Probing Electroweak Top Quark Couplings at Hadron Colliders

UB, A. Juste, L. Orr,
D. Rainwater

1. Introduction
2. $t\bar{t}\gamma$ Production
3. $t\bar{t}Z$ Production
4. Conclusions

Ulrich Baur
State University of New York at Buffalo

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:

$$\begin{aligned}\Gamma_\mu^{ttV}(s,\, q,\, \bar{q}) \quad &= \quad ie\Big\{\gamma_\mu \,\Big(F_{1V}^V(s) + \gamma_5 F_{1A}^V(s)\Big) + \\ &\qquad \frac{\sigma_{\mu\nu}}{2m_t}\,(q+\bar{q})^\nu\,\Big(iF_{2V}^V(s) + \gamma_5 F_{2A}^V(s)\Big)\Big\}\end{aligned}$$

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

$$\left|F_{iV,A}^{V}(0)\right| \leq \left(c_i^V/\Lambda\right)^2$$

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 $F_{2V,A}^{\gamma}$

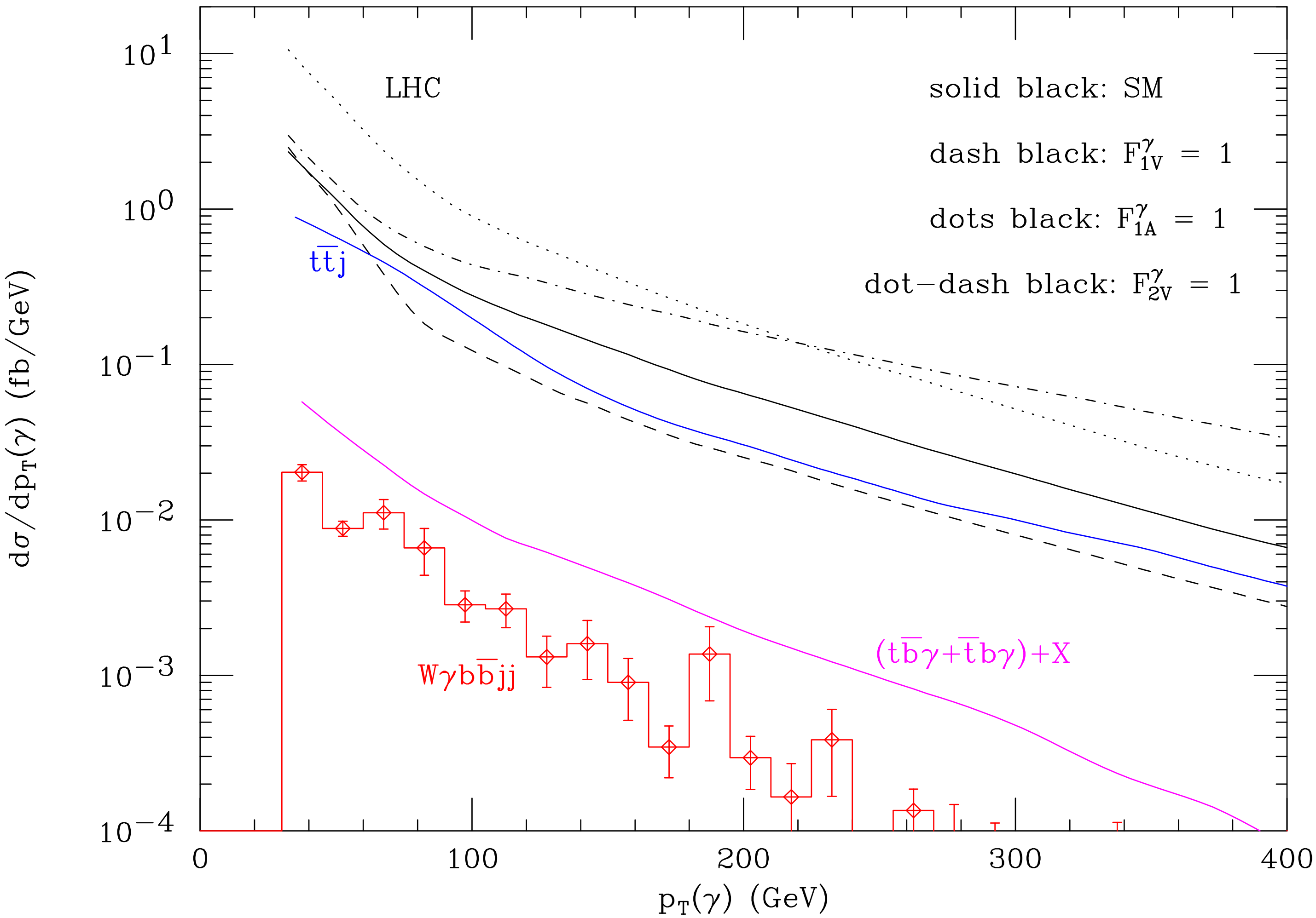
- LEP data indirectly constrain $F^Z_{1V,A}$ but not the $tt\gamma$ couplings (Larios et al.) Disadvantages:
  - ☞ constraints are (mildly) cutoff dependent
  - ☞ constraints assume no other new physics is present
- A linear e^+e^- collider promises to determine $F^V_{iV,A}$ with a precision of a few 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
- 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
- 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
    $\rightarrow$ form factor effects can be neglected if $\Lambda \geq 1$ TeV is assumed
  - ☞ gg fusion ($q\bar{q}$ annihilation) dominates at LHC (Tevatron)

