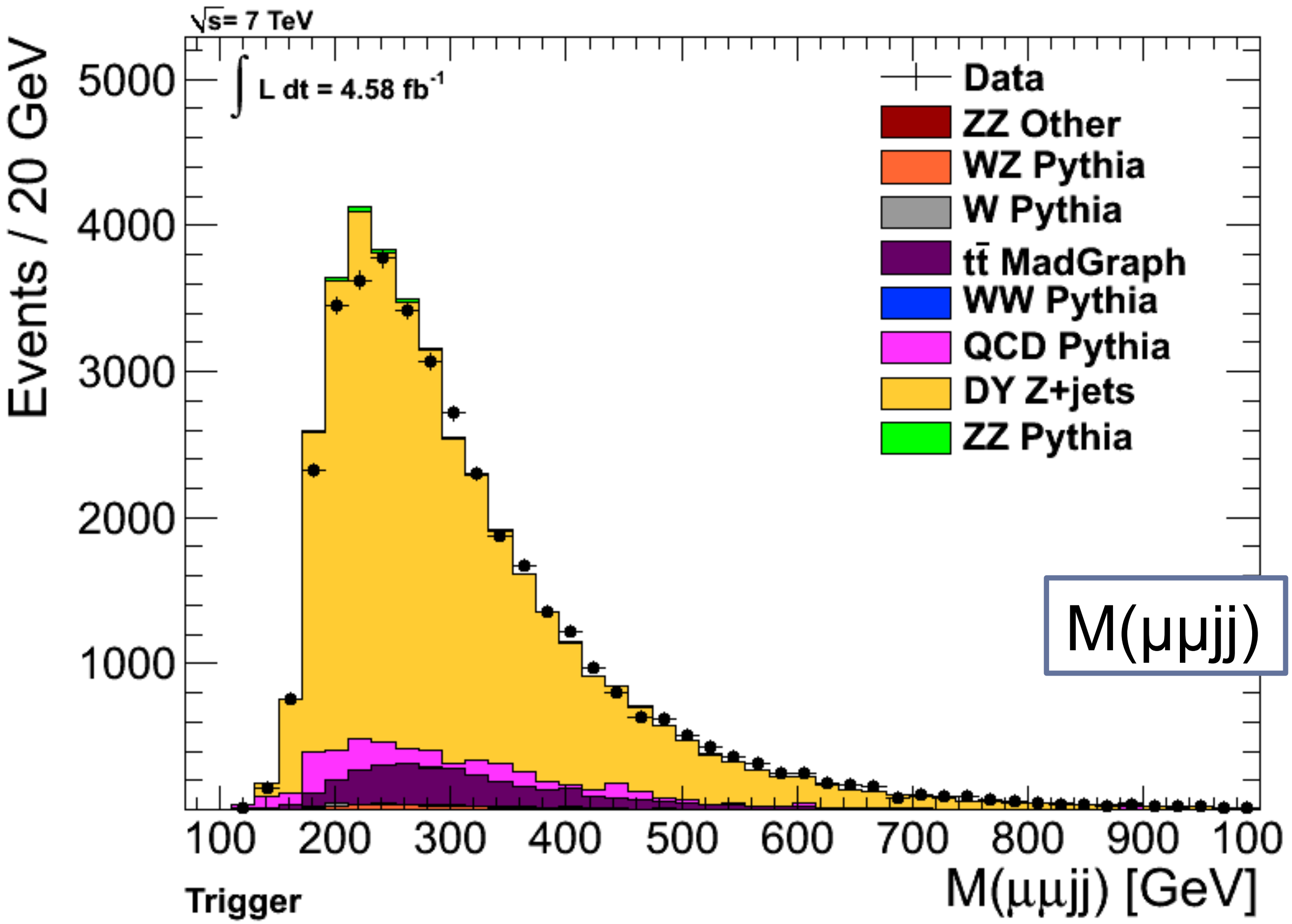


Invariant Mass

→ Muon/Jet ID and Reconstruction approximately match MC models

	Number of Events
Signal	186
Bkrd MC	38824
Total MC	39000
Data	38270

Invariant Masses at Initial Selection



Initial Invariant Combined Mass

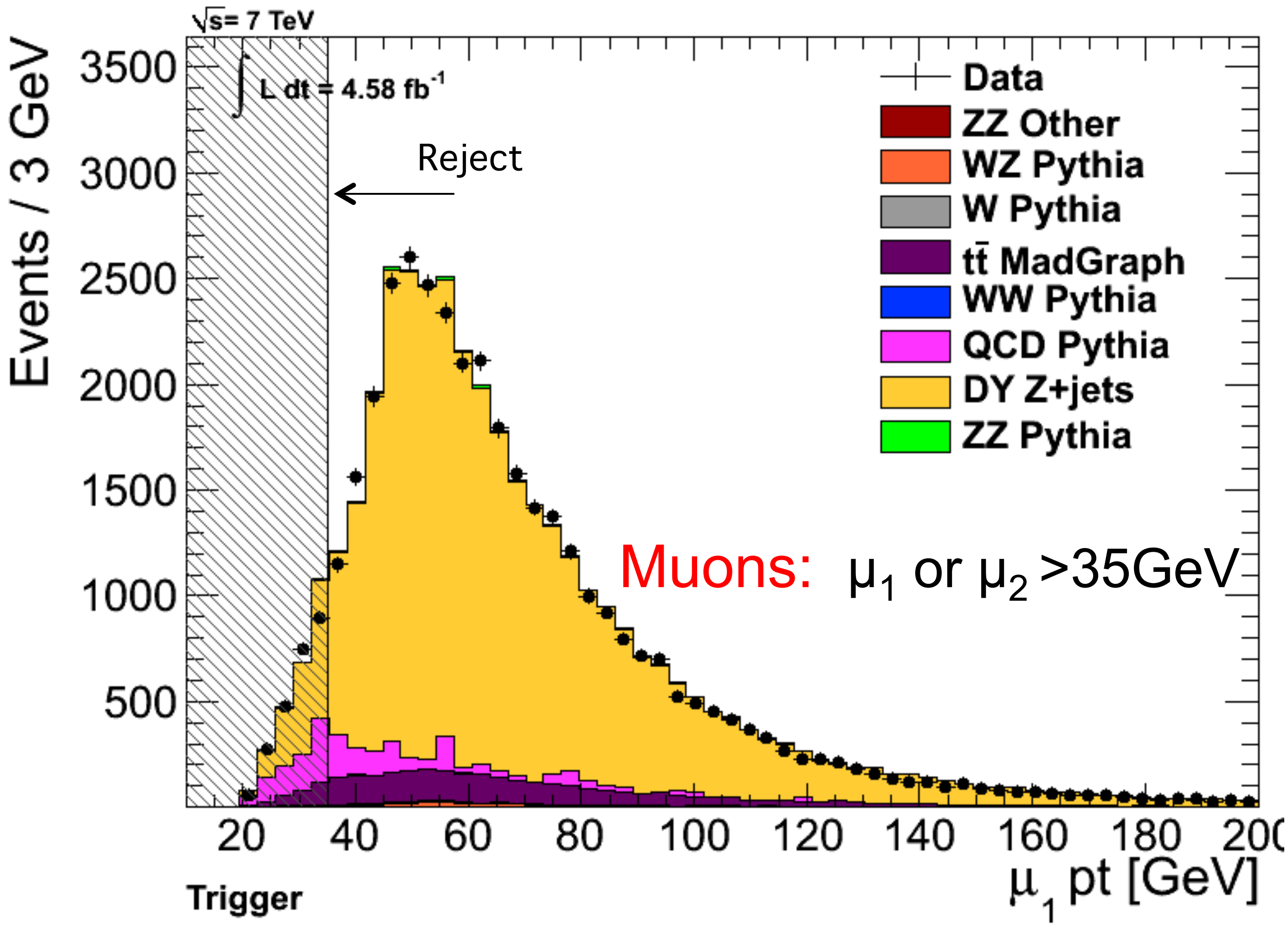
→Next Make Cuts to Select

ZZ → μμjj Signal

	Number of Events
Signal	186
Bkrd MC	38824
Total MC	39000
Data	38270

At Least One Muon with p_T > 35GeV

Kinematic cuts to preferentially select signal

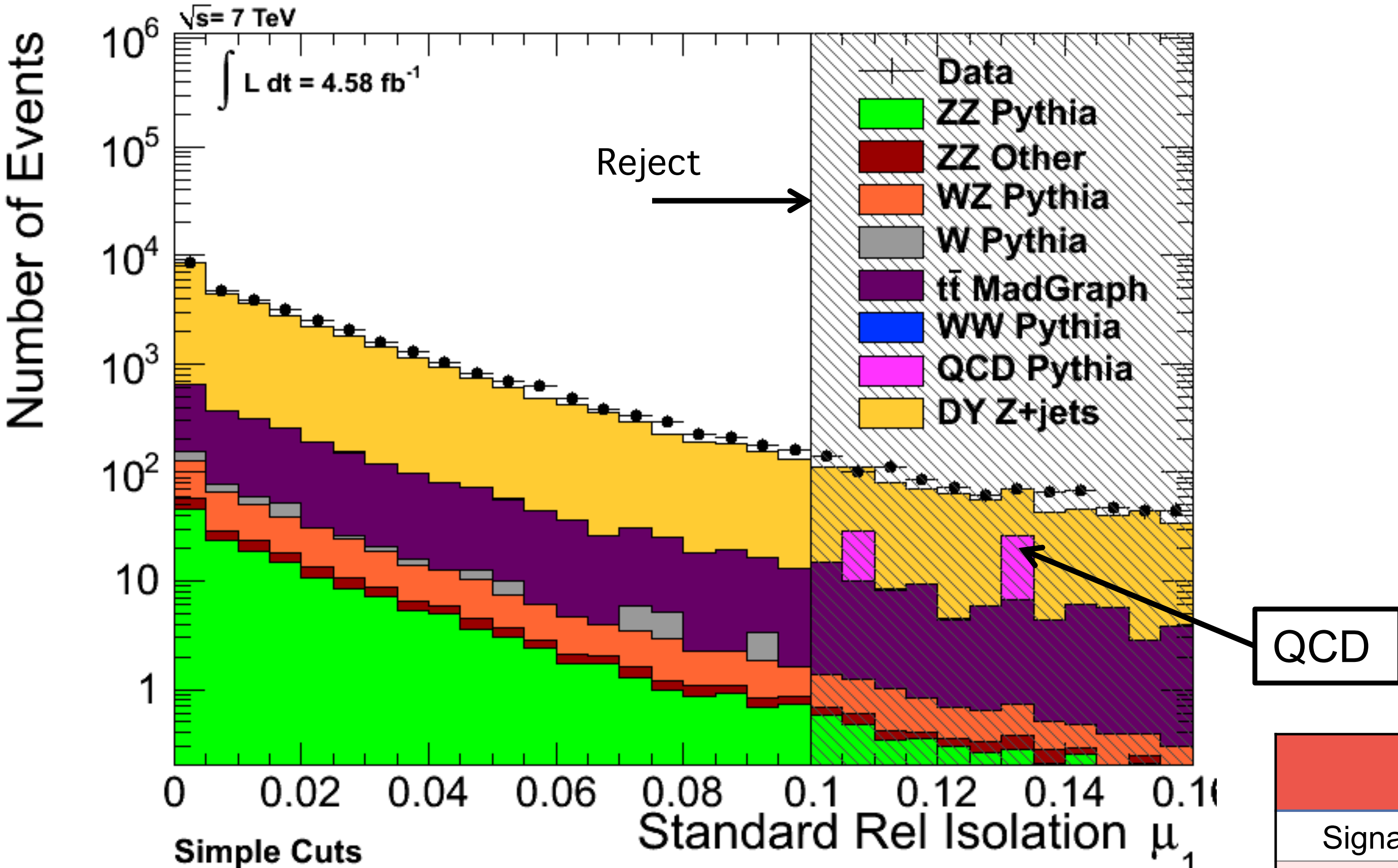


	Number of Events
Signal	180
Background	36371
Total MC	36551
Data	35918

Reduces Background by preferentially selecting a Z-> μμ decay with at least one high p_T muon

Muon Isolation

Muons should be well isolated (Not Originating from a Jet!)

