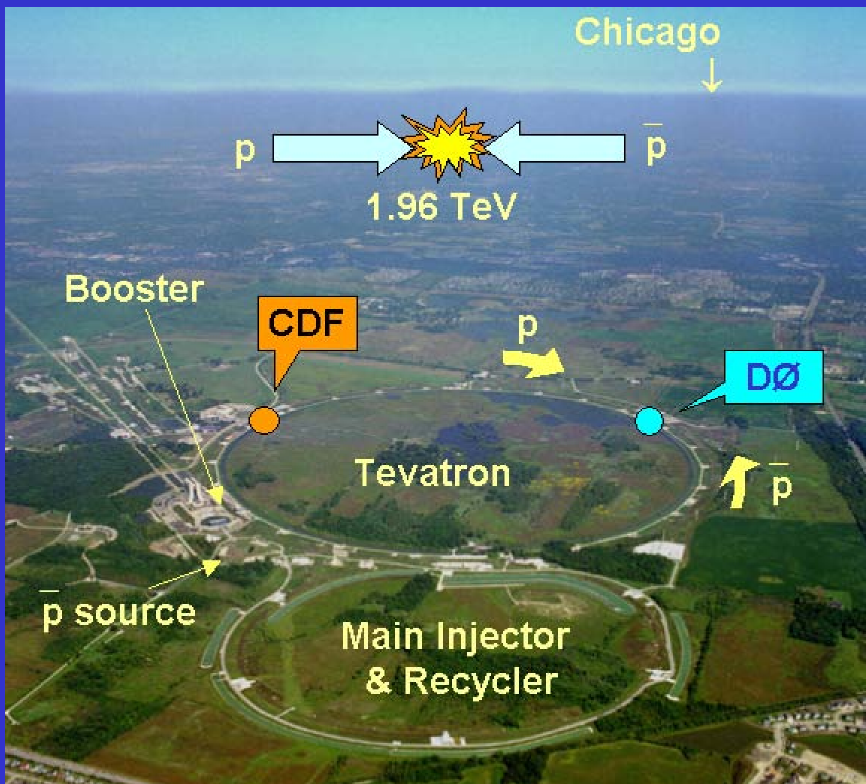
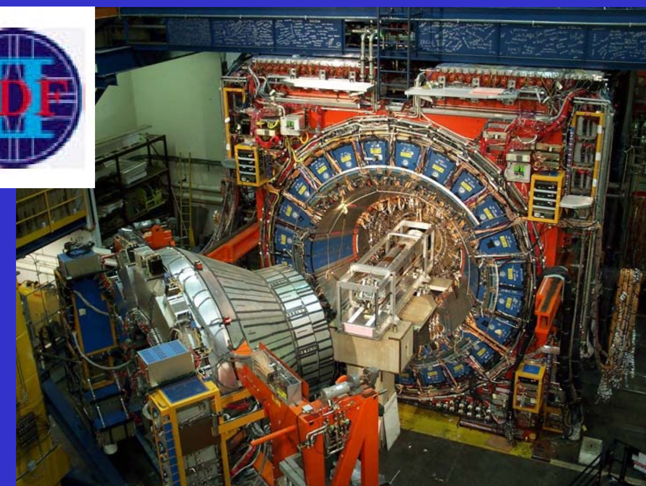
Di-Boson Measurements at the Tevatron





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for the CDF and DØ Collaborations

HCP Toronto, August 24th 2010

Physics Motivation

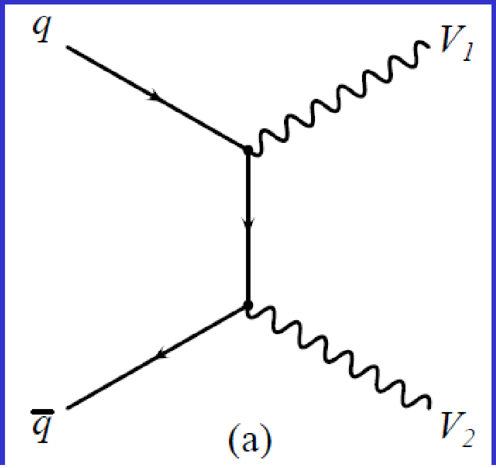
Di-boson final states:

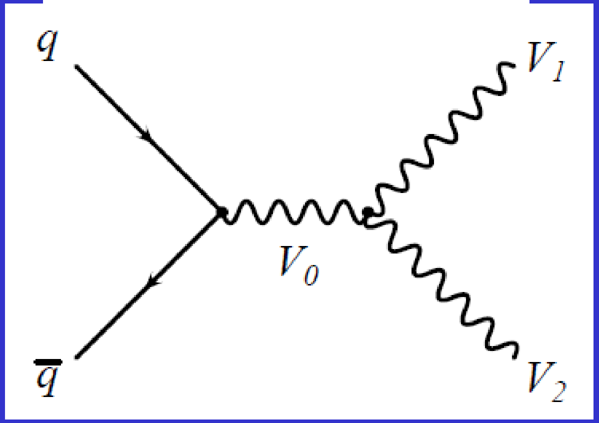
Charged: WW, WZ, Wγ

Neutral : ZZ, Zγ, (γγ)

Similar to WH, ZH, gg→H→WW.

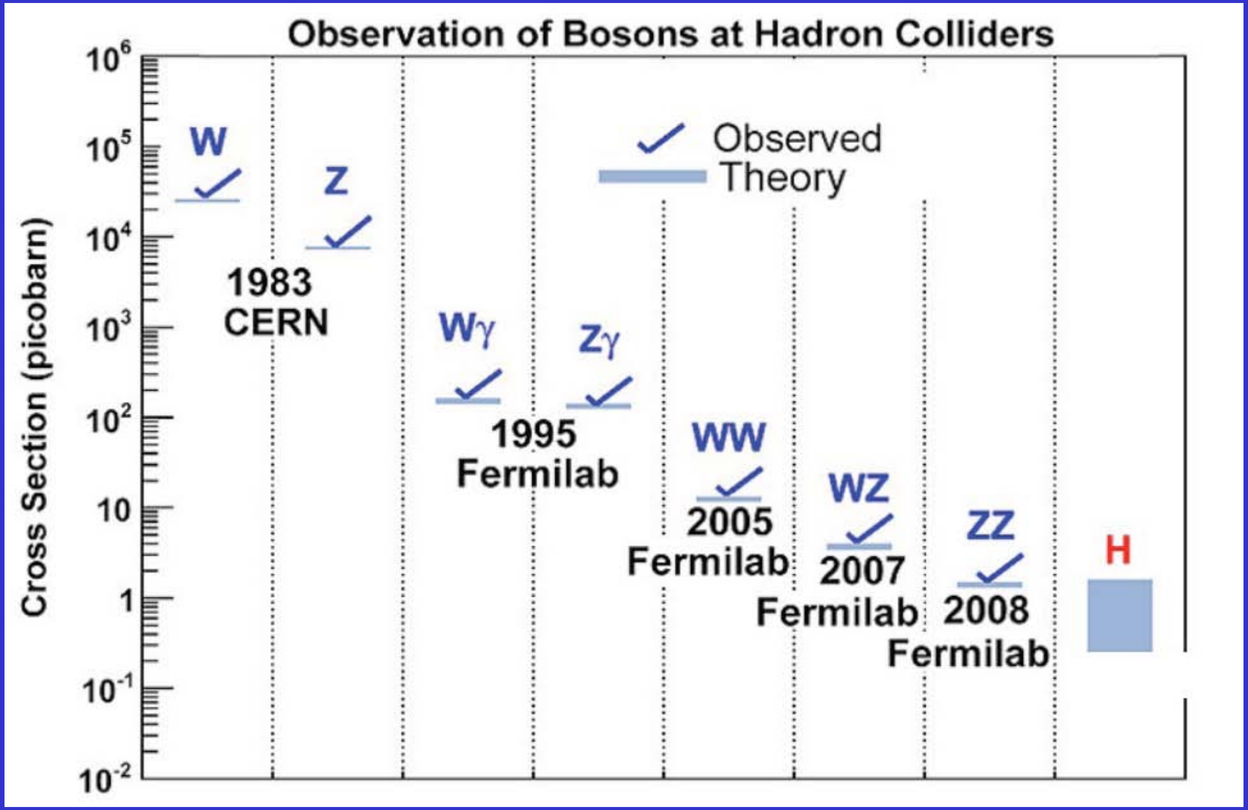
- Test the electroweak sector:
  - cross-sections, kinematic distributions, gauge-boson couplings
- Search for new particles decaying to the same final state
- Known benchmarks for Higgs search
  - demonstrate sensitivity and constrain backgrounds





V_0	V_1	V_2
W	W	γ
γ or Z	W	W
W	W	Z

Di-Boson Cross-Sections



So far, the primary measurement channel is through leptonic decays. This means that we are probing σ•B values orders of magnitude smaller. Example:

σ•B ≈ 1.5 fb for ZZ → μμμμ.

In practice, we measure final state topologies like: lepton+photon+MET (Wγ), di-lepton + photon (Zγ), photon+MET (Zγ), di-leptons + MET (WW), tri-leptons+MET (WZ), lepton+jets+MET (WW+WZ), jets+MET (WW+WZ+ZZ), four-leptons (ZZ). We often retain acceptance for new physics sources of the same final state topology: eg. Higgs, SUSY, technicolor.

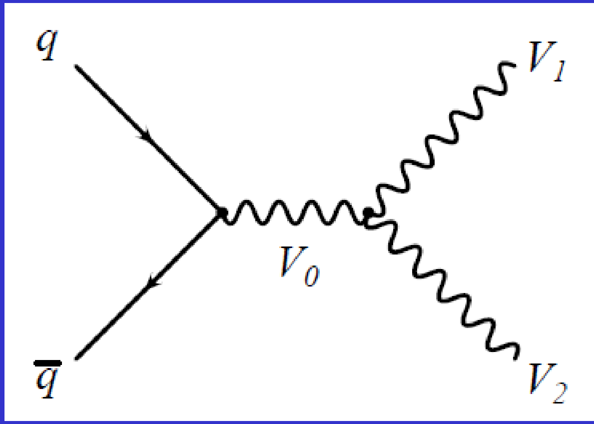
Outline

- Introduction
- $Z\gamma$ + anomalous neutral gauge couplings
- $W\gamma$
- WW
- WZ
- ZZ
- Jets + MET (WW+WZ+ZZ)
- $l\nu jj$ (WW+WZ)
- Combining charged gauge boson coupling measurements
- Summary

Charged Triple Gauge Couplings

One of the potentially most sensitive tests of the SM is the self-interactions of the gauge bosons

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i g_1^V (W^\dagger_{\mu\nu} W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\lambda_V}{M_W^2} W^\dagger_{\lambda\mu} W^\mu{}_\nu V^{\nu\lambda}$$



V_0	V_1	V_2
W	W	γ
γ or Z	W	W
W	W	Z

- Analyses usually use this C,P, and CP conserving form of an effective Lagrangian for the WWγ and WWZ vertices with up to 5 free parameters. ($g_1^\gamma = 1$)
- In the SM, $g_1^V = \kappa_V = 1$ and $\lambda_V = 0$ for V=γ,Z
- Analyses often use reduced parameter sets based on additional constraints.

$$\alpha(\hat{s}) = \frac{\alpha_0}{\left(1 + \hat{s}/\Lambda_{NP}^2\right)^n}$$

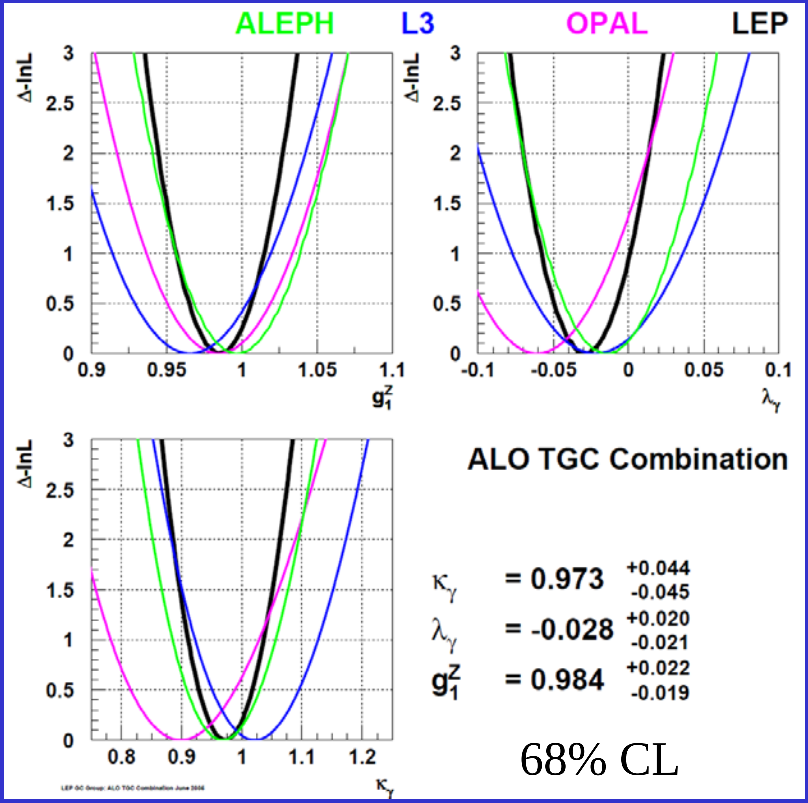
(as used at LEP2) 3-parameter
2-parameter

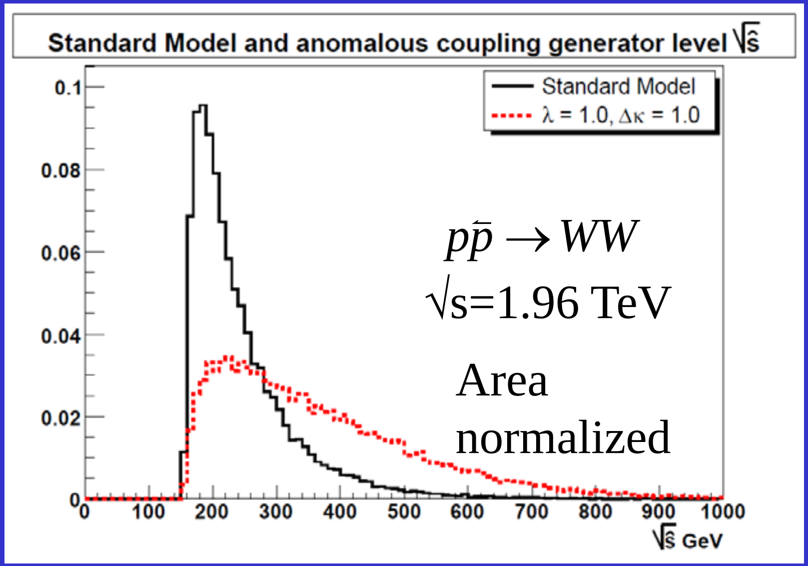
SU(2)×U(1): $\Delta\kappa_z = \Delta g_1^z - \Delta\kappa_\gamma \tan^2\theta_W, \lambda_\gamma = \lambda_z$

γWW = ZWW: $\Delta\kappa_\gamma = \Delta\kappa_z, \lambda_\gamma = \lambda_z$

Complementarity to LEP2

Experiments at LEP2 primarily tested a combination of WWγ and WWZ TGCs in ee → WW by full reconstruction of the event kinematics and cross-section measurements at √s ≤ 209 GeV.





