Theoretical predictions for processes with many legs at the LHC

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Nikhef Theory seminar

Nikhef - Netherlands

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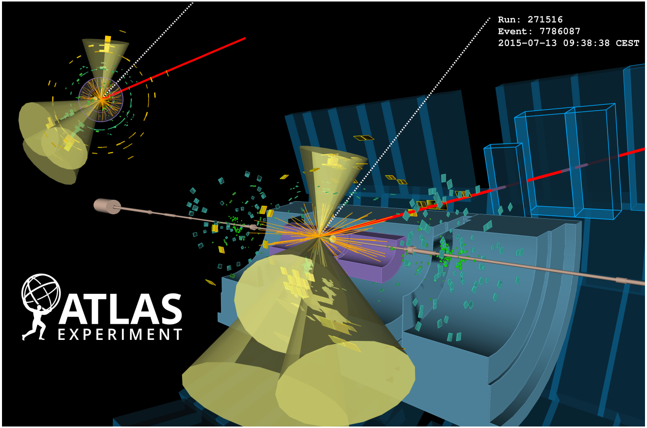
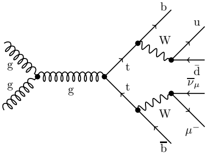
→ Illustration of Giordano Bruno's philosophical ideas

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



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

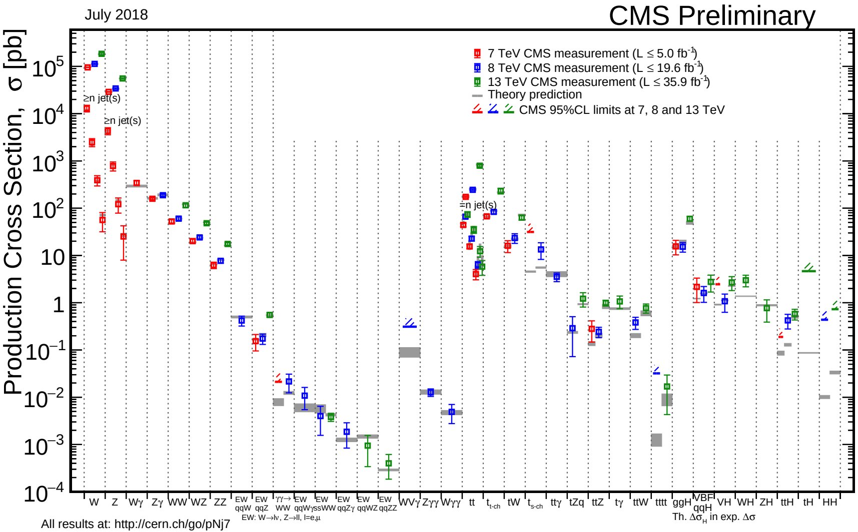


LHC programme

- 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?
- Run III
  - ?

$\rightarrow$ Precision physics on both the experimental and theoretical side

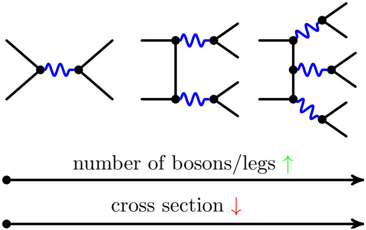
$\looparrowright$ Precise theoretical predictions comparable with measurements



→ Need for theoretical predictions for multi-leg processes!

For *new* processes

- More data → More bosons/couplings → More legs!



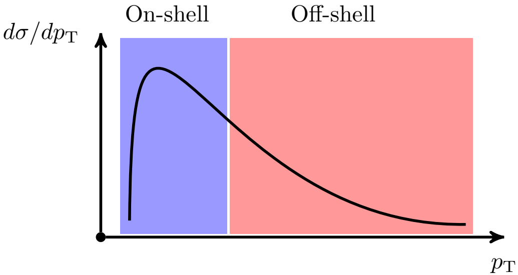
- So far LO predictions used by experiments in analysis
  → Experimental precision is calling for NLO

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%

Jakob Salfeld-Nebgen in https://indico.cern.ch/event/711256 and CMS-PAS-SMP-14-008

For *old* processes

- Final states dominated by a production process
- Example: final state $\mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$ dominated by
  $\mathrm{pp} \to \mathrm{t}^\star\bar{\mathrm{t}}^\star \to (\mathrm{W}^\star \to \nu_\mu\mu^-)\,(\mathrm{W}^\star \to \mathrm{e}^+\nu_\mathrm{e})\,\mathrm{b}\bar{\mathrm{b}}$



  On-shell region dominated by resonant production
  Off-shell region receives large non-resonant contributions
- Only $\mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$ is measured in experiments

→ During run II, the tail of the distributions will be probed
→ New physics contributions?

State of the art: high-multiplicity processes

- $2 \to 6$ processes
  off-shell top quarks, tri-boson, vector-boson scattering ...
  .. but only two computations publicly available with non-trivial resonance structure:
  $\to$ NLO QCD to off-shell tt [Ježo et al.; 1607.04538]
  $\to$ NLO EW to VBS same-sign W [Chiesa, Denner, Lang, MP; 1906.01863]

- $2 \to 7$ processes
  $\to$ NLO QCD to $\mathbf{t\bar{t}H}$ [Denner, Feger; 1506.07448]
  $\to$ NLO QCD to $\mathbf{t\bar{t}j}$ [Bevilacqua et al.; 1509.09242, 1609.01659]
  $\to$ NLO EW to $\mathbf{t\bar{t}H}$ [Denner, Lang, MP, Uccirati; 1612.07138]
  $\to$ NLO QCD to $\mathbf{Wb\bar{b}jjj}$ [Anger et al.; 1712.05721]
  $\to$ NLO QCD to $\mathbf{t\bar{t}}\gamma$ [Bevilacqua et al.; 1803.09916]

- $2 \to 8$ processes
  $\to$ NLO QCD to $\mathbf{t\bar{t}}(\mathbf{Z} \to \nu\bar{\nu})$ [Bevilacqua et al.; 1907.09359]

Outline:

- New calculations for *new* processes:
  $\rightarrow$ Full NLO for vector-boson scattering

- New calculations for *old* processes:
  $\rightarrow$ Off-shell effects for top-antitop in leptons channel
  $\rightarrow$ NLO QCD for top-antitop in leptons+jets channel

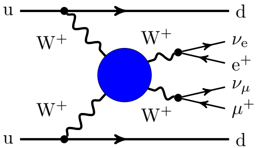
Tools

- Virtual corrections:
  - → RECOLA [Actis, Denner, Hofer, Lang, Scharf, Uccirati;]
  - → http://recola.hepforge.org/
  - → COLLIER [Denner, Dittmaier, Hofer]
  - → collier.hepforge.org
- Private multi-channel Monte Carlo MoCaNLO [Feger]
- Dipole subtraction scheme [Catani,Seymour], [Dittmaier]
- Complex-mass scheme [Denner et al.]

- New calculations for *new* processes:
  → Full NLO for vector-boson scattering

Vector-Boson Scattering (VBS) at the LHC

→ Scattering of vector bosons!



Why this is interesting:

- 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/quartic gauge coupling)
  [Buarque Franzosi, Ferrarese; 1705.02787], [Gomez-Ambrosio; 1809.04189], [Zhang, Zhou; 1808.00010], [Perez, Sekulla, Zeppenfeld; 1807.02707] [Brass, Fleper, Killian, Reuter, Sekulla; 1807.02512] ...
- ...

