Theory predictions for vector-boson scattering at the LHC

Mathieu PELLEN

Cavendish Laboratory,
University of Cambridge

IPPP Durham seminar

University of Cambridge - United Kingdom

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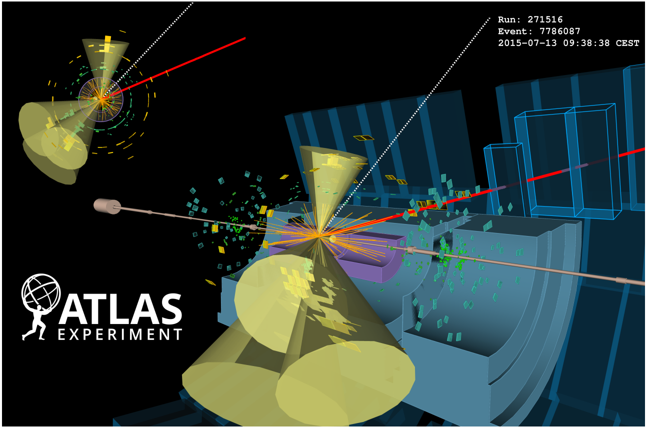
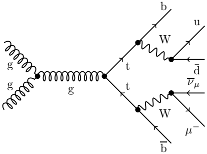
→ Illustration of Giordano Bruno's philosophical ideas

LHC: Great tool to probe fundamental interactions at high energies
→ Cross talk between experiment and theory



$$\mathrm{pp} \to \mathrm{t}^{\star}\bar{\mathrm{t}}^{\star} \to (\mathrm{W}^{\star} \to \nu_{\mu}\mu^{-})\,(\mathrm{W}^{\star} \to \mathrm{jj})\,\mathrm{b}\bar{\mathrm{b}}$$



LHC program

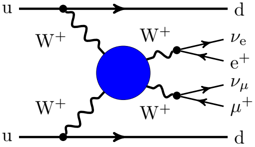
- Run I
  - Discovery of the Higgs boson
  - Exclusion of new physics parameters/models
- Run II $\rightarrow \sqrt{s} = 13\,\text{TeV}$
  - Study of the properties of the Higgs boson
  - Precision study of standard candle processes (tt, di-boson, ...)
  - Measurement of *new* SM processes (tth, **VBS**, tri-boson, ...)
  - Discovery of new physics?

→ Precision physics on both the experimental and theoretical side

↬ Precise theoretical predictions comparable with measurements

Vector-Boson Scattering (VBS) at the LHC

→ Scattering of vector bosons!



Why this is interesting:

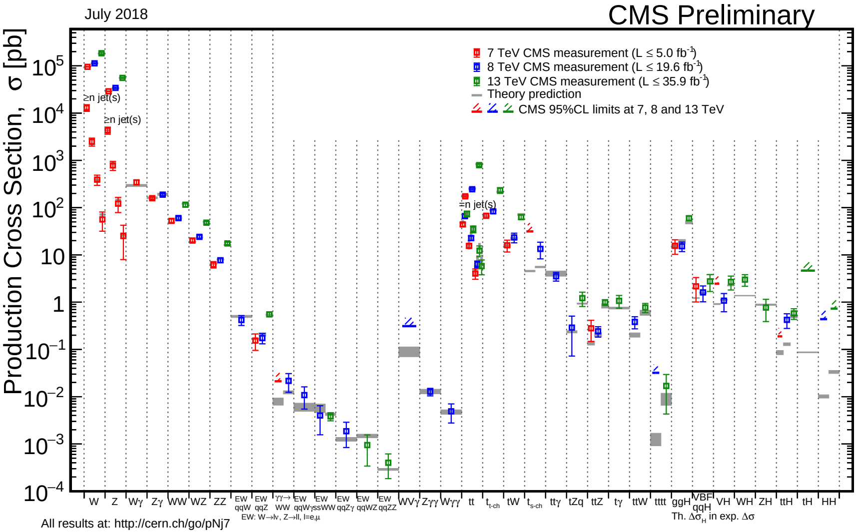
- High multiplicity process
- Key process to investigate electroweak symmetry breaking
- Crucial role of Higgs boson
- Possibility to measure SM parameters

  → Higgs width: [Campbell, Ellis; 1502.02990]
- Window to new physics (triple/quadric gauge coupling)

  [Buarque Franzosi, Ferrarese; 1705.02787], [Gomez-Ambrosio; 1809.04189], [Zhang, Zhou; 1808.00010],

  [1807.02707; Perez, Sekulla, Zeppenfeld] [Brass, Fleper, Killian, Reuter, Sekulla; 1807.02512] ...
- ...

→ Measure VBS at the LHC



→ Limited experimental precision for VBS (for now)

Experimental status (1): Measured

→ Several VBS signatures according to the final state (VV):

- $VV = \mathrm{W}^{\pm}\mathrm{W}^{\pm}$ (leptonic) → **Golden channel**
  - Low background
  - Evidence by ATLAS and CMS at Run-I [1405.6241, 1611.02428, 1410.6315]
  - Measurement by ATLAS and CMS at run-II

    [CMS-PAS-SMP-17-004; 1709.05822], [ATLAS-CONF-2018-030]
- $VV =$ WZ (leptonic)
  - Good rate but large background
  - Observation by ATLAS and CMS at Run-II

    [ATLAS-CONF-2018-033, 1812.09740], [CMS-PAS-SMP-18-001, 1901.04060]
- $VV =$ ZZ (leptonic)
  - Low cross section but good reconstruction
  - Evidence by CMS at Run-II for ZZ [1708.02812]

