Charged Higgs bosons in the 2HDM/MSSM

Contribution to the 4th Yellow Report of the LHC HXSWG

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on behalf of
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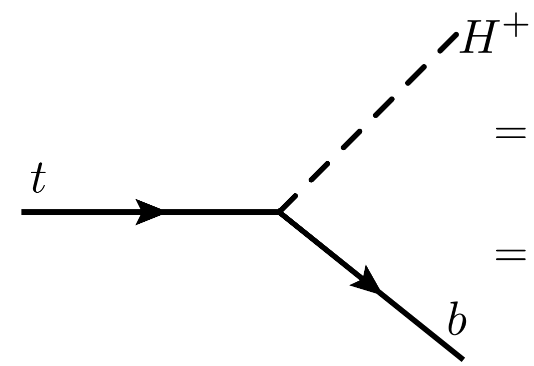
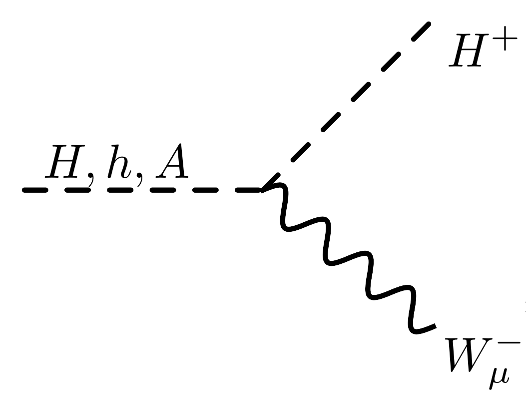
Charged Higgs boson couplings in the 2HDM

- In the 2HDM (∋MSSM), charged Higgs bosons couple either to another Higgs and a W, or to fermions
- β is related to the vevs ratio $\tan\beta = v_1/v_2$
- α is the $(\Phi_1, \Phi_2) \rightarrow (h,H)$ mixing angle
- No VVH coupling exists at tree level (feature of models with only doublets)



$$= -i\frac{1}{\tan\beta}\left(y_t P_R + y_b P_L\right) \quad \text{type I}$$

$$= -i\left(\frac{y_t}{\tan\beta} P_R + y_b \tan\beta P_L\right) \quad \text{type II}$$



$$= i\frac{g_W}{2}\cos(\beta-\alpha)p^\mu_W \quad (h)$$

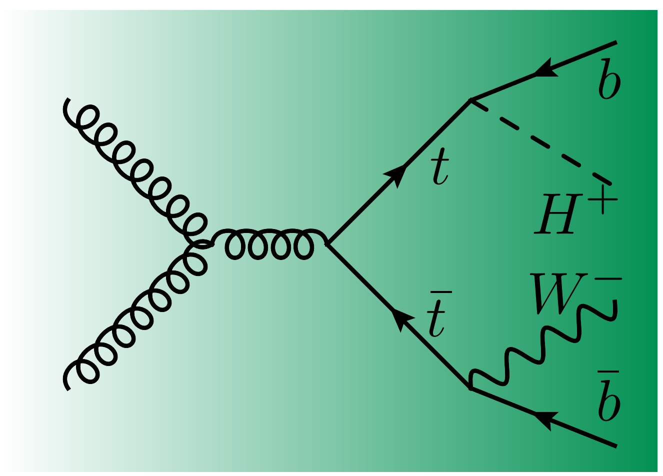
$$= i\frac{g_W}{2}\sin(\beta-\alpha)p^\mu_W \quad (H)$$

$$= i\frac{g_W}{2}p^\mu_W \quad (A)$$

Charged Higgs production in 2HDMs

- In the 2HDM, the dominant production channel depends on the Charged Higgs mass

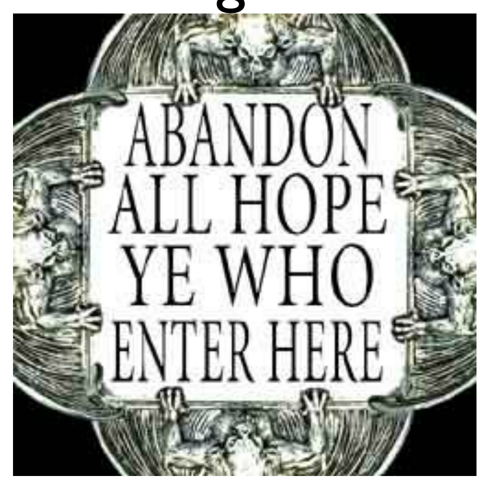
light Higgs



$M_{H^+} < M_t$

H± mostly produced in $t\bar{t}$ events. Depending on BR(t→H±b) also H±t can become important. At NLO one has to subtract on-shell tops

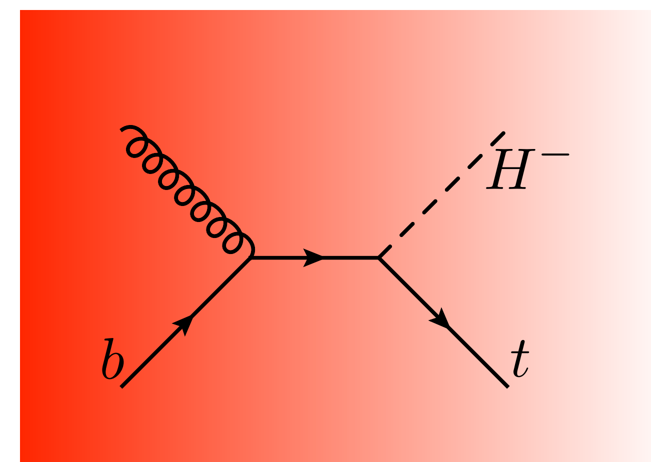
Intermediate region



$M_{H^+} \simeq M_t$

The full pp→H±W∓$b\bar{b}$ process has to be simulated.

heavy Higgs



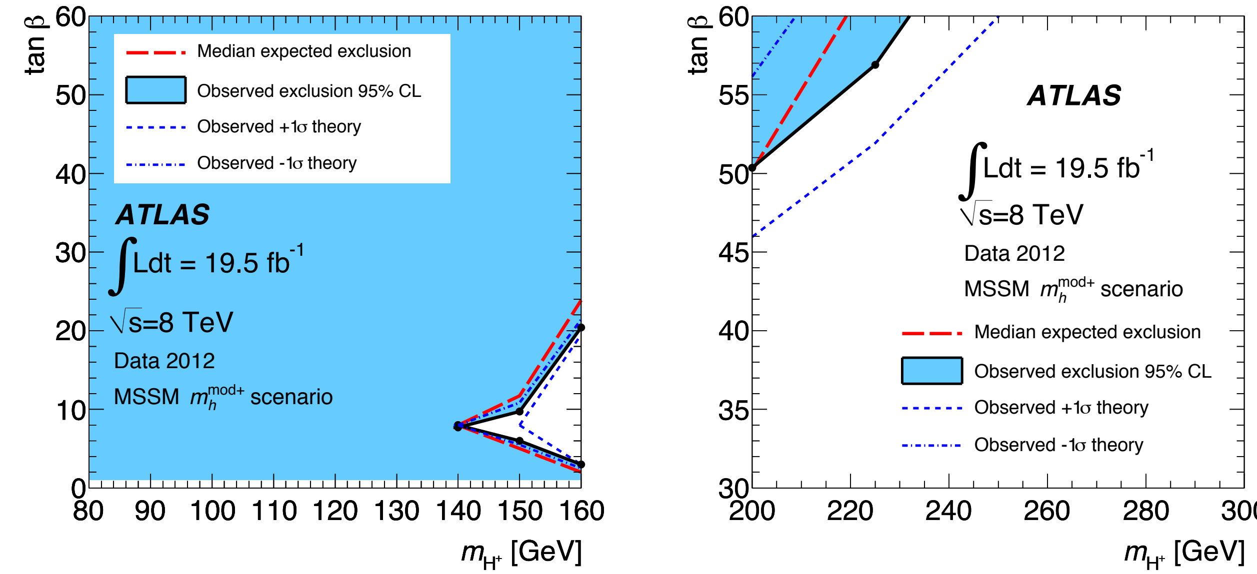
$M_{H^+} > M_t$

H± mostly produced in association with a top quark

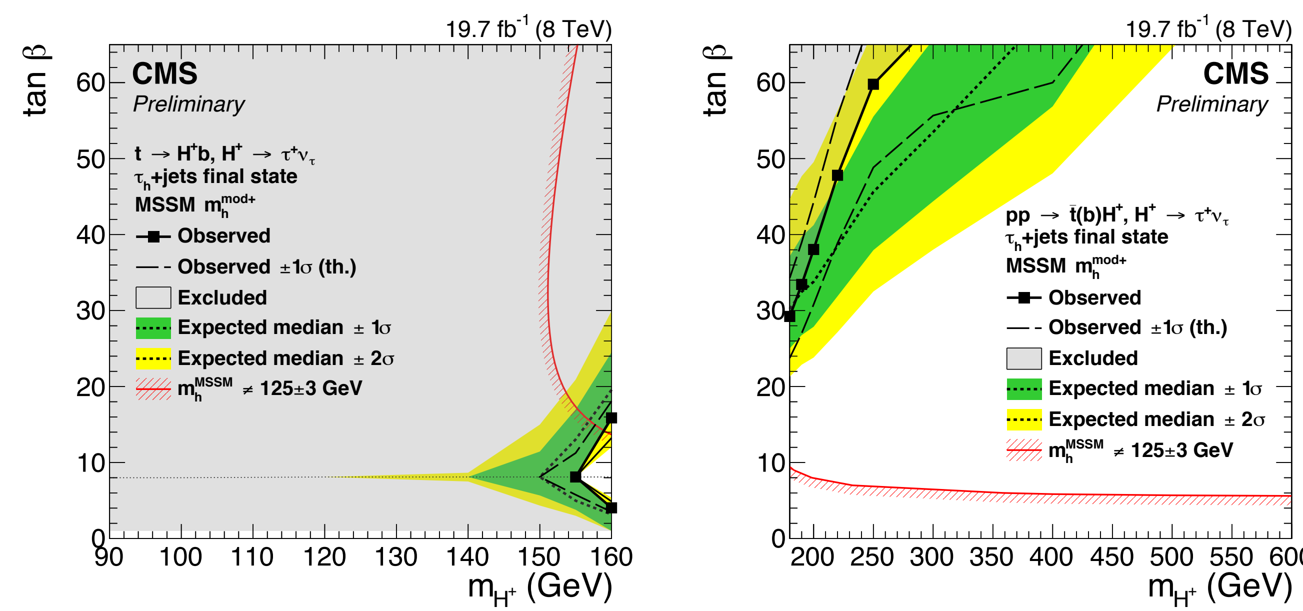
Searches at the LHC

- LHC experiments tend to exclude a light charged Higgs
- For a heavy charged Higgs, only very large values of $\tan\beta$ are excluded
- Missing mass window due to non-existence of NLO predictions for the intermediate range

