Accurate predictions for charged Higgs boson production at the LHC

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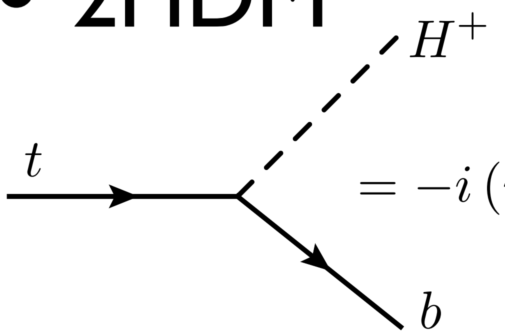
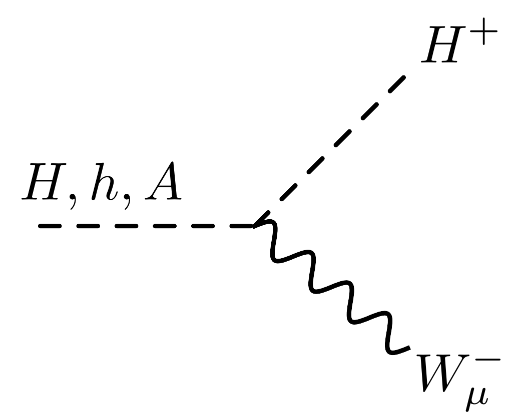
Introduction

- Various BSM scenarios (SUSY, composite Higgs, …) feature extended Higgs sectors with extra (possibly charged) scalars
- The observation of a charged Higgs boson would be a clear sign of BSM physics
- Charged Higgs production and decay modes depend on model
- In this talk
  - 2HDM

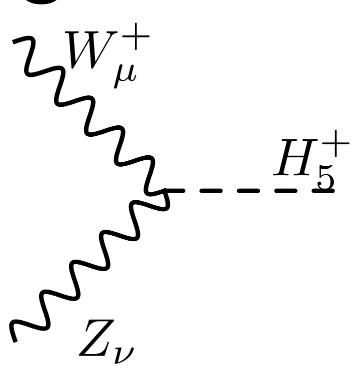


$$= -i\left(y_t P_R \cot\beta + y_b P_L \tan\beta\right)$$

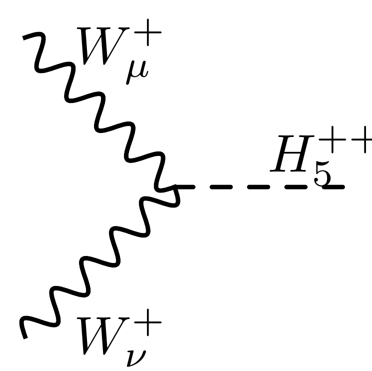


$$= i\frac{g_W}{2}\cos(\beta-\alpha)p^\mu_W \quad (h)$$
$$= i\frac{g_W}{2}\sin(\beta-\alpha)p^\mu_W \quad (H)$$
$$= i\frac{g_W}{2}p^\mu_W \quad (A)$$

  - Georgi-Machacek



$$= 2i\frac{M_W M_Z}{v} s_H g_{\mu\nu}$$

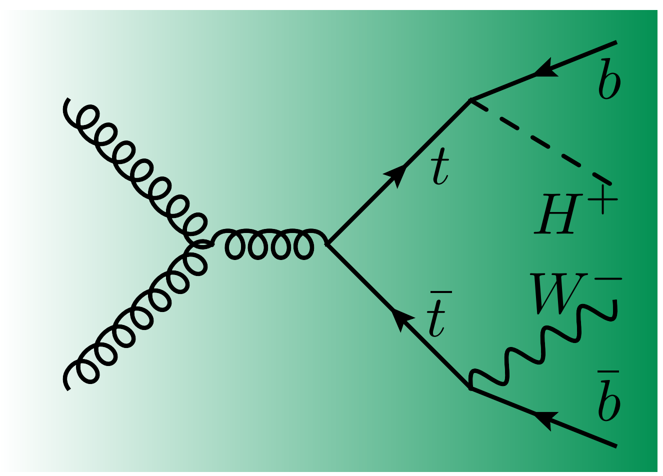


$$= 2\sqrt{2}i\frac{M_W^2}{v} s_H g_{\mu\nu}$$

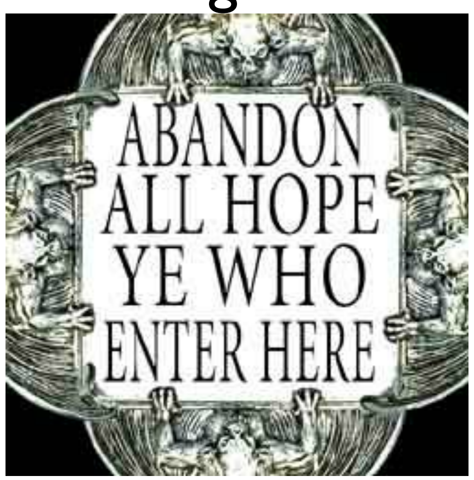
Charged Higgs production in 2HDMs

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

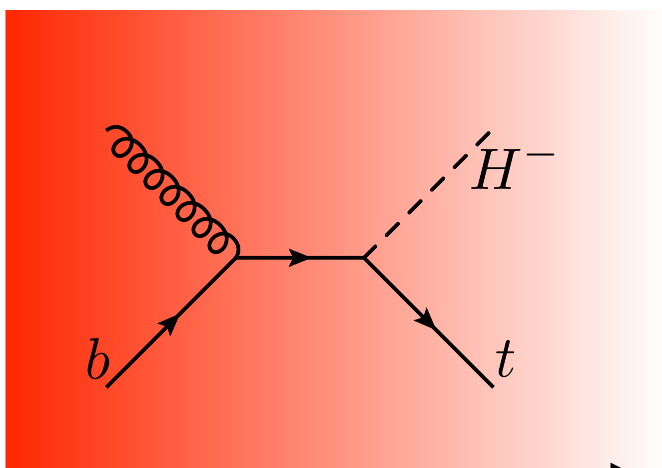
light Higgs



Intermediate region



heavy Higgs



$M_{H^+} < M_t$ | $M_{H^+} \simeq M_t$ | $M_{H^+} > M_t$

$H^\pm$ mostly produced in $t\bar{t}$ events. Depending on BR($t \to H^\pm b$) also $H^\pm t$ can become important. At NLO one has to subtract on-shell tops (see Plehn, hep-ph/0206121)

