Electroweak: RECOLA, Automation, VBS

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Outline

1. RECOLA: a one-loop matrix element generator
2. Automation: SHERPA+RECOLA
3. NLO EW corrections to VBS

Recola: REcursive Computation of One-Loop Amplitudes
[Actis, Denner, Hofer, Lang, Scharf, Uccirati; 1211.6316, 1605.01090]

- EW and QCD amplitudes in SM at NLO
- Based on recursive method for the tensor coefficient
- Based on Collier library for tensor integrals
  [Denner, Dittmaier, Hofer; 1604.06792]
  → Used also by MadLoop and OpenLoops
- Publicly available at: `https://recola.hepforge.org`
- Recola2 [Denner, Lang, Uccirati; 1705.06053] for BSM

RECOLA can compute any one-loop amplitude in the SM (in principle)

- NLO amplitudes for all helicities and colour structures
- NLO squared amplitudes
  (optionally) summed/averaged over spin and colour
- Colour- and/or spin-correlated LO squared amplitudes
  → usable for dipole subtraction

→ As simple as:

```
call define_process_rcl(1,'u u -> mu+ nu_mu e+ nu_e d d','NLO')
```

- Dynamic process generation
- No code generated
- No intermediate intervention

Features:

- Complex-mass scheme for unstable particles
- Possible isolation of resonant contributions
  → (Double-)pole approximation
- Dimensional regularisation for UV and IR singularities
  → possible to treat collinear/soft singularities in mass regularisation
- Renormalisation schemes for α:
  $\mathrm{G_F}$, $\alpha\,(0)$, and $\alpha\,(M_\mathrm{Z})$
- Arbitrary Nf-flavour renormalisation scheme for α_s
- C++ interface

Used for several NLO QCD/EW with up to $2 \to 7$

- Off-shell ZZ, NLO EW

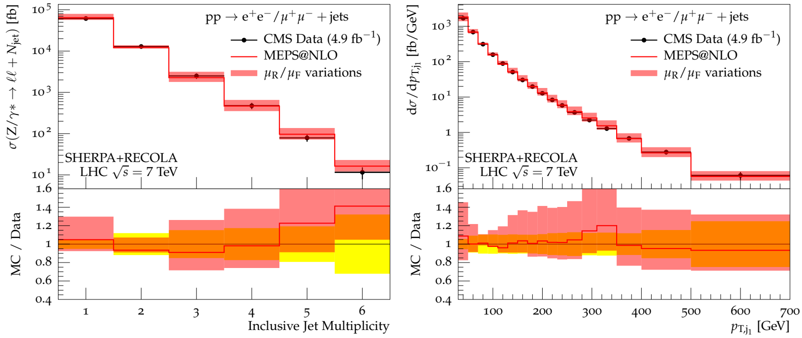
  [Biedermann, Denner, Stefan Dittmaier, Hofer, Jäger; 1611.05338, 1601.07787]
- Off-shell WW, NLO EW

  [Biedermann, Billoni, Denner, Stefan Dittmaier, Hofer, Jäger, Salfelder; 1605.03419]
- Off-shell tt, NLO EW [Denner, MP; 1607.05571]
- Off-shell tth, NLO QCD [Denner, Feger; 1506.07448]
- Off-shell tth, NLO EW [Denner, Lang, MP, Uccirati; 1612.07138]
- Off-shell VBS, NLO EW [Biedermann, Denner, MP; 1611.02951]
- Off-shell V+jets, NLO EW [Denner et al.; 1411.0916]
- Sherpa+Recola [Biedermann, Bräuer, Denner, MP, Schumann, Thompson; 1704.05783]
  NLO QCD and EW:
  - on-shell tth (vs. Les Houches report [1605.04692])
  - off-shell ZZ (vs. [Biedermann et al.; 1611.05338, 1601.07787])
  - off-shell V+jets ([Kallweit et al.; 1412.5157, 1511.08692])

Towards full automation of NLO QCD/EW...

