Electroweak corrections for LHC physics

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Introduction

Electroweak sector of the Standard Model is descibed by a broken $SU(2)_\mathrm{L} \times U(1)_\mathrm{Y}$ gauge group resulting in $U(1)_\mathrm{QED}$ and massive weak gauge bosons ($W^\pm$, Z).

Inclusive observables
Electroweak corrections are of $\mathcal{O}(\alpha)$, thus generally of $\mathcal{O}(1\%)$. Roughly, their size can be gauged by $\mathcal{O}(\alpha) \approx \mathcal{O}(\alpha_s^2)$. Important to take into account in precision measurements.

TeV scale observables
Incomplete infrared cancellation due to broken structure of the gauge group introduces logarithms of the scale of the process and that of the EW bosons. This introduces EW Sudakov logarithms which are negative and grow with the size of the kinematic invariants, e.g. p_T. Thus, $\mathcal{O}(20\%)$ corrections possible already for LHC range.

Introduction

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.

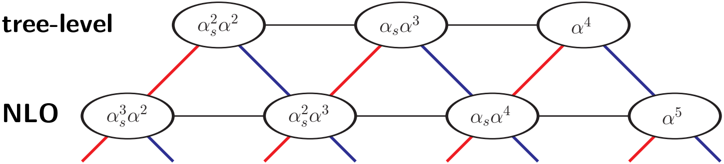
Beware of subleading orders.

Outline

Electroweak corrections for LHC physics

Higher order corrections

Example: *Vjj* production



- 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

Higher order corrections

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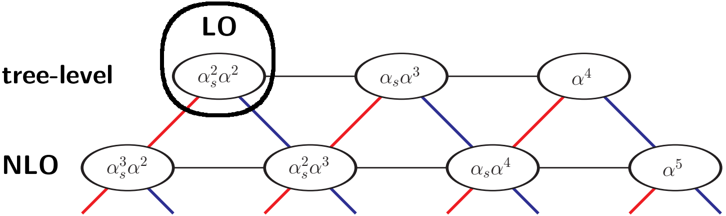

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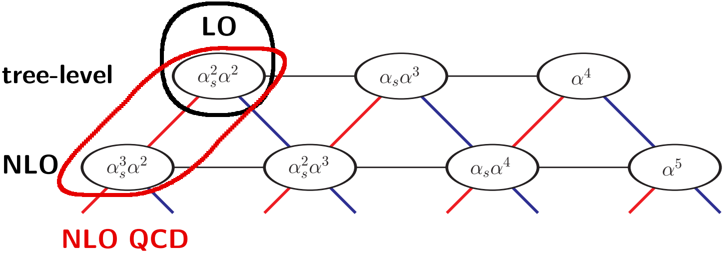

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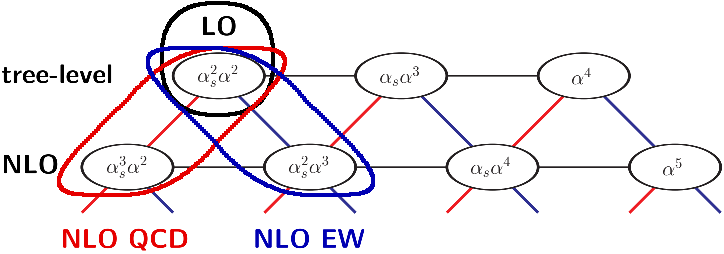

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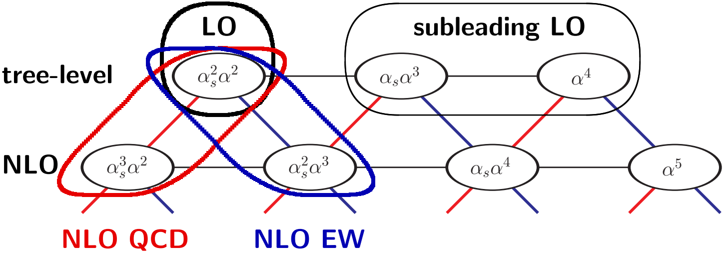

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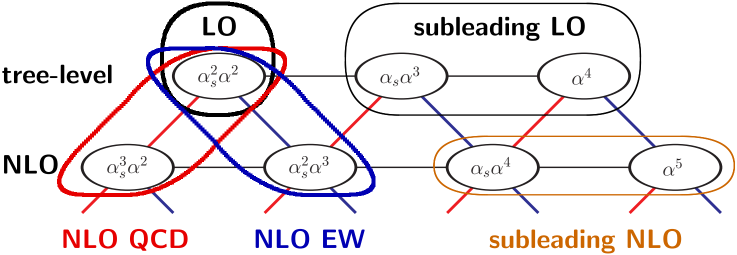

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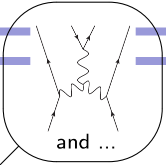

