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Electroweak corrections for LHC physics

Marek Schönherr

IPPP, Durham University





Introduction	EW for NP searches	EW for precision measurements	Electroweak corrections in MCs	Conclusions
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Overview

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Why and where are EW corrections important?

2 Electroweak corrections for New Physics searches Setup, subtleties and automation Selected results

3 Electroweak corrections for precision measurements Electroweak corrections for precision measurements Three-jet production and R_{32}

4 Electroweak corrections in MCs

Approximate inclusion in NLO QCD multijet merging

5 Conclusions

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Why and where are EW corrections important?

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Available and needed precision

Höche, Krauss, MS, Siegert '12



start of the LHC:

- QCD the great unknown
 - NLO QCD automated 🗸
 - NLO QCD multijet merging baseline MC for the LHC
 - NNLO QCD where required \checkmark

LHC Run II and beyond:

- emergence of EW corrections
 - precision measurements (sub)percent accuracy X
 - high-p_T distributions tens of percent corrections X

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Available and needed precision

Kallweit, Lindert, Maierhöfer, Pozzorini, MS '14 MS '17



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Why and where ar	e EW/ corrections important?			

Electroweak corrections

Precision measurements

Measurement that aim for subpercent experimental accuracy.

 \rightarrow theoretical predictions must keep pace

Electroweak corrections are of $\mathcal{O}(\alpha)$, thus generally of $\mathcal{O}(1\%)$. Roughly, their size can be gauged by $\mathcal{O}(\alpha) \approx \mathcal{O}(\alpha_s^2)$.

New physics searches

Search for excesses over SM background in TeV-scale observables that we could not probe until now.

Incomplete infrared cancellations due to broken structure of the EW gauge group introduces logarithms of the scale of the process and that of the EW bosons. This introduces corrections which are negative and logarithmically growing with the size of the kinematic invariants, e.g. $p_{\rm T}$. Thus, $\mathcal{O}(20\%)$ corrections possible already for LHC range.

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- new physics searches look for deviations in shape in high-p_T tails or large invariant masses
- EW corrections increase in these tails to tens of percent
 - the level of accuracy determines achievable discovery potential and exclusion bounds
 - otherwise precision data cannot be fully exploited

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Why and where an	e EW corrections important (

Electroweak corrections

Electroweak correction can often be separated in QED and genuine weak corrections.

Virtual weak corrections often studied in the context of gauge boson and jet production at large transverse momentum (EW-Sudakov suppression). Usually negative and increasing with p_{\perp} .

Real weak corrections usually constitute a separate process. However, largest BR of W/Z bosons is hadronic, thus (almost) indistinguishable in jet production. Nonetheless may constitute signal in itself.

When large scale differences occur resummation is needed in either case. Practically at LHC13/14 these scale differences are moderate.

Beware of subleading orders.

Electroweak corrections for LHC physics

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Higher order corrections





strictly defined only through order counting

- in principle must differentiate between short-distance objects (partons) and long distance objects (observable objects):
 - well known in QCD (quarks, gluons \leftrightarrow jets)
 - introduce similar concepts in EW sector for photons and leptons

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Higher order corrections



NLO QCD

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Definition of physical objects

What is a jet?

- photons and leptons must be part of a jet, but to what extent?
- democratic:
 - + straight forward, always well defined
 - many contributions
 - $\rightarrow\,$ single photons constitute a jet
 - $\rightarrow\,$ single leptons constitute a jet
- anti-tagging jets with certain flavour content:
 - + fewer contributions
 - needs a lot of care to be well-defined at all contributing orders
 - $\rightarrow\,$ anti-tag jets with too large photon content
 - $\rightarrow\,$ anti-tag jets with net lepton content
- which approach is closer to experiment depends on analysis, general anti-tagging must proceed through fragmentation functions

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Setup. subtleties and automation					

Definition of physical objects

What is a photon?

- differentiate: short-distance photon (photon as parton), long-distance photon (identified, measurable photon)
- identify through fragmentation function

$$D_{\gamma}^{\gamma}(z,\mu) = rac{lpha(0)}{lpha_{\mathsf{sd}}} \, \delta(1-z) + \mathcal{O}(lpha^2)$$

 \Rightarrow leads to $\alpha({\rm 0}){\rm -scheme}$ for identified photons

What is a lepton?

