Probing Electroweak Top Quark Couplings at Hadron and Lepton Colliders

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1 – Introduction

- Although we have discovered the top quark almost 10 years ago, we know little about its couplings to photons and Z bosons
- The most general ttV ($V = \gamma$, Z) vertex function (for on-shell V) can be written in terms of 8 form factors
  - ☞ for on-shell top quarks 4 form factors remain:

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

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

$\sigma_{\mu\nu} = (i/2)[\gamma_\mu, \gamma_\nu]$

- physics interpretation of form factors:
  - F_{1V}^V (F_{1A}^V) are the vector (axial vector) form factors
  - F_{2V}^γ is related to the anomalous magnetic moment: $F_{2V}^\gamma(0) = Q_t\,(g-2)/2$, $Q_t = 2/3$
  - F_{2A}^V violates CP and is related to electric (weak) dipole moment: $d_t^V = (e/2m_t) F_{2A}^V(0)$
- concentrate on these 4 form factors here
- assuming a dipole form factor, S-matrix unitarity restricts the low energy form factors to

$$\left| F_{iV,A}^V(0) \right| \leq \left(c_i^V / \Lambda \right)^{i+1}$$

where Λ =scale of new physics, and

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

- $b \to s\gamma$ weakly constrains $F_{2V,A}^\gamma$: $-0.2 < F_{2V}^\gamma < 0.5$, $|F_{2A}^\gamma| < 4.5$

- LEP data indirectly constrain $F^Z_{1V,A}$ but not $F^\gamma_{1V,A}$ (Larios et al.). LEP data also constrain a linear combination of F^Z_{2V} and F^γ_{2V} (Eboli et al.).

  Disadvantages:

  ☞ constraints are (mildly) cutoff dependent

  ☞ constraints assume no other new physics is present

- A linear e^+e^- collider promises to determine $F^V_{iV,A}$ with a precision of a few percent in $e^+e^- \to t\bar{t}$ for $\sqrt{s} = 500$ GeV and 200 fb^{-1} (Snowmass 2001)

  disadvantage: difficult to disentangle $tt\gamma$ and ttZ couplings

  deficiency: only one coupling at a time is varied in existing studies: how do correlations between couplings affect the limits?

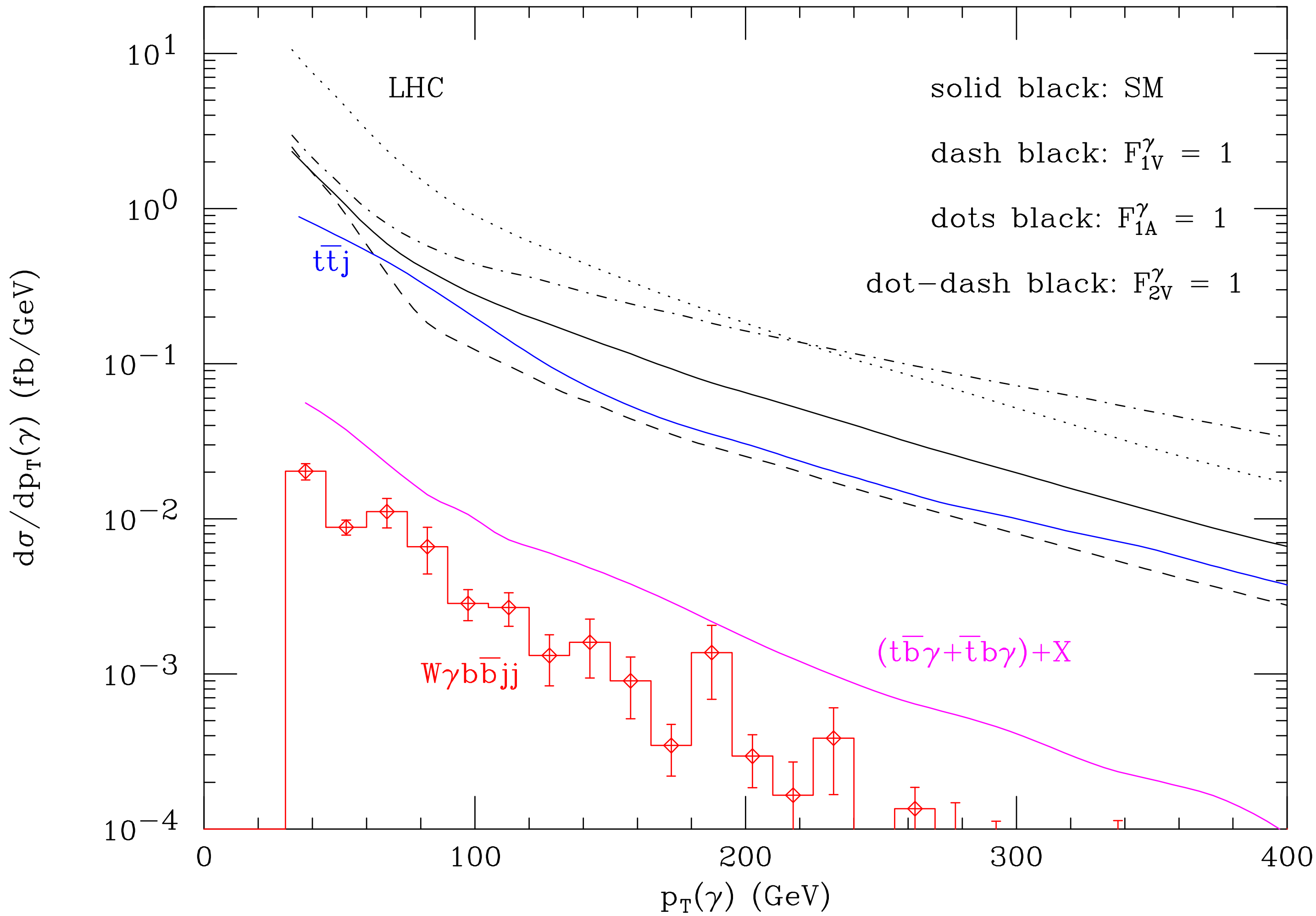
- is it possible to determine the $t\bar{t}V$ couplings at the Tevatron and/or the LHC?
  - ☞ consider $t\bar{t}\gamma$ and $t\bar{t}Z$ production
  - ☞ can separate $tt\gamma$ and ttZ couplings
  - ☞ $F^V_{1V,A}$ ($F^V_{2V,A}$) are dimension 4 (5) couplings
    → p_T distribution of photon/Z is harder for $F^V_{2V,A}$
    → and may help to discriminate F_1 and F_2 type couplings

