Off-shell effects in tt and tth production

Mathieu PELLEN

Cavendish Laboratory,
University of Cambridge

ZPW2020

Zurich - Switzerland

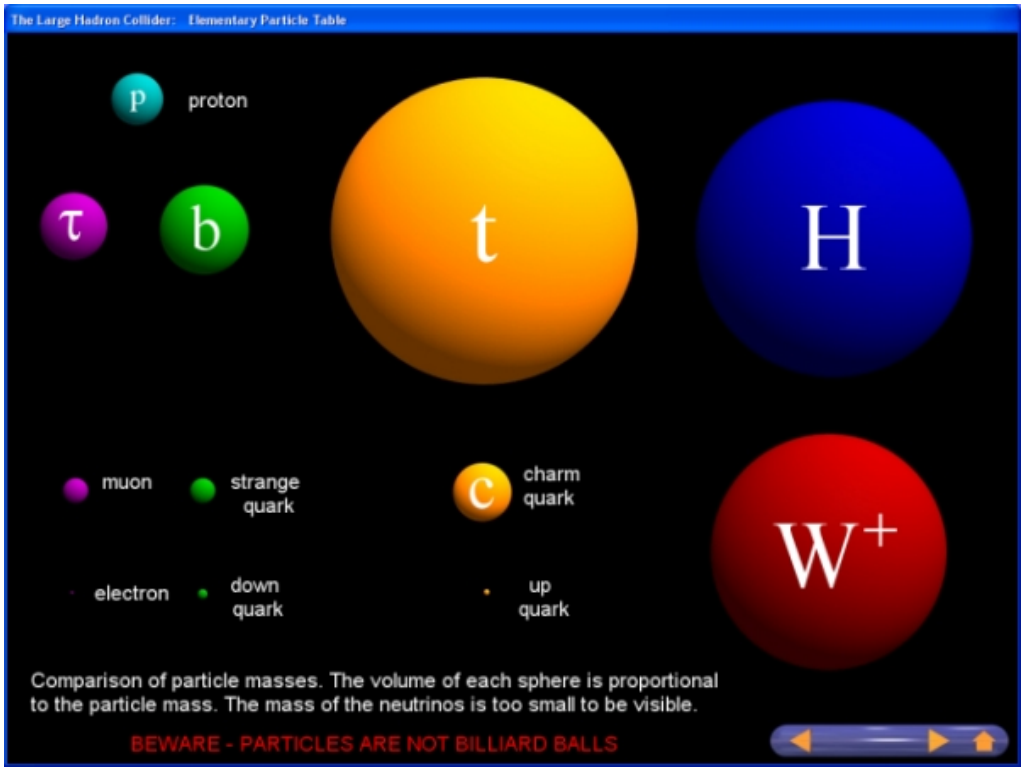
14th of January 2020

UNIVERSITY OF CAMBRIDGE

European Research Council

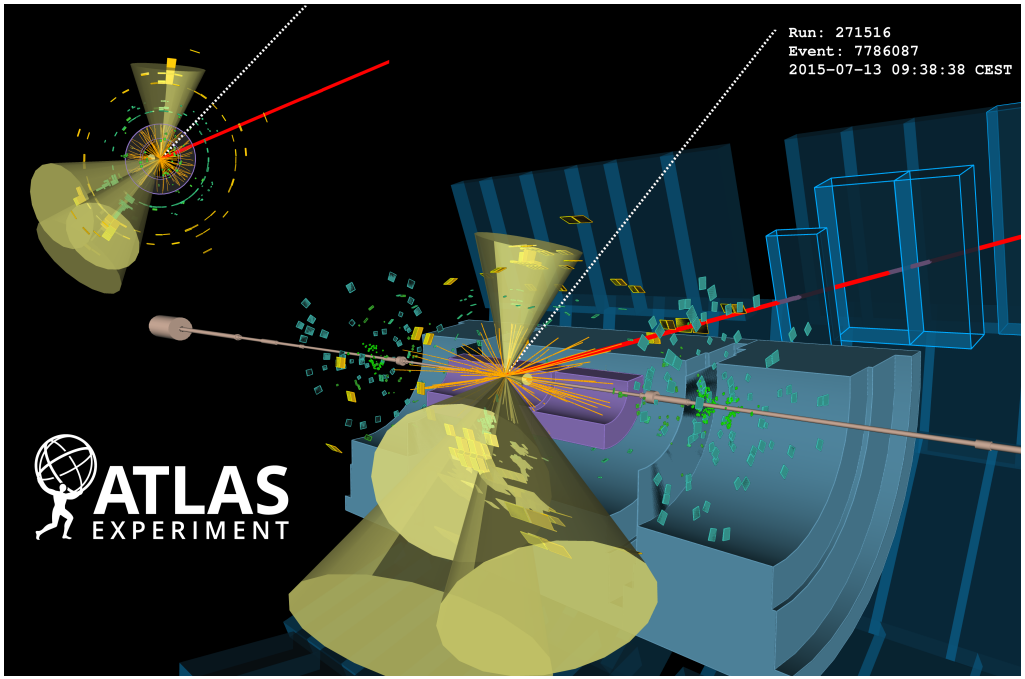
Why are top quarks and Higgs bosons interesting?

- They are the heaviest particles of the Standard Model!

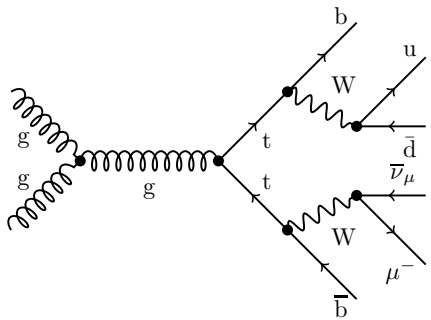


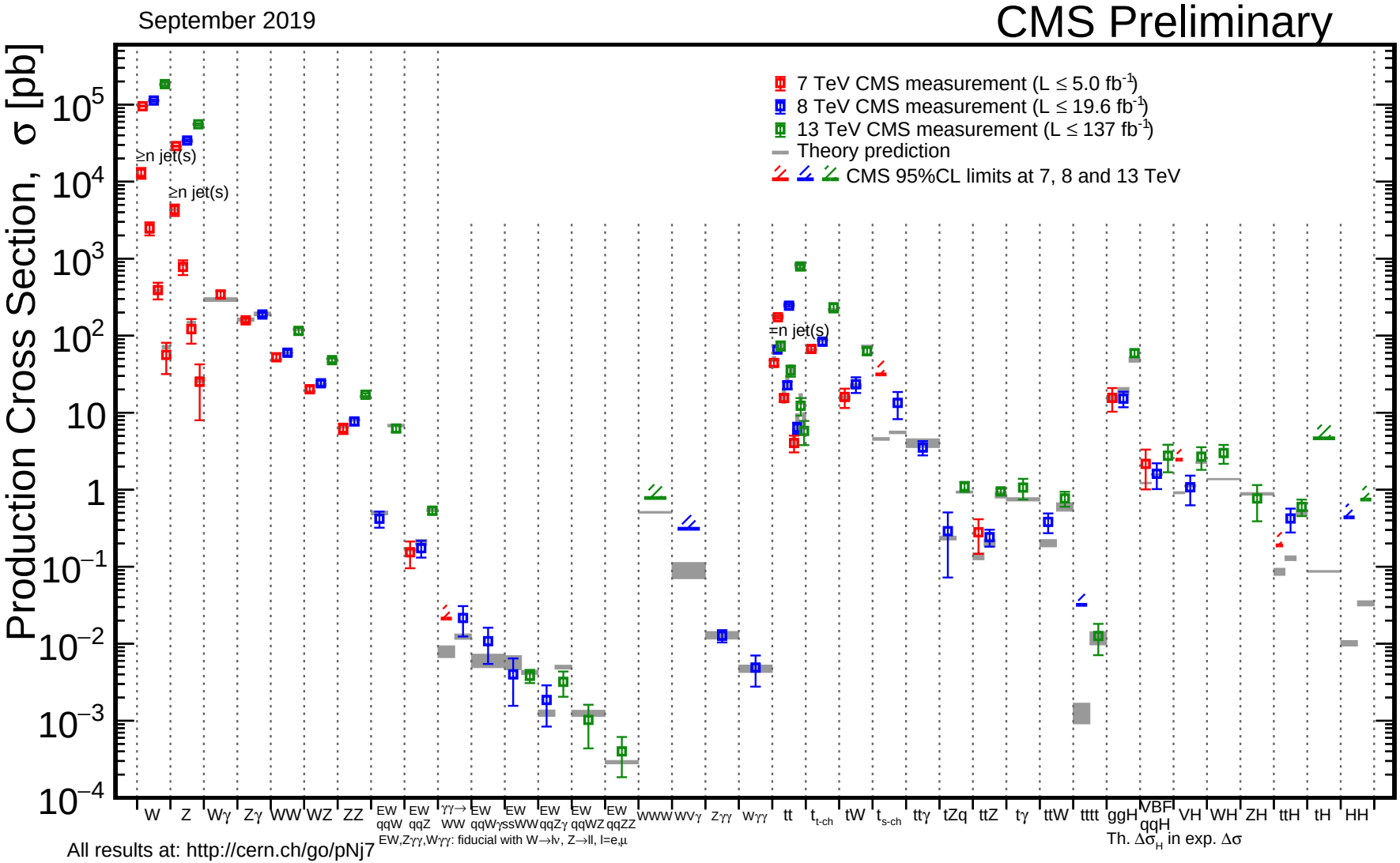
- ...

