Early Electroweak Measurements at the LHC

1. Motivation
2. W/Z production: on and off the resonance
3. Di-boson production
4. Conclusions

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1 – Introduction

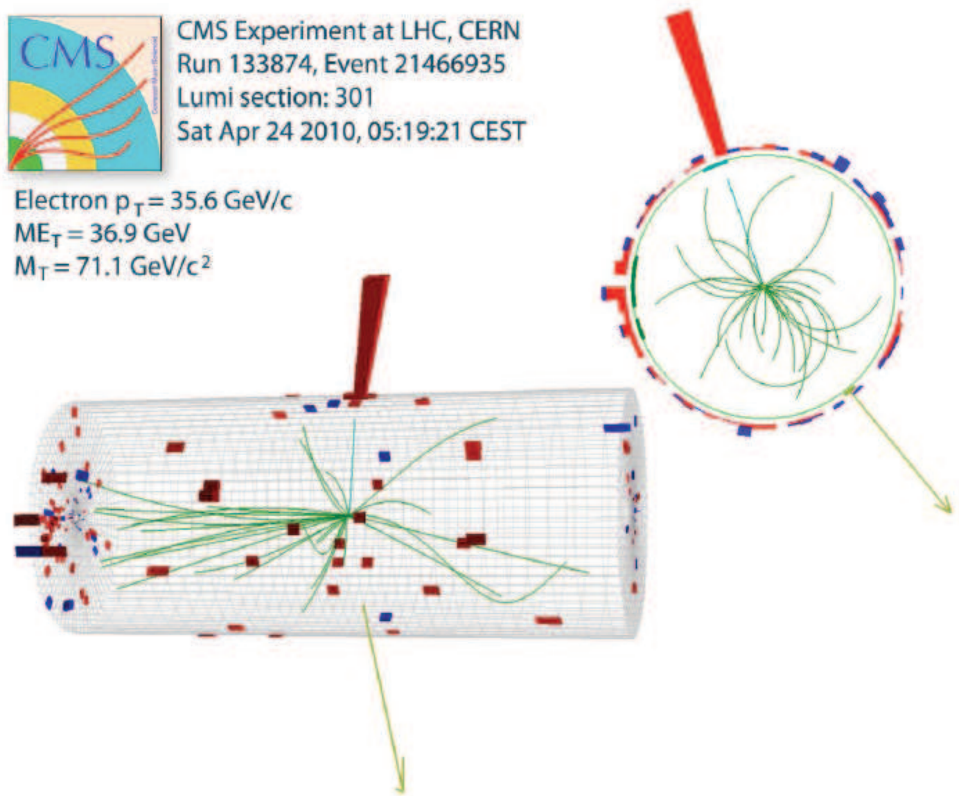
- I will concentrate on two topics:
  - ☞ W/Z production on and off the resonance
  - ☞ di-boson production: probing gauge boson self-couplings
- W/Z production:
  - ☞ Standard candles
  - ☞ W mass measurement (maybe not in the first year or so...)
  - ☞ constraining PDF's
  - ☞ search for W' and Z' resonances

- di-boson production:
  - ☞ probe WWV, $V = \gamma$, Z, vertex in $W\gamma$, WZ and WW production
  - ☞ probe $ZZ\gamma$ and $Z\gamma\gamma$ vertices in $Z\gamma$ production
  - ☞ probe $ZZ\gamma$ and ZZZ couplings in ZZ production
- I will concentrate on how higher order QCD and electroweak (EW) corrections affect measurements
- most numerical results are for $\sqrt{s} = 14$ TeV, but hold *mutatis mutandis* for $\sqrt{s} = 7$ TeV

