H^+ searches:

Summary of cH^+arged 2018 workshop & prospects

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Seoul National University

1st IUEP Mini-Workshop: Physics Opportunities at Future Colliders

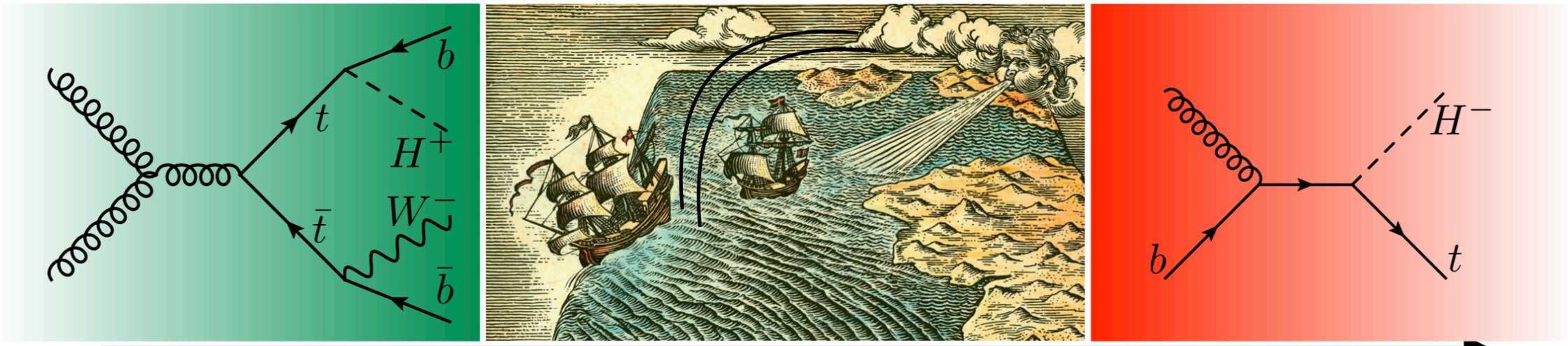
Introduction

- Charged Higgs boson is a must-be particle in most BSM hypotheses
  - Started to appear from the simplest extension of the SM Higgs scalar doublet
- Charged Higgs boson searches have been performed assuming various theories
  - 2HDMs, Georgi-Machacek, 3HDMs, etc.
- This talk summarizes recent searches & issues presented at the charged Higgs workshop held in Uppsala, and the HL/HE-LHC workshop
- H^+ is not one-and-only particle in the extended Higgs sector, here the discussions on other important processes skipped

H^+ searches

- In the 2HDM, the dominant production and decay 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.

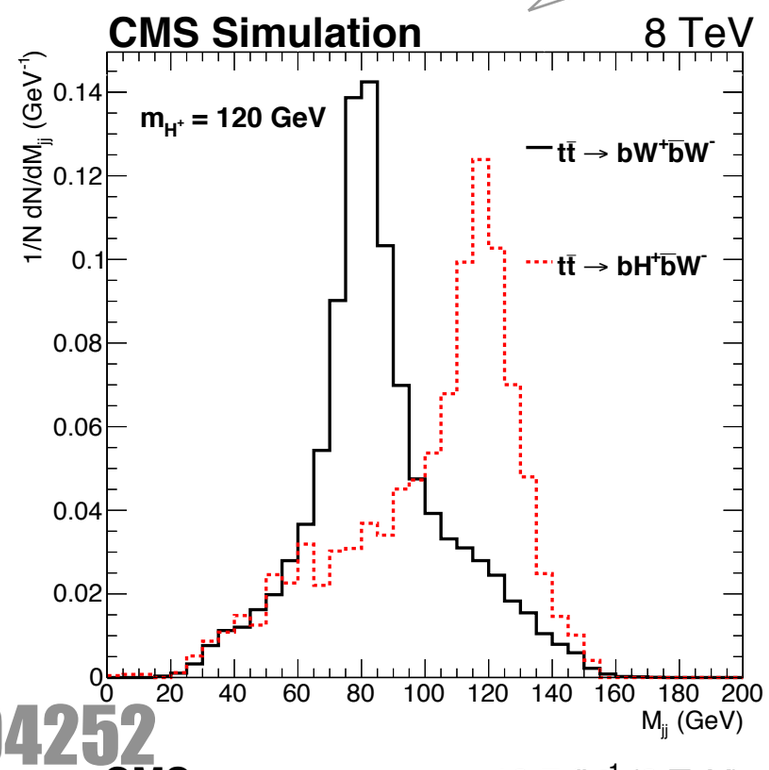
The full $pp \to H^\pm W^\mp b\bar{b}$ process has to be simulated.

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

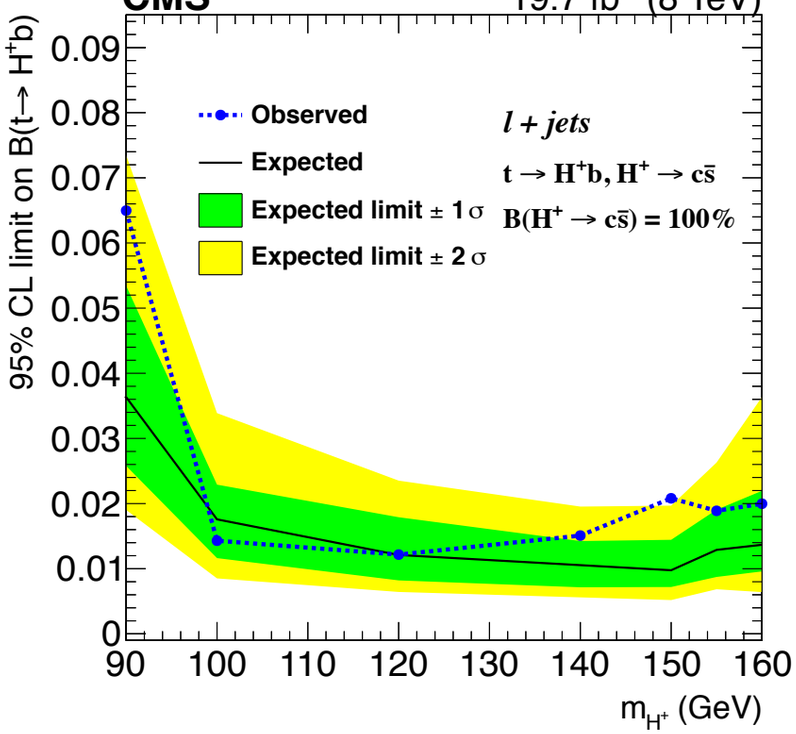
Routine searches: $H^+ \to \tau\nu$, cs, cb, tb

$H^+ \to cs$ @ 8 TeV

CMS

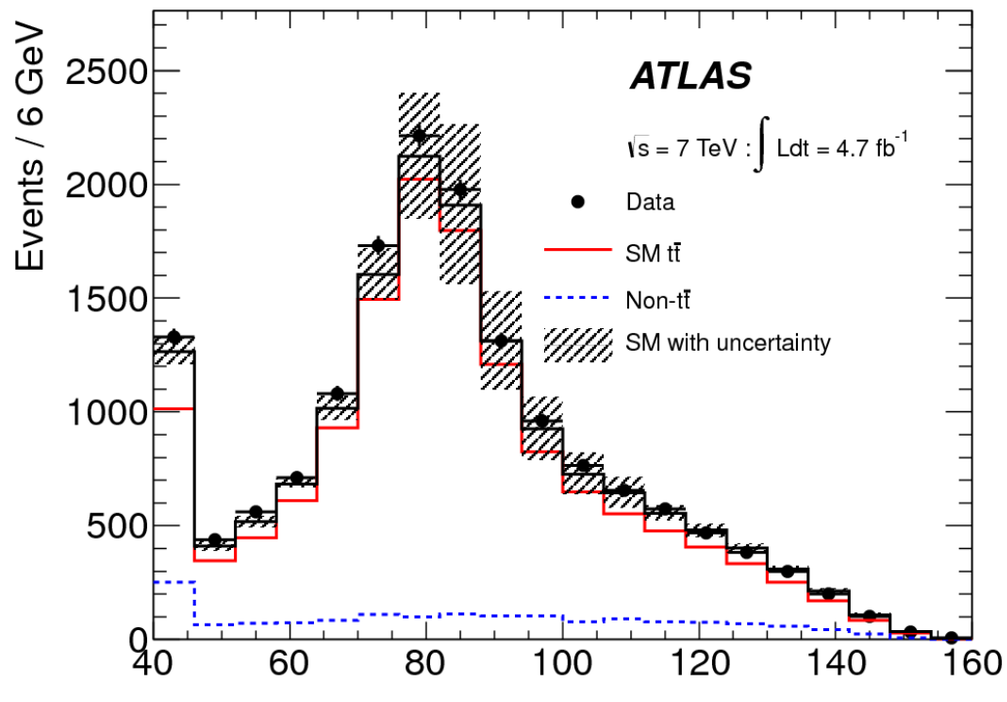


arXiv:1510.04252

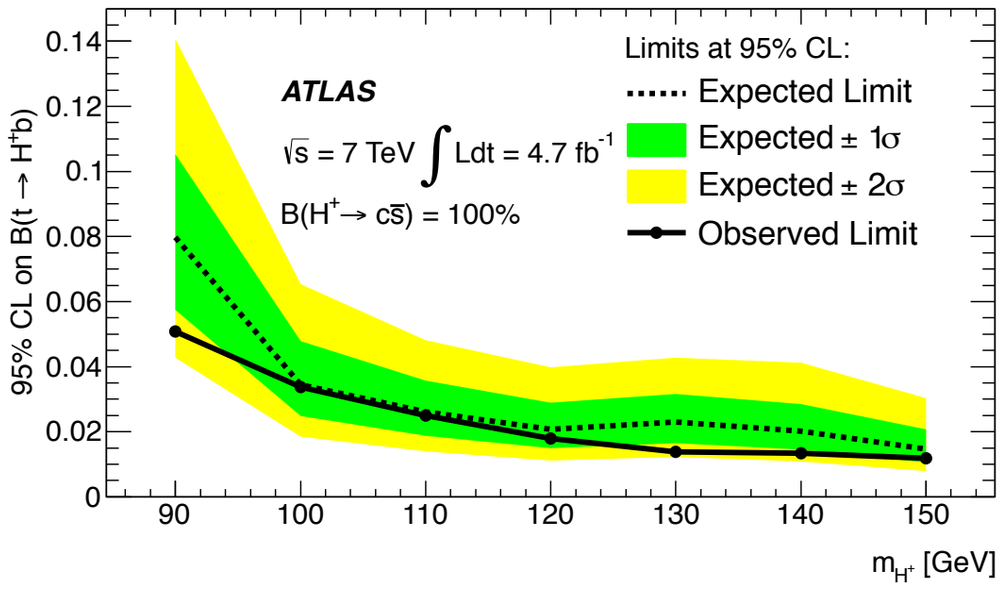


$H^+ \to cs$ @ 7 TeV

ATLAS



arXiv:1302.3694



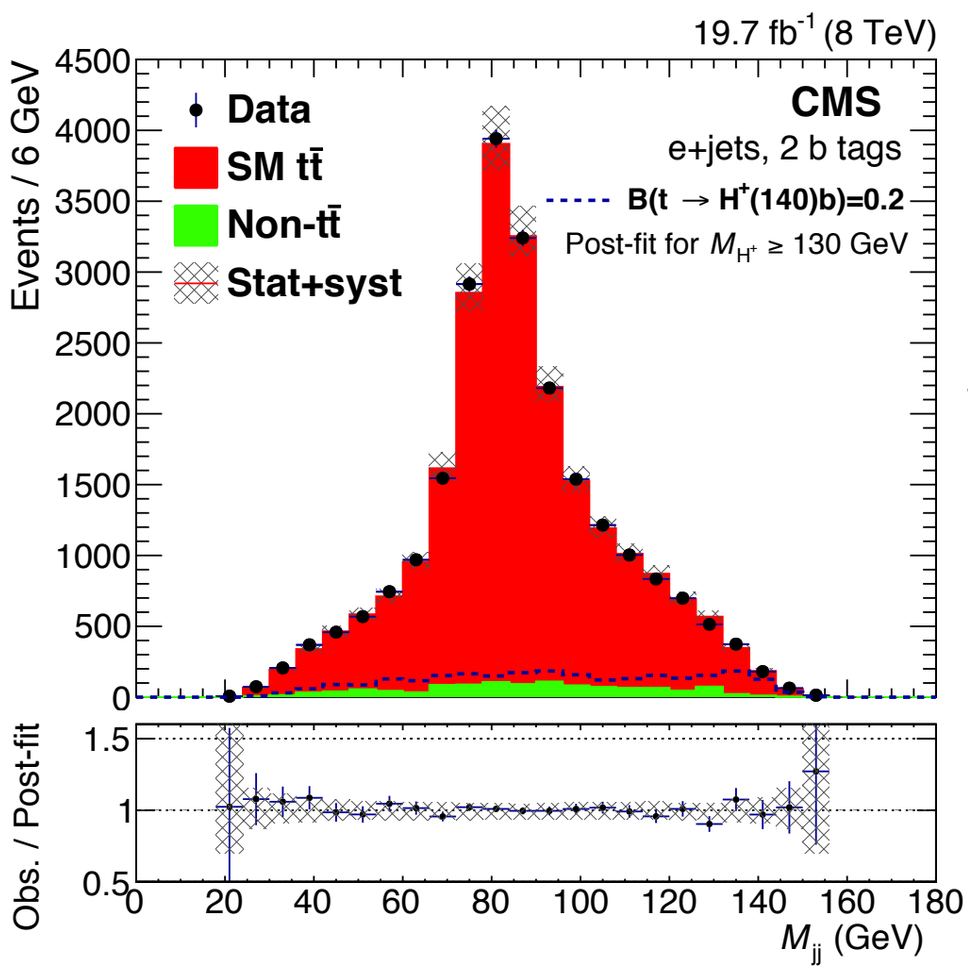
Use dijet mass discrepancy between W and H+ in fully reconstructed tt events

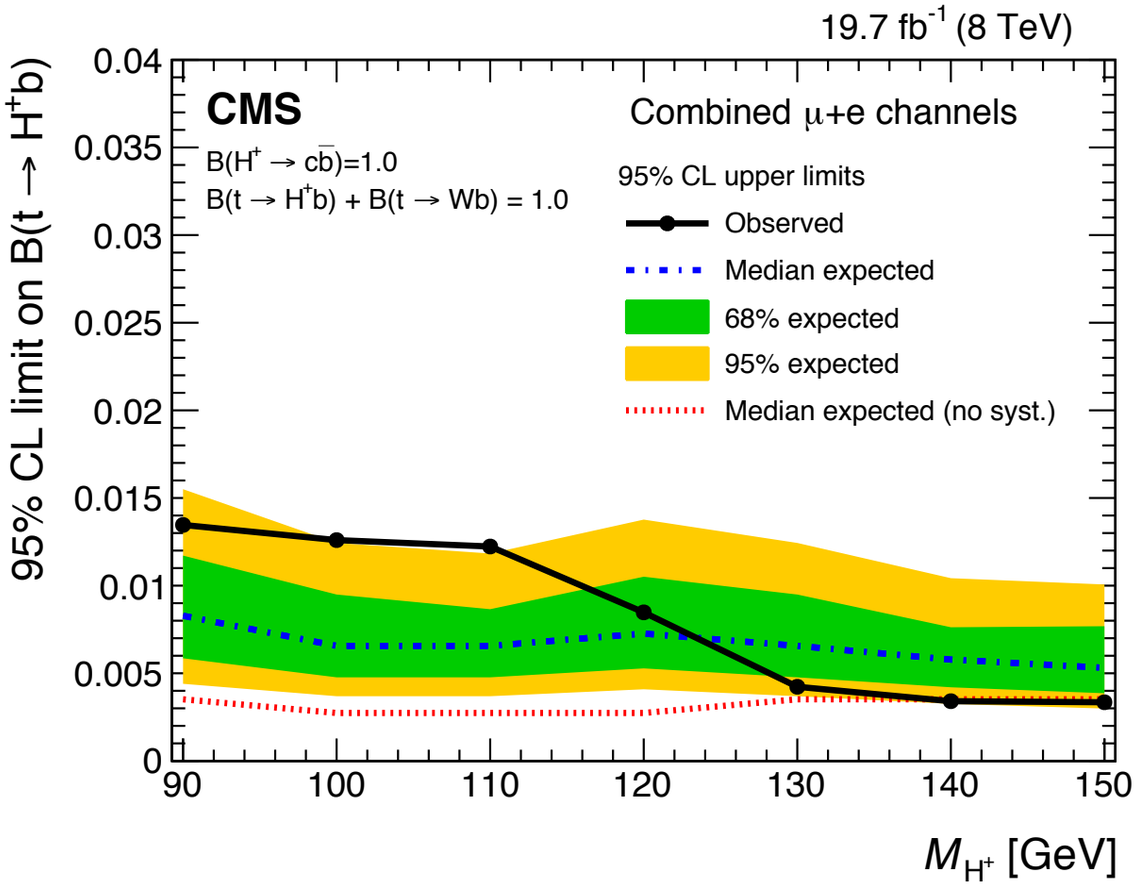
arXiv:1808.06575

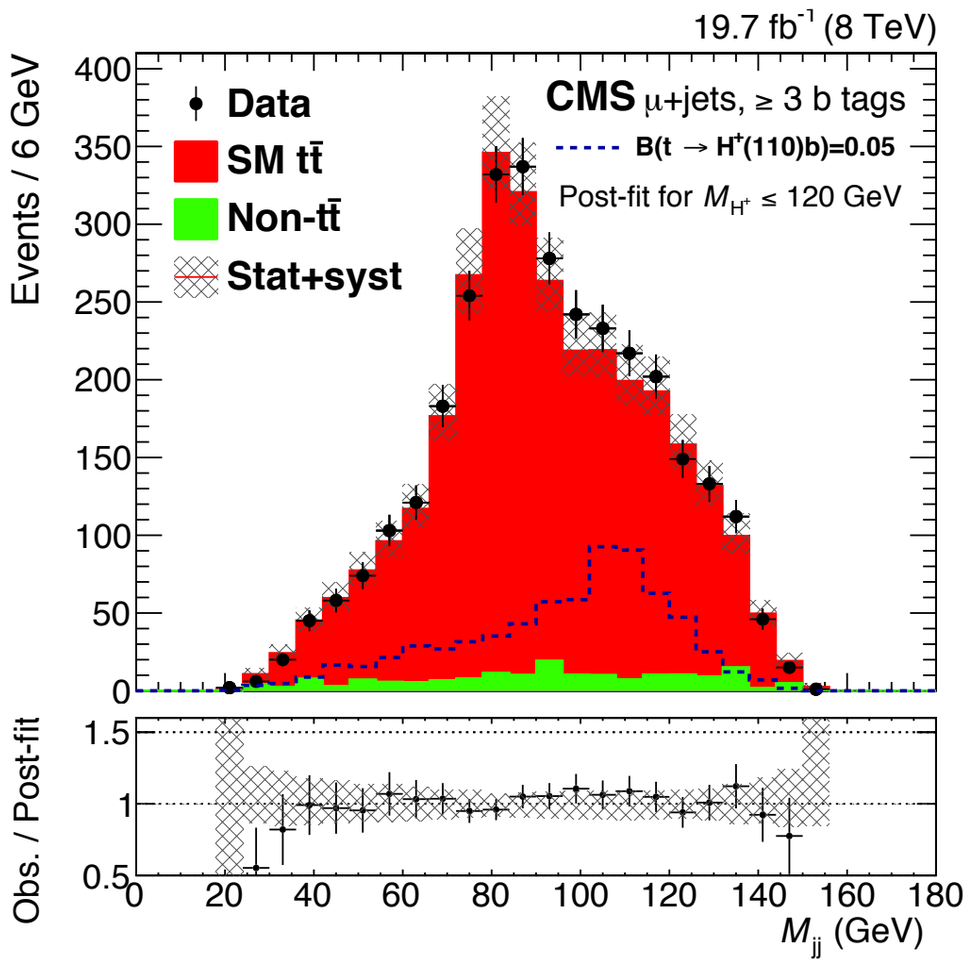
$H^+ \rightarrow cb$ @ 8 TeV

CMS only

- Dominant in type-Y of 2HDM
- First measurement of this channel
- Simultaneous fit on both 2b-tags (constrain tt) & ≥3b-tags (H^+ sensitive) dijet mass distributions



