Multijet merging for vector boson plus jets including electroweak corrections

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Outline

1. **Electroweak Corrections**
   - Sudakov Effects
   - Power Counting
   - Real Corrections
   - Automation
2. **V+jets merging**
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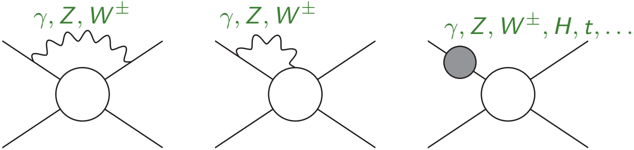
   - Leading Order Contributions
   - Pathological behaviour of V+1 jet
   - Merging via Exclusive Sums
   - The EW_virt Approximation
   - MEPS@NLO including EW corrections
3. **Conclusions**

Large Electroweak Corrections

Sudakov logarithms: vitual electroweak boson exchange between onshell legs leads to large corrections in the TeV range.



Universality and factorisation [Denner, Pozzorini '01]

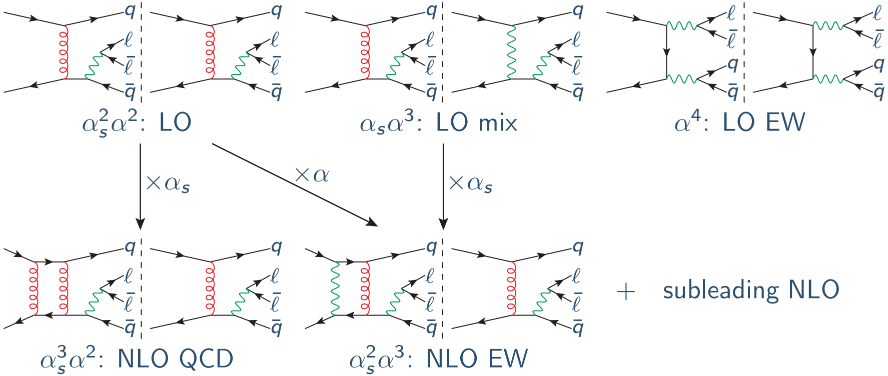
$$\delta\mathcal{M}^{\text{1-loop}}_{LL+NLL} = \frac{\alpha}{4\pi}\sum_{k=1}^{n}\left(\frac{1}{2}\sum_{k\neq\ell}\sum_{a=\gamma,Z,W^\pm} I^a(k) I^{\bar{a}}(\ell)\ln^2\frac{s_{k\ell}}{M^2} + \gamma^{\text{ew}}\ln\frac{s}{M^2}\right)\mathcal{M}_0$$

EW corrections can get larger than QCD corrections (and may not lie within QCD scale uncertainties).

$$Q \lesssim M_W:\ \alpha \sim \alpha_s^2 \qquad Q \gg M_W:\ \alpha\ln^2\frac{Q^2}{M_W^2} > \alpha_s$$

Typically $\mathcal{O}(10\%)$ effects at 1 TeV.

V+jets Perturbative Contributions



NLO EW can also be regarded as QCD corrections to LO mix
→ should include LO mix.

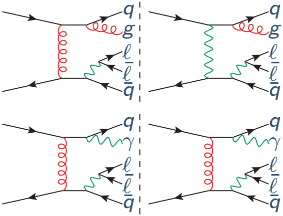
LO EW: dominated by di-boson resonances
→ overlap with *VV* production, not included here
(no problem in LO mix: no Breit-Wigner *VV* resonances)

Real Corrections

Emission of both QCD partons and photons needed to cancel IR singularities.

Considering complete $\alpha_s^n \alpha^m$ orders guarantees IR finiteness.

$\Rightarrow$ General bookkeeping of all $\mathcal{O}(\alpha_s^n \alpha^m)$ contributions needed.



Real photon emission

- Soft/collinear photons unresolved.
- Needed to cancel QED singularities.

