A Search for Exotic Particles Decaying to *WZ* in *pp* Collisions at 7 TeV

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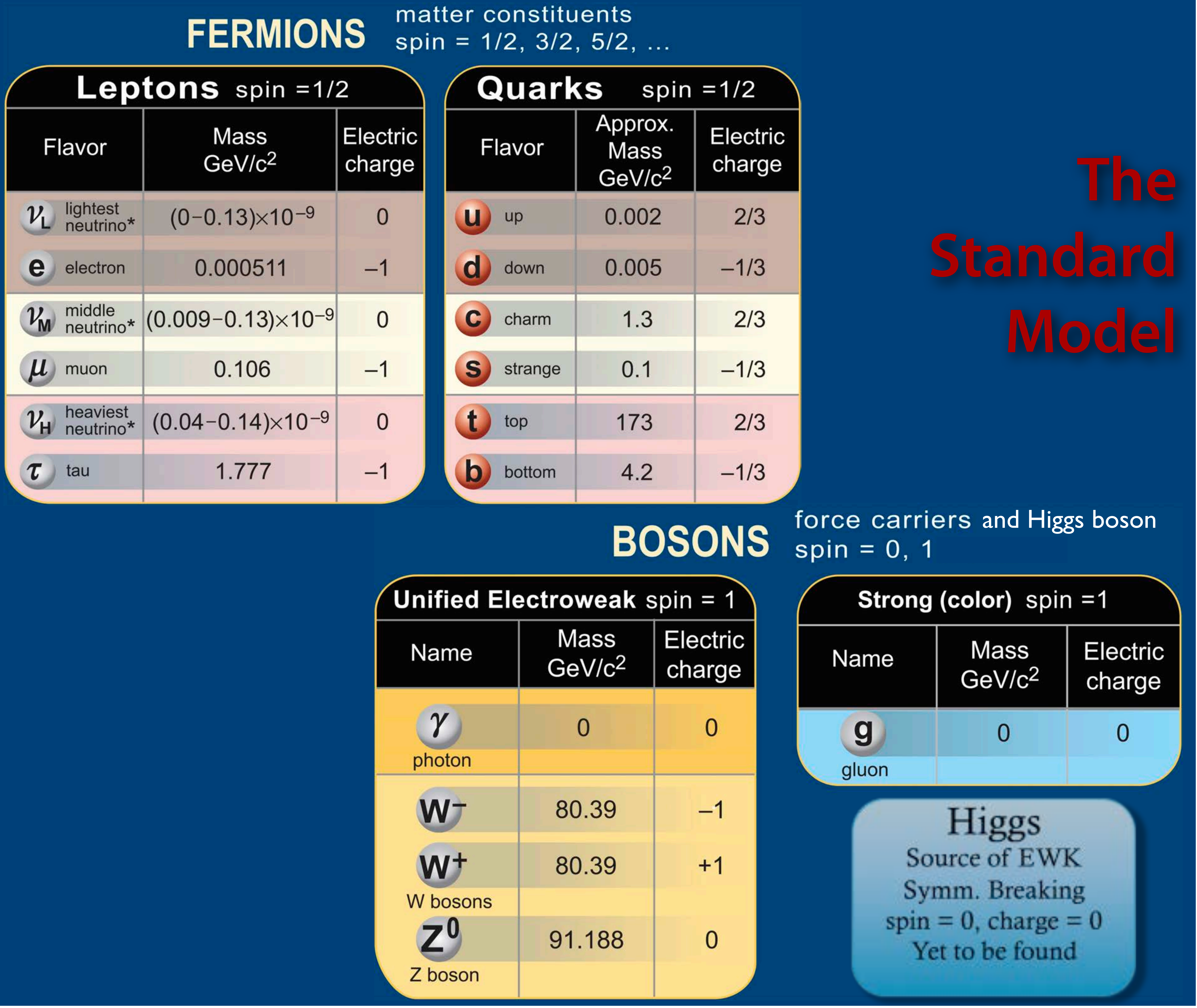
Theoretical Background

The Standard Model



FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c²	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/c²	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

force carriers and Higgs boson
spin = 0, 1

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ 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/c²	Electric charge
g gluon	0	0

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

Matter made up of 6 fermions, 6 quarks
* neutrinos have small non-zero mass
* quarks have color, form mesons and hadrons save for the top
Bosons carry forces
* W and Z boson are heavy, which requires an explanation
* Higgs not yet discovered, but expected to give mass
Strong force binds together nuclei, EM binds together atoms, weak explains nuclear processes

The Standard Model

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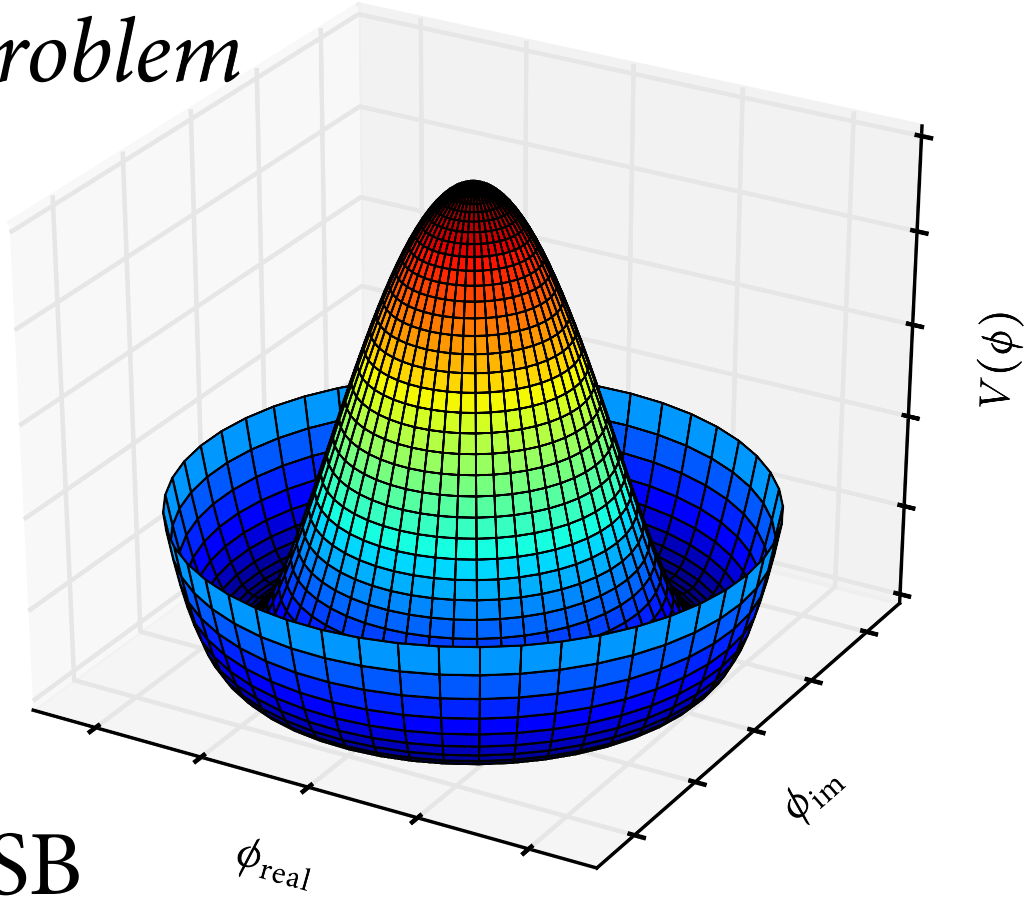
Beyond the Standard Model

In the SM, Higgs boson provides mass to *W*, *Z*, and fermions, but Elementary Higgs models...

- don't resolve the *hierarchy problem*
- are silent on *flavor physics*
- are not *dynamical*
- are *unnatural*
- are *trivial*



Compositeness theories

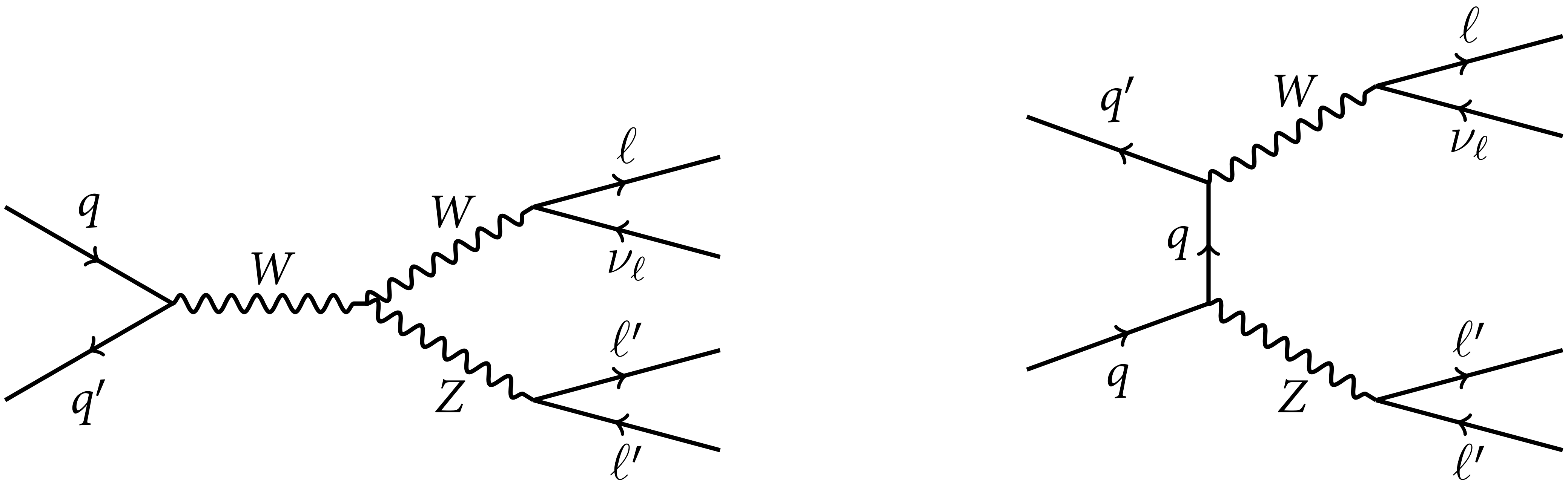
- Can provide *dynamical* EWSB while resolving naturalness, hierarchy, and triviality problems

Unification theories

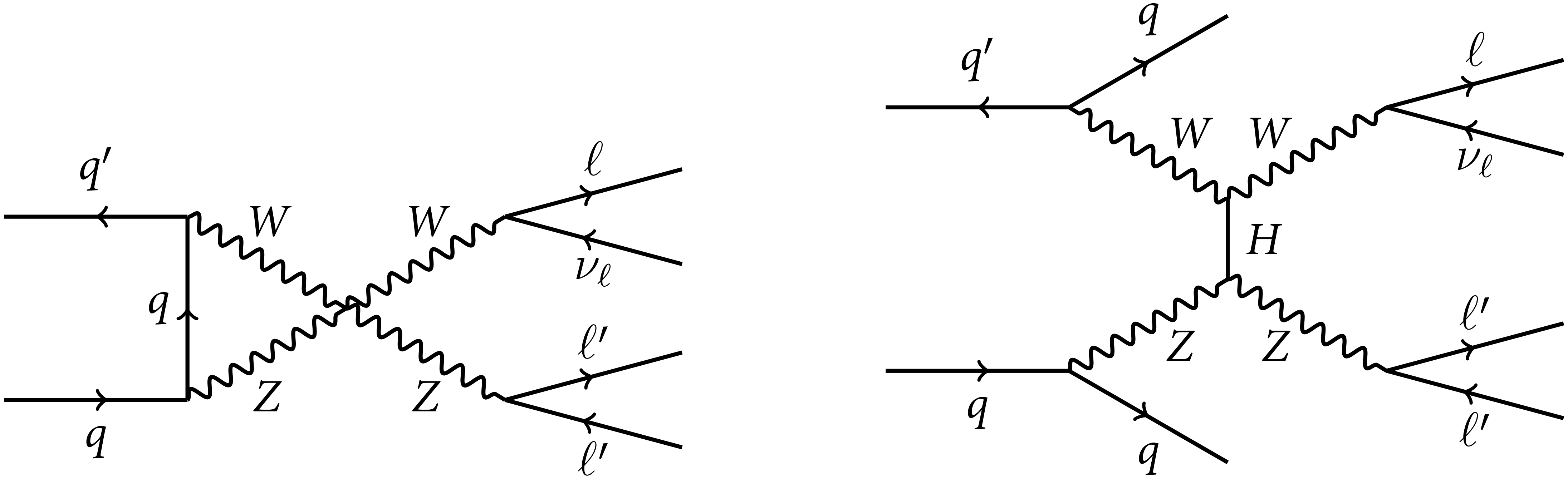
- SM + SU(2) ⇒ Larger gauge group including *W*'

* Hierarchy - vast gap between EWK (10^2) and gravity/Planck scale (10^19)
* Flavor - silent on fermion generations, masses, mixing
* Dynamical - no prediction of the VEV
* Unnatural - fine-tuning necessary to prevent divergent mass contributions
* Trivial - Requires normalized charge is zero, cutoff scale within reach
Unification is aesthetic, can explain charge symmetry of e- and p+

Production of *WZ*



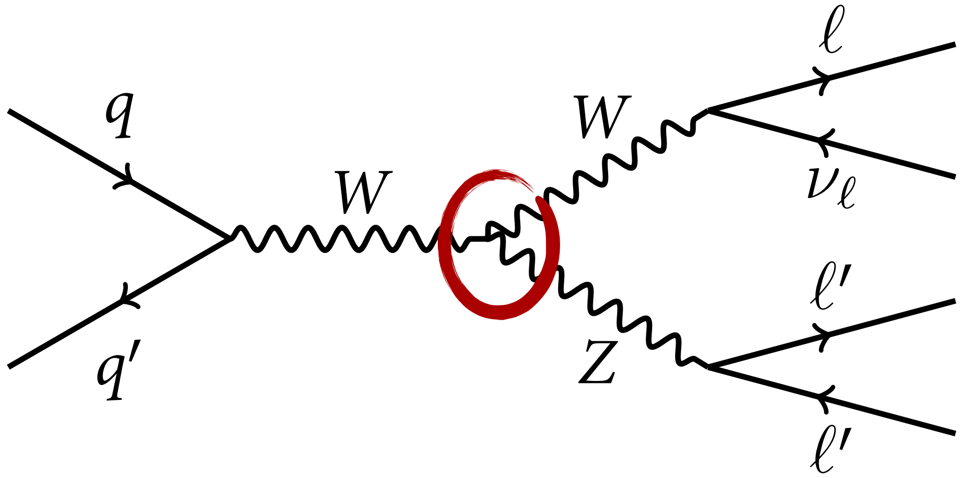
(a) *s*-channel (b) *t*-channel



(c) quartic scattering (d) Higgs-mediated scattering

Why is the diboson sector interesting?
s-channel involves TGC
Higgs scattering necessary to maintain unitarity
This mode has something to say about EWSB
TODO: Which of these dominates?

Production of *WZ*



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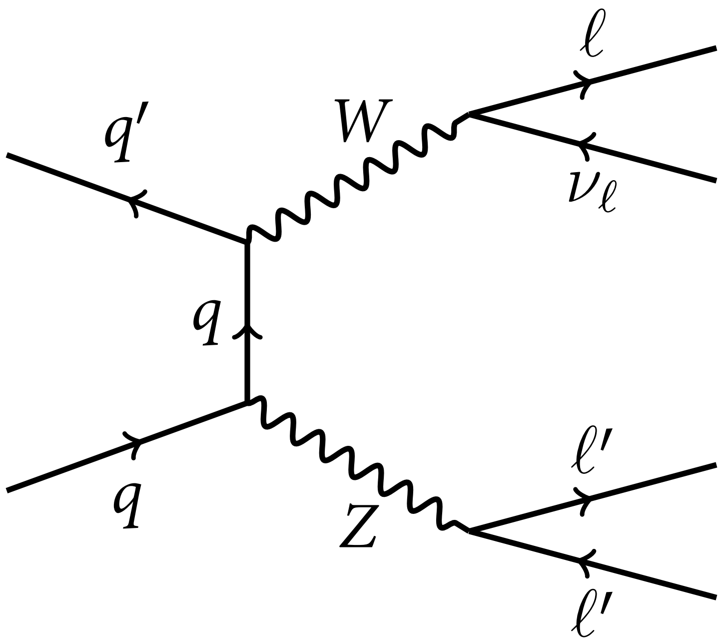
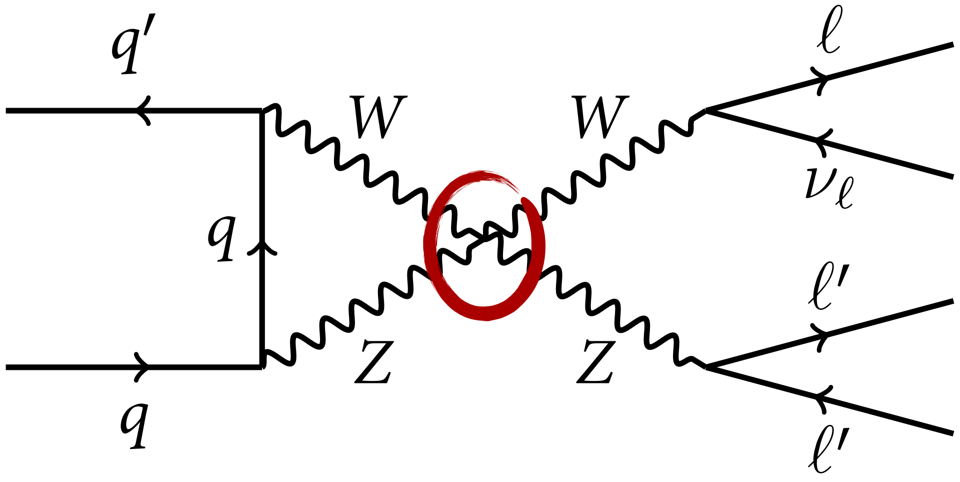
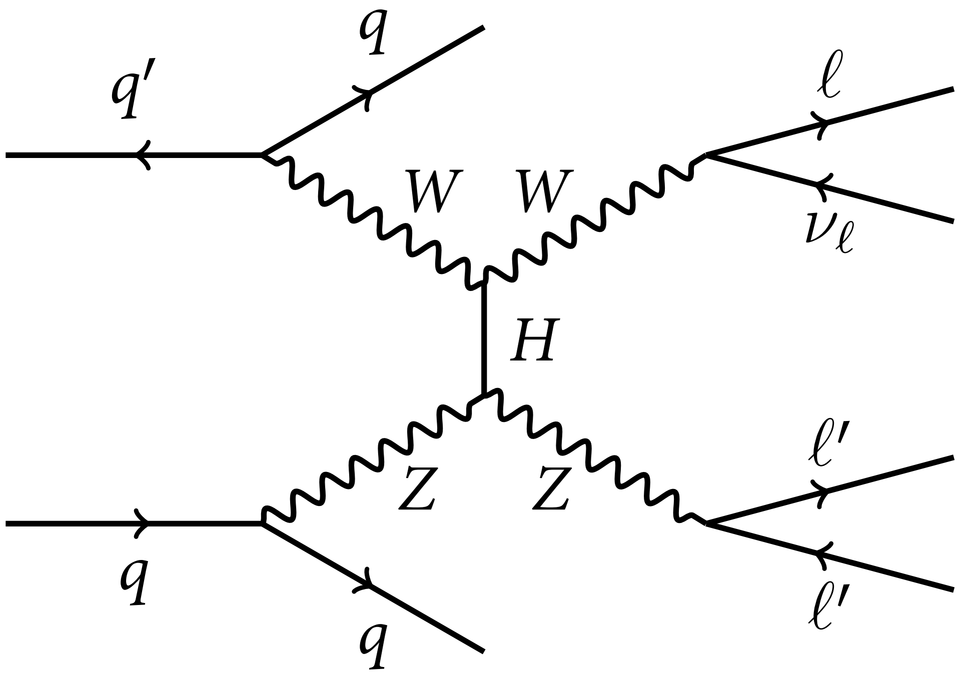


