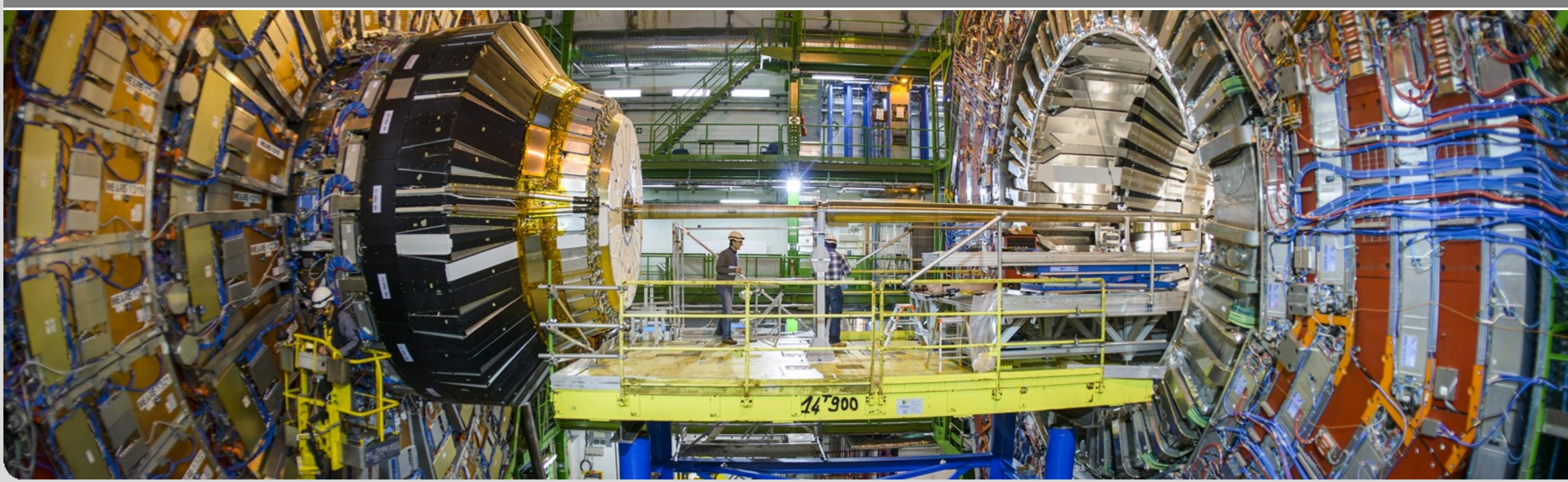
Karlsruhe Institute of Technology

Search for additional neutral MSSM Higgs bosons in the di-tau final state in pp collisions at 13 TeV

Roger Wolf

28. November 2017

INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY



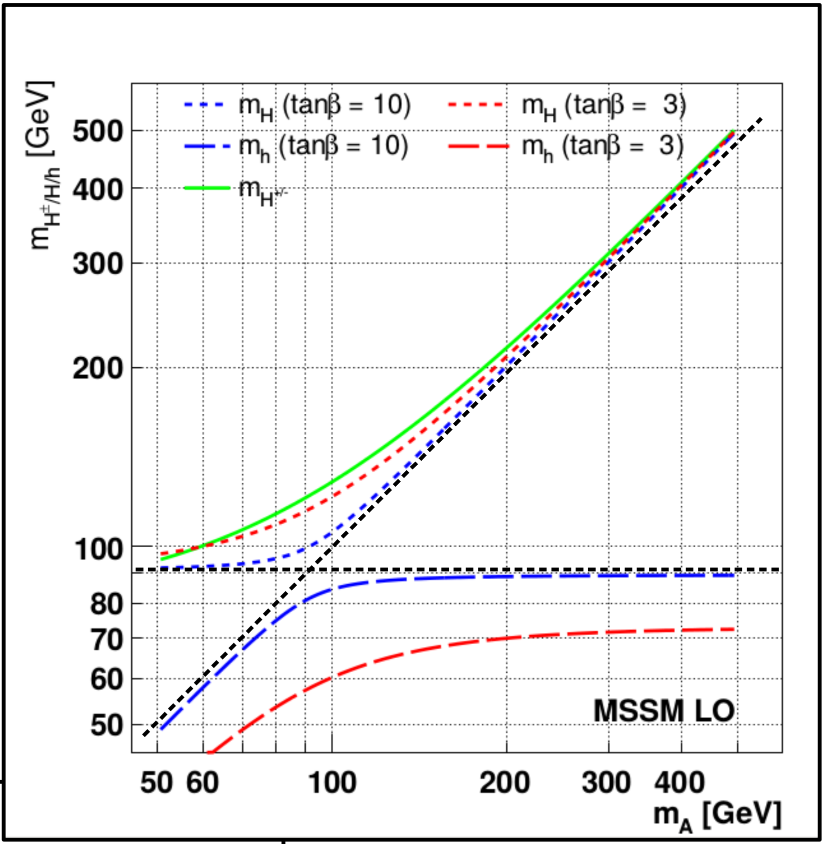
Higgs Bosons in the MSSM

- MSSM like any 2 Higgs Doublet Model (2HDM) predicts **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 at tree level:
  two free parameters: m_A , $\tan\beta = v_u/v_d$

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

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

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

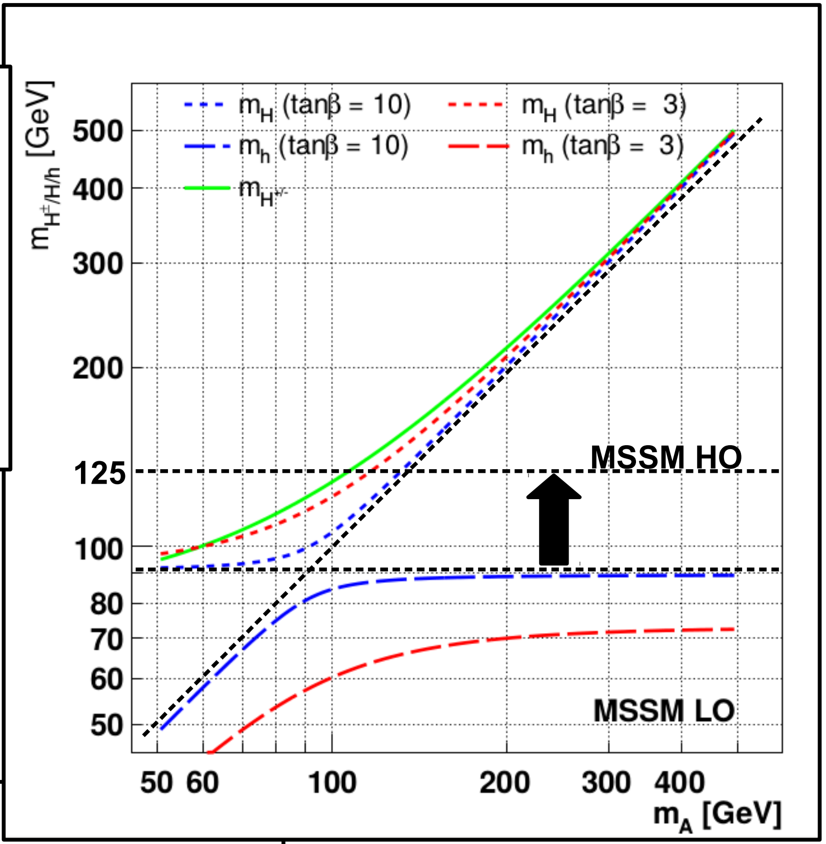
α : angle between v_u and v_b in isospace

Observed Higgs Boson mass and $\tan\beta$

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

- 30% of $m_{\rm h}$ due to higher order corrections.
- Following factors help to increase $m_{\rm h}$: large $m_{\rm t}$, large $m_{\tilde{\rm t}}$, large $X_{\rm t}$, **large** $\tan\beta$.

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



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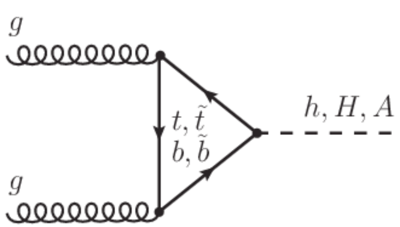
Special role of down-type fermions

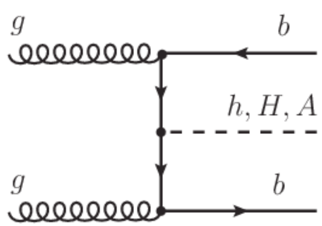
	g_{VV}/g_{VV}^{SM}	g_{uu}/g_{uu}^{SM}	g_{dd}/g_{dd}^{SM}
A	$-$	$\gamma_5 \cot\beta$	$\gamma_5 \tan\beta$
H	$\cos(\beta-\alpha) \ \to 0$	$\sin\alpha/\ \sin\beta \ \to \cot\beta$	$\cos\alpha/\cos\beta \to \tan\beta$
h	$\sin(\beta-\alpha) \ \to 1$	$\cos\alpha/\sin\beta \ \to \ 1$	$-\sin\alpha/\cos\beta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

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

Production modes:



$gg \to \phi$ ("$gg\phi$")



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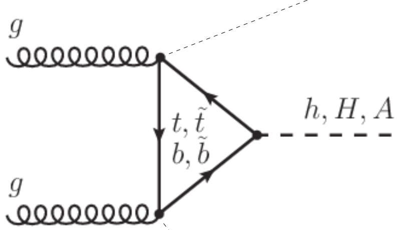

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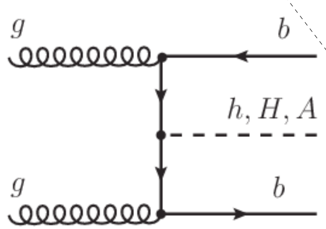

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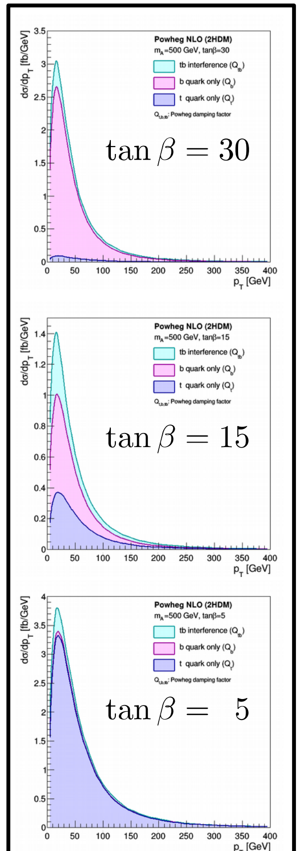

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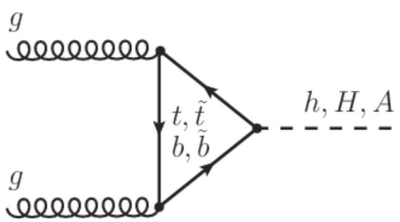

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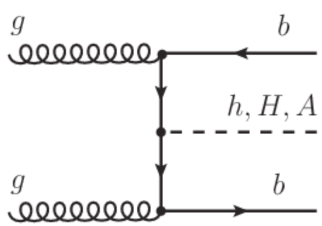
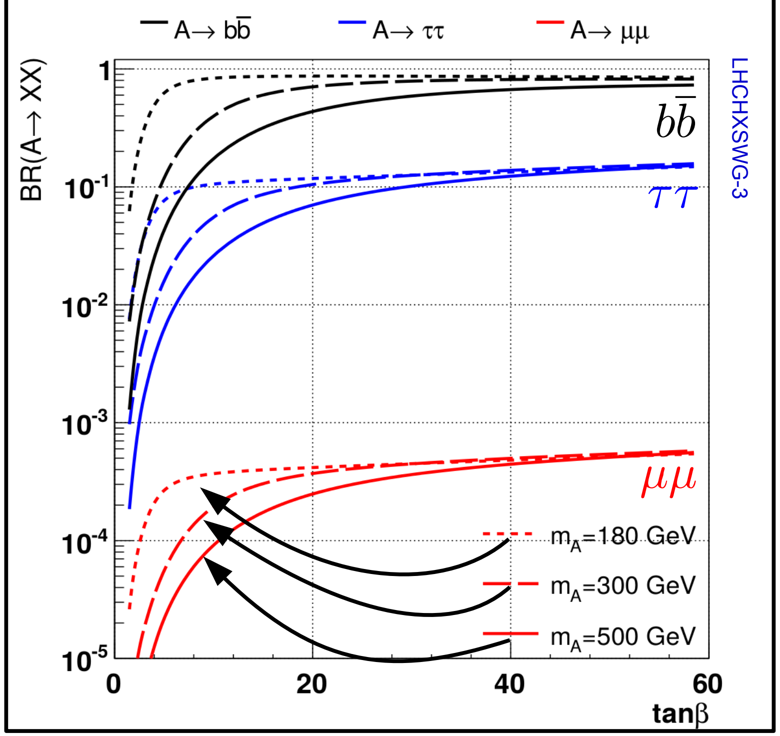


