Precise predictions for gauge-boson pair production processes at the LHC

Barbara Jäger
University of Tübingen
what’s the plan for today?

* gauge boson pair production at hadron colliders – an overview:
  * why is this class of processes important?
  * what has been done?
  * what has not yet been done?

* electroweak corrections to $pp \rightarrow W^+W^-$ and $ZZ$:
  * approximative calculations
  * details of the full calculation
  * phenomenological results

in collaboration with M. Billoni, B. Biedermann, A. Denner, S. Dittmaier, L. Hofer, L. Salfelder
what’s the plan for today?

* gauge boson pair production at hadron colliders – an overview:
  - why is this class of processes important?
  - what has been done?
  - what has not yet been done?

* electroweak corrections to $pp \rightarrow W^+W^-$:
  - the on-shell approximation
  - going beyond: the double-pole approximation
  - details of the calculation
  - phenomenological results
gauge-boson pair production

probe non-Abelian structure of the SM at high energies:

- (anomalous) triple-gauge-boson couplings
- dynamics of longitudinal massive gauge bosons
gauge-boson pair production

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\[ pp \rightarrow VV \rightarrow 4f \]

constitutes important class of background processes to:

- the Higgs search in the mode \[ pp \rightarrow H \rightarrow VV \rightarrow 4f \]
- new physics searches with leptons+\( E_T \) signatures (e.g. SUSY-particle pair production)
gauge-boson pair production

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✦ new physics searches with leptons + \( E_T \) signatures (e.g. SUSY-particle pair production)
gauge-boson pair production @ NLO QCD

\[ h_1 h_2 \rightarrow ZZ: \]
\[ \text{Ohnemus, Owens (1991) / Mele, Nason, Ridolfi (1991)} \]

\[ h_1 h_2 \rightarrow W^\pm Z: \]
\[ \text{Ohnemus (1991) / Frixione, Nason, Ridolfi (1992)} \]

\[ h_1 h_2 \rightarrow W^+W^-: \]
\[ \text{Ohnemus (1991) / Frixione (1993)} \]

including leptonic decays:

analytical expressions:
\[ \text{Dixon, Kunszt, Signer (1998) / Baur, Han, Ohnemus (1996)} \]

implementation in public code MCFM:
\[ \text{Campbell, Ellis (1999)} \]
gauge-boson pair production @ NLO QCD

\[ pp \rightarrow W^+ (\rightarrow e^+ \nu_e) W^- (\rightarrow \mu^- \bar{\nu}_\mu) \]

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numbers taken from \texttt{MCFM}: Campbell, Ellis, Williams (2011)
gauge-boson pair production @ NLO QCD

\[ pp \rightarrow W^+ (\rightarrow e^+ \nu_e) W^- (\rightarrow \mu^- \bar{\nu}_\mu) \]

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- size of NLO-QCD corrections is large and cut-dependent
- not expected from variation of central scale

\[ M_W / 2 \leq \mu_f \leq 2 M_W \] at LO (\( \leftarrow \) qg channels)
gauge-boson pair production & parton showers

NLO-QCD calculations matched with multi-purpose parton-shower programs \texttt{PYTHIA}, \texttt{HERWIG}, \texttt{SHERPA}

\textbf{MC@NLO}: Frixione, Webber (2002)

\textbf{POWHEG}: Nason, Ridolfi (2006)

\textbf{POWHEG in HERWIG++}: Hamilton (2010)

\textbf{POWHEG in SHERPA}: Höche, Krauss, Schönherr, Siegert (2010)

\textbf{POWHEG-BOX}: Melia, Nason, Röntsch, Zanderighi (2011)

\textbf{aMC@NLO}: Frederix et al. (2011)
high-$p_T$ tails: NLO+PS deviate from LO+PS results ($\leftarrow qg$)
mostly: agreement between different NLO+PS simulations
deviations between MC@NLO and POWHEG in distributions sensitive to extra jet emission
gauge-boson pair production – loop contributions

considered first by

*Dicus, Kao, Repko (1987); Glover, van der Bij (1989)*

phenomenological study for the LHC:

*Dührssen, Jakobs, van der Bij, Marquard (2005)*

inclusion of off-shell effects and heavy-quark loops:

*Binoth, Ciccolini, Kauer, Krämer (2005,2006); Binoth, Kauer, Mertsch (2008)*

gluon-induced contributions first occur at one-loop level

impact depends on cuts; can be large
towards NNLO QCD for $pp \rightarrow VV$

✔ 2-loop master integrals for $\bar{q}q \rightarrow VV$

Gehrmann, Tancredi, Weihs (2013)

Gehrmann, von Manteuffel, Tancredi, Weihs (2014)
\( pp \rightarrow WW \) at NNLO QCD!

