WZ production at Hadron Colliders

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Outline

- Introduction
- The experimental apparatus
- The data analysis
- Results
- Conclusion

Introduction

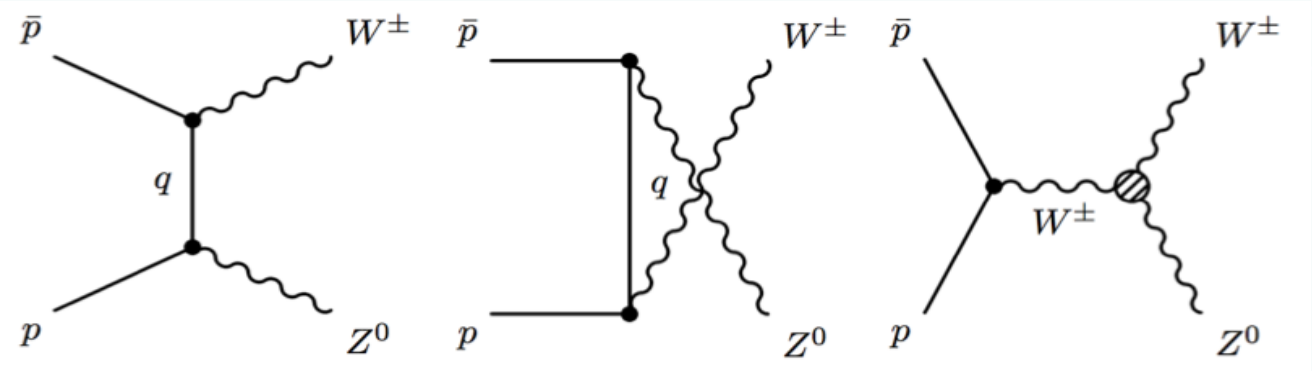
- The standard model
  - A successful theory
  - Low-energy approximation only
    1. Origin of mass
    2. Mechanism of EW symmetry breaking
    3. Hierarchy problem
    4. Origin of dark matter
    5. Etc.

How to solve puzzle(s)?

- Different theories developed
  - Higgs mechanism
  - Supersymmetry (SUSY)
  - Extra-dimensions (ED)
  - And, maybe none of those?
- Experimentally being tested
  - WZ production could be sensitive
    - Probe the SM and beyond

The WZ production

- Tree level productions
  - The triple/quadruple couplings allowed between gauge fields



- The least-well tested sector of EW interactions
  - Charged final state – could not be produced at LEP

The WWZ vertex

- The effective Lagrangian of WWZ vertex
  - *C*,*P* conserving – g^Z_1, κ_Z, λ_Z
    - SM: $g^Z_1=1$, $\kappa_Z=1$, $\lambda_Z=0$

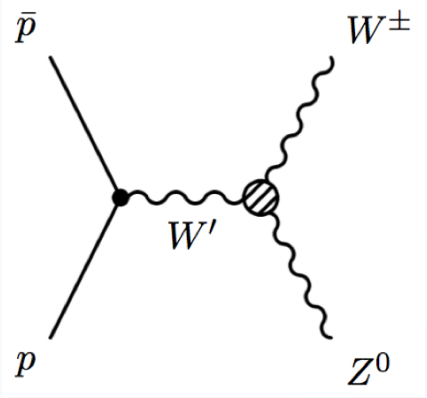
$$
\begin{aligned}
\mathcal{L}_{WWZ}/g_{WWZ} = & \, ig_1^Z(W^\dagger_{\mu\nu}W^\mu Z^\nu - W^\dagger_\mu Z_\nu W^{\mu\nu}) \\
& + i\kappa_Z W^\dagger_\mu W_\nu Z^{\mu\nu} \\
& + \frac{i\lambda_Z}{M_W^2} W^\dagger_{\rho\mu} W^\mu_\nu Z^{\nu\rho} \\
& - g_4^Z W^\dagger_\mu W^\nu(\partial^\mu Z^\nu + \partial^\nu Z^\mu) \\
& + g_5^Z \epsilon^{\mu\nu\rho\sigma}(W^\dagger_\mu \partial_\rho W_\nu - W_\nu \partial_\rho W^\dagger_\mu) Z_\sigma \\
& + \tilde{\kappa_Z} W^\dagger_\mu W^\nu \tilde{Z}^{\mu\nu} \\
& + \frac{i\tilde{\lambda}_Z}{M_W^2} W^\dagger_{\rho\mu} W^\mu_\nu \tilde{Z}^{\nu\rho},
\end{aligned}
$$

- Measure WWZ coupling
  - Direct measurement of WWZ vertex
- σ(WZ)/WWZ coupling – probe the SM

Particles we searched for…

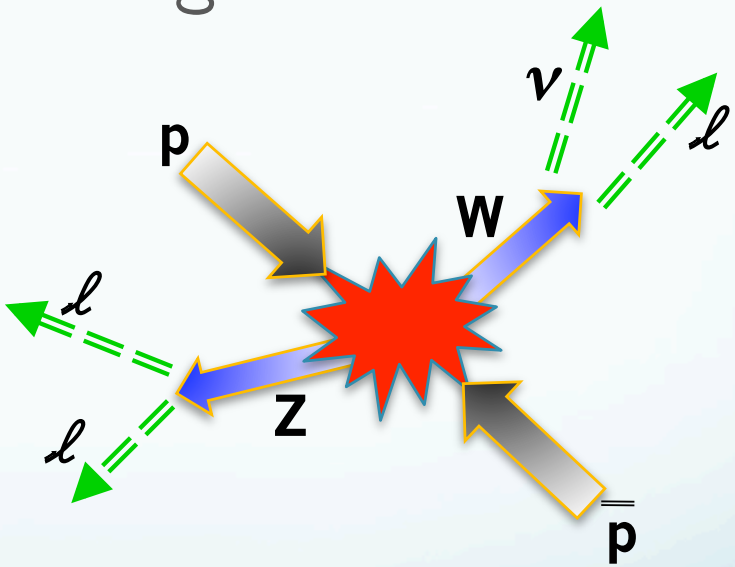
- Sequential W'
  - Similar coupling to WZ bosons
- Probe for different coupling strength between W'WZ
- Within low scale Technicolor
  - Masses of light particles < 500 GeV
  - $\rho_T^{\pm} / a_T^{\pm} \rightarrow W^{\pm} Z$ — dominant decay for heavy π_T
    - Very distinct signature, narrow resonances

$$\Gamma_{W'}(M_{W'}) = \frac{4}{3}\frac{M_{W'}}{M_W}\Gamma_W$$



Signature of WZ

- Study leptonic decay of WZ
  - Three charged leptons missing transverse energy due to neutrino
    - eeeν, eeμν, μμeν, μμμν
  - The smallest branching fraction – 0.36%
  - The clean signature



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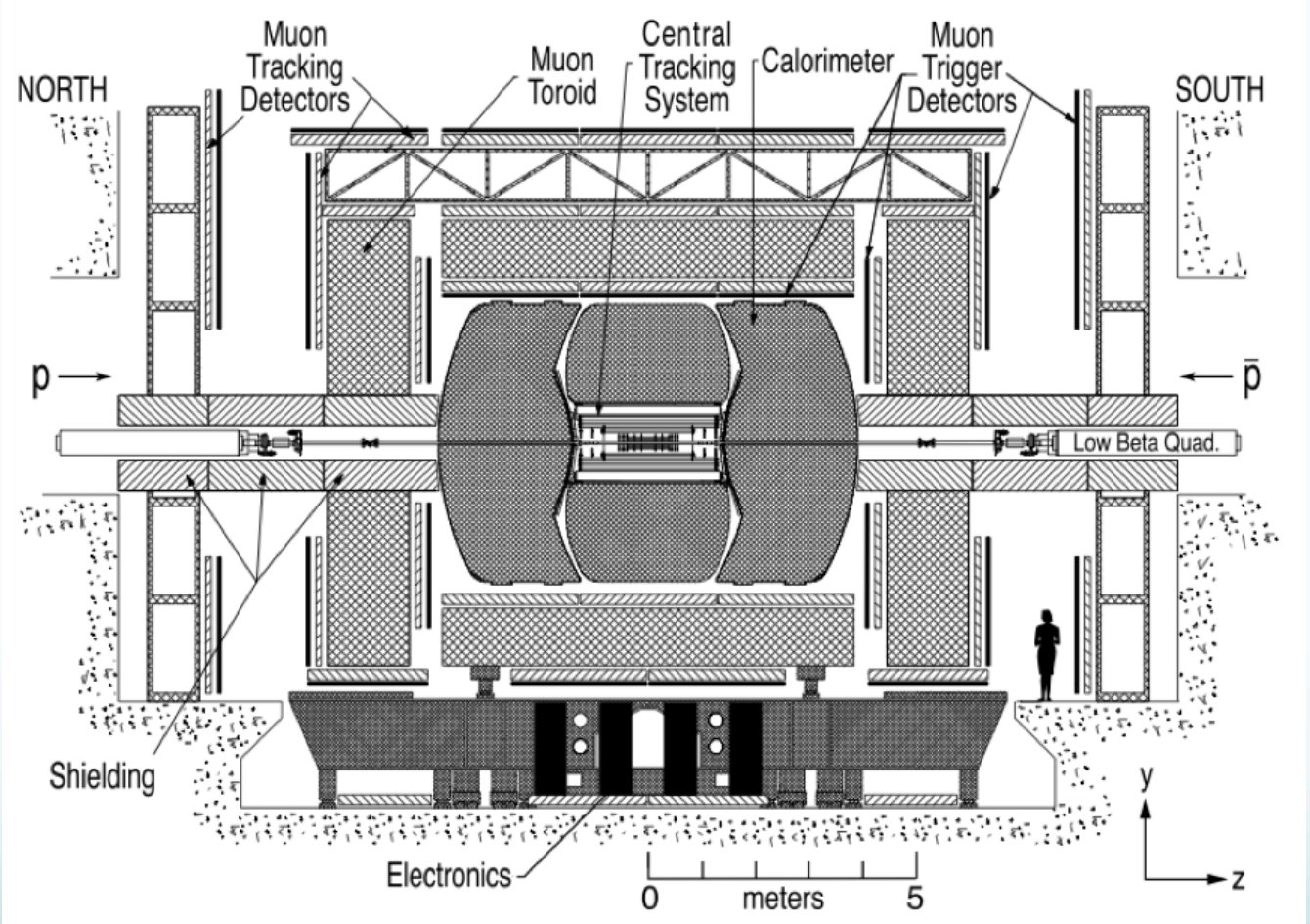
D0 detector



The results are obtained using 4.1 fb^{-1}

Outline

- Introduction
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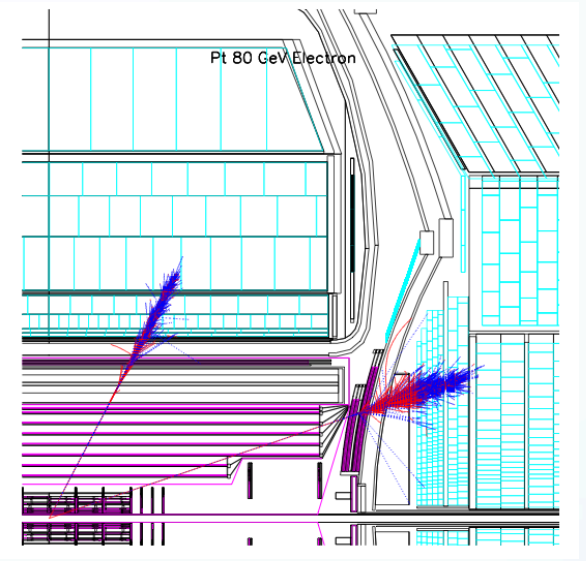
- The data analysis
  - Object identification
  - Event selection
  - Background estimation
- Results
- Conclusion

Electrons

- Reconstructed as
  - Energy deposit in calorimeter
  - Isolated track
- Identification
  - Isolation, EM fraction
  - Track match, isolation
  - Shower shape
  - Multivariable discriminators