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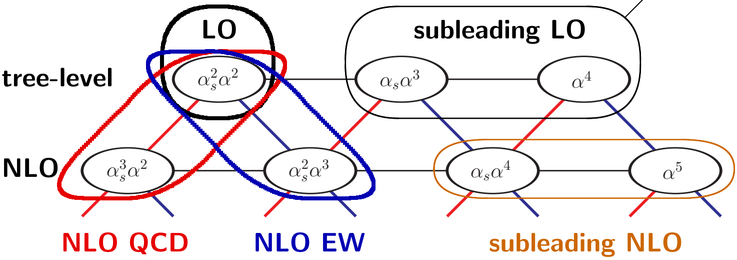

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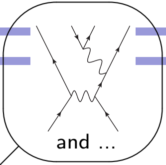

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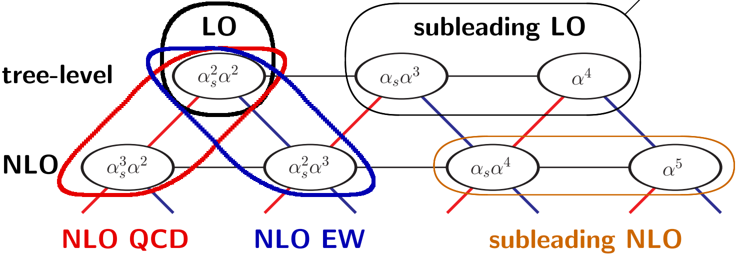

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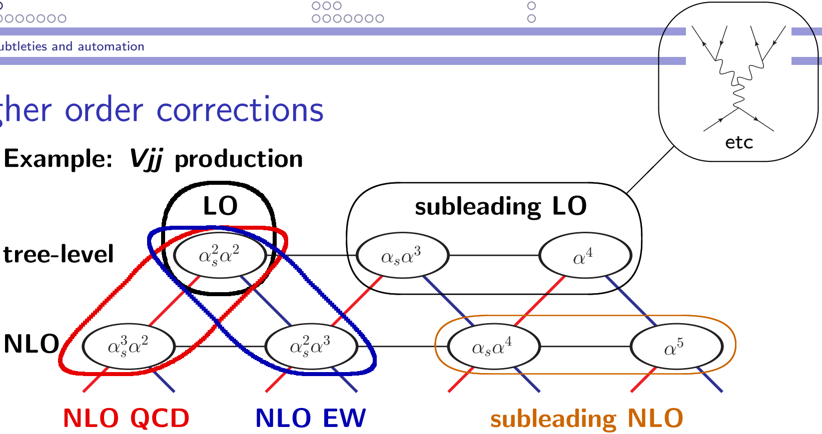

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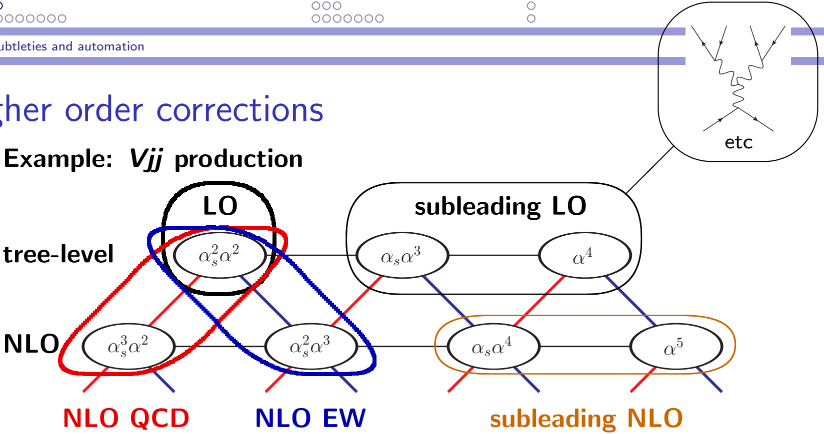

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Definition of physical objects

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
  - → single photons constitute a jet
  - → 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
  - → anti-tag jets with too large photon content
  - → anti-tag jets with net lepton content
- which approach is closer to experiment depends on analysis, general anti-tagging must proceed through fragmentation functions

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
  $$D_\gamma^\gamma(z,\mu) = \frac{\alpha(0)}{\alpha_{\mathsf{sd}}}\,\delta(1-z) + \mathcal{O}(\alpha^2)$$

$\Rightarrow$ leads to $\alpha(0)$-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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Automation

⇒ 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 arXiv:1712.07975
  - MADGRAPH — Frederix et.al. arXiv:1804.10017
- virtual corrections (EW one-loop matrix elements, renormalisation)
  - GOSAM — Chiesa et.al. arXiv:1507.08579
  - MADLOOP — Frixione et.al. arXiv:1407.0823
  - OPENLOOPS — Kallweit et.al. arXiv:1412.5157
  - RECOLA — Actis et.al. arXiv:1211.6316
- currently generally limited to fixed-order
- a number of dedicated calculations and private codes

