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SCHOOL ON PHYSICS AT LHC: "EXPECTING LHC"
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ELECTROWEAK PHYSICS AT LHC
Part III

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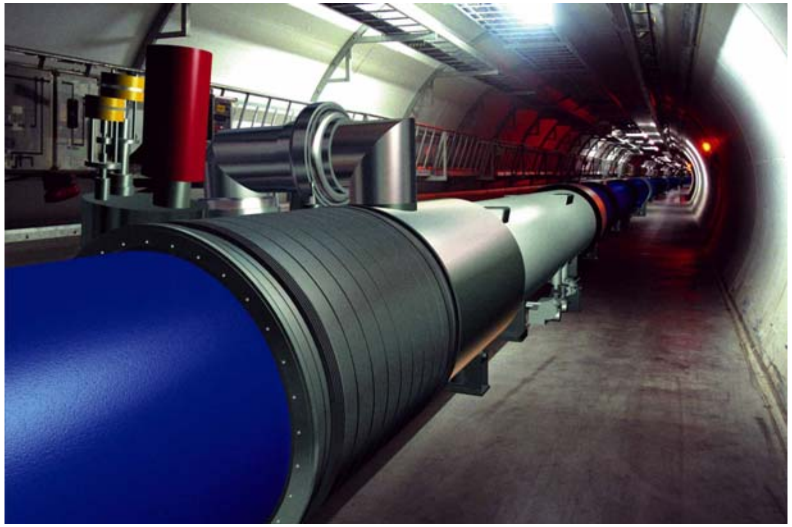
These are preliminary lecture notes, intended only for distribution to participants.

Electroweak Physics at the LHC



1. Introduction to the Standard Model
2. Electroweak Measurements at the LHC I
3. Electroweak Measurements at the LHC II

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Electroweak Measurements at the LHC II

- Plan for today:
  - ☞ Di-boson production and weak boson self-couplings
  - ☞ Probing the weak couplings of the top quark at the LHC
- good references:
  - ☞ J. Ellison and J. Wudka, Ann. Rev. Nucl. Part. Sci. 48, 33 (1998)
  - ☞ H. Aihara et al. hep-ph/9503425
  - ☞ UB et al. PRD71, 054013 (2005); PRD73, 034016 (2006)

Di-boson Production

- Physics interest:
  - ☞ background to new physics searches (WW and ZZ production background to SM Higgs search)
  - ☞ probing weak boson self-interactions
- concentrate on the latter
- plan of action:
  - ☞ theory of weak boson self-couplings
  - ☞ probing weak boson self-couplings at the LHC
  - ☞ there are three vector boson couplings (eg. WWZ) and quartic couplings (eg. $WWZ\gamma$)
  - ☞ only consider three vector boson couplings here

Theory of Weak Boson Self-couplings

- one of the consequences of non-Abelian gauge theories are the self-interactions of gauge bosons
- in QCD (SU(3) gauge theory) the gluon self-interactions lead to asymptotic freedom ($\alpha_s \to 0$ for $q^2 \to \infty$)
- gluon self-couplings:

$$\mathcal{L}_{self-int} = -\frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu}$$

where $a = 1, \ldots, 8$ and (A^a_μ is the gluon field)

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_s f^{abc} A^b_\mu A^c_\nu$$

g_s: strong coupling constant
f^{abc}: SU(3) antisymmetric structure constants

- this leads to three- and four-gluon vertices

- for electroweak interactions (SU(2)$\times$U(1) gauge theory), one gets similar expressions with the SU(2) structure constants ϵ^{ijk}
- can rewrite everything in terms of the mass eigenstates $W^{\pm}$, Z and γ
- qualitative overview of three gauge boson couplings in the Standard Model:
  - ☞ $WW\gamma$ and WWZ couplings are non-zero
  - ☞ there are no tree level couplings with neutral gauge bosons, ie. $Z\gamma\gamma$, $ZZ\gamma$ and ZZZ couplings all vanish

General $WW\gamma$ and WWZ Couplings

- If we want to test the SU(2)×U(1) gauge theory, we have to go beyond and generalize the WWV ($V=\gamma,\ Z$) couplings
- The most general effective Lagrangian consistent with electromagnetic gauge invariance and Lorentz invariance is

$$
\begin{aligned}
i\mathcal{L}_{eff}^{WWV} \quad = \quad & g_{WWV}\Big[g_1^V\left(W^\dagger_{\mu\nu}W^\mu - W^{\dagger\,\mu}W_{\mu\nu}\right)V^\nu + \kappa_V\, W^\dagger_\mu W_\nu V^{\mu\nu} \\
& + \frac{\lambda_V}{m_W^2}\, W^\dagger_{\rho\mu}W^\mu{}_\nu V^{\nu\rho} - g_4^V\, W^\dagger_\mu W_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) \\
& + i g_5^V\, \varepsilon_{\mu\nu\rho\sigma}\left((\partial^\rho W^{\dagger\,\mu})W^\nu - W^{\dagger\,\mu}(\partial^\rho W^\nu)\right)V^\sigma \\
& + i\tilde\kappa_V W^\dagger_\mu W_\nu \tilde V^{\mu\nu} + i\frac{\tilde\lambda_V}{m_W^2}\, W^\dagger_{\rho\mu}W^\mu{}_\nu \tilde V^{\nu\rho}\Big] \,.
\end{aligned}
$$

$W_{\mu\nu}=\partial_\mu W_\nu - \partial_\nu W_\mu$; same for $V_{\mu\nu}$; $\tilde V_{\mu\nu}=(1/2)\epsilon_{\mu\nu\rho\sigma}V^{\rho\sigma}$

$g_{WW\gamma}=e$; $g_{WWZ}=e\cot\theta_W$

- In the SM:

$$g_1^Z = g_1^\gamma = \kappa_Z = \kappa_\gamma = 1,$$
$$\lambda_Z = \lambda_\gamma = g_4^V = g_5^Z = g_5^\gamma = \tilde{\kappa}_V = \tilde{\lambda}_V = 0$$

- g_1^V, κ_V and λ_V respect charge conjugation (C) and parity (P)
- g_4^V and g_5^V violate C invariance
- g_4^V, $\tilde{\kappa}_V$ and $\tilde{\lambda}_V$ violate CP invariance
- for on-shell photons: $g_1^\gamma = 1$ (electric charge of W), $g_4^\gamma = g_5^\gamma = 0$ (em gauge invariance)
- higher dimensional operators do not lead to a new Lorentz structure
- they can be taken into account by allowing the couplings g_1^V, κ_V etc. to be energy dependent so-called form factors