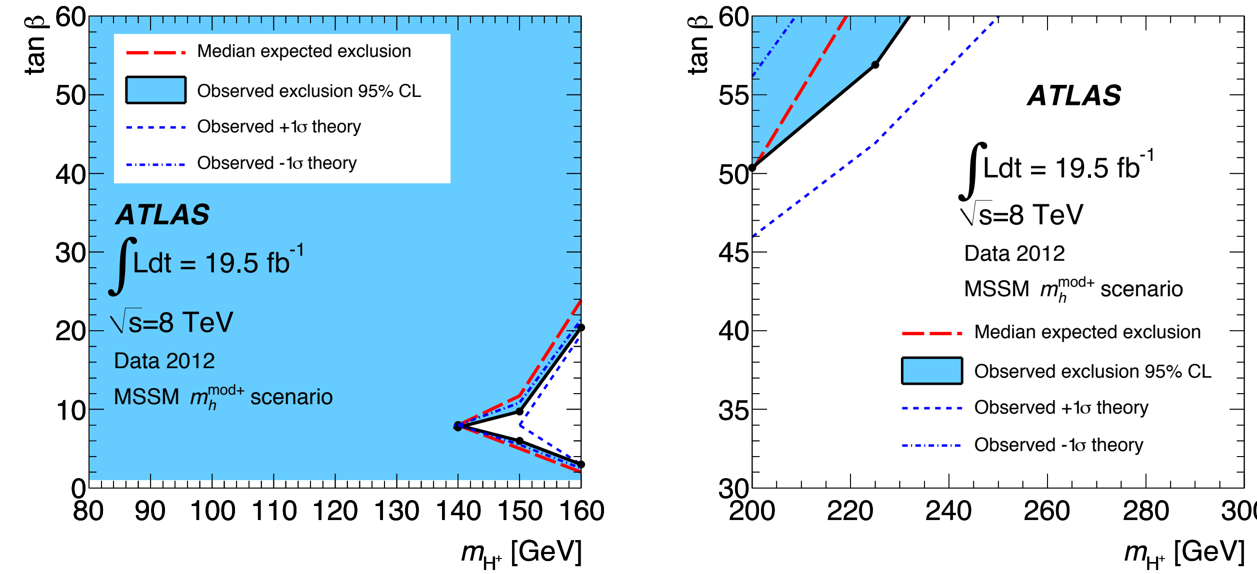
The full $pp \to H^\pm W^\mp b\bar{b}$ process has to be simulated. Computationally very demanding, but feasible

