Electroweak corrections II

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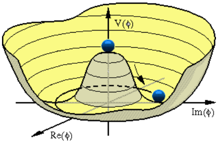
CTEQ-MCnet school 2021

Recap – The electroweak Standard Model

$$
\begin{aligned}
\mathcal{L} = & -\tfrac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + i \bar{\psi} \not{D} \psi + h.c. \\
& + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \\
& + |D_\mu \phi|^2 - V(\phi)
\end{aligned}
$$



Couplings:
g, g', α

Higgs potential:
v, μ, λ

v is commonly substituted for G_F, the muon decay constant

Masses:
m_h, m_W, m_Z, m_ℓ, m_q

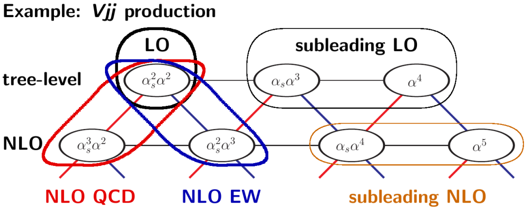
Mixing angles:
$\sin\theta_w$

Not all of them are independent!

- broken (hidden) symmetry, new (apparent) symmetry $SU(2)_L \times U(1)_Y \longrightarrow U(1)_{QED}$
- dynamically generated mass terms lead to many relations between the apparent EW parameters
  input parameters $\leftrightarrow$ derived parameters

$\Rightarrow$ not all parameters can be determined independently

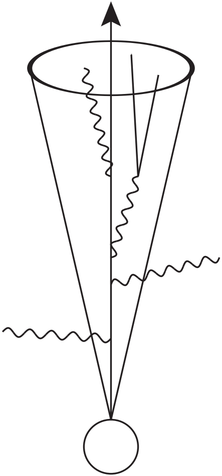
Recap – Electroweak higher order corrections



- designation of contribution given only by its order in α_s and α
- NLO QCD: all contribution with one additional power in α_s wrt. the respective Born process
  NLO EW: all contribution with one additional power in α wrt. the respective Born process
- EW corrections may not involve adding an EW particle

Recap – IR safe observables

- the presence of massless quanta necessitates observables to be insenstive to soft/collinear radiation
- differentiate: short-distance parton vs. long-distance identified and measurable object
- same solutions as in QCD: jets (a dressed lepton is the same as a jet)
- problem: all SM particles need to be involved
- need flavour tagging (γ, ℓ, ...) simplified solutions exist, in general needs fragmentation functions



Electroweak corrections II

Fixed-order calculations

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 '17
  - MADGRAPH — Frederix et.al. '18
- virtual corrections (EW one-loop matrix elements, renormalisation)
  - GOSAM — Chiesa et.al. '15
  - MADLOOP — Frixione et.al. '14
  - OPENLOOPS — Kallweit et.al. '14
  - RECOLA — Actis et.al. '12
- currently generally limited to fixed-order
- a number of dedicated calculations and private codes

Phenomenological impact – $p_\mathrm{T}(W)$

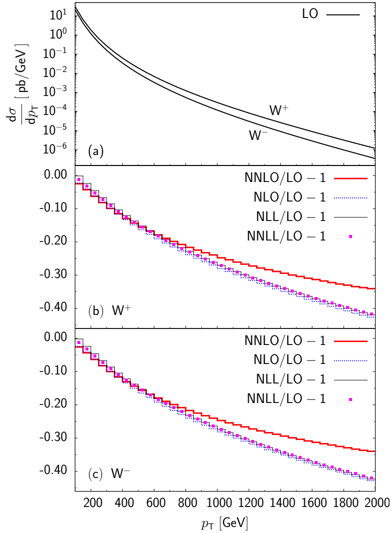
NLO EW for pp $\to Wj$

- NLO including all contribs
- NLL are univ. Sudakov logs
- NNLL process dependent limit of NLO
- NNLO $=$ NLO $+\ \frac{1}{2}$NLL^2