Experimental status (2): Not (yet) measured

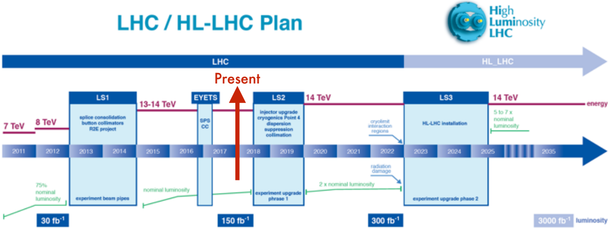
$\rightarrow$ Several VBS signatures according to the final state (VV):

- $VV = \mathrm{W}^+\mathrm{W}^-$ (leptonic)
  - VBF ($\mathrm{pp} \rightarrow \mathrm{jjH}$) + $\mathrm{H} \rightarrow \mathrm{W}^+\mathrm{W}^-$ in a larger phase space
  - Very large background from $\mathrm{t\bar{t}}$
- VV (semi-leptonic: 4 jets in the final state)
  - Large cross section but very large background
  - Used for BSM exlcusion only (for now) [ATLAS; 1609.05122, 1710.07235]
- VV (fully-leptonic: 6 jets in the final state)
  - Very large cross section but gigantic background

Measurements are only starting
$\rightarrow$ We should get excited!
$\rightarrow$ We should get theoretical predictions ready...

Slide from Jakob Salfeld-Nebgen (https://indico.cern.ch/event/711256/)

LHC Future Timeline



- **Assume scaling of uncertainties with 1/√L**

  - **dedicated studies with detector simulation for example in** CMS-PAS-SMP-14-008

Integrated Luminosity	36 fb	150 fb	300 fb	3000 fb-
Year	2016	2019	2022	2038
EW(VBS) W±W±	20%	10%	7%	2%
EW (VBS) ZZ	35%	18%	13%	6%
EW (VBS) WZ	35% personally anticipated	18%	13%	6%

36

Outline

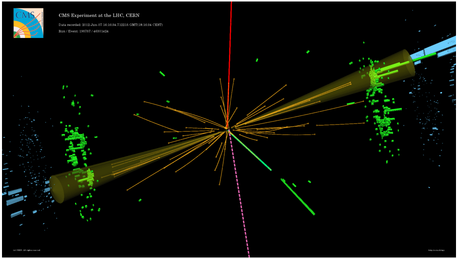
→ Presentation of (some) theory aspects of VBS (mostly SM)

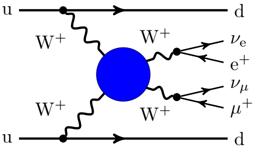
- LO
- NLO (QCD and EW)
  → focus on NLO EW
- Quality of the VBS approximation
- Beyond fixed order
- Final remarks

→ Mainly for $\mathrm{W^+W^+}$ (WZ) but stress

Common features of all VBS signatures

Vector-Boson Scattering (VBS) at the LHC





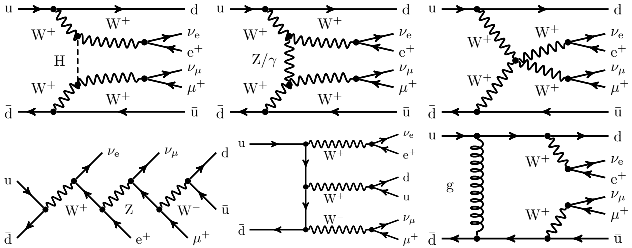
- Two jets back-to-back close to the beam pipe due to colour
  $\rightarrow$ large delta rapidity (Δy_{jj}) and invariant mass (m_{jj})
- Gauge boson produced centrally

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

→ All partonic channels to be taken into account:

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

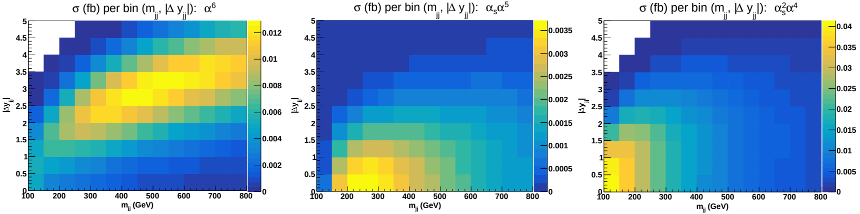
→ Tree amplitudes of order $\mathcal{O}\left(g^6\right)$ and $\mathcal{O}\left({g_\mathrm{s}}^2 g^4\right)$



Common feature of all VBS signatures

- LO contributions at: $\mathcal{O}\left(\alpha^6\right)$, $\mathcal{O}\left(\alpha_s\alpha^5\right)$, and $\mathcal{O}\left(\alpha_s{}^2\alpha^4\right)$ (EW contribution/signal, interference, and QCD contribution/background)

→ Example of $\mathrm{W}^+\mathrm{W}^+$:



[Ballestrero, MP et al.; 1803.07943]

- The contributions have different kinematic
- Need for exclusive cuts to enhance the EW contribution

  → typical cuts are $m_{\rm jj}$ and $|\Delta y_{\rm jj}|$.