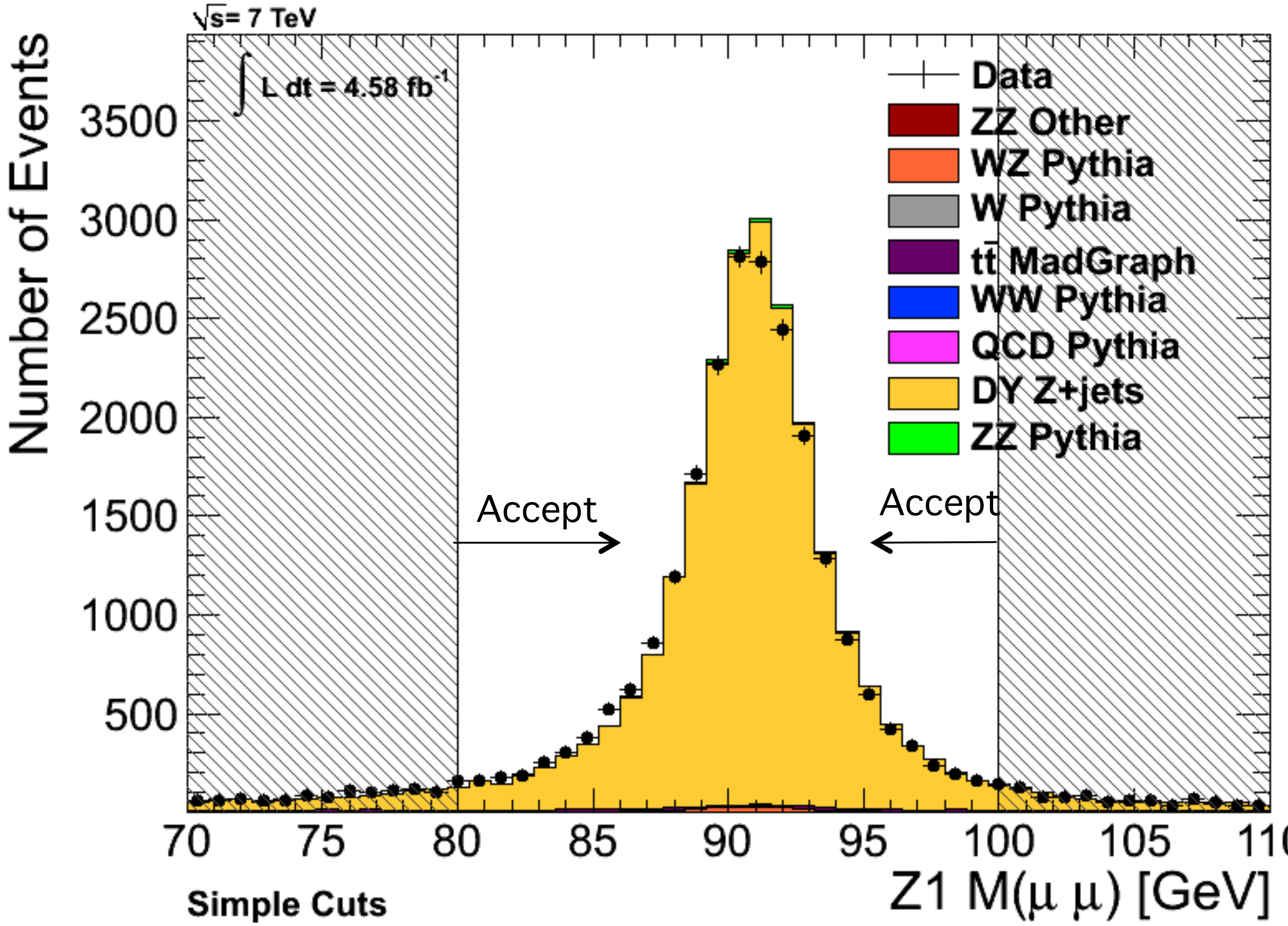


	Number of Events
Signal	152
Background	28371
Total MC	28523
Data	27890

Muons: Standard Relative Isolation < 0.1

~Eliminates QCD Background

Select Z->μμ 80GeV <M(μμ)<100 GeV

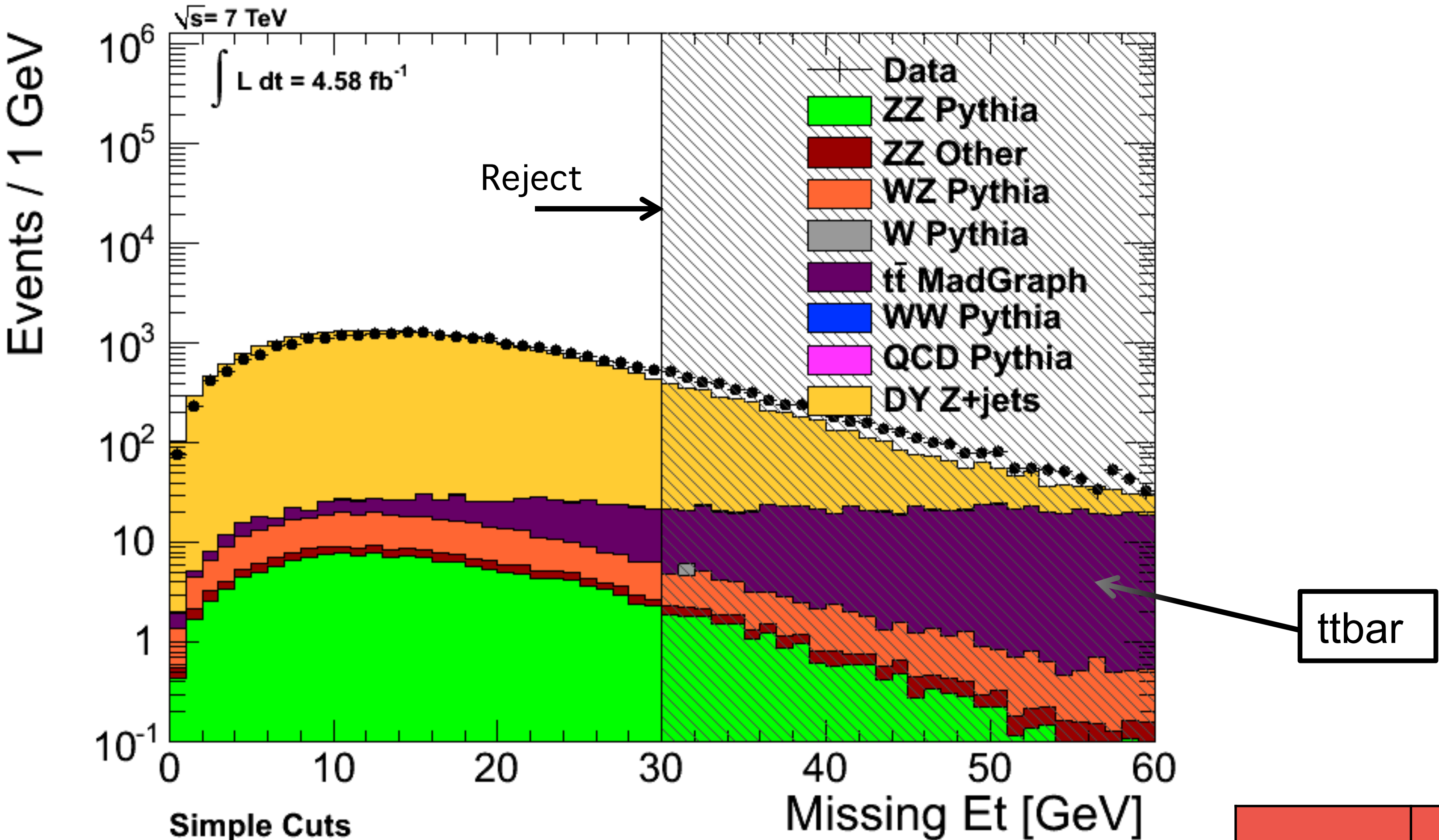


	Number of Events
Signal	129
Background	23052
Total MC	23181
Data	22825

M(μμ): 80GeV< M(μμ) <100GeV

- Select well reconstructed Z->μμ Events

Missing E_T

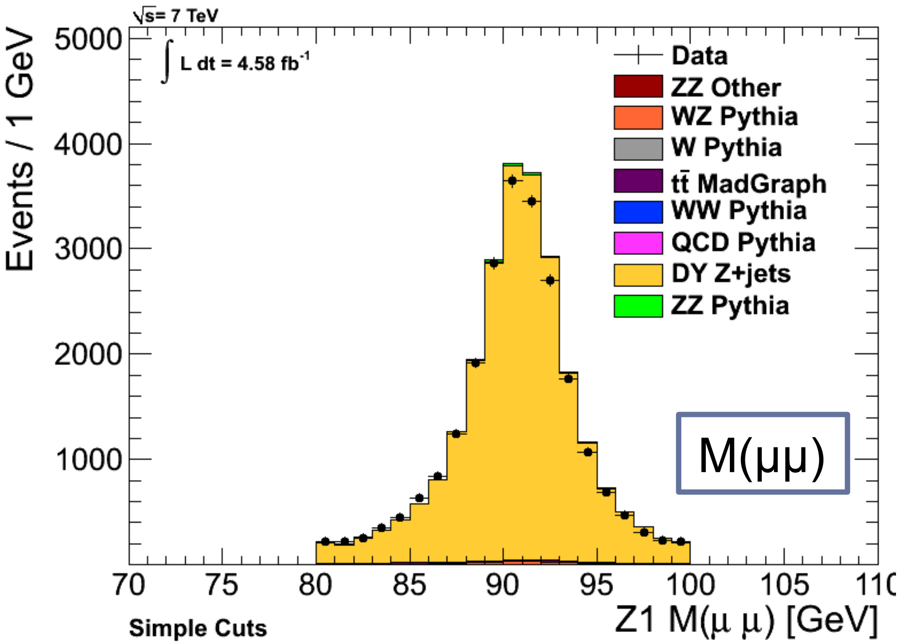


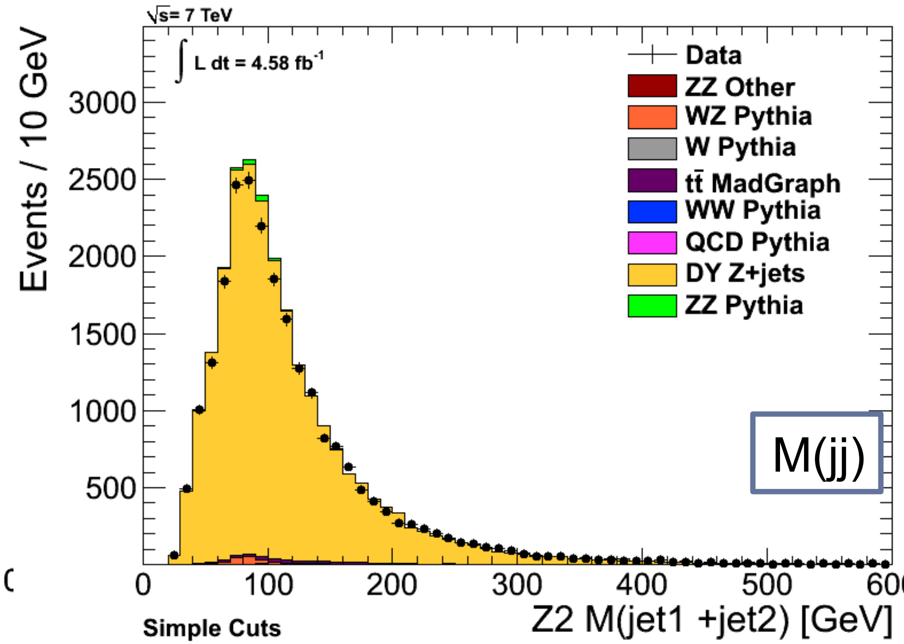
Missing E_T: ME_T <30GeV

