Precise electroweak predictions for V+multijet production

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Outline

1. General aspects of EW corrections
2. $V+$ jets
3. $pp \to Z(\ell^+\ell^-) + 2$ jets at NLO EW
4. $pp \to W + 1, 2, 3$ jets at NLO QCD+EW

NLO EW automation

NLO EW corrections at the LHC

- exceed NLO QCD uncertainties at $Q^2 \gg M_W^2$
- known for most $2 \to 2$ processes
- missing for numerous $2 \to 3, 4$ processes (with decays and NLOPS matching!)
- more involved than NLO QCD: virtual corrections involve various massive particles (γ, Z, W, H, b, t) and tend to dominate over bremsstrahlung

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
γγ	dσ @ NNLO QCD + NLO EW	q_T resummation at NNLL matched to NNLO

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

NLO EW automation and first results

- RECOLA+COLLIER: $pp \to \ell^+\ell^- jj$ [arXiv:1411.0916]
- OPENLOOPS+ MUNICH and SHERPA: $pp \to W + 1, 2, 3$ jets [arXiv:1412.5156]
- MADGRAPH5_AMC@NLO: $pp \to t\bar{t} + V$ [arXiv:1504.03446]

$\Rightarrow$ focus on general features of NLO EW calculations . . .

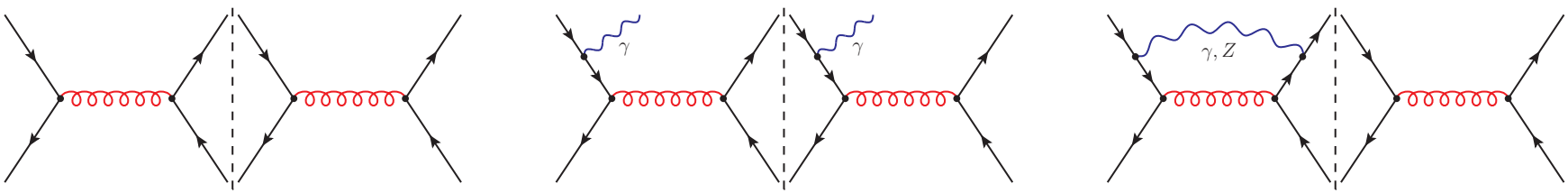
Nontrivial QCD-EW interplay

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

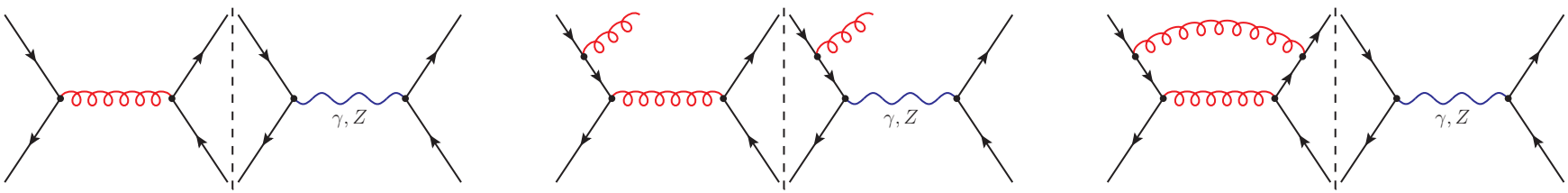
$$\underbrace{\mathcal{O}\left(\alpha_S^n \alpha^m\right)}_{\text{“QCD”}} + \underbrace{\mathcal{O}\left(\alpha_S^{n-1} \alpha^{m+1}\right)}_{\text{“EW}-\text{QCD interf.”}} + \cdots + \underbrace{\mathcal{O}\left(\alpha_S^{n-k} \alpha^{m+k}\right)}_{\text{“EW”}}$$

$\mathcal{O}\left(\alpha_S^n \alpha^{m+1}\right)$ 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



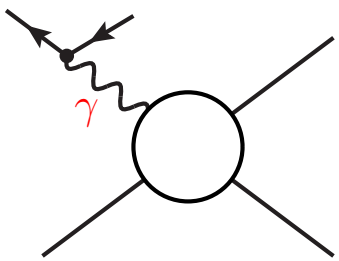
In practice above naive splitting inconsistent

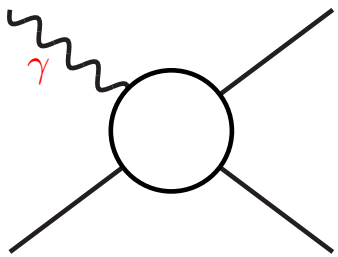
- only complete $\mathcal{O}\left(\alpha_S^{n-k} \alpha^{m+k+1}\right)$ IR finite $\Rightarrow$ nontrivial bookkeeping (automated)
- note that $\mathcal{O}(\alpha)$ corrections can involve emissions of photons and QCD-partons

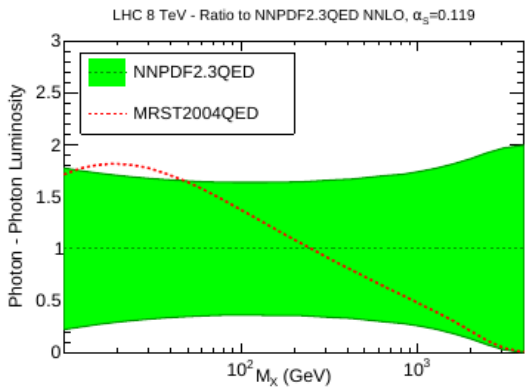
Photons

Cancellation of IS Photon singularities

- requires QED factorisation and PDF evolution [MRST2004, NNPDF2.3]
- γ-induced processes $\Rightarrow$ possible TeV-scale enhancements but large PDF uncertainty

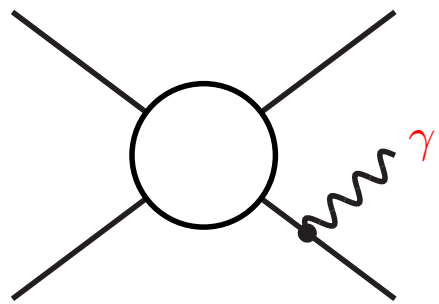






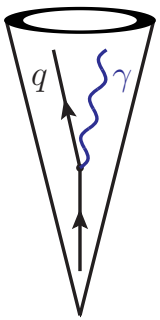
Cancellation of FS photon singularities

- requires IR subtraction method [Catani,Dittmaier,Seymour, Trocsanyi; Frixione, Kunszt, Signer]
- photon emission off quarks renders IR safe jet definition nontrivial at NLO EW

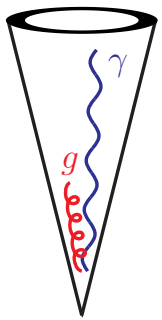


Treatment of photons inside jets at NLO EW

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



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

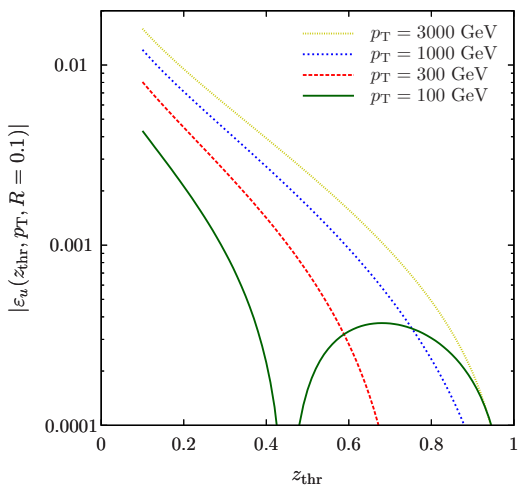


soft gluon singularities $\leftrightarrow$ hard photons inside jets: cancelled in jet-production (NLO EW) + γ-production (NLO QCD)

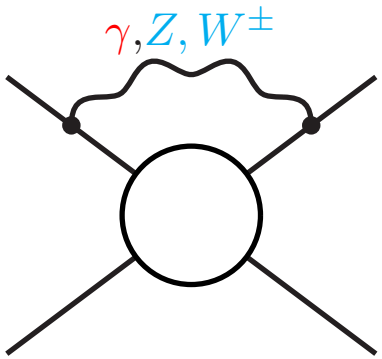
Option B: Separation of jets from photons through $E_\gamma / E_{\rm jet} < z_{\rm thr}$ inside jets

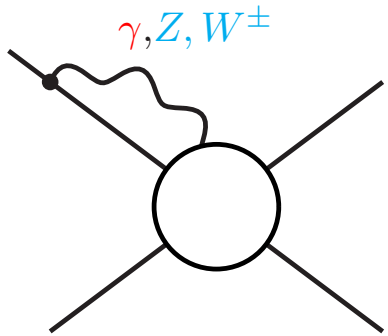
- **rigorous approach:** absorb $q \to q\gamma$ singularity into fragmentation function [1411.0916]
- **approximation:** cancel singularity via $q\gamma$ recombination in small cone $\Delta R_{q\gamma} < 0.1$ [1412.5156]

