Higgs plus single top production at the LHC

Federico Demartin
UCLouvain (CP3)

In collaboration with
F. Maltoni, K. Mawatari, M. Zaro

22.04.2015

Experimental searches

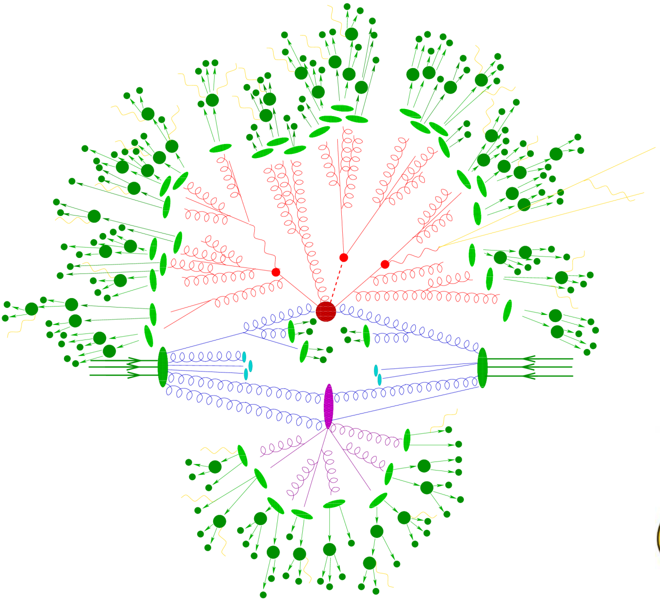
- *ATLAS*: (only as part of $t\bar{t}H$ analyses)
- *CMS*: CMS-PAS-HIG-14-001, CMS-PAS-HIG-14-015 ($H \to \gamma\gamma$, $H \to b\bar{b}$, optimized for $y_t = -y_{t,SM}$)

At the moment: limits on tH cross section (supposed > SM)

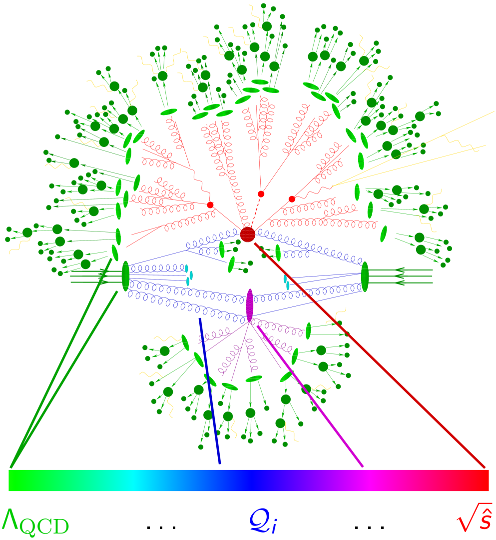
Pheno studies

- *Maltoni*, *Paul*, *Stelzer*, *Willenbrock* [arXiv:hep-ph/0106293] (LO, sig+bkg)
- *Biswas*, *Gabrielli*, *Mele* [arXiv:1211.0499] (LO, $H \to \gamma\gamma$ sig+bkg)
- *Farina*, *Grojean*, *Maltoni*, *Salvioni*, *Thamm* [arXiv:1211.3736] (NLO xsect 5F, LO distr, $H \to b\bar{b}$ sig+bkg, $\pm y_t$)
- *Ellis*, *Hwang*, *Sakurai*, *Takeuchi* [arXiv:1312.5736] (LO, sign/phase of y_t)
- *Chang*, *Cheung*, *Lee*, *Lu* [arXiv:1403.2053] (LO distr, $H \to b\bar{b}, \gamma\gamma, 4\ell, \tau^+\tau^-$ sig+bkg, detector simulation, $\pm y_t$)
- *Demartin*, *Maltoni*, *Mawatari*, *Zaro* [arXiv:1504.00611] (NLO xsect and distr, 4F/5F and other uncertainties, sign/phase of y_t)

Hadron collisions are a mess



Many scales



NON-PERT. ($\alpha_s(\mathcal{Q}) > 1$) PERT. ($\alpha_s(\mathcal{Q}) << 1$)

Logs:

$\alpha_s(\mathcal{Q}_i)^n \ln^n(\Lambda_{\rm QCD}/\mathcal{Q}_i)$

$\alpha_s(\mathcal{Q}_i)^n \ln^n\left(\mathcal{Q}_i/\sqrt{\hat{s}}\right)$

must resum if $\alpha_s \ln > 1$

might still need if $\alpha_s \ln \lesssim 1$

Powers:

$\alpha_s(\mathcal{Q}_i)^n \, (\Lambda_{\rm QCD}/\mathcal{Q}_i)^m$

$\alpha_s(\mathcal{Q}_i)^n \left(\mathcal{Q}_i/\sqrt{\hat{s}}\right)^m$

negligible only for large separation between scales

Introduce an additional perturbative scale (μ) and factorize

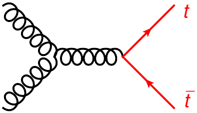
For small scale q:

- resum large logs $\alpha_s(\mu)^n \ln^n(q/\mu)$ to all orders into a PDF (or fragmentation function)
- neglect power-suppressed terms $\alpha_s(\mu)^n \, (q/\mu)^m$

For large scale $\mathcal{Q}$:

- compute both $\alpha_s(\mu)^n \ln^n(\mu/\mathcal{Q})$ and $\alpha_s(\mu)^n \, (\mu/\mathcal{Q})^m$ at a fixed order in perturbation theory
- neglect higher-orders

An example: $t\bar{t}$ production



$\Lambda_{\mathrm{QCD}} \quad \xleftrightarrow{\sim\ \times 1000} \quad 2m_t\,,\ \sqrt{\hat{s}}$

$\uparrow$

choose a scale μ here $\quad \mu$

Neglect

$\alpha_s(\mu)^n\,(\Lambda_{\mathrm{QCD}}/\mu)^m \qquad$ (set $m_q = 0$)

Resum to all orders

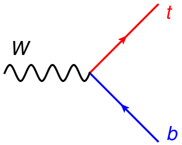
$\alpha_s(\mu)^n\,\ln^n(\Lambda_{\mathrm{QCD}}/\mu) \qquad$ into the PDFs

Fixed order

$\alpha_s(\mu)^n\,(\mu/m_t)^m$

$\alpha_s(\mu)^n\,\ln^n(\mu/m_t)$

A less trivial example: single-top production

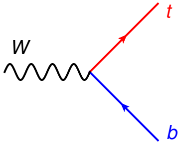


$$\Lambda_{\mathrm{QCD}} \quad \xleftrightarrow{\sim\ \times 20} \quad m_b \quad \xleftrightarrow{\sim\ \times 35} \quad m_t\,,\ \sqrt{\hat{s}}$$

↑ (naive 4F) here?

↑ (naive 5F) here?

A less trivial example: single-top production



$$\Lambda_{\mathrm{QCD}} \quad \xleftrightarrow{\sim\ \times 20} \quad m_b \quad \xleftrightarrow{\sim\ \times 35} \quad m_t\,,\sqrt{\hat{s}}$$

$\uparrow$

HERE!

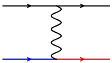
Maltoni, *Ridolfi*, *Ubiali* [arXiv:1203.6393]

Campbell, *Frederix*, *Maltoni*, *Tramontano* [arXiv:0903.0005]

A less trivial example: single-top production

$\Lambda_{\mathrm{QCD}} \quad \longleftrightarrow \quad m_b \longleftrightarrow \mu \longleftrightarrow m_t\,,\sqrt{\hat{s}}$

5-flavour scheme (5F): put b's in the initial state



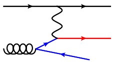
Neglect

$\alpha_s(\mu)^n\,(m_b/\mu)^m$ (set $m_b = 0$) , $\quad p_T(b)$ (at LO)

Resum to all orders

$\alpha_s(\mu)^n\,\ln^n(m_b/\mu)$ into the b PDF

4-flavour scheme (4F): generate b's in the hard scattering



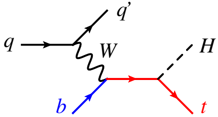
Fixed order

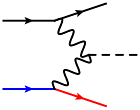
$\alpha_s(\mu)^n\,(m_b/\mu)^m$, $\quad \alpha_s(\mu)^n\,\ln^n(m_b/\mu)$, $\quad p_T(b)$

Go to NLO to reduce differences (i.e. flavour-scheme dependence)

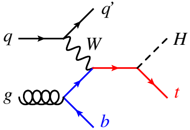
Single top plus Higgs production (tH)

