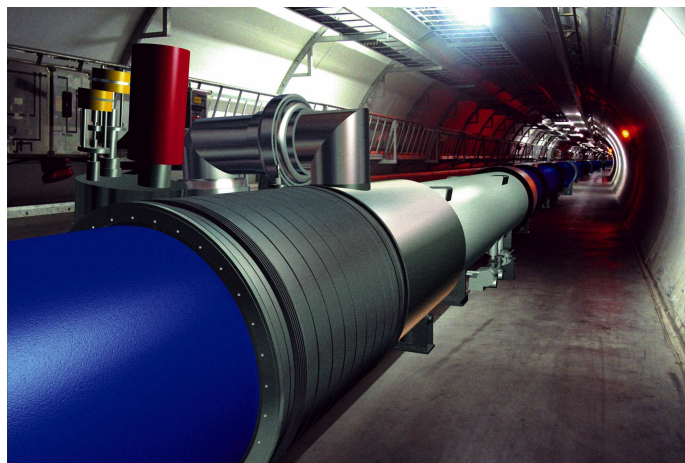


The Standard Model



1. Introduction to the Electroweak Theory
2. Introduction to Perturbative QCD
3. Probing the Standard Model at the LHC I
4. Probing the Standard Model at the LHC II

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Probing the Standard Model 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
 - ☞ High p_T top quark production 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)
 - ☞ UB, L.H. Orr, arXiv:0707.2066 [hep-ph] and references therein

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 ($\alpha_s \rightarrow 0$ for $q^2 \rightarrow \infty$)
- gluon self-couplings:

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

where $a = 1, \dots, 8$ and (A_μ^a is the gluon field)

$$G_{\mu\nu}^a = \partial_\mu A_\nu^a - \partial_\nu A_\mu^a + g_s f^{abc} A_\mu^b A_\nu^c$$

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 $SU(2)\times U(1)$ 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

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

$$\begin{aligned}
 W_{\mu\nu} &= \partial_\mu W_\nu - \partial_\nu W_\mu; \text{ same for } V_{\mu\nu}; \tilde{V}_{\mu\nu} = (1/2)\varepsilon_{\mu\nu\rho\sigma} V^{\rho\sigma} \\
 g_{WW\gamma} &= e; g_{WWZ} = e \cot \theta_W
 \end{aligned}$$

- 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)

$$\begin{aligned} \mu_W &= \frac{e}{2m_W} (g_1^\gamma + \kappa_\gamma + \lambda_\gamma) , & d_W &= \frac{e}{2m_W} (\tilde{\kappa}_\gamma + \tilde{\lambda}_\gamma) , \\ q_W &= -\frac{e}{m_W^2} (\kappa_\gamma - \lambda_\gamma) & \tilde{q}_W &= -\frac{e}{m_W^2} (\tilde{\kappa}_\gamma - \tilde{\lambda}_\gamma) . \end{aligned}$$

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

Sidebar: Unitarity

- Consider $2 \rightarrow 2$ 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**:

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

(proof only requires conservation of probability) and get:

$$\text{Im}(a_l) = |a_l|^2$$

which implies

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

- 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 $q\bar{q}' \rightarrow W\gamma$ amplitude $\mathcal{M}_{\lambda_\gamma \lambda_W}$ ($\lambda^{\gamma, W}$: γ (W) polarization; Θ : scattering angle):

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

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

- if κ, λ etc. is a constant, it must have SM value
- or, they are **momentum dependent form factors** which $\rightarrow 0$ for $\hat{s} \rightarrow \infty$
example:

$$\lambda_\gamma(\hat{s}) = \frac{\lambda_\gamma(0)}{\left(1 + \frac{\hat{s}}{\Lambda^2}\right)^2}$$

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 $\Lambda^2 = 0.71 \text{ GeV}^2$ is $\mathcal{O}(\Lambda_{QCD})$.
- special case: imposing $SU(2) \times U(1)$ 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 $\rightarrow 0$ for $\hat{s} \rightarrow \infty$
- 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
- how big are anomalous couplings in concrete models (such as SUSY)?
 - ☞ expect deviations from SM to be $\mathcal{O}(1)M_W^2/\Lambda^2$
 - ☞ for $\Lambda = \mathcal{O}(1 \text{ TeV})$: $10^{-2} - 10^{-3}$

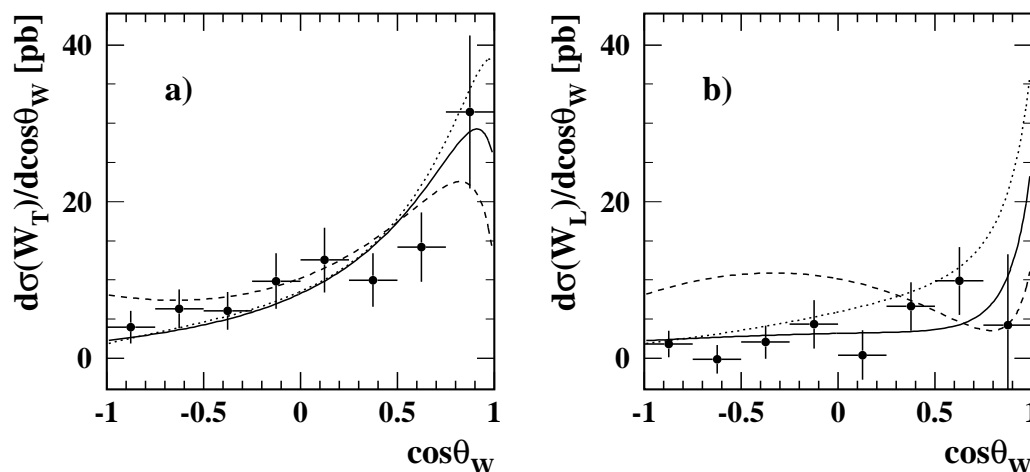
Neutral Weak Boson Couplings

- appear in $Z\gamma$ and ZZ production
- there are 4 $ZZ\gamma$, h_i^Z ($i = 1, \dots, 4$), and 4 $Z\gamma\gamma$ couplings, h_i^γ , which contribute to $q\bar{q} \rightarrow Z\gamma$
- $h_{1,3}$ ($h_{2,4}$) 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 $q\bar{q} \rightarrow ZZ$
- all these couplings have to be form factors which $\rightarrow 0$ for $\hat{s} \rightarrow \infty$ to avoid violation of unitarity