Require Low ME_T to reduce Top and W Contribution

	Number of Events
Signal	114
Background	20331
Total MC	20445
Data	19349

Invariant Masses
$M(\mu_1\mu_2)$ $M(\mu_1\mu_2 j_1 j_2)$



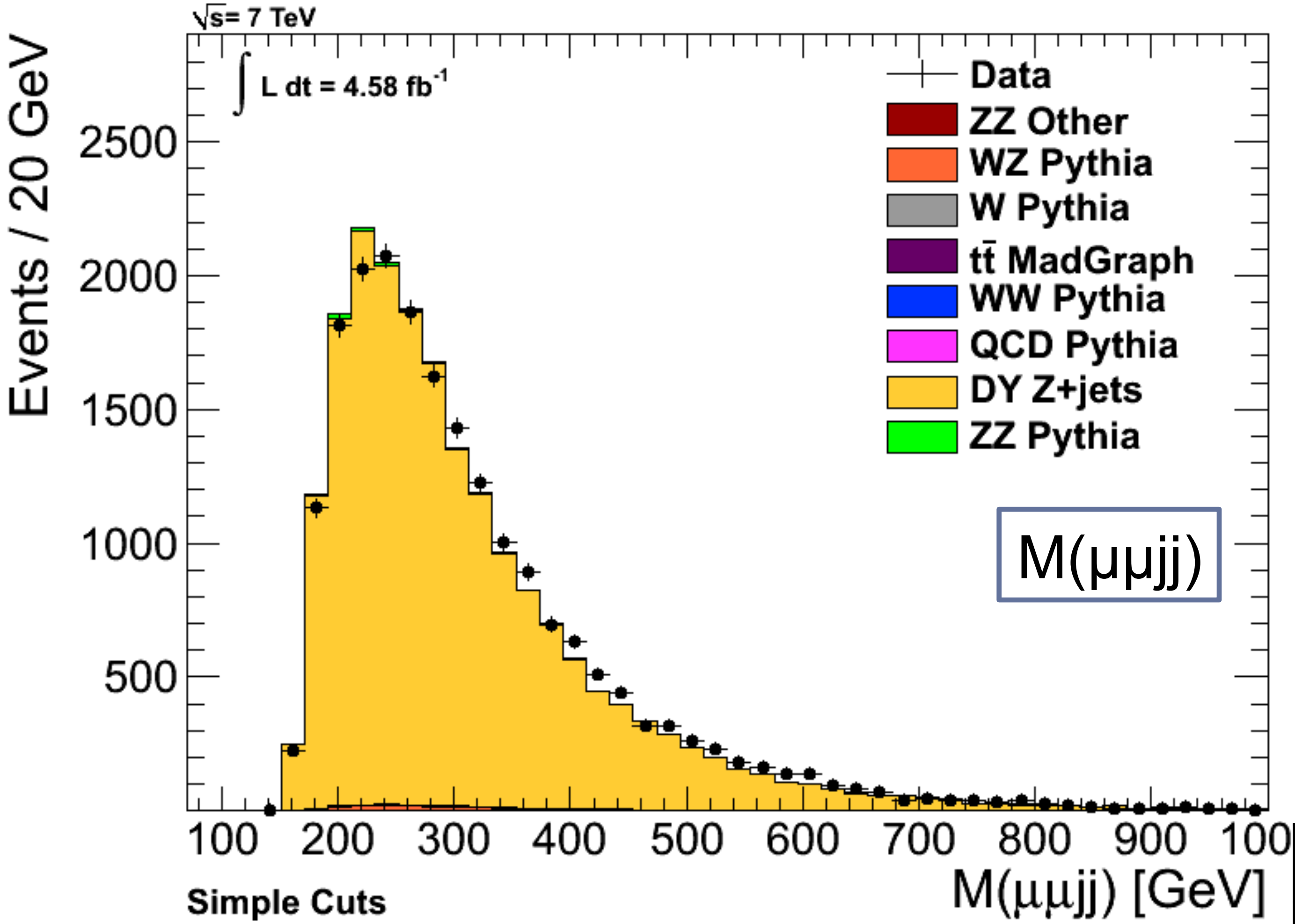


Z→μμ can be used as a candle for understanding MC

There is still a Large Z+jets background

	Number of Events
Signal	114
Background	20331
Total MC	20445
Data	19349

$M(\mu_1\mu_2j_1j_2)$



	Number of Events
Signal	114
Background	20331
Total MC	20445
Data	19349

ZZ barely visible

→Need additional handle