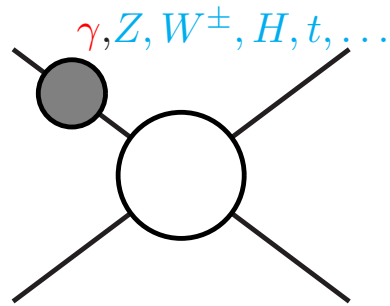
$\Rightarrow$ difference $\ll 1\%$ for typical $z_{\rm thr}$ choices



EW Sudakov logarithms I







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

$\Rightarrow$ large soft/collinear $\alpha \ln^2(Q^2/M_W^2)$ corrections

Universality and factorisation [Denner,S.P. '01] similarly as in QCD

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

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

EW Sudakov logarithms II

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

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

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

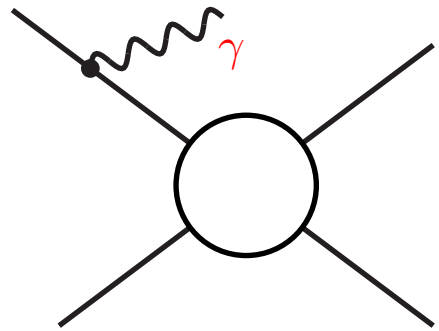
- various 2-loop results and resummations available [Bauer, Becher, Ciafaloni, Comelli, Denner, Fadin, Jantzen, Kühn, Lipatov, Manohar Martin, Melles, Penin, Pozzorini, Smirnov, . . .]

$\Rightarrow$ 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

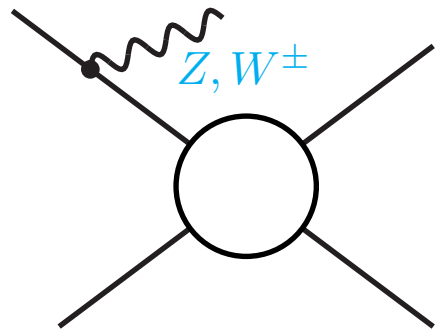


Real Z, W emission [Ciafaloni,Comelli, ...]

- **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**: modest $\ln(\hat{s}/M_W)$ cancellation (strongly dependent on process and analysis)



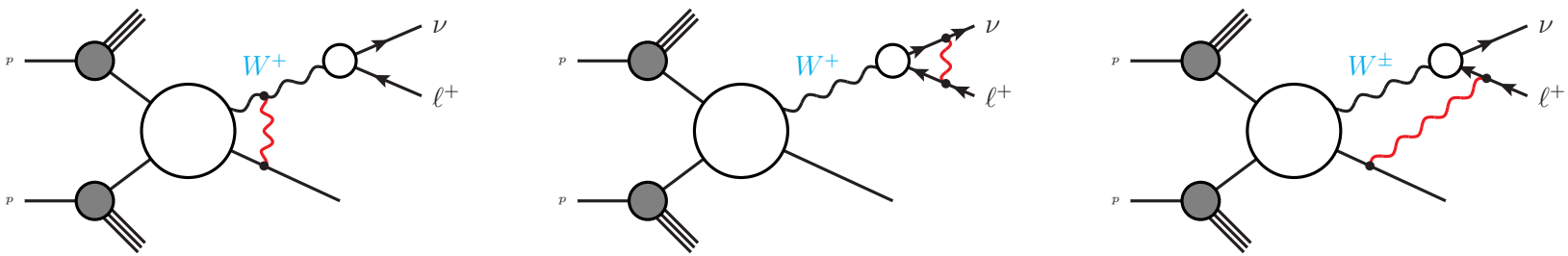
Bookkeeping of $pp \to X$ and $pp \to X + V$ processes

- important to add both contributions to physical observables while keeping them as separate processes (XV production $\ni X$ production)
- otherwise double counting, e.g. overlap of ZW, $Z(+V)$ and $W(+V)$ production
- separation trivial since Z/W emission is tree level and IR finite

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

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

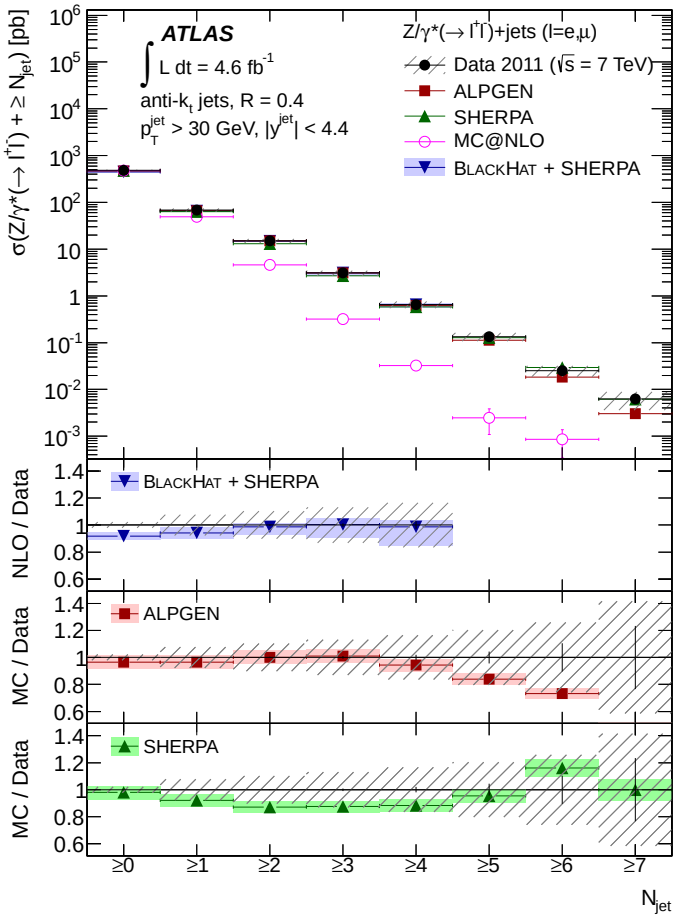
- simpler but applicability to V+multijets limited to certain $\mathcal{O}\left(\alpha_S^n \alpha^{m+1}\right)$ (see later)
- captures all large $\ln(\hat{s}/M_W^2)$ effects (present only in production sub-process)
- typical uncertainty $\lesssim$ 1–3% (apart form $\gamma^*/Z^* \to \ell^+\ell^-$ at small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

Outline

High precision in perturbative QCD

$V + 1, 2, 3, 4, (5)$ jets at NLO

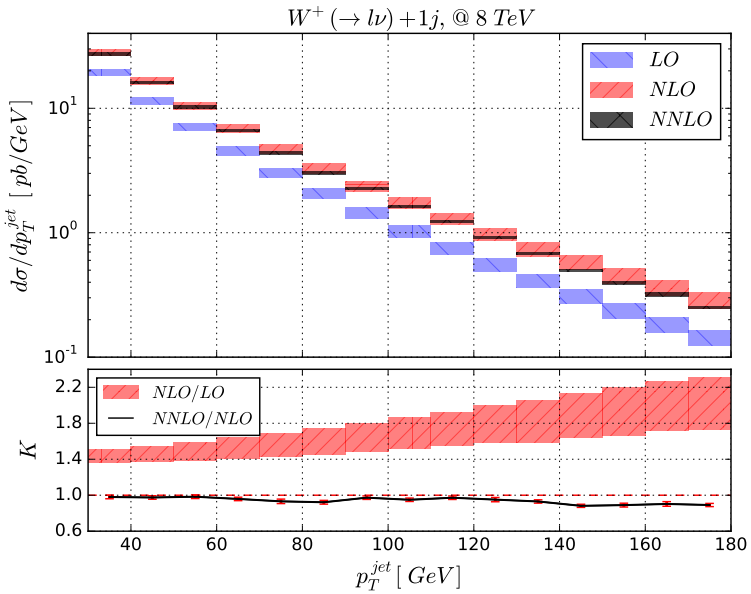
[BlackHat+Sherpa '09–'13]



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

$W + 1$ jet at NNLO

[Boughezal,Focke,Liu,Petriello '15]

