Searches for Higgs Bosons beyond the SM

On behalf of the ATLAS and CMS Collaborations

Roger Wolf

24. July 2018

Higgs sector beyond the SM

- Search for Higgs physics beyond the SM: important pillar of the Higgs physics program of the LHC experiments.

- Equally important to SM interpretations/investigation of properties of h(125).

Investigate properties of the observed Higgs boson.

→ Is h(125) THE Higgs boson of the SM?

- Properties different from SM expectation.
- Exotic decays not expected within the SM.

Search for more complex Higgs sector.

→ Is h(125) the ONLY Higgs boson?

- More than one $\mathrm{SU}(2)_\mathrm{L}$ doublet?
- Predicton of <u>many</u> BSM models (among those SUSY).

- Rich program to search for new physics in the Higgs sector. → Concentrate on those searches most relevant for the (N)MSSM.

Higgs sector in SUSY

NB: w/o CP-violation in the SUSY Higgs sector.

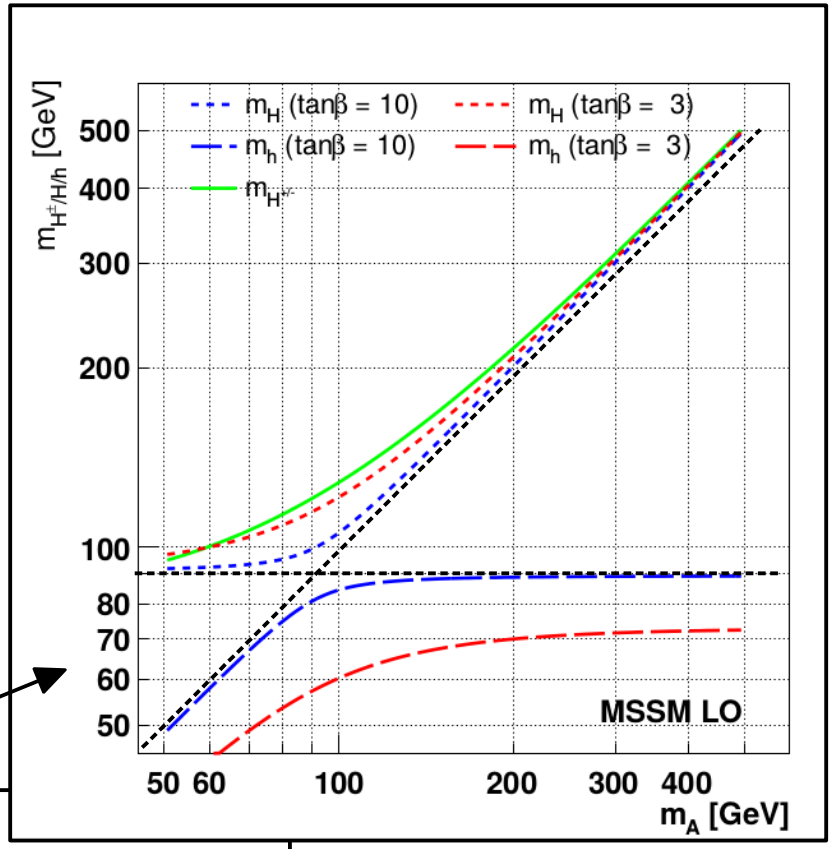
- SUSY requires @ least 2 Higgs doublets (2HDM type-II) → **five Higgs bosons**:

$$\phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}, \quad Y_{\phi_u} = +1, \quad v_u: \text{VEV}_u$$

$$\phi_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}, \quad Y_{\phi_d} = -1, \quad v_d: \text{VEV}_d$$

$$N_{\text{ndof}} = 8 - \underbrace{3}_{W,\ Z} = \underbrace{5}_{H^\pm,\ H,\ h,\ A}$$

- Strict mass requirements imposed by symmetry
- At tree level two free parameters: m_A, $\tan\beta = v_u/v_d$.



$$m^2_{H^\pm} = m^2_A + m^2_W$$

$$m^2_{H,\,h} = \frac{1}{2}\left(m^2_A + m^2_Z \pm \sqrt{\left(m^2_A + m^2_Z\right)^2 - 4m^2_A m^2_Z \cos^2 2\beta}\right)$$

$$\tan\alpha = \frac{-(m^2_A + m^2_Z)\sin 2\beta}{(m^2_Z - m^2_A)\cos 2\beta + \sqrt{\left(m^2_A + m^2_Z\right)^2 - 4m^2_A m^2_Z \cos^2 2\beta}}$$

α : angle between H and h in mass matrix

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m_h and $\tan\beta$ in the MSSM

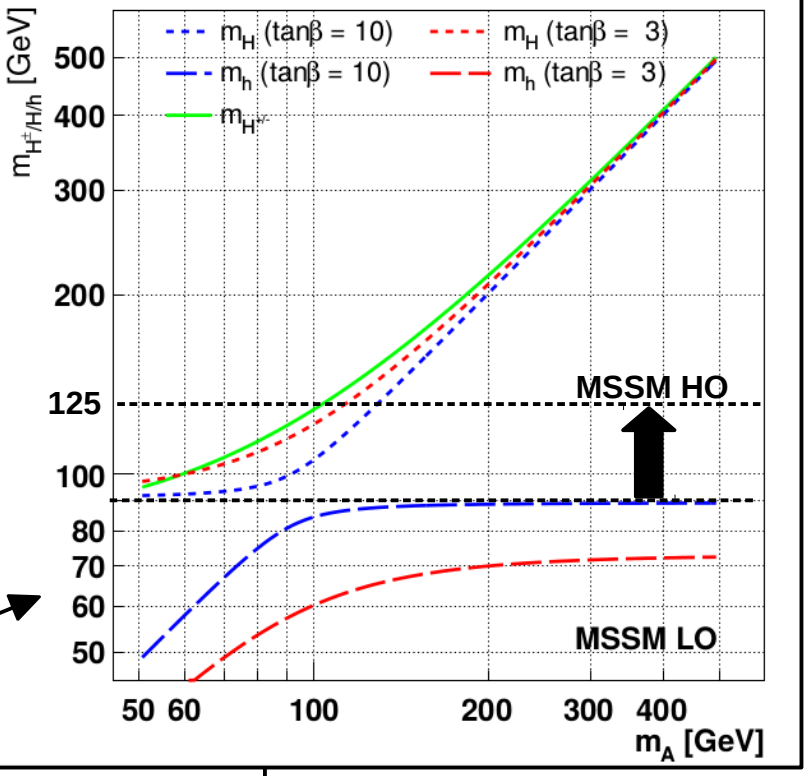
NB: w/o CP-violation in the SUSY Higgs sector.

$$m_h^2 \approx m_Z^2 \cos^2 2\beta + \Delta_{\text{rad}}$$

$$\Delta_{\text{rad}} = \frac{3}{(4\pi)^2}\frac{m_t^4}{v^2}\left(\ln\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right)$$

- +30% of m_h due to higher order corrections.
- Following factors help to increase m_h: large m_t, large $m_{\tilde{t}}$, large X_t , large $\tan\beta$.

$$X_t = m_t\,(A_t - \mu \cot\beta)$$



$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{H,\,h}^2 = \frac{1}{2}\left(m_A^2 + m_Z^2 \pm \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4 m_A^2 m_Z^2 \cos^2 2\beta}\right)$$

$$\tan\alpha = \frac{-(m_A^2 + m_Z^2)\sin 2\beta}{(m_Z^2 - m_A^2)\cos 2\beta + \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4 m_A^2 m_Z^2 \cos^2 2\beta}}$$

Also see presentation by S. Heinemeyer Wed 16:10 – 16:30.

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Down-type fermions in the MSSM

NB: w/o CP-violation in the SUSY Higgs sector.

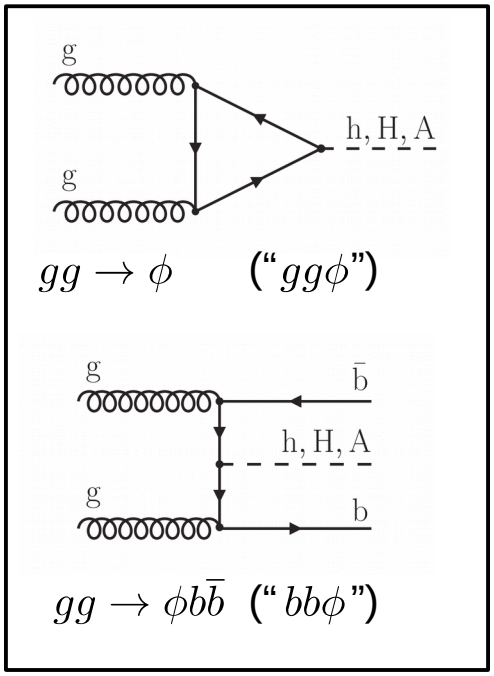
CP-odd part of coupling.

	g_{VV}	g_{uu}	g_{dd}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \to 0$	$\sin\alpha/\sin\beta \to \cot\beta$	$\cos\alpha/\cos\beta \to \tan\beta$
h	$\sin(\beta-\alpha) \to 1$	$\cos\alpha/\sin\beta \to 1$	$-\sin\alpha/\cos\beta \to 1$

Relative to corresponding couplings to a SM Higgs boson.

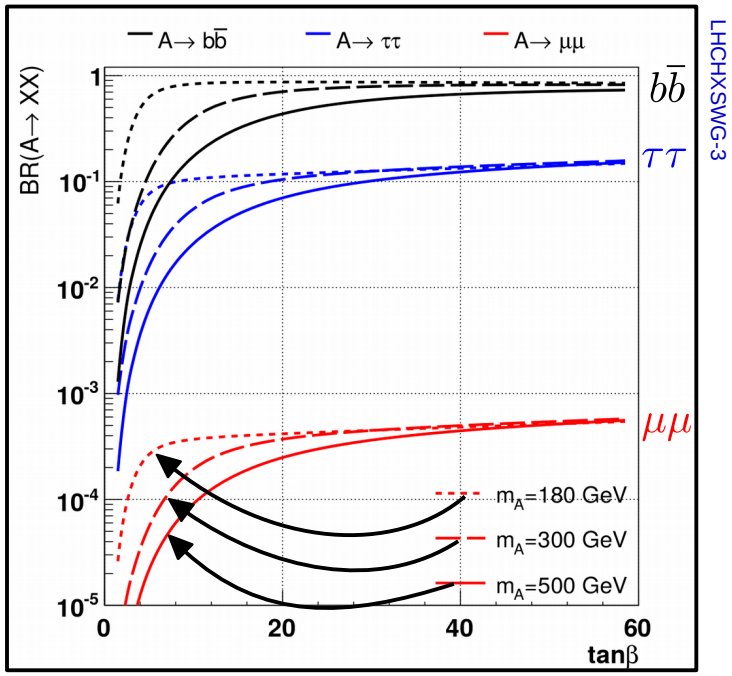
For $m_A \gg m_Z$: $\alpha \to \beta - \pi/2$ (coupling A/H to down-type fermions enhanced by $\tan\beta$).

Production modes:



X

Decay channels: m_h^{mod+}



MSSM → NMSSM Higgs sector

Also check slides by C. Beskidt Mon 15:00 – 15:20 & presentation by S. Heinemeyer Wed 18:20 – 18:40.

- Extend Higgs sector by one more singlet field S:

$$W_{\mathrm{NMSSM}} = W_{\mathrm{MSSM}} + \lambda S \phi_u \phi_d + \frac{1}{3}\kappa S^3$$

Higgs relevant part of Superpotential in the MSSM.

Coupling of S to Higgs doublet fields ϕ_u and ϕ_d.

S Self-coupling.

Mass term for light Higgs boson h_1 or h_2:

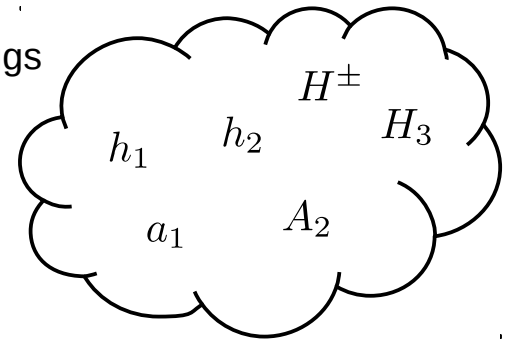
$$m_h^2 \approx m_{\mathrm{Z}}^2 \left(\cos^2 2\beta + \frac{\lambda^2}{g^2} \sin^2 2\beta \right) + \Delta_{\mathrm{rad}}$$

LO MSSM part to m_h^2.

LO NMSSM part to m_h^2.

- Solves "μ-problem".
- Adds terms to m_h^2 at LO.
- Adds more degrees of freedom:

5→7 Higgs bosons:

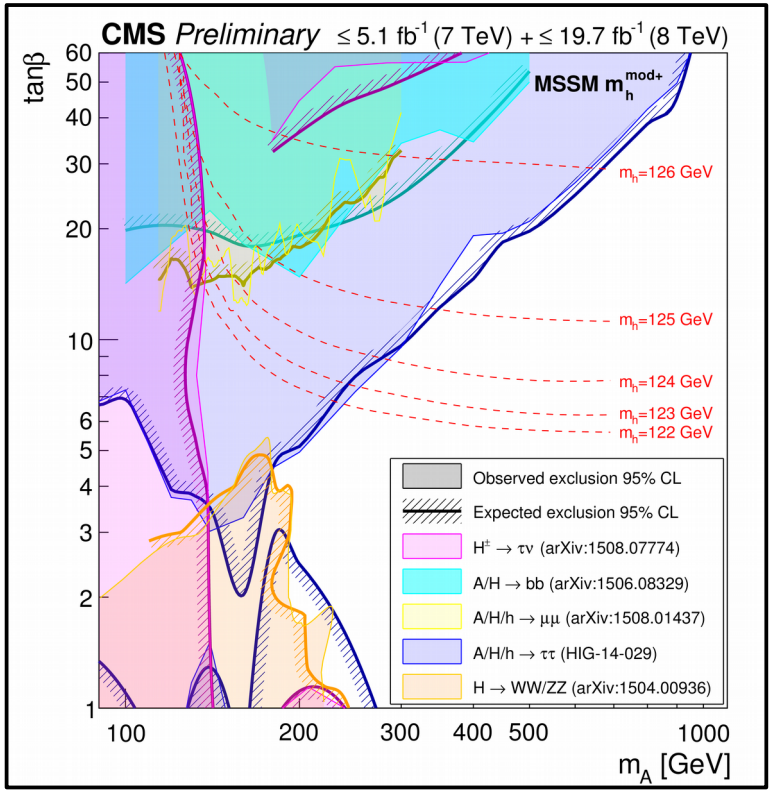


2→6 parameters @ LO: $\tan\beta$, λ, κ, A_κ, A_λ, μ_{eff}

- More complex phenomenology (14 benchmark points in YR-4!).
- Higgs bosons with large singlet admixture can become undetectable.