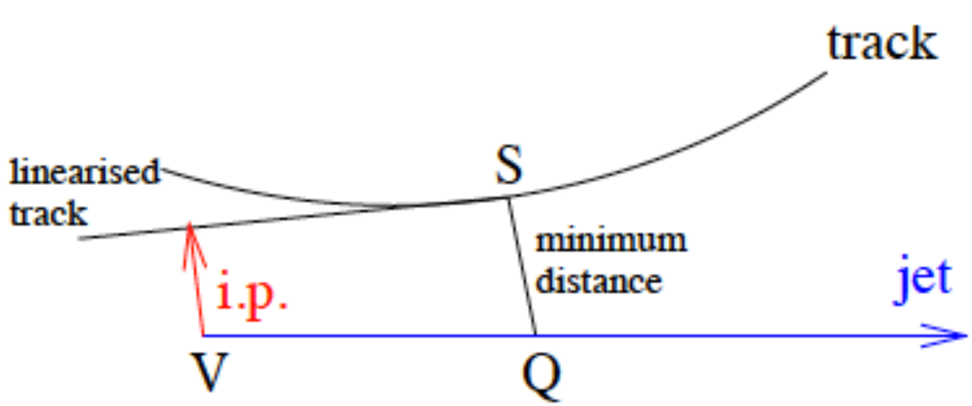
b-Jet Tagging

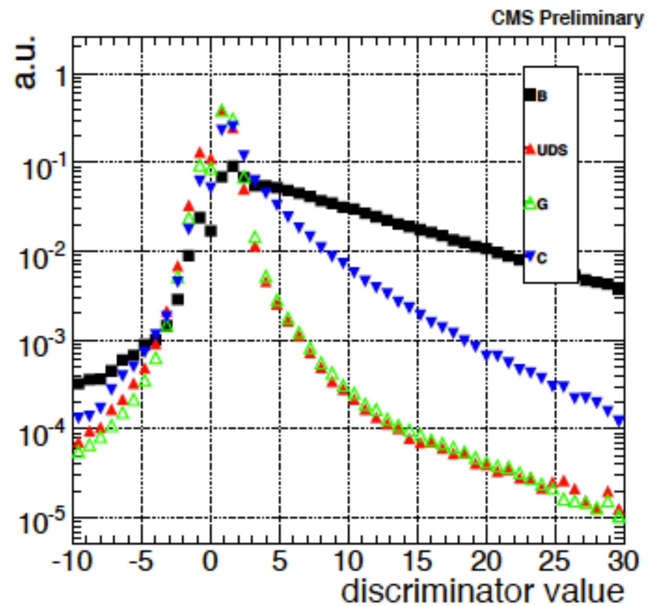
b-hadrons have a high mass and long lifetime

→Look for a displaced Jet Vertex during reconstruction

Track Counting High Efficiency B-Tagging

- Calculate the signed impact parameter of all good tracks
- Sort the parameter
- Create b-Tag Discriminator
  - → Significance of the Second Track

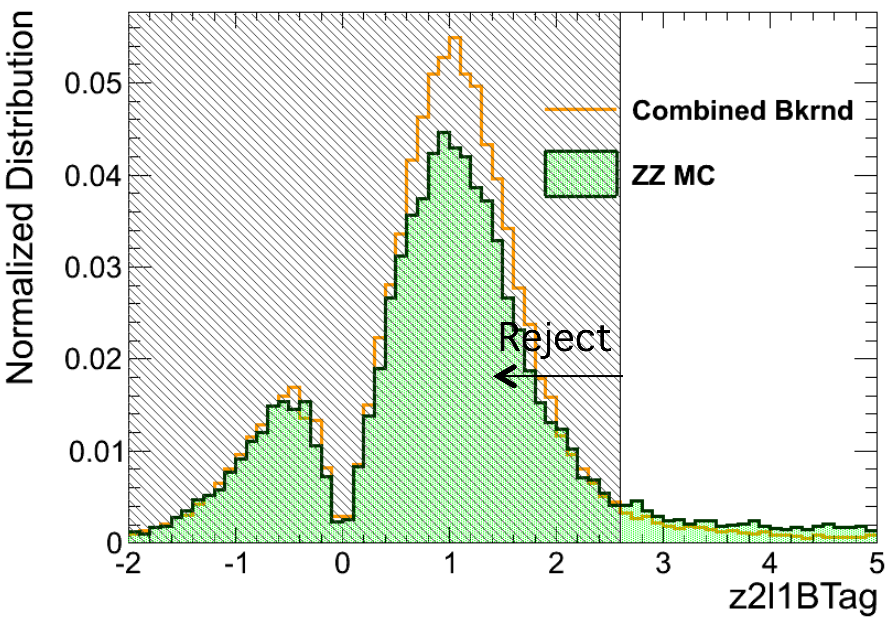




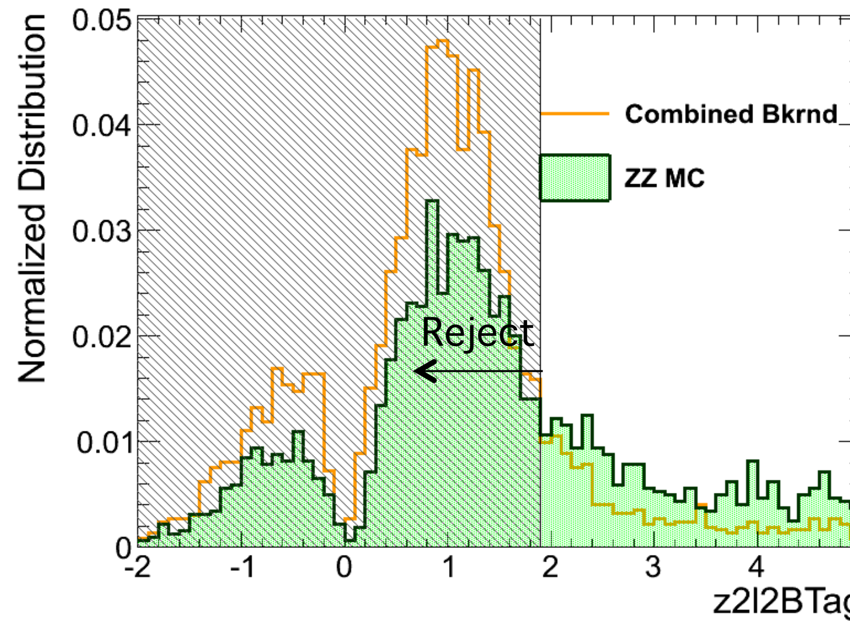
B-Tagging using Track Counting High Efficiency

