Diboson Physics at the Tevatron

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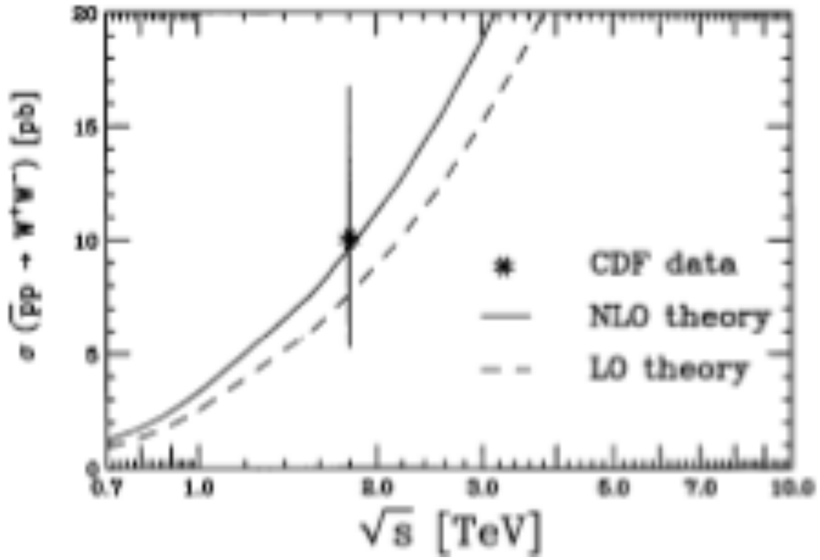
for the CDF and D0 Collaborations
HCP, 15 November 2011

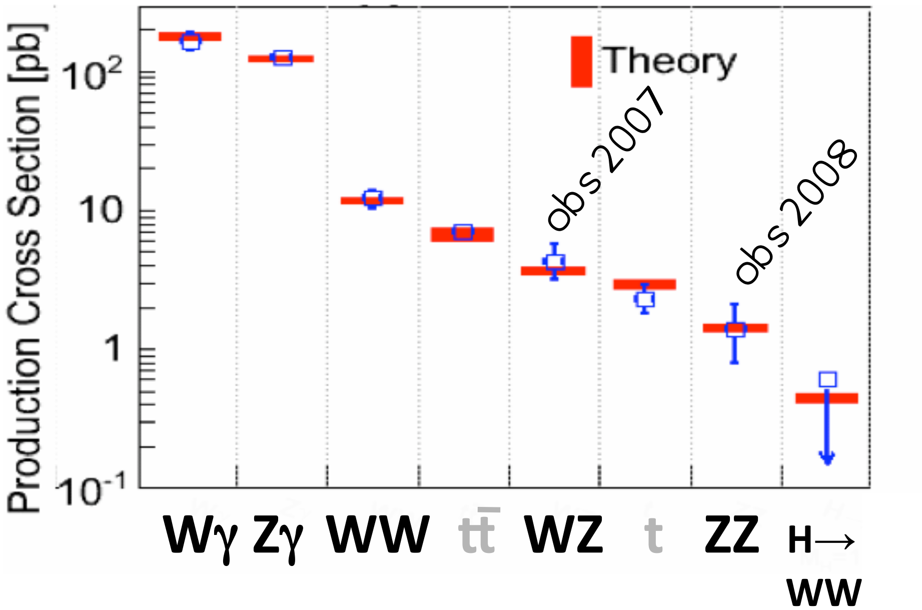
- Motivation
- V+γ physics
  - Wγ
  - Zγ
- Massive diboson physics
  - WW
  - WZ
  - ZZ
- Jet final-states
- Outlook

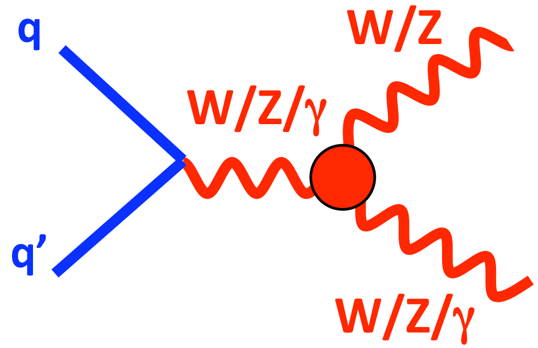
see also J-F Grivaz's talk on dibosons with Z→bb in Higgs session.

Dibosons

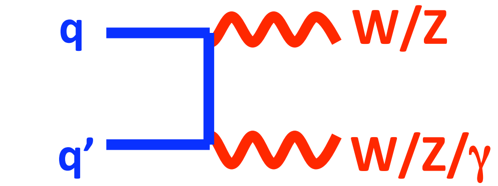
Tevatron Run 1:
Heavy diboson production:
only WW observed,
5 events above 1.2 expected bck

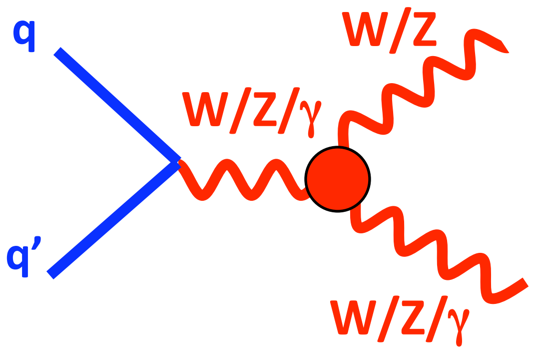






Dibosons





$$\frac{\mathcal{L}_{\rm WWV}}{g_{\rm WWV}} = i\left[g_1^{\rm V}(W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu) + \kappa^{\rm V} W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^{\rm V}}{m_{\rm W}^2} W^\dagger_{\rho\mu} W^\mu_\nu V^{\nu\rho}\right]$$

$$\mathcal{L} = -\frac{e}{M_{\rm Z}^2}\left[f_4^{\rm V}(\delta_\mu V^{\mu\beta})Z_\alpha(\delta^\alpha Z_\beta) + f_5^{\rm V}(\delta^\sigma V_{\sigma\mu})Z^{\mu\beta}Z_\beta\right]$$

EM gauge invariance and C and P conservation
$\rightarrow$ 5 independent TGCs for WW $\{g_1^Z, \kappa_Z, \kappa_\gamma, \lambda_Z, \lambda_\gamma\}$

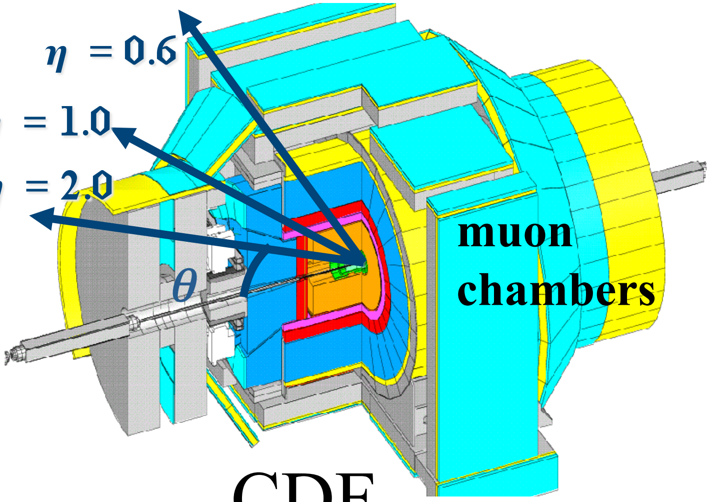
Wγ sensitive to κ_γ, λ_γ
WZ sensitive to g_1^Z, κ_Z, λ_Z

Standard Model: $g_1^Z = \kappa_Z = \kappa_\gamma = 1$ so consider Δg_1^Z, $\Delta\kappa_Z$
$\lambda_Z = \lambda_\gamma = 0$

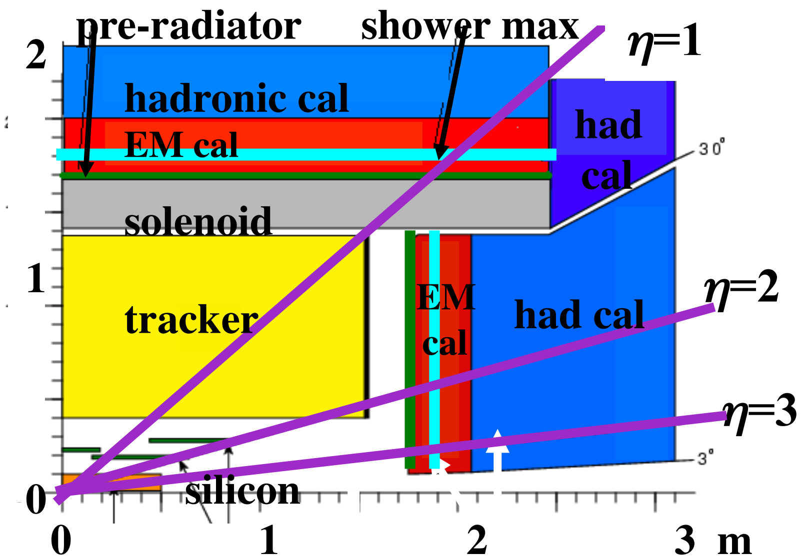
$$\Delta a(\hat{s}) = \frac{\Delta a_0}{(1+\hat{s}/\Lambda_{\rm NP}^2)^n}$$

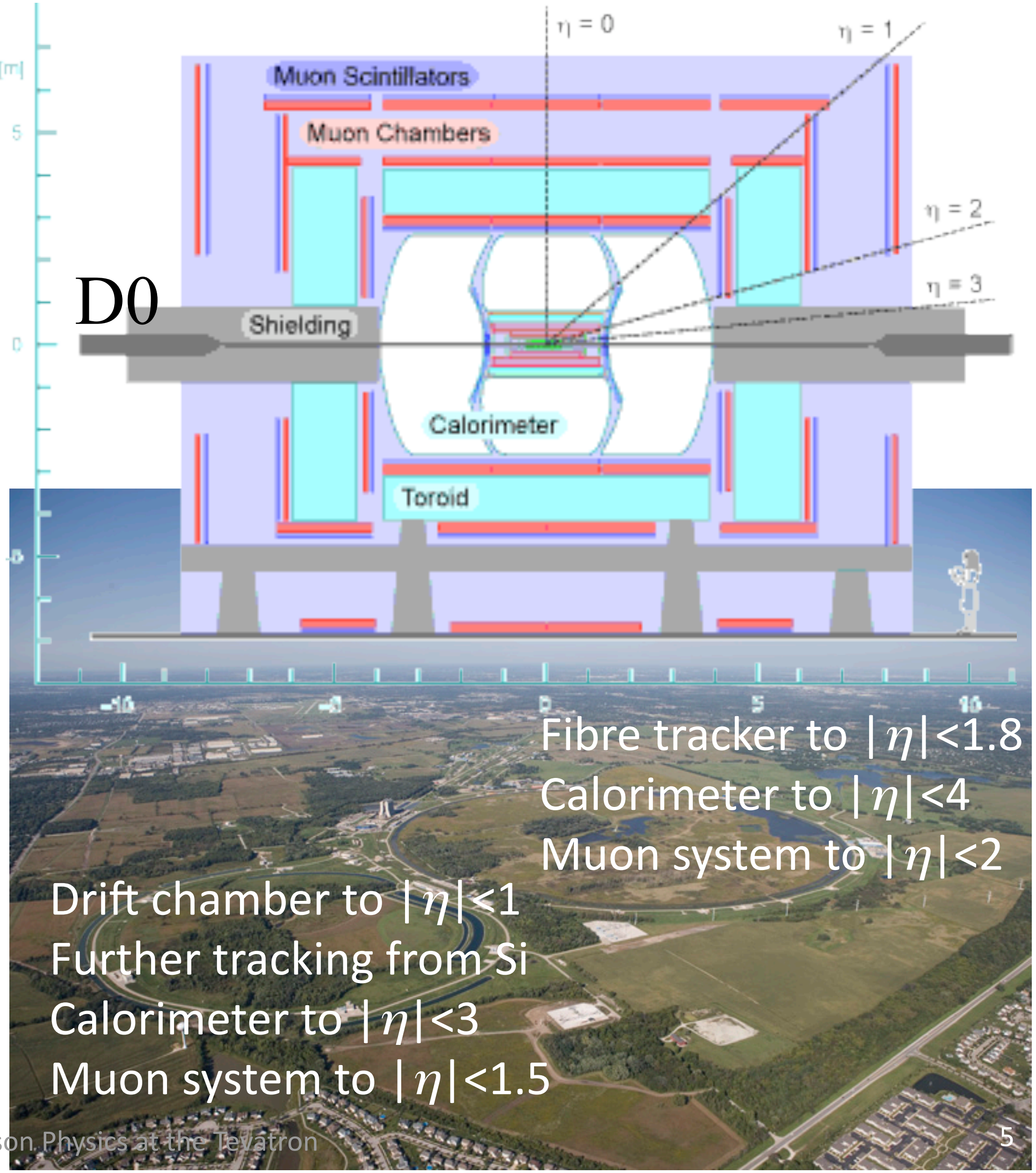
ZγZ vertex: Zγ sensitive to $h_3^Z, h_3^\gamma, h_4^Z, h_4^\gamma$
ZZγ vertex: ZZ sensitive to $f_4^Z, f_4^\gamma, f_5^Z, f_5^\gamma$ all zero in SM

Tevatron



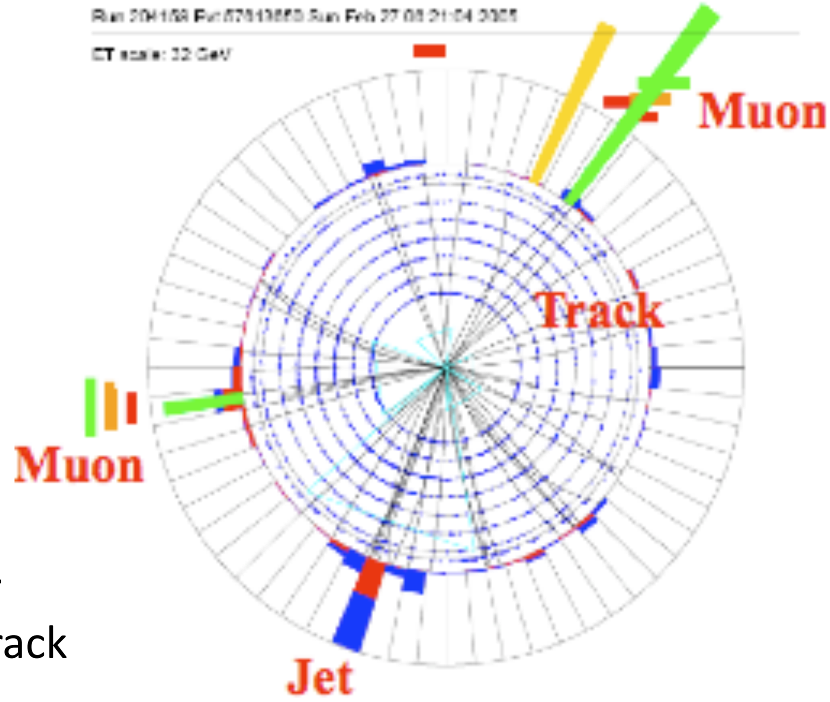
CDF



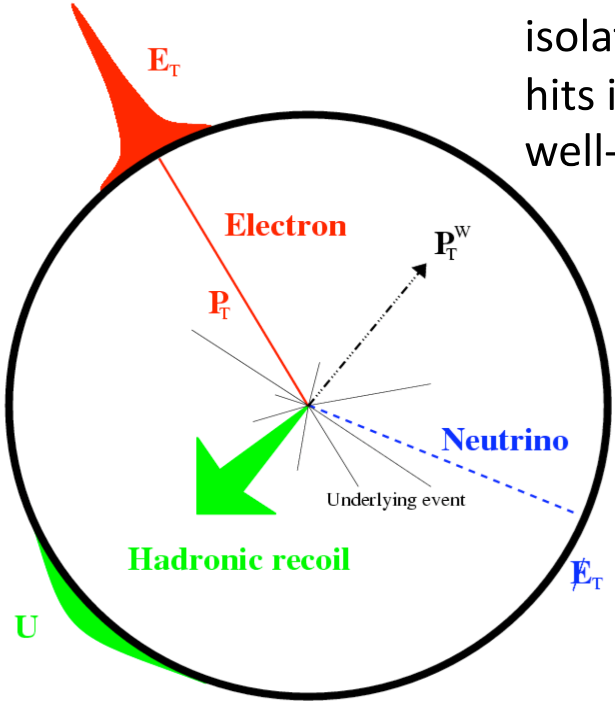


W and Z selection

Electrons:
- good EM shower shape
- small hadronic energy
- isolated in calorimeter
- well-matching good track
  - (except far forward)



Muons:
- MIP in calorimeter
- isolated
- hits in muon chamber
- well-matching good track

