Theory overview for $t\bar{t}H$ and tH production

Top2015: 8th international workshop on top quark physics

Ischia

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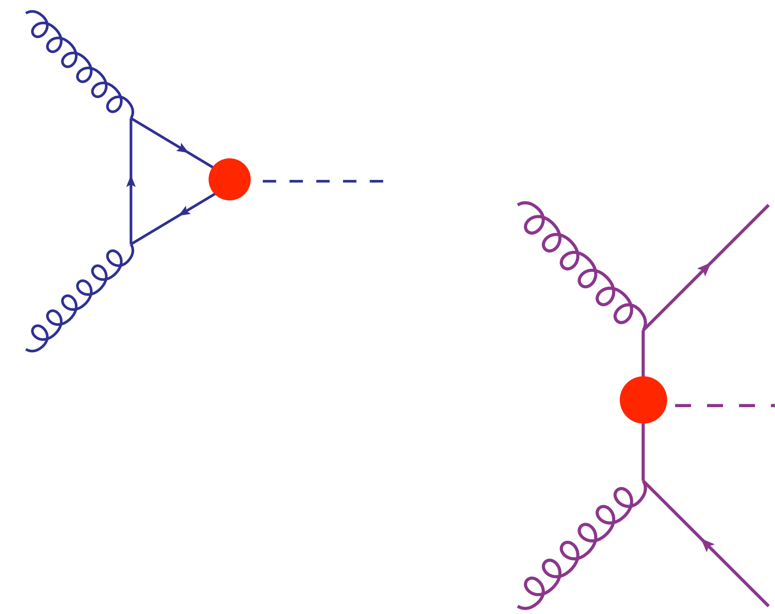
Why $t\bar{t}H$?

- It is the "last" of the main Higgs production mechanisms still to be observed
- It is directly sensitive to the top Yukawa
- Expected precision on y_t at the LHC RunII: 7-10%
- Same order as TH errors (NLO)



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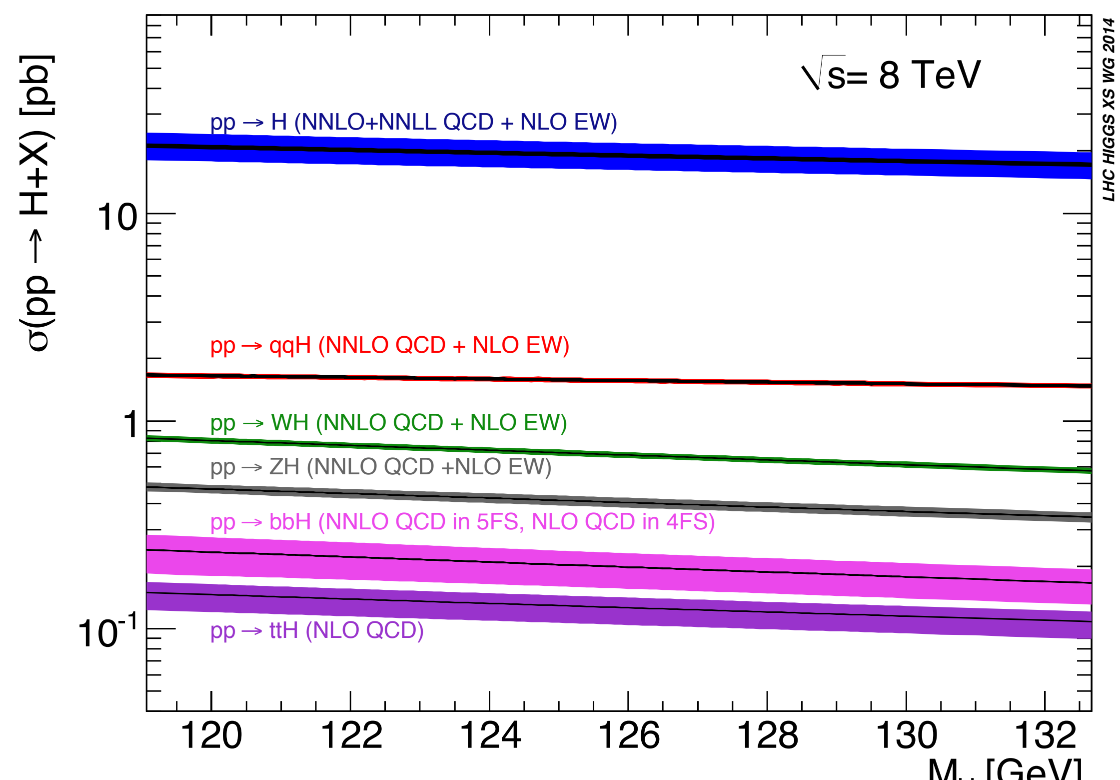
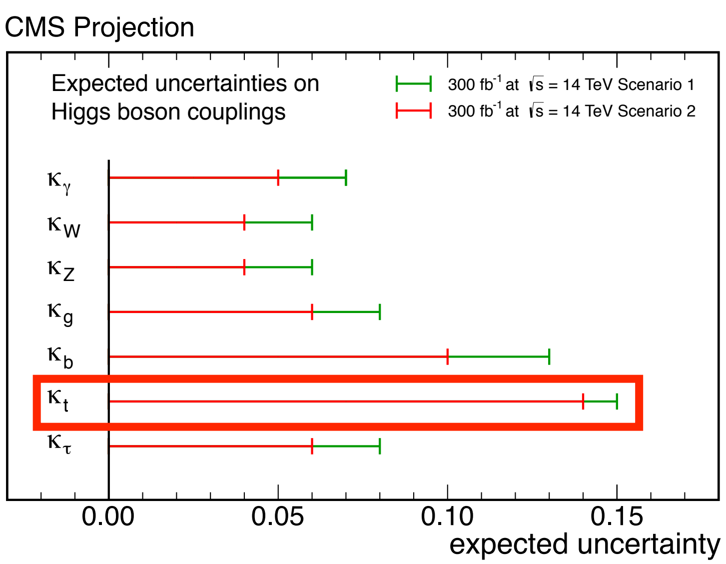
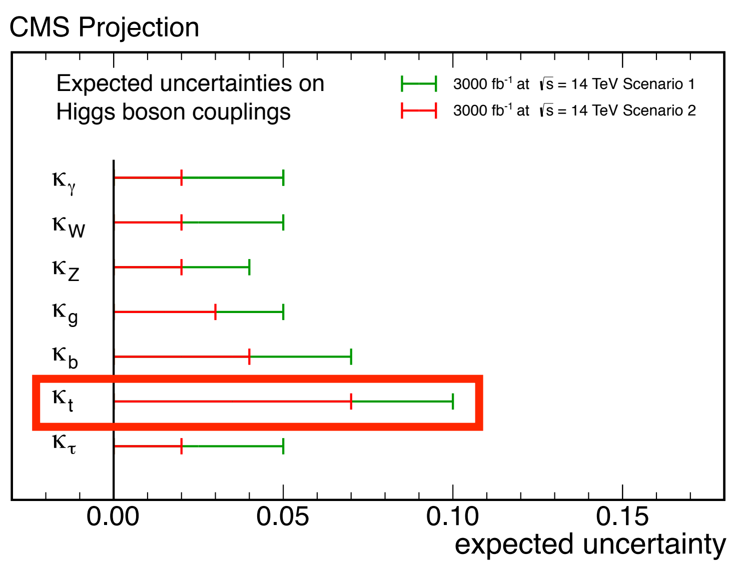


CMS-NOTE-3-002 arXiv:1307.7135





see also Peskin, arXiv:1312.4974

Outline:

- Status on higher-order predictions for signal and backgrounds
- Recent results for the signal…
  - NLO Electroweak corrections to $t\bar{t}H$
  - The importance of spin correlations
  - Accurate predictions for tH
- …and for the backgrounds
  - $t\bar{t}b\bar{b}$: beyond QCD-only
  - Recent results for $t\bar{t}VV$
- Can we go below the TH errors in the extraction of y_t?

Higher order predictions for signal and backgrounds

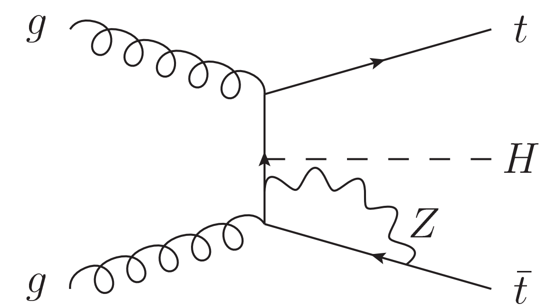
- $t\bar{t}H$
  - NLO QCD corrections (30% @ RunII)
    Beenakker et al. hep-ph/0107081 & hep-ph/0211352
    Dawson et al. hep-ph/0211438 & hep-ph/0305087
  - Matching to PS
    aMC@NLO: Frederix et al. arXiv:1104.5613
    Powhel: Garzelli et al. arXiv:1108.0387
    2015! Powheg Box: Hartanto et al. arXiv:1501.04498
  - NLO QCD corrections to $b\bar{b}\ell^+\ell^-\nu\bar{\nu}H$
    2015! Denner et al. arXiv:1506.07448
  - Weak and Electro-Weak corrections (1.5% @ RunII)
    2015! Frixione et al. arXiv:1407.0823 & arXiv:1504.03446
    Zhang et al. arXiv:1407.1110
  - Soft gluon resummation (2-6% @ RunII)
    2015! Kulesza et al. arXiv:1509.02780
- tH
  - NLO QCD corrections
    (5FS) Farina et al. arXiv:1211.3737
    (5FS) Campbell et al. arXiv:1302.3856
  - Matching to PS
    2015! (4FS and 5FS) Demartin et al. arXiv:1504.00611
    tHW see poster by F. Demartin

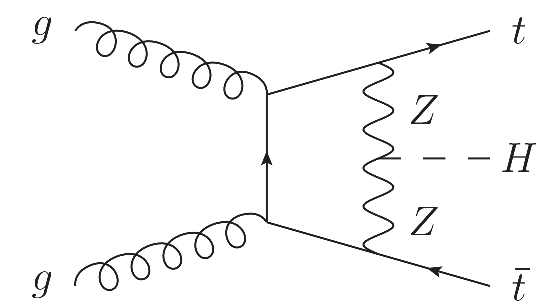
- $t\bar{t}b\bar{b}$
  - NLO QCD corrections
    Bredenstein et al. arXiv:0905.0110 & arXiv:1001.4006
    Bevilacqua et al. arXiv:0907.4723
  - Matching to PS
    Kardos et al. 1303.6201
    Cascioli et al. 1309.5912
- $t\bar{t}V$
  - NLO QCD corrections
    $t\bar{t}\gamma$ Melnikov et al. arXiv:1102.1967
    $t\bar{t}W$, $t\bar{t}\gamma^*/Z$, $t\bar{t}\gamma$ Hirschi et al. arXiv:1103.0621
    $t\bar{t}Z$ Lazopoulos et al. arXiv:0804.2220
    $t\bar{t}Z$ Kardos et al. arXiv:1111.0610
    $t\bar{t}W$ Campbell et al. arXiv:1204.5678
  - Matching to PS
    $t\bar{t}Z$ Garzelli et al. arXiv:1111.1444
    $t\bar{t}W$, $t\bar{t}Z$ Garzelli et al. arXiv:1208.2665
  - Electro-Weak corrections
    2015! $t\bar{t}W$, $t\bar{t}Z$ (and $t\bar{t}H$) Frixione et al. arXiv:1504.03446
- $t\bar{t}VV$
  - NLO QCD corrections + PS
    $t\bar{t}\gamma\gamma$ Kardos et al. arXiv:1408.0278
    2015! all $t\bar{t}VV$ Maltoni et al. arXiv:1507.05640
    2015! $t\bar{t}\gamma\gamma$ van Deurzen et al. arXiv:1509.02077

Recent results for the signal

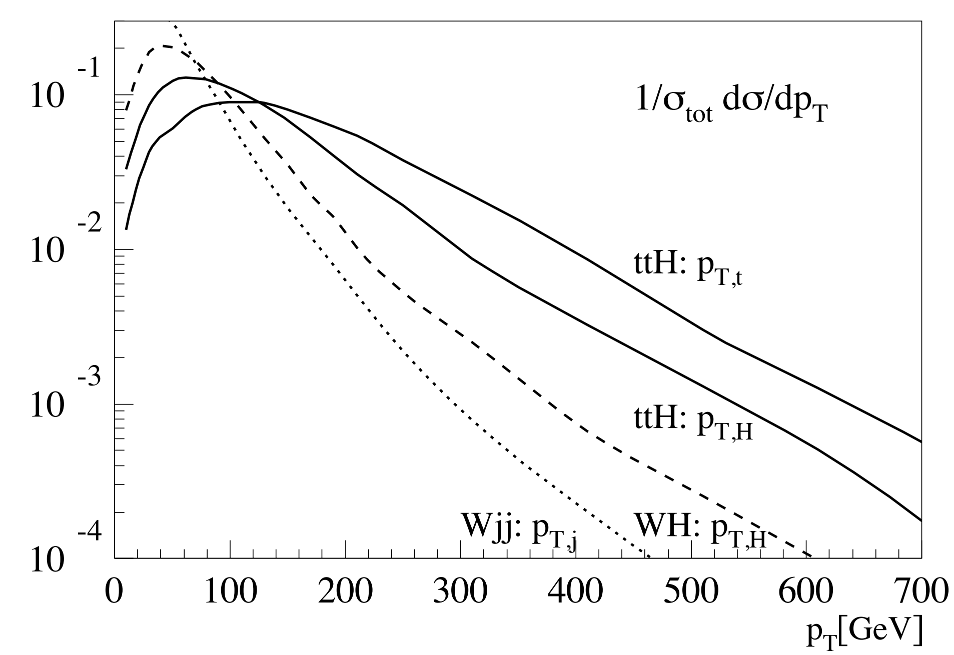
Electro-weak corrections to $t\bar{t}H$ motivation

