Electroweak corrections in the light of QCD precision

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Introduction

Electroweak correction come in two variants: virtual corrections and real emission correction.

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

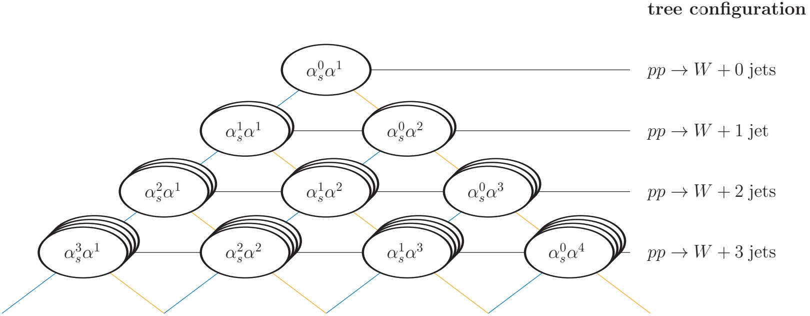
Real electroweak corrections usually constitute a separate process. However, largest BR of W/Z bosons is hadronic, thus (almost) indistinguishable in jet production. Nonetheless may constitute signal in itself.

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

Beware of subleading orders.

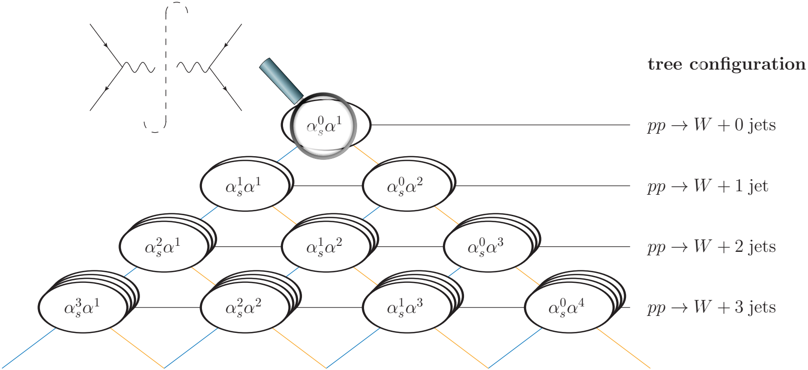
Content

Consistent setup: counting orders and defining signatures



- NLO QCD: $\alpha_s^1 = 1$ parton, only MEs from squared diagrams
- NLO EW: $\alpha^1 = 1$ photon or 1 parton,
  also MEs from interfering diagrams, resonances

Consistent setup: counting orders and defining signatures



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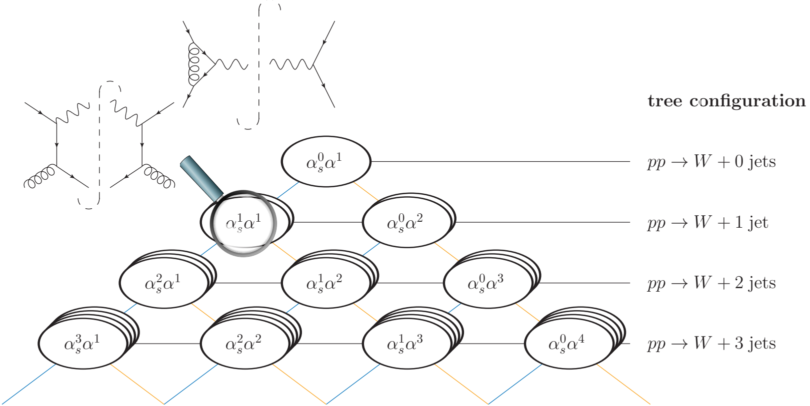

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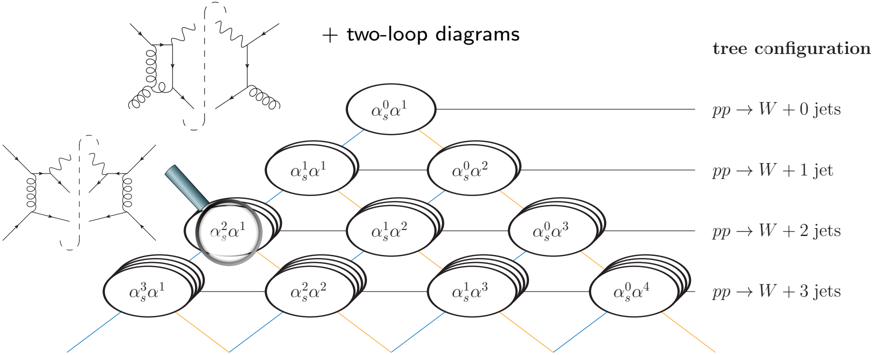