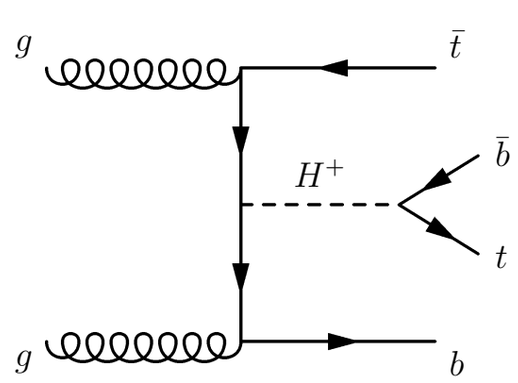




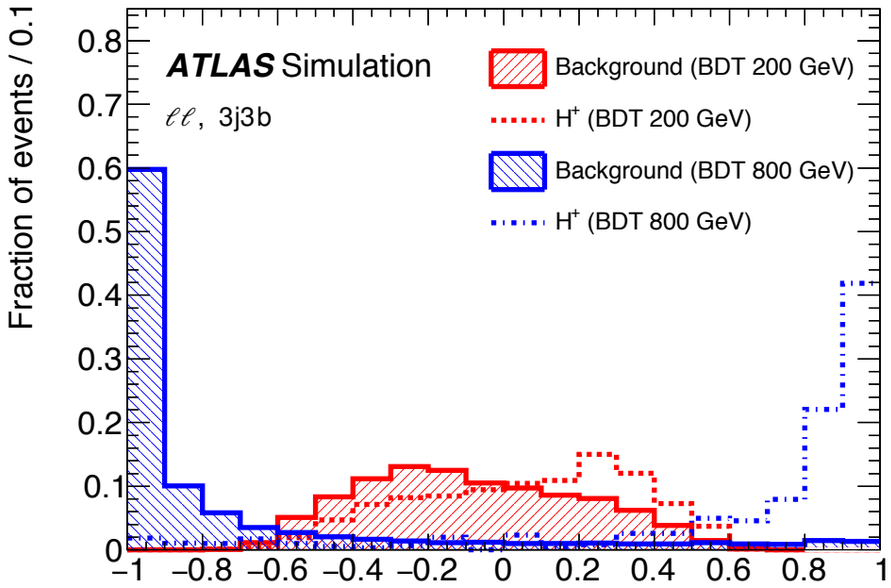
arXiv:1808.03599

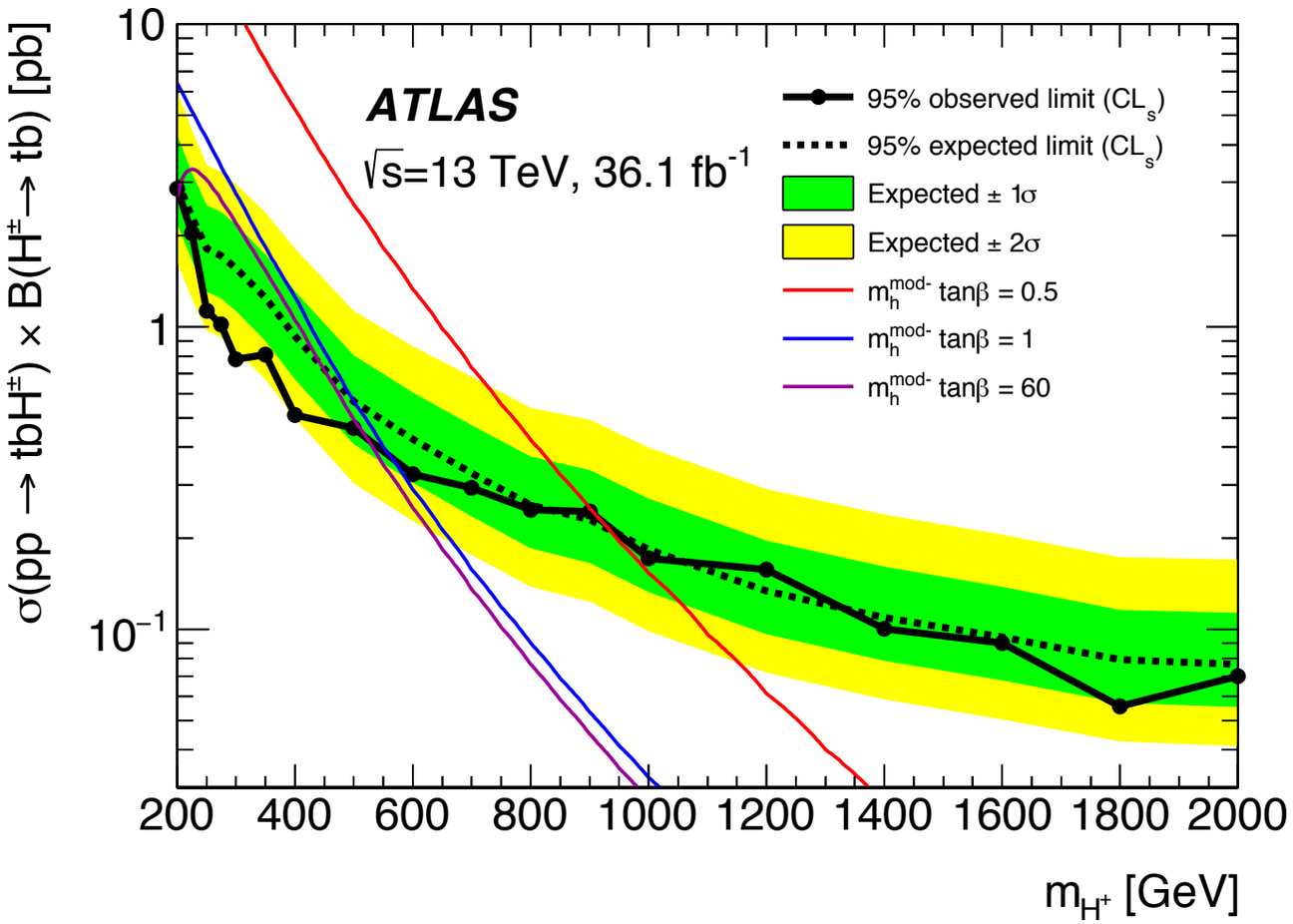
ATLAS

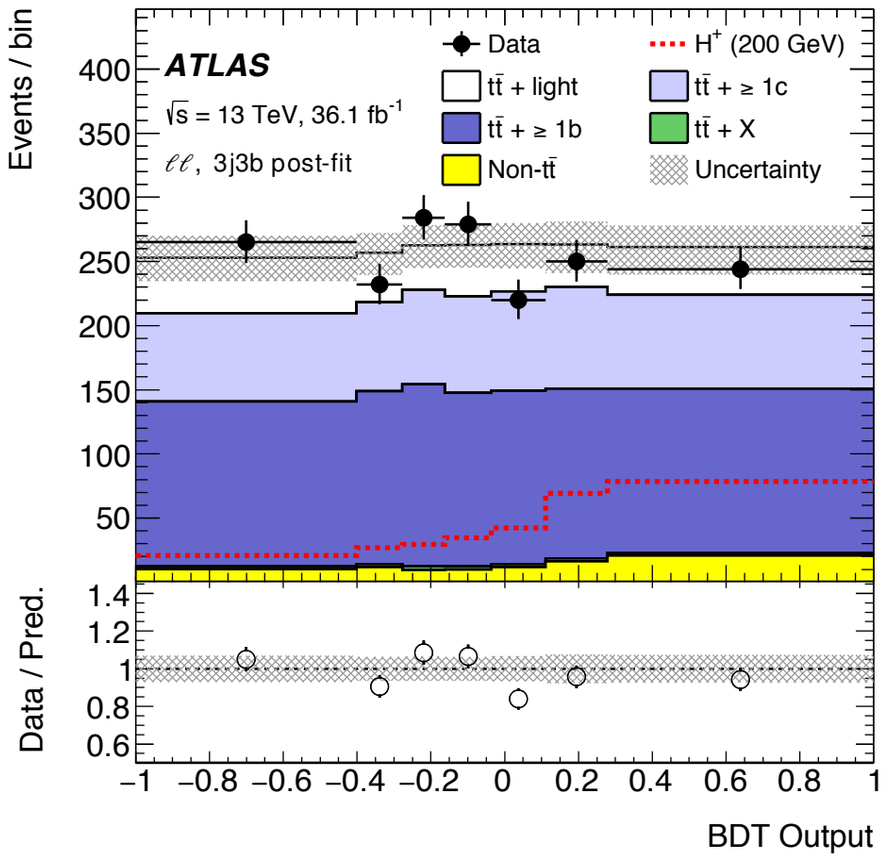
$H^+ \rightarrow tb$ @ 13 TeV



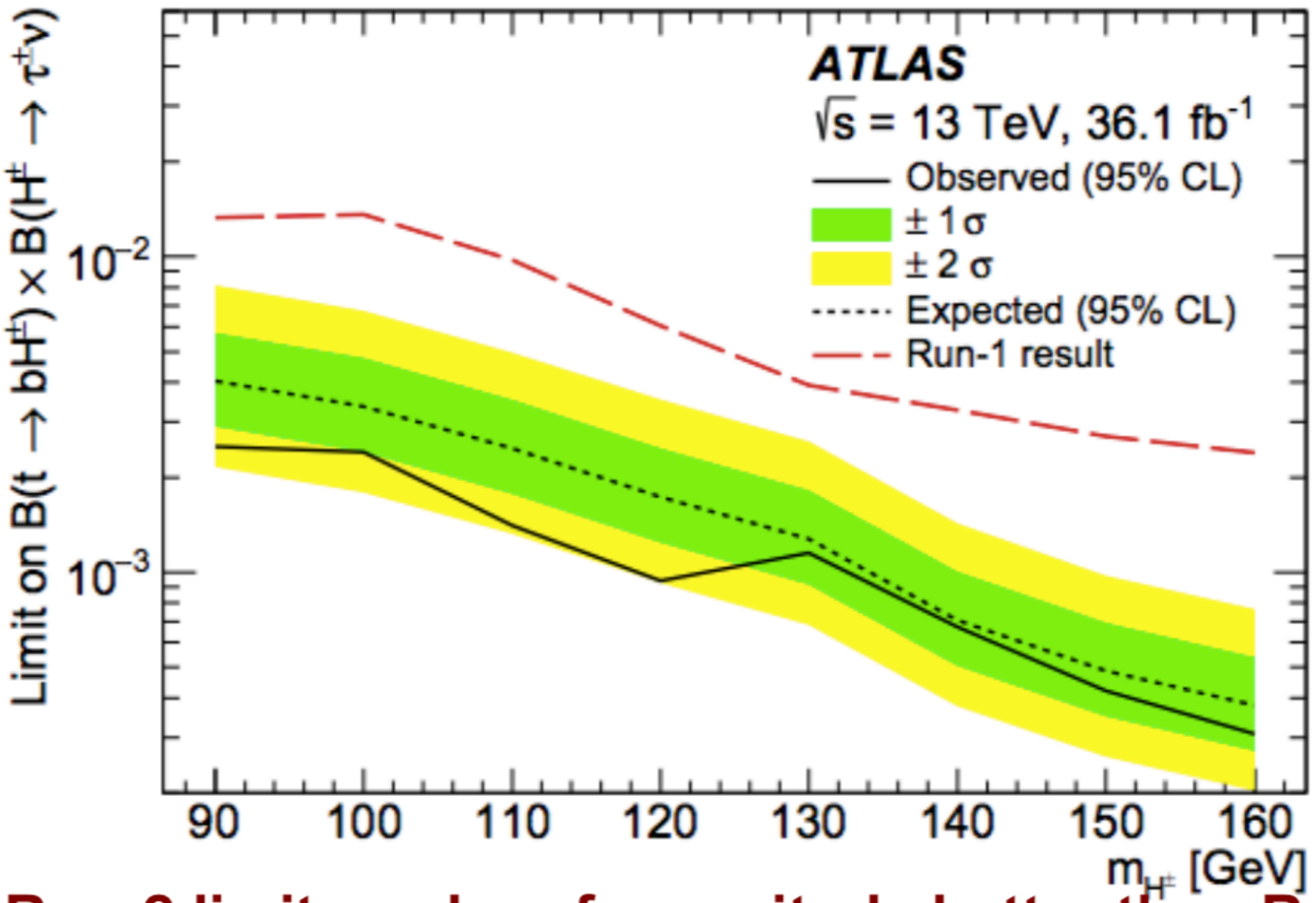
- Two OS leptons+≥3 jets (≥2 b-jets) || lepton+≥5 jets (≥3 b-jets)
- Search in m(H^+) 200—2000 GeV
- Use multivariate techniques to separate S/B
- Simultaneous fit to BDT output in SR & number of events in CR

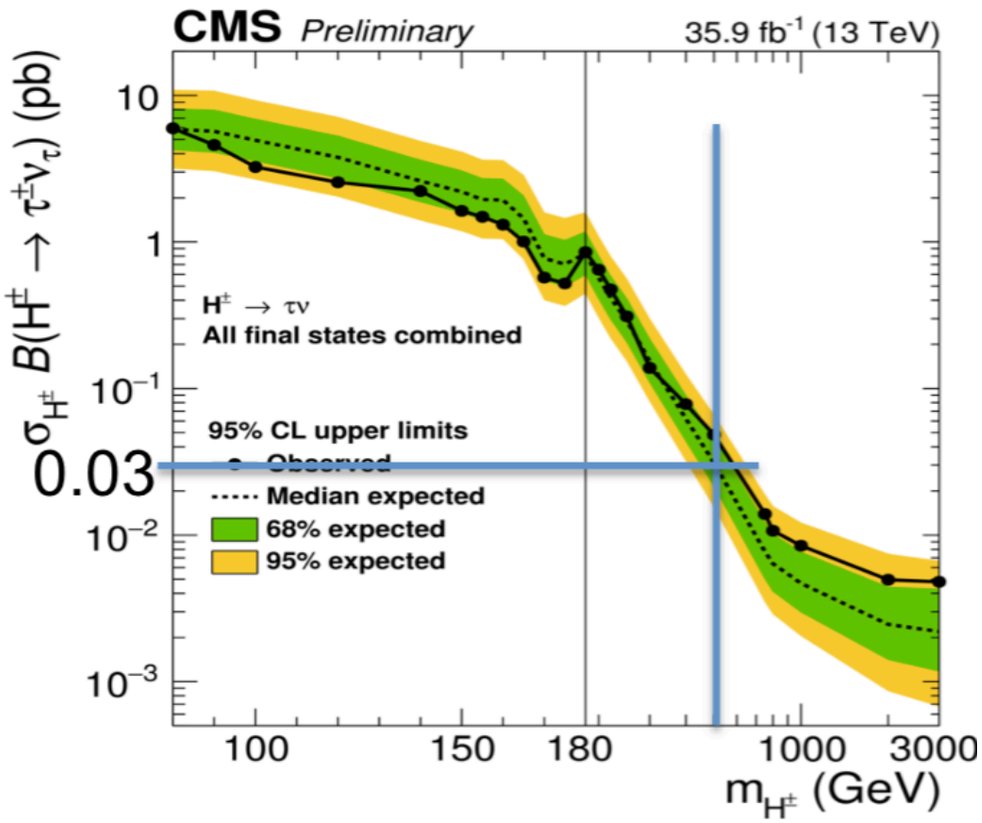


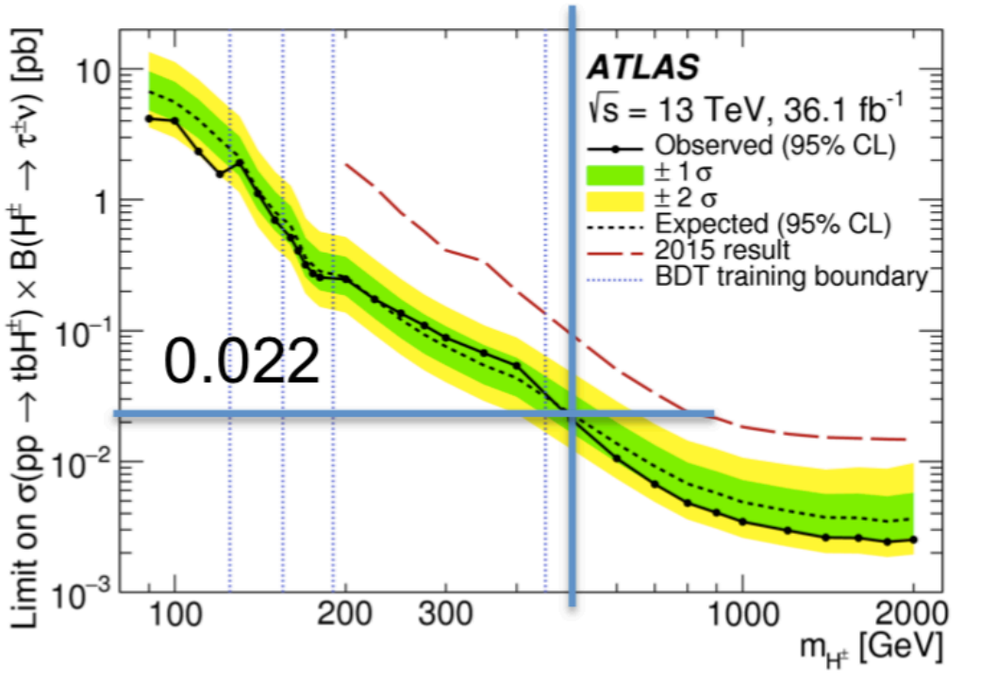




$H^+ \to \tau\nu$







Run-2 limits order of magnitude better than Run-1, even at low mass
=> analyses significantly improved

ATLAS and CMS sensitivity comparable
~same at 90/2000 GeV; 0.03 vs 0.022pb at 500 GeV

First time the new CMS results are shown!

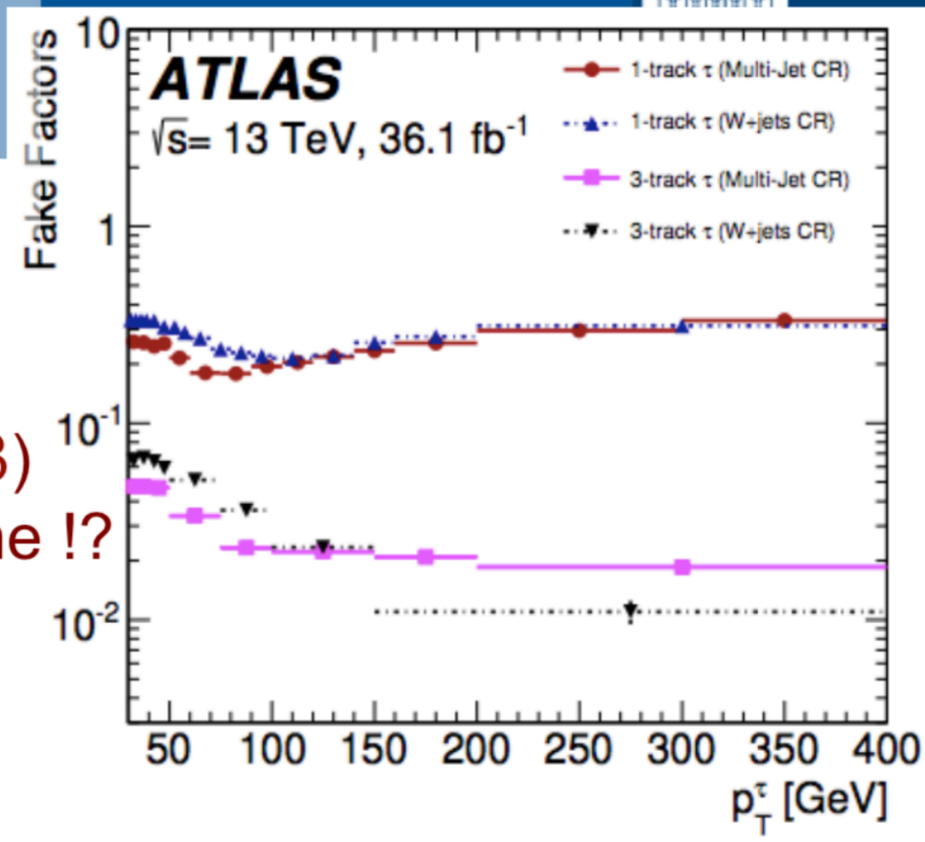
B. Burghgrave, A. Attikis, J. Eysermans

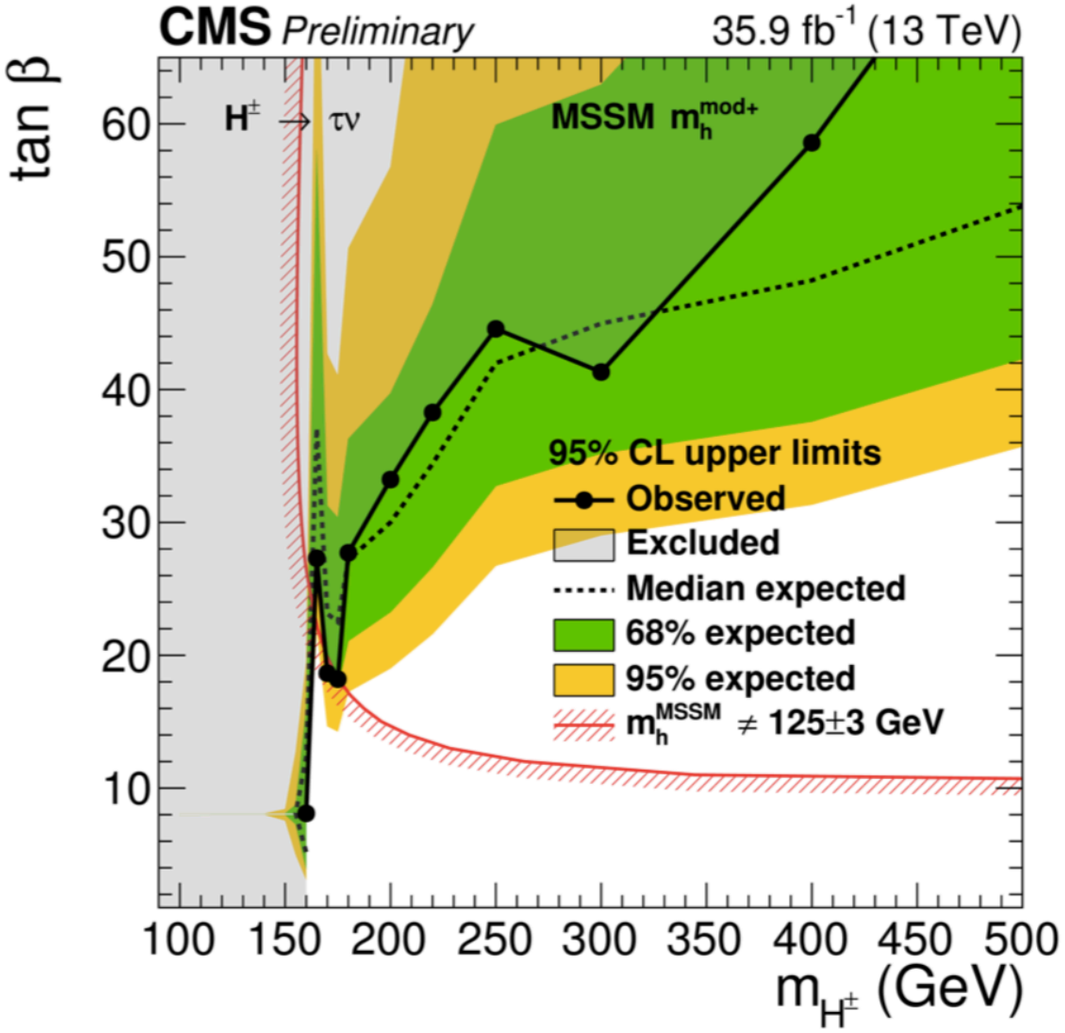
H+→τν: MSSM

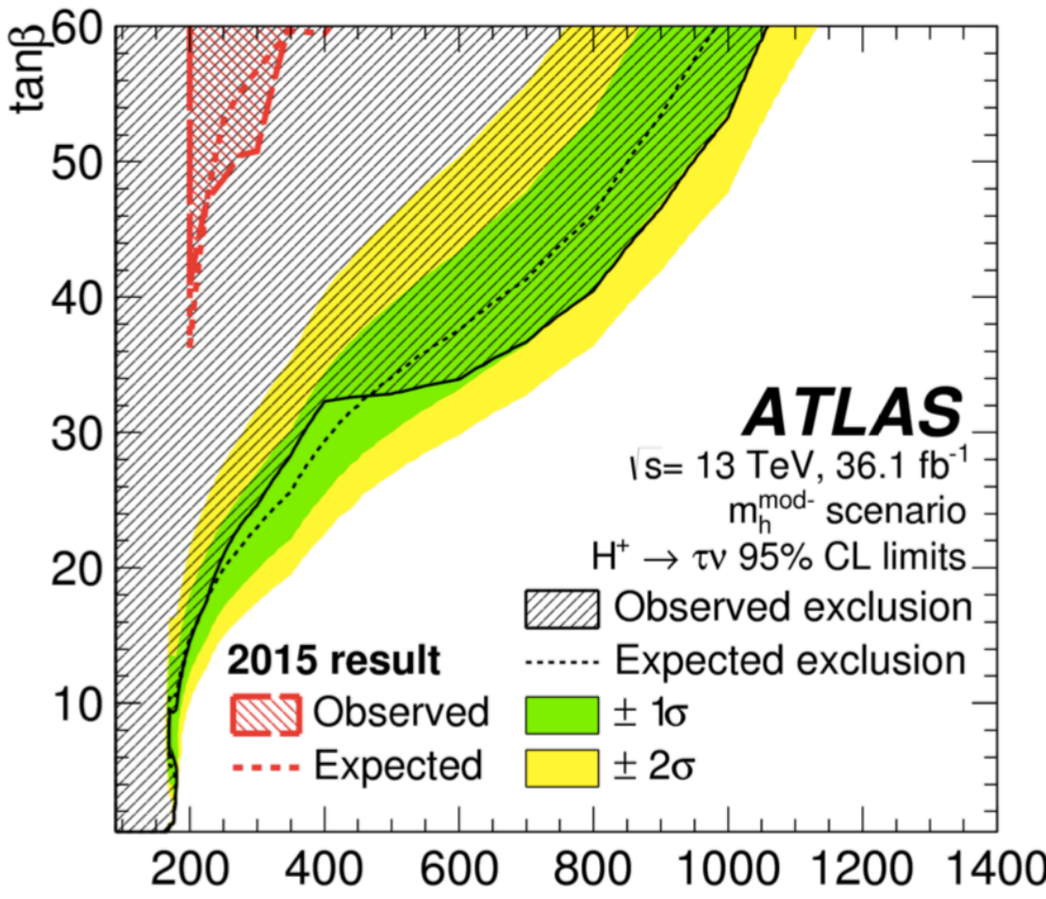
Estimating jet->tau fakes gets very sophisticated true tau: what happened to embedding (Run 1)?

