Charged Higgs boson production at the LHC: closing the $m_{H\pm} \sim m_t$ window

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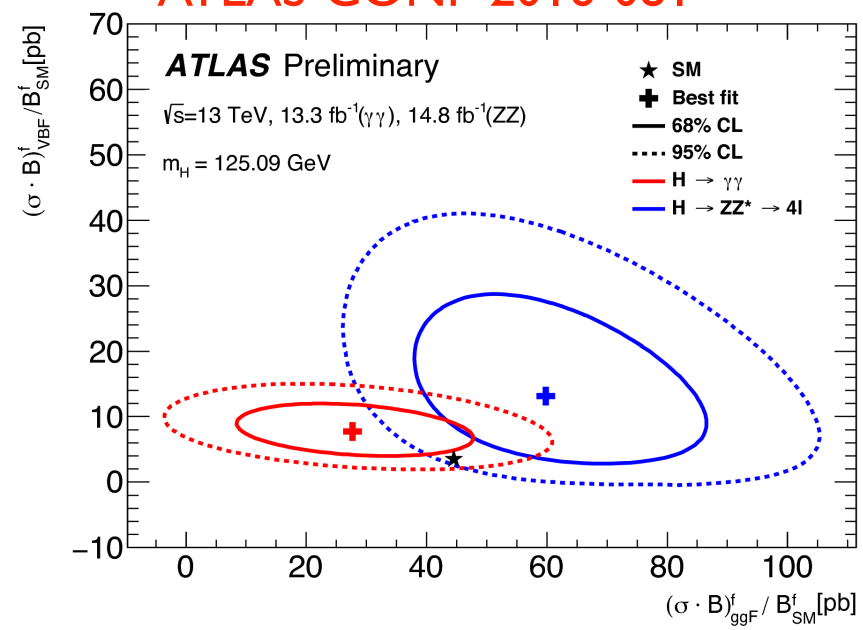
based on
Degrande, Frederix, Hirschi, Wiesemann, Ubiali, MZ, arXiv:1607.05291

HP2.6@ICAS, Buenos Aires - September 7, 2016

Higgs at the LHC

- Since the discovery of the 125 GeV Higgs boson, many efforts have been put into looking for deviations from the SM in the Higgs sector
- On the one hand, properties of the new particle look compatible with the SM (surprises may arise when errors will be reduced)
- On the other, the discovery of new particles in the Higgs sector will be a clear sign of BSM physics
- Many extension of the Higgs sector feature charged Higgs bosons

ATLAS-CONF-2016-081



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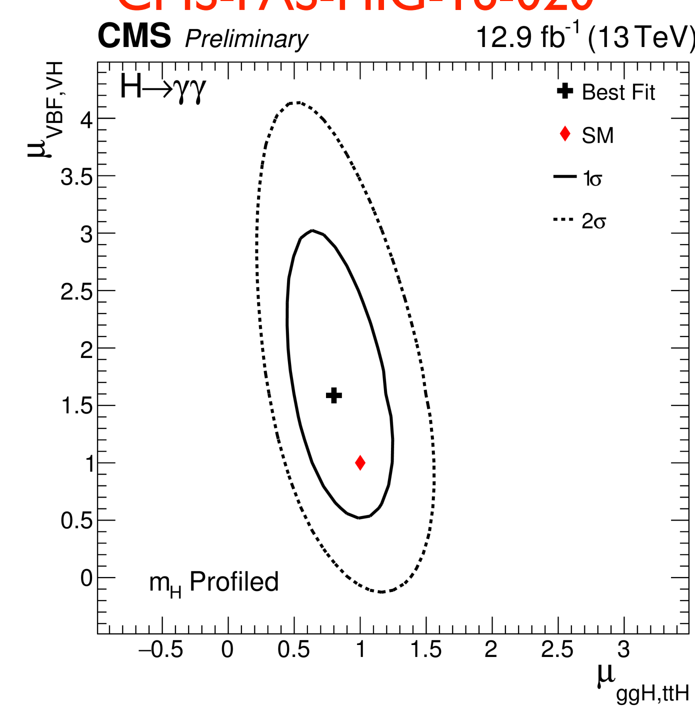
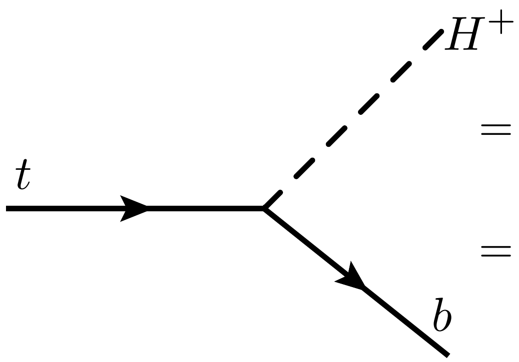


Charged Higgs couplings in the 2HDM

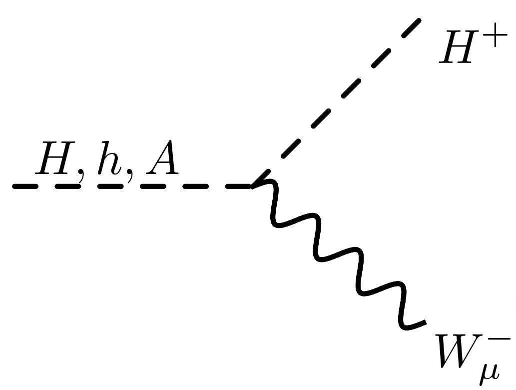
- The 2HDM is one of the simplest extension of the SM Higgs sector, featuring two neutral scalars (h,H), one neutral pseudo-scalar (A) and two charged Higgs bosons (H±)
- The most common version of the 2HDM is the so-called type-II (∋MSSM)
- In the 2HDM, charged Higgs bosons couple either to a neutral 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 $ZW^{\pm}H^{\mp}$ couplings exist at tree level. They appear in more exotic models with higher representations (triplets), such as Georgi-Machacek models

Georgi, Machacek, Nu.Ph.B262(1985)



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

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



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

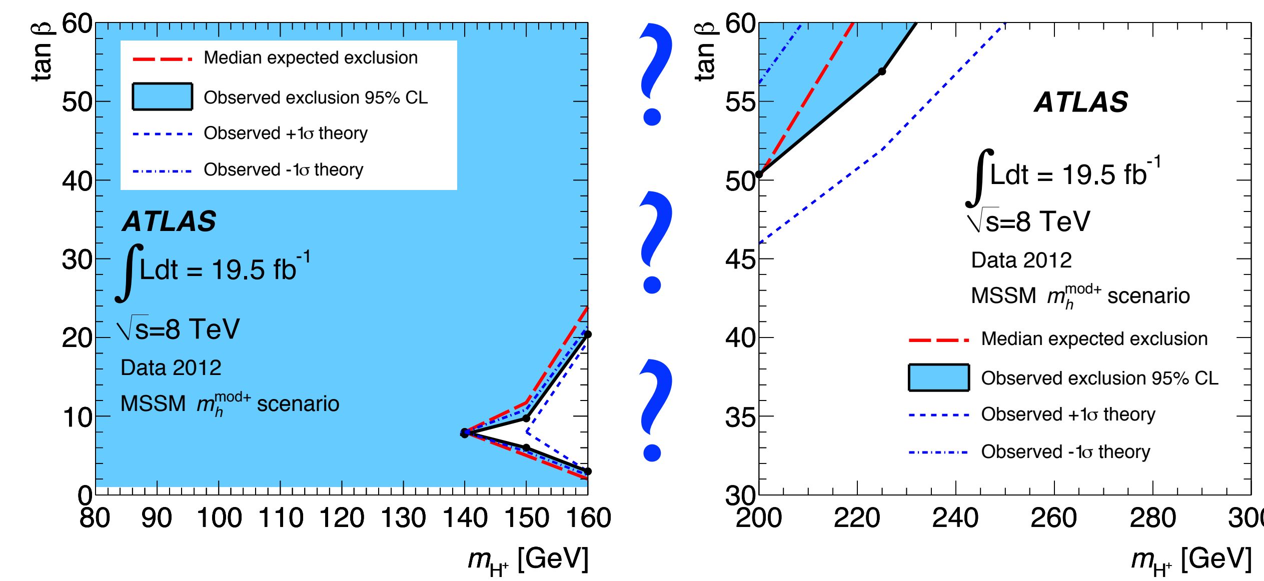
$$= i\frac{g_W}{2}\sin(\beta-\alpha)p^\mu_W \quad (H)$$