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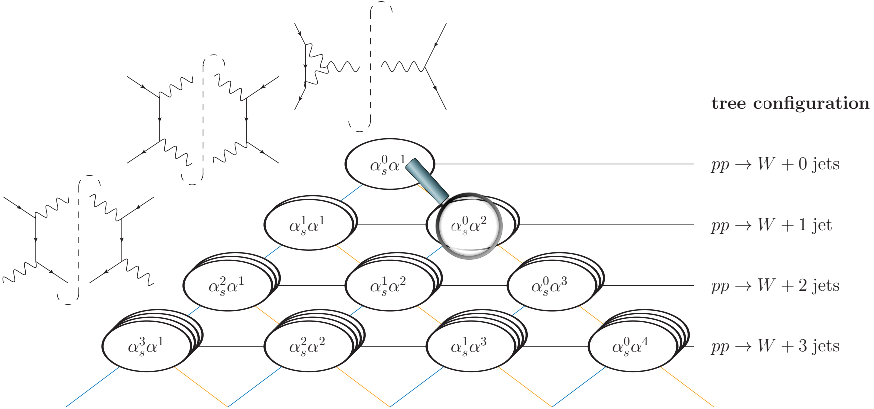

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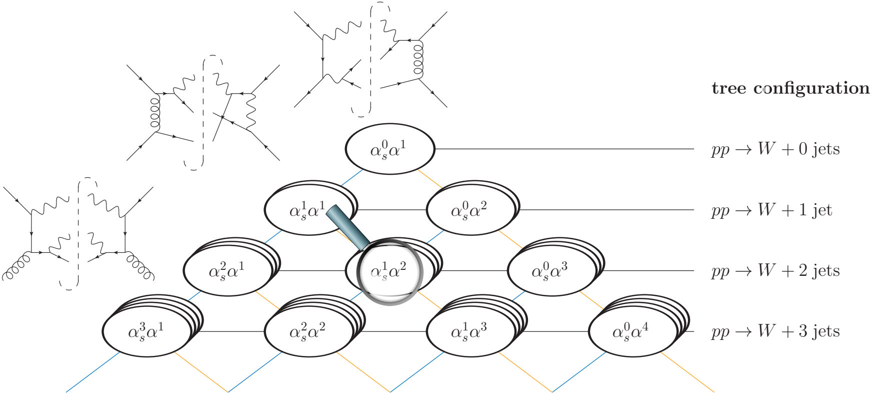

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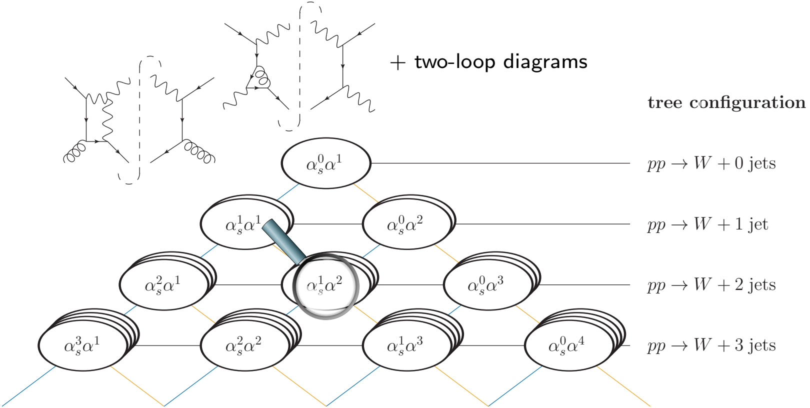

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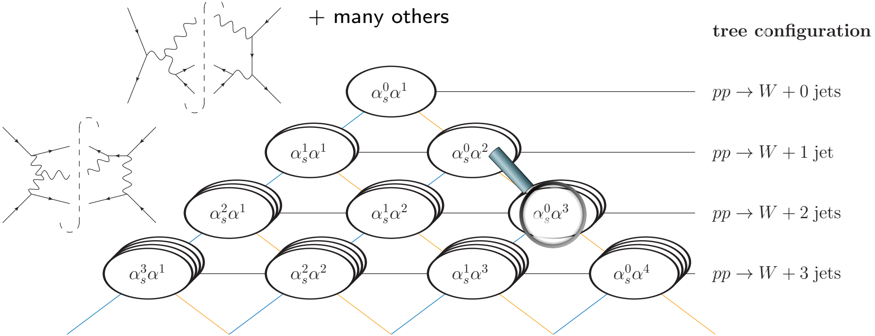

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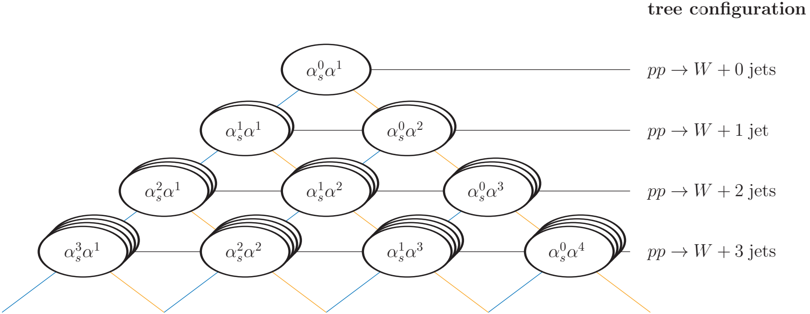

