WG3
Overview and plans

15 November 2023

Chris Hayes (ATLAS), <u>Alexis Kalogeroulos </u>(CMS), Brian Shuve, Shufang Su (Theory)

lhc-higgs-bsm-convener@cern.ch

WG3 overview

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3

Five subgroups

- <u>Extended scalar Higgs</u>

- <u>NMSSM</u>

- <u>MSSM</u>

- <u>Exotic Higgs</u>

- <u>bbH</u>

Mostly recycling plots and results presented during the workshop; all the credits go to the authors/speakers

Extended scalars

ATLAS : **Nikos Rompotis, Lidija Zivkovic** CMS : **Mariarosaria D'Alfonso, Santeri Laurila**

Theory: **Tania Roberts, Rui Santos**

The group holds regular meeting, focusing among others on

- ❖ Overlooked signatures
- ❖ Provide cross sections for 13.6 TeV
- ❖ Width and interference effects in BSM searches
- ❖ Recasts
- ❖ CPV, SM+Triplet models
- ❖ …

Extended scalars

TWIKI with additional information

- Twiki containing BRs numbers for H+->cb in the 3HDM: Hplus3HDM.
- Twiki containing cross section and BRs numbers for 2HDM: LHCHWG2HDM ("2HDM Ntuple")
- Twiki containing cross section and BRs numbers for flavorful 2HDM: LHCHWG3Flavorful2HDM.
- Twiki for LFV Higgs decay in BGL.
- Twiki for 2HDM benchmarks.
- Twiki for the Georgi-Machacek model.
- Twiki for benchmarks other than 2HDM
- Twiki for the width and interference treatment recommended for a common treatment for ATLAS and CMS analyses.
- Twiki for MSSM charged Higgs (heavy, light, intermediate masses).

Ongoing work

- Check physics case for 3HDM, LRS, CPV, SM+Triplet models, in case provide cross sections and BRs: Santos to write short summary of which code is good for which
- Interface theory constraints for an additional singlet into ScannerS: done. The latest version of ScannerS that include a large number of models with extended scalar sectors is now available, see https://arxiv.org/pdf/2007.02985.pdf . The code includes the usual theoretical constraints: stability and perturbativity and electroweak precision together with interfaces with several other codes. A description on how to check if a given point is allowed by the constraints can be done for the CxSM and is described in detail in the following presentation https://indico.cern.ch/event/640710/contributions/2599076/attachments/1463561/2261560/MSampaioWG3_20170522.pdf .
- Cross sections and BRs for 2HDM+singlet models (real & complex): Nikos Rompotis.
- Inclusion of 2HDM electroweak baryogenesis information in electroweak phase transition properties by using the BSMPT code by Maggie: Maggie, Nikos Rompotis.
- Theoretical predictions for interference effects for large width charged Higgs decays: done. Santos to write a short description of regions of parameter space that have large interference effects.
- Expand 2HDM/MSSM H+ cross sections from 2 two 3 TeV: contact.
- Provide benchmark scenarios for searches for H5 states in GM for masses below 200GeV: Heather Logan
- Provide simulation tool for loop-induced H+->W+ gamma with fermiophobic H+ in GM: Heather Logan
- TRSM benchmark points for h3-> h2 h1, various final states: Tania Robens rep.pdf: h3 -> h2 h1 into bbbb final states in the TRSM
- TRSM benchmark points for h3-> h2 h1, b bbar gamma gamma final states Tania Robens trsm_bbgaga.txt

A lot already completed; and many ongoing activities a well!

Today mostly from Tania's talk
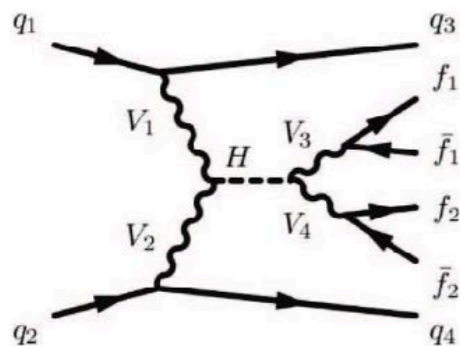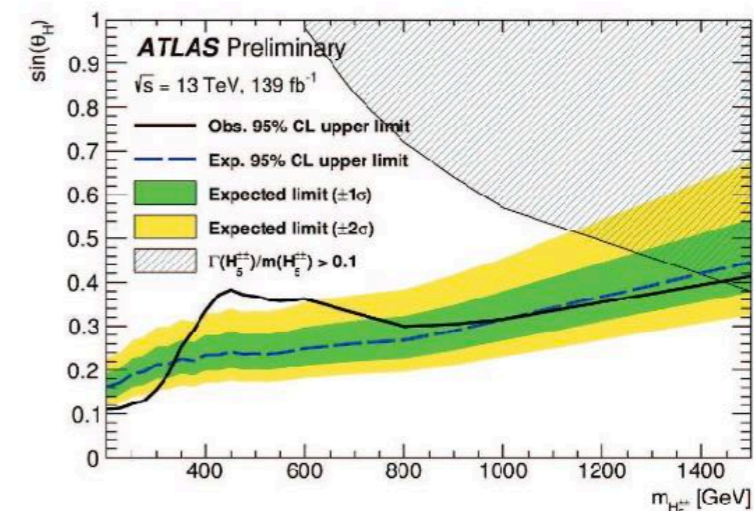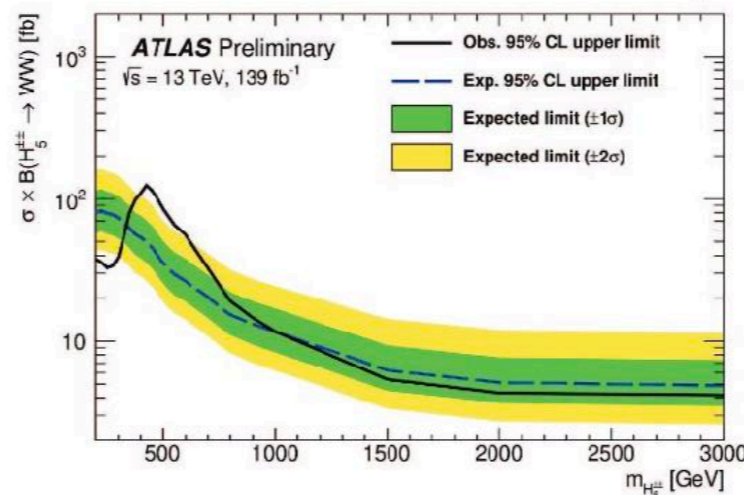
However, it is impossible to present all new results!

- ## Same sign W boson pair production

ATLAS-CONF-2023-023

Georgi-Machacek triplet model + other interpretations

Lidija Zivkovic
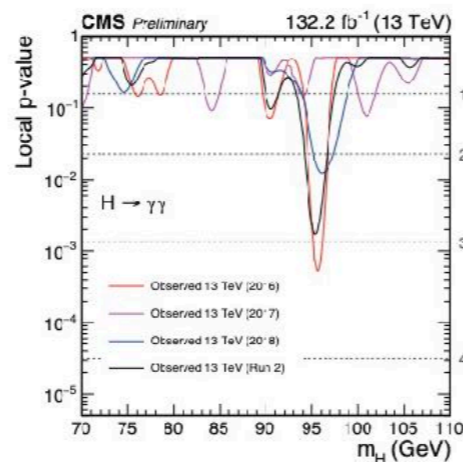Nikolaos Rompotis

LHC Higgs Workshop – November 2023

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CMS Highlights: Light Scalar Searches