2 – W/Z production: on- and off-shell

- W and Z Production has been observed at the LHC

W→eν candidate



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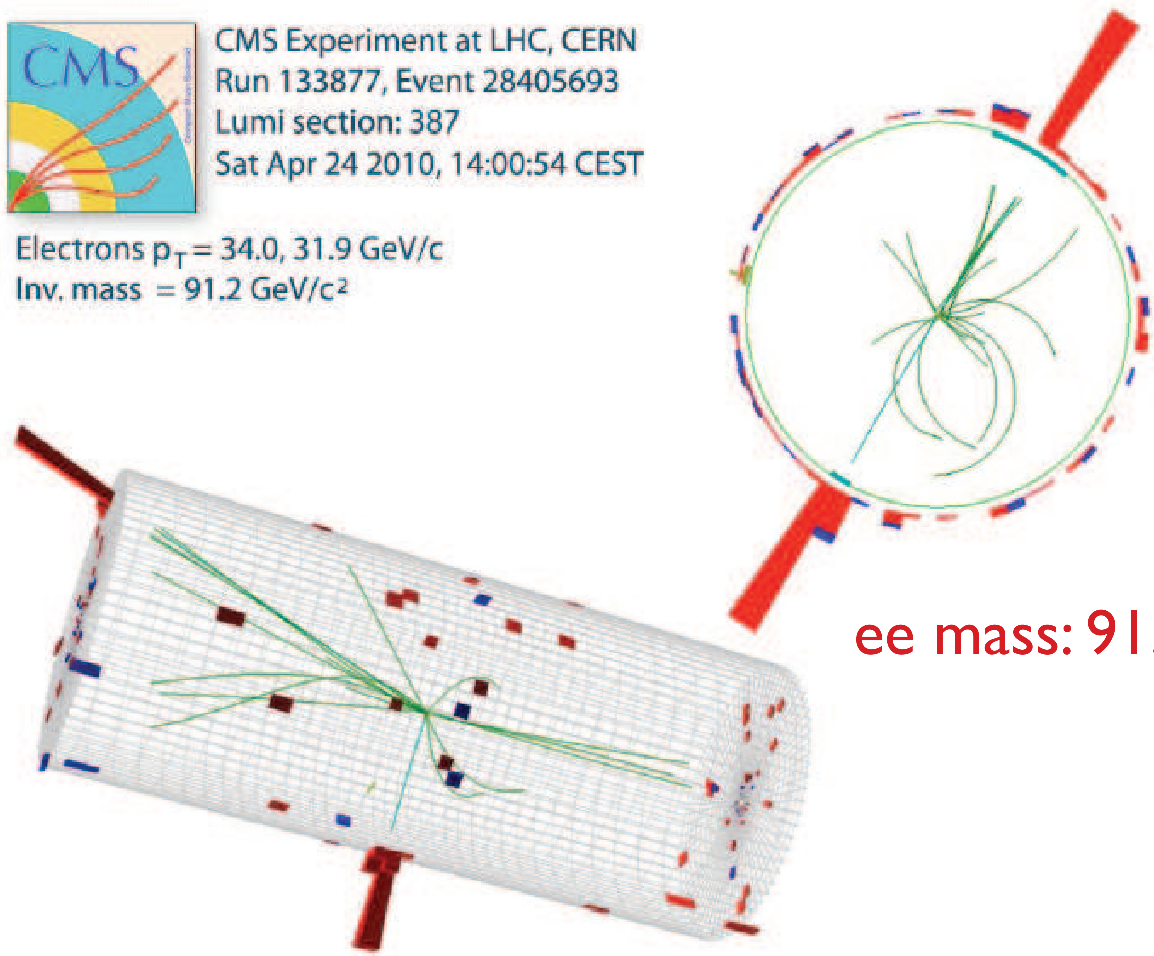
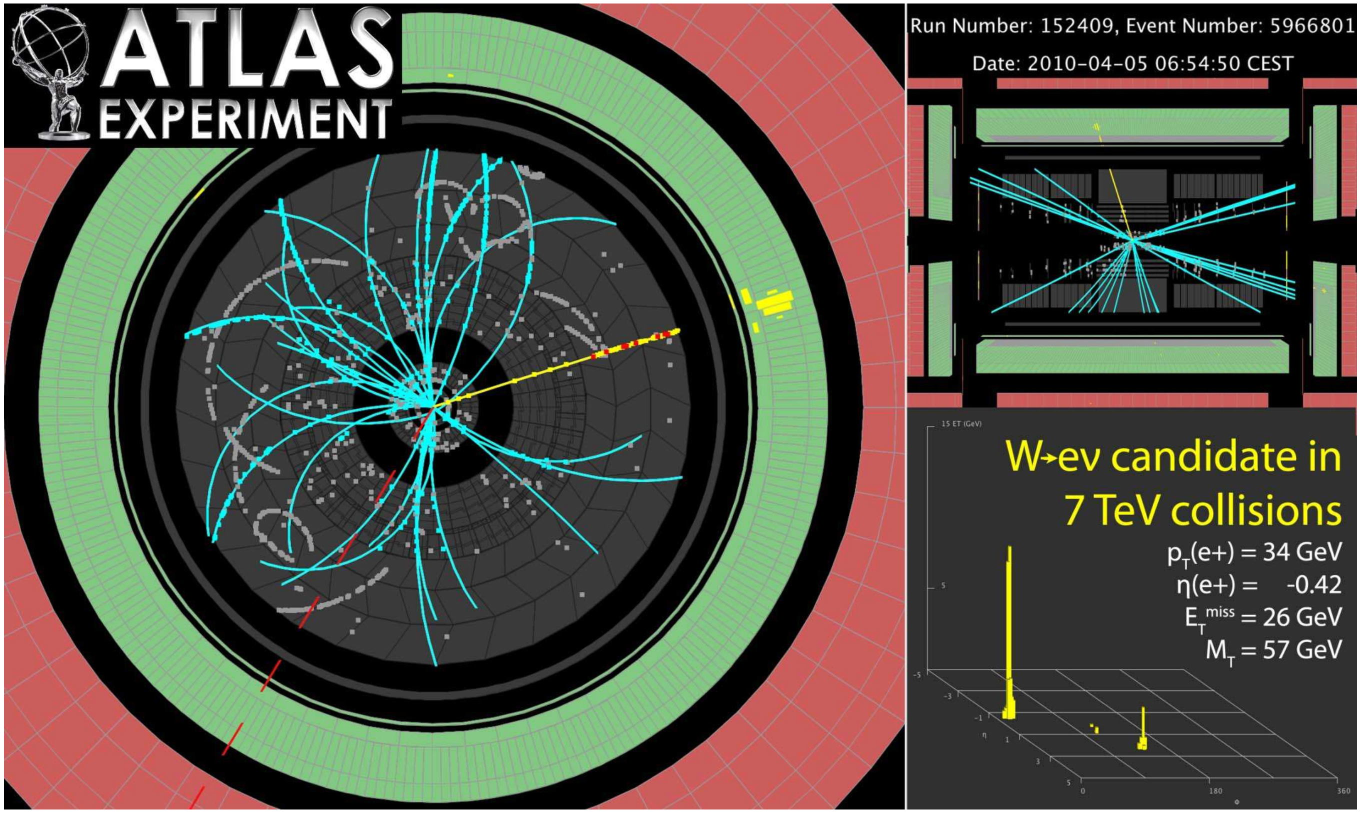
Z → ee candidate



ee mass: 91.2 GeV

W→eν Candidate



- expect a torrent of W's and Z's at the LHC in the near future
- for $\sqrt{s} = 7$ TeV:
  $\sigma(W^\pm \to \ell\nu) \approx 10.5$ nb
  $\sigma(Z \to \ell^+\ell^-) \approx 0.96$ nb
- cross section approximately doubles for $\sqrt{s} = 14$ TeV
- Status of theory calculations for W/Z production:
  - ☞ the NNLO QCD corrections to W/Z production are known in fully differential form (Melnikov, Petriello) and are available in form of a parton level MC program (FEWZ)
  - ☞ resummed NLL QCD corrections (soft gluon resummation) are known (RESBOS)
  - ☞ NLO QCD corrections have been merged with HERWIG in MC@NLO and POWHEG

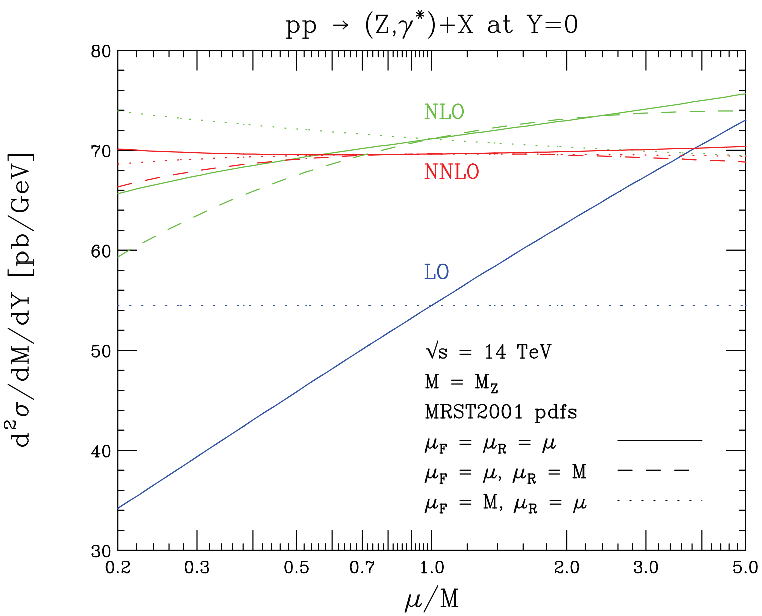
- Status of theory calculations for W/Z production (continued...)
  - ☞ several calculations of the full $\mathcal{O}(\alpha)$ EWK corrections to W/Z production exist (UB, Wackeroth [WGRAD, ZGRAD]; Bardin *et al.* [SANC]; Carloni Calame *et al.* [HORACE]; Dittmaier, Denner; Jadach *et al.* [WINHAC])
- Why do we need higher order QCD corrections?
  - ☞ LO cross sections strongly depend on the renormalization and factorization scales, μ_R and μ_F, used
  - ☞ this dependence is an artificial byproduct of truncating the perturbation series
  - ☞ the scale dependence is (usually) reduced when higher order QCD corrections are included, and NLO theory predictions tend to agree much better with actual data