Many of the collisions producing di-bosons extend significantly above the √s explored at LEP2.

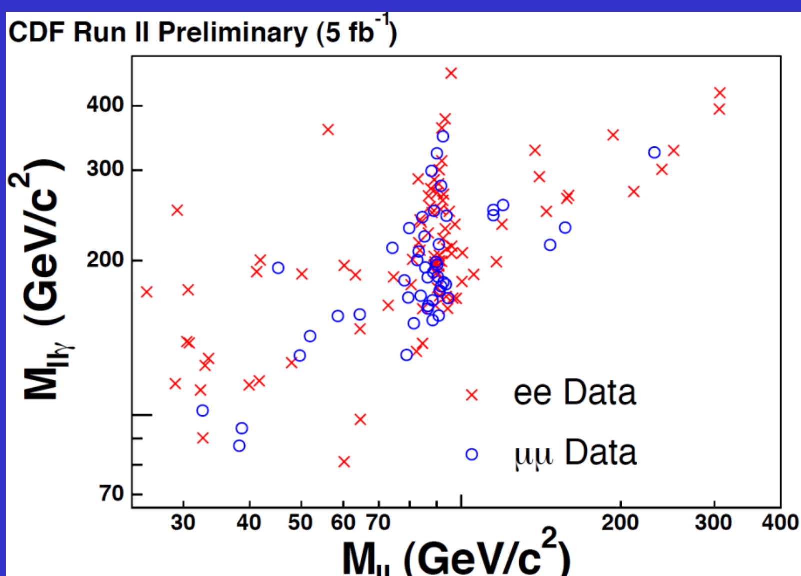
The Tevatron provides clean signatures in the leptonic decay modes to test **directly** WWγ couplings in the Wγ final state and to test **directly** WWZ couplings in the WZ final state (in addition to channels like WW).

Zγ + Anomalous Neutral TGCs

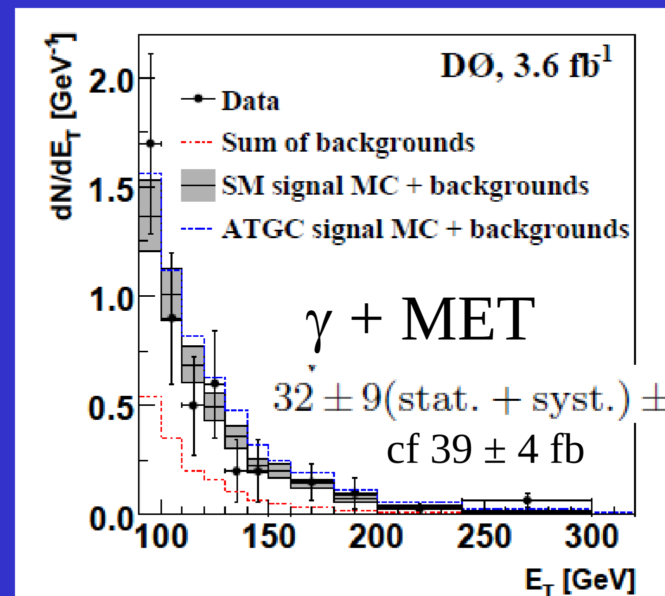
$$\mathcal{L}_{Z\gamma V} = -ie\left[\left(h_1^V F^{\mu\nu} + h_3^V \widetilde{F}^{\mu\nu}\right) Z_\mu \frac{(\Box + m_V^2)}{m_Z^2} V_\nu + \left(h_2^V F^{\mu\nu} + h_4^V \widetilde{F}^{\mu\nu}\right) Z^\alpha \frac{(\Box + m_V^2)}{m_Z^4} \partial_\alpha \partial_\mu V_\nu\right]$$

- More details see T. Phillips' talk at ICHEP and Y. Maravin's talk at Blois.
- SM has no ZZZ, ZZγ or Zγγ couplings.
- h_3, h_4 couplings conserve CP

For Zγ, explore using eeγ, μμγ and ννγ final states.
Lots of ISR and FSR ($l^+l^-\gamma$) to deal with.



+ ννγ



$$32 \pm 9(\text{stat.} + \text{syst.}) \pm 2(\text{lumi.})\ \text{fb}$$

$$\sigma(p\bar{p} \to \ell^+\ell^-\gamma + X) = 4.6 \pm 0.2 \pm 0.3 \pm 0.3\ \text{pb}$$

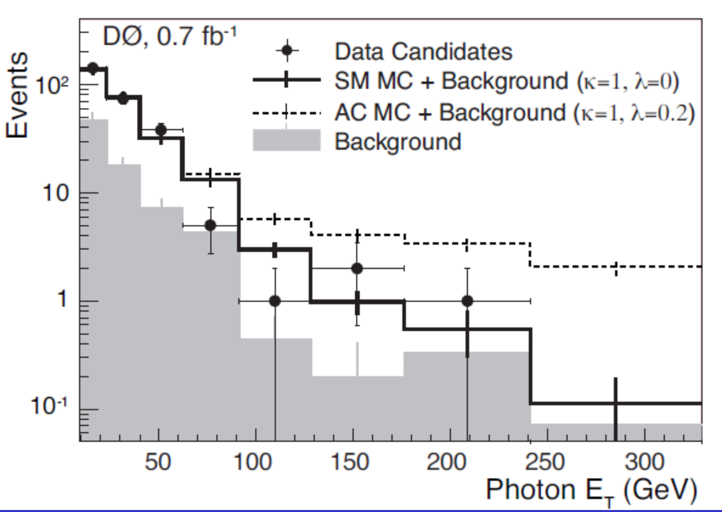
cf 4.5 ± 0.5 pb (NLO) arXiv:1004.1140
with $E_\gamma > 7$ GeV, $m_{ll} > 40$ GeV

h_3^Z	0.017	h_4^Z	0.0006
h_3^γ	0.017	h_4^γ	0.0006

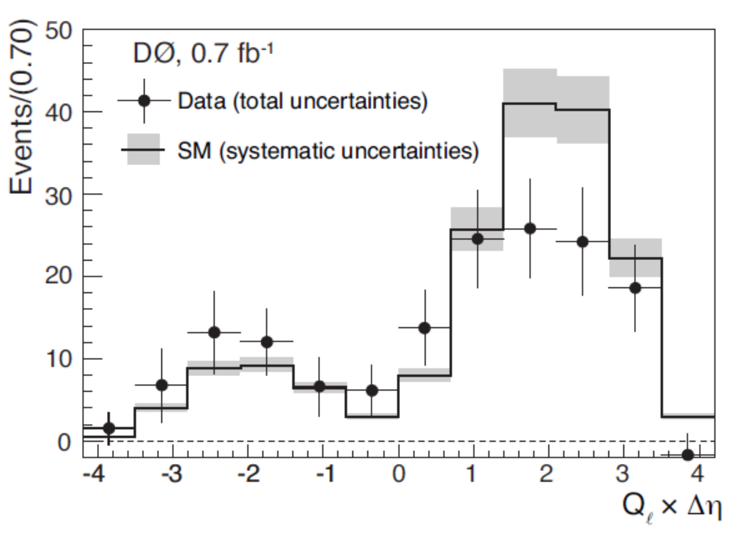
CDF Prel.
5 fb^{-1}
Λ=1.5 TeV

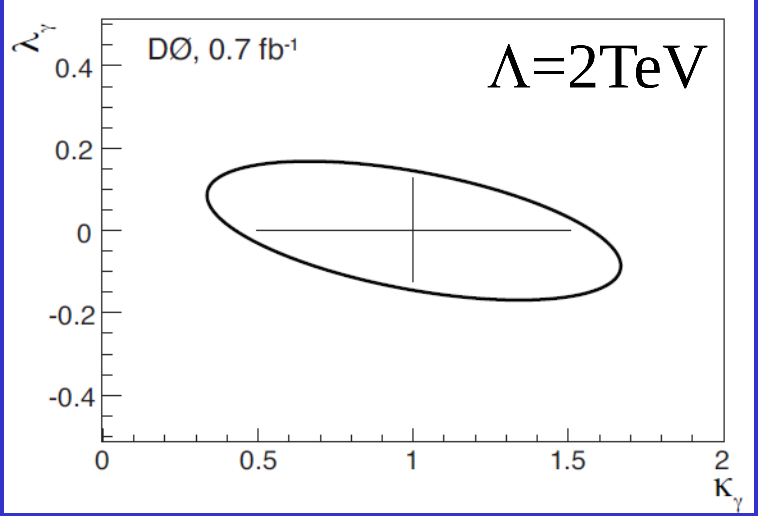
D0 Wγ→lνγ

	$e\nu\gamma$ channel	$\mu\nu\gamma$ channel
Luminosity	720 ± 44 pb^{-1}	660 ± 40 pb^{-1}
Acceptance × efficiency	0.063 ± 0.003	0.045 ± 0.003
W + jet background	$34 \pm 3.8 \pm 3.1$	$18 \pm 2.9 \pm 1.9$
$\ell e X$ background	$17 \pm 2.7 \pm 1.3$	$2.7 \pm 1.3 \pm 0.2$
$W \to \tau$ background	$1.1 \pm 0.1 \pm 0.1$	$1.4 \pm 0.2 \pm 0.1$
$Z\gamma$ background	—	$3.8 \pm 0.53 \pm 0.42$
Candidate events	180	83
Measured signal	$130 \pm 14 \pm 3.4$	$57 \pm 8.8 \pm 1.8$
SM prediction	120 ± 12	77 ± 9.4



Interference leads to radiation amplitude zero in the photon angular distribution
Studied by D0: PRL **100**, 241805 (2008)





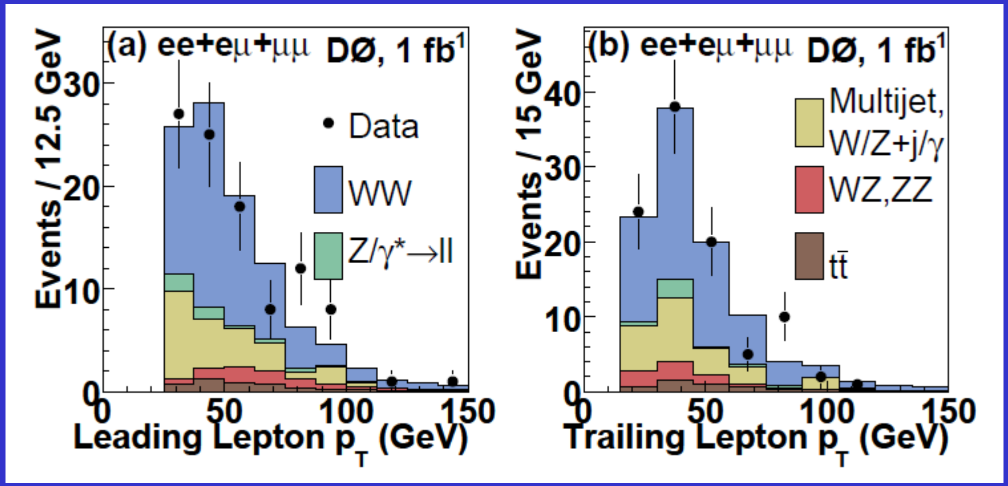
Direct test of WWγ couplings alone

D0 WW (lνlν)