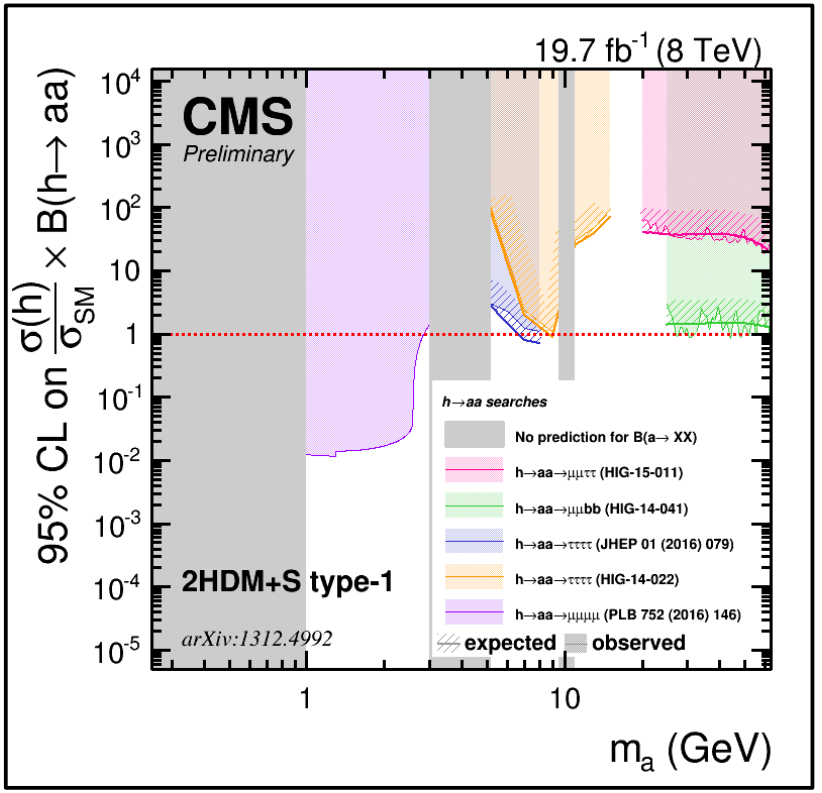
Harvest of LHC Run-1

Searches for heavy Higgs bosons in final states w/ down-type fermions



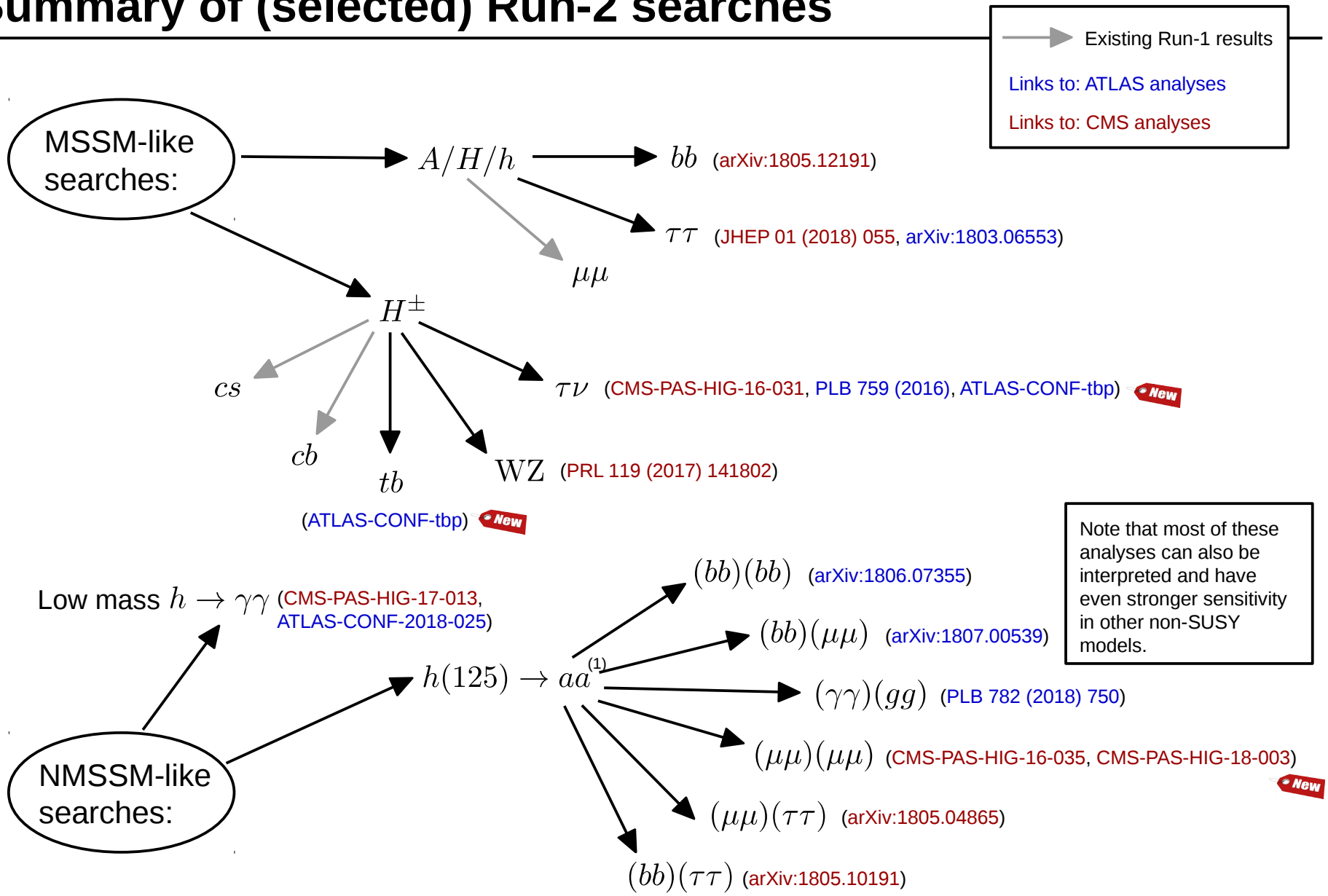
Similar plot from ATLAS

Searches for $h \to aa$ decays in various final states



- Huge parameter space in MSSM systematically explored, NMSSM exploration ramping up.
- Also more general model independent limits and effective 2HDM(+S) interpretations.

Summary of (selected) Run-2 searches



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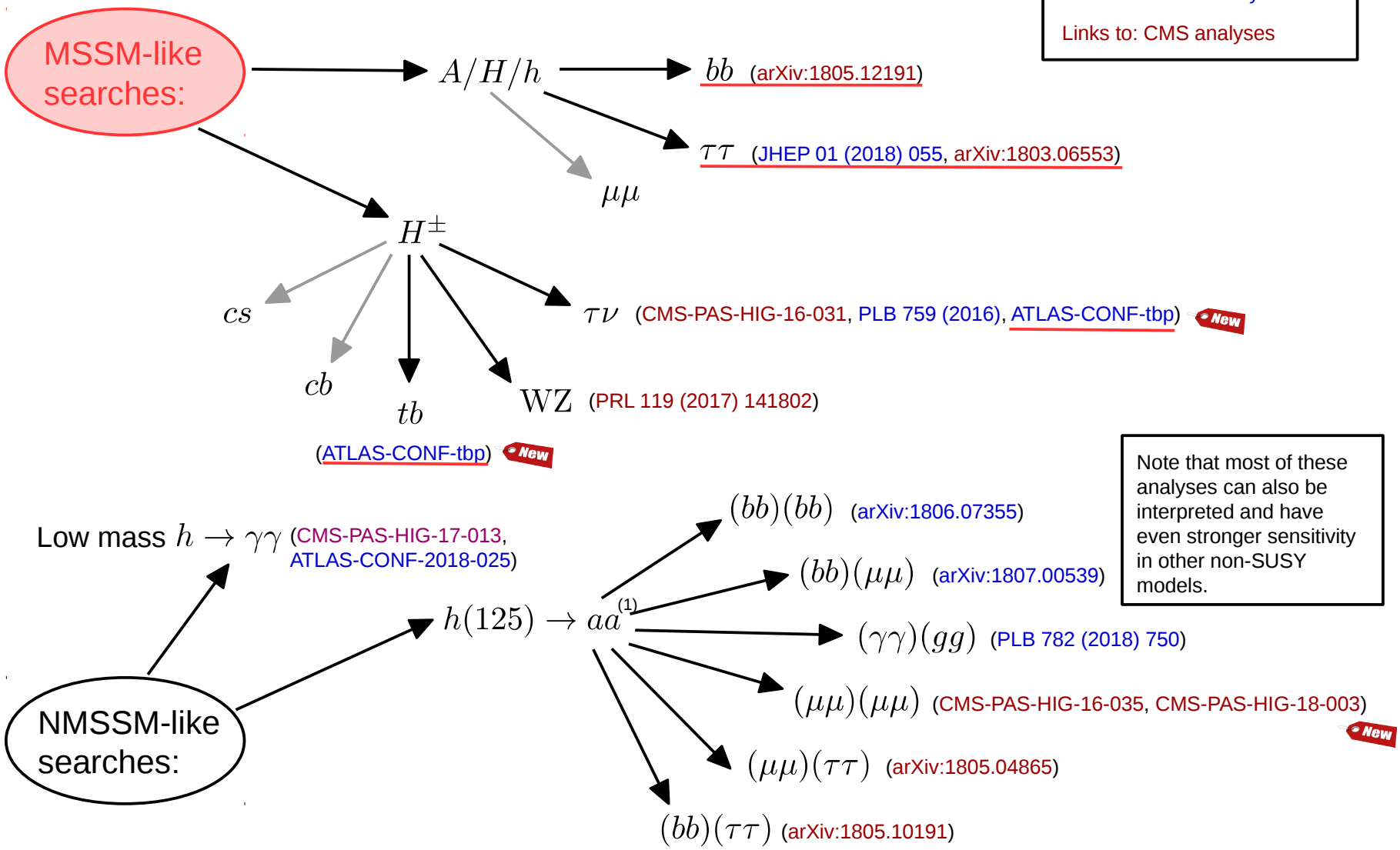
(1) Here a indicates just a Higgs boson that could be scalar or pseudo-scalar

Summary of (selected) Run-2 searches



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(1) Here a indicates just a Higgs boson that could be scalar or pseudo-scalar

arXiv:1805.12191

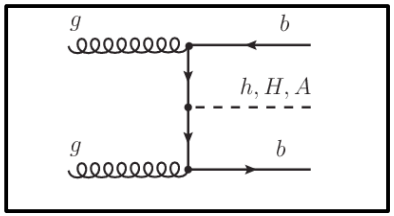
MSSM $\mathrm{H}/\mathrm{A} \to bb$

- Largest coupling and branching fraction to b quarks.
- Main challenge: background from **QCD multijet** production

Reduce input rate:

- Strict trigger requirements already @ trigger level.(1)
- Monitor efficiency w.r.t. to offline selection using tag & probe method.

Concentrate on b-associated production



Use b jets and invariant mass to distinguish signal from background

Model remaining background.

- Signal region (SR): three b-tagged high p_{T} jets (100, 100, 40 GeV).
- Control region (CR): invert b-tag requirement on third leading jet.

- Fit analytic model to data in SR.

find → Suited shapes for background model from CR.

find → Suited shapes for signal from simulation.

(1)

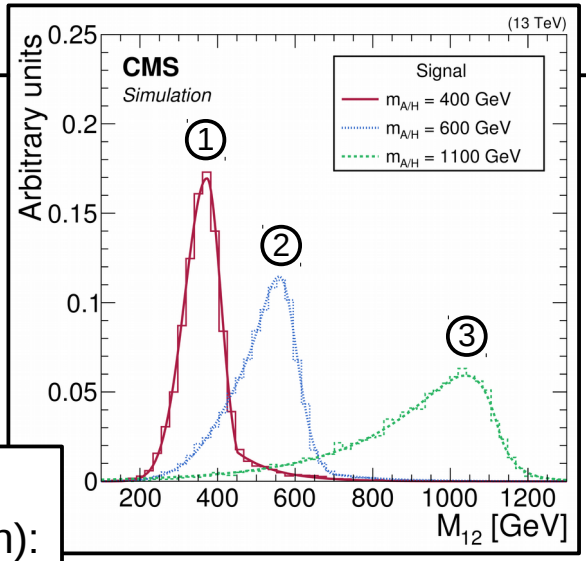
$$N_{\mathrm{j}}(p_{\mathrm{T}} > 100\,\mathrm{GeV}) \geq 2$$
$$\eta_{\mathrm{j}} > 2.4\,; \quad \Delta\eta_{\mathrm{j}} < 1.6$$

arXiv:1805.12191

Signal and background model

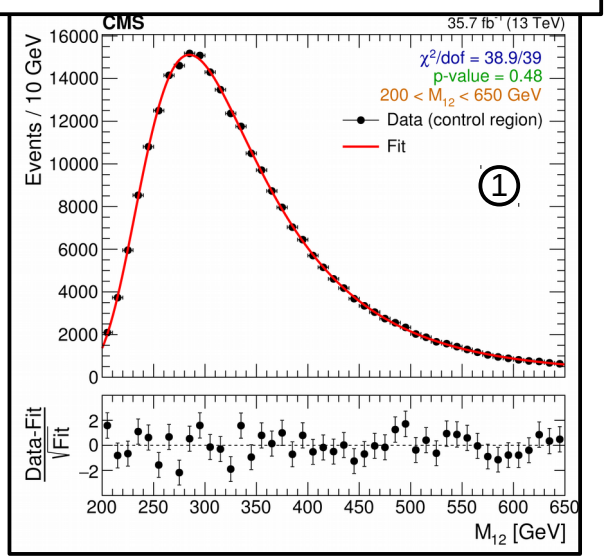
- Discriminating variable: invariant mass of two leading jets after b-tagging requirement (M_{12}).
- Different shapes of signal and background motivate separation into three (overlapping) categories in M_{12}.