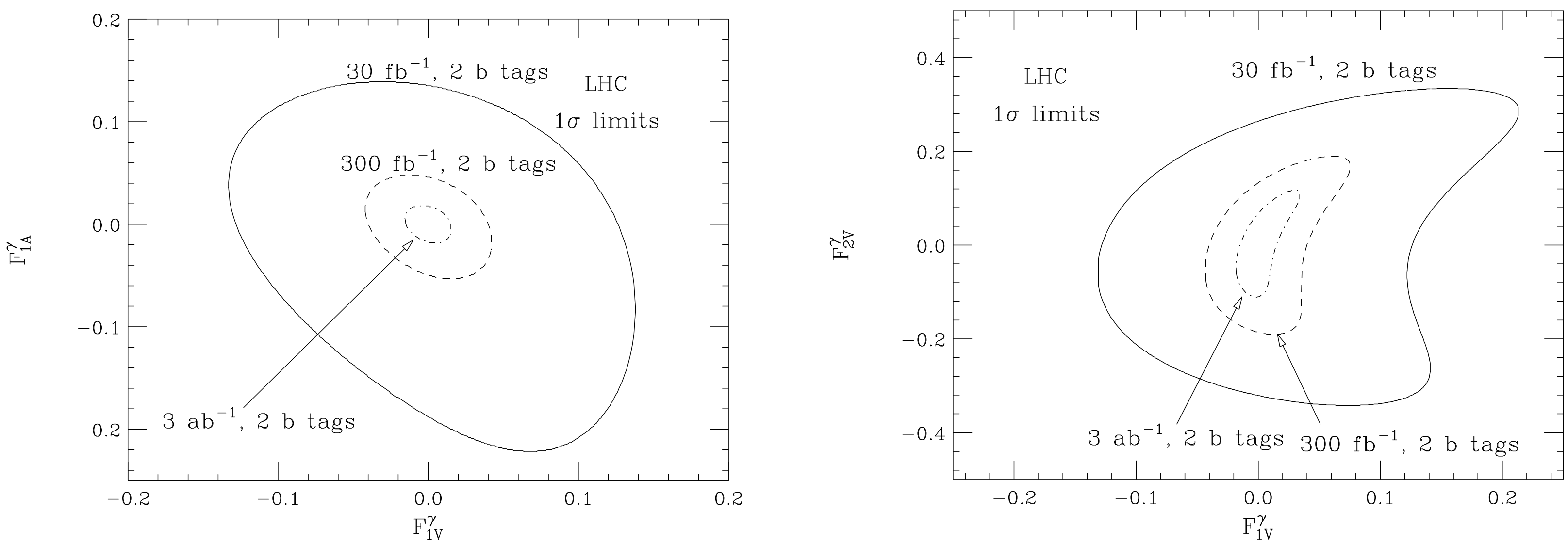
- backgrounds:
  - ☞ $W^{\pm}\gamma b\bar{b}jj$ production (non-resonant diagrams contributing to final state)
  - ☞ $t\bar{b}\gamma jj$, $\bar{t}b\gamma jj$, $t\bar{b}\gamma\ell^-\bar{\nu}$ and $\bar{t}b\gamma\ell^+\nu$ production (single resonant diagrams contributing to final state)
  - ☞ $t\bar{t}j$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