\textit{Gehrmann et al. (08/2014)}

\( \sigma \)\([pb]\) vs. \( \sqrt{s} \)\([TeV]\)

- ATLAS
- CMS

\( gg \rightarrow H \rightarrow WW^* \)

\textit{Note: improved agreement with LHC data}
$pp \rightarrow ZZ$ @ NNLO QCD!

Cascioli et al. (05/2014)
$pp \rightarrow WW$ @ NNLO QCD: going differential

Grazzini et al. (05/2016)

fully differential Monte Carlo:
allows for arbitrary cuts
and distributions/correlations of
leptonic decay products

✔ realistic predictions possible
EW corrections: generic features

naive expectation:

\[ \alpha \sim \alpha_s^2 \rightarrow \text{NLO EW} \sim \text{NNLO QCD} \ ? \]

but: systematic enhancements possible, e.g.:

- **kinematic effects**
- **photon emission** → mass-singular logs, e.g. \( \frac{\alpha}{\pi} \ln \left( \frac{Q}{m_\mu} \right) \)
- **high energies** → EW Sudakov logs, e.g. \( \frac{\alpha}{\pi} \ln^2 \left( \frac{Q}{M_W} \right) \)
EW corrections: Sudakov logarithms

typical $2 \rightarrow 2$ process: at high energy
EW corrections enhanced by large logs

\[ \ln^2 \left( \frac{Q^2}{M_{\text{W}}^2} \right) \sim 25 \text{ @ energy scale of 1 TeV} \]

universal origin of leading EW logs:

mass singularities in virtual corrections related to external lines

soft and collinear virtual gauge bosons: $\rightarrow$ double logs

soft or collinear virtual gauge bosons: $\rightarrow$ single logs
EW corrections: Sudakov logarithms

compare to QED / QCD:
IR singularities of virtuals canceled by real-emission contributions

electroweak bosons massive
→ real radiation experimentally distinguishable

non-Abelian charges of $W, Z$ are open
→ Bloch-Nordsieck theorem not applicable

M. Ciafaloni, P. Ciafaloni, Comelli; Beenakker, Werthenbach;
Denner, Pozzorini; Kühn et al., Baur; . . .
consistent calculation at NLO EW requires PDFs including $\mathcal{O}(\alpha)$ corrections and new photon PDF

**MRST2004QED**: first PDF set with $\mathcal{O}(\alpha)$ corrections

**NNPDF2.3QED (2013)**: NNPDF set with $\mathcal{O}(\alpha)$ corrections

- 2013: best PDF prediction at (N)NLO QCD + NLO QED
- PDF samples for error estimate provided
- photon PDF fitted to DIS and Drell-Yan data $(10^{-5} \lesssim x \lesssim 10^{-1})$
  (note lack of experimental information for large $x$)
- being updated; currently: NNPDF3.0QED
new physics effects in $VV$ production

general contribution to Lagrangian for $WWV$ interaction, compatible with C and P conservation:

$$\mathcal{L}_{WWV} = g_{WWV} \left[ ig_1^V (W^*_\mu V^\nu W^{\mu V^\nu} - W^\mu_{\nu V} W^{*\mu V^\nu} ) 
+ i\kappa^V W^*_\mu W^\nu_{\nu V} V^{\mu\nu} + i\frac{\lambda^V}{M_W^2} W^{*\rho\mu} W^\nu_{\nu V} V^{\nu\rho} \right]$$

supplied by form factors to tame unitarity violations at high energies:

$$\Delta g \rightarrow \Delta g \frac{(1 + M_W^2 V V / \Lambda^2)}{(1 + M_W^2 V V / \Lambda^2)^2}$$

LEP bounds:

$$\Delta g_1^Z = (-0.054, 0.028), \Delta \kappa^\gamma = (-0.117, 0.067),$$
$$\Delta \lambda^Z = \Delta \lambda^\gamma = (-0.07, 0.012)$$

(SM: $g_1^V = \kappa^V = 1$ and $\lambda^V = 0$)
higher order or new physics effects?