(b) *t*-channel



(c) quartic scattering



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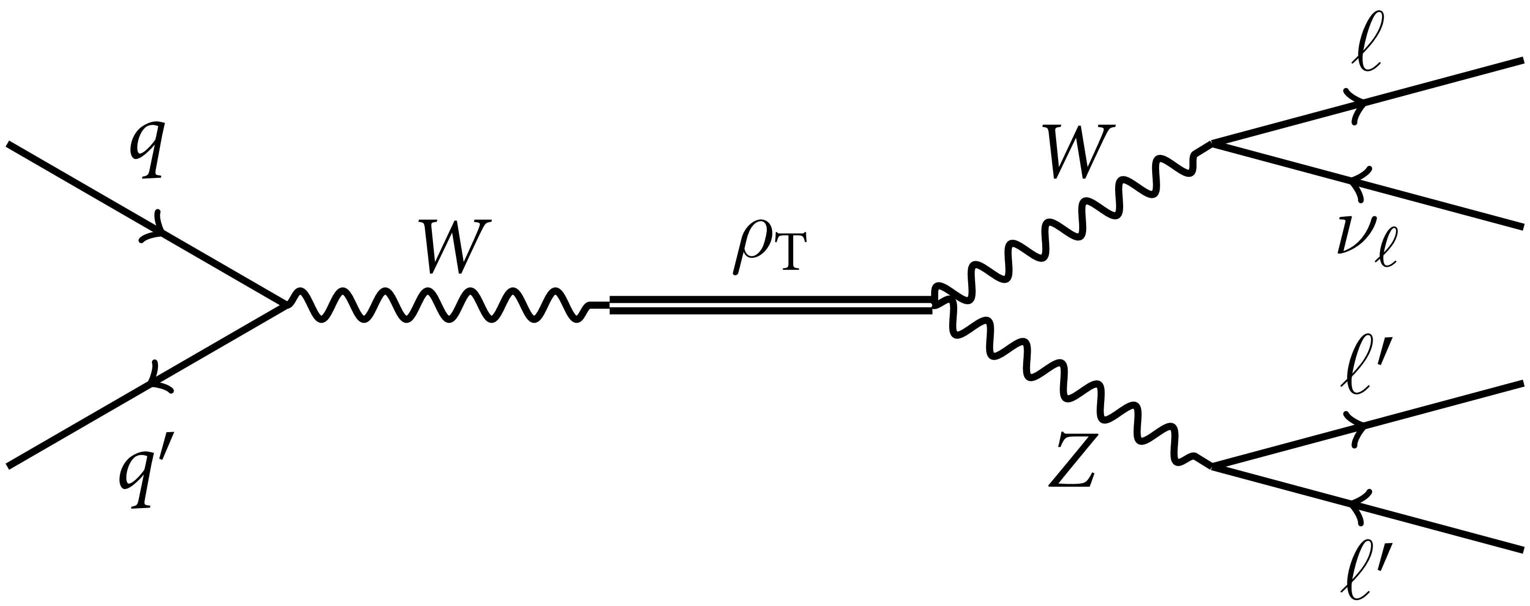
Low-Scale Technicolor

Technicolor is a compositeness theory hypothesizing a new interaction modeled on the strong force

- In QCD, the pion decay constant (93 MeV) reflects the scale of chiral symmetry breaking (~200 MeV)
- Likewise, the Higgs VEV (246 GeV) could reflect the scale at which α_{TC} becomes strong and condensates form

Low-Scale Technicolor involves a “walking” gauge coupling

- Generates realistic fermion masses
- Predicts a spectrum of new technihadrons detectable at LHC energies



Off-shell W decays to 2 techniquarks; that bound state decays to WZ
Technicolor is still viable even if we confirm a Higgs-like particle
* dynamical - the VEV~246GeV is the characteristic scale of the new interaction (like pion decay constant <-> Lambda_QCD)
* natural - eliminates scalars which need fine tuning
* asymptotic freedom necessarily non-trivial
* hierarchy explained by larger gauge group

Heavy Charged Vector Bosons (*W'*)

Extra dimension models (Kaluza-Klein)

- Postulate small, tightly curled extra dimensions
- A *W* or *Z* with quantized momentum in one of these dimensions appears to have additional mass
- Predicts a series of evenly-spaced *W'* and *Z'* states

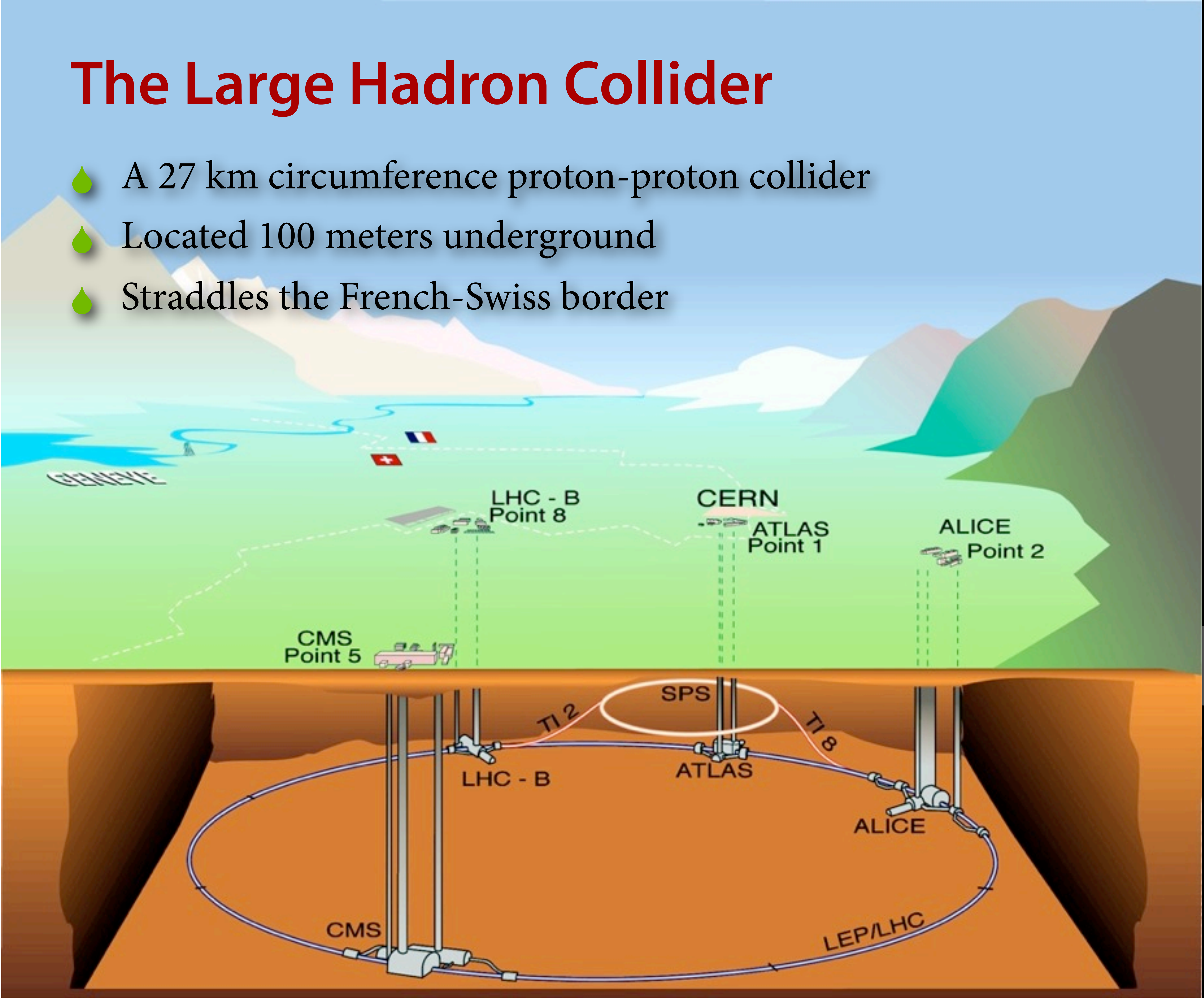
Grand Unified Theories

- Postulate larger gauge group that breaks to the SM gauge groups
- Such models necessarily predict other effective symmetries
- A new *SU*(2) group yields a *W'*

Experiment and Simulations

The Large Hadron Collider

- A 27 km circumference proton-proton collider
- Located 100 meters underground
- Straddles the French-Swiss border



This picture is looking south

Proton Collisions

$$\frac{dN}{dt} = \sigma\mathcal{L}$$

$$L = \int_{t_0}^{t} \mathcal{L}\, dt = \frac{N}{\sigma}$$

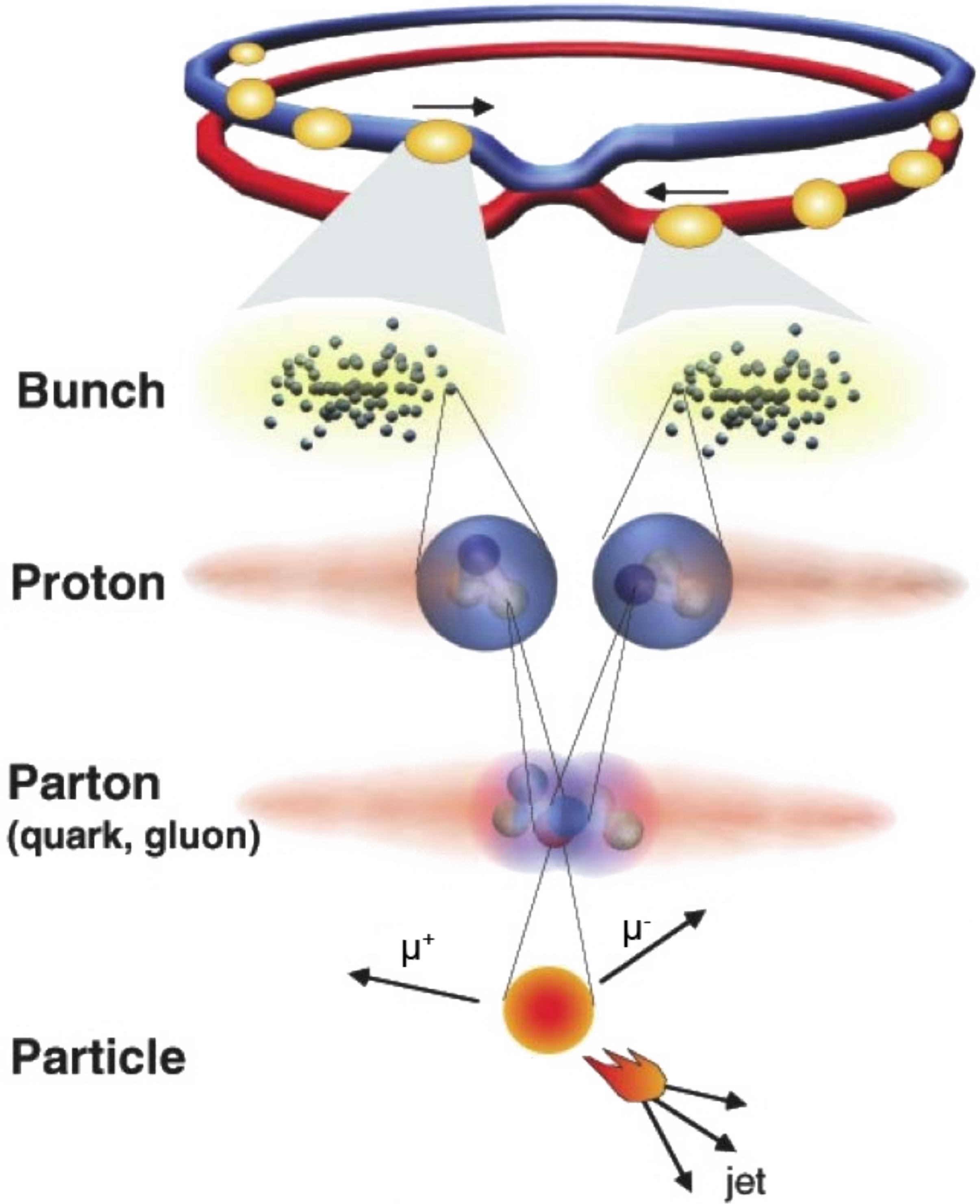
40 MHz crossing rate

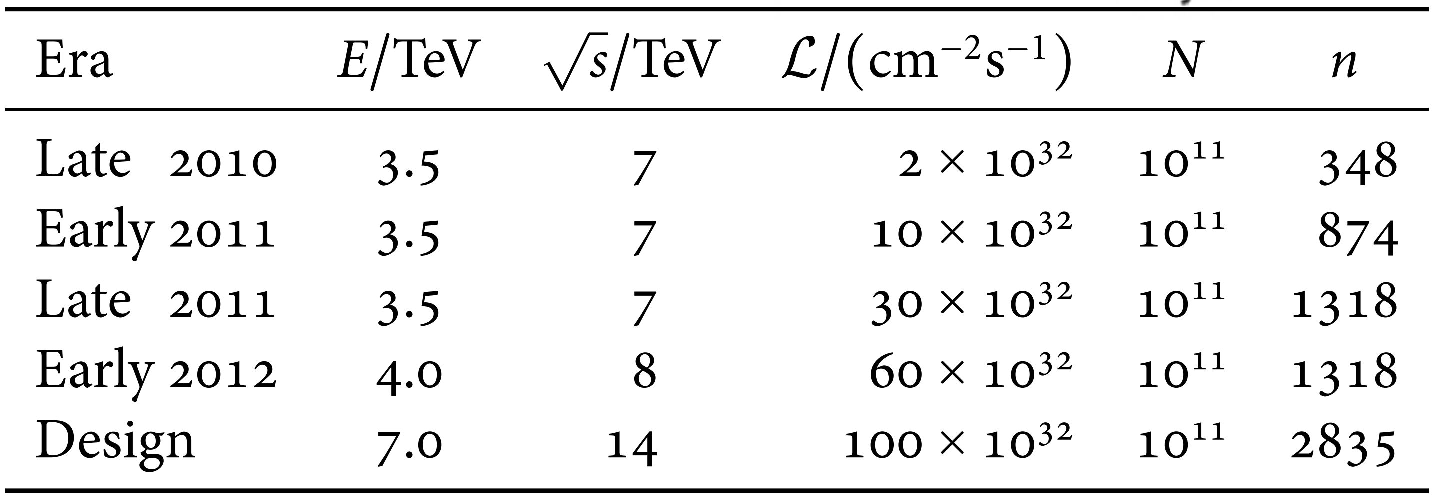
10^9 collisions/second

$\sigma(WZ)$ ~ 18.6 pb

Using ~4.98 fb^{-1} data

- ~10^5 *WZ* events
- ~1300 leptonic

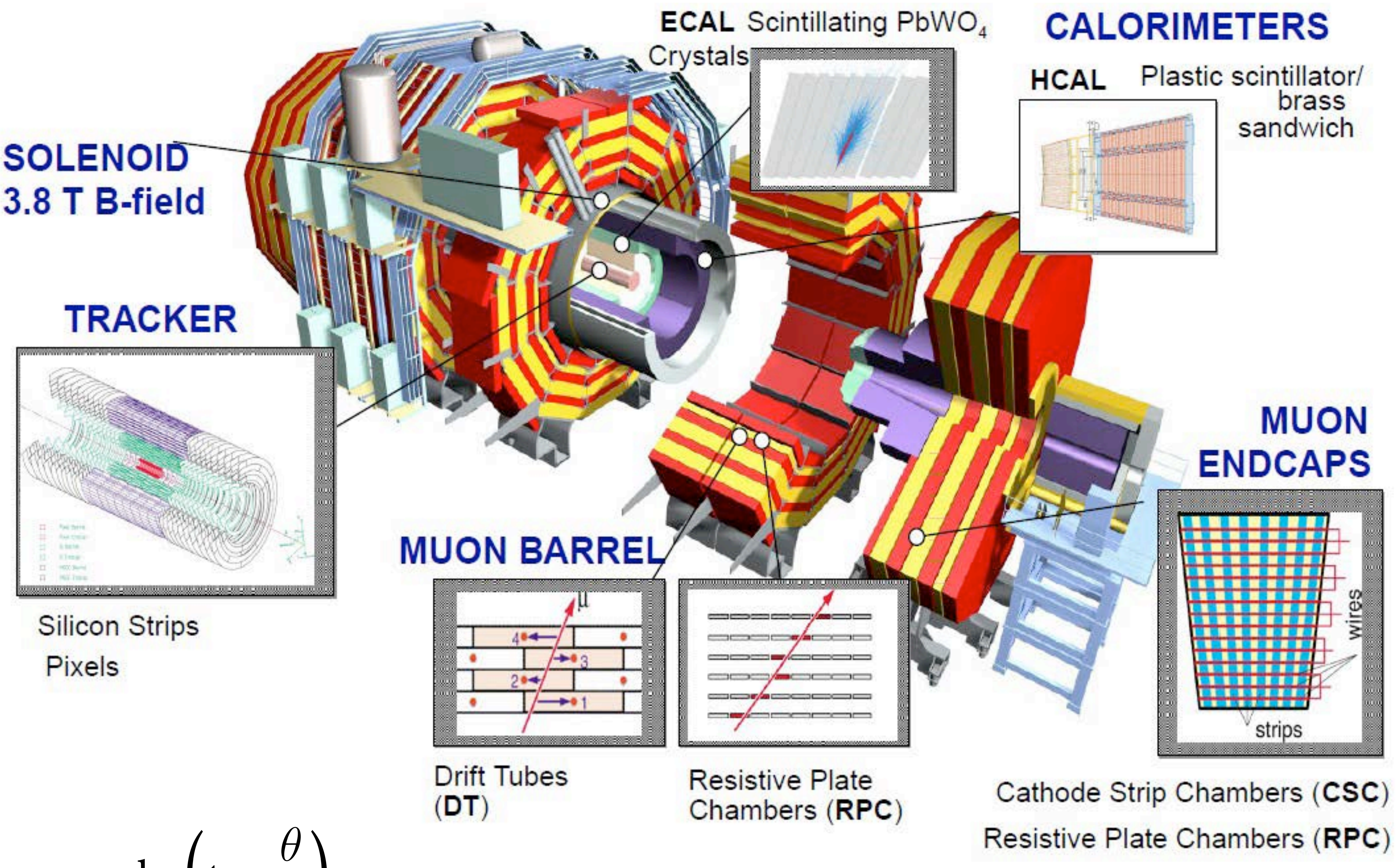




Era	E/TeV	$\sqrt{s}$/TeV	$\mathcal{L}/(\mathrm{cm}^{-2}\mathrm{s}^{-1})$	N	n
Late 2010	3.5	7	2×10^{32}	10^{11}	348
Early 2011	3.5	7	10×10^{32}	10^{11}	874
Late 2011	3.5	7	30×10^{32}	10^{11}	1318
Early 2012	4.0	8	60×10^{32}	10^{11}	1318
Design	7.0	14	100×10^{32}	10^{11}	2835

Protons are accelerated in bunches; it's the partons that interact
Number of expected events can be described by _cross section_ and _luminosity_
Cross sections measured in barns, int. lumi. is inverse cross section

