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## IFAE 2016 - GENOVA

“Ricerca di  
 $H \rightarrow h(125)h(125) \rightarrow bb\tau\tau$  e  $A \rightarrow Zh(125) \rightarrow \ell\ell\tau\tau$   
a 8 TeV in CMS”

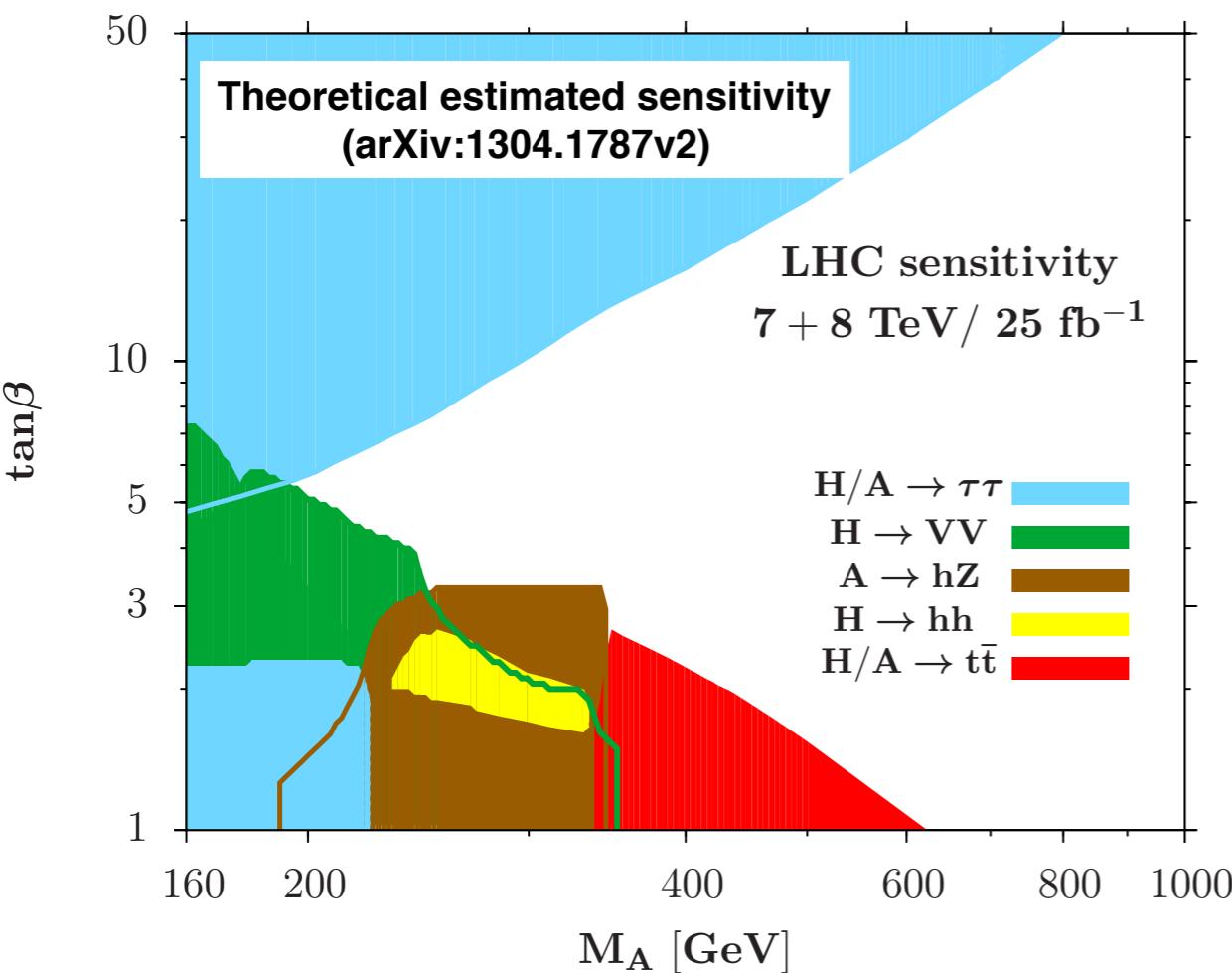
# Outline

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- Motivazione dell'analisi
- Strategia di analisi
- Risultati
  - Limiti di esclusione “*model independent*”
  - Interpretazione nei modelli *MSSM & 2HDM*
- Prospettive future

# Motivazione dell'analisi

- 2012: Scoperta del bosone di Higgs a 125 GeV ☺
- Molte domande ancora aperte (*i.e. gerarchia, materia oscura...*) ☹
- Le estensioni più semplici sono date dai modelli *2HDM* (*i.e. MSSM...*)
  - 5 bosoni di Higgs fisici: **H<sup>+</sup>, H<sup>-</sup>, A, H, h**
  - A livello “albero” sono descritti da 2 parametri: **m<sub>A</sub>, tanβ**
- $H \rightarrow hh$  &  $A \rightarrow Zh$  permettono di esplorare le regioni a basso valore di tanβ in un intervallo di massa tra 250 e 350 GeV.



## Stato finale: hh→bbττ

- Segnatura chiara
- Alti *Branching Ratio*
  - $BR(h \rightarrow bb) \sim 58\%$
  - $BR(h \rightarrow \tau\tau) \sim 6,3\%$
- Stato finale inesplorato

## Stato finale: Zh→ℓℓττ

- $Z \rightarrow ee/\mu\mu$  è interamente ricostruito
- $h \rightarrow \tau\tau$  è il secondo *Branching Ratio* tra i fermioni
- Stato finale inesplorato

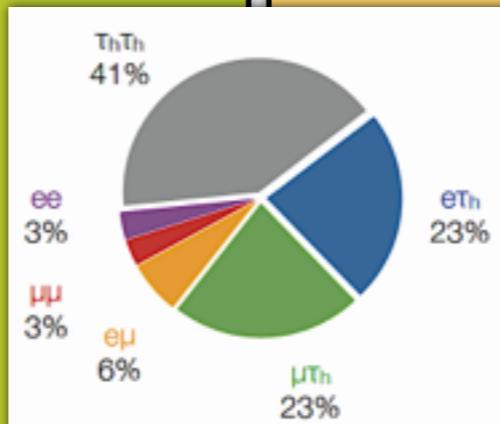
# Strategia di analisi

$H \rightarrow hh \rightarrow \tau\tau bb$

3 canali di decadimento  
(della coppia  $\tau\tau$ )

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

$\times$



$A \rightarrow Zh \rightarrow ll\tau\tau$

3 canali di decadimento  
(della coppia  $\tau\tau$ )

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

$\times$

3 categorie  
(dal  $b$ -tagging di due jet)

$2jet\text{-}0tag$      $2jet\text{-}1tag$      $2jet\text{-}2tag$

$+$

Reiezione dei fondi:  
 $70 \text{ GeV} < m_{bb} < 150 \text{ GeV}$   
 $90 \text{ GeV} < m_{\tau\tau} < 150 \text{ GeV}$

3 canali x 3 categorie

=

**9 stati finali**

2 categorie  
(dal decadimento della  $Z$ )

$Z \rightarrow e^+e^-$      $Z \rightarrow \mu^+\mu^-$

$+$

Reiezione dei fondi:  
 $L_T^h = \sum p_T^{\text{visibile}}(\tau) >$  soglia dipendente  
dal decadimento della coppia  $\tau\tau$

4 canali x 2 categorie

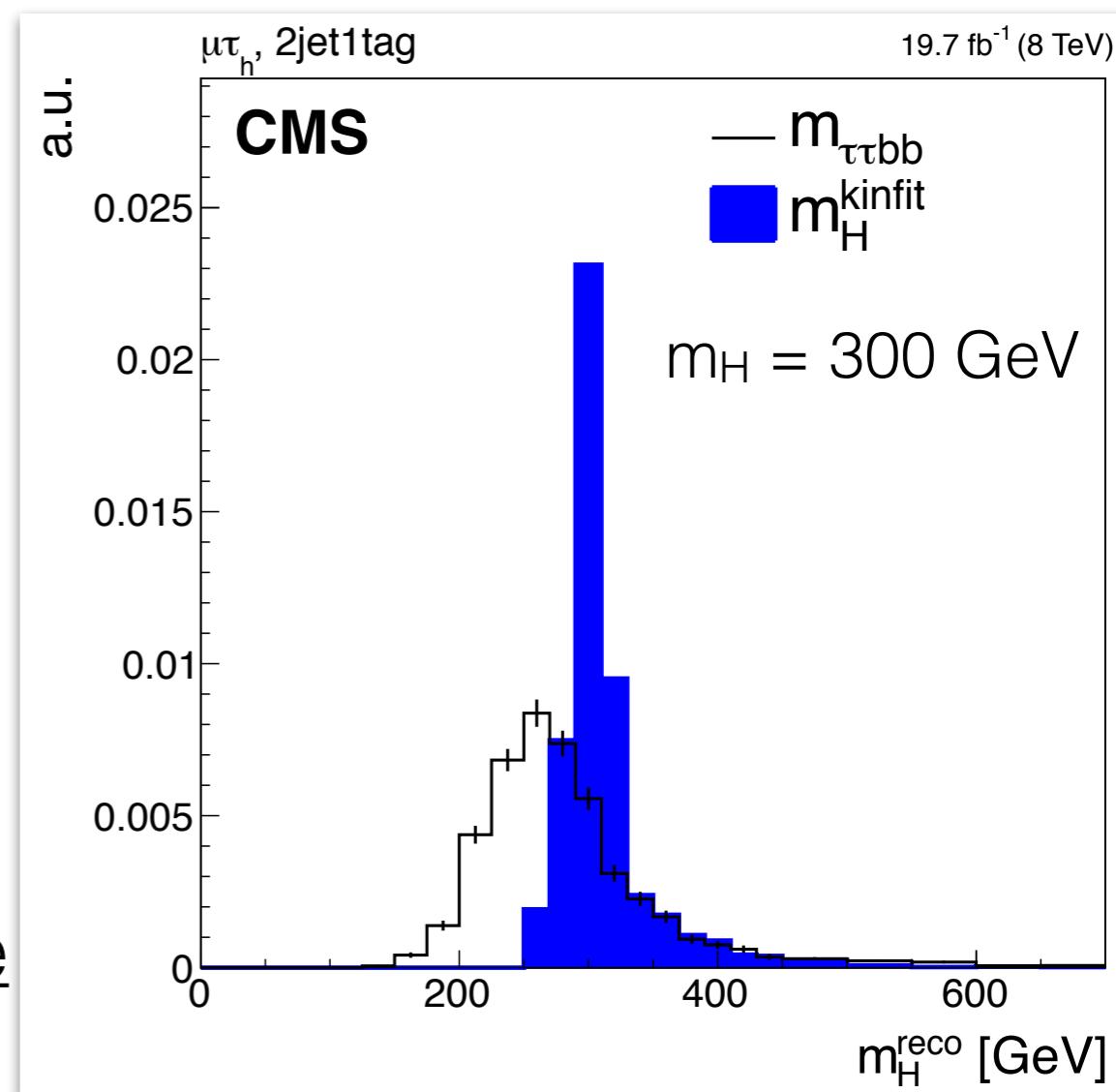
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**8 stati finali**

# Massa invariante $H \rightarrow hh \rightarrow \tau\tau bb$

La massa invariante dei quattro corpi  $\mathbf{m}_H$  è calcolata attraverso l'*algoritmo KinematicFit*:

- Prende come input i quadri-vettori ( $2b$  e  $2\tau$ ) con le loro incertezze e l'Energia Trasversa Mancante ( $\nu$  dal decadimento dei  $\tau$ ).
- Impone dei vincoli cinematici:  
$$m(\tau\tau) = m(bb) = m_h = 125 \text{ GeV}$$
- Assume l'approssimazione collinare per i prodotti di decadimento del  $\tau$ .