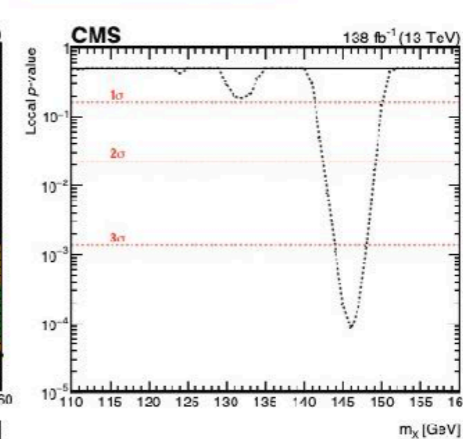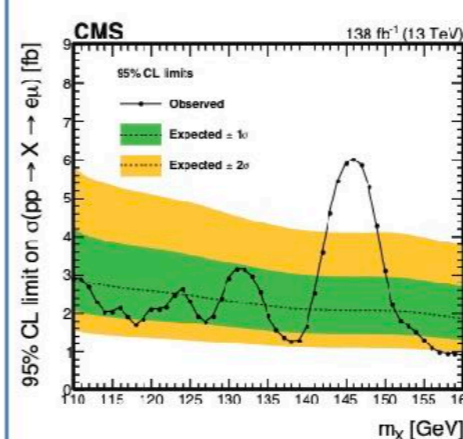✤ **Search for φ→γγ**   arXiv:2311.00130

✤ **Search for φ→eμ**   arXiv:2305.18106
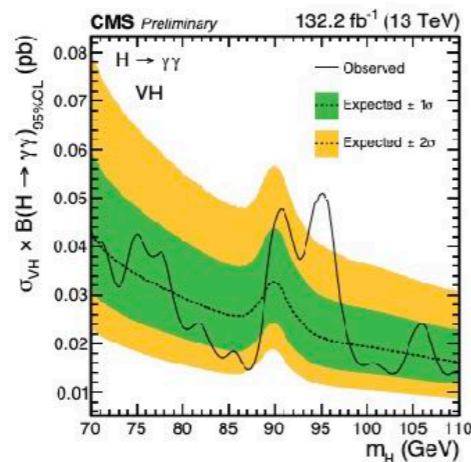
✤ Search for γγ resonance in 70–110 GeV mass range
✤ Intriguing **2.9σ** (**1.3σ** global) excess at **95.4 GeV**
  ✤ Similar to the previous CMS result at 8+13 TeV, with 2.8σ (1.3σ global) at 95.3 GeV (arXiv:1811.08459)
  ✤ ATLAS reports 1.7σ at 95 GeV (ATLAS-CONF-2023-035)
  ✤ Mild excess seen also in LEP (arXiv:hep-ex/0306033)

✤ Search for lepton-flavor violating decays, forbidden in the SM but predicted e.g. in **Type III 2HDM**
  ✤ Analysis covers the 110–160 GeV mass range
✤ Most stringent limits to date
  ✤ **3.8σ** (**2.8σ** global) excess at **146 GeV**

Extended scalars - Outlook and plans

Provide the latest theory calculations and tools to the community

❖ Update on the 13.6 TeV xsecs

- ◉ production of charged scalars i.e. p p → H+ t̄ b production split in three mass ranges

- ◉ neutral scalars : Urgently need from WG1 (SM-like scalars)

❖ Joint activities and cross-talk with other WGs

- ◉ WG2/WG3 cross-talk : CP violation and Higgs sector (study CPV w. extended sectors) - Tania's talk on <u>Wed</u>

❖ Investigate in more detail width, interference, ...

❖ Propagate further insights of the LHC Reinterpretation Forum

MSSM

ATLAS : Tim Barklow CMS : Afiq Anuar

Theory: Michael Spira, Emanuele Bagnaschi

✓ Identify interesting and relevant theoretical aspects important for experiments

✓ Provide benchmark scenarios to be used by experimental collaboration

✓ Discuss and promote possible future developments on probing the MSSM Higgs sector at the LHC

Mostly taken from Emanuele's talk

MSSM - Summary of activities

> - Scenarios/ROOT files
> - Experimental/phenomenological aspects
> - A/H Higgs transverse momentum distribution
> - Working group notes
>
> **Lines of activity**

Task	Status	Timescale ↑
Keep an eye on potentially missing signatures	In progress	Continuous
WG support to the release of experimental likelihoods	In progress	Continuous
Prioritize channels according to importance for end of LHC run2/3 or HL-LHC	In progress	Continuous
Support the experimental effort, mainteinance of the ROOT files	In progress	Continuous
Higgs $p_\perp^\phi$ public note	Planned	On hold
Provide description and common tool for BSM Higgs $p_\perp^\phi$ calculation @ NLO+PS precision for gluon fusion	Planned	On hold
A/H decay to SUSY states and corresponding ROOT files	Planned	2024
Include 13.6 TeV cross sections in the ROOT files	In progress	2024
Switch to PDF4LHC21 for the cross sections in the ROOT files	In progress	2024
Update of the ROOT files to the latest HDECAY version	Complete	July 2022
Update of the ROOT files to the latest HDECAY version	Complete	December 2021
Update of the ROOT files with new quantities (e.g. trilinear self-coupling of the SM-like Higgs)	Complete	December 2021
Update of the hMSSM ROOT file to the same cross-section setup of the other scenarios	Complete	December 2021
Release of the ROOT files on Zenodo	Complete	December 2021
Public note describing the ROOT files setup	Complete	December 2021
Update of the ROOT files of EFT scenarios with the inclusion of the SM predictions	Complete	July 2021
Release ROOT files for mh125 variants with negative μ	Complete	December 2020
Update of the ROOT files (SM BRs, **HDECAY** update, `FeynHiggs` proper version)	Complete	December 2020
Provide updated ROOT files for end RunII analyses	Complete	End 2018
Provide benchmark scenario for low **tan** β using EFT approach	Complete	End 2018
Provide new MSSM benchmark scenarios	Complete	Sept 2018
Update SM parameters for MSSM calculations to be consistent with YR recommendations for SM calculations	Complete	Sept 2018

REMINDER "Benchmark Scenarios for MSSM Higgs-Boson Searches at the LHC" for 8/13/14 TeV XS in 6 (mh$_{125}$) + 6 scenarios - last fixed version Sept/2023

MSSM - Cross sections @ 13.6 TeV

❖ No problems for ggF

❖ New xsecs w. `PDF4LHC21` (nice example of cross-groups synergy!)

   ◉ Should we consider also additional PDFs? If yes: which? and should we also do it for 8 TeV?

   ◉ For bbϕ, rescale the xsecs provided by the bbH (1508.03288, 1605.01733)

   ◉ For ttϕ, rescale the xsecs provided by the ttH

   ◉ for vϕ, rescale the numbers by VH group

   ◉ Synergy with extHiggs sector (charged higgs)

❖ Still, some caveats (like smoothing out the thresholds between different predictions) are currently been worked out

More on Emanuele's talk

Branching ratios

Neutral Higgs
$<\phi> = $ h,H,A

br_$<\phi>$_bb
br_$<\phi>$_cc
br_$<\phi>$_gamgam
br_$<\phi>$_gluglu
br_$<\phi>$_mumu
br_$<\phi>$_SUSY
br_$<\phi>$_tautau
br_$<\phi>$_tt
br_$<\phi>$_WW
br_$<\phi>$_Zgam
br_$<\phi>$_ZZ
br_H_AA
br_H_hh
br_H_WHp
br_A_Zh

Charged Higgs
$<\phi> = $ h,H,A

$\mathcal{CP}$-violating scenario
$<\phi> = $ H1,H2,H3

br_Hp_cb
br_Hp_cd
br_Hp_cs
br_Hp_munu
br_Hp_taunu
br_Hp_tb
br_Hp_ts
br_Hp_td
br_Hp_ub
br_Hp_$<\phi>$W
br_Hp_SUSY
br_t_Hpb

Neutral Higgs
$\mathcal{CP}$-violating scenario
$<\phi> = $ H1,H2,H3

br_$<\phi>$_bb
br_$<\phi>$_cc
br_$<\phi>$_gamgam
br_$<\phi>$_gluglu
br_$<\phi>$_mumu
br_$<\phi>$_SUSY
br_$<\phi>$_tautau
br_$<\phi>$_tt
br_$<\phi>$_WW
br_$<\phi>$_Zgam
br_$<\phi>$_ZZ
br_H2_H1H1
br_H3_H1H1
br_H2_WHp
br_H3_WHp
br_H2_ZH1
br_H3_ZH1