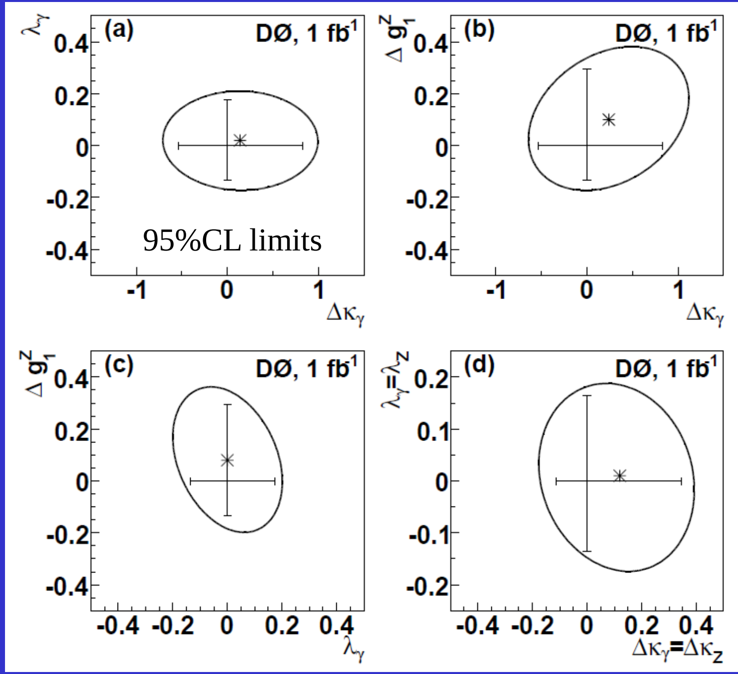
PRL 103:191801 (2009)

p_T > 25 GeV, p_T > 15 GeV
MET > 20 (eμ), 35 (μμ), 45 (ee) GeV

Process	ee	$e\mu$	$\mu\mu$
$Z/\gamma^* \to ee/\mu\mu$	0.27 ± 0.20	2.52 ± 0.56	0.76 ± 0.36
$Z/\gamma^* \to \tau\tau$	0.26 ± 0.05	3.67 ± 0.46	—
$t\bar{t}$	1.10 ± 0.10	3.79 ± 0.17	0.22 ± 0.04
WZ	1.42 ± 0.14	1.29 ± 0.14	0.97 ± 0.11
ZZ	1.70 ± 0.04	0.09 ± 0.01	0.84 ± 0.03
$W\gamma$	0.23 ± 0.16	5.21 ± 2.97	—
$W+$jet	6.09 ± 1.72	7.50 ± 1.83	0.12 ± 0.24
Multijet	0.01 ± 0.01	0.14 ± 0.13	—
$WW \to \ell\ell'$	10.98 ± 0.59	39.25 ± 0.81	7.18 ± 0.34
$WW \to \ell\tau/\tau\tau \to \ell\ell'$	1.40 ± 0.20	5.18 ± 0.29	0.71 ± 0.10
Total expected	23.46 ± 1.90	68.64 ± 3.88	10.79 ± 0.58
Data	22	64	14



Λ=2TeV



$$\sigma(p\bar{p} \to WW) = 11.5 \pm 2.1\ (\text{stat} + \text{syst}) \pm 0.7\ (\text{lumi})\ \text{pb}$$

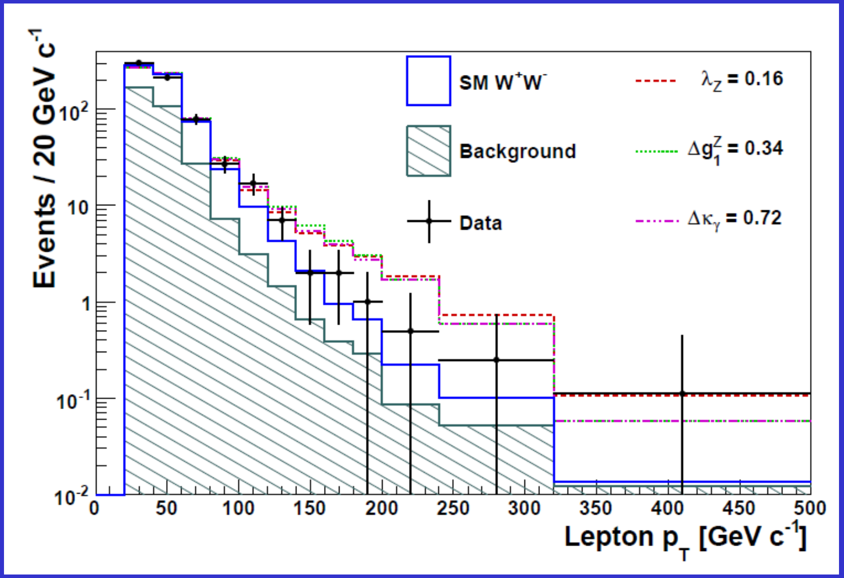
Future measurements will likely take advantage of considerable progress on improving the sensitivity for these channels in the context of the Higgs search

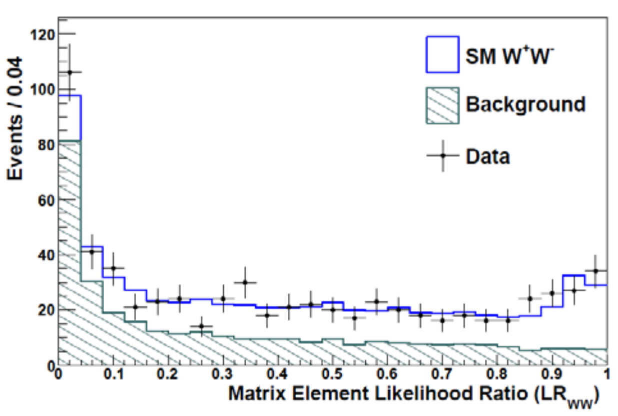
CDF WW (lνlν)

PRL 104.20180 (2010)

Process	Events
Z/γ^* (Drell-Yan)	79.8 ± 18.4
WZ	13.8 ± 1.9
$W\gamma$	91.7 ± 24.8
W + 1-jet	112.7 ± 31.2
ZZ	20.7 ± 2.8
$t\bar{t}$	1.3 ± 0.2
Total Background	320.0 ± 46.8
W^+W^-	317.6 ± 43.8
Total Expected	637.6 ± 73.0
Data	654

3.6 fb^{-1}





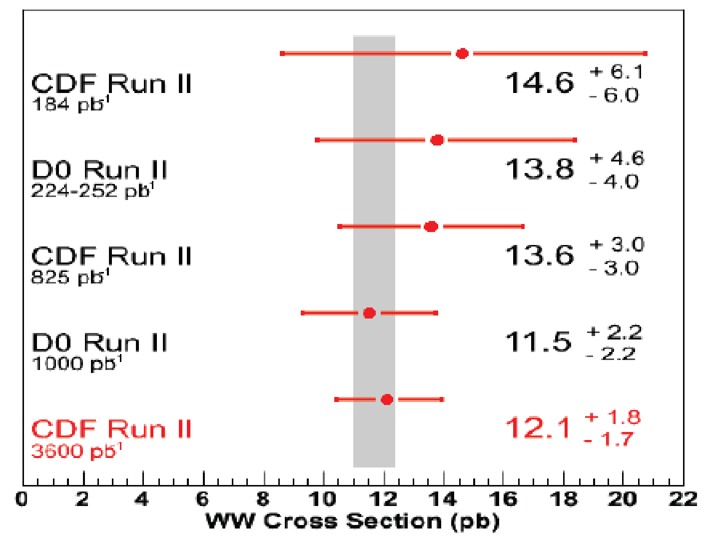
95% CL limits

	Λ (TeV)	λ_Z	Δg_1^Z	$\Delta\kappa_\gamma$
Expected	1.5	(-0.05,0.07)	(-0.09,0.17)	(-0.23,0.31)
Observed	1.5	(-0.16,0.16)	(-0.24,0.34)	(-0.63,0.72)
Expected	2.0	(-0.05,0.06)	(-0.08,0.15)	(-0.20,0.27)
Observed	2.0	(-0.14,0.15)	(-0.22,0.30)	(-0.57,0.65)

Note: observed > expected

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

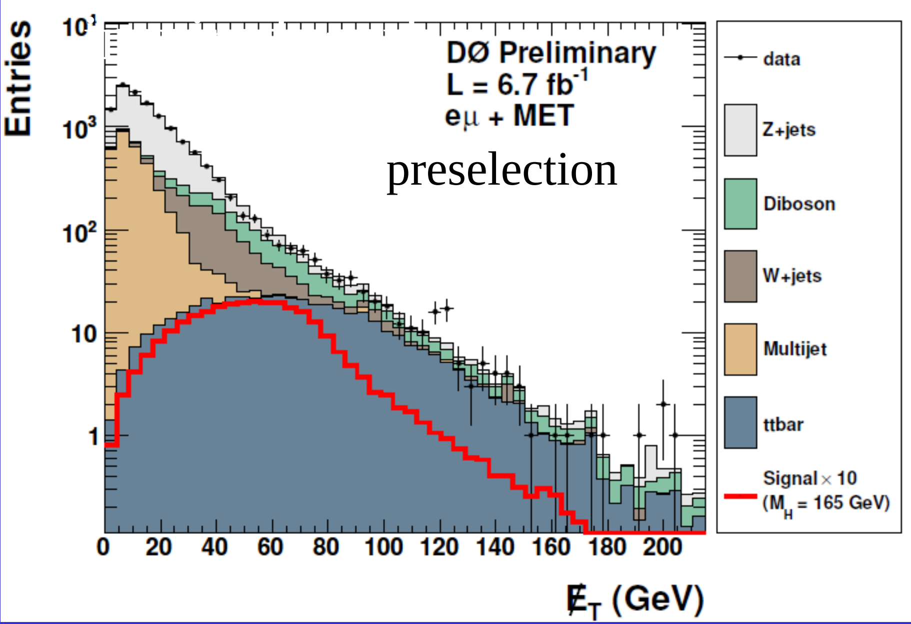
WW Cross-section Summary



NLO prediction: 11.7 ± 0.8 pb

(+ Higgs(165) : + 0.4 pb)

Current and future measurements are taking advantage of ongoing H→WW experimental developments.



CDF WZ→lνll Cross-Section I

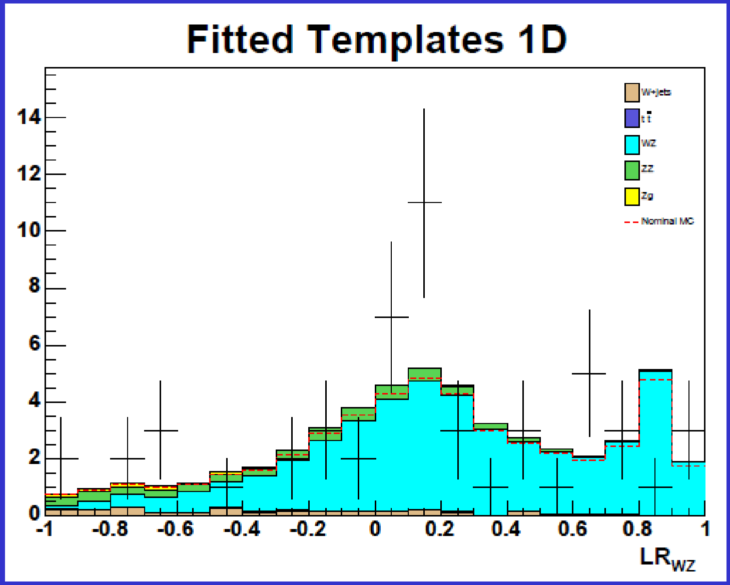
- CDF has two recent measurements of WZ cross-section.

- 12-variable NN plus ML fit to WZ Likelihood Ratio formed from ME for WW,ZZ, W+jet, Wγ using control regions to constrain background normalizations

CDF Run II $\int \mathcal{L} = 5.9\ \text{fb}^{-1}$

	WZ signal	Low $\not\!\!E_T$ Control	No-Z Control
ZZ	4.97 ± 0.66	6.97 ± 0.92	1.70 ± 0.23
Z+Jets	2.41 ± 0.59	41.4 ± 10.1	14.2 ± 3.49
$Z\gamma$	0.77 ± 0.27	71.4 ± 25.0	80.3 ± 28.2
$t\bar{t}$	0.15 ± 0.04	0.02 ± 0.005	0.32 ± 0.10
Total Background	8.29 ± 0.97	119.7 ± 27.2	96.6 ± 28.5
WZ	40.2 ± 4.06	6.25 ± 0.63	3.52 ± 0.36
Sig.+Back.	48.5 ± 4.20	126.0 ± 27.4	100.1 ± 28.6
Data	53	118	104

$$\sigma(p\bar{p} \rightarrow WZ) = 3.7 \pm 0.6(\text{stat})^{+0.6}_{-0.4}(\text{syst})(\text{pb})$$