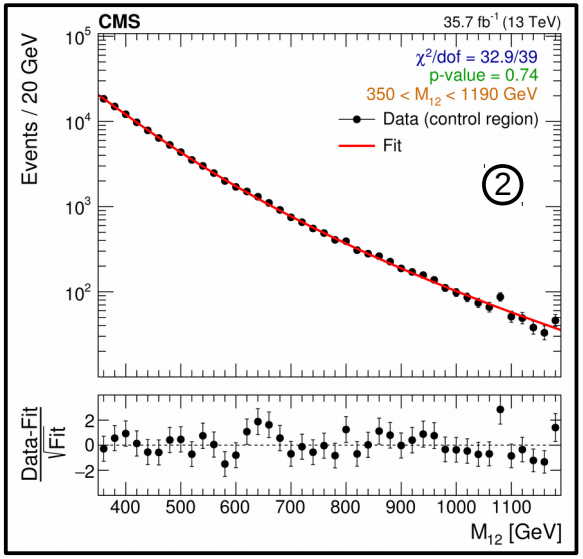
Signal shapes (from simulation):

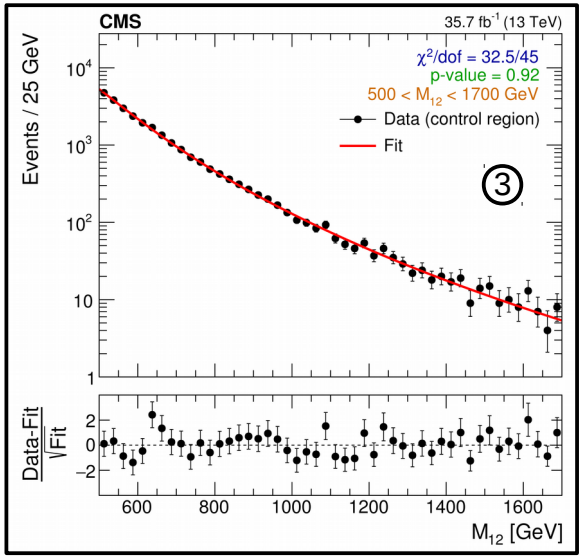


Natural width of signal <19%, experimental resolution ~25%.

Background shapes (from CR):







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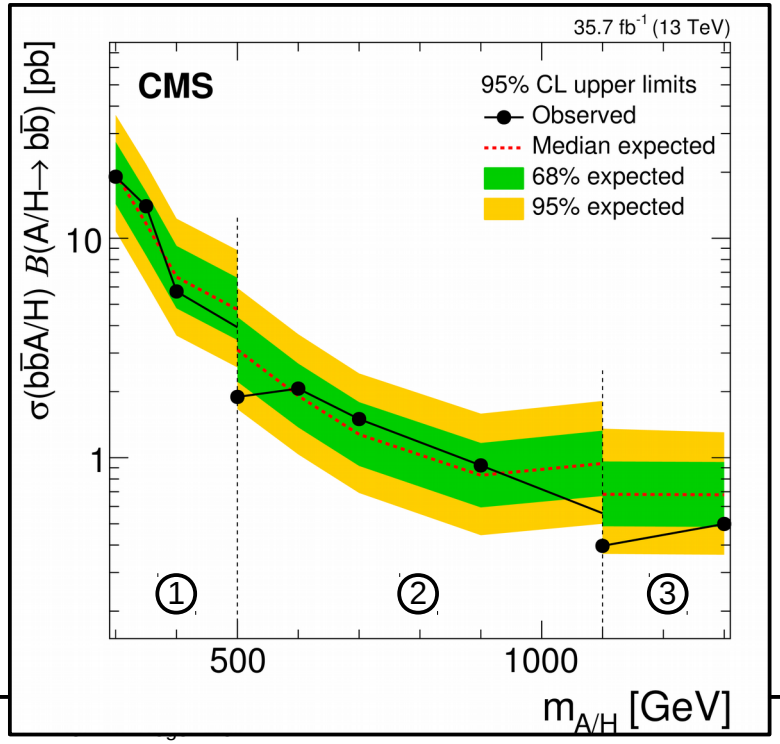
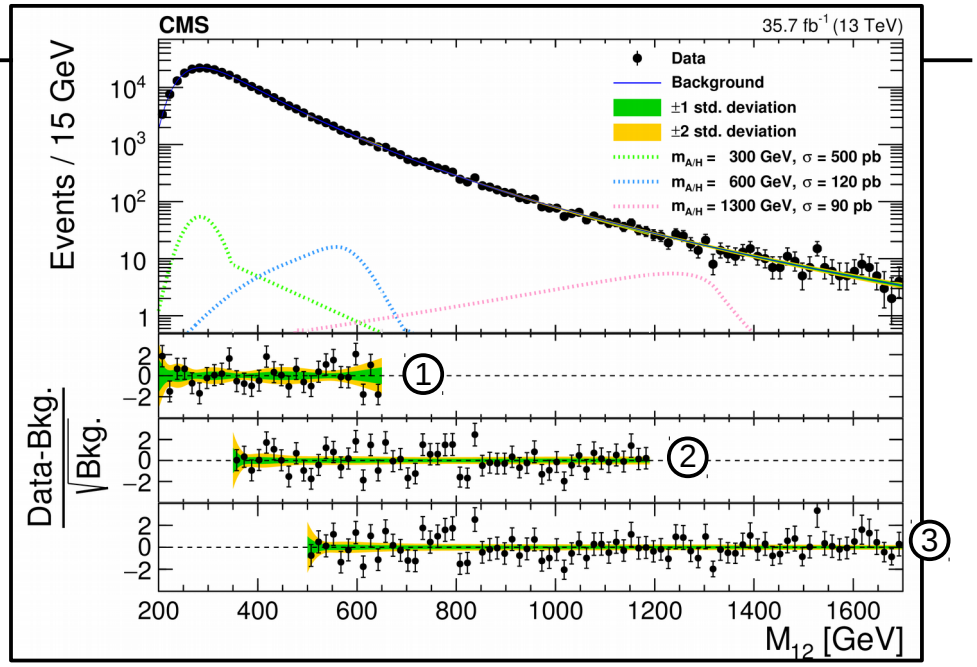
arXiv:1805.12191

Results

- Most important systematic uncertainties:
  - Potential bias due to choice of analytic functions.
  - b-tagging efficiency.
- Sensitivity significantly improved w.r.t. Run-1 analysis (Run-1 analysis reached further down in m_{A}).

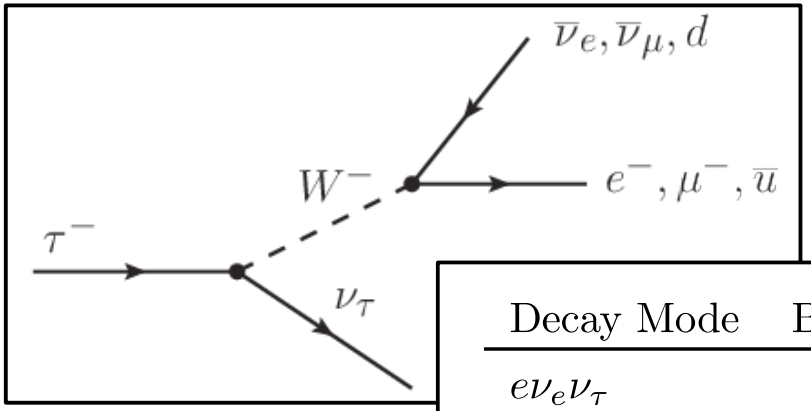




- No deviations observed from SM expectation.
  → limits on $\sigma \times \mathrm{BR}$.

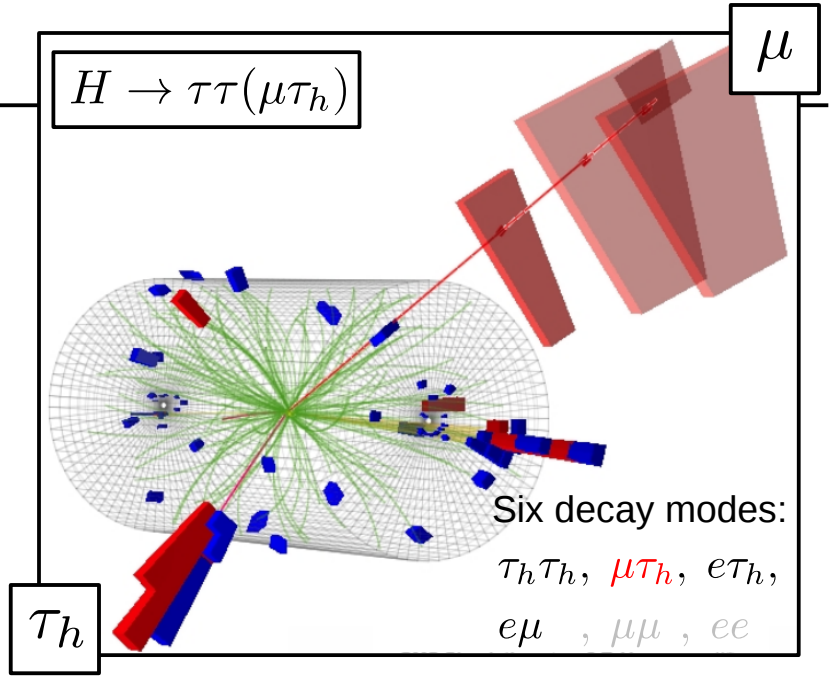
MSSM $\mathrm{H/A/h} \rightarrow \tau\tau$

- Flagship analysis in MSSM motivated BSM Higgs searches.
- Coupling enhanced + signature can be reconstructed and isolated from backgrounds.



Decay Mode	BR [%]
$e\nu_e\nu_\tau$	17.4
$\mu\nu_\mu\nu_\tau$	17.8
1-prong ν_τ	49.6
3-prong ν_τ	15.2

~90% of all $\tau\tau$ final states contain at least one τ_h.



- Search for 2 isolated high p_T leptons (e, μ, τ_h).
- Reduce obvious backgrounds ($\rightarrow \not{E}_T$).
- Reconstruct discriminating variable, related to $\tau\tau$ final state: $\mathrm{m}_{\tau\tau}, m_\mathrm{vis}, \mathrm{m}_\mathrm{T}^\mathrm{tot}, \mathrm{BDT}$.

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http://ekpwww.physik.uni-karlsruhe.de/~rwolf/

Also check slides by D. Winterbottom Mon 15:20 – 15:40.

arXiv:1803.06553

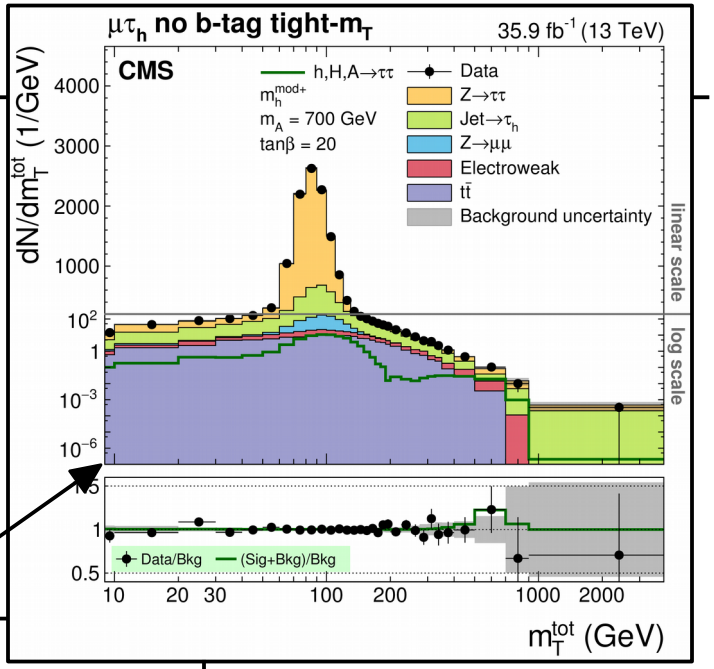
Signal extraction

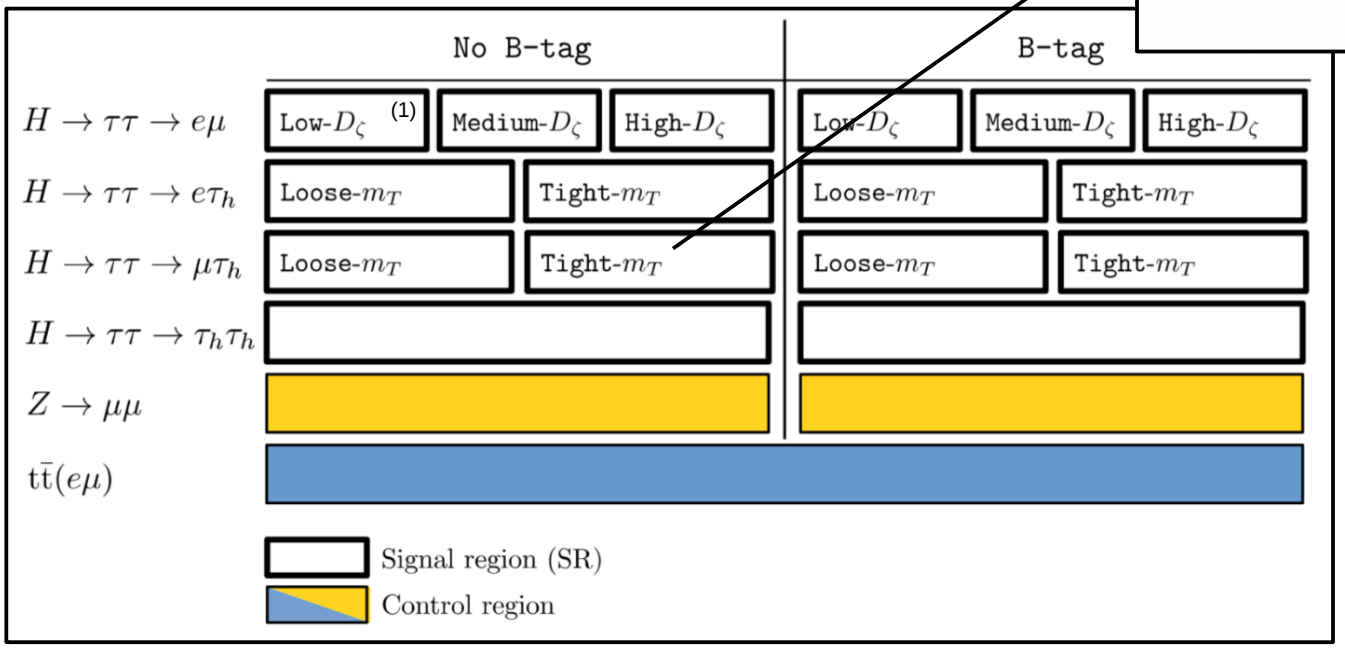
- Signal extraction based on:

$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_1}, p_{\mathrm{T}}^{\tau_2}) + m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_1}, p_{\mathrm{T}}^{\mathrm{miss}}) + m_{\mathrm{T}}^2(p_{\mathrm{T}}^{\tau_2}, p_{\mathrm{T}}^{\mathrm{miss}})}$$

- Categories exploit topological & kinematic peculiarities of MSSM motivated production:

- Sensitivity beyond 1TeV for $\tan\beta \gtrsim 20$.



