Limits on Anomalous WWγ and WWZ Couplings from DØ

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October 31st, 2006

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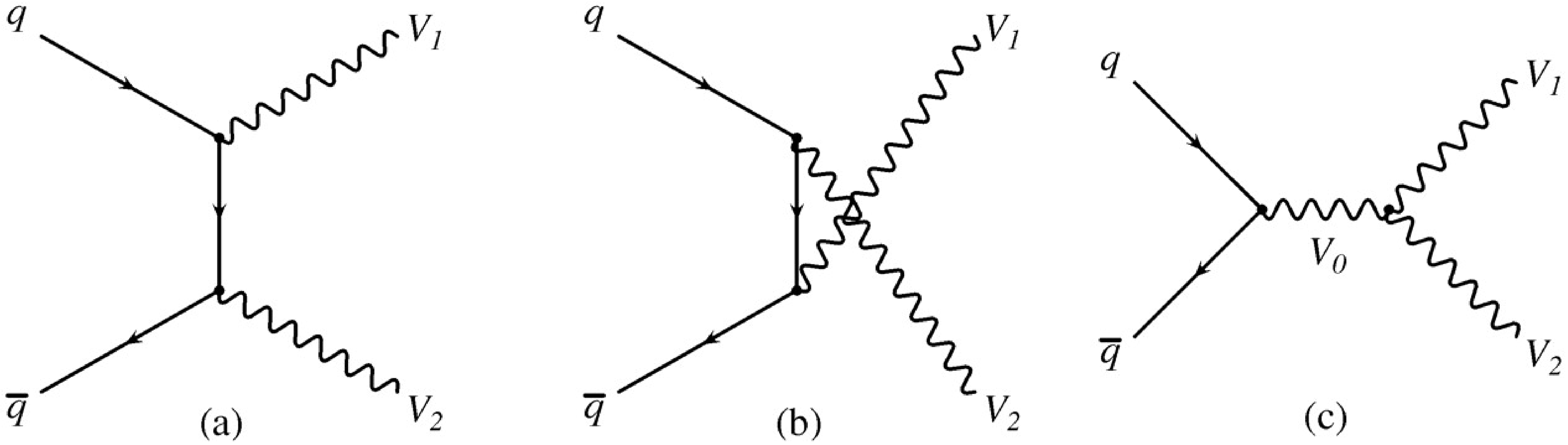
- Discuss triple gauge couplings (TGC)
  - Diboson production
  - Anomalous couplings (AC)
  - Setting coupling limits
- Review recent DØ TGC publications
  - Wγ
  - WZ
  - WW
- Future plans for anomalous coupling study

Diboson Production

- Leading order diagrams for diboson production:



- Each final state (Wγ, WW, WZ) has contributions from a triple gauge boson coupling
- Anomalous values of the triple gauge coupling disrupt the interference between these diagrams

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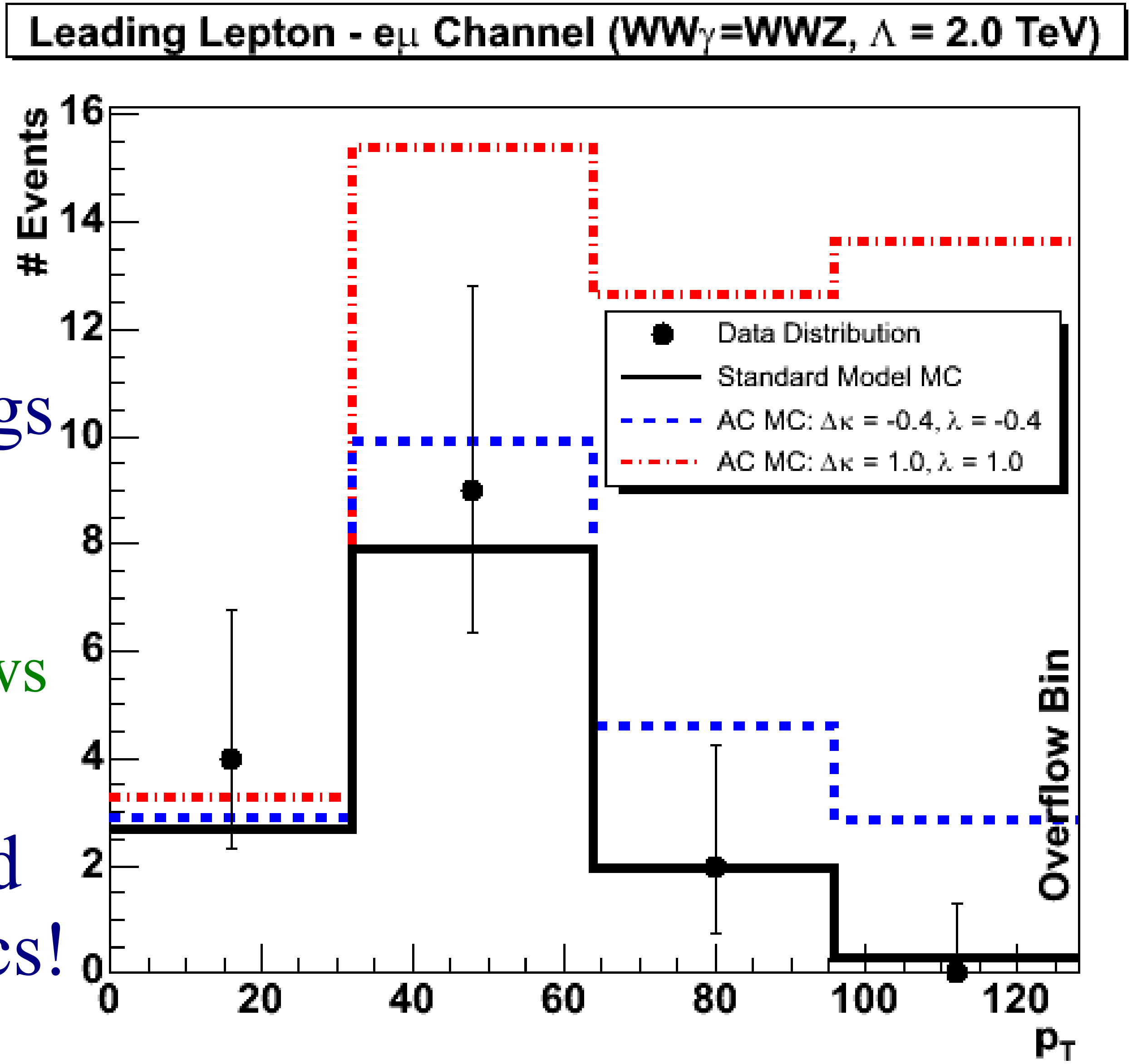
WW eμ Channel p_T Spectra

- Dashed lines demonstrate kinematic effects of introducing anomalous couplings
  - Overall cross section increases
  - p_T distribution skews to higher values
- Excess events could indicate new physics!



