$p\bar{p} \rightarrow ZZ$ Cross Section Measurement & Anomalous Couplings Limits

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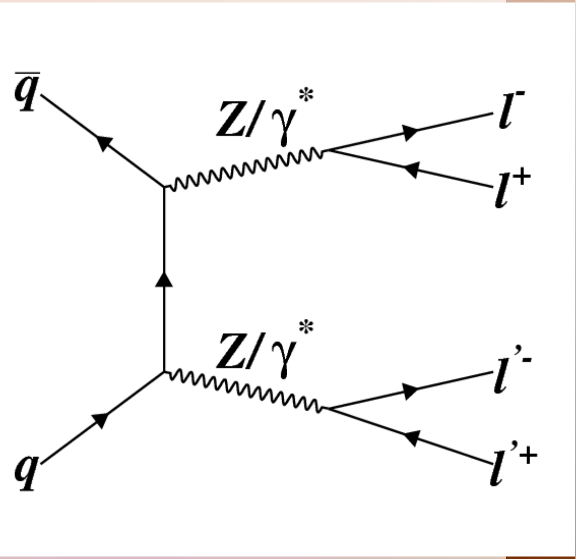
On behalf of the D0 Collaboration

Motivation and Goals

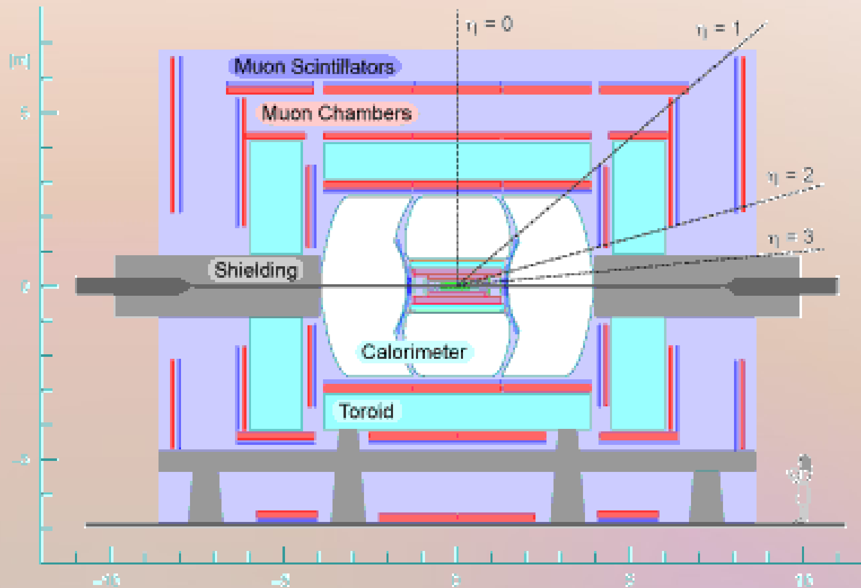


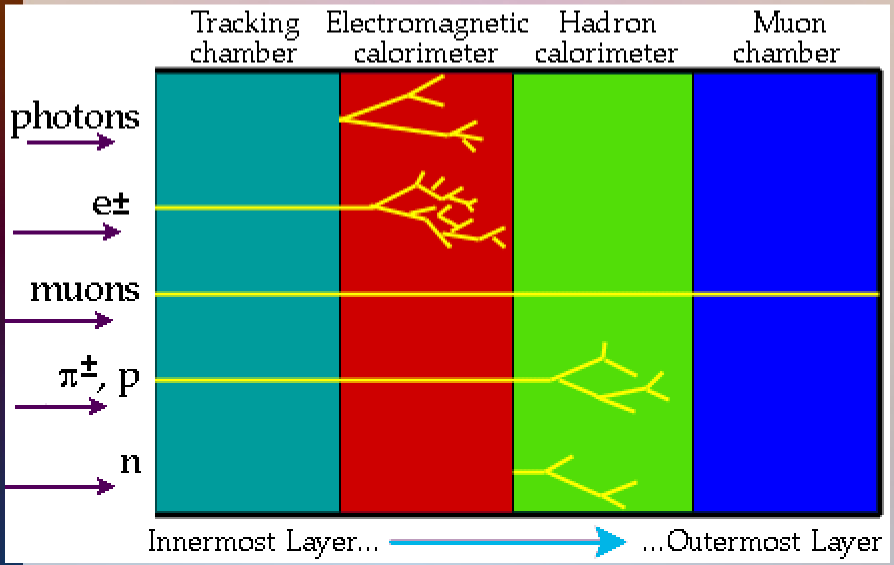
- Measured the *ZZ* cross section with 9.6 – 9.8 fb^{-1} of $p\bar{p}$ data at 1.96 TeV
  - Very pure – few processes in SM mimic 4l final state
  - Measurement with full dataset
  - Extension to Higgs boson search
- Anomalous coupling limits with up to 8.6 fb^{-1}
  - Searches for anomalous couplings have been done at D0 in *WW*, *Wγ*, and *WZ* final states separately
  - By adding data and combining final states, set tighter limits

The DØ Experiment

- A multipurpose particle detector
- Innermost detectors are the trackers, followed by calorimetry and muon chambers

Pseudorapidity $\eta = -\ln(\tan(\theta/2))$

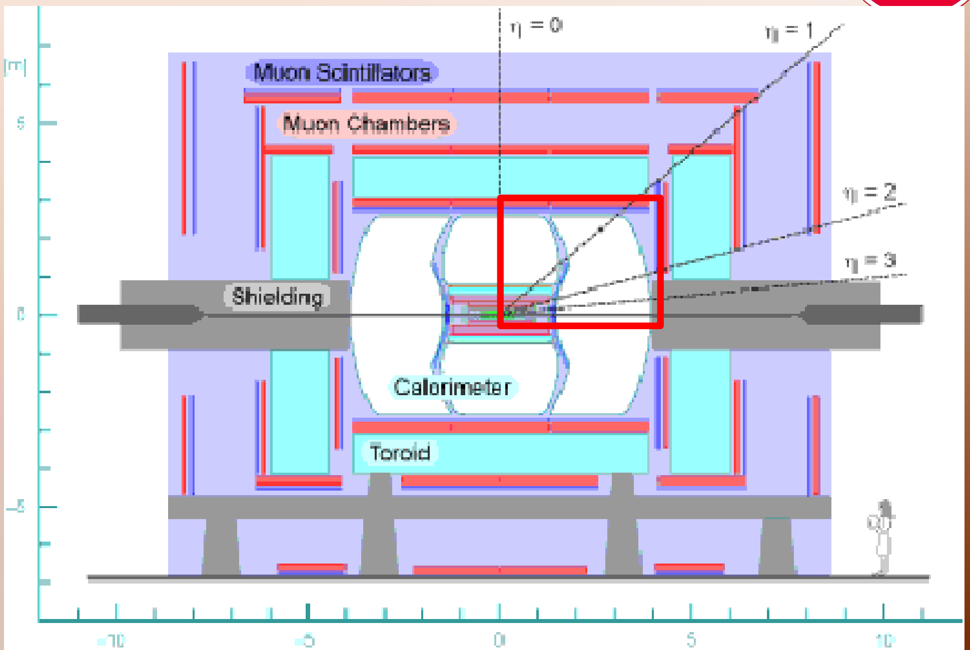


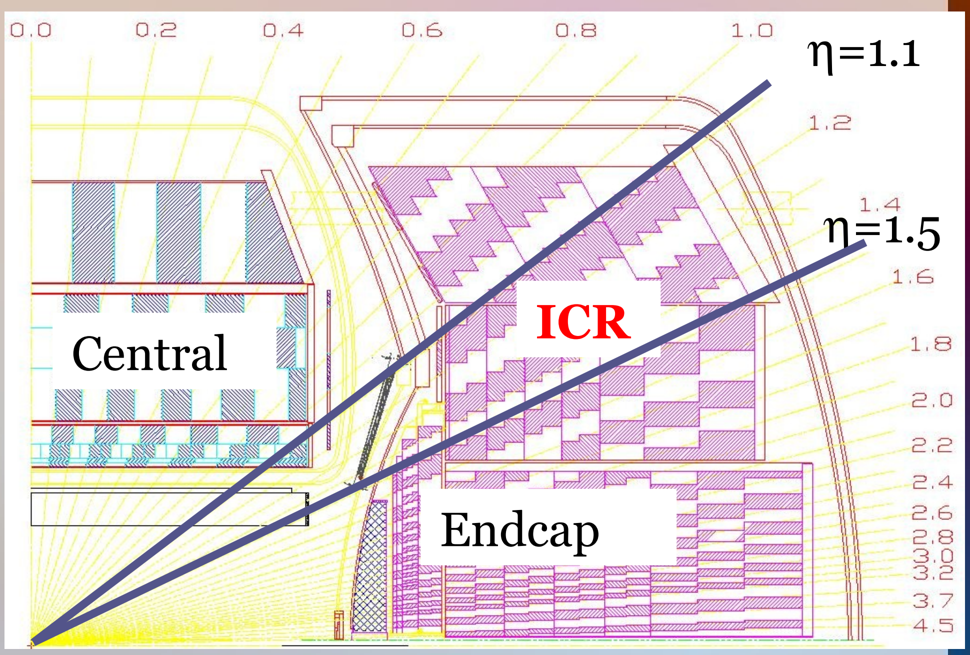


- Electron ID uses EM calorimeter + tracker
- Muon ID needs isolated track with hits in muon chambers or calorimeter deposits consistent with muon

