Likelihood Analyses in BSM Searches:
from model-independent to searches in dedicated scenarios

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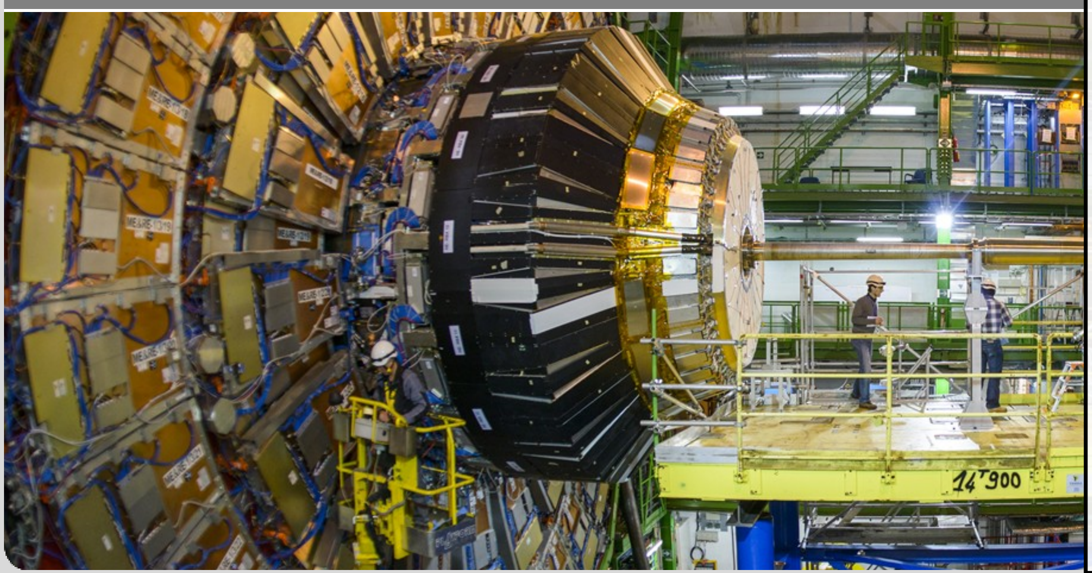
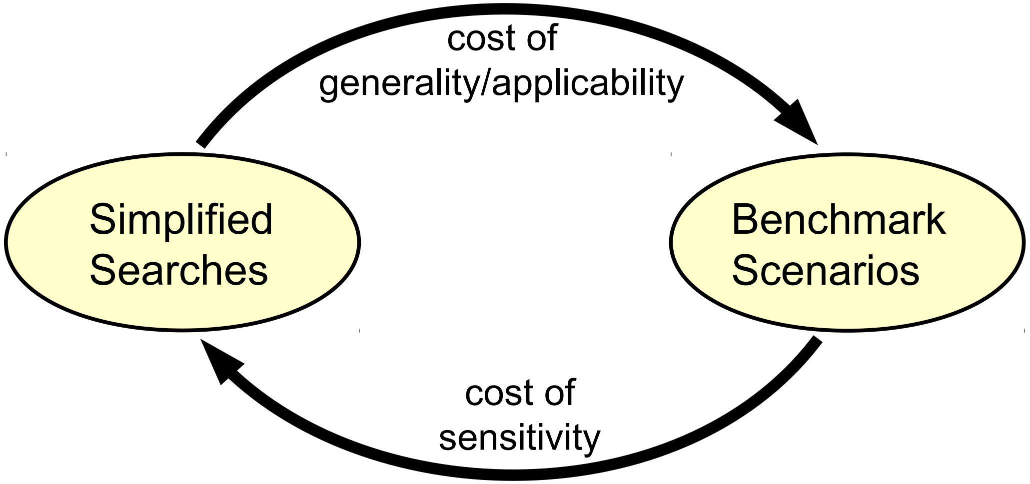


- Introduction
- Data representation in MSSM $H\rightarrow\tau\tau$ analyses
- Recall: limit setting algorithms
- "Deconstruction" of likelihood function
- Method comparison and conclusions

After discovery is before discovery (Sepp Herberger)

- After the discovery of one Higgs boson we are out for its siblings.
- In many(all?) non-trivial extensions of the SM search for not a single but several particles with well defined relations.
- Search strategies:



Common problem with many faces:

- Search for deviations from SM in generic Higgs couplings analy-ses.
- SUSY searches.
- DM searches @ colliders.
- BSM Higgs searches.

- Always do both! To be efficient try to keep the loop as concise as possible.

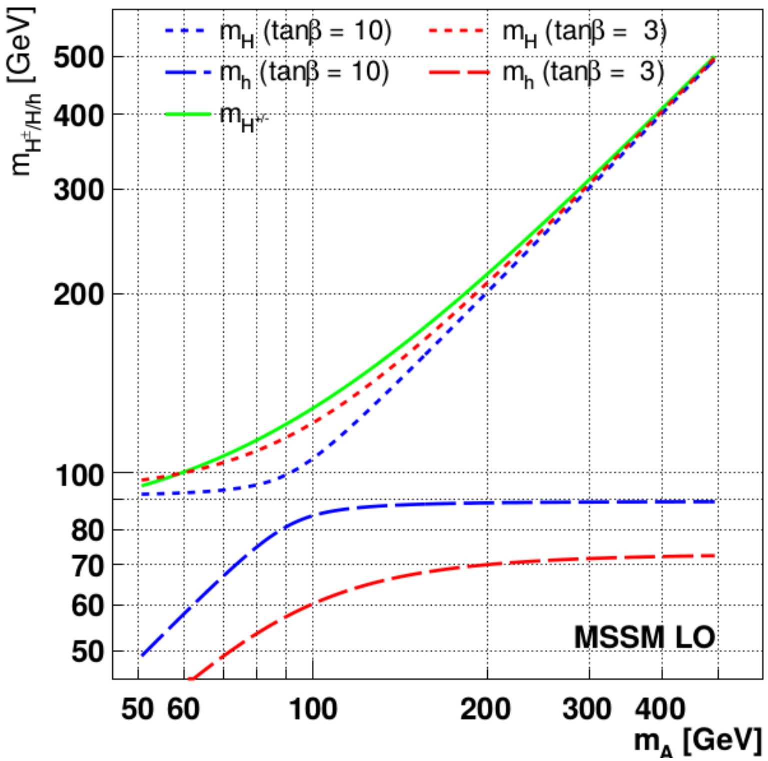
Case-study: Higgs Bosons in the MSSM

- The MSSM, like any other Two Higgs Doublet Model (THDM) predicts five Higgs bosons:

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

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

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



- Strict mass requirements at tree level:

two free parameters: m_A, $\tan\beta = \mathrm{v}_u/\mathrm{v}_d$

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

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

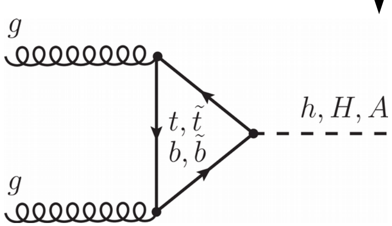
$$\tan\alpha = \frac{-(m_A^2 + m_Z^2)\sin 2\beta}{(m_Z^2 - m_A^2)\cos 2\beta + \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4m_A^2 m_Z^2 \cos^2 2\beta}}$$

(angle btw. H_u & H_d in isospace)

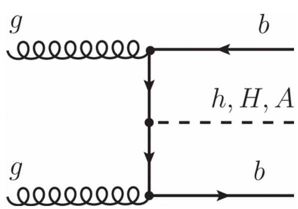
Coupling structure to neutral Higgs Bosons

	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	$\sin(\beta-\alpha) \;\to 1$	$\cos\alpha/\sin\beta \;\to 1$	$-\sin\alpha/\cos\beta \to 1$

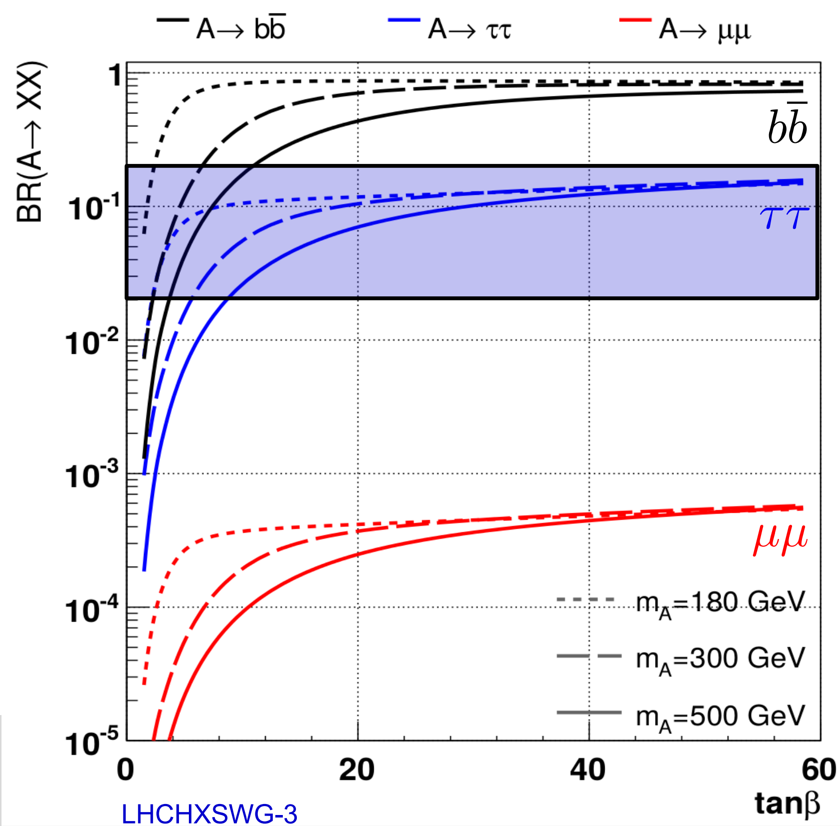
- For $m_A \gg m_Z$: $\alpha \to \beta - \pi/2$ (coupling to down-type fermions enhanced by $\tan\beta$).
- Interesting production/decay modes:



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

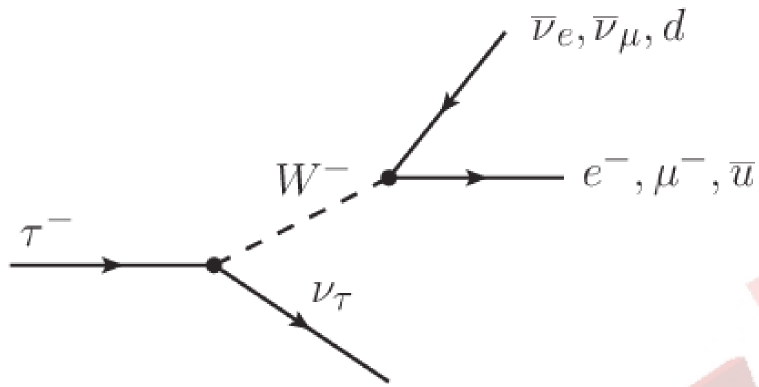


$gg \to \phi b\bar{b}$ ("$bb\phi$")

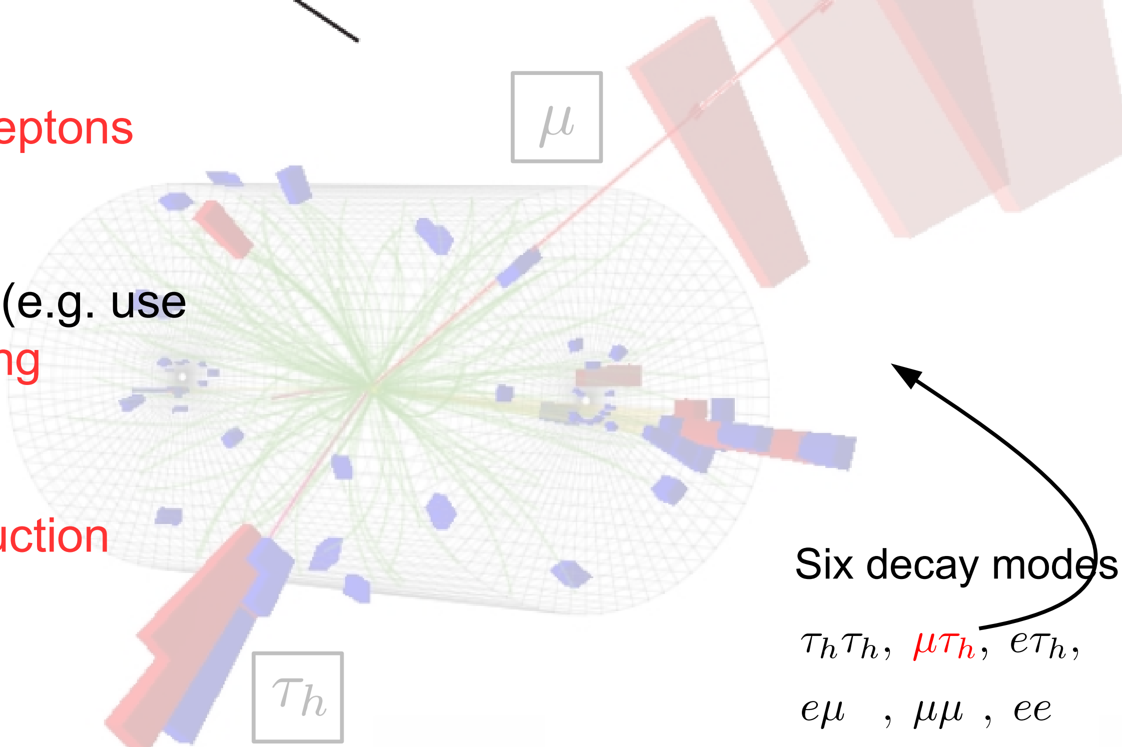


The analysis in the $H \to \tau\tau$ decay channel

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 (e.g. use $\not{E}_T$) & reconstruct discriminating variable (e.g. $m_{\tau\tau}$).
- Exploit characteristics of production mode to increase sensitivity.



Six decay modes:

$\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$,

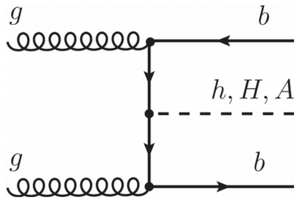
$e\mu$, $\mu\mu$, ee

Typical discriminating distributions

b-tag category:

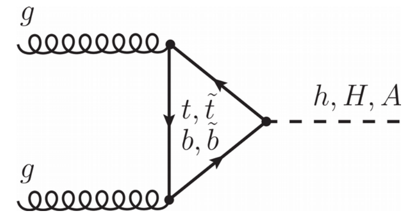
$N(b\text{-}tag) \geq 1$

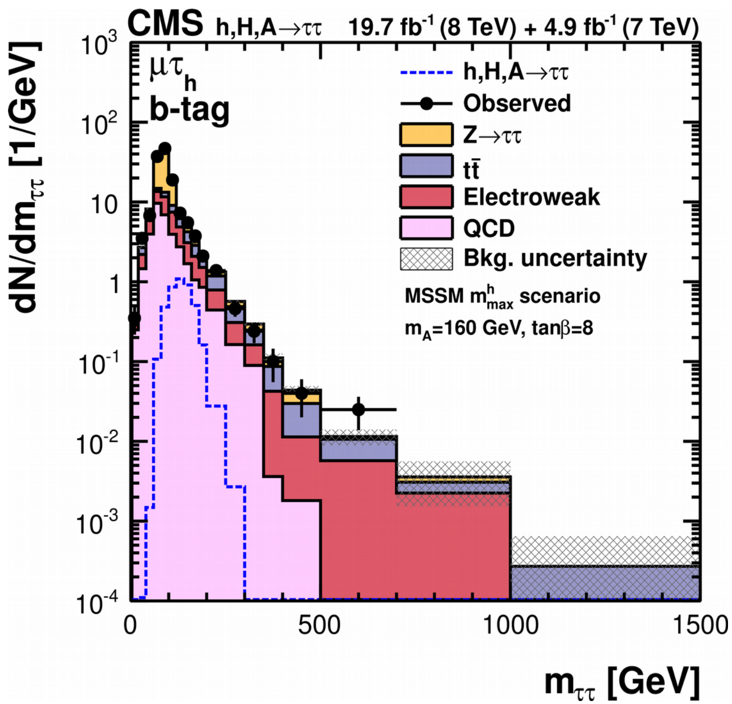
$N(Jet) \quad \leq 1$

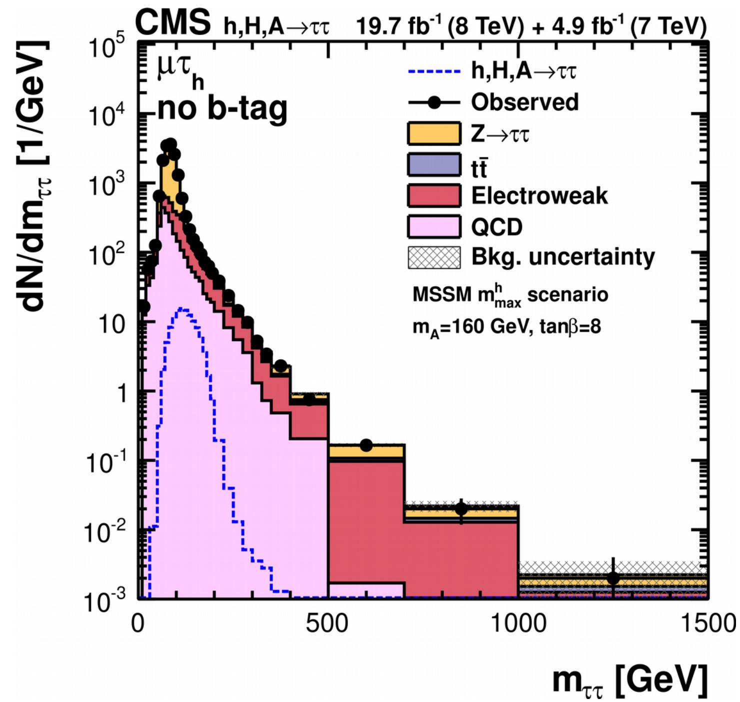


No b-tag category:

$N(b\text{-}tag) = 0$





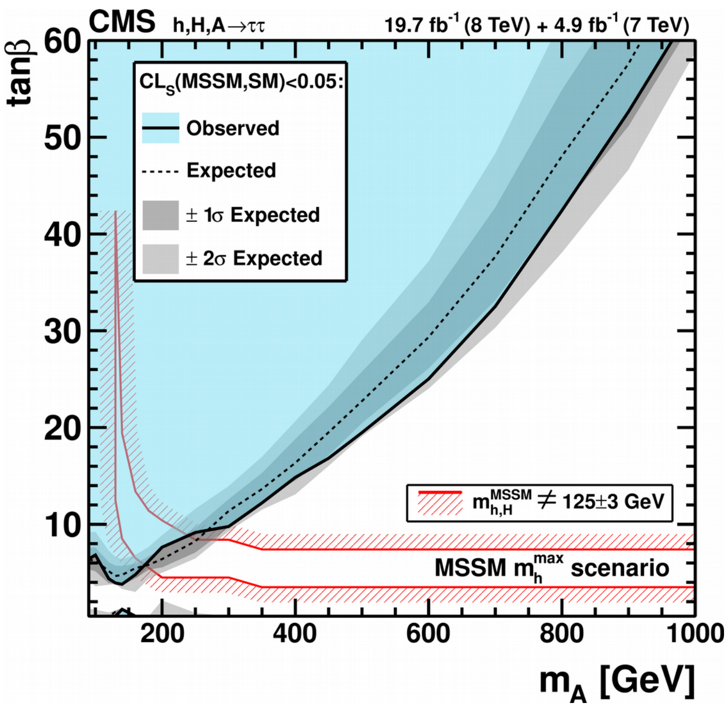


- Search for additional peak(s) in $m_{\tau\tau}$ distribution.
- Non-observation of signal → limits in parameter space of models.