- Example: $W + n$ jet production at the Tevatron (C. Berger et al., arXiv:0907.1984)

♯ of jets	CDF	LO	NLO
1	53.5 ± 5.6	$41.40(0.02)^{+7.59}_{-5.94}$	$57.83(0.12)^{+4.36}_{-4.00}$
2	6.8 ± 1.1	$6.159(0.004)^{+2.41}_{-1.58}$	$7.62(0.04)^{+0.62}_{-0.86}$
3	0.84 ± 0.24	$0.796(0.001)^{+0.488}_{-0.276}$	$0.882(0.005)^{+0.057}_{-0.138}$

- in some cases (eg. $W + 1\ jet$ production) NLO is not enough...

- when do we need NNLO corrections?
  - ☞ When NLO corrections are large and NNLO is needed to check expansion ($gg \to H$)
  - ☞ for benchmark processes where high precision is needed ($pp \to jj, W/Z$ production)
- Example: (Anastasiu et al.)



The NNLO residual scale uncertainty is $< 1\%$

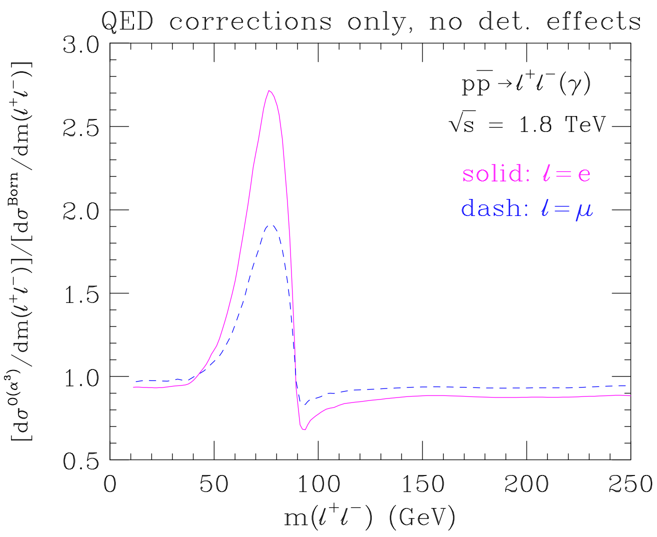
- $\mathcal{O}(\alpha)$ electroweak (EWK) corrections to W/Z production
  - ☞ 1-loop: naively of $\mathcal{O}(\alpha) \leq 1\%$
  - ☞ why bother?
  - ☞ EWK corrections may be enhanced by large
    - ➞ collinear logs: $\log(\hat{s}/m_f^2)$, relevant near the W/Z peak
    - ➞ Sudakov logs: $\log(\hat{s}/M_{W/Z}^2)$, relevant at large di-lepton masses
    - ☞ QCD corrections may be small (example: QCD corrections largely cancel in W/Z cross section ratio)
    - ☞ for consistent treatment need PDF's which include QED corrections. These are available in MRSTQED04 set (eventually will need an update to these ...)

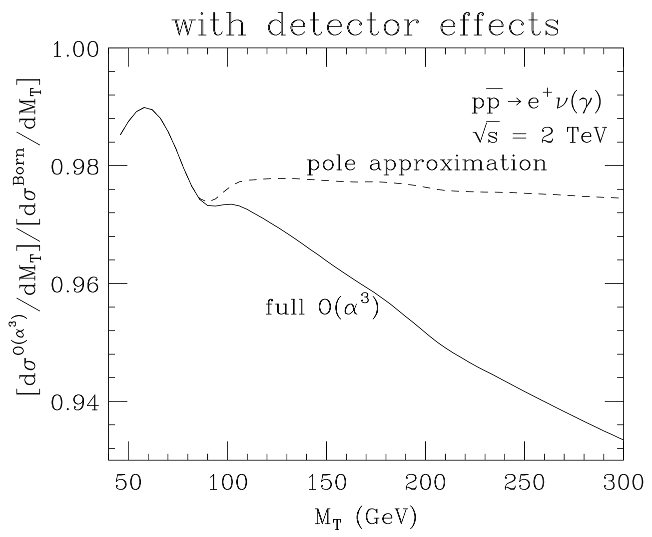
Anatomy of the EWK $\mathcal{O}(\alpha)$ Corrections

- 1-loop EWK corrections shift W and Z masses by $\mathcal{O}(100\text{ MeV})$
  - ☞ most of the effect comes from final state photon radiation
  - ☞ proportional to

$$\frac{\alpha}{\pi}\log\left(\frac{\hat{s}}{m_\ell^2}\right)$$

→ these terms together with the Sudakov logs significantly influence the $\ell^+\ell^-$ inv. mass distribution and $\ell\nu$ transverse mass distribution (pole approximation: no Sudakov logs are present)





Sidebar: W mass measurement at the LHC

- need

$$\delta M_W \approx 7 \times 10^{-3} \cdot \delta m_{top}$$

for equal contribution to M_H uncertainty from m_{top} and M_W

☞ Tevatron: $\delta m_t = 1.1$ GeV (NEW!!)

