Charged Higgs production in 2HDM including higher-orders corrections

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Prospects for Charged Higgs Discovery at Colliders - Uppsala, 3-6 October 2016

Outline

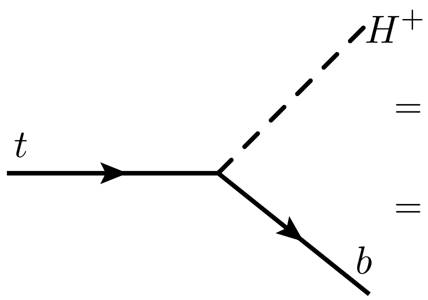
- Introduction
- Charged Higgs production mechanisms in the 2HDM
- Heavy charged Higgs
  - 4F versus 5F scheme
  - Total cross section
  - Differential distributions
- Intermediate-mass charged Higgs
- Conclusions and outlook

Introduction

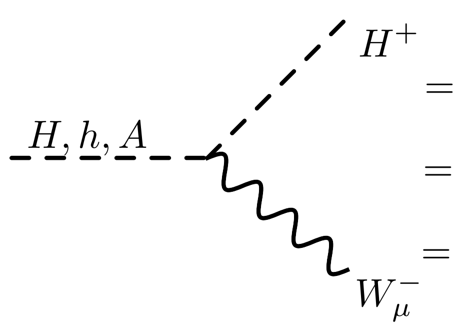
- Discovery of a charged scalar unmistakable sign of new physics

- 2HDM simplest extension of SM Higgs sector two Higgs doublets, leading to five physical scalar Higgs bosons

$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$



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



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

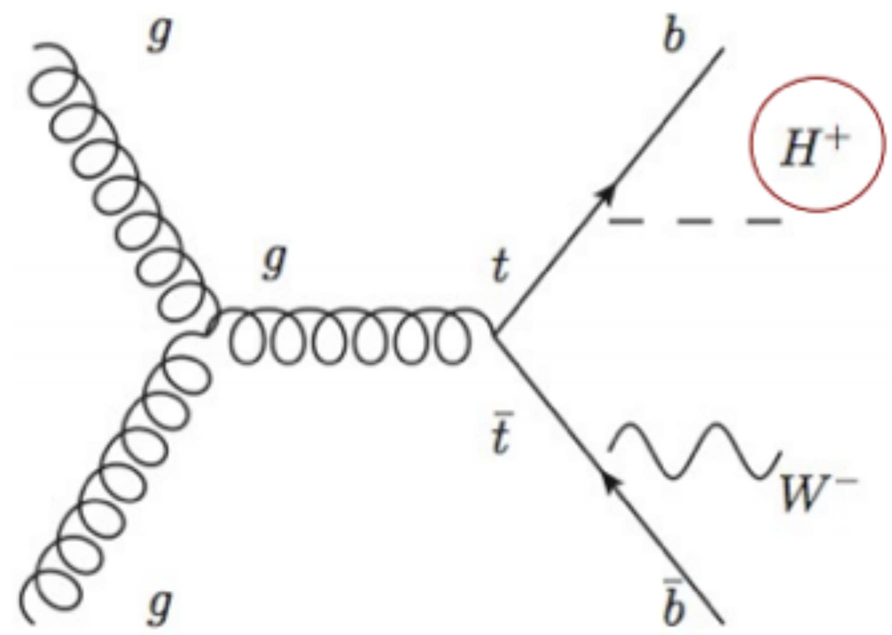
- Imposing natural flavour conservation four ways to couple the SM fermions to Higgs doublets (Type-I, Type-II, Type-III or Flipped, Type-IV or II' or Lepton Specific)

- **Type-II:** one doublet generates the mass of up-type quarks and the other of down-type quarks and charged leptons (∋MSSM)

Main production channels

LIGHT H⁺

$m_{H+} \lesssim 145$ GeV



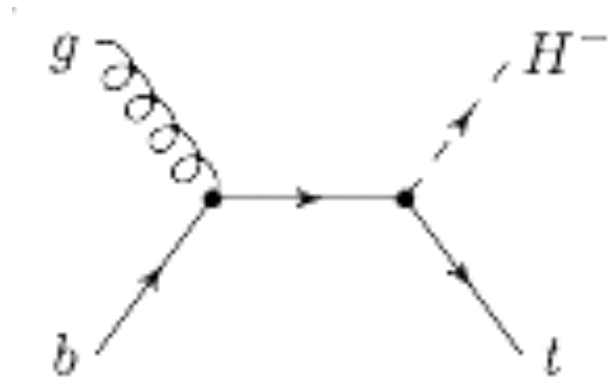
Czakon, Fiedler, Mitov [PRL 110 (2013)] - NNLO cross section for top pair production
O' Brein, Hollik [Phys. Rev. D76 (2007)] - Branching fraction for light charged Higgs
Weydert et al [Eur.Phys.J. C67 (2010)] - Diagram removal and subtraction for MC@NLO construction of H+t production

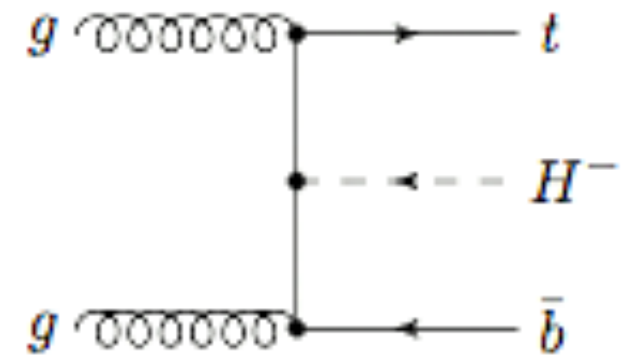
Main production channels

HEAVY H⁺

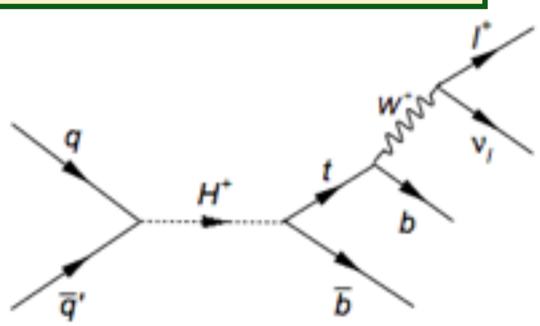
$m_{H+} \gtrsim 200$ GeV

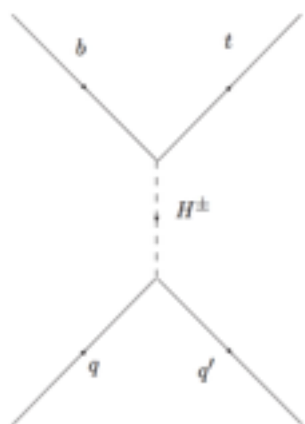
leading channel



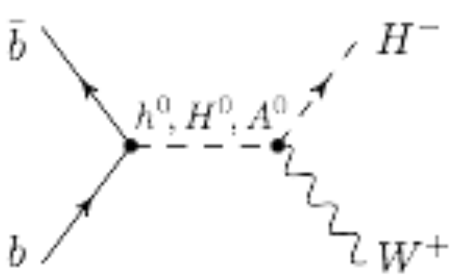


sub-leading channels





- s- and t-channel Single-top charged-Higgs mediated production
  Ahmed et al [Eur.Phys.J. C76 (2016)]
  Hashemi et al [JHEP 1602 (2016)]
  Hashemi et al Phys.Lett. B741 (2015)]
  Hashemi et al [JHEP 1311 (2013)]

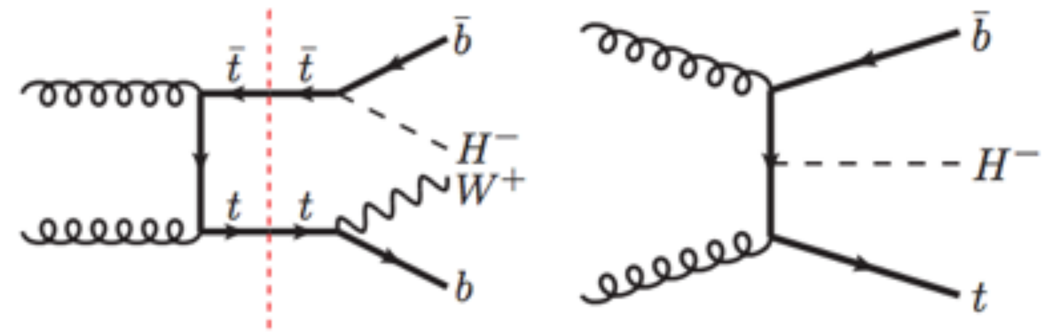


- WH± associated production
  Enberg et al [1506.04409]