2 – $t\bar{t}\gamma$ Production

- concentrate on $\ell^{\pm}\nu jjb\bar{b}\gamma$ final state and require 2 tagged b's
- signal:
  - ☞ include photon radiation off b's, W's and W decay products
  - ☞ require $\Delta R(b,\gamma) > 1$ to suppress radiation off b's
  - ☞ require $m(jj\gamma) > 90$ GeV and $(e\gamma)$ $\not{p}_T$ cluster transverse mass $m_T(e\gamma;\not{p}_T) > 90$ GeV to suppress radiation off W decay products
  - ☞ impose invariant mass and m_T cuts on bjj, $bjj\gamma$, $\ell\nu b\gamma$ and $\ell\nu b$ requiring them to be consistent with coming from top decay
  - ☞ photon transverse momenta of interest are < 500 GeV
    → form factor effects can be neglected if $\Lambda \geq 1$ TeV is assumed
  - ☞ gg fusion ($q\bar{q}$ annihilation) dominates at LHC (Tevatron)

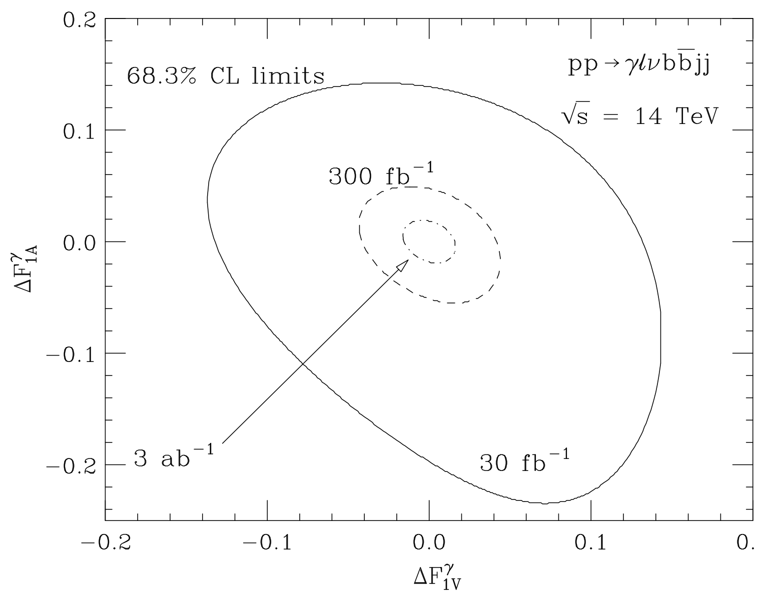
- backgrounds:
  - ☞ $W^{\pm}\gamma b\bar{b}jj$ production (non-resonant diagrams contributing to final state)
  - ☞ $t\bar{b}\gamma jj$, $\bar{t}b\gamma jj$, $t\bar{b}\gamma\ell^-\bar{\nu}$ and $\bar{t}b\gamma\ell^+\nu$ production (single resonant diagrams contributing to final state)
  - ☞ $t\bar{t}j$ production, where one jet fakes a photon
    → largest background if jet misidentification probabilities of CDF, DØ, ATLAS or CMS are used