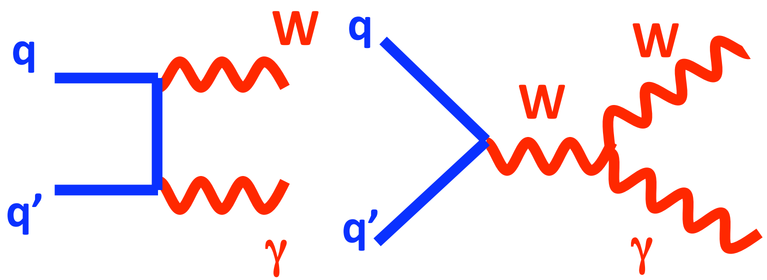


Z selection:
- 2 oppositely-charged electrons or muons
- invariant mass consistent with m_Z

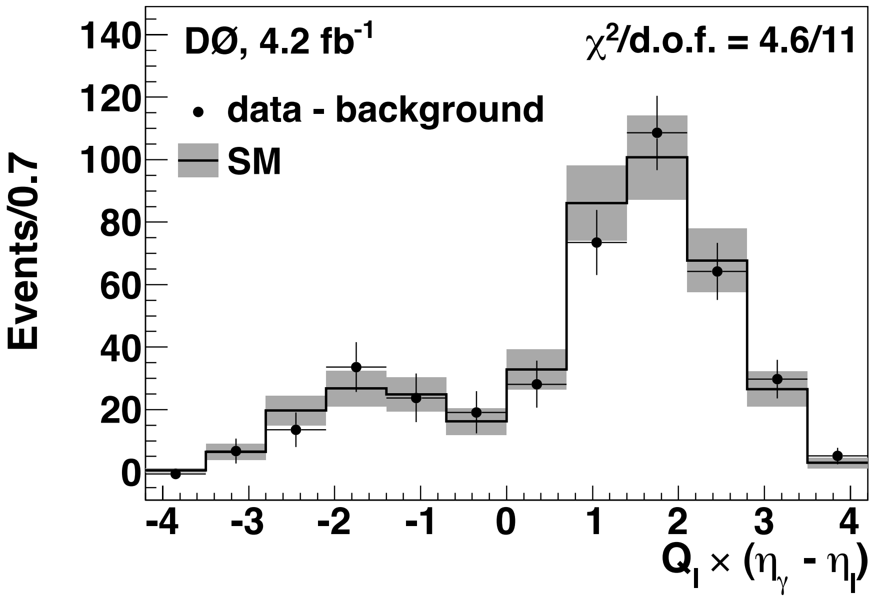
W selection:
- exactly one electron or muon
- energy imbalance in reconstructed event, associated with neutrino

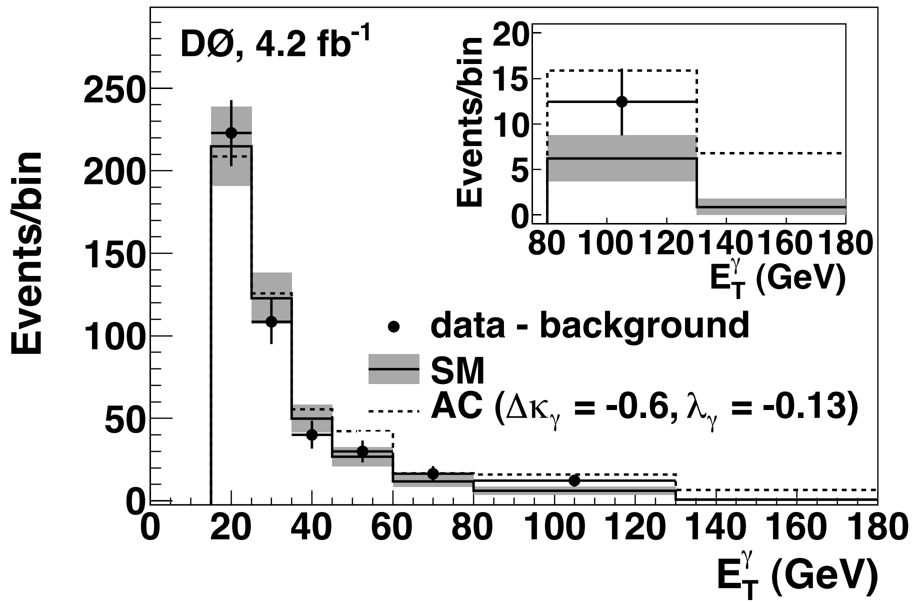
Wγ

2011 result



$E_T(e)(\mu)>25(20)$GeV
$M_T(W)>50(40)$GeV/c^2
$E_T(\gamma)>15$GeV ← NN for γ ID
$\Delta R(\ell\,\gamma)>0.7$
$M_T(\ell\,\gamma \not{E}_T)>110$GeV/$c^2$





95% CL limits (Λ=2TeV)
$-0.4 < \Delta\kappa_\gamma < 0.4$
$-0.08 < \lambda_\gamma < 0.07$

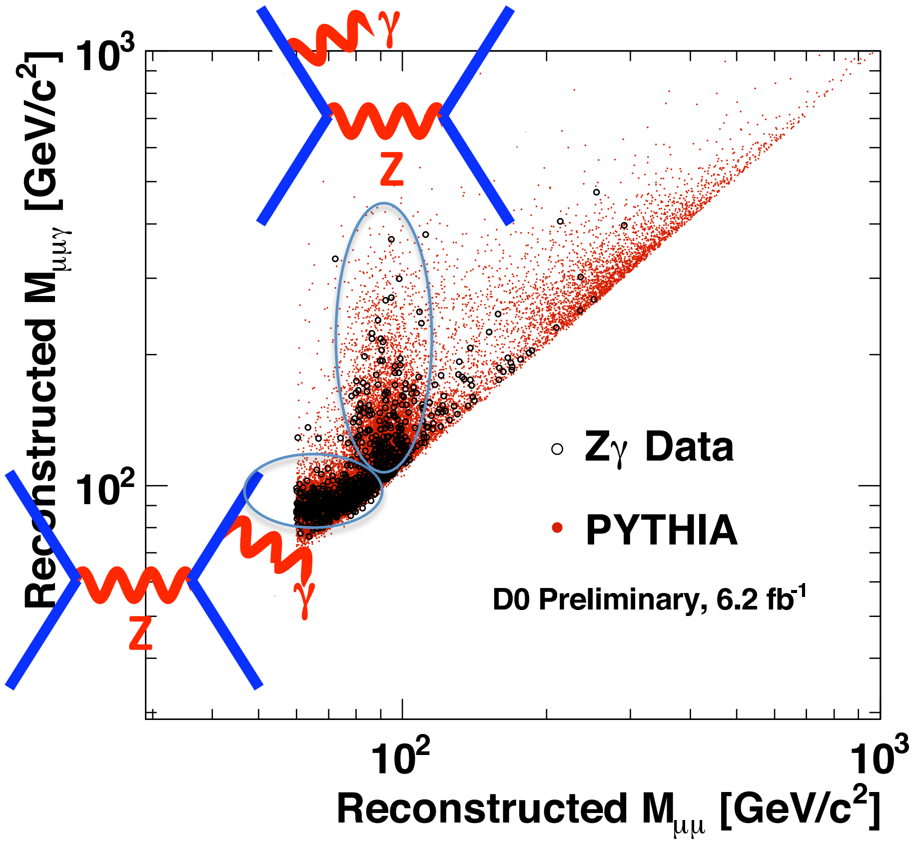
$\sigma(p\bar{p} \rightarrow W\gamma+X \rightarrow \ell\,\gamma+X) = 7.6 \pm 0.4\ (stat) \pm 0.6\ (sys)$ pb

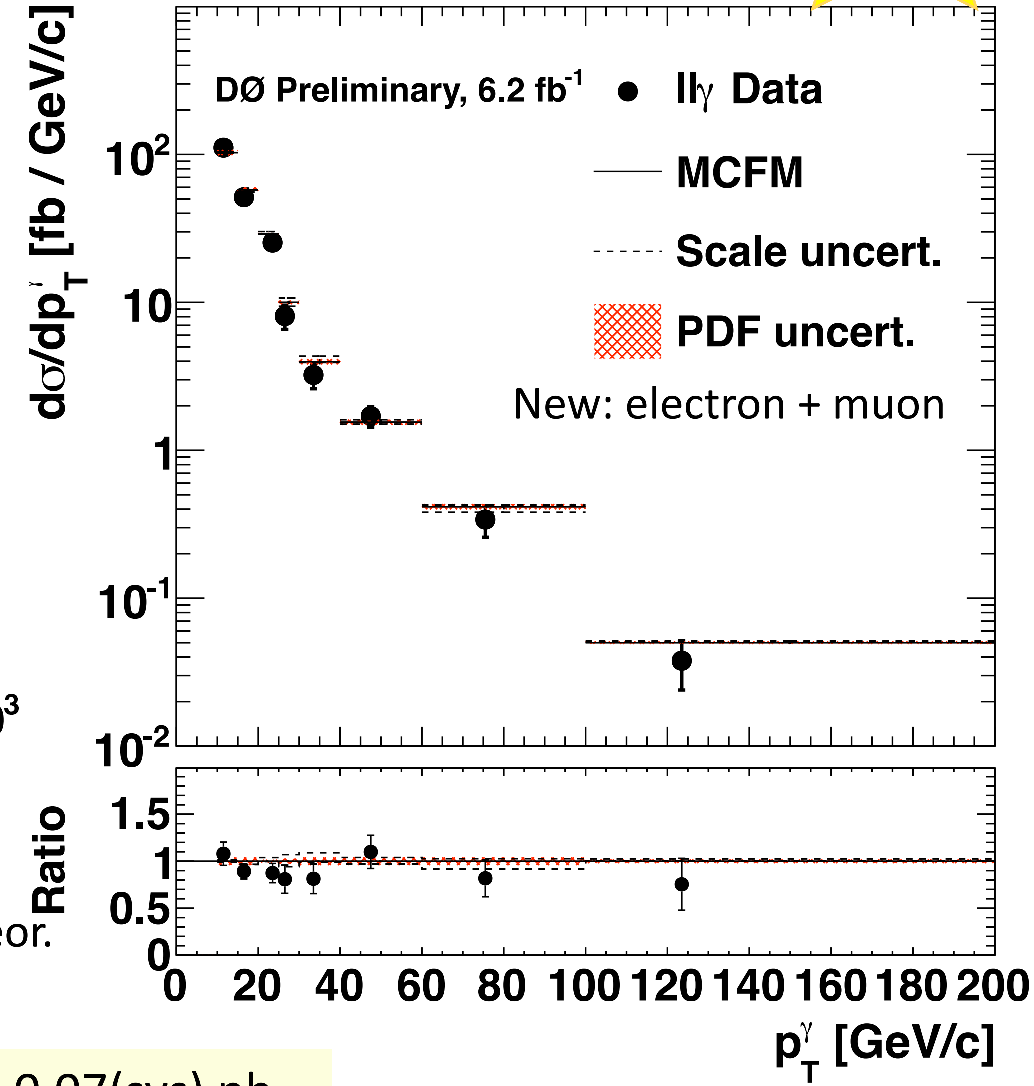
$E_T(\gamma)>15$GeV, $\Delta R(\ell\,\gamma)>0.7$ (SM: 7.6 ± 0.2 pb)

Accepted by Phys. Rev. Lett.

Zγ

New for HCP





Total cross-section uncertainty reduced by taking ratio with Z→ℓℓ and multiplying by theor.

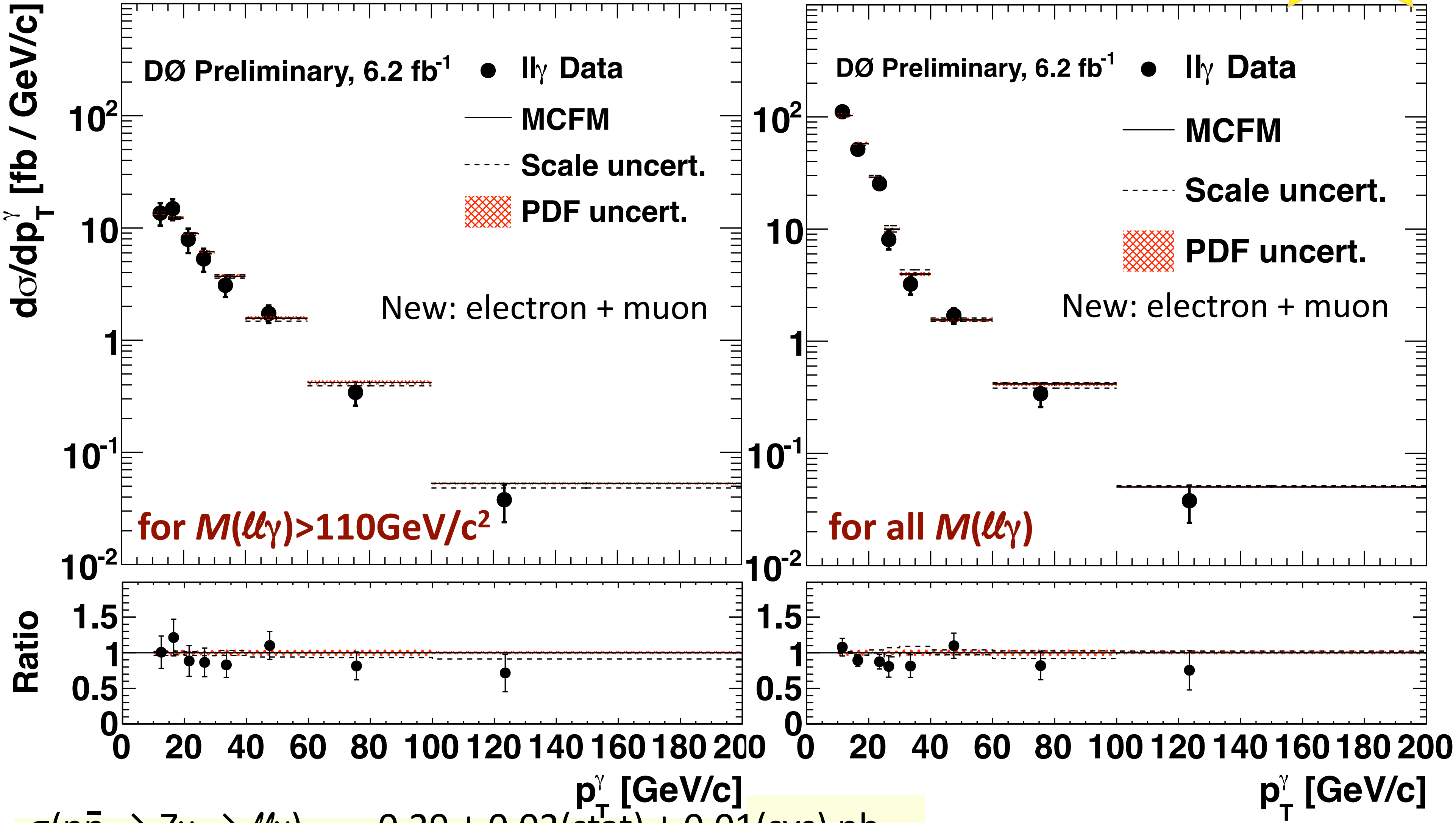
Differential through matrix inversion

$\sigma(p\bar{p} \to Z\gamma \to \ell\ell\gamma)$ = 1.09 ± 0.04(stat) ± 0.07(sys) pb

$M(\ell\ell\gamma)>60\mathrm{GeV}/c^2$; $|\eta_\gamma|<1$; $E_T(\gamma)>10\mathrm{GeV}$, $\Delta R(\ell\,\gamma)>0.7$ (SM: 1.10 ± 0.03 pb)

Zγ

New for HCP



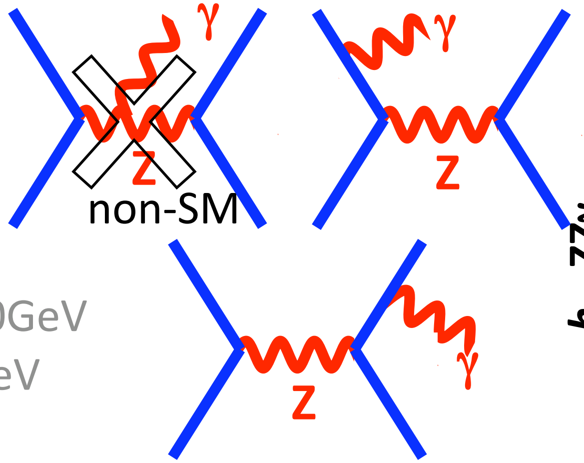
$\sigma(p\bar{p} \rightarrow Z\gamma \rightarrow \ell\ell\gamma) \;=\; 0.29 \pm 0.02(\text{stat}) \pm 0.01(\text{sys})$ pb

$M(\ell\ell\gamma)>110\text{GeV}/c^2$; $|\eta_\gamma|<1$; $E_T(\gamma)>10$GeV, $\Delta R(\ell\,\gamma)>0.7$ (SM: 0.29 ± 0.01 pb)