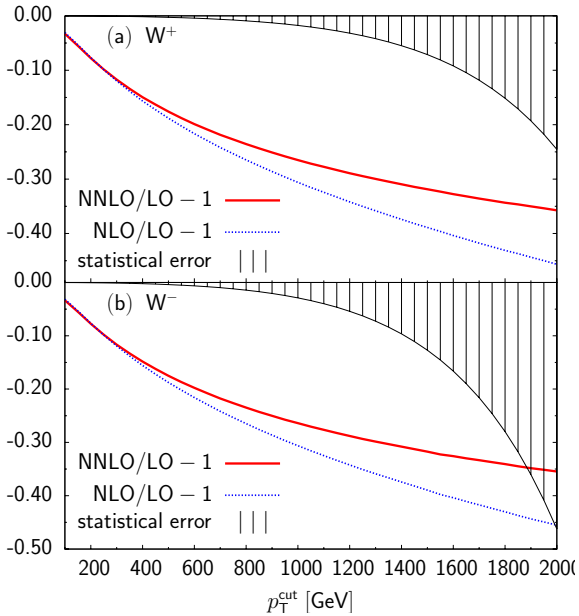


$\Rightarrow$ $\mathcal{O}\,(1\%)$ **scale uncertainty**

EW corrections

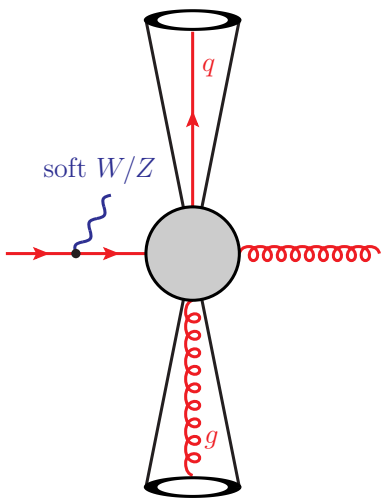
Very large EW corrections to $pp \to Z/W + 1$ jet

- 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]



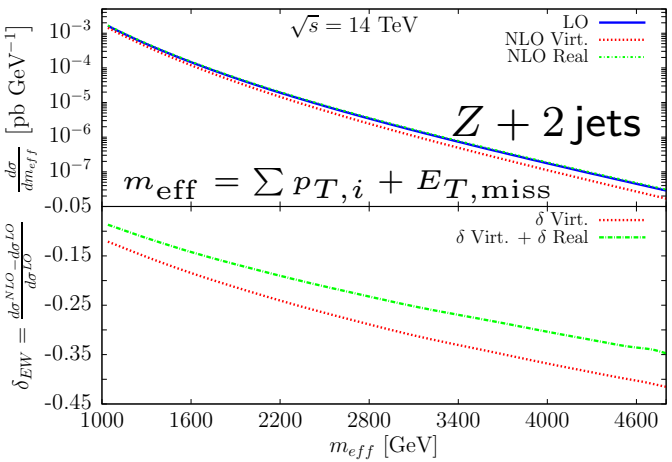
Strong motivations for V+multijets at NLO EW

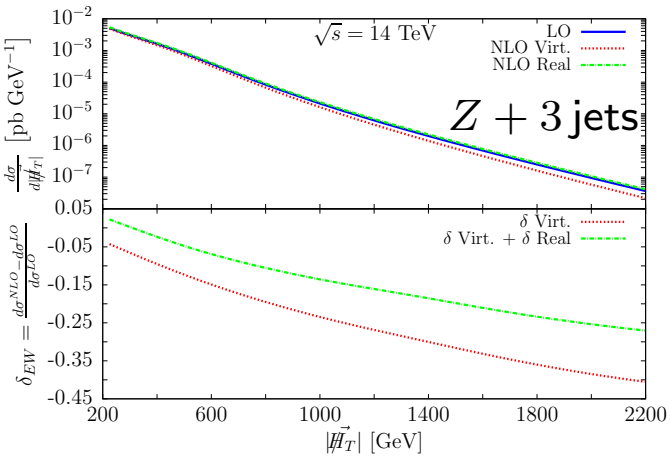
- multi-jet case: EW Sudakov poorly explored and crucial for BSM searches
- huge di-jet contributions at high jet $p_T \Rightarrow V + 1$ jet NLO EW insufficient!!
- overlap with EW processes (VBF,VV',tj, tW, $t\bar{t}$) and interference with QCD



EW Sudakov logarithms in $pp \to Z(\nu\bar{\nu}) + 2, 3$ jets [Chiesa, Montagna, Barzé, Moretti, Nicrosini, Piccinini, Tramontano '13]

$Z(\nu\bar{\nu})+$ multijet background to MET $+ 2/3j + 0\ell$ searches in ATLAS/CMS





Virtual Sudakov LL+NLL effects [Denner, S.P. '01]

- process-independent implementation in ALPGEN

$\Rightarrow$ 15–40% negative corrections in (multi)TeV range

Real emission effects from $pp \to ZZ/WW/WZ + n$-jets

- with $Z/W \to jj, \ell^+\ell^-, \ell\nu, \nu\bar{\nu}$ decays and $n = 0, \ldots 2/3$ (not fixed!)

$\Rightarrow$ modest positive correction 5–10%

Strong motivation for $pp \to V$+multijets at NLO EW!

Outline

$pp \to Z(\ell^+\ell^-) + 2\,\text{jets}$ at NLO EW [Denner, Hofer, Scharf, Uccirati '14]

Automated Tools

- Loops amplitudes: RECOLA [Actis, Denner, Hofer, Scharf, Uccirati '13] and COLLIER [Denner, Dittmaier, Hofer '14]
- Monte Carlo: in-house program

$\Rightarrow$ **Full NLO QCD+EW automation for any $2 \to 2, 3, 4$ SM process**

Application to $Z + 2$ jet production (complex mass scheme)

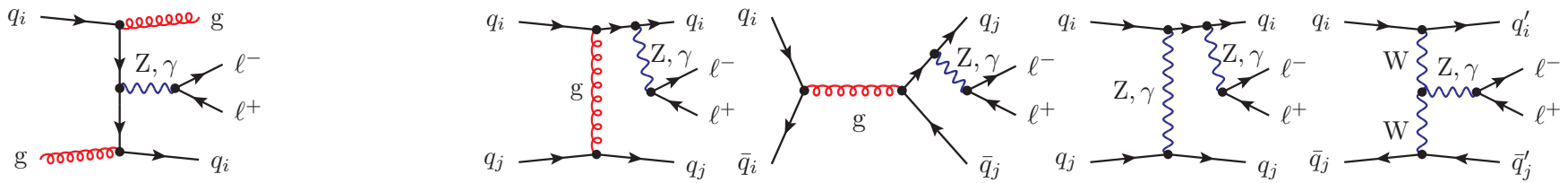
$\Rightarrow$ nontrivial $2 \to 4$ calculation for full $pp \to \ell^+\ell^- jj$ processes

$\Rightarrow$ exact treatment of γ^*/Z^* and non-resonant effects!

Off-shell effects vs $q\bar{q} \to Z^* \to \ell^+\ell^-$ pole approximation

- $1.5\%\,(11\%)$ with (without) $|M_{\ell\ell} - M_Z| < 15\,\text{GeV}$ cut

LO contributions to $\sigma_{\rm int}$



Two-quark channels

$$\Rightarrow \mathcal{O}\left(\alpha_S^2\alpha^2\right)$$

Four-quark channels

$$\Rightarrow \mathcal{O}\left(\alpha_S^2\alpha^2\right) + \underbrace{\mathcal{O}\left(\alpha_S\alpha^3\right)}_{\text{for } q_i=q_j} + \underbrace{\mathcal{O}\left(\alpha^4\right)}_{\text{VBF},ZV(jj)}$$

Integrated $\sigma_{\rm LO}$ at 13 TeV *with "standard" and VBF cuts*

- σ_{4q}/σ_{2q} from 20% (standard cuts) to 40% (VBF cuts)
- QCD dominant also with VBF cuts (but no jet veto...)
- tiny EW-QCD interference (accidental)