SM Higgs

br_HSM_bb
br_HSM_cc
br_HSM_gamgam
br_HSM_gluglu
br_HSM_mumu
br_HSM_tautau
br_HSM_tt
br_HSM_WW
br_HSM_Zgam
br_HSM_ZZ

Cross sections

Neutral Higgs
$<\phi> = $ h,H,A

$\mathcal{CP}$ violating scenario
$<\phi> = $ H1,H2,H3

xs_bb_$<\phi>$
xs_bb_$<\phi>$_down
xs_bb_$<\phi>$_up
xs_gg_$<\phi>$
xs_gg_$<\phi>$_pdfasdown
xs_gg_$<\phi>$_pdfasup
xs_gg_$<\phi>$_scaledown
xs_gg_$<\phi>$_scaleup
xs_vbf_$<\phi>$
xs_hs_Z$<\phi>$
xs_hs_W$<\phi>$
xs_tth_$<\phi>$

SM Higgs

xs_bb_HSM
xs_gg_HSM
xs_vbf_HSM
xs_hs_ZHSM
xs_hs_WHSM
xs_tth_HSM

Charged Higgs

xs_pp_Hp
xs_pp_down
xs_pp_up

Other quantities

Masses
$<\phi> = $ h,H,A,Hp

$\mathcal{CP}$-violating scenario
$<\phi> = $ H1,H2,H3,Hp

m_$<\phi>$

Couplings
$<\phi> = $ h,H,A
lam3_HHH only for M_H^{125}

rescale_gt_$<\phi>$
rescale_gb_$<\phi>$
rescale_deltab
rescale_im_deltab
lam3_hhh (lam3_HHH)
lam3_HSM
lam3_HSM_tree
alpha

Couplings
$\mathcal{CP}$-violating scenario
<i>,<j>=1,2,3

rescale_deltab
rescale_im_deltab
lam3_H1H1H1
lam3_HSM
lam3_HSM_tree
Hmix_<i><j>
alpha_tree

Total widths
$<\phi> = $ h,H,A,Hp

$\mathcal{CP}$-violating scenario
$<\phi> = $ H1,H2,H3,Hp

width_$<\phi>$
width_HSM
width_t

Interference factors
$\mathcal{CP}$-violating scenario
$<\phi> = $ H1,H2,H3

int_bb_tautau_$<\phi>$
int_gg_tautau_$<\phi>$

MSSM - Overview and plans

For A/H to SUSY states:

❖ Some scenarios have sizeable $\mathscr{BR}$ to SUSY states.

❖ The plan is provide separate ROOT files with the different channels saved separately

❖ On going discussions with experimental community

From theory side :

❖ Neutral Higgs : extension of $\mathbf{\Delta}_b$ resummation to A_b terms and EWK g. couplings

❖ Charged Higgs: extension of $\mathbf{\Delta}_t$ resummation

❖ gg ➔ A : complete SUSY-QCD calculation

   ◉ Full details on M. Spira's <u>talk</u>
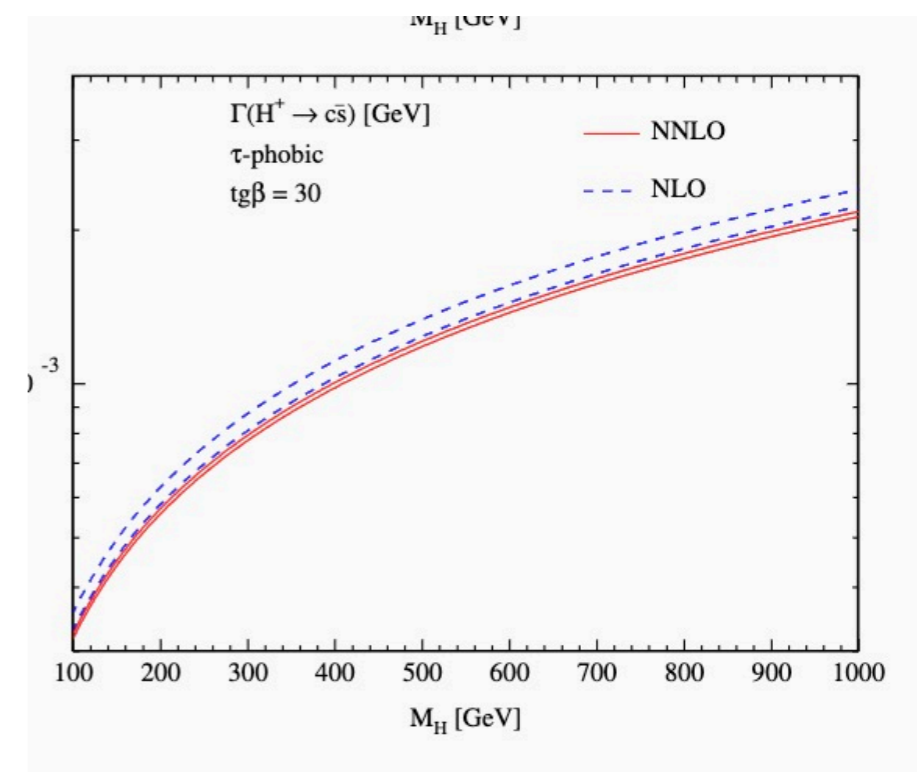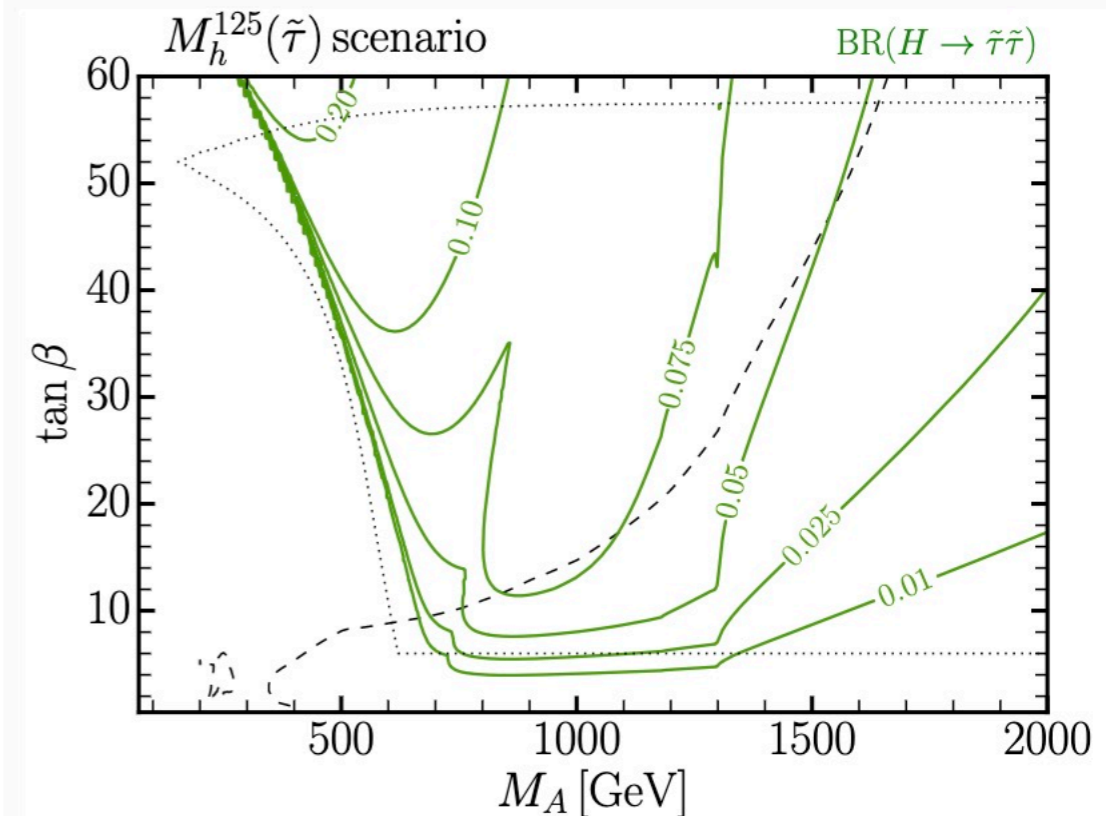
NMSSM