☞ expect $\delta m_t \approx 1$ GeV at LHC

☞ limited by non-perturbative QCD effects, which introduce theoretical uncertainty $\delta m_t = \mathcal{O}(\Lambda_{QCD})$ (renormalon uncertainty)

→ $\delta M_W < 10$ MeV should be goal for LHC

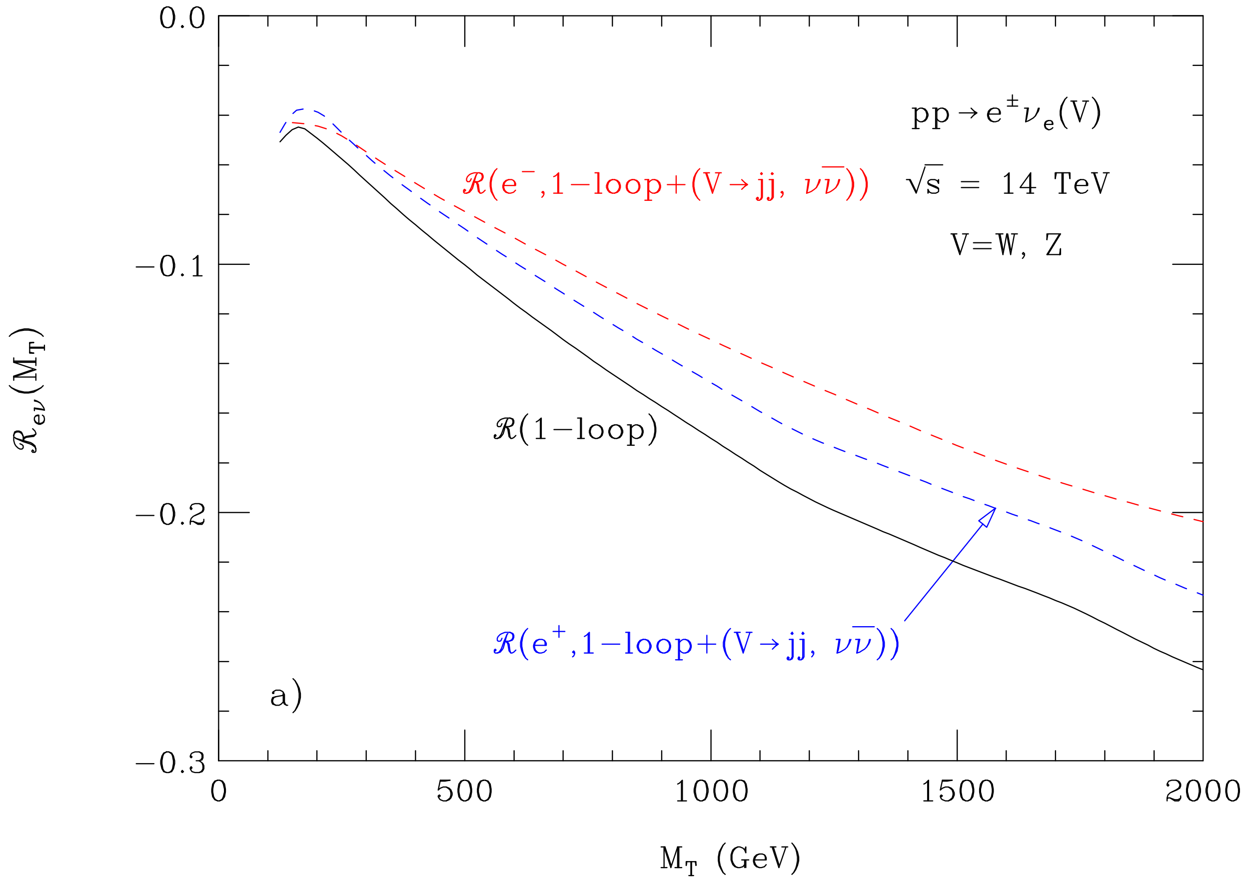
- LHC expectations (for $\sqrt{s} = 14$ TeV):
  - ☞ ATLAS: $\delta M_W = 7$ MeV for 10 fb^{-1} per lepton channel using the M_T and $p_T(\ell)$ distributions (arXiv:0805.2093)
    - → need excellent understanding of detector (lepton scale and resolution, $\not{p}_T$ resolution) to achieve this
    - → assumes that PDF uncertainties can be controlled such that they contribute only 1 MeV to δM_W
    - → assumes that needed theoretical tools will be available to achieve a 1 MeV uncertainty from unknown higher order corrections
  - ☞ CMS: $\delta M_W = 40$ MeV (20 MeV) for 1 fb^{-1} (10 fb^{-1}) using the scaled observable method and the so-called morphing method (J. Phys. G **34** (2007), N193)

    → CMS makes less aggressive assumptions on PDF and theoretical uncertainties

Electroweak Sudakov Logs

- for $\hat{s} \gg M^2_{W/Z}$, the weak corrections become large and negative
- relevant for new physics searches in $\ell\nu$ and $\ell^+\ell^-$ production (eg. W', Z' searches)
- However, EW corrections do not include real EW corrections, eg. $WW \to \ell\nu jj$ which may partially cancel the large, negative EW one-loop corrections (UB)
- answer depends on whether one looks at exclusive or inclusive Drell-Yan production

$\mathcal{R}_{e\nu}$: relative correction to LO cross section



Combining QCD and EW corrections

- QCD and EW corrections tend to cancel in the high mass region
- for accurate predictions need a calculation which combines QCD and EW corrections, preferably interfaced with PYTHIA or HERWIG
- such a calculation is also needed to achieve $\delta M_W \approx 10$ MeV or better
- The HORACE team has interfaced HORACE (EW corrections) with MC@NLO (NLO QCD corrections consistently interfaced with HERWIG)
  (arXiv:0907.0276)

- the procedure for doing this is not unique
- additive approach:

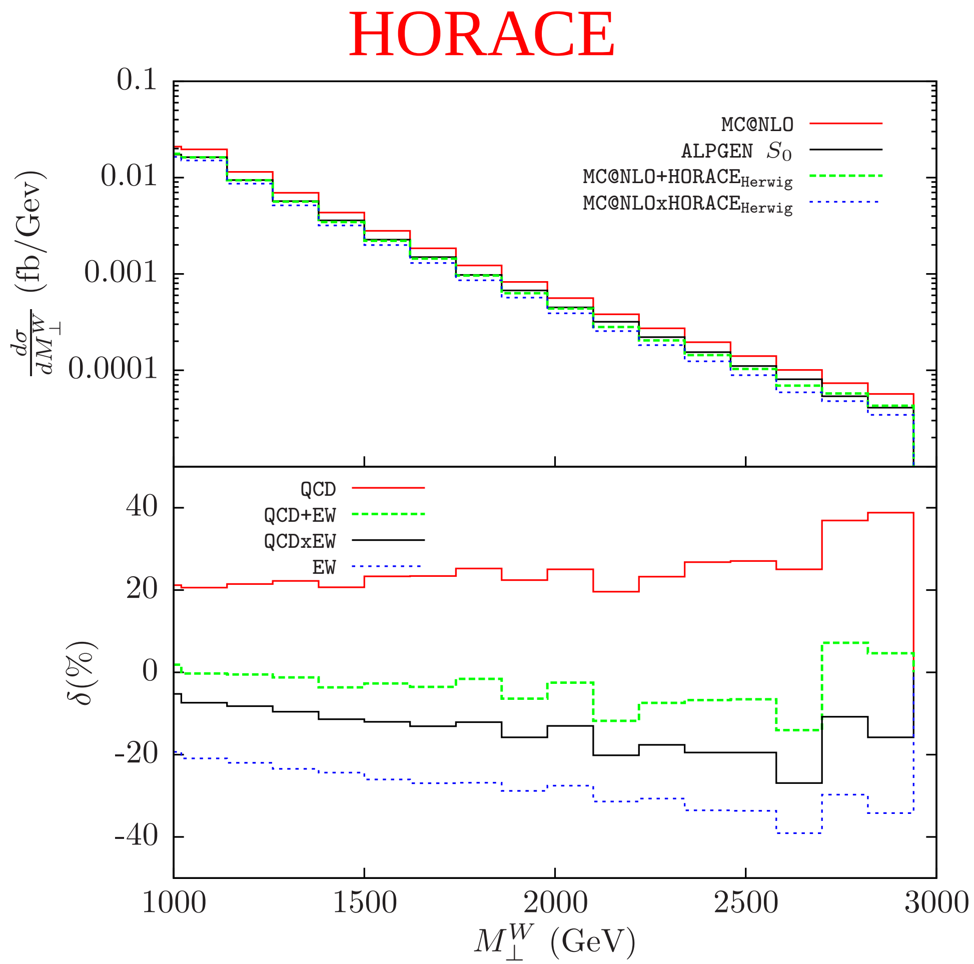
$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{QCD\&EW} = \left\{\frac{d\sigma}{d\mathcal{O}}\right\}_{MC@NLO} + \left\{\left[\frac{d\sigma}{d\mathcal{O}}\right]_{EW} - \left[\frac{d\sigma}{d\mathcal{O}}\right]_{LO}\right\}_{HERWIG\ PS}$$

