Status of EW NLO corrections for multi-boson processes

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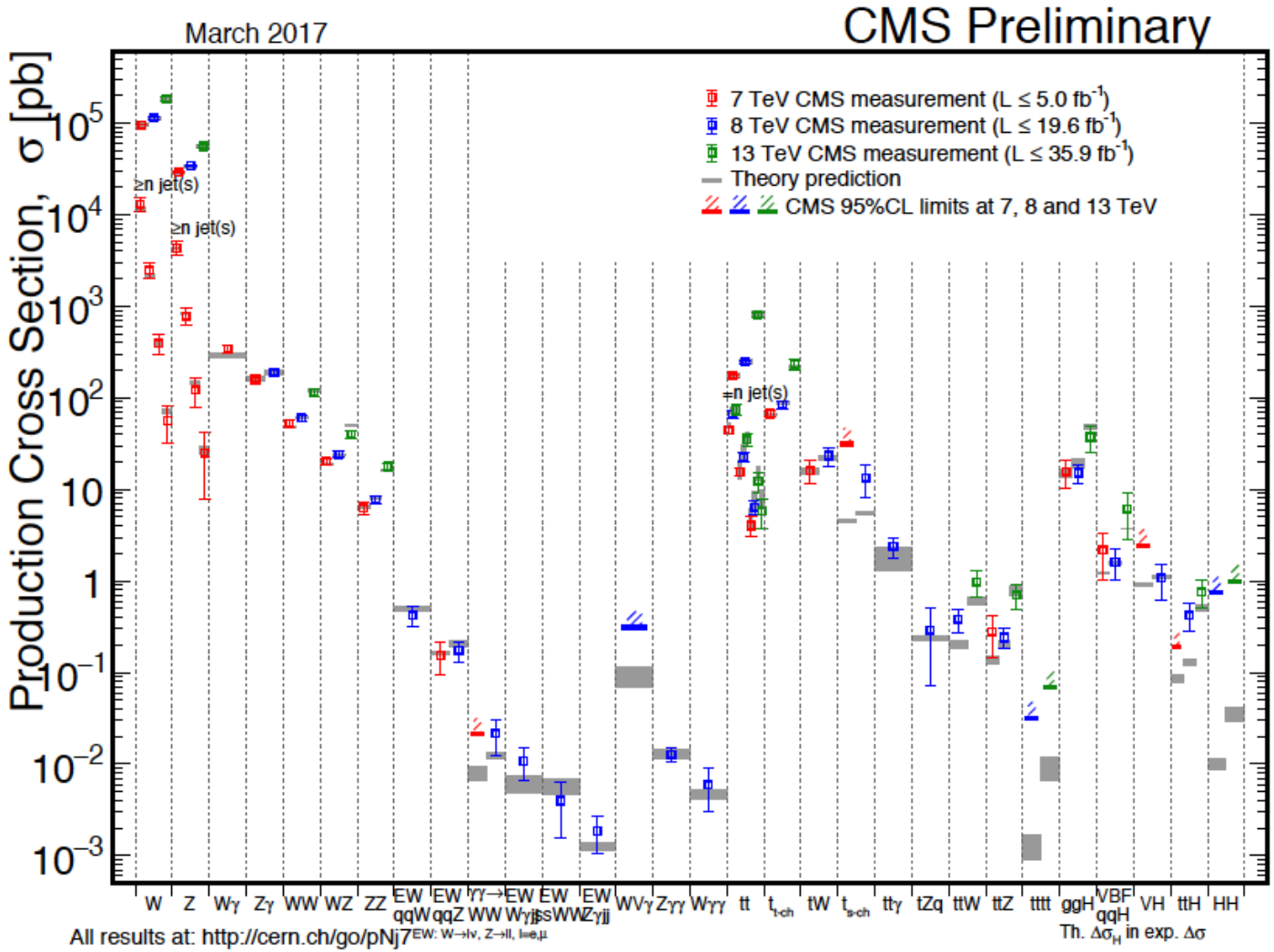
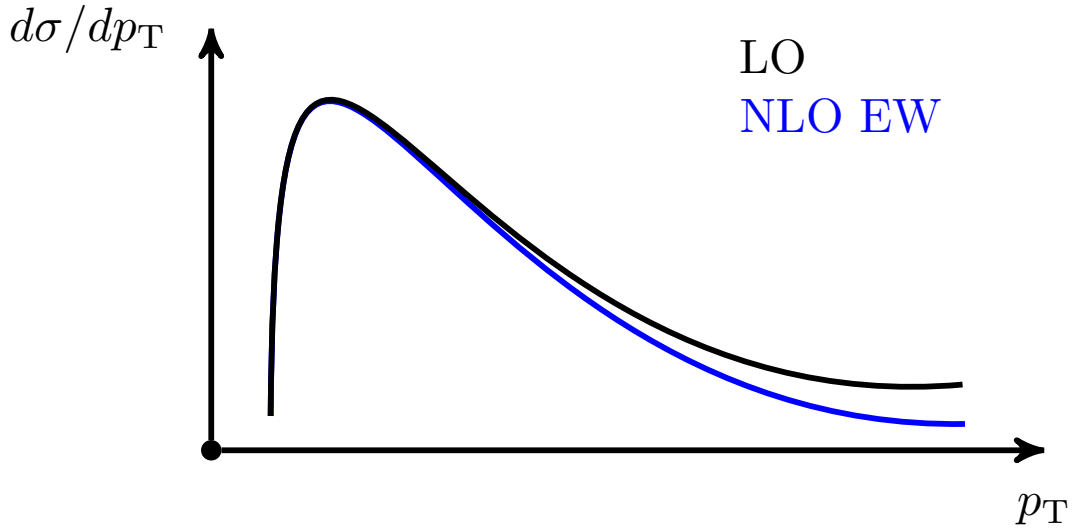


→ Precision physics in both experiment and theory

Electroweak (EW) corrections

- $\mathcal{O}(\alpha) \to \alpha \sim \alpha_s^2$
- Large in high energy region
  $\to$ Sudakov logarithms: $-\frac{\alpha}{4\pi}\log^2\left(s_{ij}/M_W^2\right)$



$\to$ During run II, the tail of the distributions will be probed
$\to$ New physics contributions?