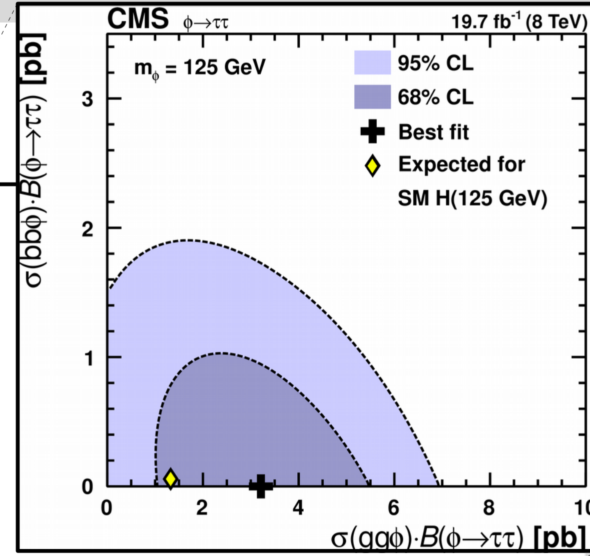
arXiv:1408.3316

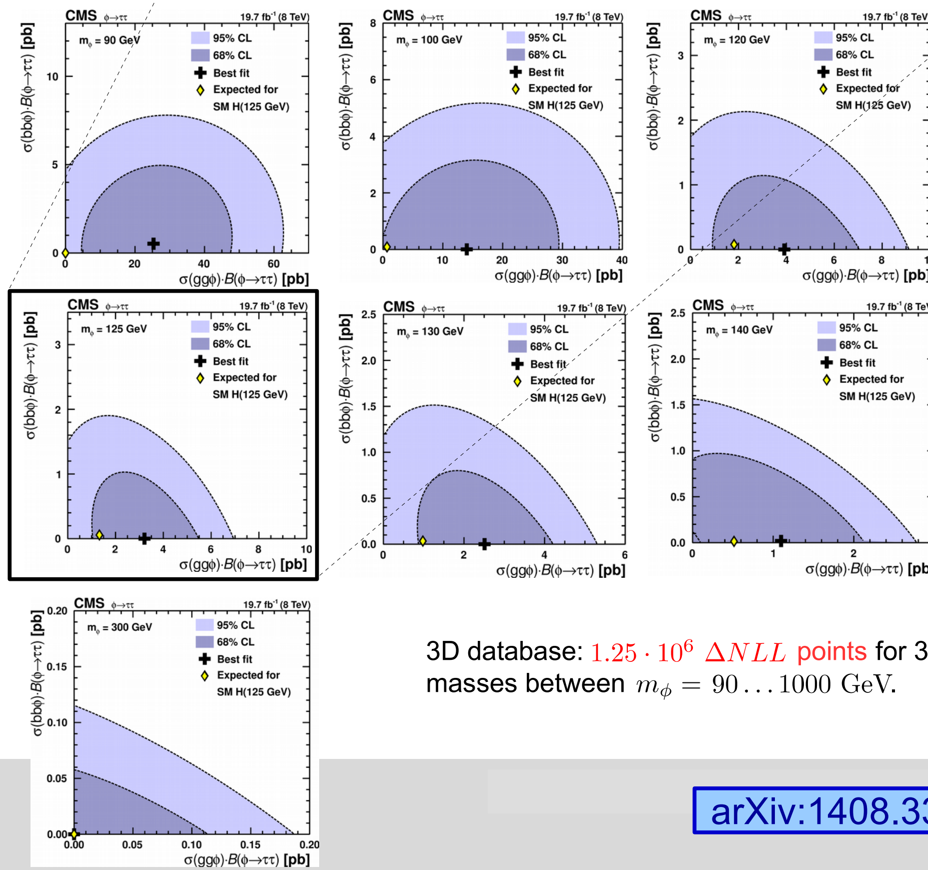
Presentation of limits …

- Full exclusion (here in the m_h^{max} scenario):



- Model independent limits (single narrow resonance search in $gg\phi$ & $bb\phi$ mode):



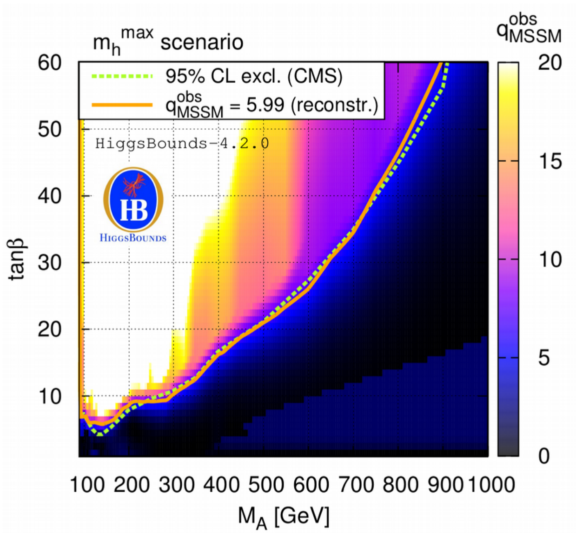


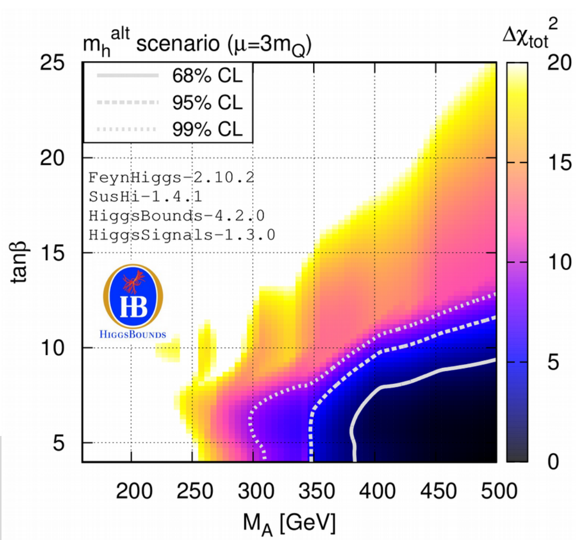
3D database: $1.25 \cdot 10^6$ ΔNLL points for 31 masses between $m_\phi = 90 \ldots 1000$ GeV.

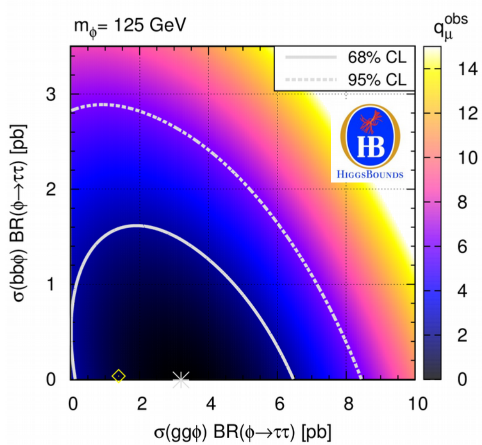
arXiv:1408.3316

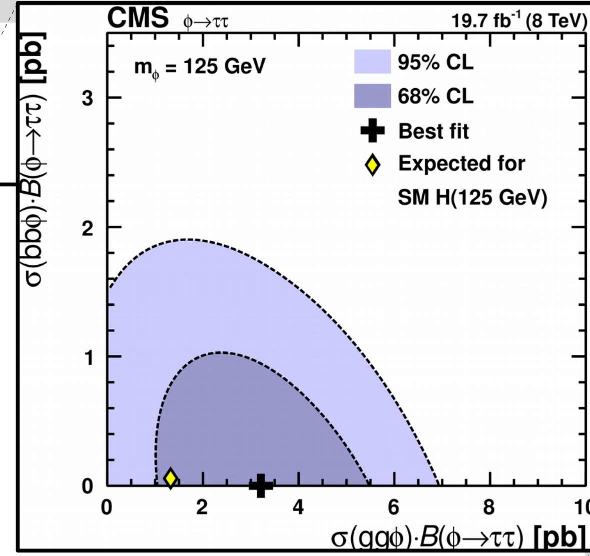
… picked up by theory

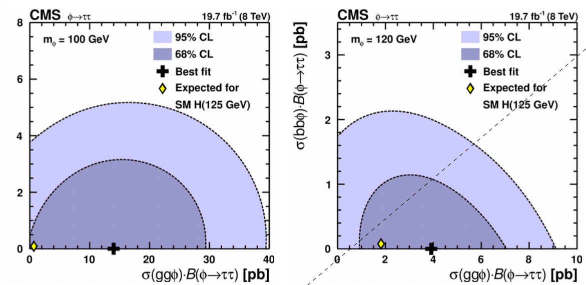
- First application to new models (using HiggsBounds): arXiv:1507.06706

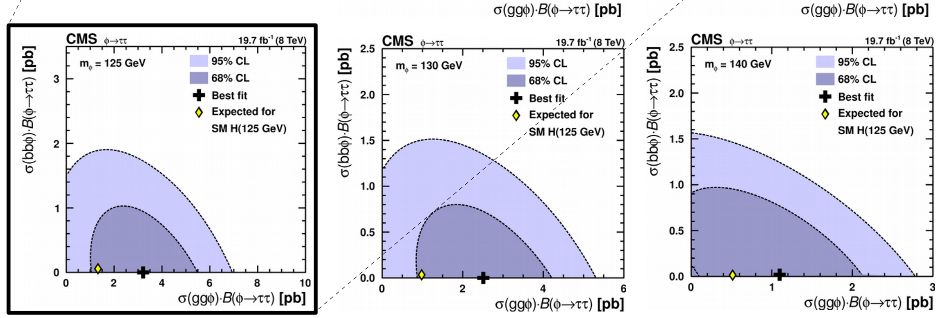


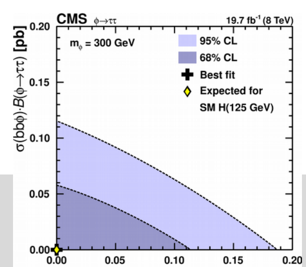










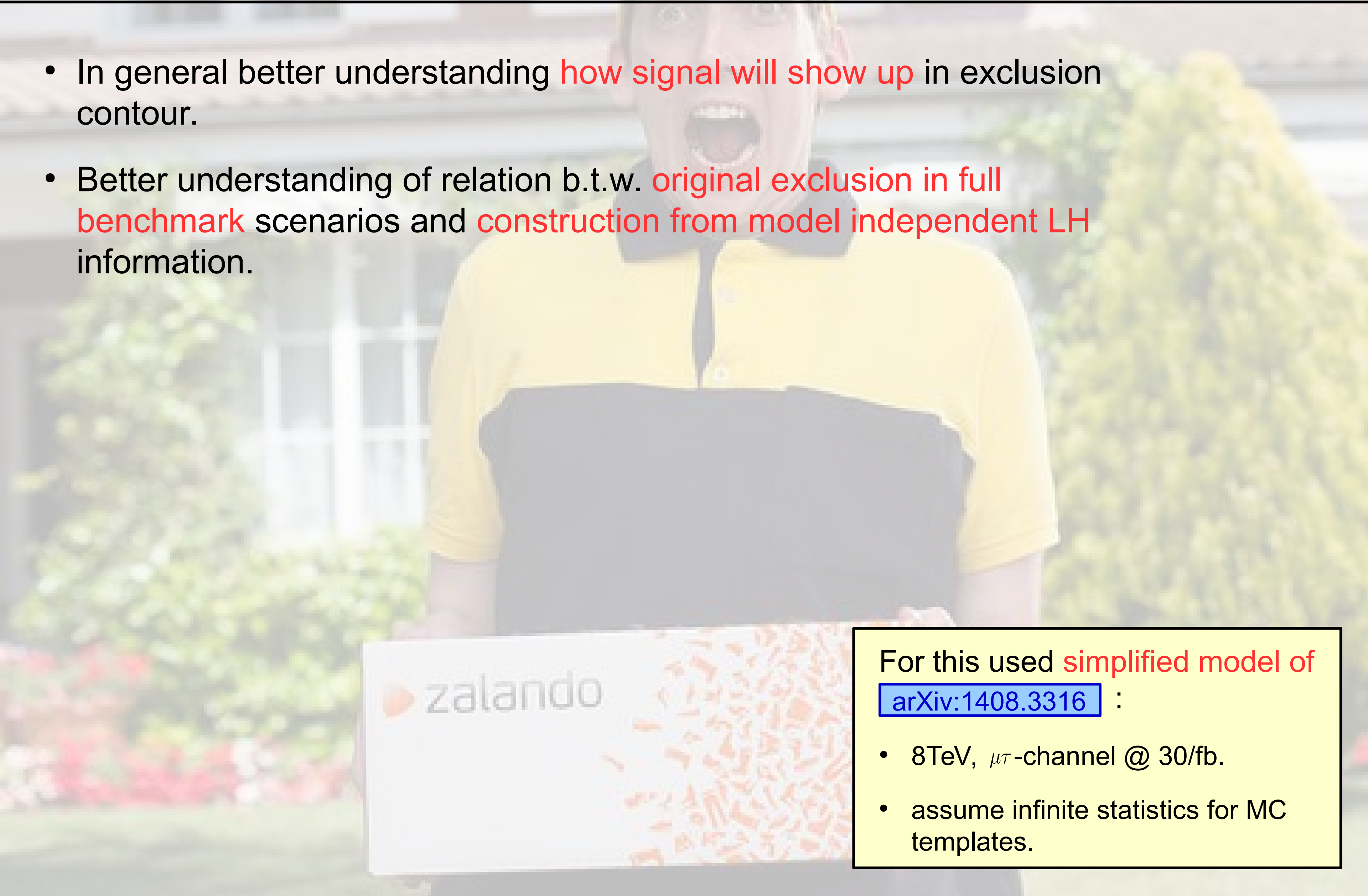


3D database: $1.25 \cdot 10^6$ ΔNLL points for 31 masses between $m_\phi = 90 \ldots 1000$ GeV.

arXiv:1408.3316

Deliverables of this study

- In general better understanding how signal will show up in exclusion contour.
- Better understanding of relation b.t.w. original exclusion in full benchmark scenarios and construction from model independent LH information.



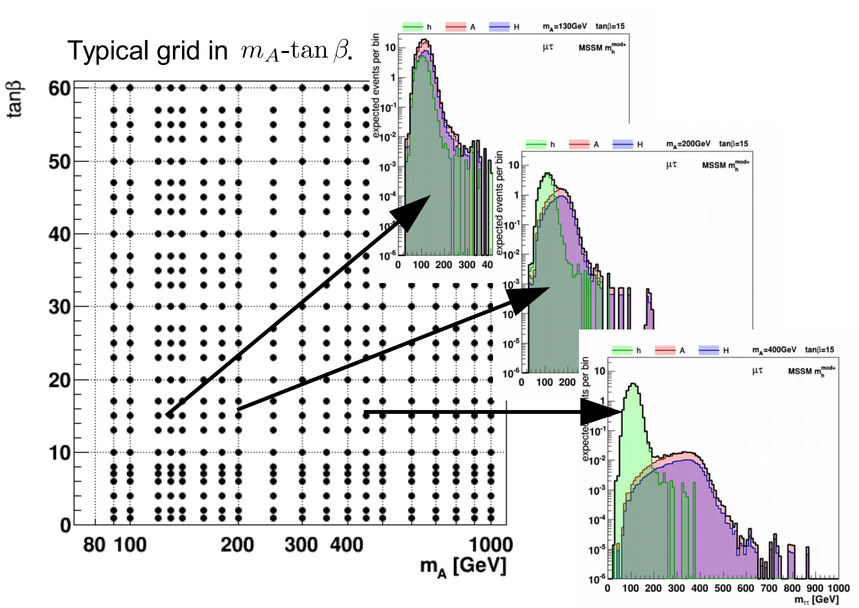
For this used simplified model of arXiv:1408.3316 :

- 8TeV, $\mu\tau$-channel @ 30/fb.
- assume infinite statistics for MC templates.

Recall: limit construction algorithms

Direct limit on full benchmark:

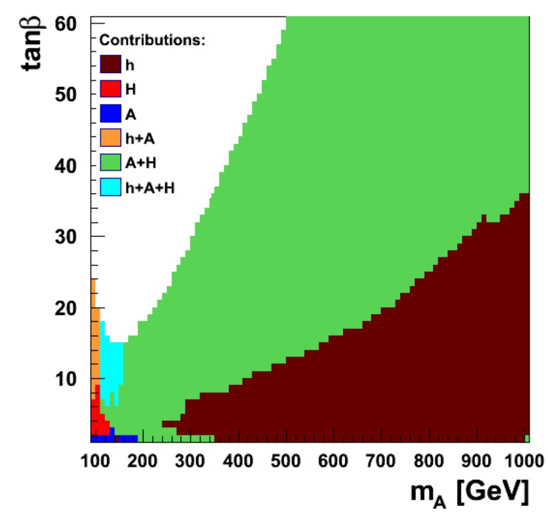
- For fixed values in $(m_A, \tan\beta)$ build templates composed of $h+H+A$ according to model.



- vary whole template (scaling factor μ).
- for fixed value of m_A find value of $\tan\beta$ where $CL_s(\mu=1)=0.05$.

Re-interpretation from LH:

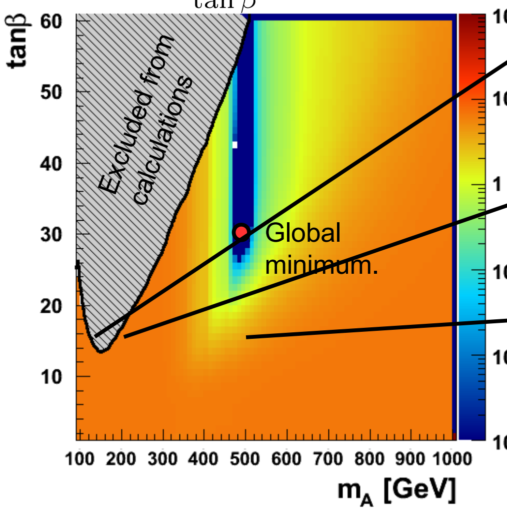
- Cluster Higgs bosons if they are close to each other (within exp. Resolution).
- Determine cluster with highest expected exclusion sensitivity (i.e. largest ΔNLL_{exp} from DB based on BG-only *Asimov* dataset).

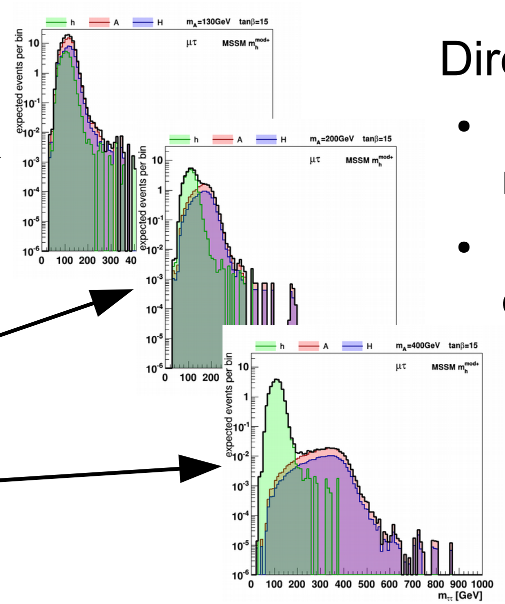


- Read off ΔNLL_{obs} for each given point of $(m_A, \tan\beta)$ from DB based on data.

LH components

$\Delta NLL^{m_A,\mu}_{\tan\beta}$

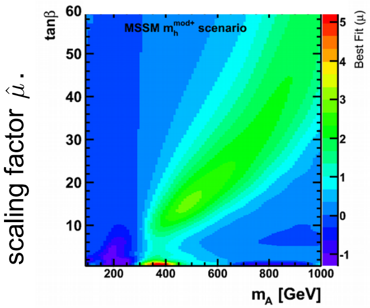




Direct limit:

- Fix template according to exact model point.
- Find best fit point. Allow for floating overall normalization ($\hat{\mu}$).