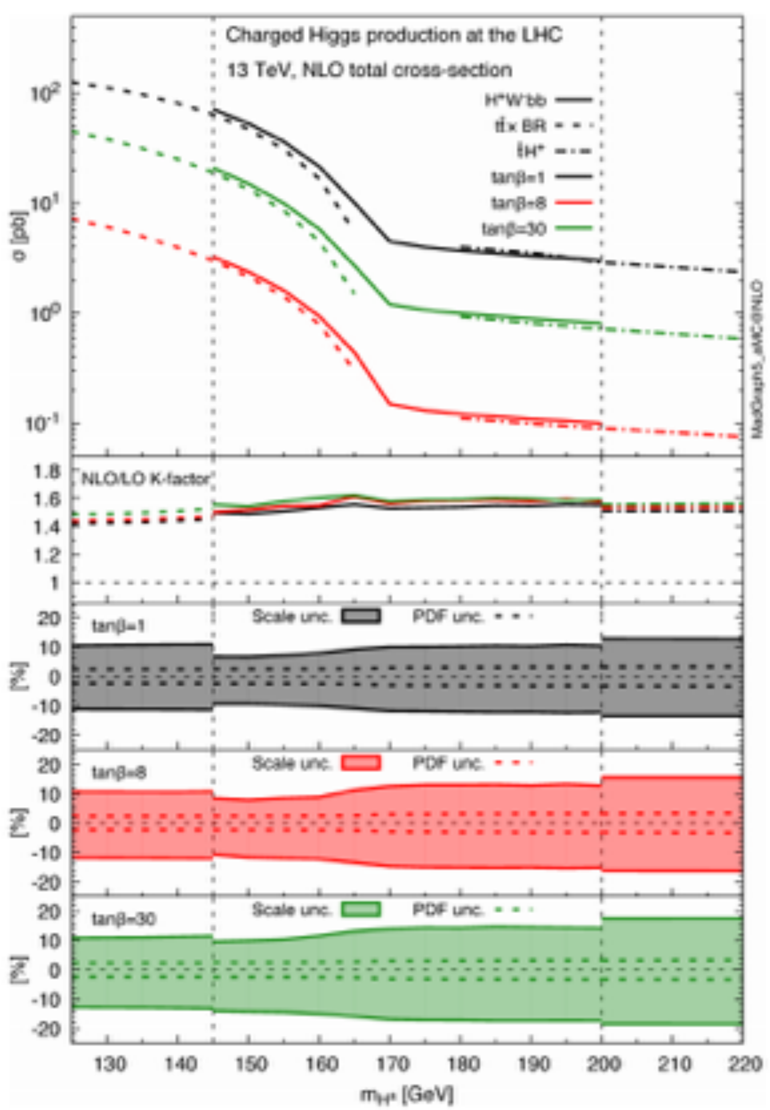
Main production channels

INTERMEDIATE H⁺

145 GeV $\lesssim m_{H+} \lesssim$ 200 GeV



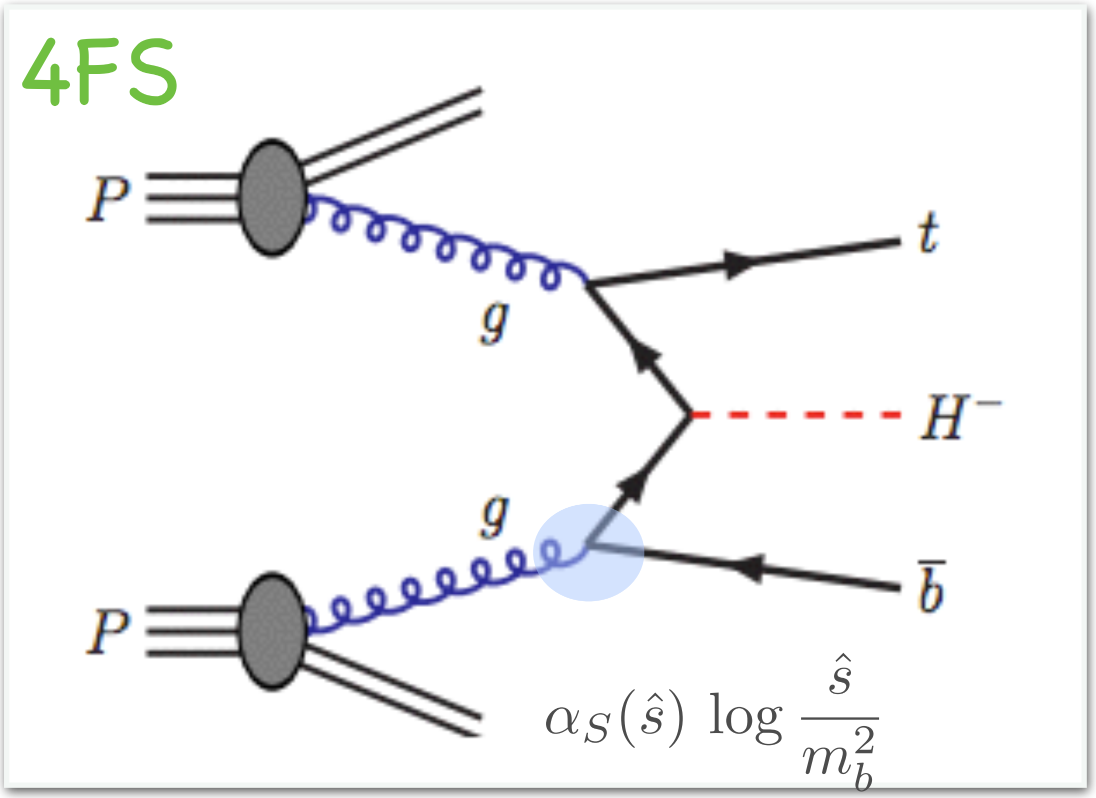
(a) (b)

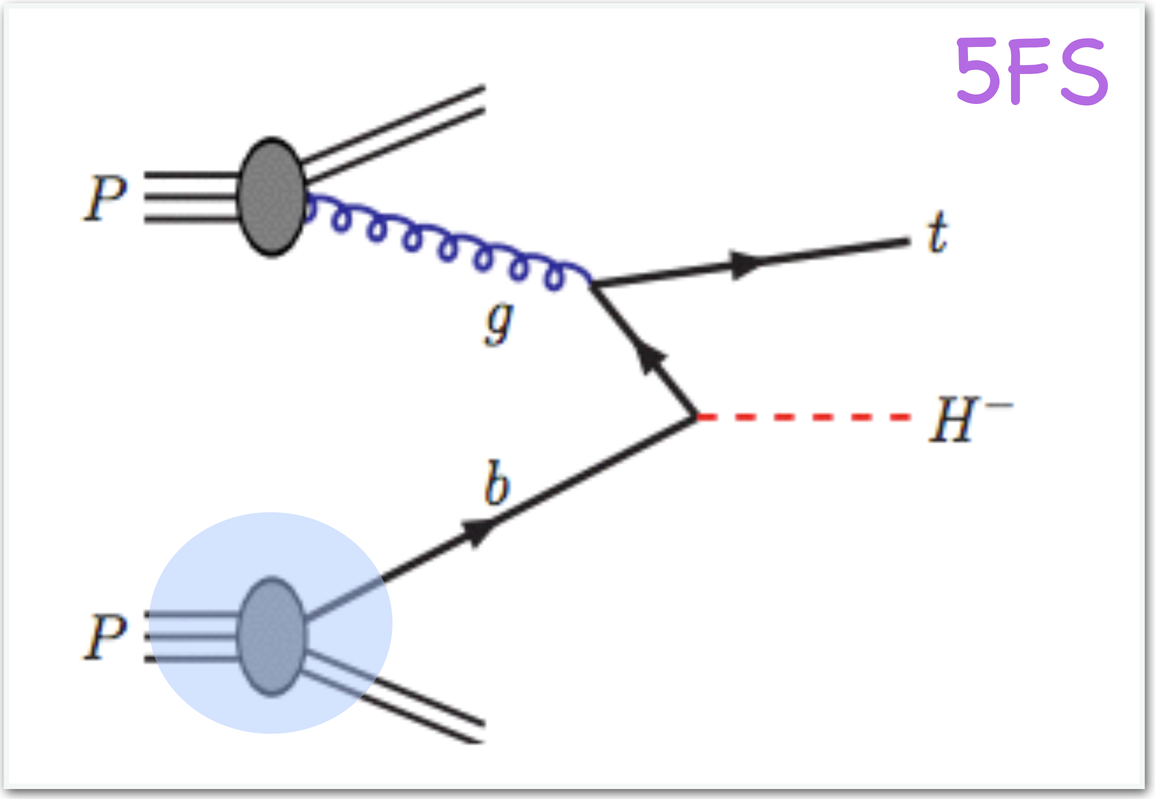


Degrande, Hirschi, MU, Wiesemann, Zaro (2016)

See Martin's talk

Heavy $H^{\pm}$ production: 4FS versus 5FS





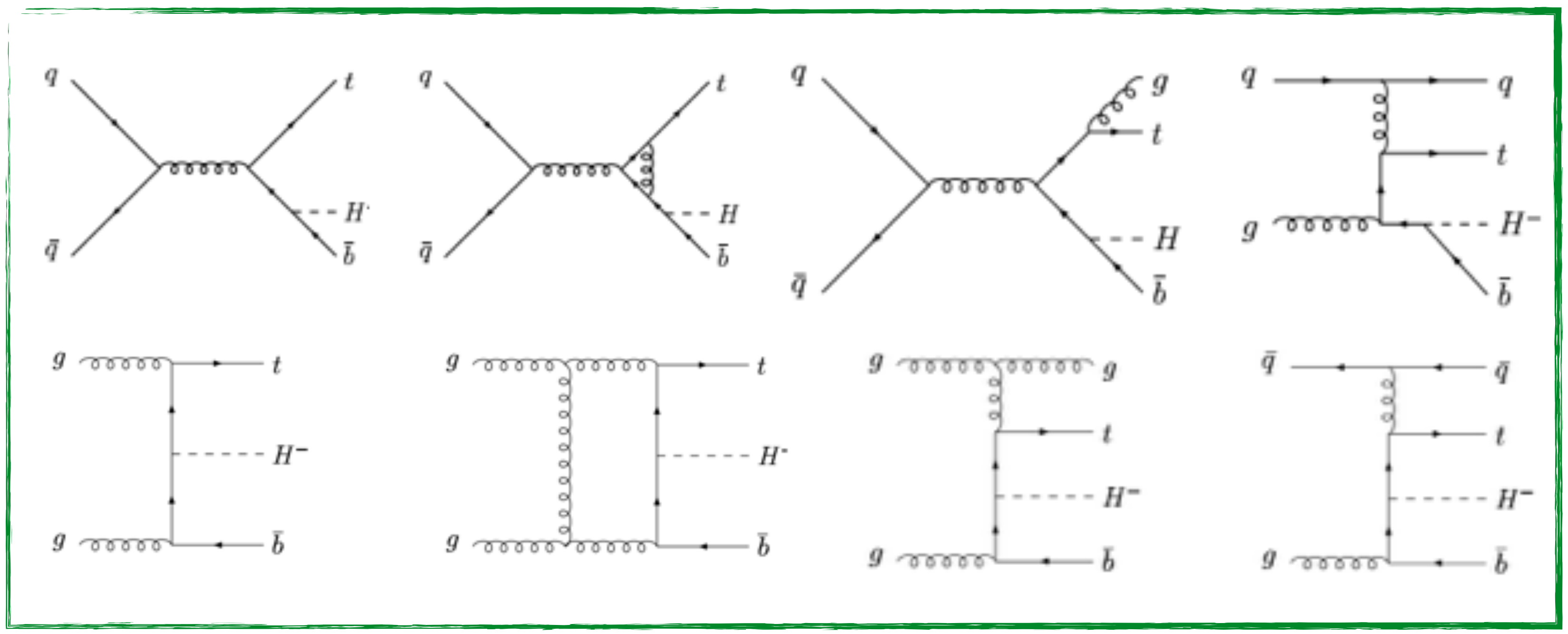
✘ It does not resum possibly large $\log(Q/m_b)$, yet it has them explicitly
✘ Computing higher orders is more involved
✔ Mass effects are there at any order
✔ Straightforward implementation in MC event generators at LO and NLO

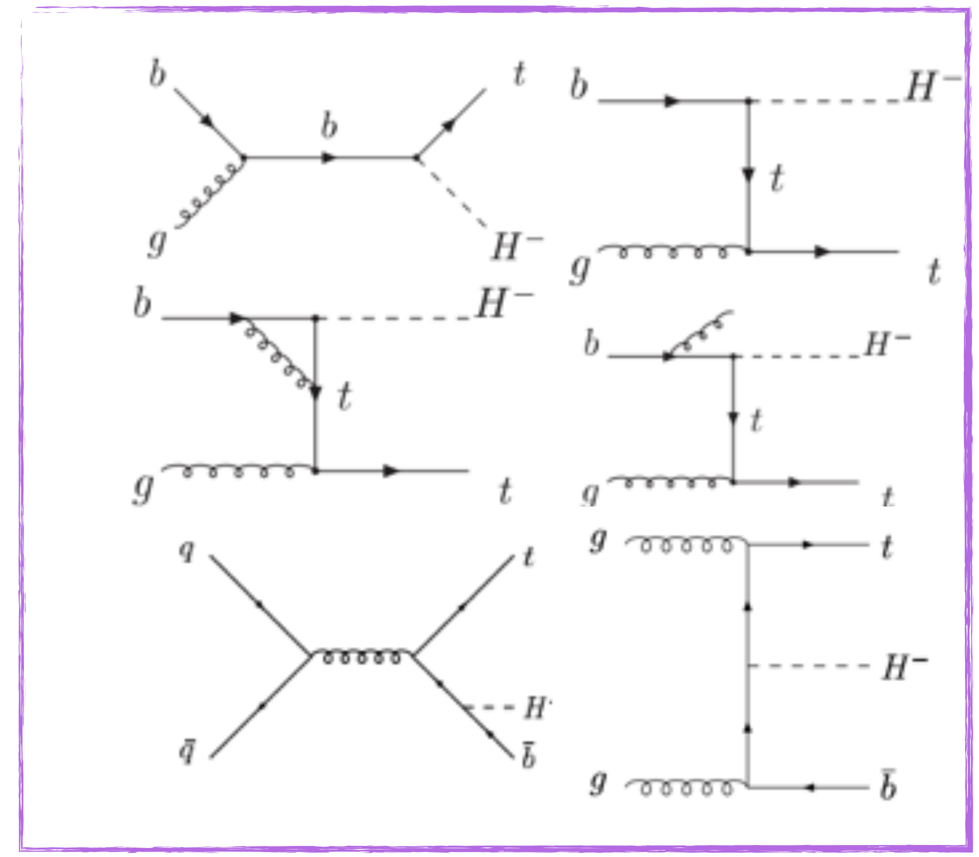
✔ It resums initial state large logs into b-PDFs leading to more stable predictions
✔ Computing higher orders is easier
✘ p_T of bottom enters at higher orders
✘ Implementation in MC depends on the gluon splitting model in the PS