☞ $p_T(\gamma)$ distribution at LHC

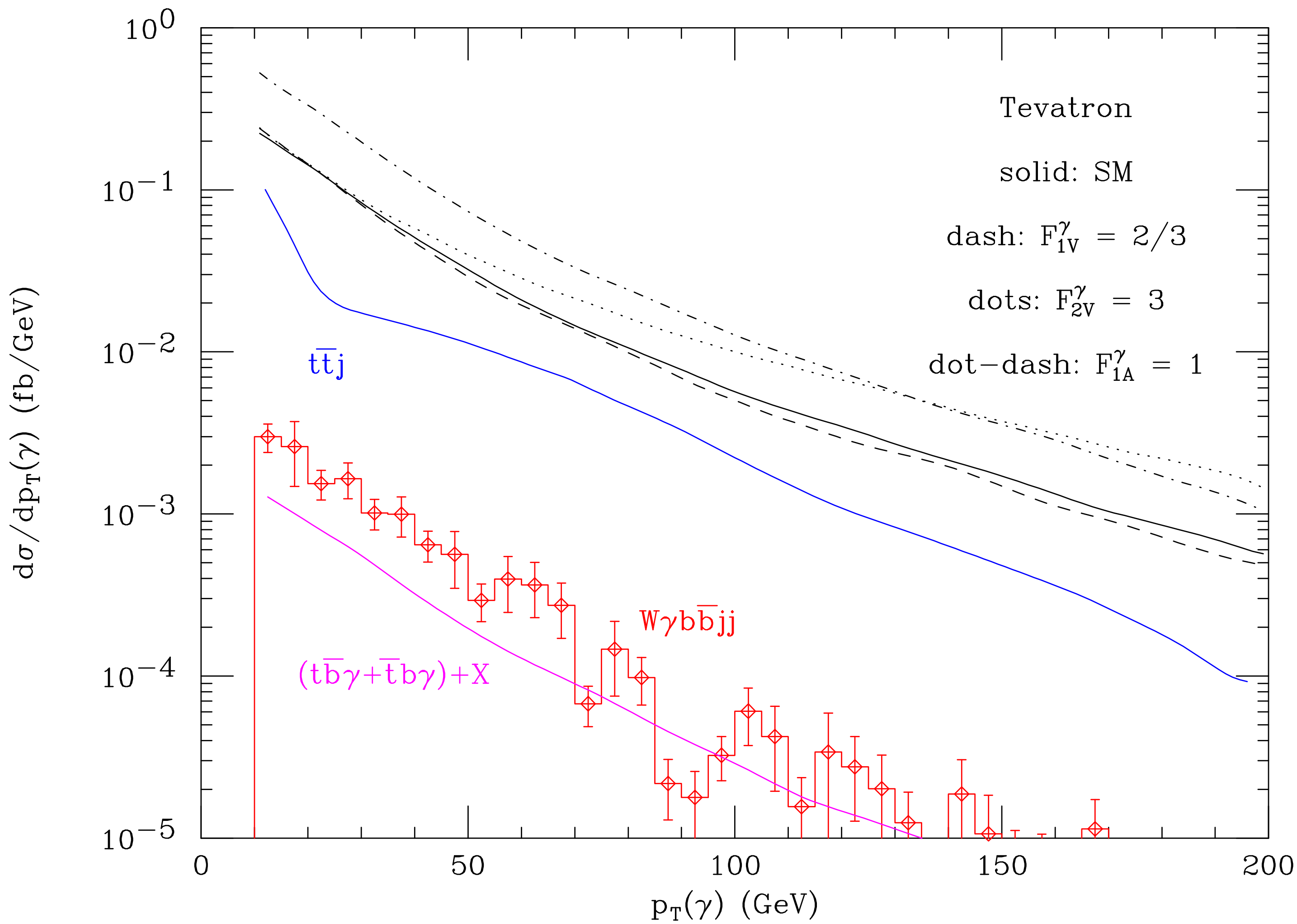


☞ background manageable

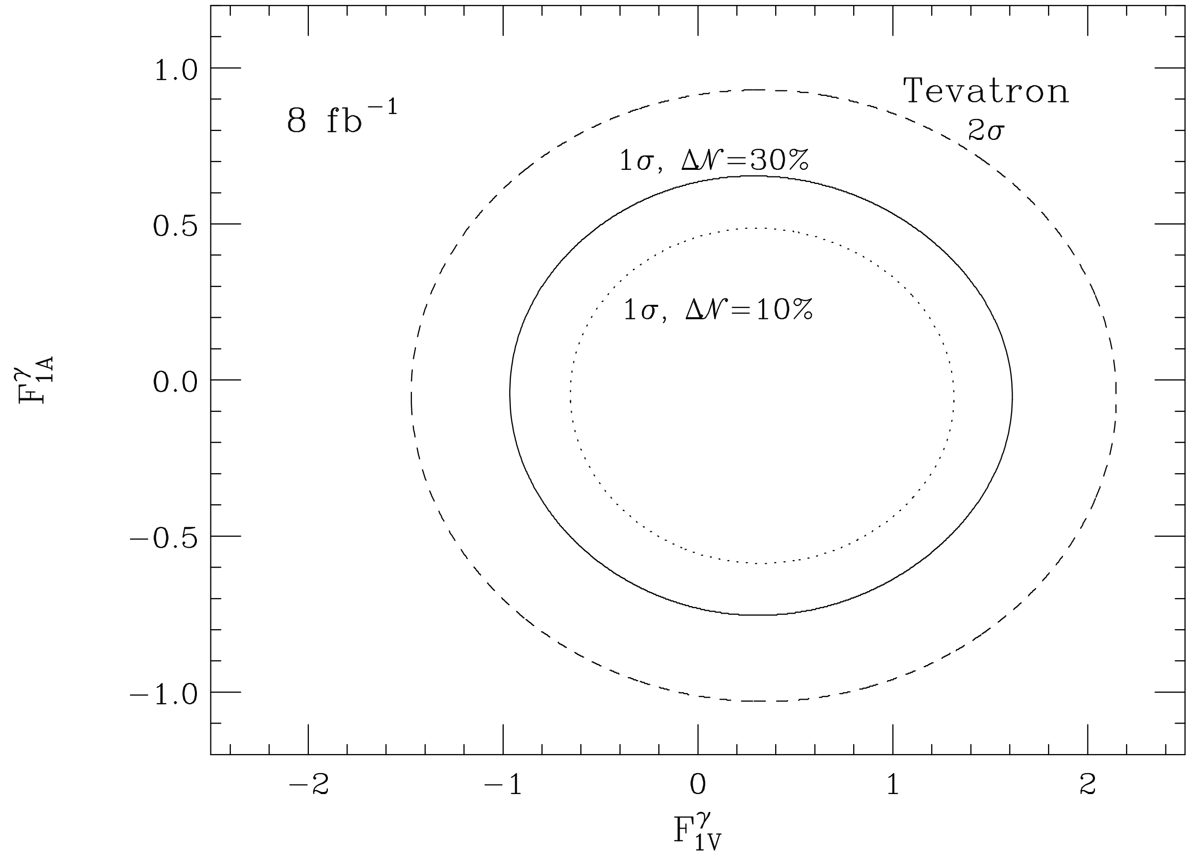
- determine sensitivity limits from χ^2 fit to $p_T(\gamma)$ distribution, assuming a 30% normalization uncertainty of the SM cross section
  - ☞ can constrain $tt\gamma$ vector and axial vector couplings to O(10%) with 30 fb^{-1}, and to a few % with 300 fb^{-1}
  - ☞ can constrain F_2^γ type couplings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