Anomalous Couplings

- Assuming EM gauge invariance and C and P conservation, the most general Lorentz invariant effective Lagrangian for triple gauge couplings is:

$$\frac{L_{WWV}}{g_{WWV}} = i\, g_1^V \left(W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu} \right) + i\, \kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + i \frac{\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu_\nu V^{\nu\lambda}$$

(where V=γ or Z, W^μ is the W^- field, $X_{\mu\nu}=\partial_\mu X_\nu - \partial_\nu X_\mu$, $g_{WW\gamma} = -e$, $g_{WWZ} = -e \cot\theta_W$, and $g_1^\gamma = 1$)

- In the Standard Model, these triple gauge coupling parameters are fully constrained
  - In SM: $g_1^Z = \kappa_Z = \kappa_\gamma = 1$ ($\Delta\kappa_\gamma \equiv \kappa_\gamma - 1 = 0$), $\lambda_Z = \lambda_\gamma = 0$
- Can be considered corrections to W's $\mathrm{EM}_{(\gamma)}$ or $\mathrm{Weak}_{(Z)}$ charge and dipole/quadrupole moments

Form Factor

- Anomalous couplings will increase the cross section and change the kinematics of diboson production, particularly at higher parton center of mass energies
- A form factor, with scale Λ, is introduced to force the coupling to vanish as s→∞

$$a(\hat{s}) = \frac{a_0}{(1+\hat{s}/\Lambda^2)^2}$$

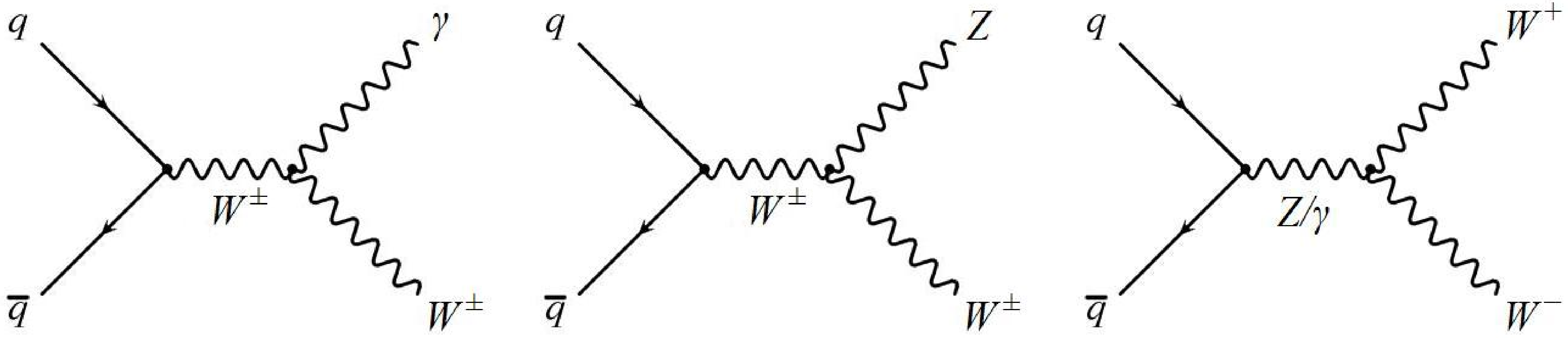
- For a given value of Λ, there is an upper limit on the coupling size, beyond which unitarity is exceeded
- Anomalous coupling limits get tighter as Λ increases, but not as quickly as unitarity limit tightens

Setting Coupling Limits

- Anomalous coupling limits must be set for a given coupling relationship and form factor combination
  - Raise Λ value in ½ TeV steps until limits violate unitarity
- Various coupling relationships can be considered:
  - WWZ couplings = WWγ couplings ($\Delta\kappa_\gamma = \Delta\kappa_Z$, $\lambda_Z = \lambda_\gamma$)
  - The Hagiwara, Ishihara, Szalapski, Zeppenfeld (HISZ) parameterization forces SU(2) × U(1) gauge symmetry
    - $\Delta\kappa_Z = \Delta\kappa_\gamma (1 - \tan^2\theta_W)$, $\Delta g_1^Z = \Delta\kappa_\gamma / (2\cos^2\theta_W)$, $\lambda_Z = \lambda_\gamma$
  - LEP TGC Working Group constraints
    - $\kappa_Z = g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W$, $\lambda_Z = \lambda_\gamma$
  - Standard Model WWZ, anomalous WWγ (& vice versa)

AC Study at the Tevatron

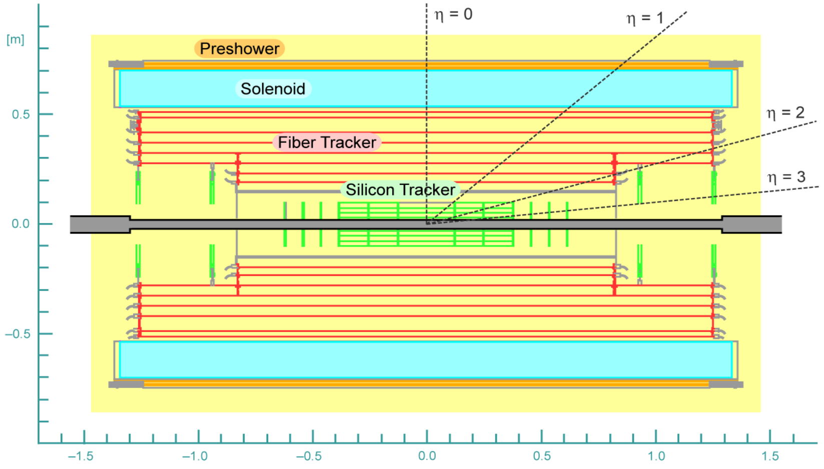
- There are unique advantages to studying triple gauge couplings at a hadron collider

