Electroweak corrections for multiparticle final states

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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

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

Automation in SHERPA

MS arXiv:1712.07975

Generalisation of CS dipoles to QCD+QED
automated identification and simultaneous subtraction of QCD and QED divergences

CS hep-ph/9605323, CDST hep-ph/0201036
D hep-ph/9904440, DKK arXiv:0802.1405

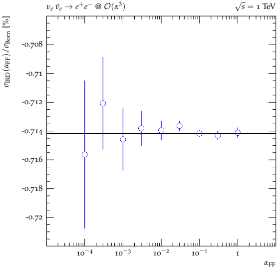
Process management and phase space integration:

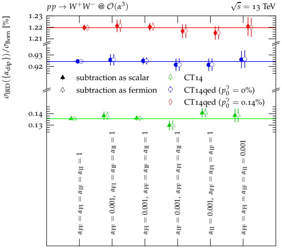
$$\mathrm{d}\sigma = \mathrm{d}\sigma_B + [\mathrm{d}\sigma_V + \mathrm{d}\sigma_I] + [\mathrm{d}\sigma_R - \mathrm{d}\sigma_S]$$

OPENLOOPS, RECOLA, GOSAM, ...

⚠ rigorous order counting mandatory ⚠

Signature definition: lepton dressing, jet definition, photon definition, etc.





NLO EW calculations with SHERPA

- SHERPA+OPENLOOPS:
  - $pp \to V + 0, 1, 2(, 3)$ jets — FCC report, EW report, LH'15; Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1412.5157, arXiv:1511.08692
  - $pp \to Zj / pp \to \gamma j$ ratio — LH'15 arXiv:1605.04692; Kallweit, Lindert, Maierhöfer, Pozzorini, MS arXiv:1505.05704
  - $pp \to \gamma/\ell\ell/\ell\nu/\nu\nu + j$ — 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
  - $pp \to t\bar{t}/t\bar{t}j$ — Gütschow, Lindert, MS arXiv:1803.00950
  - $pp \to t\bar{t}h$ — LH'15 arXiv:1605.04692
- SHERPA+GOSAM
  - $pp \to \gamma\gamma + 0, 1, 2$ jets — Chiesa et.al. arXiv:1706.09022
  - $pp \to \gamma\gamma\gamma \,/\, \gamma\gamma\ell\nu \,/\, \gamma\gamma\ell\ell$ — 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
  - $pp \to 3\ell 3\nu$ — MS arXiv:1806.00307

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Selected results

Diboson production

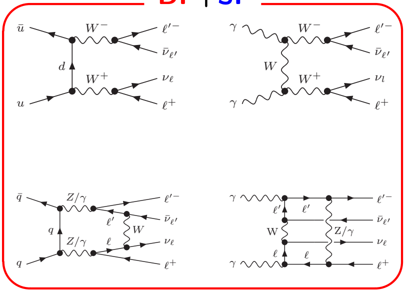
- NNLO QCD and NLO EW corrections known for all off-shell diboson channels
  - $\gamma\gamma$ — Bierweiler, Kasprzik, Kühn arXiv:1305.5402; Chiesa, Greiner, MS, Tramontano arXiv:1706.09022
  - $\ell\nu\gamma$ — Denner et.al. arXiv:1412.7421
  - $\ell\ell\gamma$ — Denner et.al. arXiv:1510.08742
  - $2\ell 2\nu$ — 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

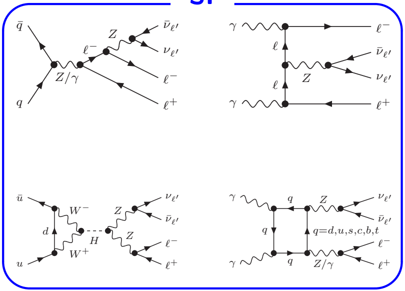
Diboson production – $2\ell 2\nu$

Kallweit, Lindert, Pozzorini, MS arXiv:1705.00598

DF+SF



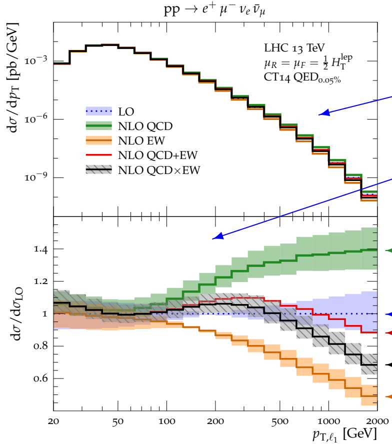
SF



- scale choice using $m_{\mathrm{T},i}^{W}$ ambiguous in SF channel, also not well motivated for ZZ channels/phase space regions