Some observations:

- CMS limit plot abruptly stops at 500 GeV
- 68%/95% expected much wider for CMS
- expected at mH=500 GeV: tan beta=54 vs 35 ($\sigma \sim \tan^2 \beta$)
  =>ATLAS 3x better, but model-independent limits ~same !?
  (see previous slide)







B. Burghgrave, A. Attikis, J. Eysermans, M. Bahmani

H^+ searches beyond 2HDM

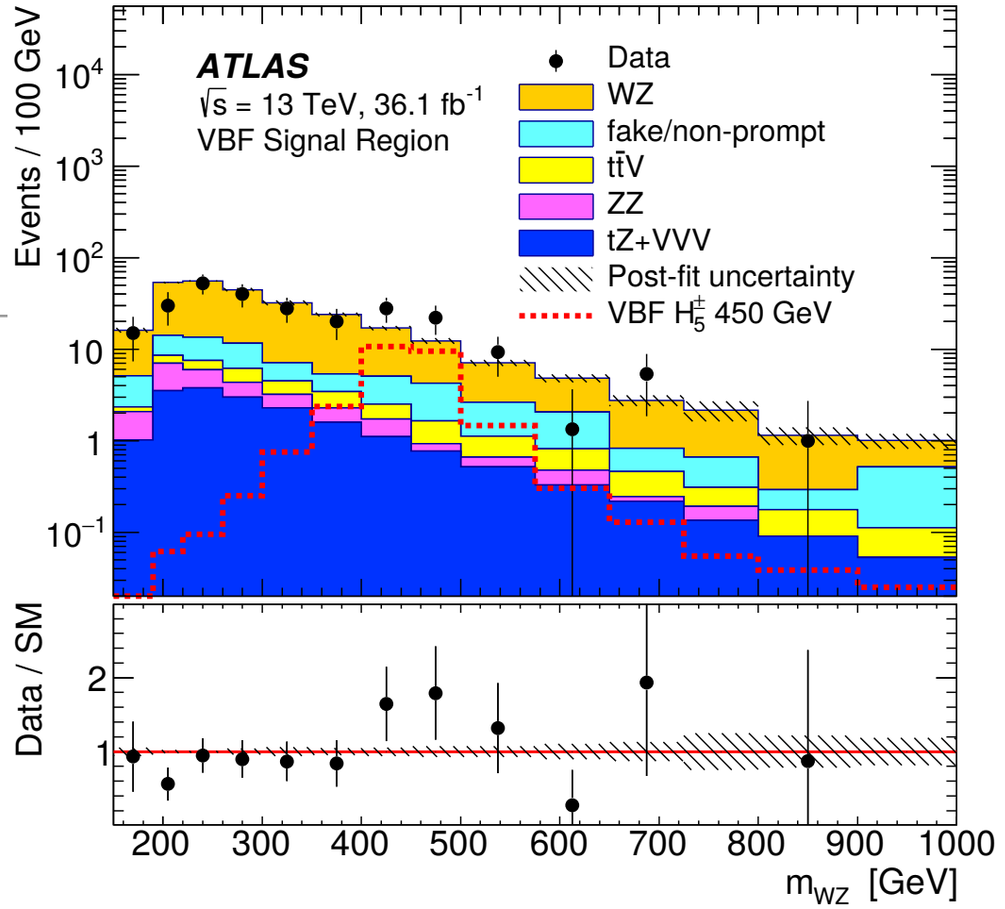
arXiv:1806.01532

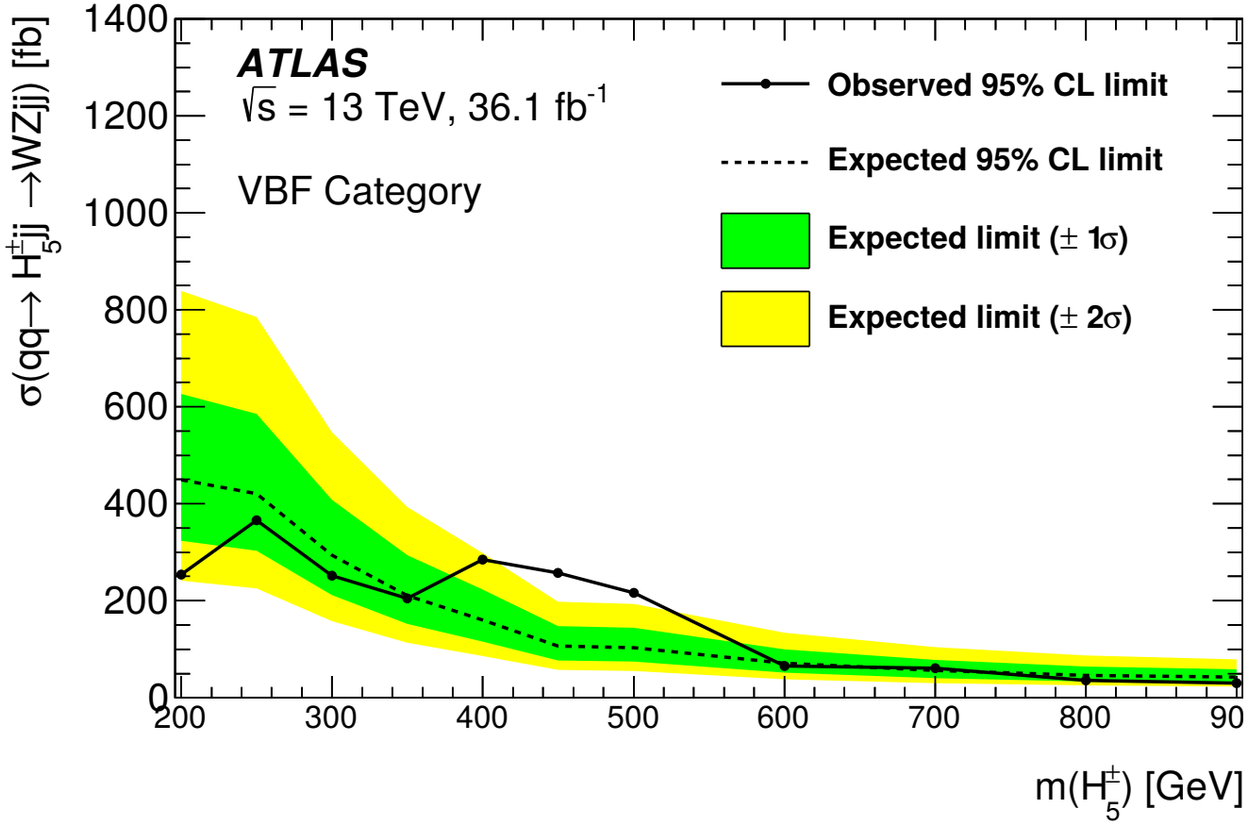
ATLAS

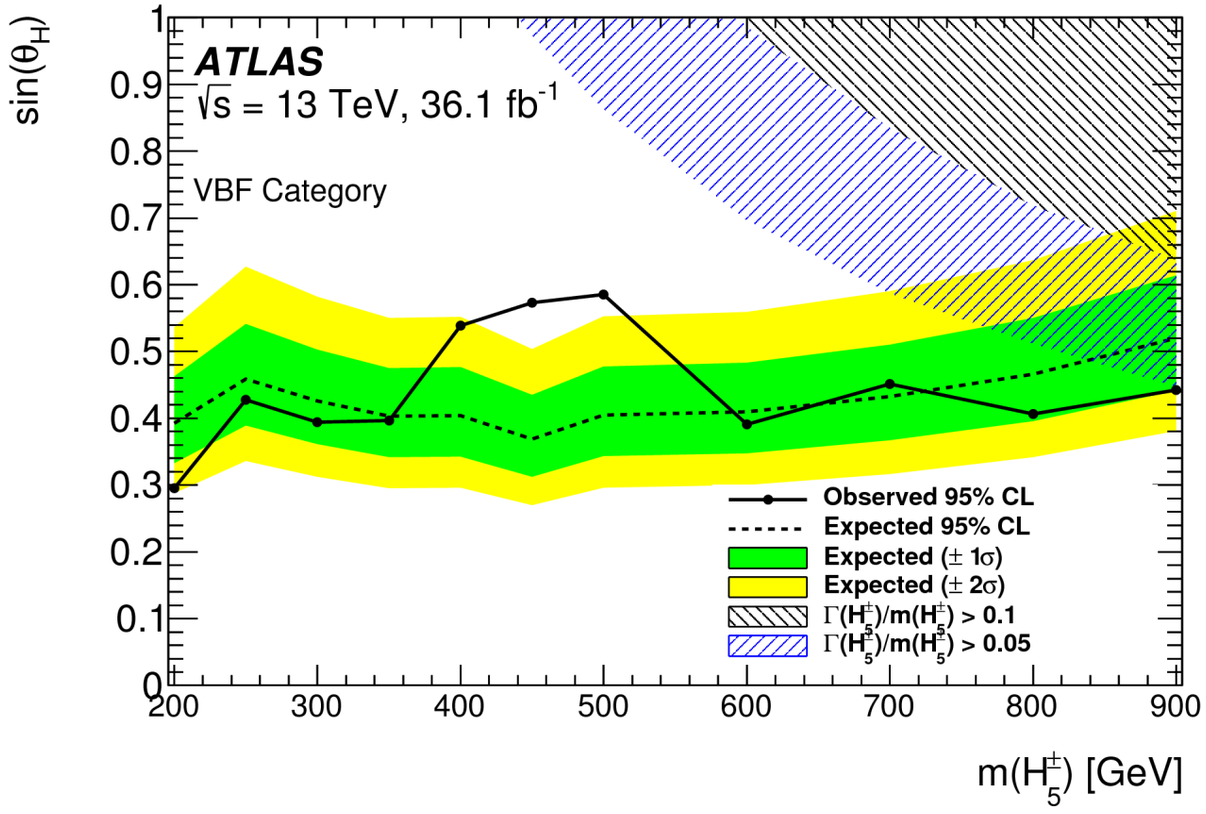
$H^+ \rightarrow WZ$ @ 13 TeV

- WZ → 3leptons & two jets with large $\Delta\eta$
- Constrained fit on M_{WZ}, derived from lepton momenta and MET

$$\sigma(\mathrm{VBF} \to H_5) = s_H^2 \sigma_1(\mathrm{VBF} \to H_5), \quad s_H \equiv \sin\theta_H = \frac{2\sqrt{2}\, v_\chi}{v}$$







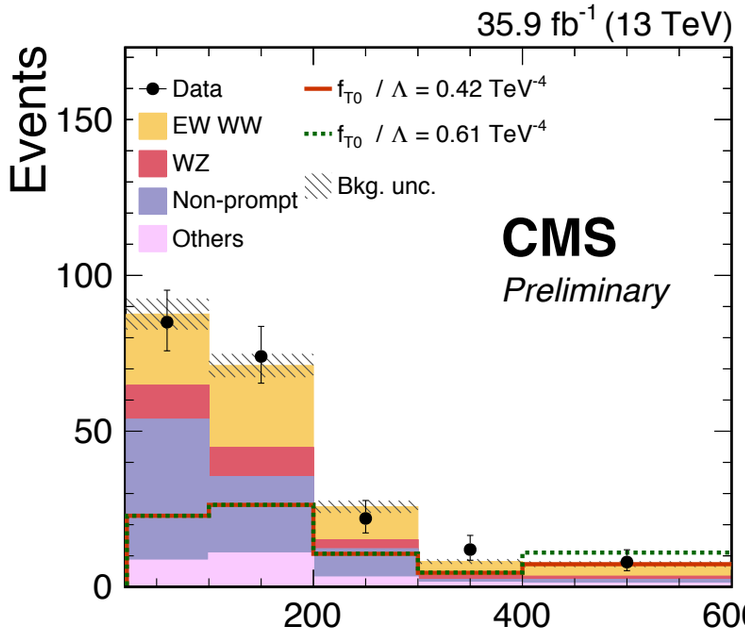
Georgi-Machacek model interpretation

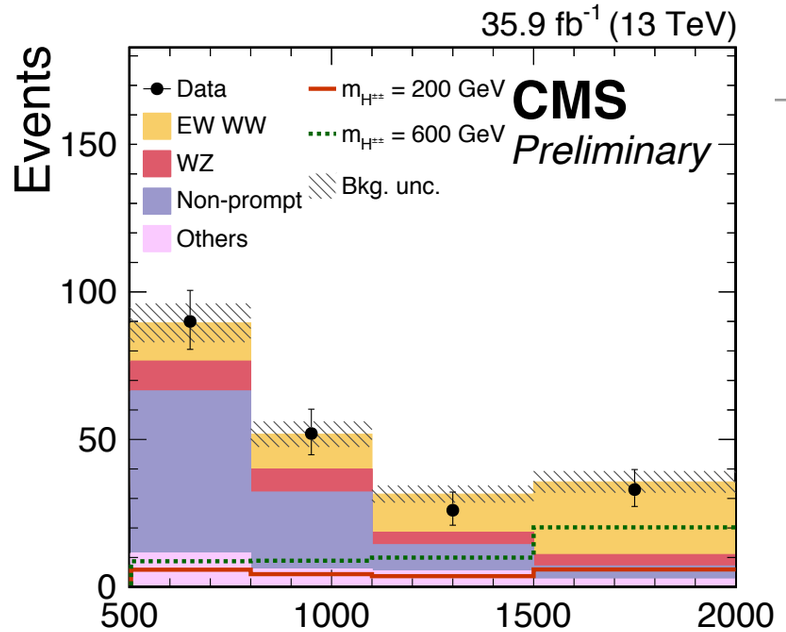
arXiv:1709.05822

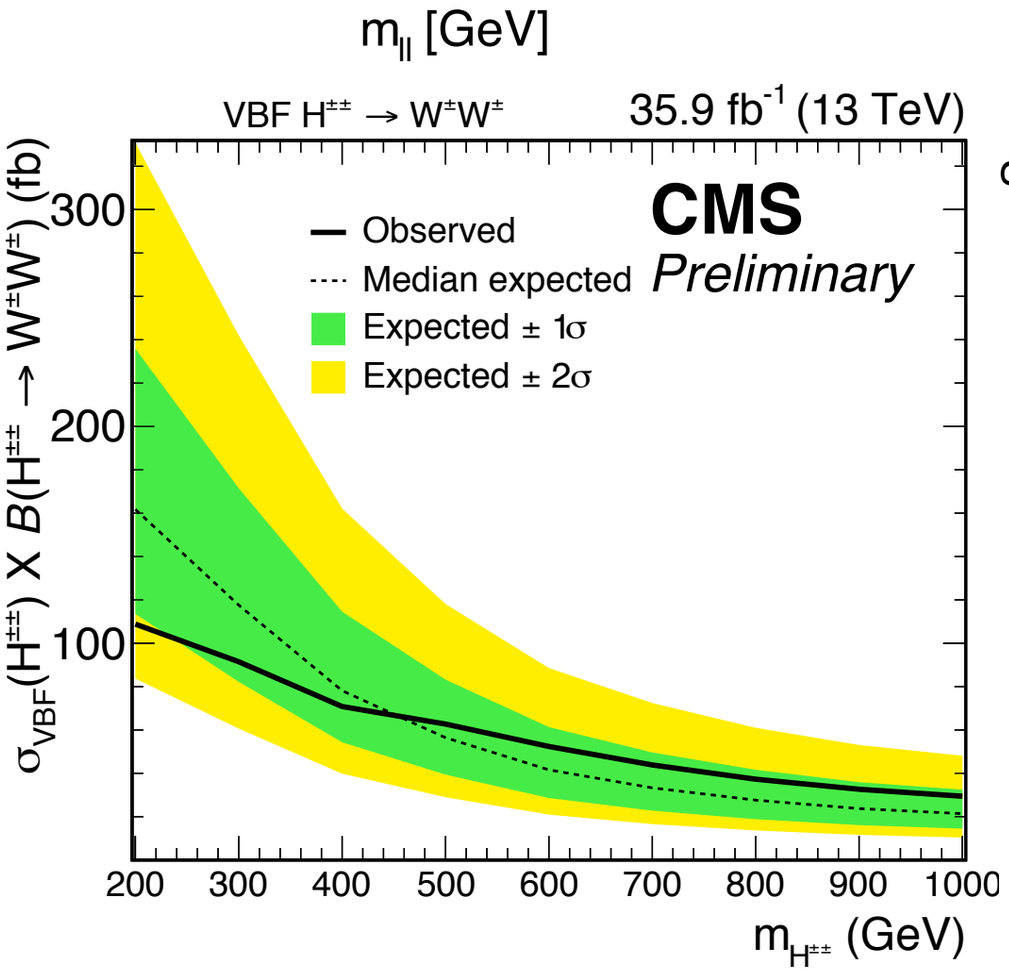
$H^{++} \rightarrow WW$ @ 13 TeV

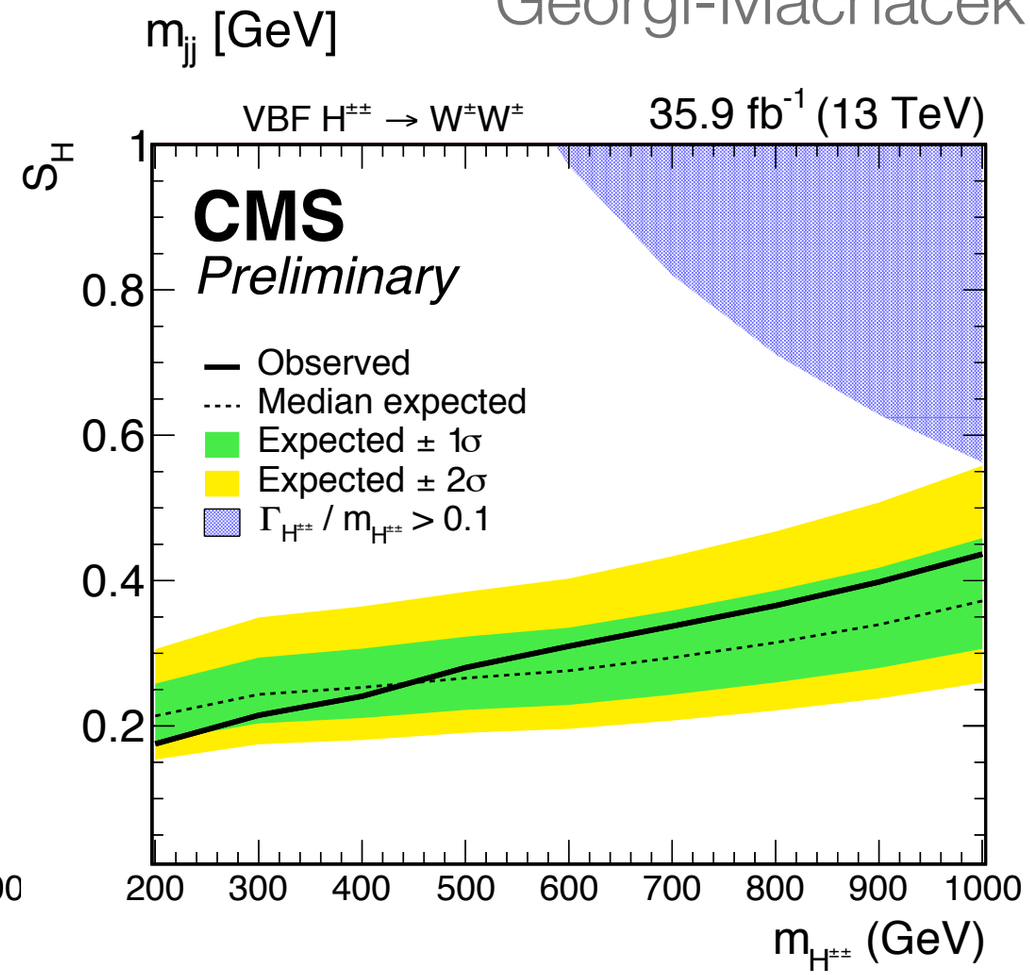
CMS

- Two isolated same-sign leptons, p_T^{miss}>40 GeV, two ak4 jets with large $\Delta\eta$
- Simultaneous fits on m_{ll} & m_{jj} and m_{jj} in WZ control region for H^+ signal extraction
- Limits interpreted in the Georgi-Machacek model





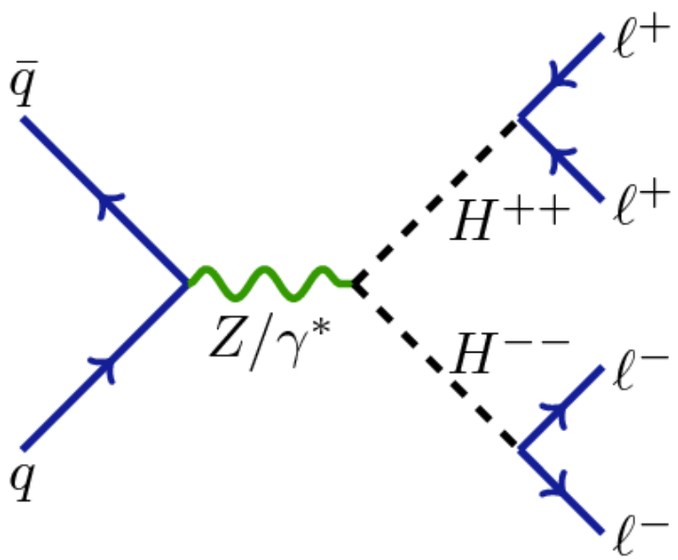




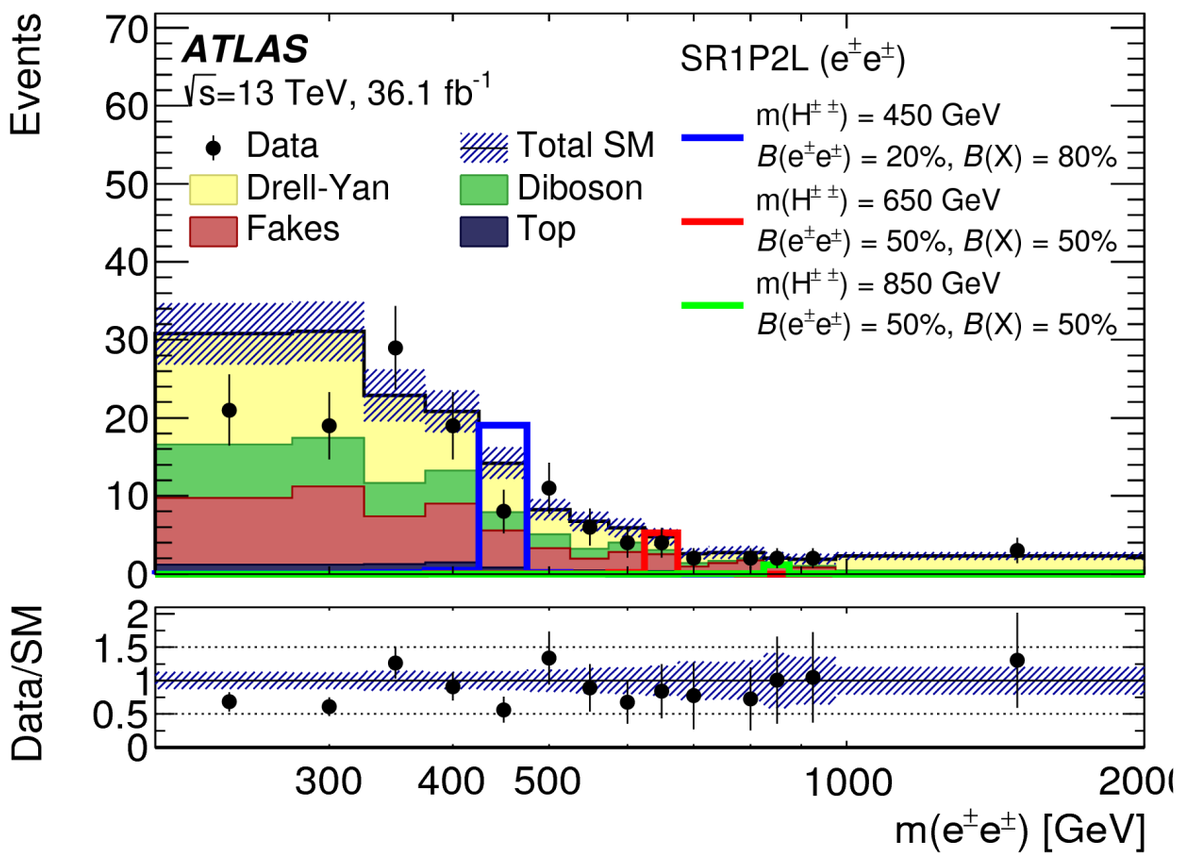
arXiv:1710.09748

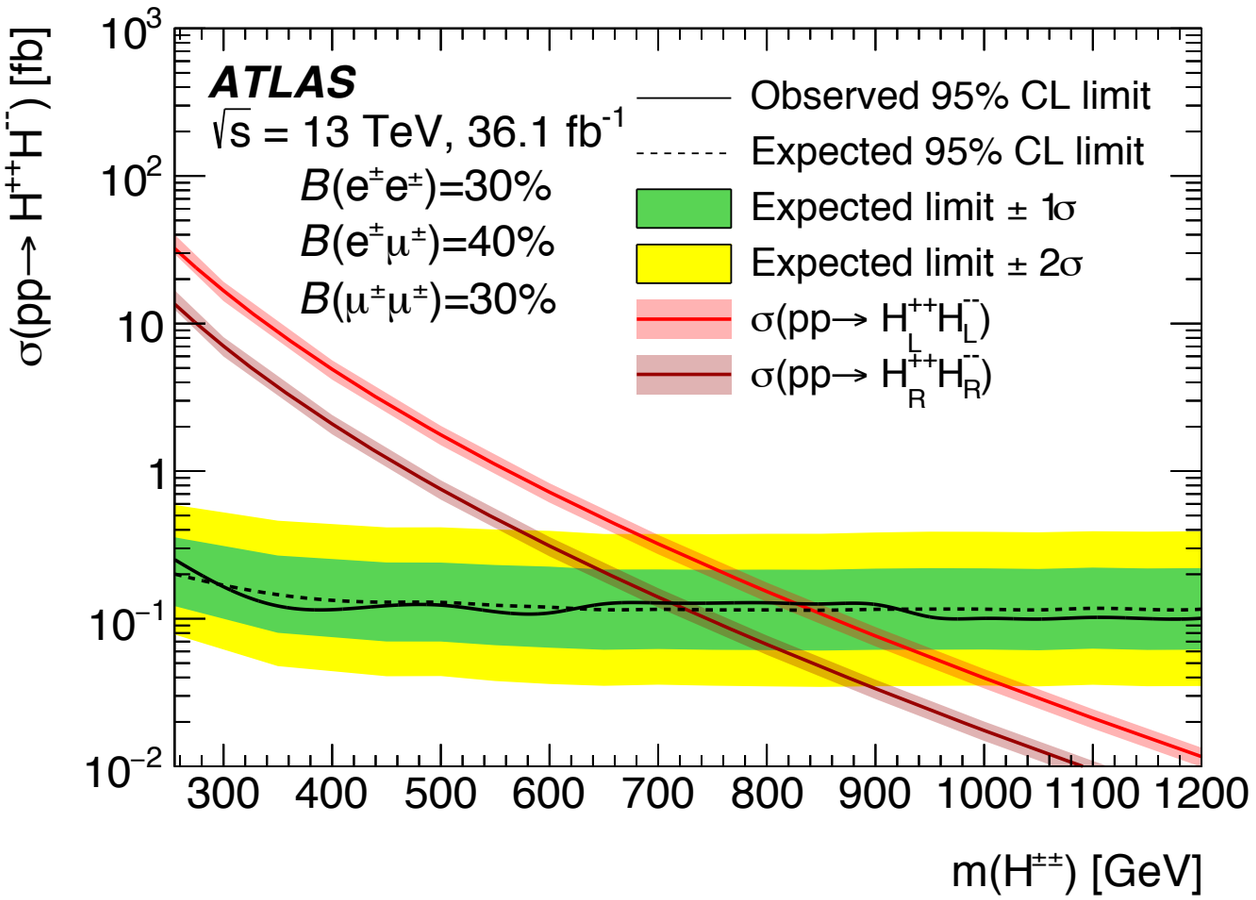
ATLAS

$H^{++}H^{--} \rightarrow l^+l^+l^-l^-$ @ 13 TeV



- Consider doubly charged Higgs pair predicted from a left-right symmetric model with additional triplets
  - targets the lepton decays → set triplet vev to exclude $H^{++} \rightarrow WW$
  - $200 \leq m(H^{\pm\pm}) \leq 1300$ GeV
- Fit on same charge pair distributions for nleptons ≥ 2, $M=(m^{++}+m^{--})/2$ for four leptons