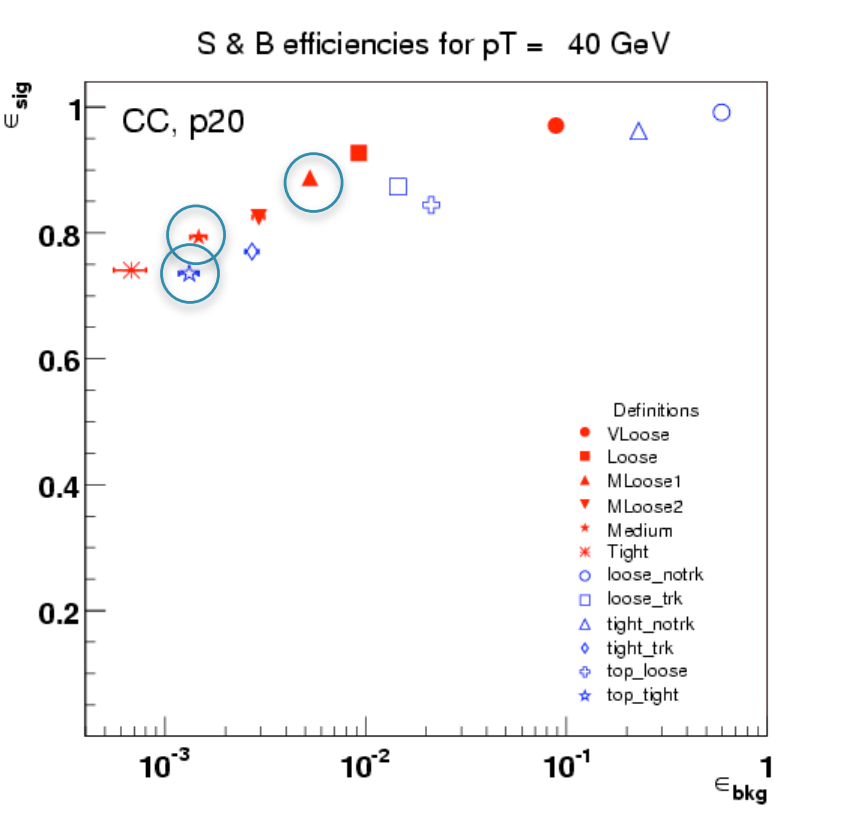


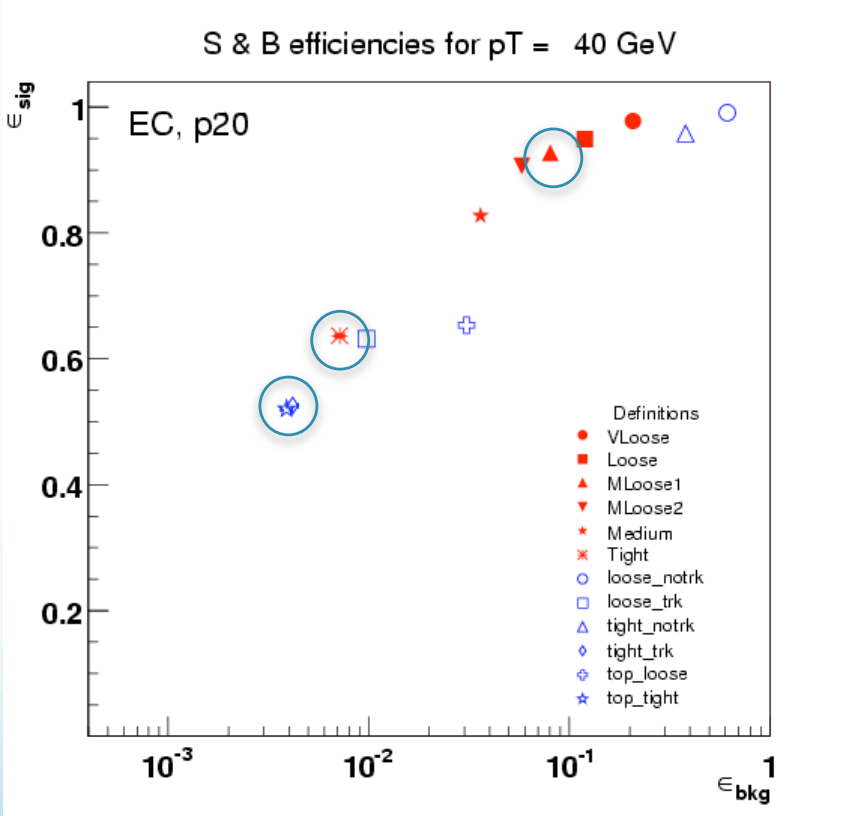
$$Iso = \frac{E_{tot}(0.4) - E_{em}(0.2)}{E_{em}(0.2)} < 0.2$$

$$emfr = \frac{E_{em}(0.2)}{E_{tot}(0.2)} > 90\%$$

Electron ID efficiency

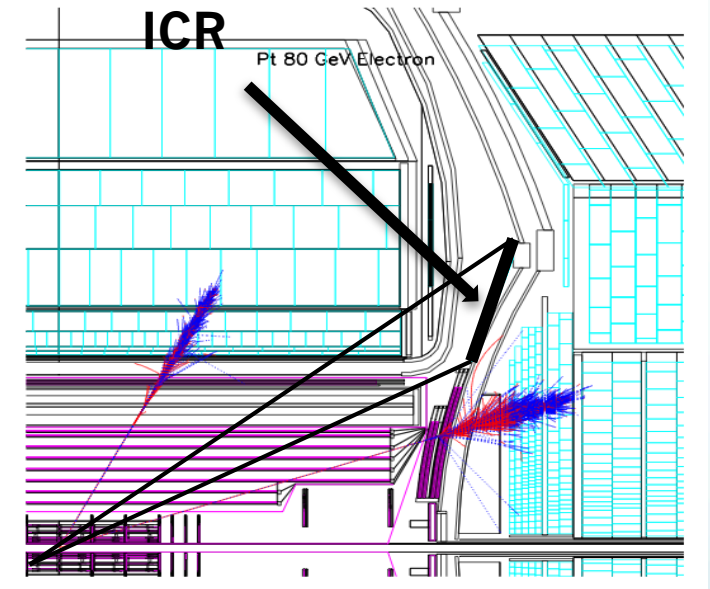
- Several definitions of electrons



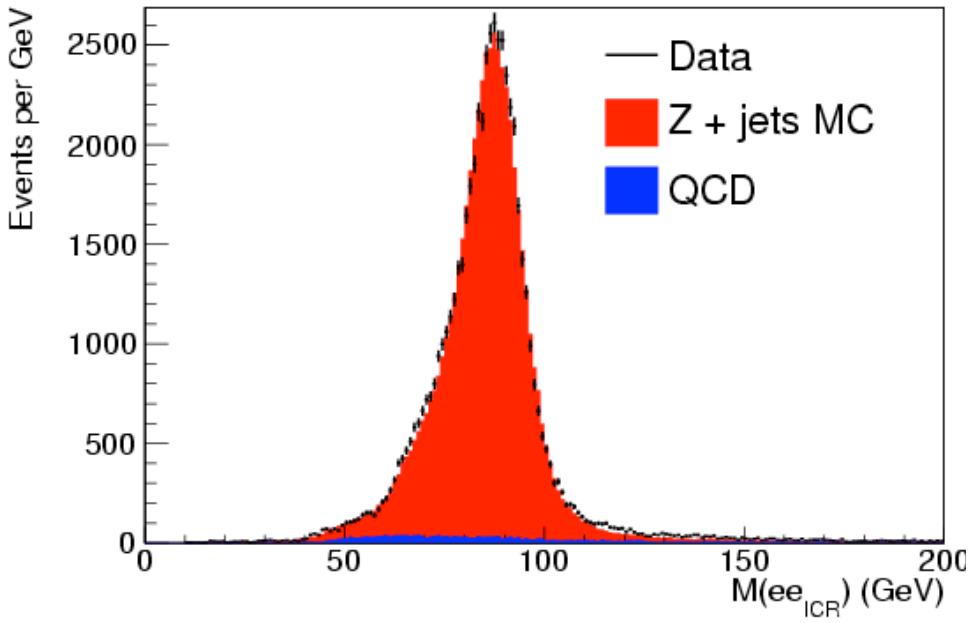


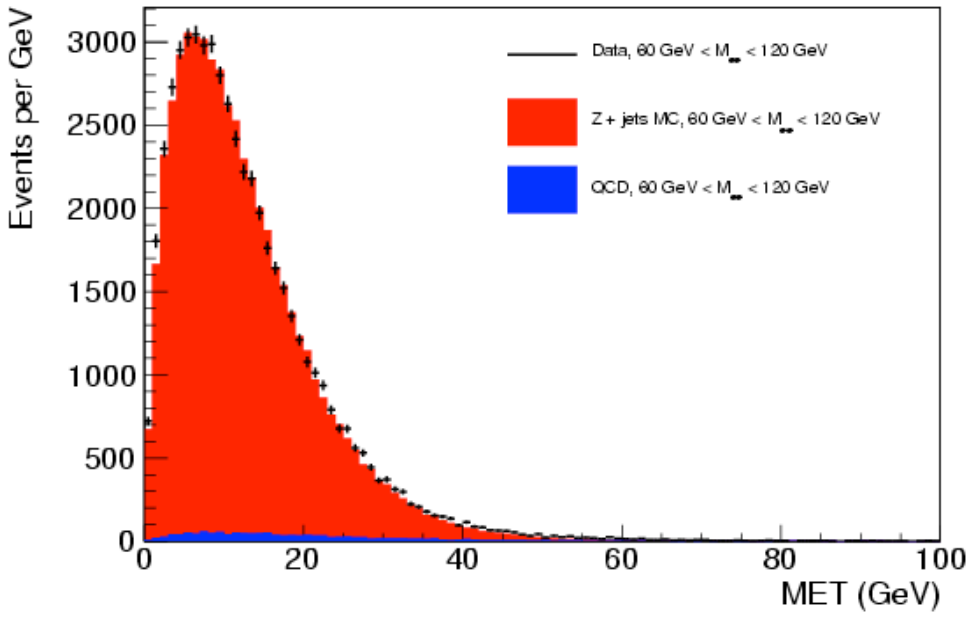
Electrons in ICR

- One of the first using ICR
  - $1.1 < |\eta| < 1.5$
  - Coarse sampling layers
    - Limited EM coverage
  - Identified as
    - E_T >10 GeV
    - p_T^{trk} > 20 GeV
    - NN to reduce background



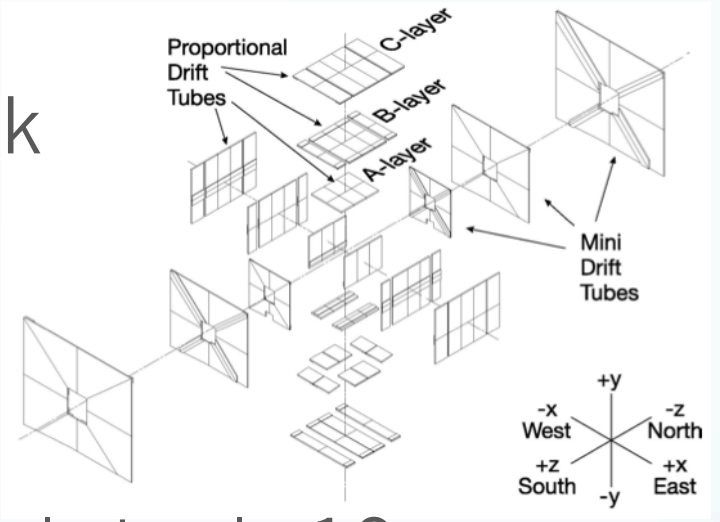
ICR electron data/MC agreement





Muons

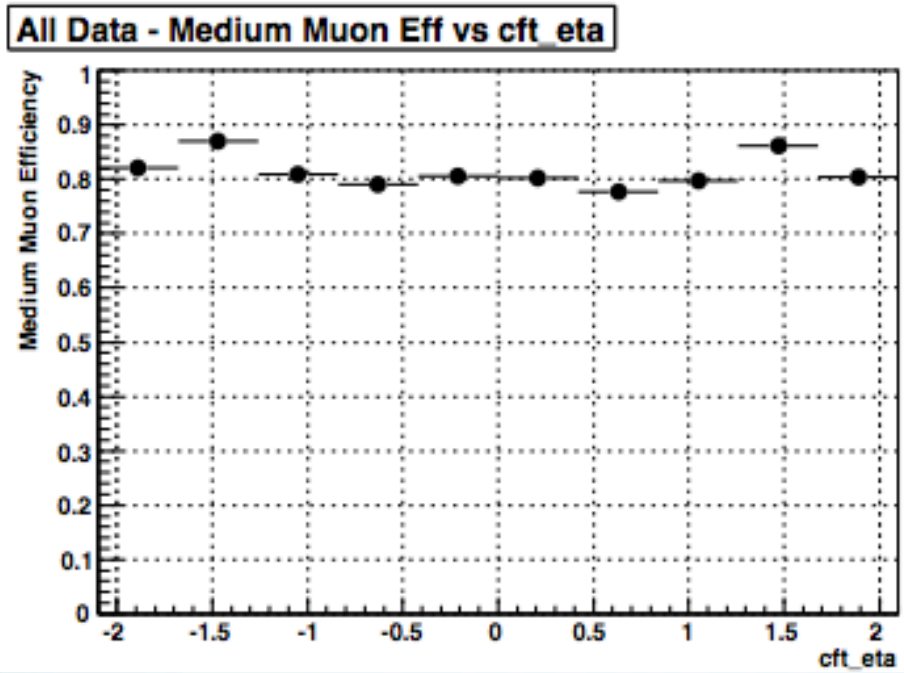
- Reconstructed as muon track matched to central track
- Different Muon qualities
  - # of hits in muon system
    - Suppress cosmic muons – $|\Delta t_{hits}|<10$ ns
  - Presence of central track
    - Matching χ^2, distance of closest approach
    - # of SMT hits
  - Isolation