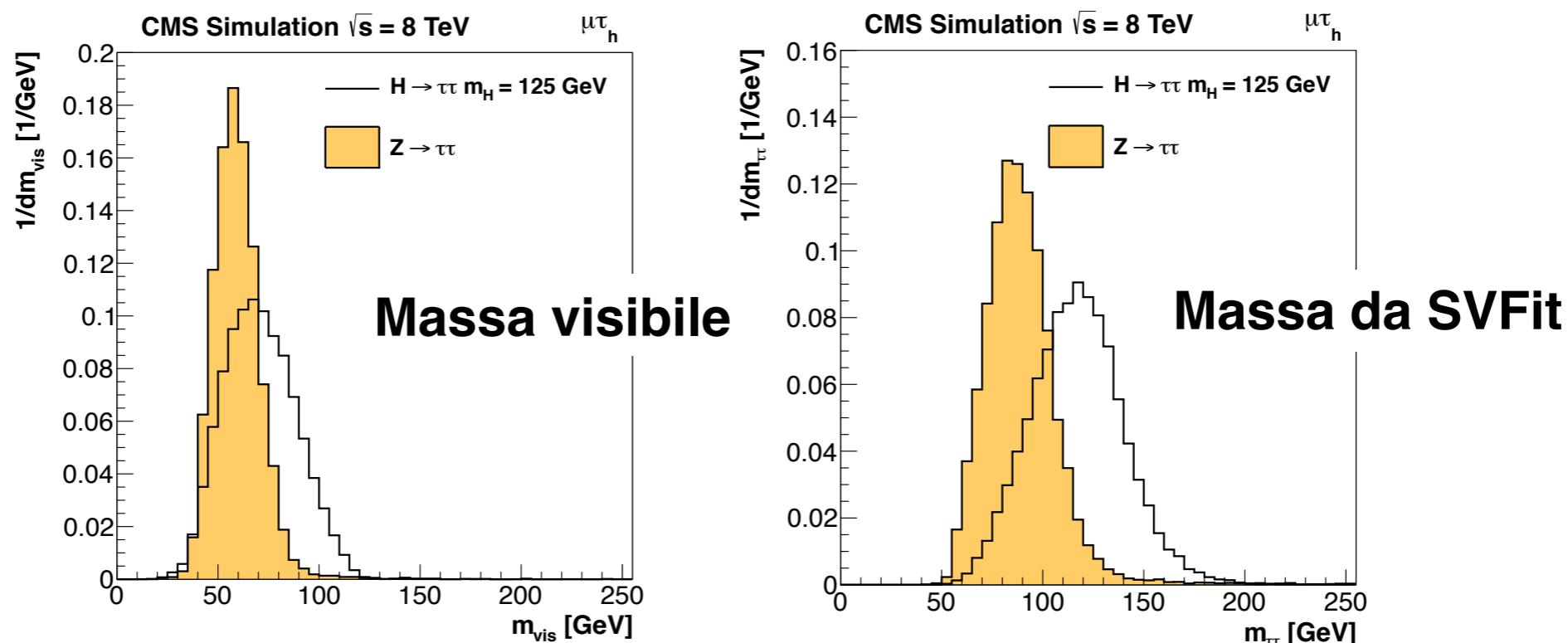
## Massa invariante $A \rightarrow Z h \rightarrow \ell\ell \tau\tau$

La massa invariante dei quattro corpi  $\mathbf{m}_A$  è calcolata a partire dall'informazione dei **quadri-vettori** dei 2 bosoni intermedi:

- **Bosone  $Z$**  ricostruito usando i quadri-vettori dei leptoni
- **Bosone  $h$**  riscostruito attraverso l'algoritmo SVFit

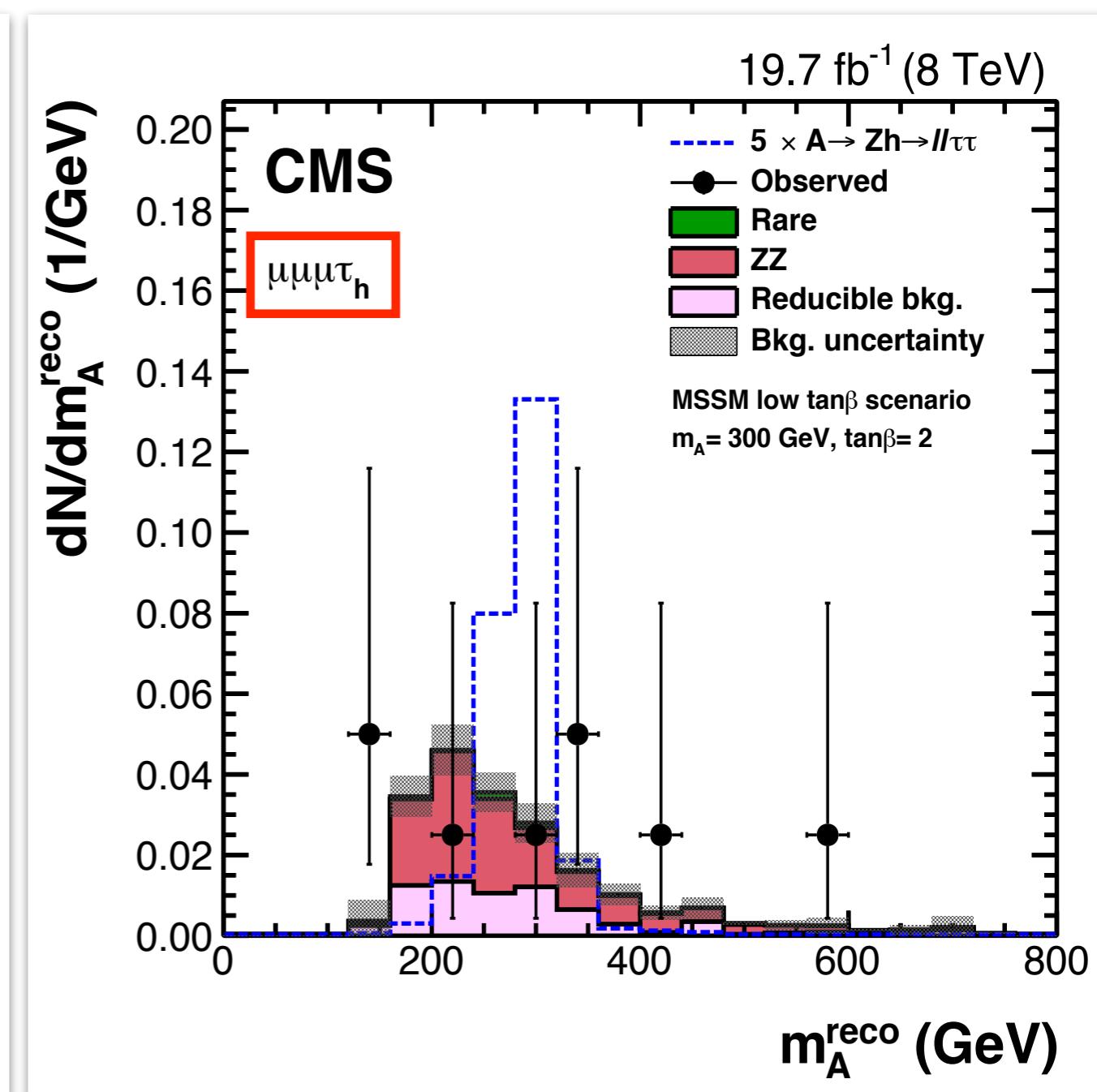
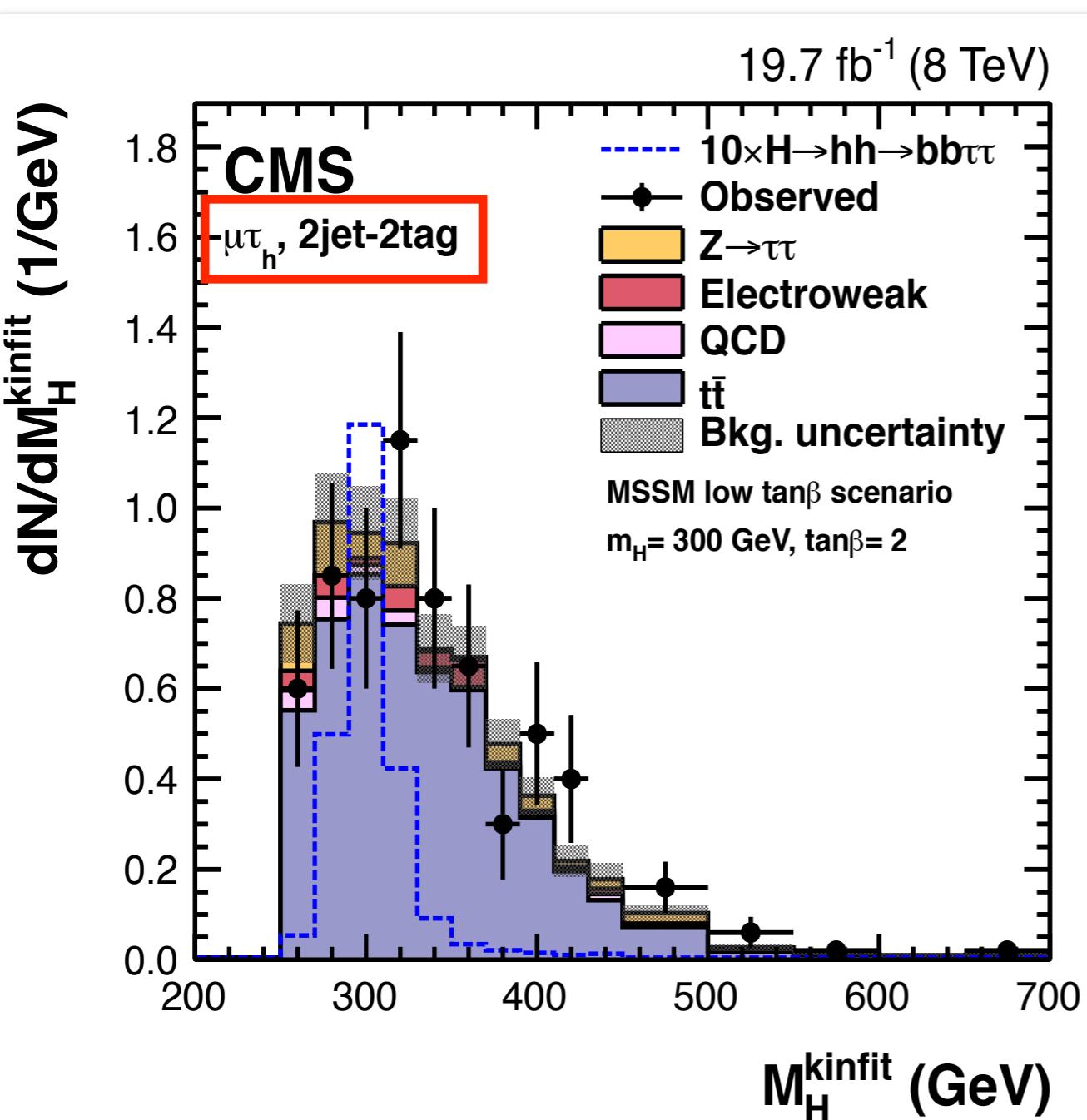
SVFit ricostruisce il bosone che decade nella coppia  $\tau\tau$ :

- Stimatore maximum likelihood
- Prende come input i quadri-momenti dei tau, la MET e le risoluzioni



# Distribuzioni di massa invariante (dati a 8 TeV)

Distribuzioni di massa invariante per i processi  $H \rightarrow hh$  e  $A \rightarrow Zh$



# Estrazione del segnale

- Le distribuzioni di massa invariante sono fittate con un maximum likelihood fit binnato.
  - Il parametro d'interesse è  $\sigma \times BR$  del segnale
  - Incertezze sistematiche trattate come parametri di nuisance
    - Differenti origini, le principali sono:
      - Sezioni d'urto
      - Luminosità
      - Leptoni: identificazione & *trigger*
      - b-tagging: efficienza & *mistag*
      - Fondi: *shape* & normalizzazione