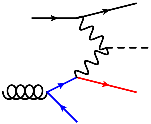
t-channel 5F

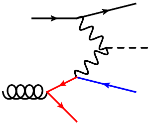


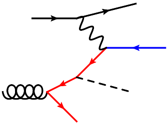


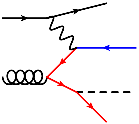
t-channel 4F



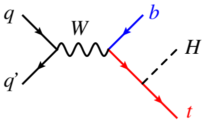


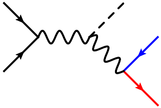




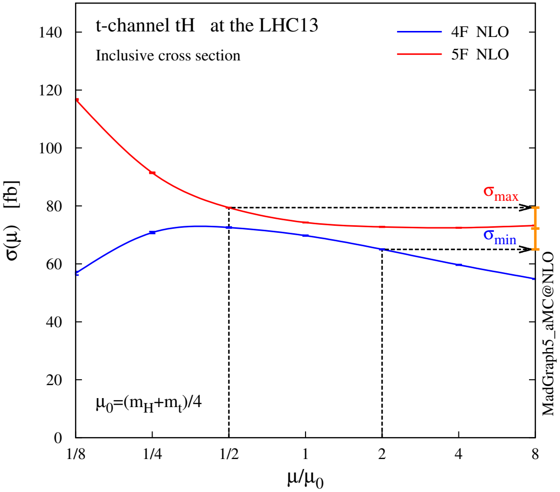


s-channel 4F





tH NLO cross section: flavour scheme (FS) and scale (μ) dependence



$\mu_R = \mu_F \equiv \mu$

FS and μ are correlated

(1) Choose μ_0 to minimize FS dependence (at NLO)

(2) Vary μ/μ_0 by 2 and take the envelope

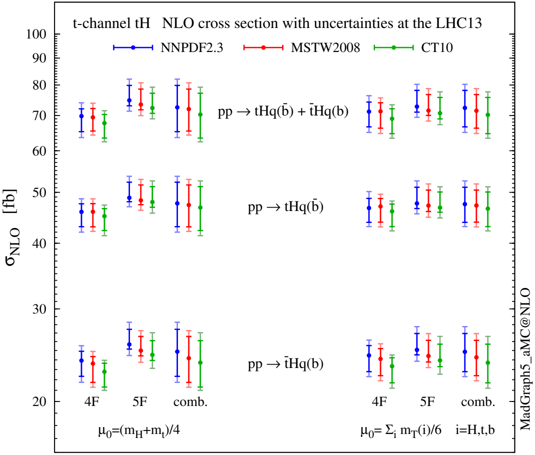
(3) Define

$$\sigma_0 \equiv (\sigma_{\max} + \sigma_{\min})/2$$

$$\delta_{\mu+\mathrm{FS}} \equiv (\sigma_{\max} - \sigma_{\min})/2$$

$$\sigma_{\mathrm{NLO}}^{\mathrm{comb.}} = \sigma_0 \pm \delta_{\mu+\mathrm{FS}}$$

tH NLO cross section: total theoretical uncertainty



PDF global fits:
NNPDF2.3, MST2008, CT10

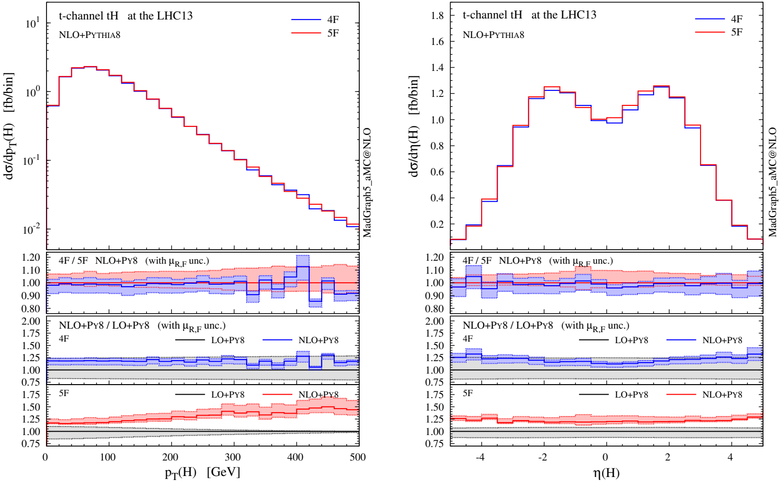
$$\alpha_s^{(5F)}(m_Z) = 0.1190 \pm 0.0012$$
$$\Leftrightarrow \alpha_s(m_b) = 0.2189 \pm 0.0042$$