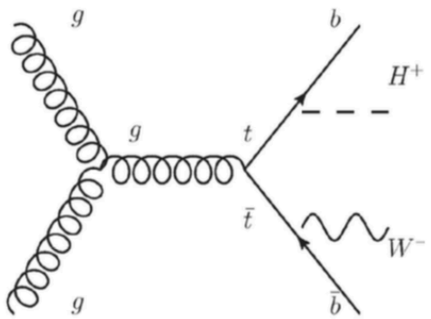


“WANTED" charged Higgs From LHC-Higgs XS WG3

By Jana Schaarschmidt

Production cross section of H^+: Overview of the recommendation

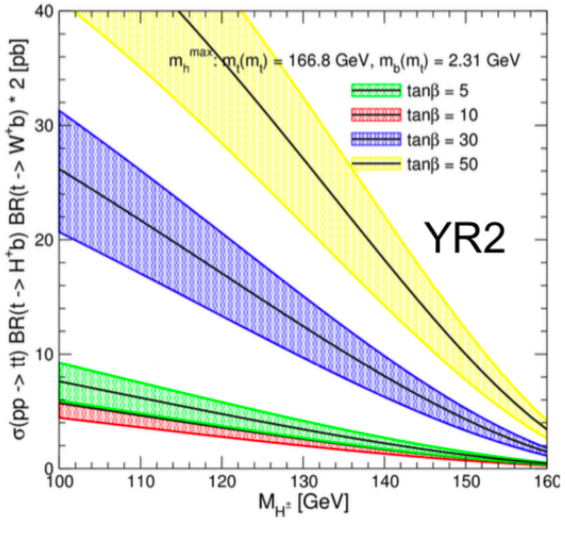
Low mass



$\sigma(pp \rightarrow tt) * BR(t \rightarrow bH^+) * BR(t \rightarrow bW)$

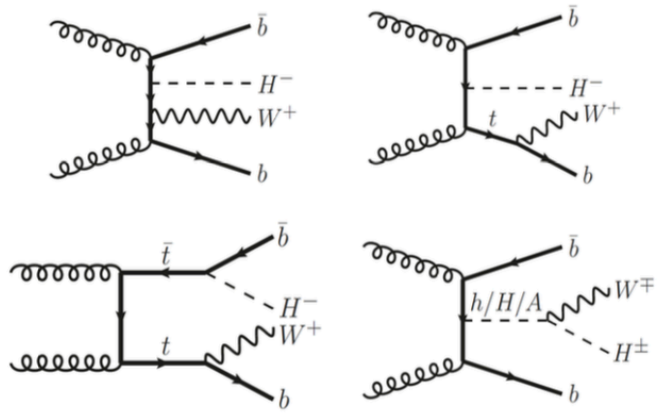
NNLO
PRL 110 (2013)

NLO: Phys. Rev. D76 (2007), hep-ph/9301237
NNLO: eg. hep-ph/9806244

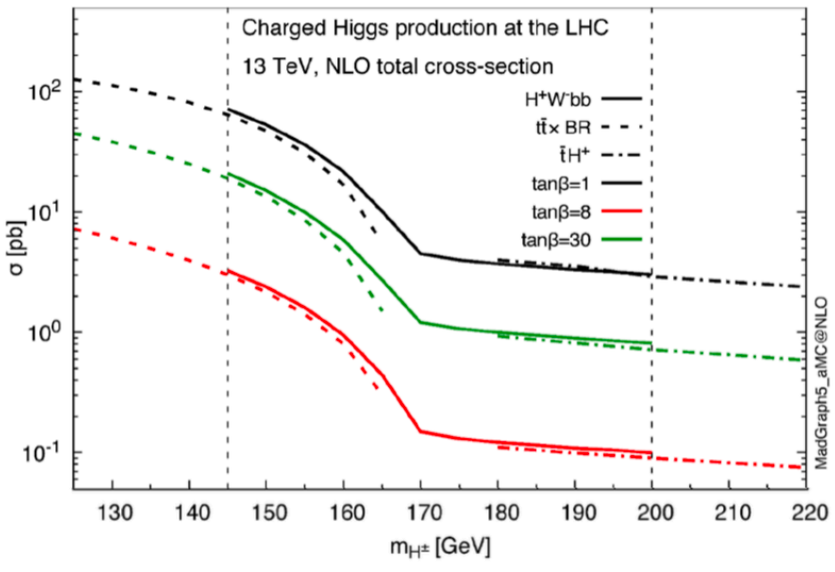


Intermediate mass

NLO $pp \rightarrow H^+W^-bb$

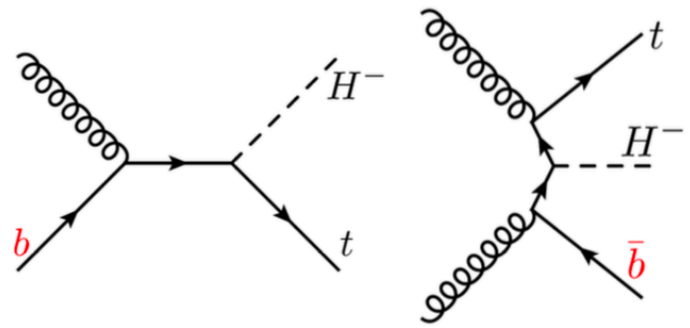


https://arxiv.org/abs/1607.05291

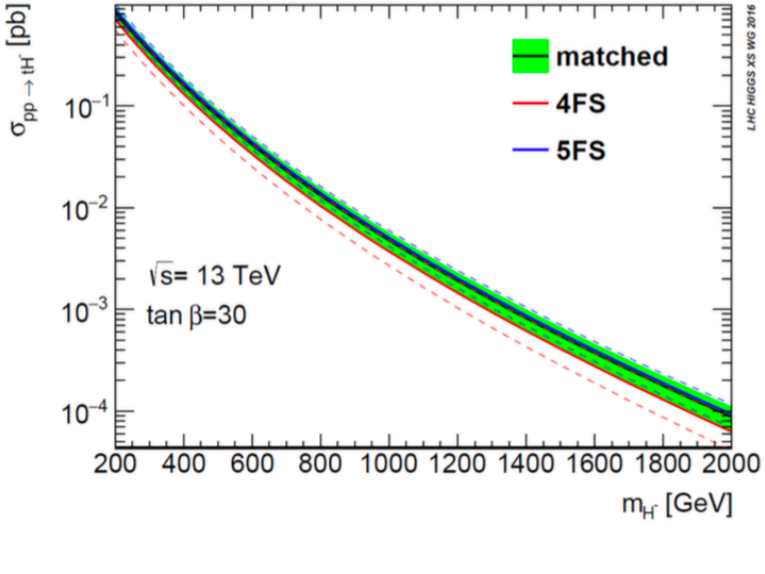


Differential cross sections at LO

High mass

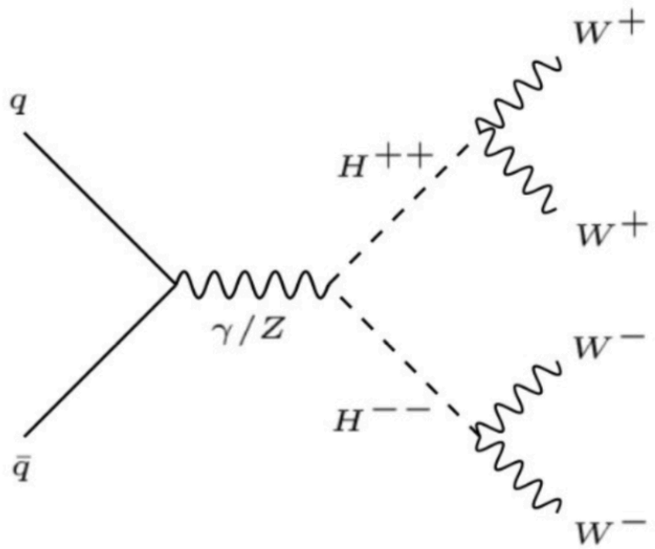


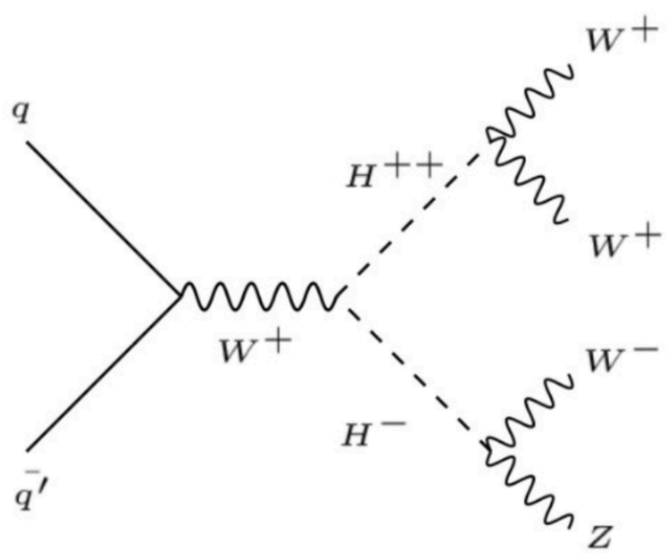
Tools: 4FS: MG5_aMCatNLO,
5FS: Prospino

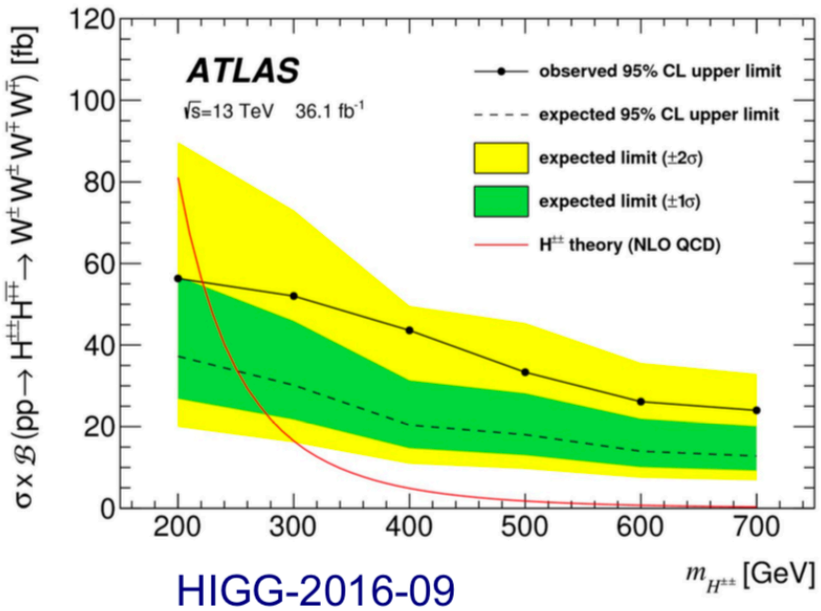


Differential cross sections at NLO

Doubly charged Higgs H++







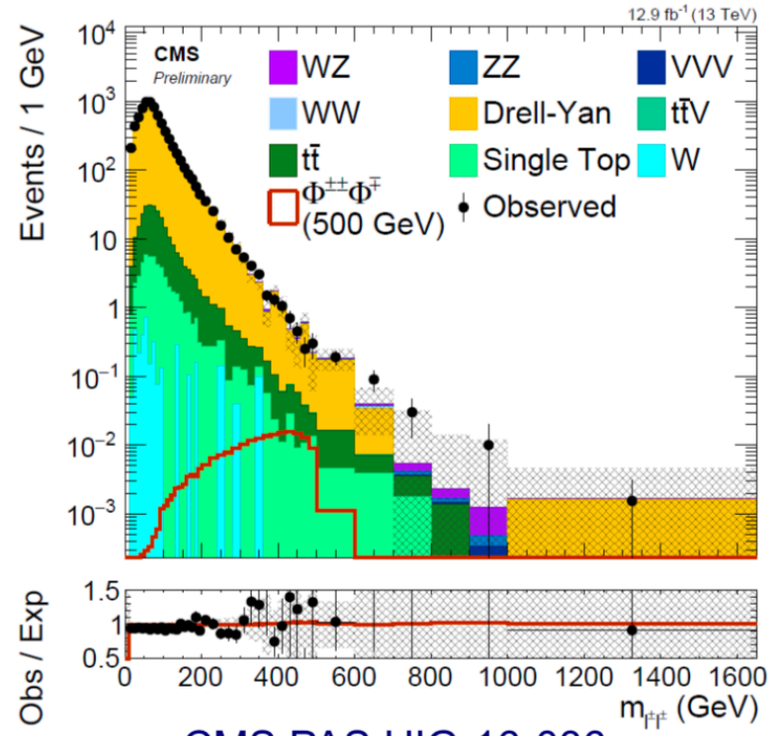
HIGG-2016-09

Recent Activity: (H. Logan et al)

Updated the MadGraph5 model file for doubly-charged Higgs production that can generate
$pp \rightarrow H^{++} H^{--} \rightarrow W^+W^+W^-W^- \rightarrow 8f$ at NLO-QCD

In the process of validating this model.

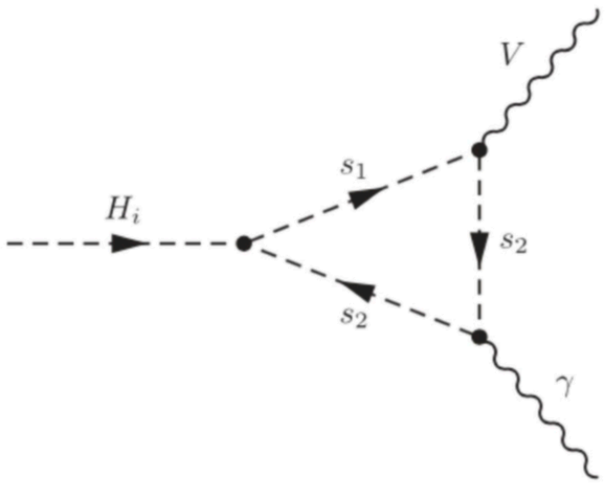
Work ongoing to develop a benchmark in the Georgi-Machacek model for H^{++} masses below 200 GeV, that is consistent with other searches and h(125) measurements.



CMS PAS HIG-16-036

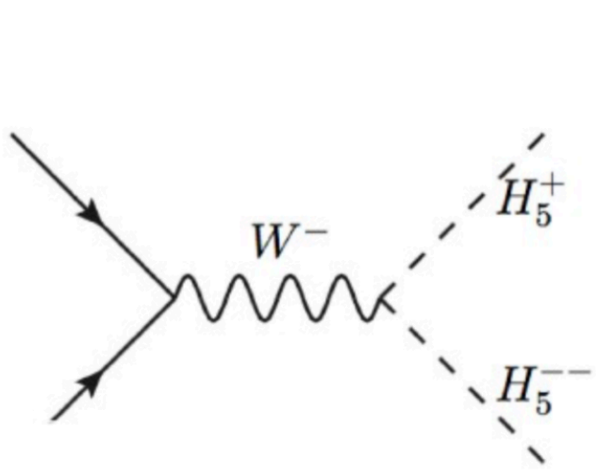
New Channel: $H^+ \rightarrow W\gamma$

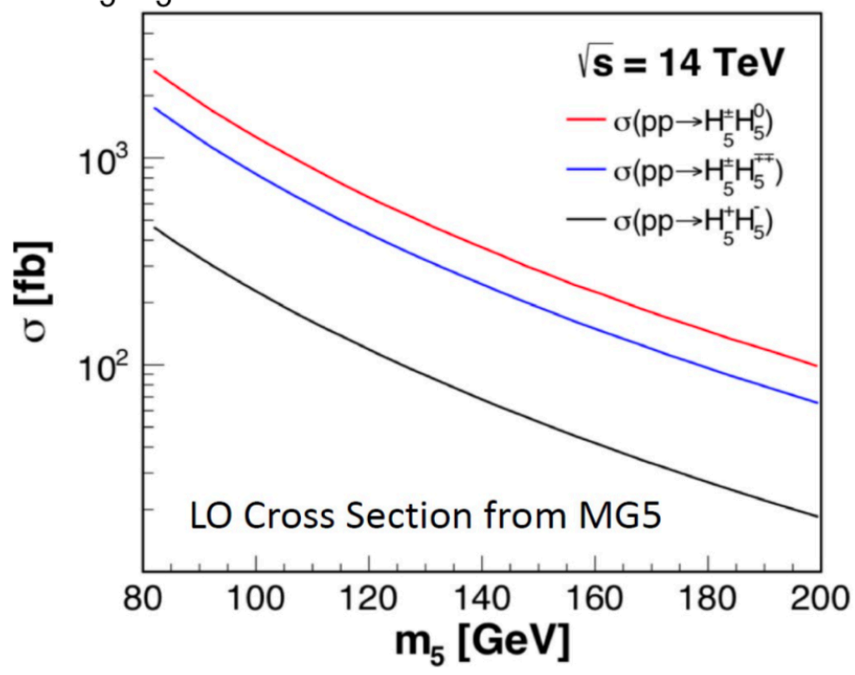
- In the 2HDM, there are no tree couplings of H^+ to WZ or $W\gamma$, but these decays can be induced on 1-loop level (similar to $H \rightarrow \gamma\gamma$, or $H \rightarrow Z\gamma$), BR ~ 10^{-3}
- In Higgs Triplett models these decays can occur on tree level → large cross sections
- Recent studies in GM model → See talk by Heather Logan at this workshop (on Wednesday)!