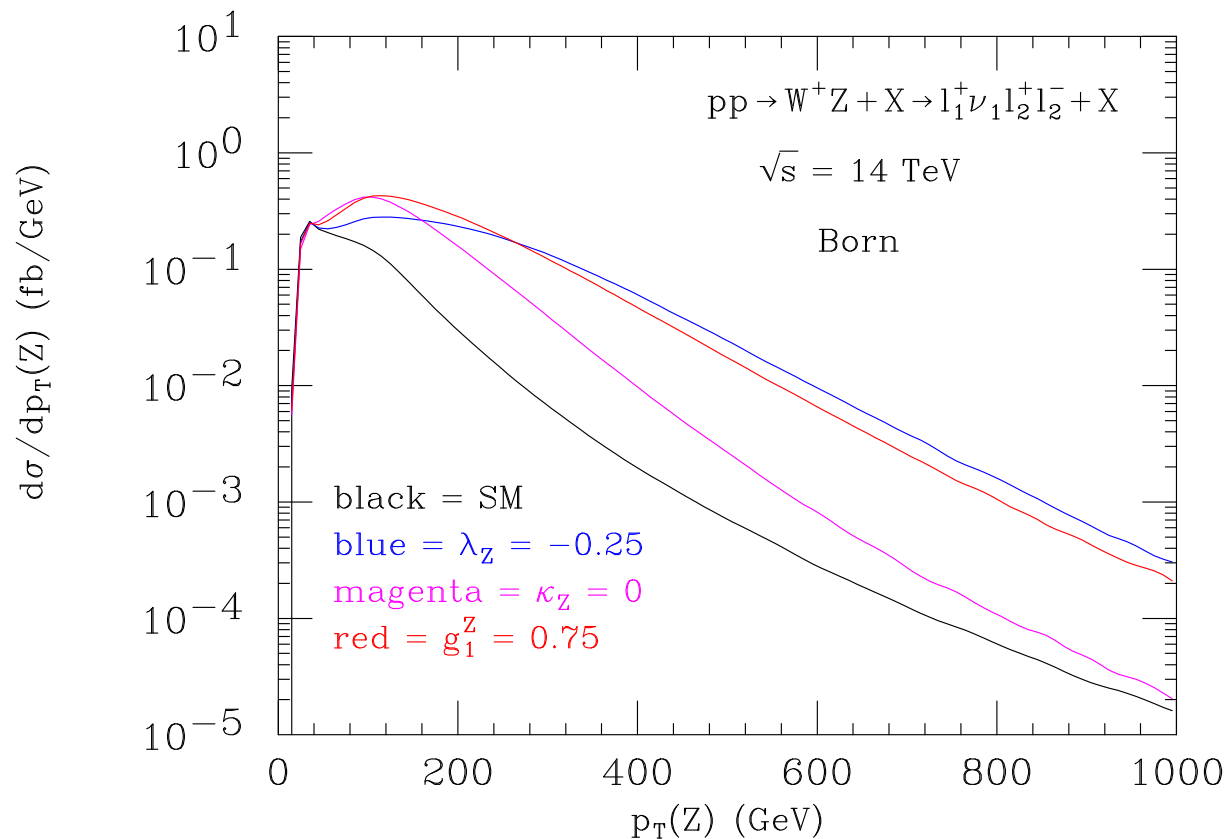
Measuring the Weak Boson Self-interactions

- 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 $e^+e^- \rightarrow W^+W^-$:

OPAL



- 👉 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 $\Lambda = 1 \text{ TeV}$):



- 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_i^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 $pp \rightarrow WW, WZ$ 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 $qg \rightarrow W\gamma q'$ and $qg \rightarrow WZ q'$
 - ☞ 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 $q_1 \bar{q}_2 \rightarrow W^\pm \gamma$: 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