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Subtleties: photons in initial state

Harland-Lang et.al. arXiv:1605.04935, Kallweit et.al. arxiv:1705.00598

NLO EW for photon initiated processes

- initial state photons are not resolved, should be treated as any other parton
- multiple sources: elastic (proton remains intact)
  inelastic (proton broken up)
- both elastic and inelastic photons evolve according to DGLAP
  $\rightarrow$ splittings $\gamma \rightarrow \gamma$, $\gamma \rightarrow q\bar{q}$, $q \rightarrow q\gamma$
  $\rightarrow$ can be combined into a single PDF as long as one is not concerned with what happens to the proton
- the photon PDF (at NLO QED) contains renormalisation factors that must be cancelled by the partonic cross section

$\Rightarrow$ renormalisation in short-distance scheme (G_μ, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...)

Subtleties: photons in final state

What is a jet?

- photons must be part of a jet, but to what extent?
- **democratic:**
  - \+ straight forward, close to experiment for many procs
  - – more subtractions (Born configs with FS photons)
  - → single photons constitute a jet
- **anti-tagging jets with too large photon content:**
  dress quarks for collinear safety,
  discard jets if $E_\gamma > z_\text{thr}\, E_\text{jet}$ (e.g. $z_\text{thr} = 0.5$)
  - \+ fewer contributions
  - – difference to experimental jet definition (usually subpercent)
  - – ill-defined at lower order NLO correction (w/ $\gamma \to q\bar{q}$ splittings)
  - → single photons do not constitute a jet

  general anti-tagging must proceed through fragmentation functions

Subtleties: photons in final state

What is a photon?

- differentiate: short-distance photon (photon as parton),
  long-distance photon (identified, measurable photon)

a) treat as identified particle, renormalise on-shell ($\alpha(0)$), no $\gamma \to ff$
$\to$ renormalisation contains IR poles
$\to$ problematic if both identified and unresolved photons in Born

b) treat democratically (just another parton), renormalise in short distance scheme (G_μ, $\alpha(m_Z)$, $\overline{\text{MS}}$, ...), include $\gamma \to ff$ splittings
$\to$ pure UV renormalisation
$\to$ if needed, identify photon through frag. function $D_\gamma^p(z,\mu)$

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

all others $D_\gamma^q(z,\mu) = \mathcal{O}(\alpha)$, $D_\gamma^g(z,\mu) = \mathcal{O}(\alpha_s\alpha)$

- identical at NLO EW, if fragmentation D_γ^q on Born is negligible

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Subtleties: photons in final state

What is a lepton?

- in principle, again differentiate between short-distance parton and long-distance identified and measurable object
- simplified as leptons not gauge bosons, thus

  $D_\ell^\ell(z,\mu) = \delta(1-z) +$QED bremsstrahlung

  $D_\ell^\gamma(z,\mu) = \mathcal{O}(\alpha)$ problematic in processes with ℓ and unresolved photons in Born

  all other $D_\ell^q(z,\mu) = \mathcal{O}(\alpha^2)$, $D_\ell^g(z,\mu) = \mathcal{O}(\alpha_s\alpha^2)$
- 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

Combination of NLO QCD and EW correction

- additive – strict fixed order expansion

$$\mathrm{d}\sigma^{\mathsf{NLO}}_{\mathsf{QCD+EW}} = \mathrm{d}\sigma^{\mathsf{LO}}\left(1 + \delta_{\mathsf{QCD}} + \delta_{\mathsf{EW}}\right)$$

- multiplicative – contains terms of $\mathcal{O}(\alpha_s\alpha)$

$$\mathrm{d}\sigma^{\mathsf{NLO}}_{\mathsf{QCD}\times\mathsf{EW}} = \mathrm{d}\sigma^{\mathsf{LO}}\left(1 + \delta_{\mathsf{QCD}}\right)\left(1 + \delta_{\mathsf{EW}}\right)$$

  this construction is expected to well approximate the true $\mathcal{O}(\alpha_s\alpha)$ in the Sudakov limit where QCD and EW corrections factorise

$\Rightarrow$ in general, difference between additive and multiplicative combination can be used to assign higher-order uncertainty

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 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