ATLAS, arXiv:1412.6663

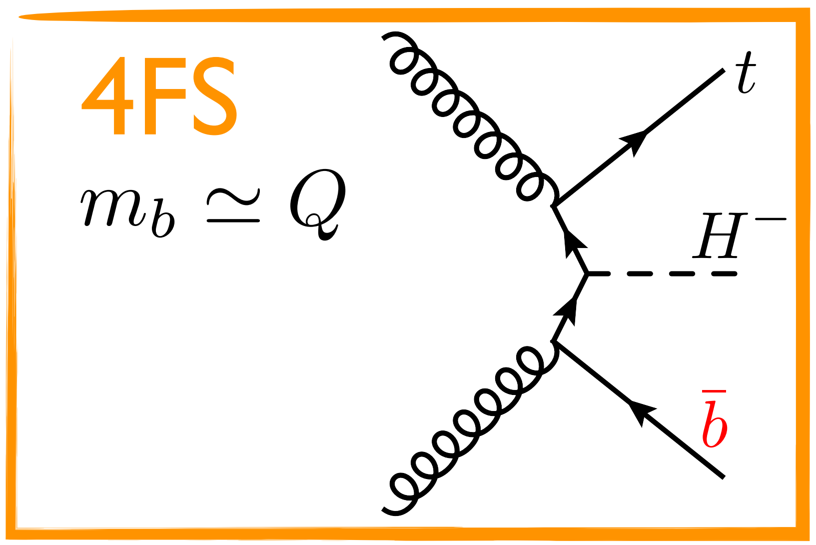


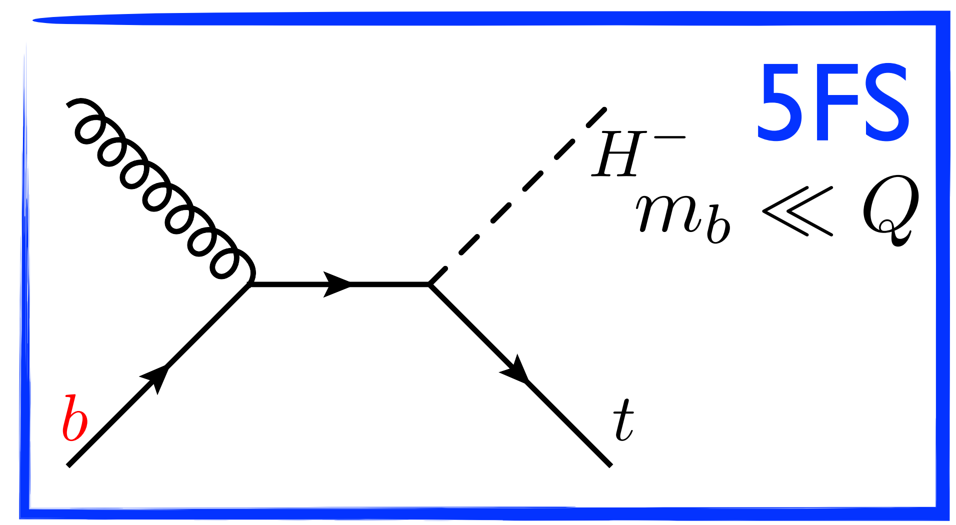
CMS, PAS HIG-14-020



Heavy charged Higgs production

- Production mechanism features b quarks in the initial state: can be described either with 4- or 5-flavour scheme





✘ 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

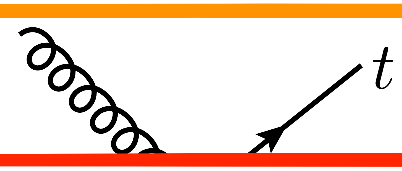
✔ Simpler process; computing HO is easier
✔ b-PDF resums $\log(m_b/Q)$ at all orders
✘ b-quark observables enter at higher orders
✘ Matching to PS requires some care (gluon splitting, momentum reshuffling, …)

Two schemes are equivalent if all orders were known
Which one to use? Can we combine them and maximise the pros?

Heavy charged Higgs production

- Production mechanism features b quarks in the initial state: can be described either with 4- or 5-flavour scheme

4FS



5FS

✘ Hi
HC
✘ Cr
log
✔ Ac
✔ Str

er

ders
on

Higher order results:

- NLO (SUSY-)QCD corrections
  Dittmaier et al, arXiv:0906.2648;
  Zhu, hep-ph/0112109, Plehn, hep-ph/0206121, Berger et al, hep-ph/0312286
- EW corrections
  Nhung et al, arXiv:1210.4087;
  Beccaria et al, arXiv:0908.1332
- Threshold resummation
  Kidonakis, arXiv:1005.4451
- Fully differential NLO+PS
  Degrande et al, arXiv:1507.02549;
  Weydert et al, arXiv:0912.3430, Klasen et al, arXiv:1203.1341

Two schemes are equivalent if all orders were known

Which one to use? Can we combine them and maximise the pros?

Matched predictions for the total cross-section

Method proposed in Flechl, Klees, Kramer, Spira, Ubiali, arXiv:1409.5615

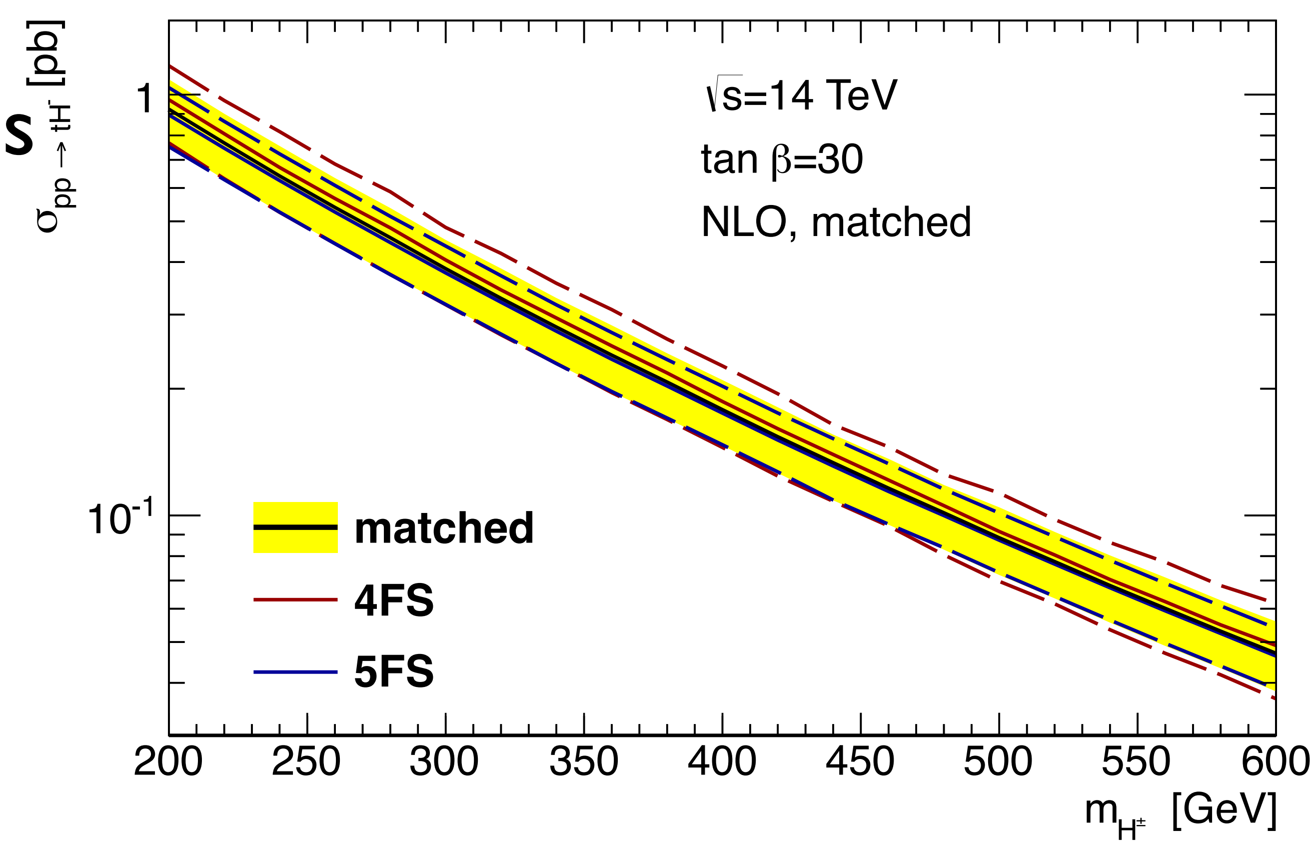
- The scale in the logs resumed in the 5FS is typically much smaller than the hard scale of the process (phase-space suppression) Maltoni, Ridolfi, Ubiali, arXiv:1203.6393