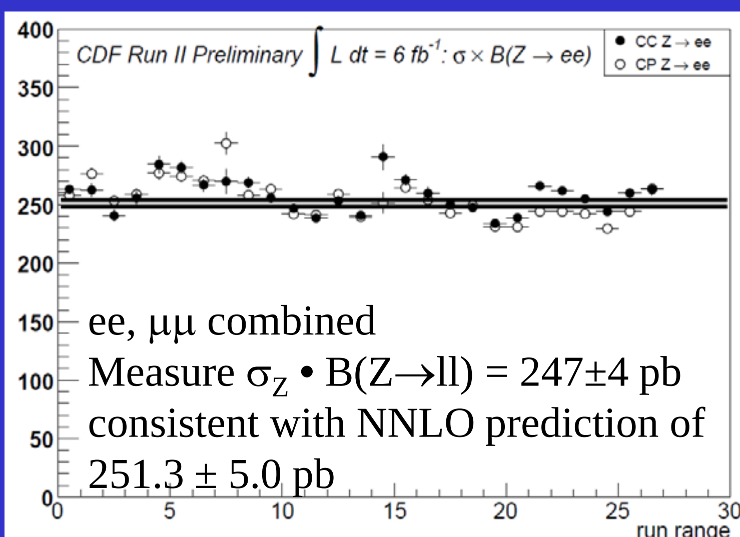


CDF WZ→lνll Cross-Section II

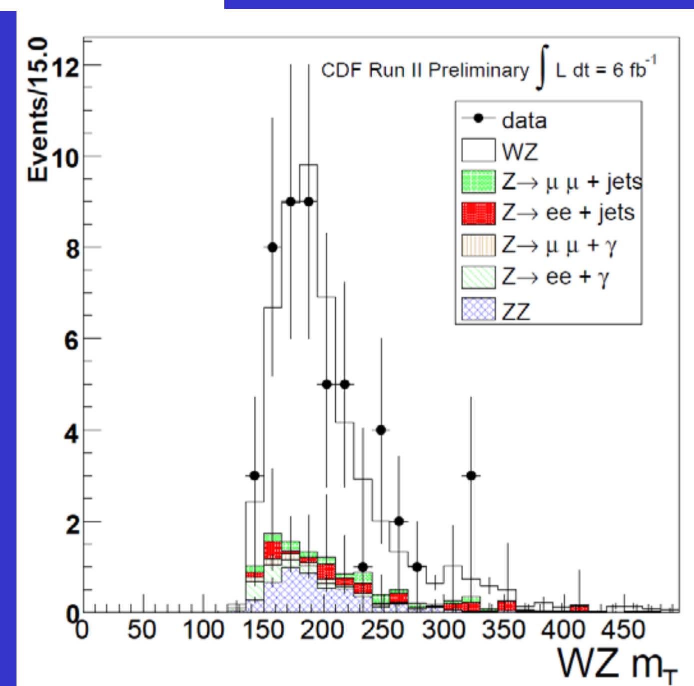
- CDF's second measurement normalizes to the NNLO Z cross-section reducing some systematics.
- Demonstrate reasonable detector stability with time wrt lumi, acceptance, lepton ID and trigger

Input	WZ(Z→ee)	WZ(Z→ $\mu\mu$)
N(signal)	28	22
Background	6.4 ± 1.2	4.8 ± 1.1
Acceptance	$(0.997 \pm 0.036\ (\text{MC stat}))\times 10^{-3}$	$(0.981 \pm 0.036\ (\text{MC stat}))\times 10^{-3}$
Scale Factors(ID+trig+reco)	0.84 ± 0.05	0.77 ± 0.05
L_{int}/fb	6.04 ± 0.36	5.86 ± 0.35

	WZ(Z→ee)	WZ(Z→ $\mu\mu$)
ZZ	2.4 ± 0.2	2.3 ± 0.2
$Z\gamma$	1.6 ± 0.6	0.7 ± 0.3
Z+jets	2.4 ± 1	1.8 ± 1
Total	6.4 ± 1.2	4.8 ± 1.1



$$\sigma(p\bar{p} \to \text{WZ}) = (4.1 \pm 0.6(stat) \pm 0.4(syst))\text{pb}$$

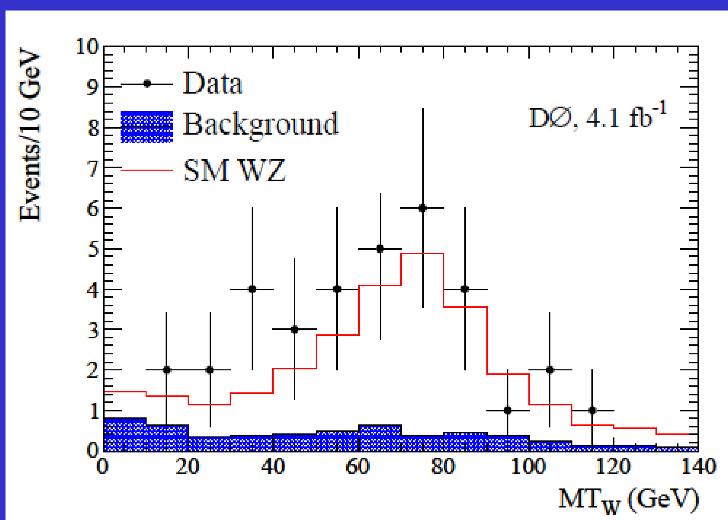


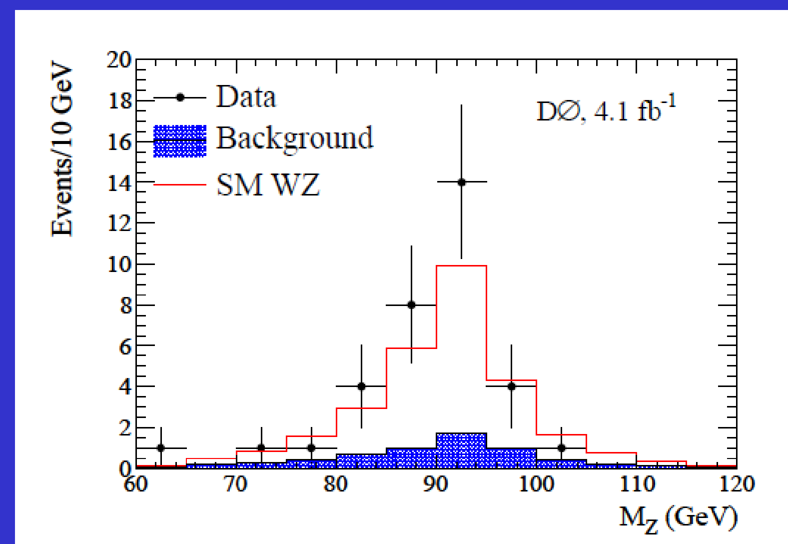
D0 WZ → lνll

arXiv:1006:0761

- Select 3 leptons (l=e,μ) each with pT > 15 GeV. Require MET > 20 GeV.
- 34 candidates

Source	eee	$ee\mu$	$e\mu\mu$	$\mu\mu\mu$
ZZ	0.39 ± 0.07	1.48 ± 0.20	0.40 ± 0.07	1.26 ± 0.23
V+jets	0.63 ± 0.17	0.56 ± 0.24	0.03 ± 0.01	0.17 ± 0.05
$Z\gamma$	0.28 ± 0.08	< 0.001	0.66 ± 0.34	< 0.001
$t\bar{t}$	0.03 ± 0.01	0.05 ± 0.01	0.04 ± 0.01	0.03 ± 0.01
Total bkg.	1.33 ± 0.21	2.11 ± 0.31	1.13 ± 0.35	1.46 ± 0.24
WZ signal	5.9 ± 0.8	6.9 ± 0.8	4.7 ± 0.6	5.8 ± 0.8
Observed	9	11	9	5



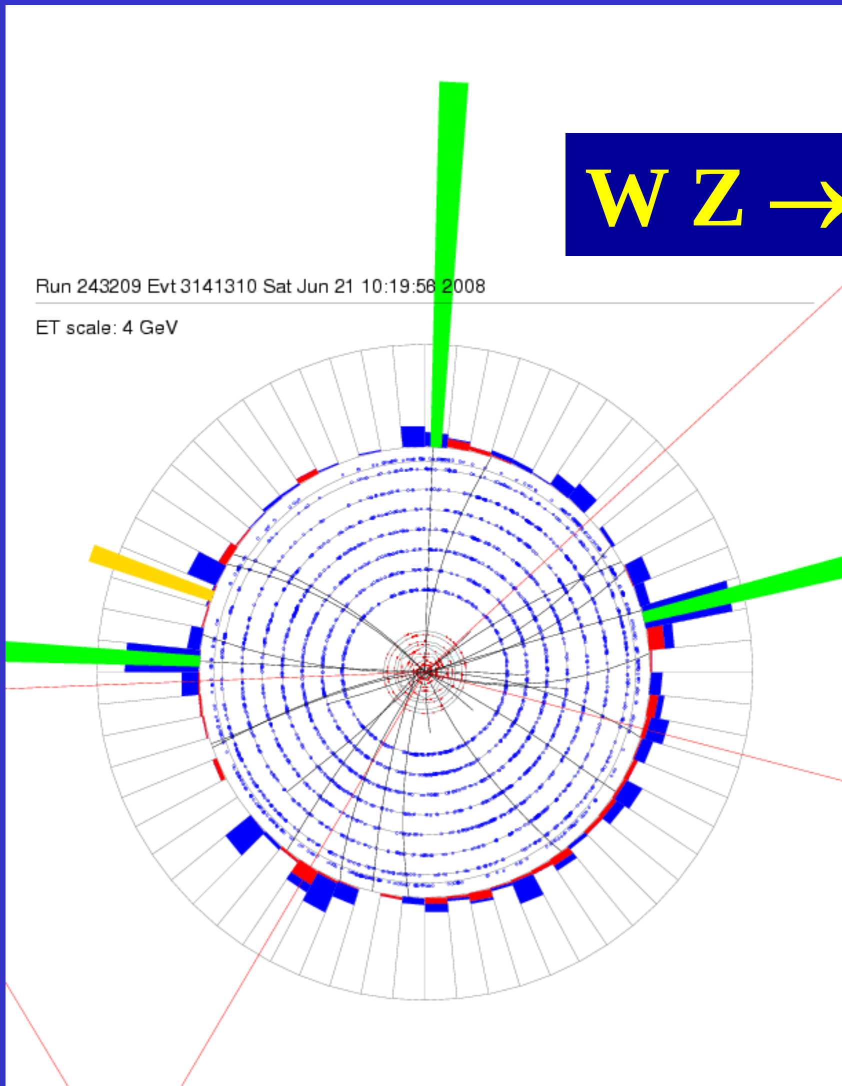


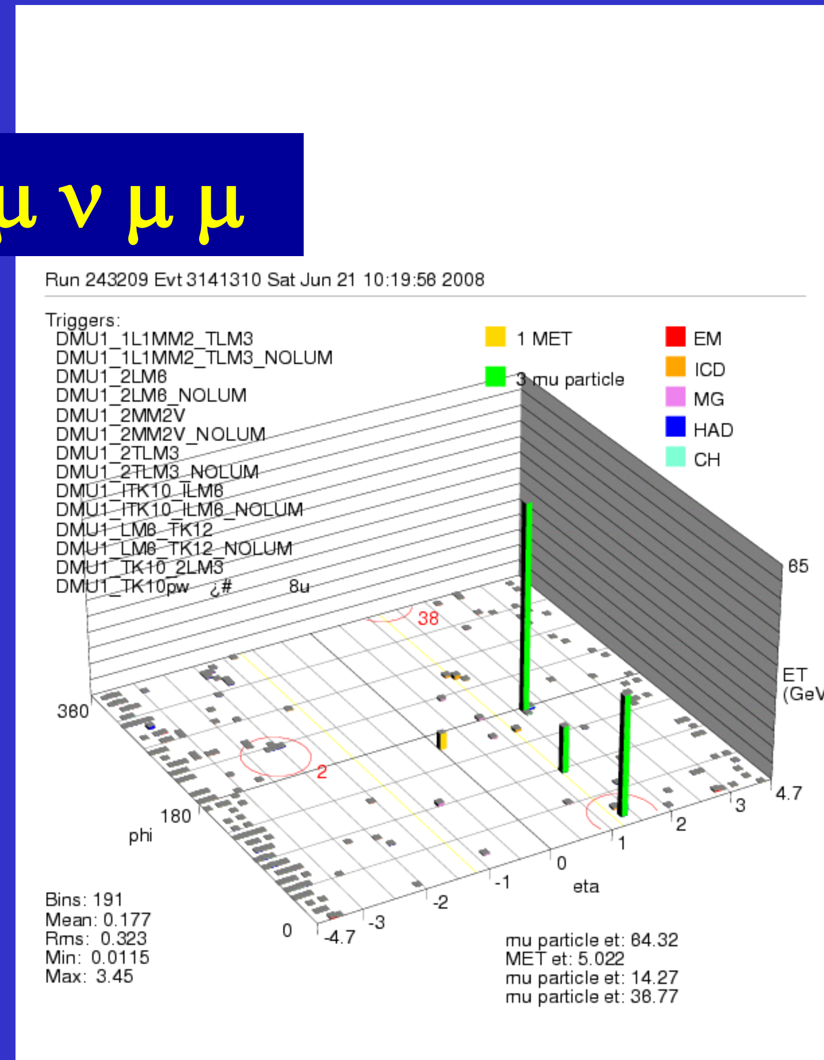
$$\sigma(WZ) \quad = \quad 3.90^{+1.01}_{-0.85} \ (\mathrm{stat} + \mathrm{syst}) \quad \pm 0.31 \ (\mathrm{lumi}) \ \ \mathrm{pb}$$