Real Z, W emission [Ciafaloni, Comelli]

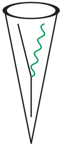
- No singularities, only partial cancellation with Sudakov logs (strongly depending on process and cuts).
- Treat as separate process.

IR-safe Treatment of Photons

"Democratic" jet algorithm: don't distinguish between jets and γs

- Cluster all massless particles (q, g, γ) on the same footing.
- Soft gluon singularities in "photon jet" cancel between EW jet production and QCD photon production.

Separation of photons from jets



- Cancel collinear $q \to q\gamma$ by recombining charged fermions and photons in a cone $\Delta R < 0.1$. [see Kallweit et al. 1412.5157]
- Distinguish photons through $E_\gamma/E_{\text{jet}} \lessgtr z_{\text{thr}}$ inside jets.
- Rigorous approach: absorb singularity into fragmentation function [see Denner at al. 1411.0916]. Difference $< 1\%$ for typical z_{thr}.

Initial state photons

- QED factorisation for IS photons and LO QED evolution in PDFs. [MRST2004QED, NNPDF2.3QED]

Automation

NLO electroweak corrections are essential for percent-level precision.
Automation is needed, but more involved than NLO QCD.

OpenLoops [Cascioli, Lindert, PM, Pozzorini]

- 1-loop and tree matrix elements, spin and colour correlations
- complex mass scheme [Denner, Dittmaier]
- Available on `http://openloops.hepforge.org`

Sherpa [Gleisberg et al.]

- Full featured Monte Carlo generator: IR subtraction, phase space integration, parton shower, multi-jet merging, hadronisation, ...
- Support for NLO EW will be included in the next major release.

MUNICH (to be published) [Kallweit]

- Very efficient multi-channel integrator.

Independent implementations carfully validated against each other.

Other MC interfaces: `Herwig++` [Bellm et al.], `POWHEG-Box` (soon) [Alioli et al.], `Whizard` (soon) [Kilian et al.].

Performance QCD vs. EW

EW corrections are moderatly slower than QCD corrections.
Most CPU expensive processes (many gluons) are similarly fast.

process	# diagrams QCD	# diagrams EW	time [ms/point] QCD	time [ms/point] EW
$d\bar{d} \to t\bar{t}$	11	33	0.27	0.69
$gg \to t\bar{t}$	44	70	1.6	2.8
$d\bar{d} \to t\bar{t}g$	114	360	4.8	13
$gg \to t\bar{t}g$	585	660	40	56
$d\bar{d} \to t\bar{t}u\bar{u}$	236	1274	12	48
$gg \to t\bar{t}gg$	8739	7614	1458	1557

CPU: i7-3770K, compiler: gfortran 4.8 using `Collier`
unpolarised $t\bar{t}$ (much faster with decays)

Ready for automated NLO EW corrections to $2 \to 4$ processes

automated NLO EW MEs: `GoSam`, `MadGraph`, `OpenLoops`, `Recola`, ...

+++ Breaking News +++

The tensor integral reduction library `Collier is public` since today.
[Denner, Dittmaier, Hofer]

A new OpenLoops version with Collier integrated is available.

- Usually faster than OPP reduction, [Ossola, Papadopoulos, Pittau] especially for low multiplicities.
- Particularly important for loop-induced processes or loop^2 for NNLO (which are very slow with OPP reduction).
- High numerical stability in double precision through expansions in small kinematic quantities [Denner, Dittmaier].
  $\rightarrow$ Little or no quadruple precision needed.

Alternative reduction library: `CutTools` [Ossola, Papadopoulos, Pittau] with scalar integrals from `OneLOop` [van Hameren].

- Reliable and reasonably fast for NLO processes with OpenLoops.
- Support for quadruple precision.