parameterize new physics by anomalous triple gauge boson couplings $\lambda, \Delta\kappa_\gamma, \Delta g_1^Z$

missing EW corrections can fake anomalous triple-gauge boson couplings
gauge-boson pair production beyond LO EW

\[ pp \rightarrow VV \rightarrow 4 \text{ leptons: } \mathcal{O}(\alpha) \text{ corrections} \]

more challenging than QCD corrections:

\[ \rightarrow \text{ first step: employ } \text{approximations:} \]

- retain only universal logarithms that are large at high energies
- double pole approximation for gauge bosons

on-shell gauge-boson pair production @ NLO EW

\[ \mathcal{O}(\alpha) \] corrections to

\[ pp \rightarrow VV \]

Bierweiler, Kasprzik, Kühn, Uccirati (2012-2013)

Baglio, Ninh, Weber (2013)

→ EW corrections negative and small
for inclusive x-secs,

but can be large and negative in tails of distributions
(universal Sudakov logarithms)
photon-induced contributions to $pp \rightarrow VV$

non-vanishing PDFs for photons in proton

→ need to consider sub-processes

of type $\gamma\gamma \rightarrowVV$ at LO

effects are small for inclusive x-secs, but up to several tens of percent for some distributions relative to dominant $qq$ processes at LO ,

→ can be of the same size as EW corrections to $\bar{q}q \rightarrow VV$, but opposite in sign
on-shell gauge-boson pair production @ NLO EW

Bierweiler, Kasprzik, Kühn, Uccirati (2012)

\[
\frac{d\sigma}{dp_{T,W^-}} \text{(pb/GeV)}
\]

\[
\delta (\%)
\]

LHC at 14 TeV
$pp \to VV$ and parton shower in HERWIG++

Gieseke Kasprzik, Kühn (2014)

- combination of fixed-order calculation for $pp \to VV$ with parton shower
- leptonic decays are handled by HERWIG++
- QCD and EW effects combined

\[ d\sigma_{QCD \times EW} = K_{weak}(\hat{s}, \hat{t}) \times d\sigma_{QCD} \]
beyond the on-shell approximation at tree-level

Resonant contributions of type
\[ \bar{q}q \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu} \]

Non-resonant contributions in all channels
NLO-EW beyond the on-shell approximation

leading order: **full off-shell calculation**

- light quark contributions \((q = u, d, c, s)\)
- \(b\bar{b}\)-induced contributions \((< 2\%)\)
- photon-induced contributions \((< 1\%)\)

real-emission and virtual contributions:

for light quark channels use **full off-shell calculation** or **double pole approximation**

(Analogous to *Racoon* approach for \(e^+e^- \rightarrow 4\) fermions

[Denner, Dittmaier, Roth, Wackeroth (1999-2002)] )
the double pole approximation (DPA)

full EW corrections to $pp \rightarrow 4$ fermions challenging

→ compute tree-level contributions exactly, resort to double pole approximation for virtuals

(analogous to Racoon approach for $e^+e^- \rightarrow 4$ fermions

[Denner, Dittmaier, Roth, Wackeroth (1999-2002)])
the double pole approximation (DPA)

- doubly-resonant diagrams fully considered
- \( \hat{=} \) expansion around poles
- expect error \( \sim \frac{\Gamma_W}{M_W} \) w.r.t full EW calculation
- structure of corrections simpler \( \rightarrow \) faster code

on-shell production

on-shell decay
the full off-shell calculation: $pp \rightarrow 4\ell$

- all resonant and non-resonant diagrams contributing to $\bar{q}q \rightarrow 4\ell$ fully considered

- complex-mass scheme for weak boson resonances:

  $$m_V^2 \rightarrow m_V^2 + im_V\Gamma_V$$

  → applicable and gauge-invariant everywhere in phase space

- tensor loop integrals (up to hexagons) evaluated with COLLIER

- per channel: $\sim 10^3$ diagrams → CPU intensive
real emission contributions

...full matrix elements for two classes of processes

\[ \bar{q}q \rightarrow \ell^+ \nu \ell^- \bar{\nu} \gamma \]

\[ \gamma q \rightarrow \ell^+ \nu \ell^- \bar{\nu} q \]

...encounter IR divergences that need to be handled with care

→ Catani-Seymour type subtraction procedure

adapted for EW corrections \[ Dittmaier (1999) \]
some more details on the calculation

∗ phase-space integration:

multi-channel integrator based on Monte-Carlo for $\gamma\gamma \rightarrow 4$ fermions

[ Bredenstein, Dittmaier, Roth (2005)]

