Accurate predictions for associated Higgs and top production

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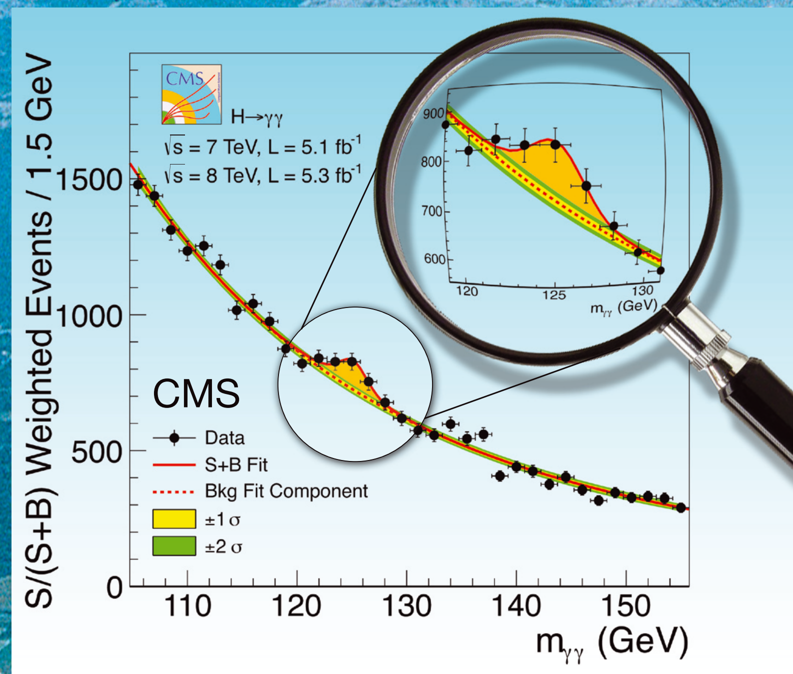
Outline:

- Introduction & Motivation
- 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?

Long long time ago (July 4th 2012)…

First observations of a new particle in the search for the Standard Model Higgs boson at the LHC

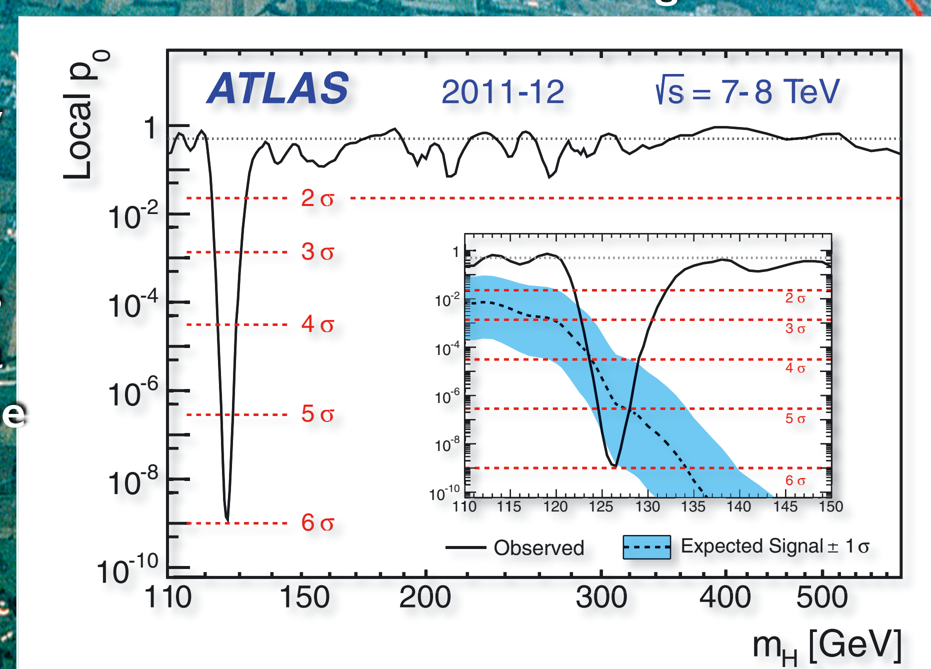


CMS PLB 716 (2012) 30-61

An excess of events is observed above the expected background, […], at a mass near 125 Gev, signalling the production of a new particle. […] The decay to two photons indicates that the new particle is a boson with spin different than one. The results presented here are consistent, within uncertainties, with expectations for the SM Higgs boson. The collection of further data will enable a more rigorous test…

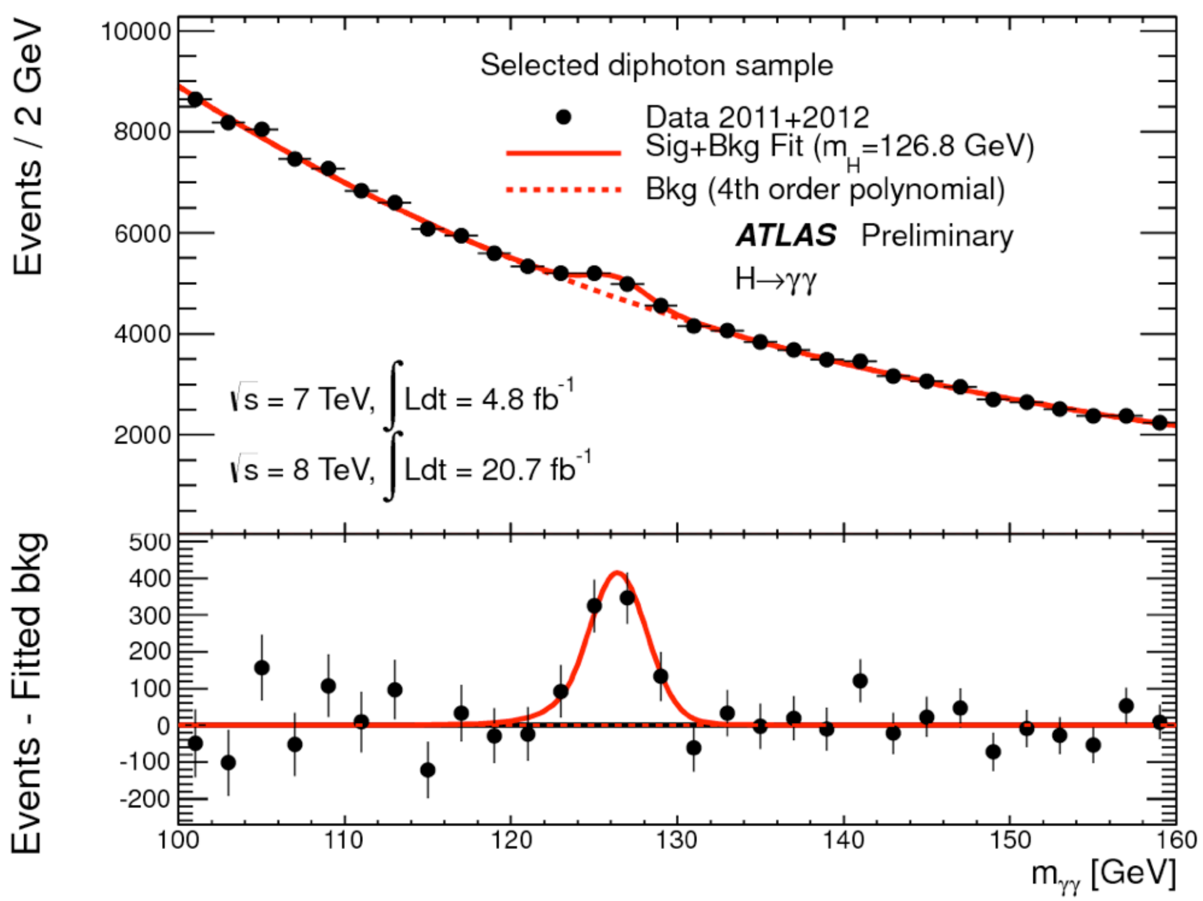
ATLAS PLB 716 (2012) 1-29

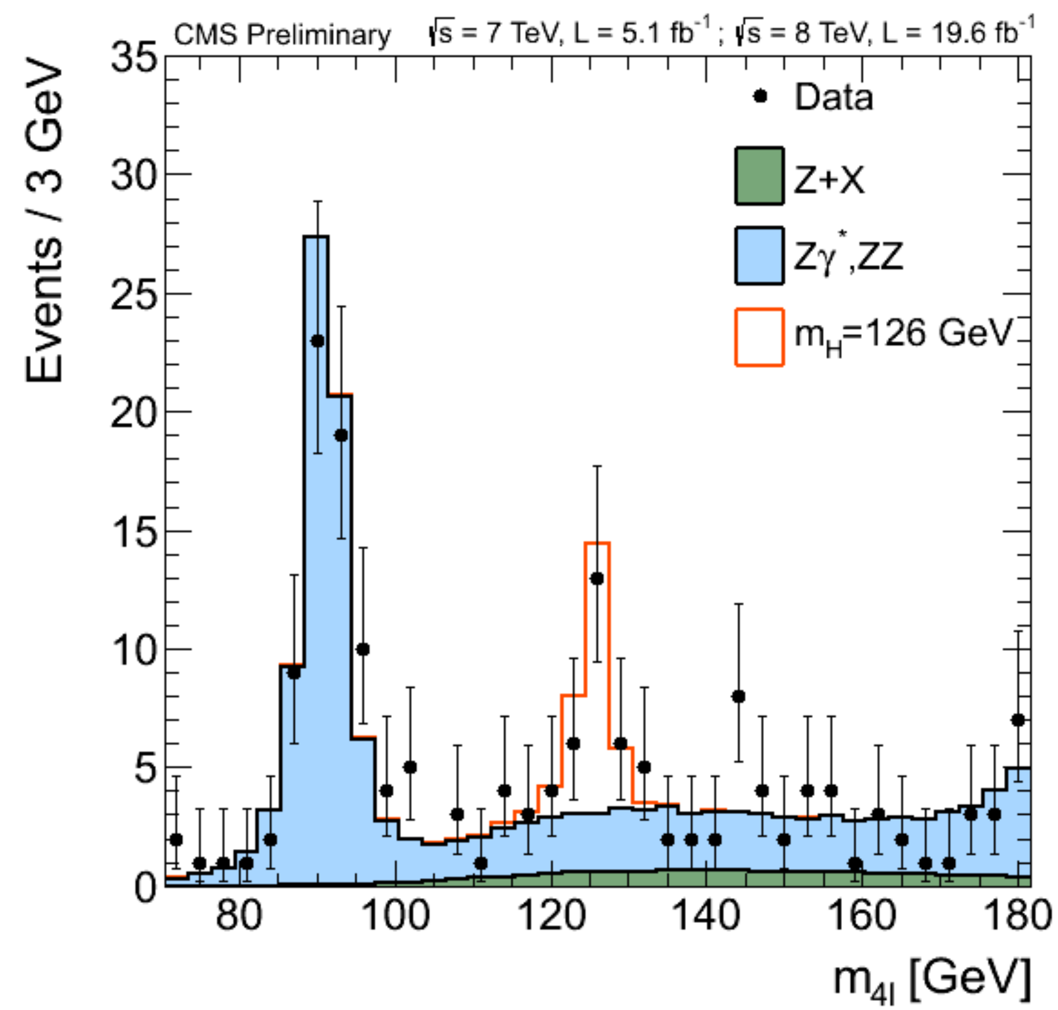
These results provide conclusive evidence for the discovery of a new particle with mass 126.0±… GeV. […] The decay to pairs of vector bosons whose net electric charge is zero identifies the new particle as a neutral boson. The observation in the diphoton channel disfavours the spin-1 hypothesis. Although these results are compatible with the hypothesis that the new particle is the SM Higgs boson, more data are needed to asses its nature in detail.



Elsevier/PLB

Any new discovery is the beginning of a new journey…





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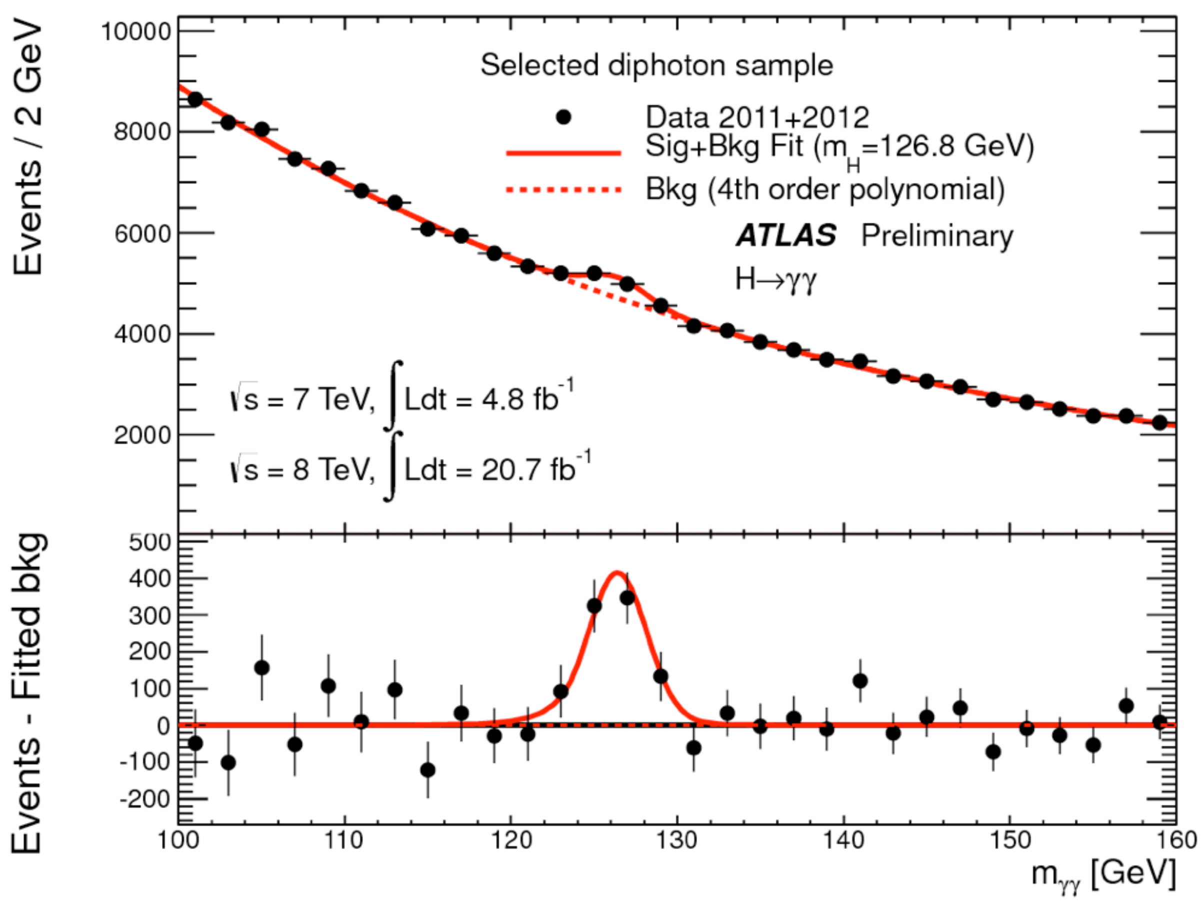