- $t\bar{t}H$ offers unique direct access to the y_t coupling
- (Electro-)weak corrections spoil the trivial y_t^2 dependence of the cross-section: crucial for precise extraction of y_t
- Boosted searches: EW corrections enhanced because of Sudakov logs ($\log(p_T/m_W)$)





Plehn, Salam, Spannowsky, arXiv:0910.5472



Electro-weak corrections to $t\bar{t}H$: setup

Frixione, Hirschi, Pagani, Shao, MZ, arXiv:1407.0823 & 1504.03446

- $\alpha(m_Z)$-scheme: $\alpha(m_Z)$, m_Z, m_W as input parameters
- m_H=125 GeV, m_t=173.3 GeV
- NNPDF 2.3 QED PDFs (including photon PDF)
- Ren./Fac. scales set to

$$\mu = \frac{H_T}{2}$$

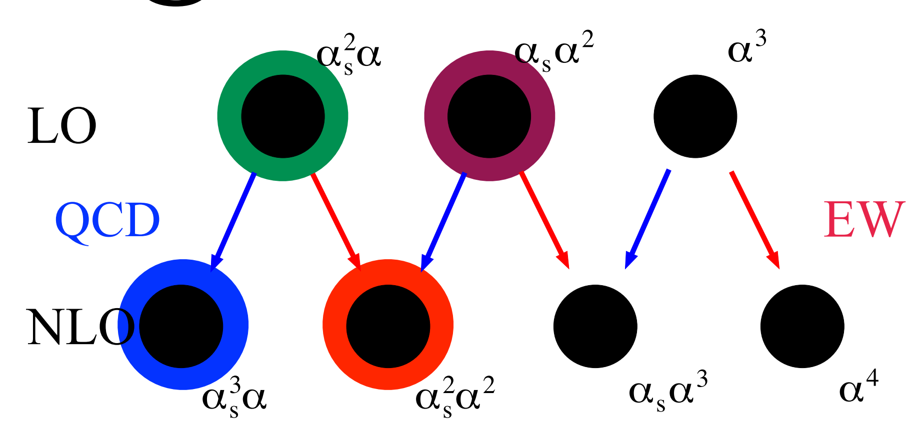
- QCD scale variations computed with

$$\frac{1}{2}\mu \leq \mu_R, \mu_F \leq 2\mu$$

- Both inclusive and boosted regime ($p_T(t,\bar{t},H)$ > 200 GeV)
- Code generated within MadGraph5_aMC@NLO
- The following terms are computed:

  LO QCD, LO EW (only $g\gamma$ and $b\bar{b}$)

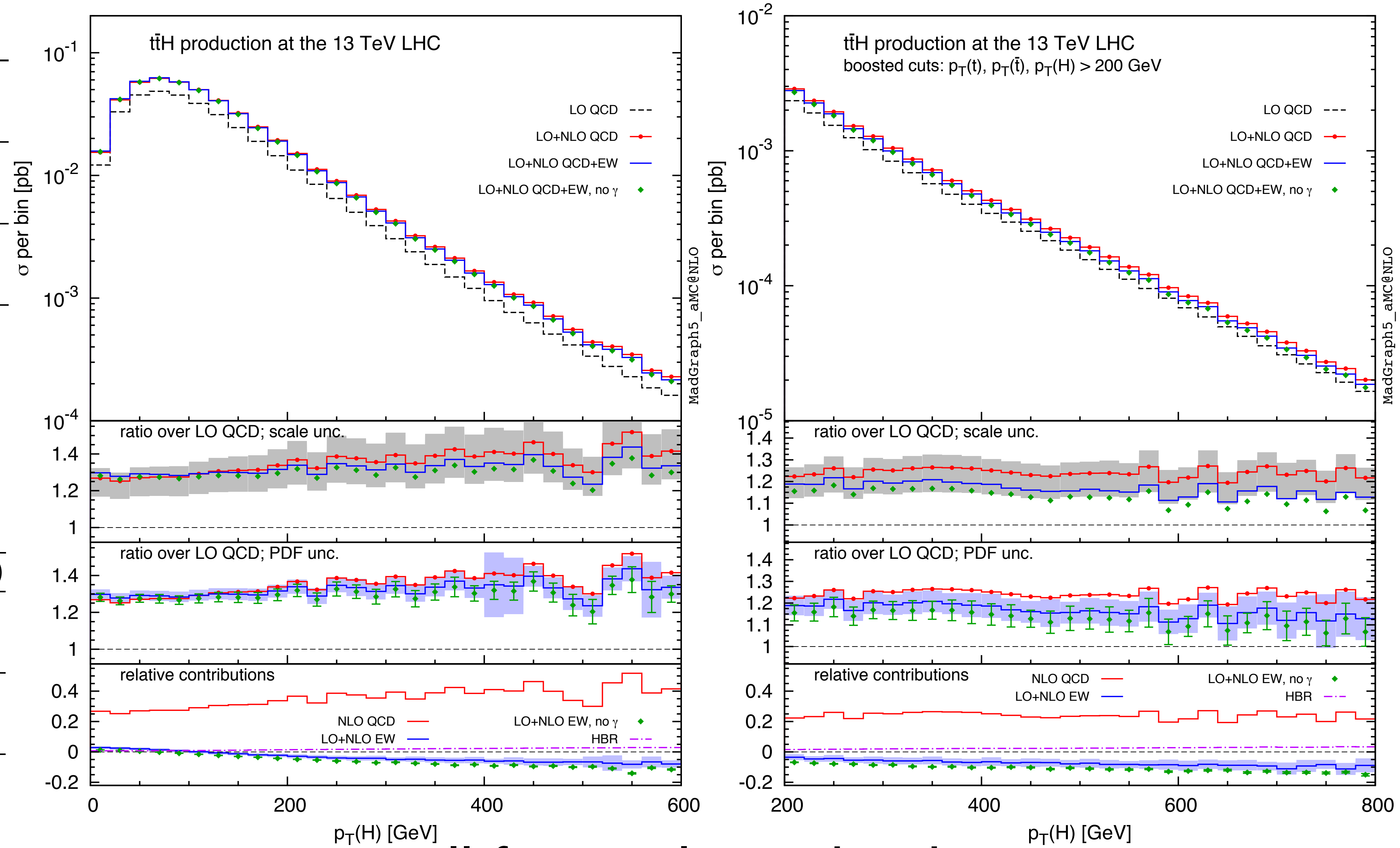
  NLO QCD, NLO EW+HBR ($t\bar{t}HV$)



Electro-weak corrections to $t\bar{t}H$: results at 13 TeV

$t\bar{t}H$: σ(pb)	13 TeV
LO QCD	$3.617 \cdot 10^{-1}$ $(1.338 \cdot 10^{-2})$
NLO QCD	$1.073 \cdot 10^{-1}$ $(3.230 \cdot 10^{-3})$
LO EW	$4.437 \cdot 10^{-3}$ $(3.758 \cdot 10^{-4})$
LO EW no γ	$-1.390 \cdot 10^{-3}$ $(-2.452 \cdot 10^{-5})$
NLO EW	$-4.408 \cdot 10^{-3}$ $(-1.097 \cdot 10^{-3})$
NLO EW no γ	$-4.919 \cdot 10^{-3}$ $(-1.131 \cdot 10^{-3})$
HBR	$3.216 \cdot 10^{-3}$ $(2.496 \cdot 10^{-4})$

$t\bar{t}H$: $\delta(\%)$	13 TeV
NLO QCD	$29.7^{+6.8}_{-11.1} \pm 2.8$ $(24.2^{+4.8}_{-10.6} \pm 4.5)$
LO EW	1.2 ± 0.9 (2.8 ± 2.0)
LO EW no γ	-0.4 ± 0.0 (-0.2 ± 0.0)
NLO EW	-1.2 ± 0.1 (-8.2 ± 0.3)
NLO EW no γ	-1.4 ± 0.0 (-8.5 ± 0.2)
HBR	0.89 (1.87)

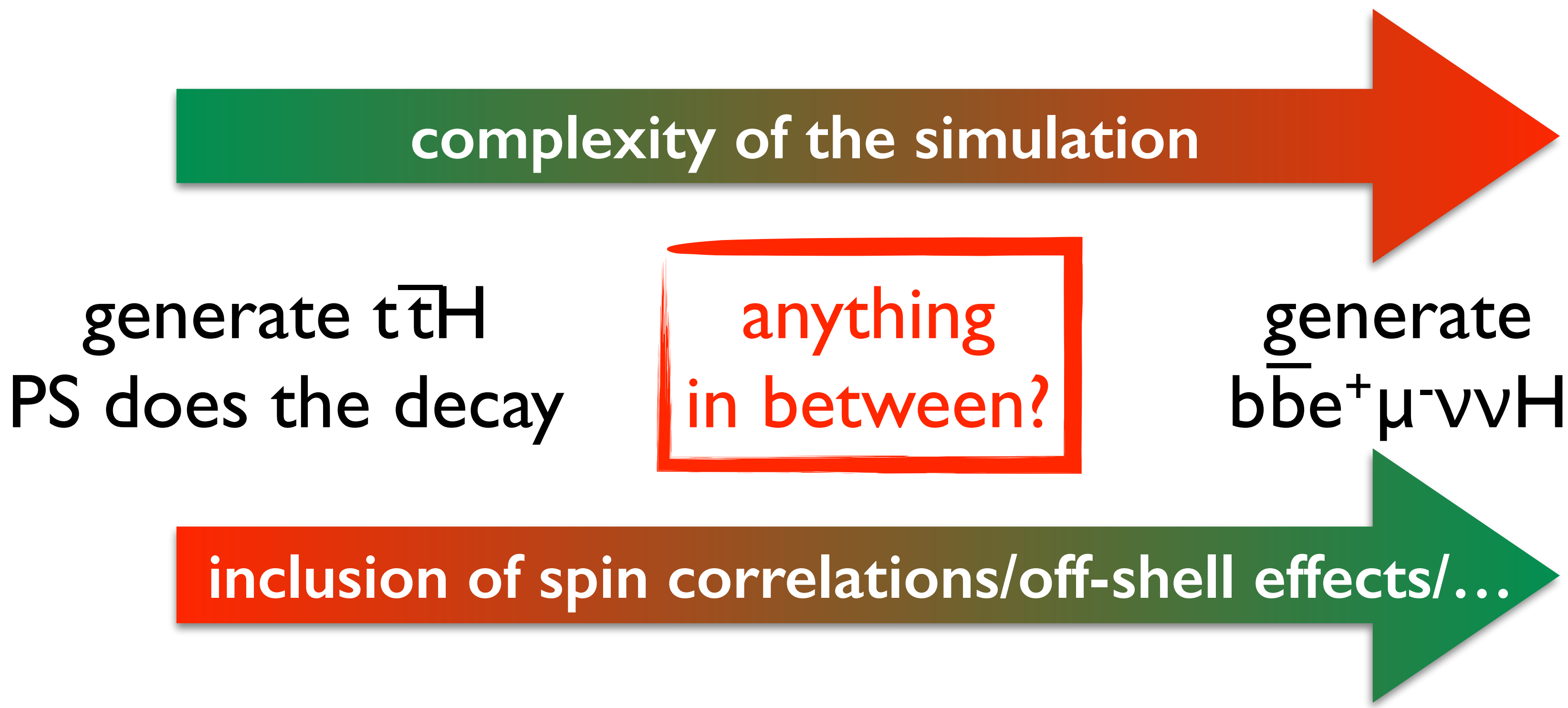


- Bottom line: EW corrections are small for total rate, but become important at large p_T; only partial compensation of Sudakov logs by HBR

More in D. Pagani's talk this afternoon

The importance of spin correlations

- Spin correlation from the top decay products carry useful information for H CP studies and to enhance signal/background
- The inclusion in a NLO+PS computation is not trivial (decay chains are gauge invariant only in the NWA)



The importance of spin correlations

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Yes!