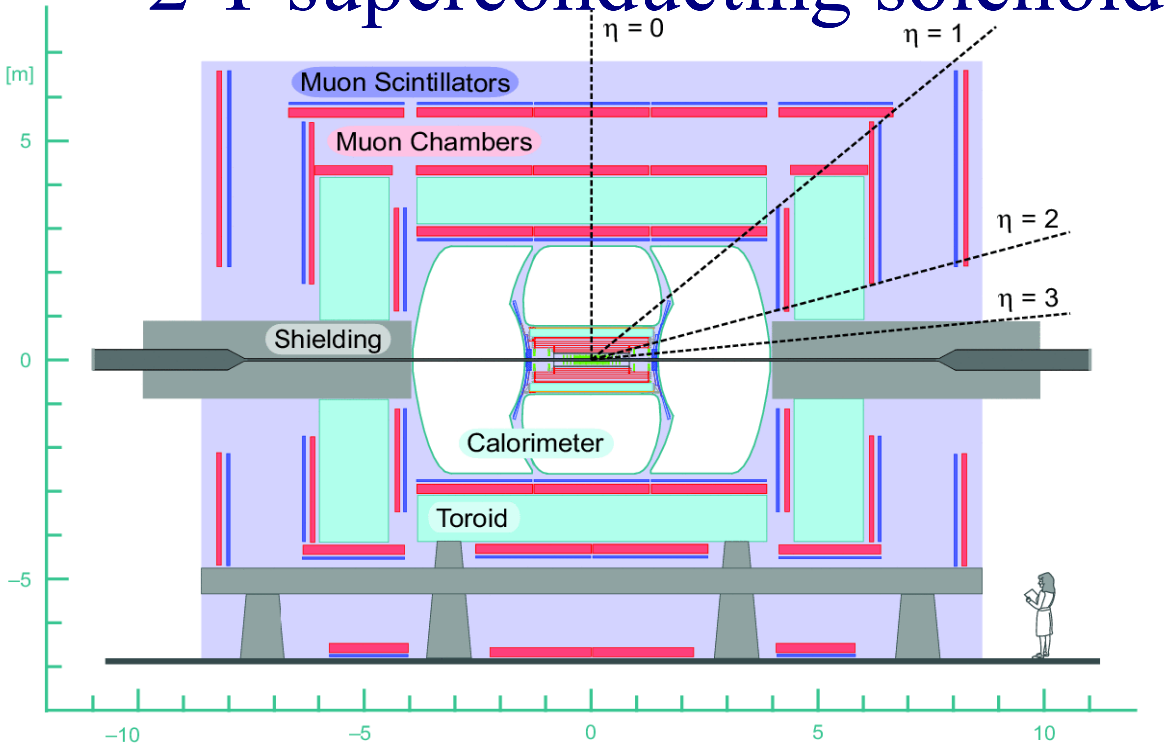


- Charged final states are available, which can probe WWγ and WWZ vertices independently
- Tevatron collisions explore a range of center of mass energies, including highest available in the world

The DØ Detector

- Multipurpose particle detector
- Silicon microstrip tracker
- Scintillating fiber tracker
- 2 T superconducting solenoid





- Central and forward preshower system
- Liquid argon and uranium calorimeter
- Muon system with 1.8 T toroidal magnet

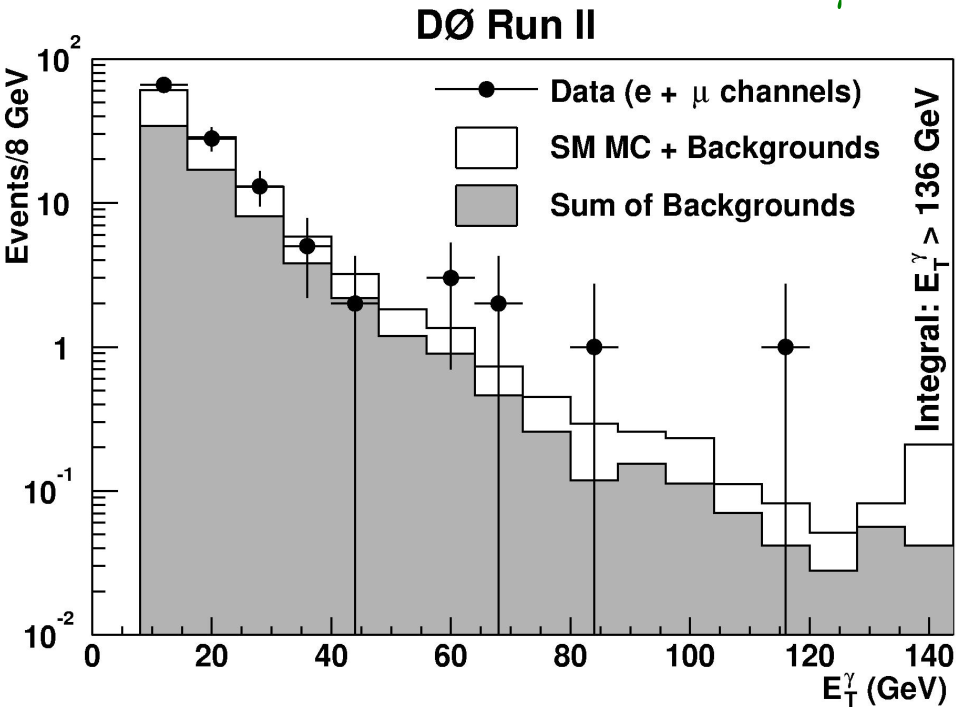
$W\gamma$ Analysis

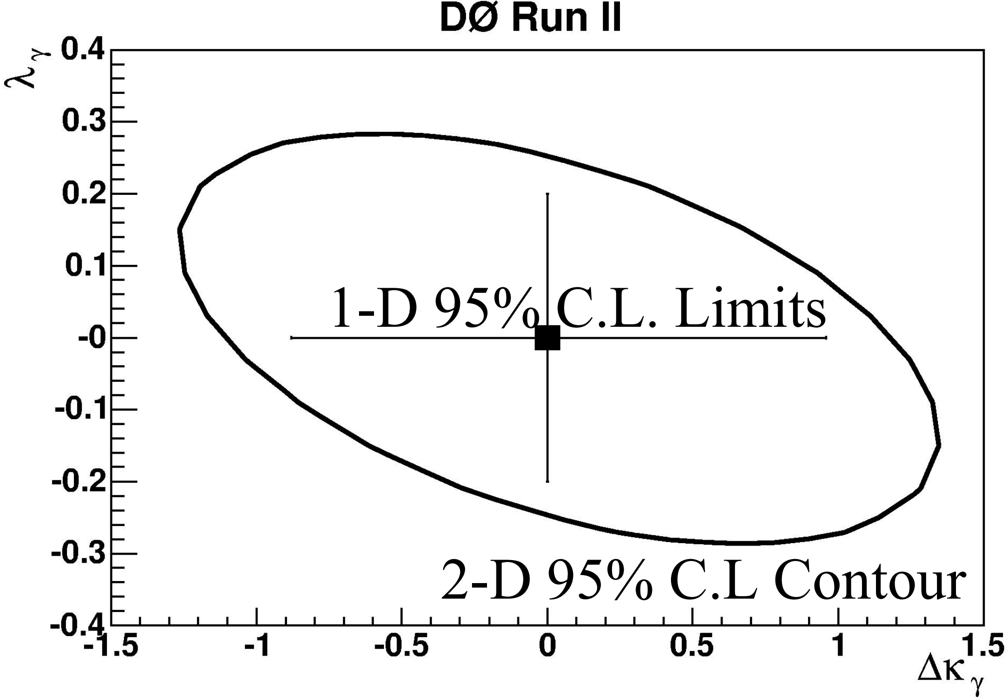
- $W\gamma$ anomalous coupling limits set during cross section analysis
  - Published in Phys. Rev. D **71**, 091108 (2005)
- The cross section analysis used the leptonic channels $p\bar{p} \rightarrow W(\gamma) + X \rightarrow \ell\nu\gamma + X$ (ℓ=e,μ) (signal, background)
  - $e\nu\gamma$: $\int \mathscr{L} dt$=162 pb^{-1}, 112 candidates (51.2±11.5, 60.8±4.5)
  - $\mu\nu\gamma$: $\int \mathscr{L} dt$=134 pb^{-1}, 161 candidates (89.7±13.7, 71.3±5.2)
- The total measured cross sections for each channel, with $E_T^\gamma > 8$ GeV and $\Delta R_{\ell\gamma} > 0.7$: (SM predicts 16.0±0.4 pb)
  - $e\nu\gamma$: 13.9 ± 2.9 (stat) ± 1.6 (syst) ± 0.9 (lum) pb
  - $\mu\nu\gamma$: 15.2 ± 2.0 (stat) ± 1.1 (syst) ± 1.0 (lum) pb