Profile of the overall scaling factor $\hat{\mu}$.



$$\Delta NLL^{m_A,\mu}_{\tan\beta} = \ln\left(\frac{\mathcal{L}(\hat{\mu},\hat{\theta}_{\hat{\mu}})\big|^{m_A}_{\tan\beta}}{\mathcal{L}(\hat{\hat{\mu}},\hat{\hat{\theta}}_{\hat{\hat{\mu}}})}\right)$$

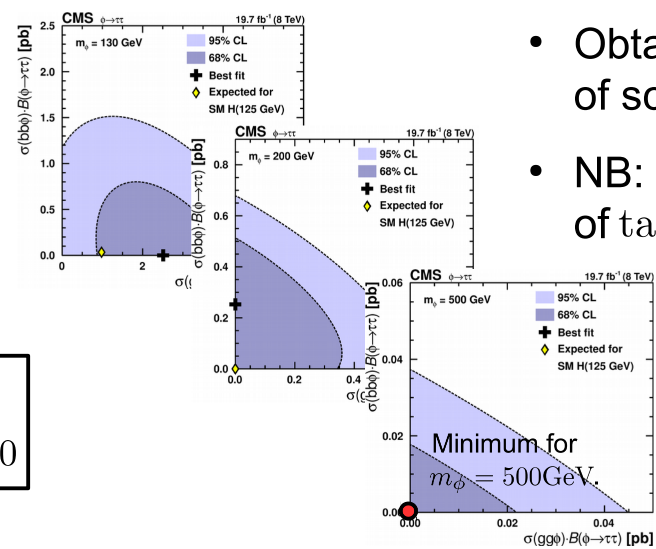
"$\Delta NLL\,(m_A,\tan\beta)$ w.r.t. global minimum with floating μ ".

Pseudo-dataset (30/fb):

BG + m_h^{mod+} $m_A = 500,\ \tan\beta = 30$

Re-interpretation:

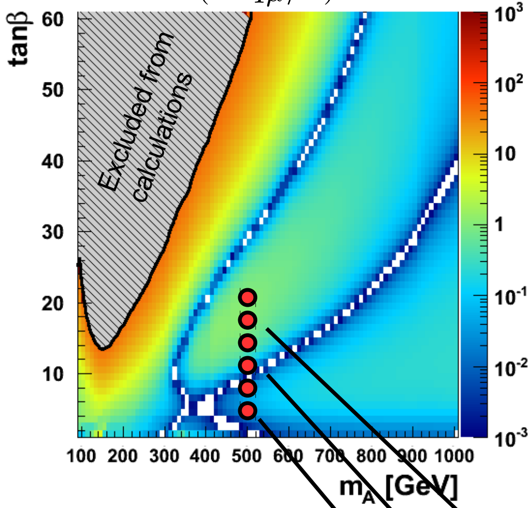
- Obtain ΔNLL from minimum of scan for given m_ϕ.
- NB: does not vary as function of $\tan\beta$.



NB: plots do not corresp. to pseudo-dataset, but to CMS publication.

LH components

$\Delta NLL(= q_\mu/2)$



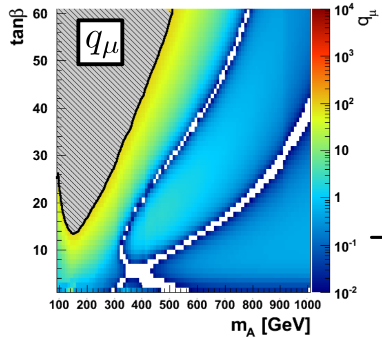
$$\Delta NLL = \ln\left(\frac{\mathcal{L}(\mu=1,\hat{\theta}_{\mu=1})\big|^{m_A}_{\tan\beta}}{\mathcal{L}(\hat{\mu},\hat{\theta}_{\hat{\mu}})\big|^{m_A}_{\tan\beta}}\right)$$

"$\Delta NLL\,(m_A, \tan\beta)$ for exact model point (with $\mu = 1$) w.r.t. floating μ".

Pseudo-dataset (30/fb):

BG + m_h^{mod+} $m_A = 500,\ \tan\beta = 30$

Fit to (pseudo-)data



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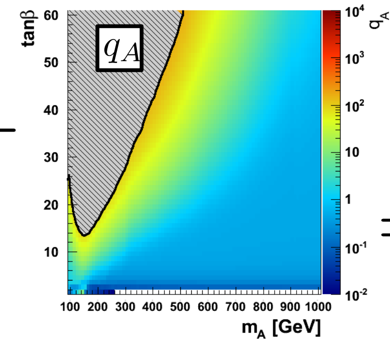
Direct limit:

Fit to BG-only *Asimov* dataset



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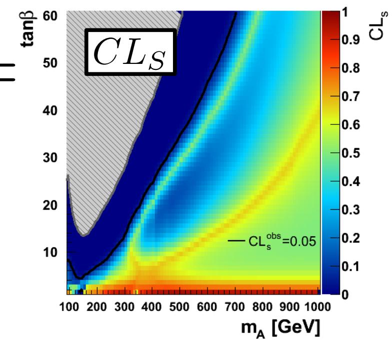
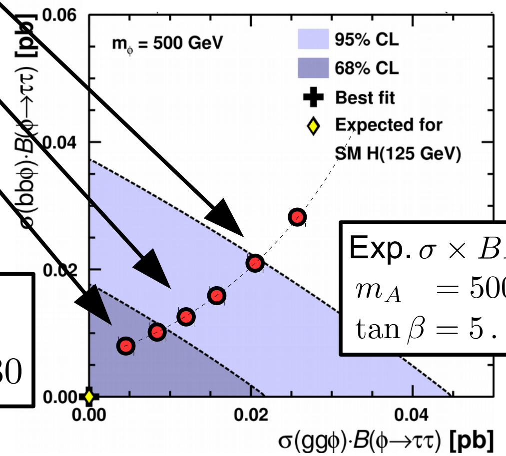


Re-interpretation:

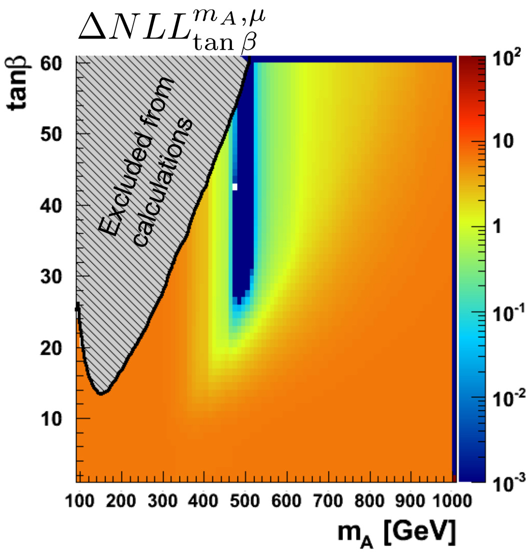
- Read off ΔNLL and apply to m_A- $\tan\beta$ plot.

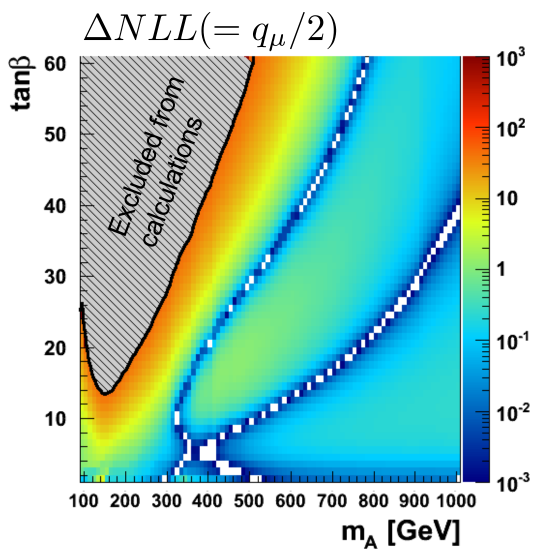


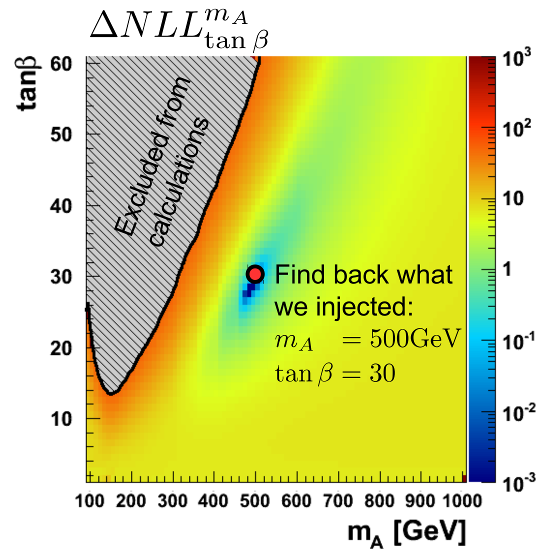
Exp. $\sigma \times BR$ for:
$m_A \ = 500$ GeV
$\tan\beta = 5\dots35$

NB: plots do not corresp. to pseudo-dataset, but to CMS publication.

LH components







Direct limit

$$\Delta NLL^{m_A,\mu}_{\tan\beta} = \ln\left(\frac{\mathcal{L}(\hat{\mu},\hat{\theta}_{\hat{\mu}})\big|^{m_A}_{\tan\beta}}{\mathcal{L}(\hat{\hat{\mu}},\hat{\hat{\theta}}_{\hat{\hat{\mu}}})}\right) + \Delta NLL = \ln\left(\frac{\mathcal{L}(\mu=1,\hat{\theta}_{\mu=1})\big|^{m_A}_{\tan\beta}}{\mathcal{L}(\hat{\mu},\hat{\theta}_{\hat{\mu}})\big|^{m_A}_{\tan\beta}}\right) = \Delta NLL^{m_A}_{\tan\beta} = \ln\left(\frac{\mathcal{L}(\mu=1,\hat{\theta}_{\mu=1})\big|^{m_A}_{\tan\beta}}{\mathcal{L}(\hat{\hat{\mu}},\hat{\hat{\theta}}_{\hat{\hat{\mu}}})}\right)$$

"$\Delta NLL\,(m_A,\tan\beta)$ w.r.t. global minimum with floating μ".

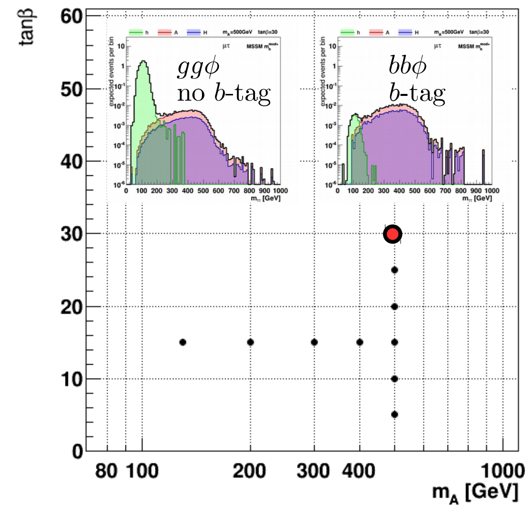
"$\Delta NLL\,(m_A,\tan\beta)$ for exact model point (with $\mu=1$) w.r.t. floating μ".

"$\Delta NLL\,(m_A,\tan\beta)$ for exact model point (with $\mu=1$) w.r.t. global minimum with floating μ".

Pseudo-dataset (30/fb):

BG + m_h^{mod+} $m_A = 500,\ \tan\beta = 30$

Walk across $(m_A, \tan\beta)$ plane

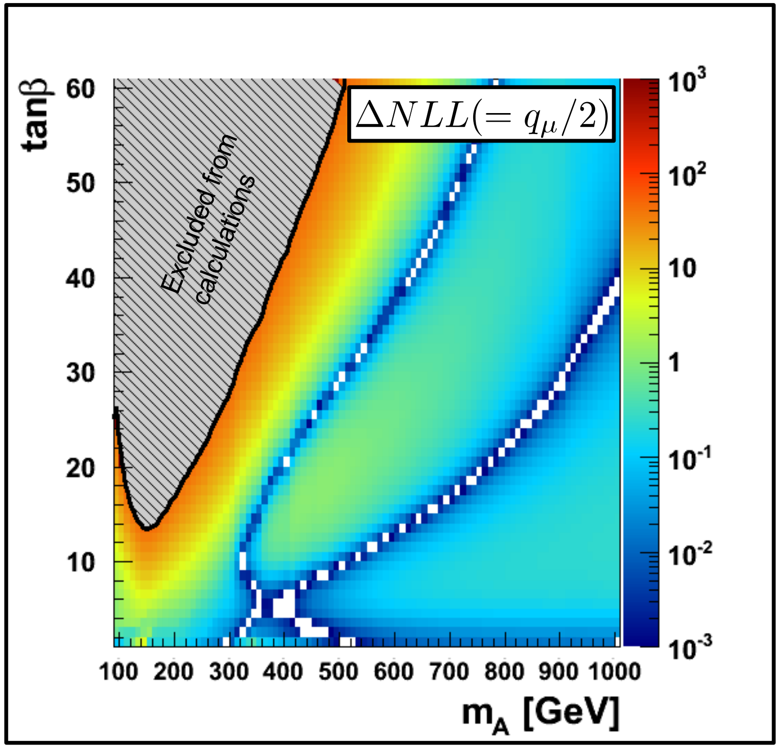


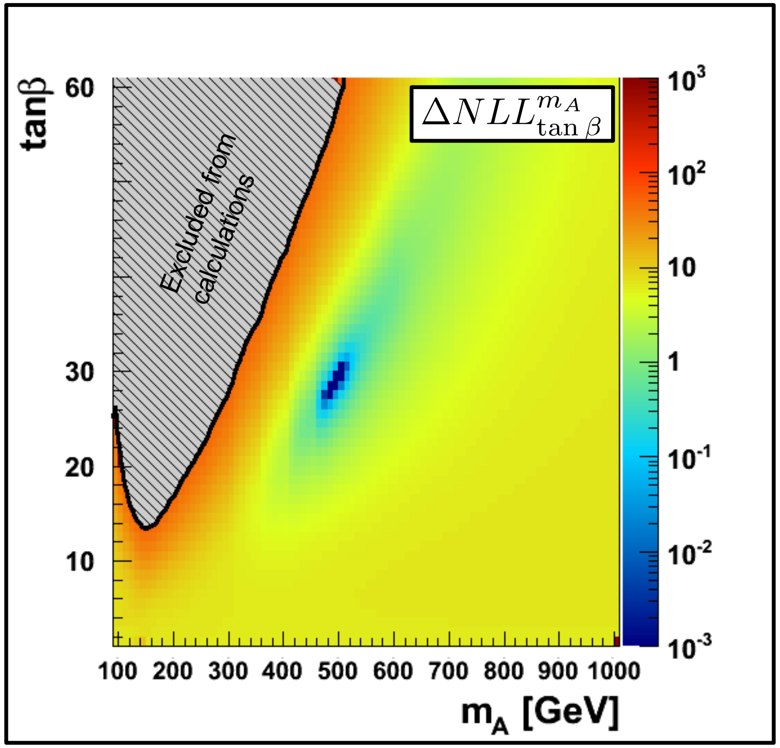
Direct limit

- Inject signal for decreasing values of $\tan\beta$:

$$m_h^{mod+} \quad m_A = 500\ \text{GeV} \quad \tan\beta = 30$$

- Investigate behavior of signal templates & likelihood.



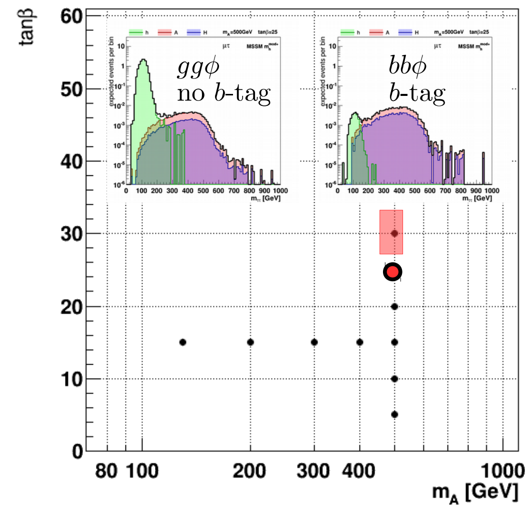


Walk across $(m_A, \tan\beta)$ plane

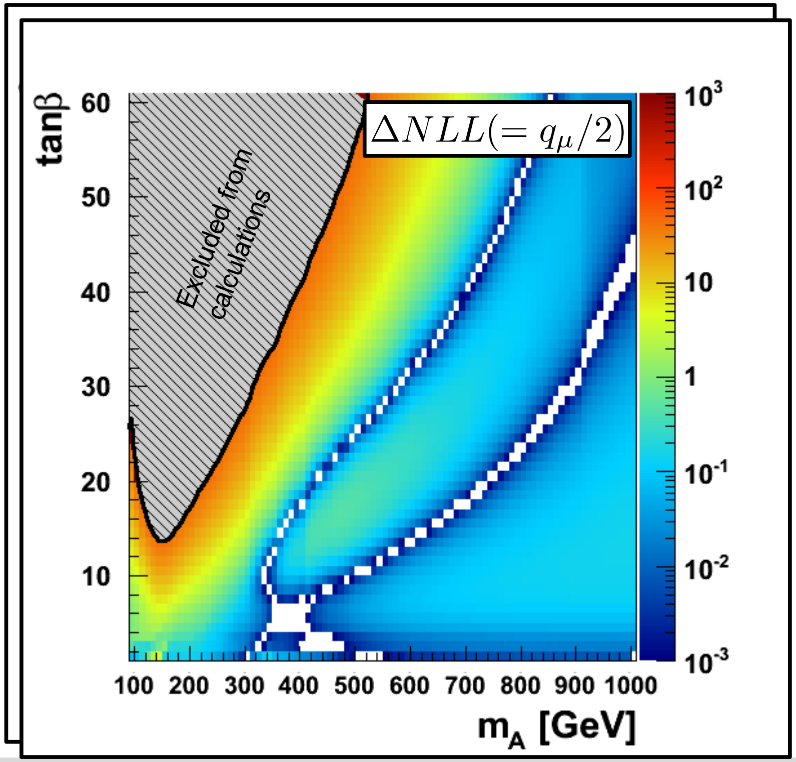
- Inject signal for decreasing values of $\tan\beta$:

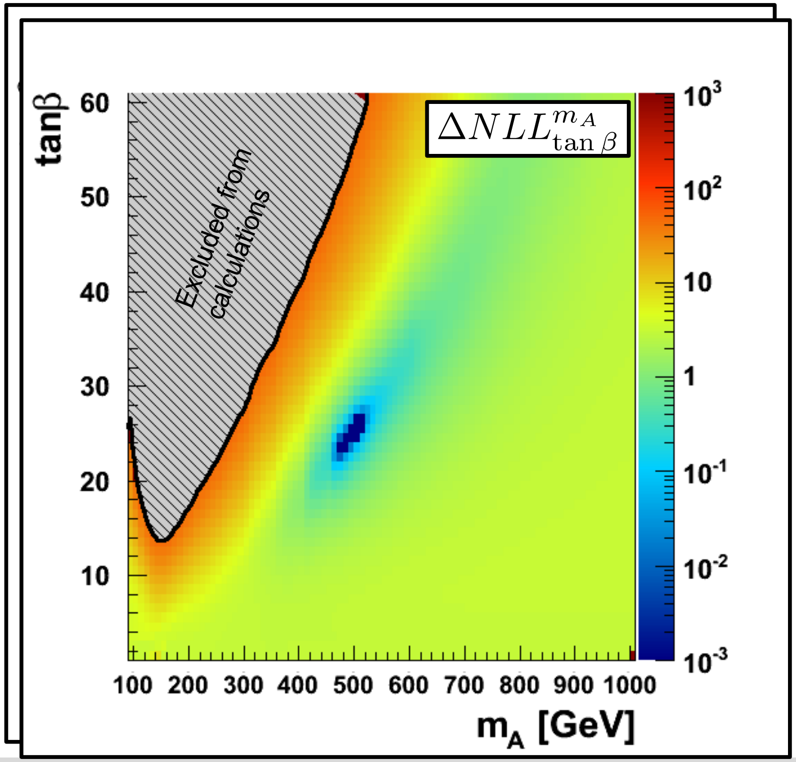
$$m_h^{mod+} \quad m_A = 500 \text{ GeV} \quad \tan\beta = 25$$

- Investigate behavior of signal templates & likelihood.