Dominant decay in fermiophobic models
Not searched for by LHC

Drell-Yan production $pp \rightarrow H_5 H_5$:



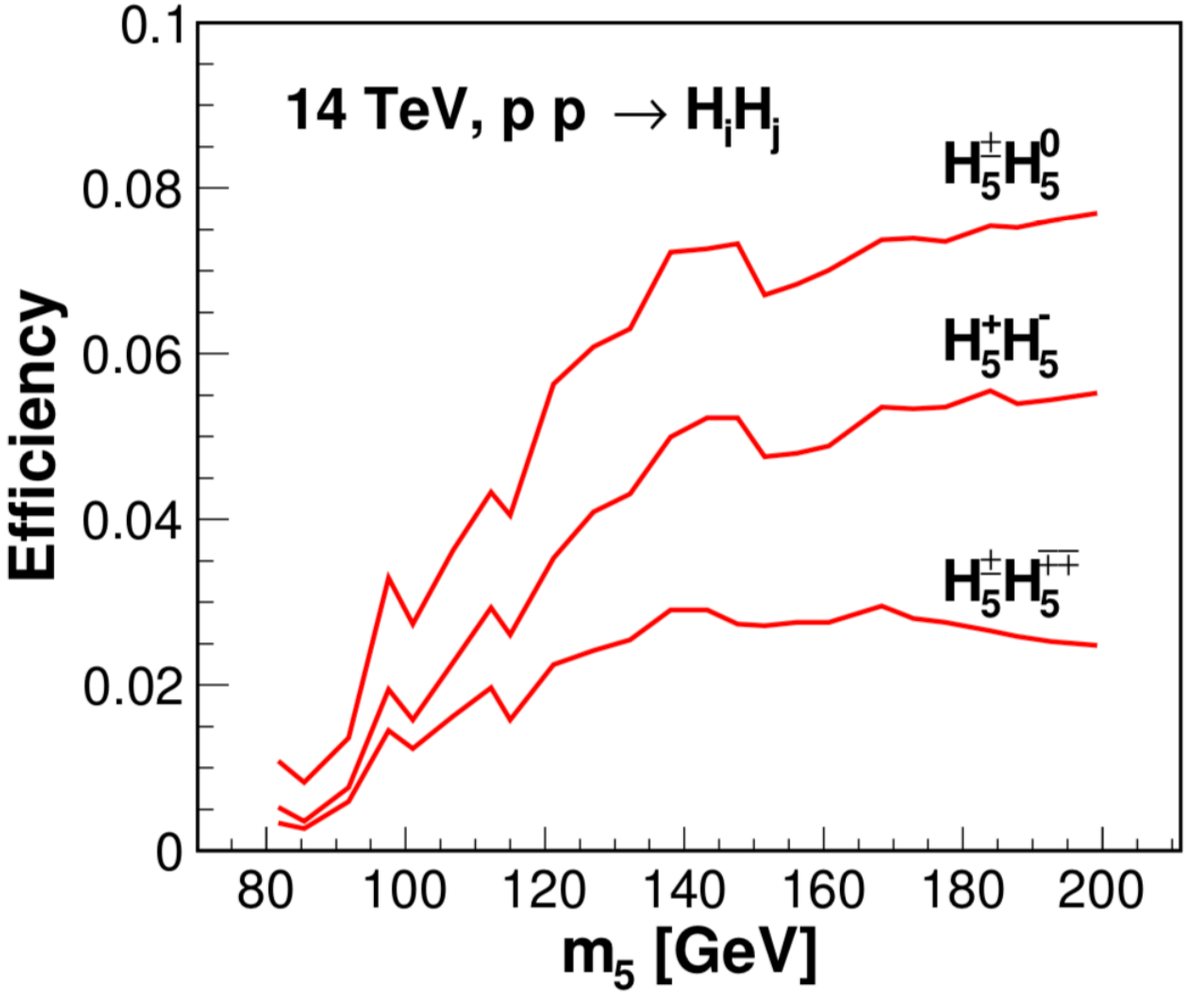


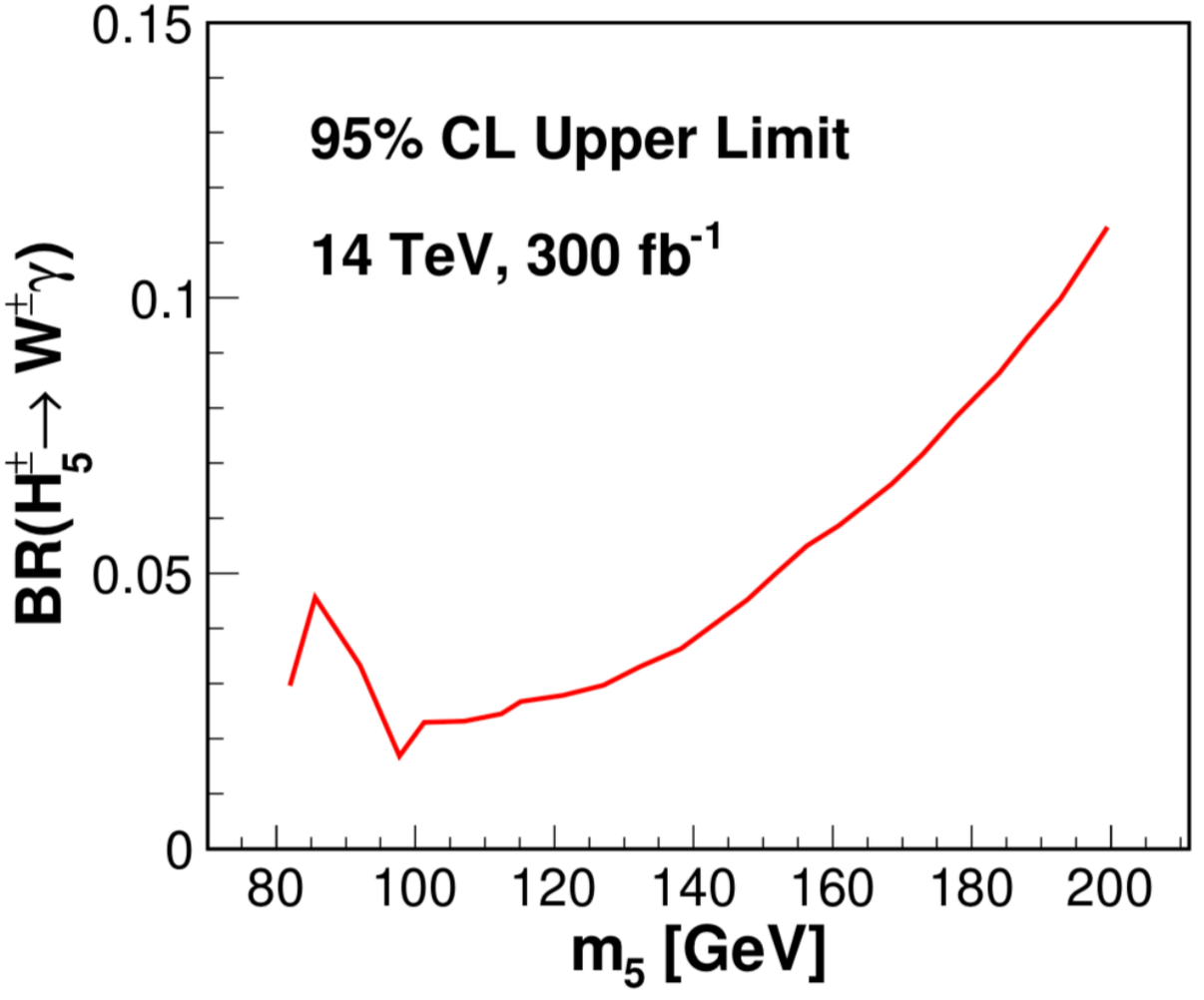
- Also potential other models: eg. „Stealth Model“ https://arxiv.org/abs/1311.4367
  Two scalar doublets and broken Z_2 symmetry (generalized Inert Doublet Model),
  one doublet is the Higgs doublet and provides EWSB, the other doublet is fermiophobic.

New Channel: $H^+ \rightarrow W\gamma$

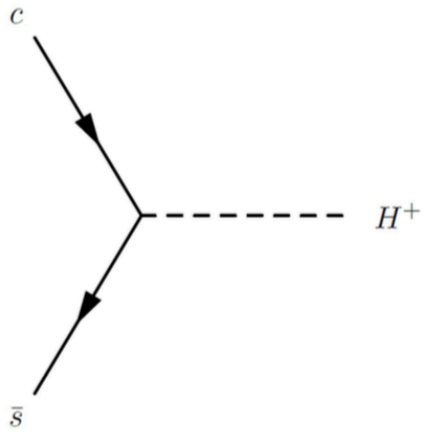
- Preliminary result by studying Delphes simulation sample
- Backgrounds: Wγ, ttγ, WWγ, WW$\gamma\gamma$, W$\gamma\gamma$, WZγ
- Analysis cuts: ≥1 lepton, ≥1 photon, ≤2 jets, 0 b-jets, MET, H_T, p_T(lepton+γ+MET), $p_{lep} \cdot q$ in fiducial region

Production of H^+





New Channel: s-channel production



s-channel production

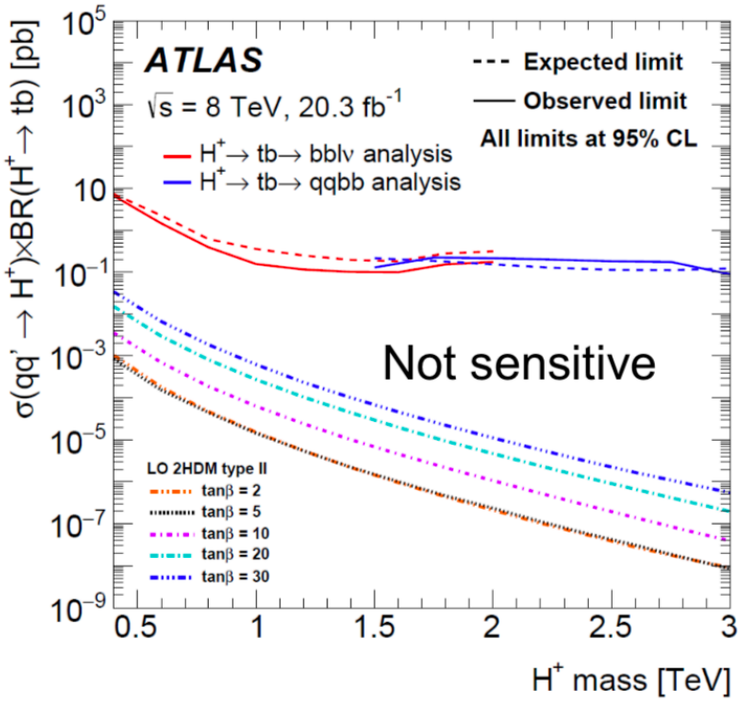
No associated top → easier from the experimental point of view:
- Mass reconstruction,
- background reduction
- can profit from W ' searches

8 TeV LO σ* BR ($H^+ \to tb$) for type-II 2HDM:

Computed using MG5 + NLOCT (1406.3030)

m_{H^+} [GeV]		tan β 0.5	1	2	10	20	30	50
400	σ × BR [fb]	14	3.8	1.1	3.6	15	34	94
	Γ [GeV]	60	15	3.8	0.72	2.3	5.2	14
800	σ × BR [fb]	0.72	0.17	0.047	0.19	0.82	1.9	5.3
	Γ [GeV]	140	36	9.0	1.6	5.2	11	32
1000	σ × BR [fb]	0.24	0.055	0.015	0.063	0.28	0.63	1.8
	Γ [GeV]	145	80	11	2	6.4	14	39
1600	σ × BR [ab]	23	3.9	0.96	4.6	20	47	140
	Γ [GeV]	280	69	17	3.1	9.9	22	61
2000	σ × BR [ab]	6.9	0.96	0.21	1.1	4.7	11	36
	Γ [GeV]	340	85	21	3.8	12	27	74
3000	σ × BR [ab]	0.89	0.07	0.0088	0.039	0.20	0.55	2.5
	Γ [GeV]	490	120	31	5.5	17	39	110

Recasting W'→tb to H^+:



HIGG-2013-28

At tanβ=50 1 TeV, only factor 1.5 smaller than tH^+ x-sec

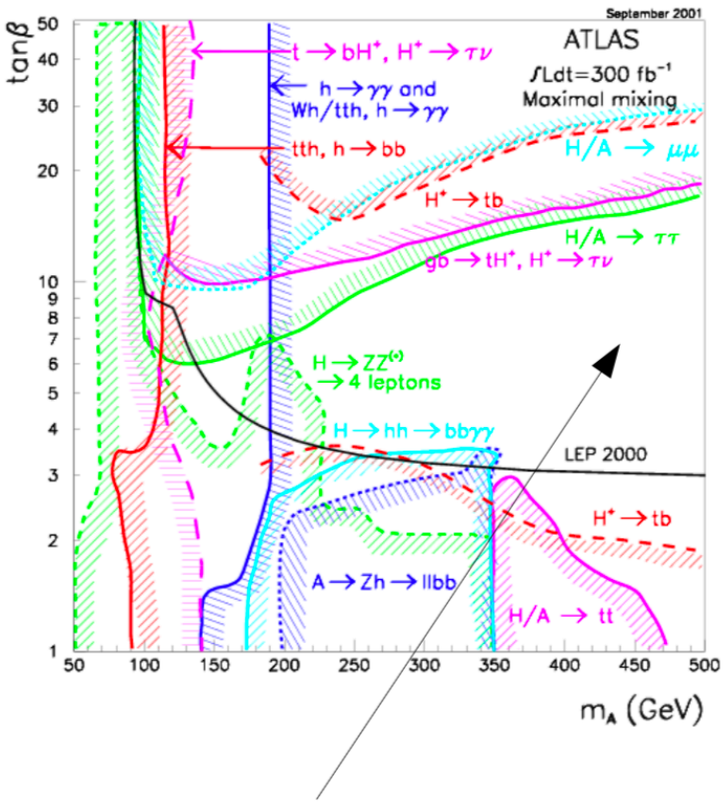
H^+ width becomes very large for low tanβ and high mass

Goal is to get official recommendation, but no progress due to lack of interests from the experiments (?)

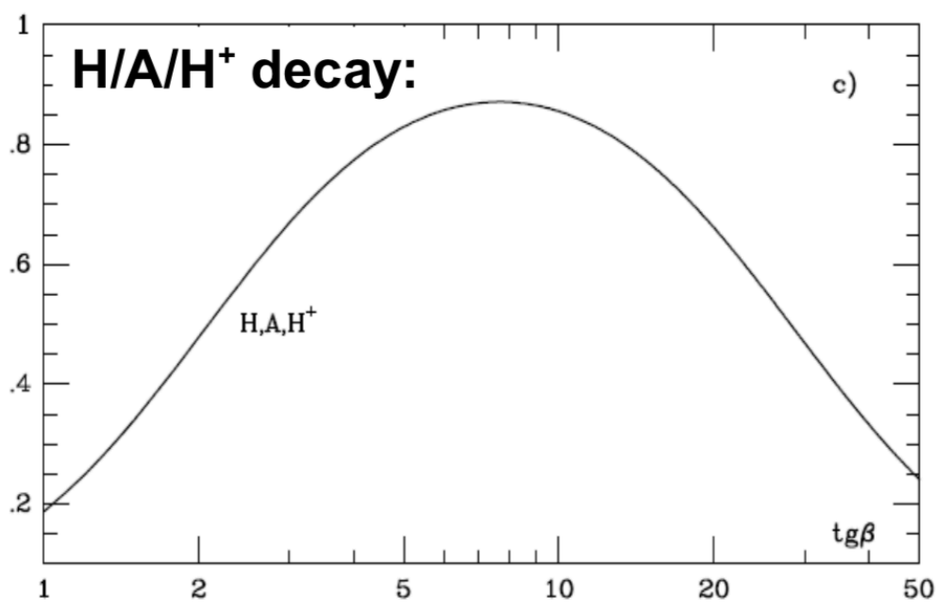
MSSM: Higgs to SUSY

Theoretical wok ongoing from S. Gori, B. Shakya and Z. Liu, to point out new possible searches for electroweak SUSY particles produced from MSSM heavy Higgs decays, ie. H → neutralinos, H → staus

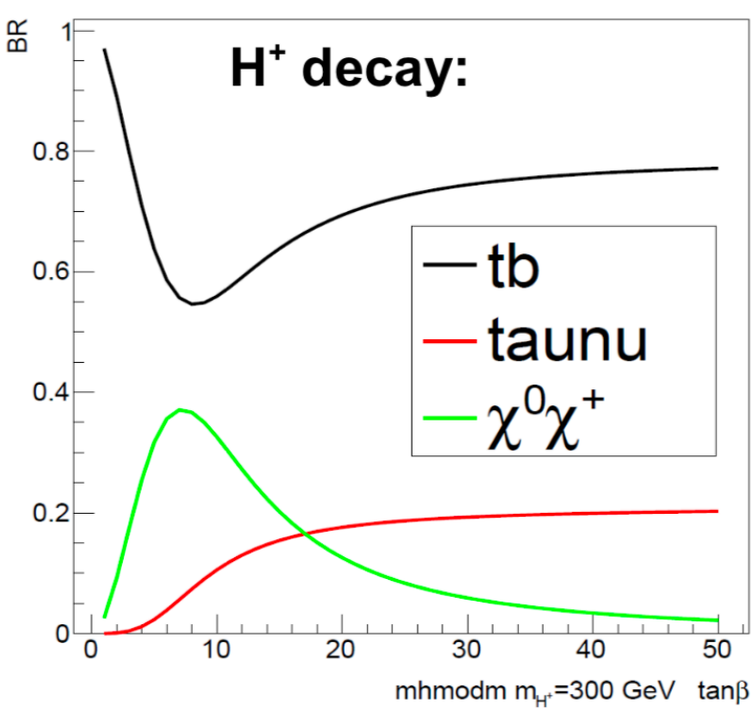
Paper coming soon!



How to cover the wedge?



Djouadi: https://cds.cern.ch/record/340786

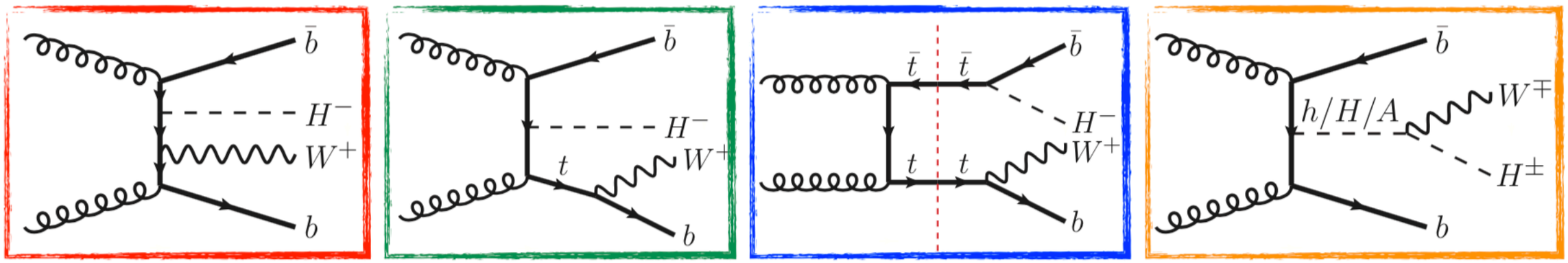


Issues?

H^+ in the intermediate region

-SUSY models where the 125 GeV Higgs is the heavy H boson can have the charged Higgs in the intermediate-mass region (arXiv: 1608.00638)
-In some of these models the light Higgs can act as a mediator to DM (arXiv:1608.06945)

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

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

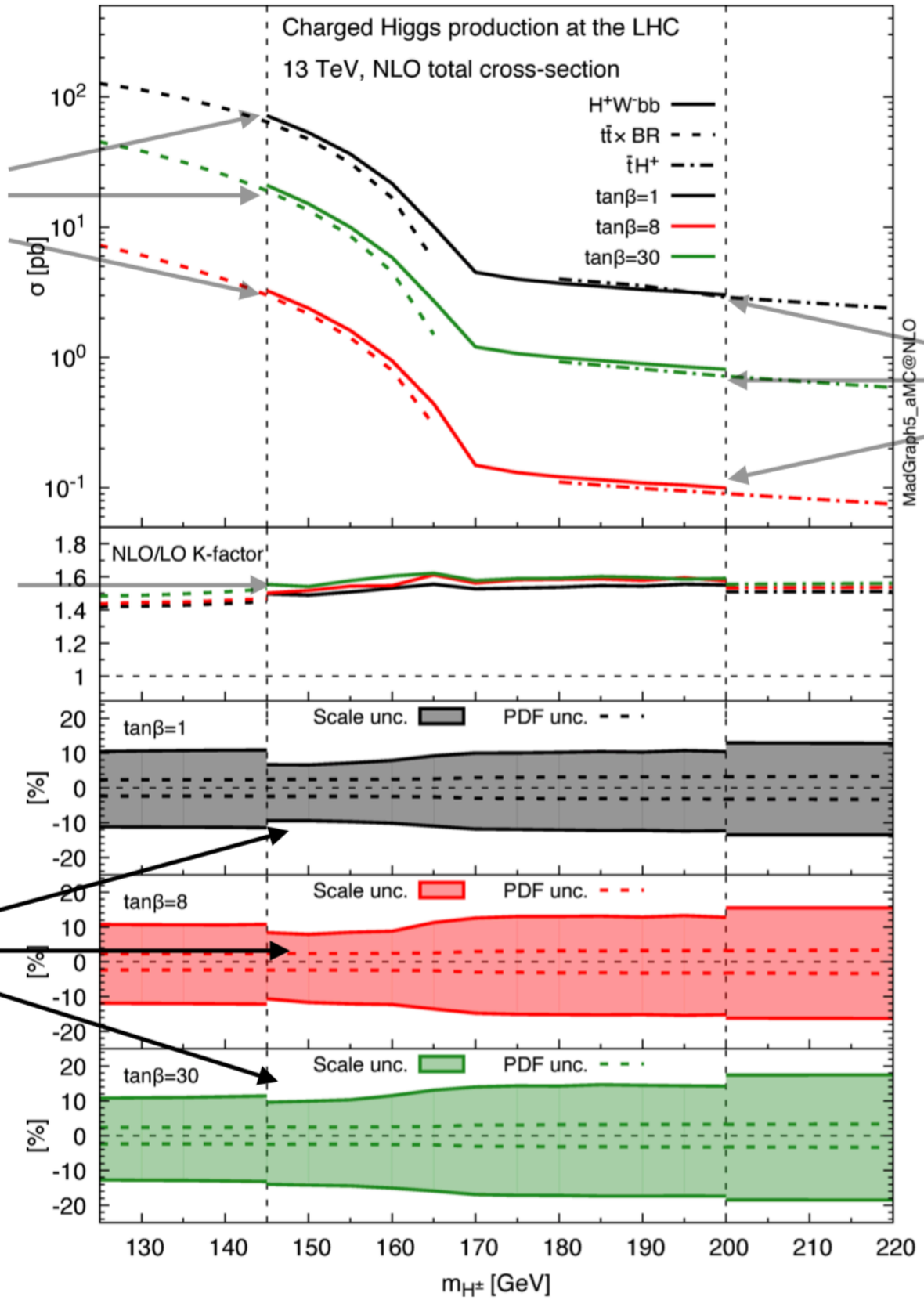
by Marco Zaro

Xsec calculation for intermediate mass

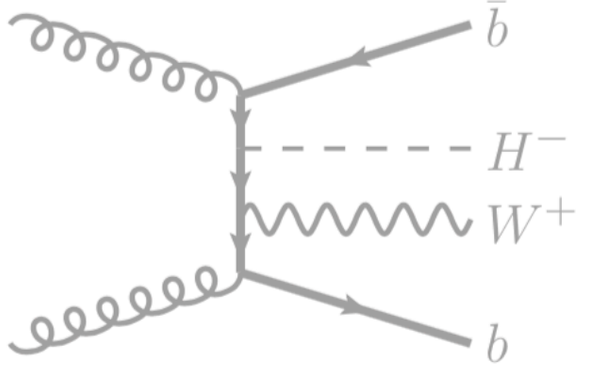
Discontinuity due to single-resonant contributions ($tW^{\pm}$ and $tH^{\pm}$)

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)



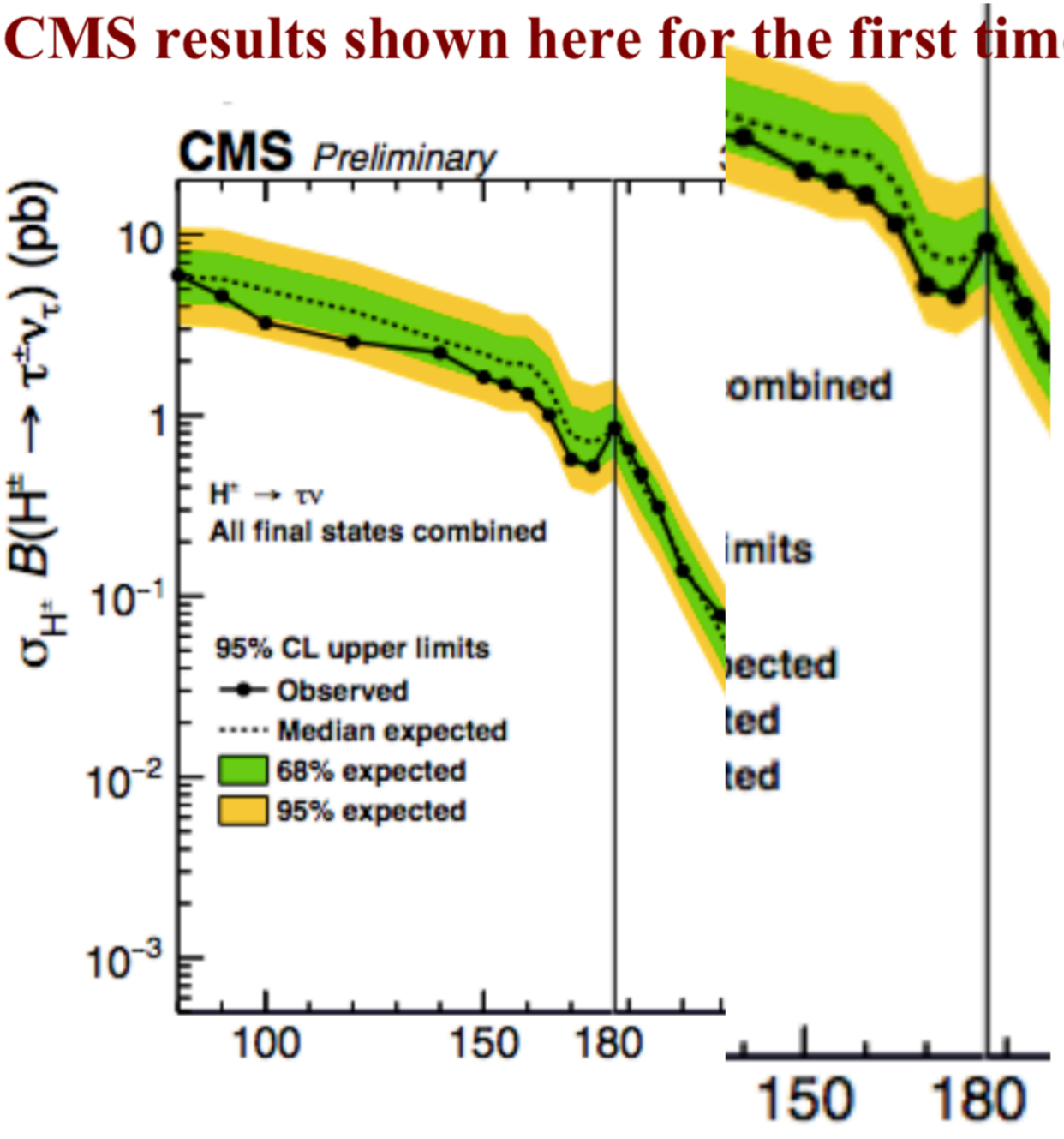
Discontinuity due to non-resonant contributions. Size of discontinuity is $\tan\beta$ dependent because of chiral couplings