High-precision observables

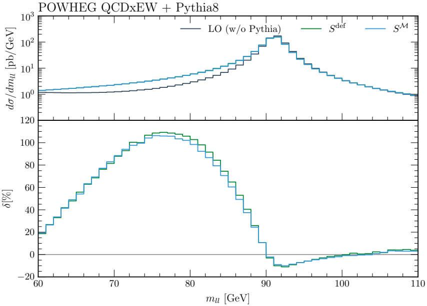
High-precision observables

Precision observables that need predictions with subpercent accuracy

- Fixed-order NLO EW $pp \to \ell\nu$ and $pp \to \ell\ell$ well known for a long time
- introduction of non-factorisable contributions (cannot be cast into form factors) that become relevant at the permille accuracy on-peak and percent (and more) off-peak
- precise operational and IR safe lepton definitions necessary
- NLOPS parton shower matched solutions exist in the POWHEG framework
  Bernaciak, Wackeroth arXiv:1201.4804
  Barze, Montagna, Nason, Nicrosini, Piccinini arXiv:1202.0465
  Mück, Oymanns arXiv:1612.04292
- more formulations needed to assess systematic, i.e. algorithmic, dependences

High-precision observables

Mück, Oymanns arXiv:1612.04292



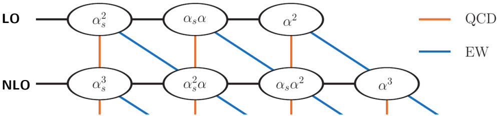
- parton shower resummation must properly account for internal resonances (W/Z)
  $\rightarrow$ resonance awareness
- coherence effects important

Observables in processes with large momentum transfers

Inclusive jet and dijet production

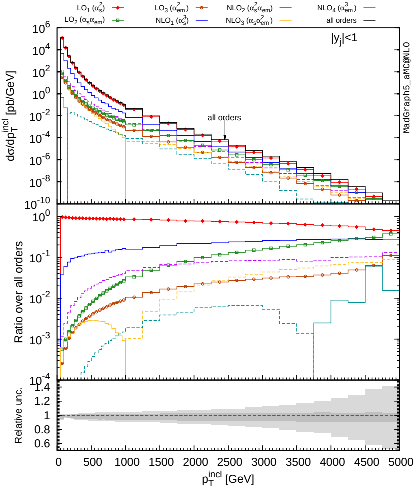
Frederix et.al. arXiv:1612.06548

Power counting:



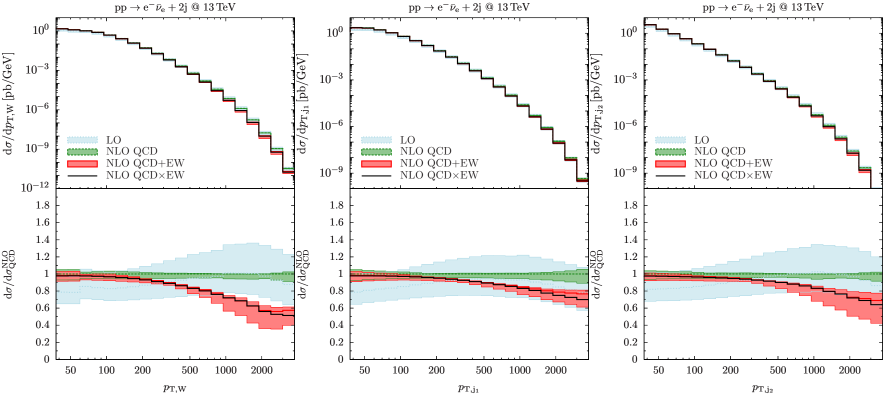
- dominated by LO ($\mathcal{O}(\alpha_s^2)$) and NLO QCD ($\mathcal{O}(\alpha_s^3)$)
- at large $p_\perp$ subleading LO ($\mathcal{O}(\alpha_s\alpha)$) contributes significantly

  Dittmaier, Huss, Speckner arXiv:1210.0438
- NLO EW relatively small



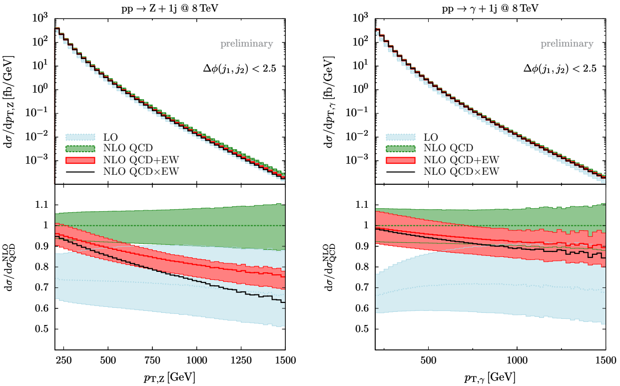
W + jets production

Kallweit, Lindert, Maierhöfer, Pozzorini, MS JHEP04(2016)021



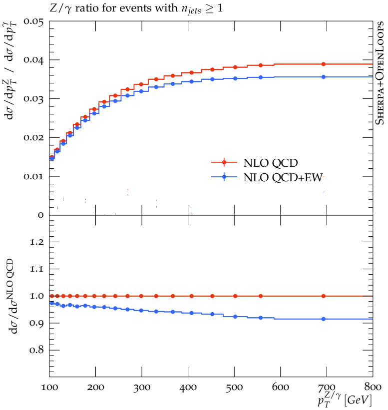
Z/γ ratio @ 8 TeV

Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1505.05704



→ EW corrections different for Z and γ

Z/γ ratio @ 8 TeV



Kallweit, Lindert, Pozzorini, MS for LH'15

- use this ratio together with Z/W-ratio to get handle on $p_\perp^Z$ in $Z \to \nu\bar{\nu}$ for NP searches
  $\to$ cf. J. Lindert's talk
- test how well data is described in $Z \to \ell\ell$

