Precision for V+jets and Dibosons

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Outline

(1) $W+1,2,3$ jets at NLO QCD+EW

S. Kallweit, J. Lindert, P. Maierhöfer, S.P., M. Schönherr, arXiv:1412.5157

(2) $\ell\ell/\ell\nu/\nu\nu+0,1,2$ jets with MEPS@NLO QCD+EW

S. Kallweit, J. Lindert, P. Maierhöfer, S.P., M. Schönherr, arXiv:1511.08692

(3) W^+W^- at NNLO QCD

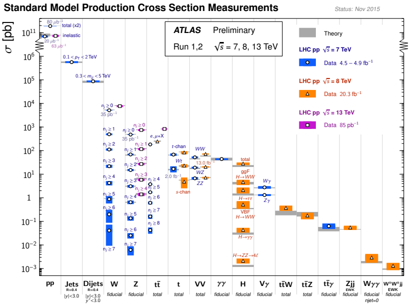
T. Gehrmannm, M. Grazzini, S. Kallweit, P. Maierhöfer, A. von Manteuffel, S.P. , D. Rathlev, L. Tancredi, arXiv:1408.5243

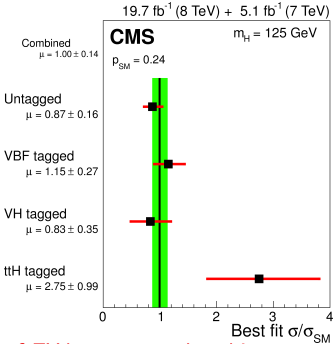
(4) $\ell\ell\nu\nu$ at NNLO QCD + NLO EW **preliminary!**

M. Grazzini, S. Kallweit, S.P. , D. Rathlev, M. Wiesemann, arXiv:16mm.nnnn

S. Kallweit, J. Lindert, S.P., M. Schönherr, arXiv:16mm.nnnn

Success of LHC and Standard Model at Run 1 (+2)





Run 1

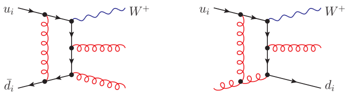
- SM promoted to realistic description of EW symmetry breaking (*at present* precision level and energy scales)
- M_H measurement ⇒ instead of disproving the SM, Run1 has turned it into a fully predictive theory – at the quantum level!

Run 2

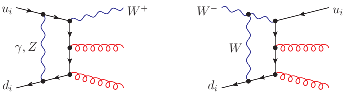
- falsify/verify SM with more stringent tests at higher precision and higher energy
- TH precision crucial for BSM sensitivity and interpretation of discoveries

NLO EW corrections

$\mathcal{O}(\alpha_S)$ QCD correction



$\mathcal{O}(\alpha)$ EW correction



Essential prerequisite for percent-level precision (Les Houches priority list)

- needed for numerous $2 \to 2, 3, 4$ processes (with decays and NLOPS matching!)
- NLO EW automation needed but more involved than NLO QCD
- virtual corrections involve various massive particles (γ, Z, W, H, b, t) and tend to dominate over real emission

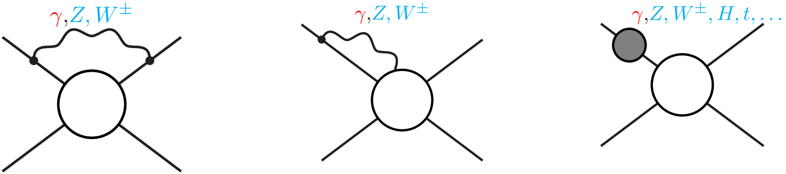
Process	State of the Art	Desired
V	dσ(lept. V decay) @ NNLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNNLO QCD and @ NNLO QCD+EW NNLO+PS
V + j(j)	dσ(lept. V decay) @ NLO QCD dσ(lept. V decay) @ NLO EW	dσ(lept. V decay) @ NNLO QCD + NLO EW
VV′	dσ(V decays) @ NLO QCD dσ(on-shell V decays) @ NLO EW	dσ(decaying off-shell V) @ NNLO QCD + NLO EW
gg → VV	dσ(V decays) @ LO QCD	dσ(V decays) @ NLO QCD
Vγ	dσ(V decay) @ NLO QCD dσ(PA, V decay) @ NLO EW	dσ(V decay) @ NNLO QCD + NLO EW
Vbb	dσ(lept. V decay) @ NLO QCD massive b	dσ(lept. V decay) @ NNLO QCD + NLO EW, massless b
VV′γ	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW
VV′V″	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW
VV′ + j	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW
VV′ + jj	dσ(V decays) @ NLO QCD	dσ(V decays) @ NLO QCD + NLO EW
$\gamma\gamma$	dσ @ NNLO QCD + NLO EW	q_T resummation at NNLL matched to NNLO

Table 3: Wishlist part 3 – Electroweak Gauge Bosons (V = W, Z)

EW vs QCD effects at the TeV frontier

$Q \lesssim M_W \Rightarrow$ order $\alpha \sim \alpha_S^2$ $\qquad$ $Q \gg M_W \Rightarrow$ order $\alpha \ln^2\left(Q^2/M_W^2\right) > \alpha_S$

EW Sudakov logarithms I



Virtual EW bosons coupling to on-shell legs at $Q^2 \gg M_W^2$

- large $\alpha \ln^2(Q^2/M_W^2)$ corrections of soft/collinear origin
- deep analogies with IR effects in QCD and notrivial symmetry breaking effects!

Universality and factorisation [Denner,S.P. '01]

$$\delta\mathcal{M}^{1-\mathrm{loop}}_{\mathrm{LL+NLL}} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left\{\frac{1}{2}\sum_{l\neq k}\sum_{a=\gamma,Z,W^\pm} I^a(k) I^{\bar{a}}(l)\ln^2\frac{\hat{s}_{kl}}{M^2} + \gamma^{\mathrm{ew}}(k)\ln\frac{\hat{s}}{M^2}\right\}\mathcal{M}_0$$

- depend on external EW charges (anomalous dimensions) and kinematic details
- large negative corrections to any LHC process at high $p_T, E_{T,\mathrm{miss}}, H_T, M_{\mathrm{inv}}, \ldots$

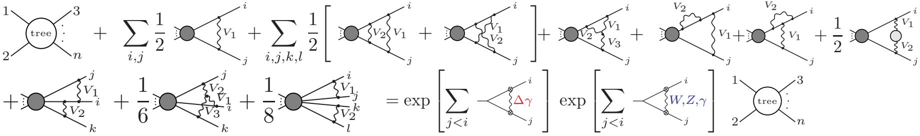
EW Sudakov logarithms II

Typical size of corrections at 1 TeV: $>10\%$ at **1-loop** and $>1\%$ at **2-loops**

$$\left(\frac{\delta\sigma_1}{\sigma_0}\right)_{\mathrm{LL}} \simeq -\frac{4\alpha}{\pi s_{\mathrm{w}}^2}\ln^2\left(\frac{1\,\mathrm{TeV}}{M_W}\right) \simeq -26.4\% \qquad \left(\frac{\delta\sigma_2}{\sigma_0}\right)_{\mathrm{LL}} \simeq +\frac{8\alpha^2}{\pi^2 s_{\mathrm{w}}^4}\ln^4\left(\frac{1\,\mathrm{TeV}}{M_W}\right) \simeq 3.5\%$$

$$\left(\frac{\delta\sigma_1}{\sigma_0}\right)_{\mathrm{NLL}} \simeq +\frac{6\alpha}{\pi s_{\mathrm{w}}^2}\ln\left(\frac{1\,\mathrm{TeV}}{M_W}\right) \simeq +15.6\% \qquad \left(\frac{\delta\sigma_2}{\sigma_0}\right)_{\mathrm{NLL}} \simeq -\frac{24\alpha^2}{\pi^2 s_{\mathrm{w}}^4}\ln^3\left(\frac{1\,\mathrm{TeV}}{M_W}\right) \simeq -4.1\%$$

Various 2-loop results and resummations available [Becher, Ciafaloni, Comelli, Denner, Fadin, Jantzen, Kühn, Lipatov, Manohar, Melles, Penin, Pozzorini, Smirnov, ...]