Reduce non-Bottom Quark Jets

Track Counting High Efficiency (CMS Standard):



First: Jet1 Bdiscriminator > 2.6



Next: Jet2 Bdiscriminator > 1.9

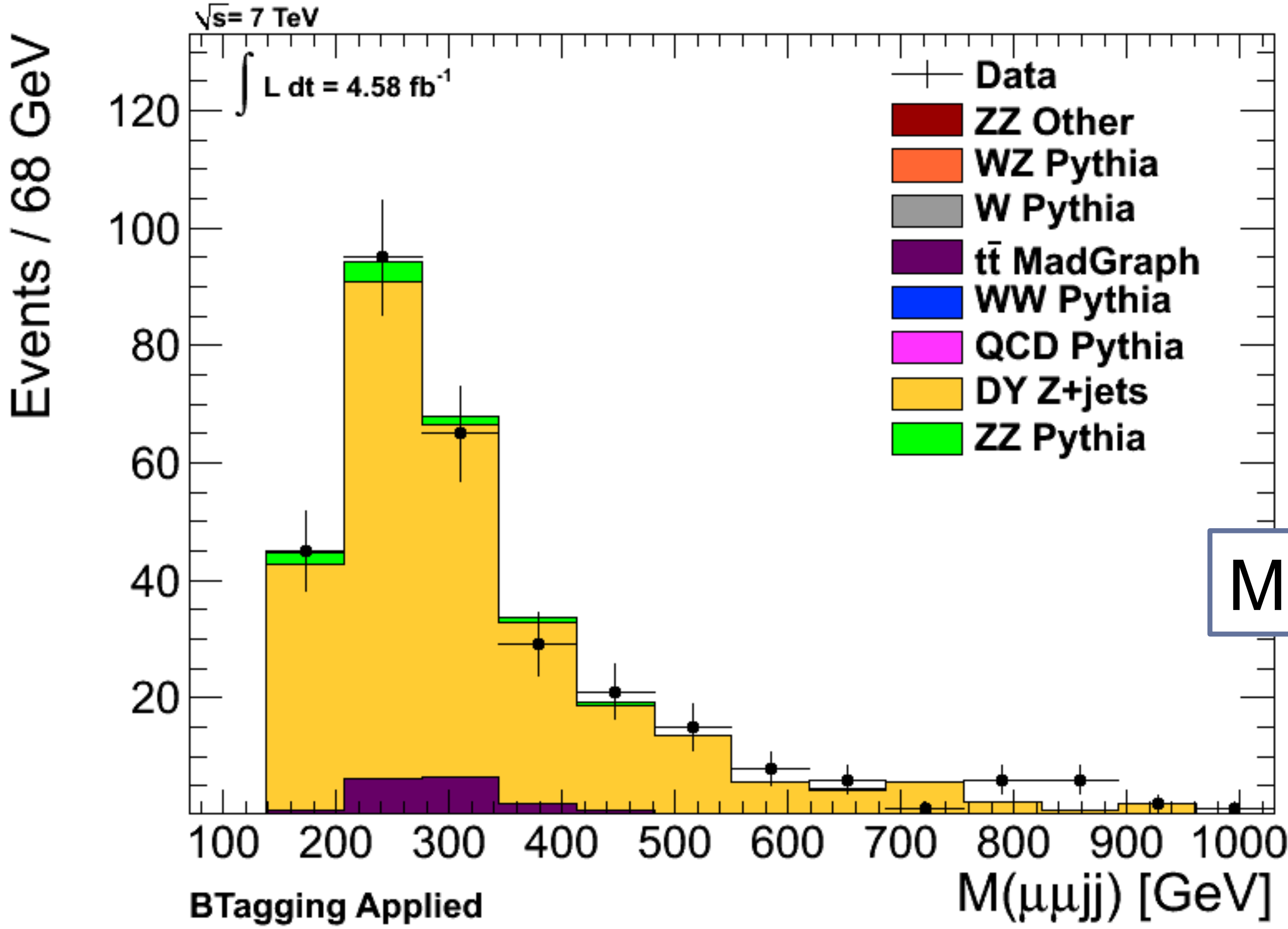
1 Btag	Number of Events
Signal	18
Background	1368
Total MC	1386
Data	1360

S/B = 1.2%

2 Btag	Number of Events
Signal	9
Background	286
Total MC	295
Data	302

S/B = 3.05%

Final Selection $M(\mu_1\mu_2j_1j_2)$

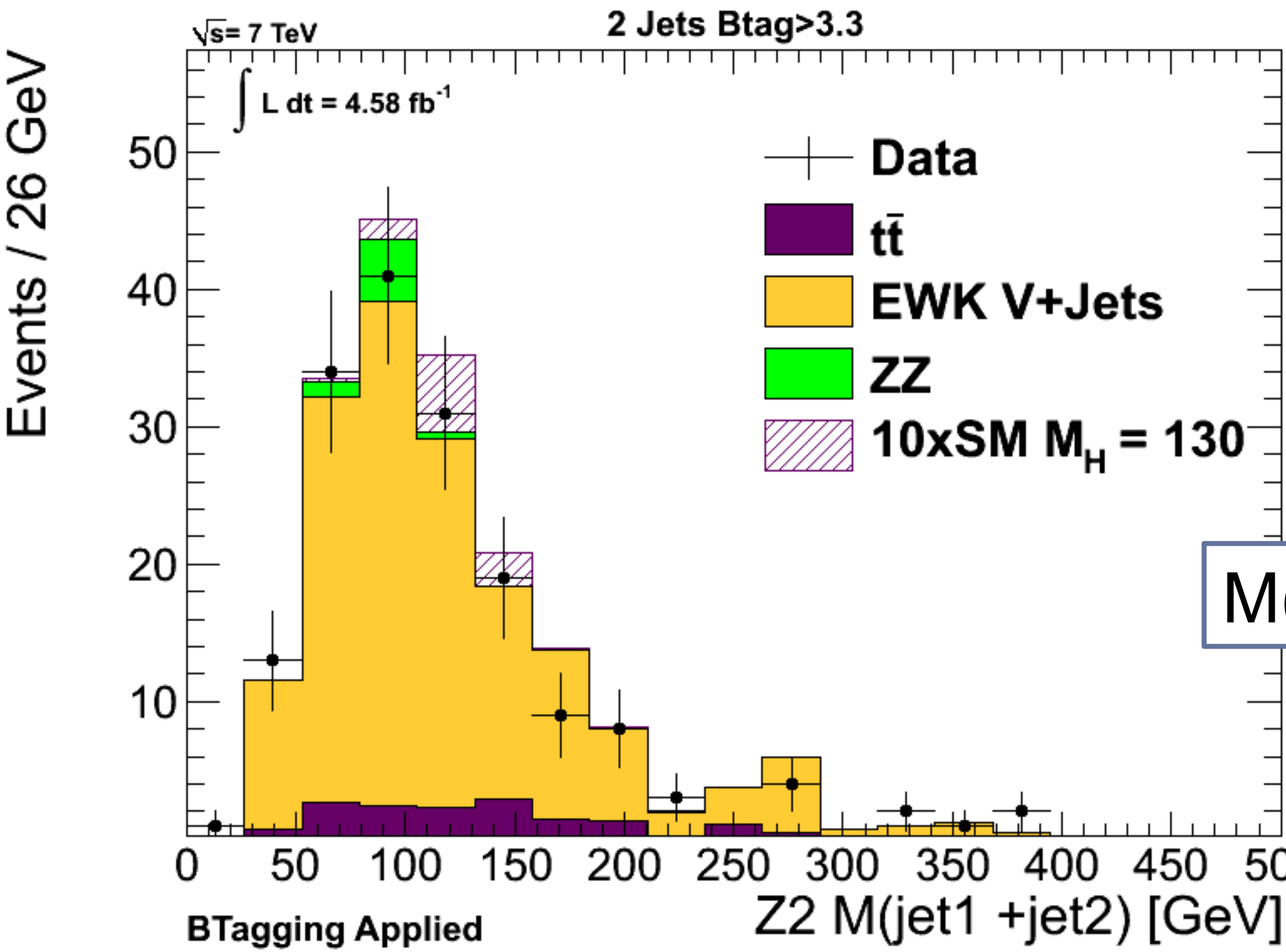


M(jj)