$gg \rightarrow \phi b\bar{b}$ ("$bb\phi$")

X

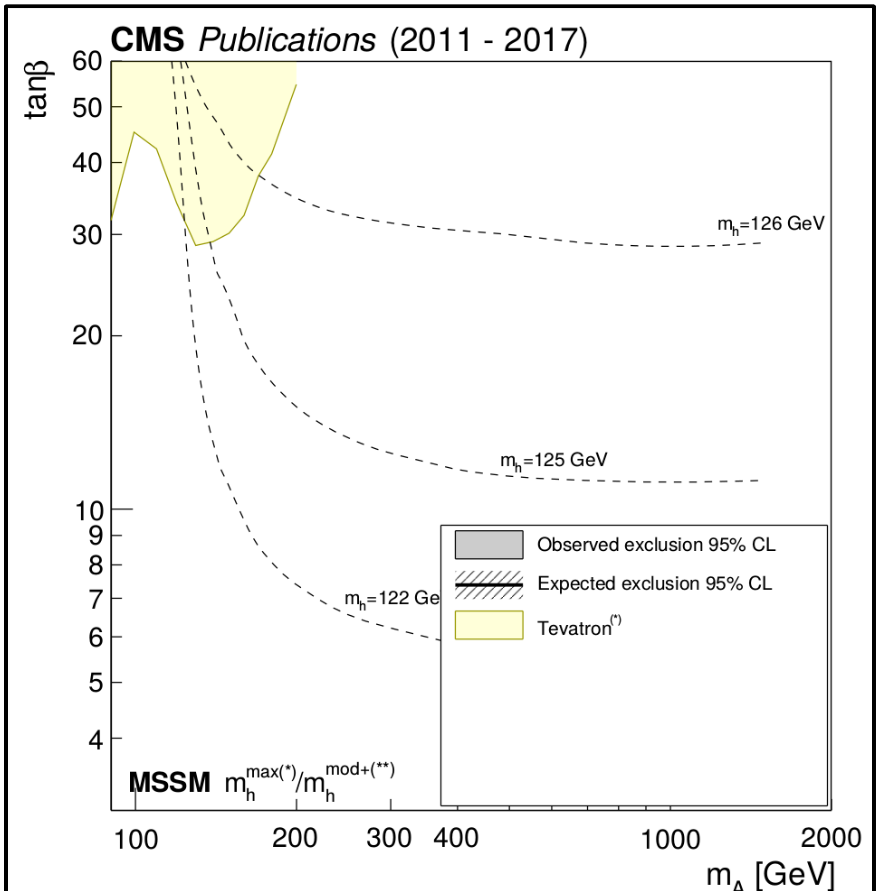
Decay channels:



Importance of the di-τ final state

- Better **experimental accessibility** of τ leptons w.r.t. b quarks wins over larger BR in hadronic LHC environment.

- History of MSSM $H \rightarrow \tau\tau$ analyses @ CMS:



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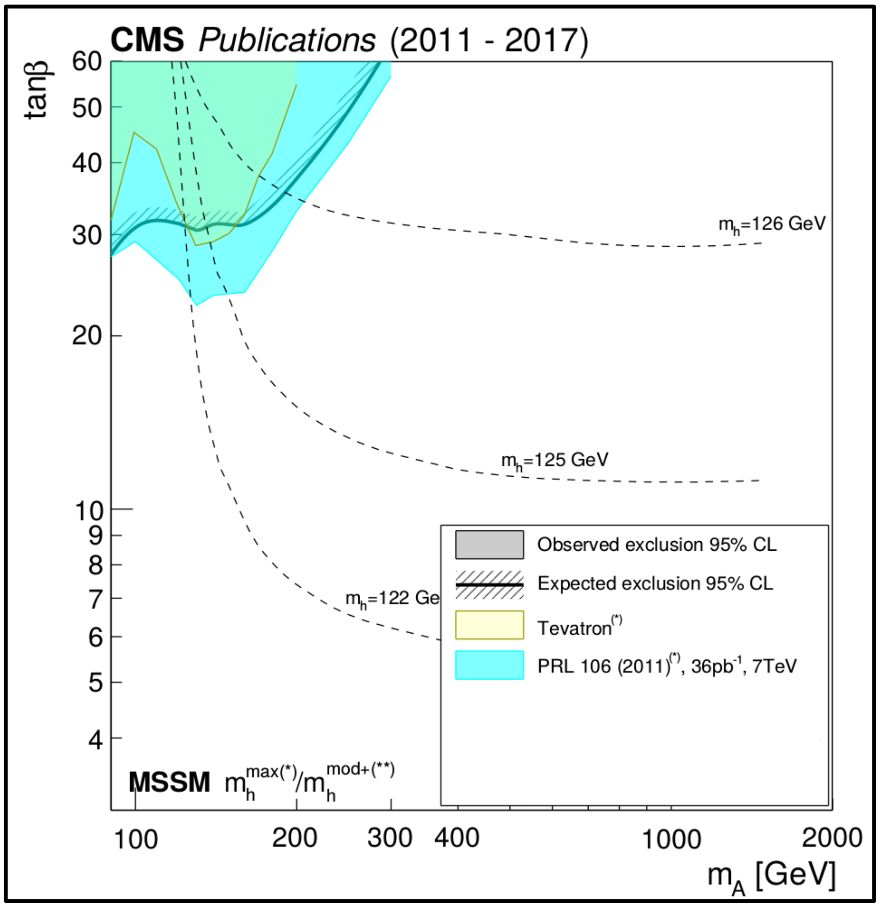

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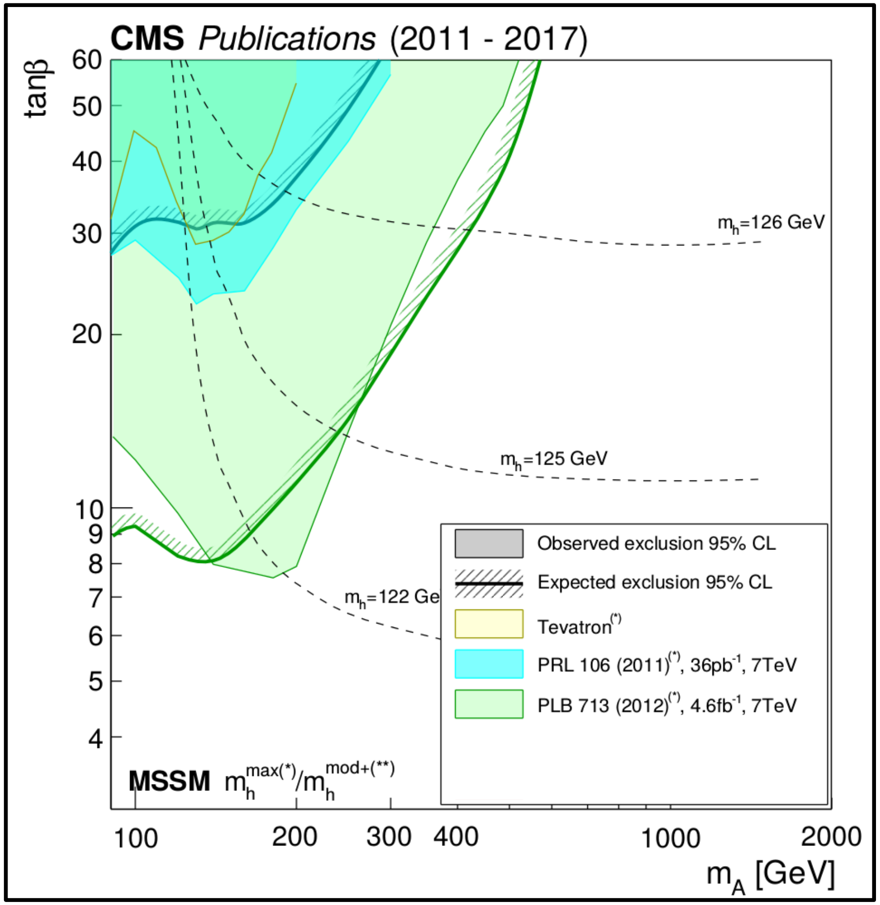

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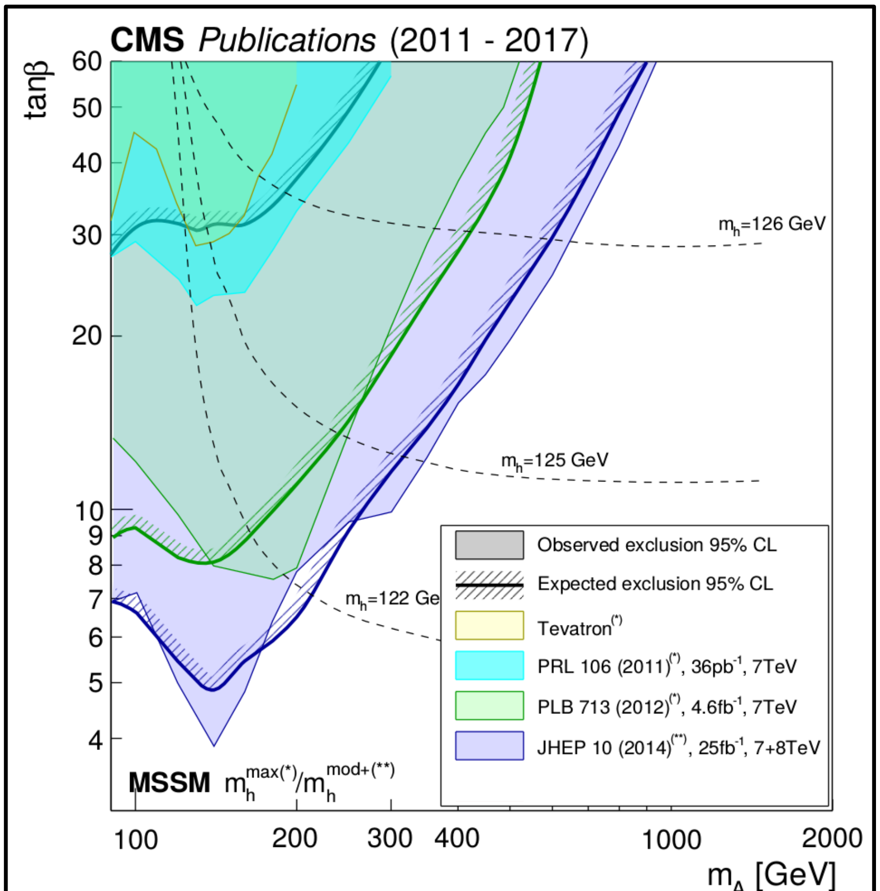

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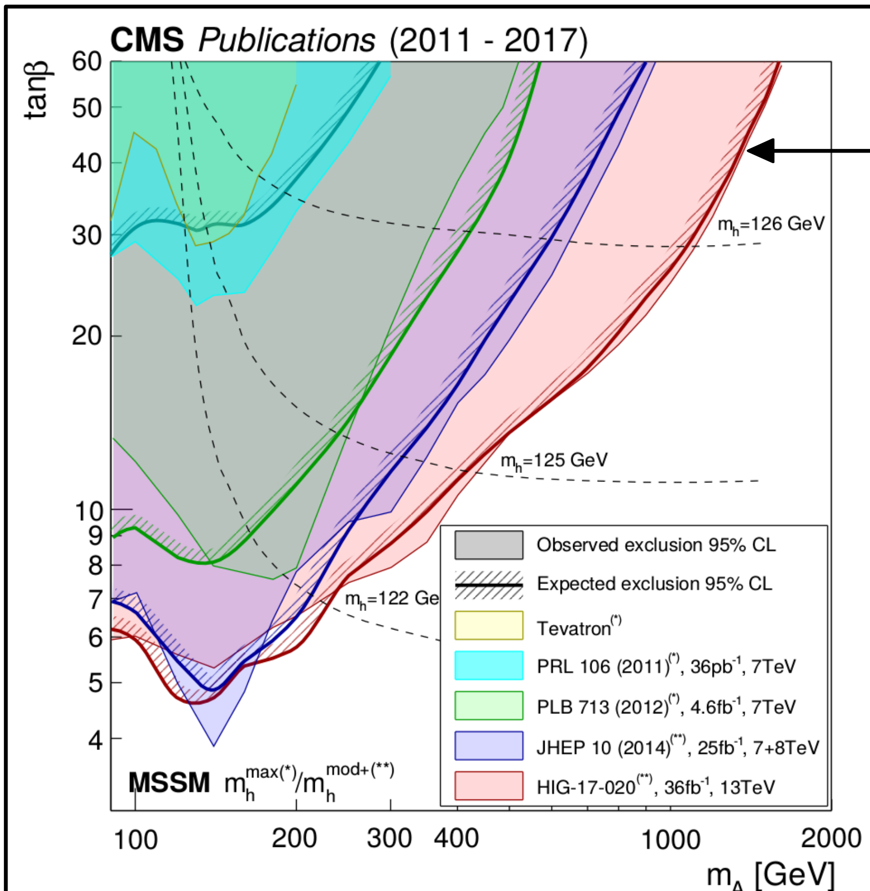

- **Brand new CMS result** discussed today (based on 36/fb @ 13TeV).