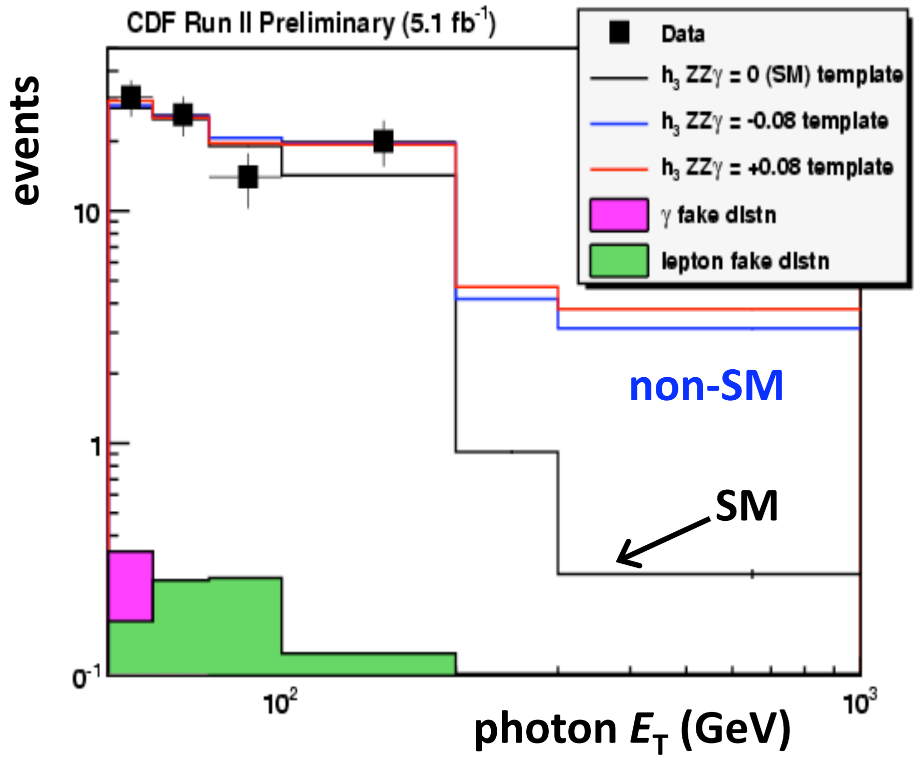
Zγ

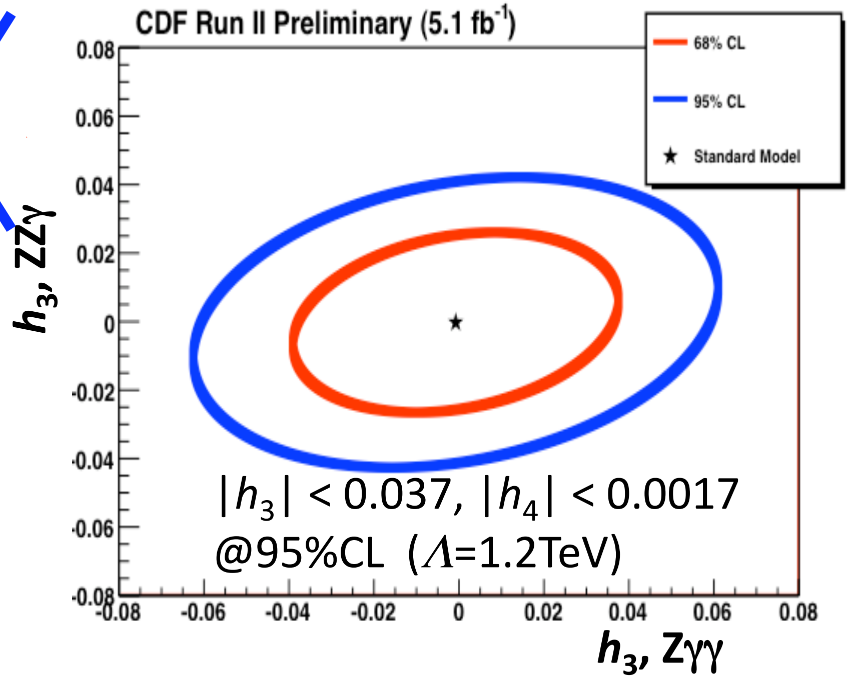
2011 result

Using (Z→ll)+γ
and (Z→νν)+γ



ee/μμ channel: $E_T(\gamma)$>50GeV
νν channel: $E_T(\gamma)$>100GeV





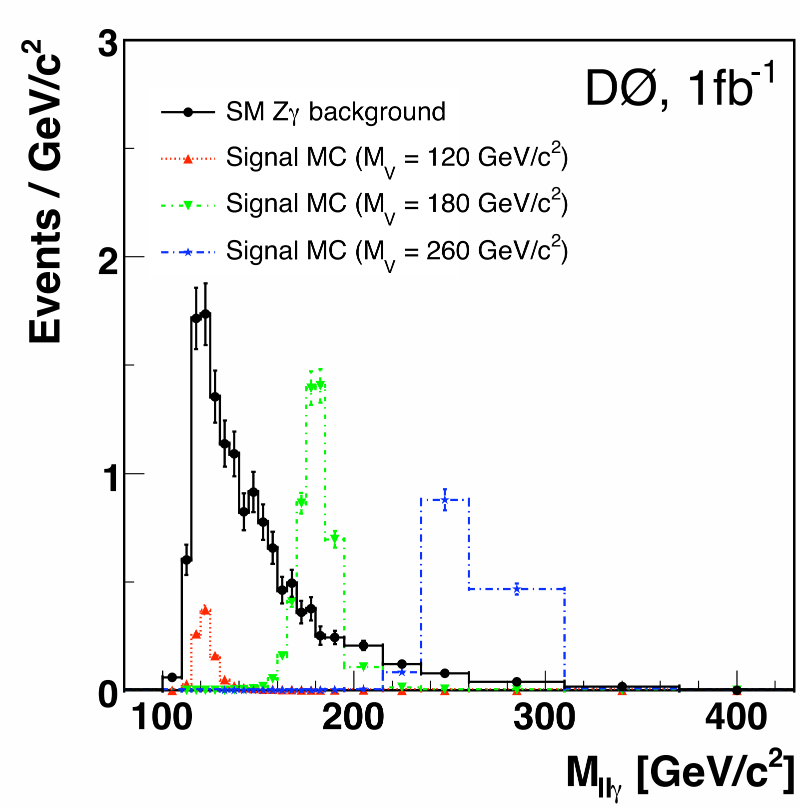
$|h_3| < 0.037$, $|h_4| < 0.0017$
@95%CL (Λ=1.2TeV)

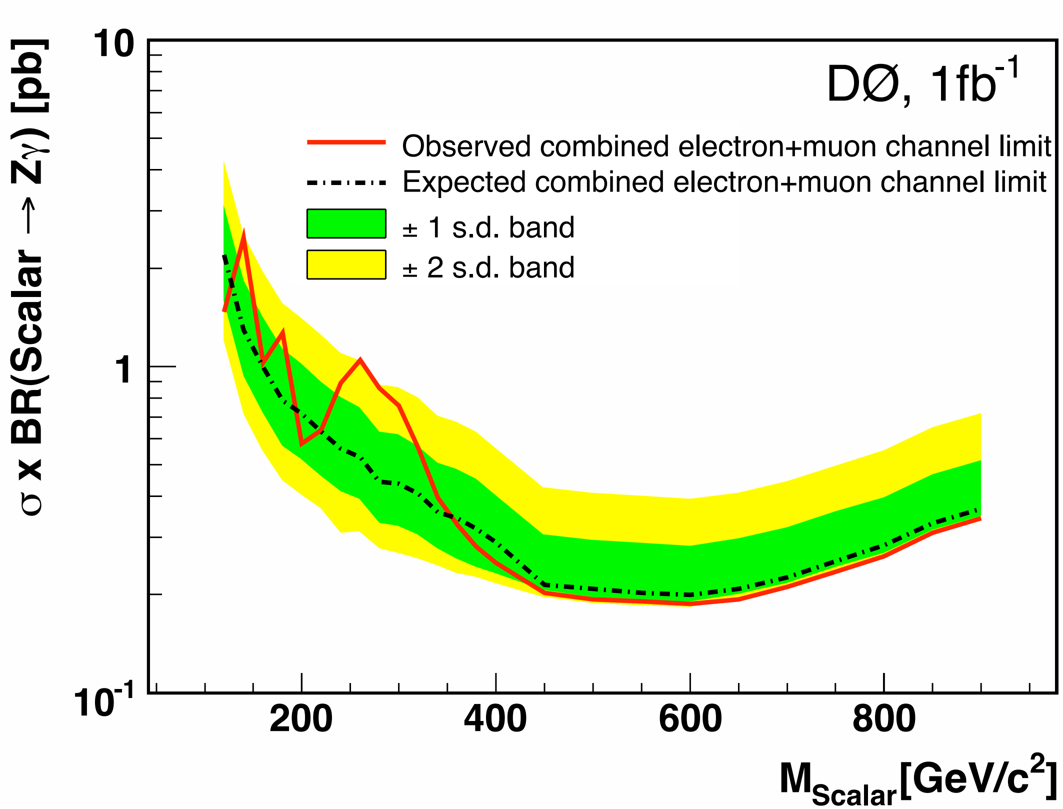
95% CL limits (Λ=1.5TeV)

$-0.020 < h_3^Z < 0.021$
$-0.0009 < h_4^Z < 0.0009$
$-0.022 < h_3^\gamma < 0.020$
$-0.0008 < h_4^\gamma < 0.0008$

Phys. Rev. Lett. **107** (2011) 051802

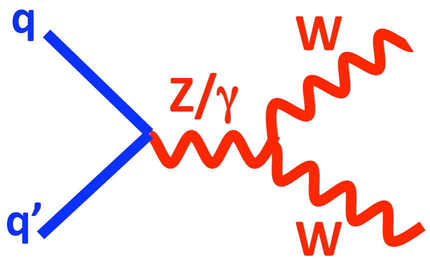
Zγ

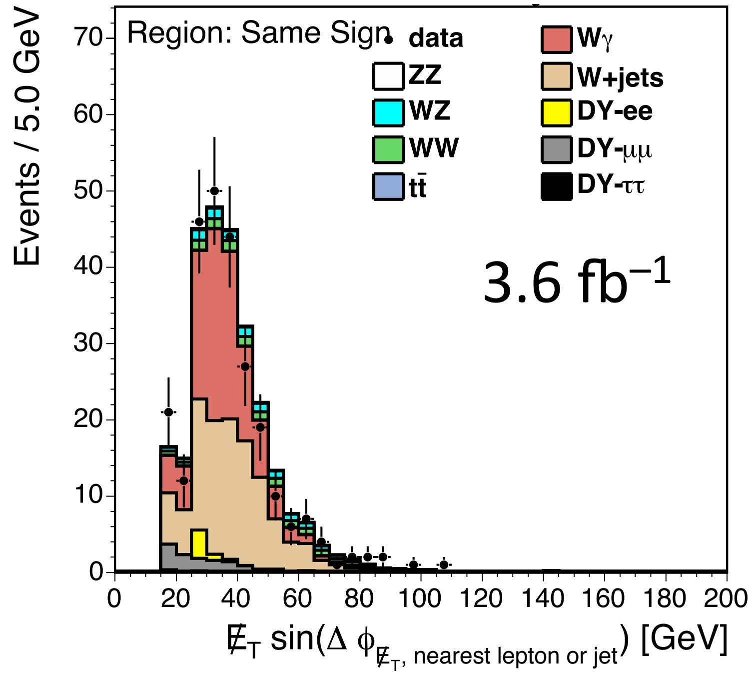


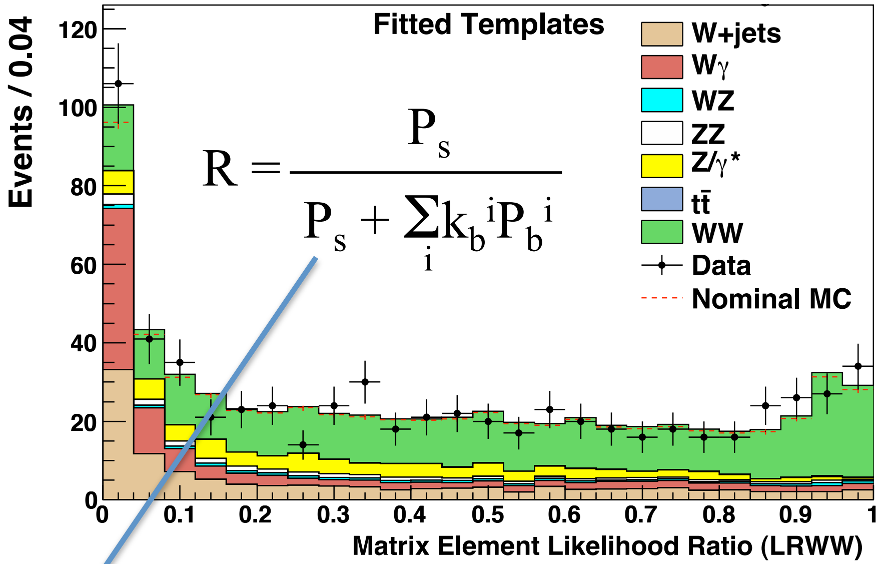


Phys. Lett. B **671** (2009) 349

WW

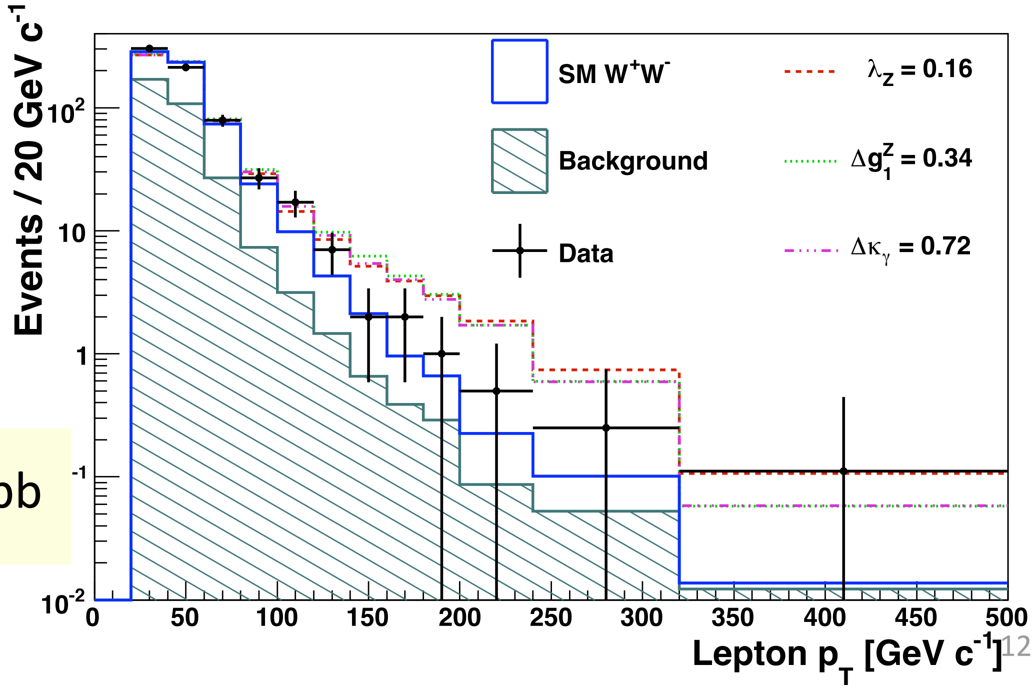






$$R = \frac{P_s}{P_s + \sum_i k_b^i P_b^i}$$

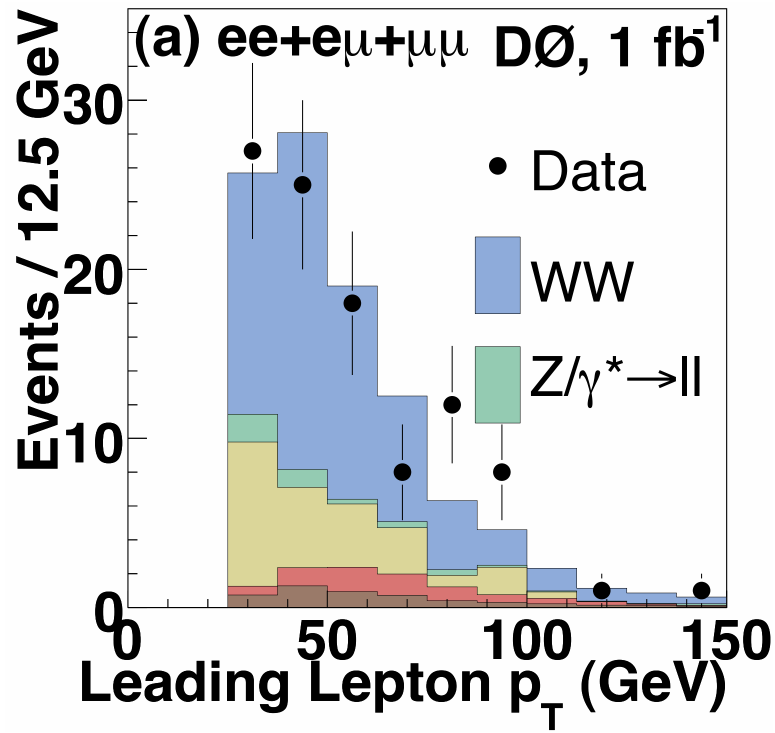
$$P(x_{\rm obs}) = \frac{1}{<\sigma>} \int \frac{d\sigma_{\rm th}(y)}{dy} \epsilon(y) G(x_{\rm obs}, y)\, dy$$