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

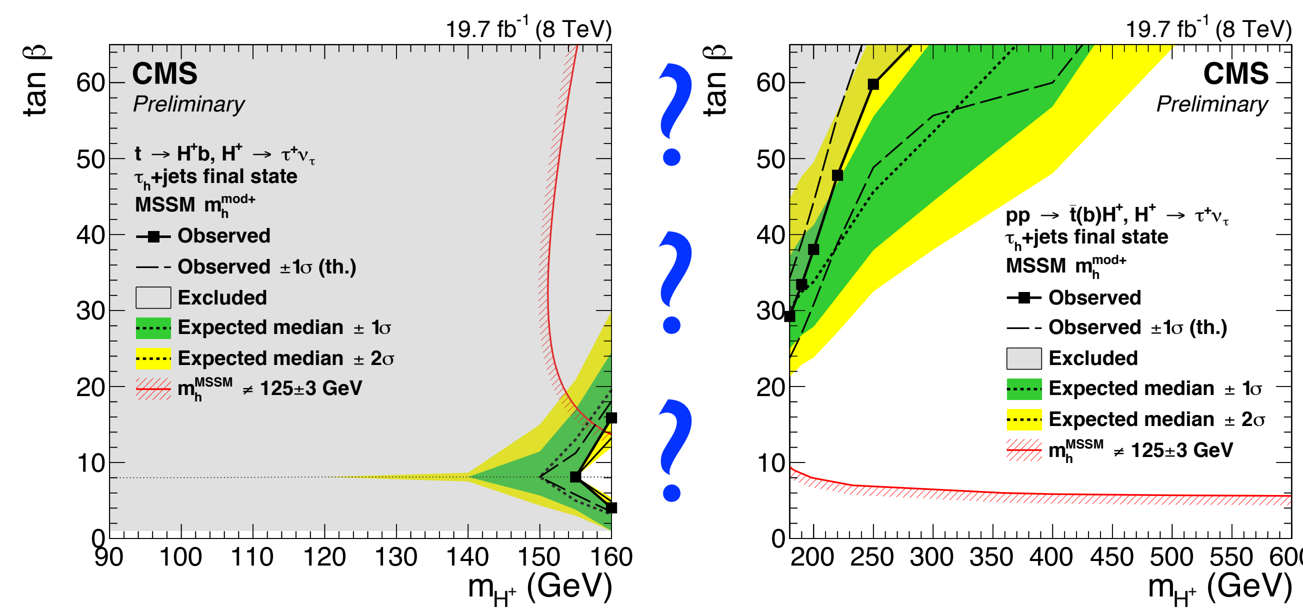
Searches at the LHC

- 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 predictions for the intermediate range beyond LO

ATLAS, arXiv:1412.6663



CMS, PAS HIG-14-020



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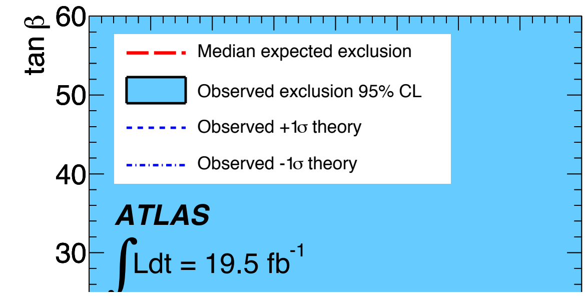
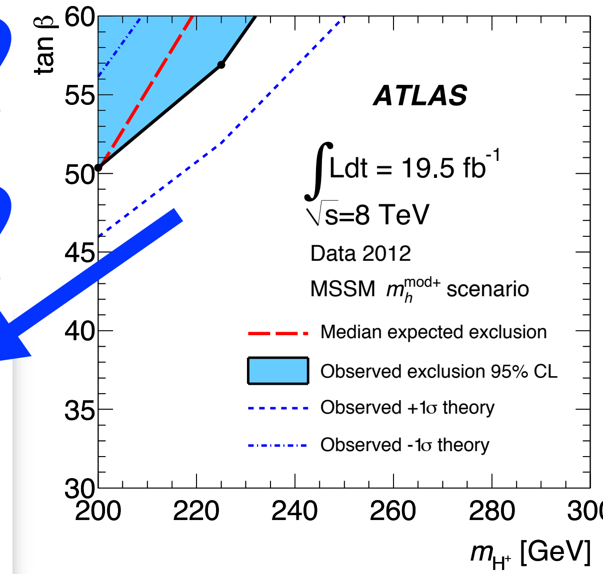
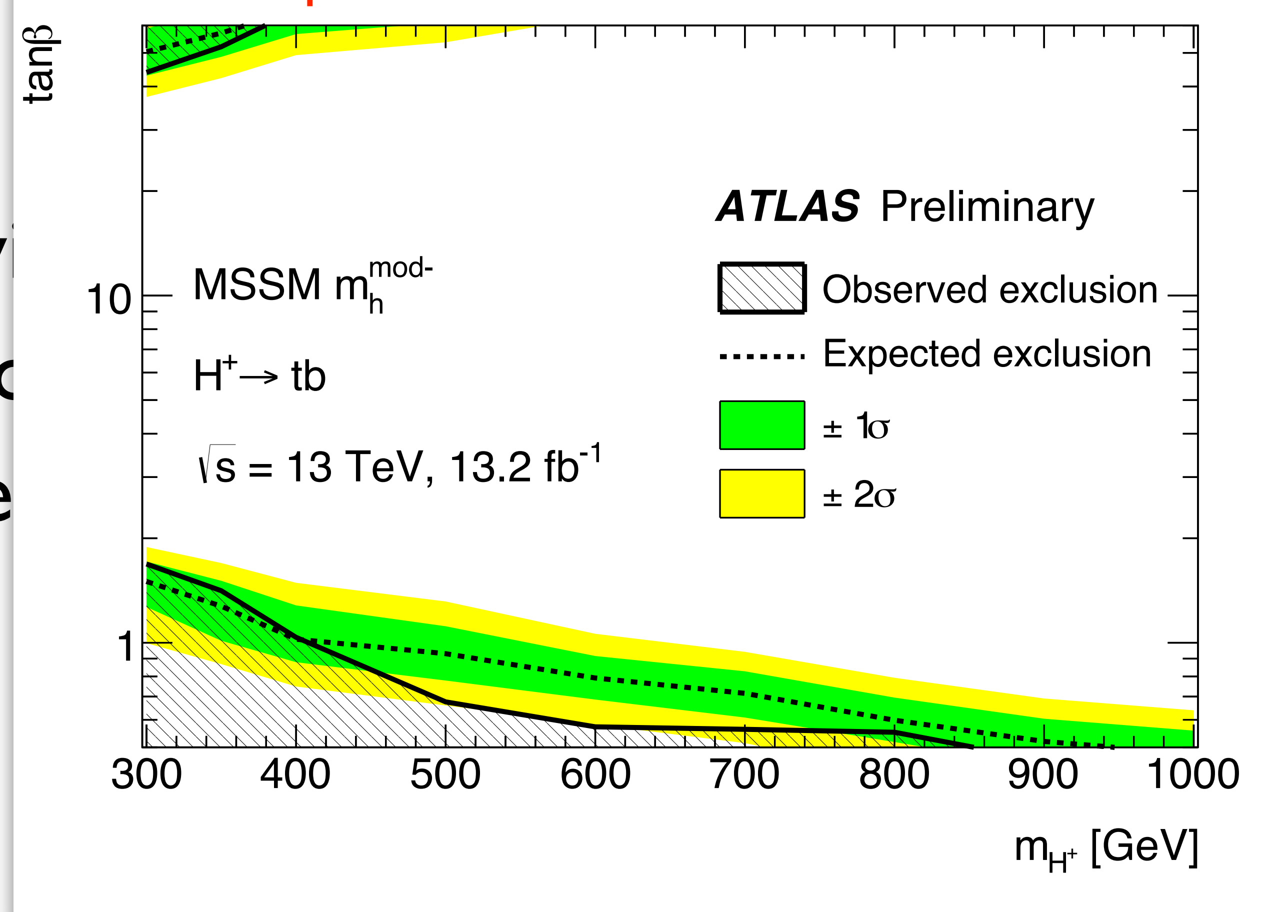
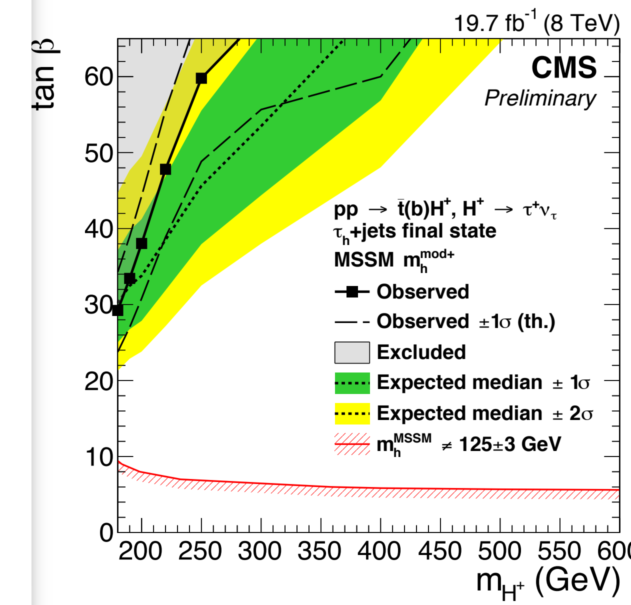