CMS-PAS-HIG-17-020

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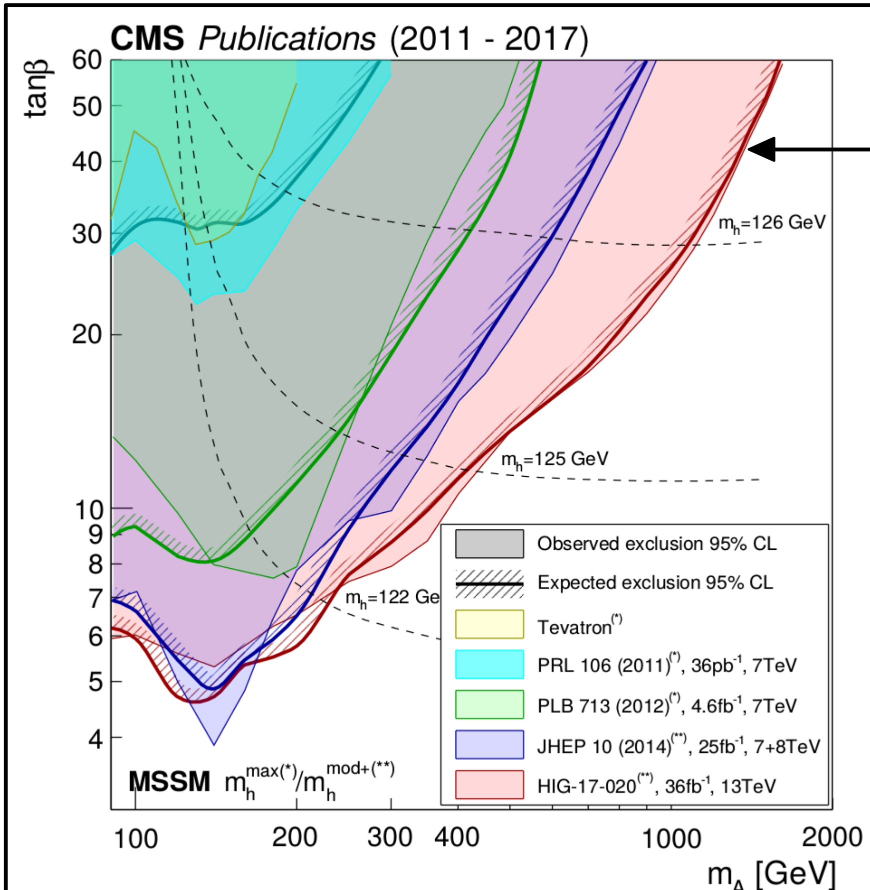
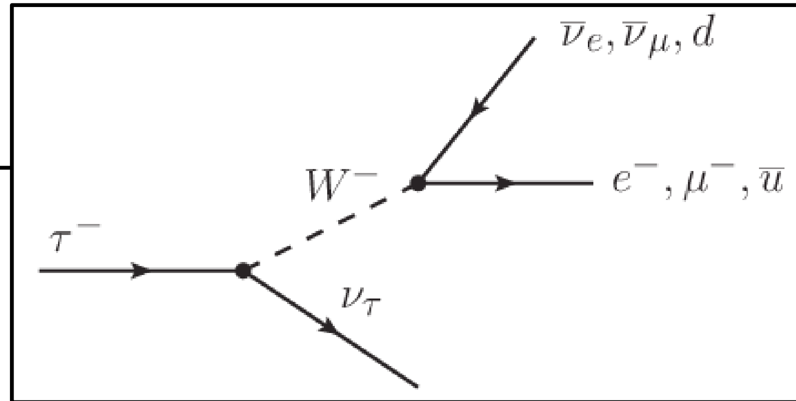


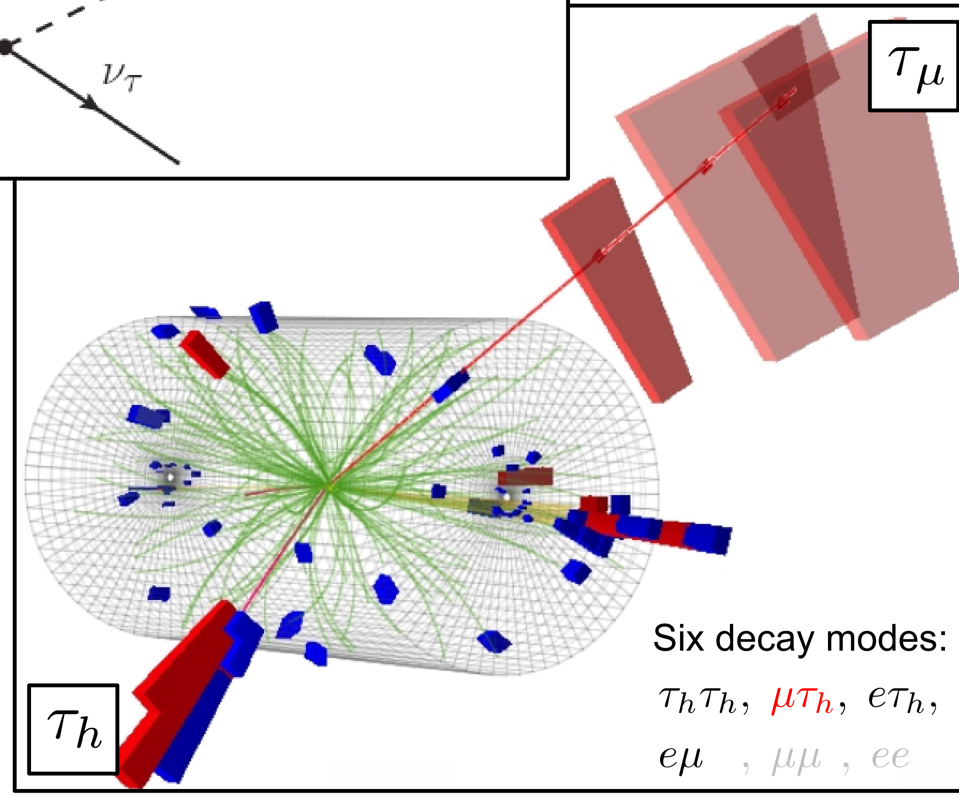
- **Brand new CMS result** discussed today (based on 36/fb @ 13TeV).

- What's special about this publication:
  - Maximally data driven background estimates.
  - Increased sensitivity due to more complex event categorization.
  - Differential signal modeling consistently @ NLO QCD accuracy.
  - Sophisticated statistical inference of signal (NB: important though not new).

Di-τ final state



Decay Mode	BR [%]
$e\nu_e\nu_\tau$	17.83
$\mu\nu_\mu\nu_\tau$	17.41
1-prong ν_τ	37.10
3-prong ν_τ	15.20



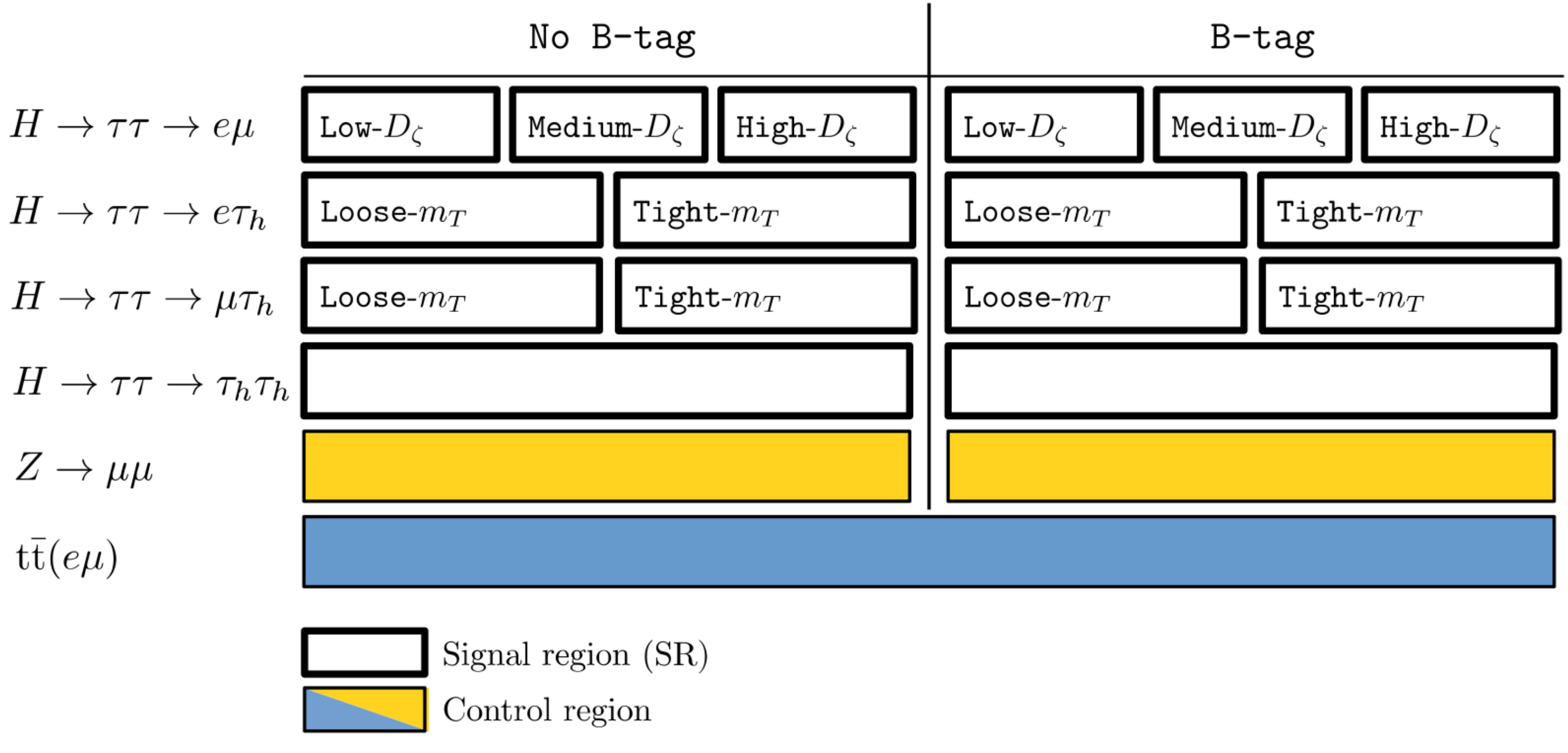
- Search for **2 isolated high p_T leptons** (e , μ ,τ_h).
- Reduce obvious backgrounds ($\rightarrow \not{E}_T$), reconstruct a discriminating variable ($\rightarrow m_{\mathrm{T}}^{\mathrm{tot}}$, explained in backup).
- **Kinematic selection**:

final state	first lepton	second lepton
$e\mu^{(1)}$	$p_T^e > 13$ GeV, $\lvert\eta^e\rvert < 2.5$	$p_T^\mu > 10$ GeV, $\lvert\eta^\mu\rvert < 2.4$
	$p_T^e > 26$ GeV, $\lvert\eta^e\rvert < 2.1$	$p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$
	$p_T^\mu > 23$ GeV, $\lvert\eta^\mu\rvert < 2.1$	$p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$
	$p_T^{\tau_h} > 40$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.1$	

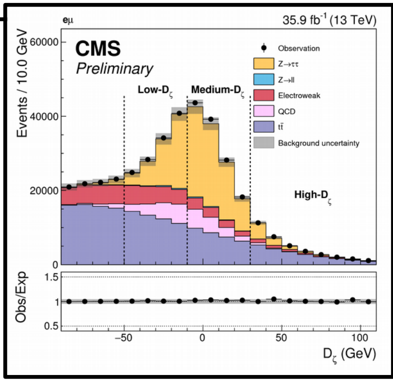
$^{(1)}$ $p_T > 24$ GeV on the higher p_T trigger match (see text).