NLO: 3.25 ± 0.19 pb

WZ Candidate Event

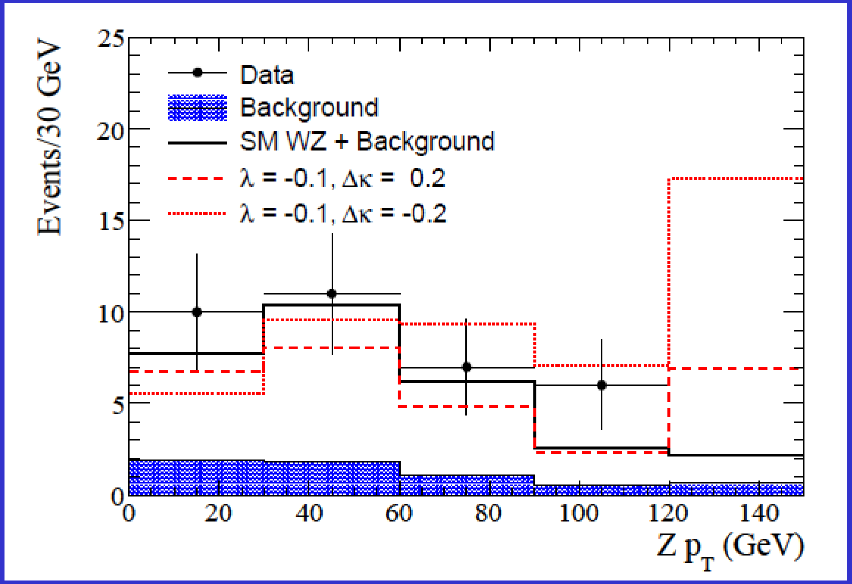
W Z → μ ν μ μ





D0 WZ → lνll

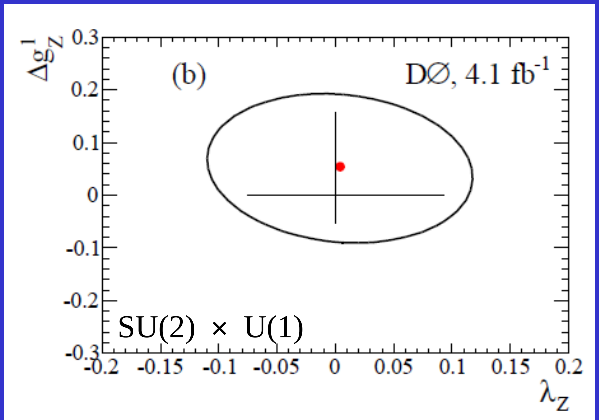
Use Z p_T distribution to test TGCs

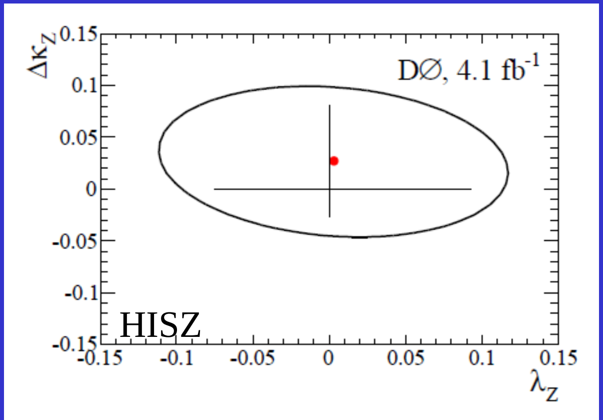


Coupling relation	95% C.L. Limit
$\Delta g_1^Z = \Delta\kappa_Z = 0$	$-0.075 < \lambda_Z < 0.093$
$\lambda_Z = \Delta\kappa_Z = 0$	$-0.053 < \Delta g_1^Z < 0.156$
$\lambda_Z = \Delta g_1^Z = 0$	$-0.376 < \Delta\kappa_Z < 0.686$
$\Delta\kappa_Z = 0$ (HISZ)	$-0.075 < \lambda_Z < 0.093$
$\lambda_Z = 0$ (HISZ)	$-0.027 < \Delta\kappa_Z < 0.080$

Λ=2TeV

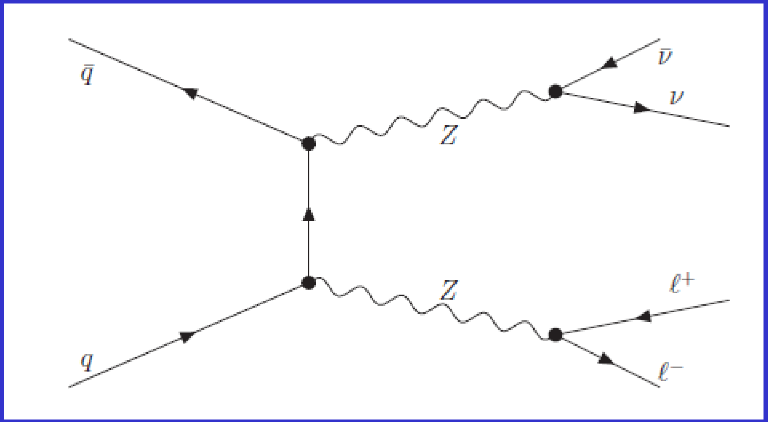
Set 95%CL limits in 2D and 1-D

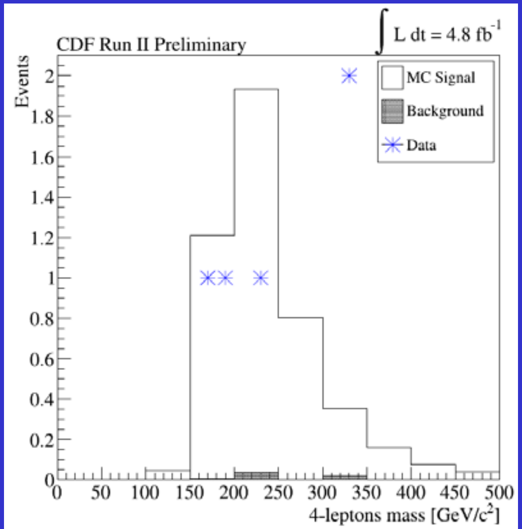




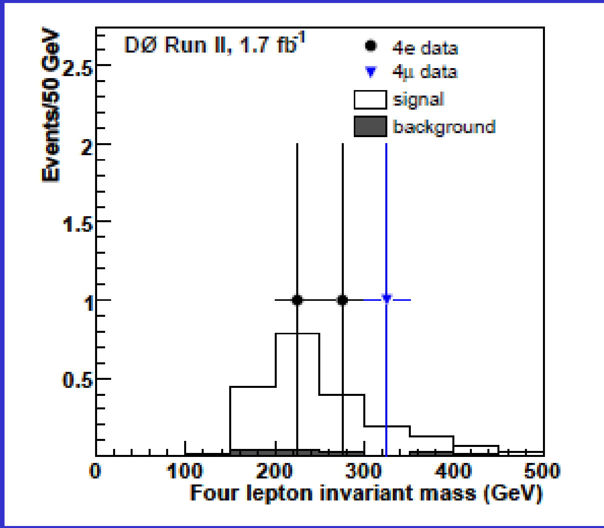
ZZ

- ZZ production at the Tevatron is now well established by both collaborations.
- Use both 4l and llνν final state.
- D0: $\sigma(ZZ) = 1.60 \pm 0.63\ (\text{stat.})^{+0.16}_{-0.17}\ (\text{syst.})\ \text{pb}$
- CDF: $\sigma_{ZZ} = 1.56^{+0.80}_{-0.63}(stat.) \pm 0.25(syst.)$ pb





SM : 1.4 ± 0.1 pb



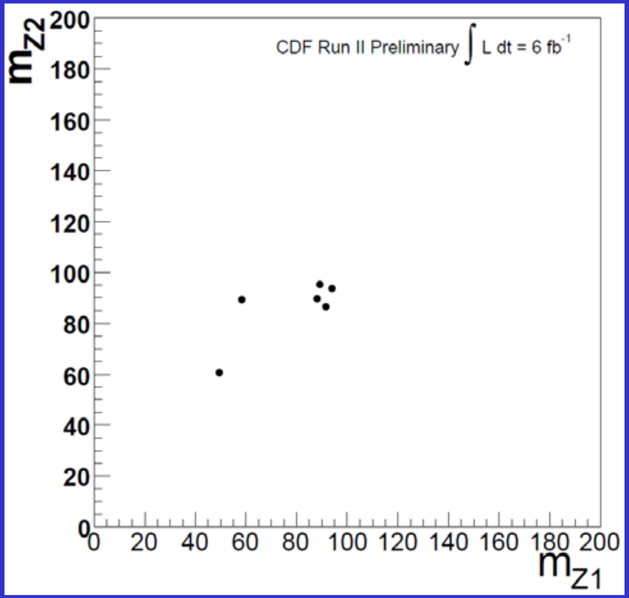
Phys. Rev. Lett. **101**, 171803 (2008),

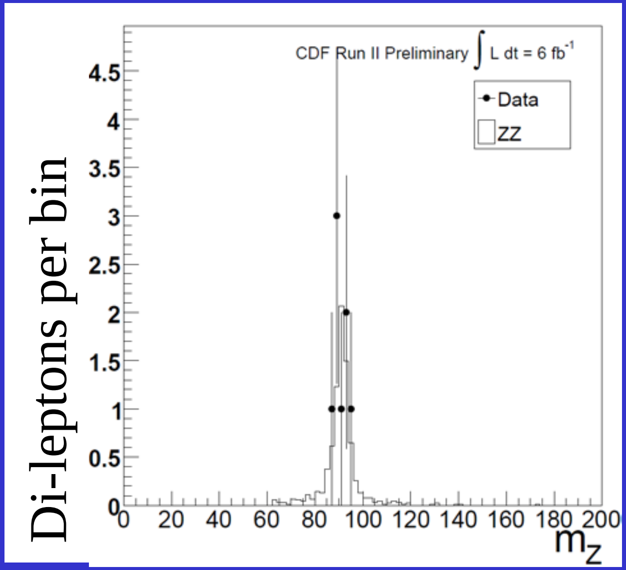
CDF ZZ→4l update

- Require 4 leptons
- p_T > 20, 15, 15, 15 GeV
- Require $|m_{ll} - m_Z| < 15$ GeV
- Require $m_{llll} < 300$ GeV
- Find 4 candidates
- Tiny background (0.01 events.)
- Normalize to Z→ll
- Measure:

$$\sigma(p\bar{p} \to ZZ) \;=\; (1.7\;^{+1.2}_{-0.7}(stat)\;\pm\;0.2(syst))\,\text{pb}$$

SM : 1.4 ± 0.1 pb



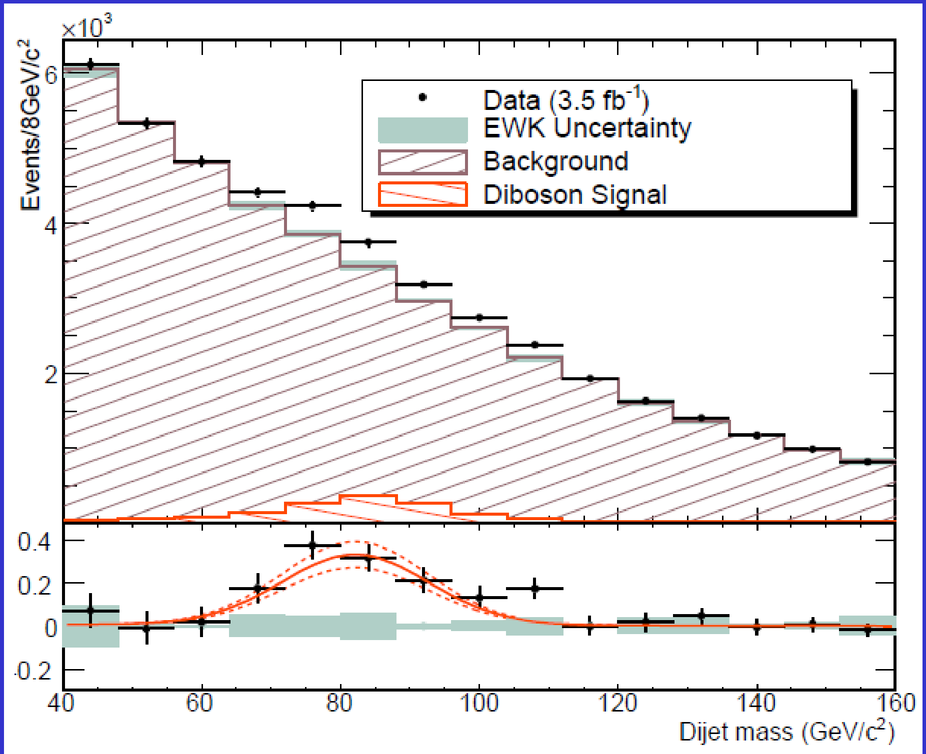


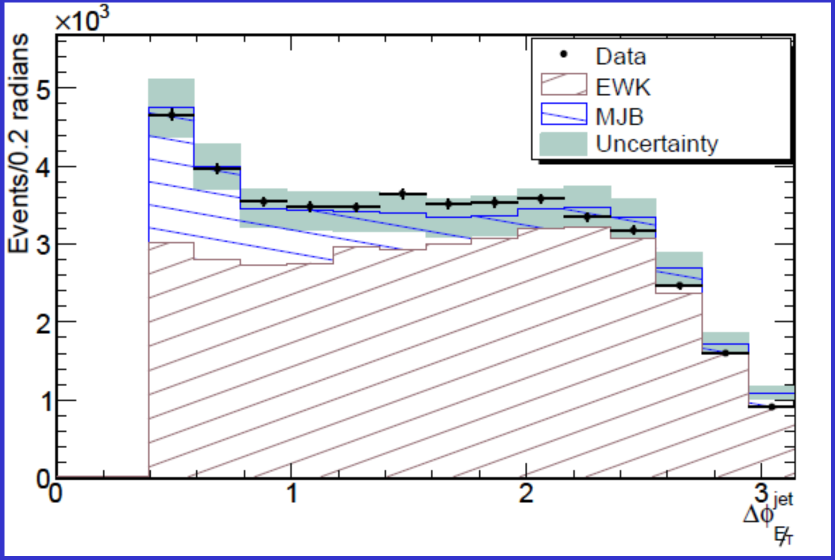
CDF: Jets + MET (WW+WZ+ZZ)