- the $WW\gamma$ couplings are related to the static moments of the W (μ_W (d_W): (magnetic (electric) dipole moment; q_W ($\tilde{q}_W$) electric (magnetic) quadrupole moment)

$$\mu_W = \frac{e}{2m_W}\left(g_1^\gamma + \kappa_\gamma + \lambda_\gamma\right) \;, \qquad d_W = \frac{e}{2m_W}\left(\tilde{\kappa}_\gamma + \tilde{\lambda}_\gamma\right) \;,$$

$$q_W = -\frac{e}{m_W^2}\left(\kappa_\gamma - \lambda_\gamma\right) \qquad \tilde{q}_W = -\frac{e}{m_W^2}\left(\tilde{\kappa}_\gamma - \tilde{\lambda}_\gamma\right) \;.$$

- Unitarity requires weak boson self-couplings to be of SM form at high energies

Sidebar: Unitarity

- Consider $2 \to 2$ elastic scattering. Differential cross section (Ω is solid angle; s squared center of mass energy)

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|\mathcal{M}|^2$$

$\mathcal{M}$: amplitude

- expand in terms of Legendre polynomials (form a complete set): partial wave decomposition

$$\mathcal{M} = 16\pi \sum_{l=0}^{\infty}(2l+1)P_l(\cos\theta)a_l$$

θ: scattering angle; a_l: spin l partial wave

- the P_l are orthonormal, so

$$\sigma = \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2$$

- now we invoke the optical theorem:

$$\sigma = \frac{1}{s} Im[\mathcal{M}(\theta = 0)]$$

(proof only requires conservation of probability) and get:

$$Im(a_l) = |a_l|^2$$

which implies

$$|Re(a_l)| \leq \frac{1}{2}$$

- amplitudes which grow with the parton center of mass energy $\sqrt{\hat{s}}$ violate unitarity at some energy scale
- example: terms proportional to κ_γ and λ_γ in $q\bar{q}' \to W\gamma$ amplitude $\mathcal{M}_{\lambda^\gamma \lambda^W}$ ($\lambda^{\gamma,W}$: γ (W) polarization; Θ: scattering angle):

$$\Delta\mathcal{M}_{\pm 0} = \frac{e^2}{\sin\theta_W} \frac{\sqrt{\hat{s}}}{2m_W} \left[\kappa_\gamma - 1 + \lambda_\gamma \mp i(\tilde{\kappa}_\gamma + \tilde{\lambda}_\gamma)\right] \tfrac{1}{2}(1 \mp \cos\Theta)$$

$$\Delta\mathcal{M}_{\pm\pm} = \frac{e^2}{\sin\theta_W} \frac{\hat{s}}{2m_W^2} \left[\lambda_\gamma \mp i\tilde{\lambda}_\gamma\right] \tfrac{1}{\sqrt{2}} \sin\Theta \,,$$

- if κ, λ etc. is a constant, it must have SM value
- or, they are momentum dependent form factors which $\to 0$ for $\hat{s} \to \infty$
  example:
  $$\lambda_\gamma(\hat{s}) = \frac{\lambda_\gamma(0)}{(1 + \frac{\hat{s}}{\Lambda^2})^2}$$
  where the form factor scale Λ is the scale of new physics (which is responsible for the anomalous weak boson self-couplings)
- this picture is similar to the proton form factor where $\Lambda^2 = 0.71$ GeV^2 is $\mathcal{O}(\Lambda_{QCD})$.
- special case: imposing SU(2)×U(1) symmetry:
  $$\begin{aligned} g_1^Z - 1 &= \frac{1}{2\cos^2\theta_W}(\kappa_\gamma - 1), \\ \kappa_Z - 1 &= \frac{1}{2}(1 - \tan^2\theta_W)(\kappa_\gamma - 1), \\ \lambda_Z &= \lambda_\gamma. \end{aligned}$$
  all other couplings vanish

- what about higher order corrections in the SM? They either have to vanish, or lead to a form factor which $\to 0$ for $\hat{s} \to \infty$
- higher order corrections to the gauge boson self-couplings in the SM lead to a form factor. The form factor scale Λ is the mass of the heaviest particle in the loop, usually either the top quark, or the Higgs boson

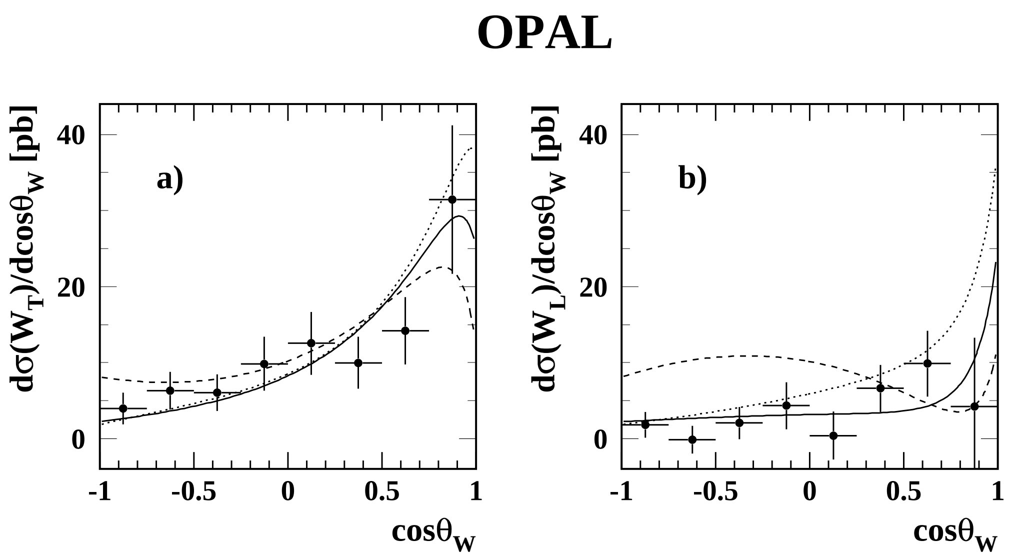
Neutral Weak Boson Couplings

- appear in $Z\gamma$ and ZZ production
- there are 4 $ZZ\gamma$, h_i^Z $(i = 1, \ldots, 4)$, and 4 $Z\gamma\gamma$ couplings, h_i^γ, which contribute to $q\bar{q} \to Z\gamma$
- $h_{1,3}$ $(h_{2,4})$ correspond to dimension 6 (8) terms in the Lagrangian
- $h_{1,2}$ $(h_{3,4})$ violate (conserve) CP
- the $Z\gamma\gamma$ vertex function vanishes if both photons are on-shell (Yang's theorem)
- there are also 2 ZZZ $(f_{4,5}^Z)$ and 2 $ZZ\gamma$ couplings $(f_{4,5}^\gamma)$ contributing to $q\bar{q} \to ZZ$
- all these couplings have to be form factors which $\to 0$ for $\hat{s} \to \infty$ to avoid violation of unitarity