→ Measurements VBS at the LHC!

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

    [ATLAS-CONF-2018-030, 1906.03203], [CMS-PAS-SMP-17-004; 1709.05822]
- $VV =$ 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

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

- $VV = \mathrm{W}^+\mathrm{W}^-$ (leptonic)
  - VBF ($\mathrm{pp} \to \mathrm{jjH}$) + $\mathrm{H} \to \mathrm{W}^+\mathrm{W}^-$ 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

→ We should get excited!

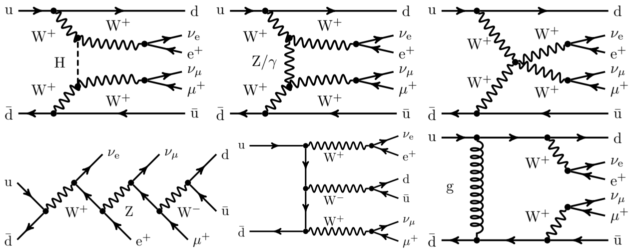
→ We should get theoretical predictions ready...

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

→ All partonic channels to be taken into account:

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

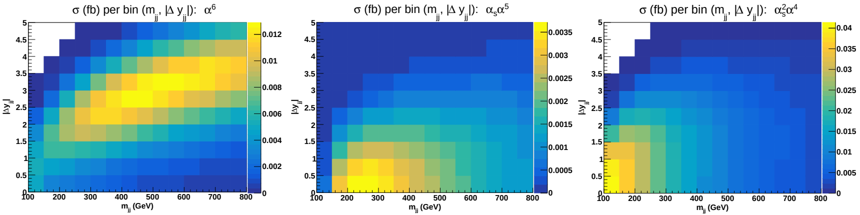
→ Tree amplitudes of order $\mathcal{O}\left(g^6\right)$ and $\mathcal{O}\left({g_\mathrm{s}}^2 g^4\right)$



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]

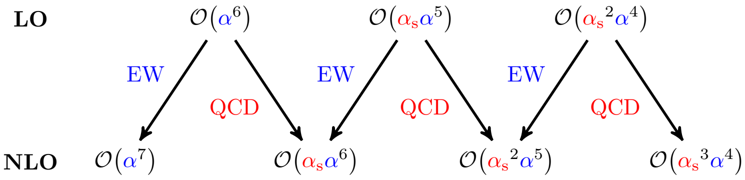
- The contributions have different kinematic
- Need for exclusive cuts to enhance the EW contribution

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

Common feature of all VBS signatures

NLO corrections

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



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

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

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

→ Combined measurement

Common feature to all VBS signatures

State of the art: $\mathrm{W}^{\pm}\mathrm{W}^{\pm}$

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s{}^2\alpha^5)$	$\mathcal{O}(\alpha_s{}^3\alpha^4)$
NLO	✓	✓	✓	✓
NLO+PS	✓	✓*	X	✓

- $\mathcal{O}(\alpha^7)$ [Biedermann, Denner, MP; 1611.02951, 1708.00268]
  → +PS: [Chiesa, Denner, Lang, MP; 1906.01863]
- $\mathcal{O}(\alpha_s\alpha^6)$ [Biedermann, Denner, MP; 1708.00268] [Jäger, Oleari, Zeppenfeld; 0907.0580]* [Denner, Hošeková, Kallweit; 1209.2389]*
  → +PS: [Jäger, Zanderighi; 1108.0864]*
- $\mathcal{O}(\alpha_s{}^2\alpha^5)$ [Biedermann, Denner, MP; 1708.00268]
- $\mathcal{O}(\alpha_s{}^3\alpha^4)$ [Biedermann, Denner, MP; 1708.00268] [Melia et al.; 1007.5313, 1104.2327], [Campanario et al.; 1311.6738]
  → +PS: [Melia et al.; 1102.4846], [Melia et al.; 1102.4846]

→ * Computations in the VBS-approximation *i.e.* t-u interferences and tri-boson contributions neglected [Ballestrero, MP et al.; 1803.07943]

State of the art: $\mathrm{W}^{\pm}\mathrm{Z}$

Order	$\mathcal{O}\left(\alpha^7\right)$	$\mathcal{O}\left(\alpha_s\alpha^6\right)$	$\mathcal{O}\left(\alpha_s{}^2\alpha^5\right)$	$\mathcal{O}\left(\alpha_s{}^3\alpha^4\right)$
NLO	✓	✓	X	✓
NLO+PS	X	✓*	X	✓

- $\mathcal{O}\left(\alpha^7\right)$ [Denner, Dittmaier, Maierhöfer, MP, Schwan; 1904.00882]
- $\mathcal{O}\left(\alpha_s\alpha^6\right)$ [Denner, Dittmaier, Maierhöfer, MP, Schwan; 1904.00882] [Bozzi et al.; hep-ph/0701105]*

  → +PS: [Jäger, Karlberg, Scheller; 1812.05118]*
- $\mathcal{O}\left(\alpha_s{}^3\alpha^4\right)$ [Campanario et al.; 1305.1623]

  → +PS: [Campanario et al.; 1305.1623]

State of the art: ZZ and $\mathrm{W^+W^-}$

Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$
NLO	✗	✓*	✗	✓
NLO+PS	✗	✓*	✗	✓

- ZZ
  - $\mathcal{O}(\alpha_s\alpha^6)$ +PS: [Jäger, Karlberg, Zanderighi; 1312.3252]*
  - $\mathcal{O}(\alpha_s^3\alpha^4)$ +PS: [Campanario et al.; 1405.3972]
- $\mathrm{W^+W^-}$
  - $\mathcal{O}(\alpha_s\alpha^6)$ +PS: [Greiner et al.; 1202.6004]*
    → +PS: [Melia et al.; 1104.2327],*
  - $\mathcal{O}(\alpha_s^3\alpha^4)$ +PS: [Jäger, Zanderighi; 1301.1695], [Rauch, Plätzer; 1605.07851]

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]
- 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] :

charged lepton:	$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$,	$\lvert y_\ell \rvert < 2.5$,	$\Delta R_{\ell\ell} > 0.3$
jets:	$p_{\mathrm{T,j}} > 30\,\mathrm{GeV}$,	$\lvert y_\mathrm{j} \rvert < 4.5$,	$\Delta R_{\mathrm{j}\ell} > 0.3$
missing energy:	$p_{\mathrm{T,miss}} > 40\,\mathrm{GeV}$,		

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

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

$\rightarrow$ 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

NLO corrections - $\mathrm{W}^+\mathrm{W}^+$

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

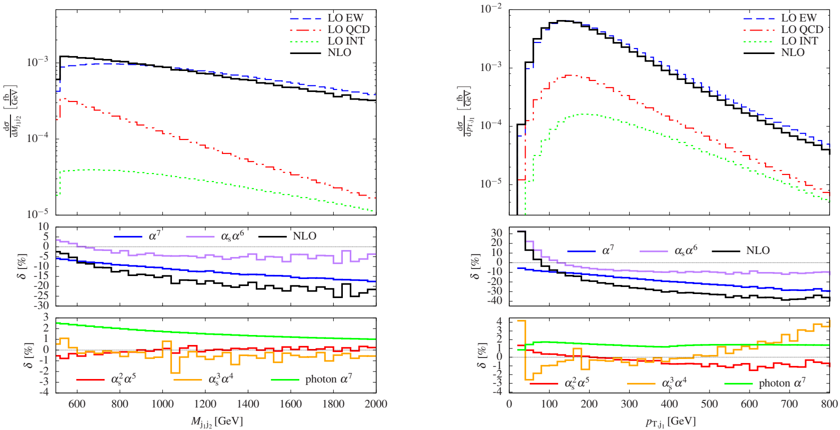
→ NLO fiducial cross sections: (normalised to σ_{LO})

