Theory predictions for top-pair production at collider experiments

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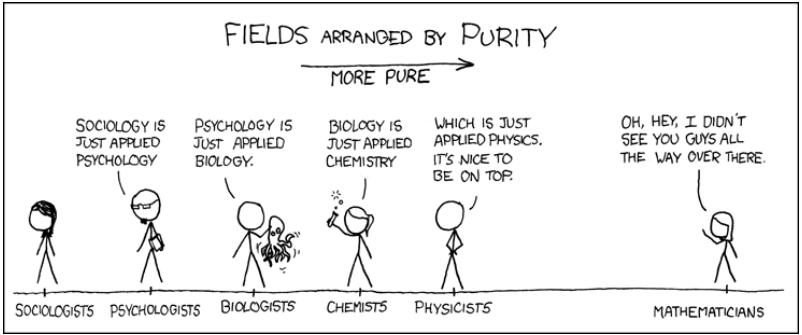
Outline:

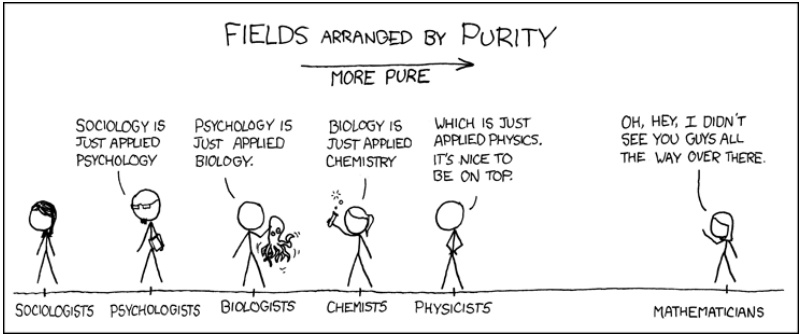
→ Predictions for top-pair production! ...

→ ... and why you want to compute them

- *lepton+jets channel (e^+e^- and LHC)*

- *Recent results on top associated production*


FIELDS ARRANGED BY PURITY
MORE PURE
SOCIOLOGY IS JUST APPLIED PSYCHOLOGY
PSYCHOLOGY IS JUST APPLIED BIOLOGY.
BIOLOGY IS JUST APPLIED CHEMISTRY
WHICH IS JUST APPLIED PHYSICS. IT'S NICE TO BE ON TOP.
OH, HEY, I DIDN'T SEE YOU GUYS ALL THE WAY OVER THERE.
SOCIOLOGISTS
PSYCHOLOGISTS
BIOLOGISTS
CHEMISTS
PHYSICISTS
MATHEMATICIANS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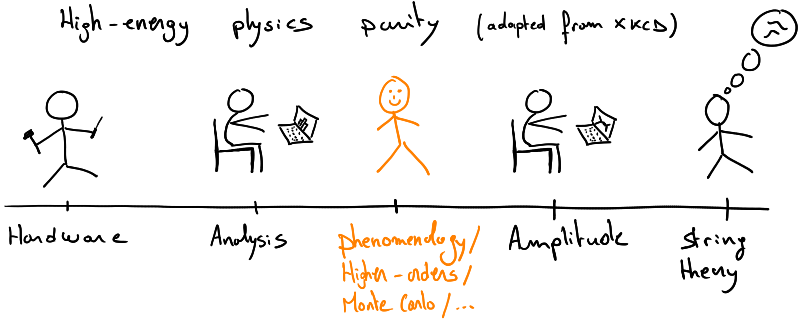
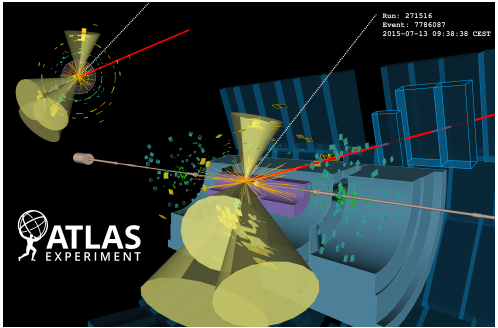
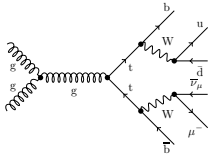

High-energy physics purity (adapted from xkcd)
Hardware
Analysis
Phenomenology/ Higher-orders/ Monte Carlo/...
Amplitude
String Theory

→ Illustration of Giordano Bruno's philosophical ideas ($\mathrm{XVI}^{th}\mathrm{century}$)

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



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



- Greatest achievement of the LHC so far:

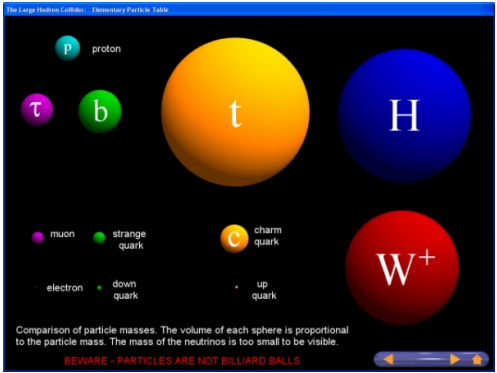
Discovery of the Higgs boson

→ Great interest in measuring properties of the Higgs boson ...

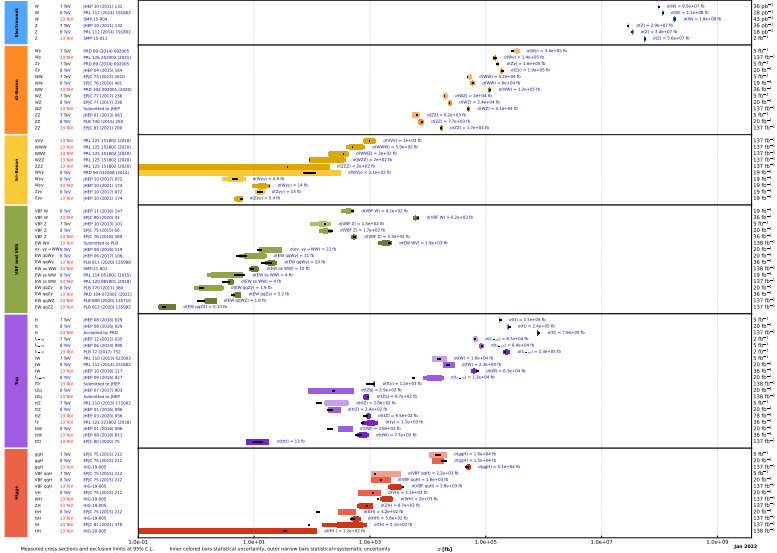
... but there are also other interesting things

Why is the top quark interesting?