Recent NLO EW computations at the LHC

Di-boson production:

- Stable W/Z [Bierweiler et al.; 1208.3147, 1305.5402], [Baglio, Le, Weber; 1307.4331]
- Approximate in HERWIG++ [Gieseke, Kasprzik, Kühn; 1401.3964]
- WW in DPA [Billoni, et al.; 1310.1564]

$\to$ Full NLO EW and off-shell computations:

- Z γ [Denner, et al.; 1510.08742]
- W γ [Denner, et al.; 1412.7421]
- WZ **[Biedermann, et al.; 1708.06938]**
- WW [Biedermann et al., 1605.03419]
- ZZ [Biedermann, et al.; 1601.07787, 1611.05338], [Biedermann, MP et al.; 1704.05783], **[Kallweit, et al.; 1705.00598]**

Recent NLO EW computations at the LHC

Tri-boson production (NWA and LO decay):

- $ZZ\gamma$ [Yong et al., 1707.03534]
- WWW **[Yong-Bai et al., 1605.00554], [Dittmaier, Huss, Knippen; 1705.03722] (on-shell)**
- WZZ [Yong-Bai et al., 1507.03693]
- ZZZ [Hong et al., 1610.05876]

Di-boson + X production (off-shell):

- $\gamma\gamma$+2jets [Fäh, Greiner; 1706.08309], [Chiesa et al.; 1706.09022]
- WWbb (tt) [Denner, MP, et al.; 1607.05571]
- WWbbH (tth) [Denner, MP; 1612.07138]
- WW2j (VBS) **[Biedermann, Denner, MP; 1708.00268, 1611.02951]**

Automatisation of NLO EW computations

- GoSam: `gosam.hepforge.org`
- MadLoop: `launchpad.net/mg5amcnlo`
  $\to$ obtained in MadGraph5_aMC@NLO (MG5)
- OpenLoops: `openloops.hepforge.org`
- Recola: `recola.hepforge.org`

Generator	Monte Carlo	Processes	Availability
GoSam	private MC	generated	soon
MadLoop	MG5	generated	soon
OpenLoops	Sherpa, private MC	libraries	soon
Recola	Sherpa, private MC	dynamical	soon

$\to$ See Steffen Schumann's talk:
Sherpa+OpenLoops and Sherpa+Recola

Biased selection

$\to$ **Biased selection:**

1. pp $\to 3\ell\nu$
2. pp $\to 2\ell 2\nu$
3. pp $\to$ WWW
4. pp $\to \mu^+\nu_\mu e^+\nu_e jj$

Content

pp $\to 3\ell\nu$ / WZ

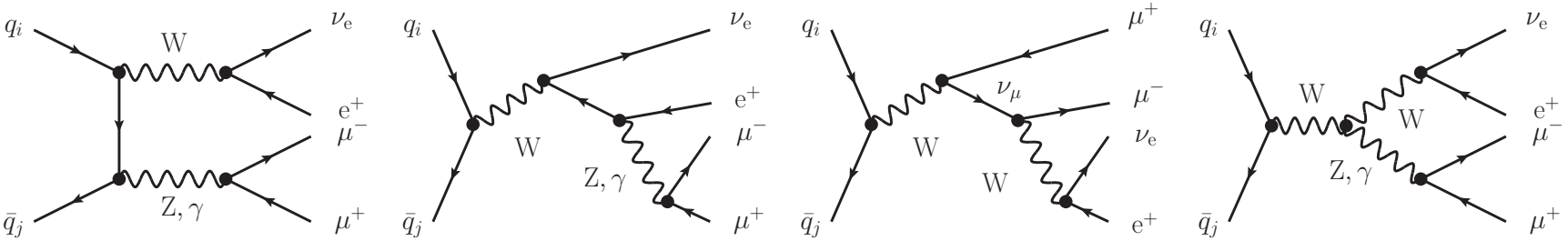
State of the art for EW computation:

Stable W/Z [Bierweiler et al.; 1208.3147, 1305.5402], [Baglio, Le, Weber; 1307.4331]

Logarithmic approximation [Gieseke, Kasprzik, Kühn; 1401.3964]

$\to$ New: **[Biedermann, Denner, Hofer; 1708.06938]**

- pp $\to \mu^+\mu^-e^+\nu_e$, $\mu^+\mu^-e^-\bar{\nu}_e$, $\mu^+\mu^-\mu^+\nu_\mu$, $\mu^+\mu^-\mu^-\bar{\nu}_\mu$
- Full NLO EW for off-shell production
- Two different set-ups:
  inclusive and anomalous triple gauge coupling (aTGC) search
- NLO photon induced contribution



