Top quark modelling

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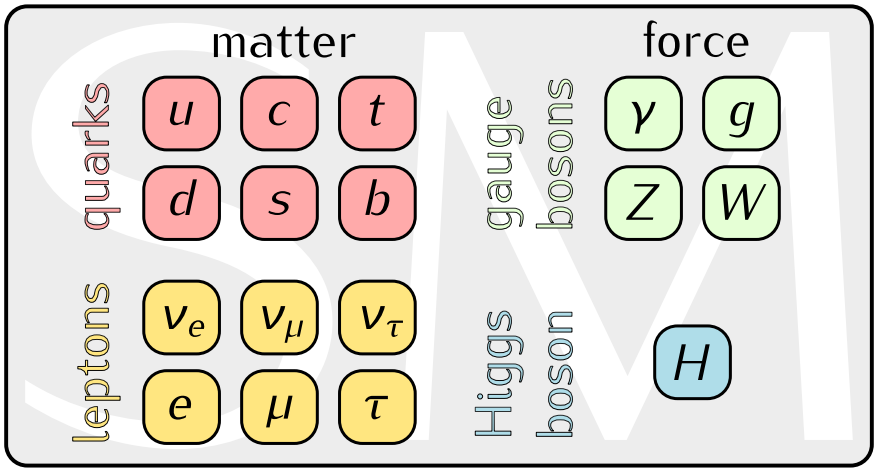
Universität Zürich[UZH]

XXXIst Rencontres de Blois

Top quark trivia

- 3rd family up-type quark



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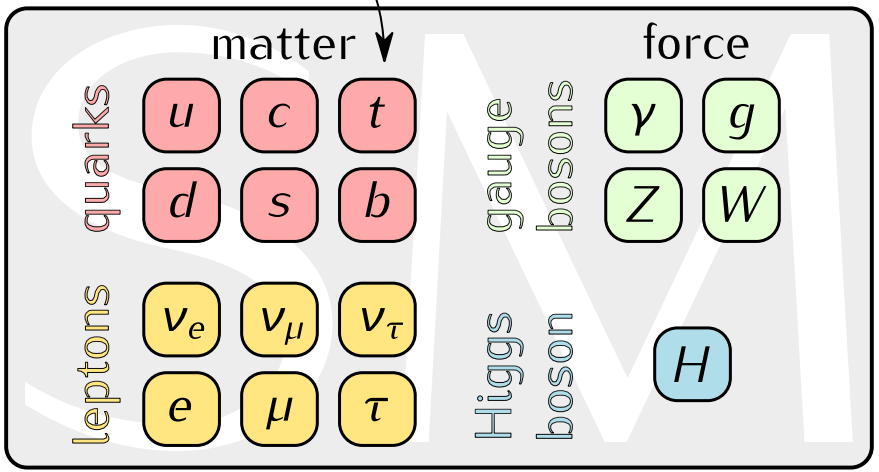

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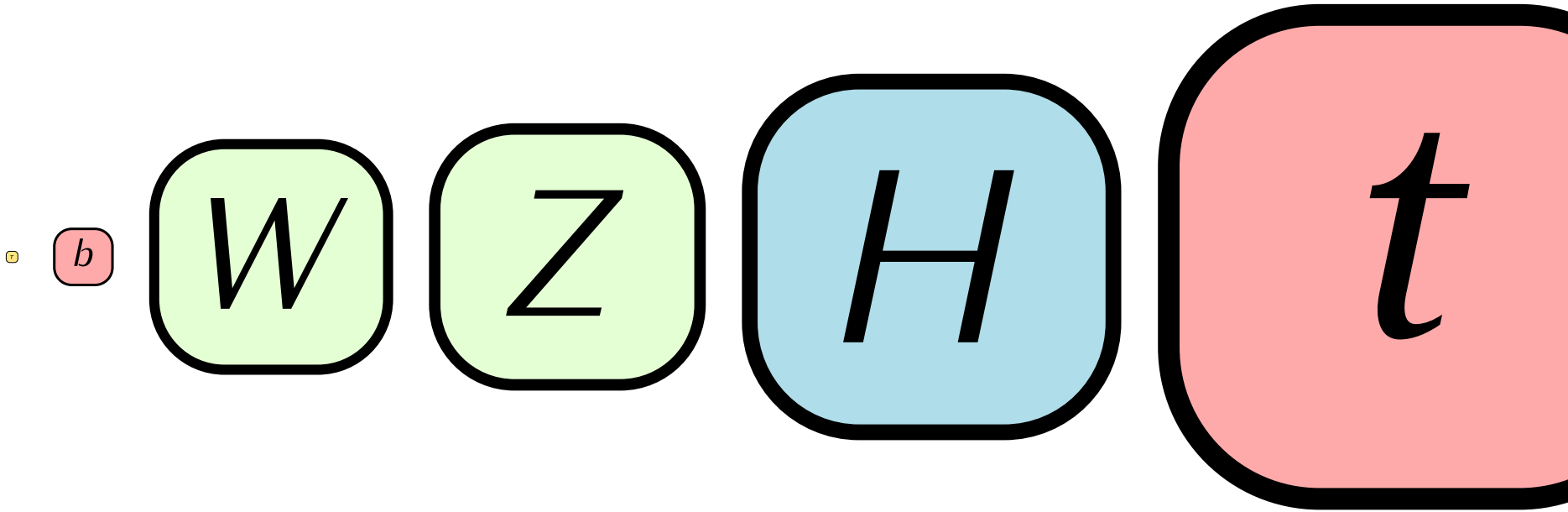

Top quark trivia

- 3rd family up-type quark
- heaviest elementary particle so far, $m_t \sim 173$ GeV
- is very short lived, $\Gamma_t \sim 1.3$ GeV
  - $\Gamma_t/m_t \sim 0.8\%$ ($\Gamma_H/m_H \ll \Gamma_t/m_t < \Gamma_W/m_W \sim \Gamma_Z/m_Z$)
  - does not hadronize, unlike any other quark
    - lifetime $\sim 5 \times 10^{-25}$ s vs. hadronization $\sim 3 \times 10^{-24}$ s $\Rightarrow$ no toponium or T-mesons: the only "bare" quark
  - decays electroweakly (EW) and almost exclusively as $t \to W + b$

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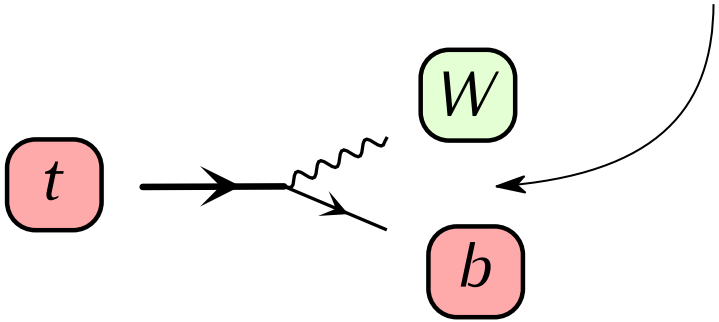

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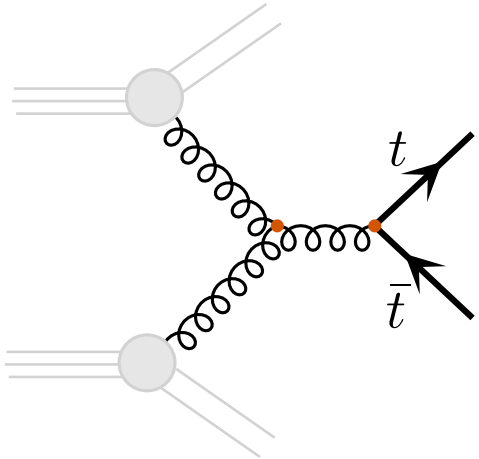
  - via strong interaction in pairs