$\Rightarrow$ $\mu_R = \mu_F = H_{\mathrm{T}}^{\text{lep}} = \sum_{i\in\{\ell^\pm\}} p_{\mathrm{T},i} + E\!\!\!/_{\mathrm{T}}$

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



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absolute prediction

relative correction wrt. LO

NLO QCD (w/ moderate jet veto)

LO

NLO QCD+EW

NLO QCD×EW

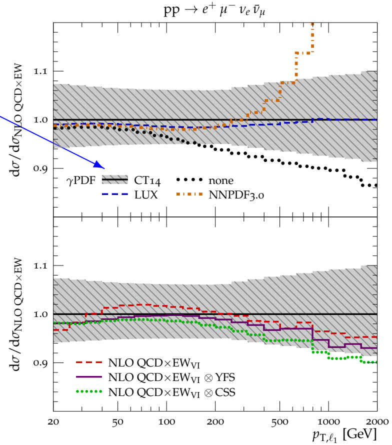
NLO EW

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

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

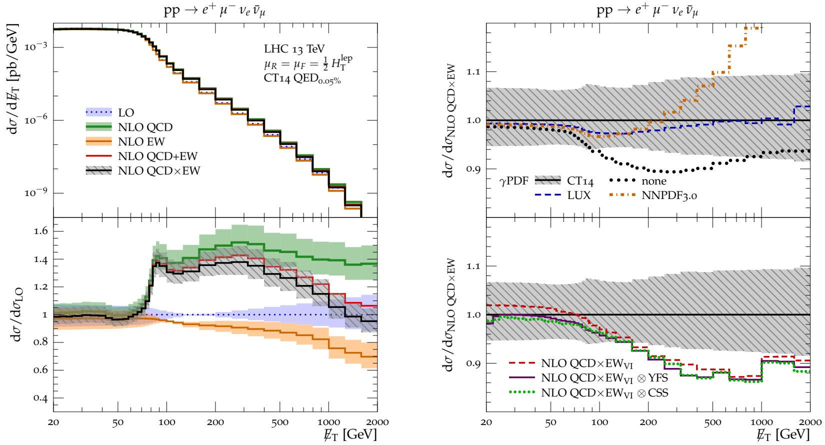
relative importance of γ-induced channels wrt. NLO QCD$\times$EW

CT14qed (baseline)	no γPDF
LUXqed	NNPDF3.0qed



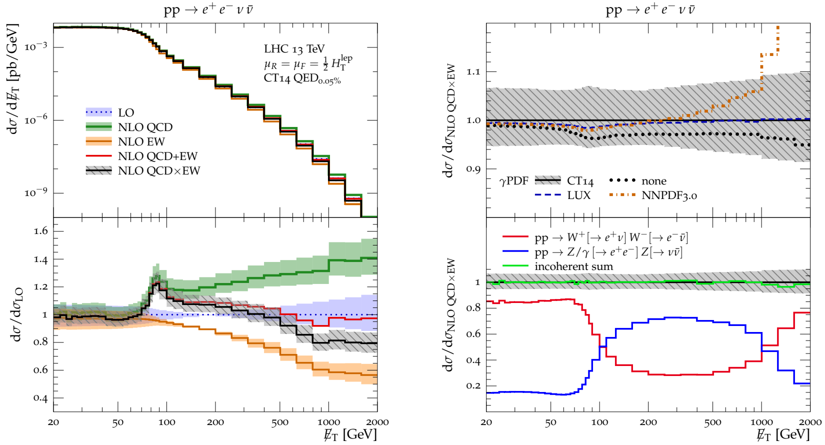
- all γPDF agree that γ-ind. $> 10\%$ for $p_T > 500$ GeV
  very good agreement between CT14qed and LUXqed

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



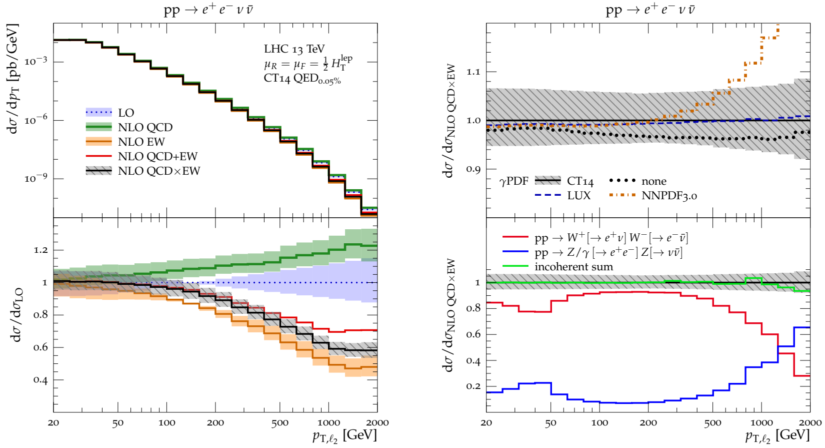
- kinematic suppression for $p_{\mathrm{T}}^{\nu\nu}$ at LO, unlocked at NLO QCD
  not present in γ-induced $\Rightarrow$ large contrib