- It is the heaviest particles of the Standard Model!



- Decay before hadronisation
- Possible window to new physics
- ...



→ **Cross-sections measurements machine!**

Precision at fixed order

More loops ...
$\rightarrow$ higher-order corrections in α_s and α

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- ☐ because I have nothing else to do
- ☐ because nobody did it before
- ☐ because it is relevant

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→ inclusion of **off-shell effects**

State of the art top-antitop production (@ lepton colliders)

- NLO QCD [Guo, Ma, Zhang, Wang; 0802.4124], [Liebler, Moortgat-Pick, Papanastasiou; 1511.02350]
  → With off-shell effects [Chokoufé Nejad et al.; 1609.03390]
- NLO EW [Fujimoto, Shimizu; Mod. Phys. Lett. A 3 (1988) 581], [Beenakker, van der Marck, Hollik; Nucl. Phys. B 365 (1991) 24–78], [Fleischer, Leike, Riemann, Werthenbach; hep-ph/0302259]
  → With ISR resummation [Quach, Kurihara; 1706.07042], [Bertone, et al.; 2207.03265]
- NNLO QCD [Gao, Zhu; 1408.5150,1410.3165], [Chen, Dekkers, Heisler, Bernreuther, Si; 1610.07897], [Bernreuther, Chen, Lu, Si; 2301.12632] (differential)
- N3LO QCD [Hoang, Mateu, Zebarjad; 0807.4173], [Kiyo, Maier, Maierhöfer, Marquard, 0907.2120] (inclusive)
- non-relativistic QCD and resummation [Hoang, Reisser, Ruiz-Femenia; 1002.3223], [Hoang, Stahlhofen; 1309.6323], [Beneke, et al.; 1506.06864], [Beneke, Maier, Rauh, Ruiz-Femenia; 1711.10429], [Bach, et al.; 1712.02220]

State of the art top-antitop production (@ LHC)

- 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 [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]

off-shell effects

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

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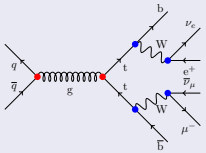
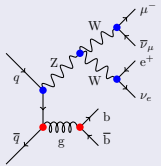
- Non-resonant contributions

→ *e.g.*



vs.



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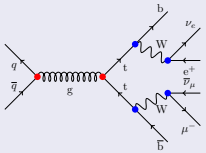

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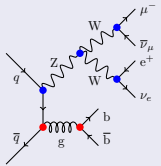
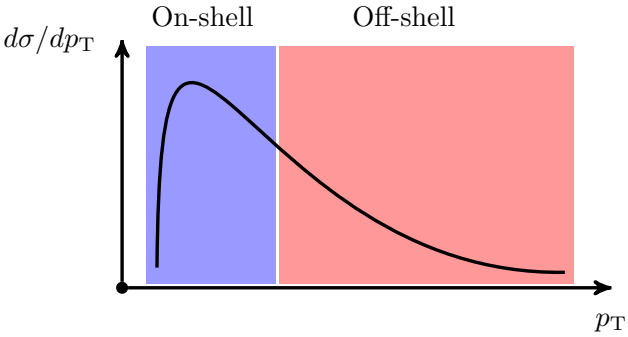


- Description of the final state
  → *e.g.* $\mathrm{pp} \to \mathrm{t\bar{t}}$ vs. $\mathrm{pp} \to \nu_\mu \mu^- \bar{\nu}_\mathrm{e} \mathrm{e}^+ \mathrm{b\bar{b}}$

→ All these effects are very much connected

off-shell effects

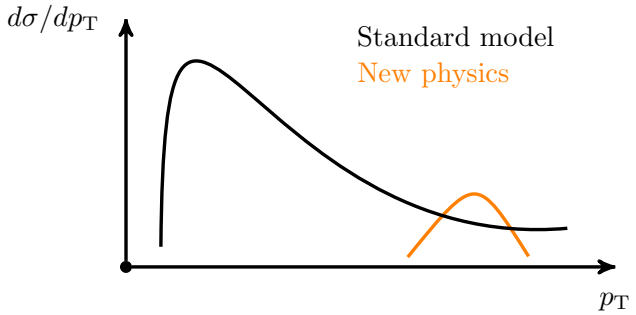
- Final states dominated by a production process
- Example: measured final state $e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ dominated by $pp \to t^\star\bar{t}^\star \to (W^\star \to \nu_\mu\mu^-)\,(W^\star \to e^+\nu_e)\,b\bar{b}$



On-shell region dominated by resonant production

Off-shell region receives large non-resonant contributions

Tail of distributions



→ During run II/III, 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 few publicly available with non-trivial resonance structure:
  $\to$ NLO QCD to off-shell tt [Ježo et al.; 1607.04538] (LHC) with POWHEG ...
  ...and [Chokoufé Nejad et al.; 1609.03390] (e^+e^-) with WHIZARD
  $\to$ QCD QCD to off-shell tt [Frederix; 1311.4893] with MADGRAPH5_aMC@NLO
  $\to$ NLO EW to VBS same-sign W [Chiesa, Denner, Lang, MP; 1906.01863] with POWHEG
  $\to$ NLO EW to WWW [Schönherr; 1806.00307] with SHERPA