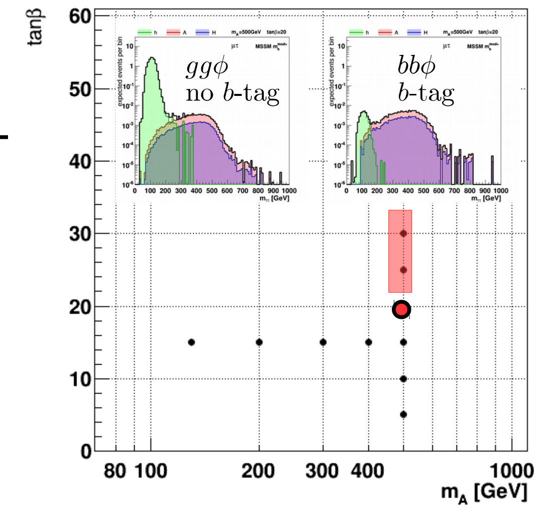


Direct limit





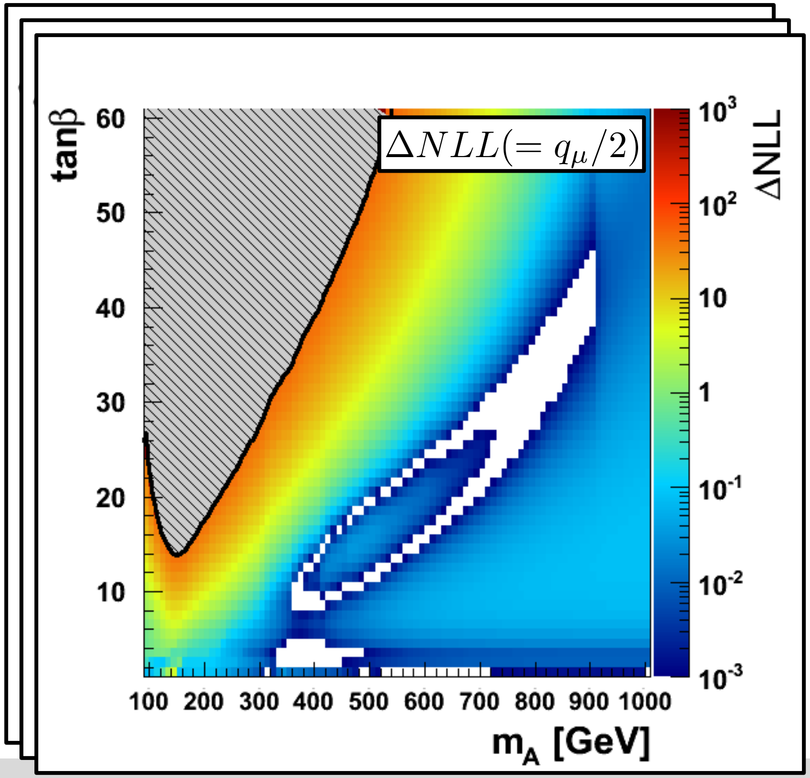
Walk across $(m_A, \tan\beta)$ plane

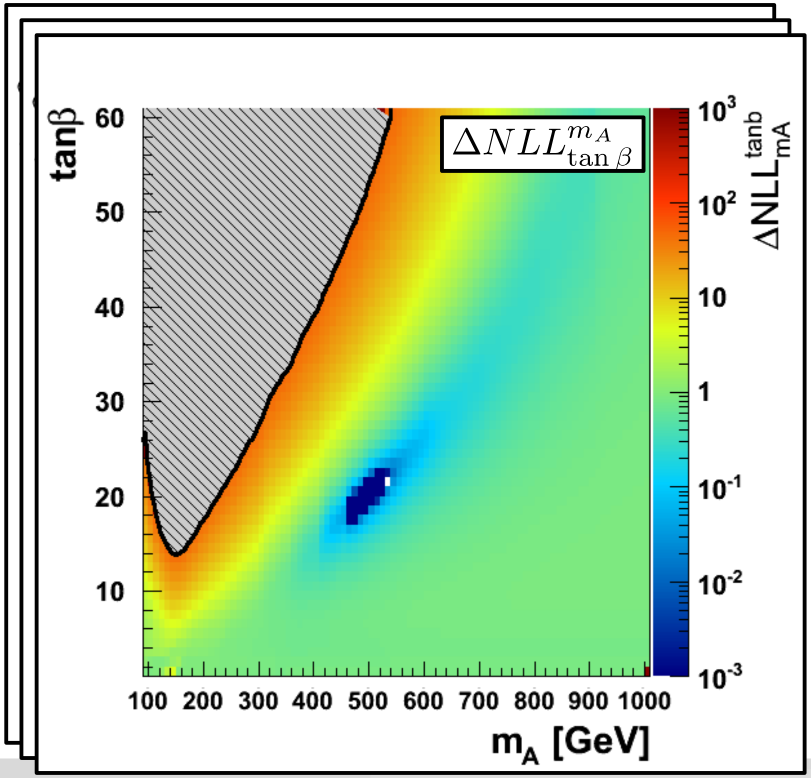


- Inject signal for decreasing values of $\tan\beta$:

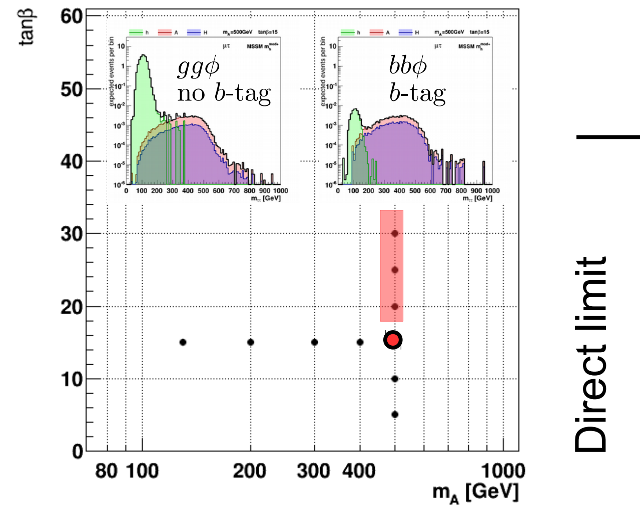
$$m_h^{mod+} \quad m_A = 500\ \text{GeV} \quad \tan\beta = 20$$

- Investigate behavior of signal templates & likelihood.





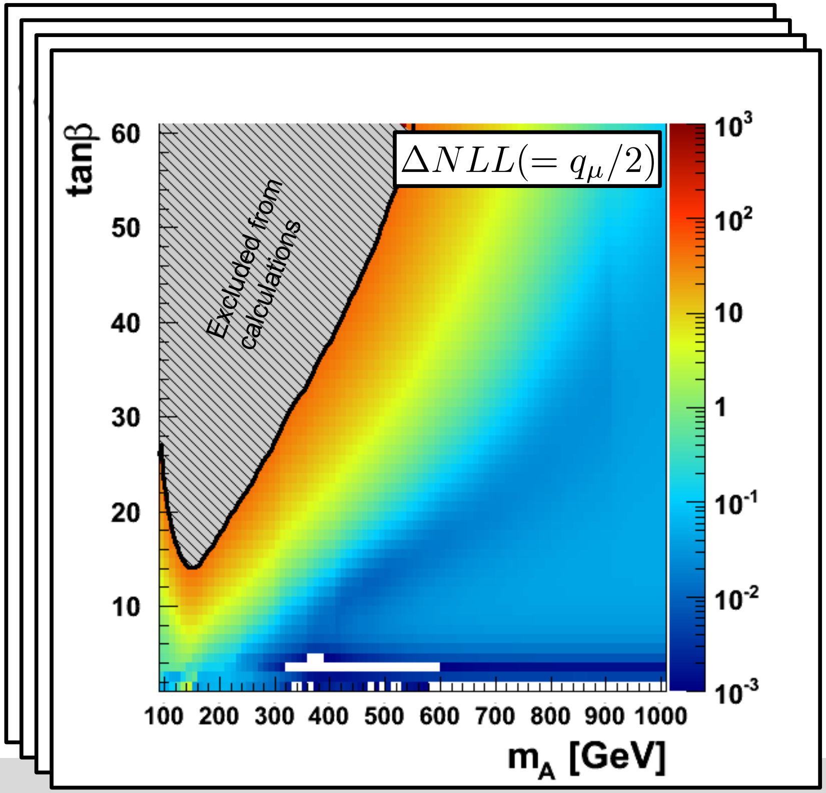
Walk across $(m_A, \tan\beta)$ plane

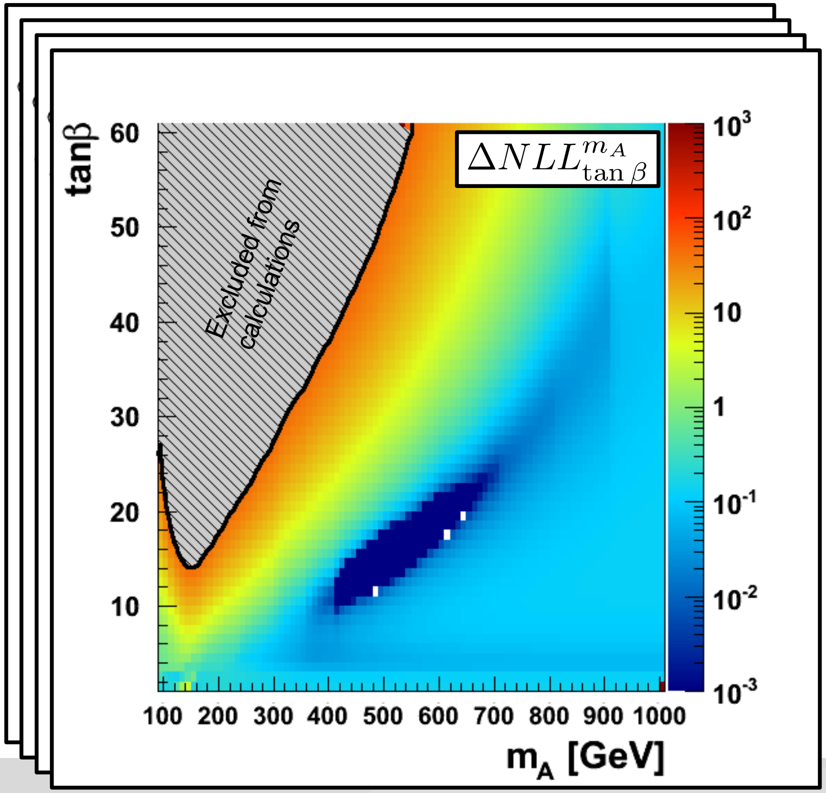


- Inject signal for decreasing values of $\tan\beta$:

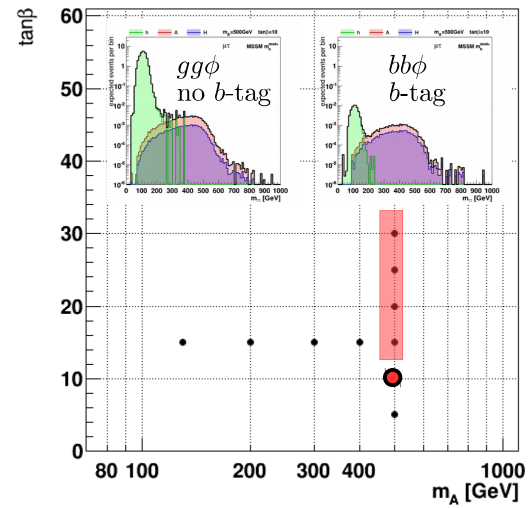
$$m_h^{mod+} \quad m_A = 500\ \text{GeV} \quad \tan\beta = 15$$

- Investigate behavior of signal templates & likelihood.





Walk across $(m_A, \tan\beta)$ plane

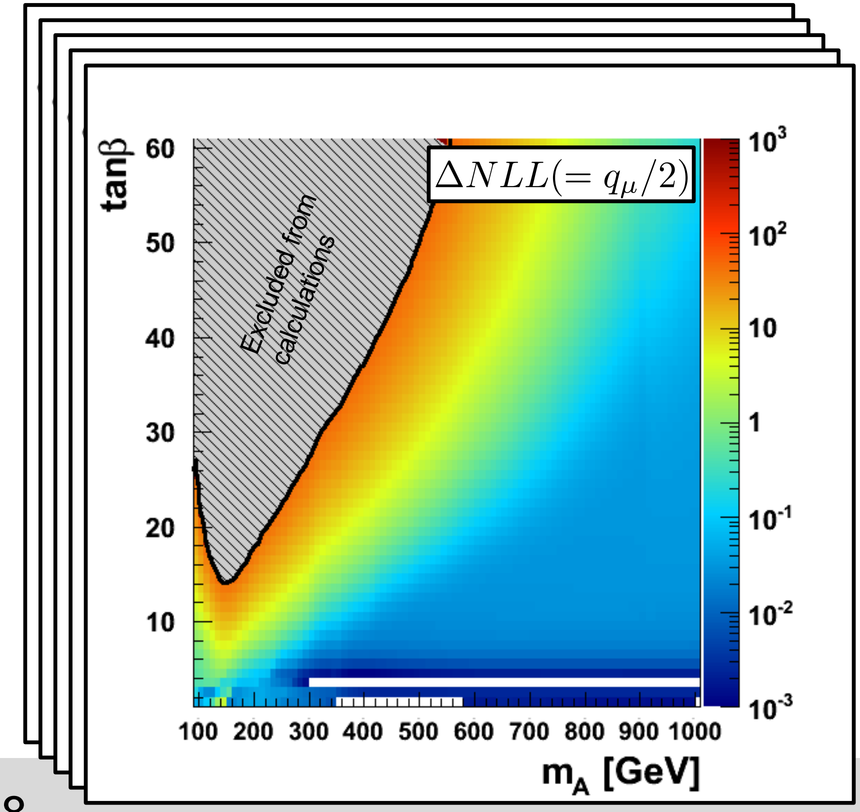


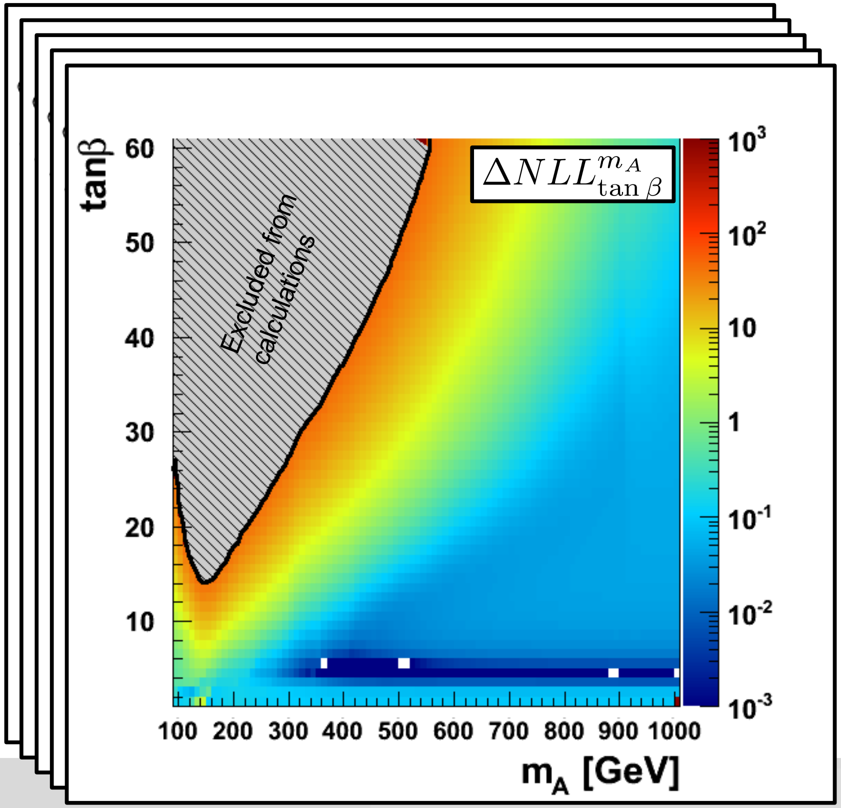
Direct limit

- Inject signal for decreasing values of $\tan\beta$:

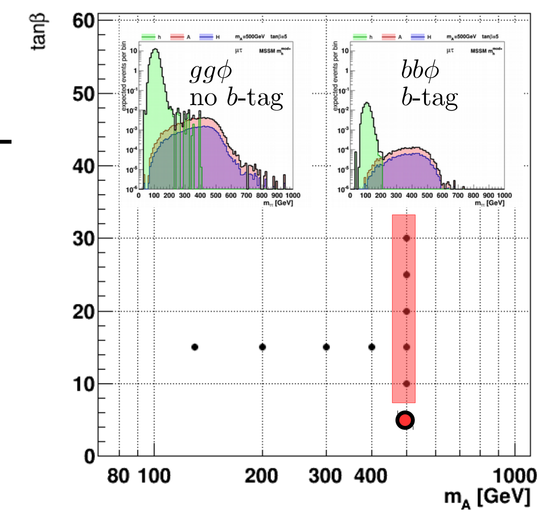
$$m_h^{mod+} \quad m_A = 500\ \text{GeV} \quad \tan\beta = 10$$

- Investigate behavior of signal templates & likelihood.





Walk across $(m_A, \tan\beta)$ plane

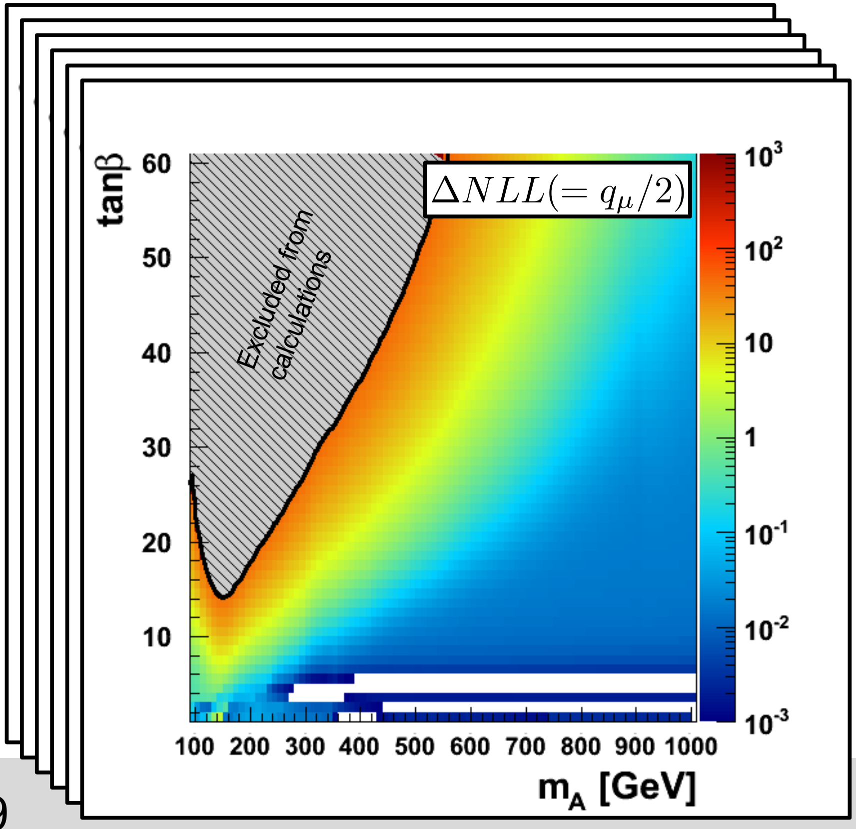


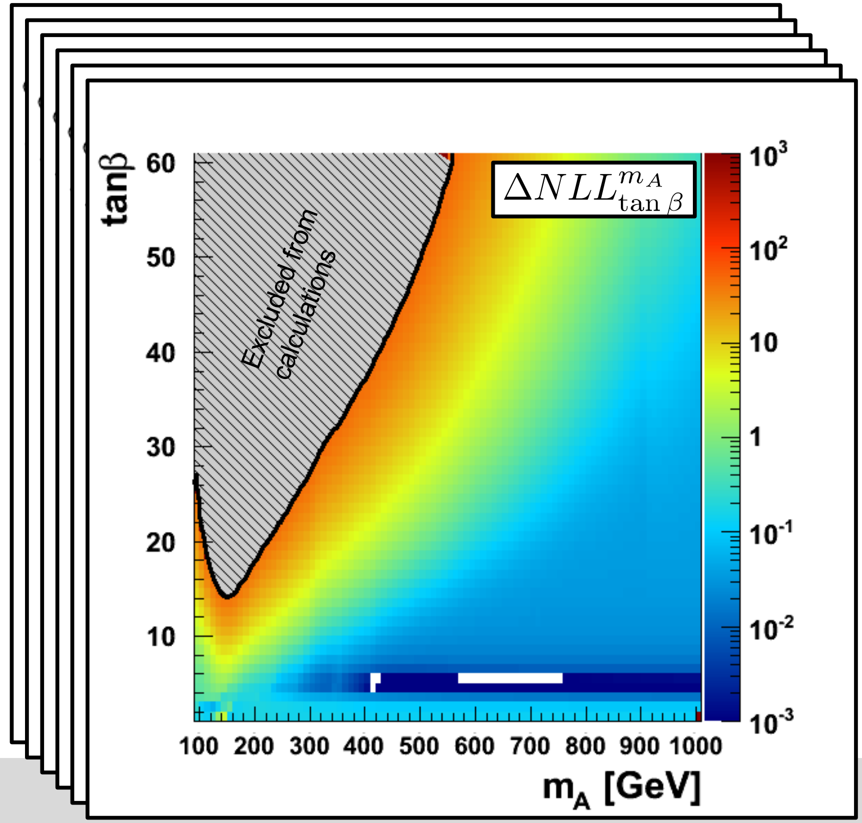
Direct limit

- Inject signal for decreasing values of $\tan\beta$:

m_h^{mod+}	$m_A = 500$ GeV	$\tan\beta = 5$

- Investigate behavior of signal templates & likelihood.



