MonteCarlos for $t\bar{t}H$

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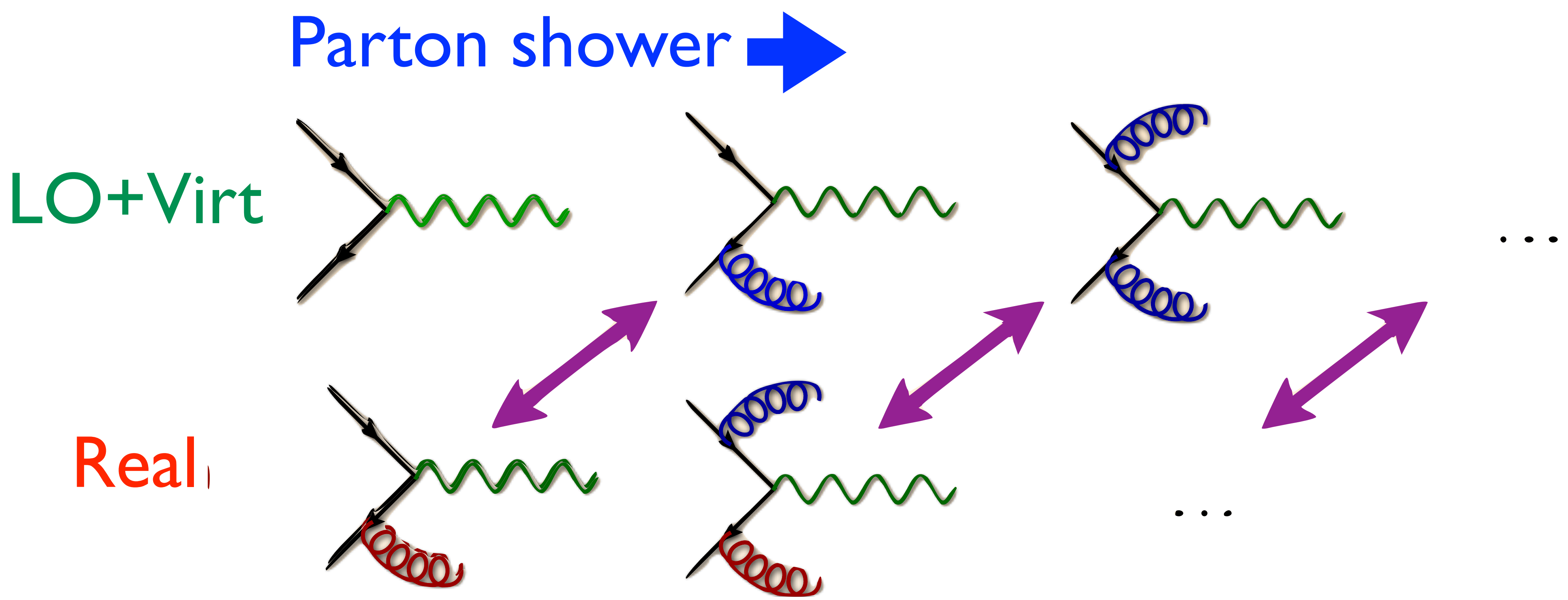
Why shall I care?

- Precision: NLO is the first order at which the assessments of theoretical uncertainties is meaningful
- Proper description of the final state: matching to PS allows one to obtain a realistic description of the final state in terms of hadrons
- Both are crucial when multivariate analyses are essential and/or when lots of backgrounds are there

$t\bar{t}H$ and MonteCarlos: outline

- NLO QCD corrections matched with PS
- Keeping spin-correlations in top decay
  - Higgs CP analyses
- Electro-Weak corrections
- What can be learnt from tH?

NLO+PS



- Emissions from the shower and from the ME must not be counted twice
- Double counting can be avoided by using the MC@NLO or Powheg method

MC@NLO: Frixione, Webber, hep-ph/0204244
Powheg: Nason, hep-ph/0409146
Frixione, Nason, Oleari, arXiv:0709.2092

MC@NLO and Powheg

- MC@NLO: avoid double counting by introducing the "MC counterterms"

$$\frac{d\sigma_{\text{“}MC@NLO\text{”}}}{dO} = \left[\int d\Phi_n (B + V + \int d\Phi_1 MC)\right] I^n_{MC}(O) + \left[\int d\Phi_{n+1}(R - MC)\right] I^{n+1}_{MC}(O)$$

S-events H-events

- MC are related to the shower Sudakov and are shower-specific

$$I^k_{MC} = \Delta + \Delta d\Phi_1 \frac{MC}{B} + \dots \qquad \Delta = \exp\left[-\int d\Phi_1 \frac{MC}{B}\right]$$

$$MC = J \frac{1}{t_{MC}} \frac{\alpha_s}{2\pi} P(z^{MC}) B$$

MC@NLO and Powheg

- Powheg: avoid double counting by generating first (hardest) emission via an ad-hoc Sudakov

$$d\sigma_{\mathrm{POWHEG}} = d\phi_n \overline{\mathcal{M}}^{(b)}(\phi_n) \left[\Delta_R(t_I, t_0; 0) + \Delta_R(t_I, t_0; k_T(\phi_r)) \frac{\mathcal{M}^{(r)}(\phi_{n+1})}{\mathcal{M}^{(b)}(\phi_n)} d\phi_r\right]$$

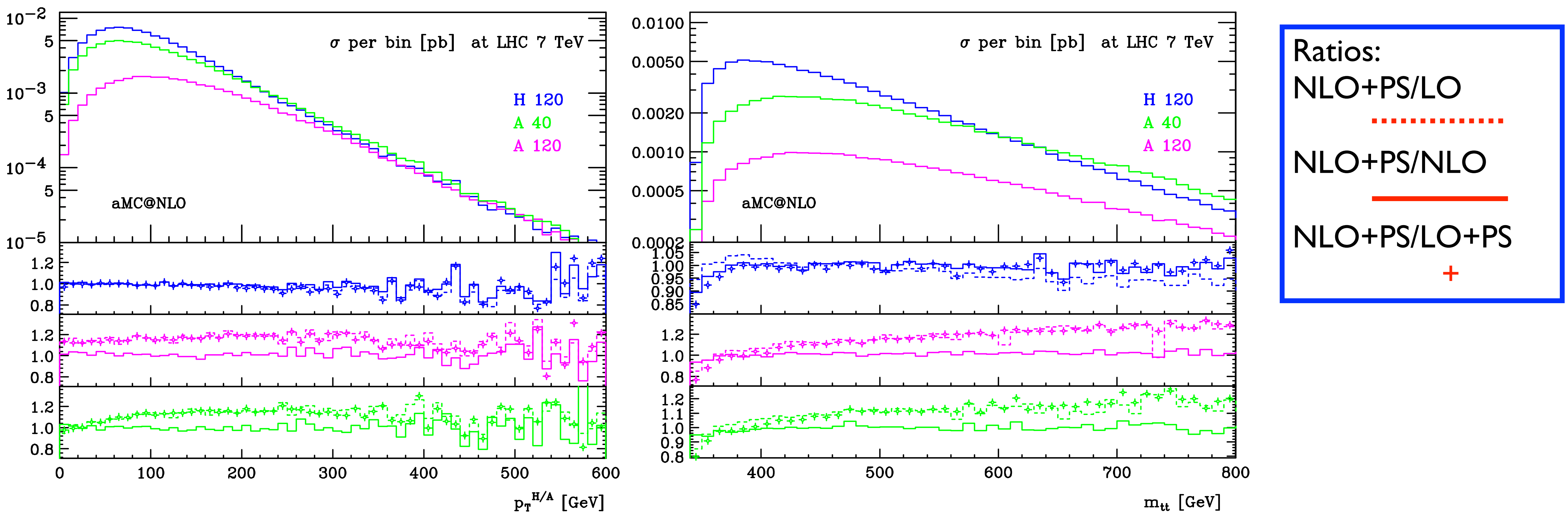
$$\Delta_R(t_I, t_0; p_T) = \exp\left[-\int_{t_0}^{t_I} d\phi'_r \frac{\mathcal{M}^{(r)}}{\mathcal{M}^{(b)}} \Theta(k_T(\phi'_r) - p_T)\right]$$

$$\overline{\mathcal{M}}^{(b)}(\phi_n) = \mathcal{M}^{(b+v+rem)}(\phi_n) + \int d\phi_r \left[\mathcal{M}^{(r)}(\phi_{n+1}) - \mathcal{M}^{(c.t.)}(\phi_{n+1})\right]$$