$$Q^2_{tHb} = M^2 \frac{(1-z)^2}{z} \qquad z = \frac{M^2}{\hat{s}}$$

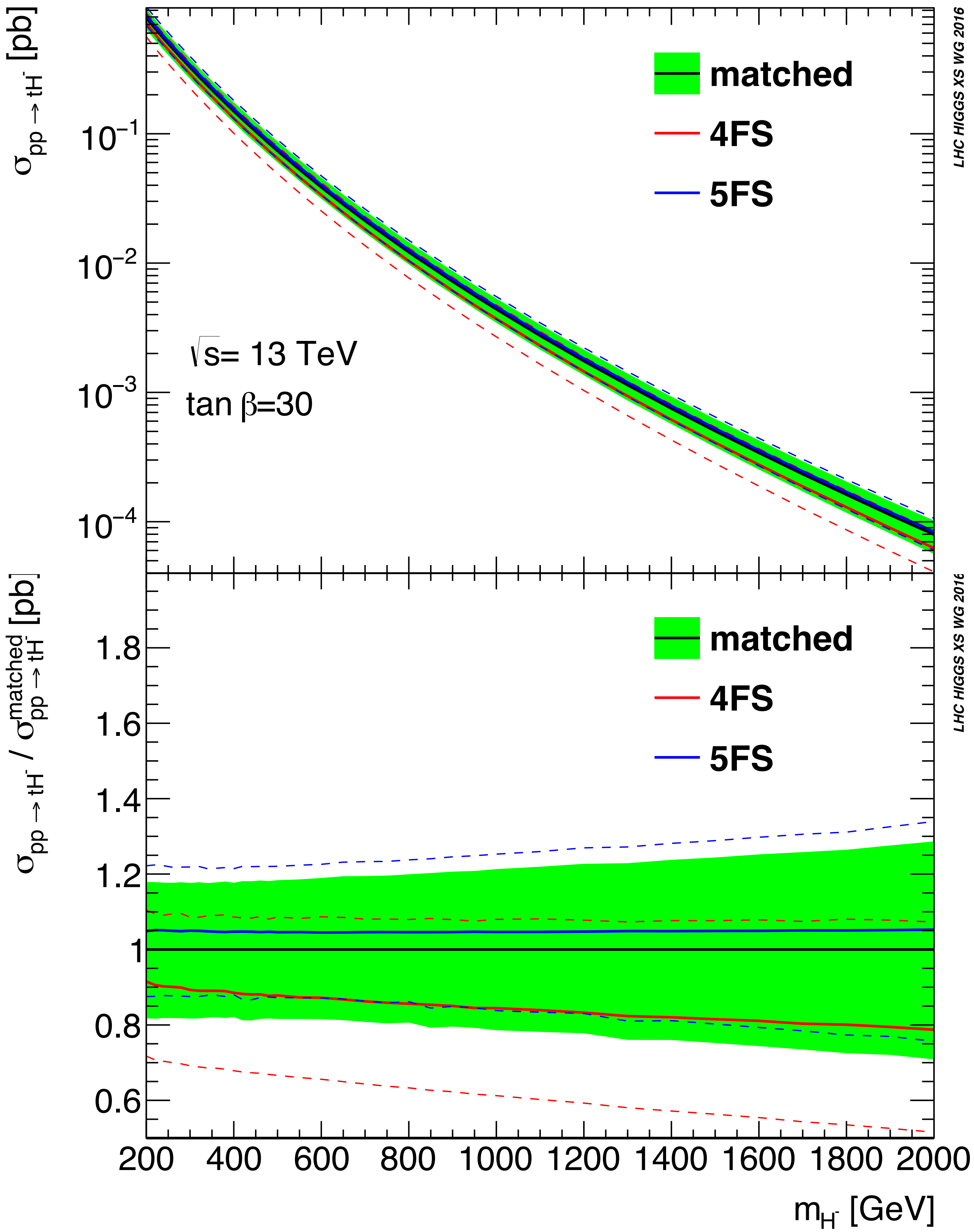
  - Set $\mu_F = \tilde{\mu}$ in the 5FS
- Include all sources of uncertainties
  - scale, PDF (PDF4LHC), m_b, α_s
- Compare 5FS, 4FS @NLO and Santander-matched prediction

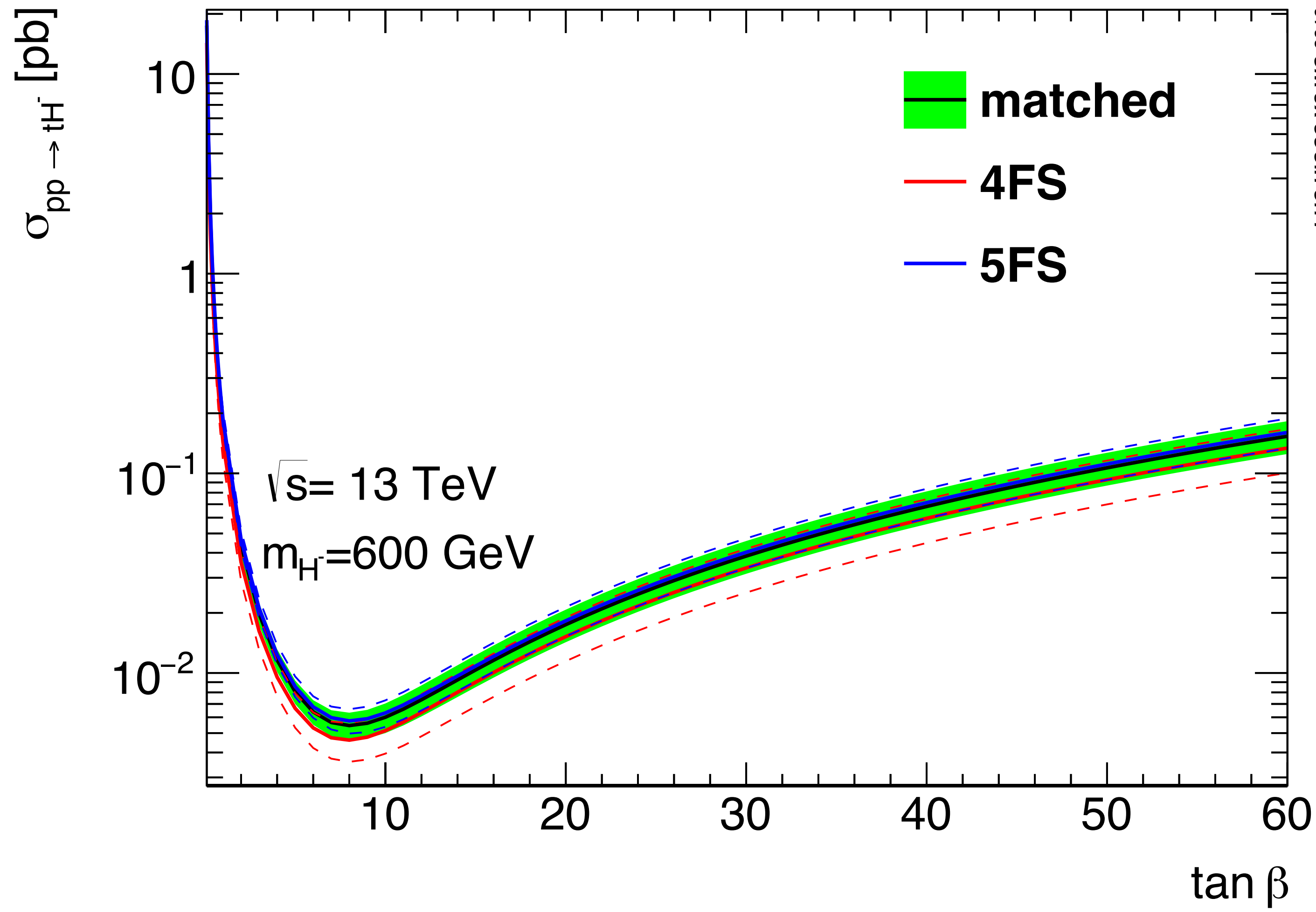
$$\sigma_{\text{matched}} = \frac{\sigma_{4\text{F}} + w\sigma_{5\text{F}}}{1+w} \qquad w = \log\frac{m_{H^\pm}}{m_b} - 2$$

	8 TeV		14 TeV	
$M_{\mathrm{H}^\pm}$ [GeV]	$\tilde{\mu}$ [GeV]	$(m_t + M_{\mathrm{H}^\pm})/\tilde{\mu}$	$\tilde{\mu}$ [GeV]	$(m_t + M_{\mathrm{H}^\pm})/\tilde{\mu}$
200	67.3	5.5	74.9	5.0
300	80.3	5.9	90.6	5.2
400	92.1	6.2	105.3	5.4
500	103.1	6.5	119.0	5.7