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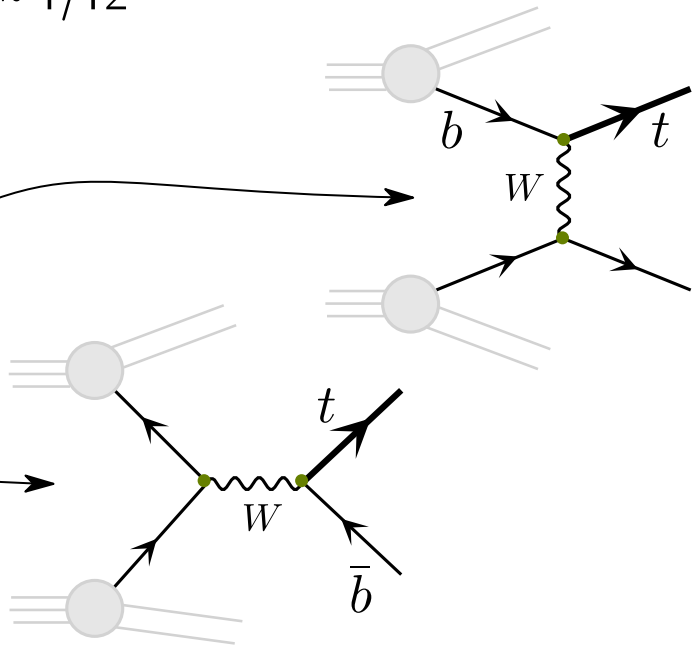

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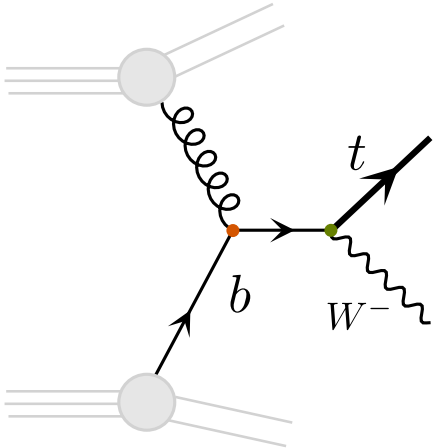
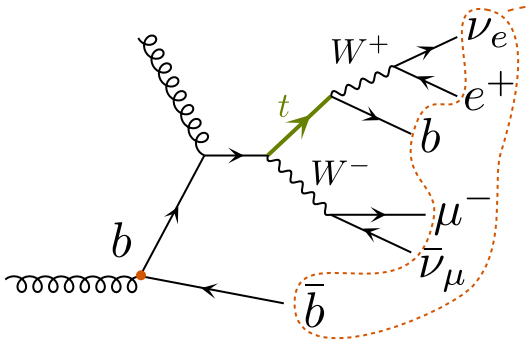


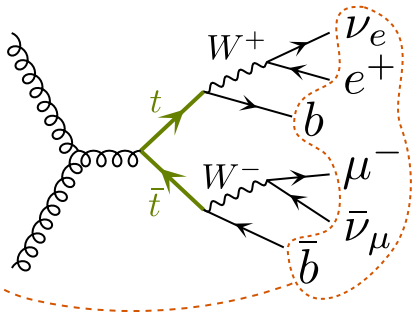
Top quark trivia

tW associated production @ NLO



same final state!

$t\bar{t}$ production @ LO



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this classification does not apply at NLO!

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- major background for many SM measurements and BSM searches

Top quark trivia

arXiv id	observable	top backgrounds
1712.02758	Higgs and Z to $\varphi\gamma$, $\rho\gamma$	———
1712.02118	long lived charginos	$t\bar{t}$
1712.02304	$H \to ZZ^* \to 4l$	$t\bar{t}$, $t\bar{t}+Z$, $t\bar{t}+H$
1712.02332	squarks and gluinos	$t\bar{t}$, Wt, ST, $t\bar{t}+W/Z/WW$
1712.01602	$d\sigma_{tW}$	duh
1711.11520	top-squark pair	$t\bar{t}$, Wt, ST, $t\bar{t}+Z$
1711.08341	soft-drop jet mass	———
1711.03301	dark matter, other NP	$t\bar{t}$, ST (small contrs)
1711.03296	$\sigma_{W^+}/\sigma_{W^-}$ and $d\sigma_W$	$t\bar{t}$, ST
1711.02692	$\sigma_{(\mathrm{di})\mathrm{jet}}$	———
1711.01901	Supersymmetry	$t\bar{t}$, ST, Wt
1710.11412	dark matter + b/t quarks	$t\bar{t}$, ST, $t\bar{t}+W/Z/\gamma/H$, $t\bar{t}+WW/t\bar{t}$, ...
1710.09560	σ isolated-γ + h.f. jet	———
1710.09748	H^{++}	$t\bar{t}$, ST, $t\bar{t}W/Z/\gamma/H$
1710.07235	WW/WZ resonances	$t\bar{t}$, ST
1710.07171	pair-produced resonances	$t\bar{t}$
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12/16 require reliable simulation of $t\bar{t}$!

Outline

- share recent developments:
  - heaviest elementary particle so far, $m_t \sim 173$ GeV
  - is very short lived, $\Gamma_t \sim 1.3$ GeV
  - couples strongly to the Higgs boson, $\alpha_t = {y_t}^2/4\pi \sim 1/12$

- review state-of-the-art of top-quark modelling:
  - via strong interaction in pairs
  - via EW interaction singly, in s & t-channels
  - mixed in association with W

Top mass

- Very precisely measured:
  - Latest ATLAS combination
    - $m_t = 172.69 \pm 0.48$ GeV
  - Latest CMS combination
    - $m_t = 172.44 \pm 0.48$ GeV
  - HL/HE LHC projections aim at $\sim 0.1\%$ accuracy

$\delta m_t / m_t = 0.28\%$

- Or is it?
  - Higher order corrections in top decay induce shape distortions in observables used for top mass determinations [Ferrario Ravasio, TJ, Nason, Oleari '18], [Heinrich et al. '17], [Bevilacqua et al. '17]
  - Top quark is a coloured object:
    - It cannot be unambiguously identified with its decay products
    - Many observables plagued by power corrections $(\Lambda/m_t)^n$ [Ferrario Ravasio et al. '19], [Hoang et al. '16, '18]

Talk by A. Hoang on Thursday 11h00

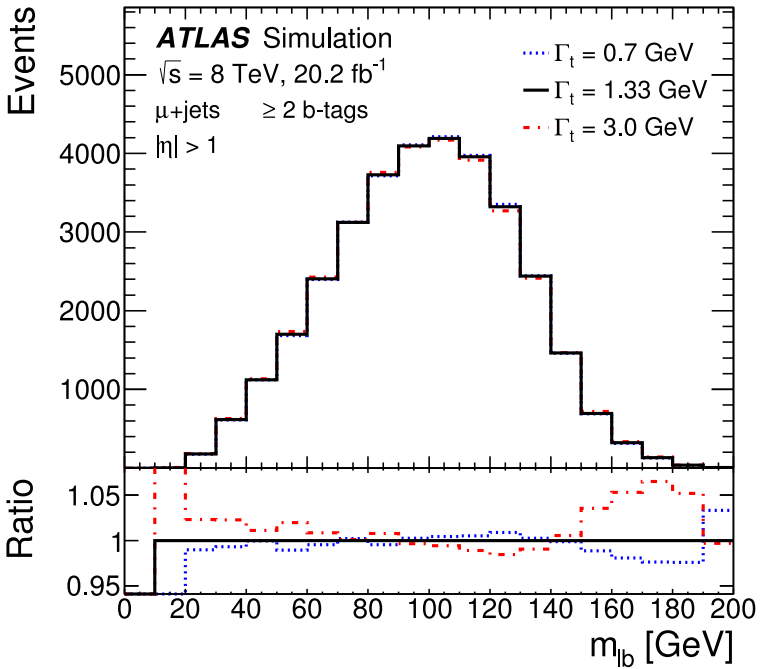
Top width

- Combination of t-channel single-top XS and $(t \to Wb)/(t \to Wq)$ ratio yields
  - $\Gamma_t = 1.36 \pm 0.02(\text{stat.})^{+0.14}_{-0.11}(\text{syst.})$ GeV
  - but assumes $\mathcal{B}(t \to Wq) = 1$