- SHERPA [Bothmann, Hoeche, Krauss, Kuttimalai, Schönherr, Schulz, Schumann, Siegert, Zapp]:
  → multi-purpose Monte Carlo, hard ME → hadronisation
  → `https://sherpa.hepforge.org`
- SHERPA+RECOLA [Biedermann, Bräuer, Denner, MP, Schumann, Thompson; 1704.05783]:
  → any process at NLO QCD and EW accuracy
  → any loop induced process
  → arbitrary flavour scheme
  → same framework as SHERPA+OPENLOOPS
- NLO QCD part of SHERPA already public, NLO EW part soon

Matching/Merging



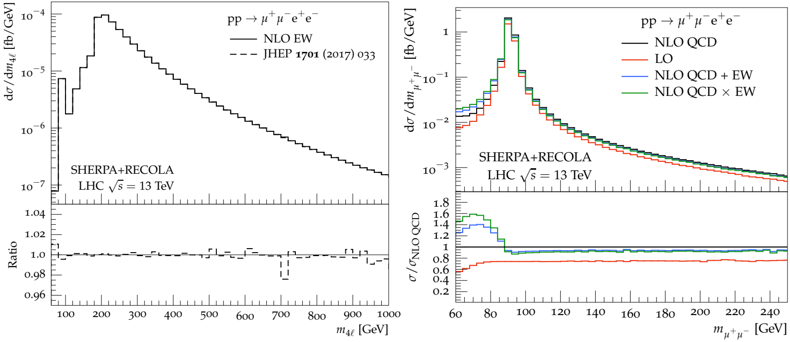
[Biedermann, Bräuer, Denner, MP, Schumann, Thompson; 1704.05783]

→ All capabilities of SHERPA are conserved with using RECOLA

$\mathrm{pp} \rightarrow \mathrm{e}^+\mathrm{e}^-\mu^+\mu^-$

- Final state dominated by ZZ pair production: $\mathrm{pp} \rightarrow \mathrm{Z}^\star\mathrm{Z}^\star \rightarrow \mathrm{e}^+\mathrm{e}^-\mu^+\mu^-$
- Background for Higgs searches, triple gauge coupling, ...
- State-of-the art at NLO EW: [Biedermann et al.; 1601.07787, 1611.05338], [Kallweit et al.; 1705.00598]
- Complicated purely EW process
- Validation vs. [Biedermann et al.; 1611.05338]

$pp \to e^+e^-\mu^+\mu^-$

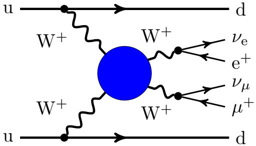


[Biedermann, Bräuer, Denner, MP, Schumann, Thompson; 1704.05783]

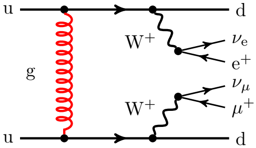
→ Non-trivial kinematic edges

→ Non-trivial processes publicly available at NLO QCD and EW

Vector-Boson Scattering (VBS)



- Crucial role of Higgs boson
- Key process to investigate electroweak symmetry breaking
- Evidence by ATLAS and CMS for Run-I [1405.6241, 1611.02428, 1410.6315]
  Measurement by CMS for run-II [CMS-PAS-SMP-17-004]
- Background process: QCD-induced process



→ Need for precise and appropriate theoretical predictions for ...
.. both VBS and the QCD-induced process:

- NLO QCD to VBS

  [Jäger, Oleari, Zeppenfeld; 0907.0580], [Denner, Hŏseková, Kallweit; 1209.2389]

- NLO QCD to QCD-induced process

  [Melia et al.; 1007.5313, 1104.2327]

- Matching to parton shower

  [Jäger and Zanderighi; 1108.0864]

  → Available in VBFNLO [1311.6738, 1404.3940] or POWHEG-Box

NLO EW calculations still missing

→ Calculation of NLO EW corrections to off-shell VBS:

$$\mathrm{pp} \to \mu^+ \nu_\mu \mathrm{e}^+ \nu_\mathrm{e} \mathrm{jj}$$

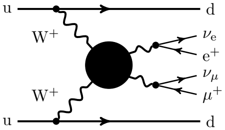
- Off-shell and non-resonant contributions
  → Realistic final state
- EW corrections can be large in certain phase space regions
  → Sudakov logarithms
- Theoretical and numerical challenge to consider $2 \to 6$ process
  → Up to 6 external charged particles and 4 intermediate resonances
  → Virtual corrections involving up to 8-point functions