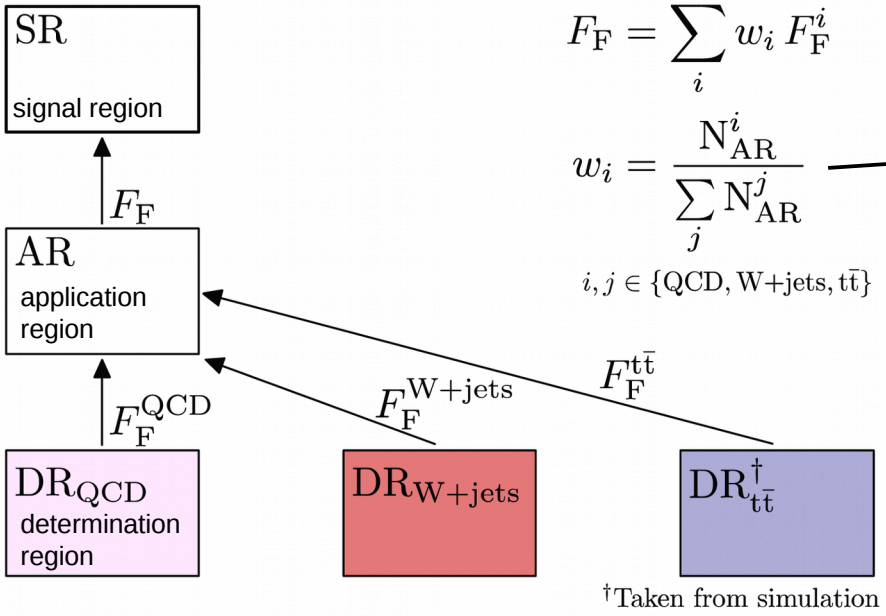


(1) Check backup for more detailed explanation of event categories.

arXiv:1803.06553

Background estimation

- $F_{\mathrm{F}}^{i} = \dfrac{N_{\mathrm{pass}}}{N_{\mathrm{fail}}}, \quad N_{\mathrm{pass}} : \#\ \text{isolated}\ \tau_{\mathrm{h}} \quad N_{\mathrm{fail}} : \#\ \text{anti-isolated}\ \tau_{\mathrm{h}}\,.$



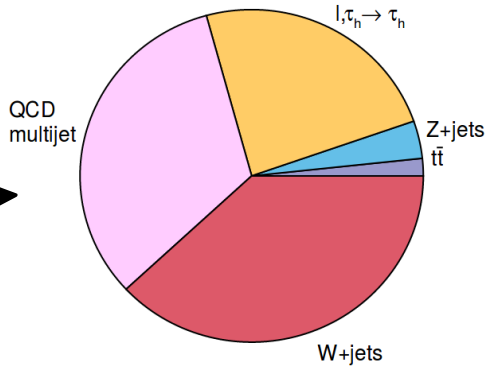
$$F_{\mathrm{F}} = \sum_i w_i\, F_{\mathrm{F}}^{i}$$

$$w_i = \frac{\mathrm{N}_{\mathrm{AR}}^{i}}{\sum_j \mathrm{N}_{\mathrm{AR}}^{j}}$$

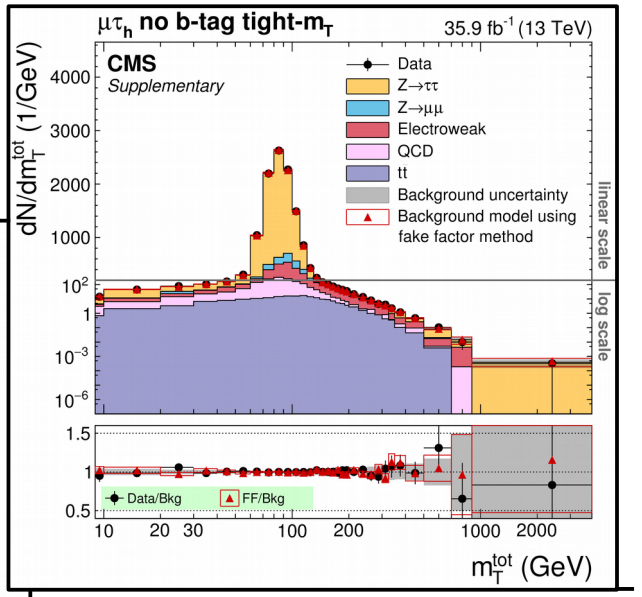
$i, j \in \{\mathrm{QCD}, \mathrm{W+jets}, \mathrm{t\bar{t}}\}$

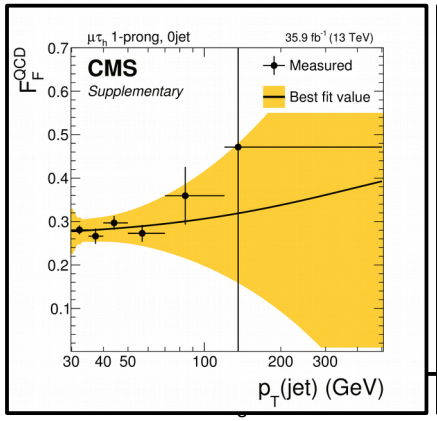
†Taken from simulation

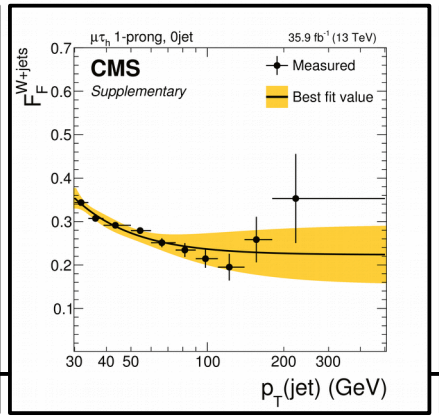
Expected event composition in AR:

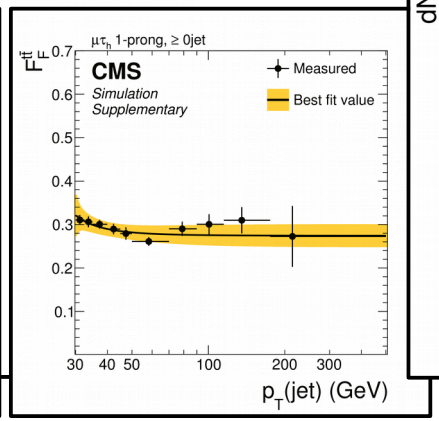


Simulation based cross check:





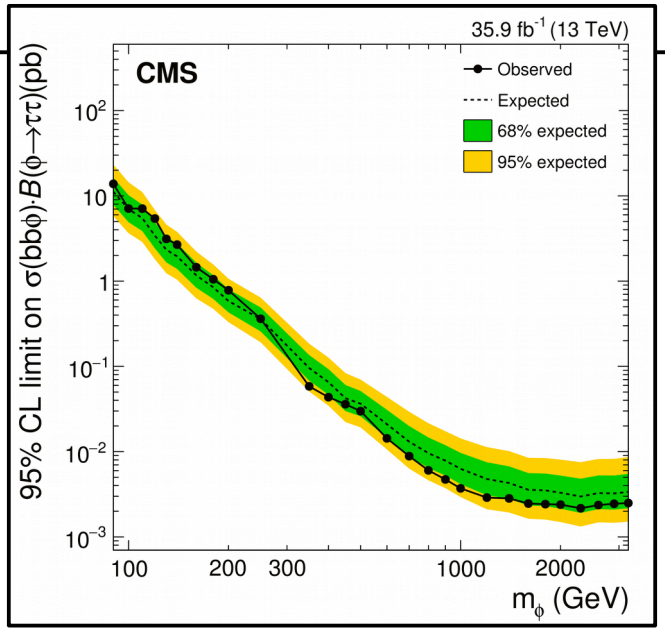


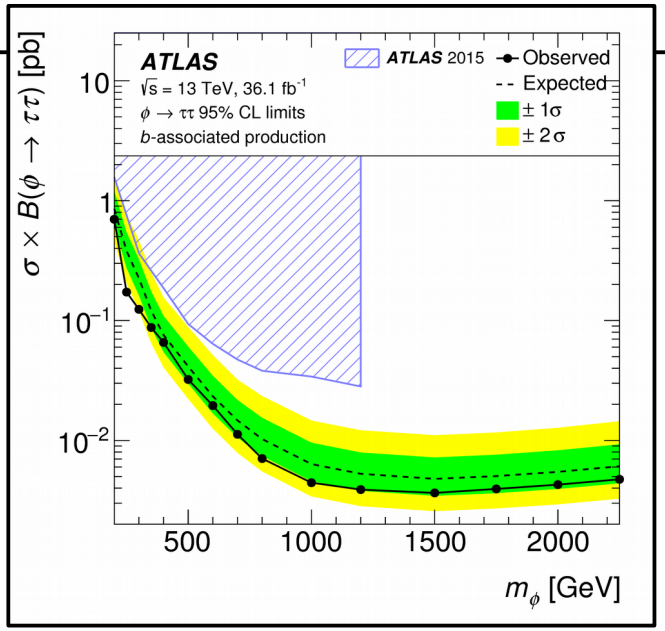


arXiv:1803.06553

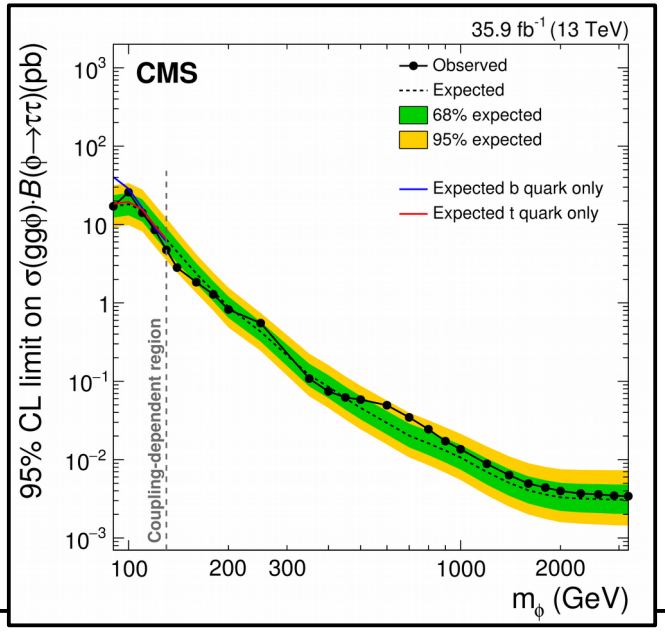
Results

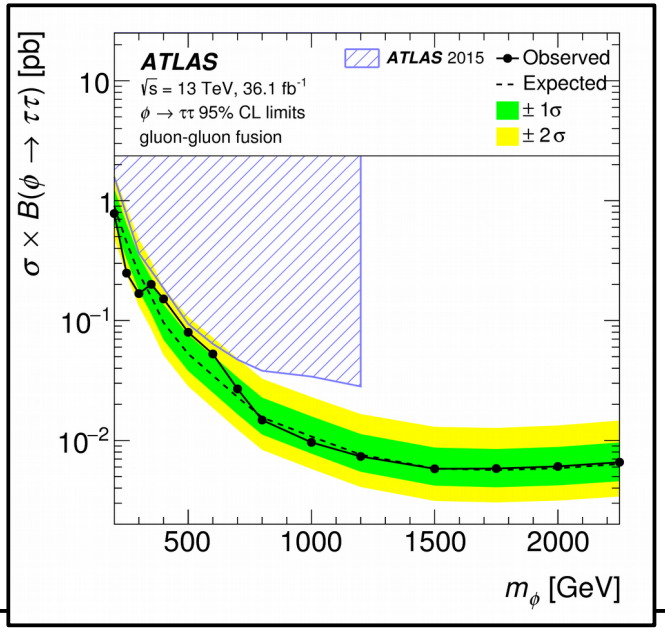
b associated production





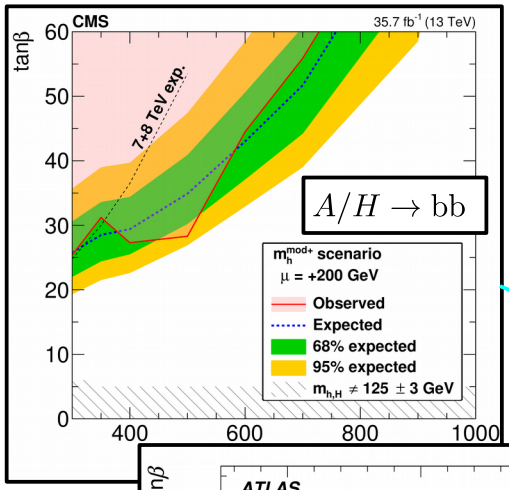
gluon fusion



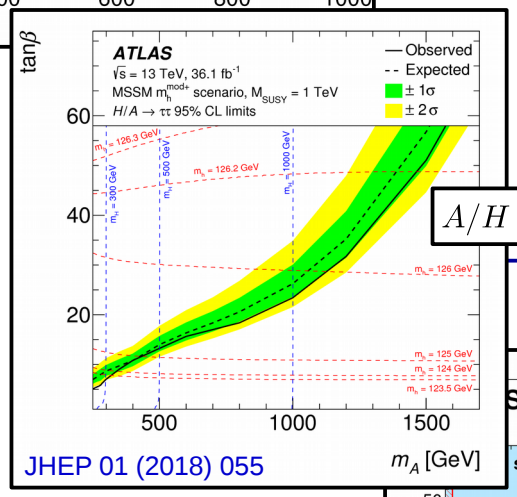


MSSM interpretation

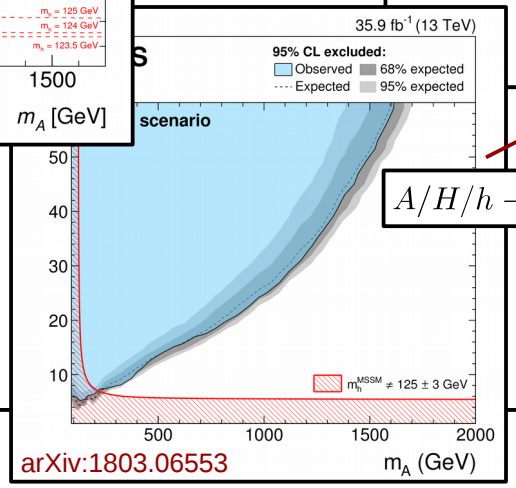
Private compilation of public results



arXiv:1805.12191



JHEP 01 (2018) 055



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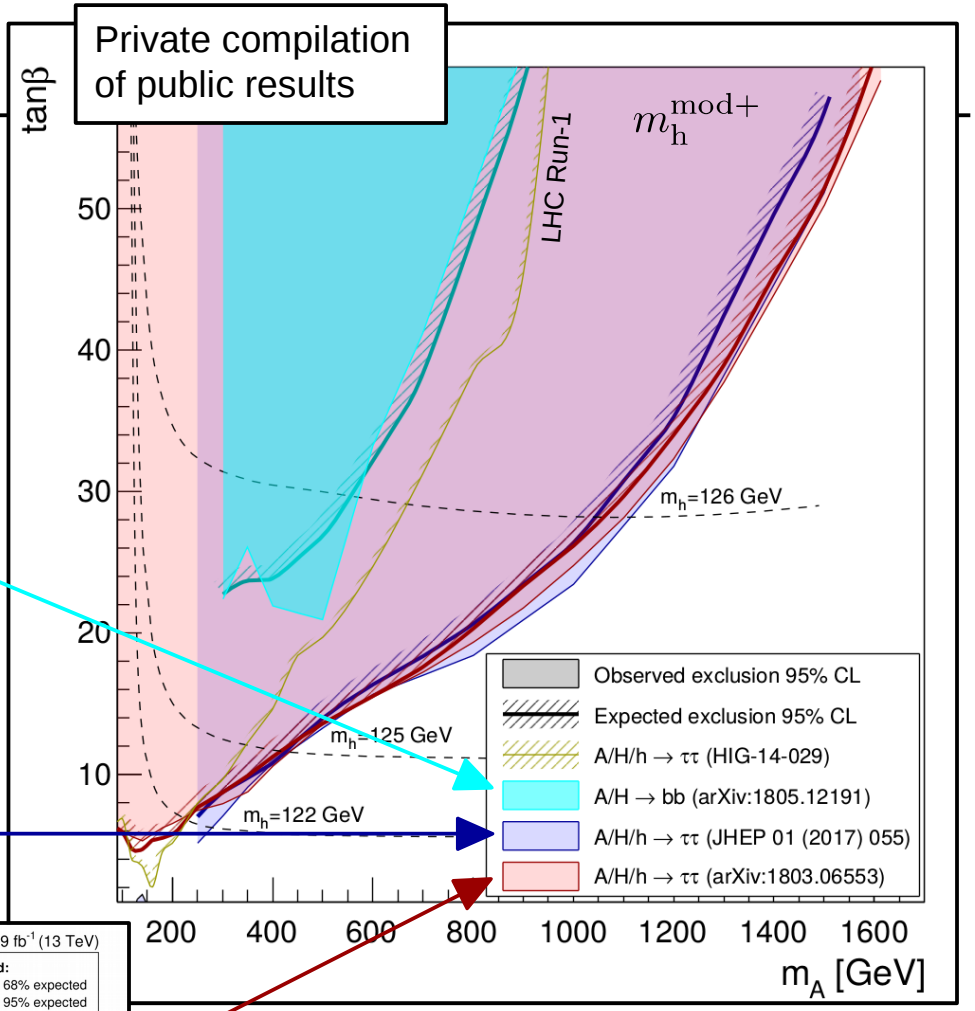


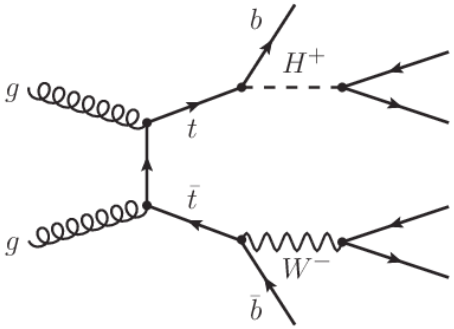
- LHC Run-2 searches for neutral SUSY Higgs bosons.
- Consistent interpretation, here in m_h^{mod+} (EPJC 73 (2013) 2552).

Charged Higgs bosons

- Smoking gun for non-trivial Higgs sector.
- Most important decays: $\mathrm{H}^{\pm} \to \tau\nu \,/\, \mathrm{tb}$

  Low & high $m_{\mathrm{H}^{\pm}}$ — High $m_{\mathrm{H}^{\pm}}$
- Two distinct production modes depending on $m_{\mathrm{H}^{\pm}}$:

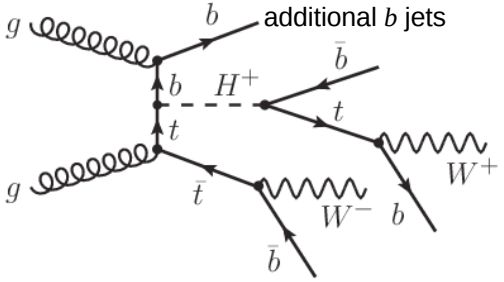
In decay ($m_{\mathrm{H}^{\pm}} < m_{\mathrm{t}}$):



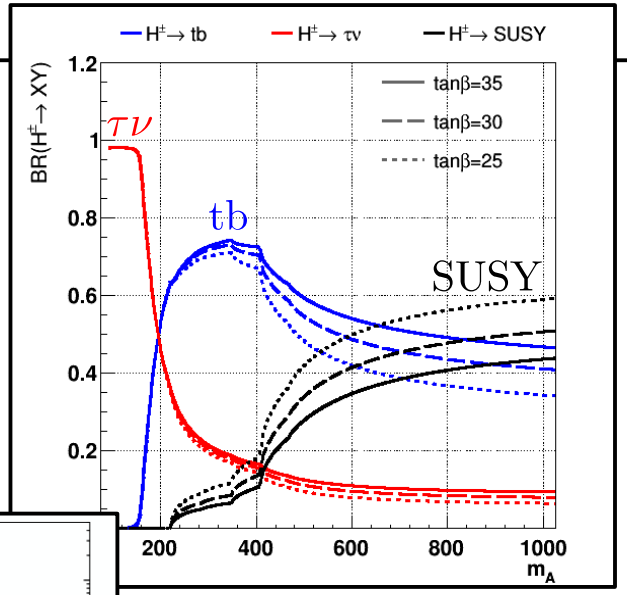
heavy flavors preferred

flavor democratic

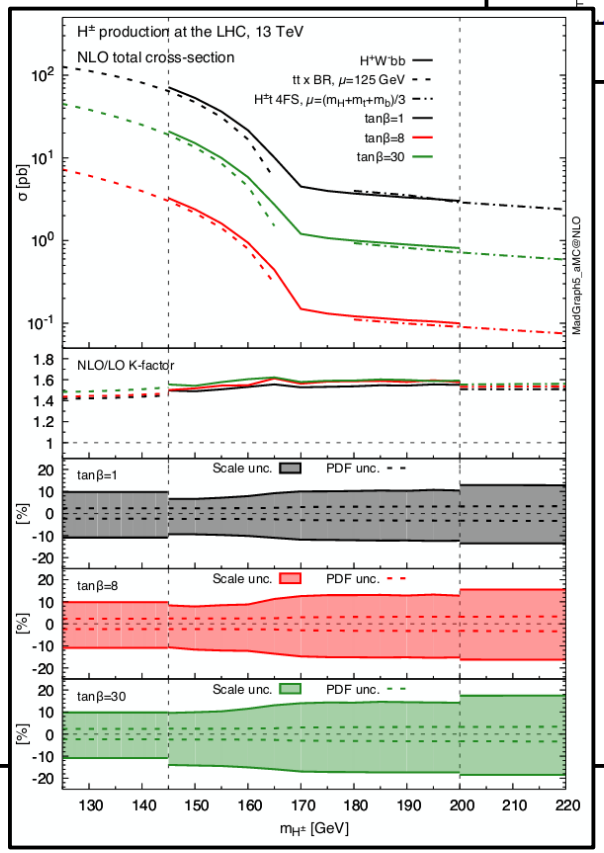
In production ($m_{\mathrm{t}} < m_{\mathrm{H}^{\pm}}$):



Decay channels: $m_{\mathrm{h}}^{\mathrm{mod+}}$



LHCHXSWG-3



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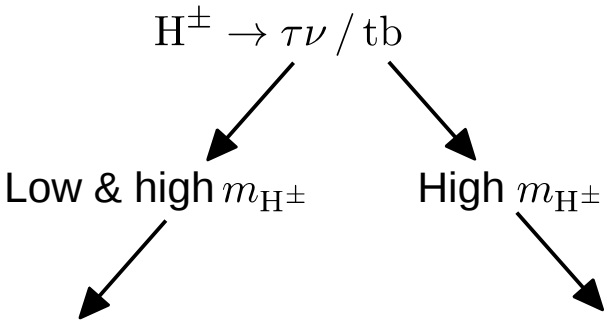
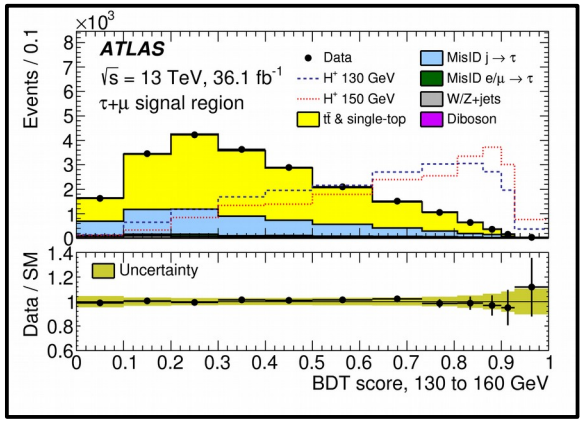
Also check slides by
C. Autermann Mon 15:40 – 16:00.

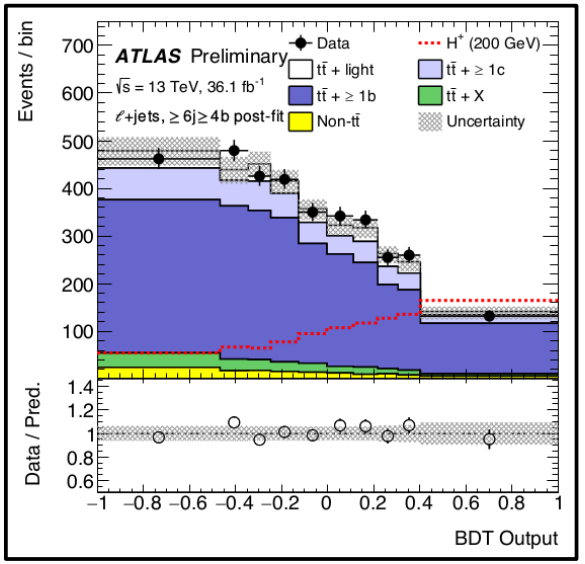
Signal extraction



- Select events with one τ_h candidate.
- $\not{E}_T$
- Discriminating variable is a BDT trained in 5 bins in $m_{H^{\pm}}$.

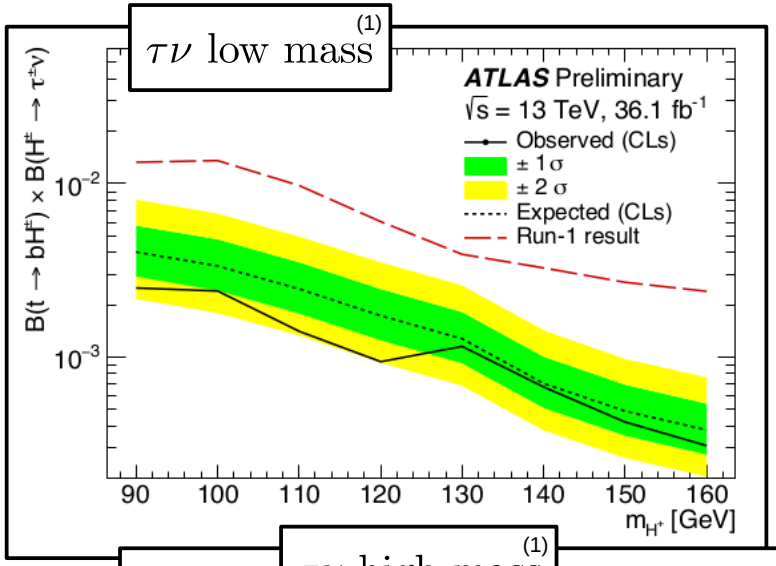


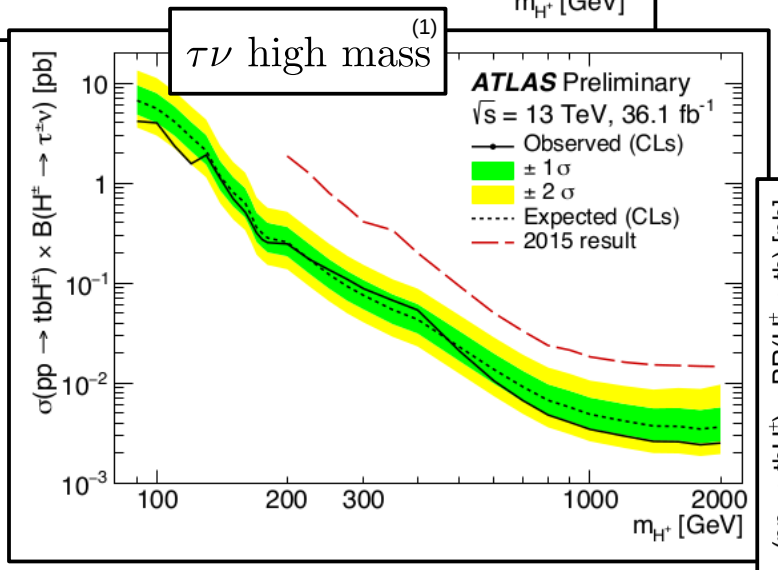
- Concentrate on fully leptonic (lepton+jets) channel of $t\bar{t}$.
- Select events with 2(1) lepton(s) and 3(5) jets.
- Categorize in number of b-tagged jets.
- Extract signal from BDT discriminant.