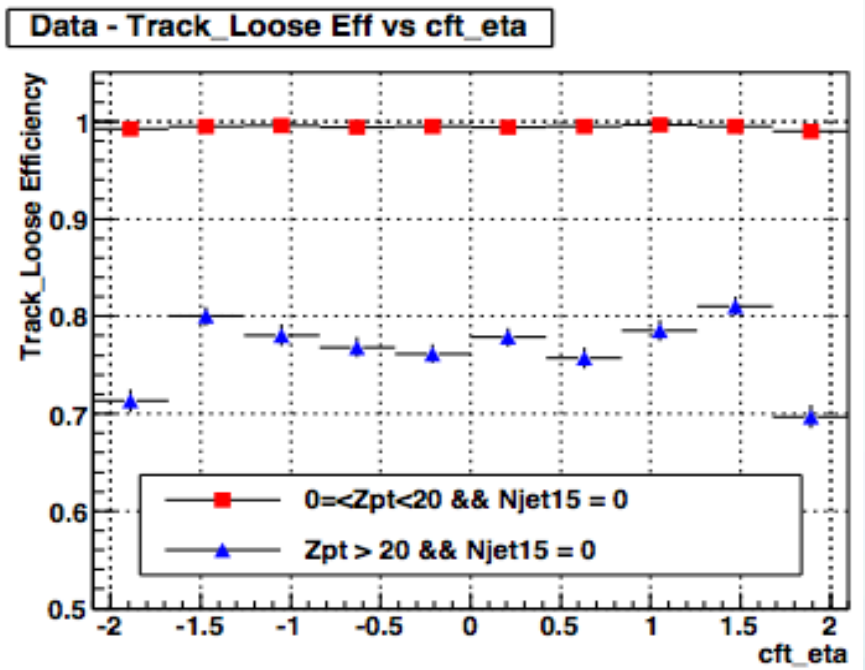


$$Iso^{cal} = \sum_{cells} E_T^{cell}(\Delta R = 0.4) - \sum_{cells} E_T^{cell}(\Delta R = 0.1)$$

$$Iso^{track} = \sum_{tracks} p_T^{track}(\Delta R = 0.5) - p_T^{\mu}$$

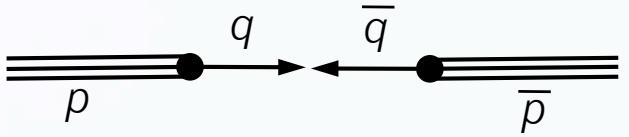
Muon ID efficiency





Missing transverse energy

- Initial state momentum not known



  - Momentum in transverse plane is ≈0
  - MET is calculated from calorimeter
    - Excluding coarse hadronic layers

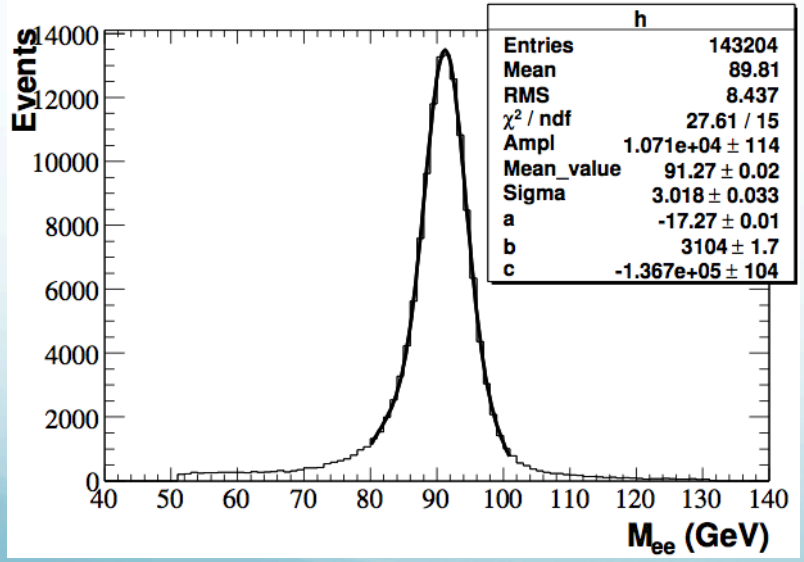
$$E_{Tx}^{miss} = -\sum_{i}^{cells} E_{Ti}\cos\phi_i \qquad E_{Ty}^{miss} = -\sum_{i}^{cells} E_{Ti}\sin\phi_i$$

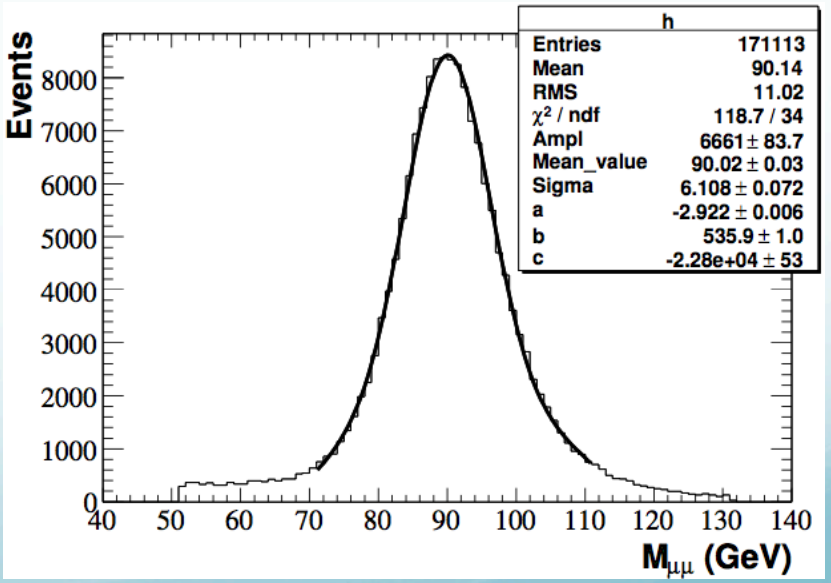
$$\overrightarrow{E_T^{miss}} = E_{Tx}^{miss}\hat{x} + E_{Ty}^{miss}\hat{y}$$

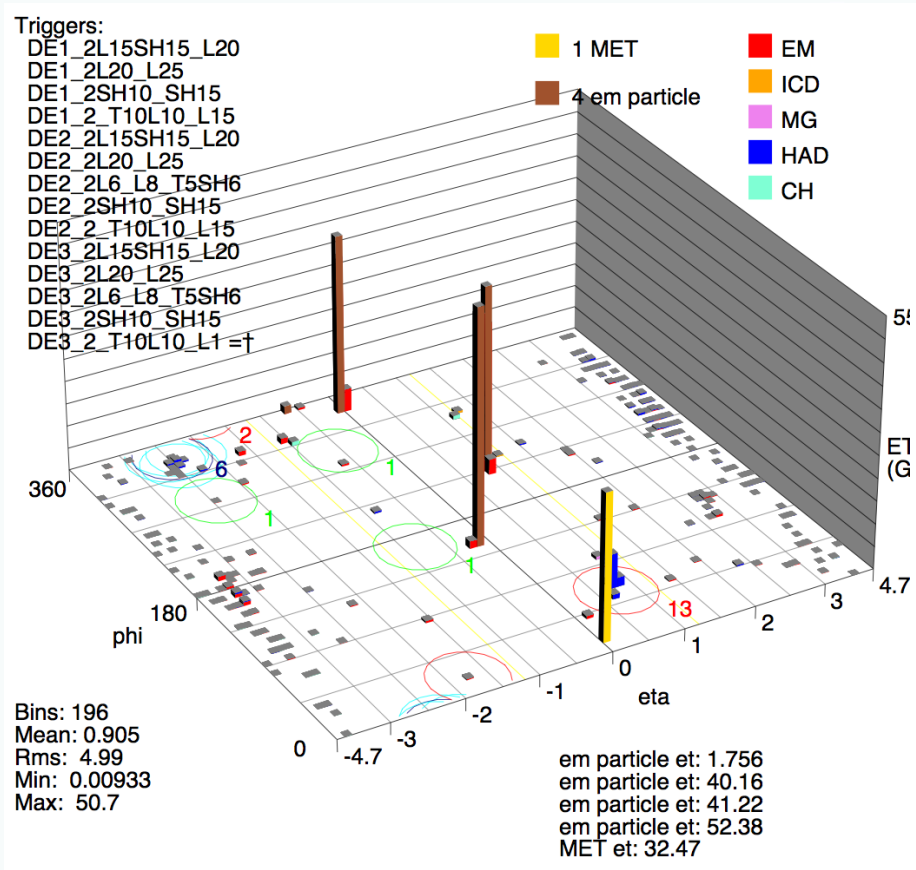
  - Corrected for muons in the event

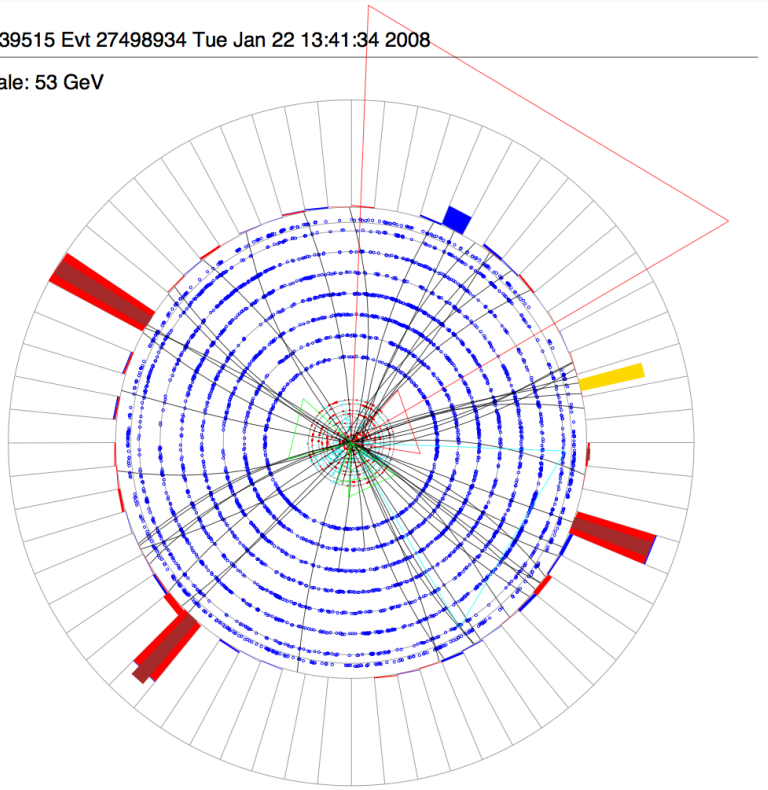
Event Selection

- Energetic leptons, spatially separated, originated from the same vertex
  - Different lepton identification for Z/W decay products
  - M(ll) consistent to Z boson mass
- Significant MET

