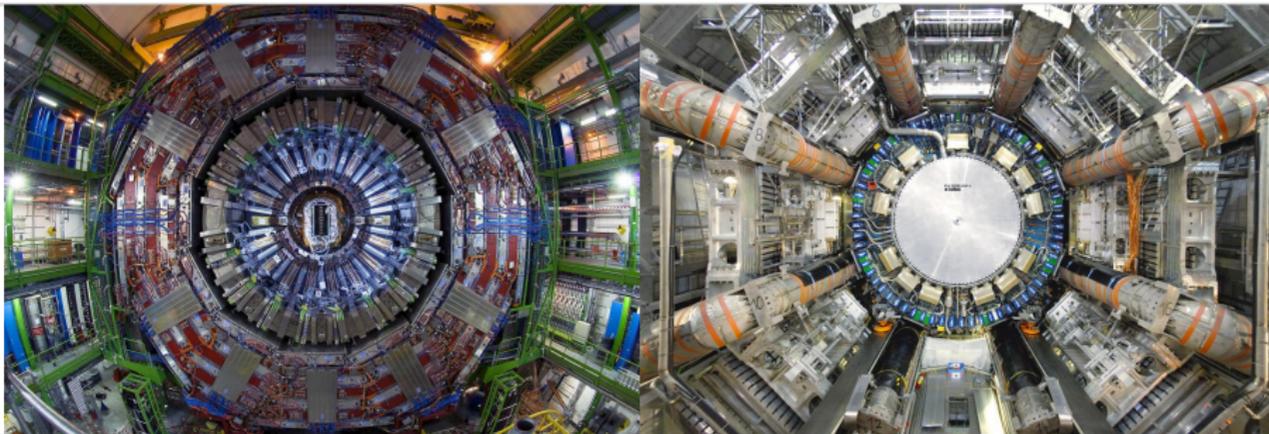


MSSM Subgroup Update (ATLAS and CMS)

LHCHXSWG Workshop, November 9 - 11, 2020

Timothy Barklow, **Artur Gottmann** on behalf of the MSSM subgroup | November 10, 2020



Experimental Results

Published Analyses from ATLAS

Results based on entire Run 2 data with 139 fb^{-1} :

- $H, A \rightarrow \tau\tau$: [doi:10.1103/PhysRevLett.125.051801](https://doi.org/10.1103/PhysRevLett.125.051801)
- $H^\pm \rightarrow tb$: [ATLAS-CONF-2020-039](https://arxiv.org/abs/ATLAS-CONF-2020-039)

Results based on 2015 & 2016 data with 36 fb^{-1} :

- $H^\pm \rightarrow \tau\nu$: [doi:10.1007/JHEP09\(2018\)139](https://doi.org/10.1007/JHEP09(2018)139)
- $H \rightarrow ZZ$ (4ℓ and $2\ell 2\nu$ for $\ell \in \{e, \mu\}$): [doi:10.1140/epjc/s10052-018-5686-3](https://doi.org/10.1140/epjc/s10052-018-5686-3)
- $H \rightarrow WW$ ($e\mu 2\nu$): [doi:10.1140/epjc/s10052-017-5491-4](https://doi.org/10.1140/epjc/s10052-017-5491-4)
- $A \rightarrow Zh$ ($2\ell 2b$ for $\ell \in \{e, \mu\}$ and $2\nu 2b$): [arXiv:1712.06518](https://arxiv.org/abs/1712.06518)
- $H \rightarrow hh$ ($4b$, $2b 2\tau$ and $2b 2\gamma$): [doi:10.1016/j.physletb.2019.135103](https://doi.org/10.1016/j.physletb.2019.135103)

Results based on 2015 & 2016 data with 27 fb^{-1} :