∗ matrix elements computed via

in-house Mathematica routines, converted into Fortran code

∗ all leading-order and real emission amplitudes compared with MadGraph

∗ independent calculation based on RECOLA ("recursive computation of one-loop amplitudes")
EW input parameter scheme

* EW parameters obtained from $G_\mu, M_W, M_Z$ via

$$\cos \theta_W = M_W / M_Z, \quad \alpha_{G_\mu} = \frac{\sqrt{2} G_\mu M_W^2 \sin^2 \theta_W}{\pi} \quad (G_\mu \text{ scheme})$$

☞ accounts for higher order corrections associated with running coupling and universal top-mass corrections to $\rho$ parameter

* contributions involving photon radiation effects: use instead $\alpha(0)$ as effective coupling

[c. f. Denner (1993)]
$pp \rightarrow WW \rightarrow e^+ \nu_e \mu^- \bar{\nu}_\mu$: phenomenological setup

**NNPDF2.3qed**
- factorization scale $\mu_F = M_W$
- photon recombination

**minimal cuts:**
- $p_{T,\ell} > 20$ GeV, $|y_\ell| < 2.5$
- jet veto: $p_{T,j} > 100$ GeV

**ATLAS cuts:**
- $p_{T,\ell} > 20$ GeV, $|y_\ell| < 2.5$
- $p_{T,\ell}^{\text{leading}} > 25$ GeV, $E_T^{\text{miss}} > 25$ GeV,
- $R_{e\mu} > 0.1$, $M_{e\mu} > 10$ GeV
- jet veto: not jets with $p_{T,j} > 25$ GeV
$pp \rightarrow W^+W^-$: cross section contributions

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full calculation very well reproduced by DPA:

LHC13 (DPA) : $\delta_{\bar{q}q}^{\text{NLO}} = -2.91\%$

ATLAS13 (DPA) : $\delta_{\bar{q}q}^{\text{NLO}} = -3.18\%$
transverse-momentum distribution (DPA)

Billoni et al. (2013)

no jet veto:

* $\delta_{\bar{q}q} = -30\%$ for $p_{T,e} = 900$ GeV (Sudakov logs)

* $\delta_{\gamma\gamma} = \text{up to } +10\%$

* $\delta_{\gamma q}$ large due to soft W emission (same effect in QCD corrections leads to huge K factors)

$\rightarrow$ apply jet veto
transverse-momentum distribution (DPA)

Billoni et al. (2013)

\[
\frac{d\sigma}{dp_{T,e}} \left[ \text{fb} \text{ GeV}^{-1} \right]
\]

\[\text{pp} \rightarrow \nu_{\mu} \mu^{+} e^{-} \bar{\nu}_{e} + X\]
\[\sqrt{s_{\text{pp}}} = 14 \text{ TeV}\]

default cuts
\[p_{T,j} < 100 \text{ GeV}\]

no jet veto:

* \(\delta_{\bar{q}q}\) up to \(-30\%\)

* \(\delta_{\gamma\gamma}\) up to \(+10\%\)

* \(\delta_{\gamma q}\) up to \(+30\%\)

→ apply jet veto:

* \(\delta_{\gamma q} < 5\%\) even at high \(p_{T}\)

* \(\delta_{\text{EW}} = -20\%\) for \(p_{T,e} = 900\) GeV
angular distributions (DPA) . . .

... in general only marginally affected by EW corrections
large negative corrections in $\bar{q}q$ channel,

positive contributions from $\gamma\gamma$ channel

→ sum of corrections moderate even at high values of $M_{e\mu}$ ($< 10\%$)
error estimate of the approximation

- error estimate of the NLO EW calculation
  (impact of missing 2-loop EW corrections):
  \[ \Delta \sim (\delta_{\text{EW}})^2 \]

- error estimate of the DPA:
  \[ \Delta_{\text{DPA}} \sim \max \left\{ \left(\delta_{\text{EW}}^{\text{DPA}}\right)^2, \frac{\alpha}{\pi} \frac{\Gamma_W}{m_W} \ln(\ldots), |\delta_{\text{EW}}^{\text{DPA}}| \times \frac{\sigma_{\text{LO}} - \sigma_{\text{DPA}}^{\text{LO}}}{\sigma_{\text{DPA}}^{\text{LO}}} \right\} \]

1. missing 2-loop EW corrections
2. missing off-shell contributions in regions where the DPA applies
3. change of NLO EW corrections due to failure of DPA
DPA versus full calculation

