# Search for $Z' \rightarrow \mu^+ \mu^-$ in 14 TeV *pp* Collisions

Preliminary Exam

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## Theoretical Background

- The Standard Model
- Motivation for a *Z′*
- *Z′* Production in *pp* Collisions

## The Experiment

- The Large Hadron Collider
- The Compact Muon Solenoid

## Monte Carlo Simulations and Analysis

- How We Simulate $Z' \rightarrow \mu^+\mu^-$ and Backgrounds
- Simulation of Muon Finding Efficiency
- Distinguishing Signal Over Background

## Conclusions & Future Plans

# The Standard Model

## Fermions (matter)

**Leptons** spin =1/2

| Flavor | Mass GeV/c$^2$ | Electric charge |
|---|---|---|
| $\nu_L$ lightest neutrino* | $(0-0.13)\times10^{-9}$ | 0 |
| e electron | 0.000511 | –1 |
| $\nu_M$ middle neutrino* | $(0.009-0.13)\times10^{-9}$ | 0 |
| $\mu$ muon | 0.106 | –1 |
| $\nu_H$ heaviest neutrino* | $(0.04-0.14)\times10^{-9}$ | 0 |
| $\tau$ tau | 1.777 | –1 |

**Quarks** spin =1/2

| Flavor | Approx. Mass GeV/c$^2$ | Electric charge |
|---|---|---|
| u up | 0.002 | 2/3 |
| d down | 0.005 | –1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | –1/3 |
| t top | 173 | 2/3 |
| b bottom | 4.2 | –1/3 |

## Bosons (forces)

**Unified Electroweak** spin = 1

| Name | Mass GeV/c$^2$ | Electric charge |
|---|---|---|
| $\gamma$ photon | 0 | 0 |
| $W^-$ | 80.39 | –1 |
| $W^+$ W bosons | 80.39 | +1 |
| $Z^0$ Z boson | 91.188 | 0 |

**Strong (color)** spin =1

| Name | Mass GeV/c$^2$ | Electric charge |
|---|---|---|
| g gluon | 0 | 0 |

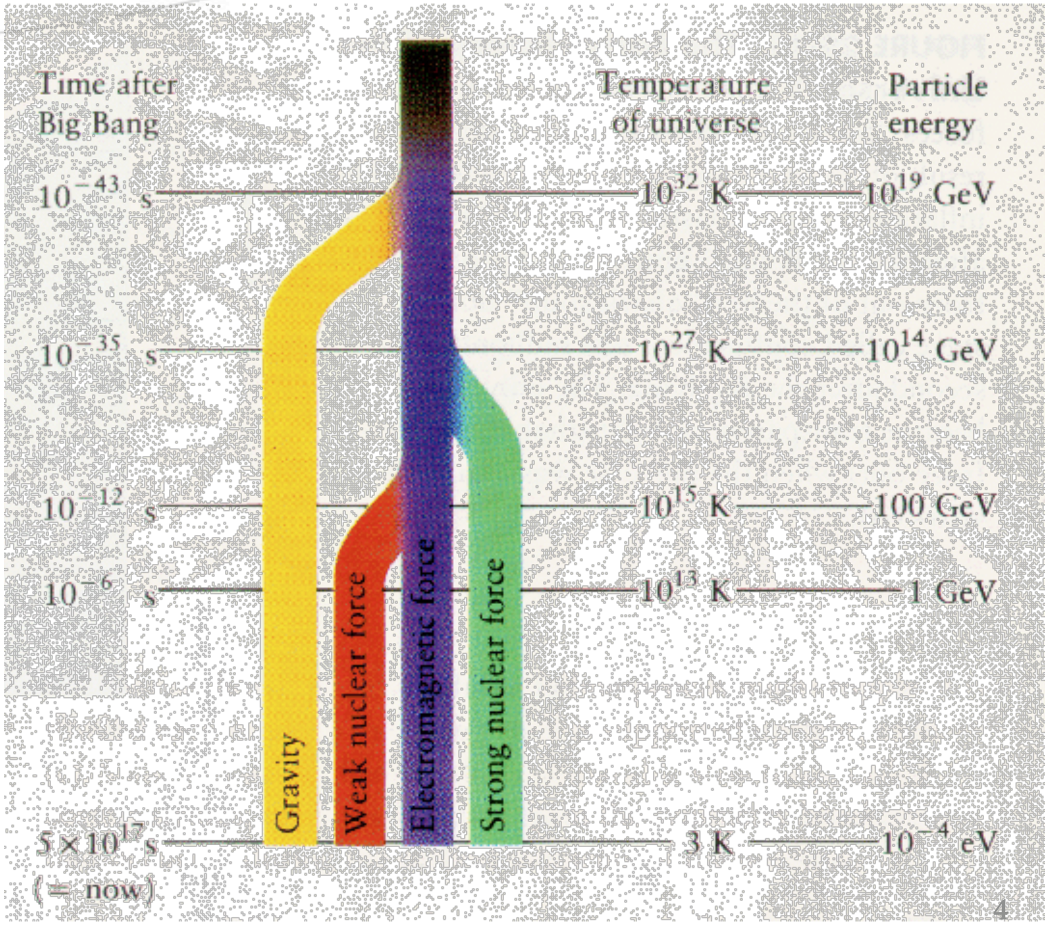
**Higgs**
Source of EWK Symm. Breaking
spin = 0, charge = 0
Yet to be found

$Z^0 \rightarrow \mu^+\mu^-$

$Z' \rightarrow \mu^+\mu^-$ ?

# Phenomena Outside the Standard Model

- The SM doesn't explain:
  - Dark matter
  - Neutrino masses
- Many new models unify the forces and account for these non-SM phenomena
  - GUTs unify SM forces
  - ToEs also include gravity
  - *Z′* particles could be a TeV-scale observable



# Motivation for a $Z'$

- A well-motivated extension to the SM
  - Derives from any extra *U(1)* symmetry
    - Many GUTs use expanded gauge groups
  - Extra dimensions could allow higher-mass excitations of the $Z^0$
- Example model: $E_6$
  - Breaks to SM, leaving two *U(1)* symmetries
  - Common GUT that can include SUSY
  - SUSY provides a dark matter candidate

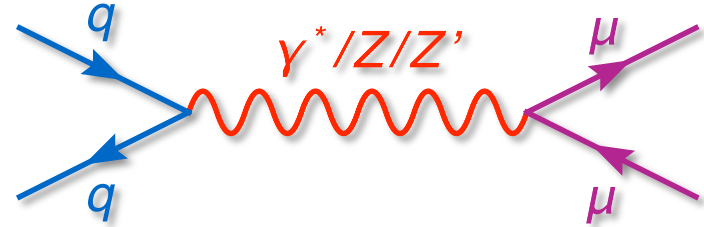
*Kaluza-Klein*, Dawn Meson

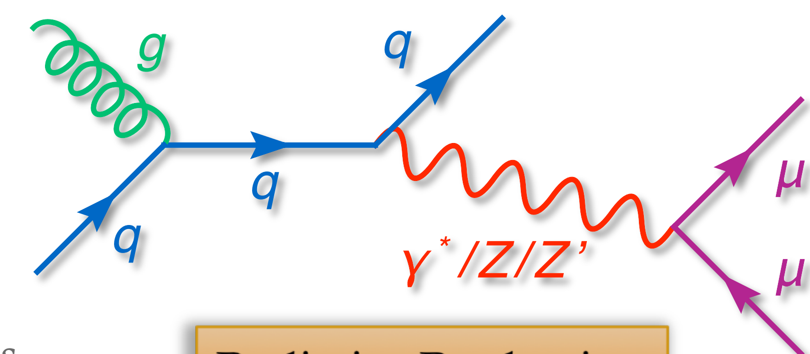
# $Z^0$ Production in 14 TeV *pp* Collisions

$Z'$ production will show a sharp resonance

- Properties of the $Z^0$
  - Neutral gauge boson coupling to weak flavor
  - $m_Z = 91.2$ GeV, produces ~ 45 GeV muons
  - Narrow resonance; width is 2.5 GeV
- $Z^0$ produced from quark-antiquark annihilation
  - No valence antiquarks in proton; sea dominates
  - Forward-backward asymmetry probes antiquark component of proton PDF
  - High energy means the $Z^0$ will be abundant
  - $\sigma_{Z,Total}$ ~ 11 nb, $\sigma_{Z \to \mu\mu}$ ~ 370 pb
- Important for $Z'$ search
  - Useful calibration to prepare for $Z'$
  - Early test of tracker & muon system efficiencies
  - Drell-Yan is primary background for $Z'$ search