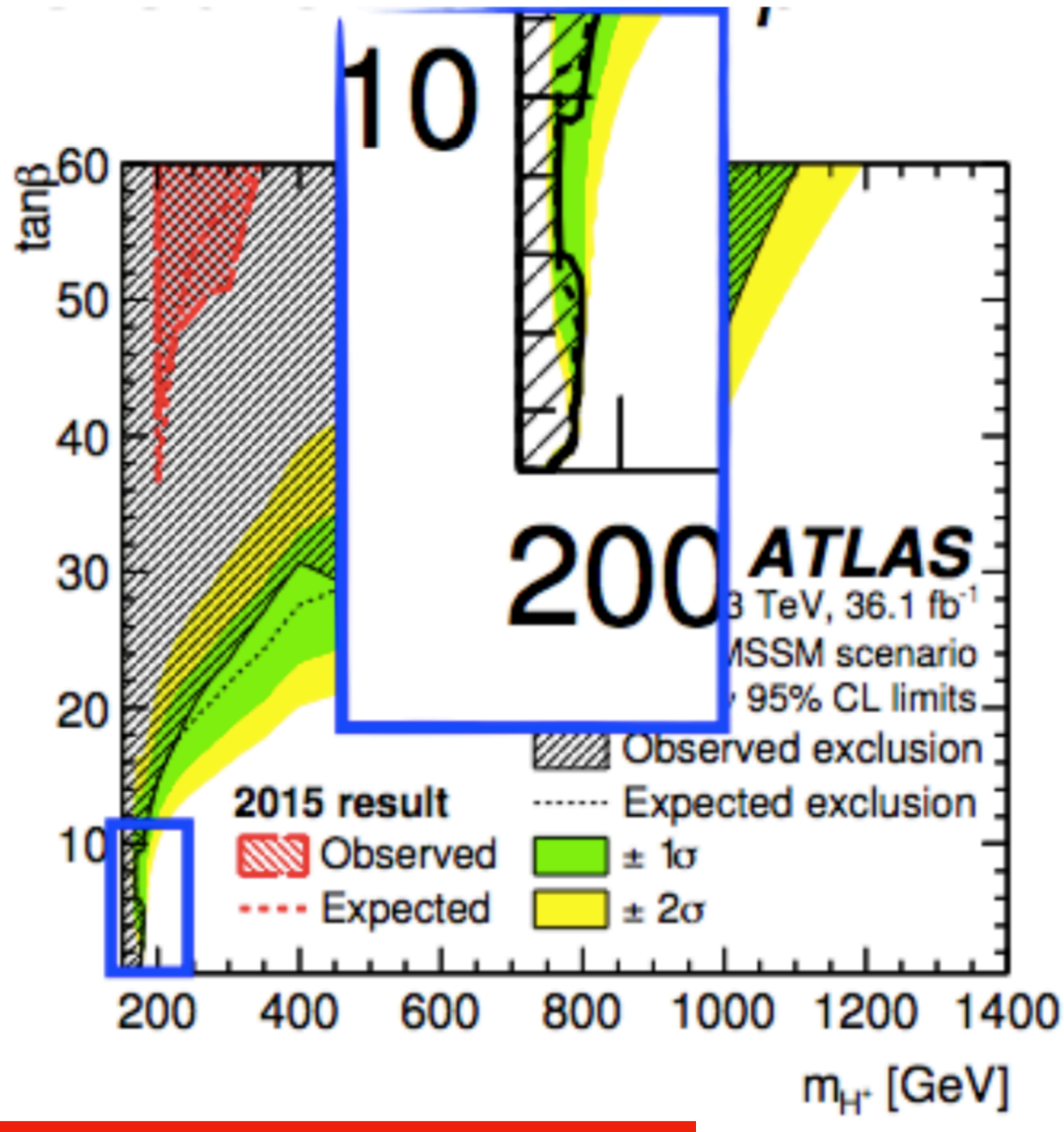


by Marco Zaro

From theory to experiment

Intermediate-range cross sections immediately (well, almost) picked up by experiments – the gap is closed
CMS results shown here for the first time



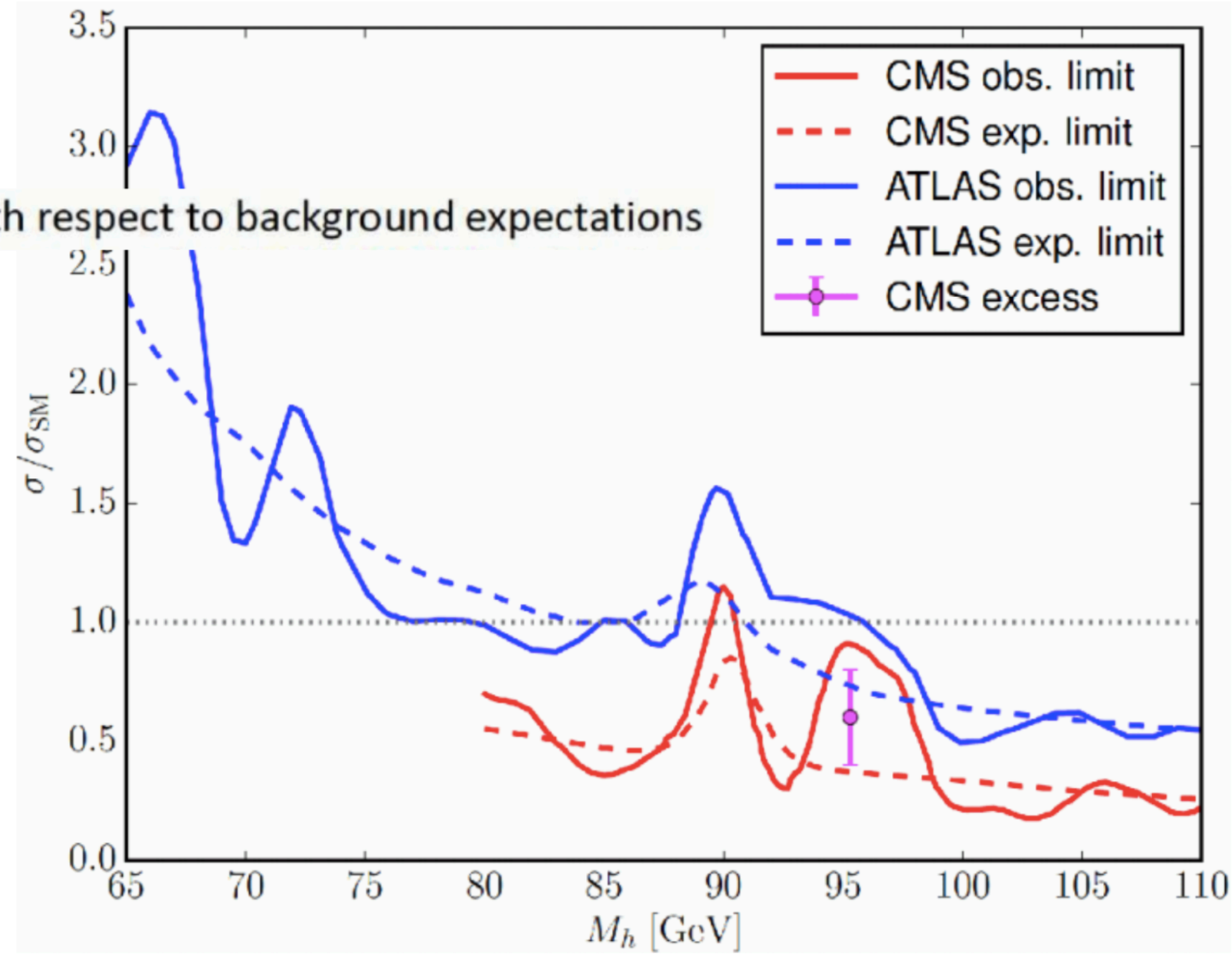


ATLAS (CMS) excluded all tanβ with m(H+)<160 (150) GeV in MSSM m_h^{mod+} scenario

A Higgs boson with m=95 GeV?

Should we get excited?
- Sven H.: Maybe…
- experiments:

- **No significant excess** with respect to background expectations

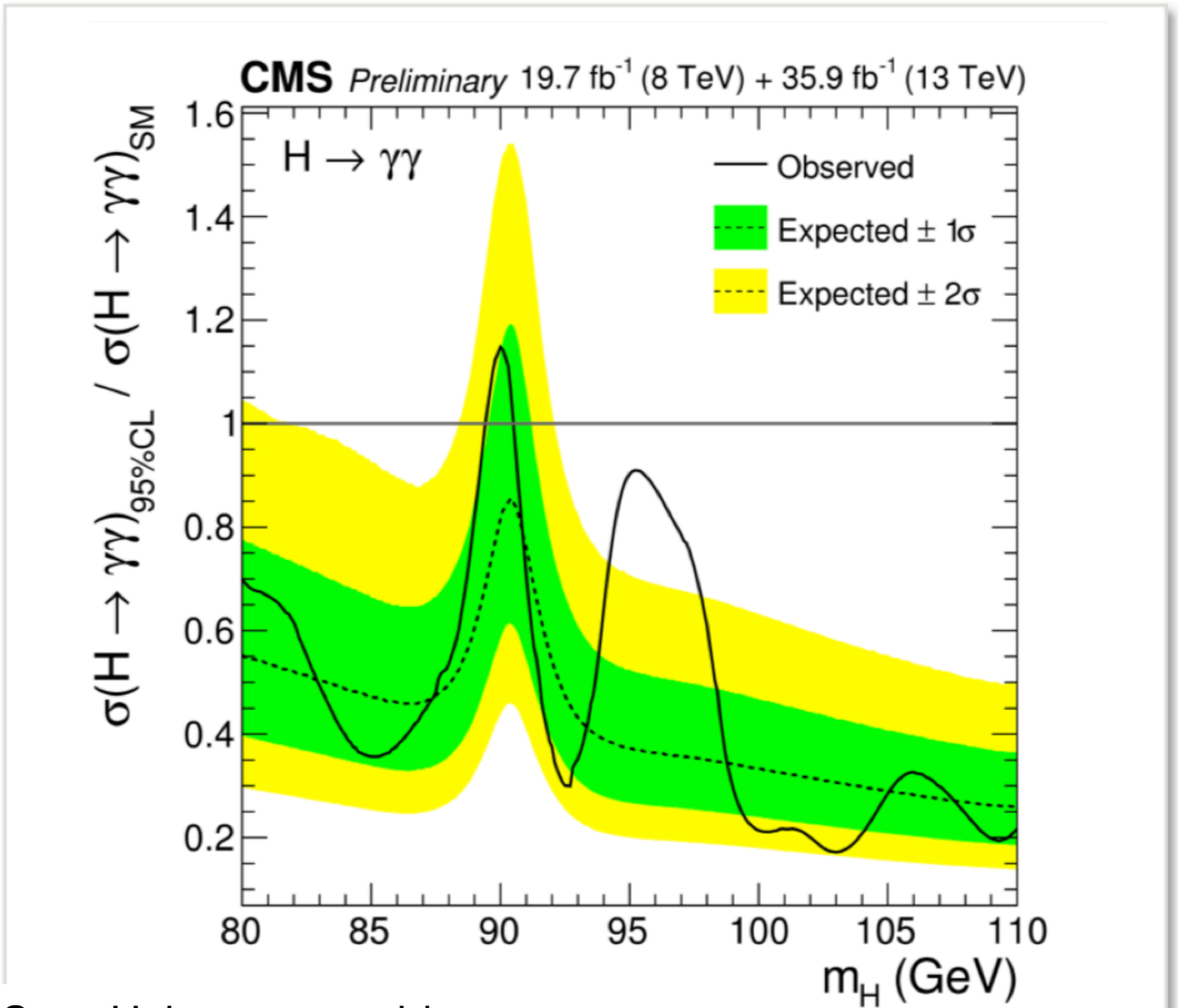


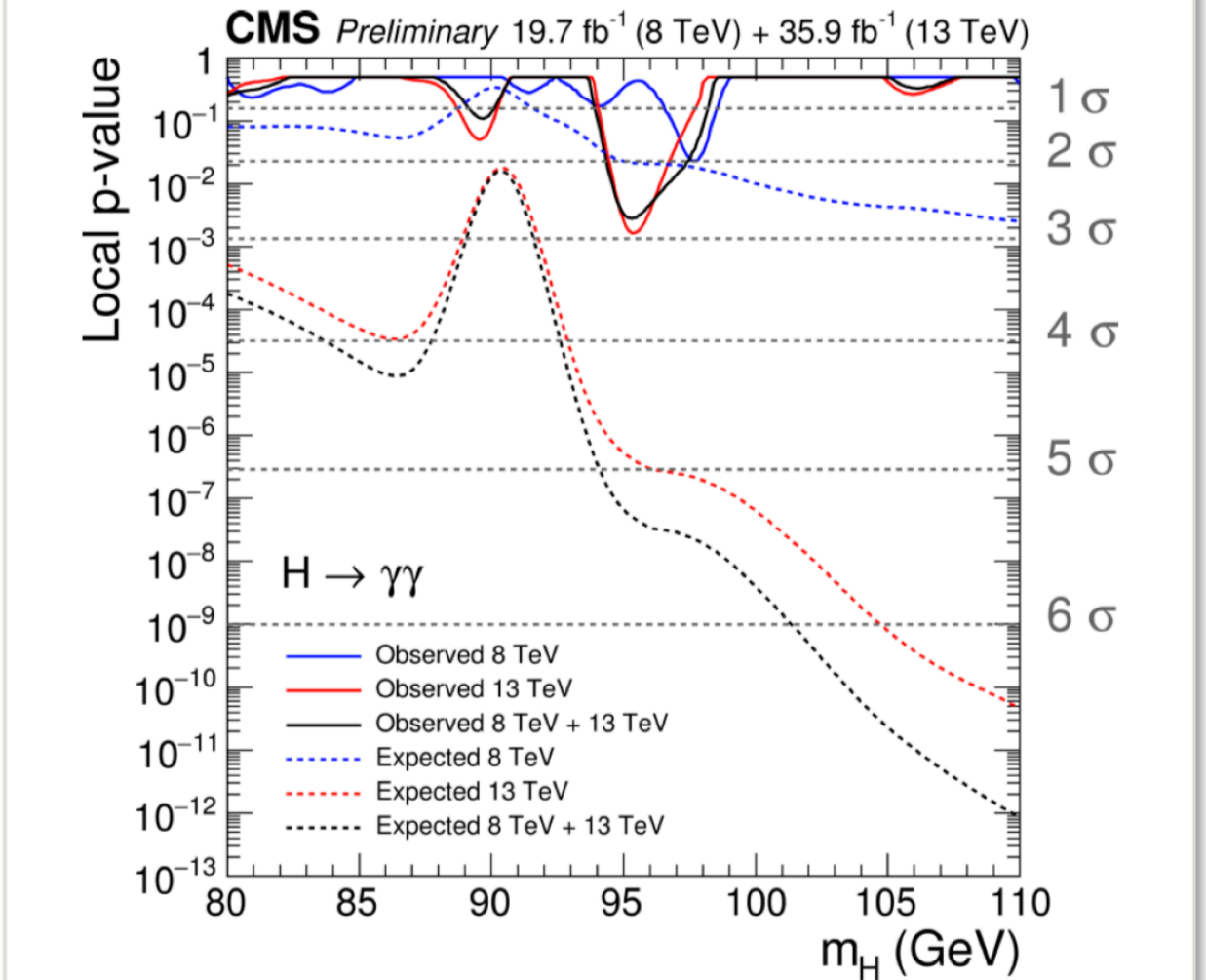
Sven Heinemeyer

CMS PAS HIG-17-013

Low mass h→γγ

- **Combined 8 TeV + 13 TeV** σ×BR limit normalized to SM expectation:
  - Production processes assumed in SM proportions
  - **No significant excess** with respect to background expectations
- Expected and observed local p-values for **8 TeV**, **13 TeV** and their **combination**





CMS PAS HIG-17-013

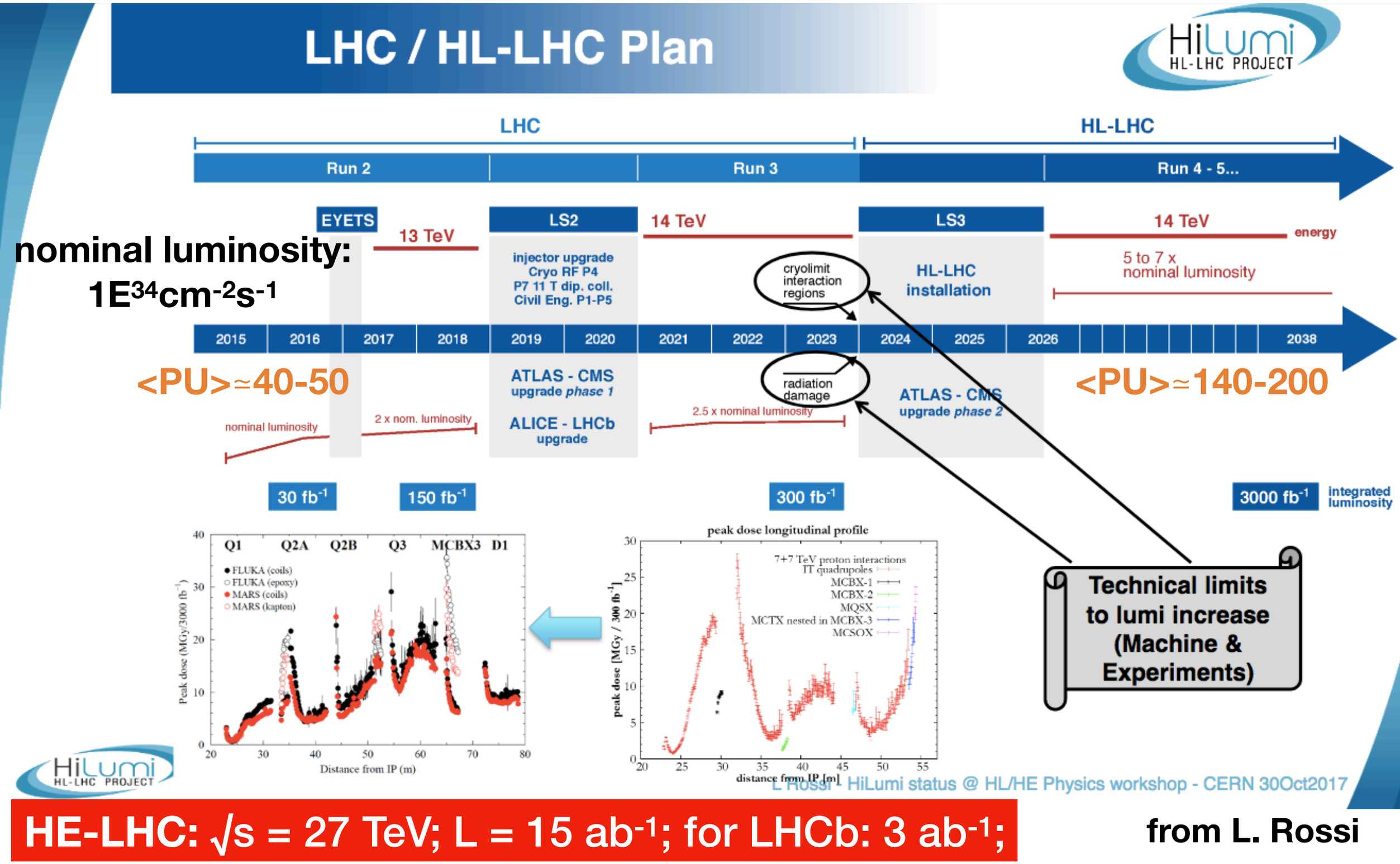
Sven Heinemeyer said,

- A light Higgs at 96 GeV?
  new CMS/ATLAS result (and old LEP result) possibly interesting!
  - NMSSM can explain CMS(/ATLAS) and LEP "excesses"
  - $\mu\nu$SSM can explain CMS(/ATLAS) and LEP "excesses"

By L. Finco

Prospects of H+ in future colliders?