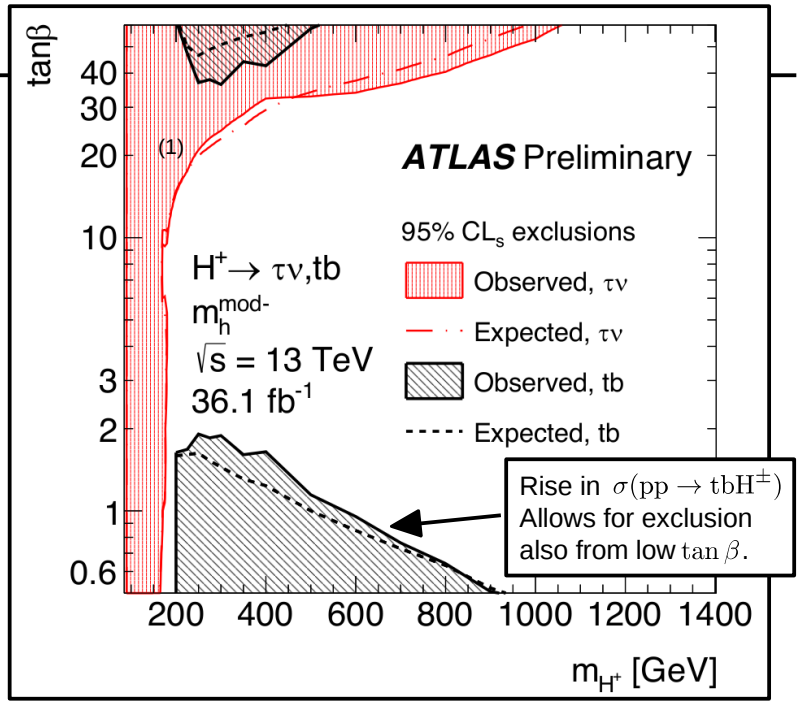


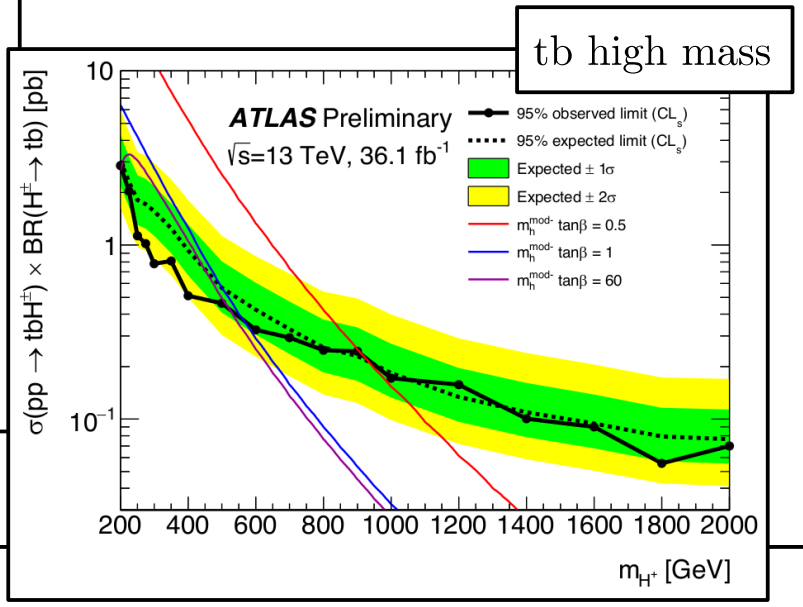
Results

(1) Note the missing gap between "low" & "high" for the first time!









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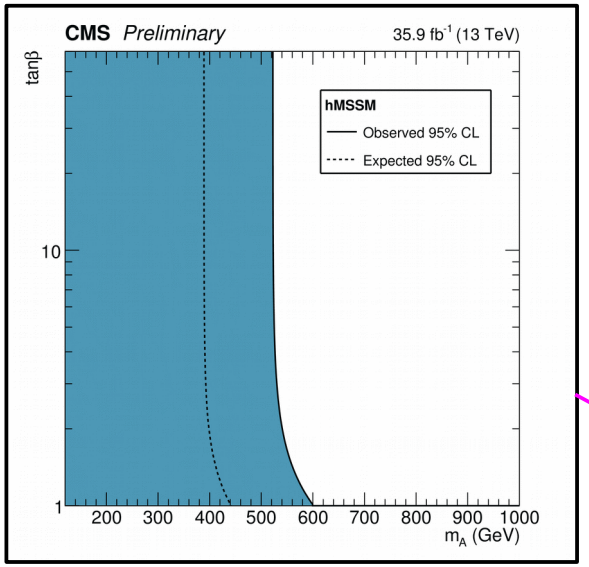
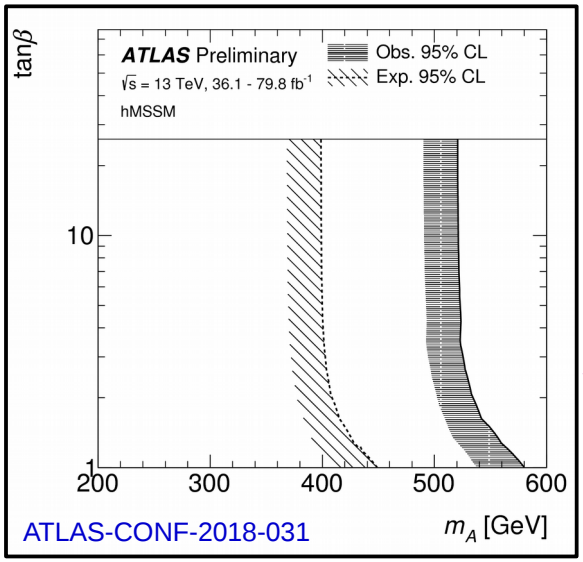
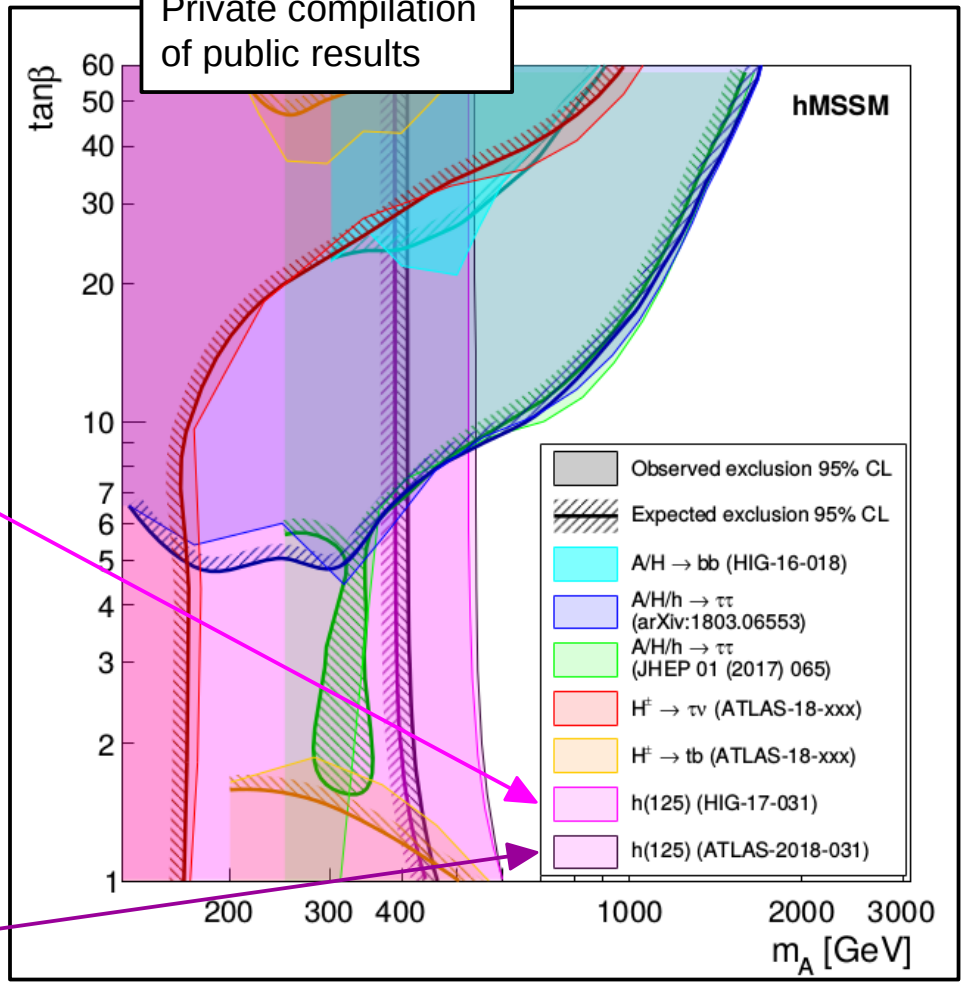
Upshot of Run-2 MSSM search results (presented here)



CMS-PAS-HIG-17-031

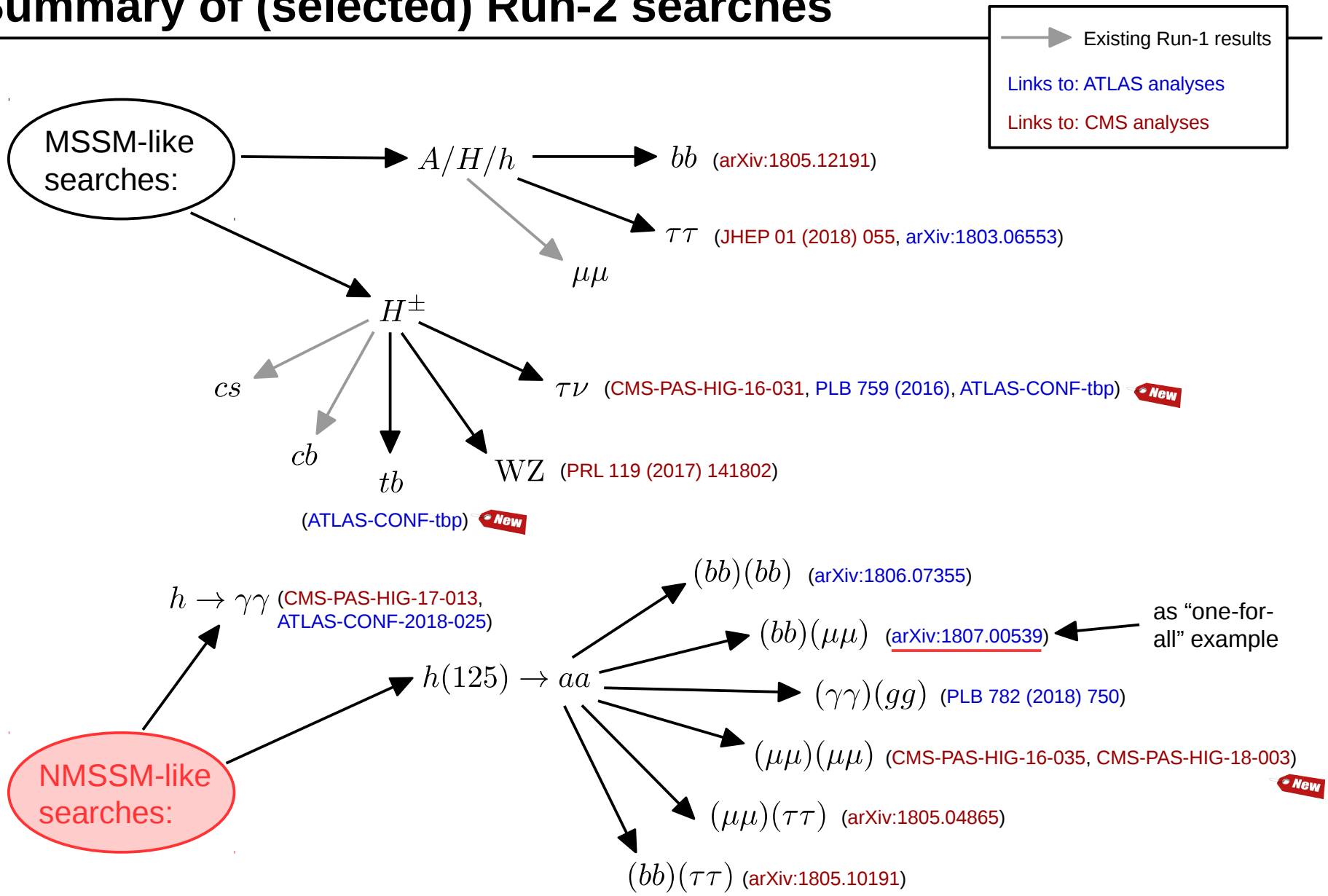


Private compilation of public results



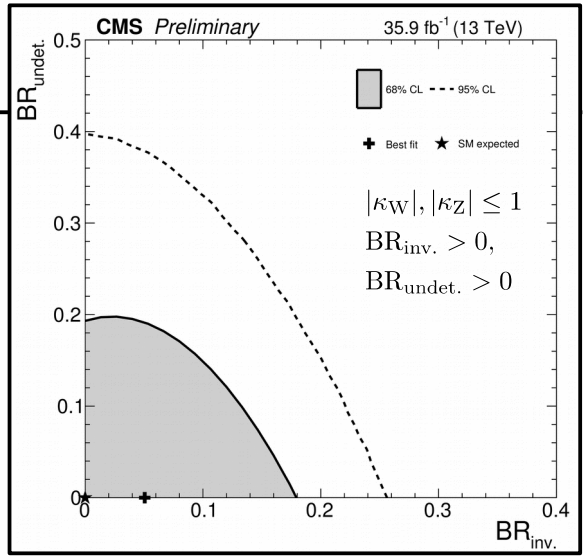
- Including exclusion estimates from h(125) coupling measurements.

Summary of (selected) Run-2 searches



$h(125) \rightarrow aa$

- Constraint on BR_{BSM} from $h(125)$ couplings fits still allows for up to 20-30% decays into unobserved particles.
- Decay chain $h(125) \rightarrow aa \rightarrow \ldots$ offers several constraints during kinematic reconstruction.
- Plethora of final states analyzed from lowest possible m_a up to $m_h/2$.



CMS-PAS-HIG-17-031

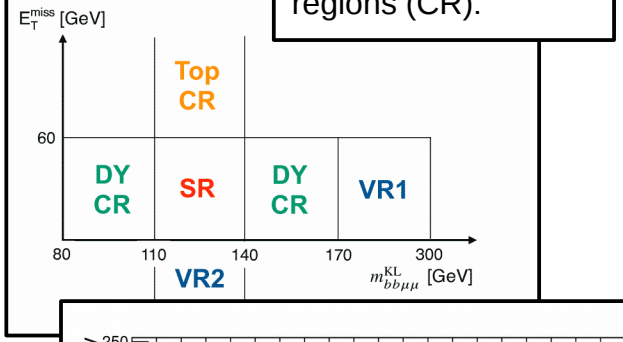
- Very low m_a searches enter boosted regimes → requires special care for reconstruction & selection (e.g. for lepton isolation requirements).
- In contrast to MSSM, sensitivity not reached, yet, to challenge the NMSSM.
- Enterprise: obtain a clear overview of the NMSSM with a manageable set of benchmark scenarios and possible exclusion planes. → Still under active research (LHCHXSWG-3).
- Limits are usually presented in form of model independent $\sigma \times \mathrm{BR}$ exclusions.
- $A \rightarrow ah \ / \ H \rightarrow hh'$ are experimentally not covered, yet.

