Electroweak Physics at the LHC

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Contents

1 Introduction

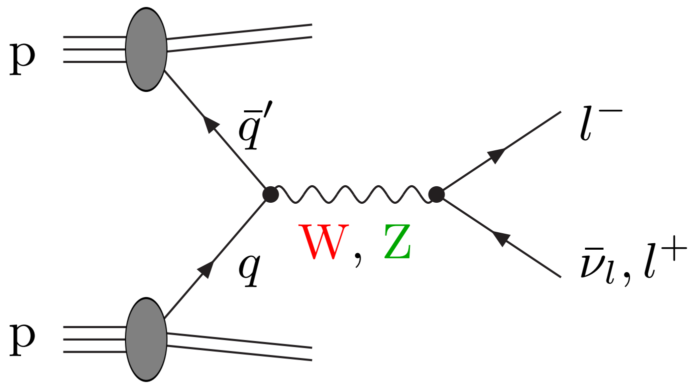
About this talk:

- Considered:
  - ◇ mainly gauge-boson processes
    $\hookrightarrow$ requirements from theory ?
  - ◇ electroweak radiative corrections
    $\hookrightarrow$ salient features, conceptual and technical issues
    what is needed, what is achievable ?
- Not or barely considered: $\rightarrow$ other talks or other workshops
  - ◇ Higgs-boson production
  - ◇ physics beyond the Standard Model
  - ◇ pure QCD processes (jet physics etc.)

  But: no clear separation possible (nor reasonable)
  - many processes involve strong and EW interactions already in LO
  - QCD $\oplus$ EW corrections in precise predictions
  - EW particles + jets
  - EW decays of heavy quarks, etc.

2 Drell–Yan processes and EW precision physics

2.1 Drell–Yan-like W and Z production



Physics goals:

- M_Z $\rightarrow$ detector calibration by comparing with LEP1 result
- $\sin^2\theta_{eff}^{lept}$ $\rightarrow$ comparison with results of LEP1 and SLC
- M_W $\rightarrow$ improvement to $\Delta M_W \sim 15\,\mathrm{MeV}$, strengthen EW precision tests
- decay widths Γ_Z and Γ_W from M_{ll} or $M_{T,l\nu_l}$ tails
- search for Z' and W' at high M_{ll} or $M_{T,l\nu_l}$
- information on PDFs

EW corrections to W production: $\mathrm{pp}(\rightarrow \mathrm{W}) \rightarrow l\bar{\nu}_l + X$

- $\mathcal{O}(\alpha)$ correction in pole approximation (PA) Baur, Keller, Wackeroth '98; Dittmaier, Krämer '02
- complete $\mathcal{O}(\alpha)$ correction
  Dittmaier, Krämer '02; Baur, Wackeroth '04; Arbuzov et al. '05; Carloni Calame et al. '06
- multi-photon radiation via leading logs
  Baur, Stelzer '99; Carloni Calame, Montagna, Nicrosini, Treccani '03; Placzek, Jadach '04

Results for $\mathcal{O}(\alpha)$ corrections:

→ more details in talk of M.Krämer

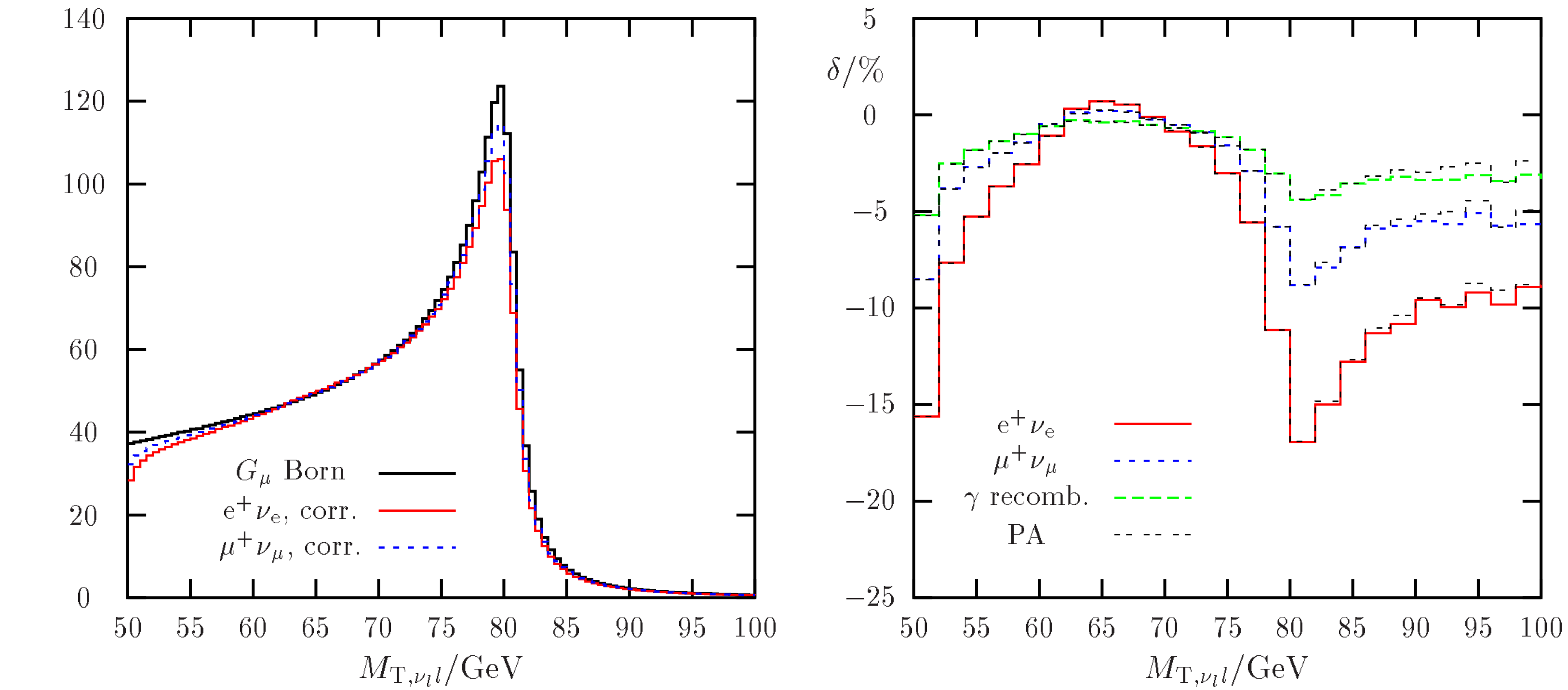
$\mathrm{pp} \rightarrow \nu_l l^+(+\gamma)$ at $\sqrt{s} = 14\,\mathrm{TeV}$ Les Houches SMH proceedings '06