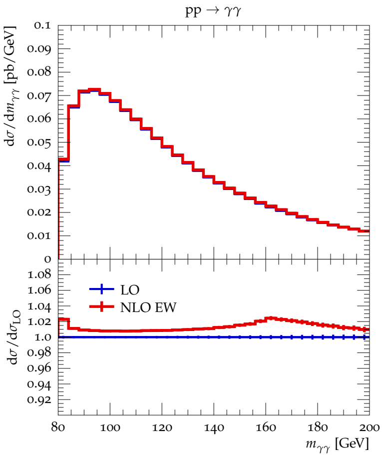
EW corrections small inclusively, but reach -30% at 1 TeV

dominated by logarithmic EW Sudakov corrections

Kühn et.al. '05,'06,'07



Phenomenological impact – diphoton production

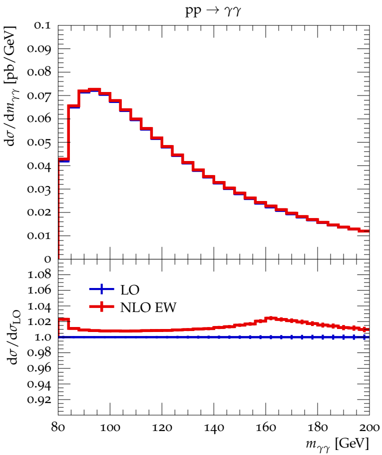


Chiesa et.al. '17

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

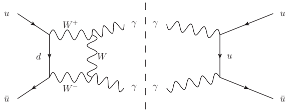
Phenomenological impact – diphoton production



Chiesa et.al. '17

NLO EW corrections to diphoton production

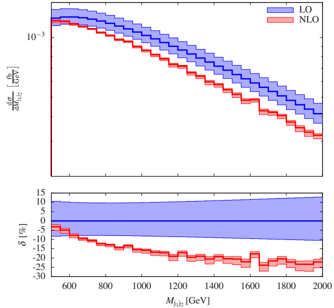
- peak-like enhancement around $m_{\gamma\gamma} = 2\, m_W$
- induced by W-box creating pseudo-resonant structures

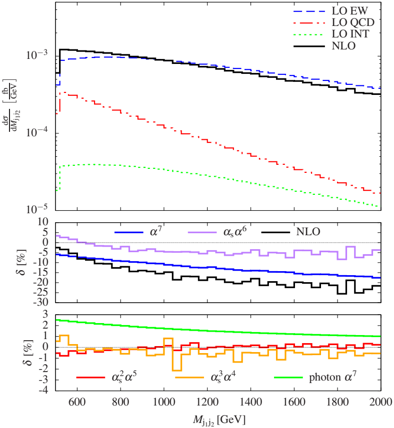


- should be accounted for in data-driven background fits in diphoton resonance searches

Phenomenological impact – VBS

$pp \to \ell^+\ell^+\nu\nu jj + X$

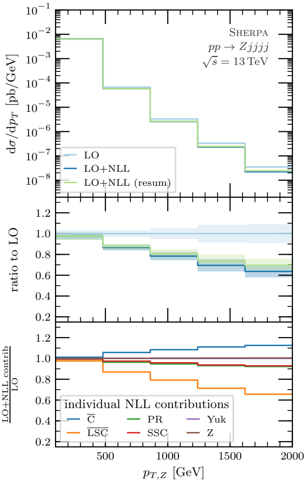




- multiple contributions at LO and NLO, Biedermann, Denner, Pellen '17
  process with largest power of α_s not dominant
- large EW corrections due to ubiquitous large momentum transfers

EW Sudakov approximation

Bothmann, Napoletano '20



Because the weak bosons are massive and real W and Z radiation (mostly) leads to distinguishable signatures.
The virtual corrections are thus not counterbalanced by real em. corrections.

In the limit that all invariants $s_{ij} \gg m_W$, the virtual weak corrections are given by logarithms of these two scales.
$\Rightarrow$ EW Sudakov logarithms

Denner, Pozzorini '00

EW corrections can easily be constructed in this limit.

