$H \to \tau\tau$ Decays

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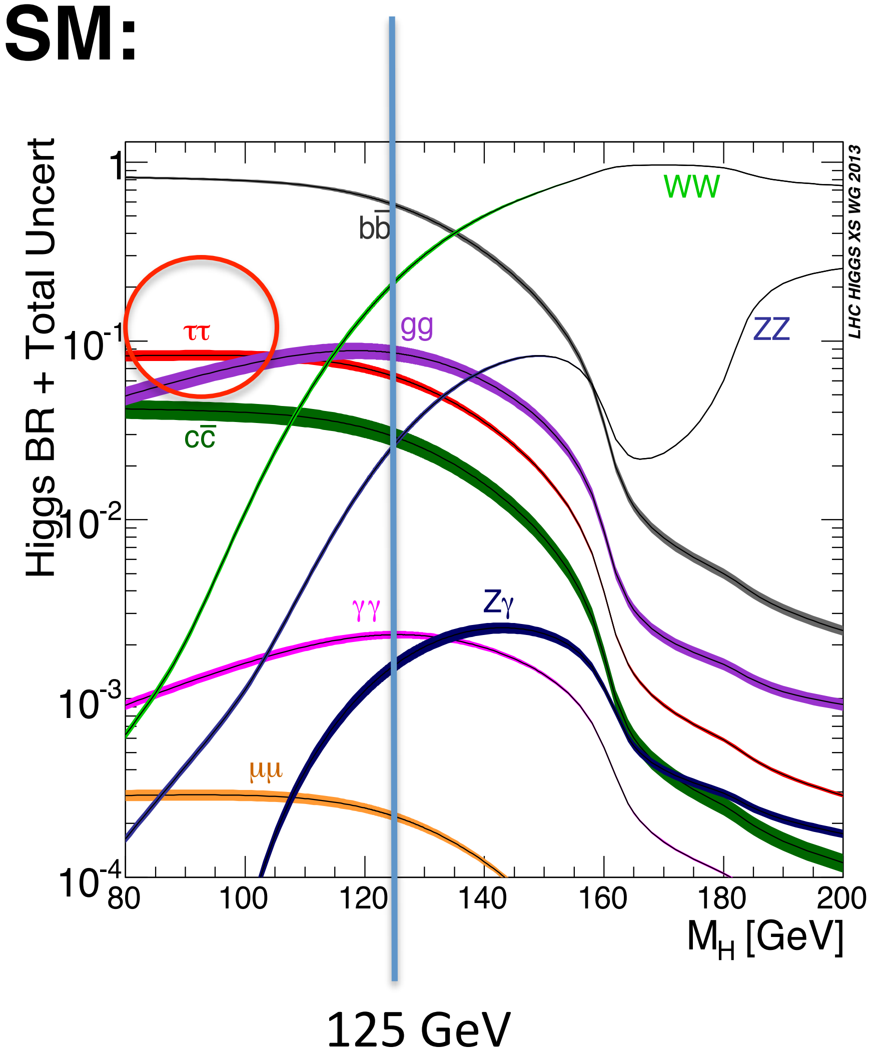
on behalf of the CMS collaboration

Outline

- Why search for $H \to \tau\tau$?
- How we search for $H \to \tau\tau$ at CMS
- What we learned about SM $H \to \tau\tau$ from Run 1
- Tau identification in Run 2
- Highlights of early Run 2 searches involving taus, including search for $H^+ \to \tau\nu$

Introduction

Searching for H → ττ from the SM:

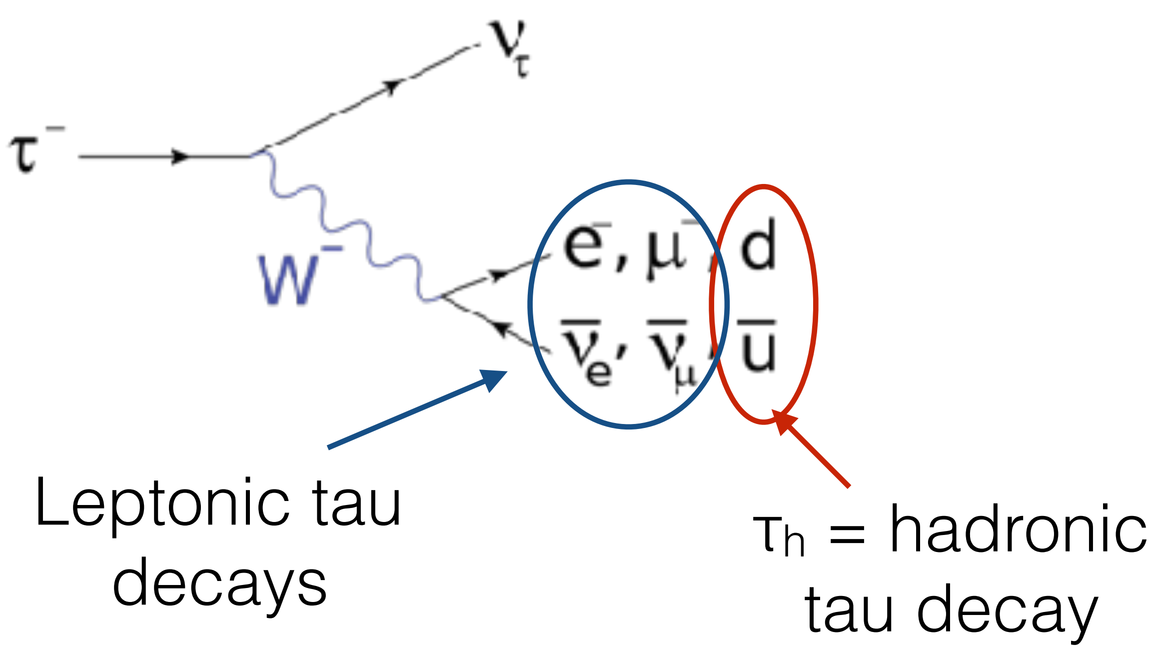


Most sensitive fermionic decay channel -> observing it essential to complete SM H picture and measure Yukawa coupling

BSM searches involving taus:

- Searches for BSM physics often involves extended Higgs sectors
- These can include possible enhanced couplings to down-type fermions, e.g. in MSSM, where tanβ = ratio of two Higgs doublets, H → ττ leads the exclusions of regions at high tanβ (more on this in MSSM talk later!)
- Taus are important probe of possible BSM Higgs

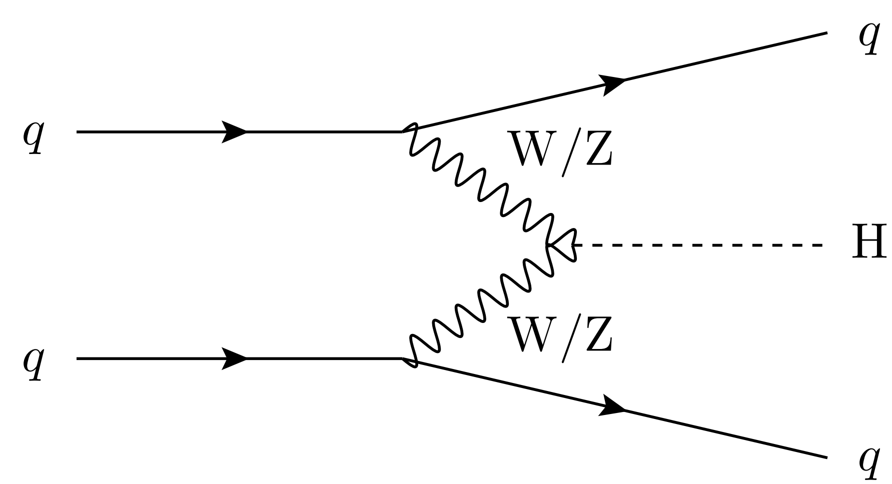
Searching for H → ττ



→ For 2 taus, 6 possible final states: **$\mu\tau_h$ $e\tau_h$ $\tau_h\tau_h$ eμ μμ** and **ee**

We often refer to these as "channels" - generally they have different background composition and are optimised separately

Additionally events are separated into "categories" based on other properties of the signal being searched for →



e.g. for the SM, VBF tagging using 2 forward jets, for MSSM analysis b-tagging to target bbH production....