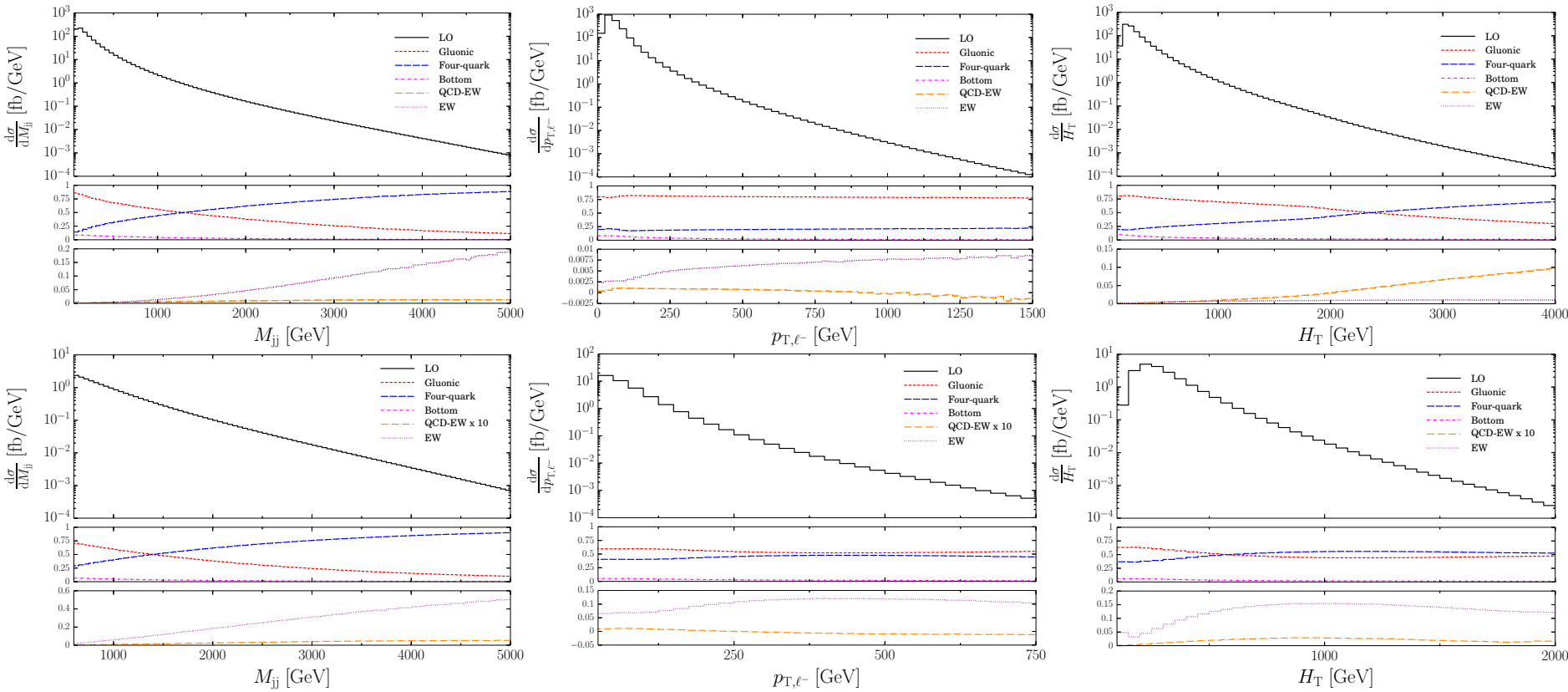
	channels			order		
cuts	$2q$	$4q$	γ-ind.	$\alpha_S^2\alpha^2$	$\alpha_S\alpha^3$	α^4
standard	80%	20%	$< 0.05\%$	99%	$< 0.1\%$	1%
VBF	60%	40%	–	93%	0.01	7%

γp and $\gamma\gamma$ induced processes of $\mathcal{O}\left(\alpha_S\alpha^3\right) + \mathcal{O}\left(\alpha^4\right) \Rightarrow 10^{-3} \times \sigma_{\rm tot}$ (neglected)

LO contributions to $\mathrm{d}\sigma_{\mathrm{LO}}/\mathrm{d}X$

standard cuts

VBF cuts



Strong kinematic dependence of 2q/4q and QCD/EW contributions

- σ_{4q}/σ_{2q} grows from 20% to 50(75)% at H_T, M_{jj}=2(4) TeV
- EW contribution enhanced from 1 to 10–20% by VBF cuts and at large M_{jj}
- EW–QCD interference ∼10% at very large H_T and $p_{T,j}$ but suppressed otherwise

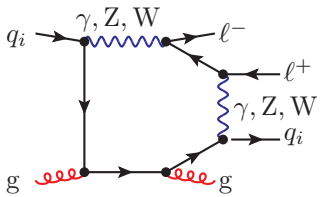
NLO EW corrections to $pp \to Z(\ell^+\ell^-) + 2\,\text{jets}$

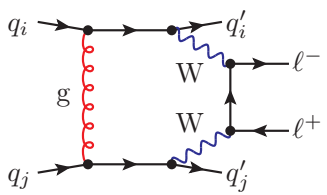
NLO EW vs full NLO SM corrections

$$\underbrace{\mathcal{O}\left(\alpha_S^3\alpha^2\right)}_{\text{“NLO QCD”}} \qquad \underbrace{\mathcal{O}\left(\alpha_S^2\alpha^3\right)}_{\text{“NLO EW”}} \qquad \mathcal{O}\left(\alpha_S^1\alpha^4\right) \qquad \mathcal{O}\left(\alpha_S^0\alpha^5\right)$$

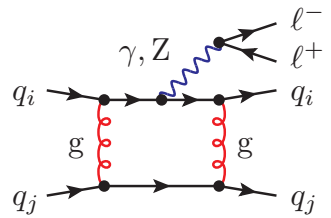
Virtual EW corrections (examples of EW/QCD loops in 2q/4q channels)

QCD Born $\times$



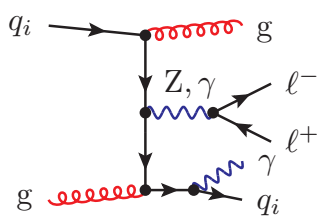


EW Born $\times$



$\Rightarrow$ $\mathcal{O}\left(1000\right)$ 1-loop diagrams with $\mathcal{O}\left(100\right)$ hexagons+pentagons per channel

Real EW corrections (examples of photon/gluon emission in 2q/4q channels)



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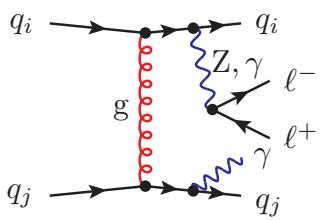
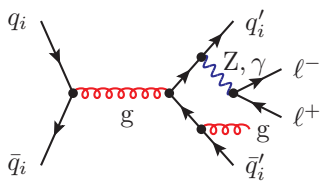
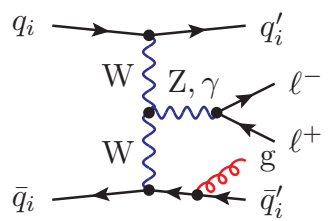




$\times$



NLO EW corrections at 13 TeV I

Integrated cross section (with standard or VBF cuts)

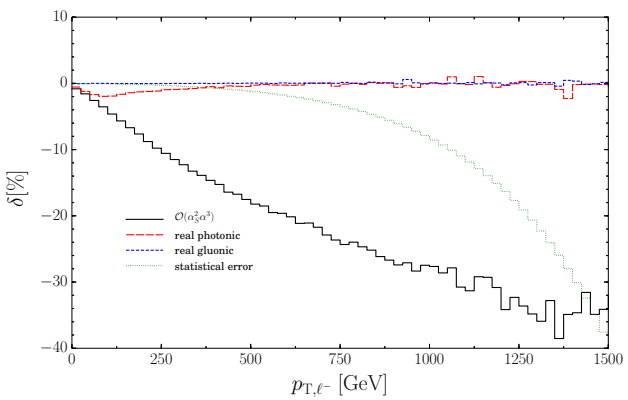
- only 2–3% negative corrections wrt LO

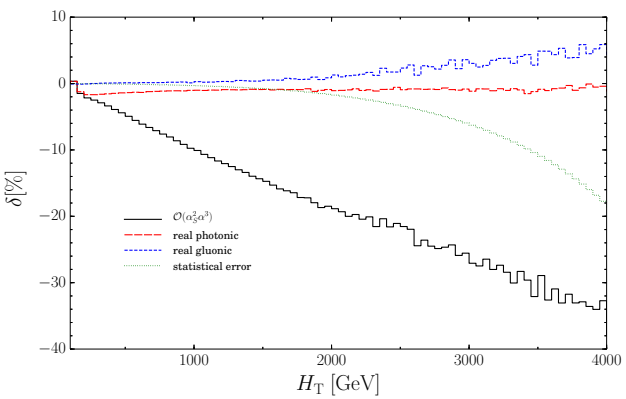
Distributions in p_T and H_T (similar results with standard and VBF cuts)

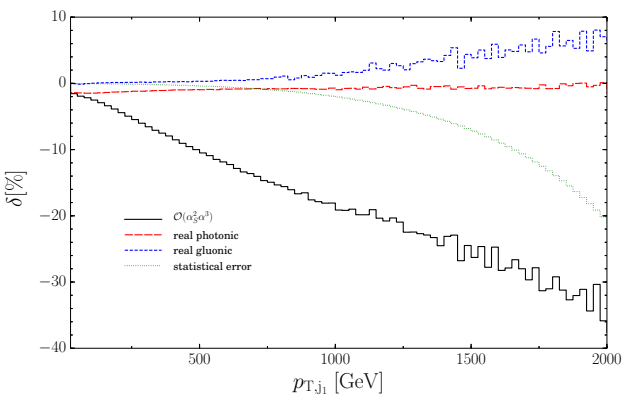
- large negative corrections of -20% to -35% in the (multi)TeV region
- dominated by virtual corrections (typical Sudakov EW behaviour)
  - photon bremsstrahlung* $\lesssim$ 1–2%
  - gluon bremsstrahlung* $\lesssim$ 1–2% apart from $p_{T,j}$ and H_T tails (+6–8%)

*($\overline{\rm MS}$ subtraction of IR sing.)