NLO EW calculations with SHERPA

- SHERPA+OPENLOOPS:
  - $pp \to \gamma/\ell\ell/\ell\nu/\nu\nu + 0, 1, 2(, 3)$ jets — FCC report, EW report, LH'15
    Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1412.5157, arXiv:1511.08692
    Lindert et.al arXiv:1705.04664
  - $pp \to Vh$ — FCC report arXiv:1607.01831
  - $pp \to 2\ell 2\nu$ — Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598
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  - $pp \to \gamma\gamma\gamma\,/\,\gamma\gamma\ell\nu\,/\,\gamma\gamma\ell\ell$ — Greiner, MS arXiv:1710.11514
- SHERPA+RECOLA
  - $pp \to V + 0, 1, 2$ j, $pp \to 4\ell$, $pp \to t\bar{t}h$ — Biedermann et.al. arXiv:1704.05783
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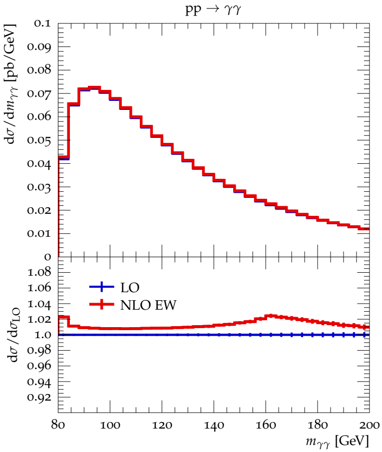
General setup

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

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

- EW parameter renormalisation in G_μ-scheme
- photon induced processes considered throughout

Diphoton production – $\gamma\gamma$



NLO EW corrections to diphoton production

- peak-like enhancement around $m_{\gamma\gamma} \approx 160\,\text{GeV}$
- 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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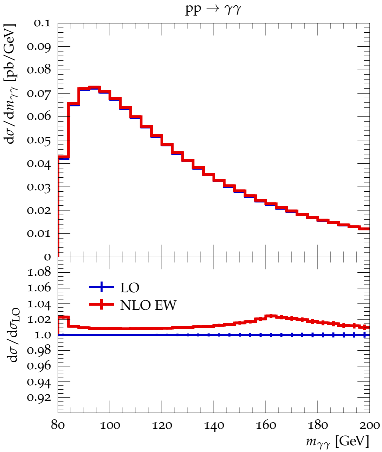
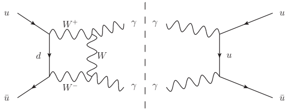


NLO EW corrections to diphoton production

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



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

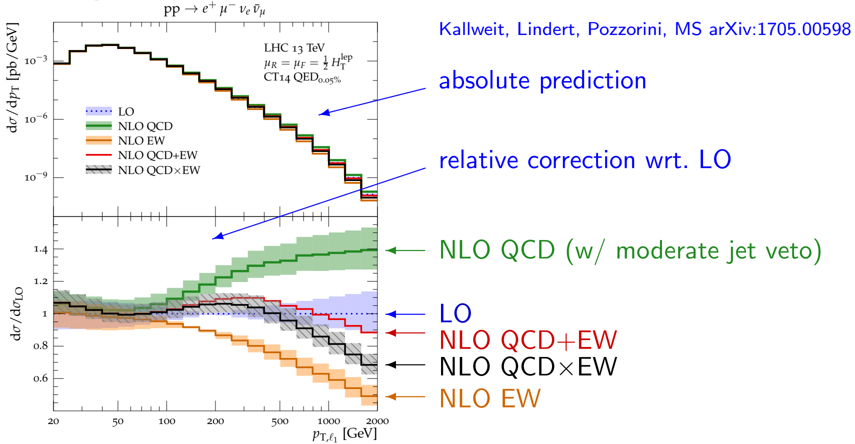
Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

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

DF	$e^+\mu^-\nu_e\bar{\nu}_\mu$	WW
SF	$e^+e^-\nu_e\bar{\nu}_e$	$WW + ZZ$
	$e^+e^-\nu_{\mu/\tau}\bar{\nu}_{\mu/\tau}$	ZZ

- incl. event selection w/ standard lepton acceptance cuts, ($p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$), $|\eta_\ell| < 2.5$), $n_f = 4$ and mild jet veto to suppress large NLO QCD corr.