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- $2 \to 7$ 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]
  - $\to$ NLO QCD to $\mathbf{t\bar{t}W}$ [Bevilacqua et al.; 2005.09427], [Denner; Pelliccioli; 2007.12089]
  - $\to$ NLO QCD to $\mathbf{t\bar{t}b\bar{b}}$ [Denner, Lang, MP; 2008.00918], [Bevilacqua et al.; 2105.08404, 2202.11186] ★
  - $\to$ NLO EW to $\mathbf{t\bar{t}W}$ [Denner, Pelliccioli; 2102.03246] ★
  - $\to$ NLO QCD to $\mathbf{t\bar{t}}(\mathbf{Z} \to \ell^+\ell^-)$ [Bevilacqua et al.; 2203.15688]
  - $\to$ NLO EW to $\mathbf{t\bar{t}Z}$ [Denner, Lombardi, Pelliccioli; 2306.13535]

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  - $\to$ NLO QCD to $\mathbf{t\bar{t}}(\mathbf{Z} \to \nu\bar{\nu})$ [Bevilacqua et al.; 1907.09359]
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  - $\to$ NLO QCD to $\mathbf{t\bar{t}b\bar{b}}$ [Denner, Lang, MP; 2008.00918], [Bevilacqua et al.; 2105.08404, 2202.11186] ⋆
  - $\to$ NLO EW to $\mathbf{t\bar{t}W}$ [Denner, Pelliccioli; 2102.03246] ⋆
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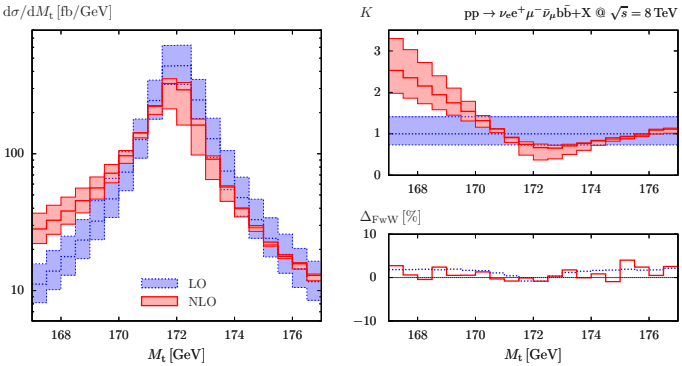
  - $\to$ NLO EW to $\mathbf{t\bar{t}Z}$ [Denner, Lombardi, Pelliccioli; 2306.13535]

- $2 \to 9$ processes
  - $\to$ NLO QCD to $\mathbf{t\bar{t}Wj}$ [Bi, Kraus, Reinartz, Worek; 2305.03802] ⋆

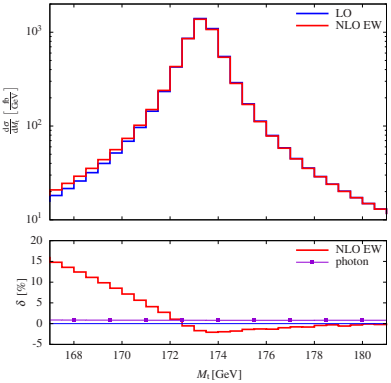
a) NLO QCD/EW to pp $\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$

NLO QCD



[Denner et al.; 1207.5018]

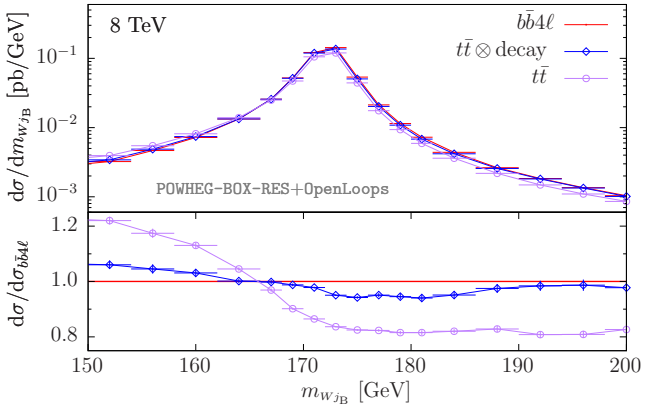
NLO EW



[Denner, MP; 1607.05571]

→ Radiative tail due to non-reconstructed jets/photons

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



[Ježo et al.; 1607.04538]

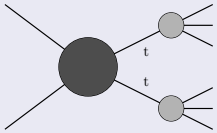
→ Different treatments of resonances

→ Inclusion of non-resonant contributions and all NLO corrections

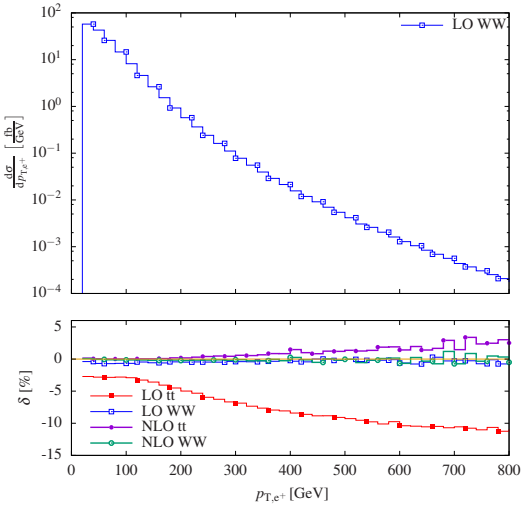
c) LO: pp $\to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$

Retain resonant contributions

$\to$ **tt**

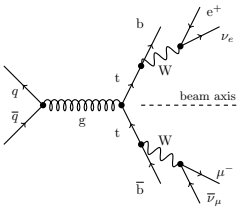


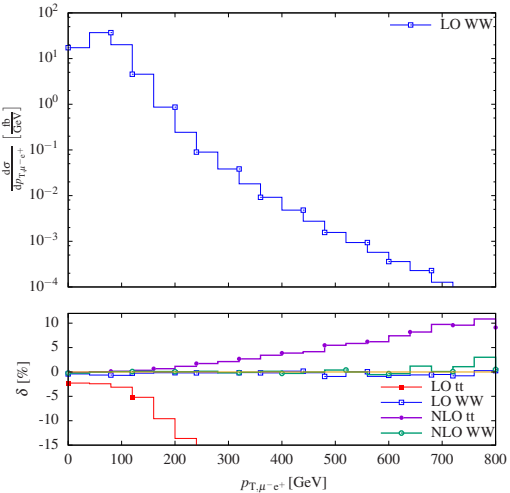
(off-shell propagators and full phase space included)