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



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

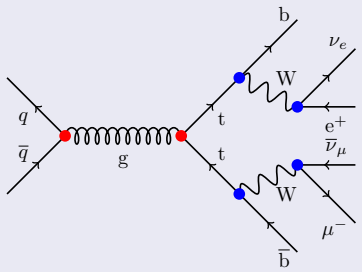


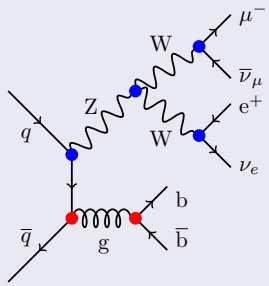


→ **Able to probe QCD, EW, and off-shell effects**

Off-shell effects

- Invariants off their mass shells
  → *e.g.* $M_{\ell\nu \mathrm{b}} \neq m_{\mathrm{top}}$

- Non-resonant contributions
  → *e.g.* 

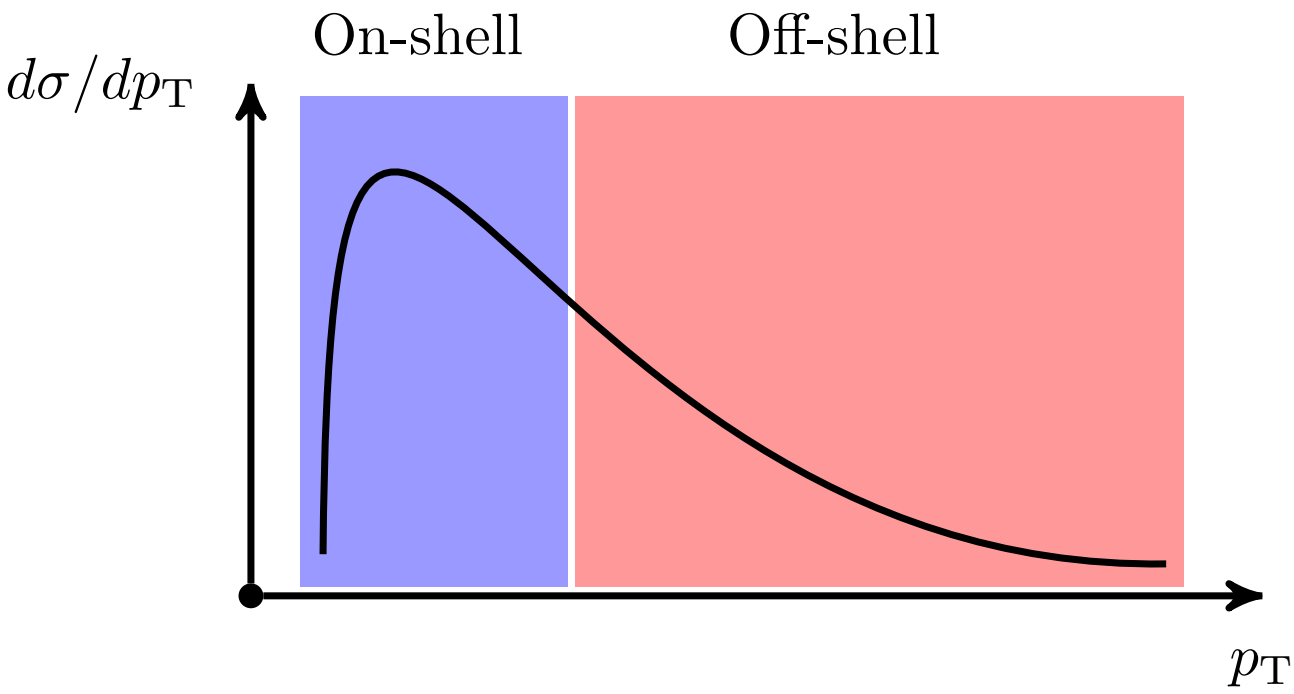
vs. 

- Description of the final state
  → *e.g.* $\mathrm{pp} \to \mathrm{t\bar{t}}$ vs. $\mathrm{pp} \to \nu_\mu \mu^- \bar{\nu}_\mathrm{e} \mathrm{e}^+ \mathrm{b\bar{b}}$

→ All these effects are very much connected

Off-shell effects

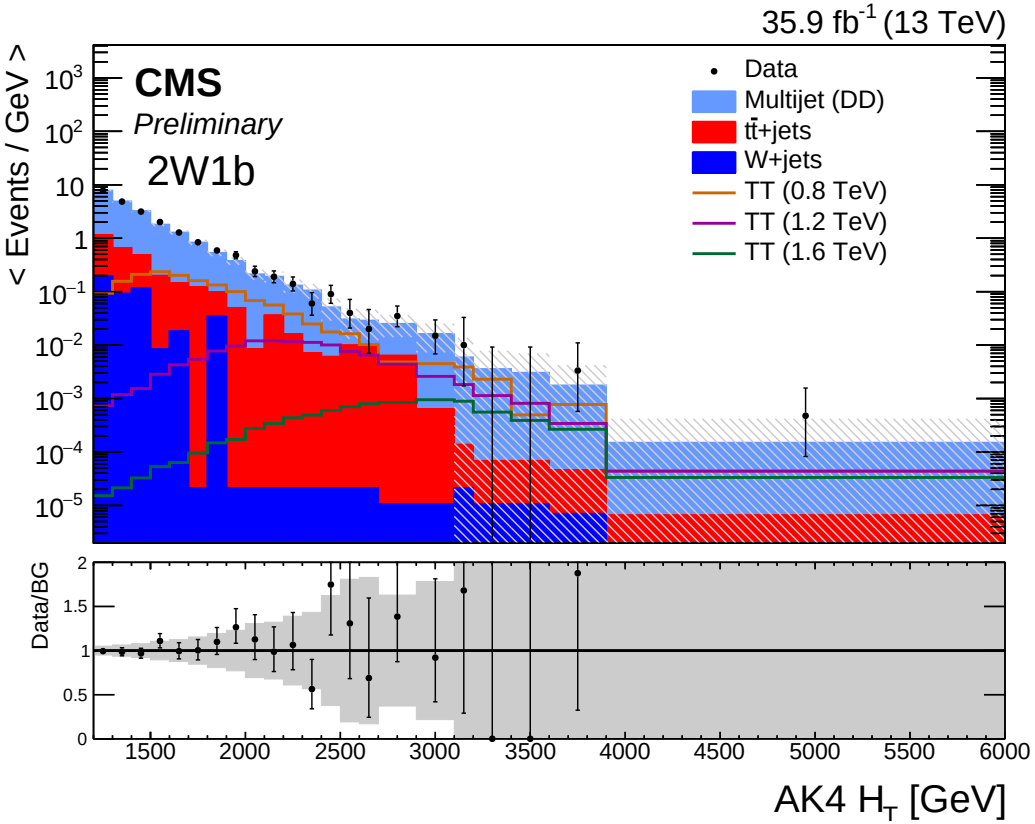
- Final states dominated by a production process
- Example: measured final state $\mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}$ dominated by $\mathrm{pp} \to \mathrm{t}^\star\bar{\mathrm{t}}^\star \to (\mathrm{W}^\star \to \nu_\mu\mu^-)\,(\mathrm{W}^\star \to \mathrm{e}^+\nu_\mathrm{e})\,\mathrm{b}\bar{\mathrm{b}}$



On-shell region dominated by resonant production

Off-shell region receives large non-resonant contributions

Tail of distributions



Search for vector-like quark [CMS-PAS-B2G-18-005]

→ During run II/III, the tail of the distributions will be probed

→ New physics contributions?

Outline:

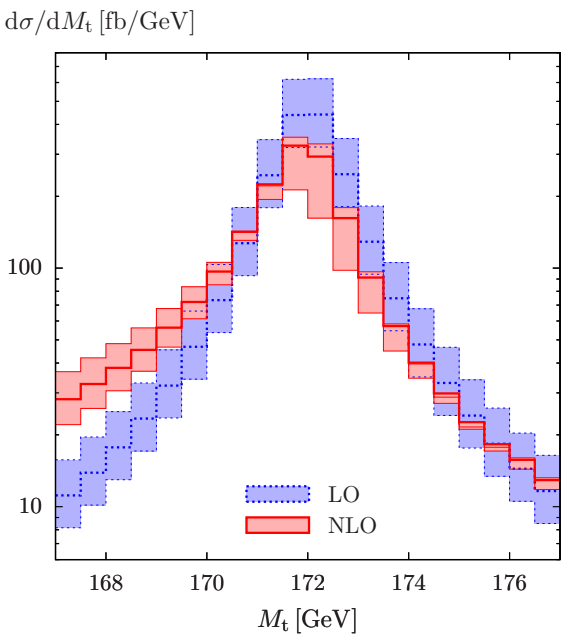
- NLO QCD/EW to pp $\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$
- NLO QCD/EW to pp $\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$
- NLO QCD to pp $\to \mu^-\bar{\nu}_\mu jjb\bar{b}$

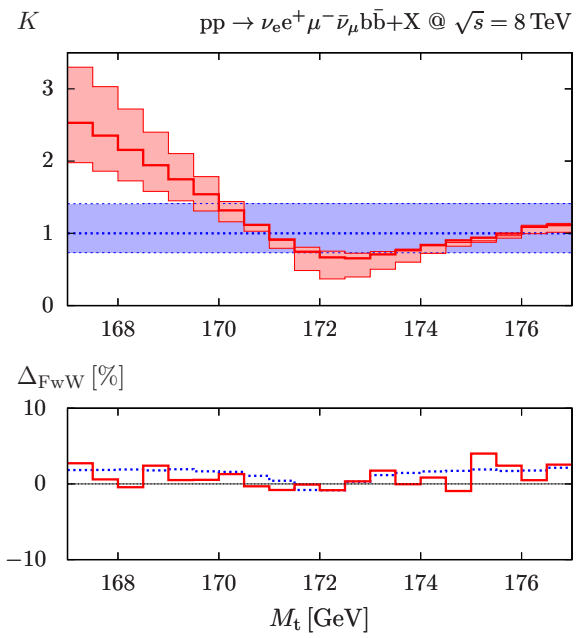
1) State of the art top-antitop production

