Production of top quark pairs at the LHC: NLO corrections and off-shell effects

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Theoretical Particle Physics seminar
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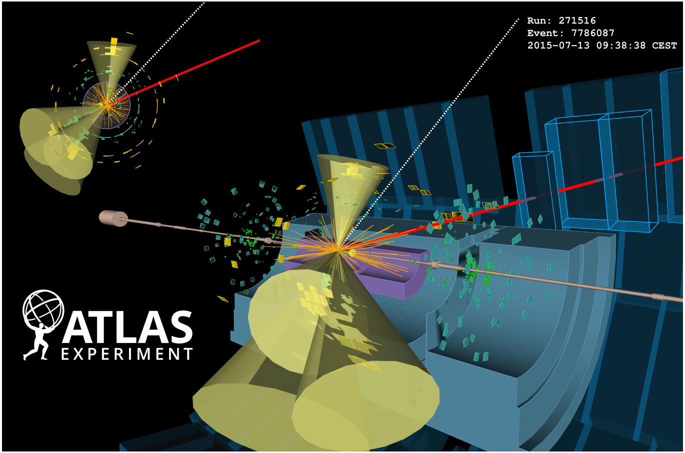
→ Illustration of Giordano Bruno's philosophical ideas

LHC: Great tool to probe fundamental interactions at high energies



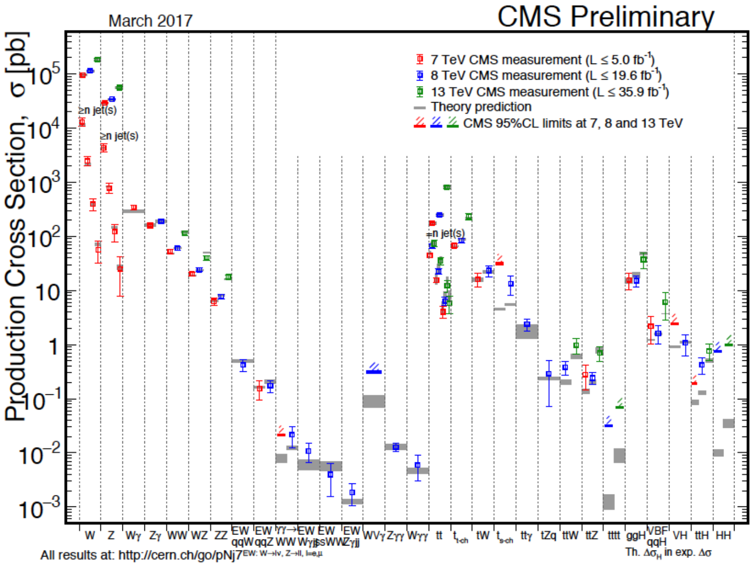
$$\mathrm{pp} \to \mathrm{t}^\star\bar{\mathrm{t}}^\star \to (\mathrm{W}^\star \to \nu_\mu\mu^-)\,(\mathrm{W}^\star \to \mathrm{jj})\,\mathrm{b}\bar{\mathrm{b}}$$

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, ...)
  - Discovery of new physics?

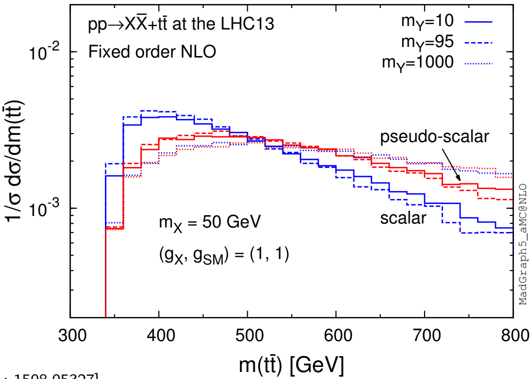
$\rightarrow$ Precision physics on both the experimental and theoretical side

$\looparrowright$ Precise theoretical predictions comparable with measurements



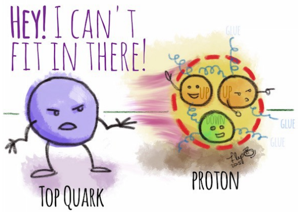
→ High experimental precision for $t\bar{t}$ production

→ Example: $t\bar{t}$ production in association with Dark Matter



[Backović, MP et al.; 1508.05327]

Discrepancies between SM predictions and experimental measurements might hint at new physics



- The top quark is the heaviest particle in the SM
- Possible window to new physics

  [Frederix, Maltoni; 0712.2355], [Arina, MP et al.; 1605.09242], [Hespel et al.; 1606.04149] + [...]

  → Tevatron asymmetry:

  BSM: [Westhoff; 1703.01983] + [...]

  SM: [Czakon et al.; 1411.3007, 1711.03945]
- Study of its interaction with Higgs boson very important
  → Yukawa coupling with Higgs boson
- Top quarks are copiously produced at the LHC
  → Standard candle at the LHC

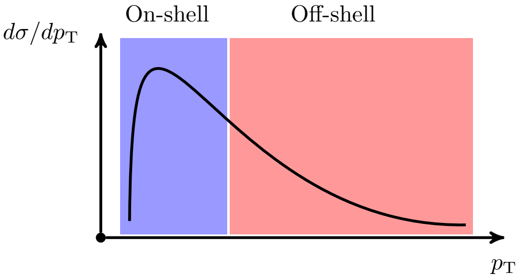
Precise study of top quarks production very important at LHC

- Need for precise theoretical predictions:
  - 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], ...
  - 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]
  - NNLO QCD [Moch et al.; 1203.6282], [Czakon et al.; 1303.6254, 1601.05375, 1606.03350], [Abelof et al.; 1506.04037], [Gao, Papanastasiou; 1705.08903]

    → Combination with NLO EW [Czakon et al.; 1705.04105]
  - Resummation [Beneke et al.; 0907.1443], [Czakon et al.; 0907.1790, 1803.07623], [Ahrens et al.; 1003.5827], [Kidonakis; 0903.2561, 1009.4935], ...
  - 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], [Ježo et al.; 1607.04538]

Focus of the presentation:
NLO corrections (QCD and EW) and off-shell effects

- 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?

Off-shell computations

- NLO QCD to fully-leptonic channel $\mathbf{t\bar{t}}$

  [Denner et al.; 1012.3975, 1207.5018], [Bevilacqua et al.; 1012.4230], [Frederix; 1311.4893], [Cascioli et al.; 1312.0546]

  $\rightarrow$ Matching to QCD PS [Ježo et al.; 1607.04538]

  $\rightarrow$ Top mass determination [Heinrich et al.; 1312.6659, 1709.08615], [Bevilacqua et al.; 1710.07515], [Ferrario Ravasio et al.; 1801.03944]

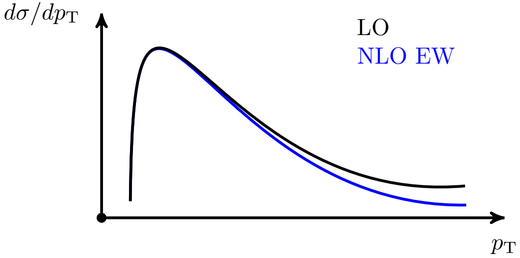
  $\rightarrow$ For the ILC [Chokoufé Nejad et al.; 1609.03390], [Bach et al.; 1712.02220]
- NLO EW to fully-leptonic channel $\mathbf{t\bar{t}}$ [Denner, MP; 1607.05571]
- NLO QCD to semi-leptonic channel $\mathbf{t\bar{t}}$ [Denner, MP; 1711.10359]
- NLO QCD to fully-leptonic channel $\mathbf{t\bar{t}H}$ [Denner, Feger; 1506.07448]

  $\rightarrow$ For the ILC [Chokoufé Nejad et al.; 1609.03390]
- NLO EW to fully-leptonic channel $\mathbf{t\bar{t}H}$

  [Denner, Lang, MP, Uccirati; 1612.07138]
- NLO QCD to fully-leptonic channel $\mathbf{t\bar{t}j}$

  [Bevilacqua et al.; 1509.09242, 1609.01659]
- NLO QCD to fully-leptonic channel $\mathbf{t\bar{t}}\gamma$ [Bevilacqua et al.; 1803.09916]

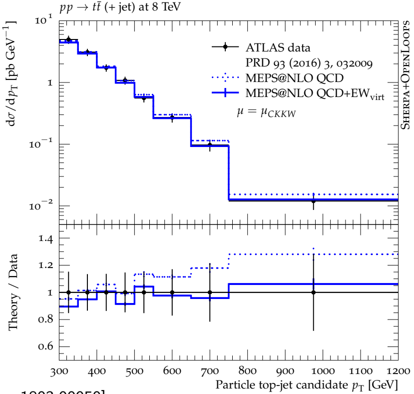
- Electroweak (EW) corrections:
  - → large in high energy region
  - → Sudakov logarithms: $-\frac{\alpha}{4\pi}\log^2\left(s_{ij}/M_{\mathrm{W}}^2\right)$



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

Theoretical predictions including NLO EW vs. data

→ Example: $pp \to t\bar{t}(+j)$



[Gütschow, Lindert, Schönherr; 1803.00950]

→ NLO EW corrections improve comparison with data

→ Including EW corrections is mandatory to match LHC precision!

Content

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

2) pp $\to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b}\bar{\mathrm{b}}\mathrm{H}$ at NLO EW (+ QCD)

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

$\to$ Conclusion

1) pp $\rightarrow \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu$b$\bar{\text{b}}$ at NLO EW

Motivations

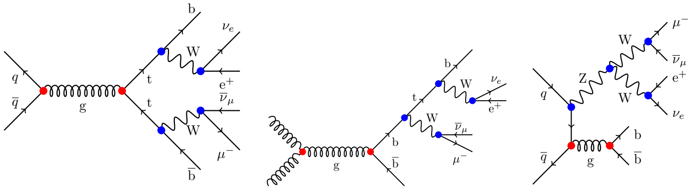
$\rightarrow$ Calculation of NLO EW corrections to off-shell $\mathrm{t\bar{t}}$ production:

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

- Off-shell, non-resonant, and interference effects
  $\rightarrow$ Realistic final state
- EW corrections can be large in certain phase-space regions
  $\rightarrow$ Sudakov logarithms
- Theoretical and numerical challenge to consider 2 $\rightarrow$ 6 process
  $\rightarrow$ 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 $\mathcal{O}\left(\alpha_\mathrm{s}^2\alpha^4\right)$



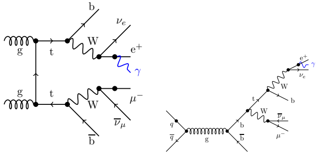
→ Not only doubly resonant top-pair contributions
- singly resonant top contributions
- non-resonant top contributions

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

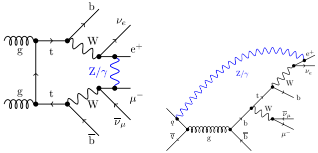
$\rightarrow$ NLO EW corrections are of order $\mathcal{O}\left(\alpha_\mathrm{s}^2\alpha^5\right)$ *i.e.* $\mathcal{O}\left(\mathrm{LO}\times\alpha\right)$

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

Real corrections:



Virtual corrections:



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

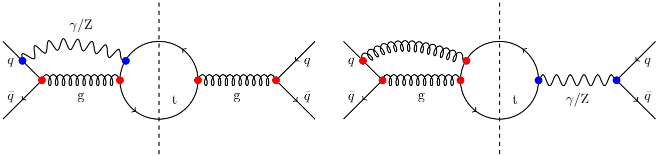
$\rightarrow$ Sudakov logarithms: $-\frac{\alpha}{4\pi}\log^2\left(s_{ij}/M_V^2\right)$

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



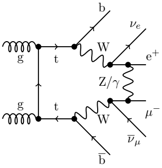
→ In the same way, interference channel: $\mathrm{g}q/\bar{q} \to \mathrm{t}^\star\bar{\mathrm{t}}^\star q/\bar{q}$

→ 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)

Tools / Techniques

→ Tree and one-loop matrix element:

RECOLA [Actis, Denner, Hofer, Lang, Scharf, Uccirati] + COLLIER [Denner, Dittmaier, Hofer]



→ In-house Monte Carlo - MoCaNLO [Feger]

→ Dipole subtraction method [Catani, Seymour], [Dittmaier]

→ Complex-mass scheme [Denner, Dittmaier et al.]

→ LHAPDF [LHAPDF collaboration]

Inputs

- 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]

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:

b jets:	$p_{\mathrm{T,b}} > 25\,\mathrm{GeV}$,	$\lvert y_{\mathrm{b}} \rvert < 2.5$
charged lepton:	$p_{\mathrm{T},\ell} > 20\,\mathrm{GeV}$,	$\lvert y_{\ell} \rvert < 2.5$
missing transverse momentum:	$p_{\mathrm{T,miss}} > 20\,\mathrm{GeV}$	
b-jet–b-jet distance:	$\Delta R_{\mathrm{bb}} > 0.4$	

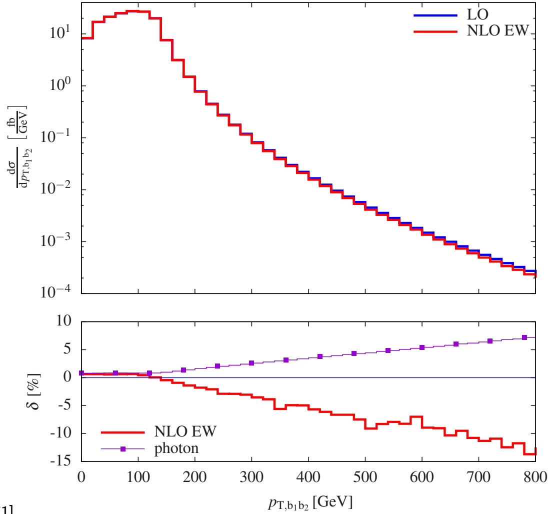
→ anti-k_{T} jet algorithm [Cacciari, Salam, Soyez]
with $R = 0.4$ for both jet clustering and photon recombination

Fiducial cross section

Ch.	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO\ EW}$ [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]

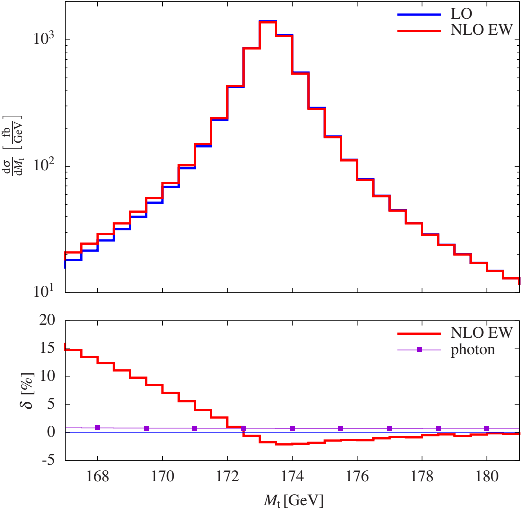
- Cross section dominated by the gg channel
- γg channel around 1%
- Small positive EW corrections
  $\rightarrow$ Negative corrections for on-shell top quarks ($\sim -1.5\%$)
  (due to the choice of the top width)



[Denner, MP; 1607.05571]

→ Sudakov logarithms → -15%

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



[Denner, MP; 1607.05571]

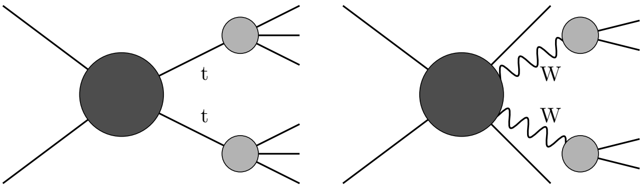
→ Radiative tail due to non-reconstructed photons

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**



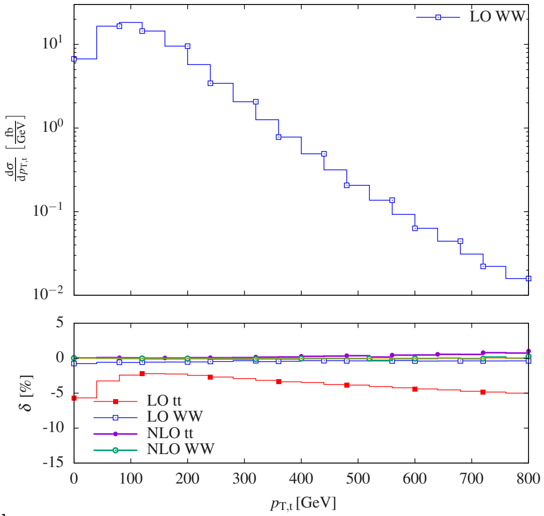
Fiducial cross sections

Ch.	$\sigma_{\rm LO}^{\rm WW\ DPA}$ [fb]	$\delta_{\rm LO}^{\rm WW\ DPA}$ [%]	$\sigma_{\rm LO}^{\rm tt\ DPA}$ [fb]	$\delta_{\rm LO}^{\rm tt\ DPA}$ [%]
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

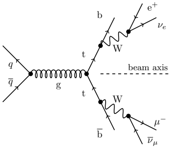
Ch.	$\sigma_{\rm NLO\ EW}^{\rm WW\ DPA}$ [fb]	$\delta_{\rm NLO\ EW}^{\rm WW\ DPA}$ [%]	$\sigma_{\rm NLO\ EW}^{\rm tt\ DPA}$ [fb]	$\delta_{\rm NLO\ EW}^{\rm tt\ DPA}$ [%]
gg	2832.9(2)	-0.046	2836.5(2)	$+0.082$
$q\bar{q}$	377.36(8)	0.047	377.23(5)	$+0.013$
pp	3210.5(2)	-0.037	3214.0(2)	$+0.072$

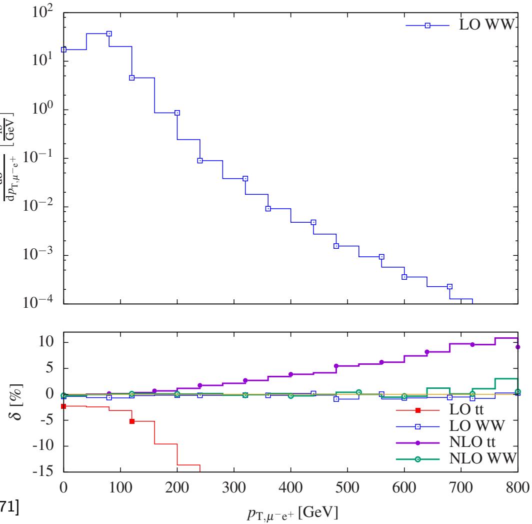
→ At NLO, both DPAs are equally good

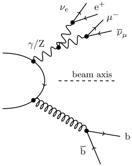


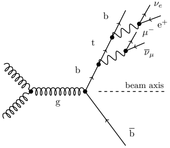
[Denner, MP; 1607.05571]

→ Both DPAs work well for top dominated observables





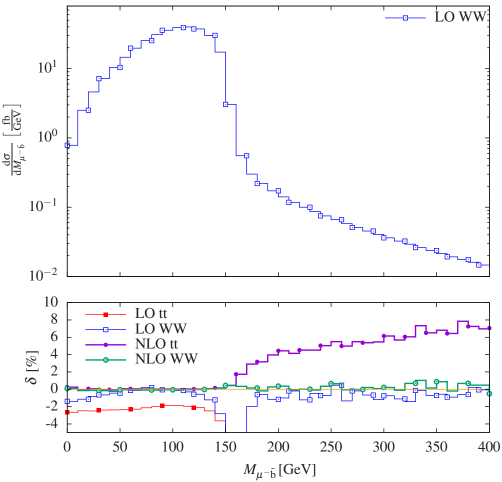




[Denner, MP; 1607.05571]

→ tt DPA is failing due to missing 0/1-top resonance contributions

Similar to WW production [Biedermann et al.; 1605.03419]



[Denner, MP; 1607.05571]

→ Kinematic edge: $M^2_{\mu^-\bar{b}} < M^2_{\bar{t}} - M^2_{W} \simeq (154\,\text{GeV})^2$

[Denner et al.; 1207.5018]

→ Only full calculation reliable for arbitrary distributions

2) pp $\to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\mathrm{b\bar{b}H}$ at NLO EW (+ QCD)

Motivations

- Discovery of Higgs boson at Run I
  $\rightarrow$ Study of its properties during Run II
- Top quark, heaviest particle in the SM
  $\rightarrow$ Yukawa coupling, new physics contributions etc.

$\mathrm{pp} \rightarrow \mathrm{t\bar{t}H}$ process is key

- Experimental status:
  $\rightarrow$ Evidence from Run-I at $\sqrt{s} = 7$ and $8\,\mathrm{TeV}$

  [CMS; 1408.1682], [ATLAS; 1506.05988], [ATLAS; 1503.05066], [ATLAS; 1409.3122], [ATLAS+CMS; 1606.02266]

  $\rightarrow$ Observation for Run-II at $\sqrt{s} = 13\,\mathrm{TeV}$

  [CMS; 1804.02610]

Need for precise predictions for $\mathrm{t\bar{t}H}$ production:

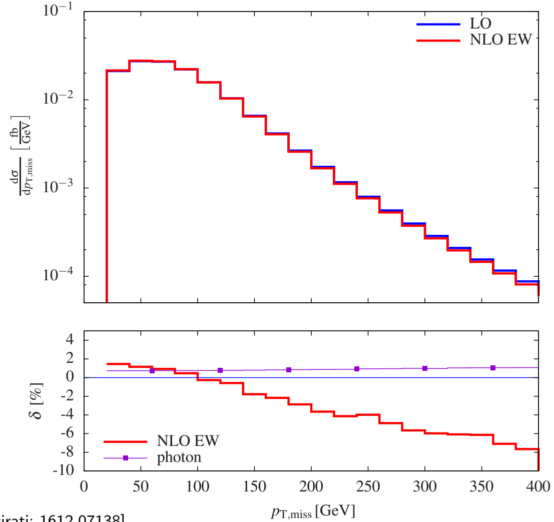
- NLO QCD [Beenakker et al.; hep-ph/0107081, hep-ph/0211352], [Dawson et al.; hep-ph/0107101, hep-ph/0305087]
- NLO EW [Frixione et al.; 1407.0823, 1504.03446], [Zhang et al.; 1407.1110]
- Resummation [Broggio et al.; 1510.01914, 1611.00049], [Kulesza et al.; 1509.02780]
- NLO QCD matched to PS [Frederix et al.; 1104.5613], [Garzelli et al.; 1108.0387], [Hartanto et al.; 1501.04498]
- NLO QCD for off-shell top quarks [Denner, Feger; 1506.07448] (LHC), [Chokoufé-Nejad et al.; 1609.03390] (Linear collider)

→ NLO EW calculations for off-shell top quarks still missing

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

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

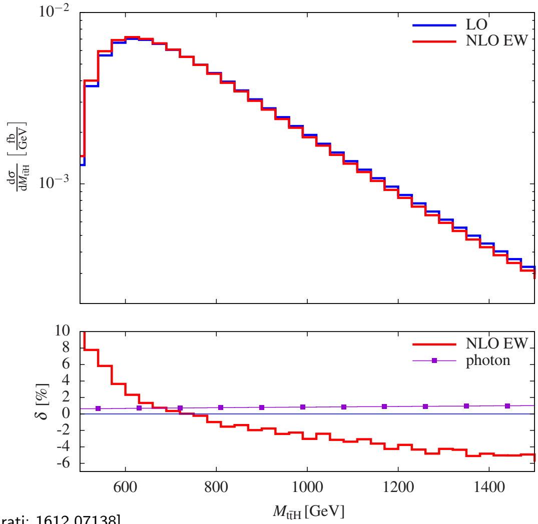
- Off-shell, non-resonant, and interference effects
  → Realistic final state
- EW corrections can be large in certain phase space-regions
  → Sudakov logarithms
- Theoretical and numerical challenge to consider $2 \to 7$ process
  → Up to 6 external charged particles and 4 intermediate resonances
  → Virtual corrections involving up to 9-point functions
- Extension of two off-shell top quark computations:
  [Denner, Feger; 1506.07448] (NLO QCD to $\mathrm{t\bar{t}H}$) and
  [Denner, MP; 1607.05571] (NLO EW to $\mathrm{t\bar{t}}$)



[Denner, Lang, MP, Uccirati; 1612.07138]

→ Sudakov logarithms → −8%

→ Small photon contributions (around +1% → LUXqed PDF)



[Denner, Lang, MP, Uccirati; 1612.07138]

→ +10% to −5% over the whole range: non-negligible effect

$$\sigma^{\rm NLO}_{\rm QCD} = \sigma^{\rm Born} + \delta\sigma^{\rm NLO}_{\rm QCD} \quad \text{and} \quad \sigma^{\rm NLO}_{\rm EW} = \sigma^{\rm Born} + \delta\sigma^{\rm NLO}_{\rm EW}$$

→ **Additive** and **multiplicative** combination:

$$\sigma^{\rm NLO}_{\rm QCD+EW} = \sigma^{\rm Born} + \delta\sigma^{\rm NLO}_{\rm QCD} + \delta\sigma^{\rm NLO}_{\rm EW}$$

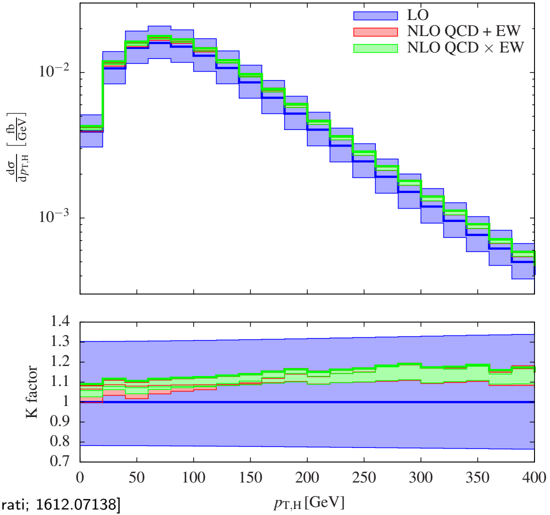
and

$$\sigma^{\rm NLO}_{\rm QCD\times EW} = \sigma^{\rm NLO}_{\rm QCD}\left(1 + \frac{\delta\sigma^{\rm NLO}_{\rm EW}}{\sigma^{\rm Born}}\right) = \sigma^{\rm NLO}_{\rm EW}\left(1 + \frac{\delta\sigma^{\rm NLO}_{\rm QCD}}{\sigma^{\rm Born}}\right)$$

→ **Results** (in [fb]):

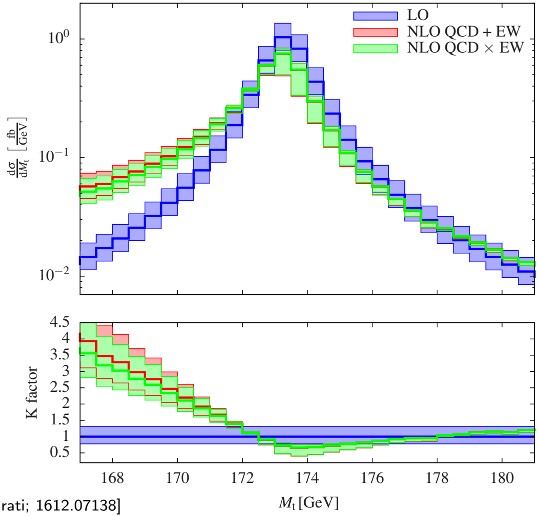
Recompute the QCD corrections of Ref. [Denner, Feger; 1506.07448] in the present set-up

$\sigma^{\rm LO}$	$\sigma^{\rm Born}$	$\sigma^{\rm NLO}_{\rm QCD}$	$\sigma^{\rm NLO}_{\rm EW}$	$\sigma^{\rm NLO}_{\rm QCD+EW}$	$\sigma^{\rm NLO}_{\rm QCD\times EW}$
2.4817(1)	2.7815(1)	2.866(1)	2.721(3)	2.806	2.804



[Denner, Lang, MP, Uccirati; 1612.07138]

→ NLO effects dominated by QCD corrections



[Denner, Lang, MP, Uccirati; 1612.07138]

→ Differences between the two combinations for large EW corrections

3) pp $\rightarrow \mu^- \bar{\nu}_\mu \mathrm{b\bar{b}jj}$ at NLO QCD

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

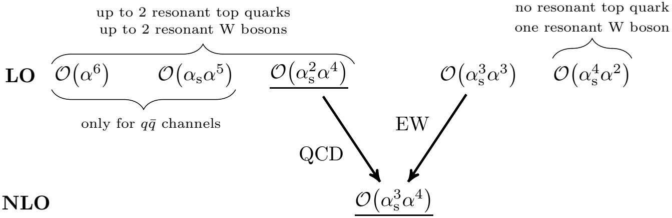
$$\mathrm{pp} \rightarrow \mu^- \bar{\nu}_\mu \mathrm{b\bar{b}jj}$$

- 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

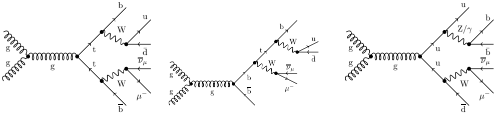
[Anger, Febres Cordero, Ita, Sotnikov; 1712.05721]: $\mathrm{W\bar{b}b} + 2\mathrm{j}$

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

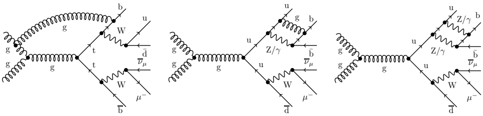
Definition



- Partonic channels featuring two resonant top quarks
- 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]:

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

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

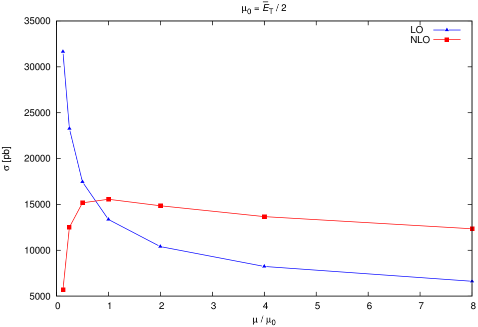
→ Additional cut to ensure a stable definition of the fiducial volume for top-quark pair production at both LO/NLO

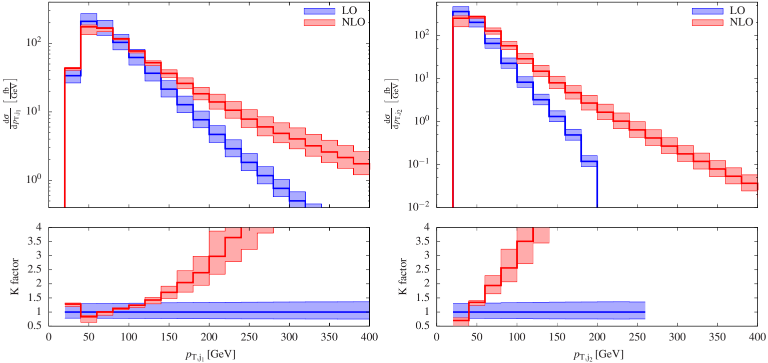
$$60\,\mathrm{GeV} < m_{\mathrm{jj}} < 100\,\mathrm{GeV}$$

Cross sections

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

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





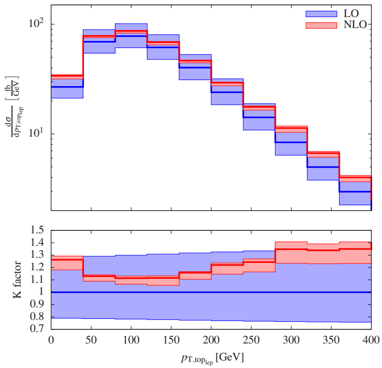
[Denner, MP; 1711.10359]

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

→ Clear effect of the cuts:

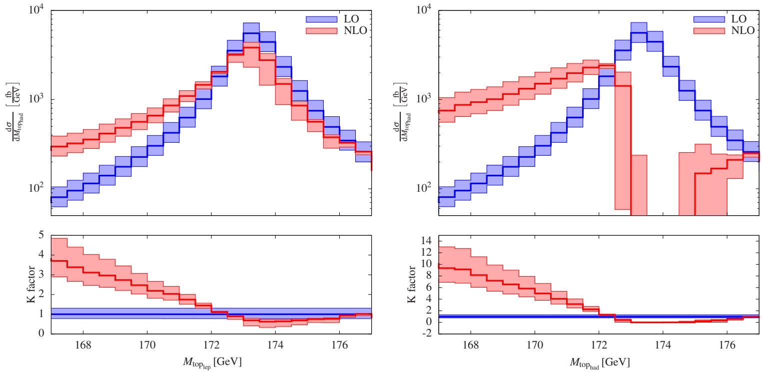
$$p^2_{T,j_2,\mathrm{max}} \sim m^2_{jj,\mathrm{max}}/\Delta R^2_{jj,\mathrm{min}} = (100)^2\,/\,(0.4)^2 = (250\,\mathrm{GeV})^2$$

→ 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

Conclusion

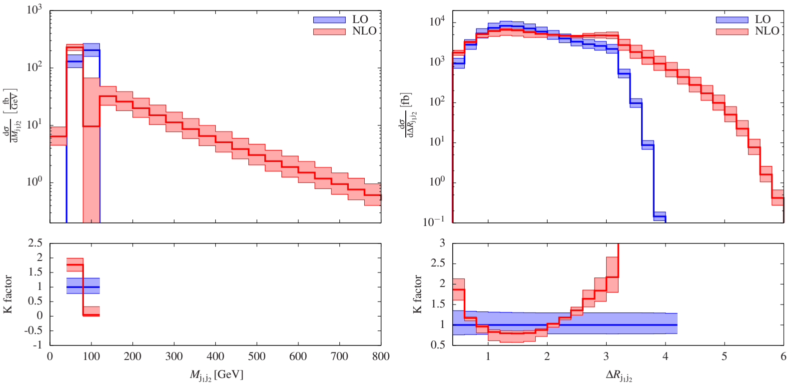
Summary

- First NLO EW calculation of the full off-shell processes $\mathrm{pp} \to \mathrm{t}^{\star}\bar{\mathrm{t}}^{\star}$ and $\mathrm{pp} \to \mathrm{t}^{\star}\bar{\mathrm{t}}^{\star}\mathrm{H}$ in the leptonic channel
- NLO EW corrections are non-negligible
  $\rightarrow$ Between $+15\%$ and -15%
- Off-shell effects can be large
  $\rightarrow$ WW double-pole approximation better than the tt one
  $\rightarrow$ Only the full calculation is always reliable
- Combination with NLO QCD corrections for $\mathrm{pp} \to \mathrm{t}^{\star}\bar{\mathrm{t}}^{\star}\mathrm{H}$
  $\rightarrow$ State-of-the art predictions comparable with experiments
- NLO QCD for $\mathrm{pp} \to \mathrm{t}^{\star}\bar{\mathrm{t}}^{\star}$ in the lepton+jets channel
  $\rightarrow$ Different corrections with respect to leptonic channel

JHEP 1608 (2016) 155 [arXiv:1607.05571]
JHEP 1702 (2017) 053 [arXiv:1612.07138]
JHEP 1802 (2018) 013 [arXiv:1711.10359]

BACK-UP

Semi-leptonic tt



[Denner, MP; 1711.10359]

Fiducial cross section (tth)

Ch.	σ_{LO} [fb]	$\sigma_{\mathrm{NLO\ EW}}$ [fb]	δ [%]
gg	2.0116(1)	2.020(1)	$+0.42$
$q\bar{q}$	0.84860(5)	0.8454(6)	-0.38
g$q(/\bar{q})$		0.00007(2)	
γg	0.02178(1)		
pp	2.8602(1)	2.866(1)	$+0.20$

- Cross section dominated by the gg channel
- γg channel below 1%
- Small positive EW corrections

Inputs (tth)

- For the renormalisation and factorisation scale:

$$\mu_{\rm dyn} = \left(m_{\rm T,t} m_{\rm T,\bar{t}} m_{\rm T,H}\right)^{\frac{1}{3}} \quad \text{with} \quad m_{\rm T} = \sqrt{m^2 + p_{\rm T}^2}$$

- G_μ scheme:

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

- Inputs:

$$\begin{aligned} m_{\rm t} &= 173.34\,\text{GeV}, & \Gamma_{\rm t} &= 1.36918\ldots\,\text{GeV} \\ M_{\rm Z}^{\rm OS} &= 91.1876\,\text{GeV}, & \Gamma_{\rm Z}^{\rm OS} &= 2.4952\,\text{GeV} \\ M_{\rm W}^{\rm OS} &= 80.385\,\text{GeV}, & \Gamma_{\rm W}^{\rm OS} &= 2.085\,\text{GeV} \\ M_{\rm H} &= 125.0\,\text{GeV} \end{aligned}$$

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

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

→ LUXqed_plus_PDF4LHC15_nnlo_100 [Manohar, Nason, Salam, Zanderighi]
with massless bottom quarks and bottom-quark PDF neglected

→ Event selection:

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

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

Top width(s) for pp $\to t^{\star}\bar{t}^{\star}H$

- $\Gamma_t^{\mathrm{LO}} = 1.449582\,\mathrm{GeV}$
  $\to$ Used for LO in the comparison with NLO QCD and EW
    $\to$ Crudest predictions
- $\Gamma_t^{\mathrm{NLO,QCD}} = 1.35029\,\mathrm{GeV}$
  $\to$ Used for LO in the comparison with NLO EW alone
    $\to$ To isolate EW effects
- $\Gamma_t^{\mathrm{NLO}} = 1.36918\,\mathrm{GeV}$ (with both NLO QCD and EW corrections)
  $\to$ Used for NLOs (NLO EW alone or NLO QCD and EW together)
    $\to$ Best predictions

Taken from Ref. [Basso, Dittmaier, Huss, Oggero; 1507.04676]