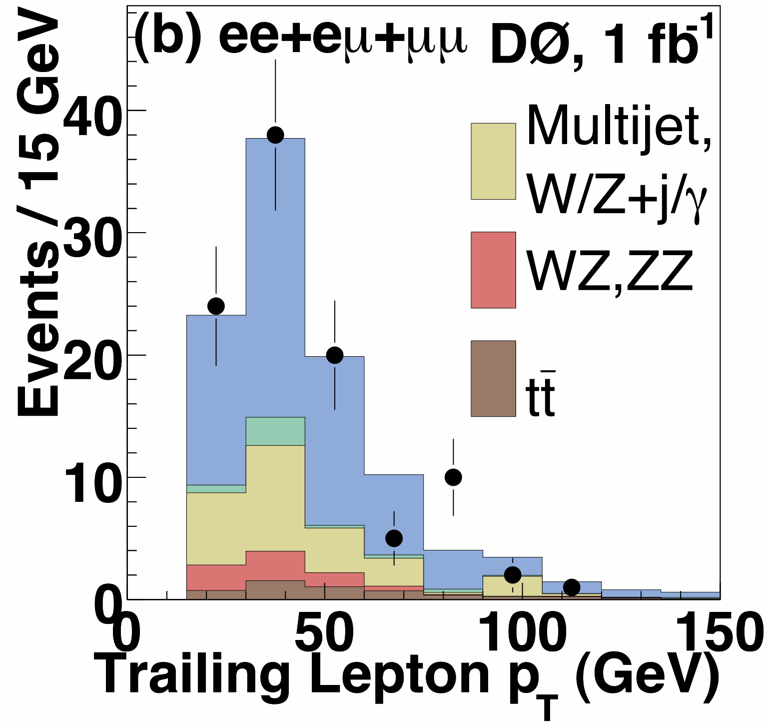


$\sigma(p\bar{p} \rightarrow WW) = 12.1 \pm 0.9(\text{stat})\ ^{+1.6}_{-1.4}\ (\text{sys})$ pb

Phys. Rev. Lett. **104** (2010) 201801

WW





95% CL limits, Λ=2TeV

$-0.54 < \Delta\kappa_\gamma < 0.83$

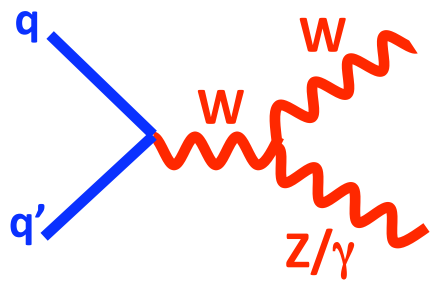
$-0.14 < \lambda_\gamma = \lambda_Z < 0.18$

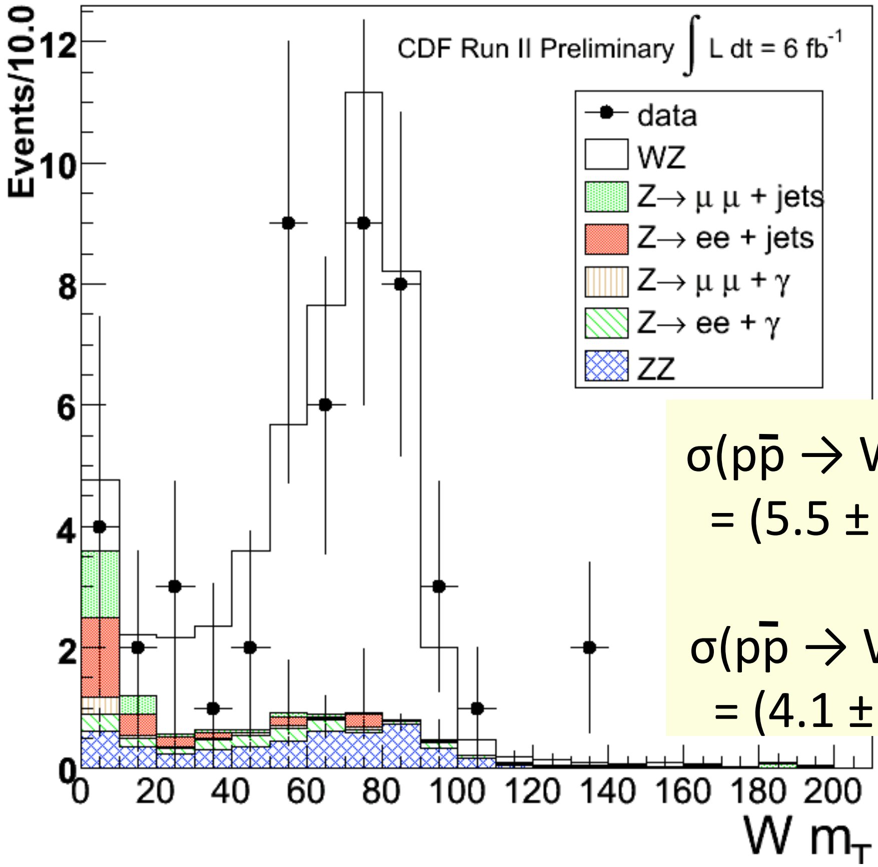
$-0.14 < \Delta g_1^Z < 0.30$

(constrained:
$\Delta\kappa_\gamma = \Delta\kappa_Z < 0.35$
$-0.14 < \lambda_\gamma = \lambda_Z < 0.18$)

Phys. Rev. Lett **103** (2009) 191801

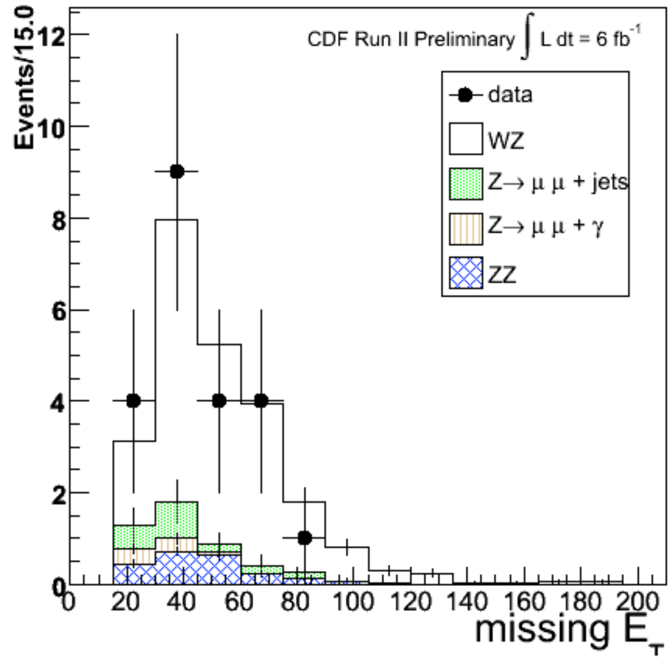
WZ

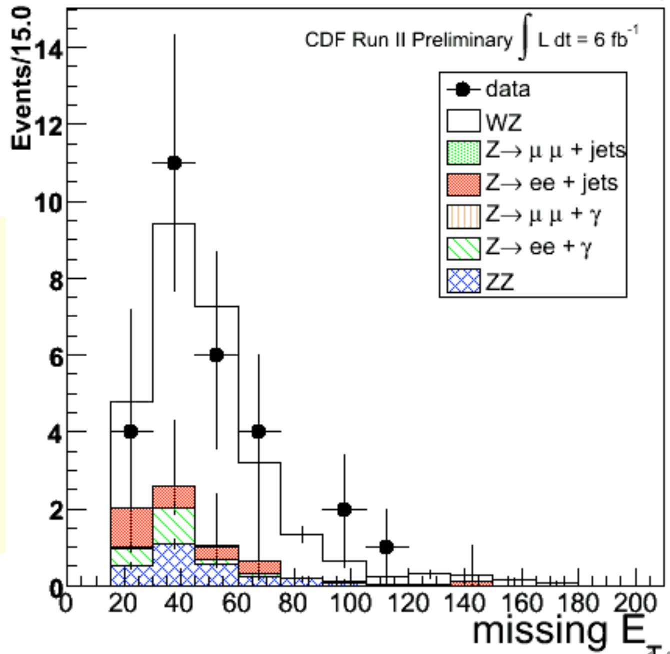




$\sigma(p\bar{p} \rightarrow WZ) / \sigma(p\bar{p} \rightarrow Z)$
$= (5.5 \pm 0.9) \times 10^{-4}$

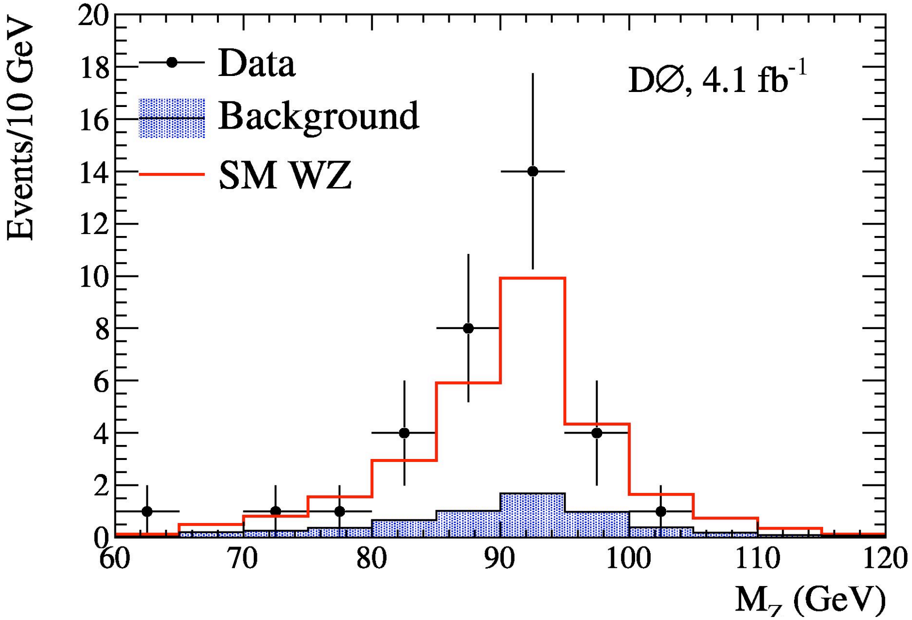
$\sigma(p\bar{p} \rightarrow WZ)$
$= (4.1 \pm 0.7)$ pb

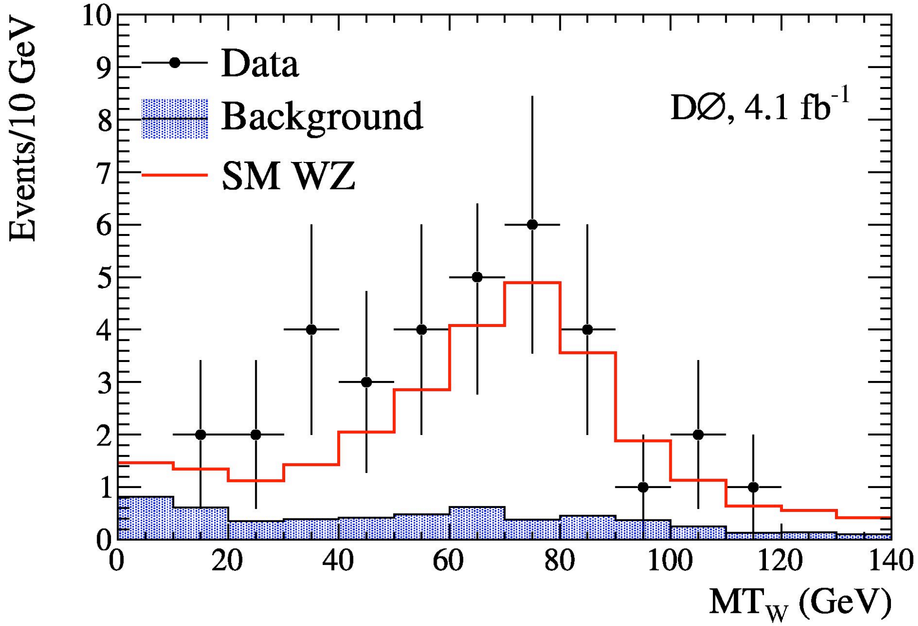


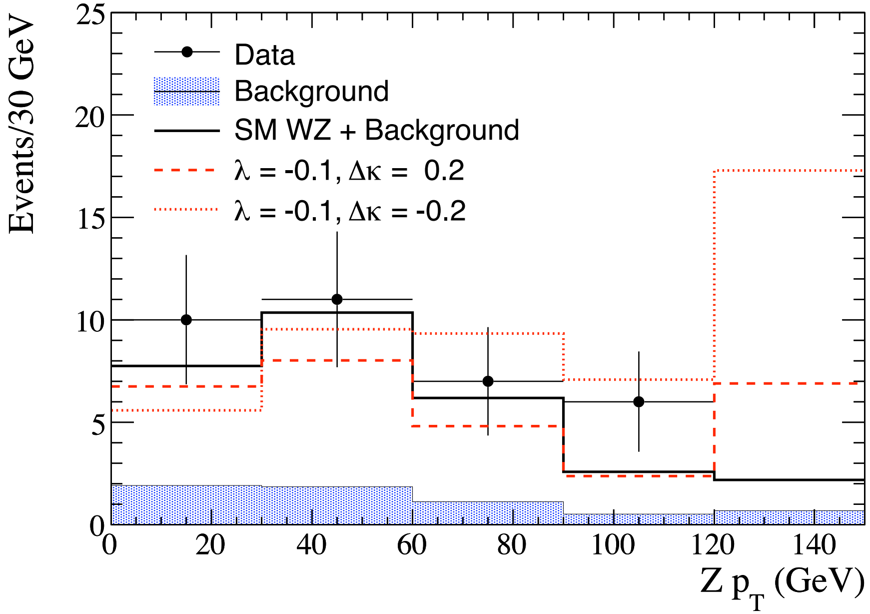


WZ

2011 result







$$\sigma(p\bar{p} \to WZ) = 3.89\,^{+1.07}_{-0.90}\ \text{pb}$$

95% CL limits, Λ=2TeV

$-0.400 < \Delta\kappa_Z < 0.675$

$-0.077 < \lambda_Z < 0.093$

$-0.056 < \Delta g_1^Z < 0.154$

(HISZ constraints:

$-0.077 < \Delta\kappa_Z < 0.093$

$-0.029 < \Delta g_1^Z < 0.080$)