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

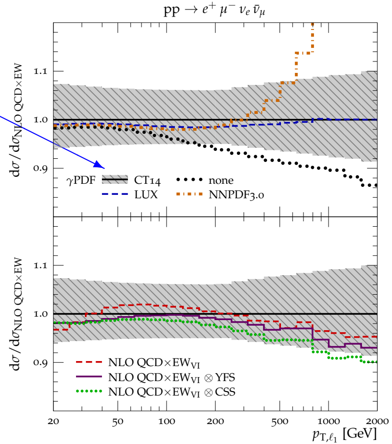


- large pos. NLO QCD, large neg. NLO EW
  → NLO QCD+EW and NLO QCD⊗EW differ significantly

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

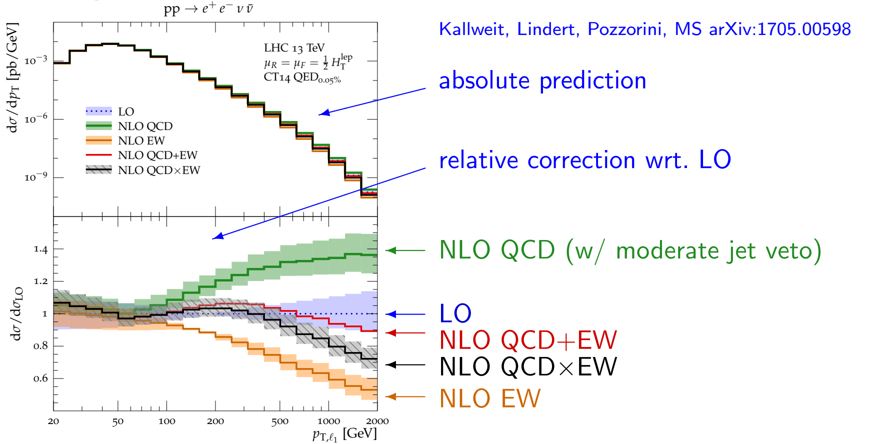
relative importance of γ-induced channels wrt. NLO QCD$\times$EW

CT14qed (baseline)	no γPDF
LUXqed	NNPDF3.0qed



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

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



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CT14qed (baseline) no γPDF
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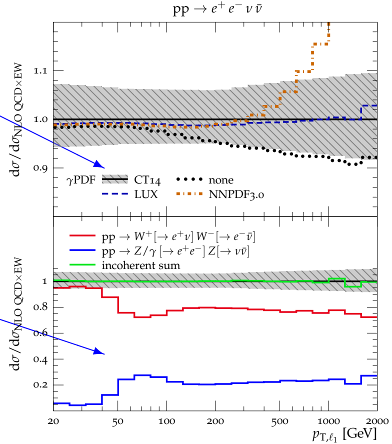
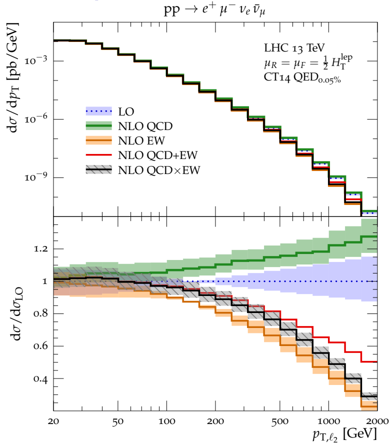
rel. contribs of WW and ZZ subtops

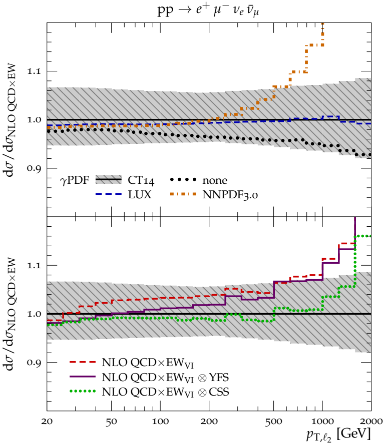
coherent $|WW+ZZ|^2$
incoherent $|WW|^2+|ZZ|^2$
only $|WW|^2$
only $|ZZ|^2$



- WW dominant throughout, ZZ only contribs 10-20%
  → overall very similar to DF case

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





- ZZ dominant at very large p_T
  $\to$ different EW corrections, take care when extrapolating

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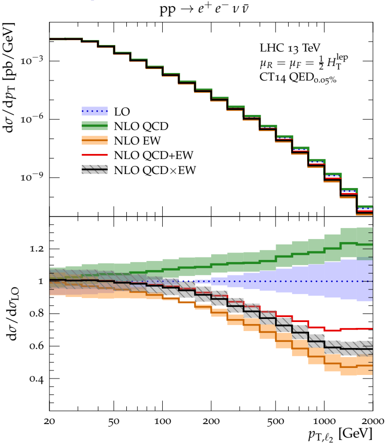