Heavy $H^{\pm}$ production: available calculations

4FS $\left(|y_t|^2, |y_b|^2, |y_b^* y_t|\right)$

$\left(|y_t|^2, |y_b|^2\right)$ 5FS





- Fixed order NLO calculation (+ SUSY corrections)
  Dittmaier et al., Phys. Rev. D83:055005 (2011)

T. Plehn, Phys. Rev. D67:014018 (2003)
S. Zhu , Phys. Rev. D67:075006 (2003)
Berger et al, Phys. Rev. D71:115012 (2005)

- EW corrections
  Nhung et al., Phys. Rev. D87:113006 (2013)

Beccaria et al., Phys. Rev. D80:053011 (2009)

- Threshold resummation up to NNLL

Kidonakis, Phys. Rev. D82:054018 (2010)

- Fully differential NLO + PS computation

Weydert et al, Eur.Phys.J. C67 (2010) [MC@NLO]
Klasen et al, Eur.Phys.J. C72 (2012) [POWHEG]
Degrande et al, JHEP 1510 (2015) [MG5_aMCatNLO]

Total cross section

- Recent comparison and matching of state-of-the-art 4FS and 5FS total xsec calculations
  Flechl, Klees, Kramer, Spira, MU, Phys.Rev. D91 (2015)

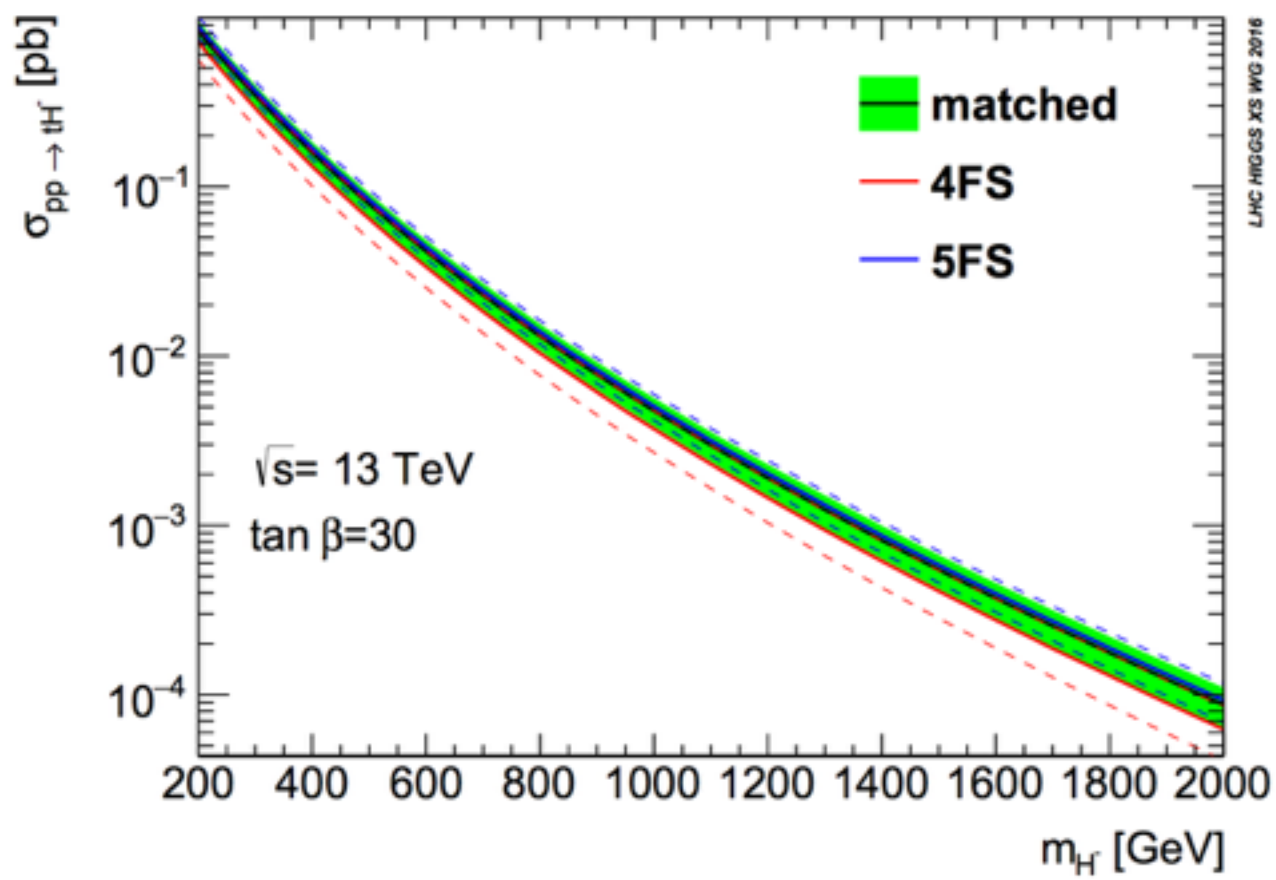
- All sources of uncertainties included (PDFs, m_b, α_s, scales, y_b) and scale settings for the 5FS motivated by kinematical study in
  Maltoni, Ridolfi, MU, JHEP 1207 (2012) 022

4FS versus 5FS

For **inclusive** xsec, where resummation nor b mass effects are essential, 4FS and 5FS pictures are not too different, once judicious scales are chosen, 5FS calculation stabilised by resummation and smaller scale variation

	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

$\approx (m_{H+} + m_t)/5$



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Santander matching:

$$\sigma = \frac{\sigma^{4FS} + w\sigma^{5FS}}{1+w}$$

$$w = \log\frac{M_{H^\pm}}{m_b} - 2$$

- Proper matched calculation NLO+NLL could also be devised using FONLL or EFT approach as for bbH
  Forte, Napoletano, MU, 1607.00389 & Phys.Lett. B751 (2015)
  Bonvini, Papanastasiou, Tackmann, 1605.01733 & JHEP 1511 (2015)

	8 TeV		14 TeV	
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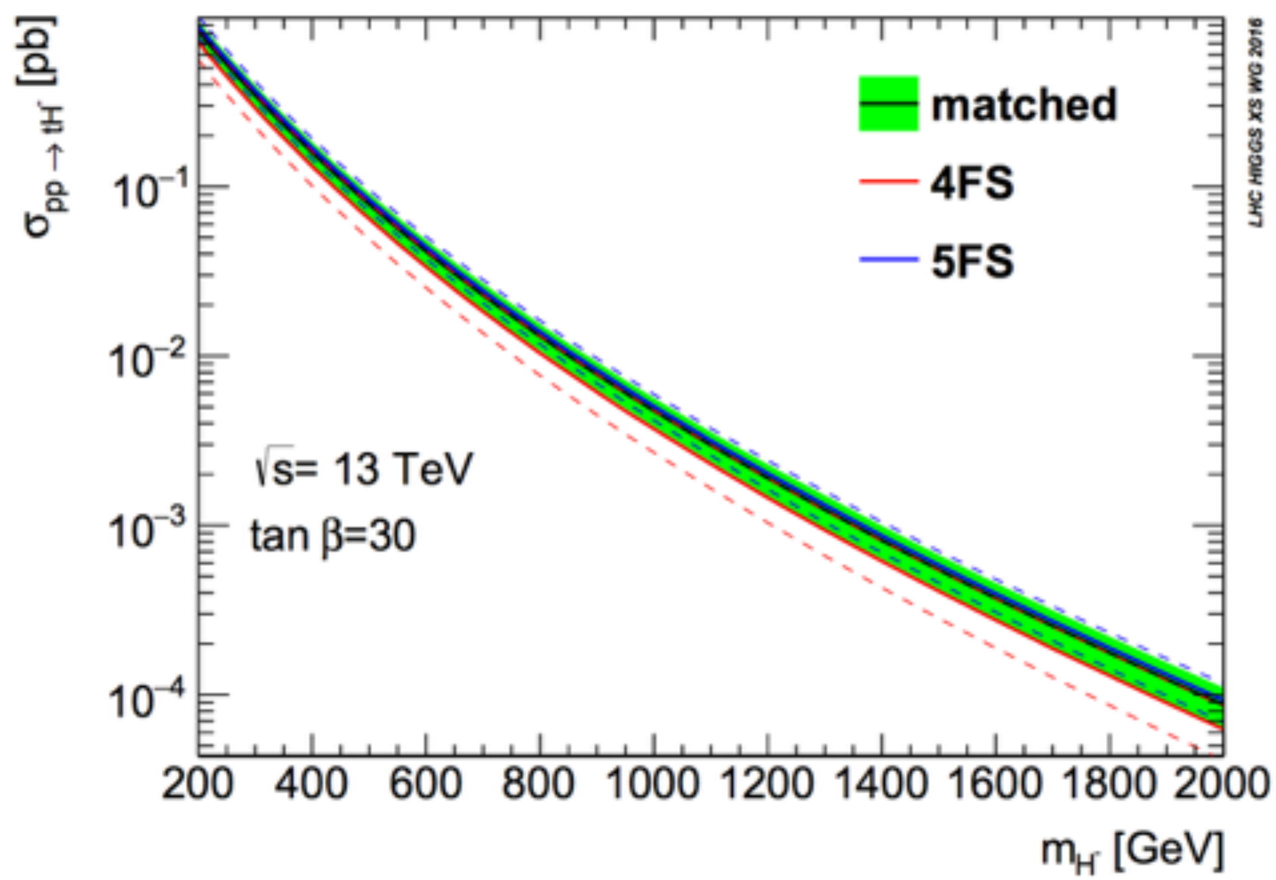
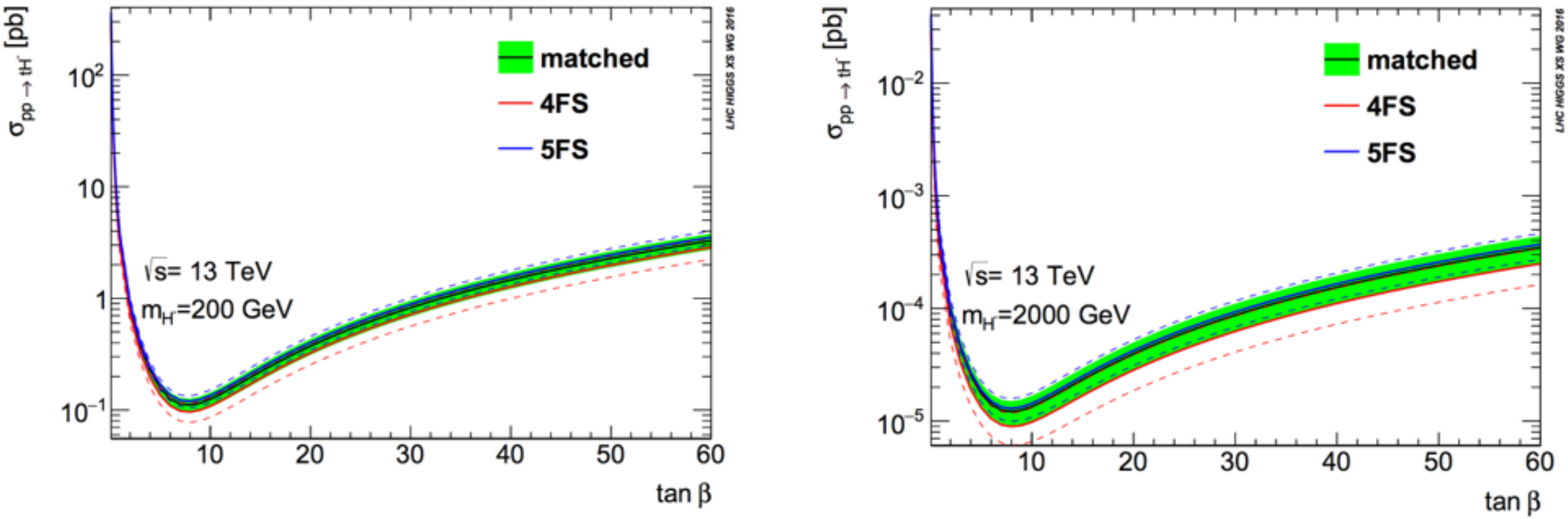