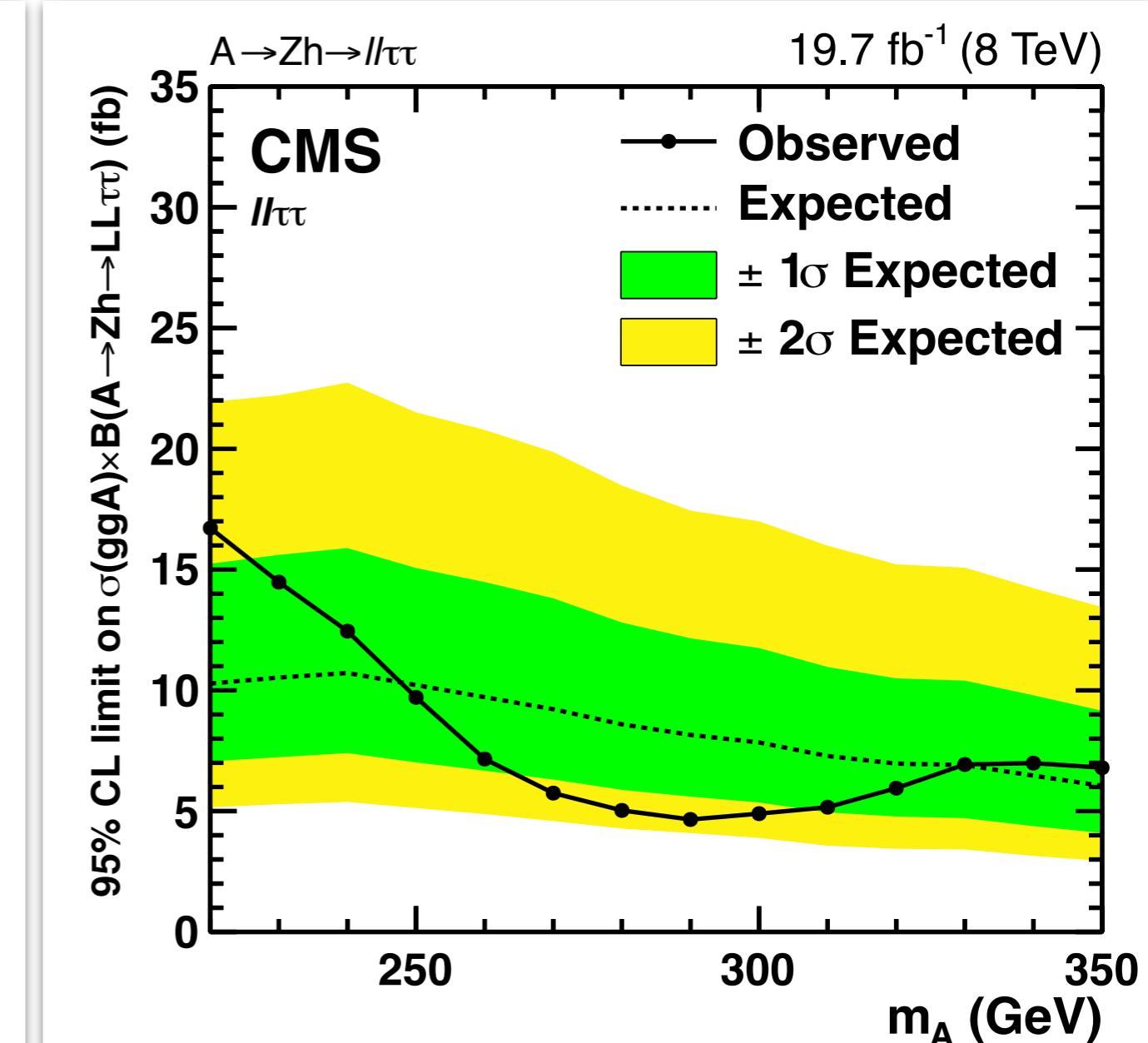
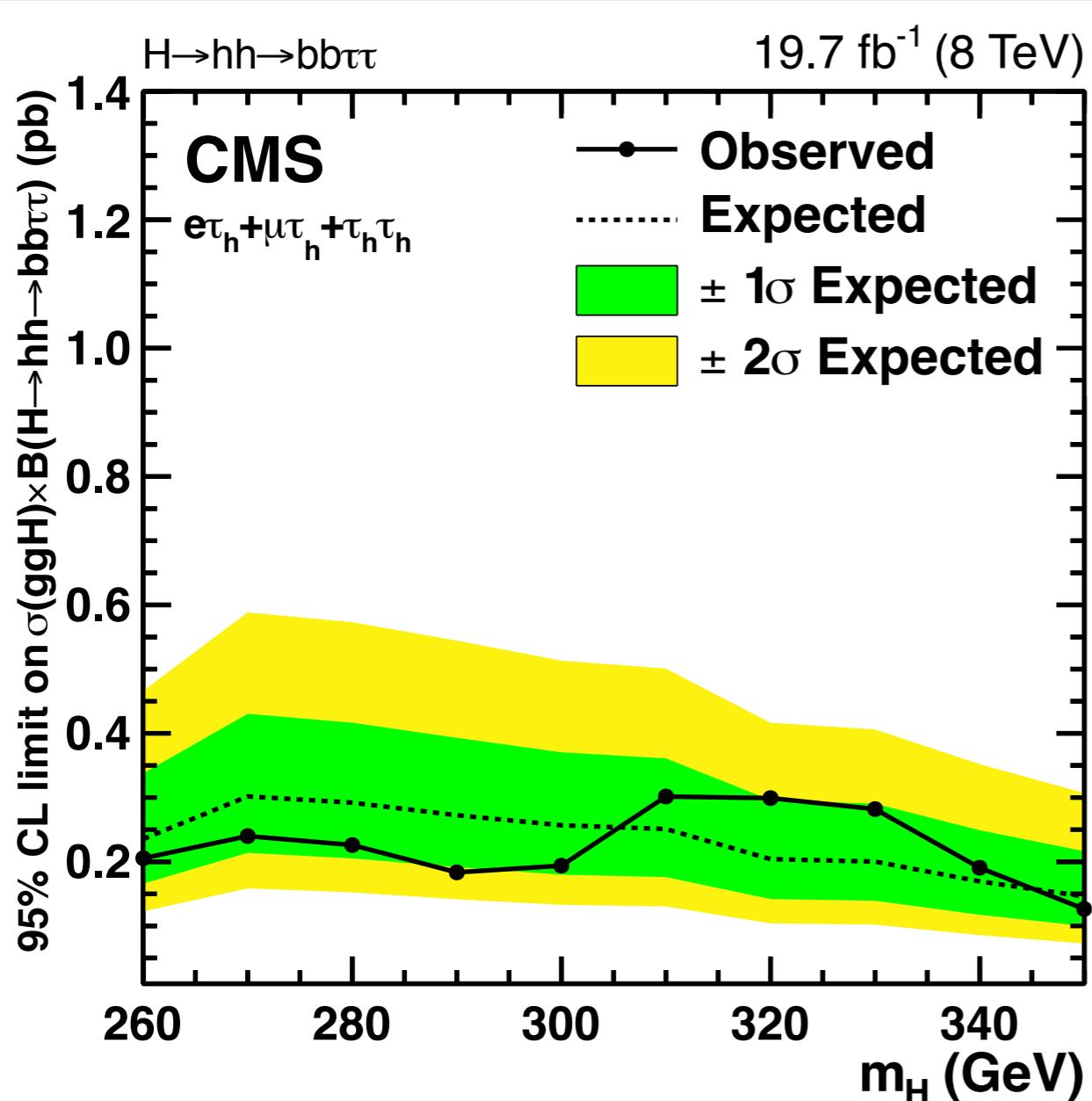
# Risultati: Limiti di Esclusione

Limiti d'esclusione “model independent”

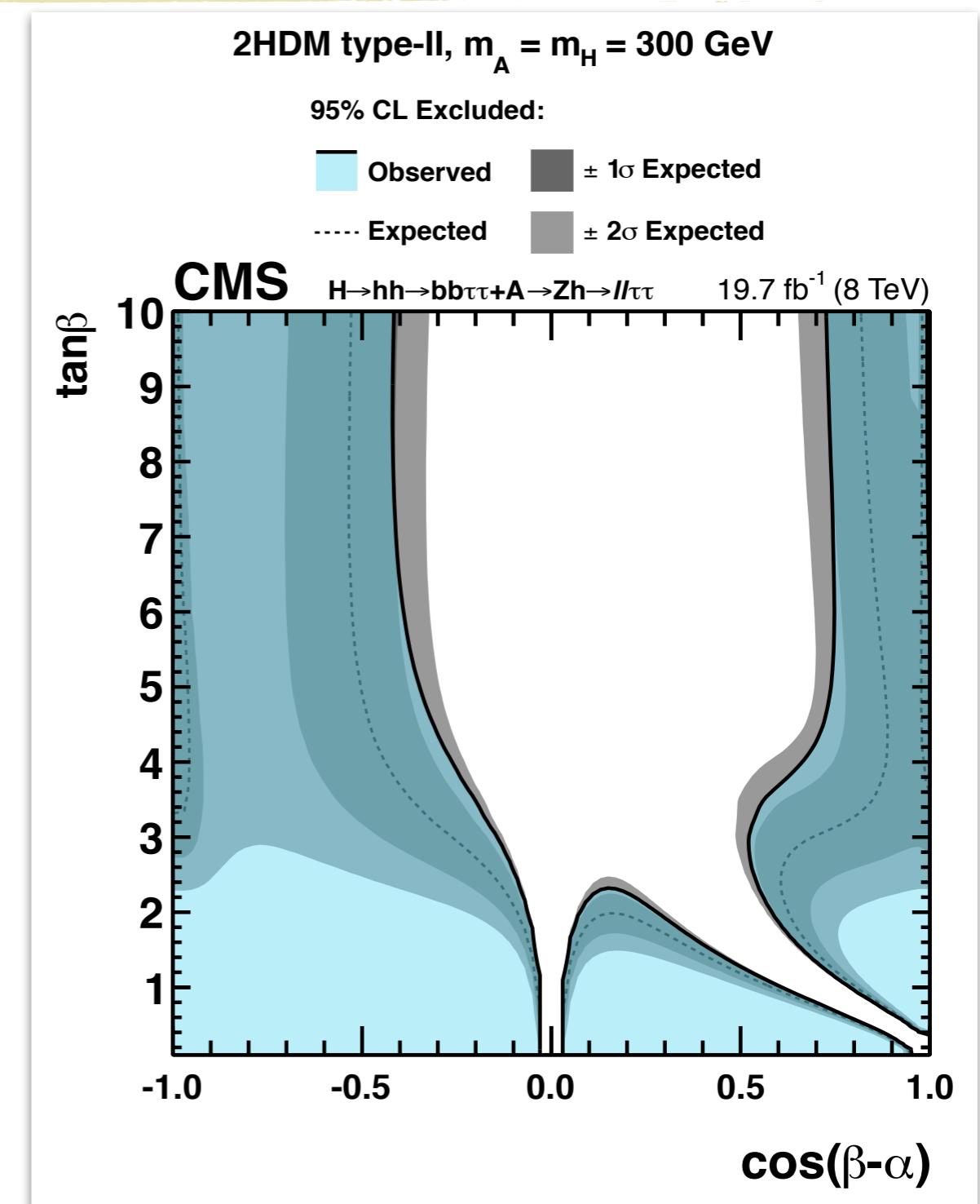
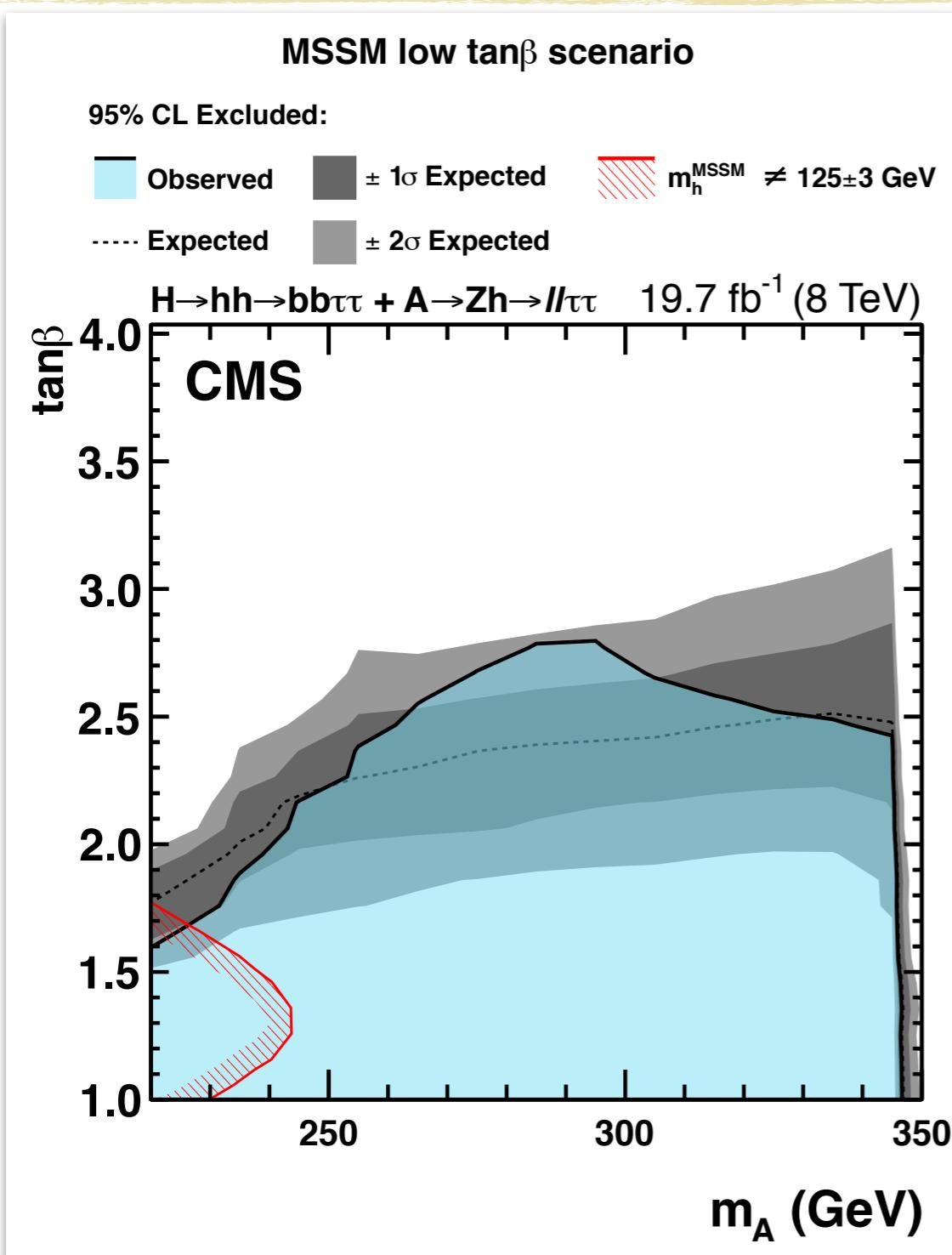
al 95% di Confidence Level su