Biedermann et al. (2016)

\[ \frac{d\sigma}{dM_{e^{-}\mu^{+}}} \text{ [fb]} \]

pp \rightarrow \nu_{\mu}\mu^{+}e^{-}\bar{\nu}_{e} + X
\sqrt{s_{pp}} = 13 \text{ TeV}
ATLAS WW setup
\mu \text{ treated coll. unsafe}

rapidity and invariant-mass distributions:
good agreement between DPA and full calculation
DPA versus full calculation

*Biedermann et al. (2016)*

\[ \frac{d\sigma}{dp_{T,e^{-}\mu^{+}}} \text{ [fb/GeV]} \]

\[ pp \rightarrow \nu_{\mu}, \mu^{+}, e^{-}, \bar{\nu}_{e} + X \]

\[ \sqrt{s_{pp}} = 13 \text{ TeV} \]

ATLAS WW setup

\[ \mu \text{ treated coll. unsafe} \]

✧ doubly-resonant diagrams strongly suppressed

✧ singly-resonant diagrams dominate:

\[ (e\mu) \text{ pair recoils against } (\nu_{\mu}, \bar{\nu}_{e}) \text{ pair} \]

☆ poor agreement between DPA and full calculation for transverse-momentum of lepton pair

Barbara Jäger, University of Tübingen

Eltville, Sept. 2016
$pp \rightarrow ZZ \rightarrow \mu^+\mu^-e^+e^-$: phenomenological setup

NNPDF2.3qed
factorization scale $\mu_F = M_Z$

Higgs-search specific cuts:

\[ p_{T,\ell} > 6 \text{ GeV}, \quad |y_\ell| < 2.5, \]
\[ \Delta R_{\ell\ell} > 0.2, \]
\[ 40 \text{ GeV} < M_{\ell_1^+\ell_1^-} < 120 \text{ GeV}, \]
\[ 12 \text{ GeV} < M_{\ell_2^+\ell_2^-} < 120 \text{ GeV}, \]
\[ M_{4\ell} > 100 \text{ GeV} \]
$pp \rightarrow \mu^+ \mu^- e^+ e^- : \text{weak and photonic corrections}$

process without charged currents at LO

→ can perform gauge-invariant decomposition into weak and photonic corrections
\[ pp \rightarrow ZZ \rightarrow \mu^+\mu^-e^+e^- : \text{cross sections} \]

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(recall: Higgs-search specific setup)

total xsec dominated by \( ZZ \) on-shell production

- ✷ weak corrections moderate
- ✷ photonic corrections negligible
pp \rightarrow ZZ \rightarrow \mu^+\mu^-e^+e^- as a Higgs background

[Biedermann et al. (2016)]

- radiative tails below
  thresholds and peaks
  (caused by cuts and
  mass spectrum)

- weak corrections change sign
  at ZZ threshold

  \rightarrow approximation based on
  global rescaling factor
  does not work
scale dependence

\[
\frac{d\sigma}{dM_{T,WW}} \left[ \text{fb} \right. \text{GeV}]
\]

\[pp \to \nu_\mu \mu^+ e^- \bar{\nu}_e + X\]
\[\sqrt{s_{pp}} = 14 \text{ TeV}\]
default cuts
\[p_{T,j} < 100 \text{ GeV}\]

choice of factorization scale:

fixed scale: \( \mu_F = \xi M_W \)

dynamical scale: \( \mu_F = \xi M_{WW} \)

\( \text{vary } \xi \text{ in range (0.5 , 2)} \)

\( \rightarrow \text{ overall change of x-sec : } \sim 8\% \)

\( \text{(mostly PDF effect)} \)
combination of QCD and EW corrections

EW corrections insensitive to scale choice

combination with QCD corrections
via factorization ansatz:

\[ d\sigma^{\text{best}} = d\sigma_{qq}^{\text{QCD}} \times \left(1 + \delta_{qq}^{\text{EW}}\right) + d\sigma_{gg} + d\sigma_{\gamma\gamma} + d\sigma_{q\gamma} \]
first computation of EW corrections to $pp \rightarrow 4$ leptons that gives **full access to leptonic final state**:

- EW corrections to integrated x-sec small
- sizable effects in **tails of distributions** (Sudakov logarithms)
- $\gamma\gamma$ induced contributions non-negligible
- $\gamma q$ induced contributions can be suppressed by **jet veto**
- scale dependence small
weak boson pair production processes provide powerful probes of the structure of the Standard Model

e.g. triple gauge boson couplings

serve as important backgrounds

... to searches for the Higgs boson
... to searches for new physics

impact of radiative corrections can be large and dependent on experimental selection criteria
→ to achieve precision required by experiment:
  · consider QCD and EW corrections
  · disregard (on-shell, high-energy, ...) approximations
Thank You.
backup slides . . .

