Higgs physics in di-τ final states with CMS

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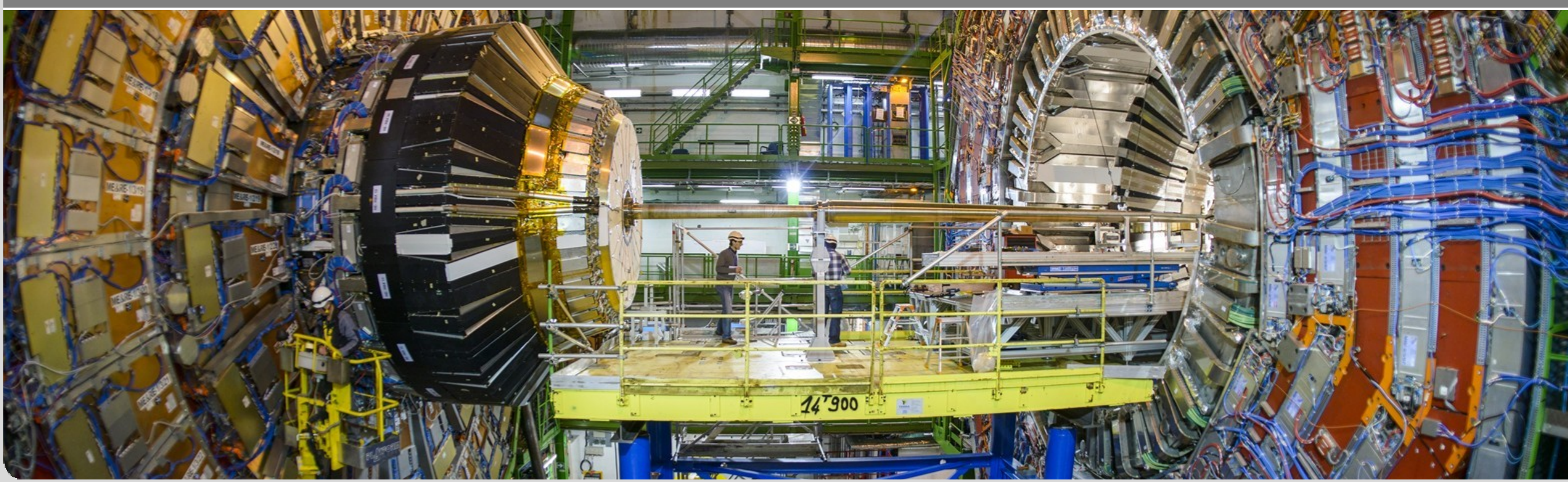
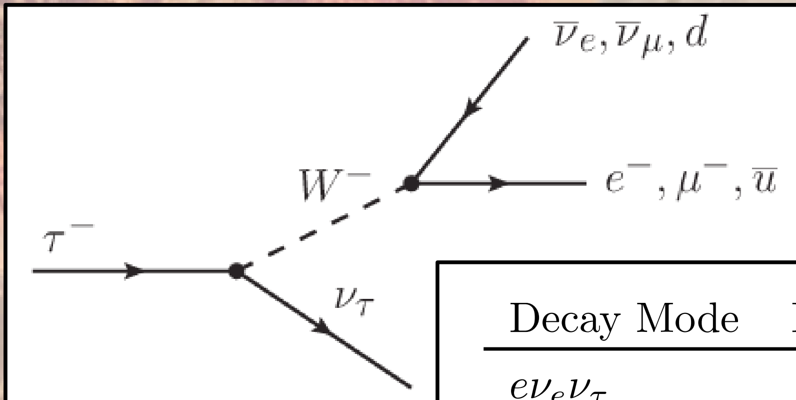
INSTITUTE OF EXPERIMENTAL PARTICLE PHYSICS (IEKP) – PHYSICS FACULTY

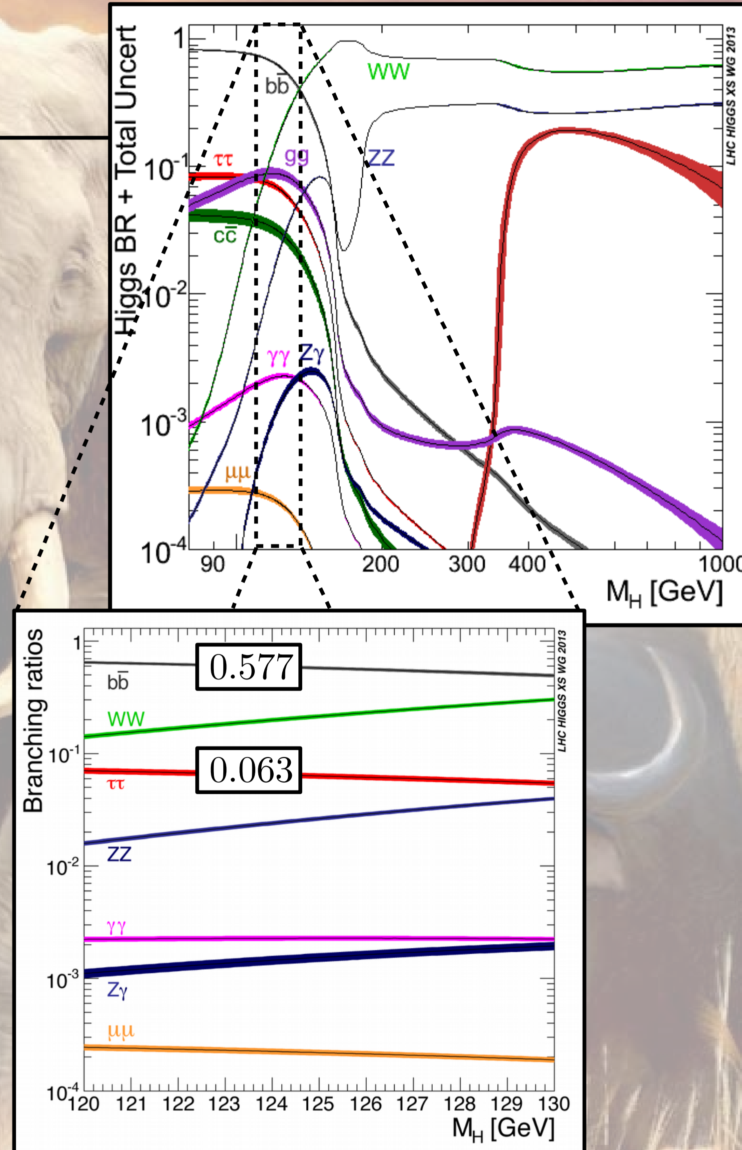


τ-leptons & LHC Higgs physics

- With 1.77 GeV the **heaviest known lepton**.



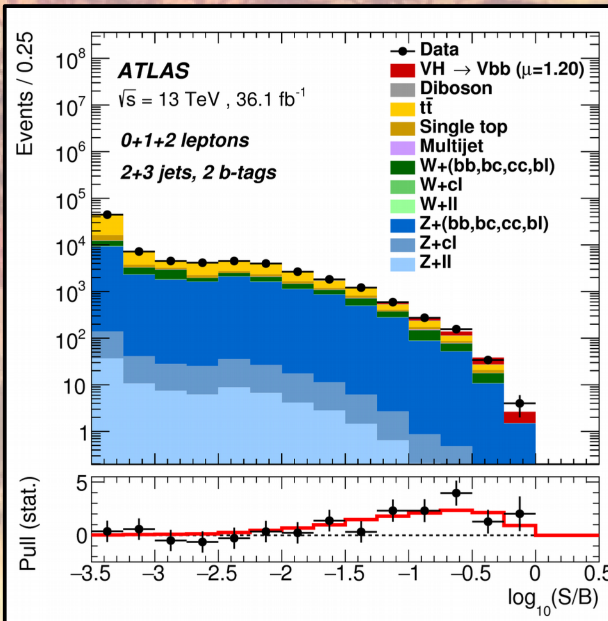
Decay Mode	BR [%]
$e\nu_e\nu_\tau$	17.83
$\mu\nu_\mu\nu_\tau$	17.41
1-prong ν_τ	37.10
3-prong ν_τ	15.20



- One of the **big five** in the investigation of the Higgs sector @ low mass.

	Channel	Resolution	S/B
$\kappa_{HVV} = \frac{2m_V^2}{v}$	$H \to \gamma\gamma$	1-2%	$\mathcal{O}(0.1)$
	$H \to ZZ$	1-2%	$\mathcal{O}(> 1)$
	$H \to WW$	20%	$\mathcal{O}(1)$
$\kappa_{Hff} = \frac{m_f}{v}$	$H \to b\bar{b}$	10%	$\mathcal{O}(0.1)$
	$H \to \tau\tau$	15%	$\mathcal{O}(0.1)$

τ-leptons & LHC Higgs physics



arxiv:1708.03299

36/fb @ 13 TeV highly sophisticated analysis leads to $3.6\,\sigma$ **evidence.**

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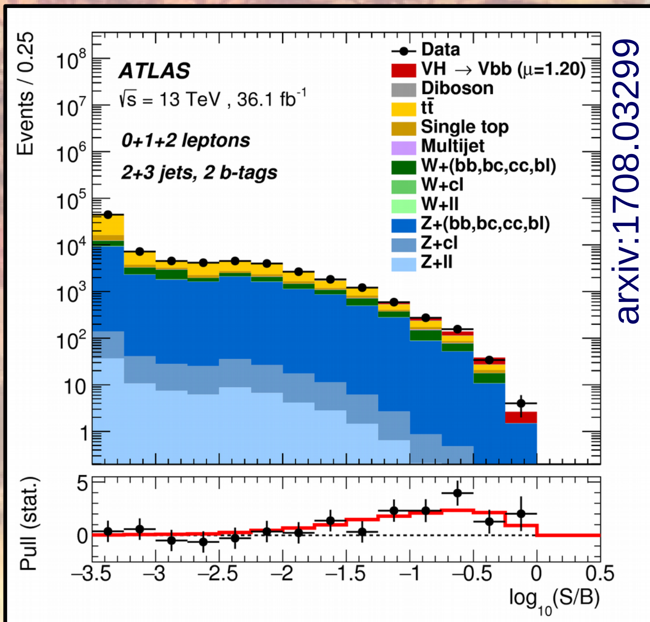

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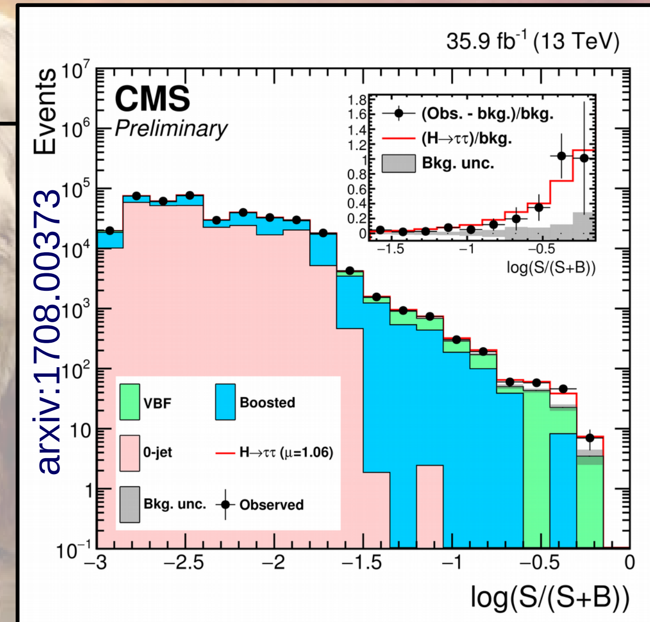

36/fb @ 13 TeV highly sophisticated analysis leads to $4.9\,\sigma$ **discovery.**

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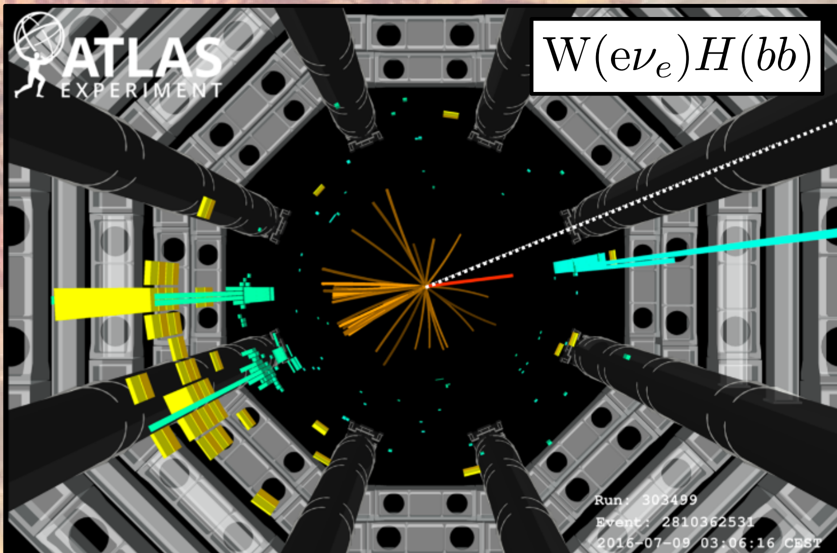
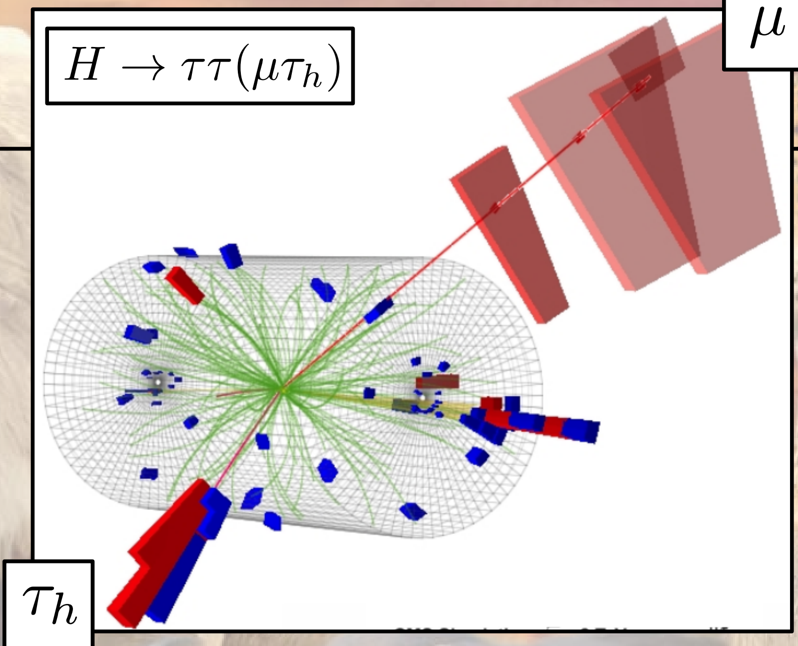
τ-leptons & LHC Higgs physics



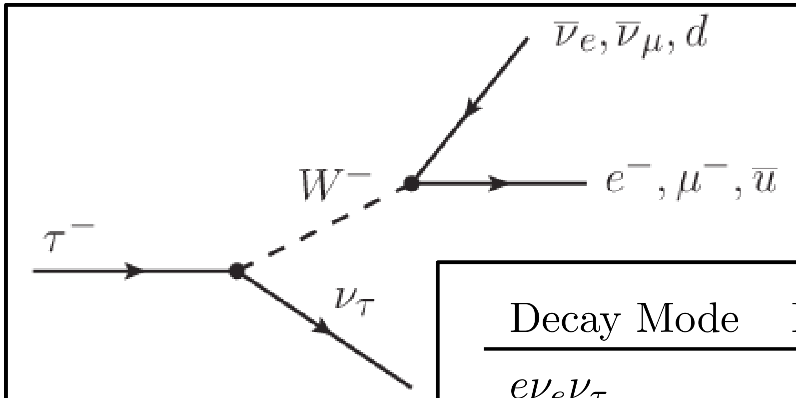
- Difficult to identify b quark initiated jets with high purity.
- b quark production in QCD quite common in hadron collider.
- Identify signal in presence of **overwhelming background**.
- Reduce **event rate** during data taking.



- Difficult to identify hadronic τ-decay with high purity (→ see next slides).
- Background that is most difficult to separate: $Z \to \tau\tau$ (→ well under control).
- Leptonic nature **easier to identify/ tag**.

Di-τ final state

- High mass allows for decays into hadrons:



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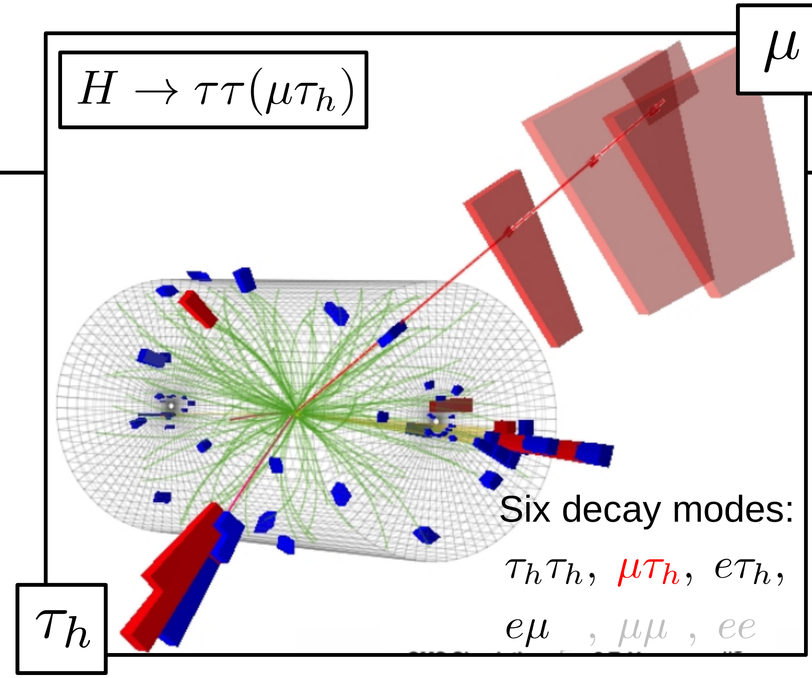

- Search for **2 isolated high** p_T **leptons** (e, μ, τ_h).
- Reduce obvious backgrounds ($\rightarrow \not{E}_T$).
- Reconstruct discriminating variable, related to di-τ final state: $\mathrm{m}_{\tau\tau}, m_{vis}, \mathrm{m}_{\mathrm{T}}^{\mathrm{tot}}, \mathrm{BDT}$.

Di-τ final state

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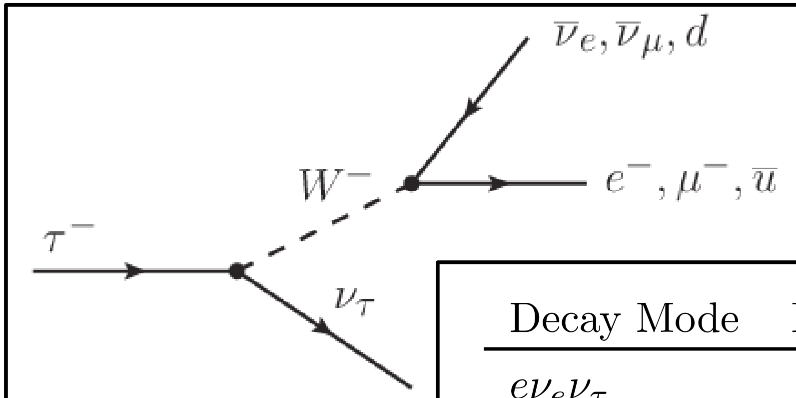

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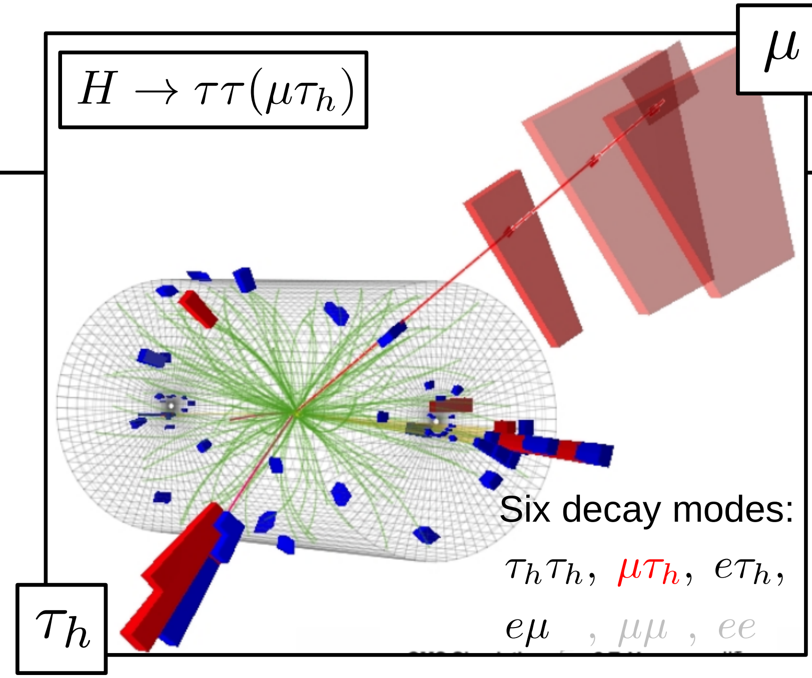
~90% of all di-τ final states contain at least one τ_h.



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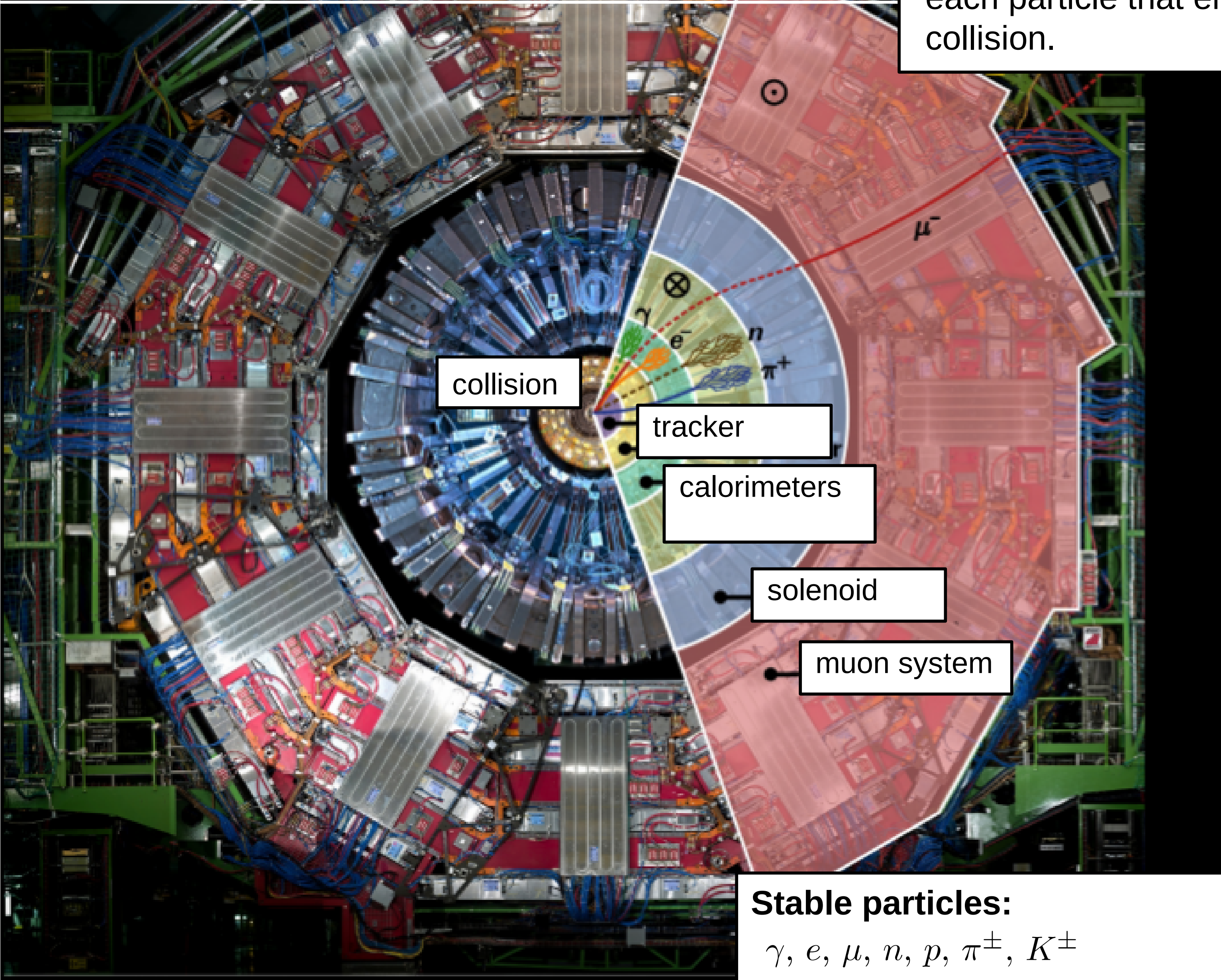
Reminder of CMS

What we want to know:

$\left(p_T \quad \eta \quad \phi \right)$ + particle type (m) from each particle that emerges the collision.

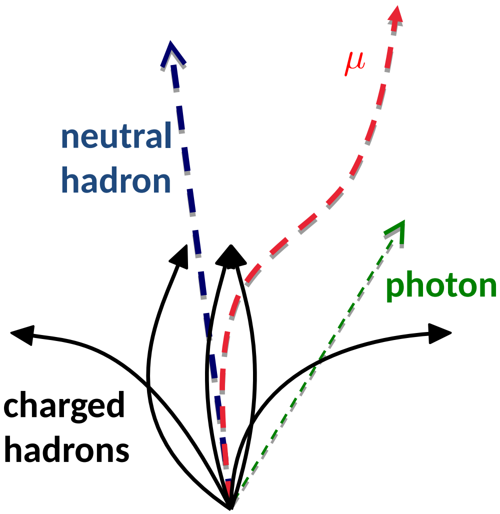


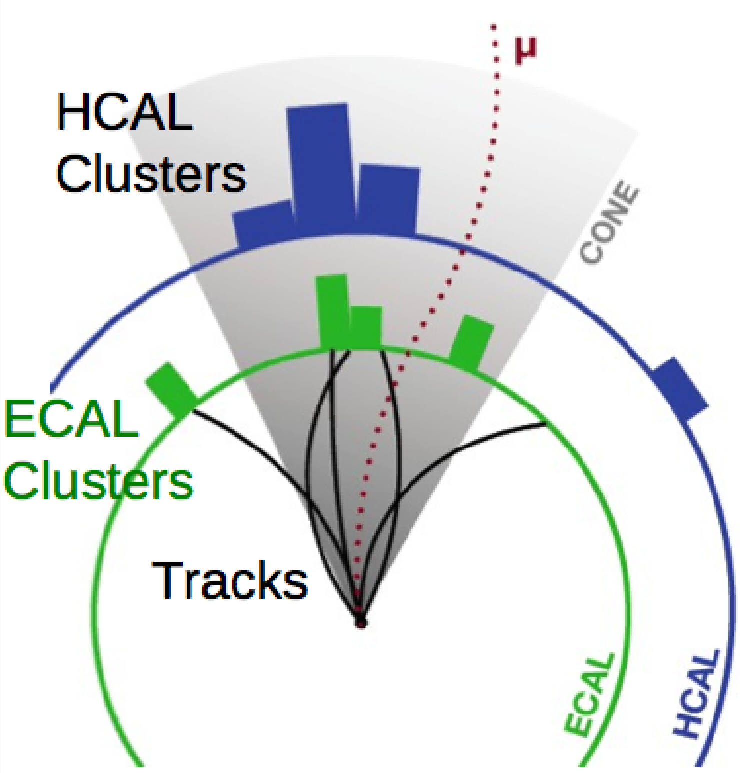
Stable particles:

$\gamma,\, e,\, \mu,\, n,\, p,\, \pi^{\pm},\, K^{\pm}$

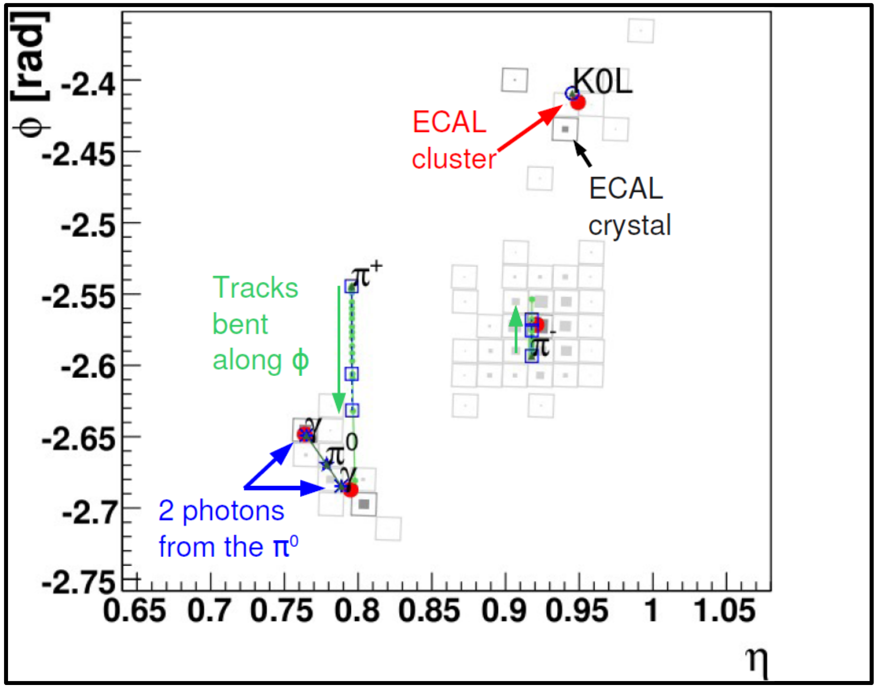
Particle reconstruction @ CMS

- **Combining all energy deposits** in the detector to obtain a unique event description.





arxiv:1706.04965



- Unambiguous list of stable particles: muons, electrons, photons, charged & neutral hadrons.