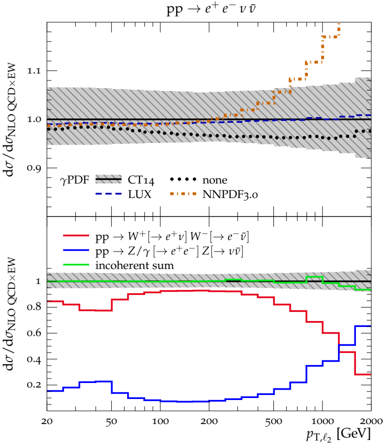

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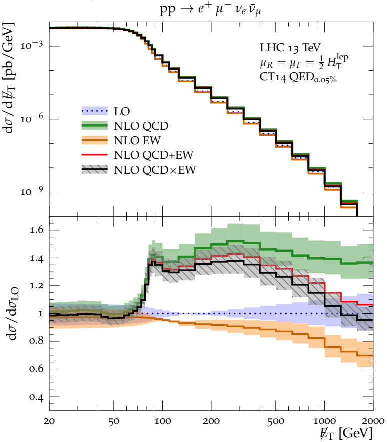

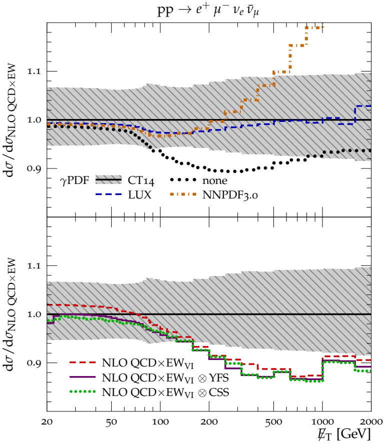

- kinematic suppression for $p_T^{\nu\nu}$ at LO, unlocked at NLO QCD
  not present in γ-induced $\Rightarrow$ large contrib

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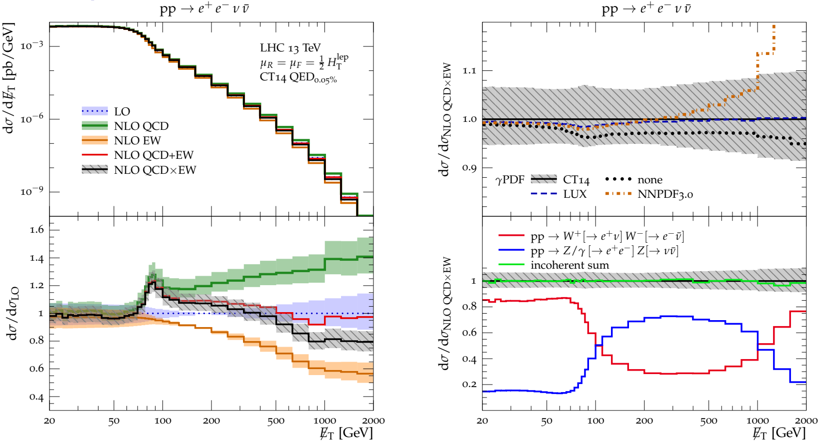

- kinematic suppression for $p_T^{\nu\nu}$ for WW, but not ZZ
  ZZ dominates for MET $> 100\,$GeV with large EW corr.

Electroweak corrections for LHC physics

Three-jet production

Dijet production

- NLO QCD
  Ellis, Kunszt, Soper PRL 69 (1992) 1496-1499
  Giele, Glover, Kosower hep-ph/9302225
- NLO EW and all subl. corrections
  Moretti, Nolten, Ross hep-ph/0606201
  Dittmaier, Huss, Speckner arXiv:1210.0438
  Frederix et.al. arXiv:1612.06548

Three-jet production

- NLO QCD
  Nagy hep-ph/0110315
- NLO EW and all subl. corrections
  Reyer, MS, Schumann arXiv:1902.01763

N-jet production

- NLO QCD known for 4- and 5-jet production
  Bern et.al. arXiv:1112.3940
  Badger et.al. arXiv:1309.6585

Contributions

- **define jets completely democratically**,
  incl. all massless visible particles of the SM (q, g, γ, ℓ)
  $p_\mathrm{T}(j_1) > 80\,\mathrm{GeV}$, $p_\mathrm{T}(j_i) > 60\,\mathrm{GeV}$ ($i > 1$)

- **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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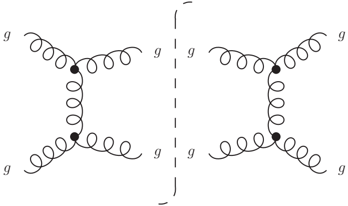

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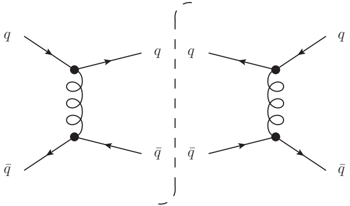

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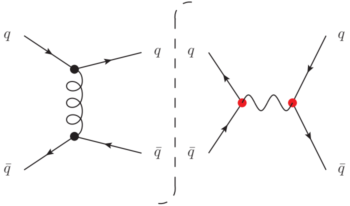
$\mathcal{O}(\alpha_s\alpha)$