Frixione, Leanen, Motylinski, Webber, arXiv:hep-ph/0702198

method automated in MadSpin (MadGraph5_aMC@NLO) and Decayer (PowHel)

Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

Garzelli, Kardos, Trocsanyi, arXiv:1405.5859

inclusion of spin correlations/off-shell effects/…

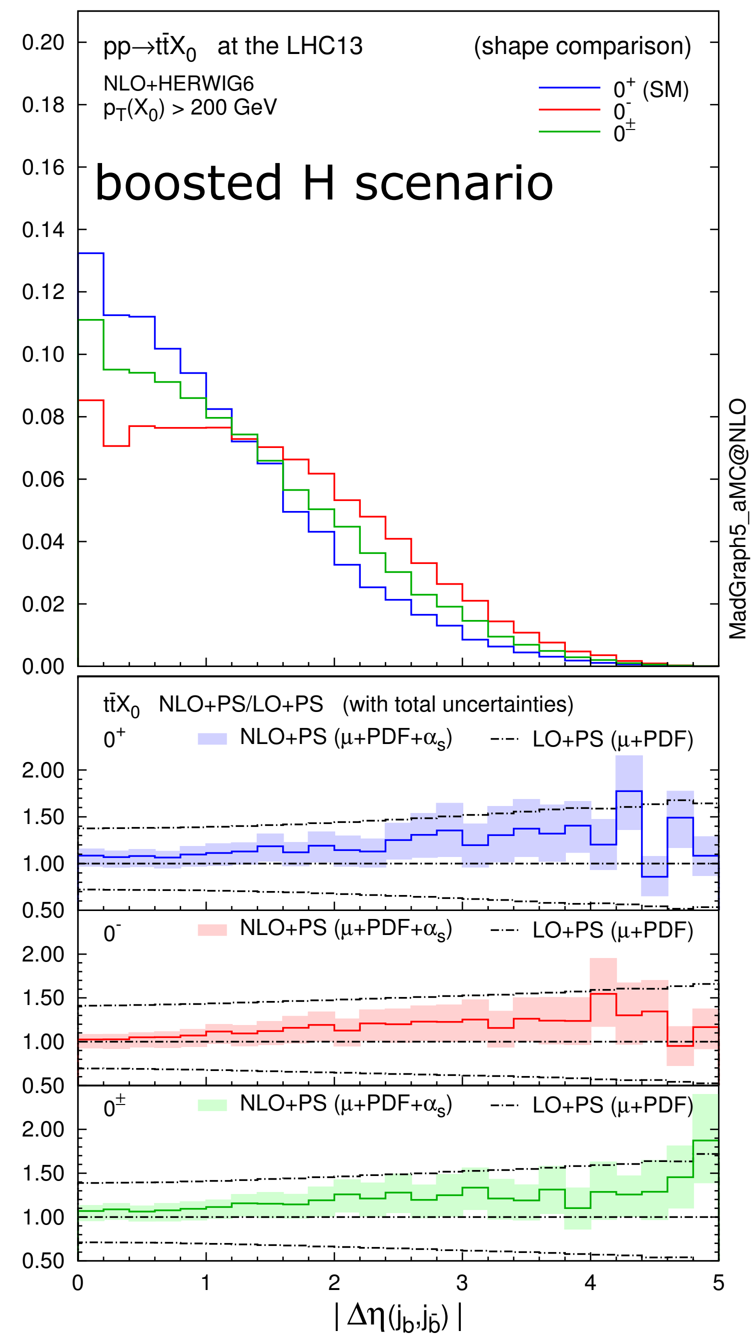
Spin correlation in $t\bar{t}H$: H CP determination

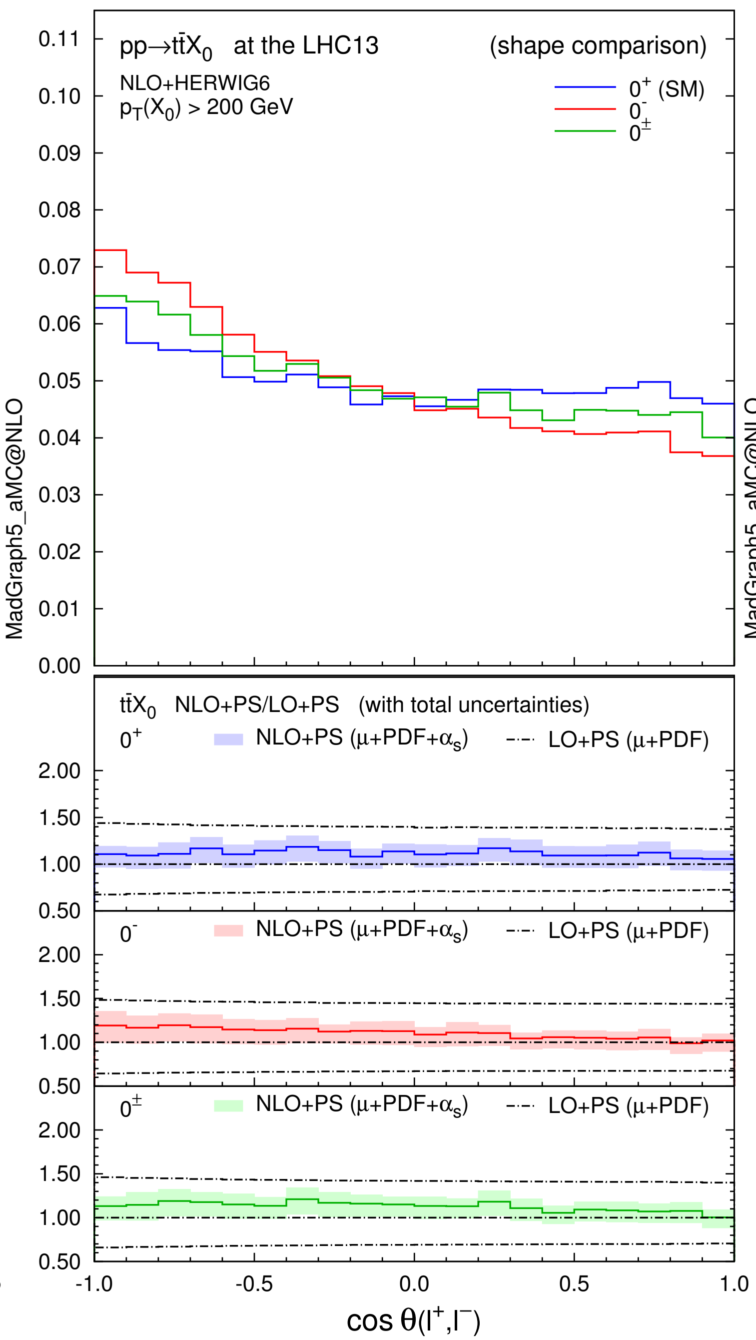
Demartin, Maltoni, Mawatari, Page, MZ, arXiv:1407.5089

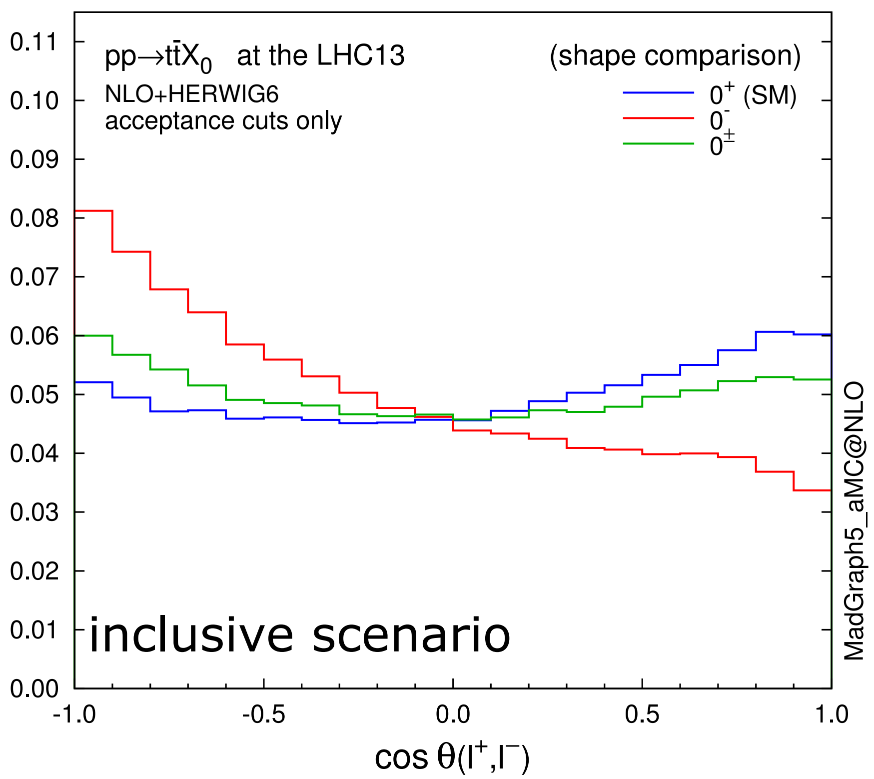
- Include CP violating ttH interaction in an effective theory approach, at NLO+PS

$$\mathcal{L}_0^t = -\bar{\psi}_t \big(c_\alpha \kappa_{Htt} g_{Htt} + i s_\alpha \kappa_{Att} g_{Att}\, \gamma_5 \big) \psi_t \, X_0$$

- Study dileptonic top decay



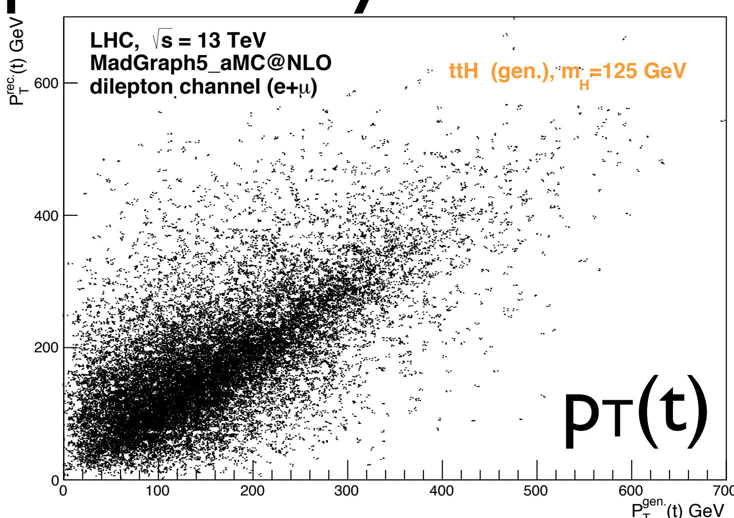


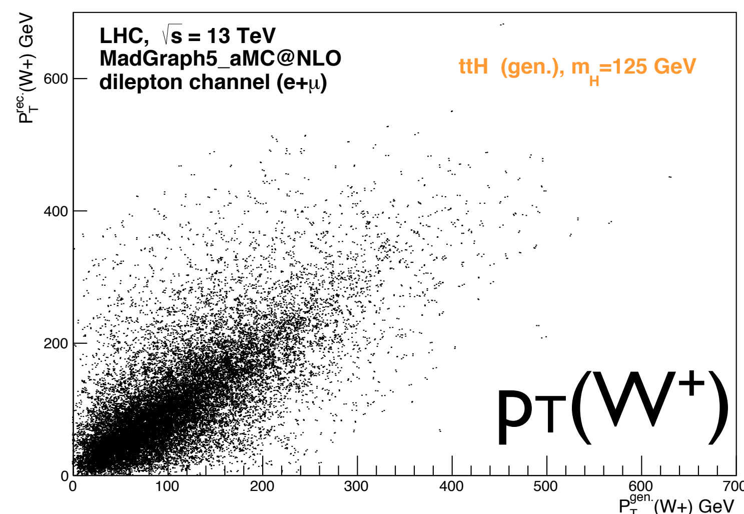


Spin correlation in $t\bar{t}H$: Improve S/B discrimination

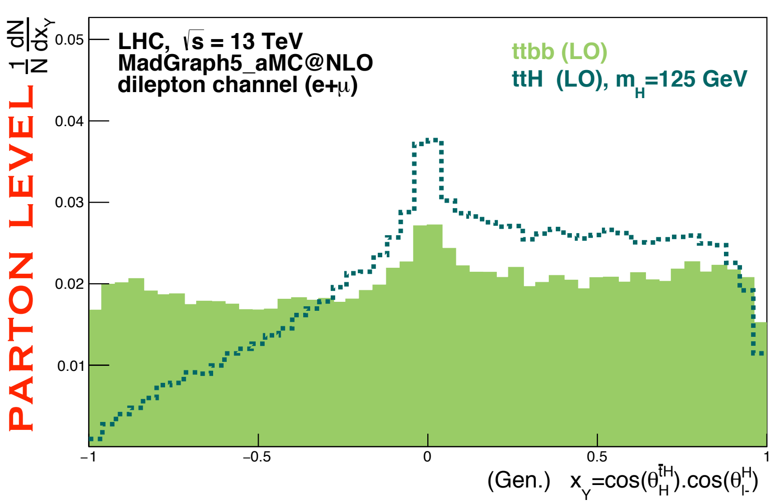
Amor dos Santos et al. arXiv:1503.07787

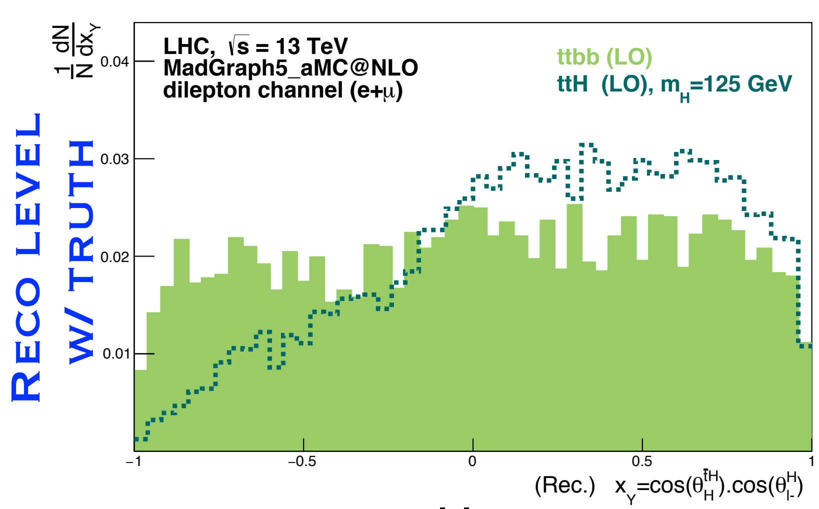
- Use information from spin correlations to separate S and B ($t\bar{t}b\bar{b}$)
- Check robustness of variables against PS / detector simulation
- Dilepton decays allow for good reconstruction of top/W