- NLO QCD [Frixione et al.; hep-ph/9503213], [Bernreuther et al.; hep-ph/0403035], [Melnikov, Schulze; 0907.3090], [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]
  → With off-shell effects for leptons+jets [Denner, MP; 1711.10359]
- 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]
  → Combined 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]

1) NLO QCD/EW to pp $\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$

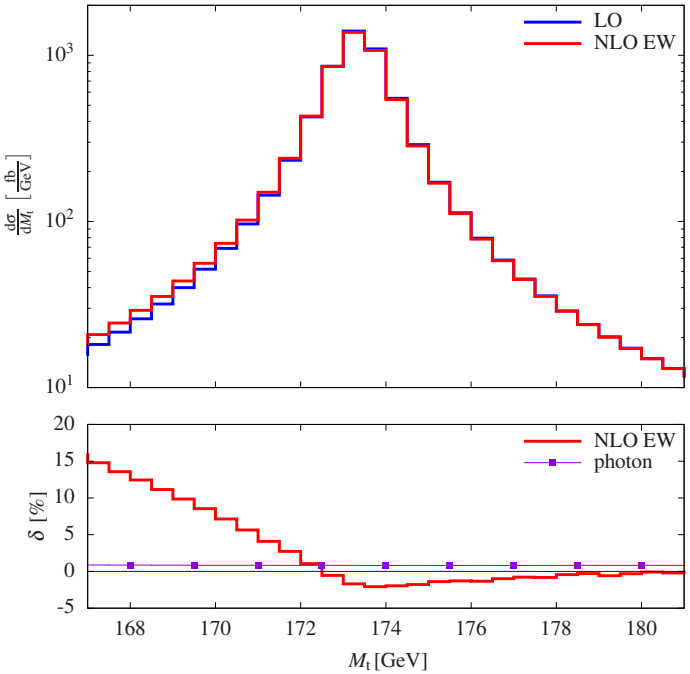
NLO QCD





[Denner et al.; 1207.5018]

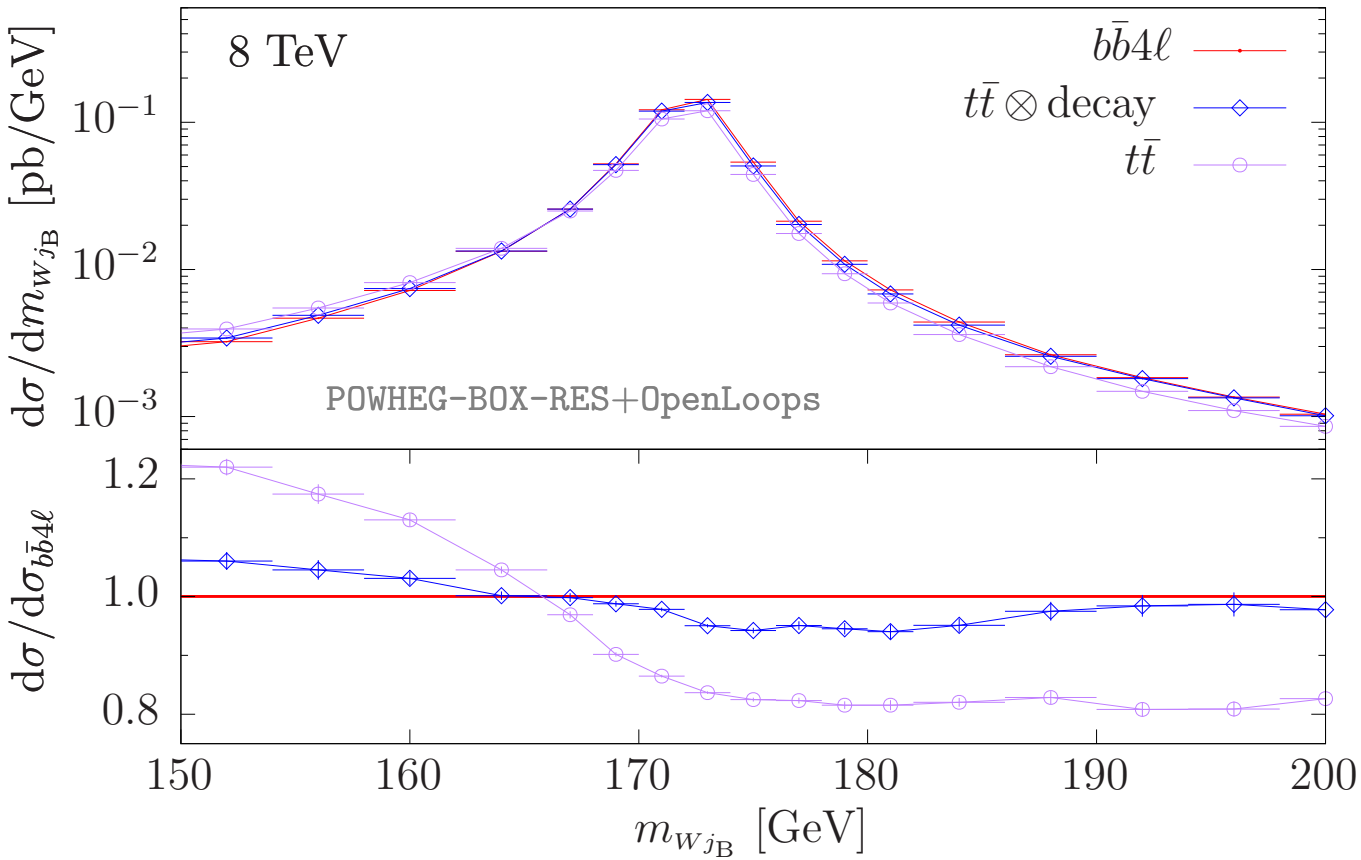
NLO EW



[Denner, MP; 1607.05571]

→ Radiative tail due to non-reconstructed jets/photons

1) NLO QCD to pp $\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$



[Ježo et al.; 1607.04538]

→ Different treatments of resonances

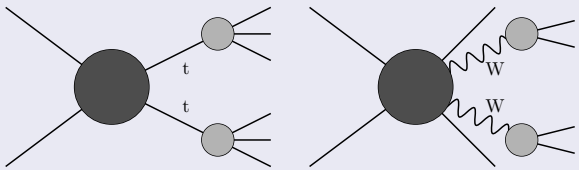
→ Inclusion of non-resonant contributions and all NLO corrections

↬ Study of top mass [Ferrario Ravasio et al.; 1801.03944, 1906.09166]

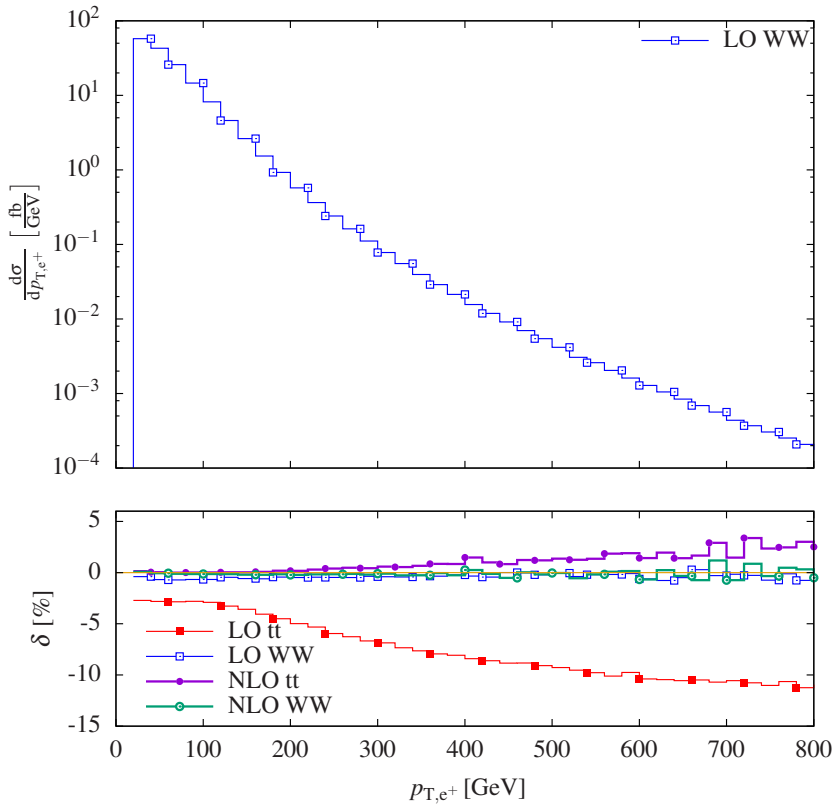
1) LO: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$

Retain resonant contributions

→ **tt** and **WW**



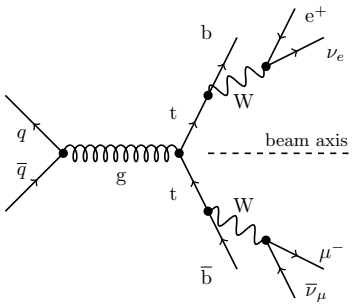
(resonant propagators and full phase space included)

