Is It Standard Model Top?
Looking for Anomalous Couplings

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Outline

- Introduction
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  - Anomalous couplings to γ, Z
- t t γ Production
  - Tevatron
  - LHC
- t t Z Production
  - LHC
- Conclusions

Introduction

- **Top is turning 10 this year!!**

  (pause to reflect on passage of time, mortality, etc…)

- **We assume it's Standard Model top:**

q = +2/3 e	**spin = 1/2**
isospin = 1/2	**I_3 = 1/2**
color triplet	**$V_{tb} \cong 1$**
SM couplings to γ, Z, W, g	

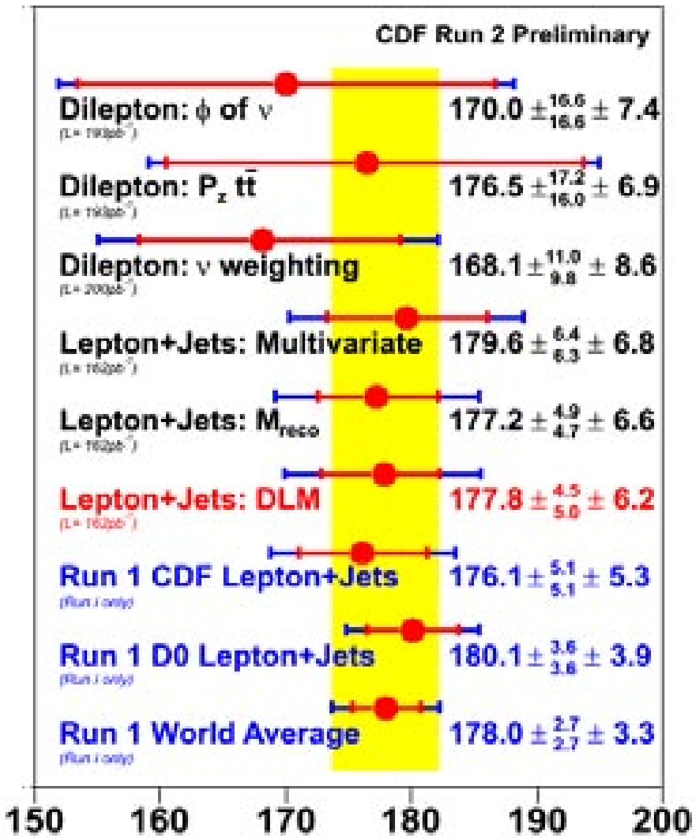
- **But what do we really know, i.e., what have we actually measured?**

Precious little!

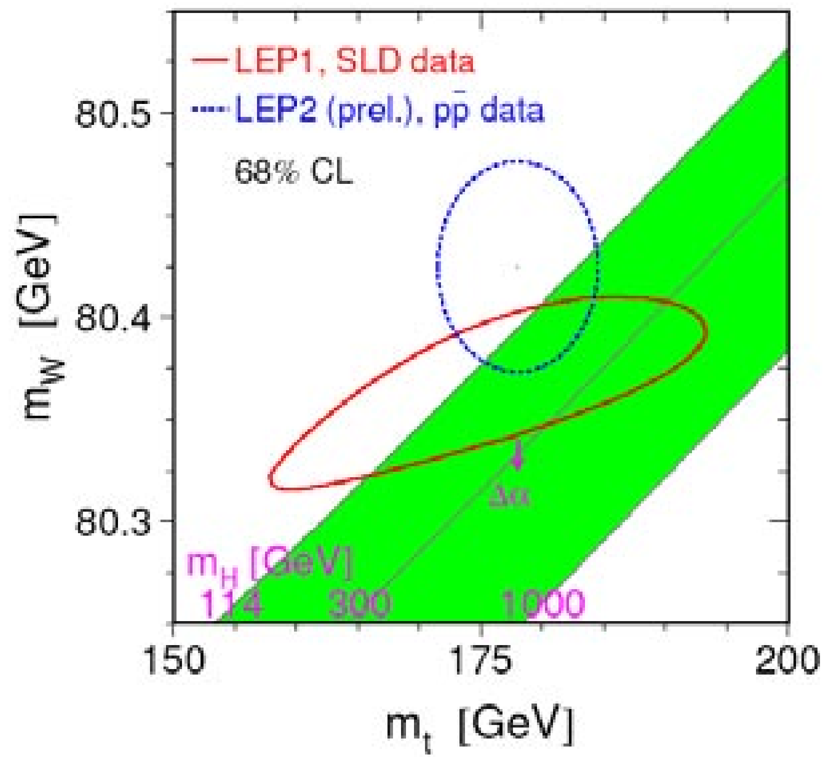
What do we know empirically about top?

- **Mass**:

m_t = 178.0 +/- 4.3 GeV

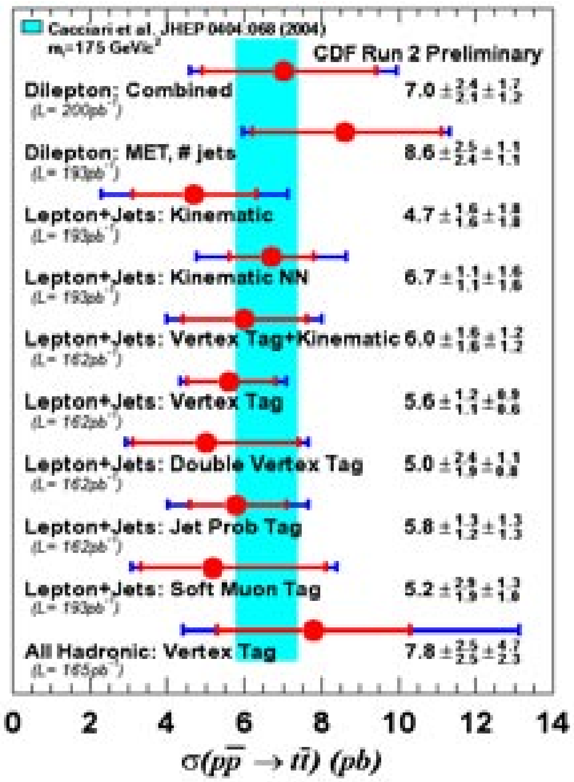


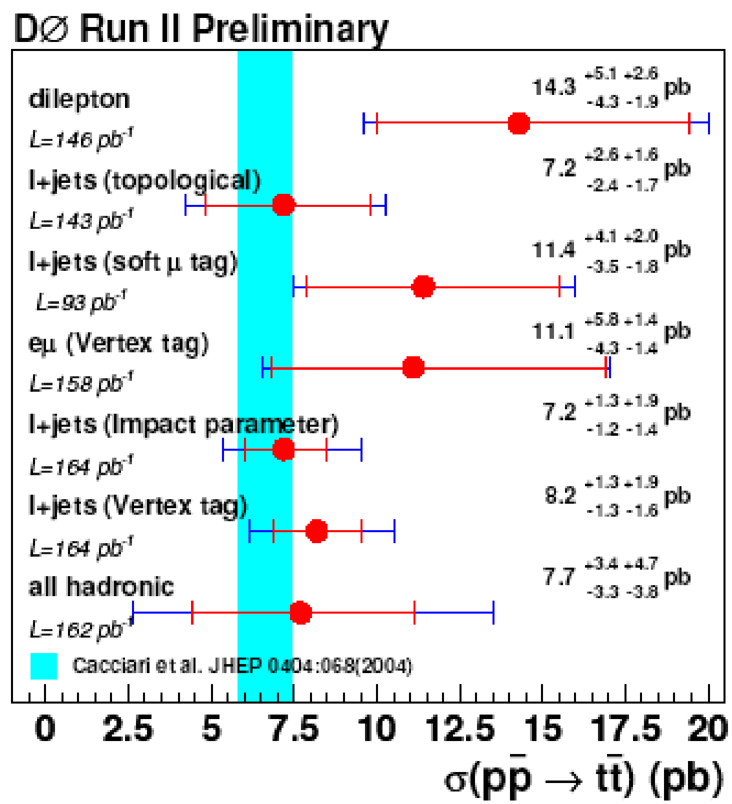
Consistent with each other and with SM Electroweak fits



What else do we know empirically about top?

- **Production cross section in p-pbar collisions:**





Consistent with SM NNLO prediction $\sigma = 6.7 + 0.7 - 0.9$ pb

What else?

Limited statistics so far, but some info on:

- **Branching ratio**
  Wb dominates
- **Nonstandard decays**
  no evidence for $H^{+/-}$ b
- **Decay kinematics**
  nothing anomalous
- **W helicity**
  consistent with V-A coupling
- **Single top**
  none seen (yet)

All consistent with SM, but not exactly precision physics.

What about top couplings to γ, Z?

- **No direct information yet.**

  Note: we could try to reconstruct the top charge from its decays, but b flavor tagging required: tough!

- **ttV (V = γ, Z) vertex function:**

  8 parameters for on-shell V

  4 for on-shell top:

$$\Gamma_\mu^{ttV}(s, q, \bar{q}) = ie\left\{\gamma_\mu \left(F_{1V}^V(s) + \gamma_5 F_{1A}^V(s)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(iF_{2V}^V(s) + \gamma_5 F_{2A}^V(s)\right)\right\}$$

m_t: top quark mass; q ($\bar{q}$): t ($\bar{t}$) four momenta

$\sigma_{\mu\nu} = (i/2)[\gamma_\mu, \gamma_\nu]$; $s = (q+\bar{q})^2$

Top couplings to γ, Z, cont.

$$\Gamma_\mu^{ttV}(s, q, \bar{q}) = ie\Big\{\gamma_\mu\left(F_{1V}^V(s) + \gamma_5 F_{1A}^V(s)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^V(s) + \gamma_5 F_{2A}^V(s)\right)\Big\}$$

- **Physics interpretation of form factors:**

  $F^V_{1V(A)}$ = vector (axial) form factor

  $F^\gamma_{2V}(0)$ ↔ anomalous magnetic moment:

  $F^\gamma_{2V}(0) = Q_t\,(g-2)$

  F^V_{2A} ↔ electric (weak) dipole moment:

  $d_t^V = -(e/2m_t)\, F^V_{2A}(0)$

  violates CP

- **SM values at tree level:**

$$F_{1V}^{\gamma,SM} = -\frac{2}{3}\,, \qquad F_{1A}^{\gamma,SM} = 0\,,$$

$$F_{1V}^{Z,SM} = -\frac{1}{4\sin\theta_W\cos\theta_W}\left(1 - \frac{8}{3}\sin^2\theta_W\right), \qquad F_{1A}^{Z,SM} = \frac{1}{4\sin\theta_W\cos\theta_W}\,,$$

$$F_{2V}^{\gamma,SM} = F_{2V}^{Z,SM} = 0\,, \qquad F_{2A}^{\gamma,SM} = F_{2A}^{Z,SM} = 0\,,$$

Constraints on form factors

- **S-matrix unitarity**

  tt->VV violates unitarity at high energies; constrain to SM values asymptotically with dipole form factor:

$$\Delta F^V_{iV,A}(k^2) = \frac{\Delta F^V_{iV,A}(0)}{(1 + k^2/\Lambda^2_{FF})^2} \quad (i = 1, 2)$$

  where $\Delta F = F - F^{SM}$; Λ = scale of new physics, and unitarity requires:

$$| F^V_{iV,A} (k^2)| \leq (c^V_i/\Lambda)^{i+1}$$

$$c_1^\gamma = 6.8\ \mathrm{TeV}, \quad c_1^Z = 5.1\ \mathrm{TeV}, \quad c_2^\gamma = 3.4\ \mathrm{TeV}, \quad c_2^Z = 2.8\ \mathrm{TeV}$$

- **Indirect constraints**

  b–>sγ weakly constrains $F^\gamma_{2V,A}$

  LEP constrains $F^Z_{1V,A}$, assuming no other new physics

Potential direct constraints

- **e^+e^- colliders: t tbar production**

  e^+e^- –> γ,Z –> t tbar, E_{cm} = 500 GeV :

  $F^V_{iV,A}$ to a few percent (Snowmass 2001)

  But: γ, Z couplings entangled (not to mention start date)

- **hadron colliders: t t V production**

  Probes couplings directly

  γ, Z couplings separable

  Potential discrimination of F_1, F_2 couplings via p_T distributions: harder spectra for dim-5 F_2 coupling

Look at ttγ production at Tevatron and LHC and ttZ production at LHC

$t\bar{t}\gamma$ Production

Signal:

- **γ radiation in top production and decay**

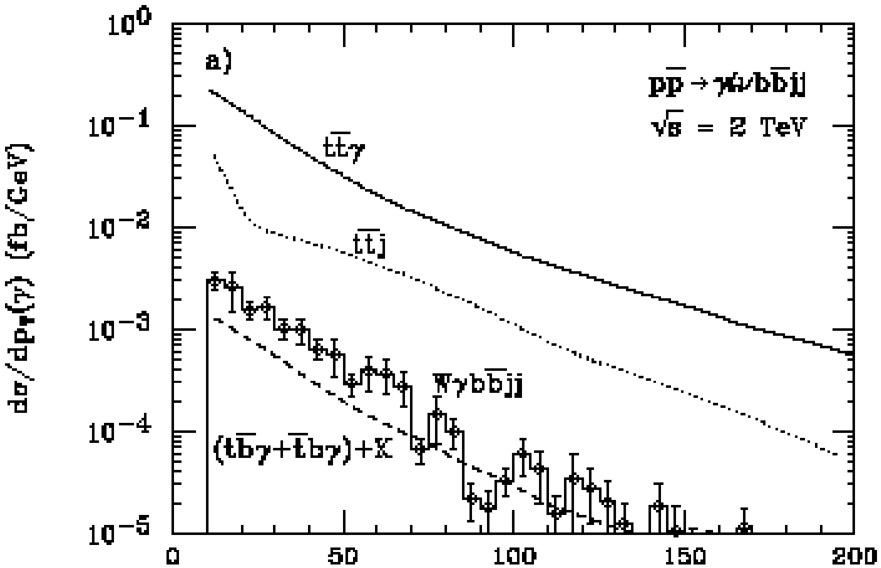
  includes radiation in decays

- **lepton + jets: $l\nu jjbb\gamma$ final state**
- **cuts:**
  - $\Delta R(b,g) > 1$ to reduce radiation off b's
  - $m(jj\gamma)$ and $m_T(e\gamma, p_T^{miss}) > 90$ GeV to suppress radiation off W decay products
  - invariant masses consistent with t decay

Backgrounds:

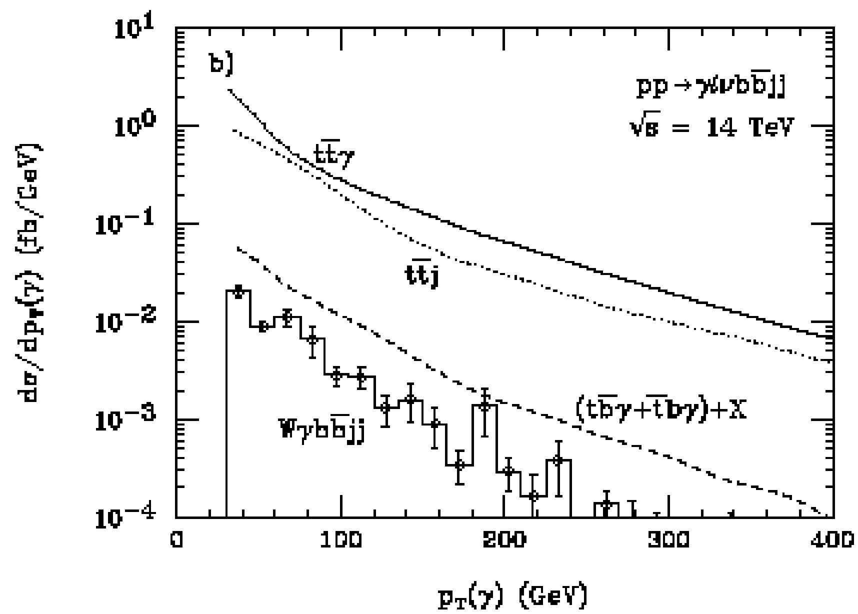
- **$Wbbjj\gamma$ (nonresonant diagrams, same final state)**
- **$tbjj\gamma$ and other singly resonant diagrams**
- **ttj where one jet fakes a photon**
  - largest background, based on exptal jet mis-i.d. probs

ttγ Production, cont.

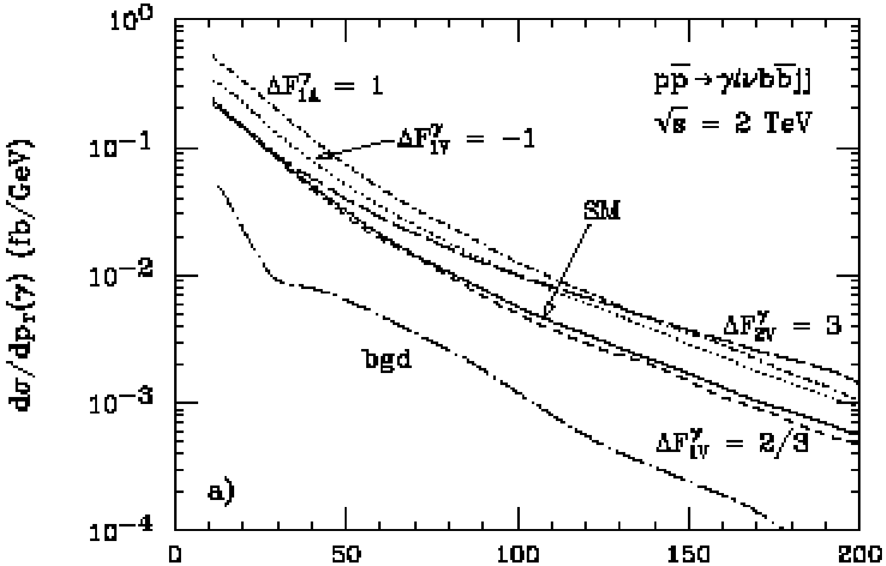


SM p_T^γ distribution, Tevatron

SM p_T^γ distribution, LHC:

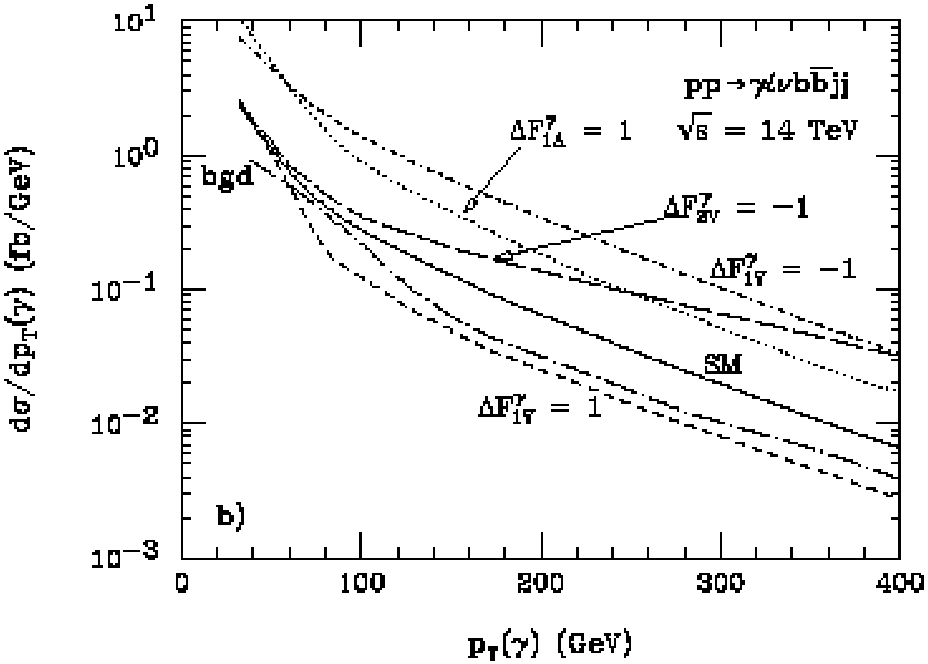


$t\bar{t}\gamma$ Production, cont.

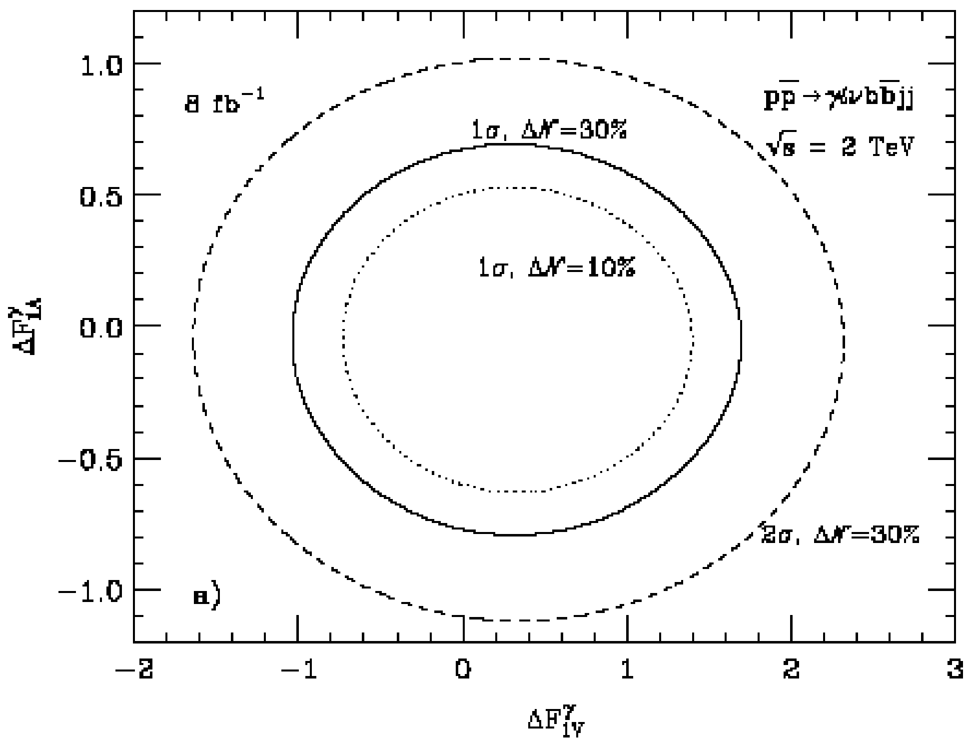


p_T^γ distributions, Tevatron nonzero ΔF

p_T^γ distributions, LHC: nonzero ΔF

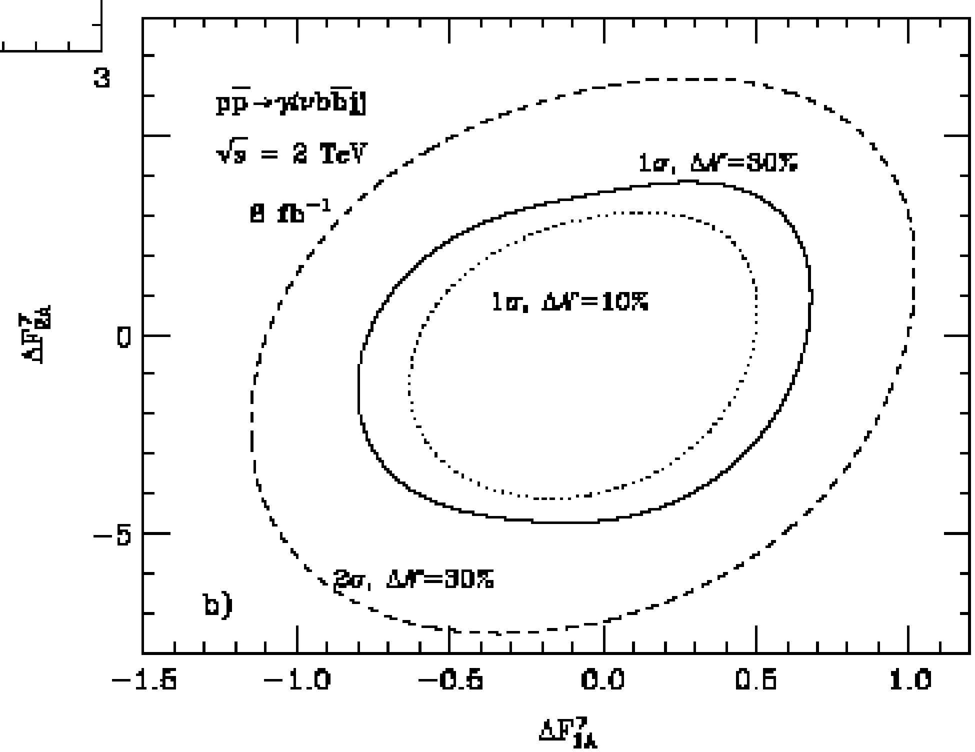


• ttγ coupling sensitivities; Tevatron:

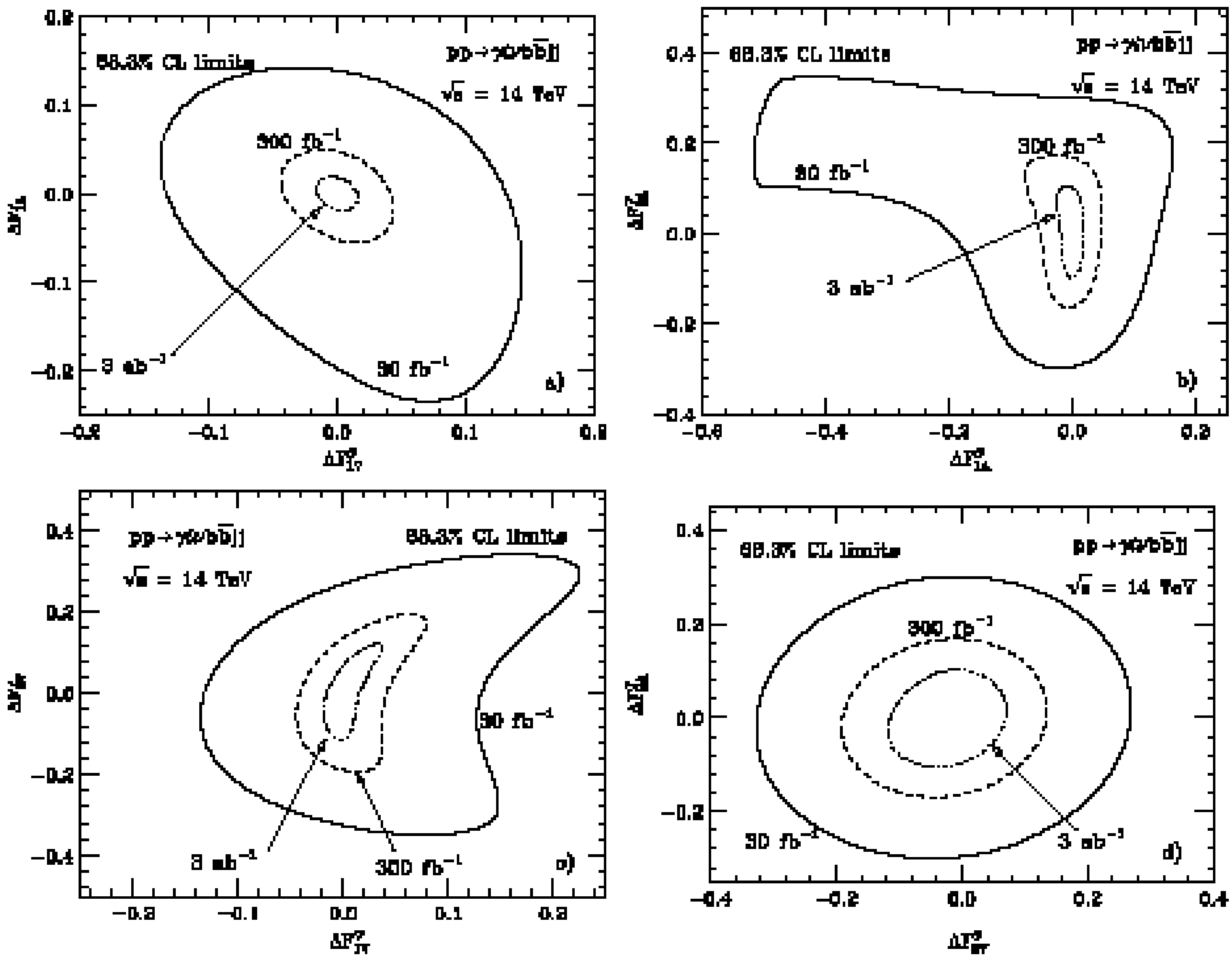


χ2 fit to p_T^{γ} distribution, assuming 30% uncertainty in SM cross section

No sensitivity to F_2 type couplings at Tevatron



• ttγ coupling sensitivities; LHC:



$t\bar{t}\gamma$ Production, cont.

- **$t\bar{t}\gamma$ coupling sensitivities; Tevatron 8 fb^{-1}:**

coupling	68.3% CL	95% CL
ΔF_{1V}^{γ}	$+1.92$ -1.20	$+2.60$ -1.88
ΔF_{1A}^{γ}	$+0.69$ -0.82	$+1.03$ -1.17
ΔF_{2V}^{γ}	$+5.16$ -5.21	$+8.49$ -8.73
ΔF_{2A}^{γ}	$+5.19$ -5.08	$+7.85$ -8.43

- **$t\bar{t}\gamma$ coupling sensitivities; LHC :**

coupling	30 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
ΔF_{1V}^{γ}	$+0.23$ -0.14	$+0.079$ -0.045	$+0.037$ -0.019
ΔF_{1A}^{γ}	$+0.17$ -0.52	$+0.051$ -0.077	$+0.018$ -0.024
ΔF_{2V}^{γ}	$+0.34$ -0.35	$+0.19$ -0.20	$+0.12$ -0.12
ΔF_{2A}^{γ}	$+0.35$ -0.36	$+0.19$ -0.21	$+0.11$ -0.14

ttZ Production

Signal:

- **LHC only; ttZ not observable at Tevatron**
- **Z radiation in top production and decay**

  almost no phase space for t –> WZb
- **leptonic Z decays: lνjjbbl^+l^- final state**