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

Contributions

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  incl. all massless visible particles of the SM (q, g, γ, ℓ)
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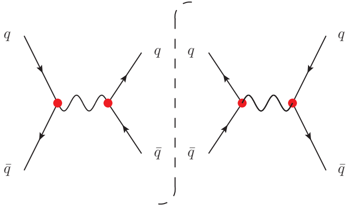
$\mathcal{O}(\alpha^2)$



hadronic DY

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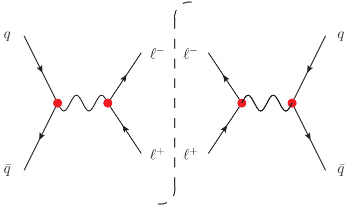

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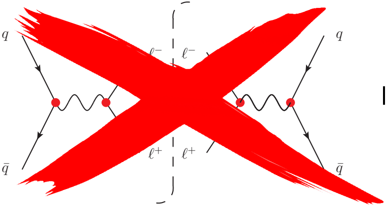

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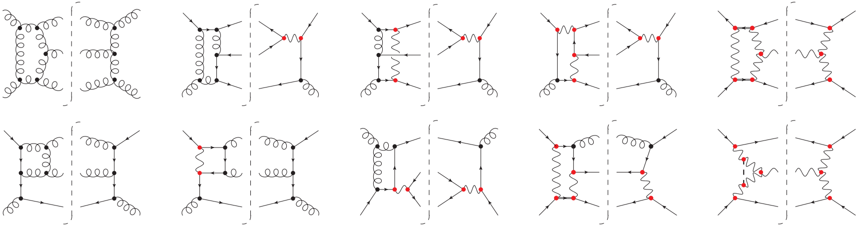
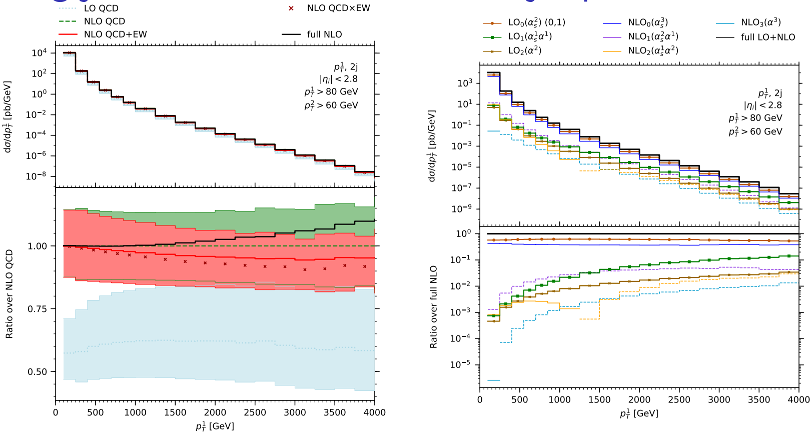
Contributions at NLO



$\mathcal{O}(\alpha_s^4)$ $\mathcal{O}(\alpha_s^3\alpha)$ $\mathcal{O}(\alpha_s^2\alpha^2)$ $\mathcal{O}(\alpha_s\alpha^3)$ $\mathcal{O}(\alpha^4)$

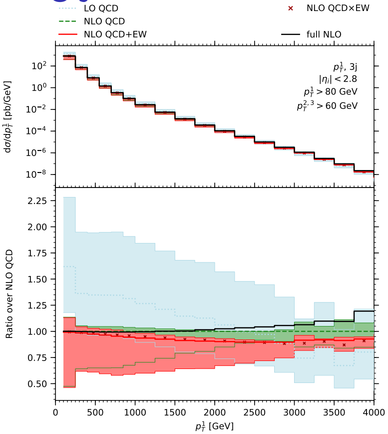
- sensitive to the full SM spectrum, incl. top quark, Higgs boson, all lepton and neutrino flavours
- real emission corrections include: $\ell\nu qg$, $\ell\ell qg$, $\ell\ell\ell\ell$, $\ell\ell\ell\nu$ final states

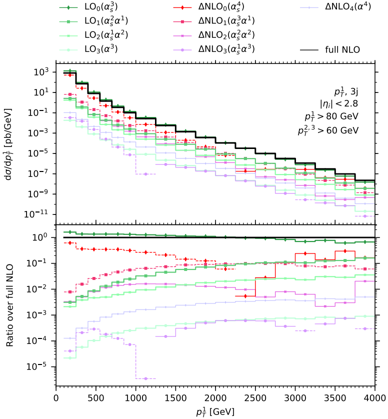
Leading jet transverse momenta in dijet production