Electroweak PDFs and parton showers

QED PDFs

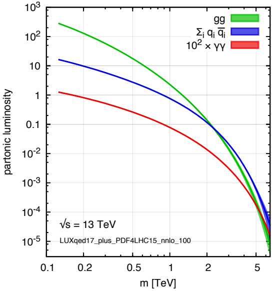
Conventional **QCD PDFs** are based on QCD splitting functions.
LO: $q \to qg$, $g \to gg$, $g \to q\bar{q}$

Current **QCD+QED PDFs** add $q \to q\gamma$ and $\gamma \to q\bar{q}$.

- $\gamma \to \ell\bar{\ell}$ typically neglected,
  justified as photon PDF driven by $q \to q\gamma$
- technically incomplete, NLO QED consistency
- lepton PDFs at $\mathcal{O}(\alpha^2)$ negligible

Other sources of photons:

- semi-classical scattering of the em-fields
  of the incident electrons/protons/ions (EPA)
  $\to$ protons stay intact
- scattering through hadronic resonances



Manohar et.al. '16

Electroweak PDFs

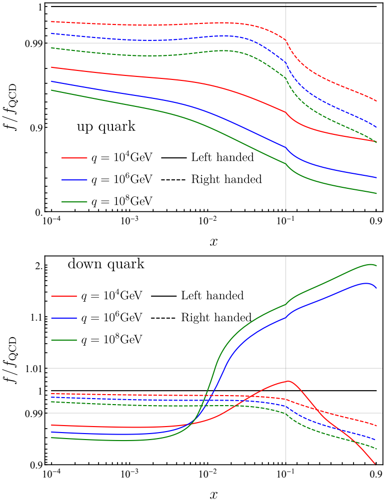
Full QCD+EW PDFs are chiral, f^{L} and f^{R} evolve differently.

In the unbroken SM

- f^{L} : $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
- f^{R} : $\mathrm{U}(1)_Y$
- $u^{\mathrm{L}} - d^{\mathrm{L}} \to 0$ as $Q^2 \to \infty$

In the broken SM the picture is a little messier and mass effects are important at accessible collider scales.

Bauer, Ferland, Webber '17



Electroweak PDFs

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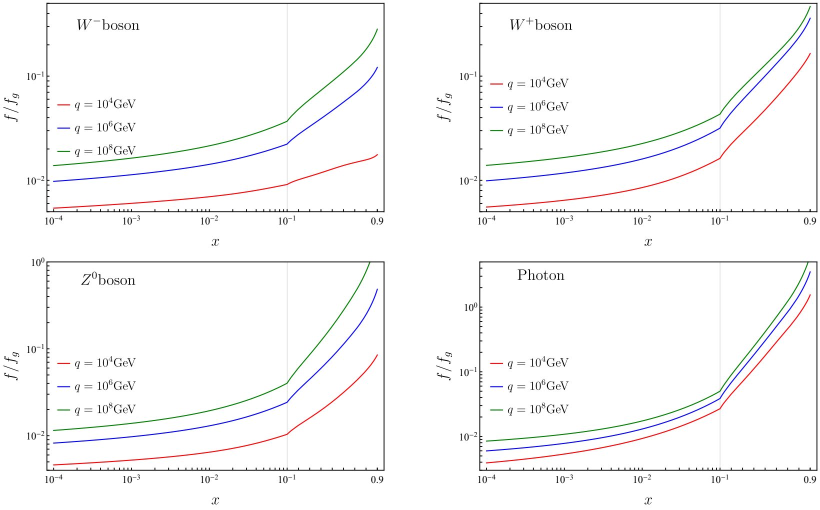

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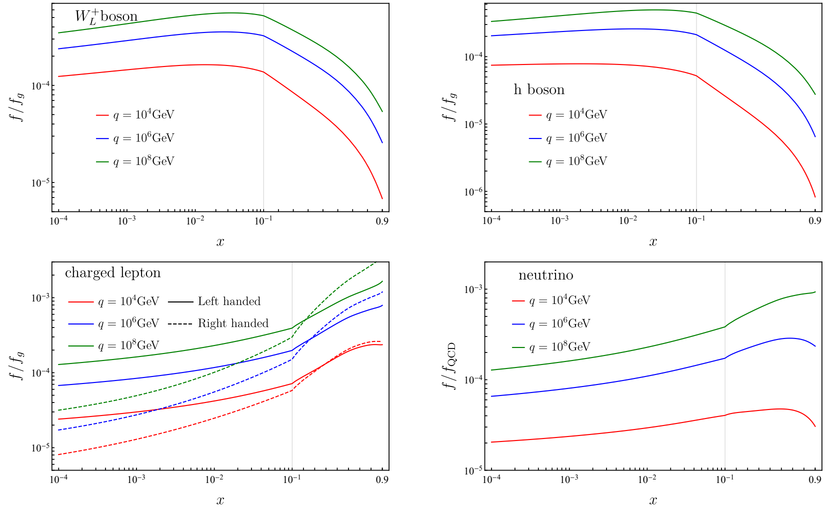