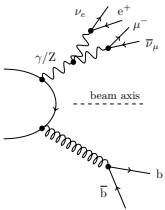


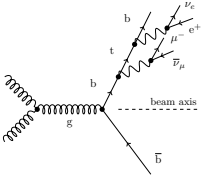
[Denner, MP; 1607.05571]

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





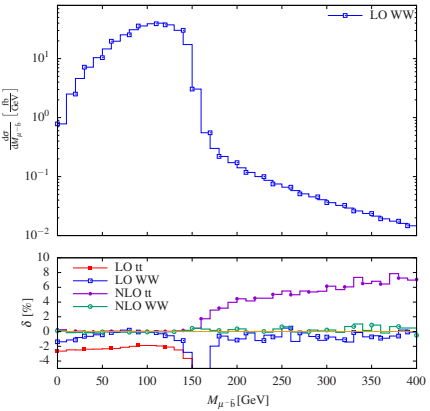




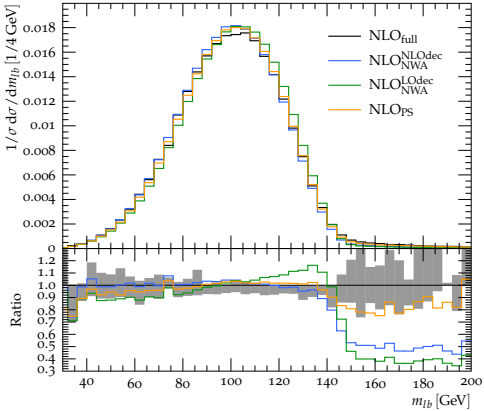
[Denner, MP; 1607.05571]

→ Even more stringent effect for exclusive observables

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

→ Large effects above threshold

→ Similar study for $t\bar{t} + j$ [Bevilacqua et al.; 1710.07515]

Tools for own calculations presented here

- Private Monte Carlo MoCaNLO @ NLO QCD + EW

  [Denner, Feger, Lombardi, MP, Pelliccioli, Schmidt, Schwan]
- Tree-level and one-loop: Recola [Actis et al.; 1211.6316, 1605.01090]
- Complex-mass scheme [Denner et al.; hep-ph/9904472, hep-ph/0505042, hep-ph/0605312]
- PDF: LHAPDF [Buckley et al.; 1412.7420]

PART I

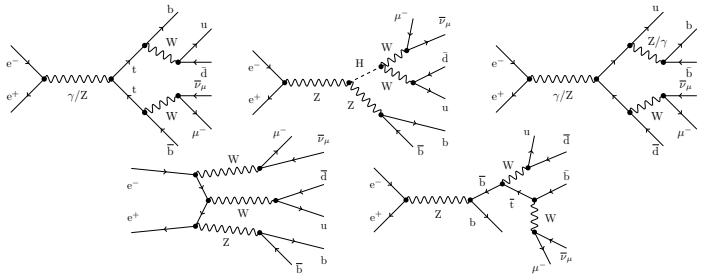
- *lepton+jets channel (e^+e^- and LHC)*

Motivations

- NLO QCD to off-shell $e^+e^- \to \mu^-\bar{\nu}_\mu b\bar{b}jj$

- Allows precise determination of top-quark mass [Seidel, Simon, Tesar, Poss;1303.3758]
- Larger cross section due to W boson branching ratio
- Better reconstruction of top quarks (only one neutrino)
- Unexplored final state for tt production (on the theoretical side beyond LO)

  $\longrightarrow$ [Amjad, et al.; 1307.8102.], [Fuster, et al.; 1411.2355], [Amjad, et al., 1505.06020], [Bernreuther, et al., 1710.06737]



Predictions for $\sqrt{s} = 365\,\text{GeV}$ and $\sqrt{s} = 1.5\,\text{TeV}$ for e^+e^- collision

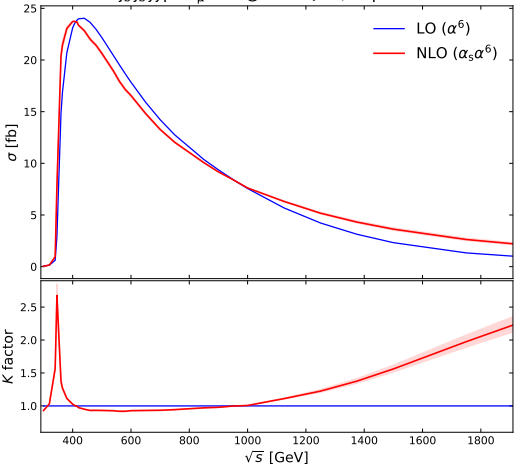
→ Event selection for *resolved topology* [ATLAS; 1708.00727], [CMS; 1610.04191]]:

light/b jets:	$p_{\text{T,j/b}} > 20\,\text{GeV}$
missing energy:	$p_{\text{T,miss}} > 20\,\text{GeV}$
angular acceptance:	$10^\circ < \theta < 170^\circ$
distance:	$\Delta R_{\ell\text{j}}, \Delta R_{\ell\text{j}_\text{b}} > 0.4$