- moderate EW corrections
- overcompensated by subleading orders

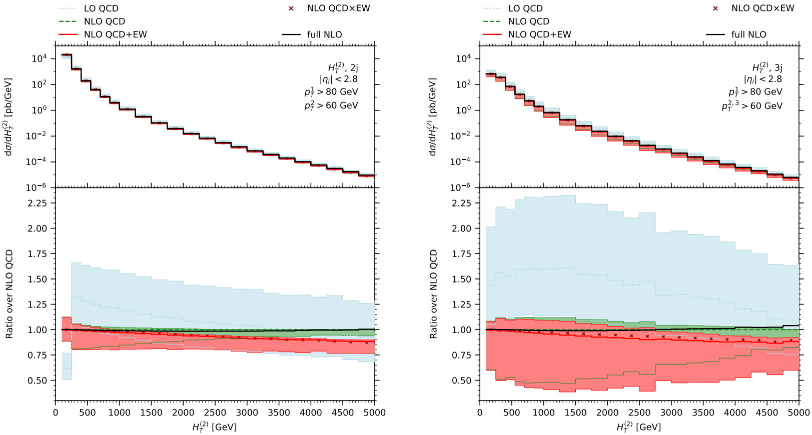
Leading jet transverse momenta in 3-jet production





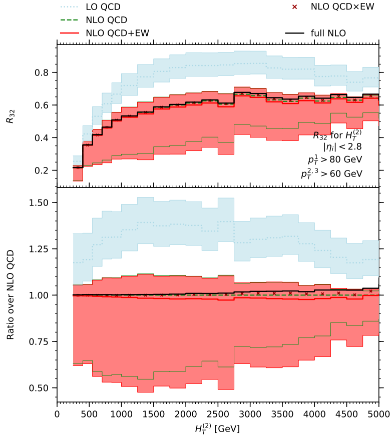
- moderate EW corrections
- overcompensated by subleading orders, can be as large as QCD corr.

$H_{\mathrm{T}}^{(2)}$



- NLO EW reduces x-sec. by $\approx 15\%$ at $H_{\mathrm{T}}^{(2)} = 2\,\mathrm{TeV}$
- again, large accidental compensations between NLO EW and subleading orders

R_{32}

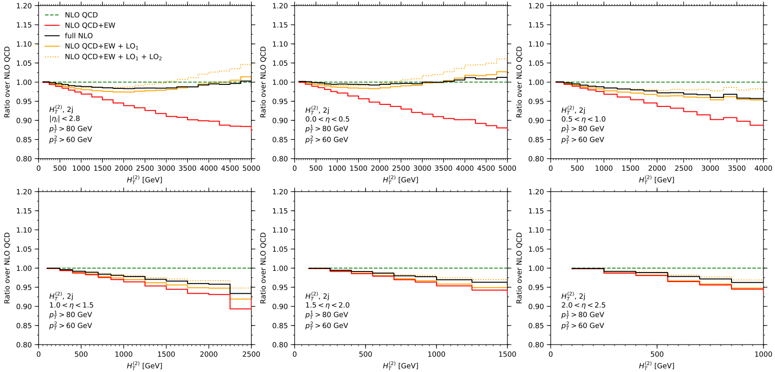


- NLO EW and subleading order contribs very similar between $2j$ and $3j$ $\Rightarrow$ R_{32} largely uneffected
- supports factorisation of NLO QCD and NLO EW correction at large $H_\mathrm{T}^{(2)}$
- scale uncertainty by synchronous scale variation