Common feature of all VBS signatures

→ LO cross sections in fiducial volume

- for $\mathrm{W^+W^+}$:

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$
σ_{LO} [fb]	1.4178(2)	0.04815(2)	0.17229(5)

[Biedermann, Denner, MP; 1708.00268]

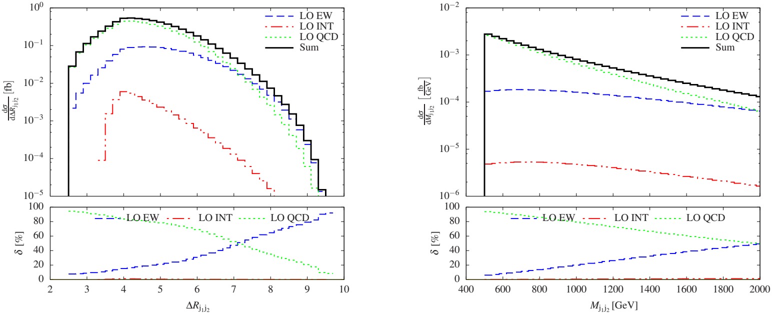
- for $\mathrm{W^+Z}$:

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$
σ_{LO} [fb]	0.25416(6)	0.006833(6)	0.9912(2)

[Andersen, MP et al.; 1803.07977 LH proceedings]

→ The relative size of the EW contribution is process dependent (87% for $\mathrm{W^+W^+}$ vs. 20% for $\mathrm{W^+Z}$)
→ Background can be overwhelming (80% *e.g.* for $\mathrm{W^+Z}$)
→ Interference usually small but not negligible (3% *e.g.* for $\mathrm{W^+W^+}$)

→ Example of WZ:



[Andersen, MP et al.; 1803.07977 LH proceedings]

→ Phase-space regions where EW contribution is dominating: very low statistics

→ Challenge for experimental collaborations

NLO computations (1)

- $W^\pm W^\pm$
  - NLO QCD to EW-induced process in VBS approximation [Jäger, Oleari, Zeppenfeld; 0907.0580], [Denner, Hošeková, Kallweit; 1209.2389]
  - NLO QCD to QCD-induced process [Melia et al.; 1007.5313, 1104.2327], [Campanario et al.; 1311.6738]
  - Matching to parton shower [Jäger, Zanderighi; 1108.0864], [Melia et al.; 1102.4846]

    → Available in VBFNLO or POWHEG-BOX
  - Full NLO QCD and EW to EW- and QCD-induced process [Biedermann, Denner, MP; 1611.02951, 1708.00268]
- $W^\pm Z$
  - NLO QCD to EW-induced process in VBS approximation [Bozzi et al.; hep-ph/0701105]
  - Matching to parton shower [Jäger, Karlberg, Scheller; 1812.05118]
  - NLO QCD to QCD-induced process [Campanario et al.; 1305.1623]

    → Available in VBFNLO and POWHEG-BOX

NLO computations (2)

- W^+W^-
  - NLO QCD to EW-induced process in VBS approximation [Jäger, Oleari, Zeppenfeld; hep-ph/0603177]
  - NLO QCD to QCD-induced process [Melia et al.; 1104.2327], [Greiner et al.; 1202.6004]
  - Matching to parton shower [Jäger, Zanderighi; 1301.1695], [Rauch, Plätzer; 1605.07851]

  → Available in VBFNLO or POWHEG-BOX
- ZZ
  - NLO QCD to EW-induced process in VBS approximation and matching to parton shower [Jäger, Karlberg, Zanderighi; 1312.3252]
  - NLO QCD to QCD-induced process [Campanario et al.; 1405.3972]

  → Available in VBFNLO or POWHEG-BOX

NLO computations - state of the art

→ All processes known at NLO QCD accuracy matched to PS

- in VBS approximation
- for both QCD-/EW-induced process
- all available in VBFNLO (apart from QCD-induced W^+W^-)
- all available in POWHEG-BOX
- possible to generate in MG5_AMC@NLO or SHERPA

→ NLO EW corrections only known for W^+W^+ (WZ preliminary)
→ Full NLO computation only known for W^+W^+
→ No NNLO computation known apart in VBF

[Cacciari et al.; 1503.02660], [Cruz-Martinez et al.; 1802.02445]

$\rightarrow$ Calculation of both NLO QCD and EW corrections to

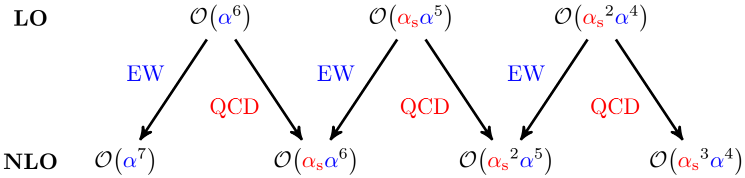
$$\mathrm{pp} \rightarrow \mu^+ \nu_\mu \mathrm{e}^+ \nu_\mathrm{e} \mathrm{jj}$$

[Biedermann, Denner, MP; 1708.00268]

- Off-shell and non-resonant contributions
  $\rightarrow$ Realistic final state
- Full calculations for NLO QCD corrections
- EW corrections can be large in certain phase space regions
  $\rightarrow$ Sudakov logarithms
- Theoretical and numerical challenge to consider $2 \rightarrow 6$ process
  $\rightarrow$ Virtual corrections involving up to 8-point functions

NLO corrections

LO contributions at $\mathcal{O}(\alpha^6)$, $\mathcal{O}(\alpha_s\alpha^5)$, and $\mathcal{O}(\alpha_s{}^2\alpha^4)$



NLO contributions at $\mathcal{O}(\alpha^7)$, $\mathcal{O}(\alpha_s\alpha^6)$, $\mathcal{O}(\alpha_s{}^2\alpha^5)$, and $\mathcal{O}(\alpha_s{}^3\alpha^4)$

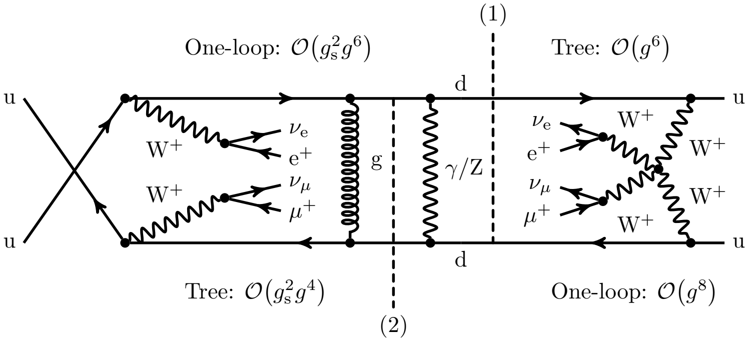
→ Order $\mathcal{O}(\alpha_s\alpha^6)$ and $\mathcal{O}(\alpha_s{}^2\alpha^5)$: QCD and EW corrections mix