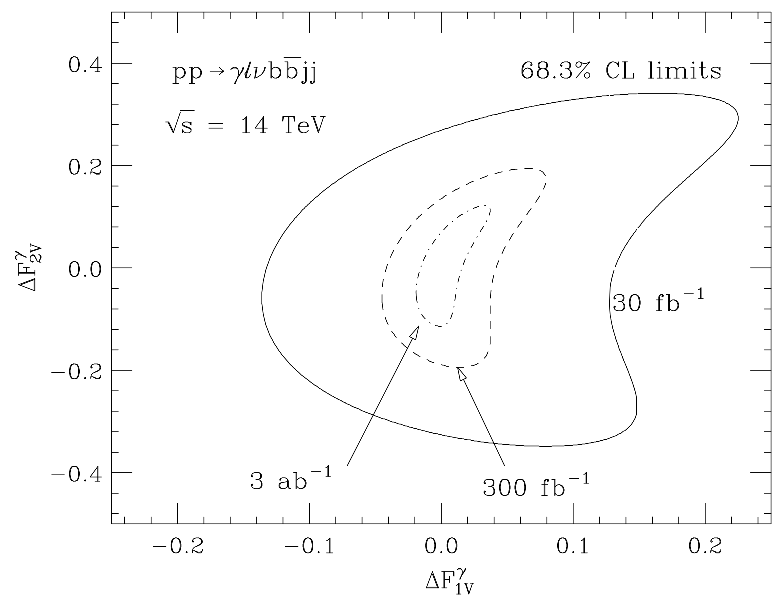
☞ $p_T(\gamma)$ distribution at LHC



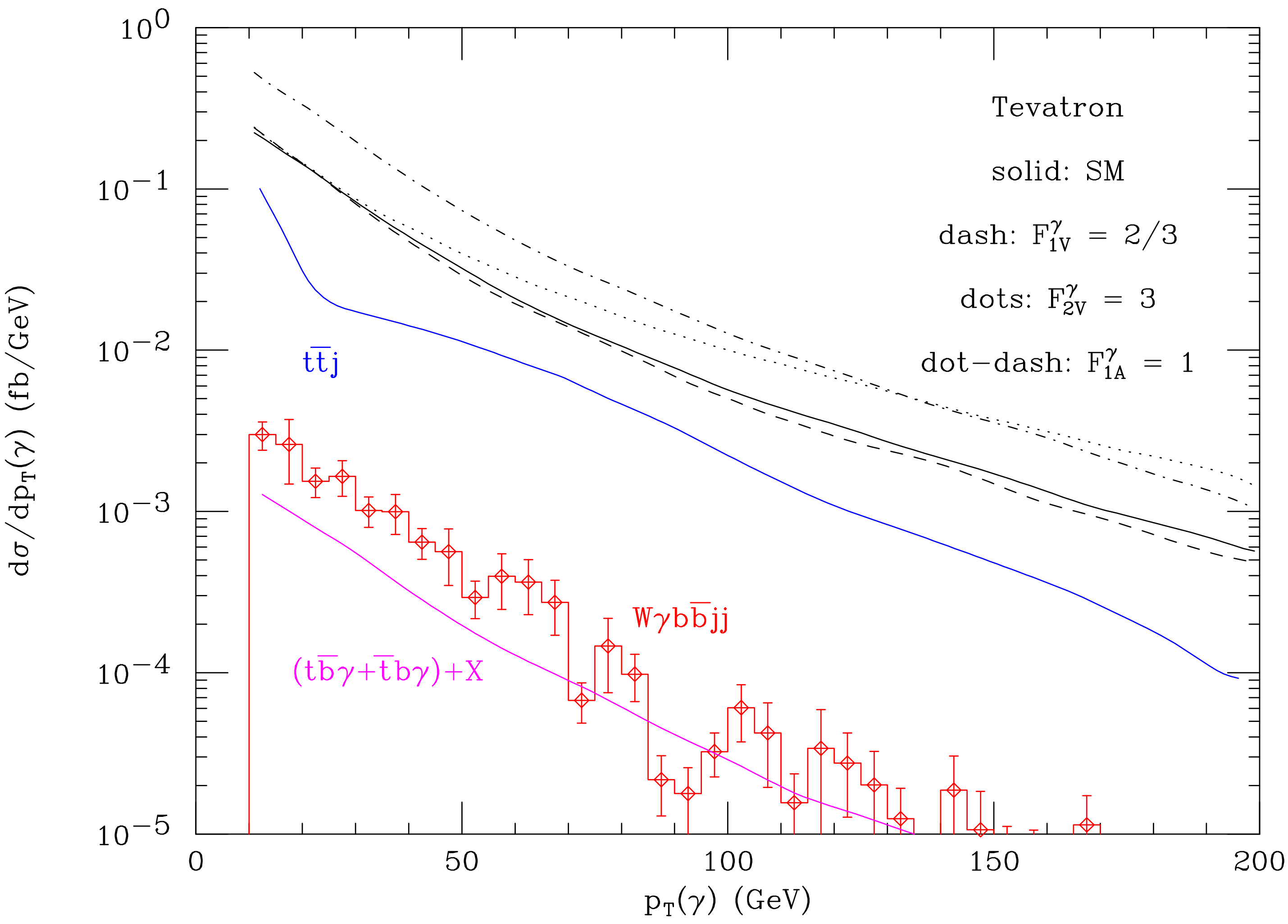
☞ background manageable

- determine sensitivity limits from χ^2 fit to $p_T(\gamma)$ distribution, assuming a 30% normalization uncertainty of the SM cross section
  - ☞ can constrain $tt\gamma$ vector and axial vector couplings to O(10%) with 30 fb^{-1}, and to a few % with 300 fb^{-1}
  - ☞ can constrain F_2^γ type couplings to O(30%) with 30 fb^{-1}, and to O(15%) with 300 fb^{-1}