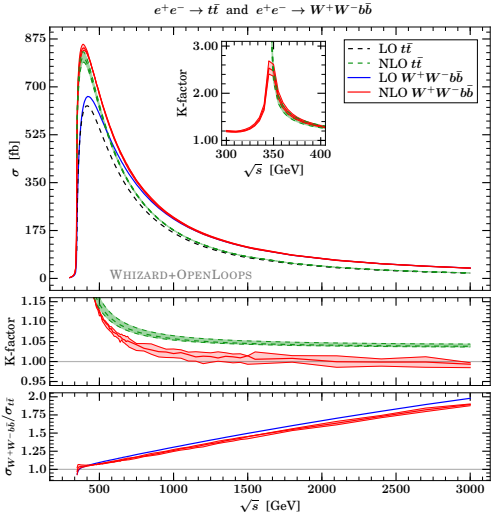
→ k_T jet algorithm with $R = 0.4$
→ Additional cut to avoid Higgs resonance

$$m_{\text{jj}\mu^+\nu_\mu} > 130\,\text{GeV}$$

letpon+jets vs. fully leptonic

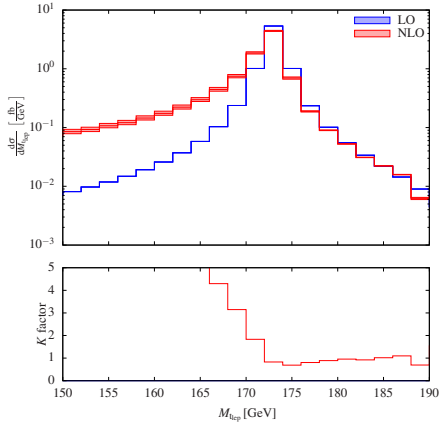


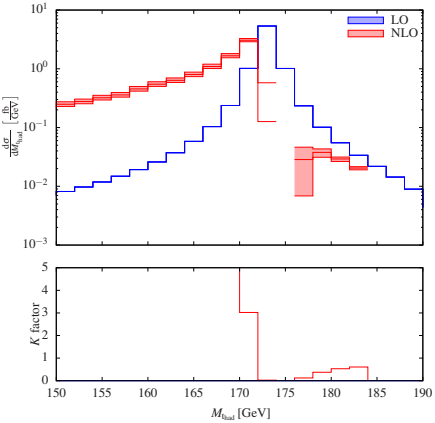
[Denner, Pellicioli, MP; 2302.04188]



[Chokoufé Nejad et al.; 1609.03390]

@ 365 GeV

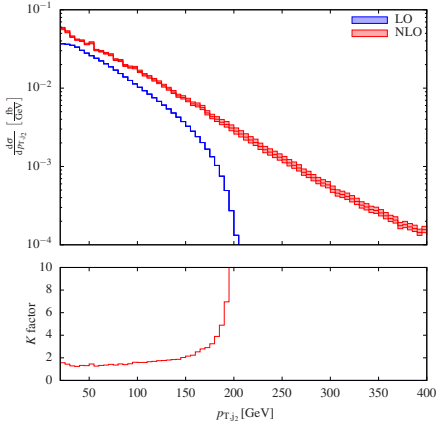


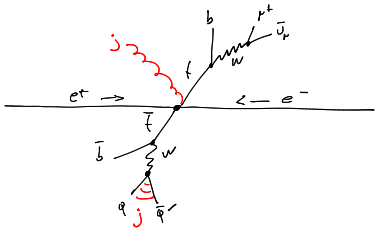


[Denner, Pellicioli, MP; 2302.04188]

→ Extreme radiative tail

@ 1.5 TeV

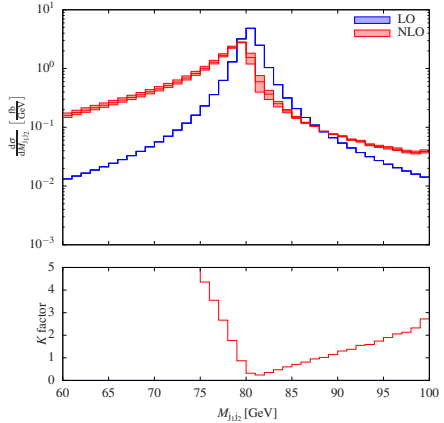


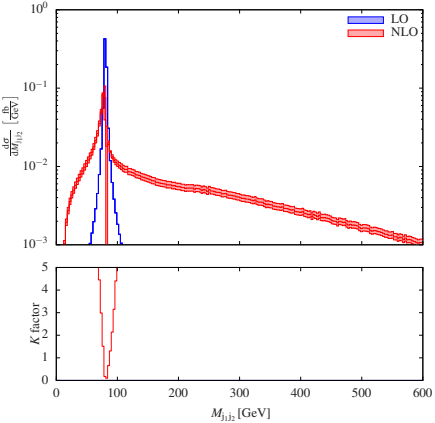


[Denner, Pellicioli, MP; 2302.04188]

→ Large corrections due to opening phase space

@ 365 GeV vs. 1.5 TeV

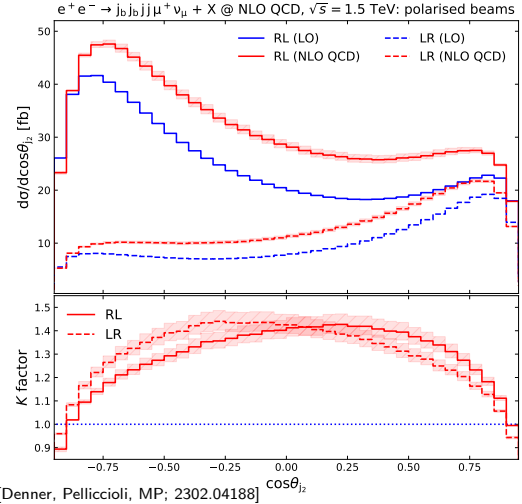


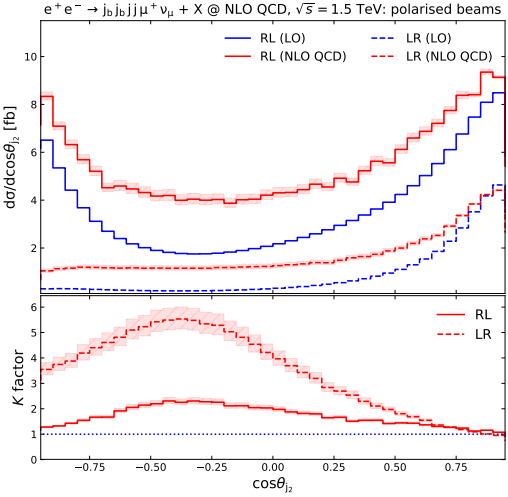


[Denner, Pelliccioli, MP; 2302.04188]