Final Combined Mass with Btagging Applied

2 Btag	Number of Events
Signal	9
Background	286
Total MC	295
Data	302

Final Selection $M(j_1 j_2)$

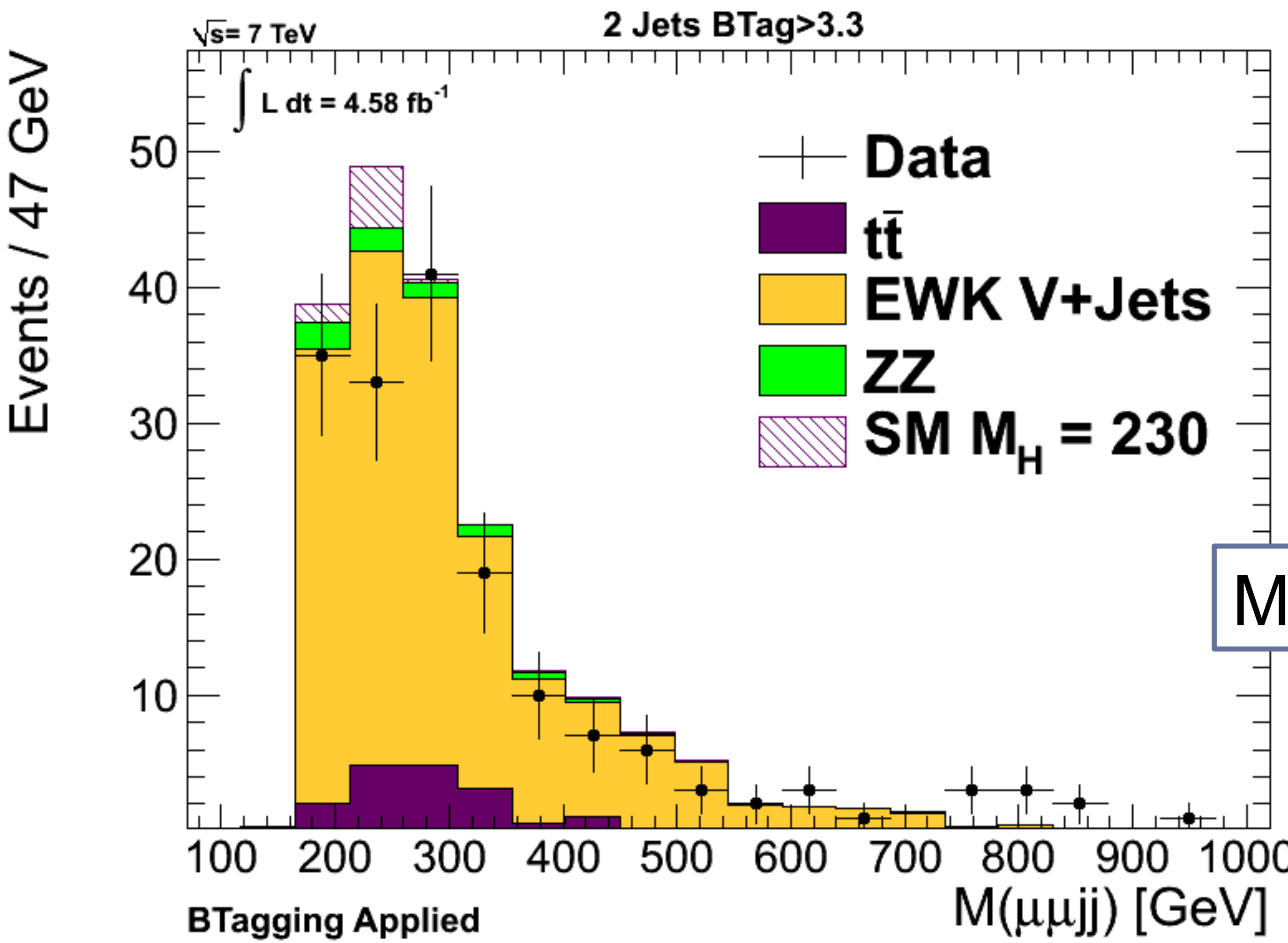


M(jj)

Opportunities to Search for a Low Mass Higgs (Jet1, Jet 2 BTag>3.3)

	Number of Events
HZ	10
Background	175
Total MC	185
Data	166

Final Selection $M(\mu_1\mu_2 j_1 j_2)$



M(μμjj)

… or a High Mass Higgs
(Jet1, Jet 2 BTag>3.3)

	Number of Events
HZZ	13
Background	172
Total MC	185
Data	166

Selection Summary

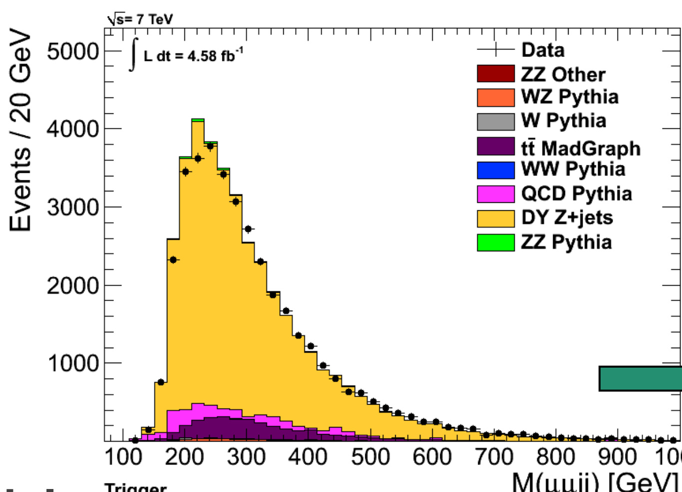
CUT	W	WW	WZ	QCD	ttbar	Z+Jets	ZZ	MC Total	DATA
Trigger Required	114	18	144	3839	2383	21220	114	42014	42014
μ_1 or μ_2>35 GeV	108	19	265	1298	2637	32001	181	36551	35918
Rel Isolation<0.1	0	15	229	0	1443	26650	152	28524	27890
80<M($\mu\mu$)<100	0	2.6	187	0	249	21719	123	22309	23526
MET< 30 [GeV]	0	0.6	158	0	38	19347	114	19675	19942
Btag j_1 >2.6	0	0	11	0	26	1362	19	1420	1539
Btag j_2>1.9	0	0	0.86	0	18.2	275	9.2	304	344

Trigger Level: μ_1,μ_2 pt>20 [GeV] jet1, jet2 pt>30 [GeV] μ_1,μ_2, j_1 j_2 |eta|<2.4

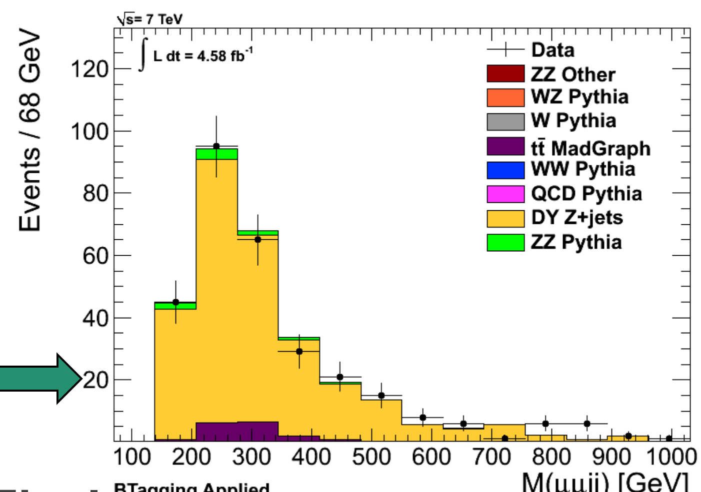
Conclusions

CMS

- ✧ Strong Contribution to Higgs Search (Particularly in Low Mass regions)
- ✧ Muon/Jet ID and Reconstruction closely match MC models
- ✧ Event Selection through P_T, ME_T, and Isolation requirements help isolate the Signal
- ✧ B-Tagging greatly improves Signal/Background