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

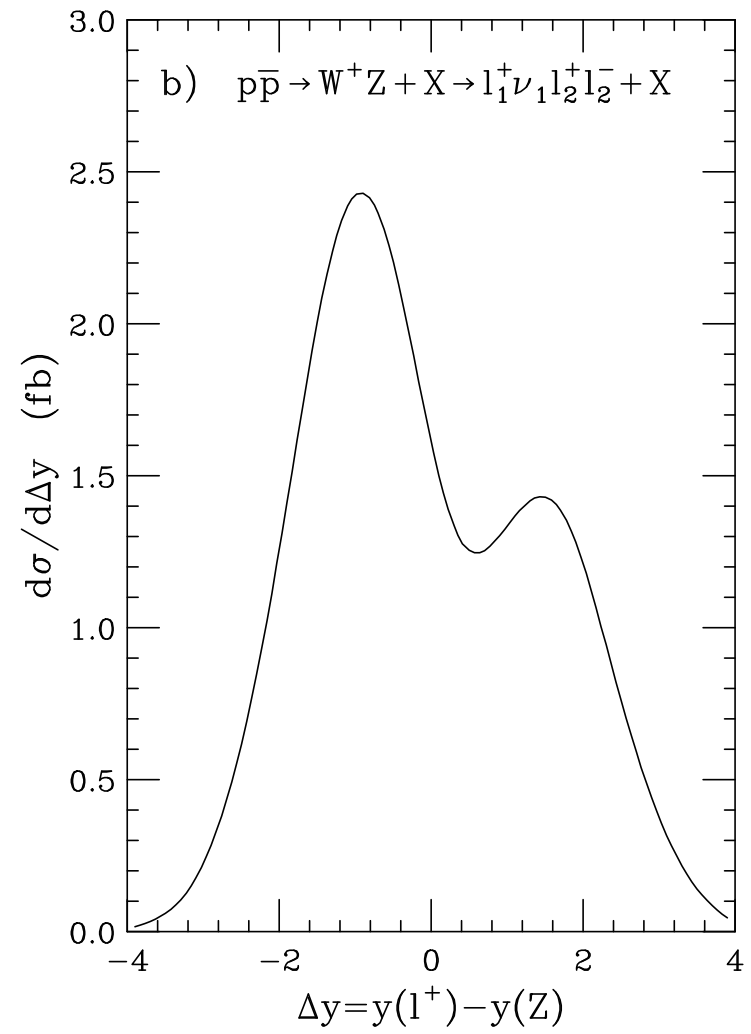
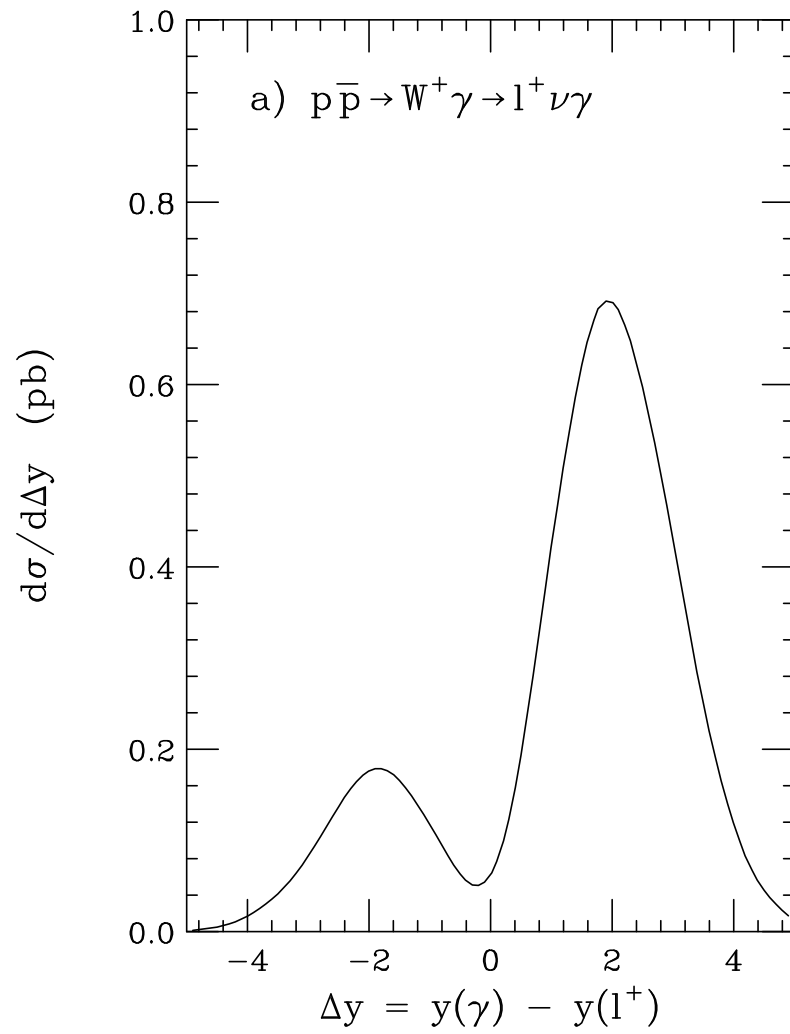
- the amplitude zeros only occur in the SM; anomalous $WW\gamma$ or WWZ couplings destroy it
- it should be possible to see the $W\gamma$ zero at the Tevatron as a dip in the

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

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

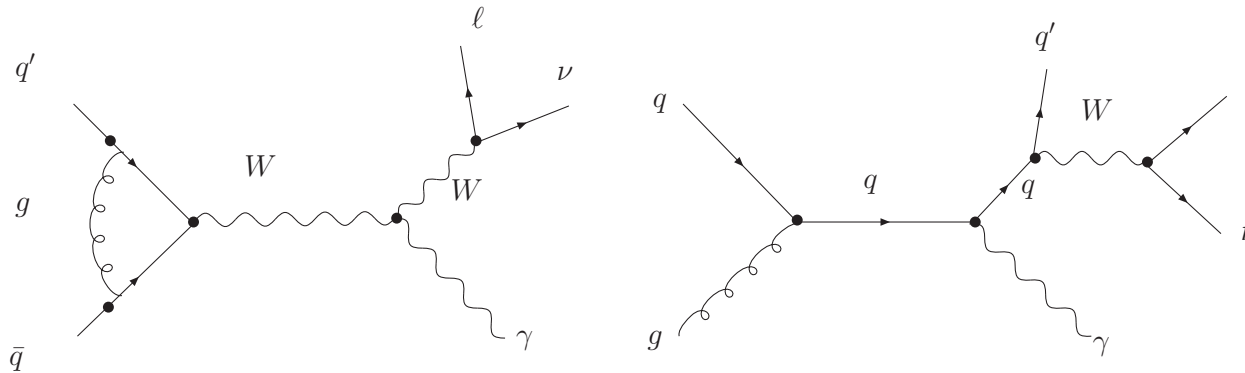
$$y = -\frac{1}{2} \log \left(\tan \frac{\theta}{2} \right)$$

- 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.