$M_{\mathrm{T},\nu_l l}/\mathrm{GeV}$	50–∞	100–∞	200–∞	500–∞	1000–∞	2000–∞
σ_0/pb						
DK	2112.2(1)	13.152(2)	0.9452(1)	0.057730(5)	0.0054816(3)	0.00026212(1)
$\delta_{\mu+\nu_\mu}/\%$						
DK	−2.75(1)	−5.03(2)	−7.98(1)	−14.43(1)	−21.99(1)	−32.15(1)
HORACE	−2.77(1)	−5.08(1)	−8.01(1)	−14.44(1)	−21.99(1)	−32.16(1)
SANC	−2.76(2)	−5.06(2)	−7.96(2)	−14.41(2)	−21.94(2)	−32.12(2)
WGRAD	−2.69(1)	−4.84(1)	−7.96(1)	−14.48(1)	−22.03(1)	−32.3(1)

↪ Large corrections at high transverse W mass $M_{\mathrm{T},\nu_l l}$!

$\mathcal{O}(\alpha)$ corrections near the Jacobian peak

Dittmaier, Krämer '02



- EW corrections sensitively depend on treatment of photon radiation
  $\hookrightarrow$ issue of inclusiveness / KLN violation causes large effects
- multi-photon radiation important near Jacobian peak
- pole approximation (PA) for W resonance
  sufficient near Jacobian peak, but not for large $M_{T,\nu_l l}$

EW corrections to Z production: $\mathrm{pp}(\to \mathrm{Z}) \to l^+ l^- + X$

- photonic $\mathcal{O}(\alpha)$ correction   Baur, Keller, Sakumoto ’97
- weak $\mathcal{O}(\alpha)$ correction   Baur, Wackeroth ’99; Brein, Hollik, Schappacher ’99; Arbuzov et al. ’06

Brein et al. ’99

$M_{\mathrm{e^+e^-}}/\,\mathrm{TeV}$	$\sigma_{\mathrm{Born}}/\,\mathrm{fb}$	$\sigma_{\mathrm{corr}}/\,\mathrm{fb}$	$\delta_{\mathrm{weak}}/\%$	$\delta_{\mathrm{exp}}/\%$
0.9 – 1.1	6.2157	5.6253	−9.5	3
1.1 – 1.5	3.5076	3.1475	−10.3	4
1.5 – 1.75	0.6028	0.5307	−12.0	9.5
1.75 – 2.0	0.2669	0.2324	−12.9	14
2.0 – 2.5	0.1888	0.1583	−16.2	17
2.5 – 3.0	0.04906	0.04023	−18.0	30
3.0 – 4.0	0.01817	0.01462	−19.5	50

$\hookrightarrow$ Large corrections at high invariant Z mass $M_{\mathrm{e^+e^-}}$!

- multi-photon radiation via leading logs
  Baur, Stelzer ’99; Carloni Calame, Montagna, Nicrosini, Treccani ’05

2.2 EW precision observables

Most important precision observables:

- M_W (direct measurement vs. muon decay)
  - ◇ mixed QCD/EW 2-loop corrections known — Djouadi, Verzegnassi '87; Djouadi '88; Kniehl, Kühn, Stuart '88; Kniehl, Sirlin '93 Djouadi, Gambino '94
  - ◇ complete EW 2-loop corrections known — Freitas, Hollik, Walter, Weiglein '00 Awramik, Czakon '02 Onishchenko, Veretin '02
  - ◇ improvements by 3-loop $\Delta\rho$ — Avdeev et al. '94; Chetyrkin, Kühn, Steinhauser '95 v.d.Bij et al. '00; Faisst et al. '03; Boughezal, Tausk, v.d.Bij '05

  $\hookrightarrow$ theoretical uncertainty $\Delta M_\mathrm{W} \sim 4\,\mathrm{MeV}$

- $\sin^2\theta_\mathrm{eff}^\mathrm{lept}$ (from various asymmetries)
  - ◇ mixed QCD/EW 2-loop and 3-loop $\Delta\rho$ corrections as for M_W
  - ◇ EW 2-loop corrections in progress (fermion loops and Higgs mass dependence complete) — Awramik, Czakon, Freitas, Weiglein '04 Hollik, Meier, Uccirati '05

  $\hookrightarrow$ theoretical uncertainty $\Delta\sin^2\theta_\mathrm{eff}^\mathrm{lept} \sim 5\times 10^{-5}$

$\hookrightarrow$ Theoretical predictions in good shape for LHC

3 Electroweak corrections — general features

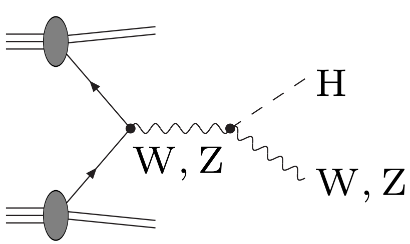
General considerations about EW corrections at hadron colliders