ATLAS : **Nikos Rompotis** CMS : **Daniel Winterbottom**

Theory: **Ulrich Ellwanger, Maggie Muhlleitner, Nausheen Shah**

✓ Initially, the group focused towards light pseudo-scalar searches e.g $h_{SM} \rightarrow aa$

✓ However, over the last few years interest has shifted towards cascade-like signatures and multi-Higgs final states e.g $H \rightarrow h_s\, h_{SM}$ / $A \rightarrow a_s h_{SM}$ - (commonly referred to as $X \rightarrow Yh$)

Mostly taken from Daniel's talk

NMSSM - Benchmarks

❖ In general, NMSSM benchmarking is not possible due to many free parameters

❖ However, the group produces maximum allowed $xsec^* \mathcal{BR}$ for specific signatures

- ◉ By tuning the parameters within allowed ranges allowed to maximise xsec

- ◉ Constraints taken into account, like mass and couplings of H_{125}, BSM searches at LHC and other experimental constraints (LEP, B-physics etc.

- ◉ More details in arxiv:2203.05049
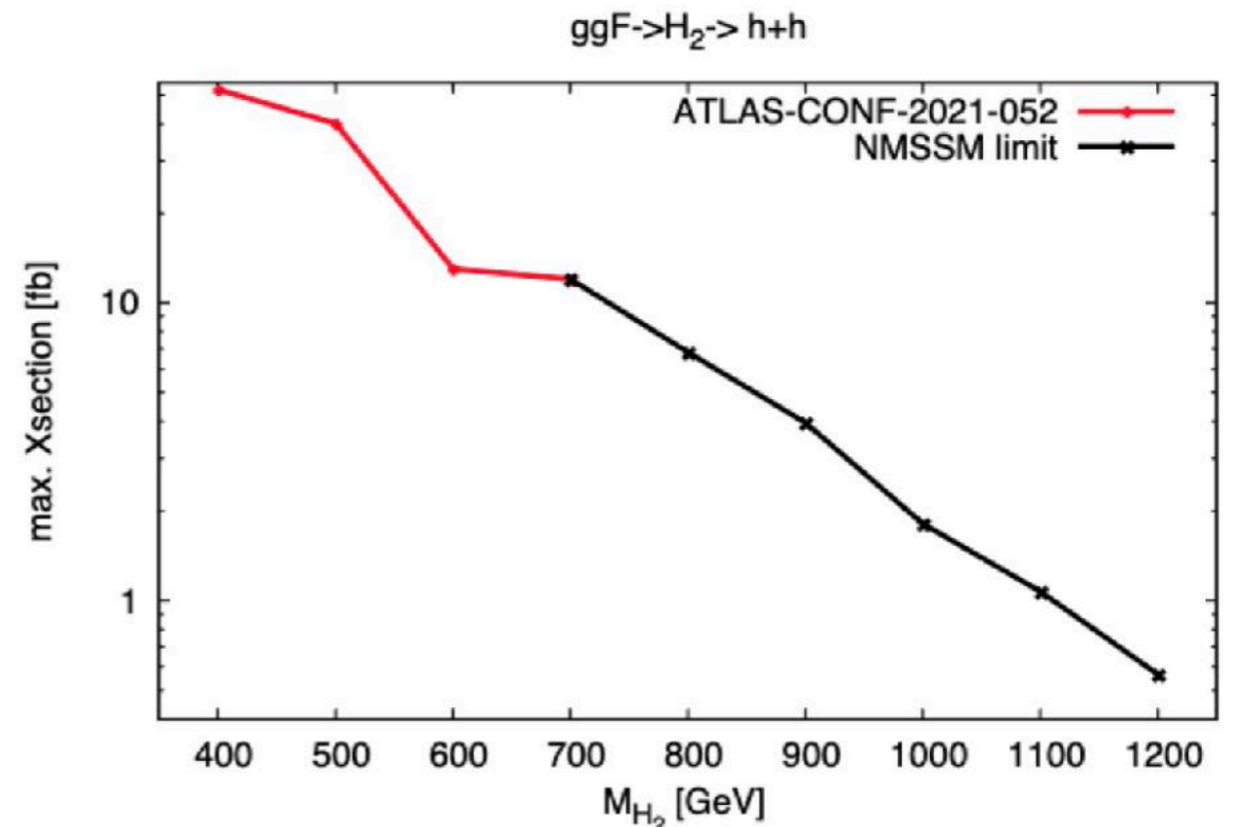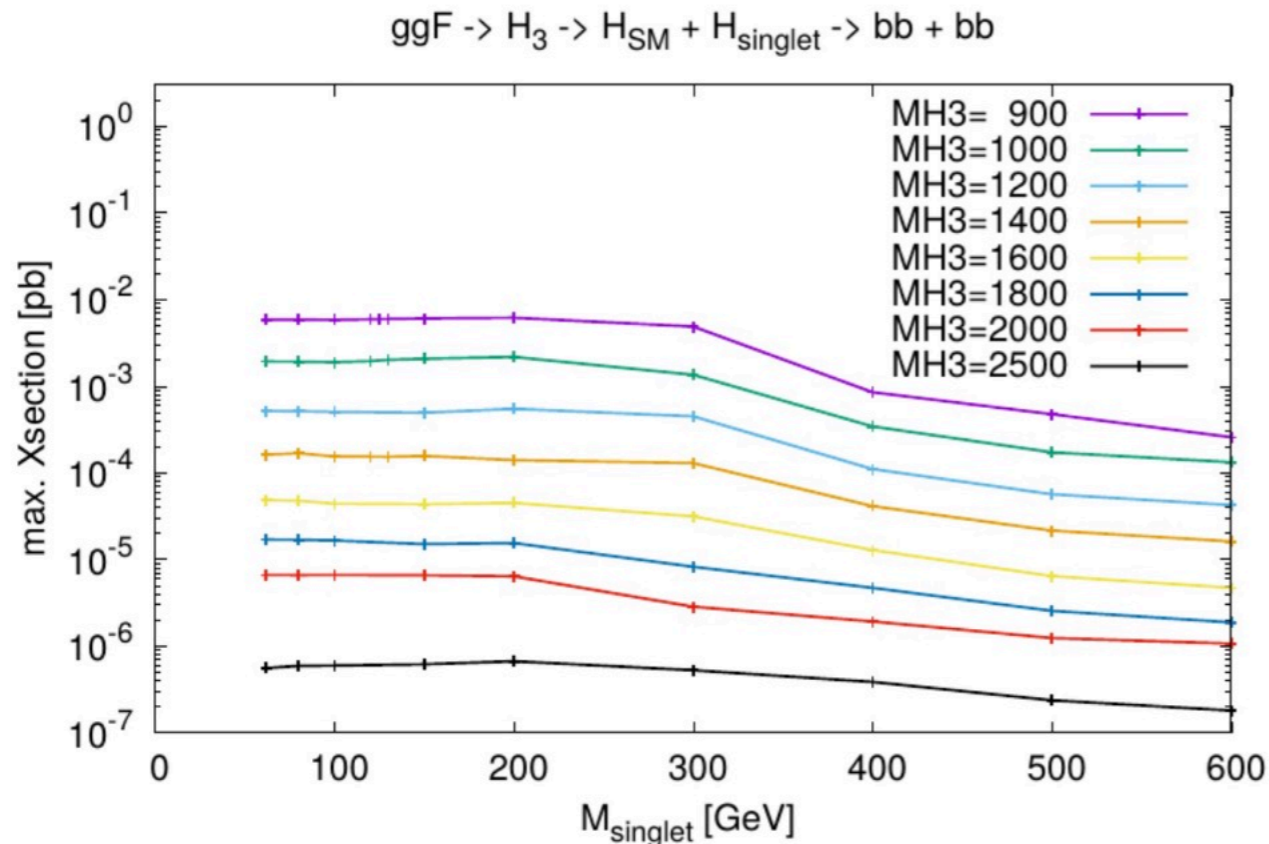
Analyses check if observed limits extend below max-allowed XSs