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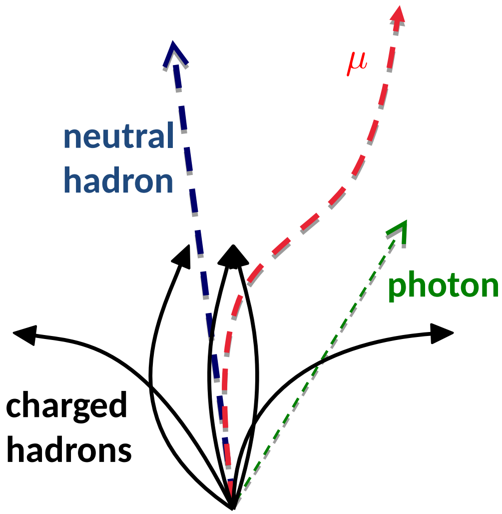
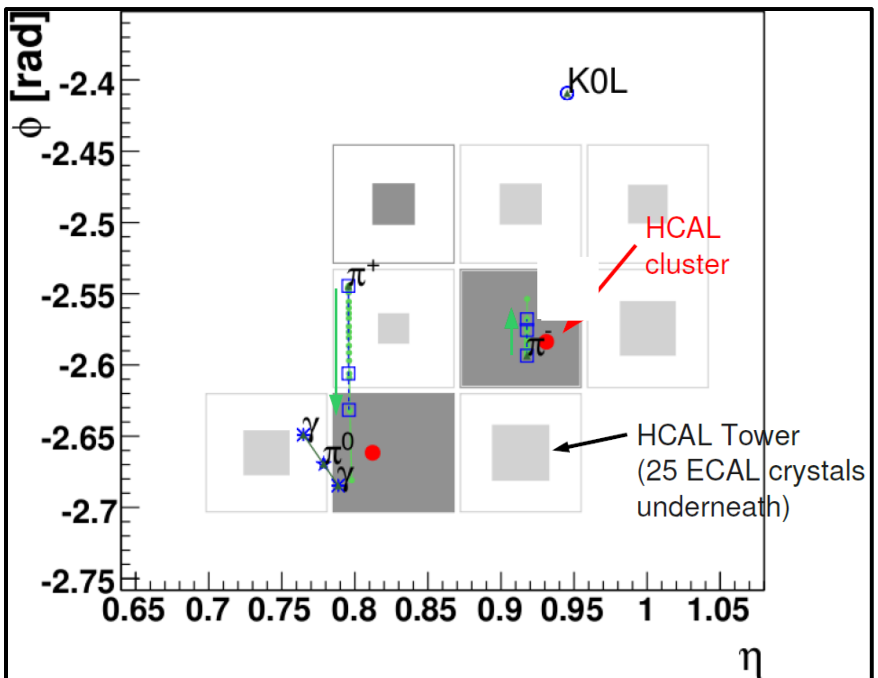
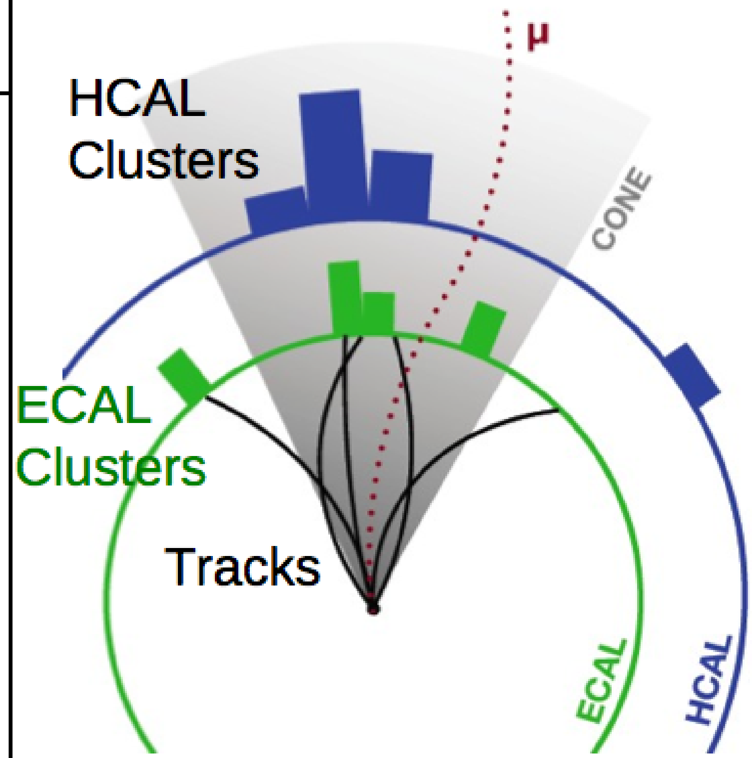




Particle Flow:



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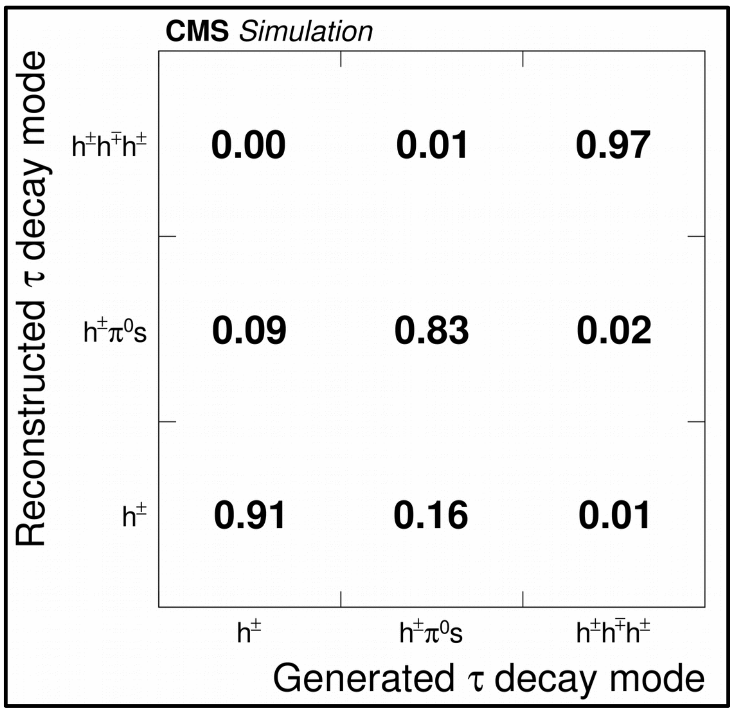
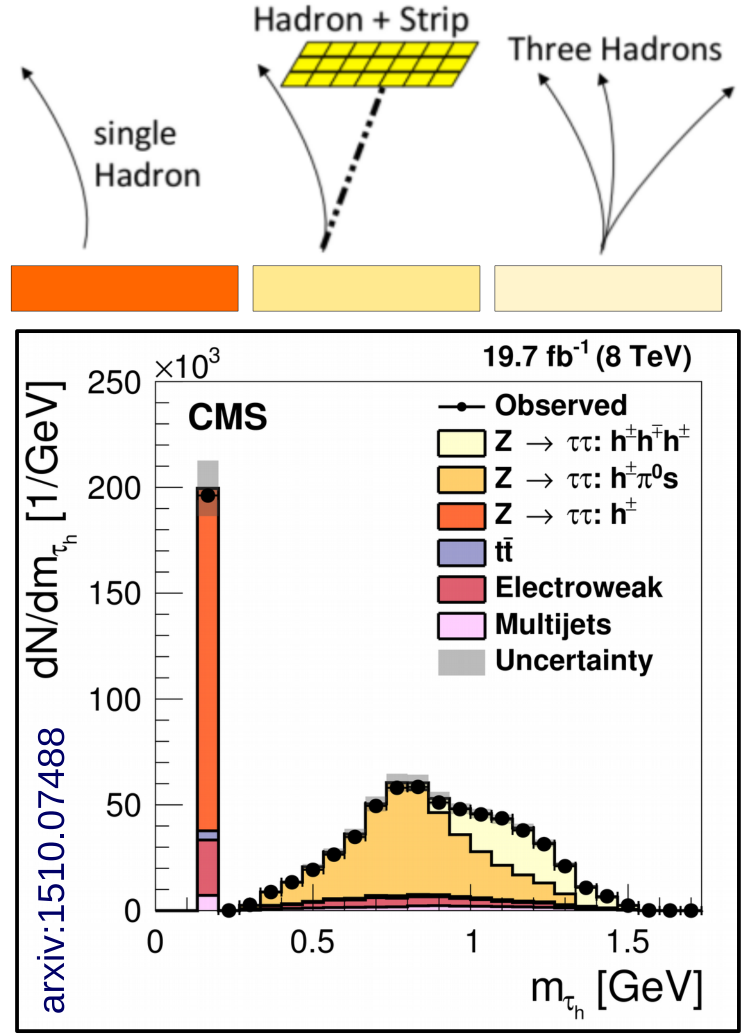
- Unambiguous list of stable particles: muons, electrons, photons, charged & neutral hadrons.

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** ($\rightarrow$ prongs).

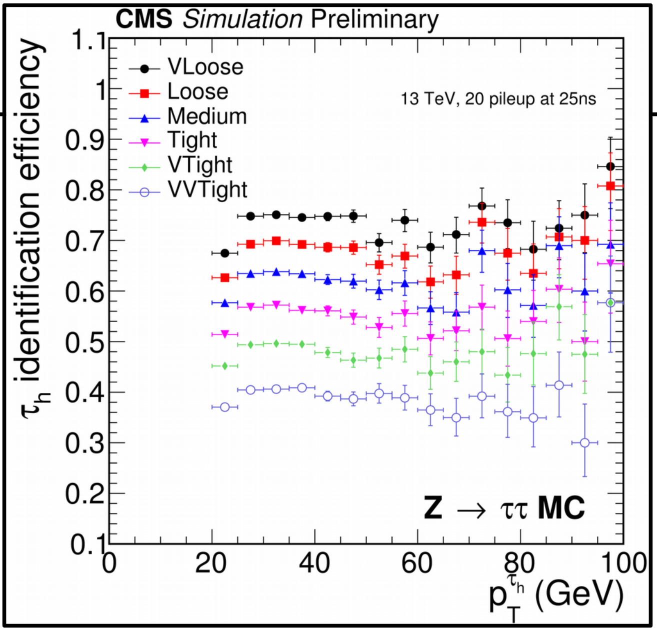


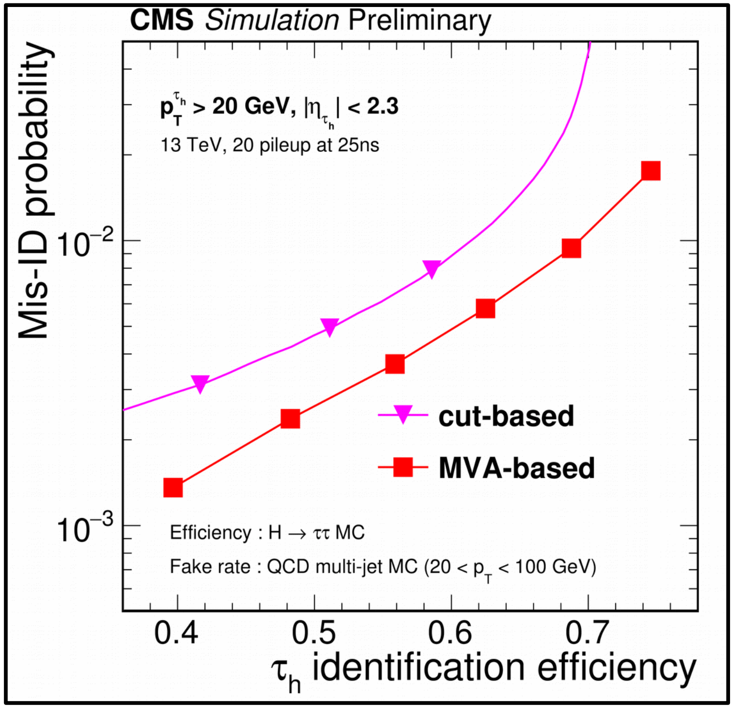


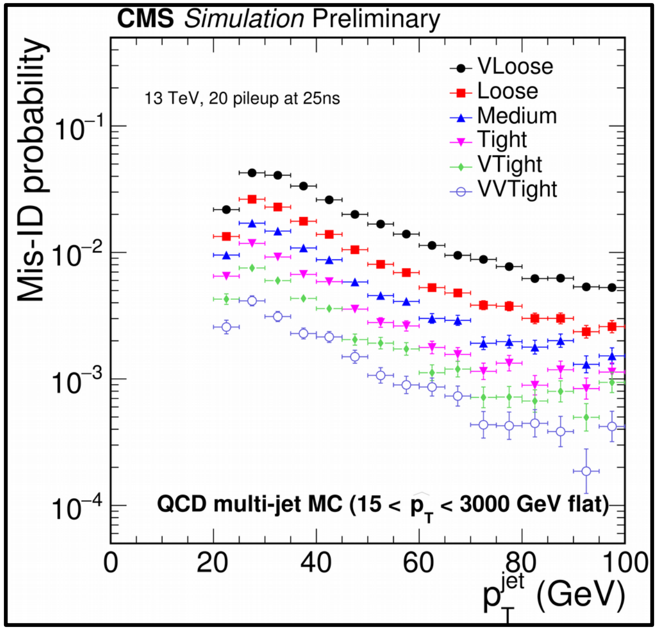
- Apply ID criteria to increase purity.

τ_h-Identification

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



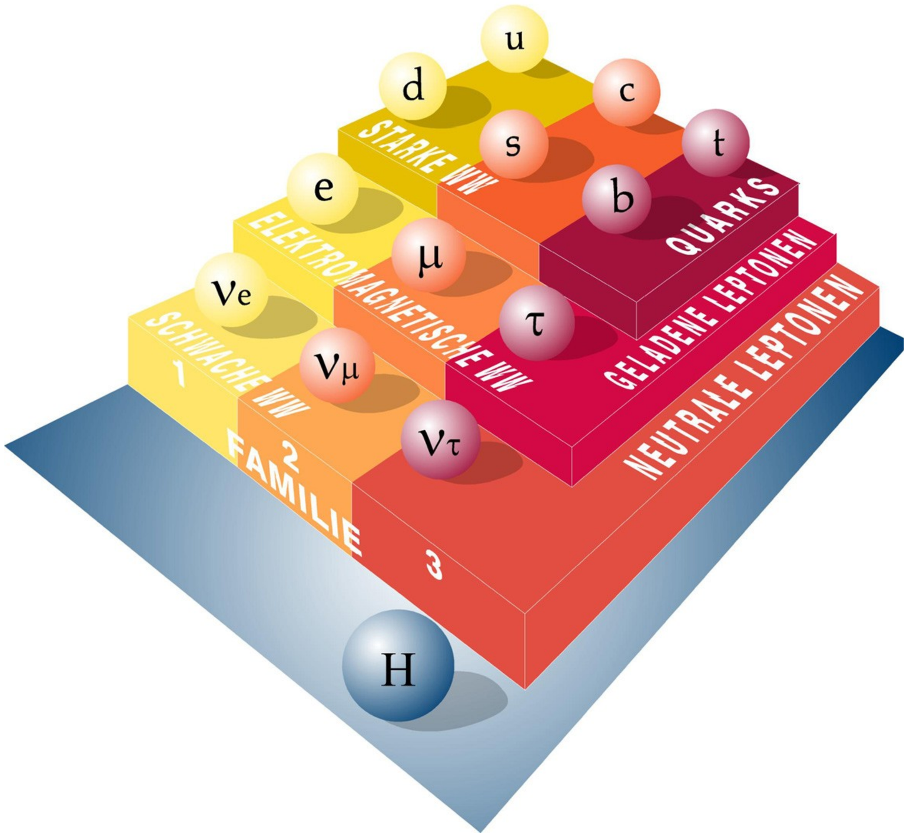




CMS-PAS-TAU-16-002

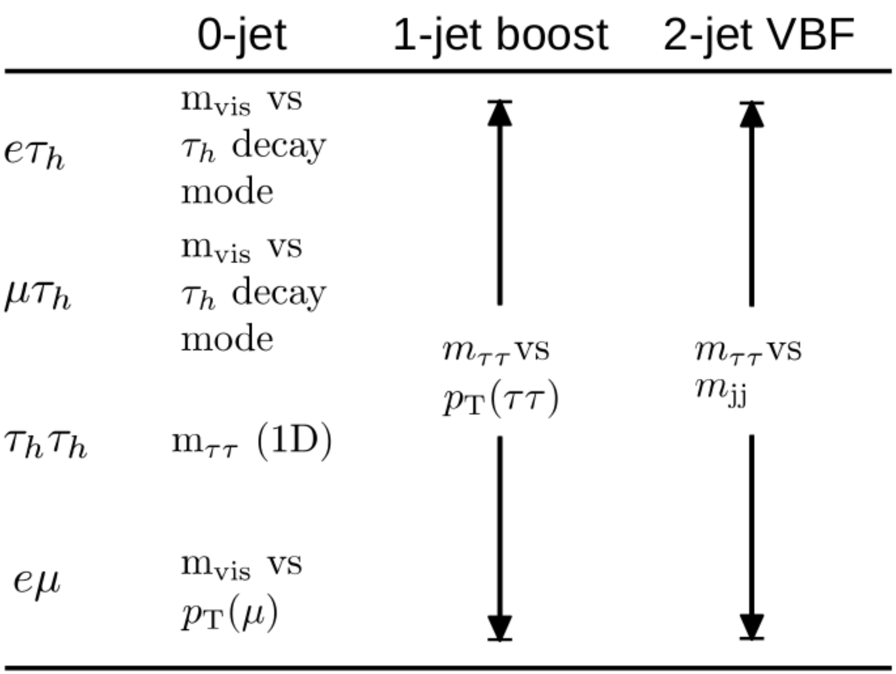
- Predefined working points used in analyses.

SM $H \to \tau\tau$ analysis



SM $H \to \tau\tau$ analysis

- Based on 36/fb @ 13 TeV, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$, $e\mu$ channel.
- Statistical inference of signal based on **1D and 2D likelihood discrimination**, depending on final state and event category.



arxiv:1708.00373

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	0-jet	1-jet boost	2-jet VBF
$e\tau_h$	m_{vis} vs τ_h decay mode		
$\mu\tau_h$	m_{vis} vs τ_h decay mode	$m_{\tau\tau}$ vs $p_T(\tau\tau)$	$m_{\tau\tau}$ vs m_{jj}
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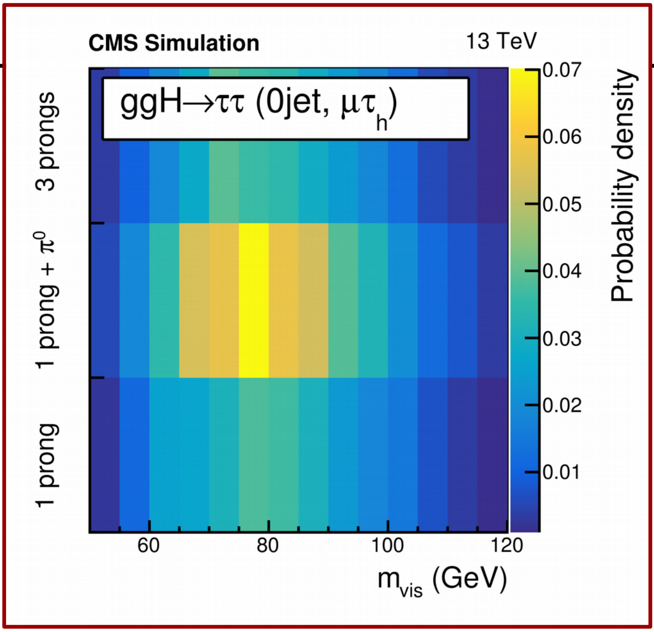

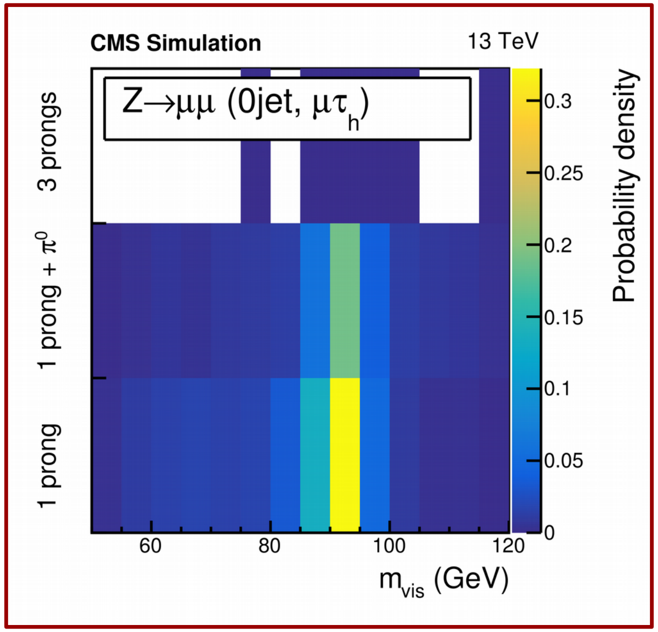

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$e\tau_h$	m_{vis} vs τ_h decay mode	$m_{\tau\tau}$ vs $p_T(\tau\tau)$ (all channels)	$m_{\tau\tau}$ vs m_{jj} (all channels)
$\mu\tau_h$	m_{vis} vs τ_h decay mode		
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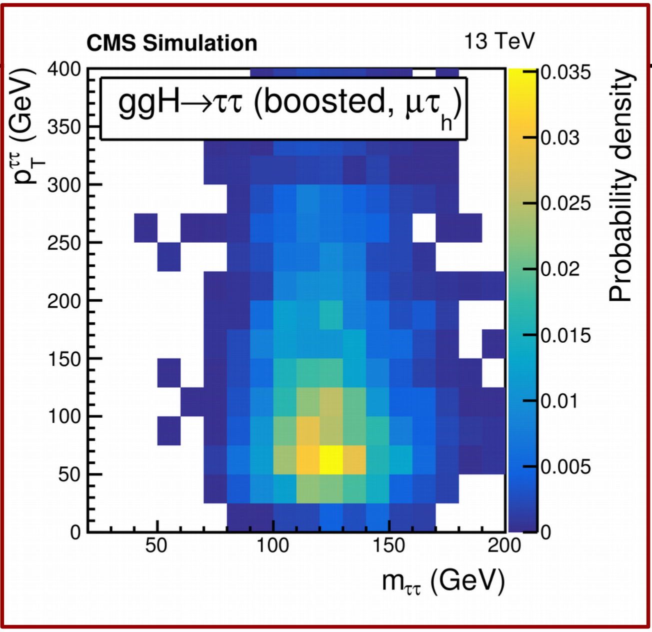