Additional event information

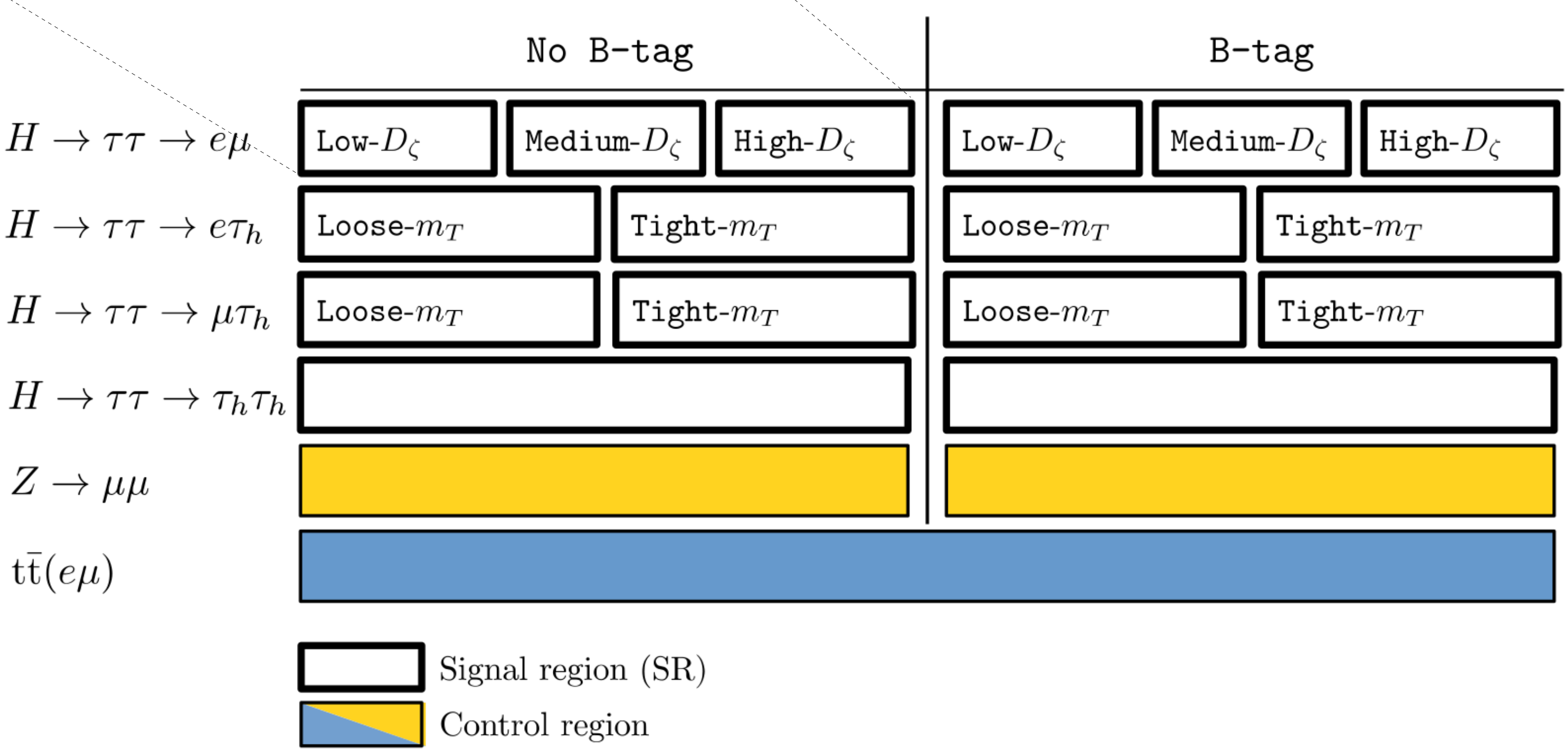
- Increase sensitivity to signal by making use of further **signal specific event information** (e.g. enhanced presence of b quarks):



Additional event information



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



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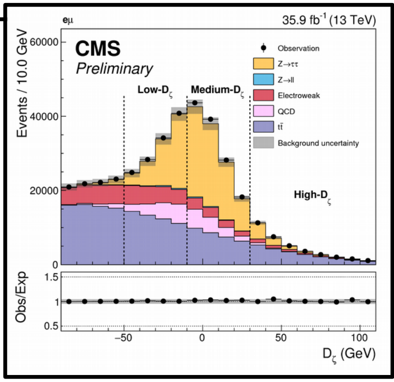

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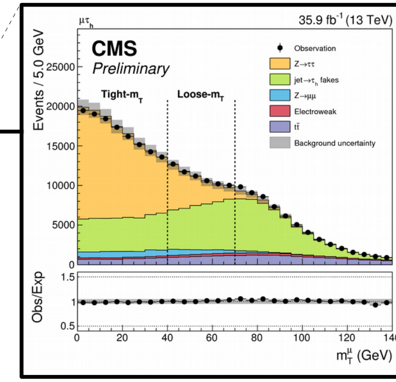
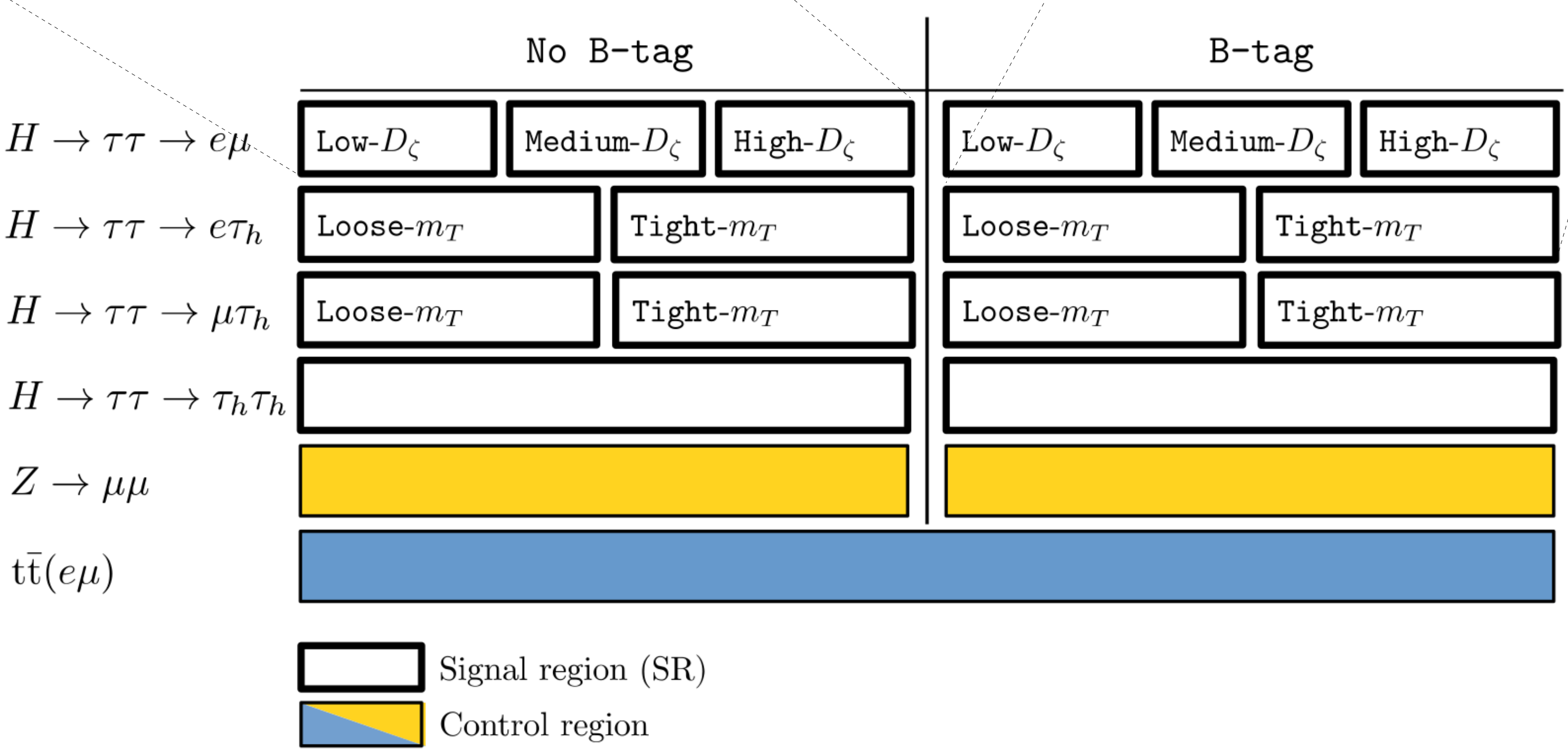


Loose-m_T category as “tail-catcher” for high mass signal.



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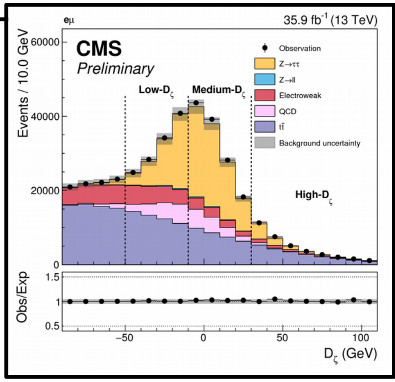

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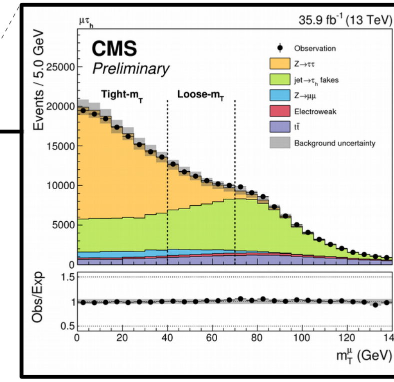

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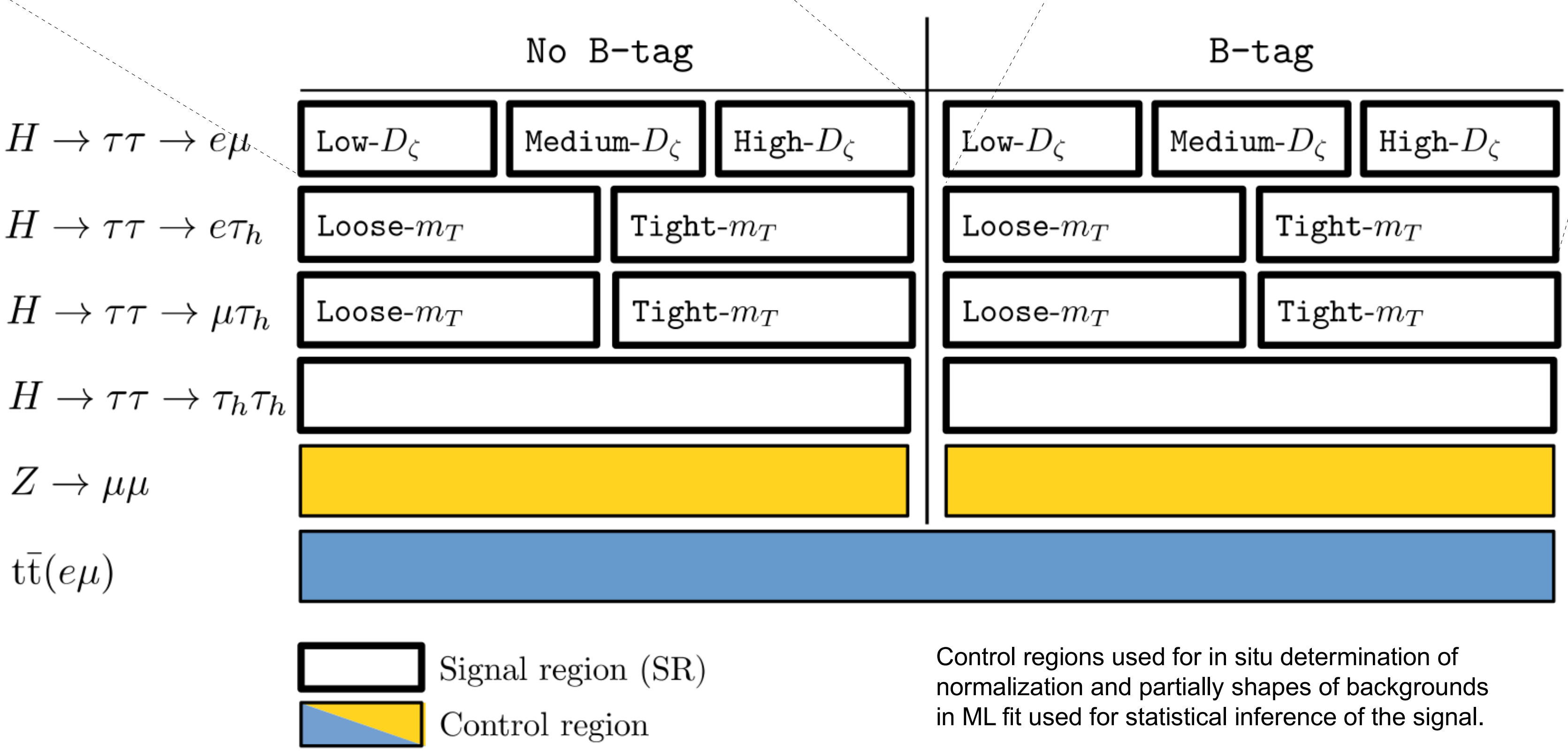
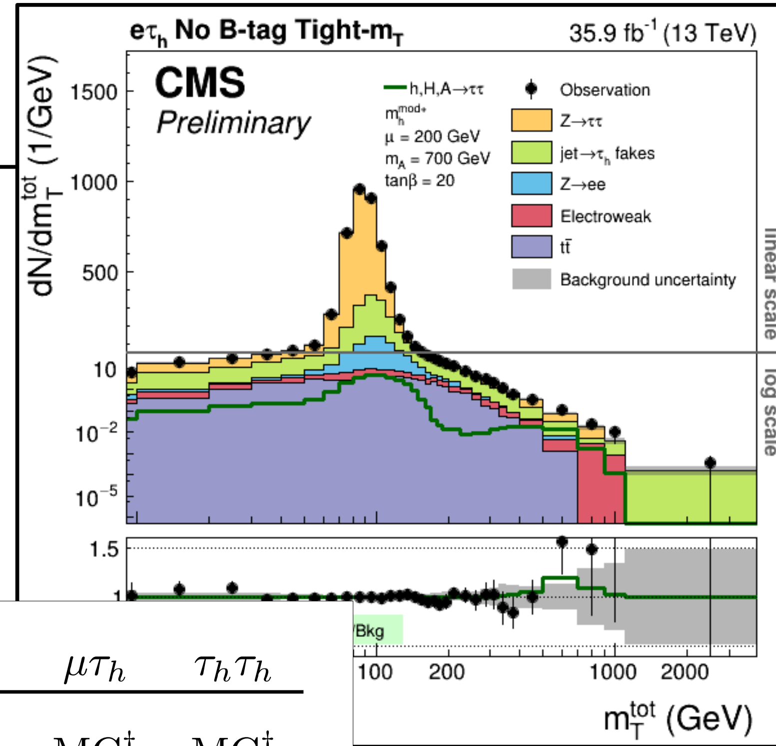