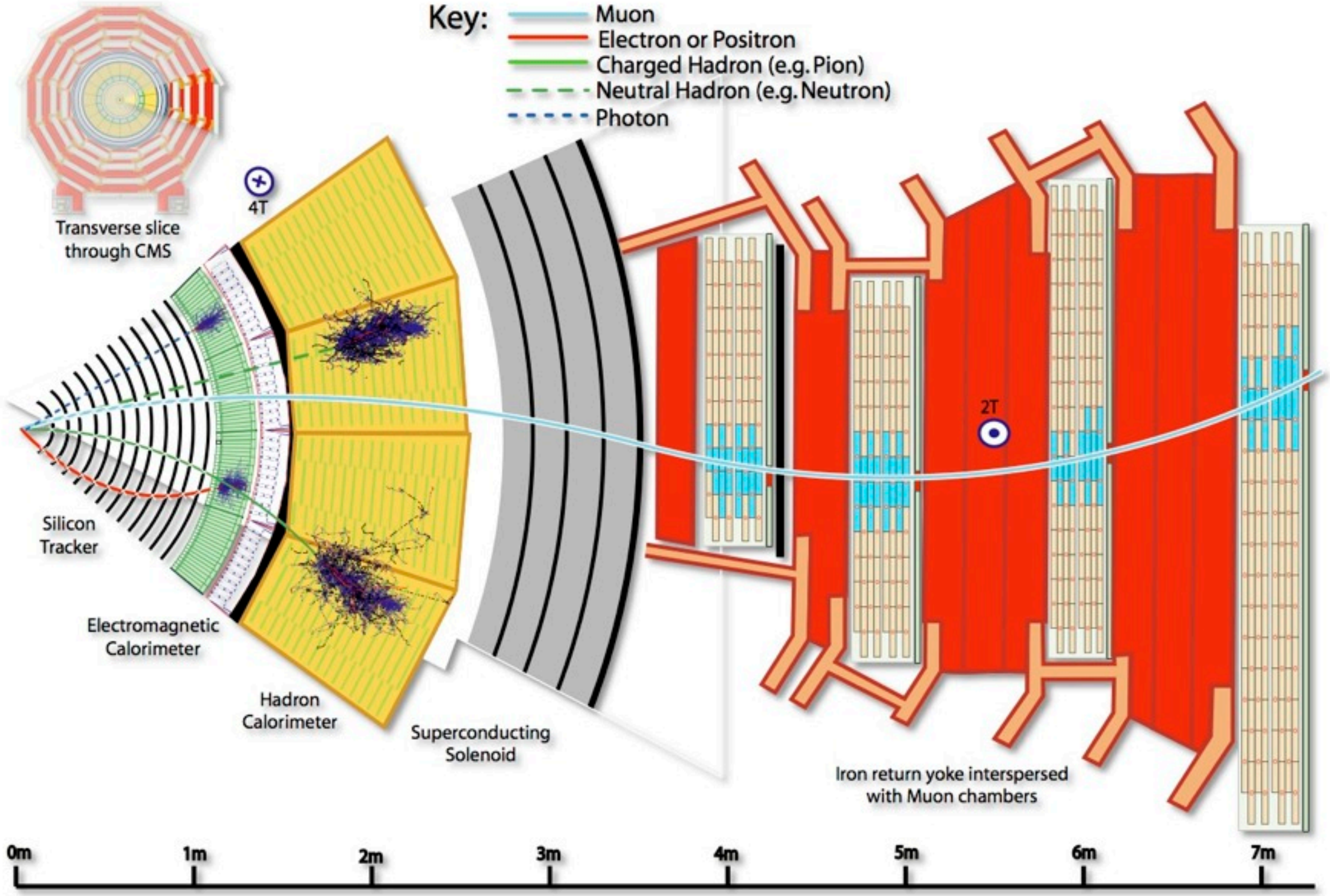
The Compact Muon Solenoid



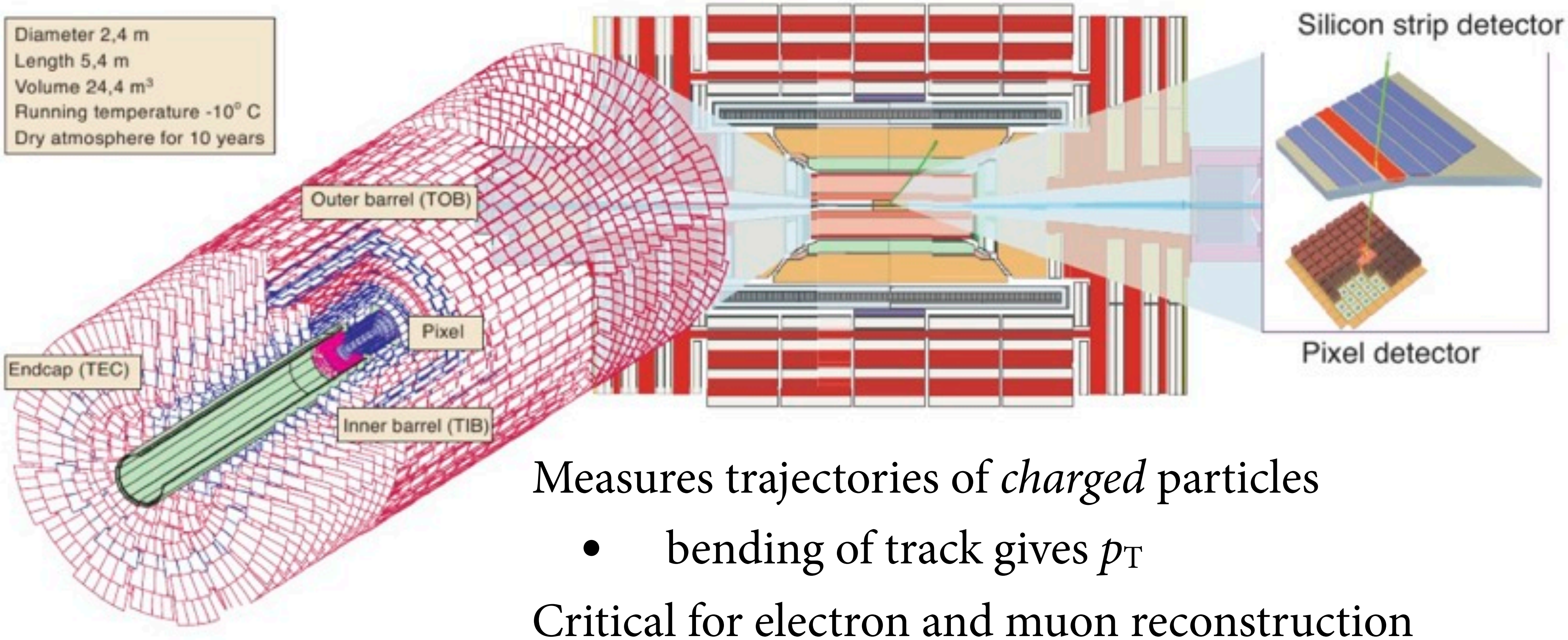
$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

Protons collide near the center of the detector, move radially outward
We use eta to describe polar angle due to detector occupancy
Tracking and calorimeters are inside solenoid
Most powerful magnet in world in terms of total magnetic energy

Particle Detection in CMS



Inner Tracker



Measures trajectories of *charged* particles

- bending of track gives p_T

Critical for electron and muon reconstruction

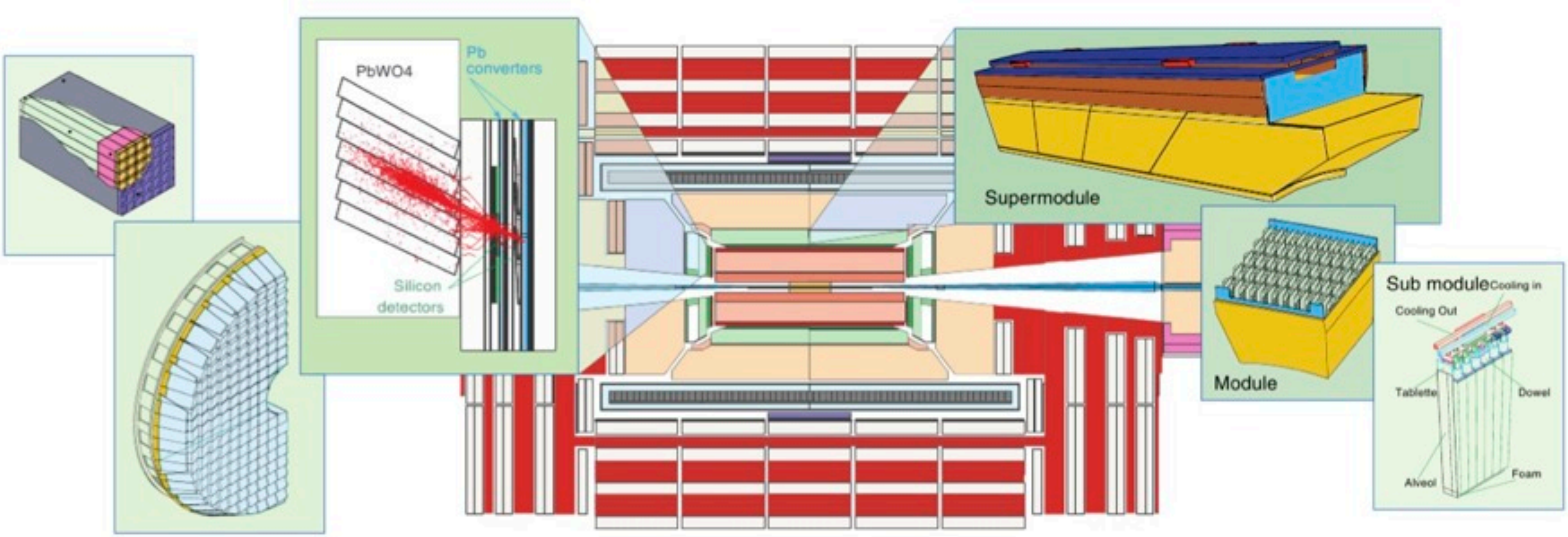
Composed of semiconducting silicon

- 210 m² of active silicon
- Coverage to 2.5 in pseudorapidity
- Pixels closest to the interaction region
- Silicon strips at larger radius

Excellent resolution: $\frac{\sigma(p_T)}{p_T} = (p_T/\mathrm{GeV/c}) \cdot 0.060\% \oplus 0.5\%$

p=qRB -- large radius (2.4m) / large field (3.8T) (dp/p ~ p/BL^2)
Good resolution (1.5% for 100 GeV object, 0.6% for 40 GeV object)
Terms are for bending power and for material interactions
0.4X - 1.8X
Critical for muons, electrons, most everything else

Electromagnetic Calorimeter



Measures energy of electrons and photons

Measures energy of charged particles in jets

Coverage to 3.0 in pseudorapidity

Composed of 76000 lead tungstate crystals

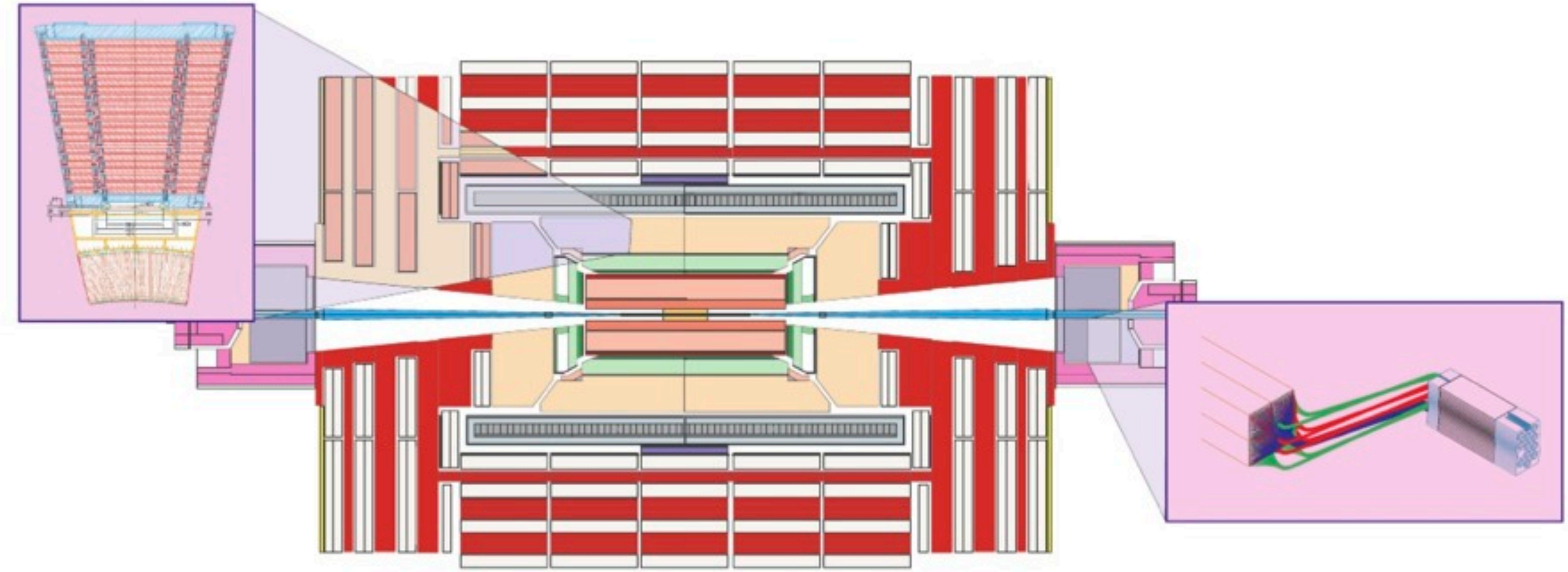
- Short radiation length ($X_0 = 0.89$ cm) (230 mm gives $25.8X_0$)
- Small Molière radius (22 mm)

Excellent resolution:

$$\frac{\sigma(E)}{E} = \frac{1}{\sqrt{E/\mathrm{GeV}}} \cdot 2.8\% \oplus \frac{1}{E/\mathrm{GeV}} \cdot 0.0415\% \oplus 0.3\%$$

Lead tungstate density 8.23 g/cm3
a) Intrinsic shower fluctuations, dead material, sampling fluctuations
b) Electronics noise
c) Detector non-uniformity, calibration uncertainty, radiation damage of active medium

Hadronic Calorimeter



Measures energy of hadrons

Complements the ECAL in jet reconstruction

Sampling calorimeter design

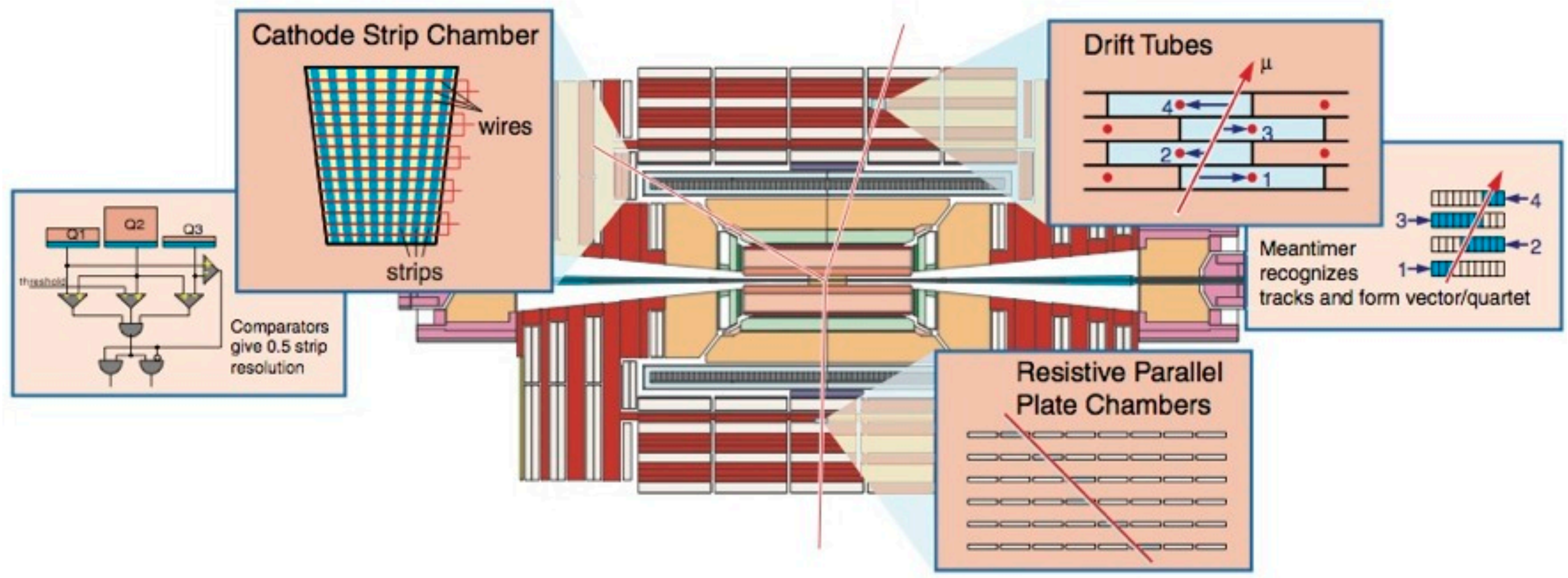
- Brass/scintillator in central region ($|\eta|<3$)

$$\frac{\sigma(E)}{E} = \frac{1}{\sqrt{E/\mathrm{GeV}}} \cdot 85\% \oplus 7.4\%$$

- Steel/quartz in forward region ($|\eta|>3$)

Scintillator consists of tiles of wavelength shifting fibre
A: stochastic term / photoelectron statistics
B: structural non-uniformities & noise
7-11 hadronic interaction lengths -> inelastic nuclear interactions

Muon System



Provides extra lever arm for muon momentum measurements

Three complementary technologies

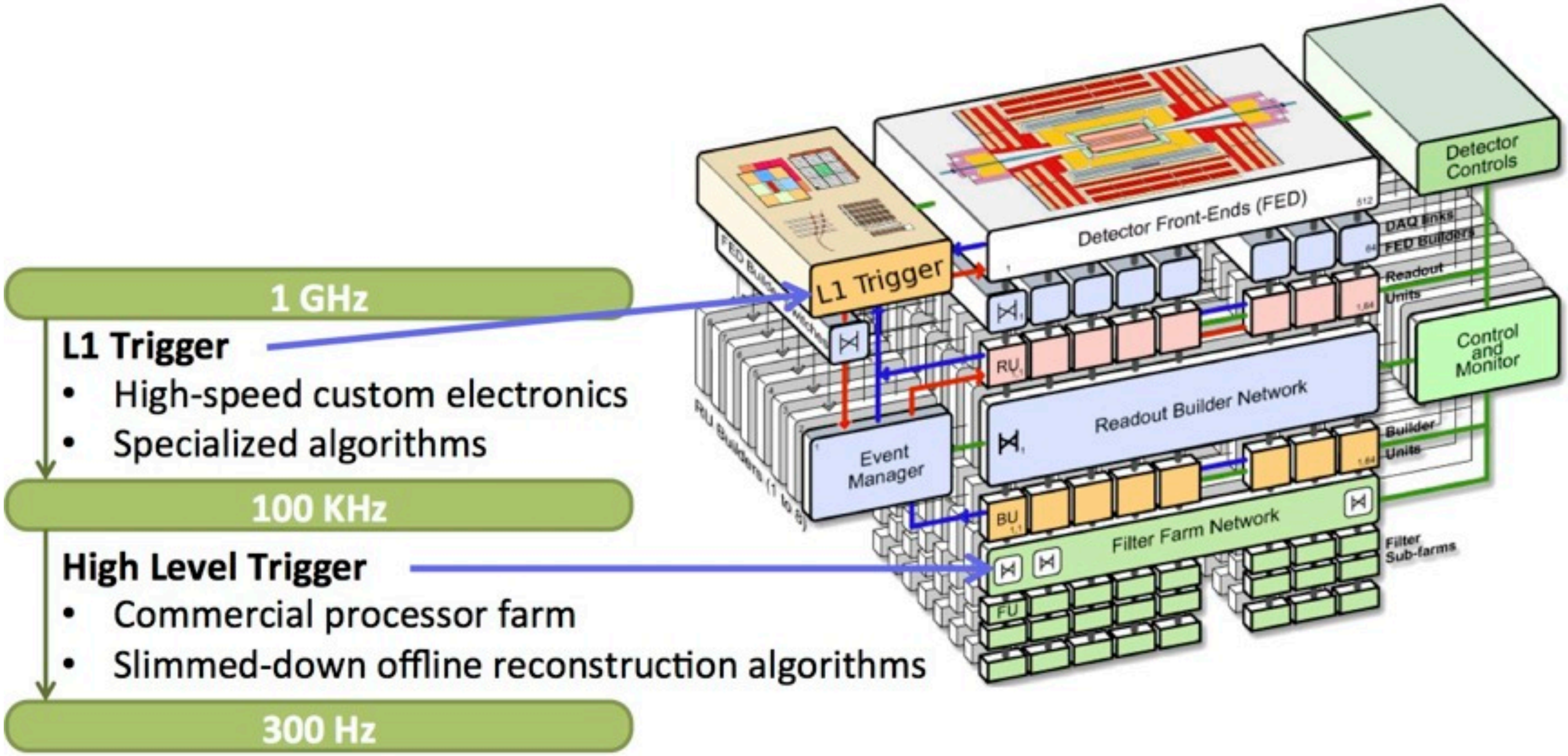
- Drift tubes (DTs) in barrel
- Cathode strip chambers (CSCs) in endcaps
- Resistive plate chambers (RPCs) in both regions for trigger