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
$\delta\sigma_{\mathrm{NLO}}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{\mathrm{NLO}}/\sigma_{\mathrm{LO}}$ [%]	-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]

NLO corrections - W^+W^+ / Separated contributions

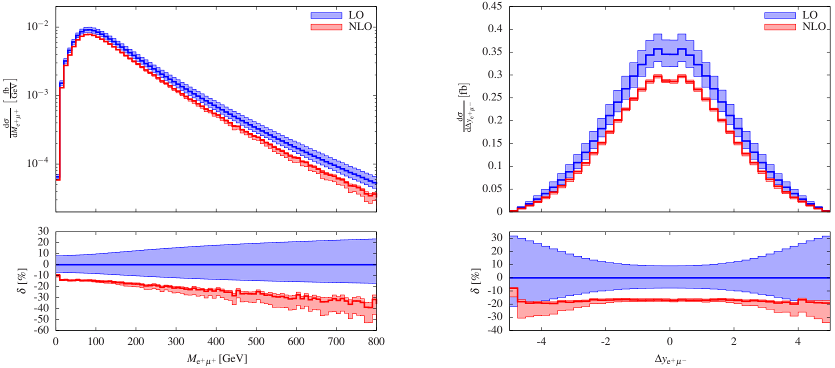


[Biedermann, Denner, MP; 1708.00268]

→ Clear hierarchy of LO contributions

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

NLO corrections - W^+W^+ / Combined predictions



[Biedermann, Denner, MP; 1708.00268]

→ Large negative corrections for the full process

→ Corrections dominated by EW correction to EW process

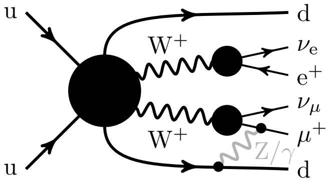
→ Bands do not overlap

NLO EW corrections

- **Large EW corrections!**
  $\rightarrow$ Confirmed for WZ [Denner, Dittmaier, Maierhöfer, MP, Schwan; 1904.00882]
- 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

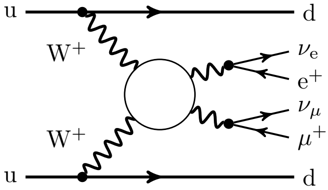
- Double-pole approximation: [Dittmaier, Schwan; 1511.01698]
  leading contribution of expansion about the resonance poles
  → Required two W bosons for the virtual contributions



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

NLO EW corrections

- Effective vector-boson approximation:



- Simplify the discussion to $\mathrm{W^+W^+} \to \mathrm{W^+W^+}$
- 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 included) (angular-dependant logarithms omitted)

NLO EW corrections

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

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

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

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

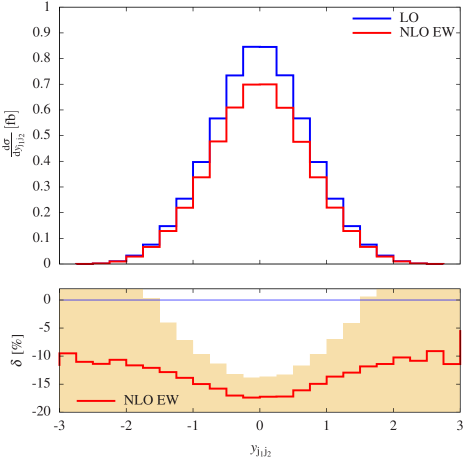
- C^{ew} larger for bosons than fermions
- $\langle m_{4\ell} \rangle$ larger for VBS (massive t-channel [Denner, Hahn; hep-ph/9711302])
  NB: $\langle m_{4\ell} \rangle \sim 250\,\mathrm{GeV}$ for $q\bar{q} \to \mathrm{W}^+\mathrm{W}^-$

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

[Biedermann, Denner, MP; 1611.02951]

→ Implemented in POWHEG for ss-WW [Chiesa, Denner, Lang, MP; 1906.01863]

NLO EW corrections



[Biedermann, Denner, MP; 1611.02951]

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

- New calculations for *old* processes:
  $\rightarrow$ Off-shell effects for top-antitop in leptons channel
  $\rightarrow$ NLO QCD for top-antitop in leptons+jets channel

State of the art top-antitop production

- NLO QCD [Melnikov, Schulze; 0907.3090], [Bevilacqua et al.; 1012.4230], [Denner et al.; 1012.3975, 1207.5018], [Frederix; 1311.4893], [Cascioli et al.; 1312.0546], [Campbell et al.; 1204.1513, 1608.03356], ...

  → With off-shell effects [Denner et al.; 1012.3975, 1207.5018], [Bevilacqua et al.; 1012.4230], [Frederix; 1311.4893], [Cascioli et al.; 1312.0546]
- NLO EW [Bernreuther et al.; hep-ph/0610335, 0804.1237, 0808.1142], [Kühn et al.; hep-ph/0508092, hep-ph/0610335], [Hollik, Kollar; 0708.1697], [Pagani et al.; 1606.01915]

  → With off-shell effects [Denner, MP; 1607.05571]
- NNLO QCD [Moch et al.; 1203.6282], [Czakon et al.; 1303.6254, 1601.05375, 1606.03350], [Abelof et al.; 1506.04037]

  → Combination with NLO EW [Czakon et al.; 1705.04105]

  → With decays [Gao, Papanastasiou; 1705.08903], [Behring et al.; 1901.05407]
- NLO QCD matched to PS [Frixione et al.; hep-ph/0305252, 0707.3088], [Höche et al.; 1402.6293], [Garzelli et al.; 1405.5859], [Campbell et al.; 1412.1828]

  → With off-shell effects [Ježo et al.; 1607.04538]

Exclusively for the leptonic channel!

Motivations

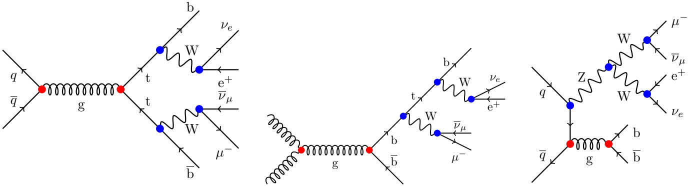
→ Calculation of NLO EW corrections to off-shell $\mathrm{t\bar{t}}$ production:

$$\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b\bar{b}}$$

- Off-shell, non-resonant, and interference effects
  → 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

LO definition - $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$

- The LO is defined at order $\mathcal{O}\left(\alpha_\mathrm{s}^2\alpha^4\right)$



$\to$ Not only doubly resonant top-pair contributions

- singly resonant top contributions
- non-resonant top contributions

$\to$ NLO EW corrections are of order $\mathcal{O}\left(\alpha_\mathrm{s}^2\alpha^5\right)$