→ At NLO: meaningless distinction between EW signal and QCD background

→ Combined measurement

Common feature to all VBS signatures

→ Theoretical version of the previous graph:



→ Typical mixed QCD-EW corrections
when having two quark lines linked by a neutral current

- Tools
  - → Virtual corrections: RECOLA [Actis, Denner, Hofer, Lang, Scharf, Uccirati]
  - + COLLIER [Denner, Dittmaier, Hofer]
  - → Private Monte Carlo MOCANLO [Feger]
  - → Dipole subtraction scheme [Catani,Seymour], [Dittmaier]
  - → Complex-mass scheme [Denner et al.]
- Inputs
  - → 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:
  - vs. MadLoops [Hirschi et al.; 1103.0621]:
    - $\mathcal{O}(\alpha^7)$ and $\mathcal{O}(\alpha_s^3\alpha^4)$
  - Two libraries in Collier [Denner, Dittmaier, Hofer; 1407.0087, 1604.06792]:
    - $\mathcal{O}(\alpha_s\alpha^6)$, $\mathcal{O}(\alpha_s^2\alpha^5)$, and $\mathcal{O}(\alpha_s^3\alpha^4)$
- NLO computations:
  - DPA for $\mathcal{O}(\alpha^7)$ (automatised in [Denner, MP et al.; 1607.05571, 1612.07138] following [Dittmaier, Schwan; 1511.01698])
  - $\mathcal{O}(\alpha_s\alpha^6)$ vs. [Denner, et al.; 1209.2389] in the VBS approximation
- IR-subtraction/finiteness:
  - Variation of α parameter [Nagy, Troscanyi; hep-ph/9806317]
  - Variation of technical cuts
  - Variation of IR-scale

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

- NNPDF3.0QED [NNPDF collaboration]
- dynamical renormalisation and factorisation scale:
  $\mu_{\rm ren} = \mu_{\rm fac} = \sqrt{p_{\rm T,j_1}\, p_{\rm T,j_2}}$
- Cuts inspired by Refs. [1405.6241, 1611.02428, 1410.6315, CMS-PAS-SMP-17-004] :

$$\begin{aligned} \text{charged lepton:} &\quad p_{\text{T},\ell} > 20\,\text{GeV}, \quad |y_\ell| < 2.5, \quad \Delta R_{\ell\ell} > 0.3 \\ \text{jets:} &\quad p_{\text{T,j}} > 30\,\text{GeV}, \quad |y_\text{j}| < 4.5, \quad \Delta R_{\text{j}\ell} > 0.3 \\ \text{missing energy:} &\quad p_{\text{T,miss}} > 40\,\text{GeV}, \end{aligned}$$

$\rightarrow$ For the two leading jet in p_T:

$$\text{jet-jet:} \quad m_\text{jj} > 500\,\text{GeV}, \quad |\Delta y_\text{jj}| > 2.5.$$

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

- anti-k_T jet algorithm [Cacciari, Salam, Soyez; 0802.1189]
  $R = 0.4$ for jet recombination and $R = 0.1$ for photon recombination

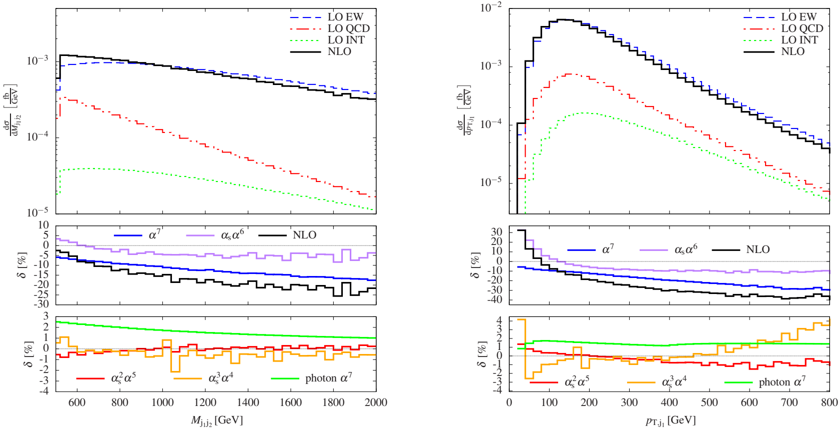
Calculation of both NLO QCD and EW corrections to
$pp \to \mu^+\nu_\mu e^+\nu_e jj$

→ NLO fiducial cross sections: (normalised to σ_{LO})

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{NLO}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	−13.2	−3.5	0.0	−0.4	−17.1

[Biedermann, Denner, MP; 1708.00268]

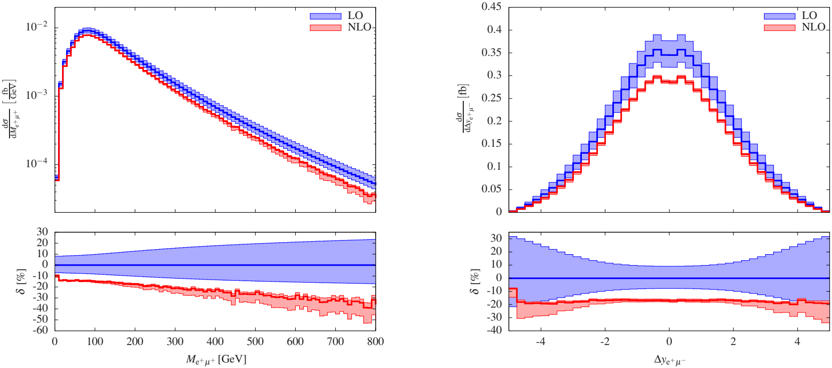
→ Large EW corrections at $\mathcal{O}(\alpha^7)$
→ Negative corrections at $\mathcal{O}(\alpha_s\alpha^6)$:
→ Photon PDF contribution at NLO (not included in NLO definitions):
+1.50% with LUXqed [Manohar et al.; 1607.04266]