- simplified as leptons not gauge bosons
- dressed lepton: masseless leptons must be dressed for IR safety
- bare lepton: massive leptons may be measured bare
- Born lepton: not an infrared-safe concept

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EW for NP searches EW for precision measurements Electroweak corrections in MCs 000000 Setup, subtleties and automation

Automation

- \Rightarrow emergence of automated frameworks for NLO EW computations along the principles of NLO QCD automation
 - Monte-Carlo frameworks (Born and real emission matrix elements, infrared subtraction, phase space generation, process coordination)
 - SHERPA MS '17
 - MADGRAPH

virtual corrections (EW one-loop matrix elements, renormalisation)

- GOSAM Chiesa et al '15
- MADLOOP Frixione et al '14
- OPENLOOPS Kallweit et.al. '14 Actis et.al. '12
- RECOLA
- currently generally limited to fixed-order
- a number of dedicated calculations and private codes

Frederix et.al. '18

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NLO E	W calculatio	ns with SHERPA		
•	SHERPA+OPENLO	OPS:		
	- pp $ ightarrow \gamma/\ell\ell/\ell$	u/ u u + 0, 1, 2(, 3) jets Kallweit, Linde	FCC report, EW report, rt, Maierhöfer, Pozzorini, MS '1 Lindert et.	LH'15 .4, '15 al. '17
	- pp $ ightarrow$ Vh		FCC repo	ort '16
	- pp $ ightarrow 2\ell 2 u$		Kallweit, Lindert, Pozzorini, M	/IS '17
	- pp $ ightarrow tar{t}/tar{t}j$		Gütschow, Lindert, M	/IS '18
	- pp $ ightarrow tar{t}h$			LH'15
•	Sherpa+GoSam			
	- $pp ightarrow \gamma\gamma + 0$, 1, 2 jets	Chiesa et.	al. '17
	- $pp \rightarrow \gamma \gamma \gamma / \gamma$	$\gamma\ell u/\gamma\gamma\ell\ell$	Greiner, M	AS '17
•	Sherpa+Recola			

- $pp \rightarrow V + 0, 1, 2$ j, $pp \rightarrow 4\ell$, $pp \rightarrow t\bar{t}h$ - $pp \rightarrow 3\ell 3\nu$

Biedermann et.al. '17 MS '18

Reyer, MS, Schumann '19

- $pp \rightarrow jj/jjj$

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	- pp $ ightarrow tar{t}/tar{t}j$		Gütschow, Lindert, M	// S '18
	- pp $ ightarrow tar{t}h$			LH'15

- SHERPA+GOSAM
 - $pp \rightarrow \gamma\gamma + 0, 1, 2$ jets Chiesa et.al. '17 - $pp \rightarrow \gamma \gamma \gamma / \gamma \gamma \ell \nu / \gamma \gamma \ell \ell$ Greiner, MS '17
- SHERPA+RECOLA
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Gütschow, Lindert, MS '18

Biedermann et.al. '17

Reyer, MS, Schumann '19

LH'15

MS '18

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Selected results				

General setup

- work with dressed leptons with $\Delta R_{
 m dress}=0.1$
- input parameters for the following calculations

$$\begin{array}{rcl} G_{\mu} &=& 1.16637 \times 10^{-5} \ {\rm GeV}^2 \\ m_W &=& 80.385 \ {\rm GeV} & & \Gamma_W &=& 2.0897 \ {\rm GeV} \\ m_Z &=& 91.1876 \ {\rm GeV} & & \Gamma_Z &=& 2.4955 \ {\rm GeV} \\ m_h &=& 125.0 \ {\rm GeV} & & \Gamma_h &=& 0.00407 \ {\rm GeV} \\ m_t &=& 173.2 \ {\rm GeV} & & \Gamma_t &=& 1.3394 \ {\rm GeV} \end{array} .$$

- EW parameter renormalisation in G_{μ} -scheme
- photon induced processes considered throughout

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Diphoton production – $\gamma\gamma$



NLO EW corrections to diphoton production

• peak-like enhancement around $m_{\gamma\gamma} pprox 160 \, {
m GeV}$

 induced by W-box creating pseudo-resonant structures

 should be accounted for in data-driven background fits in diphoton resonance searches

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Diphoton production – $\gamma\gamma$



NLO EW corrections to diphoton production

- peak-like enhancement around $m_{\gamma\gamma} = 2 m_W$
- induced by W-box creating pseudo-resonant structures



 should be accounted for in data-driven background fits in diphoton resonance searches