$$\sigma(ggH) \times BR(H \rightarrow hh \rightarrow \tau\tau bb)$$

$$\& \quad \sigma(ggA) \times BR(A \rightarrow Zh \rightarrow \ell\ell\tau\tau)$$



# Risultati: interpretazione nei modelli MSSM & 2HDM



Escluse ampie regioni a basso  $\tan\beta$  (per MSSM), ma altre porzioni dello spazio dei parametri rimangono ancora da investigare.

# Prospettive future

La naturale continuazione di questa analisi è lo studio dei dati del **Run-II**:

Nel **Run-II**:  
 $\sqrt{s}=8 \rightarrow 13 \text{ TeV}$

Incremento sezioni d'urto  
di produzione del segnale  
rispetto a quelle dei fondi

A livello di **analisi**:

- Sensitività maggiore
- Accesso a regioni di alta massa

$H \rightarrow hh \rightarrow bb\tau\tau @ 13 \text{ TeV}$

già [pubblica](#),  
MA

non ancora competitiva con  
le analisi del *Run-I* a causa  
della statistica limitata ( $2.7 \text{ fb}^{-1}$ )

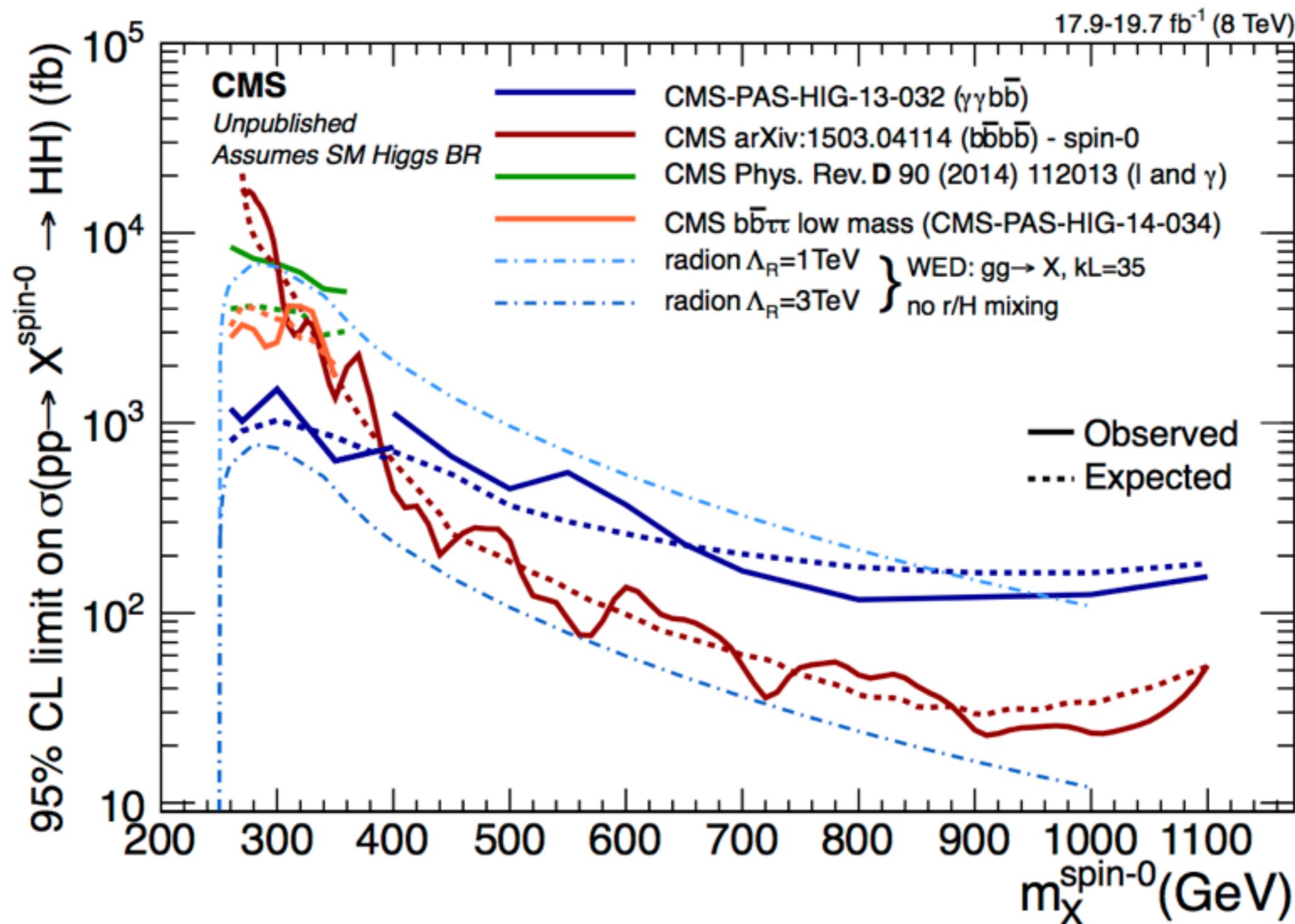
Per la fine del 2016 ci  
aspettiamo di superare la  
sensitività del *Run-I* !

Non ci resta che aspettare i nuovi dati...!

# Backup

# Limit Comparison

## Comparison with different final states



# SVFit Algorithm

Tau pair decay kinematic depend on a different number of parameters, depending on the tau pair decay:

- fully hadronic  $\rightarrow$  4 parameters
- semileptonic  $\rightarrow$  5 parameters
- leptonic  $\rightarrow$  6 parameters

Only 2 observables ( $E_x, E_y$ )  $\rightarrow$  under constrained problem  $\rightarrow$  likelihood approach

$$P(M_{\tau\tau}) = \int \delta(M_{\tau\tau} - M_{\tau\tau}(\vec{y}, \vec{a})) p(\vec{x}|\vec{y}, \vec{a}) d\vec{a}.$$

The diagram illustrates the likelihood function  $P(M_{\tau\tau})$  as a function of the tau pair mass  $M_{\tau\tau}$ . The function is defined by an integral over the parameter space  $d\vec{a}$ , where the integrand is a delta function centered around the true mass  $M_{\tau\tau}(\vec{y}, \vec{a})$ . The probability density  $p(\vec{x}|\vec{y}, \vec{a})$  is shown as a function of the observed MET value and the four-momenta of the visible decay products. Arrows point from the text labels to the corresponding parts of the equation and diagram.