- factorized approach:

$$\left[\frac{d\sigma}{d\mathcal{O}}\right]_{QCD\&EW} = \left(1 + \frac{[d\sigma/d\mathcal{O}]_{MC@NLO} - [d\sigma/d\mathcal{O}]_{HERWIG\ PS}}{[d\sigma/d\mathcal{O}]_{LO/NLO}}\right) \times \left\{\frac{d\sigma}{d\mathcal{O}_{EW}}\right\}_{HERWIG\ PS}$$

  - ➡ defined either in terms of LO or NLO cross section
  - ➡ differ at $\mathcal{O}(\alpha_s^2)$ by non-leading contributions
- the residual uncertainties resulting from the ambiguity between the additive and factorized approach are of $\mathcal{O}(\alpha\alpha_s)$

☞ they are numerically significant



→ need full $\mathcal{O}(\alpha\alpha_s)$ corrections to quantify

3 – 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
- 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

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

$W_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$; 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)

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

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

- S-matrix unitarity requires weak boson self-couplings to be of SM form at high energies
- anomalous weak boson couplings need to have a form factor behaviour such as

$$\frac{1}{(1+\frac{\hat{s}}{\Lambda^2})^n}$$

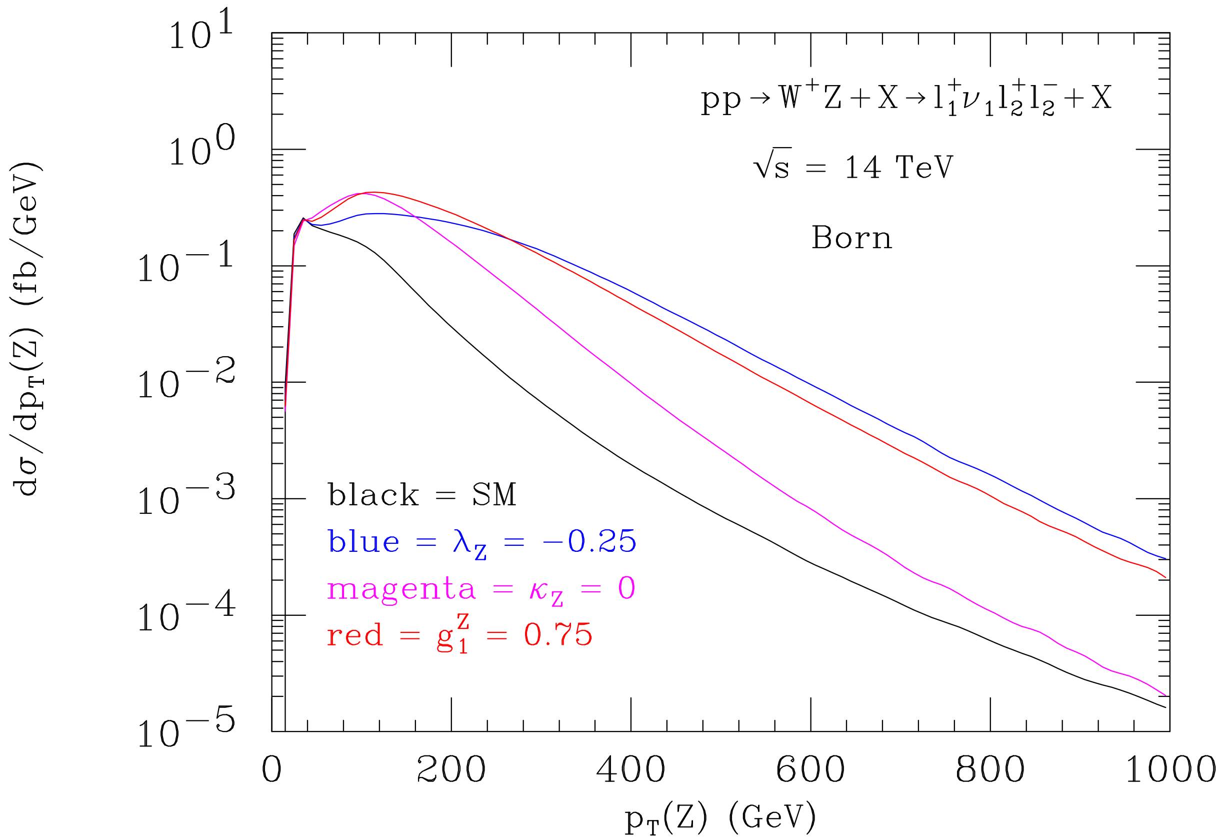
where Λ is the scale of new physics responsible for the non-standard couplings ($n = 2$ is often used)

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

- thus, non-standard gauge boson self-couplings lead to an enhanced cross section at large gauge boson transverse momenta