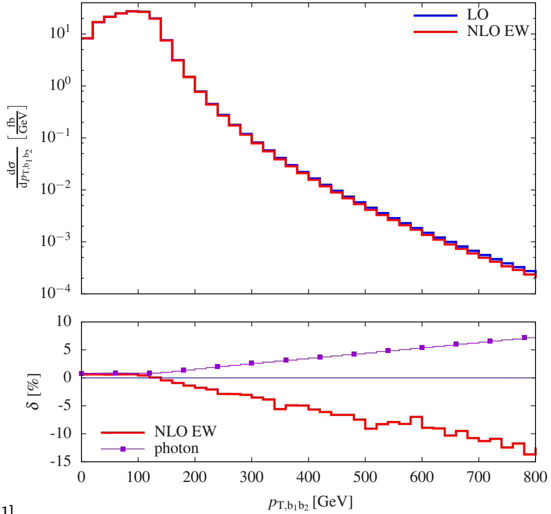
Set-up

Predictions for $\sqrt{s} = 13\text{TeV}$ at the LHC

→ NNPDF23_nlo_as_0119_qed [NNPDF Collaboration]
with massless bottom quarks and bottom-quark PDF neglected
→ Event selection:

$$\begin{aligned} \text{b jets:} &\quad p_{\text{T,b}} > 25\,\text{GeV}, \quad |y_{\text{b}}| < 2.5 \\ \text{charged lepton:} &\quad p_{\text{T},\ell} > 20\,\text{GeV}, \quad |y_\ell| < 2.5 \\ \text{missing transverse momentum:} &\quad p_{\text{T,miss}} > 20\,\text{GeV} \\ \text{b-jet–b-jet distance:} &\quad \Delta R_{\text{bb}} > 0.4 \end{aligned}$$

→ anti-k_{T} jet algorithm [Cacciari, Salam, Soyez]
with $R = 0.4$ for both jet clustering and photon recombination

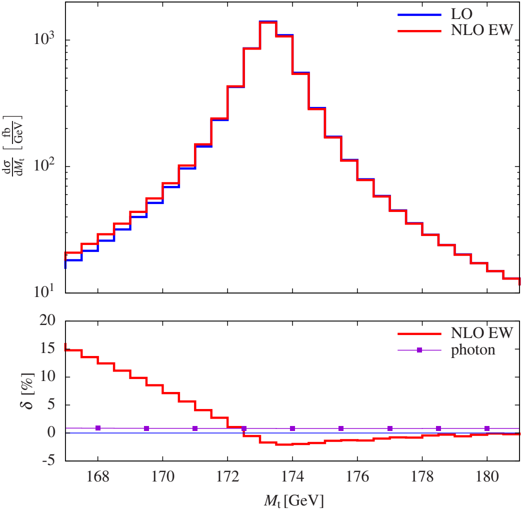


[Denner, MP; 1607.05571]

→ Sudakov logarithms → −15%

→ Large photon contributions → +6% [Pagani, Tsinikos, Zaro; 1606.01915]

(before LuxQED [Manohar et al.; 1607.04266])



[Denner, MP; 1607.05571]

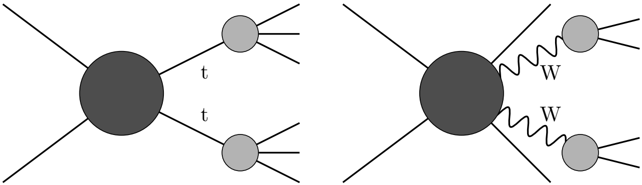
→ Radiative tail due to non-reconstructed photons

Double-pole Approximations (DPA)

(More details in Refs. [Dittmaier, Schwan; 1511.01698], [Denner, MP; 1607.05571] and therein)

- Expansion about the resonance poles
- Accounts for off-shell effects
  → Resonant propagator fully included / Full phase space
- Accounts also for non-factorisable corrections
- Applied only to the virtual corrections

→ Two DPAs considered: **tt** and **WW**



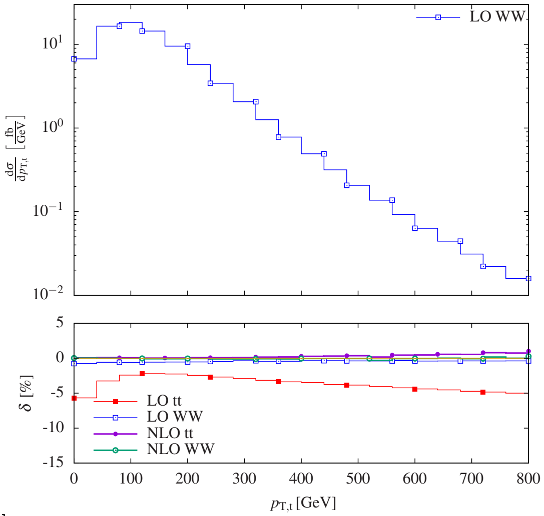
Fiducial cross sections

Ch.	$\sigma_{\mathrm{LO}}^{\mathrm{WW\ DPA}}$ [fb]	$\delta_{\mathrm{LO}}^{\mathrm{WW\ DPA}}$ [%]	$\sigma_{\mathrm{LO}}^{\mathrm{tt\ DPA}}$ [fb]	$\delta_{\mathrm{LO}}^{\mathrm{tt\ DPA}}$ [%]
gg	2808.4(6)	−0.56	2738.8(2)	−3.0
$q\bar{q}$	372.90(1)	−0.64	368.82(1)	−2.2
pp	3181.3(5)	−0.57	3107.6(2)	−2.9

→ At LO, WW DPA is better than the tt DPA

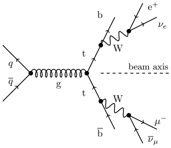
Ch.	$\sigma_{\mathrm{NLO\ EW}}^{\mathrm{WW\ DPA}}$ [fb]	$\delta_{\mathrm{NLO\ EW}}^{\mathrm{WW\ DPA}}$ [%]	$\sigma_{\mathrm{NLO\ EW}}^{\mathrm{tt\ DPA}}$ [fb]	$\delta_{\mathrm{NLO\ EW}}^{\mathrm{tt\ DPA}}$ [%]
gg	2832.9(2)	−0.046	2836.5(2)	+0.082
$q\bar{q}$	377.36(8)	0.047	377.23(5)	+0.013
pp	3210.5(2)	−0.037	3214.0(2)	+0.072

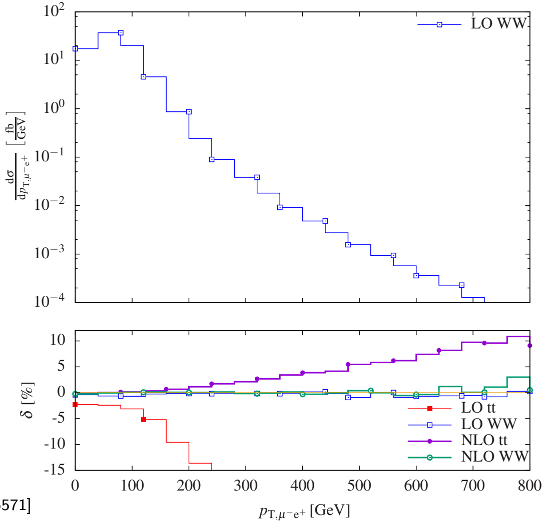
→ At NLO, both DPAs are equally good

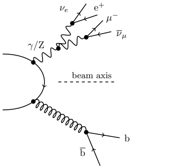


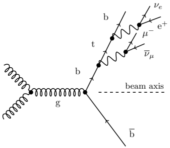
[Denner, MP; 1607.05571]