→ Stark contrast between both centre-of-mass energy

@ 365 GeV vs. 1.5 TeV





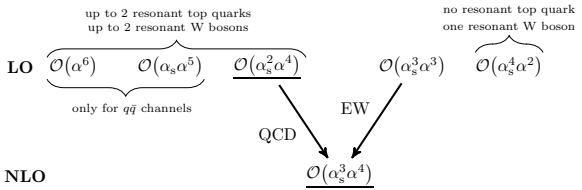
[Denner, Pelliccioli, MP; 2302.04188]

→ With polarised beams

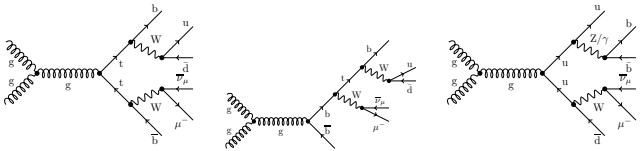
Motivations (reloaded)

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

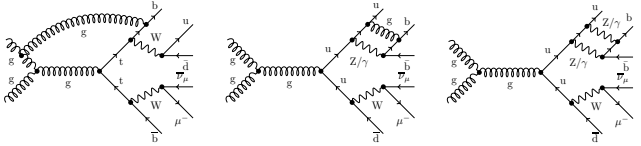
- Measured experimentally [ATLAS; 1708.00727], [CMS; 1610.04191]
- Larger cross section due to W boson branching ratio
- Better reconstruction of top quarks (only one neutrino)
- Unexplored final state for tt production (on the theoretical side)
  [Anger, Febres Cordero, Ita, Sotnikov; 1712.05721]: Wbb + 2j
  but different orders: $\mathcal{O}\left(\alpha_s^4 \alpha^2\right)$ vs. $\mathcal{O}\left(\alpha_s^4 \alpha^4\right)$



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



- NLO QCD is defined at order $\mathcal{O}\left(\alpha_s^3\alpha^2\right)$



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

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

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

→ anti-k_{T} jet algorithm [Cacciari, Salam, Soyez; 0802.1189] with $R = 0.4$

→ Additional cut to ensure stable definition of fiducial volume at both LO/NLO

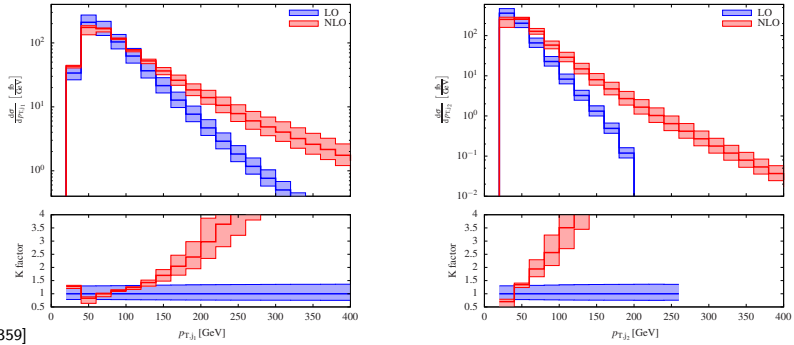
$$60\,\text{GeV} < m_{\text{jj}} < 100\,\text{GeV}$$

- Full computation for $pp \to \mu^- \bar{\nu}_\mu b\bar{b}jj$:
  $\to$ 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% without m_{jj} cut

Computation done on partonic channels with resonant top quarks



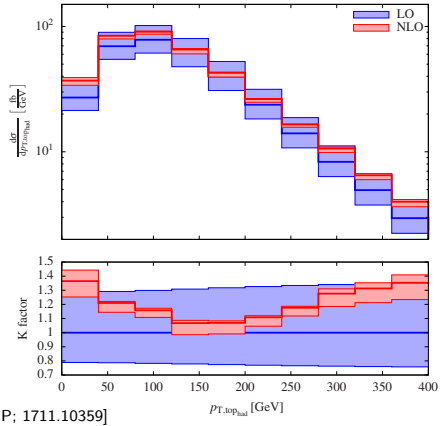
[Denner, MP; 1711.10359]

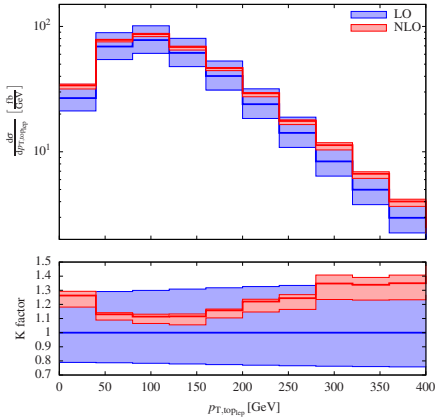
→ Large corrections toward high transverse momenta
(due to real corrections)

→ Clear effect of the cuts:

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

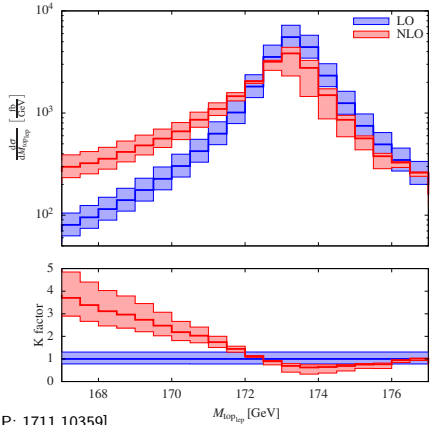
→ Scale variation band increase for high transverse momenta
(the NLO predictions become LO accurate)