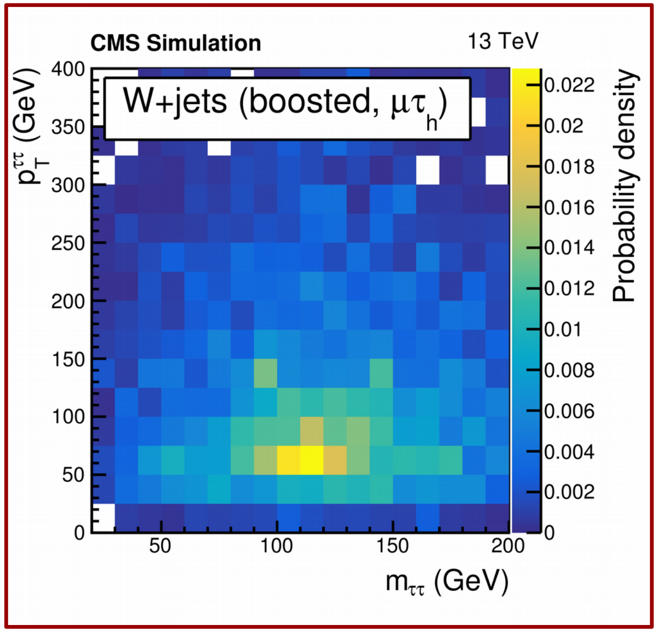

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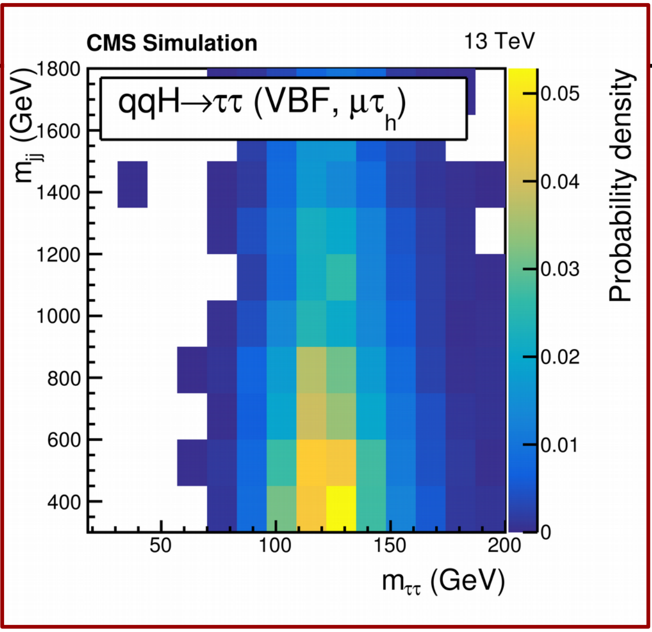
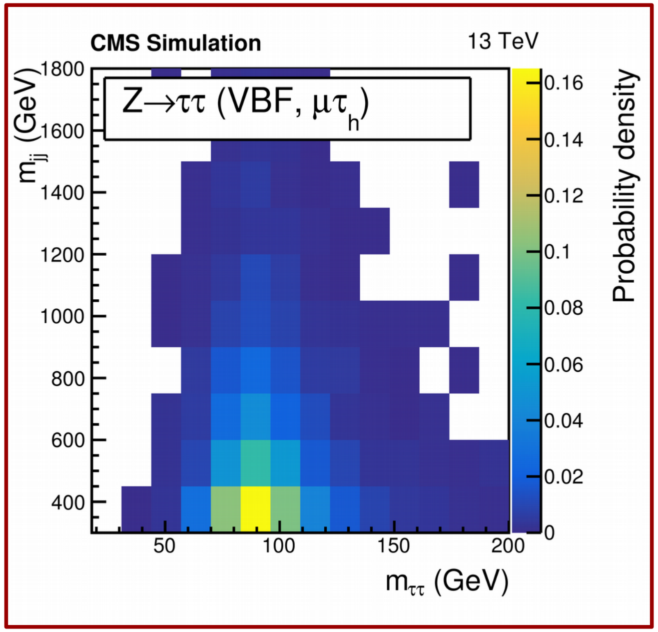
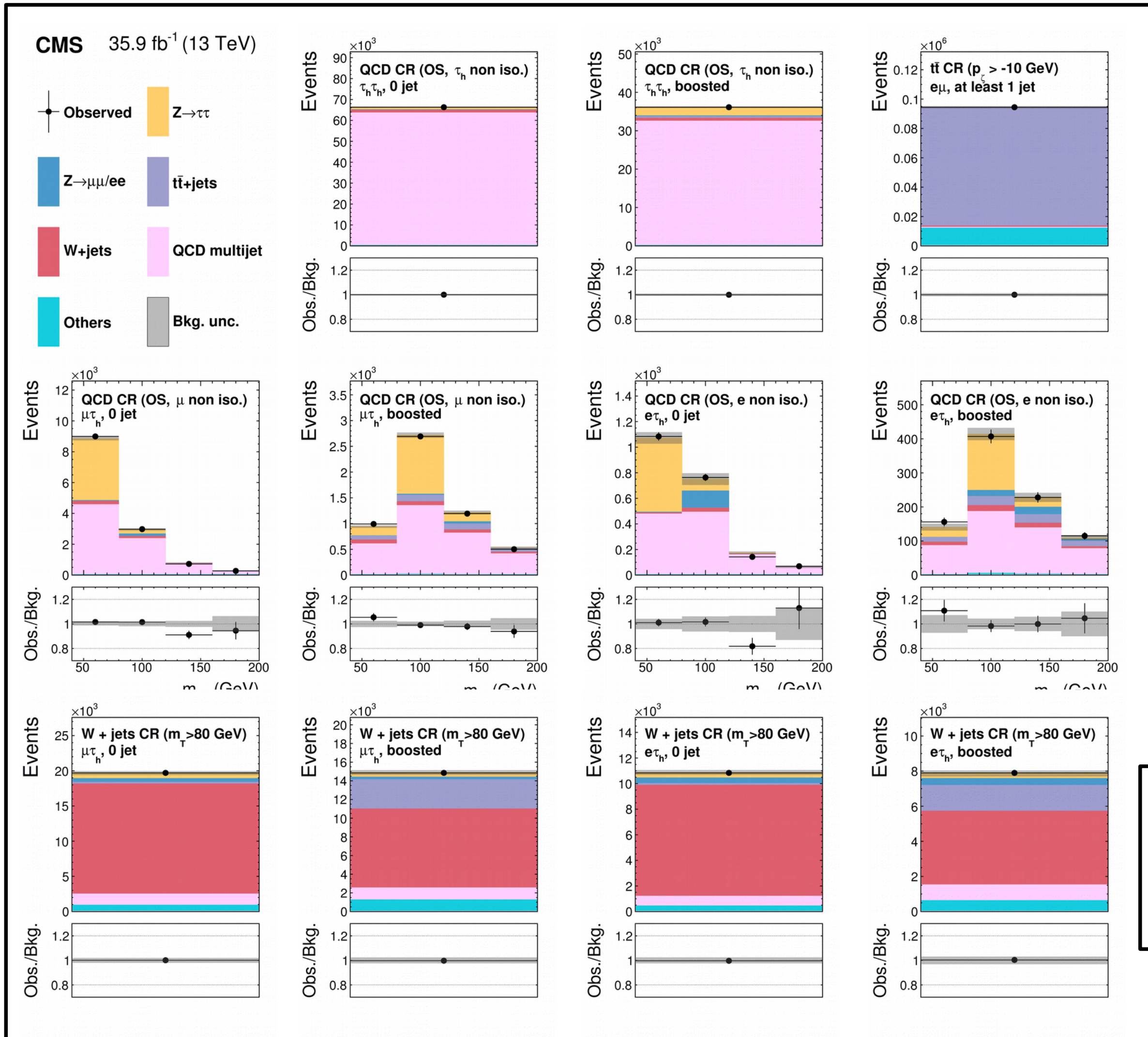




Background estimation

DY: from simulation w/ corrections from data.



Top-pair production: from simulation, normalization from control region in fit.

QCD: from events w/ same-charge of di-τ pair or anti-isolated τ.

W+jets: from simulation w/ corrections from data & controlled during fit.

Observation

- Selection of ("unrolled") input distributions for **statistical inference**:

	0-jet	1-jet boost	2-jet VBF
$e\tau_h$	m_{vis} vs τ_h decay mode		
$\mu\tau_h$	m_{vis} vs τ_h decay mode	$m_{\tau\tau}$ vs $p_T(\tau\tau)$	$m_{\tau\tau}$ vs m_{jj}
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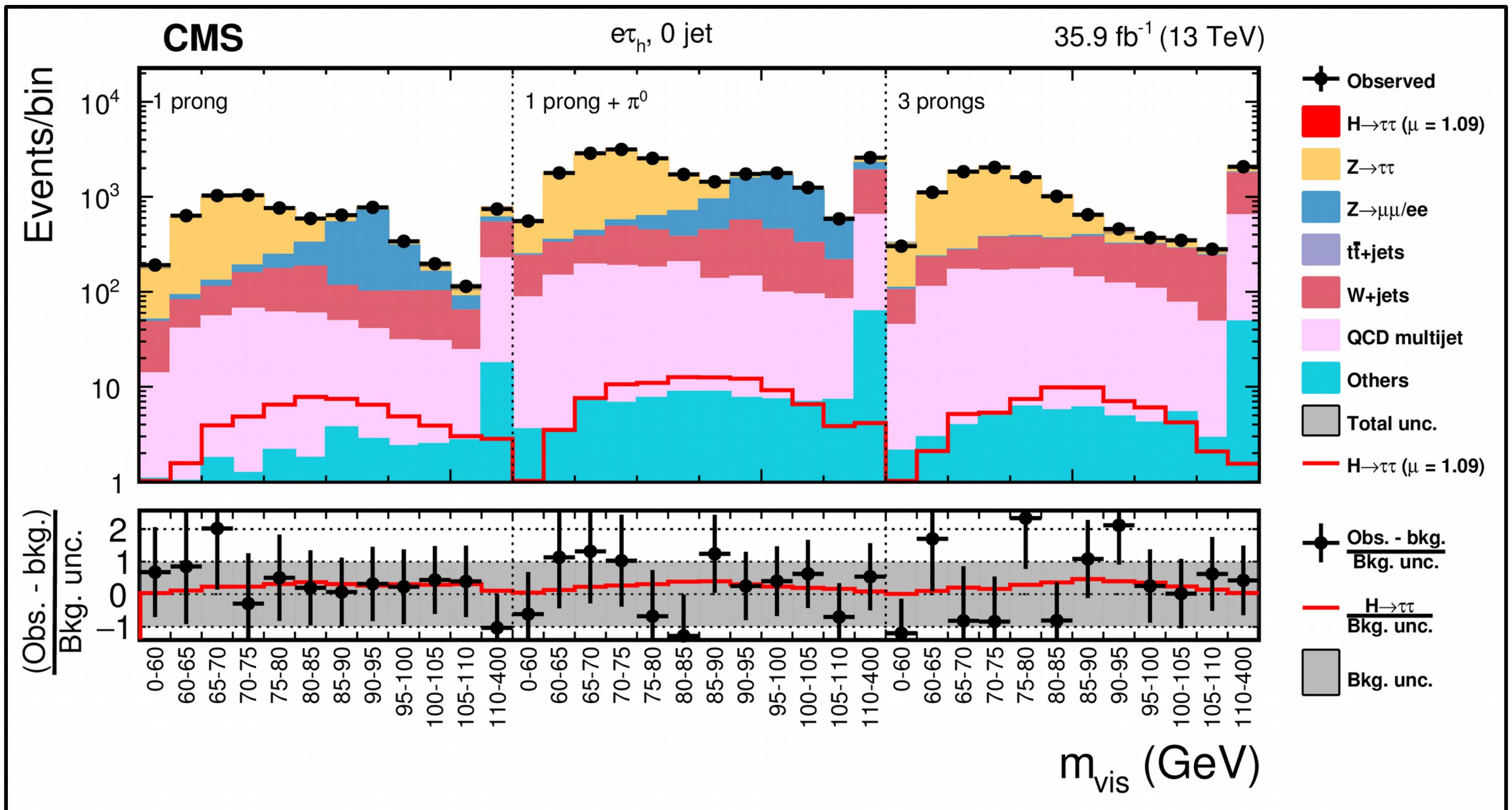

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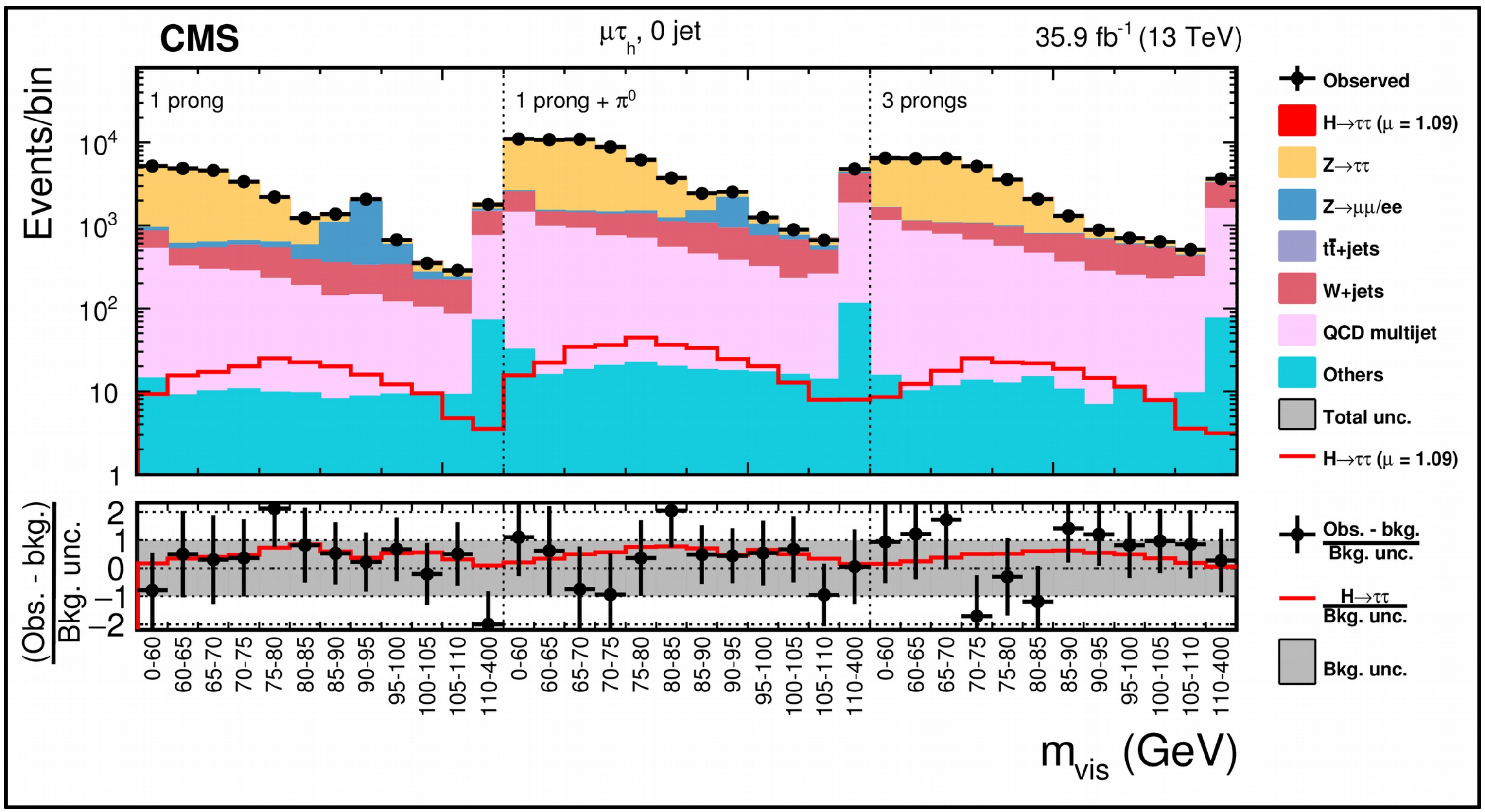

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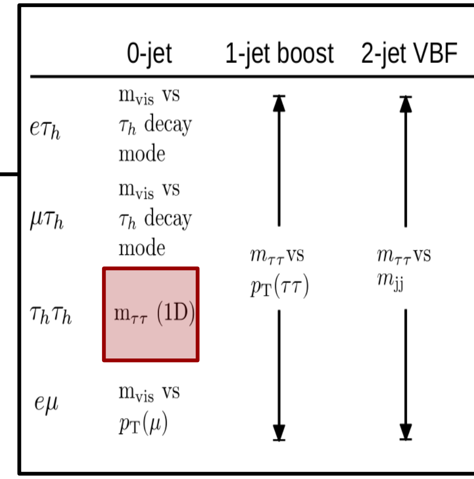

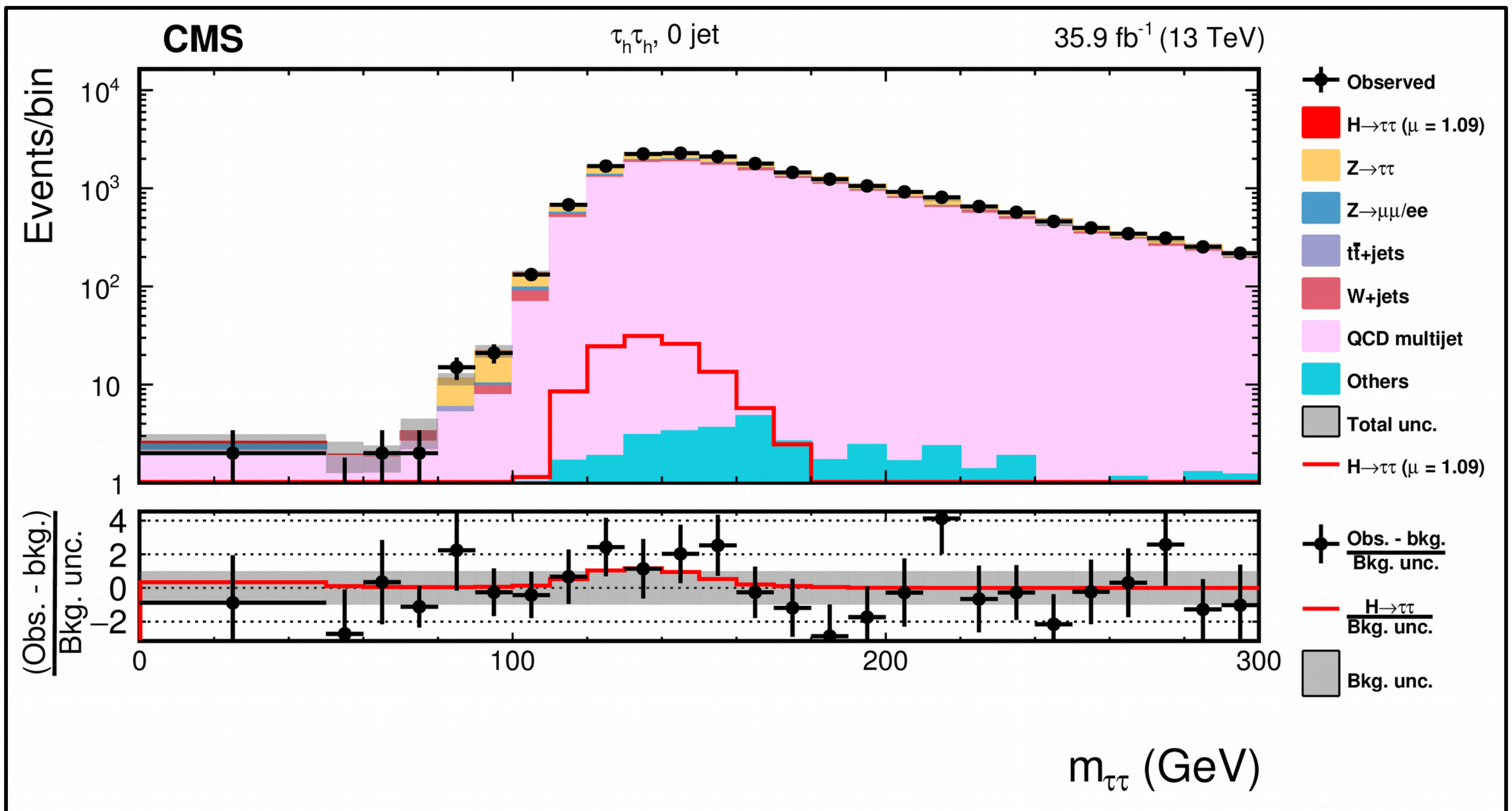

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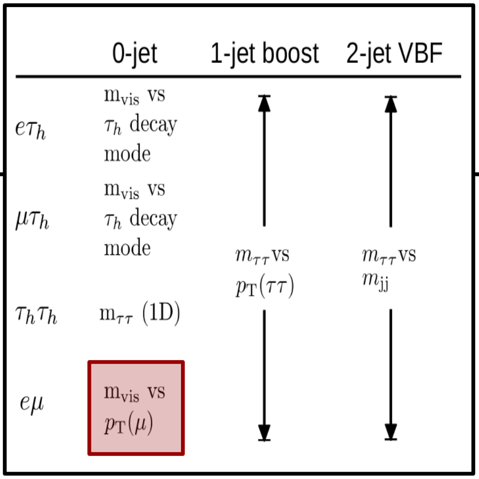

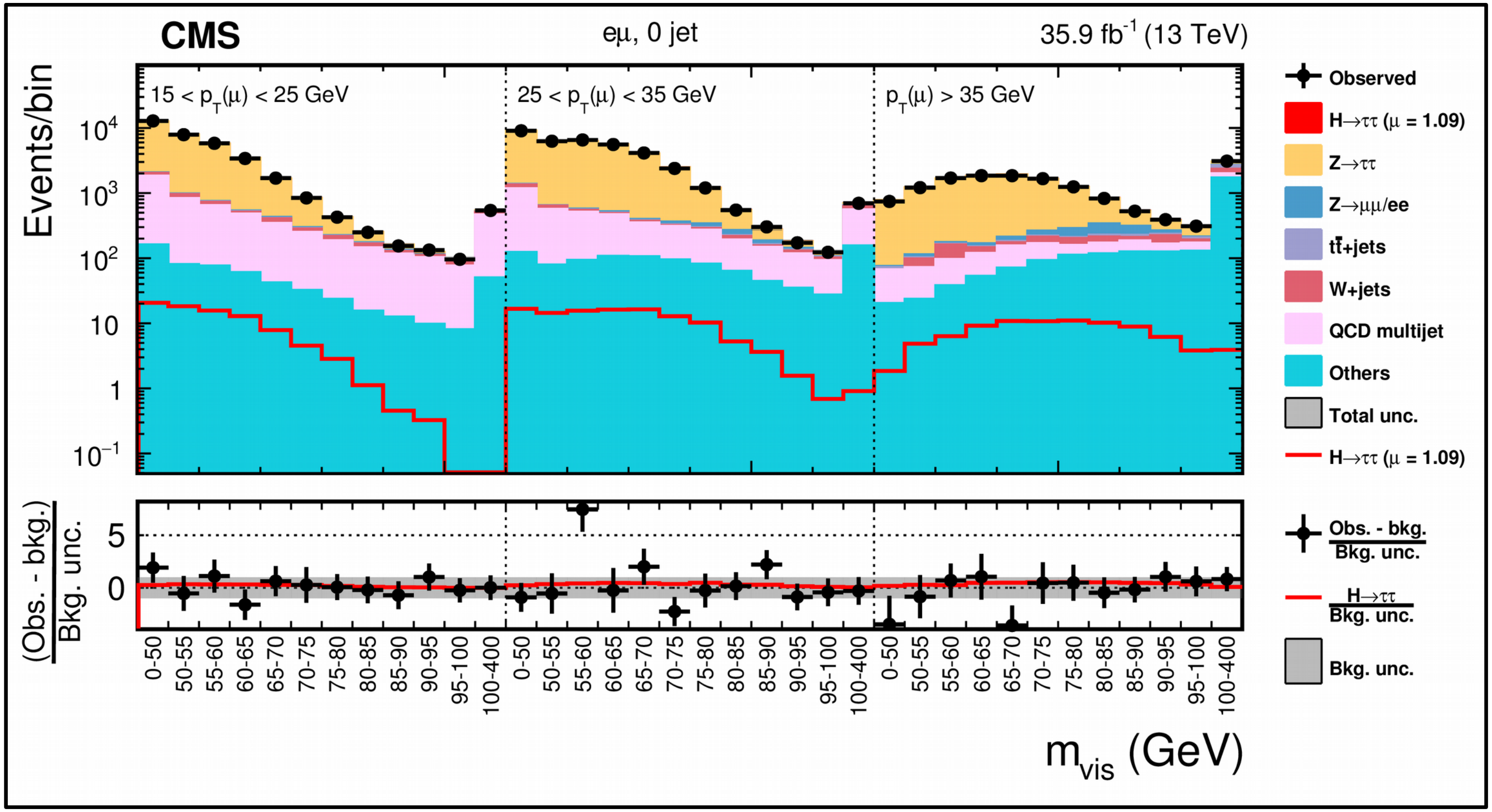

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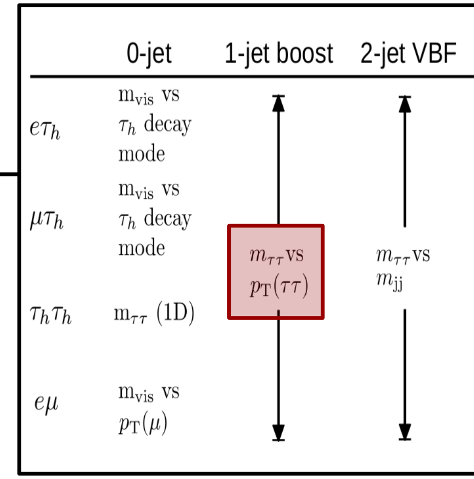

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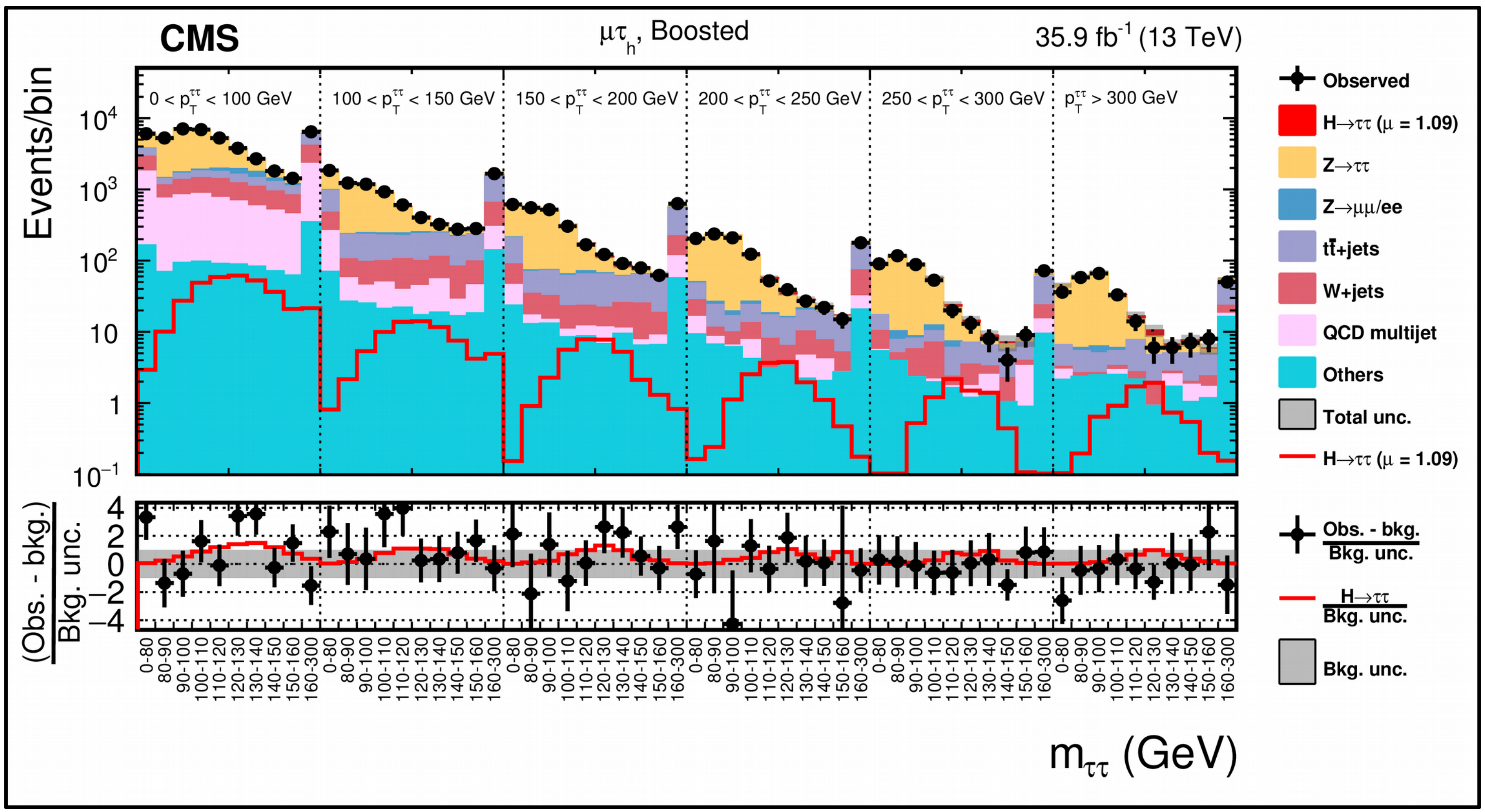

Observation

	0-jet	1-jet boost	2-jet VBF
$e\tau_h$	m_{vis} vs τ_h decay mode	↕	↕
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$\tau_h\tau_h$	$m_{\tau\tau}$ (1D)	↕	↕
$e\mu$	m_{vis} vs $p_T(\mu)$	↕	↕