- consider only events with leptonic Z decays

  ☞ $t\bar{t}Z$ production not observable at Tevatron

- consider semi-leptonic and all-hadronic $t\bar{t}$ decays

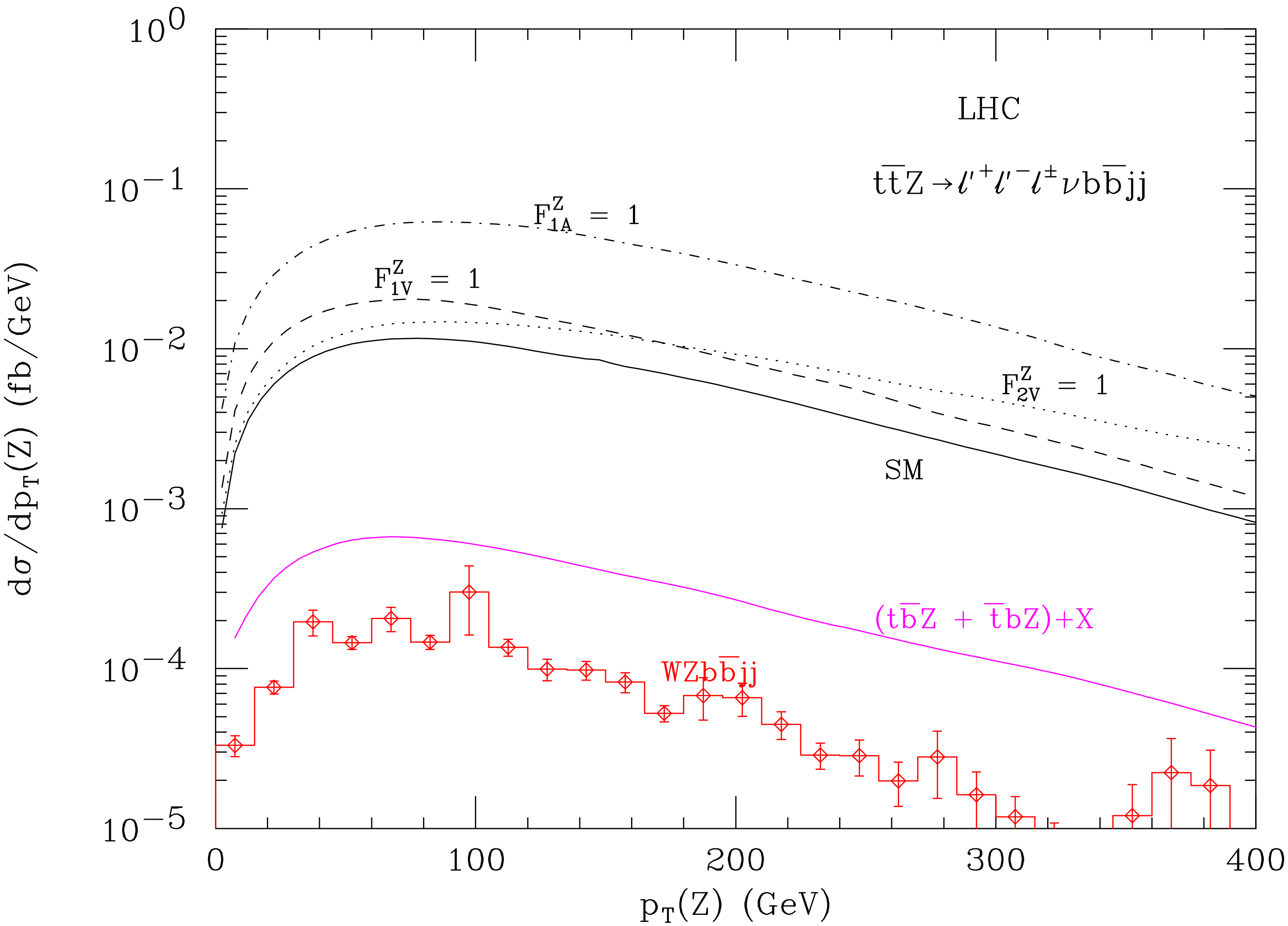
- signal: include Z emission from top decay products