ICHEP'16 update: ATLAS-CONF-2016-088 & -089

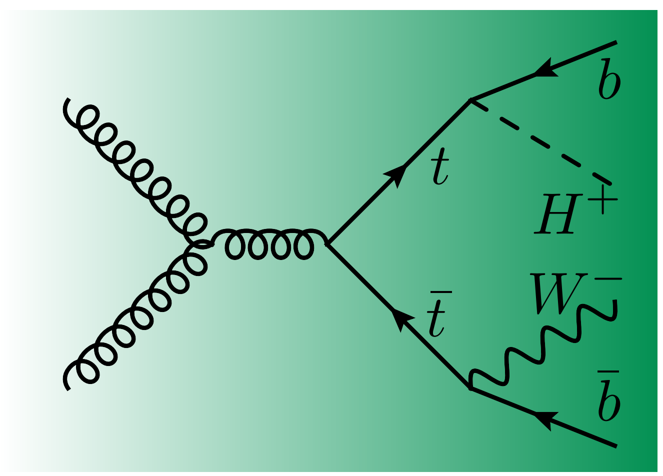




Charged Higgs production in 2HDMs

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

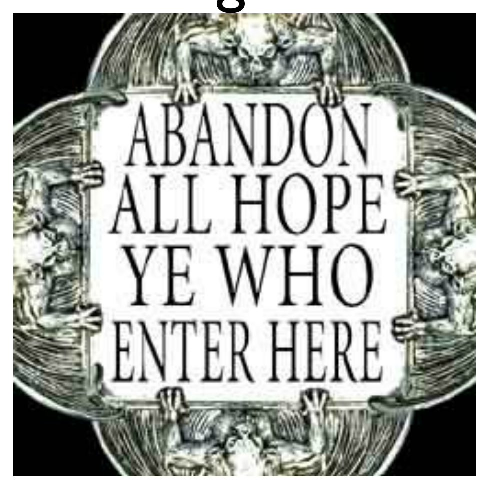
Light Higgs



$M_{H^+} < M_t$

$H^\pm$ mostly produced in $t\bar{t}$ events.

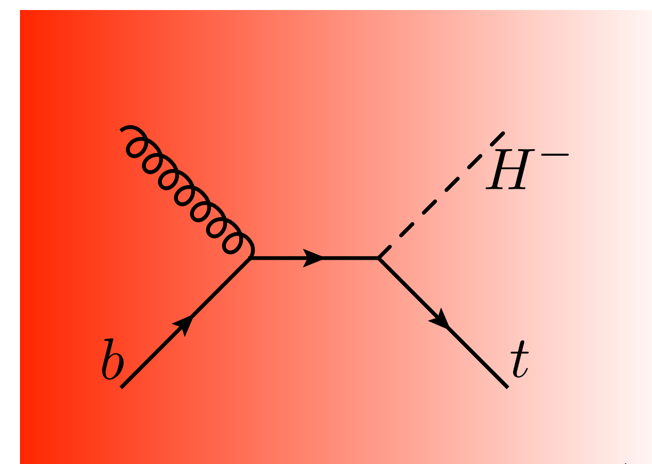
Intermediate region



$M_{H^+} \simeq M_t$

The full $pp \to H^\pm W^\mp b\bar{b}$ process has to be simulated.