PRL 103 (2009) 091803

Acceptances: 2.5% (WW), 2.6% (WZ), 2.9% (ZZ)
Expected σ (pb) 11.7, 3.6, 1.5

- MET>60 GeV
- =2 hadronic jets, E_T>25 GeV, |η| < 2.0
- 40 < m_{jj} < 160 GeV
- MET significance > 4
- Δϕ(MET-jet) > 0.4 rad
- Use tracking-based MET to constrain QCD MJB model





Azimuthal angle between MET and nearest jet

σ(WW+WZ+ZZ) =

$18.0 \pm 2.8(\text{stat}) \pm 2.4(\text{syst}) \pm 1.1(\text{lumi})$ pb,

cf 16.8 ± 0.5 pb expected

5.3σ significance

CDF lνjj (WW+WZ)

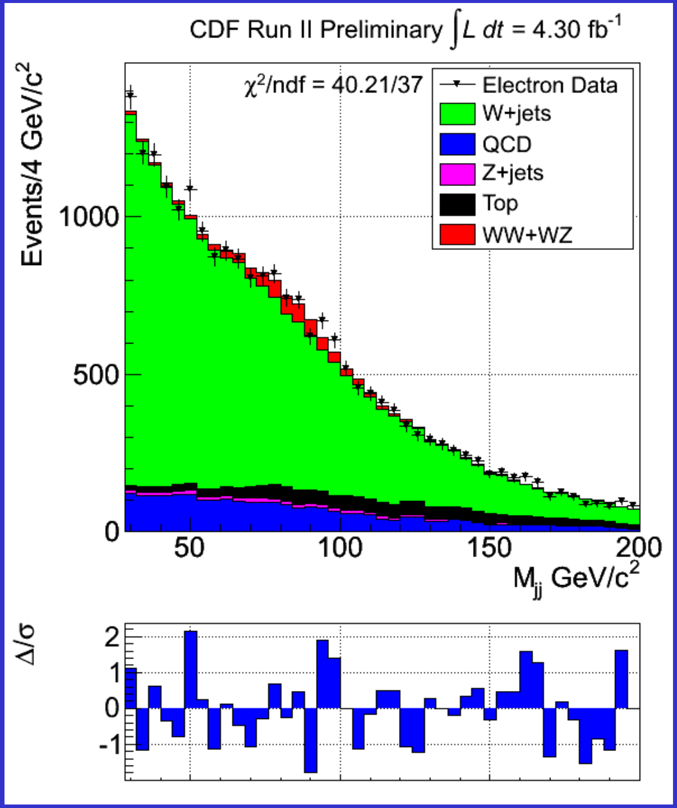
- Recent paper, PRL 104 (2010) 101801 with two separate techniques with little statistical overlap with each other or the jets+MET analysis (only ≈ 15%)
  - Di-jet mass fit (3.9 fb^{-1})
  - Matrix-element technique with event-probability discriminant (2.7 fb^{-1}) (5.4 σ)
  - Combined result: σ(WW+WZ) = 16.0±3.3 pb
  - SM expectation: 16.1 ± 0.9 pb.
- Recent updates of both
  - Di-jet mass fit (4.3 fb^{-1}) 18.1± 3.3 ± 2.5 pb
  - ME (4.6 fb^{-1}) 16.5 +3.3 – 3.0 pb

CDF $l\nu jj$ (WW+WZ) Di-jet Mass

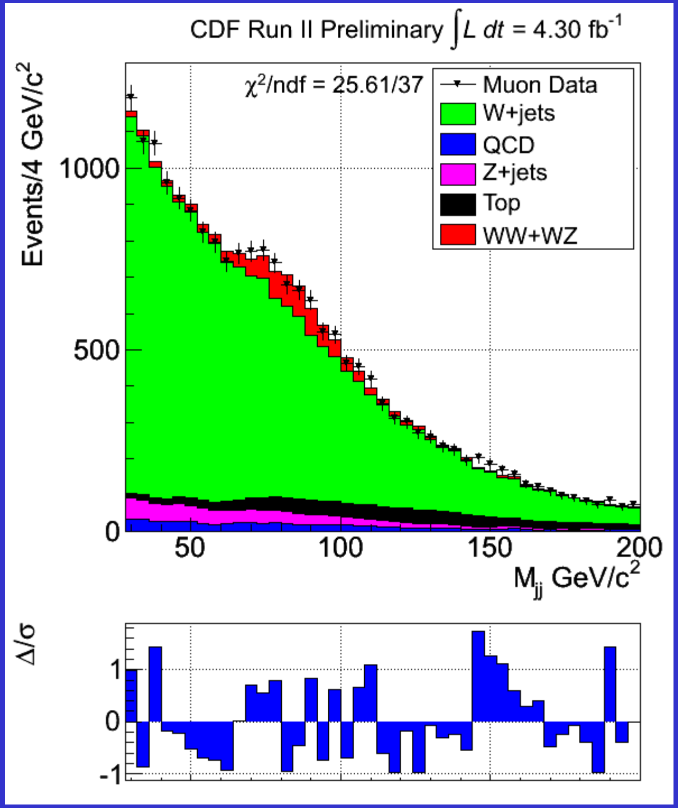
Require MET>25 GeV, di-jet p_T > 40 GeV. Leads to reasonably smoothly falling background in signal region – and visible bumps !

Sample	CEM	CMUP + CMX
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

e



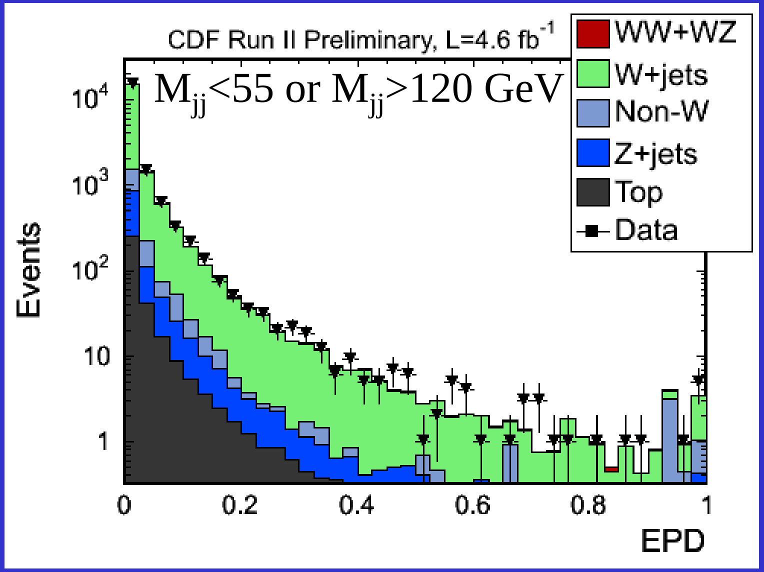
μ



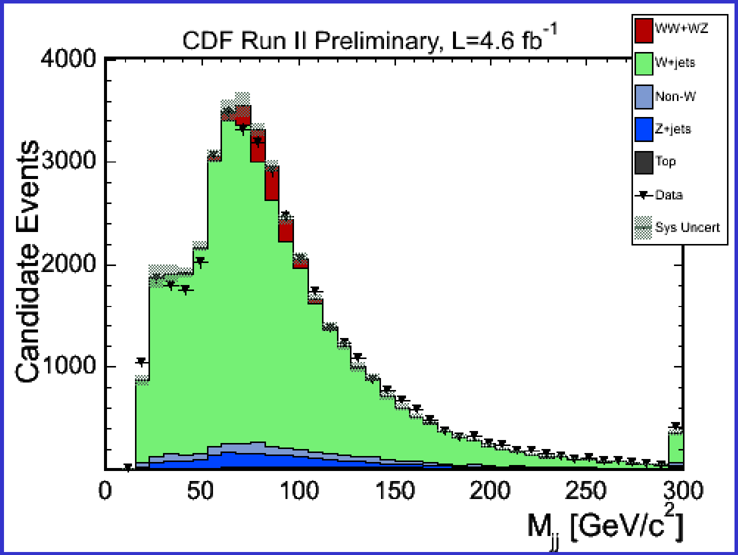
$\sigma = 13.5 \pm 4.4 \pm 1.9$ pb

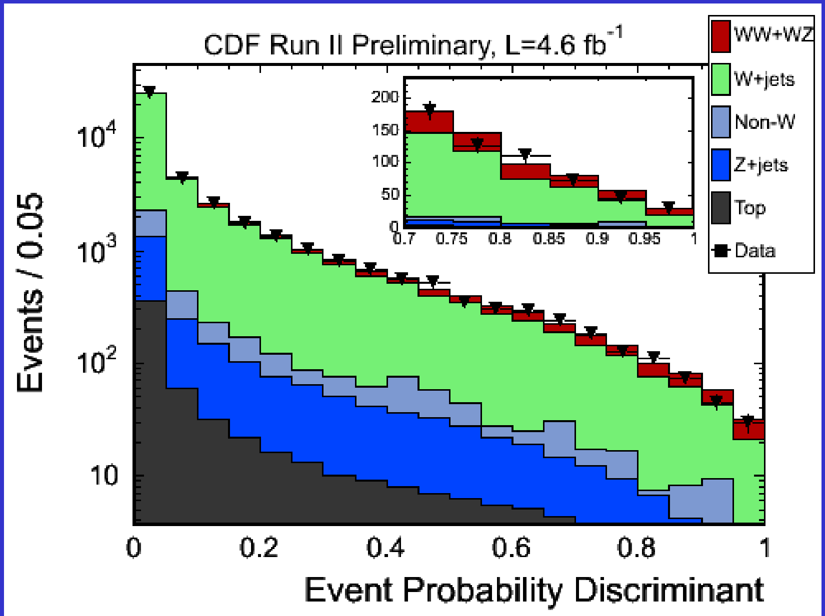
$\sigma = 23.5 \pm 4.9 \pm 3.2$ pb

CDF lνjj (WW+WZ) ME Technique

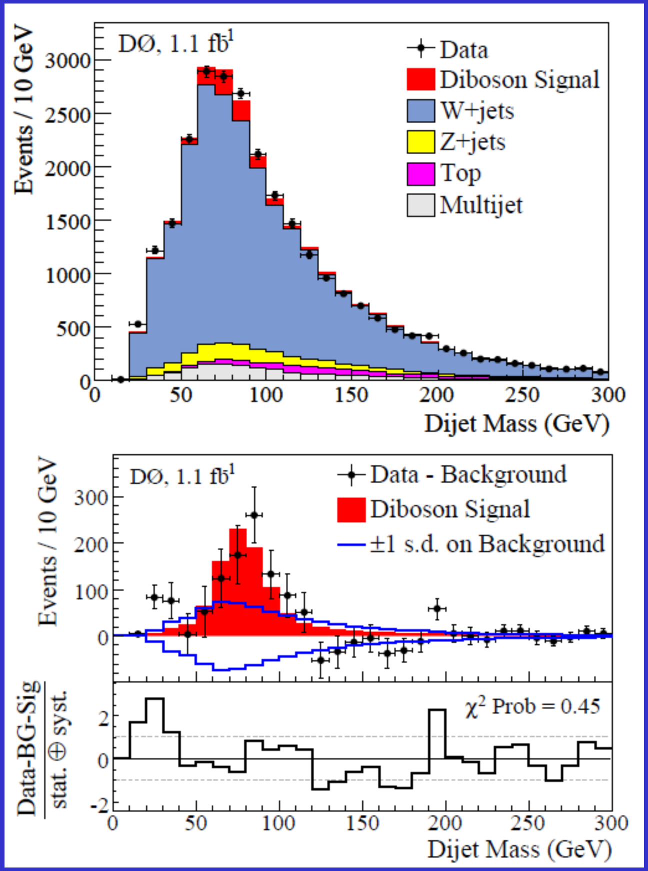


- MET>40 GeV
- Exactly 2 jets, ET>25 GeV, |η|<2.0
- Form EPD (basically a LR) from ME prob. for WW,WZ and W+jets, single top.