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



QCD corrections to Di-boson Production

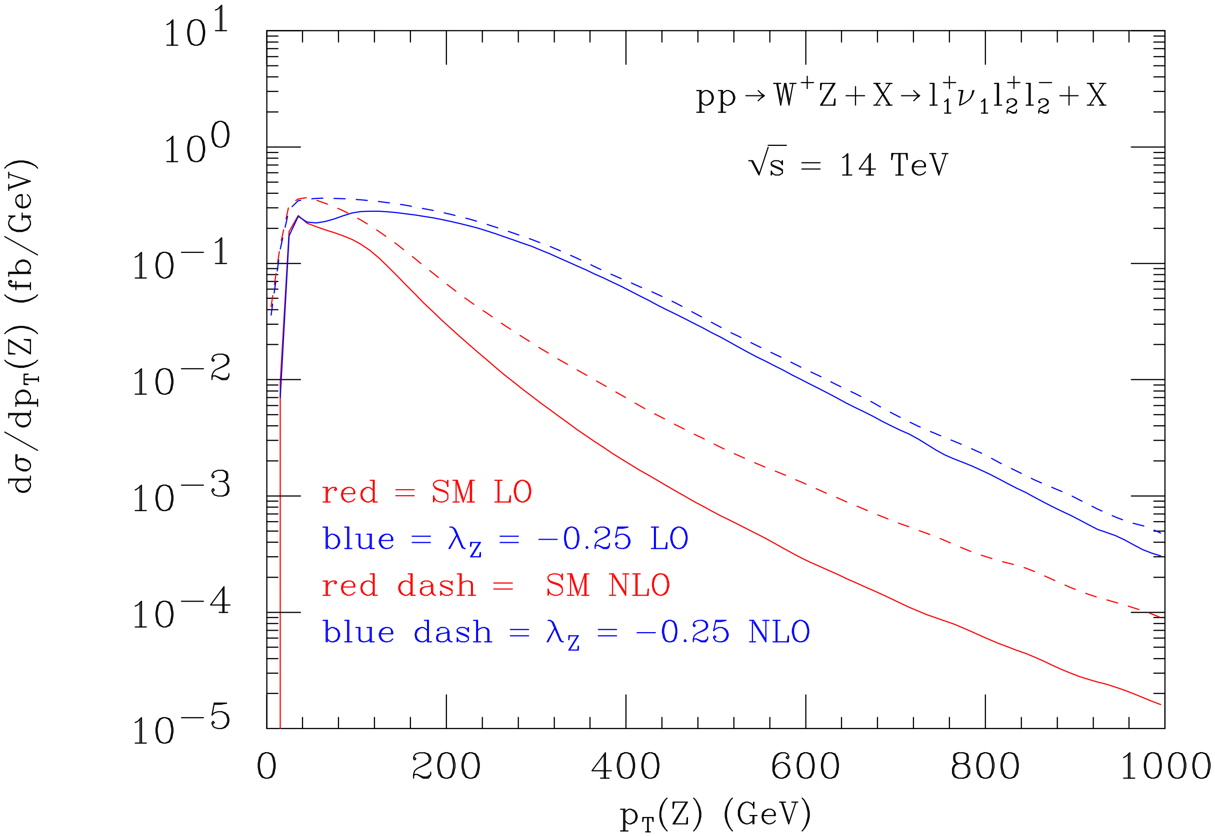
- QCD corrections to di-boson production become very large at high energies
- Reason: there is a logarithmic enhancement factor, eg, for $W\gamma$ production, the $qg \to W\gamma q'$ cross section can be written at high photon transverse momenta $p_T(\gamma)$:

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

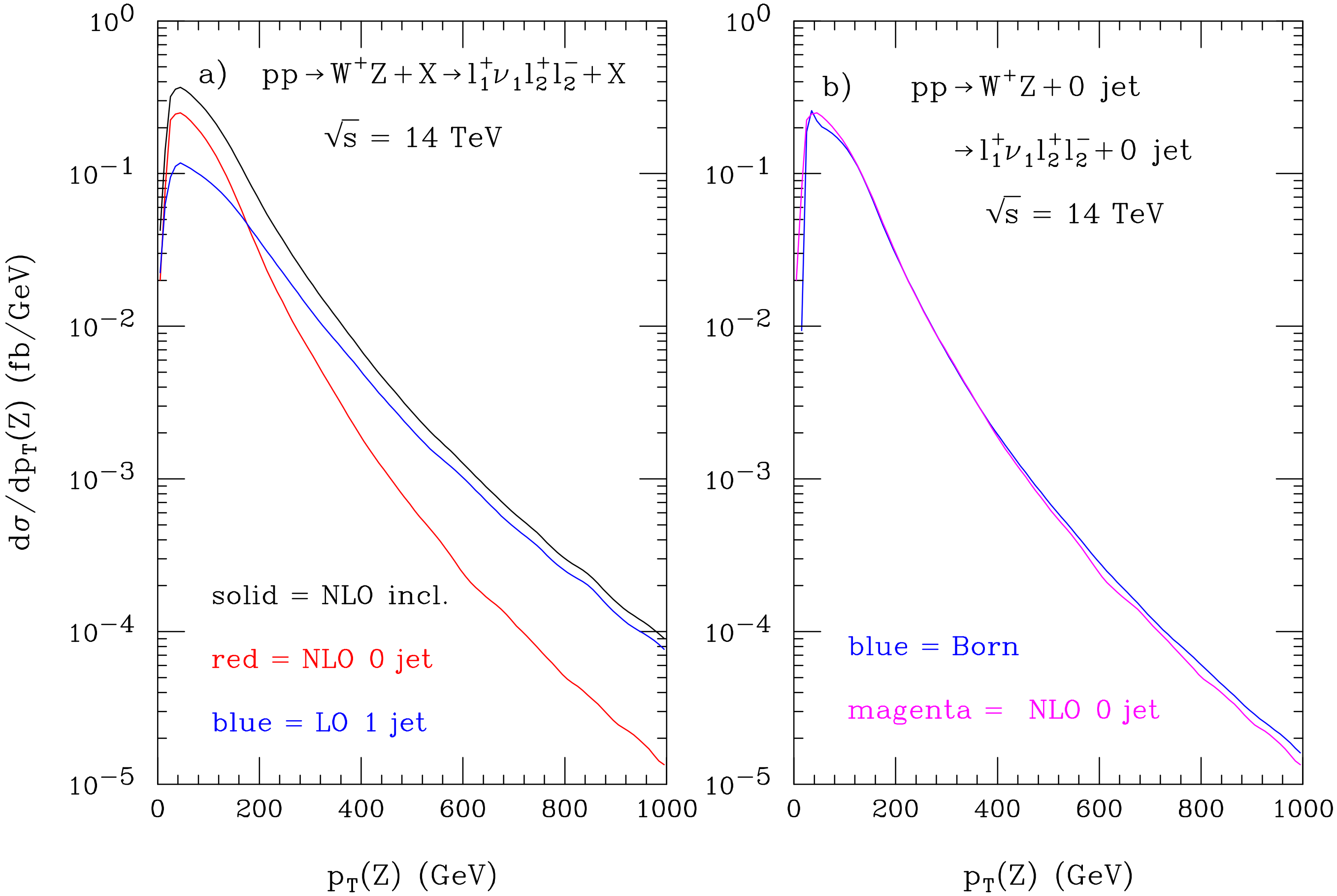
- similar expressions hold in WZ production and other processes