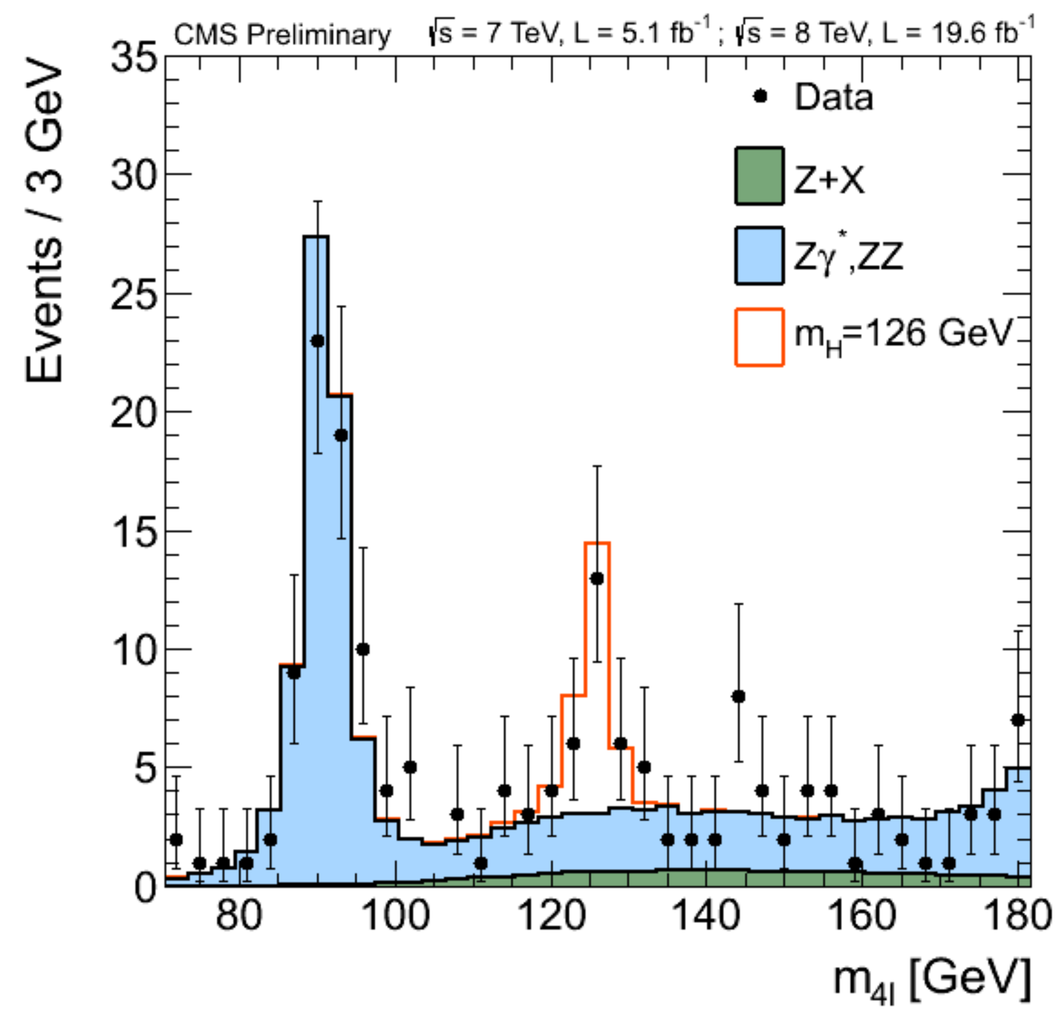

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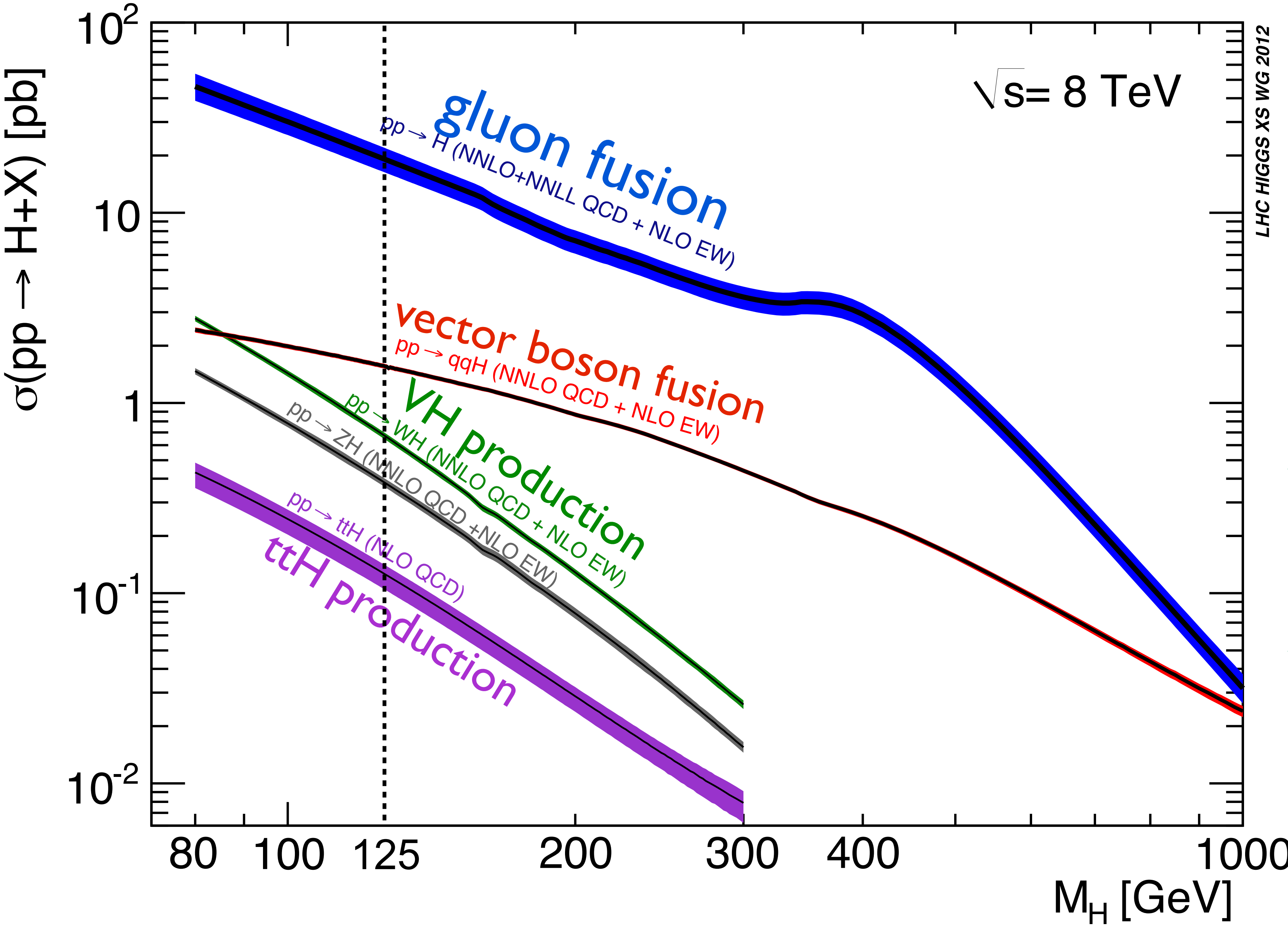
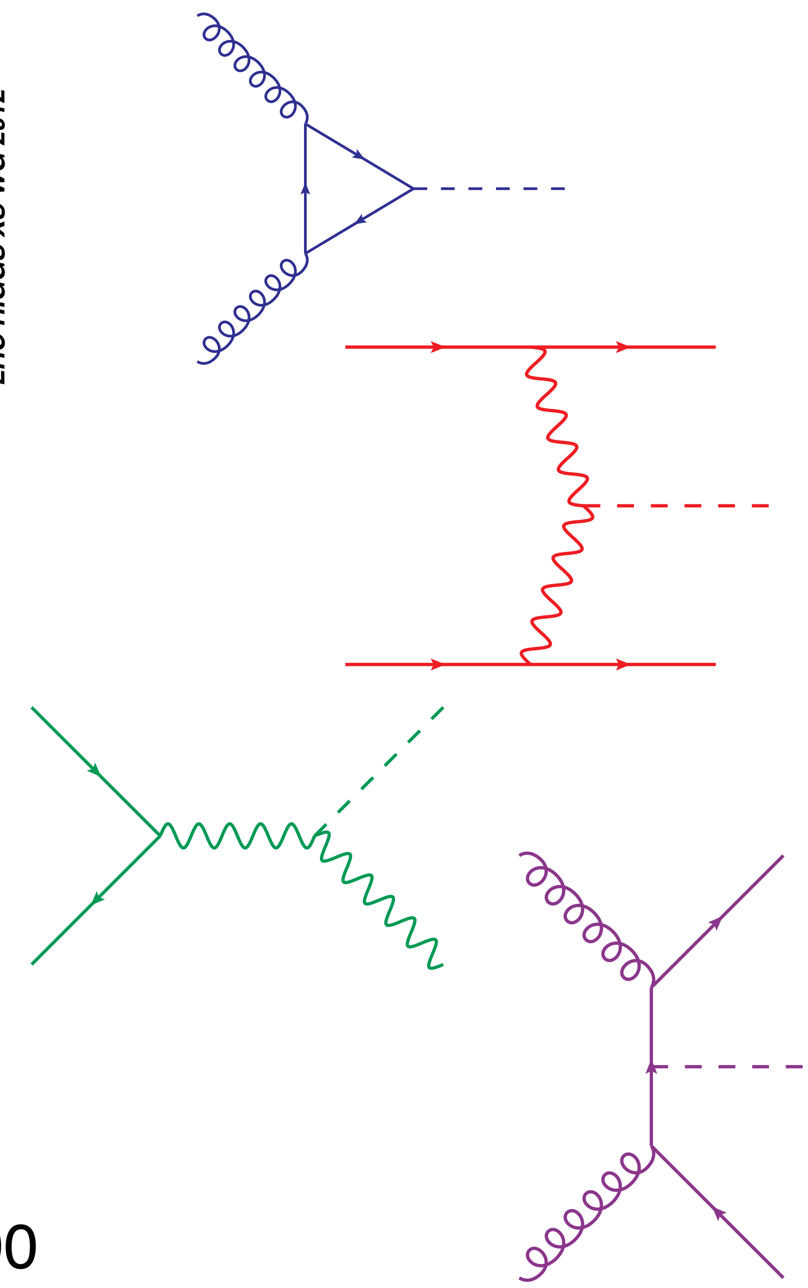
- Q: Is it *the SM* Higgs boson?

  - A: So far, it looks like it is…

How is the Higgs produced in the SM?





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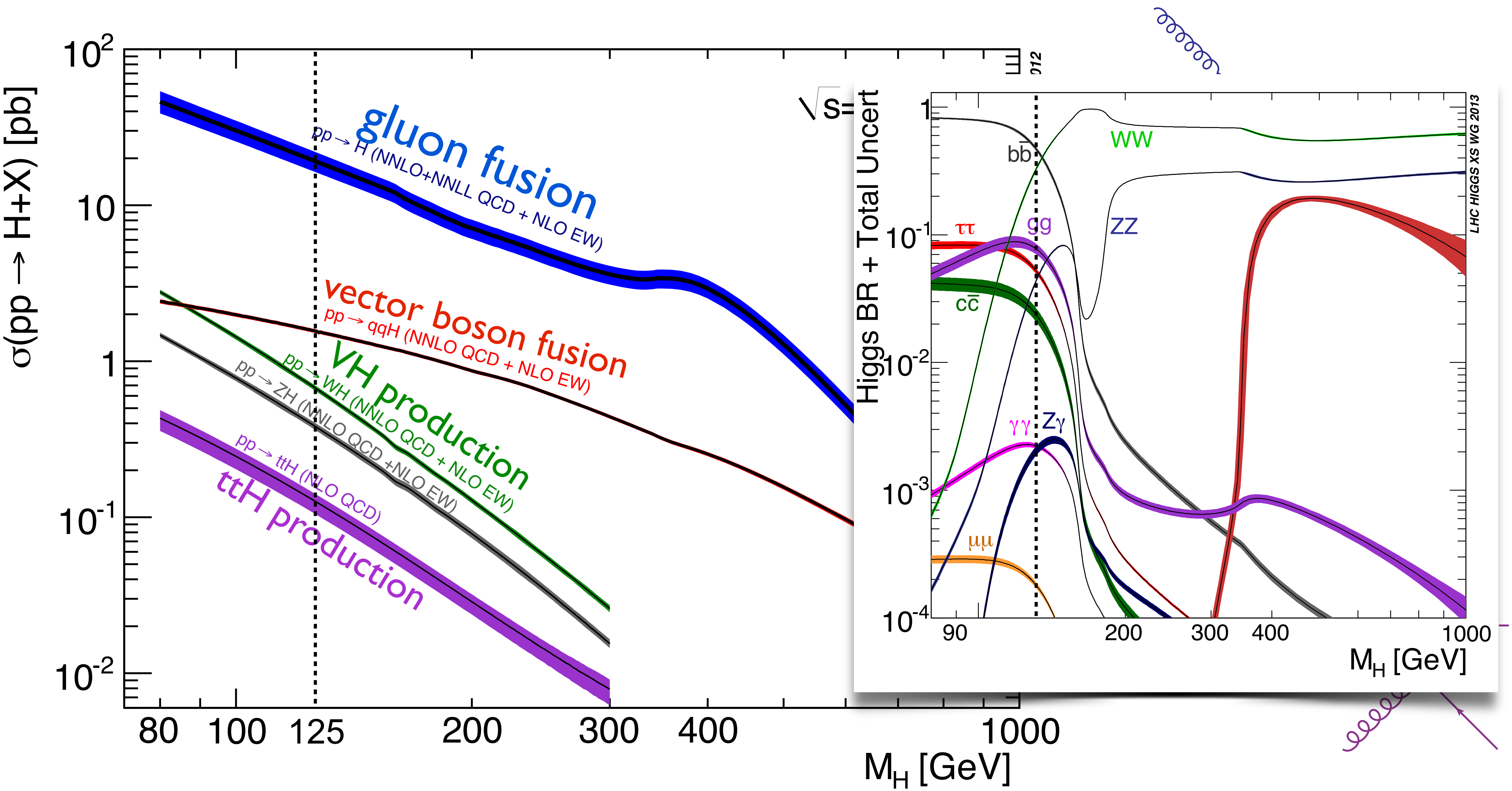
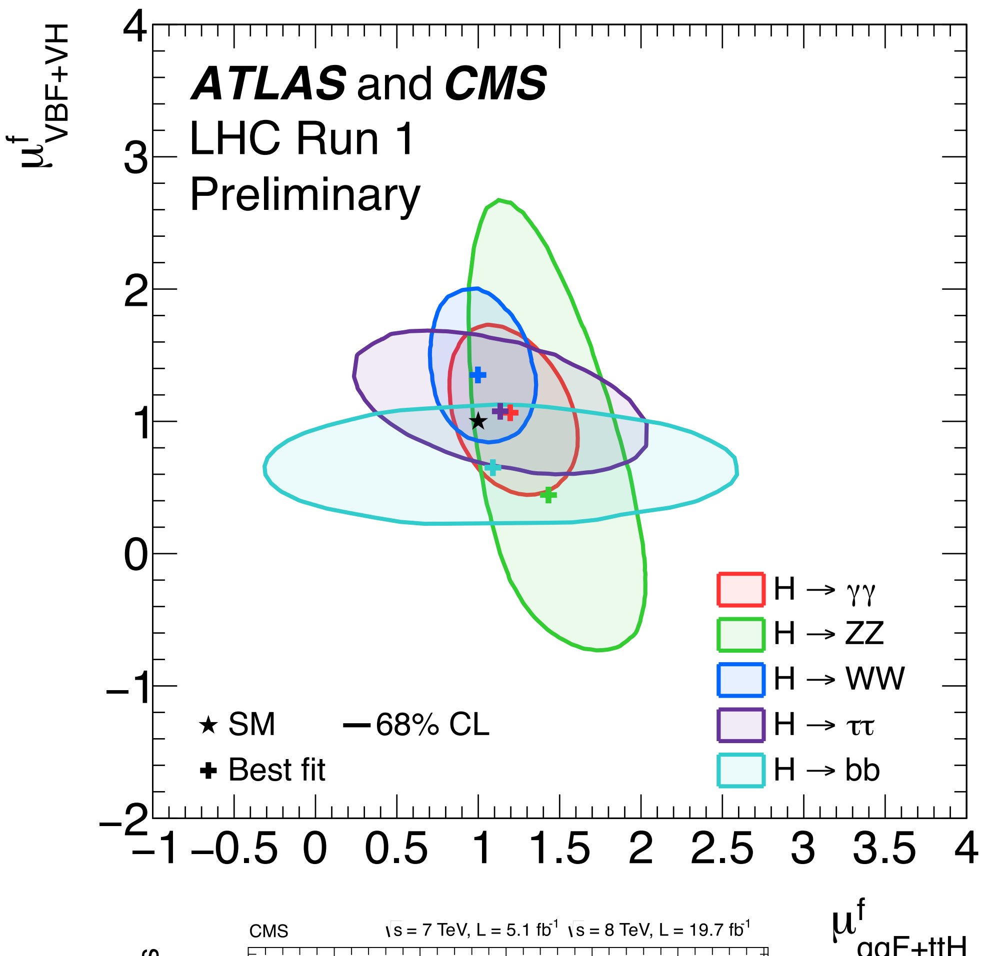
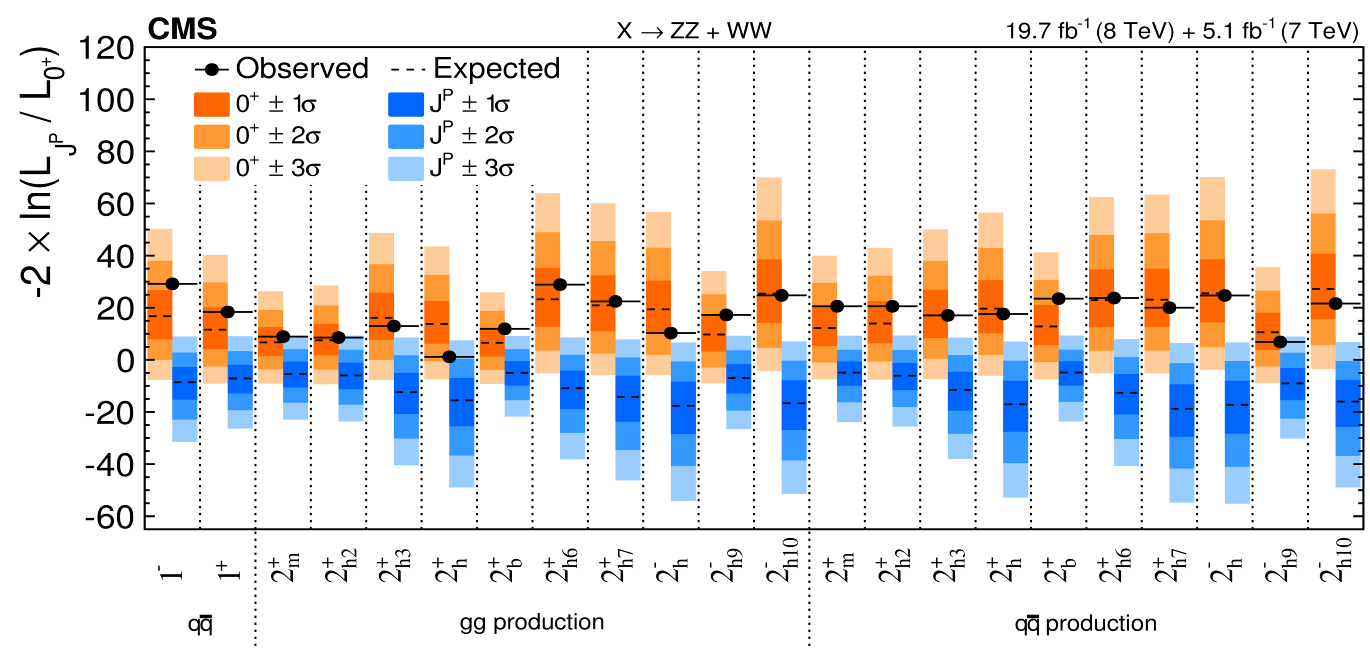
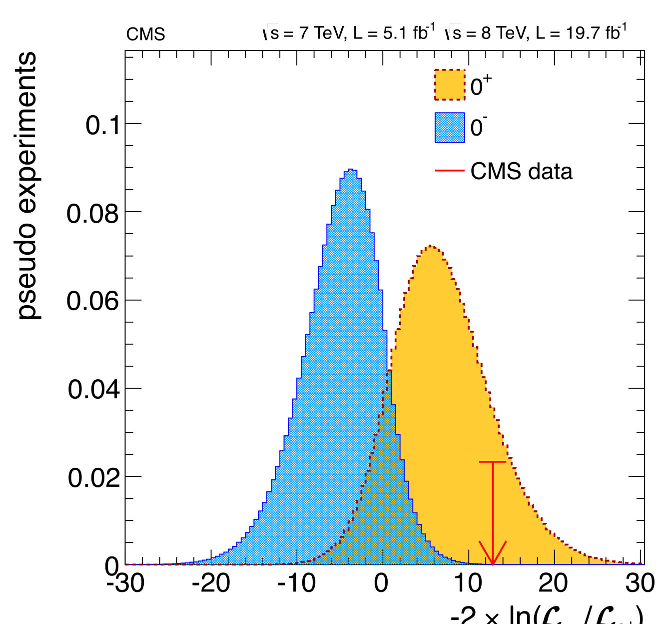
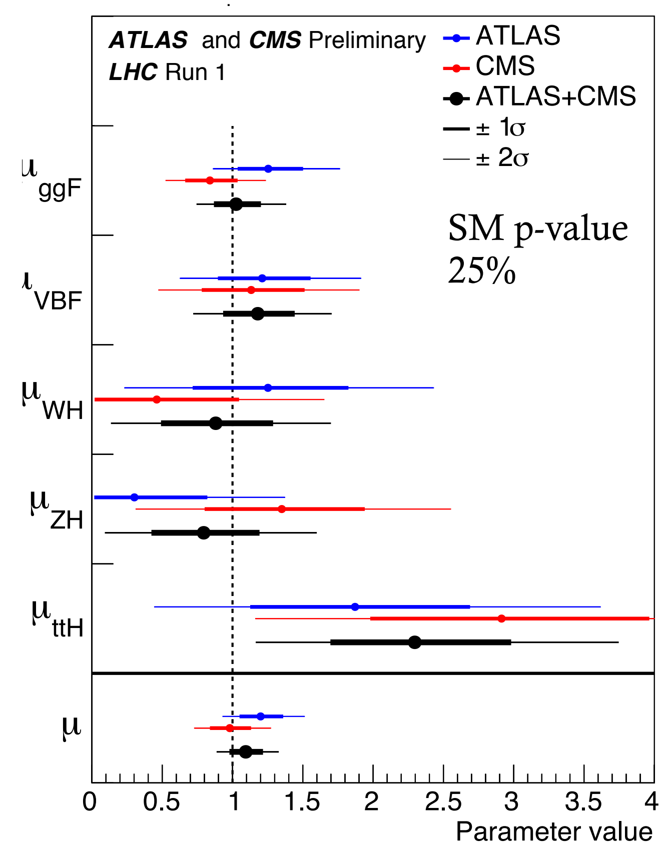