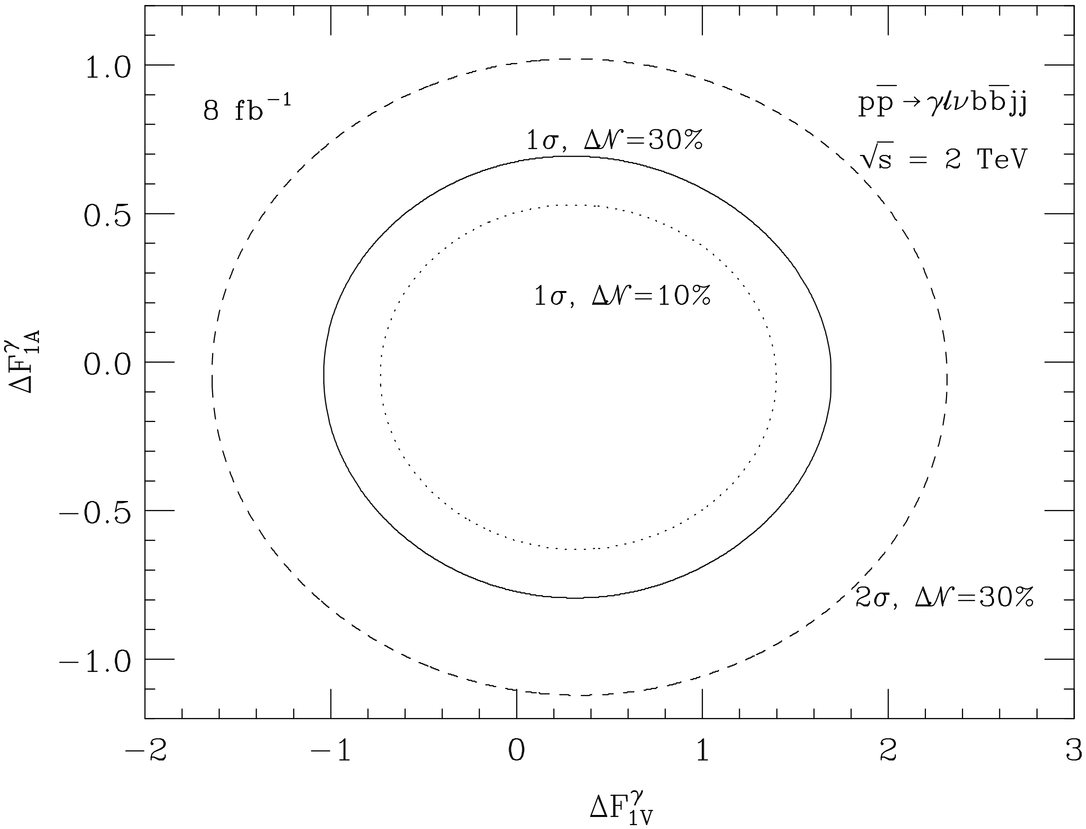




- Tevatron: reduced sensitivity due to “bgd.” from initial state radiation ($q\bar{q}$ annihilation dominates)



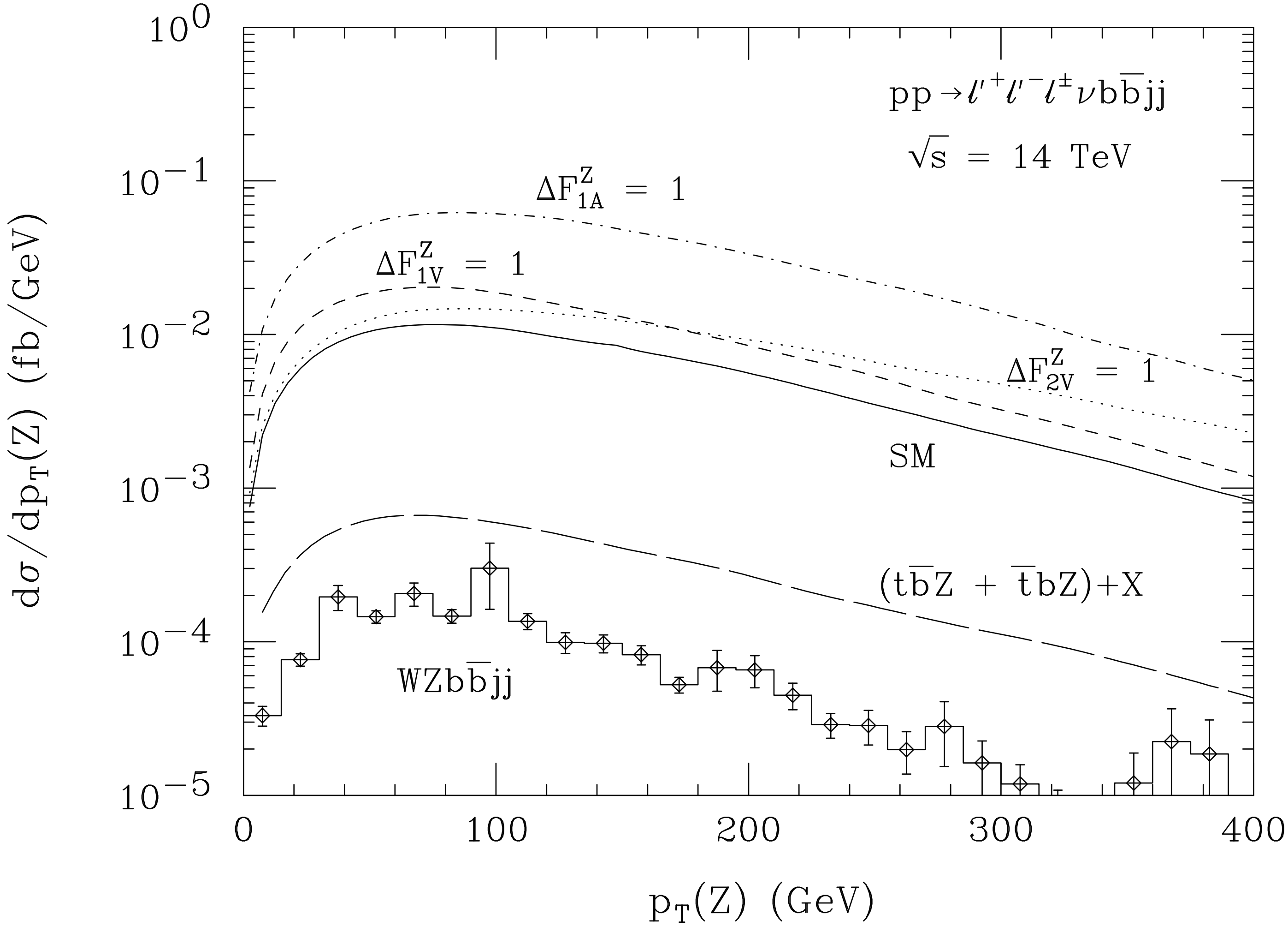
- As a result:
  - no sensitivity to F_2 type couplings
  - for ≥ 8 fb^{-1} can perform a first rough test of $tt\gamma$ vector and axial vector couplings