Wγ TGC Limits

- Photon E_T spectrum used to set AC limits
- No coupling relationships required to set limits
- $\Lambda = 2$ TeV 95% C.L. limits:

$$-0.88 < \Delta\kappa_\gamma < 0.96,\ -0.20 < \lambda_\gamma < 0.20$$

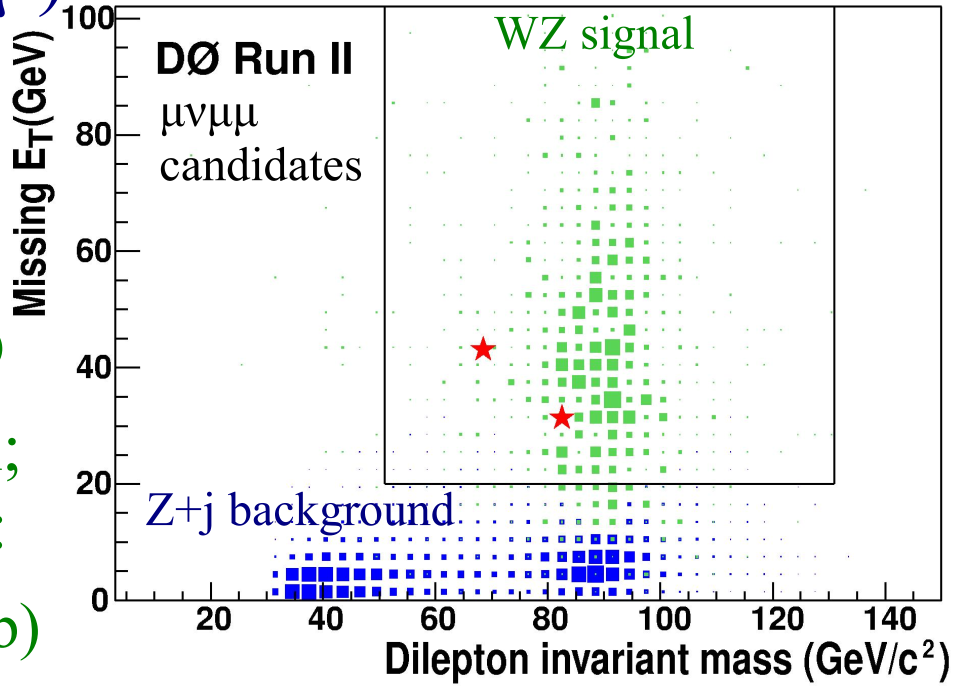




WZ Analysis

- WZ anomalous coupling limits set during ~300 pb^{-1} cross section analysis
  - Published in Phys. Rev. Lett. **95**, 141802 (2005)
- The cross section analysis used the leptonic channels $WZ \rightarrow \ell\nu\ell'\bar{\ell}'$ ($\ell = e,\mu$; $\ell' = e,\mu$)
  - 1 eνee, 2 μνμμ candidates
  - Expected 2.04±0.13 signal, 0.71±0.08 background
  - Yields $\sigma_{WZ} < 13.3$ pb (@ 95% C.L.)
  - 3.6% chance of bkg fluctuation; if interpreted as a cross section:

$$\sigma_{WZ} = 4.5^{+3.8}_{-2.6}\,\text{pb} \quad (\text{SM: } 3.7 \pm 0.1\ \text{pb})$$