Is it the SM Higgs boson?







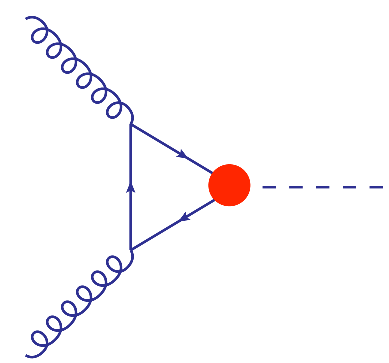


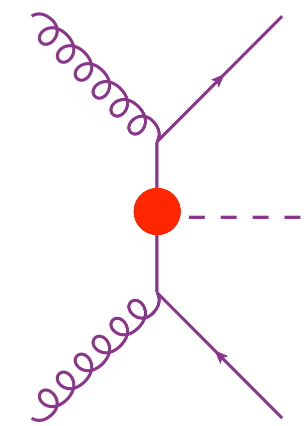
So far,
no big deviation…

…but lot of room for improvements

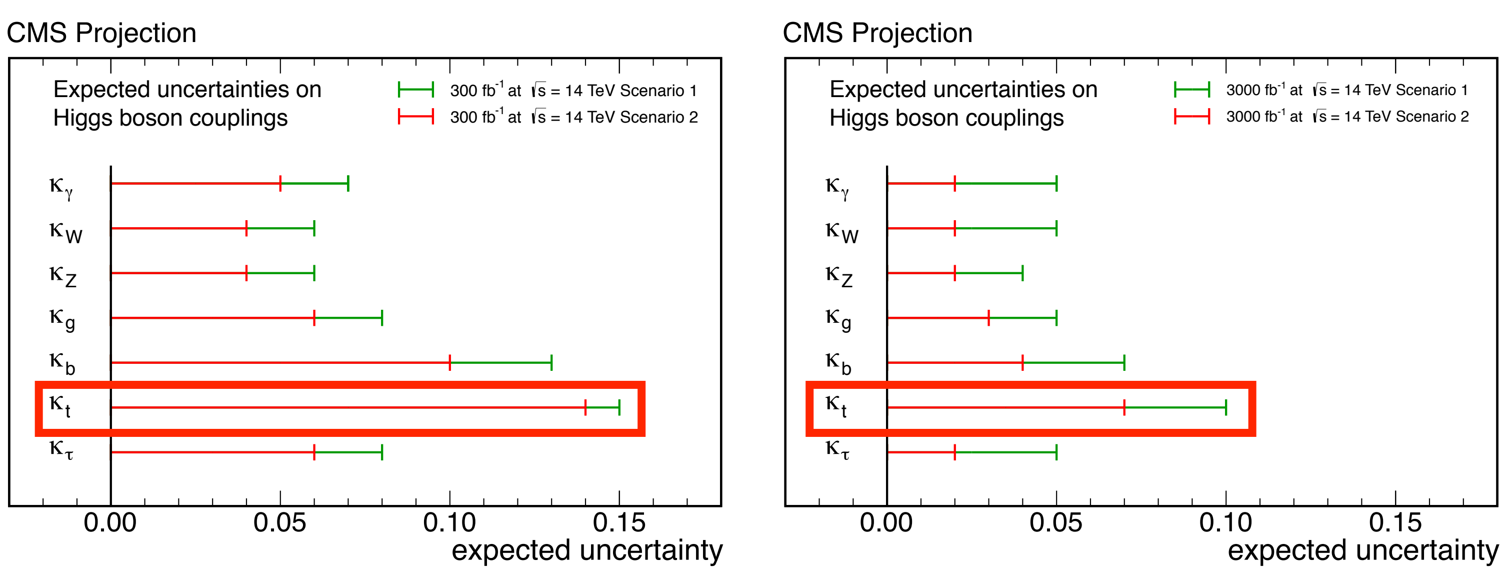
Why $t\bar{t}H$?

- 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 HL-LHC: 7-10%
- Same order as TH errors (NLO)
- Many background processes, with large rate



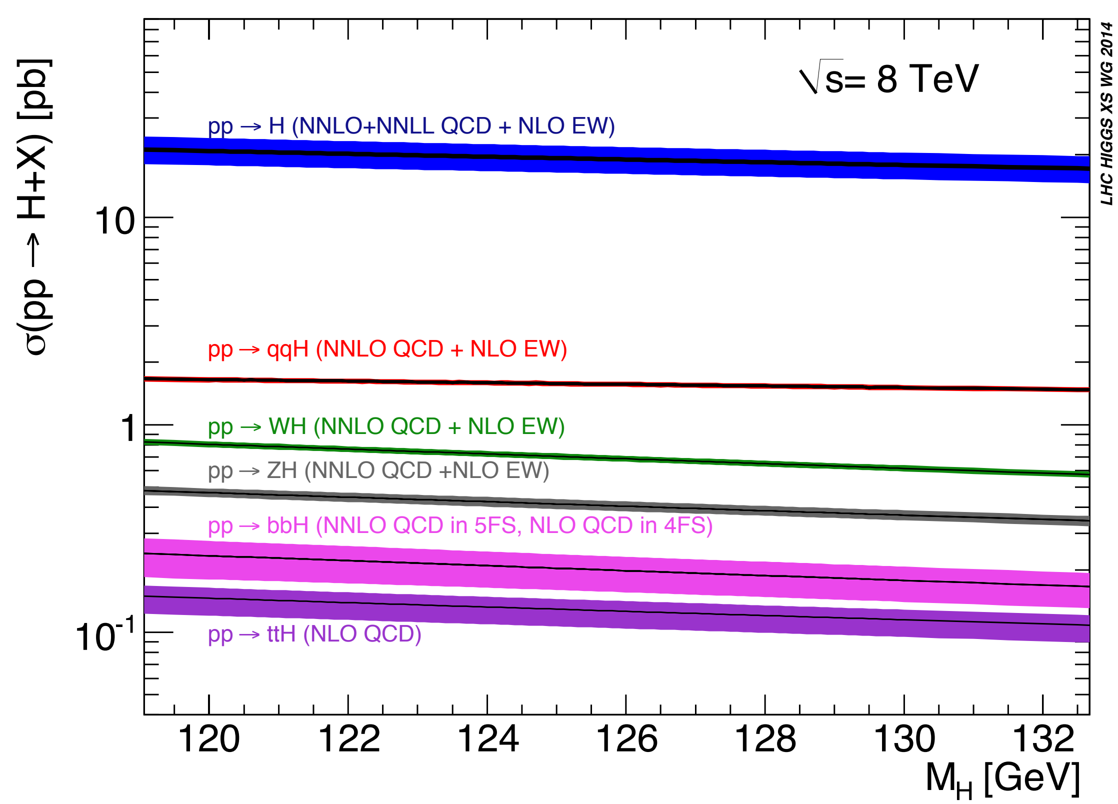


CMS-NOTE-3-002 arXiv:1307.7135



see also Peskin, arXiv:1312.4974, Moretti et al, arXiv:1510.08468

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG



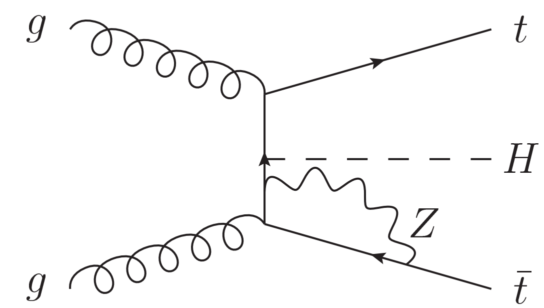
Higher order predictions for signal and backgrounds

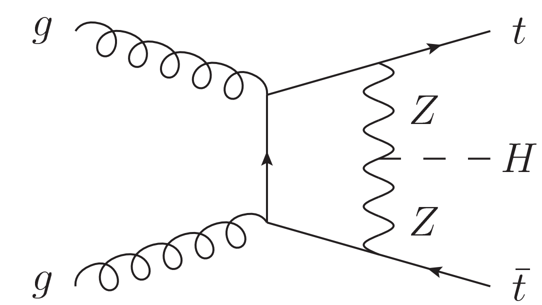
- $t\bar{t}H$
  - NLO QCD corrections (30% @ RunII)
    Beenakker et al. hep-ph/0107081 & hep-ph/0211352
    Dawson et al. hep-ph/0211438 & hep-ph/0305087
  - Matching to PS
    aMC@NLO: Frederix et al. arXiv:1104.5613
    Powhel: Garzelli et al. arXiv:1108.0387
    2015! Powheg Box: Hartanto et al. 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
    Broggio et al. arXiv:1510.01914
- 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
- $t\bar{t}b\bar{b}$
  - 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

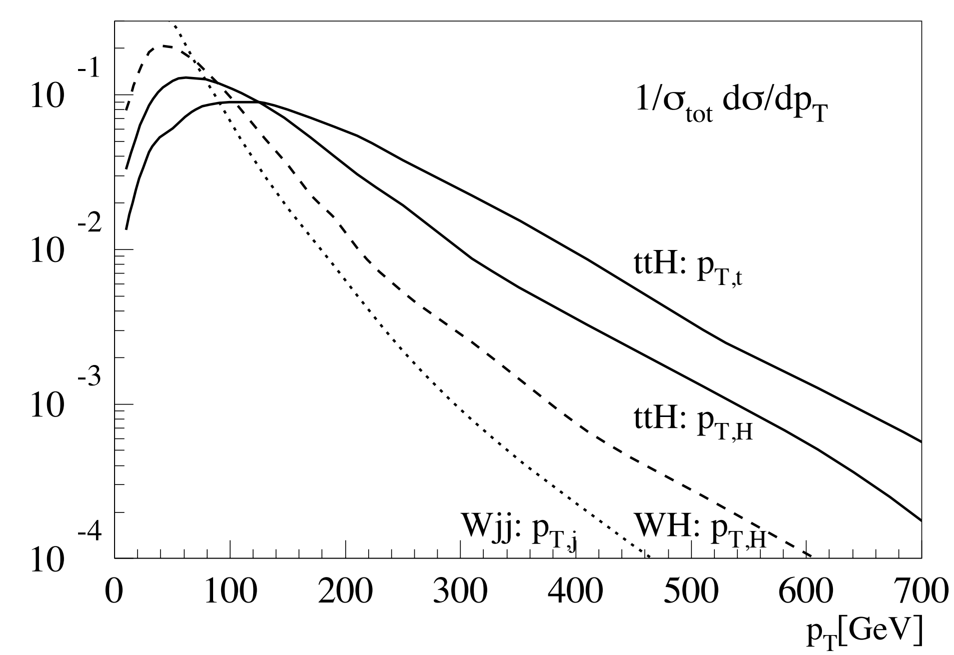
Electro-weak corrections to $t\bar{t}H$ motivation

- $t\bar{t}H$ 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



Accurate predictions: how to?