... back to the QCD corrections

- sample diagrams

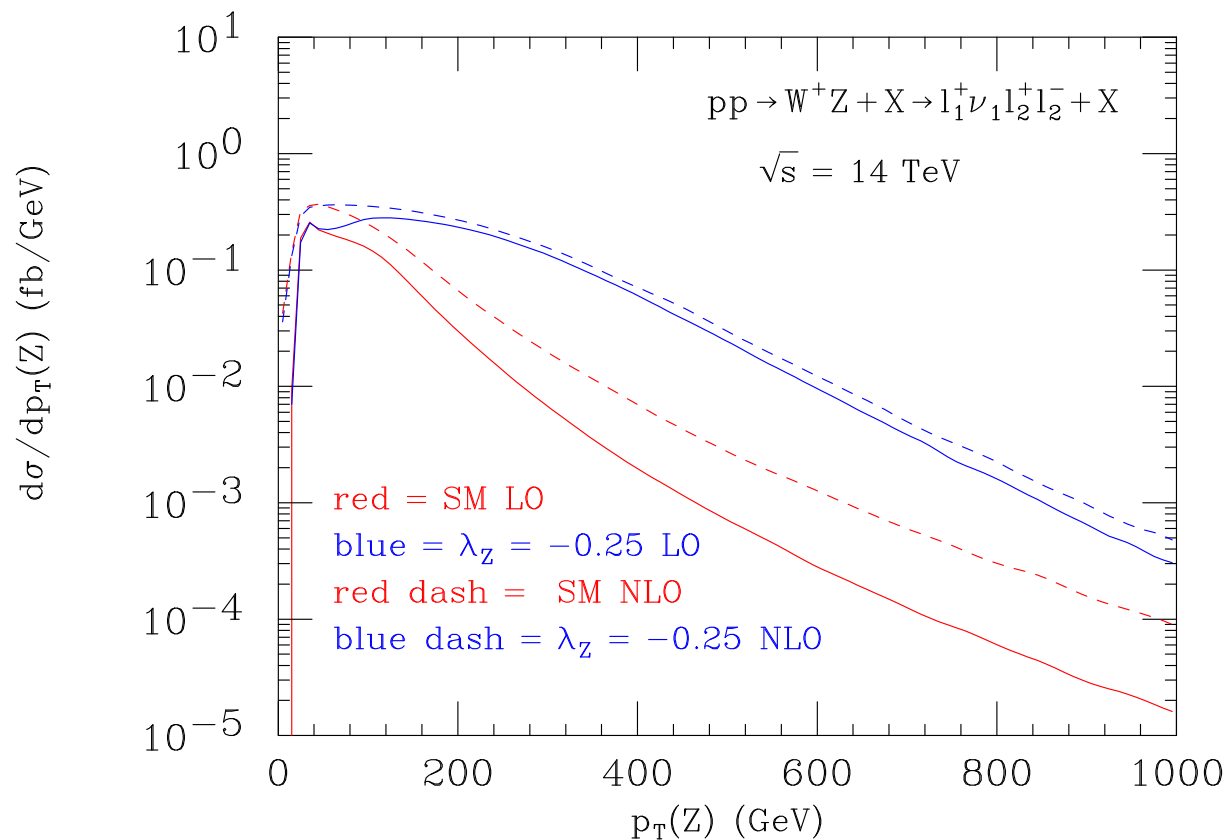


- the $qg \rightarrow W\gamma q'$ cross section can be written at high photon transverse momenta $p_T(\gamma)$:

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

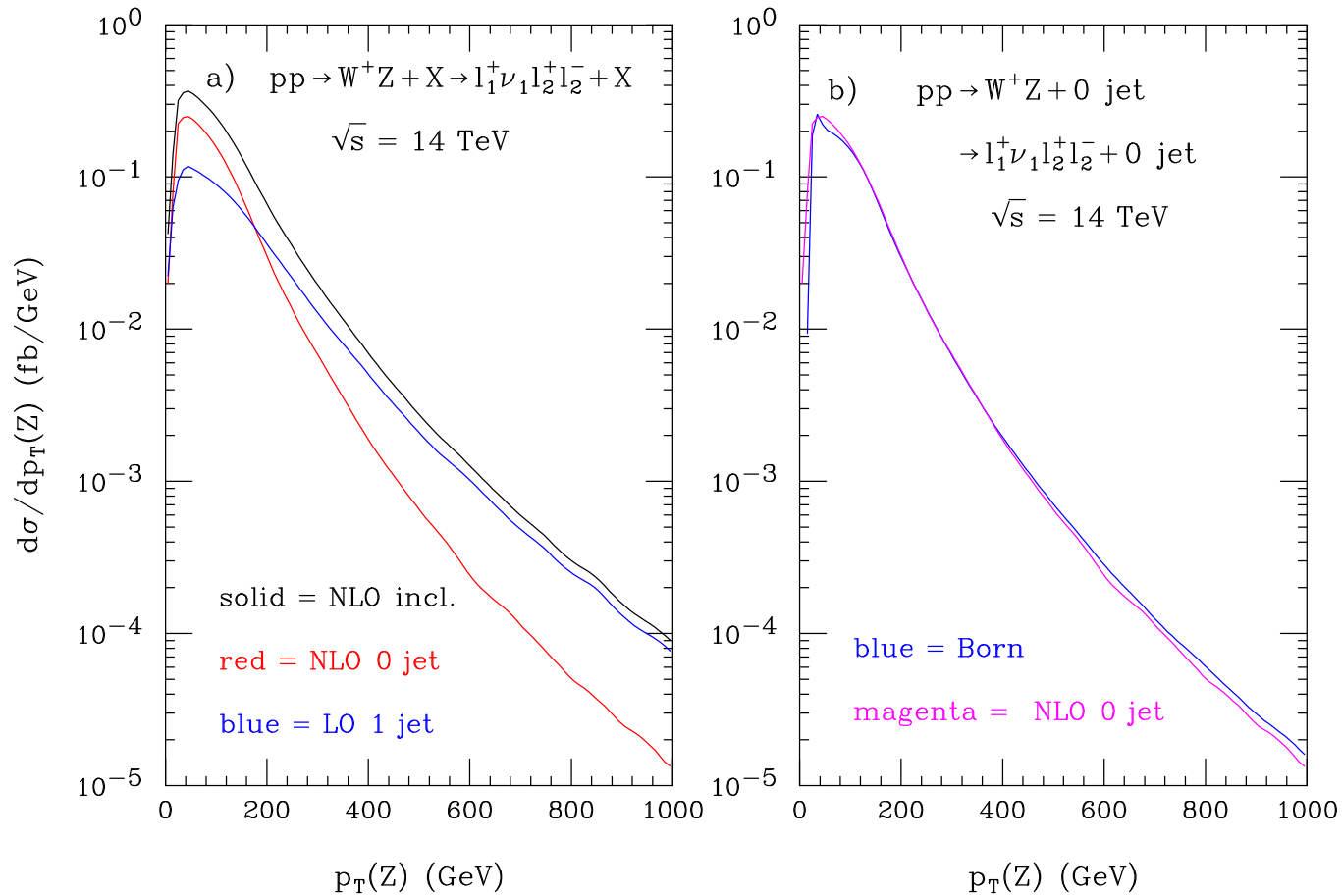
- similar expressions hold in WZ production and other processes

