

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

HiggsDays 2016

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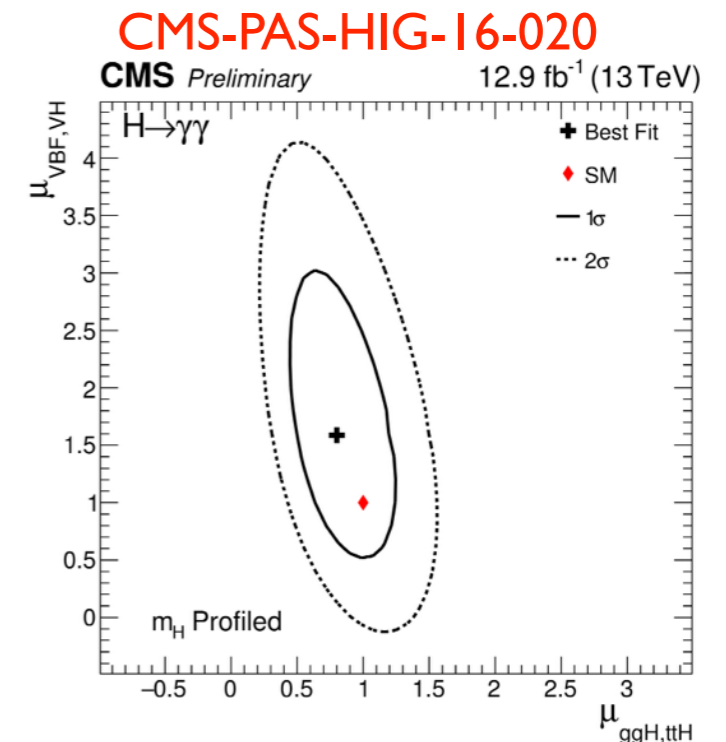
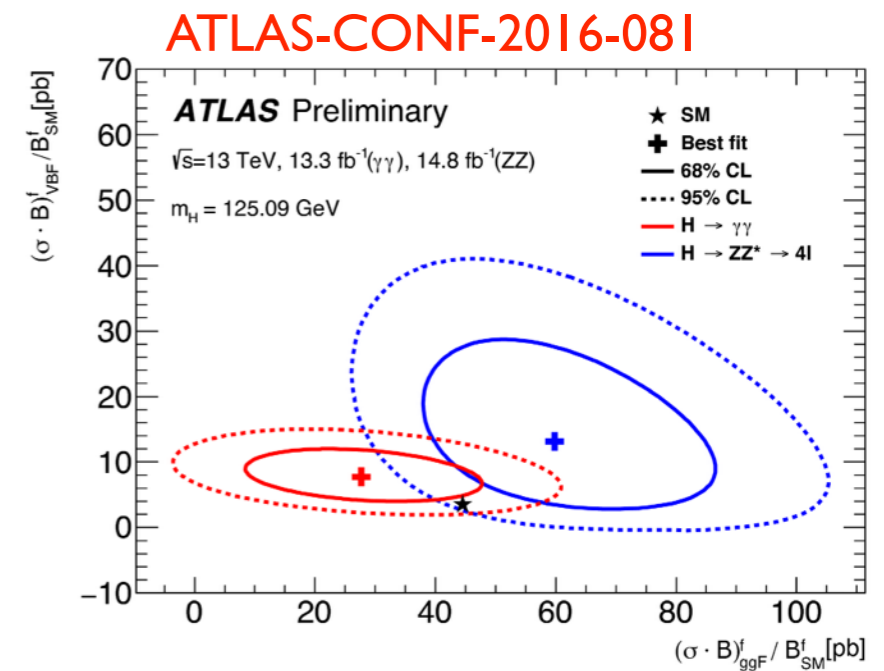
based on

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



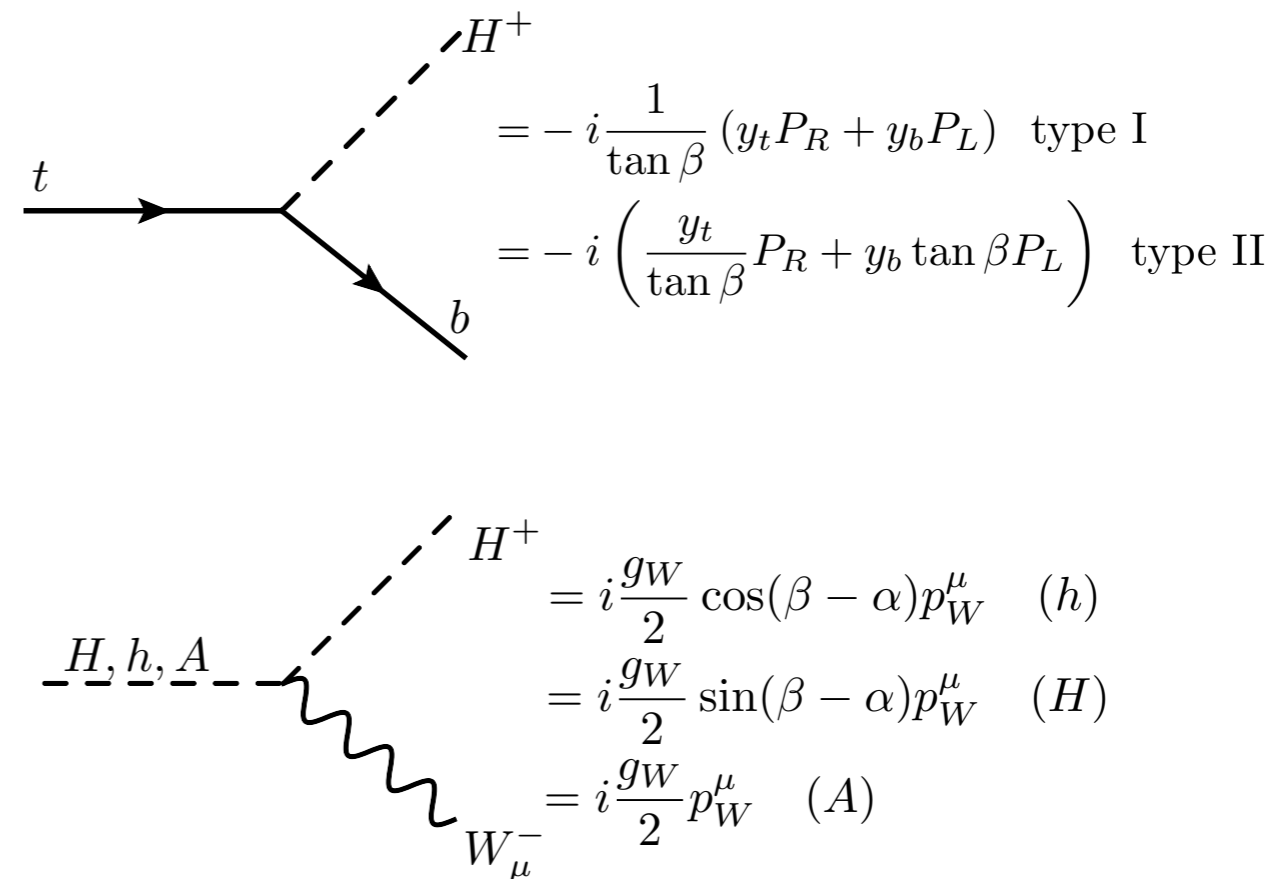
Higgs at the LHC

- 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



- 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^\pm)
- The most common version of the 2HDM is the so-called type-II (\ni 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

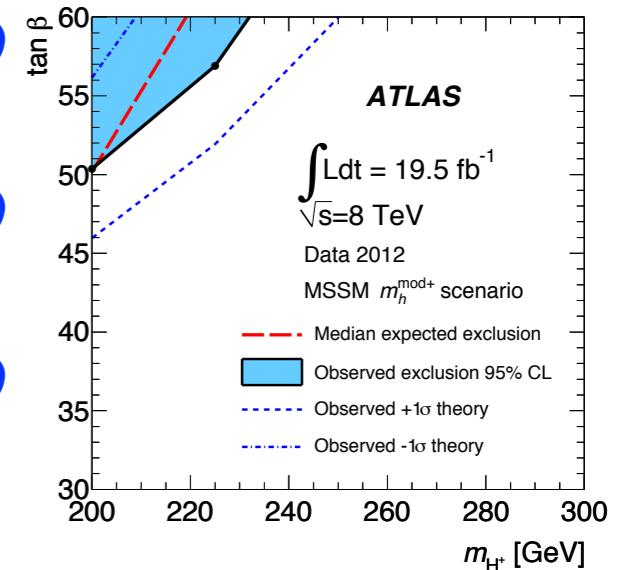
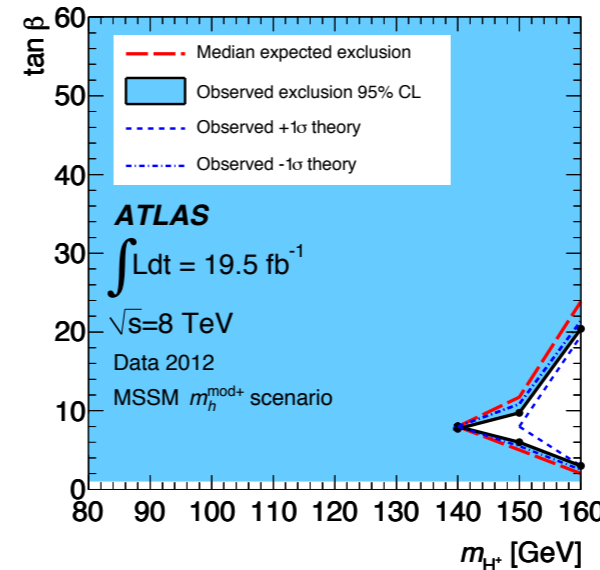
Georgi, Machacek, Nu.Ph.B262(1985)



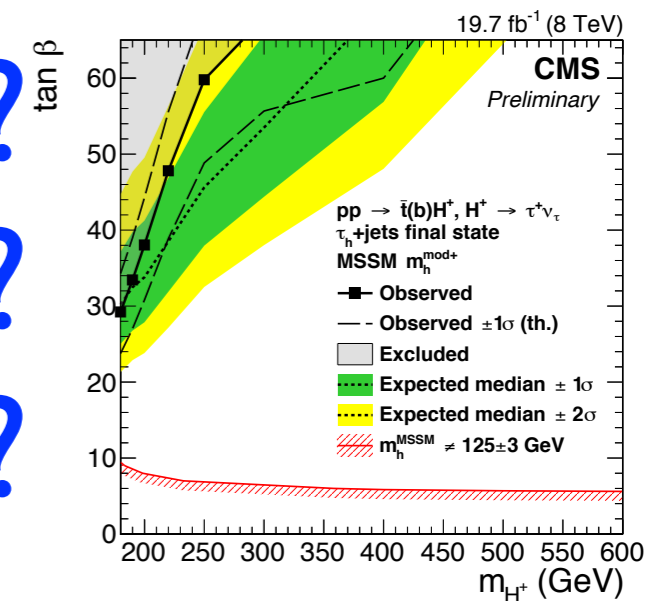
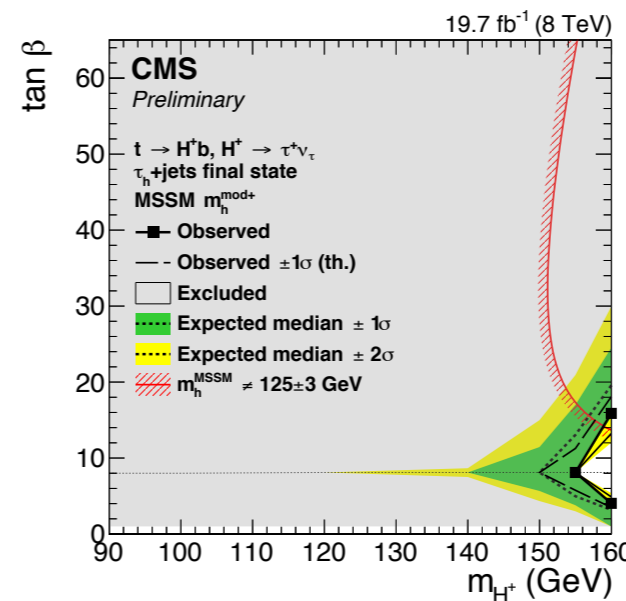
Searches at the LHC

- 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



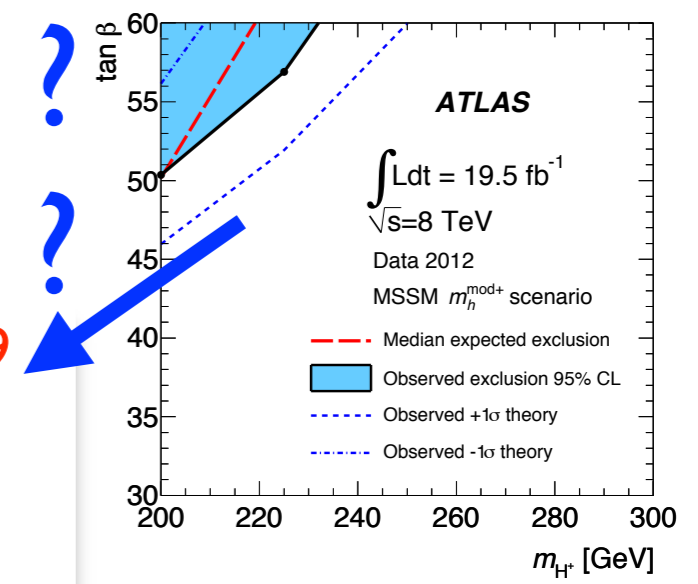
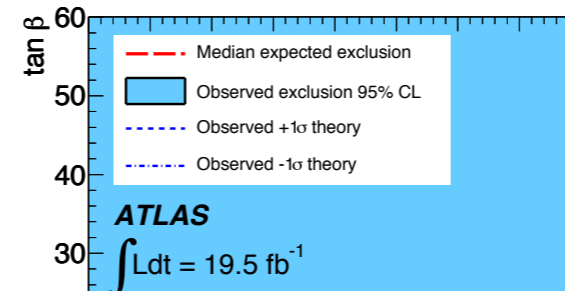
CMS, PAS HIG-14-020



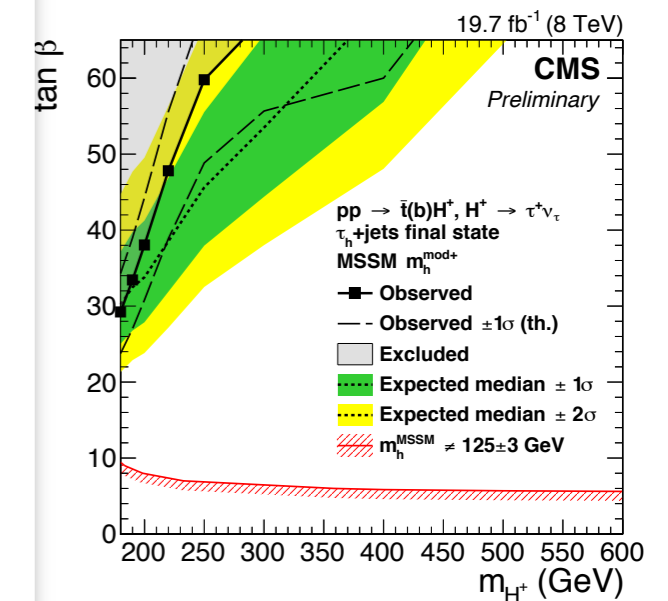
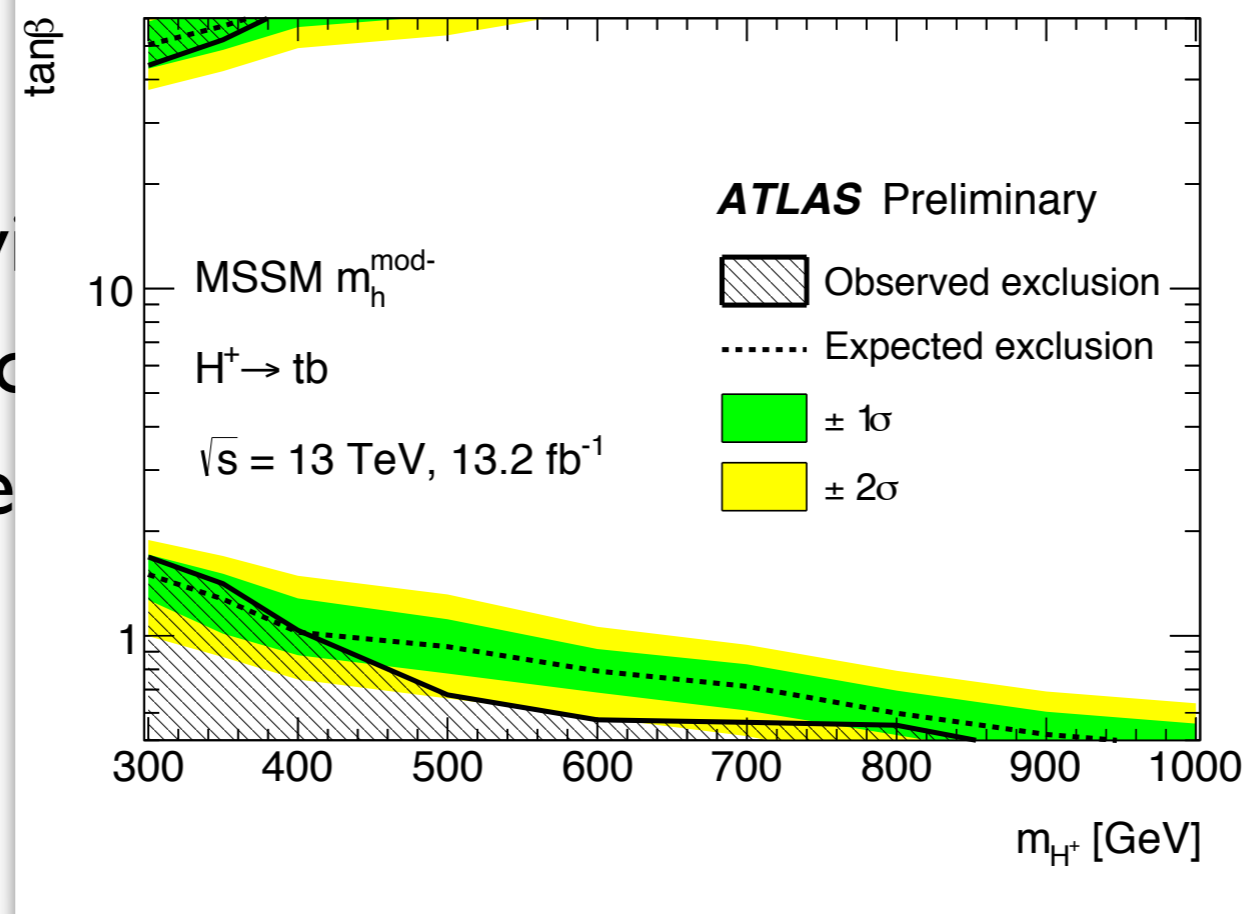
Searches at the LHC

- LHC experiments tend to exclude a light charged Higgs
- For a heavy charged Higgs, only very large $\tan\beta$ are excluded
- Missing mass with non-existence of H^\pm for the intermediate mass beyond LO

ATLAS, arXiv:1412.6663

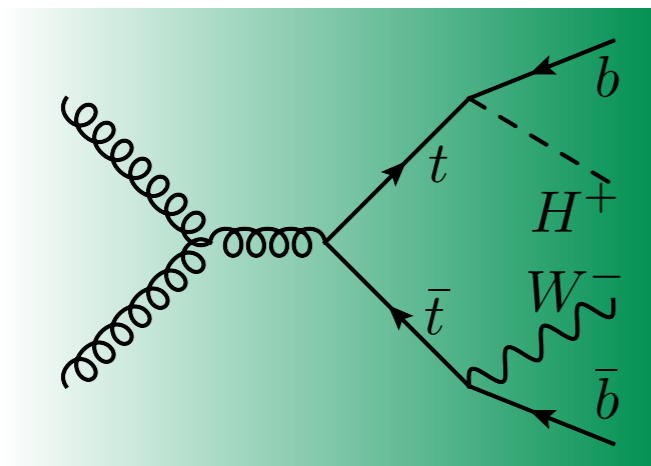


ICHEP'16 update: ATLAS-CONF-2016-088 & -089



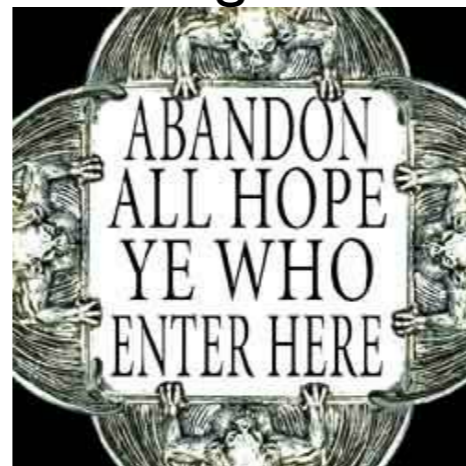
- In the 2HDM, the dominant production channel depends on the Charged Higgs mass

Light Higgs



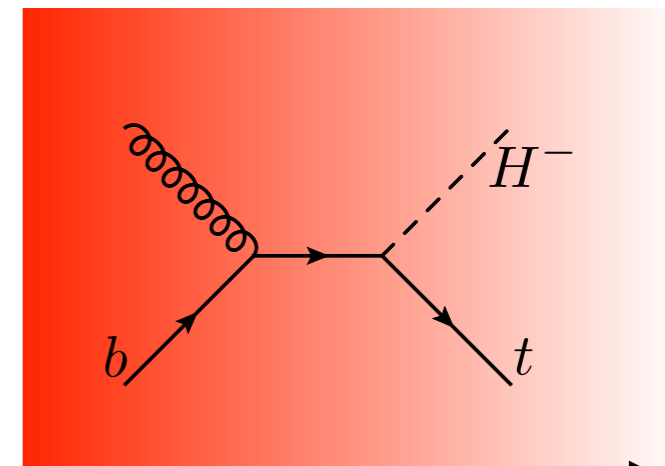
$$M_{H^+} < M_t$$

Intermediate region



$$M_{H^+} \simeq M_t$$

Heavy Higgs



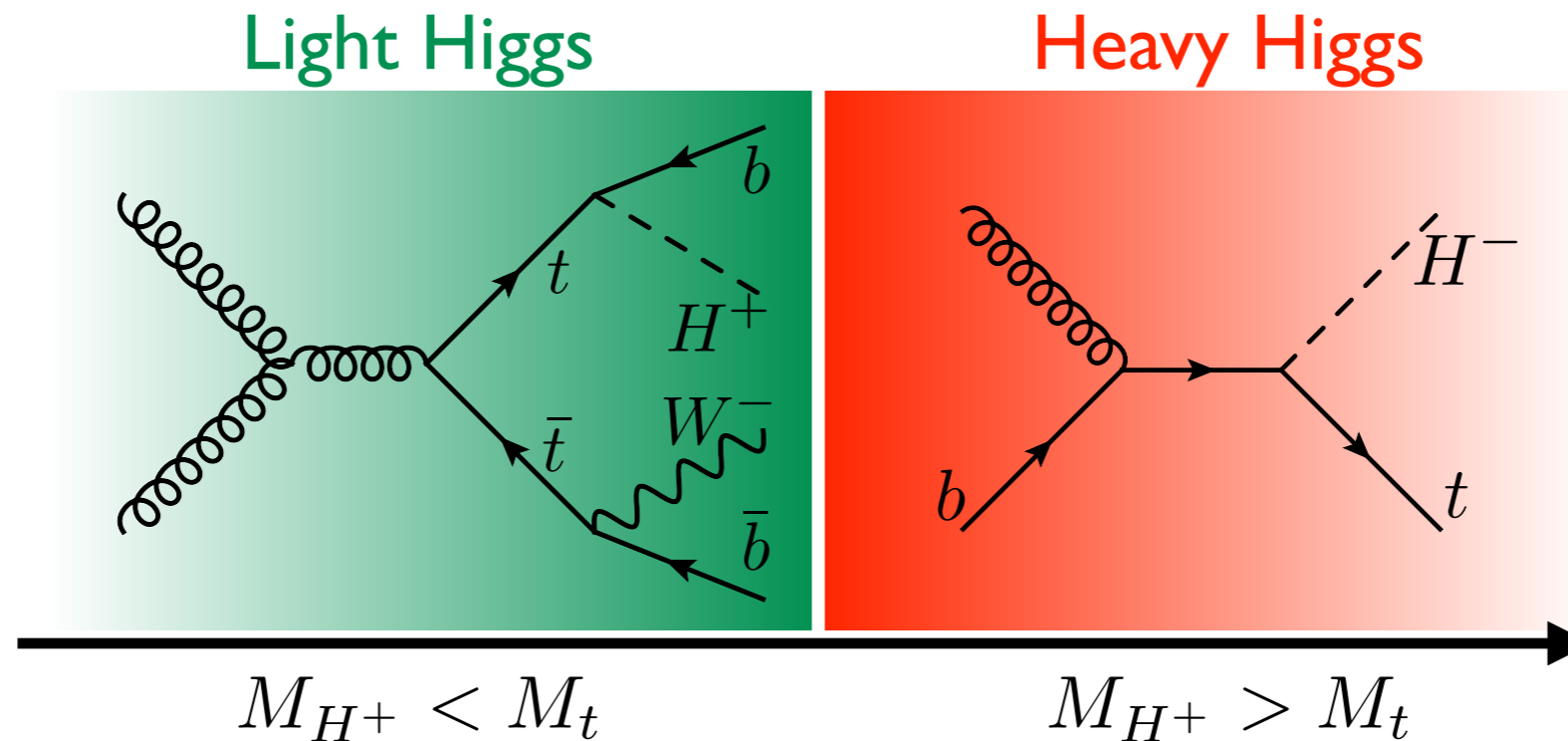
$$M_{H^+} > M_t$$

H^\pm mostly produced in $t\bar{t}$ events. The full $pp \rightarrow H^\pm W^\mp b\bar{b}$ process has to be simulated.

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

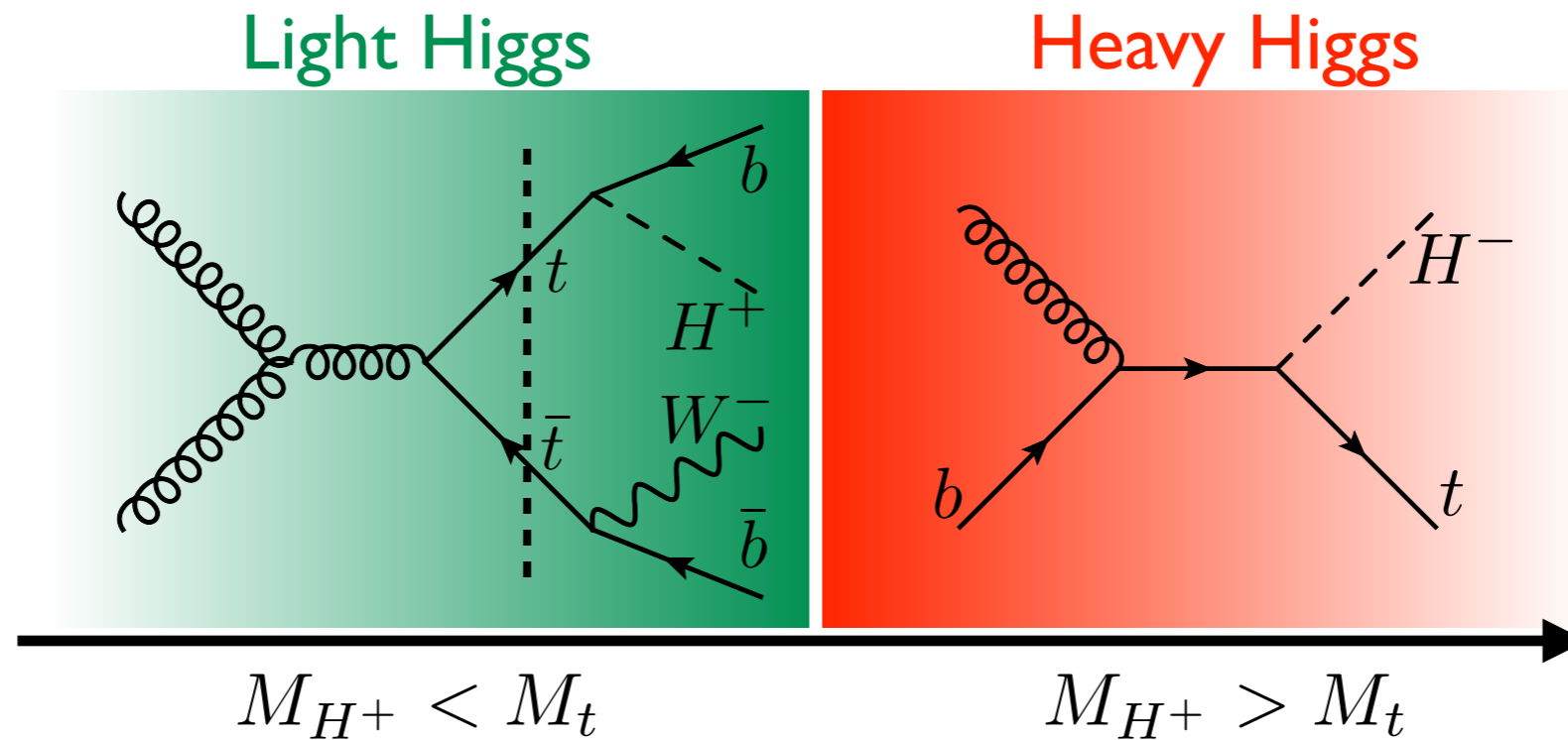
Charged Higgs production in 2HDMs

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



Charged Higgs production in 2HDMs

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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, ...
 NNLO QCD corrections to $\Gamma(t \rightarrow W^+b)$: Czarnecki et al, hep-ph/9806244, ...
 NLO (SUSY-)QCD corrections to $\Gamma(t \rightarrow H^+b)$: 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: Zhu, hep-ph/0112109, Plehn, hep-ph/0206121, Berger et al, hep-ph/0312286 (5FS); Dittmaier et al, arXiv:0906.2648 (4FS); Flechl et al, arXiv:1409.5615 (Santander-Martched)
 EW corrections: Beccaria et al, arXiv:0908.1332 (5FS); Nhung et al, arXiv:1210.4087 (4FS)
 Threshold resummation: Kidonakis, arXiv:1005.4451 (5FS)
 Fully differential NLO+PS: Weydert et al, arXiv:0912.3430, Klasen et al, arXiv:1203.1341 (5FS); Degrande et al, arXiv:1507.02549 (4FS)

Can take the $\Gamma_t \rightarrow 0$ limit

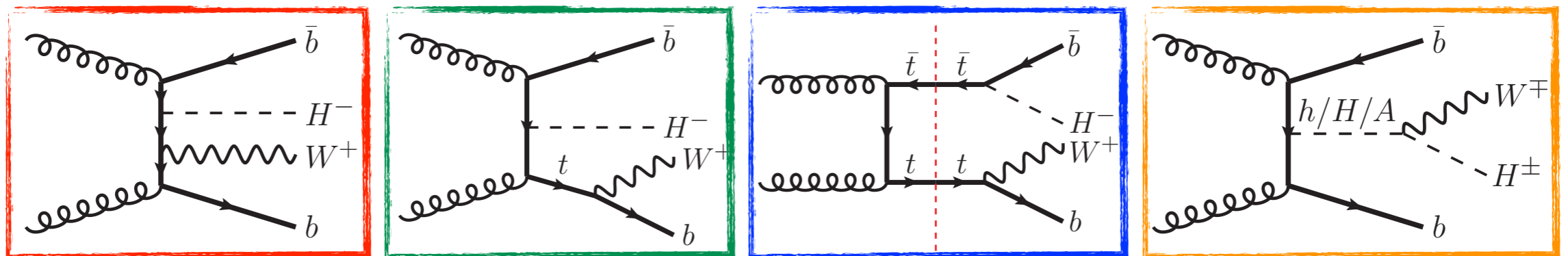
Both cases are known at or beyond NLO QCD

Intermediate-mass region



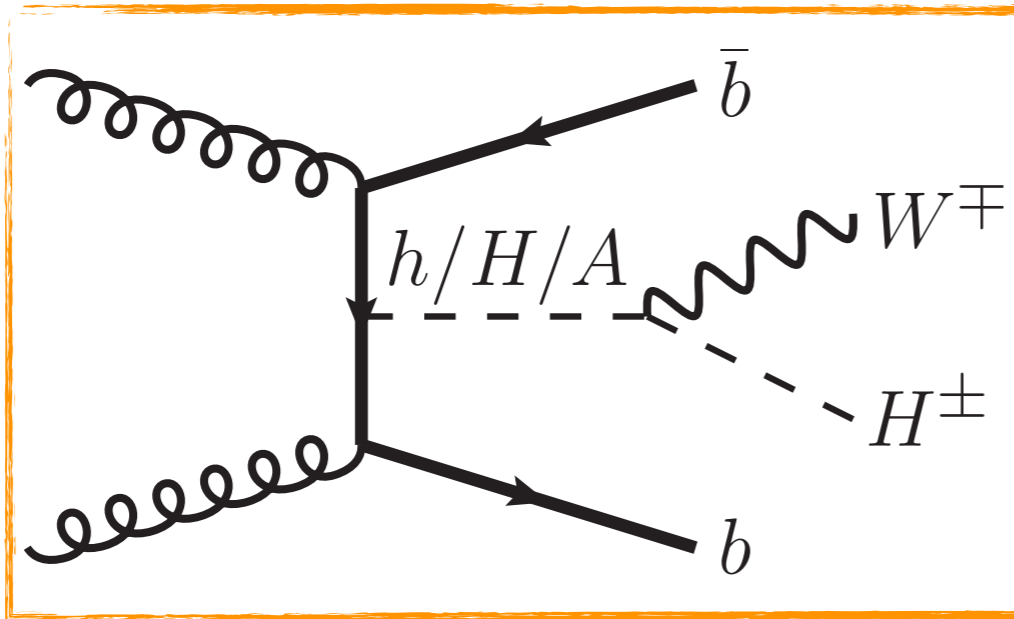
Intermediate-mass region

- The full process $pp \rightarrow H^\pm W^\mp b \bar{b}$ 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**

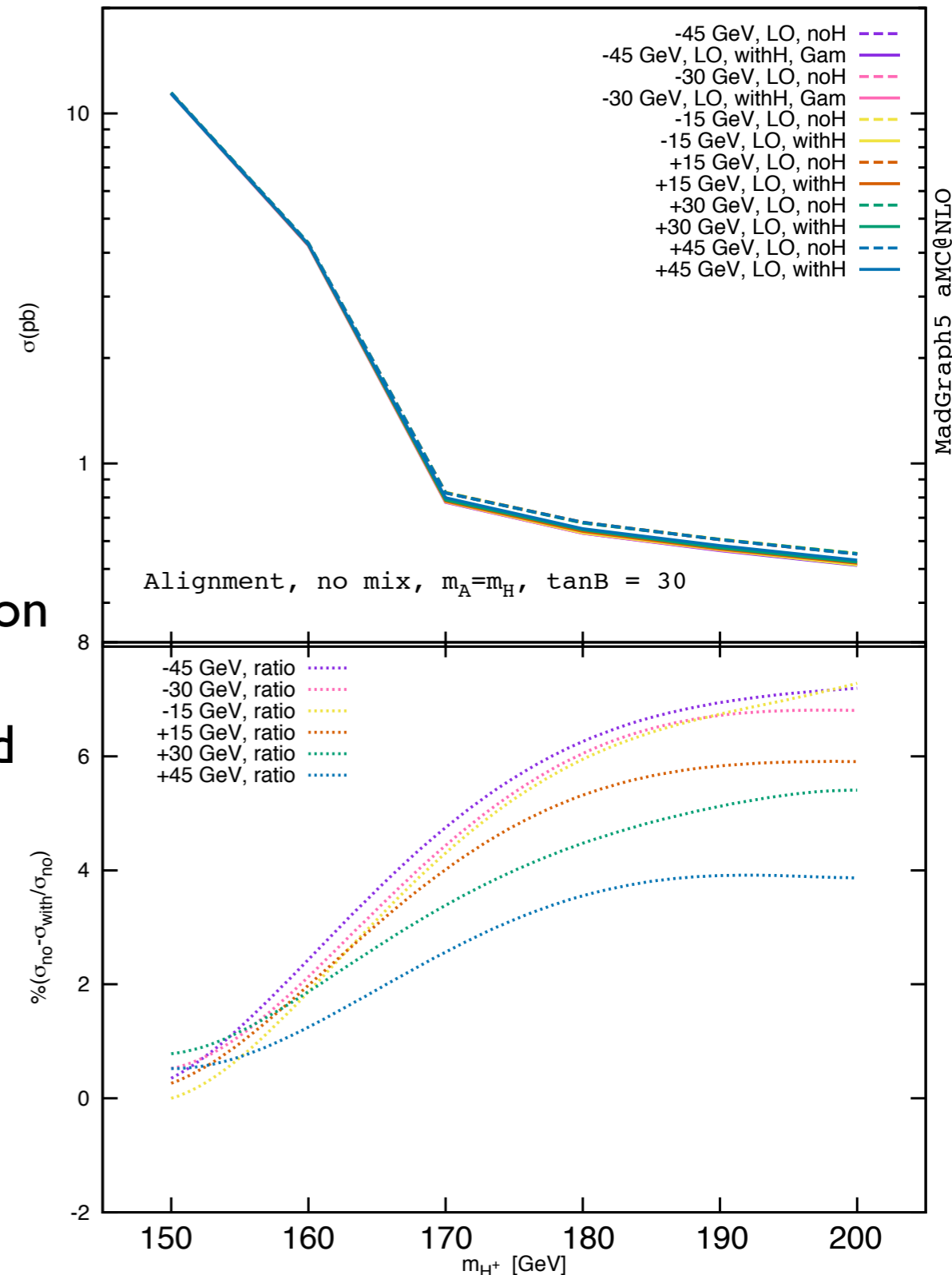


- Cross-section for $m_{H^\pm} > m_t$ ($m_{H^\pm} < m_t$) will get the dominant contribution from **single-** (**double**)-resonant diagrams
- LO total cross section has large (30-50%) theoretical errors. For accurate predictions one needs to compute NLO corrections

Effect of neutral Higgs bosons



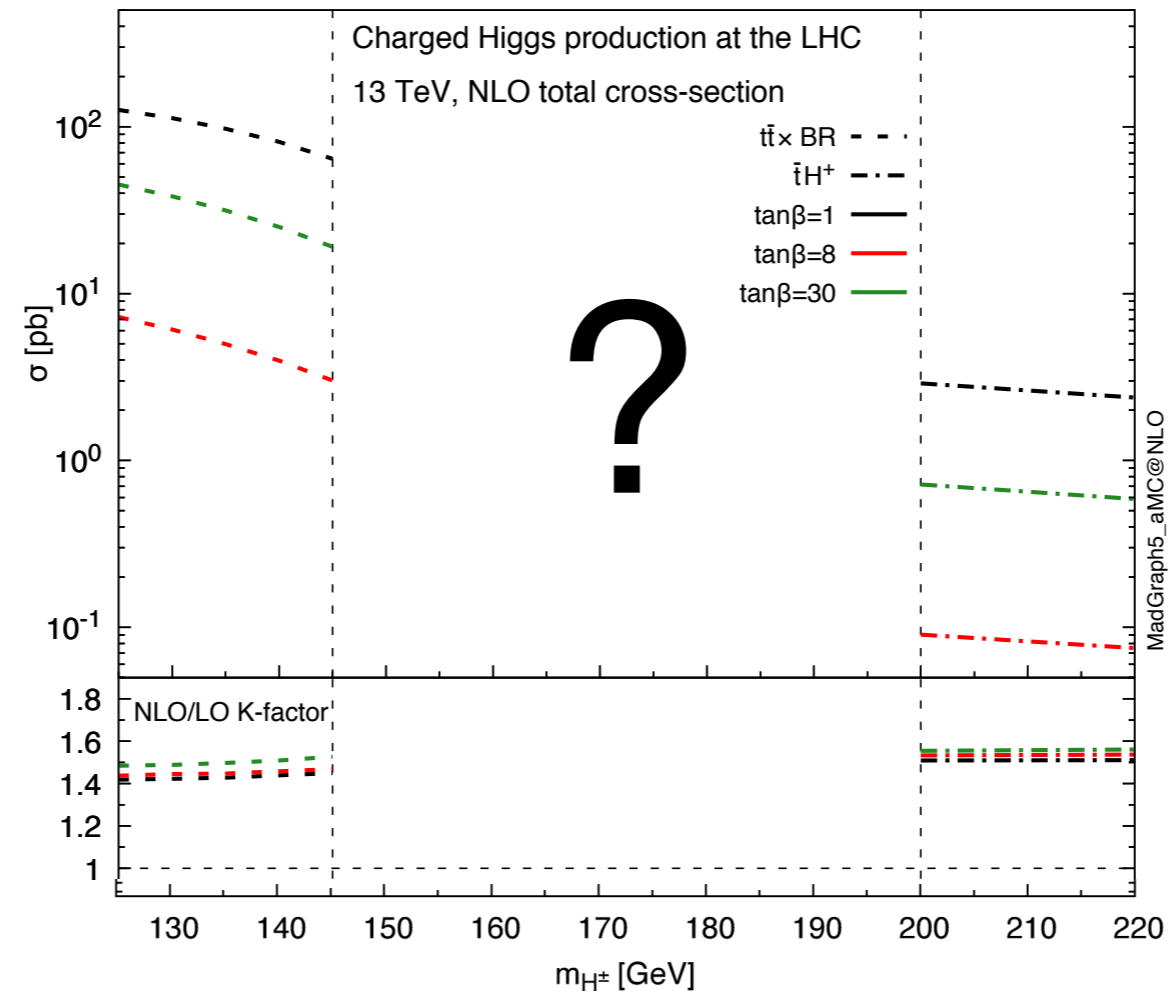
- Diagrams with neutral Higgs bosons introduce additional dependence on the $h/H/A$ masses and on the neutral Higgs mixing α .
- Assuming h to be the SM Higgs ($m_h=125$ GeV and $\cos(\beta-\alpha)\approx 0$), for non-resonant configurations ($m_{h/H/A} < m_W + m_{H^\pm}$) the contribution to the total cross section is small ($\approx 7\%$)
- 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)



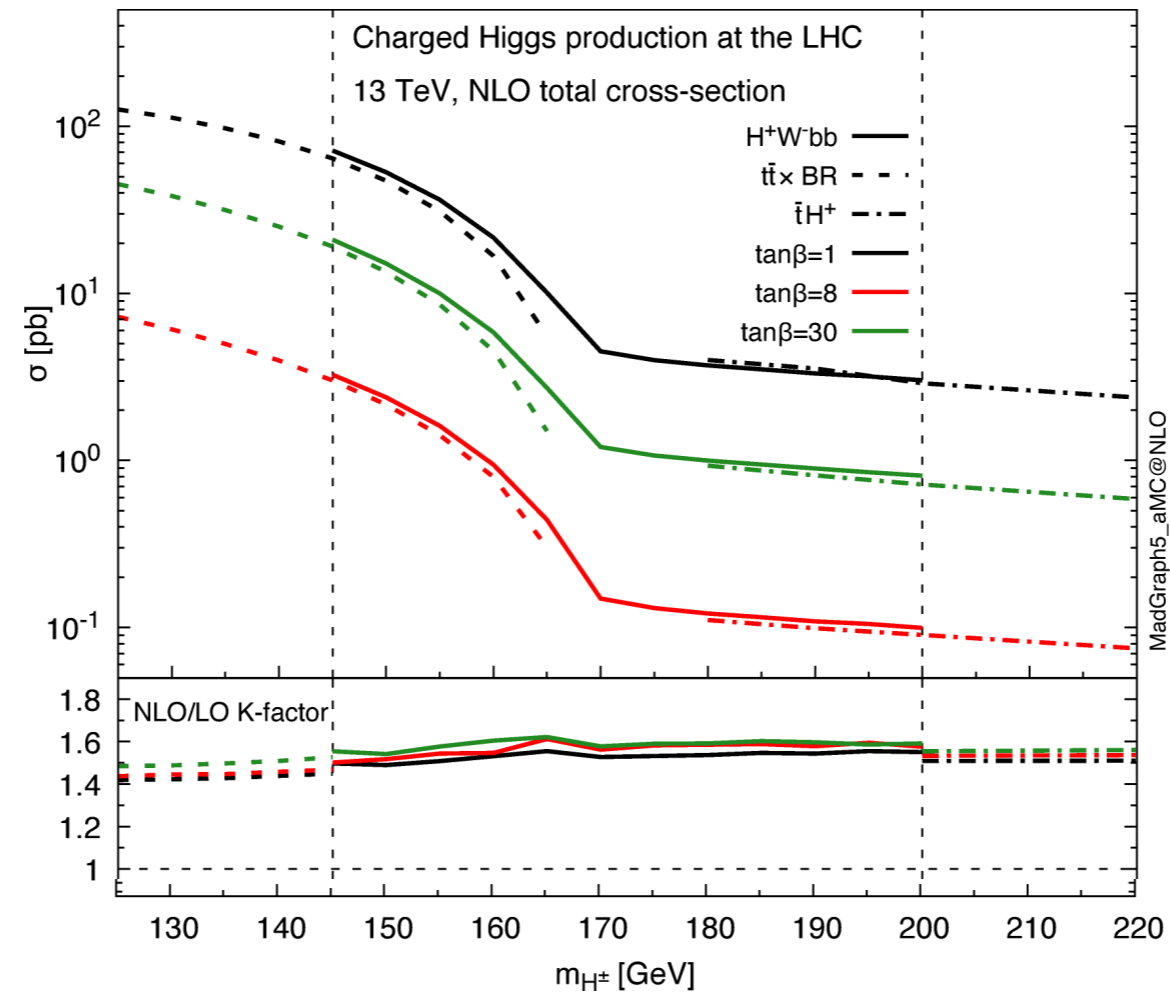
Calculation setup

- 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 $145 \text{ GeV} < m_{H^\pm} < 200 \text{ GeV}$
- Three values of $\tan\beta$ will be considered ($\tan\beta = 1, 8, 30$)
- Other input parameters follow the recommendation of the LHC HXSWG

Results

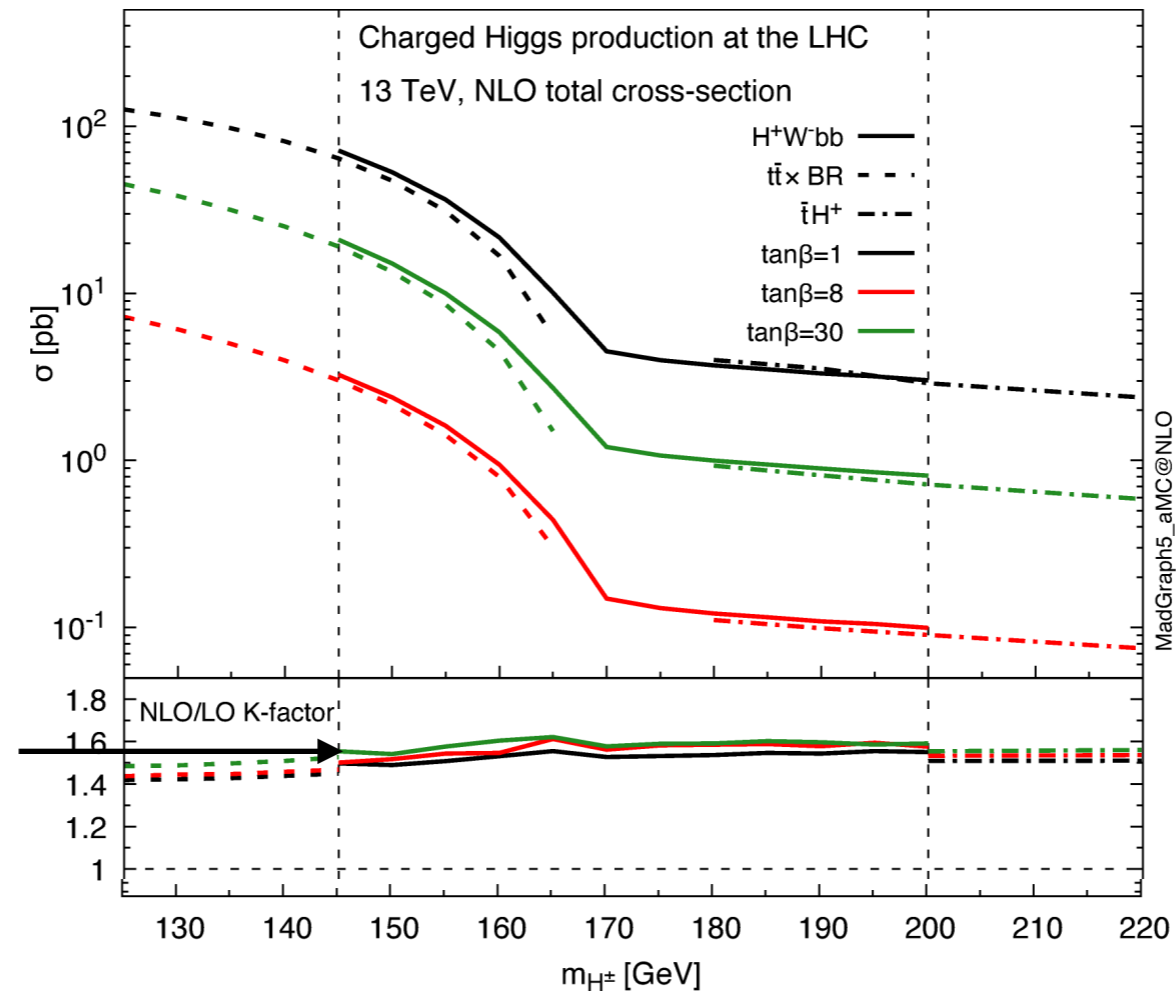


Results



Results

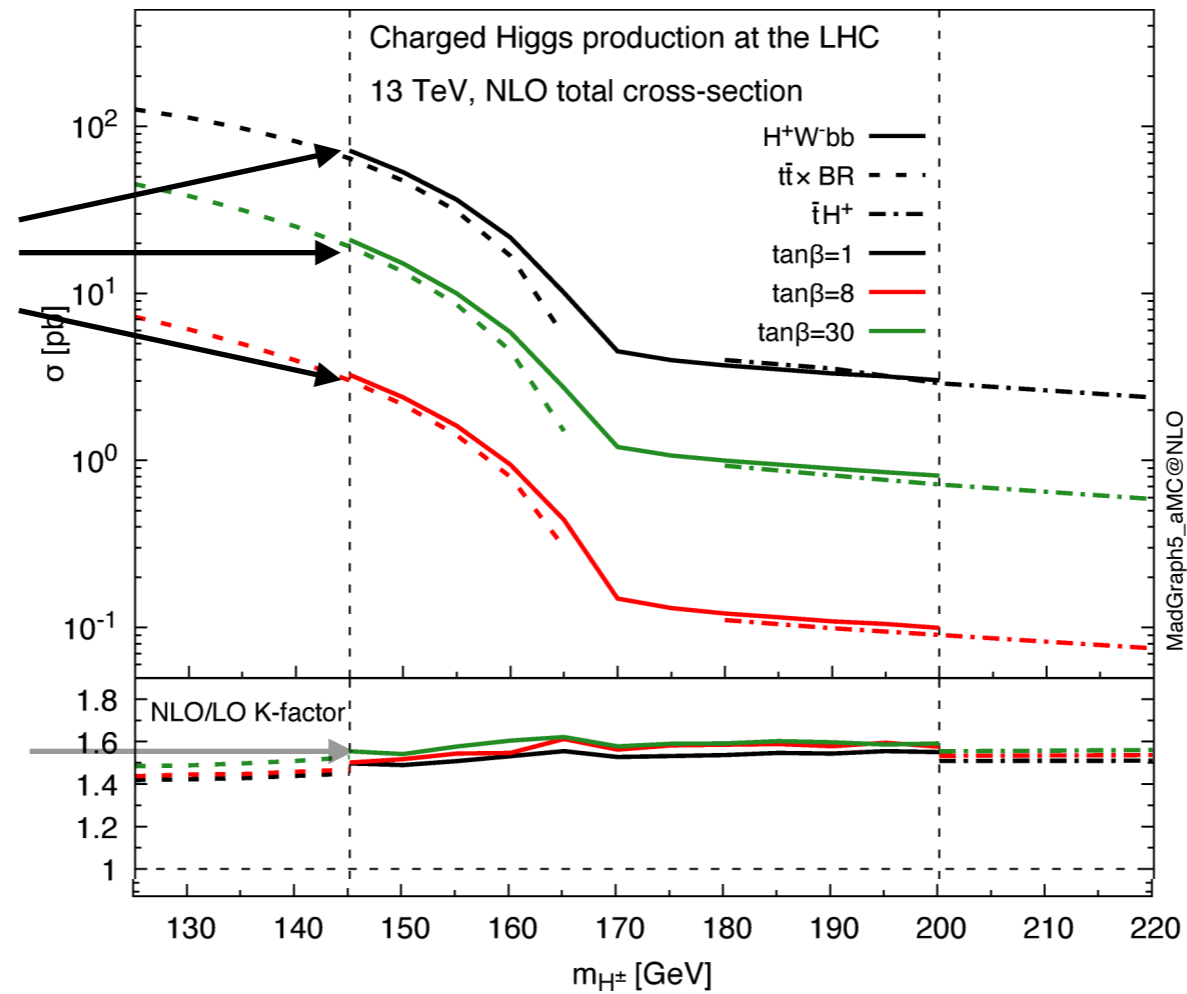
Rather constant K-factor $\sim 1.5-1.6$, with small $\tan\beta$ dependence



Results

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

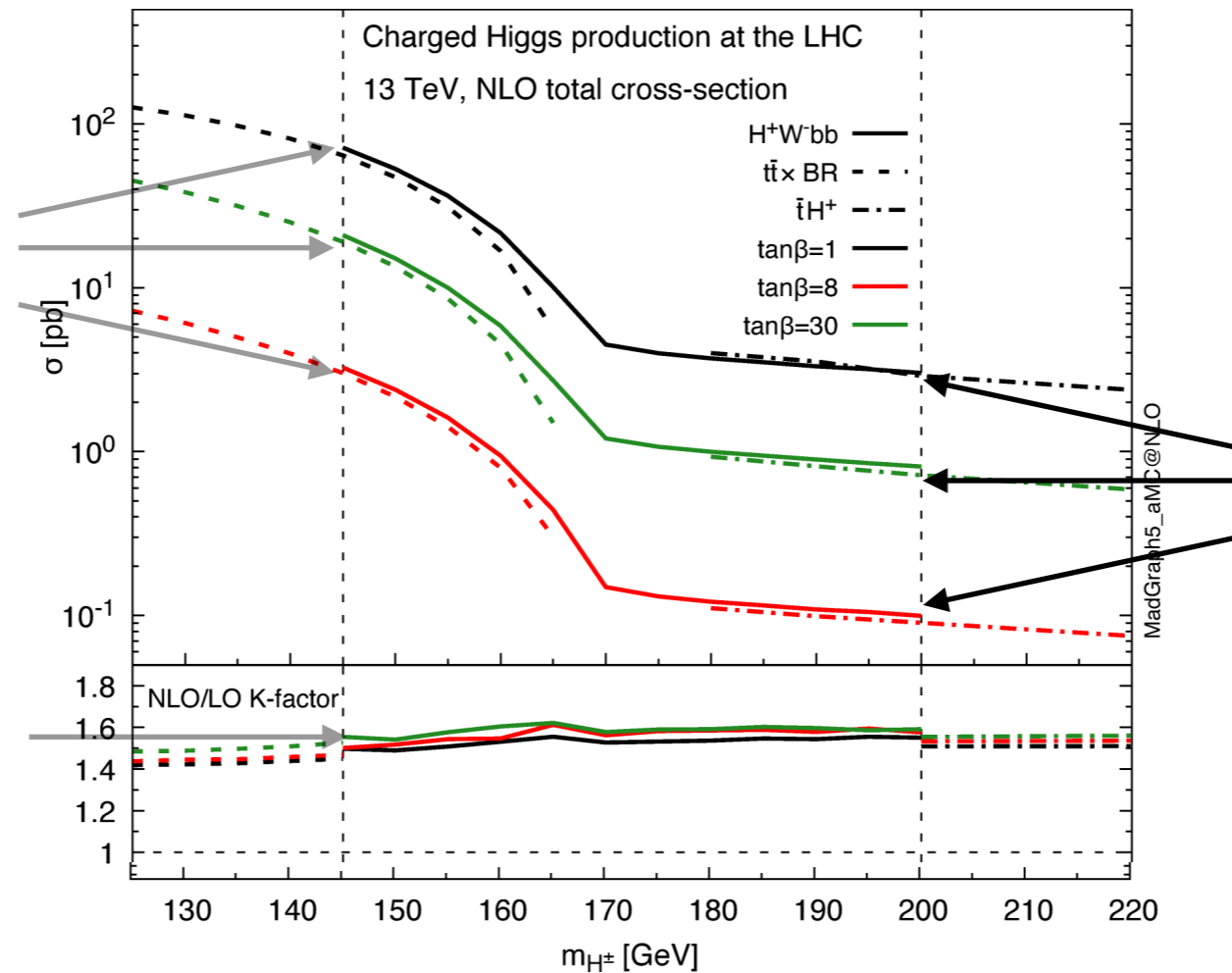
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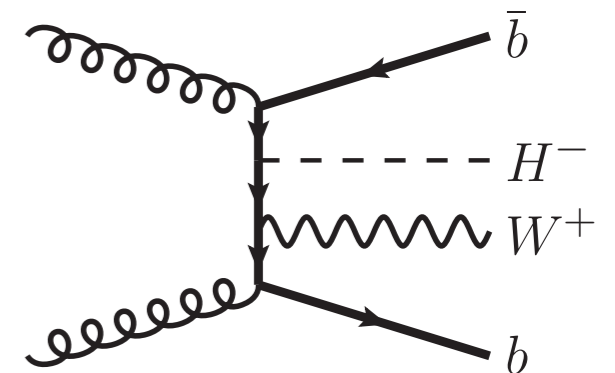
Results

Discontinuity due to single-resonant contributions (tW)

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



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

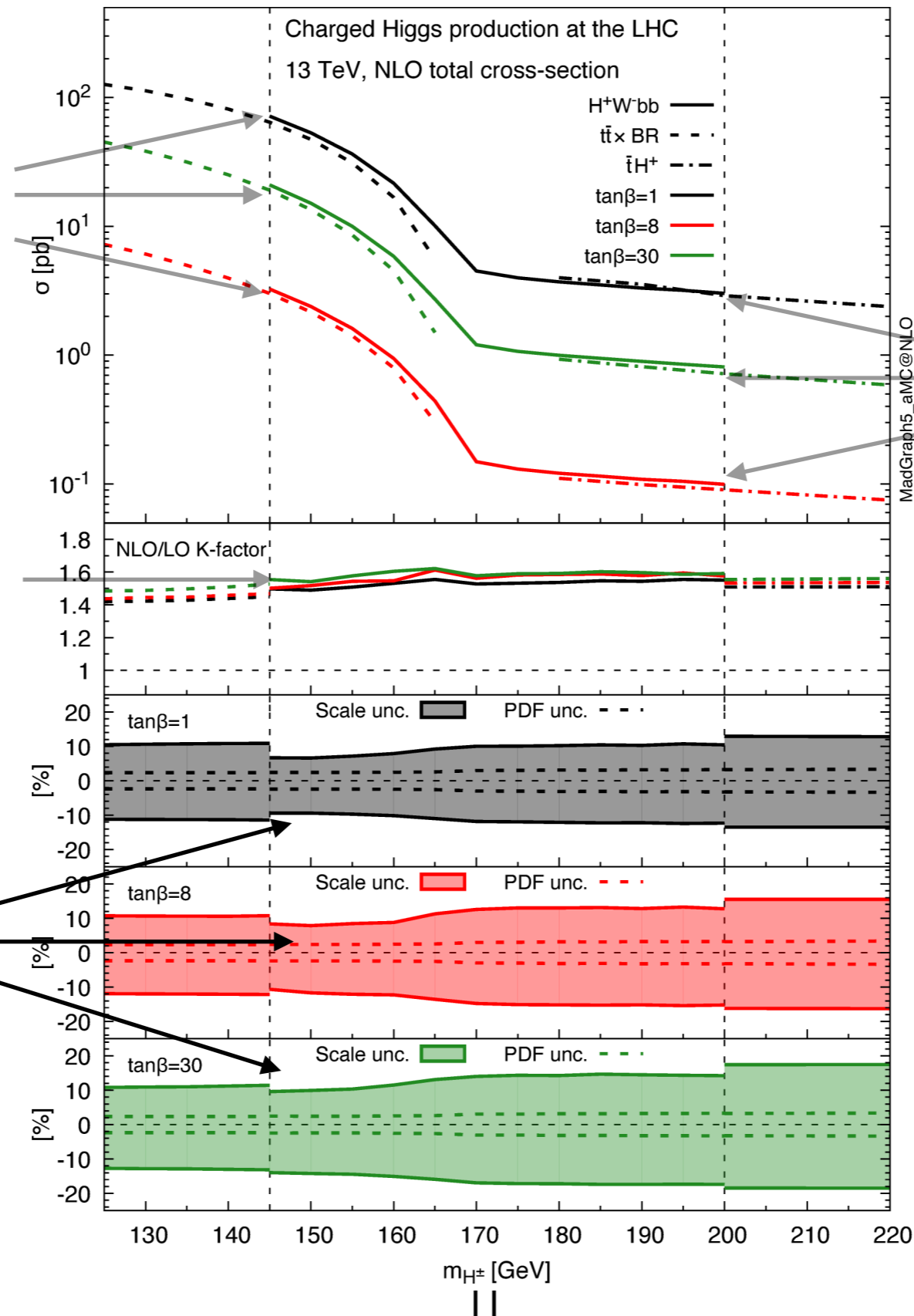


Results

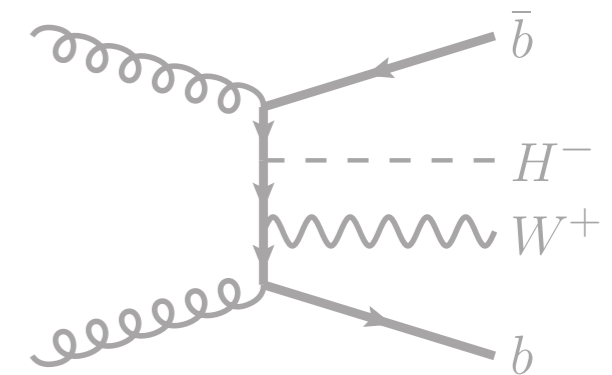
Discontinuity due to single-resonant contributions (tW)

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

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



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



to other values of $\tan\beta$

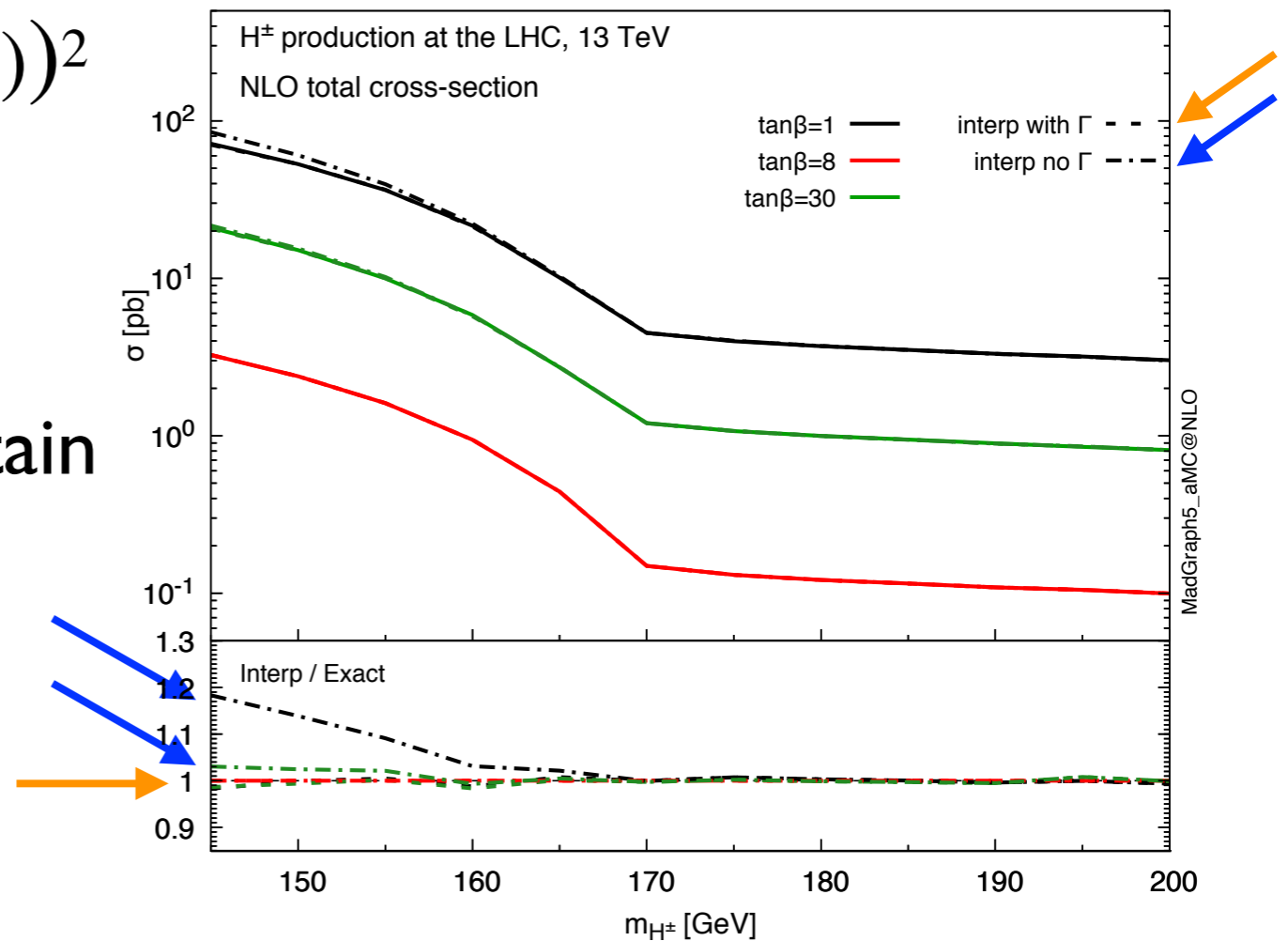
- The charged Higgs cross section receives contributions proportional to y_b^2 ($\sim \tan\beta^2$), y_t^2 ($\sim 1/\tan\beta^2$) and $y_b y_t$ (constant).
- **MADGRAPH5_AMC@NLO** has been extended in order to return the three individual contributions
- The cross section at any value of $\tan\beta$ can 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 I)

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 $pp \rightarrow H^\pm W^\mp b \bar{b}$ 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?