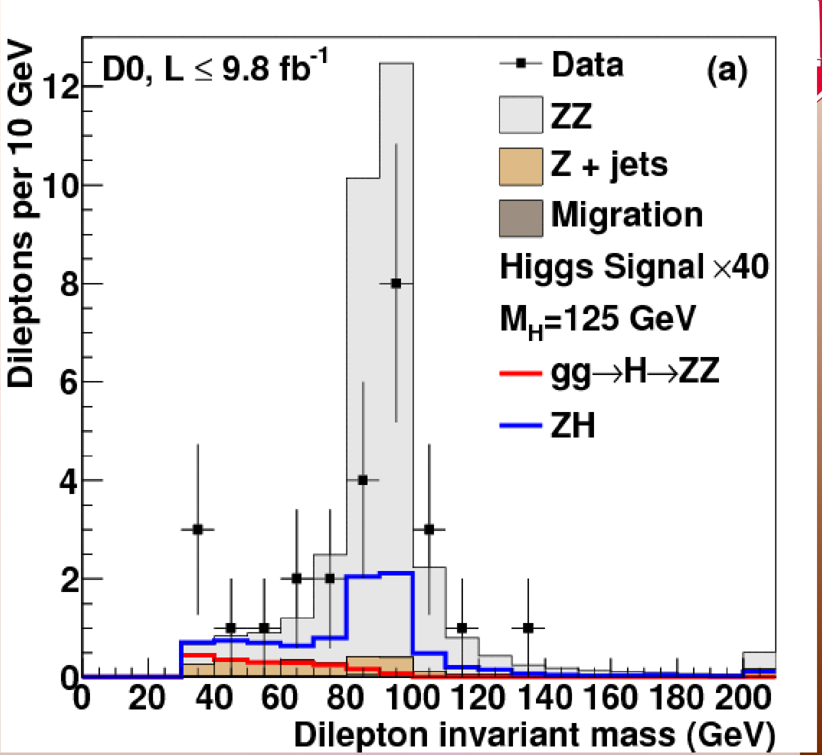
InterCryostat Region Electrons

- DØ has gap in EM Calorimeter
- ICR electrons use track matched to narrow cone of energy in hadronic calorimeter and ICD
- Adds 10% to *ZZ* acceptance
- Calorimeter energy resolution poor in ICR
  - Electron track used to estimate the p_T





ZZ Event Requirements



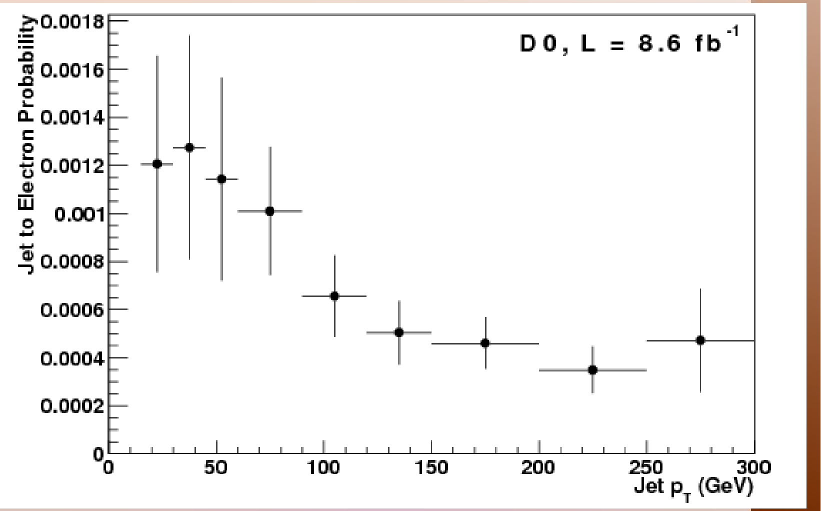
- We require M(*ll*) > 30 GeV for both reconstructed Z's
  - In 2e2μ, use M(μμ) and M(*ee*)
  - In 4μ & 4*e*, at least one pairing of leptons must pass this cut
  - In 4μ, only oppositely charged pairs considered
- In 4*e*, need at least 2 electrons in central calorimeter
  - Also in 4*e* use events that have issues with muon chambers to expand acceptance
- In 4μ, need at least 2μ with hits in muon chambers
- In 2*e*2μ, dR(*e*,μ) > 0.2 for all *e*-μ pairs

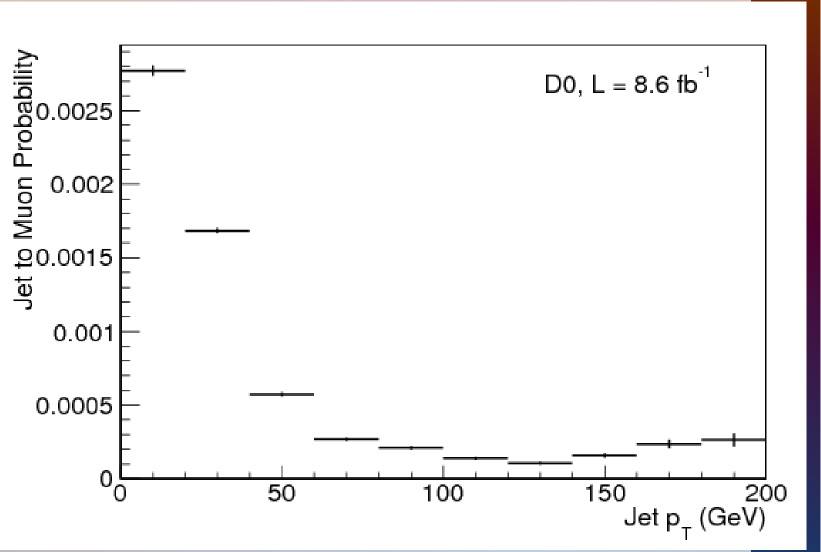
Signal and Backgrounds

- The ZZ signal acceptance is estimated with PYTHIA
- There are three main sources of background for the ZZ cross section measurement
  - Instrumental – Vector boson events with additional photon or jets misreconstructed as leptons – mostly Z + 2 jet events
  - Migration – Z/γ^* Z/γ^* events where at least one of the Z/γ^* has a mass < 30 GeV, but is reconstructed with a mass above 30 GeV
  - $t\bar{t}$, where the b-jets are mistaken for isolated leptons
  - Migration and $t\bar{t}$ estimated using MC

Instrumental Background

- Implemented in 2 steps
  - Measure j→*l* misreconstruction probabilities
  - Apply to lepton + jet events
- Misreconstruction rates measured in events triggered by a high p_T jet
- Apply rates to 2l + ≥2 jet and 3l + ≥1jet events to estimate background

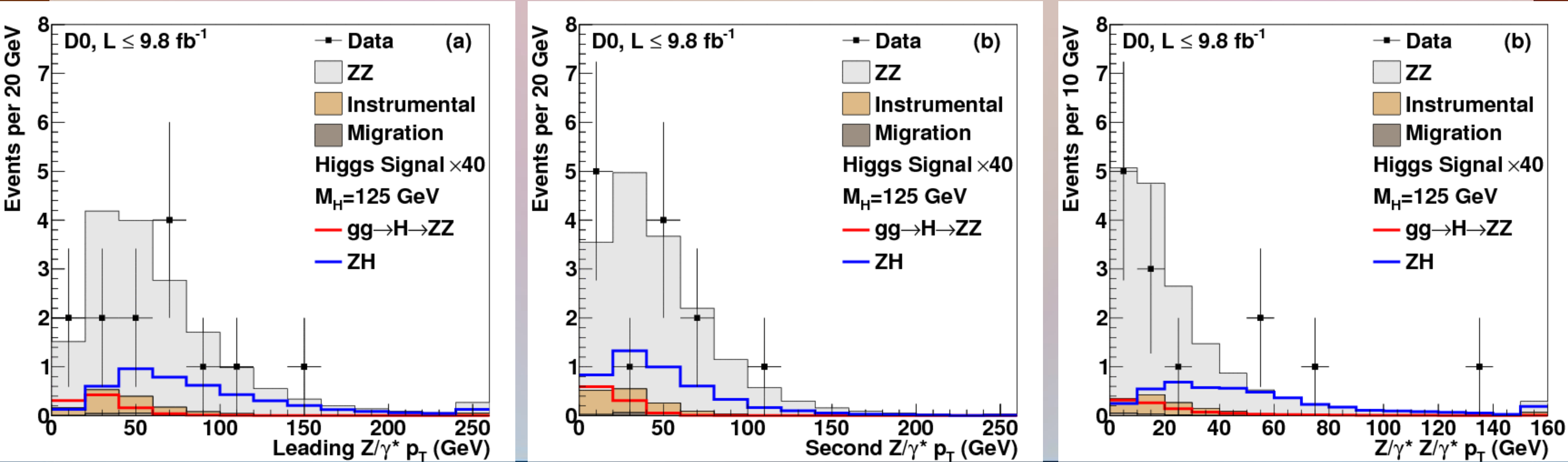




Events Yields

We divide the analysis into 8 subchannels, four in 4*e*, three in 2*e*2μ and 4μ, based on the number of electrons in the central, endcap, and intercryostat regions

Summing over all final states, expect total of **15.3 ZZ events** and **1.5 bkgd events,** with **13 events** seen in data.