[arXiv: 1709.04207]

- Template fits to reconstructed mass spectra (lepton+jets):
  - $\Gamma_t = 1.76 \pm 0.33(\text{stat.})^{+0.79}_{-0.68}(\text{syst.})$ GeV

- Recast of the [TOPQ-2017-05] measurement of m_{bl} in the Wt enriched region:
  - $\Gamma_t = 1.28 \pm 0.27(\text{stat.}) \pm 0.14(\text{syst.})$ GeV



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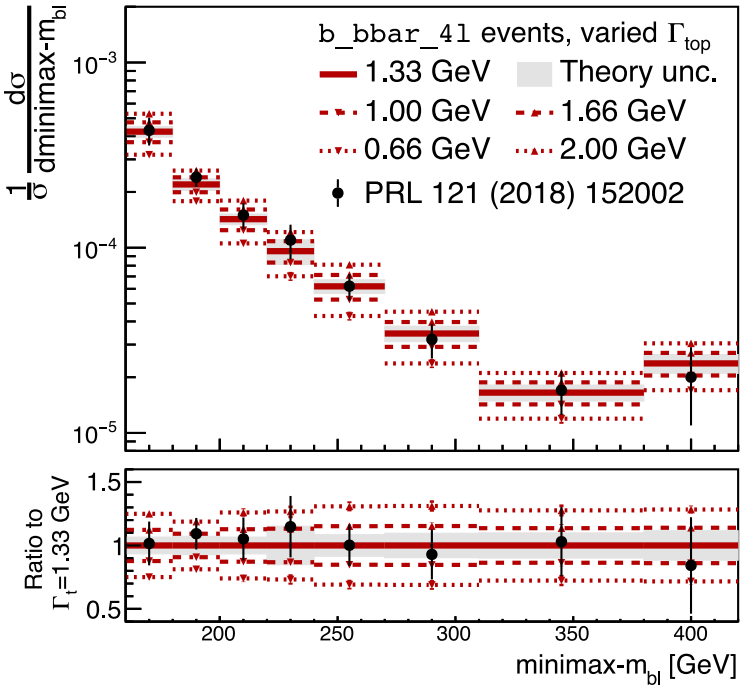
[TJ, Herwig, Nachman 2019]

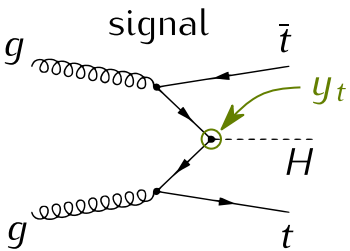


Top-Higgs coupling

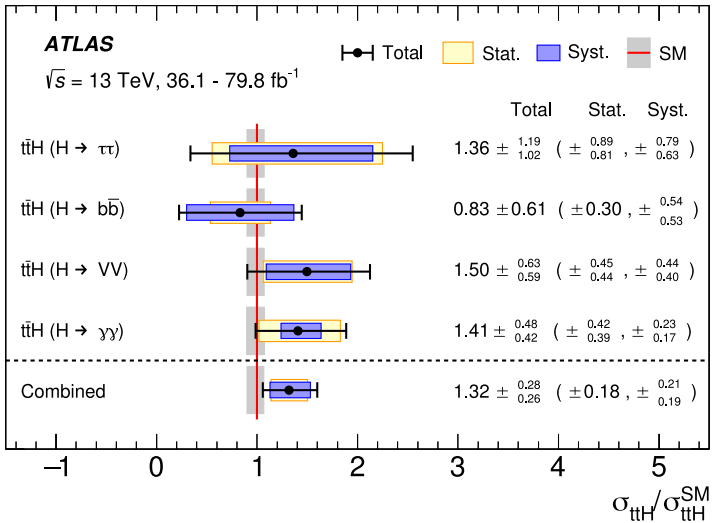
- $t\bar{t}H$ process offers a direct probe of top-quark Yukawa coupling

- Obeserved at the LHC a year ago
  - Decay channel with the largest branching ratio, ttH(bb), limited by systematics to a large extent dominated by modelling uncertainties

- State-of-the-art NLO+PS predictions barely agree within pertubative uncertainties
  - Is this an irreducible theory uncertainity?
  - Poor scale choice?
  - A bug or mismodelling of sorts?



[ATLAS HIGG-2018-13]



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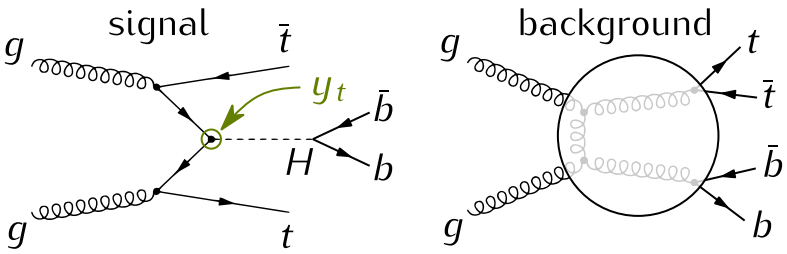
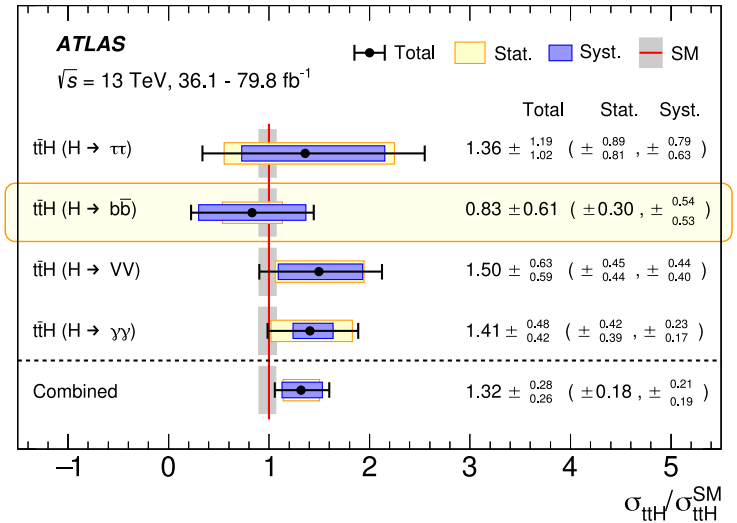


[ATLAS HIGG-2018-13]



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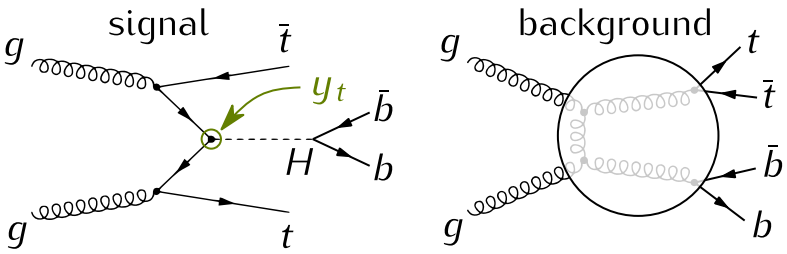
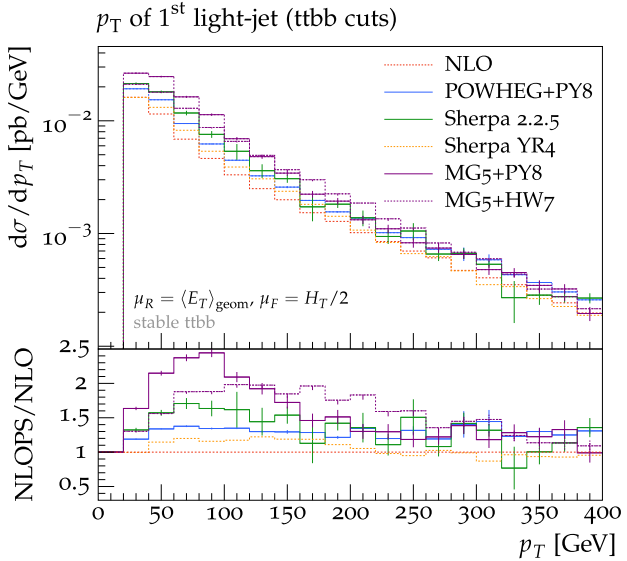