Fiducial cross section

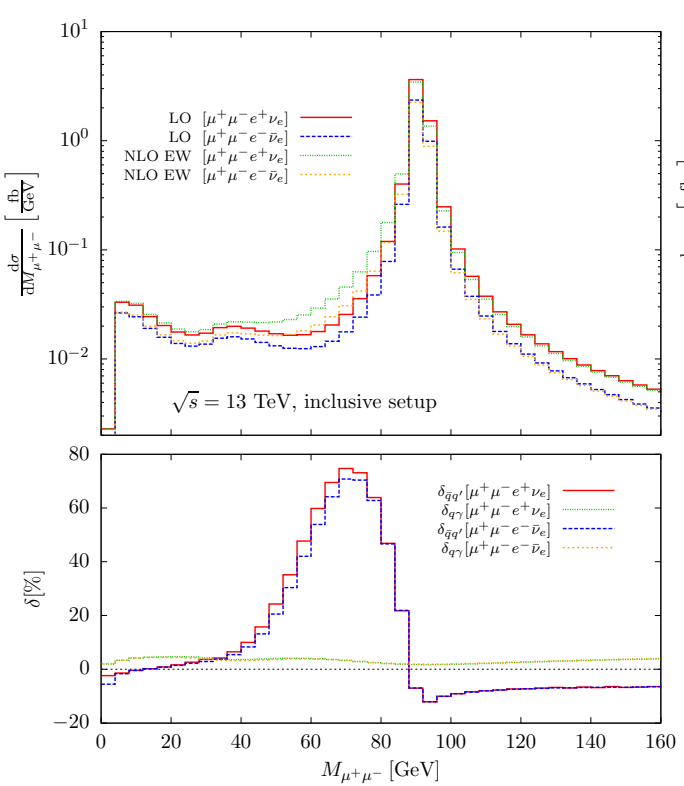
mixed flavour $[2\mu e\nu]$		σ_{LO} [fb]	$\delta_{\bar{q}q'}(\%)$	$\delta_{q\gamma}(\%)$	$\delta_{\text{NLO}}(\%)$
inclusive	$pp \to \mu^+\mu^- e^+\nu_e + X$	27.303(1)	$-3.308(5)$	$+1.9564(4)$	$-1.351(5)$
TGC	$pp \to \mu^+\mu^- e^+\nu_e + X$	19.1625(6)	$-5.986(6)$	$+1.6971(3)$	$-4.289(6)$

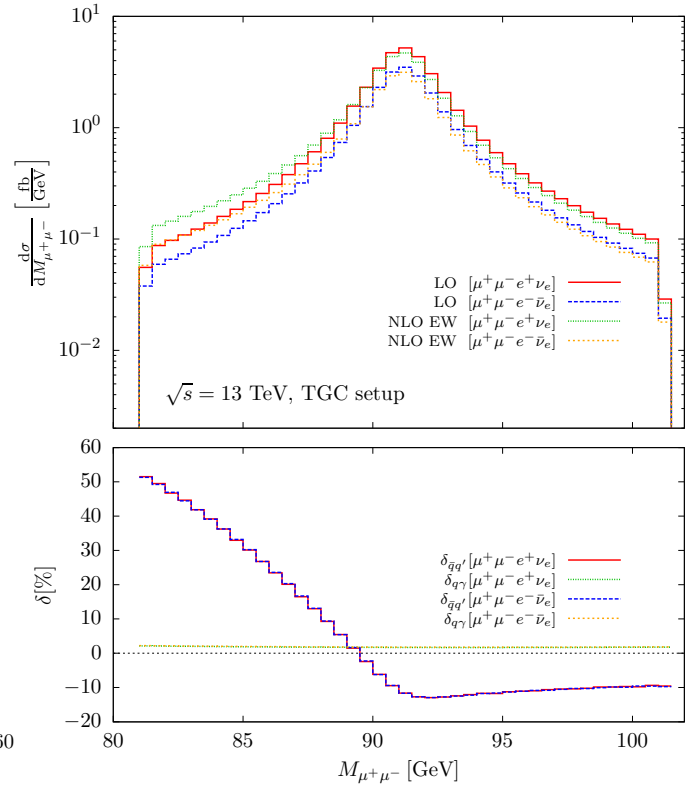
[Biedermann, Denner, Hofer; 1708.06938]

- Different LO cross sections:
  due to more exclusive cuts in TGC set-up
- Positive photon-induced contribution:
  compensating partly the qq' EW corrections
- Different qq' EW corrections according to the set-up
- -2% difference vs. on-shell calculation [Baglio, Le, Weber; 1307.4331]
  $\to$ Effect of final state radiations

pp $\to 3\ell\nu$

In TGC set-up: $M_Z - 10\,\text{GeV} < M_{\ell_Z^+,\ell_Z^-} < M_Z + 10\,\text{GeV}$





→ Radiative tail below the Z pole [Biedermann, Denner, Hofer; 1708.06938]