Two new results:

ATLAS: X→ Yh→ VVττ

CMS: hSM → aa → bbττ/bbμμ

Dedicated talks on Wed morning 1, 2
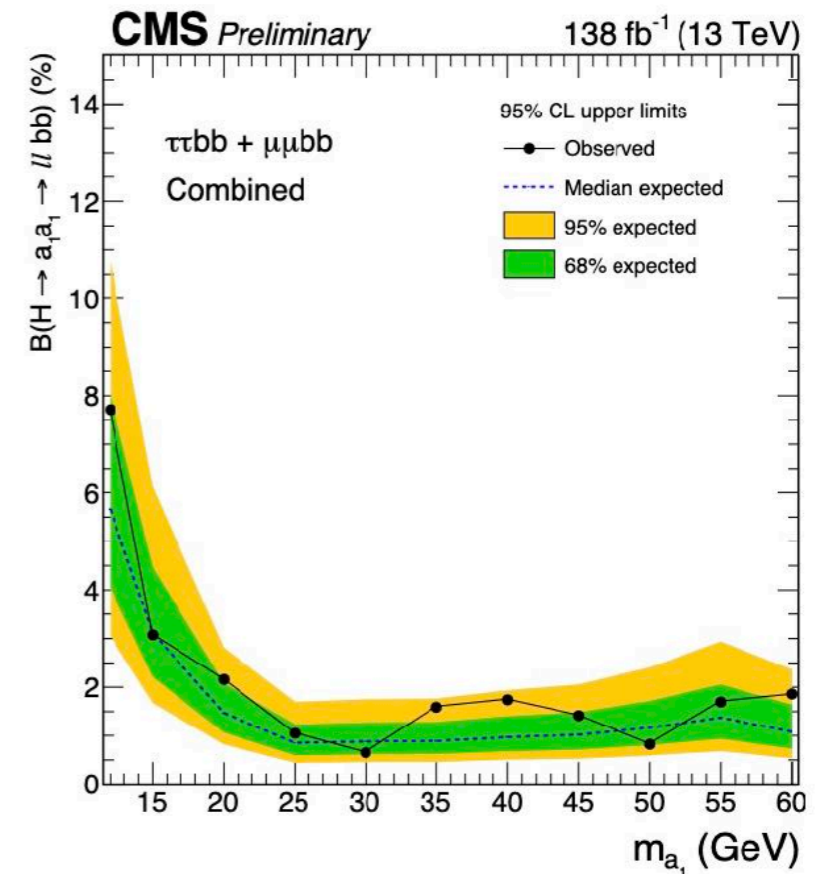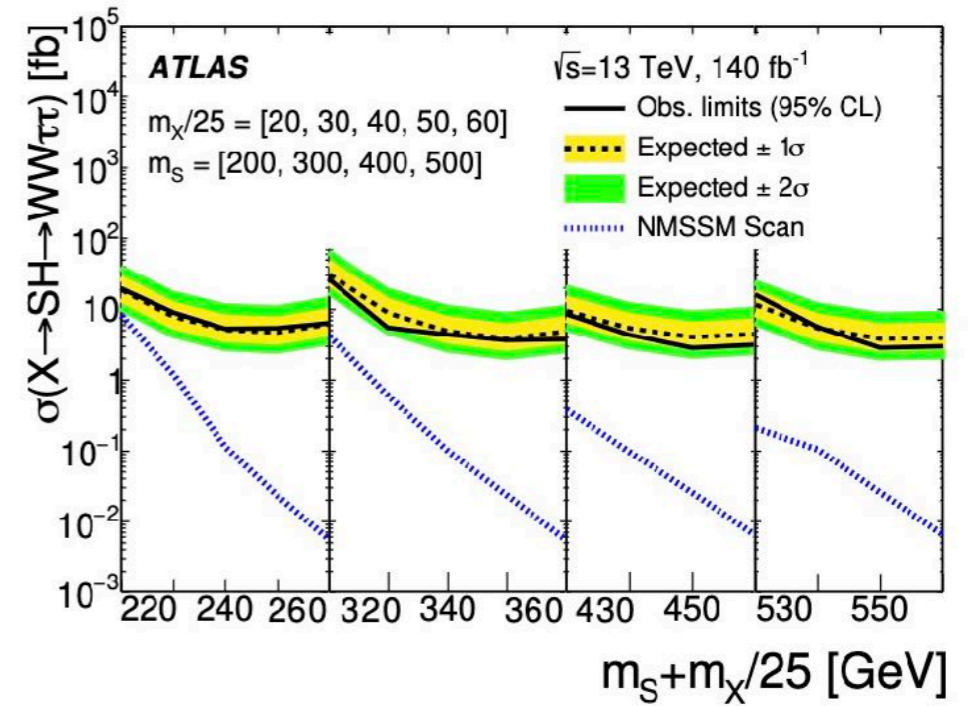
- $O((\alpha_t+\alpha_\lambda+\alpha_\kappa)^2+\alpha_t\alpha_s) \equiv O(\alpha_{new}^2)$ corrections to the ρ parameter and to M_W in the Complex NMSSM
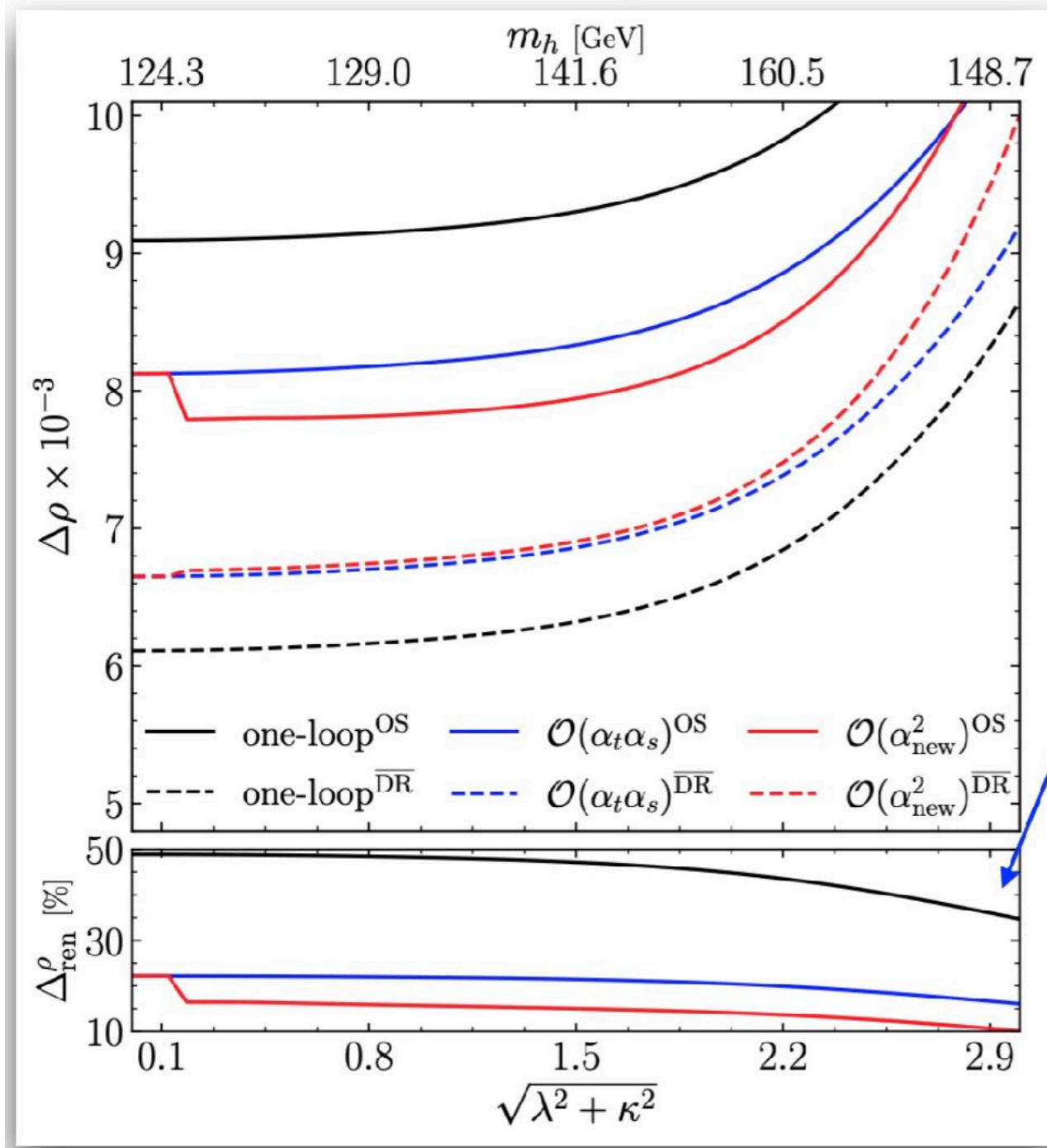
[Dao,Gabelmann,Mühlleitner,'23]