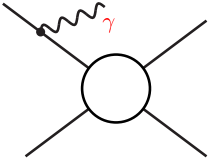


[Denner, S.P. ,Jantzen '03–'08]

$\Rightarrow$ **EW corrections crucial for SM tests and BSM searches at TeV scale**

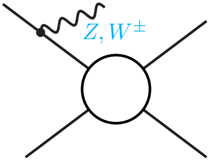
Electroweak bremsstrahlung

Real photon emission



- mandatory since soft/collinear γ unresolved
- complete cancellation of QED singularities

Real Z, W emission [Ciafaloni,Comelli]



- **inclusive emission**: only partial $\ln(\hat{s}/M_W)$ cancellation

$\leftrightarrow$ free SU(2) charges, collinear IS logs, kinematic $M_{Z,W}$ effects

- **typical experimental cuts (at LHC)**: modest $\ln(\hat{s}/M_W)$ cancellation (strongly dependent on process and analysis)
- **bottom line**: needs to be considered but should be regarded as separate (tree-level) process to avoid double counting of Z, W emissions

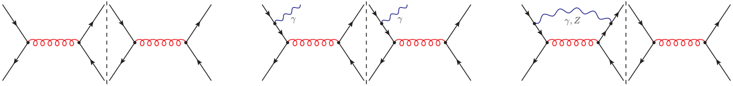
Nontrivial QCD-EW interplay in $pp \to X+ \geq 2\,$jets

$q\bar{q} \to q\bar{q} + \ldots$ cross sections receive various Born contributions

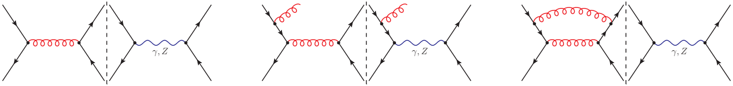
$$\underbrace{\mathcal{O}\left(\alpha_S^n \alpha^m\right)}_{\text{“QCD”}} \quad + \quad \underbrace{\mathcal{O}\left(\alpha_S^{n-1} \alpha^{m+1}\right)}_{\text{“EW}-\text{QCD interf.”}} \quad + \cdots + \quad \underbrace{\mathcal{O}\left(\alpha_S^{n-k} \alpha^{m+k}\right)}_{\text{“EW”}}$$

$\mathcal{O}\left(\alpha_S^n \alpha^{m+1}\right)$ NLO EW corrections to leading QCD Born, e.g. in $q\bar{q} \to q\bar{q}$

- EW corrections $\times$ QCD Born



- QCD corrections $\times$ EW–QCD interference

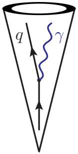


In practice

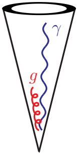
- only full $\mathcal{O}\left(\alpha_S^n \alpha^{m+1}\right)$ IR finite $\Rightarrow$ nontrivial bookkeeping (automated)
- $\mathcal{O}(\alpha)$ corrections can involve emissions of photons and QCD-partons
- protons and jets $\supset g, q, \gamma$

Treatment of photons inside jets at NLO EW

Option A: Democratic jet-algorithm approach (jets $\equiv$ photons)



collinear $q \to q\gamma$ singularities cancelled clustering q, g, γ on same footing

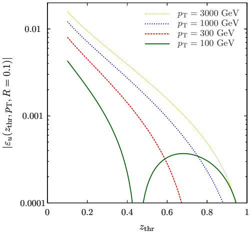


soft gluon singularities $\leftrightarrow$ hard photons inside jets: cancelled in jet-production (NLO EW) + γ-production (NLO QCD)

Option B: Separation of jets from photons through $E_\gamma/E_{\text{jet}} < z_{\text{thr}}$ inside jets

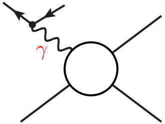
- **rigorous approach:** absorb $q \to q\gamma$ singularity into fragmentation function [1411.0916]
- **approximation:** cancel singularity via $q\gamma$ recombination in small cone $\Delta R_{q\gamma} < 0.1$ [1412.5156]

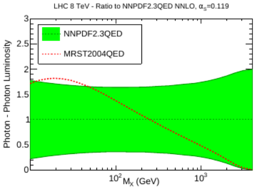
$\Rightarrow$ difference $\ll 1\%$ for typical z_{thr} choices



Photons in the initial state

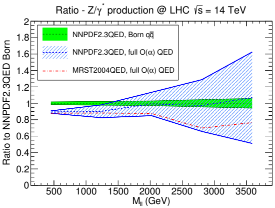
Factorisation of $q \to q\gamma$ singularities $\Rightarrow$ QED PDFs with photon

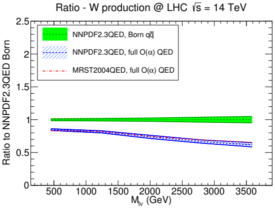


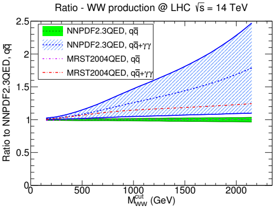


- LO QED evolution
- γ-fit to DIS+DY data (NNPDF)
- $\mathcal{O}(50\%)$ γ-uncertainty

Very large γ-induced effects with $\mathcal{O}(100\%)$ uncertainty in TeV region







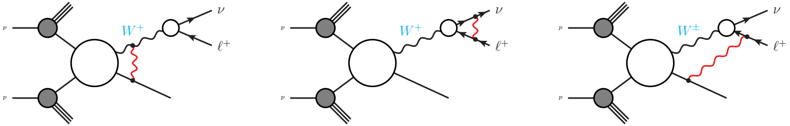
Wanted: - NLO QED PDFs

- new fit of γ-PDF with accurate high-energy data & theory [Boughezal et al.'14]

Decays of Z/W bosons

Leptonic Z and W decays are notrivial at NLO EW (in contrast to NLO QCD)

- NLO EW corrections to production×resonance×decay + non-fact corrections



Option A: complex mass scheme [Denner, Dittmaier]

- exact NLO description (always desirable)
- high complexity corresponding to total number of particles *after* decays

  e.g. $pp \to ZZ \to 4\ell$ has $2 \to 4\,(2)$ complexity at NLO EW (QCD)!

Option B: narrow-width approximation (production×decay)

- simpler but applicability to V+multijets limited to certain $\mathcal{O}\left(\alpha_S^n \alpha^{m+1}\right)$ (see later)
- captures all large $\ln(\hat{s}/M_W^2)$ effects (present only in production sub-process)
- typical uncertainty $\lesssim$ 1–3% (apart form $\gamma^*/Z^* \to \ell^+\ell^-$ at small $m_{\ell\ell}$)

NLO EW automation

Technical tour de force

- implementation of loop recursion, UV+R_2 CTs, Catani-Seymour subtraction, general $\mathcal{O}\left(\alpha_S^n \alpha^m\right)$ bookkeeping at NLO, complex masses scheme,...

First automated tools and *multi-particle* applications (2014–15)

Tools	first results	
RECOLA+COLLIER	$pp \to \ell^+\ell^- jj$	[arXiv:1411.0916]
OPENLOOPS+ MUNICH/SHERPA	$pp \to W + 1,2,3$ jets	[arXiv:1412.5156]
	$pp \to \ell\ell/\ell\nu/\nu\nu + 0,1,2$ jets	[arXiv:1511.08692]
MADGRAPH5_AMC@NLO	$pp \to t\bar{t} + V$	[arXiv:1504.03446]
GOSAM+ MADDIPOLE	$pp \to W + 2$ jets	[arXiv:1507.08579]

Full NLO QCD+EW automation [Kallweit,Lindert,Maierhöfer,S.P.,Schönherr '14]

- Loop amplitudes: OPENLOOPS [Cascioli et al. '13] and COLLIER [Denner et al. '14]
- Monte Carlo: MUNICH [Kallweit] or SHERPA [Hoeche et al.]

(implemented twice and independently for cross checks)

NLO EW automation in OpenLoops

Technical performance of 1-loop EW for $t\bar{t}+$ jets

- code size, compilation&runtime reflect moderate increase of complexity wrt QCD
- 1-loop EW similarly fast as 1-loop QCD timings up to $t\bar{t}+2$ jets

$t\bar{t}+0,1,2\,\mathrm{j}$	$n_{\mathrm{loop\ diag}}$ QCD	EW	t_{compile} [s] QCD	EW	size [MB] QCD	EW	t_{run} [ms/point] QCD	EW
$d\bar{d}\to t\bar{t}$	11	33	2.1	3.5	0.1	0.2	0.27	0.69
$gg\to t\bar{t}$	44	70	3.6	3.7	0.2	0.3	1.6	2.8
$d\bar{d}\to t\bar{t}g$	114	360	3.5	5.9	0.4	0.9	4.8	13
$gg\to t\bar{t}g$	585	660	8.2	8.8	1.4	1.6	40	56
$d\bar{d}\to t\bar{t}u\bar{u}$	236	1274	5.3	16	0.8	2.8	12	48
$d\bar{d}\to t\bar{t}d\bar{d}$	472	2140	9.5	56	1.4	1.4	30	99
$d\bar{d}\to t\bar{t}gg$	1507	4487	20	47	3.5	8.2	133	327
$gg\to t\bar{t}gg$	8739	7614	105	79	18	16	1458	1557

Timings on i7-3770K with gcc 4.8 –O0 dynamic and unpolarised $t\bar{t}$ (significantly faster with decays!)

Opens the door to multi-leg NLO EW computations

$\Rightarrow$ **NLO QCD+EW for any $2\to 2,3,4$ SM process** (just started)

$\Rightarrow$ matching to parton showers (and merging) at NLO QCD+EW (in progress)

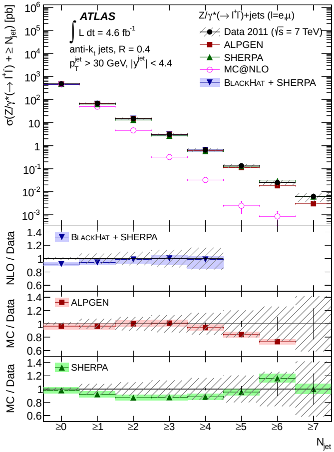
Outline

1. $W + 1, 2, 3$ jets at NLO QCD+EW
2. $\ell\ell/\ell\nu/\nu\nu + 0, 1, 2$ jets with MEPS@NLO QCD+EW
3. W^+W^- at NNLO QCD
4. $\ell\ell\nu\nu$ at NNLO QCD (+EW)

V+jets at high precision in perturbative QCD

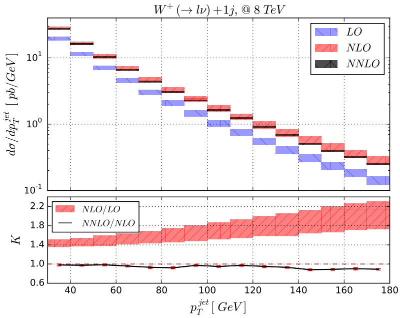
$V + 1, 2, 3, 4/5$ **jets at NLO**

[BLACKHAT+SHERPA '09–'13]