The Drell-Yan Process

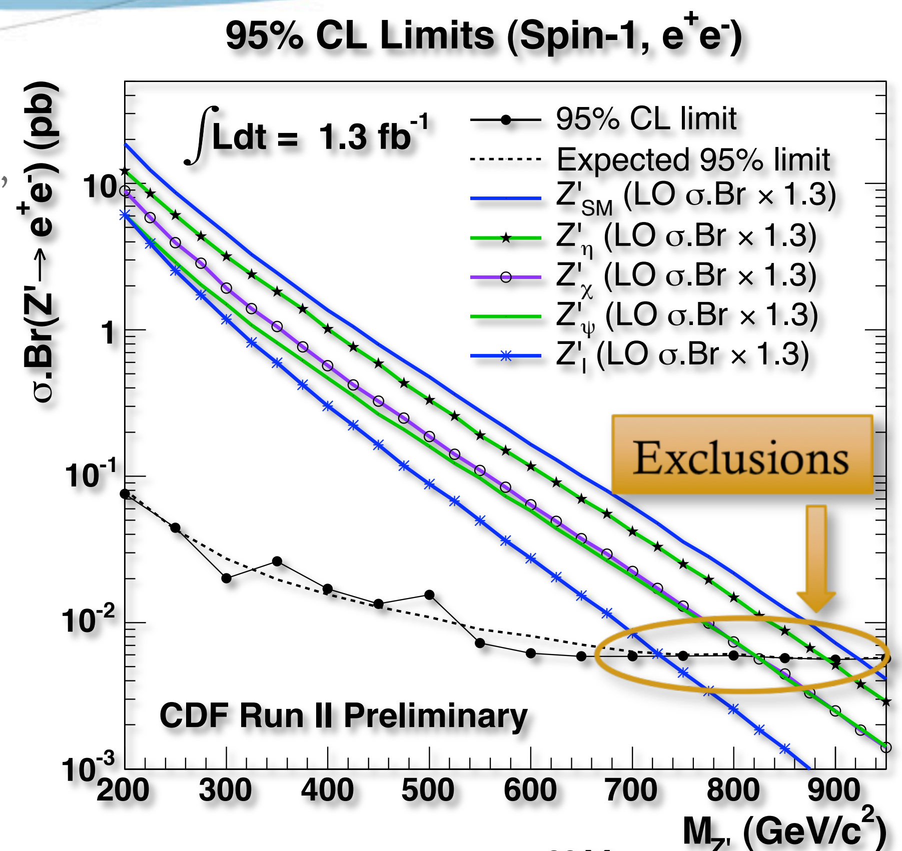



Radiative Production

# Status of $Z'$ Searches and Expected Properties

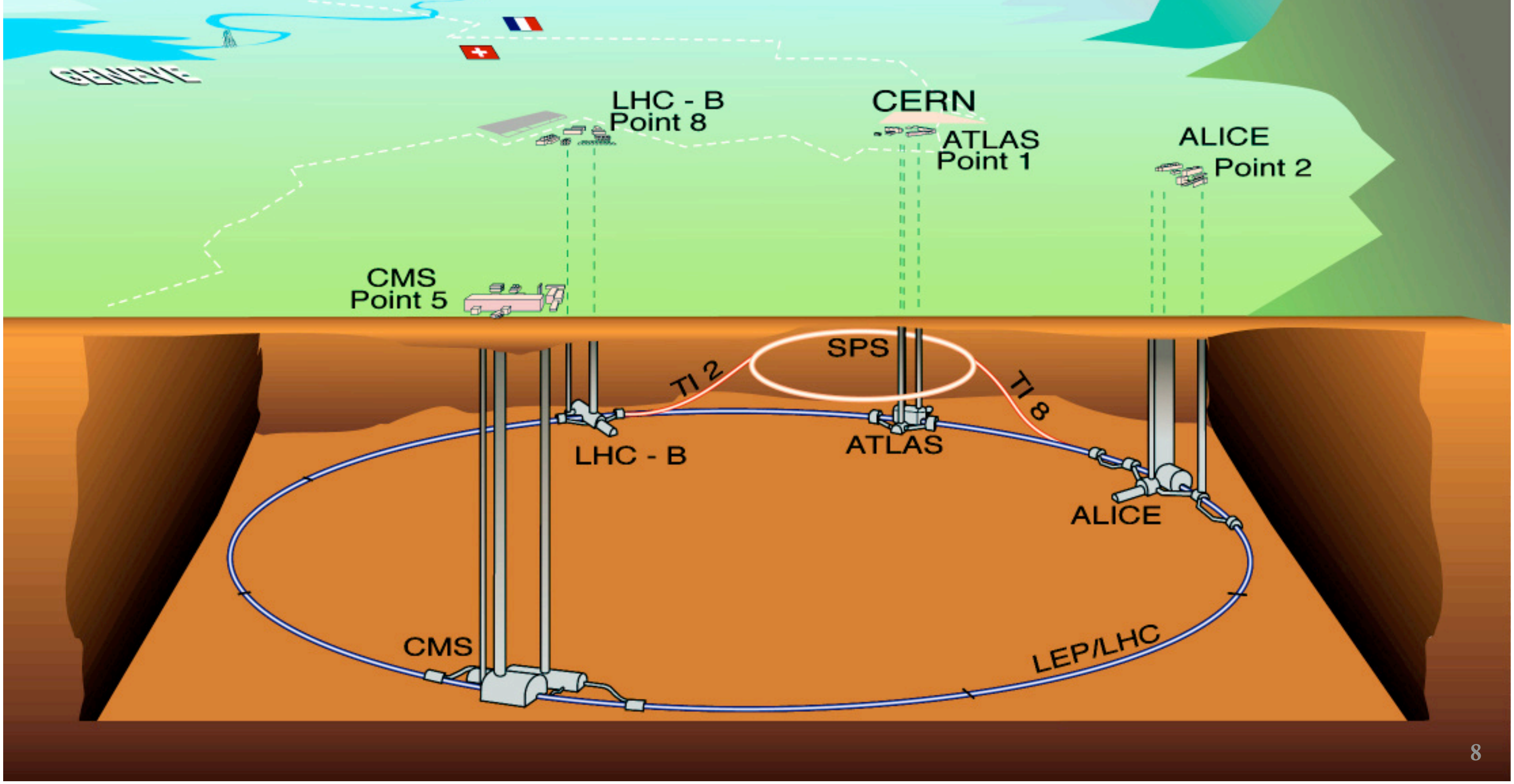
- Mass has been excluded below 900 GeV
  - Nearly exhausts Tevatron's energy reach
  - LHC should easily see 1.5 TeV in early data, eventual reach beyond 4 TeV
  - New challenges to measure 500+ GeV muons
- Expected properties
  - $\sigma$ is an exponential function of mass
    - ~ 470 fb for 1 TeV
  - Width scales with mass (0.5% to 4%)
- Models have various predictions for production cross sections and decay widths
- Large deviations from the expected width would indicate decays to new particles



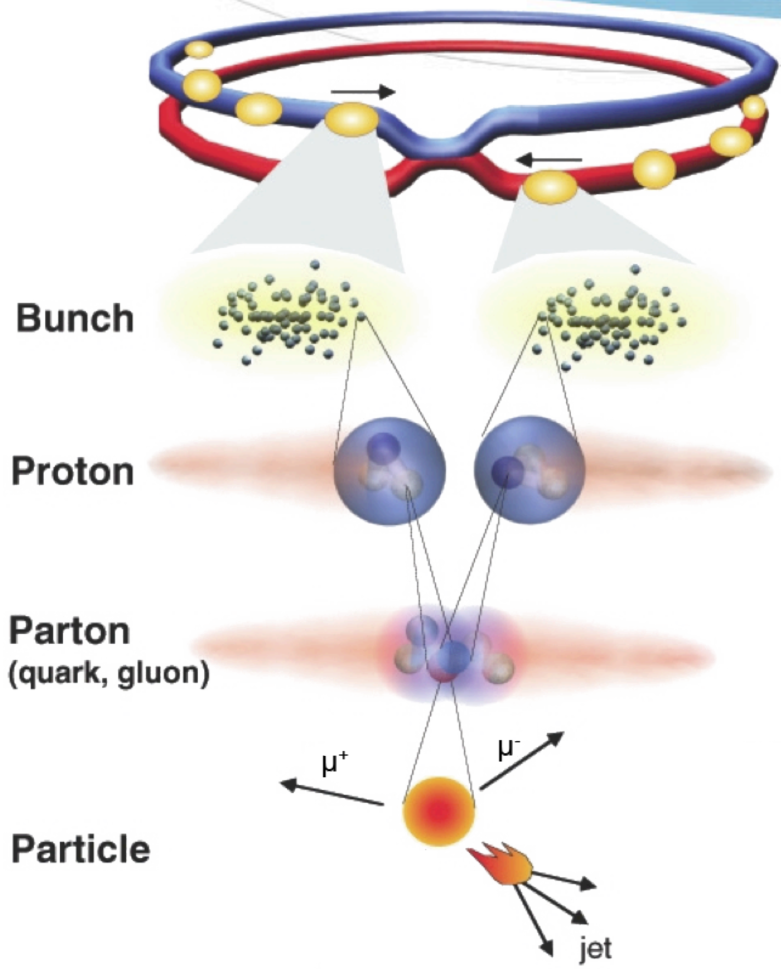

$$\sigma_{Z'} = 780\frac{c_{Z'}}{s}e^{\frac{-32M_{Z'}}{\sqrt{s}}}$$

# The Large Hadron Collider

- 14 TeV total collision energy
- Counter-rotating beams of protons
- 100 m below ground
- 27 km in circumference
- Design luminosity of $10^{34}$ $cm^2$ $s^{-1}$