Control regions used for in situ determination of normalization and partially shapes of backgrounds in ML fit used for statistical inference of the signal.

Background modeling

- Background related to jet $\rightarrow \tau_h$ misidentification estimated from data using **fake factor** (FF) method.
- Background model **cross checked** by two alternative estimation methods (MC driven, embedded).



background process	misidentification	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$Z \rightarrow \tau\tau$		MC†	MC†	MC†	MC†
$Z \rightarrow \ell\ell$	$\ell \rightarrow \tau_h$	MC	MC	MC	MC
	jet $\rightarrow \tau_h$		FF	FF	FF
Diboson+single top	$\tau/\ell \rightarrow \tau_h$	MC	MC	MC	MC
	jet $\rightarrow \tau_h$		FF	FF	FF
$t\bar{t}$	$\tau/\ell \rightarrow \tau_h$	MC†	MC†	MC†	MC†
	jet $\rightarrow \tau_h$		FF	FF	FF
W+jets	jet $\rightarrow \tau_h$	MC	FF	FF	FF
QCD	jet $\rightarrow \tau_h$	CR	FF	FF	FF

† Normalization from control region in data.

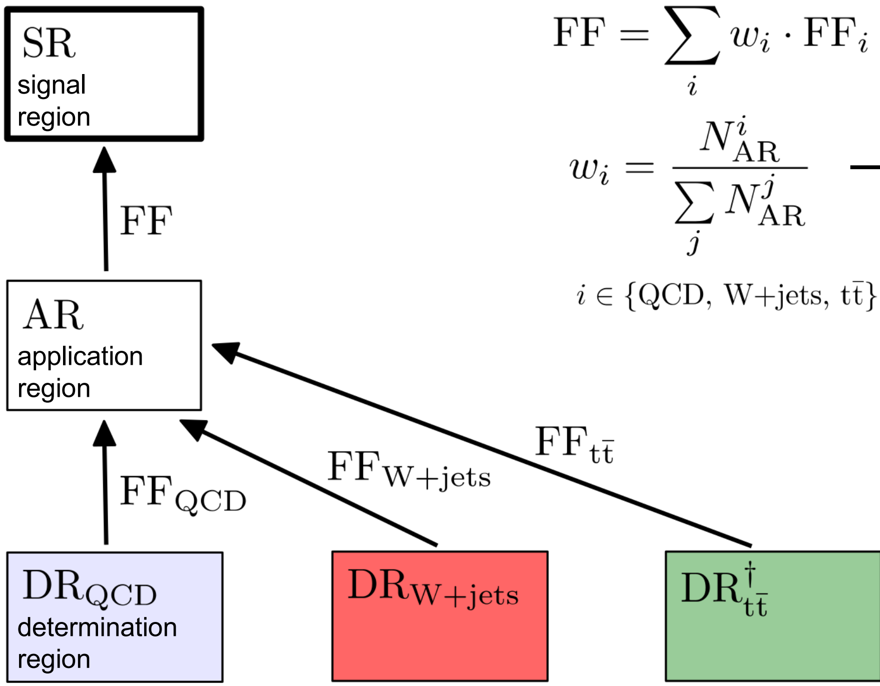
Fake factor (FF) method

- **Fake factor**: number of isolated over number of anti-isolated τ_h .

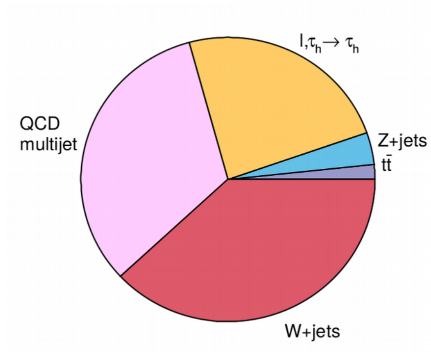
$$\mathrm{FF} = \sum_i w_i \cdot \mathrm{FF}_i$$

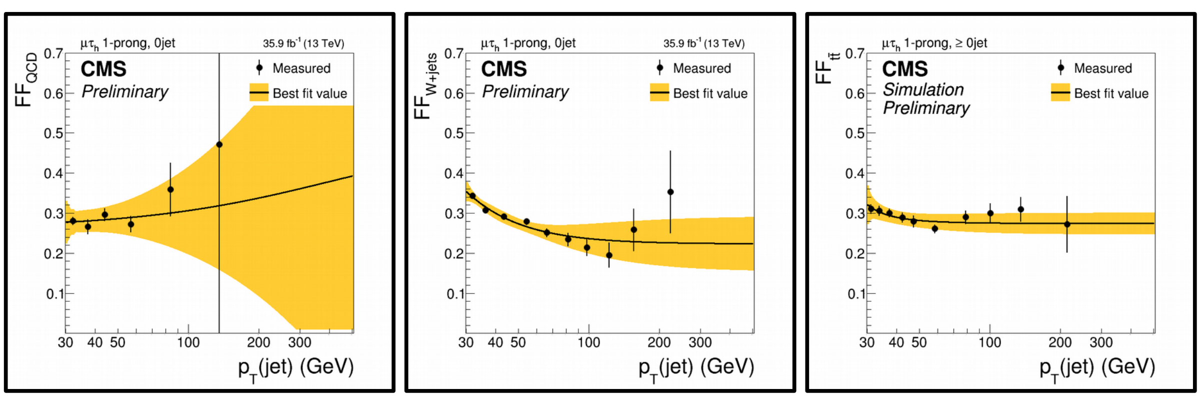
$$w_i = \frac{N^i_{\mathrm{AR}}}{\sum_j N^j_{\mathrm{AR}}}$$

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



Expected event composition in AR:





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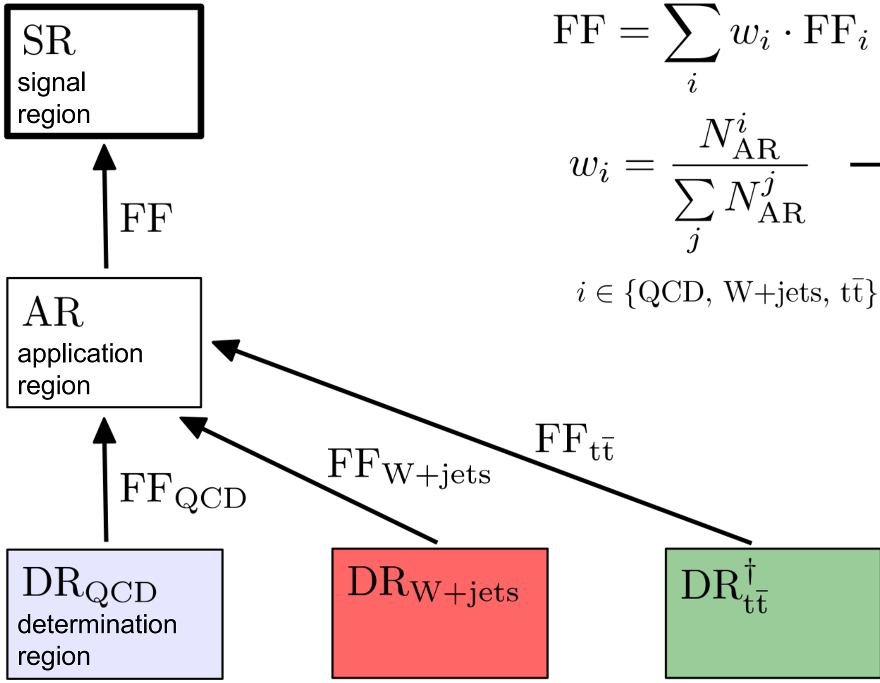

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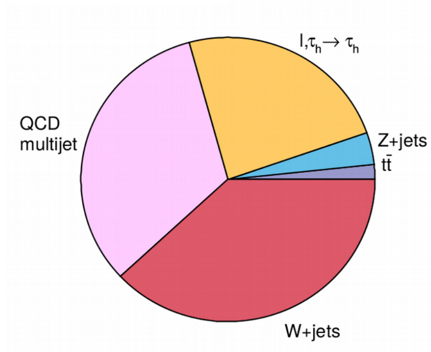
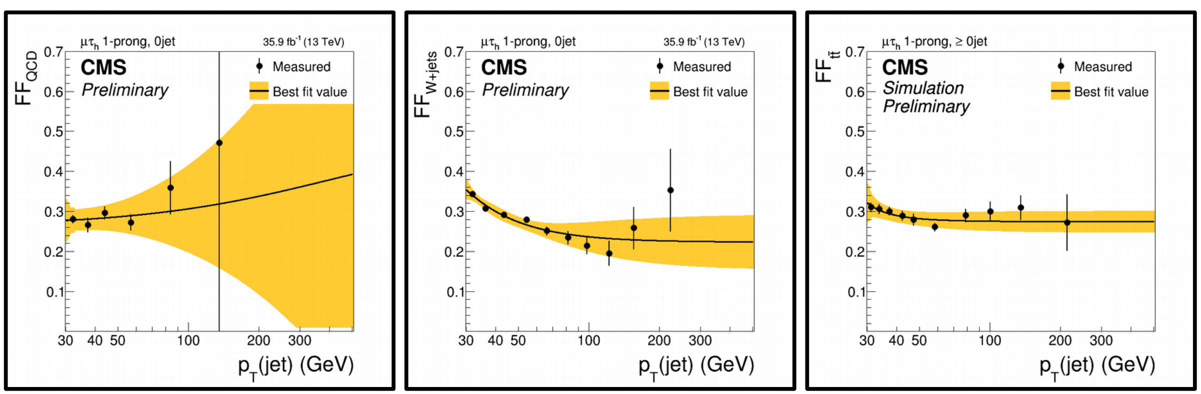
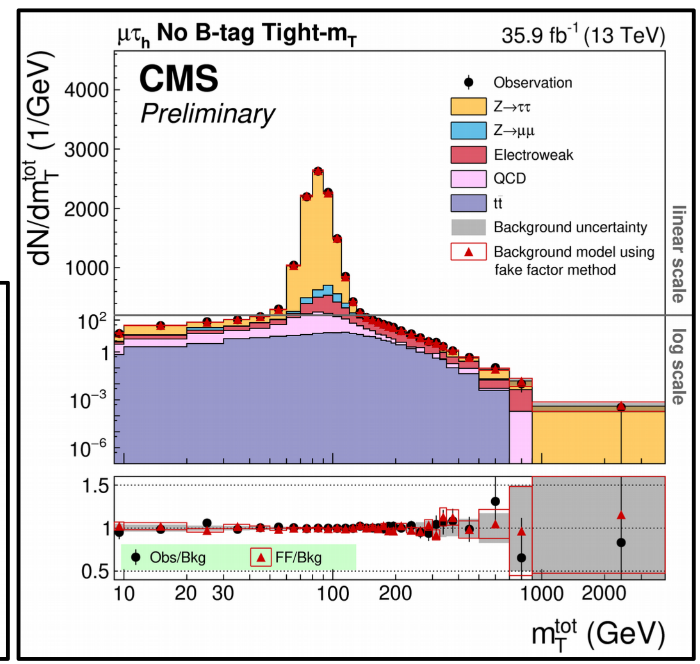