Measuring the Weak Boson Self-interactions

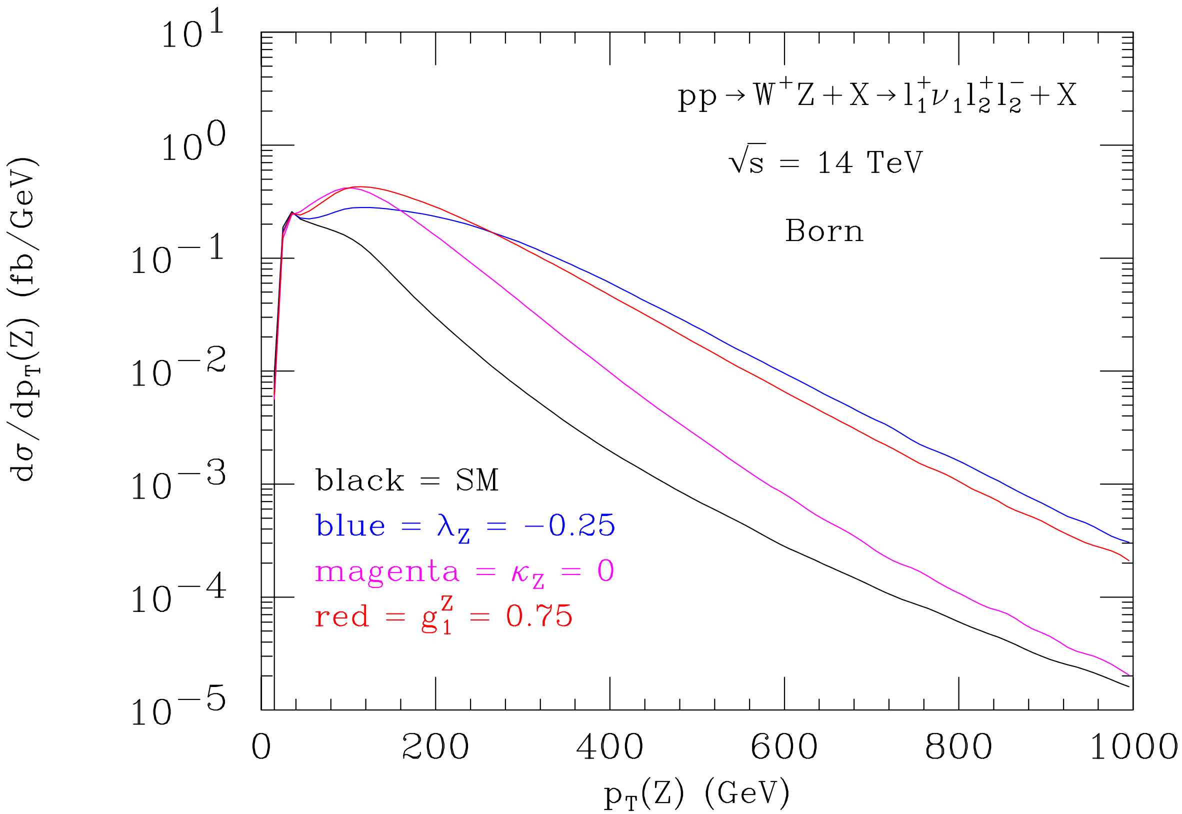
- di-boson production at e^+e^- or hadron colliders
- e^+e^- and hadron colliders test complementary aspects of anomalous gauge boson couplings:
  - ☞ in e^+e^- collisions, one probes the structure of the amplitude (ie. its dependence on the scattering angle) at a fixed energy

    example $e^+e^- \to W^+W^-$:



☞ at a hadron collider, one probes the high energy behavior of the amplitude: the incoming quarks carry only a fraction of the (anti)proton momentum with a probability distribution given by the PDF

example (form factor scale $\Lambda = 1$ TeV):



- different processes are sensitive to different couplings
  - ☞ W^+W^- production: $WW\gamma$ and WWZ couplings
  - ☞ $W\gamma$ (WZ) production: $WW\gamma$ (WWZ) couplings only
  - ☞ $Z\gamma$ production: $ZZ\gamma$ (h_1^Z) and $Z\gamma\gamma$ couplings
  - ☞ ZZ production: ZZZ and $ZZ\gamma$ (f_i^Z) couplings
- backgrounds at the LHC:
  - ☞ Vj ($V = W,\ Z$) with jet "faking" photon in $V\gamma$ production (manageable)
  - ☞ $\bar{t}t$ production in W^+W^- production (impose jet veto)
  - ☞ Vjj production in $pp \to WW$, WZ and ZZ if one weak boson decays hadronically (usually very large; require both weak bosons to decay leptonically)

QCD corrections to Di-boson Production

- QCD corrections to di-boson production become very large at high energies, especially for $W\gamma$ and WZ production
- two reasons:
  - ☞ there is a logarithmic enhancement factor in $qg \to W\gamma q'$ and $qg \to WZq'$
  - ☞ the SM LO $W\gamma$ (WZ) cross section is suppressed by a (approximate) radiation zero which is due to destructive interference between the contributing Feynman diagrams
- radiation zero in $q_1\bar{q}_2 \to W^{\pm}\gamma$: the amplitude vanishes for