$H^\pm$ mostly produced in association with a top quark

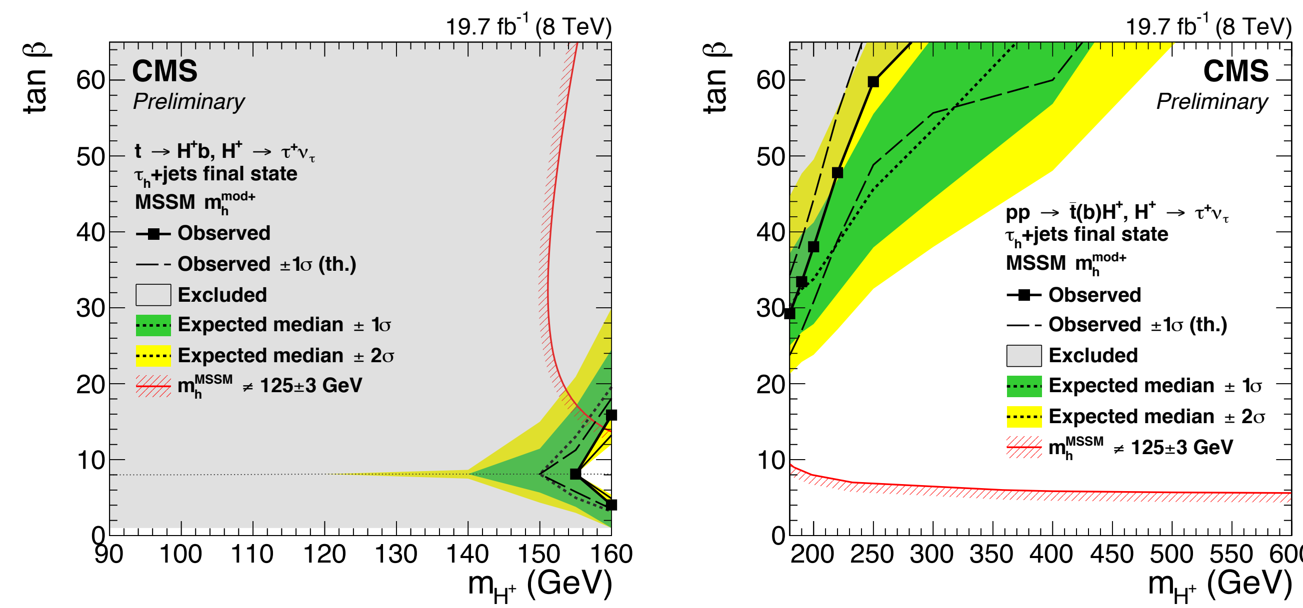
Searches at the LHC

- 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

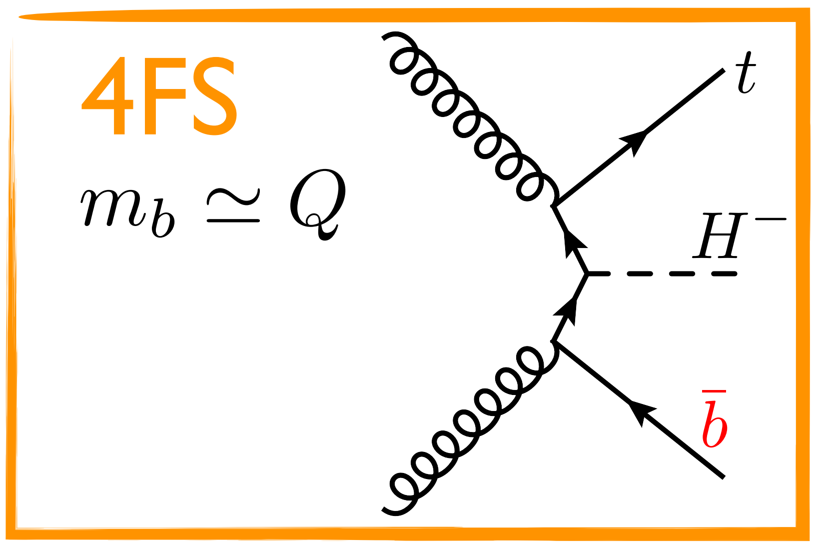


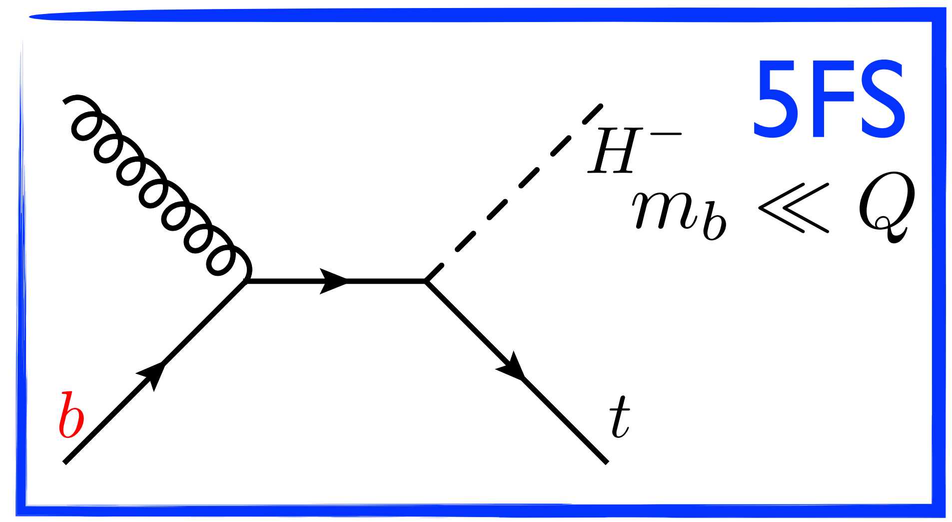
CMS, PAS HIG-14-020



Heavy charged Higgs production

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





4FS

✘ 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

5FS

✔ 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 t

H^- 5FS

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

Flechl, Klees, Kramer, Spira, Ubiali, arXiv:1409.5615

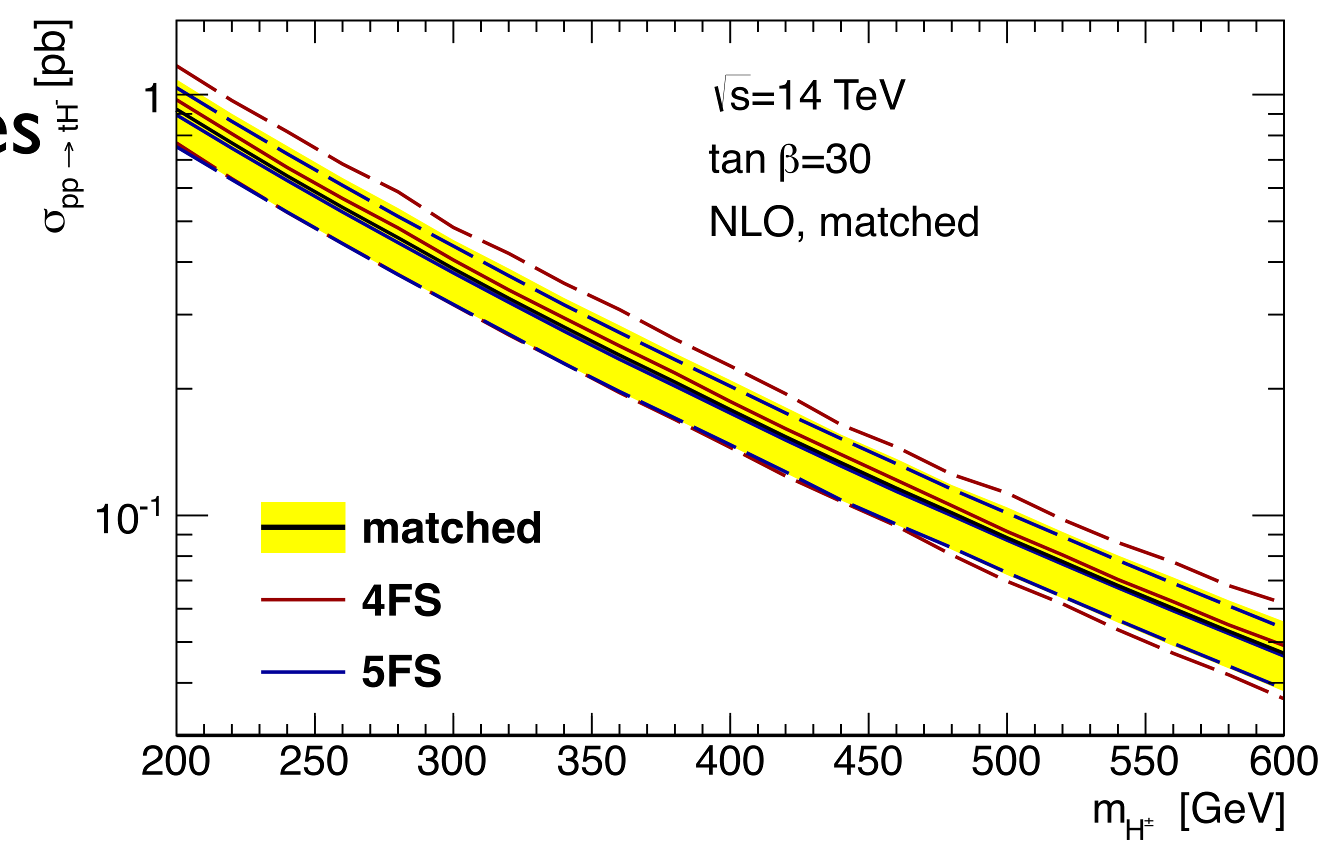