. . . for details and supplementary material
the double-pole approximation (DPA)

- on-shell production
- on-shell decay
- off-shell propagators
the double-pole approximation (DPA)

\[ \mathcal{M}_{\text{DPA}} \sim \sum_{\text{pol}} \frac{1}{k_{W^+}^2 - M_W^2 + i M_W \Gamma_W} \times \frac{1}{k_{W^-}^2 - M_W^2 + i M_W \Gamma_W} \times \mathcal{M}^{q\bar{q} \rightarrow W^+ W^-} \times \mathcal{M}^{W^+ \rightarrow \nu \ell^+} \times \mathcal{M}^{W^- \rightarrow \bar{\nu} \ell^-} \]

- on-shell production
- off-shell propagators
- on-shell decay
on-shell projection in DPA

kinematics:

\[ a(p_a) + b(p_b) \rightarrow W^+(k_+) + W^-(k_-) \]
\[ \rightarrow f_1(k_1) + \bar{f}_2(k_2) + f_3(k_3) + \bar{f}_4(k_4) \]

Gauge invariance requires on-shell kinematics in production and decay amplitudes.

→ Need to replace off-shell \( W \) momenta with on-shell projections such that

\[ k_W^2 = M_W^2 \]
virtual corrections in DPA

* factorizable corrections to production
* factorizable corrections to decay of $W^-$
* factorizable corrections to decay of $W^+$
* non-factorizable corrections (soft photon exchange)
virtual corrections in DPA

- factorizable corrections to production
- factorizable corrections to decay of $W^-$
- factorizable corrections to decay of $W^+$
- non-factorizable corrections (soft photon exchange)
factorizable virtual corrections in DPA

\[
\mathcal{M}_{\text{DPA}}^{\text{virt, fact}} \sim \sum_{\text{pol}} \frac{1}{(k_{W+}^2 - M_{W}^2 + i M_{W} \Gamma_{W})} \cdot \frac{1}{(k_{W-}^2 - M_{W}^2 + i M_{W} \Gamma_{W})} \times \left\{ \right.
\begin{align*}
&\delta \mathcal{M}^{\bar{q}q \rightarrow W^+ W^-} \times \mathcal{M}^{W^+ \rightarrow \nu \ell^+} \times \mathcal{M}^{W^- \rightarrow \bar{\nu} \ell^-} \\
+ &\mathcal{M}^{\bar{q}q \rightarrow W^+ W^-} \times \delta \mathcal{M}^{W^+ \rightarrow \nu \ell^+} \times \mathcal{M}^{W^- \rightarrow \bar{\nu} \ell^-} \\
+ &\mathcal{M}^{\bar{q}q \rightarrow W^+ W^-} \times \mathcal{M}^{W^+ \rightarrow \nu \ell^+} \times \delta \mathcal{M}^{W^- \rightarrow \bar{\nu} \ell^-} \left. \right\}
\]
virtual corrections in DPA

- factorizable corrections to production
- factorizable corrections to decay of $W^-$
- factorizable corrections to decay of $W^+$
- non-factorizable corrections (soft photon exchange)
non-factorizable virtual corrections in DPA

\[ \mathcal{M}^{\text{virt, non-fact}}_{\text{DPA}} \sim \mathcal{M}_{\text{LO, DPA}}^{\bar{q}q \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}} \times \delta_{\text{nfact}}^{\text{virt}} \]

\* non-factorizable corrections (soft photon exchange)
improved Born approximation

for $M_{WW} < 2m_W + \Delta_m$:

replace DPA with improved Born approximation
(captures dominant parts of virtual corrections)

[Denner, Dittmaier, Roth, Wackeroth (2001)]

$$d\sigma_{\.overline{q}q}^{IBA} \sim dPS \left| M_{\overline{q}q \rightarrow \ell^+\nu\ell^-\overline{\nu}}^{IBA} \right|^2 \cdot \left[ 1 + \delta_{\text{Coul}} \right] \cdot g_{\text{damp}}$$

Born type amplitudes with adjusted couplings
Coulomb singularity (damped away from threshold)