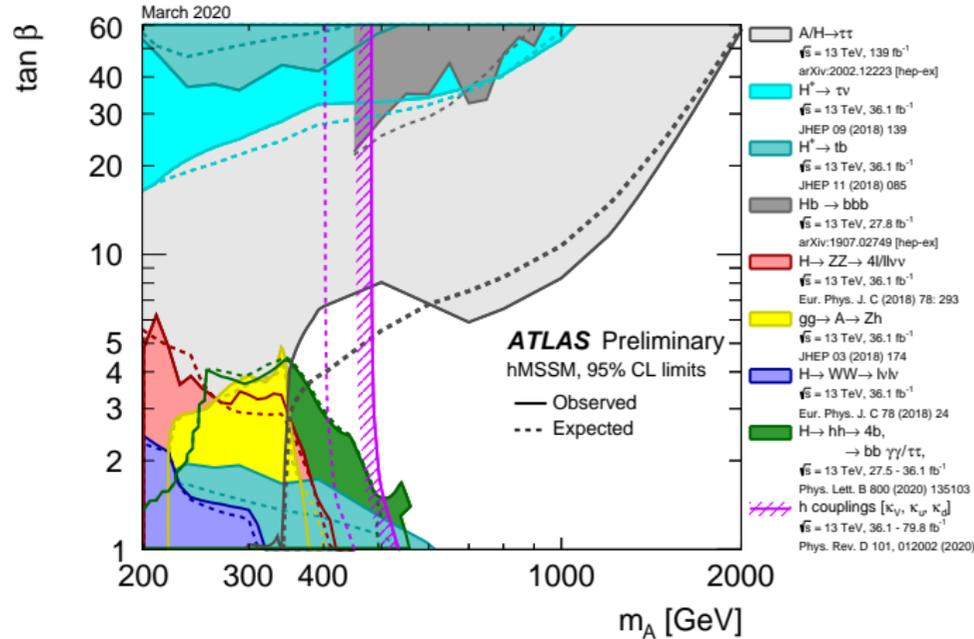
- $b(b)H \rightarrow b(b)bb$: [doi:10.1103/PhysRevD.102.032004](https://doi.org/10.1103/PhysRevD.102.032004)

Published Analyses from CMS

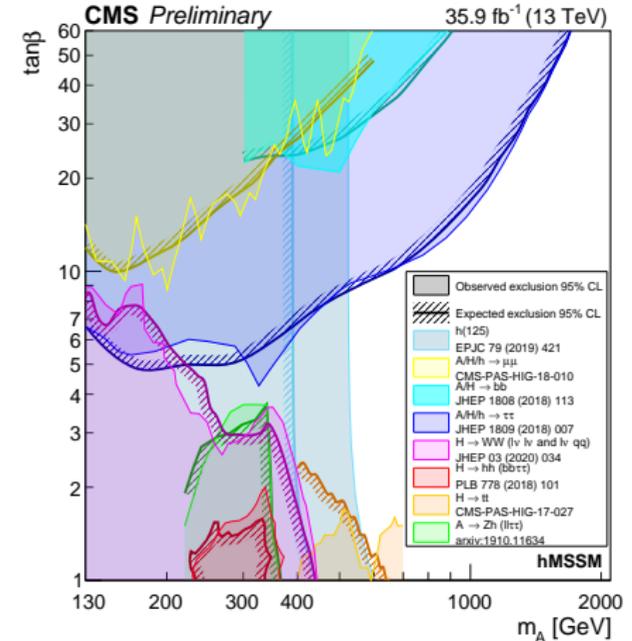
Results based on 2016 data with 35.9 fb^{-1} :