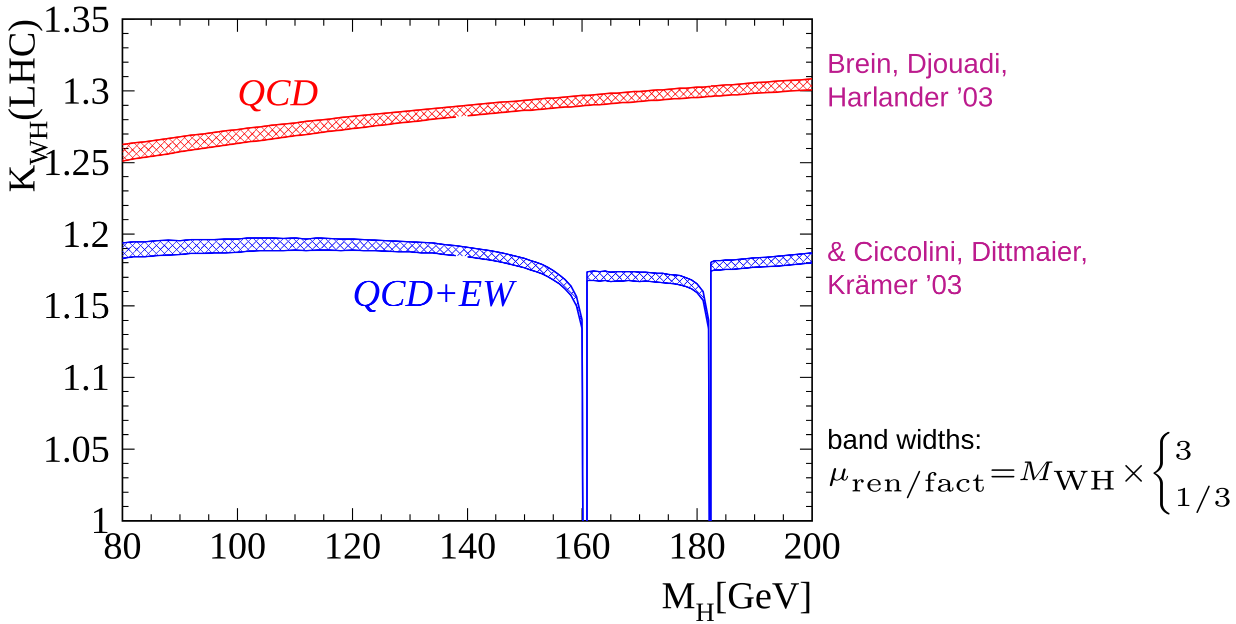
- Naively expected size:

$$\mathcal{O}(\alpha) \quad \sim \quad \mathcal{O}(\alpha_s^2)$$

NLO EW $\sim$ NNLO QCD

An example of this kind:

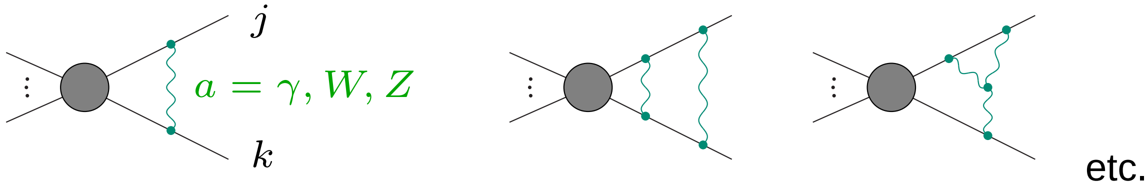




- However: systematic enhancement of EW effects due to
  - ◇ logarithms $\alpha \ln^n(M_W/Q)$, $n = 2, 1$ (Sudakov and subleading) at high scales Q
    $\hookrightarrow$ important for new-physics searches
  - ◇ kinematic effects from photon radiation off leptons (e.g. Drell–Yan)
    $\hookrightarrow$ important for reconstruction of W's, Z's, etc.

Electroweak radiative corrections at high energies

Sudakov logarithms induced by soft gauge-boson exchange



+ sub-leading logarithms from collinear singularities

Typical impact on $2 \to 2$ reactions at $\sqrt{s} \sim 1\,\mathrm{TeV}$:

$$\delta_{\mathrm{LL}}^{1-\mathrm{loop}} \sim -\frac{\alpha}{\pi s_{\mathrm{W}}^2} \ln^2\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq -26\%, \qquad \delta_{\mathrm{NLL}}^{1-\mathrm{loop}} \sim +\frac{3\alpha}{\pi s_{\mathrm{W}}^2} \ln\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq 16\%$$

$$\delta_{\mathrm{LL}}^{2-\mathrm{loop}} \sim +\frac{\alpha^2}{2\pi^2 s_{\mathrm{W}}^4} \ln^4\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq 3.5\%, \qquad \delta_{\mathrm{NLL}}^{2-\mathrm{loop}} \sim -\frac{3\alpha^2}{\pi^2 s_{\mathrm{W}}^4} \ln^3\left(\frac{s}{M_{\mathrm{W}}^2}\right) \simeq -4.2\%$$

$\Rightarrow$ Corrections still relevant at 2-loop level

Note: differences to QED / QCD where Sudakov log's cancel

- massive gauge bosons W, Z can be reconstructed
  $\hookrightarrow$ no need to add "real W, Z radiation"
- non-Abelian charges of W, Z are "open" $\rightarrow$ Bloch–Nordsieck theorem not applicable

Extensive theoretical studies at fixed perturbative (1-/2-loop) order and suggested resummations via evolution equations

Beccaria et al.; Beenakker, Werthenbach; Ciafaloni, Comelli; Denner, Pozzorini; Fadin et al.; Hori et al.; Melles; Kühn et al. '00–'06

Electroweak effects in PDFs

Analogy to QCD-improved parton model:

Collinear splittings $q \to q\gamma$, $\gamma \to q\bar{q}$ lead to quark mass singularities

$\hookrightarrow$ absorb $\alpha \ln m_q$ singularities via factorization into redefined PDFs

Previous approach: no $\mathcal{O}(\alpha)$-corrected PDFs available

$\hookrightarrow$ factorization of collinear singularities in $\mathcal{O}(\alpha)$ in $\overline{\mathrm{MS}}$ scheme

but: neglect $\mathcal{O}(\alpha)$ effects in PDFs

Estimate of neglected $\mathcal{O}(\alpha)$ effects in PDFs: Spiesberger '95, '99; Roth, Weinzierl '04

$$\Delta(\mathrm{PDF}) \lesssim 0.3\%\ (1\%) \quad \text{for} \quad x < 0.1\ (0.4), \quad \mu_{\mathrm{fact}} \sim M_{\mathrm{W}}$$