Trigger

Most LHC events are low-energy with little physics potential

The trigger reduces the 40 MHz event rate to 300 Hz for storage

Muons provide the cleanest triggering capabilities



1 GHz

L1 Trigger

- High-speed custom electronics
- Specialized algorithms

100 KHz

High Level Trigger

- Commercial processor farm
- Slimmed-down offline reconstruction algorithms

300 Hz

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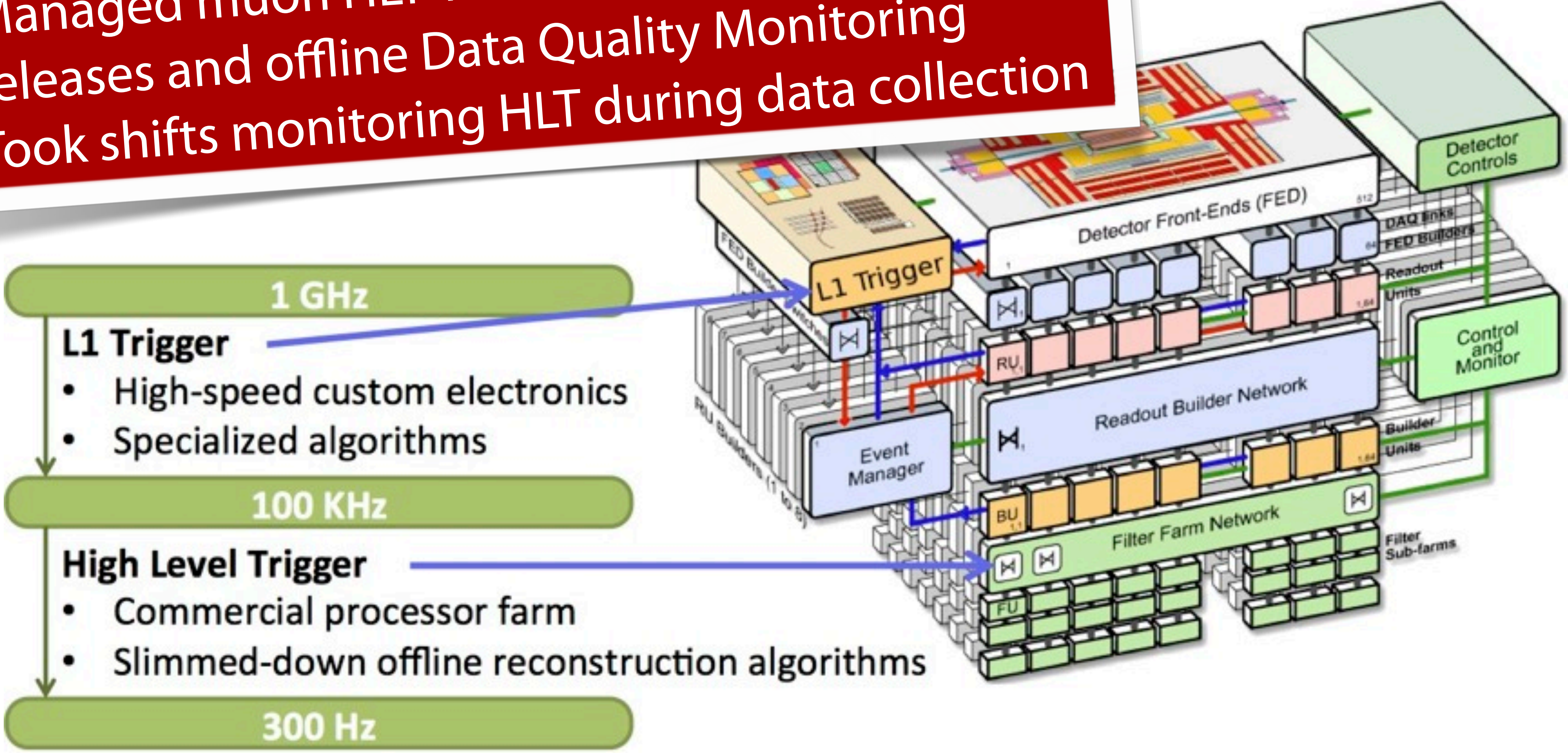
Managed muon HLT validation for software releases and offline Data Quality Monitoring

Took shifts monitoring HLT during data collection



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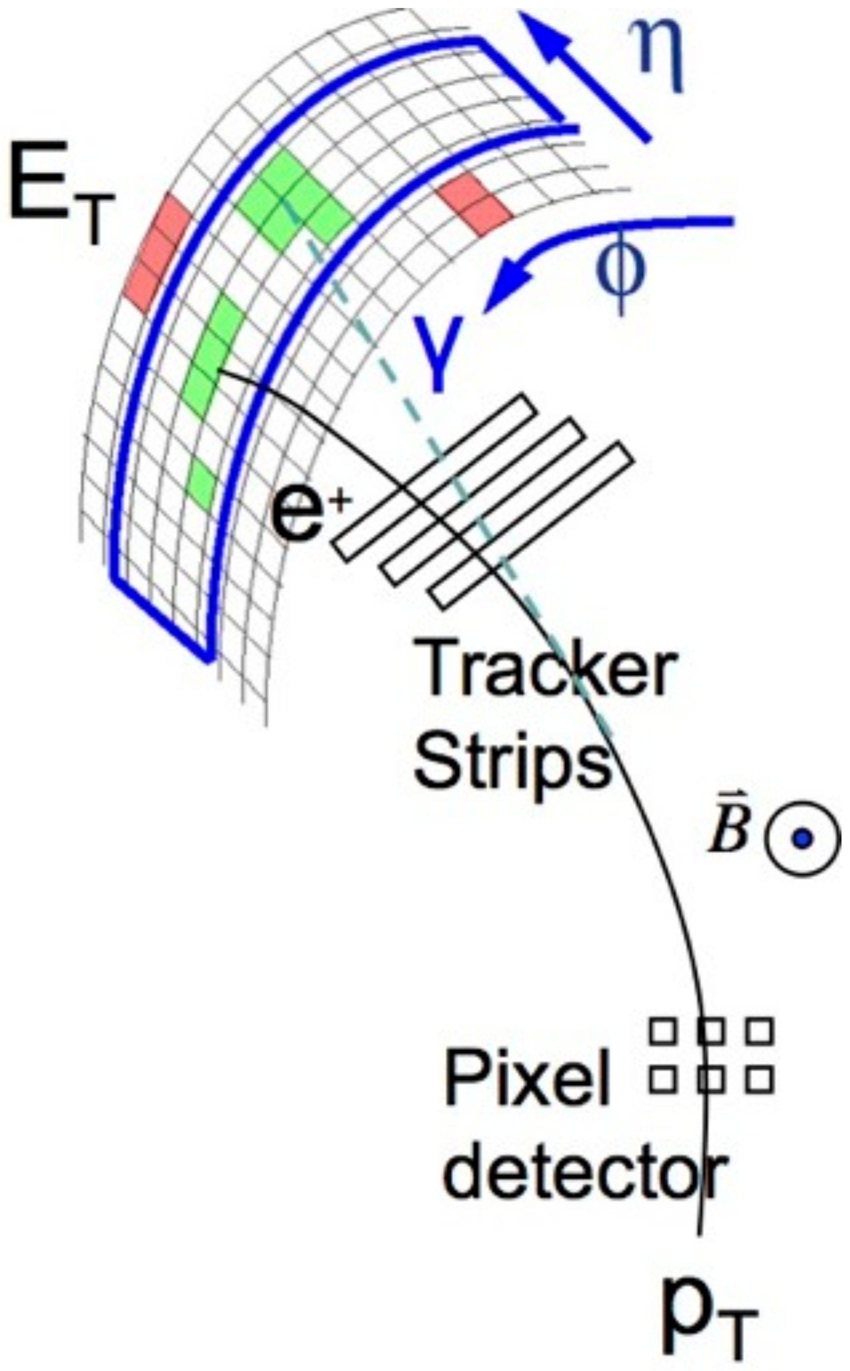
Electron Reconstruction

Combine tracking and calorimeter info

- Identify "superclusters" of energy in the ECAL
    - Energy contained in strips with significant φ width
- Match superclusters to tracks in the tracker
- Refit the track using custom electron algorithm



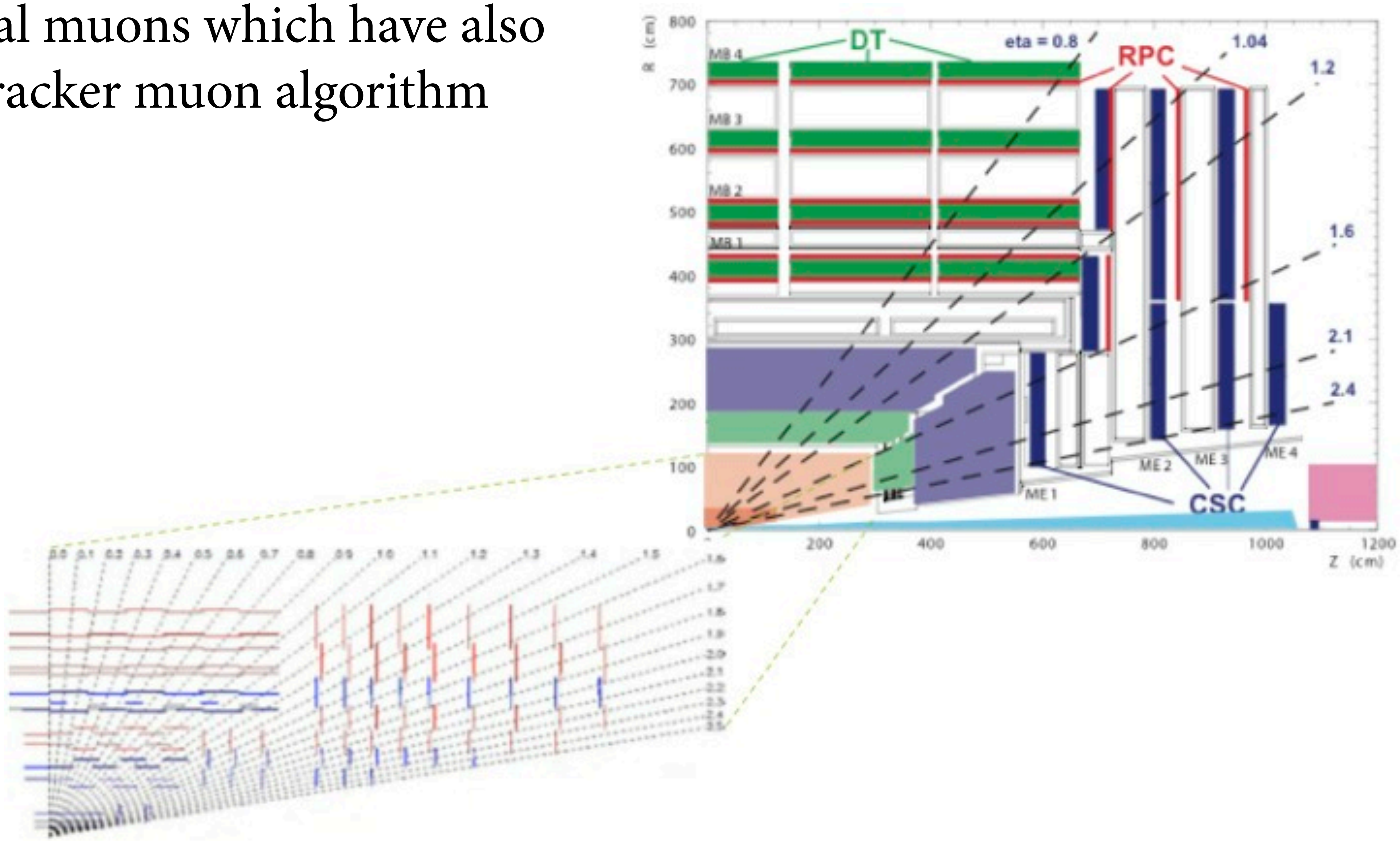
Electron and photon showers deposit their energy in several crystals in the ECAL. Approximately 94% of the incident energy of a single electron or photon is contained in 3x3 crystals, and 97% in 5x5 crystals.

Muon Reconstruction

Tracks can be reconstructed separately in the muon system and tracker

- “Global muons” seeded from muon system
- “Tracker muons” seeded from the tracker

We use global muons which have also passed the tracker muon algorithm



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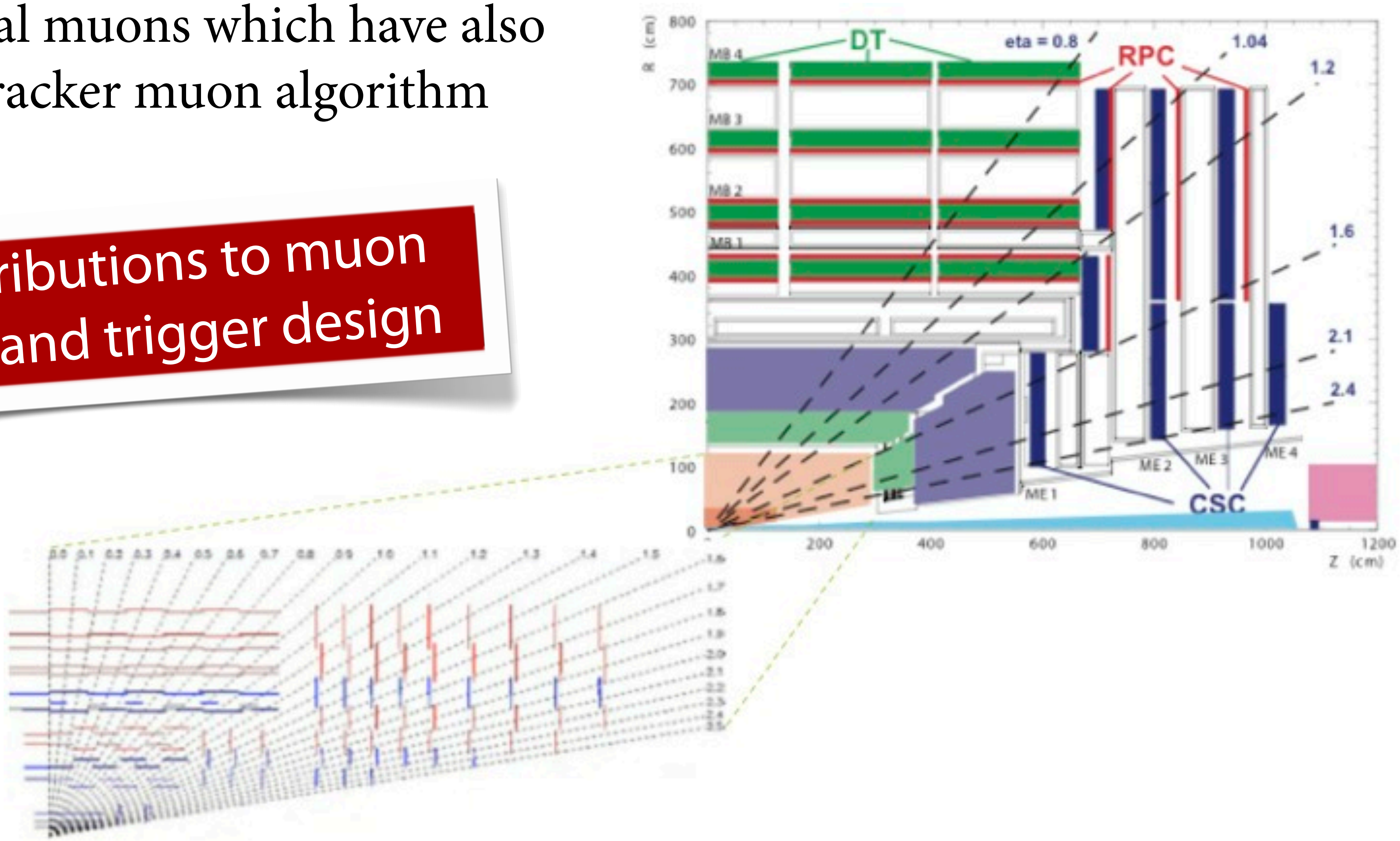
Made contributions to muon alignment and trigger design



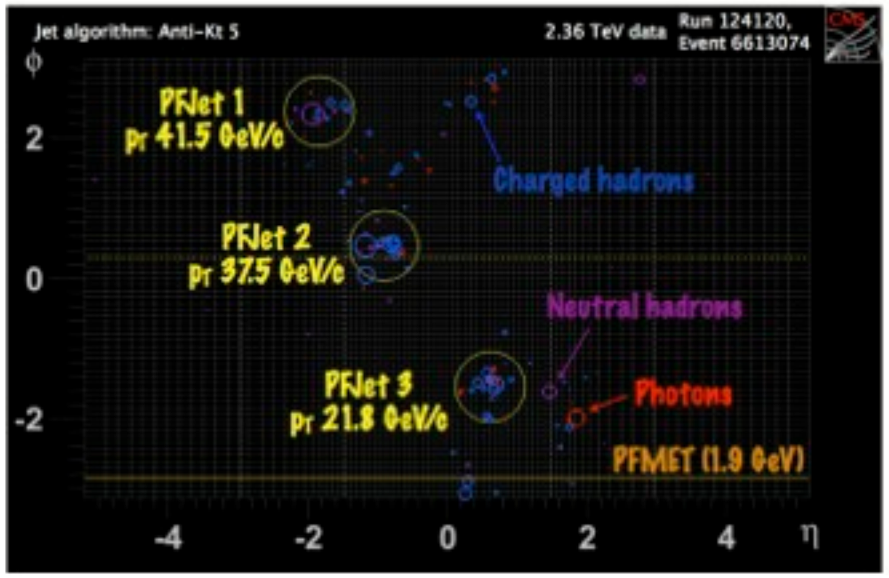
Jet Reconstruction and Missing Energy

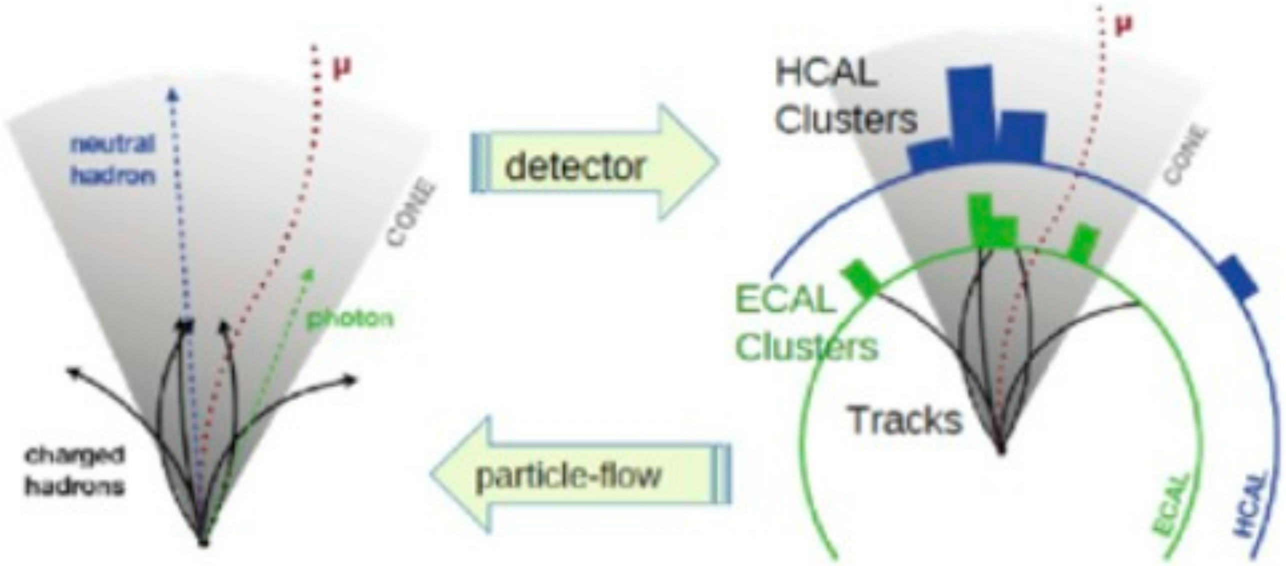
The Particle Flow algorithm combines information from all detectors for a comprehensive view