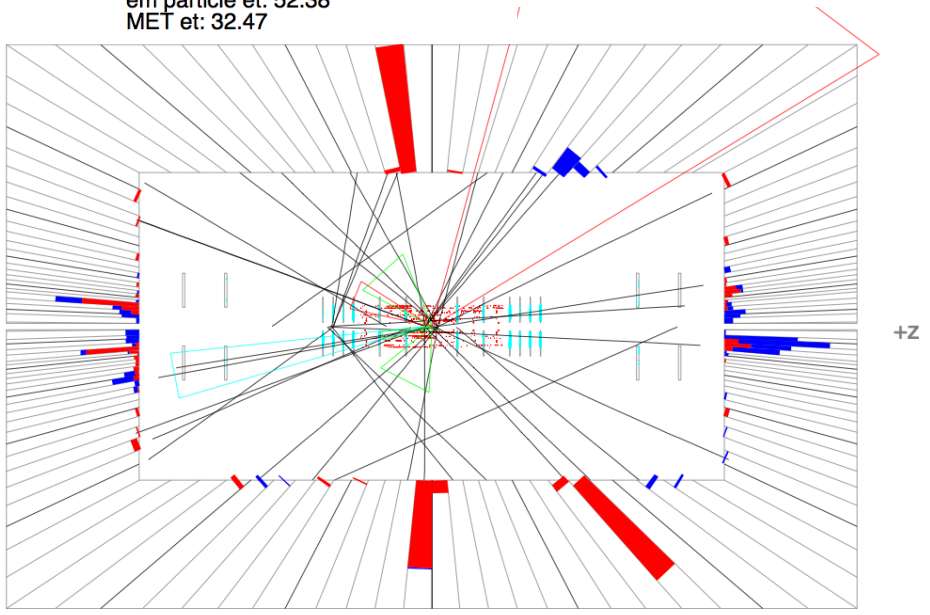




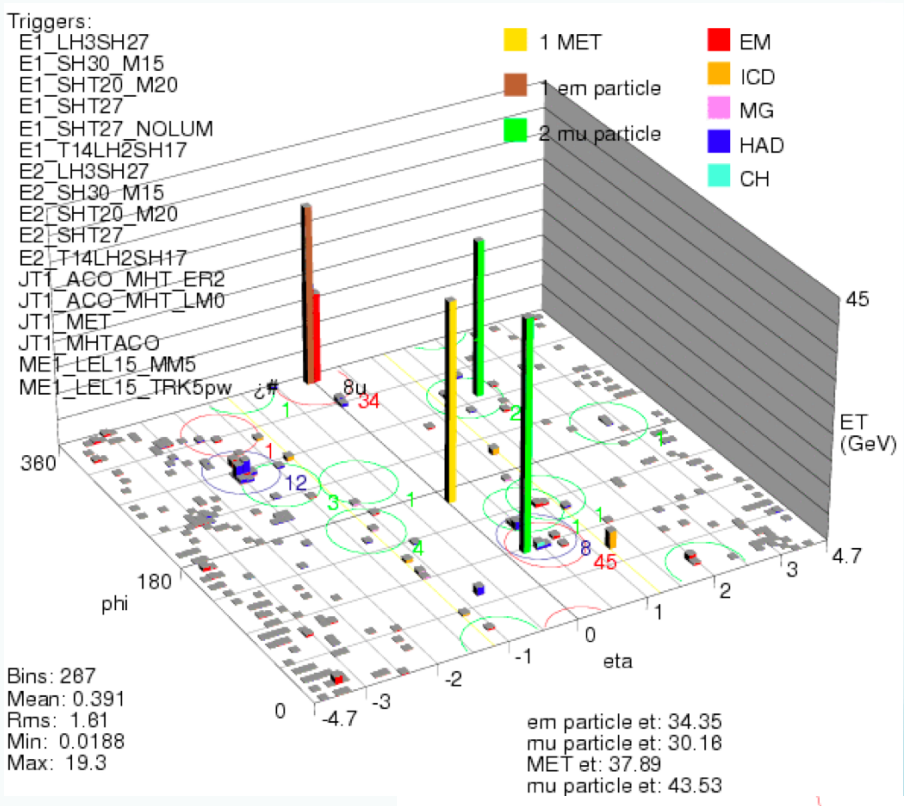


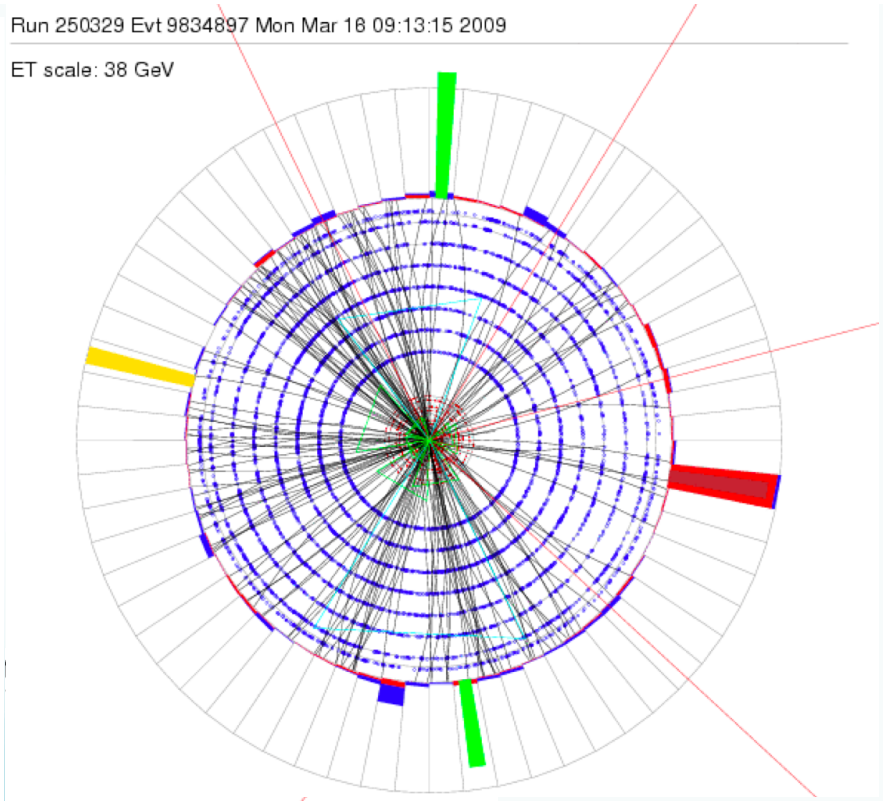


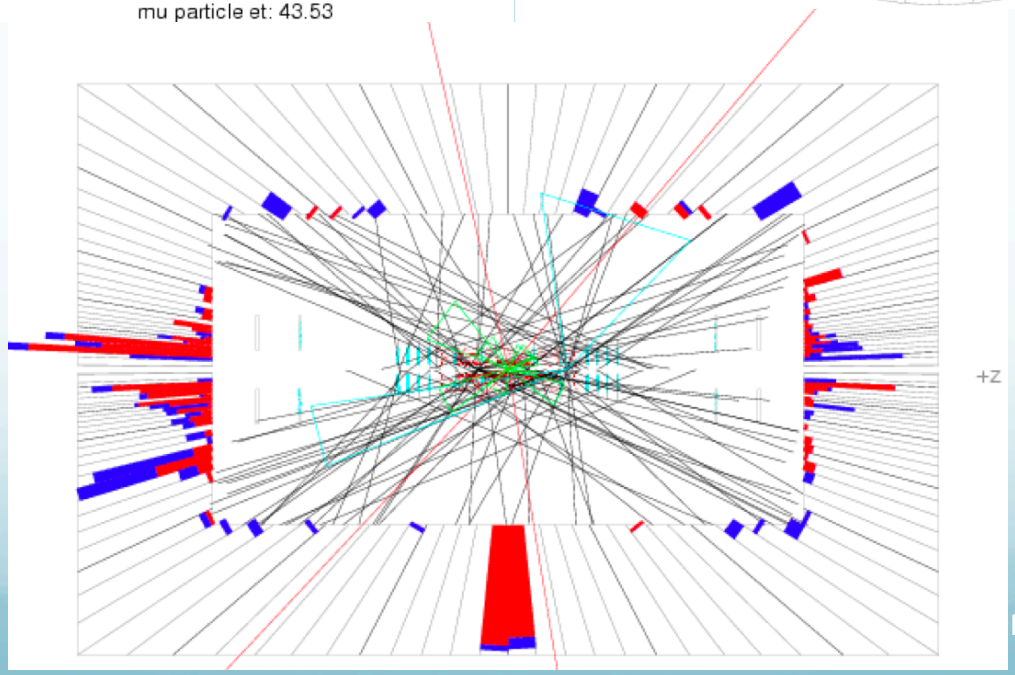
em particle et: 1.756
em particle et: 40.16
em particle et: 41.22
em particle et: 52.38
MET et: 32.47



eeeν event


Triggers:
E1_LH3SH27
E1_SH30_M15
E1_SHT20_M20
E1_SHT27
E1_SHT27_NOLUM
E1_T14LH2SH17
E2_LH3SH27
E2_SH30_M15
E2_SHT20_M20
E2_SHT27
E2_T14LH2SH17
JT1_ACO_MHT_ER2
JT1_ACO_MHT_LM0
JT1_MET
JT1_MHTACO
ME1_LEL15_MM5
ME1_LEL15_TRK5pw
1 MET
1 em particle
2 mu particle
EM
ICD
MG
HAD
CH
ET (GeV)
45
4.7
360
180
phi
0
-4.7
-3
-2
-1
0
1
2
3
eta
Bins: 267
Mean: 0.391
Rms: 1.61
Min: 0.0188
Max: 19.3
em particle et: 34.35
mu particle et: 30.16
MET et: 37.89
mu particle et: 43.53


Run 250329 Evt 9834897 Mon Mar 16 09:13:15 2009
ET scale: 38 GeV


+z

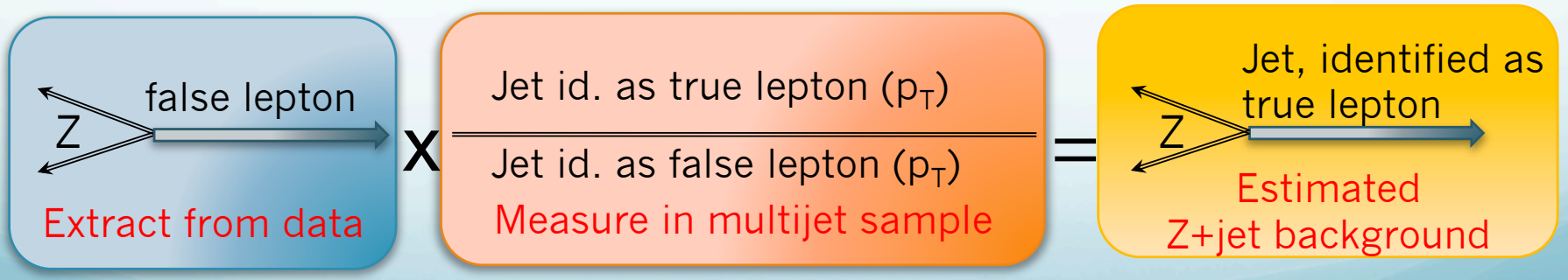
μμeν event

Are those WZ events?