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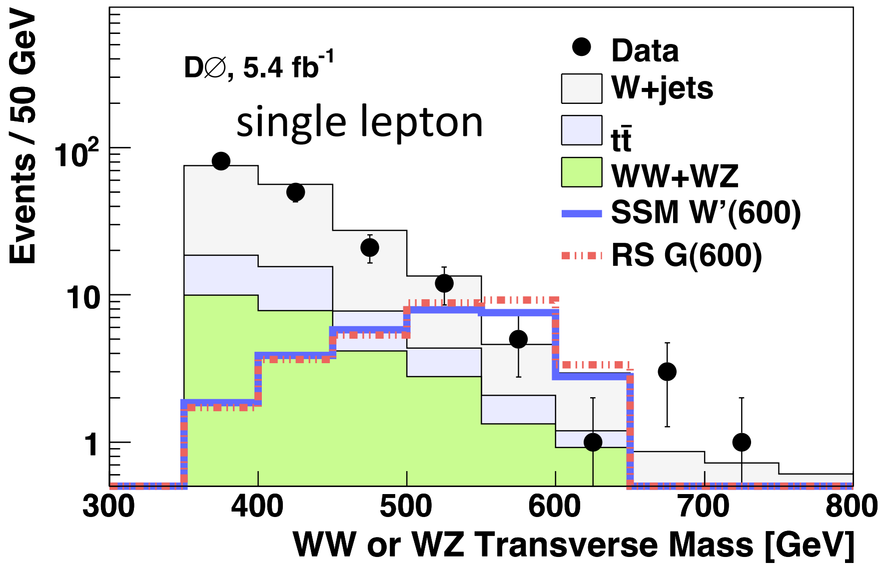
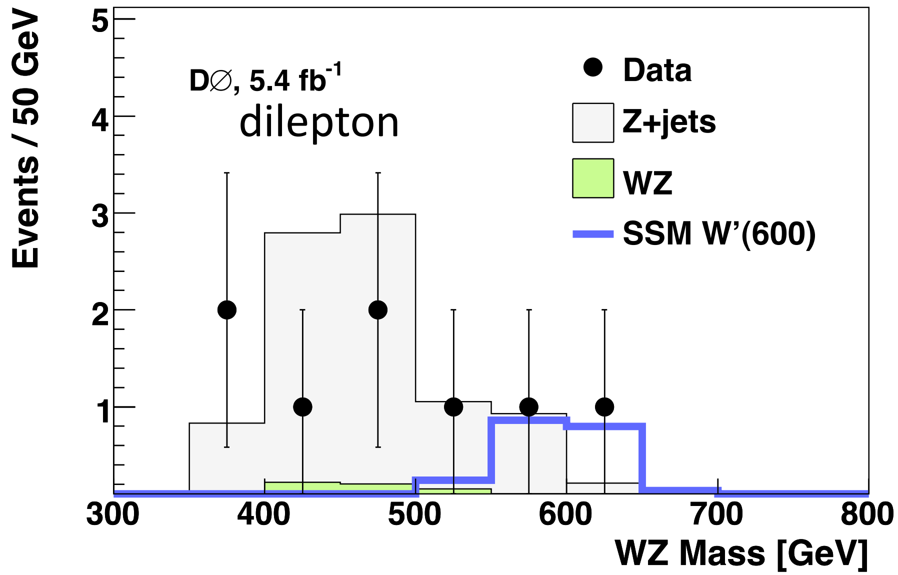
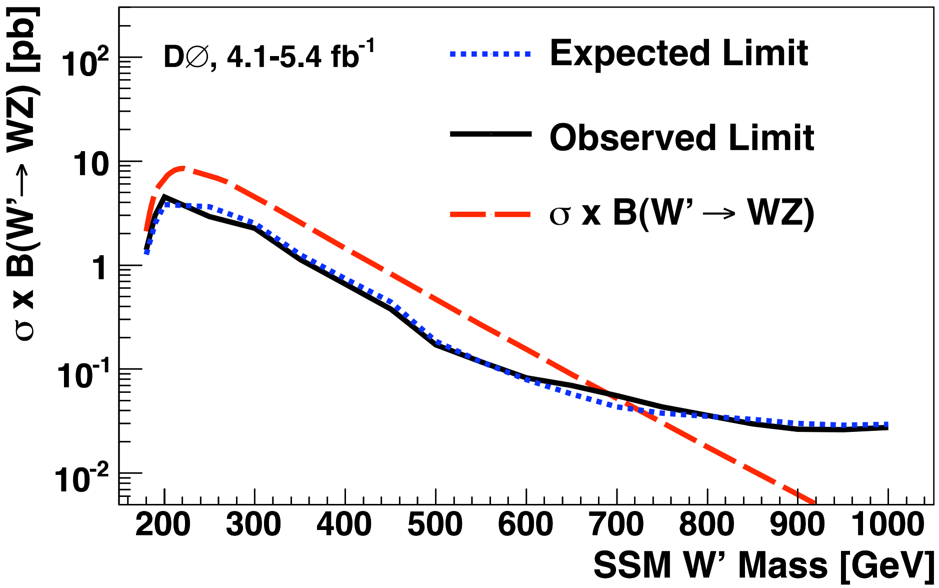
WW/WZ resonances

2011 result



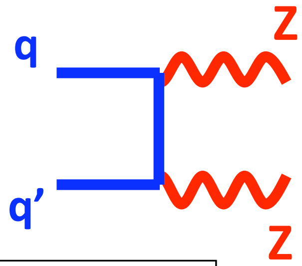


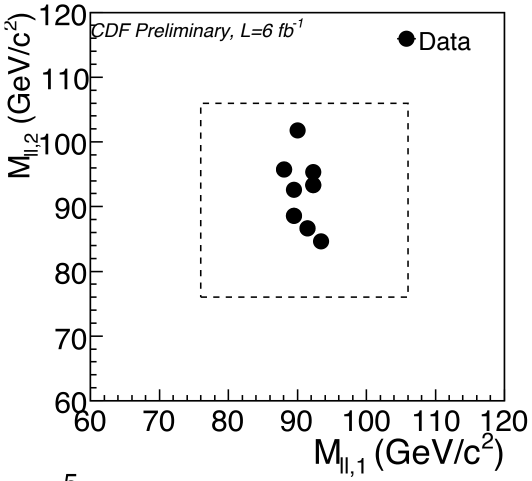


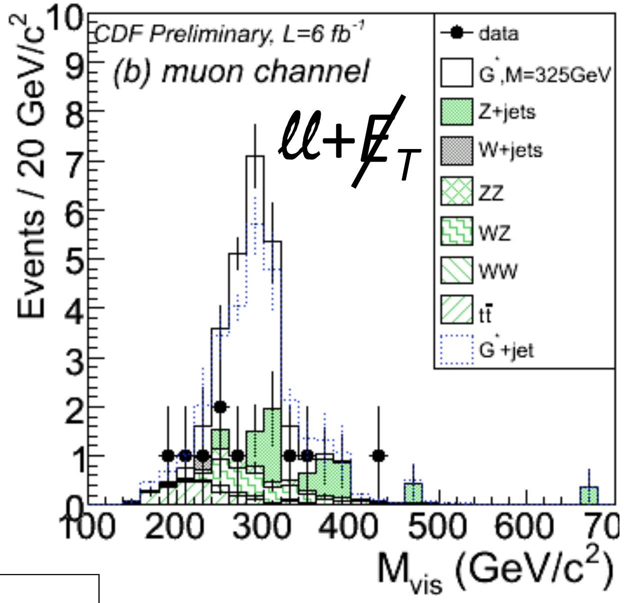
Phys. Rev. Lett. **107** (2011) 011801

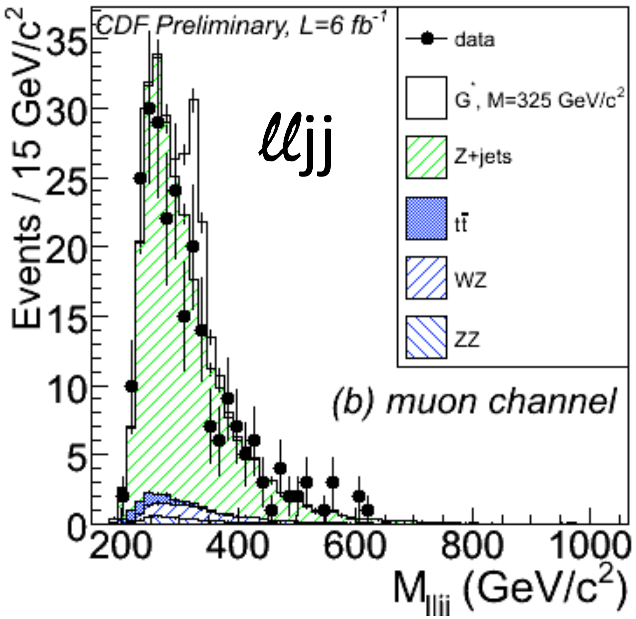
ZZ

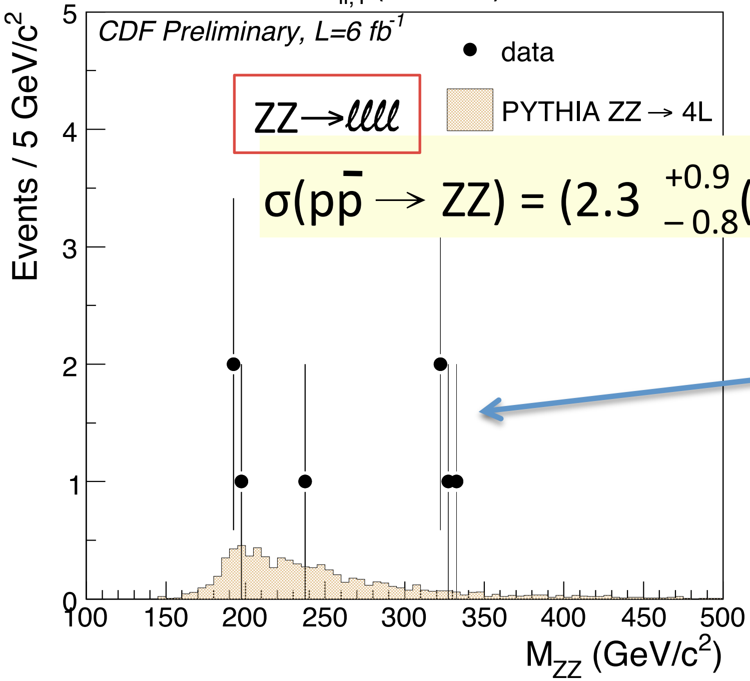
2011 result







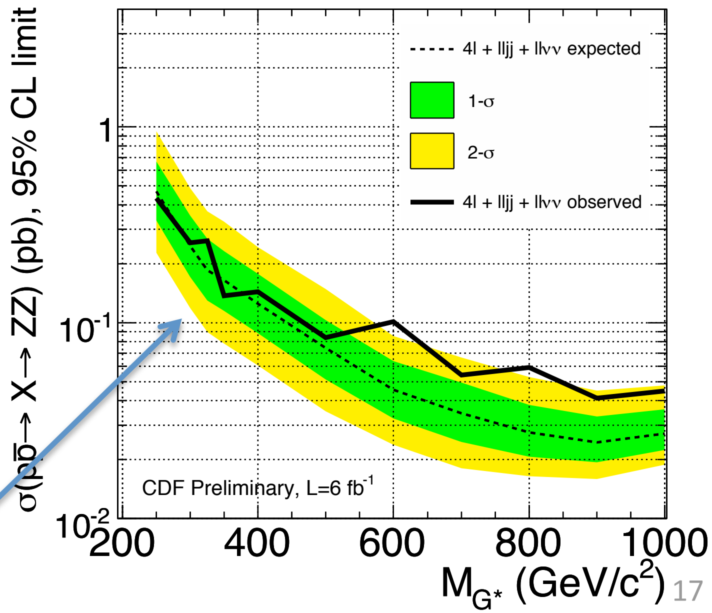




$$\sigma(p\bar{p} \to ZZ) = (2.3\ ^{+0.9}_{-0.8}(\text{stat}) \pm 0.2\ (\text{sys}))\ \text{pb}$$

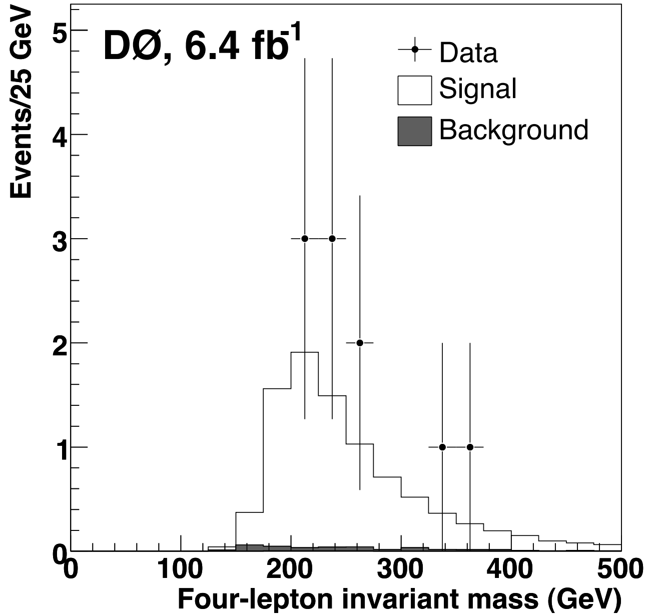
SM, NLO: (1.4± 0.1) pb

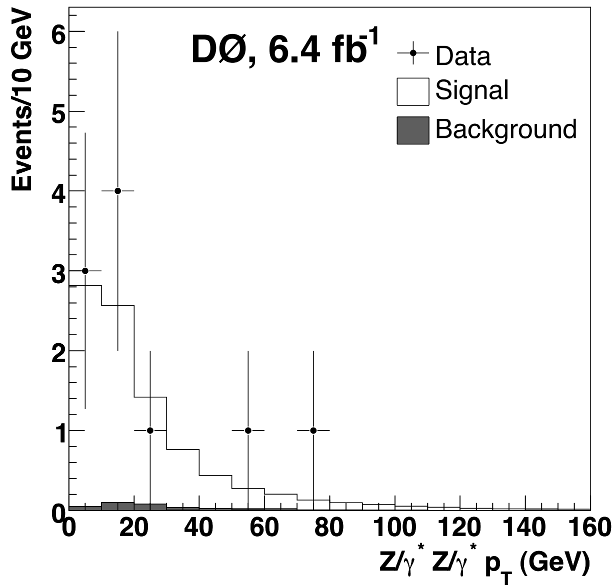
No new physics;
$\ell\ell+\not{E}_T$ and $\ell\ell jj$
channels are
more sensitive
and exclude it

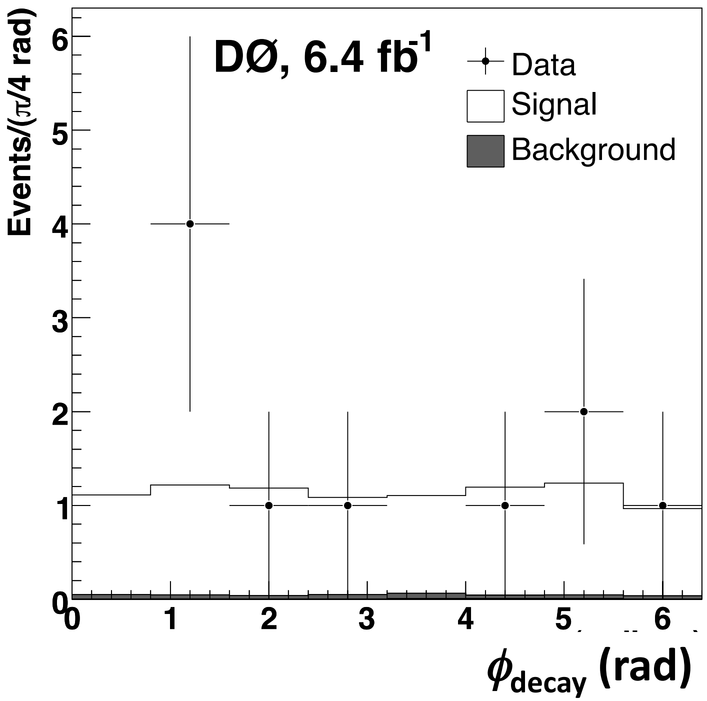


$ZZ \rightarrow \ell\ell\ell\ell$

2011 result







$\sigma(p\bar{p} \rightarrow ZZ) = (1.26^{+0.47}_{-0.37}(\text{stat}) \pm 0.14\ (\text{sys}))$ pb

SM, NLO: (1.4± 0.1) pb

Phys. Rev. D **84** (2011) 011103

Earlier 95% CL limits (Λ=1.2TeV)