- MC@NLO and Powheg are formally equivalent up to NNLO terms

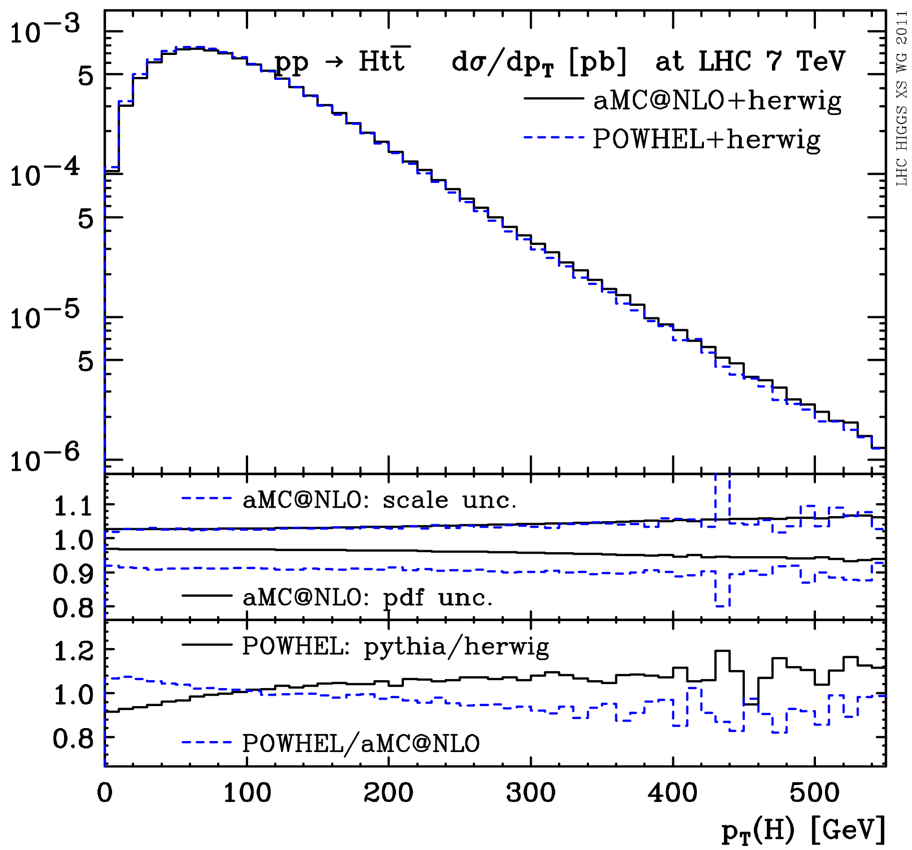
$t\bar{t}$H(/A)@NLO+PS

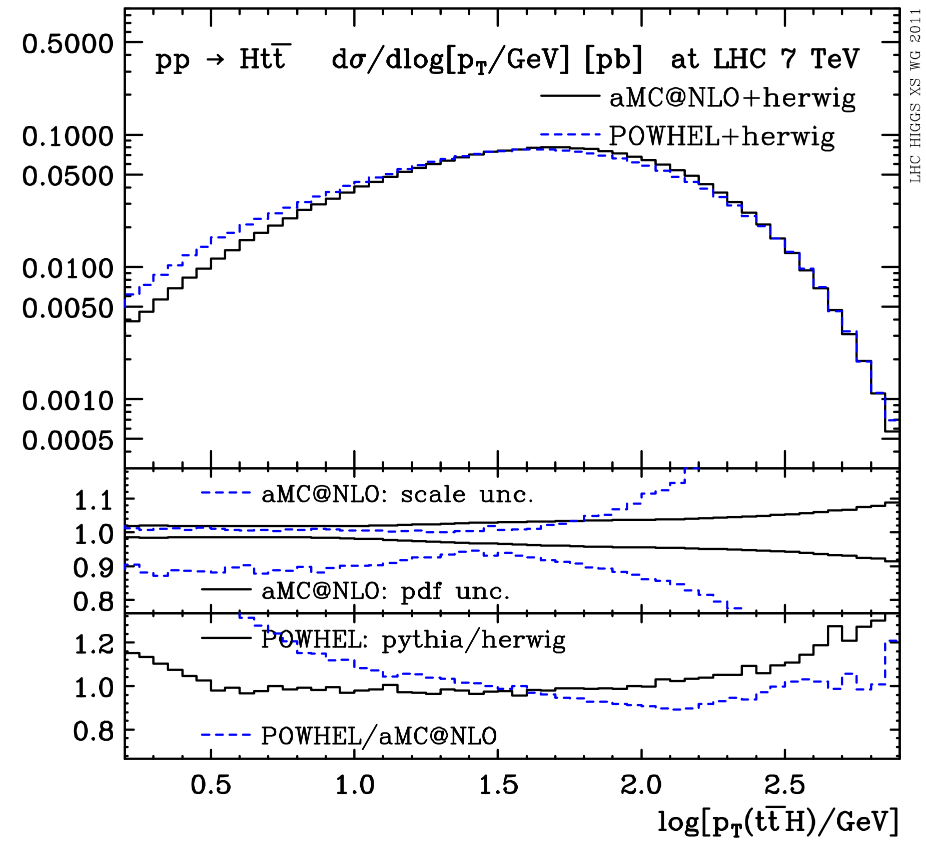
Frederix, Frixione, Hirschi, Maltoni, Torrielli, Pittau, arXiv:1104.5613



- First study of $t\bar{t}$H @NLO+PS
- $\mu=(m_T(H)m_T(t)m_T(\bar{t}))^{1/3}$, K-fact. ~1 @7TeV, 1.1@14TeV
- QCD corrections not flat

MC@NLO vs Powheg: results





- Differences are at 10-15% level for NLO-accurate observables (compatible with scale uncertainties)
- Larger differences arise for $p_T(t\bar{t}H)$:
  - sensitive to Sudakov at small p_T (even if formally NLO acc.)

Plots from HXSWG YR2 (1201.3084); Powhel, arXiv:1108.0387; aMC@NLO, arXiv:1104.5613

Spin correlations

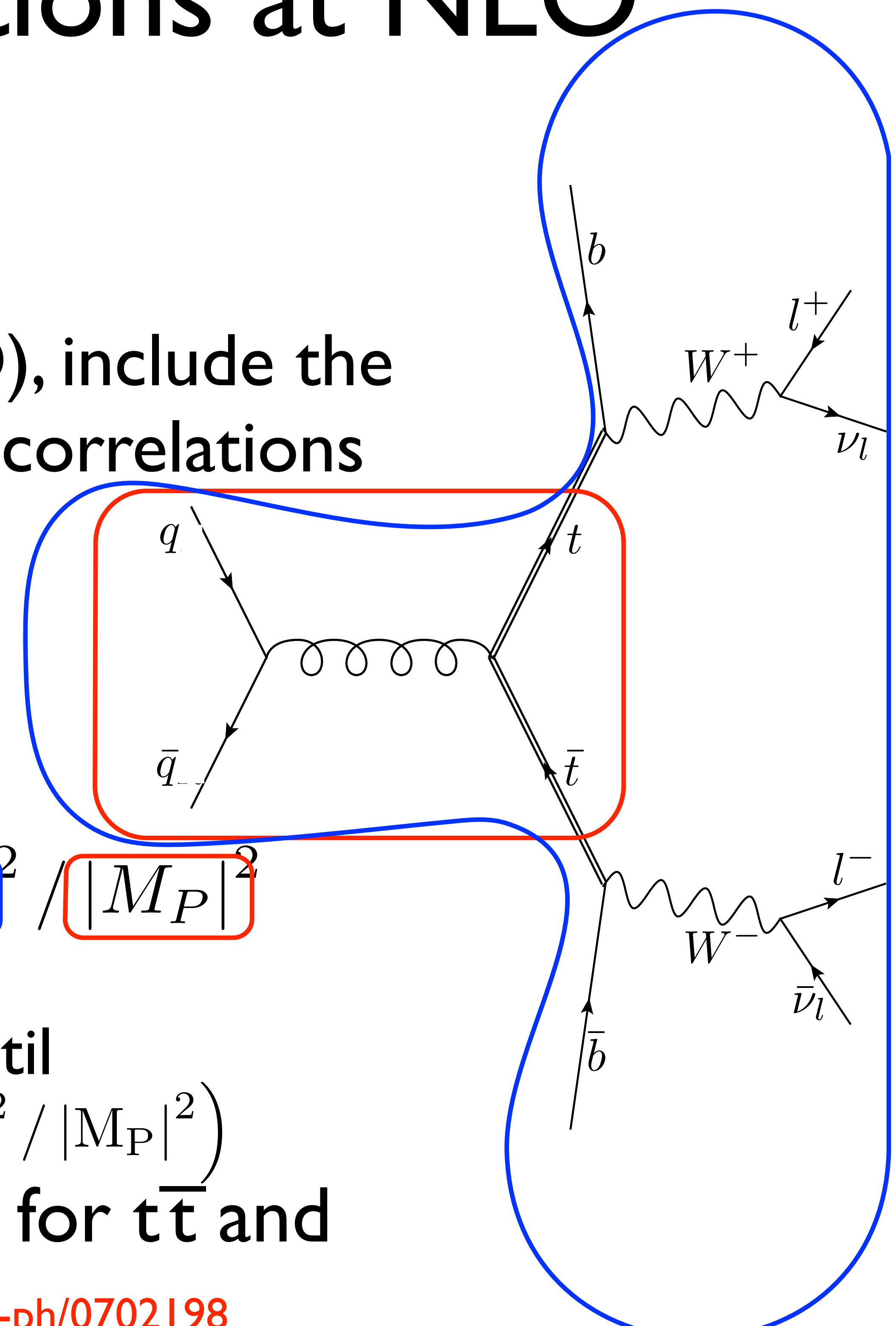
- Spin correlations from top decay products can be useful to determine Higgs CP numbers
- Inclusion at NLO is non-trivial:
  - decay chains violate gauge invariance
  - if tops are decayed by the shower, spin correlations are lost