Systematic Uncertainties

- The most significant sources of systematic uncertainty are on the signal acceptance
  - Lepton ID
    - 3.2% / muon, 3.7% / Central/Endcap electron, 6.0% / ICR electron
  - Trigger efficiency uncertainty of 1.0%,
  - electron and muon energy scale uncertainties
  - *ZZ* p_T reweighting – obtain distributions from Sherpa and Pythia, use difference as a systematic
- Background systematic uncertainties
  - Fake rate and statistical uncertainties on Z+jets background
  - 20% on $t\bar{t}$ to account for x-sec, $b \rightarrow l$ fake rate uncertainty
  - Migration has 7% x-sec uncertainty+same uncertainties as signal

Cross-Section Calculation

- To find the cross-section, we minimize the negative log-likelihood

$$-\ln(L) = \sum \sigma \times \mathrm{BR}_i \times \alpha_i \times \epsilon_i \times \int \mathcal{L} \cdot dt + N_i^{bkg} - N_i \ln\left(\sigma \times \mathrm{BR}_i \times \alpha_i \times \epsilon_i \times \int \mathcal{L} \cdot dt\right)$$

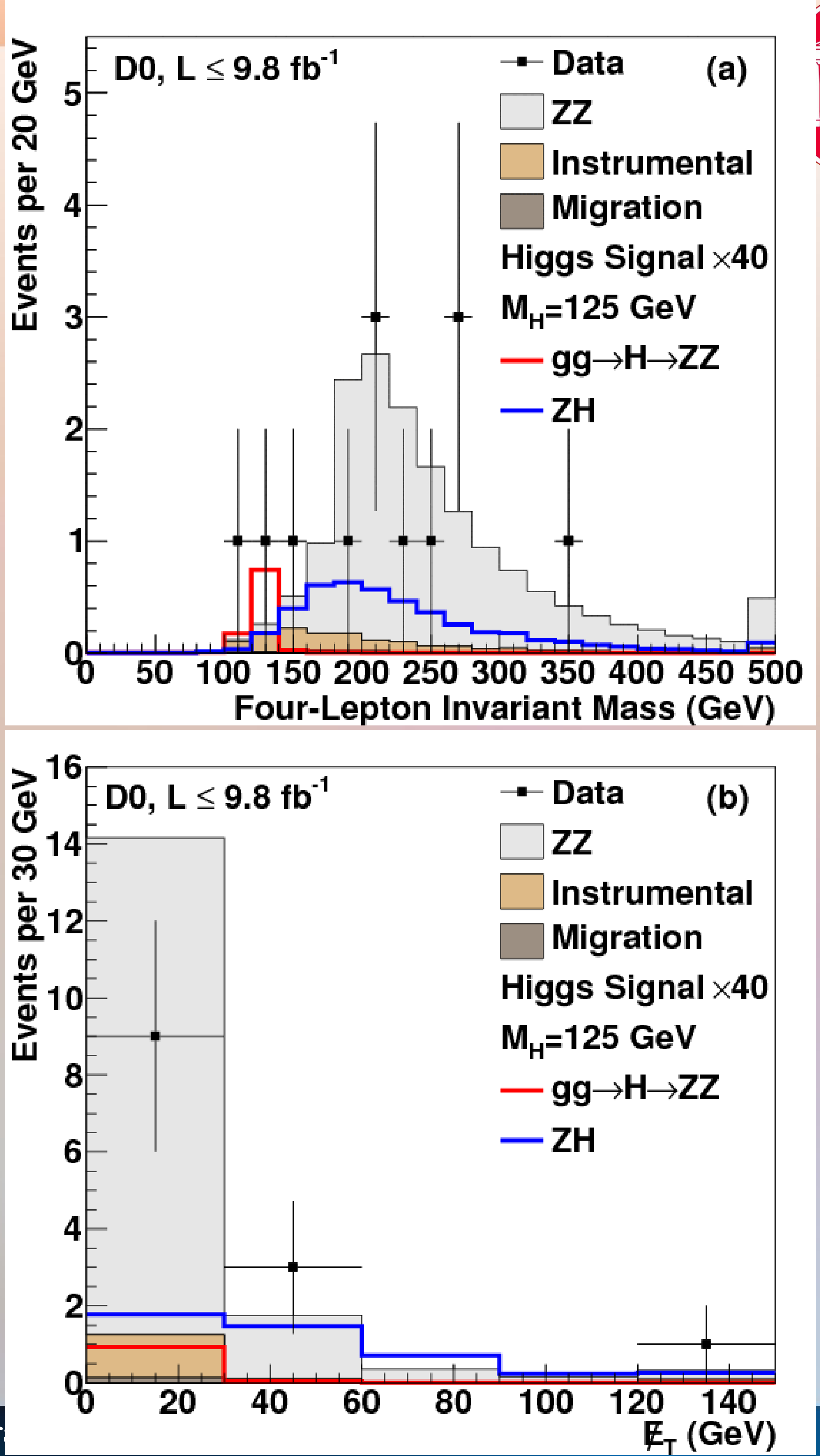
  - Include systematics by varying acceptance and backgrounds by ±1 s.d. and adding in quadrature

- $\sigma(p\bar{p} \rightarrow Z/\gamma^* \, Z/\gamma^*) = 1.26^{+0.44}_{-0.36}(stat.)^{+0.17}_{-0.15}(syst.) \pm 0.08(lumi)$ pb

- Using MCFM, apply a scale factor to obtain
  $\sigma(p\bar{p} \rightarrow ZZ) = 1.05^{+0.37}_{-0.30}(stat.)^{+0.14}_{-0.12}(syst.) \pm 0.06(lumi)$ pb
  combine with cross section measurement in $ZZ \rightarrow ll\nu\nu$ (link)
  $\sigma(p\bar{p} \rightarrow ZZ) = 1.32^{+0.29}_{-0.25}(stat.) \pm 0.12(syst.) \pm 0.04(lumi)$ pb
  in agreement with SM value of 1.4 ± 0.1 pb

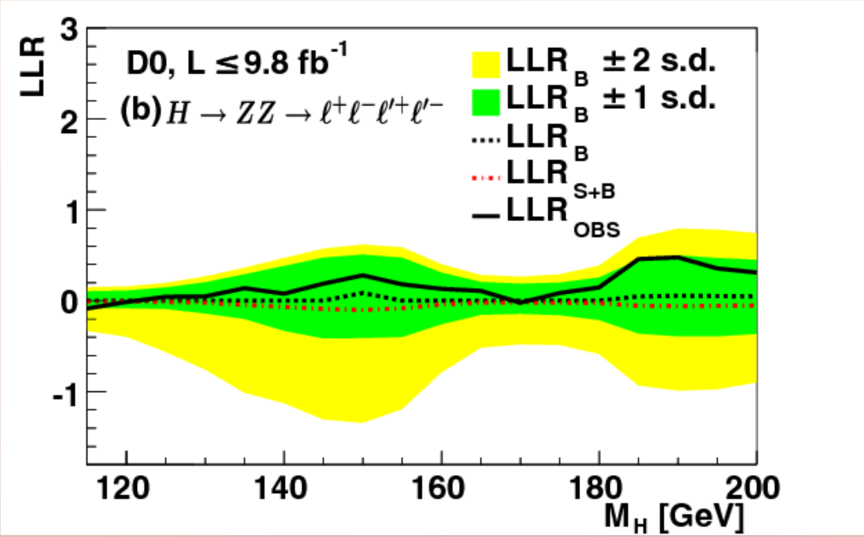
Extension to Higgs boson Search

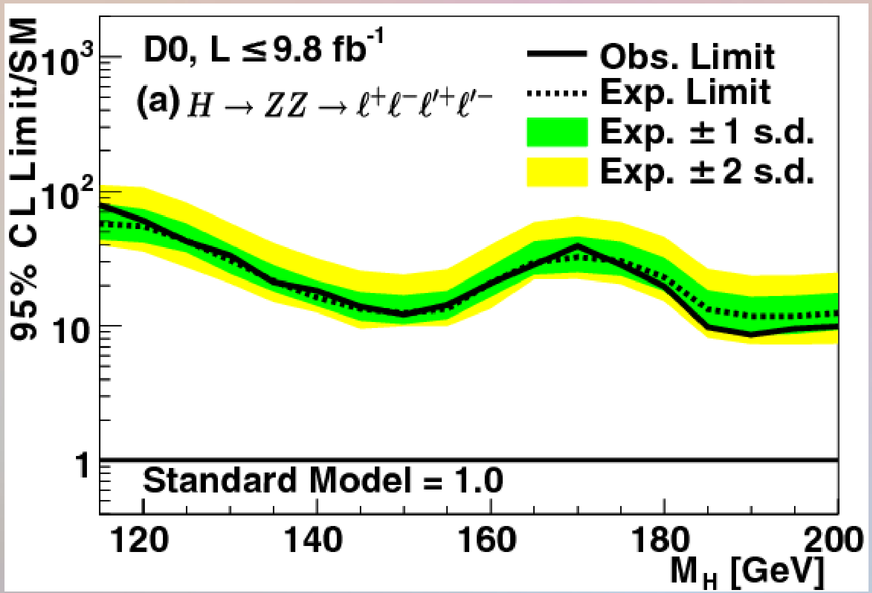
- Higgs discovered at CMS and ATLAS experiments at 125 GeV in $H \rightarrow ZZ$ and $H \rightarrow \gamma\gamma$
- We extend cross-section measurement to Higgs boson search at D0
- For missing E_T < 30 GeV, use four-lepton mass as discriminant, otherwise use missing E_T



Extension to Higgs Boson Search

- At 125 GeV, expect 0.14 Higgs boson events
- Set limits using modified frequentist approach
  - Log-likelihood ratio test statistic
- At 125 GeV, find an observed (expected) limit of 42×SM (43×SM)