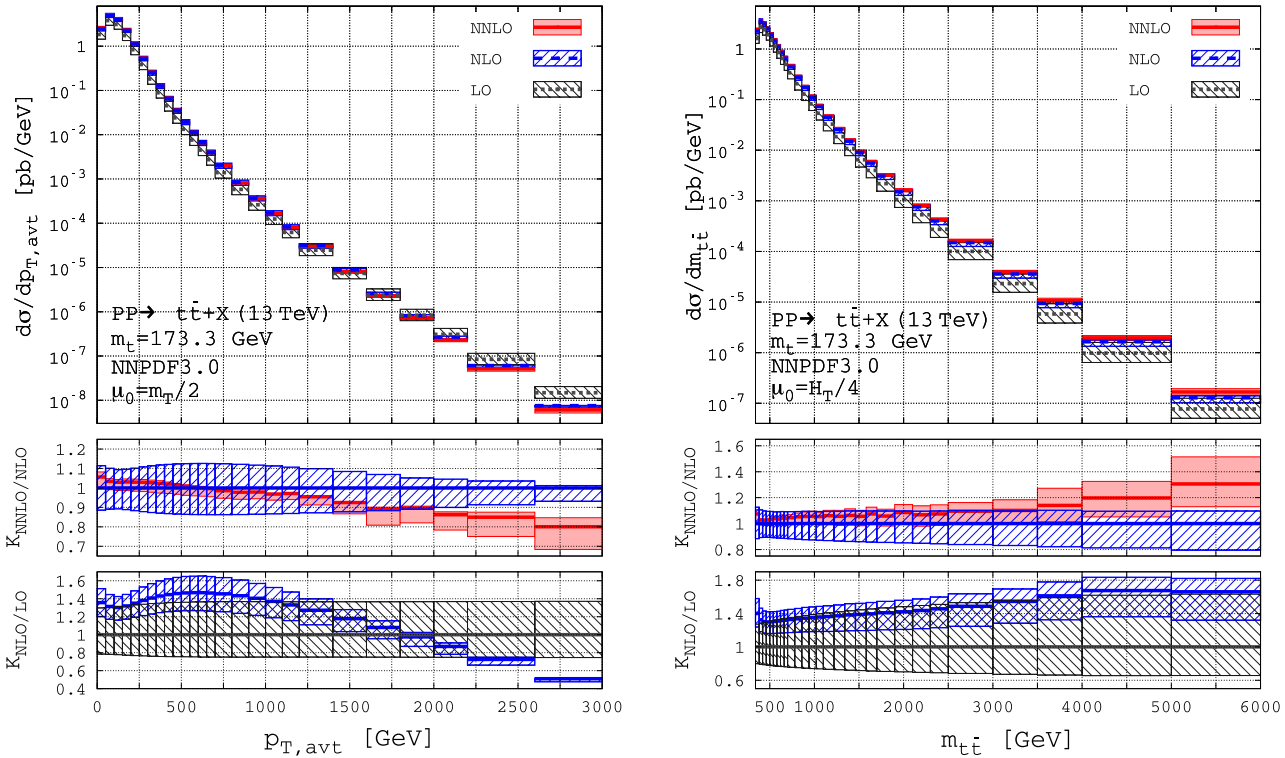
[TJ, Pozzorini et al., LHC HXSWG ttH/ttbb]



State-of-the-art: stable tops at NNLO

- Fully-differential NNLO QCD predictions for top-pair production

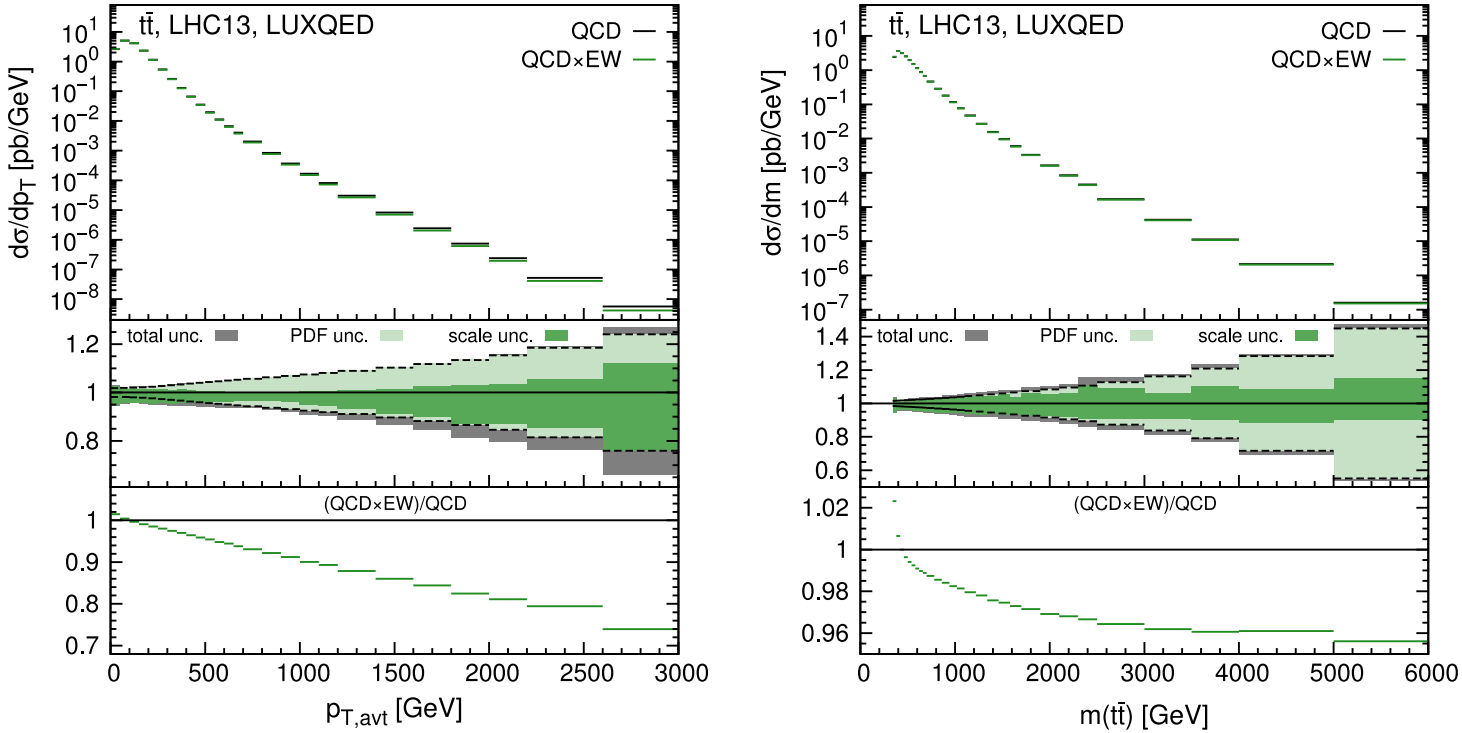
[Czakon, Heymes, Mitov 2016]