[Biedermann, Denner, MP; 1708.00268]

→ Clear hierarchy of LO contributions

→ Different behaviour of the NLO corrections (normalised to the full LO)



[Biedermann, Denner, MP; 1708.00268]

→ Large negative corrections for the full process

→ Corrections dominated by EW correction to EW process

  → Bands do not overlap

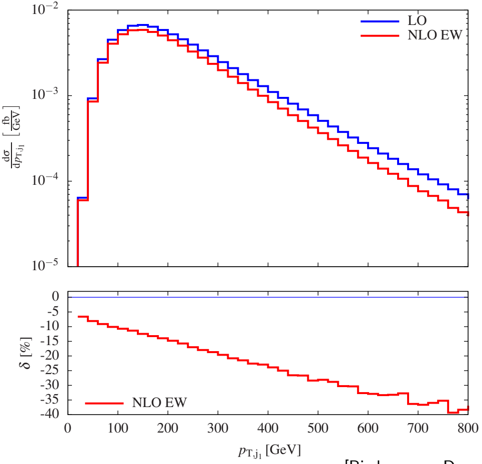
NLO corrections

Common feature of all VBS signatures

- **EW corrections $\mathcal{O}(\alpha^7)$ large with respect to LO $\mathcal{O}(\alpha^6)$**
- Correction of $\mathcal{O}(\alpha_s\alpha^6)$ are expected to be of comparable size
- Small but not negligible photon contribution
- The size of $\mathcal{O}(\alpha_s^3\alpha^4)$ depends strongly on the size of the QCD-induced process at LO

LO: $\mathcal{O}(\alpha^6)$
NLO: $\mathcal{O}(\alpha^7)$

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



[Biedermann, Denner, MP; 1611.02951]

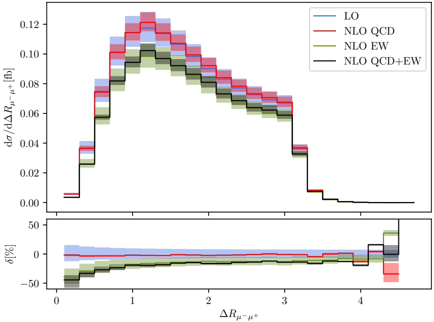
→ Huge NLO electroweak correction (!)

→ Cross section:

LO $\mathcal{O}(\alpha^6)$ [fb]	NLO EW $\mathcal{O}(\alpha^7)$ [fb]	Corrections [%]
0.255	0.214	-16.0

[Denner, Dittmaier, Maierhöfer, MP, Schwan] **Preliminary**

→ Differential distribution:



[Denner, Dittmaier, Maierhöfer, MP, Schwan] **Preliminary**

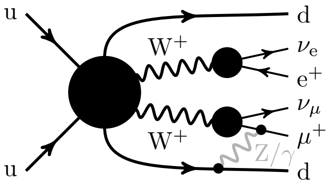
→ Also large corrections!

NLO EW corrections

- Leading behaviour dominated by:
  Sudakov logarithms (bosonic part of the virtual), $\log^2\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right)$
  $\rightarrow$ Usually in the tail of the distribution (suppressed)
  $\rightarrow$ Usually small for total cross section
  $\rightarrow$ Usually smaller than the QCD corrections
- Large corrections not due to VBS cuts
  $\rightarrow$ remove $m_{\mathrm{jj}} > 500\,\mathrm{GeV}$ and $|\Delta y_{\mathrm{jj}}| > 2.5$
  $\rightarrow$ relax $p_{\mathrm{T,j}}$ and $p_{\mathrm{T,miss}}$

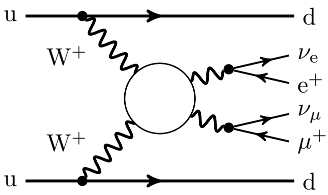
NLO EW corrections

- Double-pole approximation: [Dittmaier, Schwan; 1511.01698]
  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 $W^+W^+ \to W^+W^+$
- Leading logarithm approximation [Denner, Pozzorini; hep-ph/0010201]

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

(double EW logs, collinear single EW logs, and single logs from parameter renormalisation included) (angular-dependant logarithms omitted)

NLO EW corrections

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

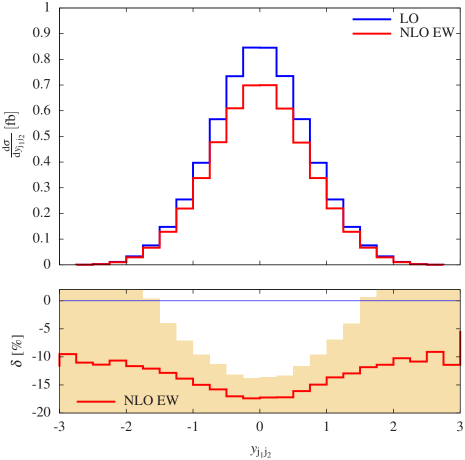
- For $Q = \langle m_{4\ell} \rangle \sim 390\,\text{GeV}$