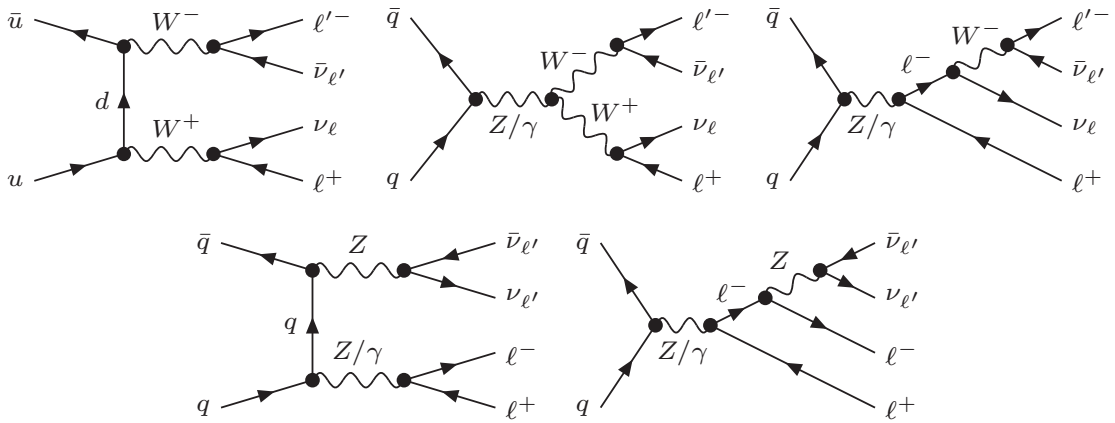
→ Sudakov logarithms: -25% at 1.5 TeV

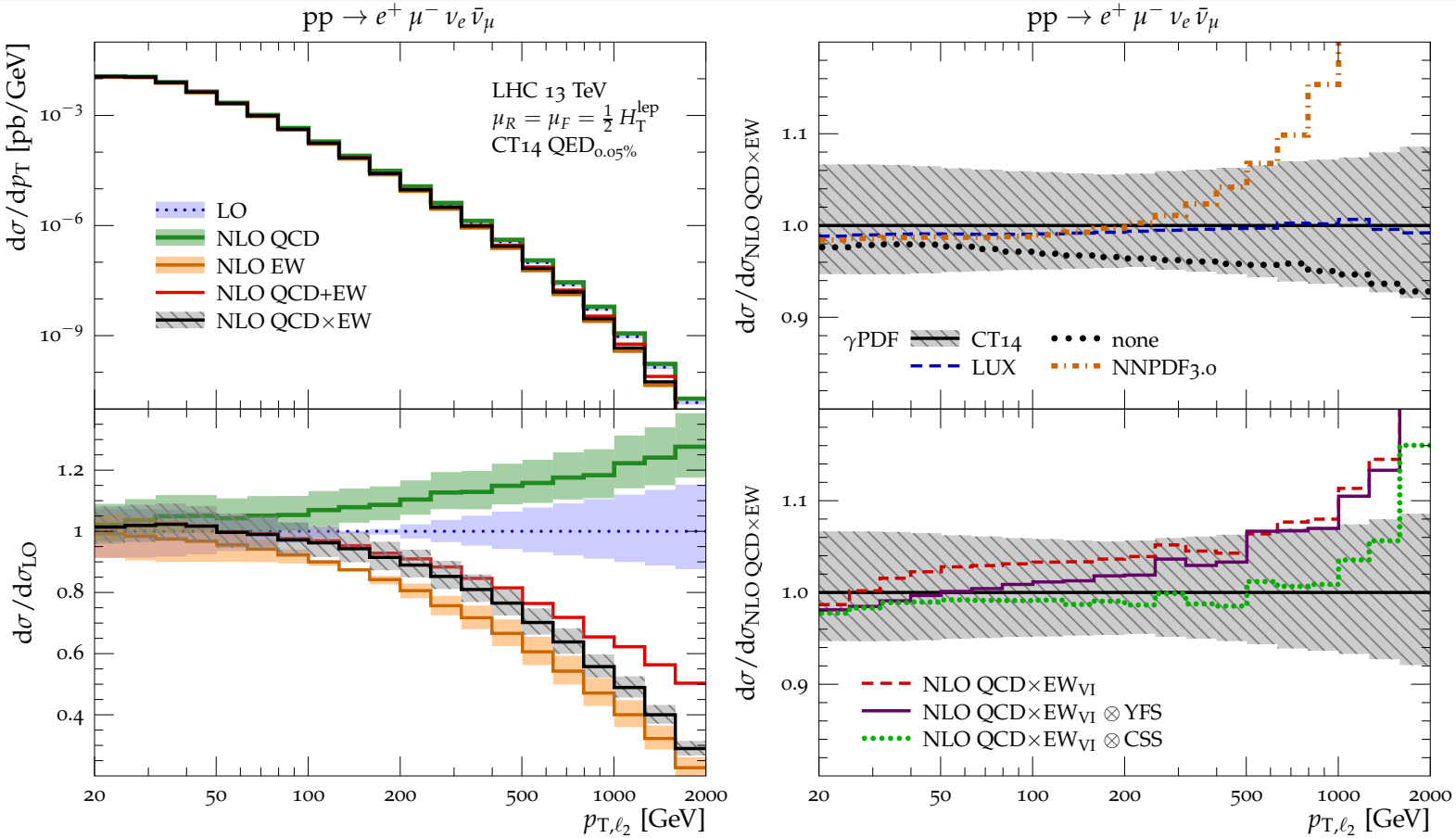
→ EW corrections are important and should be included

Content

$\to$ New: **[Kallweit, Lindert, Pozzorini, Schönherr; 1705.00598]**

- $pp \to e^+\mu^-\nu_e\bar{\nu}_\mu$, $e^+e^-\nu\bar{\nu}$
- Full NLO EW for off-shell production
- Features WW, ZZ and $Z\gamma$ production
- Combined with NLO QCD
- Study of photon induced contributions
- Done in Munich/Sherpa+OpenLoops framework