New situation: MRST2004QED set of $\mathcal{O}(\alpha)$-corrected PDFs

Martin, Roberts, Stirling, Thorne '0

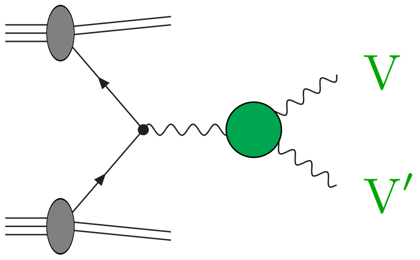
$\hookrightarrow$ new PDFs should be used if EW $\mathcal{O}(\alpha)$ corrections are included

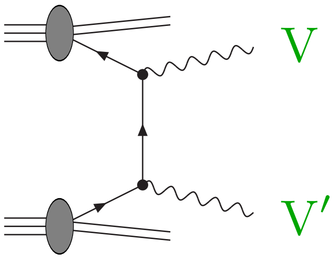
- use appropriate factorization scheme for $\mathcal{O}(\alpha)$ corrections (= DIS like)
- additional real corrections from photons in initial state
- find processes to measure $\mathcal{O}(\alpha)$ induced photon distribution

  MRST2004QED: start PDF from model assumption,
  but agreement with $\sigma_{\mathrm{ep}\to\mathrm{e}\gamma+X}$ at HERA

4 Production of EW gauge bosons

4.1 Gauge-boson pair production





$\mathrm{V}, \mathrm{V}' = \gamma, \mathrm{Z}, \mathrm{W}^{\pm}$

Physics issues:

- triple-gauge-boson couplings at high momentum transfer

  problem: “formfactor approach” to switch off unitarity violation limited (or questionable!)

- dynamics of longitudinal massive gauge bosons at high energies

  $\mathrm{W_L}, \mathrm{Z_L} \sim$ Goldstone bosons $\quad \rightarrow$ scalar sector

  strongly interacting longitudinal W/Z bosons if no Higgs exists
  $\hookrightarrow$ unitarity requires resonances

- important class of background processes to many searches, e.g. to $\mathrm{H} \to \mathrm{WW}/\mathrm{ZZ} \to 4f$

Comments to lowest-order predictions:

Predictions in general should include W/Z decays at matrix-element level in order to account for

- spin correlations
- off-shell effects of gauge bosons
  $\hookrightarrow$ include all possible diagrams and respect gauge invariance

Experience from $\mathrm{e}^+\mathrm{e}^-$ physics:

Naive approach $\dfrac{1}{k^2 - M^2} \to \dfrac{1}{k^2 - M^2 + \mathrm{i}M\Gamma(k^2)}$ violates gauge invariance

- constant width $\Gamma(k^2) = \text{const.}$ $\to$ U(1) respected, SU(2) "mildly" violated
- step width $\Gamma(k^2) \propto \theta(k^2)$ $\to$ U(1) and SU(2) violated
- running width $\Gamma(k^2) \propto \theta(k^2) \times k^2$ $\to$ U(1) and SU(2) violated
  $\hookrightarrow$ results can be totally wrong !

Better approaches: "complex-mass scheme", pole expansions, fermion-loop scheme, effective Lagrangians, etc.

see e.g. LEP2 MC workshop report CERN-2000-09-A, hep-ph/0005309

EW corrections to gauge-boson pair production

- $\mathrm{pp}(\to \mathrm{W}\gamma) \to l\bar{\nu}\gamma + X$ Accomando, Denner, Pozzorini ’01

  $\mathcal{O}(\alpha)$ correction in high-energy and pole approximations

  $\hookrightarrow \;\delta \;\sim\; -5\%\,(-24\%)$ for $p_{\mathrm{T},\gamma} \gtrsim 350\,\mathrm{GeV}\;(700\,\mathrm{GeV})$

- $\mathrm{pp} \to \mathrm{Z}\gamma + X$ Hollik, Meier ’04

  complete $\mathcal{O}(\alpha)$ correction for on-shell Z bosons

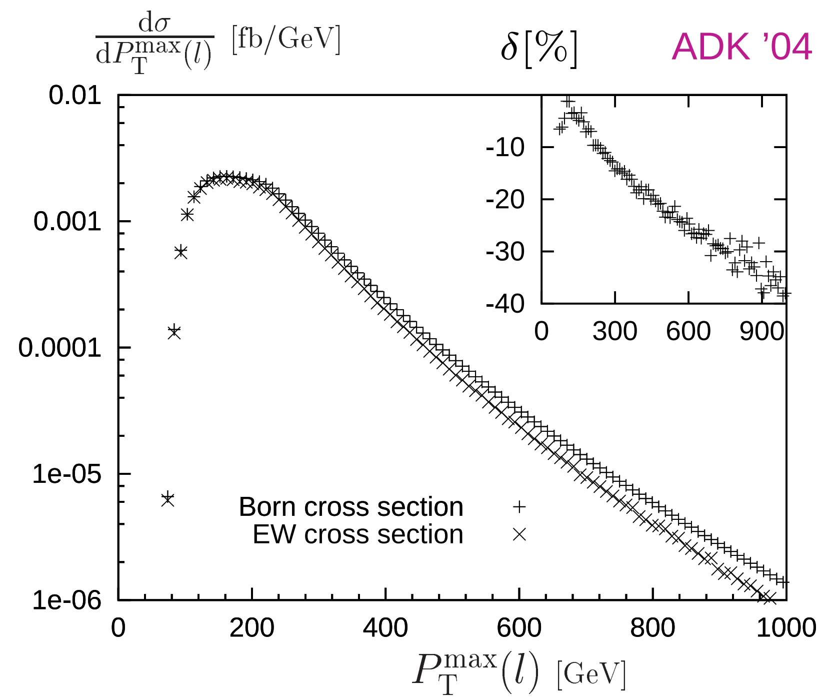
  $\hookrightarrow \;\delta \;\sim\; -20\%$ for $M_{\gamma\mathrm{Z}} \lesssim 2\,\mathrm{TeV}$

- $\mathrm{pp}(\to \mathrm{WW},\mathrm{WZ},\mathrm{ZZ}) \to 4\,\mathrm{leptons} + X$