$\Rightarrow$ $\mathcal{O}(10\%)$ **scale uncertainties**

$V + 1$ **jet at NNLO** [Boughezal et al. '15–'16; A. Gehrmann-De Ridder et al. '15]

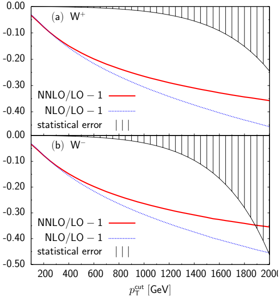


$\Rightarrow$ $\mathcal{O}(1\%)$ **scale uncertainty**

EW corrections

Very large EW corrections to $pp \to Z/W + 1$ jet

- NLO (electro)weak [Maina, Ross, Moretti '04;Kühn, Kulesza, S.P.,Schulze '04–'07]
- EW Sudakov logs beyond NLO [Kühn, Kulesza, S.P.,Schulze '04–'07; Becher, Garcia i Tormo '13]
- NLO QCD+EW with off-shell Z/W decays [Denner,Dittmaier,Kasprzik,Muck '09–'11]



Strong motivations for V+multijets at NLO EW

- multi-jet case: EW Sudakov poorly explored and crucial for BSM searches
- huge multi-jet emission rate at high jet p_T $\Rightarrow$ $V + 1$ jet NLO EW insufficient!!
- interplay of large QCD and EW corrections

$W + 1, 2, 3$ jets at NLO QCD+EW

[Kallweit,Lindert,Maierhöfer,S.P.,Schönherr '14]

Technical motivation

- investigate performance of automated tool in multi-jet regime

	$pp \to W + n$ jets @LO				$pp \to W + n$ jets @NLO				
	$\alpha_s^n \alpha$	$\alpha_s^{n-1}\alpha^2$	$\alpha_s^{n-2}\alpha^3$	$\alpha_s^{n-3}\alpha^4$	$\alpha_s^{n+1}\alpha$	$\alpha_s^{n}\alpha^2$	$\alpha_s^{n-1}\alpha^3$	$\alpha_s^{n-2}\alpha^4$	$\alpha_s^{n-3}\alpha^5$
$u_i \bar{d}_i \to W + ng$	×	-	-	-	×	×	-	-	-
$u_i \bar{d}_i \to W + q\bar{q} + (n-2)g$	×	×	×	-	×	×	(×)	(×)	-
$\gamma u_i \to d_i W + (n-1)g$	-	×	-	-	-	-	-	-	-
$\gamma u_i \to d_i W + q\bar{q} + (n-3)g$	-	×	×	×	-	-	-	-	-
$\gamma\gamma \to \bar{u}_i d_i W + (n-2)g$	-	-	×	-	-	-	-	-	-
$u_i \bar{d}_i \to W + (n+1)g$	-	-	-	-	×	-	-	-	-
$u_i \bar{d}_i \to W + q\bar{q} + (n-1)g$	-	-	-	-	×	×	(×)	-	-
$u_i \bar{d}_i \to W + q\bar{q}q'\bar{q}' + (n-3)g$	-	-	-	-	×	×	(×)	(×)	(×)
$u_i \bar{d}_i \to W + ng + \gamma$	-	-	-	-	-	×	-	-	-
$u_i \bar{d}_i \to W + q\bar{q} + (n-2)g + \gamma$	-	-	-	-	-	×	(×)	(×)	(×)

× (×) = (not) included in 1412.5156

Ingredients of NLO QCD+EW, i.e. order $\alpha_S^{n+1}\alpha + \alpha_S^n\alpha^2$

- very many crossings and flavour combinations $(u_i, d_i, q, q' \in \{u, d, c, s, b\})$
- 2000–3000 virtual EW diagrams/channel: **more complex than QCD but faster**

Note also: overlap with EW processes (VBF,VV',tj, tW, $t\bar{t}$) and interference with QCD

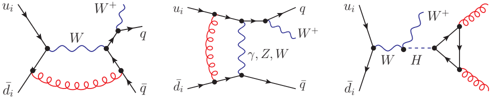
“Pseudo resonances”

External W bosons

- on-shell ($\Gamma_W = 0$) to increase reach in jet multiplicity

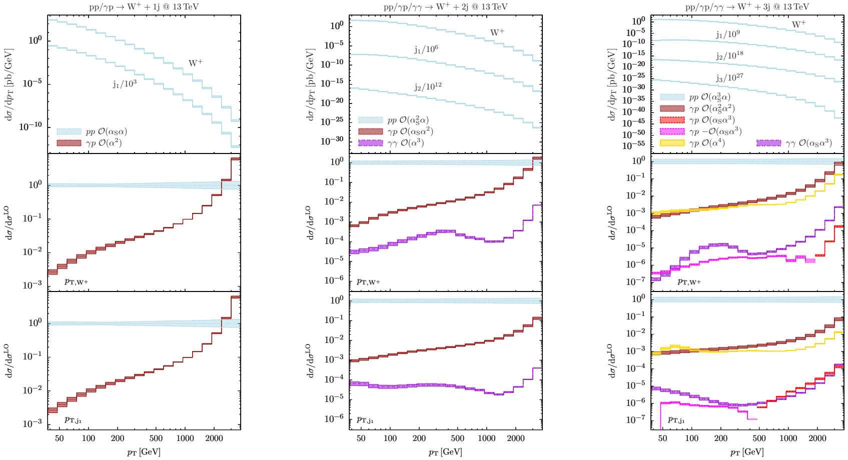
Internal t, W, Z, H propagators at NLO EW

- can go on-shell in the s-channel $\Rightarrow$ integrable singularties
- require small technical regulator $\Gamma_{\mathrm{reg}} \to 0$
- plus tricks to preserve IR EW cancellations



$$\times \, \text{QCD Born} \Rightarrow \frac{Q^2 - M^2}{(Q^2 - M^2)^2 + \Gamma_{\mathrm{reg}}^2 M^2}$$

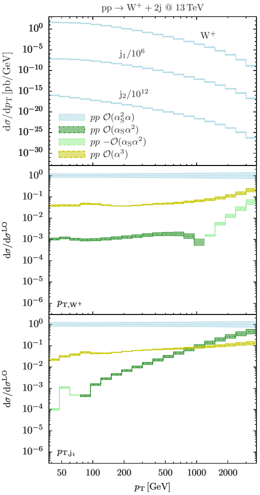
LO γ-induced contributions in $pp \to W^+ + 1, 2, 3$ jets

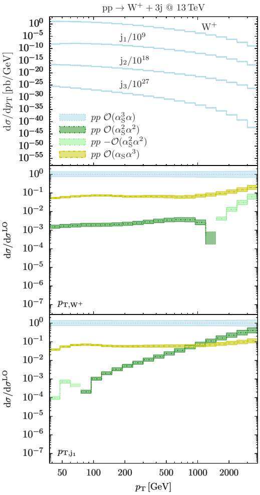


Single-γ contributions

- from $\mathcal{O}\left(10^{-3}\right)$ in σ_{int} to 5–100% at $p_{T,W}$ =1–4 TeV!
- driven by γ-PDF (NNPDF2.3 QED) at large x (huge γ-PDF uncertainty. . .)

LO EW–QCD interplay in $pp \to W^+ + 2, 3$ jets at 13 TeV





"QCD cuts" throughout

- $p_T > 30$ GeV, $\eta < 4.5$

$\Rightarrow$ QCD dominates

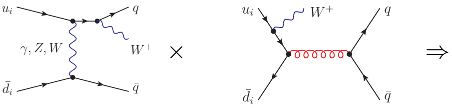
EW contributions

(WV, VBF, single-t)

- 3–6% in σ_{int}
- 10–20% at 1–4 TeV

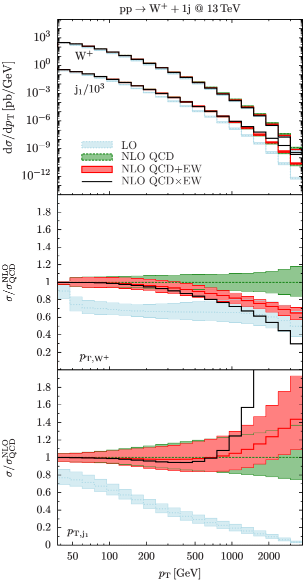
EW–QCD interference

- $\mathcal{O}\left(10^{-3}\right)$ in σ_{int}
- 10–50% at 1–4 TeV



sizable "mixed" bremsstrahlung at TeV scale!

NLO QCD+EW corrections to $pp \to W + 1\,\text{jet}$



Large NLO corrections at high $p_{T,W}$

- $+100\%$ (QCD) and -20-35% (EW)

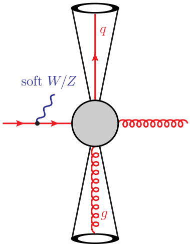
Giant NLO corrections at high jet p_T

- $+1000\%$ QCD [Rubin, Salam, Sapeta '10]
- $+10$-50% EW–QCD "mixed" bremsstrahlung!
- huge EW×QCD uncertainties!

