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

Preliminary Exam

Jeff Klukas

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
ν_L	lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e	electron	0.000511	−1
ν_M	middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ	muon	0.106	−1
ν_H	heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ	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
γ	photon	0	0
W^-	W bosons	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

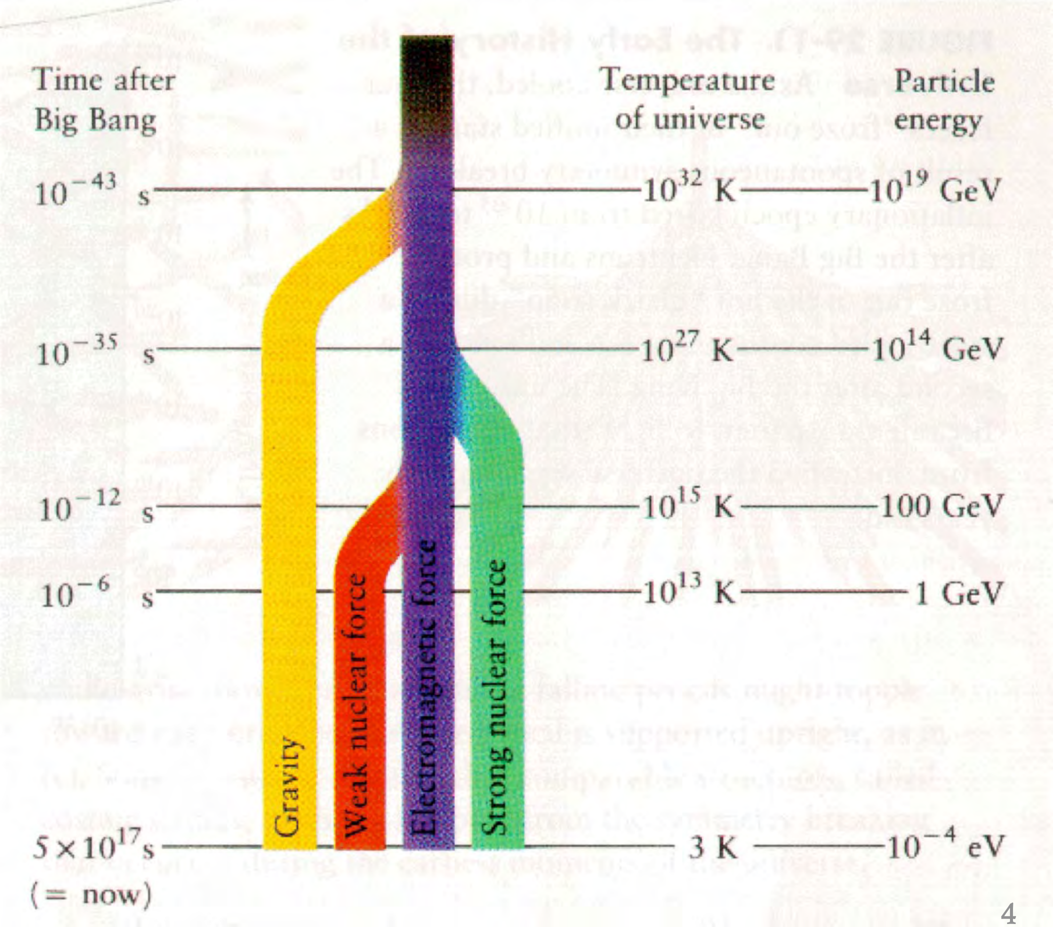
Yet to be found

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

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

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

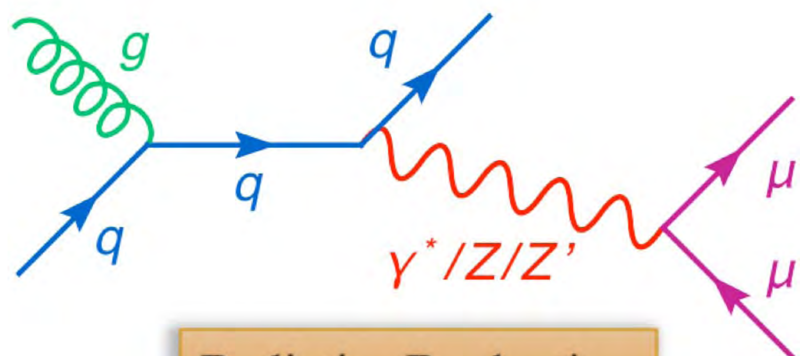
Kaluza-Klein, Dawn Meson

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, $\sigma_{Z\rightarrow\mu\mu}$ ~ 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

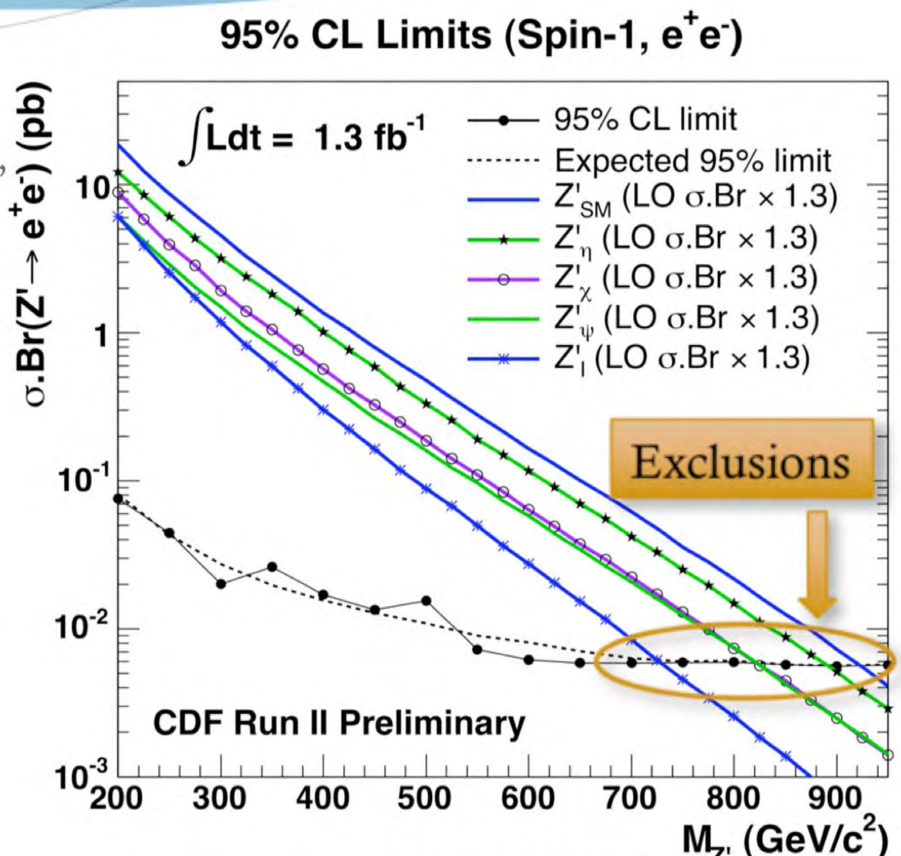
The Drell-Yan Process



Radiative Production

Status of Z' Searches and Expected Properties

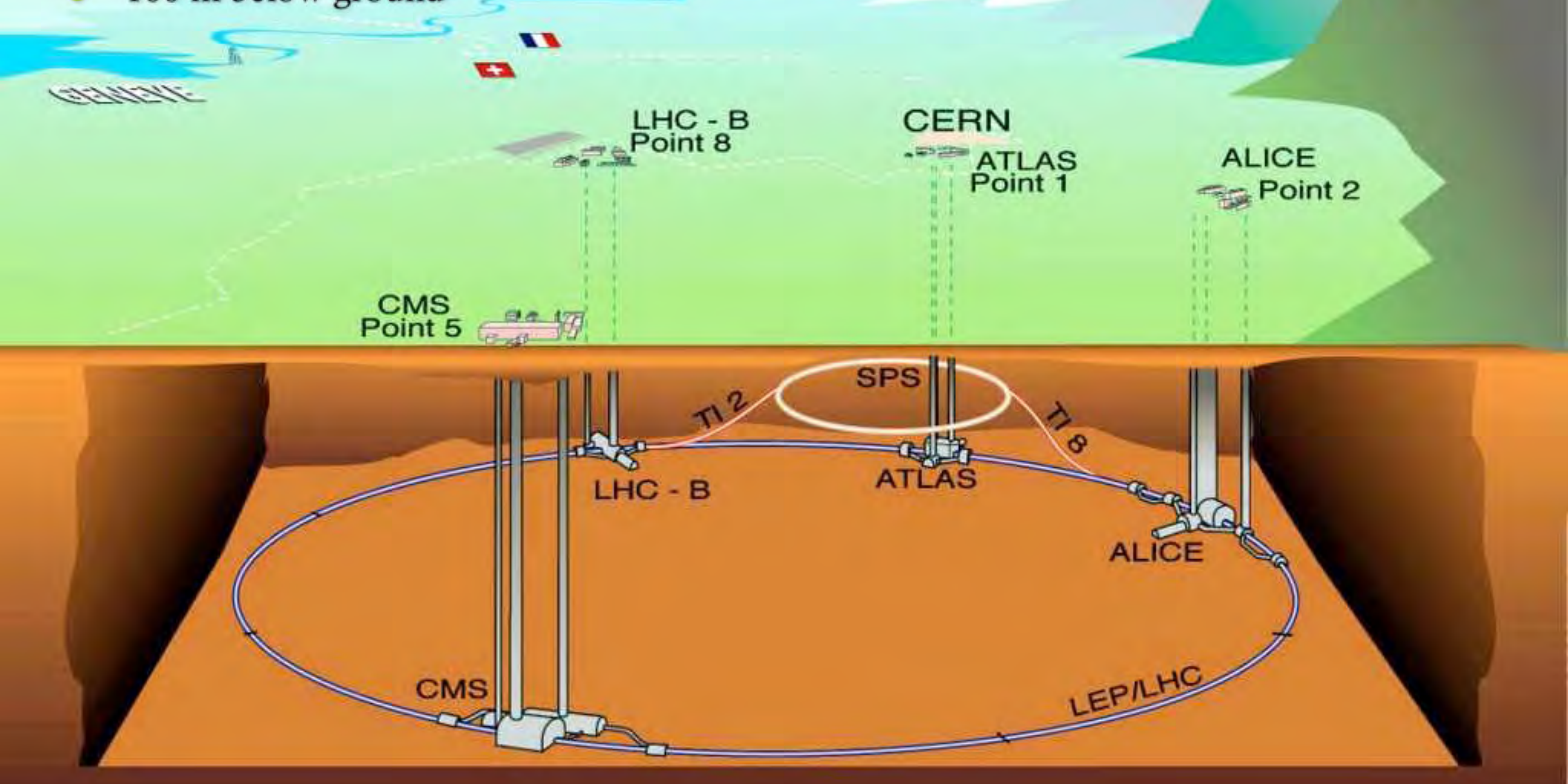
- Mass has been excluded below 900 GeV
  - Nearly exhausts Tevatron's energy reach
  - LHC should easily see 1.5 TeV in early data, eventual reach beyond 4 TeV
  - New challenges to measure 500+ GeV muons
- Expected properties
  - σ is an exponential function of mass
    - ~ 470 fb for 1 TeV
  - Width 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