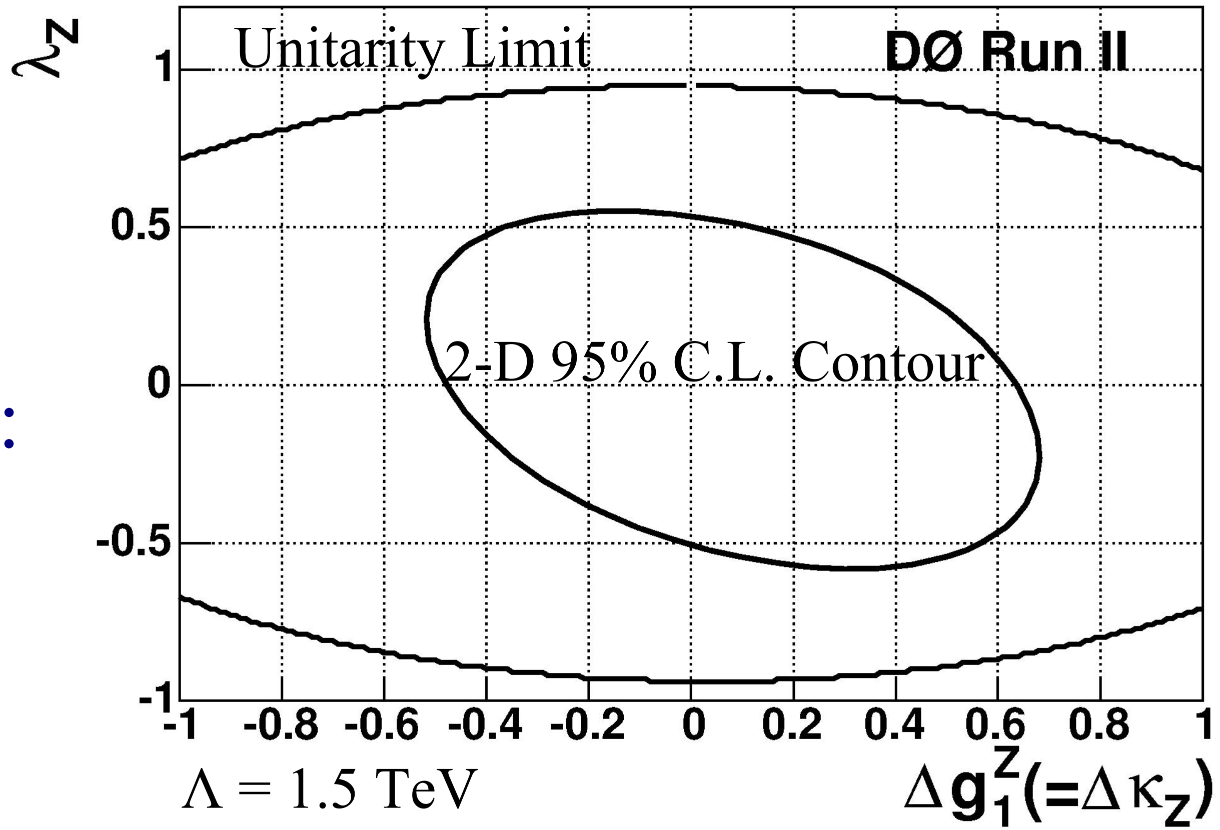


WZ TGC 95% C.L. Limits

- Total number of events used to set AC limits
  - More events are required to use kinematic dist.
- In WZ final state, with $\Delta\kappa_\gamma = 0$, LEP constraints become:

$$\Delta g_1^Z = \Delta\kappa_Z$$
$$\lambda_\gamma = \lambda_Z$$

Coupling (constraint)	$\Lambda = 1$ TeV	$\Lambda = 1.5$ TeV
λ_Z ($\Delta g_1^Z=\Delta\kappa_Z=0$)	−0.53, 0.56	−0.48, 0.48
$\Delta g_1^Z=\Delta\kappa_Z$ ($\lambda_Z=0$)	−0.49, 0.66	−0.43, 0.57
Δg_1^Z ($\lambda_Z=\Delta\kappa_Z=0$)	−0.57, 0.76	−0.49, 0.66
$\Delta\kappa_Z$ ($\lambda_Z=\Delta g_1^Z=0$)	−2.0, 2.4	–



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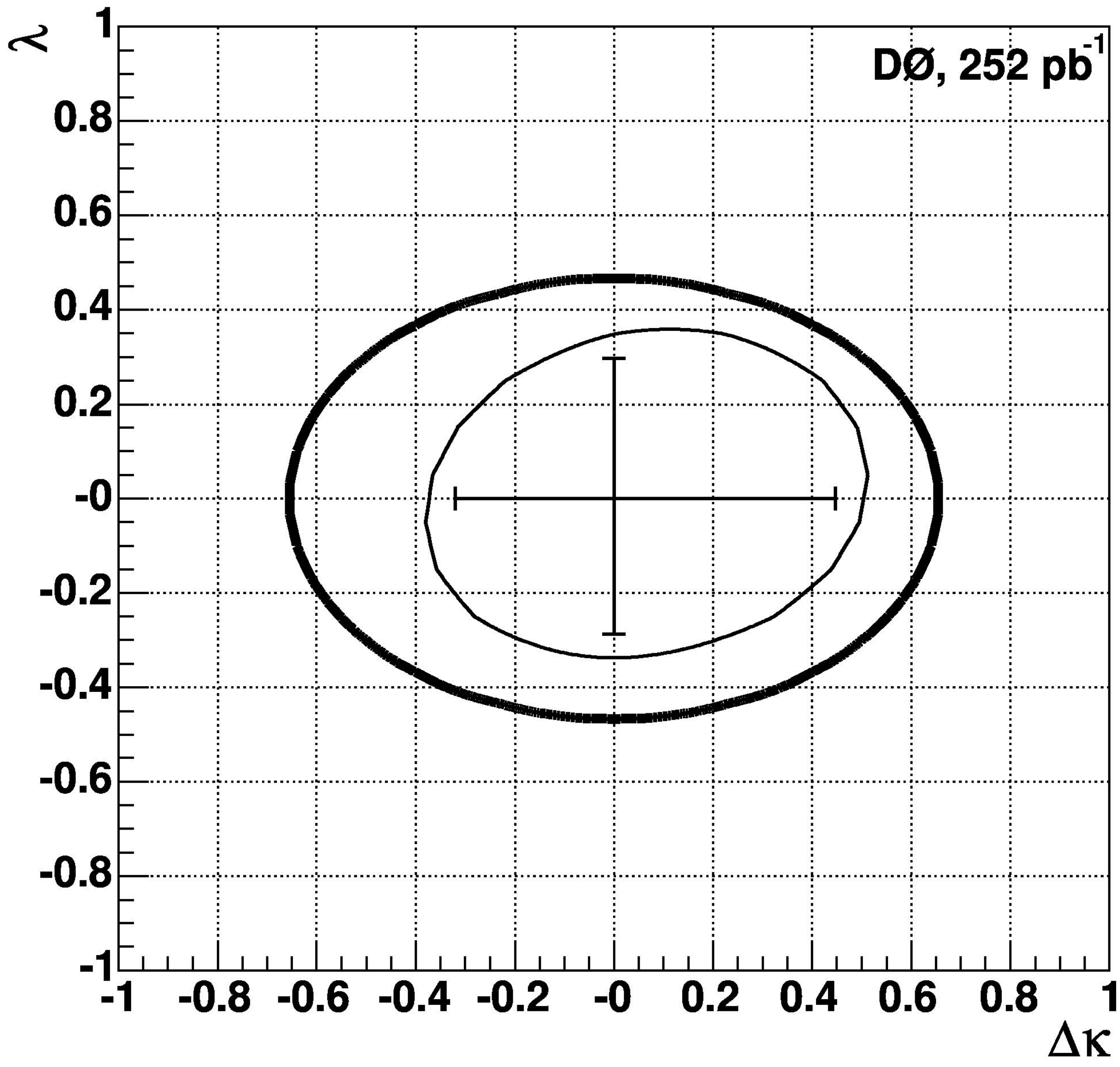
WW Analysis