$$m_b^{(o.s.)} = 4.75 \pm 0.25 \text{ GeV}$$

$$\delta^{\pm}_{\mathrm{PDF}+\alpha_s+m_b} = \sqrt{(\delta^{\pm}_{\mathrm{PDF}})^2 + (\delta^{\pm}_{\alpha_s})^2 + (\delta^{\pm}_{m_b})^2}$$

$$\delta^{\pm}_{\mathrm{tot}} = \delta^{\pm}_{\mu(+\mathrm{FS})} + \delta^{\pm}_{\mathrm{PDF}+\alpha_s+m_b}$$

tH NLO+PS distributions: Higgs (no decay)

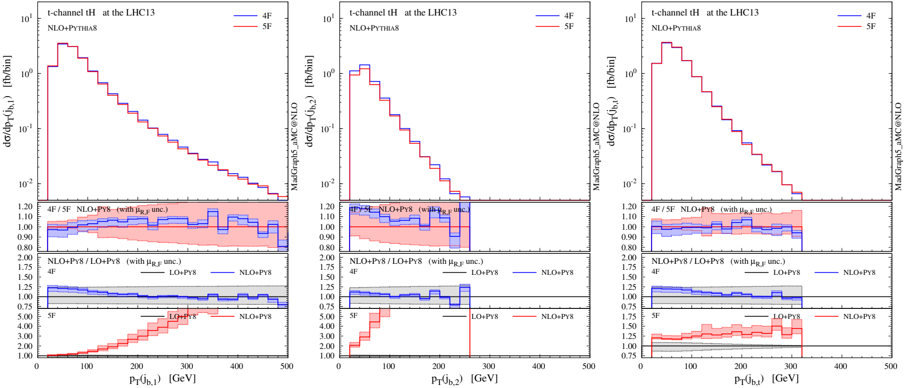


Very good agreement between 4F and 5F shapes at NLO (same for the top quark)

LO 5F provides a poor description

tH NLO+PS distributions: *b*-tagged jets

anti-k_T $\quad p_T > 30$ GeV $\quad R = 0.4 \quad |\eta| < 2.5 \quad$ no H decay, $t \to b\ell\nu_\ell$

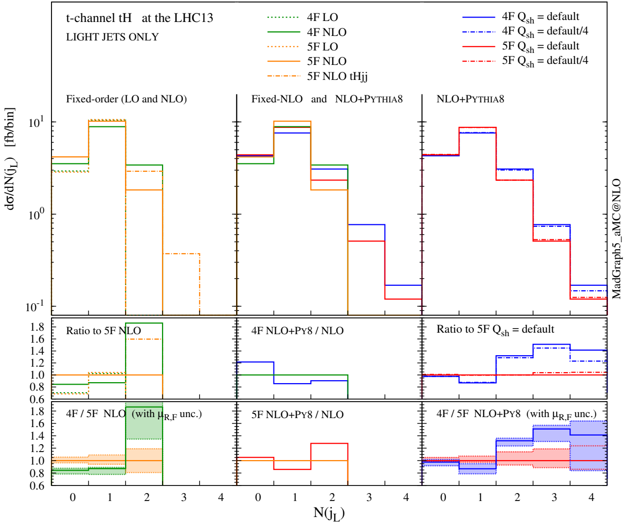


Still good agreement at NLO

1st b-jet comes from top decay in the low-p_T region,
from hard $g \to b\bar{b}$ splitting in the high-p_T tail

tH NLO+PS distributions: light jets

anti-k_T $p_T > 30$ GeV $R = 0.4$ $|\eta| < 4.5$ no H decay, $t \to b\ell\nu_\ell$