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
  $\rightarrow$ different EW corrections, take care when extrapolating

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
- 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

suppress large WZ background
$m_{\ell\ell}^{\text{SFOS}} \notin [70, 100]$
$\not{p}_\mathrm{T} > 50$ GeV

- jet veto through $\Delta\phi(\not{p}_\mathrm{T}, \ell\ell\ell) > \frac{5}{6}\,\pi$
- on-shell production known for some time

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

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1 SFOS	$e^-e^+\mu^+\bar{\nu}_e\nu_e\nu_\mu$	$WWW + WZZ$	suppress large WZ background
	$e^-e^+\mu^+\bar{\nu}_\mu\nu_\mu\nu_\mu$	WZZ	$m_{\ell\ell}^{\text{SFOS}} \notin [70, 100]$
	$e^-e^+\mu^+\bar{\nu}_\tau\nu_\tau\nu_\mu$	WZZ	$\not{p}_\mathrm{T} > 50\,\text{GeV}$
2 SFOS	$e^-e^+e^+\bar{\nu}_e\nu_e\nu_e$	$WWW + WZZ$	
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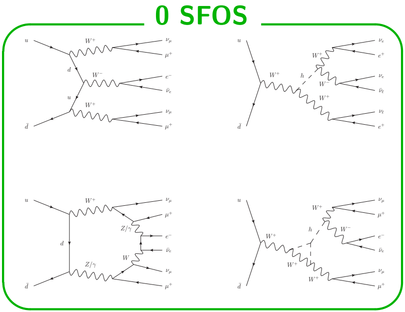

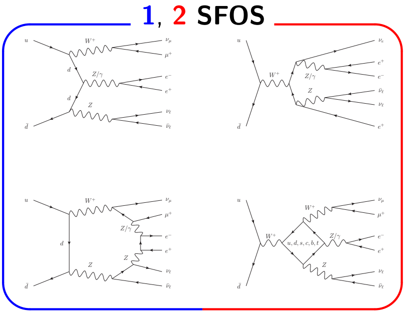

- scale choice: $\mu = \sum m_{\mathrm{T},i}^{W}$ ambiguous in all channels, also not well motivated scale choice for WZZ channels (or WZZ phase space regions)
- EW corrections largely scale independent: choose $\mu_R = \mu_F = 3\, m_W$

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

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	$m(3\ell) > 500$ GeV			
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$\boldsymbol{\ell^-\ell^+\ell^+}$	**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 %
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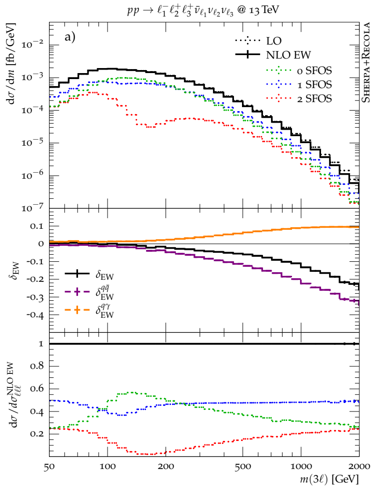
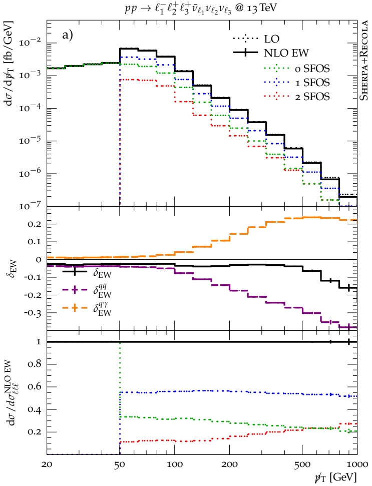
- off-shell $W^+W^+W^-$ production
- includes 0, 1, 2 SFOS processes (WWW and WZZ structures)
- EW correction (incl. γ-induced) important
- cancellations of EW corr. in $q\bar{q}$ and $q\gamma/\bar{q}\gamma$ channels highly observable dependent



Triboson production

MS arXiv:1806.00307

- 1, 2 SFOS: req. $\not{p}_{\mathrm{T}} > 50\,\mathrm{GeV}$ to suppress WZ background
- substantial γ-induced contributions
- accidental cancellations