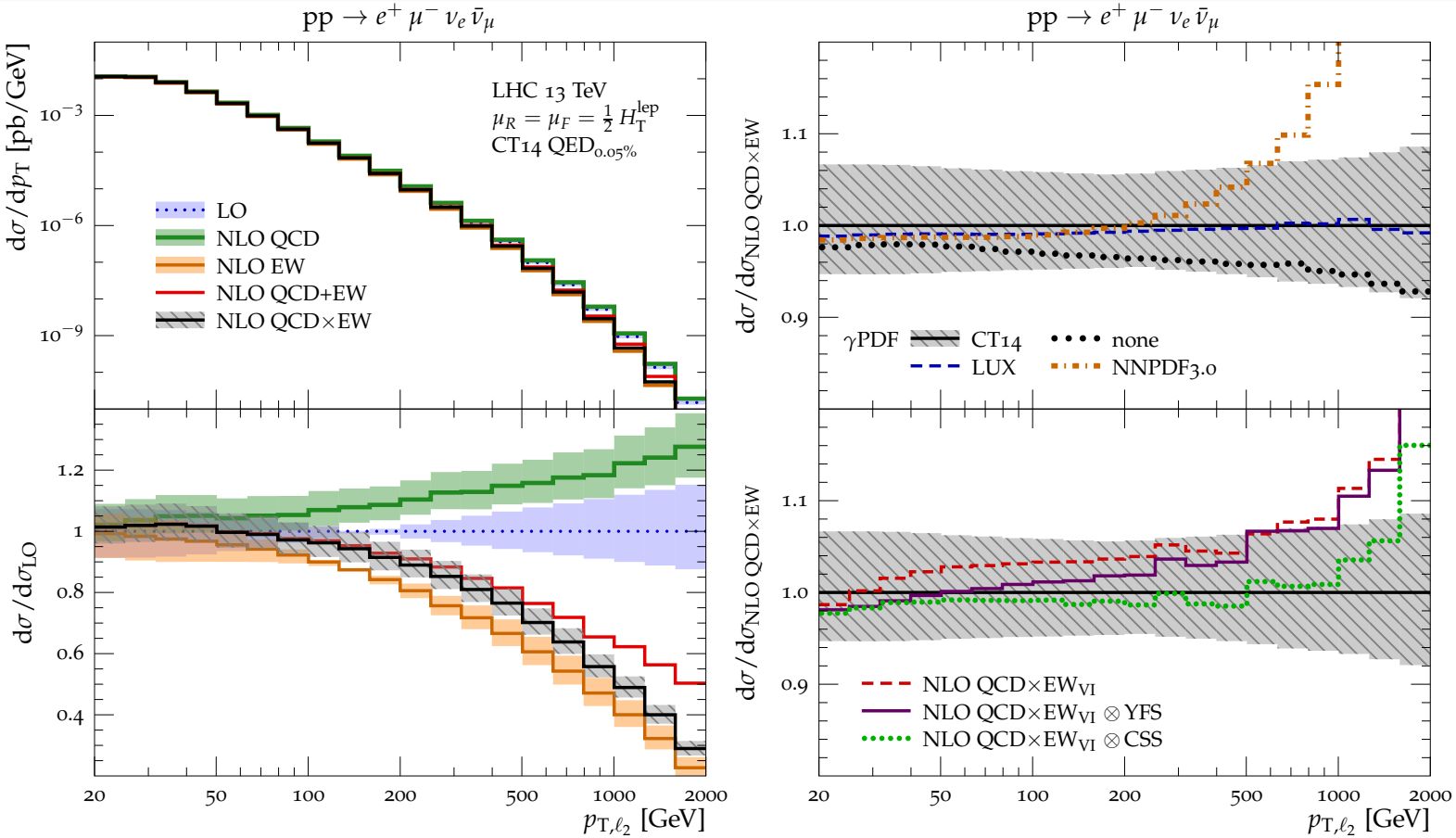


[Kallweit, Lindert, Pozzorini, Schönherr; 1705.00598]

→ Inclusion of NLO QCD

→ Comparison of different photon PDF

→ Various EW approximations



[Kallweit, Lindert, Pozzorini, Schönherr; 1705.00598]

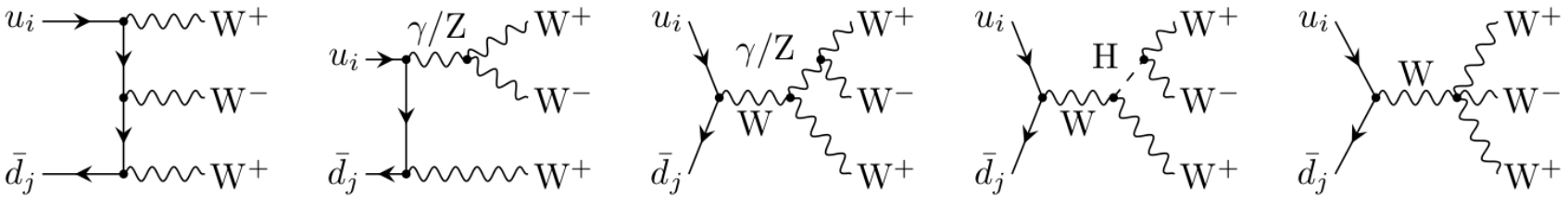
→ Any di-boson computations in Sherpa+(OpenLoops/Recola): NLO EW soon public → see Steffen Schumann's talk

→ Systematic study of EW corrections possible

Content

Two new computations available for pp $\to$ WWW:

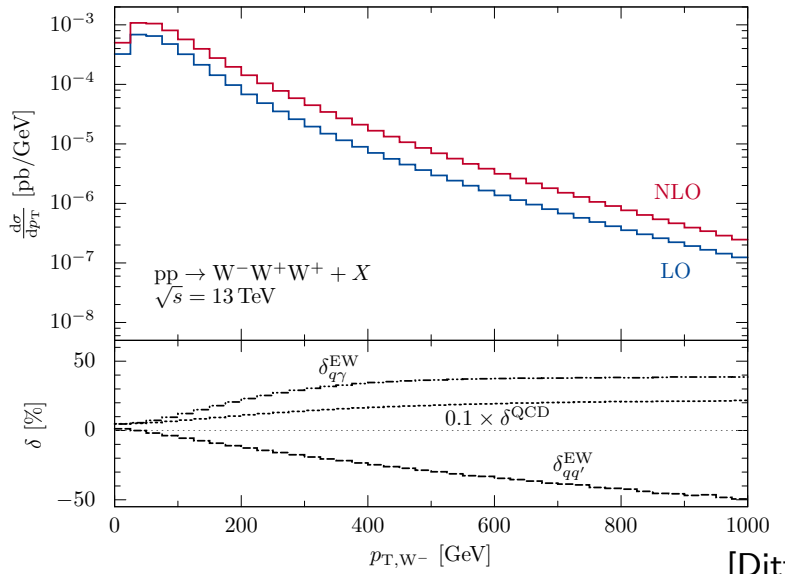
- **[Yong-Bai, Ren-You, Wen-Gan, Xiao-Zhou, Lei; 1605.00554]**
  - NLO EW to the production
  - MadSpin for NWA and LO decay
  - Study of jet veto
- **[Dittmaier, Huss, Knippen; 1705.03722]**
  - On-shell computation
  - Study of jet veto
  - Study of photon induced contribution