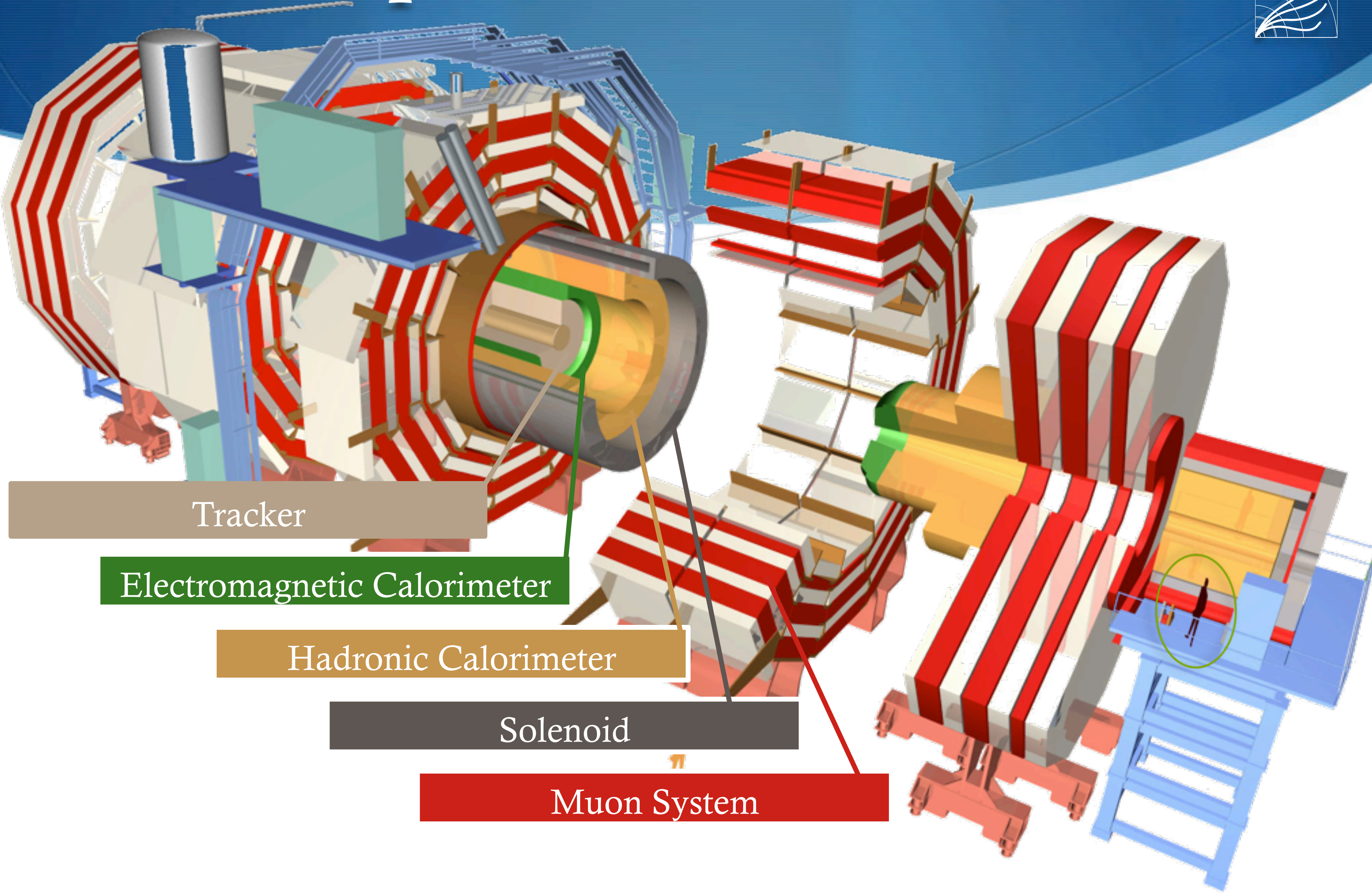


# Proton Collisions

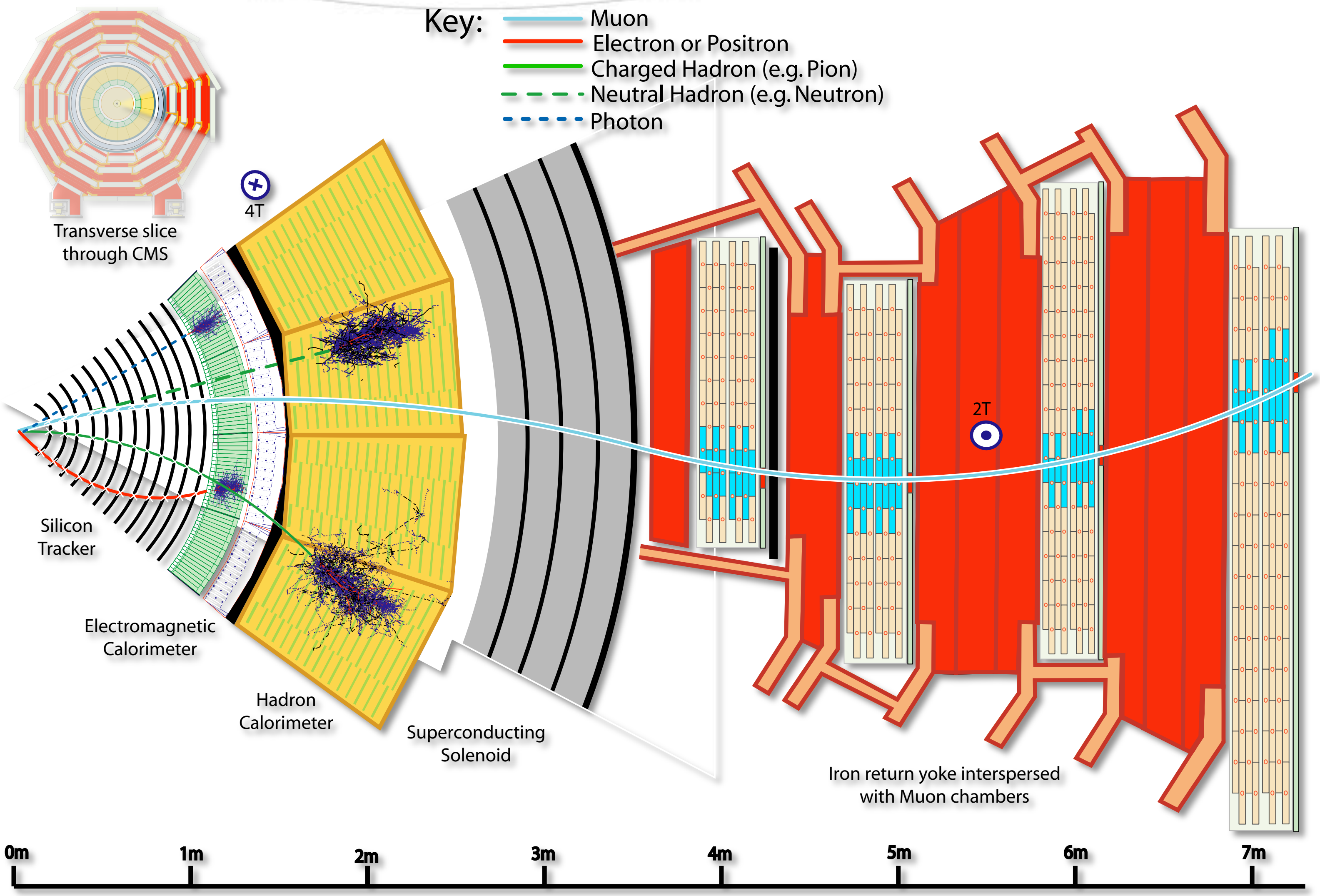


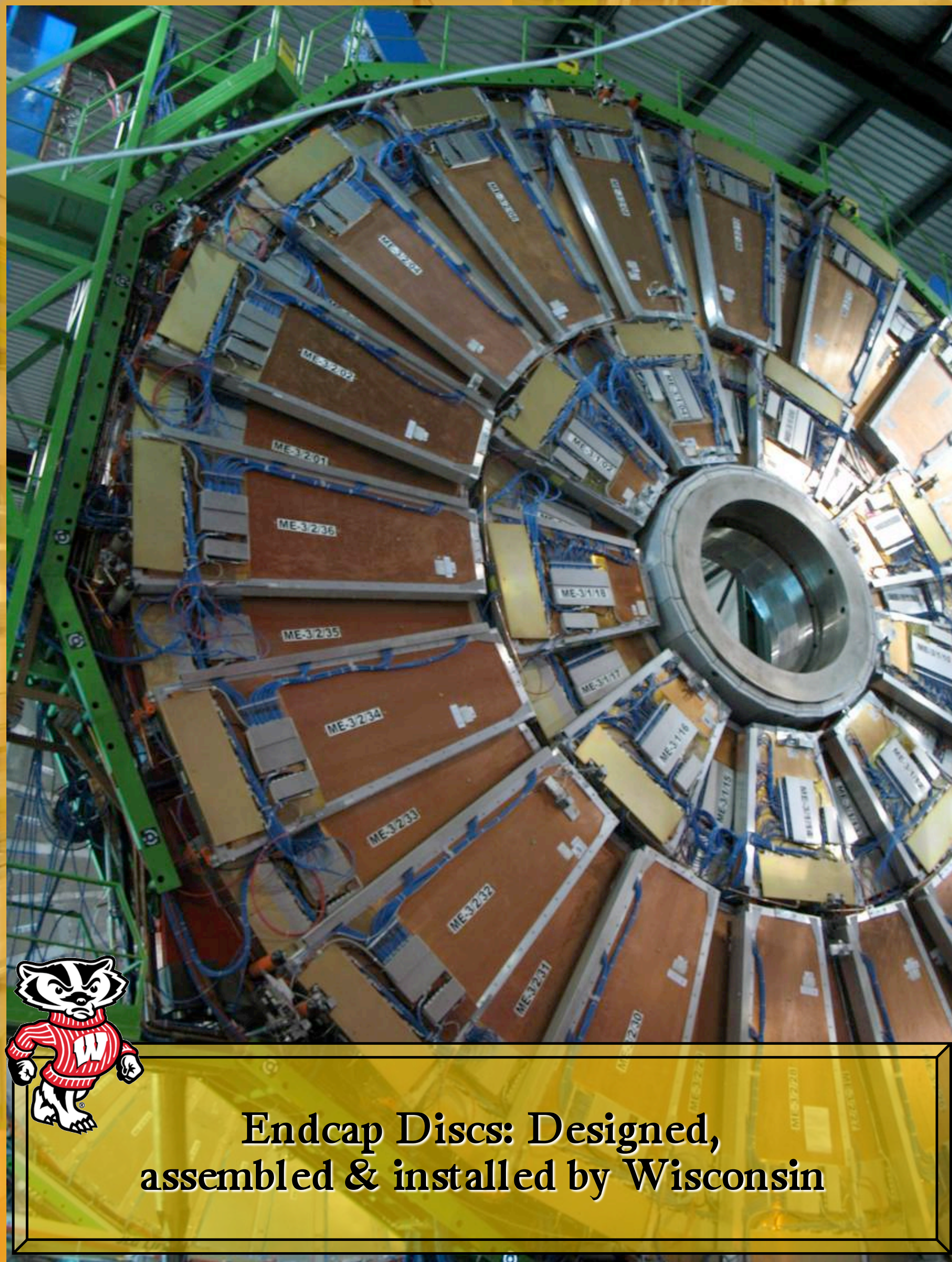

- 2835 bunches/beam
- $10^{11}$ protons/bunch
- Design luminosity = $10^{34}$ cm$^{-2}$ s$^{-1}$
- Crossing rate = 40 MHz
- $10^9$ collisions/second
- $\sigma_{Z'} \sim 470$ fb for $m_{Z'} = 1$ TeV
  - 47 events per 100 pb$^{-1}$ of data
  - 1 in $10^{11}$ interactions!
  - 1 event every 4 minutes at design luminosity

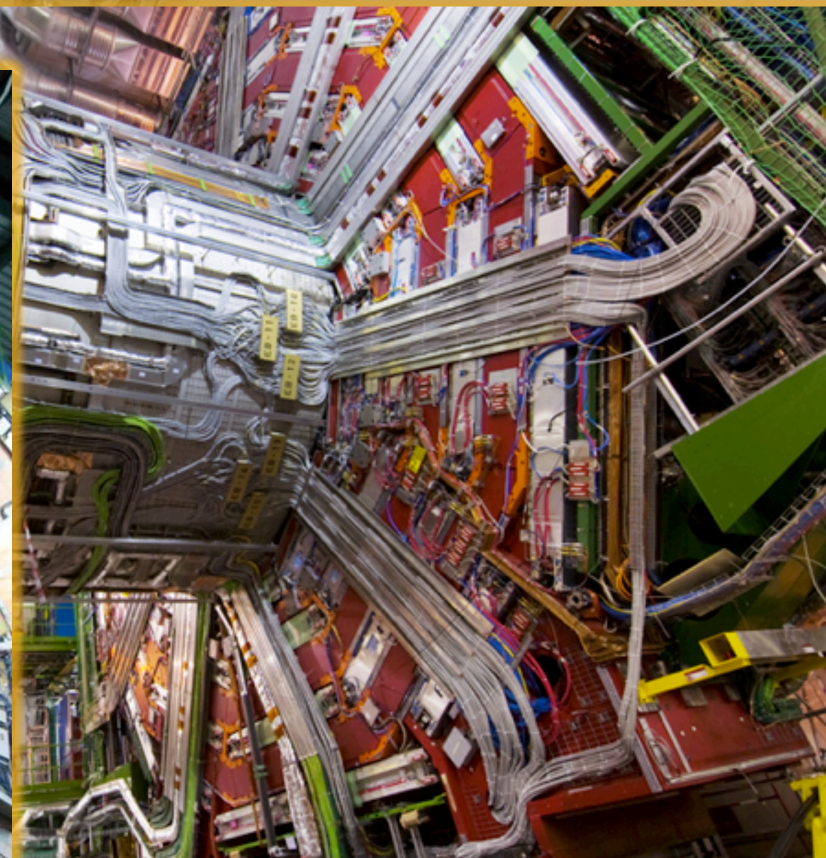
# Compact Muon Solenoid



# Particle Detection in CMS







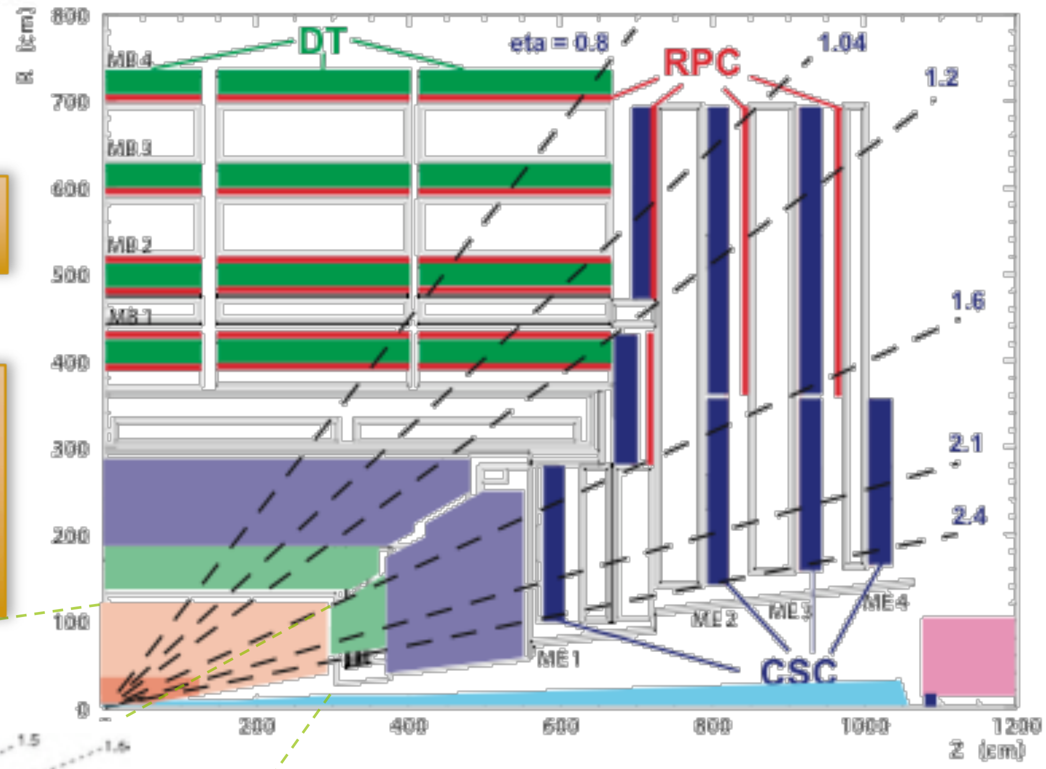
Endcap Discs: Designed, assembled & installed by Wisconsin