- Muons, then electrons, then charged and neutral hadrons
- All deposits are assigned to a particle

Jets are constructed via the anti-k_T algorithm, using a high-momentum particle as a seed and adding nearby particles, weighted by momentum

E_T^{miss} is the global imbalance from PF objects: $\vec{E}_T^{\text{miss}} \equiv -c\sum_i \vec{p}_T(i)$





anti-kT is collinear safe and infrared safe, necessary for comparison with theory
* splitting of jets and soft emissions should not affect jets

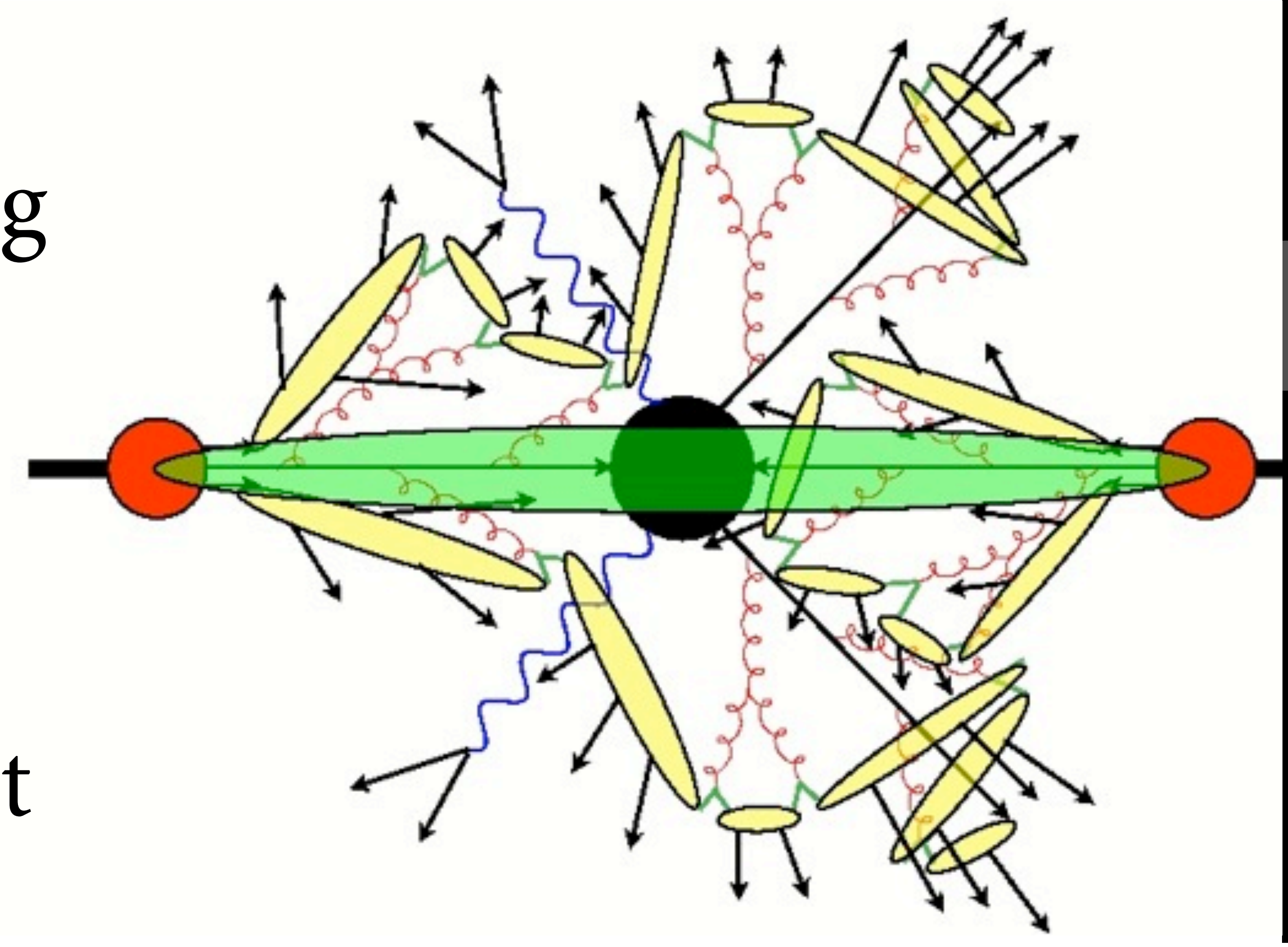
Monte Carlo Generators

MadGraph/Powheg/Pythia

- Fixed-order or leading-order matrix element calculators
- Generate multi-parton hard scatter

Pythia

- Parton showering
- Hadronization
- Initial/final state radiation
- Underlying event



* Parton shower; initial evolution of partons
* Hadronization; formation of colorless bound states from colored partons
* UE: proton remnants; described by tune
Additional pileup events are layered on top of this

Event Simulation

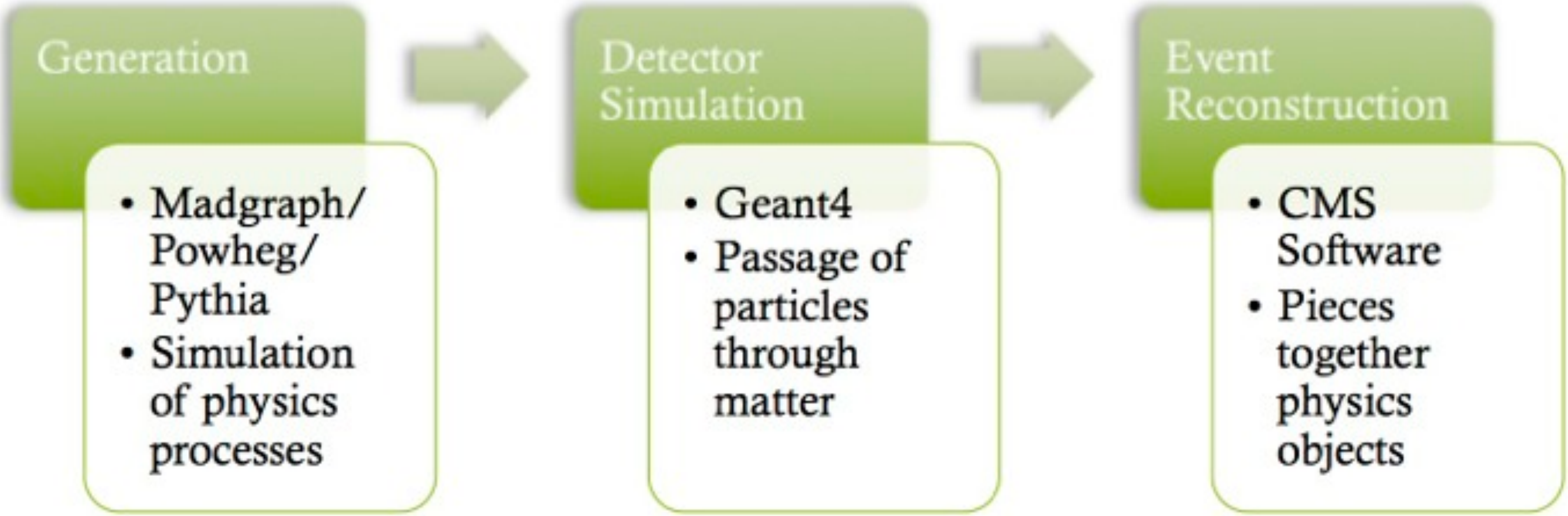
W' signal generated with Pythia, considering masses from 200 GeV/c^2 to 1500 GeV/c^2

- Used for both W' and Technicolor investigations

All backgrounds use MadGraph or Powheg

- WZ, Z+jets, ZZ, tt, WW, W+jets, $Z\gamma$, $W\gamma$
- Cross sections normalized to NLO prediction

CMS Software simulates electronics response and applies the same reconstruction algorithms as used for collision data



Generation

- Madgraph/Powheg/Pythia
- Simulation of physics processes

Detector Simulation

- Geant4
- Passage of particles through matter

Event Reconstruction

- CMS Software
- Pieces together physics objects

Reconstruction and Analysis

Reconstruction Strategy

Select events passing double-electron or double-muon triggers with thresholds of (17, 8) GeV

Build a Z candidate from the pair of leptons closest to Z mass ($60 < m_{\ell\ell} < 120$).

Reject events with a second Z candidate.

Assign the most energetic remaining lepton to the W.

Require $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV.

Electron Identification Introduction

Momentum

- Momentum required to be high enough to ensure efficiency of the trigger selection
- The requirement of high momentum suppresses jet activity which increases rapidly at low momentum

Shower shape

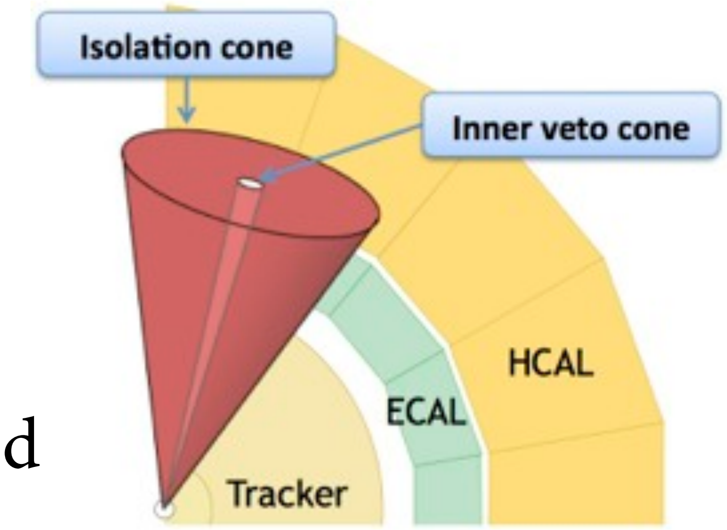
- Electrons should leave strips of deposits in the ECAL with a well-matched track; jets tend to be more spread out
- Require a small cluster width in η
- Require close matching between track and cluster positions

Conversion rejection

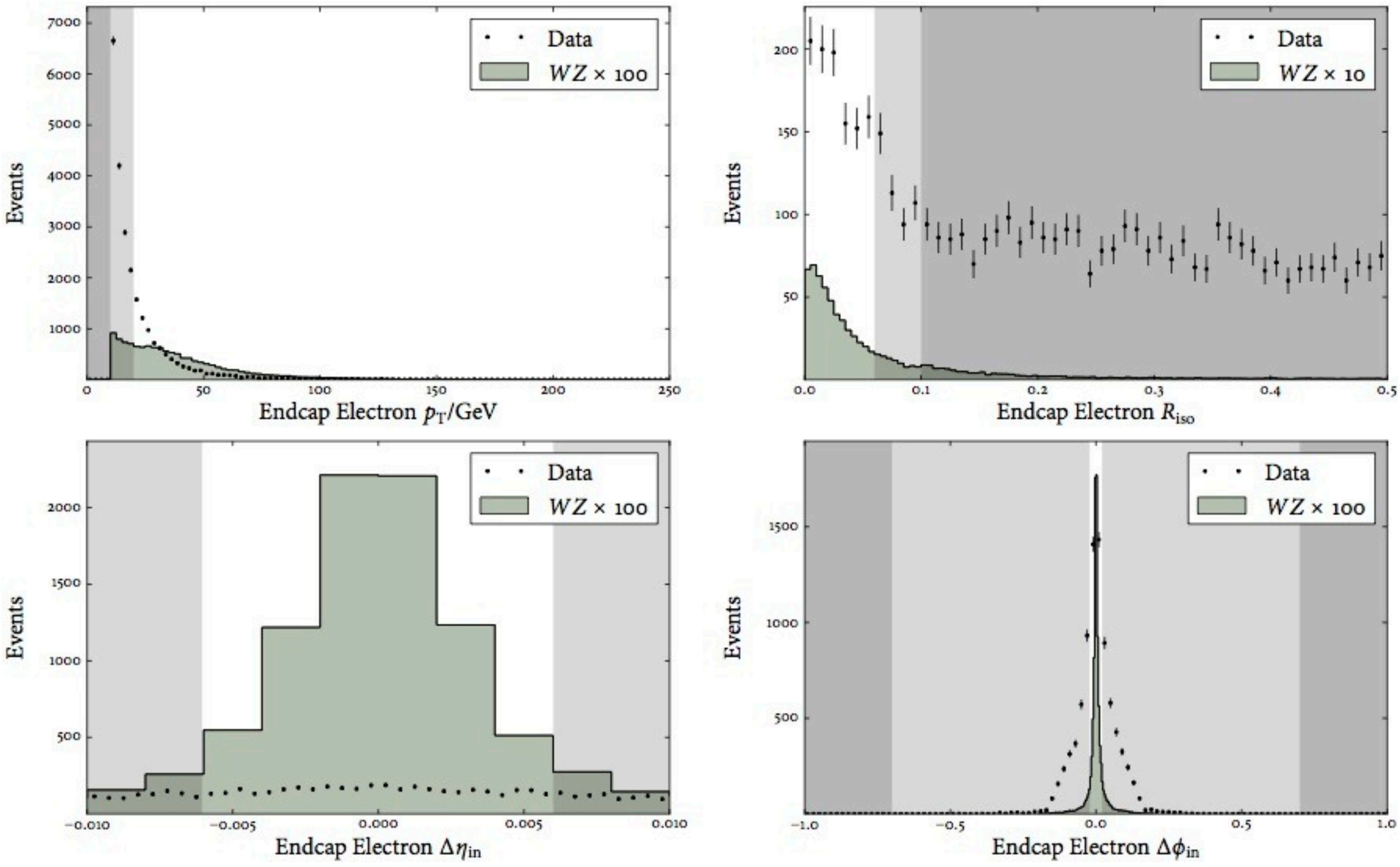
- Photons are likely to convert within the tracker, leading to electron-positron track pairs
- Reject electron tracks with close neighbors

Isolation

- Track and calorimeter activity should be localized

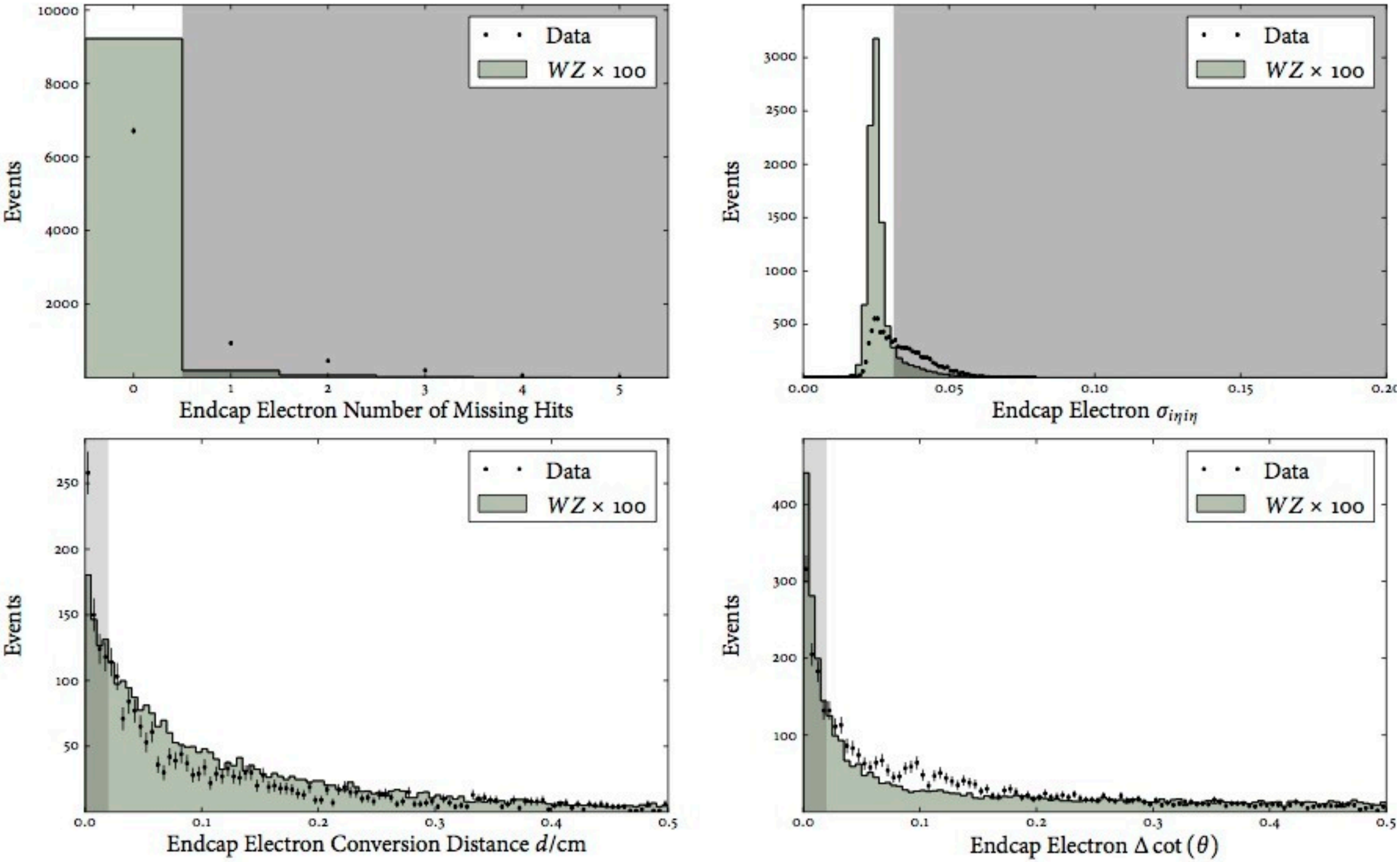


Electron Identification (1)



For pT, dark is Z1, Z2 for trigger; for others, light is W
Detain and dphiin are track matching

Electron Identification (2)



Missing hits -> reject photon conversions in tracker
sig_ietaieta is shower shape
d and dcot are conversion rejection
Tighter for barrel.

