Searches for Higgs Bosons beyond the SM

On behalf of the CMS Collaboration

Roger Wolf
08. Feb 2018

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**:

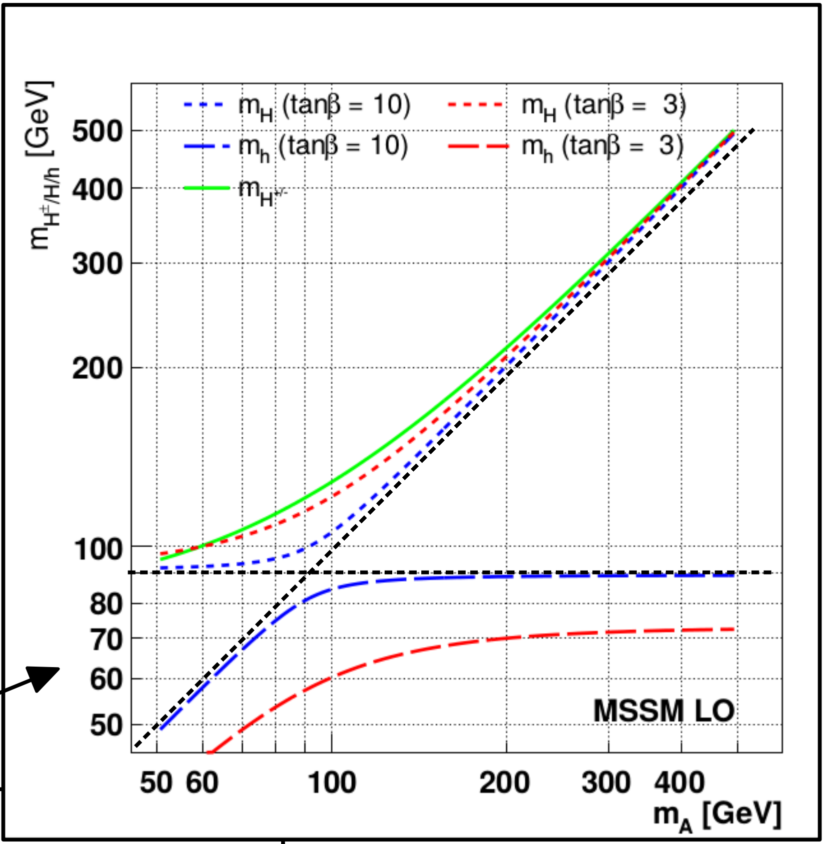
$$\phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}, \quad Y_{\phi_u} = +1, \quad v_u : \ \mathrm{VEV}_u$$

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

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

- Strict mass requirements imposed by symmetry

- At tree level two free parameters: m_A, $\tan\beta = {}^{v_u}/_{v_d}$.



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

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

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

α : angle between H and h in mass matrix

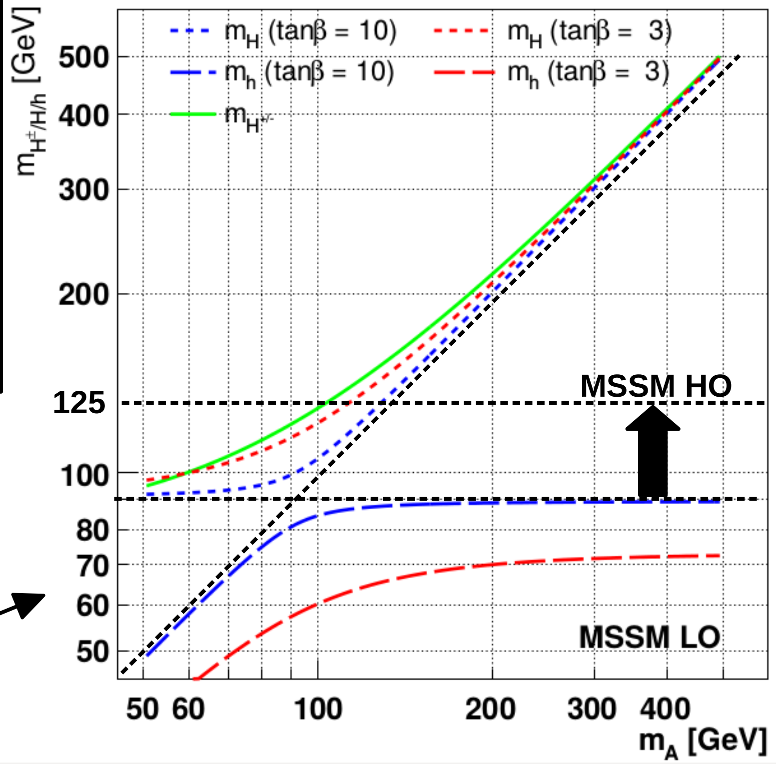
m_h and $\tan\beta$ in the MSSM

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

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

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

- +30% of m_h due to higher order corrections.
- Large values of $m_{\tilde{t}}$ for $|X_t| = \sqrt{6} m_{\tilde{t}}$ help to increase m_h .



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Down-type fermions in the MSSM

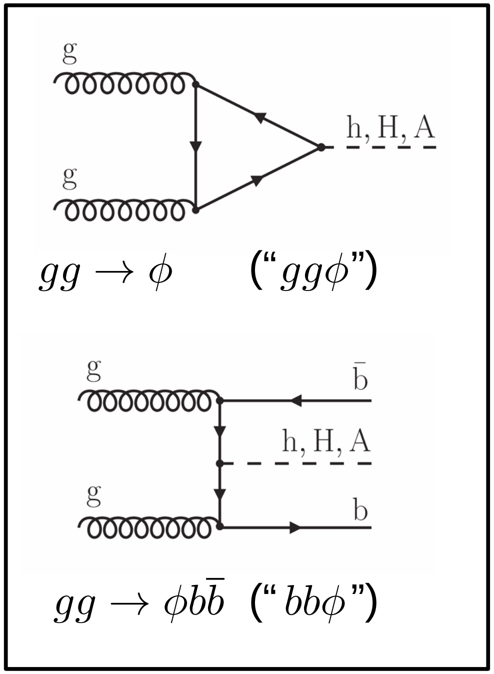
NB: w/o CP-violation in the SUSY Higgs sector.

	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 SM couplings.

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

Production modes:

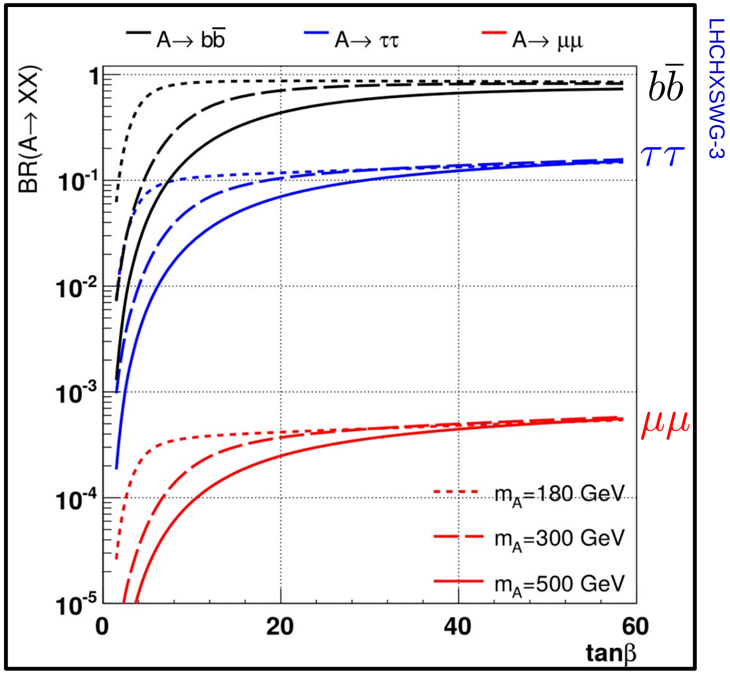


$gg\to\phi$ (“$gg\phi$”)

$gg\to\phi b\bar{b}$ (“$bb\phi$”)

X

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

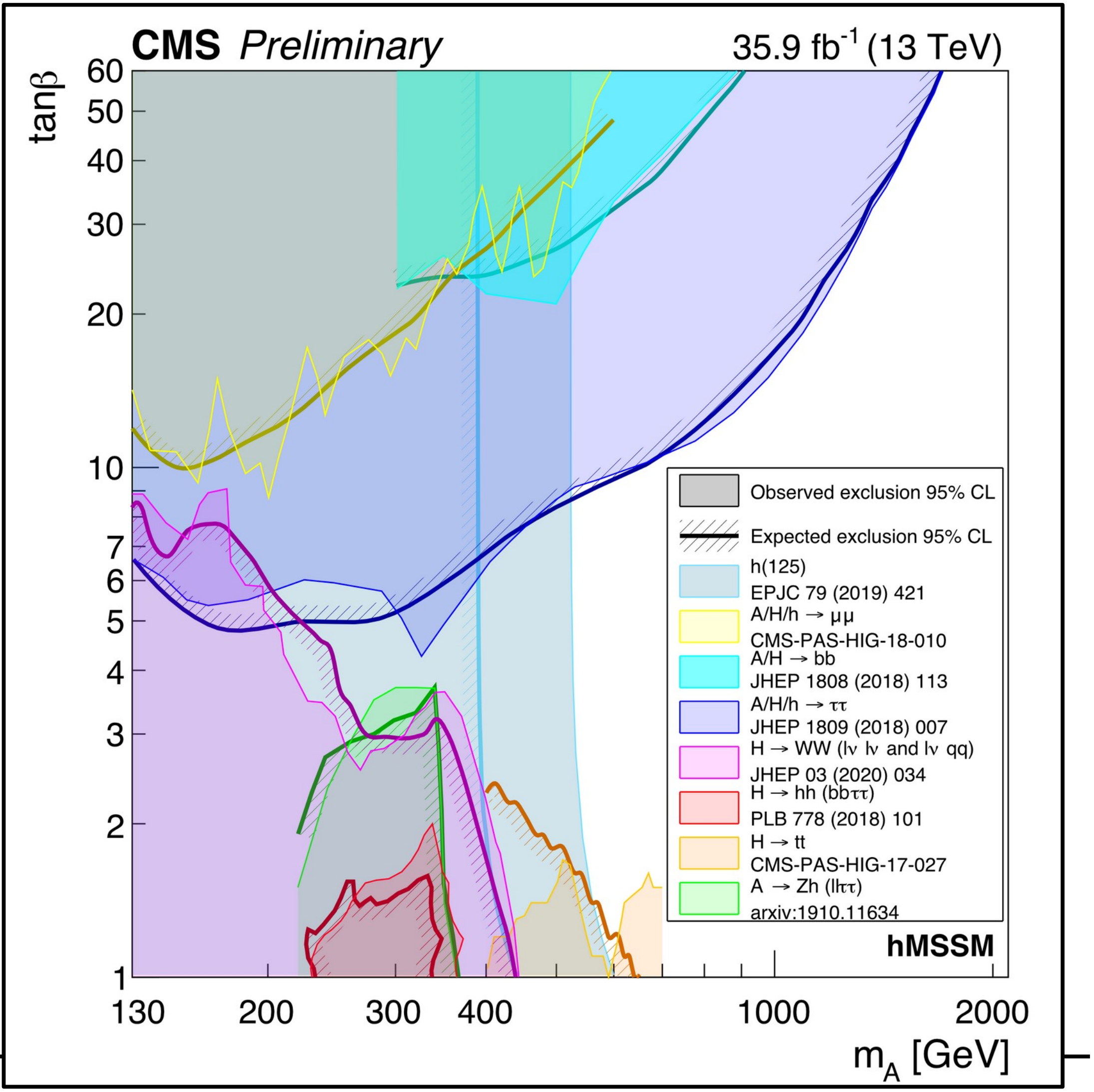


Harvest of LHC Run-2 (so far)

- Huge parameter space in MSSM systematically explored.