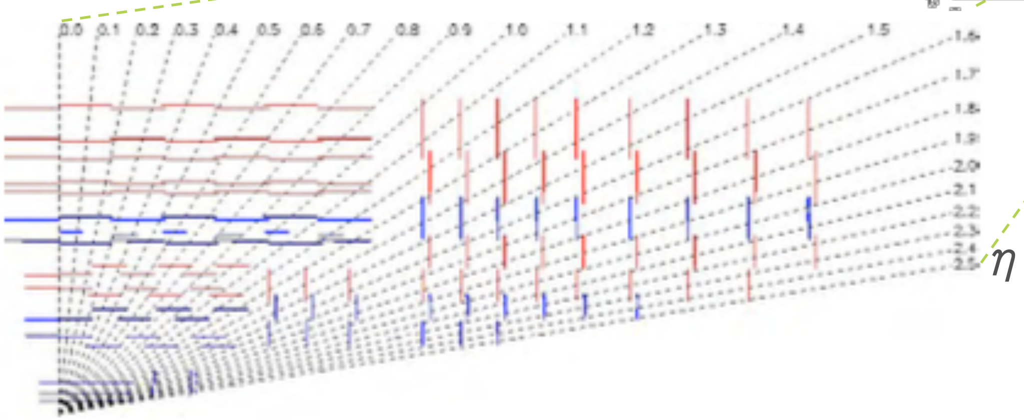
# Tracker and Muon Layout

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

Full 2π coverage in $\varphi$

Coverage in $\eta$:
  to 2.5 in tracker
  to 2.4 in muon system

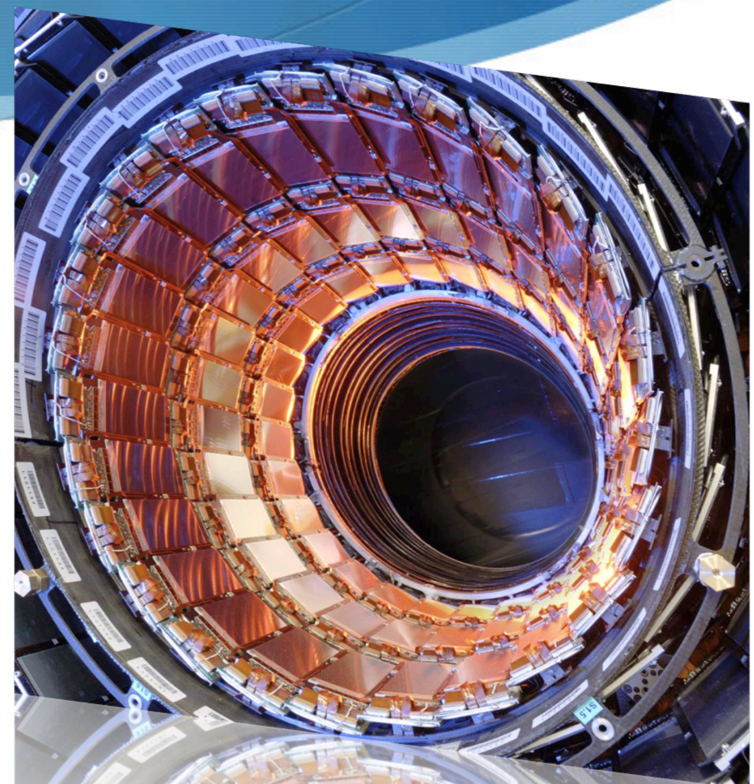



High efficiency expected over full range in $\eta$ and $\varphi$

# The CMS Tracker

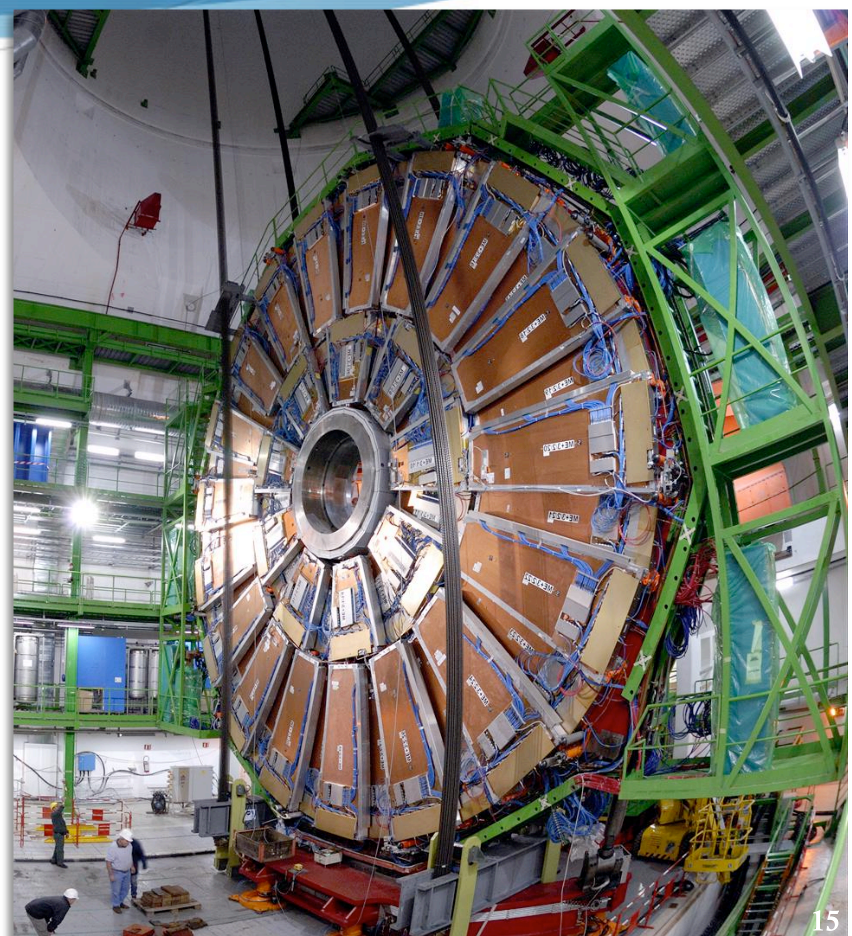
- Silicon-based tracker
  - Barrel and forward disk design
  - Silicon pixels close to beam
  - Strips at larger radius
- Excellent transverse momentum resolution
  - Strip pitch of 80-180 μm
  - Immersed in 4 T magnetic field
  - Radius = 1.2 m, Length = 5.6 m
  - 1 radiation length of material
  - For a 45 GeV muon, resolution ~ 0.8%
  - For a 1 TeV muon, resolution ~ 15%



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

# The CMS Muon System

- 3 types of detectors
  - Drift tubes in the barrel (precise)
  - Cathode strip chambers in endcaps (precise and radiation resistant)
  - Resistive plate chambers throughout (fast, redundancy for trigger)
  - Barrel region in 1.8 T return field
  - Radius = 4 to 7.5 m, Length = 20 m
  - At least 10 $\lambda$ of material before muon system, another 10 $\lambda$ to the last station
- Tracks from muon system and tracker are matched
  - For low $p_T$, the muon system provides redundant ID, but becomes key to good resolution at higher momentum
  - We can achieve a combined $p_T$ resolution better than 5% for 1 TeV muons!



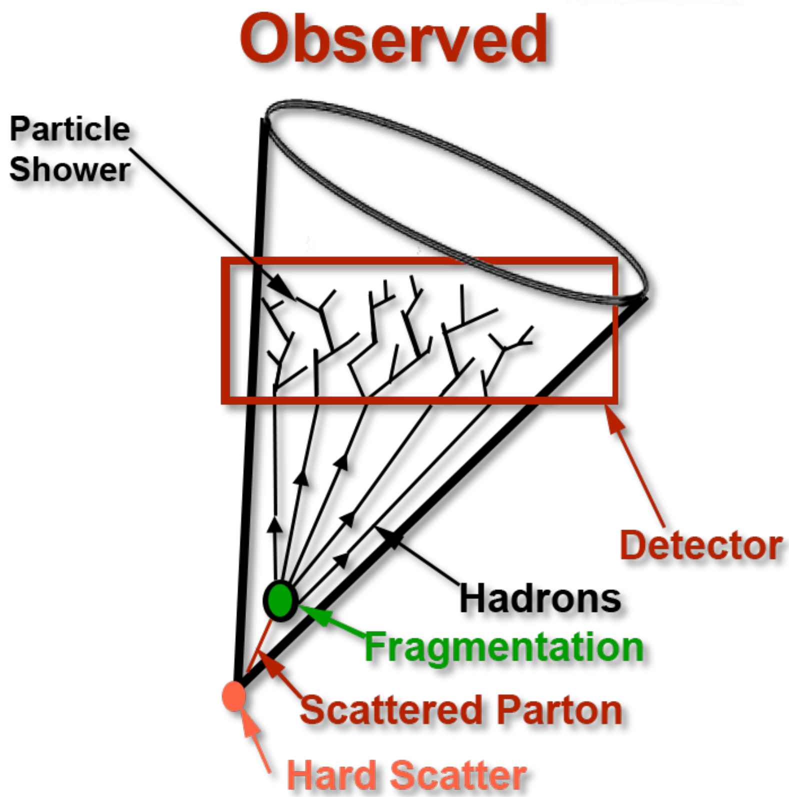
# Simulation Workflow

**Generation**
- Pythia/ Alpgen
- Simulation of physics processes

**Detector Simulation**
- Geant4
- Passage of particles through matter

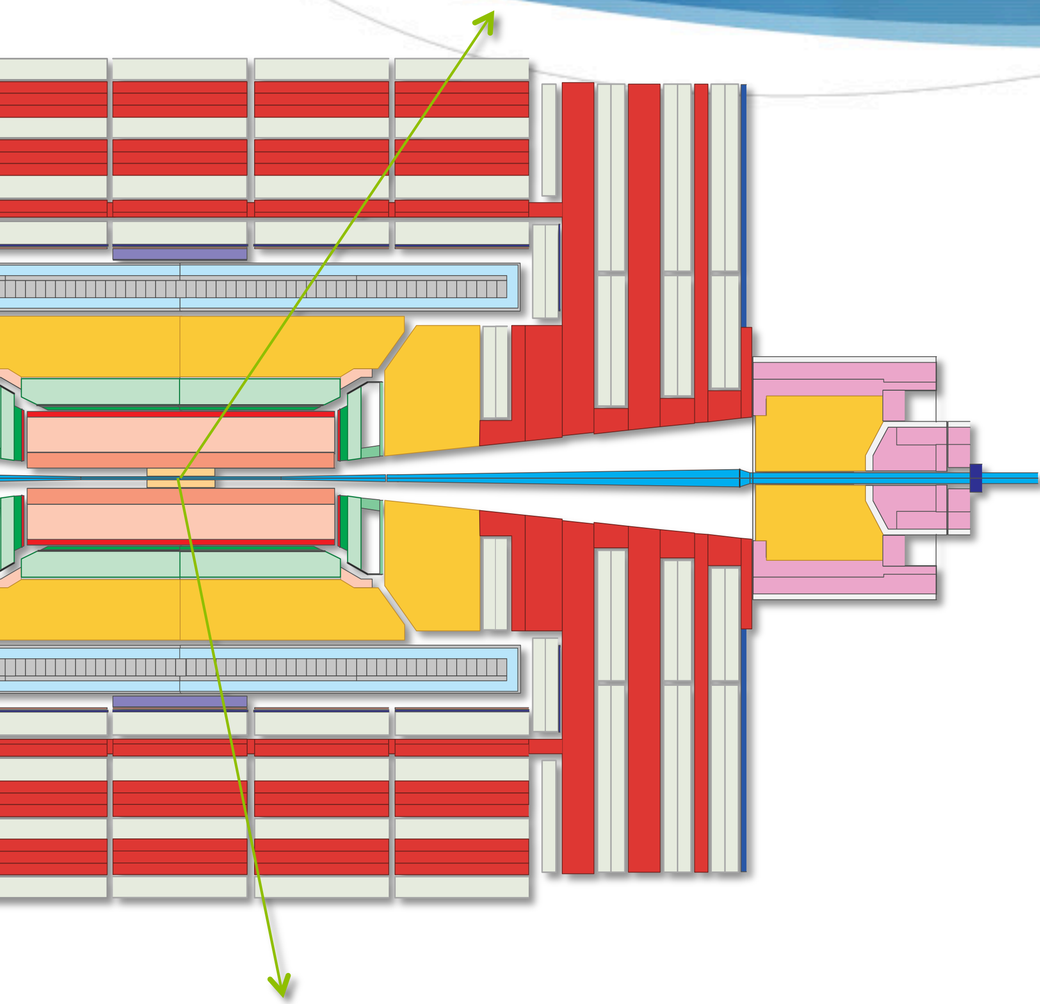
**Event Reconstruction**
- CMSSW 1.6.8
- Pieces together physics objects

# Generation of Physics Events




- Hard scattering matrix element calculations
  - Alpgen (fixed order) specifically for boson + jets processes
  - Pythia (leading order) for others
- Subsequent jet evolution using Pythia
  - Underlying event
  - Jets from initial and final state radiation
  - Fragmentation and hadronization of partons into jets