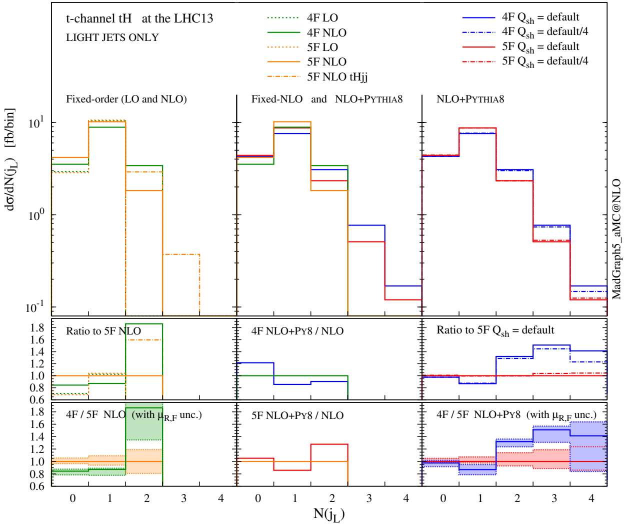


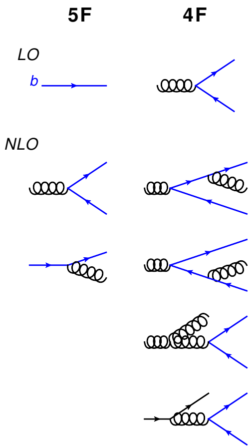
4F/5F discrepancy starts at fixed-NLO

It's reduced after the shower

It's related to the description of the $g \to b\bar{b}$ splitting

tH NLO+PS distributions: light jets





Conclusions (1)

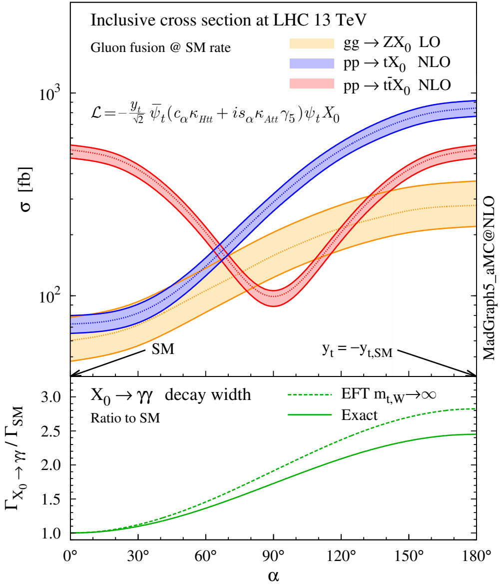
1. Both 4F and 5F are good to describe the NLO cross section
   $\Rightarrow$ combine

2. Carefully assessed the major sources of uncertainty in the cross section
   $\sigma_{\mathrm{NLO}}^{t-\mathrm{channel}} \simeq 72$ fb $\pm 8\%$ (μ+FS) $\pm 3\%$ (PDF$+\alpha_s + m_b$)
   (larger PDF uncertainty if considering systematics in the fitting procedure)

3. Both 4F and 5F are good to describe Higgs and top distributions
   (at NLO!)

4. 4F at NLO describes correctly many more distributions

Higgs characterisation: inclusive observables



$\alpha =$ CP-mixing angle

$\kappa_{Htt} = 1\,, \quad \kappa_{Att} = 2/3$

$\Rightarrow$ Gluon fusion @ SM rate $\forall\alpha$

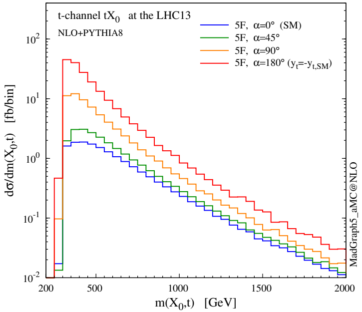
$t\bar{t}H$ helps to constrain α

tH, $gg \to ZH$ and $H \to \gamma\gamma$ further lift 2 degeneracies:

$y_t \leftrightarrow -y_t$

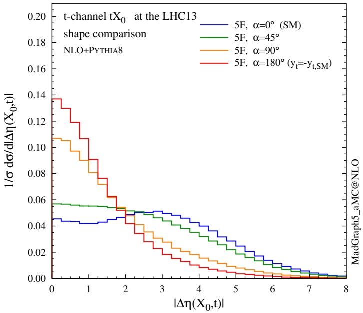
$\alpha \leftrightarrow \pi - \alpha$

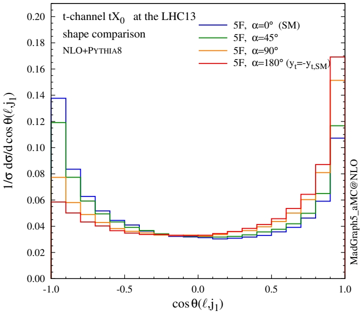
Higgs characterisation: tH distributions



New physics takes place mostly at threshold

Many observables are sensitive to n.p.!