- Expand the cross-section as a series in the couplings

LO NLO NNLO — QCD

$$d\sigma = d\sigma_0 \left[1 + \frac{\alpha_s}{2\pi}\Delta_1 + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta_2 + \dots \right.$$

$$\left. + \frac{\alpha}{2\pi}\Delta_1' + \left(\frac{\alpha}{2\pi}\right)^2 \Delta_2' + \dots \right]$$

EW

- Strong coupling dominates, but non-QCD effects must be accounted to achieve precision
- Roughly speaking: NLO EW ~ NNLO QCD

EW corrections in a nutshell

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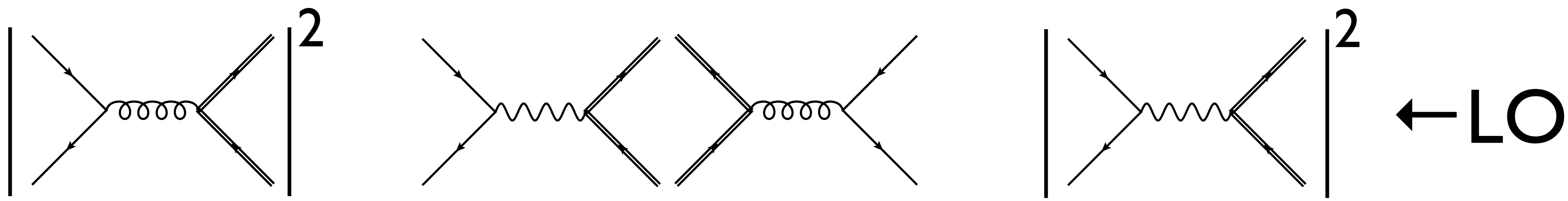
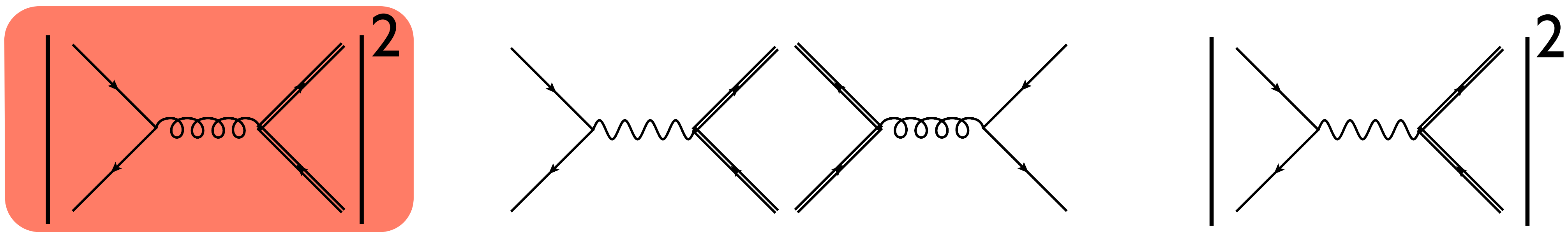


- In the general case, several coupling combinations contribute to a given process at LO

EW corrections in a nutshell



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- Typically the 'LO' is identified with the contribution with the largest power of α_s

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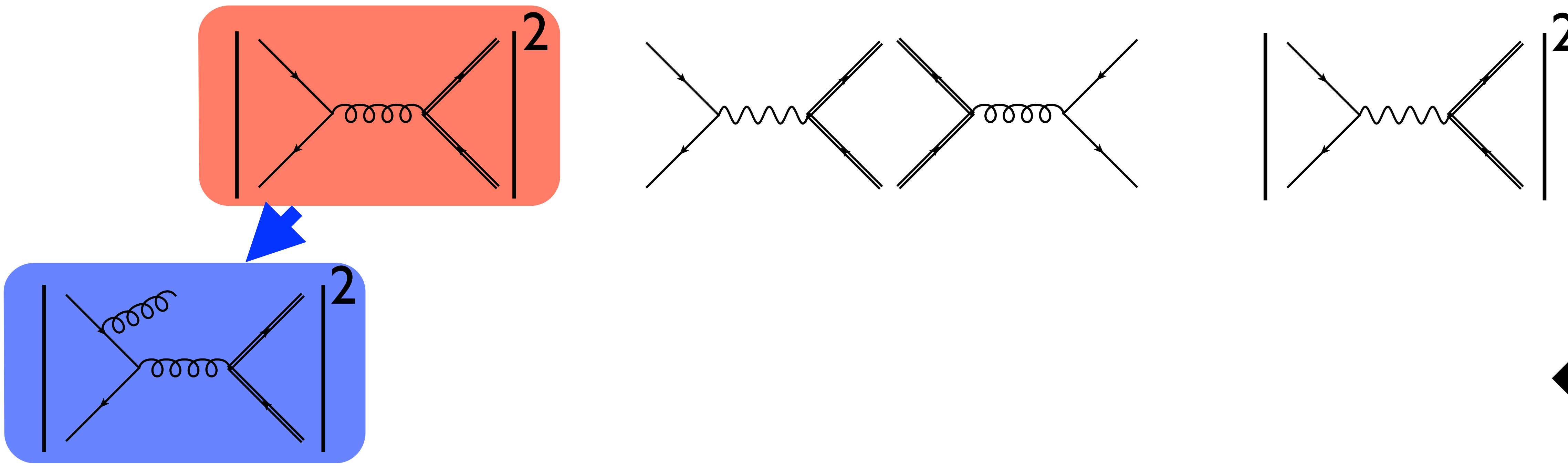

←LO

←NLO

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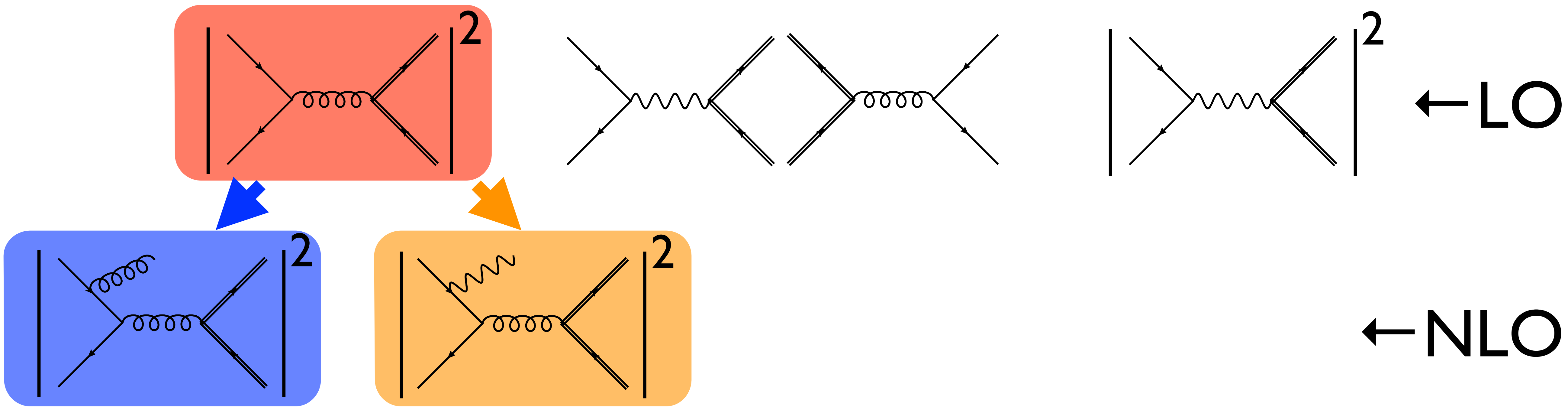
- NLO QCD corrections can be computed by attaching QCD particles to the LO

EW corrections in a nutshell



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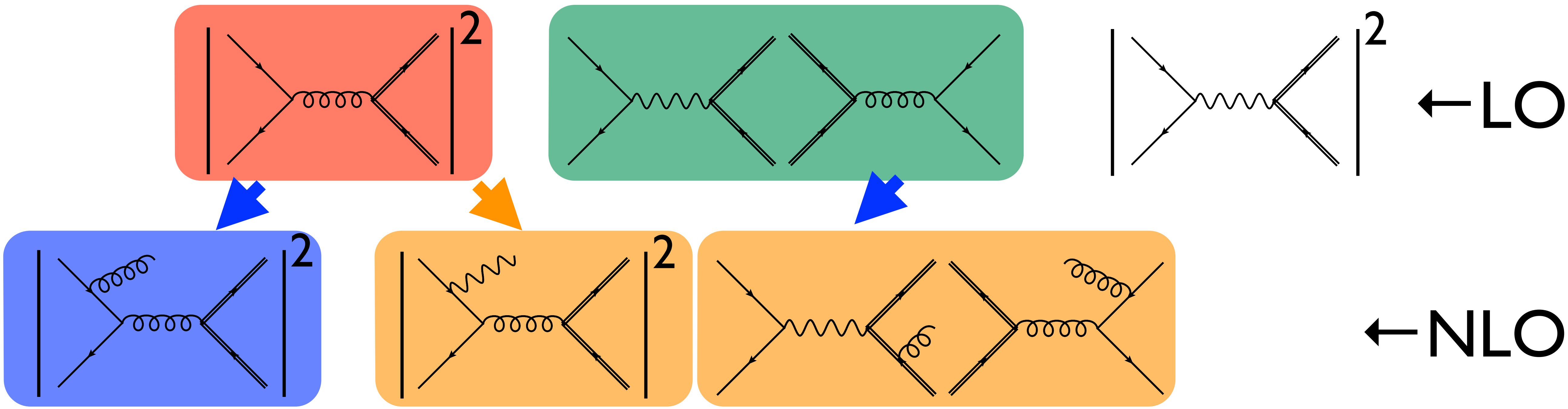
- Typically the 'LO' is identified with the contribution with the largest power of α_s
- NLO QCD corrections can be computed by attaching QCD particles to the LO
- NLO EW corrections can be computed by attaching EW particles to the LO…

EW corrections in a nutshell



- In the general case, several coupling combinations contribute to a given process at LO
- Typically the 'LO' is identified with the contribution with the largest power of α_s
- NLO QCD corrections can be computed by attaching QCD particles to the LO
- NLO EW corrections can be computed by attaching EW particles to the LO…
- … and attaching QCD particles to the LO with one less power of α_s

A bit more on Sudakov logs…

- EW corrections feature loops with heavy bosons (W/Z/H)
- These loops are finite, no need to include the corresponding real-emission
- However, when large scales are probed, they can feature large logs: $\log(M/p_T)$
- In these regimes, EW corrections are large and negative
- Question: are these logs compensated when an extra heavy boson radiation (HBR) is included?
- Some studies exist, but the answer is very process dependent
  Manohar et al, arXiv:1409.1918

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

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

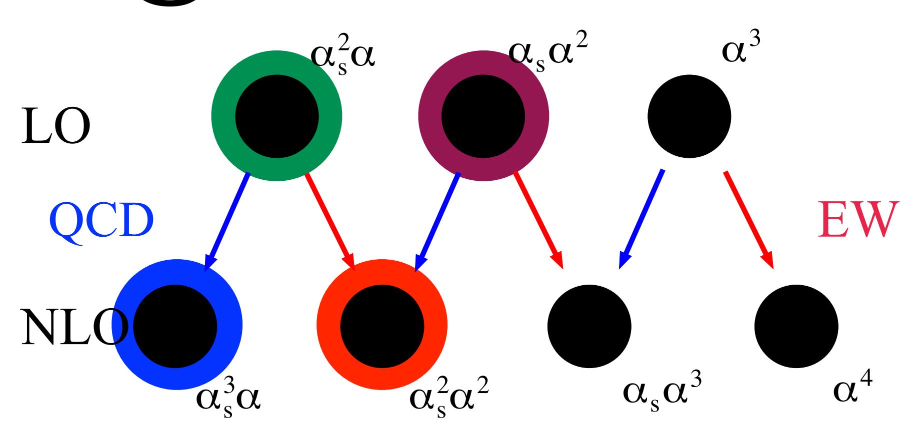
- QCD scale variations computed with

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

- 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 $b\bar{b}$)

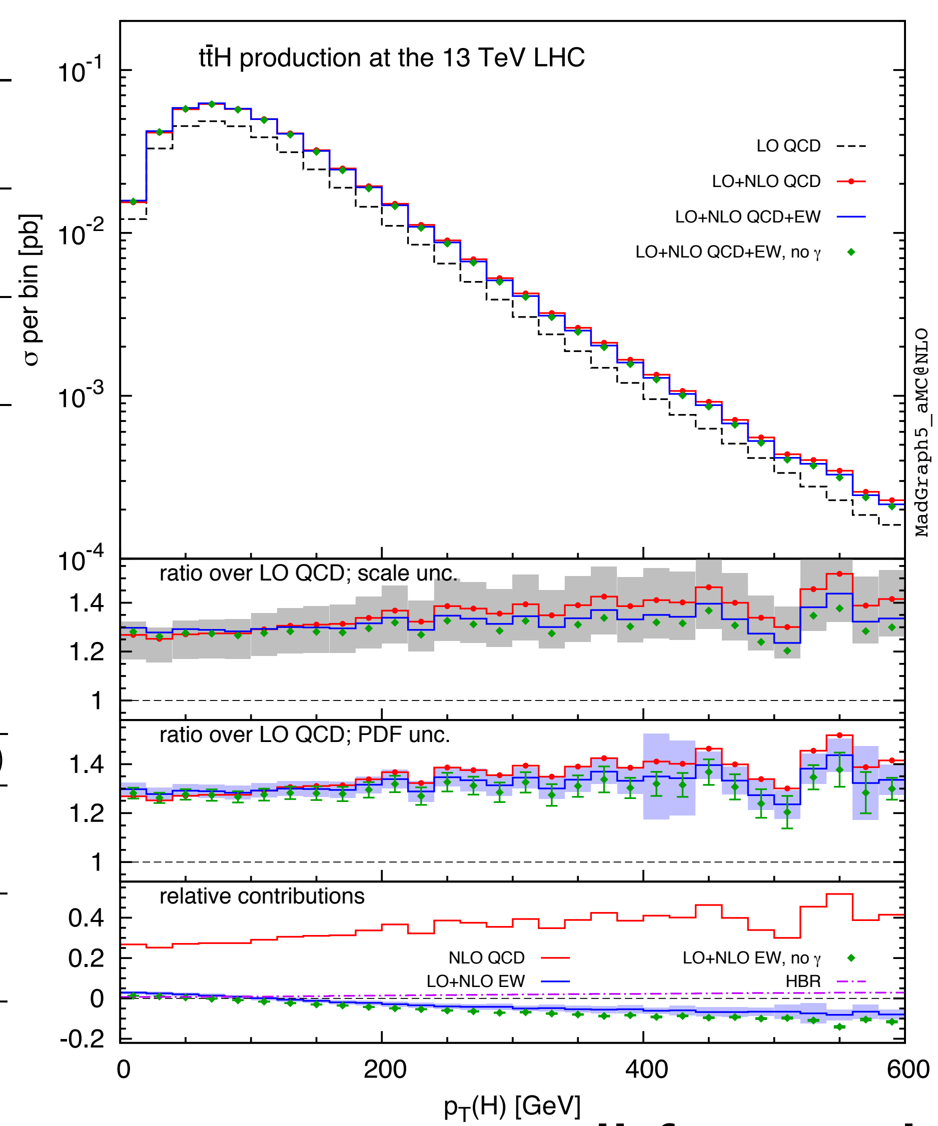
  NLO QCD, NLO EW+HBR ($t\bar{t}HV$)

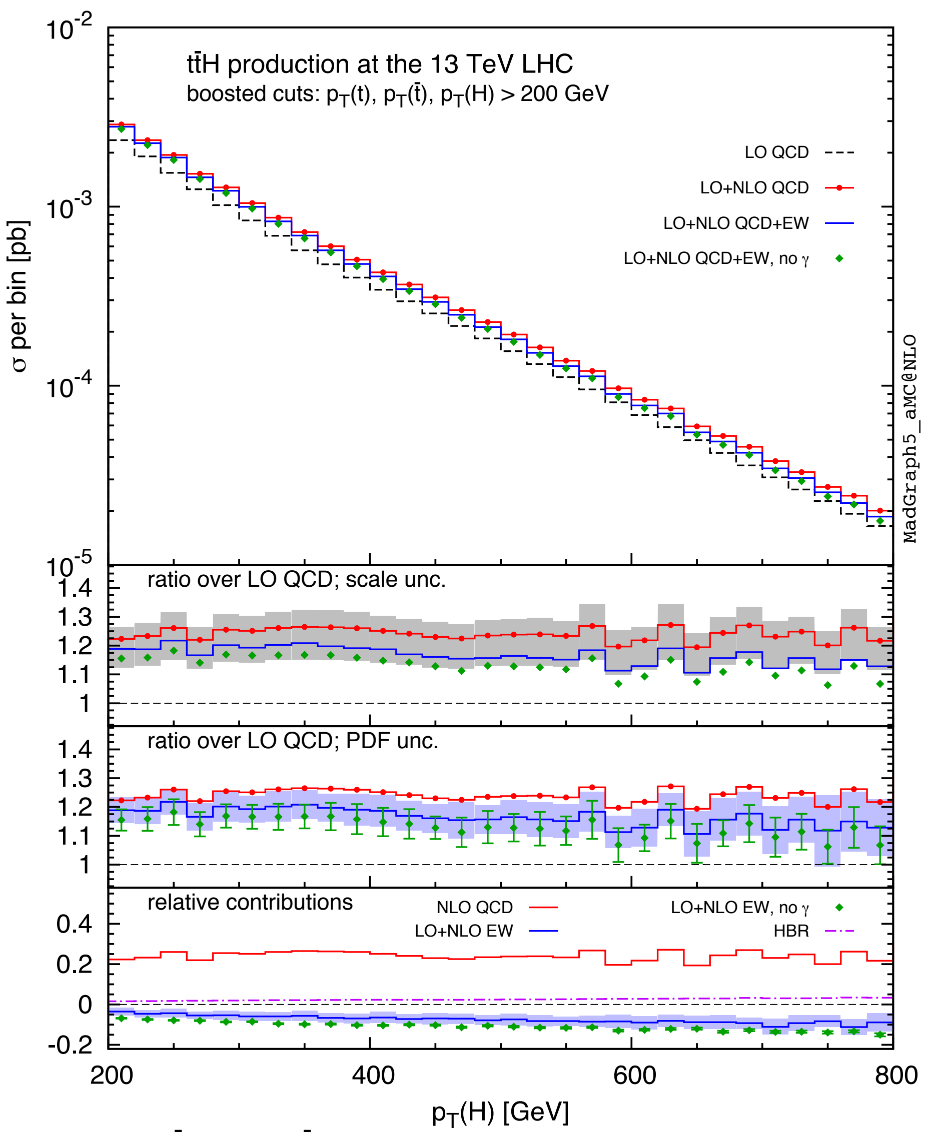


Electro-weak corrections to $t\bar{t}H$: results at 13 TeV

$t\bar{t}H$: 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

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

$t\bar{t}Z$: 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	$9.677 \cdot 10^{-3}$ $(5.743 \cdot 10^{-4})$

$t\bar{t}W^-$: σ(pb)	13 TeV
LO QCD	$1.265 \cdot 10^{-1}$ $(3.186 \cdot 10^{-3})$
NLO QCD	$6.515 \cdot 10^{-2}$ $(2.111 \cdot 10^{-3})$
LO EW	0
LO EW no γ	0
NLO EW	$-8.502 \cdot 10^{-3}$ $(-5.838 \cdot 10^{-4})$
NLO EW no γ	$-8.912 \cdot 10^{-3}$ $(-6.094 \cdot 10^{-4})$
HBR	$8.219 \cdot 10^{-3}$ $(4.781 \cdot 10^{-4})$

$t\bar{t}Z$: $\delta(\%)$	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)

$t\bar{t}W^+$: $\delta(\%)$	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)

$t\bar{t}W^-$: $\delta(\%)$	13 TeV
NLO QCD	$51.5^{+14.8}_{-13.8} \pm 2.8$ $(66.3^{+21.7}_{-19.6} \pm 3.9)$
LO EW	0
LO EW no γ	0
NLO EW	-6.7 ± 0.2 (-18.3 ± 0.8)
NLO EW no γ	-7.0 ± 0.2 (-19.1 ± 0.6)
HBR	6.50 (15.01)

- $t\bar{t}Z$ behaves similarly to $t\bar{t}H$
- $t\bar{t}W$ has much larger corrections, and larger rates for HBR However, this is mostly due to gg initiated processes

The importance of spin correlations

- Spin correlations are a quantum mechanical effect that stems from the fact that the top quark is an unstable particle, with spin≠0
- 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)

complexity of the simulation

generate $t\bar{t}H$
PS does the decay

anything
in between?

generate
$b\bar{b}e^+\mu^-\nu\nu H$

inclusion of spin correlations/off-shell effects/…

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Yes!