$$\cos\Theta = \pm\frac{1}{3}$$

Θ: scattering angle of W w/r to q_1 direction in the $W\gamma$ rest frame

- the approximate radiation zero in $W^{\pm}Z$ production is at

$$\cos\Theta = \mp\frac{1}{3}\tan^2\theta_W \approx \mp 0.1$$

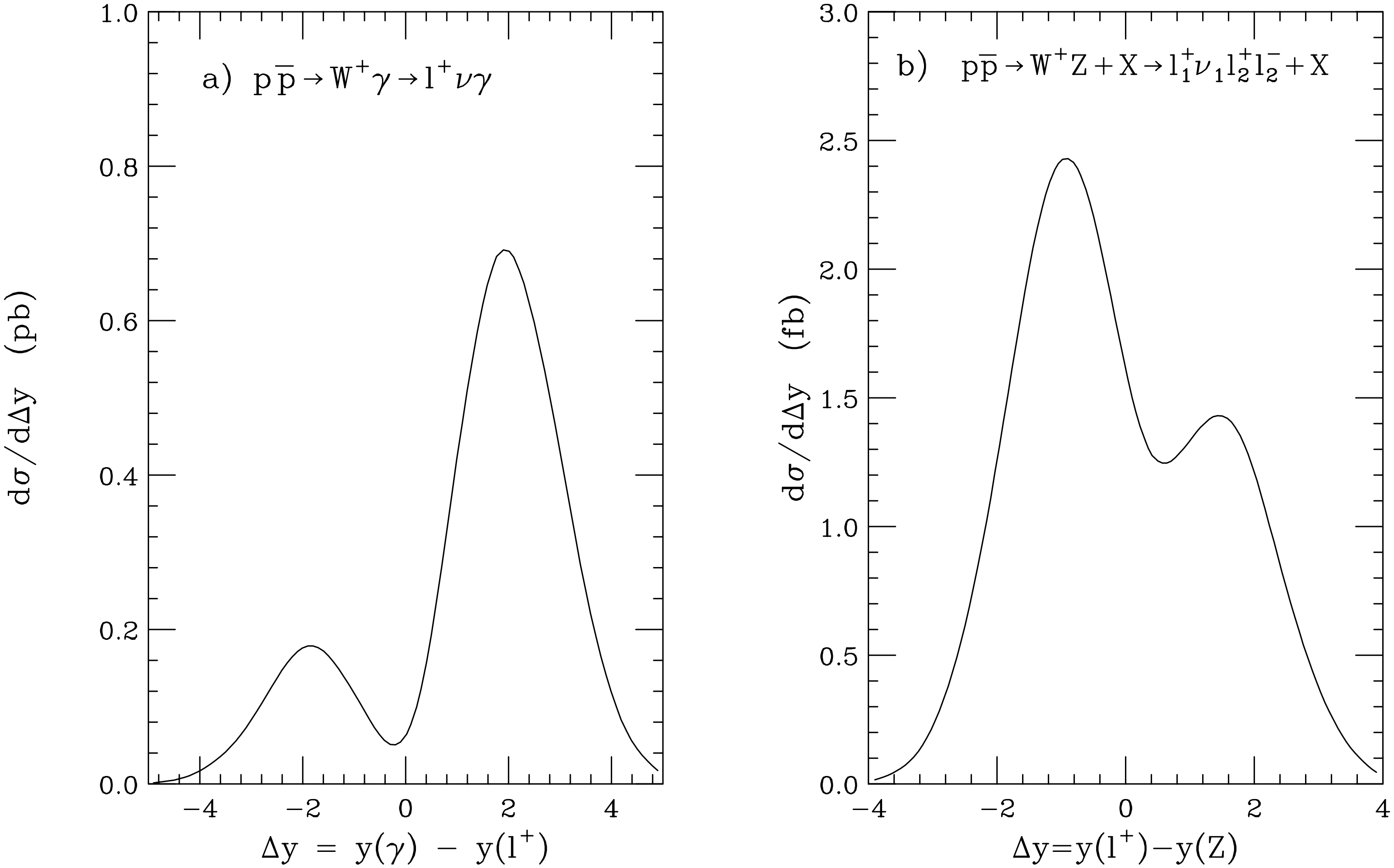
- the amplitude zeros only occur in the SM; anomalous $WW\gamma$ or WWZ couplings destroy it
- it should be possible to see the $W\gamma$ zero at the Tevatron as a dip in the

$$\Delta y = y(\gamma) - y(l)$$

distribution. y is the rapidity, which, for massless particles is related to the scattering angle by

$$y = -\frac{1}{2}\log\left(\tan\frac{\theta}{2}\right)$$

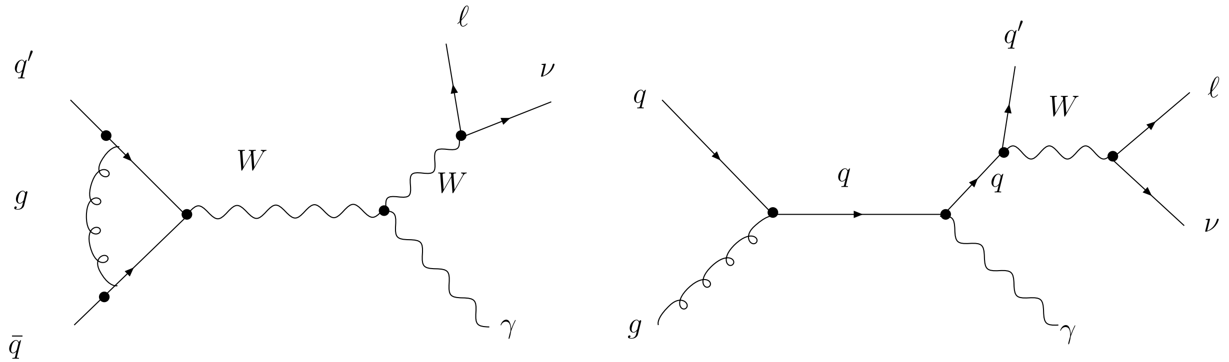
- there are not enough WZ events to see the approximate zero at the Tevatron
- at the LHC, QCD corrections essentially wash out any sign of the zeros.



a) $p\bar{p} \to W^+\gamma \to l^+\nu\gamma$
$d\sigma/d\Delta y$ (pb)
$\Delta y = y(\gamma) - y(l^+)$
1.0
0.8
0.6
0.4
0.2
0.0
−4
−2
0
2
4
b) $p\bar{p} \to W^+Z + X \to l_1^+\nu_1 l_2^+ l_2^- + X$
$d\sigma/d\Delta y$ (fb)
$\Delta y = y(l^+) - y(Z)$
3.0
2.5
2.0
1.5
1.0
0.5
0.0
−4
−2
0
2
4