Total cross section



2HDM [III = lepton-specific, IV = flipped]

- charged 2HDM couplings:

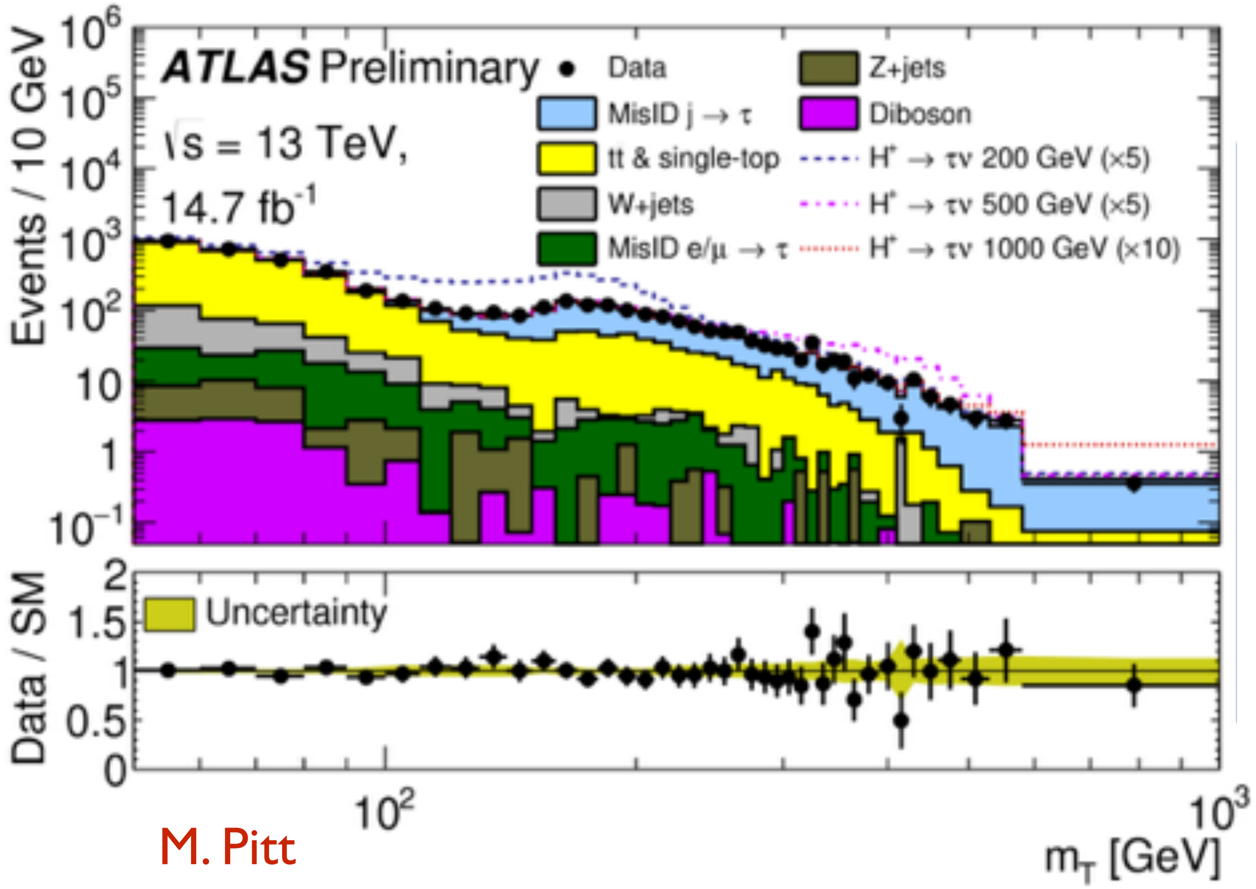
type	g_u	g_d
I/III	ctgβ	−ctgβ
II/IV	ctgβ	tgβ

$$\Rightarrow \sigma_{I/III} \approx \frac{\sigma(\mathrm{tg}\beta = 1)}{\mathrm{tg}^2\beta}$$

at per-mille accuracy [or fit of $\sigma_{tt/tb/bb}$ from grid ← exact]

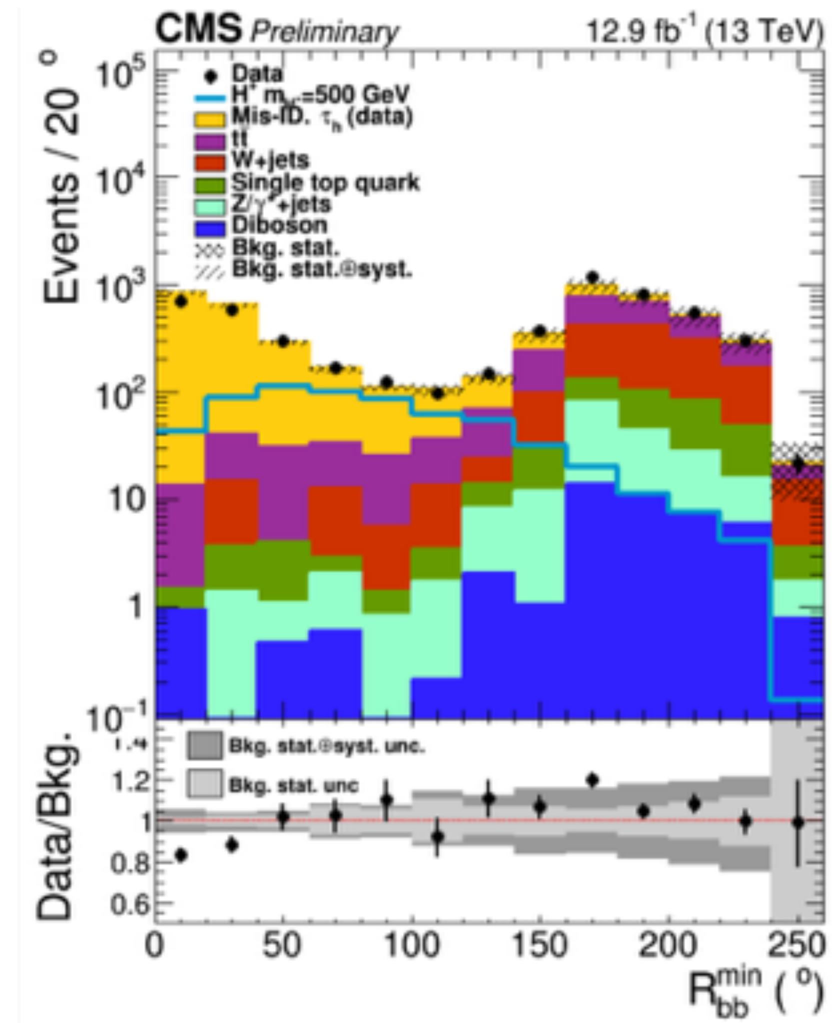
M. Spira

Differential distributions



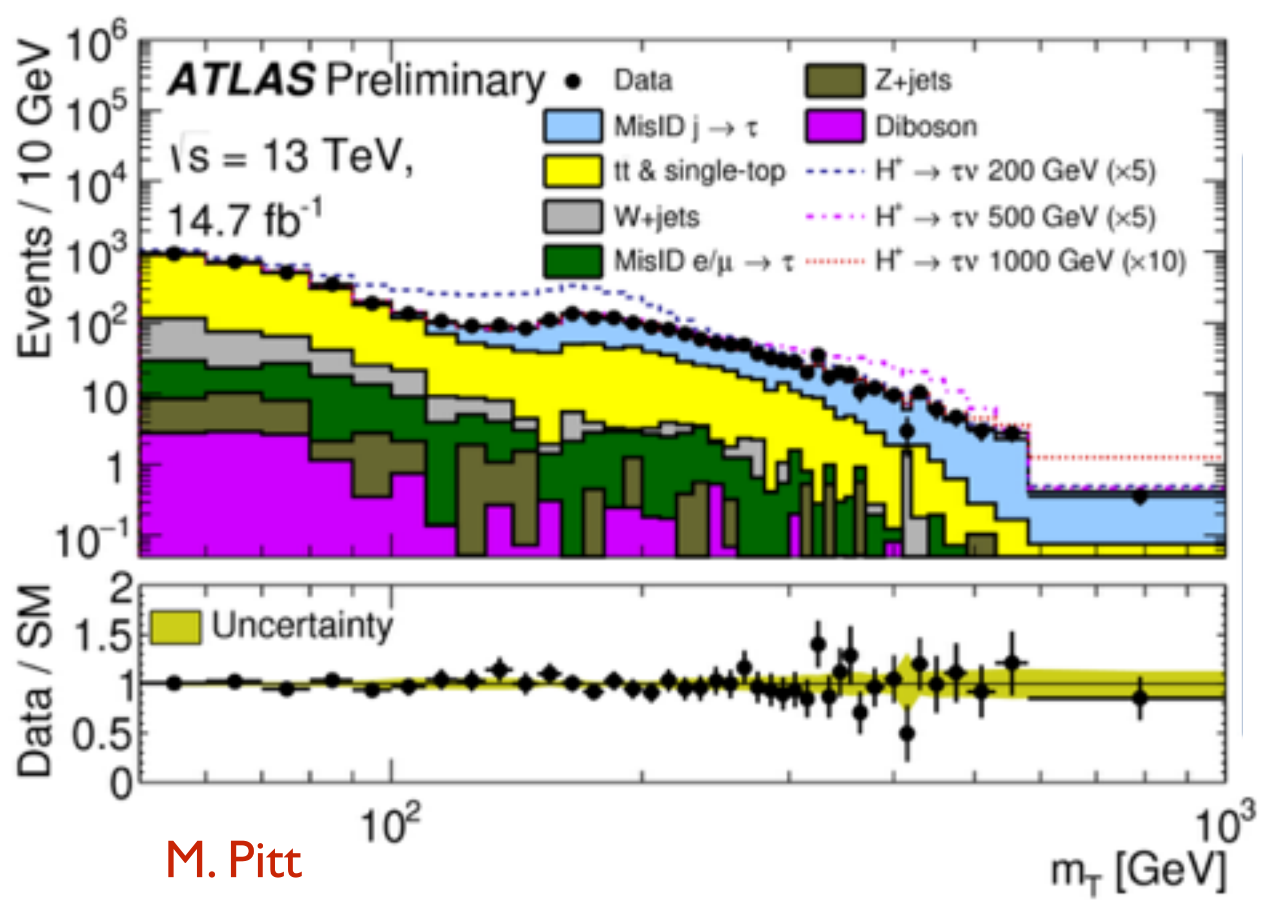
M. Pitt

S. H. Laurila



- To compare signal shapes with respect measured distributions, need fully differential predictions
- Until recently, MC@NLO [Weydert et al, Eur.Phys.J. C67 (2010)] and POWHEG [Klasen et al, Eur.Phys.J. C72 (2012)] only available in the 5FS and differences between 4FS (leading order MG5_aMCatNLO + K-factor) and 5FS was strong source of systematic uncertainty in charged Higgs searches