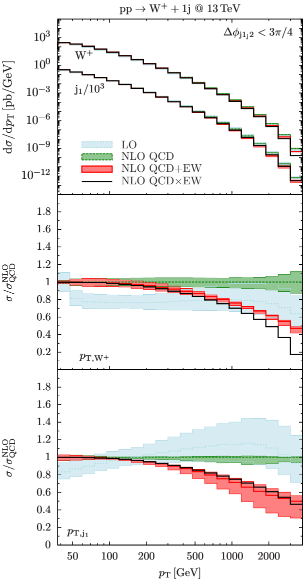
Problem of $W+$jet at high p_T

- NLO dominated by $W + 2\,$jets

⇒ **requires NLO QCD+EW for $W+$multijets!**



Same observables with "dijet-veto cut" $\phi_{jj} < \frac{3}{4\pi}$



QCD corrections

- moderate at high $p_{T,\text{jet}}$

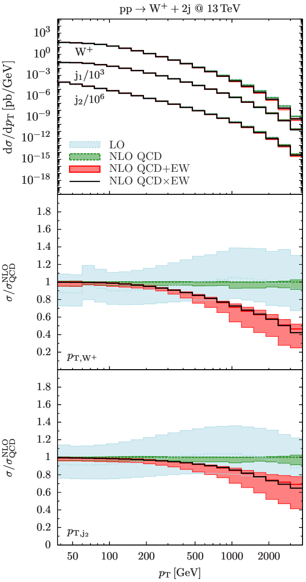
EW corrections

- Sudakov behaviour in both tails
- more pronounced: -20-50% at 1–4 TeV

Bottom line

- $W+1$ jet at NLO ok for *exclusive* case
- *inclusive* case requires $W+2$ jets at NLO!

NLO QCD+EW corrections to $pp \to W^+ + 2\,$jets



Mild QCD corrections

- small and almost p_T independent
- $\lesssim 10\%$ scale dependence at NLO

Huge Sudakov EW effects in W- and jet-p_T tails

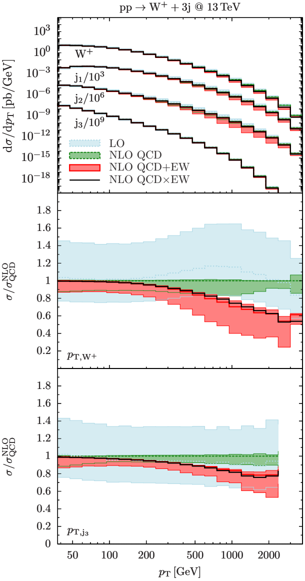
$\Rightarrow$ -30–60% at $p_{T,W}$ =1–4 TeV

$\Rightarrow$ -15–25% at $p_{T,j}$ =1–4 TeV

Bottom line

- different Sudakov behaviour of W and jets (due to hard-dijet contributions and positive QCD-EW bremmstrahlung)
- NLO well behaved (but might need EW Sudakov resummation)

NLO QCD+EW corrections to $pp \to W^+ + 3\,\mathrm{jets}$



Mild QCD corrections

- mild apart from first two jets (not shown)
- $\lesssim 10\%$ scale dependence

Huge Sudakov EW effects in W- and jet-p_T tails

$\Rightarrow$ -30–50% at $p_{T,W}$ =1–4 TeV

$\Rightarrow$ -20–30% at $p_{T,j}$ =1–4 TeV

V+multi-jet production at NLO QCD+EW

- crucial for stable prediction at high p_T!

Inclusive V+jets predictions

- key ingredient for searches at the TeV scale (e.g. H_T)
- **requires NLO QCD+EW merging of $V + 0, 1, 2, \ldots$ jets!**

Outline

1. $W + 1, 2, 3$ jets at NLO QCD+EW
2. $\ell\ell/\ell\nu/\nu\nu + 0, 1, 2$ jets with MEPS@NLO QCD+EW
3. W^+W^- at NNLO QCD
4. $\ell\ell\nu\nu$ at NNLO QCD (+EW)

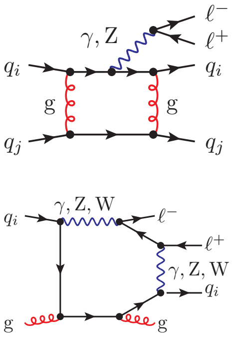
$\ell\ell/\ell\nu/\nu\nu + 0, 1, 2$ jets at NLO QCD+EW [Kallweit, Lindert, S.P., Schönherr, arXiv:1511.08692]

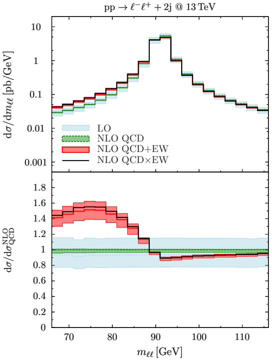
$W^\pm/Z/\gamma^*$+jets production *and* off-shell decays into ll, $\ell^-\bar{\nu}_\ell$, $\ell^+\ell^+$, $\nu_\ell\bar{\nu}_\ell$

$\Rightarrow$ realistic observables, cuts, etc ...

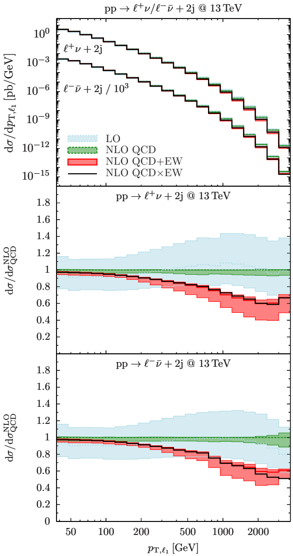
$\Rightarrow$ EW corrections to production + decay + non-factorisable effects

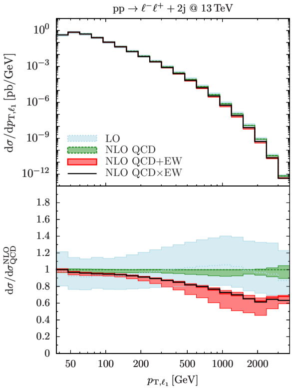
- shape corrections $\gamma^*/Z \to \ell^+\ell^-$ Breit–Wigner distribution





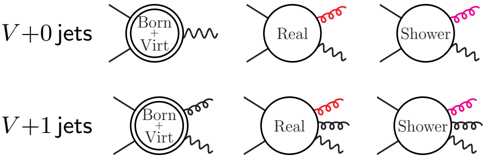
Inclusive leptonic observables





Similar behaviour as for on-shell W+jets (no extra Sudakov logs from decays)

MEPS@NLO merging [Höche, Krauss, Schönherr, Siegert '12]



- $V+n$ jets NLO+PS in region with n jets above k_T resolution scale Q_{cut}
- NLO+log accuracy in each n-jet region
- small Q_{cut} dependence $\leftrightarrow$ MEs with PS-like scale and Sudakov FFs

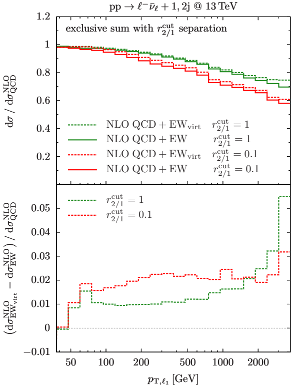
$\Rightarrow$ precise and realistic simulation of processes with abundant multijet emission

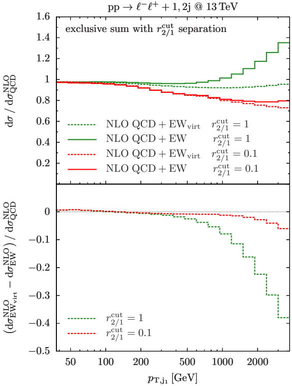
NLO QCD+EW$_{\text{virt}}$ jet merging (approximate)

+ virtual EW corrections (large and included)
+ mixed EW–QCD gluon/quark bremsstrahlung (large and included)
− real γ-emissions (typically $\mathcal{O}(1\%)$ and omitted)

$\Rightarrow$ large NLO EW corrections applied to all relevant multijet contributions

Quality of NLO QCD+EW$_{\mathrm{virt}}$ approximation





Validation based on exact "fixed-order merging" (exclusive sums)

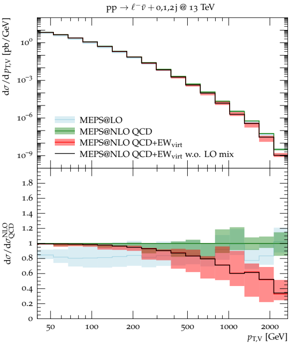
- large EW–QCD mixed bremsstrahlung (green) can be absorbed into LO MEs ($p_{T,j_2}/p_{T,j_1} = r_{2/1}^{\mathrm{cut}} > 0.1$ "merging" cut)

⇒ IR-regularised virtual EW corrections (red) agree at percent level with full NLO EW result up to $p_T \sim 1\,\mathrm{TeV}$

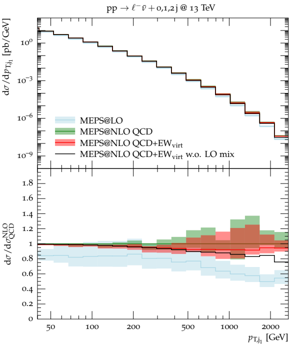
MEPS@NLO QCD+EW$_{\rm virt}$ for $\ell\ell/\ell\nu/\nu\nu + 0,1,2\,$jets

Inclusive p_T distributions for $pp \to W$+jet$+X$

- perturbative convergence also for $p_{T,\rm jet}$ (thanks to multi-jet contributions!)
- different hard sub-processes ⇔ different NLO EW behaviour (DY,Vj, jj)
- $V + 2\,$jets at NLO QCD+EW in the same sample



Large(r) EW effects at $p_{T,V} \sim$ TeV ($pp \to Vj$)



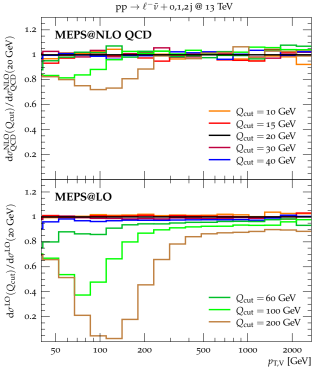
Small EW effects at $p_{T,\rm jet} \sim$ TeV ($pp \to jj$)

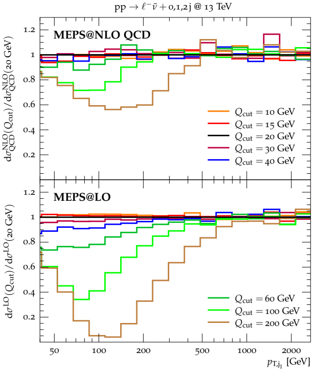
MEPS@NLO at $p_T \sim 1\,\mathrm{TeV}$ with merging cut $Q_{\mathrm{cut}} = 20\,$GeV: a good idea?!