General WWV Lorentz Invariant Lagrangian

$$\mathcal{L}_{WWV}/g_{WWV} = ig_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu V^{\nu\lambda} - g_4^V W^\dagger_\mu W_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)$$

$$+ g_5^V \epsilon^{\mu\nu\rho\sigma}(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu)V_\sigma + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + \frac{i\tilde{\lambda}_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu \tilde{V}^{\nu\lambda},$$

$$g_{WWZ} = g\cos\theta_W$$

$$g_{WW\gamma} = g\sin\theta_W$$

- V can be Z or γ

General WWV Lorentz Invariant Lagrangian

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$$g_{WWZ} = g\cos\theta_W \qquad g_{WW\gamma} = g\sin\theta_W$$

- V can be Z or γ
- In the SM, $g^Z_1 = \kappa_Z = g^\gamma_1 = \kappa_\gamma = 1$, all others = 0

General WWV Lorentz Invariant Lagrangian

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$$+ g_5^V \epsilon^{\mu\nu\rho\sigma} (W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu) V_\sigma + i\tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} + \frac{i\tilde{\lambda}_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu \tilde{V}^{\nu\lambda}, \quad g_{WWZ} = g\cos\theta_W, \quad g_{WW\gamma} = g\sin\theta_W$$

- V can be Z or γ
- In the SM, $g^Z_1 = \kappa_Z = g^\gamma_1 = \kappa_\gamma = 1$, all others = 0
  - U(1) symmetry demands $g^\gamma_1 = 1$, $g^\gamma_4 = g^\gamma_5 = 0$
- Require CP invariance → $g^V_4 = \tilde{\kappa}_V = \tilde{\lambda}_V = 0$

General WWV Lorentz Invariant Lagrangian

$$\mathcal{L}_{WWV}/g_{WWV} = ig_1^V(W_{\mu\nu}^\dagger W^\mu V^\nu - W_\mu^\dagger V_\nu W^{\mu\nu}) + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W_{\lambda\mu}^\dagger W^\mu{}_\nu V^{\nu\lambda} - g_4^V W_\mu^\dagger W_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu)$$

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$$g_{WWZ} = g\cos\theta_W \qquad g_{WW\gamma} = g\sin\theta_W$$

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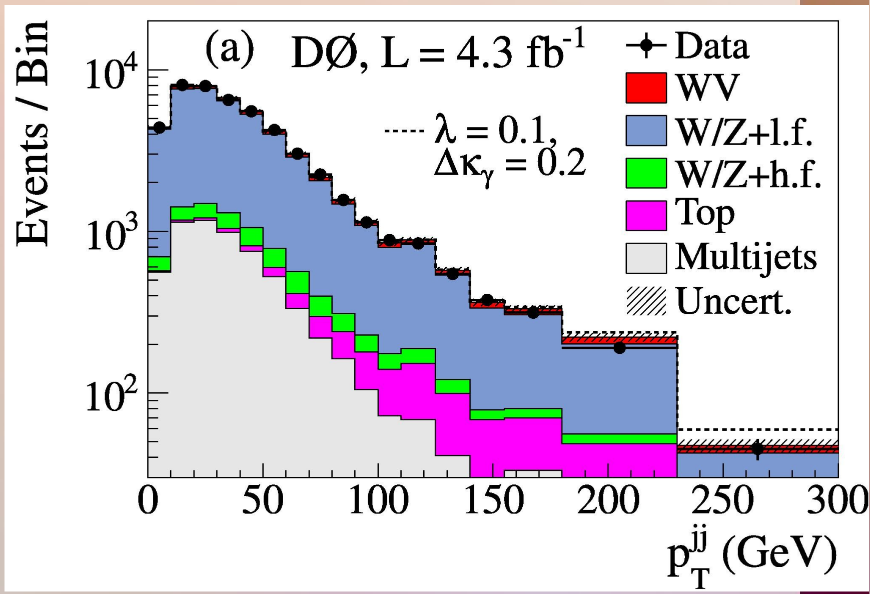
- Require CP invariance → $g^V_4 = \tilde{\kappa}_V = \tilde{\lambda}_V = 0$
- Require C, P invariance separately → $g^\gamma_5 = 0$
- Vary g^Z_1, κ_V, λ_V to set limits on anomalous couplings

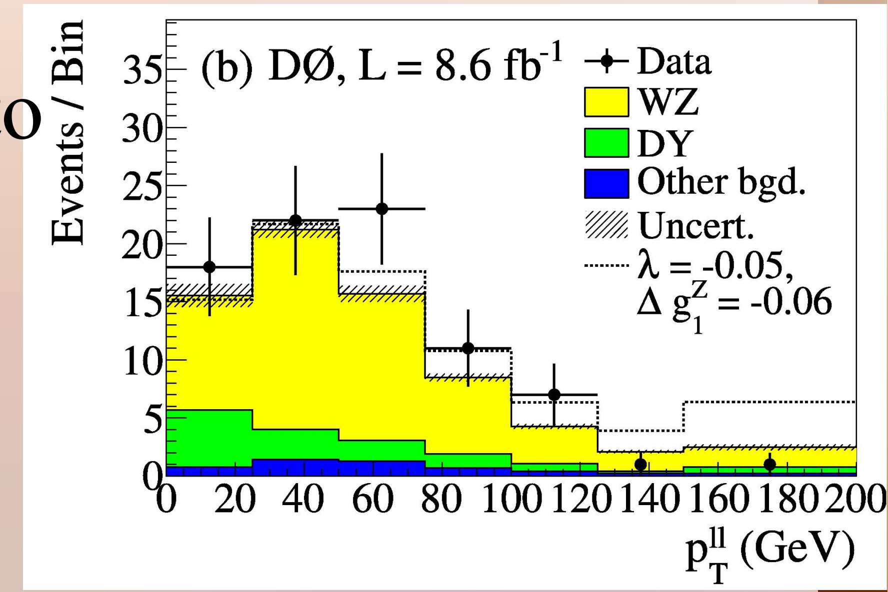
Final States

- To set limits on anomalous couplings, we consider
  - $WW \rightarrow l\nu l'\nu$ in 1.0 fb^{-1} (link)
  - $W\gamma \rightarrow l\nu\gamma$ in 4.9 fb^{-1} (link)
  - $WW+WZ \rightarrow l\nu jj$ in 1.1 fb^{-1} (link)
  - $WW+WZ \rightarrow l\nu jj$ in 4.3 fb^{-1} (new)
  - $WZ \rightarrow l\nu l'l'$ in 8.6 fb^{-1} (new)



- Cross sections in each channel have been measured
- The SM signal and most backgrounds modeled with PYTHIA+ALPGEN and ALPGEN MC, reweighed to NLO
  - Multijet backgrounds estimated using data

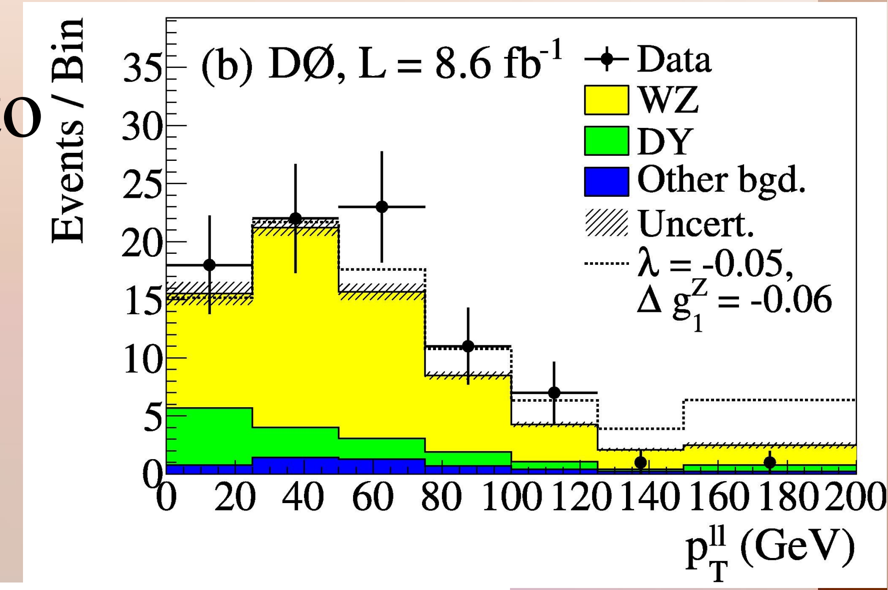
Anomalous Trilinear Gauge Couplings (ATGC)



- Use MCFM with CTEQ6L1 PDF to estimate ATGC distributions
- ATGC tend to increase cross sections at high p_T
- To avoid violating unitarity,a cut-off of Λ=2TeV is chosen at the Tevatron
  - Interpret this as the scale of new physics

Anomalous Trilinear Gauge Couplings (ATGC)

- Use MCFM with CTEQ6L1 PDF to estimate ATGC distributions
- ATGC tend to increase cross sections at high p_T
- The SM is related to the ATGC expectation by