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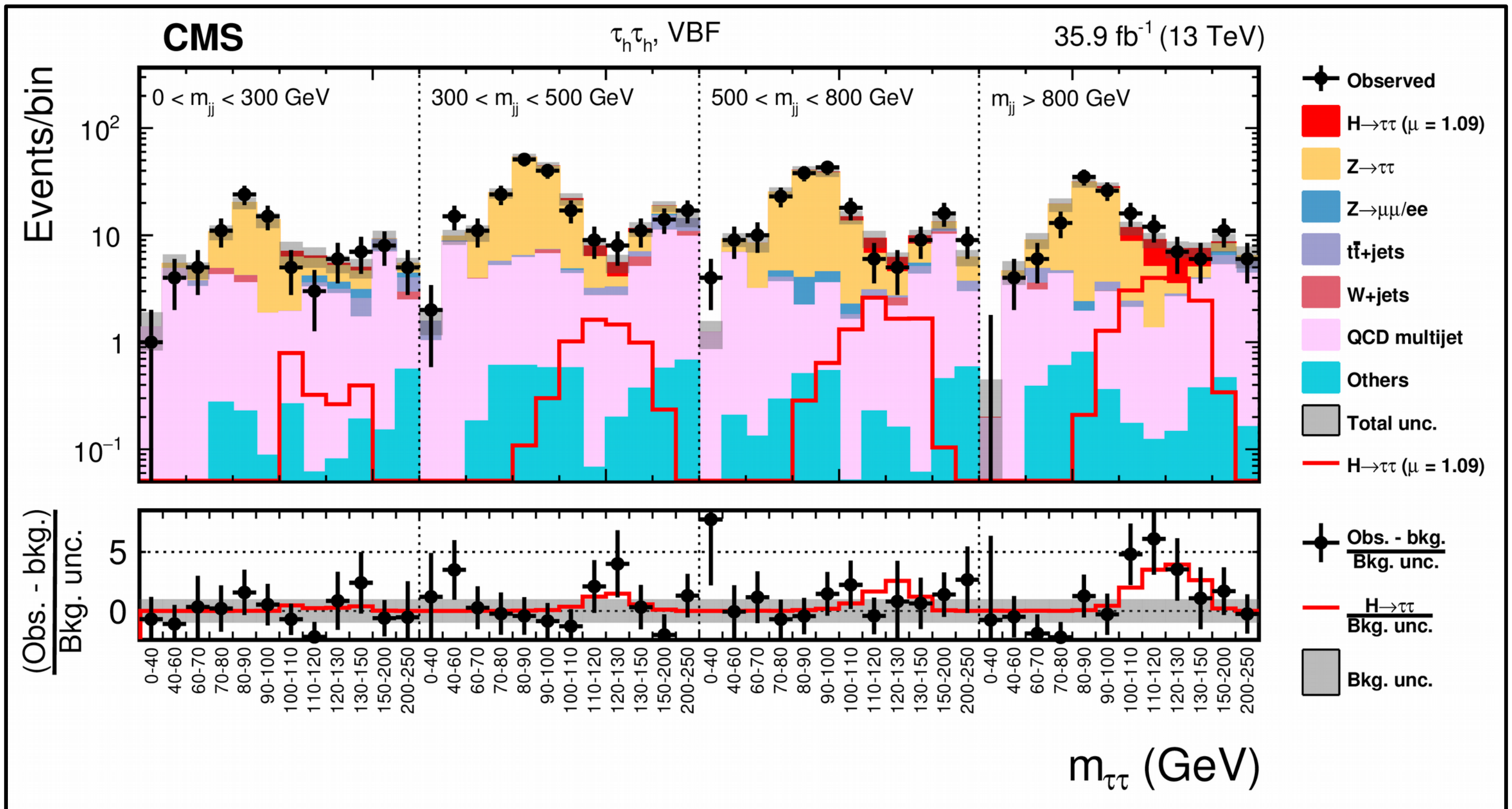
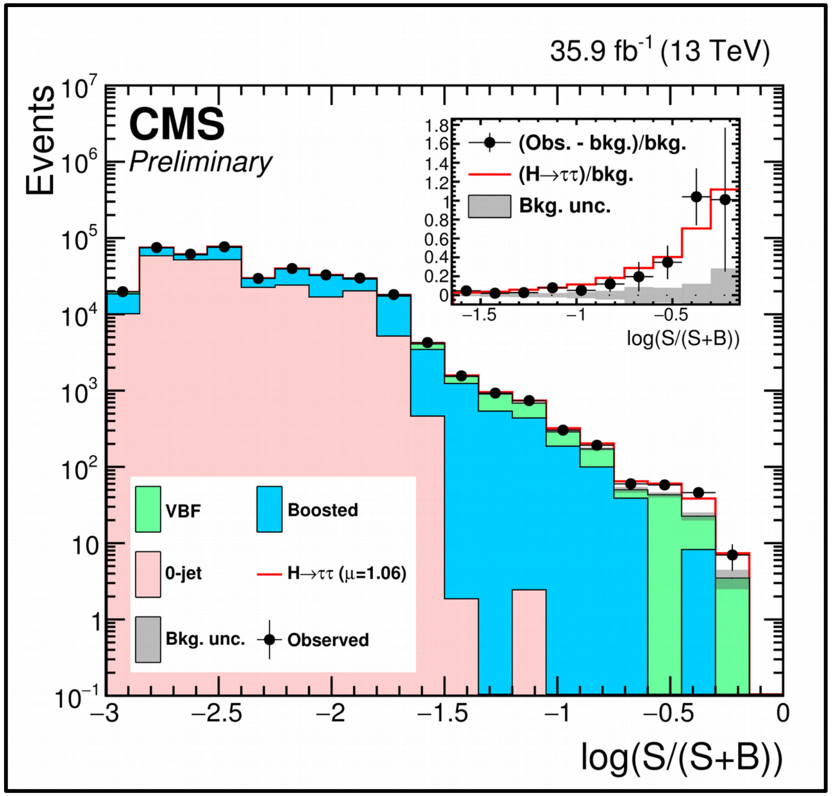
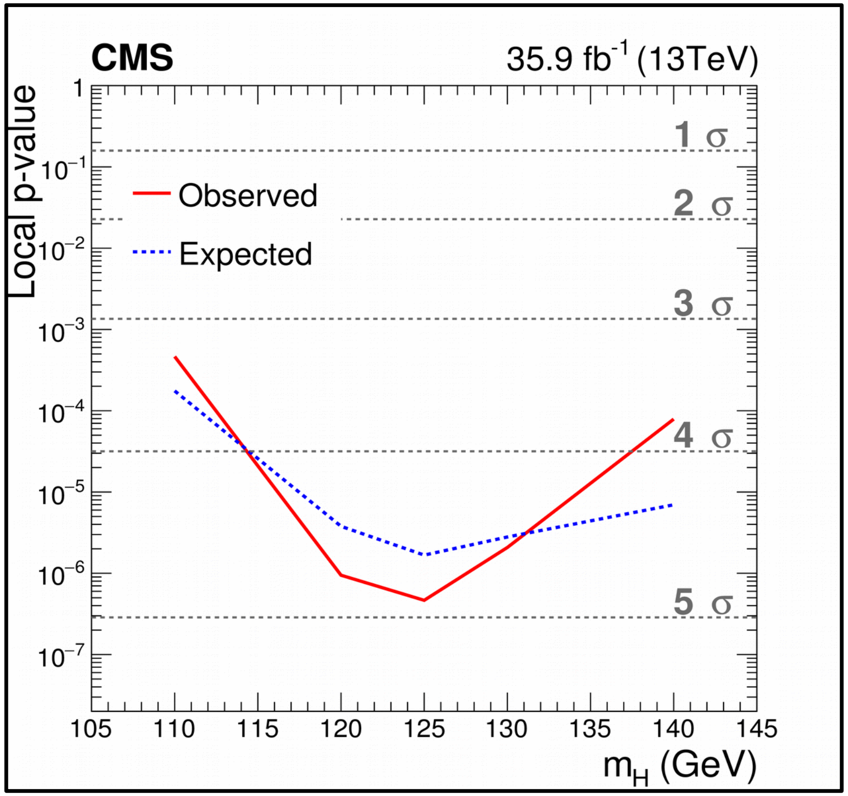


Results

- **Combined ML** fit to all distributions in all event categories:

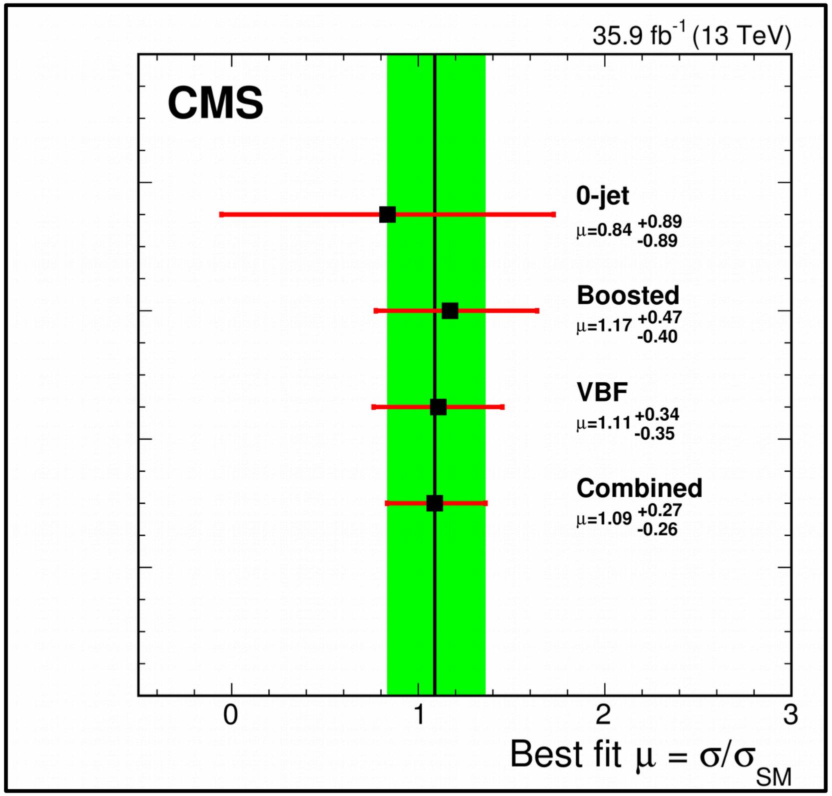


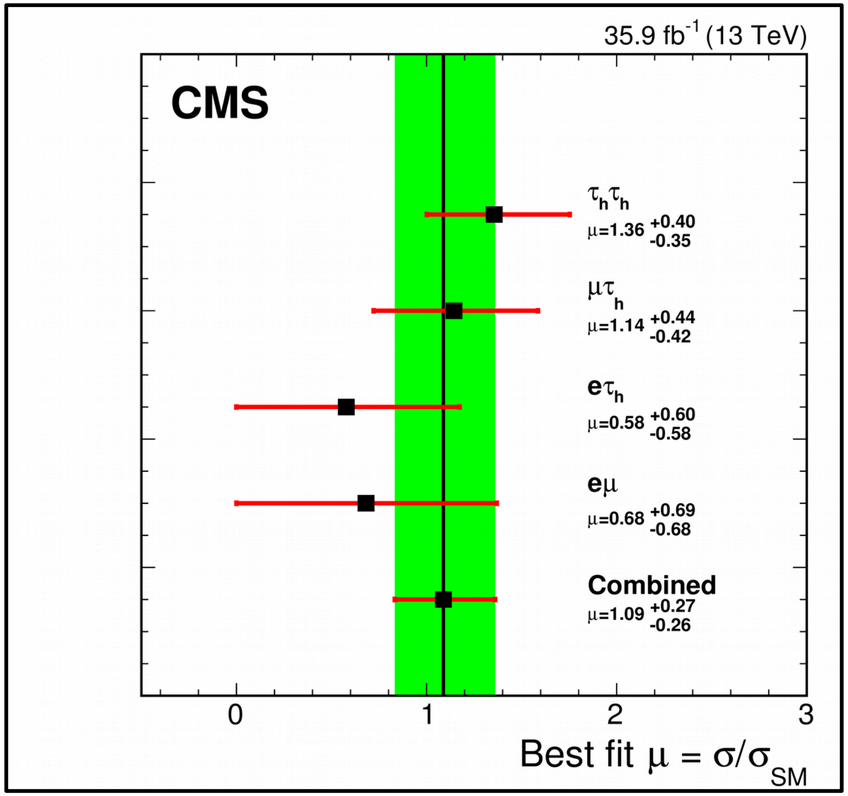


- Largest **significance** @ 125 GeV $4.9(4.7)\sigma$.
- $5.9(5.9)\sigma$ when combined with the LHC run-1 result.

Results

- **Consistency** across production modes (left) and final states (right):

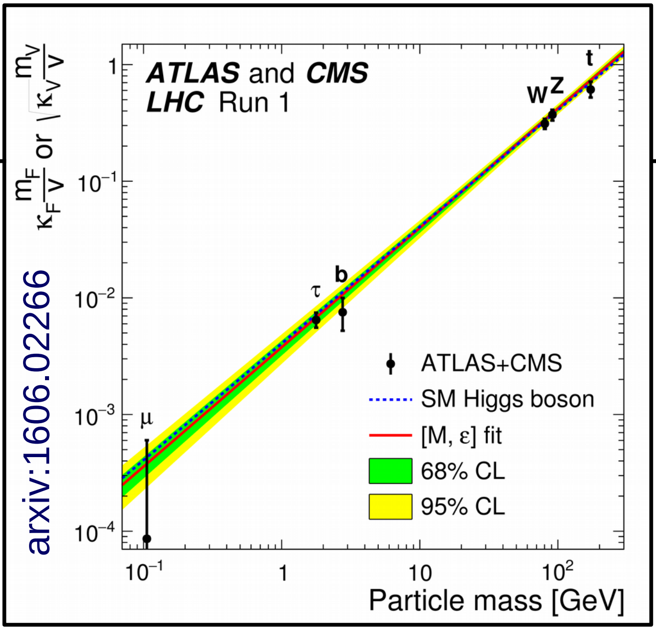




- Overall **signal strength**: $\mu = 1.09 \pm^{0.27}_{0.26}$
- Largest uncertainties equally shared b.t.w. template population, systematics, statistics ($\mathcal{O}(13\%)$), theory uncertainty $\mathcal{O}(10\%)$.

Conclusions part-I

- First single-channel, single-experiment $> 5\sigma$ **observation of coupling to fermions**.



Conclusions part-I

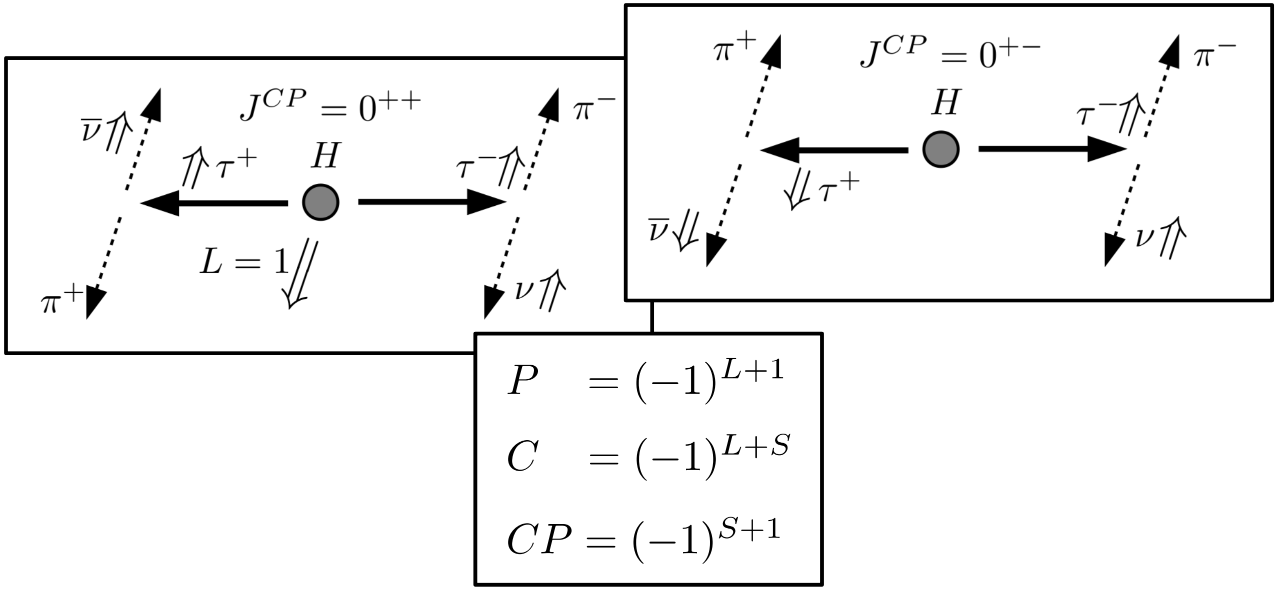
- First single-channel, single-experiment $> 5\sigma$ **observation of coupling to fermions**.
- Major source of Higgs boson events @ 125 GeV (e.g. for study of dedicated final states like VBF).

Decay Channel	$\sqrt{s} = 8$ TeV, 20 fb^{-1} inclusive	$\sqrt{s} = 13$ TeV, 300 fb^{-1} inclusive	$gg \to H$	$qq \to H$	WH	ZH	$t\bar{t}H$
$\gamma\gamma$	1k	37k	32k	2,5k	1k	750	375
ZZ	50	2k	1,75k	140	60	40	10
WW	5k	200k	175k	14k	6k	4k	1k
$b\bar{b}$	250k	10 000k	8 750k	700k	300k	200k	50k
$\tau\tau$	30k	1 000k	875k	70k	30k	20k	5k
$\mu\mu$	100	3.7k	3.2k	250	100	70	30

based on $\sigma \cdot BR$ before reconstruction

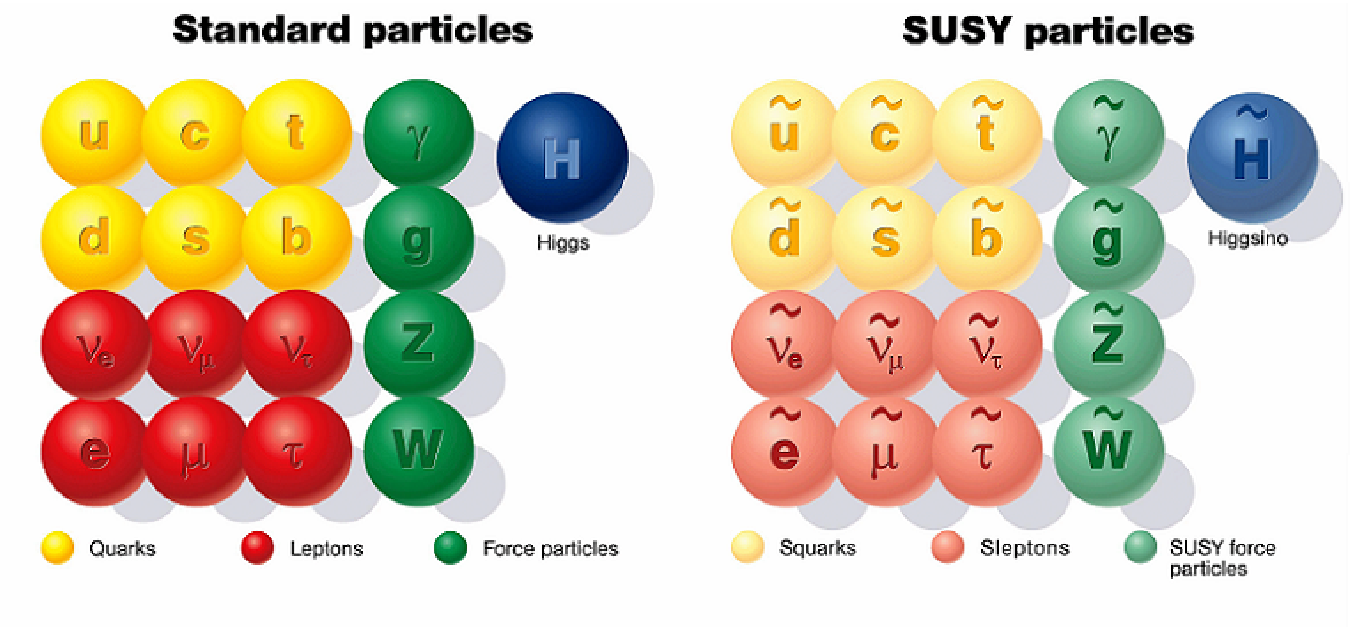
Conclusions part-I

- First single-channel, single-experiment $> 5\sigma$ **observation of coupling to fermions**.
- Major source of Higgs boson events @ 125 GeV (e.g. for study of dedicated final states like VBF).
- Only unbiased environment to measure CP of the Higgs boson:

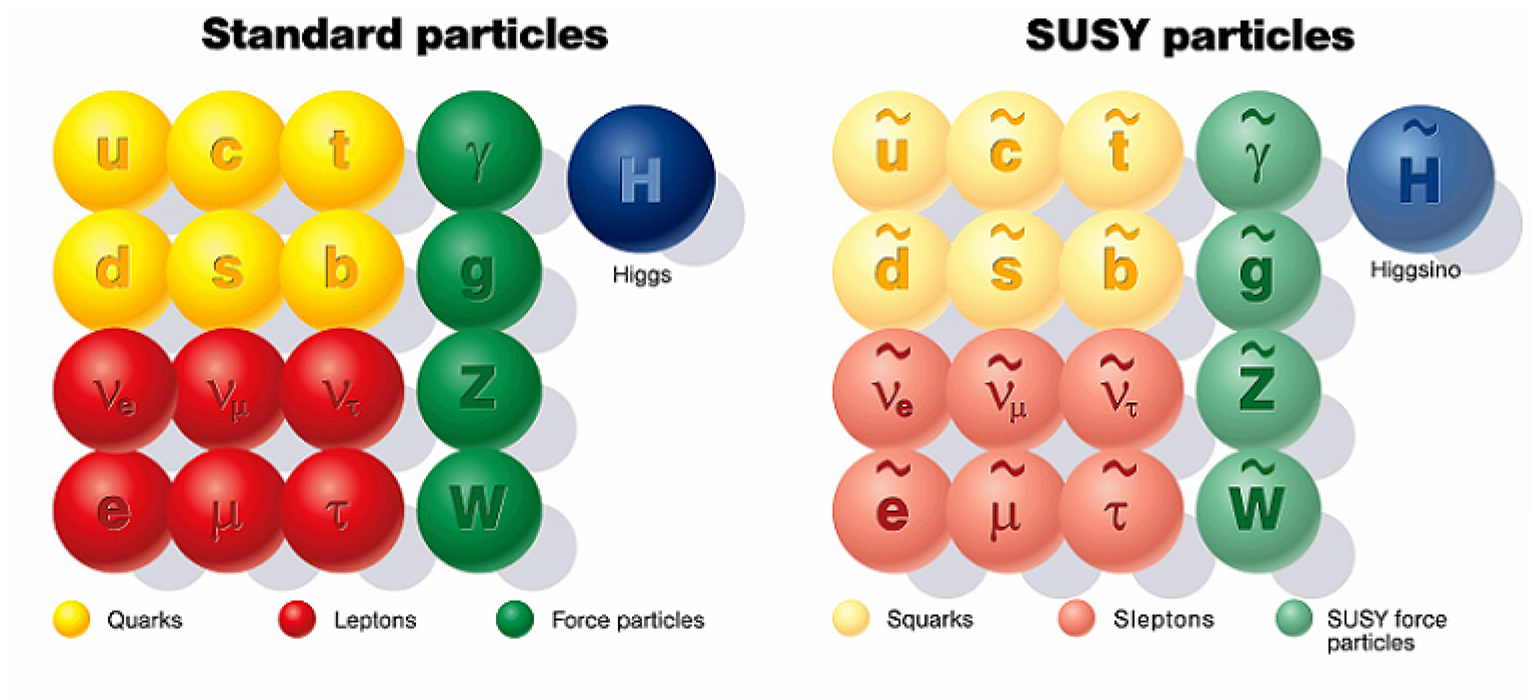


Conclusions part-I

- First single-channel, single-experiment $> 5\sigma$ **observation of coupling to fermions**.
- Major source of Higgs boson events @ 125 GeV (e.g. for study of dedicated final states like VBF).
- Only unbiased environment to measure CP of the Higgs boson:
- Prime source to search for non-trivial extended Higgs sectors (→ e.g. in SUSY, see next slides)!



MSSM $H \to \tau\tau$ analysis$^{(*)}$



(*) as proxi for a well motivated THDM extension of the SM

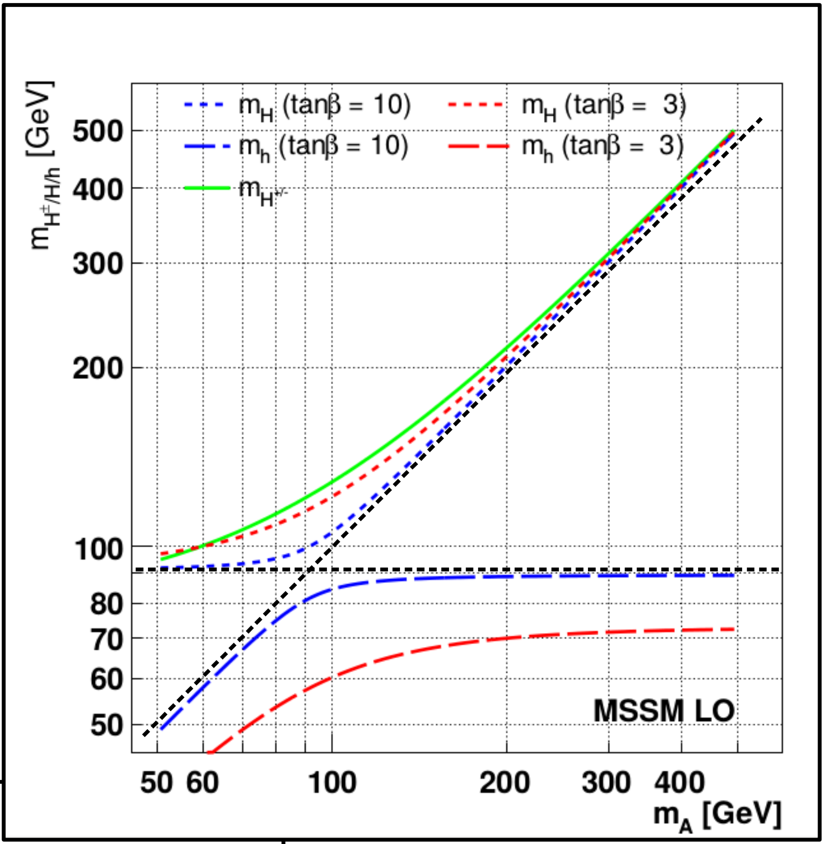
Higgs Bosons in the MSSM

- 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: $m_A,\ \tan\beta = {}^{v_u}/_{v_d}$

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

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

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

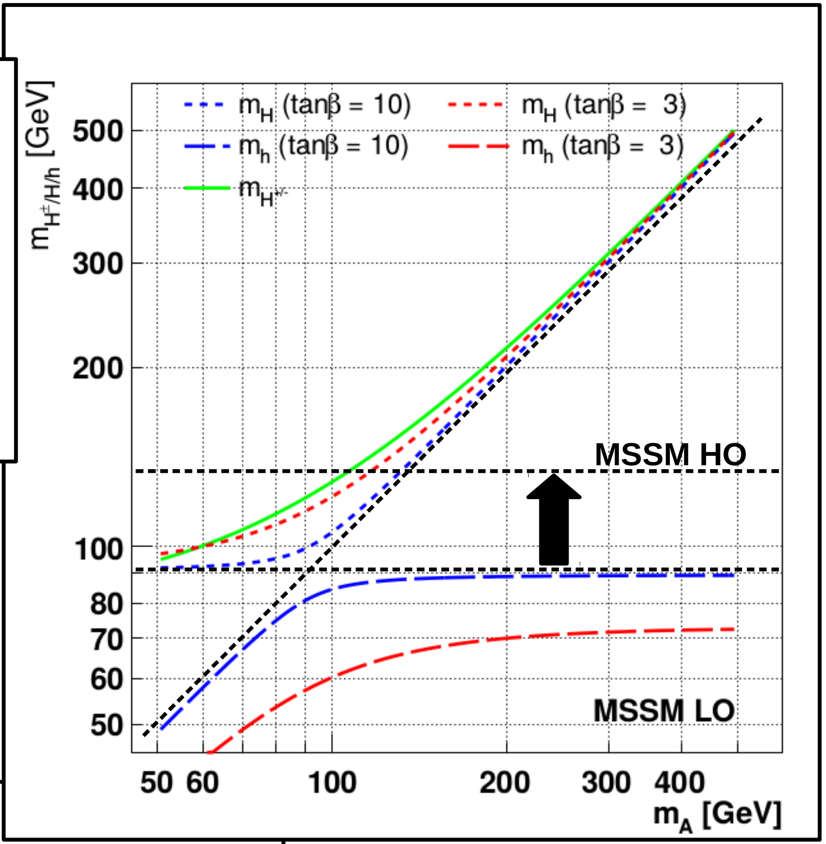
α : angle between H and h in mass matrix

Mass of observed Higgs Boson and $\tan\beta$

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

- 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 and large $\tan\beta$.