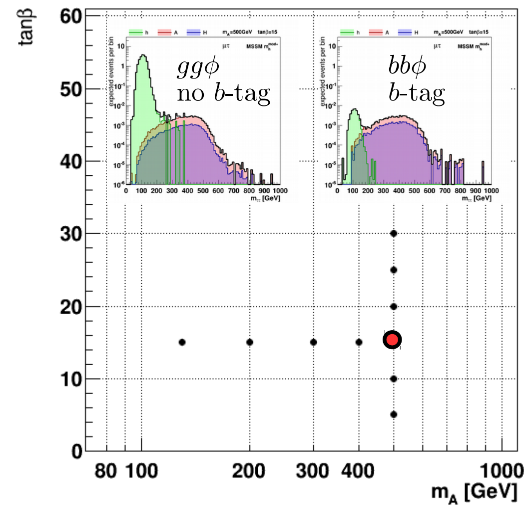


Walk across $(m_A, \tan\beta)$ plane

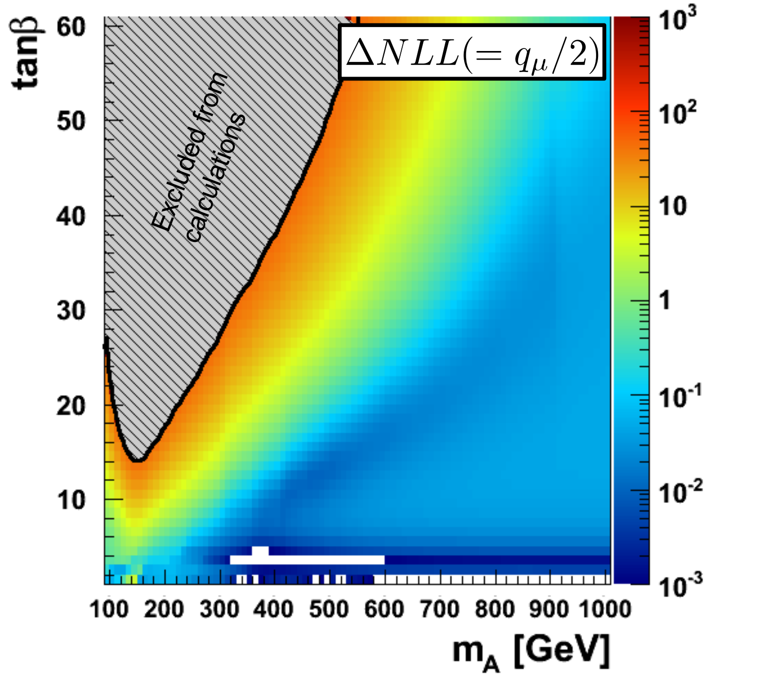
- Inject signal for decreasing values of m_A :

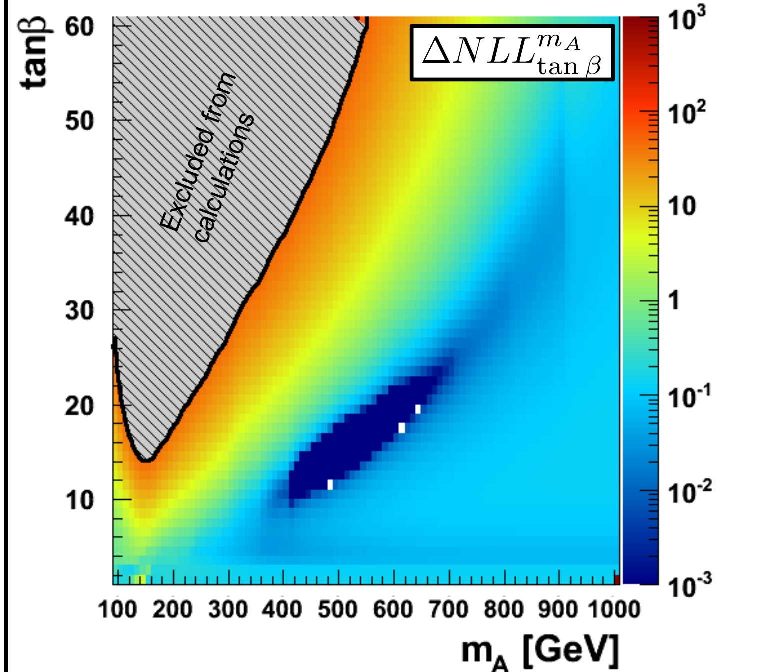
m_h^{mod+}	$m_A = 500$ GeV	$\tan\beta = 15$

- Investigate behavior of signal templates & likelihood.



Direct limit



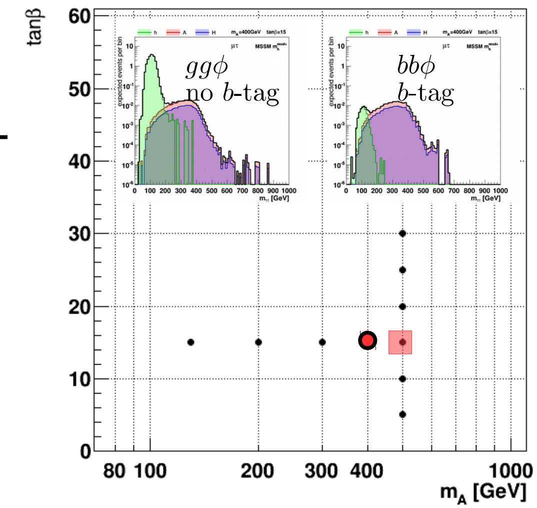


Walk across $(m_A, \tan\beta)$ plane

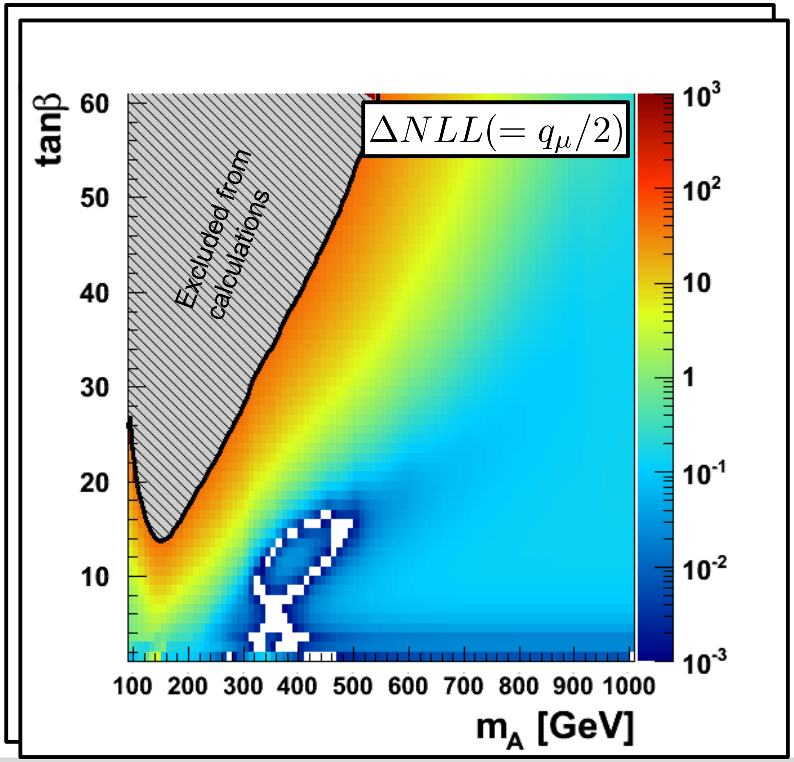
- Inject signal for decreasing values of m_A :

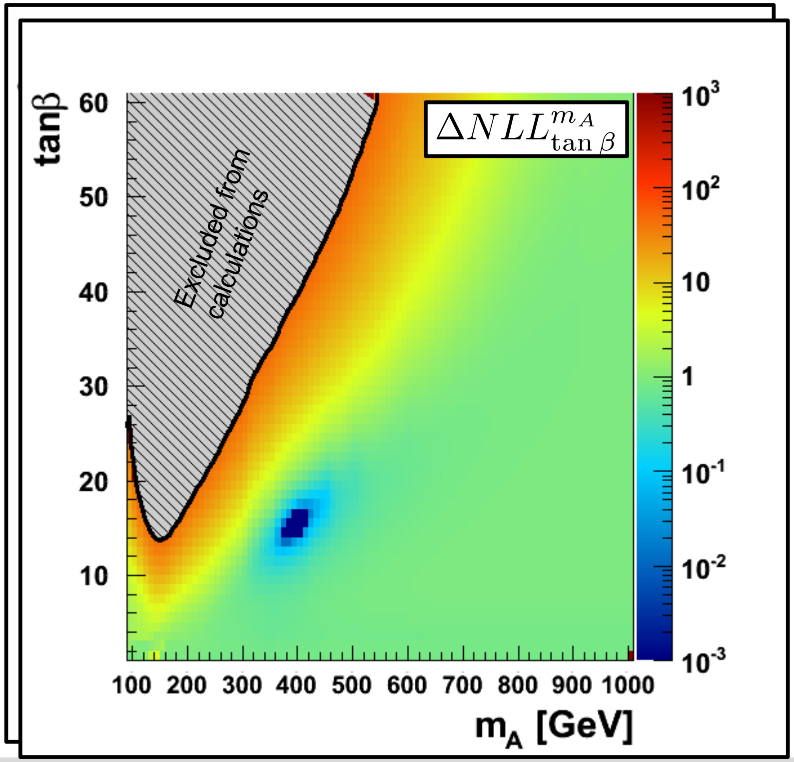
$$m_h^{mod+} \quad m_A = 400\ \text{GeV} \quad \tan\beta = 15$$

- Investigate behavior of signal templates & likelihood.



Direct limit



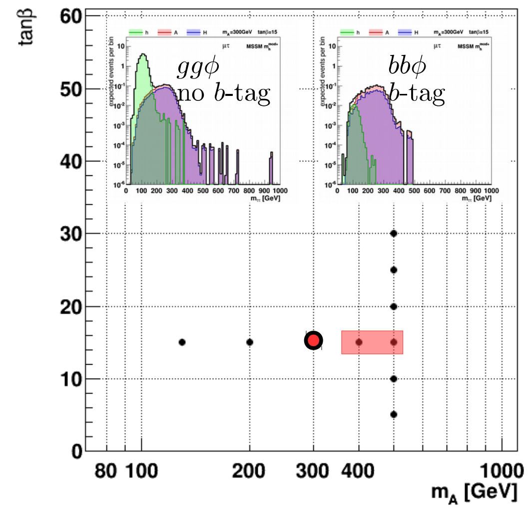


Walk across $(m_A, \tan\beta)$ plane

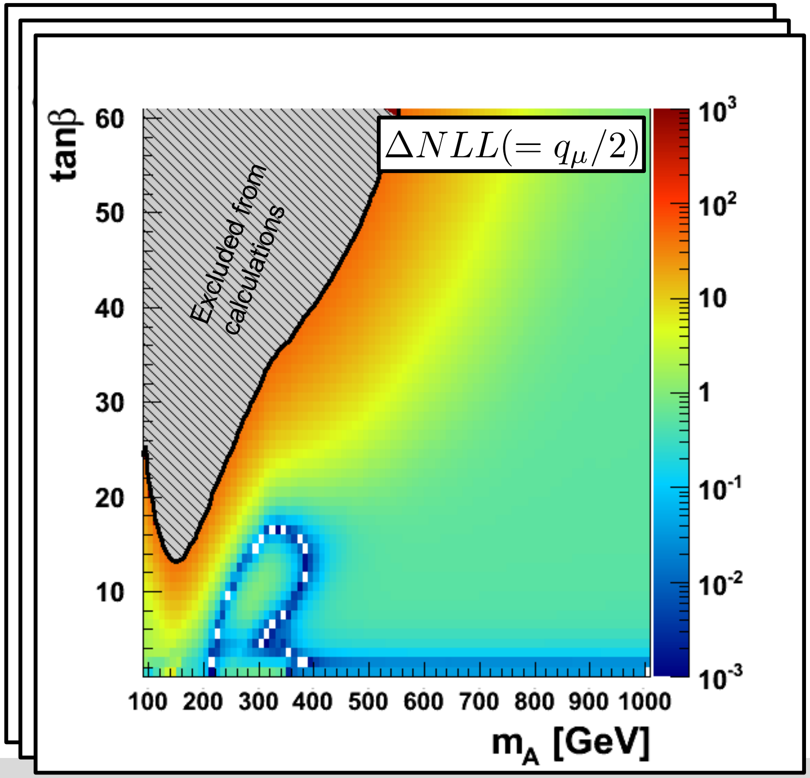
- Inject signal for decreasing values of m_A :

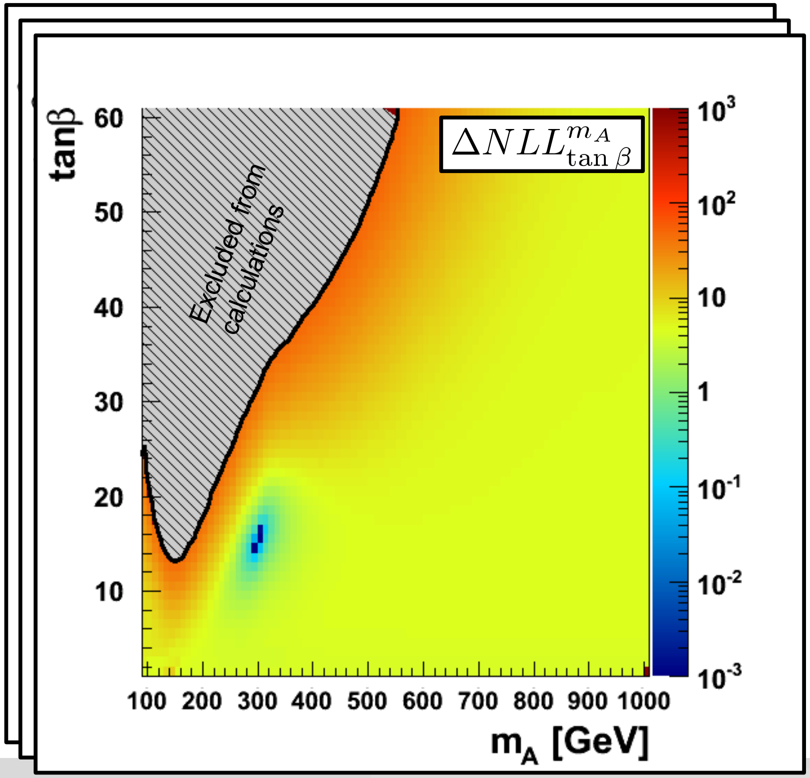
$$m_h^{mod+} \quad m_A = 300\ \text{GeV} \quad \tan\beta = 15$$

- Investigate behavior of signal templates & likelihood.