Electron Selection Summary

	Electrons from Z		Electron from W	
Requirement	EB	EE	EB	EE
Minimum trigger match E_T (GeV)	17 (8)	17 (8)	—	—
Minimum electron p_T (GeV/c)	20 (10)	20 (10)	20	20
Maximum $\sigma_{i\eta i\eta}$	0.012	0.031	0.010	0.031
Maximum $\|\Delta\eta_\mathrm{in}\|$	0.007	0.011	0.005	0.006
Maximum $\|\Delta\phi_\mathrm{in}\|$	0.800	0.700	0.027	0.021
Maximum missing track hits	0	0	0	0
Minimum d between tracks (cm)	—	—	0.02	0.02
Minimum $\Delta\cot(\theta)$ between tracks	—	—	0.02	0.02
Maximum R_iso	0.15	0.10	0.07	0.06
Minimum ΔR from any muon	0.01	0.01	0.01	0.01

Muon Selection Introduction

Our muon sample is contaminated with objects originating from jets or cosmic events

Momentum

- Momentum required to be high enough to ensure efficiency of the trigger selection
- The requirement of high momentum suppresses jet activity which increases rapidly at low momentum

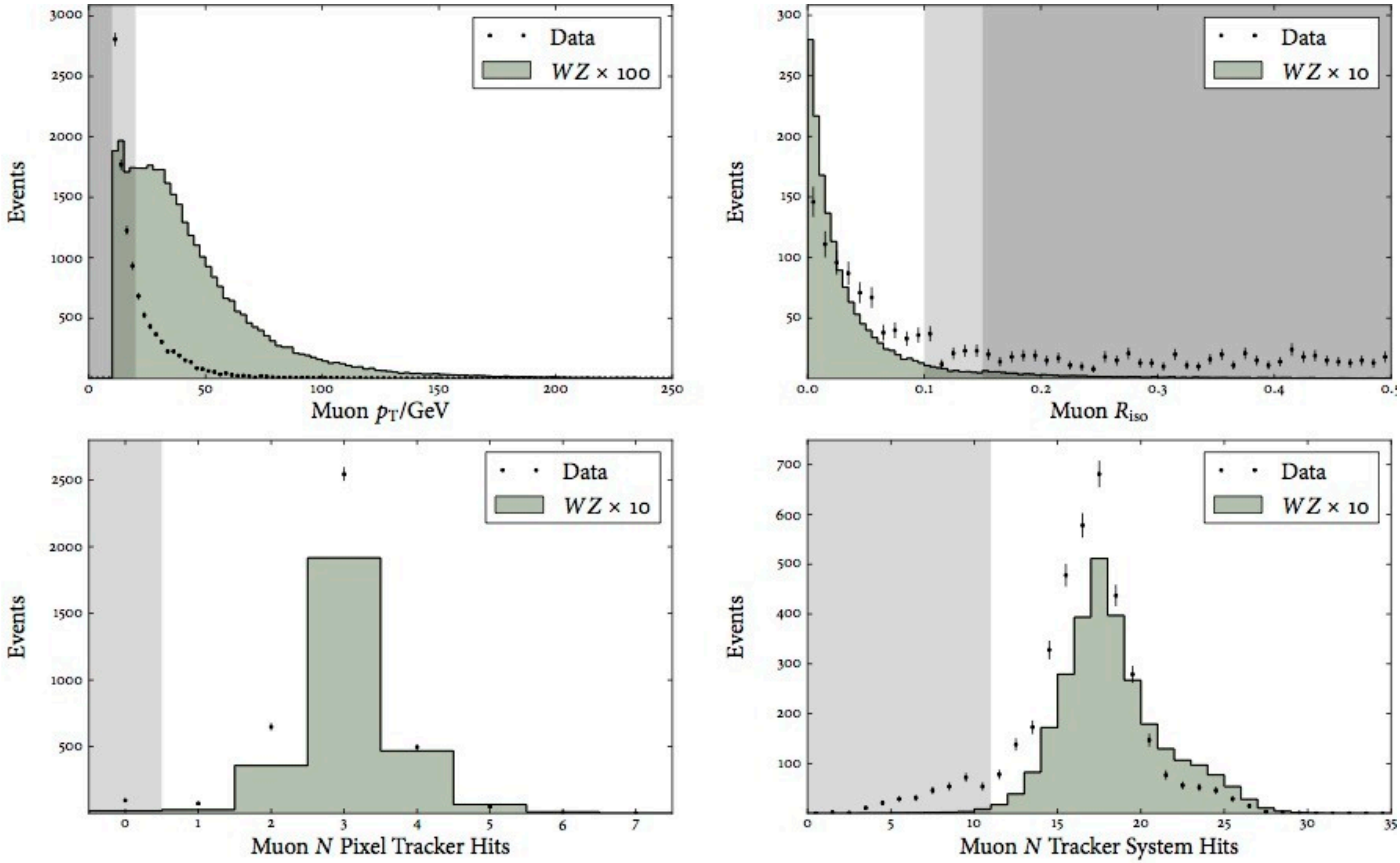
Track quality

- Muons originating from the primary vertex should have many hits distributed through the various subsystems
- Muons from jets will not point to the primary vertex

Isolation

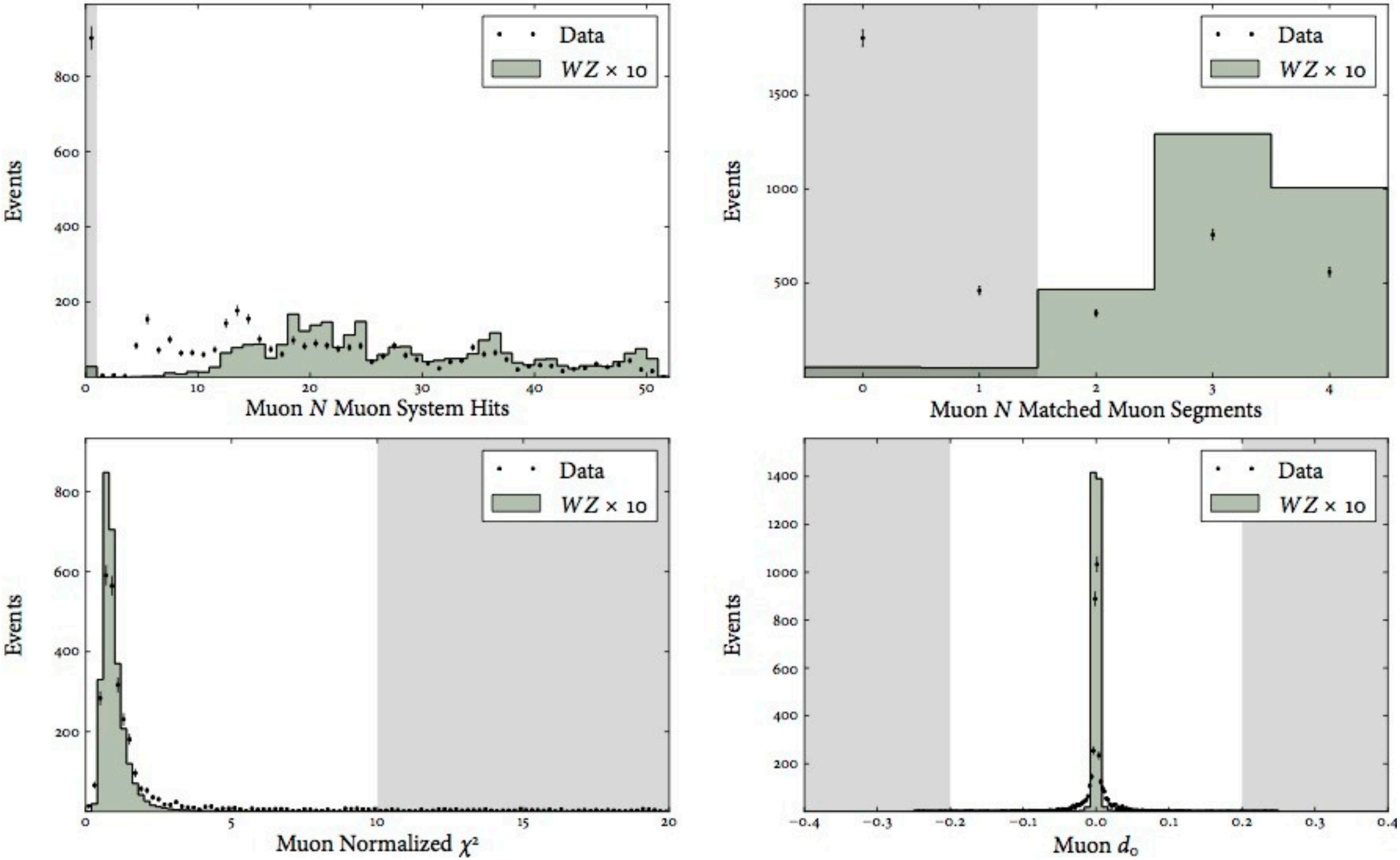
- Track and calorimeter activity should be localized

Muon Identification (1)



Npix, Ntrk suppresses decays in flight; Ntrk ensures good pT measurement

Muon Identification (2)



Nmuon, chi^2 suppresses hadronic punch-through, decays in flight
Nmatch reduces ambiguity and is consistent with the trigger
d0 for cosmics and decays in flight

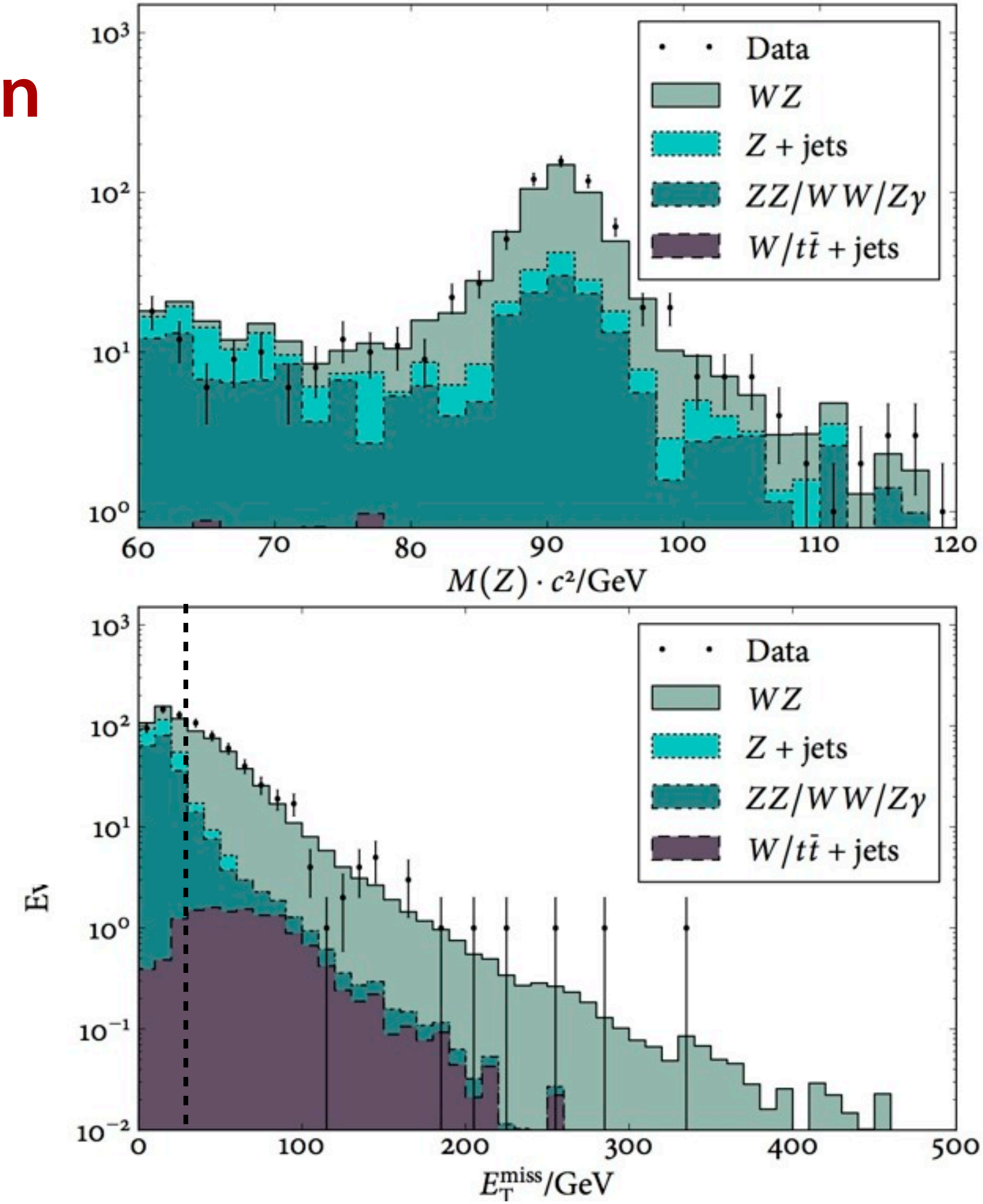
Muon Selection Summary

Minimum number of pixel hits			1
Minimum number of tracker hits			11
Minimum number of muon system hits			1
Minimum number of matched muon segments			2
Maximum normalized χ^2			10.0
Maximum impact parameter (cm)			0.2
	μ_1^Z	μ_2^Z	μ^W
Minimum trigger match p_T (GeV/c)	17	8	—
Minimum global track p_T (GeV/c)	20	10	20
Maximum R_iso	0.15	0.15	0.10

WZ Selection

We find good agreement between simulation and the trilepton data, even before *W* selection

High missing transverse energy is expected due to the escaping neutrino



Z plot
* Log plot can be deceptive; we put least significant on bottom
* For central bin, we have ~30 diboson, ~10 Z+jets, ~60 WZ
* We have already required events with 3 leptons, but no ID
MET plot
* Tight W lepton required

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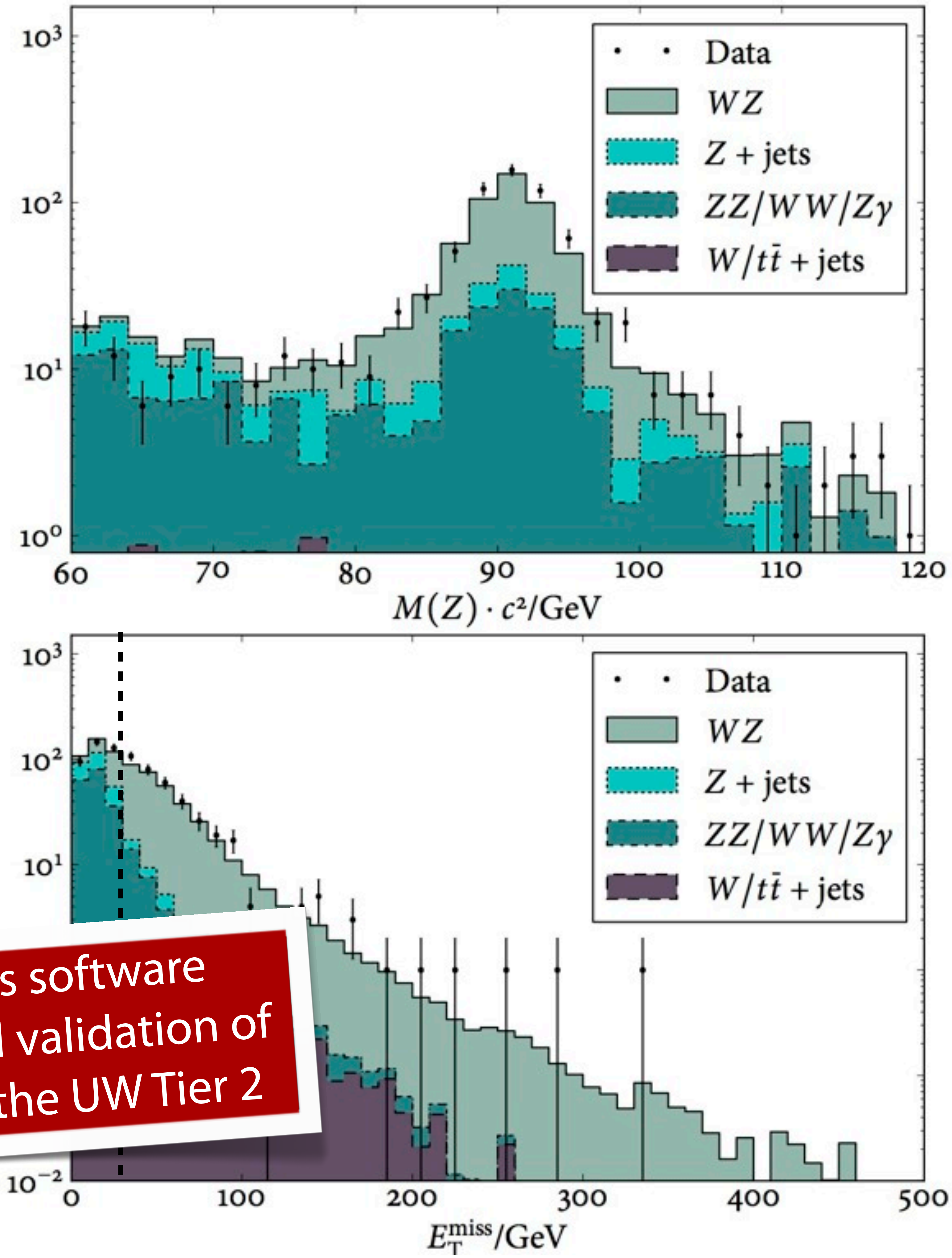

Wrote the group's analysis software
Managed processing and validation of MC and data samples at the UW Tier 2

Z plot
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Lepton Selection Efficiencies

Using "tag and probe method" to provide unbiased efficiency measurements in data

- Look for a "tag" lepton passing tight selection requirements
- Look for a second "probe" lepton passing loose selection requirements which forms a *Z* candidate with the tag
- Measure the likelihood for probes to also pass the tight selection

Measurement repeated in Monte Carlo to determine efficiency corrections.