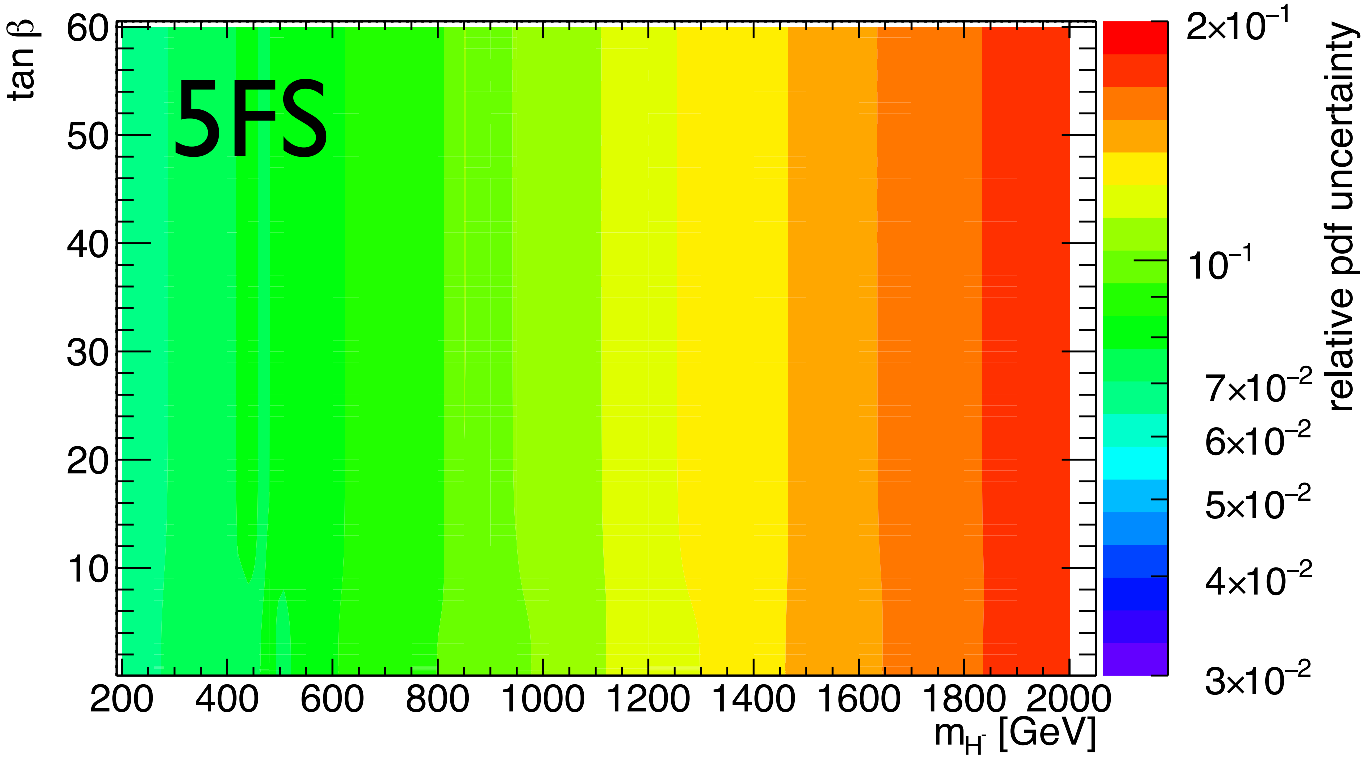
Updated Matched Predictions

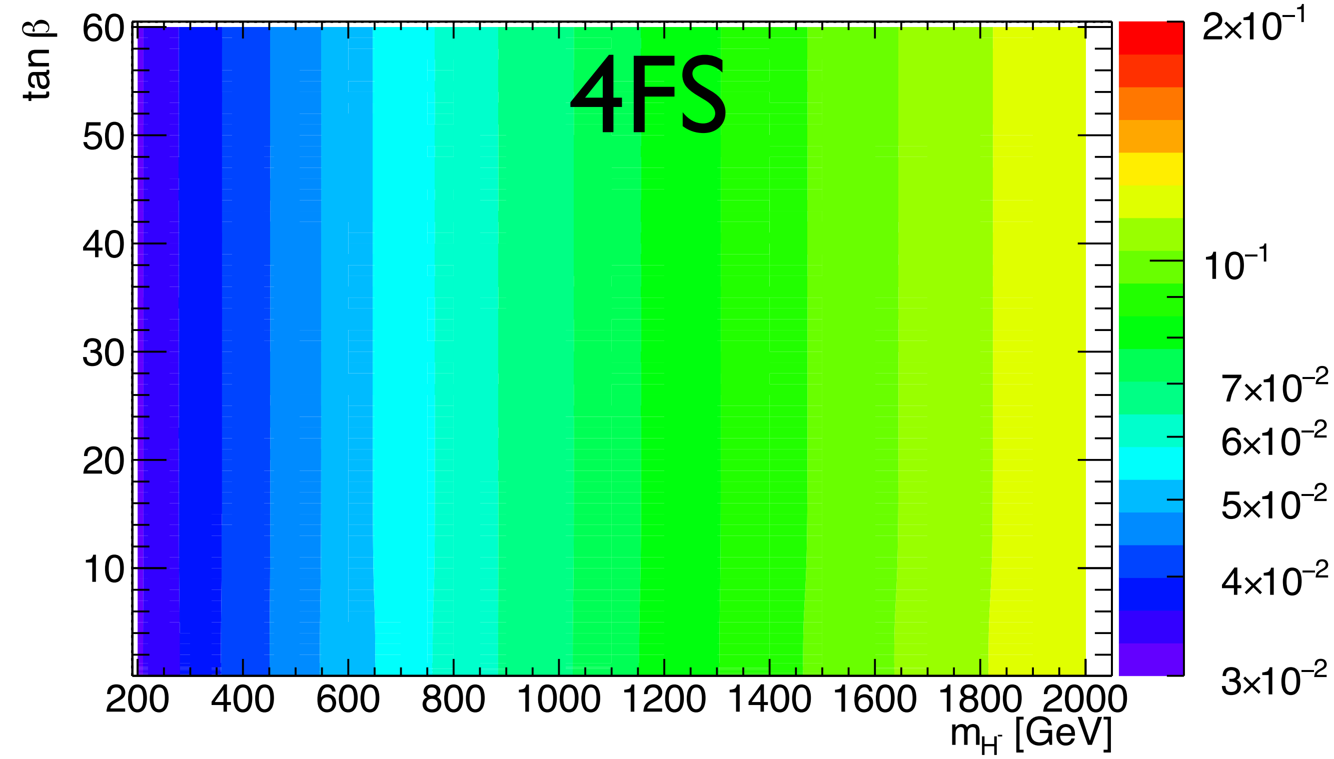




- Input parameters as in LHCHXSWG-INT-2015-006; NLO QCD
- $\tan\beta$ scan exact, no interpolation

Updated Matched Predictions: PDF errors





PDF errors roughly of the same size as in the previous computation (1409.5615)

$\sqrt{s}$ [TeV], PDF set	$m_{H^\pm}$ [GeV]	$\sigma_{\rm NLO}$ [pb]	$\delta_{\rm PDF}$ [%]	$\delta\alpha_s$ [%]	δm_b [%]
14	200	0.870	$^{+3.9}_{-3.5}$	$^{+0.0}_{-0.0}$	n.a.
CT10	400	0.171	$^{+5.7}_{-5.2}$	$^{+0.0}_{-0.0}$	n.a.
	600	0.0458	$^{+7.6}_{-6.9}$	$^{+0.5}_{-0.5}$	n.a.
14	200	0.902	$^{+2.7}_{-3.6}$	$^{+0.1}_{-0.0}$	$^{+2.9}_{-2.7}$
MSTW2008	400	0.176	$^{+4.0}_{-3.9}$	$^{+0.0}_{-0.0}$	$^{+2.9}_{-2.6}$
	600	0.0468	$^{+4.7}_{-6.1}$	$^{+0.0}_{-0.2}$	$^{+2.9}_{-2.7}$
14	200	0.913	± 2.7	± 0.8	± 1.5
NNPDF2.3	400	0.179	± 3.9	± 0.6	± 1.2
	600	0.0471	± 5.1	± 0.5	± 1.2

$\sqrt{s}$[TeV], PDF set	$m_{H^\pm}$[GeV]	$\sigma_{\rm NLO}$ [pb]	$\delta_{\rm PDF}$ [%]	$\delta\alpha_s$ [%]	δm_b [%]
14	200	0.938	n.a	n.a.	n.a.
CT10	400	0.180	n.a.	n.a.	n.a.
	600	0.0475	n.a.	n.a.	n.a.
14	200	0.972	$^{+1.1}_{-0.8}$	n.a.	$^{+2.5}_{-2.6}$
MSTW2008	400	0.186	$^{+2.2}_{-2.7}$	n.a.	$^{+2.6}_{-2.6}$
	600	0.0489	$^{+6.9}_{-5.5}$	n.a.	$^{+2.6}_{-2.5}$
14	200	0.983	± 2.6	$^{+0.1}_{-0.0}$	n.a.
NNPDF2.3	400	0.187	± 3.8	$^{+0.4}_{-0.5}$	n.a.
	600	0.0481	± 5.0	$^{+0.6}_{-0.9}$	n.a.

Beyond total cross section

- How do the two schemes compare at differential level?
- How important are m_b power effects and collinear logs for a given observable?
- Which scheme to use for signal simulations?