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

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

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

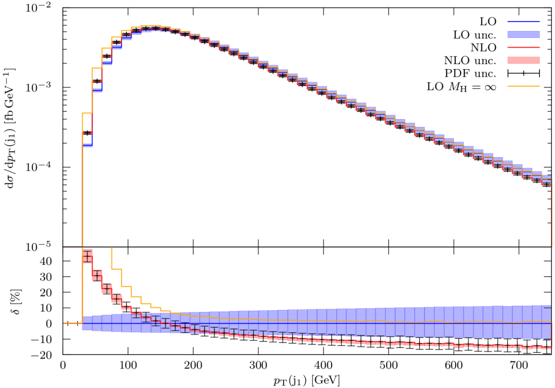
Large NLO EW corrections:
intrinsic feature of VBS at the LHC



[Biedermann, Denner, MP; 1611.02951]

→ 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 $3000\,{\rm fb}^{-1}$ → probe of the EW sector

Effects from Higgs sector

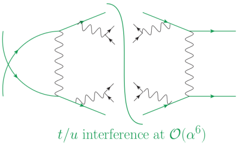


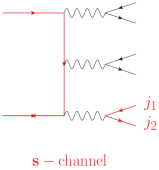
[Dittmaier, Maierhöfer, Schwan, Siegert, In: PoS RADCOR2017]

→ low p_T region sensitive to modified Higgs sector,

→ large p_T is unaffected

→ VBS approximation:
Neglecting s-channel contributions and t/u interferences
Implemented in POWHEG and VBFNLO (possibly including s-channel)





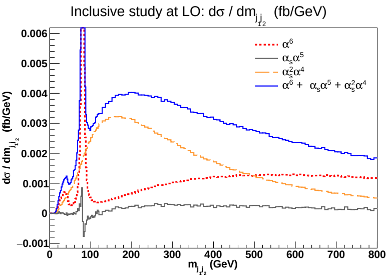
Source: Giovanni Pellicciolli

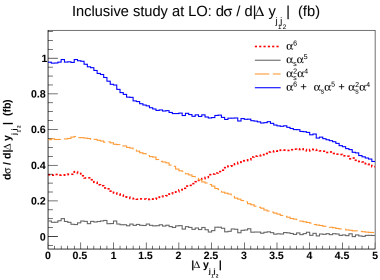
Common feature of all VBS signatures

→ Extension to NLO
Implemented in POWHEG and VBFNLO (possibly including s-channel)

→ Comparison against full computations at NLO
has never been performed before [Ballestrero, MP et al.; 1803.07943]

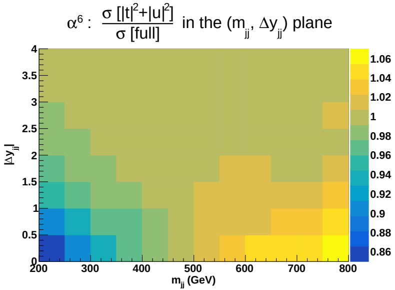
Quality of the VBS approximation (LO)

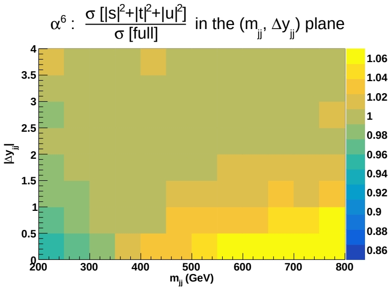




[Ballestrero, MP et al.; 1803.07943]

→ Using the full computation:
Presence of a peak at the W-boson mass (*s*-channel contribution)



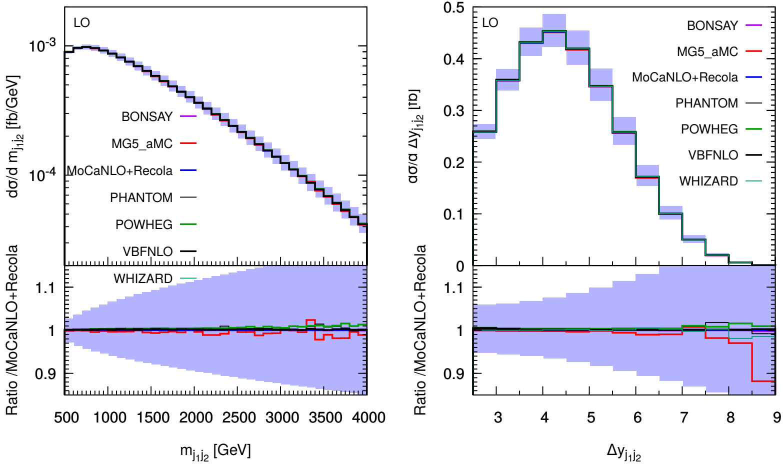


[Ballestrero, MP et al.; 1803.07943]

- For low m_{jj} and low Δy_{jj}, significant s-channel contributions
  $\rightarrow$ tri-boson contributions with resonant W-boson
- Good approximation in fiducial region for $\mathrm{W^+W^+}$
  $\rightarrow$ confirmed for $\mathrm{W^\pm Z}$ [Andersen, MP et al.; 1803.07977]

Common feature of all VBS signatures

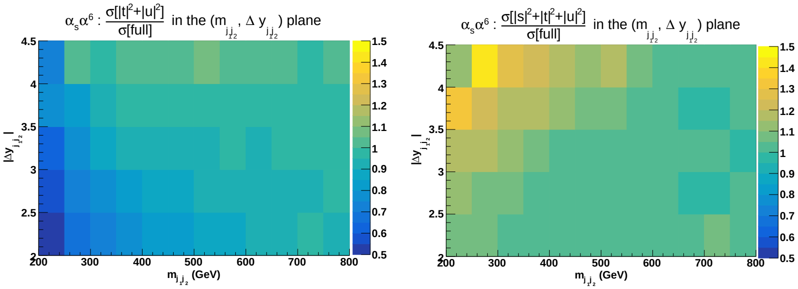
Quality of the VBS approximation (LO)