Observed MET value

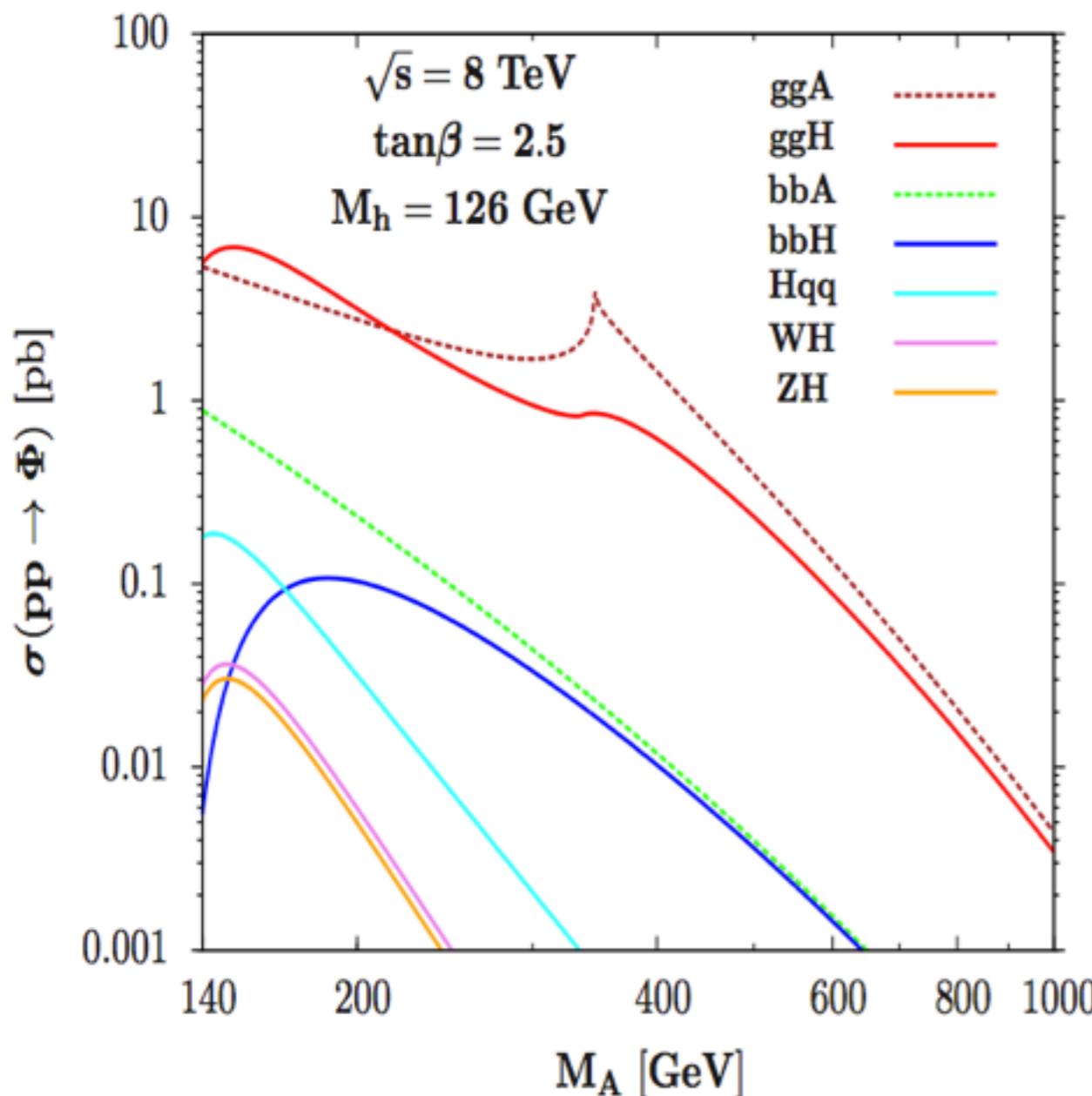
Tau pair decay kinematics

Four-momenta of visible decay products

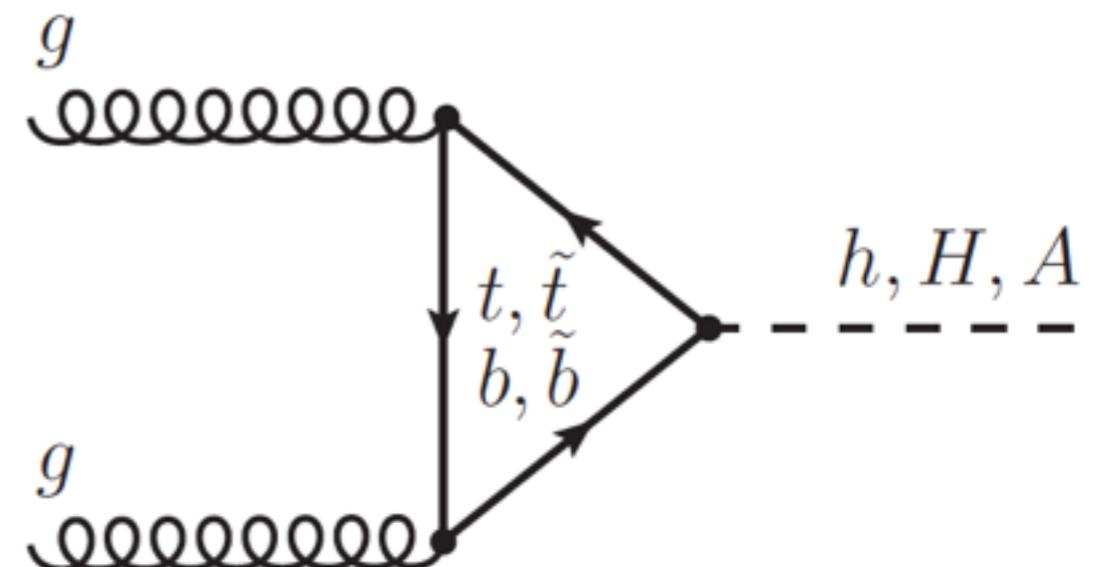
The best estimate  $M^i\tau\tau$  for the tau pair mass is the  $M^i\tau\tau$  which maximizes the probability  $P(M^i\tau\tau)$ .