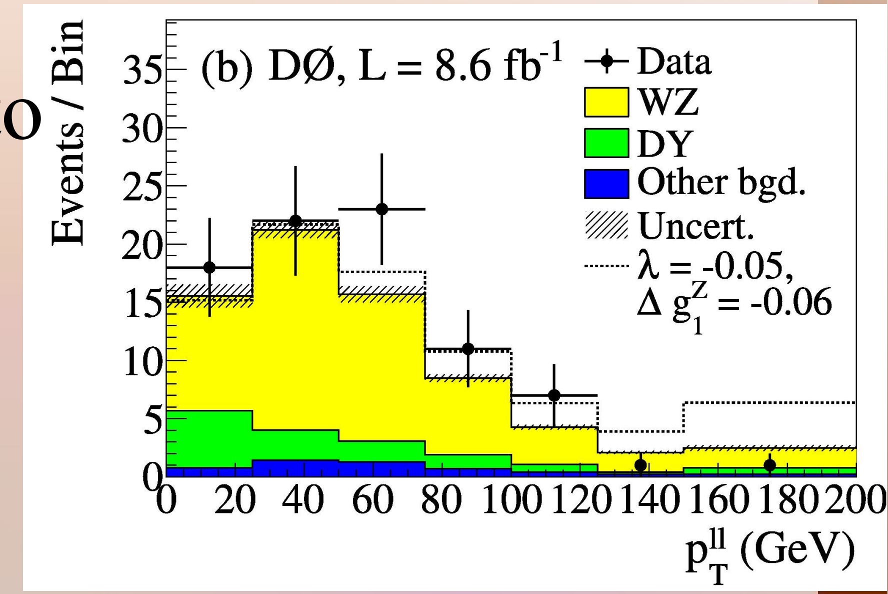


$$
\begin{aligned}
d\sigma &\propto |\mathcal{M}|^2 dx \\
&\propto |\mathcal{M}|^2_{SM} \frac{|\mathcal{M}|^2}{|\mathcal{M}|^2_{SM}} dx \\
&\propto |\mathcal{M}|^2_{SM} [1 + A\Delta\kappa + B(\Delta\kappa)^2 \\
&+ C\lambda + D\lambda^2 + E\Delta\kappa\lambda + etc...] dx \\
&\propto d\sigma_{SM} \cdot R(\Delta\kappa, \lambda, ...),
\end{aligned}
$$

where $d\sigma$ ($d\sigma_{SM}$) and $|M|^2$ ($|M|^2_{SM}$) are the ATGC (SM) differential cross section and matrix elements, respectively, and A, B, C… are reweighting coeff

Anomalous Trilinear Gauge Couplings (ATGC)

- Use MCFM with CTEQ6L1 PDF to estimate ATGC distributions
- ATGC tend to increase cross sections at high p_T



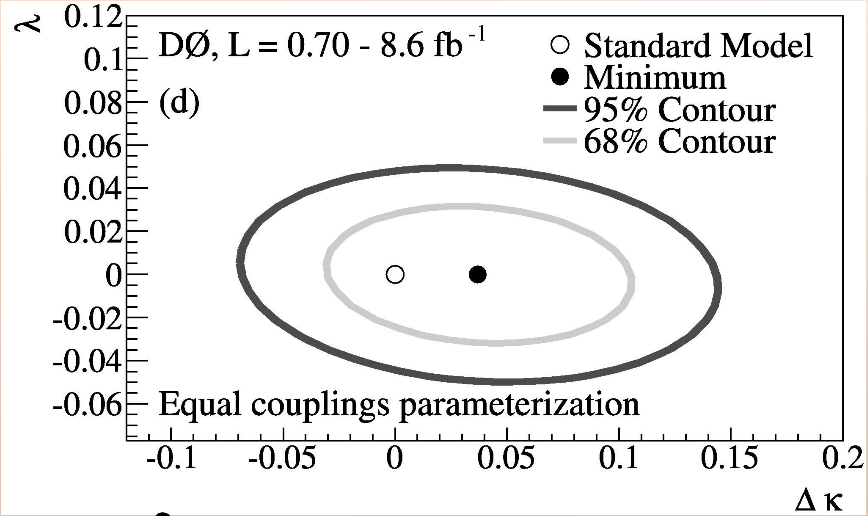
- *R* is calculated for each bin of the kinematic distributions used to set limits, and the SM MC is reweighted to match the ATGC

$$
\begin{aligned}
d\sigma &\propto |\mathcal{M}|^2 dx \\
&\propto |\mathcal{M}|^2_{SM} \frac{|\mathcal{M}|^2}{|\mathcal{M}|^2_{SM}} dx \\
&\propto |\mathcal{M}|^2_{SM} [1 + A\Delta\kappa + B(\Delta\kappa)^2 \\
&+ C\lambda + D\lambda^2 + E\Delta\kappa\lambda + etc...]dx \\
&\propto d\sigma_{SM} \cdot R(\Delta\kappa, \lambda, ...),
\end{aligned}
$$

Equal Coupling Parametrization

- For equal couplings, $\Delta\kappa = \Delta\kappa_Z = \Delta\kappa_\gamma$, $\lambda = \lambda_\gamma = \lambda_Z$

$$R\ (\Delta\kappa, \lambda) = 1 + A\Delta\kappa + B(\Delta\kappa)^2 + C\lambda + D\lambda^2 + E\Delta\kappa\lambda,$$



- To fit for limits, use minimize χ^2 with respect to Gaussian priors on on uncertainties
  - Use $p_T(ll)$ distribution of $WZ \to l\nu l'l'$ and $WW \to l\nu l'\nu$, $p_T(jj)$ of $WW+WZ \to l\nu jj$, and $E_T(\gamma)$ from $W\gamma \to l\nu\gamma$

Results for Equal couplings parameterization

Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa$	0.037	$[-0.007, 0.081]$	$[-0.049, 0.124]$
λ	0.008	$[-0.017, 0.028]$	$[-0.039, 0.042]$

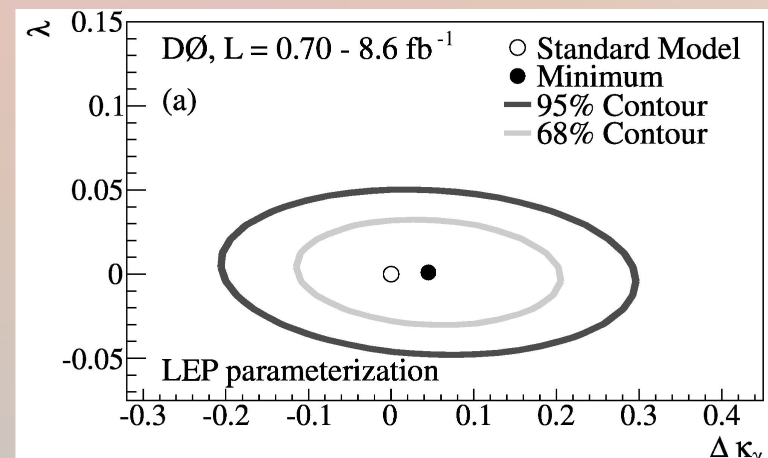
LEP Parametrization

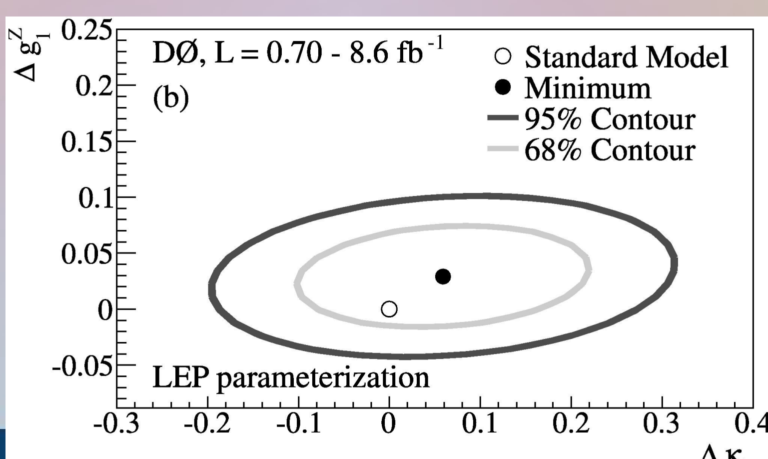
- In the LEP parametrization, $\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan 2\theta_W$, $\lambda = \lambda_\gamma = \lambda_Z$

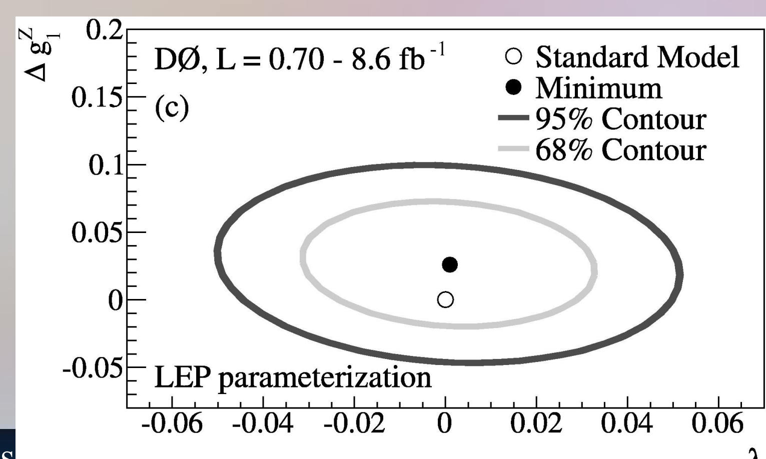
$$
\begin{aligned}
R \quad (\Delta\kappa_\gamma, \lambda, \Delta g_1) &= 1 + A\Delta\kappa_\gamma \\
+ \quad & B(\Delta\kappa_\gamma)^2 + C\lambda + D\lambda^2 \\
+ \quad & E\Delta g_1 + F(\Delta g_1)^2 + G\Delta\kappa_\gamma\lambda \\
+ \quad & H\Delta\kappa_\gamma\Delta g_1 + I\lambda\Delta g_1,
\end{aligned}
$$