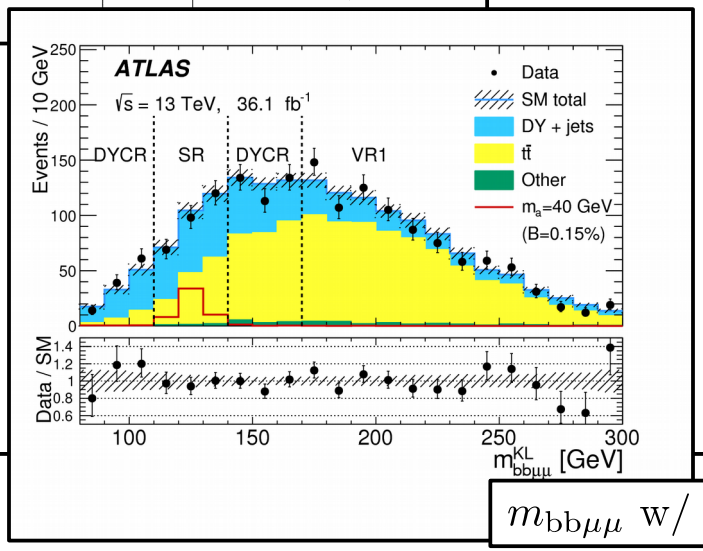
arXiv:1807.00539

$h(125) \to aa \to (bb)(\mu\mu)$ (pars pro toto)

- Select two μ's and two b-jets.
- Use kinematic constraints in likelihood discriminant (KL).[1]
- Control most important backgrounds DY and $t\bar{t}$ (50:50 in SR).

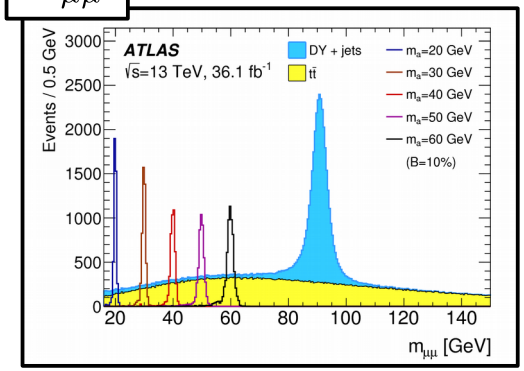
Signal (SR) & control regions (CR):



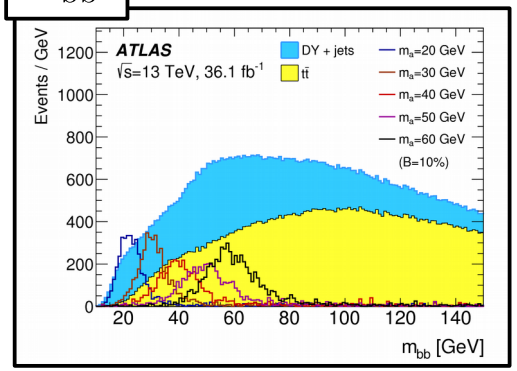


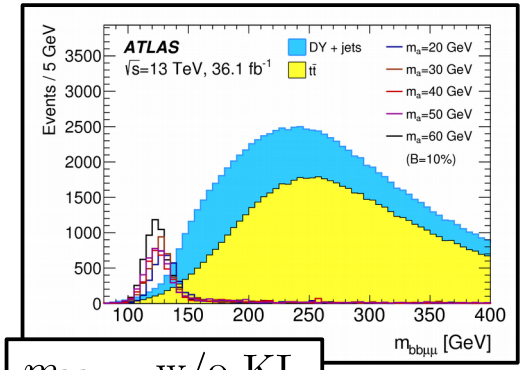
$m_{bb\mu\mu}$ w/ KL

$m_{\mu\mu}$

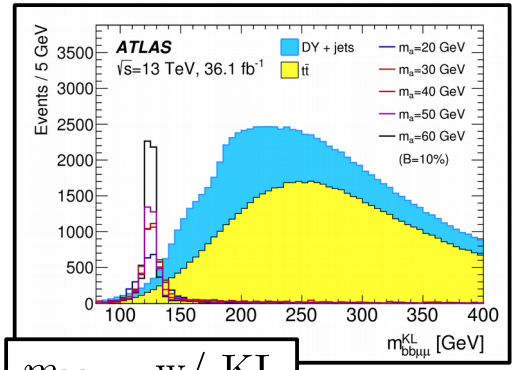


m_{bb}





$m_{bb\mu\mu}$ w/o KL



$m_{bb\mu\mu}$ w/ KL

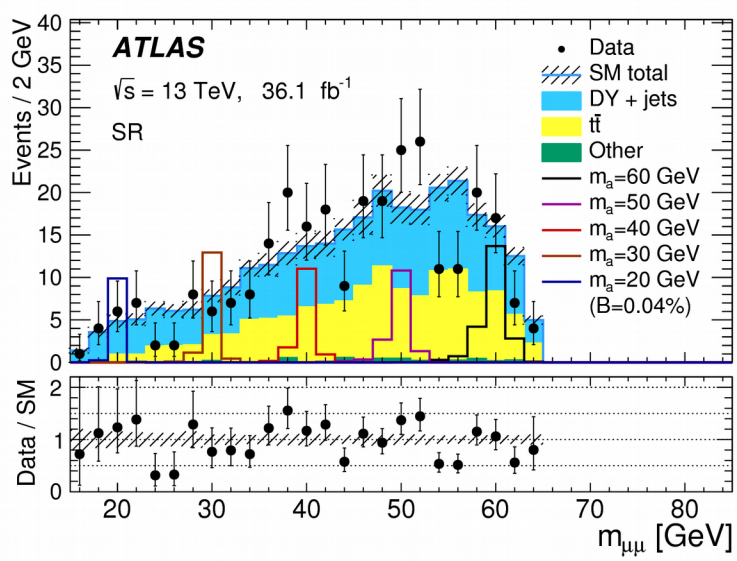
[1] Adjusts b-jet energies within experimental resolution to fulfill kinematic constraints.

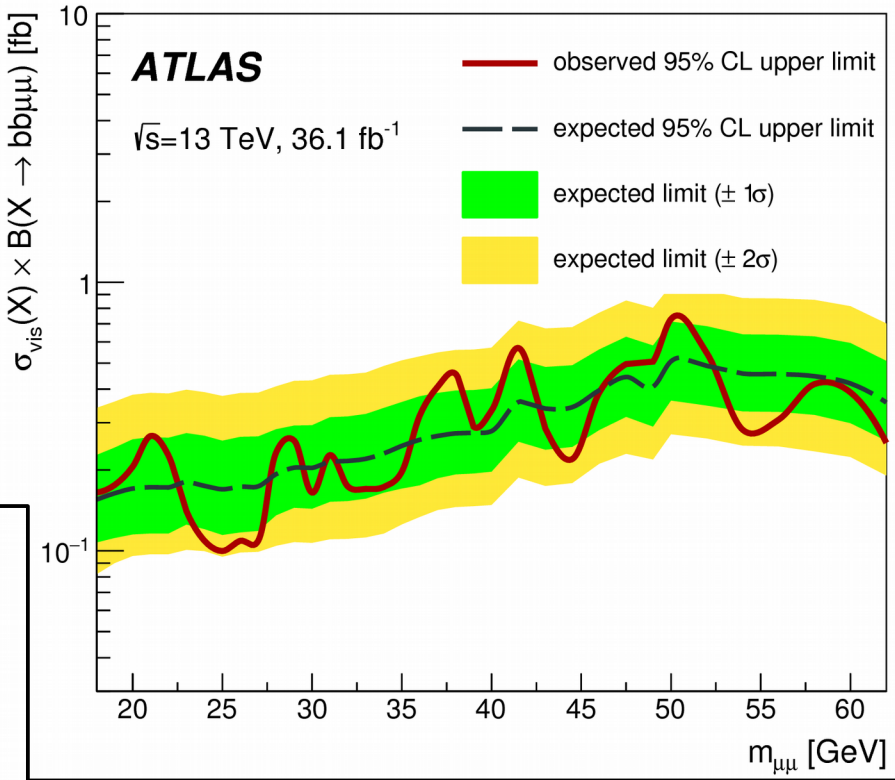
arXiv:1807.00539

Results

- No deviations observed w.r.t. SM expectation. → Limit set on $\sigma \times \mathrm{BR}$.

Discriminant for statistical inference:





Model independent limits on $\sigma \times \mathrm{BR}$.

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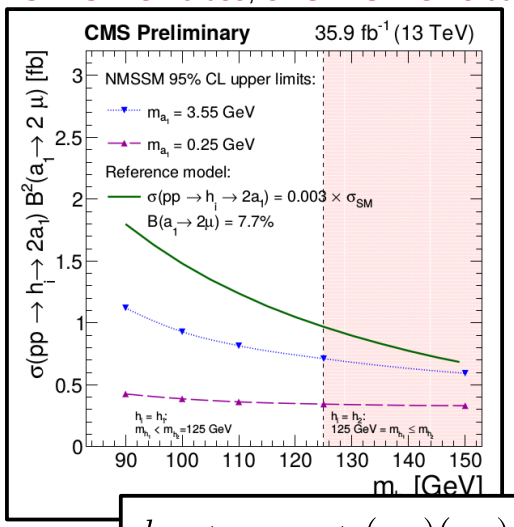
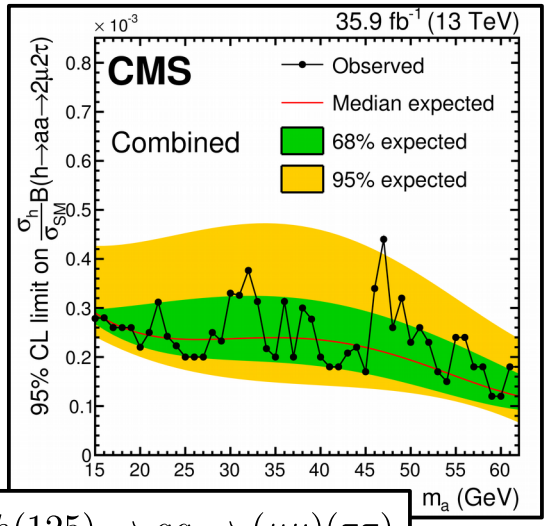
Upshot of Run-2 NMSSM search results

CMS-PAS-HIG-16-035, CMS-PAS-HIG-18-003



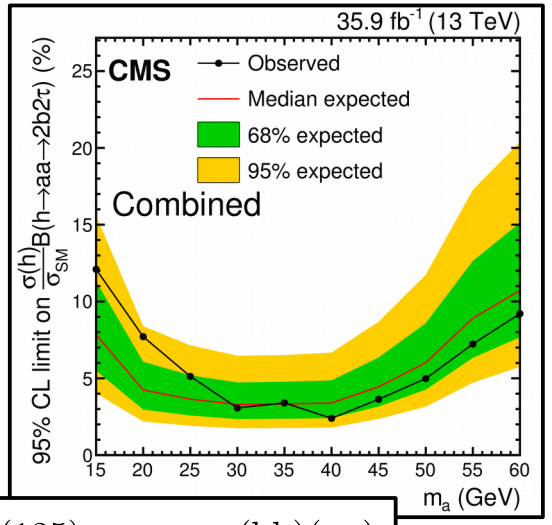
$h_i \to a_1 a_1 \to (\mu\mu)(\mu\mu)$

arXiv:1805.04865



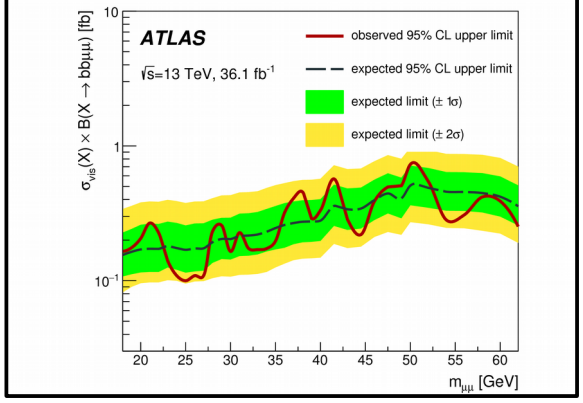
$h(125) \to aa \to (\mu\mu)(\tau\tau)$

arXiv:1805.10191



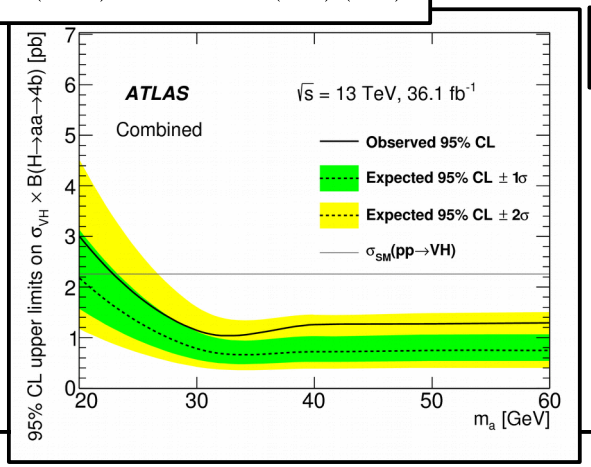
$h(125) \to aa \to (\mathrm{bb})(\tau\tau)$

$h(125) \to aa \to (bb)(\mu\mu)$



arXiv:1807.00539

$h(125) \to aa \to (\mathrm{bb})(\mathrm{bb})$



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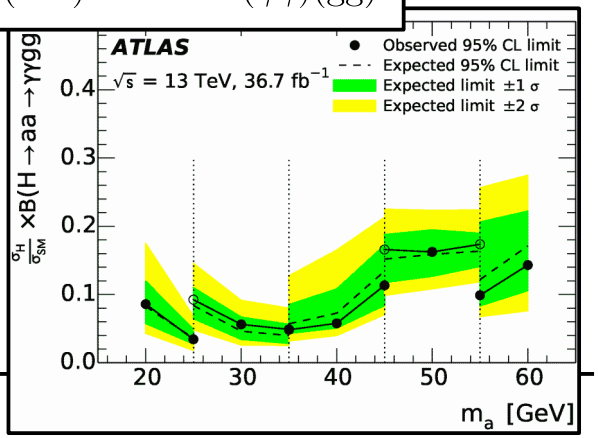
$h(125) \to aa \to (\gamma\gamma)(gg)$