LHC to High Luminosity LHC

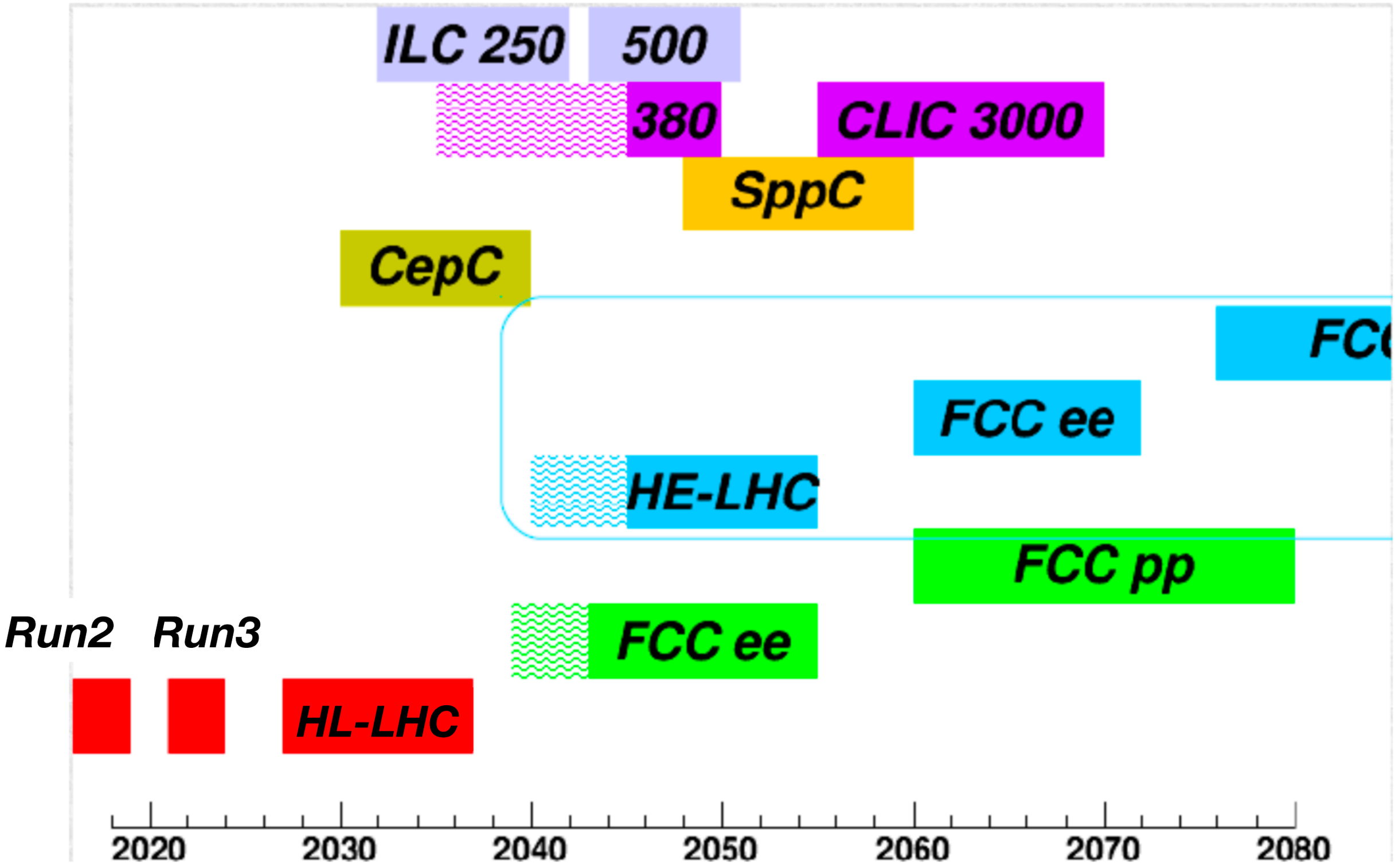


nominal luminosity: $1E^{34}cm^{-2}s^{-1}$

HE-LHC: $\sqrt{s}$ = 27 TeV; L = 15 ab^{-1}; for LHCb: 3 ab^{-1};

from L. Rossi

Future Machines

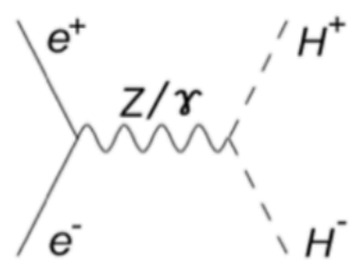


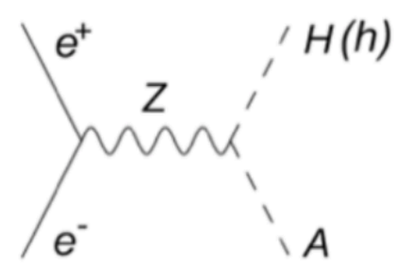
BSM Higgs at e^+e^- colliders

Discovery and precise measurement of BSM Higgs bosons if production within energy threshold

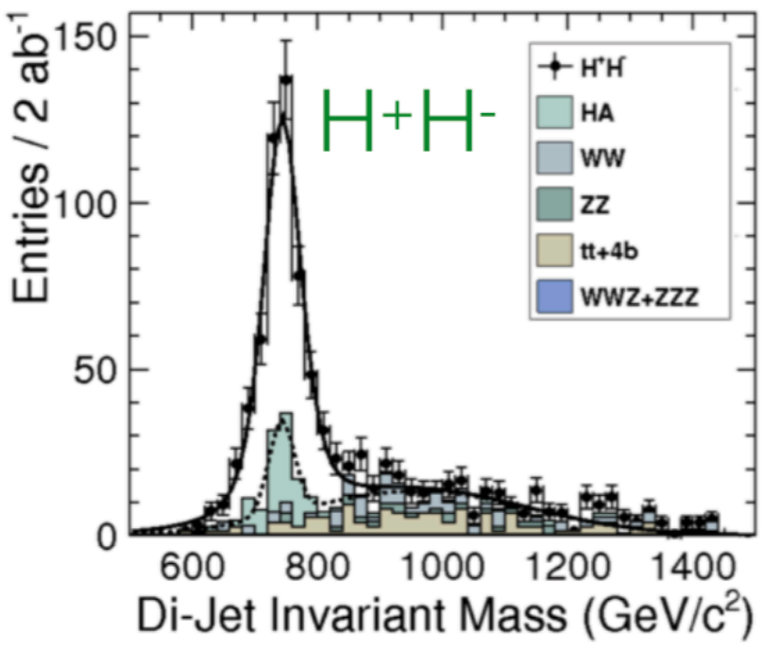
- (For higher masses associated prod. with fermions typically lower XS)
- Main decays
  - H/A → tt, bb, tau tau
  - H^+ → tb (tau ν)

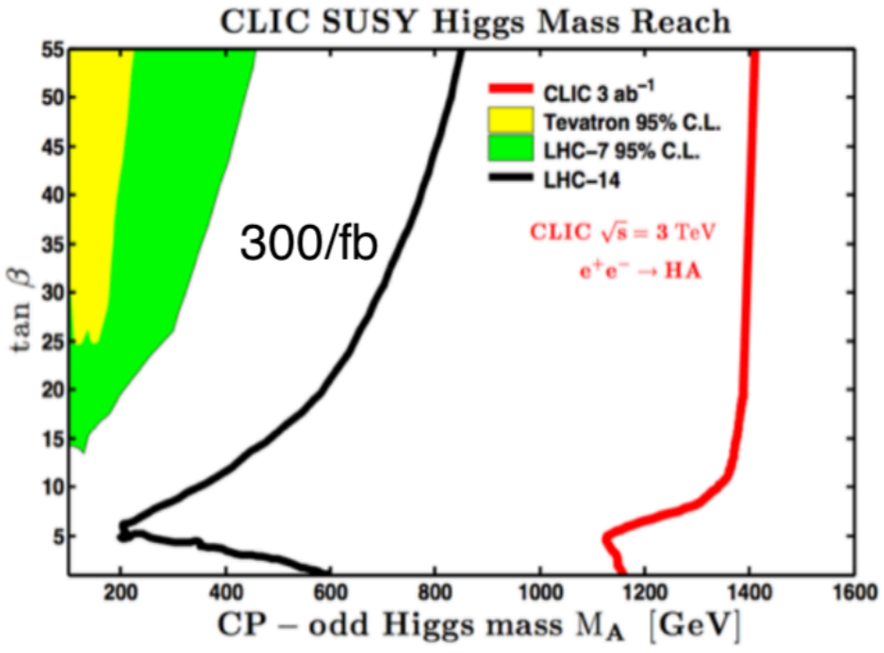
$M_{H^+} < \sqrt{s}/2, \qquad M_{H^0} + M_{A^0} < \sqrt{s}.$





- Percent level mass measurement (improve with kinematic fit)



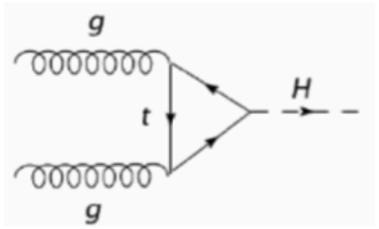


by K. Peters

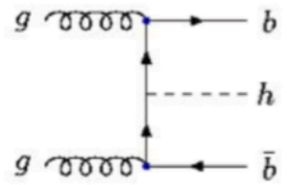
BSM Higgs at future pp colliders

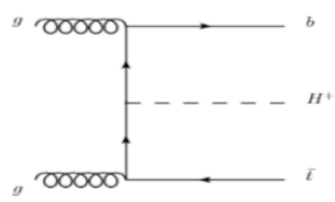
Direct searches for heavy Higgs bosons in the 2HDM

Large XS enhancement
σ(100 TeV)/σ(14 TeV)



30–50

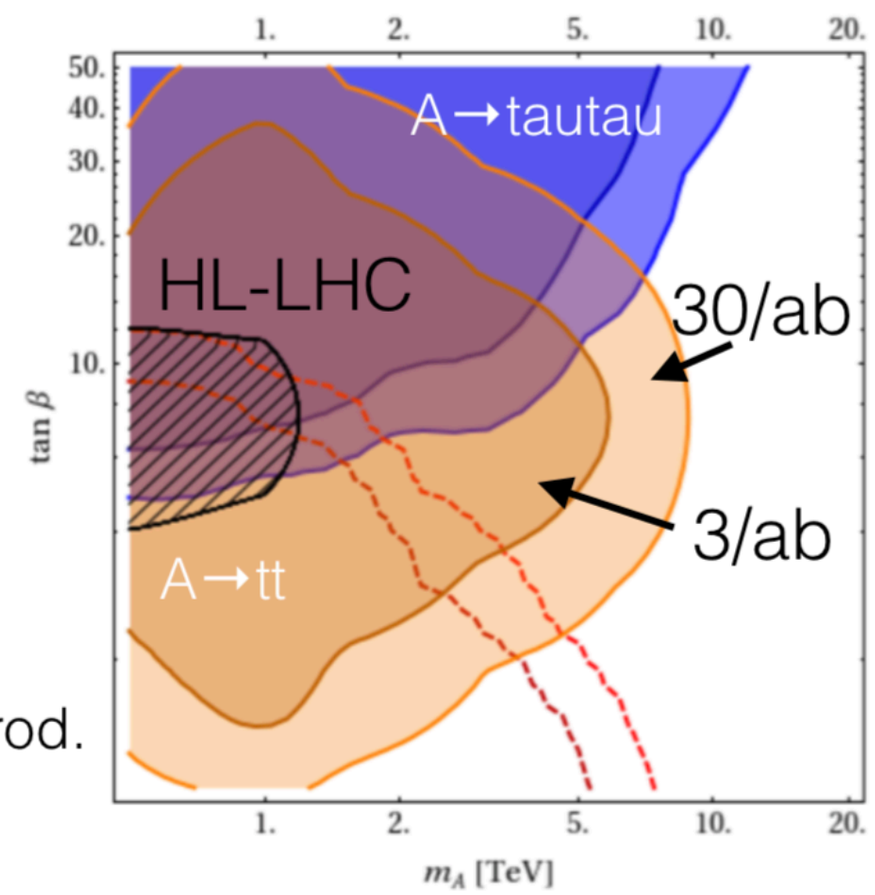




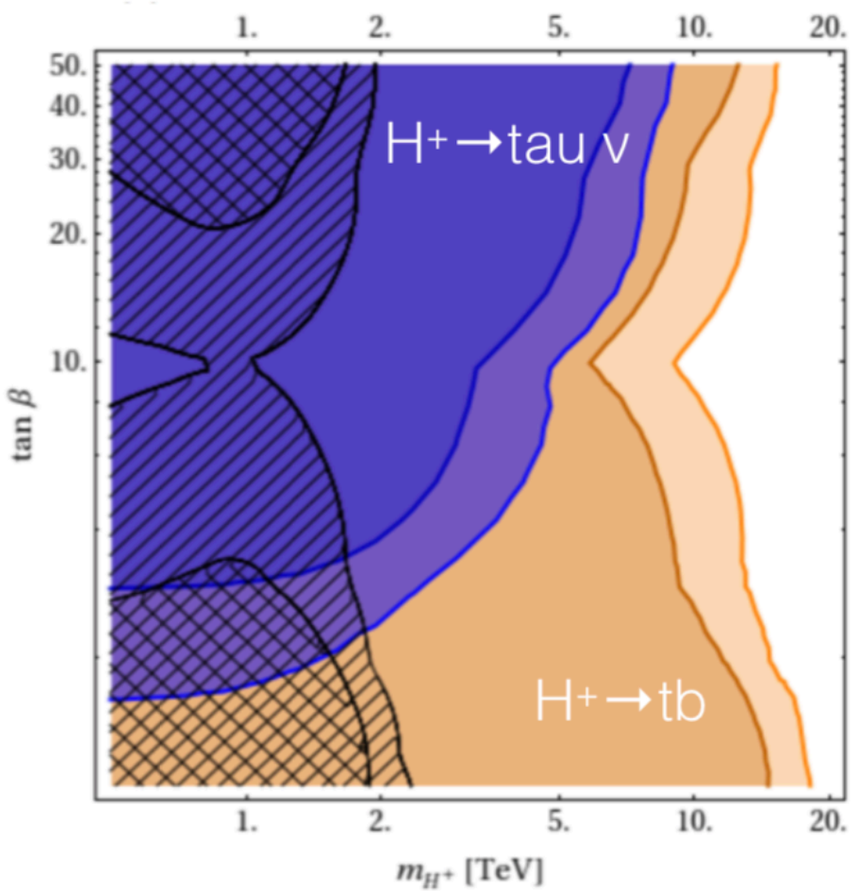
90

for mH = 500 GeV

bbH prod. only



(c) Exclusion reach for neutral Higgs



(d) Exclusion reach for charged Higgs

arXiv:1606.09408

Conclusions

- **LHC delivers** awesome results for Run 2 – and will be even more awesome in Run 3!

- The flagship analysis (e.g. A/H→ττ, H+→τν) are well-optimized and update results regularly, and other standard analysis (e.g. A/H→bb, H+→tb, cs, cb) are also routine by now

  - but **still a lot of unexplored signatures**!

    Higgs-to-SUSY (A/H→χχ, H+→χ+χ0)

    Higgs-to-Higgs (A→Zh is done, but e.g. H+→Wh/WA/Wγ)

    Higgs-to-tops (A→tt) [done by ATLAS, Run-1]

    H+ s-channel, H+ pair production, ...

    Light Higgs bosons (m<125 GeV)

  - but a lot beyond the MSSM/2HDM is already done:

    H+ → WZ in triplet models

    Vector-like quark decays

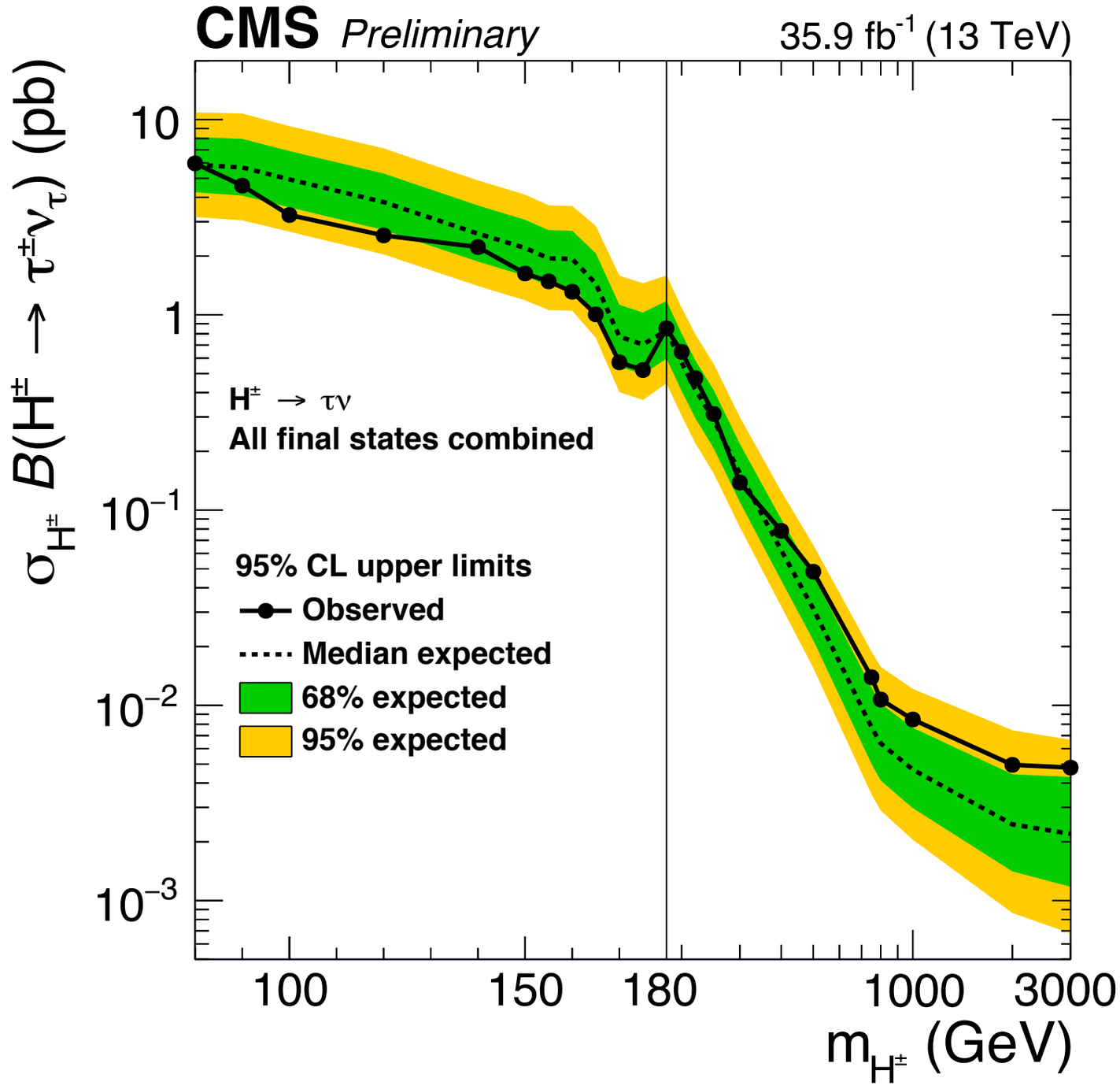
    Doubly charged Higgs...

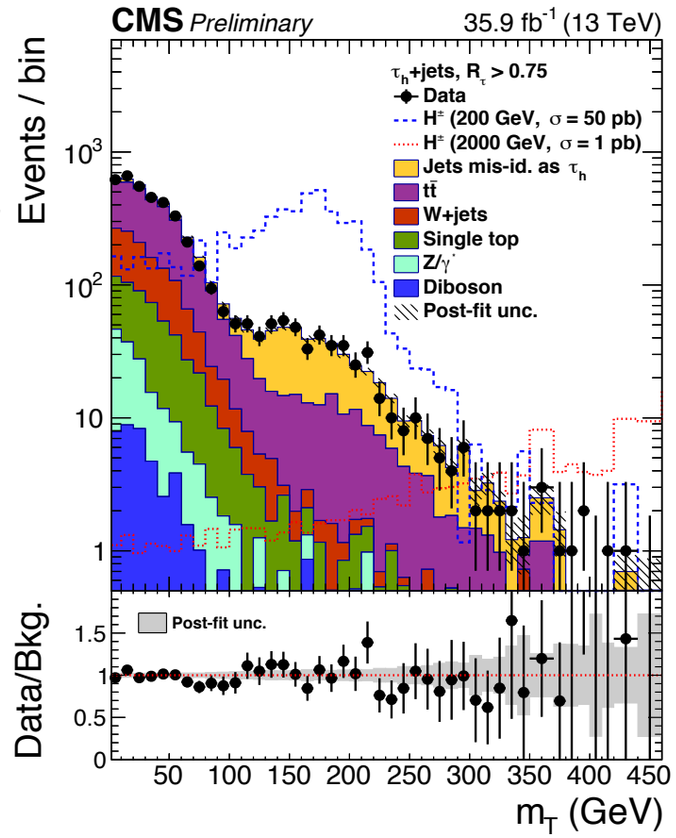
- **ATLAS and CMS** sensitivity mostly comparable, but a few (strange) **differences**
- **The future** may be bright (...or not) – future colliders?

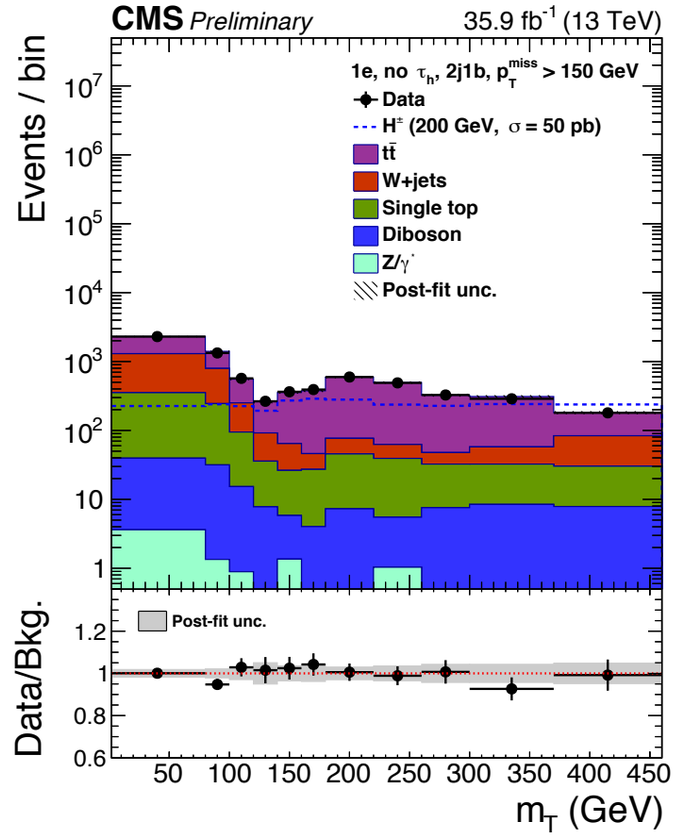
Backups

$H^+ \to \tau\nu$ @ 13 TeV

CMS





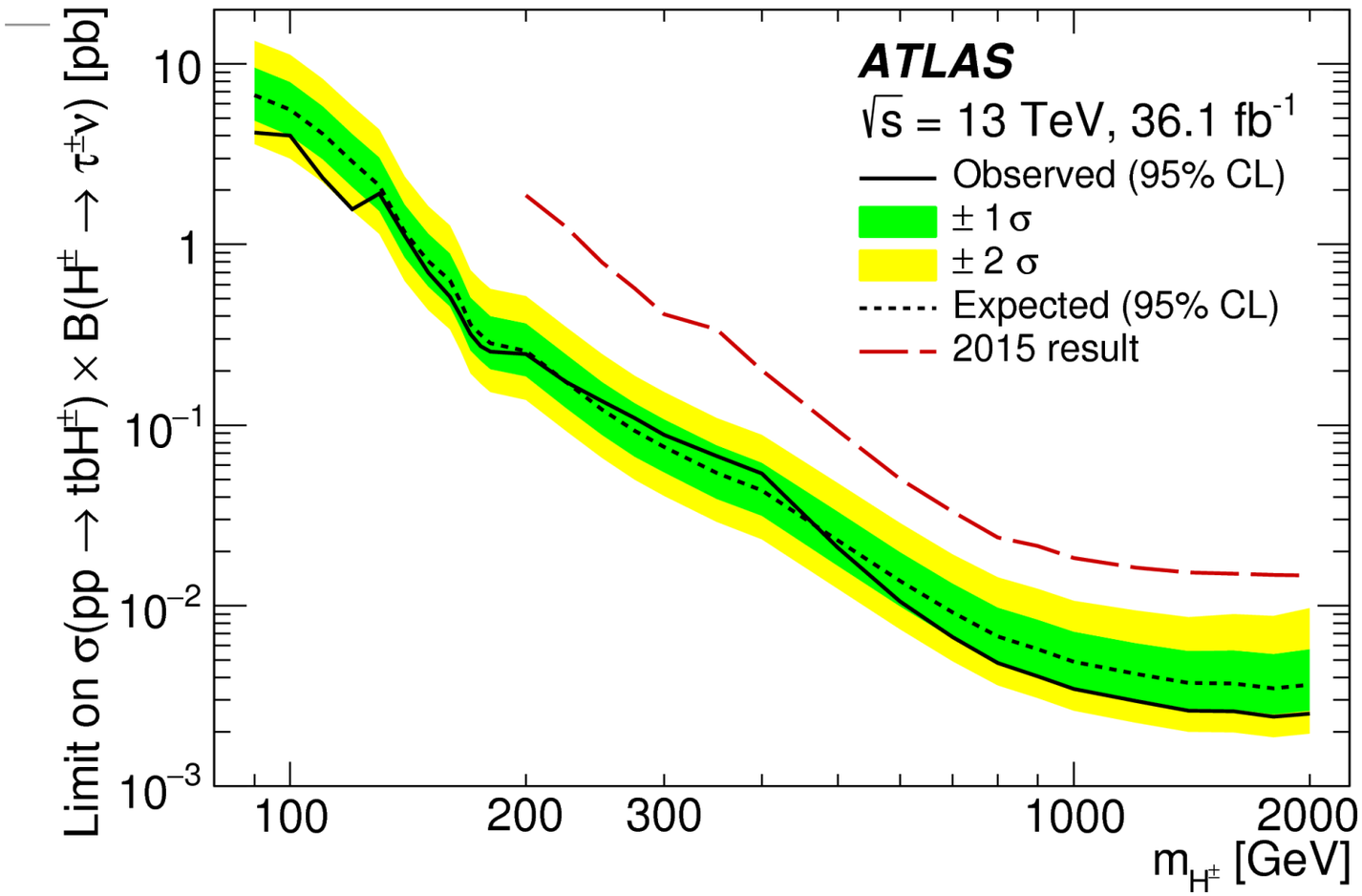


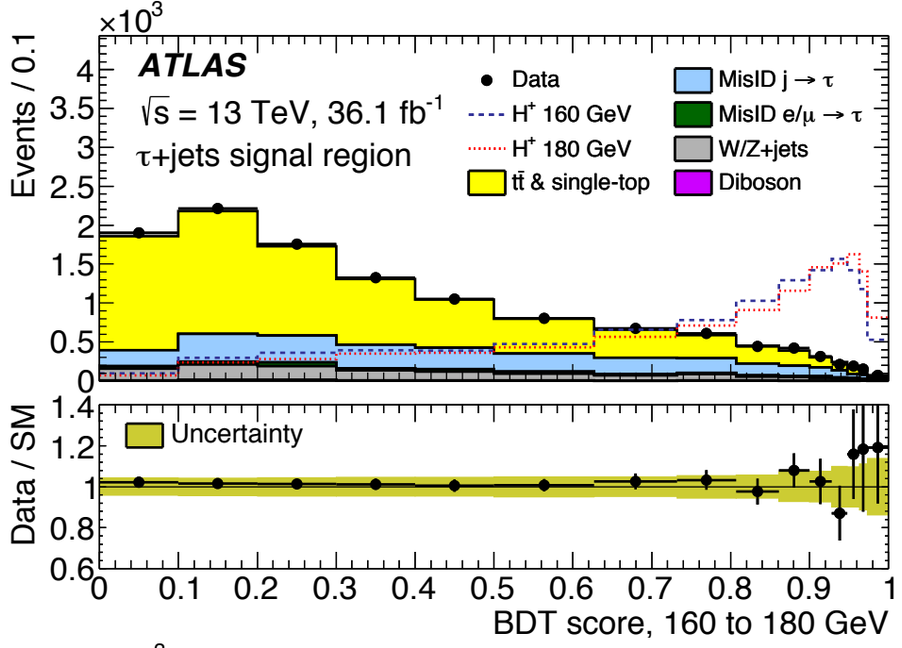
Use both τ_{had} & τ_{lep} events combining different final states