SM H → ττ search from Run 1

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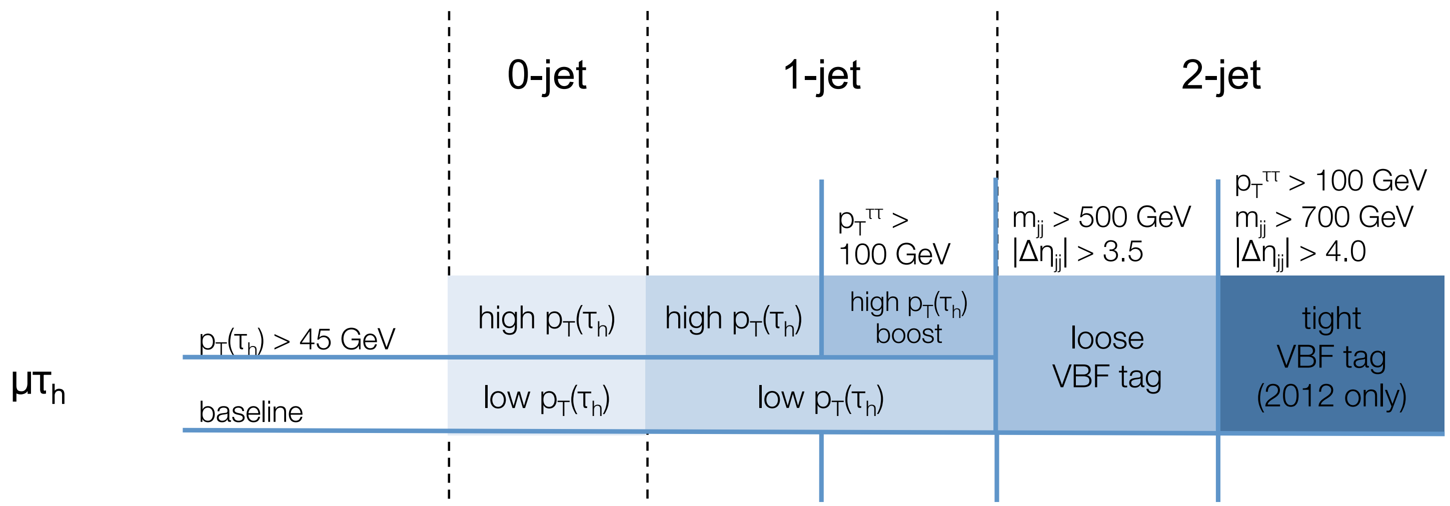