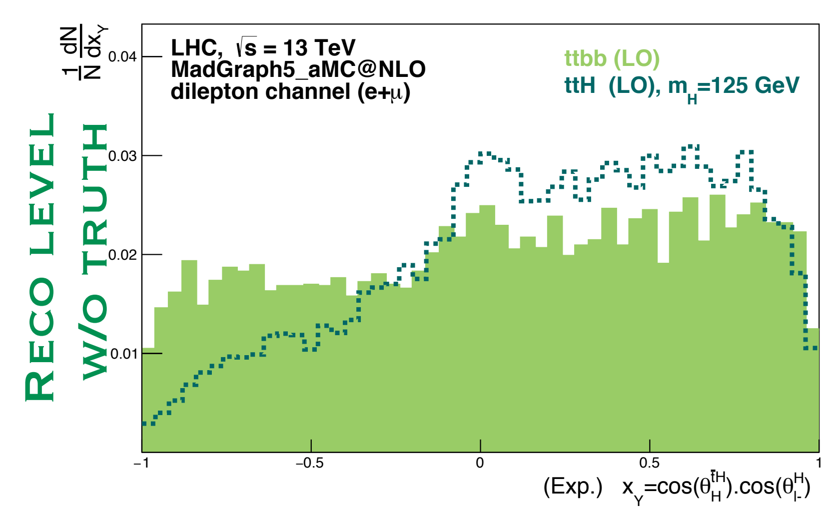




- Product of cosines can be used for S/B discrimination



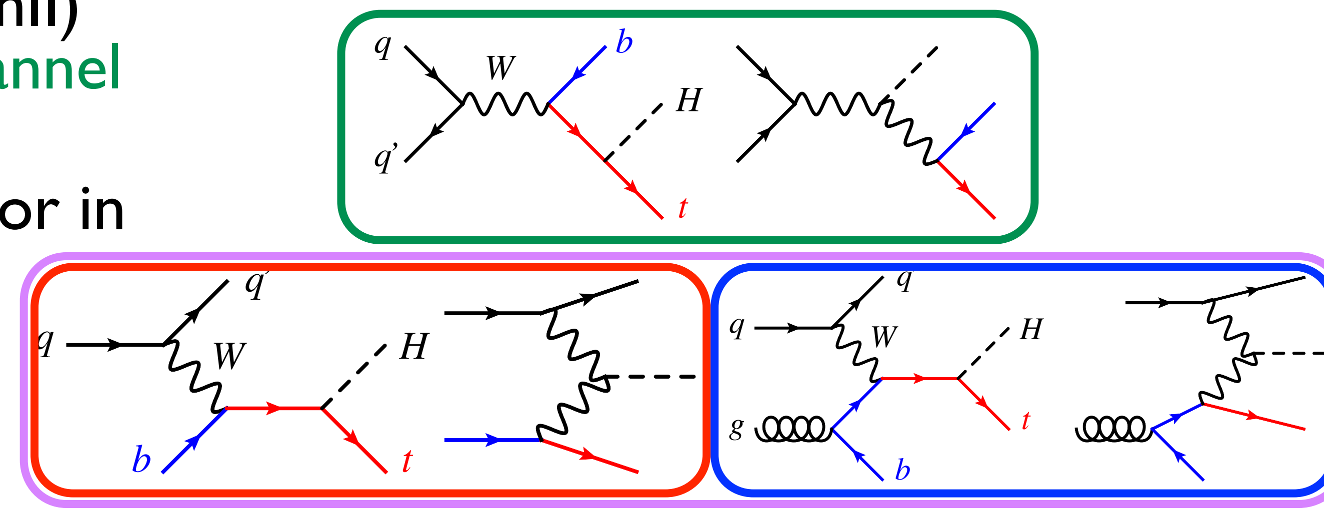


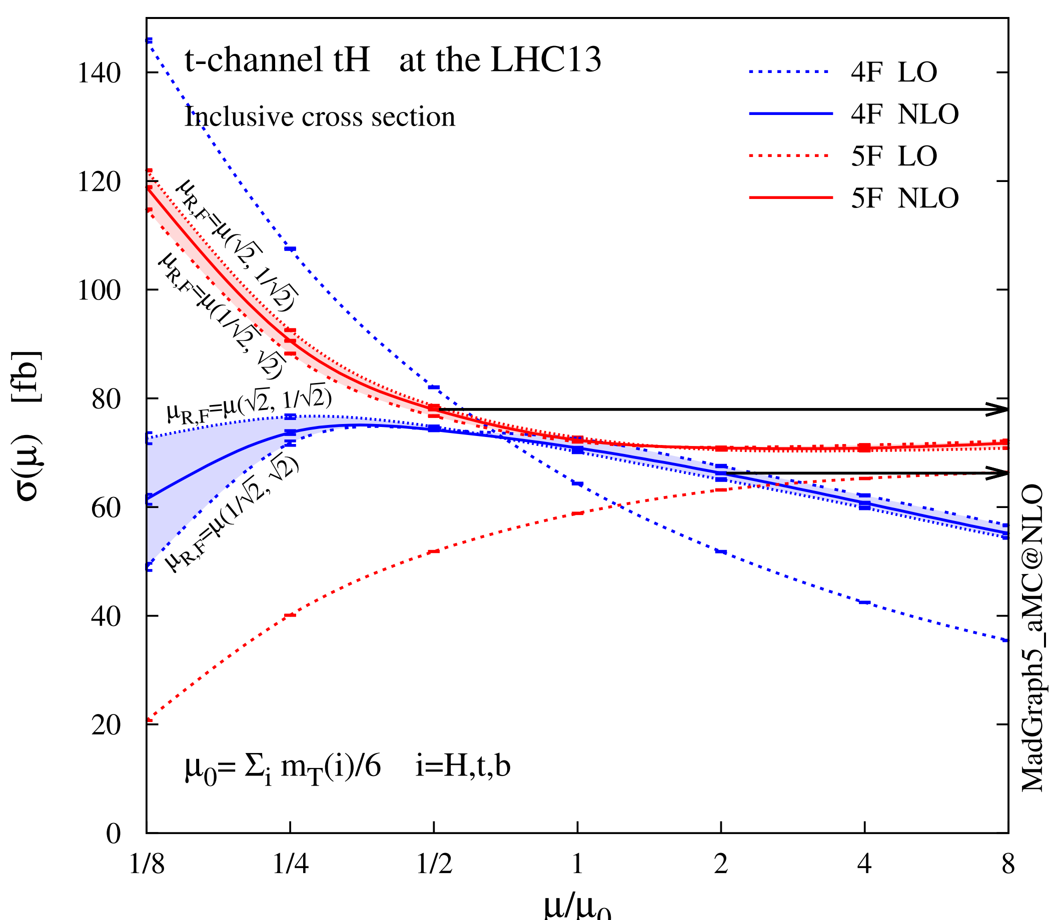


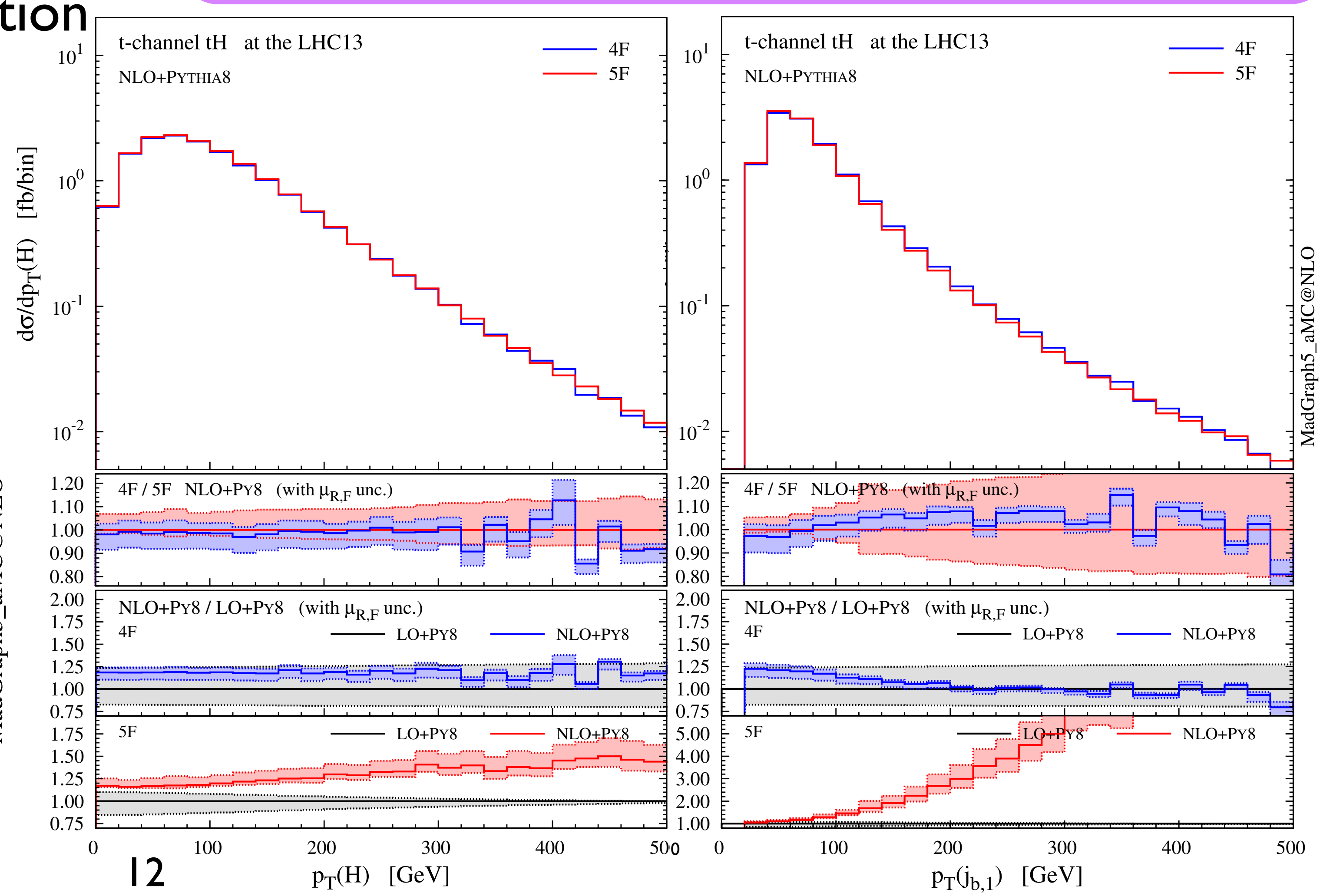
What can be learnt from tH?