- The scale in the logs resumed in the 5FS is typically much smaller than the hard scale of the process (phase-space suppression) Maltoni, Ridolfi, Ubiali, arXiv:1203.6393

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

  - 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

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

	8 TeV		14 TeV	
$M_{H^\pm}$ [GeV]	$\tilde{\mu}$ [GeV]	$(m_t + M_{H^\pm})/\tilde{\mu}$	$\tilde{\mu}$ [GeV]	$(m_t + M_{H^\pm})/\tilde{\mu}$
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



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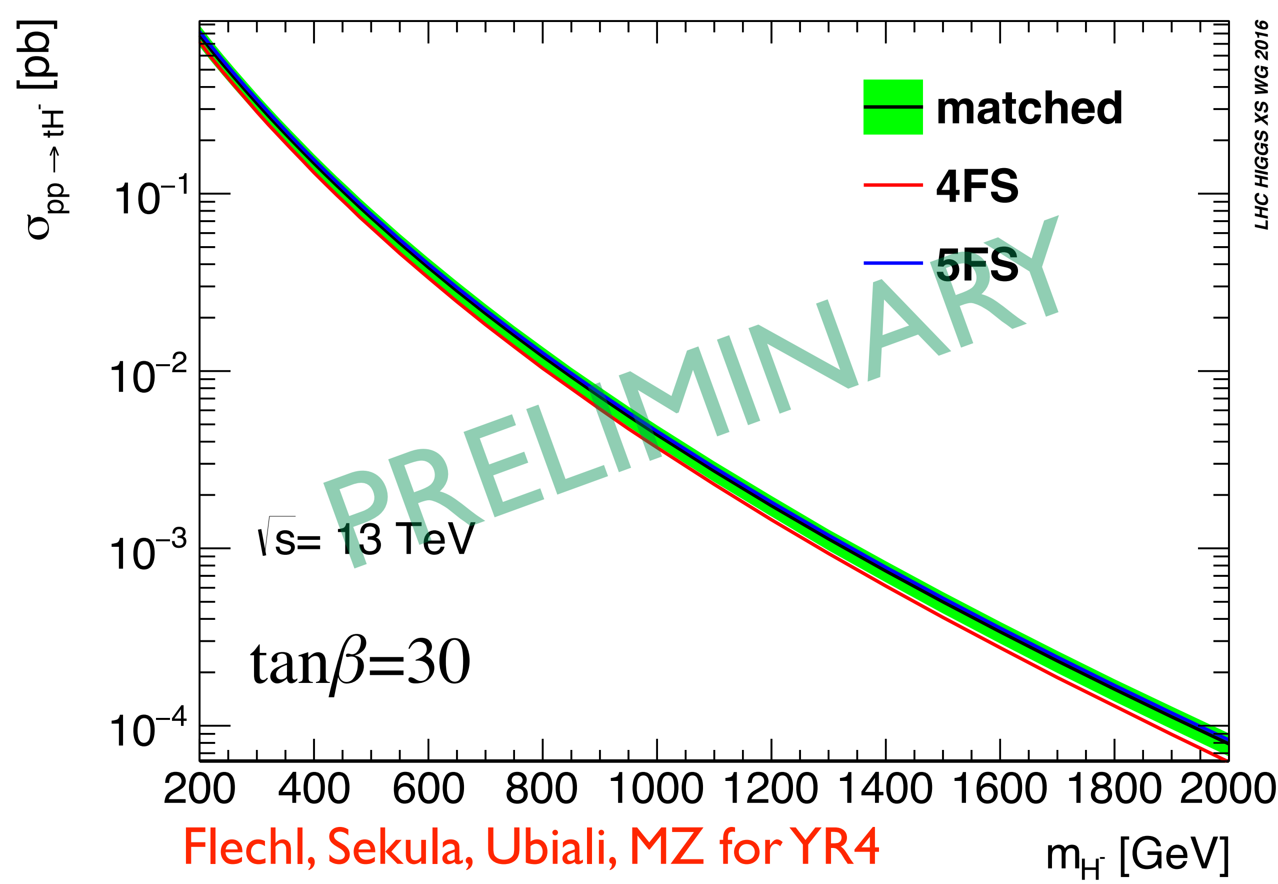