... back to the QCD corrections

- sample diagrams



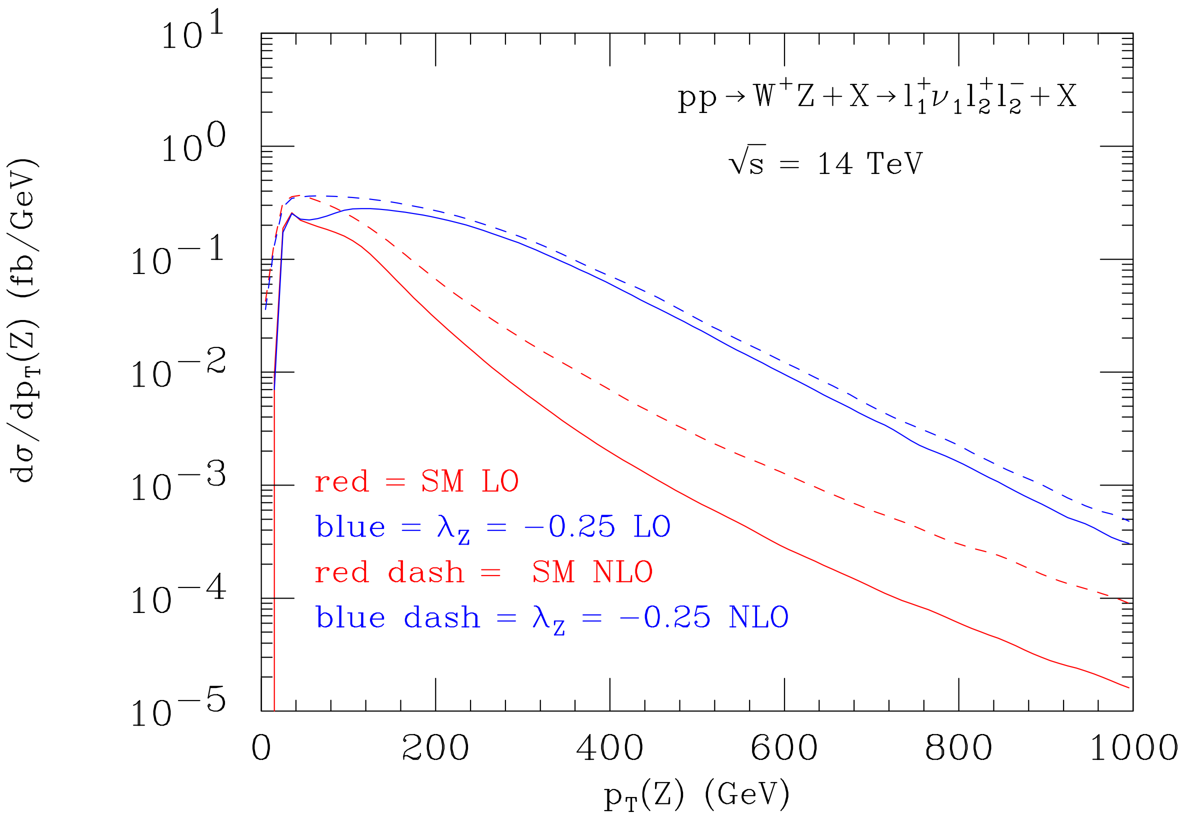
- the $qg \to W\gamma q'$ cross section can be written at high photon transverse momenta $p_T(\gamma)$:

$$d\hat{\sigma}(q_1 g \to W\gamma q_{1,2}) = d\hat{\sigma}(q_1 g \to \gamma q_1)\, \frac{\alpha}{4\pi \sin^2\theta_W}\, \log^2\left(\frac{p_T^2(\gamma)}{M_W^2}\right)$$

- similar expressions hold in WZ production and other processes

- the log enhancement is not present in diagrams with the $WW\gamma/WWZ$ vertex

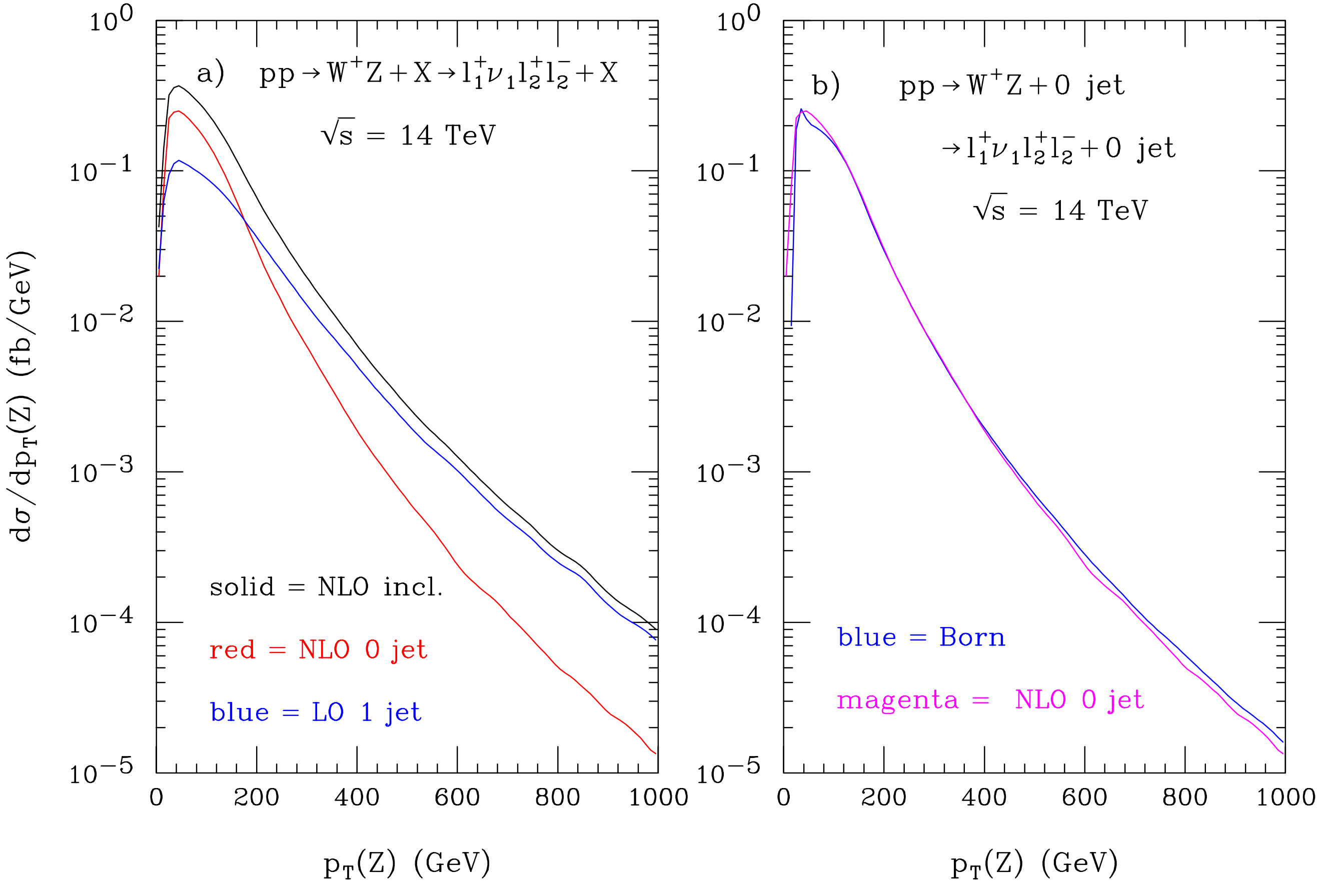
  → QCD corrections substantially reduce sensitivity to anomalous couplings