  Accomando, Denner, Pozzorini ’01
  Accomando, Denner, Kaiser ’04

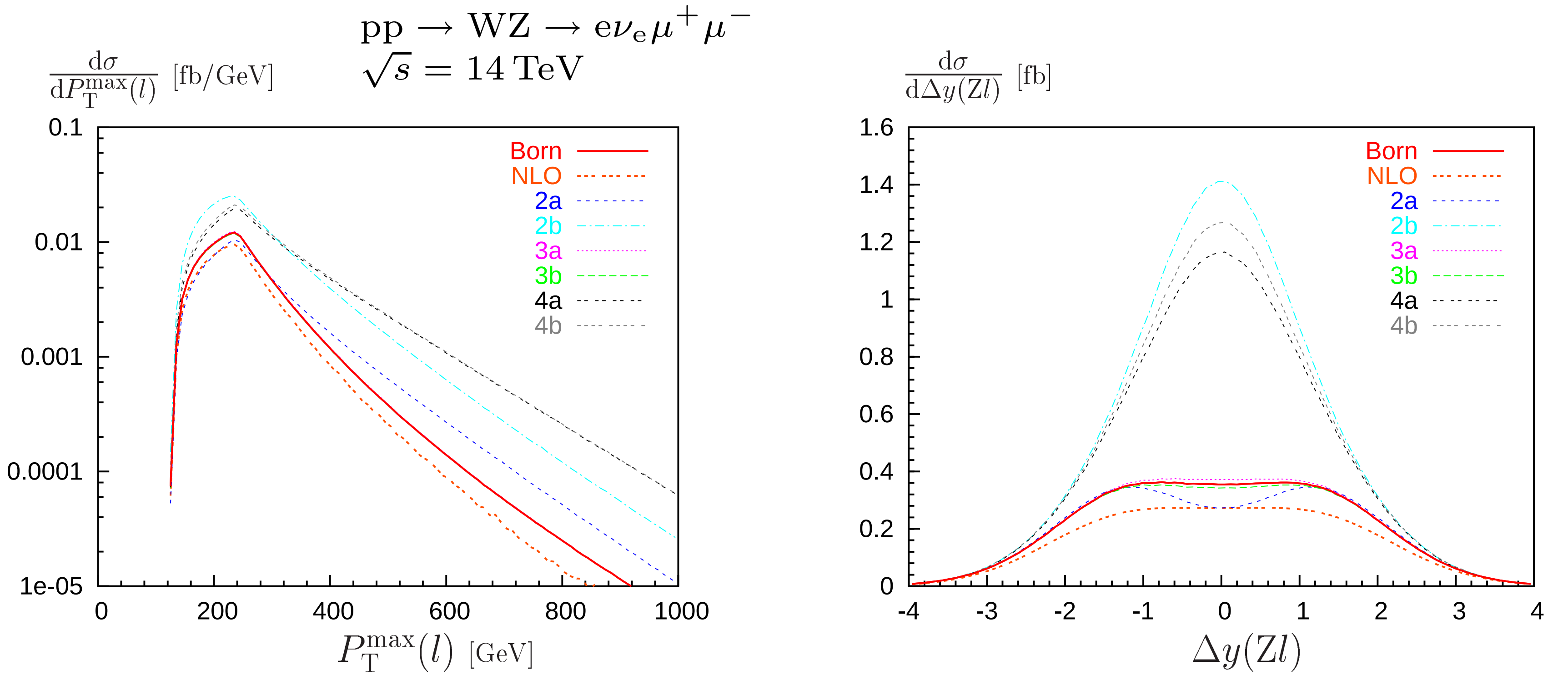
  $\mathcal{O}(\alpha)$ correction in high-energy and pole approximations

$\mathrm{pp} \to \mathrm{WZ} \to \mathrm{e}\nu_\mathrm{e}\mu^+\mu^-$ at $\sqrt{s} = 14\,\mathrm{TeV}$



EW corrections vs. anomalous TGCs in gauge-boson pair production

Recent study for $\mathrm{pp}(\to \mathrm{WW},\mathrm{WZ}) \to 4\,\mathrm{leptons} + X$ Accomando, Kaiser '05



Scenario	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ
Born	0	0	0
2a/2b	± 0.02	0	0
3a/3b	0	± 0.04	0
4a/4b	0	0	± 0.02

$$\lambda_\mathrm{Z} = \lambda_\gamma, \quad \Delta\kappa_\mathrm{Z} = \Delta g_1^\mathrm{Z} - \tan^2\theta_\mathrm{W}\Delta\kappa_\gamma$$

formfactor rescaling ($\Lambda = 1\,\mathrm{TeV}$):

$$\Delta Y \;\to\; \frac{\Delta Y}{(1+\hat{s}/\Lambda^2)^2}, \qquad \Delta Y = \Delta g_1^\mathrm{Z}, \Delta\kappa_\gamma, \lambda_\gamma$$