Reference	σ^{LO} [fb]	σ^{NLO} [fb]	δ^{QCD} [%]	$\delta^{\text{EW}}_{\text{q}\bar{\text{q}}}$ [%]	$\delta^{\text{EW}}_{\text{q}\gamma}$ [fb]
[Yong-Bai, et al.; 1605.00554]	78.645(10)	186.42(6)	106.96(4)	-4.199(5)	18.73(2)
[Dittmaier, et al.; 1705.03722]	78.65(1)	187.04(9)	107.50	-4.16	18.77

[Dittmaier, Huss, Knippen; 1705.03722]

→ Reasonable agreement between the two computations

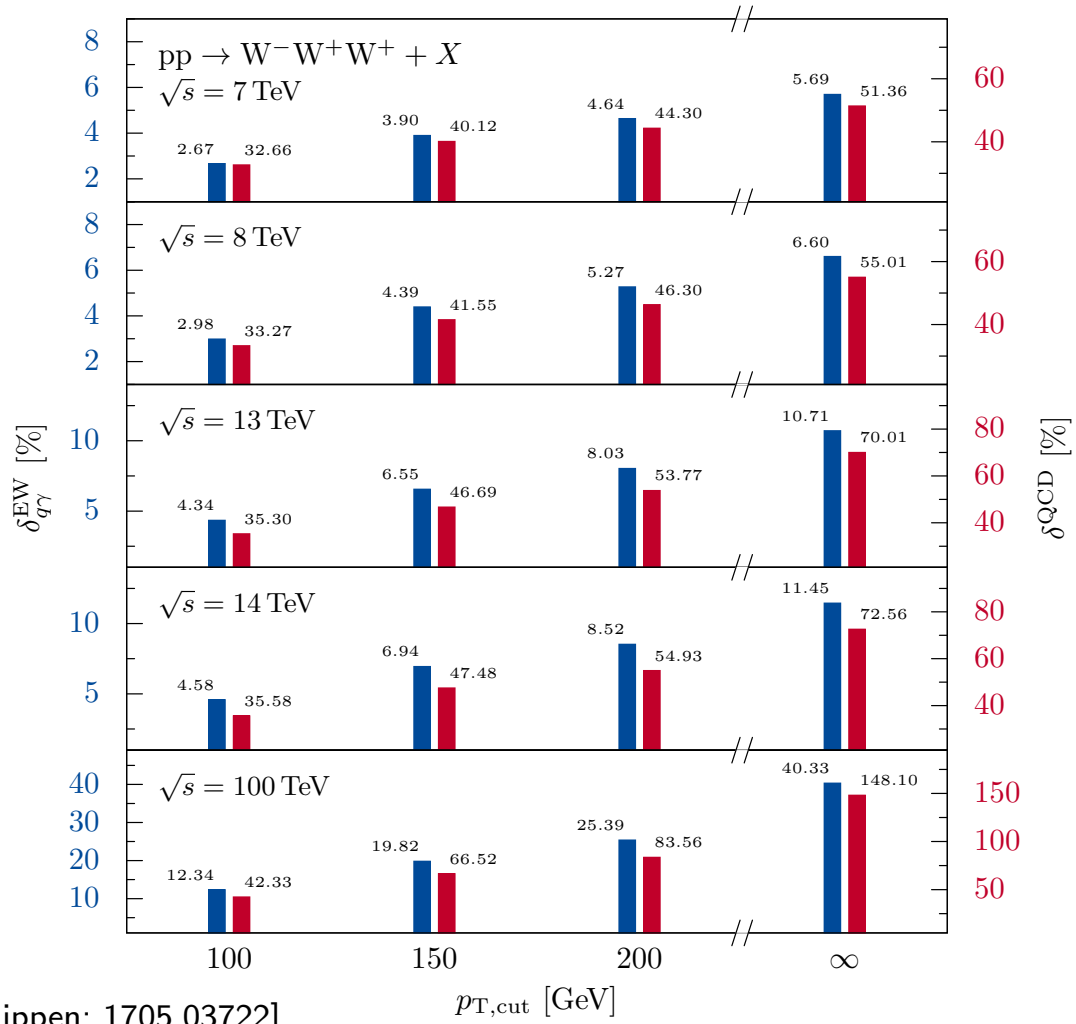


[Dittmaier, Huss, Knippen; 1705.03722]

→ Large QCD corrections

→ Positive EW corrections for γq channels

→ Typical Sudakov logarithms for qq channels



[Dittmaier, Huss, Knippen; 1705.03722]