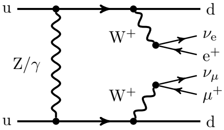
$$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$$

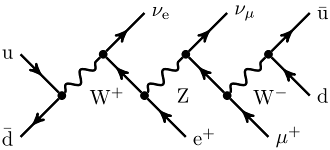
→ All partonic channels taken into account

- $\mathrm{uu} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{dd}$
- $\mathrm{u\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{s\bar{c}}$
- $\mathrm{uc} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{sd}$
- $\mathrm{\bar{d}\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{u}\bar{u}}$
- $\mathrm{u\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{u}}$
- $\mathrm{u\bar{s}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{d\bar{c}}$
- $\mathrm{\bar{s}\bar{d}} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{\bar{u}\bar{c}}$

→ The LO is defined at order $\mathcal{O}\left(\alpha^6\right)$



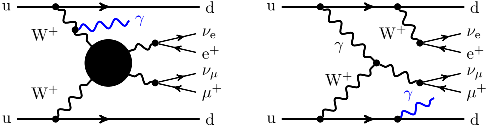




→ NLO EW corrections are of order $\mathcal{O}\left(\alpha^7\right)$

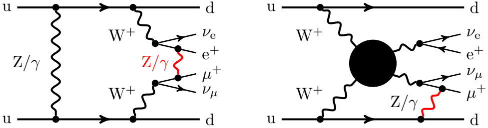
→ Include all possible real photonic corrections

$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}\gamma$

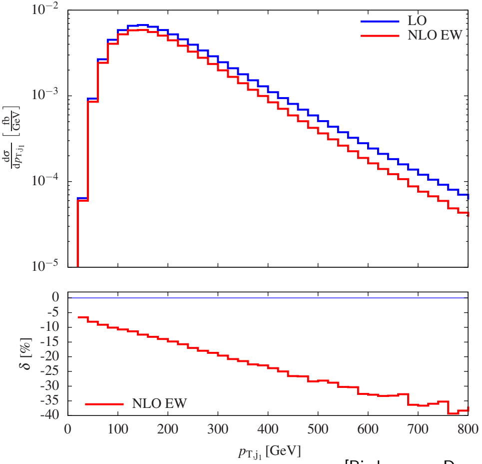


→ Include all virtual corrections

(with up to 8-point functions)



σ^{LO} [fb]	$\sigma^{\mathrm{NLO}}_{\mathrm{EW}}$ [fb]	δ_{EW} [%]
1.5348(2)	1.2895(6)	-16.0

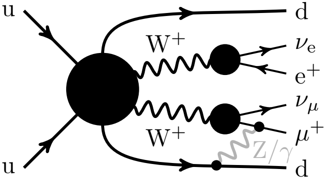


[Biedermann, Denner, MP; 1611.02951]

→ Huge NLO electroweak correction (!)

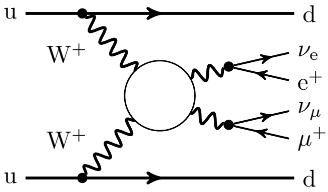
- Leading behaviour dominated by:
  Sudakov logarithms (bosonic part of the virtual)
  → Usually in the tail of the distribution (suppressed)
  → Usually small for total cross section
  → Usually smaller than the QCD corrections
- Large corrections not due to VBS cuts
  → remove $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$ and $|\Delta y_{\mathrm{jj}}| > 2.5$
  → relax $p_{\mathrm{T,j}}$ and $p_{\mathrm{T,miss}}$

- Double-pole approximation:
  leading contribution of expansion about the resonance poles
  → Required two W bosons for the virtual contributions



- Agree within 1% with full calculation
- Dominated by factorisable corrections
  → Large corrections driven by the scattering process

- Effective Vector Boson approximation:



- Simplify the discussion to $\mathrm{W^+W^+} \rightarrow \mathrm{W^+W^+}$
- Leading logarithm approximation [Denner, Pozzorini; hep-ph/0010201]

$$\sigma_{\mathrm{LL}} = \sigma_{\mathrm{LO}} \left[1 - \frac{\alpha}{4\pi} 4 C_{\mathrm{W}}^{\mathrm{ew}} \log^2 \left(\frac{Q^2}{M_{\mathrm{W}}^2} \right) + \frac{\alpha}{4\pi} 2 b_{\mathrm{W}}^{\mathrm{ew}} \log \left(\frac{Q^2}{M_{\mathrm{W}}^2} \right) \right]$$

(double EW logs, collinear single EW logs, and single logs from parameter renormalisation)

$$\sigma_{\mathrm{LL}} = \sigma_{\mathrm{LO}}\left[1 - \frac{\alpha}{4\pi} 4 C_{\mathrm{W}}^{\mathrm{ew}} \log^2\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right) + \frac{\alpha}{4\pi} 2 b_{\mathrm{W}}^{\mathrm{ew}} \log\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right)\right]$$

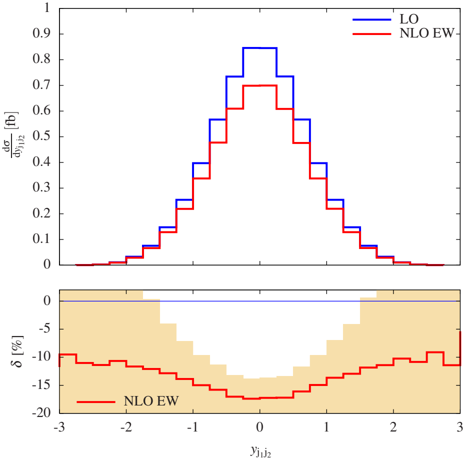
- For $Q = \langle m_{4\ell} \rangle \sim 390\,\mathrm{GeV}$

$$\delta_{\mathrm{EW}}^{\mathrm{LL}} = -16\%\ (!)$$

→ Corrections 3-4 times larger than for $q\bar{q} \to \mathrm{W}^+\mathrm{W}^+$

- C^{ew} larger for bosons than fermions
- $\langle m_{4\ell} \rangle$ larger for VBS (massive t-channel [Denner, Hahn; hep-ph/9711302])
  NB: $\langle m_{4\ell} \rangle \sim 250\,\mathrm{GeV}$ for $q\bar{q} \to \mathrm{W}^+\mathrm{W}^+$

Large NLO EW corrections:
intrinsic feature of VBS at the LHC



→ Near $y_{j_1j_2} = 0$: two jets back-to-back
Bulk of the cross section, $\sim -16\%$ corrections
→ Band: $\pm 1/\sqrt{N_{\rm obs}}$ for 3000 fb^{-1} → probe of the EW sector

Conclusion

- RECOLA: a one-loop matrix element generator

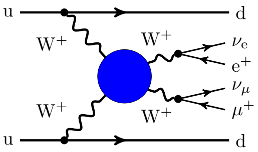
  [Actis, Denner, Hofer, Lang, Scharf, Uccirati; 1605.01090]

- SHERPA+RECOLA: Automatisation of NLO QCD/EW

  [Biedermann, Bräuer, Denner, MP, Schumann, Thompson; 1704.05783]

- NLO EW corrections to VBS: Large corrections

  [Biedermann, Denner, MP; 1611.02951]



Back-up slides

BACK-UP

- Tools
  → Virtual corrections: RECOLA [Actis, Denner, Hofer, Lang, Scharf, Uccirati]
  + COLLIER [Denner, Dittmaier, Hofer]
  → In-house Monte Carlo - MoCaNLO [Feger]
  → Dipole subtraction scheme [Catani,Seymour], [Dittmaier]
  → Complex-mass scheme [Denner et al.]
- Inputs
  → Fixed renormalisation and factorisation scale $\mu_R = \mu_F = M_{\mathrm{W}}$
  → G_μ scheme:

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu M_{\mathrm{W}}^2 \left(1 - \frac{M_{\mathrm{W}}^2}{M_{\mathrm{Z}}^2}\right) \quad \text{with} \quad G_\mu = 1.16637\times 10^{-5}\,\mathrm{GeV}$$

  → Parameters:

$$\begin{aligned} m_{\mathrm{t}} &= 173.21\,\mathrm{GeV}, & \Gamma_{\mathrm{t}} &= 0\,\mathrm{GeV} \\ M_{\mathrm{Z}}^{\mathrm{OS}} &= 91.1876\,\mathrm{GeV}, & \Gamma_{\mathrm{Z}}^{\mathrm{OS}} &= 2.4952\,\mathrm{GeV} \\ M_{\mathrm{W}}^{\mathrm{OS}} &= 80.385\,\mathrm{GeV}, & \Gamma_{\mathrm{W}}^{\mathrm{OS}} &= 2.085\,\mathrm{GeV} \\ M_{\mathrm{H}} &= 125\,\mathrm{GeV} & \Gamma_{\mathrm{H}} &= 4.07\times 10^{-3}\,\mathrm{GeV} \end{aligned}$$

Validations

- Two independent Monte Carlo integrators
- Tree-level matrix elements: MadGraph5_aMC@NLO [Alwall et al.; 1405.0301]
- One-loop matrix elements:
  - DPA
- IR-subtraction/finiteness:
  - Variation of α parameter [Nagy, Troscanyi; hep-ph/9806317]
  - Variation of technical cuts
  - Variation of IR-scale
- Born hadronic cross sections: MadGraph5_aMC@NLO

Predictions for $\sqrt{s} = 13$TeV at the LHC
$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$

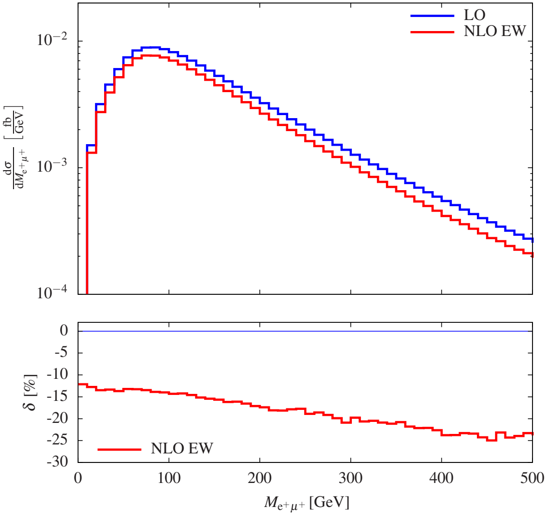
- NNPDF3.0QED [NNPDF collaboration]
- Cuts inspired by Refs. [1405.6241, 1611.02428, 1410.6315] :

$$
\begin{aligned}
\text{jets:} \quad & p_{\mathrm{T,j}} > 30\,\mathrm{GeV}, \quad & |y_\mathrm{j}| < 4.5, \\
\text{charged lepton:} \quad & p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \quad & |y_\ell| < 2.5, \\
\text{missing transverse momentum:} \quad & p_{\mathrm{T,miss}} > 40\,\mathrm{GeV}, & \\
\text{jet-jet:} \quad & m_{\mathrm{jj}} > 500\,\mathrm{GeV}, \quad & |\Delta y_{\mathrm{jj}}| > 2.5, \\
\ell\ell \text{ and } \mathrm{j}\ell \text{ distance:} \quad & \Delta R_{\ell\ell} > 0.3, \quad & \Delta R_{\mathrm{j}\ell} > 0.3.
\end{aligned}
$$

→ Final state: 2 jets, missing $p_{\mathrm{T},}$, and 2 same sign leptons

- anti-k_T jet algorithm [Cacciari, Salam, Soyez]
  $R = 0.4$ for jet recombination and $R = 0.1$ for photon recombination