- $H^\pm \rightarrow tb$ (all-jet): [doi:10.1007/JHEP07\(2020\)126](https://doi.org/10.1007/JHEP07(2020)126)
- $H^\pm \rightarrow tb$ (with electrons or muons): [doi:10.1007/JHEP01\(2020\)09](https://doi.org/10.1007/JHEP01(2020)09)
- $H^\pm \rightarrow \tau\nu$: [doi:10.1007/JHEP07\(2019\)142](https://doi.org/10.1007/JHEP07(2019)142)
- $H \rightarrow WW$ ($2\ell 2\nu$ and $\ell\nu 2q$ for $\ell \in \{e, \mu\}$): [doi:10.1007/JHEP03\(2020\)034](https://doi.org/10.1007/JHEP03(2020)034)
- $A \rightarrow Zh$ ($2\ell 2\tau$ for $\ell \in \{e, \mu\}$): [doi:10.1007/JHEP03\(2020\)065](https://doi.org/10.1007/JHEP03(2020)065)
- $H \rightarrow hh$ ($2b 2\tau$): [doi:10.1016/j.physletb.2018.01.001](https://doi.org/10.1016/j.physletb.2018.01.001)
- $H, A \rightarrow tt$: [doi:10.1007/JHEP04\(2020\)171](https://doi.org/10.1007/JHEP04(2020)171)
- $H, A \rightarrow bb$: [doi:10.1007/JHEP08\(2018\)113](https://doi.org/10.1007/JHEP08(2018)113)
- $h, H, A \rightarrow \mu\mu$: [doi:10.1016/j.physletb.2019.134992](https://doi.org/10.1016/j.physletb.2019.134992)
- $h, H, A \rightarrow \tau\tau$: [doi:10.1007/JHEP09\(2018\)007](https://doi.org/10.1007/JHEP09(2018)007)

Summaries of Results for hMSSM



ATL-phys-PUB-2020-006



public Higgs PAG Summary Plots

Types of Results provided/desired

Provided results, mostly also available on [HEPData](#):

- Model-independent upper limits on the product of cross-section and branching fraction(s) ($\sigma \cdot \text{BR}$)
- Exclusion contours in a parameter space of a benchmark model (e.g. $m_A, \tan\beta$ of MSSM)
- Model-independent likelihood scans, e.g. in $\sigma \cdot \text{BR}$ and mass of the Higgs boson
 - Currently only provided by $\phi \rightarrow \tau\tau$ analyses at [HEPData](#)

Desired likelihood scans for MSSM, as reported in [October 18, 2019](#):

Channel	Discrete parameters	Continuous parameters
$pp \rightarrow \phi + X \rightarrow \tau\tau + X$	m_ϕ	$\sigma(\text{gg}\phi) \cdot \text{BR}, \sigma(\text{bb}\phi) \cdot \text{BR}$
$pp \rightarrow \text{b(b)}\phi + X \rightarrow \text{b(b)}\text{bb} + X$	m_ϕ	$\sigma(\text{b(b)}\phi) \cdot \text{BR}$
$pp \rightarrow \phi + X \rightarrow \text{tt} + X$	$m_\phi, \Gamma_\phi/m_\phi$	$g_{\phi\leftrightarrow\text{tt}}$
$pp \rightarrow \phi + X \rightarrow \mu\mu + X$	$m_\phi, \Gamma_\phi/m_\phi$	$\sigma(\text{gg}\phi) \cdot \text{BR}, \sigma(\text{bb}\phi) \cdot \text{BR}$
$pp \rightarrow \text{tbH}^\pm + X \rightarrow \text{tb}\{\text{tb}, \tau\nu\} + X$	m_{H^\pm}	$\sigma(\text{tbH}^\pm) \cdot \text{BR}$
$pp \rightarrow \text{t} + X \rightarrow \text{bH}^\pm + X \rightarrow \text{b}\{\text{tb}, \tau\nu\} + X$	m_{H^\pm}	$\text{BR}(\text{t} \rightarrow \text{bH}^\pm) \cdot \text{BR}$

Likelihood Scans

- In general, there aren't any objections to provide such scans
- Following constraints may play a role:
 - Such scans are usually time-consuming and planned to be provided as additional material
 - There shouldn't be too many parameters to scan (e.g. up to 3 or 4)
 - In some cases (e.g. for Γ_ϕ) additional MC may be required
- Each analysis group to be approached individually to estimate the effort case by case

Questions

- Do we agree on the parameter table on the slide before?
→ Matches most the derived upper limits and exclusion contours of the analyses
- Further suggestions for parameterization?