Note: in general both corrections and anomalous couplings distort distributions

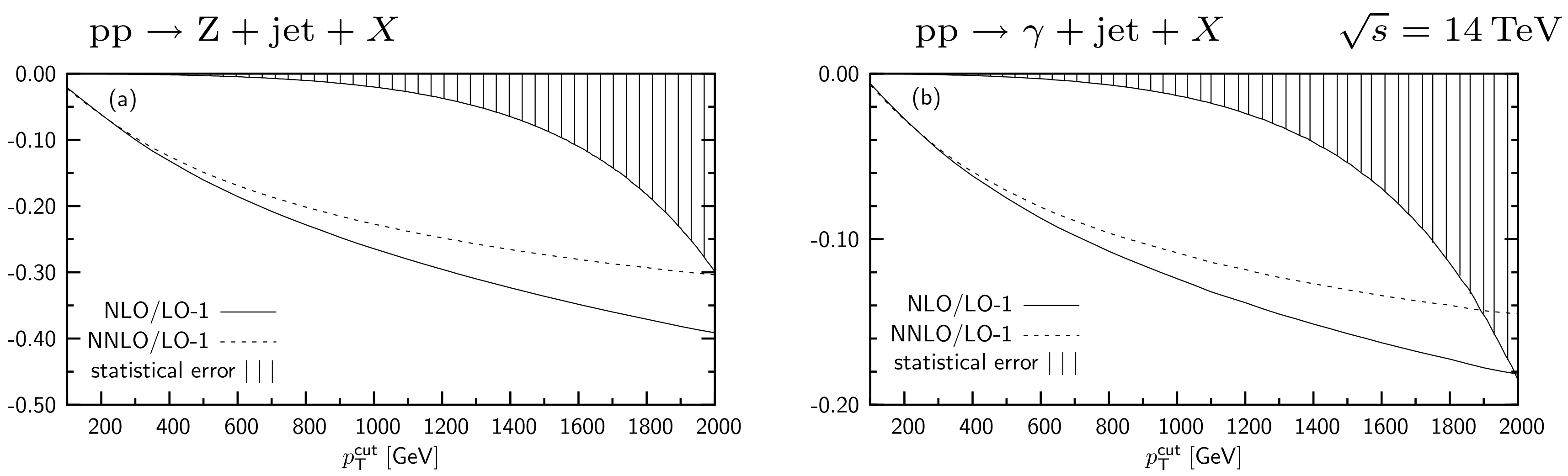
4.2 Gauge-boson + jet production

EW corrections

- $\mathrm{pp} \to \mathrm{V} + \mathrm{jet} + X \quad (\mathrm{V} = \gamma, \mathrm{Z})$
  - ◇ weak $\mathcal{O}(\alpha)$ correction — Maina, Moretti, Ross '04

    $\delta_{\mathrm{weak}} \sim -(5\text{--}15)\%$ for $p_{\mathrm{T}} \lesssim 500\,\mathrm{GeV}$

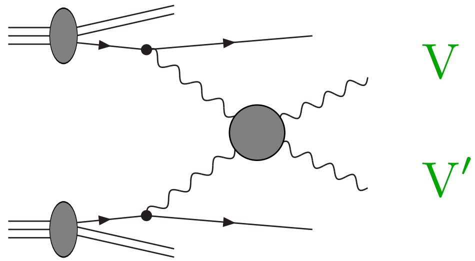
  - ◇ (NLO + NNLL) EW corrections — Kühn, Kulesza, Pozzorini, Schulze '04,'05



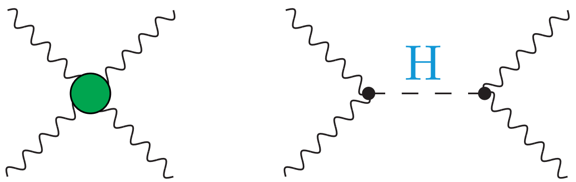
- $\mathrm{pp} \to \mathrm{W} + \mathrm{jet} + X$

  no results on EW corrections yet

4.3 Gauge-boson scattering



e.g.



Physics issues:

- link to Higgs production:
  vector-boson fusion with subsequent decay $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$
- triple and quartic gauge-boson self-interaction
  $\hookrightarrow$ high sensitivity, but again ambiguities from formfactors
- $\mathrm{V_L V_L} \to \mathrm{V_L V_L}$: strong sensitivity of to details of electroweak symmetry breaking
  if no Higgs exists $\to$ unitarity requires scalar and vector resonances

  However:

  ◇ description of resonances is "ad hoc" (different "unitarization models")
  $\hookrightarrow$ large ambiguities

  ◇ many (more qualitative) studies show that LHC could see the resonances

Comments and questions from a theorist

- Approximations made in previous predictions
  1. no QCD corrections
  2. "effective vector-boson approximation" (EVA) almost always used
     ($\sim$ Weizsäcker–Williams)
  3. equivalence theorem (ET) sometimes used (i.e. $\mathrm{V_L} \sim$ Goldstone boson)
  4. no EW corrections (some partial results on $\mathrm{VV} \to \mathrm{VV}$ known)

  Each of these approximations induces uncertainties of several 10% !
  $\hookrightarrow$ Only order of magnitude of cross sections known

  Note: improvement on 1.–3. straightforward (but hard work),
  improvement on 4. not straightforward (approximations?!)

- Situation in SM-like scenario: (i.e. no resonances apart from Higgs)
  cross sections small; large background from $q\bar{q}$ annihilation
  $\hookrightarrow$ What can still be measured and how precisely ?

- Case with low background: like-sign W-pair production ($\to \mu^+\mu^+ +$ missing p_T)
  $\hookrightarrow$ How promising is this channel ?

A step towards cleaner predictions

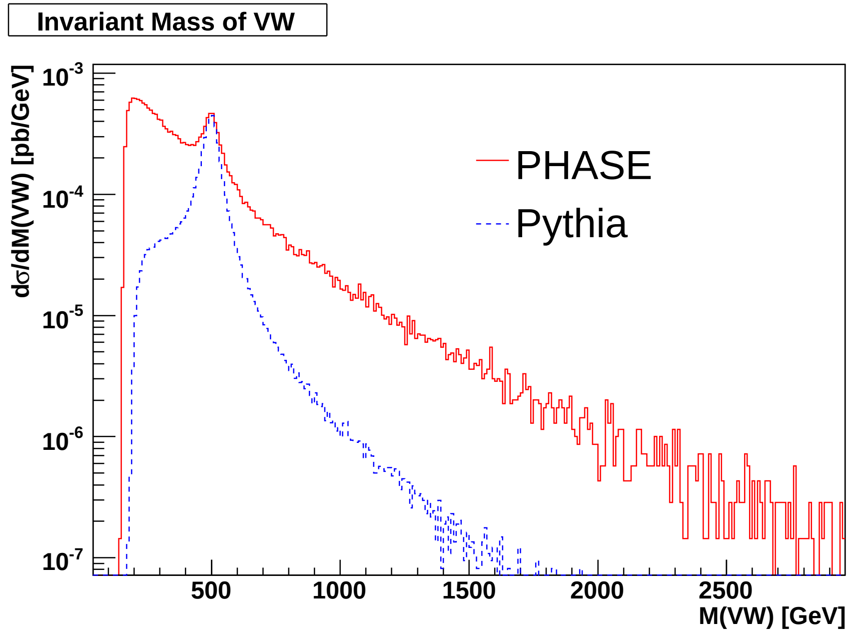
PHASE = a Monte Carlo generator employing full $2 \to 6$ matrix elements