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



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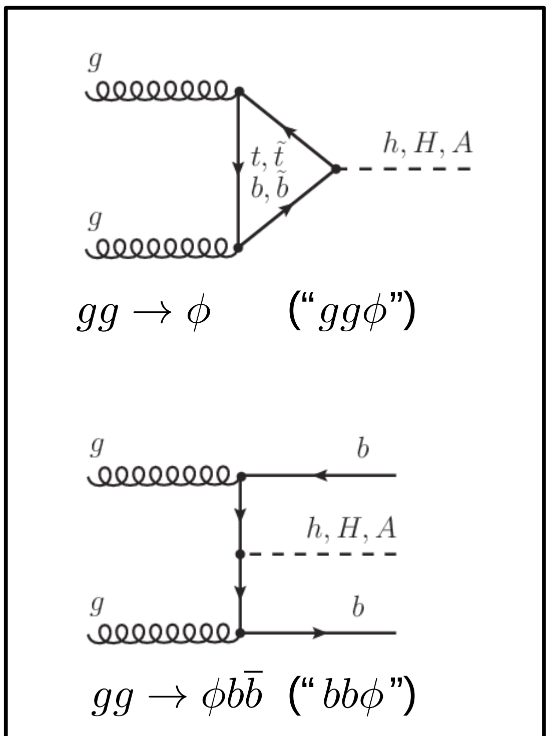
α : angle between H and h in mass matrix

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

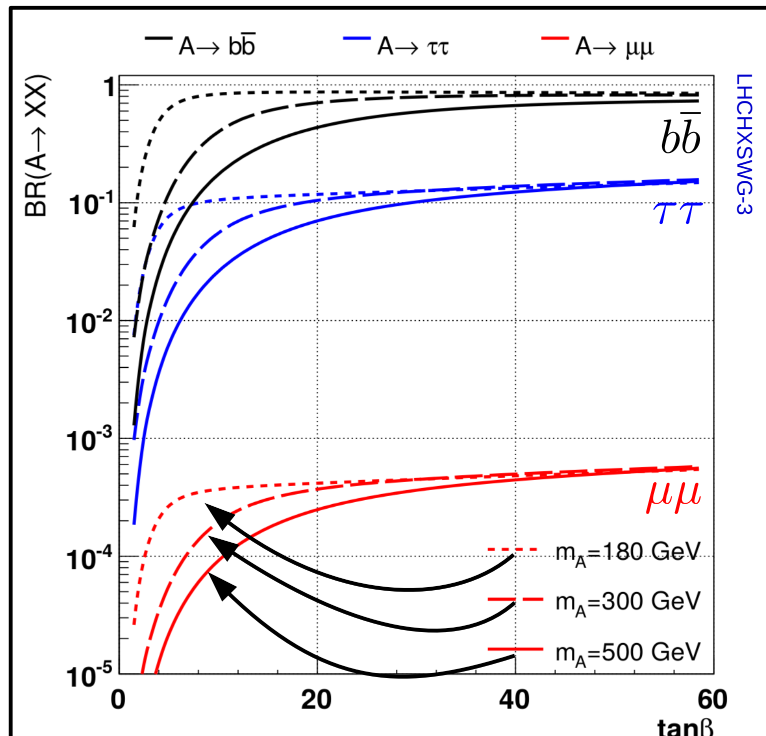
For $m_A \gg m_Z$: $\alpha \to \beta - \pi/2$ (coupling to down-type fermions enhanced by $\tan\beta$).

Production modes:

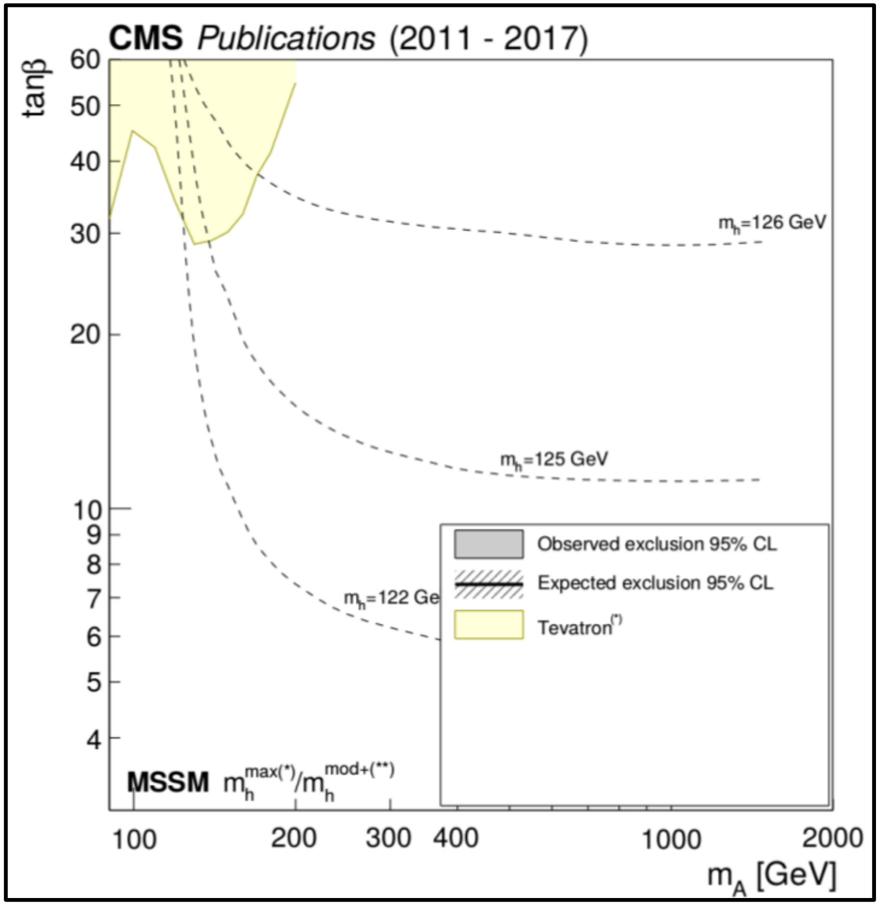


X

Decay channels:



History of MSSM $H \to \tau\tau$ searches @ CMS



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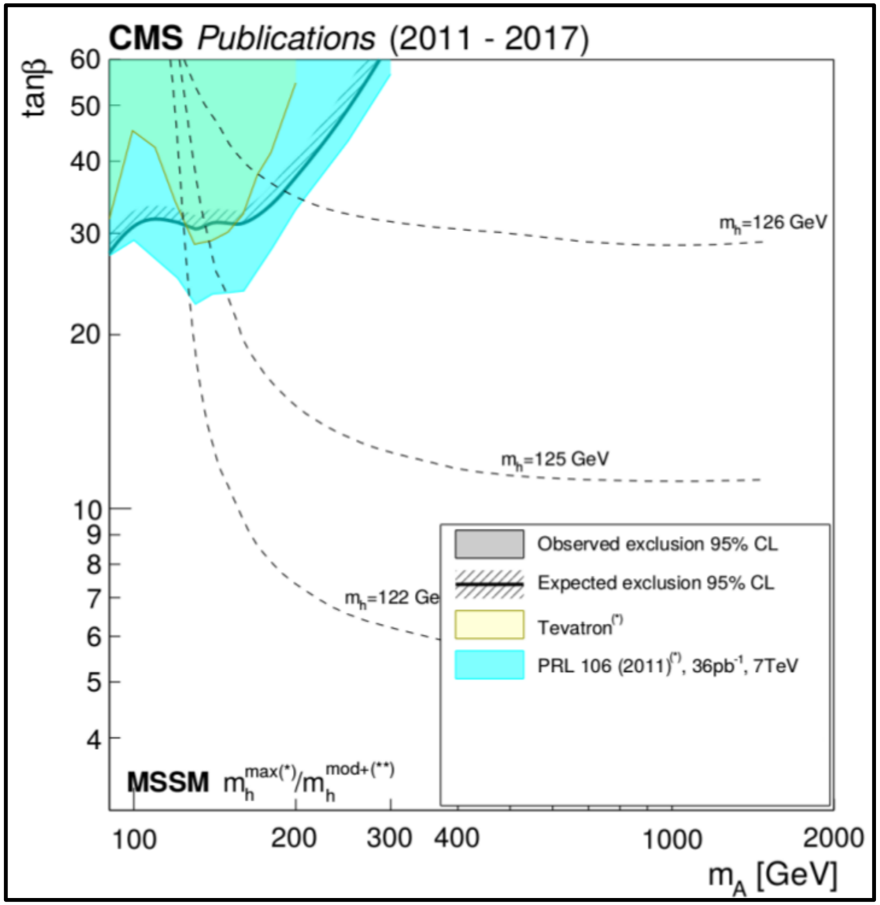

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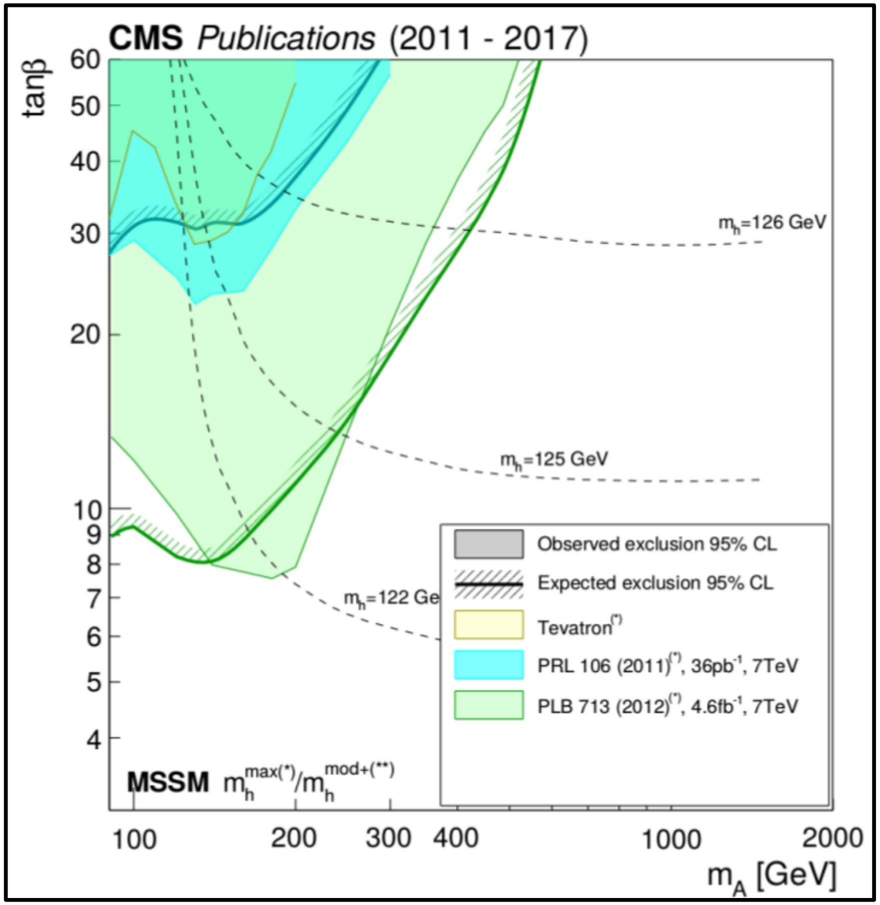

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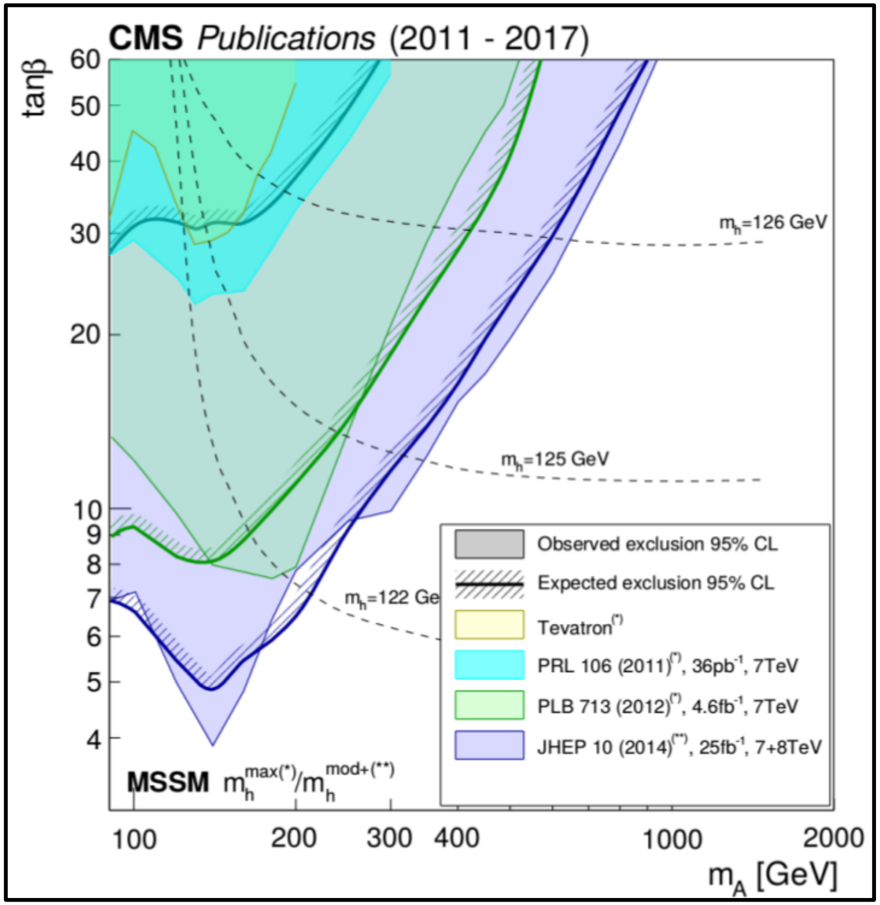

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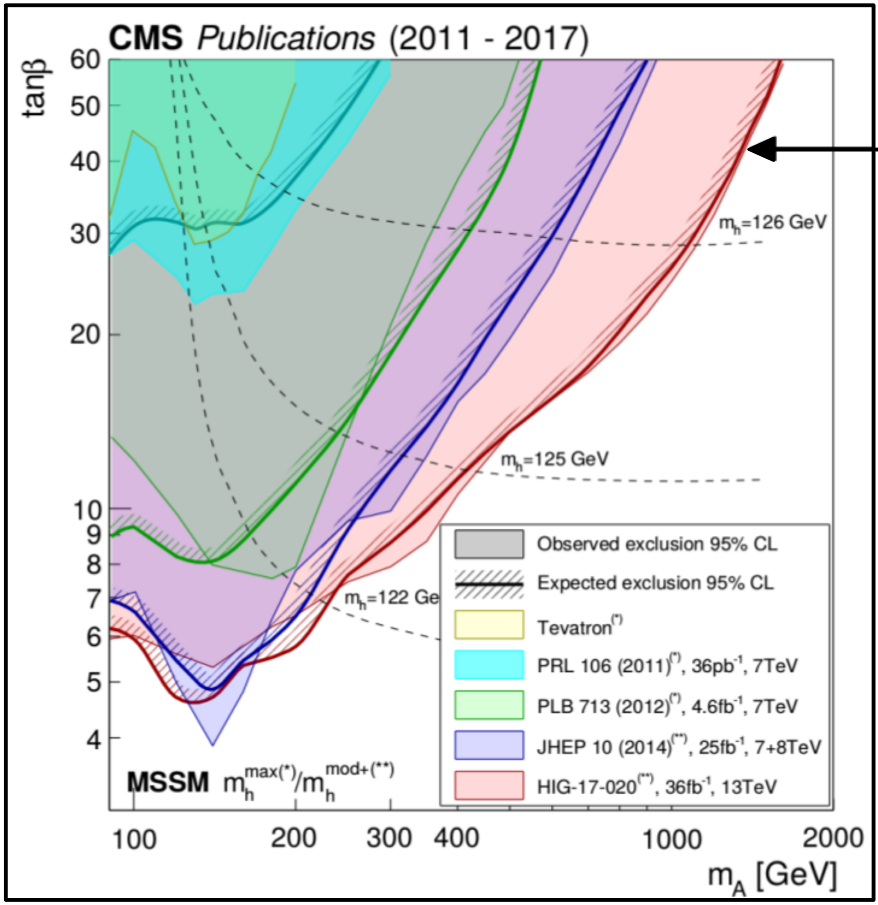
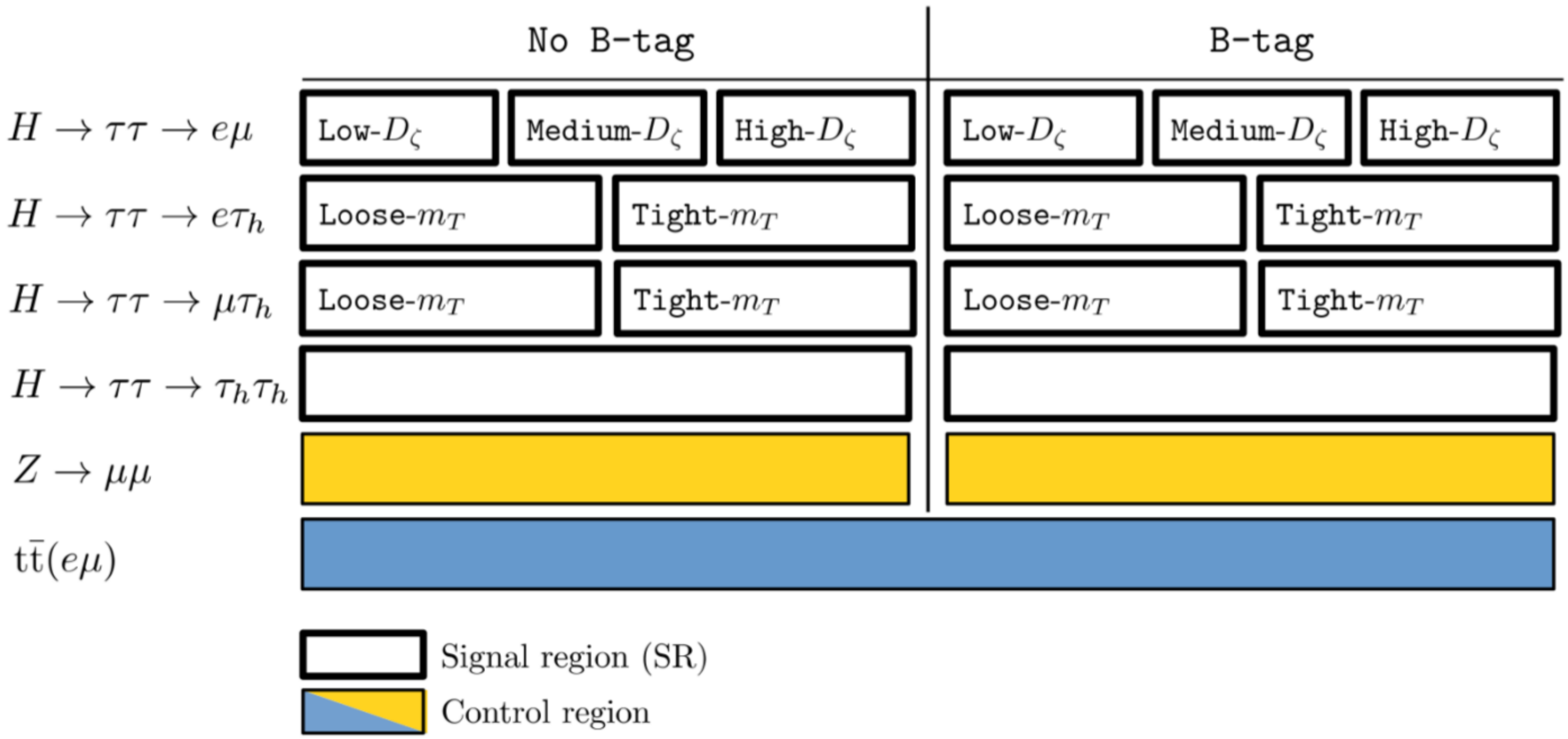


- **Brand new CMS result** discussed in the following (based on 36/fb @ 13TeV).

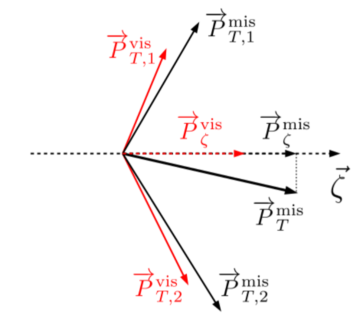
- **What's special about this publication**:
  - Maximally data driven background estimates.
  - Increased sensitivity due to more complex event categorization.
  - Differential signal modeling consistently @ NLO QCD accuracy.
  - Sophisticated statistical inference for signal.

Additional event information

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



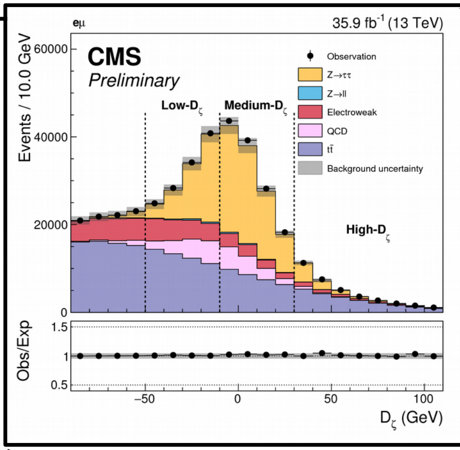
Additional event information



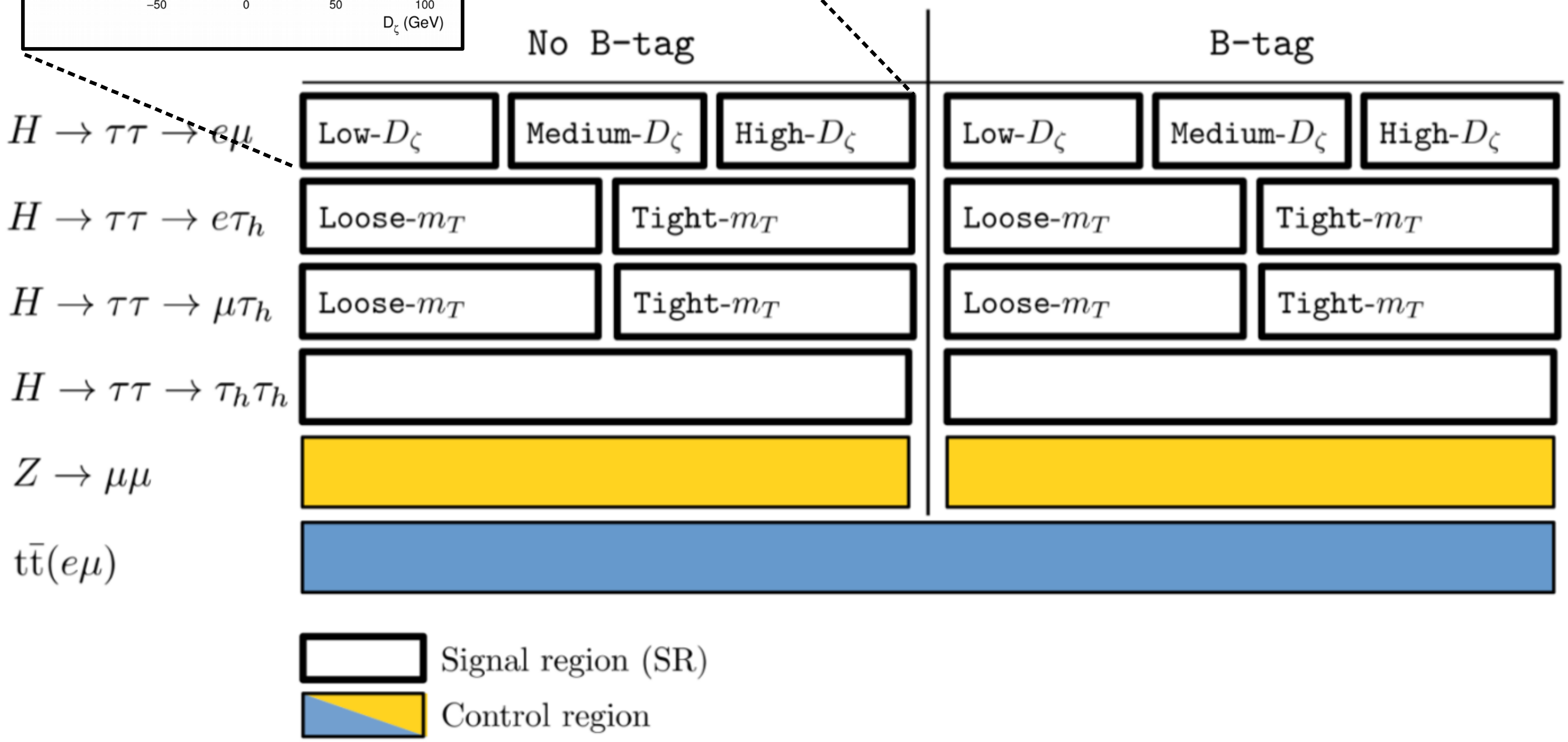
$$P_\zeta = \left(\vec{P}_{T,1}^{\rm vis} + \vec{P}_{T,2}^{\rm vis} + \vec{P}_{T}^{\rm mis}\right)\cdot\hat{\zeta}$$

$$P_\zeta^{vis} = \left(P_{T,1}^{\rm vis} + P_{T,2}^{\rm vis}\right)\cdot\hat{\zeta}$$

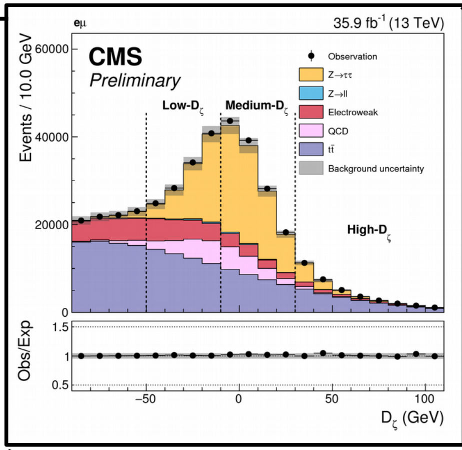
$$D_\zeta = P_\zeta - 1.85 P_\zeta^{vis}$$



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

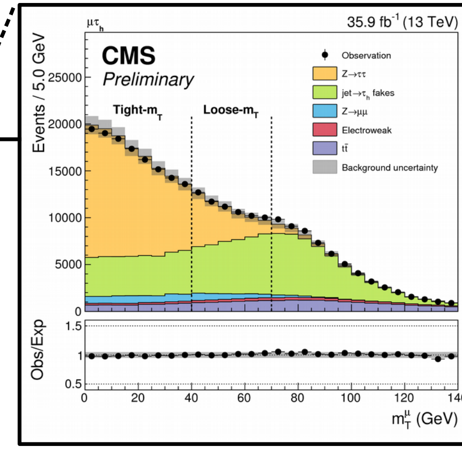


Additional event information



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

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



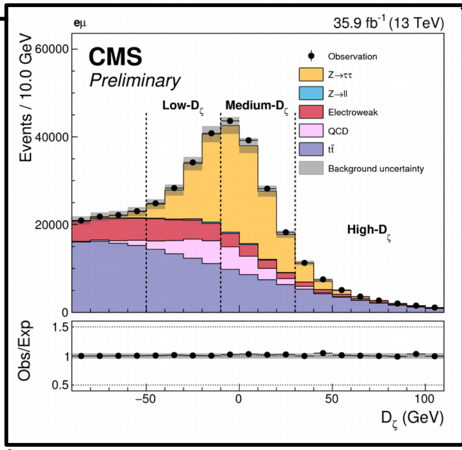
	No B-tag			B-tag		
$H \to \tau\tau \to e\mu$	Low-D_ζ	Medium-D_ζ	High-D_ζ	Low-D_ζ	Medium-D_ζ	High-D_ζ
$H \to \tau\tau \to e\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$H \to \tau\tau \to \mu\tau_h$	Loose-m_T	Tight-m_T		Loose-m_T	Tight-m_T	
$H \to \tau\tau \to \tau_h\tau_h$	(SR)			(SR)		
$Z \to \mu\mu$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

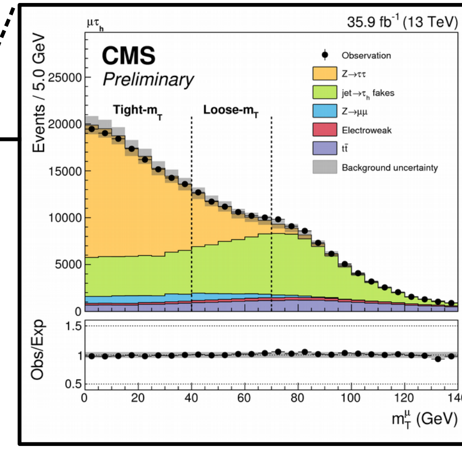
Signal region (SR)