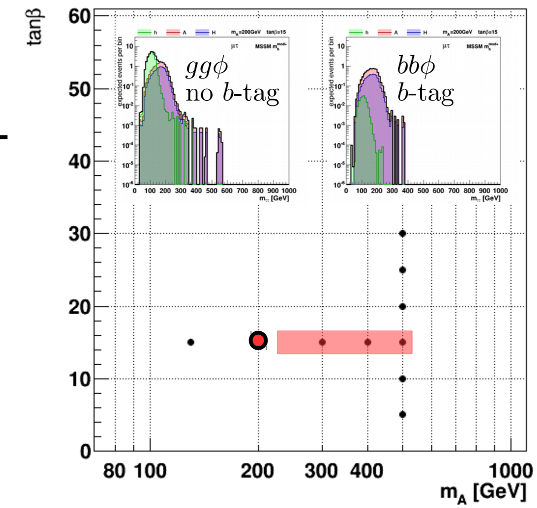


Direct limit





Walk across $(m_A, \tan\beta)$ plane

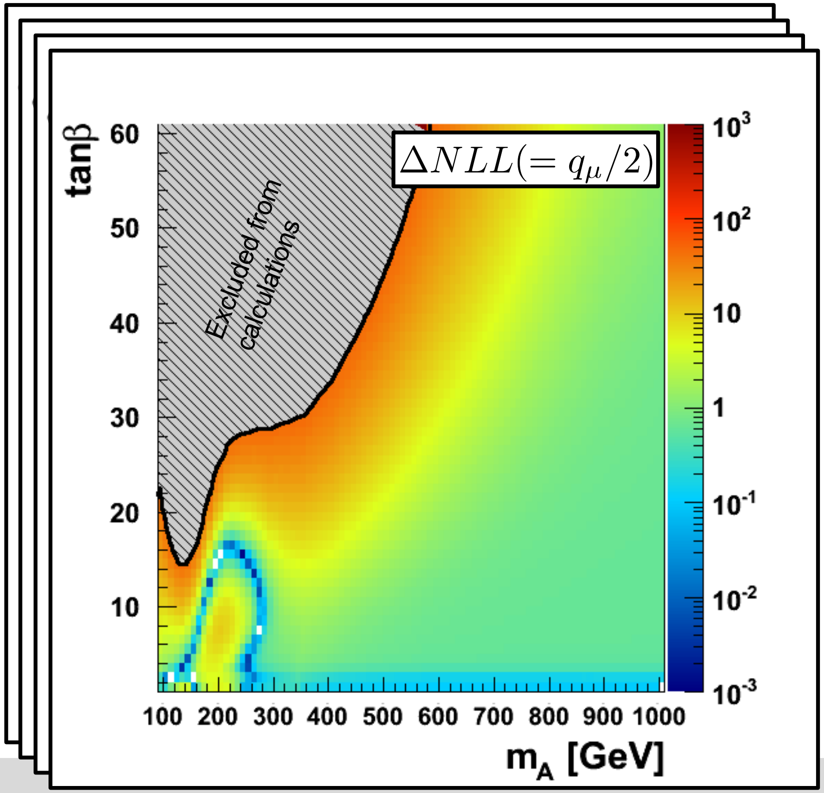


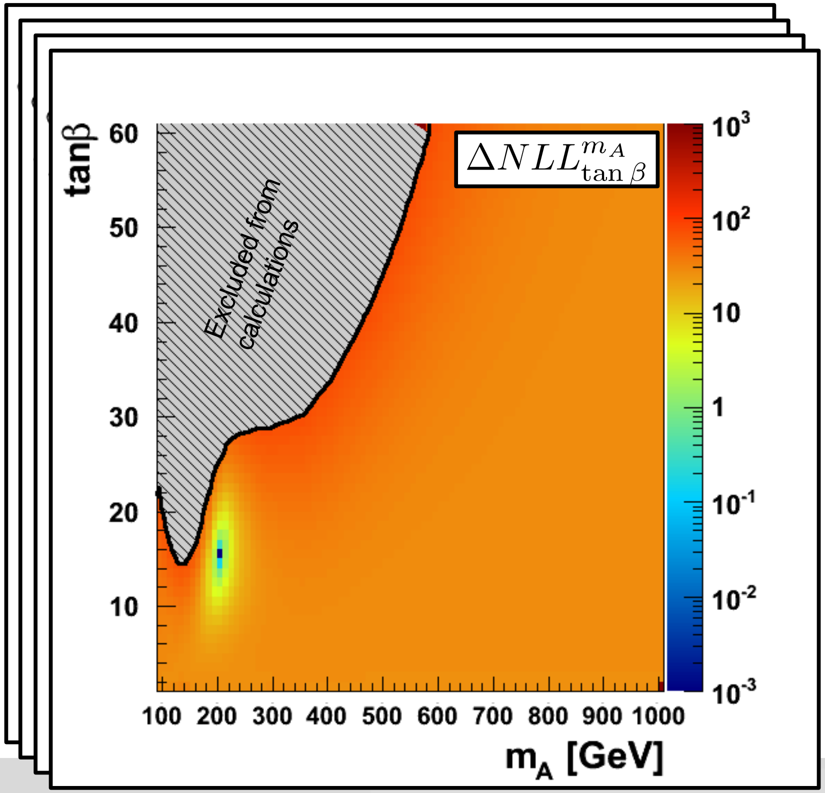
Direct limit

- Inject signal for decreasing values of m_A :

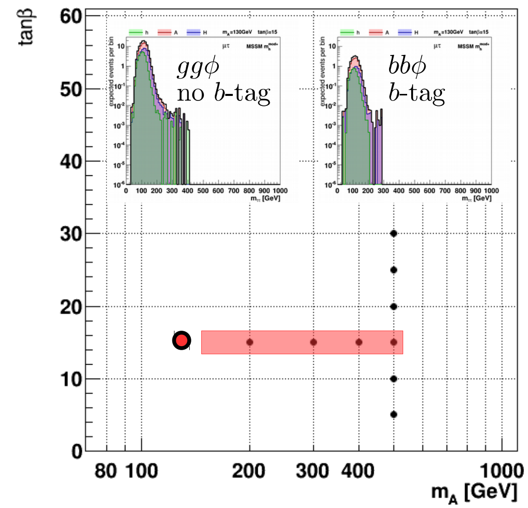
m_h^{mod+}	$m_A = 200$ GeV	$\tan\beta = 15$

- Investigate behavior of signal templates & likelihood.





Walk across $(m_A, \tan\beta)$ plane

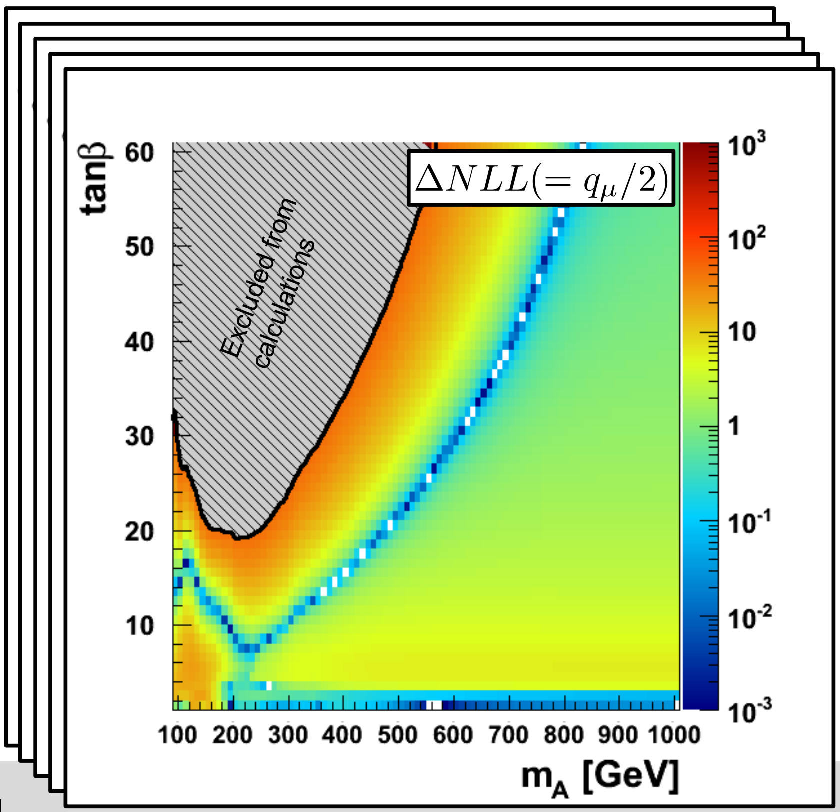


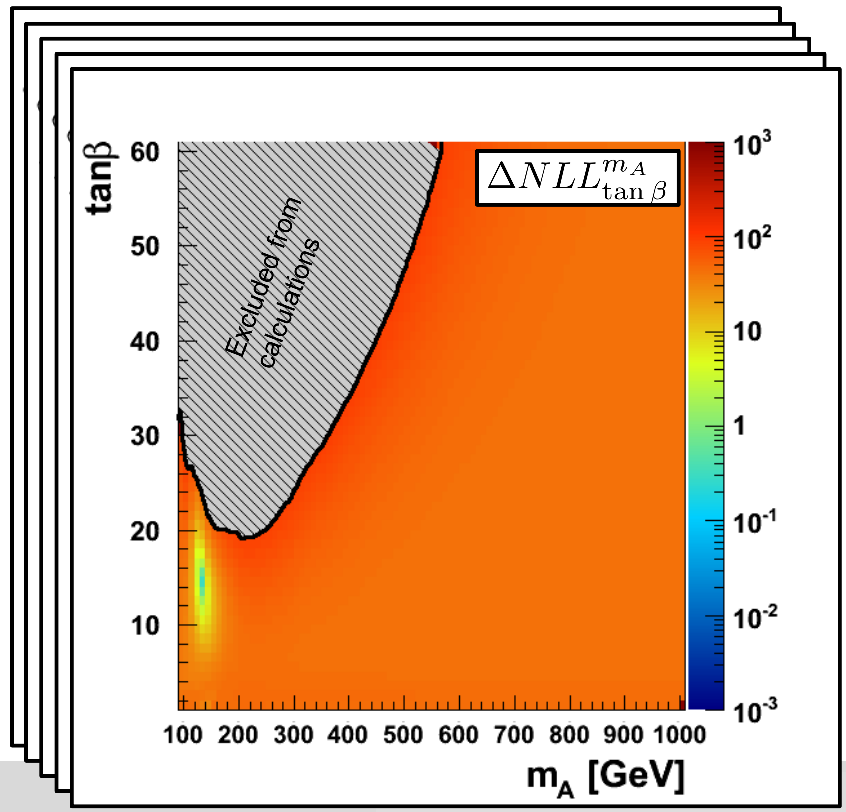
Direct limit

- Inject signal for decreasing values of m_A :

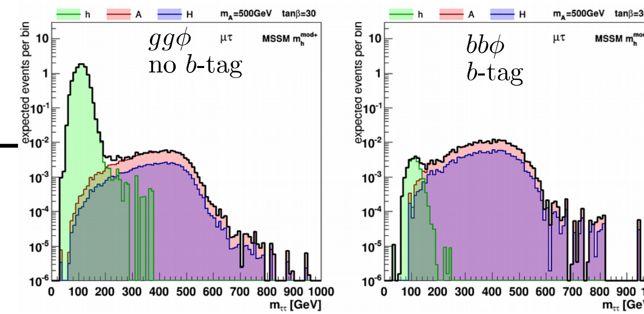
$$m_h^{mod+} \quad m_A = 130\ \text{GeV} \quad \tan\beta = 15$$

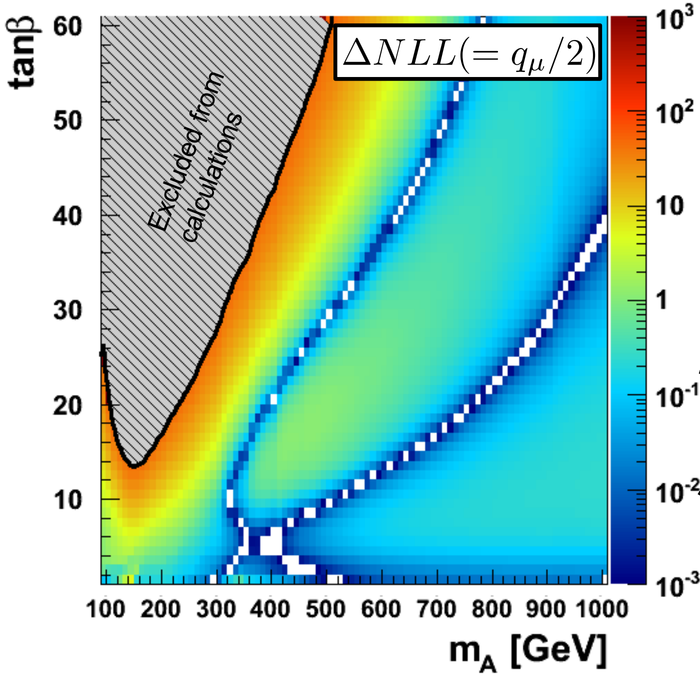
- Investigate behavior of signal templates & likelihood.



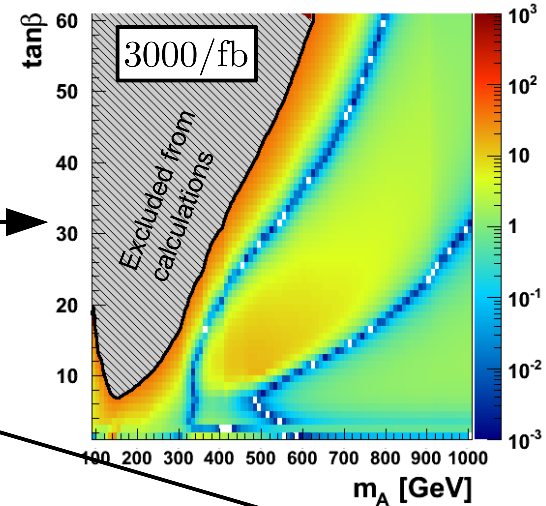


Investigating the structure of ΔNLL



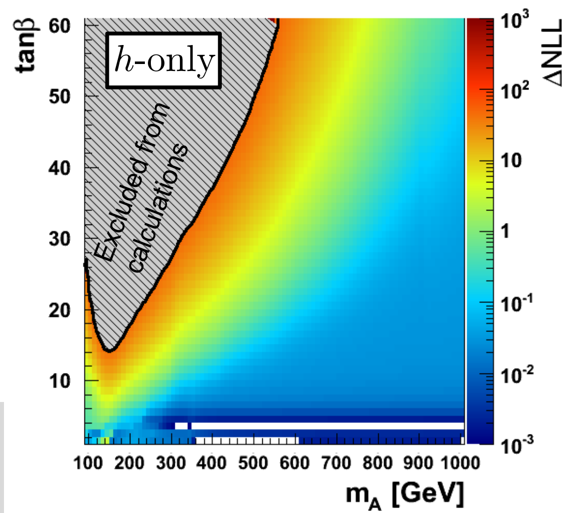


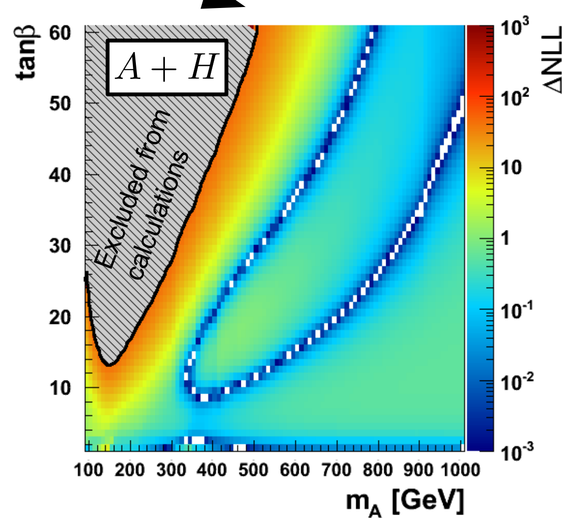
Increase target luminosity from 30/fb to 3000/fb.



Direct limit

Contributions of individual signal components to signature.

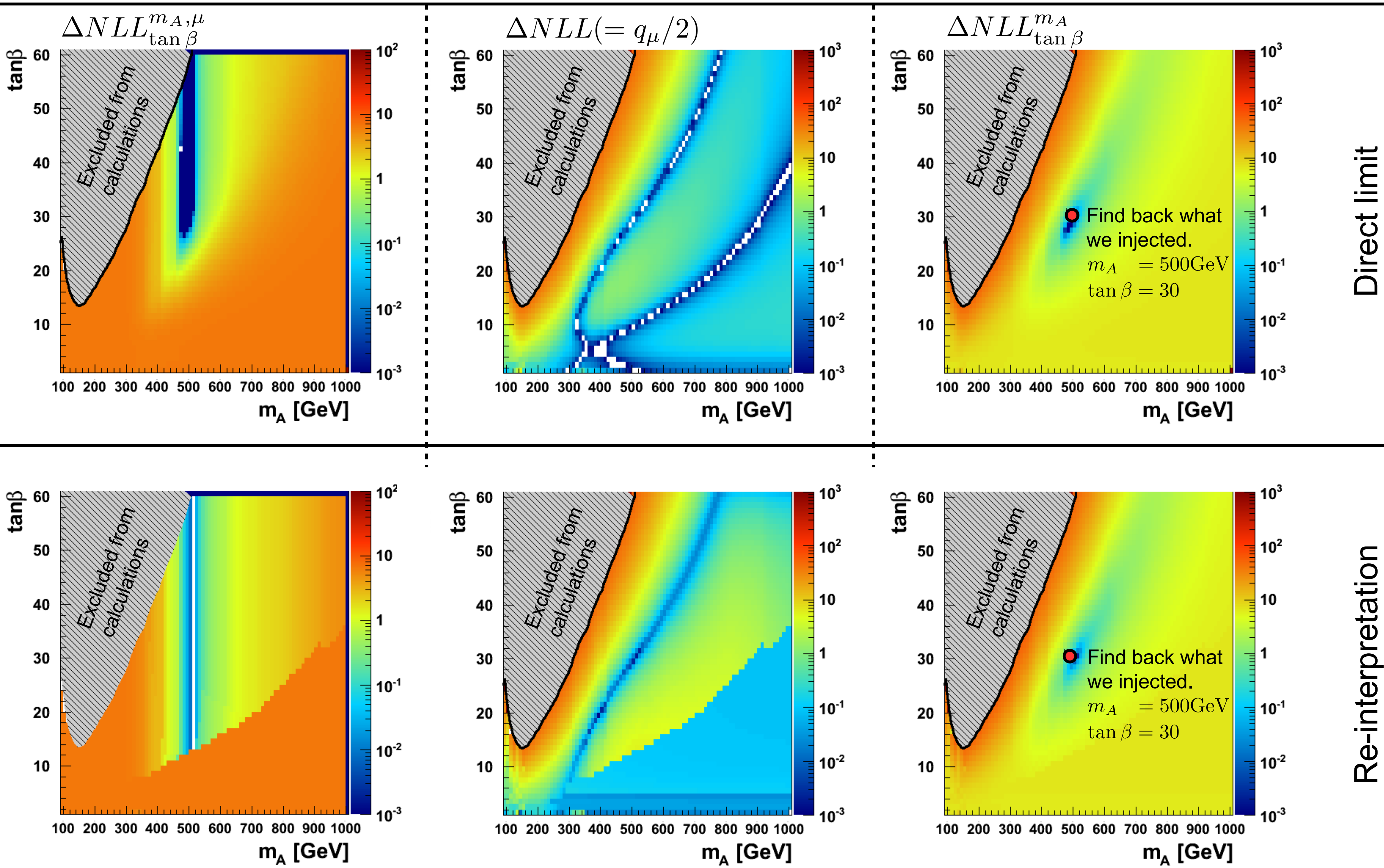




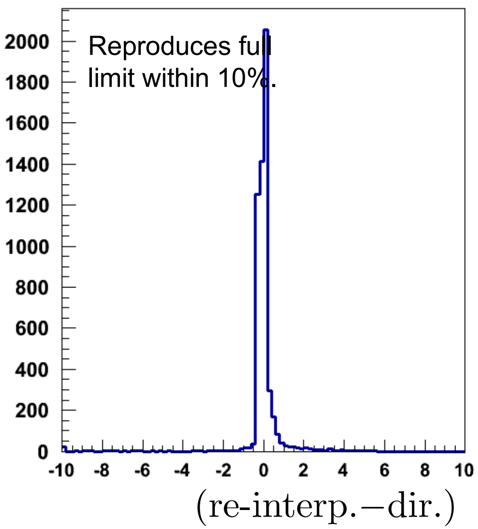
Pseudo-dataset:

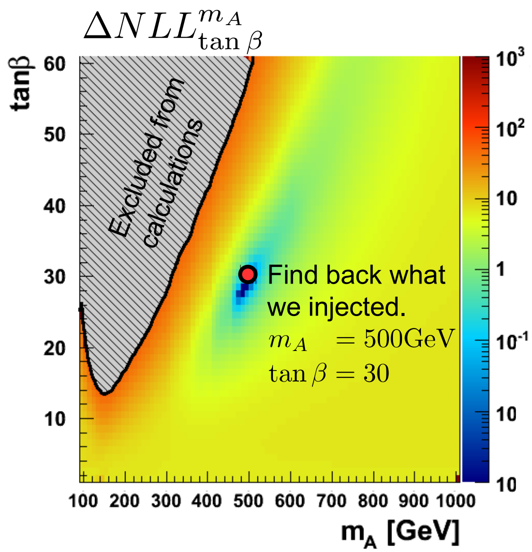
BG + m_h^{mod+} $m_A = 500, \tan\beta = 30$