→ NLO QCD and photon-induced corrections suppressed with jet veto

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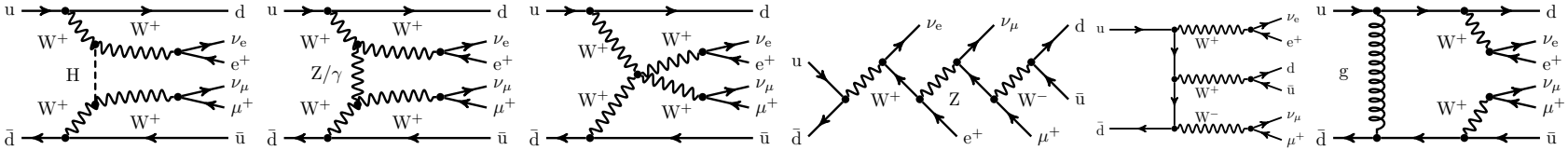
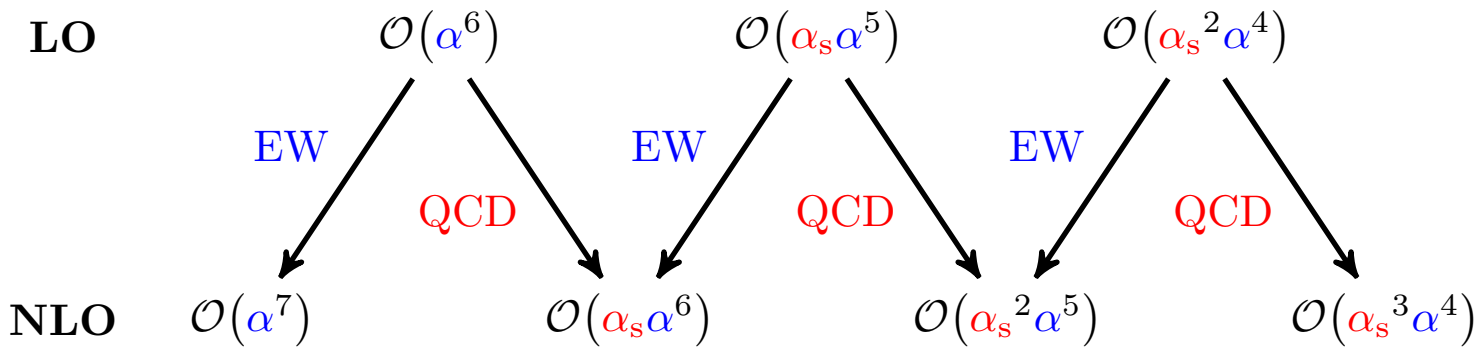
$\to$ New: **[Biedermann, Denner, MP; 1708.00268, 1611.02951]**



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 $\mathcal{O}\left(\alpha_s{}^3\alpha^4\right)$

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

$\to$ Combined measurement for pp $\to \mu^+\nu_\mu e^+\nu_e jj$

→ LO fiducial cross sections:

Order	$\mathcal{O}(\alpha^6)$	$\mathcal{O}(\alpha_s\alpha^5)$	$\mathcal{O}(\alpha_s^2\alpha^4)$	Sum
σ_{LO} [fb]	1.4178(2)	0.04815(2)	0.17229(5)	1.6383(2)

→ NLO fiducial cross sections: (normalised to $\sum \sigma_{\text{LO}}$)

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
$\delta\sigma_{\text{NLO}}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_{\text{NLO}}/\sigma_{\text{LO}}$ [%]	−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 $\mathcal{O}(\alpha_s\alpha^6)$:

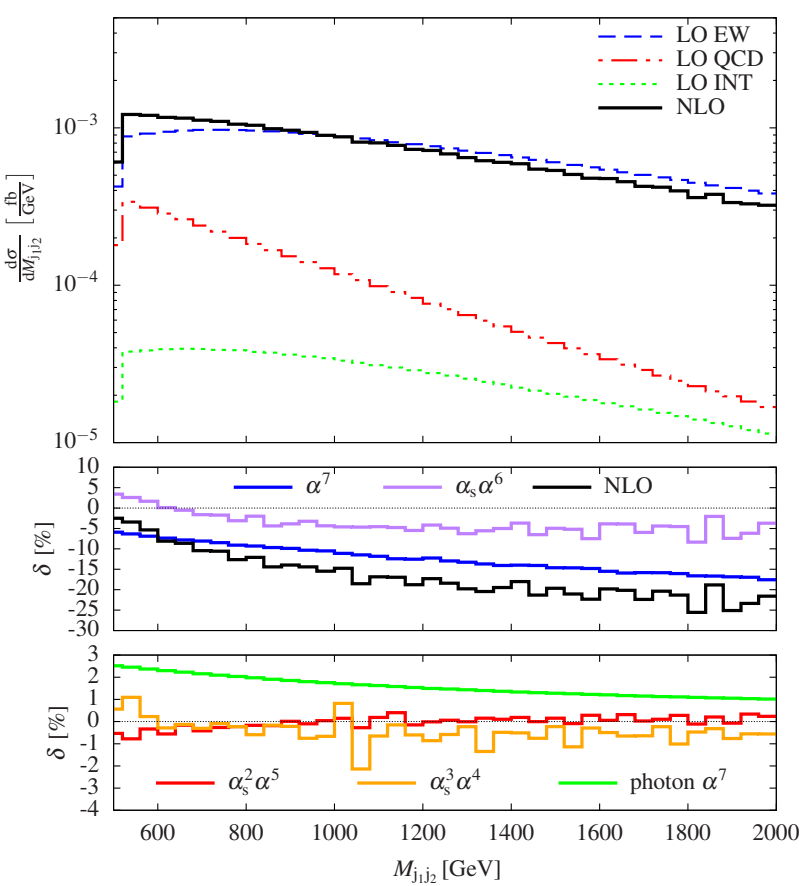
$\sim$ 0.6% difference with respect to VBS approximation
(negelecting *s*-channel and *t*-/*u*-channel interferences)