→ Both DPAs work well for top dominated observables









[Denner, MP; 1607.05571]

→ **Off-shell effects can be large**

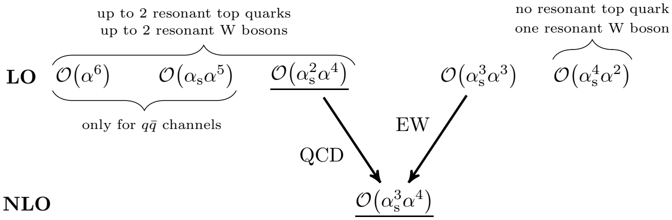
$\rightarrow$ NLO QCD to off-shell $\mathrm{t\bar{t}}$ production in the lepton+jets channel:

$$\mathrm{pp} \rightarrow \mu^- \bar{\nu}_\mu \mathrm{b\bar{b}jj}$$

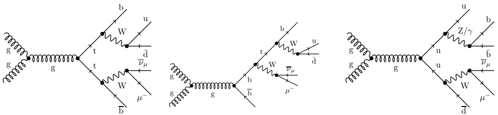
- Measured experimentally [ATLAS; 1708.00727], [CMS; 1610.04191]
- Larger cross section due to W boson branching ratio
- Better reconstruction of top quarks (only one neutrino)
- Unexplored final state for $\mathrm{t\bar{t}}$ production

  [Anger, Febres Cordero, Ita, Sotnikov; 1712.05721]: $\mathrm{W\bar{b}b} + 2\mathrm{j}$

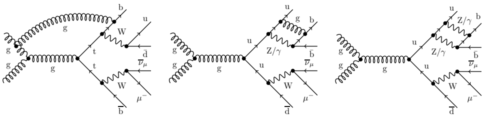
  but different orders at LO: $\mathcal{O}\left(\alpha_\mathrm{s}^4\alpha^2\right)$ vs. $\mathcal{O}\left(\alpha_\mathrm{s}^2\alpha^4\right)$



- The LO is defined at order $\mathcal{O}\left(\alpha_s^2\alpha^4\right)$



- NLO QCD corrections are of order $\mathcal{O}\left(\alpha_s^3\alpha^4\right)$



Set-up

Predictions for $\sqrt{s} = 13\text{TeV}$ at the LHC

→ Event selection for *resolved* topology [ATLAS; 1708.00727], [CMS; 1610.04191]:

$$\begin{aligned} &\text{light/b jets:} && p_{\mathrm{T,j,b}} > 25\,\mathrm{GeV}, && |y_{\mathrm{j,b}}| < 2.5 \\ &\text{charged lepton:} && p_{\mathrm{T},\ell} > 25\,\mathrm{GeV}, && |y_\ell| < 2.5 \\ &\text{b-jet–b-jet distance:} && \Delta R_{\mathrm{jj}}, \Delta R_{\mathrm{jb}}, \Delta R_{\mathrm{bb}} > 0.4 \end{aligned}$$

→ anti-k_{T} jet algorithm [Cacciari, Salam, Soyez] with $R = 0.4$

→ Additional cut to ensure a stable definition of the fiducial volume for top-quark pair production at both LO/NLO

$$60\,\mathrm{GeV} < m_{\mathrm{jj}} < 100\,\mathrm{GeV}$$

- Full computation $\mathrm{pp} \to \mu^-\bar{\nu}_\mu \mathrm{b\bar{b}jj}$
  $\to$ 32 channels
- 6 partonic channels with two resonant top quarks

$$
\begin{aligned}
\mathrm{gg} &\to \mu^-\bar{\nu}_\mu \mathrm{b\bar{b}} q_i \bar{q}_j, & q_i q_j &\in \{\mathrm{ud}, \mathrm{cs}\}, \\
q_i\bar{q}_i/\bar{q}_i q_i &\to \mu^-\bar{\nu}_\mu \mathrm{b\bar{b}} q_i \bar{q}_j, & q_i q_j &\in \{\mathrm{ud}, \mathrm{cs}\}, \\
q_i\bar{q}_i/\bar{q}_i q_i &\to \mu^-\bar{\nu}_\mu \mathrm{b\bar{b}} q_j \bar{q}_k, & q_i q_j q_k &\in \{\mathrm{ucs}, \mathrm{cud}\}, \\
q_i\bar{q}_i/\bar{q}_i q_i &\to \mu^-\bar{\nu}_\mu \mathrm{b\bar{b}} q_j \bar{q}_i, & q_i q_j &\in \{\mathrm{du}, \mathrm{sc}\}, \\
q_i\bar{q}_i/\bar{q}_i q_i &\to \mu^-\bar{\nu}_\mu \mathrm{b\bar{b}} q_j \bar{q}_k, & q_i q_j q_k &\in \{\mathrm{dcs}, \mathrm{sud}\}, \\
\mathrm{b\bar{b}}/\mathrm{\bar{b}b} &\to \mu^-\bar{\nu}_\mu \mathrm{b\bar{b}} q_i \bar{q}_j, & q_i q_j &\in \{\mathrm{ud}, \mathrm{cs}\}
\end{aligned}
$$

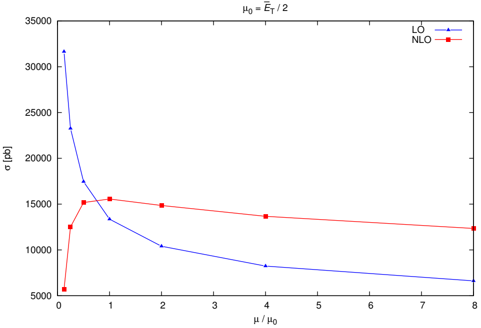
$\to$ 98% without m_{jj} cut
$\to$ 99.72% with m_{jj} cut

NLO computation done on 6 partonic channels with two resonant top quarks

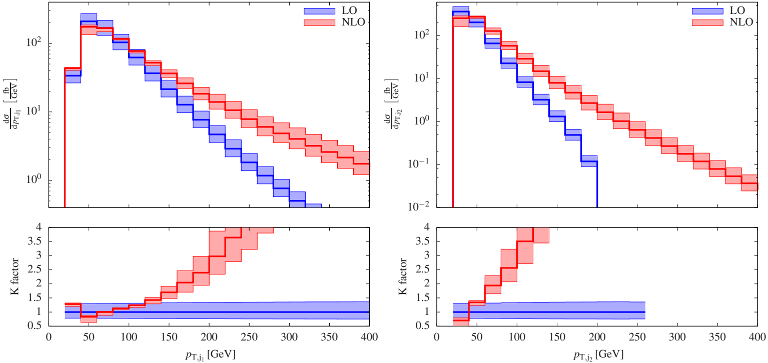
Cross sections

$$\sigma_{\rm LO} = 13.3565(6)^{+30.68\%}_{-22.09\%}\ \text{pb}$$

$$\sigma_{\rm NLO} = 15.56(7)^{+0.9(6)\%}_{-4.6(5)\%}\ \text{pb and } K_{\rm NLO} = 1.16$$



$$\mu_0 = \bar{E}_{\rm T}/2 = \frac{1}{2}\sqrt{\sqrt{m_{\rm t}^2 + p_{\rm T,t}^2}\sqrt{m_{\bar{\rm t}}^2 + p_{\rm T,\bar{t}}^2}}$$