$\Rightarrow$ NLO EW improves data description

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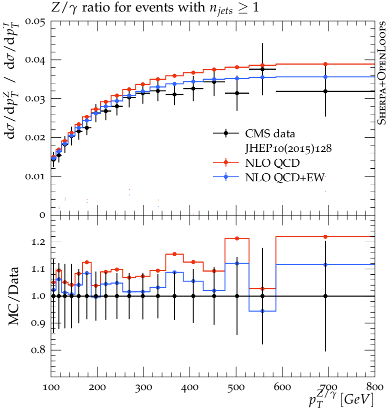

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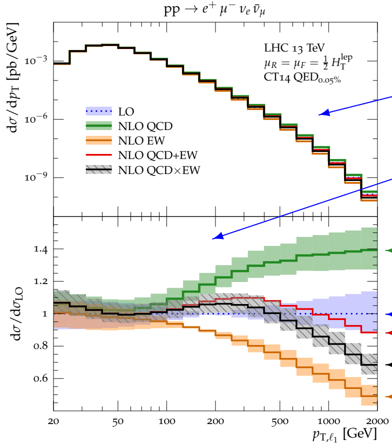
Diboson production

- NNLO QCD and NLO EW corrections known for all off-shell diboson channels
  - $\gamma\gamma$ — Bierweiler, Kasprzik, Kühn arXiv:1305.5402; Chiesa, Greiner, MS, Tramontano arXiv:1706.09022
  - $\ell\nu\gamma$ — Denner et.al. arXiv:1412.7421
  - $\ell\ell\gamma$ — Denner et.al. arXiv:1510.08742
  - $2\ell 2\nu$ — Biedermann et.al. arXiv:1605.03419; Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598
  - 4ℓ — Denner et.al. arXiv:1601.07787; Denner et.al. arXiv:1611.05338
- $2\ell 2\nu$ process of particular interest as features the interference of different resonance patterns
- study $e^+\mu^-\nu\bar{\nu}$ (DF) and $e^+e^-\nu\bar{\nu}$ (SF) production

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

Diboson production – $2\ell2\nu$ – DF



Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

absolute prediction

relative correction wrt. LO

NLO QCD (w/ moderate jet veto)

LO

NLO QCD+EW

NLO QCD×EW

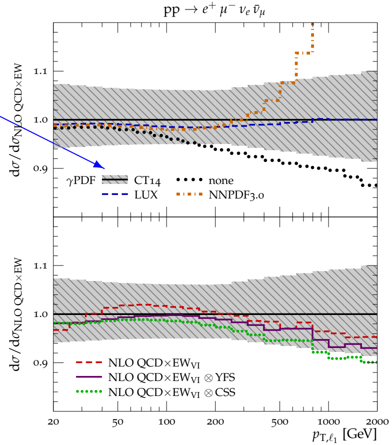
NLO EW

- large pos. NLO QCD, large neg. NLO EW
  $\to$ NLO QCD+EW and NLO QCD$\otimes$EW differ significantly

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

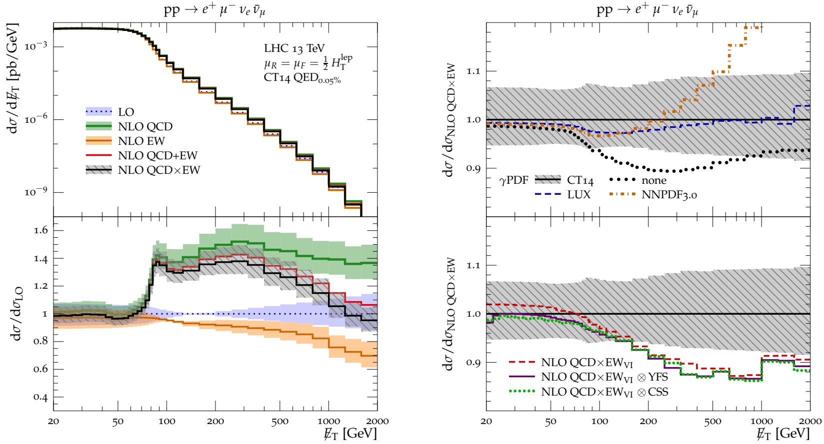
relative importance of γ-induced channels wrt. NLO QCD$\times$EW