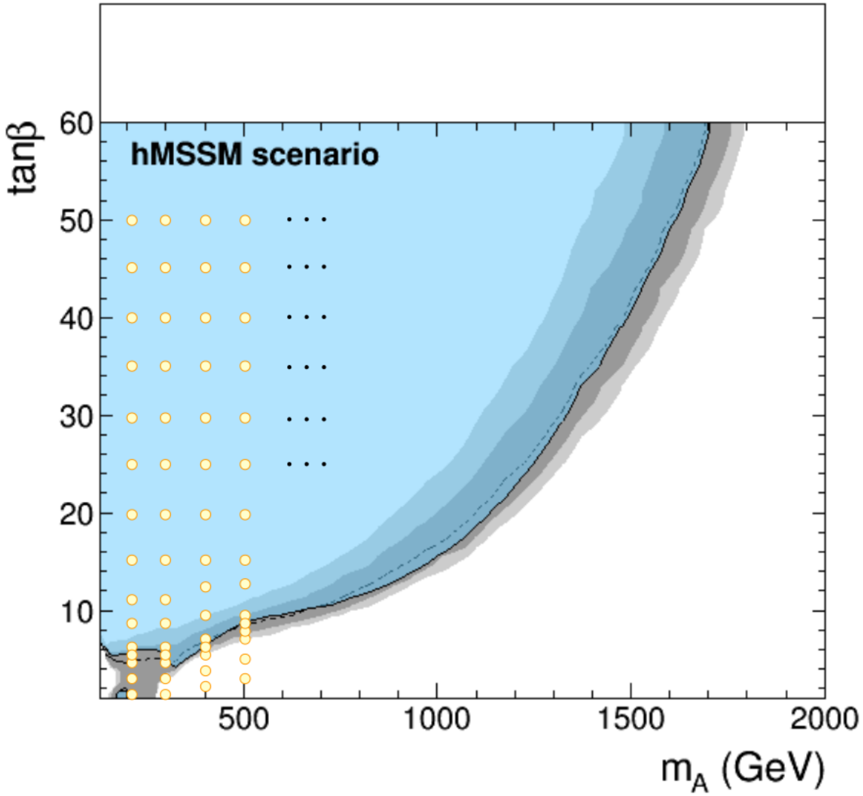
MC driven cross check



Signal modeling

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

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



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

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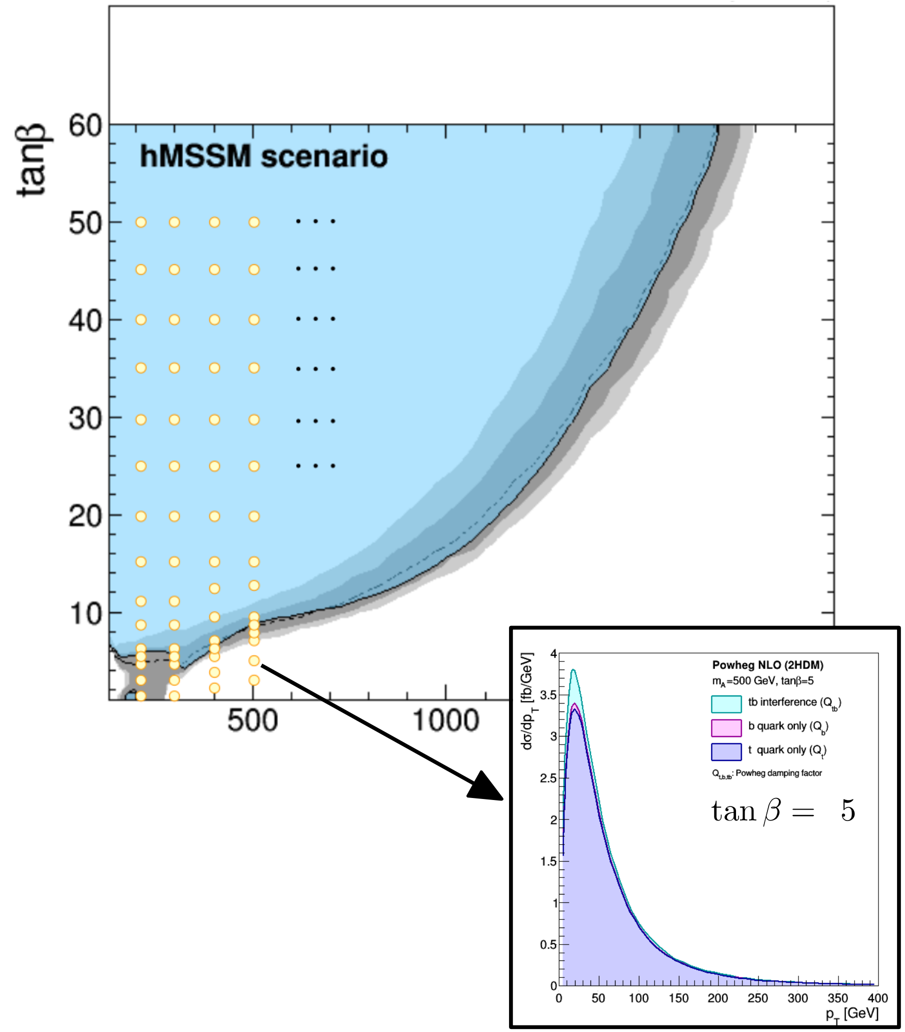

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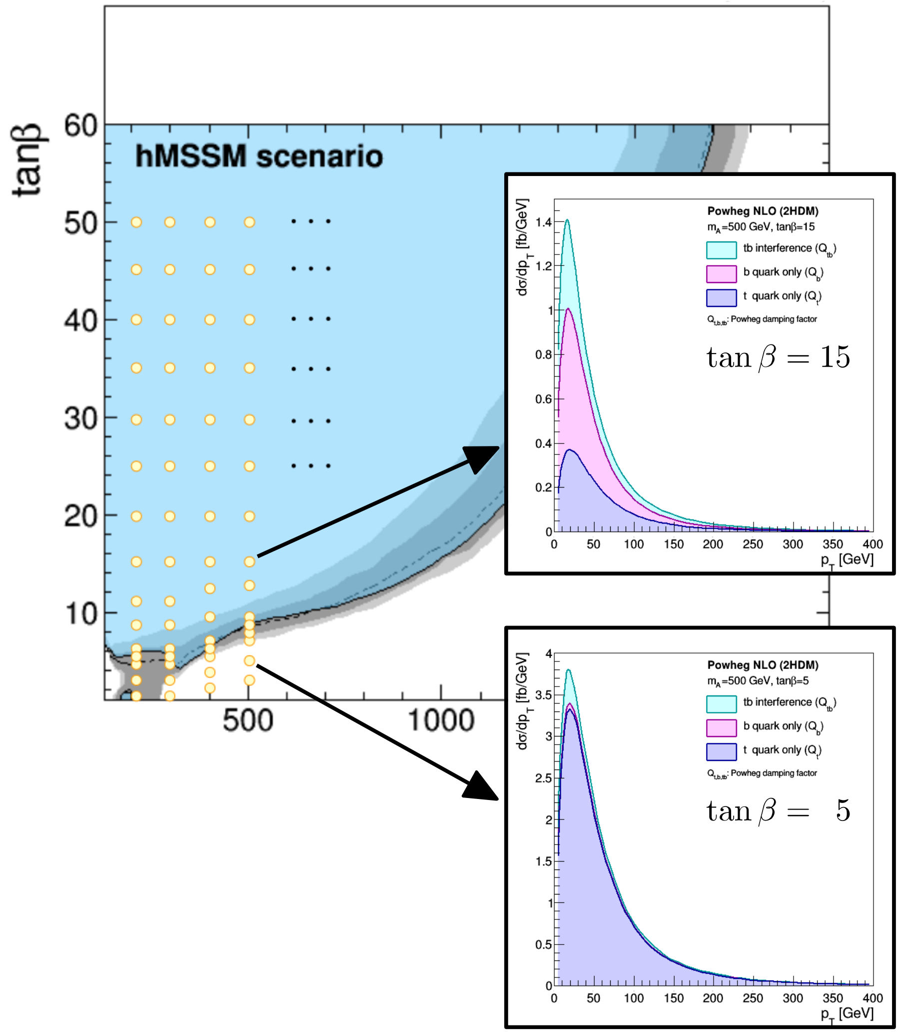

Signal modeling

Changing $p_T(A,H,h) \rightarrow$ changing signal acceptance!

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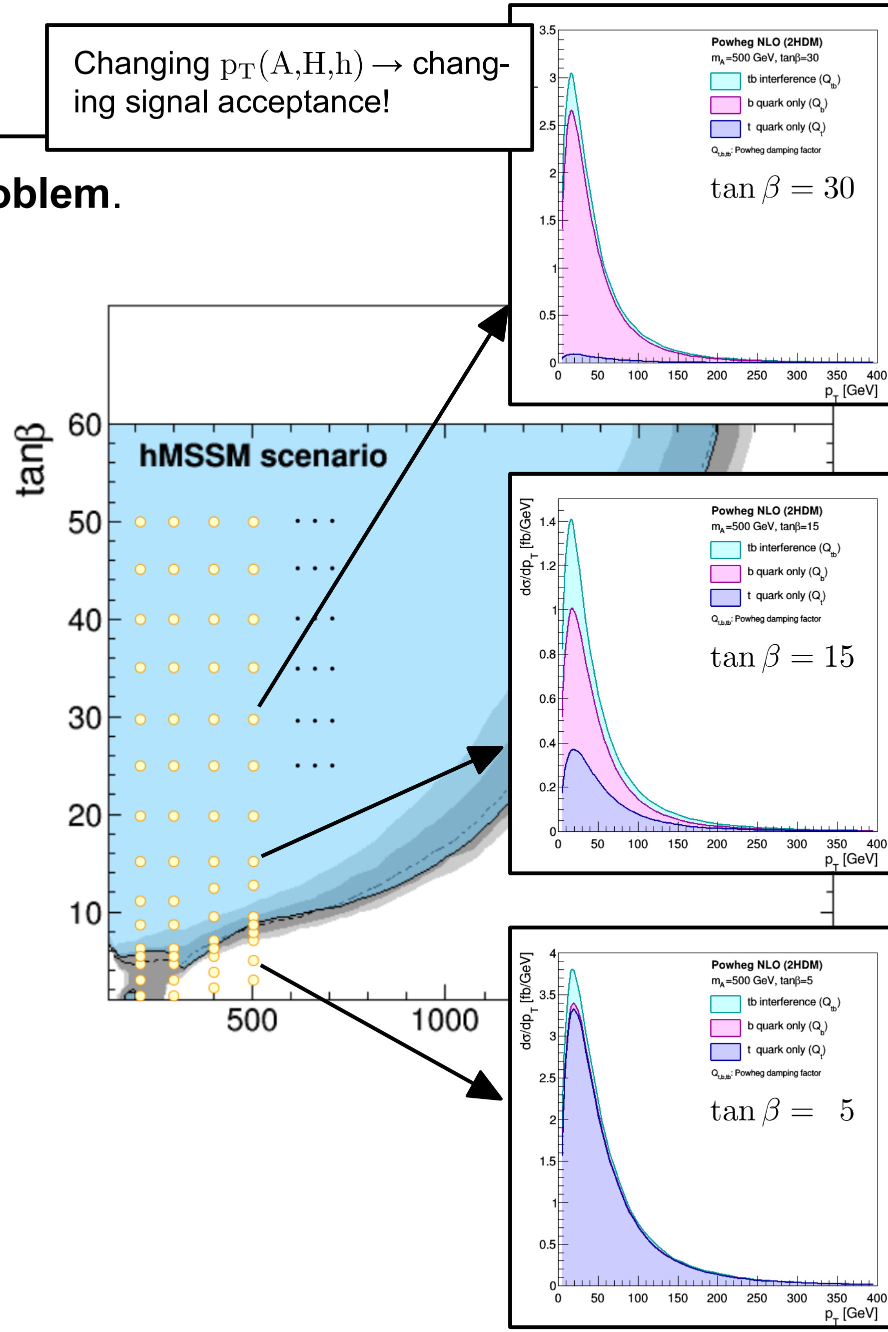

Signal modeling

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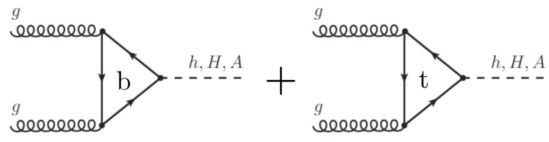
- Plus: b contribution varies as a function of $\tan\beta$.