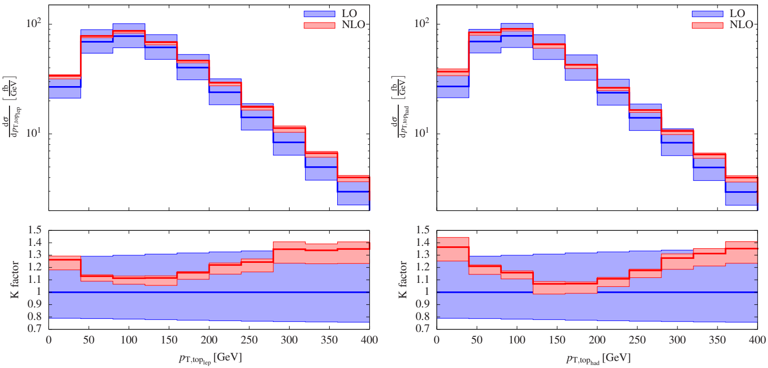
[Denner, MP; 1711.10359]

→ Large corrections toward high transverse momenta (due to real corrections)

→ Clear effect of the cuts:

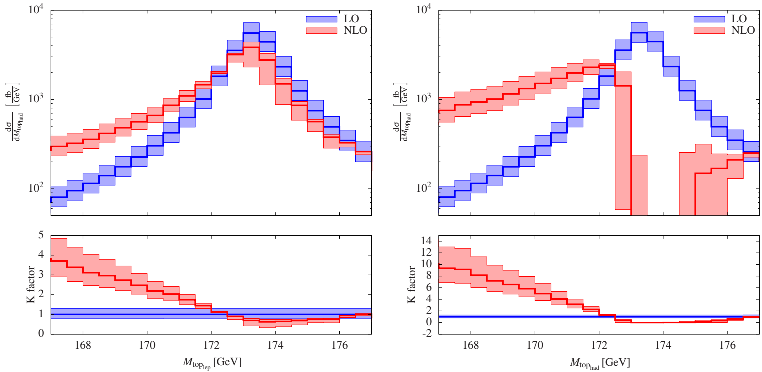
$$p^2_{\mathrm{T,j_2,max}} \sim m^2_{\mathrm{jj,max}}/\Delta R^2_{\mathrm{jj,min}} = (100)^2 / (0.4)^2 = (250\,\mathrm{GeV})^2$$

→ Scale variation band increase for high transverse momenta (the NLO predictions become LO accurate)



[Denner, MP; 1711.10359]

→ Different NLO behaviour between the hadronic and leptonic top quark



[Denner, MP; 1711.10359]

→ Different NLO behaviour between the hadronic and leptonic top quark

→ Extreme NLO effect: inclusion of higher-order effects needed

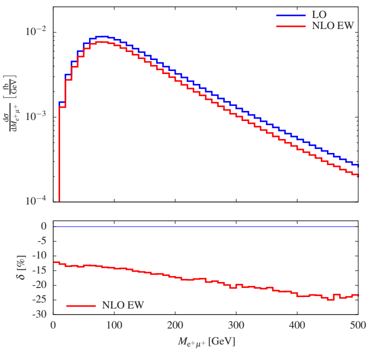
Summary

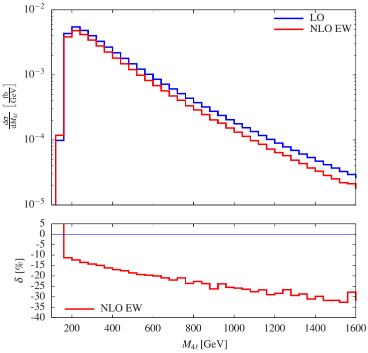
Computations of high-multiplicity processes are needed!

- New computations for *new* processes: VBS
  $\rightarrow$ Large EW corrections
- New computations for *old* processes: top-antitop production
  $\rightarrow$ Off-shell effects can be large
  $\rightarrow$ Large corrections due to specific final states

- New territories (new physics?) and lots to be done
- Exciting time ahead of us!

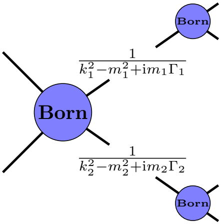
BACK-UP



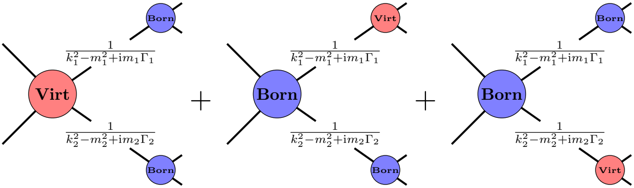


[Biedermann, Denner, MP; 1611.02951]

- At LO


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

- At NLO


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

- 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 $\mathrm{W^{\pm}W^{\pm}}$

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

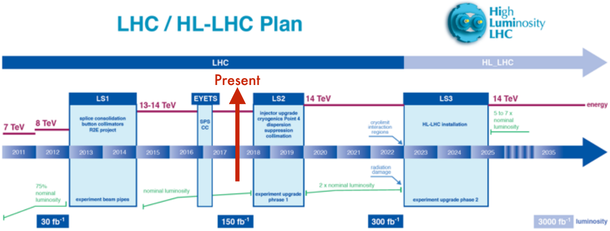
- bottom quark contributions
- top contamination:
  → tZj contributions for $\mathrm{W^{\pm}Z}$
  → tWj/t$\bar{\mathrm{t}}$ contributions for $\mathrm{W^{+}W^{-}}$

→ For $\mathrm{W^{+}W^{-}}$ or ZZ

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

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

LHC Future Timeline

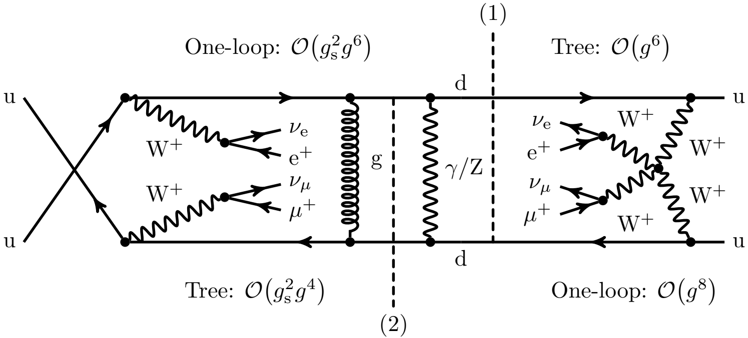


- **Assume scaling of uncertainties with 1/√L**

  - **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



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

Full NLO ss-WW

- Tools
  - $\rightarrow$ Virtual corrections: RECOLA [Actis, Denner, Hofer, Lang, Scharf, Uccirati]
  - + COLLIER [Denner, Dittmaier, Hofer]
  - $\rightarrow$ Private Monte Carlo MoCaNLO [Feger]
  - $\rightarrow$ Dipole subtraction scheme [Catani,Seymour], [Dittmaier]
  - $\rightarrow$ Complex-mass scheme [Denner et al.]
- Inputs
  - $\rightarrow$ G_μ scheme:

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

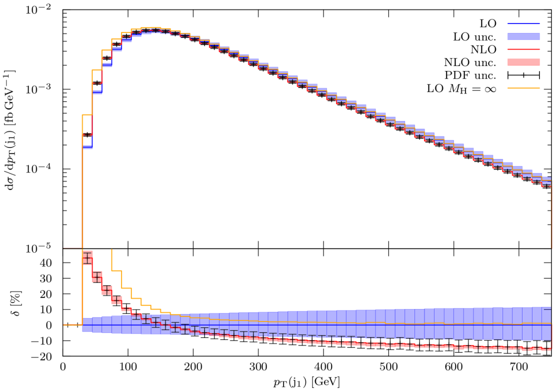
  - $\rightarrow$ Parameters:

$$\begin{aligned} m_t &= 173.21\,\text{GeV}, & \Gamma_t &= 0\,\text{GeV} \\ M_Z^{OS} &= 91.1876\,\text{GeV}, & \Gamma_Z^{OS} &= 2.4952\,\text{GeV} \\ M_W^{OS} &= 80.385\,\text{GeV}, & \Gamma_W^{OS} &= 2.085\,\text{GeV} \\ M_H &= 125\,\text{GeV} & \Gamma_H &= 4.07 \times 10^{-3}\,\text{GeV} \end{aligned}$$

Validations - Full NLO ss-WW

- 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

Effects from Higgs sector



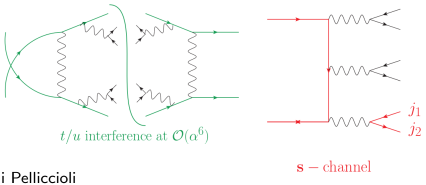
[Dittmaier, Maierhöfer, Schwan, Siegert, In: PoS RADCOR2017]

→ low p_T region sensitive to modified Higgs sector,

→ large p_T is unaffected

VBS approximation

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



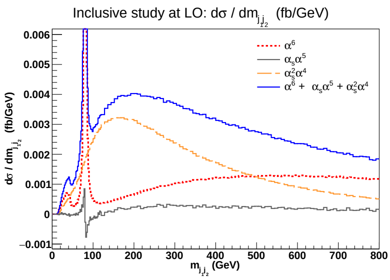
Source: Giovanni Pelliccioli

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]

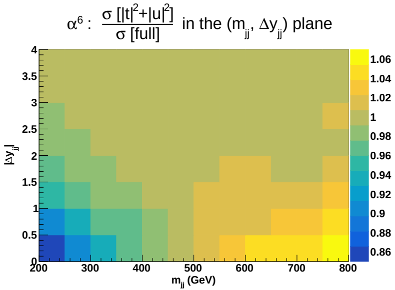
Quality of the VBS approximation (LO)

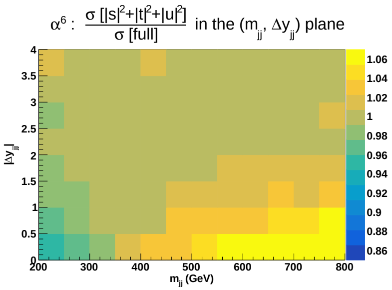


[Ballestrero, MP et al.; 1803.07943]

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

Quality of the VBS approximation (LO)



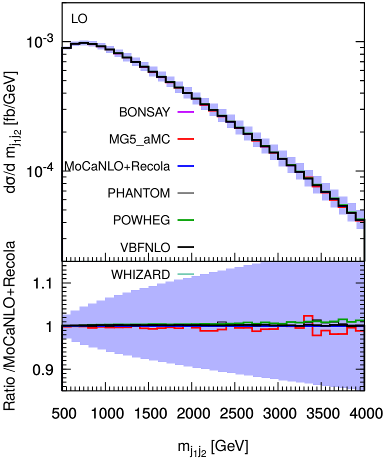


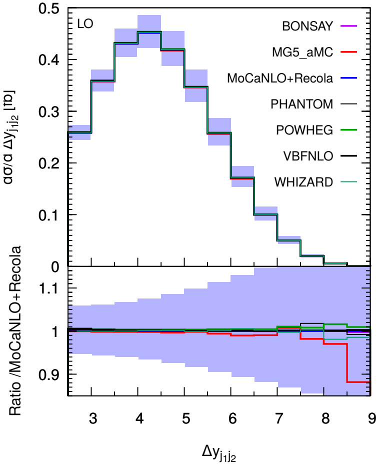
[Ballestrero, MP et al.; 1803.07943]

- 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)

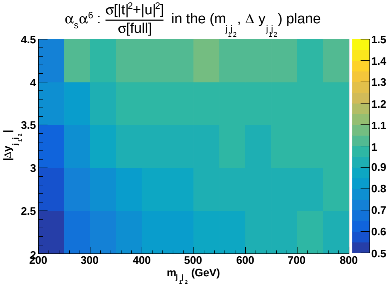


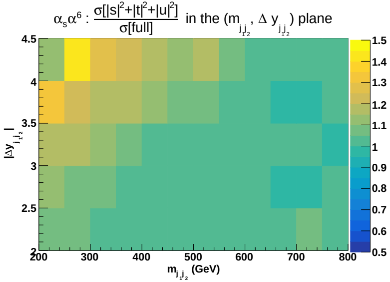


[Ballestrero, MP et al.; 1803.07943]

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

Quality of the VBS approximation (NLO)



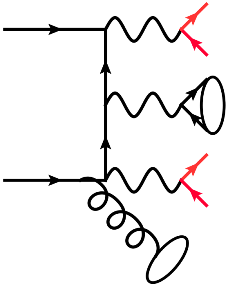


[Ballestrero, MP et al.; 1803.07943]

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

Quality of the VBS approximation (NLO)

→ Typical *s*-channel contribution:



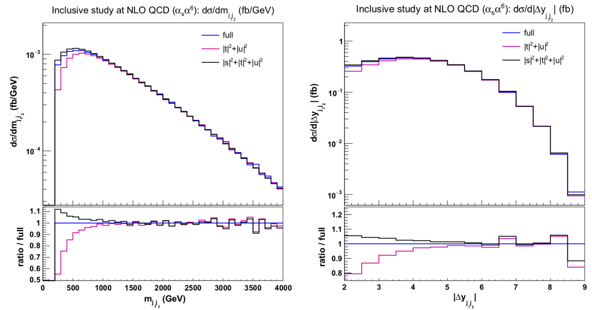
→ Less suppressed at NLO due to extra jet in the real

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

Slide from Alexander Karlberg

(https://indico.cern.ch/event/687651/contributions/3424591/

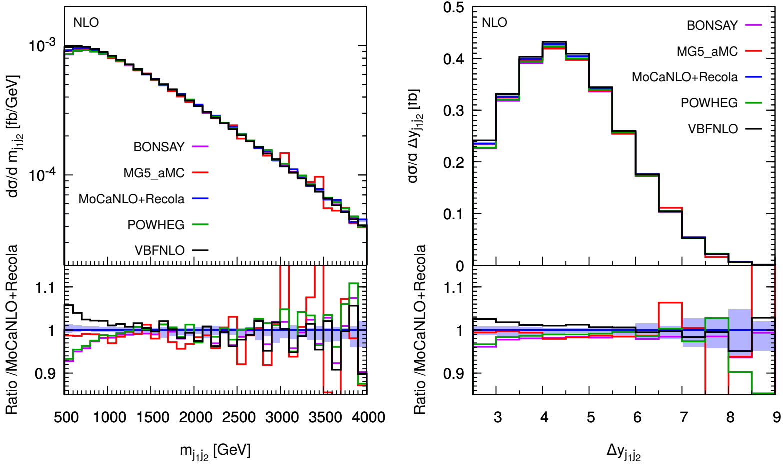
NLO contributions



- When NLO corrections are included the picture changes
- Now the VBS approximation breaks down at the $\mathcal{O}(10\%)$-level even when the cuts are moderately tight
- Since the full calculation at this order also includes EW corrections to the EW/QCD interference the separation of EW and QCD components also breaks down at this level