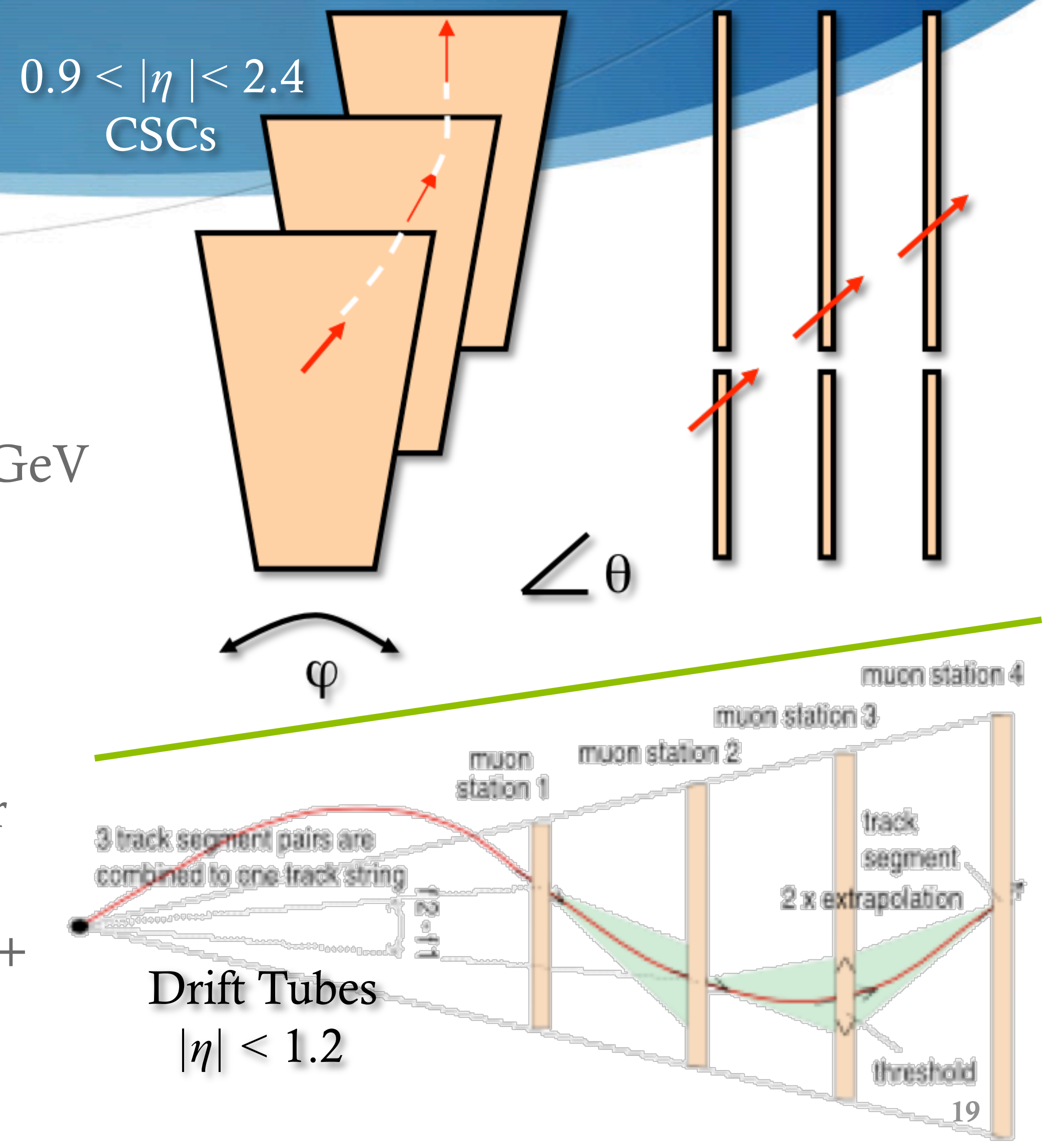
# Detector Simulation



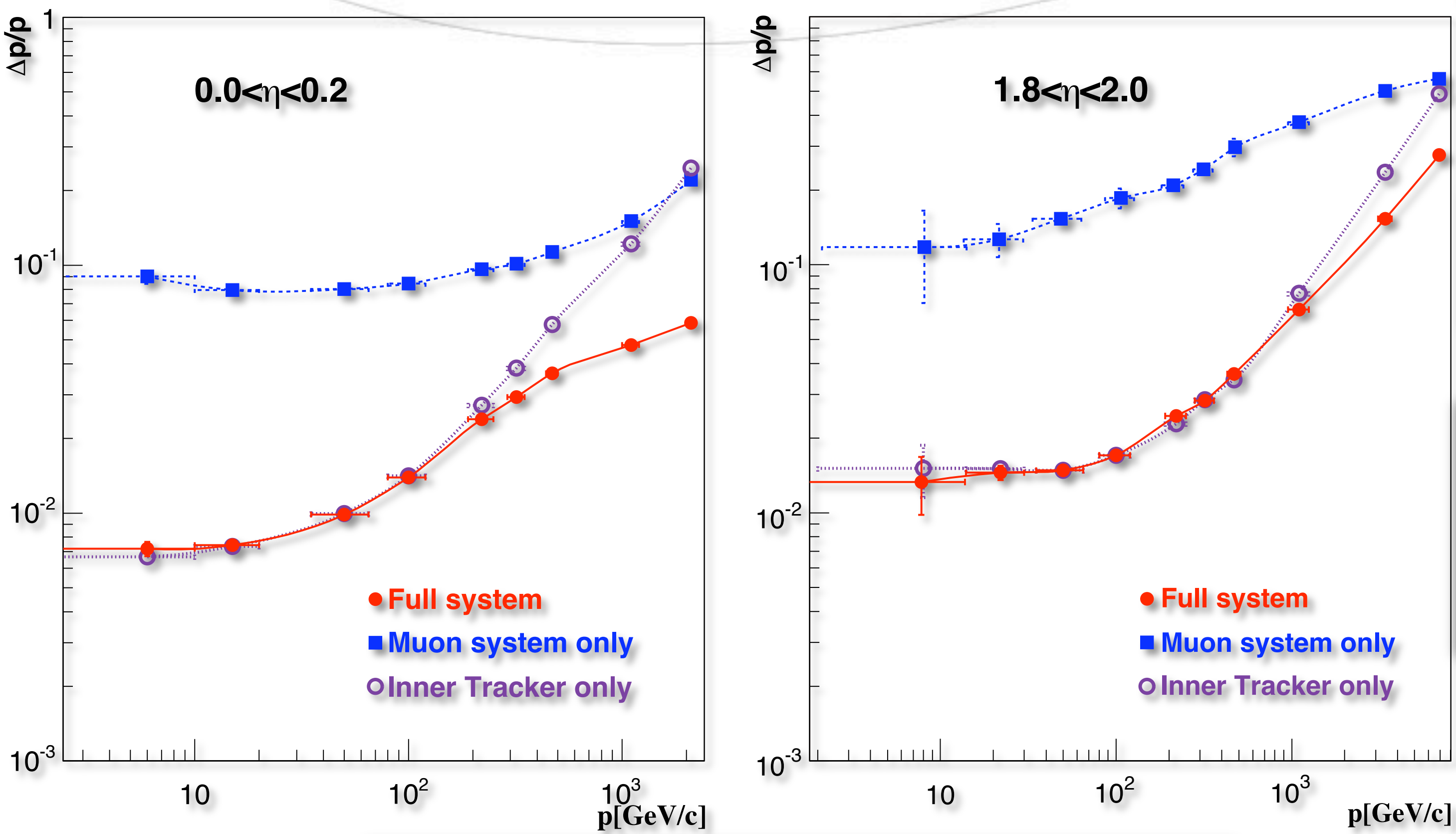
- Geant4 simulates the passage of particles through the detector
- Signal digitization is simulated for all components of detector, readout, and trigger.
- Key to understanding (eventually from data):
  - Realistic rates for mis-ID of hadrons as muons
  - Realistic detector resolutions
  - Efficiencies

# Muon Reconstruction

- Trigger
  - Early muon system info gives independent $p_T$ measurement
  - Muons from $Z'$ easily pass 20 GeV threshold
- Full reconstruction
  - Produce muon system tracks
  - Independently produce tracker system tracks
  - Perform a global fit to tracker + muon system hits



# Momentum Resolution




$$\frac{\delta M}{M} \approx \frac{1}{\sqrt{2}} \frac{\delta p}{p}$$

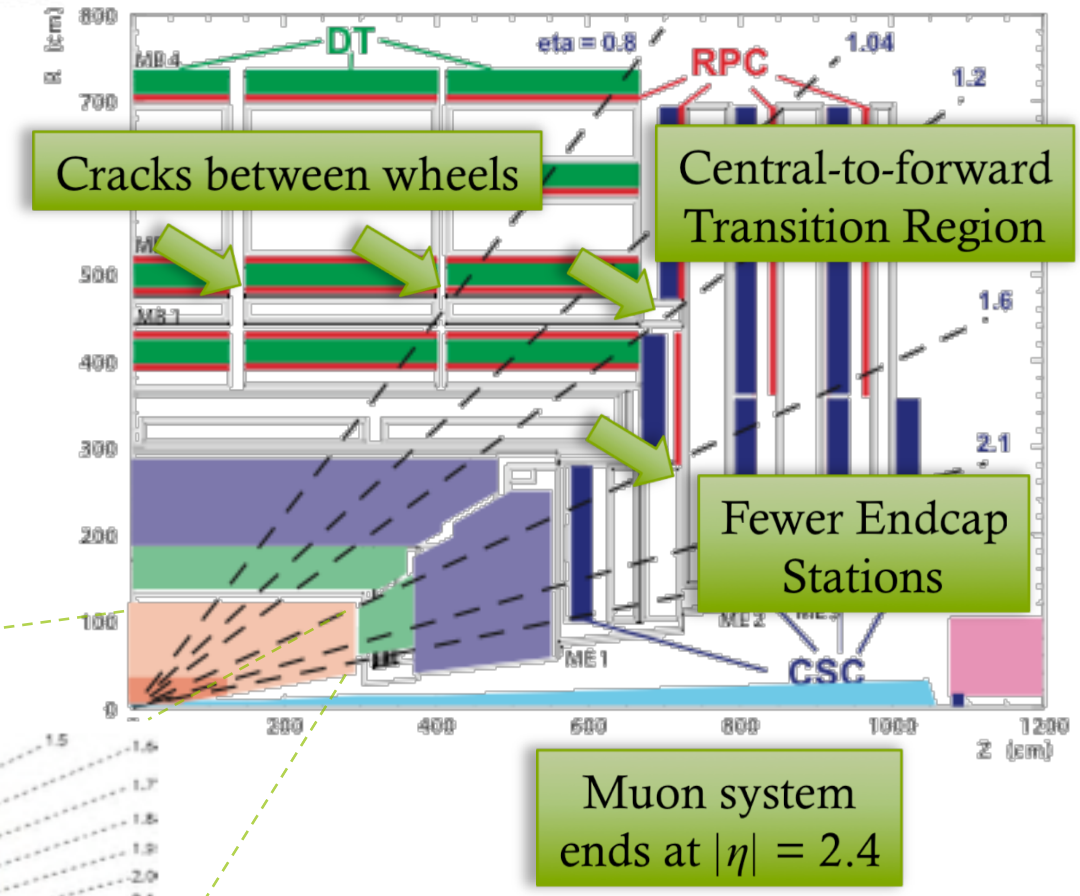
Usable resolution up to 2 TeV!

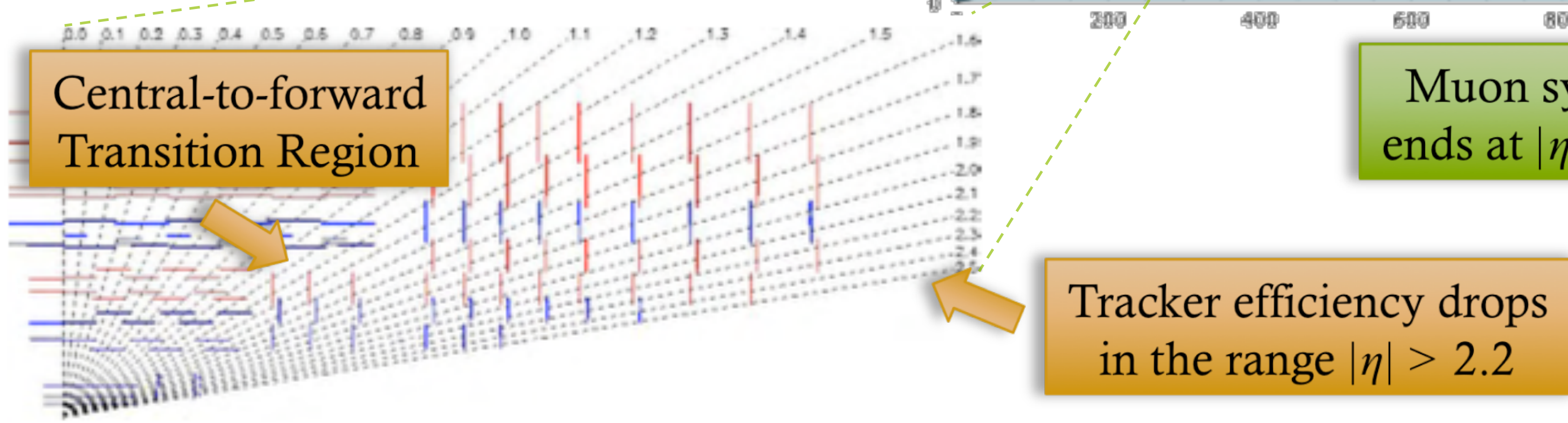
Experimental resolution on the order of larger $Z'$ width predictions