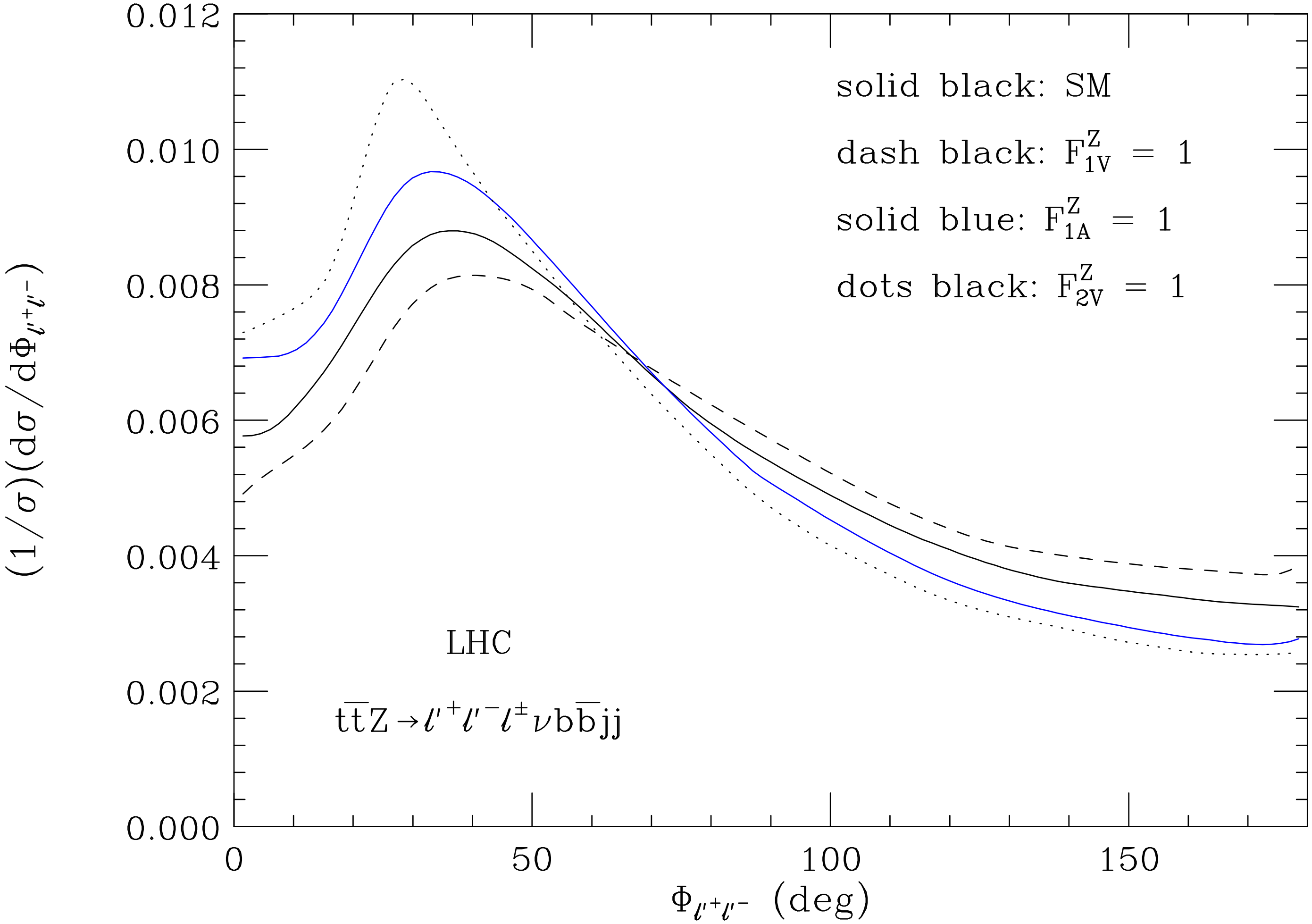
3 – $t\bar{t}Z$ Production

- first consider events with leptonic Z decays
  ☞ $t\bar{t}Z$ production not observable at Tevatron
- consider semi-leptonic and all-hadronic $t\bar{t}$ decays
- again, require 2 b-tags
- signal: include Z emission from top decay products
- (almost) no phase space for $t \to WZb$ decays: impose invariant mass and m_T cuts such that $\ell'^+\ell'^-$ pair is consistent with Z, and $\ell\nu b$ and jjb are consistent with top
- $\ell'^+\ell'^-\ell^\pm\nu b\bar{b}jj$ final state:
  ☞ backgrounds: $W^\pm Zb\bar{b}jj$, $t\bar{b}Zjj$, $\bar{t}bZjj$, $t\bar{b}Z\ell^-\bar{\nu}$ and $\bar{t}bZ\ell^+\nu$ production