- 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 $e^+e^- \rightarrow W^+W^-$

$$g_1^Z = 0.984_{-0.019}^{+0.022} \quad \text{SM : } g_1^Z = 1$$

$$\kappa_\gamma = 0.973_{-0.045}^{+0.044} \quad \text{SM : } \kappa_\gamma = 1$$

$$\lambda_\gamma = -0.028_{-0.021}^{+0.020} \quad \text{SM : } \lambda_\gamma = 0$$

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

$$-0.48 < \lambda_Z < 0.48 \quad \kappa_Z = g_1^Z = 1$$

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

- 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 LEP II 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 LEP II 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 LEP II limits is possible

☞ LHC: one can reach the 10^{-3} level

- general remarks:

☞ The LHC gets close to the region where one expects to see deviations from the SM weak boson self-couplings (but there are better ways to discover new physics)

☞ the ILC will be able to probe anomalous couplings of $\mathcal{O}(10^{-4})$. We should definitely see deviations from the SM there.

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:

$$F_{2V}^\gamma(0) = Q_t (g - 2)/2, \quad Q_t = 2/3$$

→ F_{2A}^V violates CP and is related to electric (weak) dipole moment:

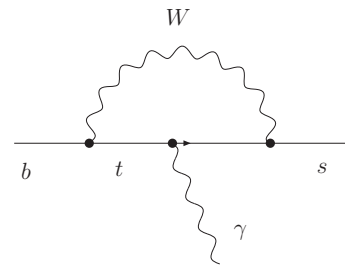
$$d_t^V = (e/2m_t)F_{2A}^V(0)$$

☞ concentrate on these 4 form factors here

● present bounds:

☞ $b \rightarrow s\gamma$ 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 $F_{iV,A}^V$ with a precision of **a few percent** in $e^+e^- \rightarrow t\bar{t}$ 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

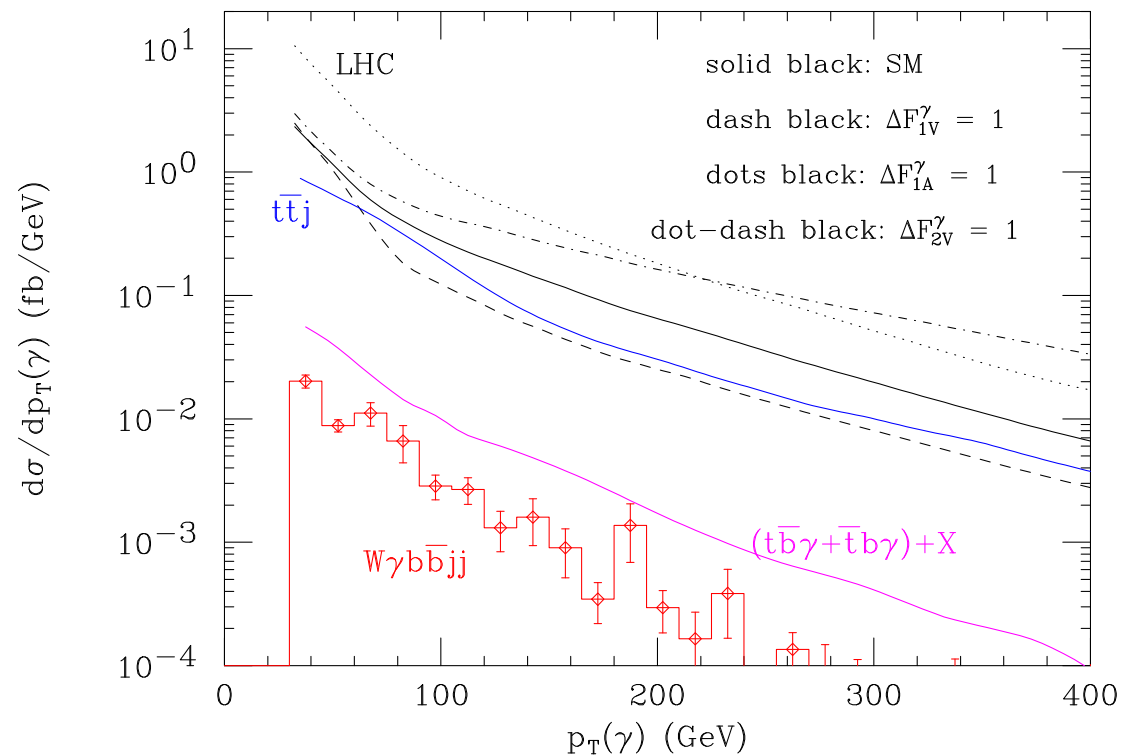
$t\bar{t}\gamma$ Production at the LHC

- concentrate on $\ell^\pm \nu jj b\bar{b}\gamma$ 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