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Diboson production – $2\ell 2\nu$ – DF and SF

Kallweit, Lindert, Pozzorini, MS '17

• study $e^+\mu^-\nu\bar{\nu}$ (DF) and $e^+e^-\nu\bar{\nu}$ (SF) production, and $e\leftrightarrow\mu$

 $\begin{array}{lll} \mathsf{DF} & e^+\mu^-\nu_e\bar\nu_\mu & WW\\ \mathsf{SF} & e^+e^-\nu_e\bar\nu_e & WW+ZZ\\ & e^+e^-\nu_{\mu/\tau}\bar\nu_{\mu/\tau} & ZZ \end{array}$

- incl. event selection w/ standard lepton acceptance cuts, $(p_{T,\ell} > 20 \text{ GeV})$, $|\eta_\ell| < 2.5)$, $n_f = 4$ and mild jet veto to suppress large NLO QCD corr.
- similar intricate interplay between different "on-shell" in $3\ell 3\nu$ production at NLO EW $$\rm MS\,{'}18$$

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all γPDF agree that γ-ind. > 10% for p_T > 500 GeV very good agreement between CT14qed and LUXqed

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 $pp \rightarrow e^+ e^- \nu \bar{\nu}$

Selected results

Diboson production – $2\ell 2\nu$ – SF



• *WW* dominant throughout, *ZZ* only contribs 10-20% \rightarrow overall very similar to DF case

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Diboson production – $2\ell 2\nu$ – DF and SF



∠∠ dominant at very large p_T
 → different EW corrections, take care when extrapolating

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Diboson production – $2\ell 2\nu$ – SF



 ZZ dominant at very large p_T → different EW corrections, take care when extrapolating

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Diboson production – $2\ell 2\nu$ – DF and SF



 kinematic suppression for p^{νν}_T at LO, unlocked at NLO QCD not present in γ-induced ⇒ large contrib

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Diboson production – $2\ell 2\nu$ – SF



• kinematic suppression for $p_T^{\nu\nu}$ for WW, but not ZZZZ dominates for MET > 100 GeV with large EW corr.

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Electroweak corrections for precision measurements

Electroweak corrections for precision measurements

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Electroweak corrections for precision measurements

Electroweak corrections for precision measurements

W, Z bosons produced with large cross section, and their decay into leptons offers a clear signature.

Large data sets, complemented by additional small data sets in low pile-up environment to control systematic uncertainties, allow for permille level accuracy in the experimental measurement.

Typical precision observables:

$$W - m_W$$

Z - sin θ_w^{eff} , A_{FB} , $A_0 \dots A_8$

To reach the desired theoretical accuracy, many different aspects need to be controled:

QCD corrections to W/Z production processes EW (mostly QED) corrections to decay kinematics parton distributions in the proton

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Electroweak corrections for precision measurements

Electroweak corrections for precision measurements



- soft photon resummation matched to NNLO QED + NLO EW
- permille accuracy in the description of the $Z \rightarrow \ell \ell$ kinematics

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Electroweak corrections for precision measurements

Determination of the strong coupling $lpha_s$

Typically, α_s at hadron colliders extracted from ratio of three-jet production to two-jet production.

Necessitates precise predictions over large kinemtatic ranges, from a few tens of GeV to the multi-TeV regime.

Dijet production

- NNLO QCD
- NLO QCD
- NLO EW and all subl. corrections

Currie et.al. '17

Ellis, Kunszt, Soper '92 Giele, Glover, Kosower '93

Moretti, Nolten, Ross '06 Dittmaier, Huss, Speckner '12 Frederix et.al. '16

Three-jet production

- NLO QCD
- NLO EW and all subl. corrections

Nagy '01

Reyer, MS, Schumann '19

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Three-jet production and R ₃₂				

 define jets completely democratically, incl. all massless visible particles of the SM (q, g, γ, ℓ) p_T(j₁) > 80 GeV, p_T(j_i) > 60 GeV (i > 1)

• anti-tag jets against leptons exclude jets with net lepton number within lepton acceptance care: jet acceptance and lepton acceptance may differ here: $|\eta(j)| < 2.8$, $|\eta(\ell)| < 2.5$

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Contributions at NLO



- sensitive to the full SM spectrum, incl. top quark, Higgs boson, all lepton and neutrino flavours
- real emission corrections include: $\ell \nu qg$, $\ell \ell qg$, $\ell \ell \ell \ell$, $\ell \ell \ell \nu$ final states

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- moderate EW corrections
- overcompensated by subleading orders

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- moderate EW corrections
- overcompensated by subleading orders, can be as large as QCD corr.