Need for comparison
at fully differential level

Fully differential comparison of 4 and 5FS at NLO

Following Degrande, Ubiali, Wiesemann, MZ, arXiv:1507.02549

- Use modern automated tool chains to generate the code, starting from the model Lagrangian
  - Generate UV/R_2 counterterms for the evaluation of loops with NLOCT Degrande arXiv:1406.3030
  - Use MadGraph5_aMC@NLO to generate the code for event generation Alwall et al. arXiv:1405.0301
- MSbar renormalisation to be preferred for y_b: logs of μ_R/m_b resummed. Add $m_b(\mu_R)$ dependence as in Wiesemann et al. arXiv:1409.5301
- b-initiated processes typically prefer scales lower than $\hat{s}$. Same argument holds also for the shower scale

- Decay top quark leptonically and keep charged Higgs stable. Typical final state with two b-jet/B-hadrons, one from top and one from ME / PS. Use MCTruth to reconstruct top

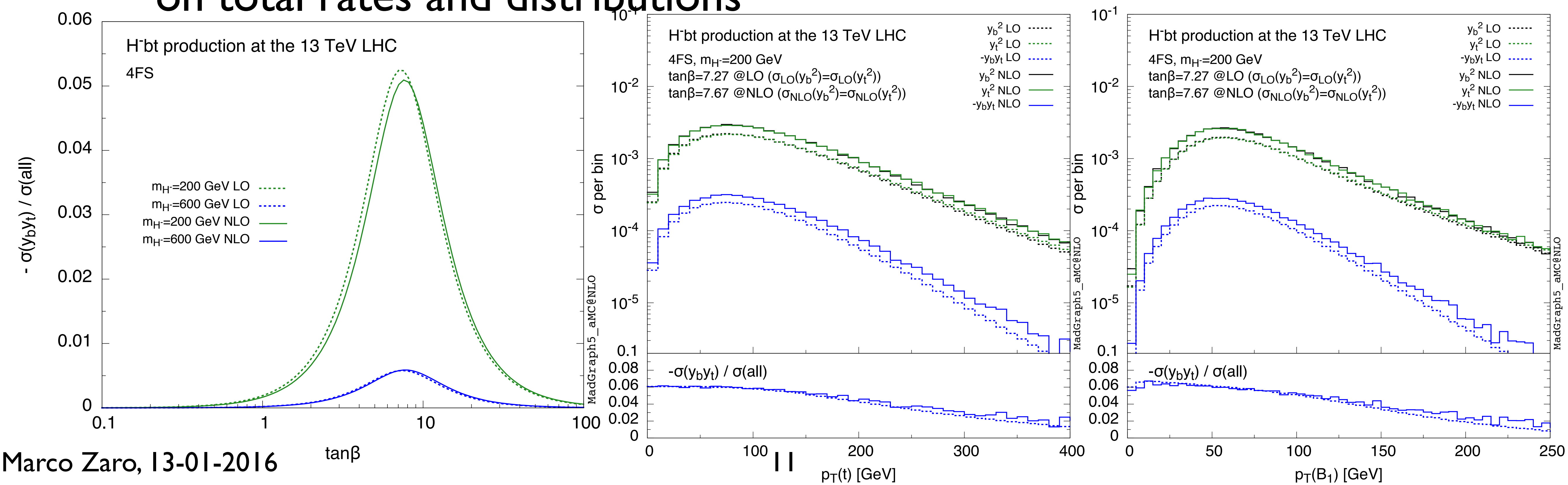
Setup and cross-section structure

- The following parameters are used

$$\sqrt{S} = 13\,\text{TeV} \qquad m_H = 200\ \text{GeV} \qquad \tan\beta = 8$$

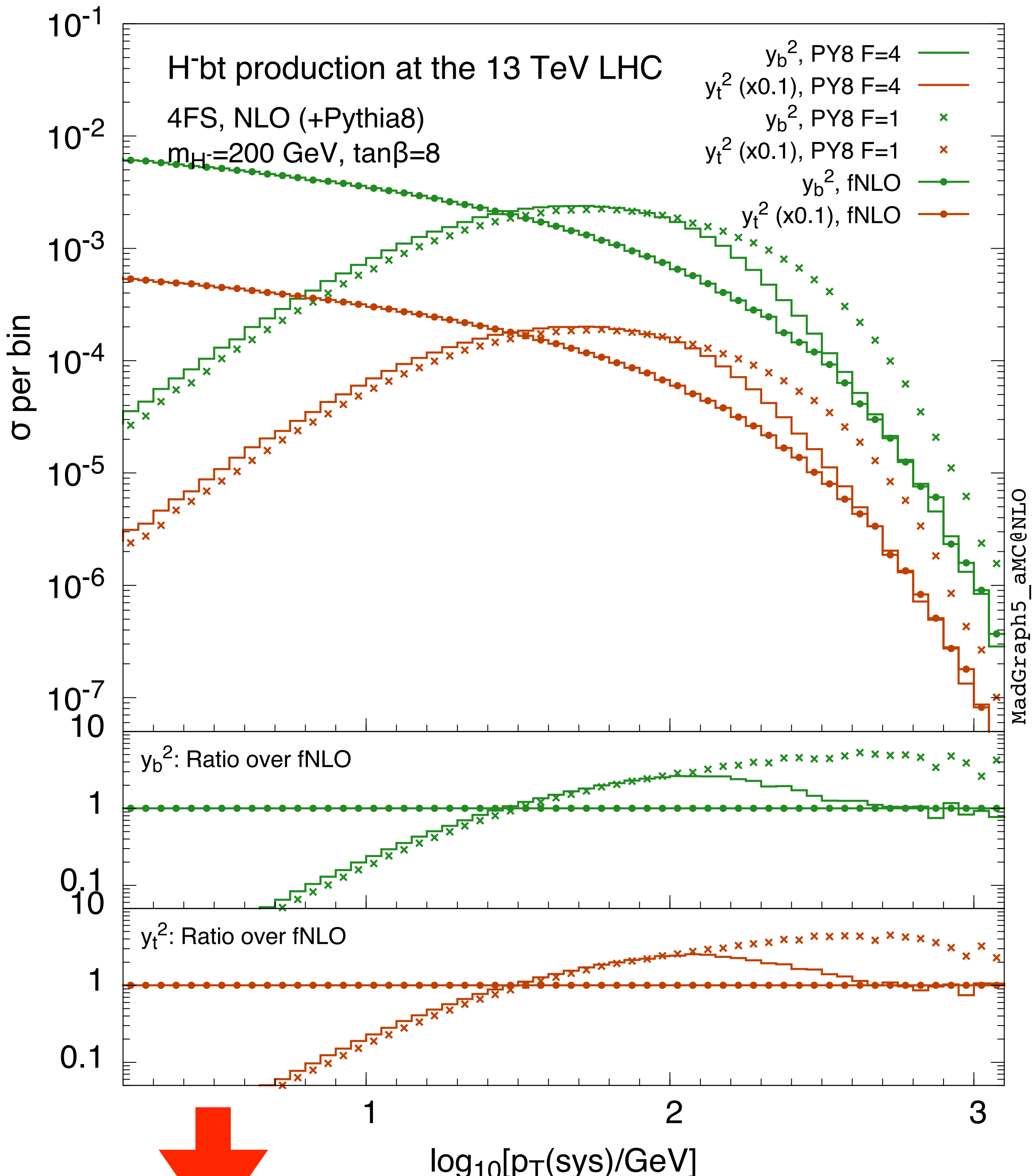
$$\mu_R = \mu_F = \mu_B = H_T/3 = \sum \sqrt{p_T(i)^2 + m(i)^2}/3$$

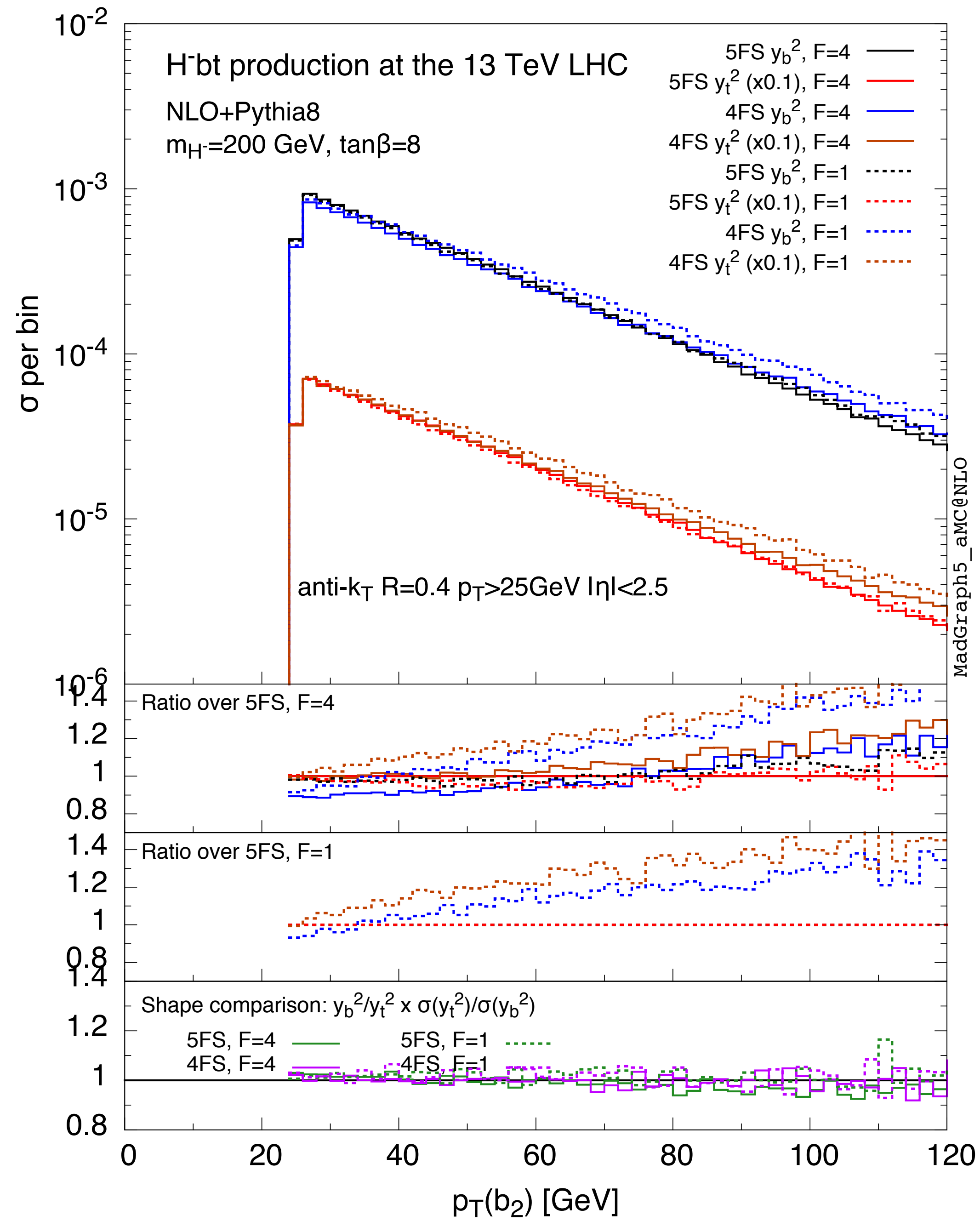
- Owing to the structure of the H$^{\pm}$tb coupling, the cross section will receive three contributions: y_b^2 ($\sim\tan\beta^2$), y_t^2 ($\sim 1/\tan\beta^2$) and $y_b y_t$ ($\tan\beta$ independent).
  - In the 5FS, the $y_b y_t$ term is null (helicity conservation)
  - In the 4FS, it is proportional to $m_b/\hat{s}$. Numerically it turns to be negligible on total rates and distributions