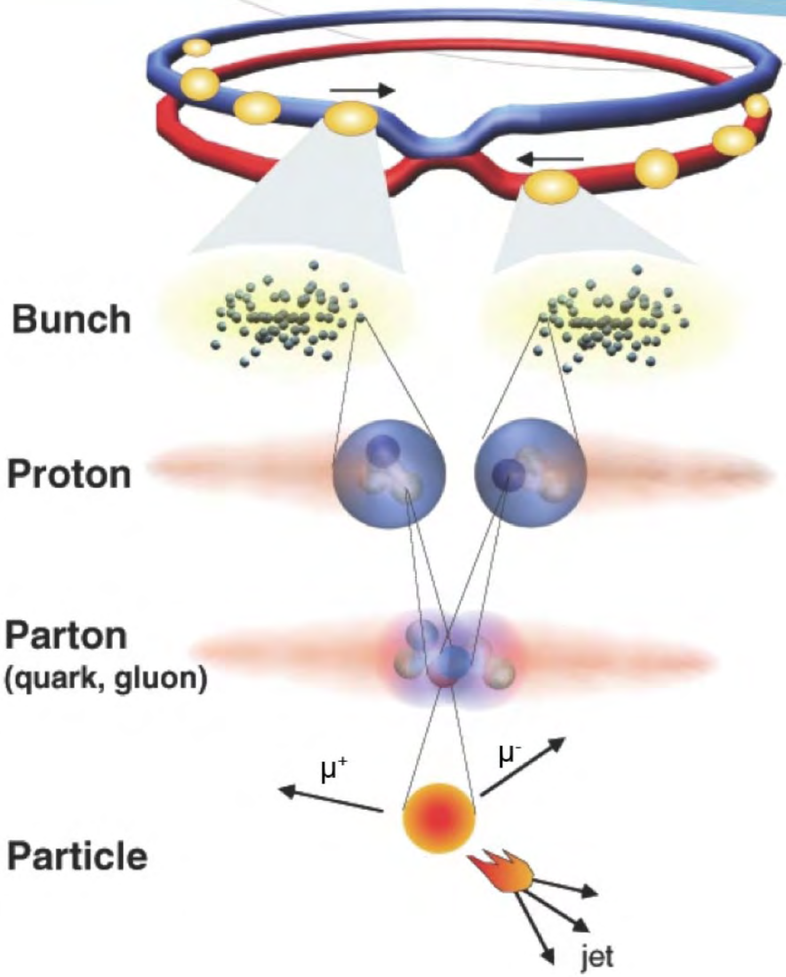
$$\sigma_{Z'} = 780 \frac{c_{Z'}}{s} e^{\frac{-32 M_{Z'}}{\sqrt{s}}}$$

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}

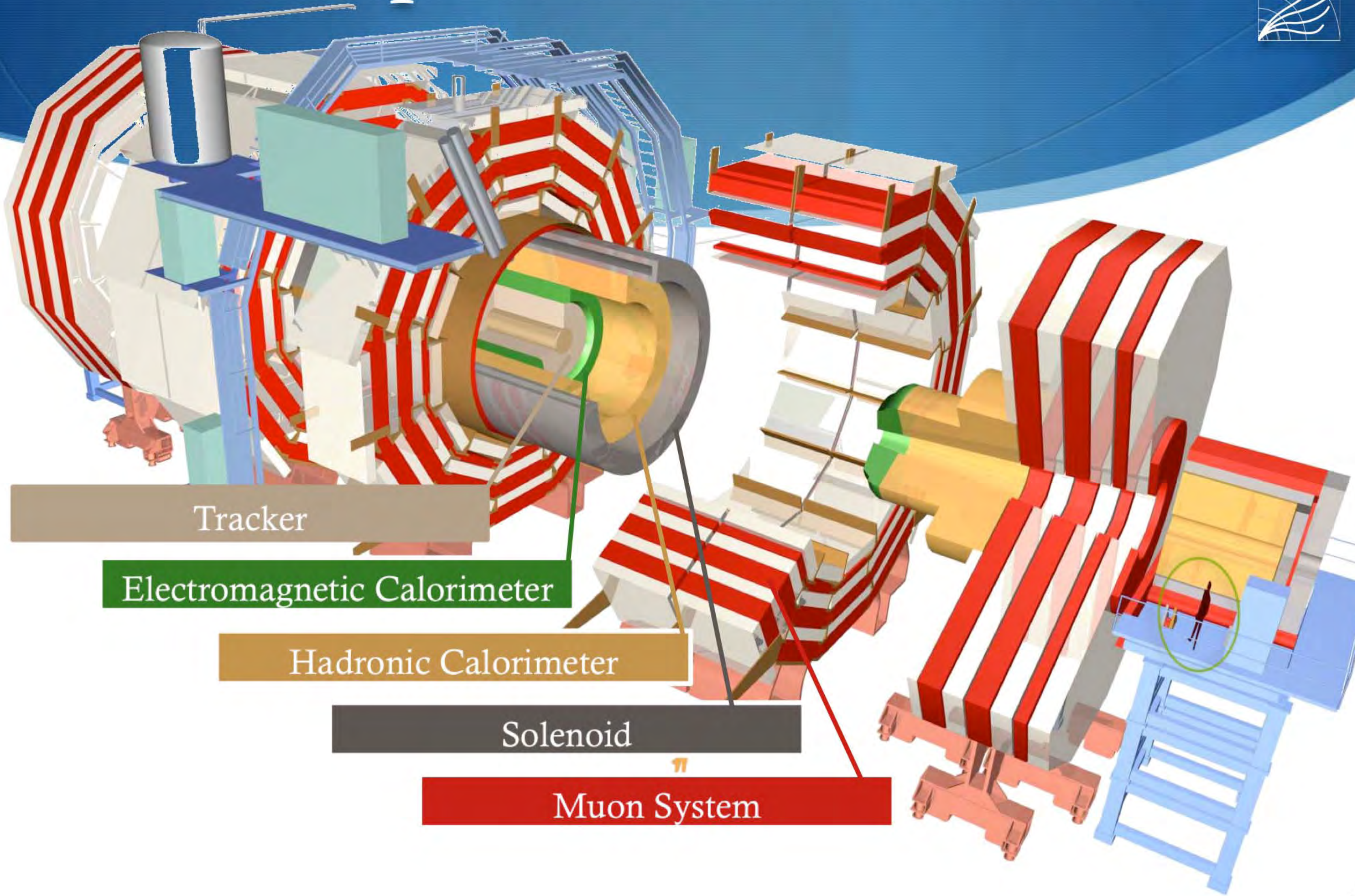


Proton Collisions

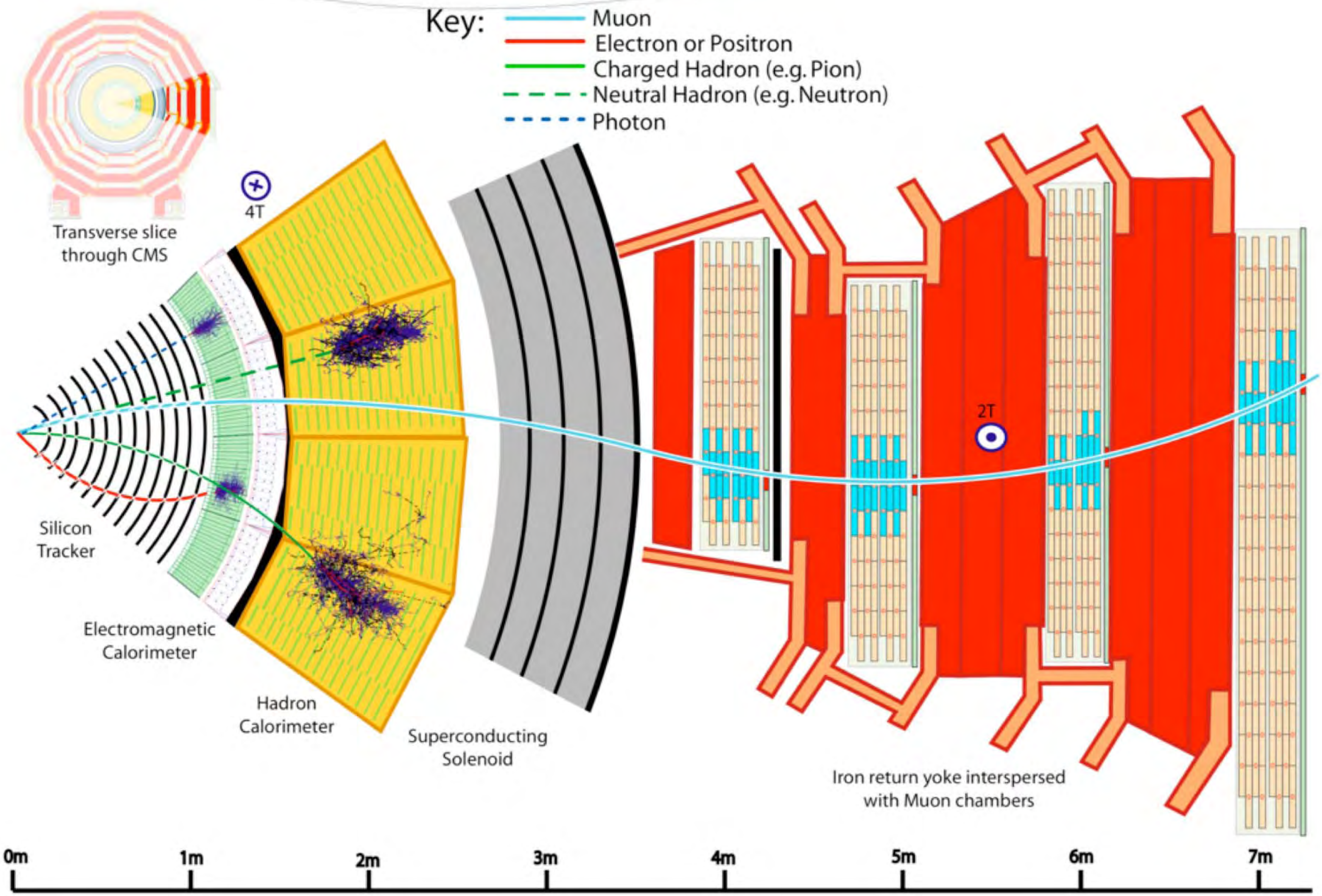


- 2835 bunches/beam
- 10^{11} protons/bunch
- Design luminosity = 10^{34} cm^{-2} s^{-1}
- Crossing rate = 40 MHz
- 10^9 collisions/second
- $\sigma_{Z'}$ ~ 470 fb for $m_{Z'}$ = 1 TeV
  - 47 events per 100 pb^{-1} of data
  - 1 in 10^{11} interactions!
  - 1 event every 4 minutes at design luminosity