State-of-the-art: stable tops at NNLO

- NNLO QCD combined with NLO EW for top-pair production

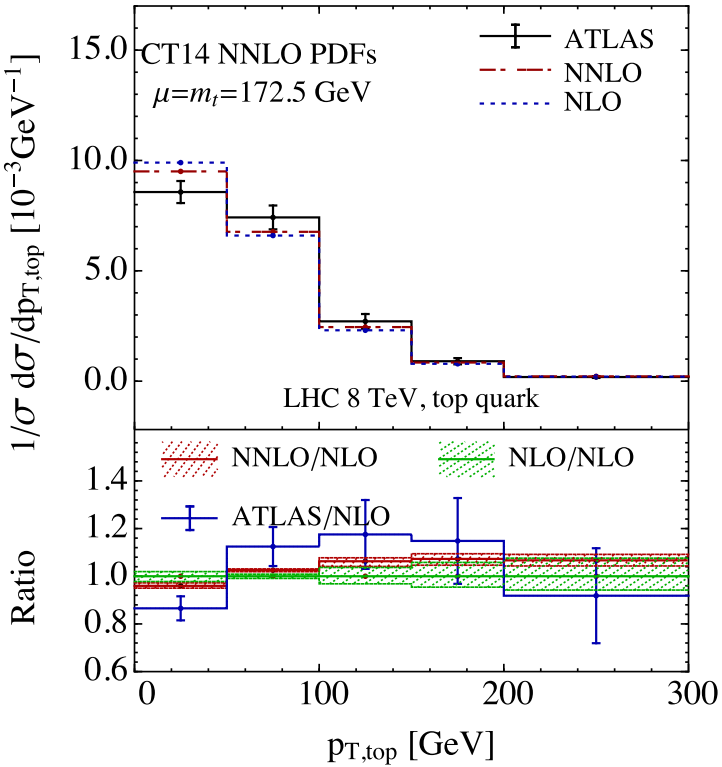
[Czakon, Heymes, Mitov, Pagani, Tsinikos, Zaro 2017]

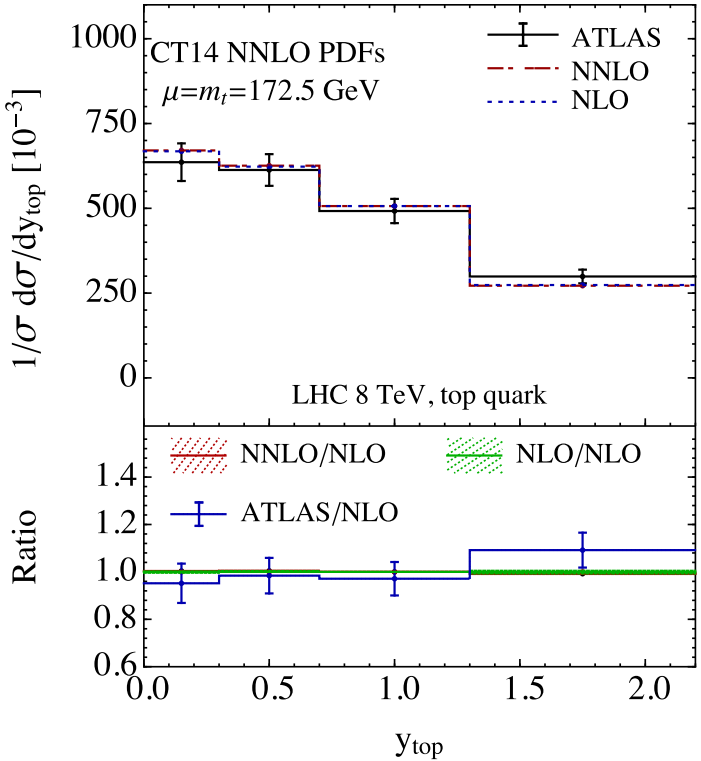


State-of-the-art: stable tops at NNLO

- Fully-differential NNLO QCD predictions for single-top production

[Gao Top 2017]





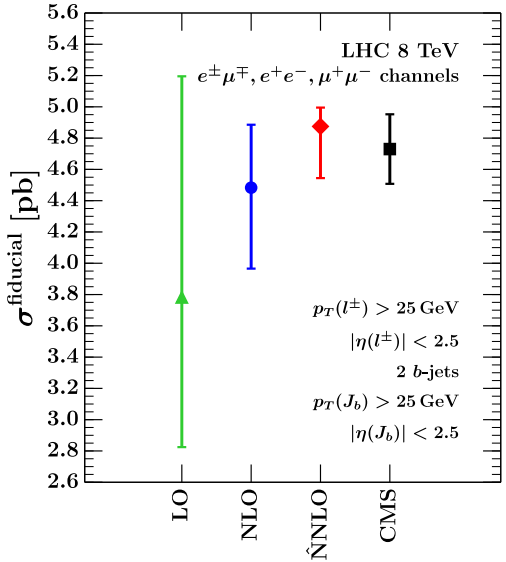
Decaying the top

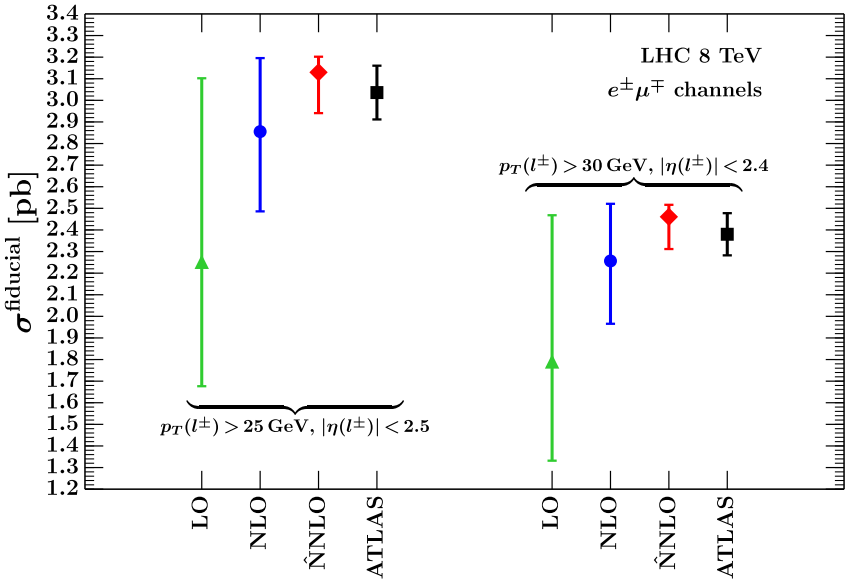
- Off-shell calculations:
  - Considering the complete process: $pp \to \ell^+\ell^-\nu\bar{\nu}b\bar{b}$
  - Technically challenging due to high multiplicity and complexity of the phase space
  - Off-shell, non-resonant effects and the interference of radiation between production and decay may be important in certain portions of the phase space
- Narrow Width Approximation (NWA):
  - Considering limit $\Gamma_t/m_t \to 0$
  - The factorization of production and the decay reduces the complexity significantly
  - It is still possible to implement crucial features of the decay like spin correlations
  - Expected error of $\mathcal{O}(\Gamma_t/m_t)$

State-of-the-art: NWA at NNLO

- Approximate NNLO QCD single top production & NNLO QCD top-decay

[Gao, Papanastasiou 2017]