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

R_{32} in different Δy-slices

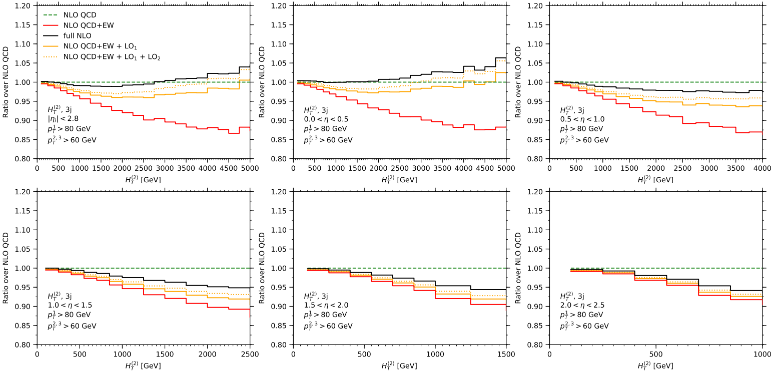
dijet production



- effects already seen in Dittmaier, Huss, Speckner arXiv:1210.0438

R_{32} in different Δy-slices

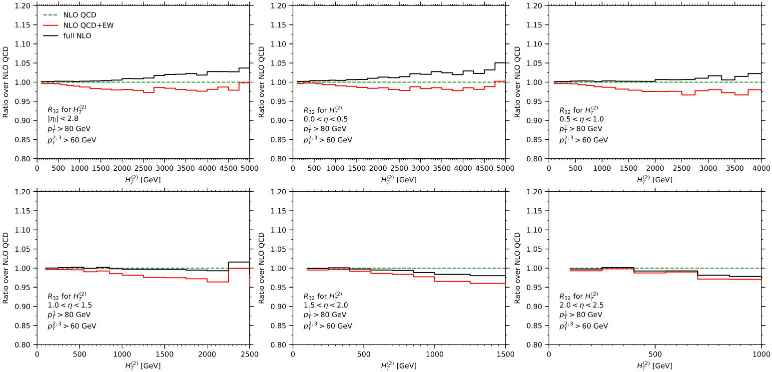
three jet production



- slightly different in 3-jet production

R_{32} in different Δy-slices

R_{32}



- different net effects in different rapidity slices

Electroweak corrections for LHC physics

Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
- taylored to large-p_T regions where EW corrections dominated by virtual W/Z exchange and RG running
- modify MC@NLO $\overline{\mathrm{B}}$-function to include NLO EW virtual corrections and integrated approx. real corrections

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

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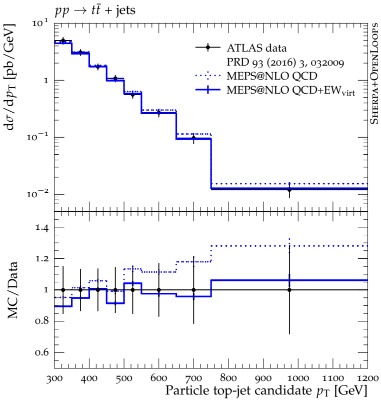
Results: $pp \to t\bar{t} + \text{jets}$



Gütschow, Lindert, MS in arXiv:1803.00950

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

  Höche, Krauss, MS, Siegert arXiv:1009.1127
- improved description of data

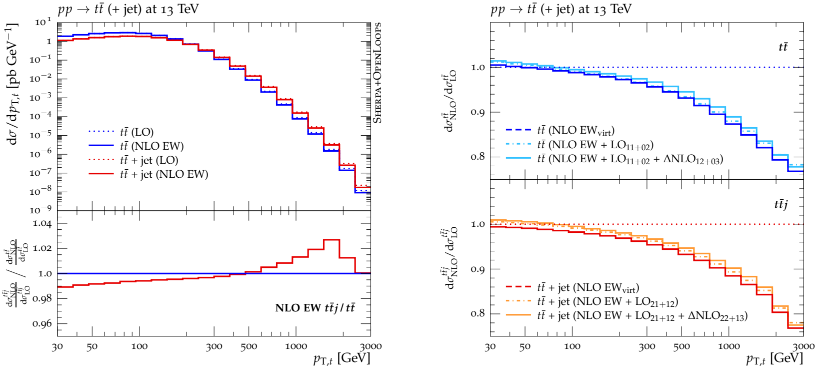
Conclusions

- electroweak effects are important at LHC, HE–LHC, FCC, etc.
- become large whenever the scale is large compared the EW scale
- NLO EW often not enough, need also subleading contribs
- precise definition of physics objects needed
  $\Rightarrow$ differentiate short-distance parton and long-distance measurable object
- can be incorporated in multijet-merged particle-level calculations to improve description in those regions
  $\rightarrow$ currently tailored to TeV-scale physics
- 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
  $\rightarrow$ can induce peaks, edges or kinks in distributions
  $\rightarrow$ includes many more pitfalls than NLO QCD

Backup

Top pair production in association with jets

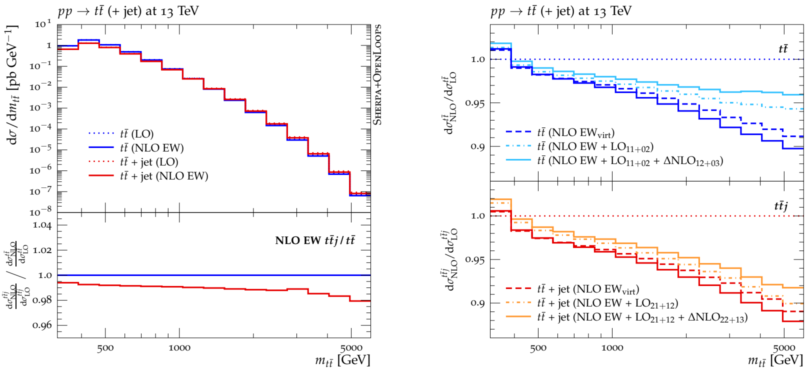
Gütschow, Lindert, MS in arXiv:1803.00950



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

Top pair production in association with jets

Gütschow, Lindert, MS in arXiv:1803.00950



Observation: subleading orders important