Heavy Higgs

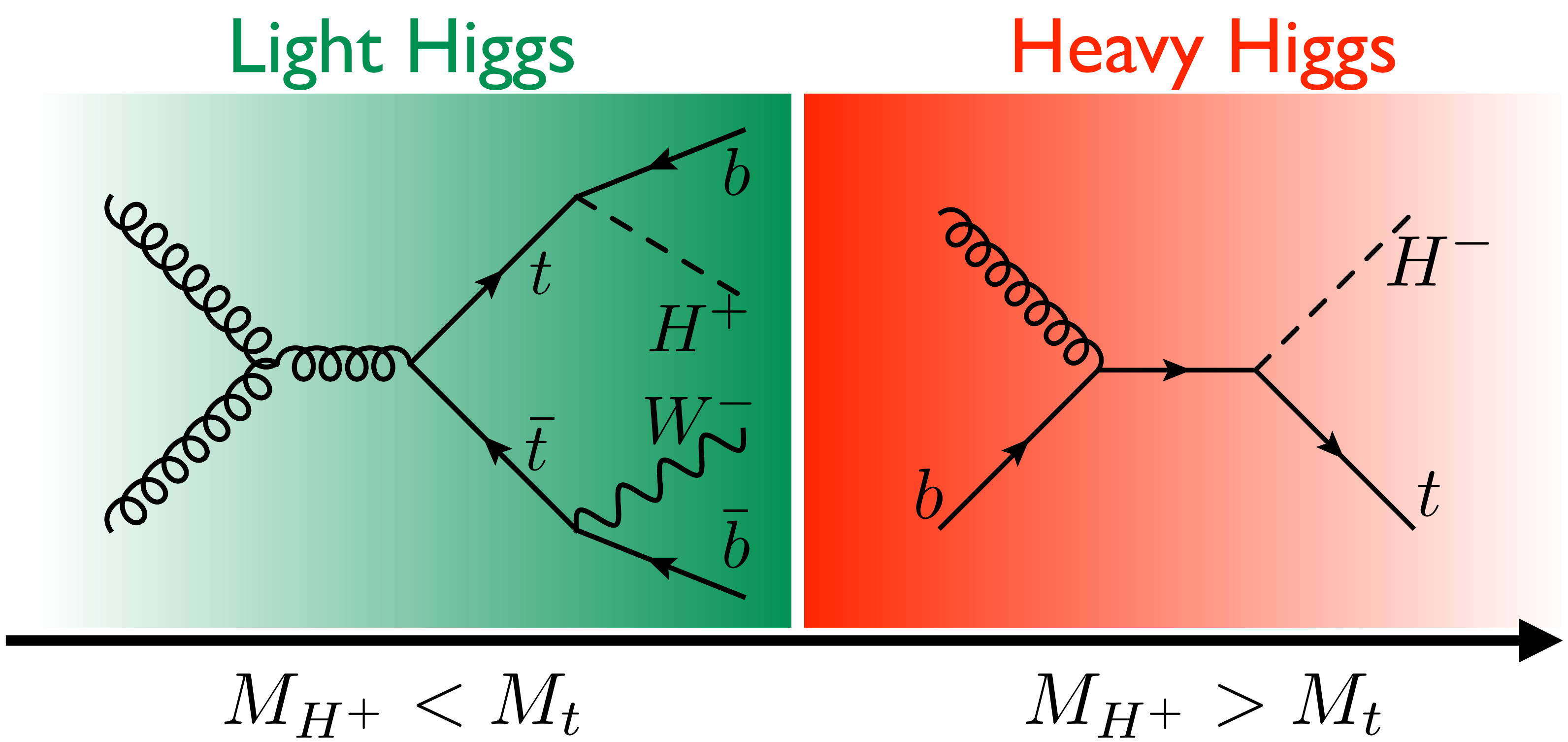


$M_{H^+} > M_t$

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

Charged Higgs production in 2HDMs

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



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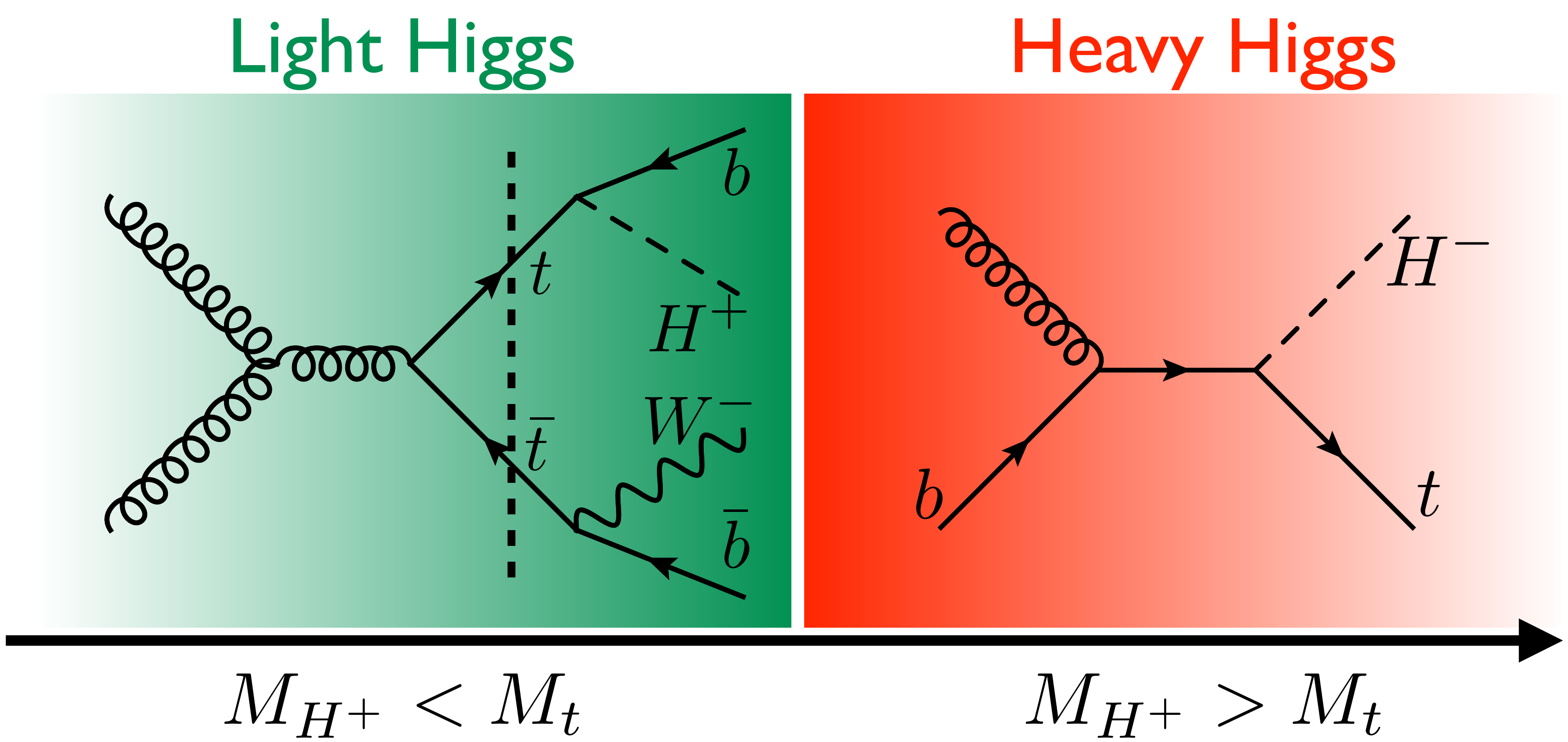


Can take the $\Gamma_t \rightarrow 0$ limit

Charged Higgs production in 2HDMs

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

Light Higgs

Top cross-section at NNLO QCD: Czakon et al, arXiv:1303.6254, arXiv:1511.00549, …
EW corrections to top cross-section: Beenakker et al., Nu.Ph.B.411(1994), Hollik et al., arXiv: 0708.1697, …
NLO (SUSY-)QCD corrections to $\Gamma(t \to H^+ b)$: Reid et al, Z.Phys.C (1990), Li et al, Phys.Rev.D (1990), Czarnecki et al., Phys.Rev.D (1993), …, Heynemeyer et al., hep-ph/9812320
…

Heavy Higgs

NLO (SUSY-)QCD corrections: Dittmaier et al, arXiv:0906.2648 (4FS); Zhu, hep-ph/0112109, Plehn, hep-ph/0206121, Berger et al, hep-ph/0312286 (5FS)
EW corrections: Nhung et al, arXiv:1210.4087 (4FS); Beccaria et al, arXiv:0908.1332 (5FS)
Threshold resummation: Kidonakis, arXiv:1005.4451 (5FS)
Fully differential NLO+PS: Degrande et al, arXiv: 1507.02549 (4FS);Weydert et al, arXiv:0912.3430, Klasen et al, arXiv:1203.1341 (5FS)

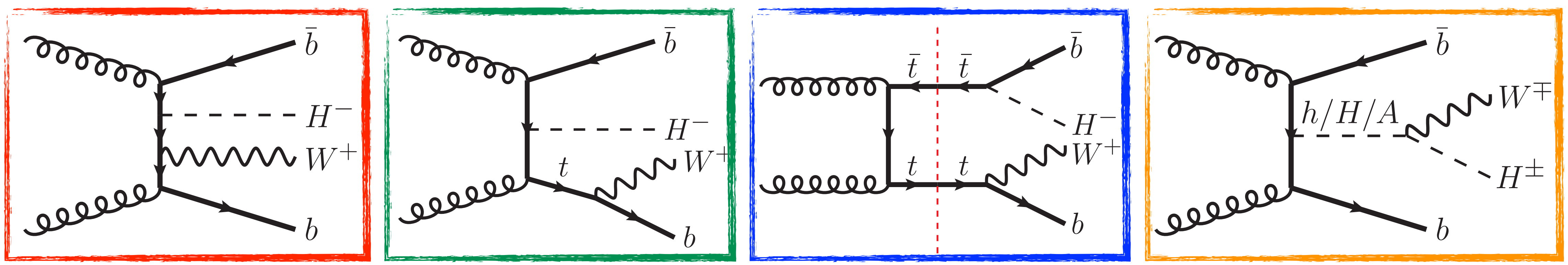
Can take the $\Gamma_t \to 0$ limit

Both cases are known at or beyond NLO QCD

Intermediate-mass region

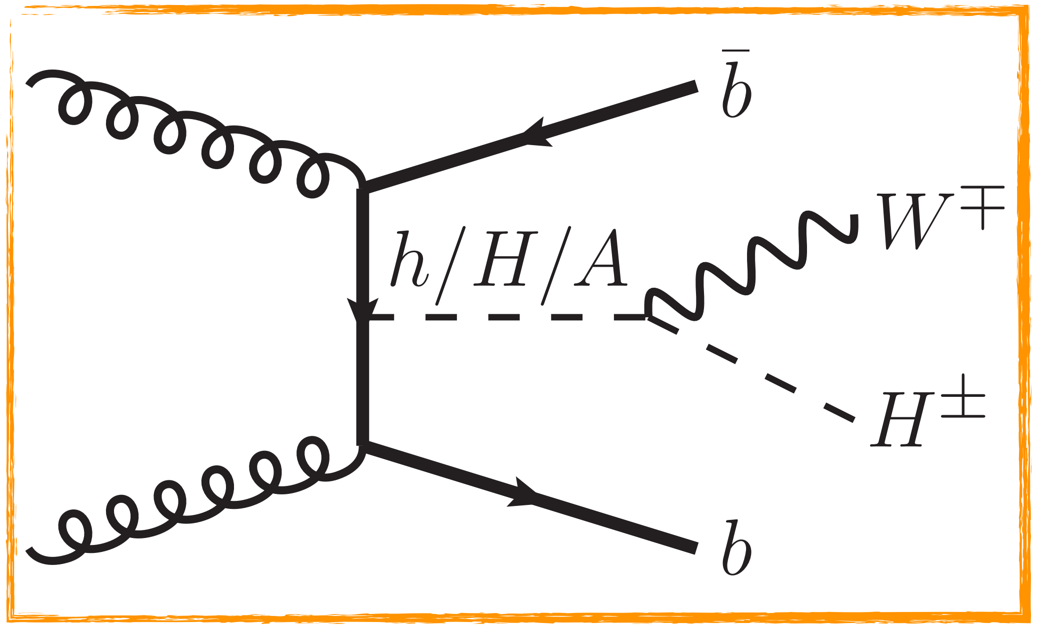
Intermediate-mass region

- The full process pp→$H^{\pm}W^{\mp}b\bar{b}$ has to be simulated, consistently including the top quark width. $\Gamma_t = \Gamma_t(m_{H\pm}, \tan\beta)$
- Diagrams with 0, 1 and 2 resonant tops contribute to the total cross-section, as well as diagrams with neutral Higgs bosons