- (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

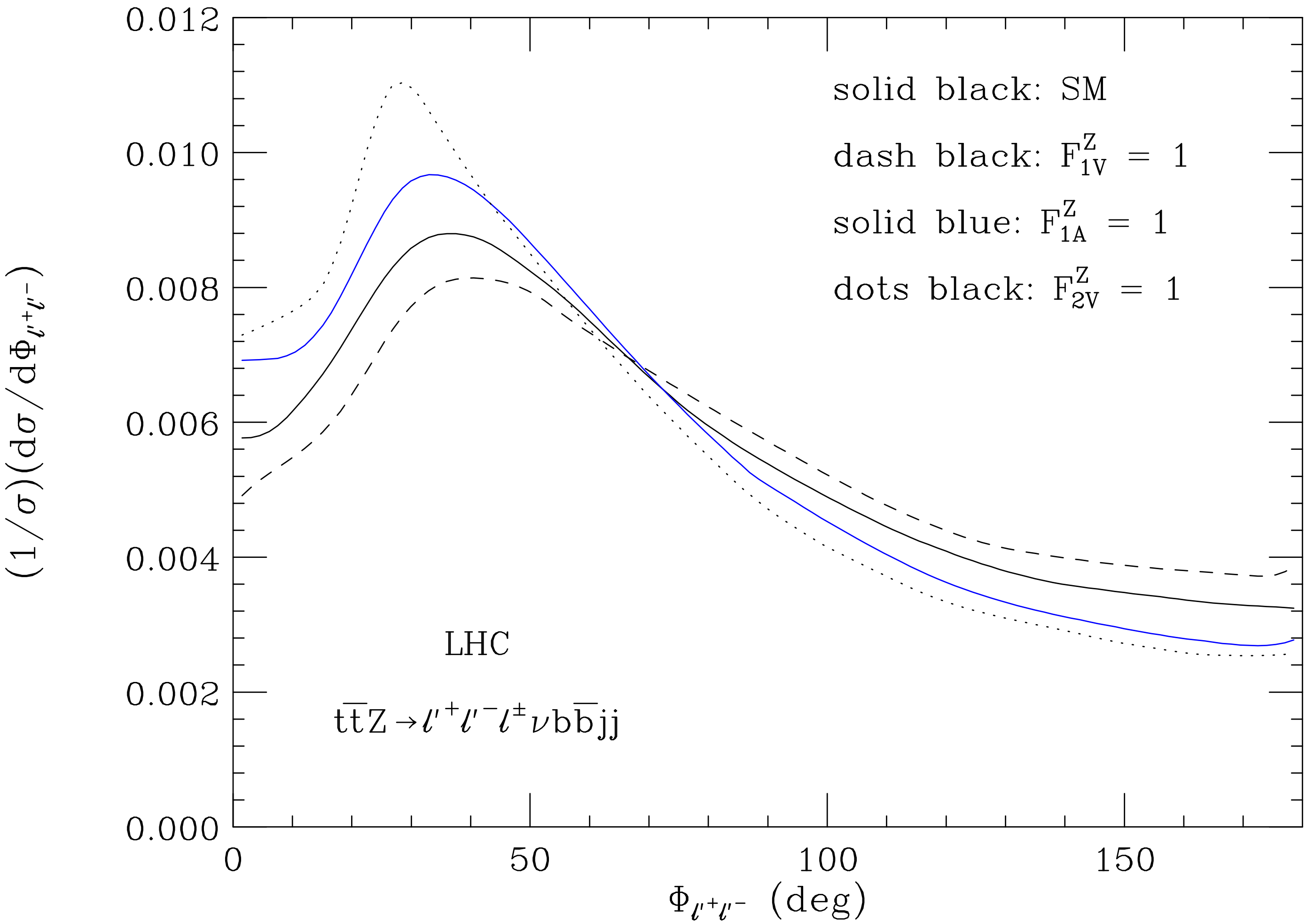
- $\ell'^+\ell'^-\ell^\pm\nu b\bar{b}jj$ final state:

  ☞ 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

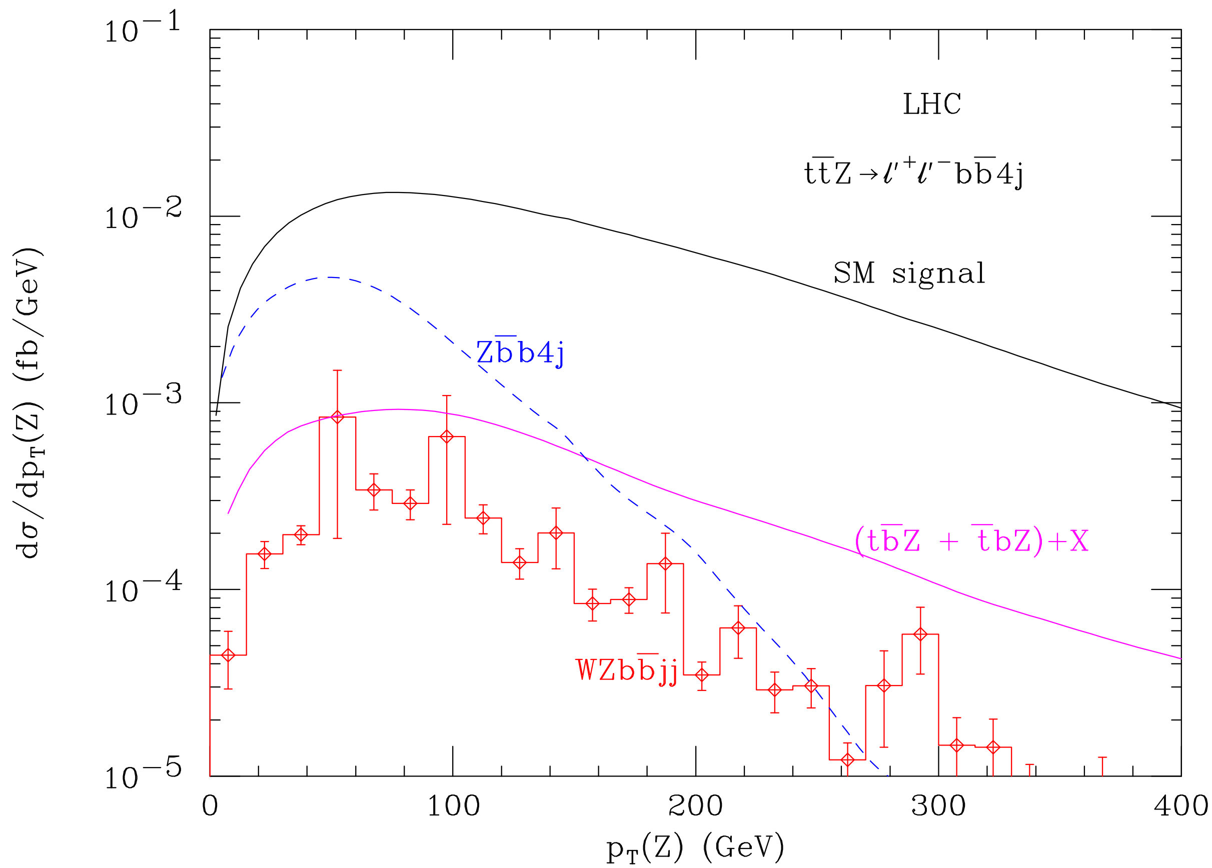


☞ distribution of opening angle of Z decay leptons also sensitive to F_1 and F_2

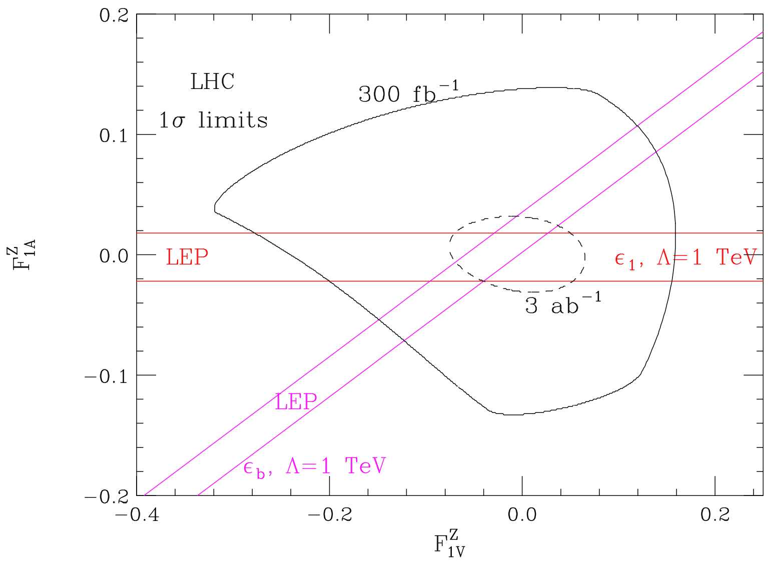


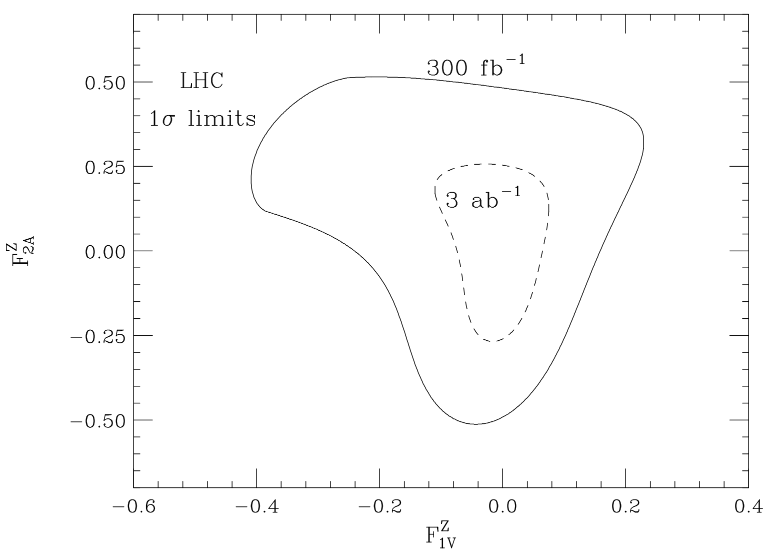
☞ all-hadronic top decays: additional background from $Zb\bar{b}4j$ production (calculated using `Alpgen`)

☞ 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 – 30% (10 – 20%) 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})





4 – Conclusions

- the Tevatron will 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 $10 - 30\%$ level.