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

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

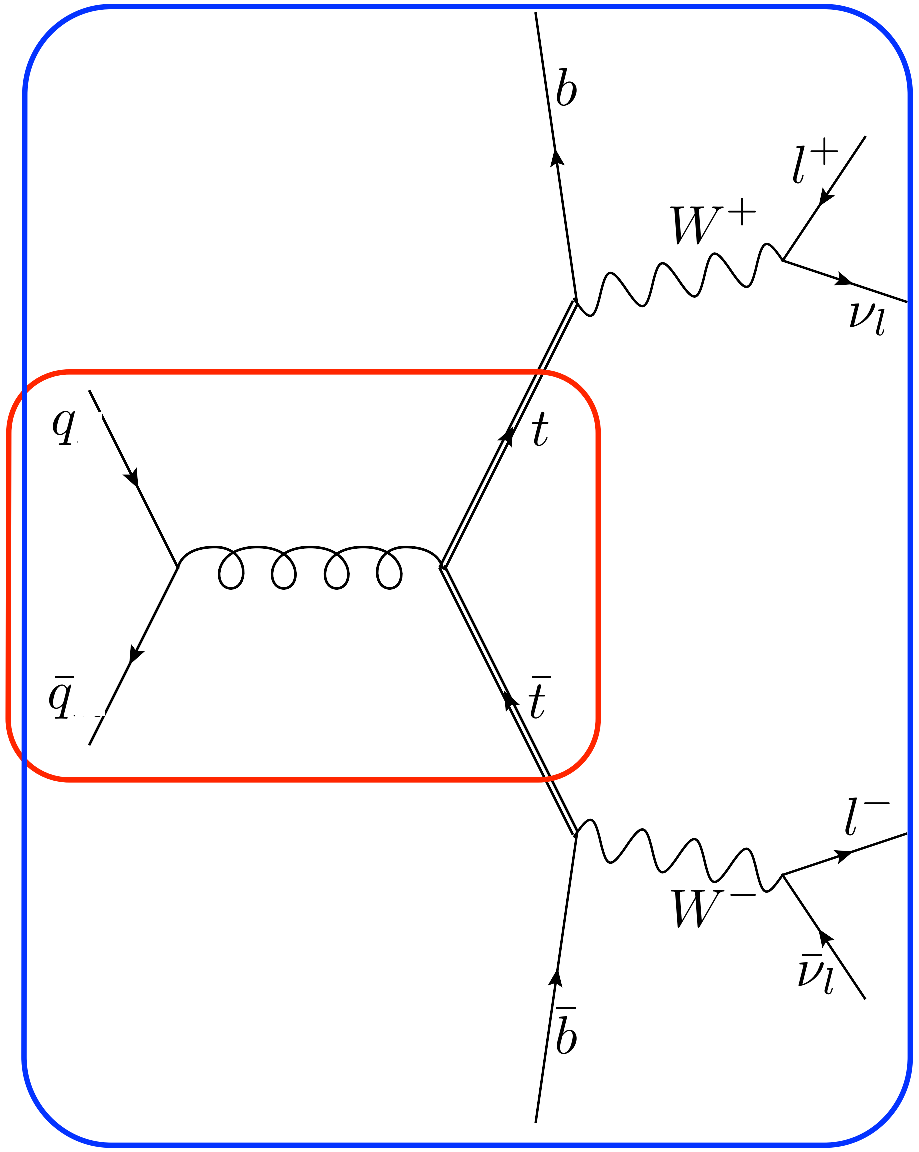
Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460
Garzelli, Kardos, Trocsanyi, arXiv:1405.5859

inclusion of spin correlations/off-shell effects/…

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 $|M_{P+D}|^2 / |M_P|^2 > \mathrm{Rand}()\ \max\left(|\mathrm{M}_{\mathrm{P+D}}|^2 / |\mathrm{M}_{\mathrm{P}}|^2\right)$
- 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



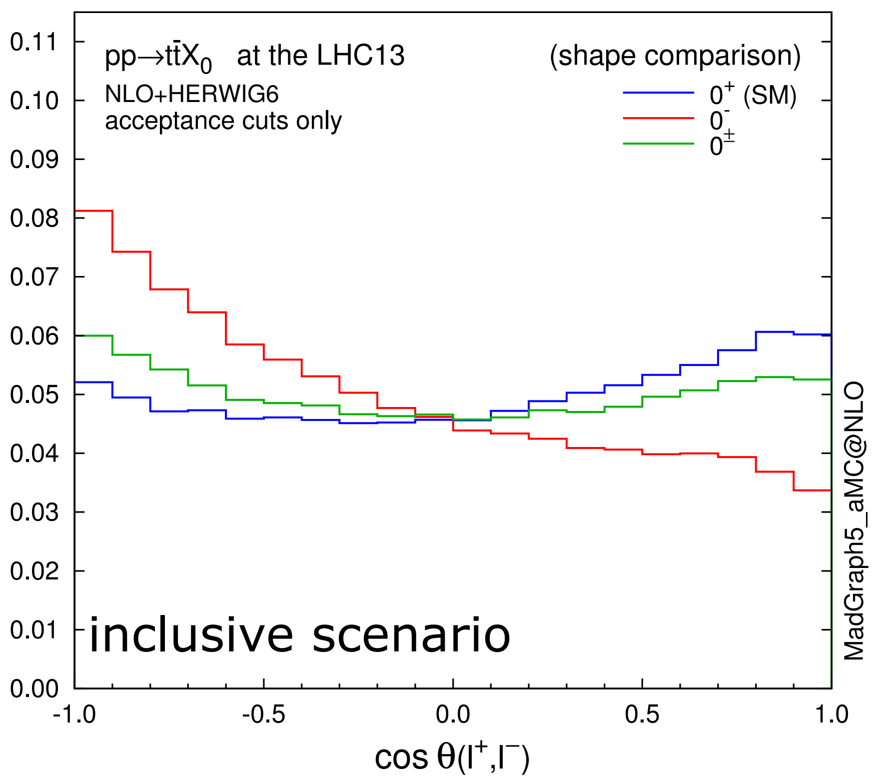
Spin correlation in $t\bar{t}H$: H CP determination

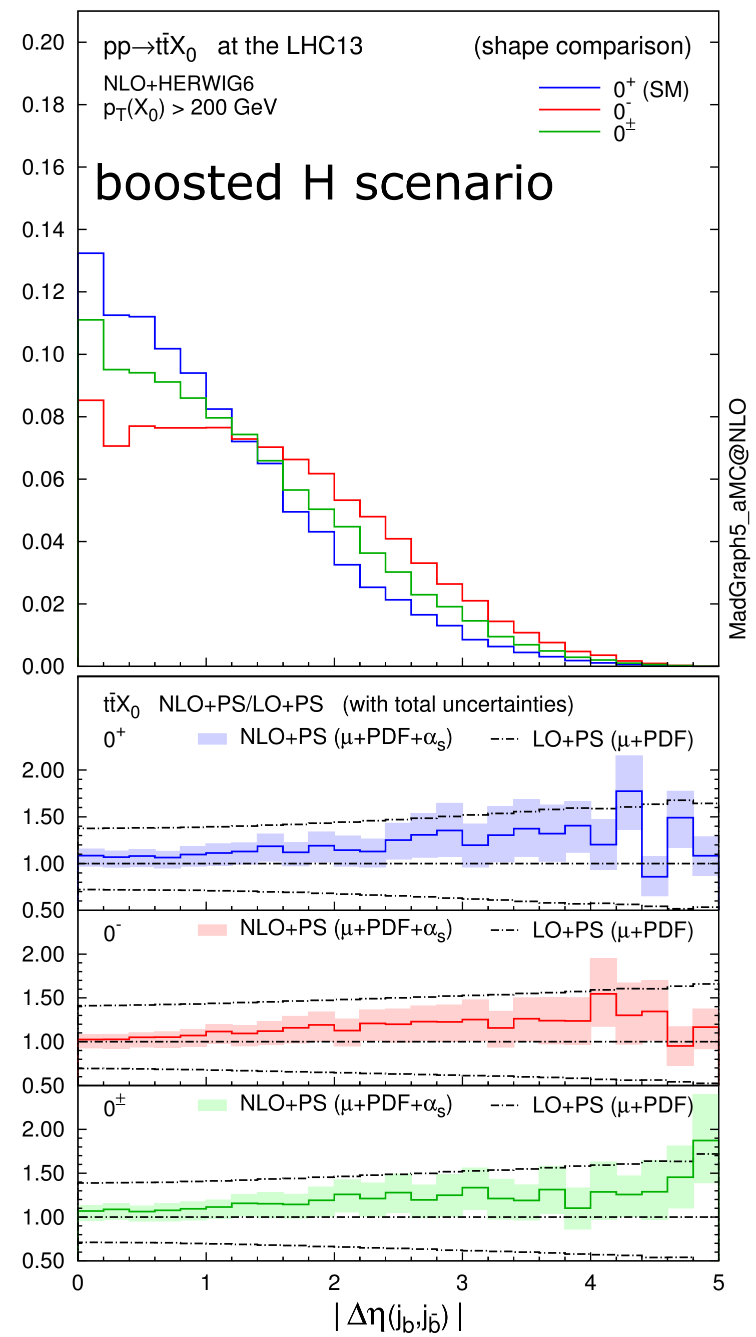
Demartin, Maltoni, Mawatari, Page, MZ, arXiv:1407.5089

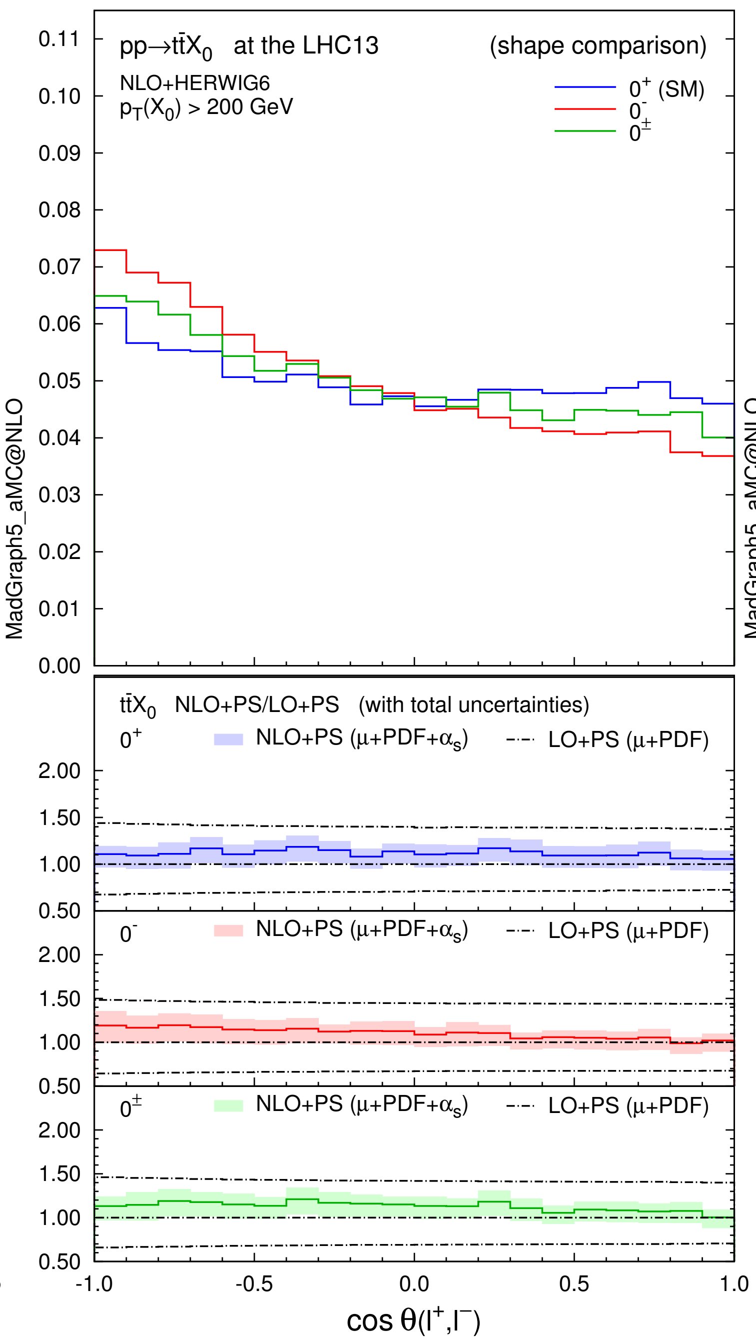
- Include CP violating $t\bar{t}H$ interaction in an effective theory approach, at NLO+PS