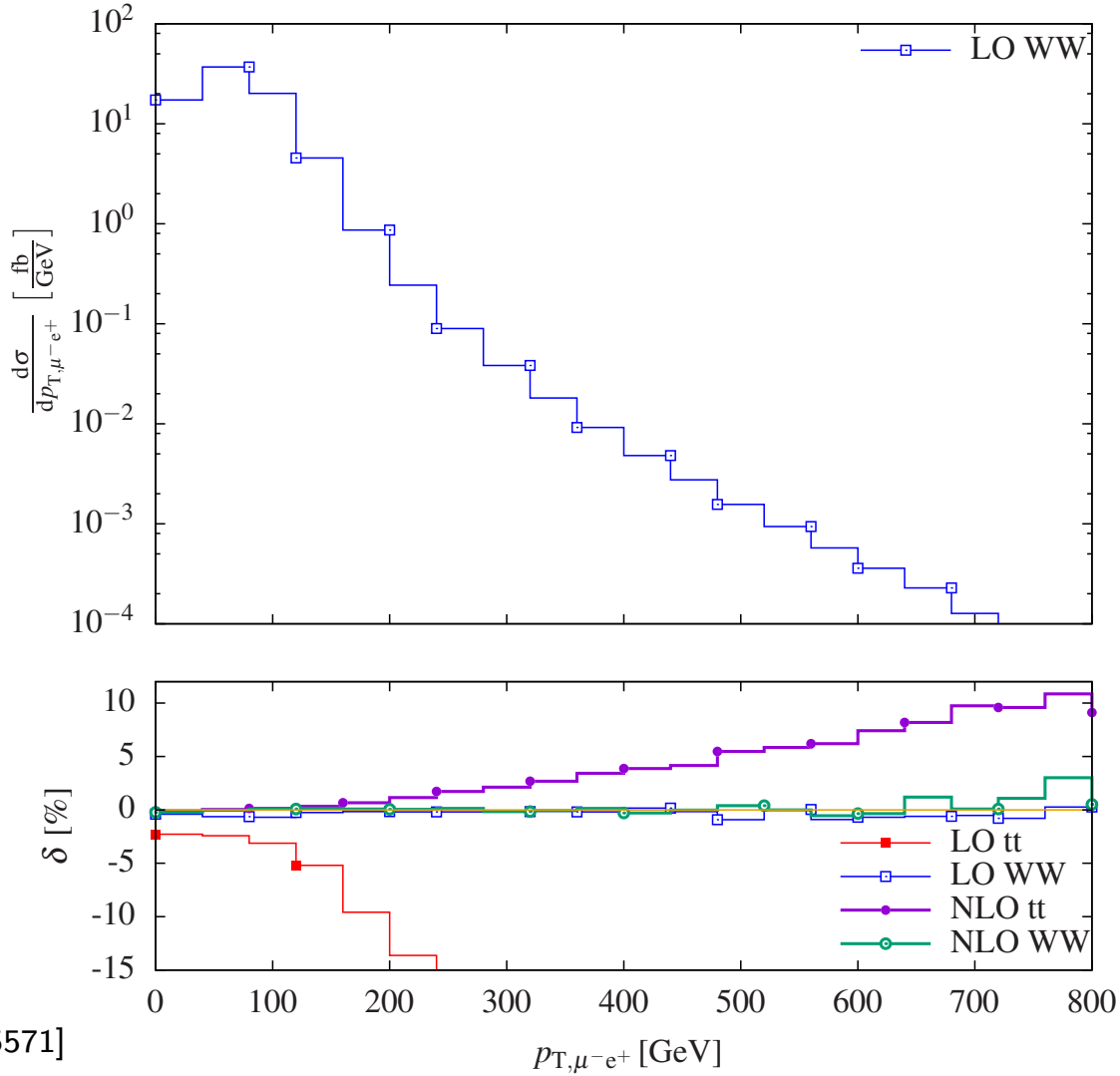


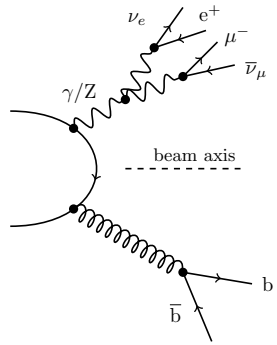
[Denner, MP; 1607.05571]

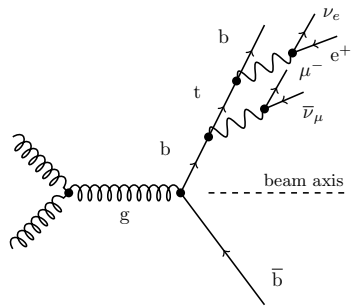
→ Effect of non-doubly resonant top contributions

1) LO: $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$





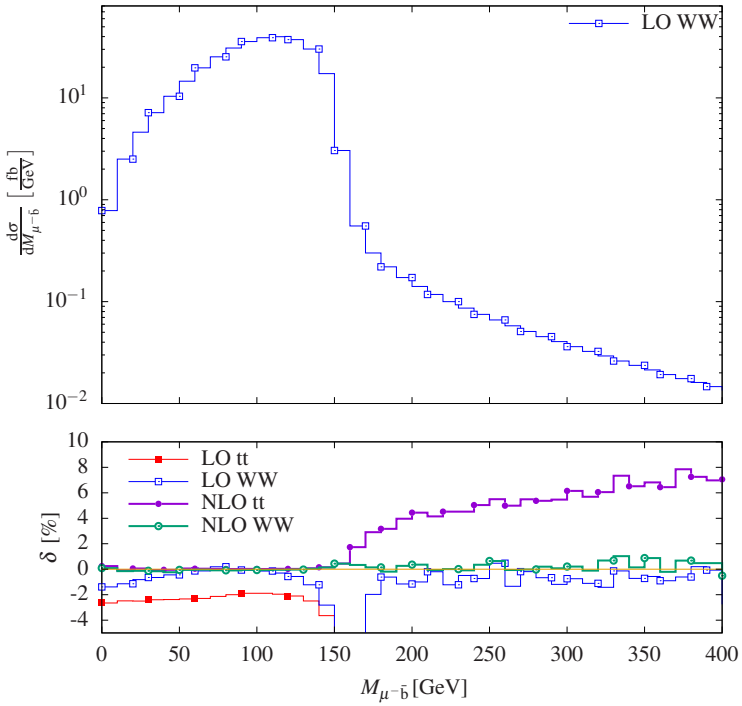




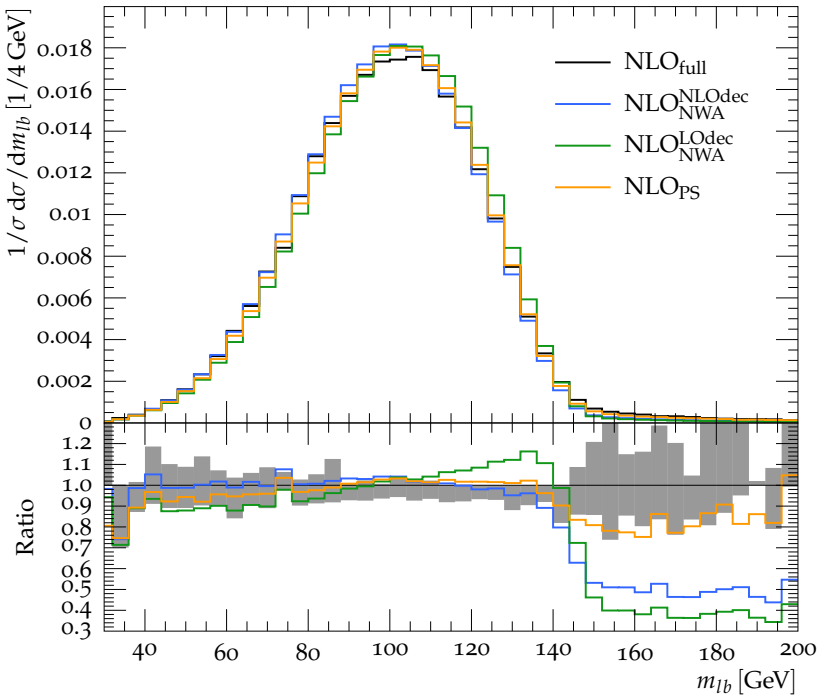
[Denner, MP; 1607.05571]

→ Even more stringent effect for exclusive observables

1) (N)LO QCD to pp $\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$



[Denner, MP; 1607.05571]



[Heinrich et al.; 1709.08615]

→ Kinematic edge: $M^2_{\mu^-\bar{b}} < M^2_{\bar{t}} - M^2_W \simeq (154\,\text{GeV})^2$
[Denner et al.; 1207.5018]

→ Large effects above threshold

2) State of the art top-antitop production and a Higgs

(with on-shell Higgs)

- NLO QCD [Beenakker et al.; hep-ph/0107081, hep-ph/0211352], [Dawson et al.; hep-ph/0107101, hep-ph/0305087]

  → With off-shell effects [Denner, Feger; 1506.07448] (LHC), [Chokoufé-Nejad et al.; 1609.03390] (Linear collider)

- NLO EW [Frixione et al.; 1407.0823, 1504.03446], [Zhang et al.; 1407.1110]

  → With off-shell effects [Denner, Lang, MP, Uccirati; 1612.07138]

- Resummation [Broggio et al.; 1510.01914, 1611.00049], [Kulesza et al.; 1509.02780]

  → Combined with NLO EW [Broggio et al.; 1907.04343]

- NLO QCD matched to PS [Frederix et al.; 1104.5613], [Garzelli et al.; 1108.0387], [Hartanto et al.; 1501.04498]