Combination of NLO QCD and EW

Two ways to combine QCD and EW corrections

$$\sigma^{\text{NLO}}_{\text{QCD+EW}} = \sigma^{\text{LO}} + \delta\sigma^{\text{NLO}}_{\text{QCD}} + \delta\sigma^{\text{NLO}}_{\text{EW}}$$

$$\sigma^{\text{NLO}}_{\text{QCD}\times\text{EW}} = \sigma^{\text{LO}}\left(1 + \frac{\delta\sigma^{\text{NLO}}_{\text{QCD}}}{\sigma^{\text{LO}}}\right)\left(1 + \frac{\delta\sigma^{\text{NLO}}_{\text{EW}}}{\sigma^{\text{LO}}}\right)$$

The difference indicates uncertainties due to missing mixed QCD-EW correction of order $\alpha_s\alpha$.

Relative corrections wrt. $\sigma^{\text{NLO}}_{\text{QCD}}$:

$$\frac{\sigma^{\text{NLO}}_{\text{QCD+EW}}}{\sigma^{\text{NLO}}_{\text{QCD}}} = \left(1 + \frac{\delta\sigma^{\text{NLO}}_{\text{EW}}}{\sigma^{\text{NLO}}_{\text{QCD}}}\right), \qquad \frac{\sigma^{\text{NLO}}_{\text{QCD}\times\text{EW}}}{\sigma^{\text{NLO}}_{\text{QCD}}} = \left(1 + \frac{\delta\sigma^{\text{NLO}}_{\text{EW}}}{\sigma^{\text{LO}}}\right)$$

Beyond fixed order

- Match to parton shower.
- Combine different jet multiplicities via MEPS@NLO.
  [Höche, Krauss, Schönherr, Siegert]

V+jets

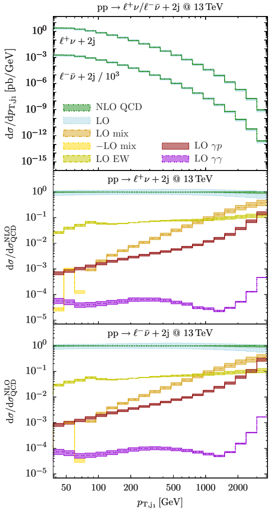
- Large cross sections and clean signatures.
- Important background in BSM searches, mono-jet dark matter searches, top physics, Higgs physics ($VH(\to b\bar{b})$).

NLO QCD for $W(Z)$+jets known up to 5(4) jets: `BlackHat` [Bern et al. '13]
NNLO QCD V+j [Boughezal et al. '15; Gehrmann-de Ridder et al. '15]
Drell-Yan mixed $\mathcal{O}(\alpha_s\alpha)$ corr. in resonance region [Dittmaier et al. '14]
NLO (electro)weak W/Z+j [Maina et al. '04; Kühn et al. '04ff]
EW Sudakov logs beyond NLO [Becher et al. '03; Kühn et al. '04ff]
Off-shell NLO EW W/Z+j [Denner et al. '09ff]
NLO EW $\ell^+\ell^-$jj: `Recola+Collier` [Denner at al. '14]
NLO EW $W + 1, 2, 3$ jets `OpenLoops+MUNICH/Sherpa` [Kallweit et al. '14]

This talk: NLO QCD+EW $\ell\ell/\ell\nu/\nu\nu + 0, 1, 2$ jets showered and merged

Note that Sudakov effects are unaffected by decays, but need decays for leptonic observables.
Here: off-shell decays. Much more involved than leptonic decays in QCD.

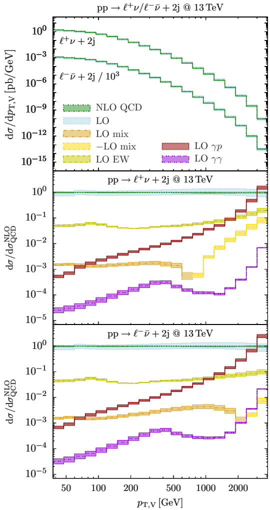
Leading Order Vjj contributions



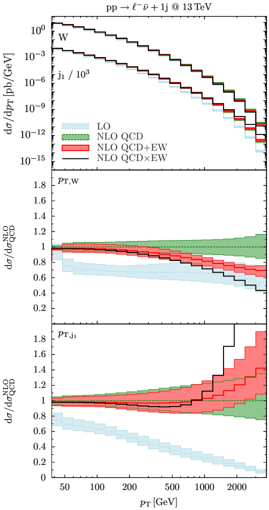
LO mix becomes large in the TeV range.