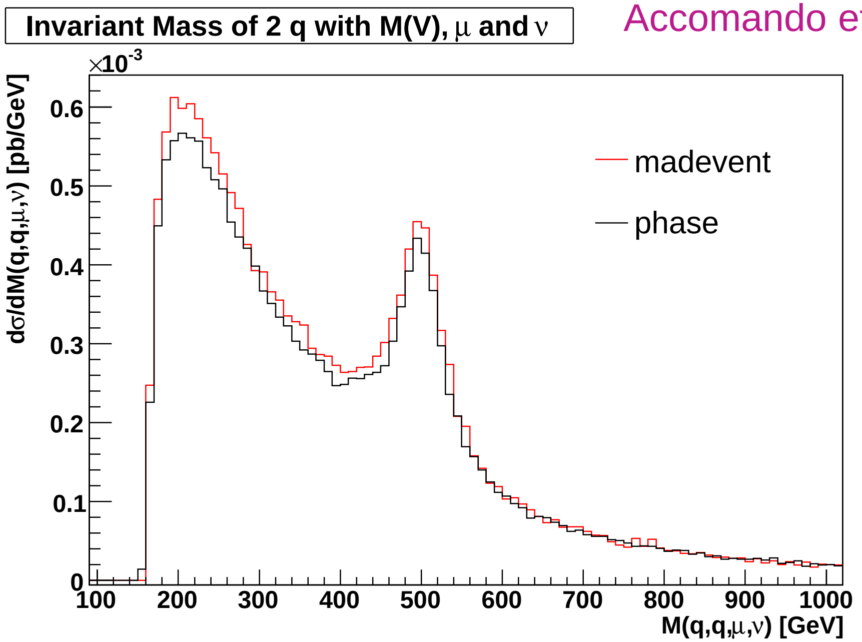
- no ET, no EVA
- no QCD and EW corrections

Accomando, Ballestrero, Bolognesi, Maina, Mariotti '05

Comparison of different approaches:

example: processes containing $\mathrm{VW} \to \mathrm{VW}$ with $M_\mathrm{H} = 500\,\mathrm{GeV}$





Accomando et al. '05

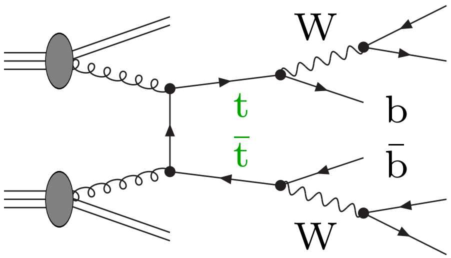
Phase: all EW $2 \to 6$ diagrams, no EVA, no ET, but no QCD diagrams

Pythia: only EVA with longitudinal vector bosons

Madevent: no EVA, but on-shell approximation for produced VW pair

5 Electroweak issues in heavy-quark and jet production

5.1 Heavy-quark pair production



Physics goals:

- more precise measurement of m_t $\rightarrow$ crucial for EW precision tests
- top-spin physics
  $\hookrightarrow$ careful inclusion of decays with spin correlations
- processes with additional jets or EW gauge bosons:
  - $t\bar{t}\gamma$ / $t\bar{t}Z$ production: direct verification of Q_t, v_t and a_t
  - $t\bar{t}(+\text{jet}/\gamma/Z)$ important background processes to searches, e.g. to $t\bar{t}H$

  Note: neither QCD nor EW corrections known to this process type yet

EW corrections to heavy-quark production

- $pp \to t\bar{t} + X$
  - ◇ weak $\mathcal{O}(\alpha)$ correction to σ_{tot} Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth '94

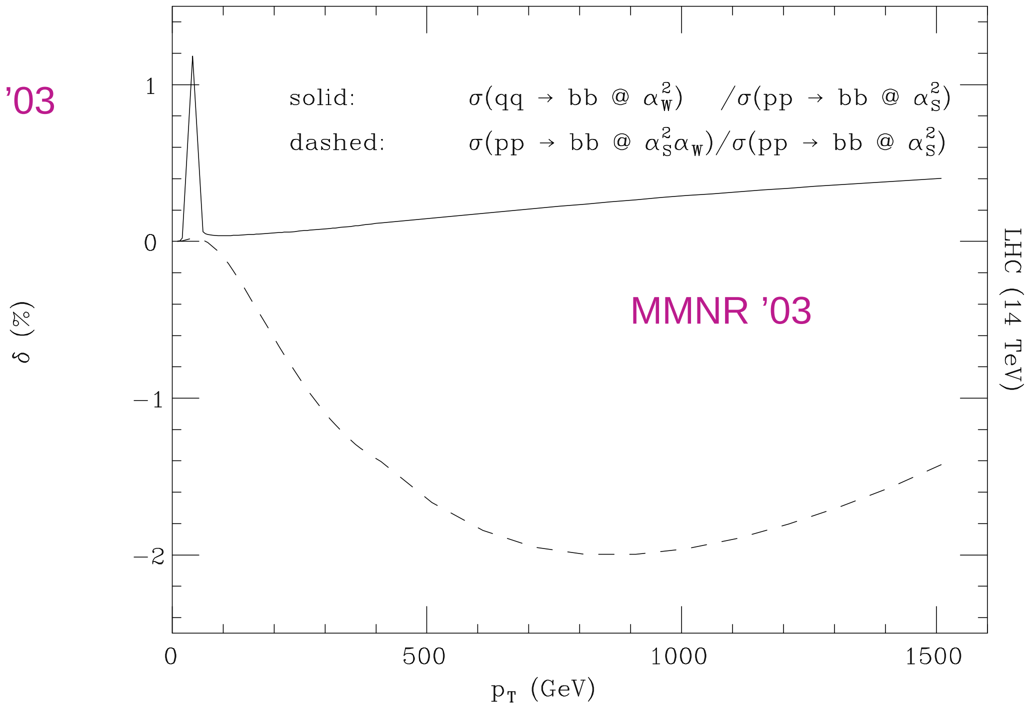
    $\delta_{\mathrm{weak}} \sim$ a few %
  - ◇ weak $\mathcal{O}(\alpha)$ correction to σ_{tot} in THDM and MSSM Hollik, Mösle, Wackeroth '97