- however: at high p_T, most events have a hard jet

  ➜ a jet veto helps to get the QCD under control and restore sensitivity to anomalous couplings

  example: no jets with $p_T(j) > 50$ GeV



Present and Future Limits on Anomalous Couplings

- LEP II results: limits for g_1^Z, κ_γ, λ_γ (assuming $\lambda_\gamma = \lambda_Z$, $\kappa_Z = g_1^Z - (\kappa_\gamma - 1)\tan^2\theta_W$) from $e^+e^- \to W^+W^-$

$$g_1^Z = 0.984^{+0.022}_{-0.019} \qquad \mathrm{SM}: g_1^Z = 1$$
$$\kappa_\gamma = 0.973^{+0.044}_{-0.045} \qquad \mathrm{SM}: \kappa_\gamma = 1$$
$$\lambda_\gamma = -0.028^{+0.020}_{-0.021} \qquad \mathrm{SM}: \lambda_\gamma = 0$$

- sample Tevatron Run II result: first direct limits on WWZ couplings from $WZ \to 3$ leptons production (DØ, 0.3 fb^{-1}, $\Lambda = 1.5$ TeV, 95% CL)

$$-0.48 < \lambda_Z < 0.48 \qquad \kappa_Z = g_1^Z = 1$$
$$0.51 < g_1^Z < 1.66 \qquad \lambda_Z = \kappa_Z - 1 = 0$$

- limits scale roughly like $(\int \mathcal{L}dt)^{1/4}$

  → expect bounds on $WW\gamma$, WWZ couplings in the range of 0.15 – 0.45 for 2 fb^{-1} in Run II

- LHC: rule of thumb: limits for λ (κ, g_1^Z) are in the 10^{-3} (10^{-2}) range, with a significant dependence on Λ
  improvement up to a factor 10 over LEPII results

- neutral gauge boson couplings

  ☞ example: $Z\gamma\gamma$ and ZZg couplings from LEP and DØ:

$-0.13 < h_1^Z < 0.13$	$-0.23 < h_1^Z < 0.23$
$-0.078 < h_2^Z < 0.071$	$-0.02 < h_2^Z < 0.02$
$-0.20 < h_3^Z < 0.07$	$-0.23 < h_3^Z < 0.23$
$-0.05 < h_4^Z < 0.12$	$-0.019 < h_4^Z < 0.019$

$-0.056 < h_1^\gamma < 0.055$	$-0.23 < h_1^\gamma < 0.23$
$-0.045 < h_2^\gamma < 0.045$	$-0.02 < h_2^\gamma < 0.02$
$-0.049 < h_3^\gamma < 0.008$	$-0.23 < h_3^\gamma < 0.23$
$-0.002 < h_4^\gamma < 0.034$	$-0.019 < h_4^\gamma < 0.019$

  ☞ at the end of Run II bounds will be about a factor 2 better

  ☞ at the LHC one can reach the 10^{-3} (10^{-4}) range for $h_{1,3}^V$ ($h_{2,4}^V$) with strong dependence on Λ

- ZZZ and $ZZ\gamma$ couplings in ZZ production:
  - ☞ only results from LEPII so far (95% CL):

$$-0.17 < f_4^\gamma < 0.19 \qquad -0.30 < f_4^Z < 0.28$$

$$-0.34 < f_5^\gamma < 0.38 \qquad -0.36 < f_5^Z < 0.38$$

  - ☞ Run II expectation for 2 fb^{-2}: about a factor 2 improvement over LEPII limits is possible
  - ☞ LHC: one can reach the 10^{-3} level

Measuring the $tt\gamma$ and ttZ couplings at the LHC

- the top quark was discovered 11 years ago, but we know little about its coupling to weak bosons
- focus on $tt\gamma$ and ttZ couplings here
- 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:

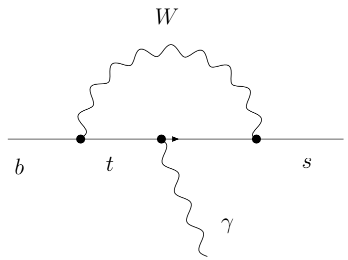
$$\Gamma_\mu^{ttV}(s,\, q,\, \bar{q}) = -ie\left\{\gamma_\mu\left(F_{1V}^V(s) + \gamma_5 F_{1A}^V(s)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^V(s) + \gamma_5 F_{2A}^V(s)\right)\right\}$$

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

- present bounds:
  - ☞ $b \to s\gamma$ data weakly constrain $F_{2V,A}^\gamma$: $-0.2 < F_{2V}^\gamma < 0.5$, $|F_{2A}^\gamma| < 4.5$



  - ☞ LEP data indirectly constrain $F_{1V,A}^Z$ but not $F_{1V,A}^\gamma$

- The ILC 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}
  disadvantage: difficult to disentangle $tt\gamma$ and ttZ couplings
- LHC:
  - ☞ consider $t\bar{t}\gamma$ and $t\bar{t}Z$ production
  - ☞ can separate $tt\gamma$ and ttZ couplings