Initial



Final

Going Forward

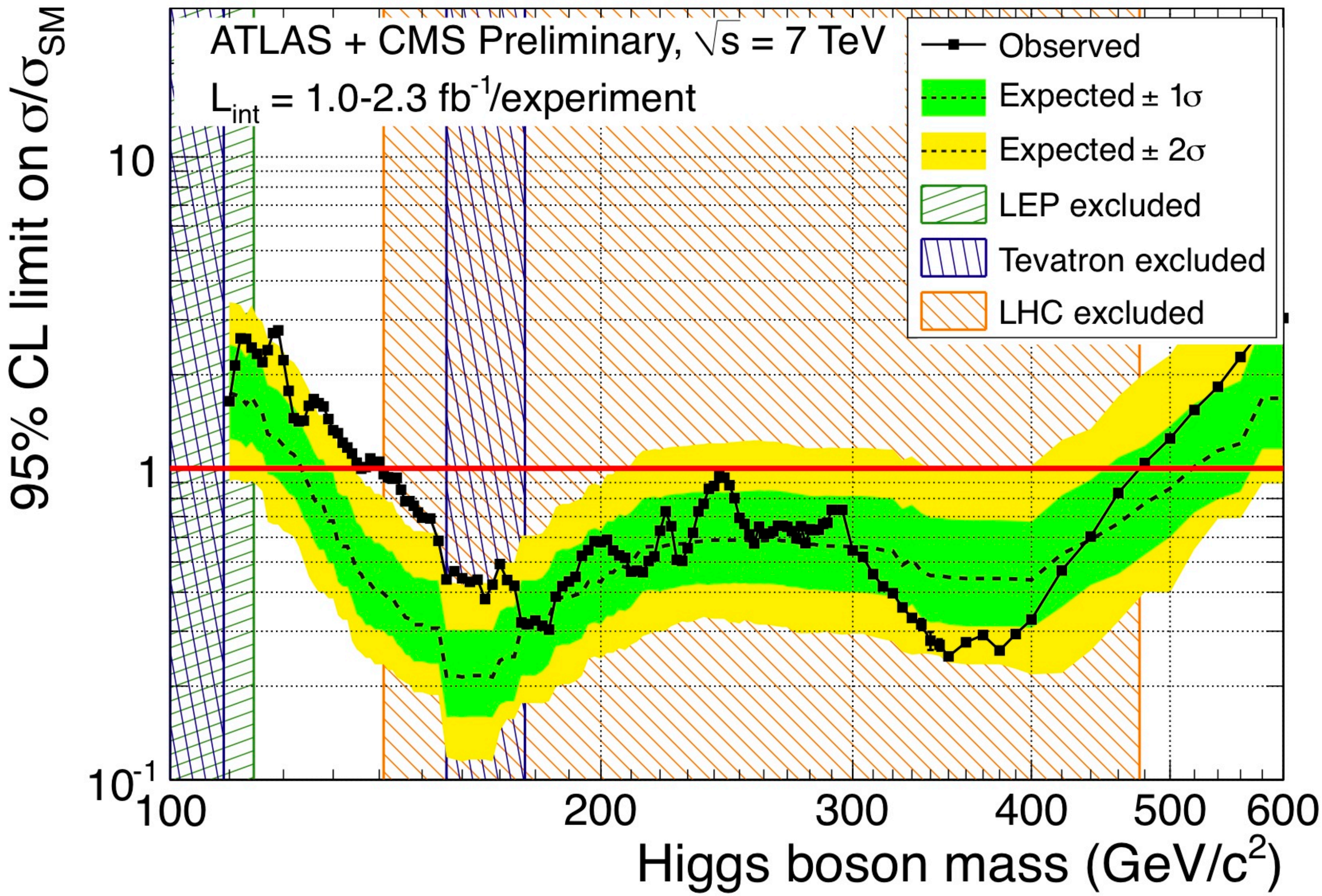
- Efficiency corrections need to be evaluated and applied
- Evaluate more Methods of Jet Discrimination
- Improve Signal Significance
- Diboson Cross-Section Measurement
- Find the Higgs

Back Up Slides

CMS

Higgs Experimental Limits

CMS



Event Simulation less significant backgrounds

All Simulated Samples normalized to 4.58 fb^{-1}

Important but less Significant Backgrounds

W+jets

- σ = 31314 pb
- 80×10^{6} events generated with Pythia
- Event weight = 3.8×10^{-4}

QCD

- σ = 84679 pb
- 25×10^{6} events generated with Pythia
- Event weight = 3.3×10^{-3}

WZ

- σ = 18.2 pb
- 4.2×10^{6} events generated with Pythia
- Event weight = 1×10^{-6}