- NLO EW statistically relevant up to $H_T = 5\,\text{TeV}$ at $L = 300\,\text{fb}^{-1}$



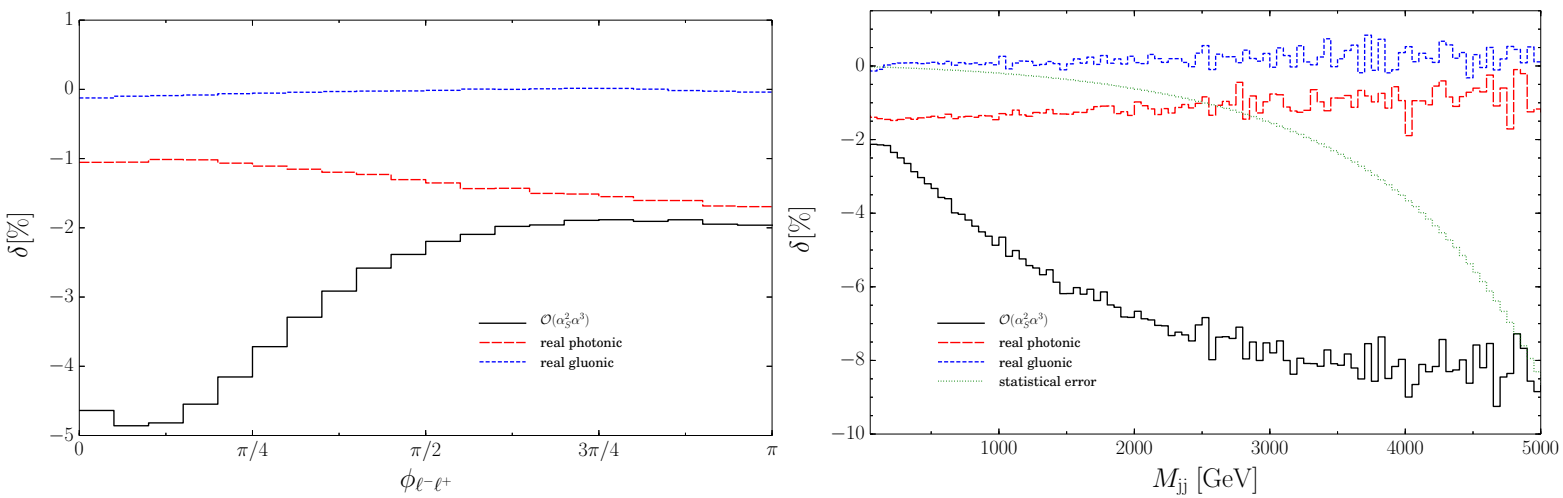




NLO EW corrections at 13 TeV II

Angular and M_{jj} distributions (similar results with standard and VBF cuts)

- only mild corrections: $\lesssim 5\%$ in general and $\lesssim 10\%$ in M_{jj} tail
- slight shape deformation of $\phi_{\ell^+\ell^-}$
- no strong Sudakov enhancement at $M_{jj} = 5\,\text{TeV}$ (dominated by scale $t \ll M_{jj}$)



Outline

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

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

Automated Tools

- Loop amplitudes: OpenLoops [Cascioli, Lindert, Maierhöfer,S.P. '13] and Collier [Denner, Dittmaier, Hofer '14]
- Monte Carlo: Munich [Kallweit] or Sherpa [Hoeche, Hoeth, Krauss, Schoenherr, Schumann, Siegert, Zapp]

$\Rightarrow$ **Full NLO QCD+EW automation for any $2 \to 2, 3, 4$ SM process**

Application to W+multijet production

$\Rightarrow$ investigate technical performance of tools for multi-jet case

$\Rightarrow$ go up to $N_{\text{jets}} = 3$ keeping on-shell W (stable or NWA decay)

$\Rightarrow$ investigate N_{jets}-dependence of NLO EW

Generic partonic channels for $pp \to W^+ + n$ jets $(n \leq 3)$

	$pp \to W + n$ 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

Automated bookkeeping crucial

- many crossings and flavour combinations $(u_i, d_i, q, q' \in \{u, d, c, s, b\})$

LO contributions from $2q$, $4q$, γ- and $\gamma\gamma$-induced channels

- $2q$: QCD
- $4q$: QCD, EW $\supset$ VBF, $WV(jj)$, $t(Wb)j$, $Wt(jjj)$ and QCD-EW interf.

NLO contributions of order $\alpha_S^{n+1}\alpha$ and $\alpha_S^n \alpha^2$

- $\mathcal{O}(\alpha_S)$ corrections to LO QCD
- $\mathcal{O}(\alpha)$ corrections to LO QCD $\equiv \mathcal{O}(\alpha_S)$ corrections to LO EW–QCD interf.

Technical aspects

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

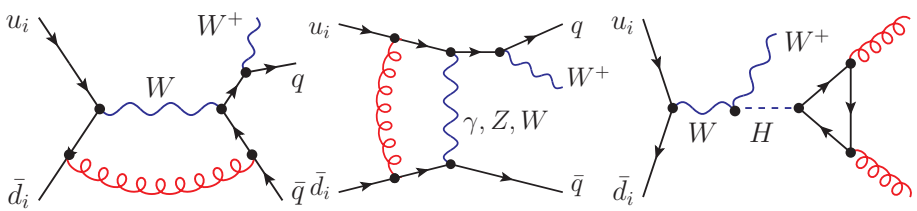
Channel	QCD trees	EW trees	QCD 1-loop	EW 1-loop
$u_i\bar{d}_i \to W^+ g$	2	-	11	32
$u_i\bar{d}_i \to W^+ q\bar{q}$	2 (4)	7 (14)	33 (66)	105 (210)
$u_i\bar{d}_i \to W^+ gg$	8	-	150	266
$u_i\bar{d}_i \to W^+ q\bar{q}g$	12 (24)	33 (66)	352 (704)	1042 (2084)
$u_i\bar{d}_i \to W^+ ggg$	54	-	2043	2616

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

On-shell external W and "pseudo resonances"

- external W stable ($\Gamma_W = 0$) but small $\Gamma_{\rm reg} \to 0$ for s-channel t, W, Z, H propagators in QCD×EW interf

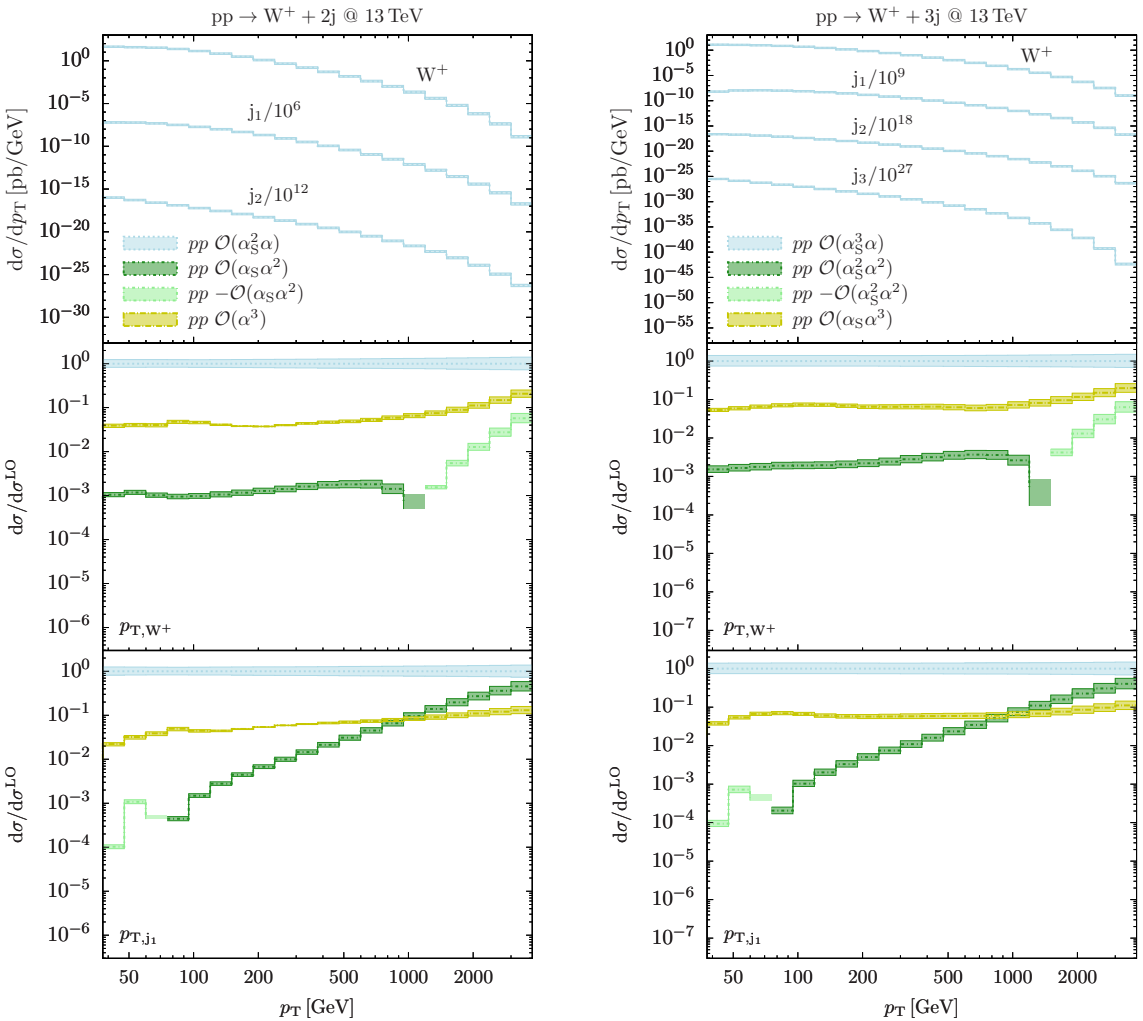
(IR EW singularities tricky...)