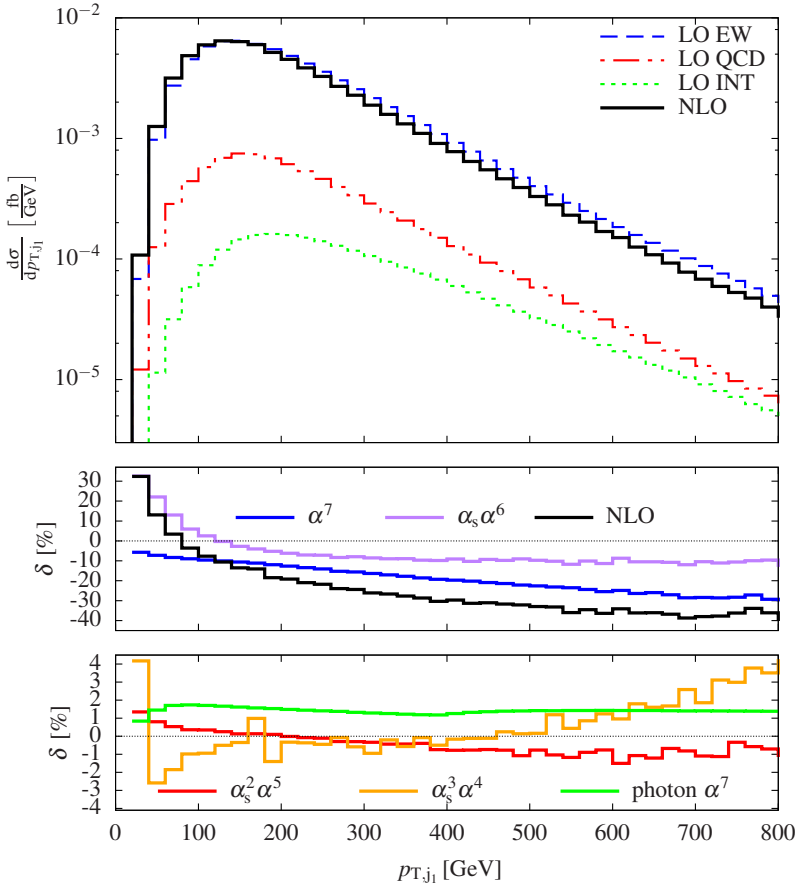
→ Tuned comparison against [Denner, et al.; 1209.2389] and [Jäger, et al.; 0907.0580]

→ VBS approximation in RECOLA

→ 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

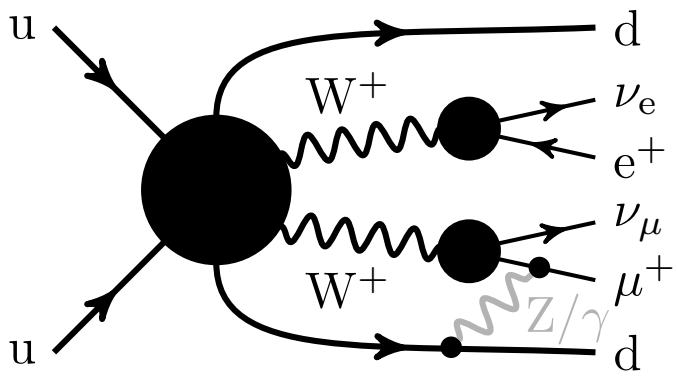
→ Different behaviour of the NLO corrections (normalised to the full LO)

$\to$ Large NLO electroweak correction (!) at order $\mathcal{O}(\alpha^7)$
$\delta_{\text{EW}}^{\text{NLO}} = -16\%$ when normalised to the LO EW process

[Biedermann, Denner, MP; 1611.02951]

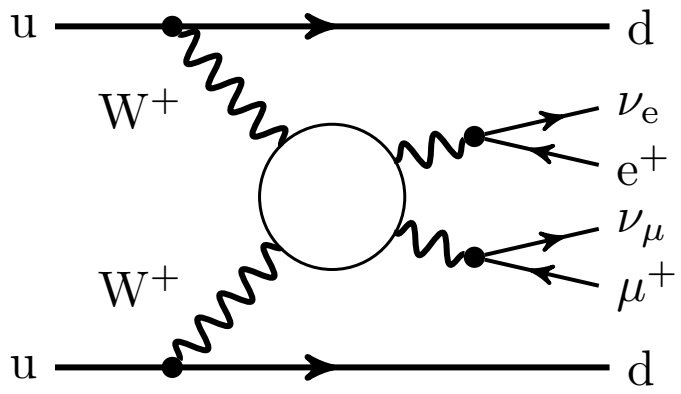
- Leading behaviour dominated by:
  Sudakov logarithms (bosonic part of the virtual), $\log^2\left(\frac{Q^2}{M_W^2}\right)$
  $\to$ Usually in the tail of the distribution (suppressed)
  $\to$ Usually small for total cross section
  $\to$ Usually smaller than the QCD corrections
- Large corrections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

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



- Agree within 1% with full calculation [Biedermann, Denner, MP; 1611.02951]
- Dominated by factorisable corrections
  $\to$ 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]

  [Biedermann, Denner, MP; 1611.02951]

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

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

[Biedermann, Denner, MP; 1611.02951]

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

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

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

→ 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

Conclusion

- **NLO EW corrections are very relevant for Run II**
- Recent computations for di-boson production:
  - pp $\to 3\ell\nu$ [Biedermann, Denner, Hofer; 1708.06938]
  - pp $\to 2\ell 2\nu$ [Kallweit, Lindert, Pozzorini, Schönherr; 1705.00598]
- **Progresses in automation of NLO EW**
- All tri-boson computations known in NWA with LO decay
  - Example: pp $\to$ WWW

    [Yong-Bai et al., 1605.00554], [Dittmaier, Huss, Knippen; 1705.03722] (on-shell)
- New off-shell computations for $2 \to 6/7$ processes
  - pp $\to \mu^+\nu_\mu e^+\nu_e jj$ [Biedermann, Denner, MP; 1611.02951, 1708.00268]

Back-up slides

BACK-UP

[Biedermann, Denner, MP; 1611.02951, 1708.00268]

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

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

  charged lepton: $p_{T,\ell} > 20\,\text{GeV}, \quad |y_\ell| < 2.5, \quad \Delta R_{\ell\ell} > 0.3$

  jets: $p_{T,j} > 30\,\text{GeV}, \quad |y_j| < 4.5, \quad \Delta R_{j\ell} > 0.3$

  missing energy: $p_{T,miss} > 40\,\text{GeV},$

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

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

  $\to$ Final state: 2 jets, missing $p_{T,}$, 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