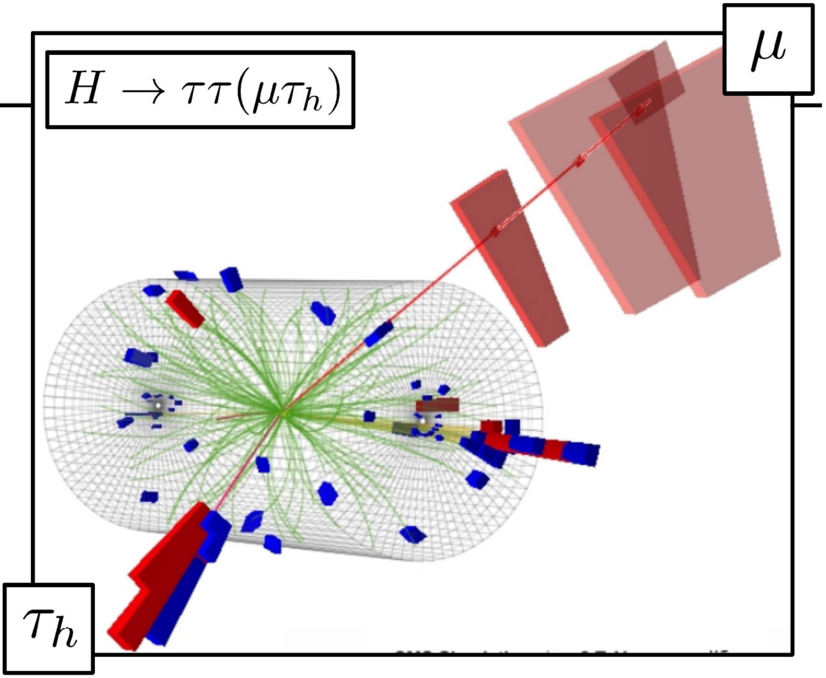
- Large values of $\tan\beta$ constrained by H/A searches in down type fermion final states.

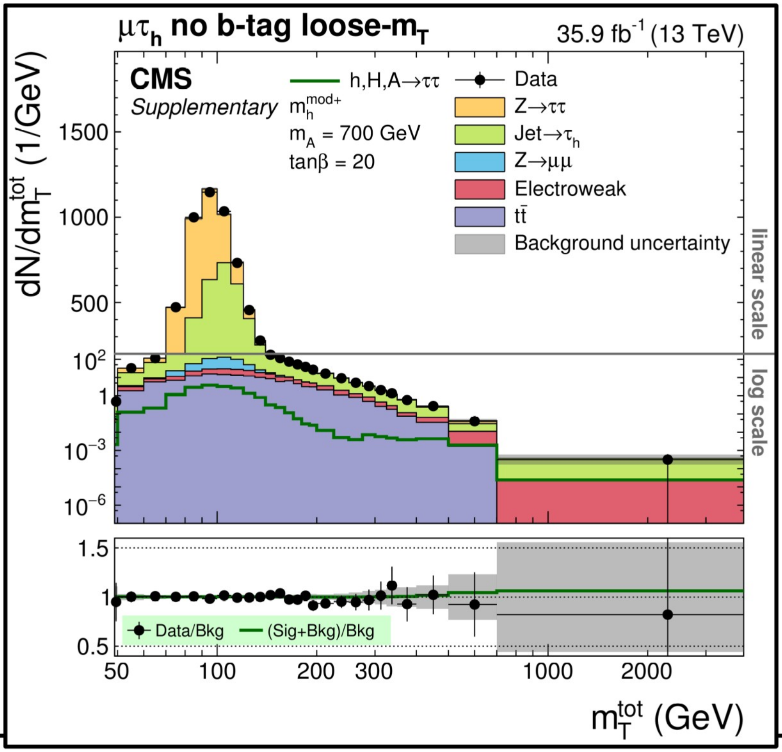
- Summary plot (status 03/2020) only exploits only ¼ of Run-2 dataset.



Di-τ final state

- Search for **2 isolated high p_T leptons** ($e,\ \mu\,,\tau_h$).
- Reduce obvious backgrounds, control what can't be reduced.
- Reconstruct discriminating variable, related to di-τ final state.





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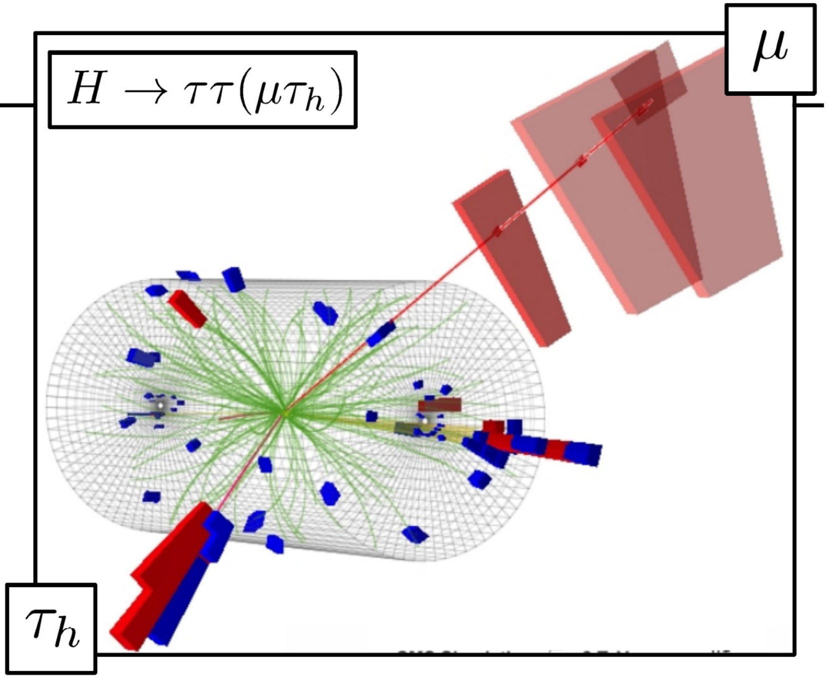
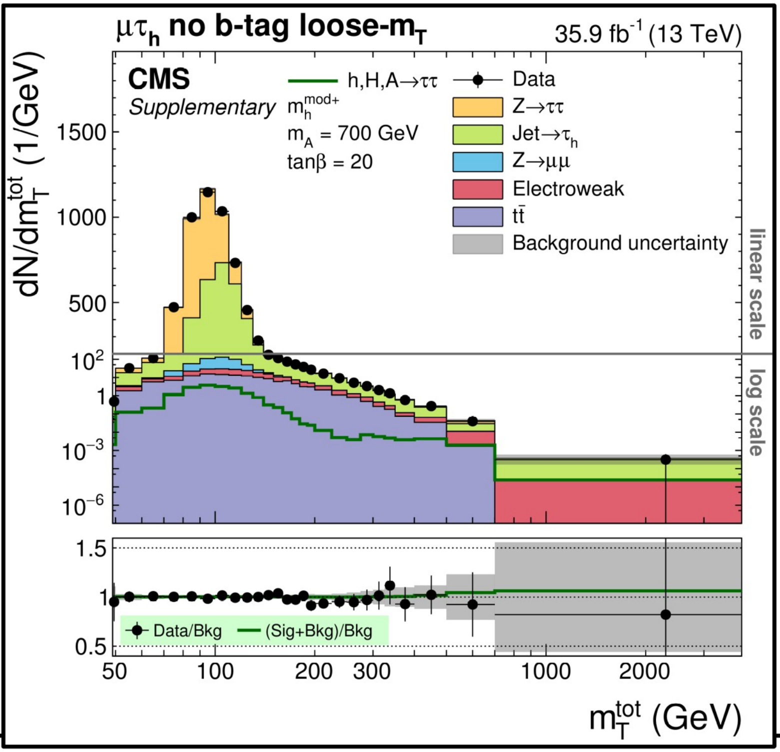
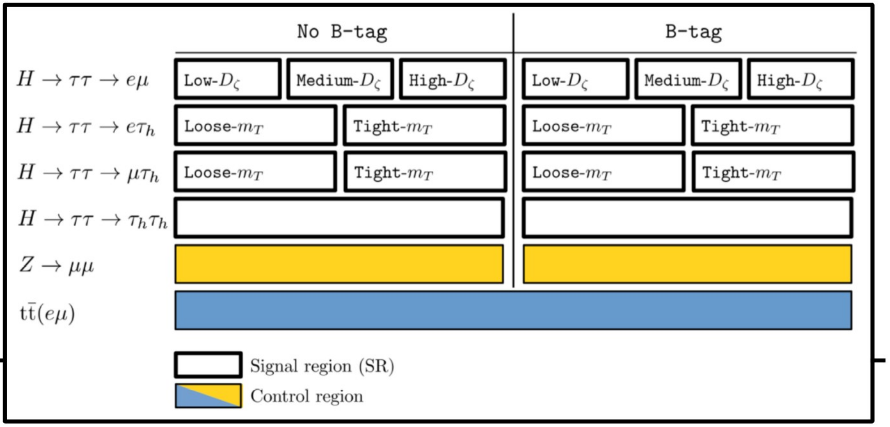




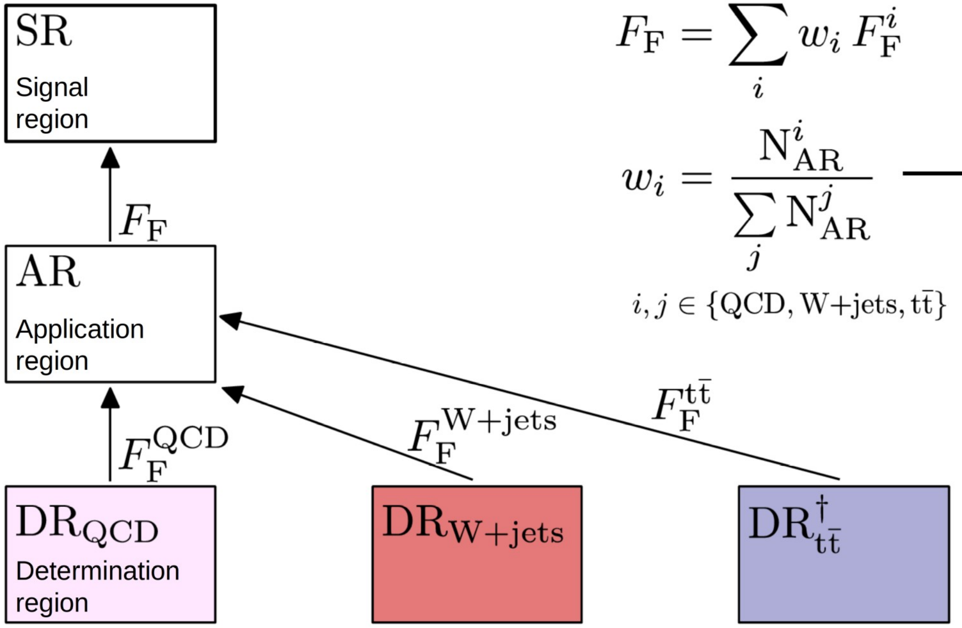
- Usually large fraction of BGs ($\rightarrow \mathrm{Jet} \rightarrow \tau_h$ and $\mathrm{Z} \rightarrow \tau\tau$ modeled from data.
- Simple event categories enhance sensitivity.