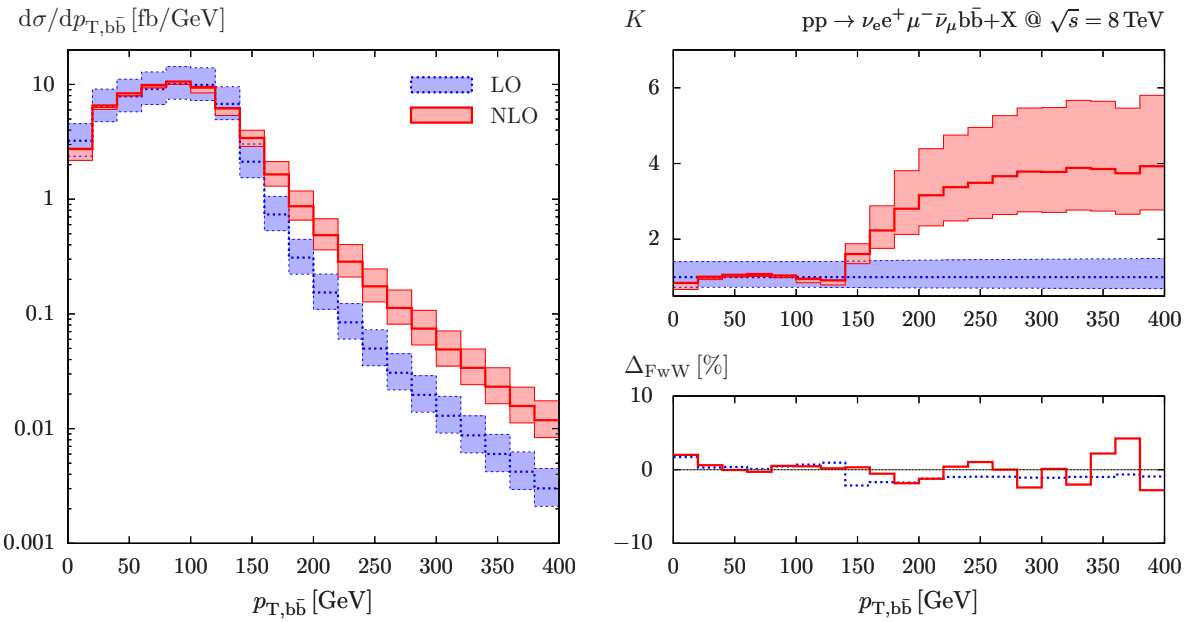
2) NLO QCD tt vs. ttH

→ ttH is tt with an extra Higgs

Expectations:

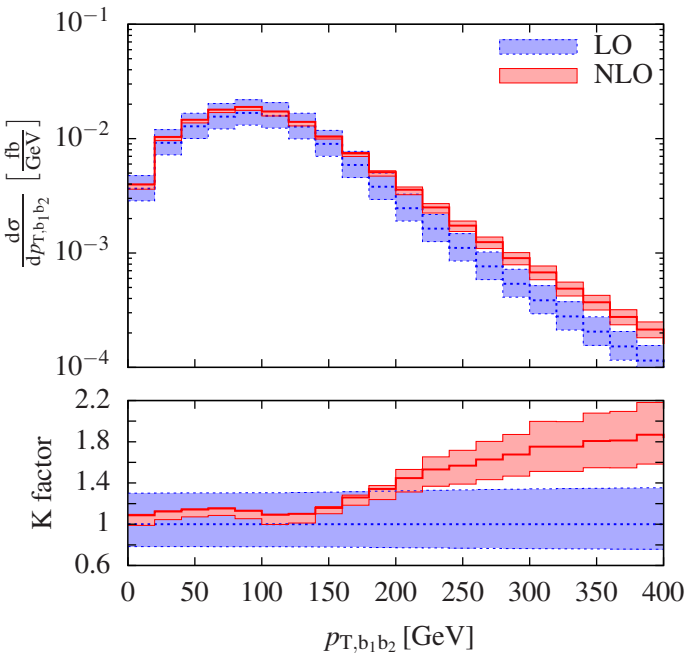
- Rather similar corrections
- Slightly different kinematic

NLO QCD to tt



[Denner et al.; 1207.5018]

ttH

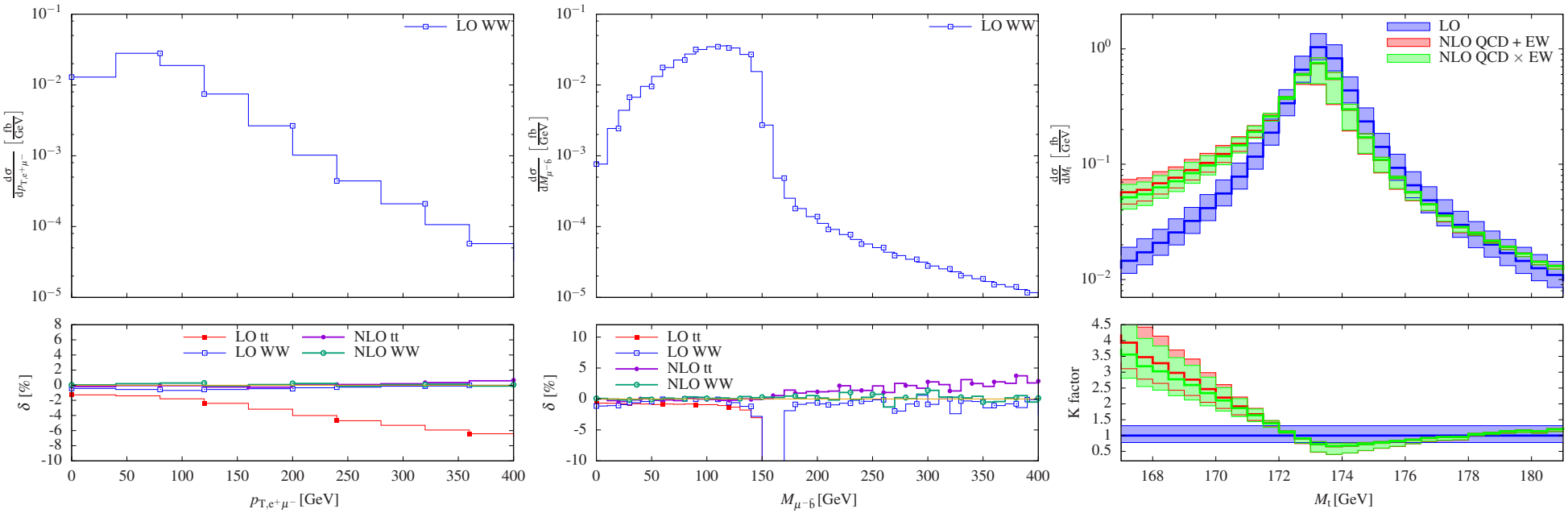


[Denner, Feger; 1506.07448]

2) pp $\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$

NLO QCD+ EW to pp $\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}H$

[Denner, Feger; 1506.07448], [Denner, Lang, MP, Uccirati; 1612.07138]



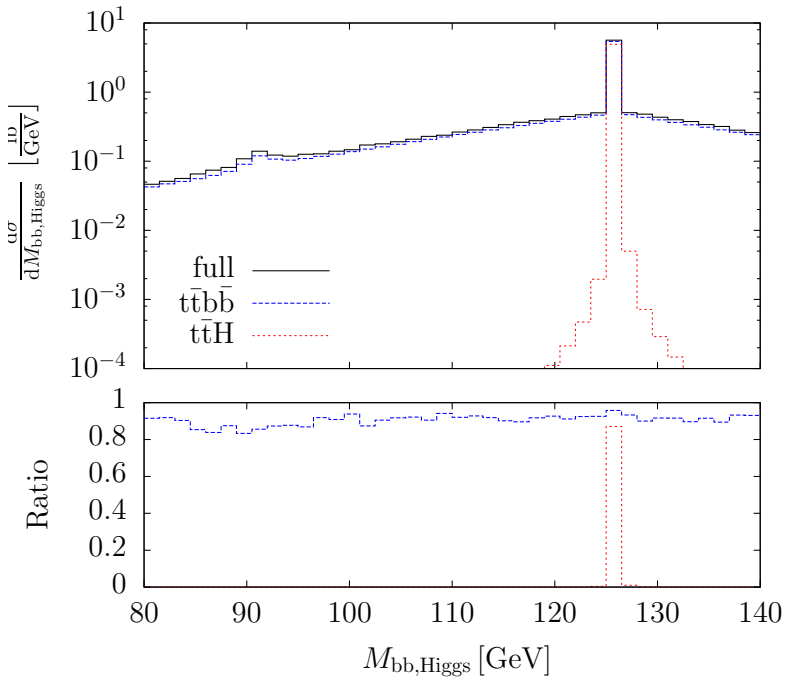
[Denner, Lang, MP, Uccirati; 1612.07138]

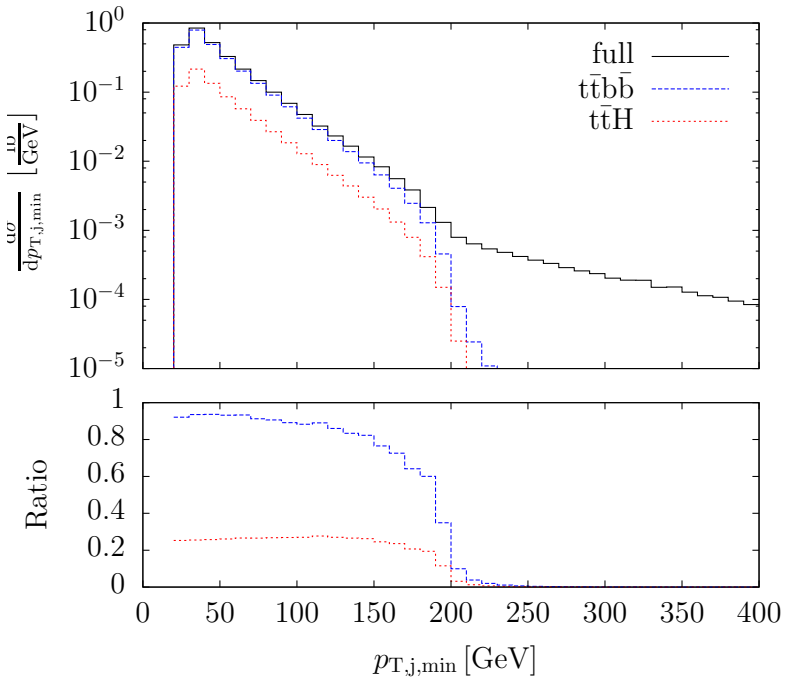
→ Effect of non-resonant contributions smaller with respect to tt