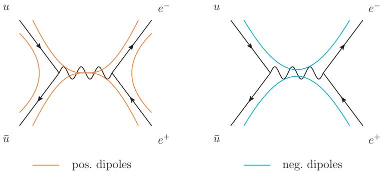
QED parton showers

QED parton showers follow the same principle as QCD parton showers.
Add $f \to f\gamma$ and $\gamma \to f\bar{f}$ splitting functions. → Stefan's lectures

However, QCD is SU(3) whereas QED is U(1).
Hence, while in QCD a large-N_c expandsion is sensible,
dropping $\frac{1}{N_c^2}$ terms, $\frac{1}{1^2}$ in QED is not such a small number.

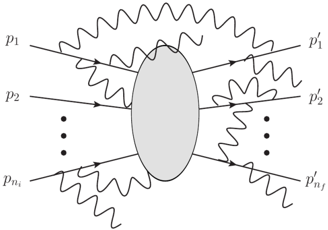
Thus, parton showers typically miss the soft-wide-angle radiation pattern.

Example: $u\bar{u} \to e^+e^-$, 6 dipoles (4 opposite sign, 2 same sign)



all dipoles contribute on equal footing

Soft-photon resummation



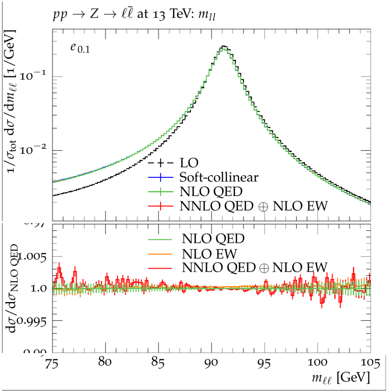
- universal soft-photon limit of all-order QED amplitudes (Abelian nature and fermion masses/ absence of divergent photon splittings essential) Yennie, Frautschi, Suura '61

$$\mathrm{d}\sigma^{\mathsf{YFS}} = \sum_{n_\gamma} \frac{1}{n_\gamma!}\,\mathrm{d}\Phi\, e^{Y} \prod_{i=1}^{n_\gamma} \left[\mathrm{d}\Phi_{k_i}\cdot\alpha\,\tilde{S}(k_i)\right] \left[\tilde{\beta}_0 + \sum_{i=1}^{n_\gamma} \frac{\tilde{\beta}_1(k_i)}{\tilde{S}(k_i)} + \ldots\right]$$

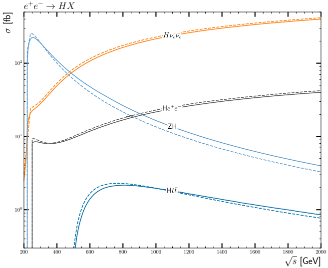
- coherent multiple soft-photon emission from Eikonals $\tilde{S}$
- re-orders perturbative series in terms of hard-remainders $\tilde{\beta}_i$ defined on reduced phase spaces in multiphoton configurations