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

- Study dileptonic top decay



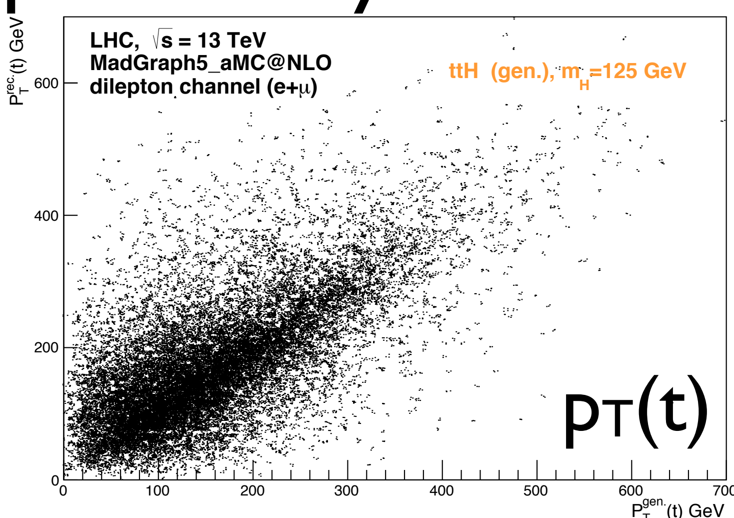


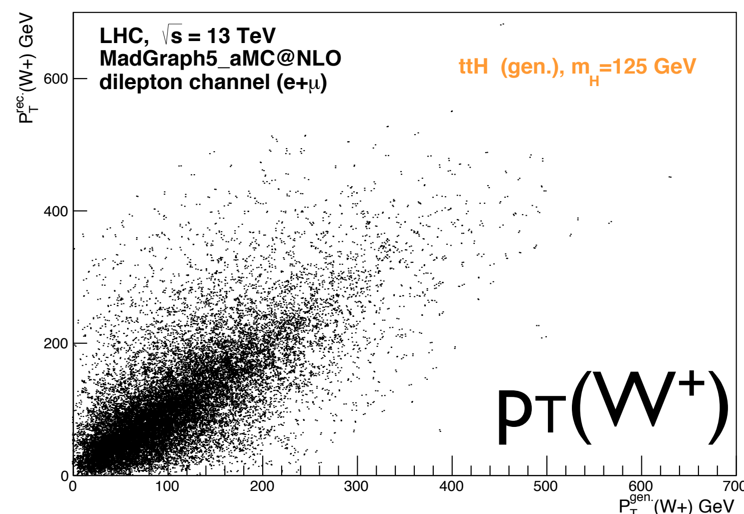


Spin correlation in $t\bar{t}H$: Improve S/B discrimination

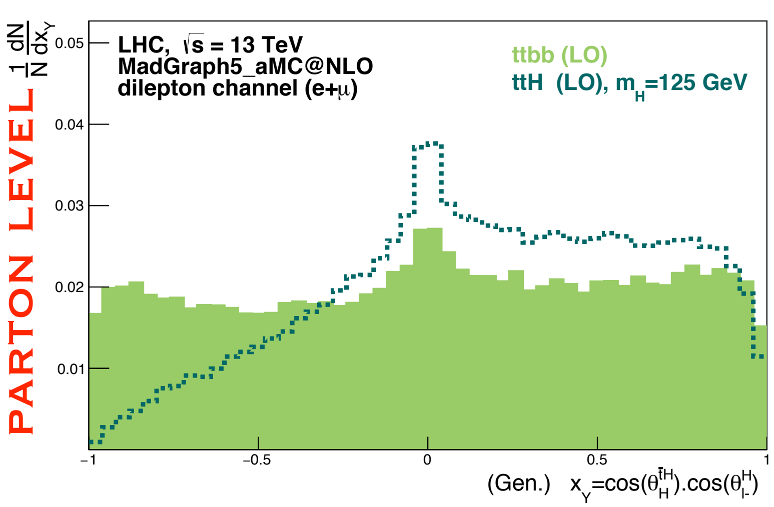
Amor dos Santos et al. arXiv:1503.07787

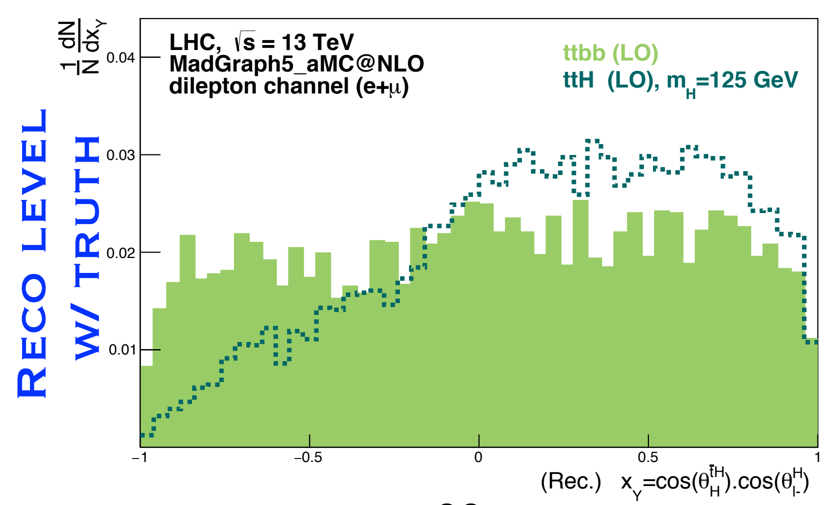
- Use information from spin correlations to separate S and B ($t\bar{t}b\bar{b}$)
- Check robustness of variables against PS / detector simulation
- Dilepton decays allow for good reconstruction of top/W

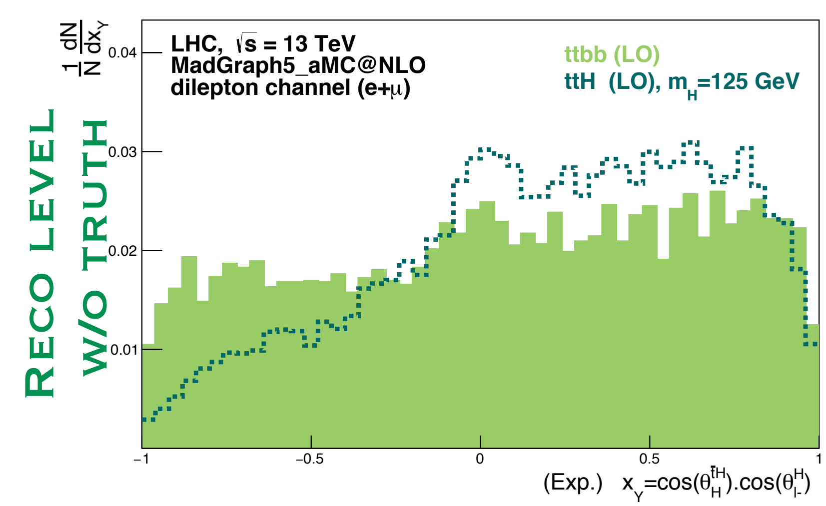




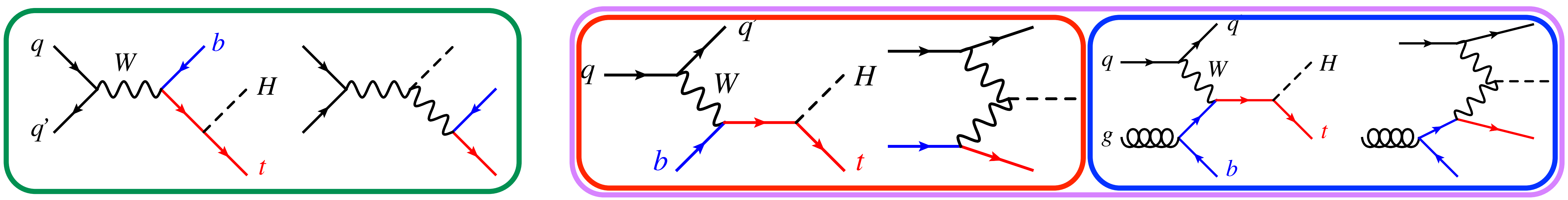
- Product of cosines can be used for S/B discrimination







What can be learnt from tH?



- tH: rather rare process (σ_{NLO}<100 fb at RunII)
- t-channel dominant production mode, s-channel much suppressed (σ_{NLO}<3fb)
- Can be described either in the 4FS (m_b>0) or in the 5FS (m_b=0)
- Two schemes are equivalent if all order were known. However, at a given order, each one has advantages and drawbacks

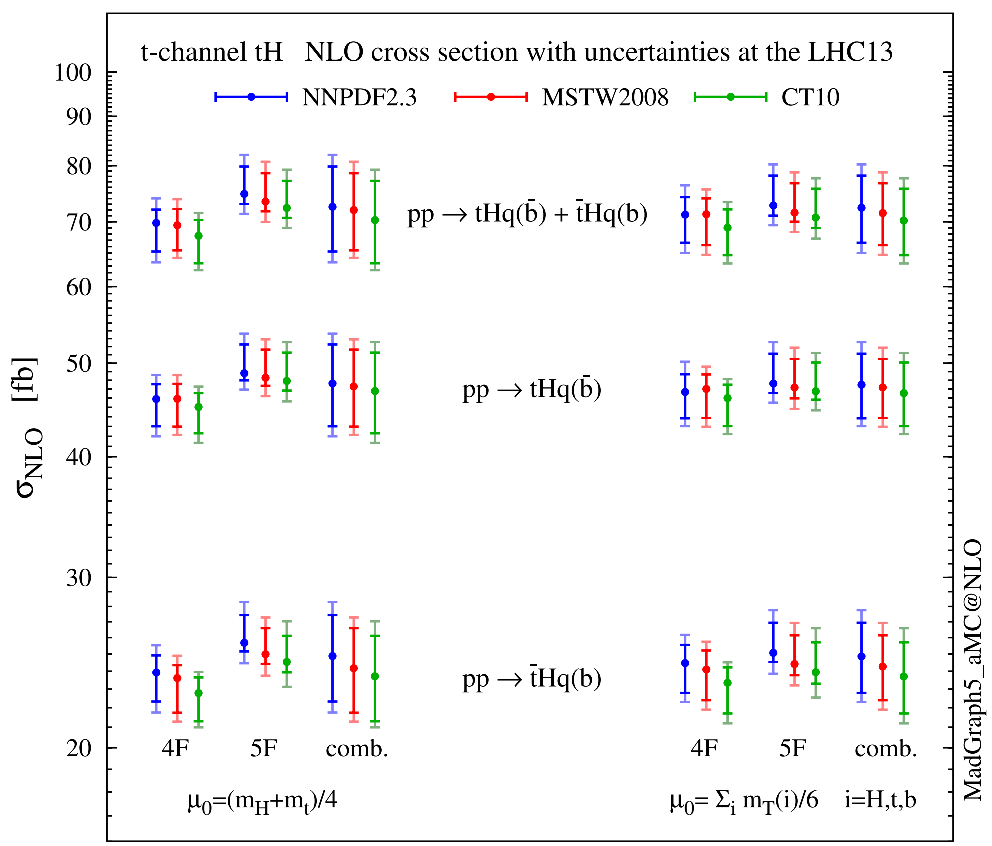
✔Simpler process; computing HO is easier ✔b-PDF resums log(m_b/Q) at all orders ✘b-quark observables enter at higher orders ✘Matching to PS requires some care (gluon splitting, momentum reshuffling, …)	✘Higher multiplicity process; computing HO more involved ✘Cross section can be affected by large log(m_b/Q) ✔Accounts for b-mass effects ✔Straightforward to match to PS

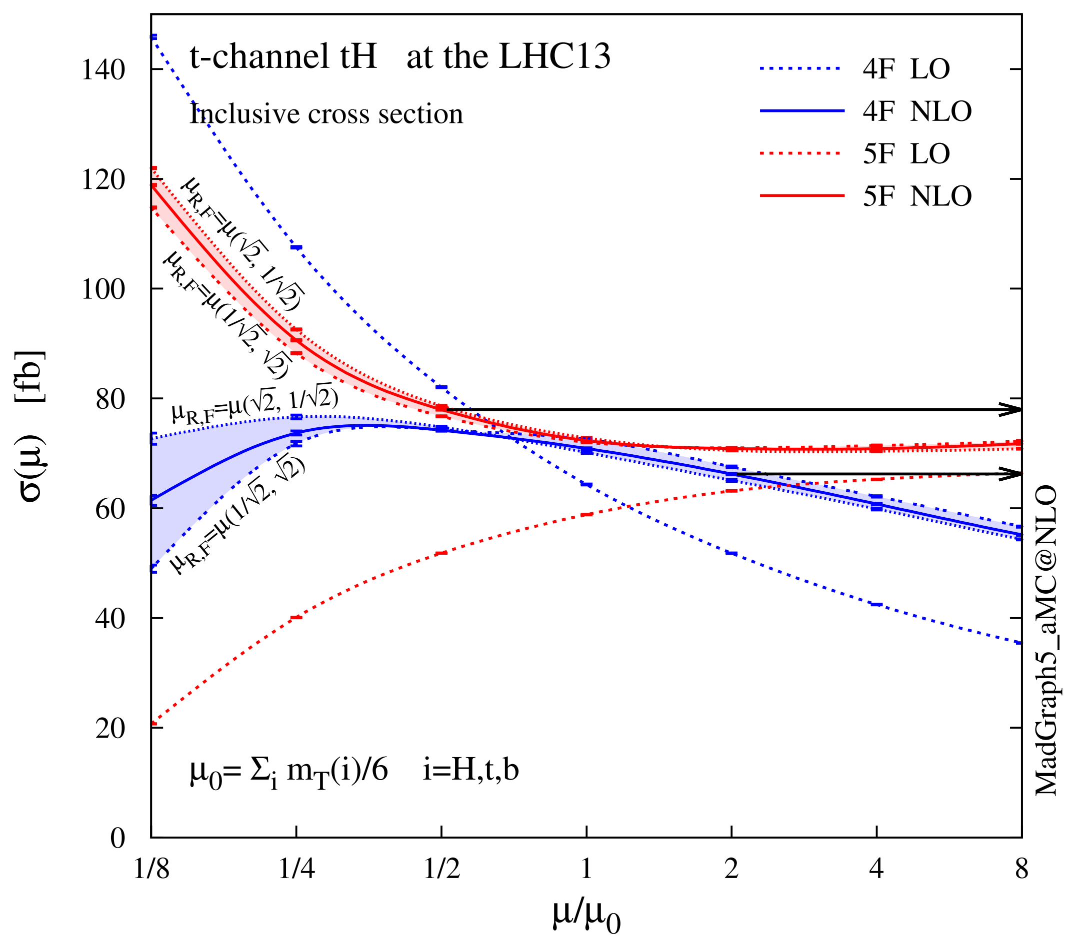
- NLO corrections (and wise scale choice) improve agreement between two schemes

Accurate predictions for tH

Demartin, Maltoni, Mawatari, MZ, arXiv:1504.00611

- NLO corrections, scale choice (processes with b quarks prefer low scales) and accounting for all sources of uncertainties bring close the two predictions for the total cross section…