☞ $p_T(Z)$ distribution: effect of anomalous couplings similar to $t\bar{t}\gamma$ case

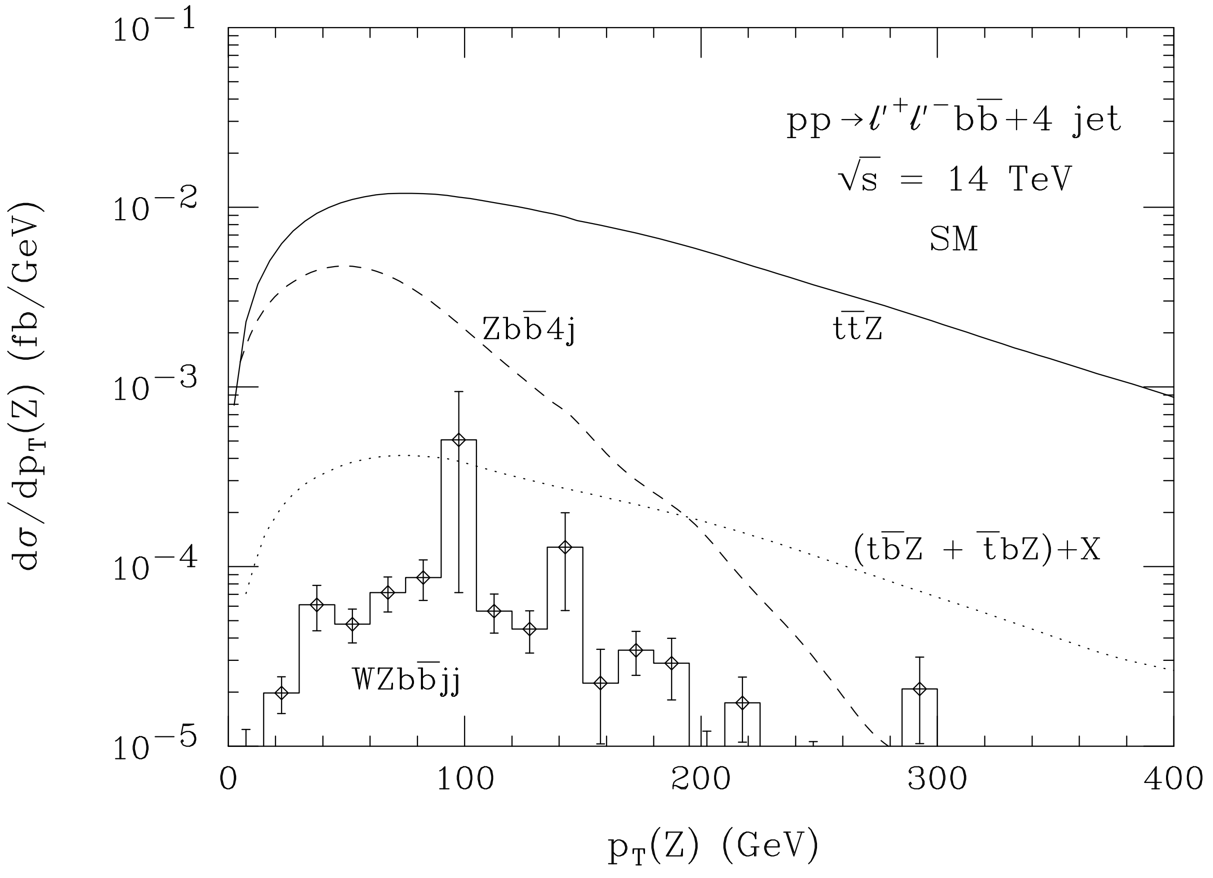


☞ distribution of opening angle of Z decay leptons also sensitive to F_1 and F_2

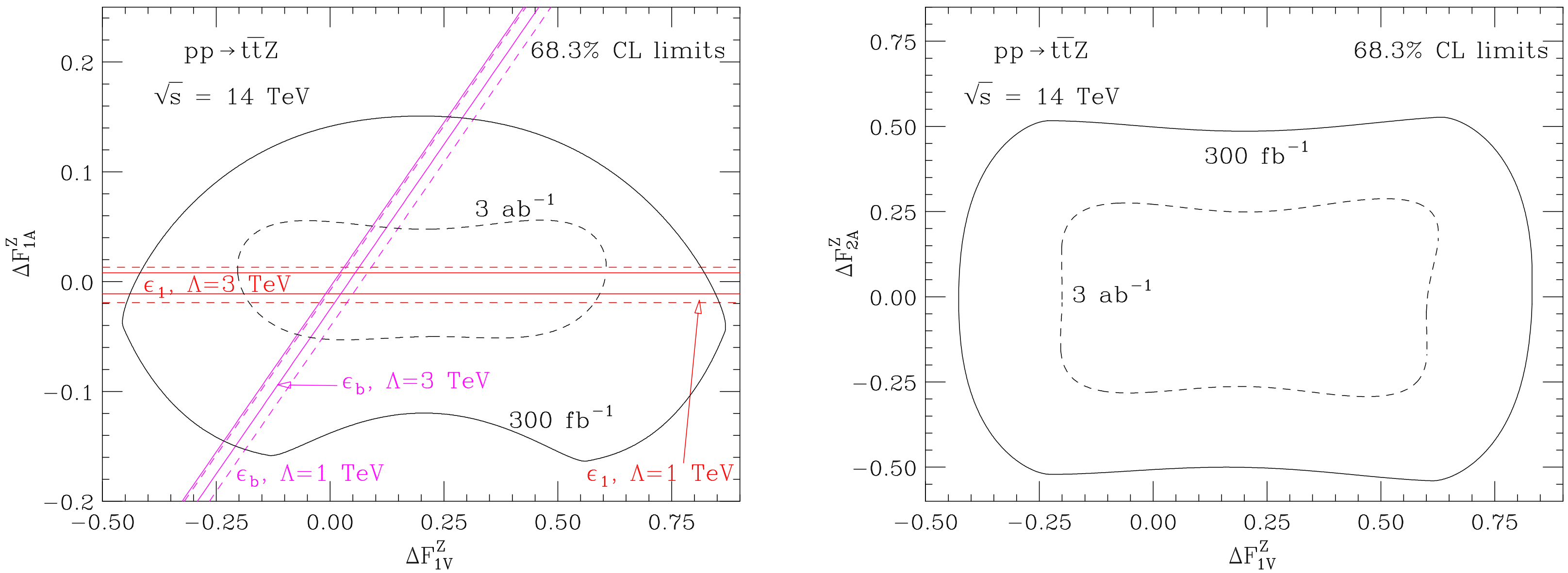


☞ all-hadronic top decays: additional background from $Zb\bar{b}4j$ production (calculated using `Alpgen`)

☞ manageable if bjj (jj) systems are required to be consistent with top (W)