Planned Analyses

ATLAS:

- light charged Higgs search $t \rightarrow H^\pm b \rightarrow bcb \sim$ Moriond 2021
- \sim Summer 2021:
 - Charged Higgs search in $H^\pm \rightarrow \tau\nu$, $H^\pm \rightarrow tb$ and $H^\pm \rightarrow W^\pm h$ final states
 - $\phi \rightarrow \gamma\gamma$ with b-jets
 - b-associated $\phi \rightarrow bb$

CMS:

- All analyses to be updated to full Run 2
- Next to come: $H \rightarrow \tau\tau$, $H \rightarrow bb$, $H \rightarrow \mu\mu$ (\sim Moriond 2021/Summer 2021)

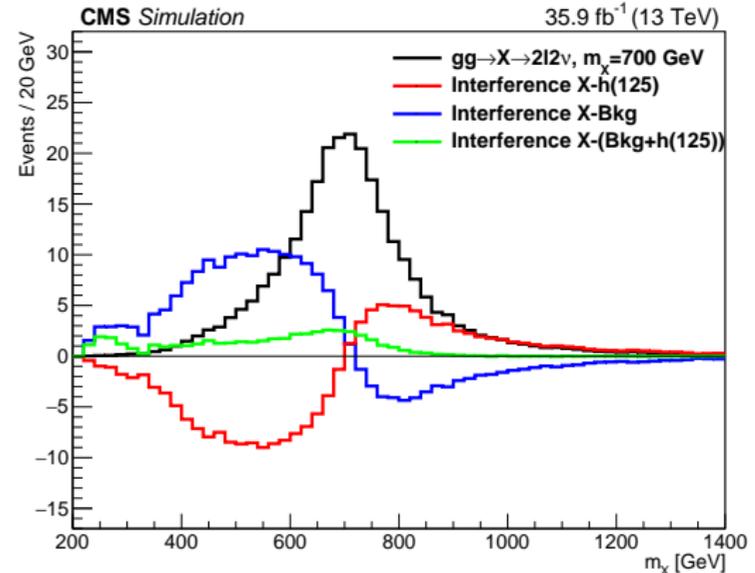
Sidenote to the published analyses listed before:

- Chosen by having MSSM specific content, many more analyses with e.g. 2HDM focus are present at public pages

Signal Modelling

Interference Effects

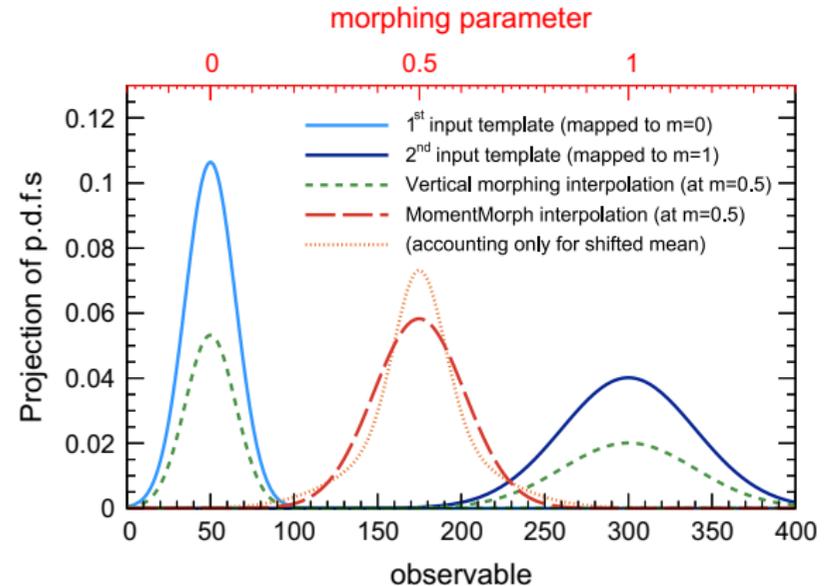
- Some analyses (e.g. $H \rightarrow tt$ and $H \rightarrow WW$) consider interference signal \leftrightarrow background
- Possible solutions:
 - Production of appropriate MC samples taking the interference effects into account
 - Event-by-event reweighting can be also applied to the nominal signal shape



from [doi:10.1007/JHEP03\(2020\)034](https://doi.org/10.1007/JHEP03(2020)034)