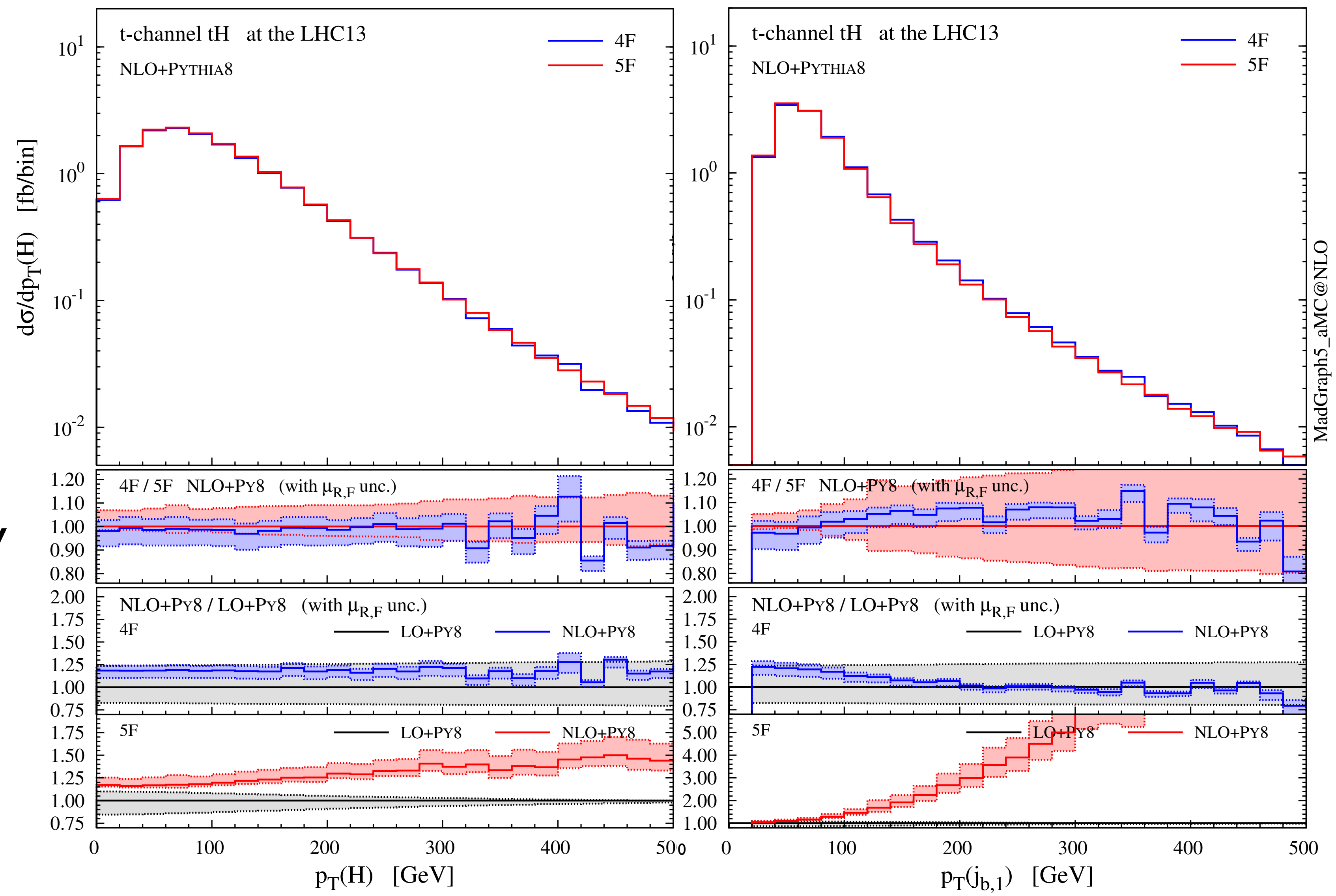


Accurate predictions for tH

Demartin, Maltoni, Mawatari, MZ, arXiv:1504.00611

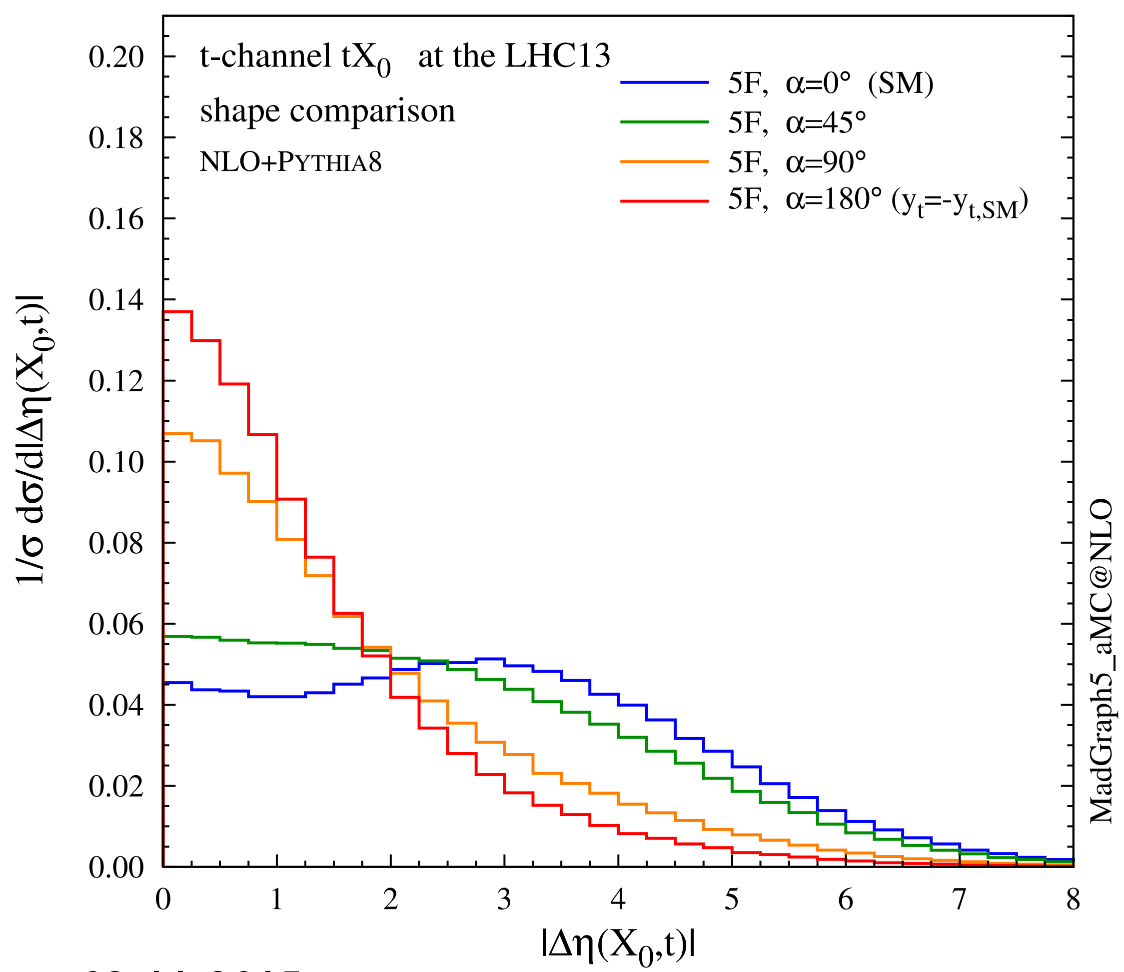
- … and for differential distribution as well

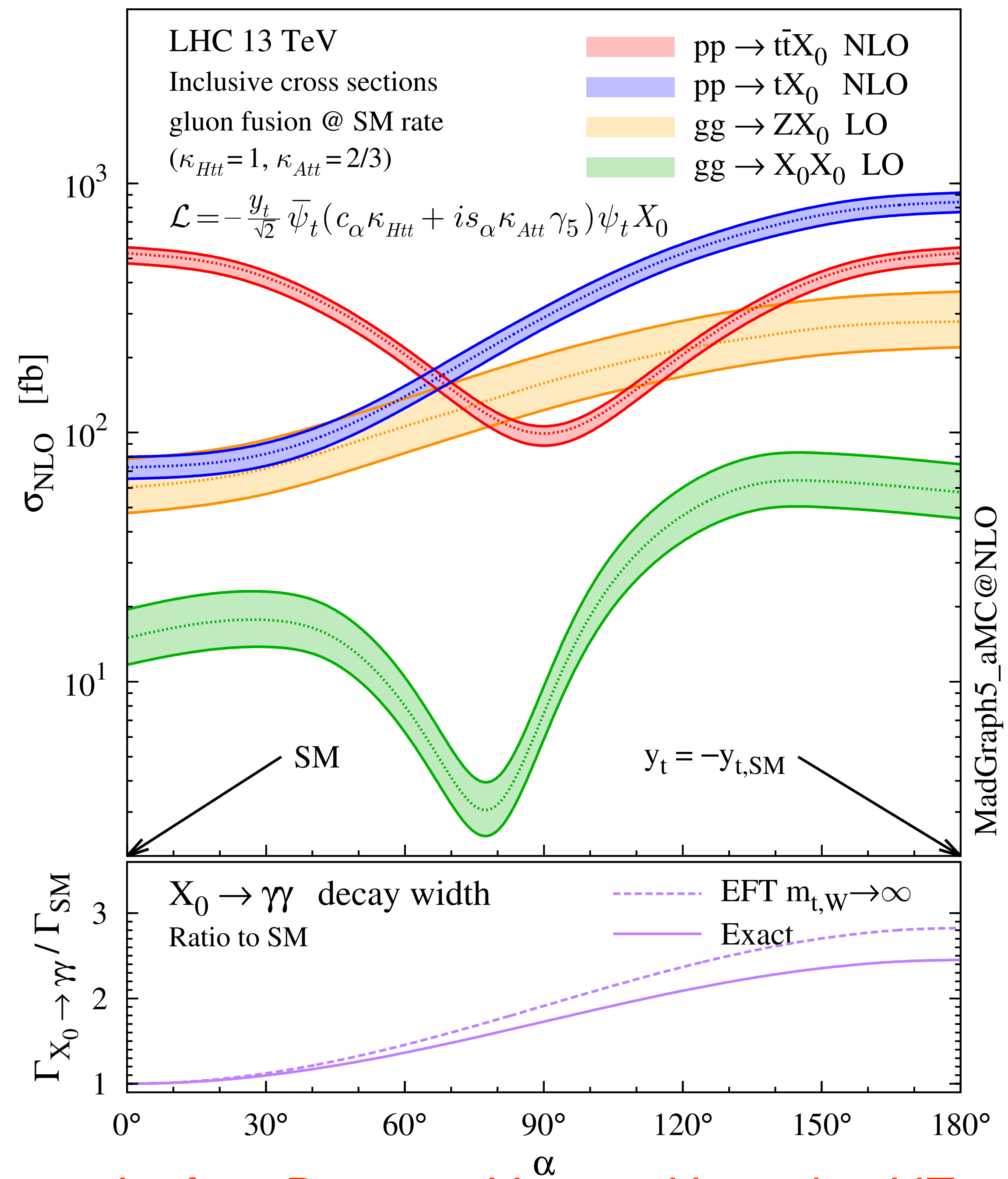
- NLO predictions in the two schemes agree remarkably well even for observables which are sensitive to the b-quark kinematics, e.g. $p_T(j_b^1)$
- Note that the K-factors for the tow scheme can be very different
- 4FS to be preferred for fully differential studies



What can be learnt from tH?

- It is not just a QCD exercise…
- In the SM, diagrams where the Higgs couple with the W and with the top interfere destructively
- tH is one of the few processes (with H→γγ gg→HZ and gg→$t\bar{t}$) sensitive to the sign of y_t
- A flipped sign gives a factor ~10 enhancement



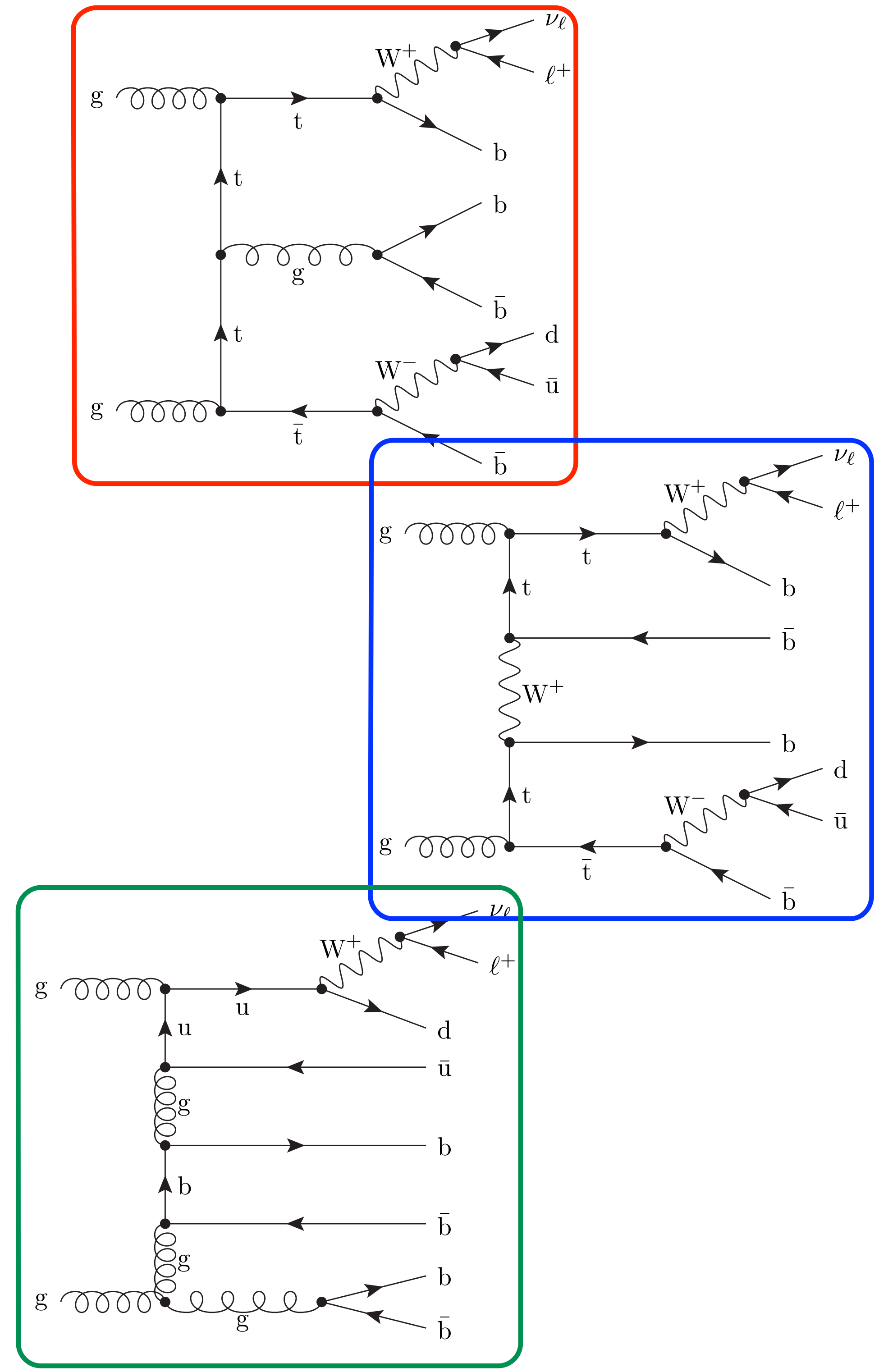


plot from Demartin, Mawatari, Vryonidou, MZ, arXiv:1505.07081

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

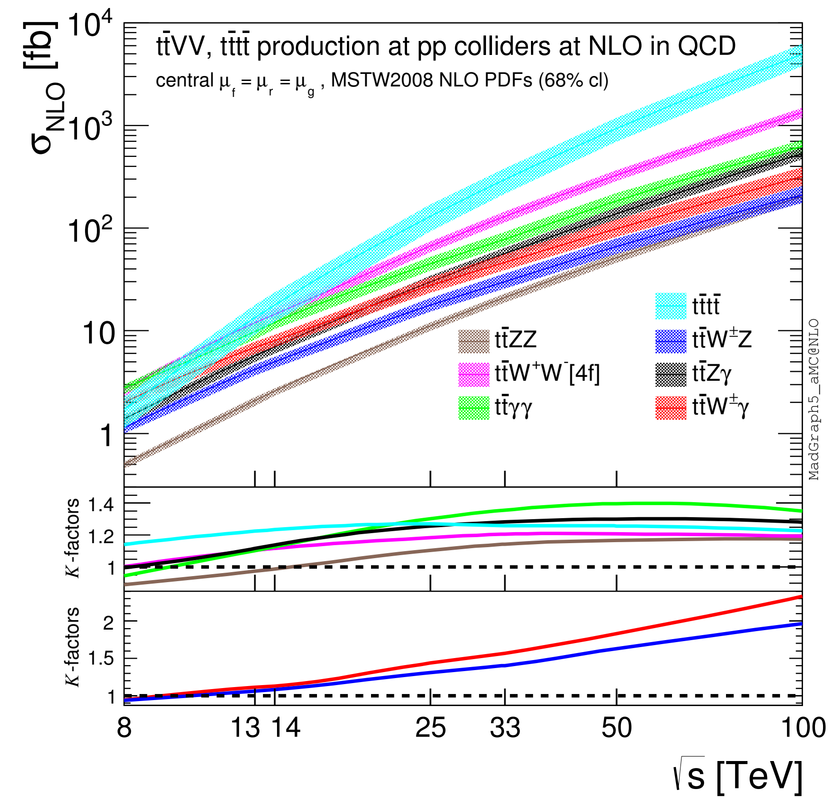
(how large are they in the $t\bar{t}H$ signal region?)

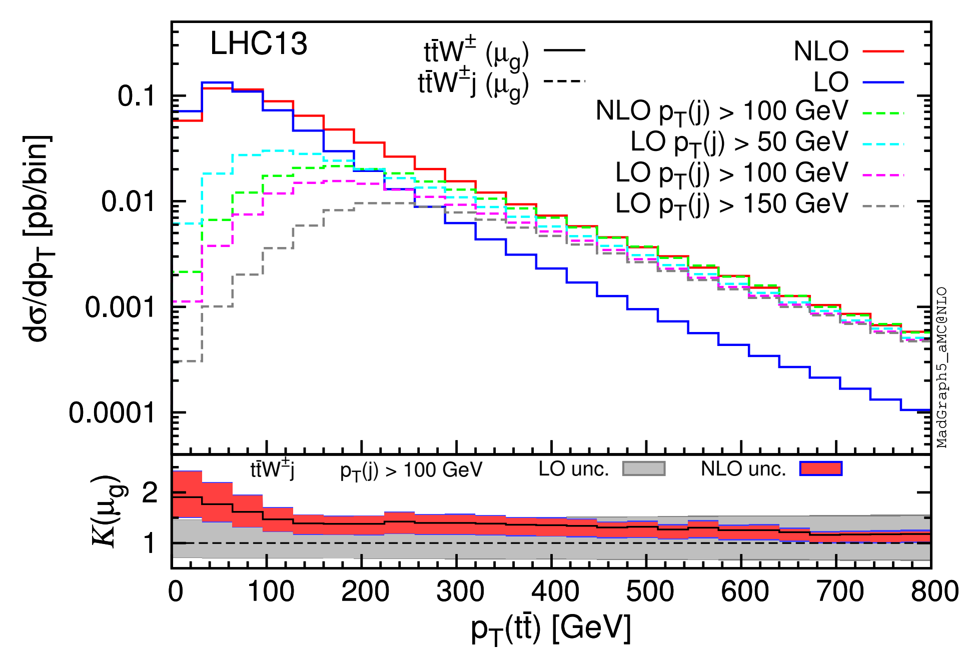
$t\bar{t}b\bar{b}$ provides a reasonable approximation to the full process