$$\sigma^{\mathrm{tot}}_{\mathrm{MSSM}} \propto \Big| \quad\cdots\quad + \quad\cdots\quad \Big|^2$$



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

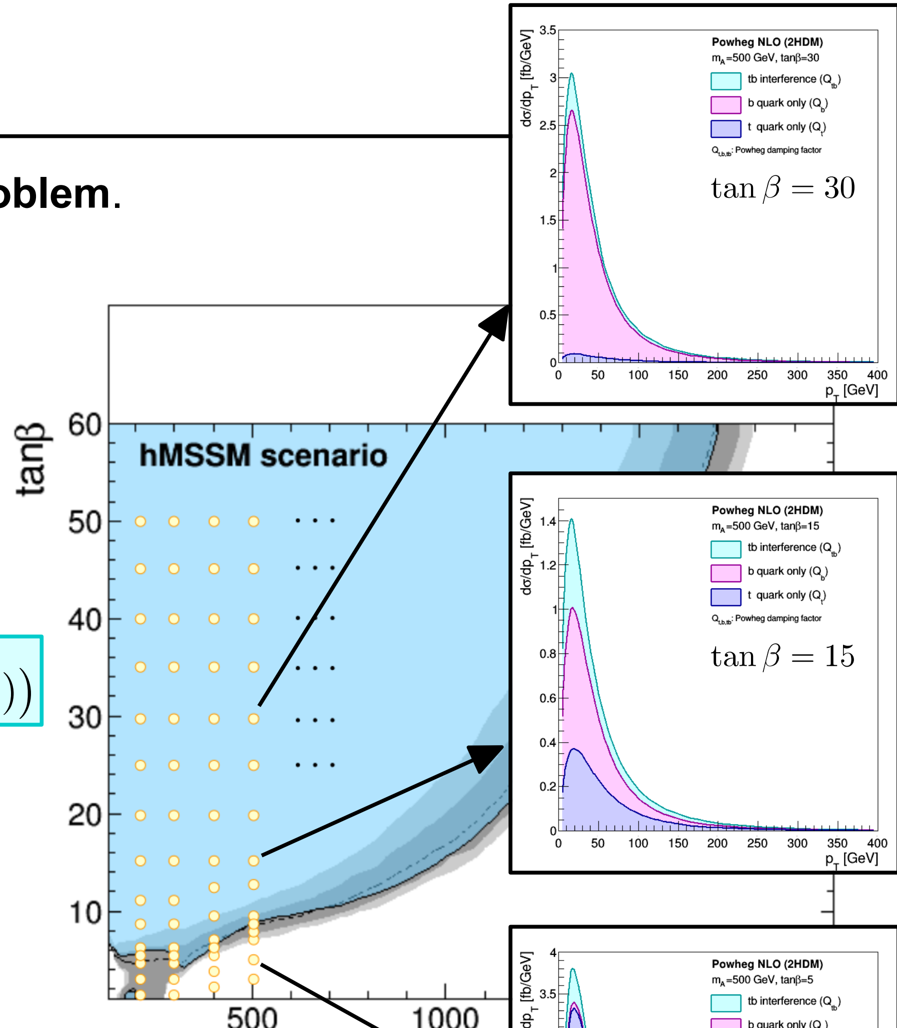
$$+ \boxed{\left(\sigma^{\mathrm{t+b}}_{\mathrm{MSSM}}\left(Q_{\mathrm{tb}}\right) - \sigma^{\mathrm{t}}_{\mathrm{MSSM}}\left(Q_{\mathrm{tb}}\right) - \sigma^{\mathrm{b}}_{\mathrm{MSSM}}\left(Q_{\mathrm{tb}}\right)\right)}$$

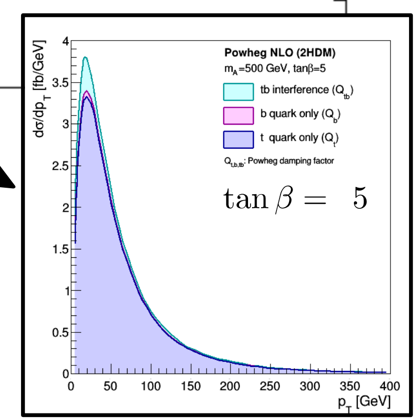
$\times Y_{\mathrm{t}}^2$ $\qquad \times Y_{\mathrm{t}}\, Y_{\mathrm{b}}$ $\qquad \times Y_{\mathrm{b}}^2$

t quark alone

tb-interference

b quark alone

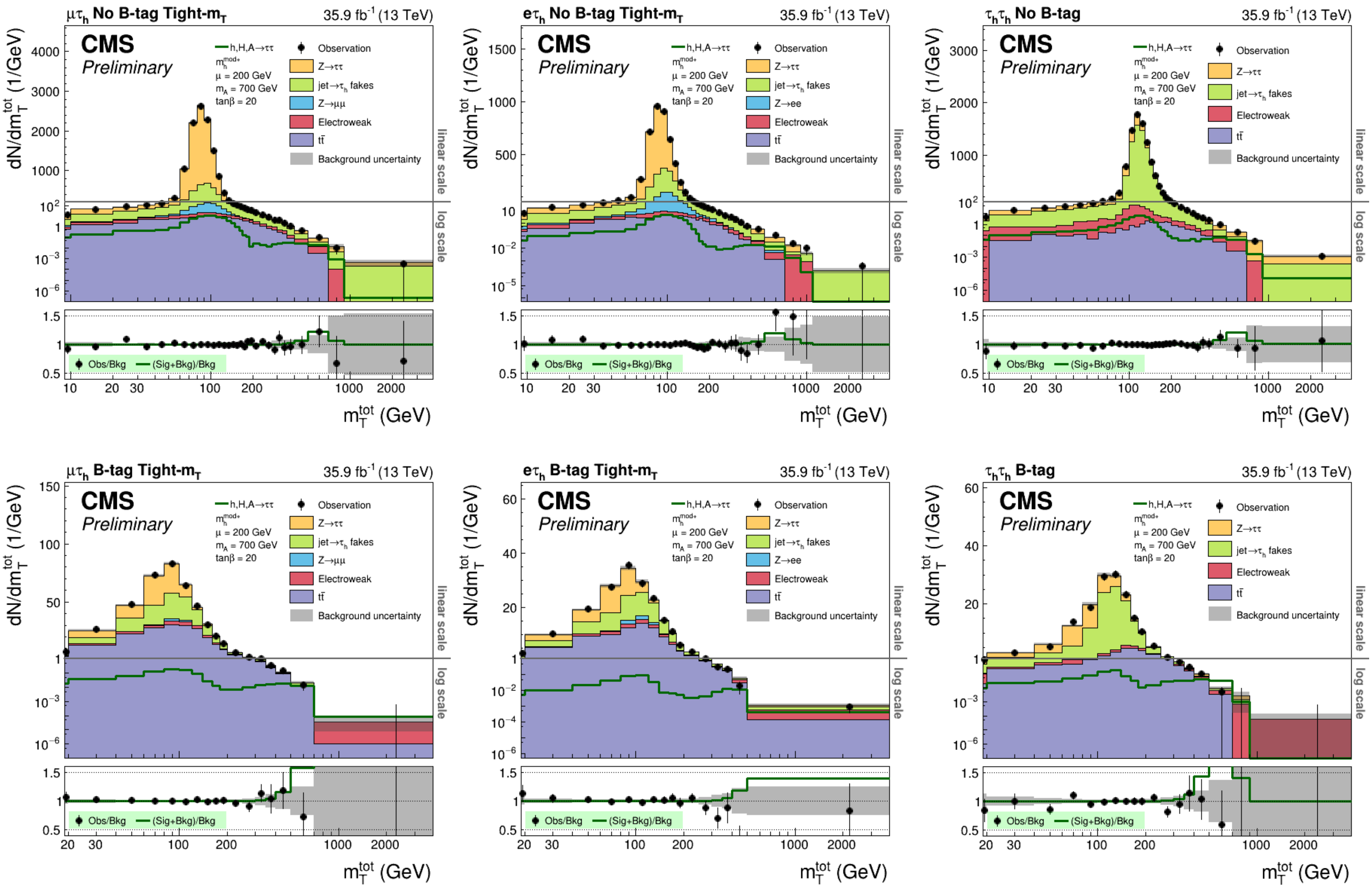




- Taking into account all $\tan\beta$ enhanced SUSY corrections & non-trivial $\tan\alpha$ dependency for H/h.
- Worked out in collaboration with E. Bagnaschi and S. Liebler in frame of LHCHXSWG-3.

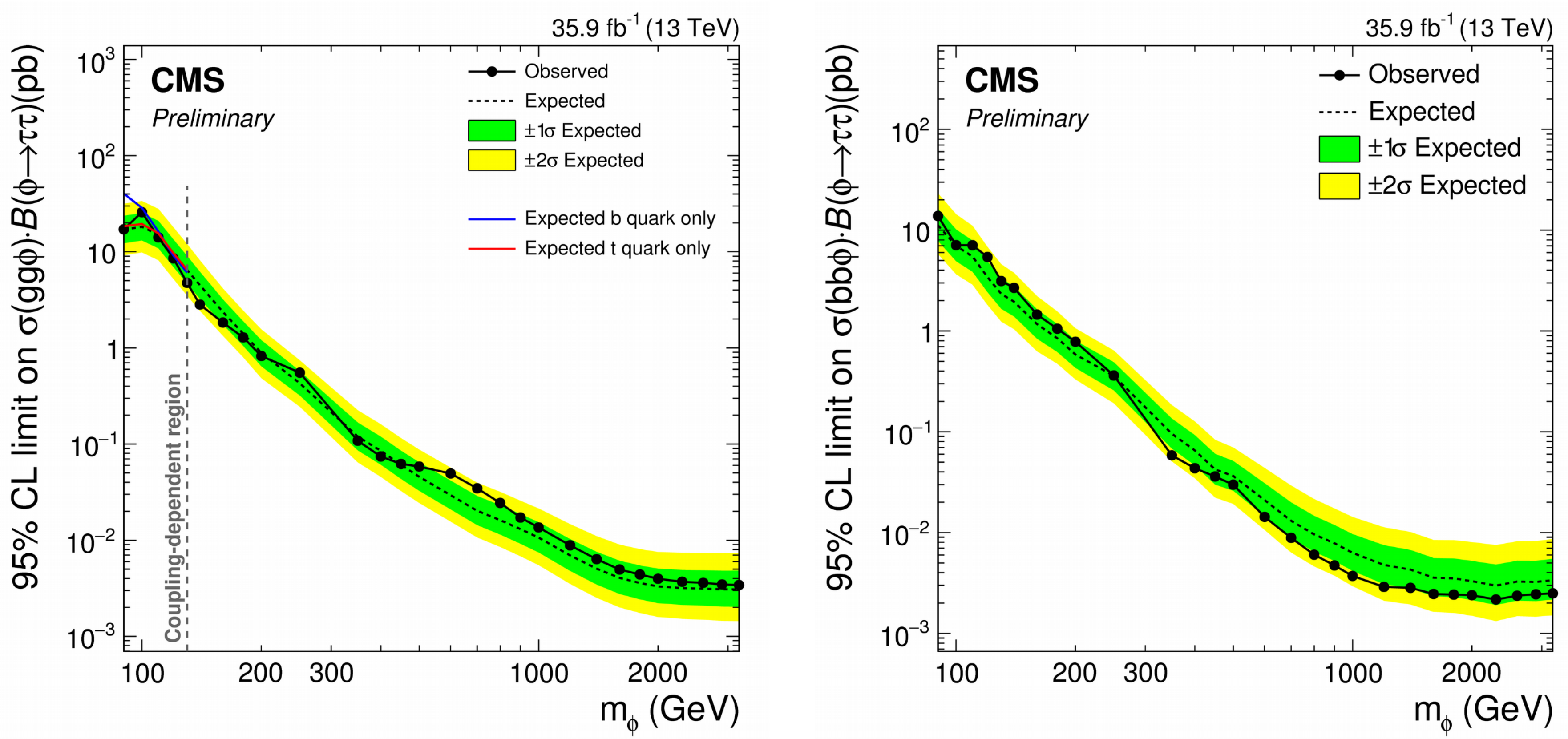
Observation

Shown are the most sensitive categories with an MSSM $m_{\mathrm{h}}^{\mathrm{mod+}}$ hypothesis with $m_{\mathrm{A}} = 700\ \mathrm{GeV}$ and $\tan\beta = 20$ fitted to the data