# Higgs Production

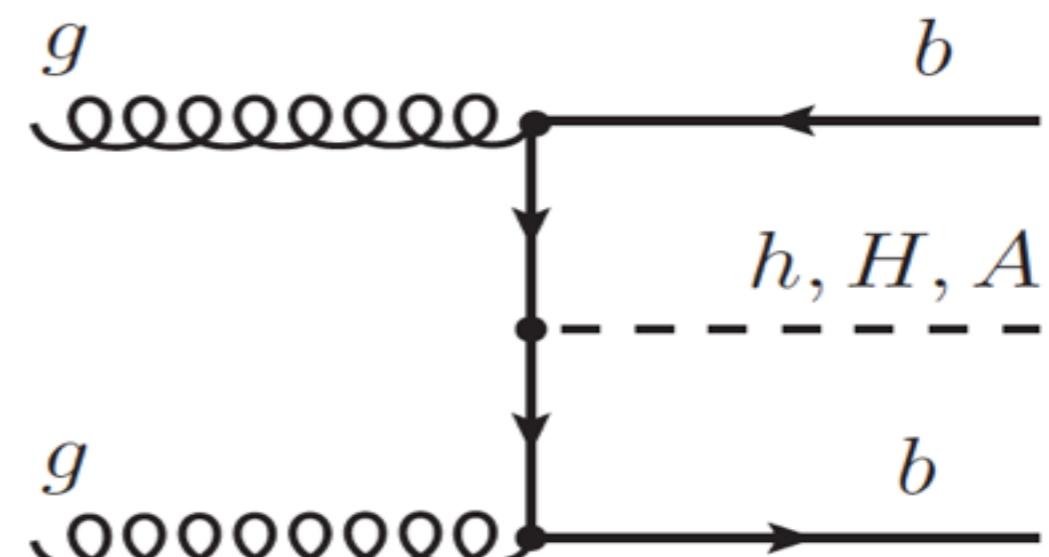
## Higgs production



## Gluon fusion

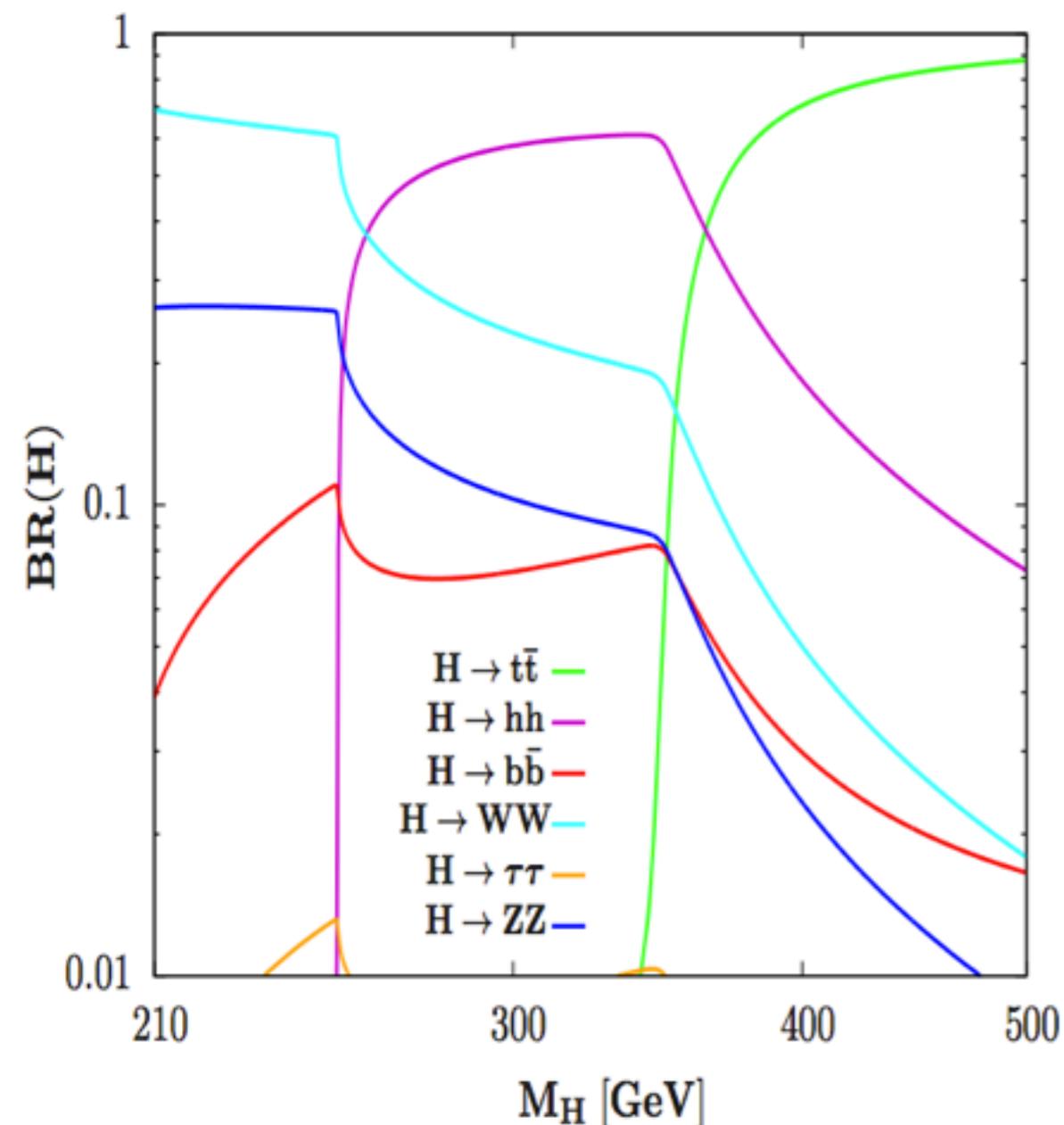


## bb associated production

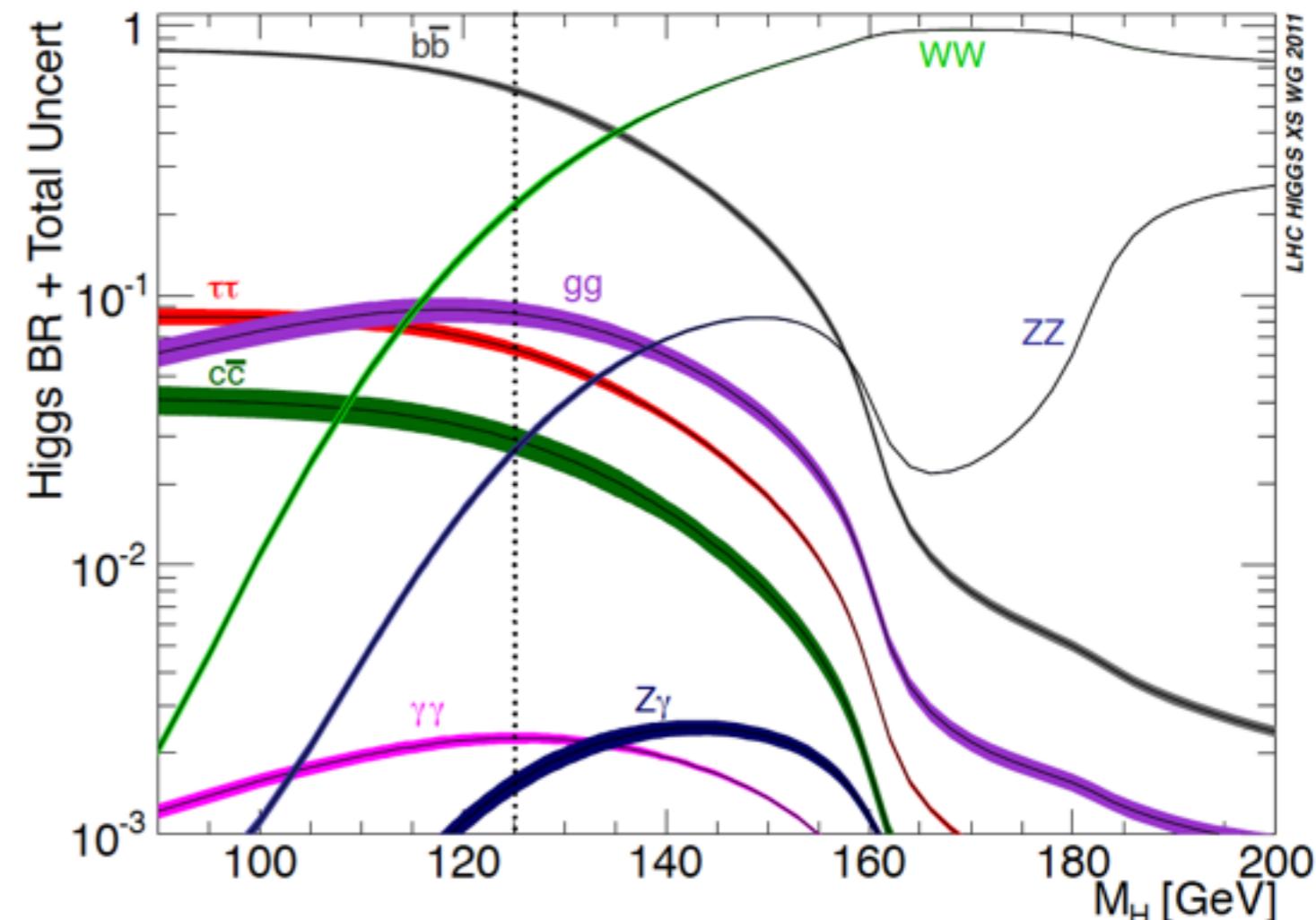


# Higgs Branching Ratios

## H Branching Ratios



## h Branching Ratios



# Systematic Uncertainties

$A \rightarrow Zh \rightarrow \ell\ell\tau\tau$

Systematic uncertainties common to all channels.

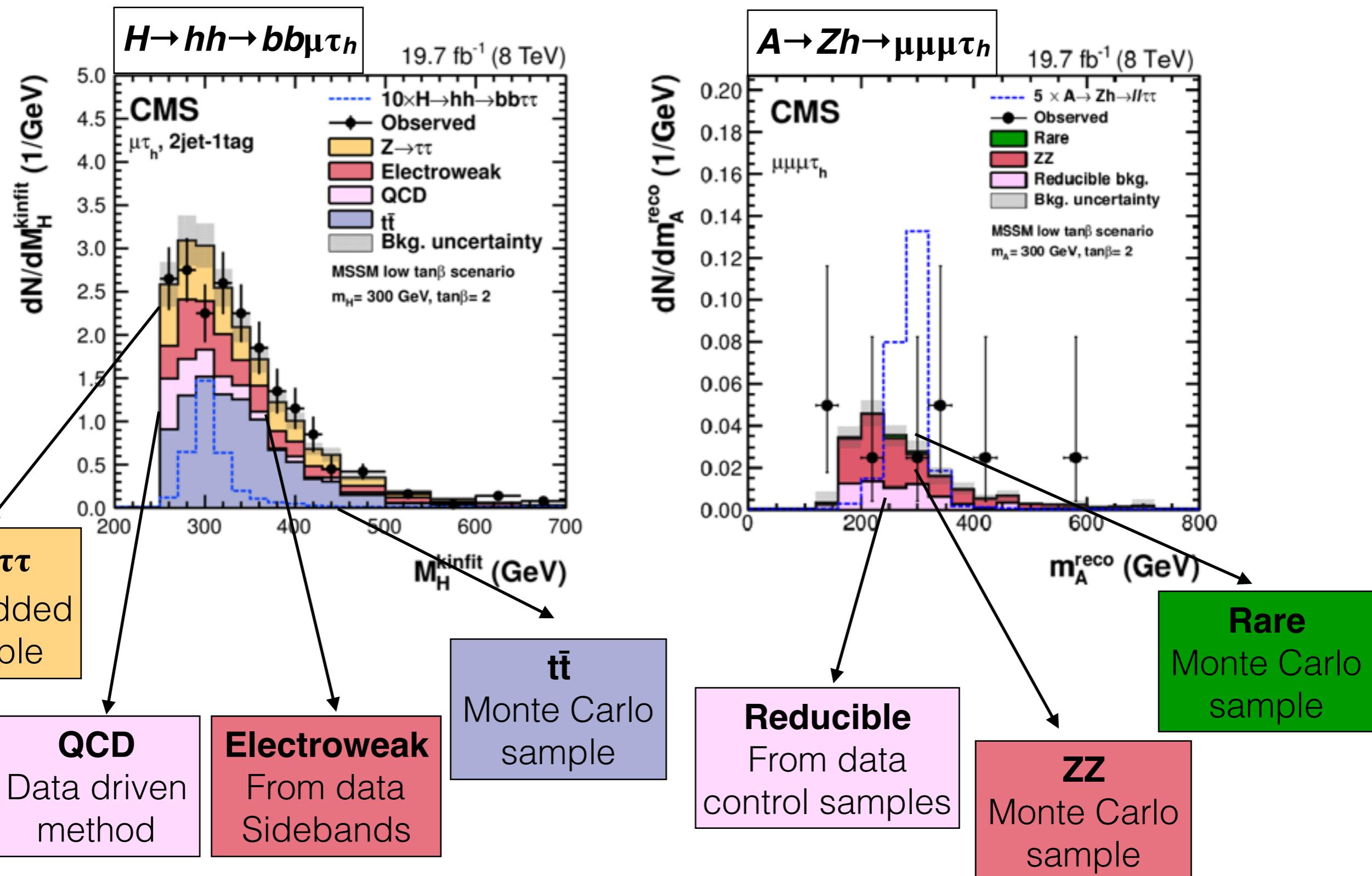
Source	Uncertainty
Luminosity measurement	2.2-2.6%
Muon trigger efficiency	1%
Muon ID/Iso/ES	2%
Electron trigger efficiency	1%
Electron ID/Iso/ES	2%
Tau ID/Iso	6%(12%)
Tau ES	3%(6%)
Btag	1%
PDF for $q\bar{q} \rightarrow ZZ$	5%
PDF for $gg \rightarrow ZZ$	10%
QCD scale for $q\bar{q}$	2.6-6.7%
QCD scale for $gg \rightarrow ZZ$	24-44%
QCD scale for VHs	2.9%
Reducible background estimate	15-50%
$\sigma_{TTZ}$	50%
$\sigma_{WWZ}$	50%
$\sigma_{WZZ}$	50%
$\sigma_{ZZZ}$	50%

# Systematic Uncertainties

$H \rightarrow hh \rightarrow bb\tau\tau$

		Event yield uncertainty by event category		
Experimental uncertainties	Uncertainty	2jet-0tag	2jet-1tag	2jet-2tag
Integrated luminosity 8 TeV	2.6%	2.6%	2.6%	2.6%
Jet energy scale	shape 1–10%	shape 1–7%	shape 1–5%	shape 1–10%
$\cancel{E}_T$				
Electron identification and trigger	2%	2%	2%	2%
Muon identification and trigger	2–3%	2–3%	2–3%	2–3%
Tau-lepton identification and trigger	8%	8–19%	8–19%	8–19%
b-tagging efficiency	1–70%	1–8%	1–5%	1–70 <sup>1</sup> %
b-mistag rate	1–5%	1%	1–4%	1–5%
Normalization, Z production	3.3%	3.3%	3.3%	3.3%
$Z \rightarrow \tau\tau$ : category selection	5%	5%	5%	6%
Normalization, $t\bar{t}$	10%	10%	10%	10%
Normalization, di-boson	15%	15%	15%	15%
Normalization, QCD Multijet	10–100%	10%	40%	60–100%
Normalization, W+jets	10–100%	10%	40%	100%
Normalization, $Z \rightarrow ee$ : e misidentified as $\tau_h$	20–40%	20%	20%	40%
Normalization, $Z \rightarrow \mu\mu$ : $\mu$ misidentified as $\tau_h$	30–60%	30%	60%	60%
Normalization, $Z+jets$ : jet misidentified as $\tau_h$	20–90%	20%	20–25%	70–90%
Tau-lepton energy scale	shape	shape	shape	shape

# Background Estimation



# Objects selection ( $H \rightarrow hh \rightarrow bb\tau\tau$ )

## $\mu\tau_h$ channel

- $\mu$ :  $p_T > 20$  GeV  
 $|\eta| < 2.1$
- $\tau_h$ :  $p_T > 20$  GeV  
 $|\eta| < 2.3$

## $e\tau_h$ channel

- $e$ :  $p_T > 24$  GeV  
 $|\eta| < 2.1$
- $\tau_h$ :  $p_T > 20$  GeV  
 $|\eta| < 2.3$

## $\tau_h\tau_h$ channel

- $\tau_h(1)$ :  $p_T > 45$  GeV ;  $|\eta| < 2.1$
- $\tau_h(2)$ :  $p_T > 45$  GeV ;  $|\eta| < 2.1$
- $\text{charge}(\tau_1) = - \text{charge}(\tau_2)$

+

- $\text{charge}(e/\mu) = - \text{charge}(\tau)$
- *loose* isolation criteria
- $m_T = \sqrt{2p_T \text{MET} (1 - \cos \Delta\phi)} < 30$  GeV

+

- 2 jets per event:
- $p_T > 20$  GeV
  - $|\eta| < 2.4$

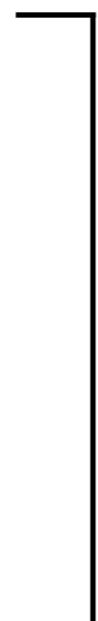
# Objects selection ( $A \rightarrow Z h \rightarrow \ell\ell \tau\tau$ )

## Z → μμ

- $\mu_1$ :  $pT > 20 \text{ GeV}$ ;  $|\eta| < 2.4$
- $\mu_2$ :  $pT > 10 \text{ GeV}$ ;  $|\eta| < 2.4$

## Z → ee

- $e_1$ :  $pT > 20 \text{ GeV}$ ;  $|\eta| < 2.5$
- $e_2$ :  $pT > 10 \text{ GeV}$ ;  $|\eta| < 2.5$



- $60 \text{ GeV} < m(ee/\mu\mu) < 120 \text{ GeV}$
- +     • ambiguity  $\rightarrow m(ee/\mu\mu)$  closest to  $m_Z$

## $h \rightarrow \tau\tau (\rightarrow e\mu/e\tau_h/\mu\tau_h/\tau_h\tau_h)$

- $\mu$ :  $pT > 10 \text{ GeV}$ ;  $|\eta| < 2.4$
- $e$ :  $pT > 10 \text{ GeV}$ ;  $|\eta| < 2.5$
- $\tau_h$ :  $pT > 21 \text{ GeV}$ ;  $|\eta| < 2.3$

## CLs method

$$\mathcal{L} = \prod_i Poisson(n_i; \nu_i, \theta) \cdot \prod_j Constraint(\theta_j; \tilde{\theta}_j)$$