Compact Muon Solenoid



Particle Detection in CMS



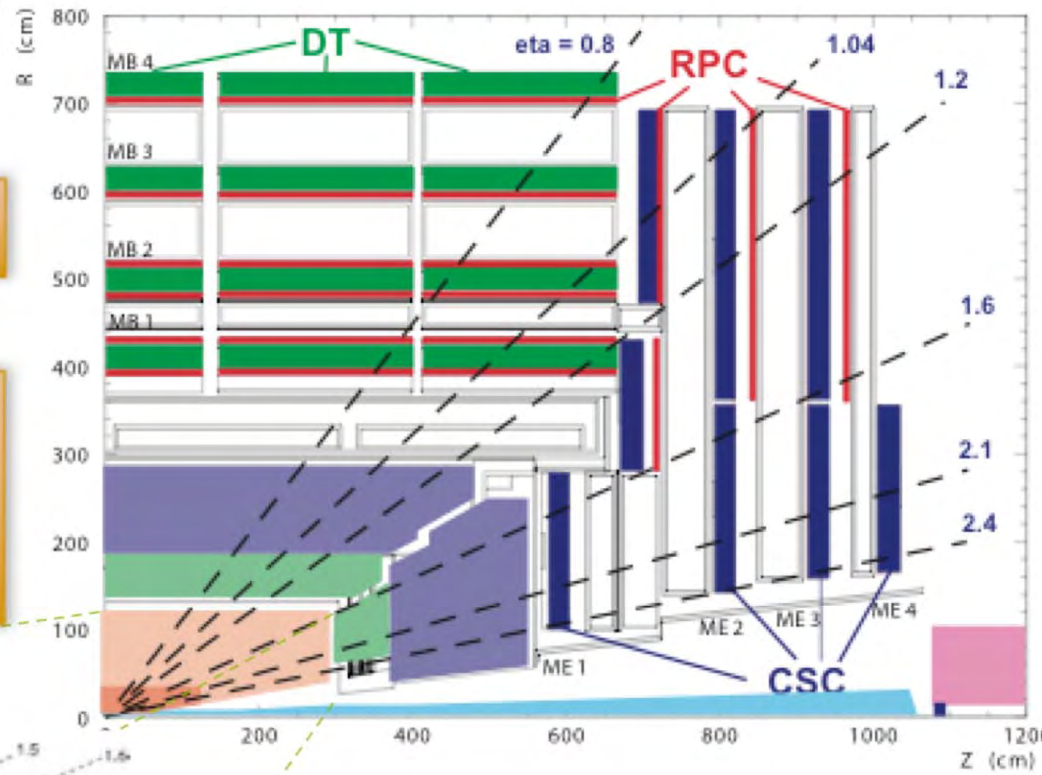
Endcap Discs: Designed,
assembled & installed by Wisconsin

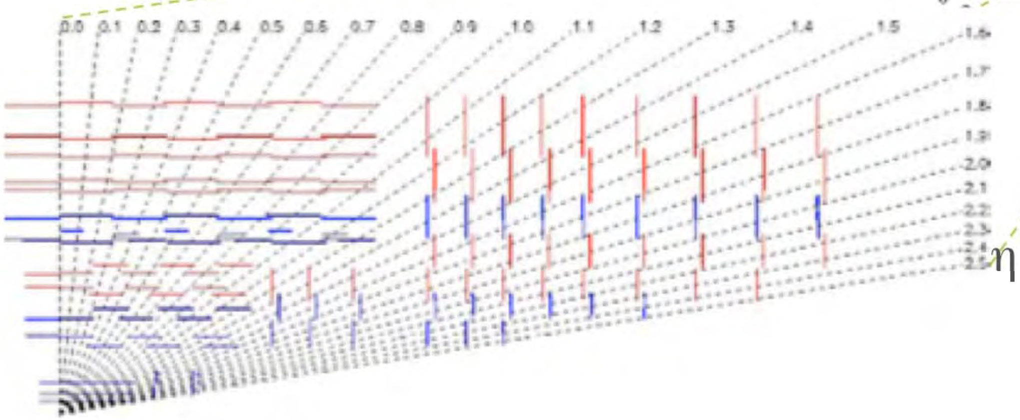
Tracker and Muon Layout

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

Full 2π coverage in φ

Coverage in η:
- to 2.5 in tracker
- to 2.4 in muon system

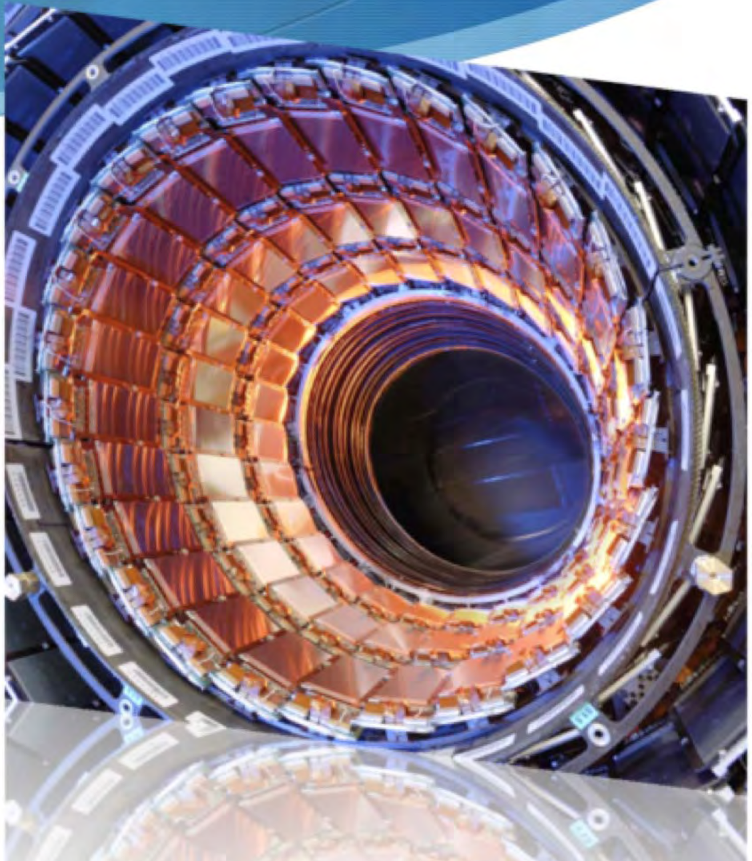




High efficiency expected over full range in η and φ

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%

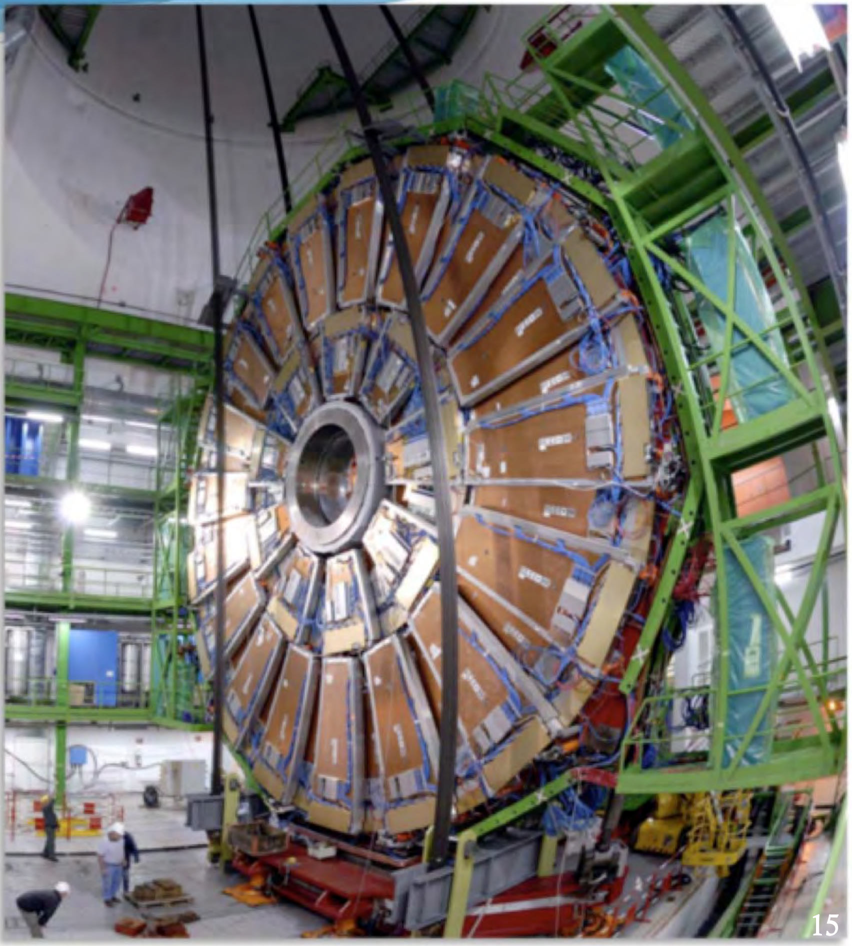


$$\frac{\delta p_t}{p_t} = \left(\frac{p_t}{TeV} 15\%\right) \oplus 0.5\%$$

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 λ of material before muon system, another 10 λ 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