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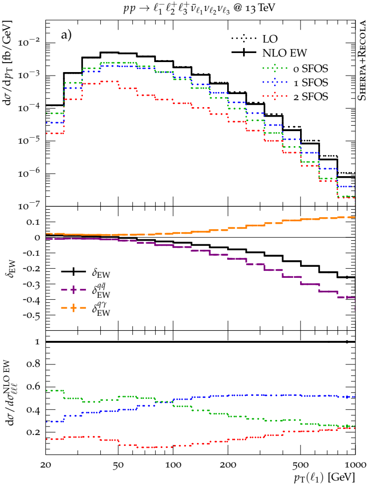

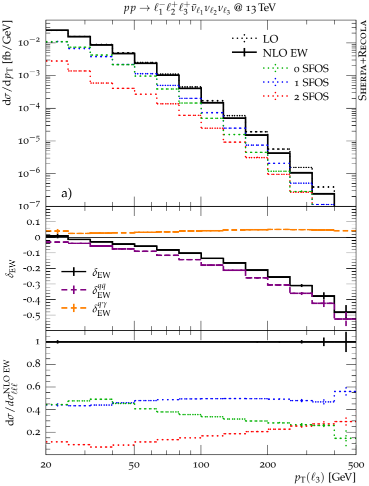

Electroweak corrections in particle-level event generation

- incorporate approximate electroweak corrections in SHERPA's NLO QCD multijet merging (MEPS@NLO)
- 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
  $\rightarrow$ validated at fixed order, found to be reliable,
  diff. $\lesssim 5\%$ for observables not driven by real radiation

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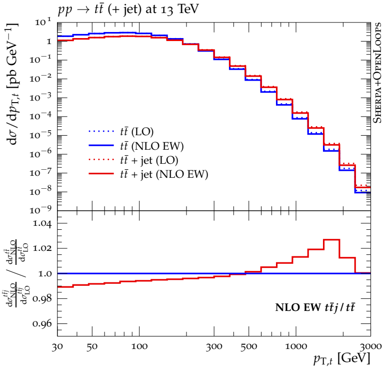
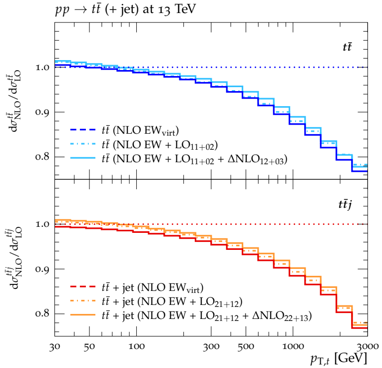
Top pair production in association with jets

Gütschow, Lindert, MS in arXiv:1803.00950





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

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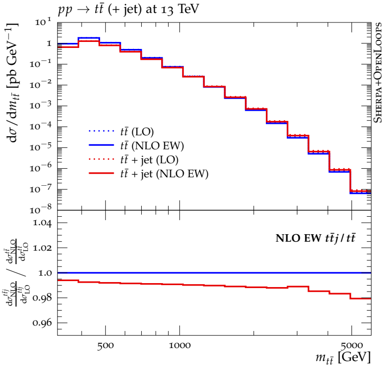
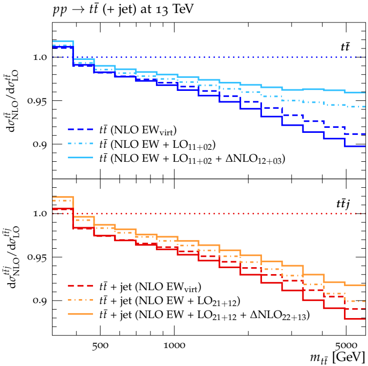
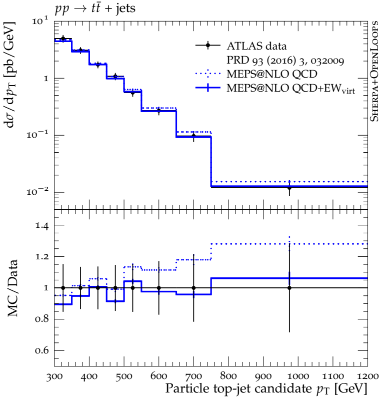




Observation: subleading orders important

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
- approx. EW corr. for $0,1j$ FS
- 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
- can be incorporated in multijet merging to improve description in those regions
  $\Rightarrow$ included since SHERPA-2.2.1 (now SHERPA-2.2.6)
- 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

http://sherpa.hepforge.org

Thank you for your attention!

Backup

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