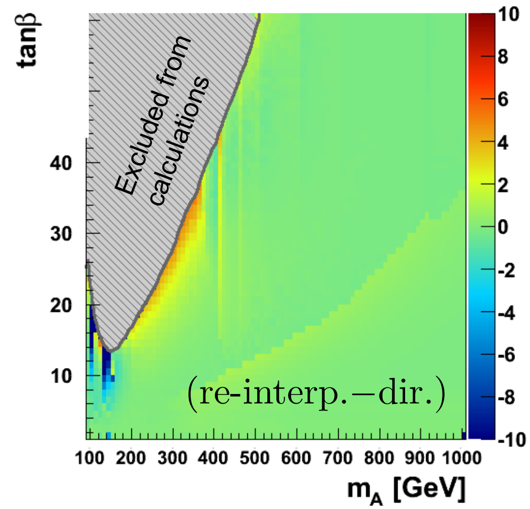
Method comparison

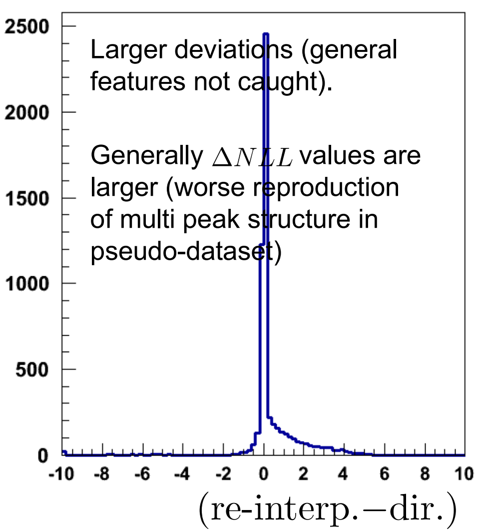


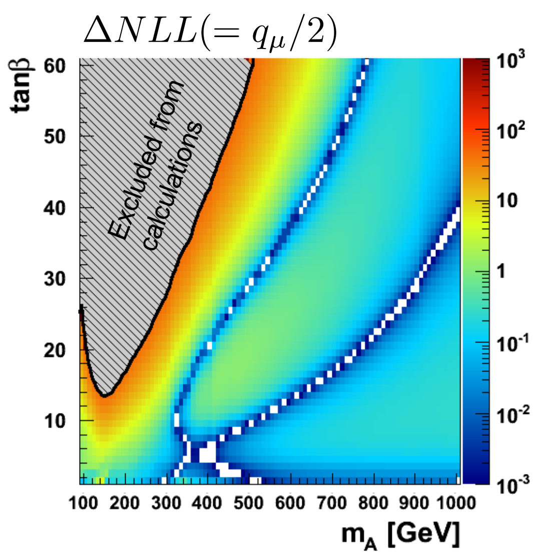
Method comparison (more quantitative)

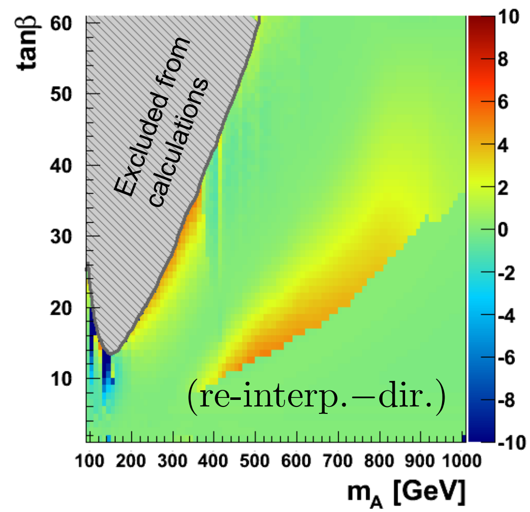




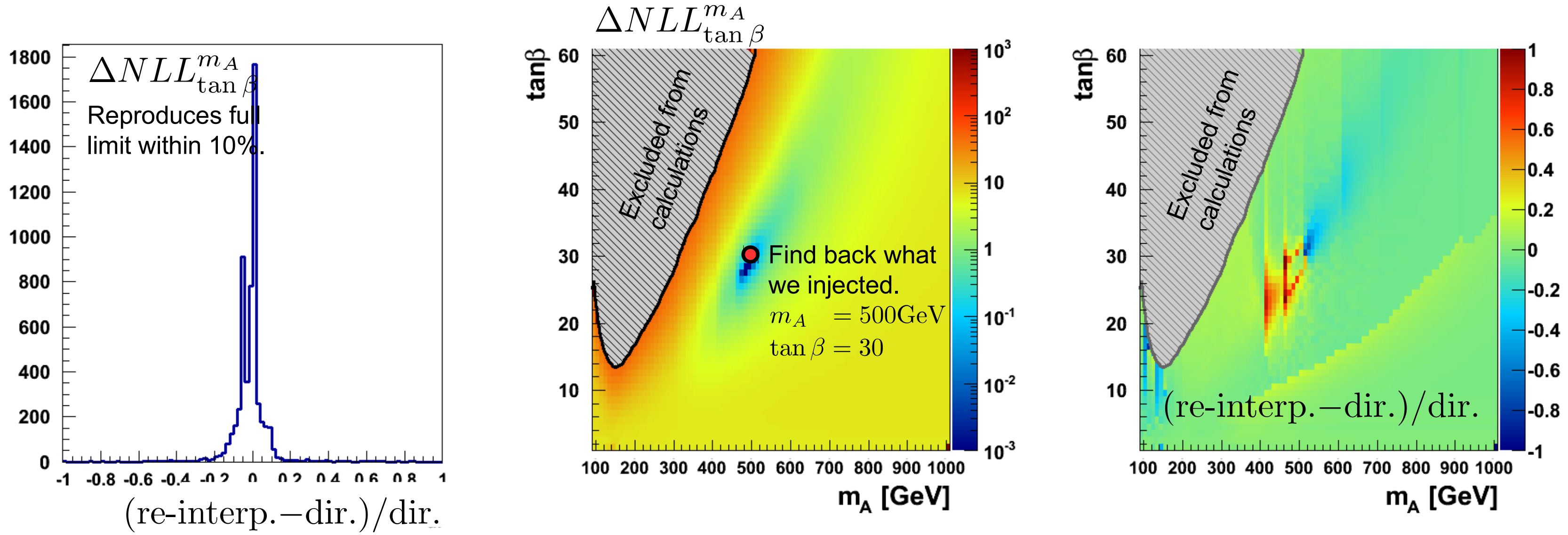




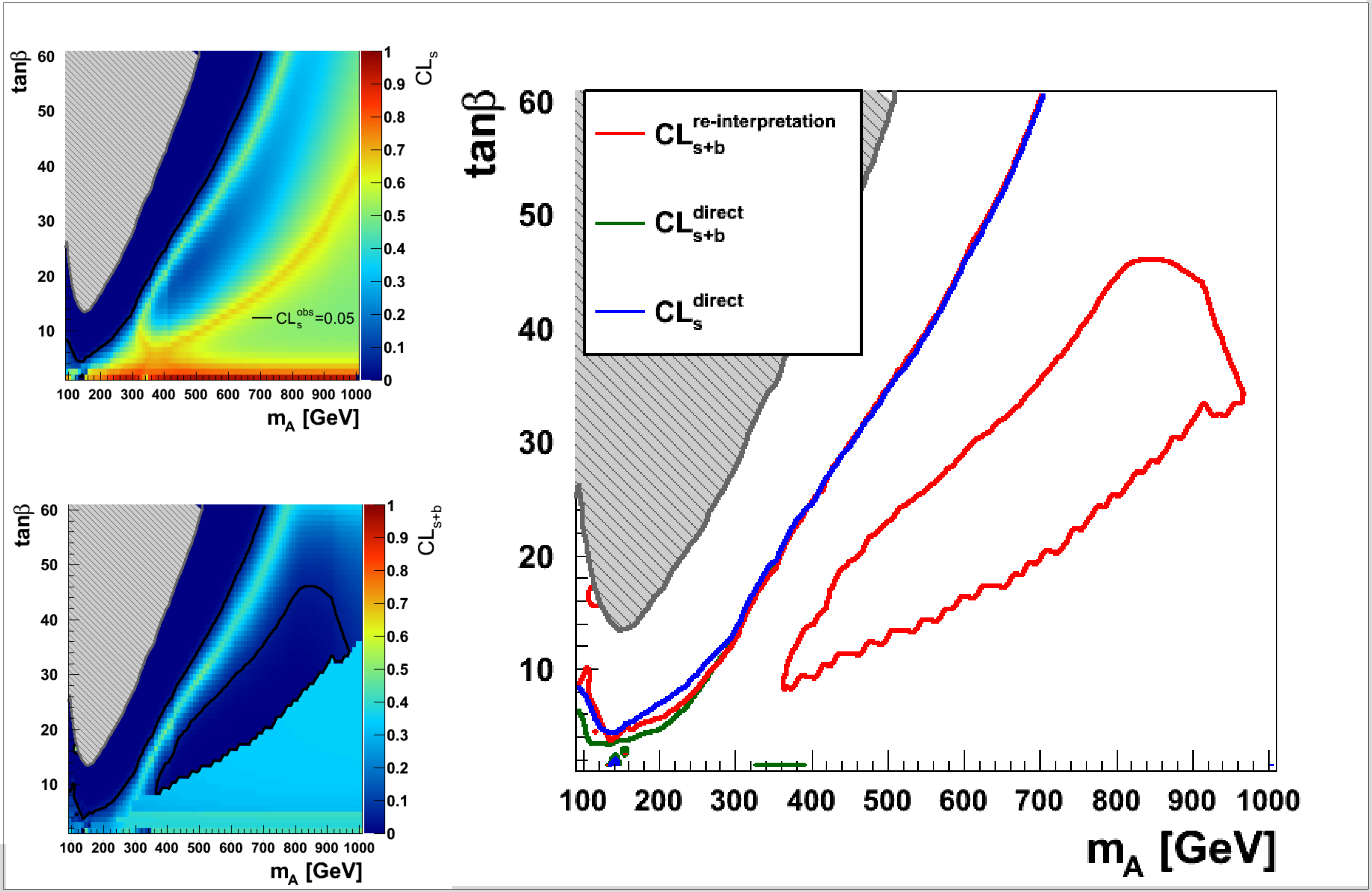




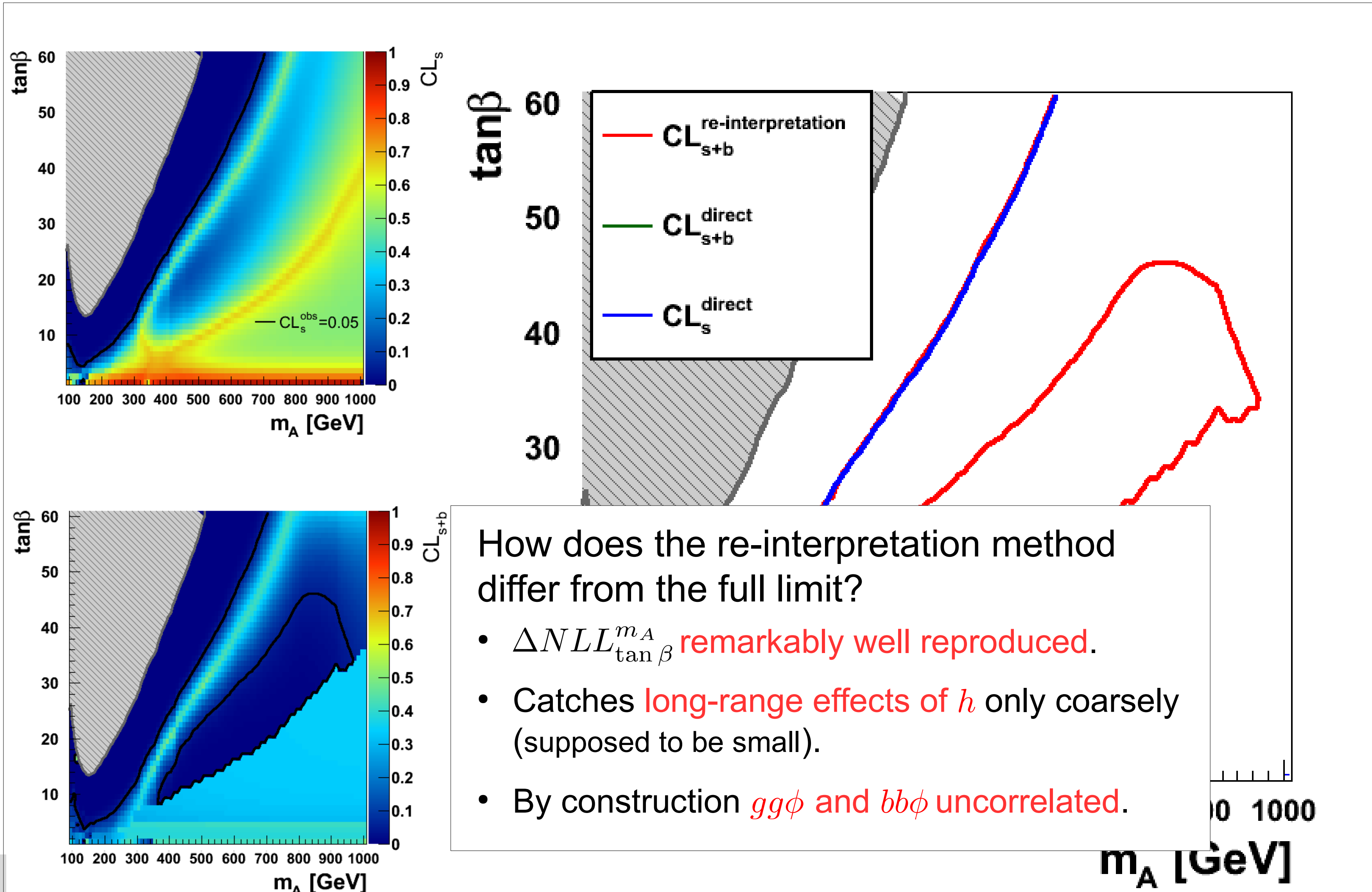
Method comparison (more quantitative)



Method comparison (exclusion contour)



Method comparison (exclusion contour)



How does the re-interpretation method differ from the full limit?

- $\Delta NLL^{m_A}_{\tan\beta}$ remarkably well reproduced.
- Catches long-range effects of h only coarsely (supposed to be small).
- By construction $gg\phi$ and $bb\phi$ uncorrelated.

Conclusions

- Started thorough investigation of likelihood function approach generally used to set exclusion contours in neutral MSSM Higgs Boson searches.

- Genuine MSSM signal would give notice in form of non-trivial exclusion contours "ahead of discovery" (reveal information about exact model parameters already).

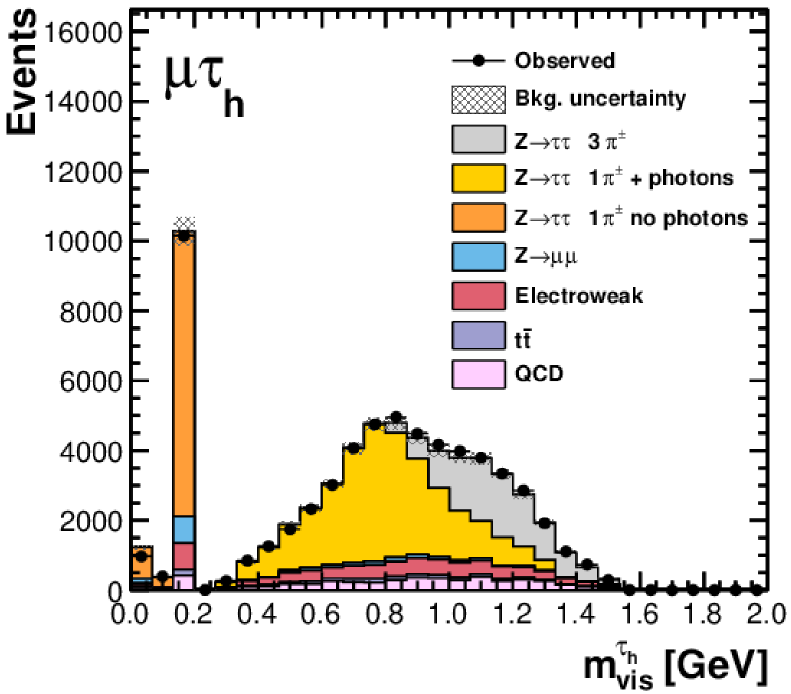
- CMS has provided a large DB of likelihood values of a model independent search, which allows re-interpretation in form of full pledged models.

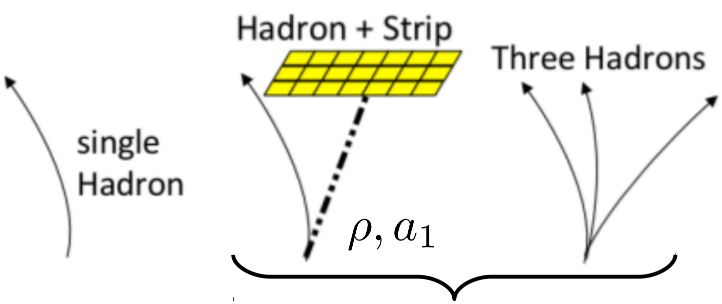
- The similarities and differences of both interpretation methods have been investigated.
  - Long-range correlations of $A+H+h$.
  - CL_S versus CL_{S+B}.
  - Correlated cross section between $gg\phi$ and $bb\phi$.

- Big playground to increase our general understanding!

Backup

Reconstruction of hadronic τ-leptons

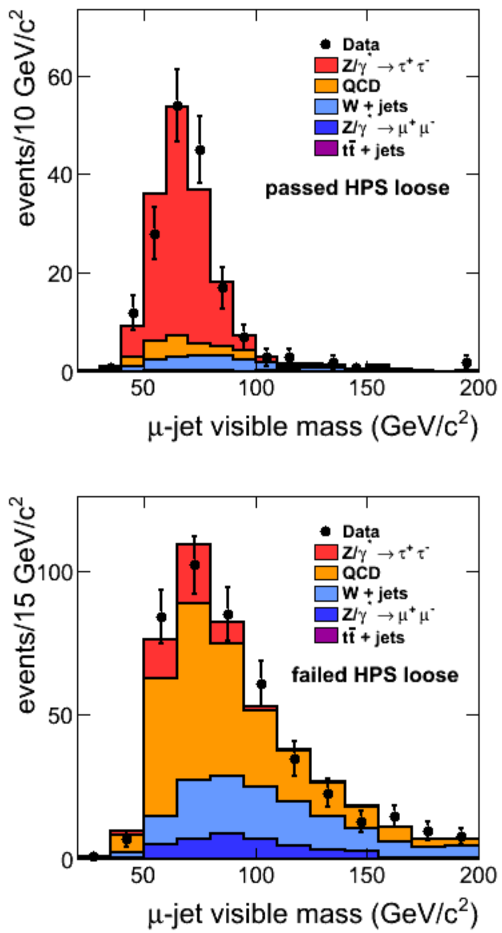




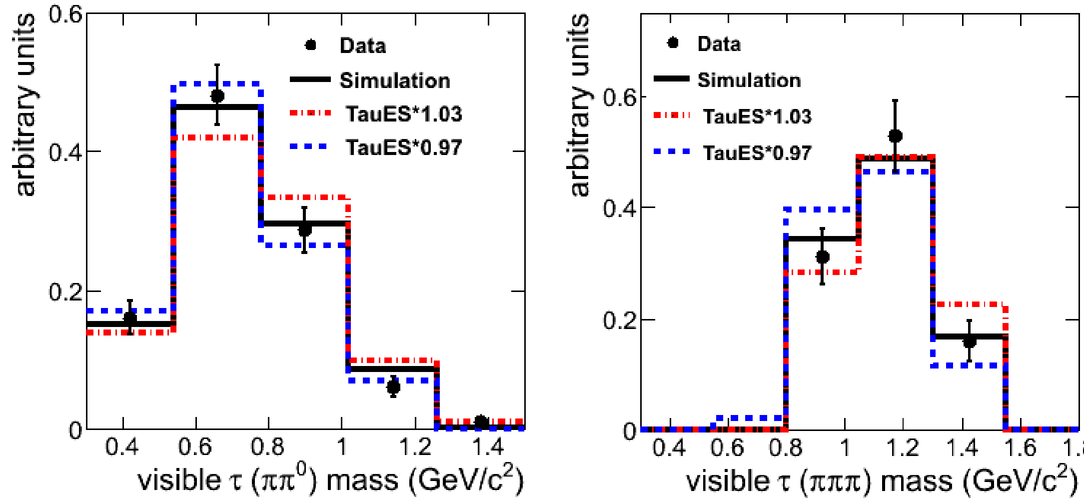
- Exploit particle flow algorithm: distinguish between γ, neutral and charged hadron .
  - Isolation (based on energy deposits in vicinity of reconstructed τ_h candidate).
  - Discrimination against electrons (based on shower shape & E/p).
  - Discrimination against muons.
  - Allows for independent cross check of τ_h energy calibration (use 3% uncert.).
  - Efficiency $\approx 60\%$ ($\approx 3\%$ fakerate), flat as function of $p_T(\tau_h)$ and $N(vtx)$.