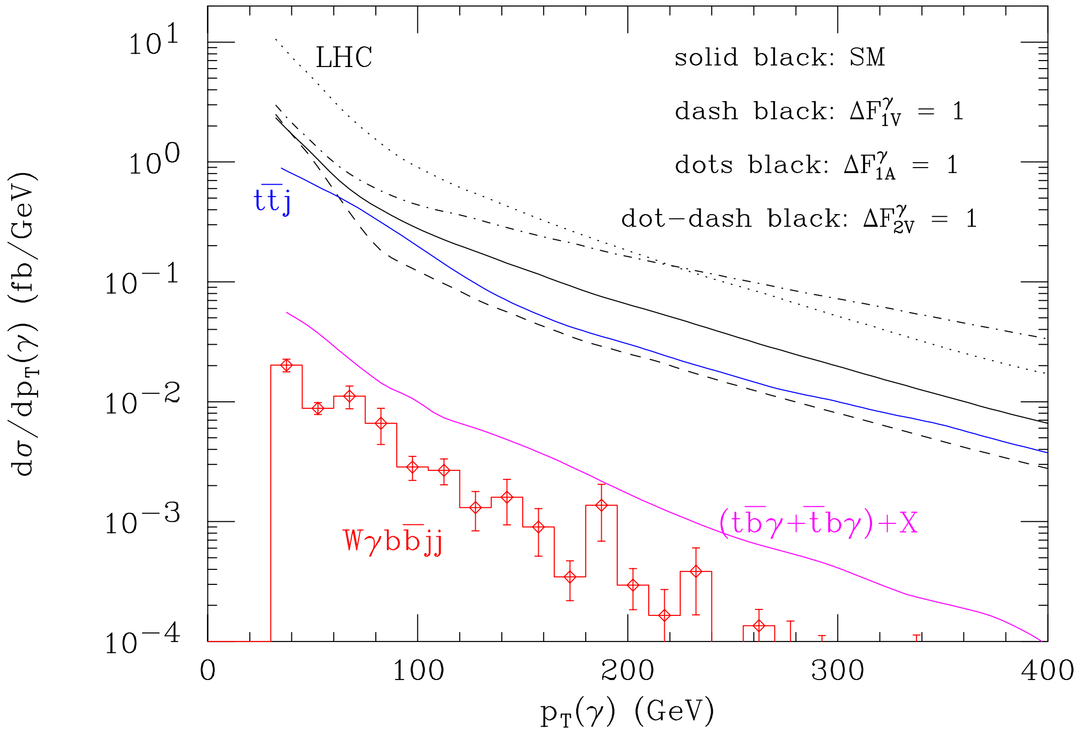
$t\bar{t}\gamma$ Production at the LHC

- concentrate on $\ell^\pm \nu jjb\bar{b}\gamma$ final state and require 2 tagged b's
- signal:
  - ☞ impose cuts to suppress photon radiation off b-quarks and 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
- 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

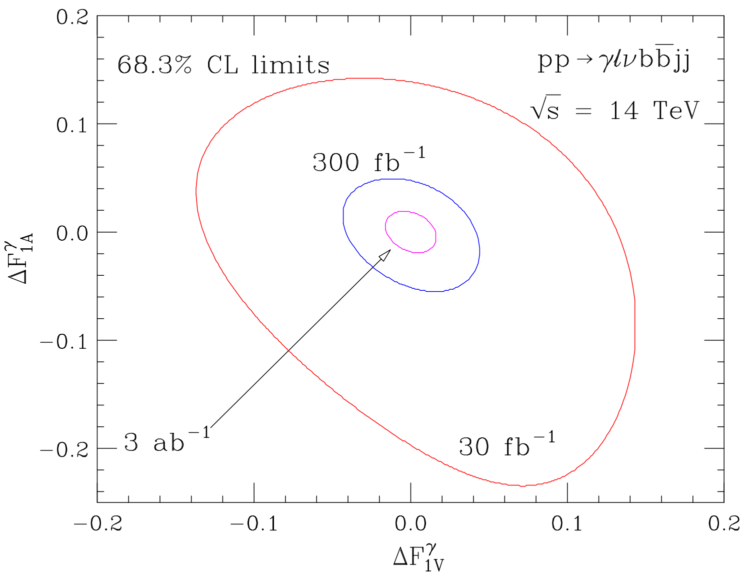
→ largest background if jet misidentification probabilities of CDF, DØ, ATLAS or CMS are used

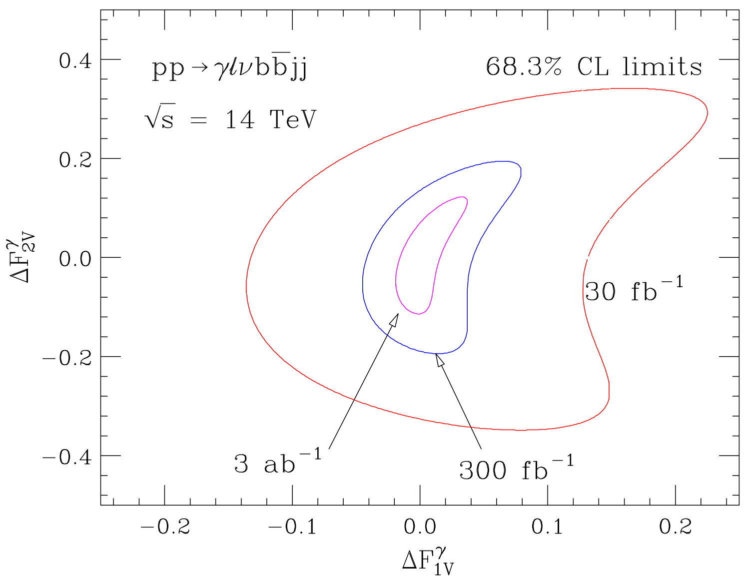
- $p_T(\gamma)$ distribution at LHC ($\Delta F_i^V = F_i^V - F_i^{V,SM}$)



☞ background manageable

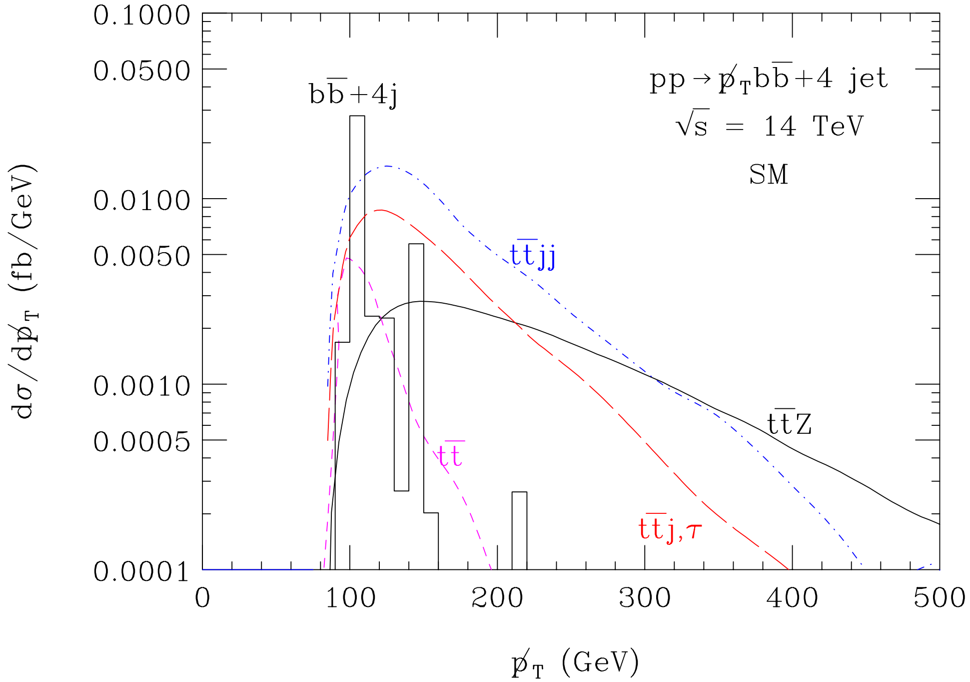
- determine sensitivity limits from χ^2 fit to $p_T(\gamma)$ distribution, assuming a 30% normalization uncertainty of the SM cross section
  - ☞ can constrain $tt\gamma$ vector and axial vector couplings to O(10%) with 30 fb^{-1}, and to a few % with 300 fb^{-1}
  - ☞ can constrain F_2^γ type couplings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