MC simulation of isolated single muons

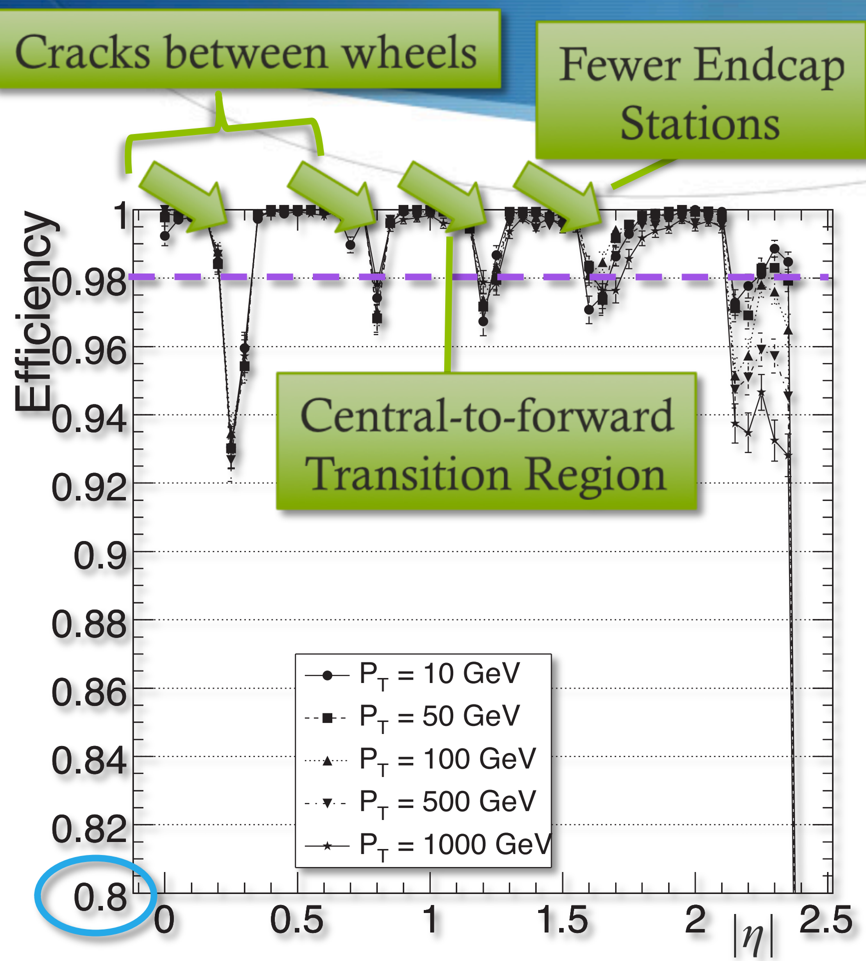
# Sources of Inefficiency

- Barrel Region
  - $|\eta| < 0.9$
- Overlap Region
  - $0.9 < |\eta| < 1.2$
- Endcap Discs
  - $|\eta| > 1.2$

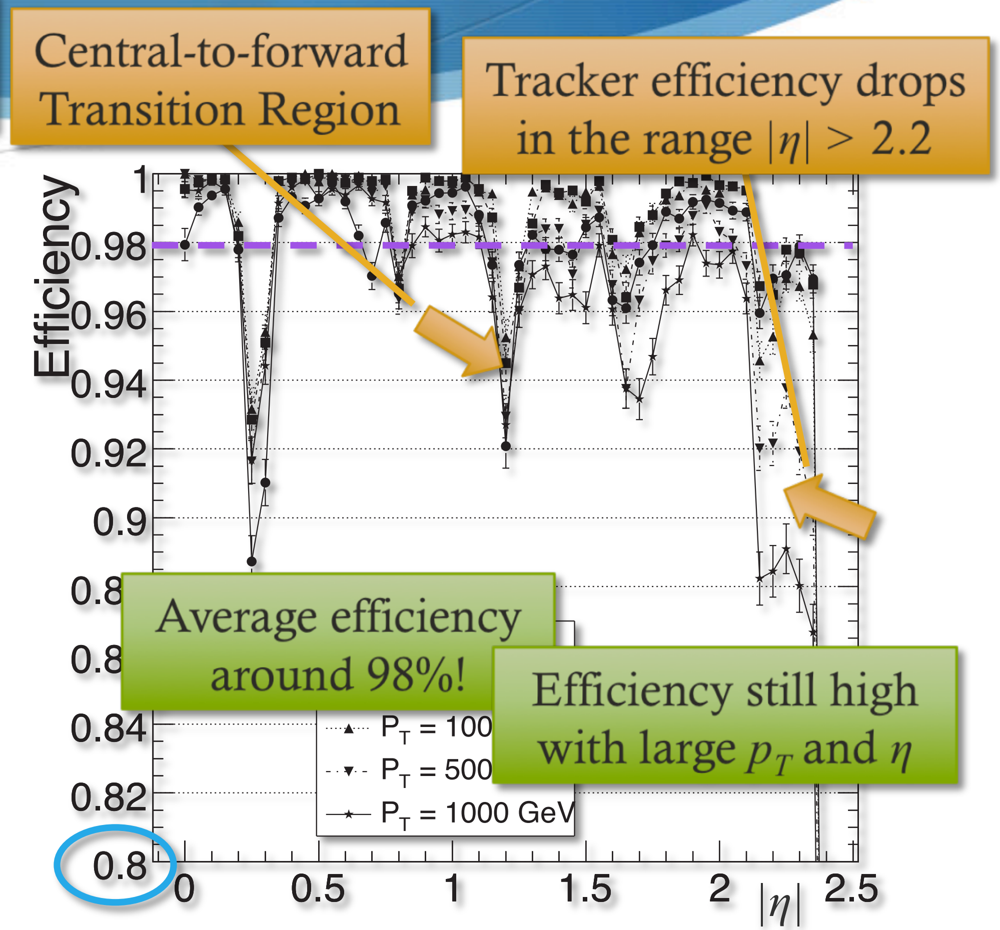


# Reconstruction Efficiency




Muon system alone



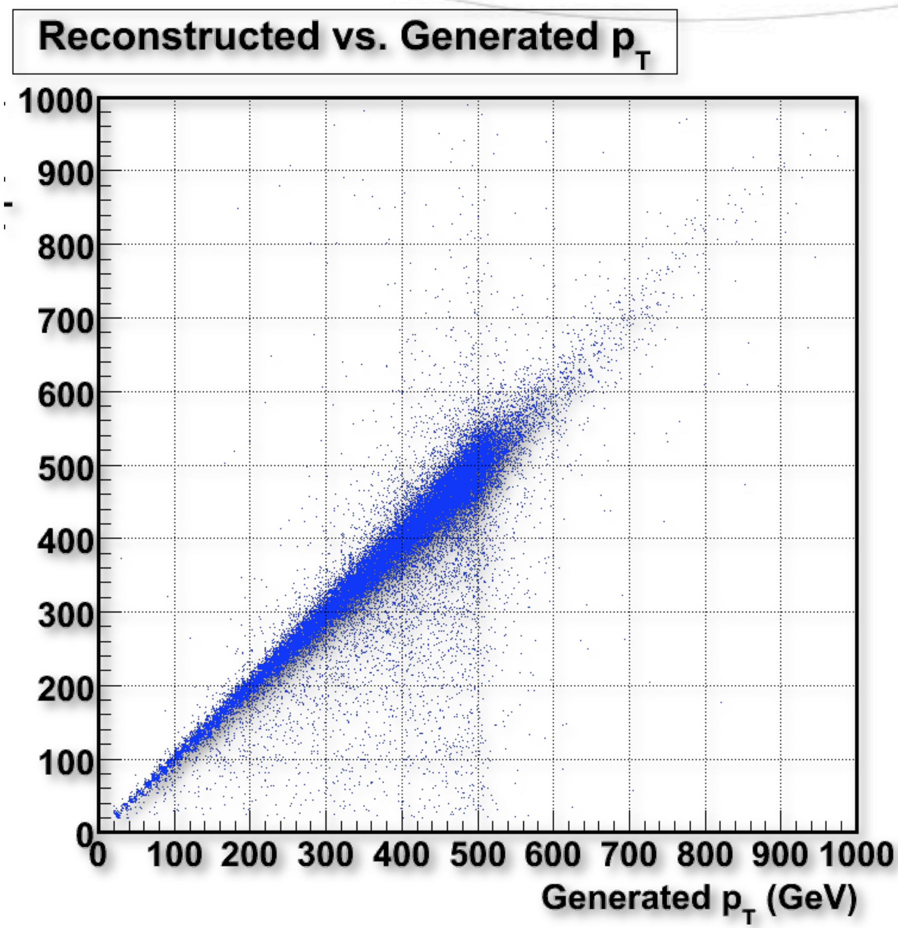

Combined fit from muon system + tracker

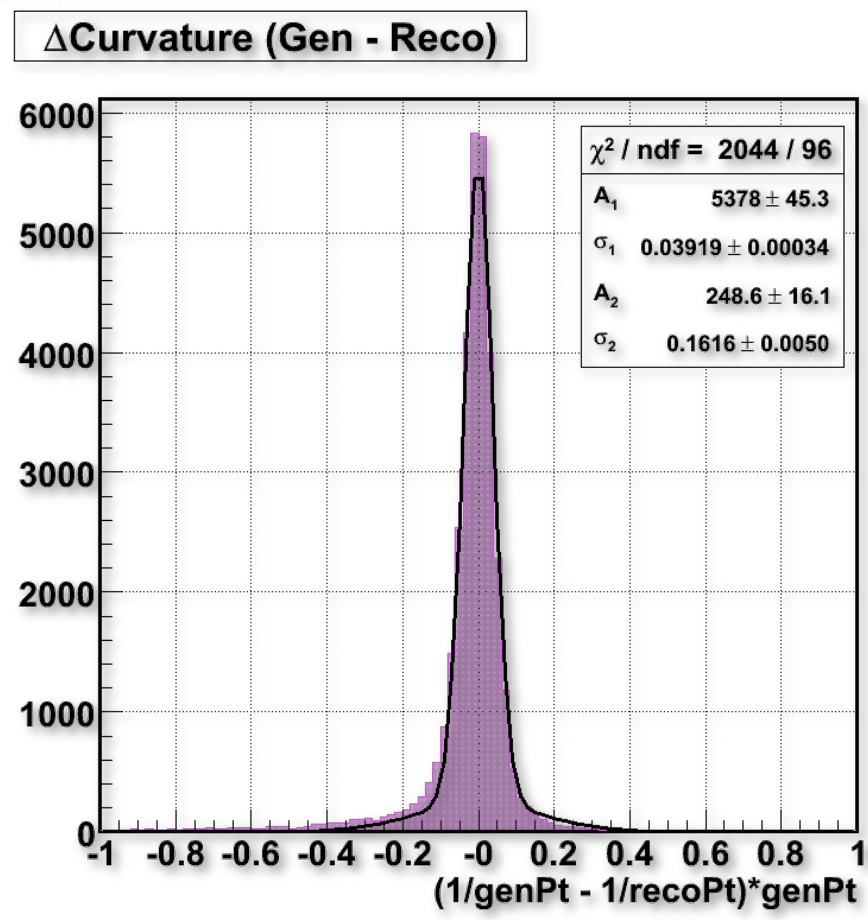
# Outline of Analysis

- Simulated Z′ data
  - $m_{Z'}$ = 1 TeV, just beyond Tevatron limit
  - $Z'_{SSM}$ with SM couplings included in Pythia
  - One of the highest $\sigma$ models: 470 fb
  - Width may be detectable (3% of mass)
- Preparation for data-taking
  - Determine acceptance of $Z'$ events
  - Compare backgrounds and signal to choose cuts
  - Apply our selection cuts to determine sensitivity