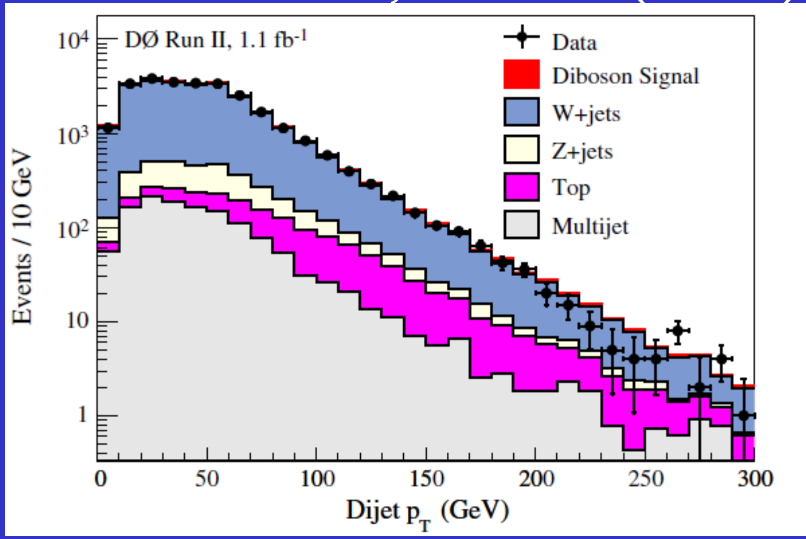


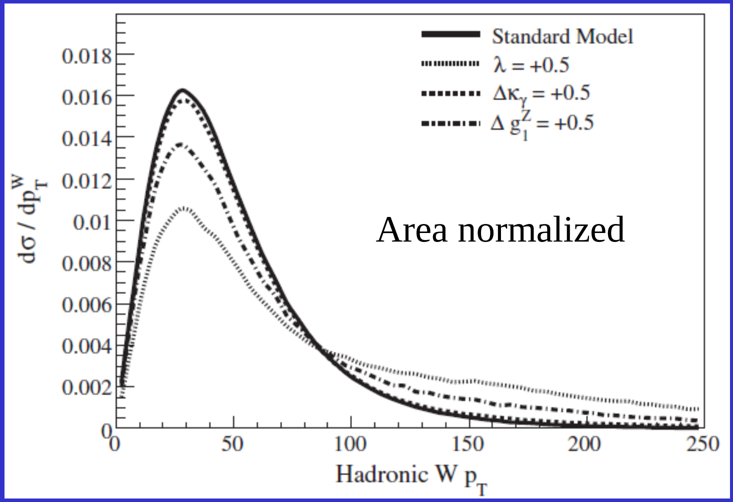
lνjj WW+WZ (D0)



Use di-jet p_T to constrain TGCs

PRD **80**, 053012 (2009)





σ(WW+WZ) (pb) =

$20.2 \pm 2.5(\text{stat}) \pm 3.6(\text{sys}) \pm 1.2(\text{lum})$

PRL **102** (2009) 161801.

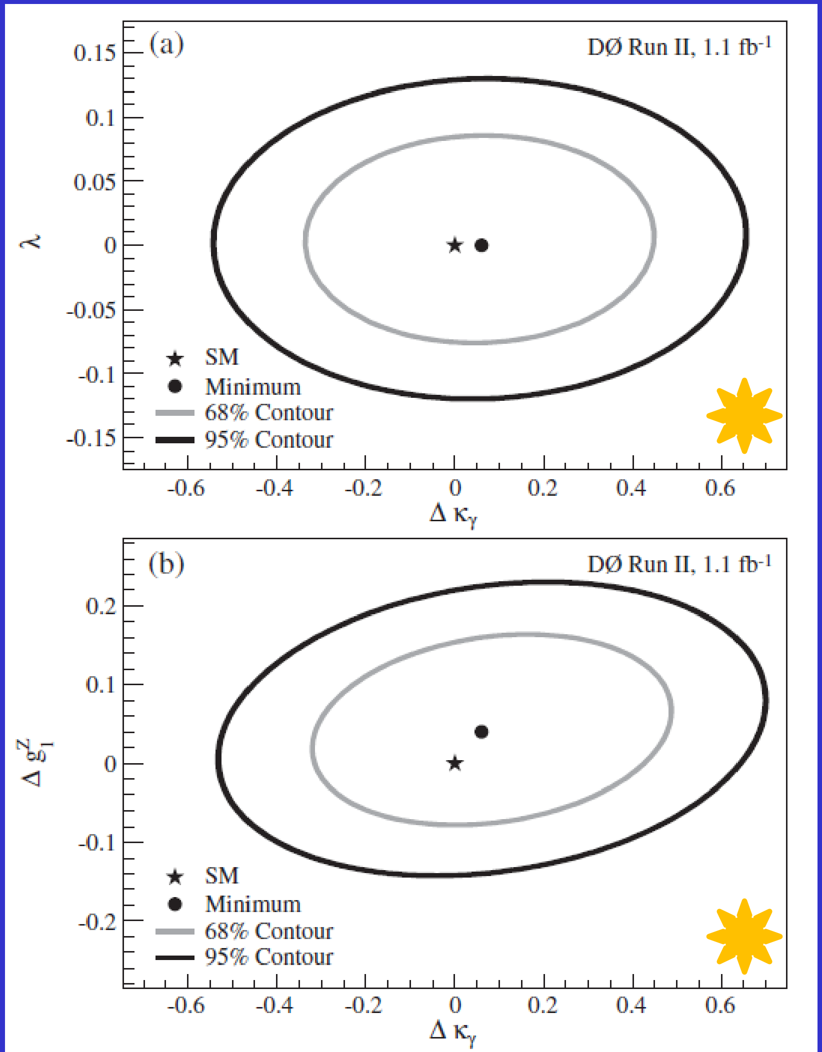
D0 lνjj (WW+WZ) TGC constraints

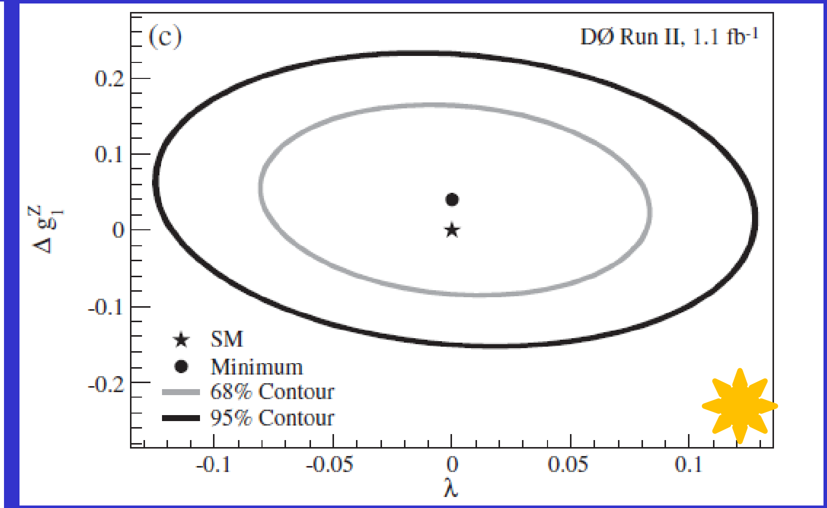
SU(2)×U(1)

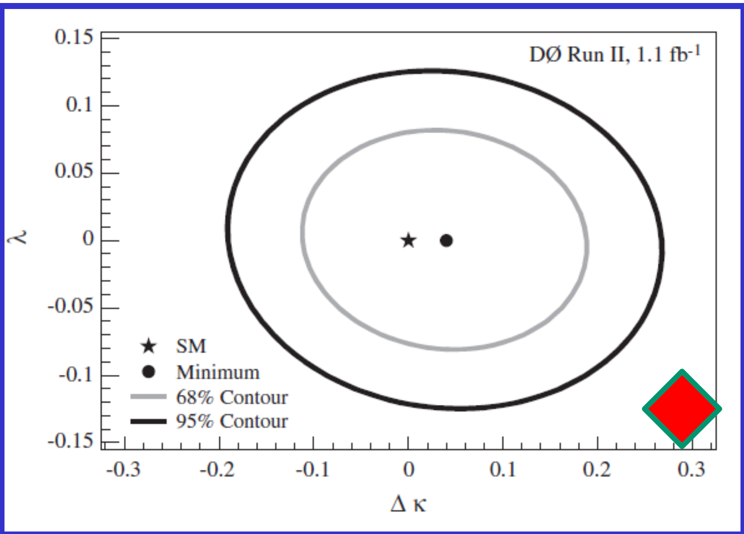
Equal couplings

Λ=2TeV

PRD **80**, 053012 (2009)







D0 Charged TGC combination

arXiv:0907:4952

Combine 1fb^{-1} results from Wγ, WW, WZ, WW+WZ. Recent WZ analysis not included.

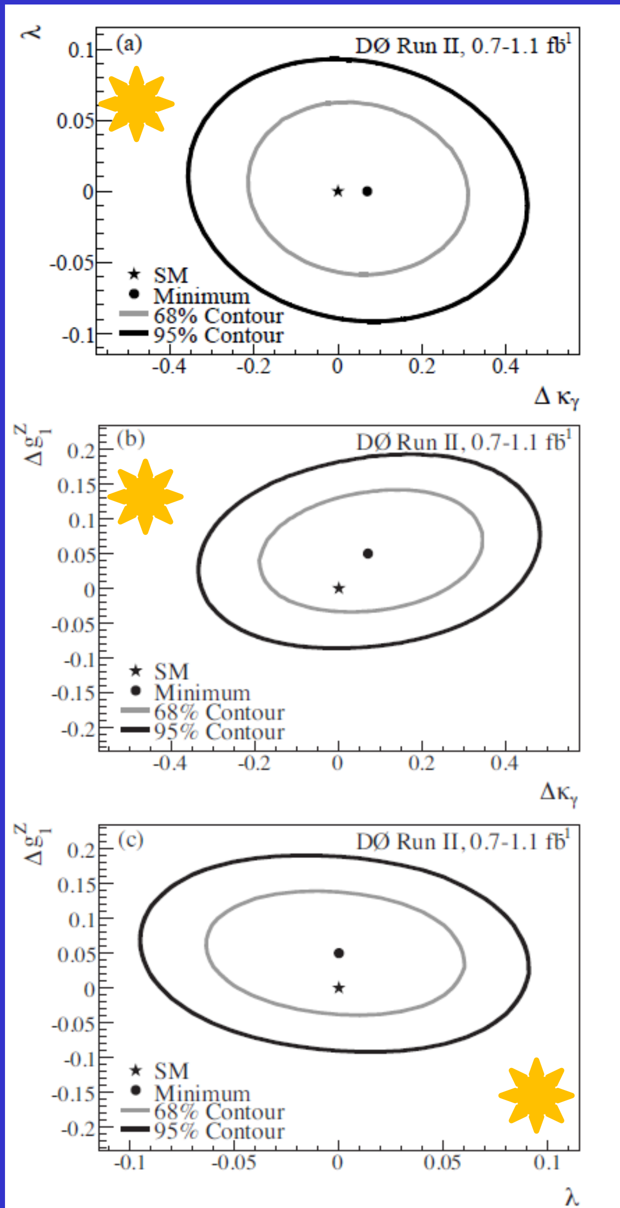
$$\mu_W = \frac{e}{2M_W}(g_1^\gamma + \kappa_\gamma + \lambda_\gamma)$$

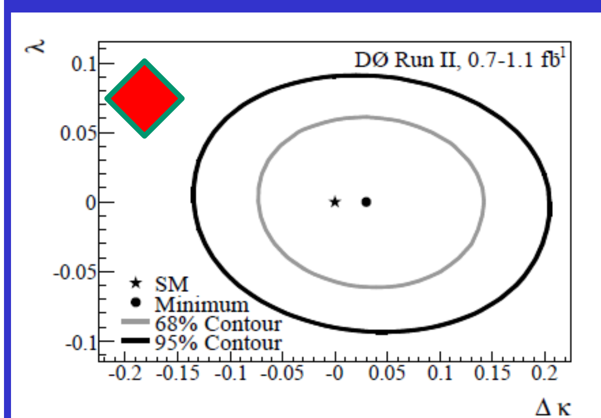
$$q_W = -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$$

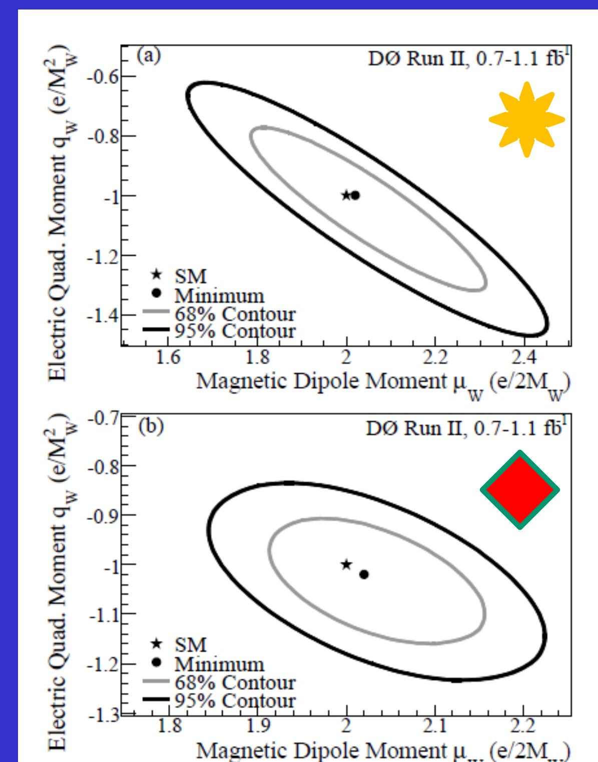
Λ=2TeV

SU(2)×U(1)