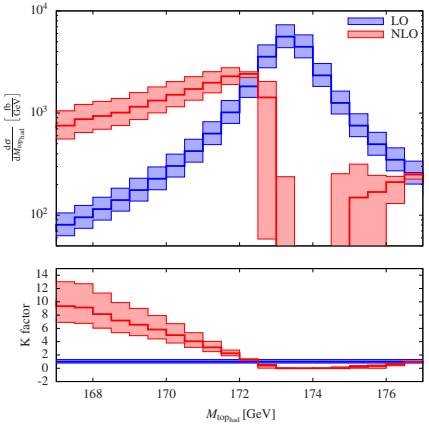




[Denner, MP; 1711.10359]

→ Different behaviour hadronic vs. leptonic top quark





[Denner, MP; 1711.10359]

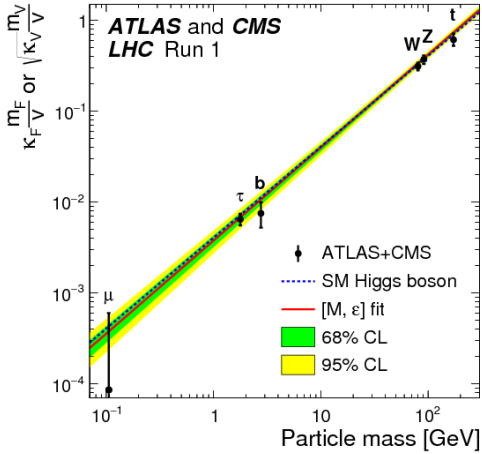
→ Different NLO behaviour between the hadronic and leptonic top quark

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

PART II

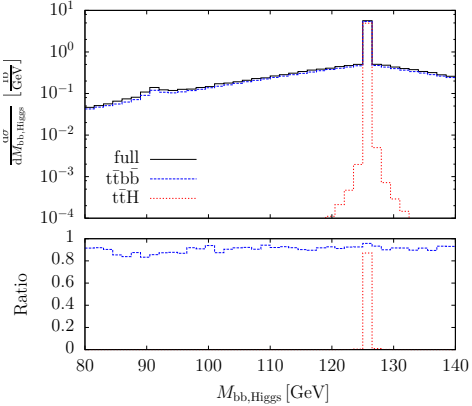
- *Recent results on top associated production*

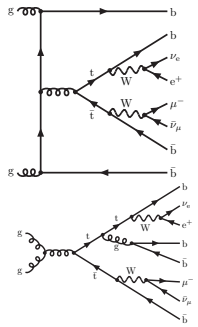
Yukawa coupling

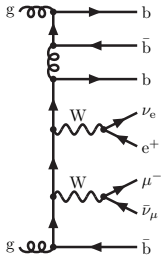


→ Couplings to Higgs and masses are proportional

Full process: $pp \to \ell^+\nu_\ell jjb\bar{b}b\bar{b}$, background to $pp \to t\bar{t}(H \to b\bar{b})$!

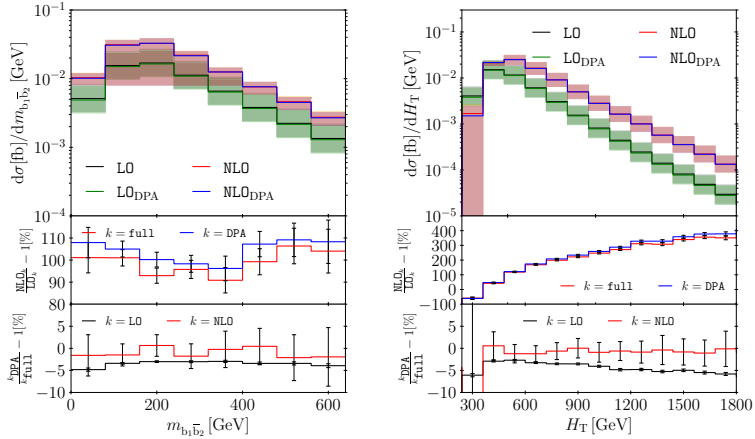






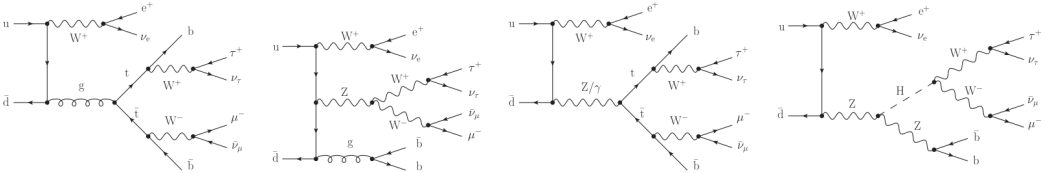
[Denner, Feger, Scharf; 1412.5290]

NLO QCD to $\mathbf{t\bar{t}b\bar{b}}$ [Denner, Lang, MP; 2008.00918]



- 100% corrections
- Moderate off-shell effects

NLO QCD + EW to $\mathbf{t\bar{t}W}$ [Denner; Pellicciolli; 2102.03246]



NLO QCD + EW to $\mathbf{t\bar{t}W}$ [Denner; Pelliccioli; 2102.03246]

→ on-shell vs. off-shell

$\delta[\%]$	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
LO_2	-	-	-
LO_3	0.8	0.9	1.1
NLO_1	34.8 (7.0)	50.0 (25.7)	63.4 (42.0)
NLO_2	−4.4 (−4.8)	−4.2 (−4.6)	−4.0 (−4.4)
NLO_3	11.9 (8.9)	12.2 (9.1)	12.5 (9.3)
NLO_4	0.02 (−0.02)	0.04 (−0.02)	0.05 (−0.01)

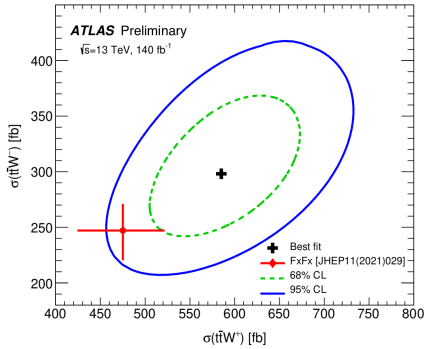
[Frederix, Pagani, Zaro; 1711.02116]