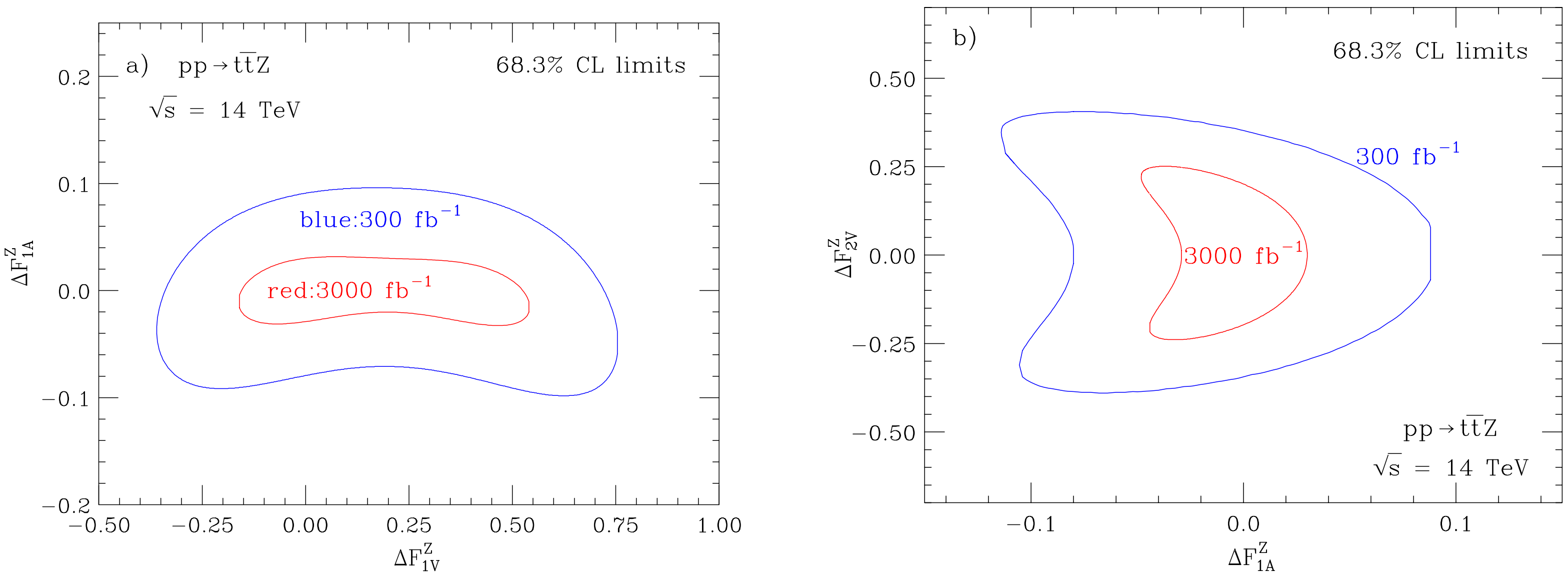


$t\bar{t}Z$ Production at the LHC

- There are three interesting final states:
  - ☞ $Z \to \ell^+\ell^-$ and $t\bar{t} \to \ell^\pm \nu b\bar{b}jj$
  - ☞ $Z \to \ell^+\ell^-$ and $t\bar{t} \to b\bar{b} + 4$ jets
  - ☞ $Z \to \bar{\nu}\nu$ and $t\bar{t} \to b\bar{b} + 4$ jets
- only for the last process are the backgrounds substantial



- $t\bar{t}Z$ cross section smaller than $t\bar{t}\gamma$ cross section: need more integrated luminosity
  - ☞ can constrain ttZ vector (axial vector) couplings to $35 - 75\%$ (10%) with $300\ \mathrm{fb}^{-1}$, and to $16 - 55\%$ (3%)with $3000\ \mathrm{fb}^{-1}$ (SuperLHC (SLHC): $10\times$ LHC luminosity)
  - ☞ can constrain F_2^Z type couplings to O(40%) with $300\ \mathrm{fb}^{-1}$, and to O(25%) with $3000\ \mathrm{fb}^{-1}$



- Why is it of interest to measure the ttZ couplings?
- many models of new physics predict anomalous ttZ couplings (in addition to new particles etc.)
- Models such as top-seesaw models and Little Higgs models have an up-type quark singlet χ
  - ☞ χ and the top quark mix
  - ☞ which in turn changes the coupling of the lefthanded top quark to the Z boson:

$$\Delta F_{1V}^{Z} = -\Delta F_{1A}^{Z} = F_{1A}^{Z,SM} \sin^2\theta_L$$

where θ_L is the $\chi_L - t_L$ mixing angle

- Bounds achievable at the (S)LHC:

$$\sin^2\theta_L < 0.084\ (0.16) \quad \text{at } 68.3\%\ (95\%) \text{ CL for } 300\ \text{fb}^{-1}$$
$$\sin^2\theta_L < 0.030\ (0.06) \quad \text{at } 68.3\%\ (95\%) \text{ CL for } 3000\ \text{fb}^{-1}$$

- A more concrete example: $SU(5)/SO(5)$ Littlest Higgs model with T-parity:

$$\sin^2\theta_L = \frac{\lambda_T^2 v^2}{2m_T^2}$$

where $v \approx 246$ GeV, m_T = mass of heavy top quark partner, T, ($\simeq \chi$) and $\lambda_T = tTh$ coupling (h =Higgs boson)

$$\frac{m_T}{\lambda_T} > 600\ (430)\ \text{GeV} \quad \text{at } 68.3\%\ (95\%) \text{ CL for } 300\ \text{fb}^{-1}$$
$$\frac{m_T}{\lambda_T} > 1000\ (710)\ \text{GeV} \quad \text{at } 68.3\%\ (95\%) \text{ CL for } 3000\ \text{fb}^{-1}$$

- The LHC will be able to find a T quark if $m_T \leq 2$ TeV (ATLAS study)

- measuring the ttZ couplings gives information on λ_T