Control region

Additional event information

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





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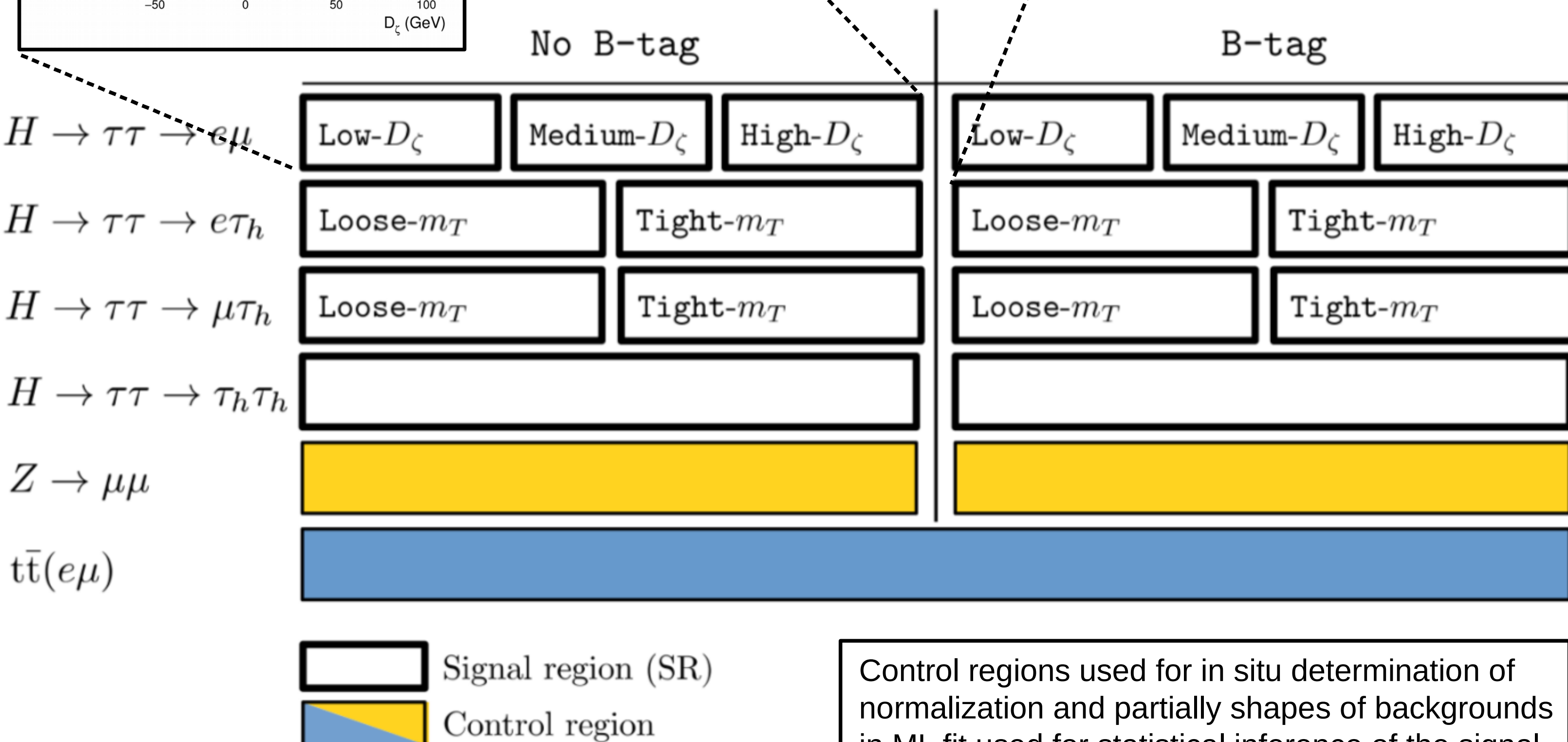
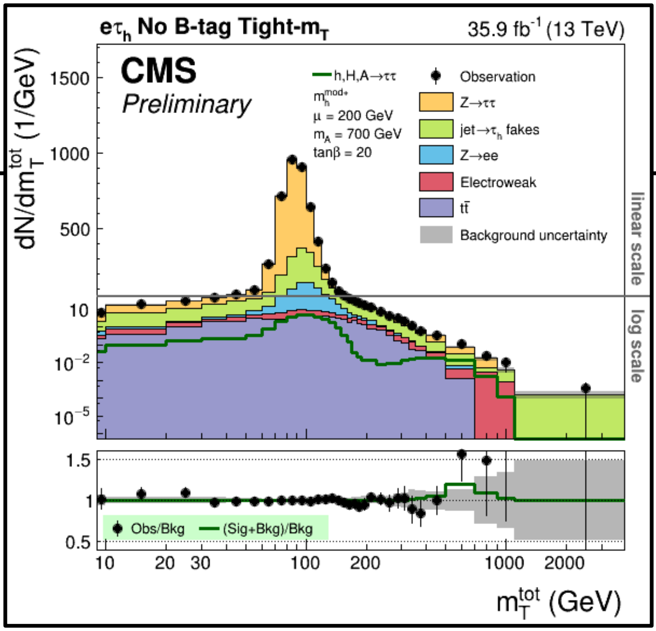


Control regions used for in situ determination of normalization and partially shapes of backgrounds in ML fit used for statistical inference of the signal.

Background modeling

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



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

† Normalization from control region in data.

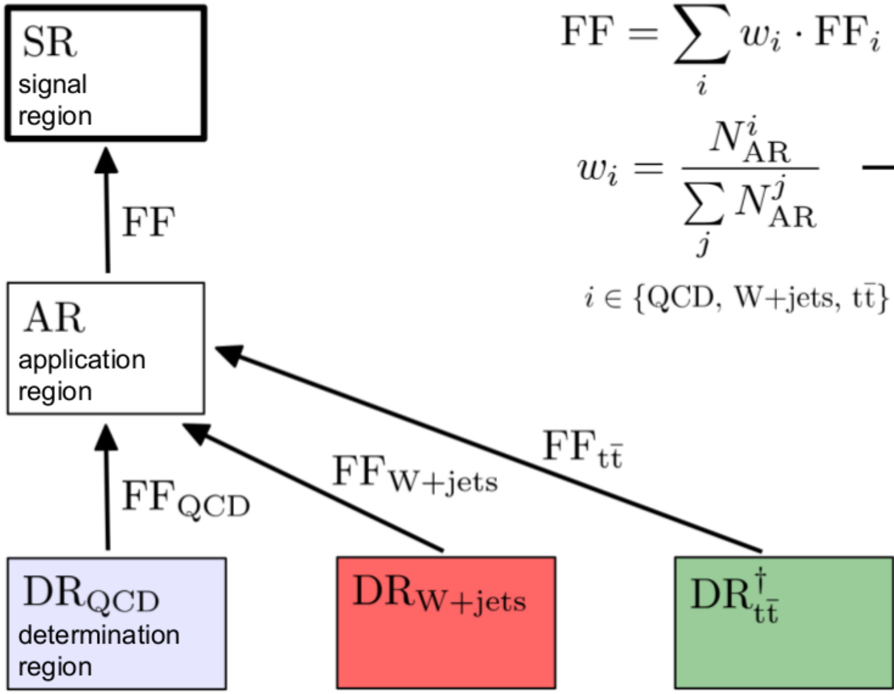
Fake factor (FF) method

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

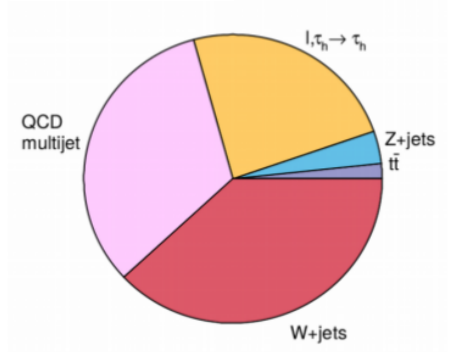
$$\mathrm{FF} = \sum_i w_i \cdot \mathrm{FF}_i$$

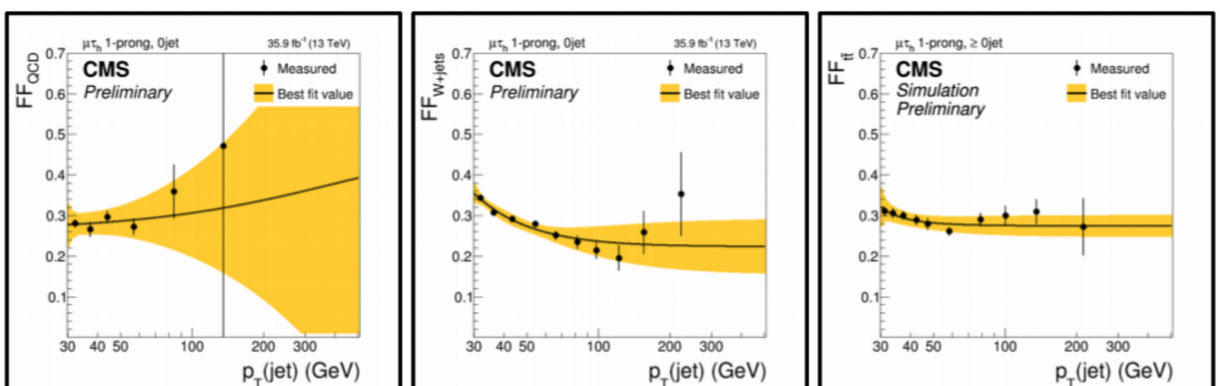
$$w_i = \frac{N^i_{\mathrm{AR}}}{\sum_j N^j_{\mathrm{AR}}}$$

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



Expected event composition in AR:





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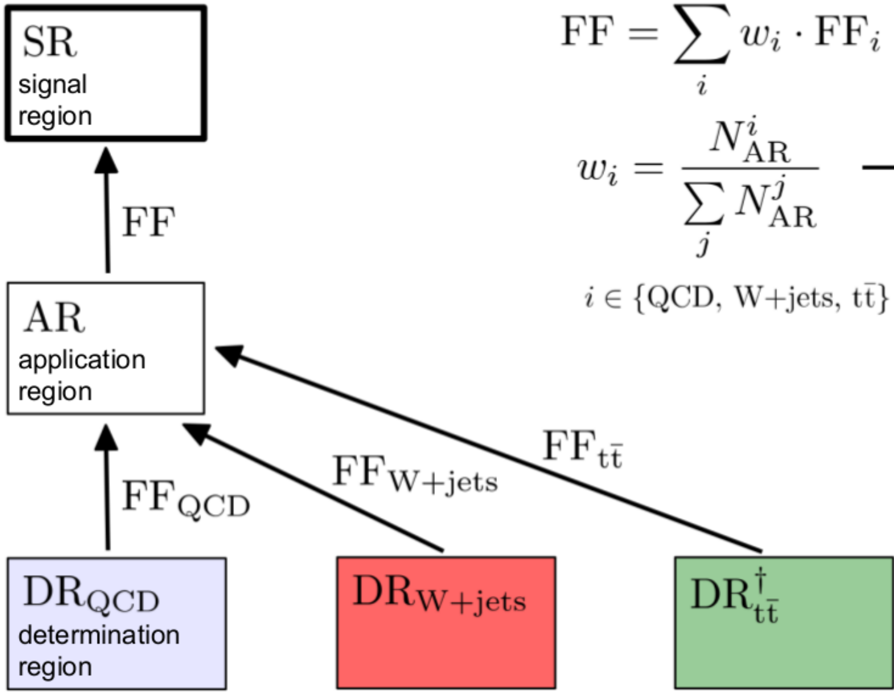
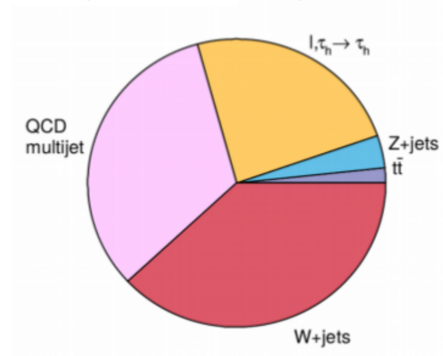


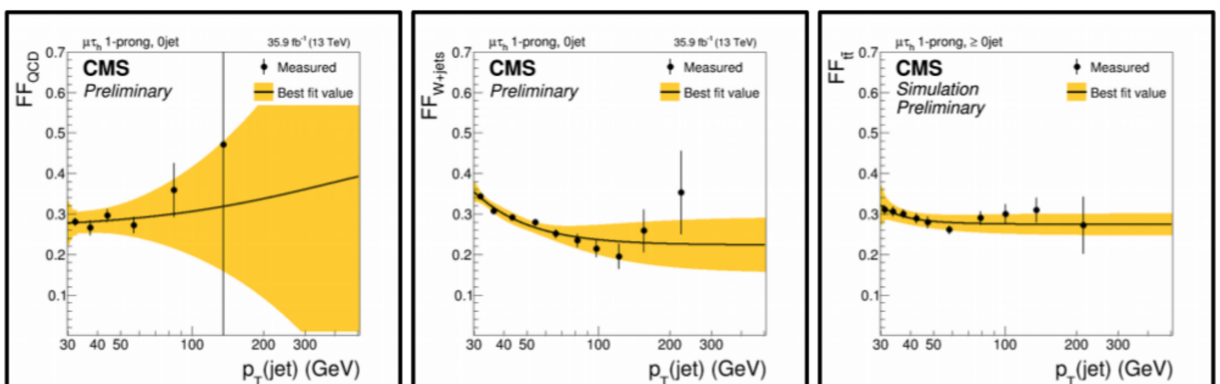
$$FF = \sum_i w_i \cdot FF_i$$

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

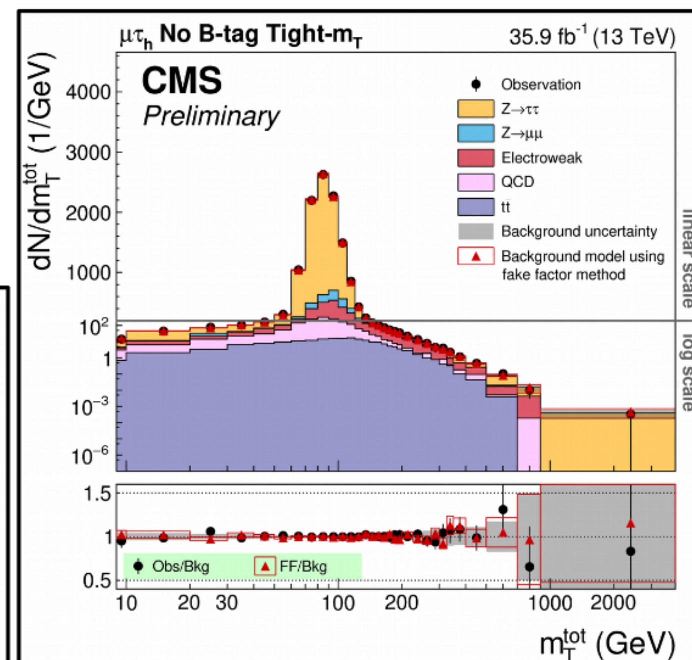
$$i \in \{\mathrm{QCD,\ W{+}jets,\ t\bar{t}}\}$$

Expected event composition in AR:





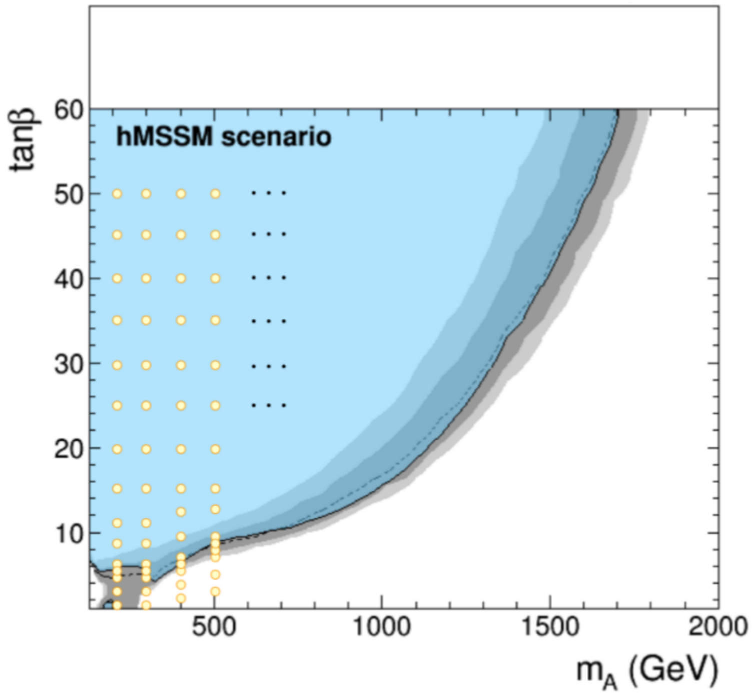
MC driven cross check



Signal modeling

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

- $p_T(A, H, h)$@ 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 parameter space to obtain limit at significance level α.

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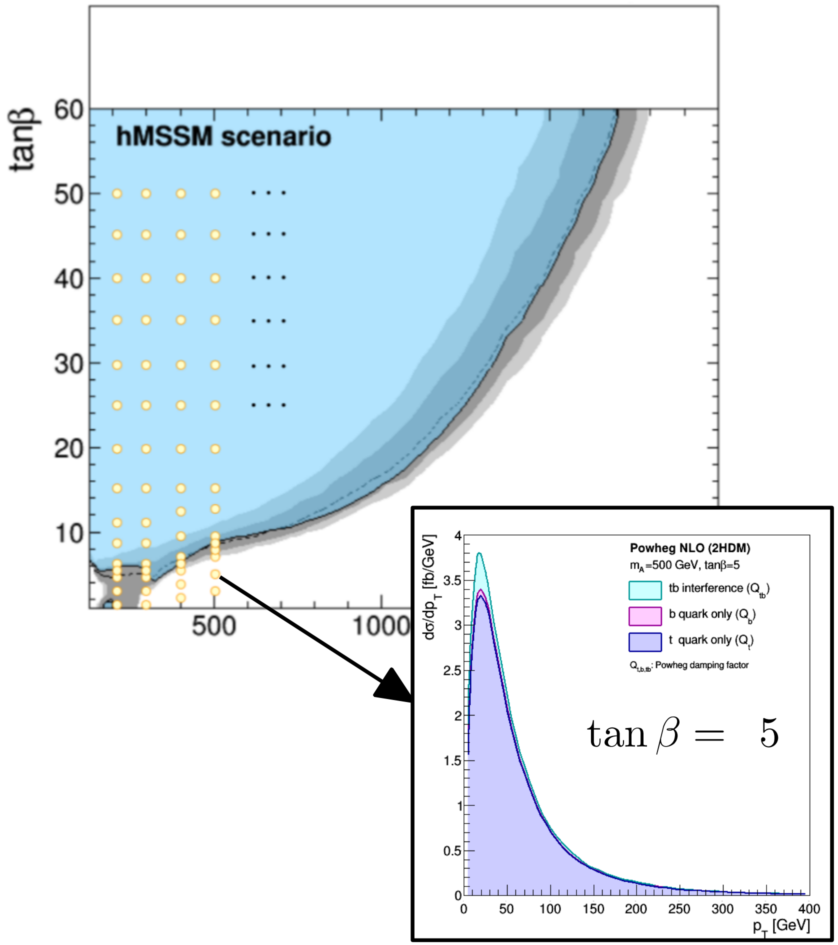

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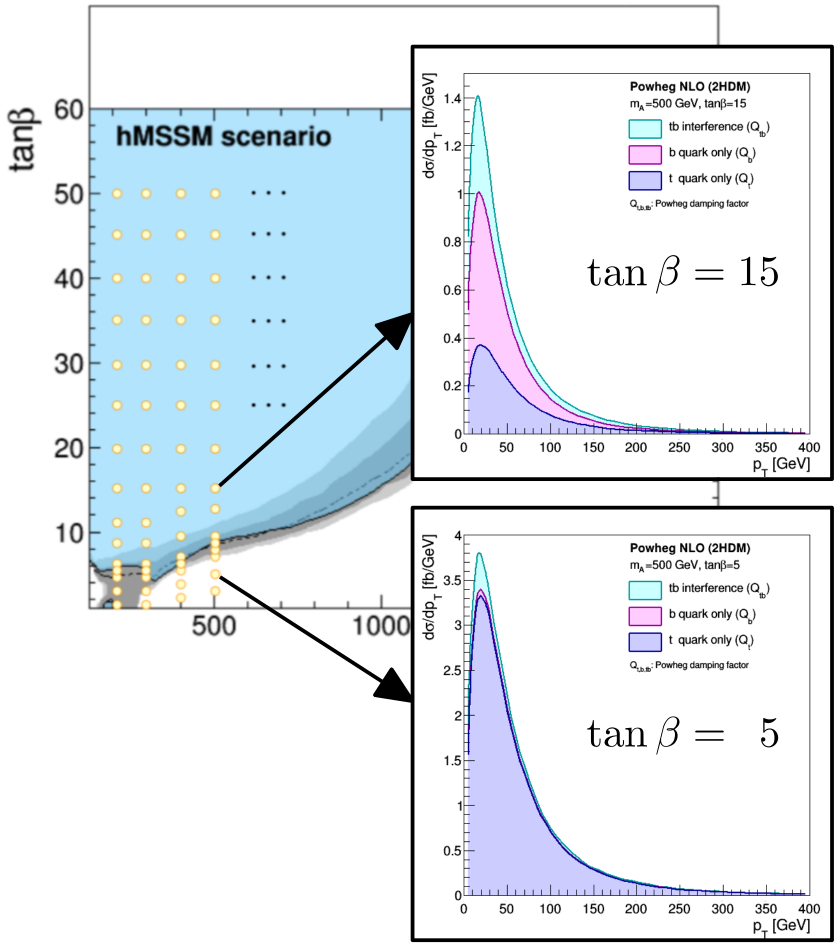

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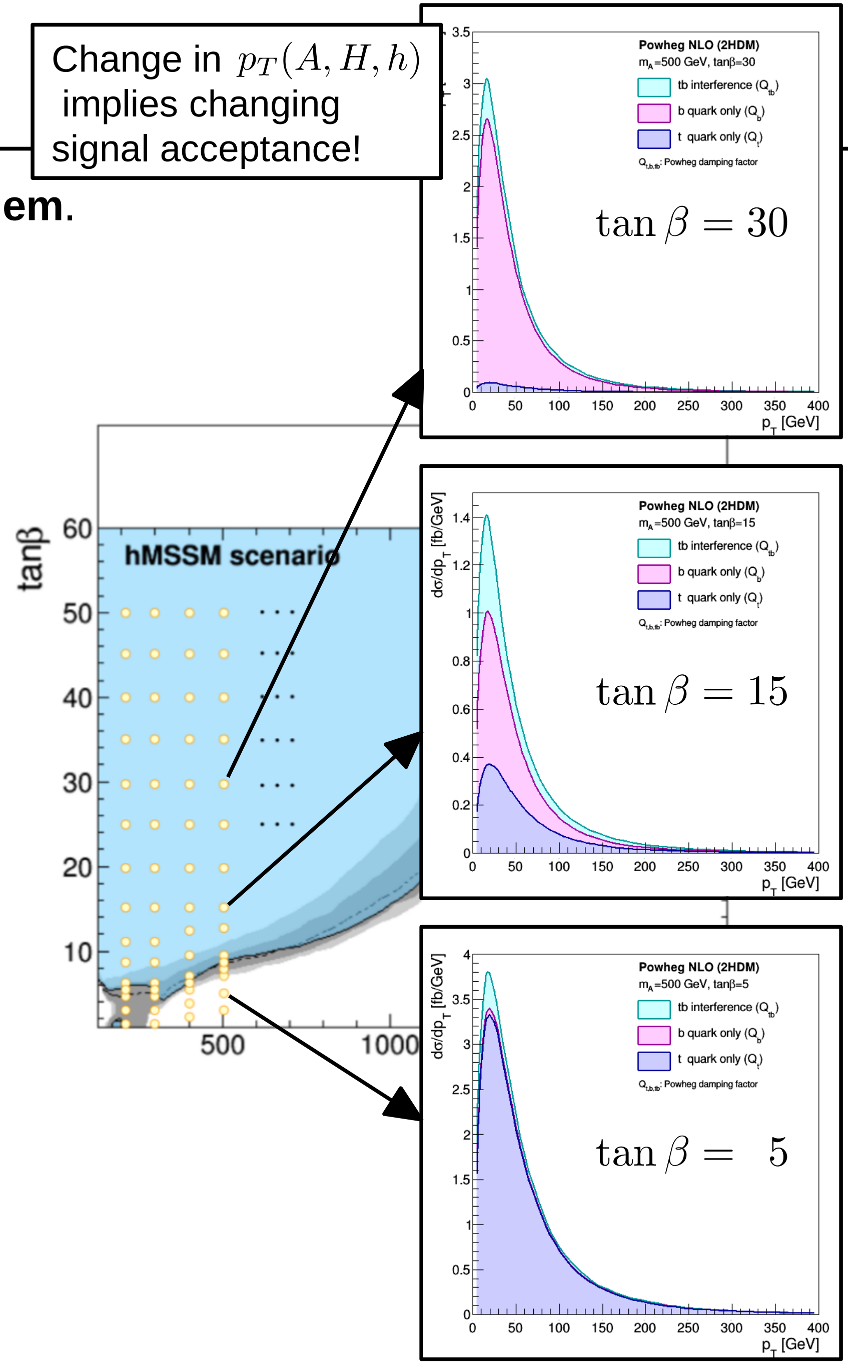