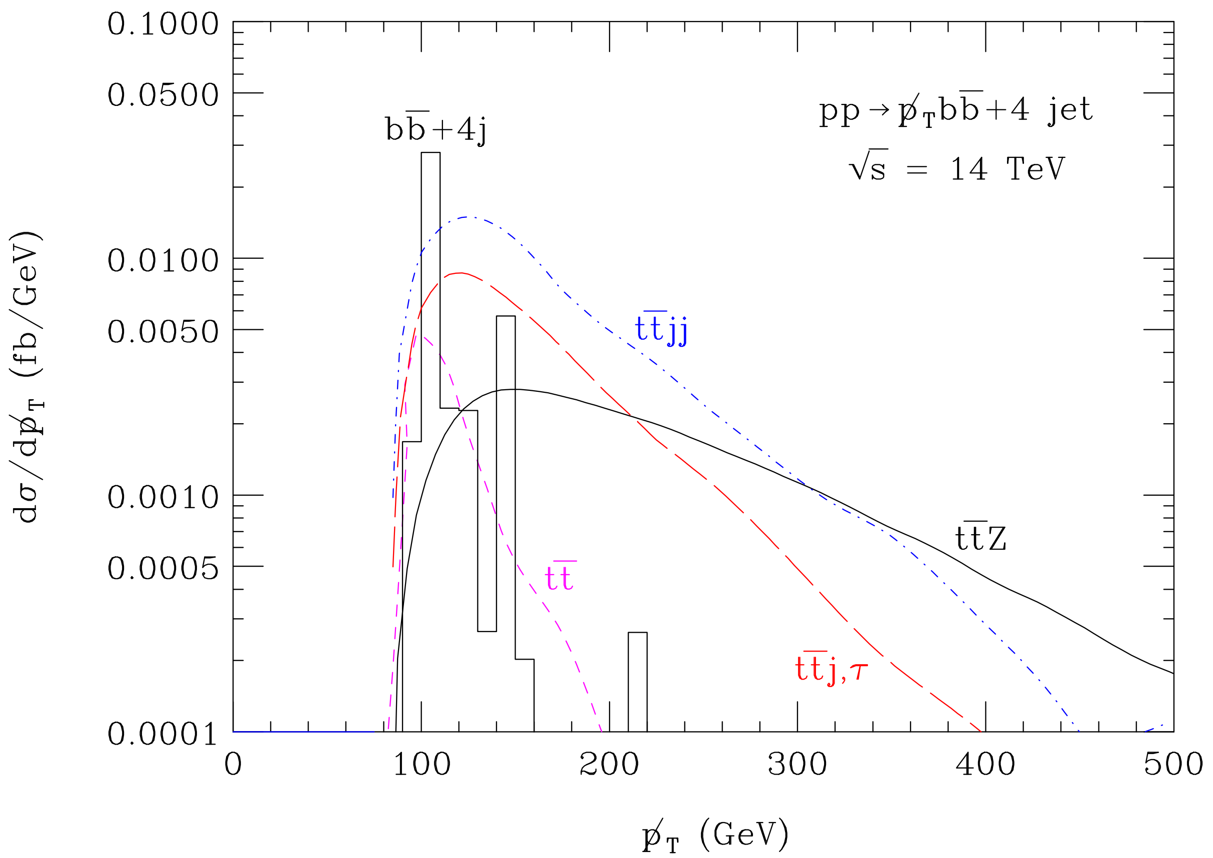
- obtain sensitivity limits from $p_T(Z)$ and $\Phi_{\ell'^+\ell'^-}$ distributions, assuming 30% normalization uncertainty of SM cross section and two tagged b's
  - ☞ can test $F^Z_{1V,A}$ at the $15 - 85\%$ ($6 - 60\%$) level for 300 fb^{-1} (3000 fb^{-1}, SuperLHC)
  - ☞ can test $F^Z_{2V,A}$ at the 50% (30%) level for 300 fb^{-1} (3000 fb^{-1})