Differential distributions



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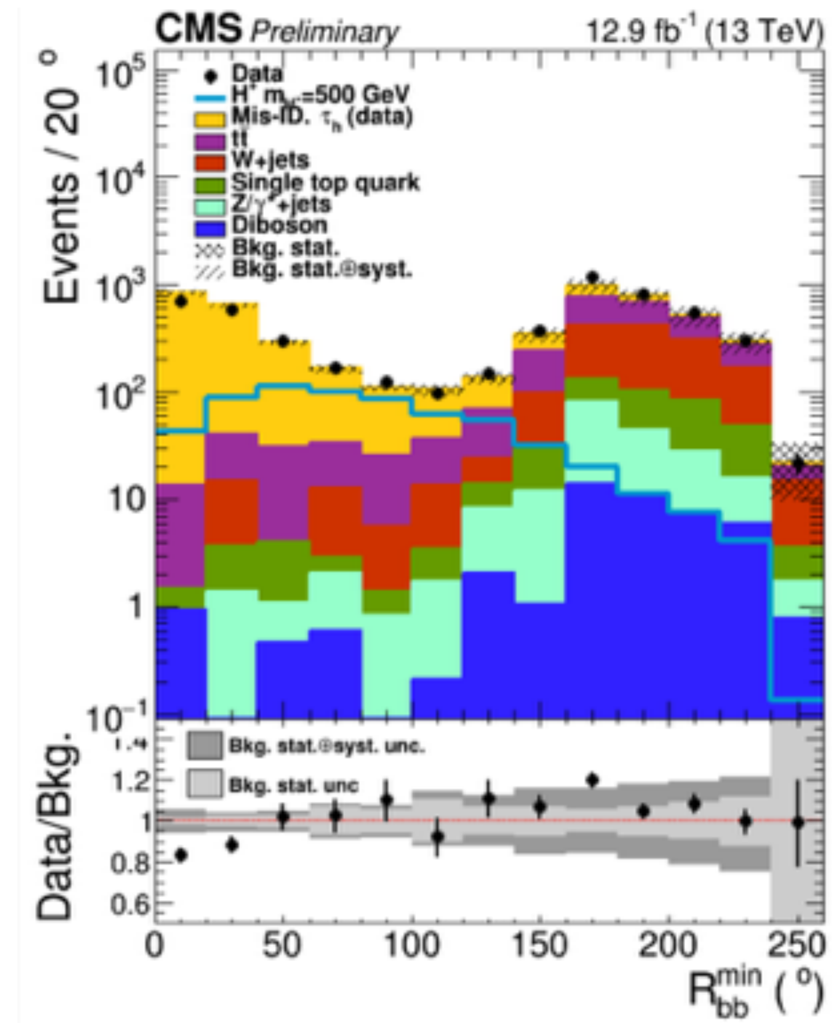
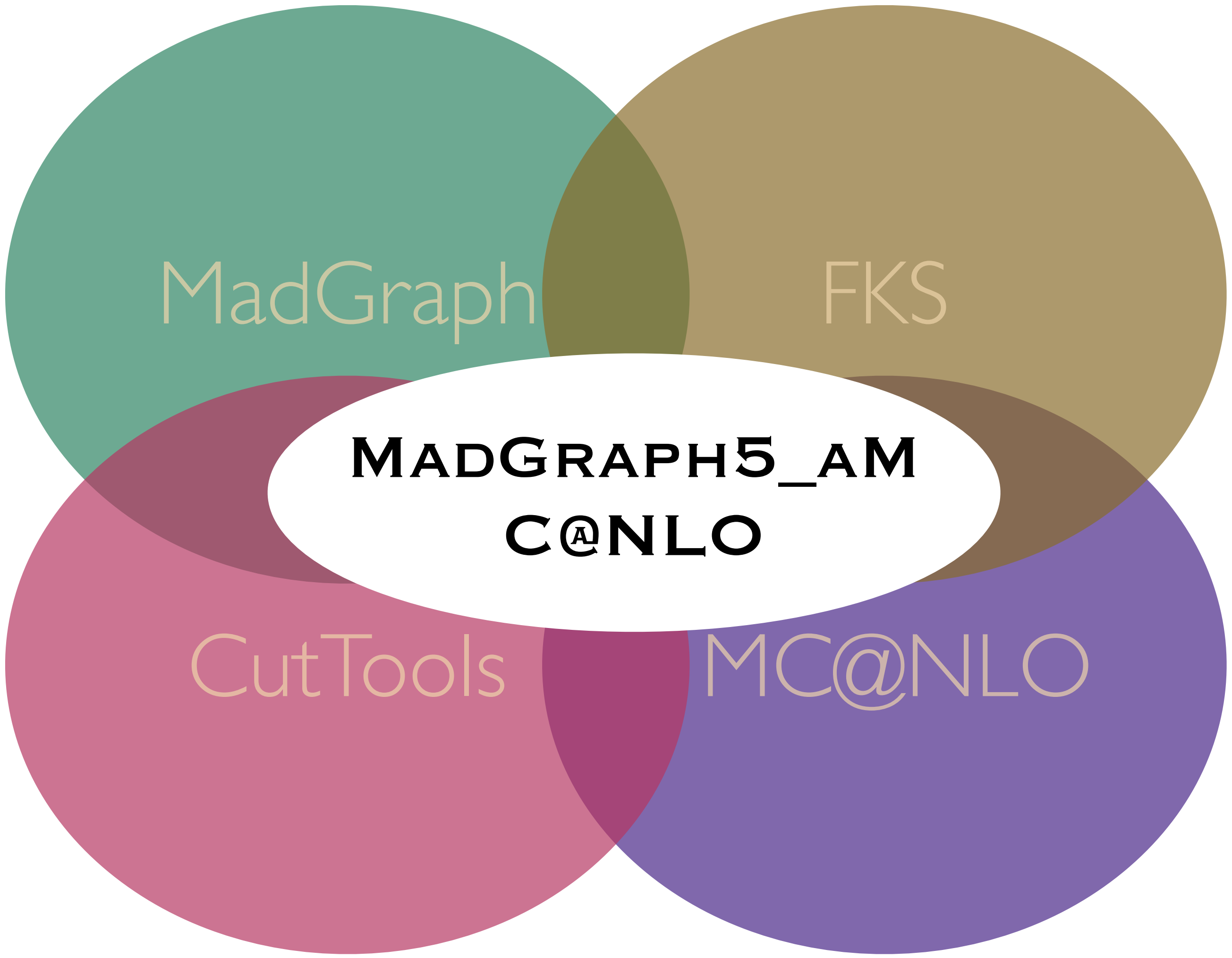


- In case of differential distributions - whether missing higher order logs or power-suppressed terms are more important - it is observable-dependent
- NLO picture is modified (and improved) by matching with PS
- In 5FS backward evolution of initial-state b will generate B hadrons even at $O(\alpha_s^0)$
- In 4FS small-pT initial state emissions effectively resummed by PS

4FS versus 5FS

Differential distributions

Implementation of 2HDM and charged Higgs production in the 4FS and 5FS schemes in the automatic framework provided by MadGraph5_aMC@NLO [Degrande, MU, Wiesemann, Zaro JHEP 1510 (2015)]



M. Zaro

- NLO results: FKS method for IR subtraction and OPP integral-reduction procedure for one-loop matrix elements
- NLO+PS: MC@NLO method
- Scale and PDF uncertainties obtained 'on the fly', without the need of extra runs
- Models resulting into a set of rules (UFO) are now generated automatically [C.Degrande 1406.3030]
- R2 and UV counter-terms automatically generated. Tested and validated in the 2HDM case

Alwall, Frederix, Frixione, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Hirschi, Zaro arXiv:1405.0301

Differential distributions

Degrande, MU, Wiesemann, Zaro
JHEP 1510 (2015)

- Computation split up in Y_b^2 and Y_t^2 terms. Maximum relative contribution of interference term $Y_b Y_t$ assessed (5% at most for tanB = 8 and mH = 200 GeV, smaller in all other cases)

- $\overline{\text{MS}}$ renormalised bottom Yukawa coupling to compare with existing calculations and resum large logs of (μ_R/m_b). Top Yukawa coupling renormalised in the on-shell scheme. $m_b(\mu_R)$ scale dependence included via re-weighting

$$\bar{m}_b(\bar{m}_b) = 4.34\,\text{GeV} \qquad M_b = 4.75\,\text{GeV} \qquad M_t = 172.5\,\text{GeV}$$

- PDFs: NNPDF23 NLO 4FS and 5FS at NLO
  NNPDF30 LO 4FS and 5FS at LO

$$\sqrt{S} = 13\,\text{TeV} \qquad m_H = 200, 600\,\text{GeV} \qquad \tan\beta = 8$$

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

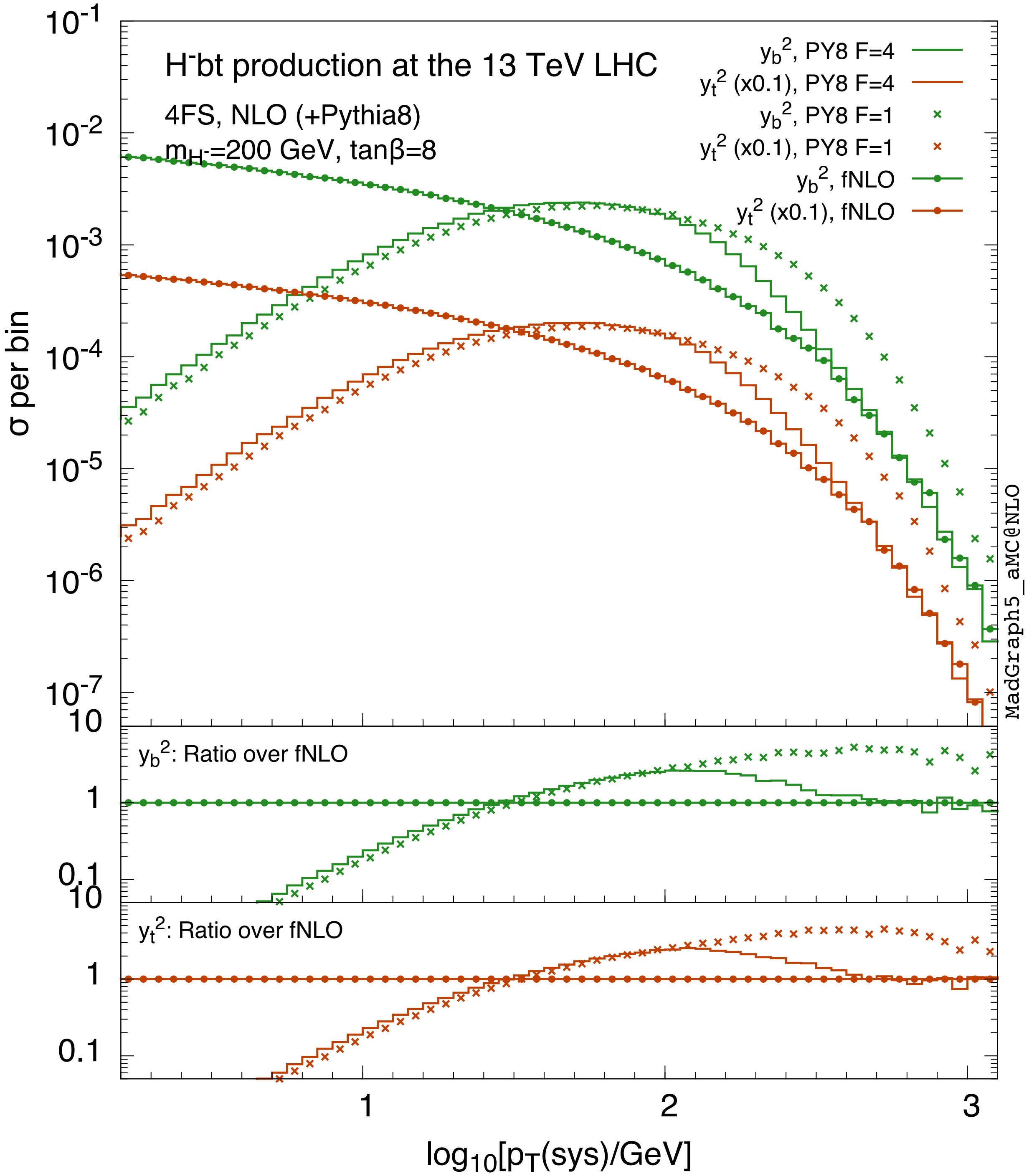
Distribution shapes do not depend on value of tan(β)!