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

- can be extended to $W \to \ell\nu$ decays in NWA but not to full NLO SM

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



"QCD cuts" throughout

- $p_T > 30\,\text{GeV}$, $\eta < 4.5$

$\Rightarrow$ QCD dominates

EW contributions

(WV, VBF, single-t)

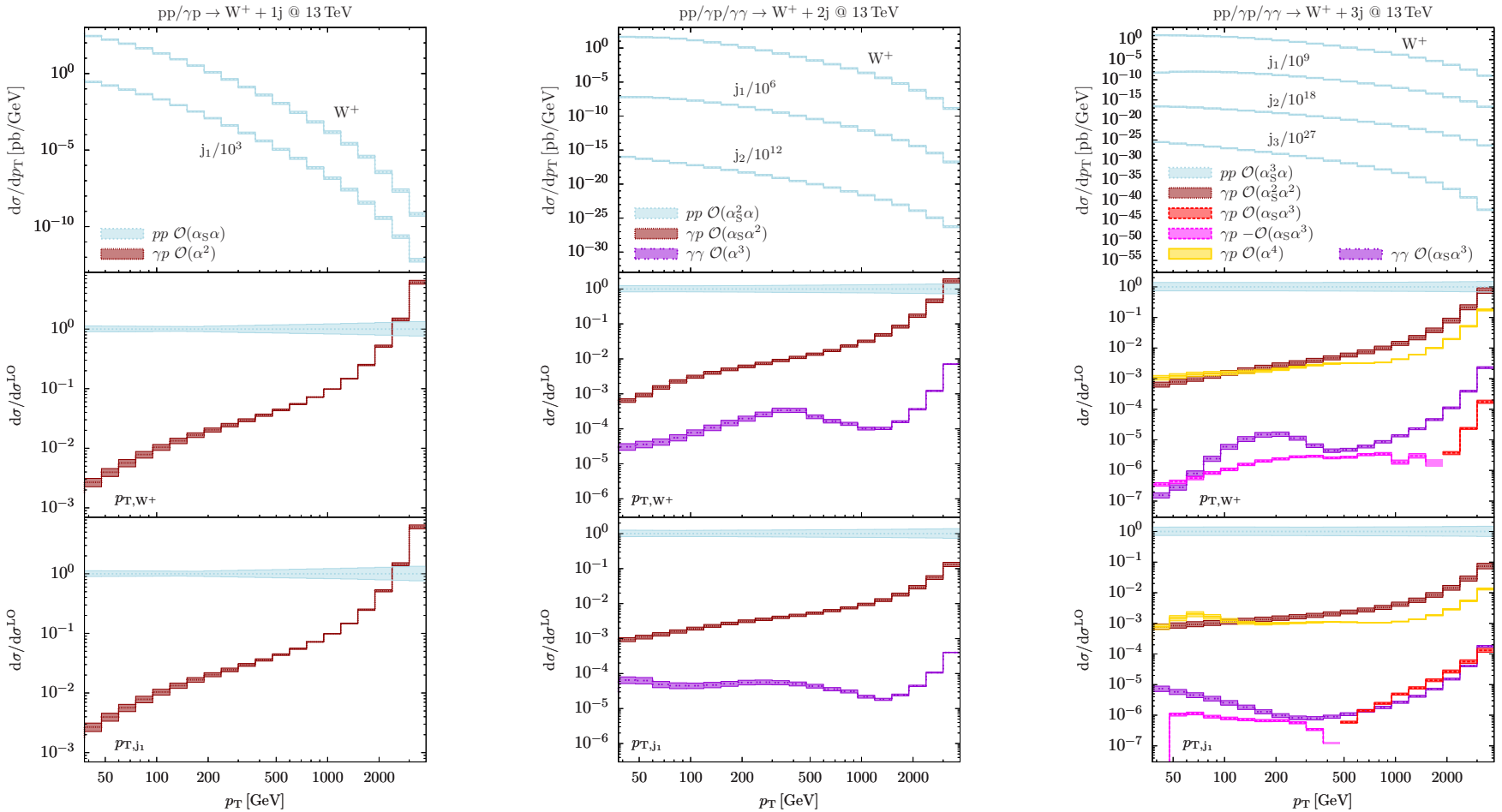
- 3–6% in σ_{int}
- 10–20% at 1–4 TeV

EW–QCD interference

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

$\Rightarrow$ **nontrivial QCD–EW interplay at the TeV scale** (with V+jets "QCD cuts")

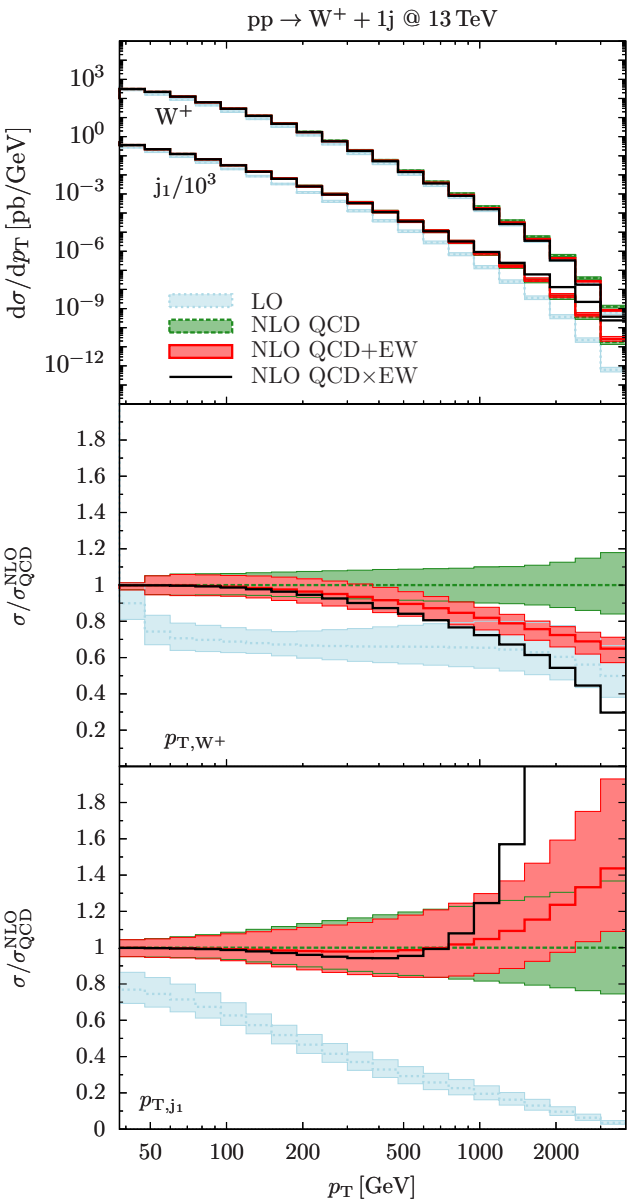
LO γ-induced contributions in $pp \to W^+ + 1, 2, 3$ jets



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. . .)