Choice of shower scale

pltos from Degrande, Ubiali, Wiesemann, MZ, arXiv:1507.02549





Reduced shower scale to be preferred improves NLO+PS/fNLO matching at high-p_T

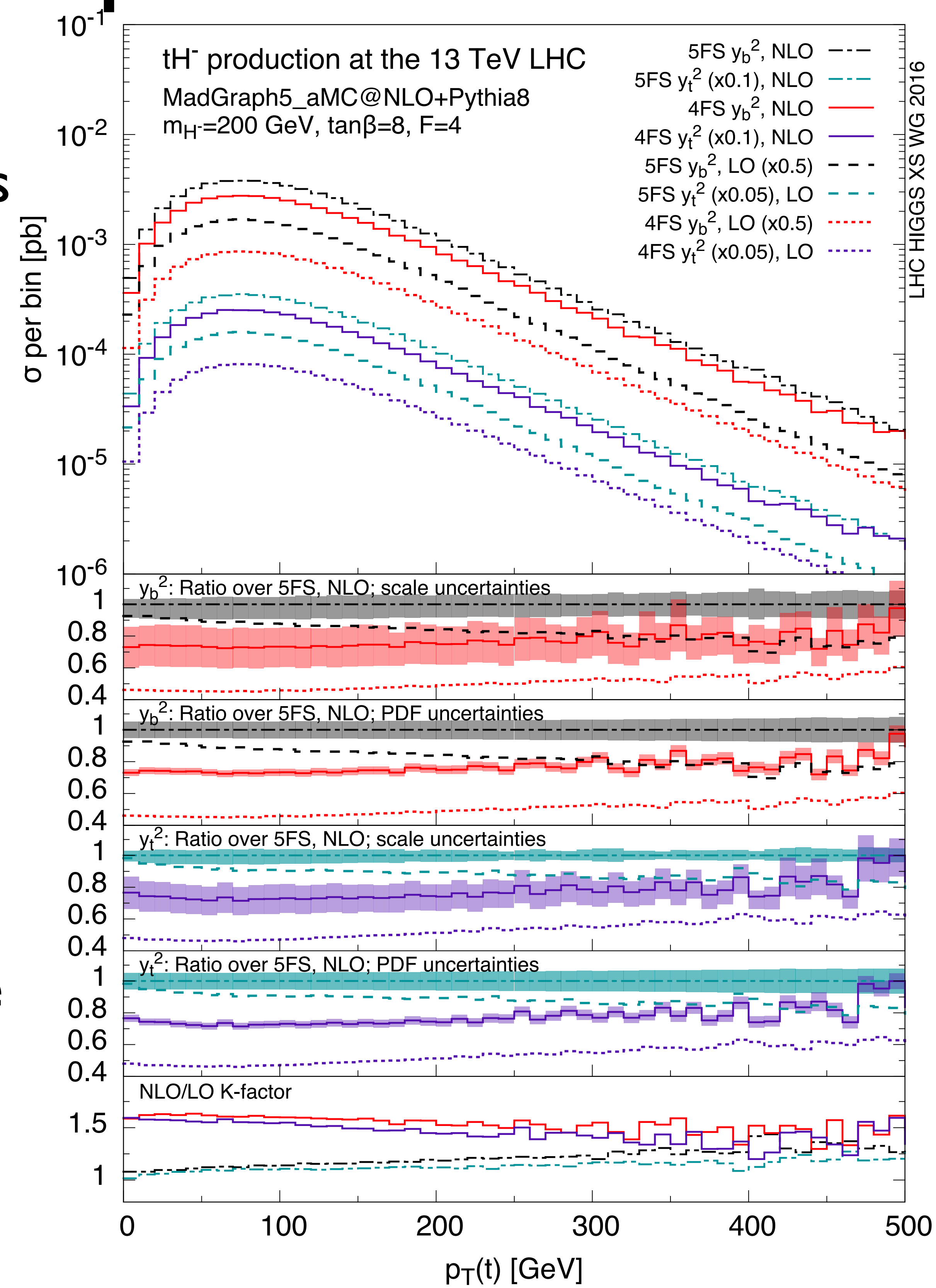
Consequence:
better agreement at differential level between the two schemes

Updated 5FS vs 4FS comparison

- Same setup as in 1507.02549, with parameters as in LHCHXSWG-INT-2015-006. In particular:
  - PDF4LHC 2015 NLO PDFs (4 and 5FS), both for LO and NLO
  - m_b running at 4 loops from $m_b(m_b)$ to $m_b(\mu_R)$; scale variations at 2 loops, both for LO and NLO
  - Only show results matching with Pythia 8, for the reduced shower scale (F=4)
  - Very similar behaviour of predictions as in 1507.02549

4FS vs 5FS: Updated comparison

- NLO corrections improve the shape agreement between the two schemes
- Very good agreement for b-inclusive observables ($p_T(t), p_T(H)$)
- Agreement remains quite good for more exclusive observables ($p_T(b_2)$), despite the large K-factors and uncertainties for 5FS
- Very exclusive observables ($p_T(B_2)$) show larger discrepancies in regions where mass-effects are enhanced
- Bottom line: 4FS gives a better description in particular for exclusive observables and less systematics due to PS matching



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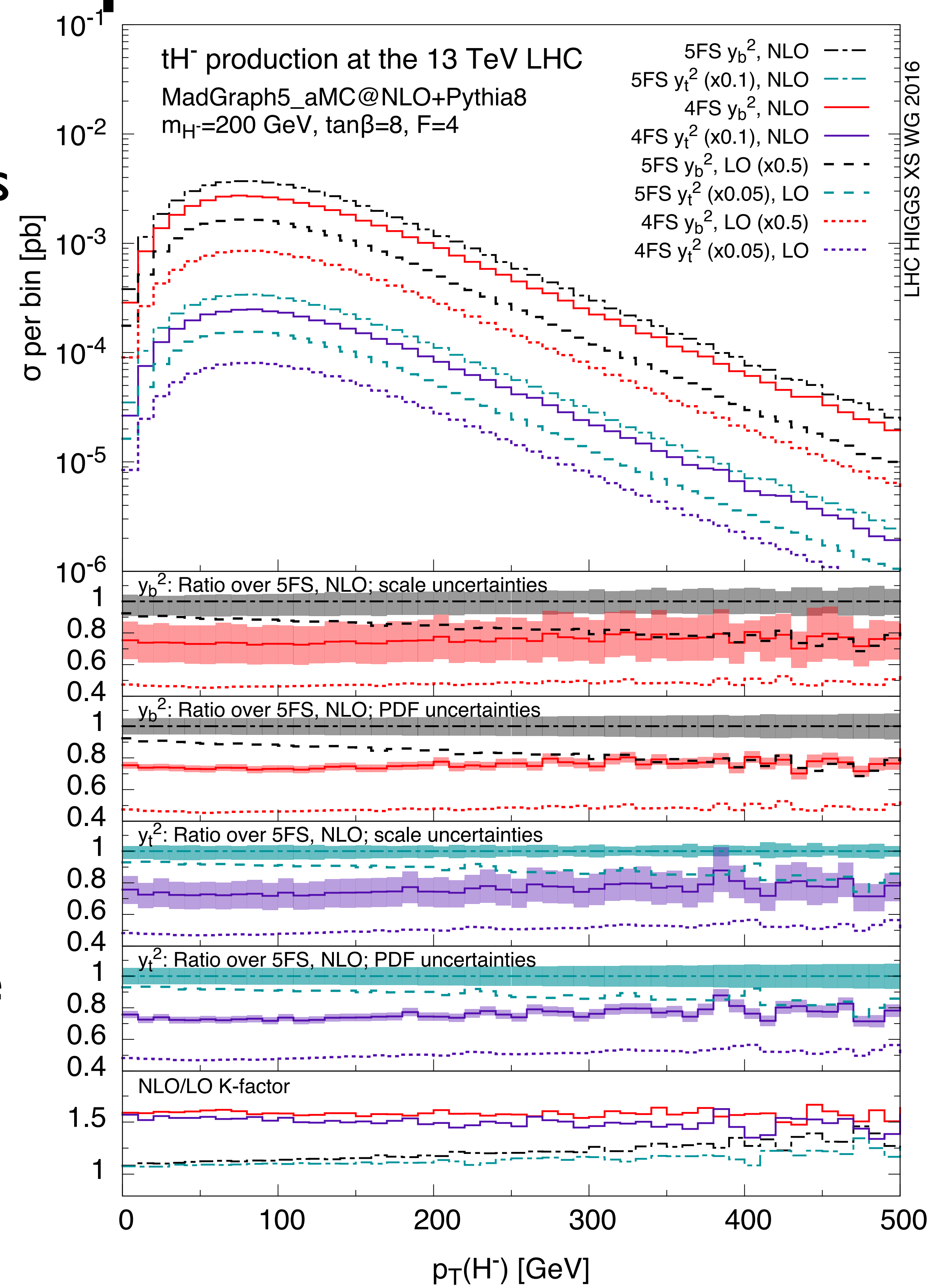