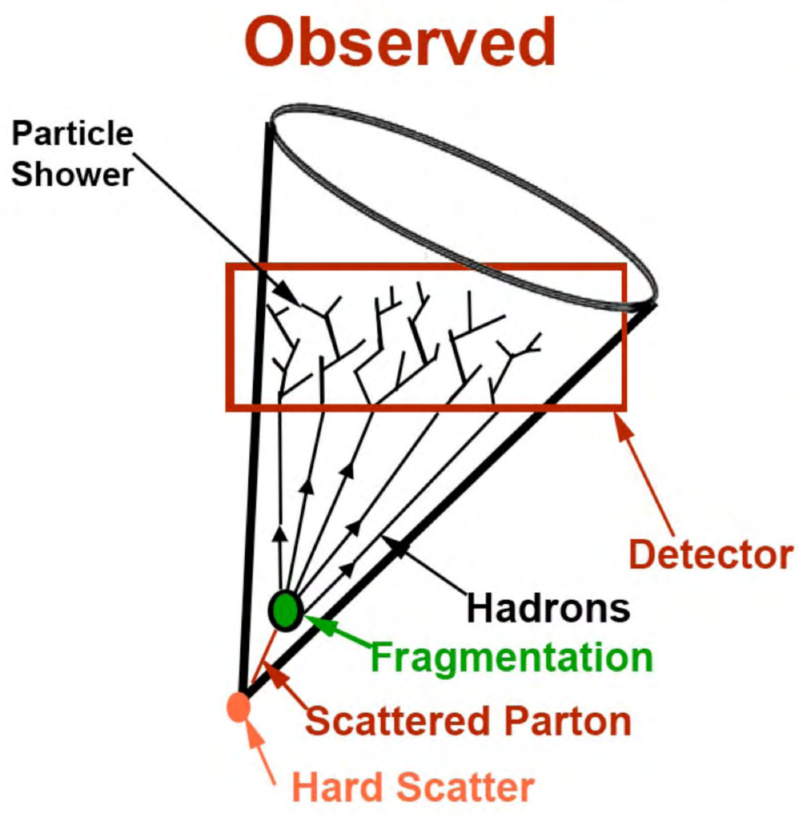
- Geant4
- Passage of particles through matter

→

Event Reconstruction

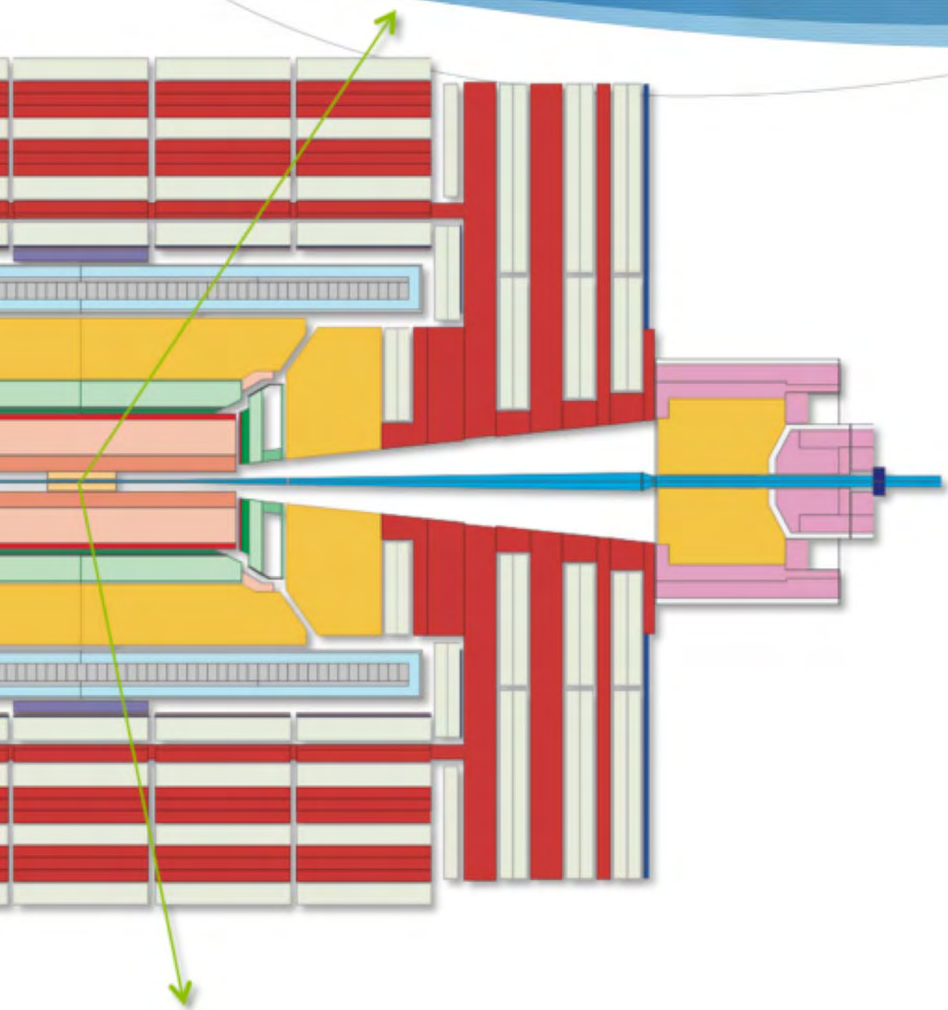
- CMSSW 1.6.8
- Pieces together physics objects

Generation of Physics Events



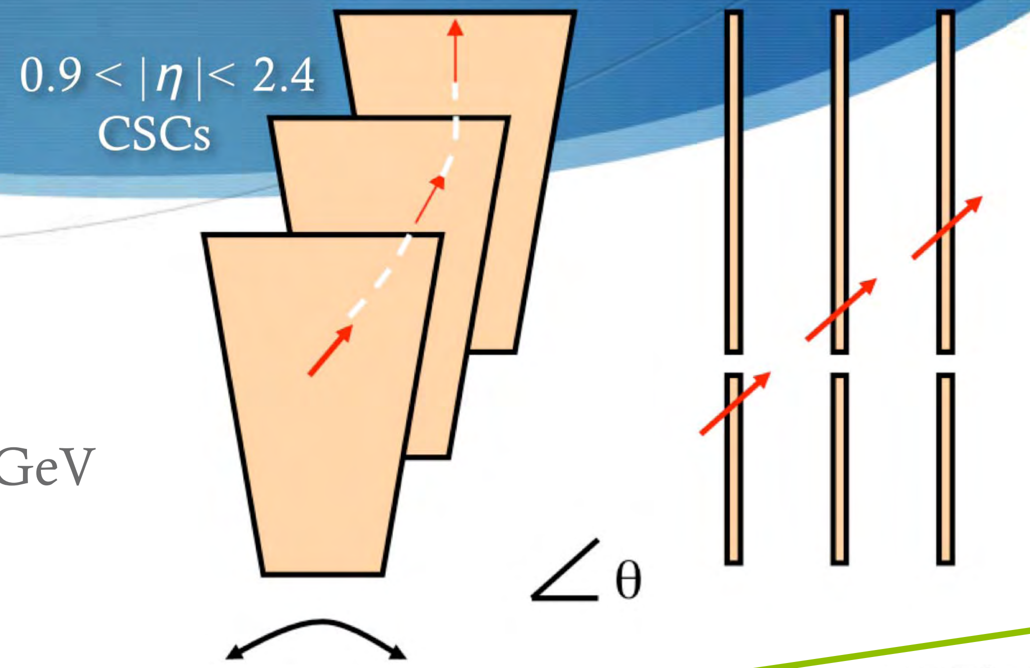
- Hard scattering matrix element calculations
  - Alpgen (fixed order) specifically for boson + jets processes
  - Pythia (leading order) for others
- Subsequent jet evolution using Pythia
  - Underlying event
  - Jets from initial and final state radiation
  - Fragmentation and hadronization of partons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

Detector Simulation

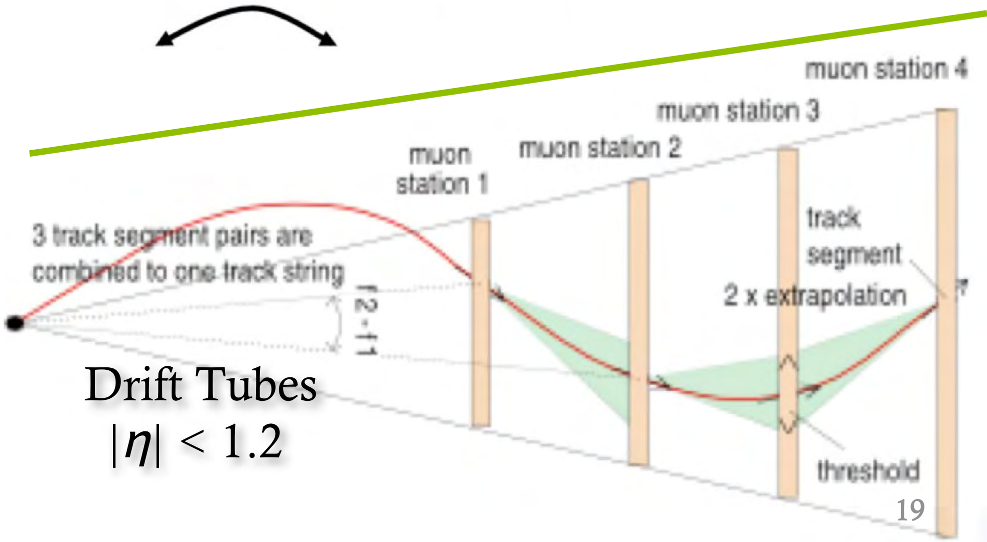


- Geant4 simulates the passage of particles through the detector
- Signal digitization is simulated for all components of detector, readout, and trigger.
- Key to understanding (eventually from data):
  - Realistic rates for mis-ID of hadrons as muons
  - Realistic detector resolutions
  - Efficiencies