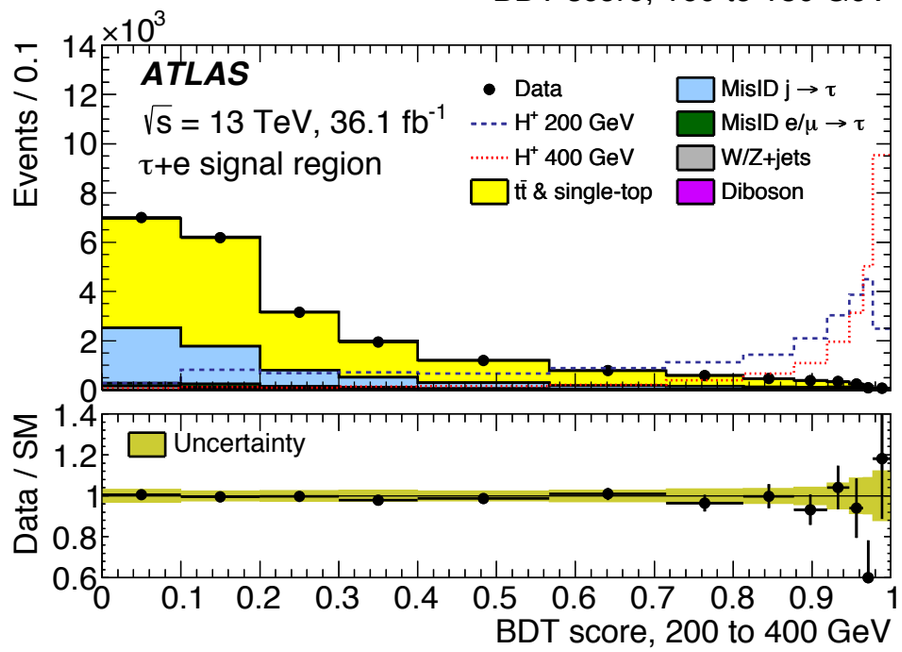
arXiv:1807.07915

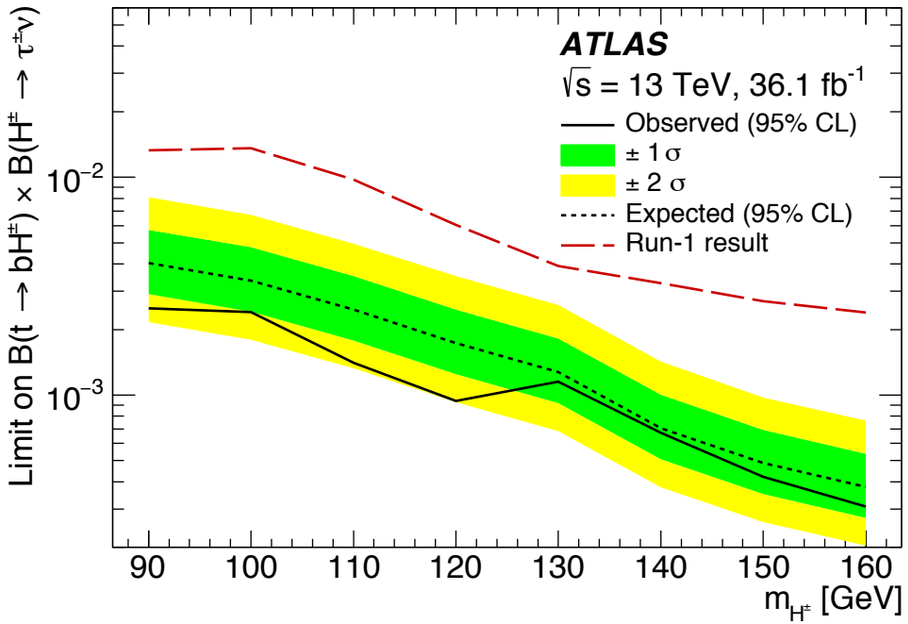
ATLAS

$H^+ \to \tau\nu$ @ 13 TeV

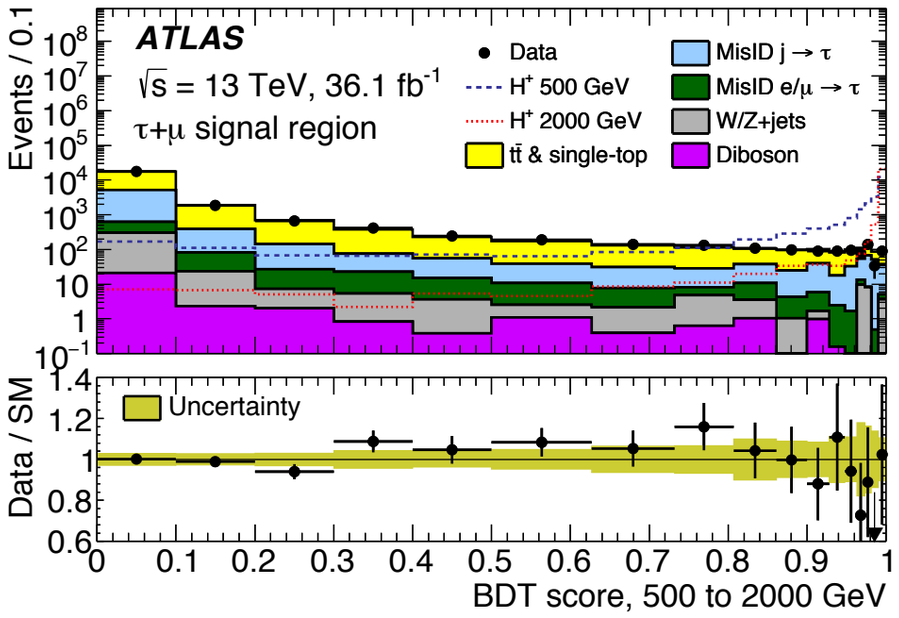








- Using events with τ_{had}+≥3 jets & τ_{had}+lepton
- First search performed in the intermediate region

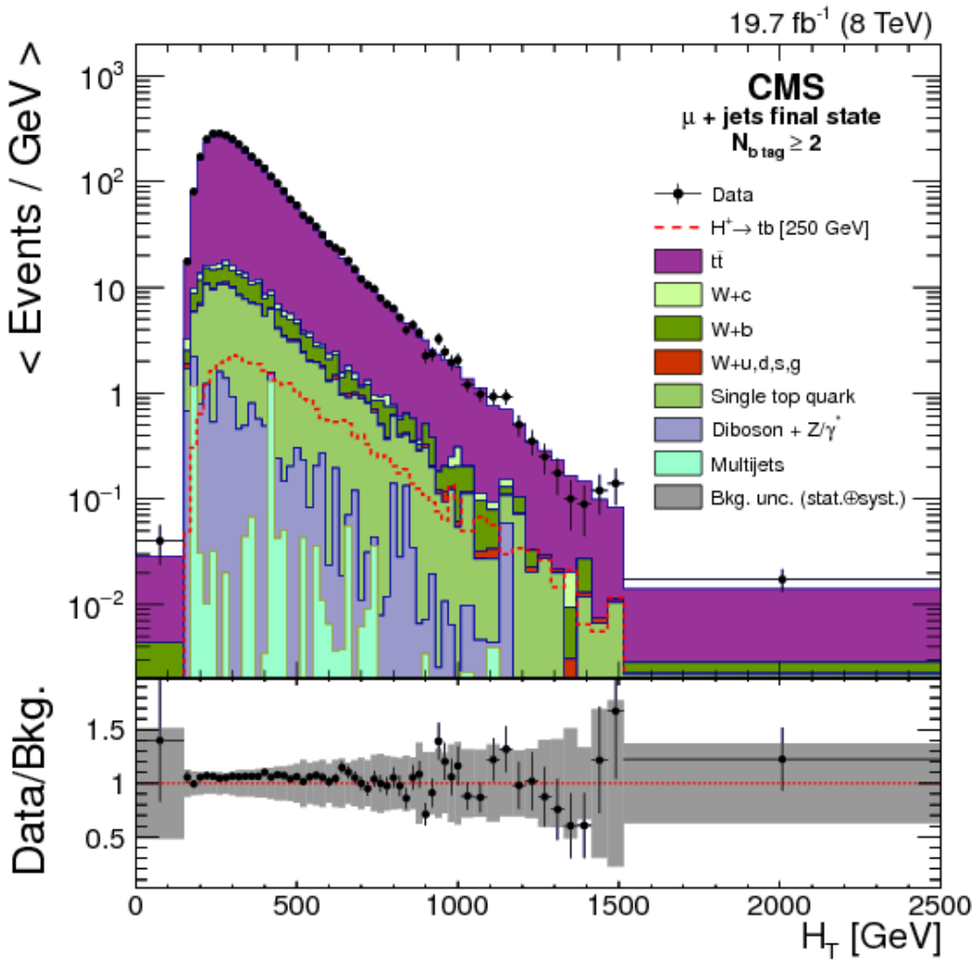


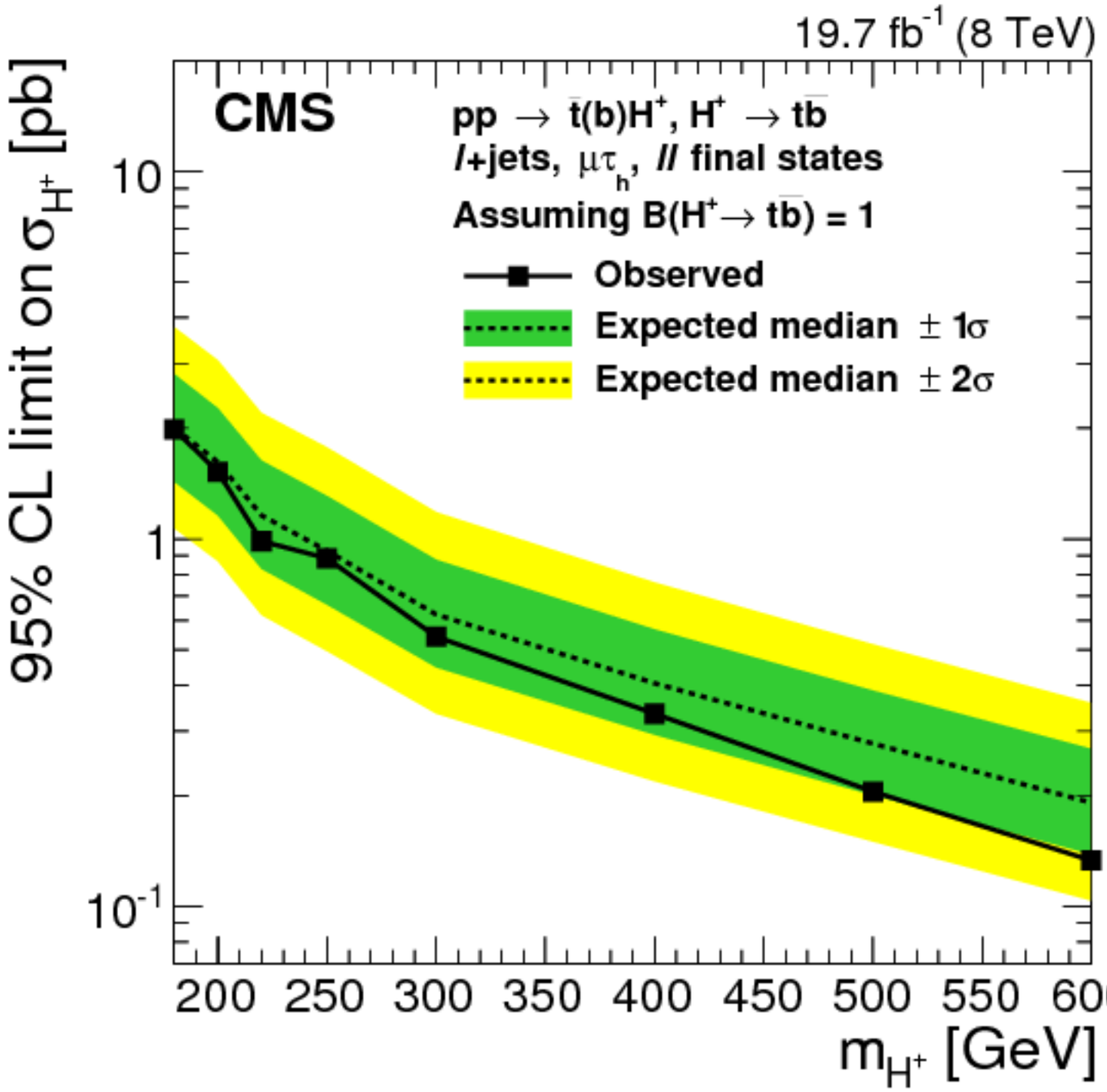
arXiv:1508.07774

CMS

$H^+ \rightarrow tb$ @ 8 TeV

- Combining the results obtained from three different final states
- H^+ signal is extracted based on the kinematic distributions of each channel





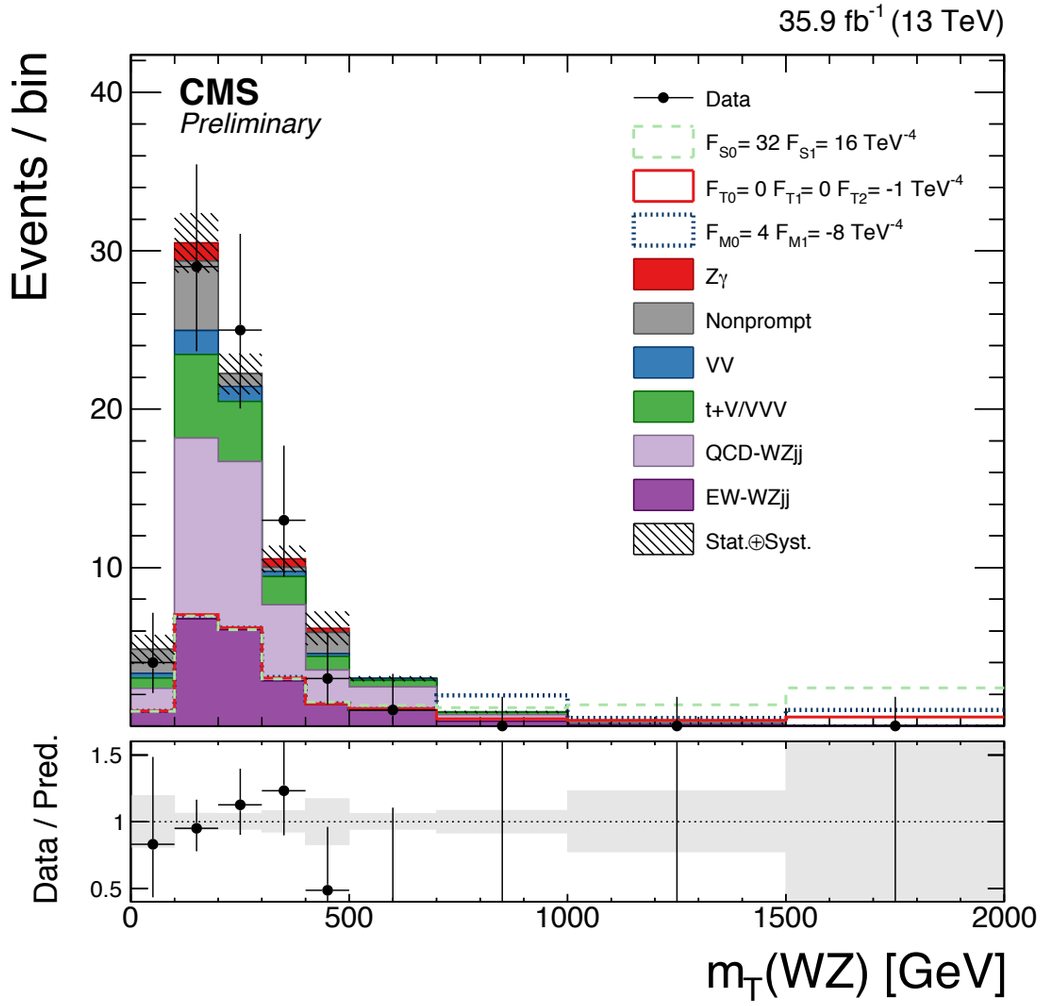
$H^+ \rightarrow WZ$ @ 13 TeV

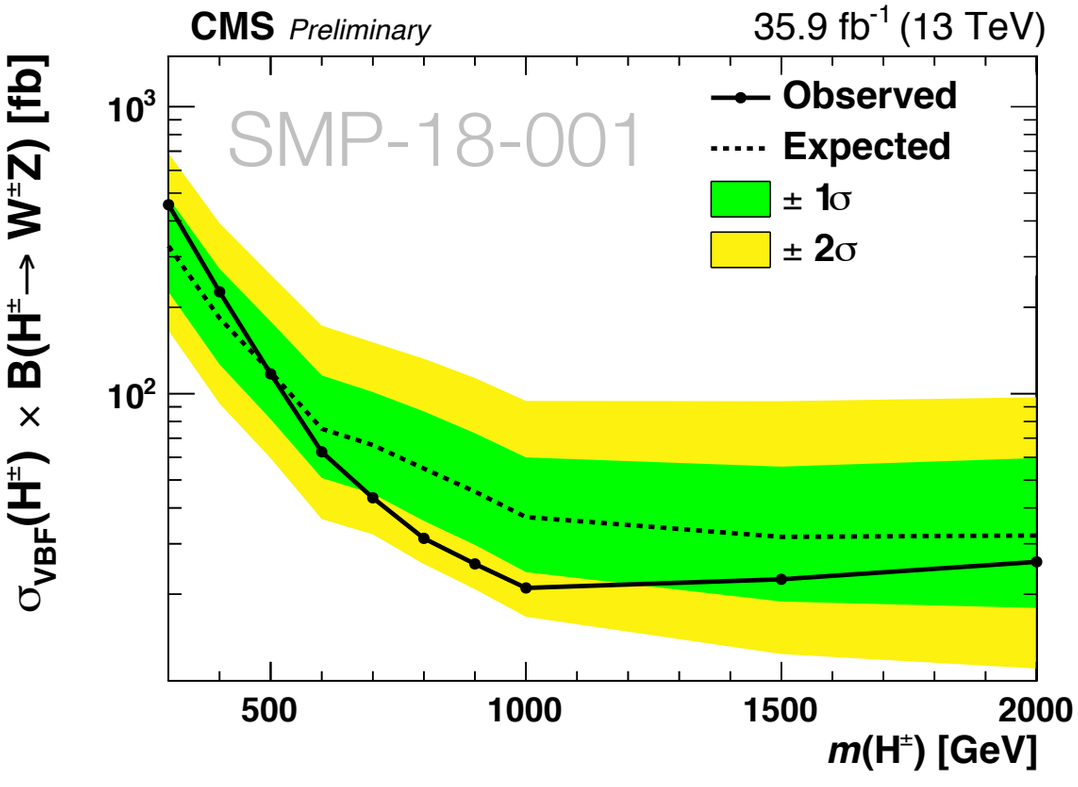
CMS

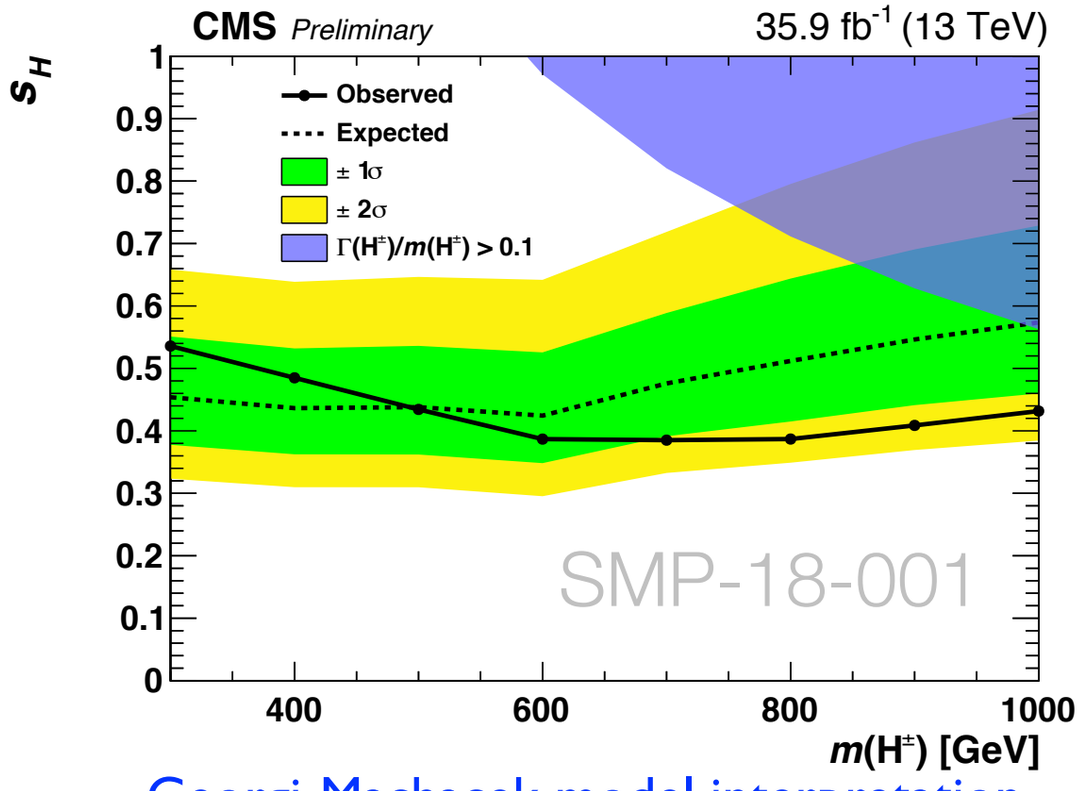
- WZ → 3leptons & two jets with large $\Delta\eta$
- Reconstruct transverse mass of WZ and extract the signal

$$m_{\mathrm{T}}(\mathrm{WZ}) = \sqrt{(E_{\mathrm{T}}(\mathrm{W}) + \mathrm{E}_{\mathrm{T}}(\mathrm{Z}))^2 - (\mathbf{p}_{\mathrm{T}}(\mathrm{W}) + \mathbf{p}_{\mathrm{T}}(\mathrm{Z}))^2}$$

$$\sigma(\mathrm{VBF} \to H_5) = s_H^2 \sigma_1(\mathrm{VBF} \to H_5), \quad s_H \equiv \sin\theta_H = \frac{2\sqrt{2}\, v_\chi}{v}$$







Georgi-Machacek model interpretation

arXiv:1808.01899

ATLAS

$H^{++} \rightarrow WW$ @ 13 TeV

- Type-II seesaw comprising the scalar sector of a Y=2 scalar triplet with SM scalar doublet
- $pp \rightarrow H^{\pm\pm}H^{\mp\mp} \rightarrow W^{\pm}W^{\pm}W^{\mp}W^{\mp}$ for m($H^{\pm\pm}$) of 200—700 GeV
- two SS leptons+two hadronic Ws (njets≥3)
- three leptons+one hadronic W & fully leptonic Ws
- Selection optimized for each signal using TMVA