Results for LEP parameterization

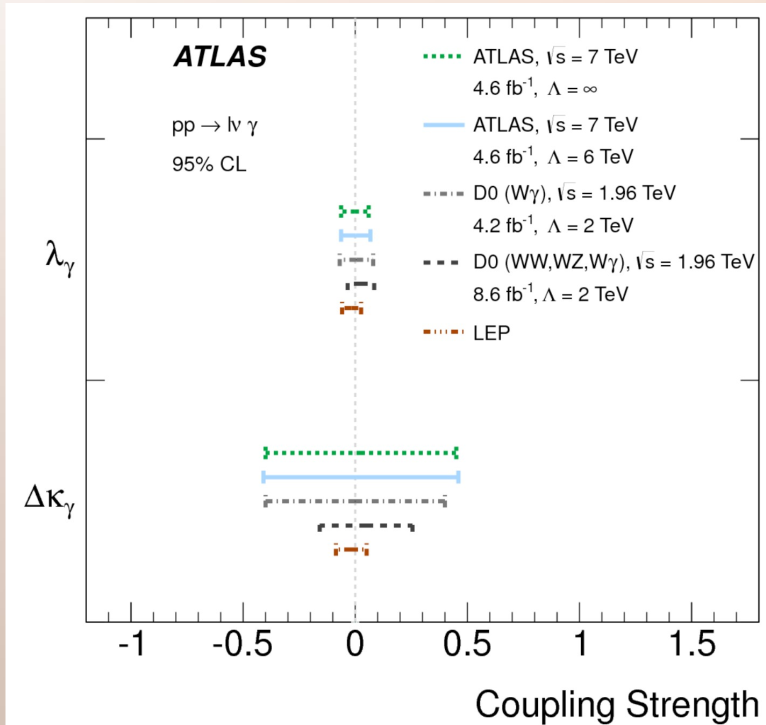
Parameter	Minimum	68% C.L.	95% C.L.
$\Delta\kappa_\gamma$	0.048	$[-0.057, 0.154]$	$[-0.158, 0.255]$
Δg_1^Z	0.022	$[-0.008, 0.054]$	$[-0.034, 0.084]$
λ	0.007	$[-0.015, 0.028]$	$[-0.036, 0.044]$

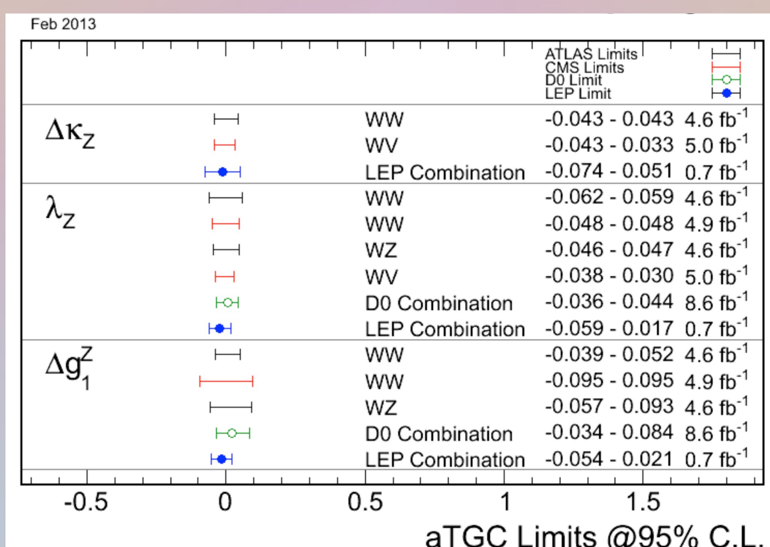






Comparison with LHC Results





- Limits are competitive with recent results from ATLAS and CMS
- Hard to compare directly, because ATLAS and CMS use $\Lambda \rightarrow \infty$ or 6 TeV
  - As Λ increases, the limits become tighter

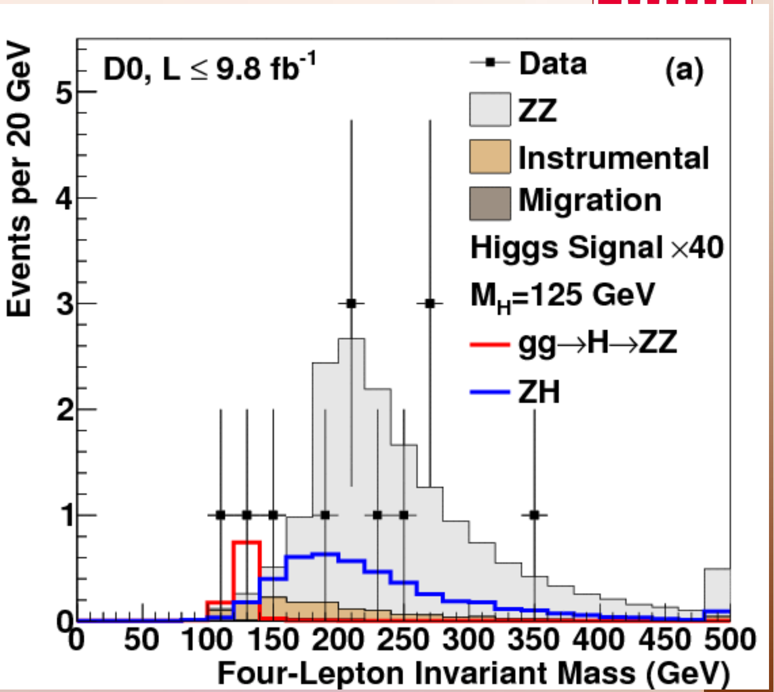
Comparison tables from S. Hassani's talk at Moriond EW 2013

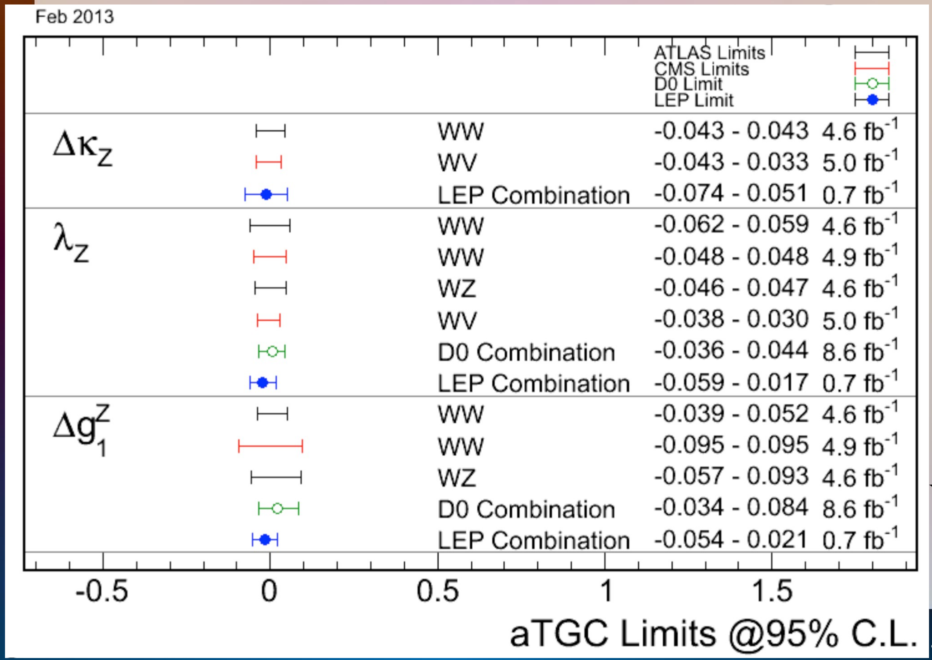
Conclusion

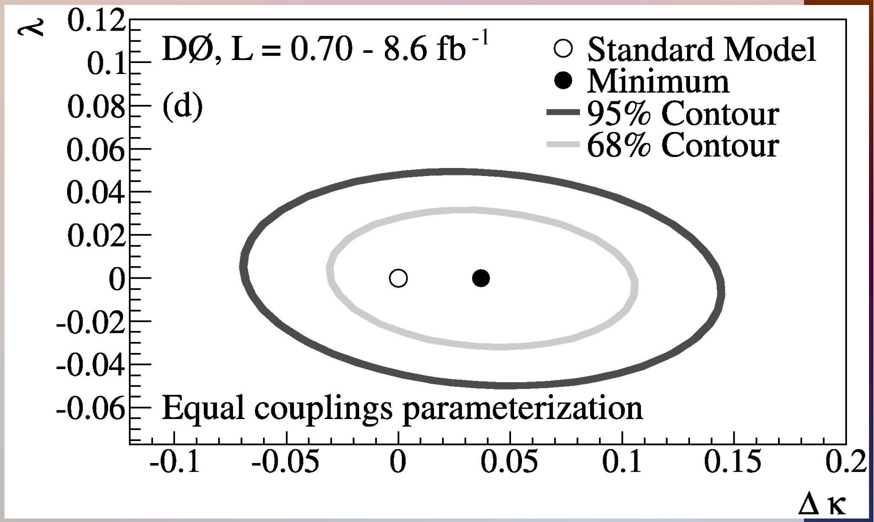
- Have measured the $p\bar{p} \rightarrow Z/\gamma^* \, Z/\gamma^*$ cross section at 1.96 TeV (arXiv:1304.5422)

$$1.26^{+0.44}_{-0.36}(stat.)^{+0.17}_{-0.15}(syst.)\pm 0.08(lumi)\ \text{pb}$$

- Set improved limits on ATGC
  Phys. Lett. B 718, 451 (2012)