Muon Reconstruction

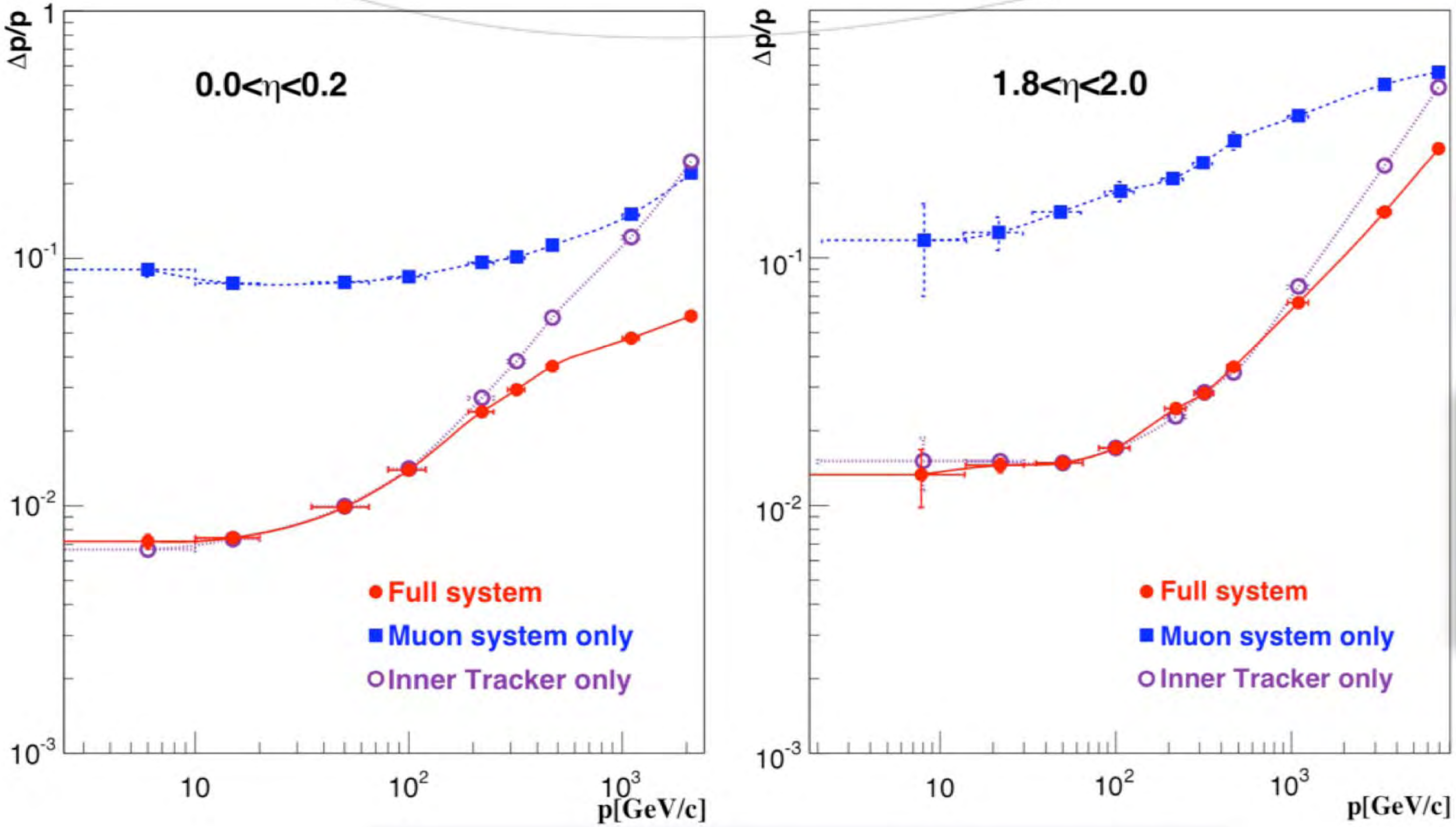


- Trigger
  - Early muon system info gives independent p_T measurement
  - Muons from Z' easily pass 20 GeV threshold
- Full reconstruction
  - Produce muon system tracks
  - Independently produce tracker system tracks
  - Perform a global fit to tracker + muon system hits



Momentum Resolution

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



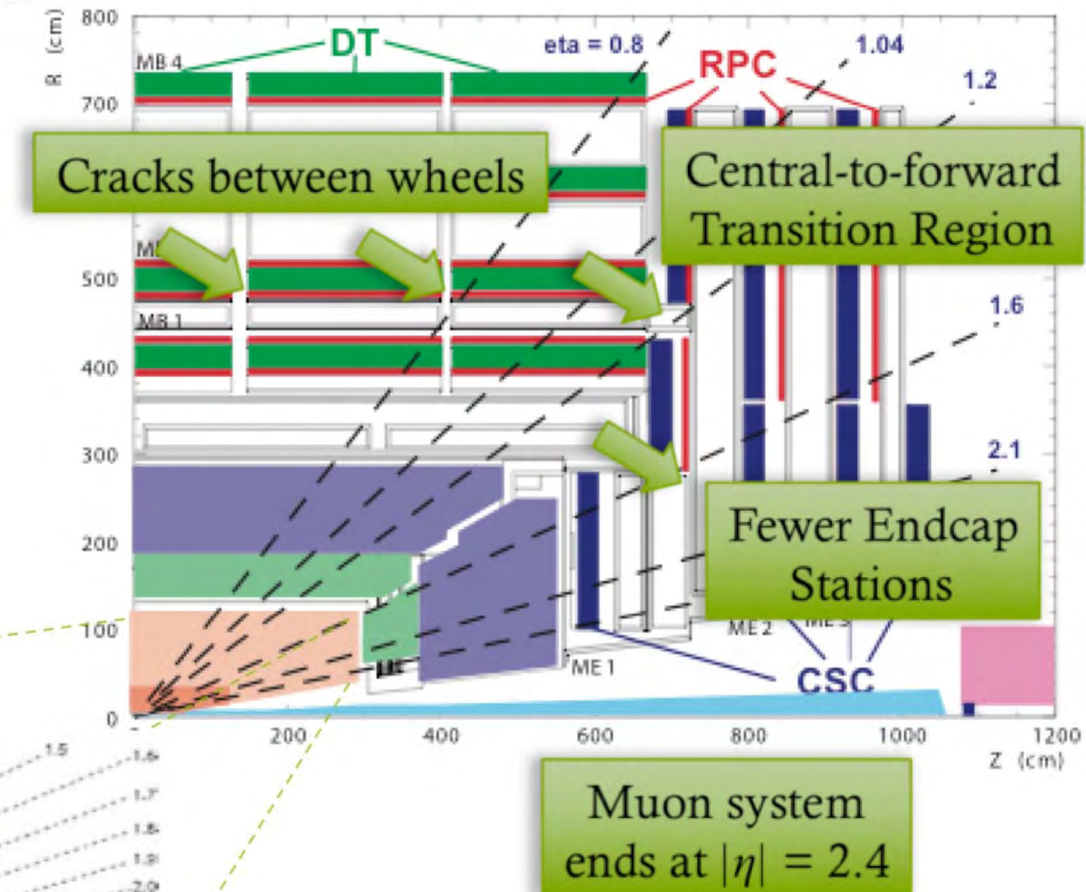
Usable resolution up to 2 TeV!

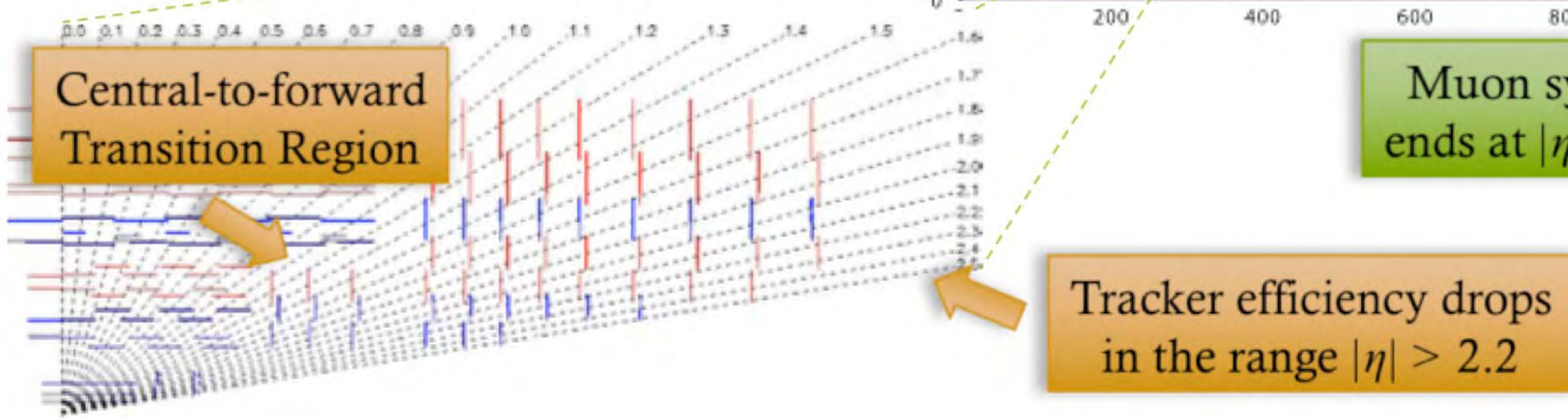
Experimental resolution on the order of larger Z' width predictions