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

  → QCD corrections substantially reduce sensitivity to anomalous couplings (UB, J. Ohnemus, T. Han)



- 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



- Scale dependence:

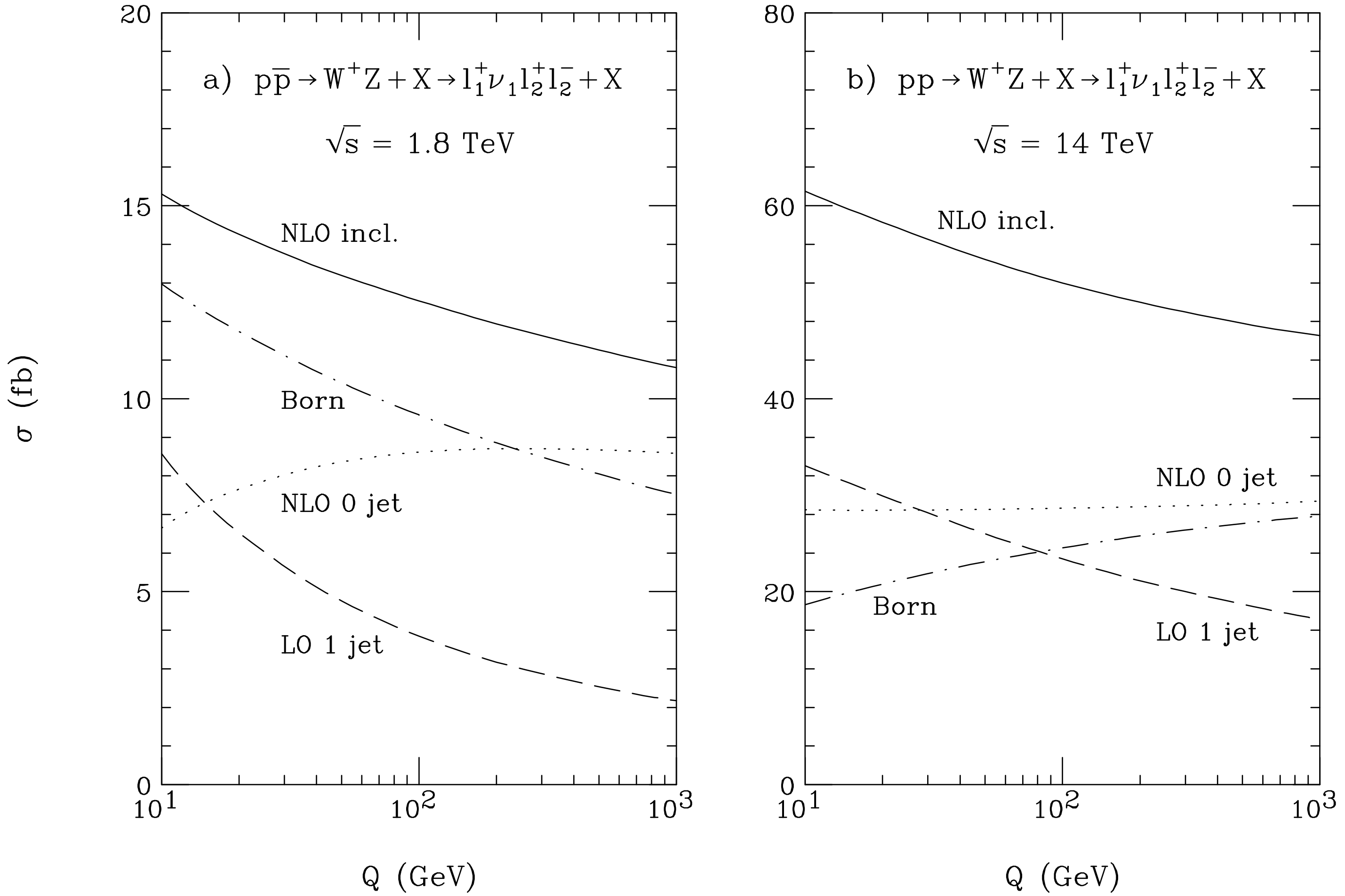
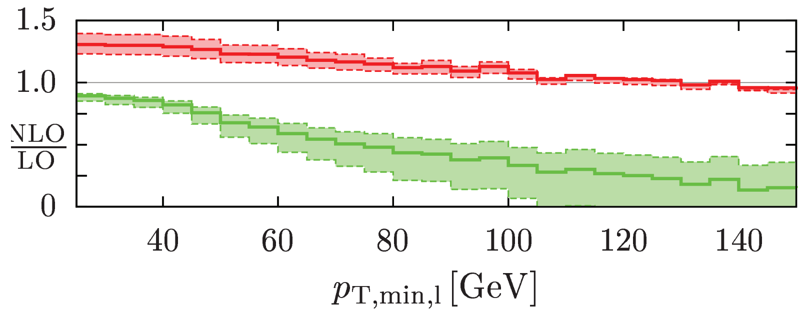


Figure 13

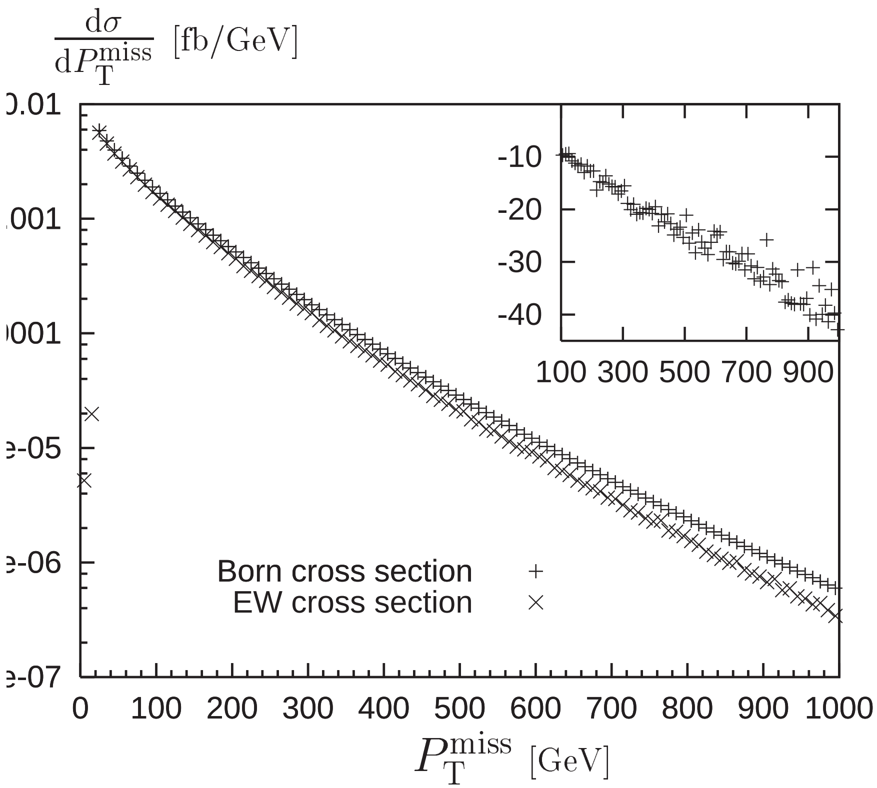
- Since the (LO) $WZ + 1$ jet cross section dominates, the scale dependence is not reduced in the inclusive NLO cross section
- Need $WZ + 1$ jet production at NLO QCD for that
- However, once a jet veto is imposed, the scale dependence in $WZ + 0$ jet production appears to be very small
- This could be very misleading!
- NLO QCD corrections to $WZ + 1$ jet production (Campanario et al., arXiv:1006.0390) (red: inclusive NLO; green: exclusive NLO [no 2nd hard jet])