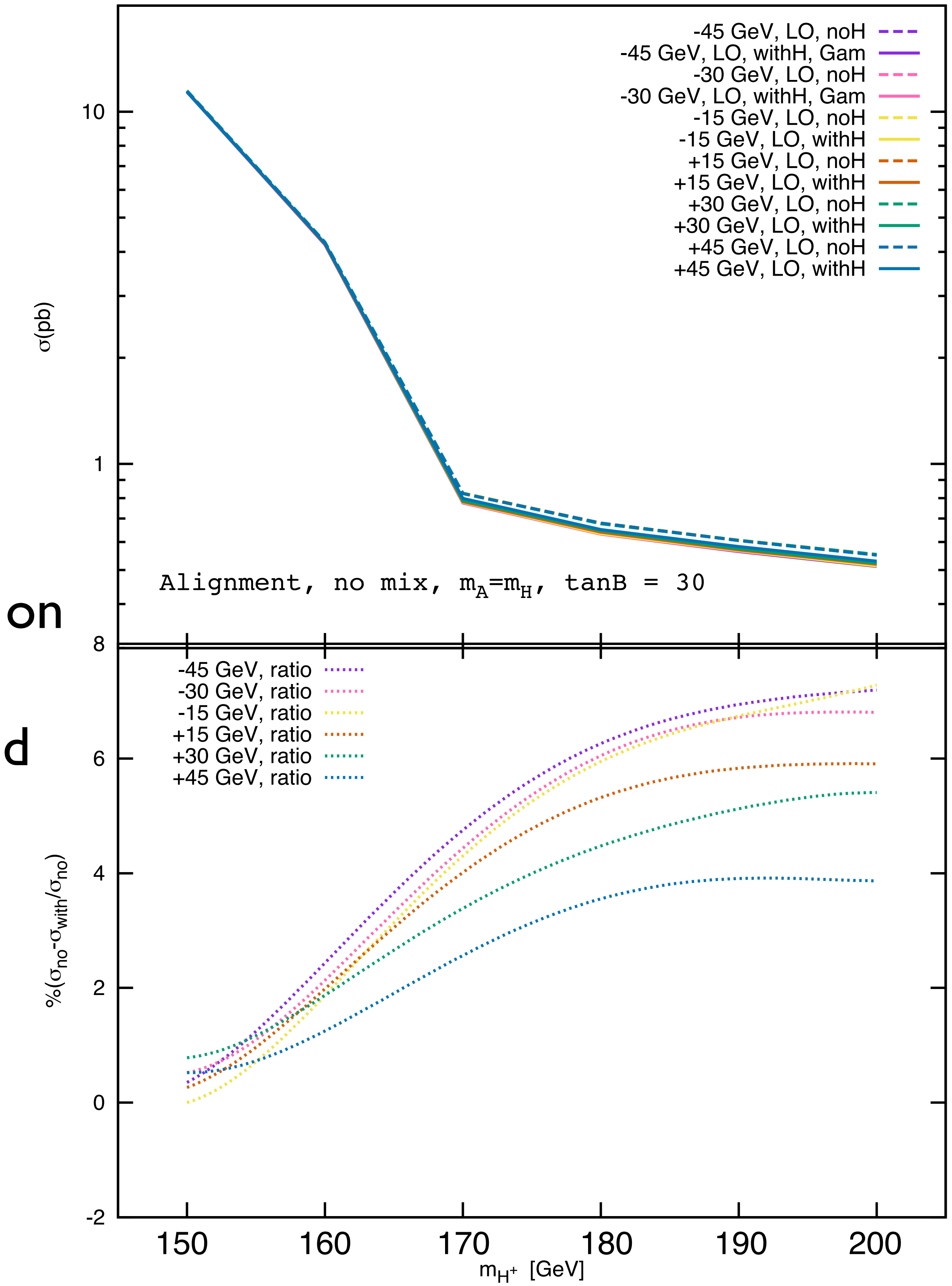


- Cross-section for $m_{H\pm} > m_t$ ($m_{H\pm} < m_t$) will get the dominant contribution from single- (double)-resonant diagrams
- LO total cross section has large (30-50%) theoretical errors. For accurate predictions one needs to compute NLO corrections

Effect of neutral Higgs bosons



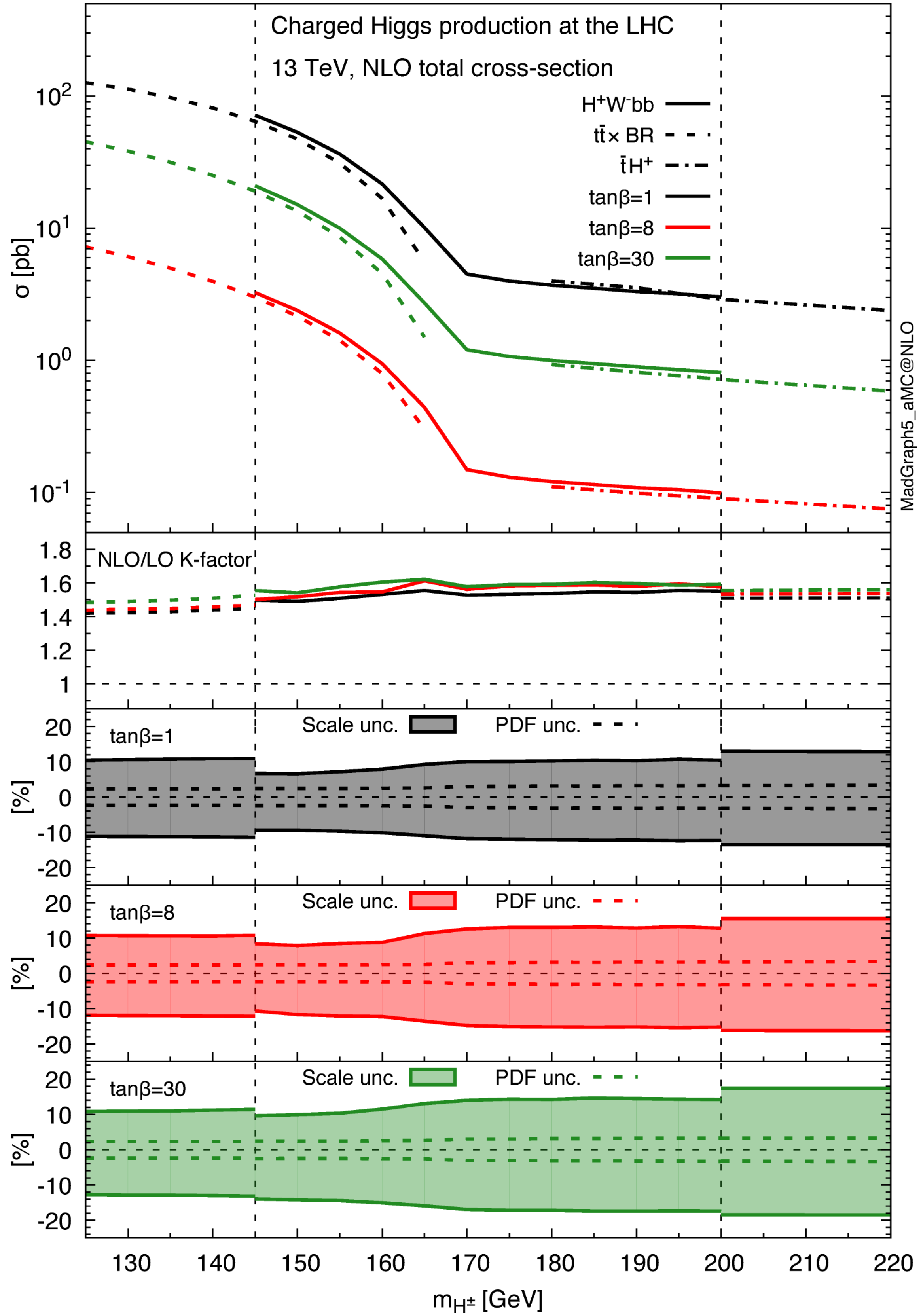
- Diagrams with neutral Higgs bosons introduce additional dependence on the $h/H/A$ masses and on the neutral Higgs mixing α.
- Assuming h to be the SM Higgs (m_h=125 GeV and $\cos(\beta\text{-}\alpha)\simeq 0$), for non-resonant configurations ($m_{h/H/A}<m_W+m_{H\pm}$) the contribution to the total cross section is small (≲7%)
- In practice, these diagrams will be neglected
- Cross section will just depend on $m_{H\pm}$ and $\tan\beta$ (same as the heavy/light case)