ρ Parameter:

- 2-loop corrections are significant

- theory uncertainty (through renorm. scheme variation) reduced at 2-loop:

one-loop: 55%
$O(\alpha_t\alpha_s)$: 22%
$O(\alpha_{new}^2)$: 16%

New results implemented in NMSSMCALC 5.2

NMSSM - Outlook and plans

❖ Provide theory predictions in the form of maximally $xsec^* \, \mathcal{BR}''$

  ◉ Valuable for experiments to compare results vs the most optimistic scenarios

❖ Newest 2-loop corrections to the ρ parameter and M_W are now available

❖ Strong interplay between theory and experiments:

  ◉ Still, some areas of improvement have been identified, (ie properly citing relevant work)

  ◉ Several active discussions how to get a clearer version of benchmarks accounting for experimental limits

❖ Need to coordinate efforts if more cross-sections for more mass-points are needed

  ◉ Not always trivial to produce

  ◉ Finer grids?

Exotic Higgs decays

ATLAS : **Verena Martinez**

CMS: **Alexis Kalogeropoulos**

LHCb: **Carlos Vazquez Sierra**
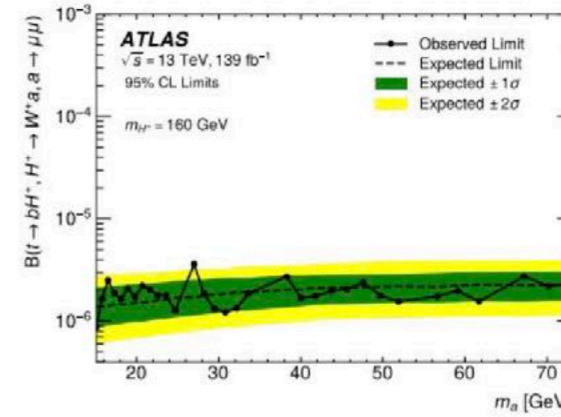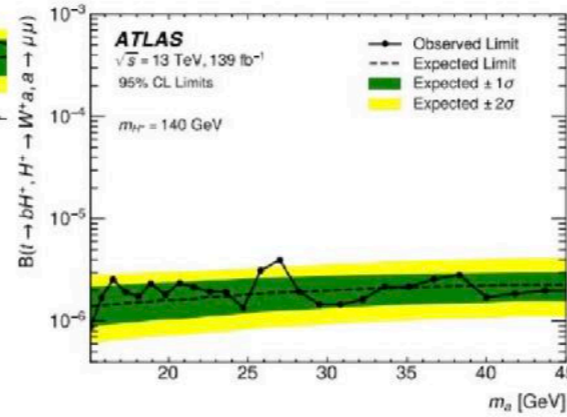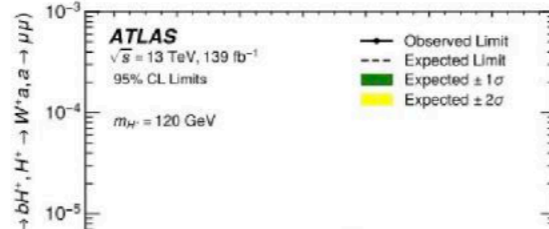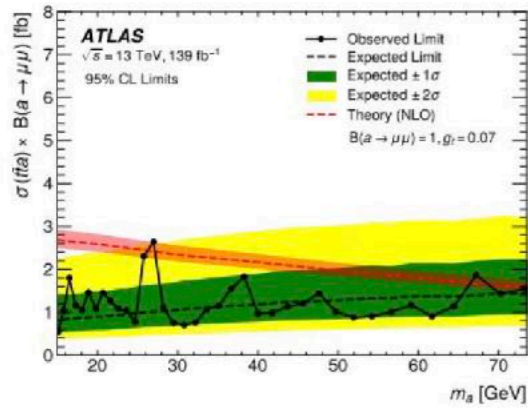
Theory: **Andrea Thamm, Brian Shuve**

✓ Inform, aggregate, and make recommendations for H_{125} decays to BSM states

✓ Uncovered signatures / suppressed modes

Mostly taken from Carlo's talk

Associated production w. top quark

UL@95% in production x-sections for the two benchmarks, after fit to m(μμ)
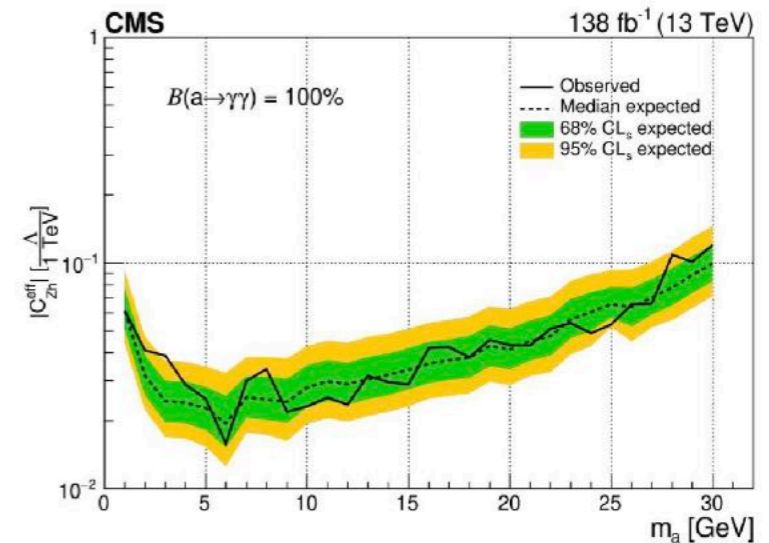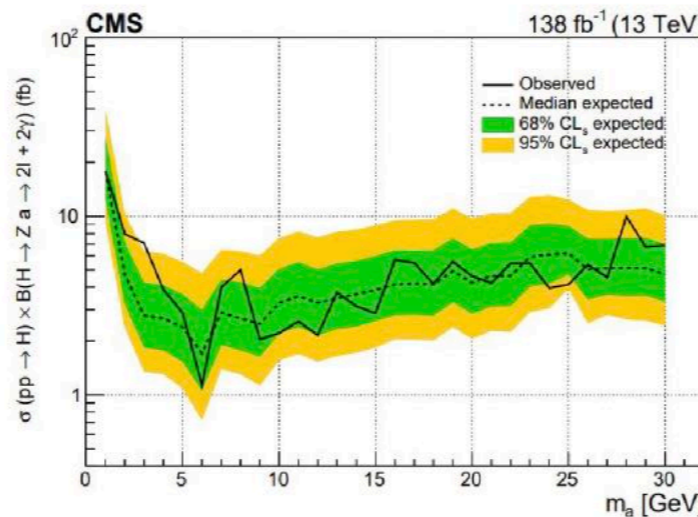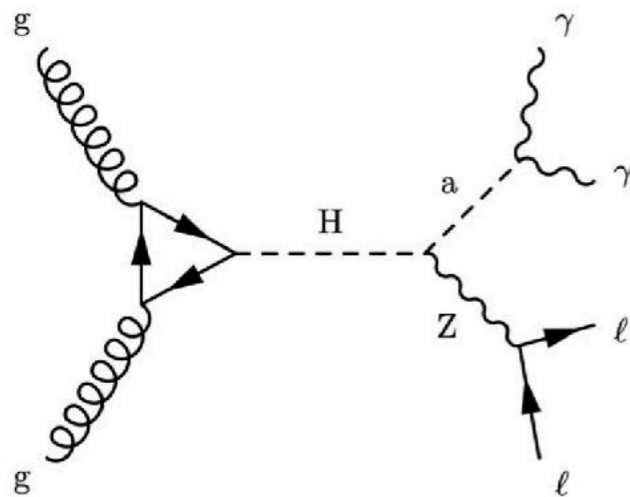