Demartin, Maltoni, Mawatari, MZ, arXiv:1504.00611

- tH: rather rare process (σ_{NLO}<100 fb at RunII)
- t-channel dominant production mode, s-channel much suppressed (σ_{NLO}<3 fb)
- Can be described either in the 4FS (m_b>0) or in the 5FS (m_b=0)
- NLO corrections (and wise scale choice) improve agreement between two schemes
- 4FS to be preferred for signal simulation

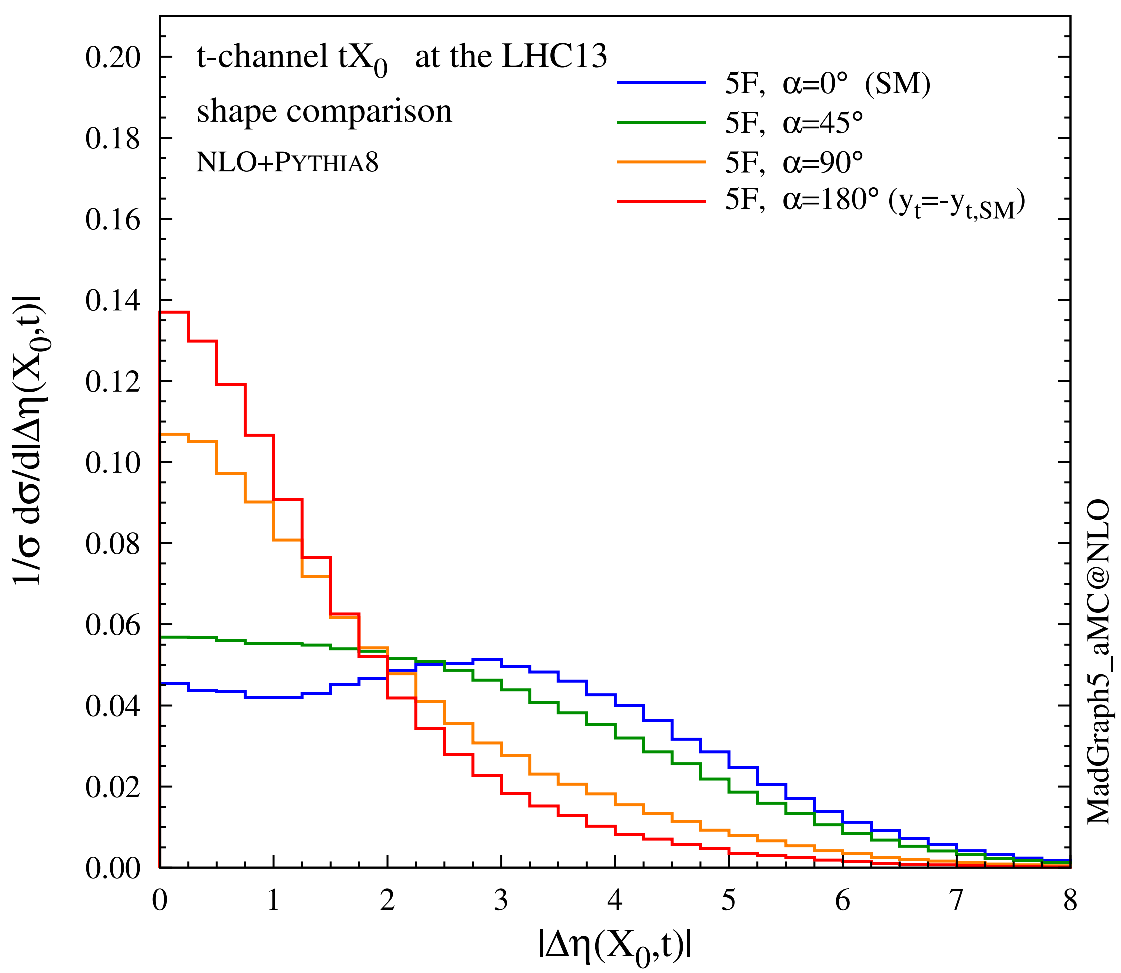


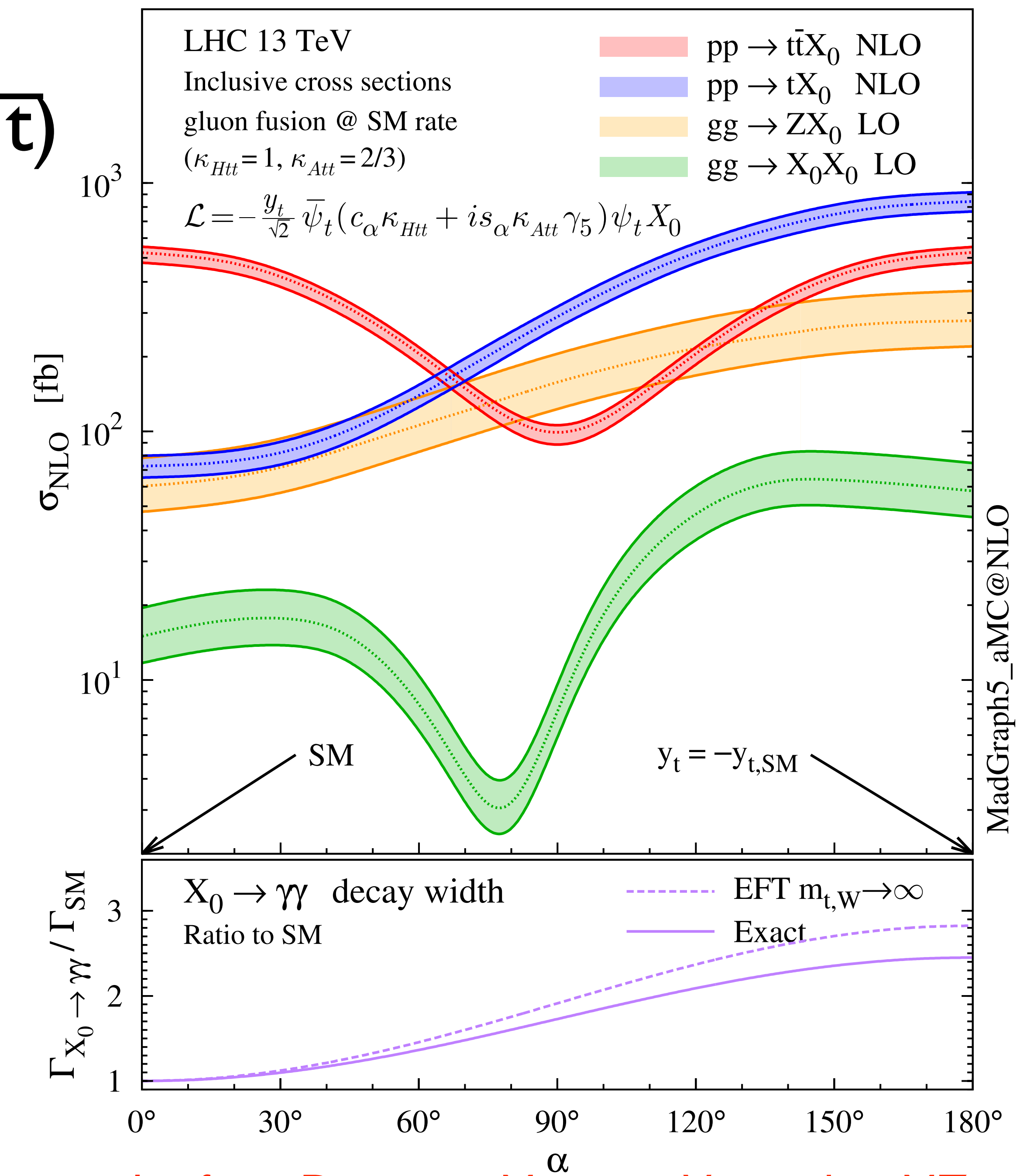




A peculiar process

- tH is one of the few processes (with H→γγ gg→HZ and gg→$t\bar{t}$) sensitive to the sign of y_t



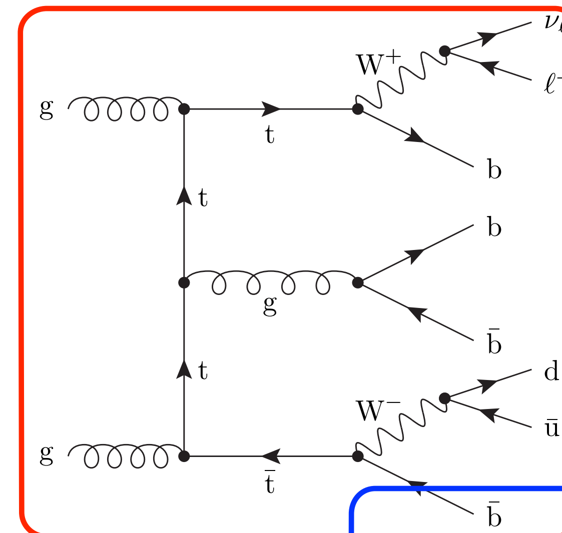


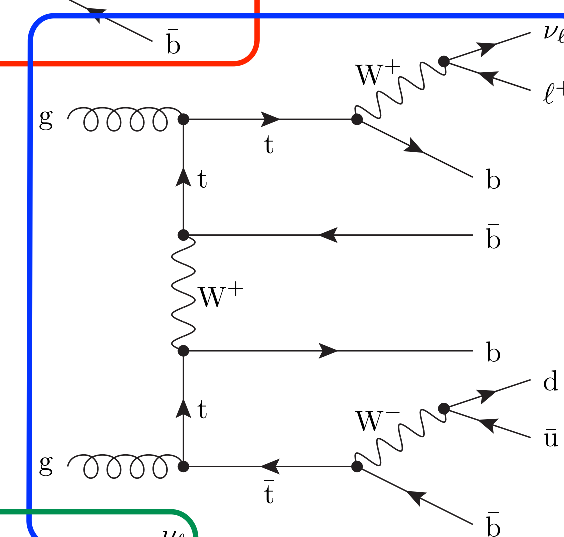
plot from Demartin, Mawatari, Vryonidou, MZ, arXiv:1505.07081

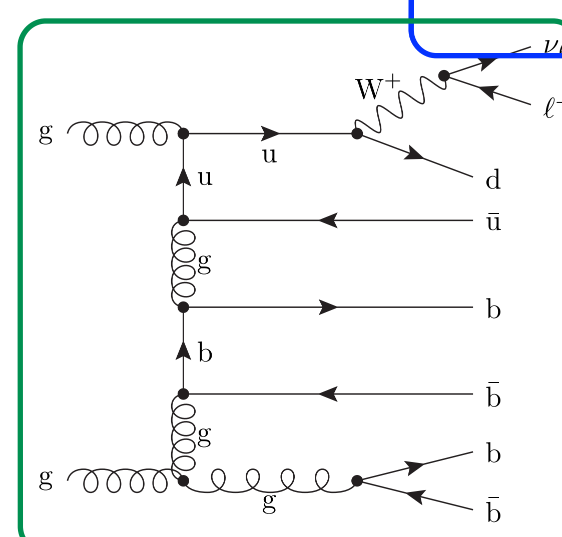
Recent results for the backgrounds

$t\bar{t}b\bar{b}$: going beyond the pure-QCD contribution

- $t\bar{t}b\bar{b}$ is usually studied with stable tops and including only contributions of QCD origin (LO at α_s^4)
- Are we missing anything?
  - What is the effect of non-pure-QCD diagrams (and of interferences between different orders)?
  - Are non-resonant contributions important?







$t\bar{t}b\bar{b}$ beyond QCD-only: Setup and results

Denner, Feger, Scharf, arXiv:1412.5290

- Simulation done at LO
- Semi-leptonic top decay
- Standard cuts on final state leptons, missing-E_T and (b-)jets
- Non-QCD effects are large (60% of QCD-only) for $t\bar{t}b\bar{b}$
- Interference between orders: -6% for gg, -5% on sect (rather flat on most of the distributions)
- Non-resonant effects: +3% on gg-qq (with similar interferences), +8% on xsect due to new partonic channels

$pp \to t\bar{t}b\bar{b} \to l\nu jjb\bar{b}b\bar{b}$

pp	Cross section (fb)				
	$\mathcal{O}((\alpha^4)^2)$	$\mathcal{O}((\alpha_s\alpha^3)^2)$	$\mathcal{O}((\alpha_s^2\alpha^2)^2)$	Sum	Total
$q\bar{q}$	0.018134(6)	2.4932(9)	0.9199(2)	3.4312(9)	3.4366(6)
gg	–	7.818(4)	16.650(9)	24.47(1)	23.010(7)
$\sum$	0.018134(6)	10.311(4)	17.570(9)	27.90(1)	26.446(7)

$pp \to l\nu jjb\bar{b}b\bar{b}$

pp	Cross section (fb)					
	$\mathcal{O}((\alpha^4)^2)$	$\mathcal{O}((\alpha_s\alpha^3)^2)$	$\mathcal{O}((\alpha_s^2\alpha^2)^2)$	$\mathcal{O}((\alpha_s^3\alpha)^2)$	Sum	Total
gq	–	0.231(4)	0.370(2)	0.365(1)	0.966(4)	0.944(9)
$g\bar{q}$	–	0.0421(6)	0.0679(3)	0.0608(2)	0.1708(7)	0.167(1)
$qq^{(\prime)}$	0.001471(2)	0.0575(5)	0.1106(2)	0.07871(9)	0.2483(6)	0.2478(8)
$q\bar{q}$	0.01973(3)	2.531(6)	0.957(1)	0.00333(1)	3.511(6)	3.538(4)
gg	–	8.01(2)	17.19(6)	0.00756(2)	25.21(6)	23.71(6)
$\sum$	0.02120(3)	10.87(2)	18.69(6)	0.516(2)	30.10(6)	28.60(6)

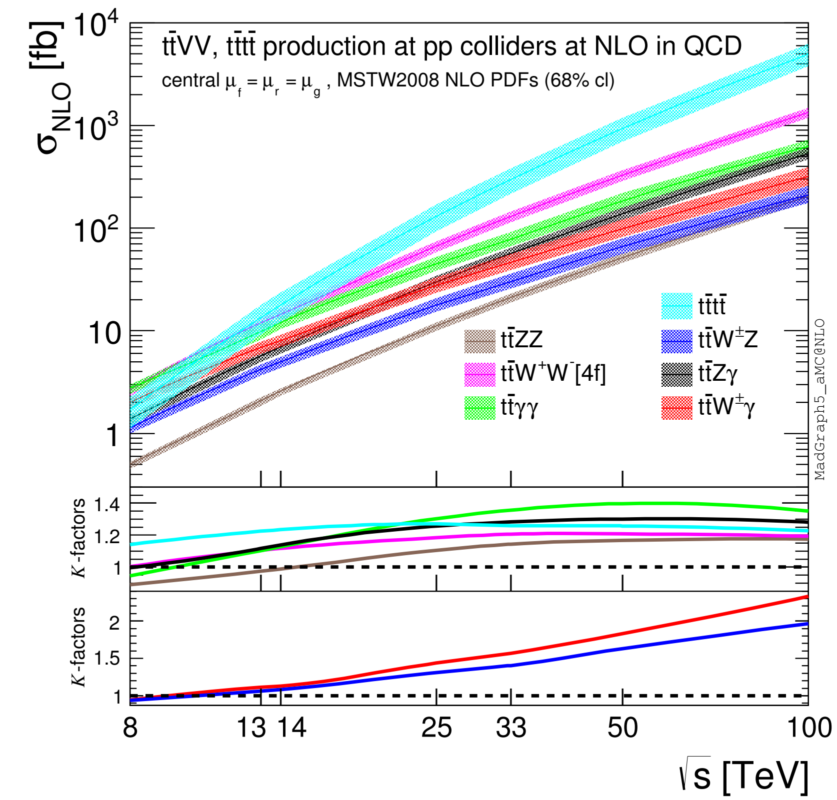
Bottom line: non-QCD effects may be important (how large are they in the $t\bar{t}H$ signal region?)