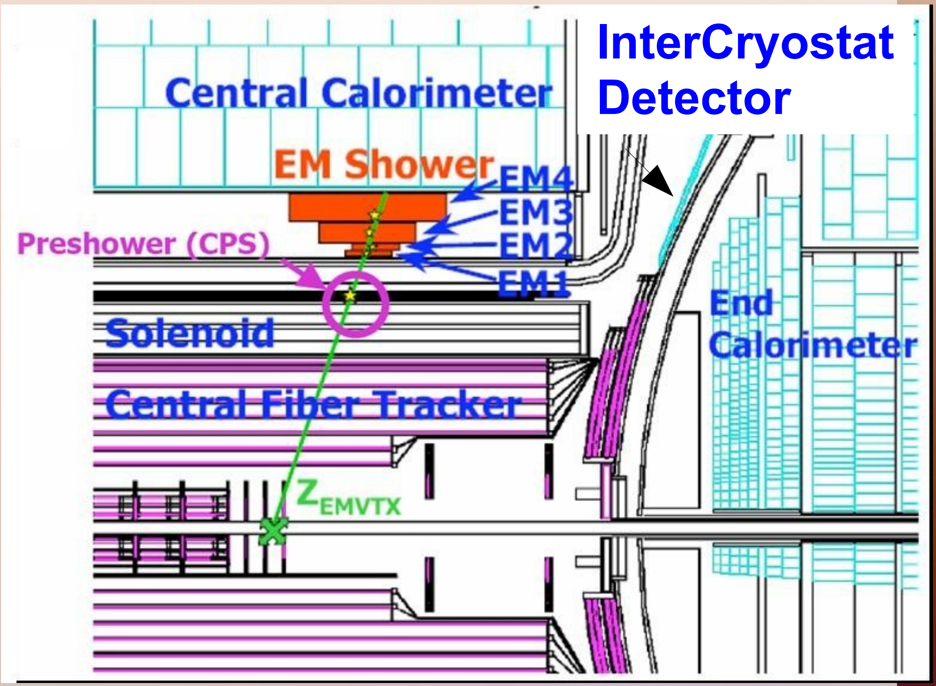


Direct comparisons difficult as ATLAS & CMS set $\Lambda\rightarrow\infty$

Backup Slides

Electron and Photon ID

- Both e & γ are identified by deposits of energy in EM
  - Separate e from γ using tracking information
  - In ZZ, tracking cuts relaxed to improve acceptance
  - Calorimeter used to estimate p_T



- The ZZ and WZ analysis use ICR electrons
  - Limited to no EM calorimeter coverage between CC and EC
  - Require a track matched to calorimeter cluster
  - Track used to estimate p_T
- Multivariate techniques to separate electrons from jets

Z+jets Background

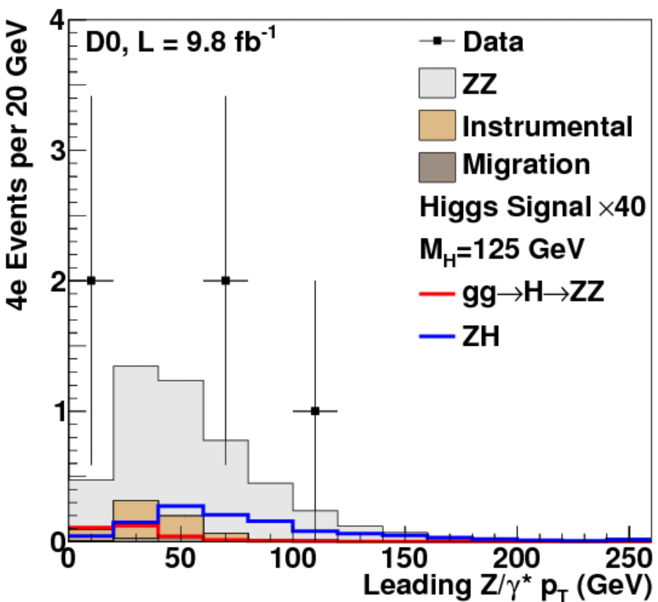
- Implemented in 2 steps
  - The j→l fake rates measured in QCD sample
  - Fake rates applied to lepton+jet events to estimate Z+jet bkgd
- Fake rates calculated using a tag-and-probe method
  - the highest p_T jet in used as tag
  - $\Delta\phi$(tag,probe) > 3.0
- The fake rate = N(probe jets within dR < 0.5 of a good lepton)/N(probe jets)

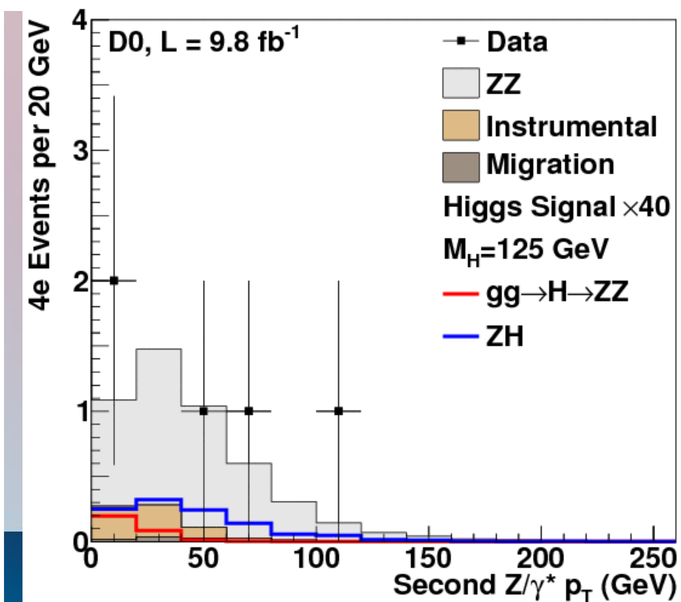
Z+jets Background

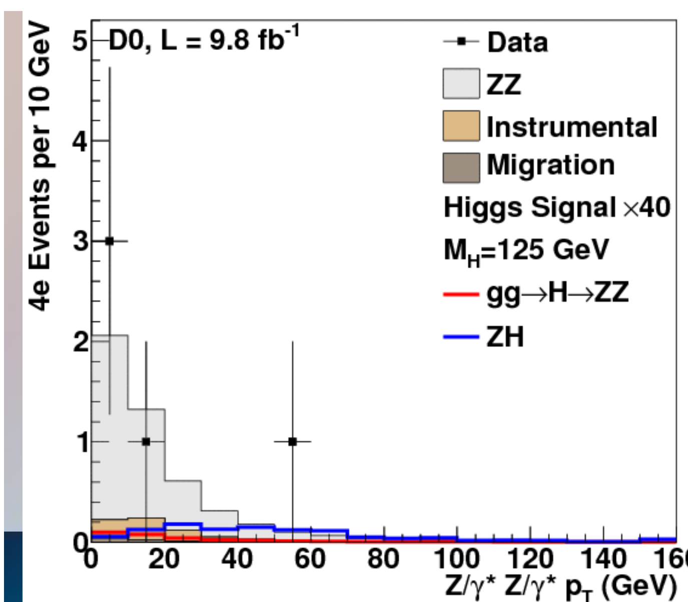
- In the 4e final state, we apply the fake rates to a 3e+jet sample
  - accounts for j→e and γ→e
- In 2e2μ final state, the total background is given by $N(\mu\mu e+j)\times f_e - N(\mu\mu+jj)\times f_e^2 + N(ee+jj)\times f_\mu$
  - Negative term accounts for double counting of jets in μμe+j final state
  - Considered in 4e final state, found to be negligible
- In 4m final state, fake rate applied to 2μ+2j events

Event Yields – 4e final State

	2 CC 2 EC	3 CC 1 EC	4 CC	$\geq$ 2 CC 1 ICR
Instrumental backg.	$0.15 \pm 0.01 \pm 0.03$	$0.12 \pm 0.01 \pm 0.02$	$0.05 \pm 0.01 \pm 0.01$	$0.29 \pm 0.04 \ ^{+0.03}_{-0.12}$
Migration	$0.014 \pm 0.001 \pm 0.002$	$0.023 \pm 0.001 \pm 0.004$	$0.025 \pm 0.001 \pm 0.004$	$0.024 \pm 0.001 \pm 0.003$
Total non-ZZ background	$0.17 \pm 0.01 \pm 0.03$	$0.14 \pm 0.01 \pm 0.02$	$0.08 \pm 0.01 \pm 0.01$	$0.32 \pm 0.04 \ ^{+0.03}_{-0.12}$
Expected t-channel $Z/\gamma^* \ Z/\gamma^*$	$0.48 \pm 0.01 \pm 0.07$	$1.14 \pm 0.01 \pm 0.17$	$1.03 \pm 0.01 \pm 0.15$	$1.47 \pm 0.01 \pm 0.19$
Observed Events	0	1	2	2