LO EW throughout of $\mathcal{O}(10\%)$, but dominated by VV resonances.

Photon induced channels:
permille effect in the total cross section, but reach $\mathcal{O}(1)$ at a few TeV.
PDF uncertainties (not shown) are huge.



$\ell\nu + 1\,$jet inclusive



Setup: $\sqrt{s} = 13\,\text{TeV}$, $E_T^{\text{miss}} > 25\,\text{GeV}$,
$p_{T,j} > 30\,\text{GeV}$, $|\eta_j| < 4.5$, $\mu_0 = \hat{H}_T/2$
$p_{T,\ell} > 20\,\text{GeV}$, $|\eta_\ell| < 2.5$

Inclusive cross section: $\sim$1% EW corrections.

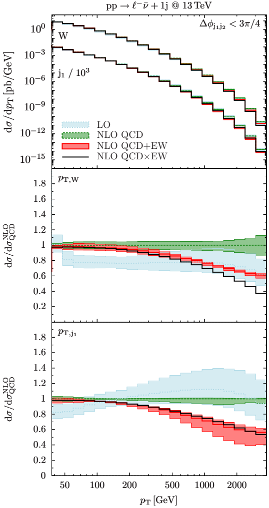
W boson-p_T

- 100% QCD correction in the tail.
- Sudakov effects exceed -20% at 1 TeV.

Jet-p_T

- Huge QCD corrections. [Rubin, Salam, Sapeta]
- No visible EW Sudakov behaviour.
- Dominated by di-jet configurations (from real corrections, i.e. effectively LO)

$\ell\nu + 1$ jet Exclusive



Remove back-to-back di-jet configurations with the cut $\Delta\phi_{j_1 j_2} < \frac{3\pi}{4}$.

→ **Significant improvement**

- Moderate QCD corrections.
- Sudakov behaviour restored.

Lessons learned

- Inclusive W+jet requires W+2j at NLO.
- EW corrections in distributions are large and exceed QCD scale uncertainties at a few 100 GeV.

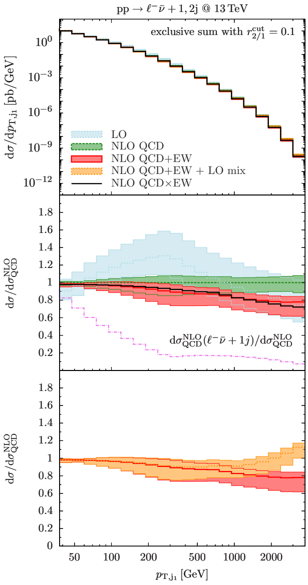
V+1j ∪ V+2j via Exclusive Sums

Partition phase space according to $r_{1/2} = \frac{p_{\mathrm{T,j_2}}}{p_{\mathrm{T,j_1}}}$

- $r_{1/2} < r_{1/2}^{\mathrm{cut}} \rightarrow V$+1j
- $r_{1/2} > r_{1/2}^{\mathrm{cut}} \rightarrow V$+2j

Results

- Huge QCD corrections from V+1j stabilised.
- Shows EW Sudakov behaviour.
- Small difference between QCD+EW and QCD×EW.
- Large effects due to EW quark bremsstrahlung, added as LO mix.



NLO QCD+EW Merging

Problem: Exact EW multi-jet merging is not yet available.

Goal: include EW effects in MEPS@NLO QCD merging.

Merging: match to parton shower, limit shower emissions to $Q < Q_{\text{cut}}$ (merging cut) and use matrix elements with an additional jet above.