Including spin correlations at NLO

- Wish-list:
  - For a given event sample (LO or NLO), include the decay of final state particles with spin correlations
  - Generate decayed unweighted events
- Solution:
  - Read event
  - Generate decay kinematics
  - Reweight the event with ratio $|M_{P+D}|^2 \, / \, |M_P|^2$
  - Or do secondary unweighting
    - Generate many decay configurations until

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

- This was been done for the first time for $t\bar{t}$ and singletop Frixione, Leanen, Motylinski, Webber, arXiv:hep-ph/0702198



Including spin correlations at NLO

- How to deal with (a)MC@NLO events?
- Spin correlations usually have tiny effects on observables
  - Include them at tree level
- For H (*n*+*1* body) events, use decayed real-emission matrix-element
- For S (*n* body) events, use decayed born matrix-element
- This guarantees NLO accuracy for observables related to production (e.g. top p_T)
- This includes spin correlation for observables related to production + decay
- Method automated in the MadSpin module in MadGraph5_aMC@NLO

Artoisenet, Frederix, Mattelaer, Rietkerk, arXiv:1212.3460

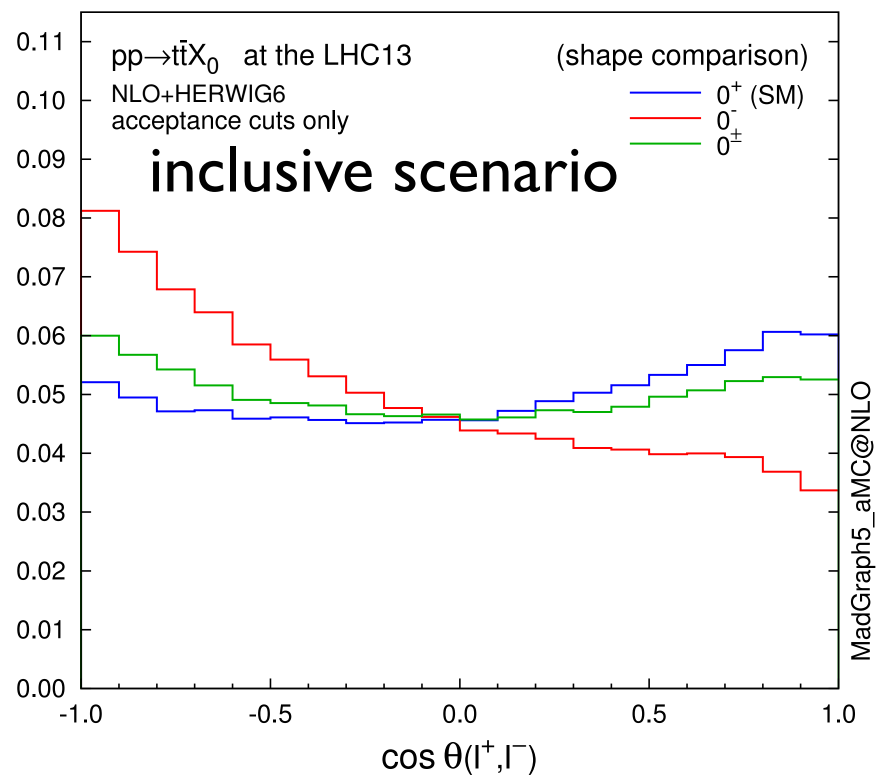
Higgs CP and $t\bar{t}H$

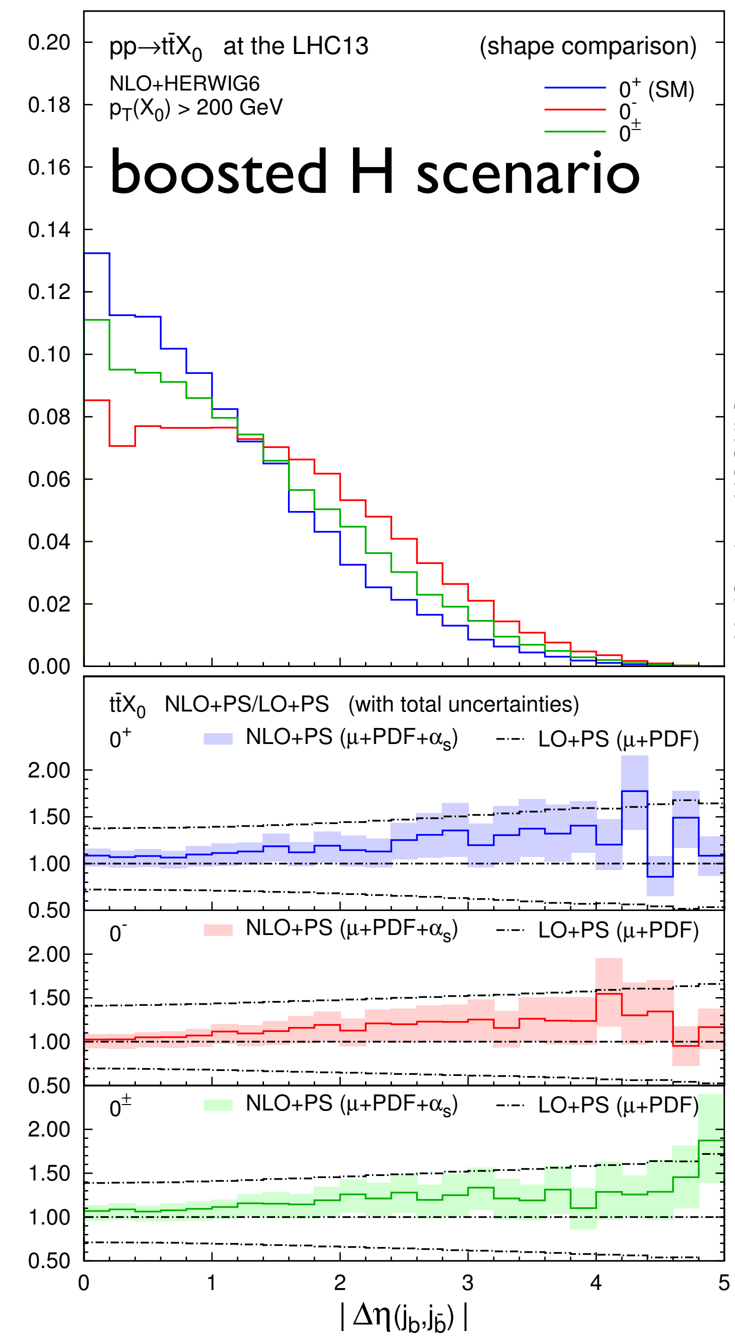
Demartin, Maltoni, Mawatari, Page, MZ, arXiv:1407.5089