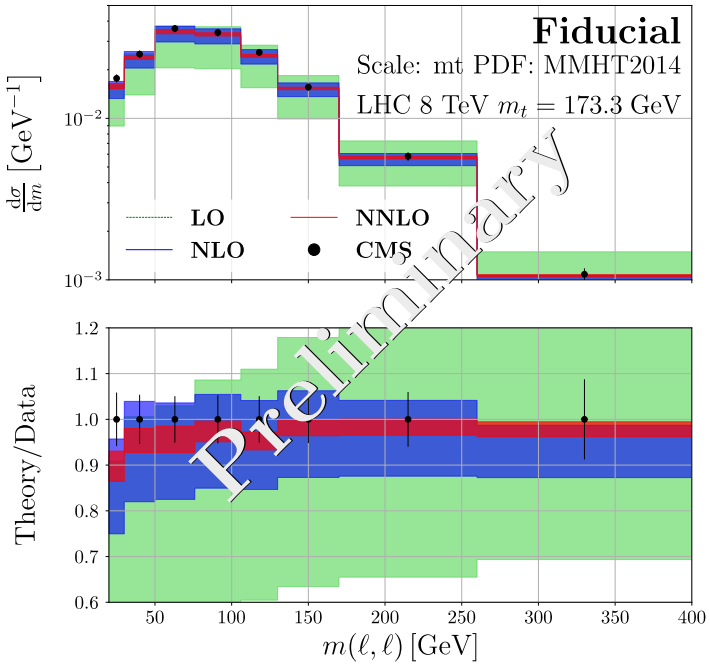


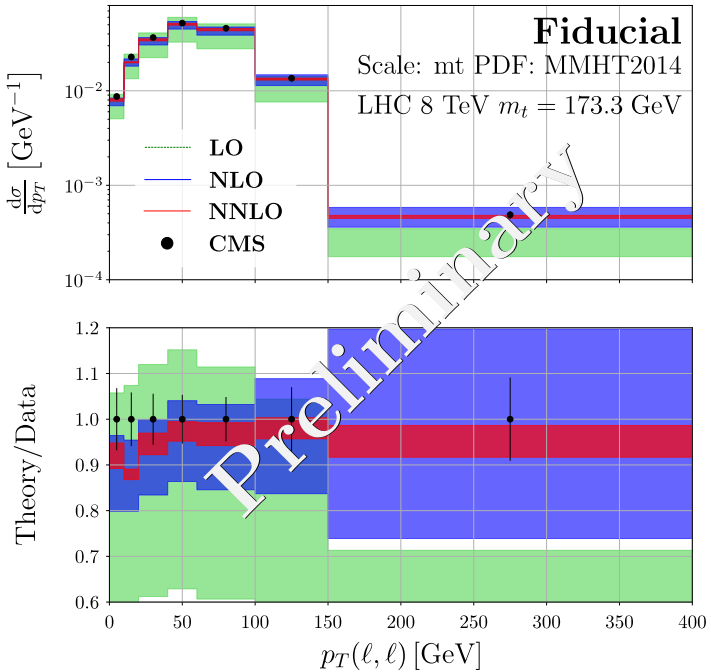


State-of-the-art: NWA at NNLO

- NNLO QCD top-pair production & NNLO QCD top-decay

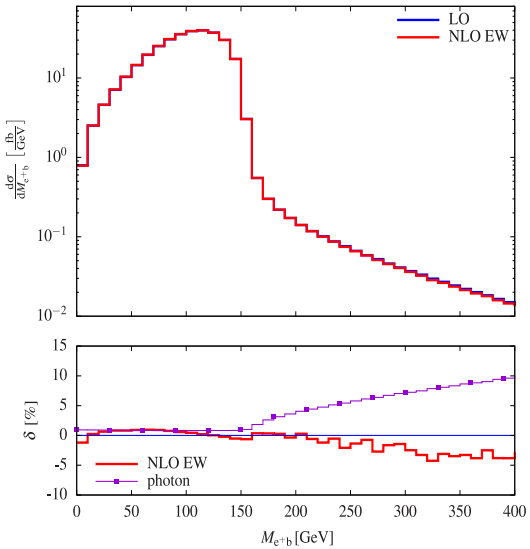
[Poncelet LHCP19]





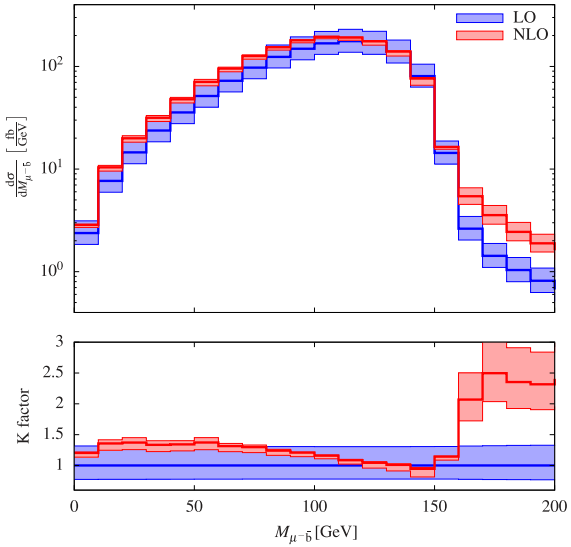
State-of-the-art: Off-shell at NLO

- offshell $t\bar{t}$, leptons @ NLO EW



[Denner, Pellen 2016]

- offshell $t\bar{t}$, lepton+jets @ NLO QCD



[Denner, Pellen 2017]

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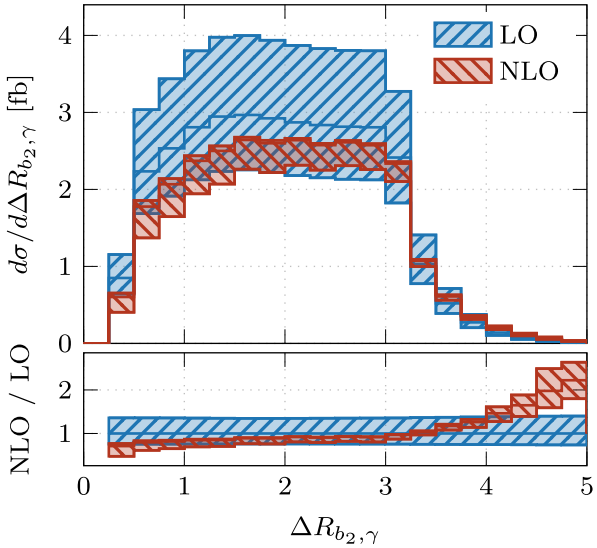


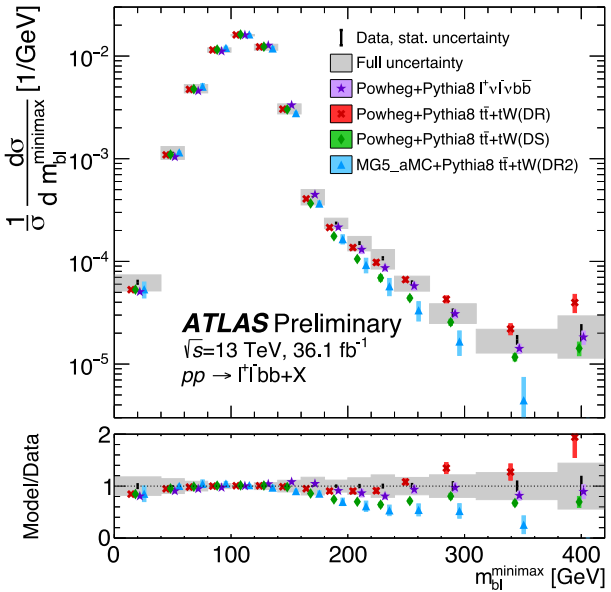
[Bevilacqua, Hartanto, Kraus, Weber, Worek 2018]