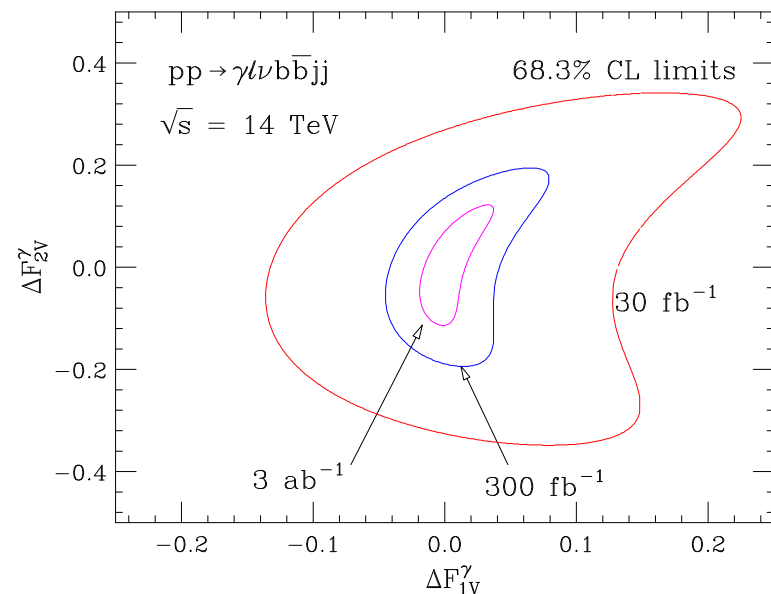
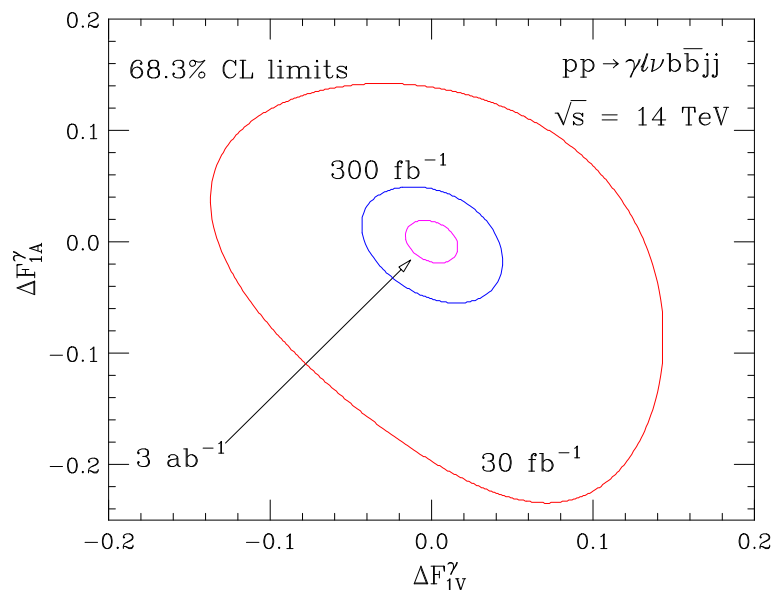
→ largest background if jet misidentification probabilities of CDF, DØ, ATLAS or CMS are used