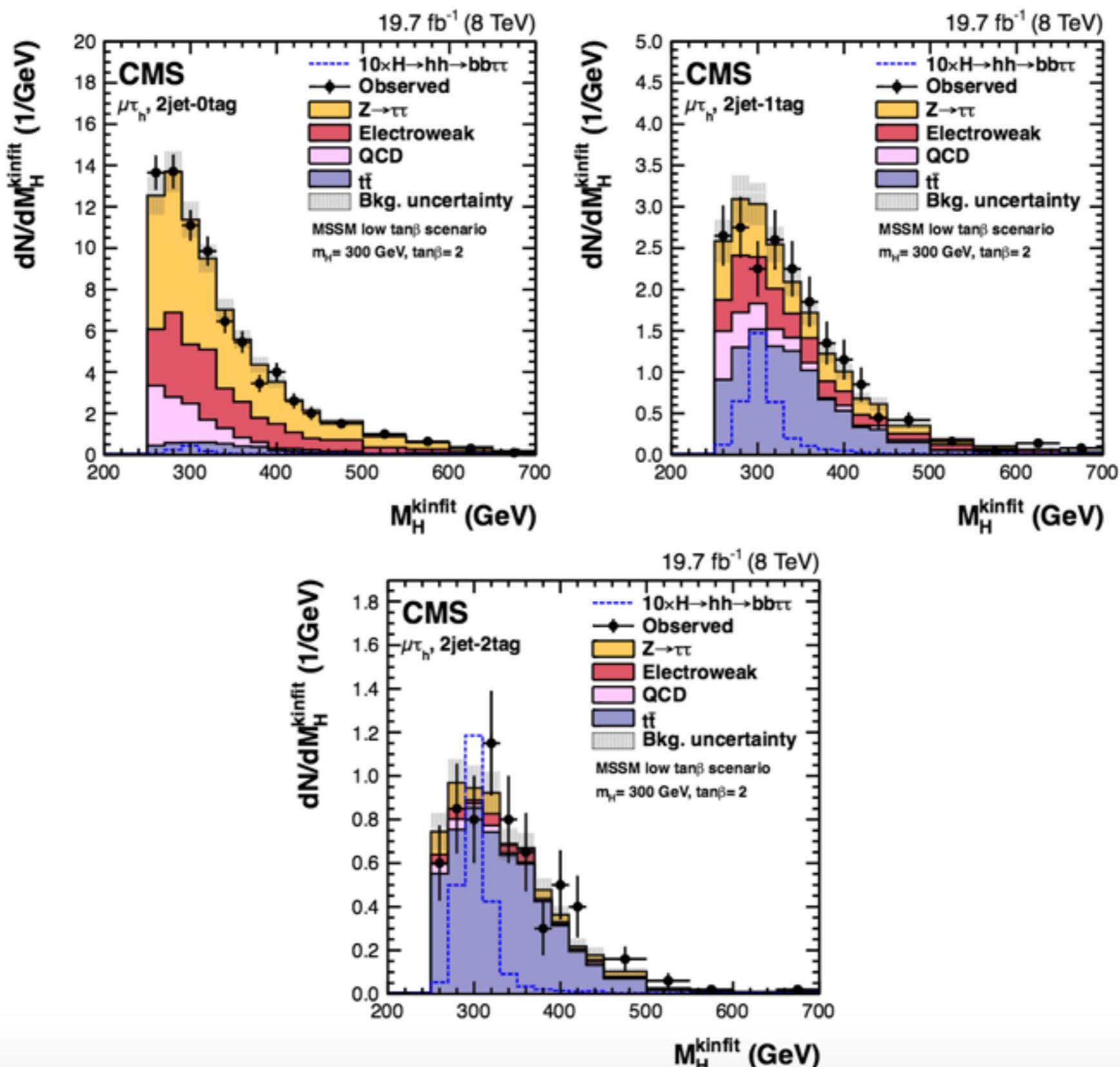
$$q_\mu = -2 \ln \frac{\mathcal{L}(data|s+b)}{\mathcal{L}(data|b)}$$

$$p_\mu = P(q_\mu \leq q_\mu^{obs} | \mu \cdot s + b) = \int_{q_\mu^{obs}}^{\infty} f(q_\mu | \mu, \hat{\theta}_\mu^{obs}) dq_\mu$$

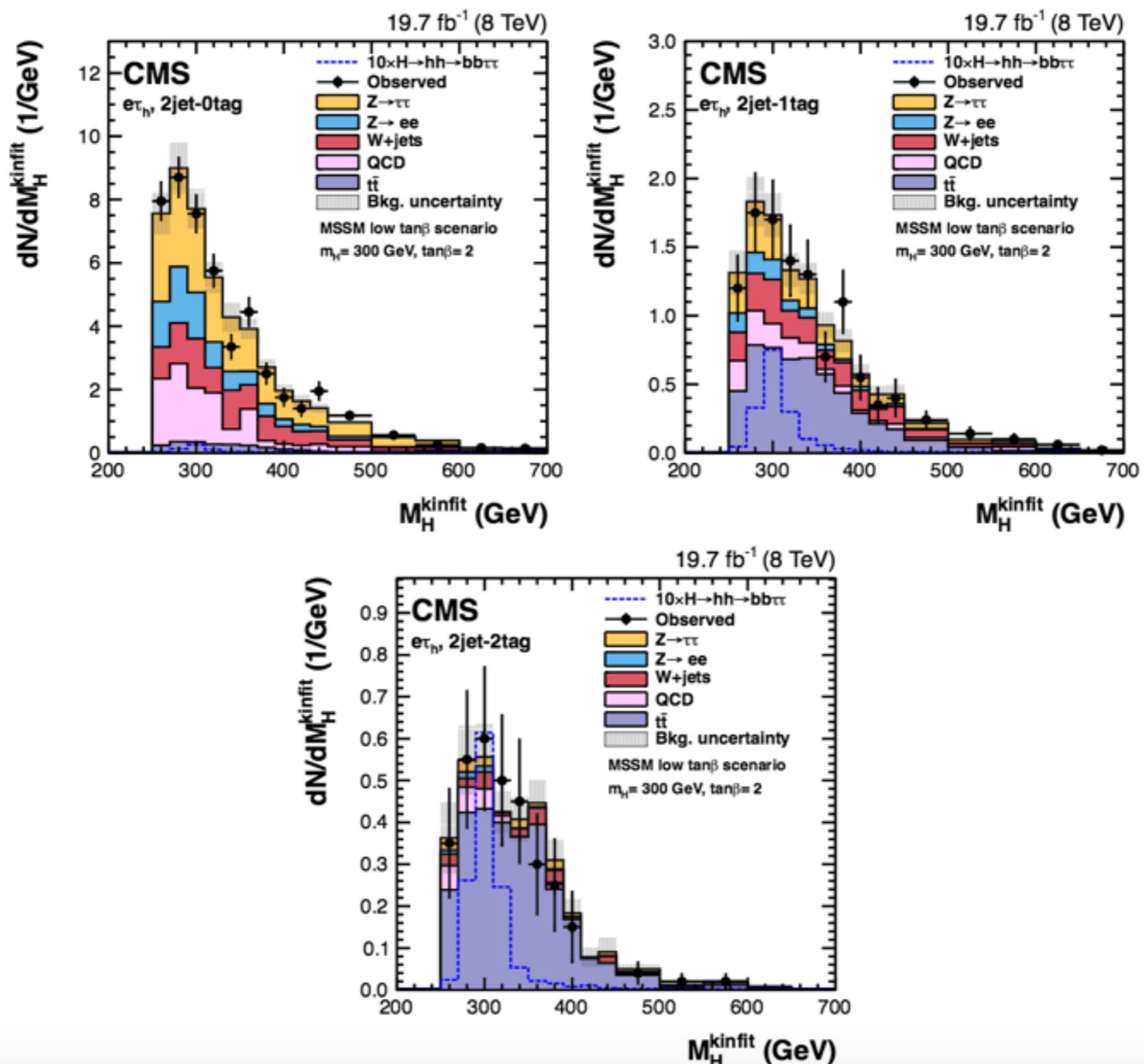
$$1 - p_b = P(q_\mu \leq q_\mu^{obs} | b - only) = \int_{q_0^{obs}}^{\infty} f(q_\mu | 0, \hat{\theta}_0^{obs}) dq_\mu$$

$$CL_S(\mu) = \frac{p_\mu}{1 - p_b}$$

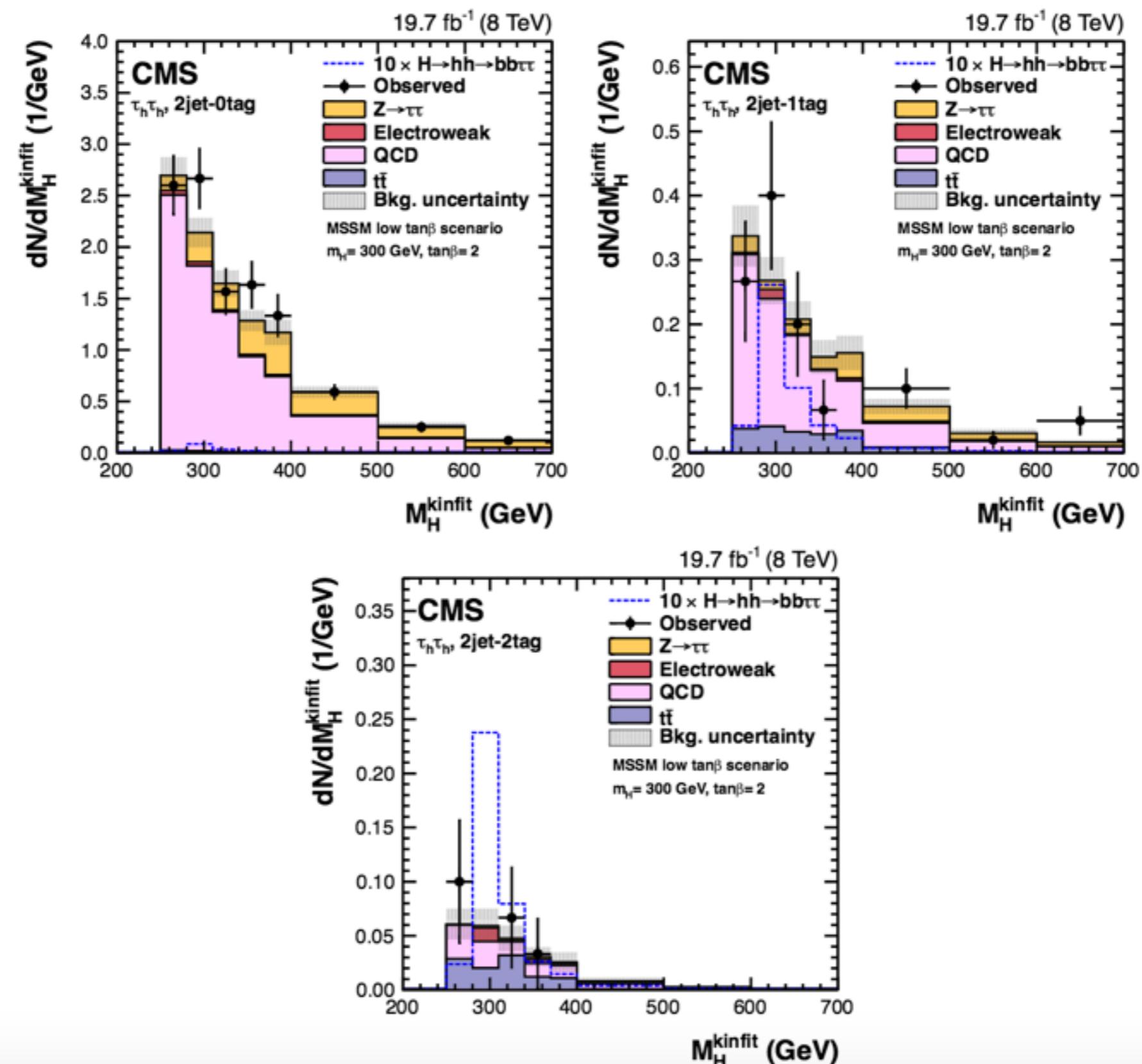
# Hhh mass distributions : $\mu\tau_h$ channel