$-0.28 < f_{40}^{Z} < 0.28$

$-0.26 < f_{40}^{\gamma} < 0.26$

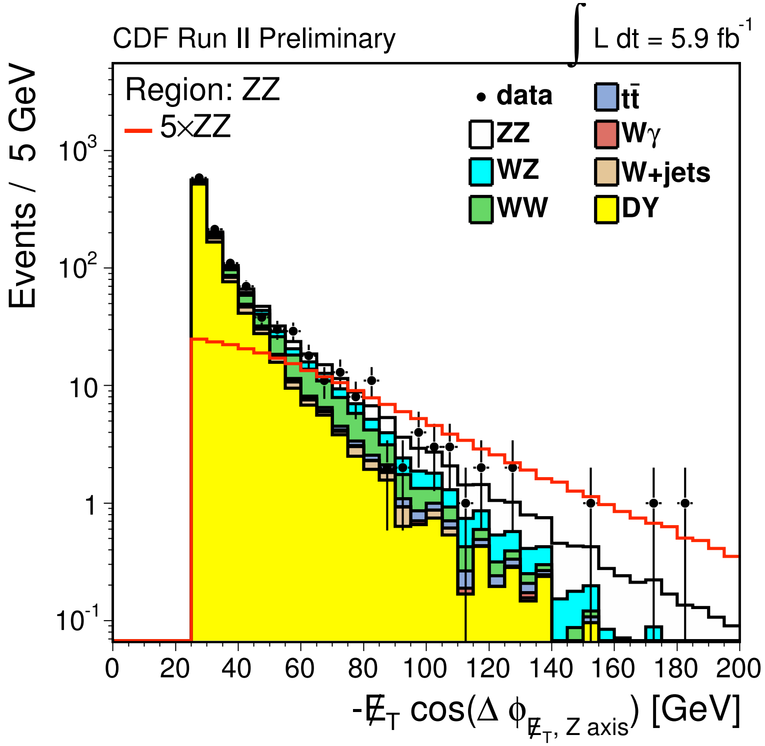
$-0.31 < f_{50}^{Z} < 0.29$

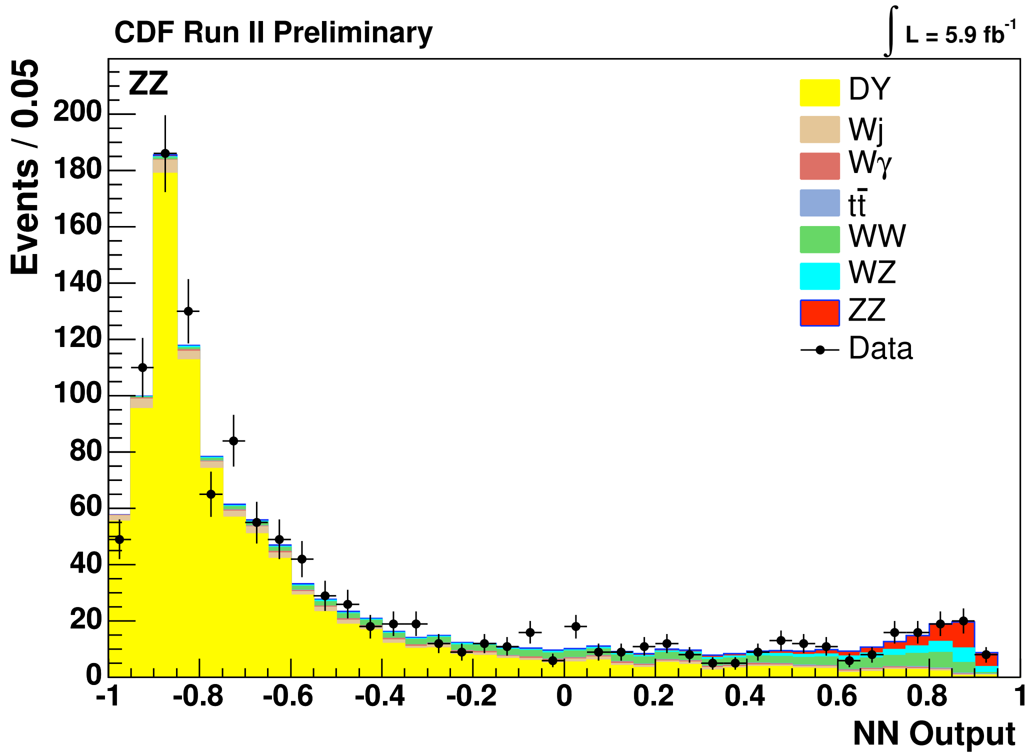
$-0.30 < f_{50}^{\gamma} < 0.28$

Phys. Rev. Lett. **100** (2008) 131801

ZZ→ℓℓνν

2011 result

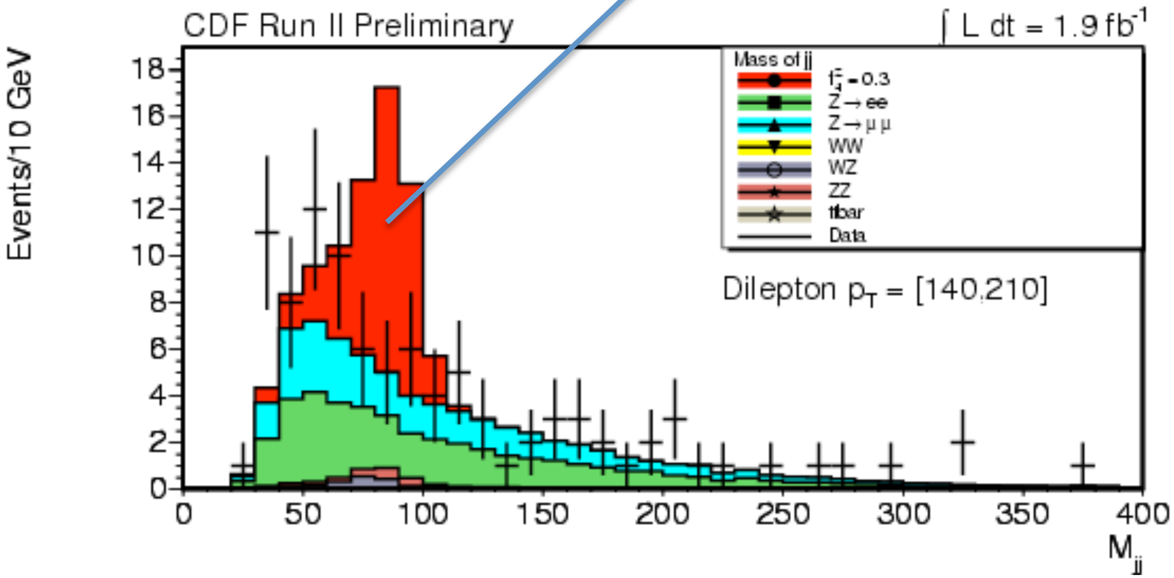




$$\sigma(p\bar{p} \to ZZ) = 1.45^{+0.45}_{-0.42}(stat.)^{+0.41}_{-0.30}(syst.)\ \mathrm{pb}$$

$ZZ \rightarrow \ell\ell jj$

f_4^Z=0.3



95% CL limits (Λ=1.2TeV)

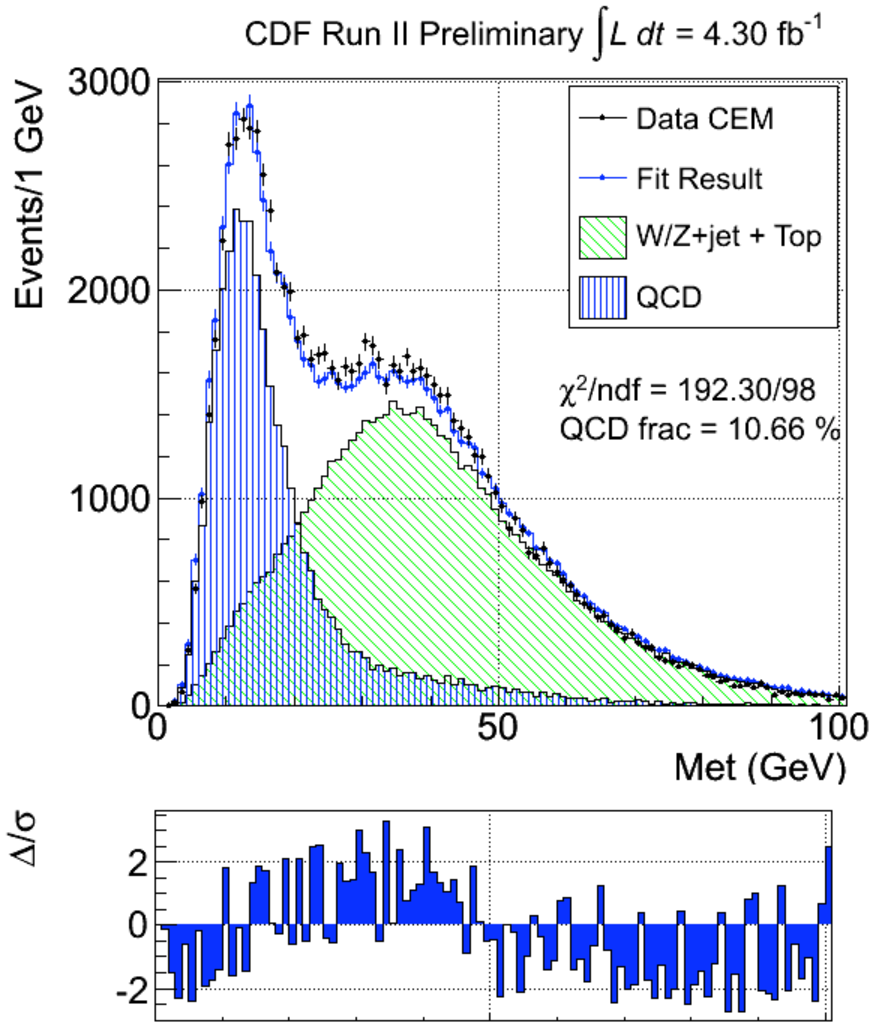
$-0.12 < f_4^Z < 0.12$

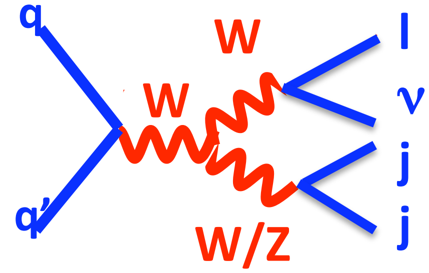
$-0.10 < f_4^\gamma < 0.10$

$-0.13 < f_5^Z < 0.12$

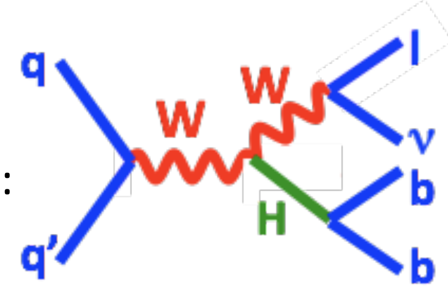
$-0.11 < f_5^\gamma < 0.11$

WW/WZ → $\ell\nu jj$



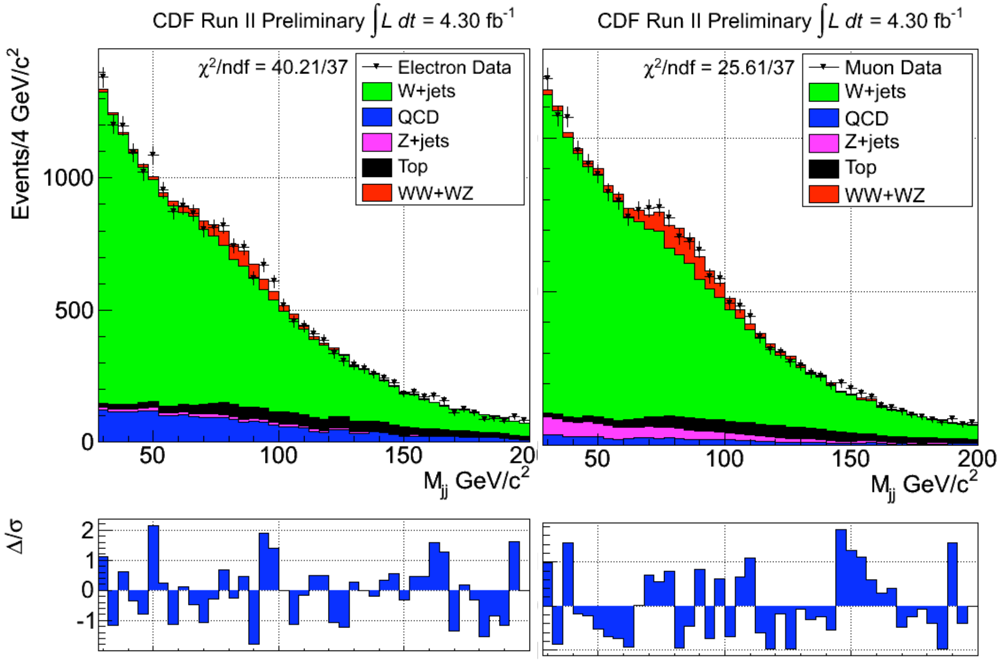


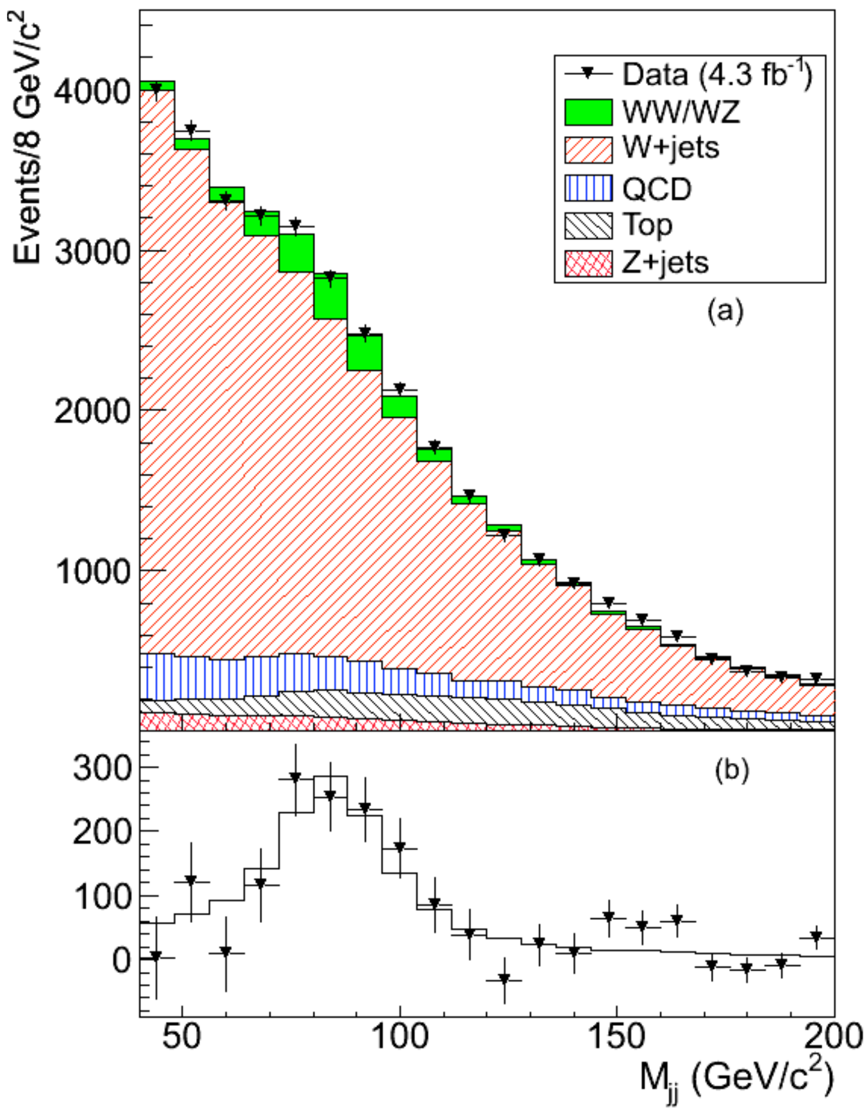
Similar final state to low-mass Higgs:



Sample	Electrons	Muons
MC W +jets	18010 ± 531	16673 ± 482
MC Z+jets	353 ± 42	966 ± 115
diboson	750 ± 68	651 ± 59
top	1324 ± 134	1149 ± 115
QCD (from data)	2314 ± 462	639 ± 159
Total MC + QCD	22751	20078
data	22204 ± 149	19738 ± 141

WW/WZ → $\ell\nu jj$

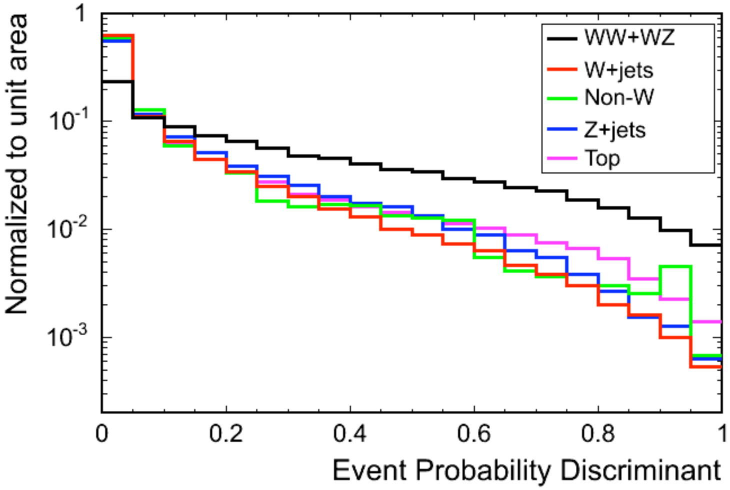




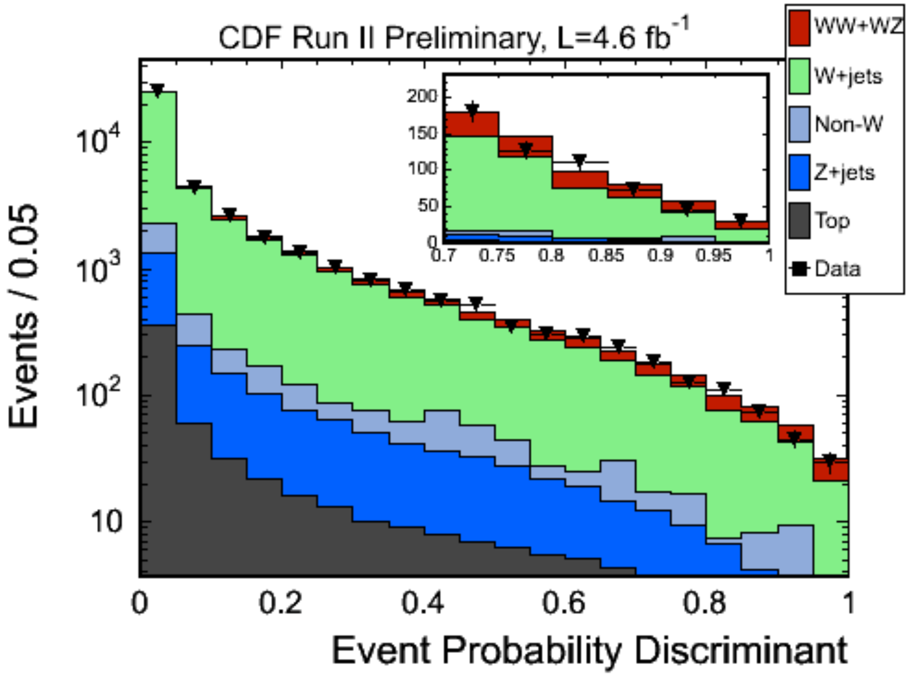
σ(WW+WZ)
= 18.1 ± 3.3(stat) ± 2.5(sys) pb