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

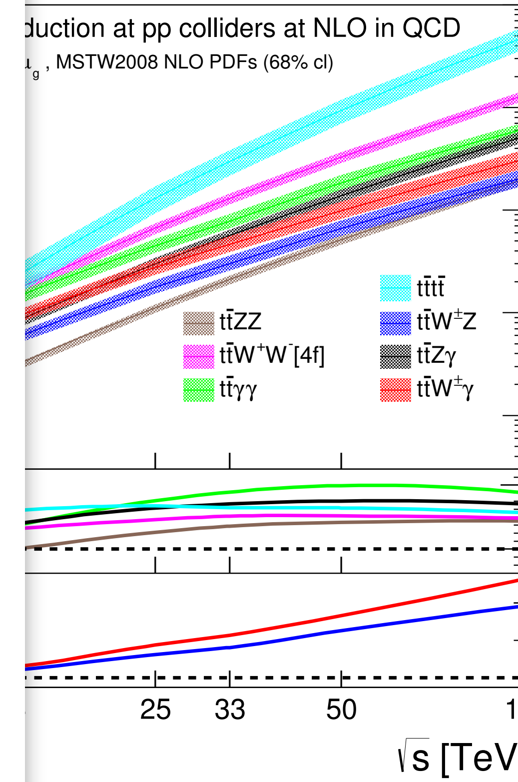


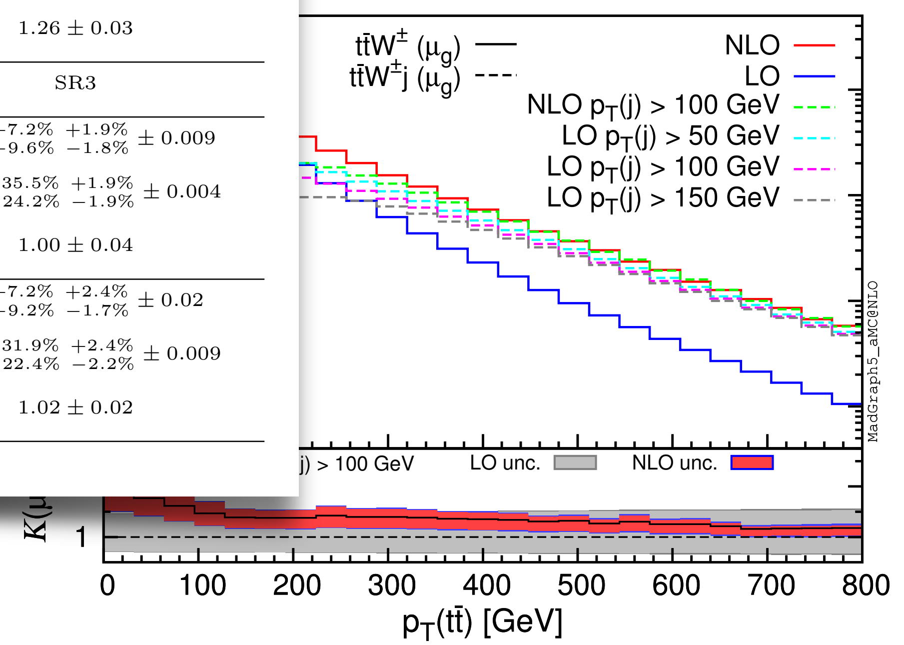


Recent results

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

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





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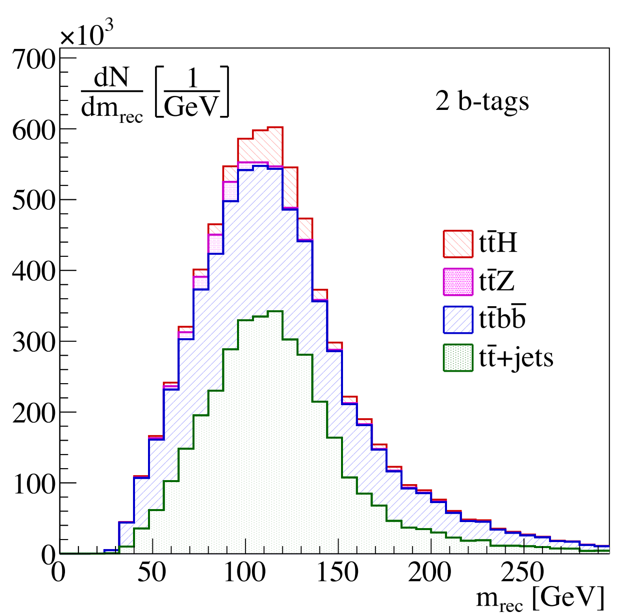
  - Almost identical kinematics boundaries (m_Z~m_H)
    Correlated PDF and m_t systematics

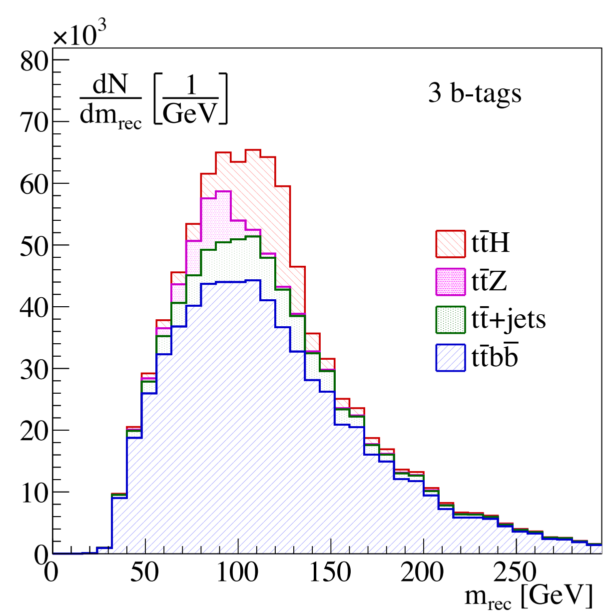
100T[illegible]			
MSTW[illegible]			[illegible]9% / [illegible]2%
CT1[illegible]	[illegible]	$m_t = y_t v = 174.1$ GeV	[illegible]6% / [illegible]0% / $0.592^{+1.27\%}_{-2.00\%}$
NNPDF2.3	$0.584^{+1.29\%+0.0493\%}_{-2.01\%-0.0493\%}$	$m_t = y_t v = 172.5$ GeV	$0.576^{+1.27\%}_{-1.99\%}$
		$m_H = 126.0$ GeV	$0.575^{+1.25\%}_{-1.95\%}$

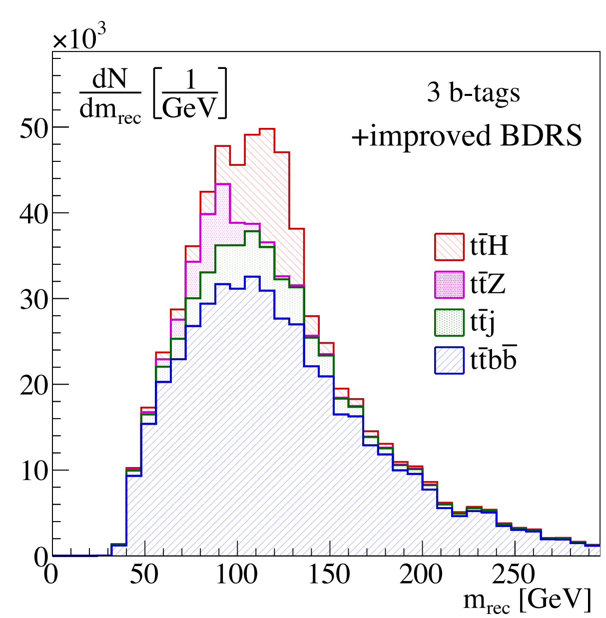
With 20ab^{-1}, the ratio N_H/N_Z can be measured at 1% (stat. unc.)

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)

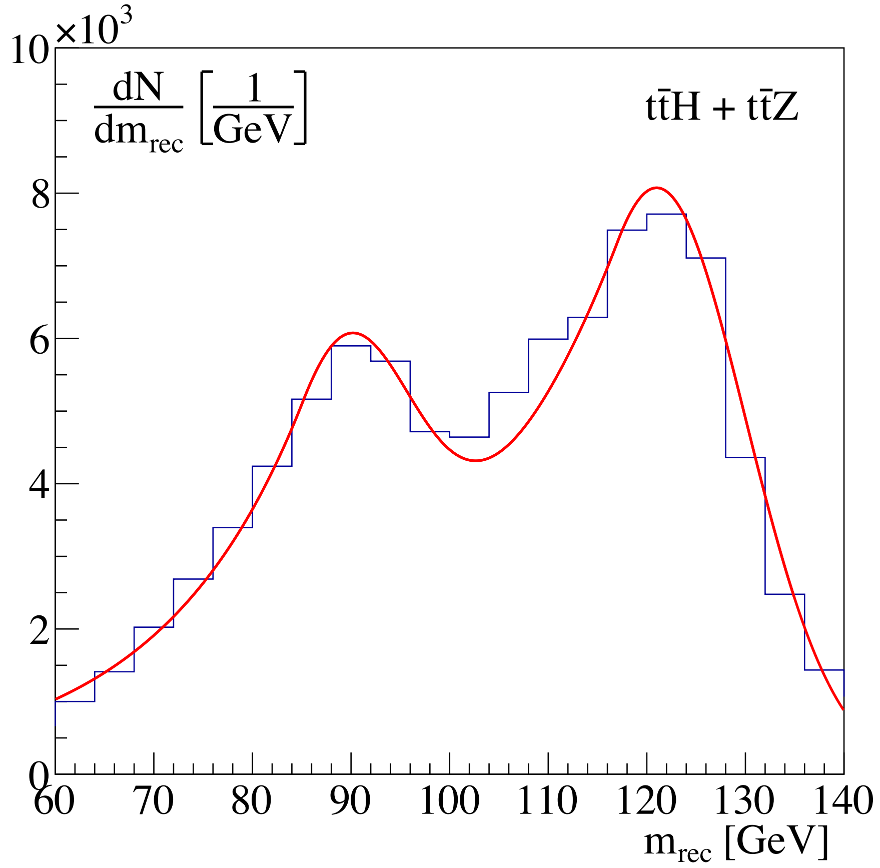






Signal extraction

- 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 $N_S=0.013N_S$
- $N_H/N_Z=2.80\pm0.03$, with systematic and theoretical uncertainties cancelling in the ratio



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

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

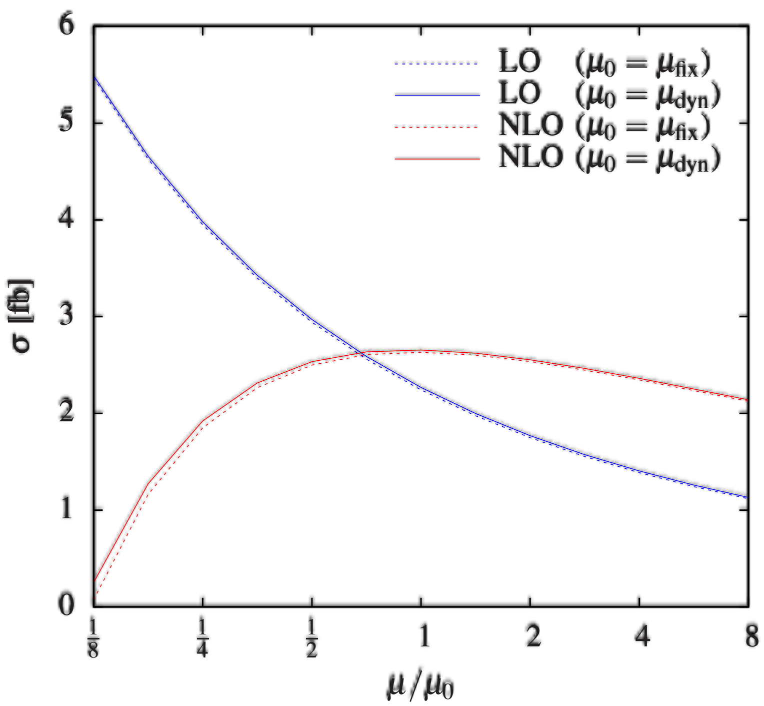
$$p_{\mathrm{T,b}} > 25\,\mathrm{GeV}, \quad |\eta_b| < 2.5$$
$$p_{\mathrm{T,l}} > 20\,\mathrm{GeV}, \quad |\eta_{\mathrm{l}}| < 2.5$$
$$p_{\mathrm{T,miss}} > 20\,\mathrm{GeV}$$
$$\Delta R_{\mathrm{bb}} > 0.4$$

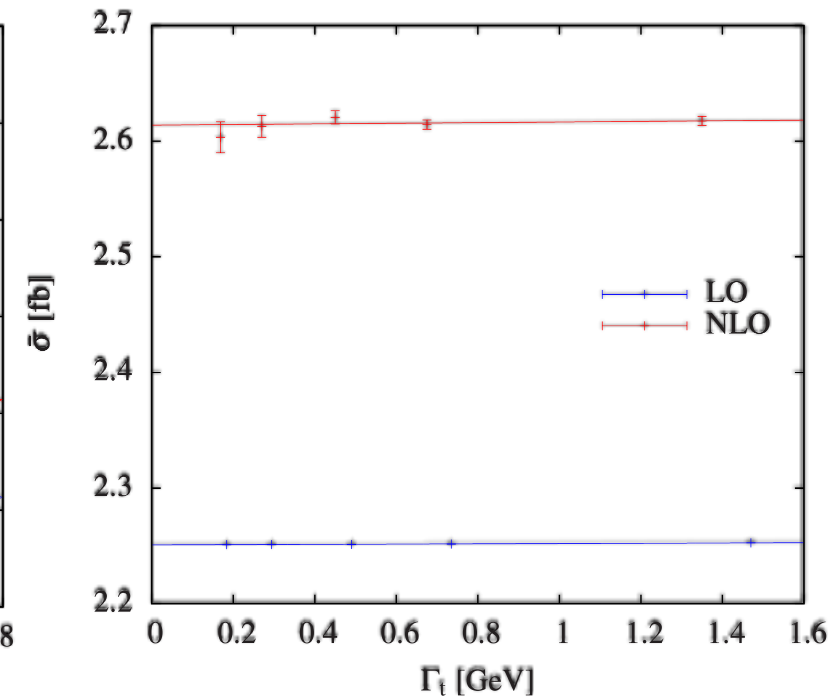
- Compare results with fixed or dynamical scales

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

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

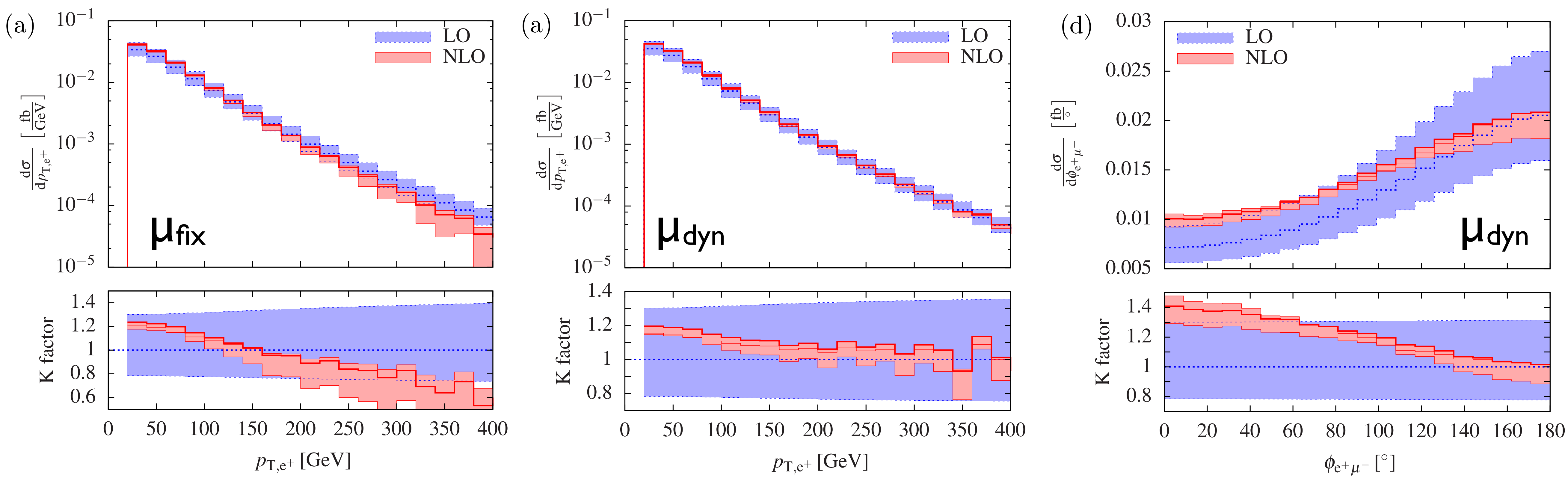
μ_0	ch.	$\sigma_{\rm LO}$ [fb]	$\sigma_{\rm NLO}$ [fb]	K
$\mu_{\rm dyn}$	gg	$1.5938(1)^{+33.8\%}_{-23.6\%}$	$2.026(3)^{-16.1\%}_{+0.9\%}$	1.271(2)
	$q\bar{q}$	$0.67520(5)^{+24.1\%}_{-18.1\%}$	$0.495(2)^{-39.5\%}_{+17.2\%}$	0.733(2)
	$g\overset{(-)}{q}$		$0.1347(7)^{+298\%}_{-152\%}$	
	pp	$2.2690(1)^{+30.9\%}_{-22.0\%}$	$2.656(3)^{-4.6\%}_{-3.8\%}$	1.171(1)
$\mu_{\rm fix}$	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)