Flechl, Sekula, Ubiali, MZ for YR4

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

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

    $\sqrt{S} = 13\,\mathrm{TeV} \qquad m_H = 200, 600\,\mathrm{GeV} \qquad \tan\beta = 8$
- M $\mu_R = \mu_F = \mu_B = H_T/3 = \sum \sqrt{p_T(i)^2 + m(i)^2}/3$ $_b$: 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 $\hat{s}$. Check if this argument holds also for the shower scale
- Keep H^- stable, decay top quark leptonically
  →One b-jet from top and one from matrix element / shower

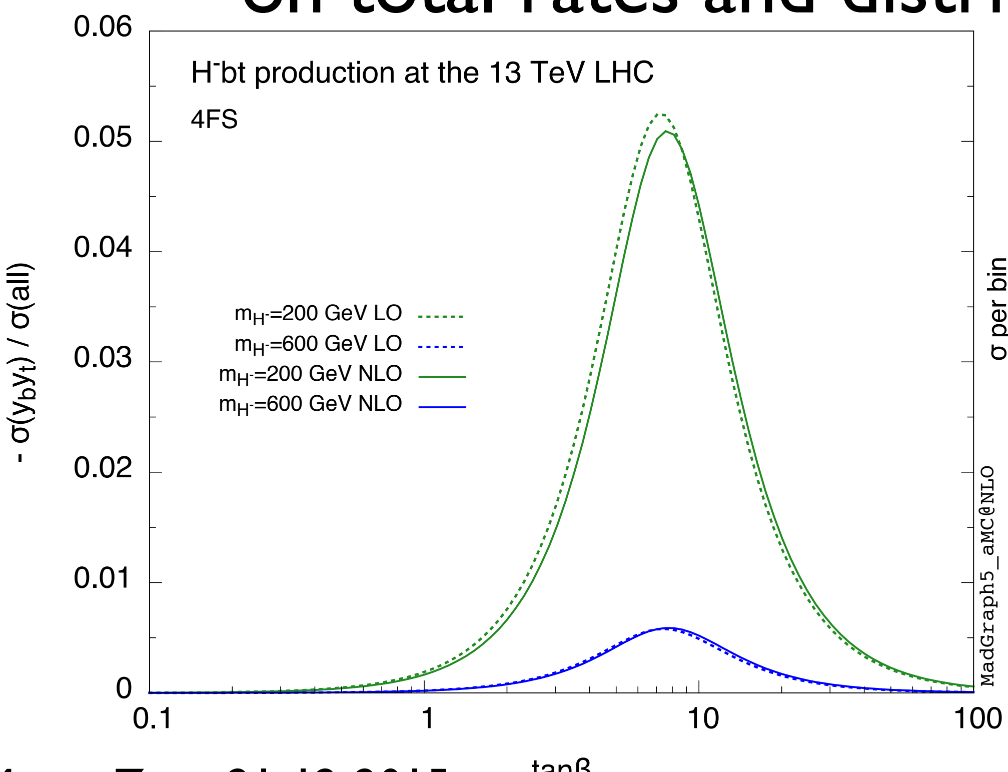
Setup and cross-section structure

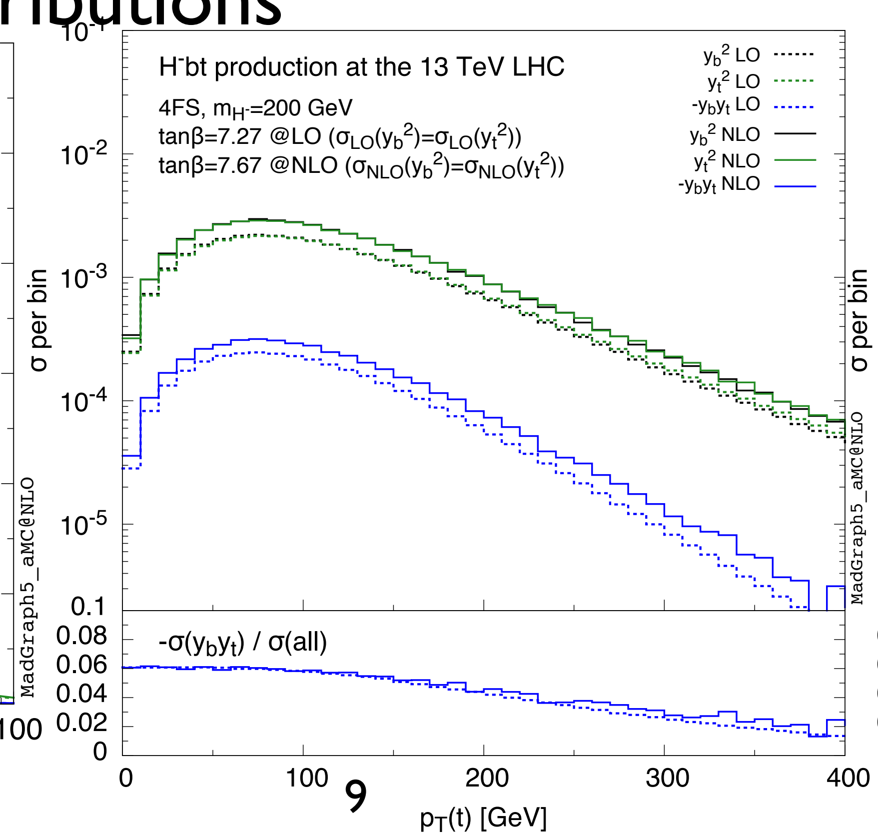
- The following parameters are used

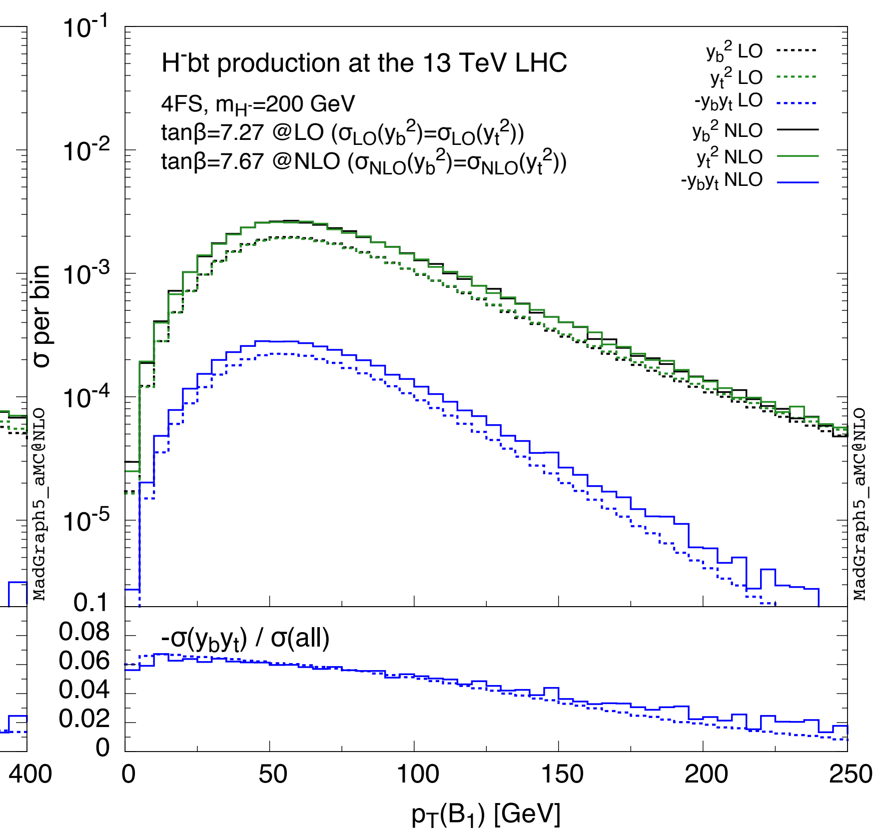
$$\sqrt{S} = 13\,\text{TeV} \qquad m_H = 200\ \text{GeV} \qquad \tan\beta = 8$$

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

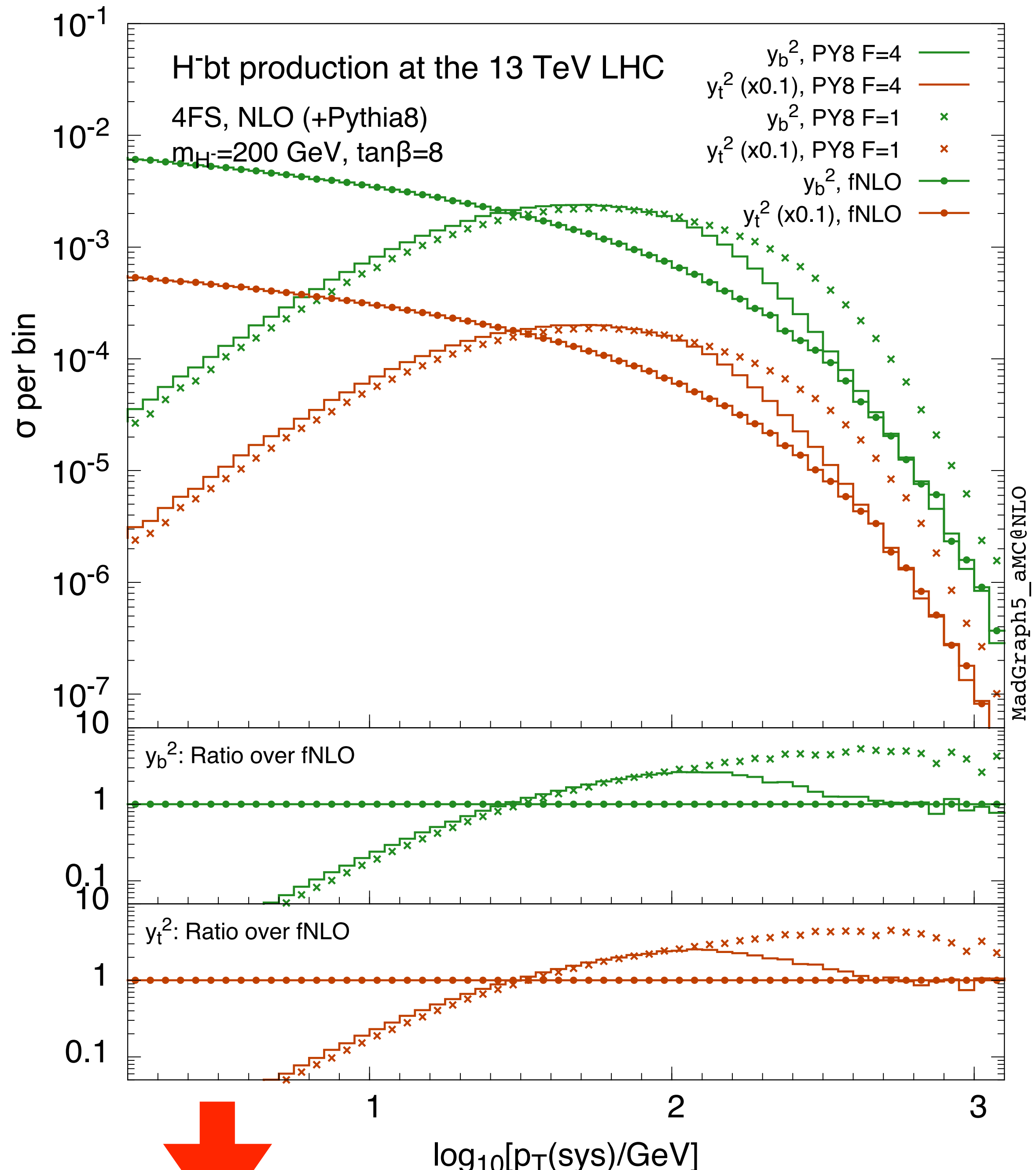
- Owing to the structure of the $H^{\pm}tb$ coupling, the cross section will receive three contributions: y_b^2 ($\sim\tan\beta^2$), y_t^2 ($\sim 1/\tan\beta^2$) and $y_b y_t$ ($\tan\beta$ independent).
  - In the 5FS, the $y_b y_t$ term is null (helicity conservation)
  - In the 4FS, it is proportional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