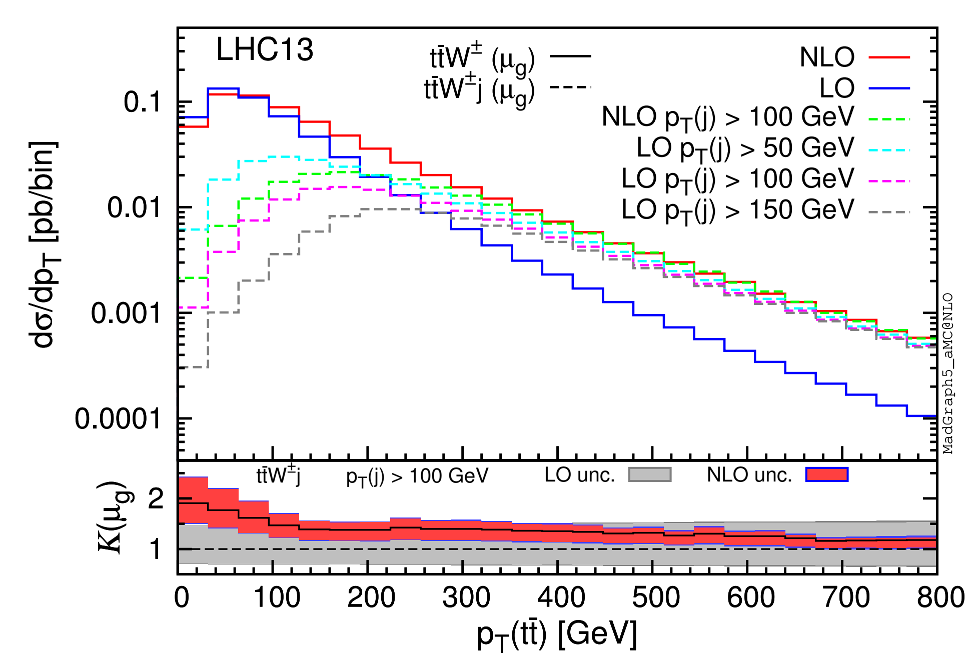
$t\bar{t}b\bar{b}$ provides a reasonable approximation to the full process

Recent results for $t\bar{t}VV$

Maltoni, Tsinikos, Pagani, arXiv:1507.05640

- All $t\bar{t}$+1,2V processes studied at NLO +PS accuracy
- NLO corrections essential for realistic phenomenology
  - K-factor ~ 2 @100TeV for $q\bar{q}$ initiated processes @LO
  - Huge K factors in $p_T(t\bar{t})$ for $t\bar{t}V$ due to recoil against hard jets; further corrections ($t\bar{t}Vj$ @NLO) found to be small
- Detailed study in the context of $t\bar{t}H$ searches

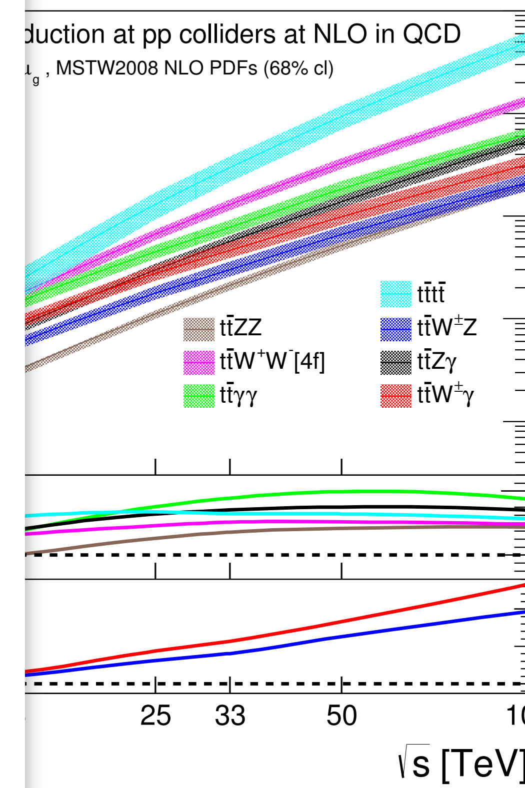


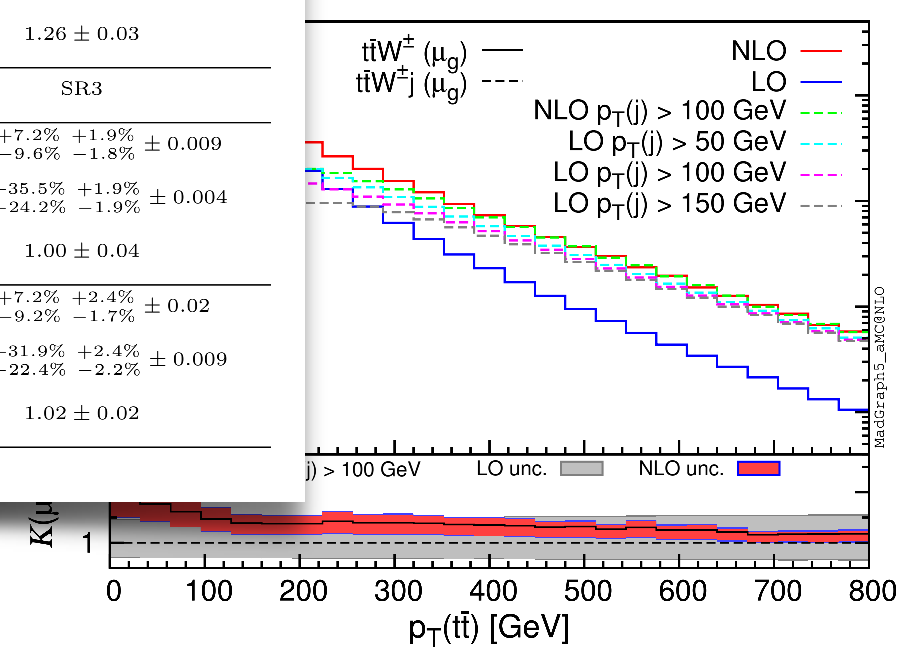


Recent results

- All $t\bar{t}$+1,2 ...
  +PS accur...
- NLO corr...
  phenomen...
  - K-factor...
    processe...
  - Huge K ...
    recoil ag...
    correcti...
    small
- Detailed s...
  searches

13 TeV σ[fb]		SR1	SR2	SR3
$t\bar{t}H(H \to WW^*)$	NLO+PS	$1.54^{+5.1\%\ +2.2\%}_{-9.0\%\ -2.6\%} \pm 0.02$	$1.47^{+5.2\%\ +2.0\%}_{-9.0\%\ -2.4\%} \pm 0.02$	$0.095^{+7.4\%\ +2.0\%}_{-9.7\%\ -2.4\%} \pm 0.002$
	LO+PS	$1.401^{+35.6\%\ +2.1\%}_{-24.4\%\ -2.2\%} \pm 0.008$	$1.355^{+35.2\%\ +2.0\%}_{-24.1\%\ -2.2\%} \pm 0.008$	$0.0855^{+34.9\%\ +2.0\%}_{-24.0\%\ -2.2\%} \pm 0.0007$
$K = 1.10$	K^{PS}	1.10 ± 0.02	1.09 ± 0.02	1.11 ± 0.02
$t\bar{t}H(H \to ZZ^*)$	NLO+PS	$0.0437^{+5.5\%\ +2.3\%}_{-9.2\%\ -2.8\%} \pm 0.0004$	$0.119^{+6.3\%\ +2.1\%}_{-9.6\%\ -2.5\%} \pm 0.002$	$0.0170^{+5.0\%\ +2.0\%}_{-8.5\%\ -2.4\%} \pm 0.0003$
	LO+PS	$0.0404^{+36.1\%\ +2.2\%}_{-24.6\%\ -2.3\%} \pm 0.0002$	$0.1092^{+35.3\%\ +2.0\%}_{-24.2\%\ -2.2\%} \pm 0.0008$	$0.0152^{+34.7\%\ +1.9\%}_{-23.9\%\ -2.1\%} \pm 0.0001$
$K = 1.10$	K^{PS}	1.08 ± 0.01	1.09 ± 0.02	1.12 ± 0.02
$t\bar{t}H(H \to \tau^+\tau^-)$	NLO+PS	$0.563^{+4.6\%\ +2.2\%}_{-8.8\%\ -2.7\%} \pm 0.007$	$0.669^{+6.0\%\ +2.1\%}_{-9.4\%\ -2.6\%} \pm 0.008$	$0.0494^{+7.1\%\ +2.1\%}_{-9.9\%\ -2.5\%} \pm 0.0007$
	LO+PS	$0.513^{+35.9\%\ +2.2\%}_{-24.5\%\ -2.3\%} \pm 0.003$	$0.611^{+35.4\%\ +2.1\%}_{-24.2\%\ -2.2\%} \pm 0.003$	$0.0438^{+35.1\%\ +2.0\%}_{-24.1\%\ -2.2\%} \pm 0.0003$
$K = 1.10$	K^{PS}	1.10 ± 0.02	1.10 ± 0.01	1.13 ± 0.02
$t\bar{t}W^\pm$	NLO+PS	$5.77^{+15.1\%\ +1.6\%}_{-12.7\%\ -1.2\%} \pm 0.07$	$2.44^{+13.1\%\ +1.7\%}_{-11.6\%\ -1.4\%} \pm 0.01$	-
	LO+PS	$4.57^{+27.7\%\ +1.8\%}_{-20.2\%\ -1.9\%} \pm 0.03$	$1.989^{+27.5\%\ +1.8\%}_{-20.0\%\ -1.9\%} \pm 0.007$	-
$K = 1.22$	K^{PS}	1.26 ± 0.02	1.23 ± 0.01	-
$t\bar{t}Z/\gamma^*$	NLO+PS	$1.61^{+7.7\%\ +2.0\%}_{-10.5\%\ -2.5\%} \pm 0.02$	$2.70^{+9.0\%\ +2.0\%}_{-11.2\%\ -2.5\%} \pm 0.03$	$0.280^{+9.8\%\ +1.9\%}_{-11.0\%\ -2.3\%} \pm 0.003$
	LO+PS	$1.422^{+36.8\%\ +2.2\%}_{-24.9\%\ -2.3\%} \pm 0.008$	$2.21^{+36.4\%\ +2.1\%}_{-24.7\%\ -2.2\%} \pm 0.01$	$0.221^{+35.8\%\ +2.0\%}_{-24.4\%\ -2.2\%} \pm 0.001$
$K = 1.23$	K^{PS}	1.13 ± 0.02	1.23 ± 0.01	1.27 ± 0.01
$t\bar{t}W^+W^-$	NLO+PS	$0.288^{+8.0\%\ +2.3\%}_{-11.1\%\ -2.6\%} \pm 0.003$	$0.201^{+7.4\%\ +2.1\%}_{-10.7\%\ -2.3\%} \pm 0.003$	$0.0116^{+6.9\%\ +2.2\%}_{-10.2\%\ -2.3\%} \pm 0.0002$
	LO+PS	$0.260^{+38.4\%\ +2.3\%}_{-25.5\%\ -2.3\%} \pm 0.001$	$0.181^{+38.0\%\ +2.2\%}_{-25.3\%\ -2.2\%} \pm 0.001$	$0.01073^{+37.7\%\ +2.2\%}_{-25.1\%\ -2.2\%} \pm 0.00008$
$K = 1.10$	K^{PS}	1.11 ± 0.01	1.11 ± 0.01	1.08 ± 0.02
$t\bar{t}t\bar{t}$	NLO+PS	$0.340^{+27.5\%\ +5.5\%}_{-25.8\%\ -6.4\%} \pm 0.004$	$0.211^{+27.4\%\ +5.2\%}_{-25.6\%\ -6.1\%} \pm 0.003$	$0.0110^{+27.0\%\ +5.0\%}_{-25.5\%\ -5.9\%} \pm 0.0002$
	LO+PS	$0.271^{+80.9\%\ +4.6\%}_{-41.5\%\ -4.6\%} \pm 0.001$	$0.166^{+80.3\%\ +4.4\%}_{-41.4\%\ -4.4\%} \pm 0.001$	$0.00871^{+79.8\%\ +4.2\%}_{-41.2\%\ -4.2\%} \pm 0.00007$
$K = 1.22$	K^{PS}	1.26 ± 0.02	1.27 ± 0.02	1.26 ± 0.03
13 TeV σ[ab]		SR1	SR2	SR3
$t\bar{t}ZZ$	NLO+PS	$9.60^{+3.5\%\ +1.8\%}_{-8.4\%\ -1.8\%} \pm 0.06$	$5.02^{+3.7\%\ +1.8\%}_{-8.3\%\ -1.7\%} \pm 0.04$	$0.249^{+7.2\%\ +1.9\%}_{-9.6\%\ -1.8\%} \pm 0.009$
	LO+PS	$9.71^{+36.3\%\ +1.9\%}_{-24.5\%\ -1.9\%} \pm 0.02$	$5.08^{+35.9\%\ +1.9\%}_{-24.3\%\ -1.9\%} \pm 0.02$	$0.250^{+35.5\%\ +1.9\%}_{-24.2\%\ -1.9\%} \pm 0.004$
$K = 0.99$	K^{PS}	0.99 ± 0.01	0.99 ± 0.01	1.00 ± 0.04
$t\bar{t}W^\pm Z$	NLO+PS	$62.0^{+9.0\%\ +2.2\%}_{-10.2\%\ -1.6\%} \pm 0.7$	$27.9^{+9.2\%\ +2.3\%}_{-10.3\%\ -1.7\%} \pm 0.5$	$0.91^{+7.2\%\ +2.4\%}_{-9.2\%\ -1.7\%} \pm 0.02$
	LO+PS	$60.2^{+32.2\%\ +2.4\%}_{-22.6\%\ -2.3\%} \pm 0.3$	$26.4^{+32.0\%\ +2.4\%}_{-22.5\%\ -2.2\%} \pm 0.2$	$0.893^{+31.9\%\ +2.4\%}_{-22.4\%\ -2.2\%} \pm 0.009$
$K = 1.06$	K^{PS}	1.03 ± 0.01	1.06 ± 0.02	1.02 ± 0.02