Calculation setup

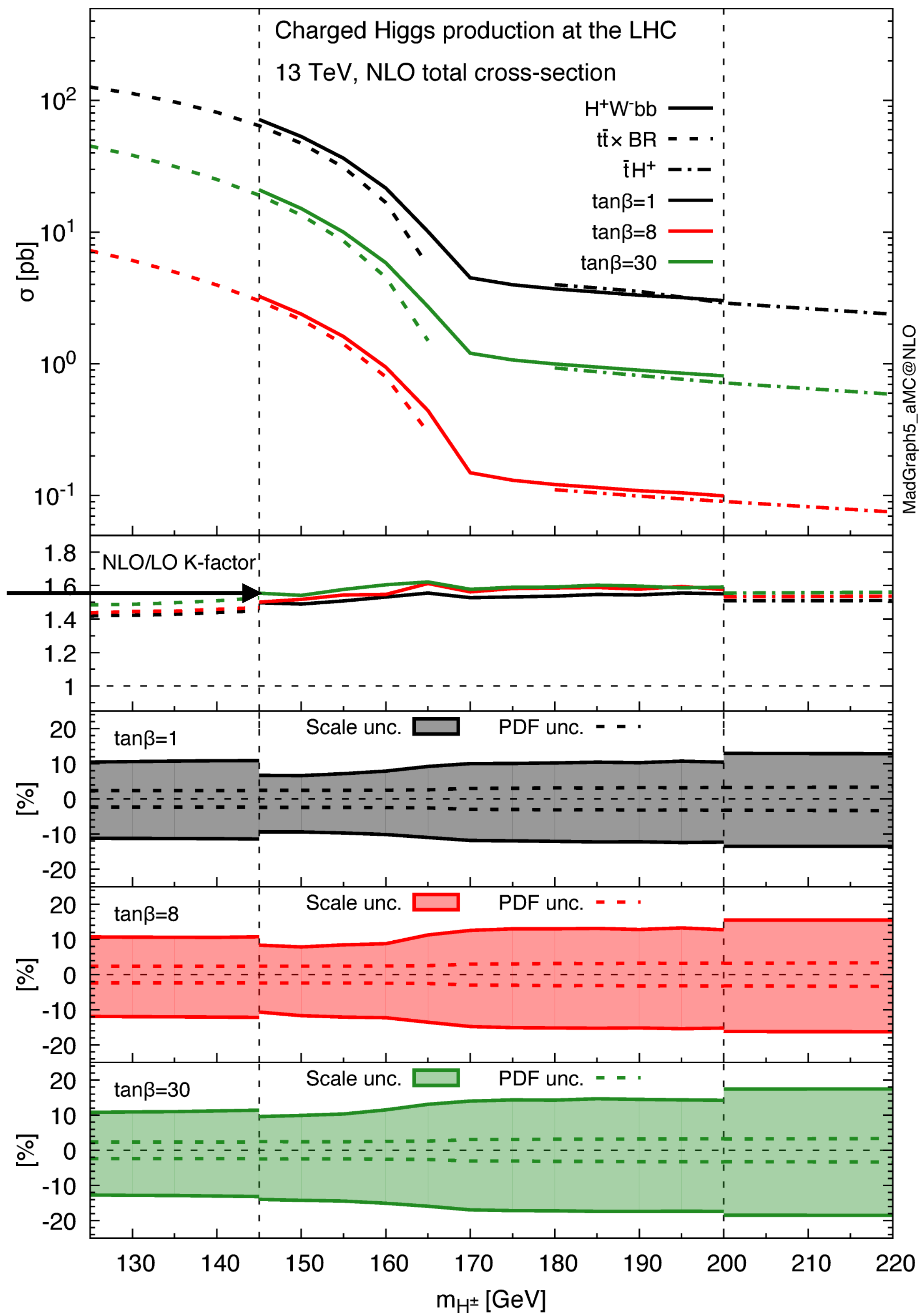
- Computation carried out with MadGraph5_aMC@NLO, improved with resonance-aware FKS subtraction Frederix et al. arXiv:1603:01178
- Focus on type-II 2HDM
- Use massive bottom quarks (4FS). Use `PDF4LHC_nlo_nf4` PDFs
- Complex top-mass (and Yukawa) scheme to include the top width in a gauge-invariant way. Γ_t computed at NLO for every ($m_{H\pm}$, $\tan\beta$) point
- Use a fixed central scale, $\mu_{R/F}$=125 GeV
  - Matches scales used in the light- and heavy-Higgs regions
  - Scale uncertainties obtained by varying independently up/down of a factor 2
- Use the $\overline{\text{MS}}$ scheme for y_b renormalisation (introduces extra μ_R dependence)
- Scan 145 GeV < $m_{H\pm}$ < 200 GeV
- Three values of $\tan\beta$ will be considered ($\tan\beta$ =1, 8, 30)
- Other input parameters follow the recommendation of the LHC HXSWG

Results



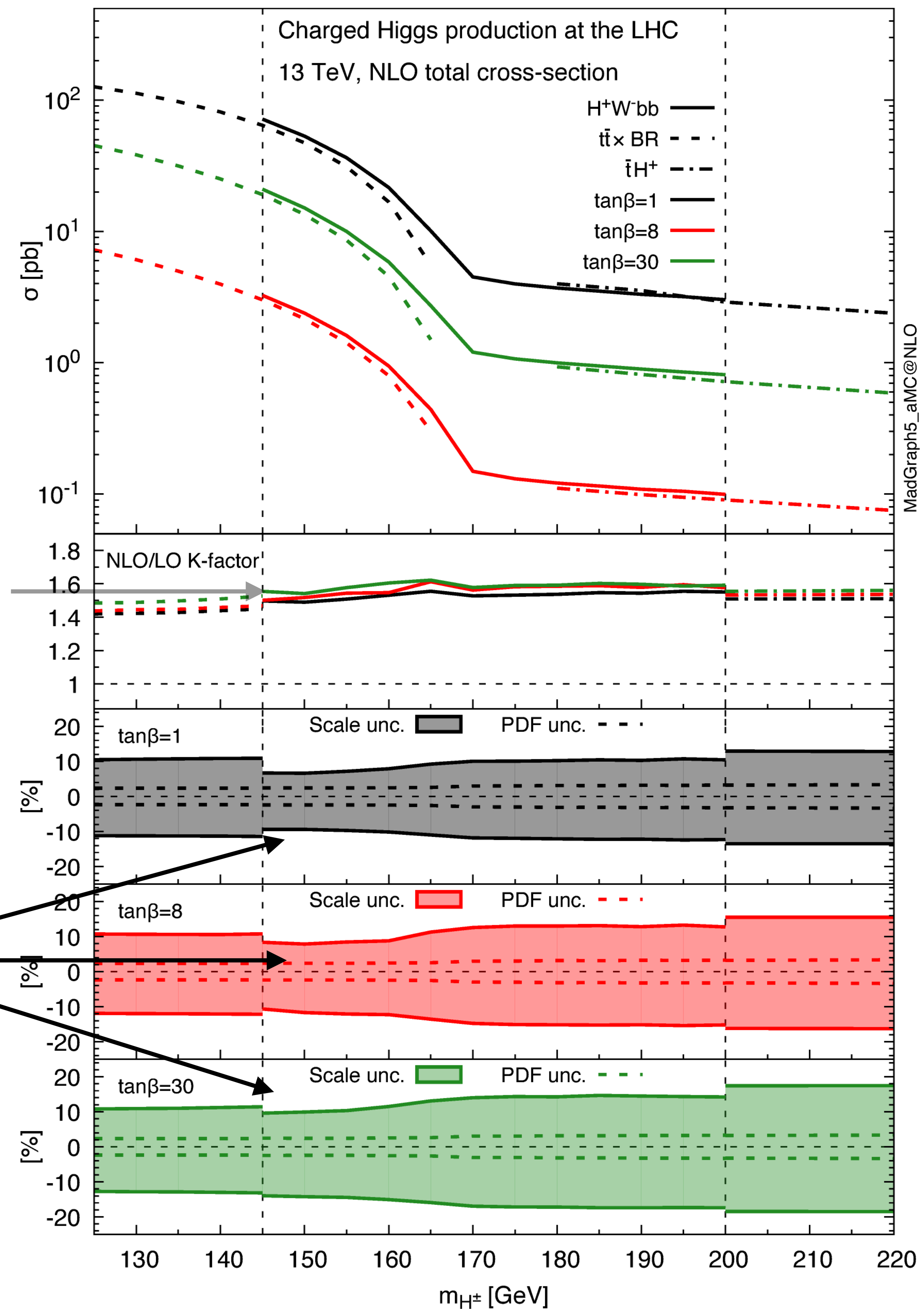
Marco Zaro, 07-09-2016

Results



Rather constant K-factor ~ 1.5-1.6, with small $\tan\beta$ dependence

Results



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Scale uncertainties reduced to 10-20% (larger for large $\tan\beta$ because of extra dependence in y_b)

Results

Discontinuity due to single-resonant contributions ($tW^{\pm}$ and $tH^{\pm}$)

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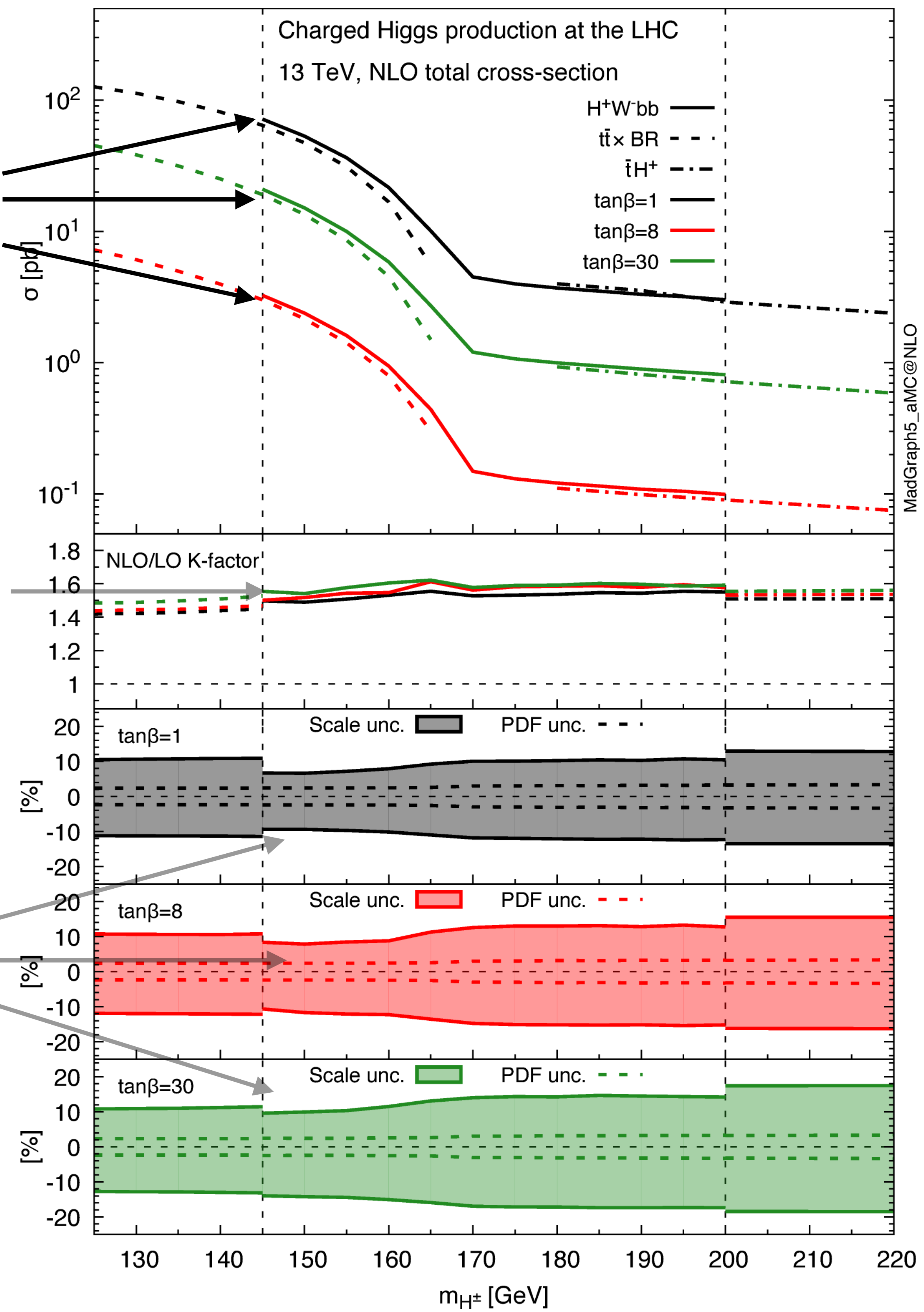

Results

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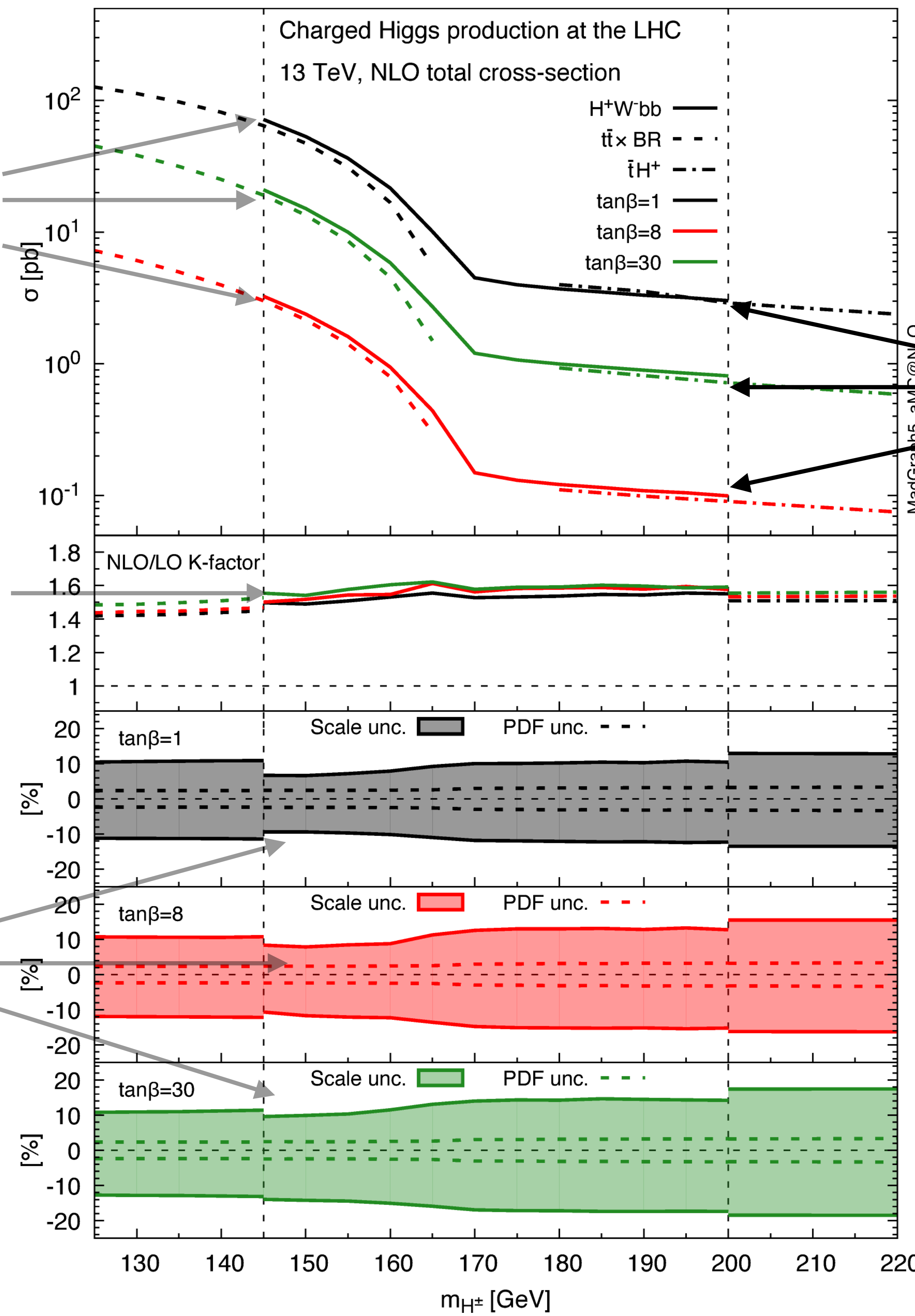
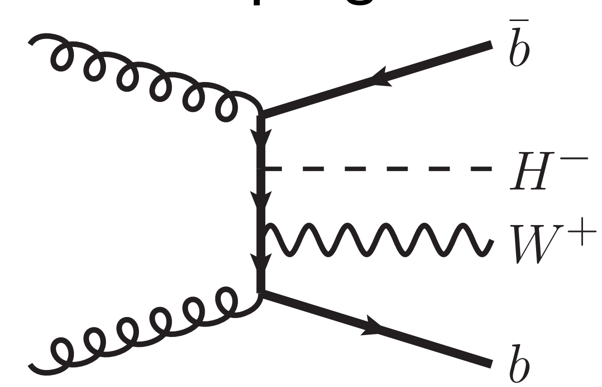


Discontinuity due to non-resonant contributions.
Size of discontinuity is $\tan\beta$ dependent because of chiral couplings



Extension to other values of $\tan\beta$

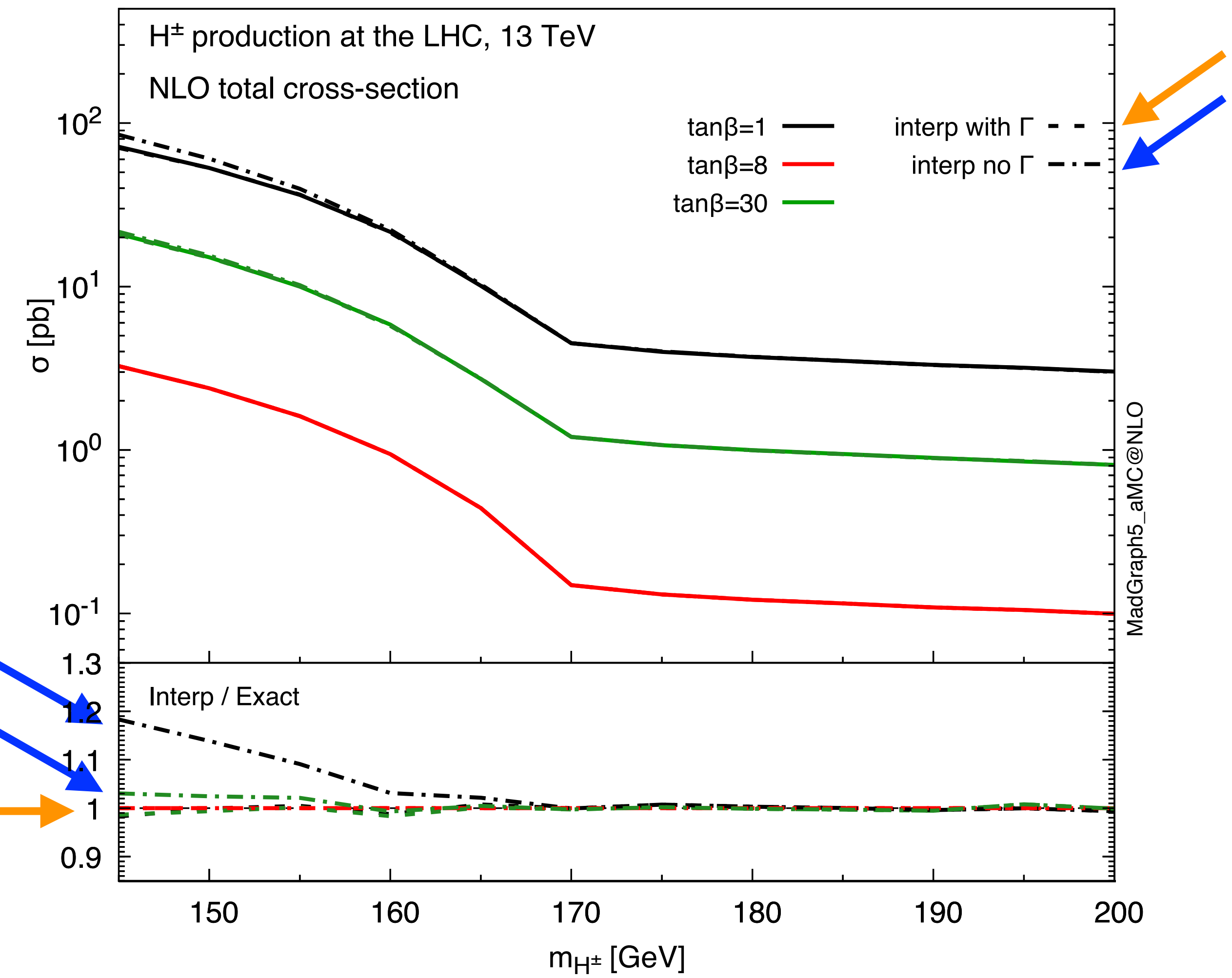
- The charged Higgs cross section receives contributions proportional to y_b^2 ($\sim\tan\beta^2$), y_t^2($\sim 1/\tan\beta^2$) and $y_b y_t$ (constant).
- MadGraph5_aMC@NLO has been extended in order to return the three individual contributions
- The cross section at any value of $\tan\beta$ can be computed as

$$\sigma(\tan\beta') = \left[\left(\frac{\tan\beta'}{\tan\beta}\right)^2 \sigma_{y_b^2}(\tan\beta) + \sigma_{y_b y_t}(\tan\beta) + \left(\frac{\tan\beta}{\tan\beta'}\right)^2 \sigma_{y_t^2}(\tan\beta)\right] \times \left(\frac{\Gamma_t(\tan\beta)}{\Gamma_t(\tan\beta')}\right)^2$$

- The formula was cross-checked by recomputing our results at $\tan\beta=1$ and $\tan\beta=30$, starting from $\tan\beta=8$. Agreement below 1% was found
- This formula can be also extended to obtain the charged Higgs cross section in other 2HDM scenarios (e.g. type 1)

Extension to other values of $\tan\beta$

- The factor $(\Gamma_t(\tan\beta)/\Gamma_t(\tan\beta))^2$ compensates for the width dependence of the double-resonant contribution
- Its inclusion is crucial to obtain the correct cross section at low masses
- Width effects are reduced when approaching the top threshold



$$\sigma(\tan\beta') = \left[\left(\frac{\tan\beta'}{\tan\beta}\right)^2 \sigma_{y_b^2}(\tan\beta) + \sigma_{y_b y_t}(\tan\beta) + \left(\frac{\tan\beta}{\tan\beta'}\right)^2 \sigma_{y_t^2}(\tan\beta)\right] \times \left(\frac{\Gamma_t(\tan\beta)}{\Gamma_t(\tan\beta')}\right)^2$$

Conclusions & Outlook

- The discovery of a charged Higgs boson will be a clear sign of BSM physics
- We provided NLO predictions for the charged Higgs cross-section are available for $m_{H^\pm} \sim m_t$, making accurate predictions available in all the mass range
- The full $pp \to H^\pm W^\mp b\bar{b}$ process interpolates well between the low- and high- mass region
- NLO K-factor is 1.5-1.6, with little $m_{H^\pm}$, $\tan\beta$ dependence
- NLO corrections reduce scale uncertainties to 10-20%
- Future studies: what is the impact of NLO corrections on differential observables?