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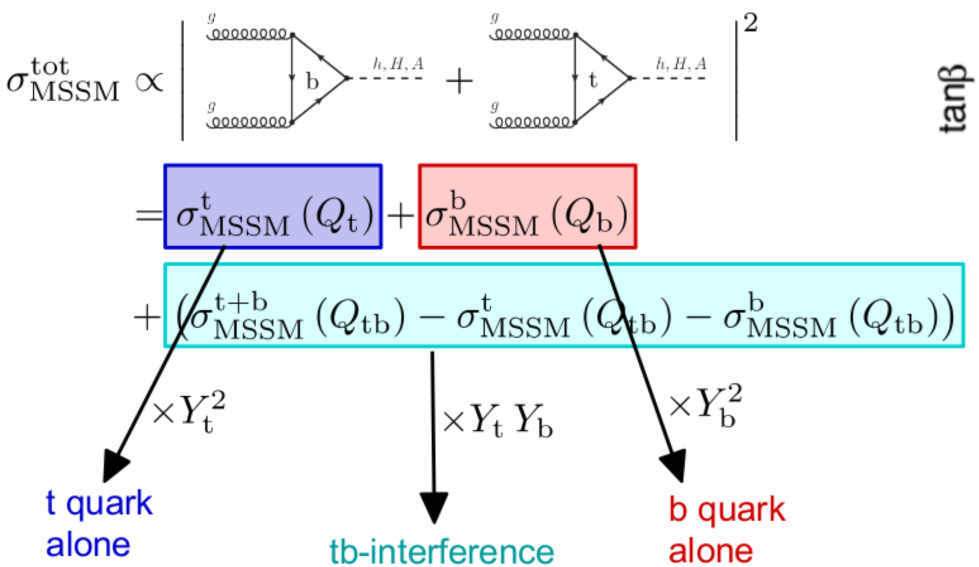
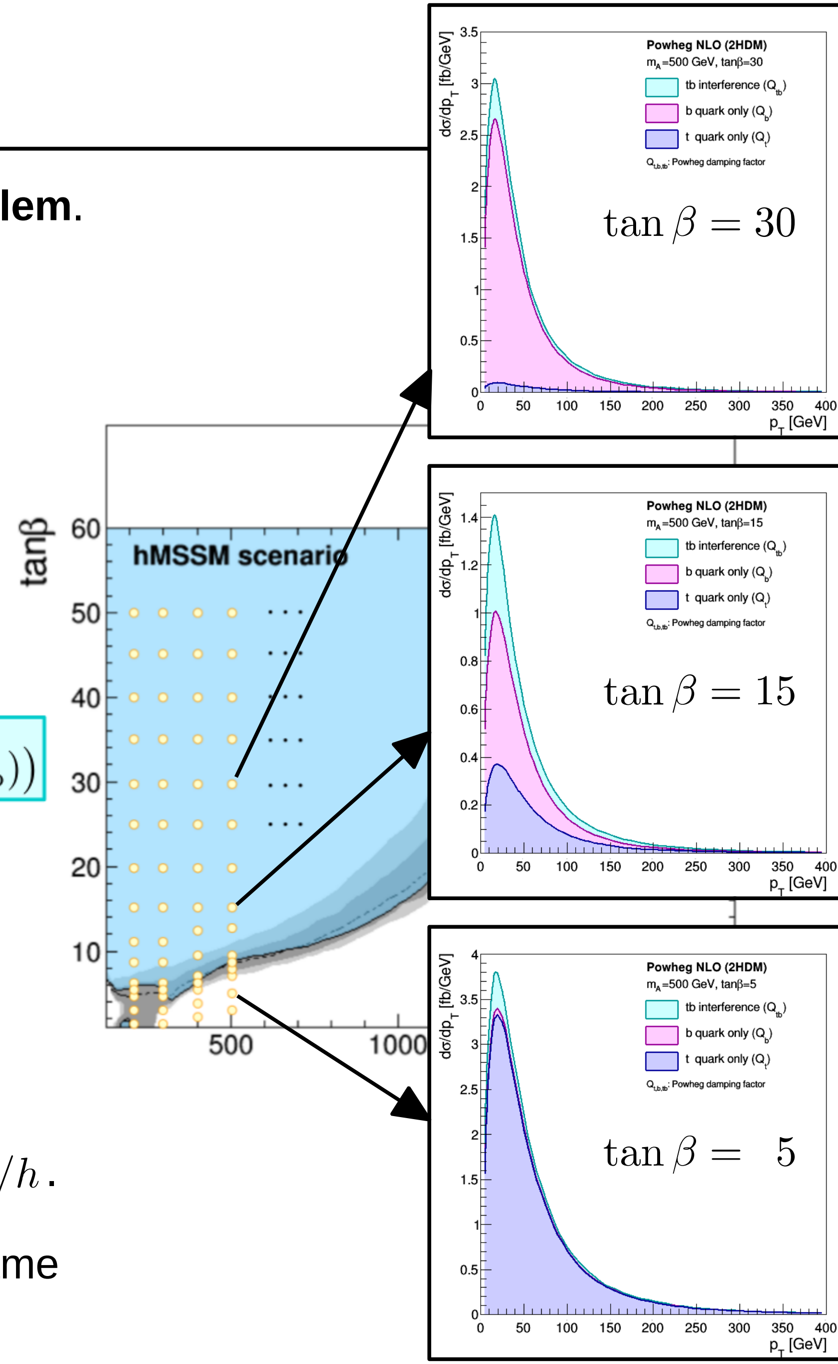
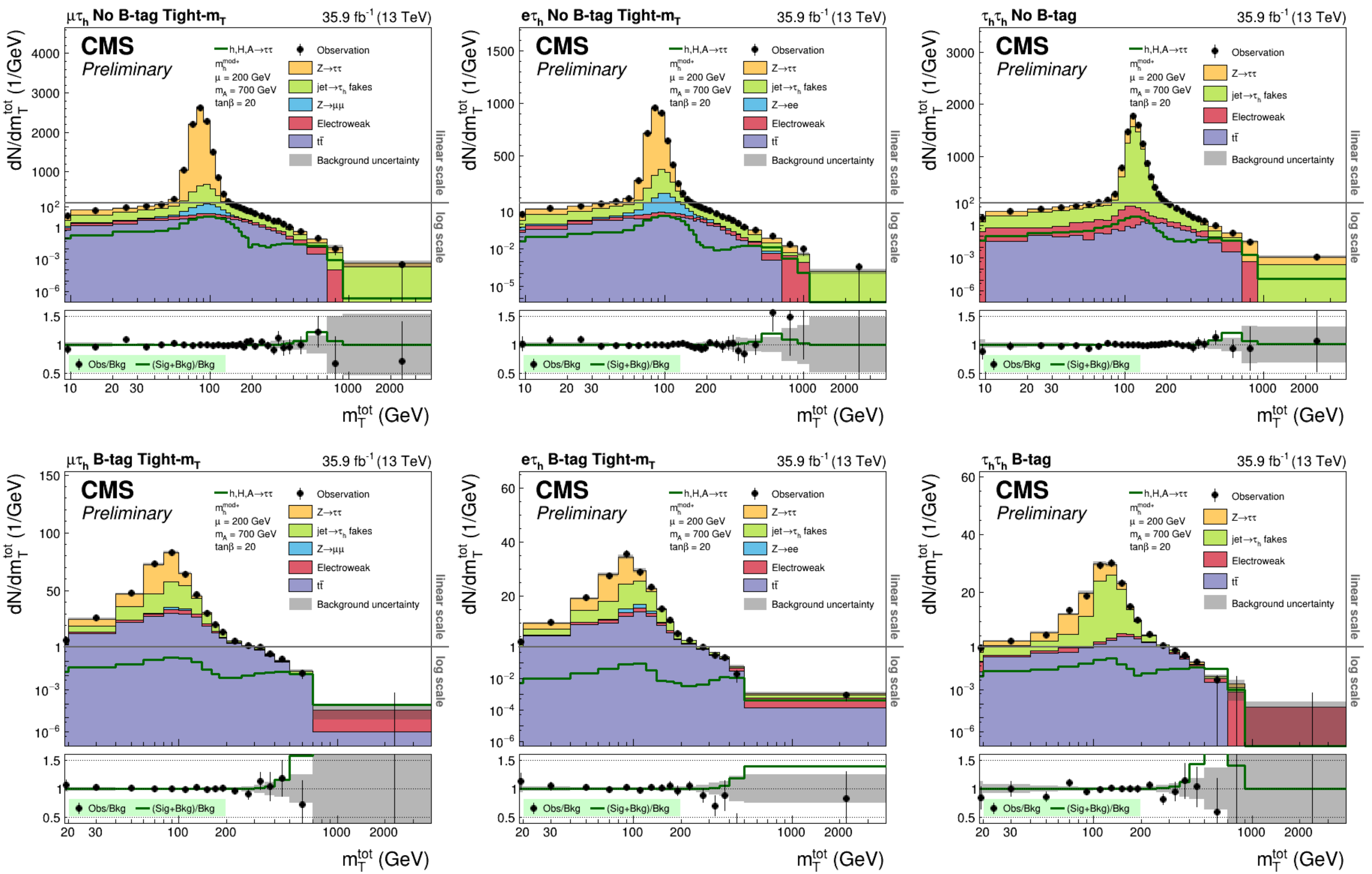




- Taking into account all $\tan\beta$ enhanced SUSY corrections and non-trivial $\tan\alpha$ dependency for H/h.
- Worked out with E. Bagnaschi and S. Liebler in frame of LHCHXSWG-3.

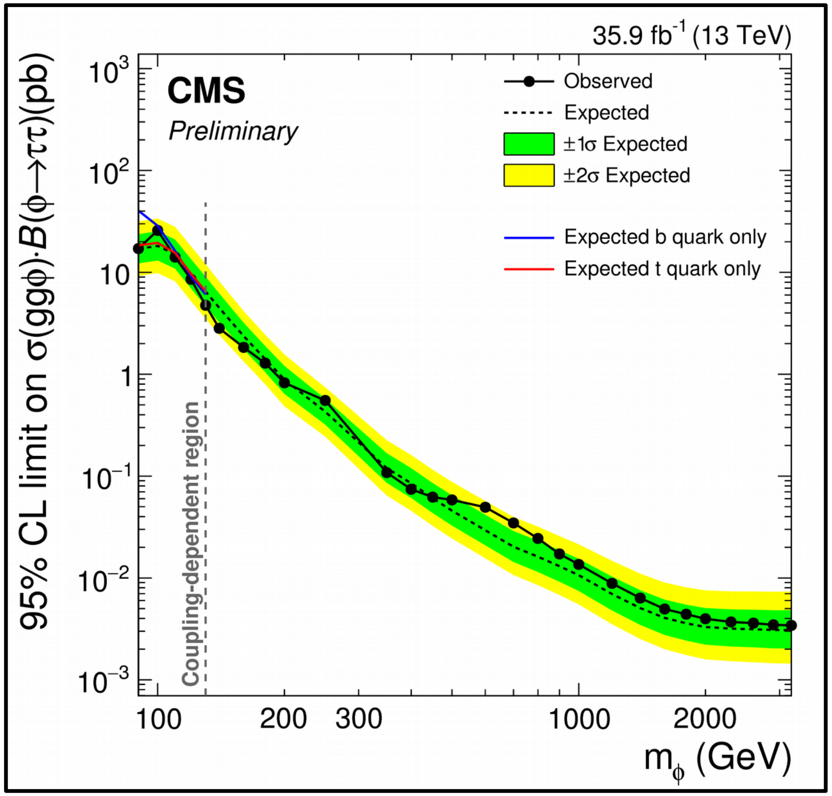
Observation

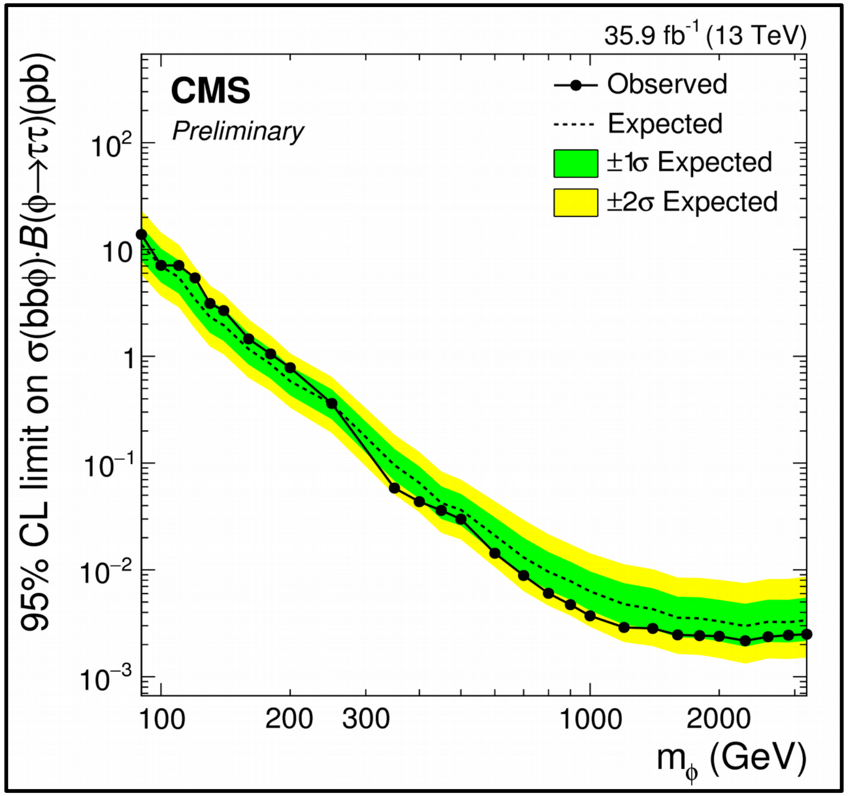
Shown are the most sensitive categories with an MSSM $m_h^{\mathrm{mod+}}$ hypothesis w/ $m_A = 700$ GeV and $\tan\beta = 20$ fitted to the data.



Model independent limits

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





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

Model independent limits

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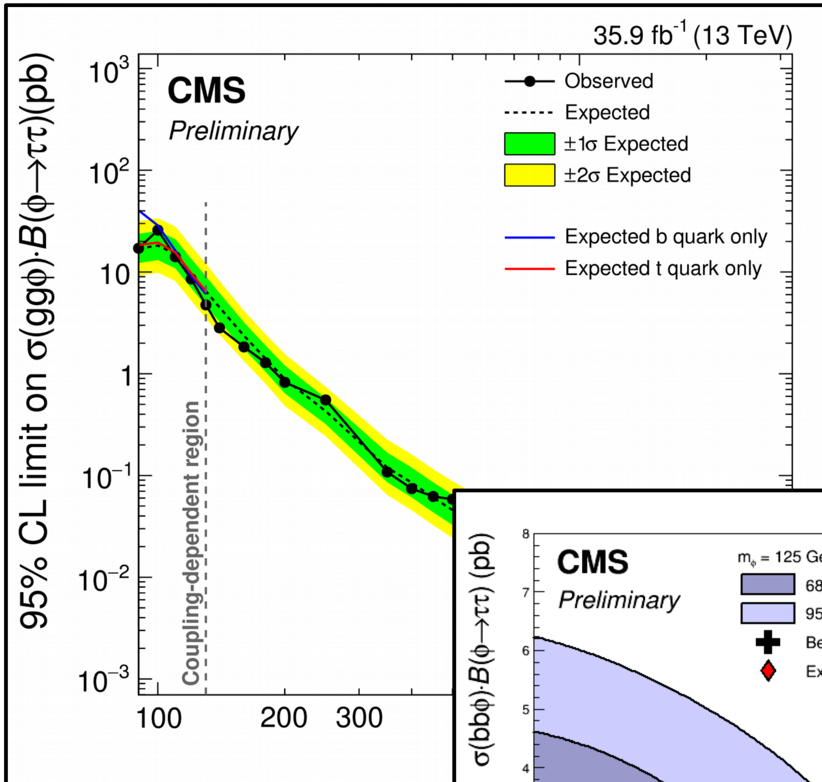
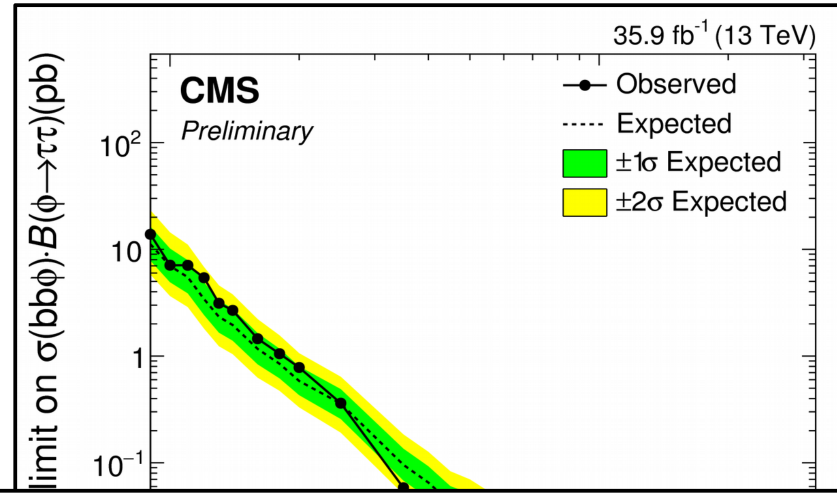
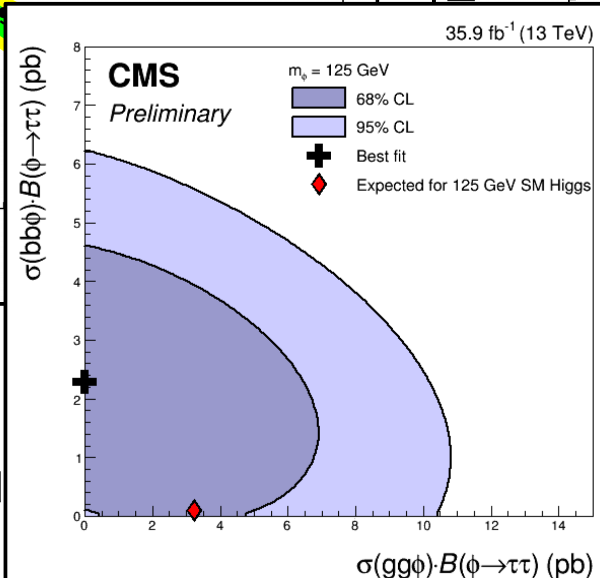




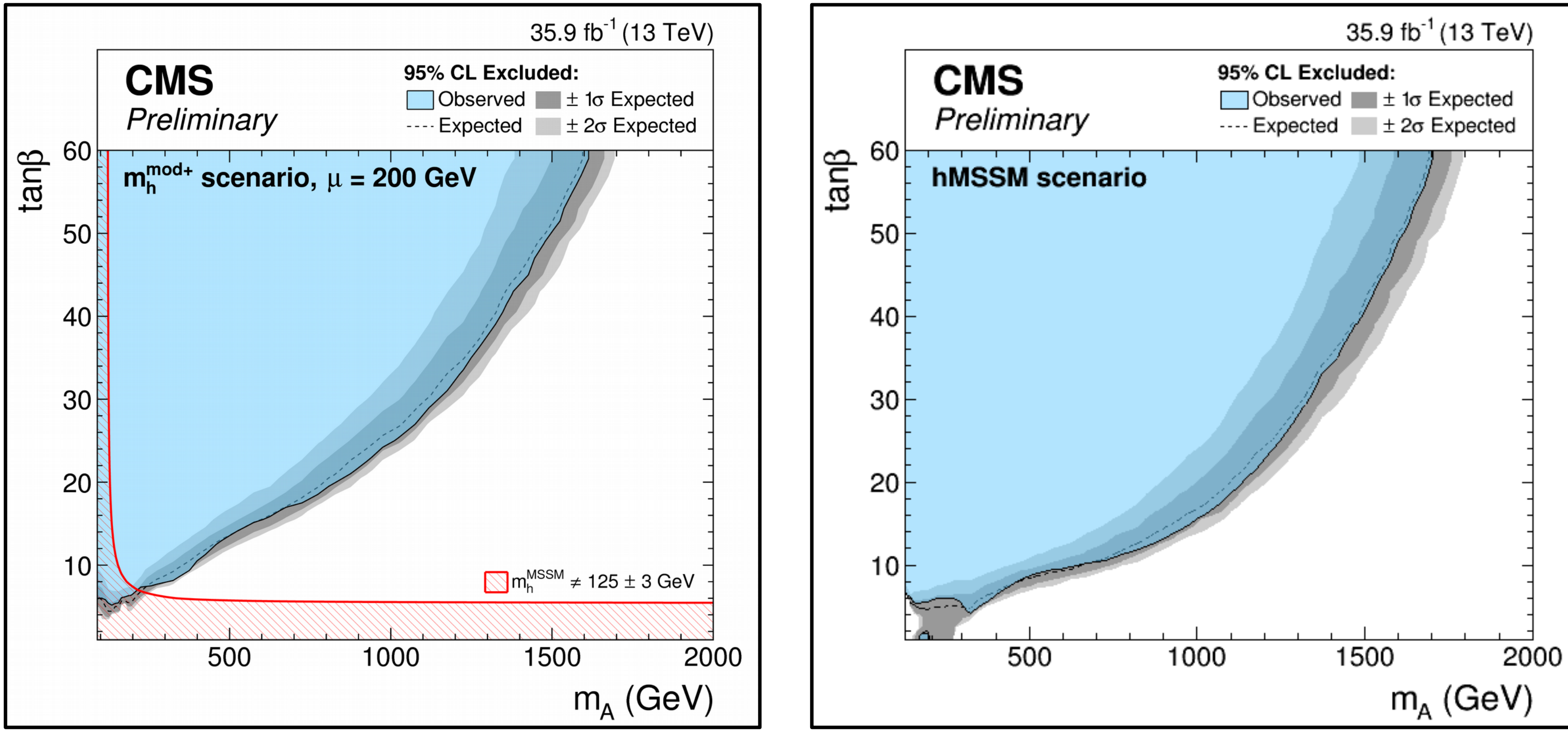


- Provide 3D likelihood scan (40k points for 28 mass points).
- Allows for more sophisticated re-interpretation of the data in alternative/new models/scenarios (→ e.g. arxiv:1507.06706).

- No deviation beyond 2σ
- Cross checks discussed Janek Bechtel.

Model dependent exclusion contours

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



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

Summary

- Di-τ is one of the **most interesting final states** in the Higgs physics program of the LHC.
  - Best access to Higgs boson **couplings to fermions**.
  - **Large event yields** still reasonably well accessible (e.g. for studies of specific production modes).
  - Most interesting final state to **search for extensions** of the SM Higgs sector.
- CMS had a very successful year 2017 with two major publications on SM and MSSM Higgs physics in the di-τ final state on the full dataset of 2016.
- We are well prepared to analyze the full LHC run-2 dataset from 2019 on. Looking forward to these analyses.

Backup

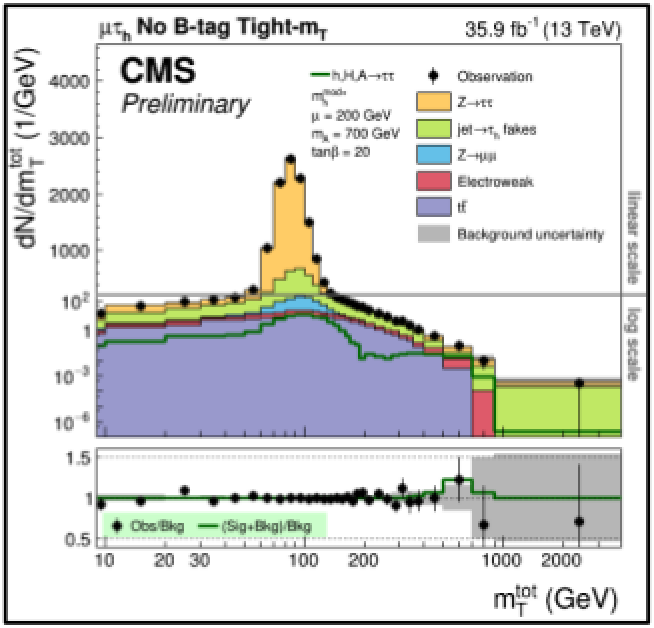
Discriminating variable $\mathrm{m}_{\mathrm{T}}^{\mathrm{tot}}$

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

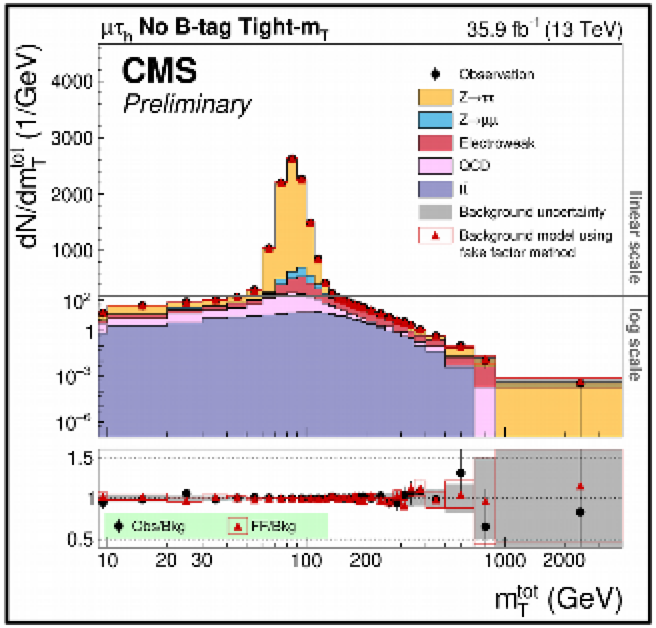
$$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{m_{\mathrm{T}}^2(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_1^{\mathrm{vis}}) + m_{\mathrm{T}}^2(E_{\mathrm{T}}^{\mathrm{miss}}, \tau_2^{\mathrm{vis}}) + m_{\mathrm{T}}^2(\tau_1^{\mathrm{vis}}, \tau_2^{\mathrm{vis}})}\,,$$

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

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

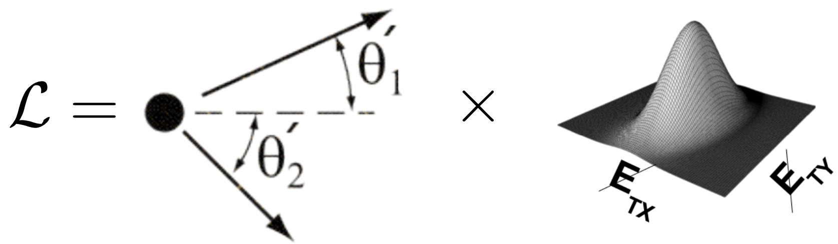


MC driven cross check

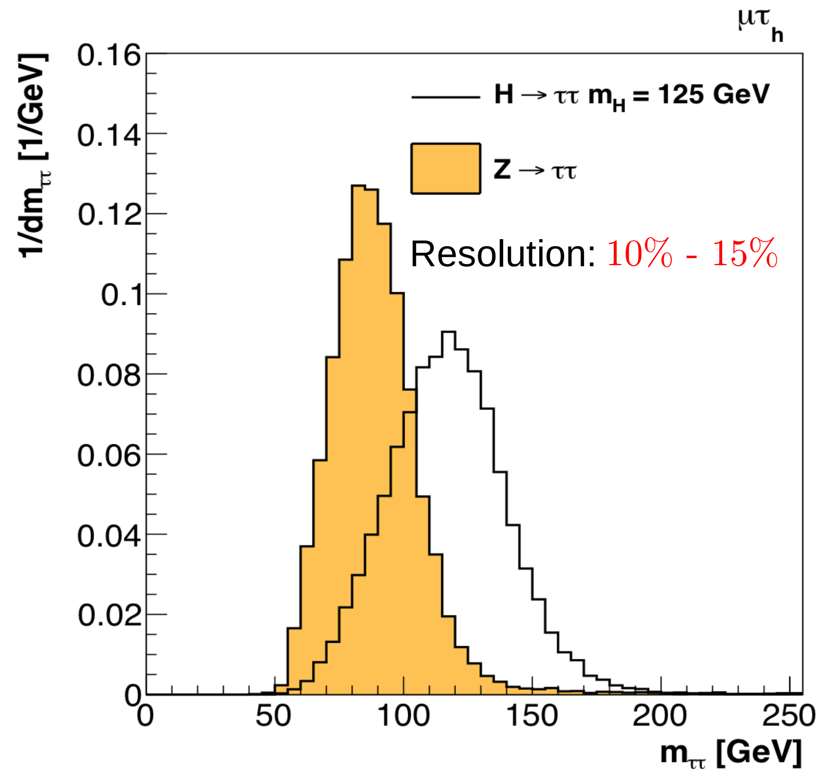


Reconstruction of $m_{\tau\tau}$

- Likelihood approach:



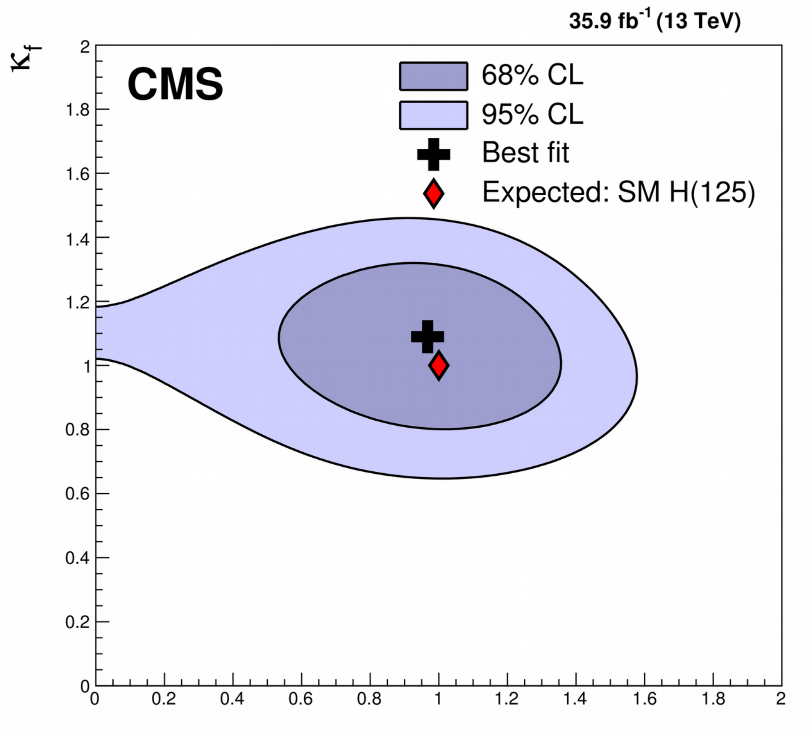
- ME for leptonic τ decay or phase space kinematics of 2-body decay of τ_h .
- Estimate of expected $\not{E}_T$ resolution on event by event basis.
- Inputs: visible decay products, x-, y-component of $\not{E}_T$.
- Free parameters: φ , θ^*, ($m_{\nu\nu}$) per τ.