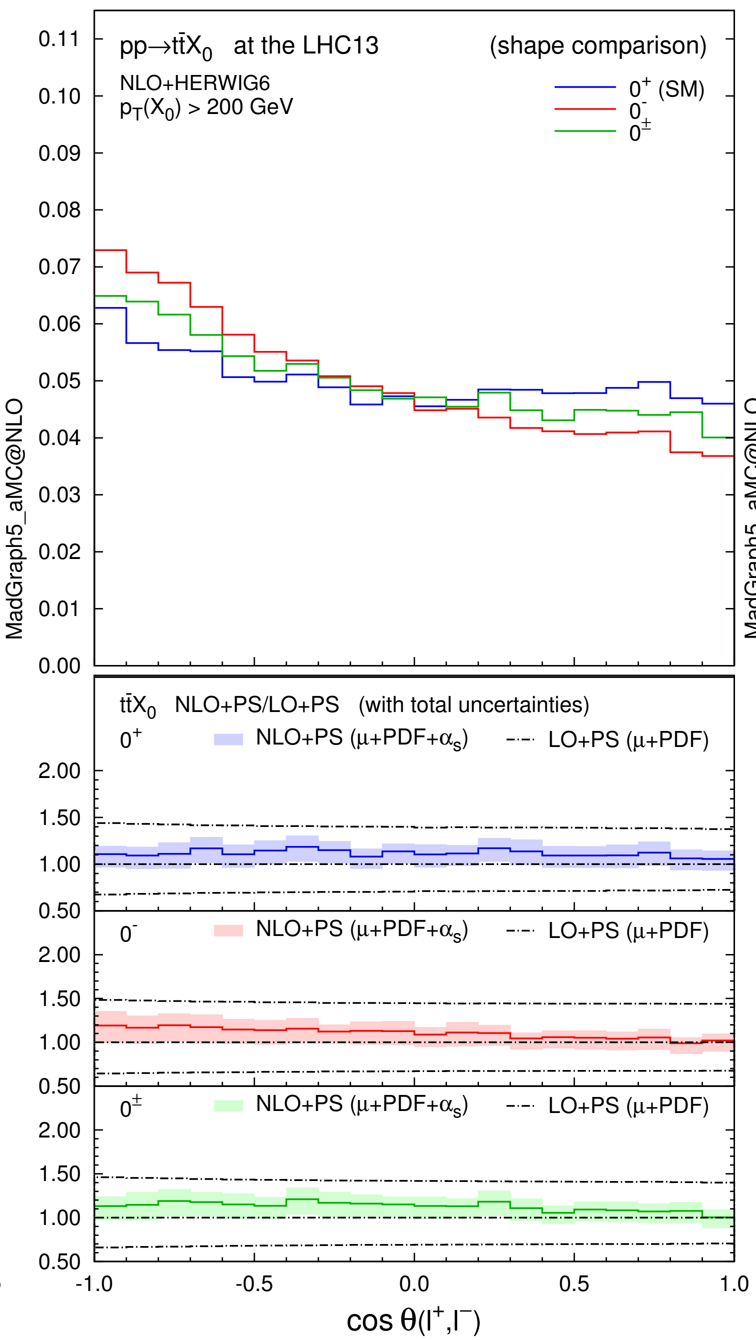
- Include CP violating ttH interaction in an effective theory approach

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

- Study dileptonic top decay







Higgs CP and $t\bar{t}H$

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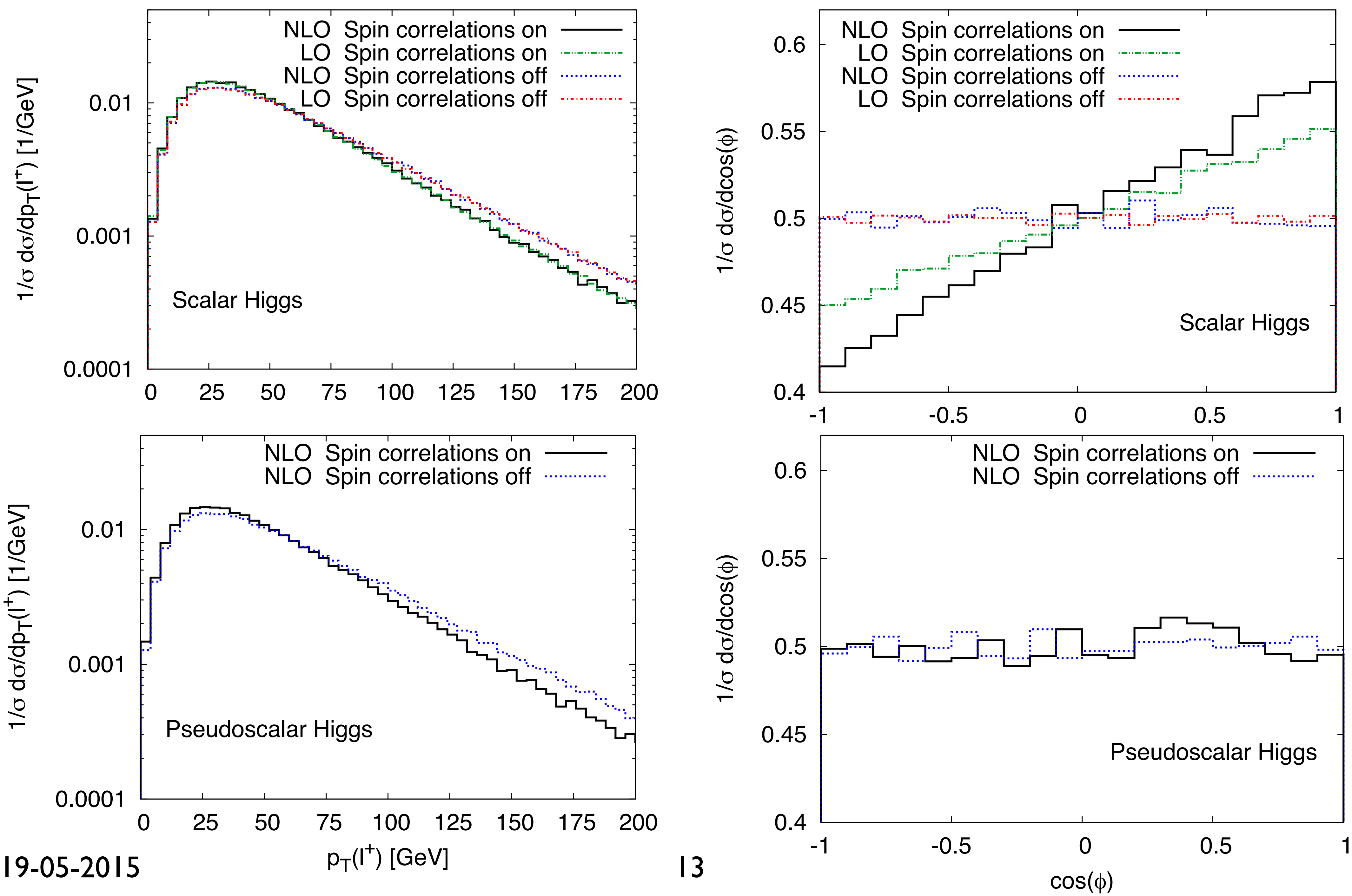
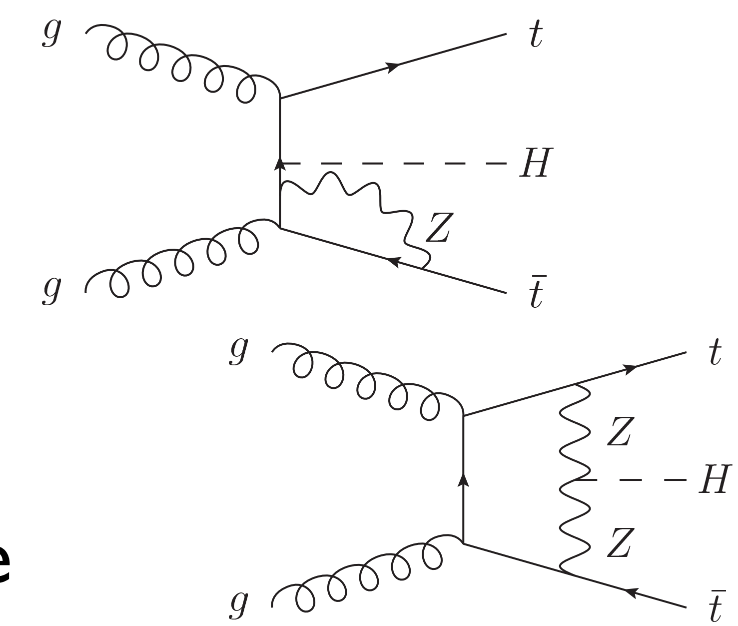
- Inclusion of spin correlation is crucial for CP studies