CT14qed (baseline)	no γPDF
LUXqed	NNPDF3.0qed



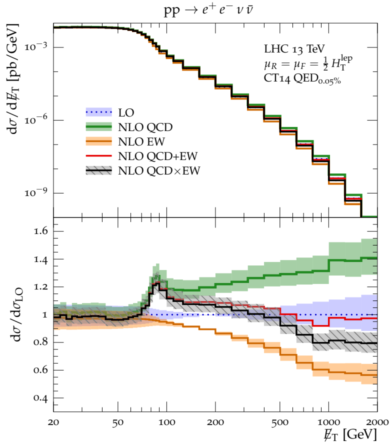
- all γPDF agree that γ-ind. $> 10\%$ for $p_T > 500$ GeV
  very good agreement between CT14qed and LUXqed

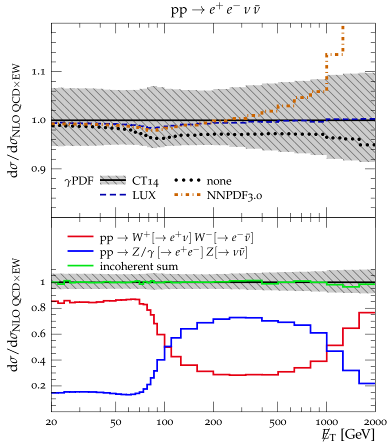
Diboson production – $2\ell 2\nu$ – DF



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

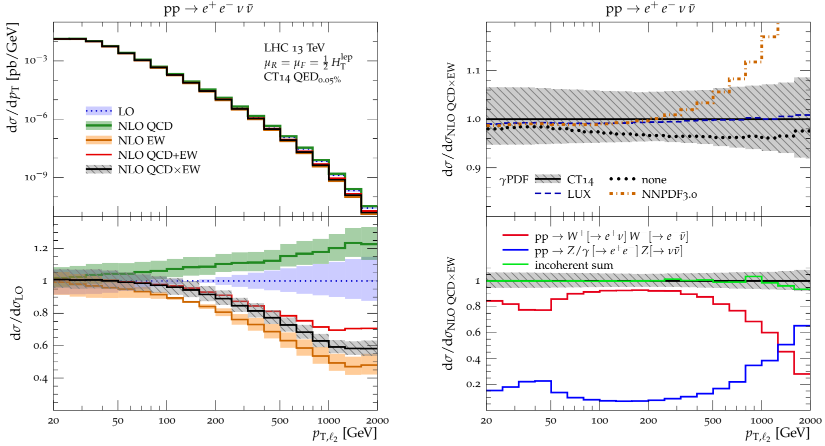
Diboson production – $2\ell 2\nu$ – SF





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

Diboson production – SF



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

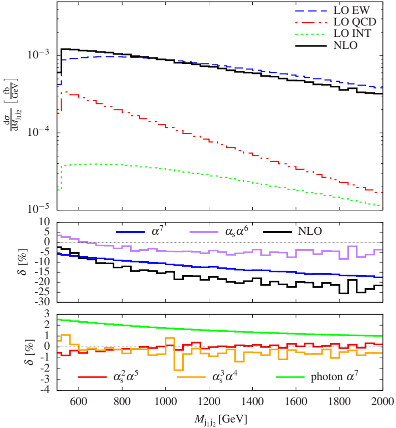
Vector boson scattering

VBS in $W^+W + jj$ channel

- LO: $\boldsymbol{\alpha^6}$, $\alpha^5\alpha_s$, $\alpha^4\alpha_s^2$
  NLO: $\boldsymbol{\alpha^7}$, $\boldsymbol{\alpha^6\alpha_s}$, $\alpha^5\alpha_s^2$, $\alpha^4\alpha_s^3$
- genuine $2 \to 6$ process at NLO EW with 2 resonances (contribs w/ 3 resonances tiny in VBS phase space)
- sizeable NLO corrections

→ details see M. Pellen's talk yesterday

Biedermann, Denner, Pellen arXiv:1708.00646



Triboson production

MS arXiv:1806.00307

- fully off-shell triboson production in $W^+W^+W^-$ channel
- genuine NLO EW $2 \to 6$ calculation with 3 resonances
- competing resonance structures
- contribs from 0 SFOS ($e^-\mu^+\mu^+\bar{\nu}\nu\nu$), 1 SFOS ($e^-e^+\mu^+\bar{\nu}\nu\nu$) and 2 SFOS ($e^-e^+e^+\bar{\nu}\nu\nu$) processes, and $e \leftrightarrow \mu$

0 SFOS	$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	WWW
1 SFOS	$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	$WWW + WZZ$
	$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	WZZ
	$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	WZZ
2 SFOS	$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	$WWW + WZZ$
	$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	WZZ