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

☐ Signal region (SR)
◩ Control region

FF method

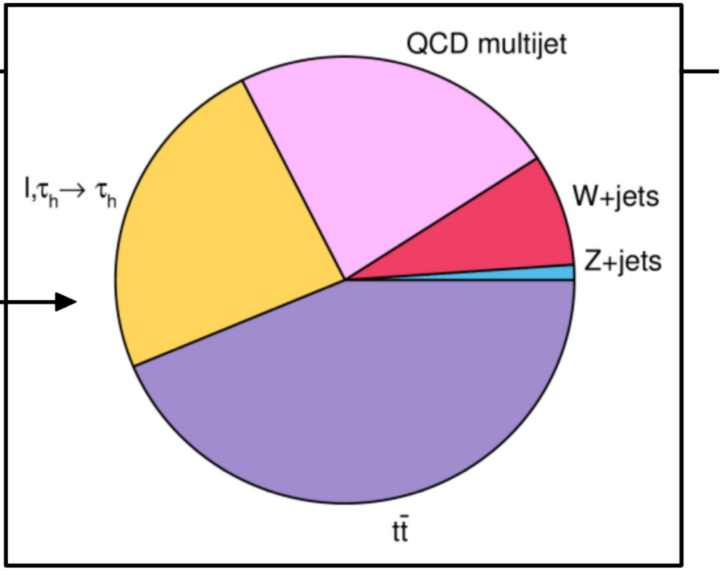


$$F_\mathrm{F} = \sum_i w_i\, F_\mathrm{F}^i$$

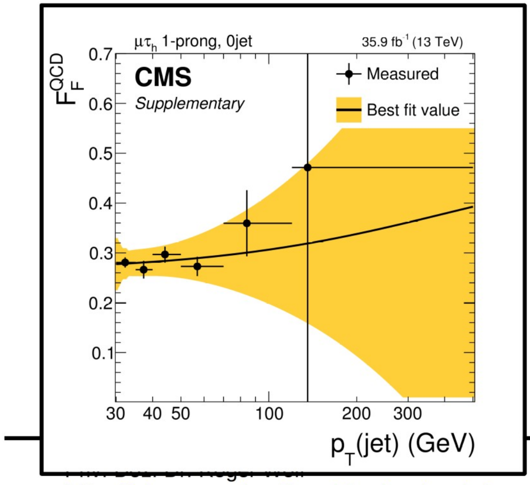
$$w_i = \frac{\mathrm{N}^i_\mathrm{AR}}{\sum_j \mathrm{N}^j_\mathrm{AR}}$$

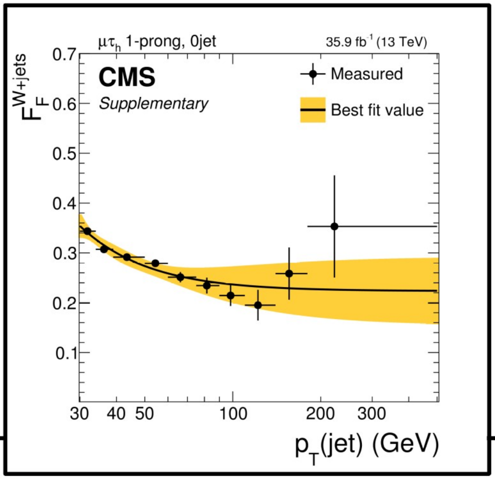
$$i, j \in \{\mathrm{QCD}, \mathrm{W{+}jets}, \mathrm{t\bar{t}}\}$$

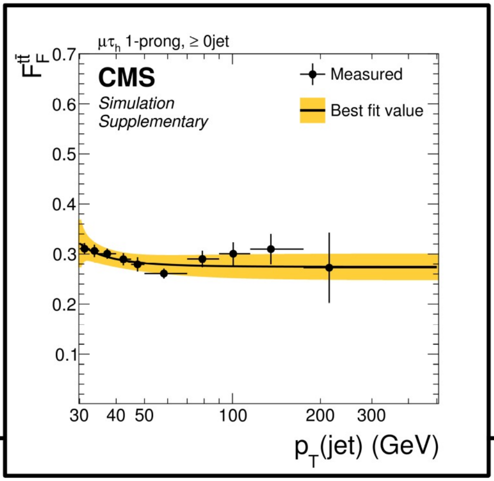
†Taken from simulation



$$F_\mathrm{F} = \frac{\text{tight } \tau\text{-ID}}{\text{loose } \wedge \neg \text{tight } \tau\text{-ID}}$$



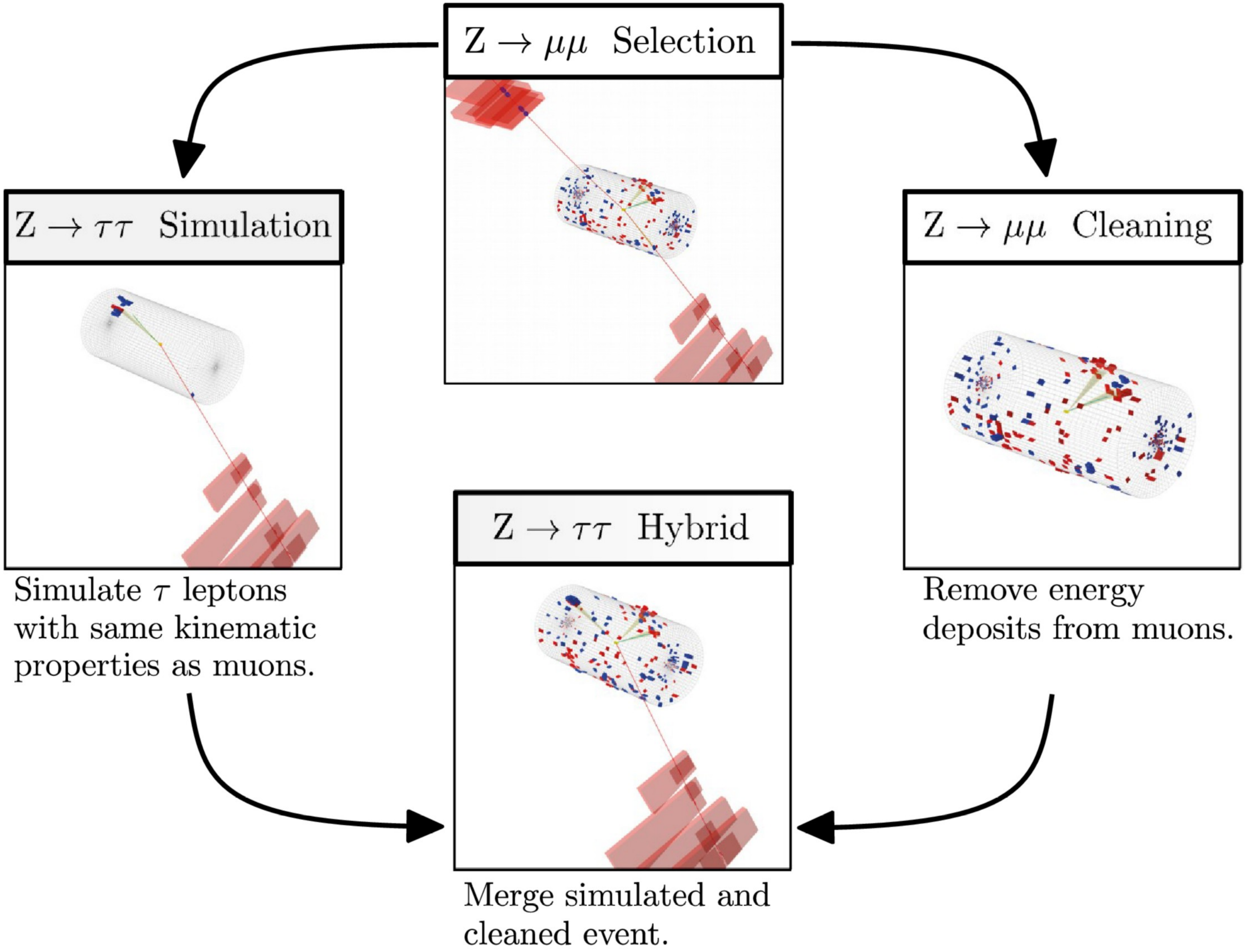




JHEP 09 (2018) 007

τ-embedding

JINST 14 (2019) P06032



$Z \rightarrow \mu\mu$ Selection

$Z \rightarrow \tau\tau$ Simulation

Simulate τ leptons with same kinematic properties as muons.

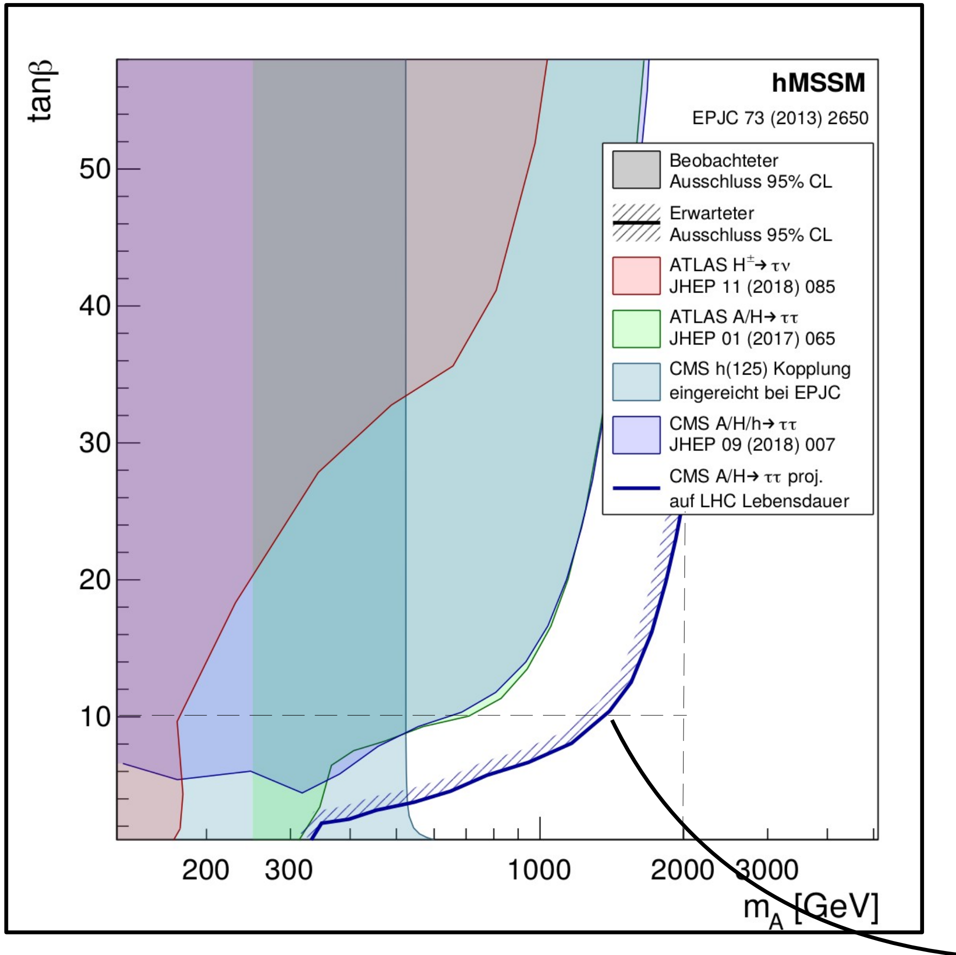
$Z \rightarrow \mu\mu$ Cleaning

Remove energy deposits from muons.