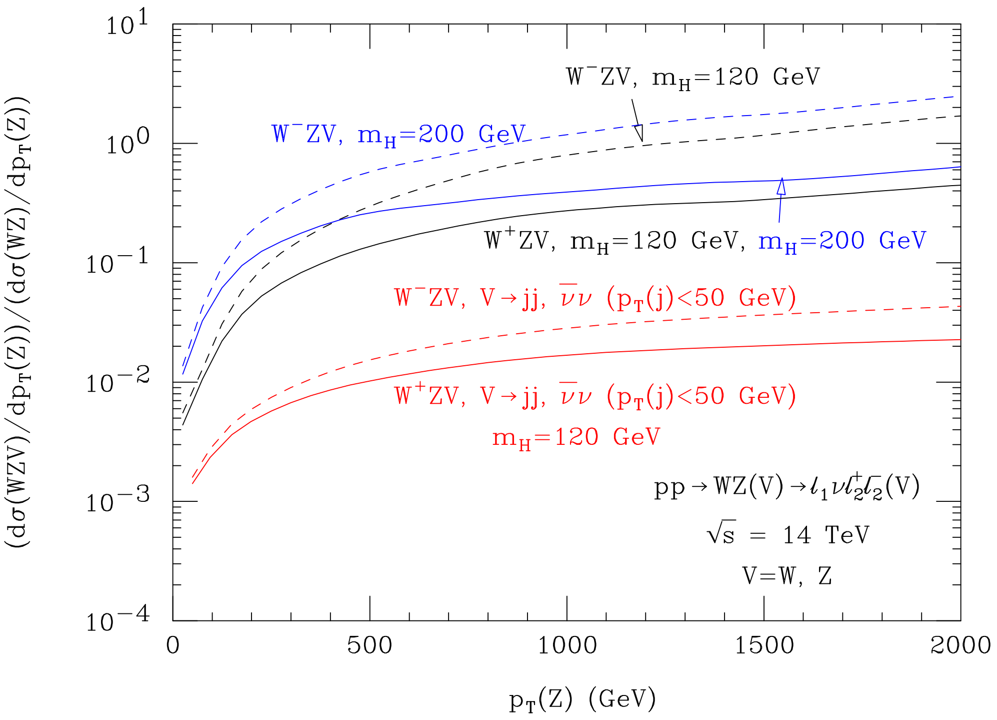
- scale dependence (μ is varied by a factor 2 up or down) is small at low minimum $p_T(l)$, and thus in the total cross section, it is large at higher p_T
- need to check for WZ and other diboson production processes

EWK Corrections to WZ Production

- As in single W/Z production, large Sudakov logs appear in in EWK radiative corrections to di-boson production at large p_T
- Example: WZ production (Accomando, Denner, Kaiser)



- EWK corrections to WZ production are substantial (but smaller than the inclusive NLO QCD corrections) and negative
- but, for inclusive $WZ + X$ production, weak boson emission processes (WZV, $V = W$, Z production) may largely compensate the 1-loop corrections (UB)



Scrutinizing the WWZ vertex at 7 TeV

- recent study by Eboli et al., arXiv:1006.3562
- consider WW and WZ production
- current bounds (from $e^+e^- \to WW$ and WZ production at the Tevatron) and expected bounds from the LHC @ 7 TeV with 1 fb^{-1}

☞ C and P conserving couplings

coupling	PDG bounds	WZ 2σ limits	WW 2σ limits
Δg_1^Z	$-0.016^{+0.022}_{-0.019}$	$[-0.055, 0.094]$	$[-0.33, 0.56]$
$\Delta\kappa_Z$	$-0.076^{+0.059}_{-0.056}$	$[-0.27, 0.55]$	$[-0.088, 0.11]$
λ_Z	$-0.088^{+0.060}_{-0.057}$	$[-0.051, 0.054]$	$[-0.055, 0.056]$

☞ C and/or P violating couplings

coupling	PDG bounds	WZ 2σ limits	WW 2σ limits
g_5^Z	-0.07 ± 0.09	$[-0.18, 0.19]$	$[-0.53, 0.51]$
g_4^Z	-0.30 ± 0.17	$[-0.08, 0.08]$	$[-0.48, 0.48]$
$\tilde{\kappa}_Z$	$-0.12^{+0.06}_{-0.04}$	$[-0.40, 0.40]$	$[-0.38, 0.38]$
$\tilde{\lambda}_Z$	-0.09 ± 0.07	$[-0.053, 0.053]$	$[-0.055, 0.055]$

- form factor effects are still quite small at 7 TeV, but not at 14 TeV
- can improve current bounds on λ_Z, g_4^Z and $\tilde{\lambda}_Z$ (λ_Z and $\tilde{\lambda}_Z$) in WZ (WW) production with early LHC data
- further significant improvements (factor of 4 or more) at 14 TeV with 100 fb^{-1}

4 – Conclusions

- EarlyLHC data provide an opportunity to calibrate detectors with well understood processes such as W and Z production
- These are theoretically fairly well understood, although there open questions on how to combine QCD and EWK corrections
- EWK radiative corrections may become large at high p_T
- Early LHC data offer an opportunity to improve bounds on weak boson couplings in di-boson production
- NLO QCD and EWK corrections in di-boson processes may be large, but this depends on whether one does an exclusive or inclusive analysis (ie. jet veto yes, or no)

This talk was prepared in a 100% Microsoft free environment