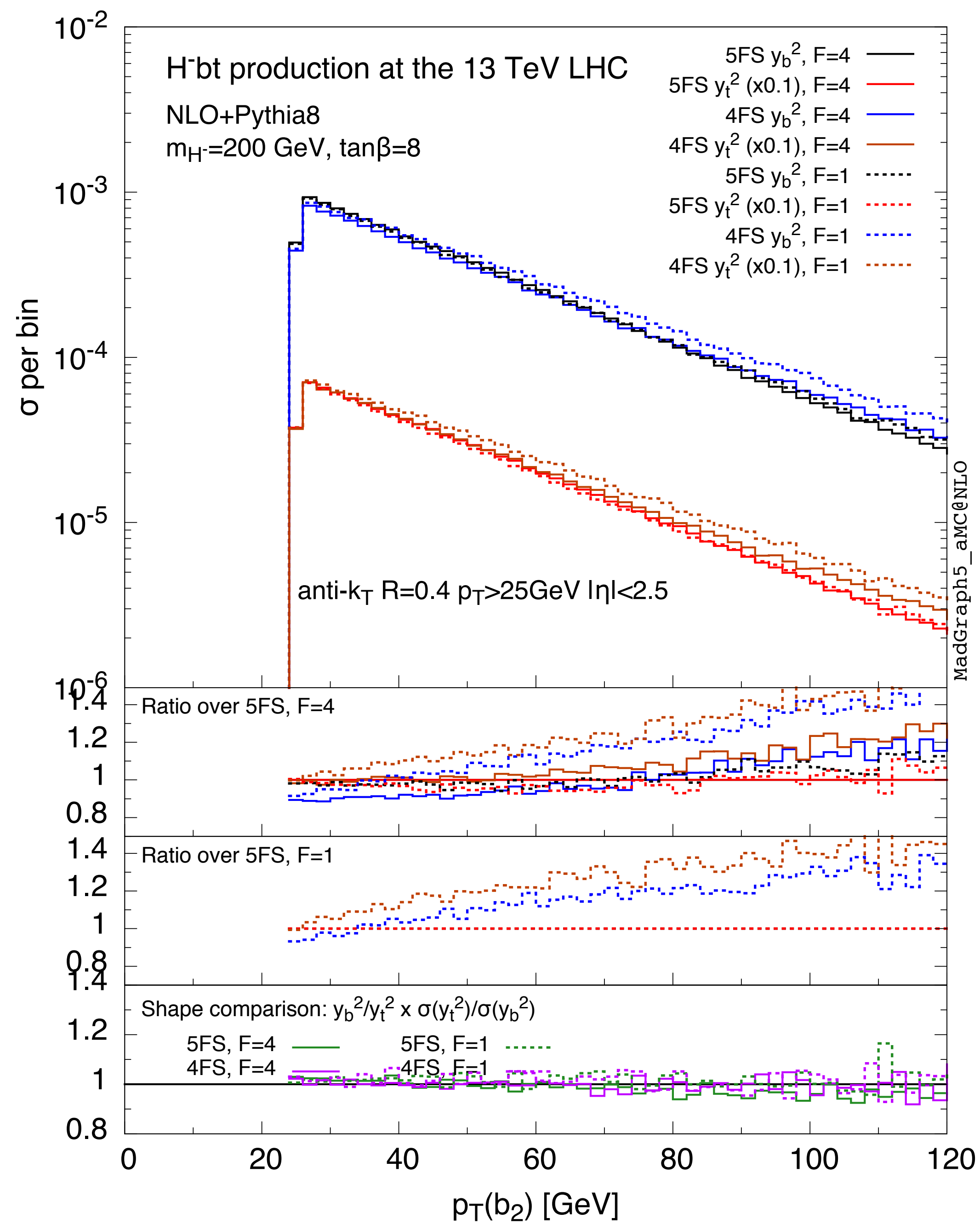






Choice of shower scale

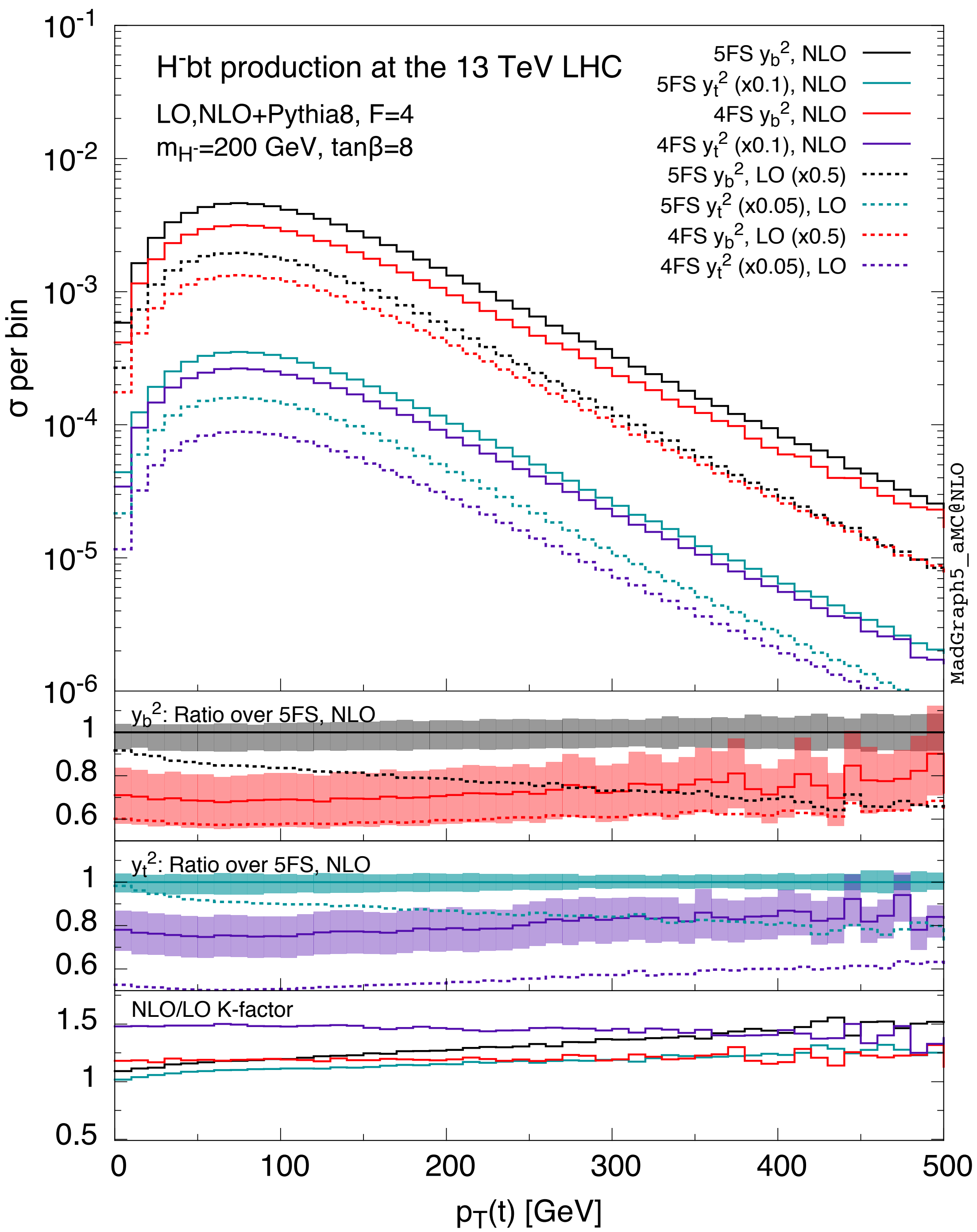


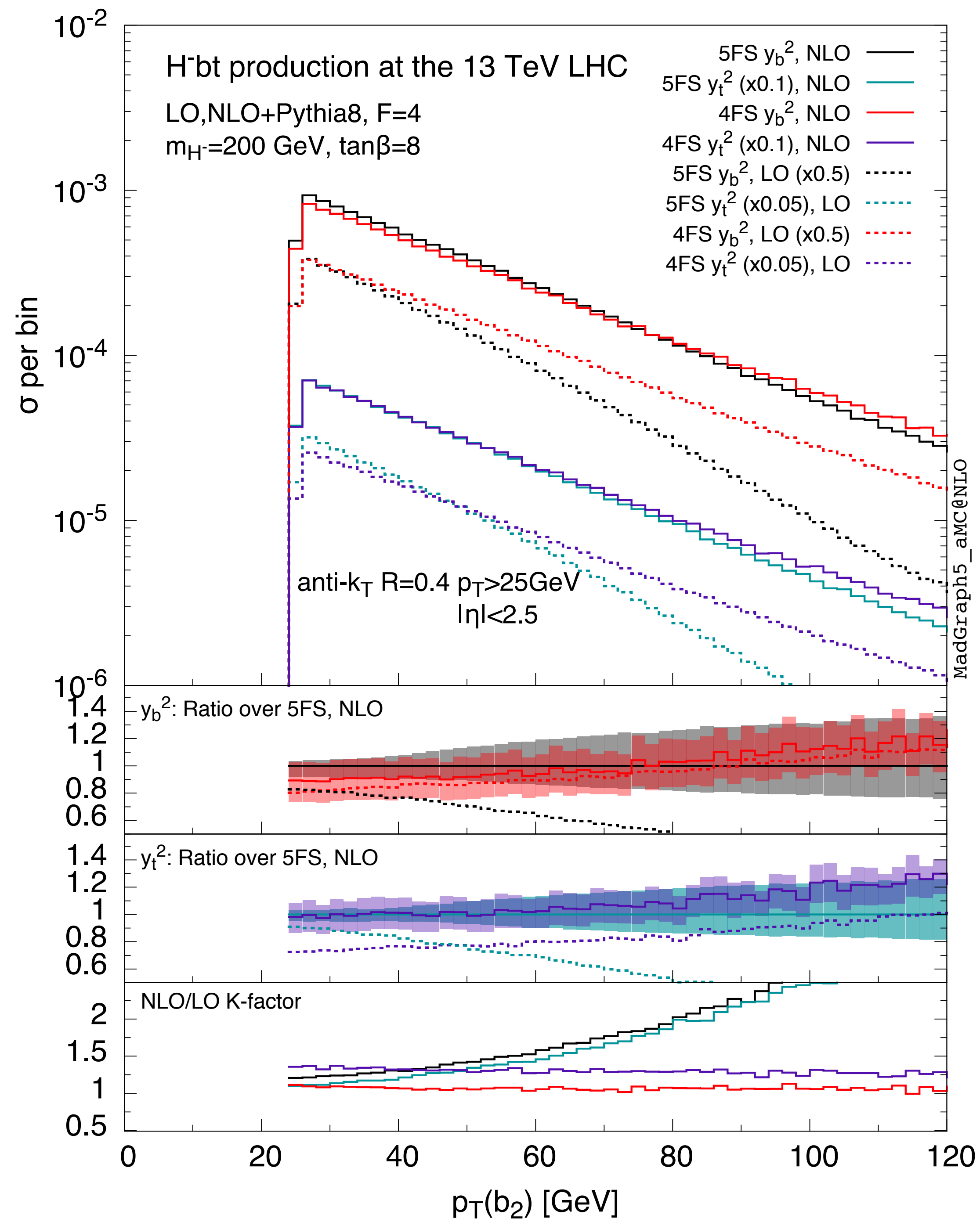


Reduced shower scale to be preferred improves NLO+PS/fNLO matching at high-p_T