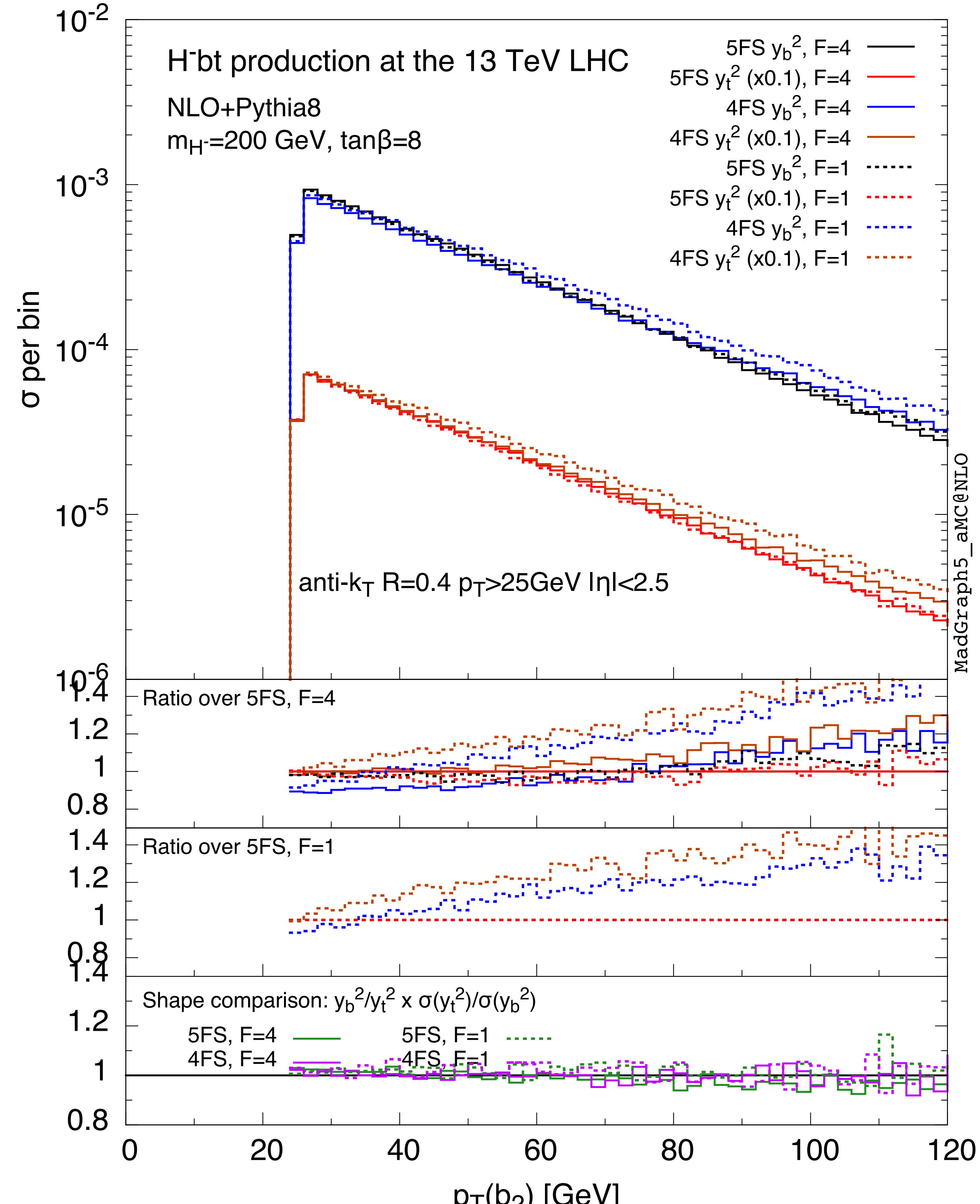
- Charged Higgs is stable and top decays leptonically
  ⇒ one b-jet from top and one from matrix element

$$\frac{0.1}{F}\sqrt{\hat{s}} \leq \mu_{sh} \leq \frac{1}{F}\sqrt{\hat{s}},$$

- Explored the dependence of distributions on μ_{sh} (largest hardness accessible to showers)
  — Compare default shower scale (F=1) to reduced shower scale (F=4)

Choice of shower scale

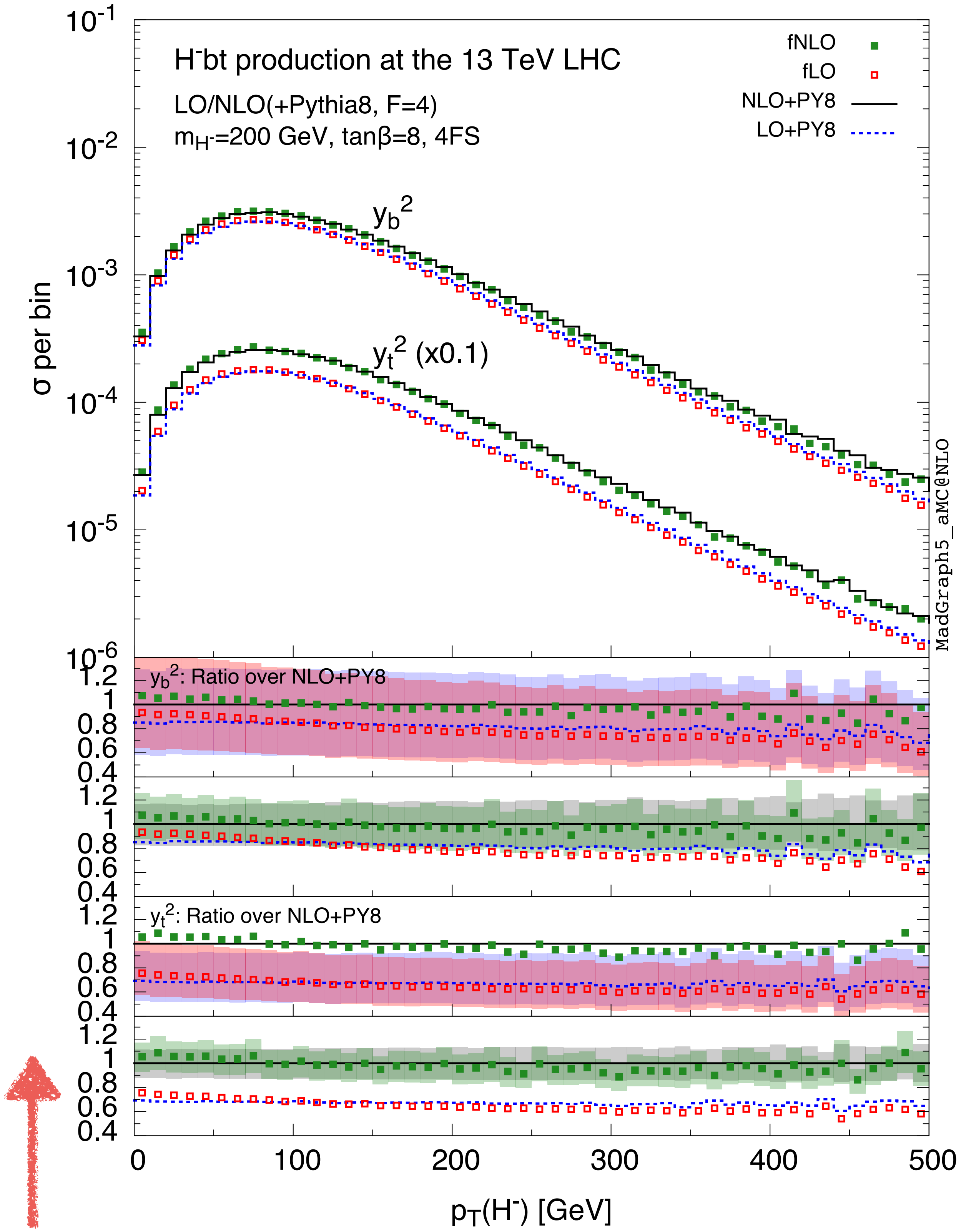


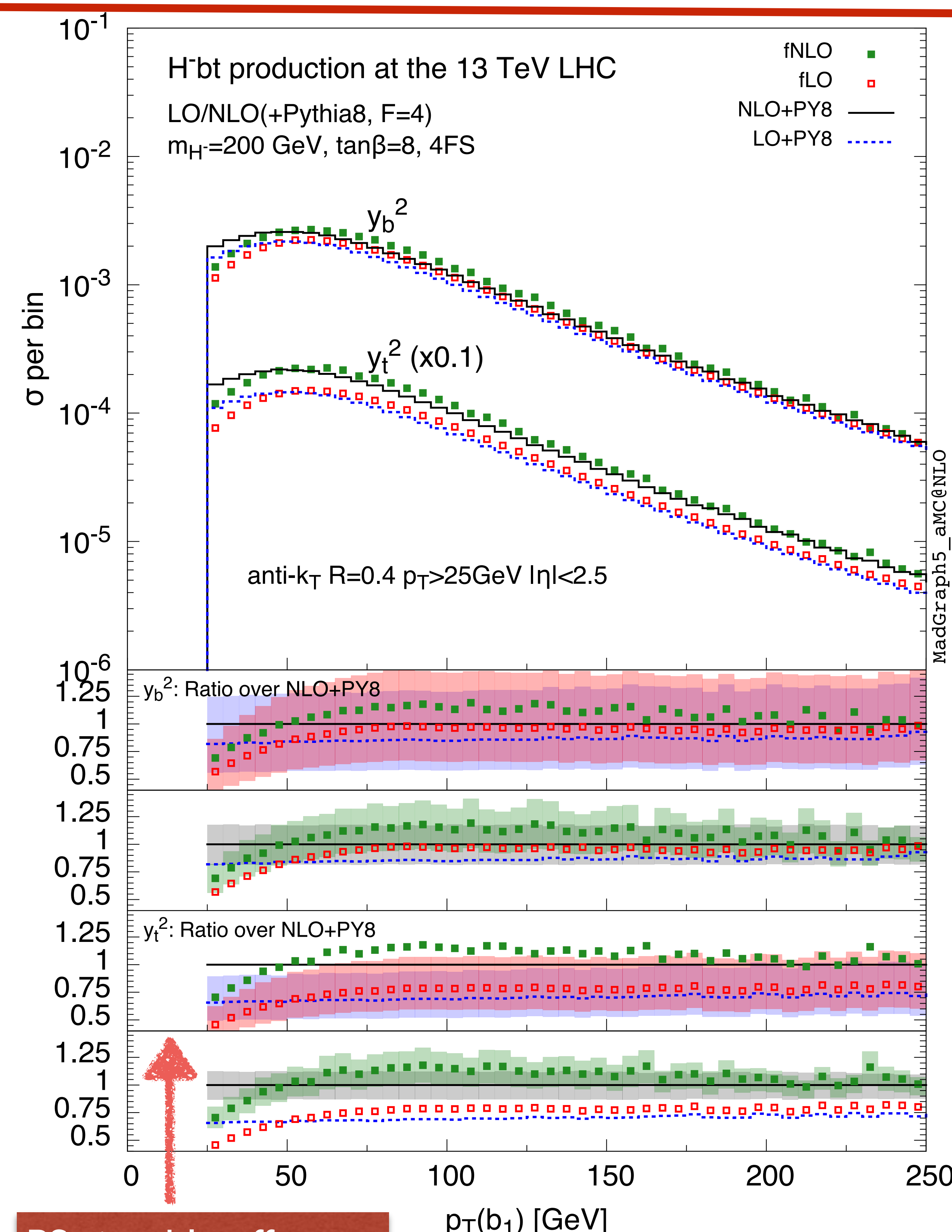


Lower shower scale than default one improves matching between FO and shower-resummed results at large p_T