Distributions extra



Extra RECOLA (1)

$$\mathcal{A}_1 = \sum_t c^{(t)}_{\hat{\mu}_1\cdots\hat{\mu}_{r_t}} T^{\hat{\mu}_1\cdots\hat{\mu}_{r_t}}_{(t)} + \mathcal{A}_{\mathrm{CT}} + \mathcal{A}_{\mathrm{R2}}$$

$c^{(t)}_{\hat{\mu}_1\cdots\hat{\mu}_{r_t}}$: tensor coefficient (TC) → [van Hameren; 0905.1005]
$T^{\hat{\mu}_1\cdots\hat{\mu}_{r_t}}_{(t)}$: tensor coefficient
→ COLLIER [Denner, Dittmaier, Hofer; 1604.06792]
$\mathcal{A}_{\mathrm{CT}}$: counter terms
$\mathcal{A}_{\mathrm{R2}}$: $D-4$ dim part of the contraction between TIs and TCs

Extra RECOLA (2)

- g_s renormalisation:

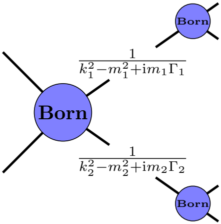
$$\delta Z_{g_\mathrm{s}} = -\frac{\alpha_\mathrm{s}\left(Q^2\right)}{4\pi}\left[\left(\frac{11}{2}-\frac{N_\mathrm{l}}{3}\right)\left(\Delta_\mathrm{UV}+\ln\frac{\mu_\mathrm{UV}^2}{Q^2}\right)-\frac{1}{3}\sum_q\left(\Delta_\mathrm{UV}+\ln\frac{\mu_\mathrm{UV}^2}{m_q^2}\right)\right]$$

$\rightarrow$ contribution from active flavours renormalised within $\overline{\mathrm{MS}}$ scheme and the inactive flavours subtracted at zero momentum transfer

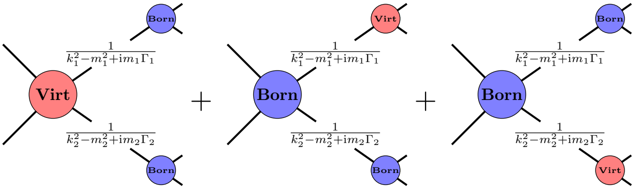
- On-shell scheme: real part of self-energy for CT. Imaginary part of the mass kept only for the propagator.
- G_F scheme: $\alpha = \frac{\sqrt{2}G_\mathrm{F}}{\pi} Re\left(M_\mathrm{W}^2\right)\left(1-\frac{Re\left(M_\mathrm{W}^2\right)}{Re\left(M_\mathrm{Z}^2\right)}\right)$

DPA (1) [Dittmaier, Schwan; 1511.01698]

- At LO



- At NLO



DPA (2) [Dittmaier, Schwan; 1511.01698]

- Factorisable corrections

$$\mathcal{M}_{\mathrm{virt,fact,PA}} = \sum_{\lambda_1,\ldots,\lambda_r} \left(\prod_{i=1}^{r} \frac{1}{K_i}\right) \Bigg[\mathcal{M}_{\mathrm{virt}}^{I\to N,\overline{R}} \prod_{j=1}^{r} \mathcal{M}_{\mathrm{LO}}^{j\to R_j} + \mathcal{M}_{\mathrm{LO}}^{I\to N,\overline{R}} \sum_{k=1}^{r} \mathcal{M}_{\mathrm{virt}}^{k\to R_k} \prod_{j\neq k}^{r} \mathcal{M}_{\mathrm{LO}}^{j\to R_j}\Bigg]_{\left\{\overline{k}_l^2 \to \hat{\overline{k}}_l^2 = M_l^2\right\}_{l\in\overline{R}}}$$

- Non-factorisable corrections:

$$2\mathrm{Re}\left\{\mathcal{M}^{*}_{\mathrm{LO,PA}}\mathcal{M}_{\mathrm{virt,nfact,PA}}\right\} = \left|\mathcal{M}_{\mathrm{LO,PA}}\right|^2 \delta_{\mathrm{nfact}}$$

- On-shell projection
- DPA applied to virtual corrections and I-operator
- Full Born and Real contributions: