Status of the intermediate-mass region: First steps into *terra incognita*

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cHarged 2018

Netherlands Organisation for Scientific Research

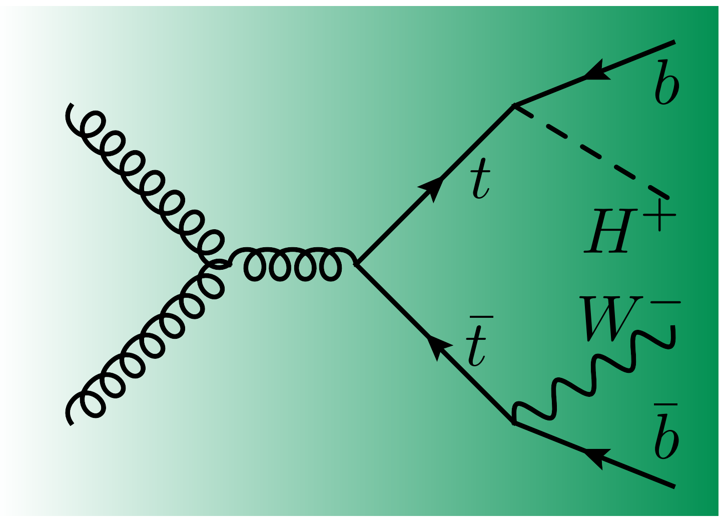
Charged Higgs production in 2HDMs

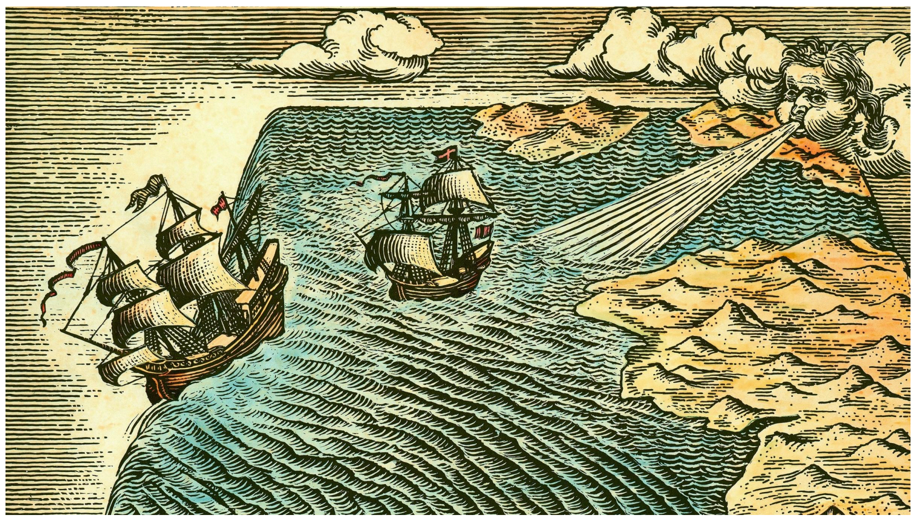
- In the 2HDM, the dominant production channel depends on the Charged Higgs mass

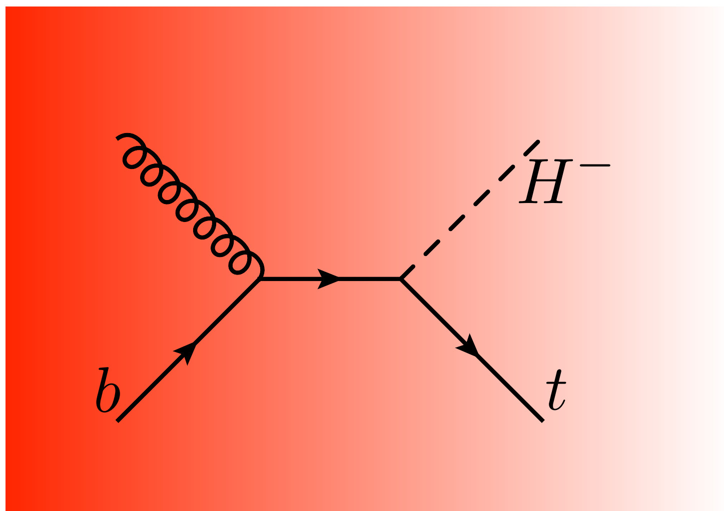
Light Higgs

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.

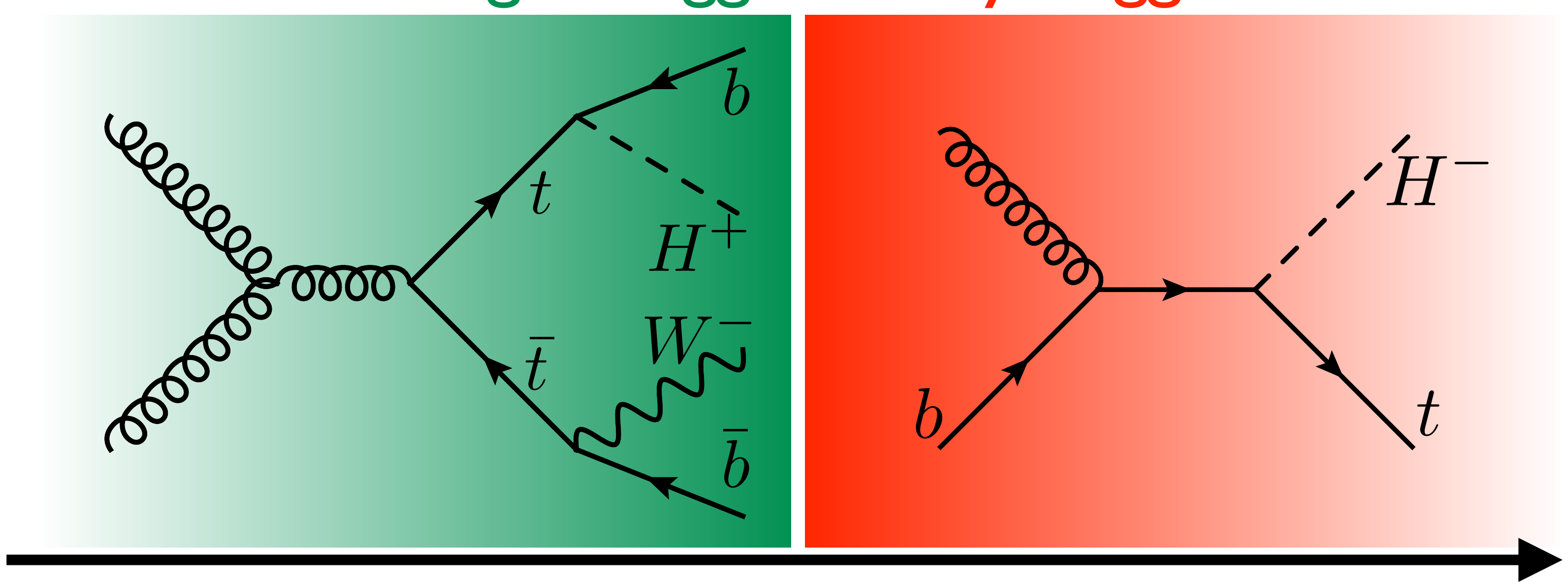
The full $pp \to H^\pm W^\mp b\bar{b}$ process has to be simulated.

$H^\pm$ 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

Light Higgs Heavy Higgs



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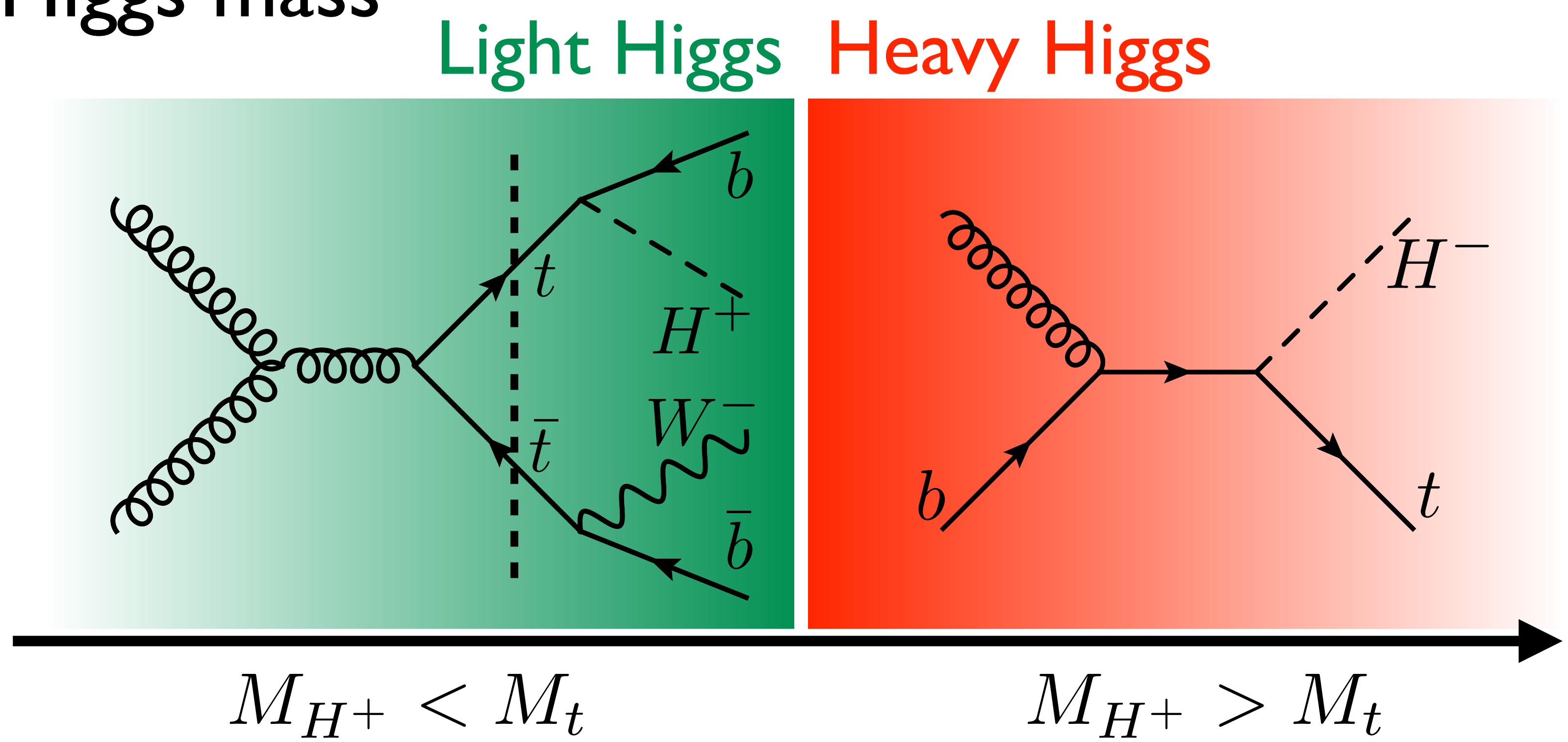


Can take the $\Gamma_t \to 0$ limit

Charged Higgs production in 2HDMs

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

Light Higgs | **Heavy 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 $\Gamma(t\to W^+b)$: Czarnecki et al, hep-ph/9806244, …
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
…

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)

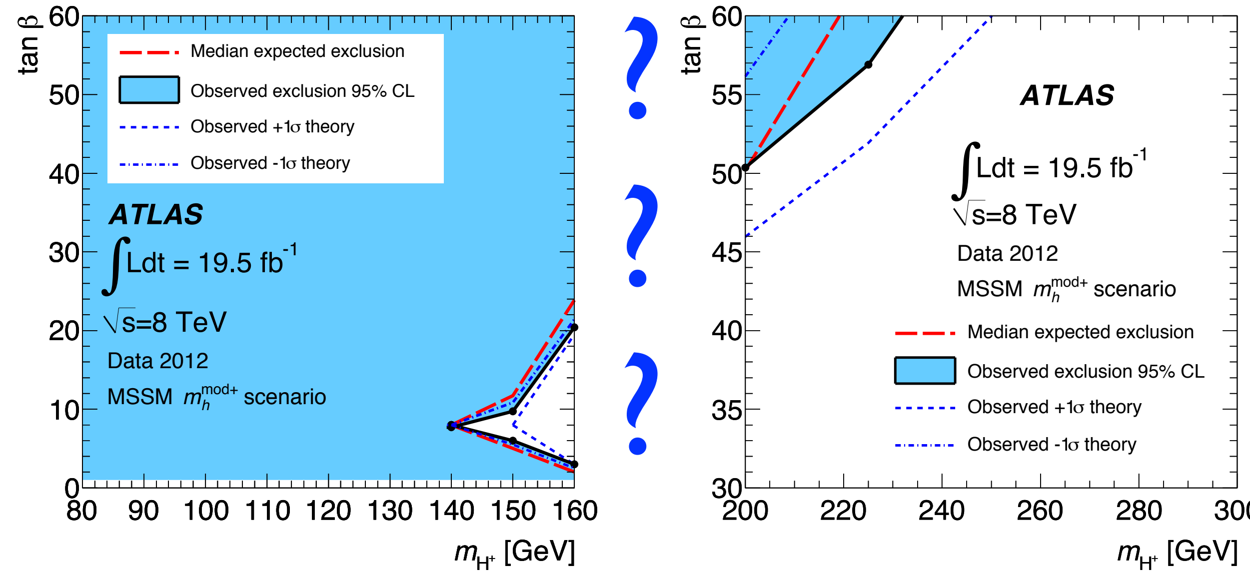
Can take the $\Gamma_t\to 0$ limit

Both cases are known at or beyond NLO QCD

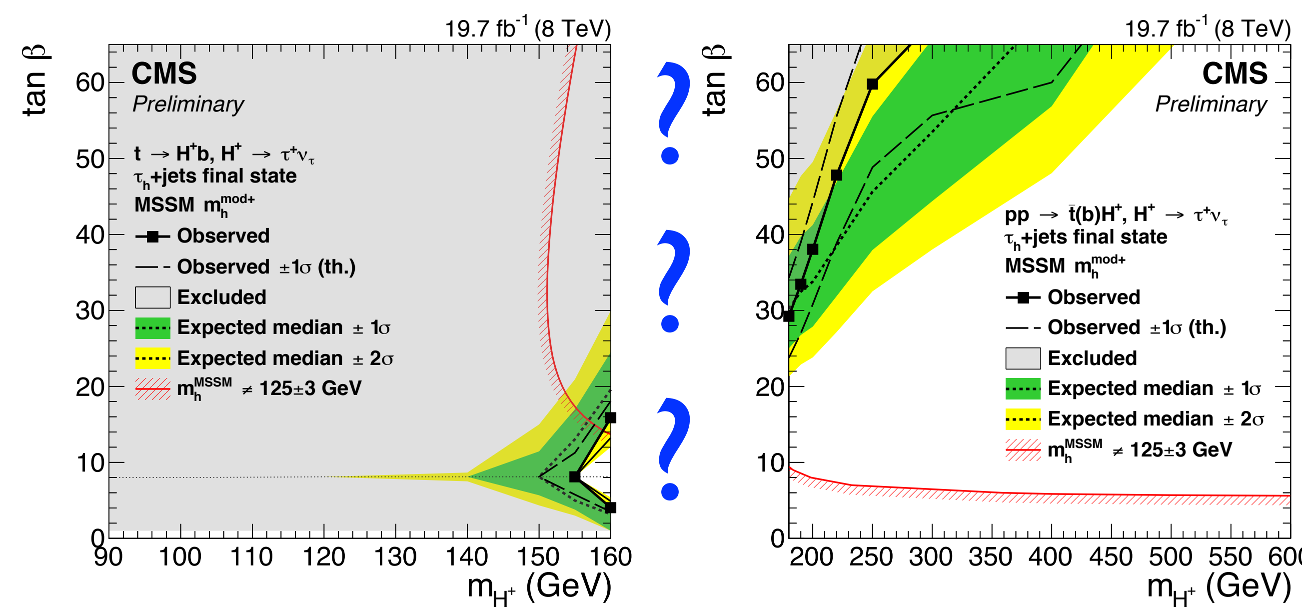
How we did searches at the LHC

- 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

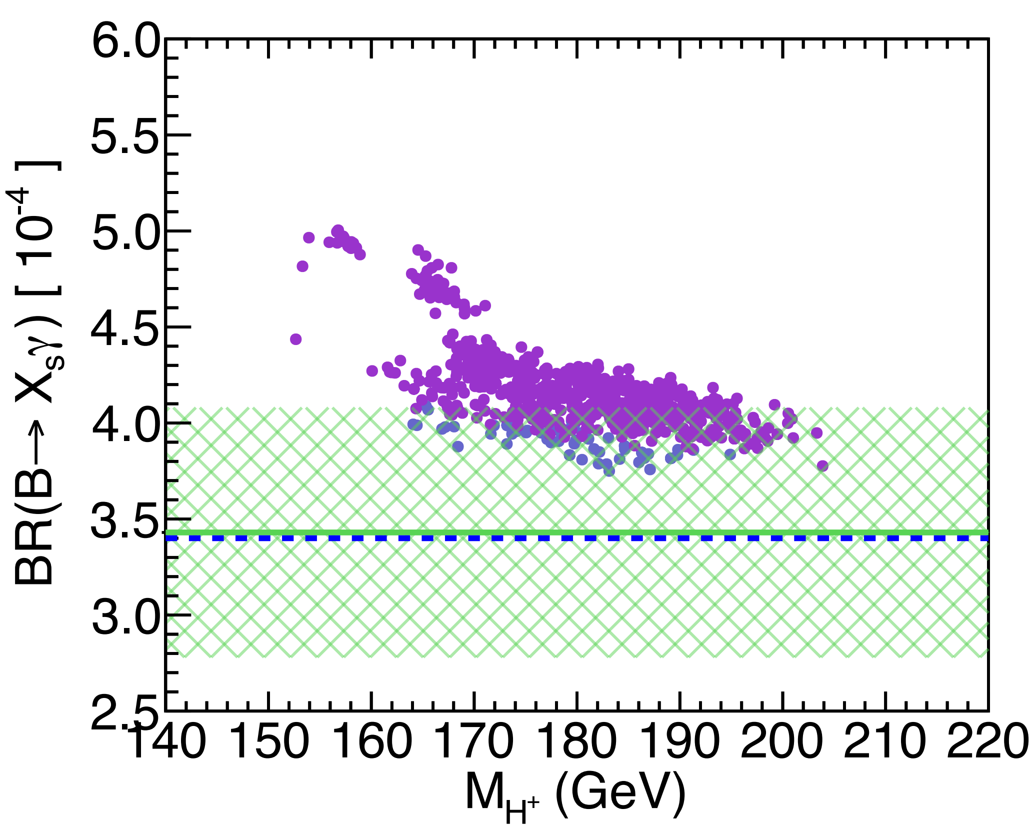


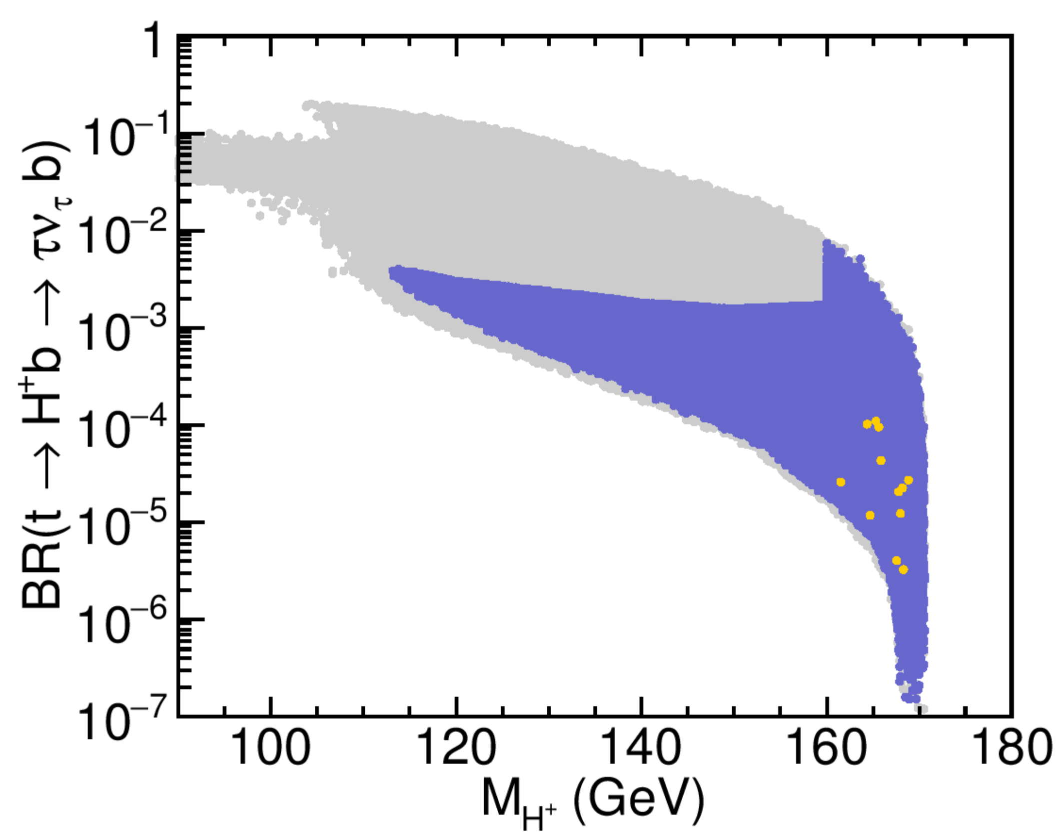
CMS, PAS HIG-14-020



Why to care about the intermediate-mass region?

- Because it is there
- SUSY models where the 125 GeV Higgs is the heavy H boson can have the charged Higgs in the intermediate-mass region
  Bechtle, Haber, Heinemeier, Stal, Stefaniak, Weiglein, Zeune, arXiv:1608.00638
- In some of these models the light Higgs can act as a mediator to DM
  Profumo, Stefaniak, arXiv:1608.06945



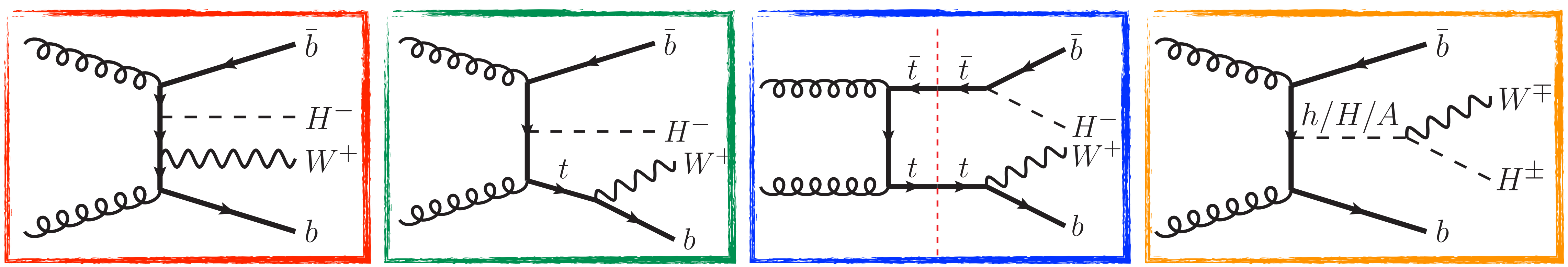


Getting ready to sail

Getting accurate predictions for the intermediate-mass region

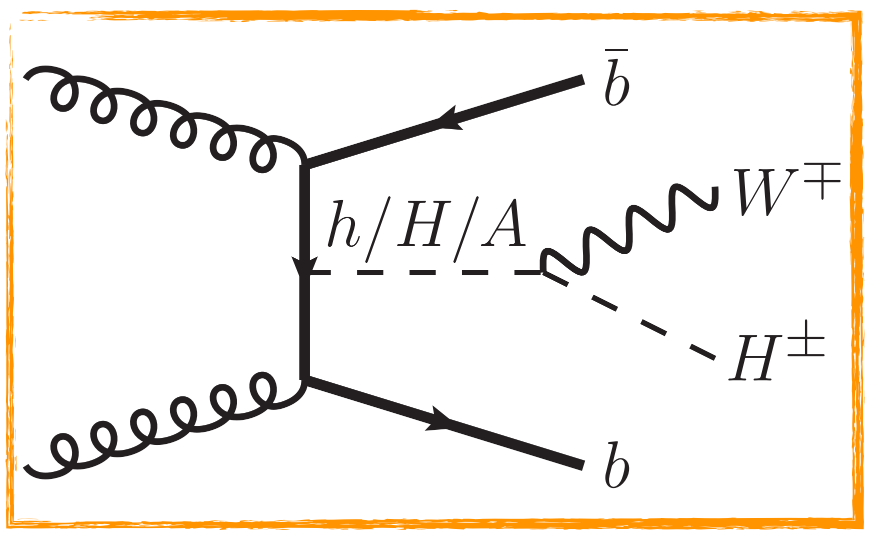
Degrande, Frederix, Hirschi, Ubiali, Wiesemann, MZ, arXiv:1607.05291

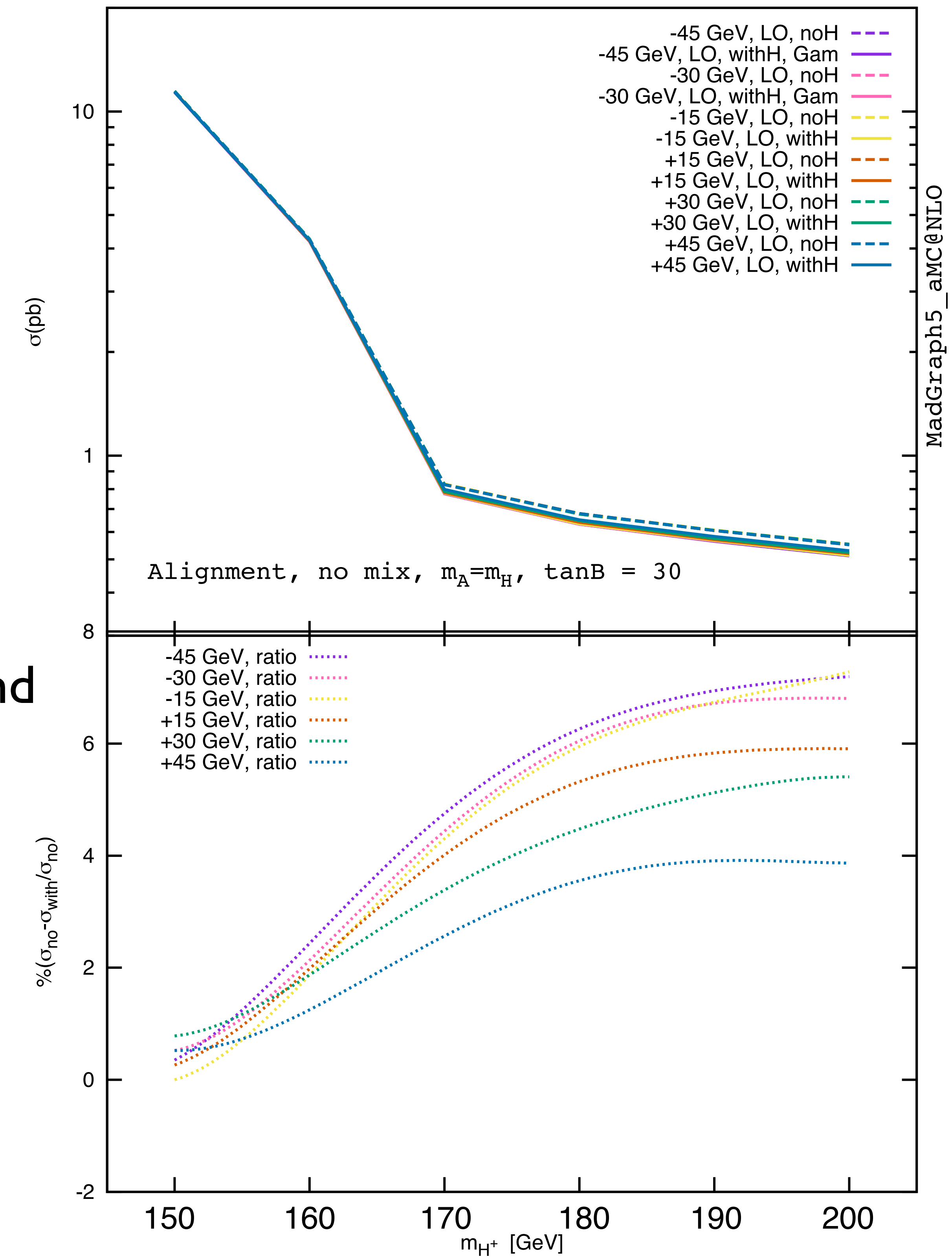
- The full process $pp \rightarrow H^{\pm}W^{\mp}b\bar{b}$ has to be simulated, consistently including the top quark width. $\Gamma_t = \Gamma_t(m_{H\pm}, \tan\beta)$
- Diagrams with 0, 1 and 2 resonant tops contribute to the total cross-section, as well as diagrams with neutral Higgs bosons



- 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



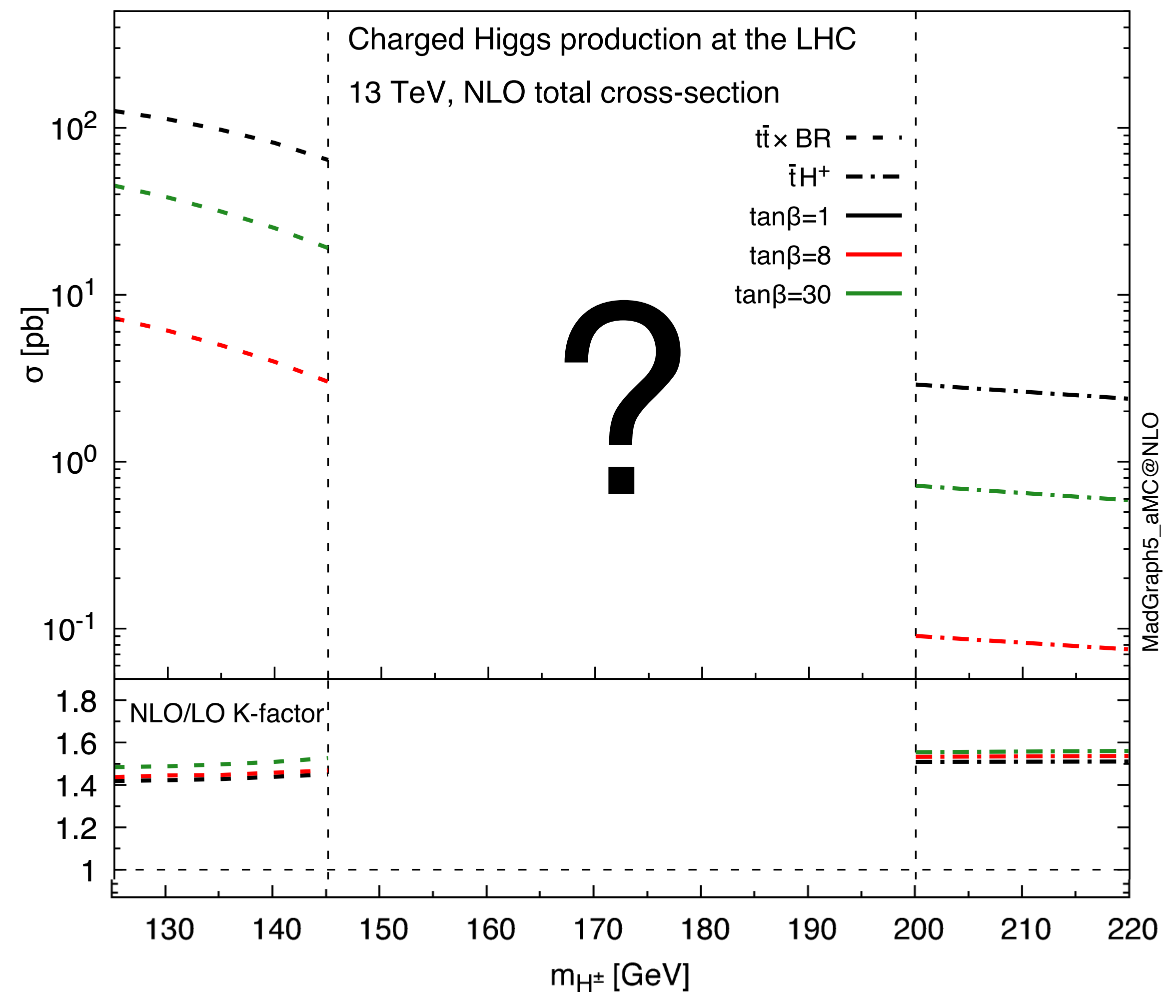


- Diagrams with neutral Higgs bosons introduce additional dependence on the $h/H/A$ masses and on the neutral Higgs mixing α.
- Assuming h to be the SM Higgs (m_h=125 GeV and $\cos(\beta\text{-}\alpha)\simeq 0$), for non-resonant configurations ($m_{h/H/A}<m_W+m_{H\pm}$) the contribution to the total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

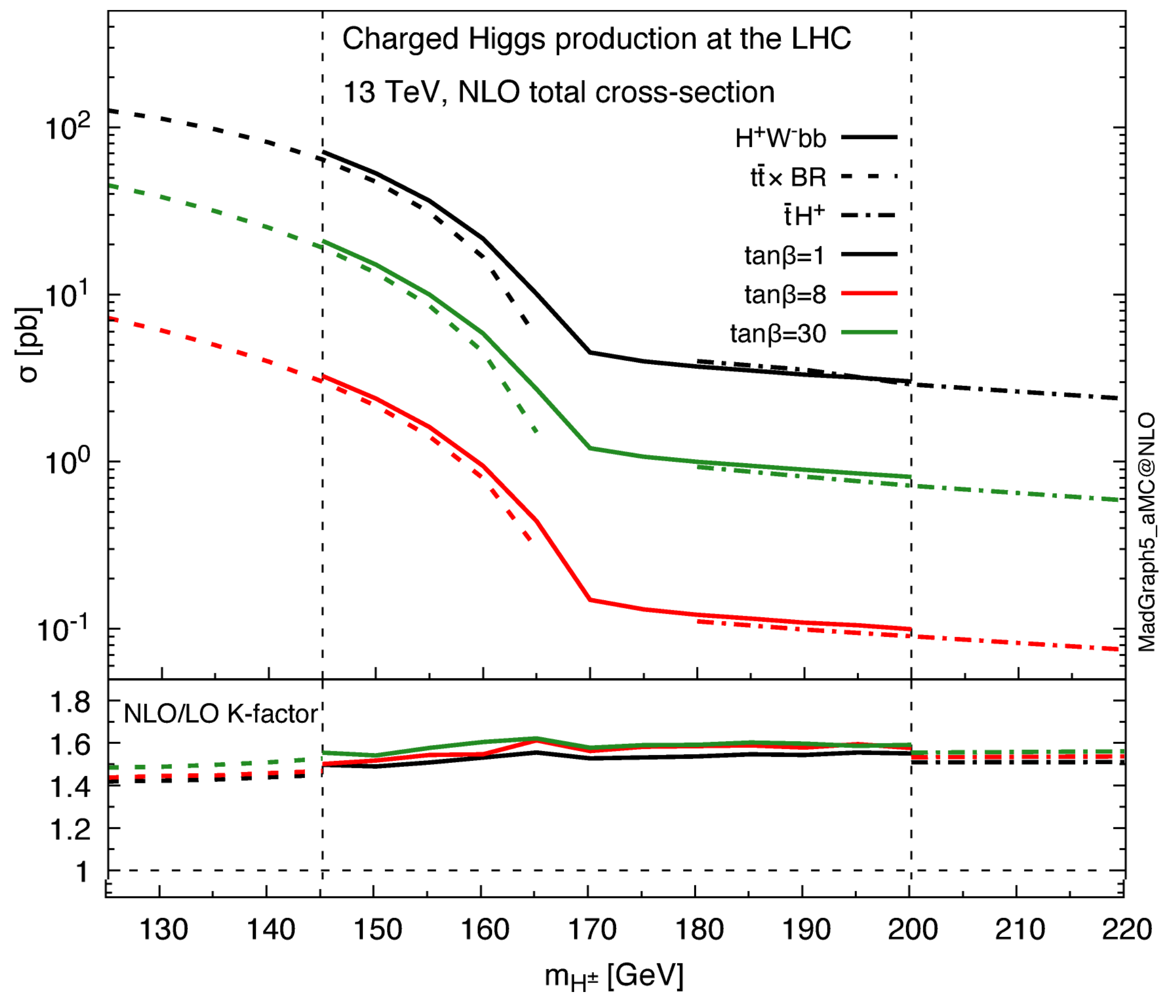
Calculation setup

- Computation carried out with MADGRAPH5_AMC@NLO, improved with resonance-aware FKS subtraction Frederix et al. arXiv:1603:01178
- Focus on type-II 2HDM (extension to MSSM and other 2HDMs will be discussed)
- 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 ($m_{H\pm}$, tanβ) 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 tanβ will be considered (tanβ =1, 8, 30)
- Other input parameters follow the recommendation of the LHC HXSWG

Results


Charged Higgs production at the LHC
13 TeV, NLO total cross-section
tt̄× BR
t̄H⁺
tanβ=1
tanβ=8
tanβ=30
?
σ [pb]
MadGraph5_aMC@NLO
NLO/LO K-factor
m_H± [GeV]

Results



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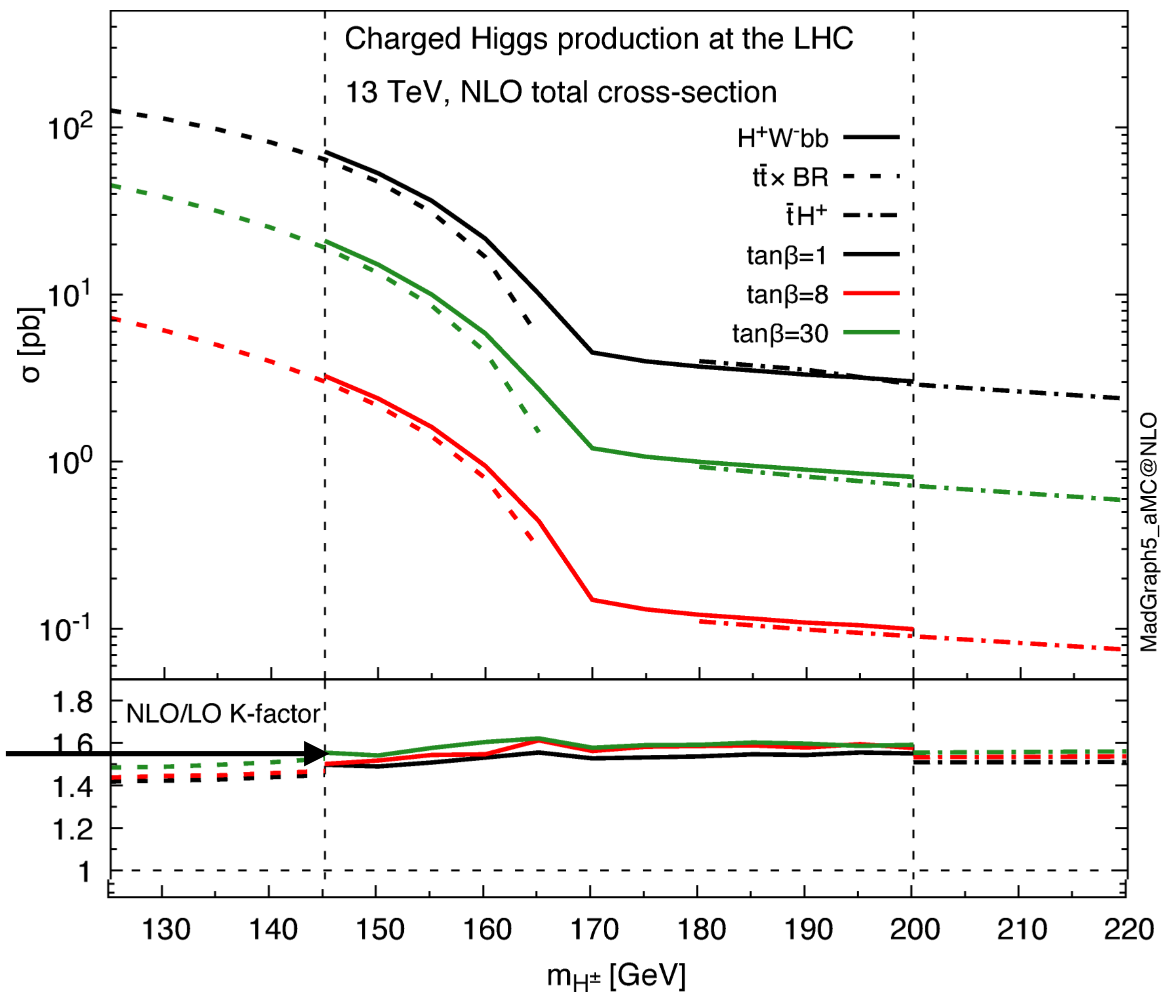
Results

Rather constant K-factor ~ 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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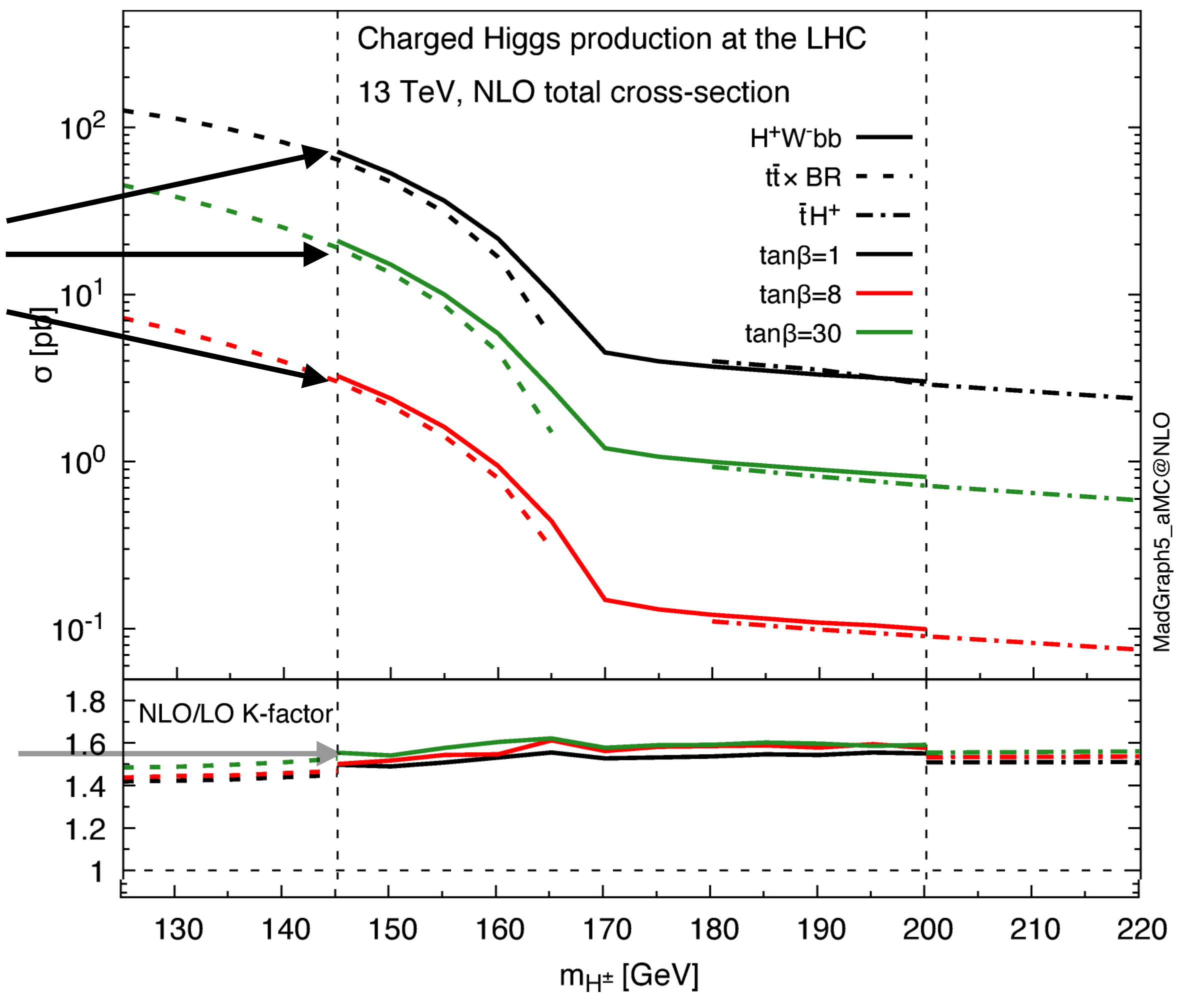

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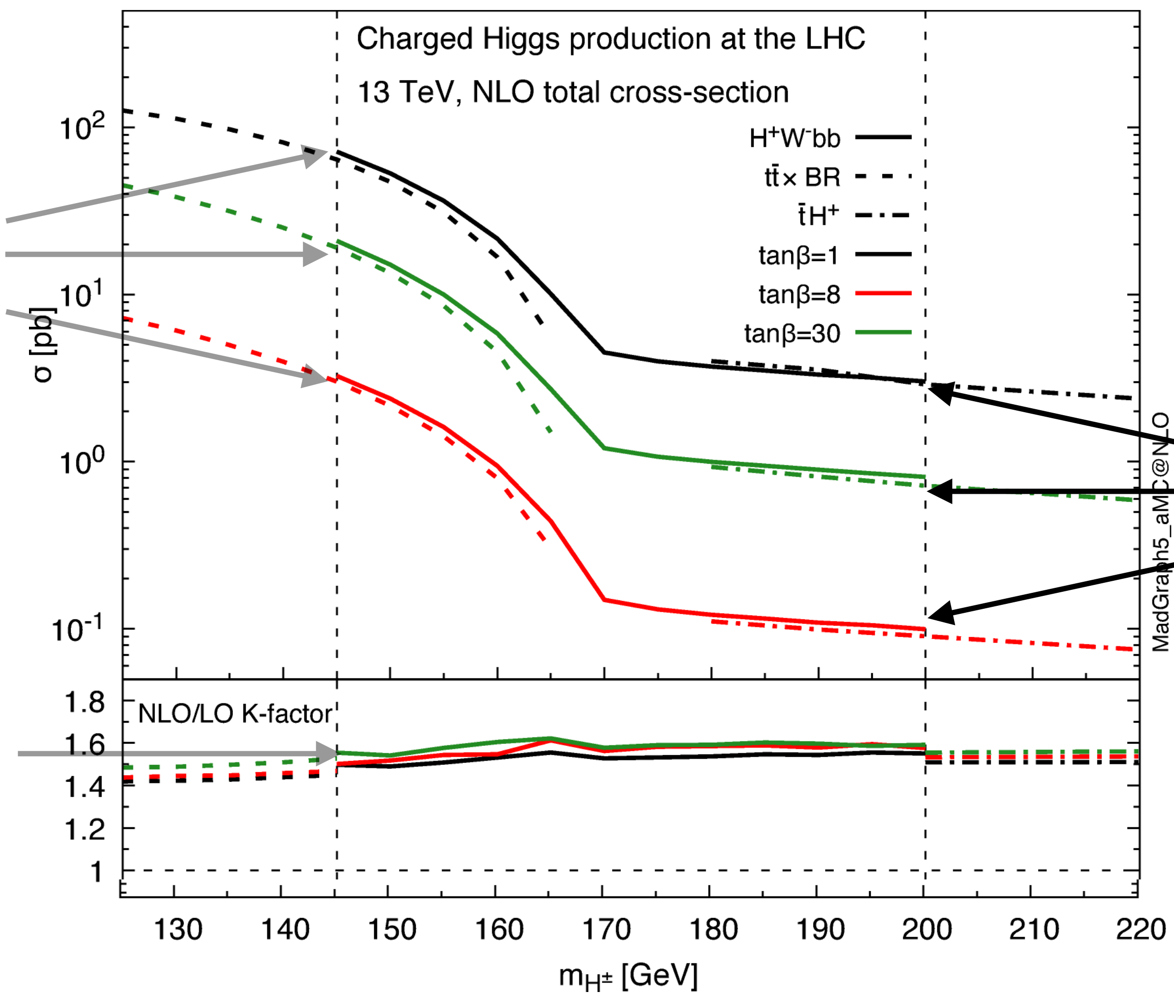
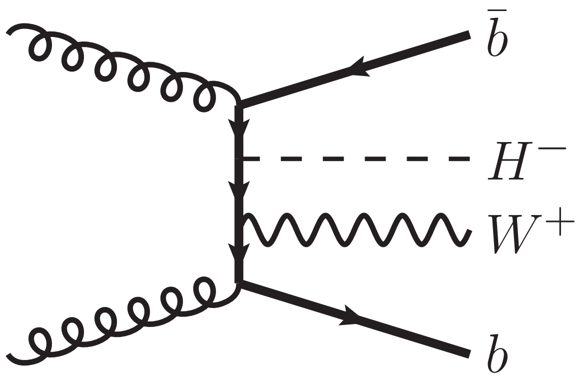


Discontinuity due to non-resonant contributions. Size of discontinuity is $\tan\beta$ dependent because of chiral couplings

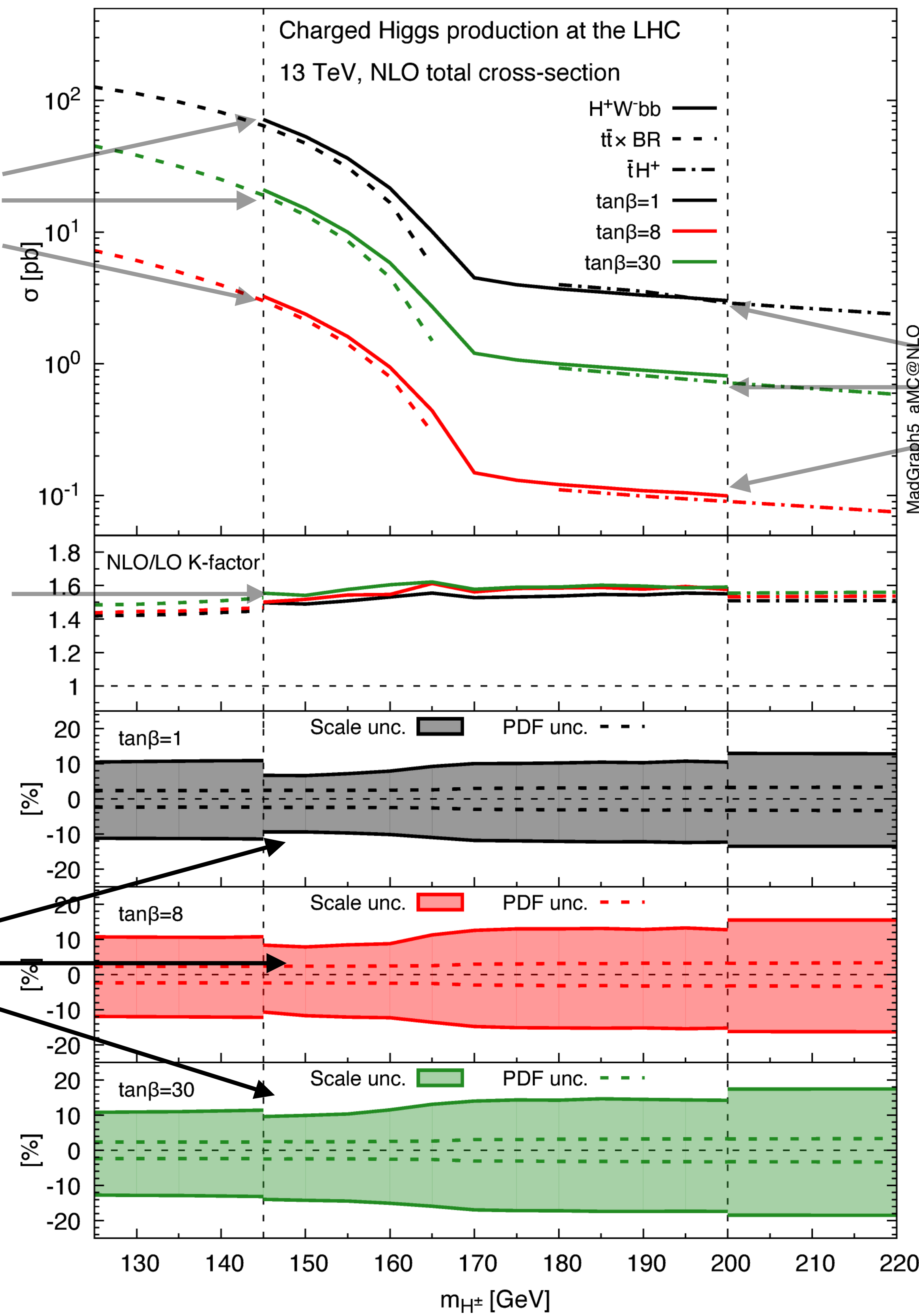


Results

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

Rather constant K-factor ~ 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)



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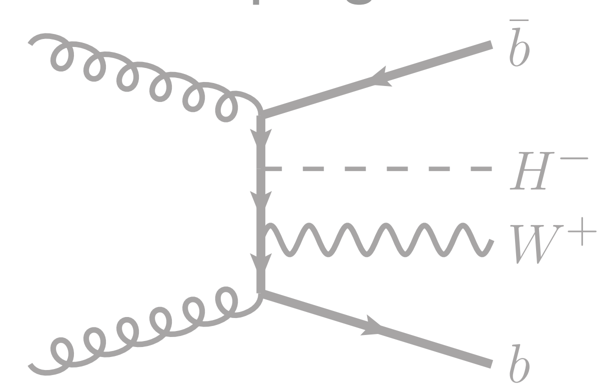


Extension to other values of tanβ or different 2HDMs

- The charged Higgs cross section receives contributions proportional to y_b^2 (~tanβ^2), y_t^2(~1/tanβ^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 tanβ can be computed as

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

- Cross-checked by recomputing our results at tanβ=1 and tanβ=30, starting from tanβ=8. Agreement below 1% was found
- Can be extended to obtain the charged Higgs cross section in other 2HDM scenarios (e.g. type I or MSSM with Δ_b corrections)

$$\sigma^{\mathrm{t-I}}(\tan\beta') = \frac{\sigma^{\mathrm{t-I}}(\tan\beta = 1)}{(\tan\beta')^2} \times \left(\frac{\Gamma_t(\tan\beta)}{\Gamma_t(\tan\beta')}\right)^2$$

- ($m_{H\pm}$, tanβ) grids for type-I and II 2HDM available at https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGMSSMCharged

2. SUSY QCD NLO corrections

- The leading SUSY QCD corrections can be added as usual for the heavy H+ case
  - Δb corrections
  - Same simple arithmetic trick to fold them in without knowledge of the three individual terms [from the LHC H XS WG twiki]
    - Find the delta_b value corresponding to tb
    - Calculate tbeff = tb/sqrt{1 + delta_b}
    - Using the cross sections without SUSY-QCD NLO corrections, get the cross section which corresponds to tbeff (!)
    - Multiply the result from the previous bullet with 1/(1 + delta_b) => this is your cross section

- Note that for $\tan\beta<10$, non-factorizable corrections can become significant – O(10%)

Martin Flechl, cHarged 2016

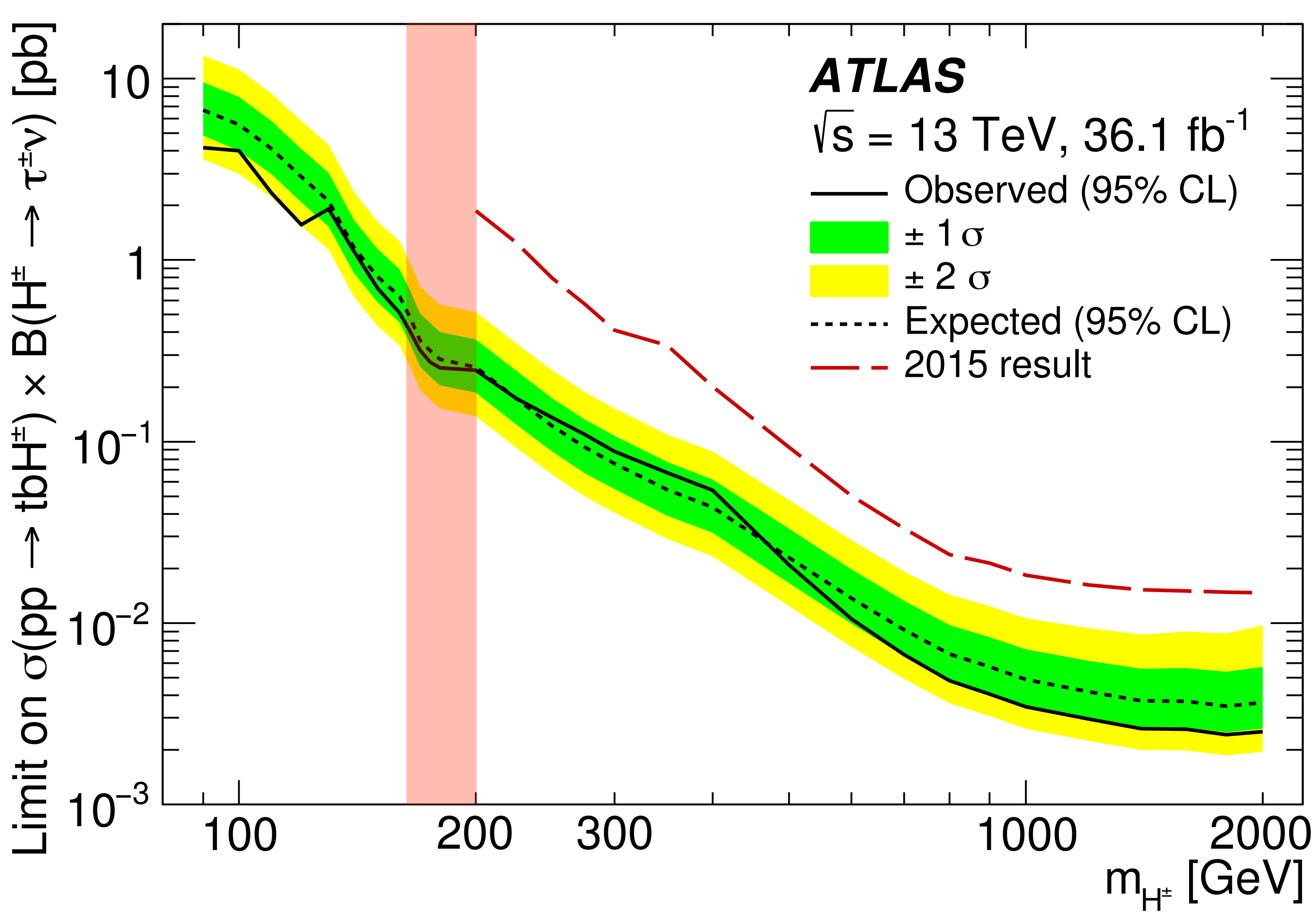
Recommendations for signal simulation

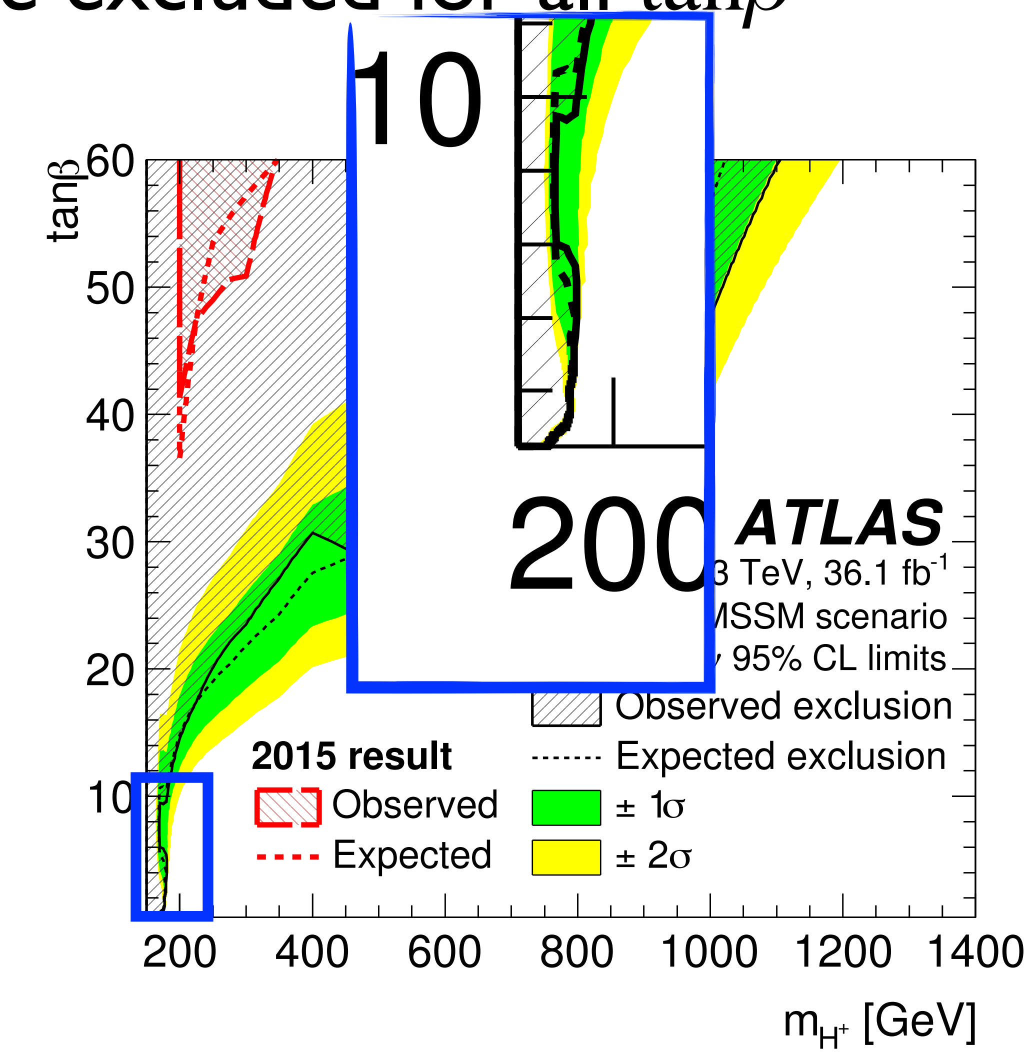
https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/chargedHiggs

- Since a fully-differential NLO computation does not exist, current recommendations for signal simulation rely on LO events, normalised to NLO cross section
- This makes it possible also to add contributions with the extra scalars (h/H/A), which can be evaluated at LO
- More refined approaches can also be performed (reweight jet multiplicity, …)
- Questions for our experimental colleagues:
  - Is this enough?
  - What is on your wish-list?
  - Any other obstacle that us (theorists) should help removing?

First steps in a new land

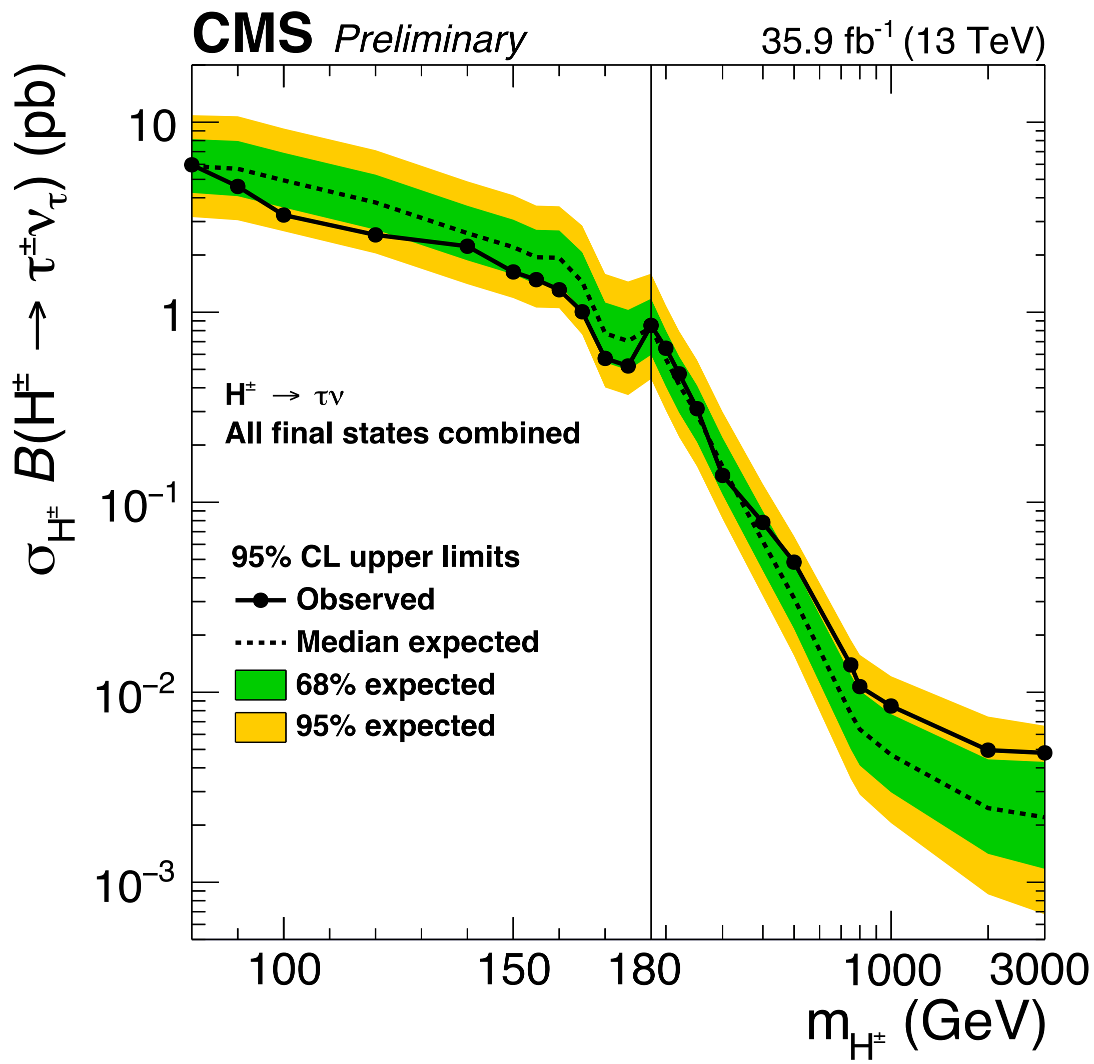
- Very recently, ATLAS published updated searches for $H^{\pm}\to\tau\nu$ including the intermediate-mass range
  (arXiv:1807.07915, see Blake Oliver Burghgrave's talk this morning)
- Charged Higgses below 160 GeV are excluded for all $\tan\beta$

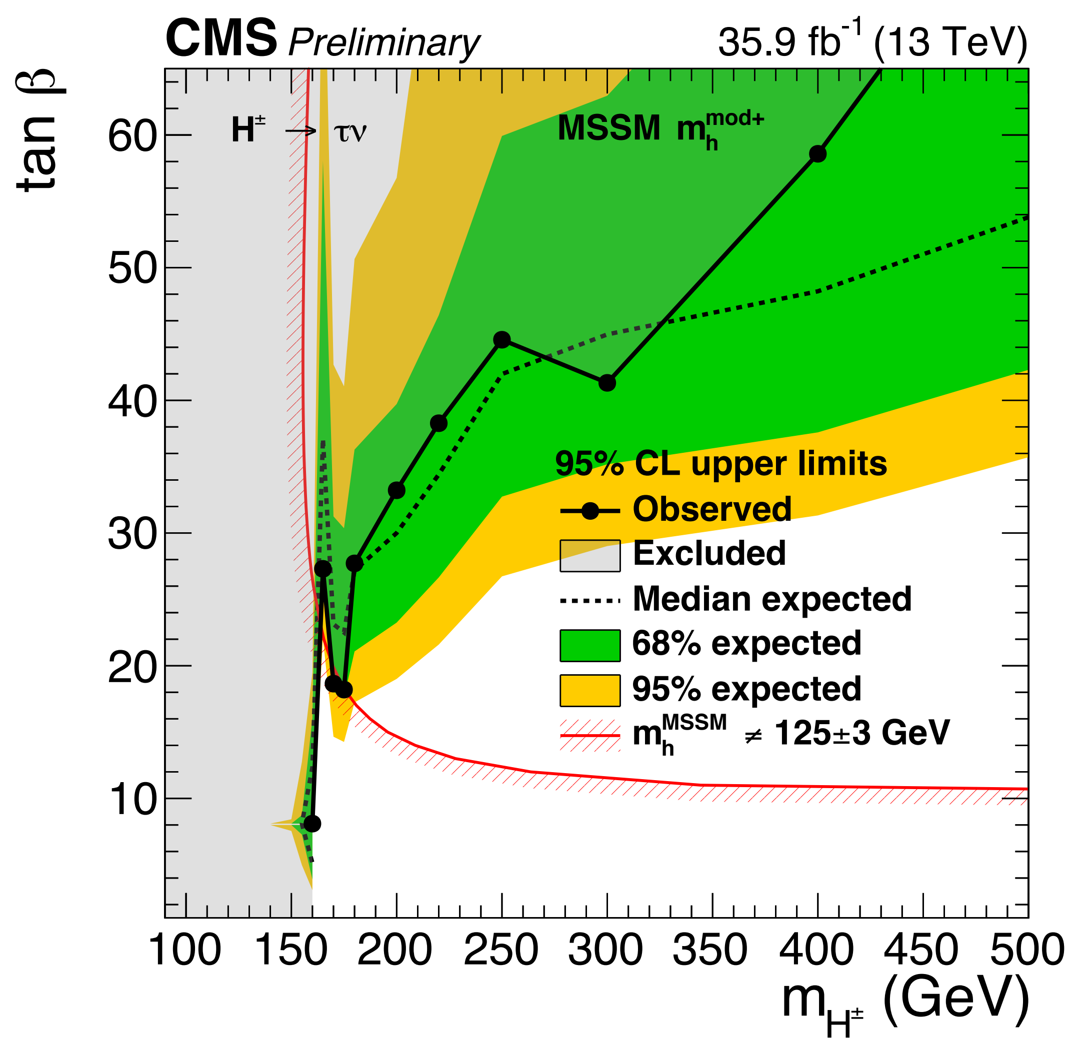




First steps in a new land

- CMS has followed yesterday!
  (CMS-PAS-HIG-18-014, see Alexandros Attikis and Jan Eyserman's talks this morning)
- All $\tan\beta$ values excluded up to 150 GeV





Conclusions & Outlook

- The discovery of a charged Higgs boson will be a clear sign of BSM physics
- NLO predictions for the charged Higgs cross-section have been made 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 and scale uncertainties reduced to 10-20%
- Full $\tan\beta$ scan (for type-II and type-I 2HDM) available on https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGMSSMCharged
- First analyses in the intermediate-mass region published by ATLAS and CMS, with 36 fb^{-1}. Masses up 160 GeV / 150 GeV excluded in the hMSSM /MSSM m_H^{mod+}