- Three leptons + MET can be mimicked
  - Physics
    - ZZ production
  - Instrumental backgrounds
    - Z+jets
      - Jet(s) is identified as an electron/muon
    - $Z\gamma$
      - γ is identified as an electron
    - ttbar, W+jets – negligible

Estimation of Z+jets I

- Jet – spray of hadrons
  - Fake lepton, mainly electron
    - Track(s)
    - Energy deposit in calorimeter. e.g.: $\pi^0 \rightarrow \gamma\gamma$
  - Genuine non-isolated leptons
    - Semi-leptonic decay of heavy flavor quarks

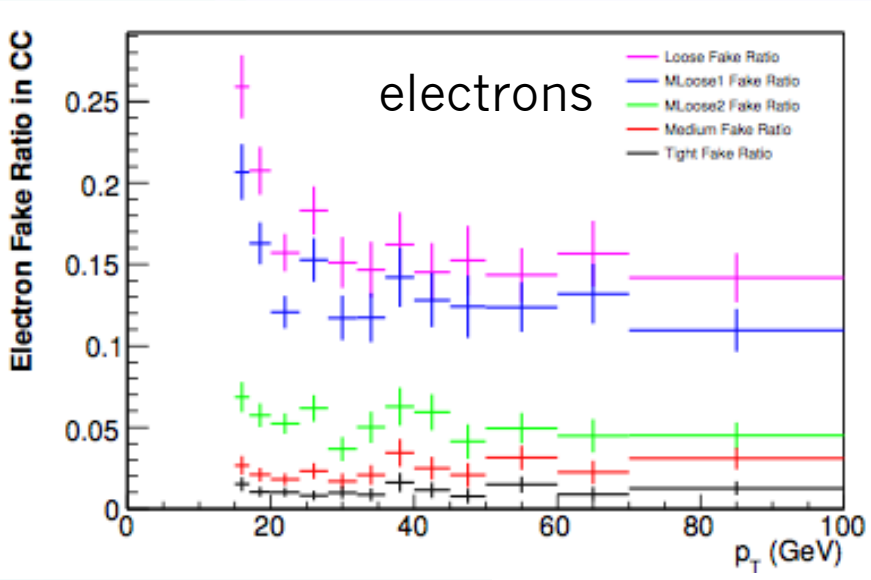


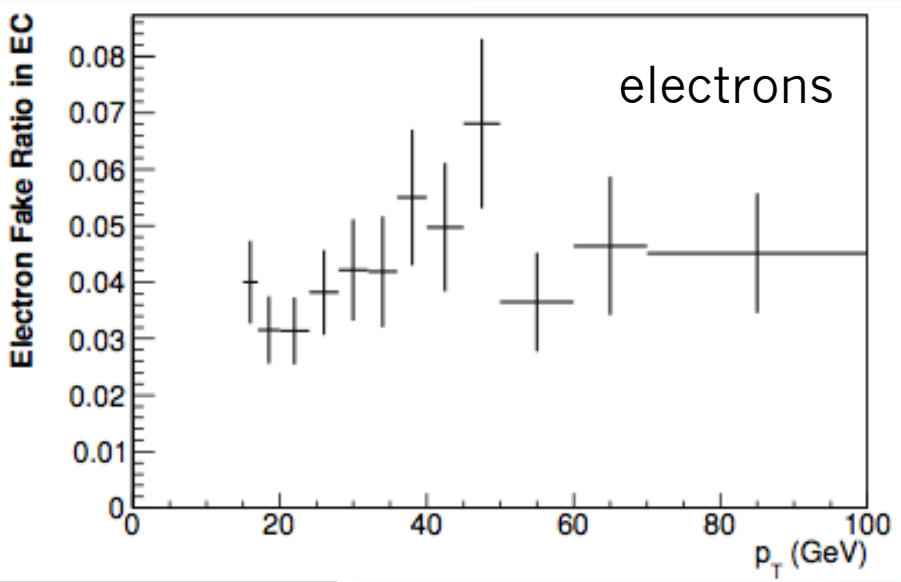
Estimation of Z+jets II

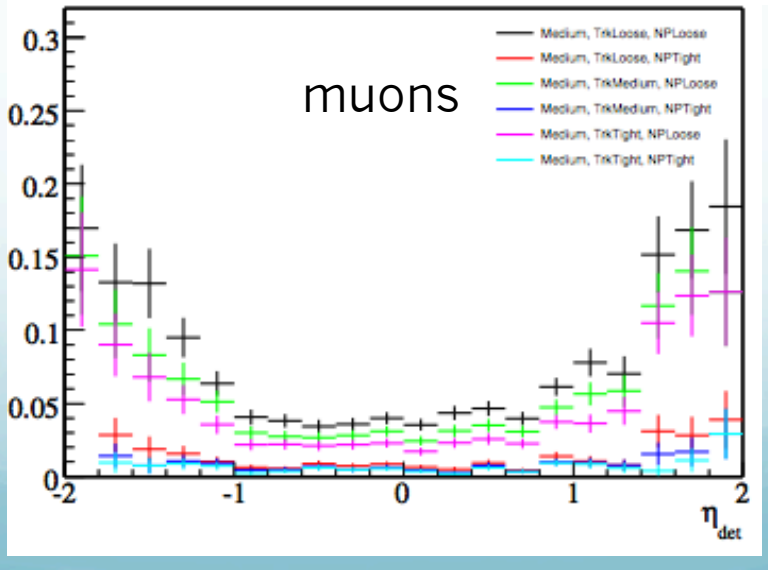
- Misidentification ratio measurement
  - Good quality jet
  - MET < 10 GeV
    - Avoid contamination from W events
  - Look for “false” lepton away from jet
    - Electron – shower shape inconsistent
    - Muon – non-isolated track

$$fr(p_T) = \frac{dN_{"true"}/dp_T}{dN_{"false"}/dp_T} \qquad fr(\eta) = \frac{dN_{"true"}/d\eta}{dN_{"false"}/d\eta}$$

Misidentification ratios





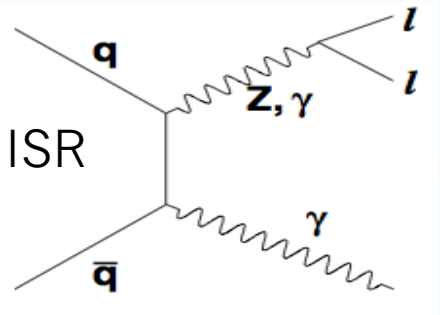


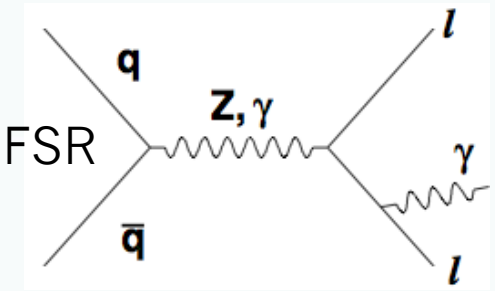
Estimation of Z+jets III

- Z+"false" lepton sample – for each channel
  - Limited statistics
- Systematic effects
  - The statistics in multijet sample
  - MET cut for measurement of mis-id ratios
    - Vary up to MET < 20 GeV
      - Difference is assigned as systematic unc.
  - ΔR(jet,"fasle"lep) – negligible effect

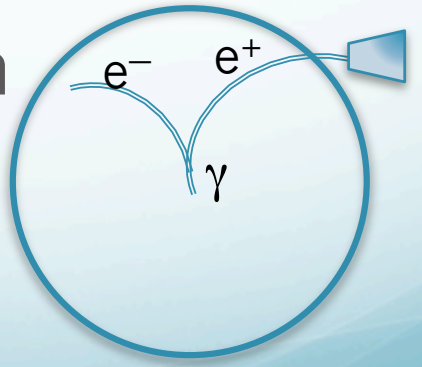
Estimation of Zγ I

- Background to W+Z→eν+Z channels
  - Initial and final state radiation



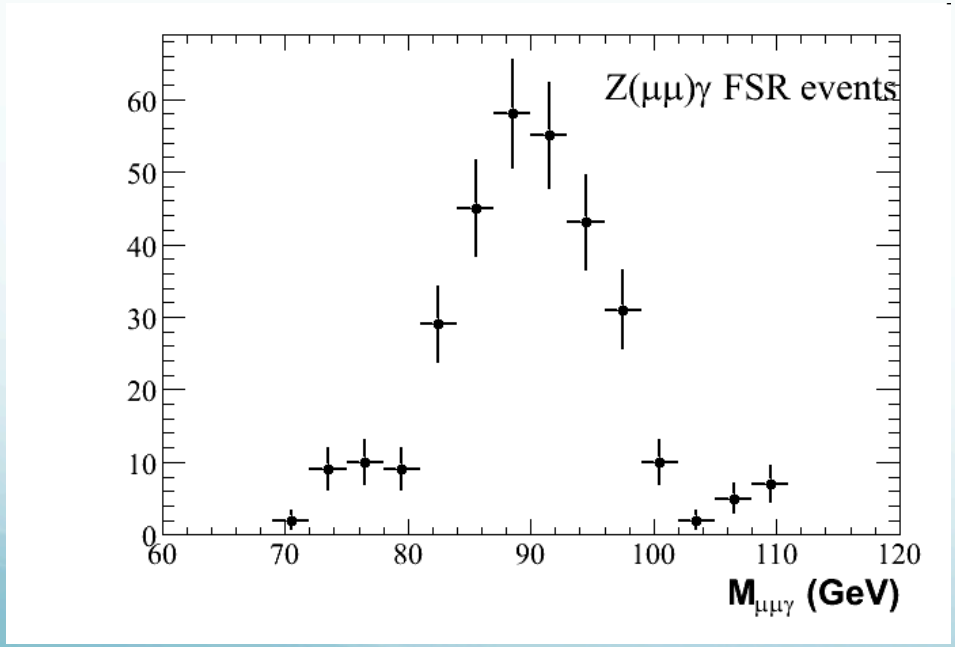


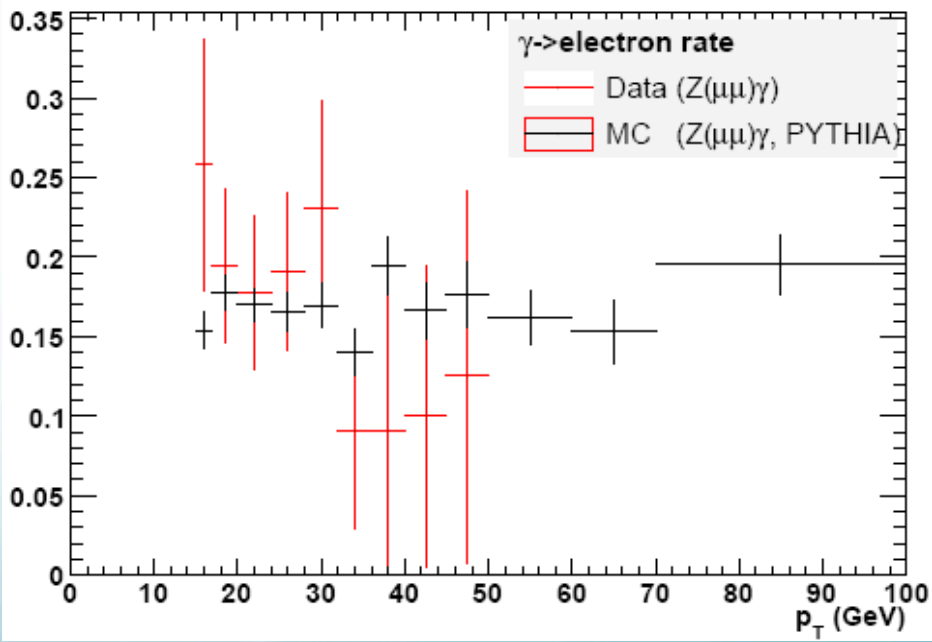
- Photon is misidentified as electron
  - Conversion $\gamma \rightarrow e^+e^-$
  - Track mismatch



Estimation of Zγ II

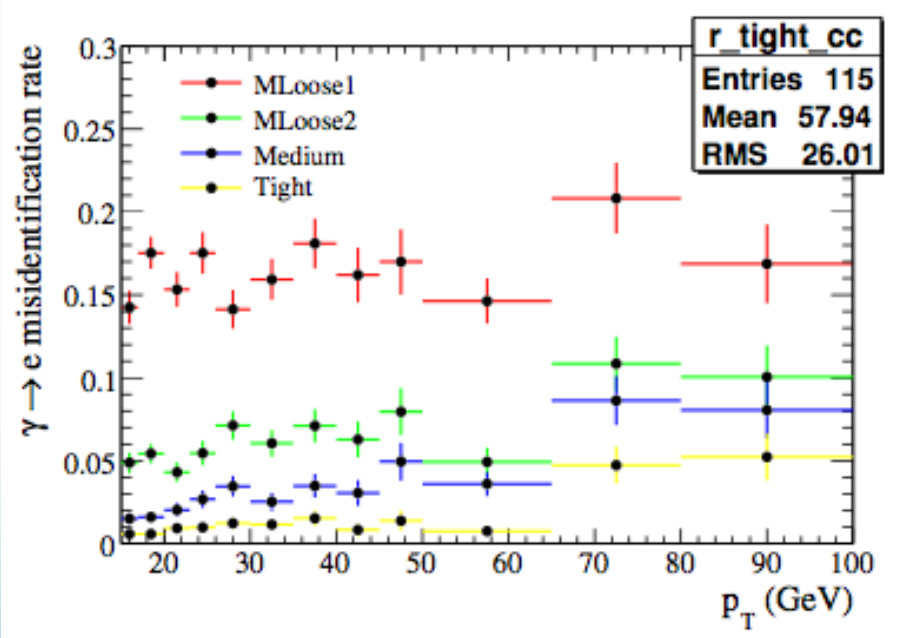
- Measure the misidentification rate
  - Z(μμ)γ FSR in data
    - M(μμγ) consistent with the Z boson mass
  - Z(μμ)γ ISR in MC