$t\bar{t}Z \to \not{p}_T b\bar{b} + 4\text{j}$

- now consider $pp \to t\bar{t}Z$ with $Z \to \bar{\nu}\nu$ and $t\bar{t} \to b\bar{b} + 4\text{j}$
- advantage: the cross section is about a factor 5 larger than for $\ell'^+\ell'^-\ell^\pm\nu b\bar{b}jj$ final state
- require ≥ 3 jets with $p_T(j) > 50$ GeV, $\not{p}_T > 5\ \text{GeV}^{1/2}\sqrt{\sum E_T}$ and 2 b tags
- main backgrounds:
  - ☞ $pp \to t\bar{t}$ and $b\bar{b} + 4\text{j}$ production with badly mismeasured jets
  - ☞ $pp \to t\bar{t}jj$ with $t\bar{t} \to \ell\nu b\bar{b} + 2\text{j}$ where charged lepton is lost
  - ☞ $pp \to t\bar{t}j$ with $t\bar{t} \to \tau\nu b\bar{b} + 2\text{j}$ and $\tau \to$ hadrons

- signal dominates at sufficiently high values of $\not{p}_T$



☞ the $\not{p}_T b\bar{b} + 4$j final state improves the limits on anomalous ttZ couplings by $20-40\%$

4 – LHC - ILC Comparison

- $e^+e^- \to t\bar{t}$ studies (Snowmass resource book) use a different parameterization of the ttV vertex:

$$\Gamma_\mu^{ttV}(s,\, q,\, \bar{q}) \;=\; ie\left\{\gamma_\mu\,\left(\widetilde{F}_{1V}^V(s)+\gamma_5\widetilde{F}_{1A}^V(s)\right)\right. \\ \left. +\frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^V(s)+\gamma_5\widetilde{F}_{2A}^V(s)\right)\right\}$$

- $\widetilde{F}_{iV,A}^V$ and $F_{iV,A}^V$ are related by

$$\widetilde{F}_{1V}^V = -\left(F_{1V}^V+F_{2V}^V\right)\,, \quad \widetilde{F}_{1A}^V = -F_{1A}^V\,,$$
$$\widetilde{F}_{2V}^V = F_{2V}^V\,, \quad \widetilde{F}_{2A}^V = -iF_{2A}^V\,.$$

- ILC parameters used in Snowmass study: $\sqrt{s} = 500$ GeV, linear polarization $\mathcal{P}(e^-) = \mathcal{P}(e^+) = 0.8$,
only one coupling is varied at a time

coupling	LHC, 300 fb^{-1}	e^+e^-
$\Delta\widetilde{F}^{\gamma}_{1V}$	$+0.043$ -0.041	$+0.047$ -0.047, 200 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{1A}$	$+0.051$ -0.048	$+0.011$ -0.011, 100 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{2V}$	$+0.038$ -0.035	$+0.038$ -0.038, 200 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{2A}$	$+0.16$ -0.17	$+0.014$ -0.014, 100 fb^{-1}
$\Delta\widetilde{F}^{Z}_{1V}$	$+0.34$ -0.72	$+0.012$ -0.012, 200 fb^{-1}
$\Delta\widetilde{F}^{Z}_{1A}$	$+0.079$ -0.091	$+0.013$ -0.013, 100 fb^{-1}
$\Delta\widetilde{F}^{Z}_{2V}$	$+0.26$ -0.34	$+0.009$ -0.009, 200 fb^{-1}
$\Delta\widetilde{F}^{Z}_{2A}$	$+0.35$ -0.35	$+0.052$ -0.052, 100 fb^{-1}

- The ILC is able to achieve better limits for the ttZ couplings
- The LHC is competitive for some $tt\gamma$ couplings
- it appears likely that the LHC will accumulate 300 fb^{-1} before the ILC achieves $100 - 200$ fb^{-1}

  ☞ it is worthwhile measuring the ttV couplings at the LHC
- LHC and Tevatron limits can potentially be improved by including single b-tagged final states (at the cost of an increased background)
- biggest drawback of current ILC study of ttV couplings: no correlations between different ttV couplings are taken into account

  It is worthwhile launching a new study of $e^+e^- \to t\bar{t}$

5 – Conclusions

- the Tevatron may be able to perform a very rough first test of the $tt\gamma$ vector and axial vector couplings, if ≥ 8 fb^{-1} can be achieved
- the LHC will be able to perform the first precision measurement of the $tt\gamma$ couplings $(3 - 10\%)$
- the determination of the ttZ couplings at the LHC is limited to the $10 - 80\%$ level.
- The ILC will be able to measure both $tt\gamma$ and ttZ couplings at the few percent level.