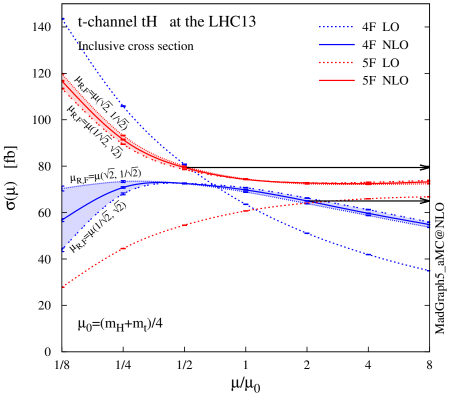
Conclusions (2)

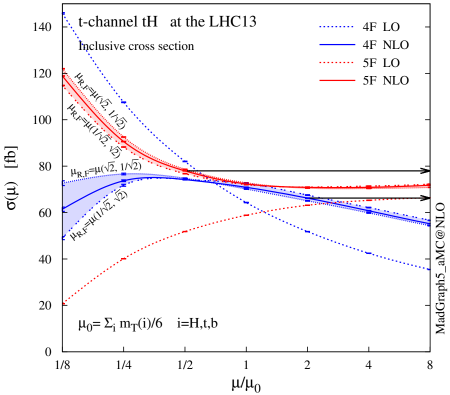
1. Global analysis of different Higgs productions/decays improve measurements and lift degeneracies in GF or $t\bar{t}H$
2. Higgs plus single top is a rare process, but provides a variety of observables sensitive to BSM physics
   $\Rightarrow$ very interesting for Higgs characterisation

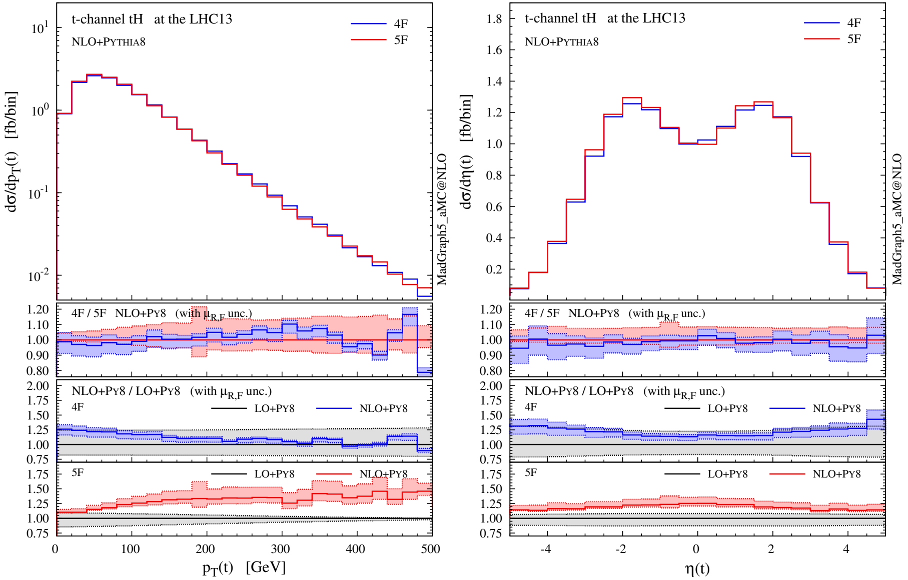
NB: Pheno studies are fully automatic, importing the `HC_NLO_X0` model inside the `MadGraph5_aMC@NLO` framework

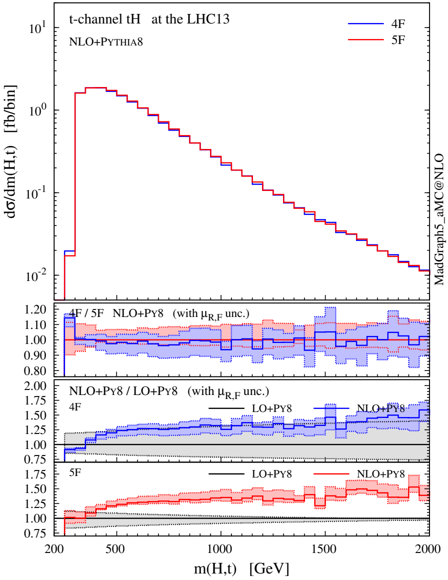
Thanks for your attention!