- The WW anomalous coupling analysis used data from the most recent WW cross section result from DØ
  - WW cross section: Phys. Rev. Lett. **94**, 151801 (2005)
  - WW TGC Limits: Phys. Rev. D **74**, 057101 (2006)
- The cross section analysis used the leptonic channels $WW \rightarrow \ell^- \nu \ell^+ \bar{\nu}$ ($\ell = e, \mu$) (signal, background)
  - ee: $\int \mathscr{L} dt = 252\ \mathrm{pb}^{-1}$, 6 candidates (3.26±0.05, 2.30±0.21)
  - eμ: $\int \mathscr{L} dt = 235\ \mathrm{pb}^{-1}$, 15 candidates (10.8±0.1, 3.81±0.17)
  - μμ: $\int \mathscr{L} dt = 224\ \mathrm{pb}^{-1}$, 4 candidates (2.01±0.05, 1.94±0.41)
- The total measured cross section was: (SM: 13.0-13.5 pb)

$$13.8^{+4.3}_{-3.8}\,(\mathrm{stat})^{+1.2}_{-0.9}\,(\mathrm{syst}) \pm 0.9\,(\mathrm{lum})\,\mathrm{pb}$$

WW 2-D TGC 95% C.L. Limits



- Leading and trailing lepton p_T distributions used to set limits
- $\Lambda = 2$ TeV contour assuming $\Delta\kappa_\gamma = \Delta\kappa_Z$ and $\lambda_Z = \lambda_\gamma$ shown
  - The bold outer curve is the unitarity limit, the inner curve is the 2-D 95% C.L. contour, and the cross denotes the 1-D limits

WW 1-D TGC 95% C.L. Limits

Coupling (constraint)	Λ (TeV)	95% C.L. Limits
$\lambda_\gamma=\lambda_Z$ ($\Delta\kappa_\gamma=\Delta\kappa_Z=0$)	1.5	−0.31, 0.33
$\Delta\kappa_\gamma=\Delta\kappa_Z$ ($\lambda_\gamma=\lambda_Z=0$)	1.5	−0.36, 0.47
$\lambda_\gamma=\lambda_Z$ ($\Delta\kappa_\gamma=\Delta\kappa_Z=0$)	2.0	−0.29, 0.30
$\Delta\kappa_\gamma=\Delta\kappa_Z$ ($\lambda_\gamma=\lambda_Z=0$)	2.0	−0.32, 0.45
$\lambda_\gamma=\lambda_Z$ (HISZ)	1.5	−0.34, 0.35
$\Delta\kappa_\gamma$ (HISZ)	1.5	−0.57, 0.75
λ_Z (SM WWγ, $\Delta\kappa_Z=0$)	2.0	−0.39, 0.39
$\Delta\kappa_Z$ (SM WWγ, $\lambda_Z=0$)	2.0	−0.45, 0.55
λ_γ (SM WWZ, $\Delta\kappa_\gamma=0$)	1.0	−0.97, 1.04
$\Delta\kappa_\nu$ (SM WWZ, $\lambda_\nu=0$)	1.0	−1.05, 1.29

Future Outlook

- In the coming months, the Wγ, WZ and WW cross section and associated anomalous coupling limit analyses will be completed using 1 fb^{-1} of data
  - While the anomalous coupling limit sensitivity scales as the fourth root of luminosity, the larger data set will allow better use of event kinematics to tighten TGC limits
- Each of these processes gives a unique handle on triple gauge couplings
- In the future, we plan on combining the results from all three diboson processes to improve the sensitivity of our anomalous triple gauge coupling studies

Summary of Results

- Tightest published limits from DØ for each coupling, when the other four couplings are at their SM values:

95% C.L. Limit	Λ (TeV)	Channel
$-0.49 < \Delta g_1^Z < 0.66$	1.5	WZ
$-0.45 < \Delta\kappa_Z < 0.55$	2.0	WW
$-0.39 < \lambda_Z < 0.39$	2.0	WW
$-0.88 < \Delta\kappa_\gamma < 0.96$	2.0	Wγ
$-0.20 < \lambda_\gamma < 0.20$	2.0	Wγ

- Next round of results using 1 fb^{-1} are coming soon
- Combining results across diboson channels will further increase DØ sensitivity to these couplings

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Backup Slides

Comparison to LEP Results

- The LEP collaborations produced combined results
  - Final combined results, errors quoted at 68% C.L.:

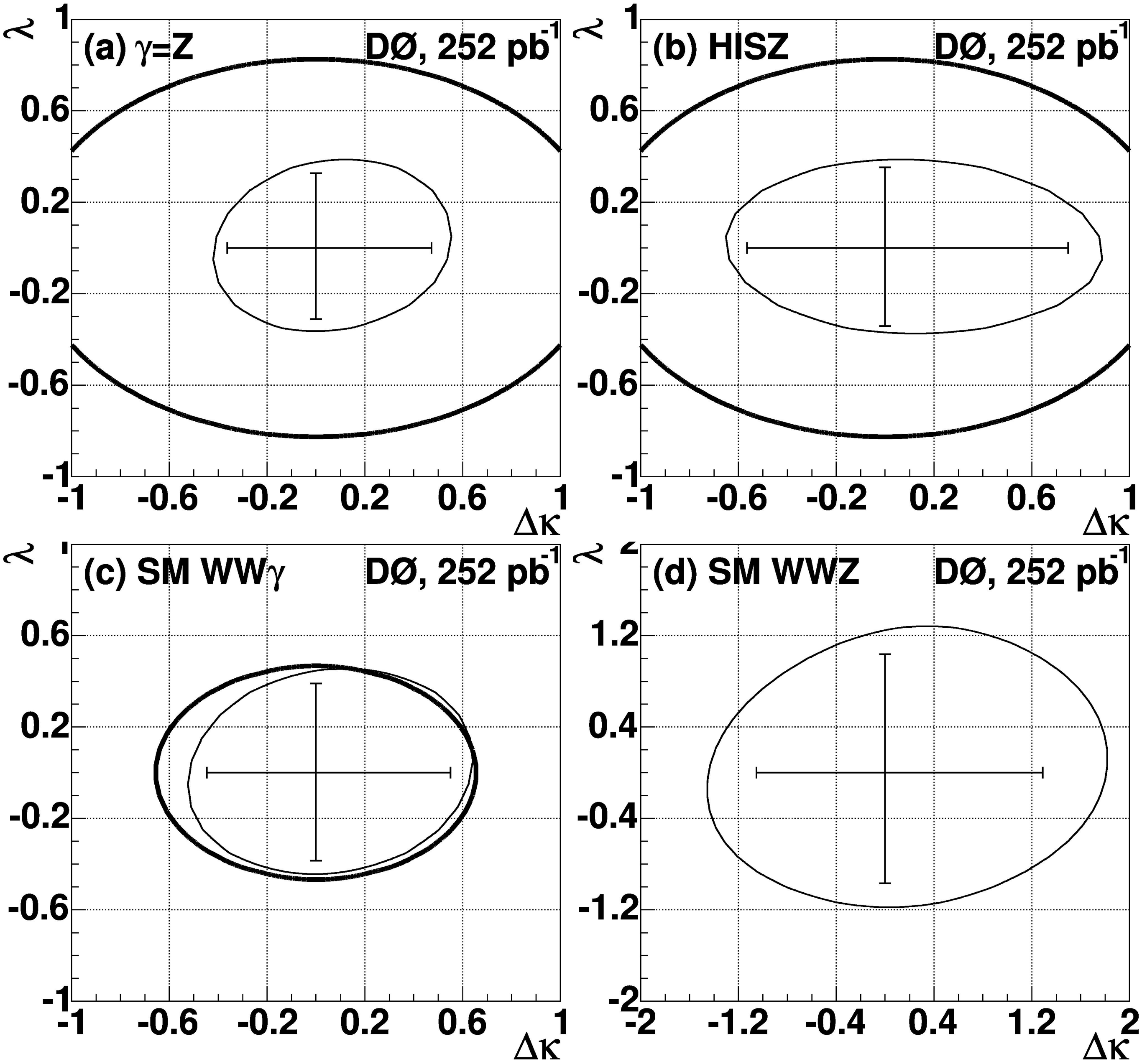
$$g_1^Z = 0.984^{+0.022}_{-0.019} \quad \kappa_\gamma = 0.973^{+0.044}_{-0.045} \quad \lambda_\gamma = -0.028^{+0.020}_{-0.021}$$