[Ballestrero, MP et al.; 1803.07943]

→ In single-differential distributions in fiducial region at LO: hardly any differences especially compared to QCD-scale band

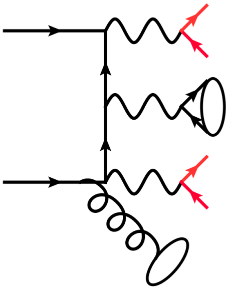
Quality of the VBS approximation (NLO)



[Ballestrero, MP et al.; 1803.07943]

- The approximations are in general worse at NLO
- Approximation can fail by up to 20% even in fiducial region
  → OK now for current experimental precision but might be important in the future
- Similar behaviour expected for other signatures:
  → but harder to predict
  → full computation not available for other signatures (yet)

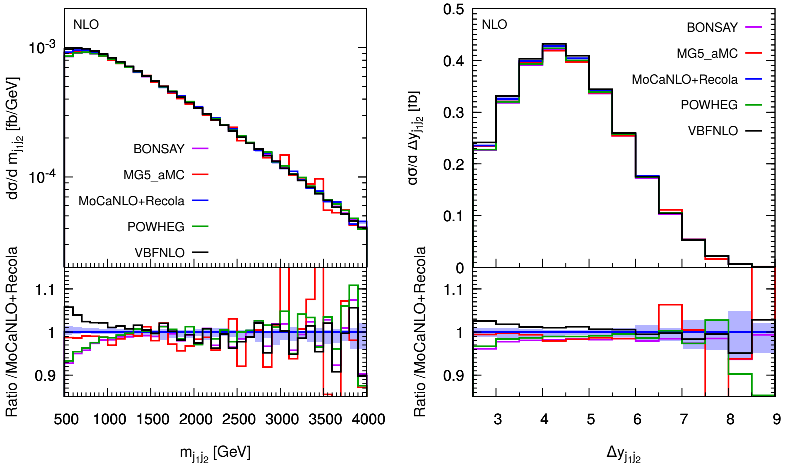
→ Typical *s*-channel contribution:



→ Less suppressed at NLO due to extra jet in the real

Similar effect for tt production at NLO QCD in lepton+jet channel [Denner, MP; 1711.10359]

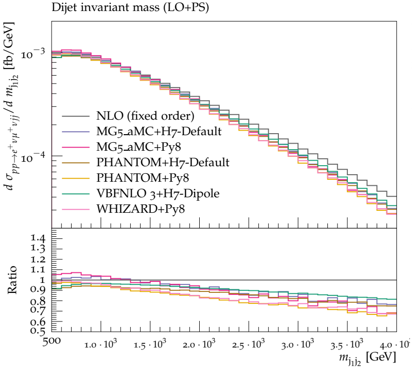
Quality of the VBS approximation (NLO)

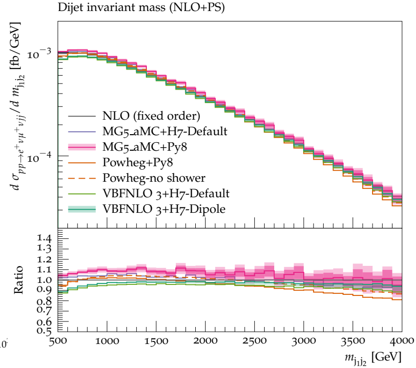


[Ballestrero, MP et al.; 1803.07943]

- Differences lie outside the band

  → relevant for precision measurements



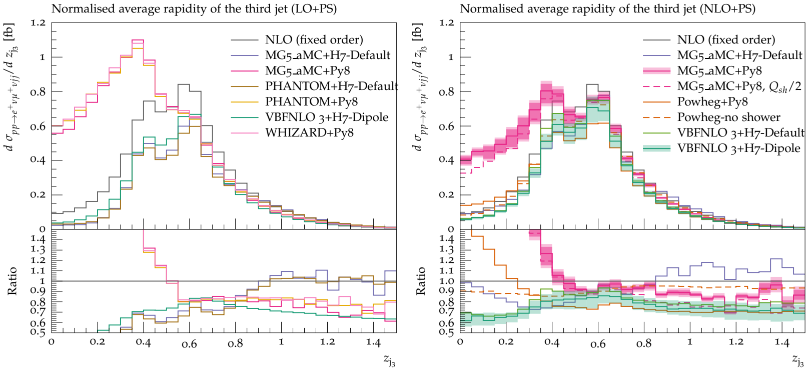


[Ballestrero, MP et al.; 1803.07943]

→ Reasonable agreement at both LO (left) and NLO (right) for observables defined at LO

→ NB: input parameters (masses, widths, PDF, scales) all set to common values

Beyond fixed order (2)



[Ballestrero, MP et al.; 1803.07943]

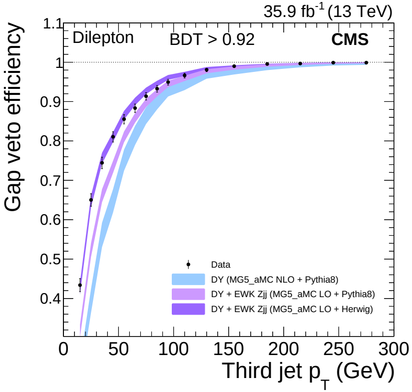
→ Very large differences for observables related to the third jet (only defined at NLO)

→ Different treatment of recoil in PYTHIA

→ Triggered similar study in ATLAS with SHERPA

[ATL-PHYS-PUB-2019-004]

→ Also observed by CMS in VBF-Z production [CMS; 1712.09814] (*i.e.* pp → jjZ)



→ Processes with larger cross sections ...