- potentially very large uncertainties from uncancelled $N_c^{-1}\alpha_s^2 \log^3(1\,\mathrm{TeV}/Q_{\mathrm{cut}})$ terms $\Leftrightarrow$ combination of exclusive $V + 0, 1, 2\,$jet subsamples

Stability of p_T spectra wrt $10\,\mathrm{GeV} < Q_{\mathrm{cut}} < 200\,\mathrm{GeV}$ variations

- $p_T \lesssim M_W$ region requires $Q_{\mathrm{cut}} \lesssim 40\,\mathrm{GeV}$ to avoid shower “holes”
- at $p_T \sim$ 1–2 TeV **impressive stability wrt very conservative Q_{cut} variations!**

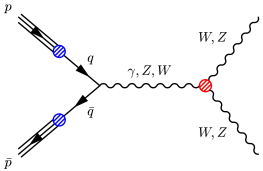




Outline

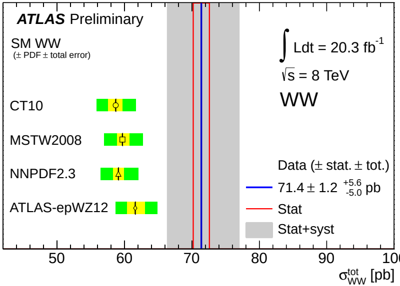
1. $W + 1, 2, 3$ jets at NLO QCD+EW
2. $\ell\ell/\ell\nu/\nu\nu + 0, 1, 2$ jets with MEPS@NLO QCD+EW
3. W^+W^- at NNLO QCD
4. $\ell\ell\nu\nu$ at NNLO QCD (+EW)

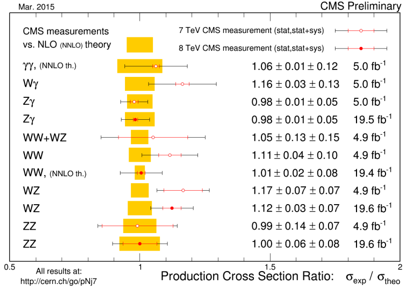
Diboson production at LHC



- test SU(2)×U(1) gauge structure
- interplay with $H \to VV$
- Diboson resonances at TeV scale, ...

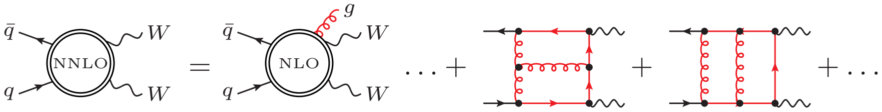
Tensions between NLO QCD and preliminary Run1 measurements





$\sim 2.5\,\sigma$ **(20%) excess in** $\sigma^{\text{ATLAS}}_{W^+W^-} \simeq 3 \times \sigma(H \to W^*W)$

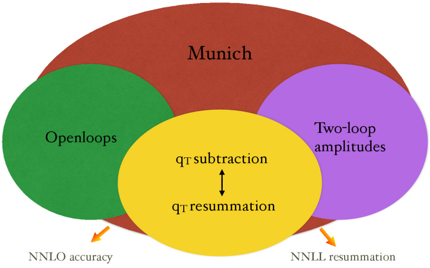
Diboson production at NNLO+NNLL with MATRIX



Flexible NNLO+NNLL framework based on q_T-subtraction [Catani, Grazzini '06]

Kallweit

Cascioli
Maierhöfer
Lindert
S.P.



Gehrmann, Tancredi
von Manteuffel, Weihs;
Caola, Henn, Melnikov
Smirnov, Smirnov

Grazzini, Kallweit, Rathlev, Wiesemann

⇒ **predictions for $Z\gamma, W\gamma$ at NNLO and ZZ, WW at NNLO+NNLL** [2013–15]

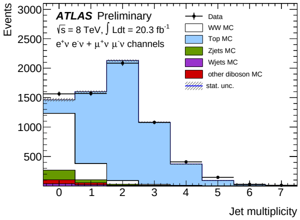
Definition of top-free W^+W^- production

Experimental definition (ATLAS/CMS)

(1) top-supressing jet veto

(2) subtraction of remnant top backgrounds

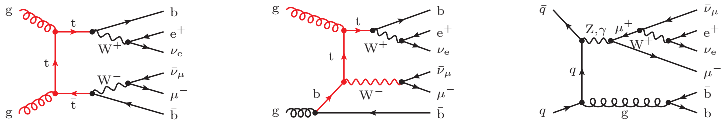
(3) W^+W^- extrapolation to full phase space



Top-free definition of *inclusive* WW cross section

- **huge top contamination** from $pp \to W^\pm t \to W^+W^-b$ (40% at NLO) and $pp \to t\bar{t} \to W^+W^-b\bar{b}$ (400% at NNLO)
- **b-quarks emissions** needed to cancel collinear $g \to b\bar{b}$ singularities $(m_b = 0)$

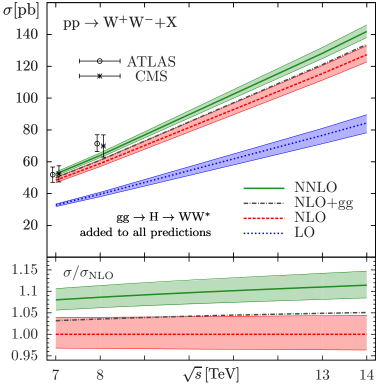
$\Rightarrow$ exclude b-quark emissions in the 4F scheme $(m_b > 0)$



NNLO predictions for $pp \to W^+W^-$ [Gehrmann et al. '14]

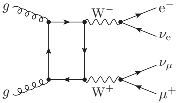
Unexpectedly large QCD corrections

- $+58\%$ NLO and $+12\%$ NNLO at 14 TeV
- well beyond expected size from scale uncertainties and $gg \to W^+W^-$ $(+4\%)$



Residual scale uncertainty

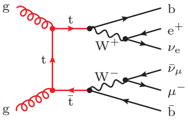
- 3% NNLO scale variation
- consistent with NLO correction to $gg \to W^+W^-$ [Melnikov et al. '15]

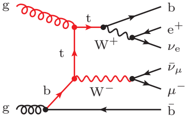


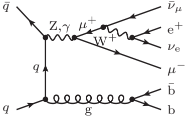
Comparison with ATLAS and CMS data

- NNLO reduces significance of excess in preliminary measurements and is consistent with WW cross sections published by ATLAS and CMS

Ambiguities of top-free definition of $pp \to W^+W^-$



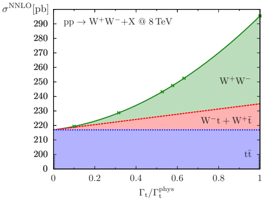




Uncertainty of 4F-scheme definition $(m_b > 0)$

- **b-emission veto** $\Rightarrow \ln(m_b/M_W)$ **enhanced terms** wrt definition that includes b-emissions

$\Rightarrow$ might jeopardize NNLO accuracy of 3%!



Alternative 5F-scheme definition $(m_b = 0)$

$$\lim_{\xi_t \to 0} \sigma^{5F}_{\text{full}}(\xi_t \Gamma_t) = \xi_t^{-2} \left[\sigma^{5F}_{t\bar{t}} + \xi_t\, \sigma^{5F}_{Wt} + \xi_t^2\, \sigma^{5F}_{W^+W^-}\right]$$

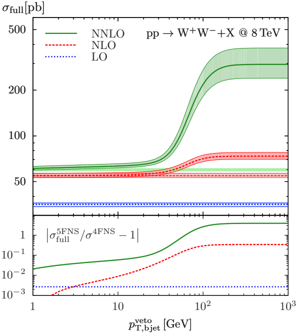
- **b-emissions included** and **“top-subtraction”** using Γ_t-scaling

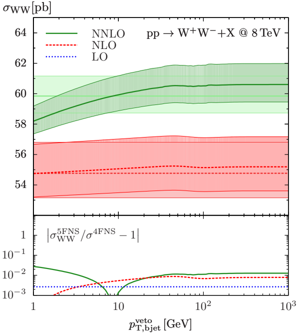
$\Rightarrow$ 1-2% agreement between NNLO 4F/5F predictions!

Basis for percent-level precision tests of W^+W^- physics!