Is a 1% measurement of y_t possible? Ratios (and the FCC) can help…

Mangano, Plehn, Reimitz, Schell, Shao, arXiv:1507.08169

- $t\bar{t}H$ and $t\bar{t}Z$ are quite similar processes, with rather large theoretical uncertainties (~10%).
  - Dominant production mode (gg) has identical diagrams Correlated QCD corrections, scale and α_S systematics

NLO QCD	$\sigma(t\bar{t}H)$ [pb]	$\sigma(t\bar{t}Z)$ [pb]	$\sigma(t\bar{t}H)/\sigma(t\bar{t}Z)$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

  - Almost identical kinematics boundaries (m_Z~m_H) Correlated PDF and m_t systematics

100TeV	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
MSTW2008	$0.585^{+1.29\%+0.0526\%}_{-2.02\%-0.0758\%}$
CT10	$0.584^{+1.27\%+0.189\%}_{-1.99\%-0.260\%}$
NNPDF2.3	$0.584^{+1.29\%+0.0493\%}_{-2.01\%-0.0493\%}$

	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
default	$0.585^{+1.29\%}_{-2.02\%}$
$\mu_0 = m_t + m_{H,Z}/2$	$0.580^{+1.16\%}_{-1.80\%}$
$m_t = y_t v = 174.1$ GeV	$0.592^{+1.27\%}_{-2.00\%}$
$m_t = y_t v = 172.5$ GeV	$0.576^{+1.27\%}_{-1.99\%}$
$m_H = 126.0$ GeV	$0.575^{+1.25\%}_{-1.95\%}$

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  - Almost identical kinematics boundaries (m_Z~m_H)
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100T
MSTW
CT1
NNPDF2.3 $0.584^{+1.29\%+0.0493\%}_{-2.01\%-0.0493\%}$

$m_t = y_t v = 174.1$ GeV $0.592^{+1.27\%}_{-2.00\%}$
$m_t = y_t v = 172.5$ GeV $0.576^{+1.27\%}_{-1.99\%}$
$m_H = 126.0$ GeV $0.575^{+1.25\%}_{-1.95\%}$

With 20ab^{-1}, the ratio N_H/N_Z can be measured at 1% (stat. unc.)

Conclusions:

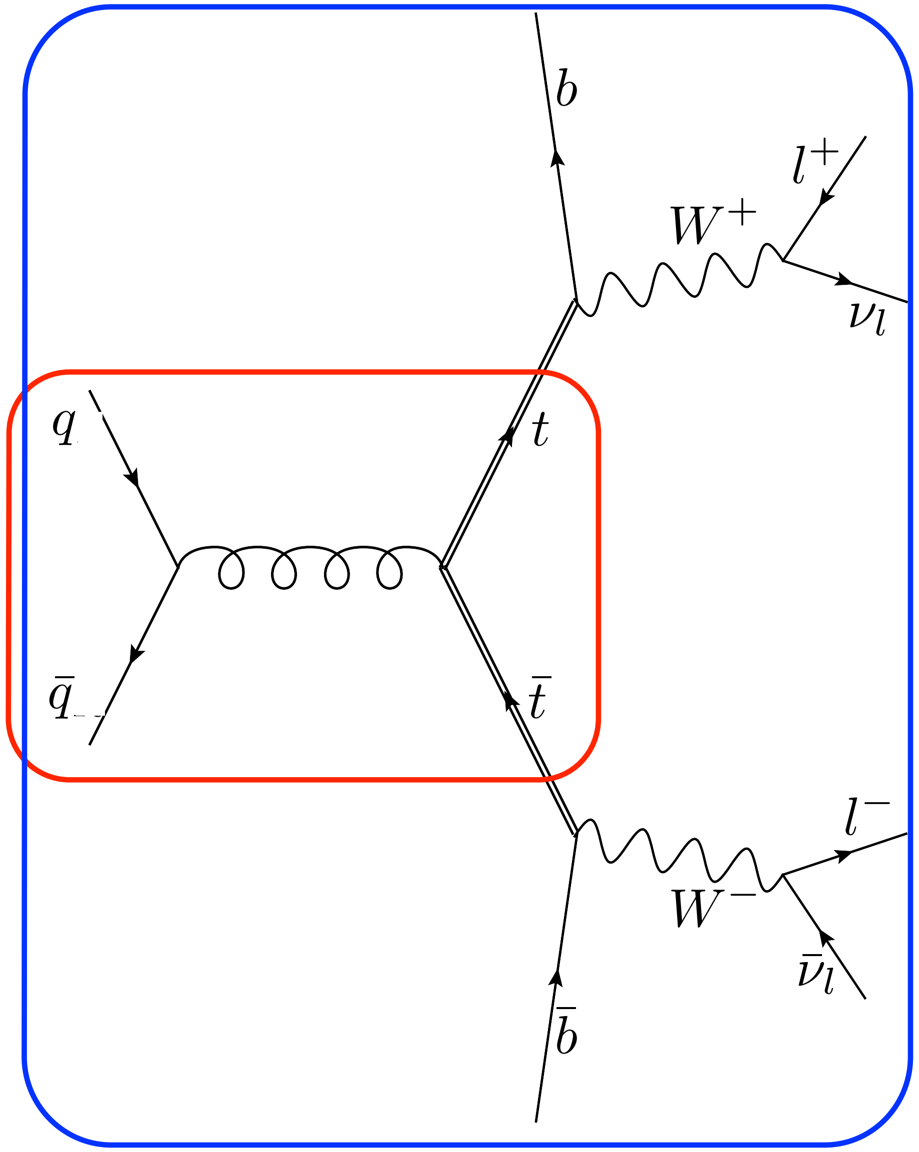
- $t\bar{t}H$ (and tH) are crucial processes to study the top/Higgs sector
  - Sensitive to top Yukawa (and its sign) and to Higgs CP properties
- Need for precise predictions both for total cross section and fully differential studies
  - NLO+PS available for signal and all main backgrounds
  - $t\bar{t}H$ @ NLO+NLL recently computed
  - NLO EW corrections available for $t\bar{t}H/Z/W$
  - tH NLO+PS predictions available in the 4FS → better description at fully differential level
  - Non-QCD effects can be important for $t\bar{t}b\bar{b}$ simulation
- Spin correlations have to be included in simulations for Higgs CP studies and to enhance S/B discrimination
- The FCC can help for a precise determination of y_t
  - First studies have just appeared

Backup slides

Including spin correlations at NLO

Frixione, Leanen, Motylinski, Webber, arXiv:hep-ph/0702198

- Generate events (to be showered) for the production process M_P
- Before showering, produce a decayed event file starting from the undecayed events
- Exploit the fact that $|M^2_{P+D}|/|M^2_P|$ is bounded from above
- The generation of unweighted decayed events is possible: generate many kinematics configurations until $|M_{P+D}|^2 / |M_P|^2 > \text{Rand}()\ \max\left(|\mathrm{M_{P+D}}|^2 / |\mathrm{M_P}|^2\right)$
- In NLO computations use only tree-level matrix elements (with n or n+1 particles)
- Loop effects on spin correlation assumed to be negligible
- Automated in MadSpin (MadGraph5_aMC@NLO) and Decayer (PowHel) Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460 Garzelli, Kardos, Trocsanyi, arXiv:1405.5859



Recent results for $t\bar{t}V$ and $t\bar{t}VV$

Frixione, Hirschi, Pagani, Shao, MZ, arXiv:1504.03446

- NLO Electroweak corrections recently computed for $t\bar{t}Z/W$ (and $t\bar{t}H$)

$t\bar{t}Z$: σ(pb)	13 TeV
LO QCD	$5.282 \cdot 10^{-1}$ ($1.955 \cdot 10^{-2}$)
NLO QCD	$2.426 \cdot 10^{-1}$ ($7.856 \cdot 10^{-3}$)
LO EW	$-2.172 \cdot 10^{-4}$ ($4.039 \cdot 10^{-4}$)
LO EW no γ	$-5.771 \cdot 10^{-3}$ ($-6.179 \cdot 10^{-5}$)
NLO EW	$-2.017 \cdot 10^{-2}$ ($-2.172 \cdot 10^{-3}$)
NLO EW no γ	$-2.158 \cdot 10^{-2}$ ($-2.252 \cdot 10^{-3}$)
HBR	$5.056 \cdot 10^{-3}$ ($4.162 \cdot 10^{-4}$)

$t\bar{t}W^+$: σ(pb)	13 TeV
LO QCD	$2.496 \cdot 10^{-1}$ ($7.749 \cdot 10^{-3}$)
NLO QCD	$1.250 \cdot 10^{-1}$ ($4.624 \cdot 10^{-3}$)
LO EW	0
LO EW no γ	0
NLO EW	$-1.931 \cdot 10^{-2}$ ($-1.490 \cdot 10^{-3}$)
NLO EW no γ	$-1.988 \cdot 10^{-2}$ ($-1.546 \cdot 10^{-3}$)
HBR	$9.677 \cdot 10^{-3}$ ($5.743 \cdot 10^{-4}$)

$t\bar{t}Z$: δ(%)	13 TeV
NLO QCD	$45.9^{+13.2}_{-15.5} \pm 2.9$ ($40.2^{+11.1}_{-15.0} \pm 4.7$)
LO EW	0.0 ± 0.7 (2.1 ± 1.6)
LO EW no γ	-1.1 ± 0.0 (-0.3 ± 0.0)
NLO EW	-3.8 ± 0.2 (-11.1 ± 0.5)
NLO EW no γ	-4.1 ± 0.1 (-11.5 ± 0.3)
HBR	0.96 (2.13)

$t\bar{t}W^+$: δ(%)	13 TeV
NLO QCD	$50.1^{+14.2}_{-13.5} \pm 2.4$ ($59.7^{+18.9}_{-17.7} \pm 3.1$)
LO EW	0
LO EW no γ	0
NLO EW	-7.7 ± 0.2 (-19.2 ± 0.7)
NLO EW no γ	-8.0 ± 0.2 (-20.0 ± 0.5)
HBR	3.88 (7.41)

- $t\bar{t}Z$: corrections are slightly larger than $t\bar{t}H$, with similar overall behaviour
- $t\bar{t}W$ receives sizeable EW corrections even in the un-boosted regime

More in D. Pagani's talk this afternoon

NLO QCD corrections to $b\bar{b}e^{+}\mu^{-}\nu\nu H$

Denner, Feger, arXiv:1506.07448

- All simulations of $t\bar{t}H$ done either with stable tops or including decays in the NWA
- First computation that consistently includes off-shell and non-resonant effects (unified description of $t\bar{t}H$, tWH, …)
- All matrix elements computed with RECOLA (up to 7-points loops) in the complex-mass scheme
- Two b-jets (anti-k_T, R=0.4) and two leptons required with