$Z \rightarrow \tau\tau$ Hybrid

Merge simulated and cleaned event.

Reach & challenges



- Sensitivity reach up to $m_A \approx 2\,\mathrm{TeV}$ for LHC@13TeV.
- Take $A/H/h$ into account when comparing to benchmark models.
- Models have to cope with the properties we observe for h .
- Will become especially challenging for $\tan\beta \lesssim 10$.
- In addition dedicated analyses explicitly target low $\tan\beta$.

Projection of simple $\mathrm{A}/\mathrm{H} \rightarrow \tau\tau$ analysis to 3000/fb.

Low $\tan\beta$ and m_h

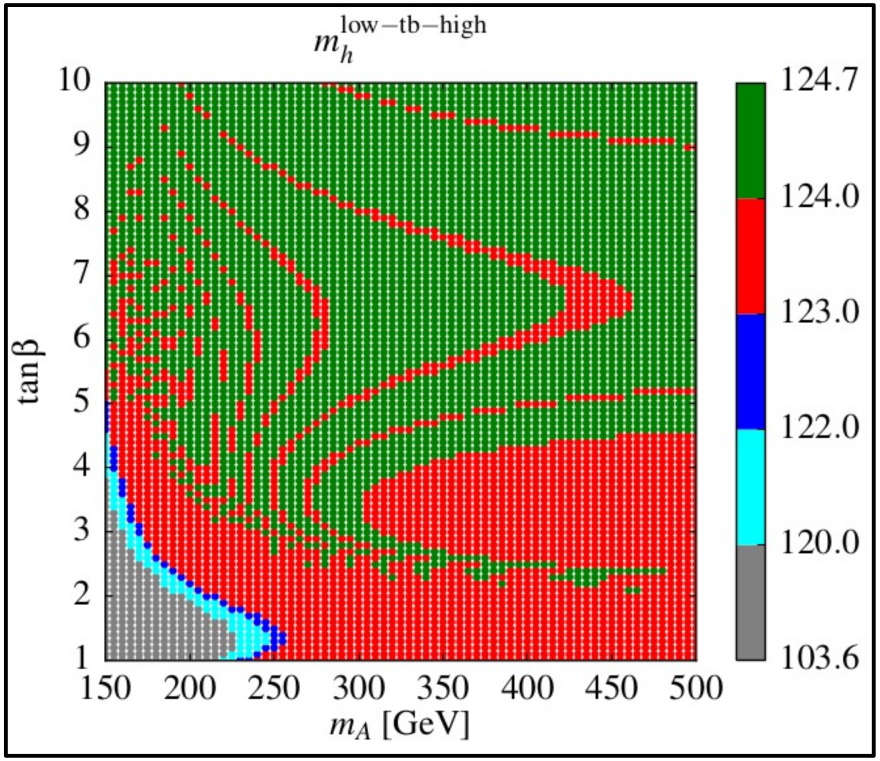
- Already after Run-1 LHC Higgs WG addressed low $\tan\beta$ region taking knowledge of m_h into account with two dedicated benchmark models: “hMSSM” and “low-tb-high”.

- **“low-tb-high”:**
  - Benchmark parameters adapted to match $m_h \approx 125\,\mathrm{GeV}$ for each value of $\tan\beta$.
  - Required values of $m_{\tilde{t}}$ up to 100 TeV.

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

  - m_h estimate required consideration of large log’s of $\tan(m_{\tilde{t}}/m_t)$.

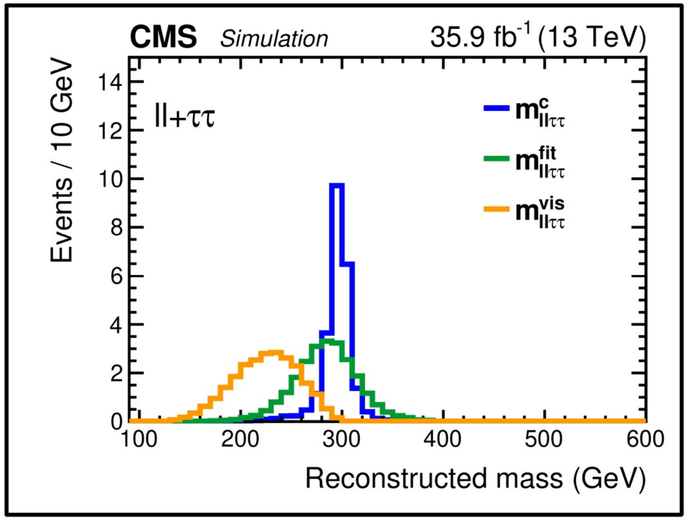
- In the meantime a model exploiting an EFT approach to resum such log’s has been provided by EPJ C (2019) 79 ($M_{h,\mathrm{EFT}}^{125}$).

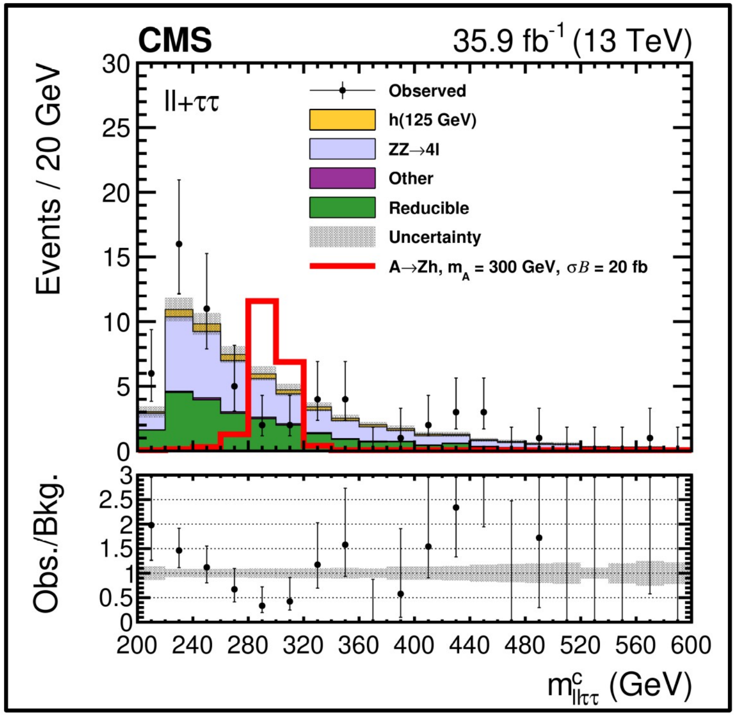


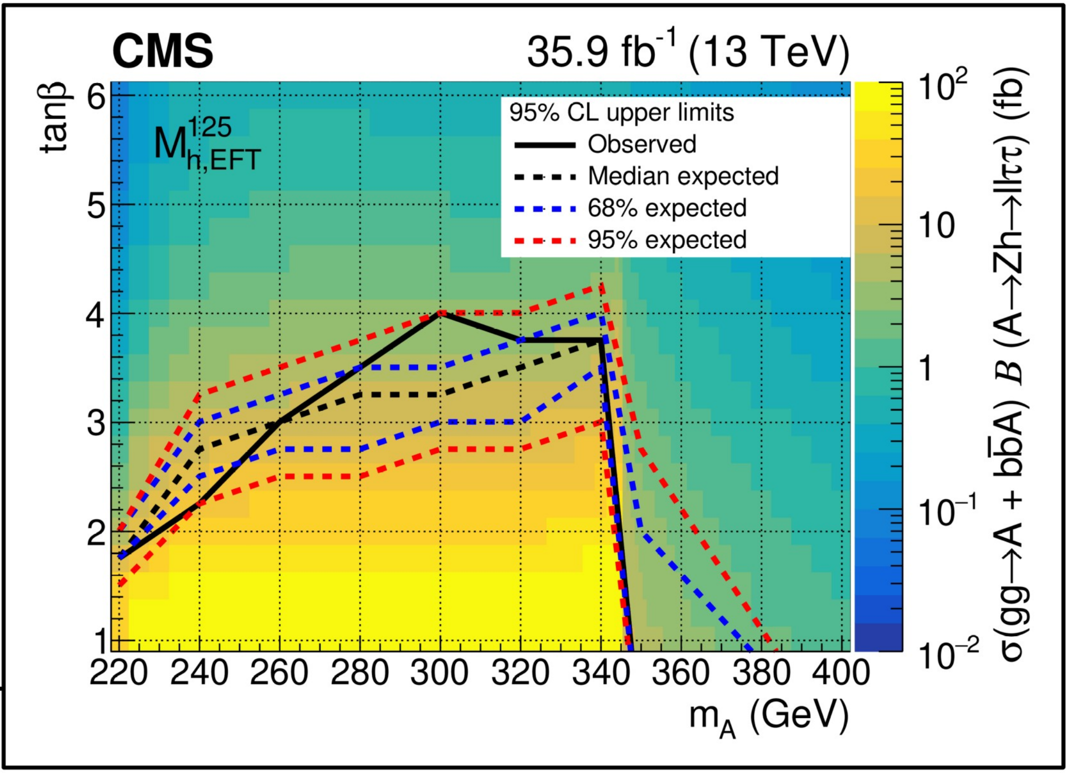
LHCHXSWG-INT-2015-004

$A \to \mathrm{Z}(\ell\ell)h(\tau\tau)$

- A more recent analysis explicitly targeting low $\tan\beta$.
- A production via gluon fusion and in association with b-quarks:
- Exploiting kinematic fit of $\ell\ell + \tau\tau$ as discriminating observable.