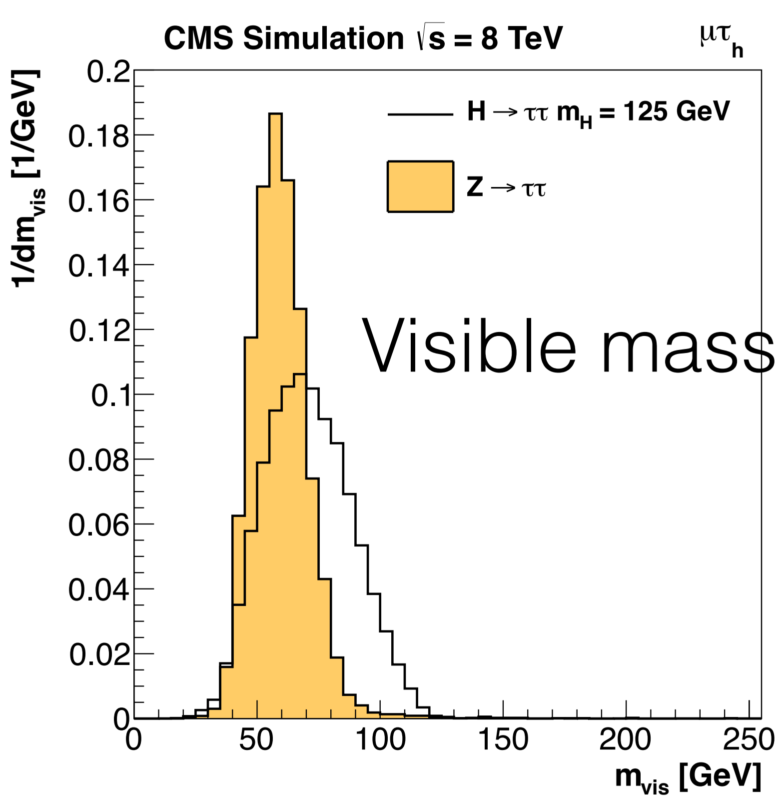
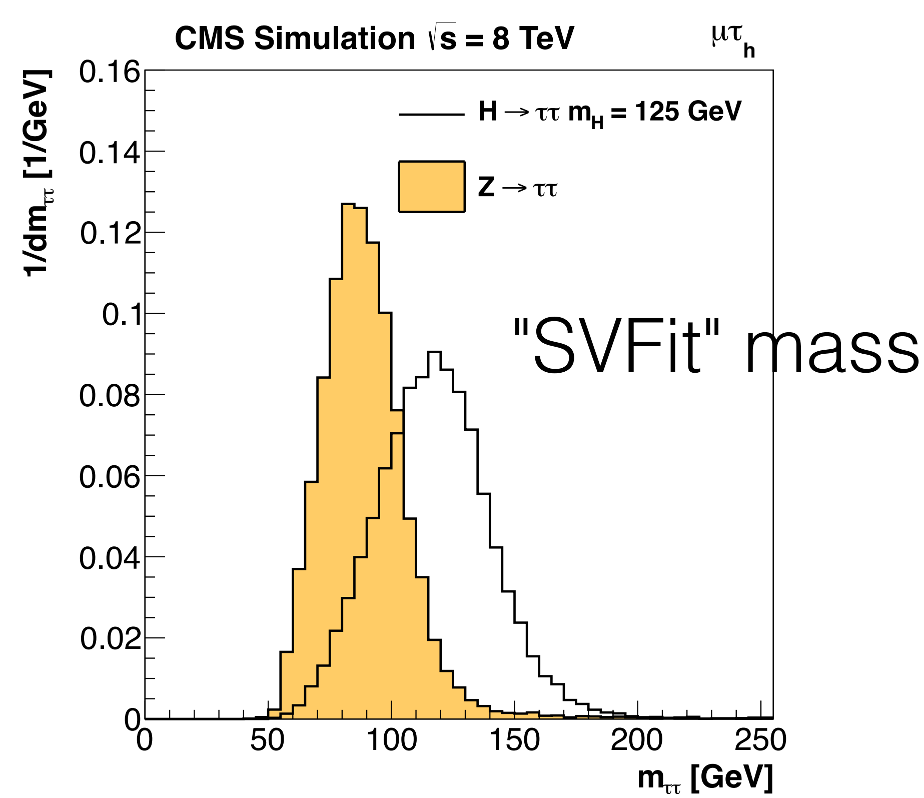