MC simulation of isolated single muons

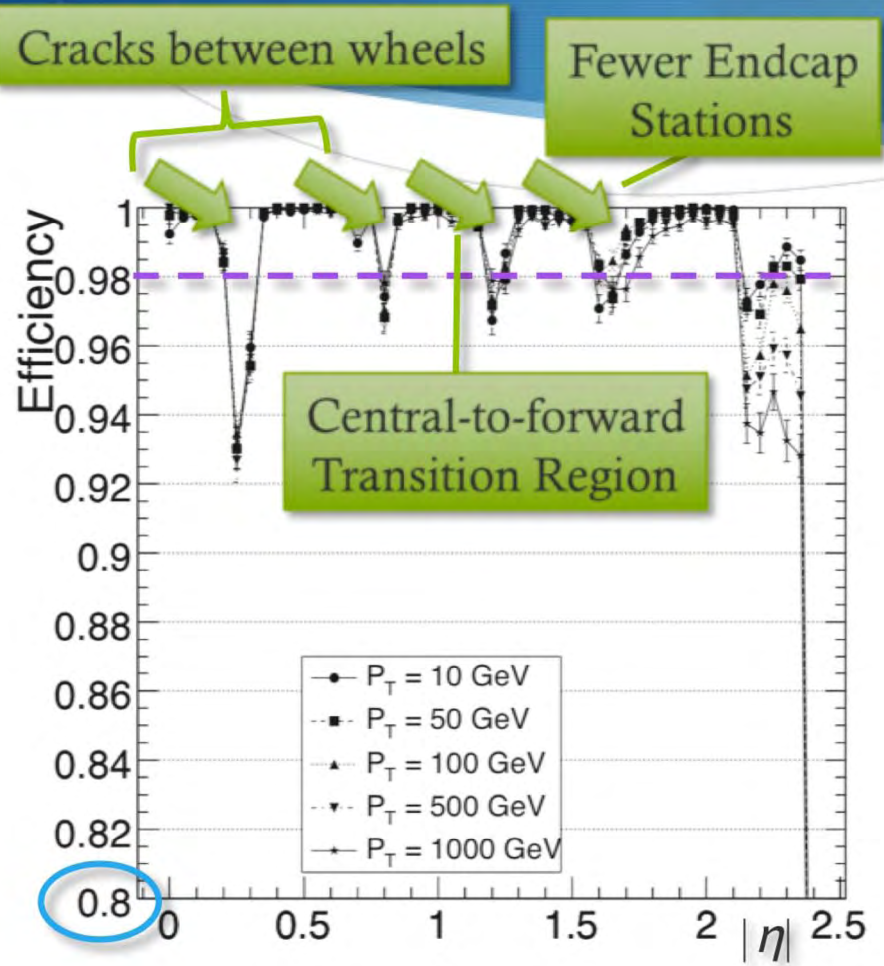
Sources of Inefficiency

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

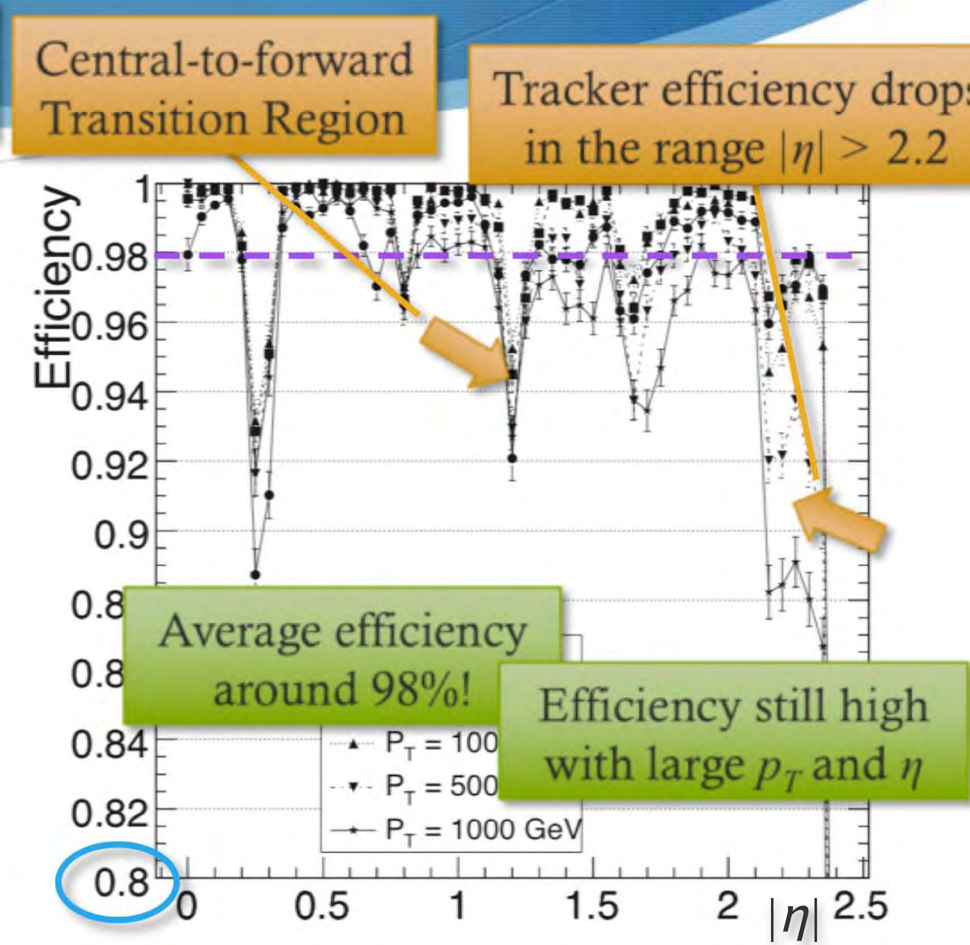




Reconstruction Efficiency



Muon system alone



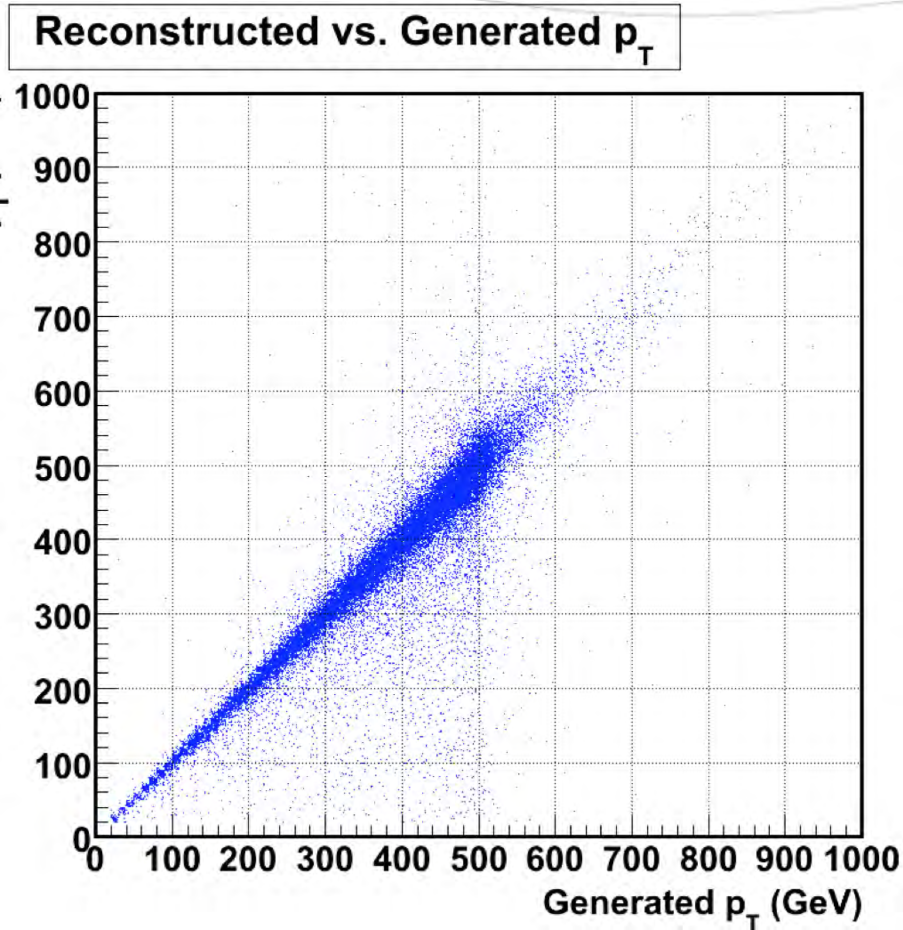
Combined fit from muon system + tracker

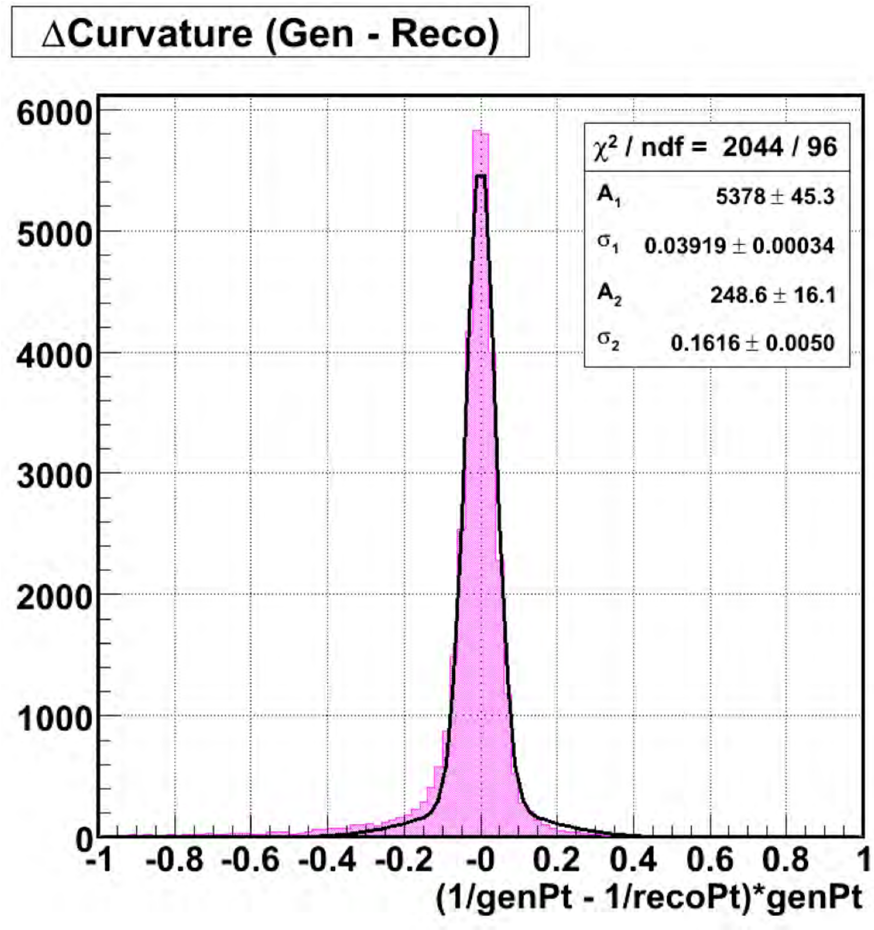
Outline of Analysis

- Simulated Z' data
  - $m_{Z'} = 1$ TeV, just beyond Tevatron limit
  - Z'_{SSM} with SM couplings included in Pythia
  - One of the highest σ 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