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

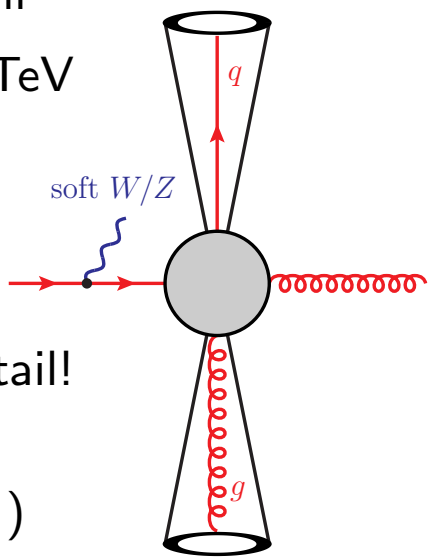


Inclusive $\sigma(pp \to W + 1, 2, 3\,\text{jets})$ $(p_{T,j} > 30\,\text{GeV})$

- $\lesssim 1\%$ EW correction

W-boson p_T (Sudakov behaviour)

- $+100\%$ QCD correction in the tail
- -20–35% EW correction at 1–4 TeV
- large extra EW×QCD correction!

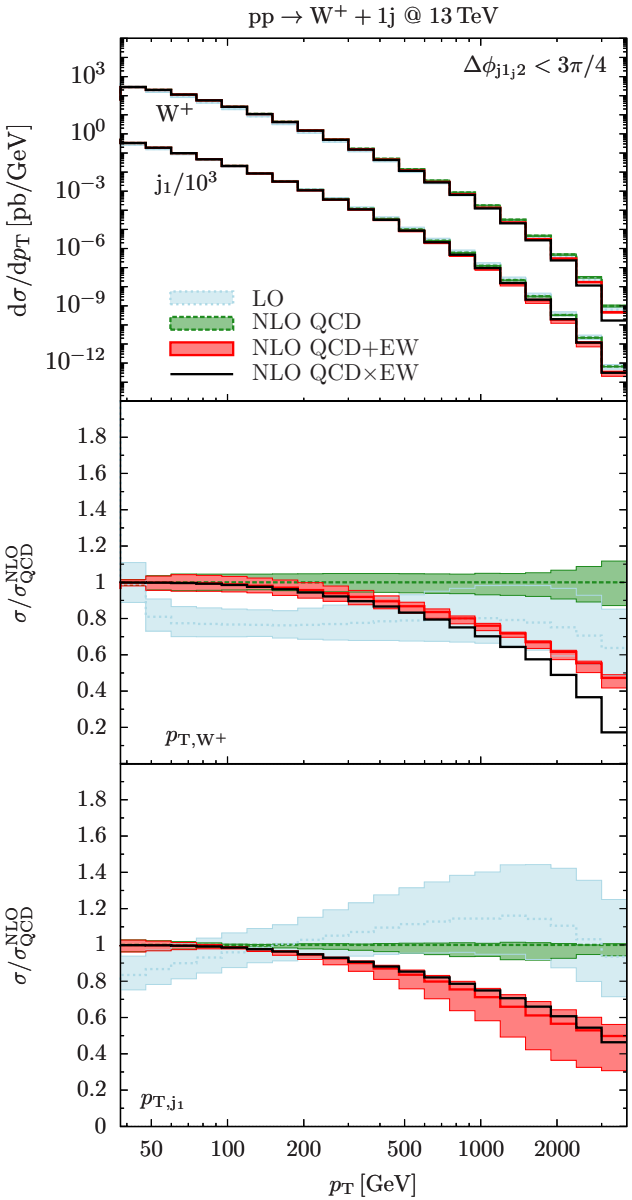


Jet p_T (di-jet dominance)

- factor-10 QCD correction in the tail!
- *positive* 10–50% EW correction (QCD-EW quark bremsstrahlung!)

⇒ **pathologic (large uncertainties)!**

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



QCD corrections

- still sizable in $p_{T,W}$ tail but moderate at high $p_{T,\text{jet}}$

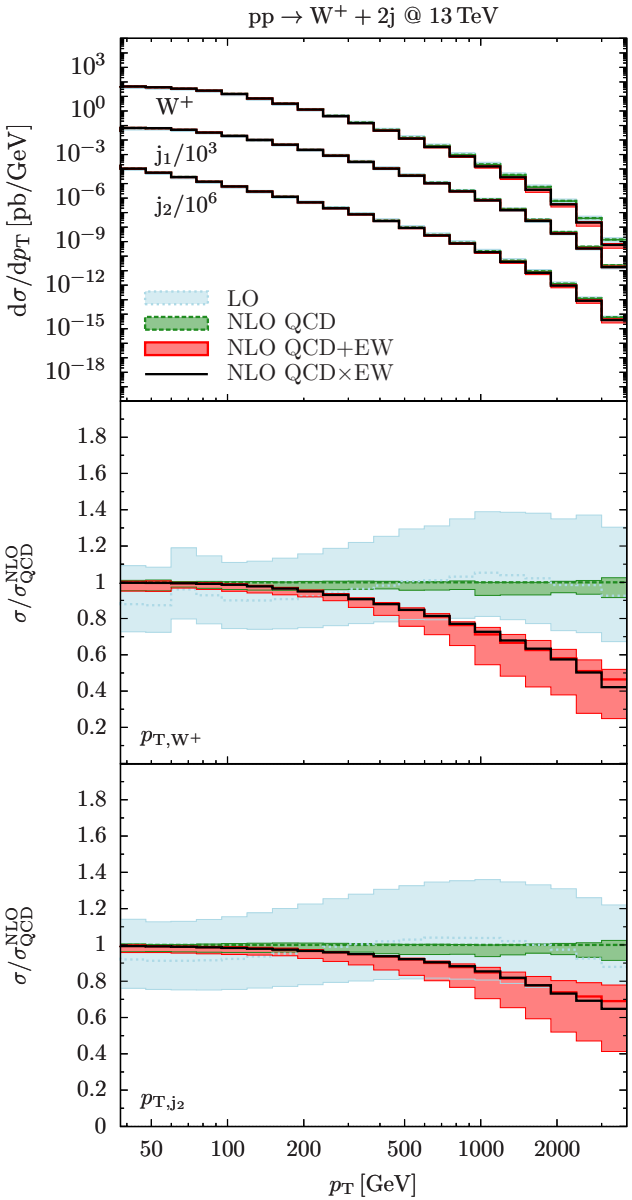
EW corrections

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

Bottom line

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

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



QCD corrections

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

EW corrections

- Sudakov effects in W- and jet-p_T tails

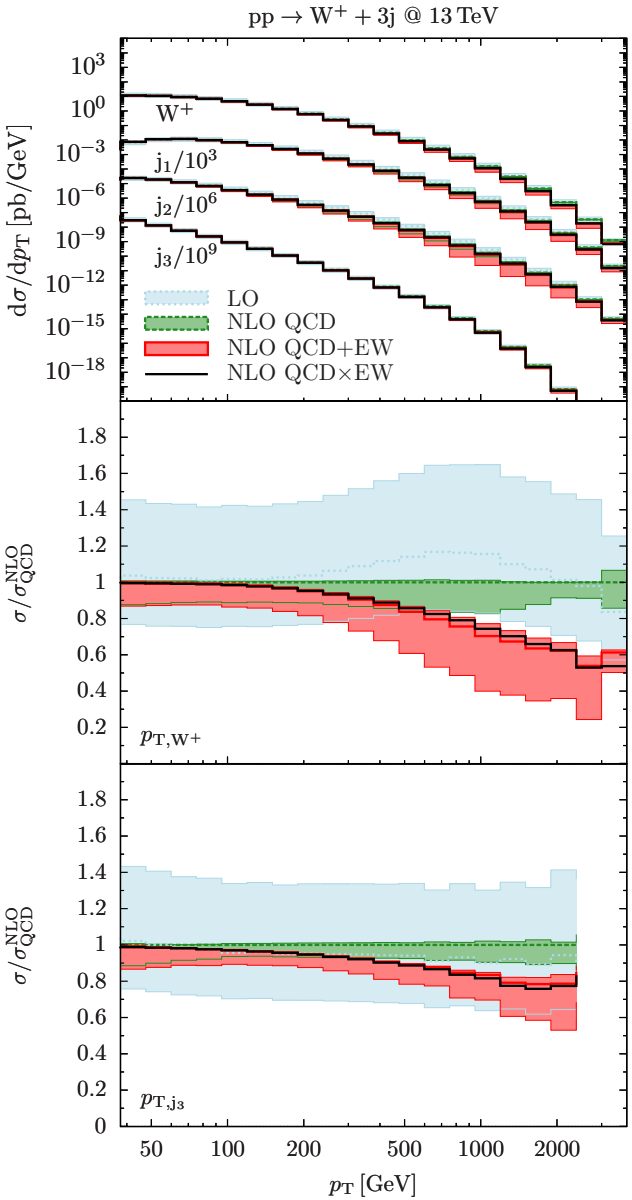
$\Rightarrow$ -30–60% at $p_{T,W}$ =1–4 TeV