Targeting gluon fusion and VBF production (also combined with dedicated ZH + WH analyses)

Full di-tau mass reconstructed using likelihood based algorithm:



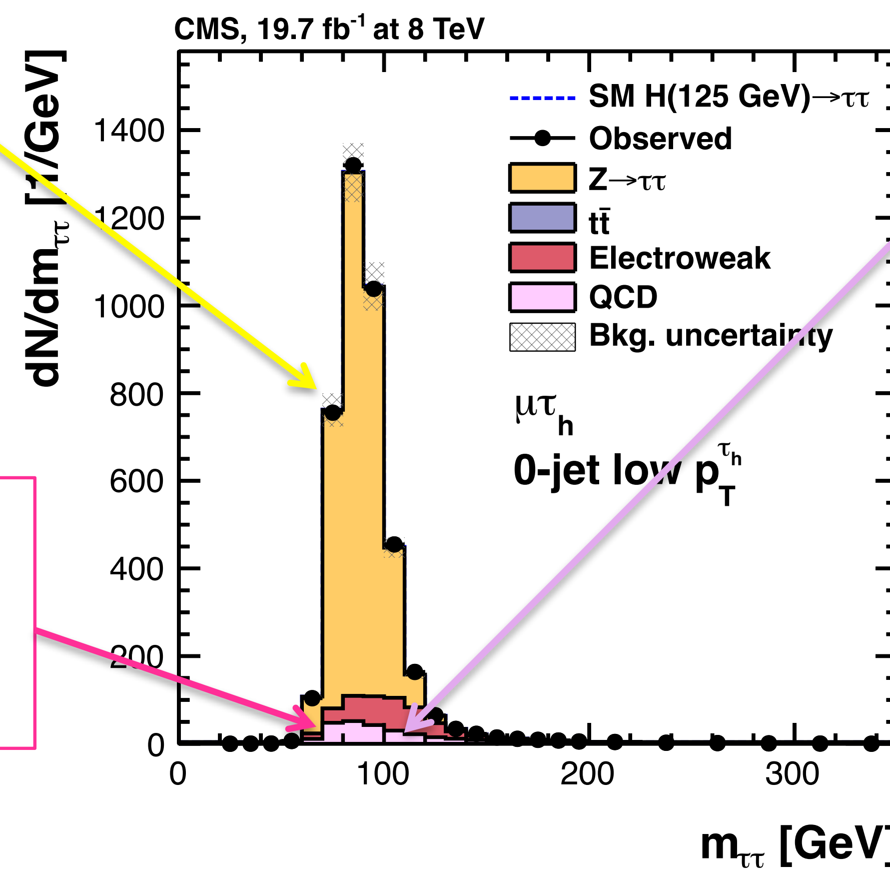


Backgrounds to $H \to \tau\tau$

- Use data driven methods for background estimation
- Background dominated 0 jet category used to constrain backgrounds:

Z→ττ
Uses Z→μμ **data embedded** with simulated τ's.

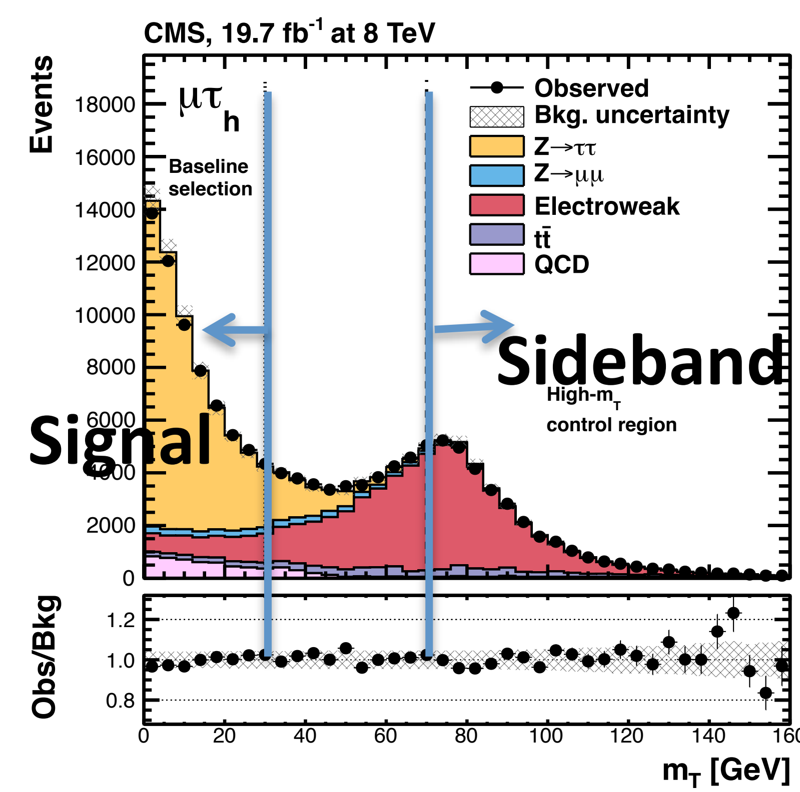
EWK (W+jets)
Normalization from **high m_T sideband in data**.
Shape from MC.