    $\delta_{\mathrm{weak}} \lesssim 10\%$

- $pp \to b\bar{b} + X$

  Maina, Moretti, Nolten, Ross '03

  weak $\mathcal{O}(\alpha)$ correction



5.2 Jet pair production

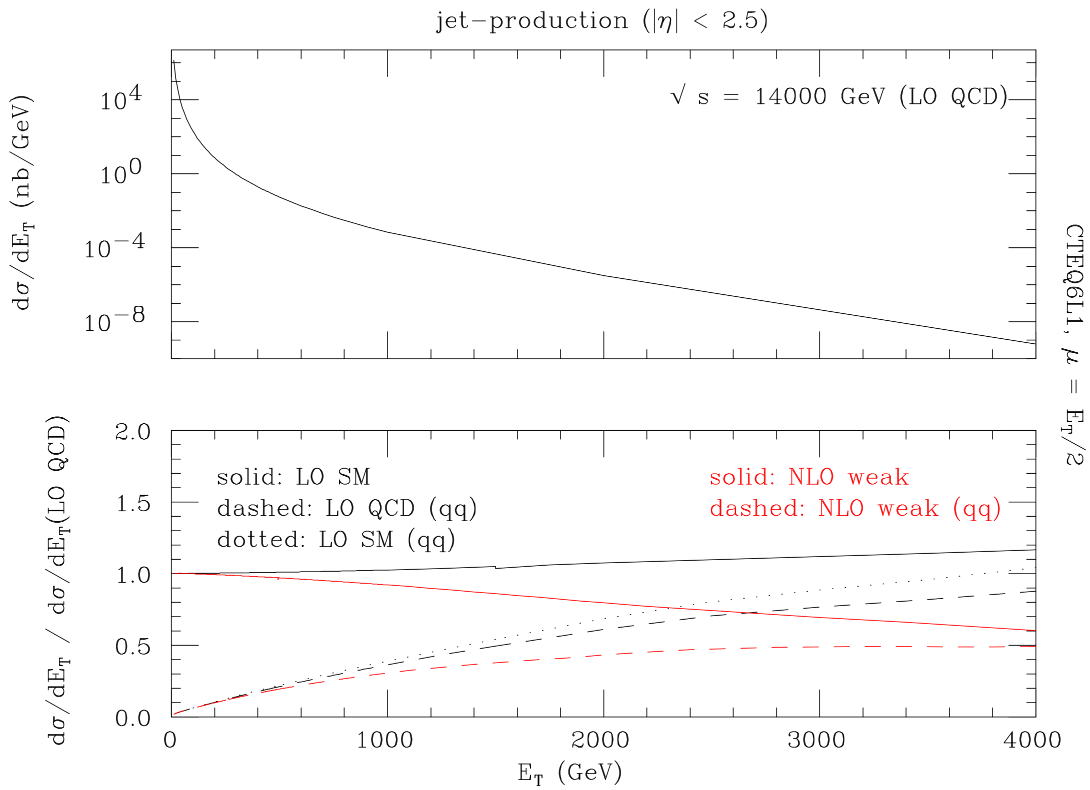
EW corrections

- high-E_T jets at the LHC
  Moretti, Nolten, Ross '05,'06

  weak $\mathcal{O}(\alpha)$ correction

  $$\delta \sim -20\% \, (-40\%)$$

  for $E_\mathrm{T} = 2\,\mathrm{TeV}\,(4\,\mathrm{TeV})$



Note:

EW corrections δ would be partially compensated by real W and Z radiation !

$\hookrightarrow$ sensitivity to jet definition

6 Conceptual and technical issues — the current frontier

- Structure of EW corrections at high energies
  - 1-loop structure completely known, 2-loop structure partially known
  - resummation procedure suggested, but not rigorously proven

- Consistent description of corrections to resonance processes
  - pole expansions either via explicit matrix elements or effective field theories
  - "complex-mass scheme" suggested and applied to $\mathrm{ee}\to\mathrm{WW}\to 4f$ at one loop

- Monte Carlo techniques for many-particle processes
  - fast evaluation of matrix elements (spinor versus recursion techniques)
  - multi-channel Monte Carlo integration (generic approach, automatization)
  - matching of matrix element calculations and parton showers at NLO

- Loop techniques for multi-leg processes
  - Passarino–Veltman reduction fails in presence of small Gram determinants
    $\hookrightarrow$ expansion or semi-numerical methods in problematic regions
  - $2 \to 4$ processes is current frontier at one loop ($\mathrm{ee} \to 4f$, $\mathrm{ee} \to \nu\nu\mathrm{HH}$)

- NNLO calculations
  - EW corrections to decays or vertex corrections (M_W, $\sin^2\theta^{\mathrm{lept}}_{\mathrm{eff}}$, $gg \to \mathrm{H}$)
  - 2-loop amplitudes for massless $2 \to 2$ and $1 \to 3$ with one off-shell leg known
  - subtraction techniques for evaluation of real corrections in progress

7 Conclusions

Electroweak physics at the LHC — final comments and some open questions

- Higgs physics
  $\hookrightarrow$ a subject of its own (not considered in this talk)
- Precision studies of Drell–Yan processes
  - ◇ Are EW NNLO corrections needed ?
- Gauge-boson self-interaction
  - ◇ use full matrix-element calculations as far as possible !
  - ◇ How well can $\mathrm{VV} \to \mathrm{VV}$ be measured in SM-like case ?
- Studies at high scales (searches, etc.)
  - ◇ approximations for EW corrections beyond NLO ?
- General issues
  - ◇ combination of EW and QCD corrections (not even done for Drell–Yan)
  - ◇ EW effects in PDFs (relevance of photon PDF?)
  - ◇ thorough estimates of theoretical uncertainties !