Masses and Decay Widths

- Signal templates produced for a finite number of masses and (relative) widths
 → Therefore m_ϕ and Γ_ϕ/m_ϕ rather discrete
- Intermediate parameter points can be obtained as follows:
 - For binned signal templates, applying morphing algorithms
 - Analytic signal modelling allows for continuous parameterization



from [doi:10.1016/j.nima.2014.10.033](https://doi.org/10.1016/j.nima.2014.10.033)

Neutral Higgs Boson Production

Main production modes that can be considered in MSSM:

- Scalars h, H : $gg\phi, bb\phi, VBF \phi$
 - VBF for H , relevant for e.g. $H \rightarrow WW$ analysis
 - VBF for h , important contribution e.g. for the $\tau\tau$ channel, if h is taken into account
- Pseudoscalar A : $gg\phi, bb\phi$

Based on these contributions following signal modelling can be done:

- H, A in addition to BG or BG + h_{SM}
- h, H, A + BG, compared with BG or BG + h_{SM}

→ Important for the hypothesis testing to be performed

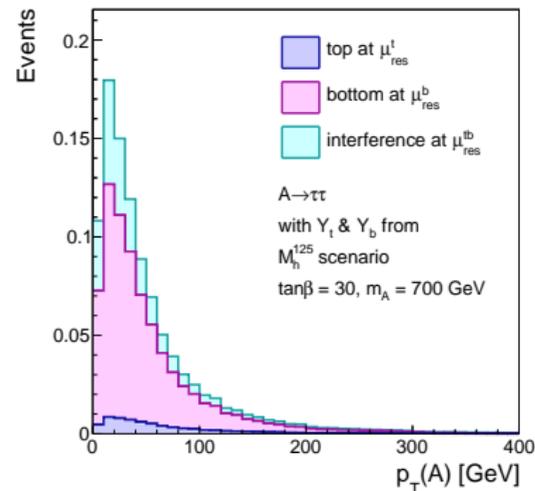
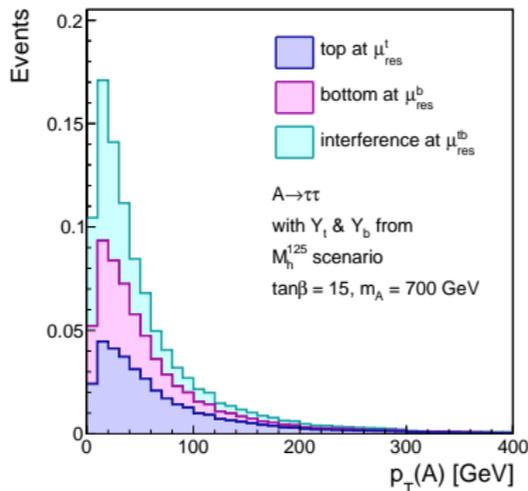
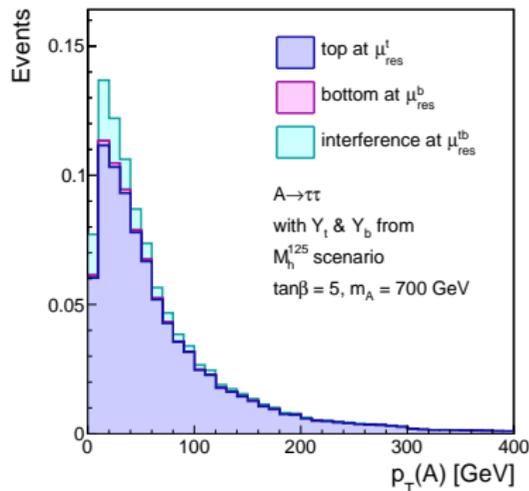
B-associated Production

- Studies were performed for b-jet acceptance differences reported in YR4 between POWHEG and Madgraph 5 at NLO QCD
- These differences can be reduced by adjusting the resummation parameter, e.g. Q_{sh} in Madgraph 5 at NLO QCD
- Uncertainties to be taken into account for the chosen MC generator:
 - b-jet acceptance: (μ_R, μ_F) variations, resummation scale uncertainties
 - Residual difference between POWHEG and Madgraph 5, mostly visible in $p_T(\phi)$
- Details in [Abdollah's talk](#)

Question

- Usually, such uncertainties are implemented with a Gaussian prior
- For which variation would a flat prior be more suitable? Probably for resummation scale?