tt**a**, **a→μμ**

tt, t→b**H**±, **H**±→W**a**, **a→μμ**
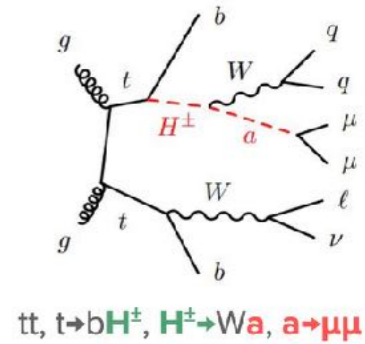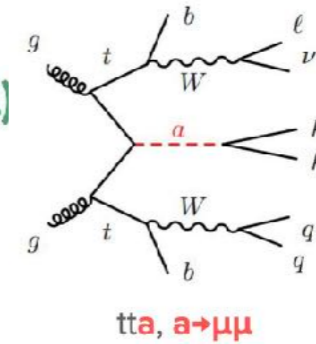
ATLAS:2304.12247

2.6σ local excess in m(a) = 27 GeV.

Limits compatible with SM.

CMS:2311.00130

UL@95% CL on ZH eff. coupling with B(a→γγ)=1, and on production x-sections:

H→aZ, **a→γγ**, **Z→ee/μμ**

SM compatible, excess for m(a)=3 GeV of **2.6 (1.3)σ** local (global) significance.

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Exotic Higgs decays - Results

Although still many unexplored channels, we had a decent number of new results :

✓ Exclusive Higgs decays into γ{ω/K*} [ATLAS:PLB 847 (2023) 138292]

✓ Search for a new Z' gauge boson in 4μ decays [ATLAS:JHEP 07 (2023) 90]

✓ Dark showers using data scouting [2303.04167]

✓ Trigger-level track reconstruction for exotic signatures [2211.05720]

✓ Exotic Higgs decays in VBF + γ [2306.01901]

✓ Higgs coupling deviations [2202.01228]

✓ Associated production w. top quark (ATLAS:2304.12247, CMS:2311.00130)

✓ Search for h➤aa➤ 2μ2b/2b2τ CMS:http://cds.cern.ch/record/2853298 (Pallabi on Wed)

✓ Search for h➤aa➤ 4γ ATLAS:http://cds.cern.ch/record/2867933 (Peter on Wed)

Exotic Higgs decays - Overview and plans

❖ Identify still uncovered and challenging signatures

　◉ Benchmarks for ALPs to γ/g decays, and for semi-visible decays (ff+MET)

　◉ Reinterpretation of prompt decays to LLP scenarios

　◉ Higgs to invisible

　◉ …

❖ Ramp up activities: more regular meetings, review of current status etc Run3 etc

❖ Always relevant :

　◉ Suggest common benchmarks for searches

　◉ Identify synergies with other sub-working groups and with other working groups, e.g. LLPC LLPs WG and DM WG.

(b)bH

ATLAS : **Tim Barlow**

CMS: **Chayanit Asawatangtrakuldee**

Theory: **Michael Spira, Marius Wiesemann**

✓ Provide inclusive and exclusive cross-sections for bbh production and Monte-Carlo generation tools.

✓ The cross-section calculation in **BSM** is the shared responsibility with WG3/MSSM

Not a dedicated talk this time

Material comes from M.Zaro, M.Spira, M.Wiesemann and Javier's talk

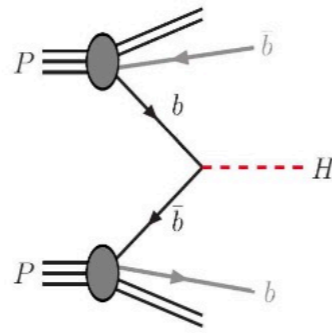# Associated bbH production

4-flavour scheme
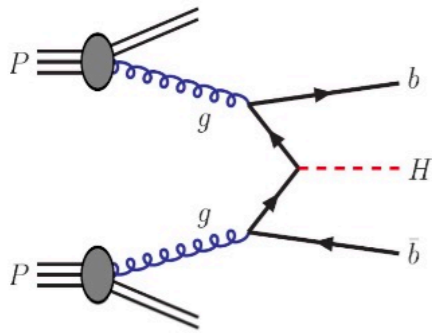
- massive b's
- potentially large logs $\ln(m_b/Q)$
- power terms $(m_b/Q)^n$
- involved $2 \to 3$ at LO
- 2 exclusive b's at LO
- b(-tag) well defined

5-flavour scheme

- massless b's
- resummation into b-PDFs
- —
- simple $2 \to 1$ at LO
- exclusive b's at higher orders
- b part of light jets

▶ **total cross section:**
  - total rates: new consistently matched 4+5FS predictions
  - two independent approaches in perfect agreement
  - good agreement with empirical Santander result
  - recommendation: NLO+NNLL$_{\mathrm{partial}}$+$y_b y_t$ reference prediction, mentioning that it was checked against FONLL

▶ **MC generation:**
  - use 4FS NLO+PS for bbH signal simulation
  - three MC generators available for bbH in 4FS
  - good agreement among them (in particular: shape-wise)
  - reasonable agreement with merged 5FS computation
  - recommendation: use at least two MCs to address systematics

  "open" issue: acceptances quite MC dependent

- Putting all together, asking for 1 b jet (ak$_T$, R=0.4, p$_T$>30 GeV, $|\eta|$<2.5)
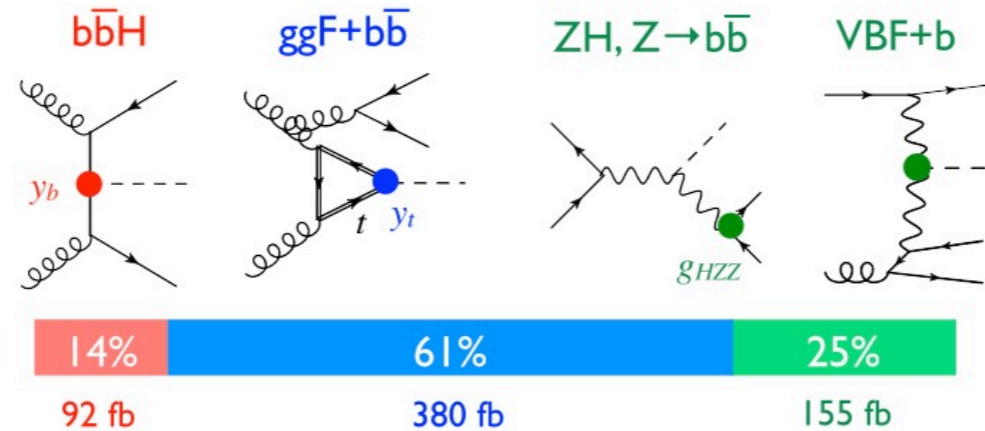
bbH final state is only marginally sensitive to y_b