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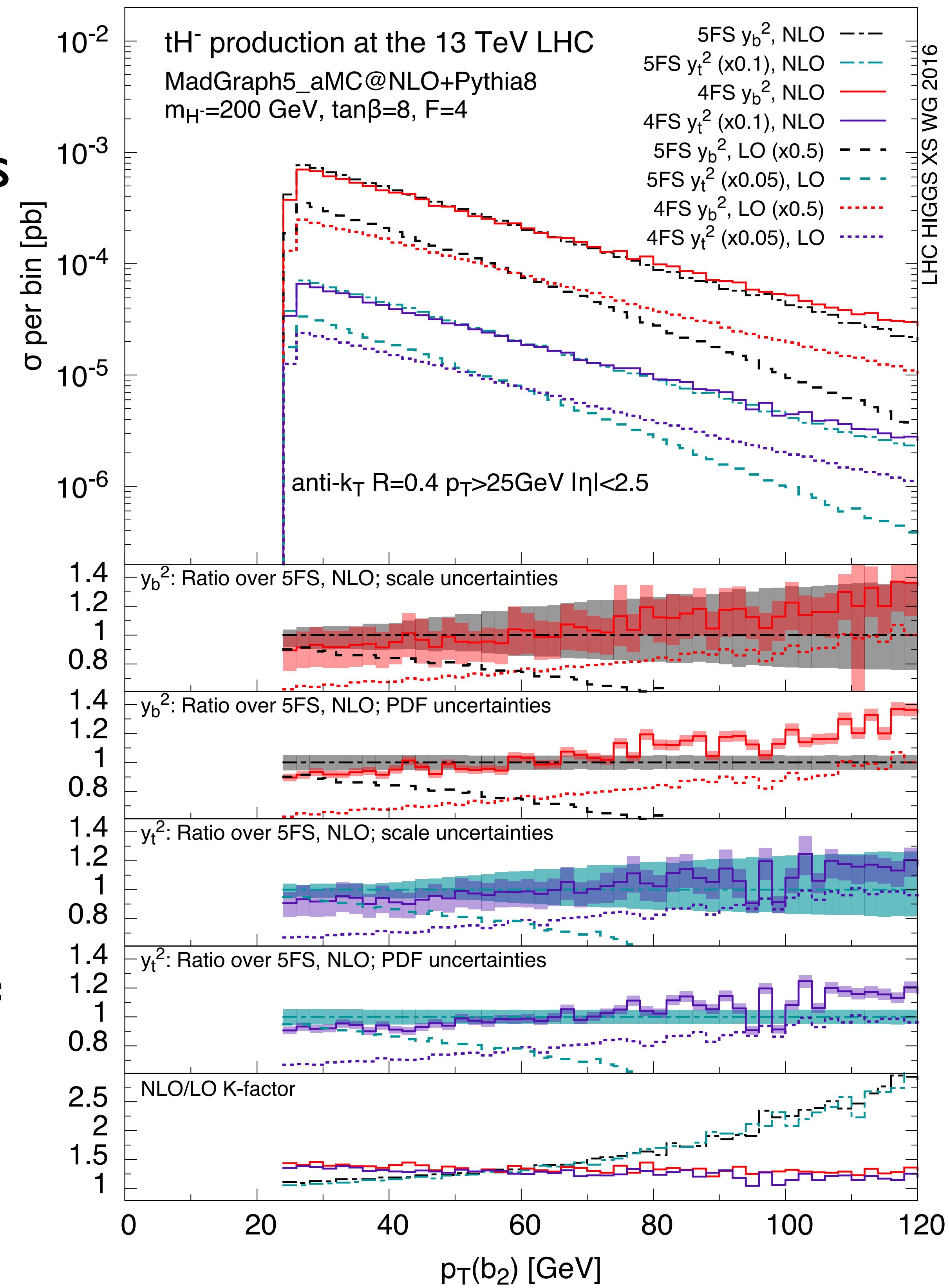