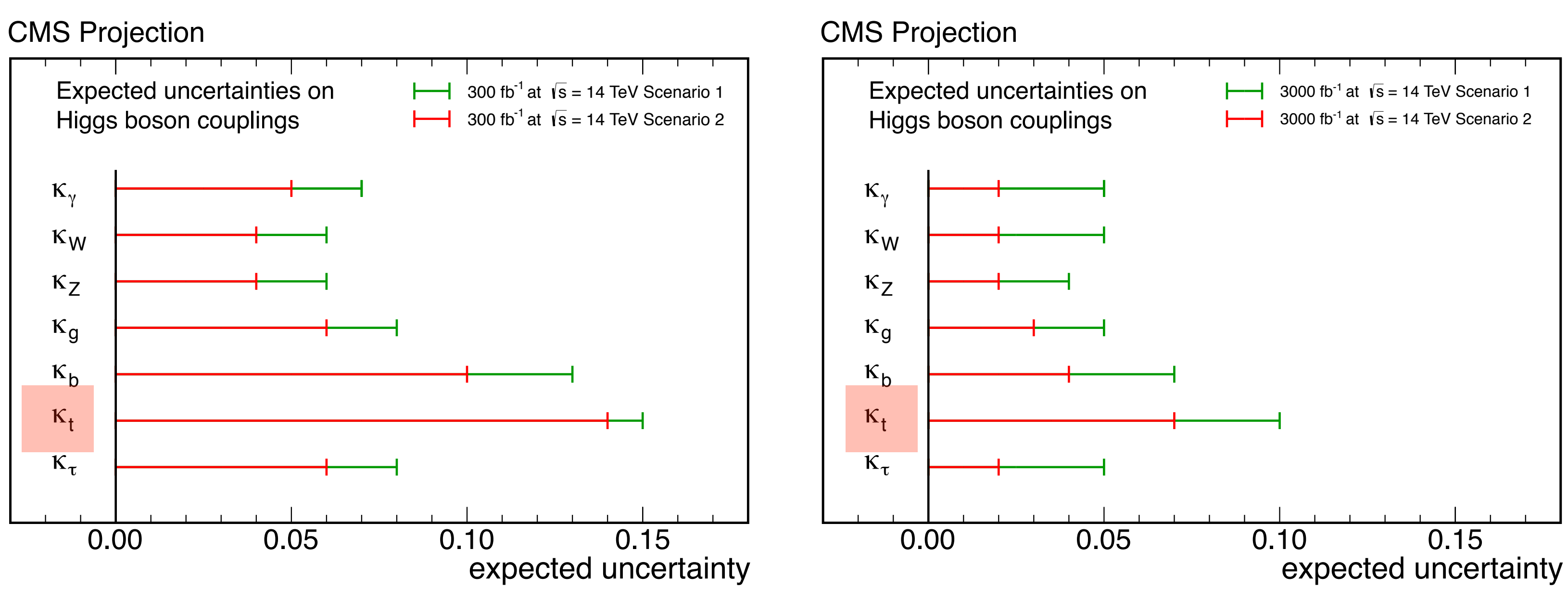


Electro-weak corrections to $t\bar{t}H$: motivation

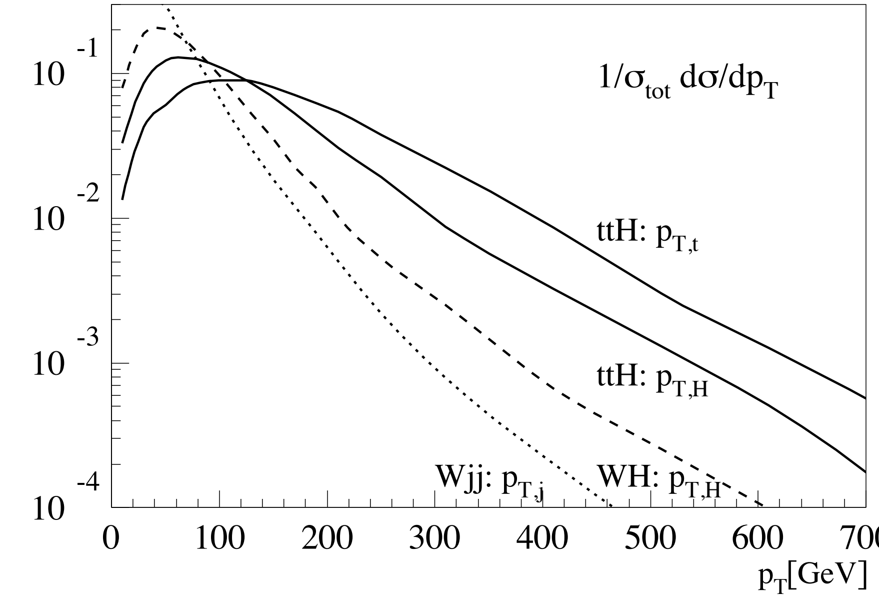
Frixione, Hirschi, Pagani, Shao, MZ, arXiv:1407.0823 & 1504.03446

- $t\bar{t}H$ 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 (expected accuracy 15/10% at 300/3000 fb^{-1})
- 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