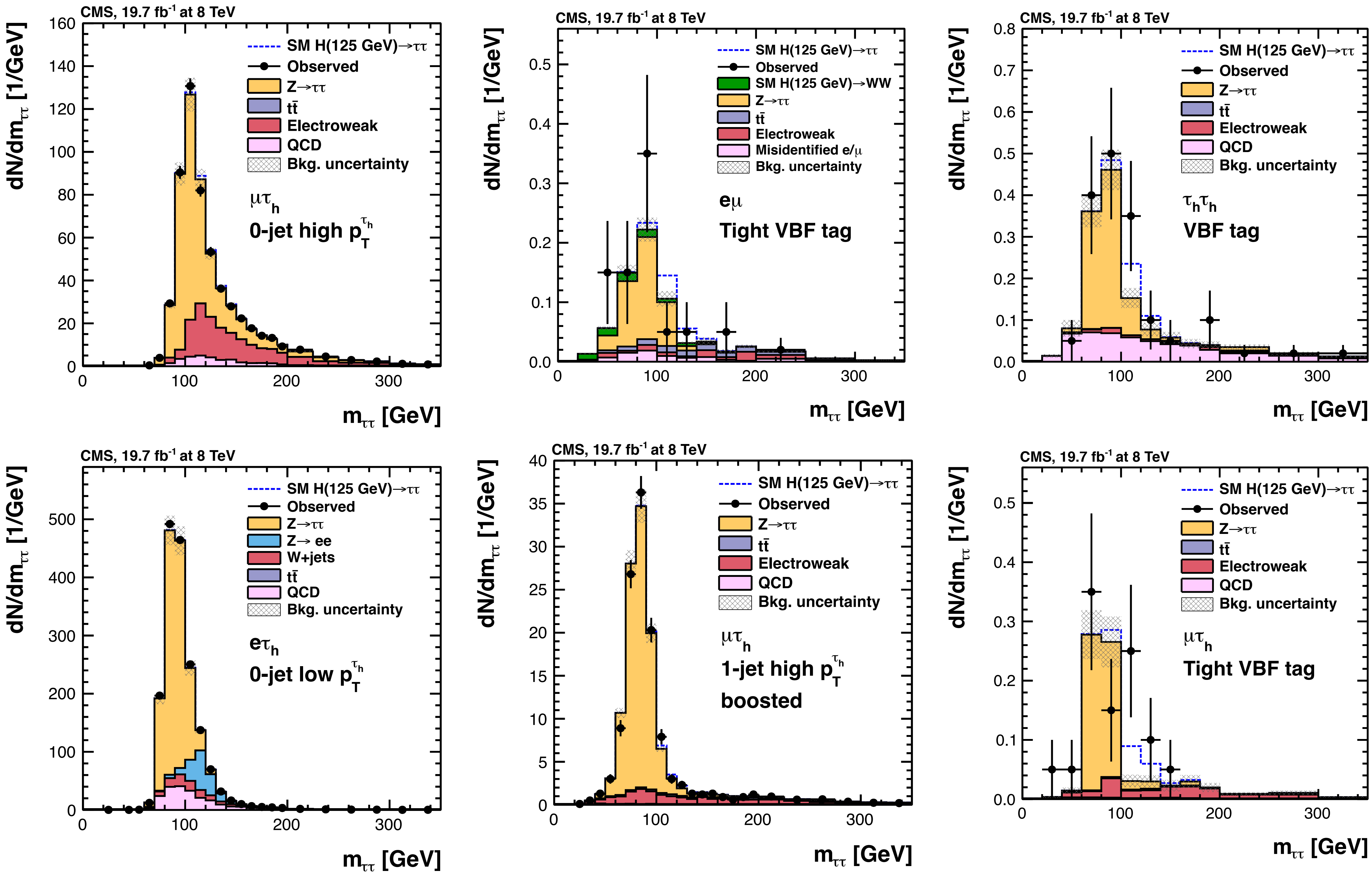
QCD
Measured in **same-sign control region.**

m_T = transverse mass between lepton and E_T^{miss}

Strategy:
- **Suppress QCD with isolated leptons.**
- **m_T < 30 GeV cut to suppress W+Jets.**
- **Extract signal from binned maximum-likelihood fit to $m_{\tau\tau}$. Combine channels and categories.**