- Comparable 95% C.L. limits from DØ:
  - $-0.43 < \Delta g_1^Z < 0.57$; $-0.62 < \Delta\kappa_\gamma < 0.82$; $-0.2 < \lambda_\gamma < 0.2$

    (WZ LEP @ Λ=1.5) (WW HISZ @ Λ=1.5) (Wγ @ Λ=2)
- There may be an order of magnitude difference, but...
  - Tevatron can produced charged final states
  - Center of mass energy varies at Tevatron (& goes higher!)
  - These results are from individual diboson channels, from only one detector at Fermilab...wait for combined results!

WW 2-D TGC 95% C.L. Limits

- More 2-D limits:
  - a) WWZ=WWγ @ Λ = 1.5 TeV
  - b) HISZ @ Λ = 1.5 TeV
  - c) SM WWγ @ Λ = 2.0 TeV
  - d) SM WWZ @ Λ = 1.0 TeV
- Bold line is the unitarity limit, when applicable



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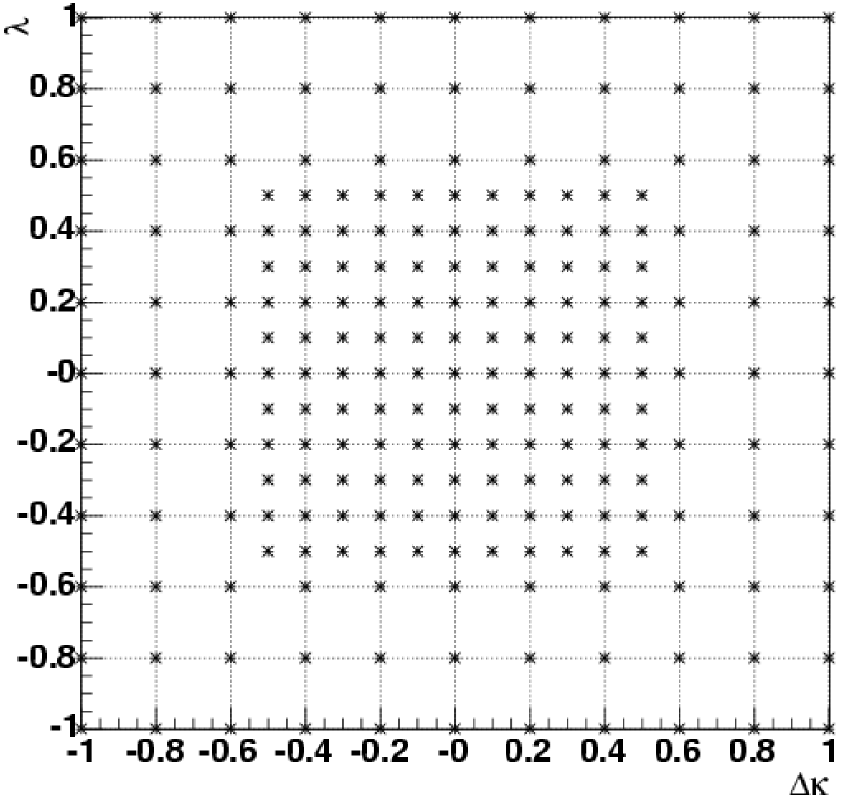
WW Monte Carlo Grid

- For a given Λ and coupling parameterization, a set of Monte Carlo data is generated at each point of a grid in (Δκ, λ) space
- Process the MC, accounting for most of the cuts used in the WW x-section analysis
- Scale the MC to match eff. of each channel, to account for cuts not possible in MC
- Bin the results for leading and trailing leptons by p_T