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- NLO EW and subleading order contribs very similar between 2j and 3j
 - \Rightarrow R_{32} largely uneffected
- supports factorisation of NLO QCD and NLO EW correction at large $H_{\rm T}^{(2)}$
- scale uncertainty by synchronous scale variation

\Rightarrow safe to use R_{32} with NLO QCD MCs for α_s extraction

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R_{32} in different Δy -slices



• effects already seen in Dittmaier, Huss, Speckner '12

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R_{32} in different Δy -slices



• slightly different in 3-jet production

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R_{32} in different Δy -slices



different net effects in different rapidity slices

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Electroweak corrections for LHC physics

Introduction

Why and where are EW corrections important?

- 2 Electroweak corrections for New Physics searches Setup, subtleties and automation Selected results
- 3 Electroweak corrections for precision measurements Electroweak corrections for precision measurements Three-jet production and R₃₂

4 Electroweak corrections in MCs Approximate inclusion in NLO QCD multijet merging

5 Conclusions

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Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
- taylored to large- $p_{\rm T}$ regions where EW corrections dominated by virtual W/Z exchange and RG running
- modify MC@NLO B-function to include NLO EW virtual corrections and integrated approx. real corrections

$$\overline{\mathrm{B}}_{n,\mathsf{QCD}+\mathsf{EW}_{\mathsf{virt}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathsf{QCD}}(\Phi_n) + \mathrm{V}_{n,\mathsf{EW}}(\Phi_n) + \mathrm{I}_{n,\mathsf{EW}}(\Phi_n) + \mathrm{B}_{n,\mathsf{mix}}(\Phi_n)$$

- real QED radiation can be recovered through standard tools (parton shower, YFS resummation)
- simple stand-in for proper QCD+EW matching and merging

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exact virtual contribution

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Results: $pp \rightarrow t\bar{t} + jets$



Gütschow, Lindert, MS in '18

- $pp \rightarrow t\bar{t} + 0, 1j$ @NLO + 2, 3, 4j@LO
- additional LO multiplicities inherit electroweak corrections through MENLOPS differential *K*-factor

Höche, Krauss, MS, Siegert '10

improved description of data

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Conclusions

- electroweak effects are important at LHC, HE–LHC, FCC, etc.
- become large whenever the scale is large compared the EW scale
- can be incorporated in multijet merging to improve description in those regions
 - \Rightarrow included since SHERPA-2.2.1 (now SHERPA-2.2.8)
- automation of NLO EW follows on the heels of NLO QCD
 - \rightarrow much more care with consistent schemes and order counting
 - \rightarrow very rich phenomenology
 - \rightarrow includes many more pitfalls than NLO QCD
 - \Rightarrow included in next major SHERPA release (SHERPA-3.0)

http://sherpa.hepforge.org

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Thank you!

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Backup

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Top pair production in association with jets

 $\rightarrow t\bar{t}$ (+ jet) at 13 TeV $pp \rightarrow t\bar{t}$ (+ jet) at 13 TeV 10¹ $d\sigma/dp_{\Gamma,t}$ [pb GeV⁻¹] ti 10 10/10/doli 10 10 0.9 10 ····· tī (LO) tī (NLO EWvirt) 10 +# (NLO EW + LO11+02) tī (NLO EW) 10 (NI O FW + LO11 + 22 + ΔNLO12+03) 0.8 $\cdots t\bar{t} + iet (LO)$ tf + jet (NLO EW) 10 10 tīi 10 1.04 $d\sigma_{NLO}^{i\bar{l}j}/d\sigma_{LO}^{j\bar{l}j}$ 0100 1.02 0.9 0.98 (NLO EW, int) et (NLO EW + LO21+12) NLO EW tīi/tī 0.1 ΔNLO₂₂₊₁₃ 0.96 p_{T,t} [GeV] p_{T,t} [GeV] 100 300 500 1000 50 100 1000 30 50 20 300 500

Gütschow, Lindert, MS in '18

Observation: NLO EW factorises from additional jet activity when rather inclusive on jet definition

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Top pair production in association with jets

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Observation: subleading orders important