... but similar topologies ...

... can help to improve on the predictions for VBS

Summary

Presentation mainly based on results for $W^{\pm}W^{\pm}$ (with a bit of WZ)

- Full NLO corrections [Biedermann, Denner, MP; 1708.00268]
  $\rightarrow$ Only the measurement of the full process is meaningful
- NLO EW corrections to VBS [Biedermann, Denner, MP; 1611.02951]
  $\rightarrow$ Intrinsic feature of VBS at the LHC
- Comparison of theoretical predictions

  [Ballestrero, MP et al.; 1803.07943]

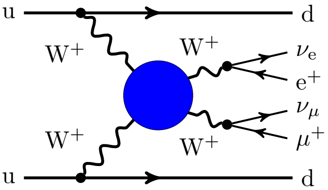
  $\rightarrow$ Effect of parton shower can be sizeable

All these effects will be measurable in the future!

Going toward making VBS a precision test of the Standard Model

- Experiment: Start of VBS measurements
  → better measurements, new signatures measured etc.
- Theory: Significant progresses
  → NLO corrections, VBS approximation, parton shower etc.

- VBS are challenging both theoretically and experimentally
- Significant interest in the theory and experimental community
- New territories (new physics!) and lots to be done
- Exciting time ahead of us!



BACK-UP

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

- NNPDF3.0QED [NNPDF collaboration]
- dynamical renormalisation and factorisation scale:
  $\mu_{\rm ren} = \mu_{\rm fac} = \sqrt{p_{\rm T,j_1}\, p_{\rm T,j_2}}$
- Cuts inspired by Refs. [1405.6241, 1611.02428, 1410.6315, CMS-PAS-SMP-17-004] :

$$\begin{aligned} \text{charged lepton:} &\quad p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}, \quad |y_\ell| < 2.5, \quad \Delta R_{\ell\ell} > 0.3 \\ \text{jets:} &\quad p_{\mathrm{T,j}} > 30\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5, \quad \Delta R_{\mathrm{j}\ell} > 0.3 \\ \text{missing energy:} &\quad p_{\mathrm{T,miss}} > 40\,\mathrm{GeV}, \end{aligned}$$

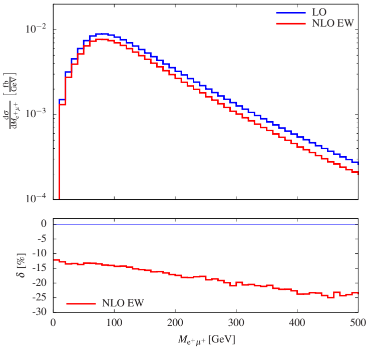
→ For the two leading jet in p_{T}:

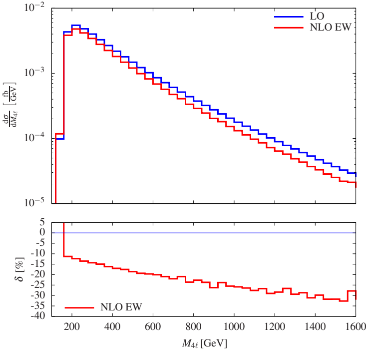
$$\text{jet-jet:} \quad m_{\mathrm{jj}} > 500\,\mathrm{GeV}, \quad |\Delta y_{\mathrm{jj}}| > 2.5.$$

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

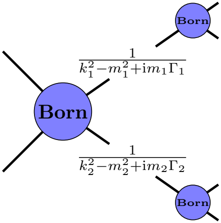
- anti-k_{T} jet algorithm [Cacciari, Salam, Soyez; 0802.1189]
  $R = 0.4$ for jet recombination and $R = 0.1$ for photon recombination

Distributions extra

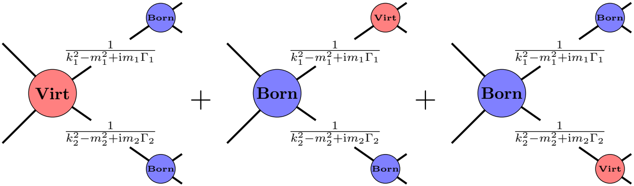




- At LO


Born
Born
Born
$\frac{1}{k_1^2-m_1^2+im_1\Gamma_1}$
$\frac{1}{k_2^2-m_2^2+im_2\Gamma_2}$

- At NLO


Virt
Born
Born
$\frac{1}{k_1^2-m_1^2+im_1\Gamma_1}$
$\frac{1}{k_2^2-m_2^2+im_2\Gamma_2}$
+
Born
Virt
Born
$\frac{1}{k_1^2-m_1^2+im_1\Gamma_1}$
$\frac{1}{k_2^2-m_2^2+im_2\Gamma_2}$
+
Born
Born
Virt
$\frac{1}{k_1^2-m_1^2+im_1\Gamma_1}$
$\frac{1}{k_2^2-m_2^2+im_2\Gamma_2}$

- Factorisable corrections

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

- 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:

Background processes

→ For $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$

- no bottom quark contributions:
  "top-jets" in the final state that have different signature
- no top contamination
- no g contributions due to charge conservation

→ For $\mathrm{W}^{+}\mathrm{W}^{-}$ or $\mathrm{W}^{\pm}\mathrm{Z}$

- bottom quark contributions
- top contamination:
  → tZj contributions for $\mathrm{W}^{\pm}\mathrm{Z}$
  → tWj/t$\bar{\mathrm{t}}$ contributions for $\mathrm{W}^{+}\mathrm{W}^{-}$

→ For $\mathrm{W}^{+}\mathrm{W}^{-}$ or ZZ

- Large loop-induced gg contributions
  part of the NNLO corrections to the QCD-induced process $\mathcal{O}\left(\alpha_{\mathrm{s}}\alpha^{5}\right)$