see talk by Kraus at 18h10

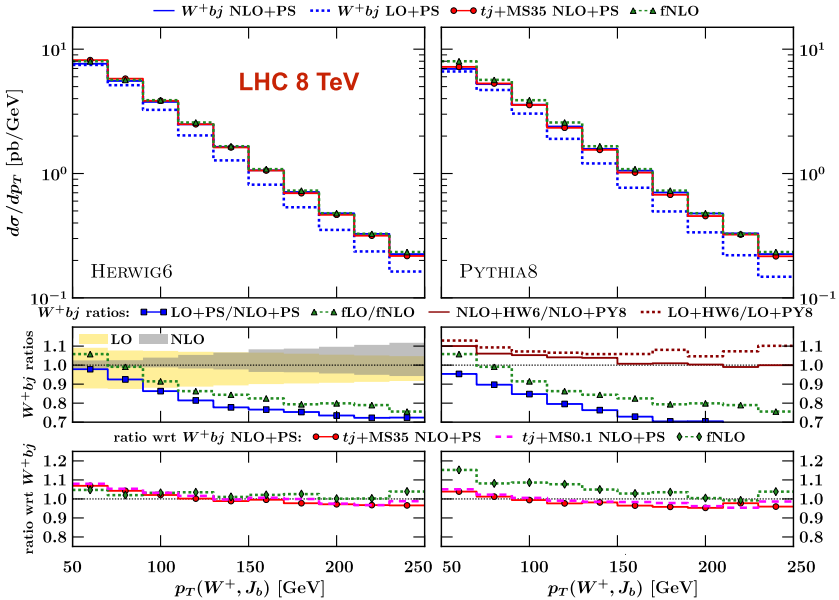
State-of-the-art: Off-shell at NLO+PS

- offshell $t\bar{t}$, leptons @ POWHEG

[TJ, Lindert, Nason, Oleari, Pozzorini 2016]



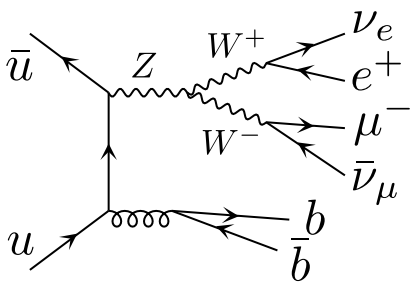
- offshell single top, leptons @ MC@NLO

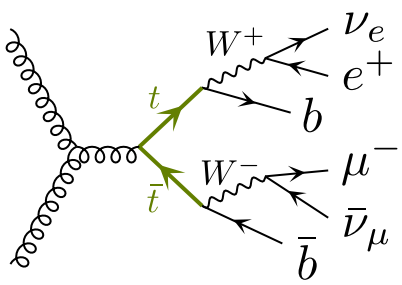


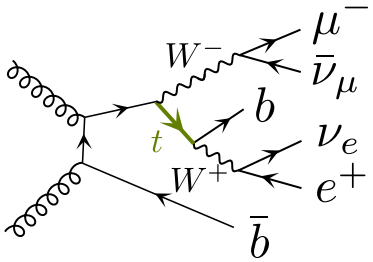
[Frederix, Frixione, Papanastasiou, Prestel, Torrielli 2016]

[TJ, Nason 2015]

$t\bar{t}$ & tW in POWHEG BOX RES: b_bbar_4l



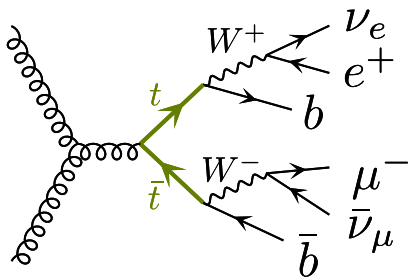




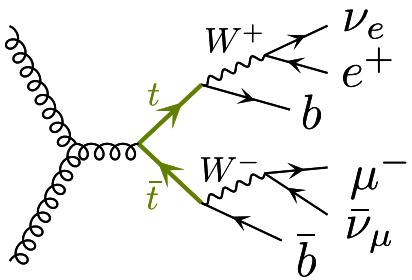
- $pp \to \ell^+ \nu_\ell \, l^- \bar{\nu}_l \, b \, \bar{b}$ production at NLO
- Resonance-aware matching to parton showers [TJ, Nason, 2015]
- Exact spin correlations* and exact off-shell effects
- W hadronic decays work in progress
- Generator: `b_bbar_4l` [TJ, Lindert, Nason, Oleari, Pozzorini, 2016]

$t\bar{t}$ & tW in POWHEG BOX RES: b_bbar_4l

Traditional NLOPS



Multiple-radiation-improved NLOPS (allrad)



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- Exact spin correlations* and exact off-shell effects
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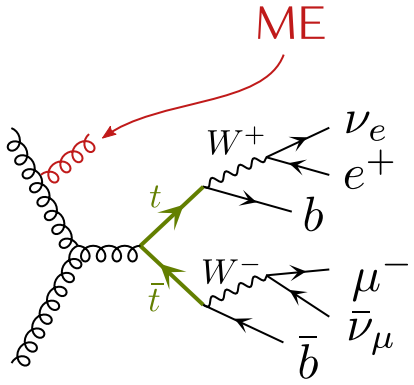
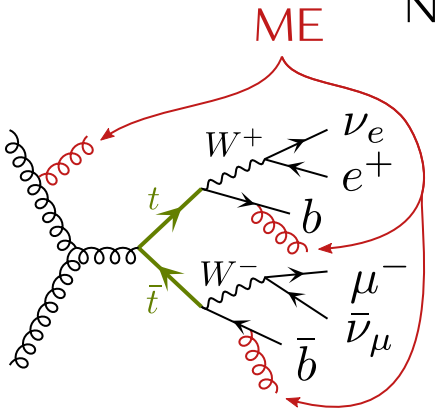
- Generator: b_bbar_4l [TJ, Lindert, Nason, Oleari, Pozzorini, 2016]
- Multiple emissions described using the matrix element via the allrad feature

$t\bar{t}$ & tW in POWHEG BOX RES: b_bbar_4l

Traditional NLOPS



Multiple-radiation-improved NLOPS (allrad)



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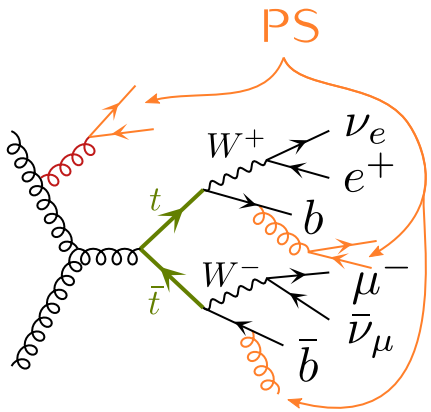
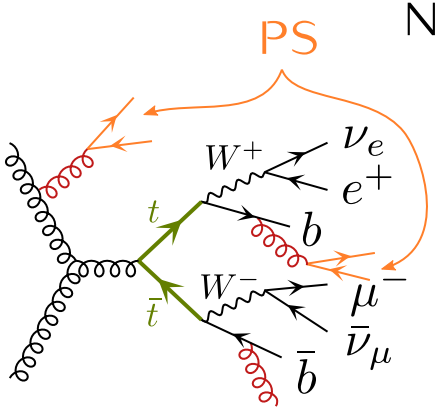
$t\bar{t}$ & tW in POWHEG BOX RES: b_bbar_4l

Traditional NLOPS



Multiple-radiation-improved NLOPS (allrad)



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State-of-the-art: beyond Standard Model

- A convenient way to parametrize new physics (NP) in a model-independent fashion: SMEFT
  - SMEFT: QFT describing and IR limit of a given UV complete theory

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i^{N_{d5}} \frac{c_i}{\Lambda}\mathcal{O}_i^{(5)} + \sum_i^{N_{d6}} \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i^{N_{d7}} \frac{c_i}{\Lambda^3}\mathcal{O}_i^{(7)} + \sum_i^{N_{d8}} \frac{c_i}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$