Consequence: lower shower scale brings 4FS and 5FS predictions closer

4FS differential distributions

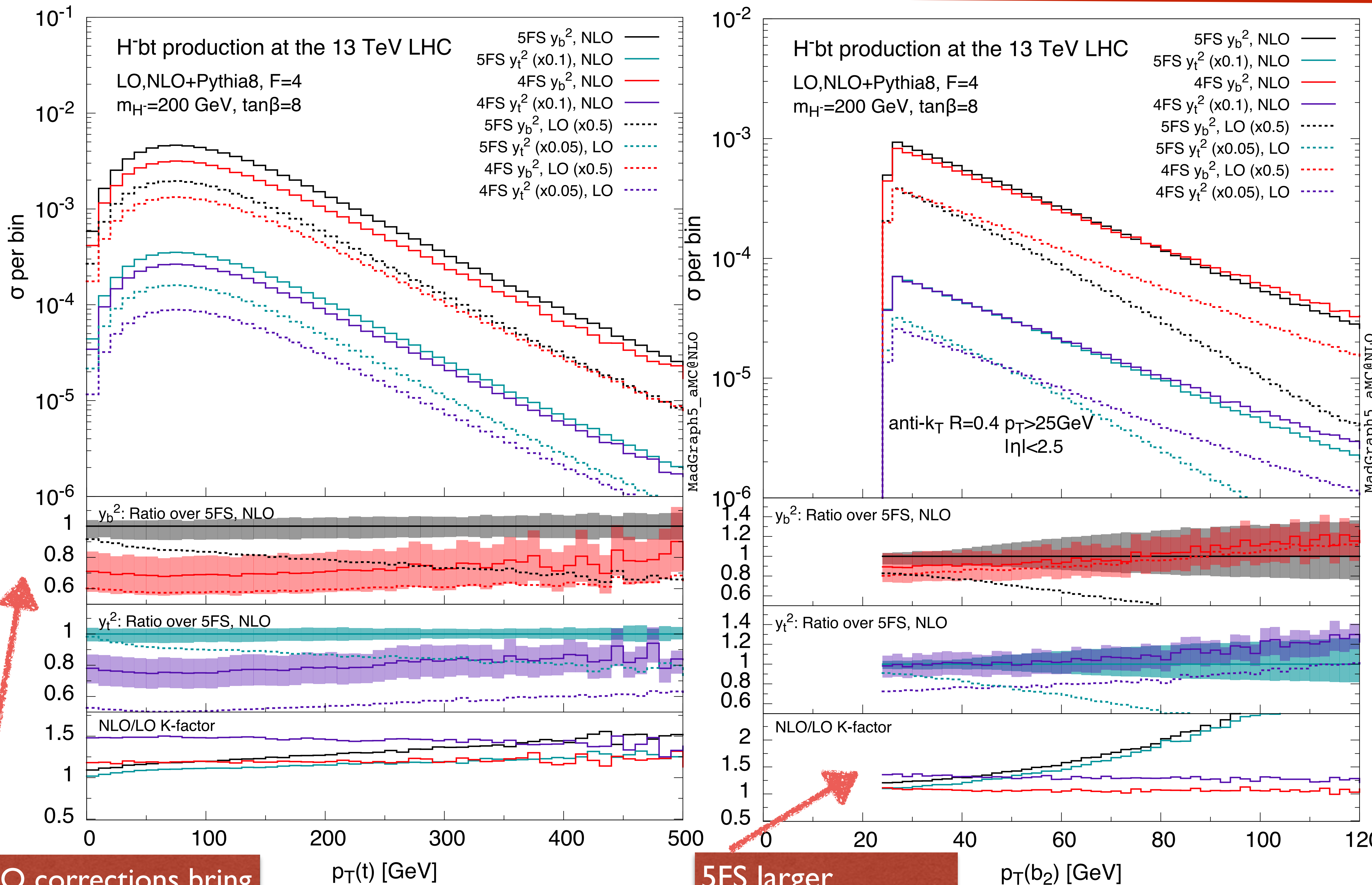




NLO mostly affect normalisation
PS negligible effects

PS sizeable effects
at small pT of b-jets

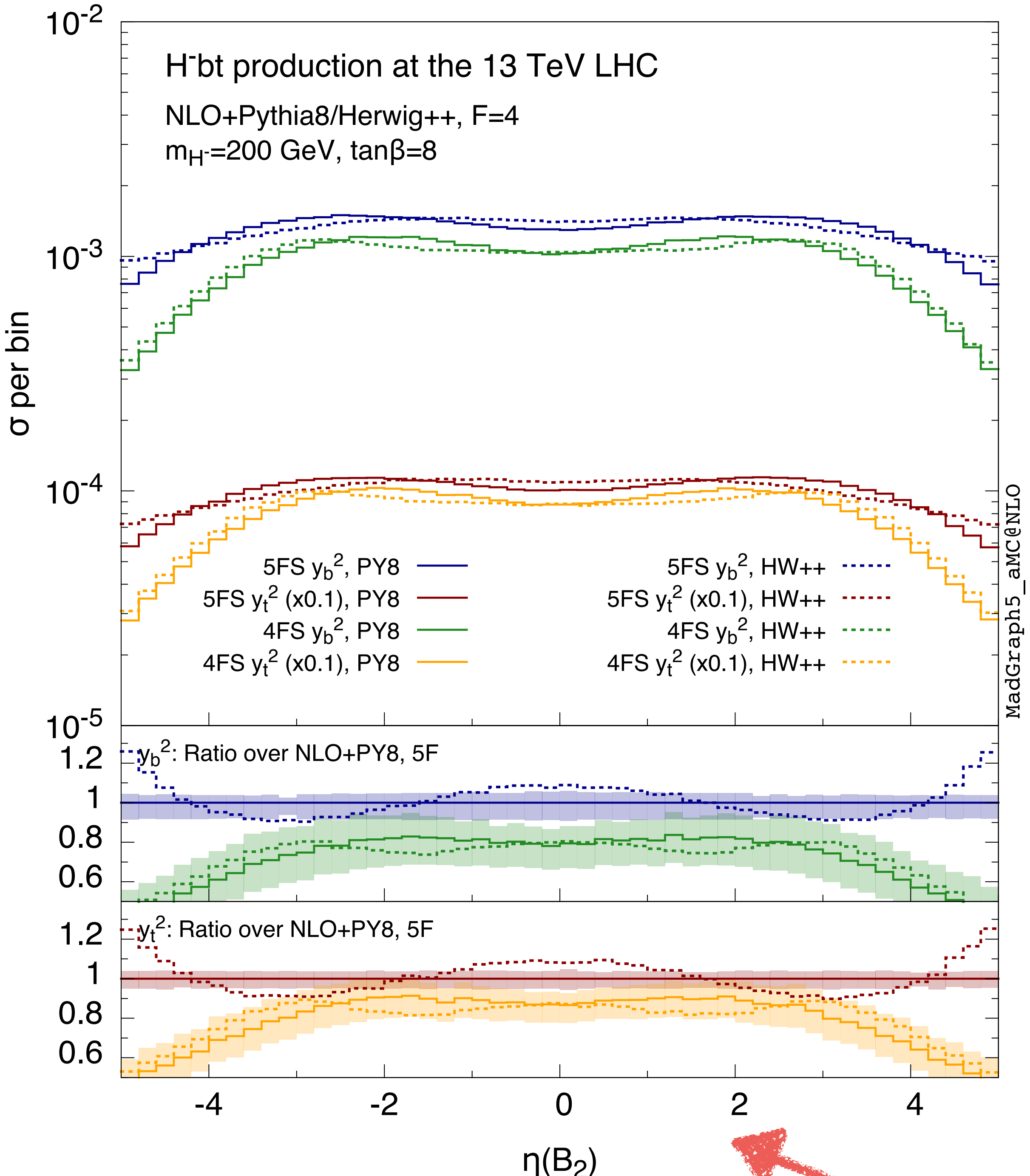
4FS versus 5FS

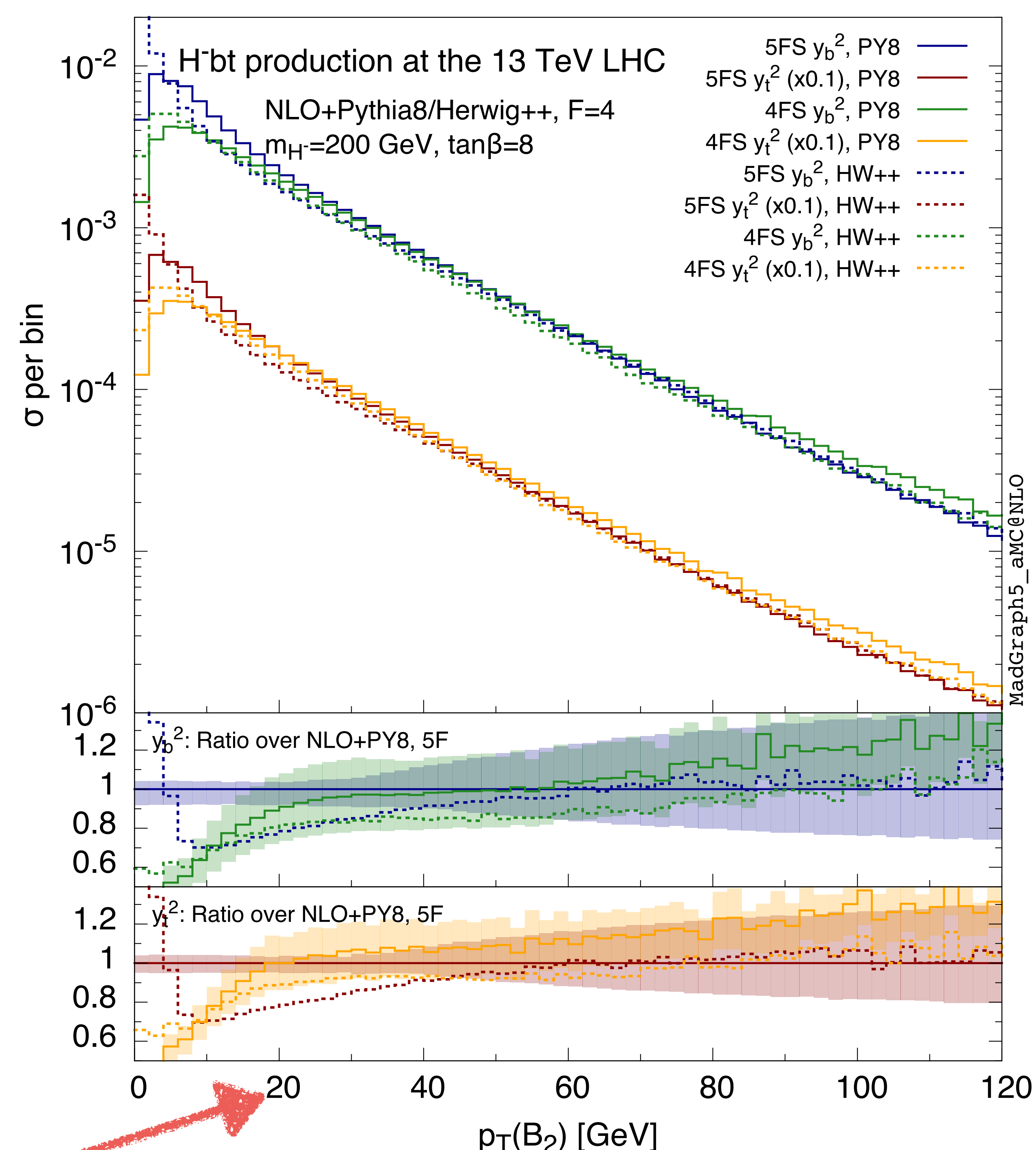


NLO corrections bring 4FS and 5FS close for inclusive observables

5FS larger uncertainties and K-factor

4FS versus 5FS

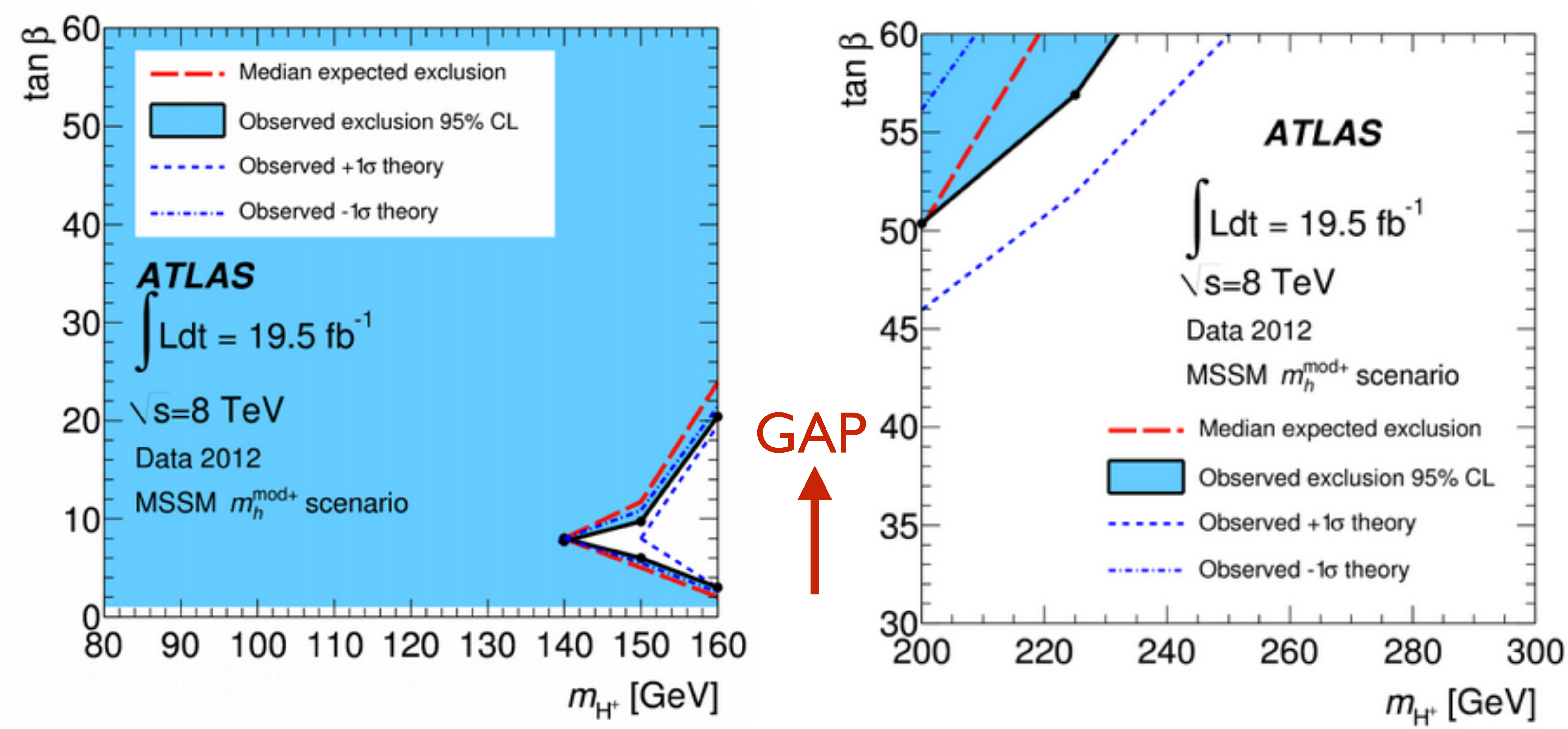




5FS exhibit stronger dependence on the Monte Carlo for b-exclusive observables

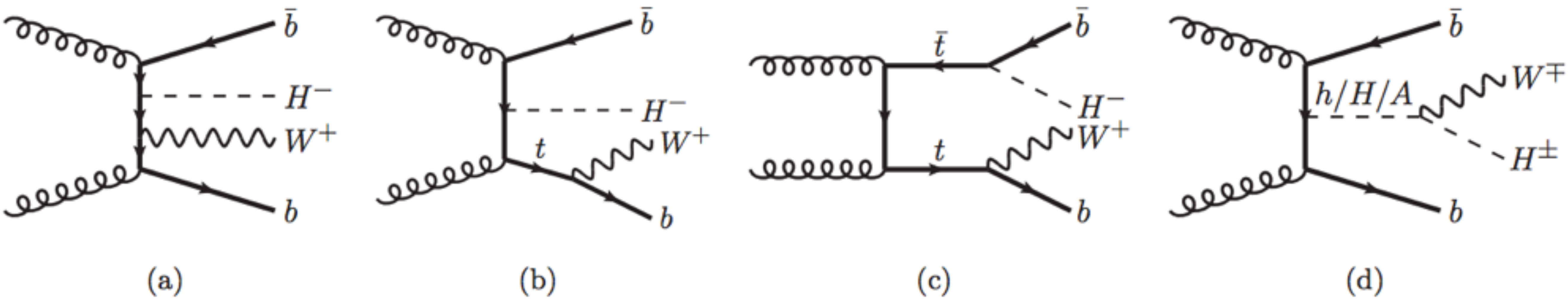
4FS to be preferred for observables exclusive in b

Intermediate-mass range



- Intermediate region has not been studied in the Run I
- LO total cross section has large (30-50%) theoretical errors. For accurate predictions one needs to compute NLO correction. Need a MC tool to simulate the signal in the region in which charged Higgs mass close to top mass.

Intermediate-mass range



- The full process $pp \to H^\pm W^\mp b\bar{b}$ has to be simulated, consistently including the top quark width, which is a function of $m_{H\pm}$ and $\tan\beta$
- Diagrams with 0, 1 and 2 resonant tops contribute to the total cross-section+ diagrams with neutral Higgs bosons
- Cross-section for $m_{H\pm}>m_t$ ($m_{H\pm}<m_t$) will get the dominant contribution from single- (double)-resonant diagrams

Intermediate-mass range

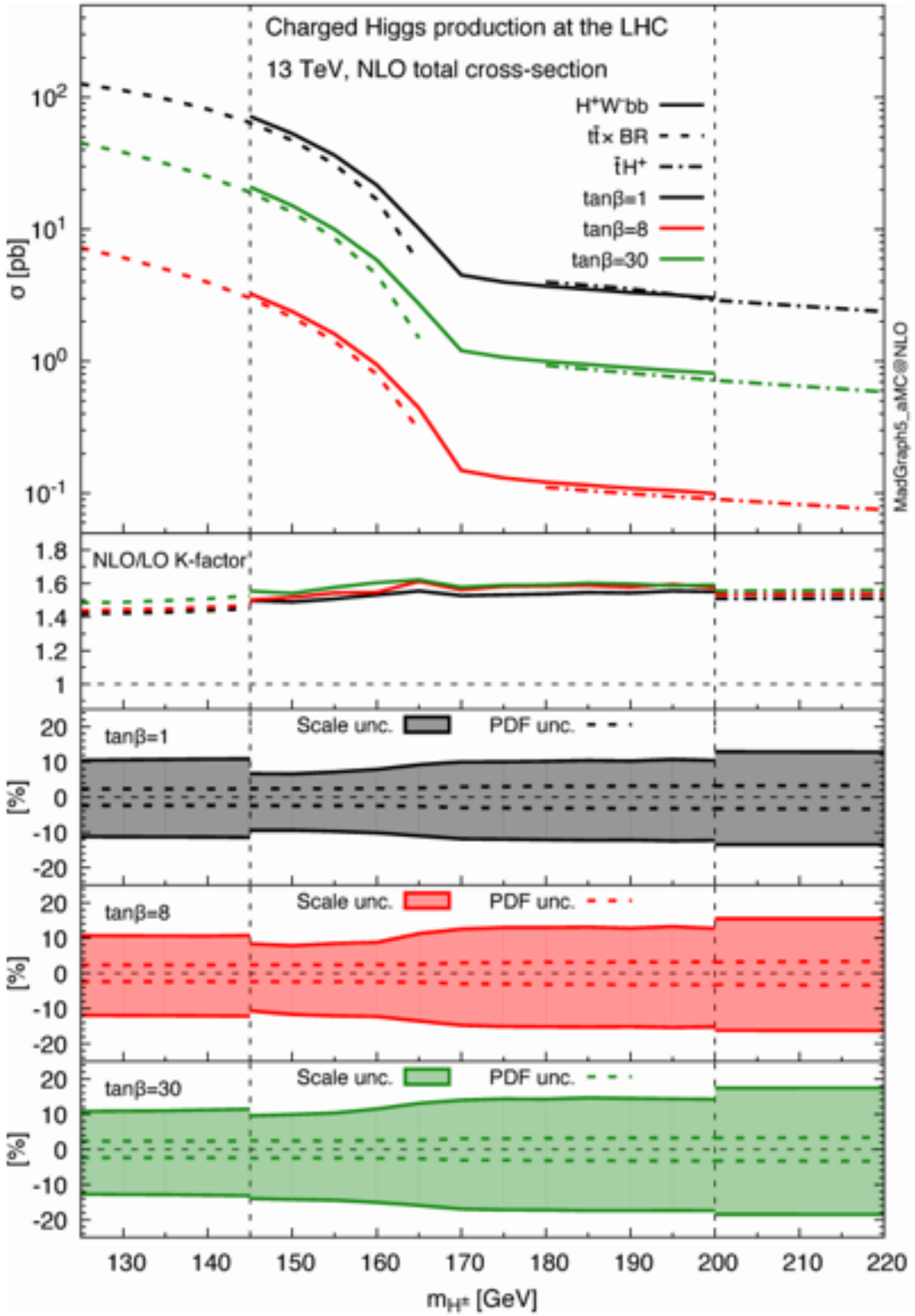