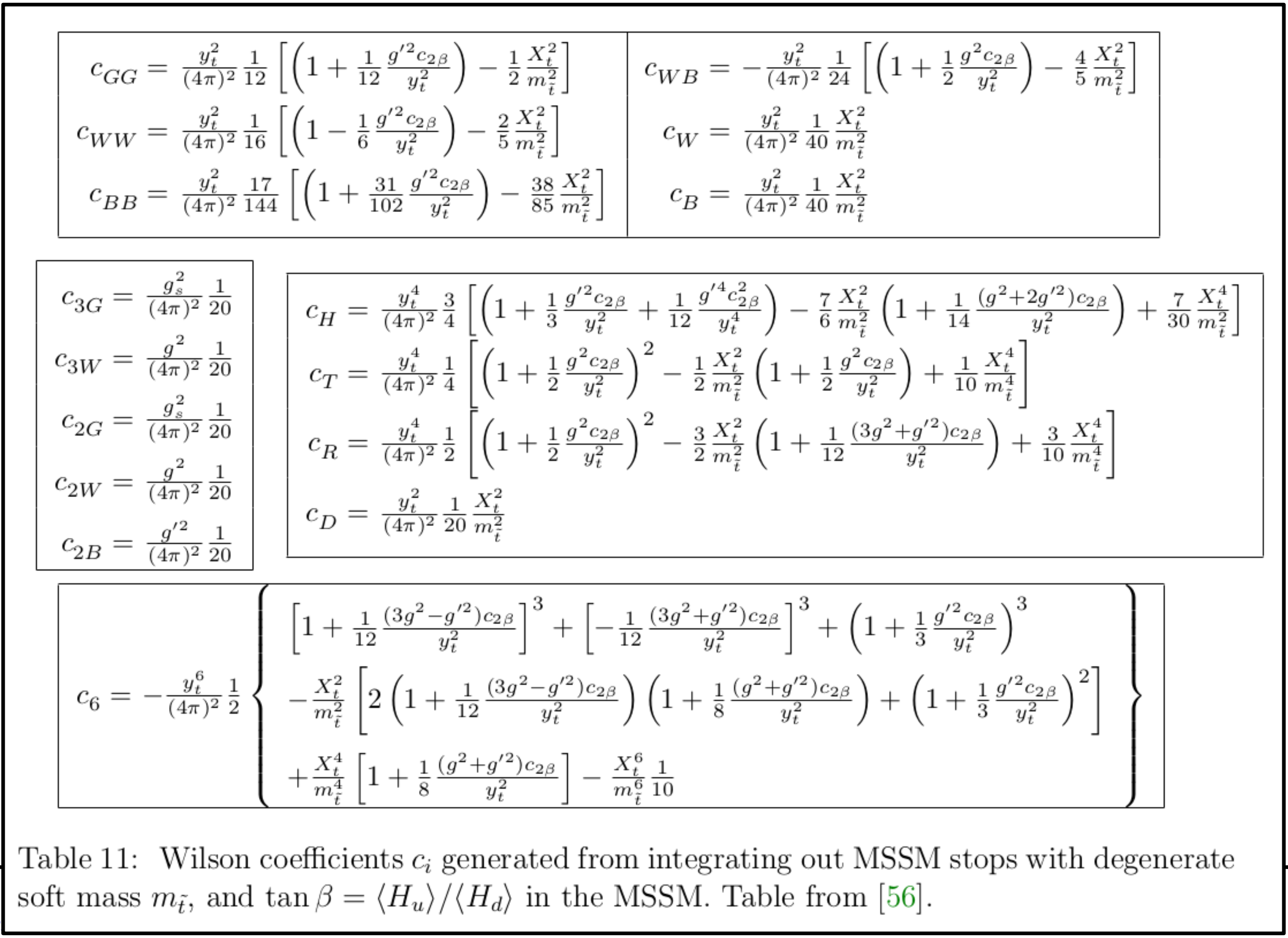




Translation tables MSSM ↔ EFT

- LHC Higgs WG-2 has also provided translation tables between MSSM parame-ters and EFT Wilson coefficients (in the SILH basis) in LHC-HXSWG-2019-006.

- Here an example is shown for the marginalisation of large degenerate “*stop*” masses.



$$c_{GG} = \frac{y_t^2}{(4\pi)^2}\frac{1}{12}\left[\left(1+\frac{1}{12}\frac{g'^2 c_{2\beta}}{y_t^2}\right)-\frac{1}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\right]$$

$$c_{WW} = \frac{y_t^2}{(4\pi)^2}\frac{1}{16}\left[\left(1-\frac{1}{6}\frac{g'^2 c_{2\beta}}{y_t^2}\right)-\frac{2}{5}\frac{X_t^2}{m_{\tilde{t}}^2}\right]$$

$$c_{BB} = \frac{y_t^2}{(4\pi)^2}\frac{17}{144}\left[\left(1+\frac{31}{102}\frac{g'^2 c_{2\beta}}{y_t^2}\right)-\frac{38}{85}\frac{X_t^2}{m_{\tilde{t}}^2}\right]$$

$$c_{WB} = -\frac{y_t^2}{(4\pi)^2}\frac{1}{24}\left[\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{y_t^2}\right)-\frac{4}{5}\frac{X_t^2}{m_{\tilde{t}}^2}\right]$$

$$c_W = \frac{y_t^2}{(4\pi)^2}\frac{1}{40}\frac{X_t^2}{m_{\tilde{t}}^2}$$

$$c_B = \frac{y_t^2}{(4\pi)^2}\frac{1}{40}\frac{X_t^2}{m_{\tilde{t}}^2}$$

$$c_{3G} = \frac{g_s^2}{(4\pi)^2}\frac{1}{20}$$

$$c_{3W} = \frac{g^2}{(4\pi)^2}\frac{1}{20}$$

$$c_{2G} = \frac{g_s^2}{(4\pi)^2}\frac{1}{20}$$

$$c_{2W} = \frac{g^2}{(4\pi)^2}\frac{1}{20}$$

$$c_{2B} = \frac{g'^2}{(4\pi)^2}\frac{1}{20}$$

$$c_H = \frac{y_t^4}{(4\pi)^2}\frac{3}{4}\left[\left(1+\frac{1}{3}\frac{g'^2 c_{2\beta}}{y_t^2}+\frac{1}{12}\frac{g'^4 c_{2\beta}^2}{y_t^4}\right)-\frac{7}{6}\frac{X_t^2}{m_{\tilde{t}}^2}\left(1+\frac{1}{14}\frac{(g^2+2g'^2)c_{2\beta}}{y_t^2}\right)+\frac{7}{30}\frac{X_t^4}{m_{\tilde{t}}^2}\right]$$

$$c_T = \frac{y_t^4}{(4\pi)^2}\frac{1}{4}\left[\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{y_t^2}\right)^2-\frac{1}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{y_t^2}\right)+\frac{1}{10}\frac{X_t^4}{m_{\tilde{t}}^4}\right]$$

$$c_R = \frac{y_t^4}{(4\pi)^2}\frac{1}{2}\left[\left(1+\frac{1}{2}\frac{g^2 c_{2\beta}}{y_t^2}\right)^2-\frac{3}{2}\frac{X_t^2}{m_{\tilde{t}}^2}\left(1+\frac{1}{12}\frac{(3g^2+g'^2)c_{2\beta}}{y_t^2}\right)+\frac{3}{10}\frac{X_t^4}{m_{\tilde{t}}^4}\right]$$

$$c_D = \frac{y_t^2}{(4\pi)^2}\frac{1}{20}\frac{X_t^2}{m_{\tilde{t}}^2}$$

$$c_6 = -\frac{y_t^6}{(4\pi)^2}\frac{1}{2}\left\{\begin{aligned}&\left[1+\frac{1}{12}\frac{(3g^2-g'^2)c_{2\beta}}{y_t^2}\right]^3+\left[-\frac{1}{12}\frac{(3g^2+g'^2)c_{2\beta}}{y_t^2}\right]^3+\left(1+\frac{1}{3}\frac{g'^2 c_{2\beta}}{y_t^2}\right)^3\\&-\frac{X_t^2}{m_{\tilde{t}}^2}\left[2\left(1+\frac{1}{12}\frac{(3g^2-g'^2)c_{2\beta}}{y_t^2}\right)\left(1+\frac{1}{8}\frac{(g^2+g'^2)c_{2\beta}}{y_t^2}\right)+\left(1+\frac{1}{3}\frac{g'^2 c_{2\beta}}{y_t^2}\right)^2\right]\\&+\frac{X_t^4}{m_{\tilde{t}}^4}\left[1+\frac{1}{8}\frac{(g^2+g'^2)c_{2\beta}}{y_t^2}\right]-\frac{X_t^6}{m_{\tilde{t}}^6}\frac{1}{10}\end{aligned}\right\}$$

Table 11: Wilson coefficients c_i generated from integrating out MSSM stops with degenerate soft mass $m_{\tilde{t}}$, and $\tan\beta = \langle H_u\rangle/\langle H_d\rangle$ in the MSSM. Table from [56].

Conclusions

- MSSM searches (as an important example of UV theories) → integral part of CMS search programme.

- Experimental results challenge MSSM models and will even more with full Run-2 and Run-3 data.

- Kinematic reach at LHC is up to 2 TeV. Low values of require large values of $m_{\tilde{t}}$ to match $m_h \approx 125\,\mathrm{GeV}$, which will be one of the strongest challenges to the MSSM.

- EFT based models have been developed to address low $\tan\beta$ region. Translation tables between MSSM parameters and Wilson coefficients have been provided by LHC Higgs WG.

Backup

arXiv:1805.12191

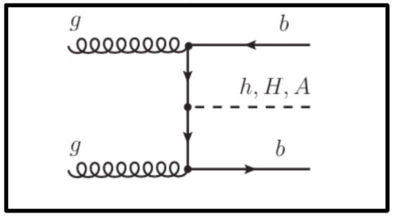
MSSM $\mathrm{H/A}\rightarrow bb$

- 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 signal from simulation.

find

Suited shapes for background model from CR.

(1)

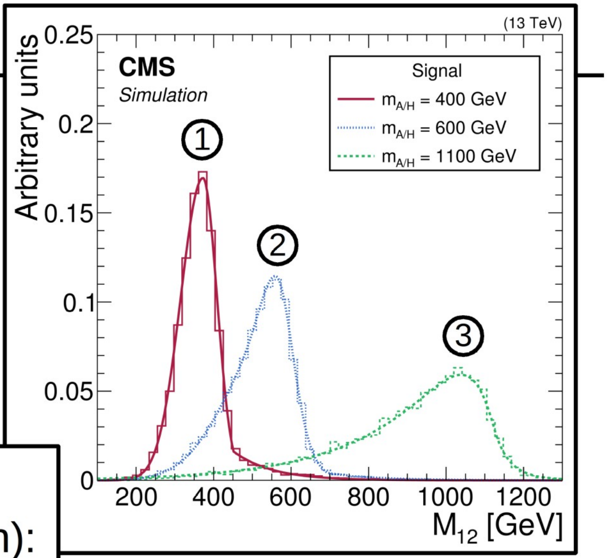
$$N_{\mathrm{j}}(p_{\mathrm{T}} > 100\,\mathrm{GeV}) \geq 2$$
$$\eta_{\mathrm{j}} > 2.4\,; \quad \Delta\eta_{\mathrm{j}} < 1.6$$

arXiv:1805.12191

Signal and background model

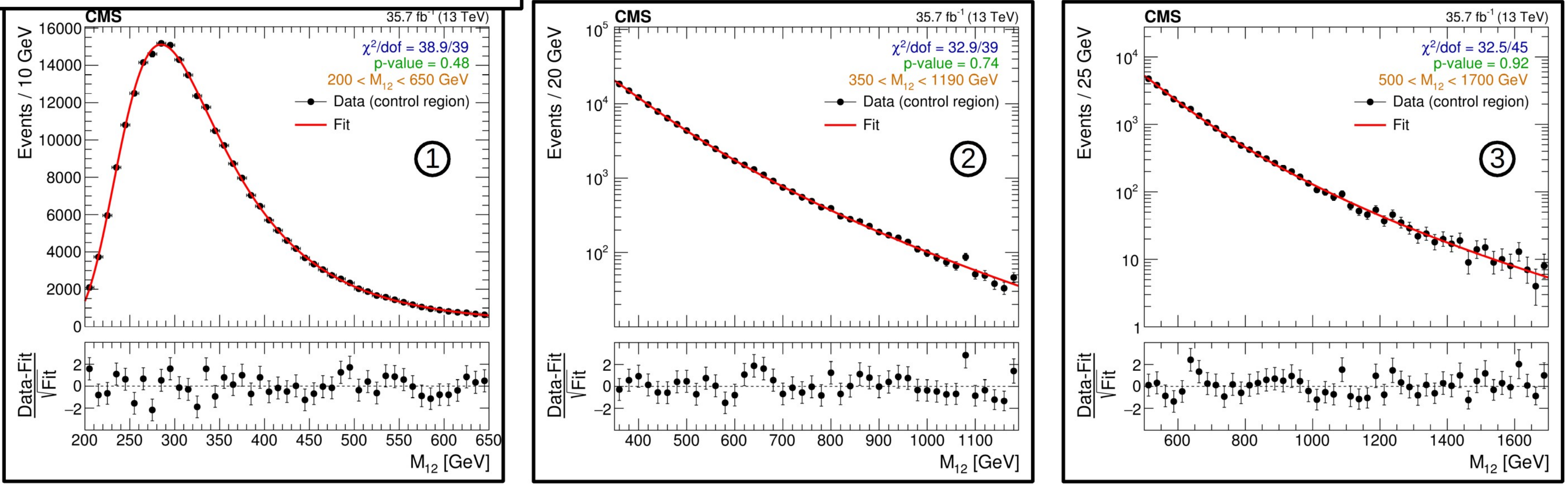
- Discriminating variable: invariant mass of two leading jets after b-tagging requirement (M_{12}).
- Different shapes of signal and background motivate separation into three (overlapping) categories in M_{12} .