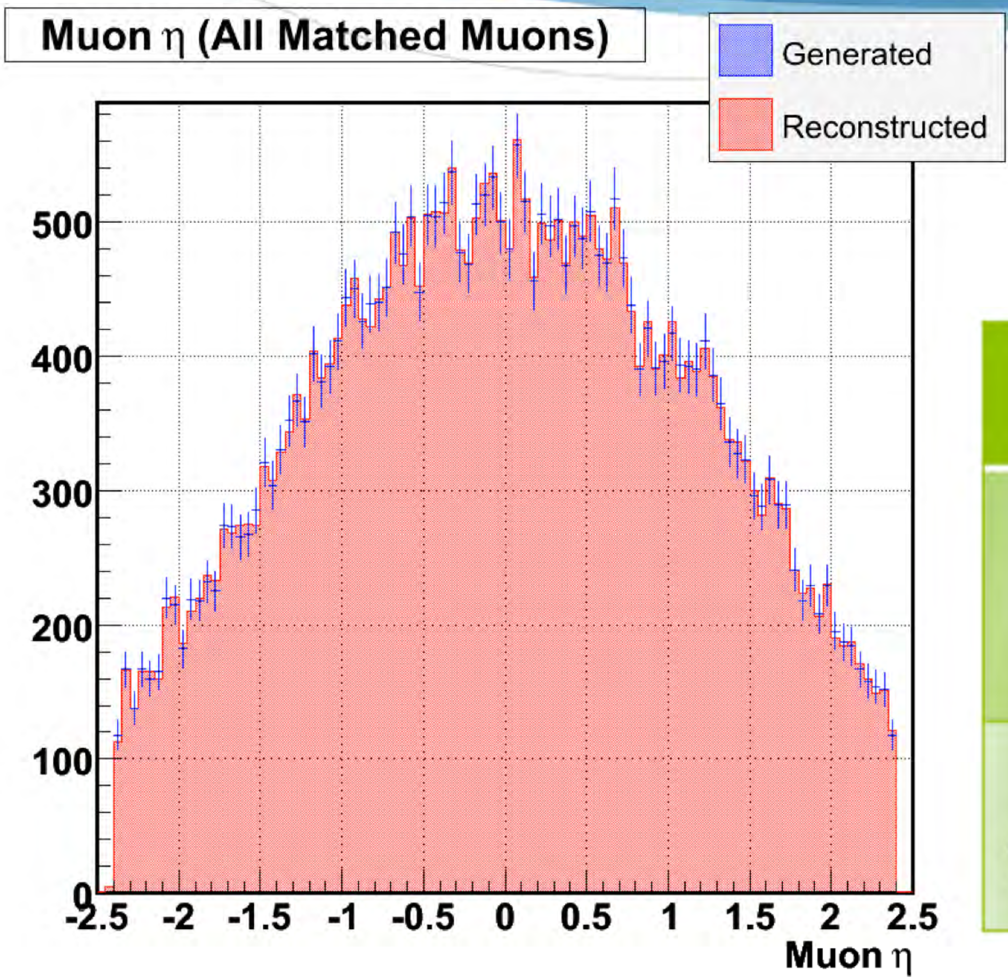
Gen/Reco Muon Matching

4% p_T resolution agrees with previous simulations





Fiducial Cuts

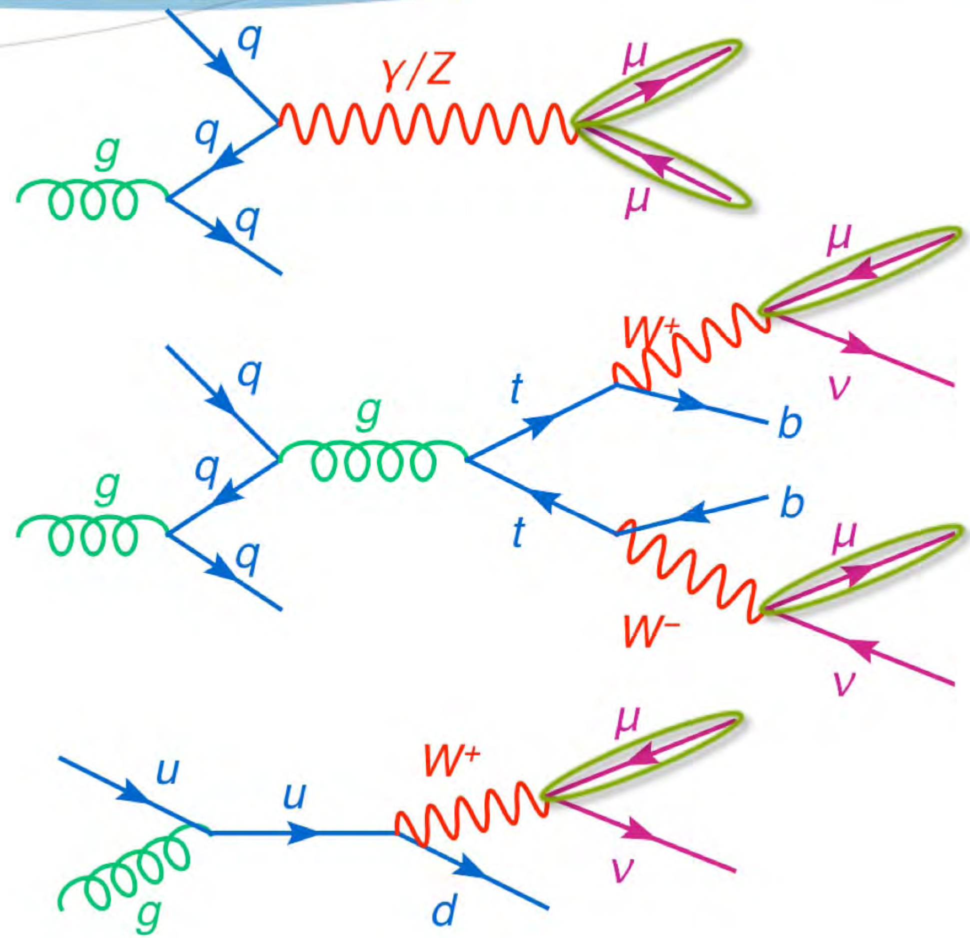


Distribution becomes more central with greater mass

Requirements	Yield/ Efficiency
Fiducial Cuts (generator quantities) $p_T > 20$ GeV $\lvert\eta\rvert < 2.4$	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}

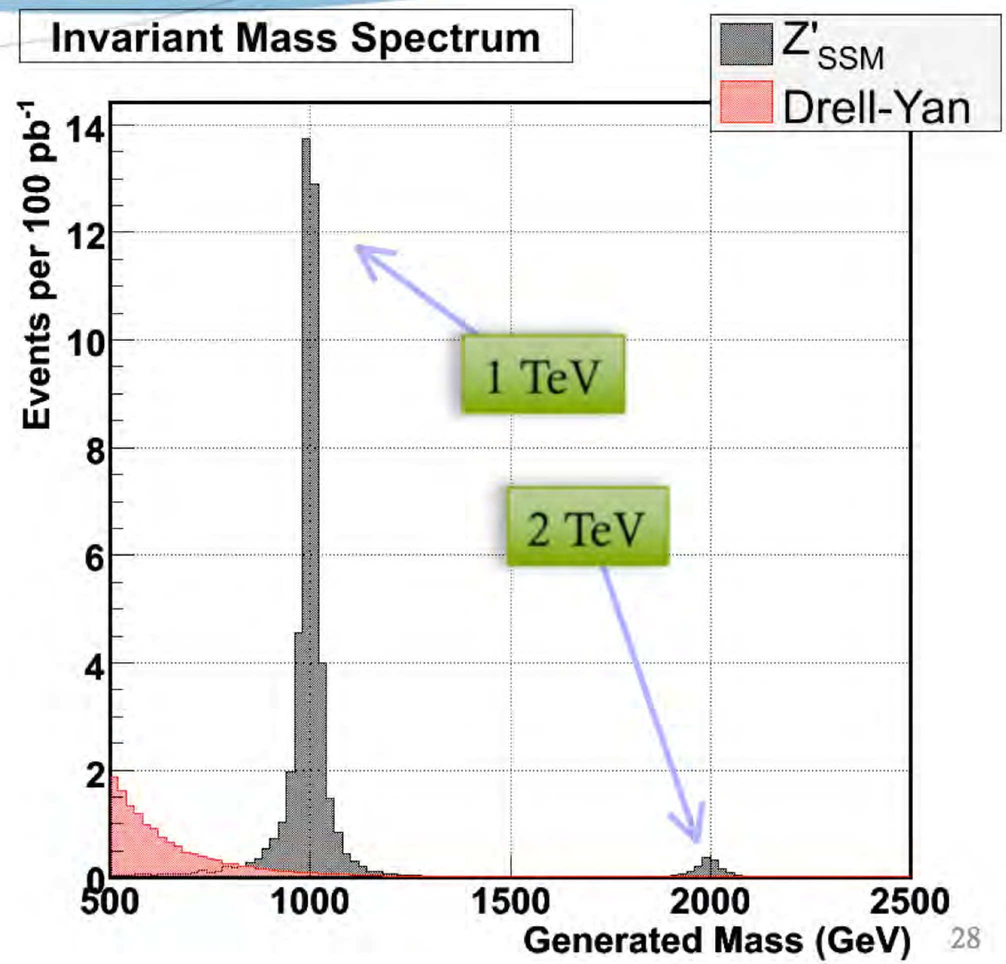
Signal	Drell-Yan	Top-antitop	Boson+jets
Peak in mass distribution	Peak at much lower mass	No peak	No peak
Muons isolated in tracker	Muons isolated in tracker	Muons produced with jets	Muons produced with jets
Muons in 500 GeV range (48 pairs)	Few muons in the 500 GeV range (7 pairs)	Muons in 80 GeV range	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