Equal couplings





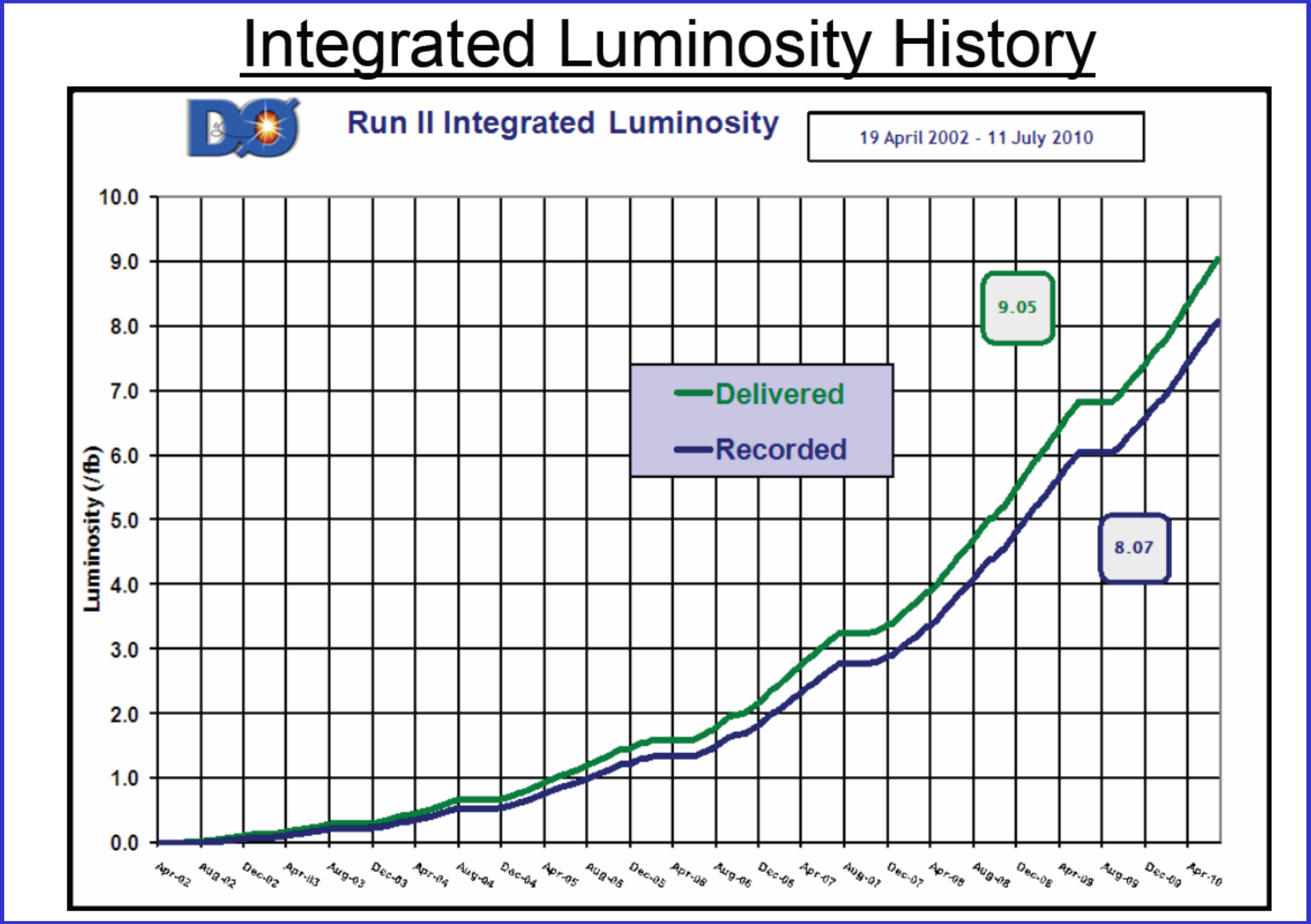


Outlook & Summary

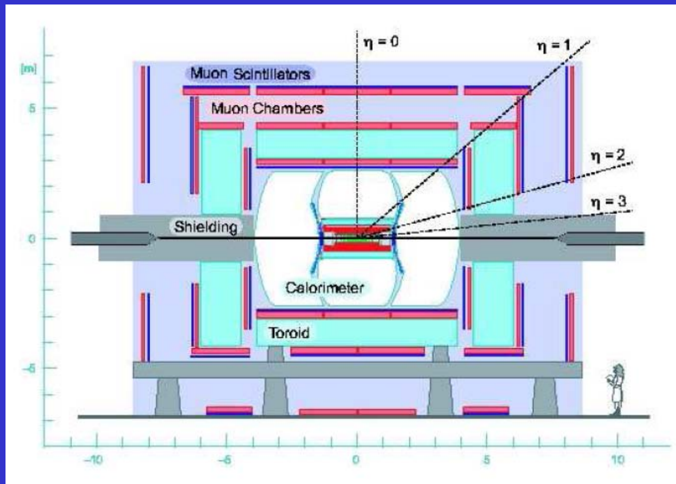
- With 8 fb^{-1} per experiment and prospects for doubling the integrated luminosity, diboson physics is very much alive and well at the Tevatron.
  - Current data-sets, once fully analyzed and exploited, promise a wealth of information on interactions at mass scales in the few-100 GeV range.
  - So far all expected di-boson processes have been observed and measurements are in accord with theoretical predictions – but often with relatively large statistical errors – so still room for surprises.
- Increased statistics, and maturing analysis techniques are leading to measurements in challenging channels.
  - Channels like WW, trileptons, jets+MET and lνjj, test electroweak interactions, provide benchmark channels relevant to the Higgs quest, and also lend themselves to Higgs searches themselves.
- In a few years, the LHC hopefully will have many more collisions to sift through and at a higher energy. For now, p-pbar at 1.96 TeV at L up to 4×10^{32} may not be that novel – but it sure continues to be fun – and scientifically compelling!

Backup Slides

Tevatron Luminosity

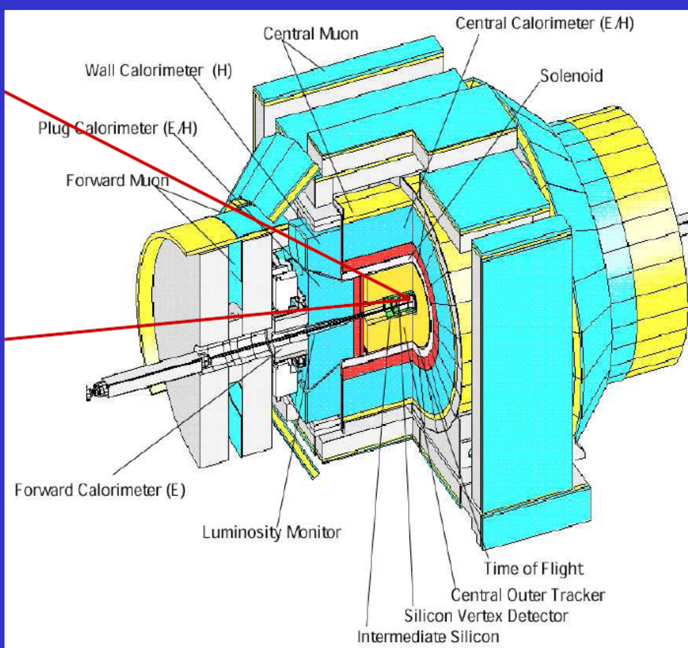


Detectors



D∅: calorimetry and μ coverage

- 2T Solenoid
- tracker to R = 52 cm
- RunIIb: Layer 0 Silicon. Upgrades to trigger



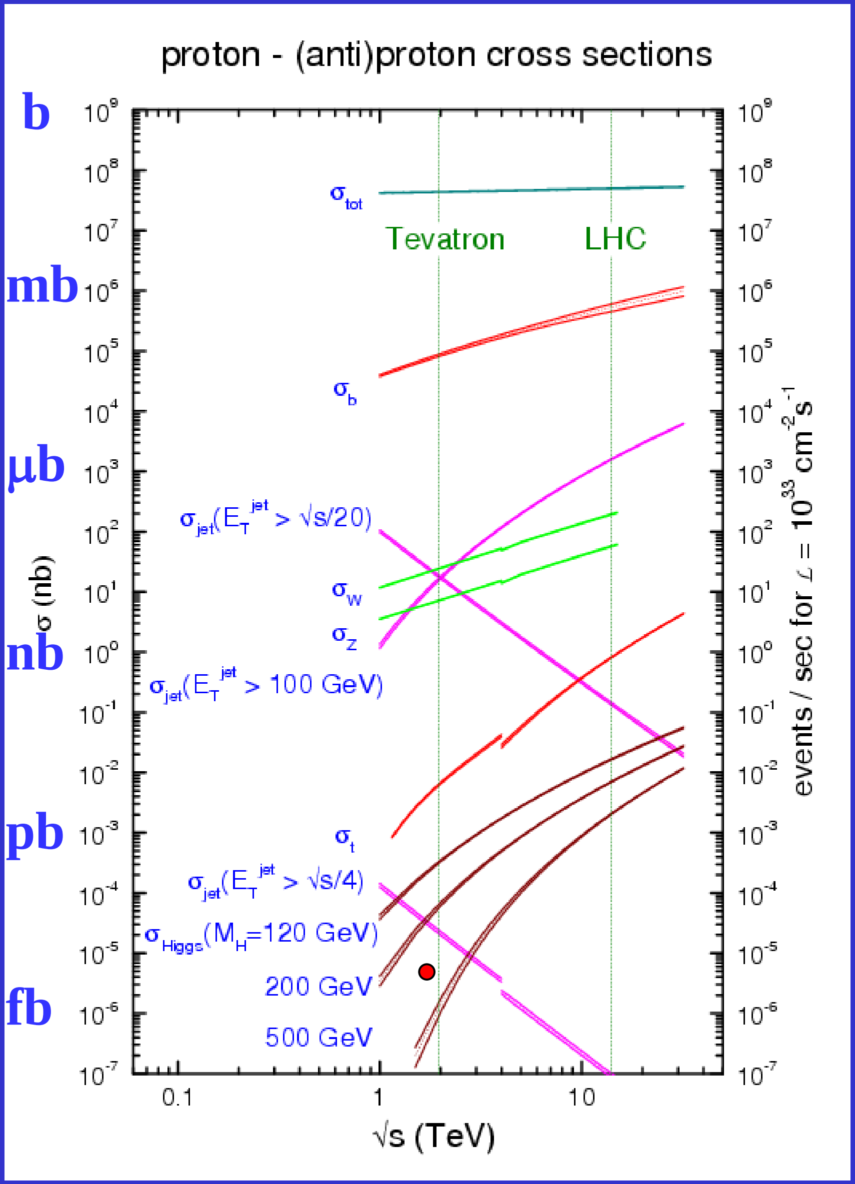
CDF: general purpose

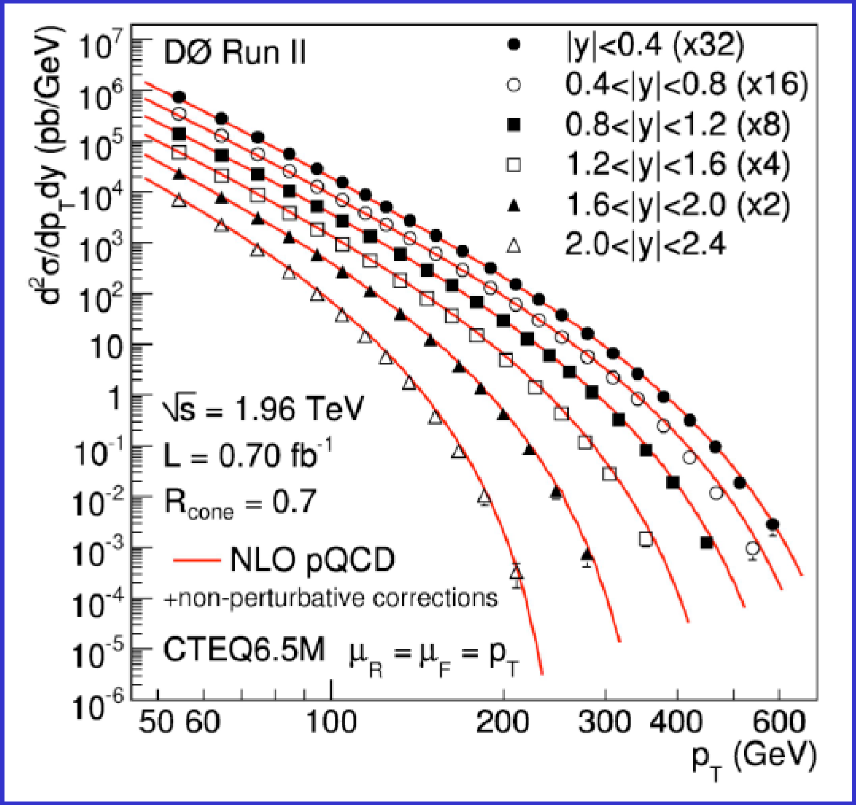
- 1.4T Solenoid
- High precision tracker (R = 1.4m)

Both detectors have Si VTX detectors optimized for b-tagging

Tevatron: 1.7 MHz BX frequency $\langle n_{int} \rangle$ on average ≈ 4 (store start ≈ 10)

Hadron Collider Physics





Physics program depends a lot on being able to reconstruct jets reliably and requiring leptons to reduce QCD bkgds. Control lepton-id and trigger efficiencies using $Z \to l\,l$ samples.

All measured cross-sections typically have 6% normalization uncertainty

γγ

- See slides from M. Martinez talk yesterday.

$ZZ \rightarrow 4l$

- Previous CDF result

Candidate	leptons	M_{ll-1}	M_{ll-2}	4 lepton invariant mass
1	$trk\mu/\mu\mu$	90.5 GeV/c^2	88.5 GeV/c^2	324.8 GeV/c^2
2	$trk\mu/\mu\mu$	91.6 GeV/c^2	94.2 GeV/c^2	169.4 GeV/c^2
3	$ee/\mu\mu$	93.0 GeV/c^2	86.4 GeV/c^2	191.9 GeV/c^2
4	$ee/\mu\mu$	93.3 GeV/c^2	79.7 GeV/c^2	229.2 GeV/c^2
5	$\mu\mu/\mu\mu$	91.7 GeV/c^2	55.1 GeV/c^2	325.0 GeV/c^2

- Yielded 5 candidates consistent with SM expectation
- ZZ resonance search in m_{llll} > 300 GeV region in progress.