PLB 782 (2018) 750

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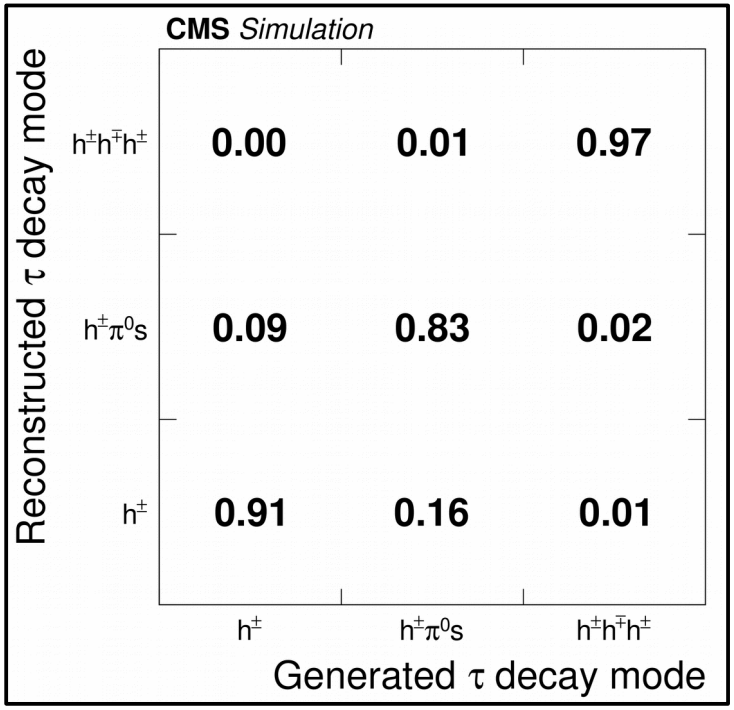
Conclusion

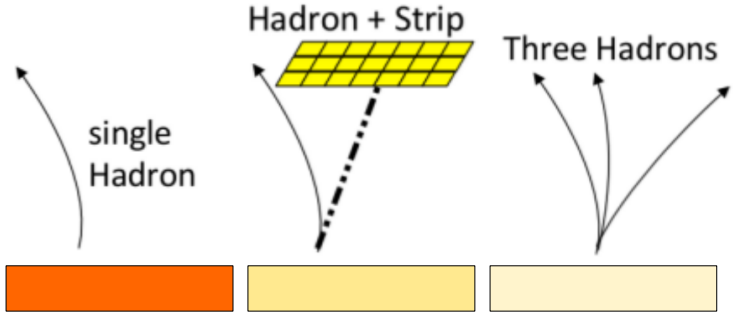
- Very successful start of BSM Higgs boson searches for LHC Run-2.
- Rich program of (SUSY motivated) BSM Higgs boson searches.
- Both experiments ATLAS and CMS show very compatible and consistent results. Unfortunately no discoveries, yet.
- Current publications: milestones towards the analysis of the full LHC Run-2 dataset.
- In addition to established MSSM portfolio large number of evolving NMSSM motivated analyses.
- Looking forward to high quality, highly sophisticated analyses of the full LHC Run-2 dataset with more than 100/fb!

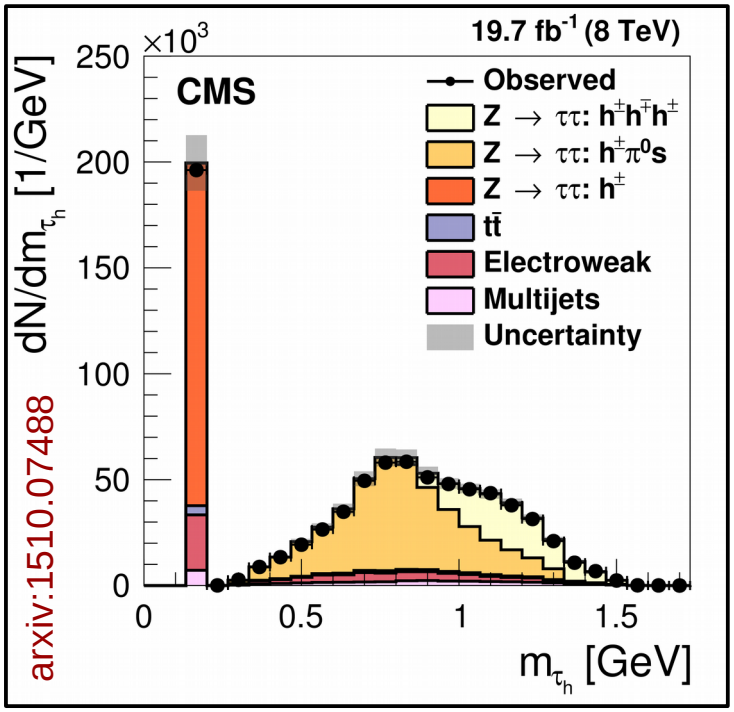
Backup

Hadronic τ-decay

- Start from anti- k_T clustered jets of particle flow objects with opening parameter of 0.4.
- Require **one or three high p_T charged hadrons** (→ prongs).



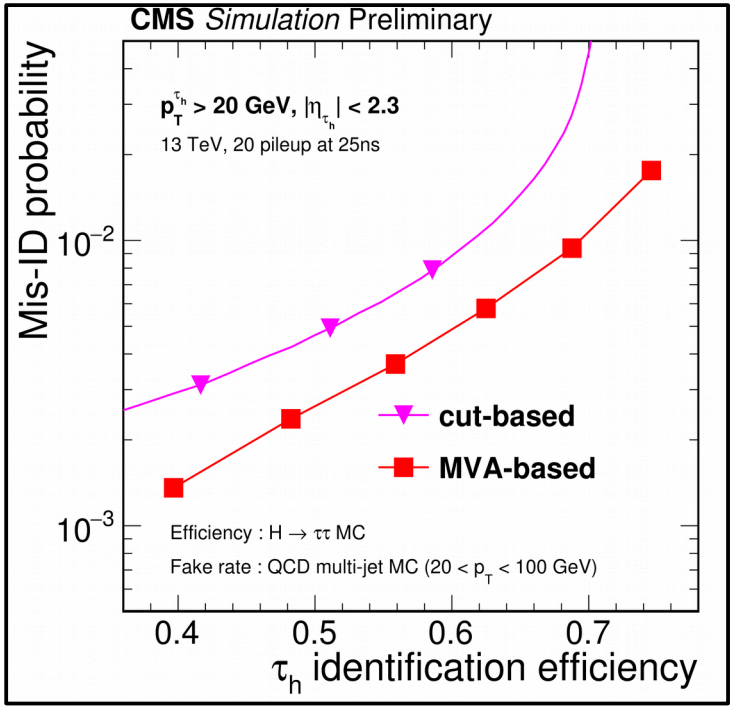




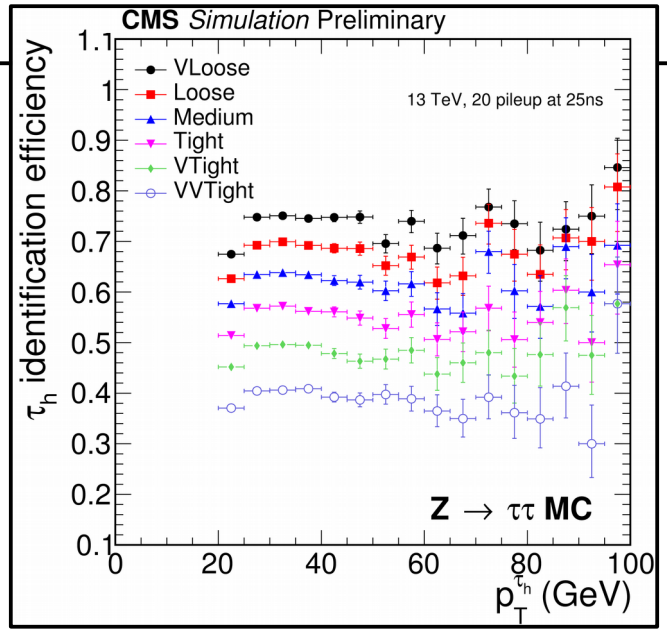
- Apply ID criteria to increase purity.

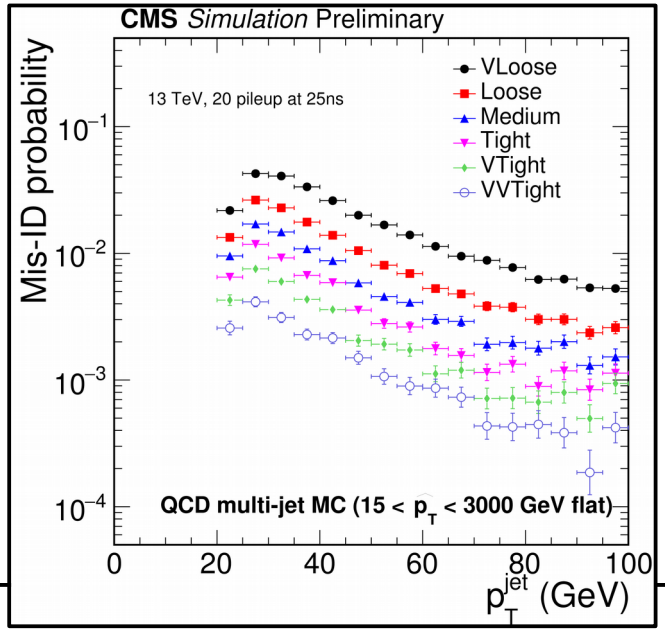
Hadronic τ-decay

- **MVA based τ_h -identification**: energy deposits close to τ-candidate + impact parameter information on prongs.
- Discrimination against muons and electrons.



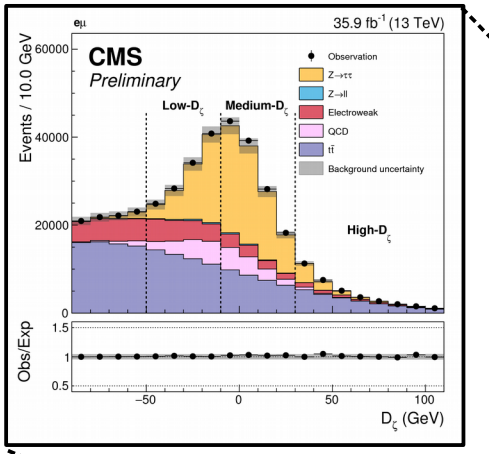
- Predefined working points used in analyses.

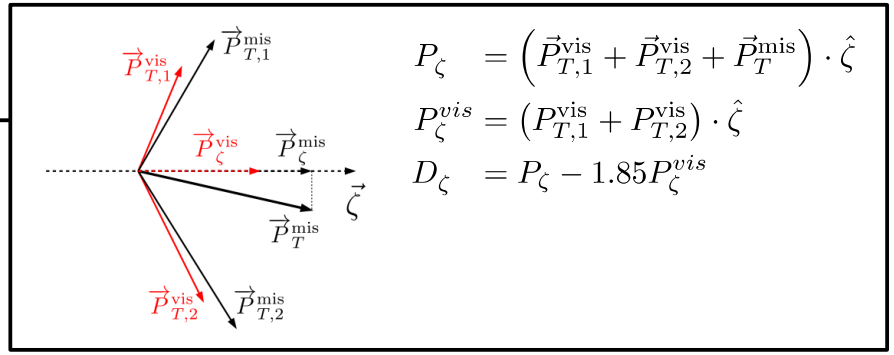




CMS-PAS-TAU-16-002

Additional event information





$$P_\zeta = \left(\vec{P}^{\text{vis}}_{T,1} + \vec{P}^{\text{vis}}_{T,2} + \vec{P}^{\text{mis}}_{T}\right) \cdot \hat{\zeta}$$
$$P^{vis}_\zeta = \left(P^{\text{vis}}_{T,1} + P^{\text{vis}}_{T,2}\right) \cdot \hat{\zeta}$$
$$D_\zeta = P_\zeta - 1.85 P^{vis}_\zeta$$

Exploit different S/B composition especially for high mass signal.

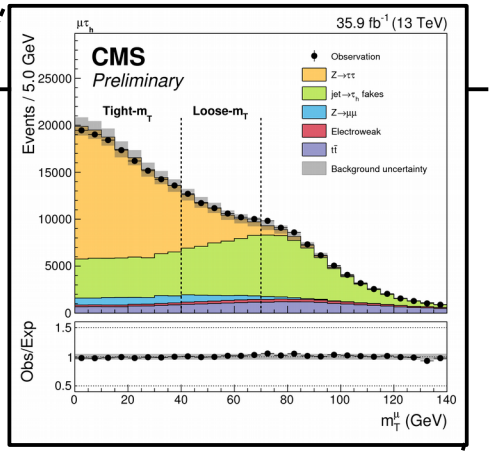
	No B-tag			B-tag		
$H \to \tau\tau \to e\mu$	Low-D_ζ	Medium-D_ζ	High-D_ζ	Low-D_ζ	Medium-D_ζ	High-D_ζ
$H \to \tau\tau \to e\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$H \to \tau\tau \to \mu\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$H \to \tau\tau \to \tau_h\tau_h$						
$Z \to \mu\mu$						
$t\bar{t}(e\mu)$						

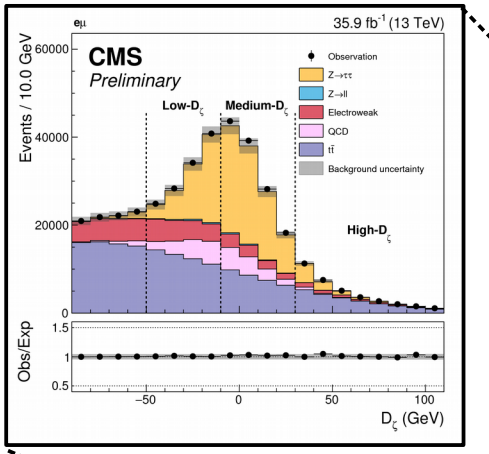
Signal region (SR)

Control region

Additional event information

Loose-m_T category as "tail-catcher" for high mass signal.





Exploit different S/B composition especially for high mass signal.

	No B-tag			B-tag		
$H \to \tau\tau \to e\mu$	Low-D_ζ	Medium-D_ζ	High-D_ζ	Low-D_ζ	Medium-D_ζ	High-D_ζ
$H \to \tau\tau \to e\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$H \to \tau\tau \to \mu\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$H \to \tau\tau \to \tau_h\tau_h$						
$Z \to \mu\mu$						
$t\bar{t}(e\mu)$						

Signal region (SR)

Control region

Control regions used for in situ determination of normalization and partially shapes of backgrounds in ML fit used for statistical inference of the signal.