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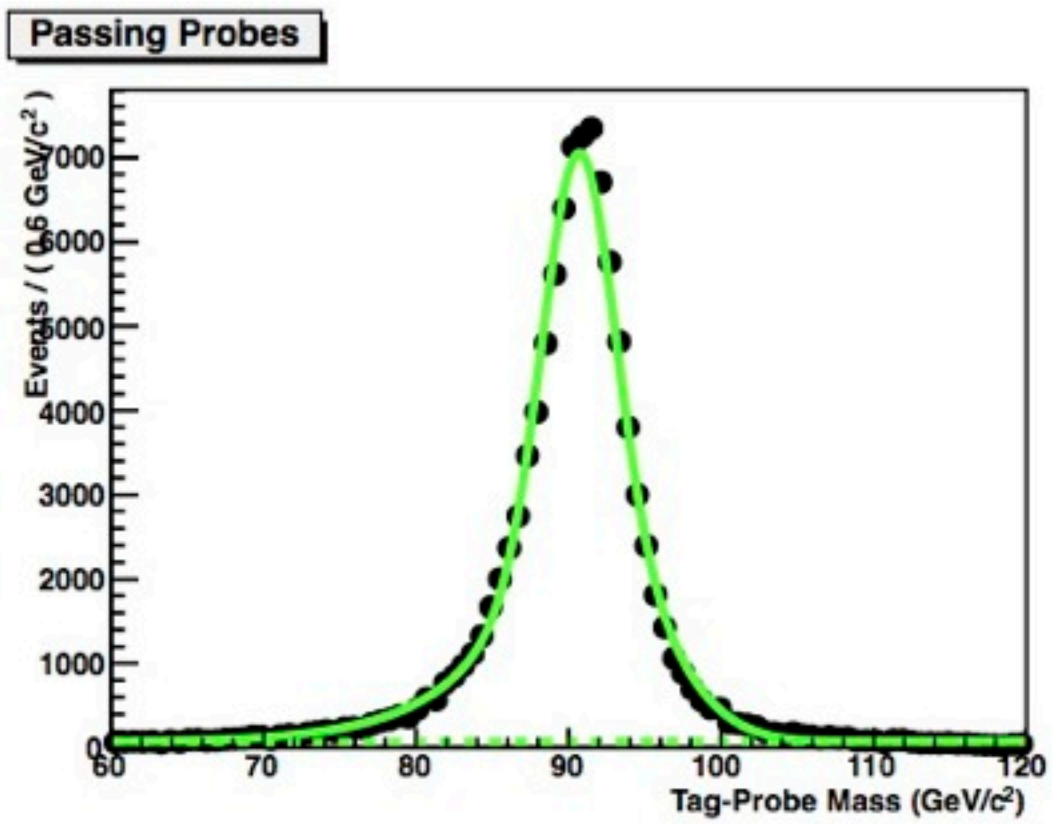
- Measure the likelihood for probes to also pass the tight selection

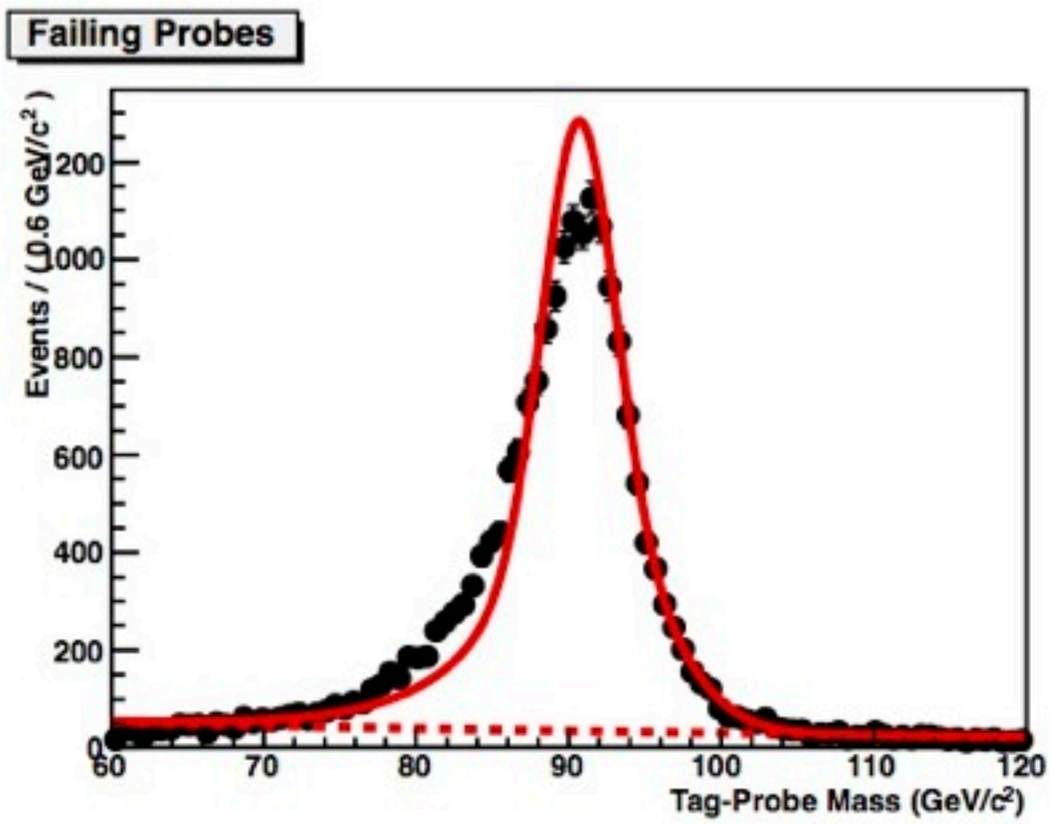
Measurement repeated in Monte Carlo to determine efficiency corrections.

Adapted central CMS tools to perform these tag and probe measurements; Expanded capabilities to respond to needs for the analysis

Electron Selection Efficiency

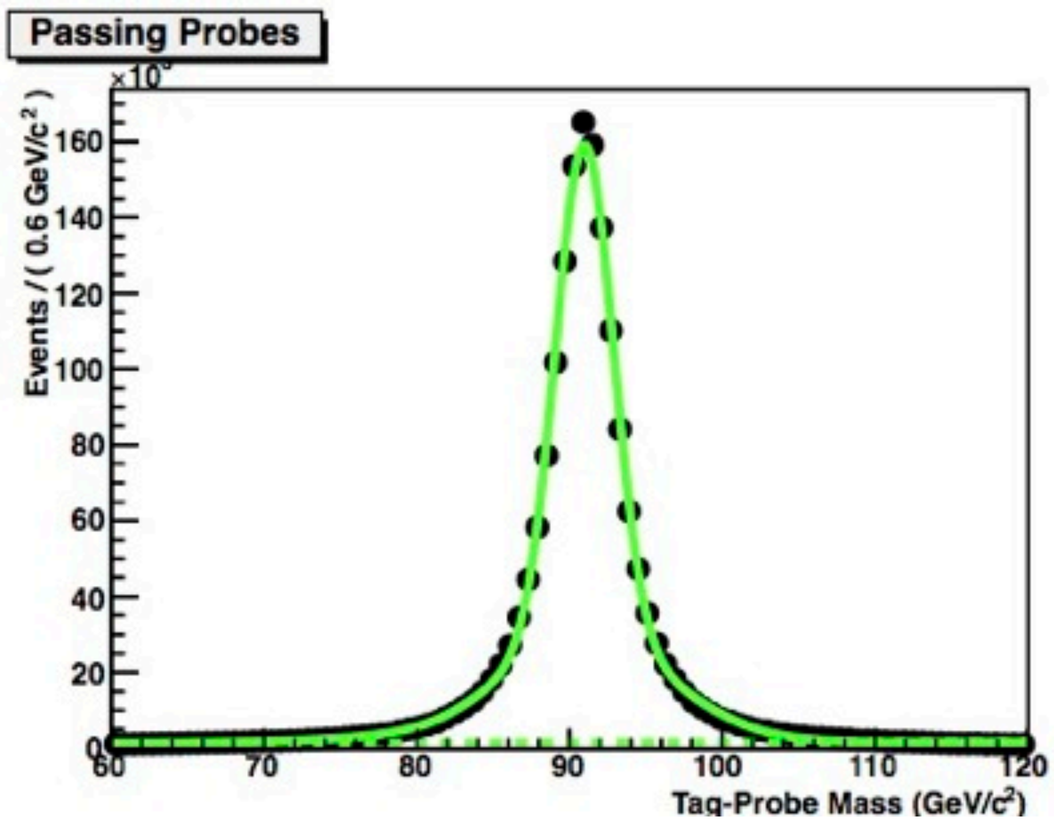
Efficiency		Data/%	MC/%	Ratio $\left(\frac{\text{Data}}{\text{MC}}\right)$
Identification	(W)	84.8 ± 0.1	84.9 ± 0.1	0.999 ± 0.001
Isolation	(W)	85.6 ± 0.1	81.7 ± 0.1	1.047 ± 0.002
Identification	(Z)	97.4 ± 0.1	97.6 ± 0.1	0.998 ± 0.001
Isolation	(Z)	97.9 ± 0.1	97.3 ± 0.1	1.006 ± 0.001
Trigger	$(E_T > 17\,\text{GeV})$	95.8 ± 0.1	98.2 ± 0.1	0.976 ± 0.001
Trigger	$(E_T > 8\,\text{GeV})$	95.8 ± 0.1	98.2 ± 0.1	0.976 ± 0.001

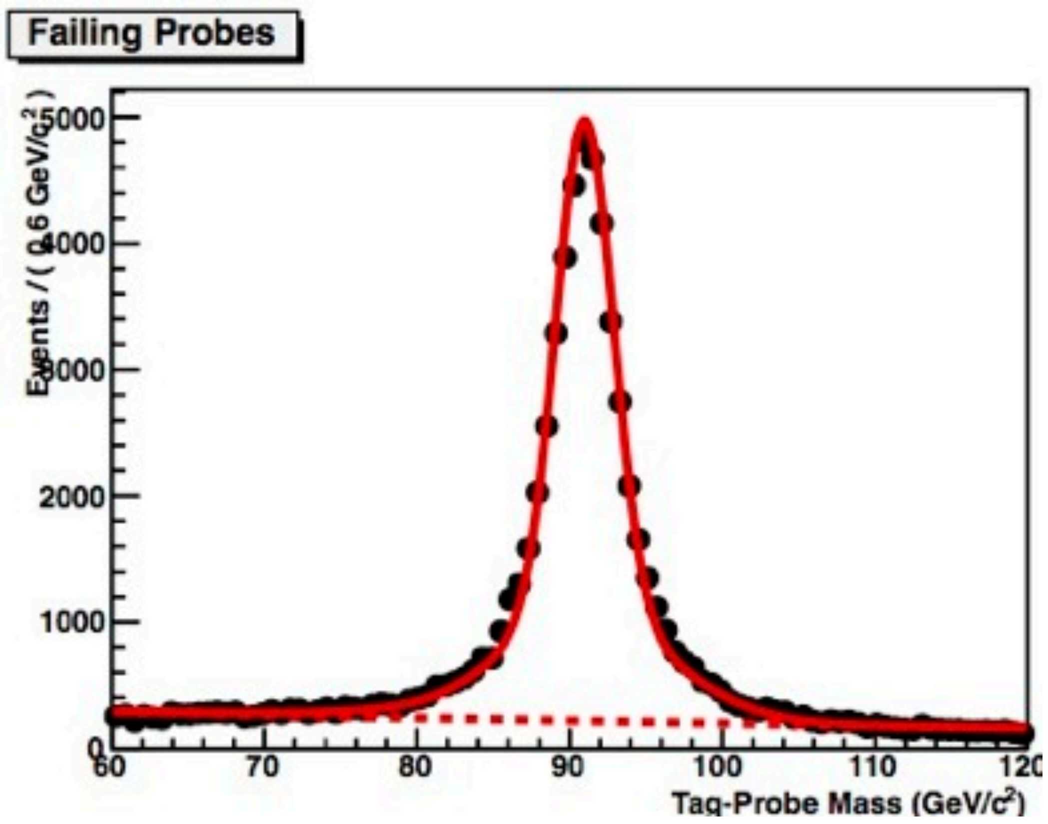




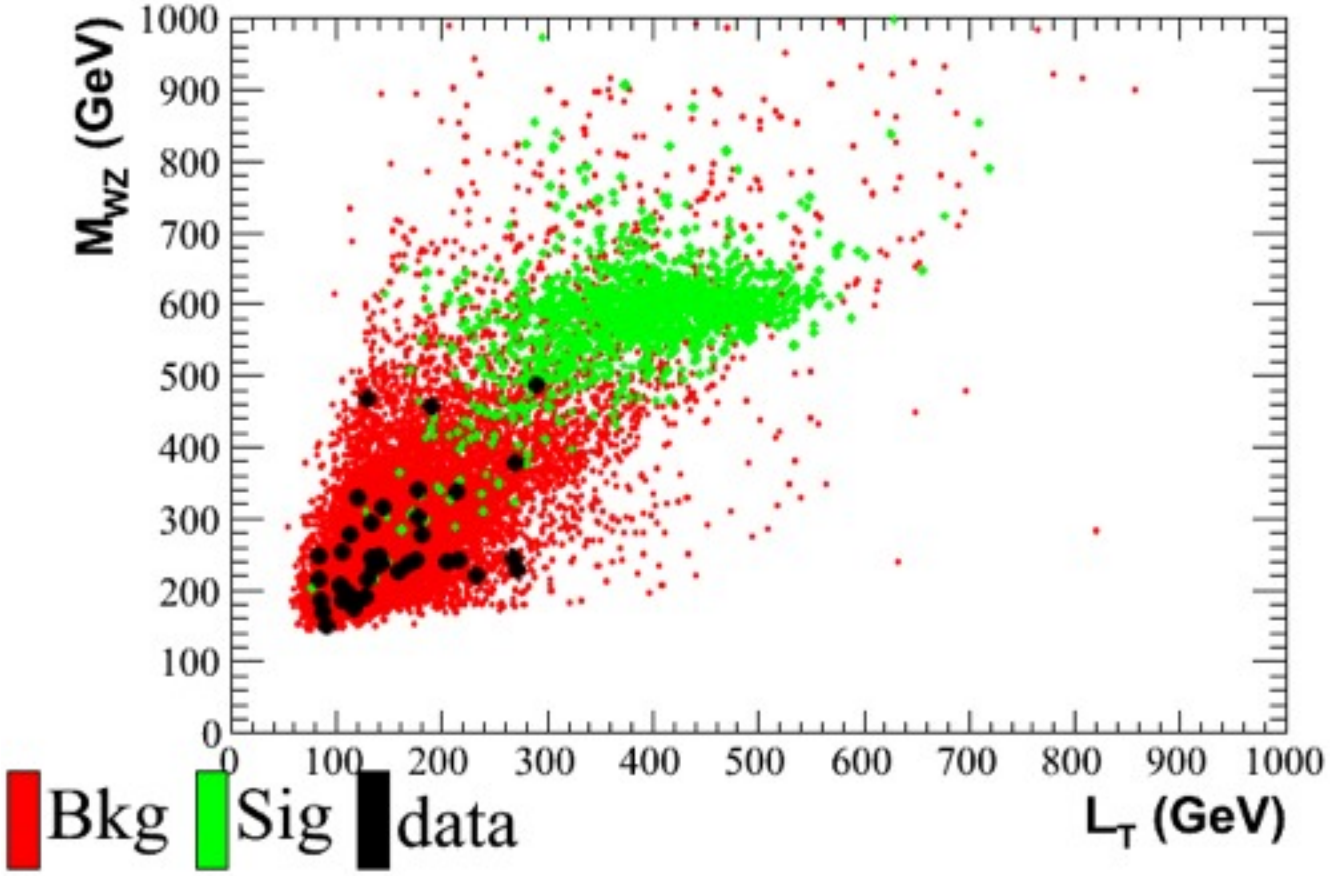
Muon Selection Efficiency

Efficiency	Data/%	MC/%	Ratio ($\frac{\text{Data}}{\text{MC}}$)
Reconstruction (STA)	98.4 ± 0.1	98.2 ± 0.5	1.002 ± 0.005
Reconstruction (TRK)	98.9 ± 0.1	99.3 ± 0.5	0.995 ± 0.005
Identification	97.1 ± 0.1	97.7 ± 0.1	0.994 ± 0.001
Isolation	95.2 ± 0.1	92.5 ± 0.2	1.030 ± 0.002
Trigger (p_T > 17 GeV/c)	95.3 ± 0.1	94.9 ± 0.1	1.004 ± 0.001
Trigger (p_T > 8 GeV/c)	95.3 ± 0.1	94.9 ± 0.1	1.004 ± 0.001





Identifying a Resonance



$$L_T = \sum_i p_T(\ell_i)$$

- Resonant events will be energetic, leading to leptons with higher average p_T than SM WZ
- L_T capitalizes on the strength of CMS for lepton reconstruction

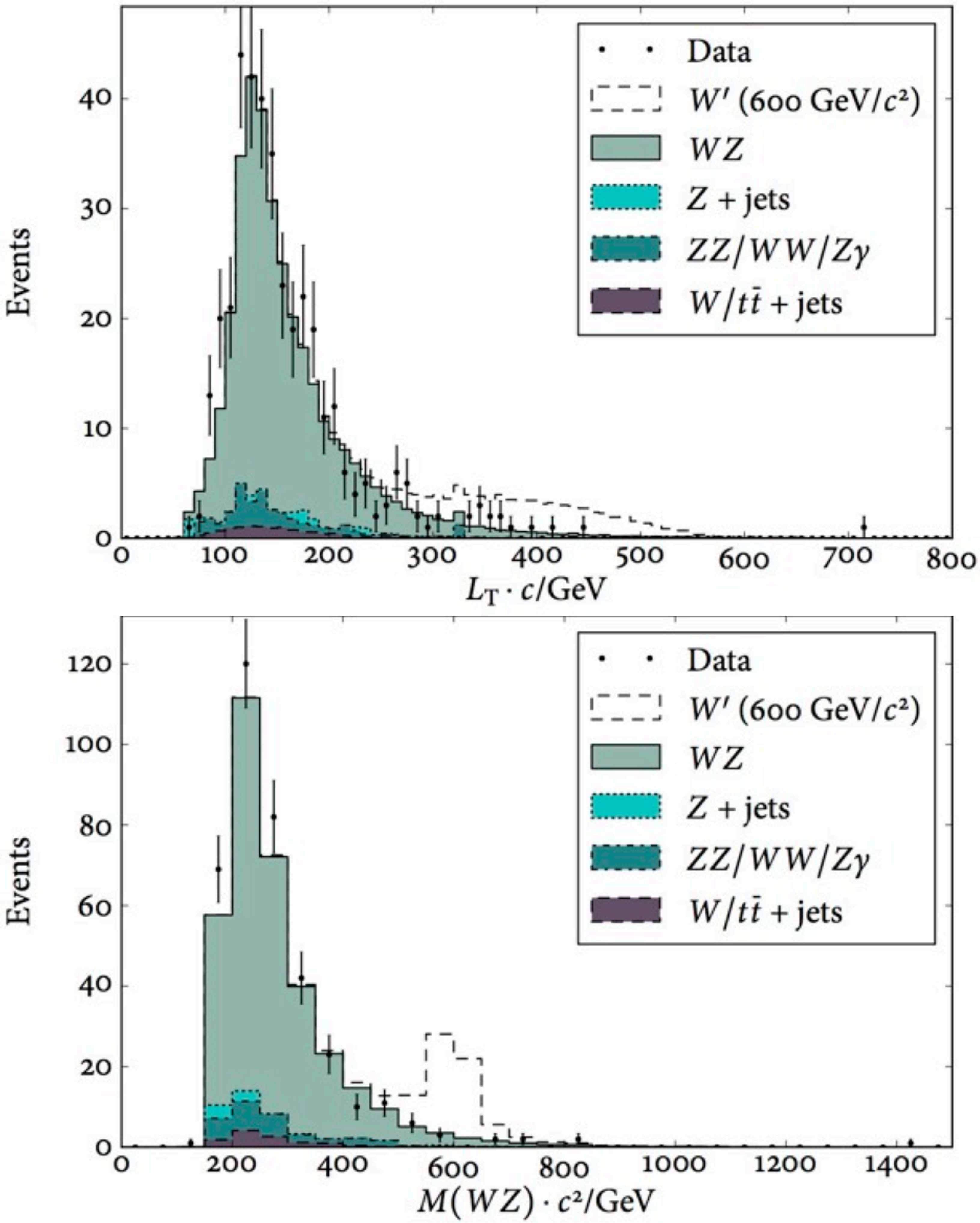
WZ Invariant Mass

- The leptons and MET can be combined to estimate the invariant mass of the system
- Resolution limited by lack of neutrino p_z and reliance on MET
- Invariant mass will be clustered around a central value for a new exotic particle

Requirements are optimized simultaneously for each mass hypothesis

Resonance

	Selection	
$M(W')$	$L_{\mathrm{T}}^{\mathrm{min}}$	w_M
200	—	20
250	150	40
300	160	40
400	220	80
500	230	100
600	290	120
700	360	160
800	400	180
900	400	280
1000	400	360
1100	400	420
1200	400	520
1300	400	560
1400	400	580
1500	400	600



Systematic Uncertainties

Uncertainties on efficiencies

- Detector performance (scales and resolutions)
- Theoretical models (choice of PDF, *k*-factors)
- Measured by varying parameter