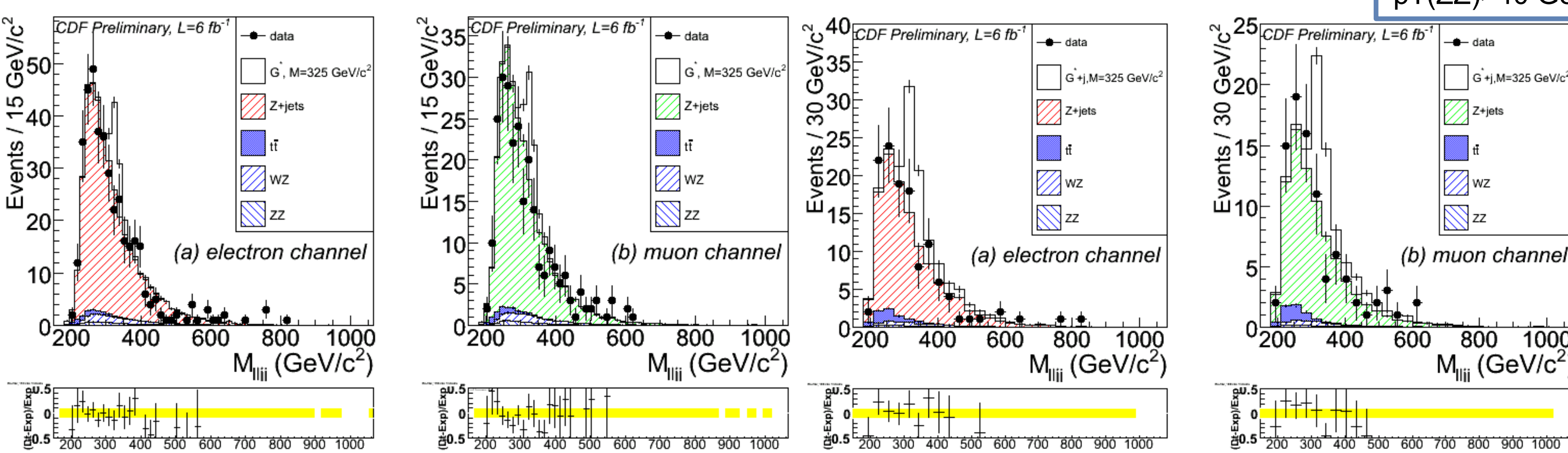
WW

- σ = 43 pb
- 4.2×10^{6} events generated with Pythia
- Event weight = 4×10^{-6}

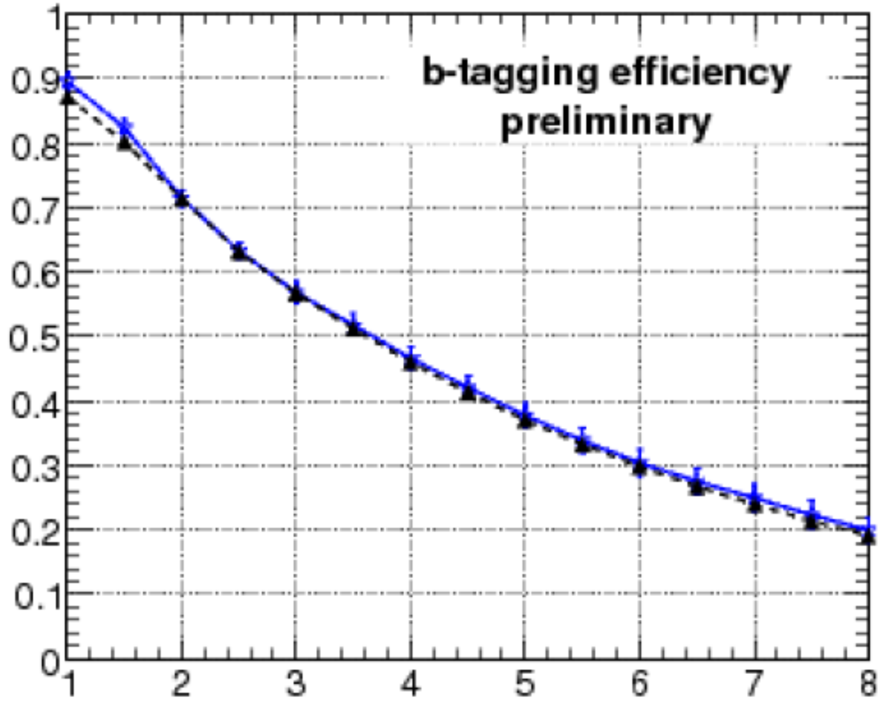
Tevatron Diboson Measurements

Experiment	Results
CDFII 1.96TeV 6.1fb^{-1} ZZ→llll	σ(pp→ZZ) = 2.18 ±0.63±0.13 pb Expected signal 10.4, observed 14
CDFII 1.96TeV 7.1fb^{-1} WZ→llnunu	σ(pp→WZ) = 4.1 ±0.7 pb ~ 50 events
D0 Run II, 1.7fb^{-1} ZZ→llll	σ(pp→ZZ) = 1.4 ±0.43(stat)±0.14 pb (sys) ~ 10 events

pT(ZZ)>40 GeV

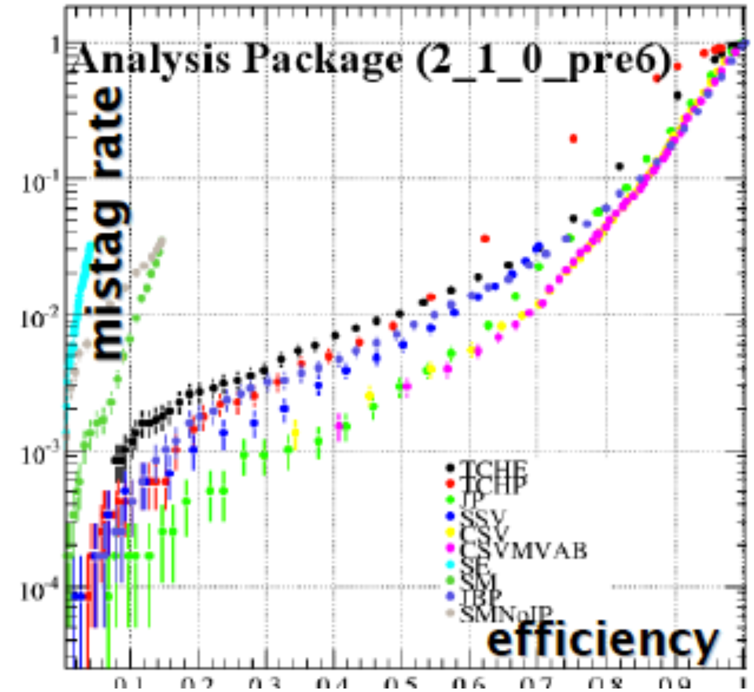


TCHE Efficiency

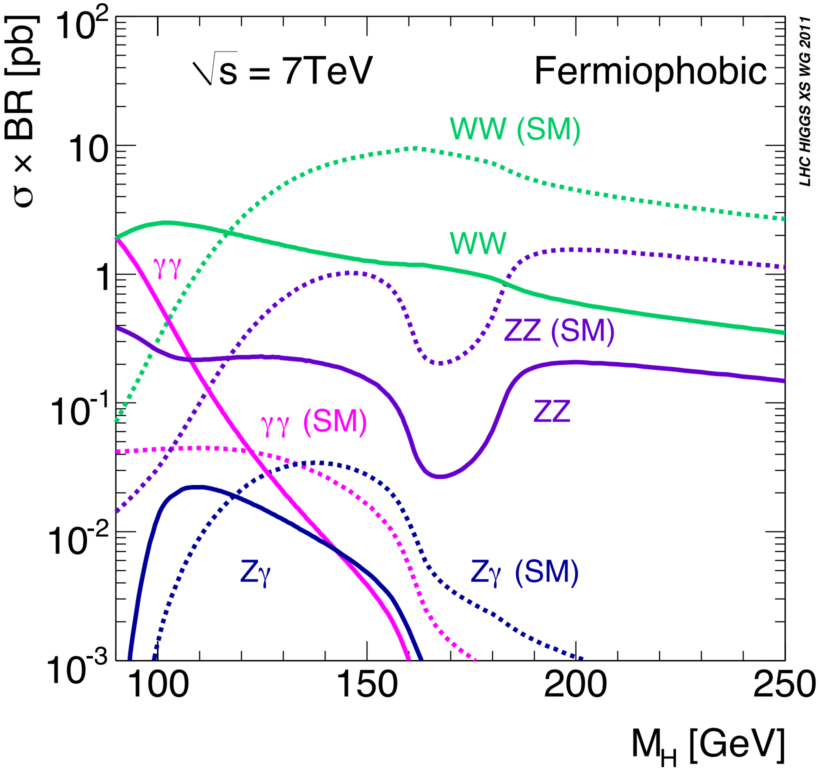


Bdiscriminant (Significance of 2nd track)

$$d_0 Sig = \frac{d_0}{\sigma(d_0)}$$



Fermiophobic Higgs



Fermiophobic higgs cross-sections

Muon Requirements

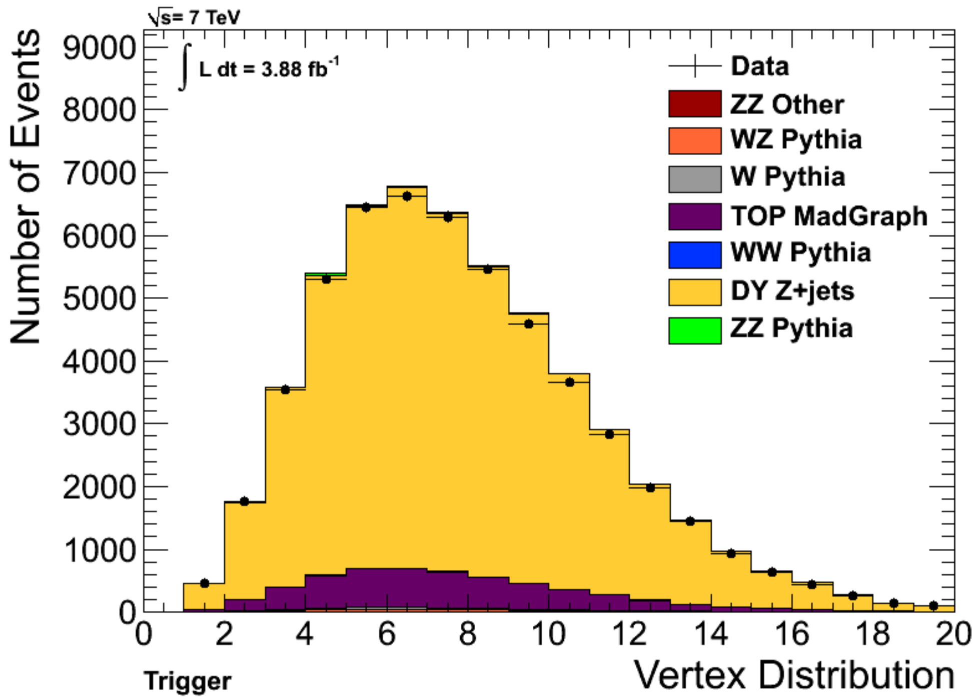
Muon Requirements	
dxdy Vertex	<2mm
Max χ^2 Value	10
Tracker Hits	$\geq$10
Pixel Hits	$\geq$ 1
Muon Chamber Hits	$\geq$1
Muon Chamber Matches	$\geq$2

Correct the Vertex Distribution for Pile Up

Monte Carlo Samples are created without knowledge of the Event Pile Up in the Detector

→ Re-weight the Monte Carlo Vertex Distribution to match the Data Vertex Distribution

Vertices Pile Up Reweighted



Monte Carlo Pile Up Reweighting is used in the analysis