Signal shapes (from simulation):



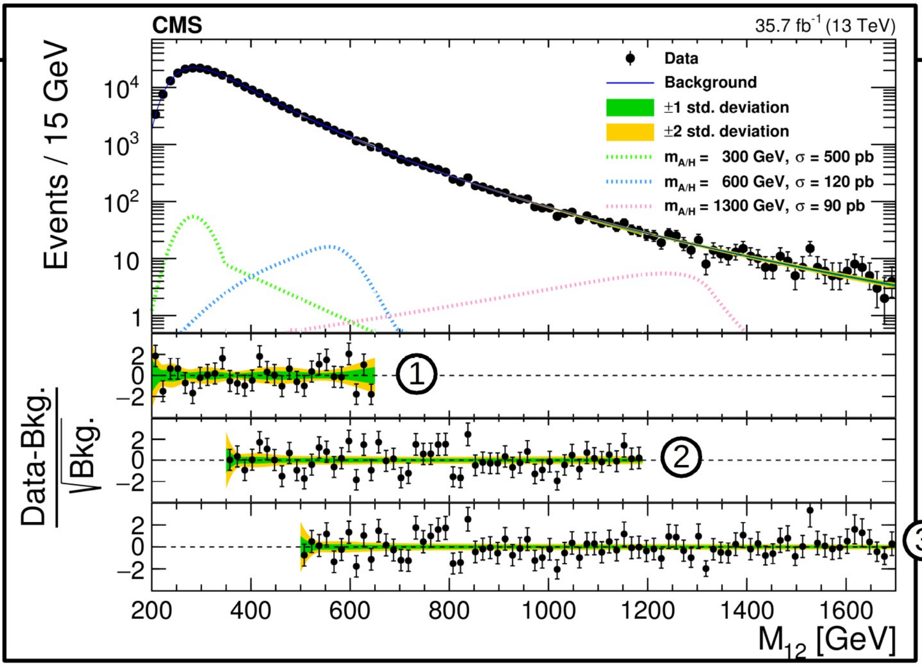
Natural width of signal <19%, experimental resolution ~25%.

Background shapes (from CR):

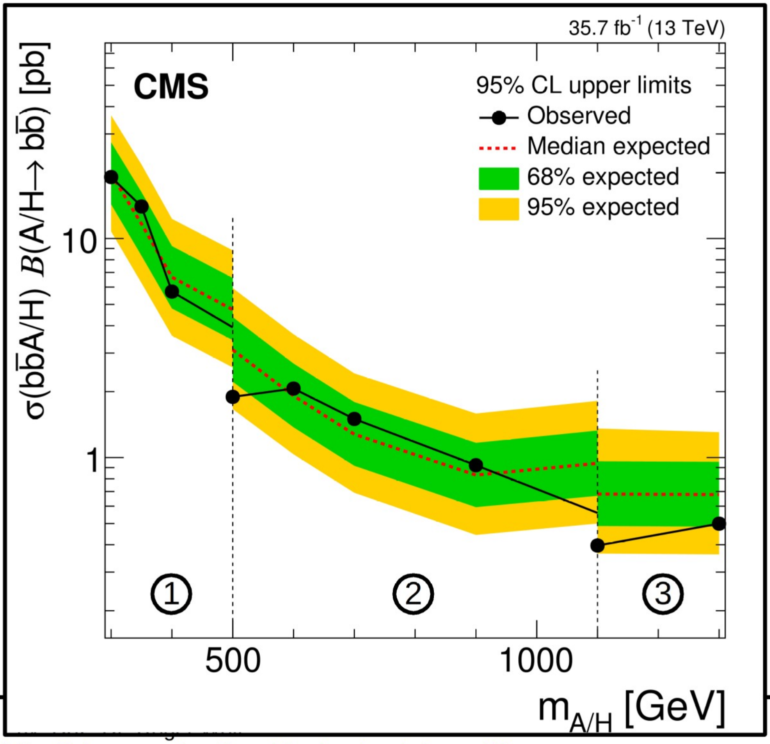


Results

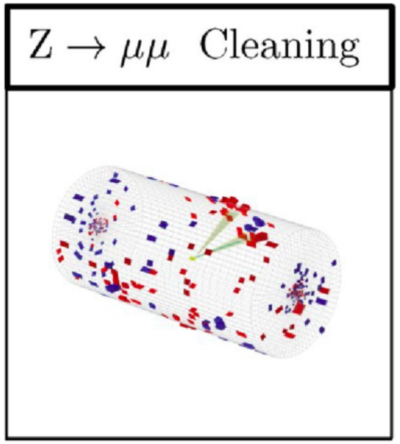
- Most important systematic uncertainties:
  - Potential bias due to choice of analytic functions.
  - b-tagging efficiency.
- Sensitivity significantly improved w.r.t. Run-1 analysis (Run-1 analysis reached further down in m_{A}).



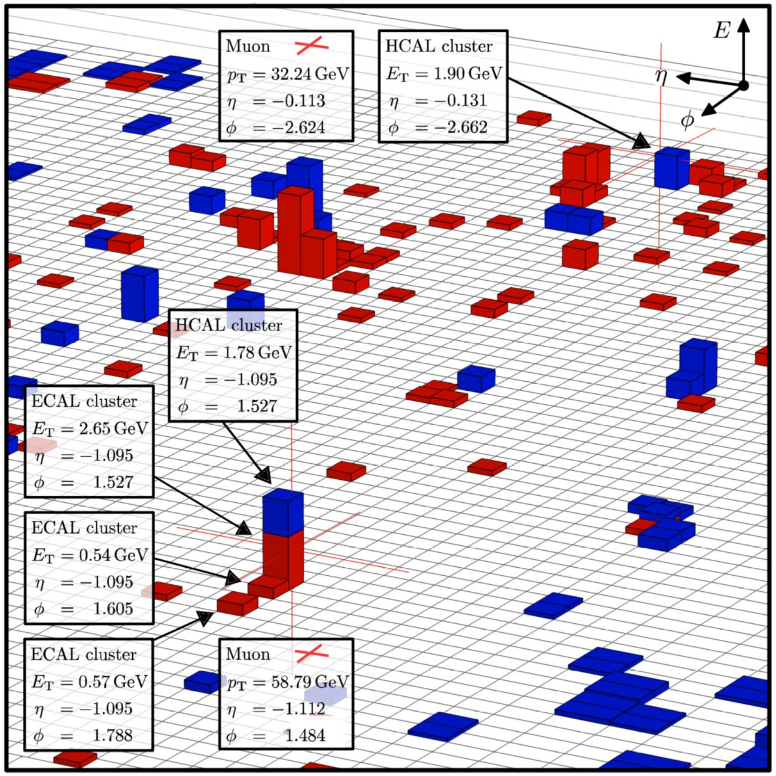
- No deviations observed from SM expectation. → limits on $\sigma \times \mathrm{BR}$.



τ-embedding


$Z \rightarrow \mu\mu$ Cleaning

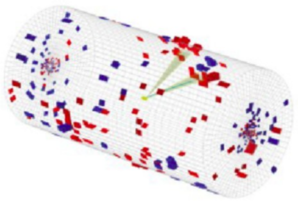
Before:



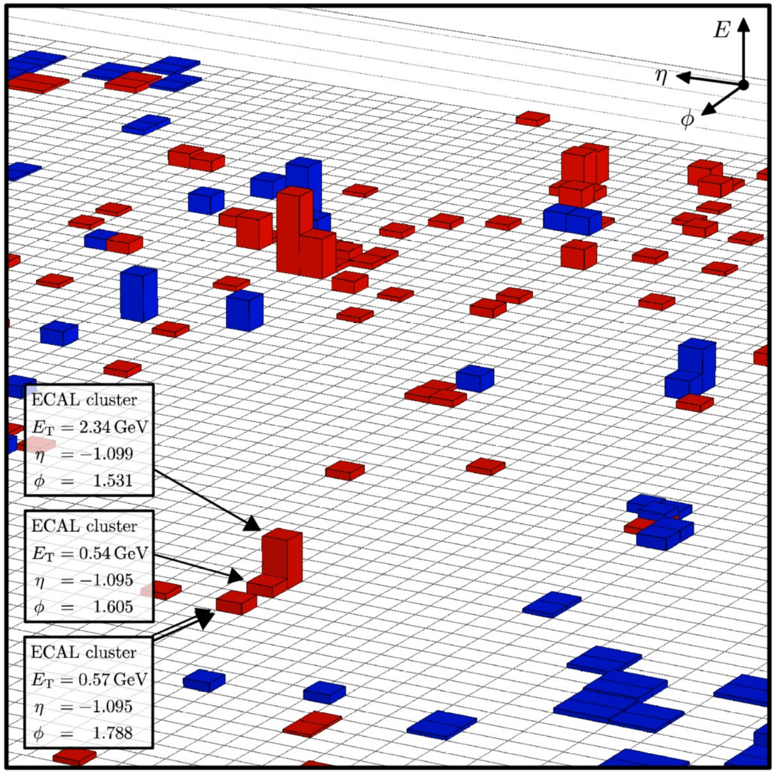
JINST 14 (2019) P06032

τ-embedding

$Z \rightarrow \mu\mu$ Cleaning



After:



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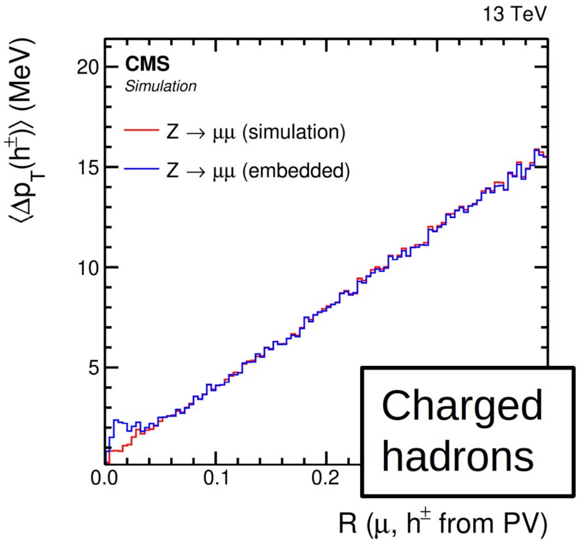
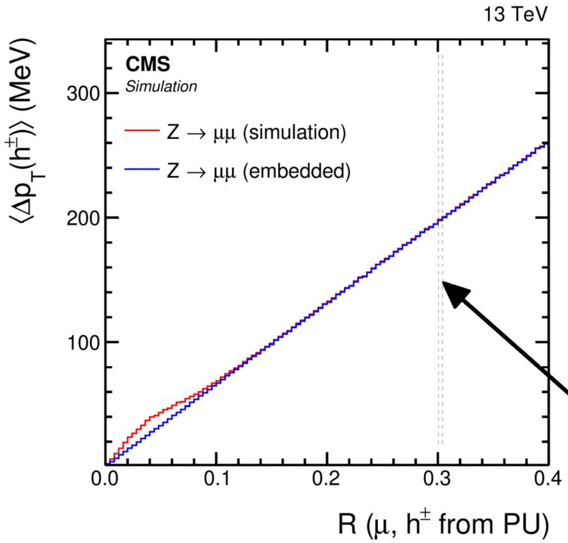
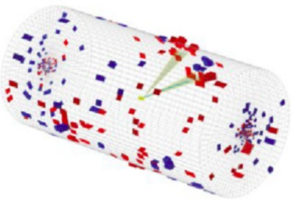
τ-embedding



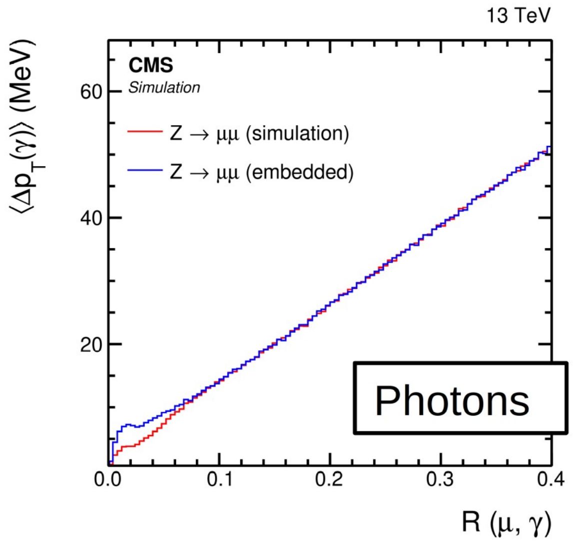
Charged hadrons



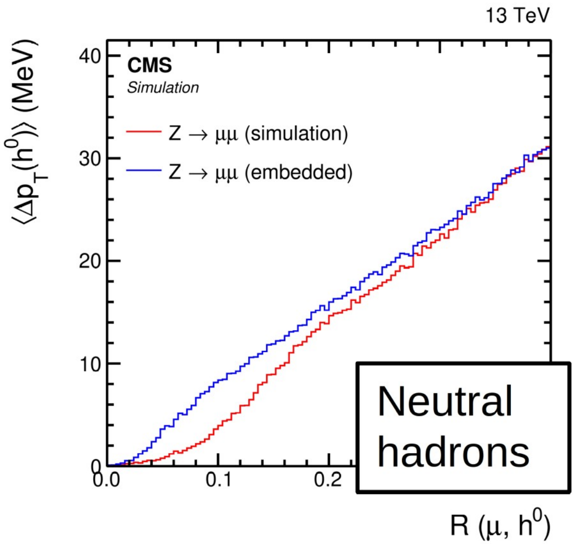
Z → μμ Cleaning



Control particle flux close to μ to level of **140 MeV**

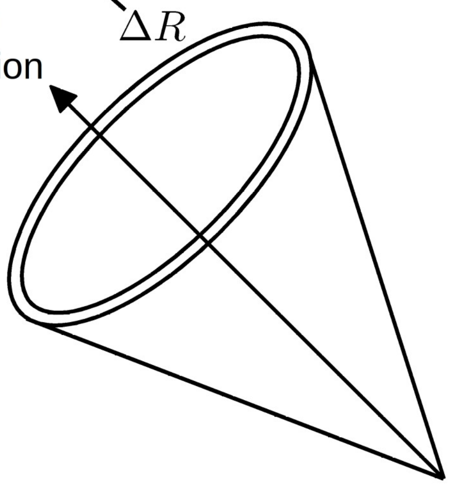


Photons



Neutral hadrons

Muon direction



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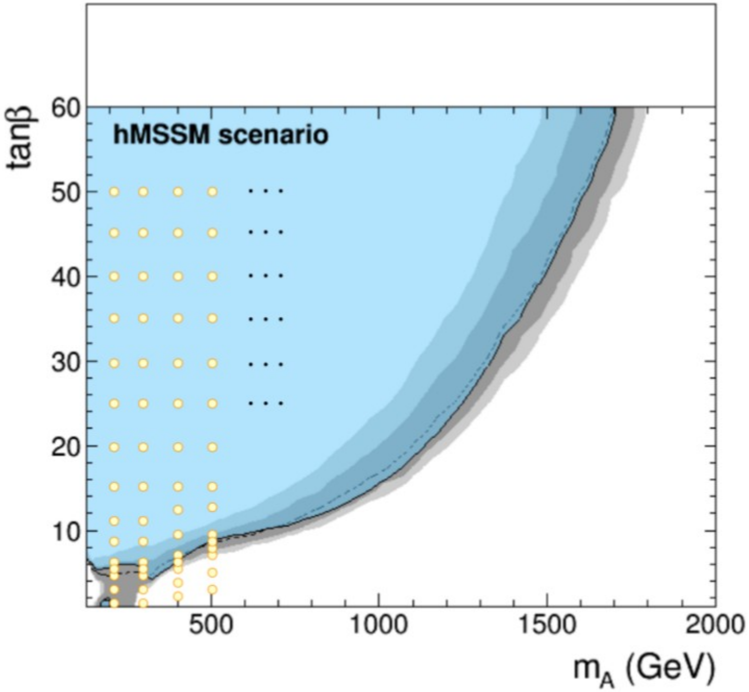
Signal modeling

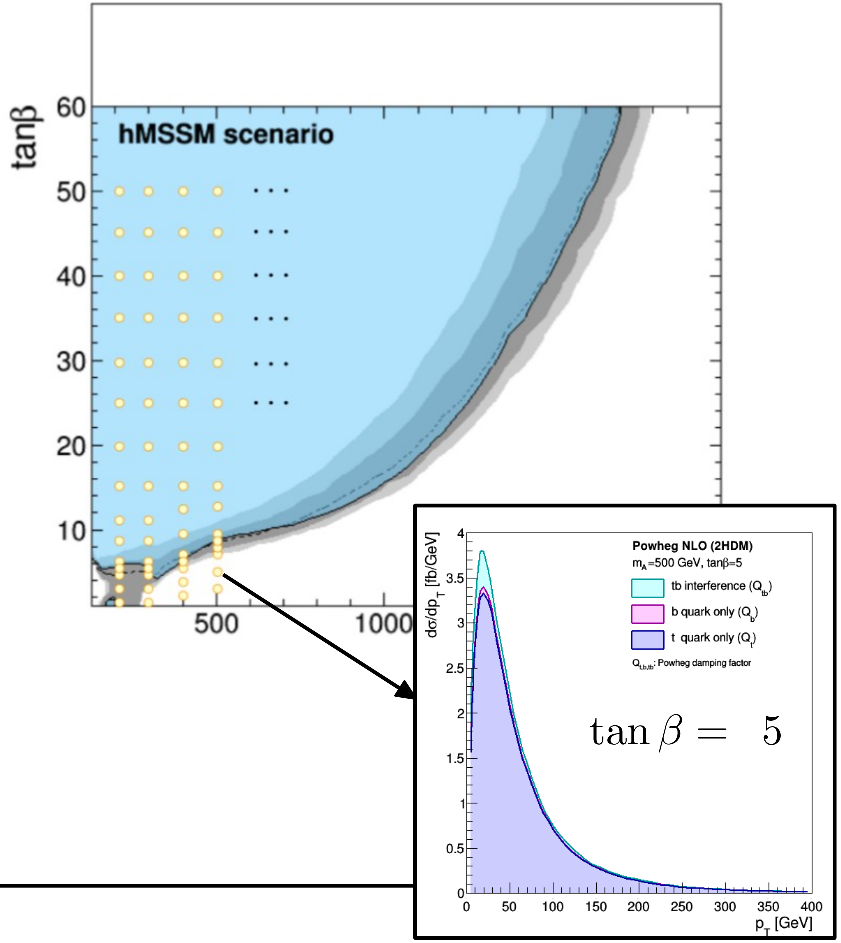
Test MSSM vs SM hypothesis: allows for well defined statistical problem, even when reaching sensitivity to the 125 GeV Higgs boson.



- Typical scan to determine exclusion contours in specific models.
- Determine CLs in each point in parameter space to obtain limit at significance level α.

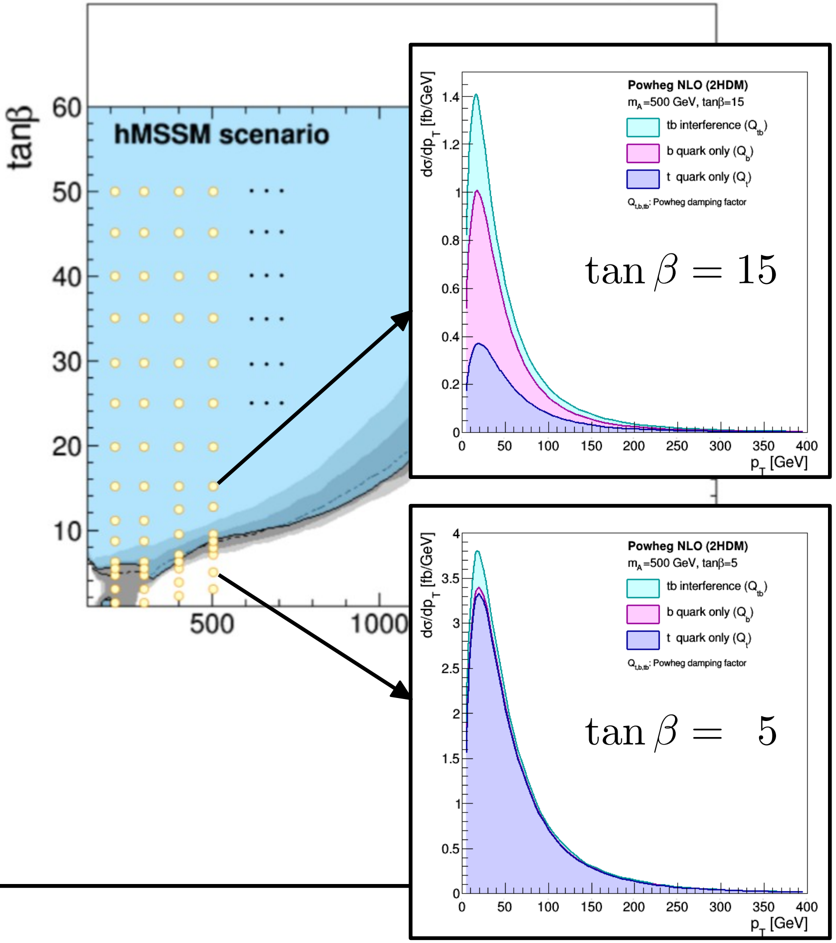
Signal modeling

- $p_T(A, H, h)$@ NLO QCD + PS → **multiscale problem**.
- Plus: b contribution varies as a function of $\tan\beta$.