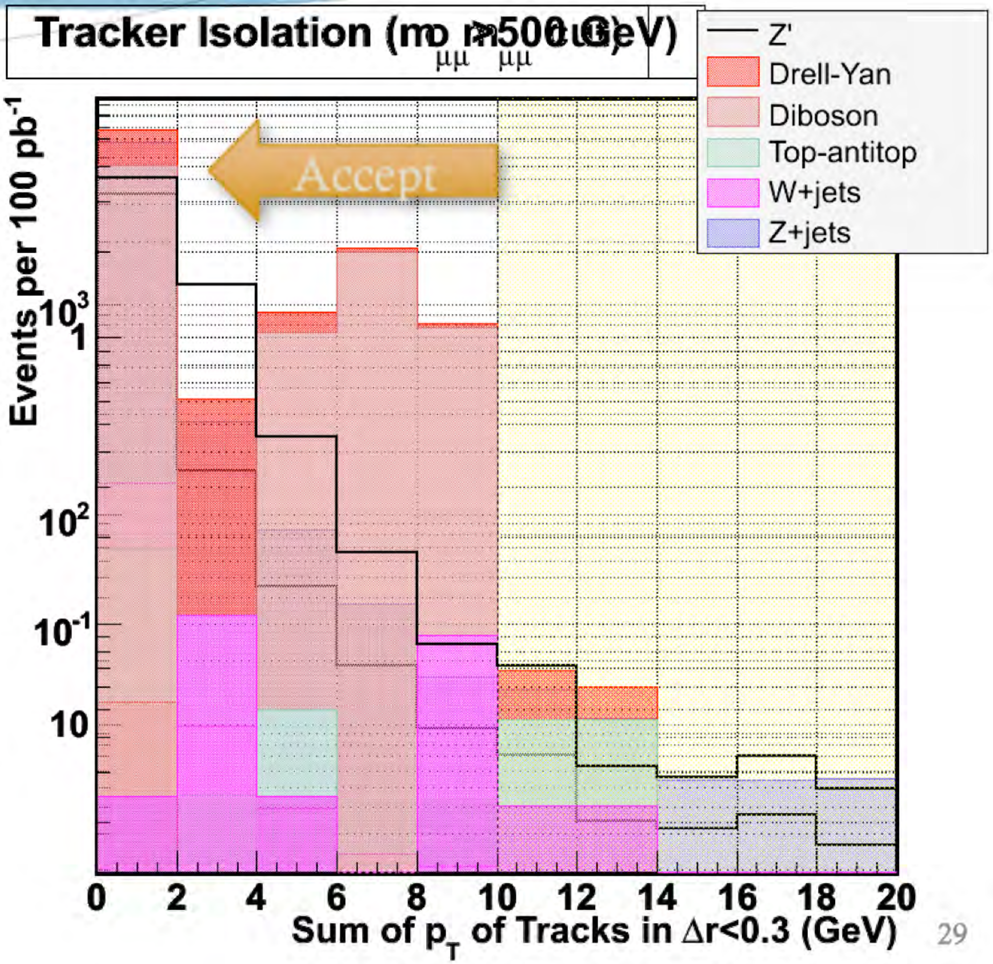


Muon Isolation

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

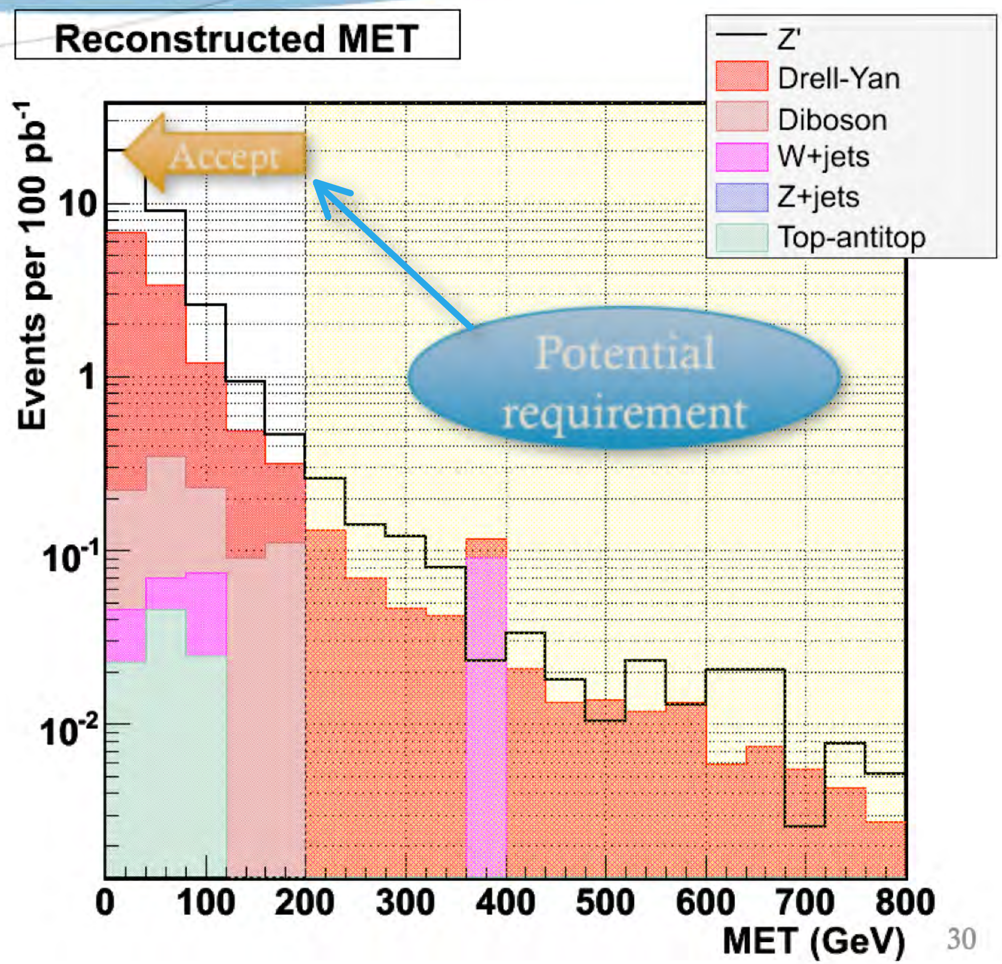
$$\Delta r = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$$



Missing E_T

100 pb^{-1}

May be useful for suppressing *W*+jets



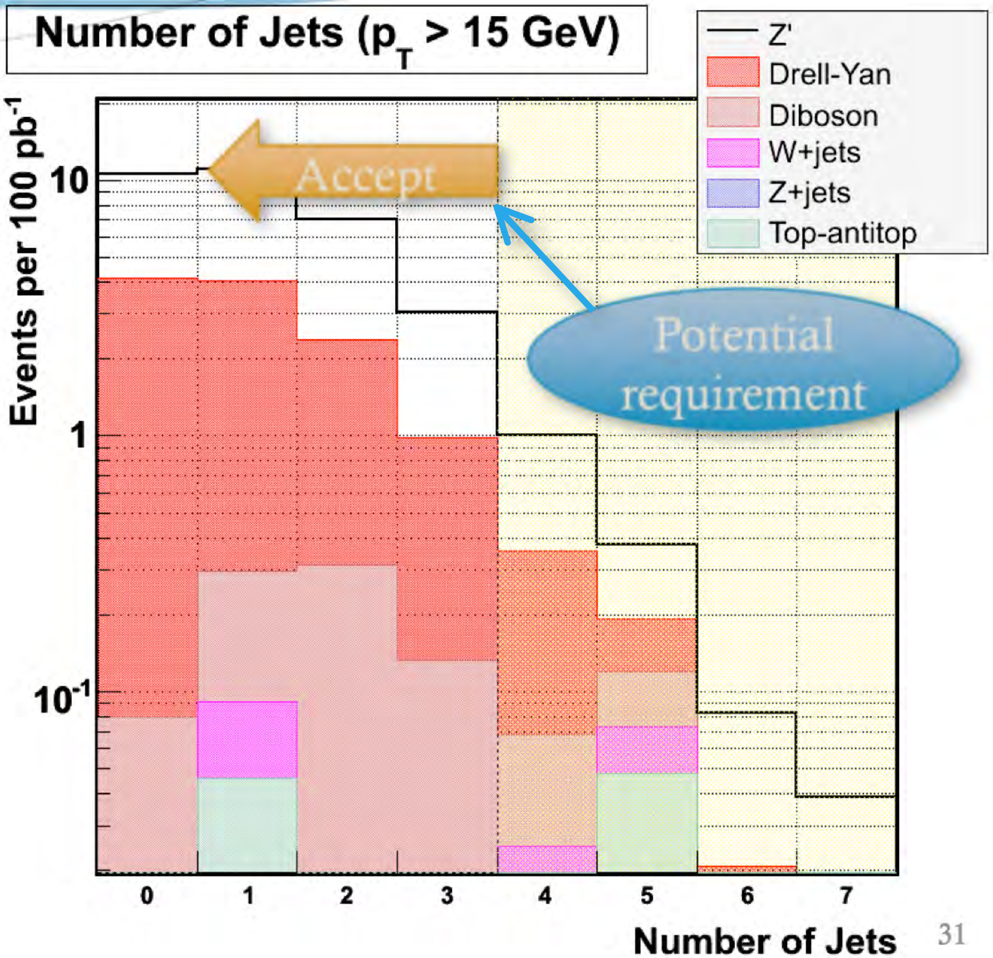
- Large false MET found for all samples in reconstruction
- For lower $\sigma_{Z'}$:
  - Potential requirement of MET below 200 GeV

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}

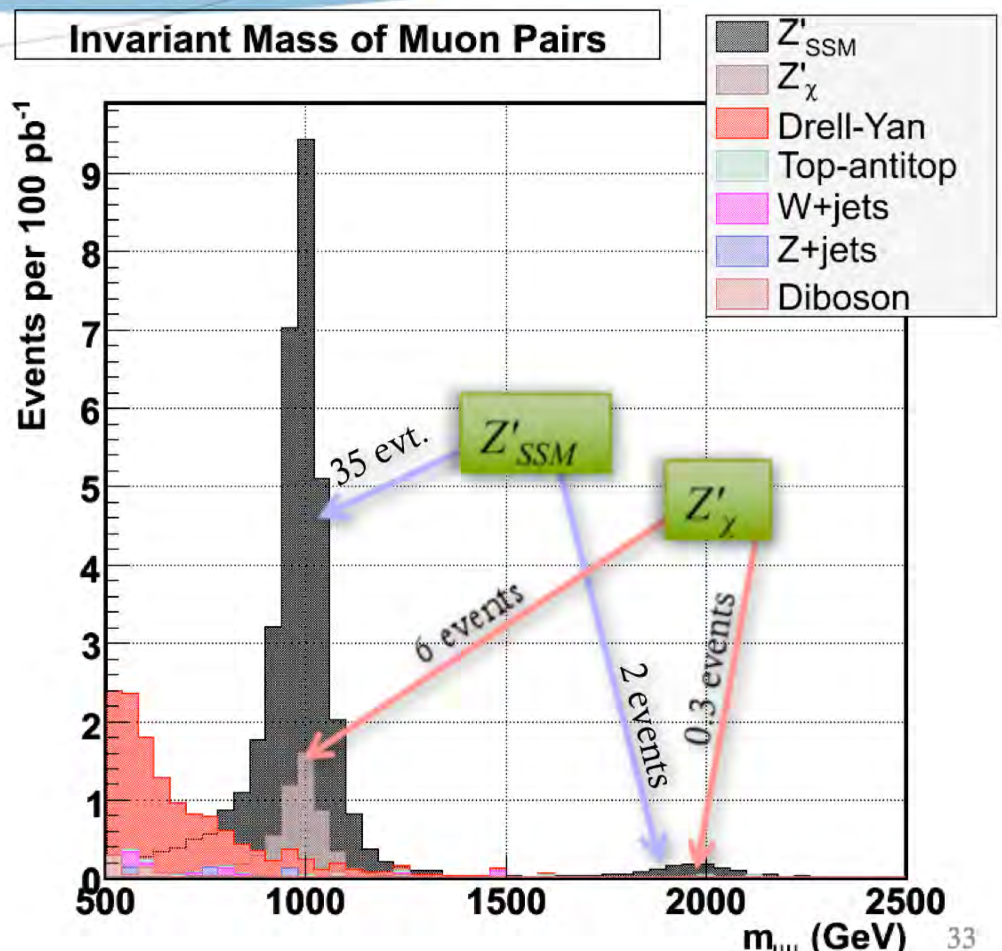
	1 TeV Z′	Drell-Yan	Top-antitop	Boson+jets
Acceptance, Reconstruction, $m_{\mu\mu} > 500$ GeV	35.2 (78% of generated)	12.0	.14	.34
Muons isolated $\Sigma p_T < 10$ GeV	35.0 (75% of generated)	11.9	.09	.29
MET < 200 GeV	33.1	11.1	.09	.10
Fewer than 4 jets	31.6	10.7	.05	.05

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'_{χ} is from an E_6 model
- Other Z' models have a much lower σ 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