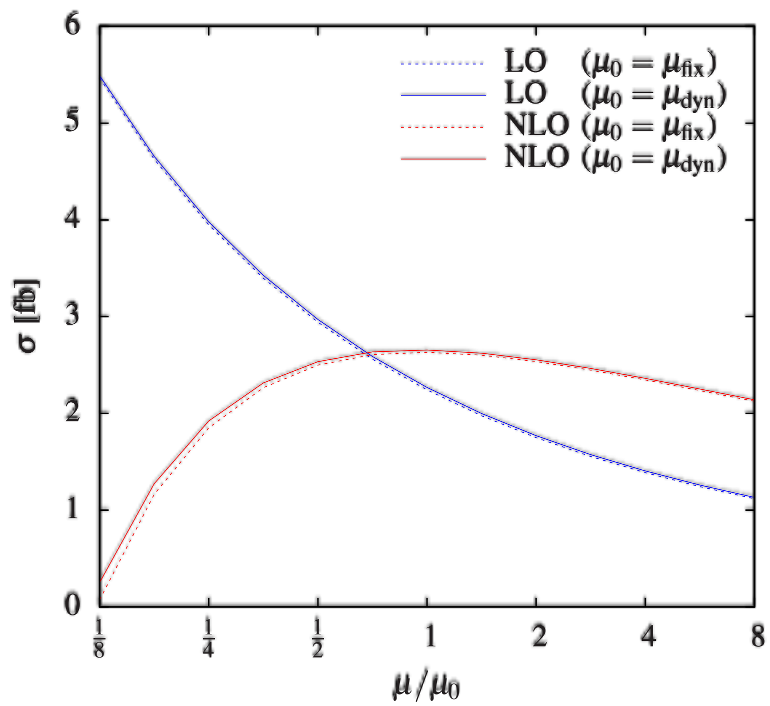
$$p_{\mathrm{T,b}} > 25\,\mathrm{GeV}, \quad |\eta_b| < 2.5$$
$$p_{\mathrm{T,l}} > 20\,\mathrm{GeV}, \quad |\eta_{\mathrm{l}}| < 2.5$$
$$p_{\mathrm{T,miss}} > 20\,\mathrm{GeV}$$
$$\Delta R_{\mathrm{bb}} > 0.4$$

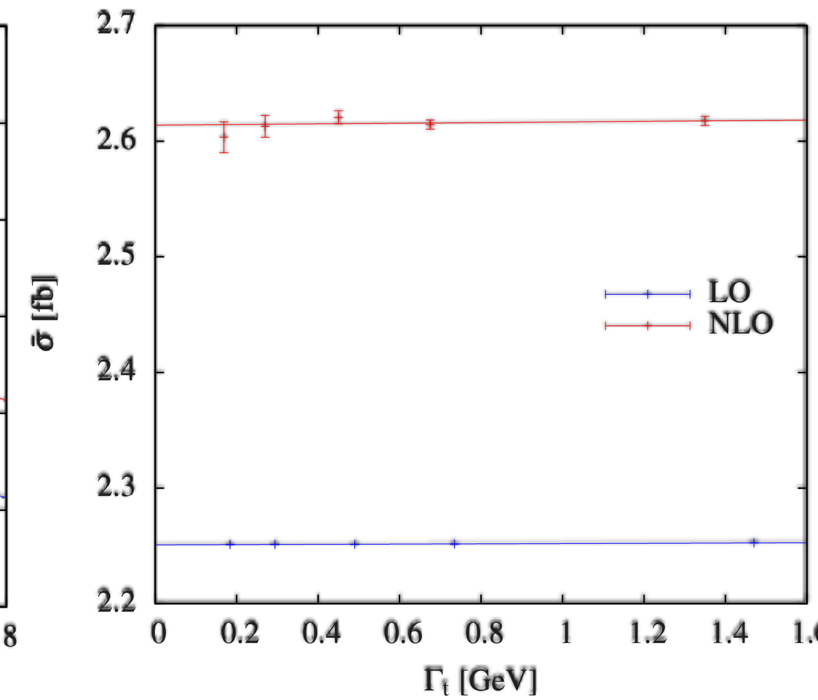
- Compare results with fixed or dynamical scales

$$\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = m_{\mathrm{t}} + \tfrac{1}{2} M_{\mathrm{H}} = 236\,\mathrm{GeV}$$
$$\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = (m_{\mathrm{t,T}}\, m_{\bar{\mathrm{t}},\mathrm{T}}\, m_{\mathrm{H,T}})^{1/3}$$

NLO QCD corrections to $b\bar{b}e^+\mu^-\nu\nu H$: Results

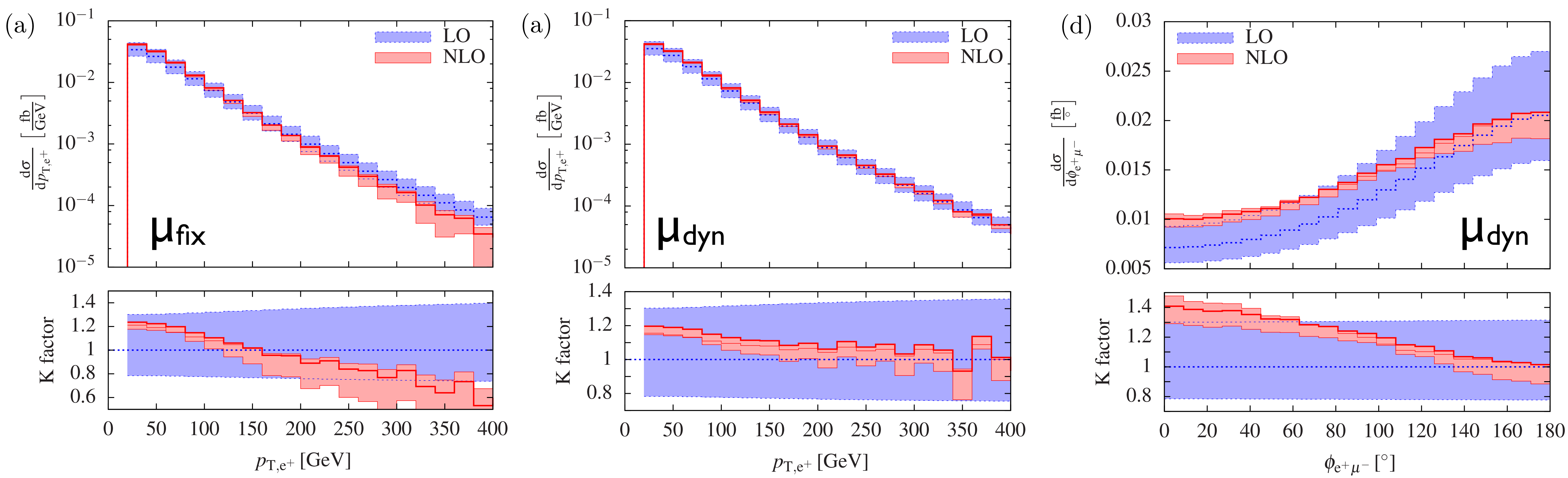
μ_0	ch.	σ_{LO} [fb]	σ_{NLO} [fb]	K
μ_{dyn}	gg	$1.5938(1)^{+33.8\%}_{-23.6\%}$	$2.026(3)^{-16.1\%}_{+0.9\%}$	1.271(2)
	$q\bar{q}$	$0.67520(5)^{+24.1\%}_{-18.1\%}$	$0.495(2)^{-39.5\%}_{+17.2\%}$	0.733(2)
	$g\overset{(-)}{q}$		$0.1347(7)^{+298\%}_{-152\%}$	
	pp	$2.2690(1)^{+30.9\%}_{-22.0\%}$	$2.656(3)^{-4.6\%}_{-3.8\%}$	1.171(1)
μ_{fix}	gg	$1.5713(1)^{+34.0\%}_{-23.7\%}$	$2.010(3)^{-16.5\%}_{+1.0\%}$	1.279(2)
	$q\bar{q}$	$0.67235(5)^{+24.3\%}_{-18.2\%}$	$0.496(2)^{-39.3\%}_{+17.0\%}$	0.738(2)
	$g\overset{(-)}{q}$		$0.1260(7)^{+312\%}_{-159\%}$	
	pp	$2.2436(1)^{+31.1\%}_{-22.1\%}$	$2.632(3)^{-5.1\%}_{-3.7\%}$	1.173(1)





- Small (<1%) effect of scale choice on total cross section
- Important reduction of scale uncertainties at NLO
- K-factor similar to $t\bar{t}H$ with same scale settings
- Finite width effects of the order of Γ_t/m_t

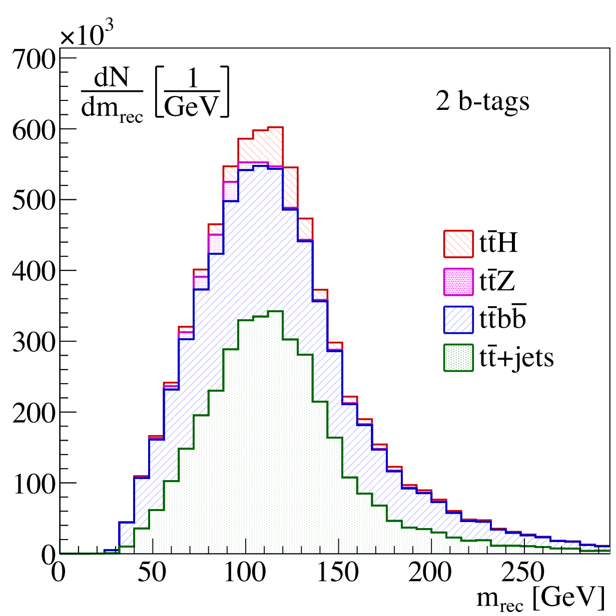
NLO QCD corrections to $b\bar{b}e^{+}\mu^{-}\nu\nu H$: differential distributions

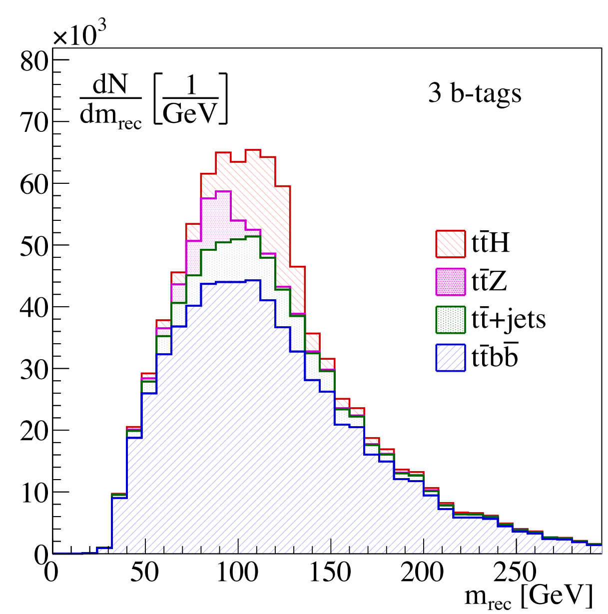


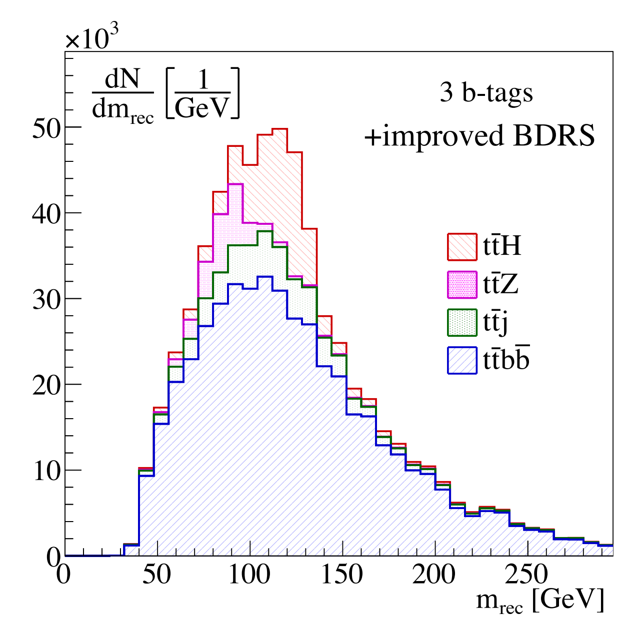
- The dynamic-scale choice yields a flatter K-factor for many observables
- Still, K-factors are far from flat for most observables (in particular those related to correlations between decay products of the two tops)

Background processes and selection cuts

- Leading backgrounds to be simulated are $t\bar{t}b\bar{b}$, $t\bar{t}Z$, $t\bar{t}$+jets
- Simulated semileptonic top decay, Higgs and Z decay to $b\bar{b}$
- Require:
  - One isolated lepton, $|y_\ell|<2.5$, $p_T(\ell)>15$GeV
  - Two fat jets (C/A, R=1.8, $p_T>200$GeV)
    - One HepTopTagged jet
    - One BDRS Higgs Tagged jet, with 2 b-tags inside
    - An extra b-tag in the "rest" of the event (to suppress $t\bar{t}$+jets)







Signal extraction

- Subtract the background by interpolating the two sidebands regions $m_{bb} \in [0,60]$ GeV U [160, 300] GeV
- In the signal region ($m_{bb} \in [104,136]$ GeV one expects 44700 signal events, with S/B ~0.33 (at 20ab^{-1})
- Assuming perfect background subtraction the stat. error on signal is N_S=0.013N_S
- N_H/N_Z=2.80±0.03, with systematic and theoretical uncertainties cancelling in the ratio