Uncertainties on correction factors

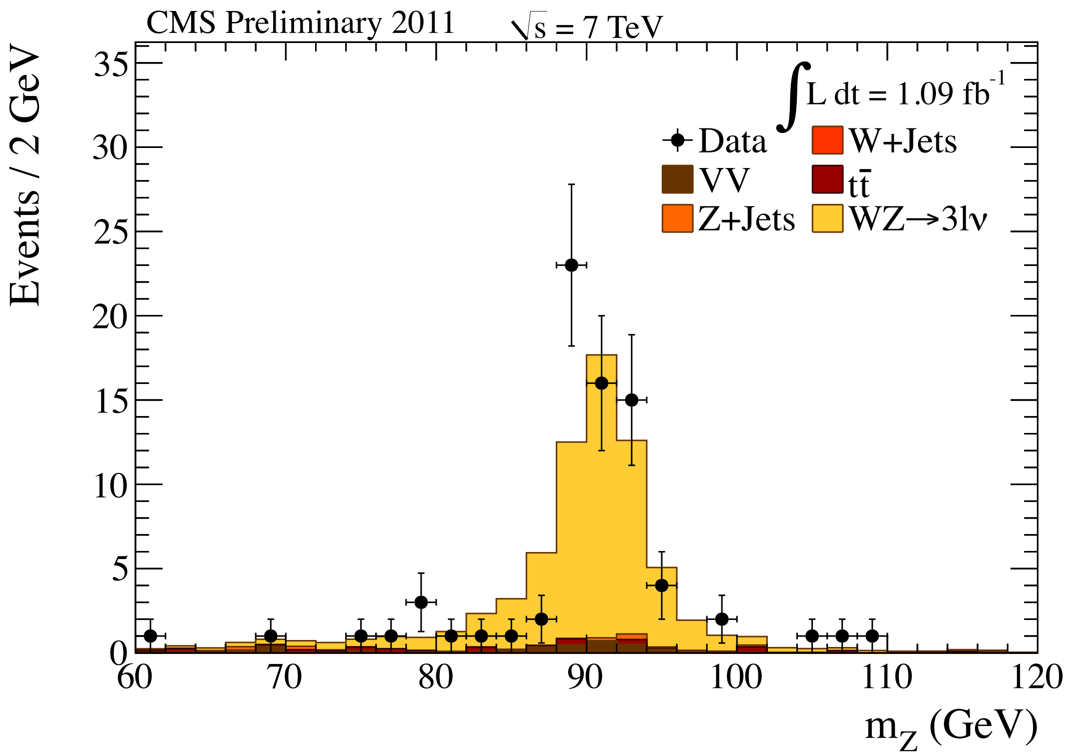
- Based on tag and probe measurements
- Measured by varying fitting function

Uncertainties on background yields

- Estimated from kinematic distributions of MadGraph at LO vs. MCFM at NLO

Results

Cross Section Measurement Approach



Performed summer 2011 with 1.09 fb^{-1} integrated luminosity

Cross section determined separately in each of the 4 decay channels

$$\sigma = \frac{N_{\text{signal}}}{A \cdot \epsilon \cdot \mathcal{L}}$$

$$\sigma = (1 - f_\tau)\frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{F} \cdot \rho \cdot \mathcal{L}}$$

$$N_{\text{bkg}} = P_{\text{fake}} \cdot N_{\text{jet}} + N_{\text{MC}}^{ZZ} + N_{\text{MC}}^{Z\gamma}$$

Channel	A/%	$\mathcal{F}$/%	ρ	N_{obs}	$(\sigma \times \text{BR})$/fb
$e^+e^-e^\pm$	48.2 ± 0.3	19.3 ± 0.3	0.97 ± 0.07	22	86 ± 22 ± 8 ± 5
$e^+e^-\mu^\pm$	48.8 ± 0.3	23.4 ± 0.3	1.00 ± 0.06	20	60 ± 17 ± 5 ± 4
$\mu^+\mu^-e^\pm$	43.2 ± 0.3	19.0 ± 0.3	0.94 ± 0.04	13	53 ± 18 ± 4 ± 3
$\mu^+\mu^-\mu^\pm$	45.4 ± 0.3	24.9 ± 0.3	0.97 ± 0.04	20	60 ± 16 ± 4 ± 4

Cross Section Measurement Results

A best-fit combination is performed, accounting for correlated systematics

The result agrees well with the theoretical prediction:

$$\sigma_{\text{obs}} = 17.0 \pm 2.4(\text{stat.}) \pm 1.1(\text{syst.}) \pm 1.0(\text{lumi.})\,\text{pb}$$

$$\sigma_{\text{NLO}} = 18.6 \pm 1.0\,\text{pb}$$

Effect on $\mathcal{F}$ (%)	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$
Electron energy scale	1.7	0.3	0.9	—
Muon p_T scale	—	0.5	0.2	0.9
$E_{\text{T}}^{\text{miss}}$ Resolution	0.5	0.5	0.5	0.5
$E_{\text{T}}^{\text{miss}}$ Scale	0.3	0.2	0.1	0.1
Pileup	3.1	0.8	1.6	1.6
PDF	1.0	1.0	1.0	1.0
NLO effect	2.5	2.5	2.5	2.5
Total	4.5	2.9	3.3	3.3

Effect on ρ (%)	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$
Electron trigger	1.5	1.5	—	—
Electron reconstruction	2.7	1.8	0.9	—
Electron ID and isolation	5.9	5.0	3.2	—
Muon trigger	—	—	1.1	1.1
Muon reconstruction	—	0.7	1.5	2.2
Muon ID and isolation	—	0.7	1.5	1.9
Total	6.7	5.6	4.2	3.6

Effect on WZ Yield (%)	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$
$\sigma(ZZ)$	0.2	0.4	0.3	0.4
$\sigma(Z\gamma)$	0.5	0.1	0.1	0.1
$\sigma(t\bar{t})$	1.3	1.3	0.9	0.5
P_{fake}	3.3	4.9	5.2	4.2

Resonance Measurement

We find no significant excess, so we seek to set limits on the cross sections for exotic particles

We set limits at 95% C.L. (confidence level) using a $\mathrm{CL_s}$ likelihood-based technique

Limits are interpreted in terms of SSM *W'* and various configurations of Low-Scale Technicolor

$M(W')c^2$/GeV	σ_{LO}/ pb
200	1.324×10^{0}
250	1.118×10^{0}
300	6.337×10^{-1}
400	2.040×10^{-1}
500	7.915×10^{-2}
600	3.620×10^{-2}
700	1.806×10^{-2}
800	9.857×10^{-3}
900	5.551×10^{-3}
1000	3.322×10^{-3}
1100	2.041×10^{-3}
1200	1.289×10^{-3}
1300	8.333×10^{-4}
1400	5.395×10^{-4}
1500	3.606×10^{-4}

Limit calculator takes in observed yield, background yield, lumi, efficiency, and errors

Selection Criteria and Yields

	Selection		Event Yields				Limit/pb	
$M(W')$	L_T^{min}	w_M	N_{data}	$N_{\text{MC}}^{\text{background}}$	$N_{\text{MC}}^{\text{signal}}$	$\epsilon_{\text{MC}}^{\text{signal}}/\%$	$\sigma_{\text{exp}}^{\text{upper}}$	$\sigma_{\text{obs}}^{\text{upper}}$
200	—	20	52	47.3 ± 0.7	300 ± 10	8.0 ± 0.4	0.064	0.072
250	150	40	40	32.2 ± 0.9	280 ± 10	8.8 ± 0.4	0.043	0.061
300	160	40	23	22.9 ± 0.7	330 ± 10	18 ± 1	0.017	0.017
400	220	80	7	12.0 ± 0.2	167 ± 4	29 ± 1	0.0066	0.0047
500	230	100	9	8.0 ± 1.0	91 ± 2	41 ± 1	0.0037	0.0047
600	290	120	2	3.2 ± 0.1	45.9 ± 0.8	45 ± 1	0.0022	0.0020
700	360	160	2	1.69 ± 0.09	24.4 ± 0.4	48 ± 1	0.0018	0.0021
800	400	180	1	0.96 ± 0.07	14.5 ± 0.2	52 ± 2	0.0013	0.0015
900	400	280	0	0.97 ± 0.07	9.5 ± 0.2	61 ± 2	0.0012	0.0010
1000	400	360	0	0.72 ± 0.06	5.97 ± 0.09	65 ± 2	0.0011	0.0010
1100	400	420	0	0.52 ± 0.05	3.57 ± 0.06	63 ± 1	0.0010	0.0010
1200	400	520	0	0.39 ± 0.04	2.04 ± 0.03	58 ± 1	0.0011	0.0011
1300	400	560	0	0.32 ± 0.04	1.12 ± 0.02	50 ± 1	0.0013	0.0012
1400	400	580	0	0.17 ± 0.03	0.52 ± 0.01	36 ± 1	0.0017	0.0017
1500	400	600	0	0.12 ± 0.02	0.28 ± 0.01	30 ± 1	0.0021	0.0020

Separate LT and mass window criteria for each mass hypothesis
Windows bigger as width of resonance increases; also detector resolution
Criteria optimized simultaneously

Systematic Errors

	$E_{\mathrm{T}}^{\mathrm{miss}}$ Scale		$\sigma(E_{\mathrm{T}}^{\mathrm{miss}})$		Pileup		$p_{\mathrm{T}}(\mu)$ Scale		$E_{\mathrm{T}}(e)$ Scale		$\sigma(\mathrm{PDF})/\%$	
$M(W')$	$\frac{\sigma_B}{B}/\%$	$\frac{\sigma_S}{S}/\%$	$\frac{\sigma_B}{B}/\%$	$\frac{\sigma_S}{S}/\%$	$\frac{\sigma_B}{B}/\%$	$\frac{\sigma_S}{S}/\%$	$\frac{\sigma_B}{B}/\%$	$\frac{\sigma_S}{S}/\%$	$\frac{\sigma_B}{B}/\%$	$\frac{\sigma_S}{S}/\%$	W'	WZ
200	0.99	0.01	0.52	1.9	1.7	0.31	0.45	3.1	1.0	1.9	2.370	3.2
250	0.24	0.90	0.59	1.3	2.2	0.58	2.5	1.6	3.1	2.5	2.370	3.4
300	1.1	0.49	0.72	0.97	1.9	2.0	2.2	0.51	4.3	1.3	2.370	3.3
400	1.7	0.43	0.77	0.53	2.2	0.71	1.9	1.0	4.2	2.2	2.764	3.2
500	1.8	0.38	0.91	0.36	2.6	2.3	1.7	0.71	3.6	1.5	3.181	3.6
600	1.3	0.10	1.4	0.30	1.7	1.6	3.1	0.55	4.8	1.6	3.704	4.0
700	2.4	0.15	1.7	0.23	3.0	0.82	5.3	0.91	4.2	1.7	4.198	4.7
800	3.9	0.28	1.9	0.20	4.0	1.4	3.9	0.87	4.3	1.7	4.624	4.8
900	2.3	0.24	1.9	0.13	3.6	1.6	3.0	0.72	6.4	0.94	5.135	6.3
1000	2.7	0.03	2.4	0.12	0.36	1.4	5.0	0.37	8.7	0.49	5.695	8.9
1100	1.1	0.16	2.2	0.13	0.83	1.1	2.6	0.15	6.7	0.51	6.088	7.8
1200	0.16	0.13	2.6	0.12	1.3	1.2	2.8	0.34	13	0.54	6.516	12
1300	0.70	0.10	2.9	0.12	1.3	1.9	4.7	0.12	5.7	0.38	7.349	28
1400	4.7	0.10	3.7	0.14	2.3	1.4	4.2	0.46	8.2	0.85	7.760	7.8
1500	0.01	0.02	4.2	0.19	0.92	2.6	0.72	0.37	11	1.3	8.471	0.0

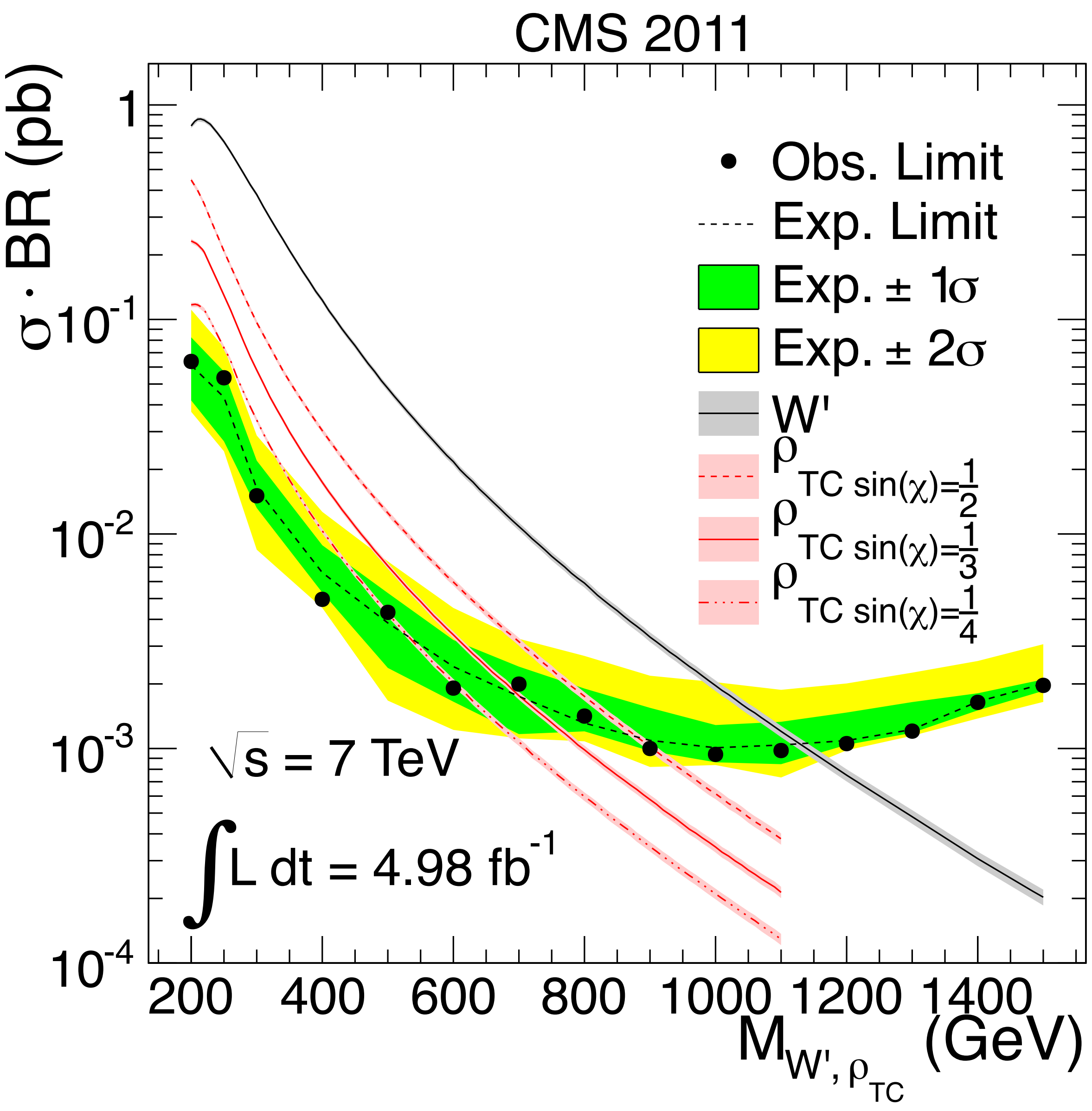
Scale uncertainties affect yields after full selection; estimated from sim
PDF uncertainties affect cross sections (uncertainty on alpha_s)
Lumi error is 2.2%

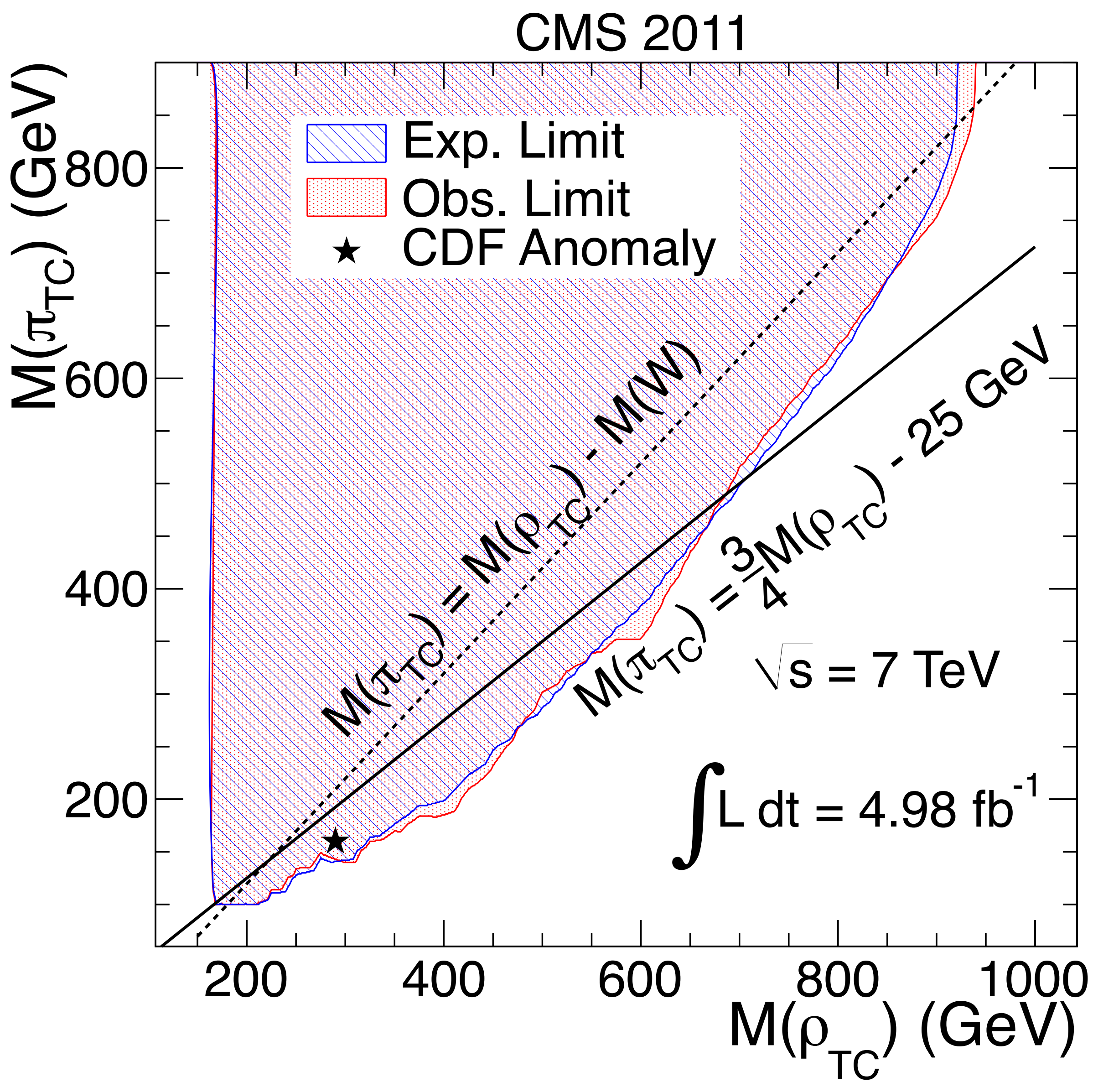
Interpretation of Limits

$M(W') > 1143$ GeV/c^2 within SSM

$M(\rho_T) > 687$ GeV/c^2 or $M(\rho_T) < 167$ GeV/c^2

Rules out Technicolor interpretation of the CDF anomaly





Explain plots in detail
D0 excludes M(W’) < 520
D0 used the parameters shown on the dotted line, they exclude 208 < M < 408; we exclude 180 < M < 938

Conclusions and Outlook

Conclusions and Outlook

Measured $\sigma(WZ)$ with 1.09 fb^{-1} data

- Best measurement at 7 TeV
- Will be updated with 4.98 fb^{-1} including limits on anomalous gauge couplings

Set world's best limits on new exotic particles decaying to *WZ*

- Raised limit on SSM *W'* from 520 to 1143
- Raised limit on ρ_T from 408 to 938
- Ruled out TC interpretation of CDF anomaly
- Expect significantly extended reach in 2012 with 8 TeV energy and ~4 times data

Backup

Resonance Measurement

We find no significant excess, so we seek to set limits on the cross sections for exotic particles

We set limits at 95% C.L. (confidence level) using a $\mathrm{CL_s}$ likelihood-based technique

- Define test statistic
- Find σ for which $\mathrm{CL_s} = 5\%$
- Expected limit based on 1000 background-only MC *pseudoexperiments*
- Event yield modeled as Poisson
- Luminosity and efficiencies modeled as Gaussian

$M(W')c^2/\mathrm{GeV}$	$\sigma_{\mathrm{LO}}/\,\mathrm{pb}$
200	1.324×10^{0}
250	1.118×10^{0}
300	6.337×10^{-1}
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Limit calculator takes in observed yield, background yield, lumi, efficiency, and errors