Gluon Fusion



from <http://cds.cern.ch/record/2742868>

$$\hat{\sigma} = \left(\frac{\hat{Y}_t}{Y_t} \right)^2 \sigma_t(\mu_t) + \left(\frac{\hat{Y}_b}{Y_b} \right)^2 \sigma_b(\mu_t) + \left(\frac{\hat{Y}_t \hat{Y}_b}{Y_t Y_b} \right) (\sigma_{t+b}(\mu_{tb}) - \sigma_t(\mu_{tb}) - \sigma_b(\mu_{tb}))$$

Gluon Fusion

$$\hat{\sigma} = \left(\frac{\hat{Y}_t}{Y_t}\right)^2 \sigma_t(\mu_t) + \left(\frac{\hat{Y}_b}{Y_b}\right)^2 \sigma_b(\mu_b) + \left(\frac{\hat{Y}_t \hat{Y}_b}{Y_t Y_b}\right) (\sigma_{t+b}(\mu_{tb}) - \sigma_t(\mu_{tb}) - \sigma_b(\mu_{tb}))$$

- At NLO in QCD, $p_T(\phi)$ has different shape depending on the choice of $\tan\beta$
 - Multi-problem, that can be addressed with three different resummation scales
- To reduce computational effort, produce **one** inclusive sample per mass at a chosen scale μ_{incl} .
- Reweight its $p_T(\phi)$ to the three contributions **t-only**, **b-only**, and **tb-interference**
 - Individual contributions not dependent on $\tan\beta$
- Put these contributions together to one with the ratios of Yukawa coupling factors \hat{Y}/Y , which depend on $\tan\beta$.
- Uncertainties on (μ_t, μ_b, μ_{tb}) can be introduced as 3 individual nuisance parameters acting on the corresponding contribution
 - **Flat** prior should be used, since no scale value is more preferred than other

Vector Boson Fusion

- Produce MC with SM couplings chosen at first
- Reweight the contribution inclusively by:
 - $H: \cos(\beta - \alpha)^2 \cdot BR$
 - $h: \sin(\beta - \alpha)^2 \cdot BR$
- A strong sensitivity to the SM-like scalar (usually h) by proper categorization can be exploited in an MSSM analysis.
Details: <http://cds.cern.ch/record/2742868>
- With Run 2 could be sensitive to 5-10% deviations from SM expectation
→ VBF production can be useful to check MSSM predictions for BR

MSSM Benchmark Scenarios

Available Scenarios

In total 11 MSSM scenarios to be tested:

- $M_h^{125}, M_{h, \text{EFT}}^{125}$
- $M_h^{125}(\tilde{\chi}), M_{h, \text{EFT}}^{125}(\tilde{\chi})$
- $M_h^{125}(\tilde{\tau})$
- $M_h^{125}(\text{alignment})$
- $M_{h_1}^{125}(\text{CPV})$
- $M_h^{125, \mu^-} (\mu = -1, -2, -3 \text{ TeV})$
- new hMSSM

Question

- For analyses, a subset is included in the publication, the remaining ones as additional material
- OK to define e.g. $M_h^{125}, M_h^{125}(\tilde{\chi}),$ and $M_h^{125}(\tilde{\tau})$ as the main ones?
- Is such a choice analysis dependent?

Uncertainty Treatment

Uncertainty sources for $\sigma \cdot \text{BR}$ provided with MSSM benchmark scenarios,
e.g. dependent on $m_A, \tan\beta$

- $gg\phi$: p.d.f. + α_s uncertainties, and (μ_R, μ_F) uncertainties
- $bb\phi$: a single, total theory uncertainty

Question

Can be implemented as a nuisance parameter with a Gaussian prior. Is that correct?