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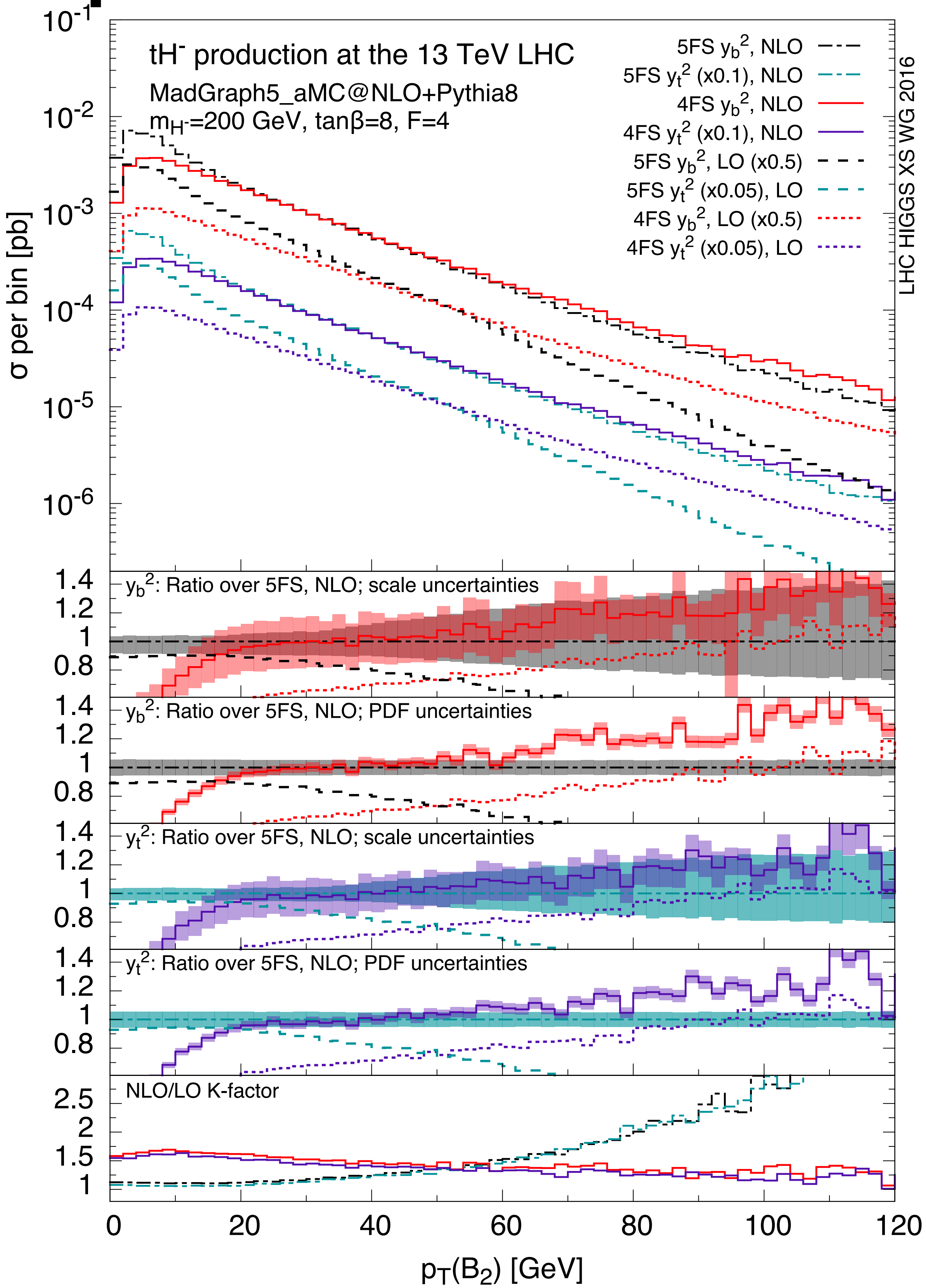
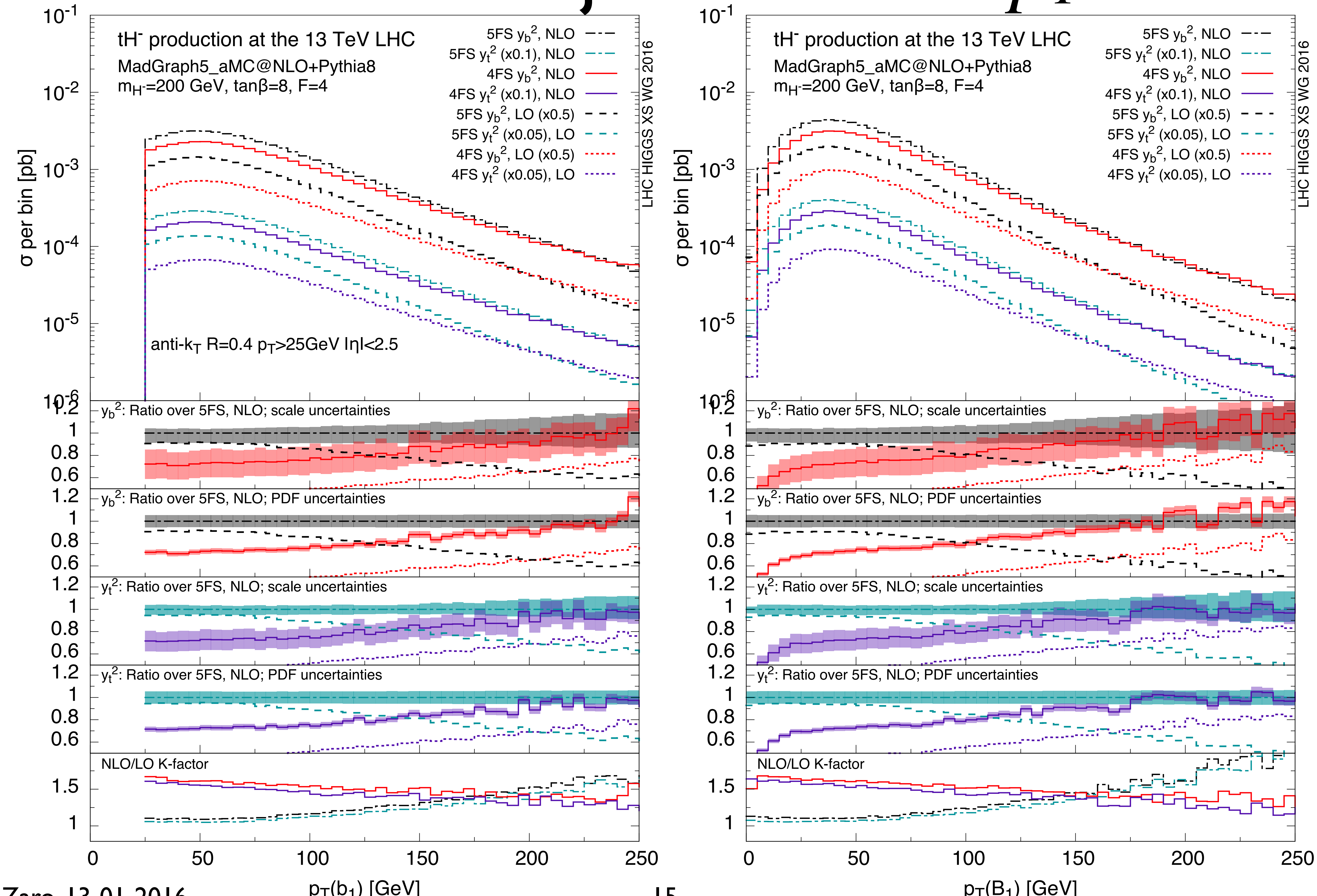
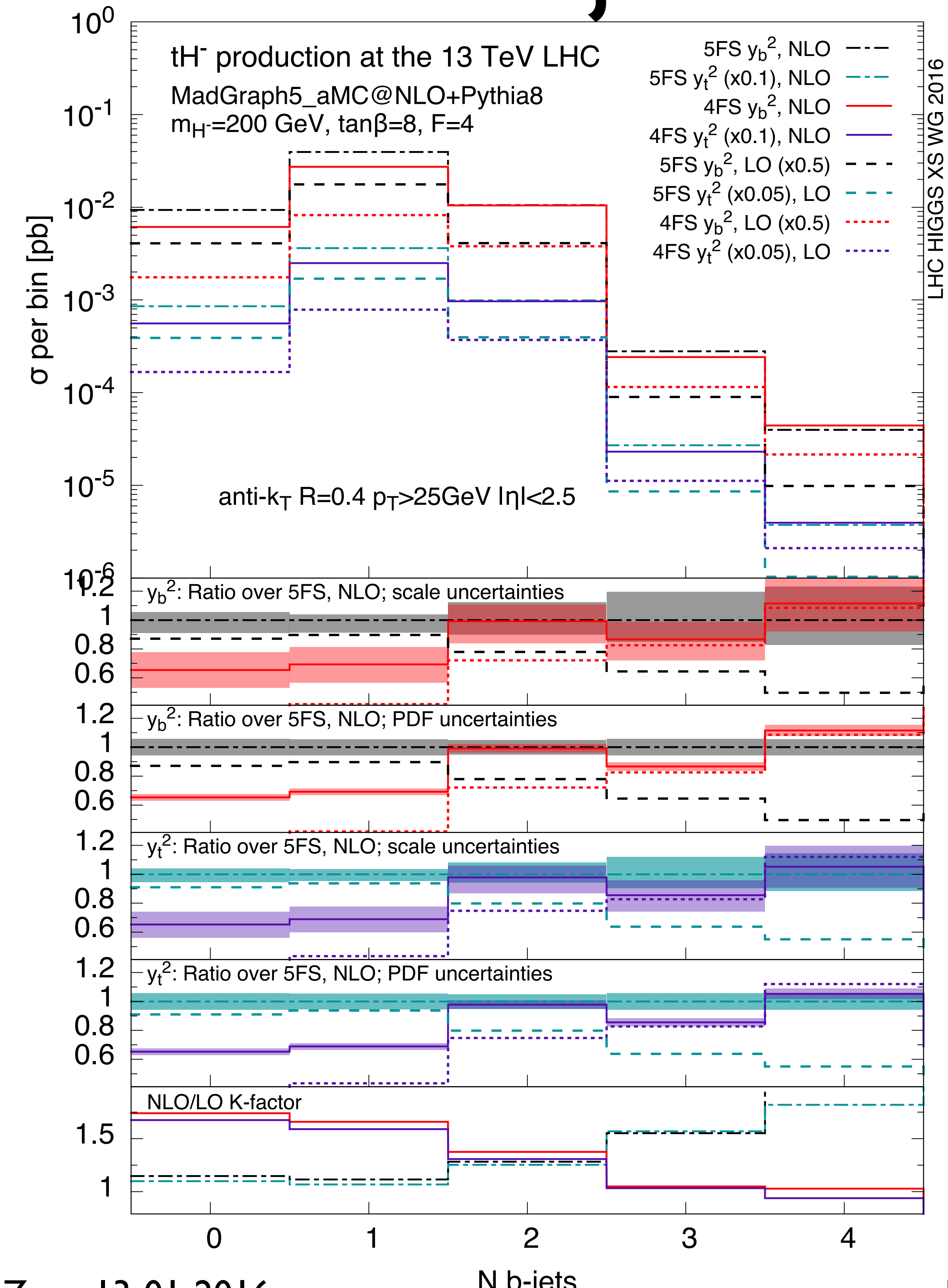
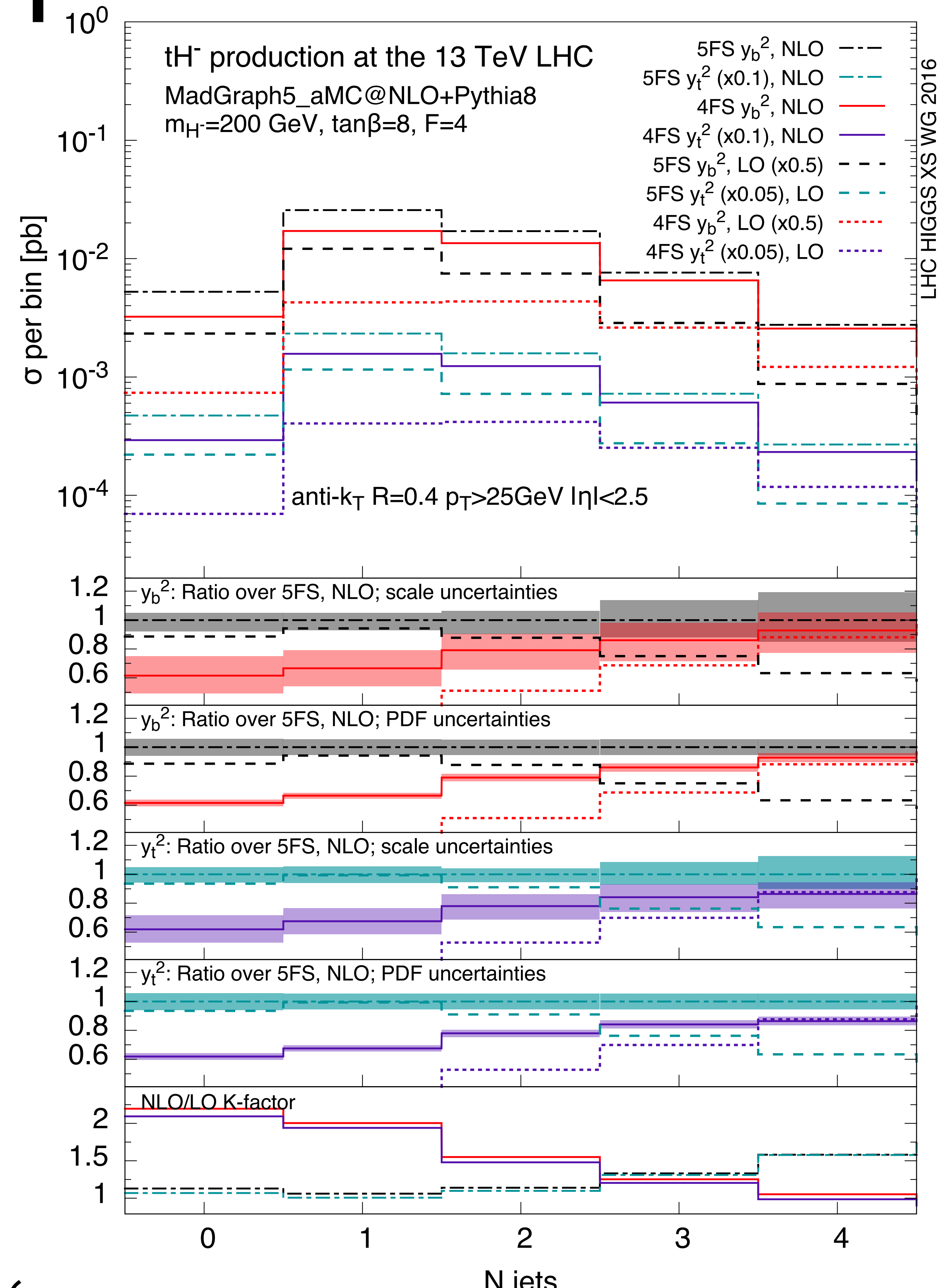


Other observables: hardest b-jet/B-hadron p_T



Other observables: jet multiplicities





Summary:

- Santander-matched cross section updated with new prescriptions
- New 4FS computation (and comparison with the 5FS) at NLO +PS available and included in YR4
- To do:
  - For the YR4:
    - Finish the write-up of the Charged Higgs section
    - Find a recommendation for differential predictions (use 4FS?)
  - Beyond YR4:
    - Provide accurate predictions for the intermediate mass range