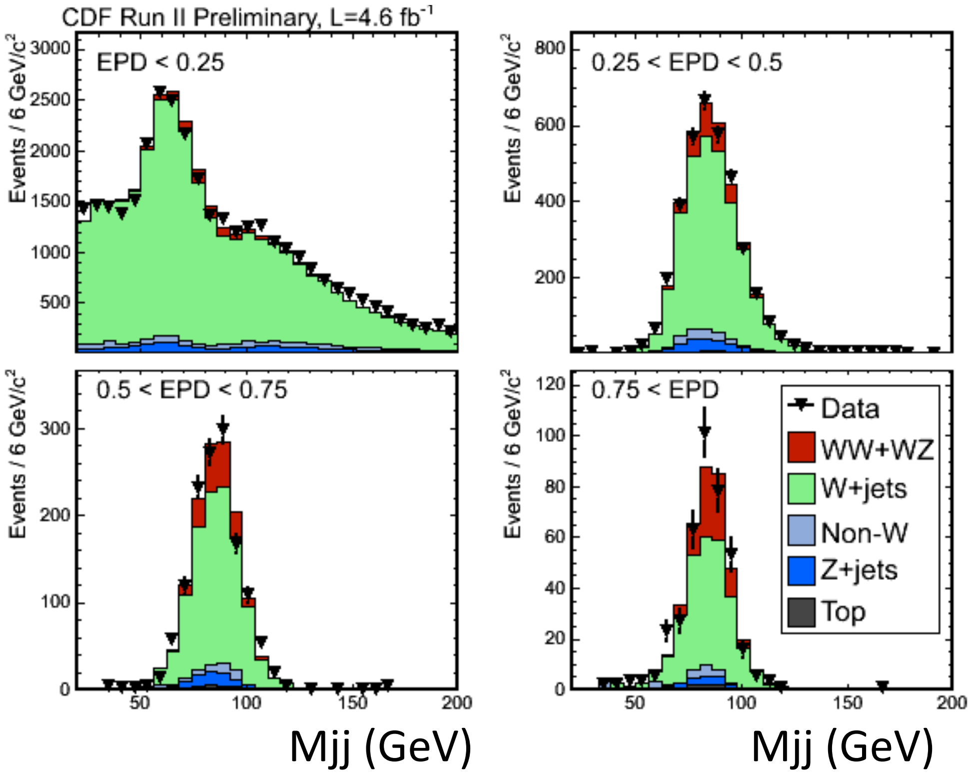
5.2σ significance

WW/WZ → $\ell\nu jj$



Use matrix element techniques



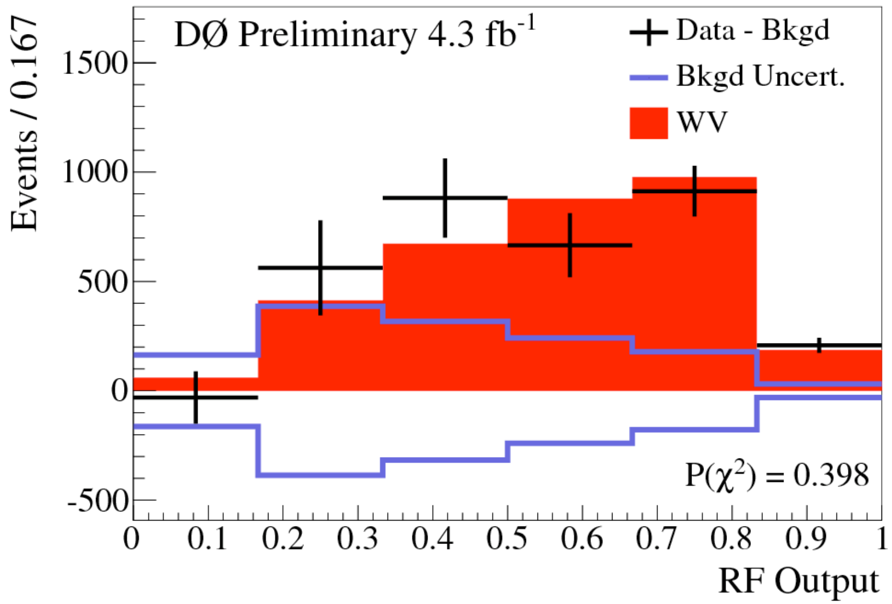


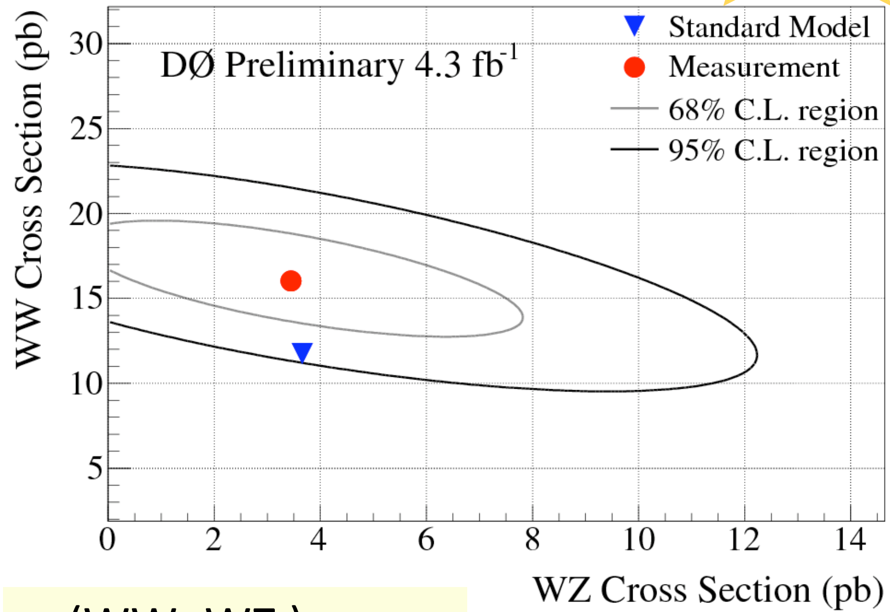
σ(WW+WZ)
= 16.5 $^{+3.3}_{-3.0}$ pb

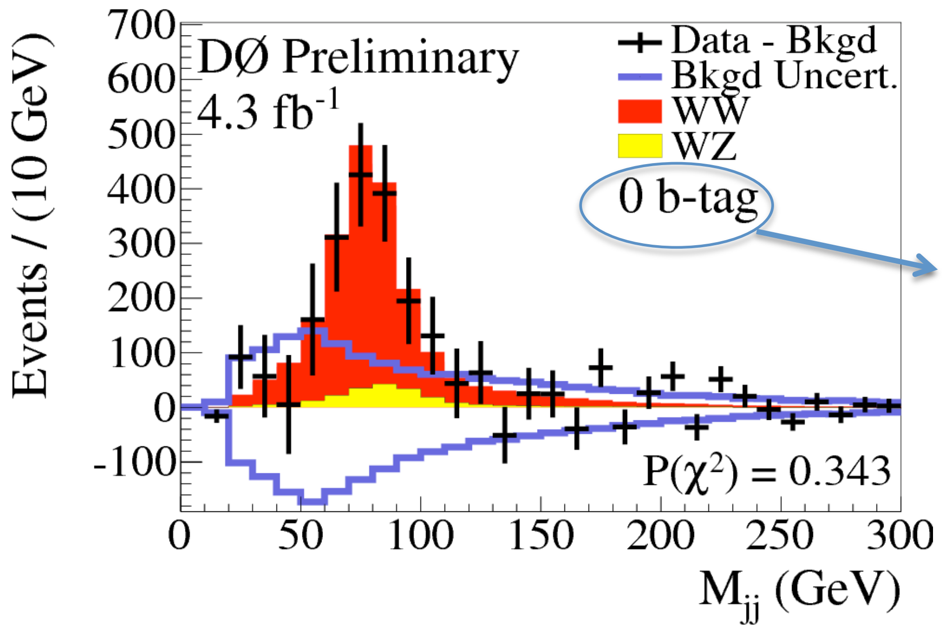
5.4σ significance

WW/WZ → $\ell\nu jj$

New for HCP







σ(WW+WZ)
$= 19.6\ ^{+3.1}_{-3.0}$ pb

8σ significance

For more, see J-F Grivaz's talk on dibosons with Z→bb in Higgs session.

From $1\mathrm{fb}^{-1}$ results:
95% CL limits, Λ=2TeV

$-0.44 < \Delta\kappa_\gamma < 0.55$
$-0.10 < \lambda_Z=\lambda_\gamma < 0.11$
$-0.12 < \Delta g_1^Z < 0.20$

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TGCs

All 95% CL

D0 Wγ 4.2/fb

$-0.4 < \Delta\kappa_\gamma < 0.4$

$-0.08 < \lambda_\gamma < 0.07$

D0 WZ 4.1/fb (Λ=2TeV)

$-0.400 < \Delta\kappa_Z < 0.675$

$-0.077 < \lambda_Z < 0.093$

$-0.056 < \Delta g_1^Z < 0.154$

D0 1/fb Combination

$-0.29 < \Delta\kappa_\gamma < 0.38$

$-0.08 < \lambda_Z < 0.08$

$-0.07 < \Delta g_1^Z < 0.16$

D0 WW 1/fb (Λ=2TeV)

$-0.54 < \Delta\kappa_\gamma < 0.83$

$-0.14 < \lambda_\gamma = \lambda_Z < 0.18$

$-0.14 < \Delta g_1^Z < 0.30$

D0 WW/WZ $\rightarrow \ell\nu jj$ 1/fb (Λ=2TeV)

$-0.44 < \Delta\kappa_\gamma < 0.555$

$-0.10 < \lambda_Z = \lambda_\gamma < 0.11$

$-0.12 < \Delta g_1^Z < 0.20$

CDF Zγ 5.1/fb (Λ=1.5TeV)

$-0.020 < h_3^Z < 0.021$

$-0.0009 < h_4^Z < 0.0009$

$-0.022 < h_3^\gamma < 0.020$

$-0.0008 < h_4^\gamma < 0.0008$

D0 ZZ->4L 1/fb (Λ=1.2TeV)

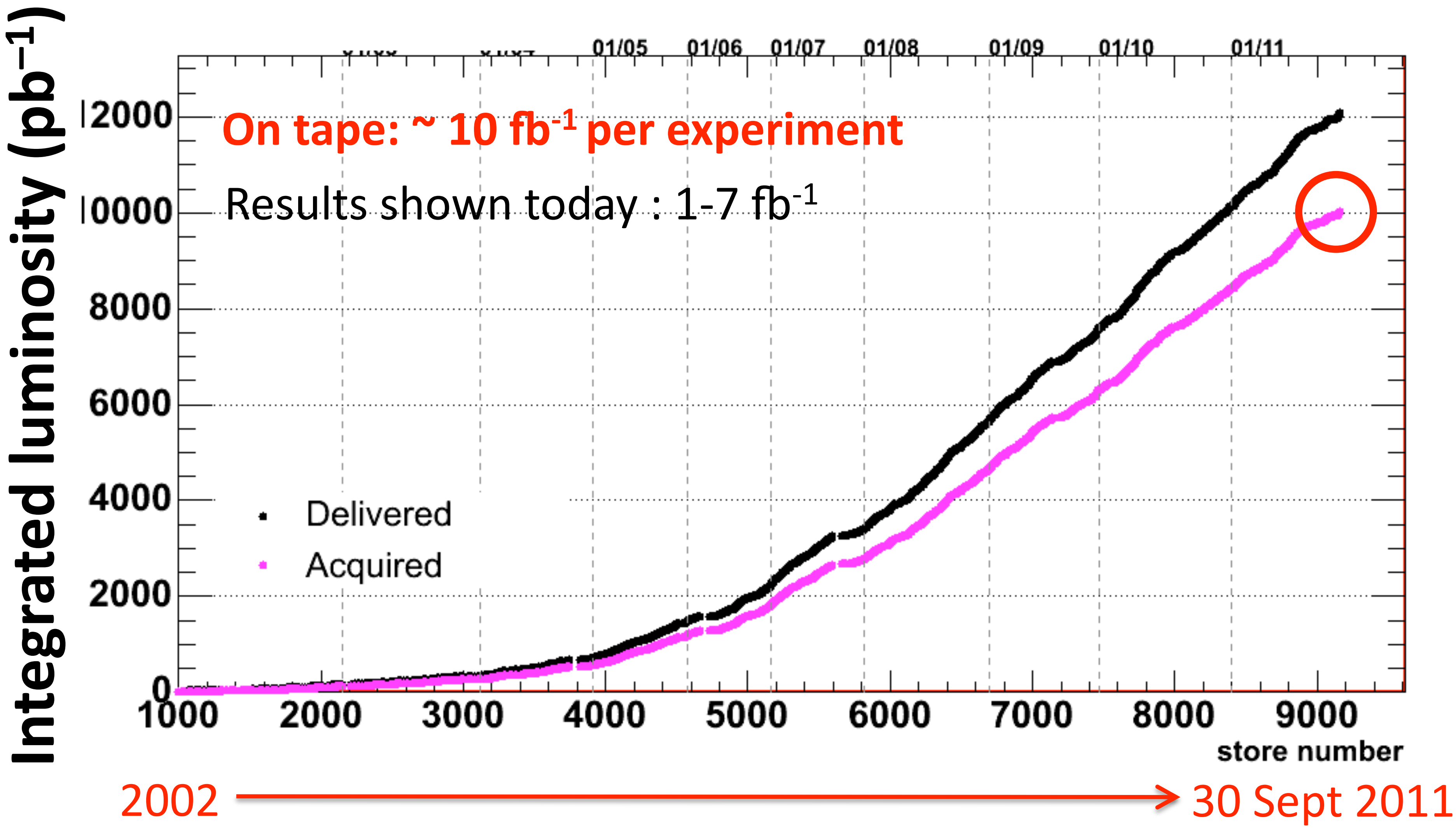
$-0.28 < f_4^Z < 0.28$

$-0.26 < f_4^\gamma < 0.26$

$-0.31 < f_5^Z < 0.29$

$-0.30 < f_5^\gamma < 0.28$

Outlook



Integrated luminosity (pb^{-1})
01/05
01/06
01/07
01/08
01/09
01/10
01/11
12000
10000
8000
6000
4000
2000
0
On tape: ~ 10 fb^{-1} per experiment
Results shown today : 1-7 fb^{-1}
Delivered
Acquired
1000
2000
3000
4000
5000
6000
7000
8000
9000
store number
2002
30 Sept 2011