	$\mu_0^{(c)}$		$\mu_0^{(d)}$		$\mu_0^{(e)}$	
perturbative order	σ (fb)	ratio	σ (fb)	ratio	σ (fb)	ratio
$\mathrm{LO}_{\mathrm{QCD}}$ $(\alpha_s^2\alpha^6)$	$0.2218(1)^{+25.3\%}_{-18.8\%}$	1	$0.1948(1)^{+23.9\%}_{-18.1\%}$	1	$0.2414(1)^{+26.2\%}_{-19.3\%}$	1
$\mathrm{LO}_{\mathrm{EW}}$ (α^8)	$0.002164(1)^{+3.7\%}_{-3.6\%}$	0.010	$0.002122(1)^{+3.7\%}_{-3.6\%}$	0.011	$0.002201(1)^{+3.7\%}_{-3.6\%}$	0.009
NLO_1 $(\alpha_s^3\alpha^6)$	0.0147(6)	0.066	0.0349(6)	0.179	0.0009(7)	0.004
NLO_2 $(\alpha_s^2\alpha^7)$	-0.0122(3)	-0.055	-0.0106(3)	-0.054	-0.0134(4)	-0.056
NLO_3 $(\alpha_s\alpha^8)$	0.0293(1)	0.131	0.0263(1)	0.135	0.0320(1)	0.133
$\mathrm{LO}_{\mathrm{QCD}}$+$\mathrm{NLO}_1$	$0.2365(6)^{+2.9\%}_{-6.0\%}$	1.066	$0.2297(6)^{+5.5\%}_{-7.3\%}$	1.179	$0.2423(7)^{+3.5\%}_{-5.2\%}$	1.004
$\mathrm{LO}_{\mathrm{QCD}}$+$\mathrm{NLO}_2$	$0.2094(3)^{+25.0\%}_{-18.7\%}$	0.945	$0.1840(3)^{+23.8\%}_{-17.9\%}$	0.946	$0.2277(4)^{+25.9\%}_{-19.2\%}$	0.944
$\mathrm{LO}_{\mathrm{EW}}$+$\mathrm{NLO}_3$	$0.03142(4)^{+22.2\%}_{-16.8\%}$	0.141	$0.02843(6)^{+20.5\%}_{-15.6\%}$	0.146	$0.03425(7)^{+22.8\%}_{-17.0\%}$	0.142
LO+NLO	$0.2554(7)^{+4.0\%}_{-6.5\%}$	1.151	$0.2473(7)^{+6.3\%}_{-7.6\%}$	1.270	$0.2628(9)^{+4.3\%}_{-5.9\%}$	1.089

[Denner; Pelliccioli; 2102.03246]

- Large cancellations between various orders
- Similar picture for on-shell and off-shell computation

Persistent tension in $t\bar{t}W$ data



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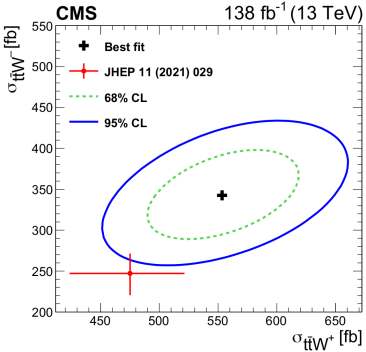
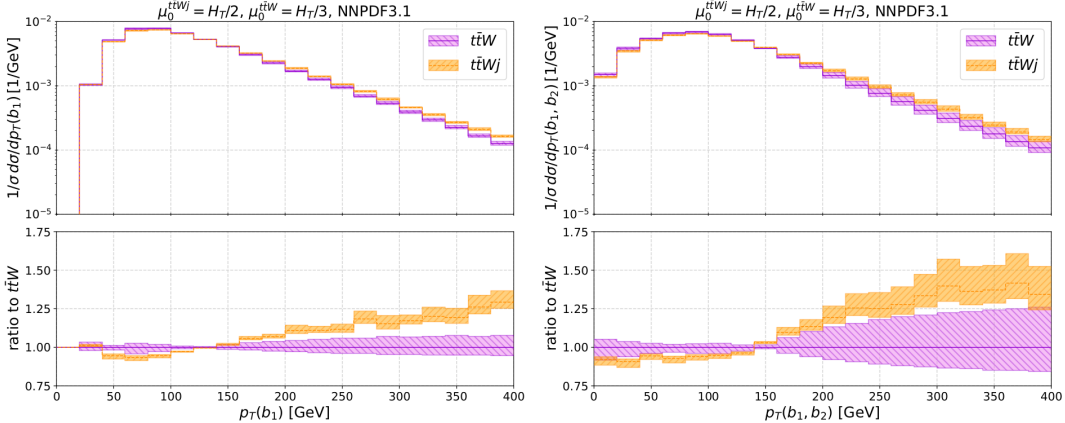


[CMS; 2208.06485]

- Theory prediction: [Frederix, Tsinikos; 2108.07826]
  - → merged prediction with EW corrections
  - → more events than expected

NLO QCD to $t\bar{t}Wj$ [Bi, Kraus, Reinartz, Worek; 2305.03802]



- Non-negligible contributions in certain phase space
- ⚠ Not a merged prediction (selection on extra jet for $t\bar{t}Wj$)

Summary - off-shell production of top quarks

- Wealth of multi-legs computations
- Wealth of physics effects
- Outlook: make these computations available to th. and exp. communities

Summary - off-shell production of top quarks

- Wealth of multi-legs computations
- Wealth of physics effects
- Outlook: make these computations available to th. and exp. communities

- Decisive information for SM measurements
  $\rightarrow$ Precision programme at the LHC (and future colliders)
- Crucial interplay between theory and experiment
  $\rightarrow$ Big impact on physics results

BACK-UP