Model independent limits

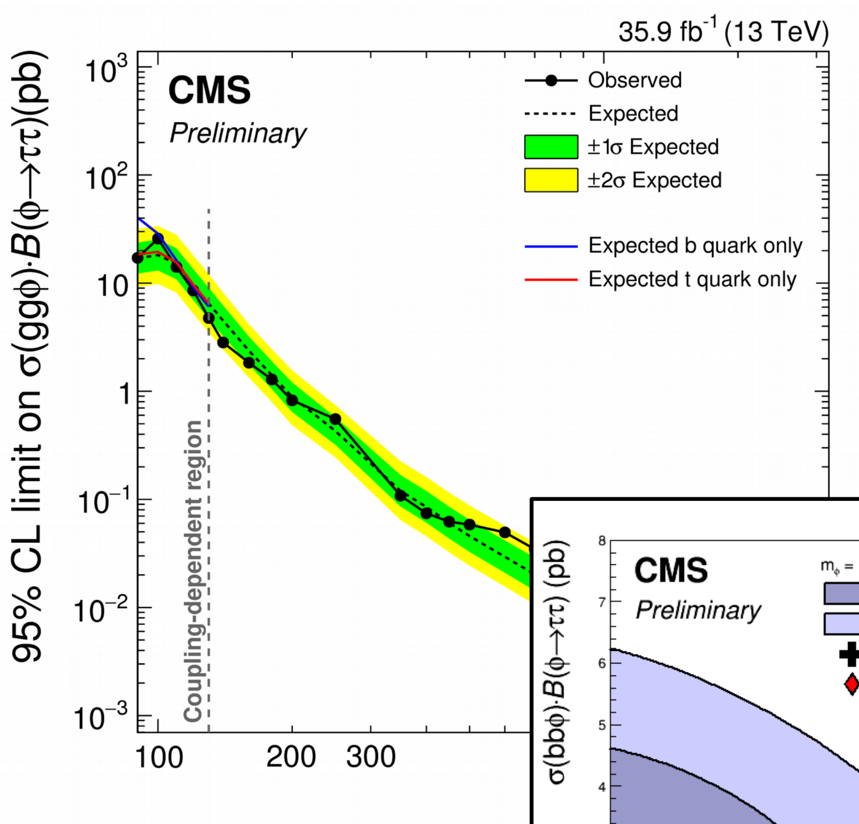
- Narrow width approximation, **two parameters of interest** $\mu_{gg\phi}$ and $\mu_{bb\phi}$:

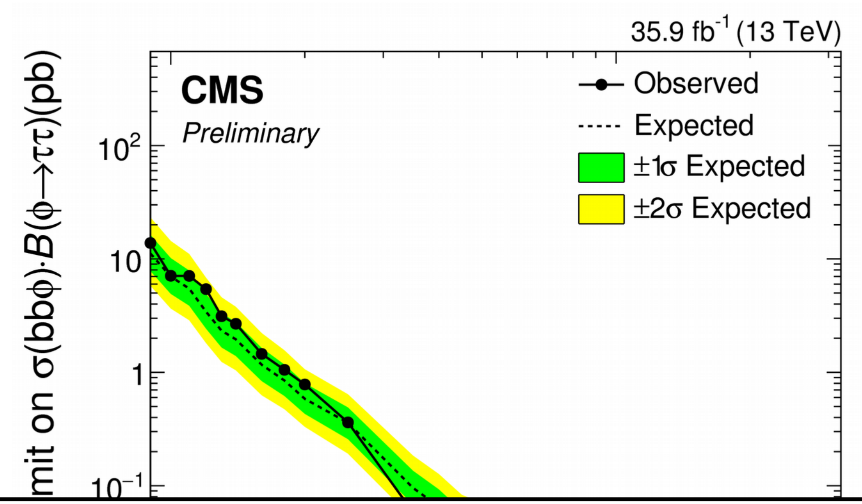


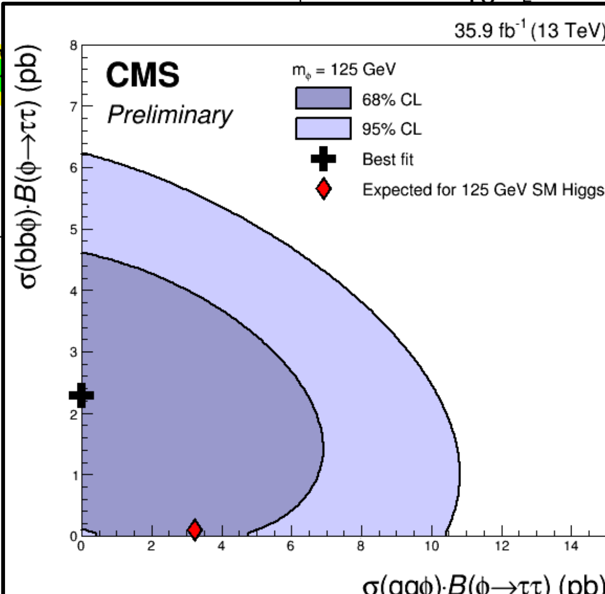
- No deviation beyond 2 sigma found.
- Cross checks discussed e.g. in Ph.D. thesis from Rene Caspart and master thesis from Janek Bechtel.

Model independent limits

- Narrow width approximation, **two parameters of interest** $\mu_{gg\phi}$ and $\mu_{bb\phi}$:



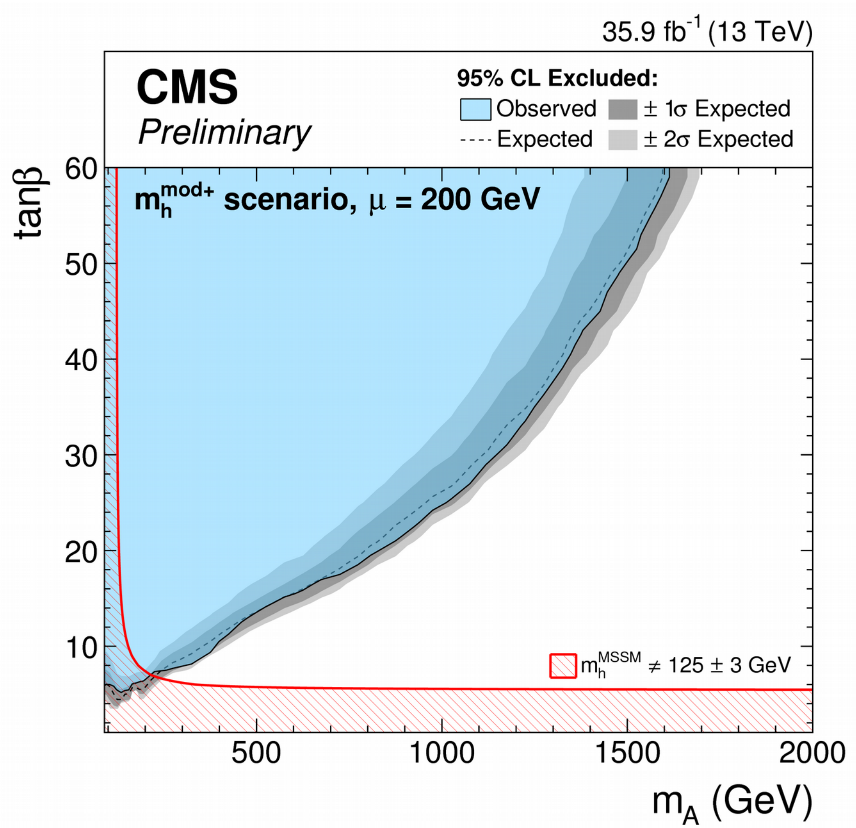


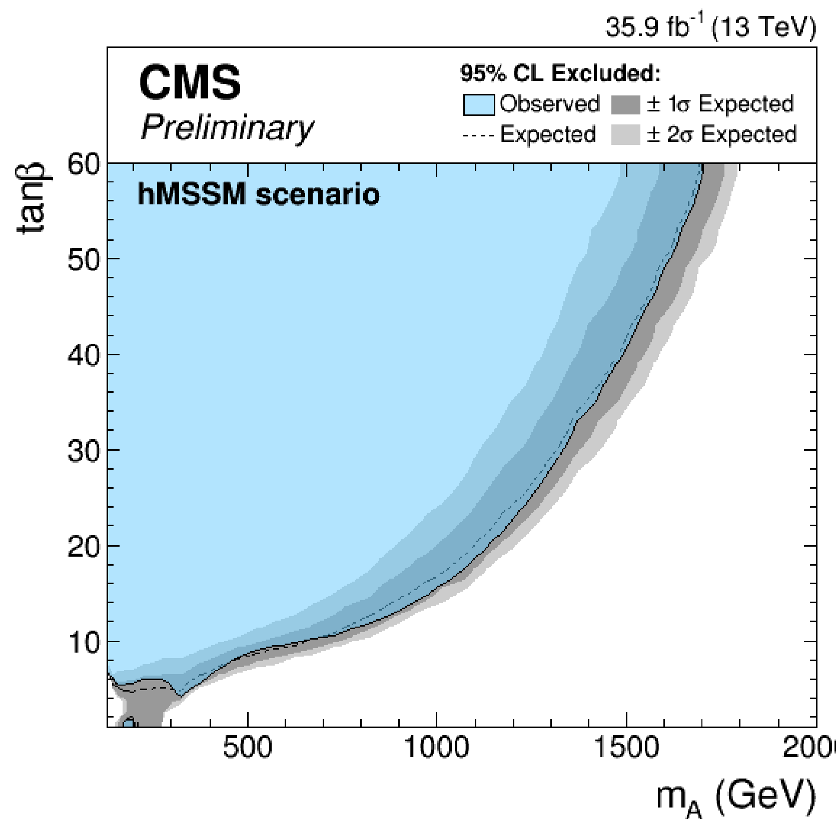


- Provide 3D likelihood scan (40k points x 28 masses)
- Allows for more sophisticated re-interpretation in alternative/ new models/scenarios (→ e.g. arXiv:1507.06706)

Model dependent exclusion contours

- Exclusion contours in **predefined benchmark models**:





- In general: parameter space explored down to $\tan\beta \gtrsim 6$ for $m_A \lesssim 250$ GeV and up to $m_A \leq 1600$ GeV.

Summary

- CMS has released the first MSSM $H \to \tau\tau$ LHC run-2 analysis (CMS-PAS-HIG-17-020).
- Flagship analysis of CMS in the BSM Higgs program.
- Preliminary result, as shown here, entered CMS wide review and will be submitted to JHEP, as soon as possible.
- Analysis significantly extends the explored parameter space for models of more complex Higgs sectors (→ serious investigation up to the TeV scale).
- Upcoming paper will set many standards for the end of LHC run-2 and subsequent analyses (→ analysis techniques, signal modeling, statistical inference, …).

Backup

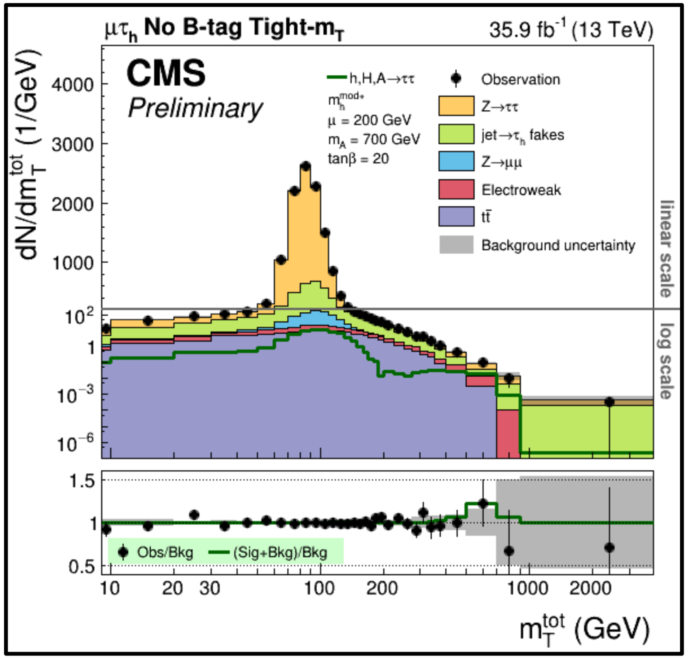
Discriminating variable

$$\tau_1^{\rm vis} = \mu,\, e,\, \tau_h \qquad \tau_2^{\rm vis} = \mu,\, \tau_h$$

$$m_{\rm T}^{\rm tot} = \sqrt{m_{\rm T}^2(E_{\rm T}^{\rm miss}, \tau_1^{\rm vis}) + m_{\rm T}^2(E_{\rm T}^{\rm miss}, \tau_2^{\rm vis}) + m_{\rm T}^2(\tau_1^{\rm vis}, \tau_2^{\rm vis})}\,,$$

$$m_{\rm T}(1,2) = \sqrt{2 p_{\rm T}(1) p_{\rm T}(2)(1 - \cos\Delta\phi(1,2))},$$

- Backgrounds like $t\bar{t}$, W+jets and QCD multijet are more spread as for invariant di-τ mass



MC driven cross check