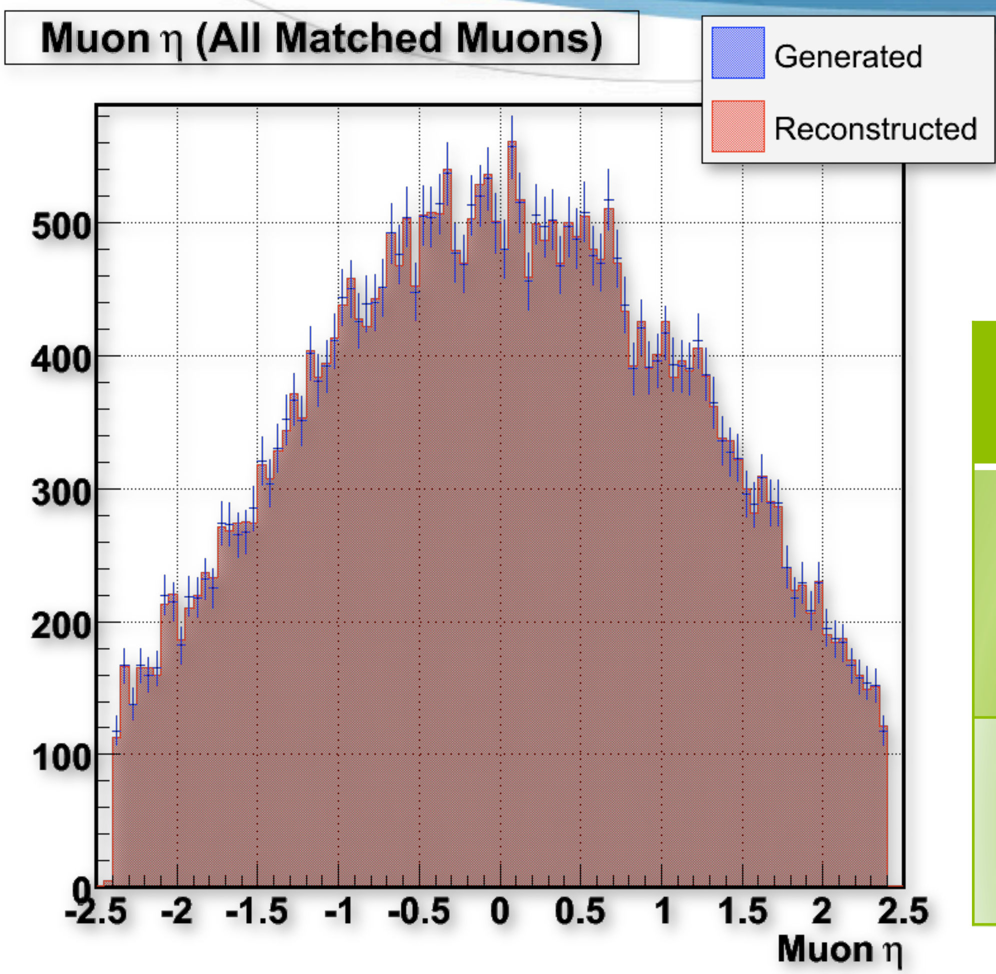
# Gen/Reco Muon Matching

4% $p_T$ resolution agrees with previous simulations



# Fiducial Cuts

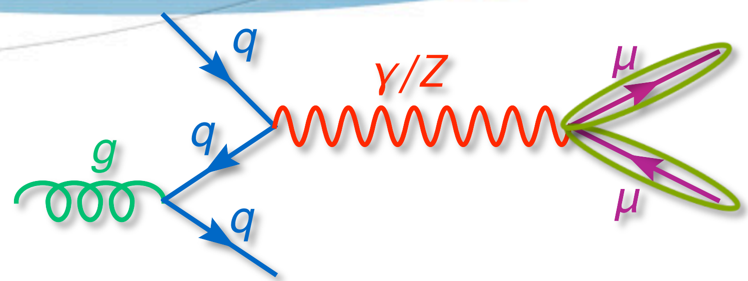



Distribution becomes more central with greater mass

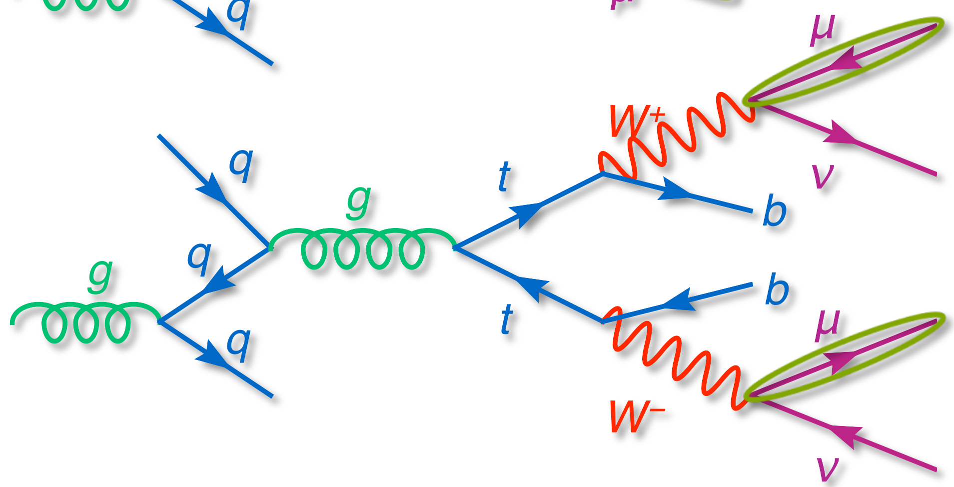
| Requirements | Yield/ Efficiency |
|---|---|
| Fiducial Cuts (generator quantities) $p_T > 20$ GeV $\|\eta\| < 2.4$ | 82% ±0.3% |
| Reconstruction Tracking+Muon System | 78% ±0.3% |

# Backgrounds to $Z' \rightarrow \mu^+\mu^-$

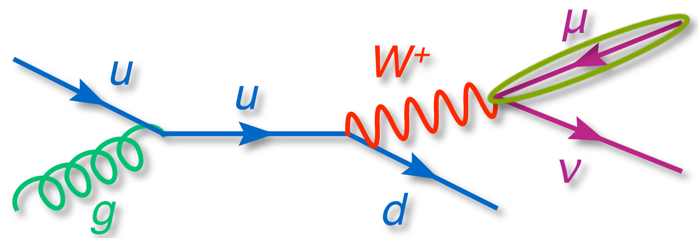
- High-mass Drell-Yan
  - Only major background




- Top-antitop decay to muons
  - Produces a pair of $W$+jets events




- $W$+jets and $Z$+jets
  - Energetic jets produce muons from hadron decay



# Distinguishing Signal vs. Background

100 $pb^{-1}$

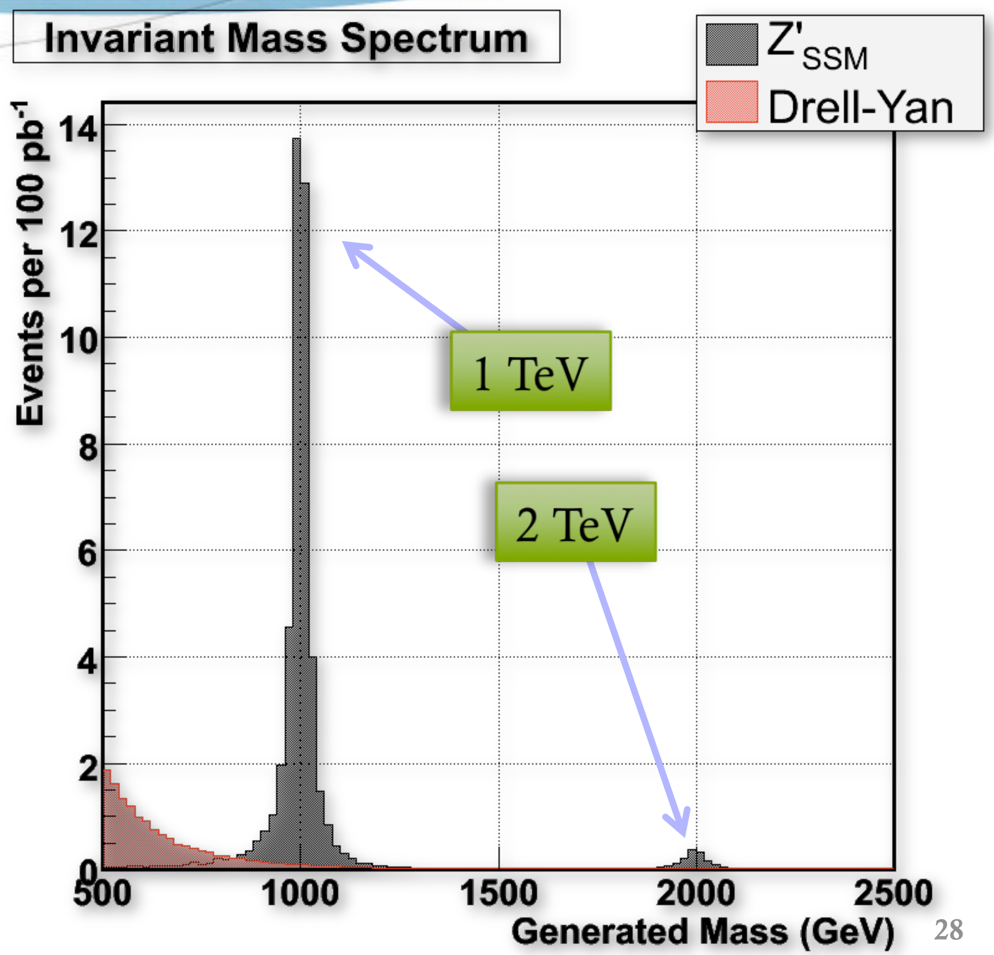
| Signal | Drell-Yan | Top-antitop | Boson+jets |
|---|---|---|---|
| Peak in mass distribution | Peak at much lower mass | No peak | No peak |
| Muons isolated in tracker | Muons isolated in tracker | Muons produced with jets | Muons produced with jets |
| Muons in 500 GeV range (48 pairs) | Few muons in the 500 GeV range (7 pairs) | Muons in 80 GeV range | Muons in 40 GeV range |
| No intrinsic missing $E_T$ | No neutrinos | 2 neutrinos | 1 neutrino for W +jets |
| Few energetic jets | No jets | 2 or more jets | 1 or more jets |

# Drell-Yan

100 $pb^{-1}$

- Primary irreducible background is Drell-Yan with high mass
- Drell-Yan Sample from Pythia
  - Selected only $m_{\mu\mu} > 500$ GeV
  - As $m_{\mu\mu}$ increases, cross section for Drell-Yan drops more quickly than for $Z'$
  - 48 events for $m_{Z'} = 1$ TeV
  - 2 events for $m_{Z'} = 2$ TeV

Peak for $Z'$ should be clearly visible over this distribution

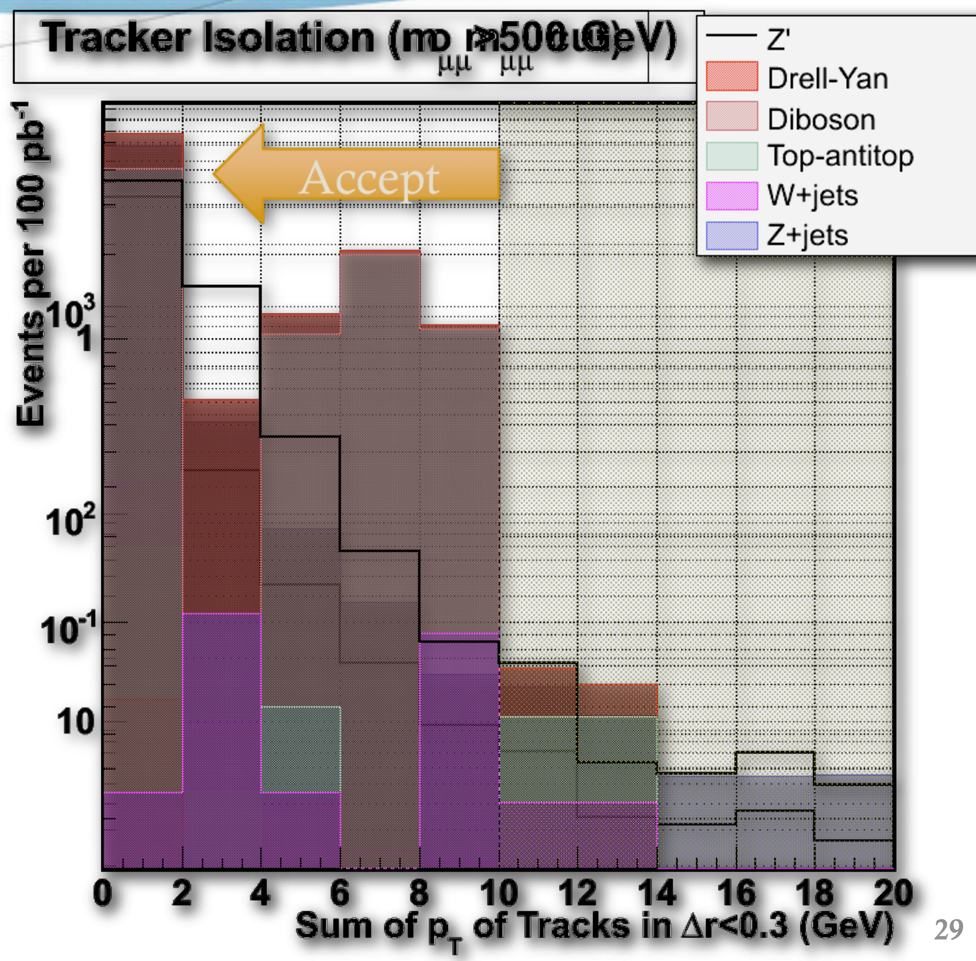


# Muon Isolation

100 pb$^{-1}$

- Calculate muon isolation
  - Cone of $\Delta r < 0.3$
  - Sum $p_T$ of tracks in cone
- Muons from $W$ have many closely associated jets. Top events have many jets.
- $Z'$ events have few jets, so muons should be isolated