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

Bottom line

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

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



QCD corrections

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

EW corrections

- Sudakov effects in W- and jet-p_T tails

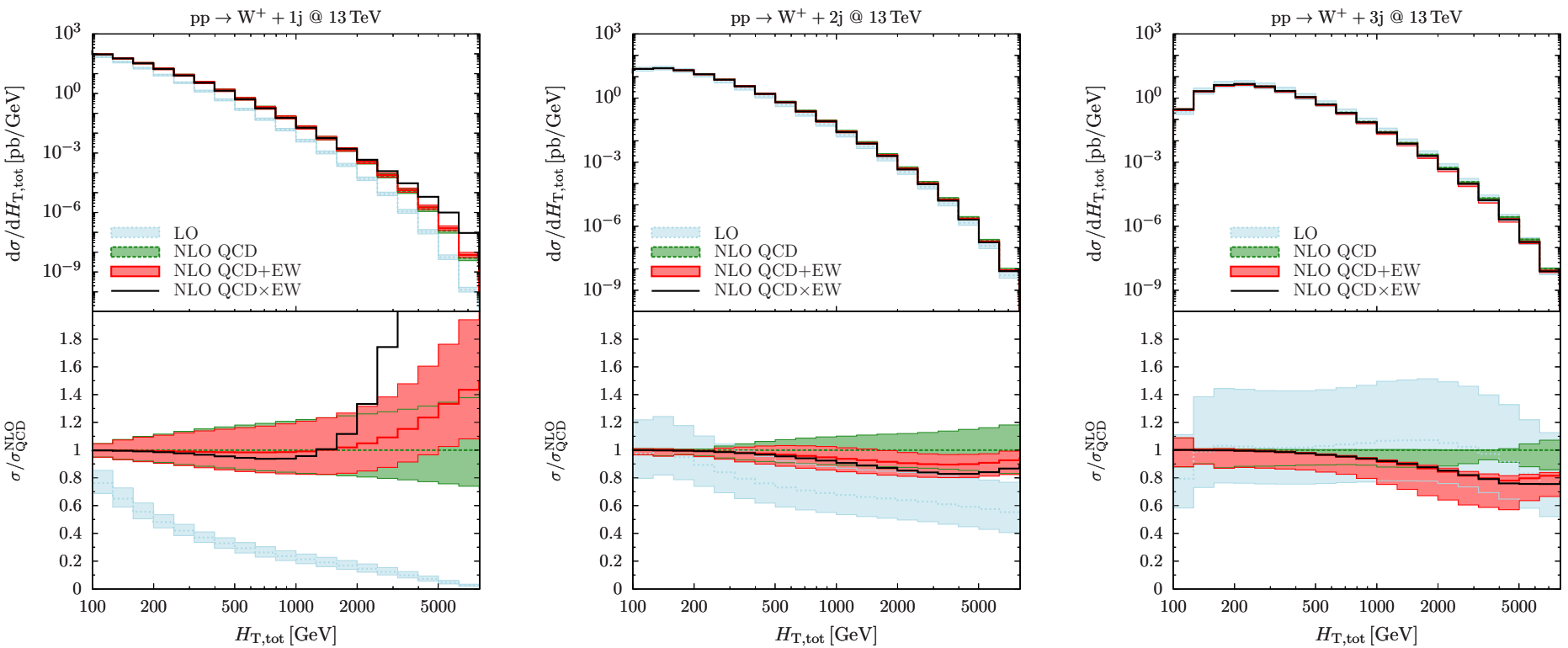
$\Rightarrow$ -30–50% at $p_{T,W}$ =1–4 TeV

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

Bottom line

- similar picture as for $W + 2\,\text{jets}$

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



- first exciting results
- 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!)

Summary and Outlook

NLO QCD+EW for V+multijets

- EW corrections crucial at the TeV scale
- large QCD radiation calls for EW+QCD corrections for multi-jet final states

NLO QCD+EW automation

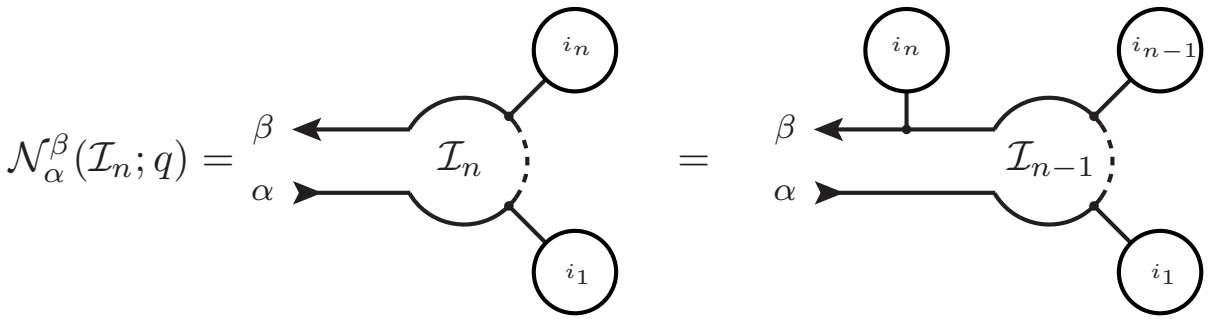
- applicable to any $2 \to 2, 3, 4$ SM process
- various nontrivial physics features (EW-QCD interplay, decays, "overlapping" processes, jet/photon definition, ...)

Next steps

- full NLO SM predictions
- how to disentangle W+multijets from VBF and WW/WZ, tj, Wt, tt production×decays?
- NLO QCD+EW matching and multi-jet merging
- ...

Backup slides

NLO amplitudes with OpenLoops



OpenLoops approach [Cascioli, Maierhöfer, Pozzorini '12]

- numerical recursion for "loop-momentum dependent trees"

$$\sum_{r=0}^{n} \mathcal{N}^{\beta}_{\mu_1\dots\mu_r;\alpha}(\mathcal{I}_n)\; q^{\mu_1}\dots q^{\mu_r} \;=\; \left(Y^{\beta}_{\gamma\delta} + q^{\nu}\; Z^{\beta}_{\nu;\gamma\delta}\right) \sum_{r=0}^{n-1} \mathcal{N}^{\beta}_{\mu_1\dots\mu_r;\alpha}(\mathcal{I}_{n-1})\; q^{\mu_1}\dots q^{\mu_r}$$

- automated & fast generation of NLO QCD MEs for any $2 \to 4\,(5)$ SM process
  - (1-loop)×tree and (1-loop)^2 amplitudes
  - trees including helicity and colour correlations

- High speed at runtime with tensor reduction (COLLIER [Denner, Dittmaier, Hofer]) and/or OPP reduction (CUTTOOLS [Ossola, Papadopolous, Pittau '07])

OpenLoops Public Release

OpenLoops 1.0 [Cascioli, Lindert, Maierhöfer, Pozzorini]

- publicly available since Sept '14 at
  `openloops.hepforge.org`

- library with more than 100 hadron-collider processes at NLO QCD available

- svn download

```
$ svn co http://openloops.hepforge.org/
svn/OpenLoops/branches/public ./OpenLoops
```

- installation of OpenLoops with selected processes

```
$ cd ./OpenLoops
$ ./scons
$ ./openloops libinstall pptt j,ppzjjj,...
```

NLO simulations with OpenLoops & MC tools

Complete NLO automation through interfaces with various Monte Carlo Tools

- SHERPA [Hoeche, Hoeth, Krauss, Schoenherr, Schumann, Siegert, Zapp]

  $\Rightarrow$ S–MC@NLO matching to SHERPA shower and MEPS@NLO multi-jet merging

- MUNICH [multi-purpose parton-level Monte Carlo by S. Kallweit]

  $\Rightarrow$ very fast integration at NLO (Catani–Seymour) and NNLO (q_{T} subtraction)

- BLHA and/or native interfaces for MATCHBOX (HERWIG), POWHEG and other MC tools

OpenLoops applications at (N)NLO QCD

Results for $2 \to 4$ processes with massive b-quarks and off-shell top quarks

- S–MC@NLO for $pp \to t\bar{t}b\bar{b}$ with $m_b > 0$ [Cascioli, Maierhöfer, Moretti, Pozzorini, Siegert, arXiv:1309.5912]
- NLO for $pp \to W^+W^-b\bar{b}$ with $m_b > 0$ [Cascioli, Kallweit, Maierhöfer, Pozzorini, arXiv:1312.0546]

NLO merging with OpenLoops+Sherpa and Herwig

- MEPS@NLO for $\ell\ell\nu\nu$+0,1 jets, [Cascioli, Höche, Krauss, Maierhöfer, Pozzorini, 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, Pozzorini, Schönherr, Thompson arXiv:1403.7516]
- MEPS@NLO for $t\bar{t}$+0,1,2 jets, [Höche, Krauss, Maierh "ofer, Pozzorini, Schönherr, Siegert arXiv:1402.6293]

NNLO calculations for di-bosons and $t\bar{t}$ with OpenLoops+Munich

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