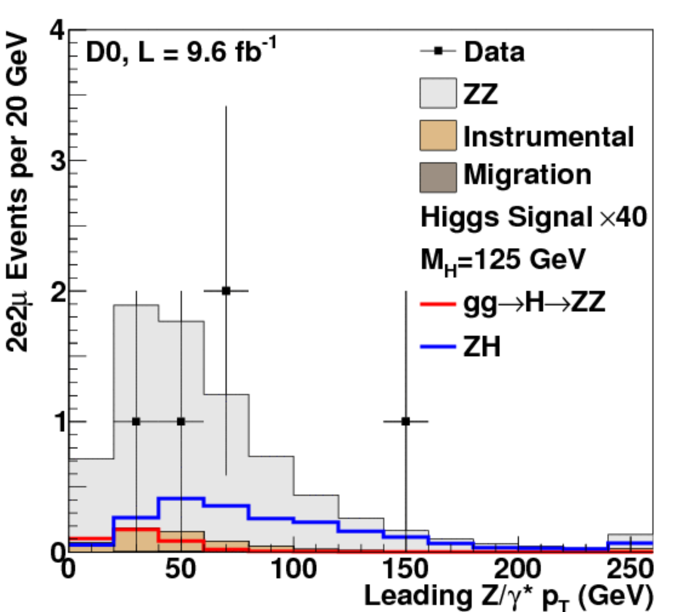


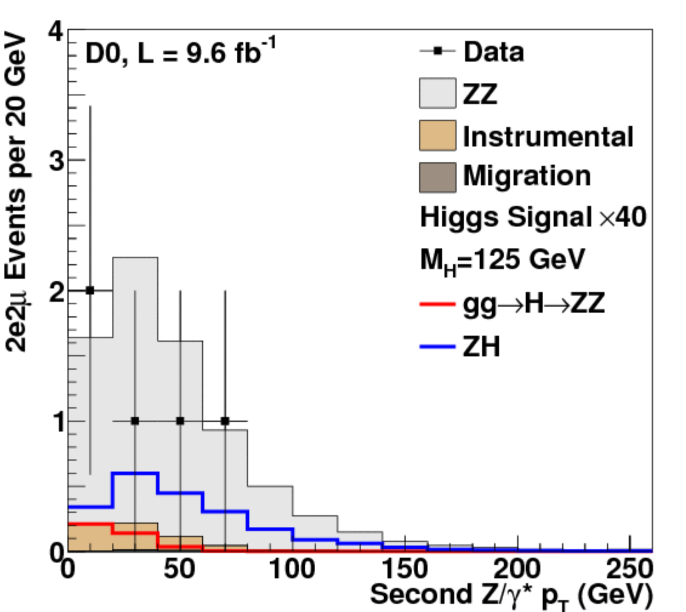


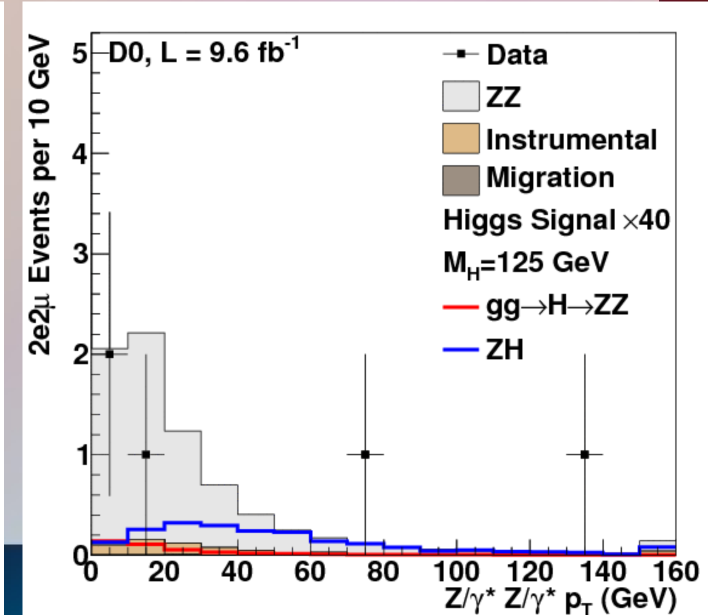


Event Yields - 2e2μ Final State

	0 CC	1 CC	2 CC
Instrumental backg.	$0.11 \pm 0.01 \pm 0.03$	$0.21 \pm 0.01 \pm 0.04$	$0.27 \pm 0.01 \pm 0.04$
$t\bar{t}$	$(0.2\ ^{+0.3}_{-0.1} \pm 0.6) \times 10^{-2}$	$(1.0\ ^{+0.5}_{-0.3} \pm 0.2) \times 10^{-2}$	$(0.3\ ^{+0.2}_{-0.1} \pm 0.3) \times 10^{-2}$
Migration	$(2.1\ ^{+0.9}_{-0.7}\ ^{+0.3}_{-1.0}) \times 10^{-3}$	$(5.0 \pm 0.8\ ^{+0.6}_{-1.4}) \times 10^{-3}$	$(4.8\ ^{+0.6}_{-0.5} \pm 1.0) \times 10^{-3}$
Cosmic rays	< 0.001	< 0.003	< 0.006
Total non-ZZ background	$0.12 \pm 0.01 \pm 0.03$	$0.23 \pm 0.01 \pm 0.04$	$0.27 \pm 0.01 \pm 0.04$
Expected t-channel $Z/\gamma^*\ Z/\gamma^*$	$0.43 \pm 0.01 \pm 0.06$	$2.37 \pm 0.02 \pm 0.28$	$4.13 \pm 0.03 \pm 0.49$
Observed Events	2	1	2



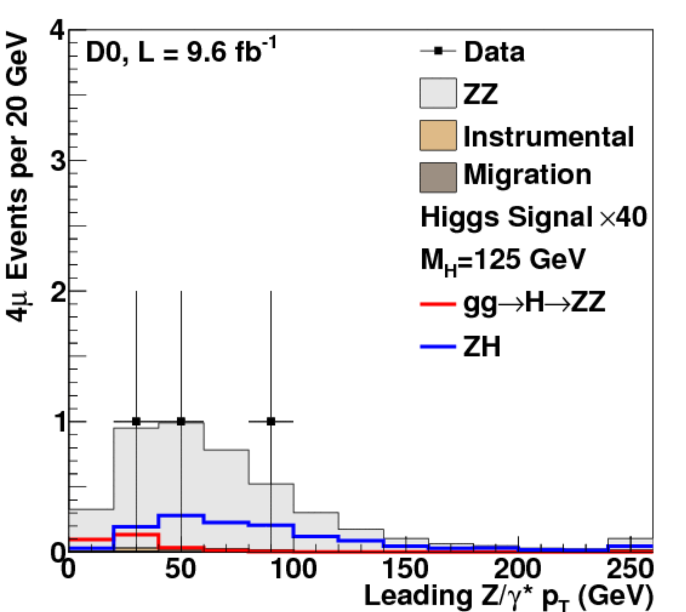


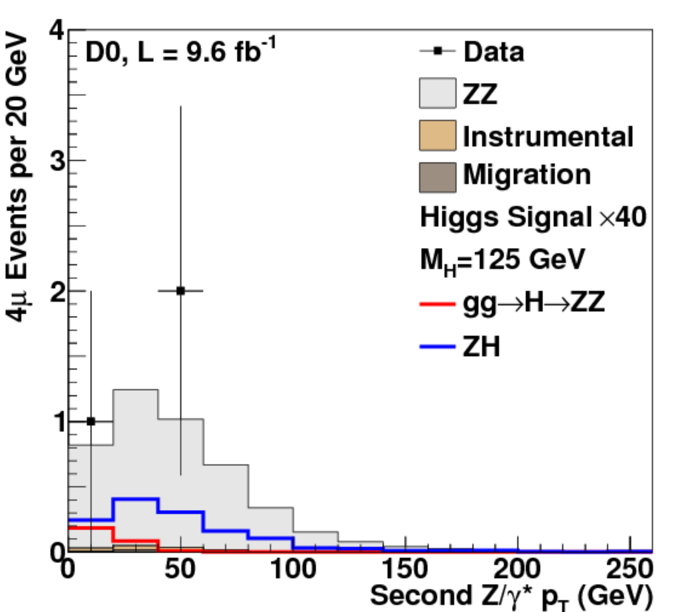


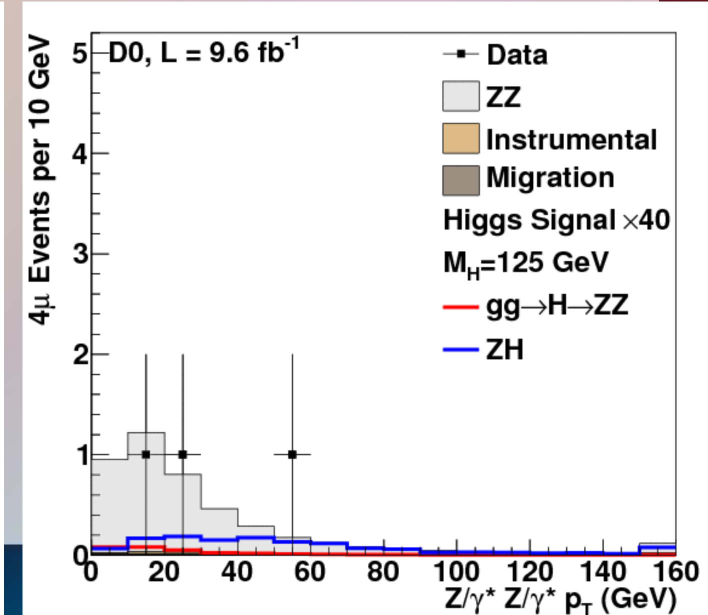
Events Yields – 4μ Final State and Total

	Number of Events
Instrumental backg.	$0.12 \pm 0.01 \, ^{+0.07}_{-0.05}$
Migration	$(0.34 \pm 0.02 \, ^{+0.07}_{-0.04}) \times 10^{-1}$
Cosmic rays	<0.01
Total non-ZZ background	$0.15 \pm 0.01 \, ^{+0.07}_{-0.05}$
Expected t-channel Z/γ^* Z/γ^*	$4.26 \pm 0.02 \pm 0.43$
Observed Events	3

Summing over all final states, expect total of **15.3 ZZ events** and **1.5 bkgd events**, with **13 events** seen in data.







Higgs Systematics

- The same lepton ID and lepton energy resolution systematics that were applied to the non-resonant ZZ MC have been applied to the ZH and gg->ZZ MC.
- We assume the SM non-resonant ZZ cross section when doing the Higgs Search, with a 7% cross section uncertainty
- We have a 6.2% uncertainty on the ZH cross section, and a 10.9% uncertainty on the $gg \rightarrow H$ cross section.