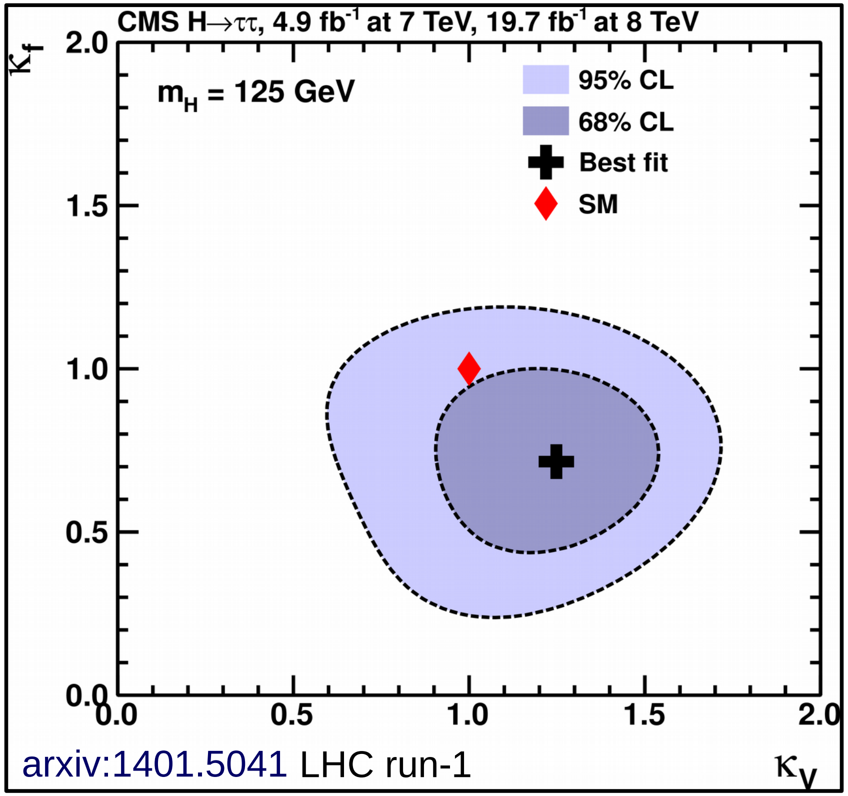
- Find minimum of $\mathcal{L}$ for given $m_{\tau\tau}$ and scan over all possible values of $m_{\tau\tau}$ to find global minimum.

2D likelihood scans

- **Coupling** to fermions and vector bosons:



arxiv:1708.00373 LHC run-2



arxiv:1401.5041 LHC run-1

- These plots include $H \to WW$ as signal process; κ_V driven by VBF & $e\mu$.

Higgs: CP properties (from $H \to f\bar{f}$)

- Obtain P from an angular momentum analysis of the QM system:

Orbital momentum:	$\times$	Intrinsic parity of fermions:
$P(Y_l^m(\theta,\varphi)) = (-1)^l \cdot Y_l^m(\theta,\varphi)$		$P(f) = (+1)\cdot f \qquad P(\bar{f}) = (-1)\cdot f$

- Obtain C from $P \times (\pm 1)$ for permutations of objects (→spin statistics):

$$|1,\pm1\rangle = |{}^1\!/_2,\pm{}^1\!/_2\rangle \otimes |{}^1\!/_2,\pm{}^1\!/_2\rangle$$

$$|1,\quad 0\rangle = \sqrt{\frac{1}{2}}\left(|{}^1\!/_2,+{}^1\!/_2\rangle \otimes |{}^1\!/_2,-{}^1\!/_2\rangle + (|{}^1\!/_2,-{}^1\!/_2\rangle \otimes |{}^1\!/_2,+{}^1\!/_2\rangle\right)$$

$(+1)$ under permutations.

$$|0,\quad 0\rangle = \sqrt{\frac{1}{2}}\left(|{}^1\!/_2,+{}^1\!/_2\rangle \otimes |{}^1\!/_2,-{}^1\!/_2\rangle - (|{}^1\!/_2,-{}^1\!/_2\rangle \otimes |{}^1\!/_2,+{}^1\!/_2\rangle\right)$$

(-1) under permutations.

- For two fermion system:

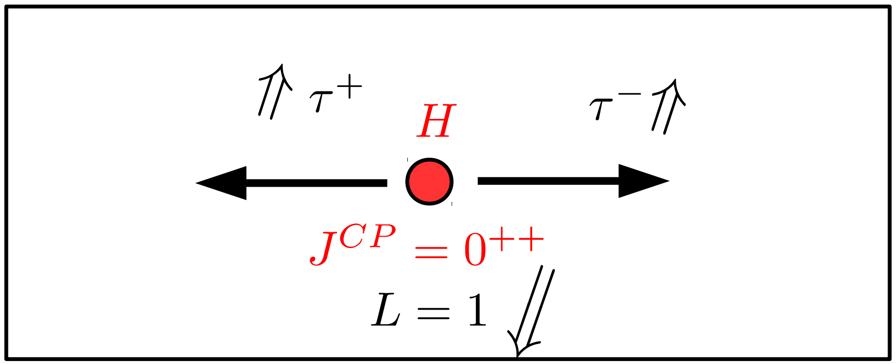
$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$
$$CP = (-1)^{S+1}$$

→ CP of parent particle translates into spin configuration of two fermion system.

Higgs: CP properties (from $H \to f\bar{f}$)

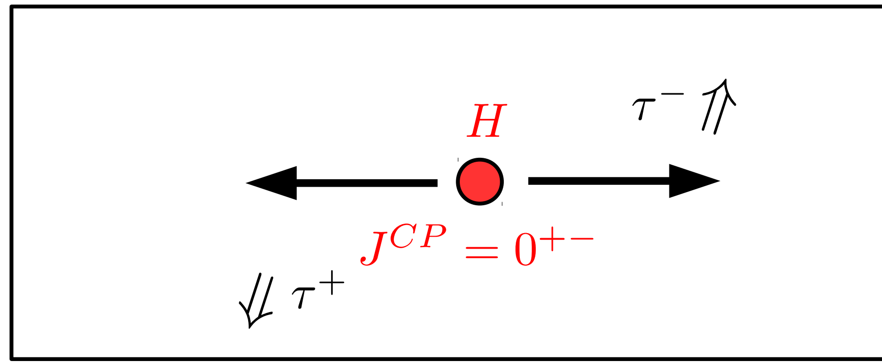
CP-even:

$L = 1 \qquad S = 1$



CP-odd:

$L = 0 \qquad S = 0$



- For two fermion system:

$$
\begin{aligned}
P &= (-1)^{L+1} \\
C &= (-1)^{L+S} \\
CP &= (-1)^{S+1}
\end{aligned}
$$

CP of parent particle translates into spin configuration of two fermion system.

Higgs: CP properties (from $H \to \tau\tau$)

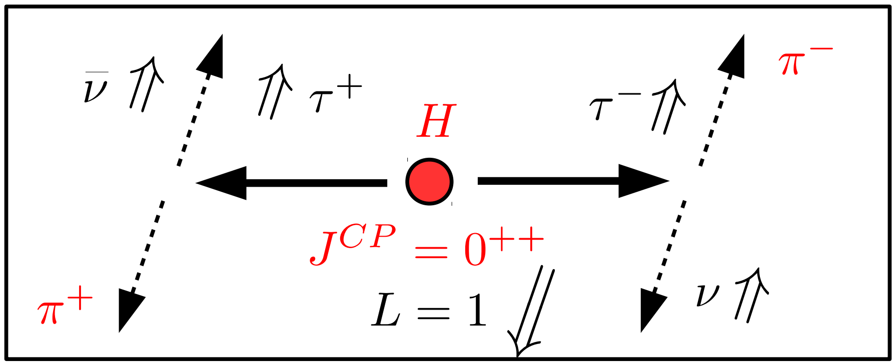
E.g. $\tau^- \to \pi^- \nu$ makes spin configuration detectable!

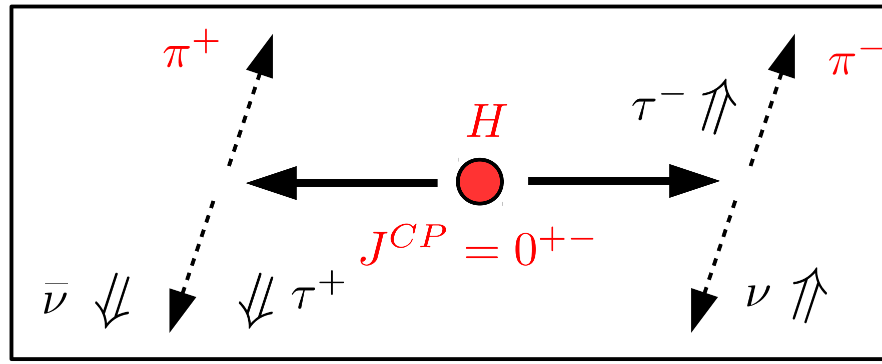
CP-even:

$L = 1 \quad S = 1$

CP-odd:

$L = 0 \quad S = 0$





Decay width: $\Gamma_{H\to\tau\tau} \propto 1 - \vec{s}_z^{\,-} \cdot \vec{s}_z^{\,+} + \underbrace{\cos(2\phi)\left(\vec{s}_T^{\,-} \cdot \vec{s}_T^{\,+}\right)}_{CP\text{-even}} - \underbrace{\sin(2\phi)\left[\left(\vec{s}_T^{\,-} \times \vec{s}_T^{\,+}\right) \cdot \hat{\vec{k}}^{-}\right]}_{CP\text{-odd}}$

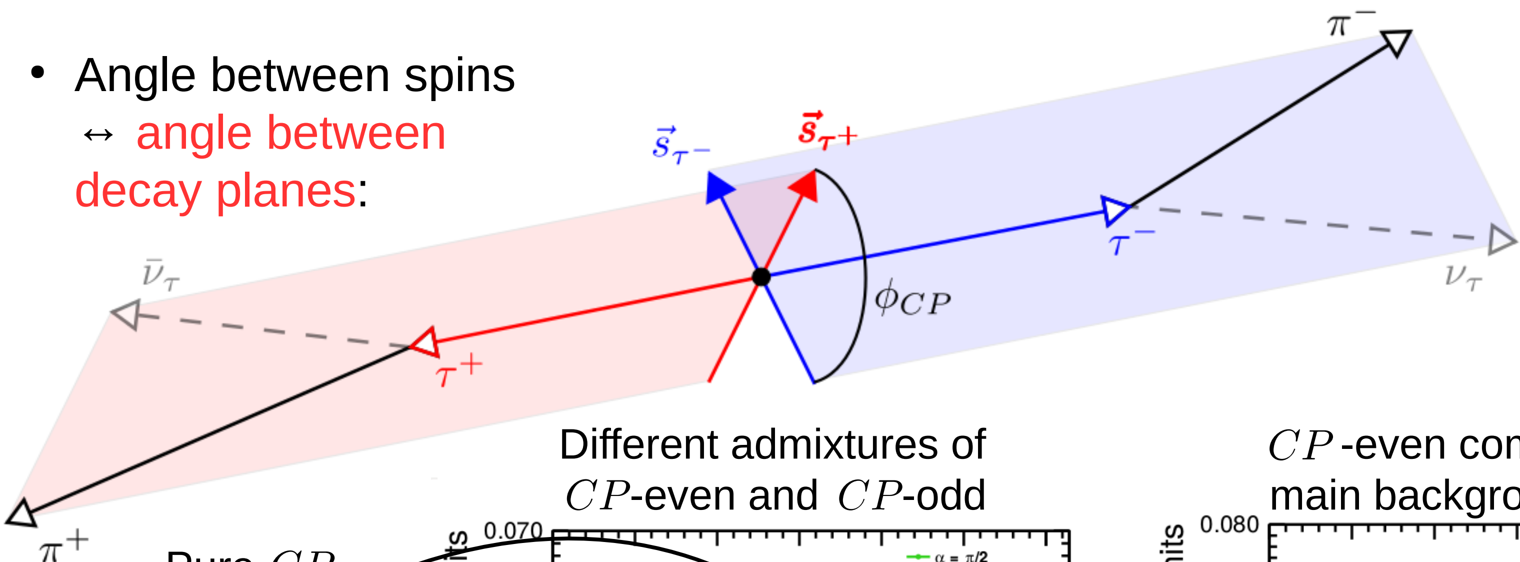
- For two fermion system:

$$P = (-1)^{L+1}$$
$$C = (-1)^{L+S}$$
$$CP = (-1)^{S+1}$$

CP of parent particle translates into spin configuration of two fermion system.

Transverse spin polarization in the di-τ system

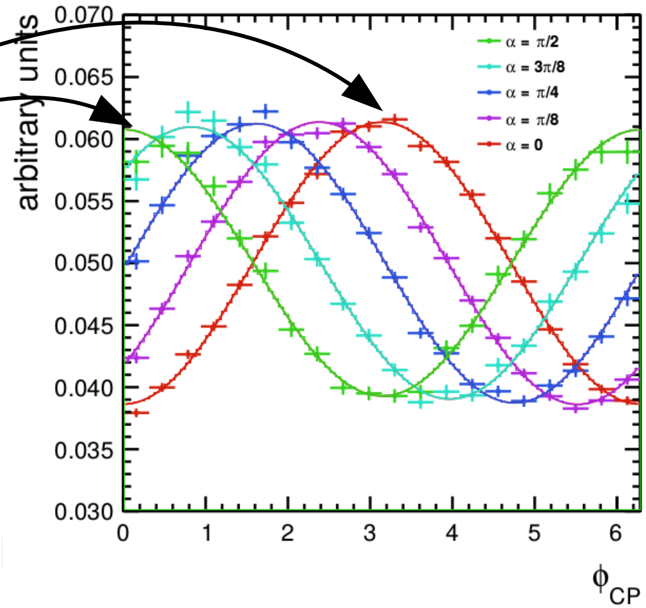
- Angle between spins $\leftrightarrow$ angle between decay planes:



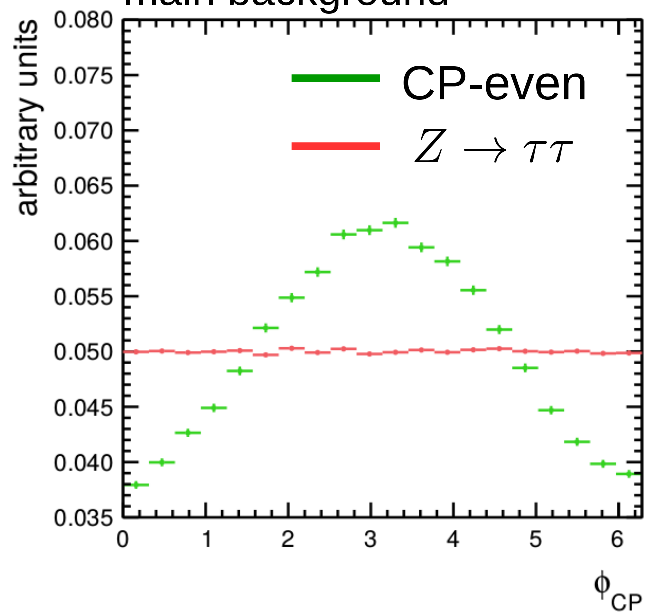
Different admixtures of CP-even and CP-odd

Pure CP-even

Pure CP-odd



CP-even compared to main background



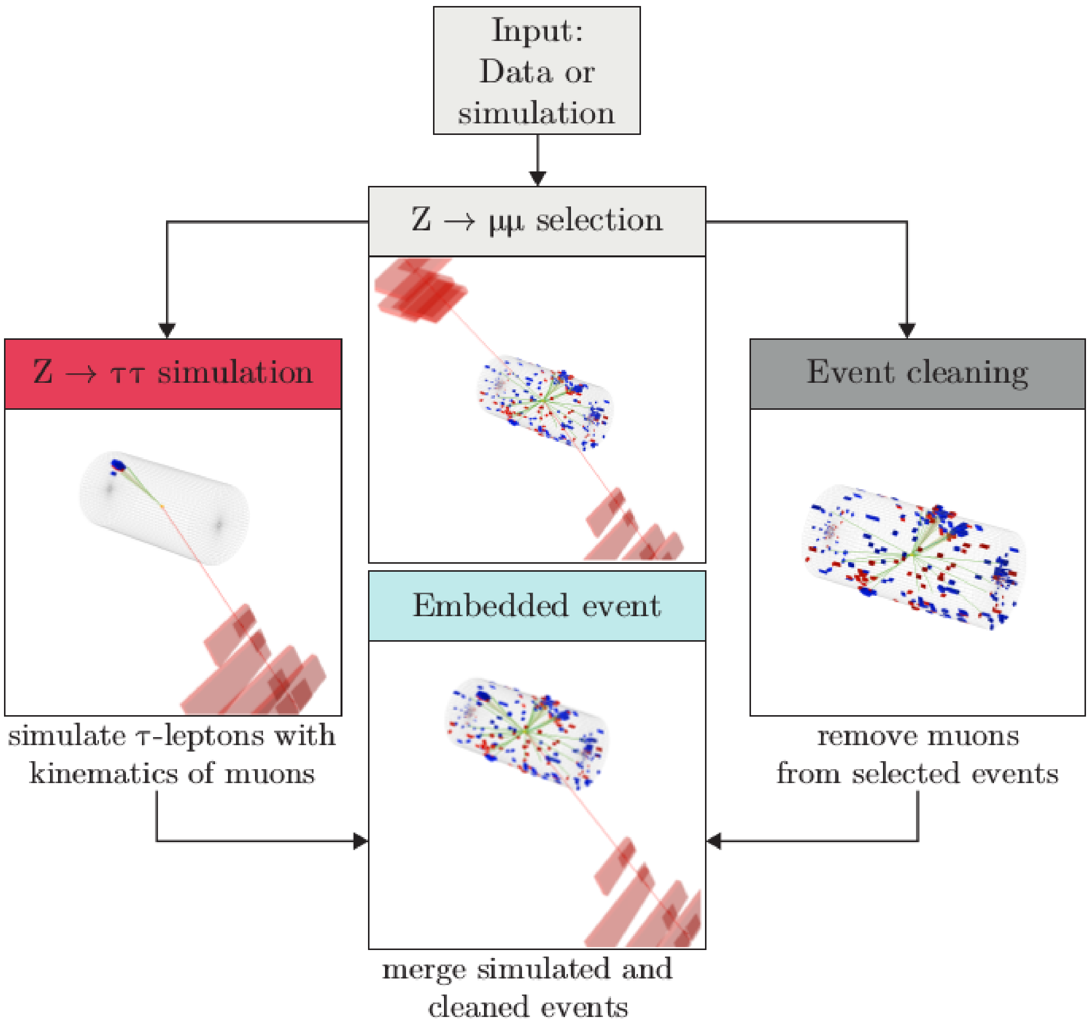
arXiv:0812.1910

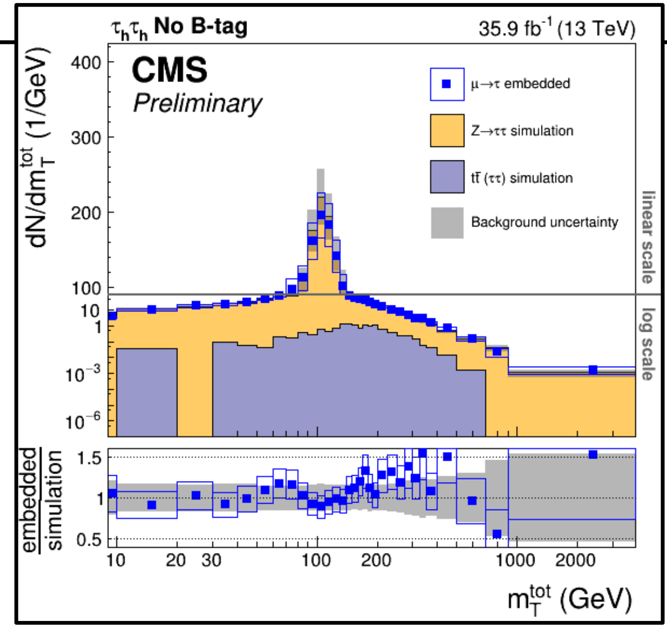
arXiv:1108.0607

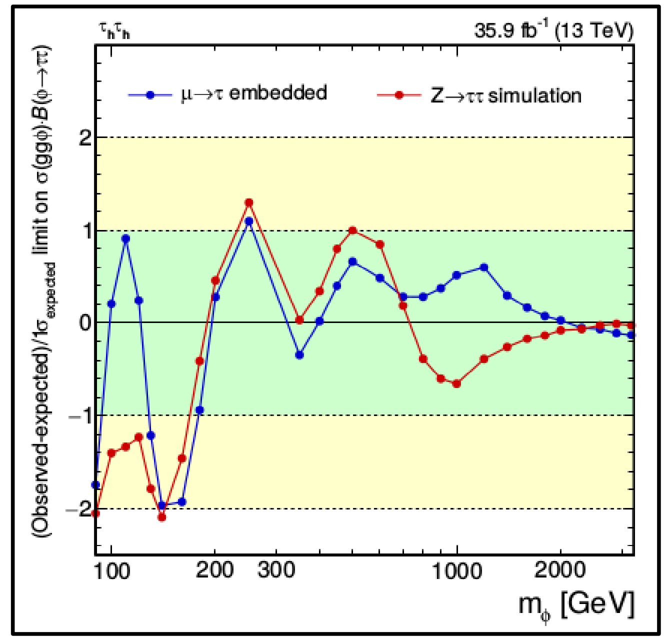
arXiv:1408.0798

Embedding cross check

- Replace muons in $Z \to \mu\mu$ events in data by simulated τ decays:

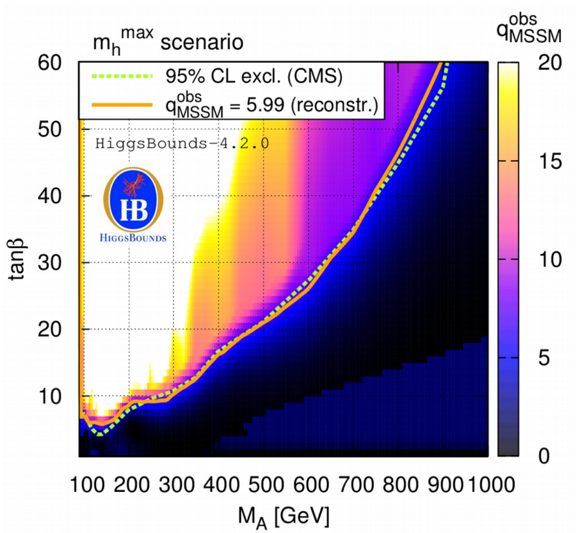


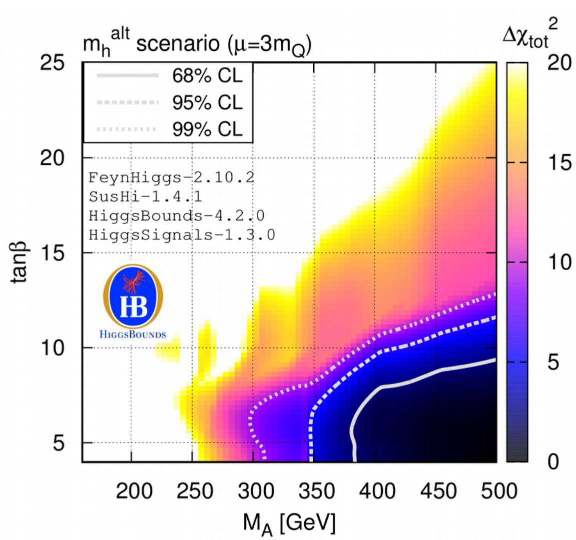


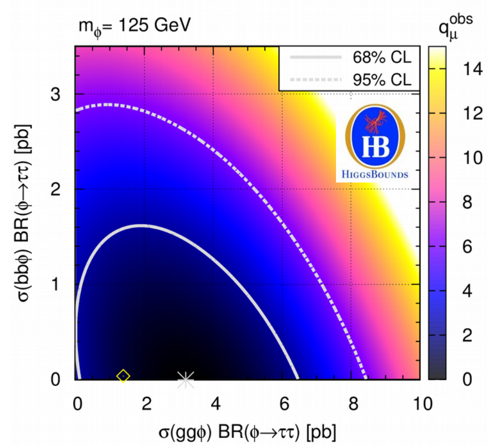


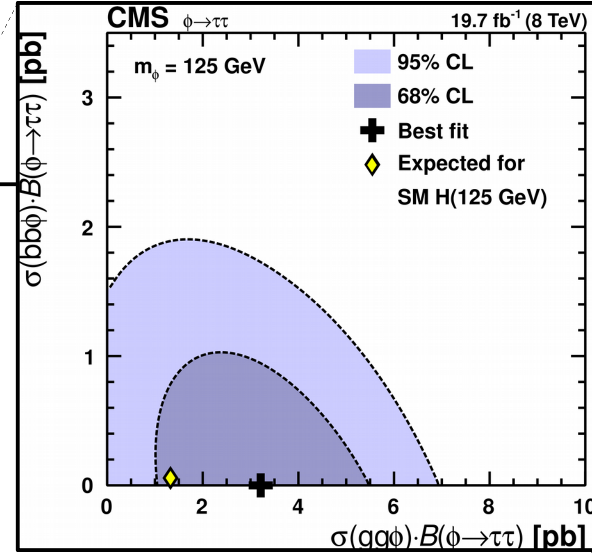
2D NLL picked up by theory

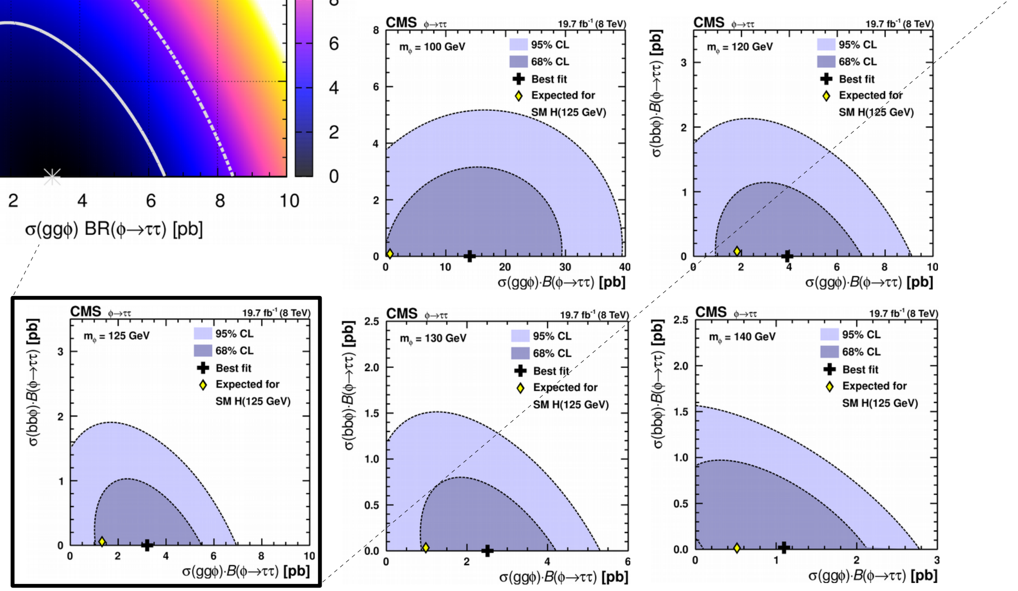
- First application to new models (using HiggsBounds): arXiv:1507.06706

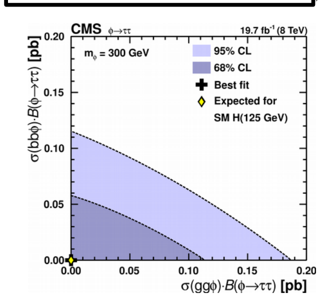












3D database: $1.25 \cdot 10^6$ ΔNLL points for 31 masses between $m_\phi = 90 \ldots 1000$ GeV.

arXiv:1408.3316

Comparison ATLAS vs CMS