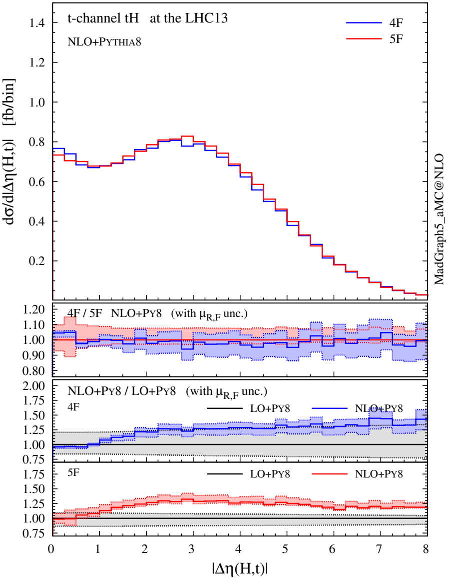
backup slides

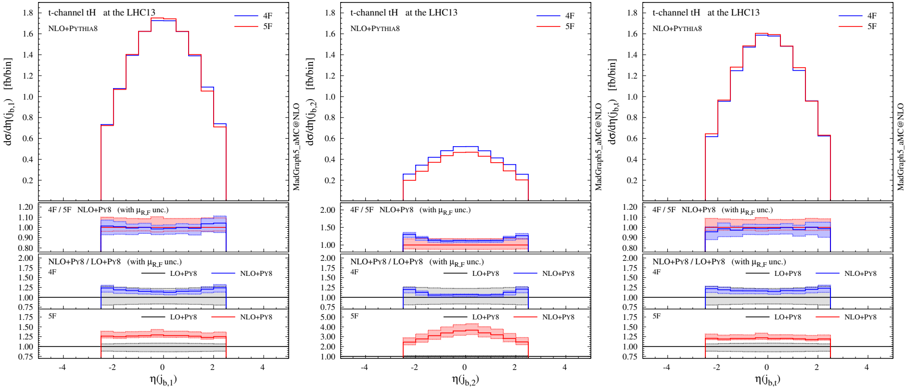

t-channel tH at the LHC13
Inclusive cross section
4F LO
4F NLO
5F LO
5F NLO
σ(μ) [fb]
μ/μ0
μ0=(mH+mt)/4
MadGraph5_aMC@NLO

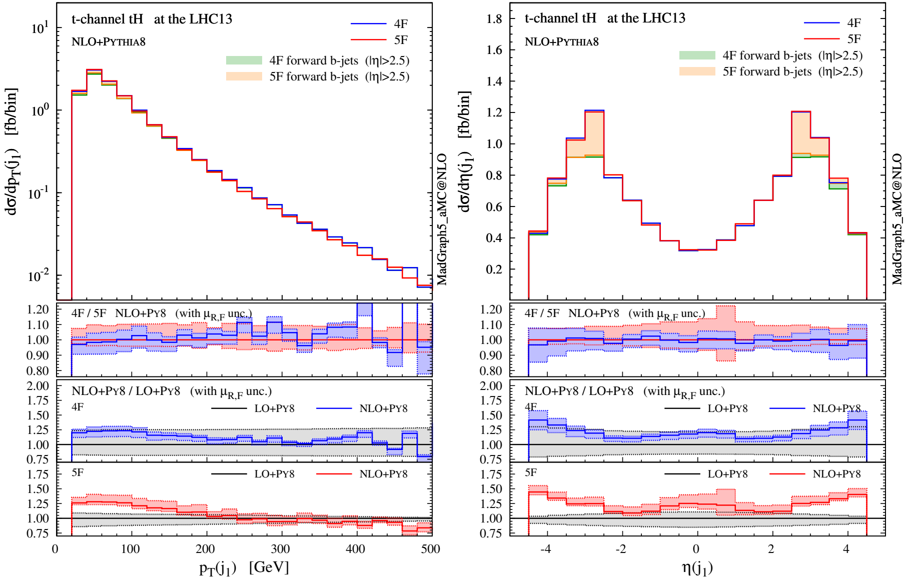

t-channel tH at the LHC13
Inclusive cross section
4F LO
4F NLO
5F LO
5F NLO
σ(μ) [fb]
μ/μ0
μ0= Σi mT(i)/6 i=H,t,b
MadGraph5_aMC@NLO