Signal modeling

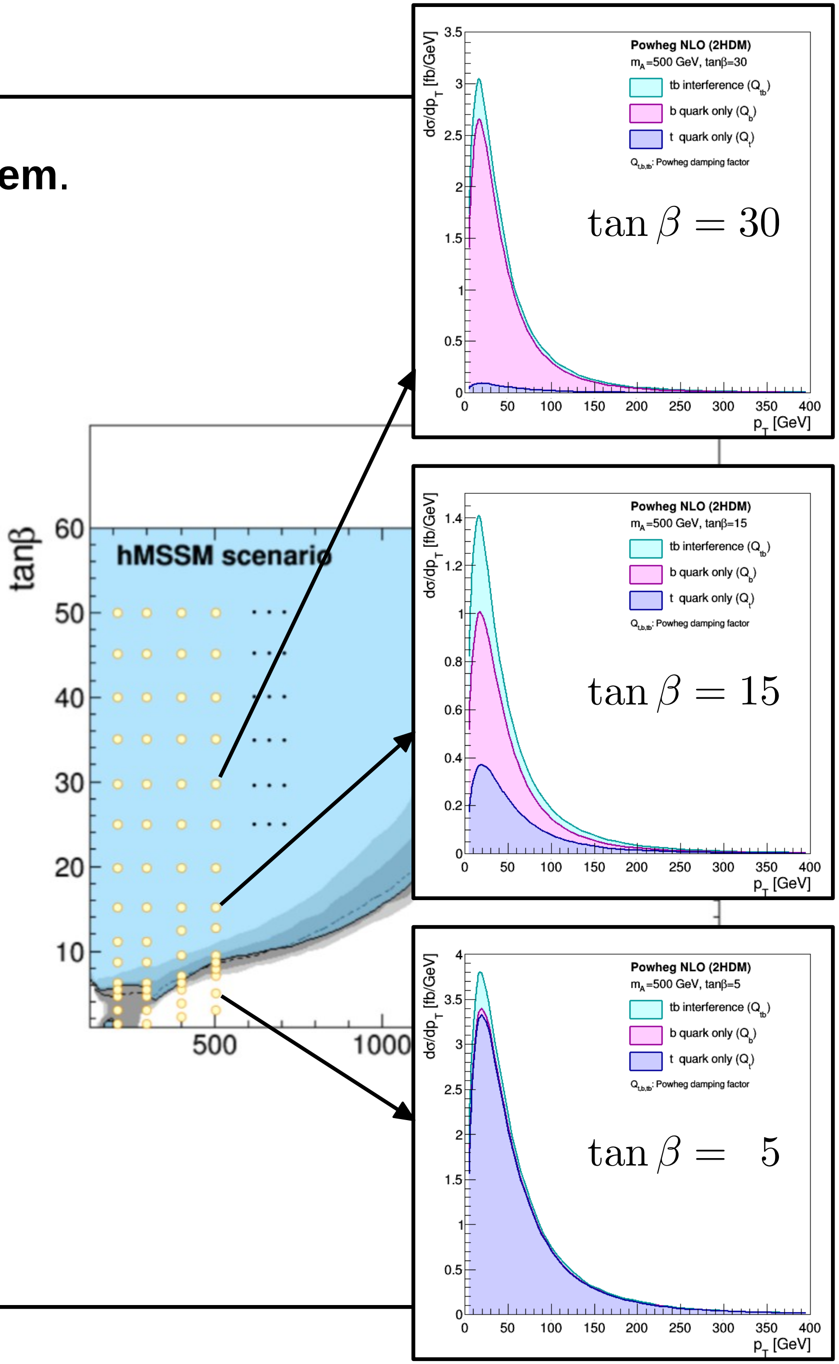
- $p_T(A,H,h)$@ NLO QCD + PS → **multiscale problem**.
- Plus: b contribution varies as a function of $\tan\beta$.



Signal modeling

- $p_T(A,H,h)$@ NLO QCD + PS → **multiscale problem**.
- Plus: b contribution varies as a function of $\tan\beta$.

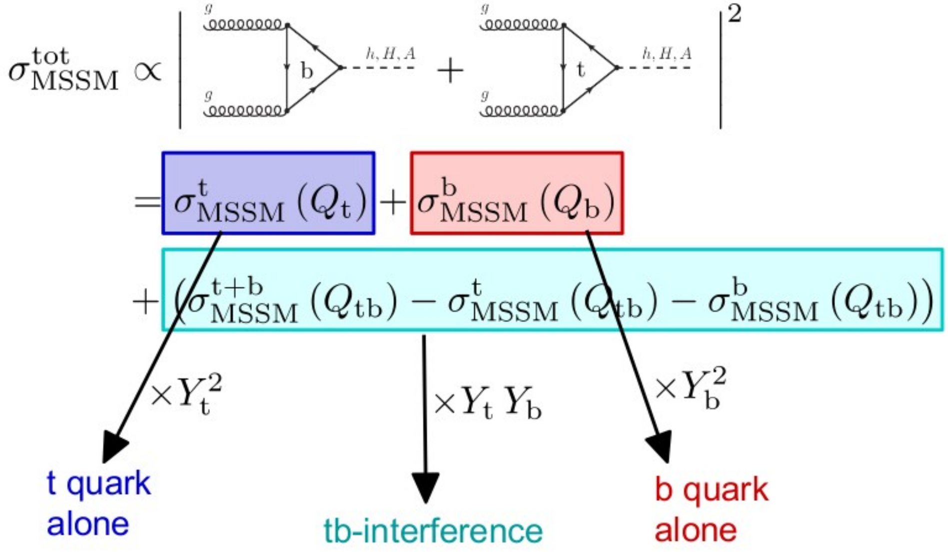
Change in $p_T(A,H,h)$ implies change in signal acceptance.



Signal modeling

Check ETP-KA/2018-07
for more details.

- $p_T(A,H,h)$@ NLO QCD + PS → **multiscale problem**.
- Plus: b contribution varies as a function of $\tan\beta$.



$$\sigma^{\rm tot}_{\rm MSSM} \propto \left| \quad + \quad \right|^2$$

$$= \boxed{\sigma^{\rm t}_{\rm MSSM}\left(Q_{\rm t}\right)} + \boxed{\sigma^{\rm b}_{\rm MSSM}\left(Q_{\rm b}\right)}$$

$$+ \boxed{\left(\sigma^{\rm t+b}_{\rm MSSM}\left(Q_{\rm tb}\right) - \sigma^{\rm t}_{\rm MSSM}\left(Q_{\rm tb}\right) - \sigma^{\rm b}_{\rm MSSM}\left(Q_{\rm tb}\right)\right)}$$

$\times Y_{\rm t}^2$

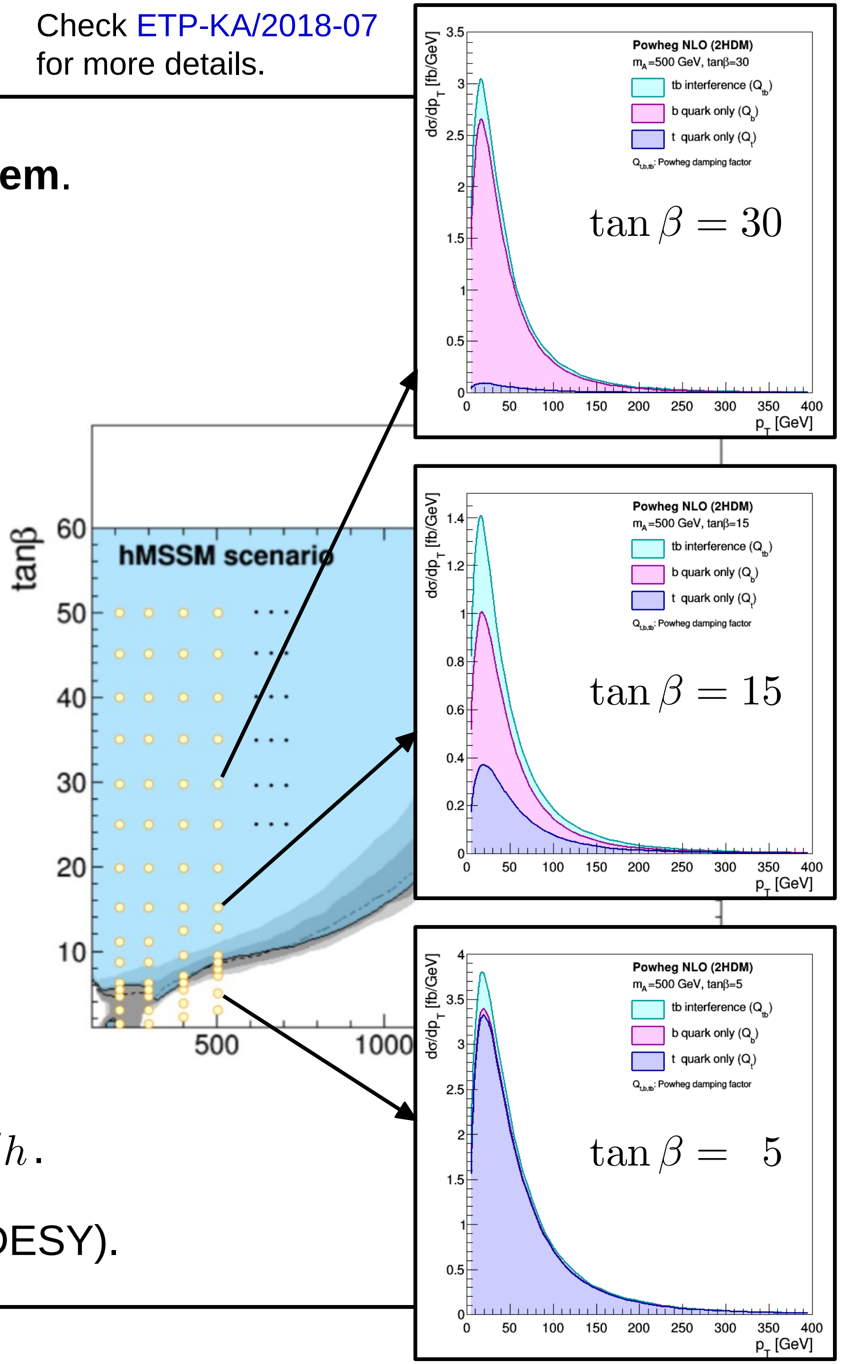
t quark
alone

$\times Y_{\rm t}\, Y_{\rm b}$

tb-interference

$\times Y_{\rm b}^2$

b quark
alone



- Taking into account all $\tan\beta$ enhanced SUSY corrections and non-trivial $\tan\alpha$ dependency for H/h.
- Developed with S. Liebler (KIT) and E. Bagnashi (DESY).