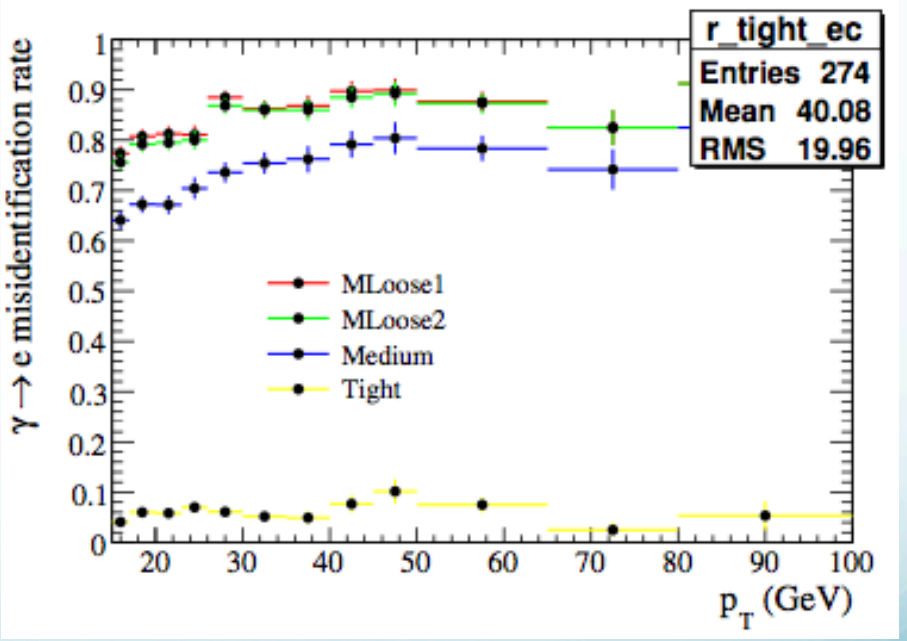




Misidentification rates

- For tight selection misidentification probability is small



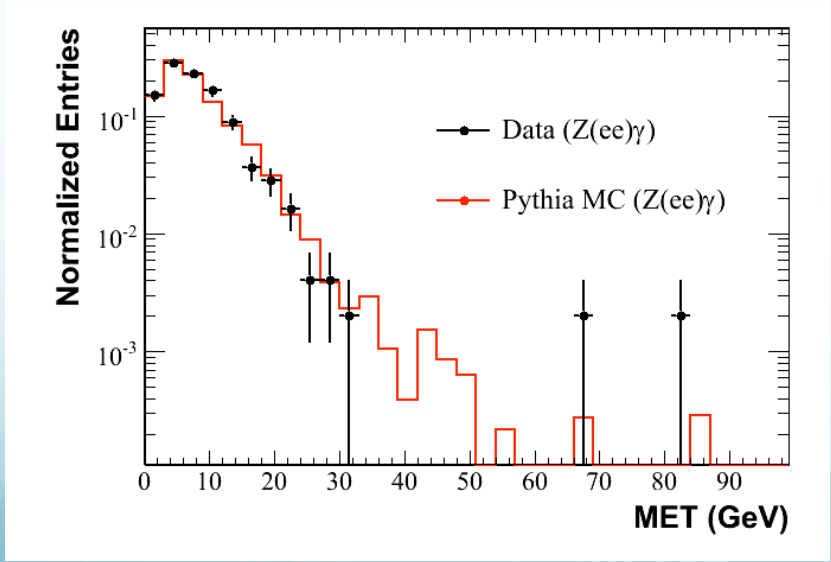


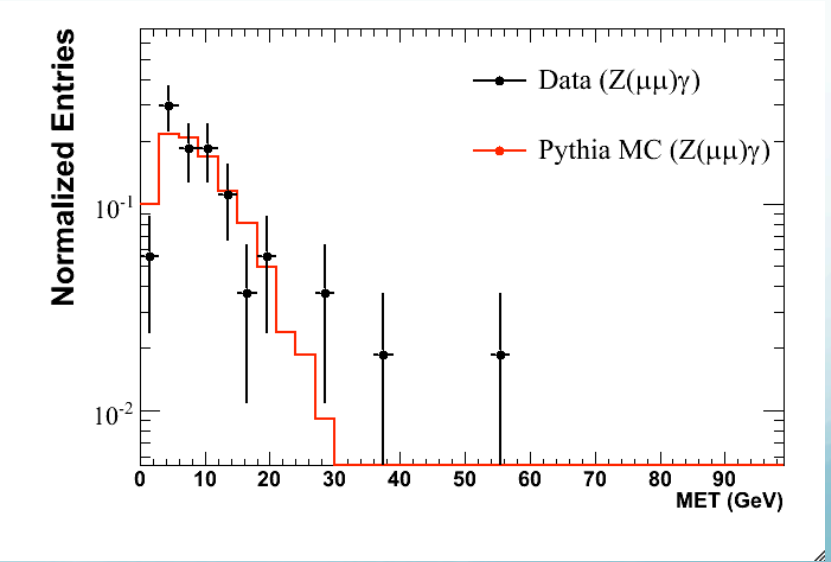
Estimation of Zγ III

- Use Baur Zγ MC sample
  - $\sigma^{NLO} \times Br(Z \to ll) = 2.89 \pm 0.15$ pb

$$N_{Z\gamma} = \sigma_{ll\gamma} \times L_{data} \times Acc \times \varepsilon \times f_{\gamma \to e}$$

- The largest systematics due to MET





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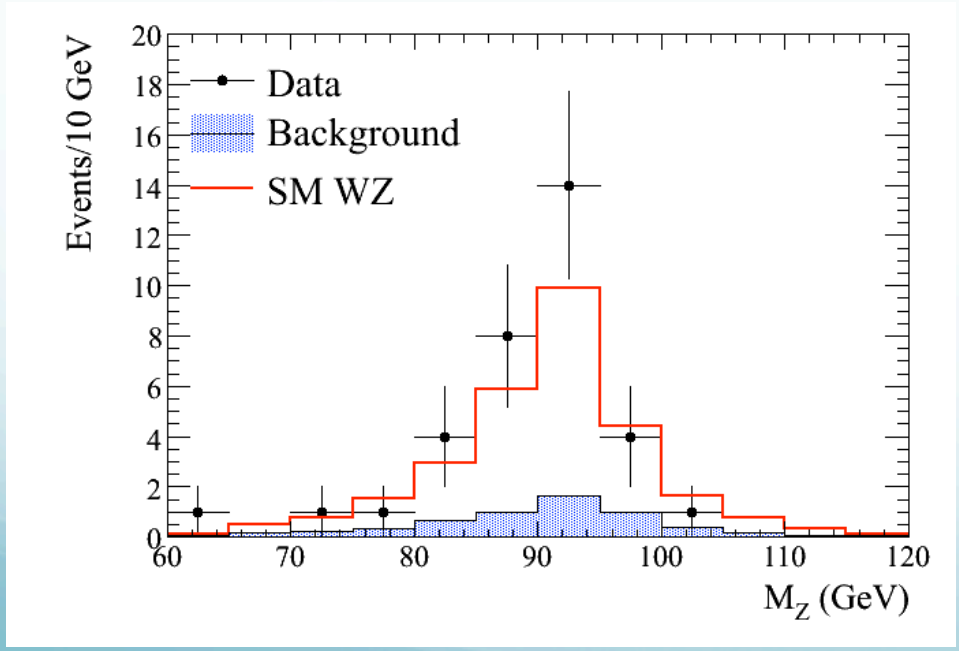
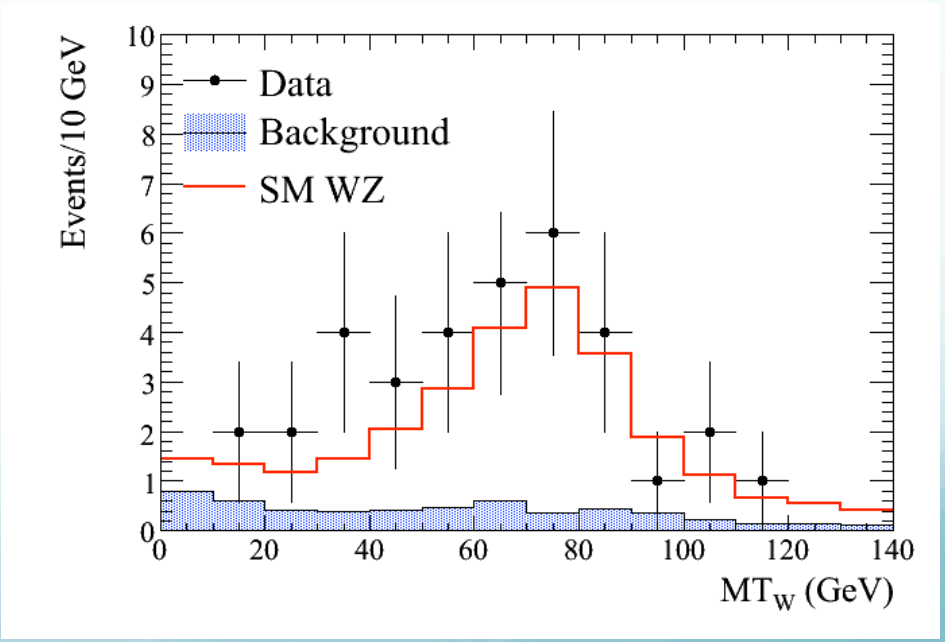
Measurement of WZ cross section and limits on WWZ couplings

In review for publication

Event Yields

- Selection yields
  - Observed 34 candidates
  - Expected signal 23.3 ± 0.2 (stat.)
  - Estimated background 6.0 ± 0.4 (stat.)





WZ Cross Section

- The cross section is calculated as

$$\sigma \times Br(WZ \rightarrow lll\nu) = \frac{N_{obs} - N_{bkg}}{Acc \times \varepsilon \times L}$$

Channel	Cross section (pb)
eee	$5.14 + 2.56 - 1.90(stat + syst) \pm 0.31(lumi)$
$ee\mu$	$4.36 + 2.18 - 1.66(stat + syst) \pm 0.27(lumi)$
$e\mu\mu$	$5.46 + 2.44 - 1.91(stat + syst) \pm 0.33(lumi)$
$\mu\mu\mu$	$1.95 + 1.50 - 1.08(stat + syst) \pm 0.11(lumi)$
$ee_{ICR}e$	$1.34 + 3.11 - 1.34(stat + syst) \pm 0.08(lumi)$
$ee_{ICR}\mu$	$3.75 + 3.74 - 2.51(stat + syst) \pm 0.23(lumi)$

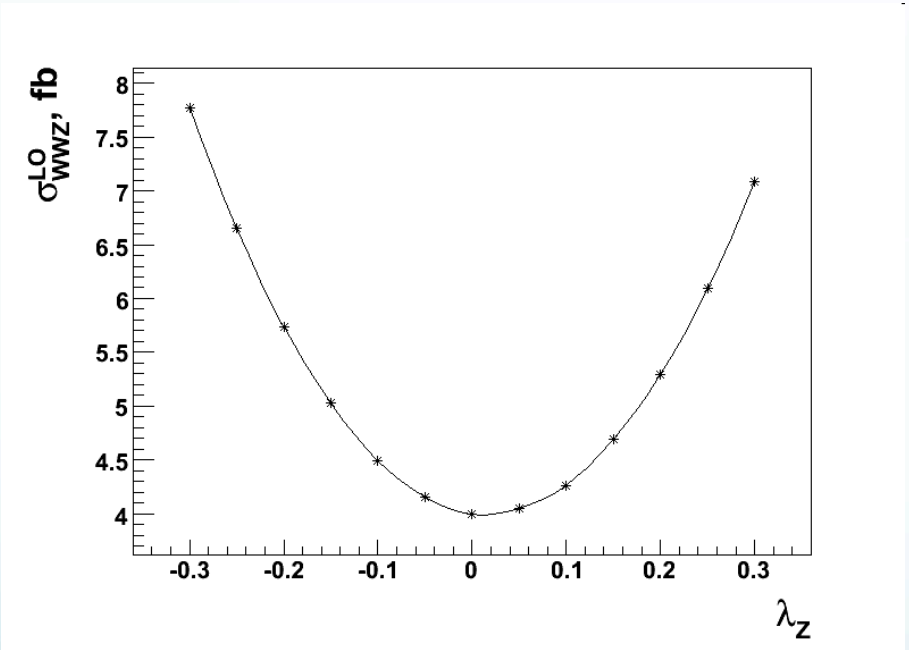
Sources	Relative Uncert.
Electron id	5%
Muon id	4%
ICR el. id	6%
PDFs	5%
σ(ttbar)	5%
σ(ZZ)	10%
MET on Zγ	30-50%
V+jets	20-30%
Luminosity	6.1%