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

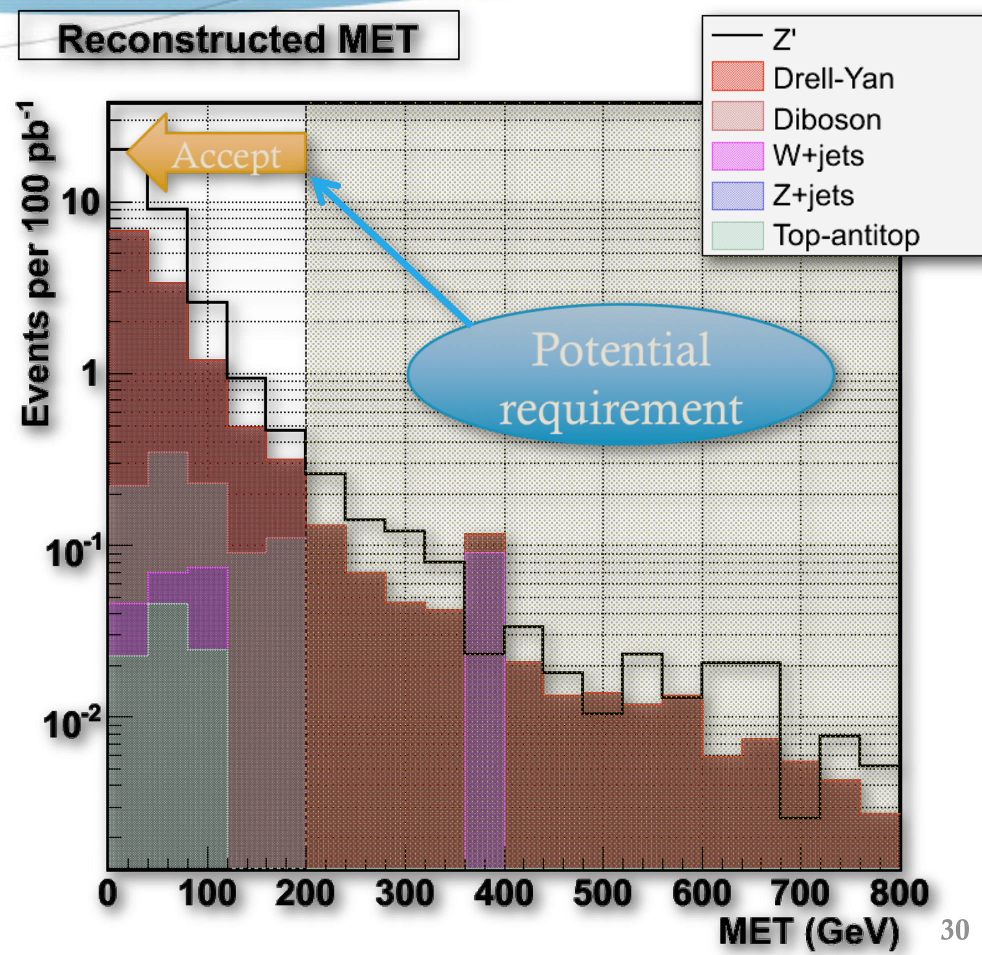


# Missing $E_T$

100 $pb^{-1}$

May be useful for suppressing *W*+jets

- Large false MET found for all samples in reconstruction
- For lower $\sigma_{Z'}$:
  - Potential requirement of MET below 200 GeV

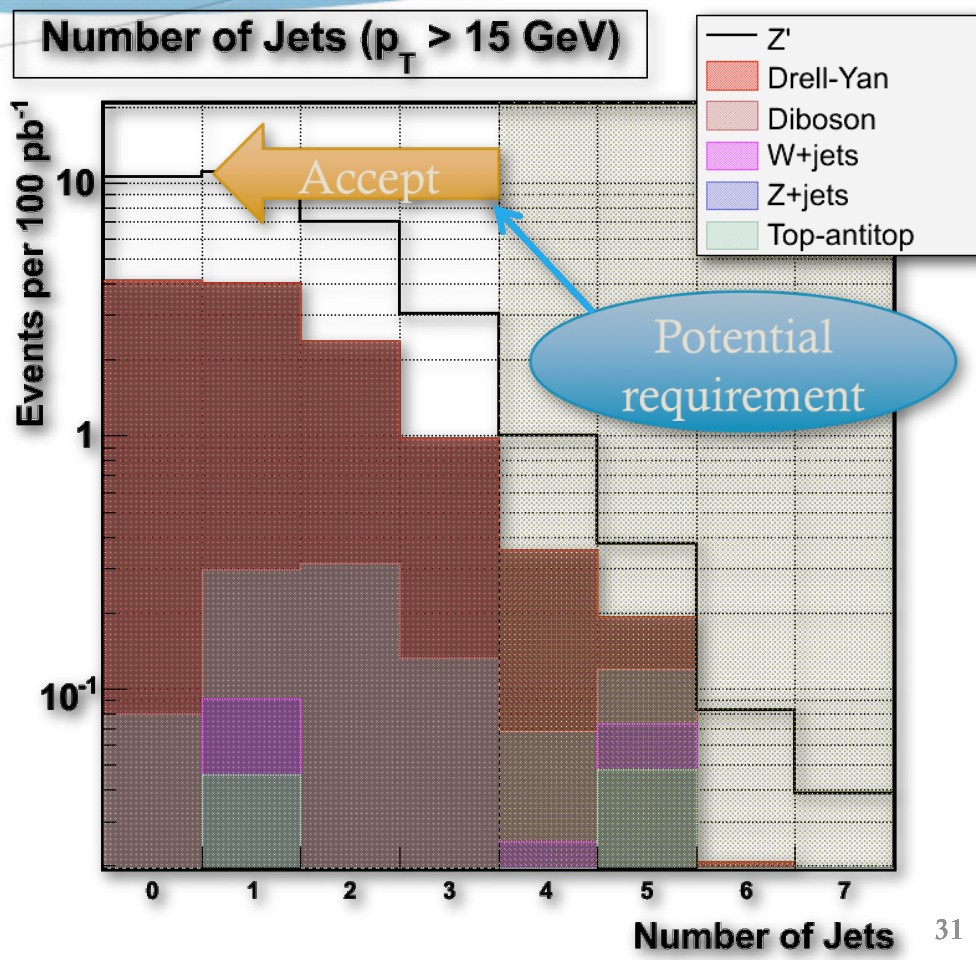


# Jets from Signal and Background

100 pb$^{-1}$

May be useful for suppressing top and *W*+jets

- Nearly all top background has 4 or more jets
- Also eliminates some boson + jets background
- For lower $\sigma_{Z'}$:
  - Potential requirement of fewer than 4 jets



# Event Selection

100 $pb^{-1}$

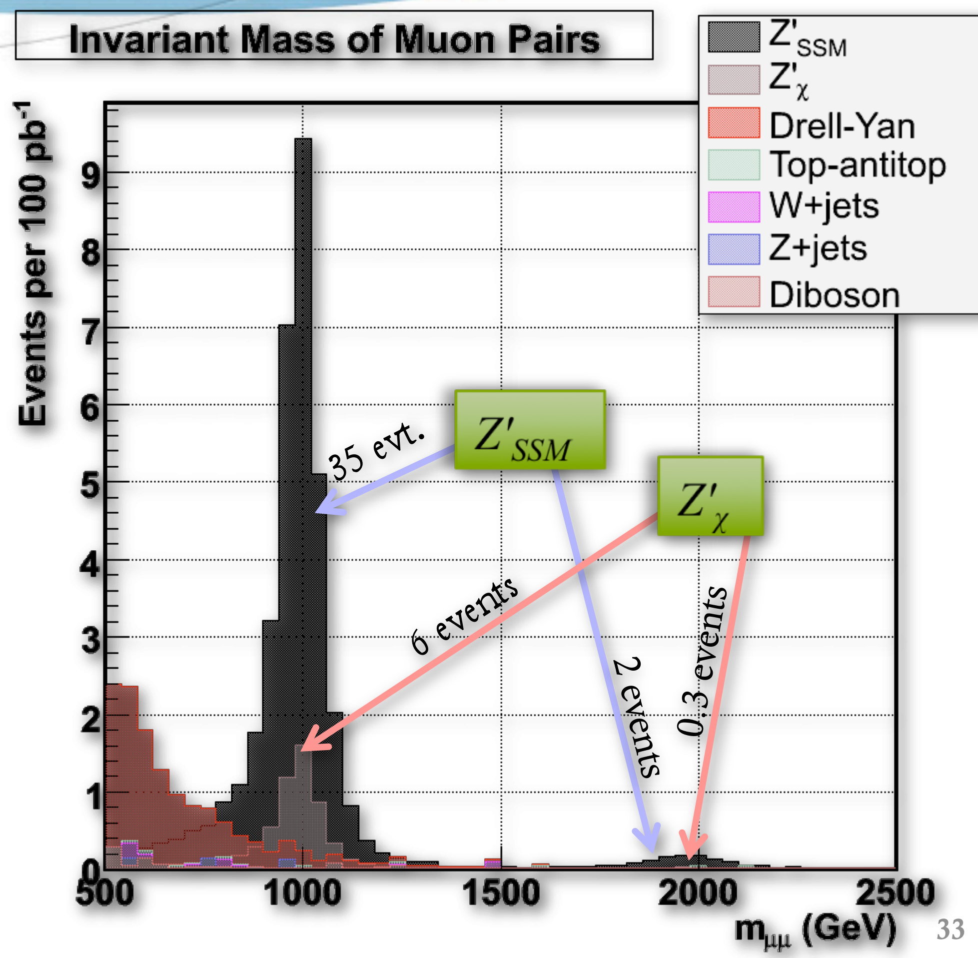
| | 1 TeV Z′ | Drell-Yan | Top-antitop | Boson+jets |
|---|---|---|---|---|
| Acceptance, Reconstruction, $m_{\mu\mu} > 500$ GeV | 35.2 (78% of generated) | 12.0 | .14 | .34 |
| Muons isolated $\Sigma p_T < 10$ GeV | 35.0 (75% of generated) | 11.9 | .09 | .29 |
| MET < 200 GeV | 33.1 | 11.1 | .09 | .10 |
| Fewer than 4 jets | 31.6 | 10.7 | .05 | .05 |

Potential Requirements

# Reconstructed Z′

100 pb$^{-1}$

- The $Z'_{SSM}$ at 1 TeV should be observable well before 100 pb$^{-1}$ have been recorded
- Higher mass $Z'$s will require more data
- $Z'_\chi$ is from an $E_6$ model
- Other $Z'$ models have a much lower $\sigma$ and possibly lower mass, i.e. gravitons
  - Consider additional cuts



# Conclusions & Next Steps

- Conclusions
  - $Z^0$ analysis will be an important calibration for early data
  - With the first 100 $pb^{-1}$ of data, we can find a light $Z'$ and distinguish the signal from backgrounds
- Next Steps
  - Increase muon finding efficiency
  - Produce larger background samples
  - First CMS data
    - Measure muon finding efficiencies
    - Measure rates for misidentification of hadrons as muons
    - Analyze backgrounds in the region below 500 GeV
  - Apply complete analysis to CMS data
  - Apply analysis techniques to $W'$ search