Performance of Hadronic τ Reconstruction

- Control efficiency within $\pm 7\%$ using tag & probe methods:



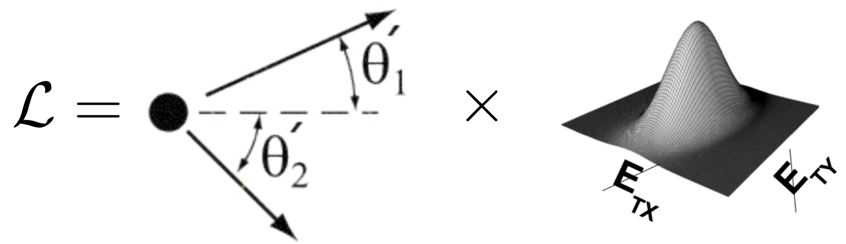
- Control τ_h energy scale within $\pm 3\%$ from fits to $m_{\tau,\mathrm{vis}}$:



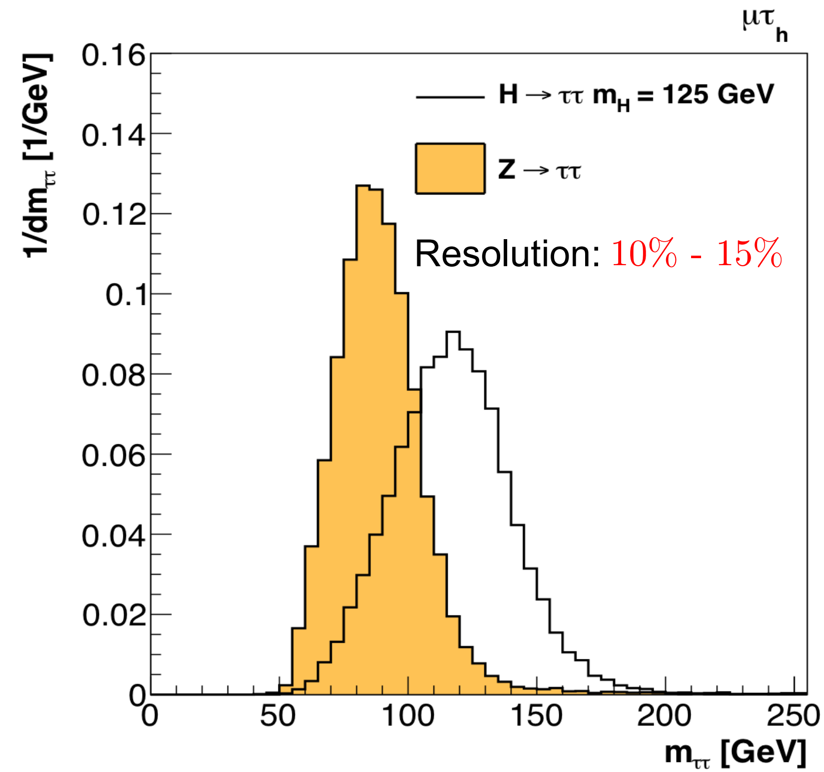
- Uncertainties further constrained by maximum likelihood fit in the statistical inference for signal extraction.

Reconstruction of $m_{\tau\tau}$

- Likelihood approach:



- ME for leptonic τ decay or phase space kinematics of 2-body decay of τ_h .
- Estimate of expected $\not{E}_T$ resolution on event by event basis.
- Inputs: visible decay products, x-, y-component of $\not{E}_T$.
- Free parameters: φ , θ^*, ($m_{\nu\nu}$) per τ.



- Find minimum of $\mathcal{L}$ for given $m_{\tau\tau}$ and scan over all possible values of $m_{\tau\tau}$ to find global minimum.

Control of backgrounds

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tt

- From simulation.
- Normalization from sideband.

$Z \to \tau\tau$

- Embedding (in $Z \to \mu\mu$ replace μ by sim τ).
- Norm from $Z \to \mu\mu$.

$Z \to \ell\ell$

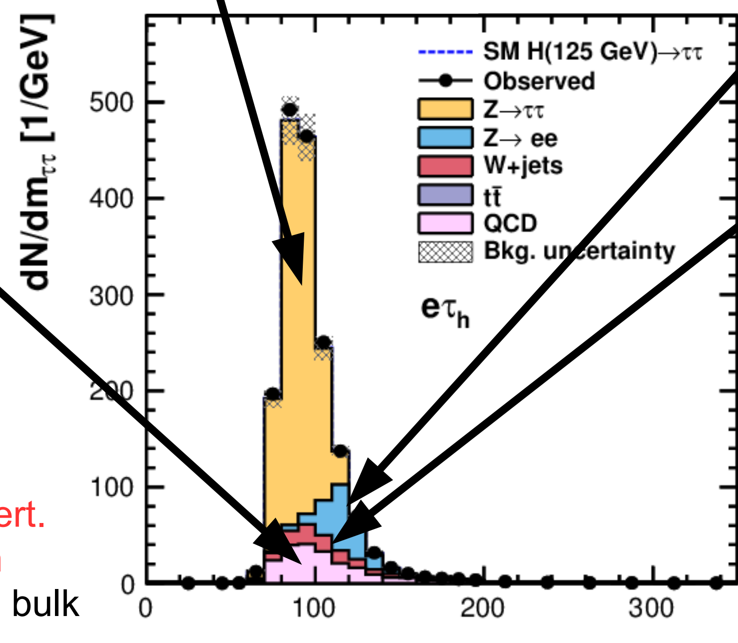
- From simulation
- Corrected for $jet \to \tau$ or $e/\mu \to \tau$ fakerate.

QCD multijet

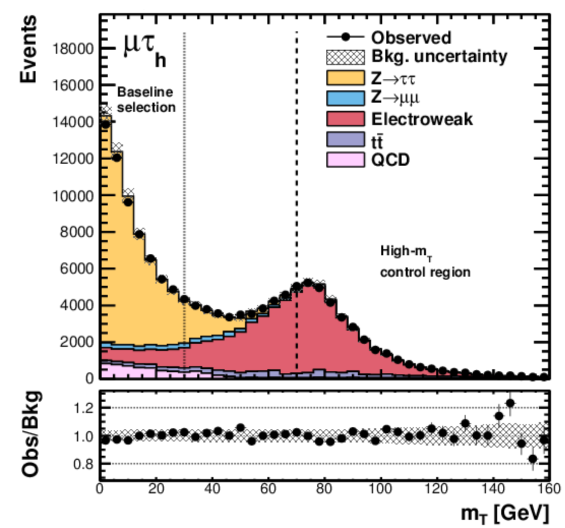
- Normalization & shape taken from LS/OS or fakerate.

$W + jets$, Diboson

- From simulation
- Normalization from sidebands.



Taken from arXiv:1401.5041

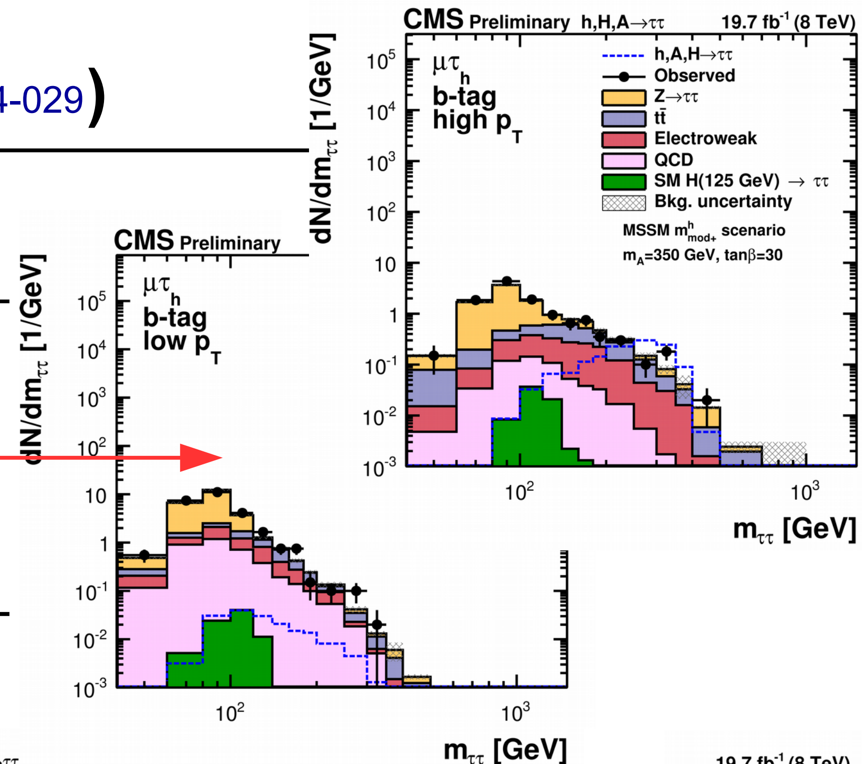


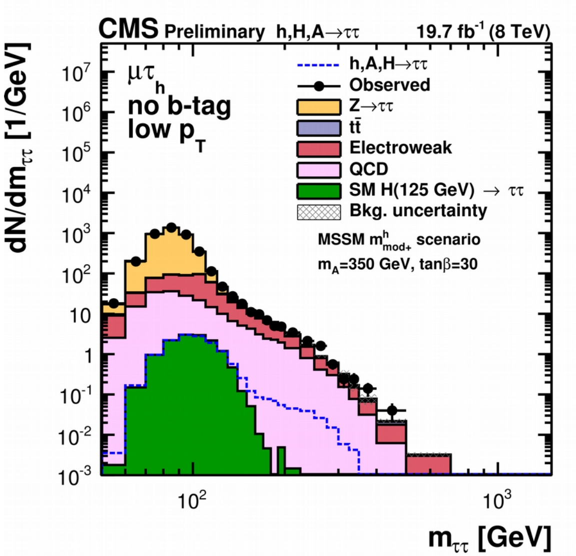
- Full consideration of uncert. due to limited statistics in control or MC samples in bulk of distributions.

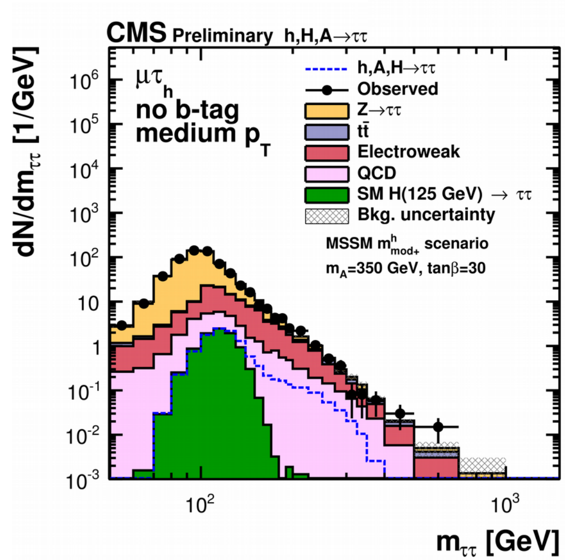
 arXiv:1408.3316

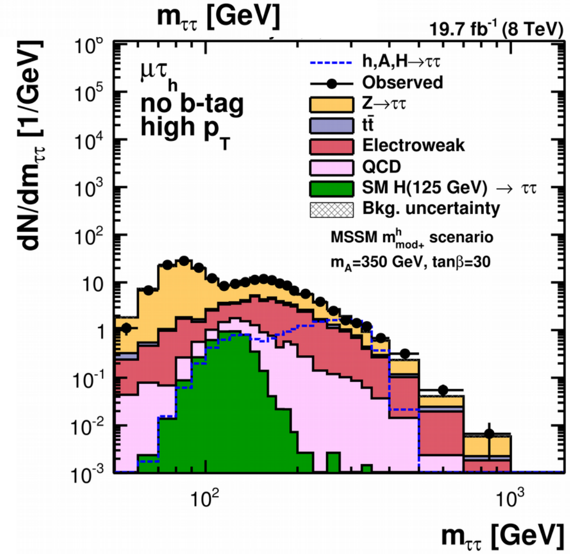
$H \to \tau\tau$: results (CMS, CMS-PAS-HIG-14-029)

	no b-tag			b-tag	
	(*) low	medium	high	low	high
$\mu\mu$		$m_{\tau\tau} \times m_{\mu\mu}$		$m_{\tau\tau} \times m_{\mu\mu}$	
$e\mu$		$m_{\tau\tau}$		$m_{\tau\tau}$	
$\mu\tau_h$	$m_{\tau\tau}$	$m_{\tau\tau}$	$m_{\tau\tau}$	$m_{\tau\tau}$	$m_{\tau\tau}$
$e\tau_h$	$m_{\tau\tau}$	$m_{\tau\tau}$	$m_{\tau\tau}$	$m_{\tau\tau}$	$m_{\tau\tau}$
$\tau_h\tau_h$	$m_{\tau\tau}$	$m_{\tau\tau}$	$m_{\tau\tau}$	$m_{\tau\tau}$	$m_{\tau\tau}$





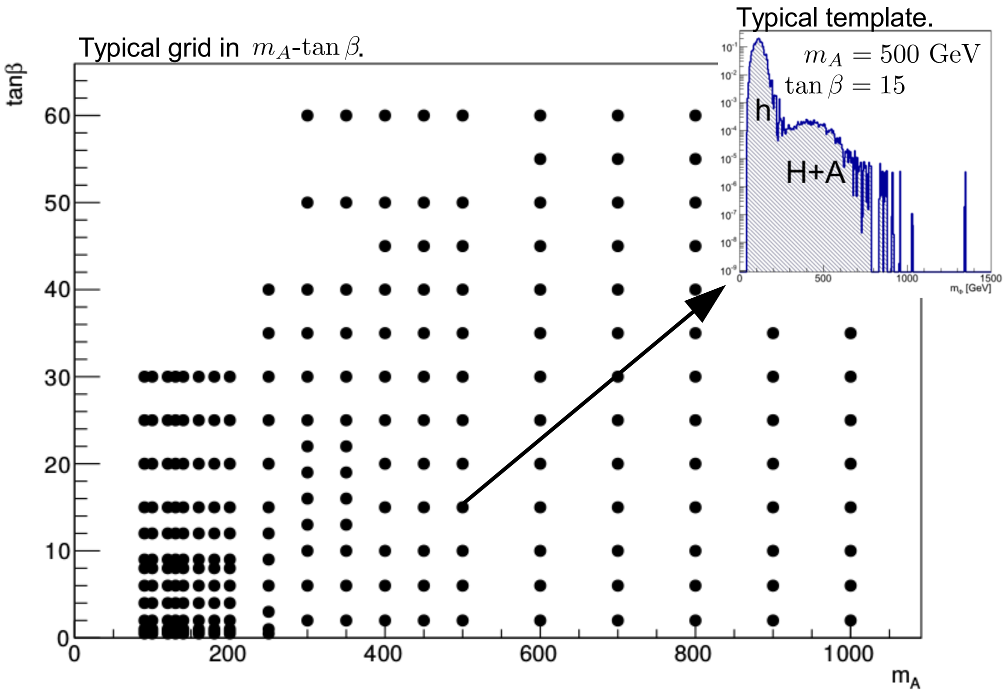




(*) categorization based on $p_T(\tau_h), p_T(\ell_1)$.

Reprise of MSSM model dependent limit setting

- For fixed values in m_A and $\tan\beta$ build templates composed of $h+H+A$ according to model:



- With this template perform fit to data with single signal strength modifier μ.

$$q_\mu = -2\ln\left(\frac{\mathcal{L}(\mu,\hat{\theta}_\mu)}{\mathcal{L}(\hat{\mu},\hat{\theta})}\right)\Bigg|_{\mu\cdot s+b}$$

NB: $\mu = 1$ hits the proper model for given m_A-$\tan\beta$.

- Do the same with a BG-only template:

$$q_A = -2\ln\left(\frac{\mathcal{L}(\mu,\hat{\theta}_\mu)}{\mathcal{L}(\hat{\mu},\hat{\theta})}\right)\Bigg|_{b\text{-only}}$$

- Calculate (asymptotic) CL_s value:

$$CL_s = \frac{1-\Phi(\sqrt{q_\mu})}{\Phi(\sqrt{q_A}-\sqrt{q_\mu})}$$

- For the 95% CL exclusion contour: for fixed value of m_A find value of $\tan\beta$ with $CL_s(\mu=1)=0.05$.

LH construction as used by HiggsBounds

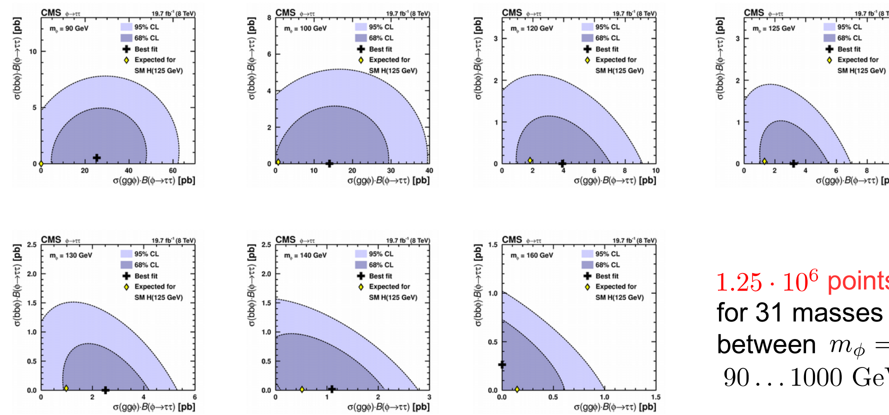
- Cluster Higgs bosons if they are close to each other, i.e:

$$d_{ij} = \frac{|m_i - m_j|}{\max(m_i, m_j)} < 0.2$$ [8]

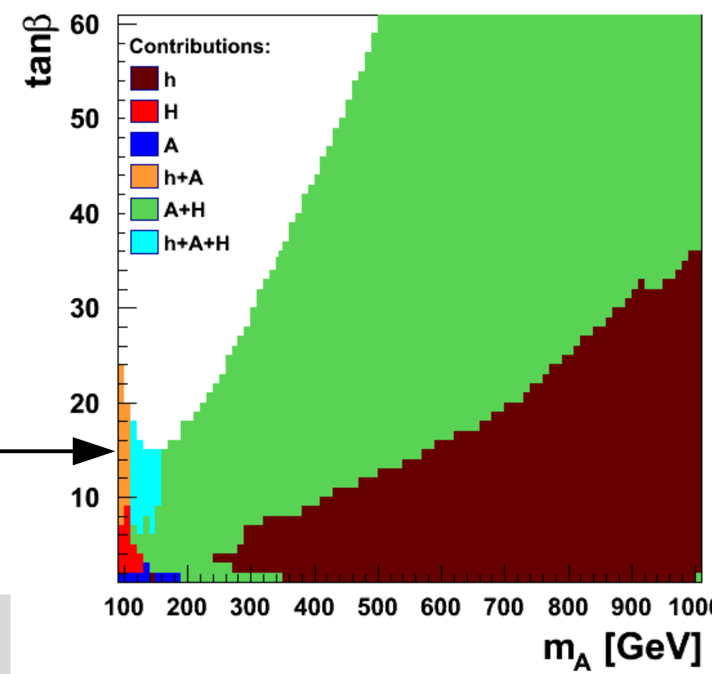
- Cluster obtains a mass of $\sigma_k \times BR_k$[9] weighted mean of m_i and m_j and a cross section of $\sum \sigma_k \times BR_k$, according to model and point in m_A and $\tan\beta$.

- Determine cluster with highest expected sensitivity (i.e. largest value of ΔNLL_{exp} from DB based on BG-only Asimov dataset).

- Read off observed value of ΔNLL_{obs} for selected point of $(m_A, \tan\beta)$ from DB.



$1.25 \cdot 10^6$ points for 31 masses between $m_\phi = 90 \ldots 1000$ GeV.



[8] given by experimental $m_{\tau\tau}$ resolution. [9] $k = i, j$.