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



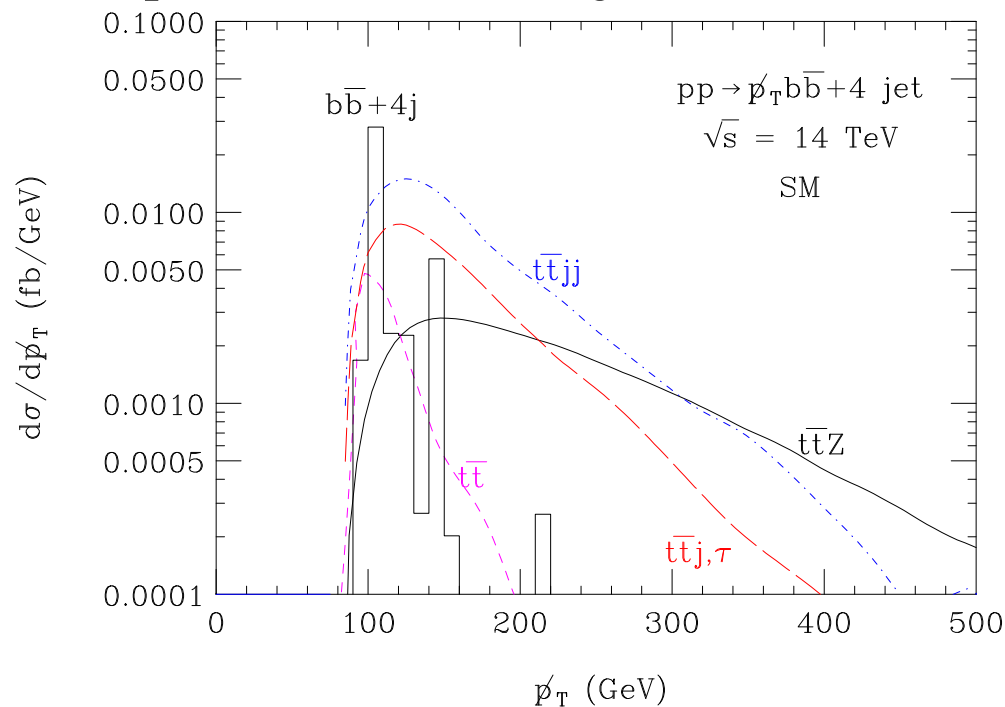
☞ background manageable

- 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}**

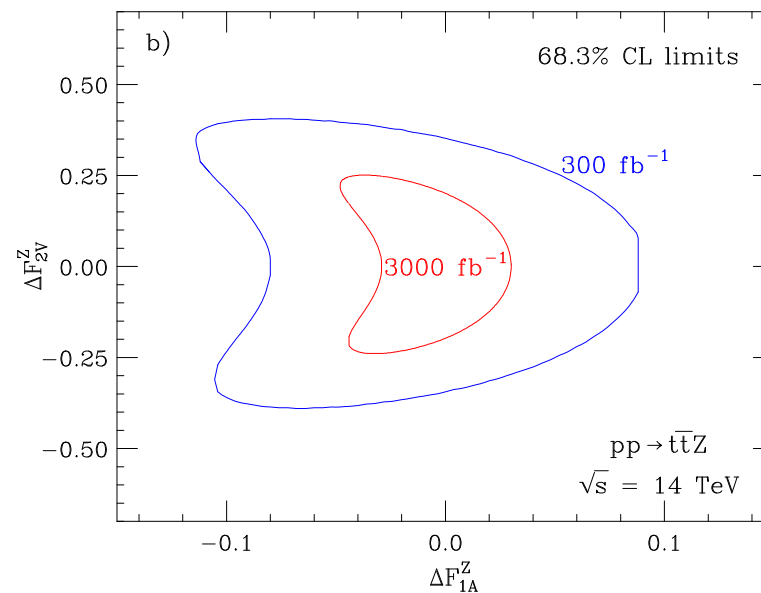
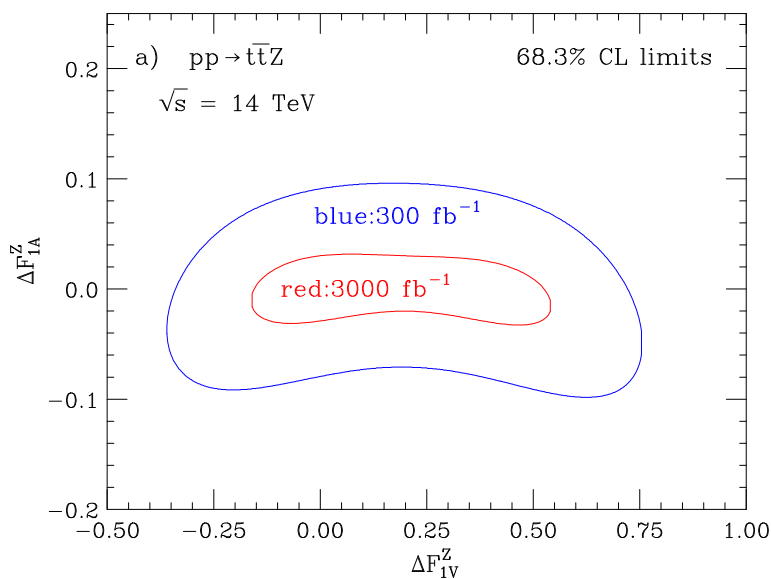


$t\bar{t}Z$ Production at the LHC

- There are three interesting final states:
 - ➡ $Z \rightarrow l^+ l^-$ and $t\bar{t} \rightarrow l^\pm \nu b\bar{b} j j$
 - ➡ $Z \rightarrow l^+ l^-$ and $t\bar{t} \rightarrow b\bar{b} + 4$ jets
 - ➡ $Z \rightarrow \bar{\nu} \nu$ and $t\bar{t} \rightarrow b\bar{b} + 4$ 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 fb^{-1} , and to 16 – 55% (3%) with 3000 fb^{-1} (SuperLHC (SLHC): $10\times$ LHC luminosity)
- ☞ can constrain F_2^Z type couplings to $O(40\%)$ with 300 fb^{-1} , and to $O(25\%)$ with 3000 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:

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

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

- 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)

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

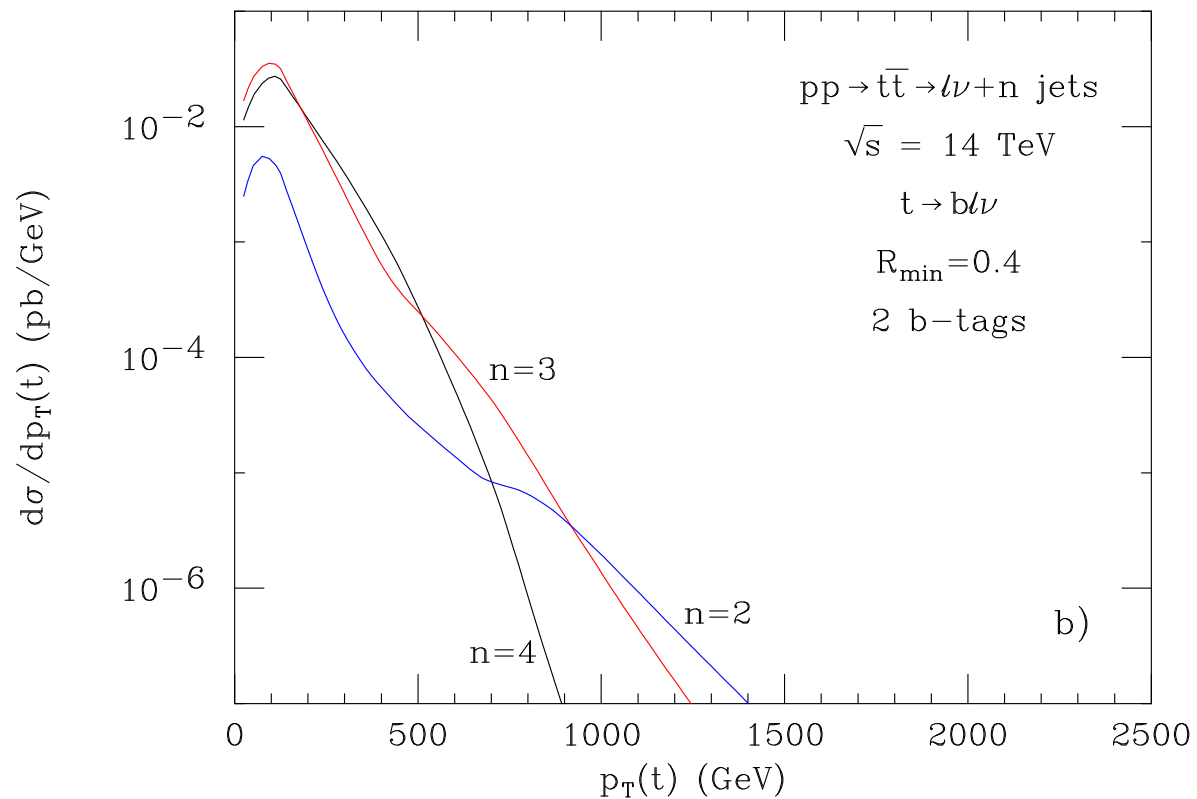
$$\frac{m_T}{\lambda_T} > 1000 \text{ (710) GeV} \quad \text{at 68.3\% (95\%) CL for } 3000 \text{ fb}^{-1}$$