- $\alpha(m_Z)$-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

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

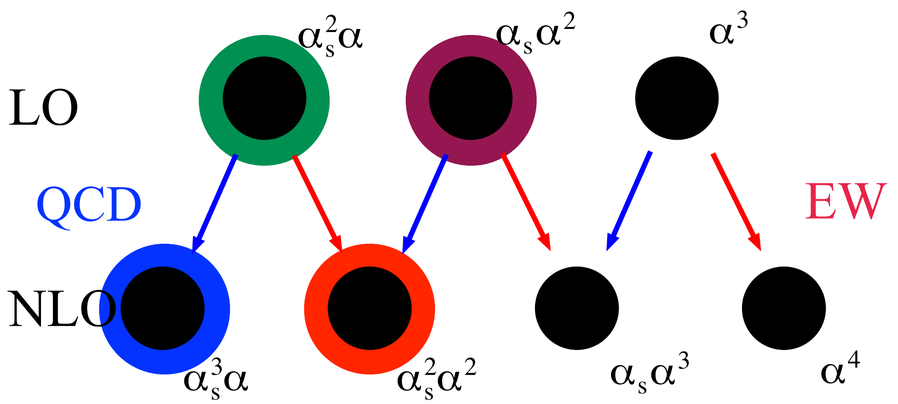
- QCD scale variations computed with

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

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

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

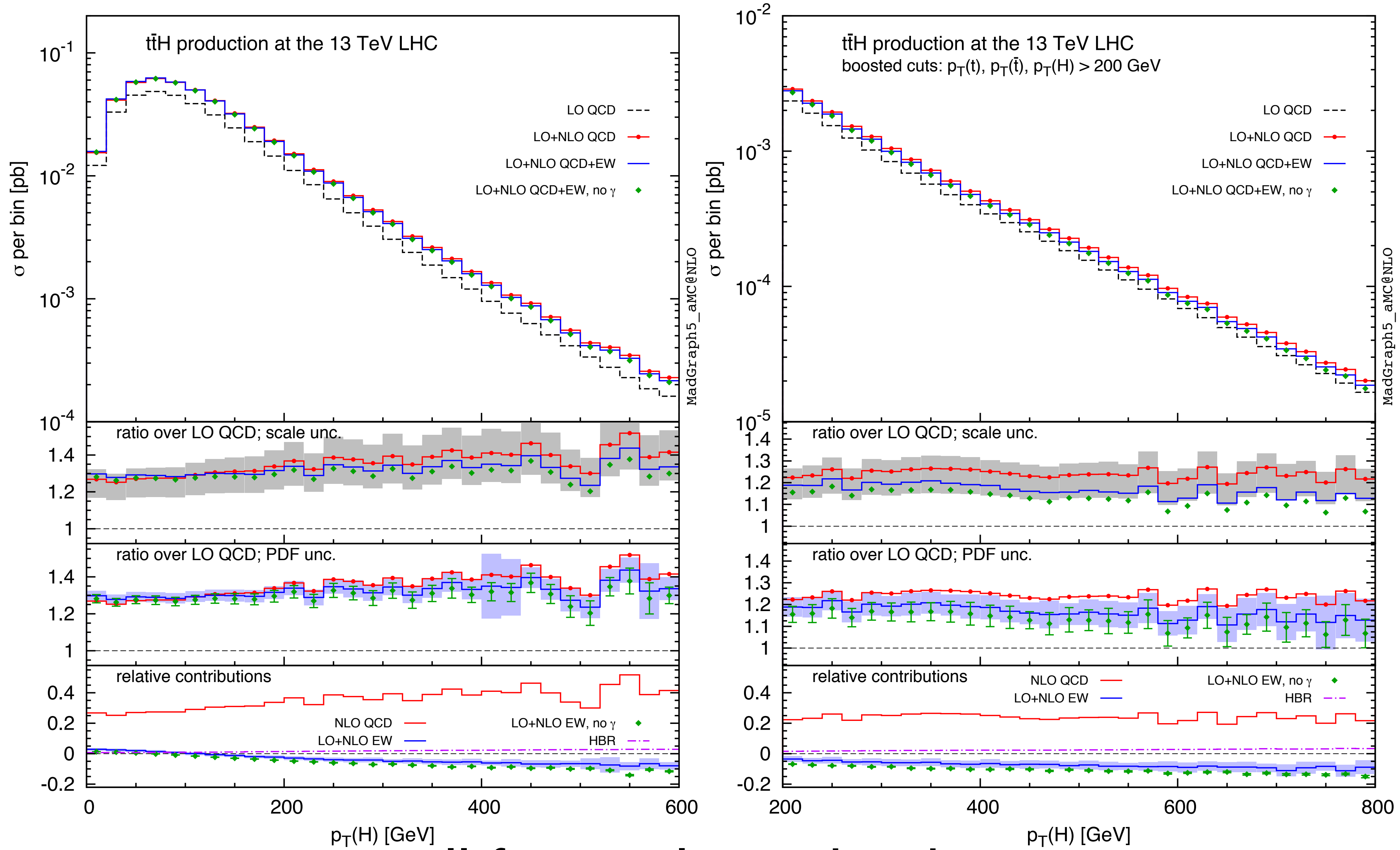
  NLO QCD, NLO EW (+HBR)



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

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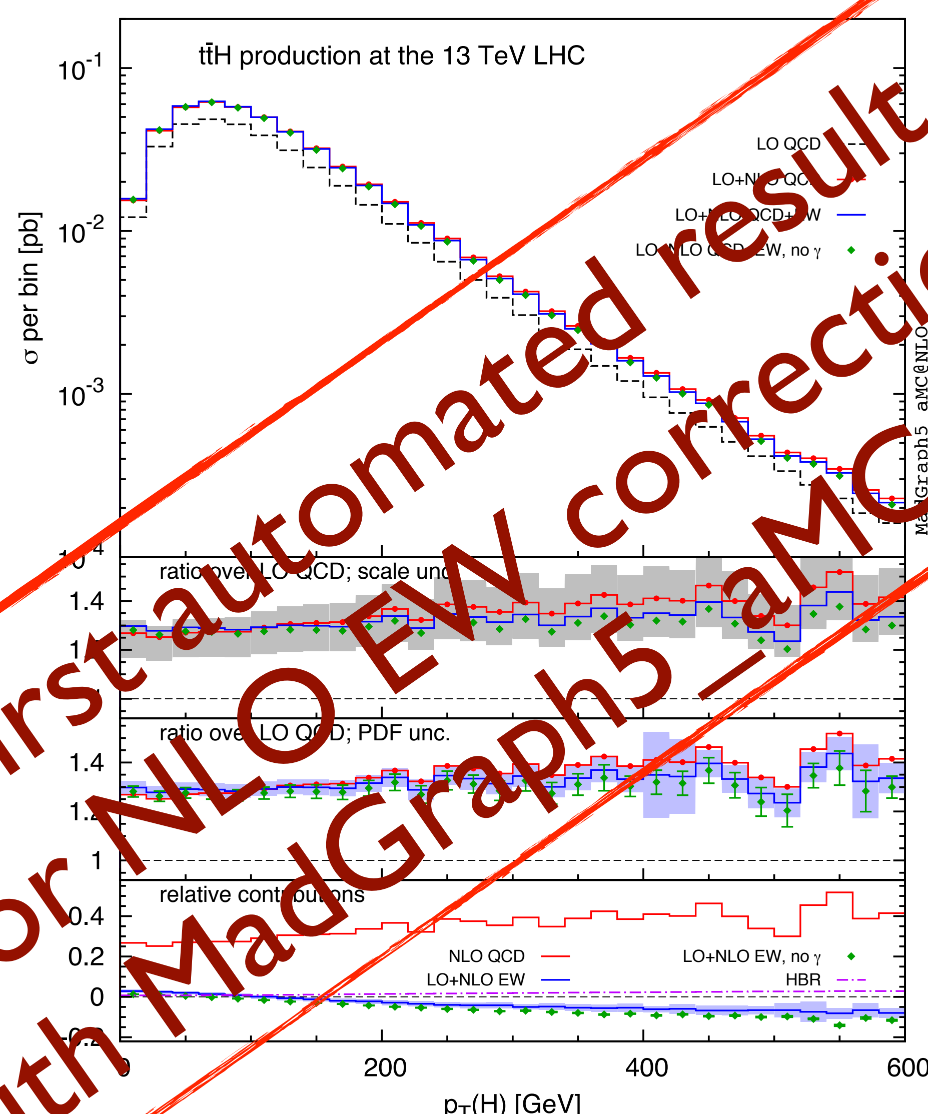
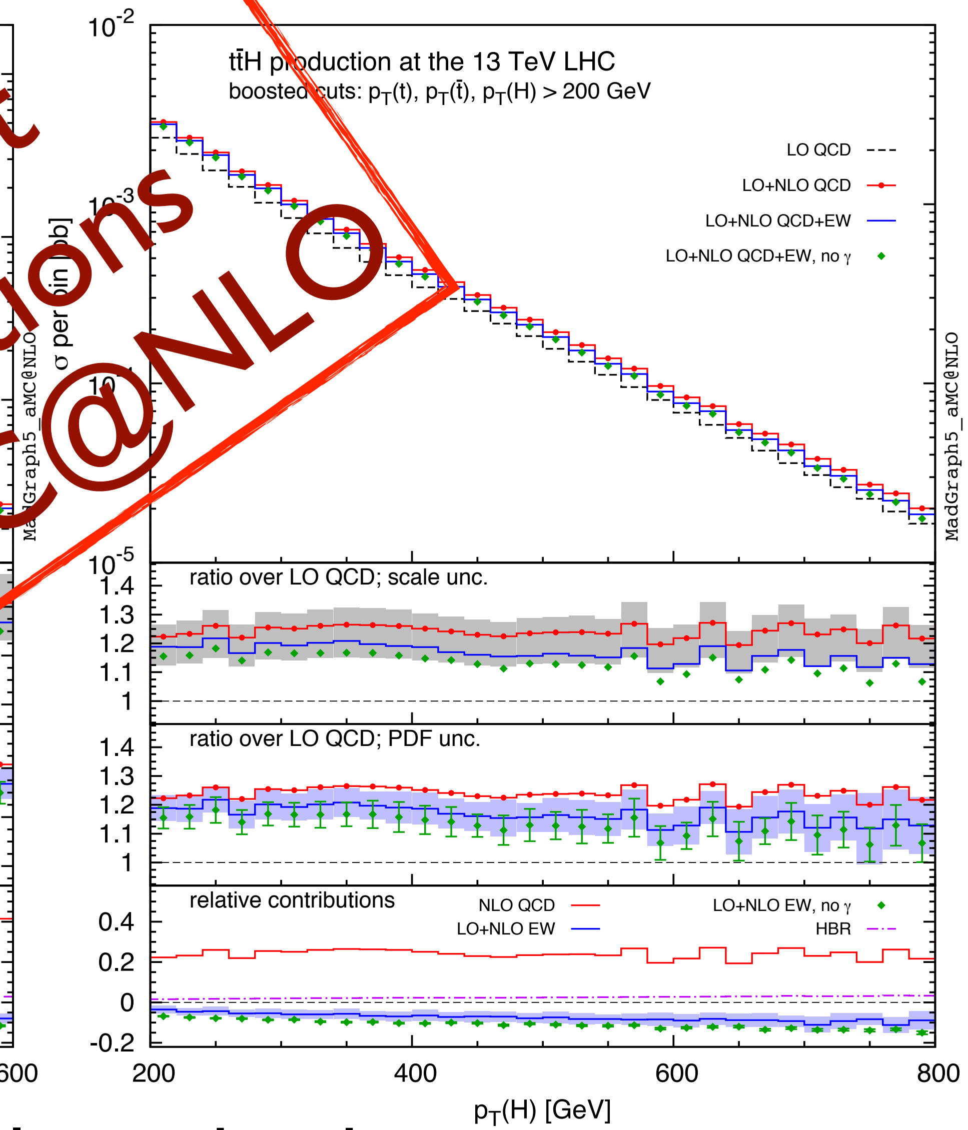