Consequence:
better agreement at differential level between the two schemes

4FS vs 5FS

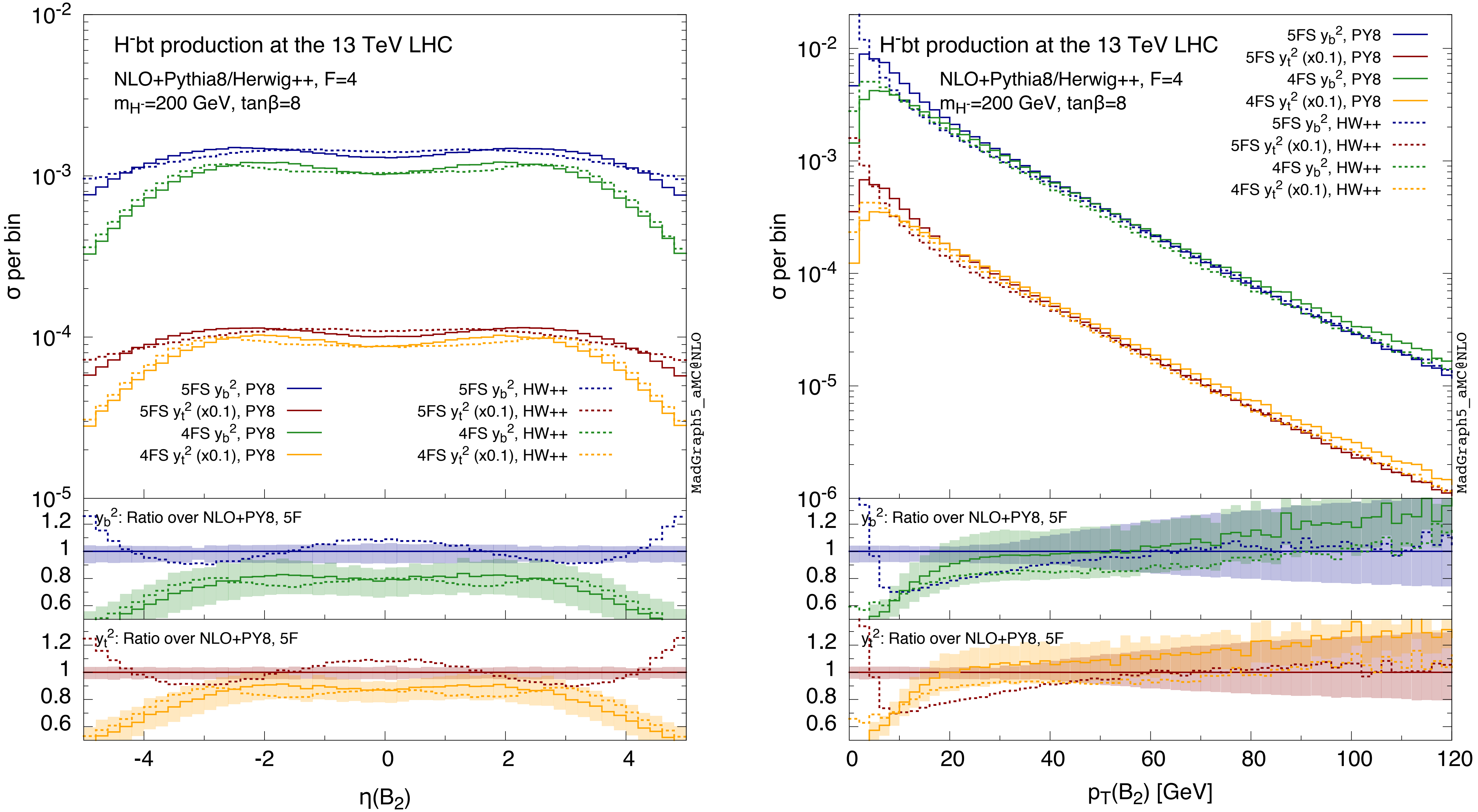




NLO corrections improve the agreement between schemes (despite very different K-factors)