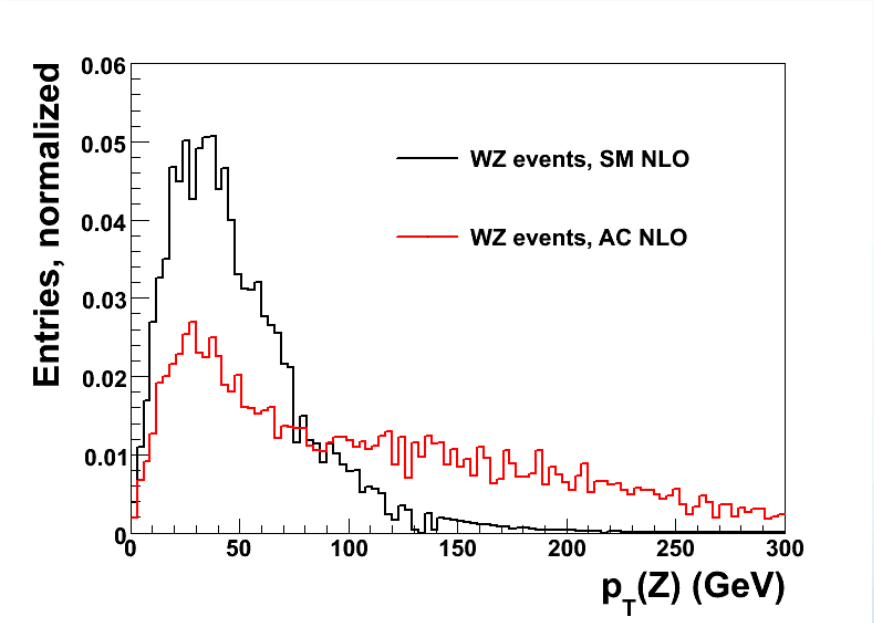
$$\sigma = 3.91^{+0.98}_{-0.83}(stat. + syst.) \pm 0.24(lumi.)\,pb$$

The best measurement to date of WZ cross section!

Anomalous WZ production

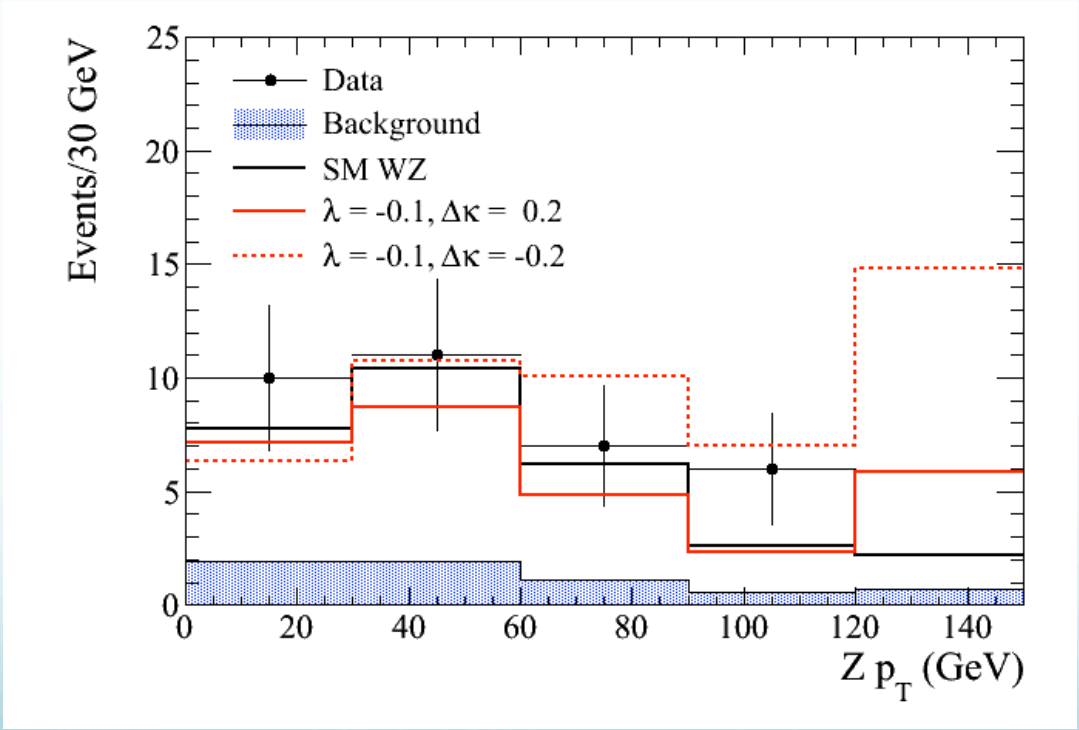
- Observables

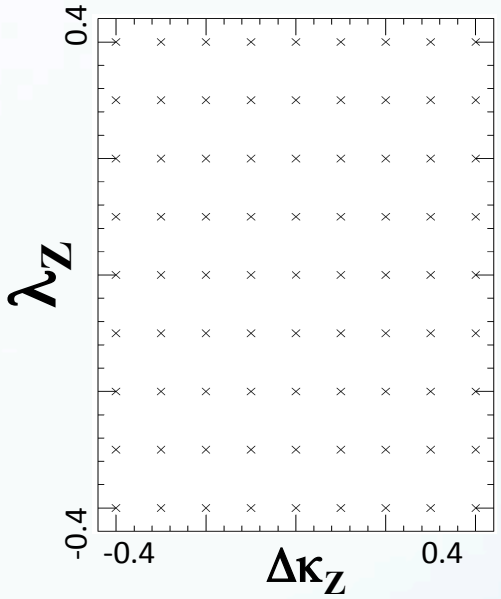




AC signal

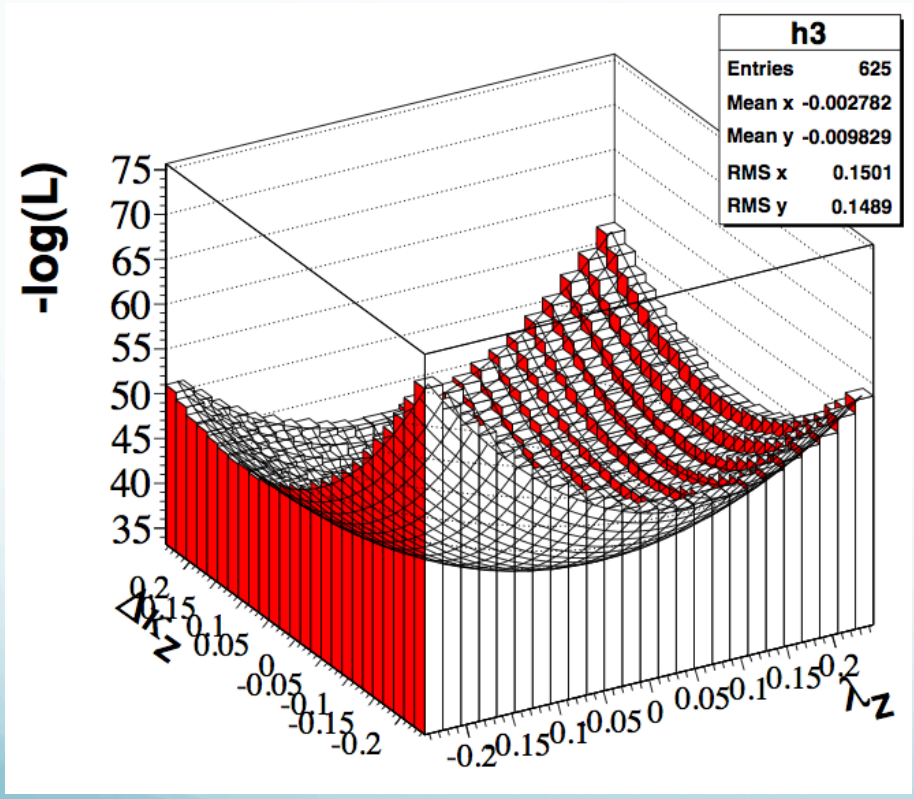
- Use MCFM generator

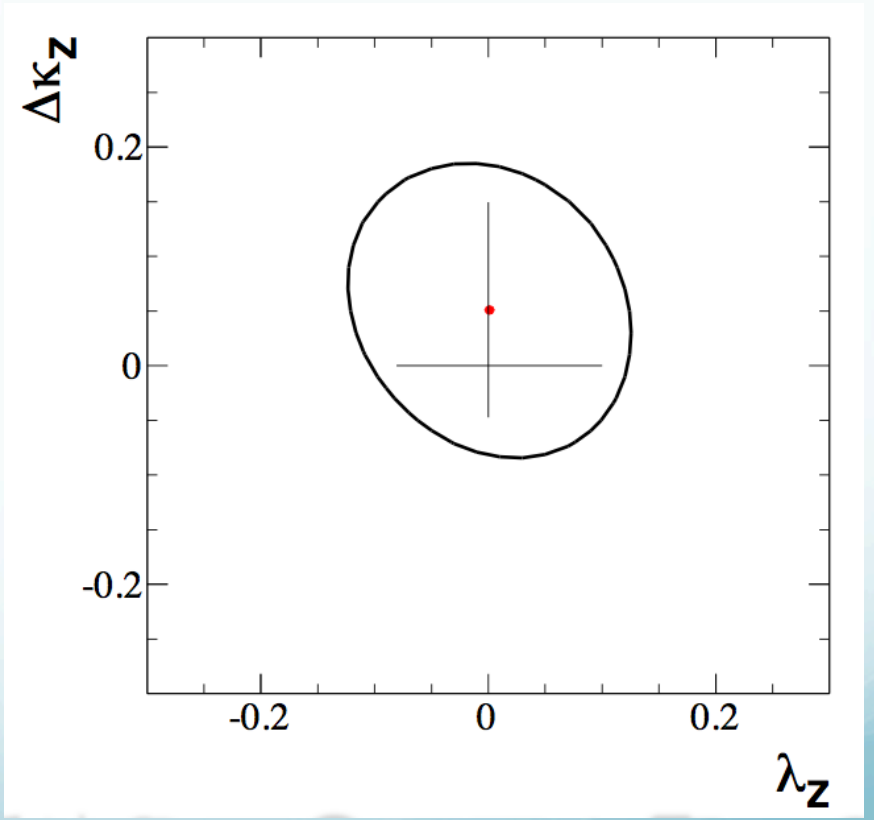




Limit setting

- Using negative log-likelihood method





Limits

- WWZ and WWγ coupling relation
  - LEP: $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W, \lambda_Z = \lambda_\gamma$
  - HISZ: $\Delta\kappa_Z = \Delta\kappa_\gamma(1-\tan^2\theta_W)/2, \Delta g_1^Z = \Delta\kappa_\gamma/2\cos^2\theta_W, \lambda_Z = \lambda_\gamma$
  - Equal couplings: $\Delta\kappa_Z = \Delta\kappa_\gamma, \lambda_Z = \lambda_\gamma, \Delta g_1^Z = \Delta g_1^\gamma = 0$

Coupling Relation	95% C.L. Limit
LEP	$-0.08 < \lambda_Z < 0.10$ $-0.05 < \Delta\kappa_Z < 0.15$
HISZ	$-0.08 < \lambda_Z < 0.10$ $-0.05 < \Delta\kappa_Z < 0.16$
EQUAL	$-0.08 < \lambda_Z < 0.10$ $-0.26 < \Delta\kappa_Z < 0.72$

The best limits on WWZ couplings obtained from the direct measurement of the WWZ vertex!