This holds true in the SM, and BSM for O(1) effects on y_b

For extra Higgs bosons ($\neq$125 GeV), estimates of sensitivity should account for all the backgrounds
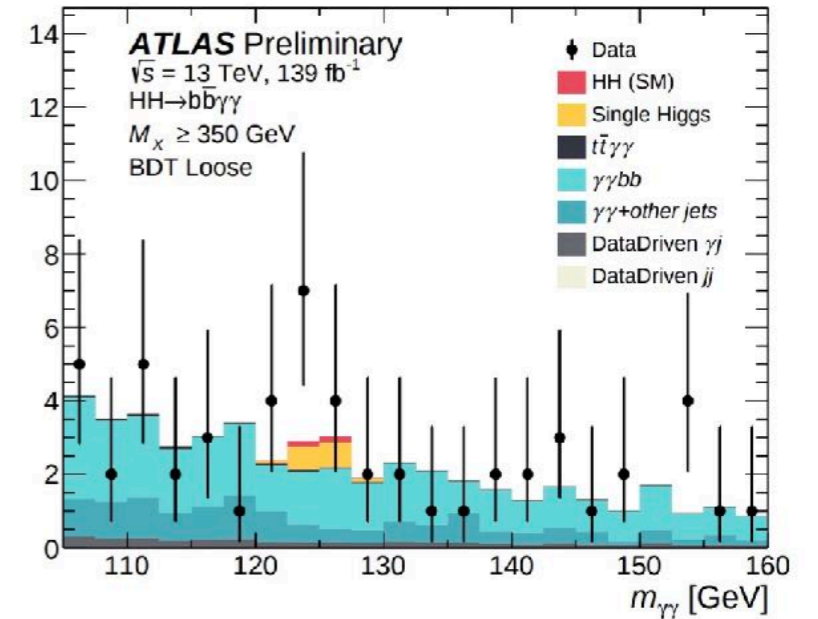
Higgs decay remains the most effective way to constrain y_b
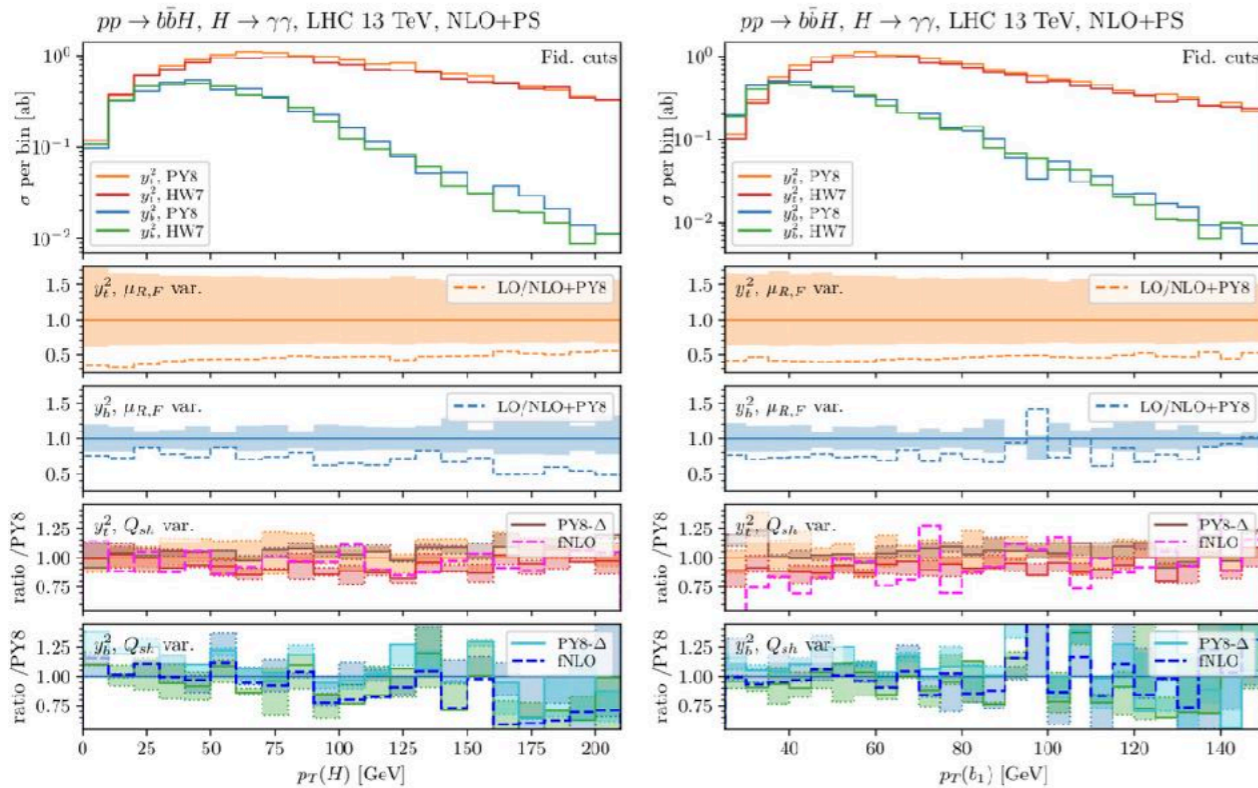
(b)bH : NLO+PS study on bbH for HH

bbH can have a strong impact on HH production

HH comes a very small xsec ➜ we need to control very well the bkg (including uncert)

Differential distributions

- Top Yukawa contribution prefers harder H/b jet, due to contributions with hard gluon recoiling against H
- Nice agreement in the shapes obtained with PY8 and HW7

Impact on HH searches

- Result from ggF NNLOPS close to upper uncertainty band of NLO 4FS
- Larger differences for low invariant masses
- Size and uncertainties of this background are reduced in our NLO 4FS calculation

  ⬇

  Positive impact on HH searches

- We have propagated the new NLO 4FS rates to an ATLAS search in the $2b2\gamma$ channel [2112.11876] as well as the $2b2\tau$ channel [2209.10910]

  ↘ Rescaled NNLOPS sample to NLO 4FS rates

- Subtlety: NNLOPS sample also used for b-jet mistagging estimate! Only rescale the true b-jet contribution (80% of the full sample)
- We also replace the 100% uncertainty by the NLO 4FS scale uncertainties
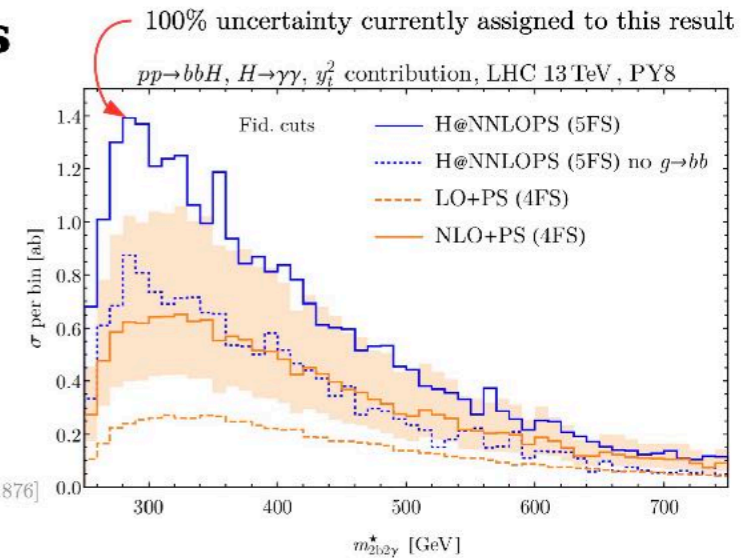
Improvement in XS limits	Current	HL-LHC
$2b2\gamma$	~2%	~5%
$2b2\tau$	~10%	~20%

Larger improvement in $2b2\tau$ due to analysis being less stat. dominated, plus larger relative contribution from single Higgs background

More details on Javier's talk

Summary

❖ All WG3 sub-groups have a quite packed list of ongoing/to-do/wish list

  ◉ Some have or may get higher priority than others (like providing 13.6 TeV xsecs)

❖ We can always improve the experiment–theory interactions and cross-talks

❖ Identify uncovered and interesting scenarios that can already be looked at with Run2 data, as it will take some time to benefit from Run3 - what are we missing?

  ◉ What about employing also new tools, like taggers, ParticleNet etc?

❖ Some groups are thinking about creating some document that can be used as a reference (YR…?)