- on-shell production known for a while

Yong-Bai et.al. arXiv:1605.00554, Dittmaier, Huss, Knippen arXiv:1705.03722

Triboson production

MS arXiv:1806.00307

	inclusive			
	LO [fb]	δ_{EW}	$\delta_{q\bar{q}}^{\text{EW}}$	$\delta_{q\gamma/\bar{q}\gamma}^{\text{EW}}$
$\boldsymbol{\ell^-\ell^+\ell^+}$	**0.4209**	**−2.0 %**	**−5.2 %**	**3.2 %**
$e^-e^+e^+$	0.0212	−3.4 %	−7.1 %	3.6 %
$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	0.0206	−3.4 %	−7.0 %	3.6 %
$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	0.0006	−5.4 %	−9.5 %	4.1 %
$e^-e^+\mu^+$	0.0938	−1.4 %	−5.4 %	4.1 %
$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	0.0924	−1.4 %	−5.4 %	4.1 %
$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	0.0007	−2.9 %	−6.1 %	3.2 %
$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	0.0007	−2.7 %	−6.2 %	3.5 %
$e^-\mu^+\mu^+$	0.0955	−2.2 %	−4.6 %	2.4 %
$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	0.0955	−2.2 %	−4.6 %	2.4 %

- large accidental and cut dependent cancellations of Sudadov-type neg. EW corrections and γ-induced pos. contribs w/ extra jet activity

Triboson production

MS arXiv:1806.00307

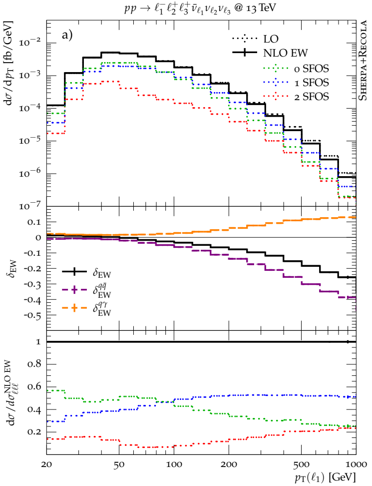
	$m(3\ell) > 500$ GeV			
	LO [fb]	δ_{EW}	$\delta_{q\bar{q}}^{\mathrm{EW}}$	$\delta_{q\gamma/\bar{q}\gamma}^{\mathrm{EW}}$
$\boldsymbol{\ell^-\ell^+\ell^+}$	**0.0338**	**−7.7 %**	**−16.3 %**	**8.6 %**
$e^-e^+e^+$	0.0031	−10.1 %	−18.3 %	8.2 %
$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	0.0029	−9.9 %	−18.3 %	8.3 %
$e^-e^+e^+\bar{\nu}_{\mu/\tau}\nu_{\mu/\tau}\nu_e$	0.0001	−13.4 %	−19.8 %	6.4 %
$e^-e^+\mu^+$	0.0081	−6.8 %	−16.6 %	9.8 %
$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	0.0079	−6.5 %	−16.5 %	10.0 %
$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	0.0001	−11.9 %	−18.0 %	6.1 %
$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	0.0001	−11.2 %	−17.8 %	6.6 %
$e^-\mu^+\mu^+$	0.0057	−7.7 %	−14.8 %	7.0 %
$e^-\mu^+\mu^+\bar{\nu}_e\nu_\mu\nu_\mu$	0.0057	−7.7 %	−14.8 %	7.0 %

- large accidental and cut dependent cancellations of Sudadov-type neg. EW corrections and γ-induced pos. contribs w/ extra jet activity

Triboson production

MS arXiv:1806.00307

- off-shell $W^+W^+W^-$ production
- includes 0, 1, 2 SFOS processes (WWW and WZZ structures)
- EW correction (incl. γ-induced) important
- cancellations of EW corr. in $q\bar{q}$ and $q\gamma/\bar{q}\gamma$ channels highly observable dependent



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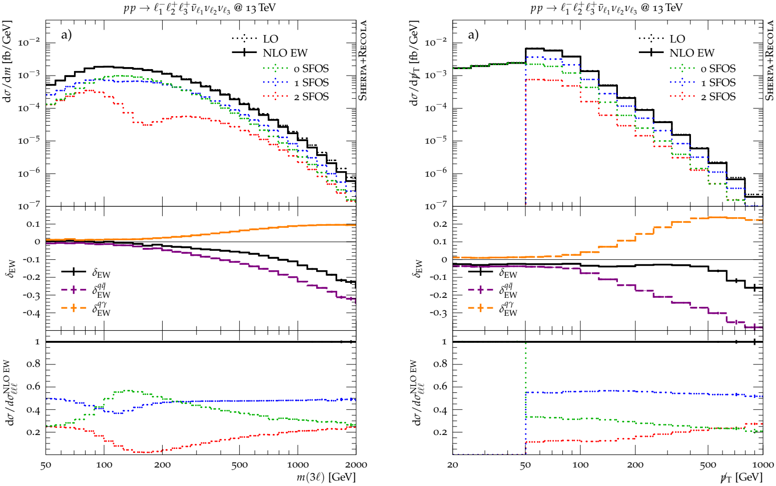