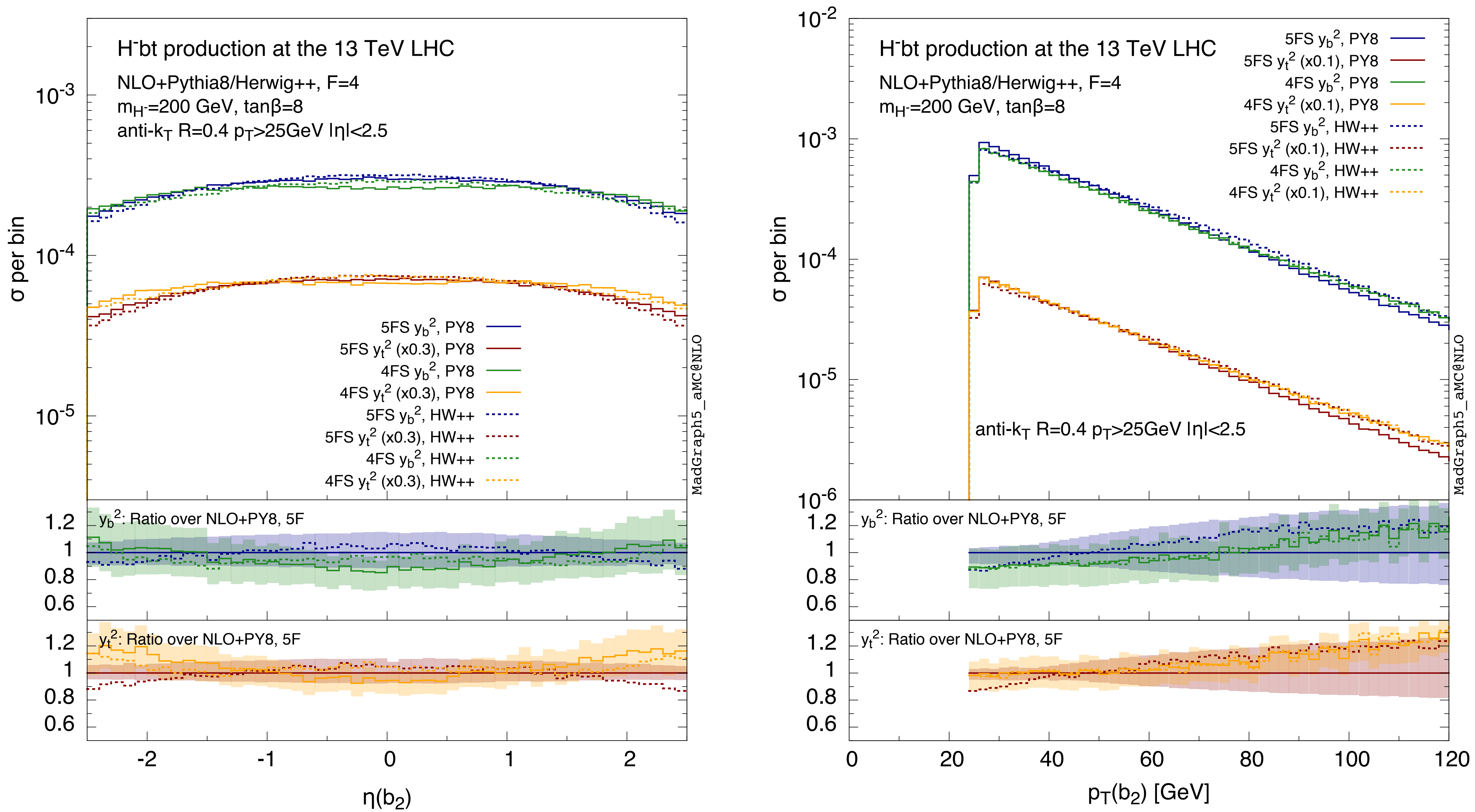
5FS has larger K-factors and uncertainties
4FS gives more accurate description of b-exclusive observables

4FS vs 5FS



b-exclusive observables show
stronger dependence on PSMC in the 5FS

4FS vs 5FS



Differences remain also for more inclusive (b-jet) observables

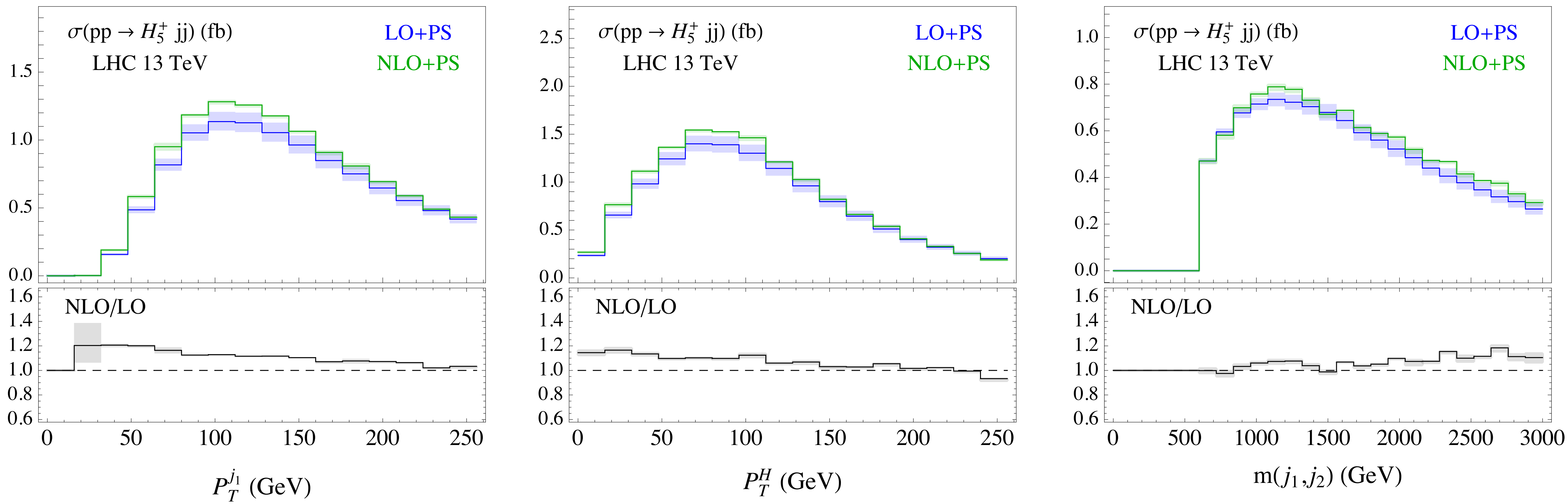
similar results also for mH=600 GeV

Charged Higgs boson production in triplet models

- In 2HDMs no HVV vertex exists at tree-level
- HVV vertices can be there when the Higgs(es) live in larger SU(2) representations
- Georgi-Machacek models: Higgses in triplets, preserving custodial symmetry
- After symmetry breaking, a five-plet of Higgs bosons appears
  - One neutral (H_5^0), two singly-charged ($H_5^{\pm}$), two doubly charged ($H_5^{\pm\pm}$) Higgs bosons
  - Higgs bosons only couple to W/Z bosons: VBF is dominant production mode
- GM phenomenology at NLO+PS now possible with automated tools (NLOCT+MG5_aMC@NLO)

Georgi-Machaceck phenomenology at NLO

Degrande, Hartling, Logan, Peterson, MZ, arXiv:1512:01243



- H_5^+ production in VBF, with standard VBF cuts, matched to PY8
- M_H=340 GeV
- Not flat K-factors for VBF
- GM model @NLO soon available on FeynRules website https://feynrules.irmp.ucl.ac.be/wiki/NLOModels

Conclusions

- The discovery of a charged Higgs boson at the LHC would be a clear sign of BSM physics
- Lot of recent and ongoing progress towards providing accurate predictions for cross section and realistic signal modelling
- Santander-matched predictions available for the total cross section
- Fully differential predictions for charged Higgs production in the 2HDM available for the first time in the 4FS at NLO+PS
  - Better description of b-kinematics
  - Better matching to PS, less effects due to reshuffling
- Automated tools make it possible to have accurate predictions for virtually any model
  - Example: Georgi-Machacek