Search for new resonances

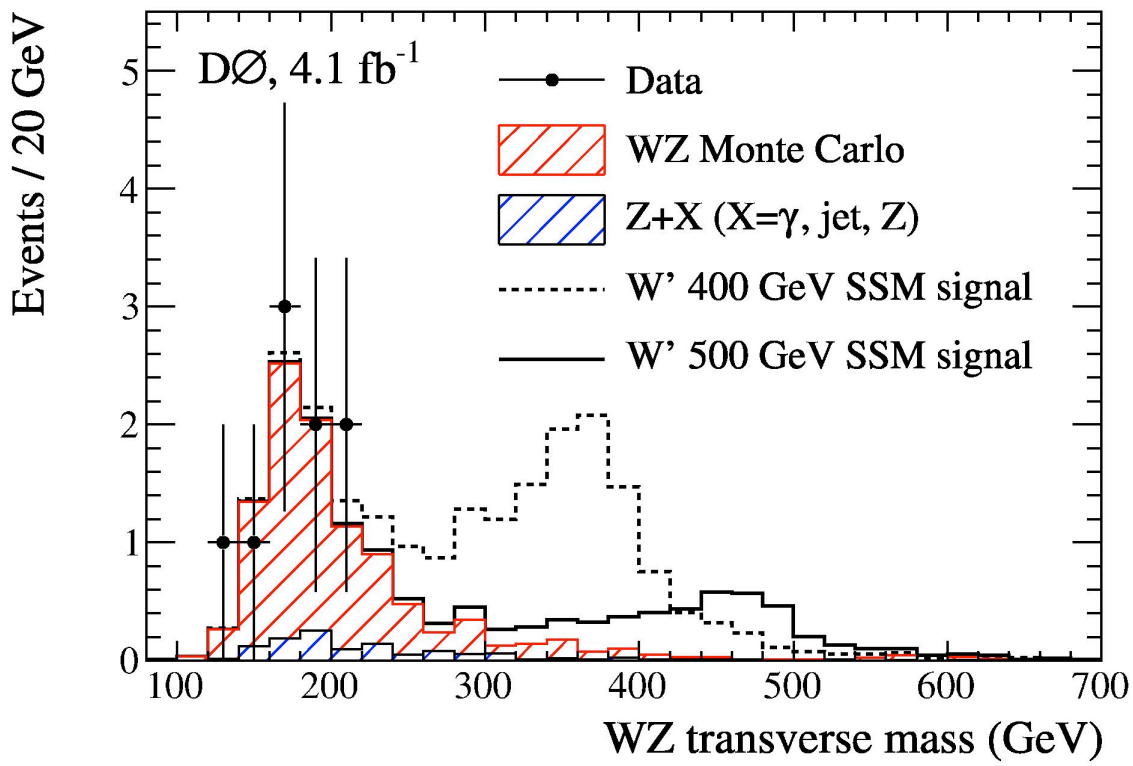
Phys.Rev.Lett.:104,061801(2010)
arXiv:0912.0715v3 [hep-ex]

Signal Selection

- Signal is generated by Pythia
  - W' and Technicolor resonances
- WZ production is an additional background
  - The standard 3l+MET event selection
    - Apply tighter thresholds
    - **$\Delta R(l^i,l^j) > 1.2$** – removes significant background contribution

Event Yields

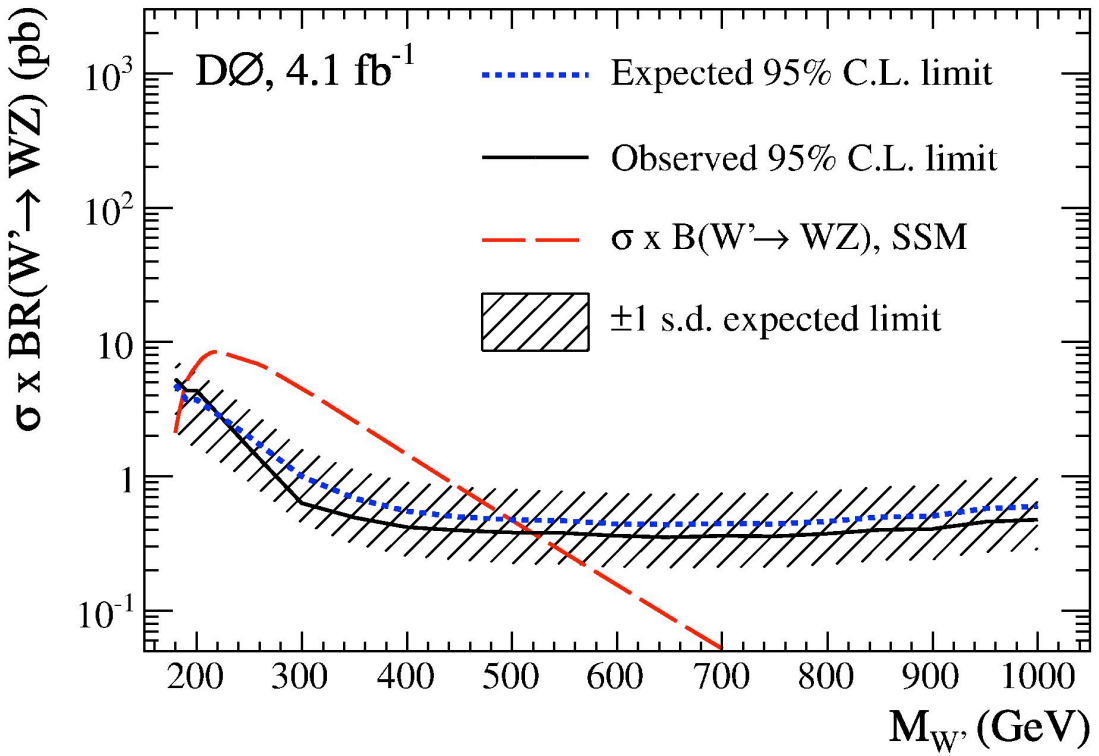
Source	Events
W' (500 GeV)	**4.4 ± 1.1**
WZ	9.0 ± 1.5
ZZ	1.0 ± 0.2
Z+jets	0.2 ± 0.1
Zg	0.1 ± 0.1
Total bkg.	**10.2 ± 1.6**
Observed	**9**



Very good agreement with the SM background prediction

Limits on W'→WZ

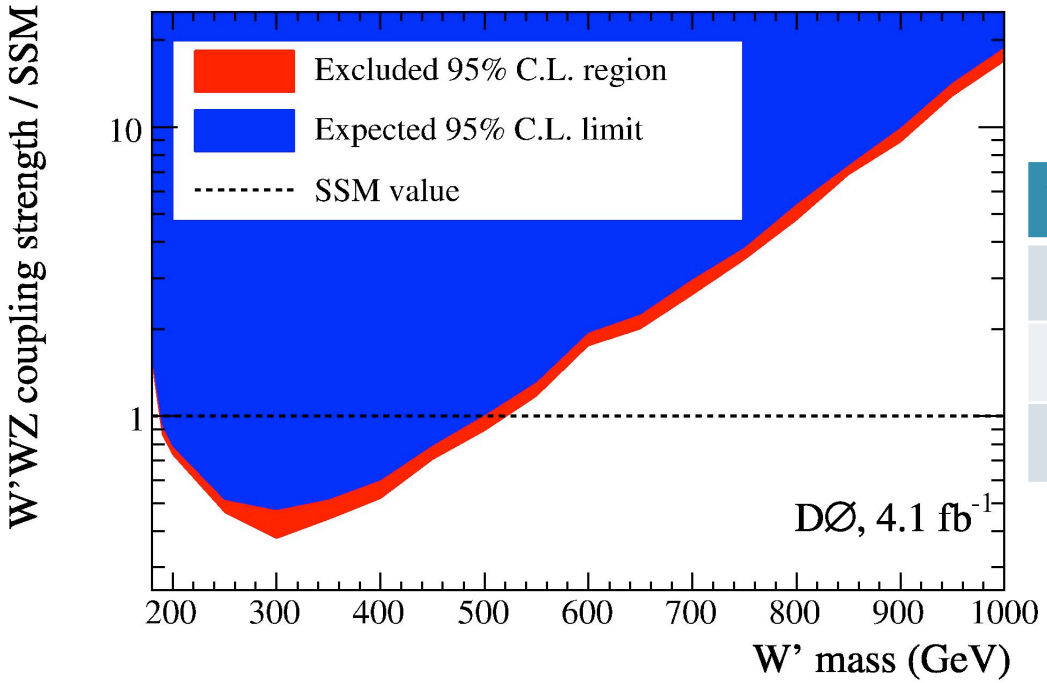
- We exclude sequential W'
  - 188 GeV < M(W') < 520 GeV (*obs.*)
  - 188 GeV < M(W') < 497 GeV (*exp.*)



W'WZ coupling

- Variation of coupling affects on σ(W') and Br(W'→WZ)

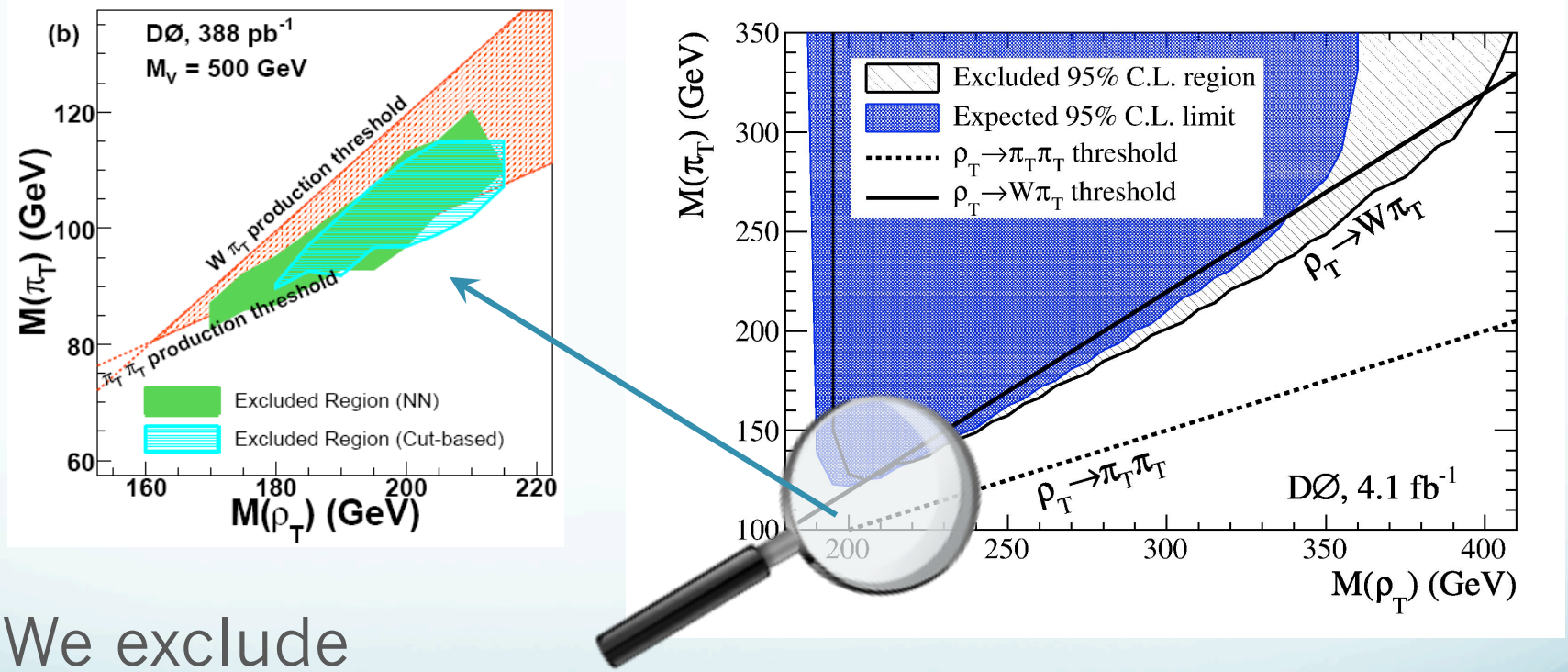
$$W^{'}WZ = \alpha \times WWZ(SM) \times \frac{M^2(W)}{M^2(W^{'})}$$



W'WZ	Obs. (GeV)	Exp. (GeV)
1 (SSM)	520	497
4	767	752
9	903	881

Limits on $\rho_T \rightarrow WZ$

- Previous searches in $\rho_T \rightarrow W\pi_T \rightarrow l\nu bq$
  - Excluded $M(\rho_T) < 220$ GeV (DØ)



- We exclude
  - 208 GeV < $M(\rho_T)$ < 400 GeV at 95% C.L. (*obs.*)
  - 201 GeV < $M(\rho_T)$ < 339 GeV at 95% C.L. (*exp.*)

Summary

- Extensive study of WZ process at DØ
  - The best measurement of $\sigma(p\bar{p}\rightarrow WZ)$ and limits WWZ couplings
  - The first search for X→WZ
    - Limits on SSM W', W'WZ couplings
    - The first limits on $\rho_T\rightarrow WZ$ – excludes almost all allowed phase space
      - Technicolor is not dead yet!