  also all-hadronic top decays
- **cuts:**

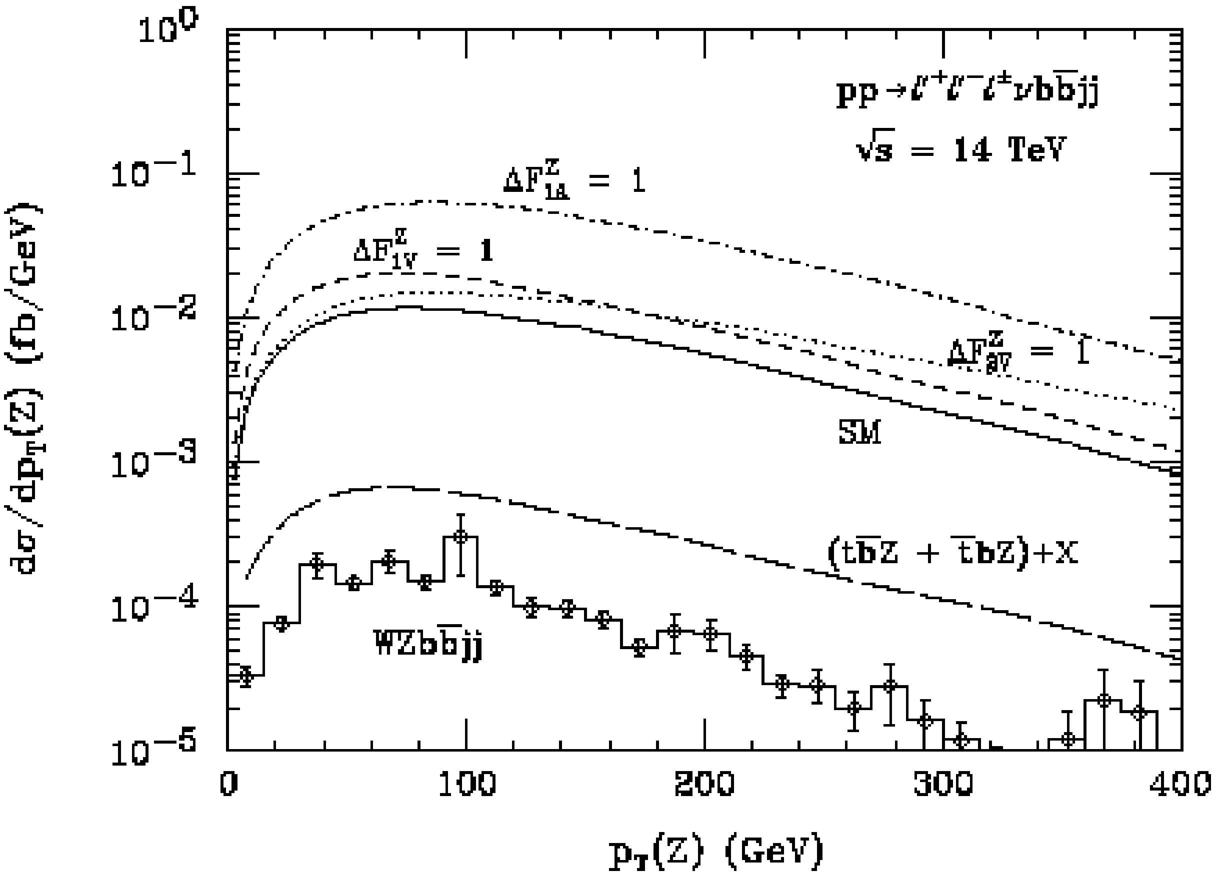
  invariant mass and m_T cuts for l^+l^- consistent with Z decay and blν, bjj consistent with top

Backgrounds:

- **WZbbjj (nonresonant diagrams, same final state)**
- **tbjjZ and other singly resonant diagrams**

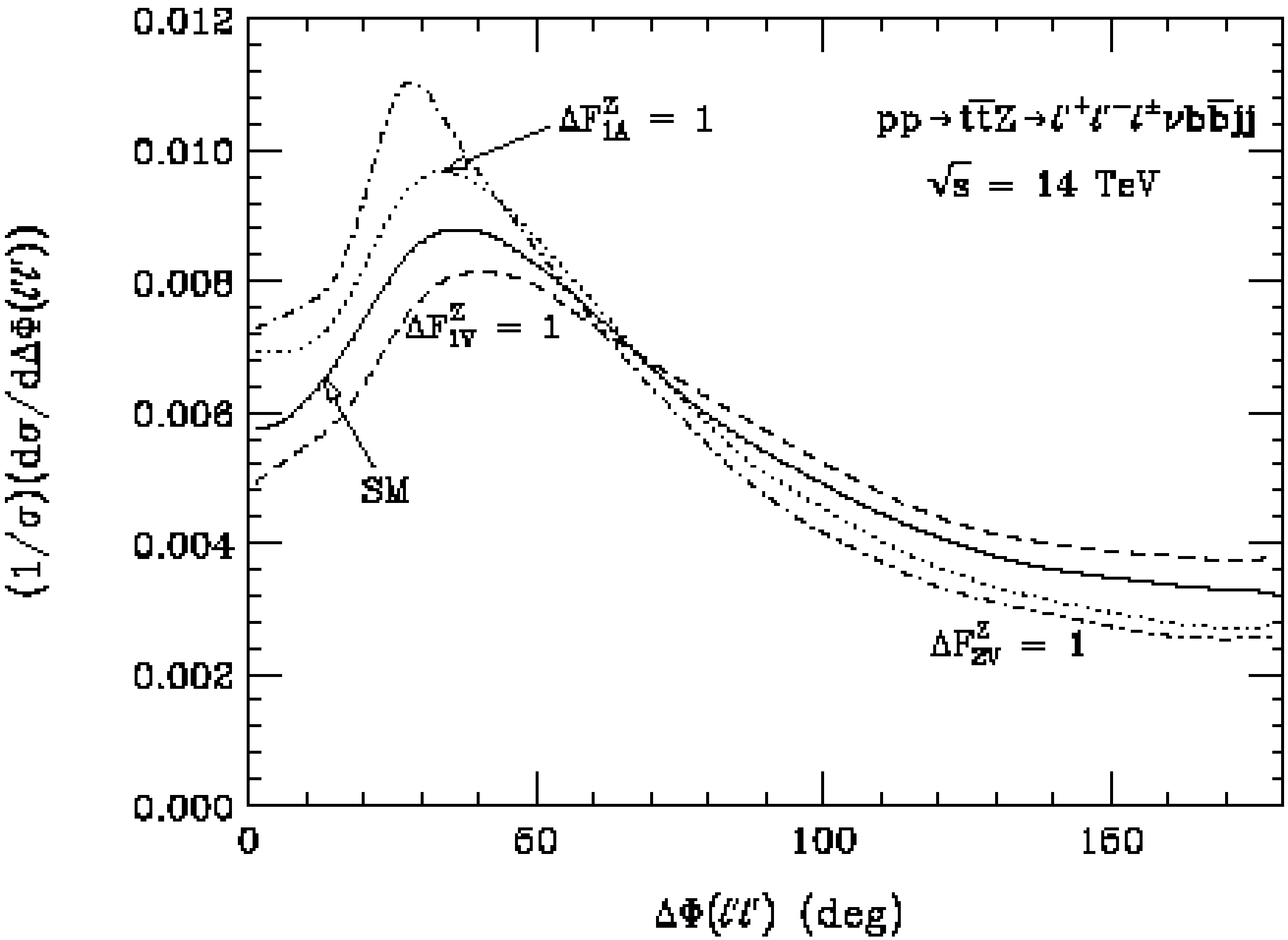
ttZ Production, cont.

p_T^Z distribution, LHC:



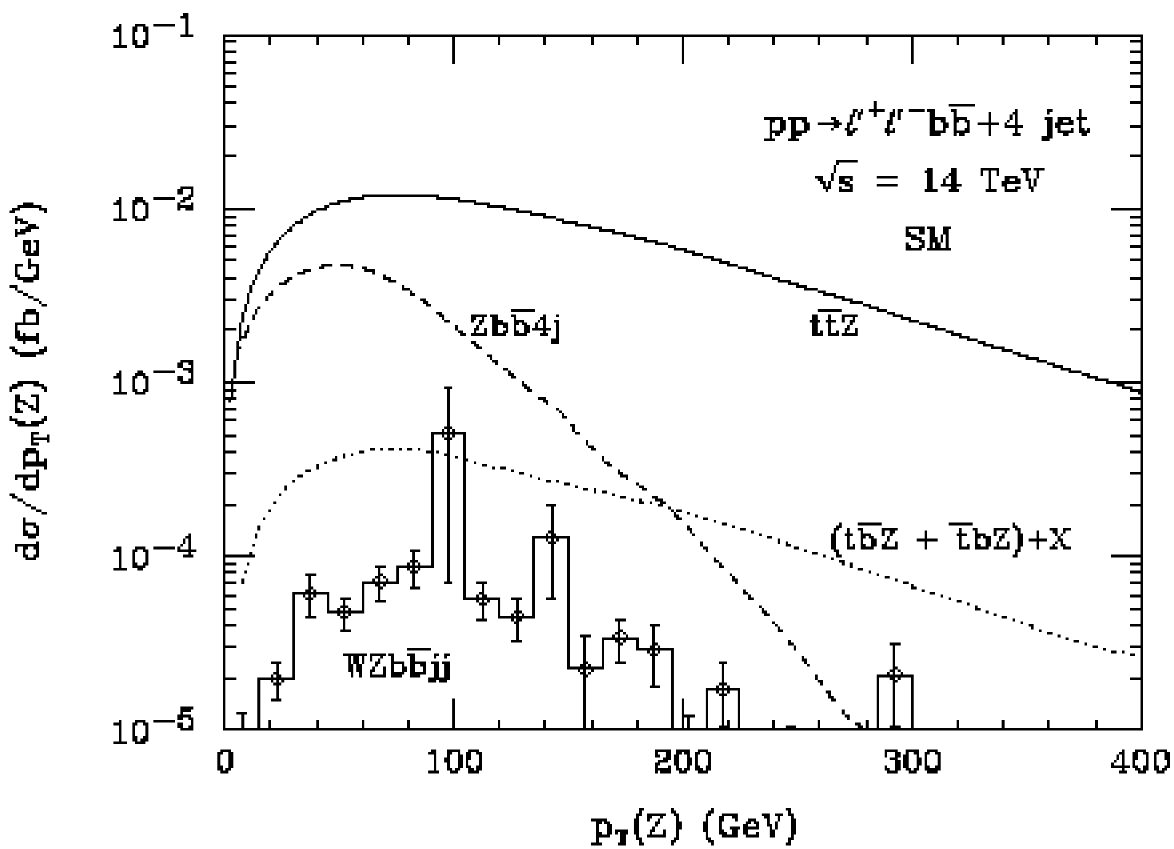
ttZ Production, cont.

Z decay lepton opening angle at LHC:



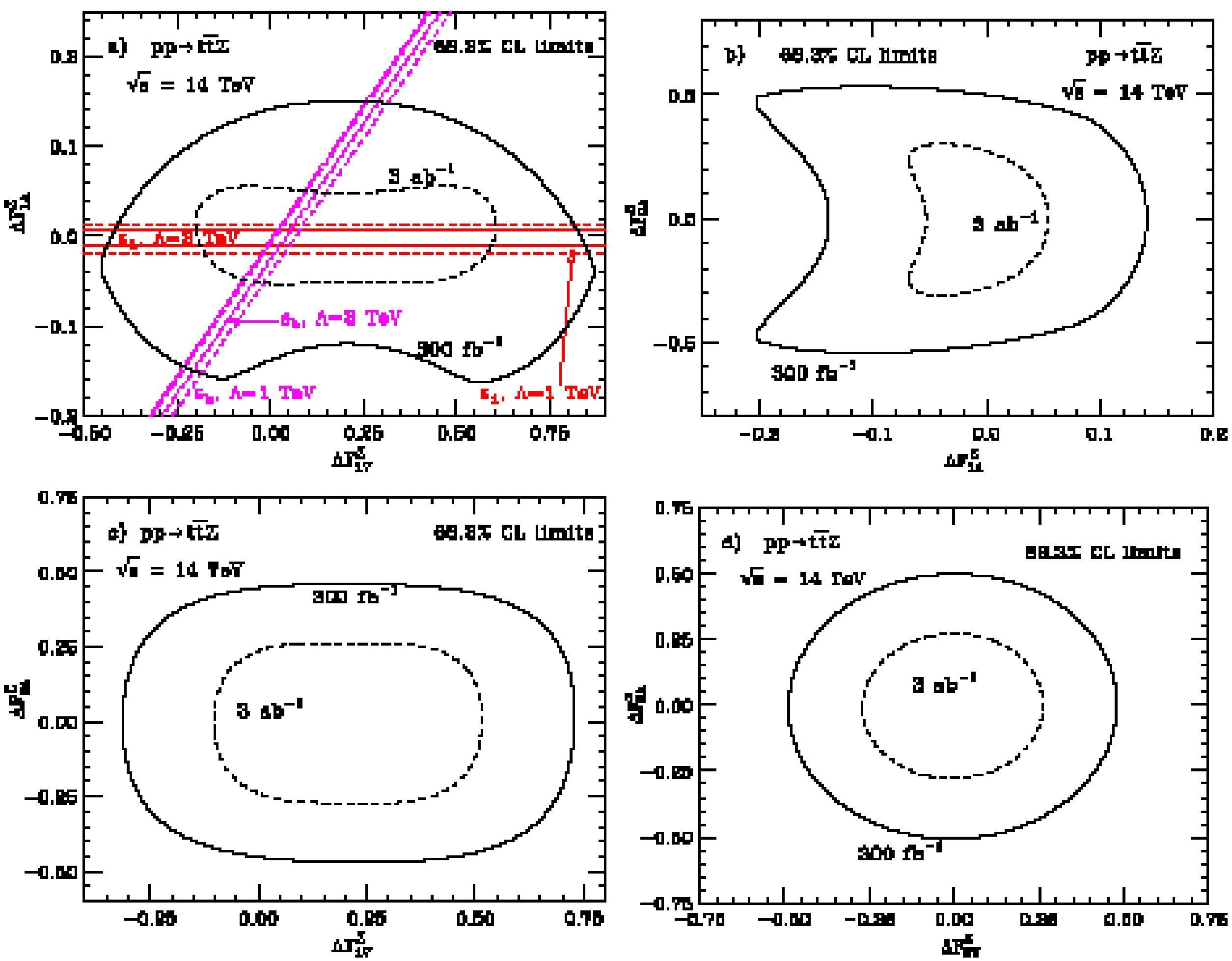
ttZ Production, cont

All-hadronic top decays;
includes additional Zbb4j bckgrnd



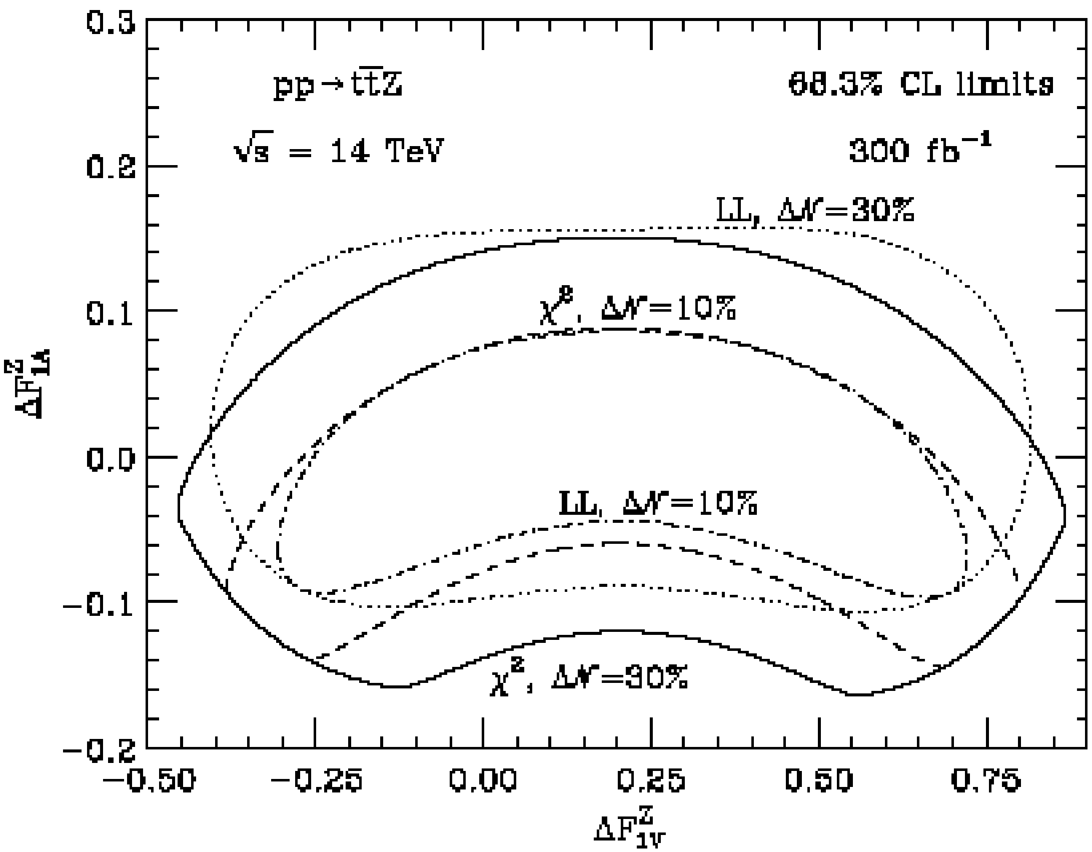
- **ttZ coupling sensitivities; LHC:**

χ2 fit to p_T^{γ}, Φ_{ll} distributions, assuming 30% uncertainty in SM cross section



ttZ Production

ttZ coupling sensitivities; LHC: effect of different statistical methods



ttZ Production

ttZ coupling sensitivities; LHC:

coupling	300 fb^{-1}	3000 fb^{-1}
ΔF_{1V}^Z	$^{+0.87}_{-0.46}$	$^{+0.62}_{-0.22}$
ΔF_{1A}^Z	$^{+0.15}_{-0.20}$	$^{+0.056}_{-0.074}$
ΔF_{2V}^Z	$^{+0.52}_{-0.52}$	$^{+0.30}_{-0.29}$
ΔF_{2A}^Z	$^{+0.54}_{-0.53}$	$^{+0.30}_{-0.31}$

ttV Production: Comparison to e^+e^-

coupling	LHC, 300 fb^{-1}	e^+e^- [19]
$\Delta\widetilde{F}_{1V}^{\gamma}$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, 200 fb^{-1}
$\Delta\widetilde{F}_{1A}^{\gamma}$	$^{+0.051}_{-0.048}$	$^{+0.011}_{-0.011}$, 100 fb^{-1}
$\Delta\widetilde{F}_{2V}^{\gamma}$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, 200 fb^{-1}
$\Delta\widetilde{F}_{2A}^{\gamma}$	$^{+0.16}_{-0.17}$	$^{+0.014}_{-0.014}$, 100 fb^{-1}
$\Delta\widetilde{F}_{1V}^{Z}$	$^{+0.43}_{-0.83}$	$^{+0.012}_{-0.012}$, 200 fb^{-1}
$\Delta\widetilde{F}_{1A}^{Z}$	$^{+0.14}_{-0.14}$	$^{+0.013}_{-0.013}$, 100 fb^{-1}
$\Delta\widetilde{F}_{2V}^{Z}$	$^{+0.38}_{-0.50}$	$^{+0.009}_{-0.009}$, 200 fb^{-1}
$\Delta\widetilde{F}_{2A}^{Z}$	$^{+0.50}_{-0.51}$	$^{+0.052}_{-0.052}$, 100 fb^{-1}

Conclusions

- **Directly measured information about top is limited; we know virtually nothing about its couplings to g, Z**

- **ttγ vector and axial couplings at Tevatron:**

  Good news: first test possible

  Bad news: needs 8 fb^{-1}

- **ttγ vector and axial couplings at LHC**

  First precision measurement (3-10%) possible

- **ttZ couplings at LHC**

  10-30% measurements possible

  (But stay tuned for Z->$\nu\nu$ case)