Electroweak corrections in event generation

- incorporation of approximate electroweak corrections
  - Electroweak Sudadov form factors in multiplicative correction

$$\overline{\mathrm{B}}_{n,\mathsf{QCD}\times\mathsf{EW}_{\mathsf{sud}}}(\Phi_n) = \overline{\mathrm{B}}_{n,\mathsf{QCD}}(\Phi_n)\,\cdot\,\Delta_{\mathsf{EW,sud}}$$

  - Electroweak virtuals in additive correction

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

- real emission corrections can be recovered to good accuracy by standard tools (parton showers, YFS resummation)
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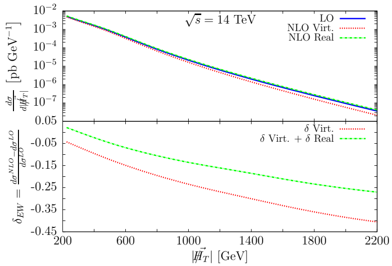
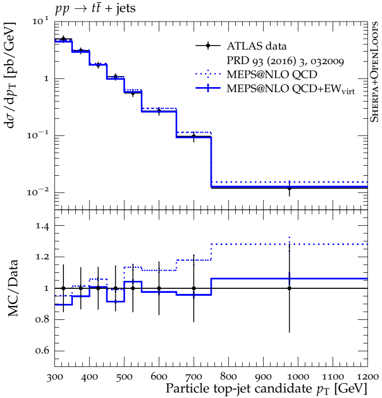
Example: $pp \to t\bar{t} + \text{jets}$

Chiesa et.al. in arXiv:1305.6837



ALPGEN LO+EW Sudadov

Gütschow, Lindert, MS in arXiv:1803.00950



SHERPA MEPS@NLO QCD+EW$_{\text{virt}}$

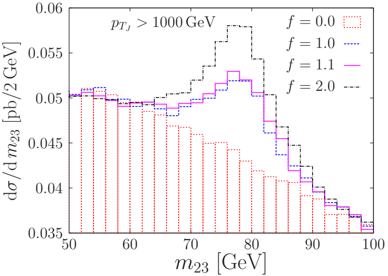
Electroweak boson emission

EW parton showers

- QED parton showers well known and available in every major shower
- full EW parton suffer from highly spin-dependent splitting functions, but parton showers are generally spin-avaraged
- IS kernels contain ratio of PDFs (change in x,Q,flavour)
- two practical implementations exist Christiansen, Sjöstrand arXiv:1401.5238
  Krauss, Petrov, MS, Spannowsky arXiv:1403.4788
- new developments (mainly in context of PDF evolution)
  Chen, Han, Tweedie arXiv:1611.00788
  Bauer, Ferland, Webber arXiv:1703.08562

Example: W radiation off jets

Krauss, Petrov, MS, Spannowsky arXiv:1403.4788



Substructure of high-$p_\perp$ jet

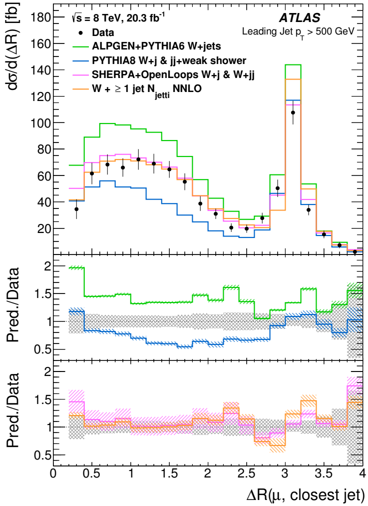
- discard leading microjet as likely from leading quark
- use m_{23} as em. gluons tend to be softer then decay prod. of em. W
- accept candidate if $m_{23} \in [70, 86]$ GeV
- $f = 0$ (QCD only), $f = 1$ (SM)

⇒ large, but continuous QCD background, clear signal shape

⇒ more W emissions with hight $p_\perp$, but peak shifts

Use leptonic W decays in low statistics environment (but no mass reconstruction)

NLO EW predictions for $\Delta R(\mu, j_1)$



ATLAS arXiv:1609.07045

- measurement of radiation pattern of W boson off jets
- require jet with $p_T > 500$ GeV measure $\Delta R(\mu, j)$
- two regions:
  1) $\Delta R \gtrsim \pi$: Wj config
     $\to p_T^W > 500$ GeV
     EW corr. to $Wj \approx -20\%$
  2) $\Delta R \lesssim \pi$: Wjj config
     $\to W$ soft
     real W radiation off dijets

Conclusions

- electroweak effects are important not only in precision measurements but also in measurements of processes with large momentum transfers
- become large whenever the scale is large compared the EW scale can reach tens of percent here, mostly negative
- EW corrections have a much richer structure than QCD thanks to the presence of multiple gauge bosons of different masses and interference between different topologies
- automated tools for fixed-order calculations publically available soon
- inclusion of approximate EW Sudakov-type corrections publically available for MC
- general QCD+EW NLOPS still missing
  (solutions for selected processes exist)

Thank you for your attention!