First automated result for NLO EW corrections with MadGraph5_aMC@NLO

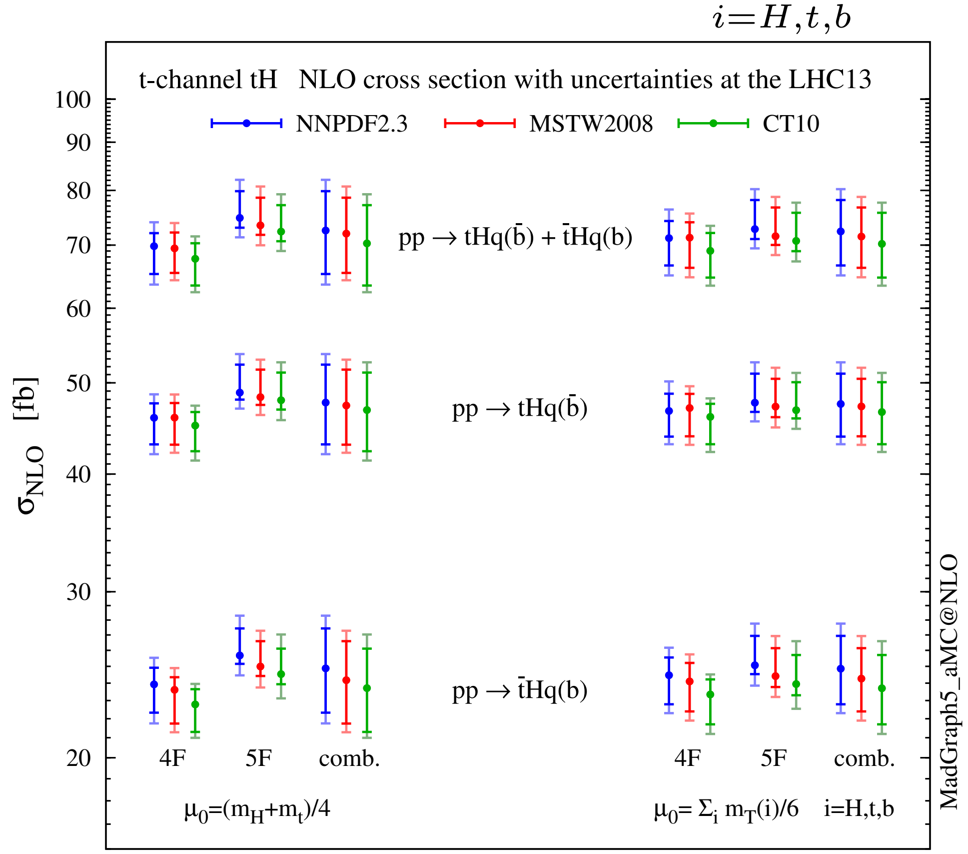
- Bottom line: EW corrections are small for total rate, but become important at large p_T; only partial compensation of Sudakov logs by HBR

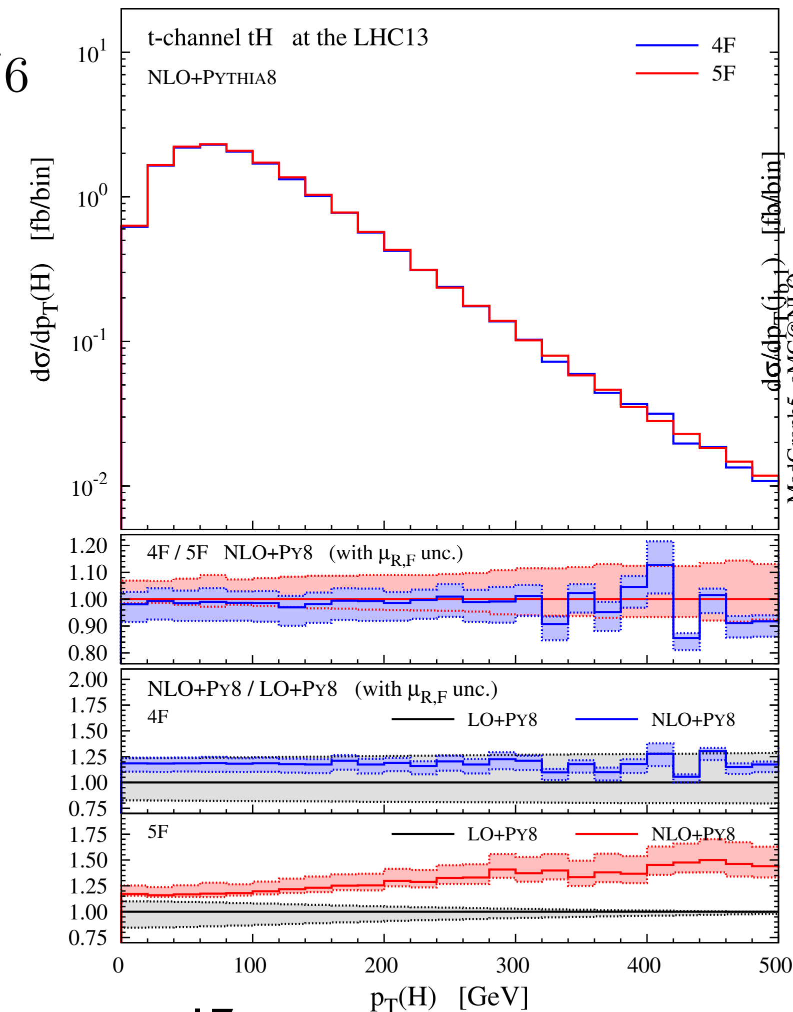
What can be learnt from tH?

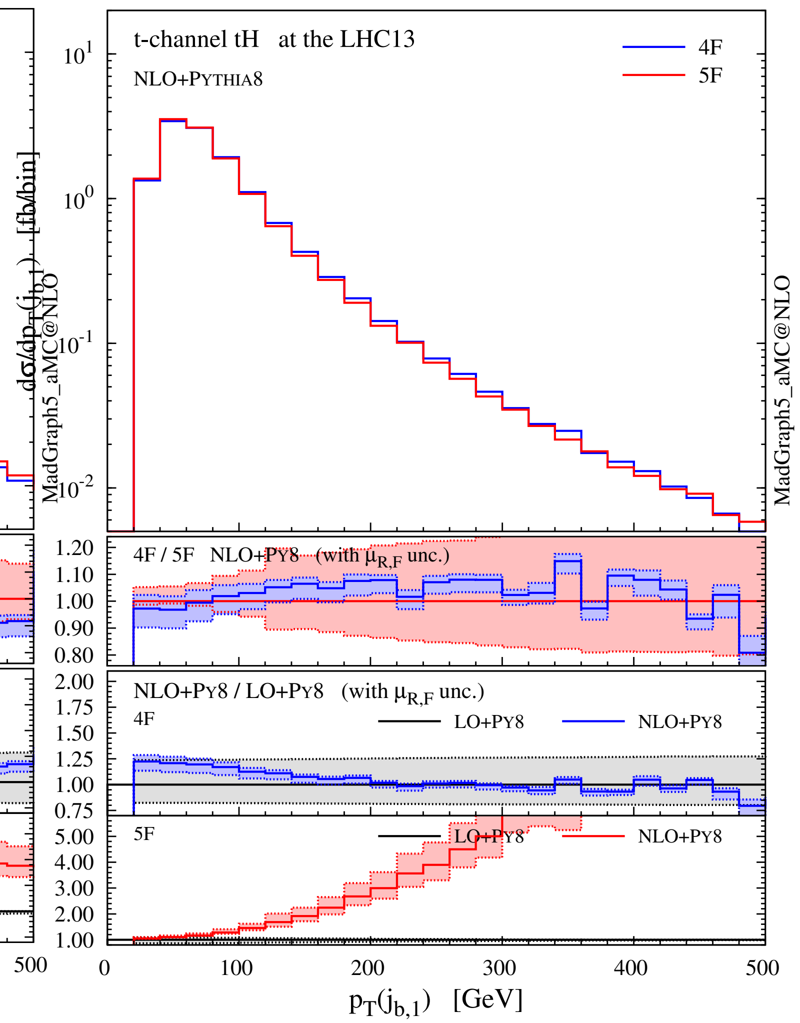
Demartin, Maltoni, Mawatari, MZ, arXiv:1504.00611