- Computation done with MadGraph5_aMC@NLO, improved with resonance-aware FKS subtraction
  Frederix et al. arXiv:1603:01178

- Complex top-mass (and Yukawa) scheme to include the top width in a gauge-invariant way. Γ_t computed at NLO for every ($m_{H\pm}$, tanβ) point

- Use massive bottom quarks (4FS).

- Use a fixed central scale, $\mu_{R/F}$=125 GeV

- Use the $\overline{\text{MS}}$ scheme for y_b renormalisation (introduces extra μ_R dependence)



Conclusions

- Lot of progress in the past year in simulation of heavy and intermediate-mass charged Higgs boson (thanks to Higgs XS Working Group)

- For heavy charged Higgs boson Santander-matched predictions for wide range of masses and tanB in type-II 2HDM, generalisable to other types

- Fully differential calculation at NLO and NLO+PS in 4FS (and 5FS) in MG5
https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/chargedHiggs
— NLO corrections quite flat for observables inclusive in b-kinematics
— PS corrections significantly modify spectra of b-exclusive observables
— Lower shower scale than default well-motivated by hard/soft physics matching

- 4FS versus 5FS comparison at the level of total and differential cross sections
— Compatible results for observables inclusive in b-kinematics
— Lower shower scale brings predictions closer to each other
— 4FS more reliable and less MC-dependent for observables exclusive in b-kinematics - recommended

- New total xsec calculation for simulation of signal in intermediate mass region, simulation of the differential distribution under discussion