Unive Zurich

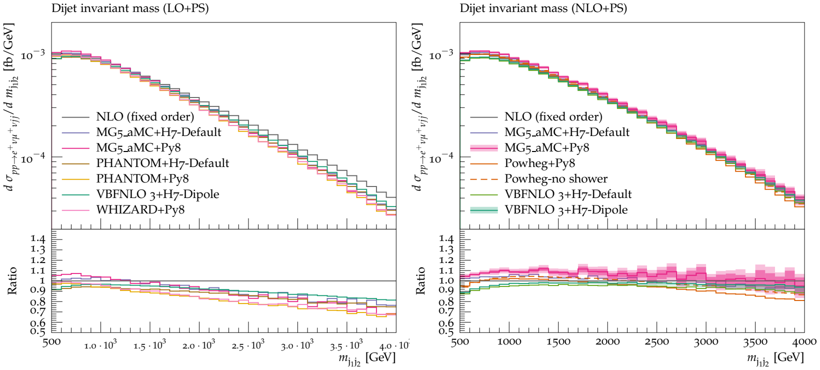
Quality of the VBS approximation (NLO)



[Ballestrero, MP et al.; 1803.07943]

- Differences lie outside the band
  → relevant for precision measurements

Beyond fixed order (1)

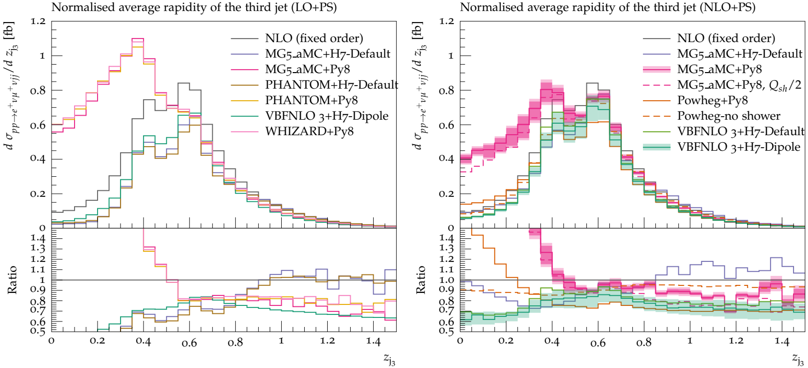


[Ballestrero, MP et al.; 1803.07943]

→ 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]

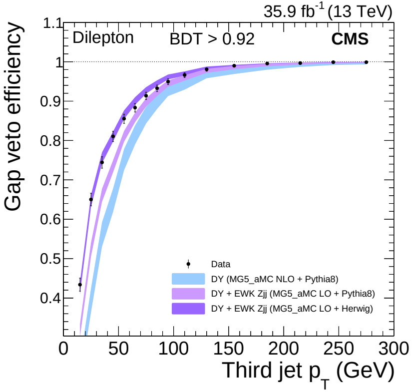
→ Very large differences for observables related to the third jet (only defined at NLO)

→ 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 ...

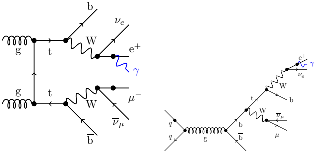
... but similar topologies ...

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

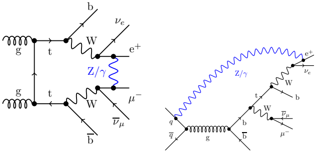
$\to$ NLO EW corrections are of order $\mathcal{O}\left(\alpha_\mathrm{s}^2\alpha^5\right)$ *i.e.* $\mathcal{O}\left(\mathrm{LO}\times\alpha\right)$

$\sigma_\mathrm{NLO} = \sigma_\mathrm{Born}\left[\alpha_\mathrm{s}^2\alpha^4\right] + \sigma_\mathrm{Real}\left[\alpha_\mathrm{s}^2\alpha^5\right] + \sigma_\mathrm{Virt}\left[\alpha_\mathrm{s}^2\alpha^5\right]$

Real corrections:



Virtual corrections:



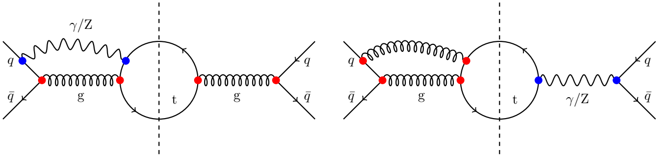
$\to$ No V =W, Z radiation considered (experimentally different signature)

$\to$ Sudakov logarithms: $-\frac{\alpha}{4\pi}\log^2\left(s_{ij}/M_V^2\right)$

NLO EW definition - $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$

→ NLO EW corrections are of order $\mathcal{O}\left(\alpha_\mathrm{s}^2\alpha^5\right)$

- → Two types of virtual corrections
- → Interference of EW and QCD processes



- → In the same way, interference channel: $\mathrm{g}q/\bar{q} \to \mathrm{t}^\star\bar{\mathrm{t}}^\star q/\bar{q}$

→ QCD corrections of photon induced $\mathcal{O}\left(\alpha_\mathrm{s}\alpha^5\right)$: $\mathrm{g}\gamma \to \mathrm{t}^\star\bar{\mathrm{t}}^\star$
(neglected here as Born contribution is already small)

Inputs - NLO EW tt

- For the renormalisation and factorisation scale:

$$\mu_{\mathrm{fix}} = m_{\mathrm{t}}$$

- G_μ scheme:

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

- Inputs:

$$\begin{aligned} m_{\mathrm{t}} &= 173.34\,\mathrm{GeV}, & \Gamma_{\mathrm{t}} &= 1.36918\ldots\ \mathrm{GeV} \\ M_{\mathrm{Z}}^{\mathrm{OS}} &= 91.1876\,\mathrm{GeV}, & \Gamma_{\mathrm{Z}}^{\mathrm{OS}} &= 2.4952\,\mathrm{GeV} \\ M_{\mathrm{W}}^{\mathrm{OS}} &= 80.385\,\mathrm{GeV}, & \Gamma_{\mathrm{W}}^{\mathrm{OS}} &= 2.085\,\mathrm{GeV} \\ M_{\mathrm{H}} &= 125.9\,\mathrm{GeV} \end{aligned}$$

→ Top width at NLO EW and QCD [Basso, Dittmaier, Huss, Oggero; 1507.04676]

Fiducial cross section - NLO EW tt

Ch.	σ_{LO} [fb]	$\sigma_{\mathrm{NLO\ EW}}$ [fb]	δ [%]
gg	2824.2(2)	2834.2(3)	0.35
$q\bar{q}$	375.29(1)	377.18(6)	0.50
$gq(/\bar{q})$		0.259(4)	
γg	27.930(1)		
pp	3199.5(2)	3211.7(3)	0.38

[Denner, MP; 1607.05571]

- Cross section dominated by the gg channel
- γg channel around 1%
- Small positive EW corrections
  $\rightarrow$ Negative corrections for on-shell top quarks ($\sim -1.5\%$)
  (due to the choice of the top width)