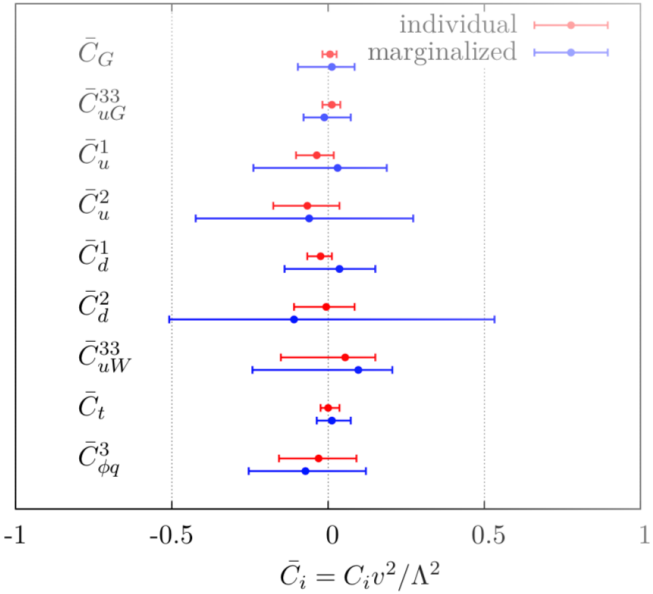
  - Λ NP decoupling scale, c_i unconstrained coefficients, $\mathcal{O}_i$ operators
- SMEFiT framework: predictions available at (N)NLO QCD for SM and SMEFT [Hartland et al. '19]

Class	Notation	Degree of Freedom	Operator Definition
$QQQQ$	OQQ1	c_{QQ}^{1}	$2C_{qq}^{1(3333)} - \frac{2}{3}C_{qq}^{3(3333)}$
	OQQ8	c_{QQ}^{8}	$8C_{qq}^{3(3333)}$
	OQt1	c_{Qt}^{1}	$C_{qu}^{1(3333)}$
	OQt8	c_{Qt}^{8}	$C_{qu}^{8(3333)}$
	OQb1	c_{Qb}^{1}	$C_{qd}^{1(3333)}$
	OQb8	c_{Qb}^{8}	$C_{qd}^{8(3333)}$
	Ott1	c_{tt}^{1}	$C_{uu}^{(3333)}$
	Otb1	c_{tb}^{1}	$C_{ud}^{1(3333)}$
	Otb8	c_{tb}^{8}	$C_{ud}^{8(3333)}$
	OQtQb1	c_{QtQb}^{1}	$C_{quqd}^{1(3333)}$
	OQtQb8	c_{QtQb}^{8}	$C_{quqd}^{8(3333)}$
$QQqq$	O81qq	$c_{Qq}^{1,8}$	$C_{qq}^{1(i33i)} + 3C_{qq}^{3(i33i)}$
	O11qq	$c_{Qq}^{1,1}$	$C_{qq}^{1(ii33)} + \frac{1}{6}C_{qq}^{1(i33i)} + \frac{1}{2}C_{qq}^{3(i33i)}$
	O83qq	$c_{Qq}^{3,8}$	$C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)}$
	O13qq	$c_{Qq}^{3,1}$	$C_{qq}^{3(ii33)} + \frac{1}{6}(C_{qq}^{1(i33i)} - C_{qq}^{3(i33i)})$
	O8qt	c_{tq}^{8}	$C_{qu}^{8(ii33)}$
	O1qt	c_{tq}^{1}	$C_{qu}^{1(ii33)}$
	O8ut	c_{tu}^{8}	$2C_{uu}^{(i33i)}$
	O1ut	c_{tu}^{1}	$C_{uu}^{(ii33)} + \frac{1}{3}C_{uu}^{(i33i)}$
	O8qu	c_{Qu}^{8}	$C_{qu}^{8(33ii)}$
	O1qu	c_{Qu}^{1}	$C_{qu}^{1(33ii)}$
	O8dt	c_{td}^{8}	$C_{ud}^{8(33ii)}$
	O1dt	c_{td}^{1}	$C_{ud}^{1(33ii)}$
	O8qd	c_{Qd}^{8}	$C_{qd}^{8(33ii)}$
	O1qd	c_{Qd}^{1}	$C_{qd}^{1(33ii)}$
$QQ+V,G,\varphi$	OtG	c_{tG}	$\text{Re}\{C_{uG}^{(33)}\}$
	OtW	c_{tW}	$\text{Re}\{C_{uW}^{(33)}\}$
	ObW	c_{bW}	$\text{Re}\{C_{dW}^{(33)}\}$
	OtZ	c_{tZ}	$\text{Re}\{-s_W C_{uB}^{(33)} + c_W C_{uW}^{(33)}\}$
	Off	$c_{\varphi tb}$	$\text{Re}\{C_{\varphi ud}^{(33)}\}$
	Ofq3	$c_{\varphi Q}^{3}$	$C_{\varphi q}^{3(33)}$
	OpQM	$c_{\varphi Q}^{-}$	$C_{\varphi q}^{1(33)} - C_{\varphi q}^{3(33)}$
	Opt	$c_{\varphi t}$	$C_{\varphi u}^{(33)}$
	Otp	$c_{t\varphi}$	$\text{Re}\{C_{u\varphi}^{(33)}\}$

State-of-the-art: beyond Standard Model

- Two frameworks available in the top-quark sector:

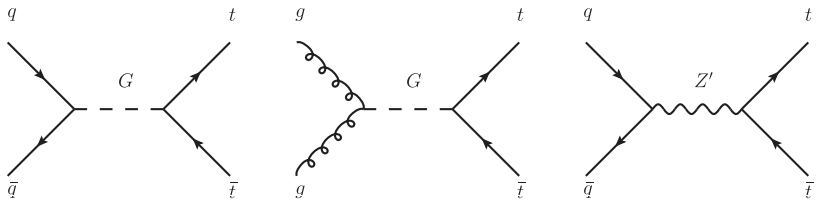
Topfitter [Buckley et al. '15]



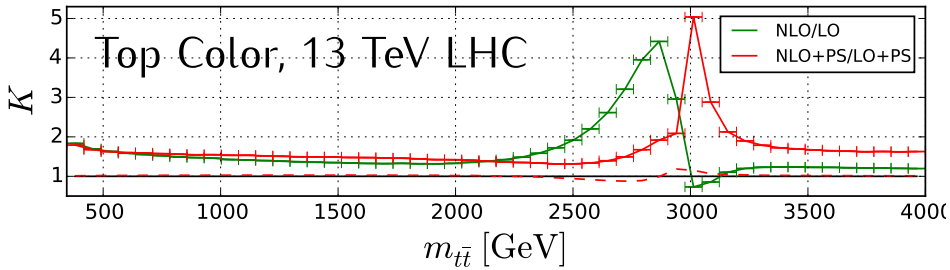
SMEFiT [Hartland et al. '19]

State-of-the-art: beyond Standard Model

- Traditional approach – assume a specific BSM extension with generic couplings:



  - $t\bar{t}$ via KK graviton or Z' at NLO QCD: [Gao et al. '10]
  - $t\bar{t}$ via Z' at NLO QCD: [Caola et al. '12]
  - $t\bar{t}$ via Z' at NLO QCD + PS: [Bonciani, TJ, Klasen, Lyonnet, Schienbein '15]
  - $t\bar{t}, t\bar{b}$ via W'/Z' at NLO QCD + PS: [Altakach, TJ, Klasen, Schienbein in prep.]



Summary

- Experiment: Top quark properties measured to unprecedented precision
- Theory: We have seen and continue to see a tremendous progress in our understanding of processes involving top quakrs
  - NNLO QCD
  - NNLO QCD + NLO EW
  - NNLO QCD production × NNLO QCD decay
  - Fully off-shell calculations at FO NLO and matched to parton showers
  - NLO QCD (+PS) beyond the Standard Model

† Apologies for not mentioning so many wonderful top-quark related results