→ Radiative tail due to non-reconstructed jets/photons still present

2) LO pp $\to \ell^+\nu_\ell$jjb$\bar{\text{b}}$b$\bar{\text{b}}$

- Full: pp $\to \ell^+\nu_\ell$jjb$\bar{\text{b}}$b$\bar{\text{b}}$ at $\mathcal{O}\left(\alpha^8\right)$, $\mathcal{O}\left(\alpha_s^2\alpha^6\right)$, $\mathcal{O}\left(\alpha_s^4\alpha^4\right)$
- ttbb: pp $\to$ t$\bar{\text{t}}$b$\bar{\text{b}} \to \ell^+\nu_\ell$jjb$\bar{\text{b}}b\bar{\text{b}}$ at $\mathcal{O}\left(\alpha^8\right)$, $\mathcal{O}\left(\alpha_s^2\alpha^6\right)$, $\mathcal{O}\left(\alpha_s^4\alpha^4\right)$
- tth: pp $\to$ t$\bar{\text{t}}$H $\to \ell^+\nu_\ell$jjb$\bar{\text{b}}$b$\bar{\text{b}}$ at $\mathcal{O}\left(\alpha_s^2\alpha^6\right)$





[Denner, Feger, Scharf; 1412.5290]

$\to$ In the full calculation, jets are not only coming from top decays

$\hookrightarrow$ large effects at high transverse momentum

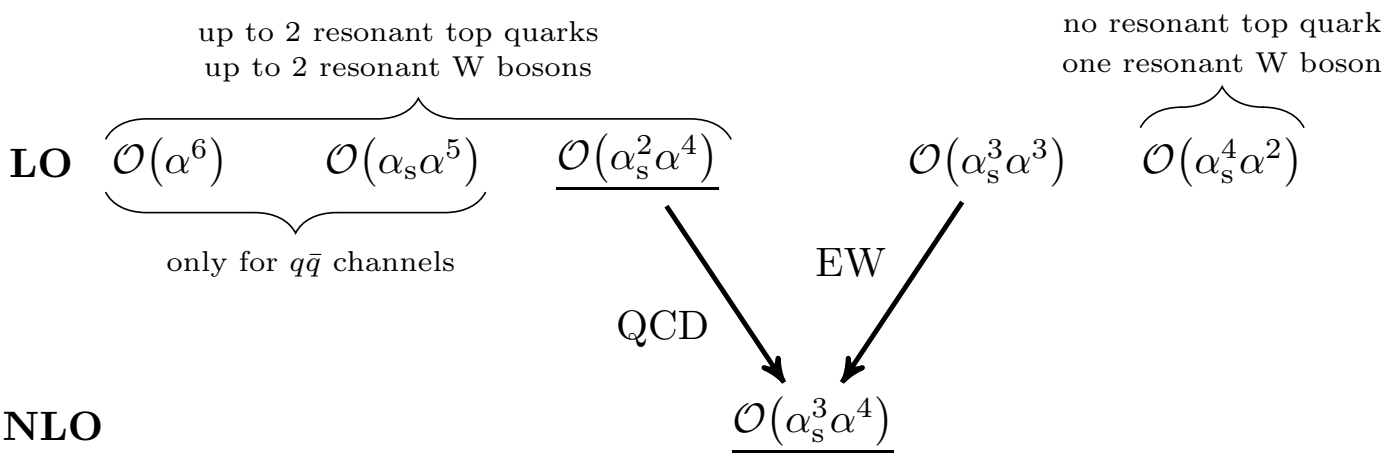
3) NLO QCD to off-shell pp $\to \mu^- \bar{\nu}_\mu \mathrm{b}\bar{\mathrm{b}}\mathrm{jj}$

- 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 $\mathrm{t}\bar{\mathrm{t}}$ production

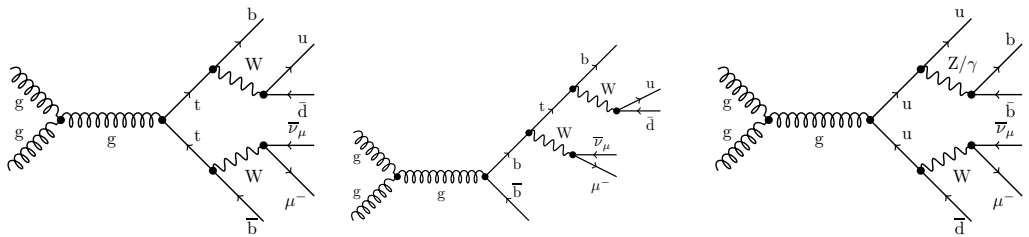
  [Anger, Febres Cordero, Ita, Sotnikov; 1712.05721]: $\mathrm{W}\bar{\mathrm{b}}\mathrm{b} + 2\mathrm{j}$

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

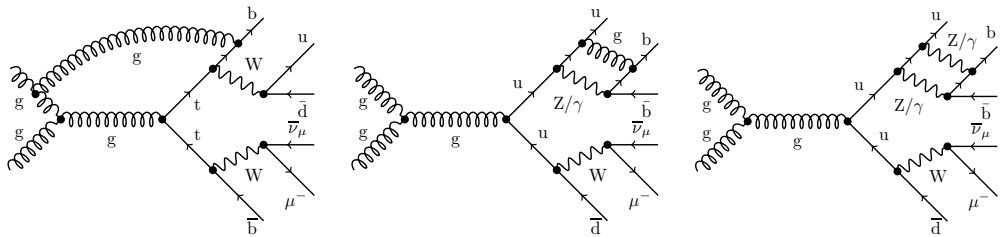
3) NLO QCD to off-shell pp $\to \mu^- \bar{\nu}_\mu b\bar{b}jj$ - Definition



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



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



3) NLO QCD to off-shell pp $\to \mu^- \bar{\nu}_\mu b\bar{b}jj$ - Set-up

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

$\to$ Event selection for *resolved* topology [ATLAS; 1708.00727], [CMS; 1610.04191]:

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

$\to$ anti-k_T jet algorithm [Cacciari, Salam, Soyez] with $R = 0.4$

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

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

3) NLO QCD to off-shell pp $\to \mu^- \bar{\nu}_\mu b\bar{b}jj$

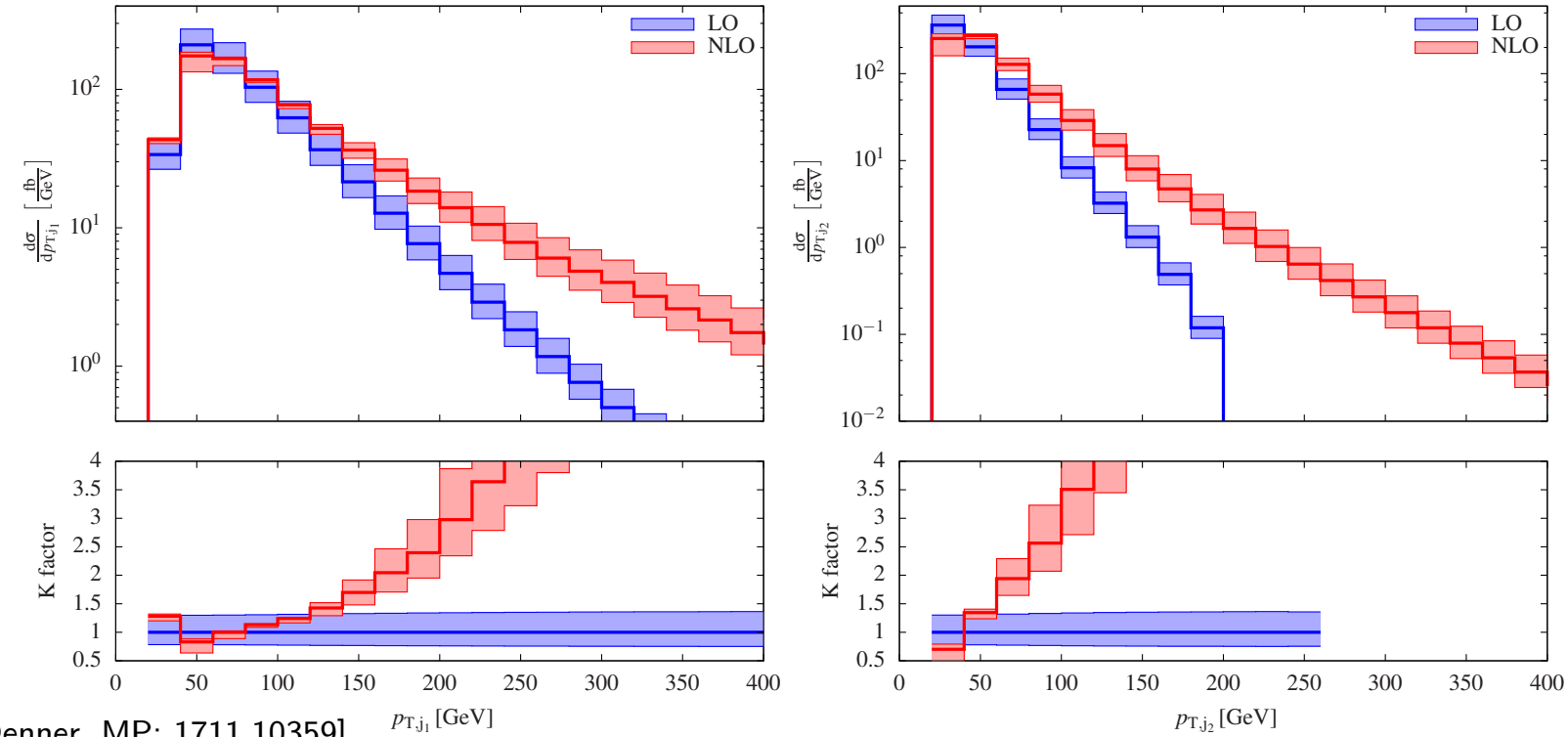
- Full computation pp $\to \mu^- \bar{\nu}_\mu b\bar{b}jj$
  $\to$ 32 partonic channels
- 6 partonic channels with two resonant top quarks

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

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

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

3) NLO QCD to off-shell $pp \to \mu^- \bar{\nu}_\mu b\bar{b}jj$



[Denner, MP; 1711.10359]

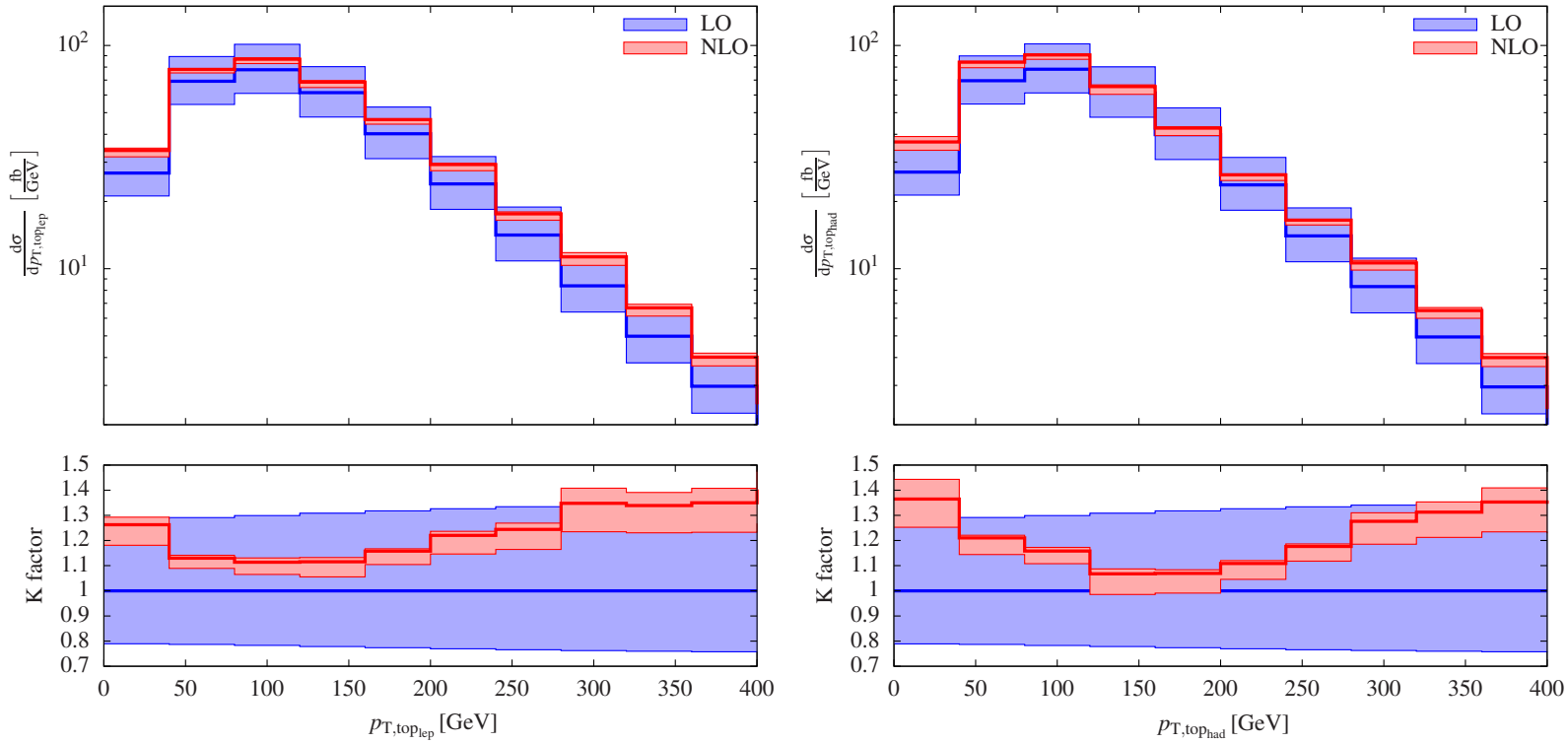
→ Large corrections toward high transverse momenta
(due to real corrections)

→ Clear effect of the cuts:

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

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

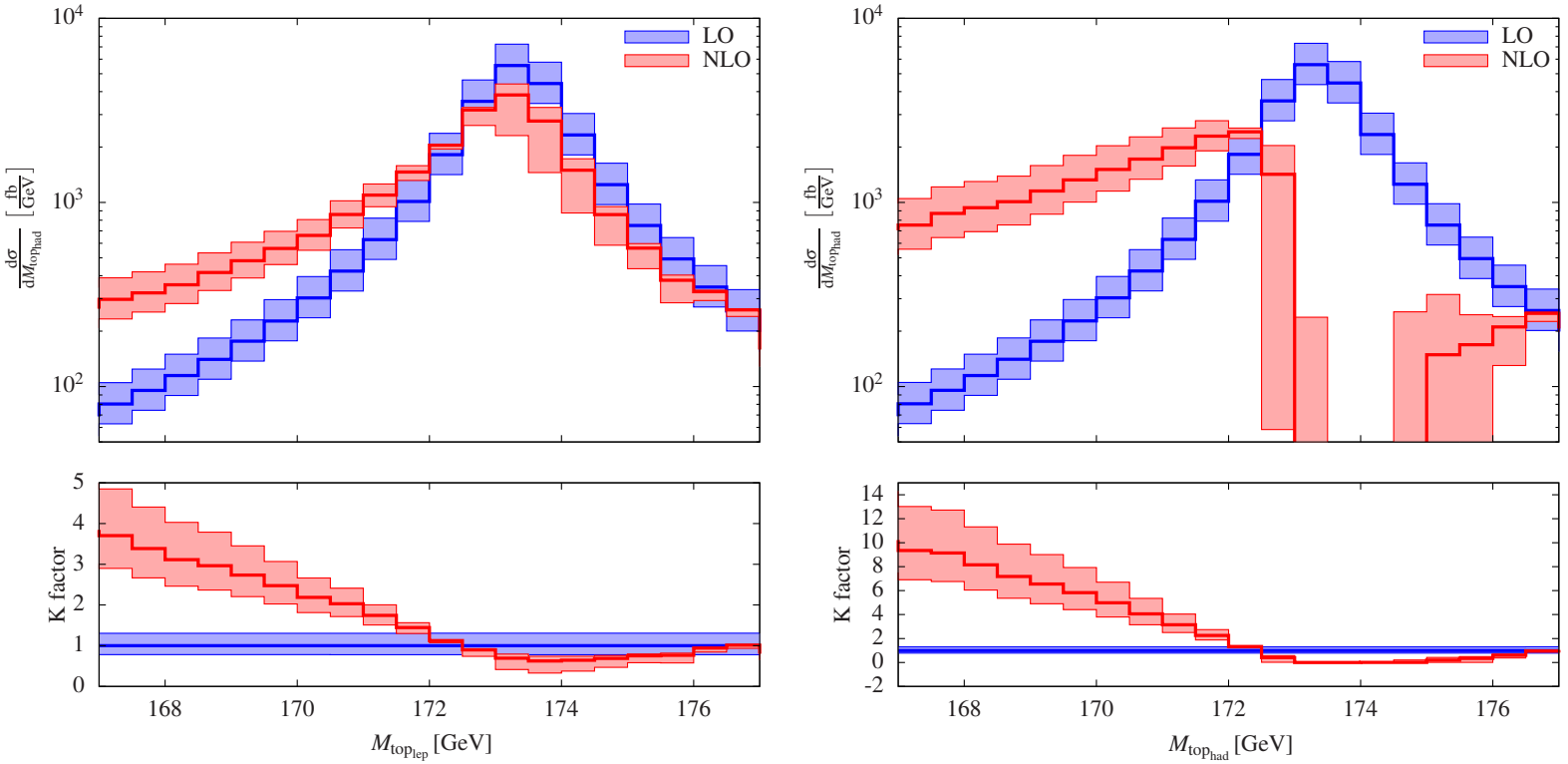
3) NLO QCD to off-shell pp $\to \mu^- \bar{\nu}_\mu b\bar{b}jj$



[Denner, MP; 1711.10359]

$\to$ Different NLO behaviour between the hadronic and leptonic top quark

3) NLO QCD to off-shell pp $\to \mu^- \bar{\nu}_\mu b\bar{b}jj$



[Denner, MP; 1711.10359]

$\to$ Different NLO behaviour between the hadronic and leptonic top quark

$\to$ Extreme NLO effect: inclusion of higher-order effects needed

Summary

Off-shell effects can be large!

- Invariants off their mass shells
- Non-resonant contributions
- Description of the final state

Examples in:

- $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}$
- $pp \to e^+ \nu_e \mu^- \bar{\nu}_\mu b\bar{b}H$
- $pp \to \ell^+ \nu_\ell jjb\bar{b}b\bar{b}$
- $pp \to \mu^- \bar{\nu}_\mu jjb\bar{b}$

$\to$ New territories to explore (new physics?)

BACK-UP

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.]

Set-up - NLO EW tt

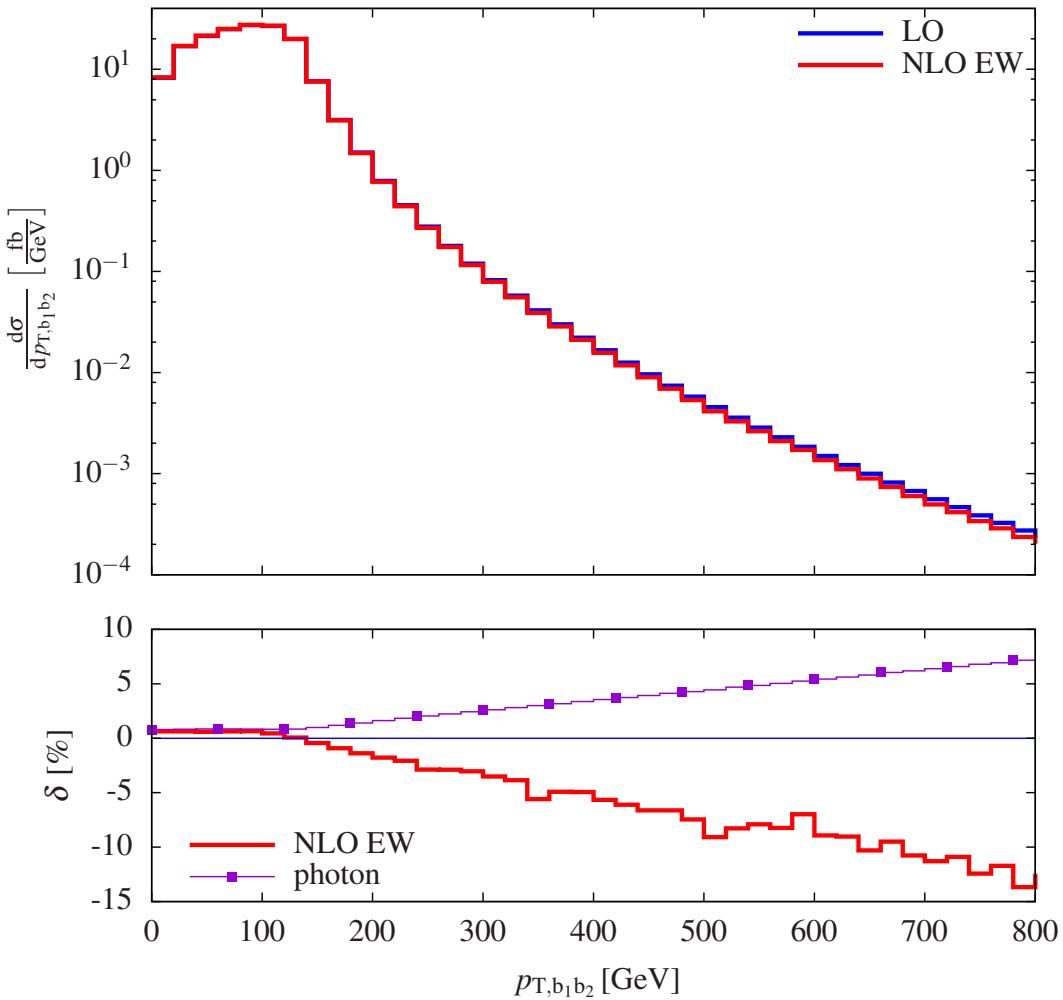
Predictions for $\sqrt{s} = 13\text{TeV}$ at the LHC

$\rightarrow$ $\mathrm{NNPDF23\_nlo\_as\_0119\_qed}$ [NNPDF Collaboration]
with massless bottom quarks and bottom-quark PDF neglected
$\rightarrow$ Event selection:

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

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

NLO EW tt



[Denner, MP; 1607.05571]

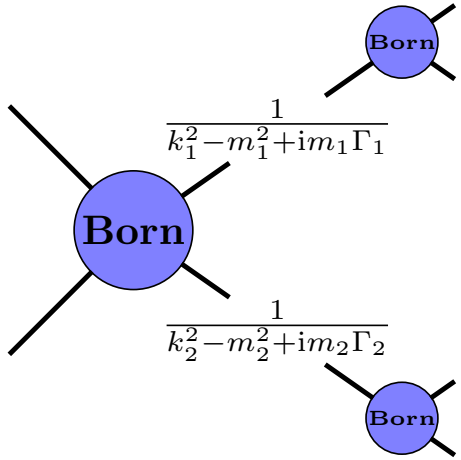
→ Sudakov logarithms → -15%

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

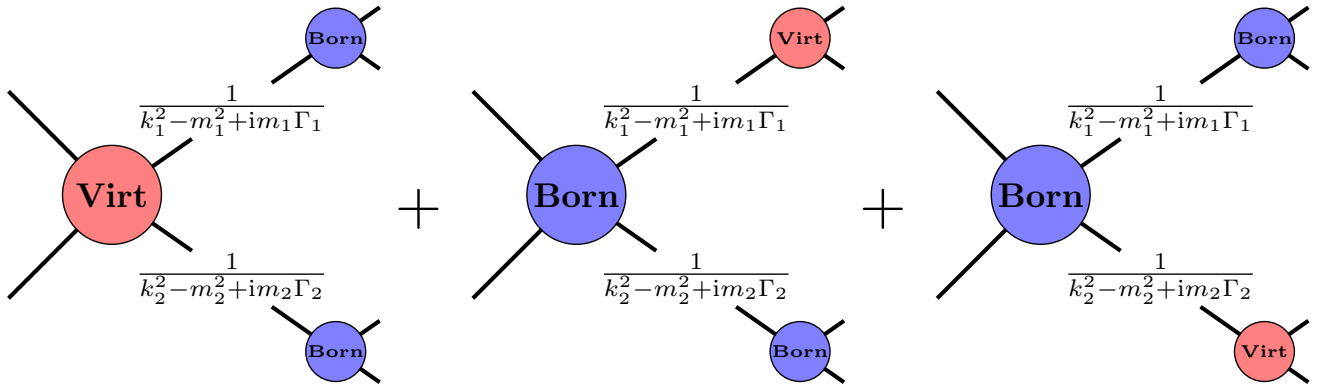
(before LuxQED [Manohar et al.; 1607.04266])

DPA (1) [Dittmaier, Schwan; 1511.01698]

- At LO



- At NLO



DPA (2) [Dittmaier, Schwan; 1511.01698]

- Factorisable corrections

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

- Non-factorisable corrections:

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

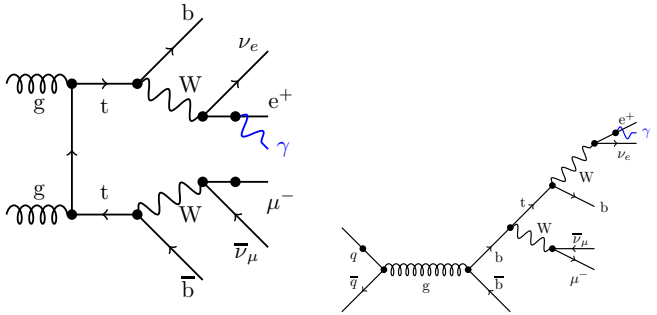
- On-shell projection
- DPA applied to virtual corrections and I-operator
- Full Born and Real contributions:

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

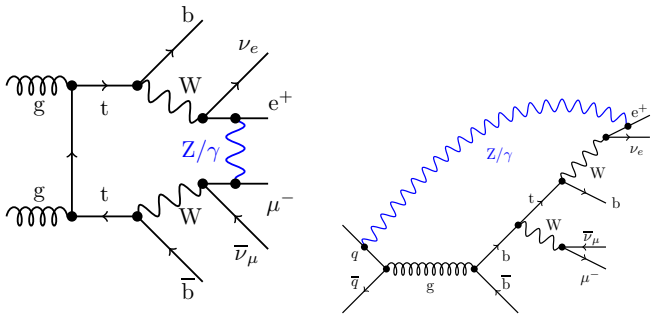
→ NLO EW corrections are of order $\mathcal{O}\left(\alpha_s^2\alpha^5\right)$ *i.e.* $\mathcal{O}\left(\mathrm{LO} \times \alpha\right)$

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

Real corrections:



Virtual corrections:



→ No V =W, Z radiation considered (experimentally different signature)

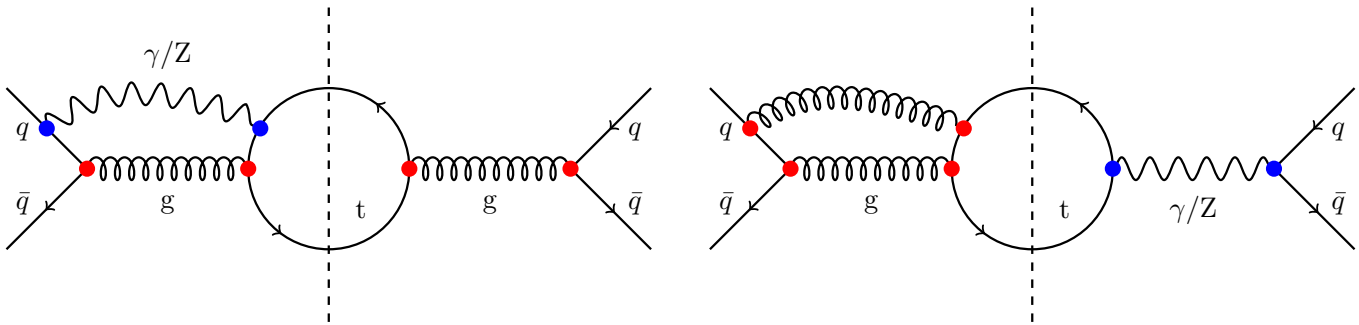
→ Sudakov logarithms: $-\frac{\alpha}{4\pi}\log^2\left(s_{ij}/M_V^2\right)$

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:

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

- G_μ scheme:

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

- Inputs:

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

→ 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)