- tH: rather rare process (σ_{NLO}<100 fb)
- 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

$$\mu_0^d = H_T/6 = \sum_{i=H,t,b} m_T(i)/6$$

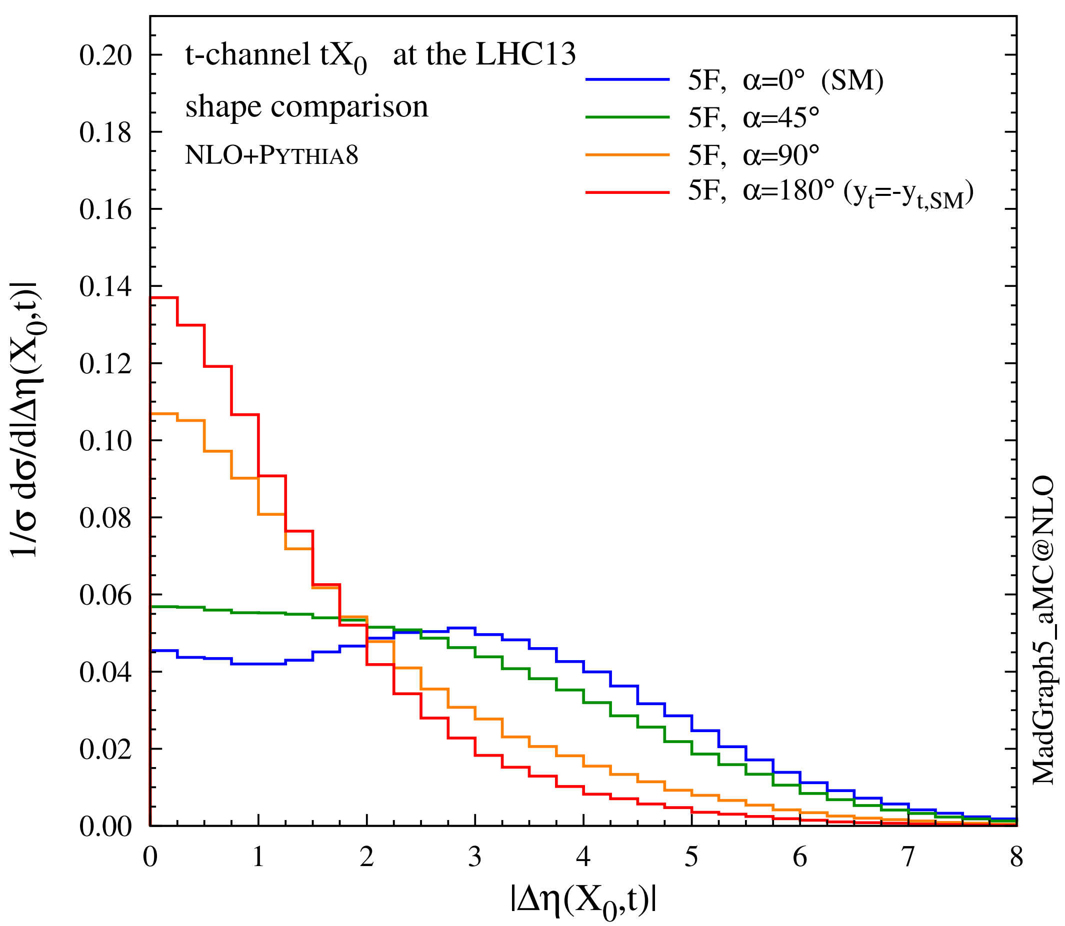


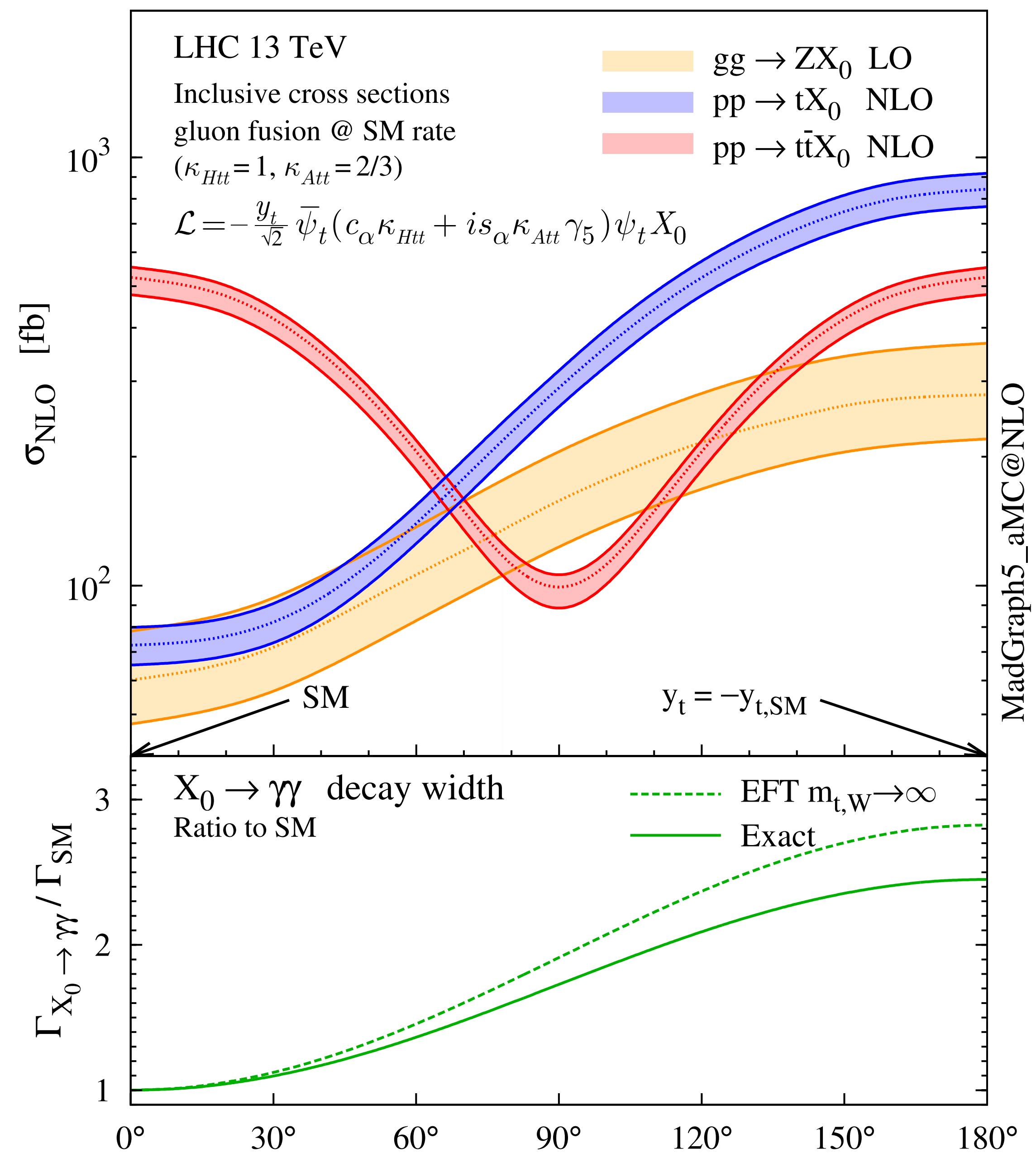




What can be learnt from tH?

- tH is one of the few processes (with H→γγ and gg→HZ) sensitive to the sign of y_t





plot by F. Demartin

Conclusions

- NLO+PS MC are essential tools for ttH simulations
- ttH simulations available both in Powheg and aMC@NLO
- Spin correlation effects are important, need to be included consistently for accurate simulations
- EW corrections can be relevant for boosted searches. Automation of EW corrections in progress (by many groups)
- tH can give useful information in view of the HL-LHC run. Sensitive to sign of y_t