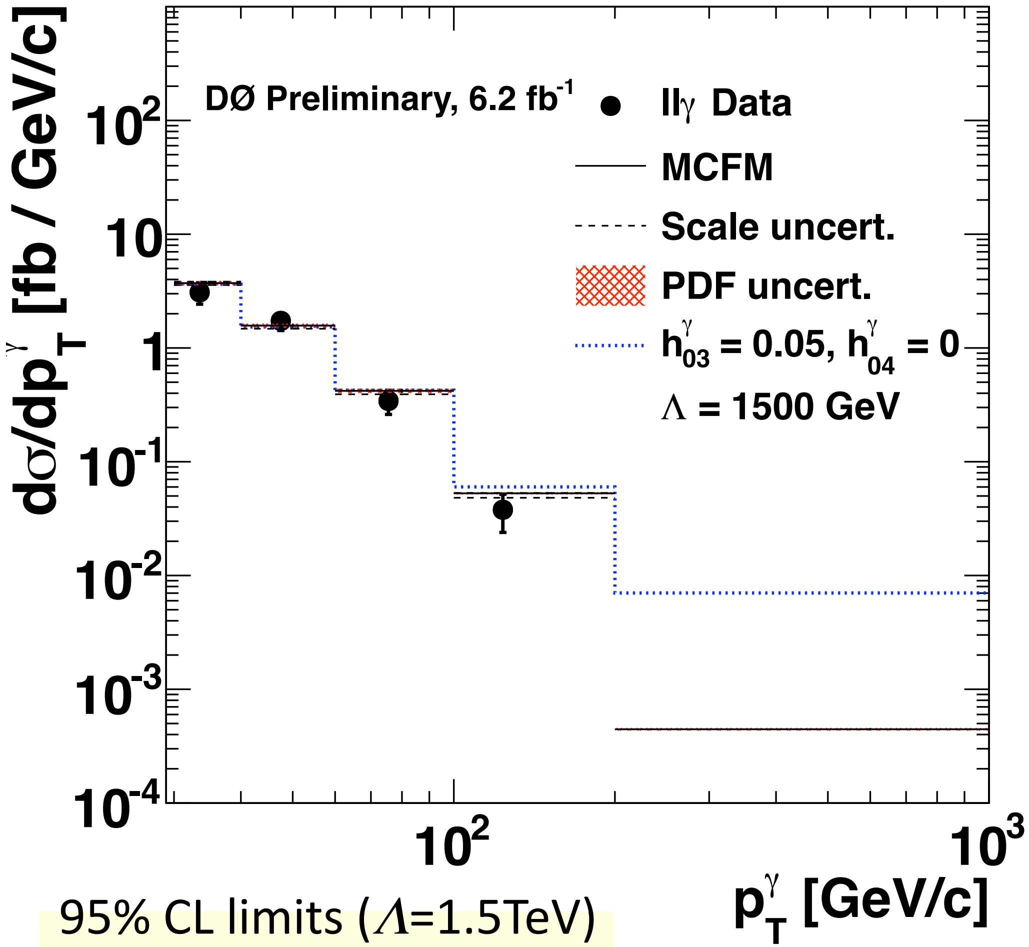
Outlook

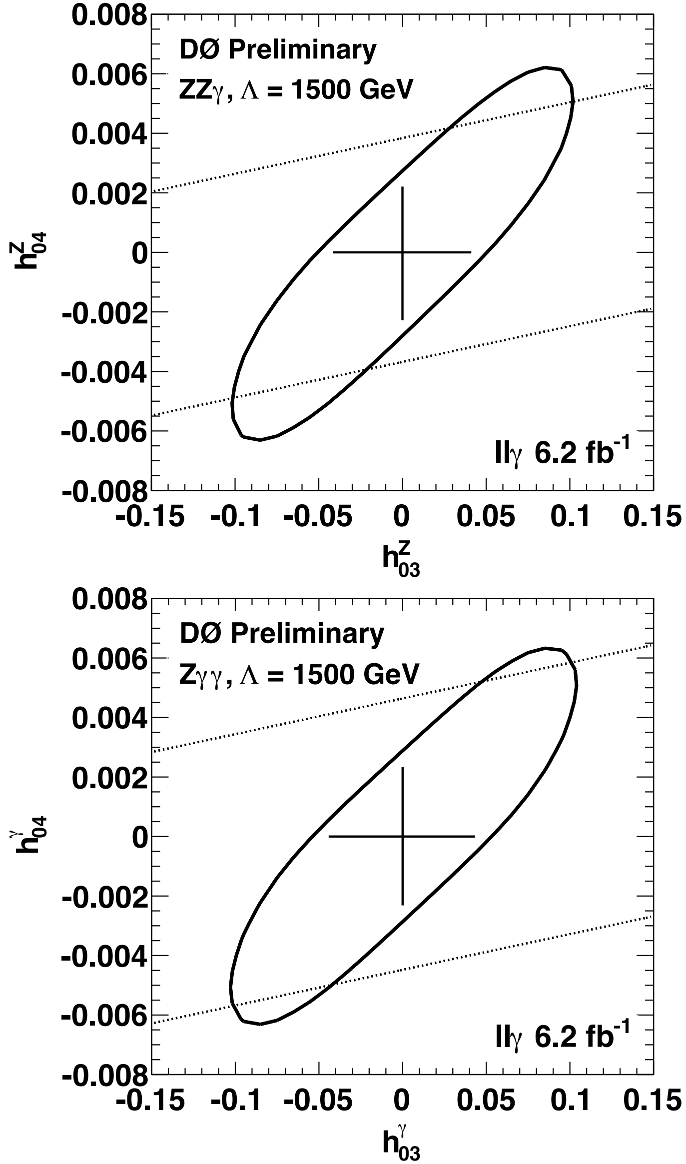
- Rich programme of Tevatron diboson physics

- Huge advances over ten years of Run 2
  - testing standard model
  - probing for new physics
  - underpinning symmetry-breaking searches

$Z\gamma$

New for HCP





95% CL limits (Λ=1.5TeV)

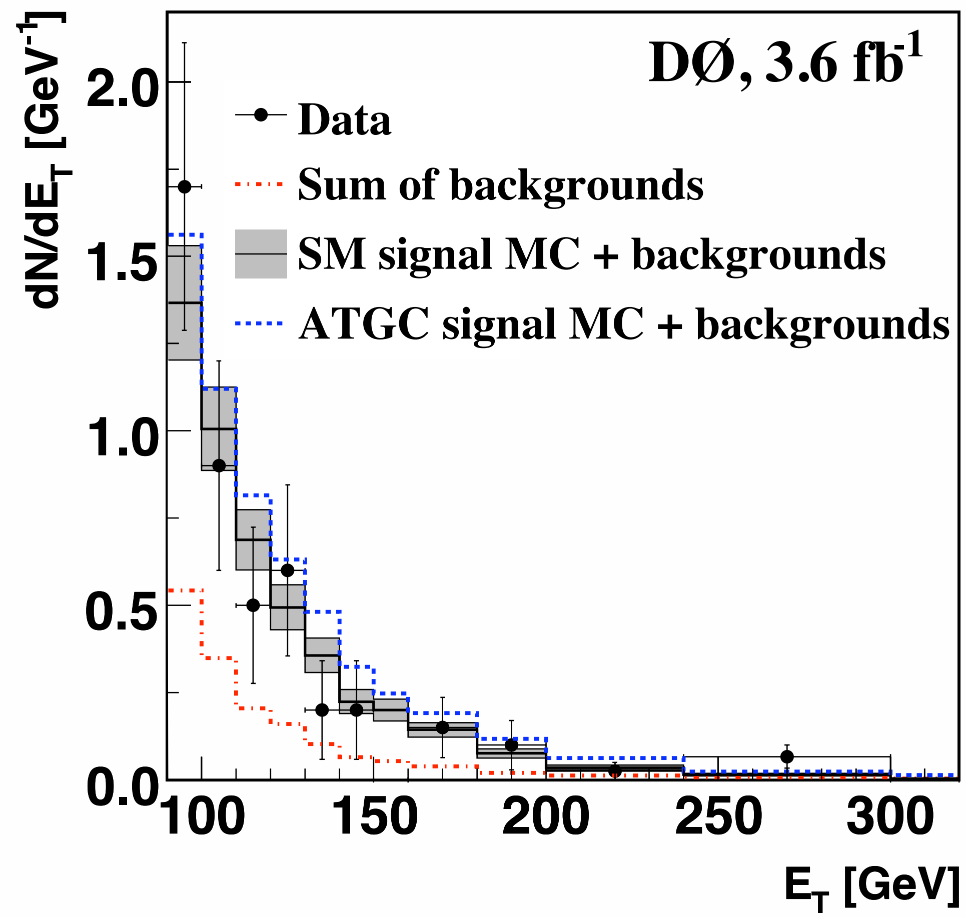
$-0.026 < h_3^Z < 0.026$

$-0.0013 < h_4^Z < 0.0013$

$-0.027 < h_3^\gamma < 0.027$

$-0.0004 < h_4^\gamma < 0.0004$

Zγ



$\sigma(p\bar{p} \to Z\gamma \to \nu\nu\gamma)$ = 32 ± 9(stat+sys) ± 2(lumi) fb

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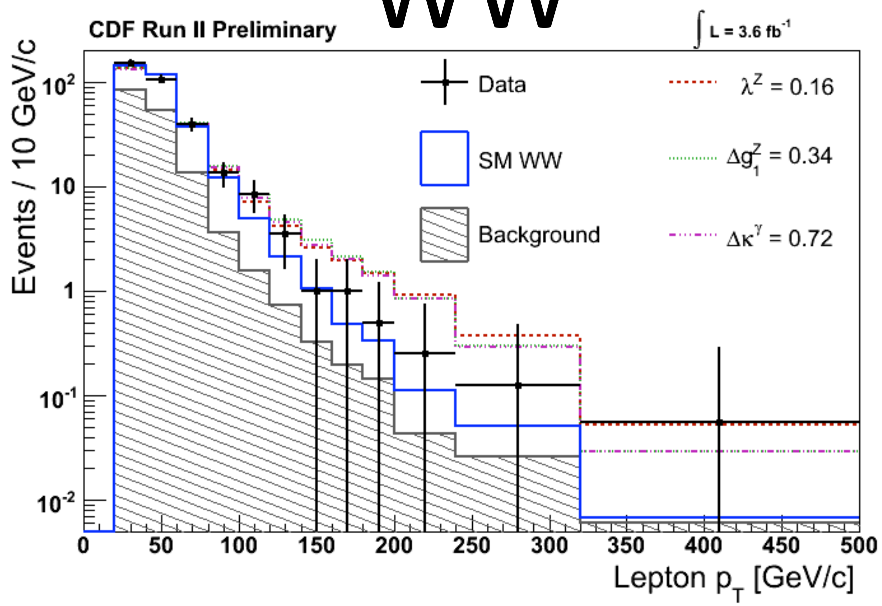
$|\eta_\gamma|<1.1$; $E_T(\gamma)>90$GeV

(SM: 39 ± 4 fb)

WW



Limits, Expected Limits and Probabilities for Obtaining Observed Limits (tex)

CDF Preliminary Results at $3.6 fb^{-1}$

Λ	λ^Z	Δg_1^Z	$\Delta\kappa^\gamma$
2.0TeV	(-0.14,0.15)	(-0.22,0.30)	(-0.57,0.65)
1.5TeV	(-0.16,0.16)	(-0.24,0.34)	(-0.63,0.72)

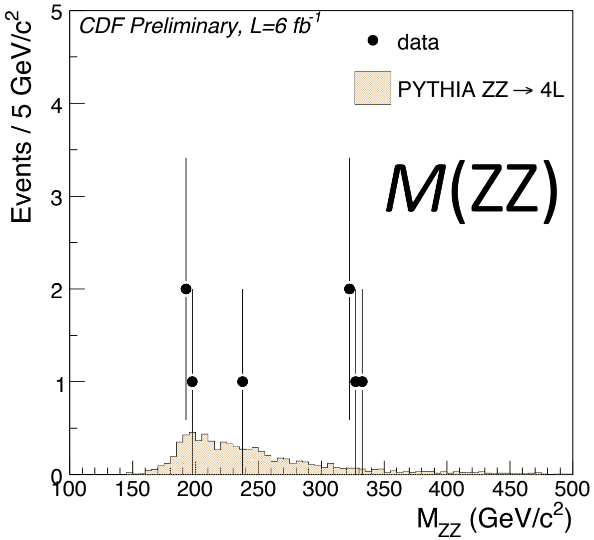
CDF Expected Limits at $3.6 fb^{-1}$

Λ	λ^Z	Δg_1^Z	$\Delta\kappa^\gamma$
2.0TeV	-0.05 - 0.06	-0.08 - 0.15	-0.20 - 0.27
1.5TeV	-0.05 - 0.07	-0.09 - 0.17	-0.23 - 0.31

Probability of Observed Limits

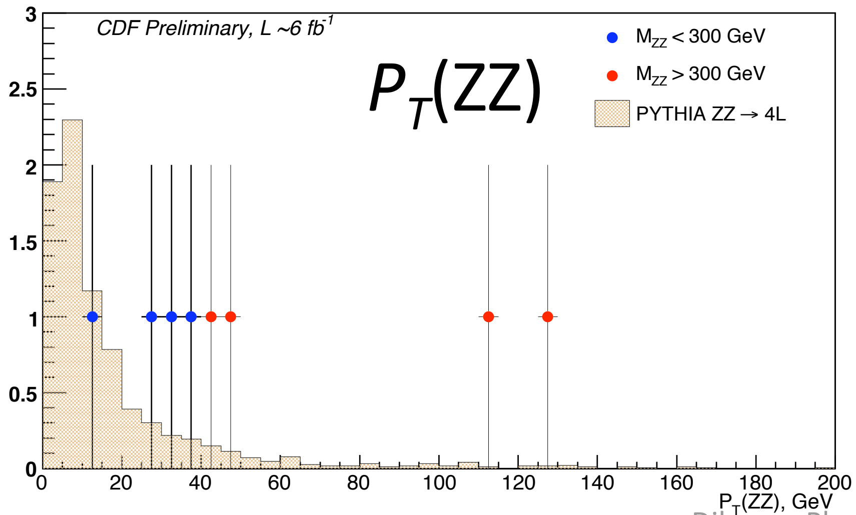
Λ	λ^Z	Δg_1^Z	$\Delta\kappa^\gamma$
2.0TeV	7.1%	7.3%	7.2%
1.5TeV	7.6%	7.4%	7.3%

$ZZ \to 4\ell$



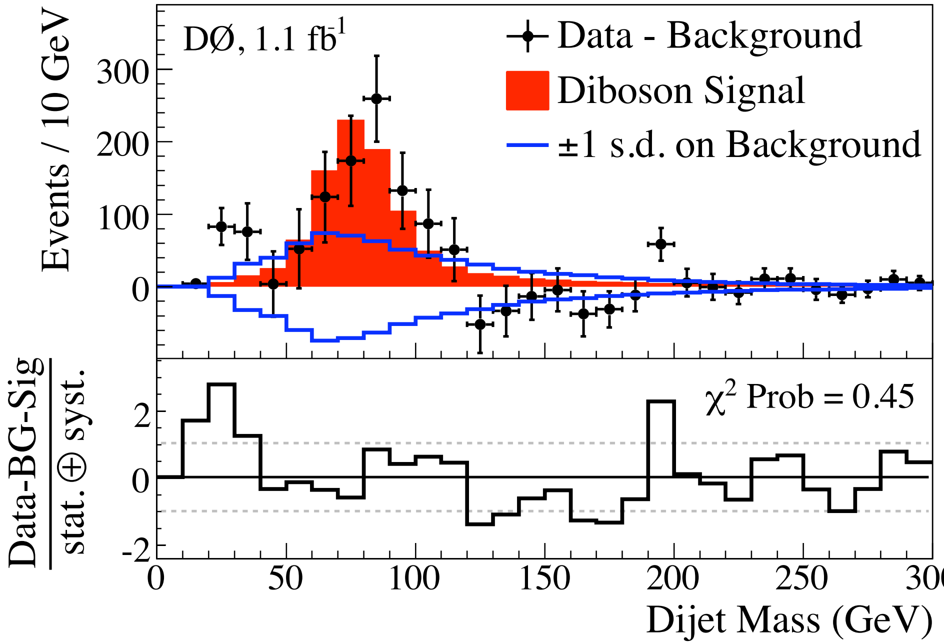
Very general goodness-of-fit test:
p-value is fraction of PEs that have KS distance greater than that of observed distribution: 0.14

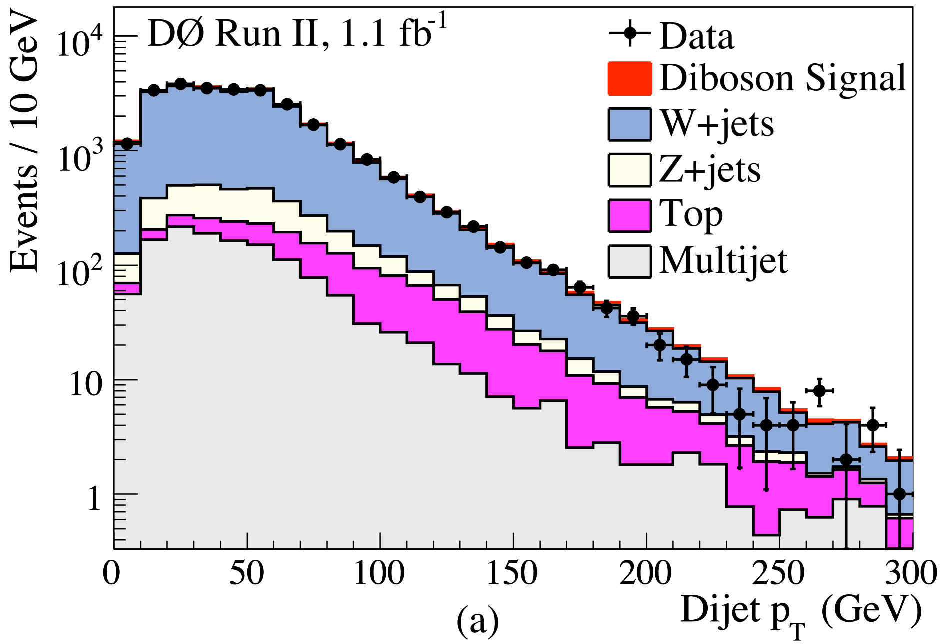
More powerful test statistic for resonance search: ratio of bck and bck+sig likelihoods (bck= SM M(ZZ); sig= Gaus with width = detector resolution at mean)
p-value is fraction of PEs that have likelihood ratio L_{SM}/L_{SM+G} lower than data: $(1–2)\times10^{-3}$



For P_T: no physics model, so p-value is fraction of PEs sampled from SM distribution that have KS distance greater than that observed: $(1–2)\times10^{-4}$

WW/WZ → $\ell\nu jj$





95% CL limits, Λ=2TeV

$-0.44 < \Delta\kappa_\gamma < 0.55$

$-0.10 < \lambda_Z = \lambda_\gamma < 0.11$

$-0.12 < \Delta g_1^Z < 0.20$

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