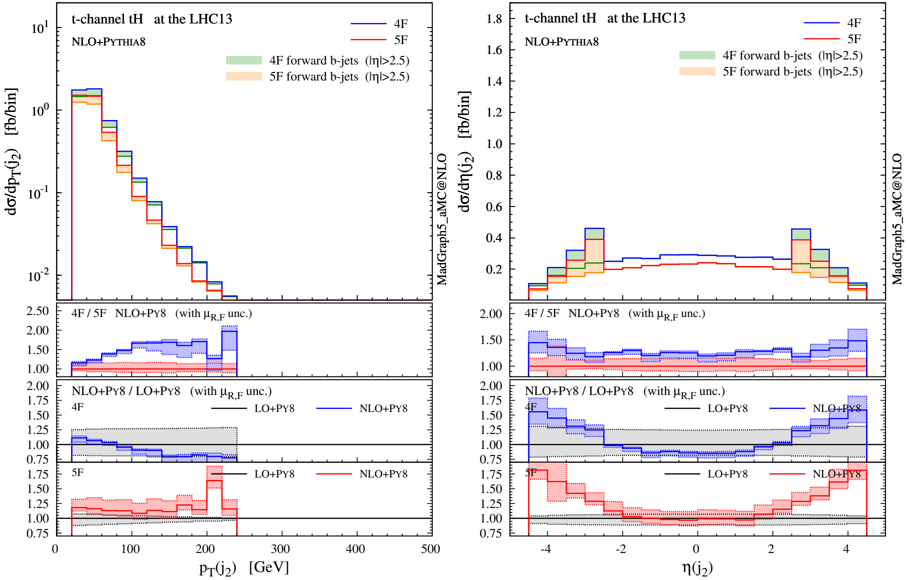

t-channel tH at the LHC13
NLO+PYTHIA8
4F
5F
dσ/dp_T(t) [fb/bin]
MadGraph5_aMC@NLO
4F / 5F NLO+PY8 (with μ_R,F unc.)
NLO+PY8 / LO+PY8 (with μ_R,F unc.)
LO+PY8
NLO+PY8
p_T(t) [GeV]
dσ/dη(t) [fb/bin]
η(t)


t-channel tH at the LHC13
NLO+PYTHIA8
4F
5F
dσ/dm(H,t) [fb/bin]
MadGraph5_aMC@NLO
4F / 5F NLO+PY8 (with μR,F unc.)
NLO+PY8 / LO+PY8 (with μR,F unc.)
LO+PY8
NLO+PY8
m(H,t) [GeV]


t-channel tH at the LHC13
NLO+PYTHIA8
4F
5F
dσ/d|Δη(H,t)| [fb/bin]
MadGraph5_aMC@NLO
4F / 5F NLO+PY8 (with μR,F unc.)
NLO+PY8 / LO+PY8 (with μR,F unc.)
LO+PY8
NLO+PY8
|Δη(H,t)|


t-channel tH at the LHC13
NLO+PYTHIA8
4F
5F
dσ/dη(j_{b,1}) [fb/bin]
dσ/dη(j_{b,2}) [fb/bin]
dσ/dη(j_{b,t}) [fb/bin]
MadGraph5_aMC@NLO
4F / 5F NLO+PY8 (with μ_{R,F} unc.)
NLO+PY8 / LO+PY8 (with μ_{R,F} unc.)
LO+PY8
NLO+PY8
η(j_{b,1})
η(j_{b,2})
η(j_{b,t})


t-channel tH at the LHC13
NLO+PYTHIA8
4F
5F
4F forward b-jets (|η|>2.5)
5F forward b-jets (|η|>2.5)
dσ/dp_T(j_1) [fb/bin]
MadGraph5_aMC@NLO
4F / 5F NLO+PY8 (with μR,F unc.)
NLO+PY8 / LO+PY8 (with μR,F unc.)
LO+PY8
NLO+PY8
p_T(j_1) [GeV]
dσ/dη(j_1) [fb/bin]
η(j_1)


t-channel tH at the LHC13
NLO+PYTHIA8
4F
5F
4F forward b-jets (|η|>2.5)
5F forward b-jets (|η|>2.5)
dσ/dp_T(j_2) [fb/bin]
MadGraph5_aMC@NLO
4F / 5F NLO+PY8 (with μ_R,F unc.)
NLO+PY8 / LO+PY8 (with μ_R,F unc.)
LO+PY8
NLO+PY8
p_T(j_2) [GeV]
dσ/dη(j_2) [fb/bin]
η(j_2)

s-channel ($\simeq 3$ fb) $<<$ t-channel, but very different shapes!