- 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

High p_T Top Quark Production at the LHC

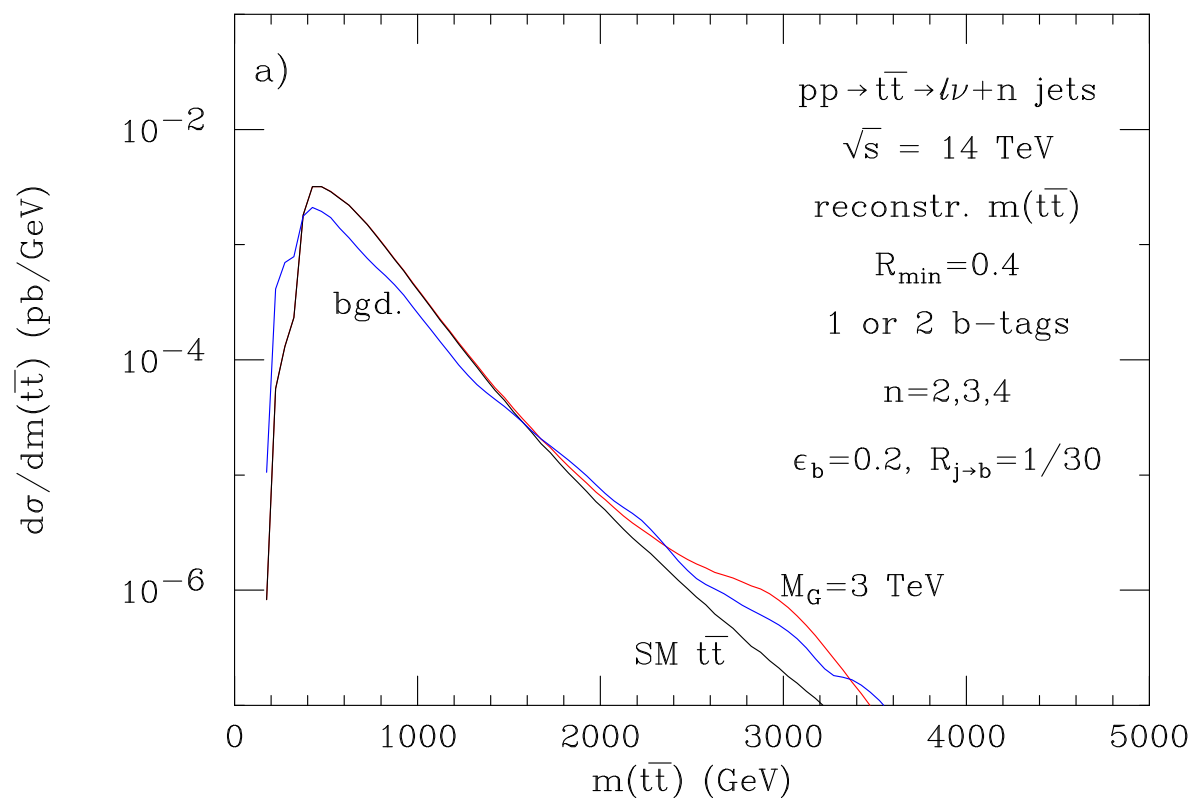
- why this is of interest: most models of new physics predict resonances in the TeV region which couple to $t\bar{t}$
examples: topcolor, Randall Sundrum, Little Higgs
- in some models resonances couple mainly to $t\bar{t}$ (bulk RS models)
→ searching for $t\bar{t}$ resonances only way to find those particles
- for top quarks with energies in the TeV region: **top quark decay products are highly collimated due to Lorentz boost**
- now, lets look at $t\bar{t}$ with $t \rightarrow b\ell\nu$ and $\bar{t} \rightarrow \bar{b}jj$
because the t, \bar{t} decay products are highly collimated, some or all of the $\bar{t} \rightarrow \bar{b}jj$ jets may merge and the lepton may not be isolated
- imposing standard isolation cuts on jets **and** requiring 4 jets in $t\bar{t} \rightarrow \ell\nu b\bar{b}jj$ events will greatly reduce the observable rate in the TeV region
→ **consider $\ell\nu + n$ jet events with $n < 4$**

- what about non-isolated leptons?
bad idea! need those to trigger the event
- gain from $\ell\nu + n$ jet events with $n < 4$



- in $\ell\nu + 2$ jet events: one jet has inv. mass close to m_{top} , but is tagged as a b -jet (“ t -jet”)
- potential problem with $\ell\nu + n$ jet events with $n < 4$: $W + n$ jets background could be larger, since it occurs at lower order in perturbation theory
- **WAIT! It gets worse**
 - ☞ at large energies, the b -tagging efficiency **decreases by a factor 3**
 - ☞ and the light quark mistagging probability **increases by a factor 3**
 - ☞ may significantly worsen the S/B ratio
- impose (cluster transverse) mass cuts to reduce background to acceptable level
- **background:** need to calculate $Wb\bar{b} + \text{jets}$, $Wb + \text{jets}$, $W + \text{jets}$, $t\bar{b} + \text{jets}$, $t + \text{jets}$, Wt , Wjt and Wbt production

- This looks like serious work!
- The calculation is facilitated by using automatic tools. We use ALPGEN for $Wb\bar{b} + \text{jets}$ and $W + \text{jets}$, and MadEvent for all other processes
- when its all said and done ...



- the red curve is for a bulk RS KK gluon of mass $M_G = 3$ TeV (these states couple strongly to quarks, but not to gluons)
- when combining 2, 3 and 4 jet final states and channels with one and two b -tags, the background is non-negligible, but manageable
- get about 100 signal and 400 background events for $m(t\bar{t}) > 2$ TeV, *ie.* a 5σ effect
- the background has a more negative effect on weakly coupled resonances (*eg.* Little Higgs Z' , bulk RS KK graviton)