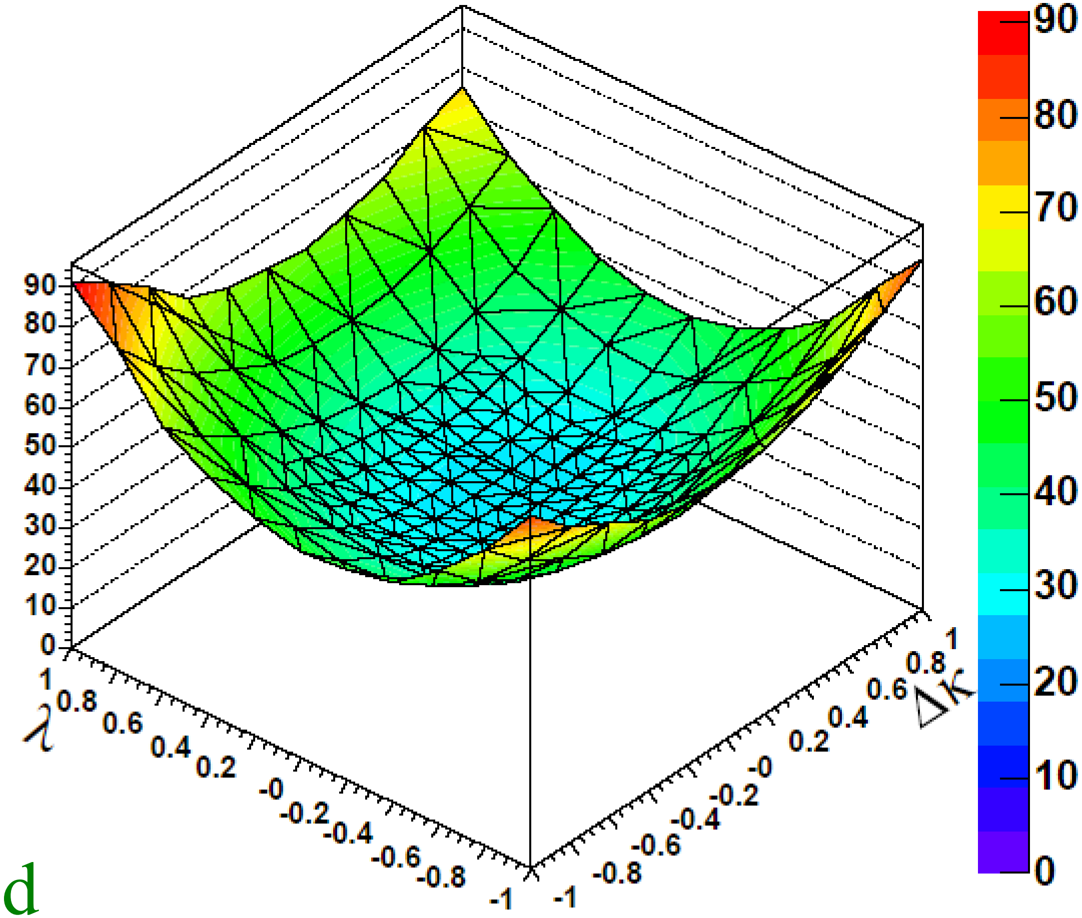


WW Likelihood Comparison

- MC p_T distributions are compared to the real data events by calculating a bin-by-bin likelihood
  - Each bin assumed to have Poisson distribution with mean equal to the sum of signal and background MC bins
  - Errors on signal and background distributions accounted for by weighting with Gaussian distributions
  - Correlations between signal and background across channels are small and handled separately
  - Assume luminosity uncertainty 100% correlated across channels
- All three channels together included in calculation of negative log likelihood for each grid point

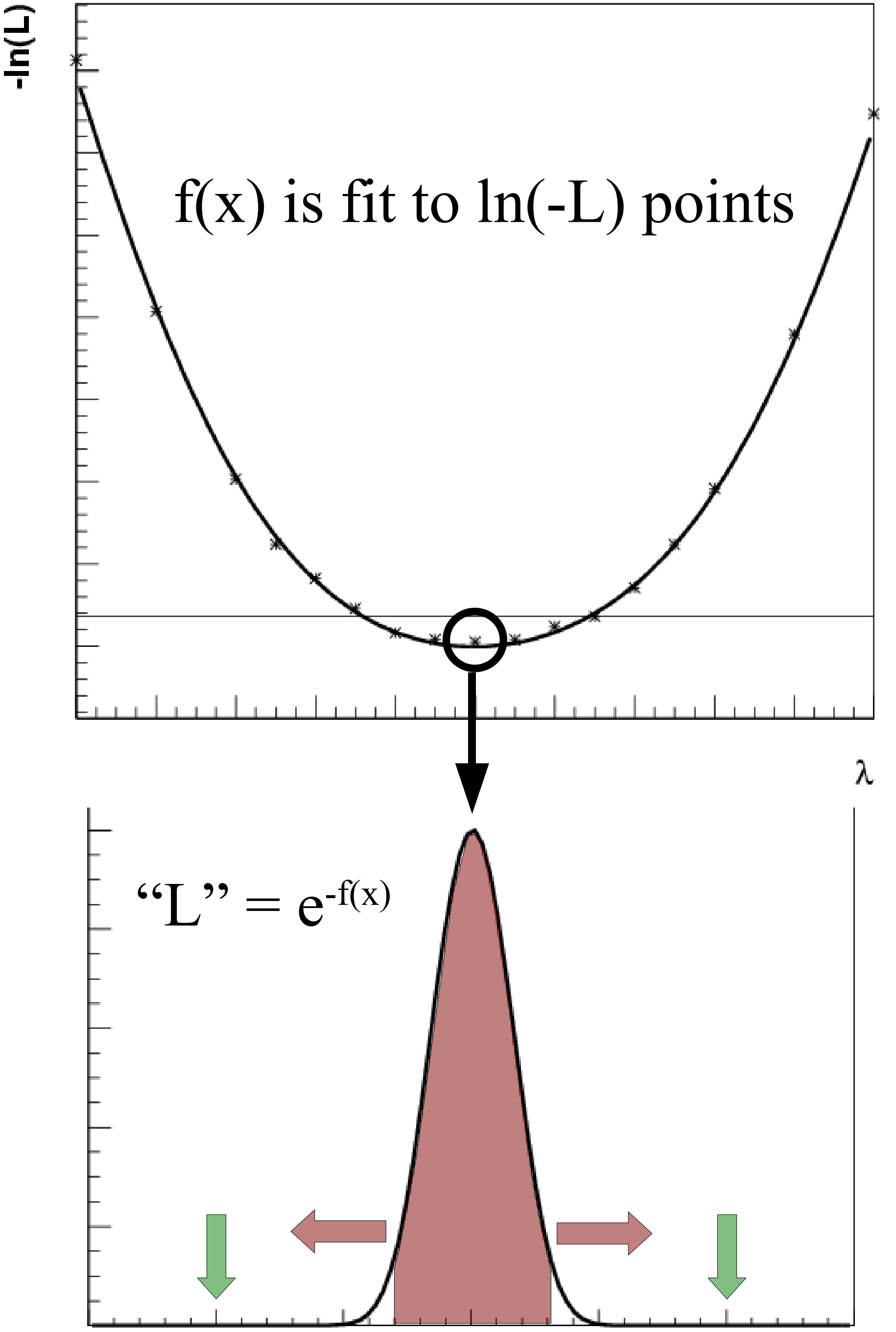
Determining Coupling Limits

- Limits are extracted by fitting a 6th order polynomial to the negative log likelihood
- 1-D limits:
  - Fit curve to Δκ or λ axis
  - Integrate curve to find 95% confidence level
- 2-D limits:
  - Fit a surface to entire grid
  - Integrate surface to find 95% confidence level contour line



Setting 1-D Limits

- First, create likelihood:
  - f(x) is fit to -ln(L)
  - Create “L” = exp(-f(x))
- Integrate total area within the MC grid boundaries, out to cutoff at grid edge
- Test integration limit pairs of equal likelihood, starting from max. likelihood
- Stop when ratio of sample area to “total” area > 0.95



Find 95% of total area between cutoff points

Setting 2-D Limits

- Similar to 1-D case, except λ-axis divided into 100 slices for performing numerical integration
  - Determine & integrate a new 1-D function for each λ slice
  - Searching for contour line of equal likelihood containing 95% of total volume within cutoff at MC grid edge