Top subtraction vs jet veto

Top resonances, $g \to b\bar{b}$ singularities and b-jet veto ($p_{\mathrm{T}} < p^{\mathrm{veto}}_{\mathrm{T},bjet}$)





Full 5F cross section vs 4F

- top contamination huge at large $p^{\mathrm{veto}}_{\mathrm{T},bjet}$ and 10% at $10\,$GeV, where sensitivity to singularity shows up
- no "robust" W^+W^- definition

Top-free 5F cross section vs 4F

- very stable top subtraction at $p^{\mathrm{veto}}_{\mathrm{T},bjet} > 10\,$GeV
- 1% agreement with 4FNS

  $\Rightarrow$ **NNLO prediction solid!**

Outline

1. $W + 1, 2, 3$ jets at NLO QCD+EW
2. $\ell\ell/\ell\nu/\nu\nu + 0, 1, 2$ jets with MEPS@NLO QCD+EW
3. W^+W^- at NNLO QCD
4. $\ell\ell\nu\nu$ at NNLO QCD (+EW)

WW production and decay at NNLO QCD [Grazzini, Kallweit, S.P., Rathlev, Wiesemann, arXiv:16mm.nnnn] (all results preliminary)

Tools

- MATRIX framework
- 2-loop helicity amplitudes [Gehrmann, von Manteuffel, Tancredi, 1503.04812]

Full $pp \to \mu^+ e^- \nu_\mu \bar{\nu}_e$ process

$\Rightarrow$ decays with off-shell + non-resonant effects

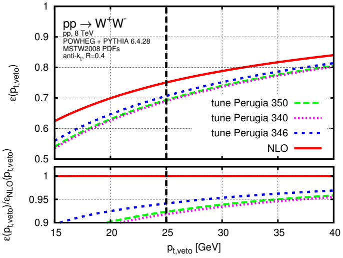
$\Rightarrow$ WW background in $H \to WW^*$ signal region

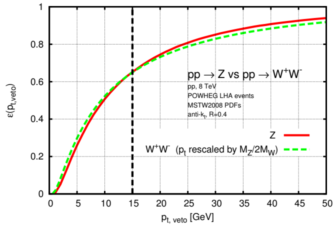
$\Rightarrow$ differential observables, fiducial cuts

Jet veto efficiency

- crucial for extrapolation of fiducial measurements to full phase space
- Monte Carlo mismodeling might bias inclusive $\sigma_{WW}^{\mathrm{EXP}}$ (?)

Jet veto efficiency in $pp \to WW$ [Monni, Zanderighi arXiv:1410.4745]





POWHEG jet-veto efficiency at 25 GeV

(1) 7–8% reduction wrt NLO

(2) Powheg veto efficiency for $pp \to Z$ at

$$p_{T,\text{veto}}^{Z} = M_Z/(2M_W)p_{T,\text{veto}}^{WW} \sim 15\,\text{GeV}$$

is consistent with (1)

(3) NNLO+NNLO veto efficiency for $pp \to Z$ [Banfi, Monni, Salam, Zanderighi 1206.4998] at 15 GeV is consistent with (2)

Precision calculations mandatory

- NNLO should be enough for effects $\lesssim 10\%$
- NNLO+NNLL for $p_{T,WW}$ available [Grazzini, Kallweit, Rathlev, Wiesemann 1507.02565]

Setup for total and fiducual $\mu^+ e^- \nu_\mu \bar{\nu}_e$ cross sections

Standard ATLAS/CMS fiducial cuts

- WW selection: 25 GeV jet veto & cuts on $p_{T,\ell}$, η_ℓ, $E_{T,\text{miss}}, \ldots$
- $H \to WW^*$ selection: additional cuts on $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$ and $p_{T,\ell\ell}$

Essential inputs

- 4-flavour NNPDF3.0 and b-quark veto (checked against 5F top-subtraction)
- N^{k}LO with N^kLO PDFs and NLO′ with NNLO PDFs
- $\mu_R = \mu_F = M_W$

Inclusive cross section

	σ [fb]		$\sigma/\sigma_{\rm NLO}-1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	425.4 $^{+2.8\%}_{-3.6\%}$	779.0 $^{+5.7\%}_{-6.7\%}$	-31.8%	-35.4%
NLO	623.4 $^{+3.6\%}_{-2.9\%}$	1205 $^{+3.9\%}_{-3.1\%}$	0	0
NLO'	636.0 $^{+3.6\%}_{-2.8\%}$	1236 $^{+3.9\%}_{-3.1\%}$	$+\ 2.0\%$	$+\ 2.5\%$
NLO'+gg	655.8 $^{+4.3\%}_{-3.3\%}$	1287 $^{+4.8\%}_{-3.7\%}$	$+\ 5.2\%$	$+\ 6.8\%$
NNLO	690.4 $^{+2.2\%}_{-1.9\%}$	1371 $^{+2.6\%}_{-2.3\%}$	$+10.7\%$	$+13.8\%$

$+11\,(14)\%$ **NNLO corrections wrt NLO at 8 (13) TeV**

- +2 (3)% from NNLO PDFs
- +3 (4)% from $gg \to WW$ **only** $\sim 1/3$ **of total NNLO correction**
- +6 (7)% remnant NNLO correction **large & positive!**

Off-shell effects

- negative 2% off-shell correction to absolute rates
- K-factors consistent with on-shell calculation

Cross section with WW cuts

	σ [fb]		$\sigma/\sigma_{\mathrm{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$147.2^{+3.4\%}_{-4.4\%}$	$233.0^{+6.6\%}_{-7.6\%}$	-3.8%	$-\ 1.3\%$
NLO	$153.1^{+1.9\%}_{-1.6\%}$	$236.2^{+2.8\%}_{-2.4\%}$	0	0
NLO'	$156.7^{+1.8\%}_{-1.4\%}$	$243.8^{+2.6\%}_{-2.2\%}$	$+2.4\%$	$+\ 3.2\%$
NLO'+gg	$166.4^{+1.3\%}_{-1.3\%}$	$267.3^{+1.5\%}_{-2.1\%}$	$+8.7\%$	$+13.2\%$
NNLO	$164.2^{+1.3\%}_{-0.8\%}$	$261.5^{+1.9\%}_{-1.2\%}$	$+7.2\%$	$+10.7\%$

$+7\,(11)\%$ **NNLO corrections wrt NLO at 8 (13) TeV**

- $+2\,(3)\%$ from NNLO PDFs
- $+6\,(10)\%$ from $gg \to WW$ $\sim 4/3$ **of total NNLO correction**
- $-1.5\,(2.5)\%$ remnant NNLO correction **small & negative!**

Jet veto

- suppresses all (N)NLO corrections driven by QCD radiation
- increases relative importance of gg (insensitive to jet veto at LO)

Cross section with $H \to WW$ cuts

	σ [fb]		$\sigma/\sigma_{\rm NLO} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$45.92\,^{+4.0\%}_{-5.0\%}$	$71.16\,^{+7.2\%}_{-8.2\%}$	$-\ 4.4\%$	$-\ 2.6\%$
NLO	$48.05\,^{+1.9\%}_{-1.7\%}$	$73.09\,^{+2.7\%}_{-2.4\%}$	0	0
NLO'	$49.32\,^{+1.7\%}_{-1.6\%}$	$75.58\,^{+2.5\%}_{-2.2\%}$	$+\ 2.7\%$	$+\ 3.4\%$
NLO'+gg	$53.50\,^{+2.0\%}_{-1.5\%}$	$85.23\,^{+2.5\%}_{-2.5\%}$	$+11.3\%$	$+16.6\%$
NNLO	$52.30\,^{+1.6\%}_{-1.0\%}$	$82.32\,^{+2.4\%}_{-2.6\%}$	$+\ 8.9\%$	$+12.6\%$

$+9\,(13)\%$ NNLO corrections wrt NLO at 8 (13) TeV

- $+3\%$ from NNLO PDFs
- $+9\,(13)\%$ from $gg \to WW$ $\sim 4/3$ **of total NNLO correction**
- $-2.5\,(4)\%$ remnant NNLO correction **small & negative!**

Similar behaviour as for WW cuts

Acceptance with WW cuts

	$A = \sigma^{\mathrm{WW-cuts}}/\sigma^{\mathrm{incl}}$		$A/A_{\mathrm{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$0.3461^{+0.6\%}_{-0.7\%}$	$0.2992^{+0.8\%}_{-1.0\%}$	$+41.0\%$	$+52.6\%$
NLO	$0.2455^{+4.4\%}_{-4.7\%}$	$0.1960^{+4.4\%}_{-4.7\%}$	0	0
NLO'+gg	$0.2537^{+3.5\%}_{-3.7\%}$	$0.2077^{+3.2\%}_{-3.1\%}$	$+\ 3.3\%$	$+\ 6.0\%$
NNLO	$0.2378^{+1.3\%}_{-0.9\%}$	$0.1907^{+1.2\%}_{-0.9\%}$	$-\ 3.2\%$	$-\ 2.7\%$

-3% NNLO corrections wrt NLO at 8 (13) TeV

- $+3\,(6)\%$ from $gg \to WW$ $\Rightarrow$ **NLO$'$+gg unreliable!**
- $-6.5\,(9)\%$ remnant NNLO correction **c.f. -7-8% POWHEG correction to $\varepsilon_{\mathrm{veto}}$**