Scale choice: $\alpha_s^N(\mu^2_{\text{CKKW}}) = \alpha_s^{N-M}(\mu^2_{\text{core}})\,\alpha_s(t_1)\ldots\alpha_s(t_M)$

$2 \to 2$ core process: clustering via inverse parton shower.

$$\mu_{\text{core},\ell\ell} = m_{\ell\ell}, \quad \mu_{\text{core},V\text{j}} = \frac{1}{2}E_{\text{T},V}, \quad \mu_{\text{core,jj}} = \frac{1}{2}\left(\frac{1}{s} - \frac{1}{t} - \frac{1}{t}\right)^{-\frac{1}{2}}$$

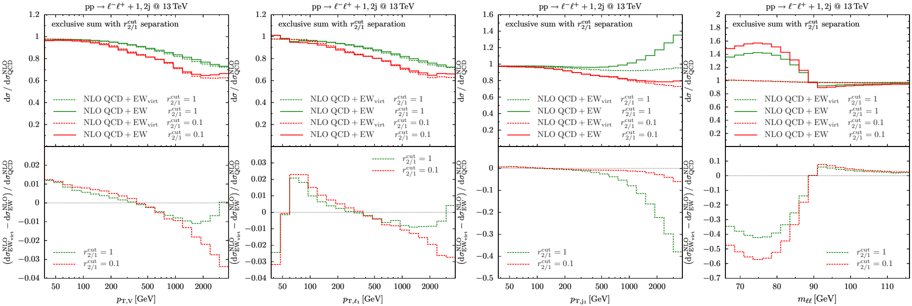
Dominant EW corrections (Sudakov logs) arise from virtual corrections.
Effects due to photon radiation typically $< 1\%$.

Define the $\mathbf{EW_{virt}}$ approximation:

Include $V_{n,\text{EW}}(\Phi_n) + I_{n,\text{EW}}(\Phi_n)$ in the n-jet matrix elements,
i.e. soft/collinear photon emission is taken into account inclusively.

$\mathrm{EW}_{\mathrm{virt}}$ Accuracy

The exclusive sums approach allows us to study the accuracy of the $\mathrm{EW}_{\mathrm{virt}}$ approximation.

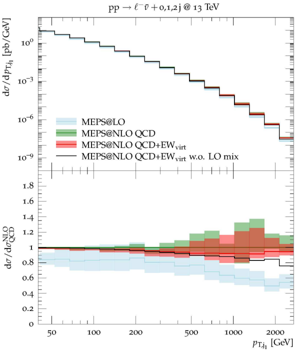


- Percent-level agreement between full NLO EW and IR regularised virtual EW corrections (red).
- *Exception:* $m_{\ell\ell}$ requires exclusive photon radiation off leptons.

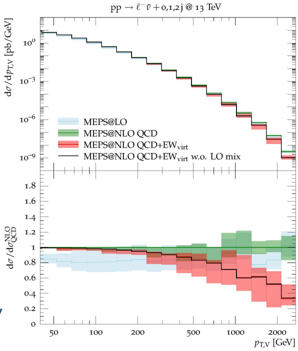
MEPS@NLO QCD+EW Inclusive V+jets

Stable QCD+EW predictions without need for a $\Delta\Phi_{j_1 j_2}$ cut.

Suited for direct use by experimental collaborations.



$Q_{cut} = 20$ GeV



Small EW effects in the TeV range ($pp \to jj$ core process likely).
LO mix compensates Sudakov effects.

Large EW effects in the TeV range ($pp \to Vj$ core process likely).

Conclusions

Sudakov effects: electroweak corrections are large

- Several 10% effects in the TeV range for some observables.
- Can exceed QCD scale uncertainties at a few 100 GeV.

First multijet merged results including electroweak corrections

- Fully off-shell NLO QCD+EW for $\ell\ell/\ell\nu/\nu\nu$ + up to 2 jets.
- $\mathrm{EW}_{\mathrm{virt}}$ approximation captures dominant EW effects in the TeV range (exception: $m_{\ell\ell}$ distributions).
- Merging is essential for (otherwise pathological) inclusive Vj.

Outlook / work in progress

- Add QED shower.
- Include matrix elements with photon radiation via LO merging.
- Make use of automated NLO EW frameworks on a large scale!