Soft-photon resummation

Krauss, Lindert, Linten, MS '18



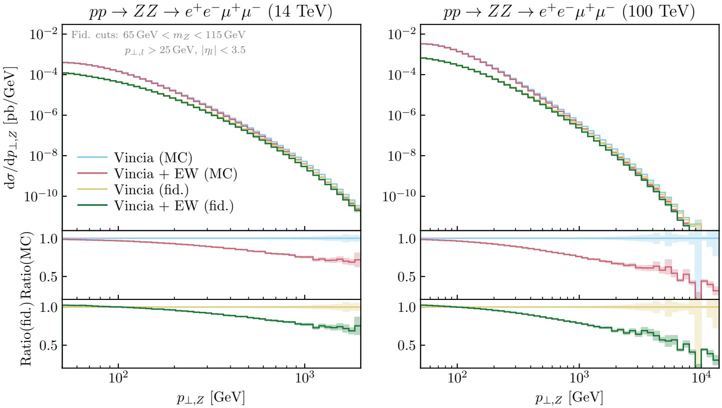
Krauss, Price, MS tbp



- method of choice for past and future e^+e^- machines

EW parton showers

Extend splitting functions to EW sector.
One crucial caveat: they are spin dependent.



Brooks, Skands, Verheyen '21

Electroweak corrections in event generators

Electroweak corrections in event generators

Goal:
We want to include exact NLO EW corrections in an event generator, in addition to the NLO QCD ones.

Solution:
NLO QCD+EW matching (MC@NLO, POWHEG), structurally works the same as NLO QCD alone.

→ Simon's lectures

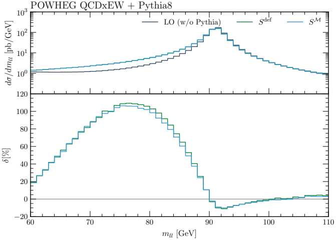
Main problem:
The EW SM is full of masses and resonances.
Implementations exist for the most important processes. (V, VV, ..)

Electroweak corrections in event generators

Mück, Oymanns '16

NLO QCD+EW matched calculation

NLO QCD and NLO EW matched simultaneously



$$\mathrm{d}\sigma^{\text{QCD+EW}}_{\text{POWHEG}} = \mathrm{d}\Phi_B\,\overline{\mathrm{B}}^{\text{QCD+EW}}\left\{\Delta^{\text{QCD+EW}}(t_c) + \int_{t_c}\mathrm{d}t\,\frac{\mathrm{R}^{\text{QCD}}+\mathrm{R}^{\text{EW}}}{\mathrm{B}}\,\Delta^{\text{QCD+EW}}(t)\right\}$$

Electroweak corrections in event generators

However, if only the large corrections in the Sudakov regime are sought, there is an easy way to incorporate them in multijet merging methods used for ATLAS/CMS's baseline samples. → Simon's lecture

- modify MC@NLO $\overline{\mathrm{B}}$-function to include NLO EW virtual corrections and integrated approx. real corrections

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

- 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 ($\mathrm{V}_{n,\mathrm{EW}}$)

approximate integrated real contribution ($\mathrm{I}_{n,\mathrm{EW}}$)

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optionally include subleading Born

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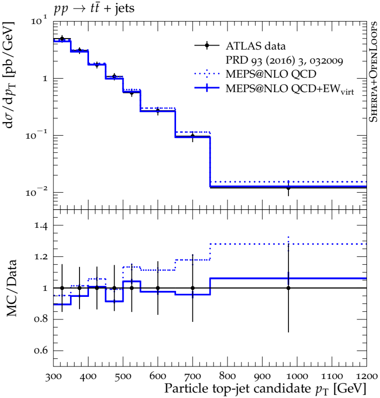
Results: $pp \to t\bar{t} + \text{jets}$

Gütschow, Lindert, MS in '18



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

  Höche, Krauss, MS, Siegert '10
- improved description of data

Summary

- inclusive EW corrections are small (in an appropriate ren. scheme), $\mathcal{O}(1\ldots5\%)$
- EW corrections for observables dominated by large-momentum-transfer processes receive logarithmic corrections, $\mathcal{O}(-10\ldots-50\%)$
- ubiquitous multiple mass scales can induce bumps, edges, kinks due to resonances and thresholds introduced at higher-orders
- while photon PDFs are phenomenologically relevant, full EW PDFs may start to become relevant at the FCC
- EW corrections in event generators available and improve data description

Questions:

1. Why do EW corrections generally increase with the typical momentum transfer of the interaction?
2. How do EW PDFs differ from the standard QCD ones?
3. Can an existing parton shower easily accommodate EW splitting functions?
4. How can NLO EW corrections be incorporated in event generators?