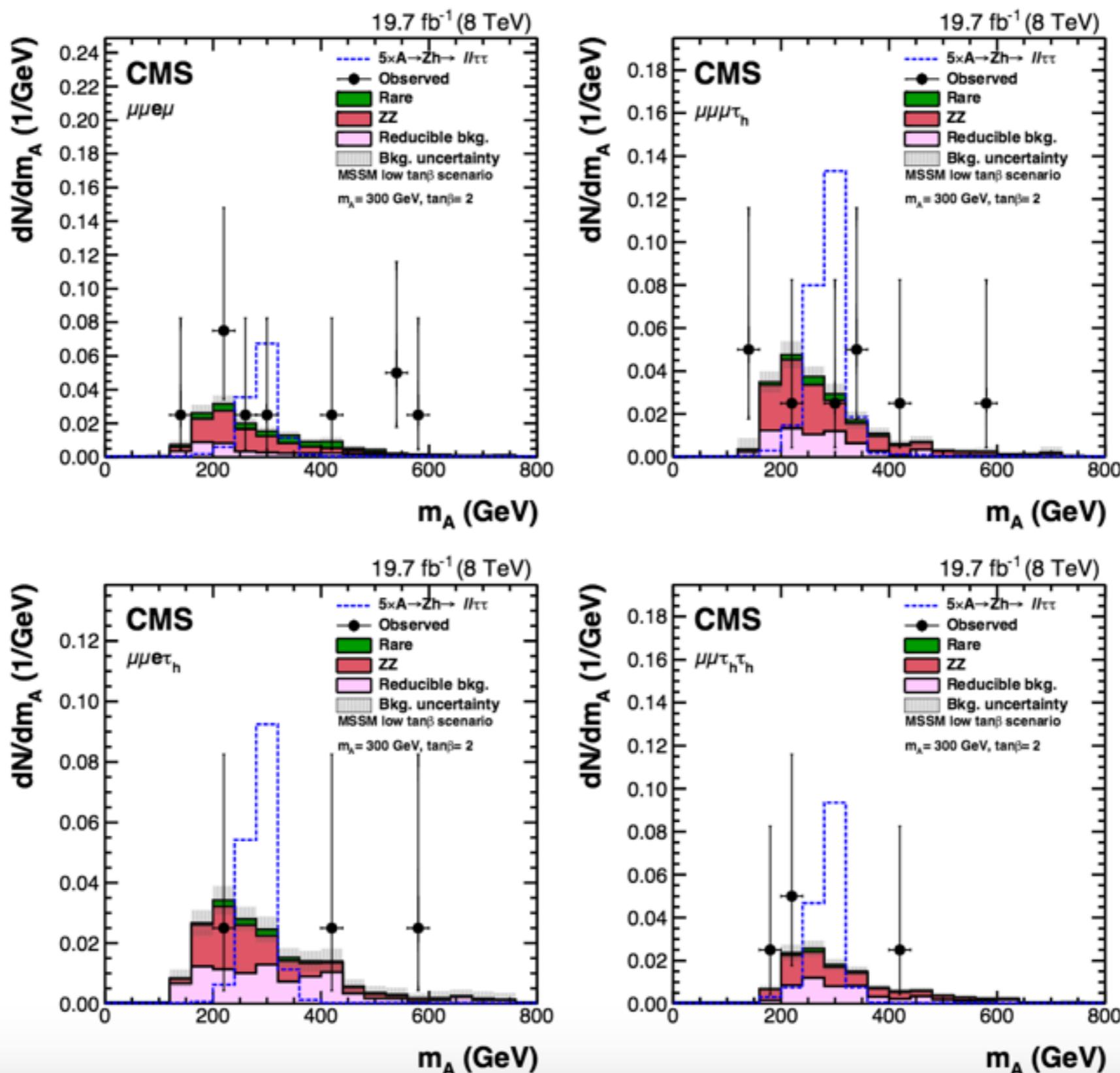
# Hhh mass distributions : $e\tau_h$ channel



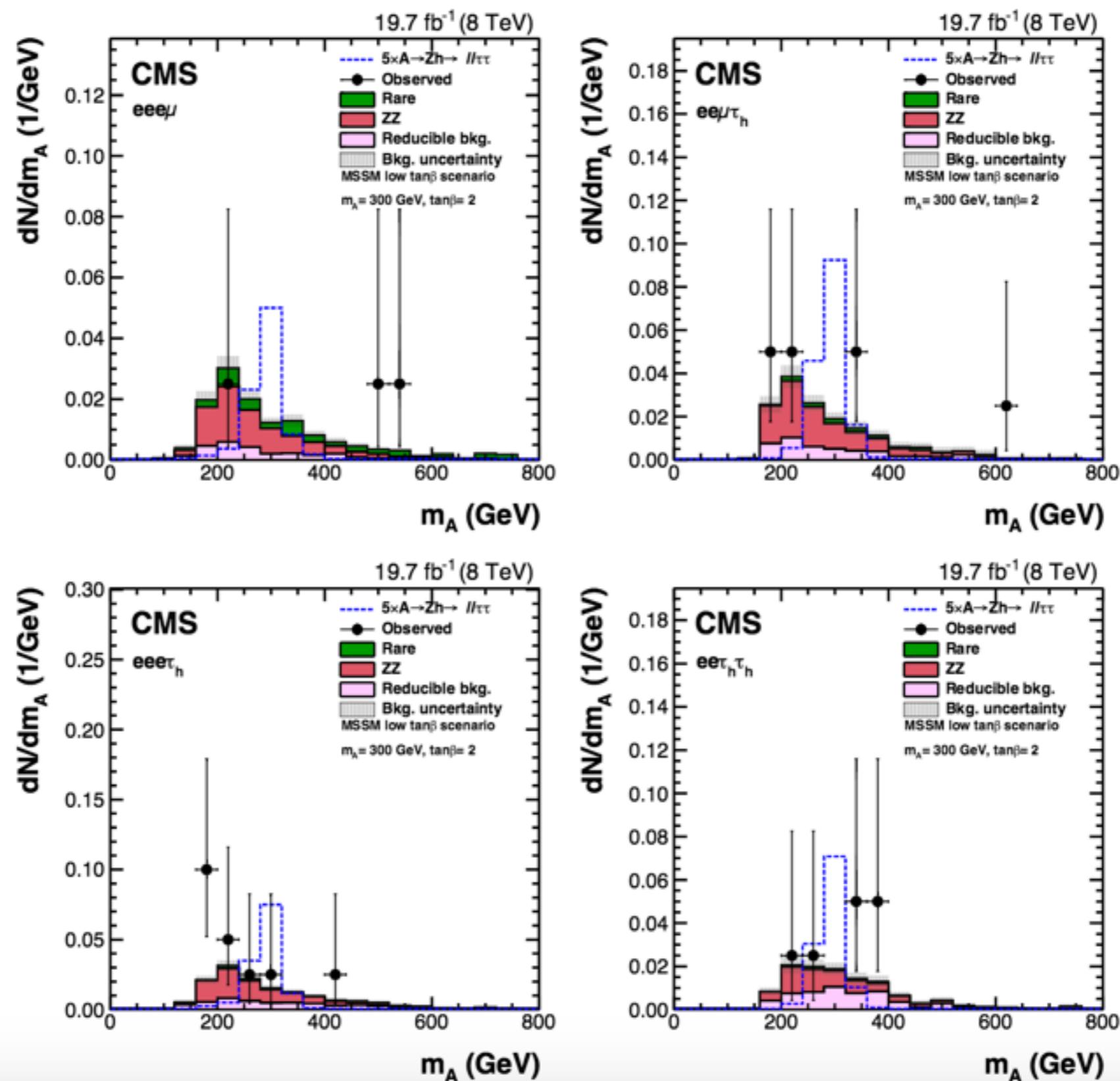
# Hhh mass distributions : $\tau_h\tau_h$ channel



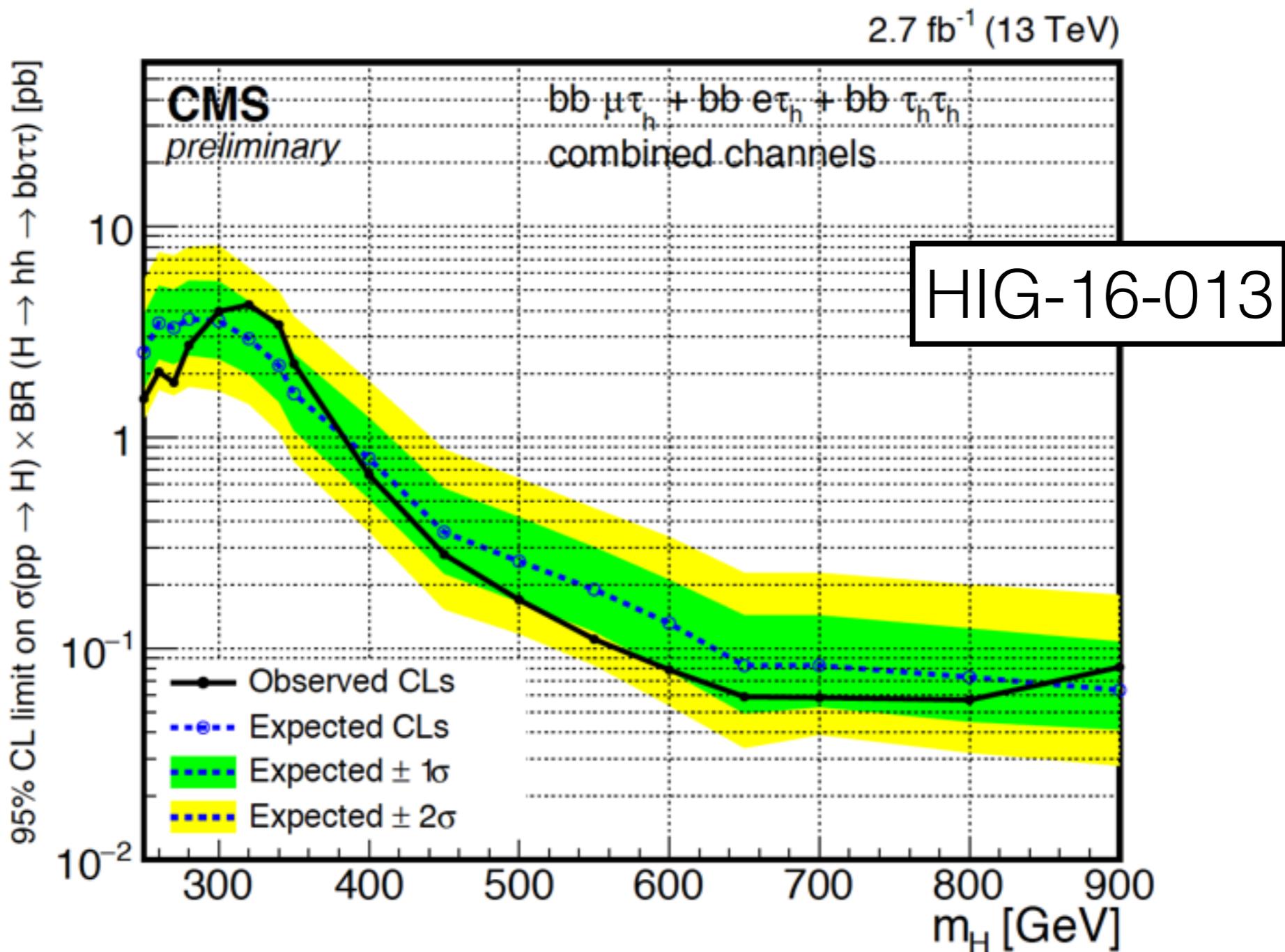
# Azh mass distributions : $Z \rightarrow \mu\mu$ channel



# Azh mass distributions : Z $\rightarrow$ ee channel



# Preliminary result with 13 TeV data



Preliminary exclusion limit observed with CMS data at 13 TeV for the  $H \rightarrow hh \rightarrow bb\tau\tau$  decay. Presented at Moriond. Pre-approved (HIG-16-013)

“Model independent search for Higgs boson pair production  
in the  $bb\tau^+\tau^-$  final state.”

- High mass region
- Only the fully hadronic tau decay