Acceptance with $H \to WW$ cuts

	$A = \sigma^{\mathrm{H-cuts}}/\sigma^{\mathrm{incl}}$		$A/A_{\mathrm{NLO}} - 1$	
$\sqrt{s}$	8 TeV	13 TeV	8 TeV	13 TeV
LO	$0.1080\ ^{+1.2\%}_{-1.4\%}$	$0.09135^{+1.5\%}_{-1.7\%}$	$+40.1\%$	$+50.6\%$
NLO	$0.07706^{+4.3\%}_{-4.6\%}$	$0.06065^{+4.3\%}_{-4.5\%}$	0	0
NLO'+gg	$0.08157^{+3.1\%}_{-3.1\%}$	$0.06623^{+2.7\%}_{-2.5\%}$	$+\ 5.9\%$	$+\ 9.2\%$
NNLO	$0.07575^{+1.2\%}_{-0.8\%}$	$0.06005^{+1.1\%}_{-0.9\%}$	$-\ 1.7\%$	$-\ 1.0\%$

$-2\,(1)\%$ NNLO corrections wrt NLO at 8 (13) TeV

- $+6\,(9)\%$ from $gg \to WW$ $\Rightarrow$ **NLO$'$+gg unreliable!**
- $-8\,(10)\%$ remnant NNLO correction

Non-gg NNLO correction: summary

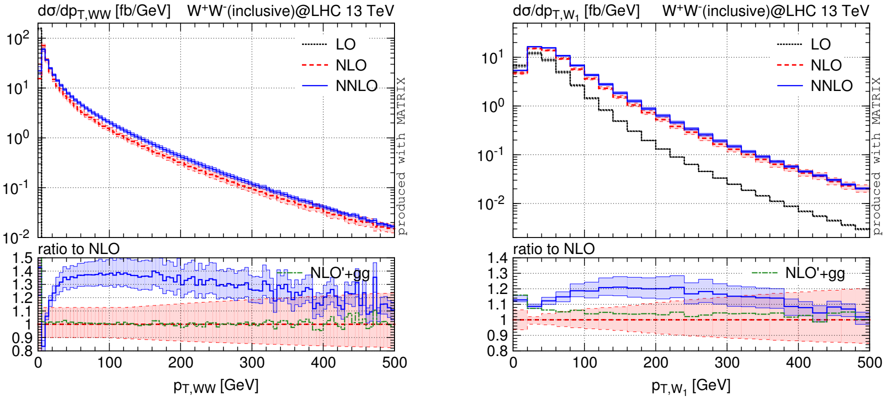
- positive and large for σ_{incl} but negative and rather small for $\sigma_{\mathrm{fiducial}}$

$\Rightarrow$ **constant global K-factors not appropriate!**

$\Rightarrow$ **use NNLO everywhere!**

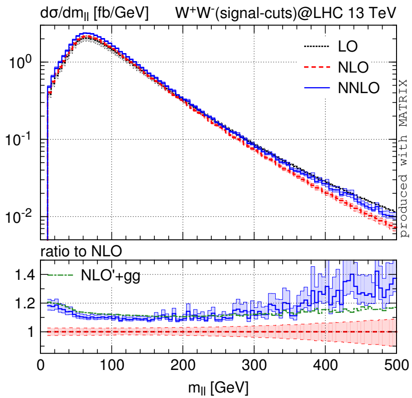
Differential distributions (inclusive phase space)

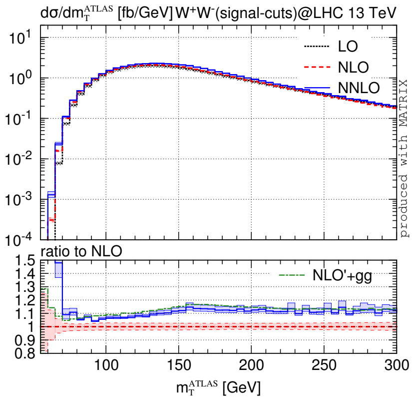
Sizable non-gg corrections for observables sensitive to QCD radiation



Differential distributions (WW cuts)

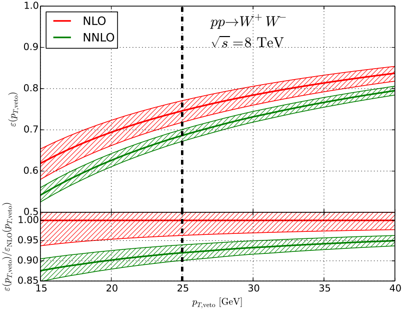
Negligible non-gg shape corrections for inclusive leptonic observables





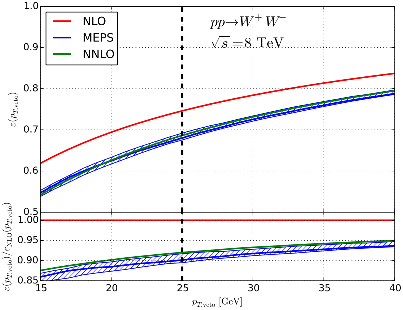
Jet-veto efficiency for $pp \to W^+W^-$ [Grazzini, Kallweit, Moretti, S.P, Rathlev (preliminary)]

NNLO vs NLO



- fiducial region of ATLAS (CMS) measurement involves jet veto at $p_T = 25(30)$ GeV
- NNLO correction of -8% wrt NLO
- NNLO seems consistent with Powheg

NNLO vs MEPS@NLO (Sherpa)



- MEPS@NLO $\Rightarrow$ 1st emission at NLO + LLs + particle level
- quite stable wrt scale variations
- consistent with NNLO

$\ell\ell\nu\nu$ at NLO EW [Kallweit, Lindert, Maierhöfer, S.P., Schönherr,arXiv:16mm.nnnn] (all results preliminary)

NLO EW treatment of $WW \to \ell\ell\nu\nu$ decays

- pole approximation [Billoni, Dittmaier,Jäger, Speckner arXiv:1310.1564]
  - $\Rightarrow$ applicable above WW threshold

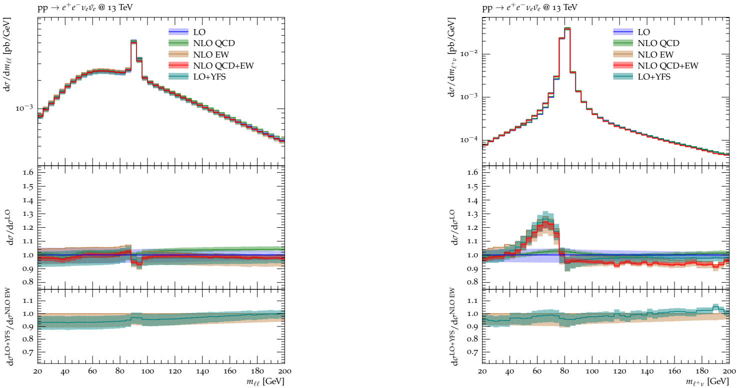
- full $pp \to \ell\ell\nu\nu$ process [Kallweit et al. arXiv:16mm.nnnn]
  - $\Rightarrow$ exact off-shell + non-resonant effects
  - $\Rightarrow$ crucial for $H \to WW^*$ signal region

Tools and possible high-precision simulations (in the future)

- OpenLoops+Munich $\Rightarrow$ NLO EW with NNLO+NNLL QCD in Matrix
- OpenLoops+Sherpa $\Rightarrow$ NLO EW with MEPS@NLO or UN^{2}LOPS [Höche, Li, Prestel]

ZZ and WW resonances in same-flavour $\ell\ell\nu\nu$ channel

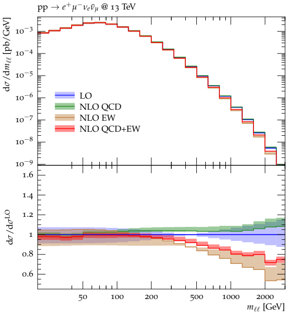
- significant distortion of resonance shape due to QED radiation
- well approximated by YFS QED shower [Schönherr] in SHERPA



Large Sudakov EW effects

NLO QCD+EW corrections to $m_{\ell\ell}$

- small QCD corrections (WW cuts with jet veto)
- very large EW Sudakov effects

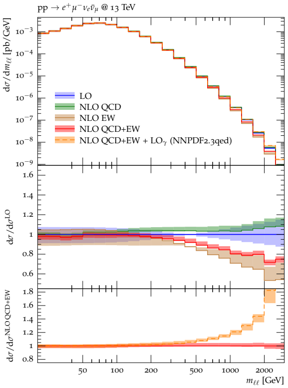


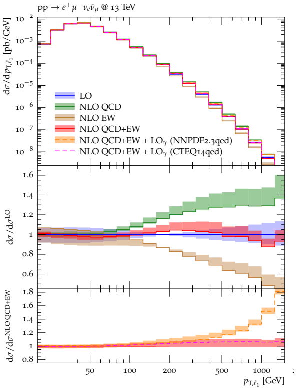
Large $\gamma\gamma \to WW$ contributions (?)

Photon-induced effects

- potentially huge impact in TeV region but $\mathcal{O}(100\%)$ PDF uncertainty
- WW precision can be exploited to constrain γ-PDF...

  ...possibly without biasing $X \to WW$ searches at 750 GeV...





Summary and Outlook

V+multi-jets at NLO QCD+EW

- huge QCD and EW effects in BSM backgrounds at TeV scale
- MEPS@NLO QCD+EW merging to contol QCD$\times$EW interplay

WW at NNLO QCD + NLO EW

- large QCD corrections beyond NLO+gg to total rate and acceptance-cut efficiency
- large EW Sudakov and $\gamma\gamma \to WW$ effects at TeV scale

Widely automated tools OpenLoops, Sherpa, Munich, Matrix

- NNLO QCD+NLO EW for wide range of processes
- automated framework also for NNLO+NNLL, MEPS@NLO, UN^{2}LOPS, ...

Backup slides

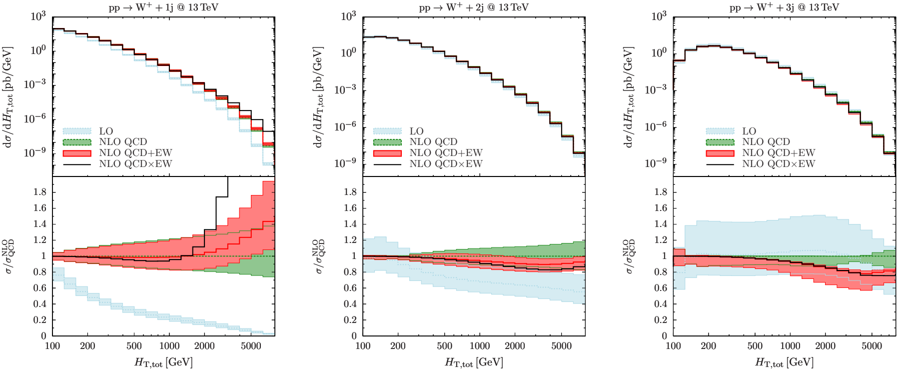
NLO QCD vs EW complexity in $pp \to W + 1, 2, 3$ jets

Number of diagrams in $pp \to W + 1, 2, 3$ jets (in parenthesis: $q = u_i, d_i$ case)

Channel	QCD trees	EW trees	QCD 1-loop	EW 1-loop
$u_i \bar{d}_i \to W^+ g$	2	-	11	32
$u_i \bar{d}_i \to W^+ q\bar{q}$	2 (4)	7 (14)	33 (66)	105 (210)
$u_i \bar{d}_i \to W^+ gg$	8	-	150	266
$u_i \bar{d}_i \to W^+ q\bar{q}g$	12 (24)	33 (66)	352 (704)	1042 (2084)
$u_i \bar{d}_i \to W^+ ggg$	54	-	2043	2616

- moderate growth of complexity wrt NLO QCD (up to 3× more loop diagrams)
- 1-loop QCD and EW similarly fast ⇒ 0.1% stat precision for $W + 1, 2, 3$ jets at NLO QCD+EW costs 13, 210, 6300 CPU h (dominated by NLO QCD!)

NLO corrections to $H_{T,\text{tot}}$ in $pp \to W^+ + 1, 2, 3\,\text{jets}$



- NLO QCD in $H_{T,\text{tot}}$ tail well behaved only starting from $W + 3\,\text{jets}$ (calls for NLO multi-jet merging)
- only -20% EW corrections at very high $H_{T,\text{tot}}$ (more if also $p_{T,W}$ is high!)

NNLO ingredients

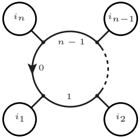
Technical ingredients of NNLO calculation of on-shell $pp \to W^+W^-$

- Two-loop master integrals [Gehrmann,Tancredi, von Manteuffel, Weihs '13–'14]; see also [Caola, Henn, Melnikov, Smirnov '14]
- Two-loop amplitudes [Gehrmann,Tancredi, von Manteuffel]
- IR stable one-loop amplitudes with OpenLoops [Cascioli, Maierhöfer, S.P. '12] Collier [Denner,Dittmaier,Hofer '05] CutTools [Ossola,Papadopoulos,Pittau '08] OneLoop [van Hameren '11]
- fast multi-channel MC [Kallweit, Rathlev] with dipole subtraction [Catani, Seymour '96] and NNLO q_{T} subtraction [Catani, Grazzini '07]

OpenLoops method [Cascioli, Maierhöfer, S.P. '11]

Strategy

- handle all process-dependent one-loop ingredients via tree-like algorithm
- hybrid "tree–loop" approach ⇒ very high speed and flexibility [Van Hameren '09]
- diagrammatic representation

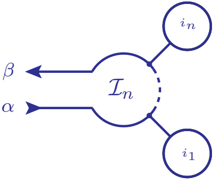


$$= \int \frac{\mathrm{d}^D q\, \mathcal{N}(\mathcal{I}_n; q)}{D_0 D_1 \dots D_{n-1}} = \underbrace{\sum_{r=0}^{R} \mathcal{N}_{\mu_1 \dots \mu_r}(\mathcal{I}_n)}_{\text{numerical recursion [OpenLoops]}} \underbrace{\int \frac{\mathrm{d}^D q\, q^{\mu_1} \dots q^{\mu_r}}{D_0 D_1 \dots D_{n-1}}}_{\text{tensor integrals [Denner, Dittmaier]}}$$

OpenLoops recursion [Cascioli, Maierhöfer, S.P '11]

Recursive merging of *q-dependent* trees

$$\sum_{r=0}^{n} \mathcal{N}^{\beta}_{\mu_1\dots\mu_r;\alpha}(\mathcal{I}_n)\; q^{\mu_1}\dots q^{\mu_r} =$$



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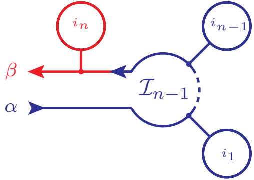
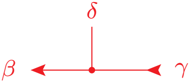


Interaction terms depend only on $\mathcal{L}_{\text{int}}$ $\Rightarrow$ *automation!*

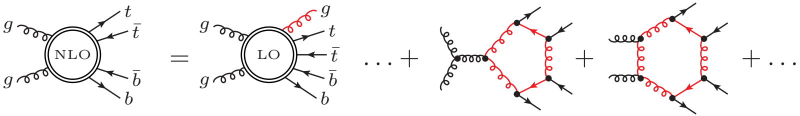


$$= \quad Y^{\beta}_{\gamma\delta} + Z^{\beta}_{\nu;\gamma\delta}\; q^{\nu}$$

Recursion for polynomial coefficients $\Rightarrow$ *very high speed!*

$$\mathcal{N}^{\beta}_{\mu_1\dots\mu_r;\alpha}(\mathcal{I}_n) = \left[Y^{\beta}_{\gamma\delta}\; \mathcal{N}^{\gamma}_{\mu_1\dots\mu_r;\alpha}(\mathcal{I}_{n-1}) + Z^{\beta}_{\mu_1;\gamma\delta}\; \mathcal{N}^{\gamma}_{\mu_2\dots\mu_r;\alpha}(\mathcal{I}_{n-1}) \right] \; w^{\delta}(i_n)$$

OpenLoops 1.0 [Cascioli, Lindert, Maierhöfer, S.P. '14]



Automated generator of NLO QCD matrix elements (>30'000 lines of code)

- public library with more than 100 LHC processes at `openloops.hepforge.org`

Interface to multi-purpose Monte Carlo programs

- Munich [Kallweit] ⇒ very powerful (N)NLO parton level MC
- Sherpa [Höche, Krauss, Schönherr, Siegert et al.] ⇒ NLO matching and merging
- Powheg [Nason, Oleari et al.]
- Herwig [Gieseke, Plätzer wt al.]
- Geneva [Alioli, Bauer, Tackmann et al.]
- Whizard [Kilian, Ohl, Reuter et al.]

Completely automated NLO simulations for any $2 \to 2, 3, 4$ SM processes at LHC

State-of-the-art applications in Top, EW and Higgs physics

NLO QCD+EW

- S–MC@NLO for $pp \to t\bar{t}b\bar{b}$ with $m_b > 0$ [Cascioli, Maierhöfer, Moretti, S.P., Siegert, arXiv:1309.5912]
- NLO for $pp \to W^+W^-b\bar{b}$ with $m_b > 0$ [Cascioli, Kallweit, Maierhöfer, S.P., arXiv:1312.0546]
- NLO QCD+EW for $W + 1, 2, 3$ jets [Kallweit, Lindert, Maierhöfer, S.P., Schönherr, arXiv:1412.5157]
- NLO QCD+EW for $\ell\ell/\ell\nu/\nu\nu + 0, 1, 2$ jets [Kallweit, Lindert, Maierhöfer, S.P., Schönherr, arXiv:1511.08692]

NLO merging

- MEPS@NLO for $\ell\ell\nu\nu$+0,1 jets, [Cascioli, Höche, Krauss, Maierhöfer, S.P., Siegert, arXiv:1309.0500]
- (1-loop)^2 merging for $pp \to HH$+0,1 jets, [Maierhöfer, Papaefstathiou, arXiv:1401.0007]
- MEPS@NLO for WWW+0,1 jets, [Höche, Krauss, S.P., Schönherr, Thompson arXiv:1403.7516]
- MEPS@NLO for $t\bar{t}$+0,1,2 jets, [Höche, Krauss, Maierhöfer, S.P., Schönherr, Siegert arXiv:1402.6293]

NNLO QCD

- $pp \to \gamma Z$ and γW [Grazzini, Kallweit, Rathlev, Torre, arXiv:1309.7000; arXiv:1504.01330]
- $q\bar{q} \to t\bar{t}$ [Abelof, Gehrmann–de Ridder, Maierhöfer, S.P., arXiv:1404.6493]
- $pp \to ZZ$ [Cascioli, Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, S.P., Rathlev, Tancredi, Weihs, arXiv:1405.2219]
- $pp \to W^+W^-$ [Gehrmann, Grazzini, Kallweit, Maierhöfer, von Manteuffel, S.P., Rathlev, Tancredi arXiv:1408.5243]