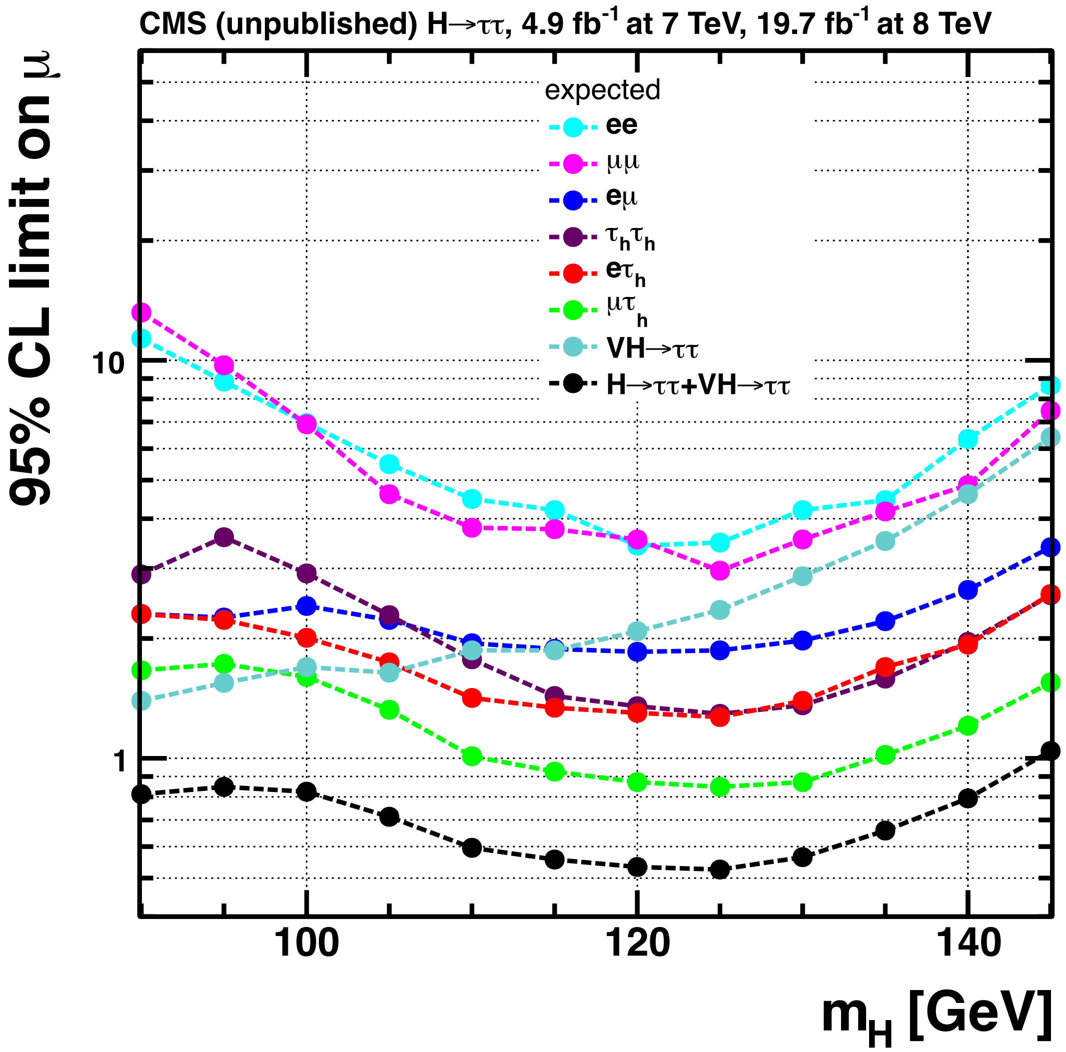


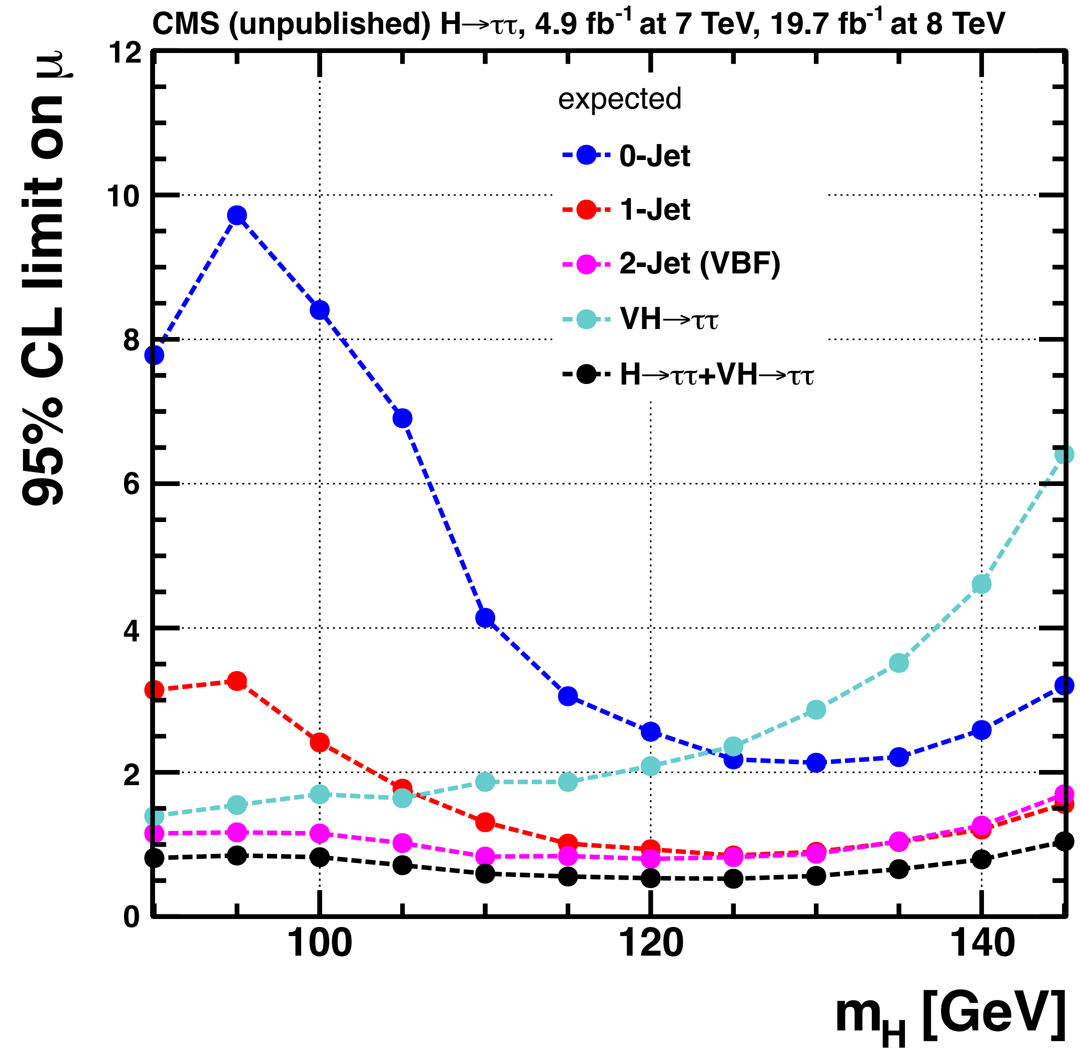
Mass plots at 8 TeV



increasing signal sensitivity

Channel comparison

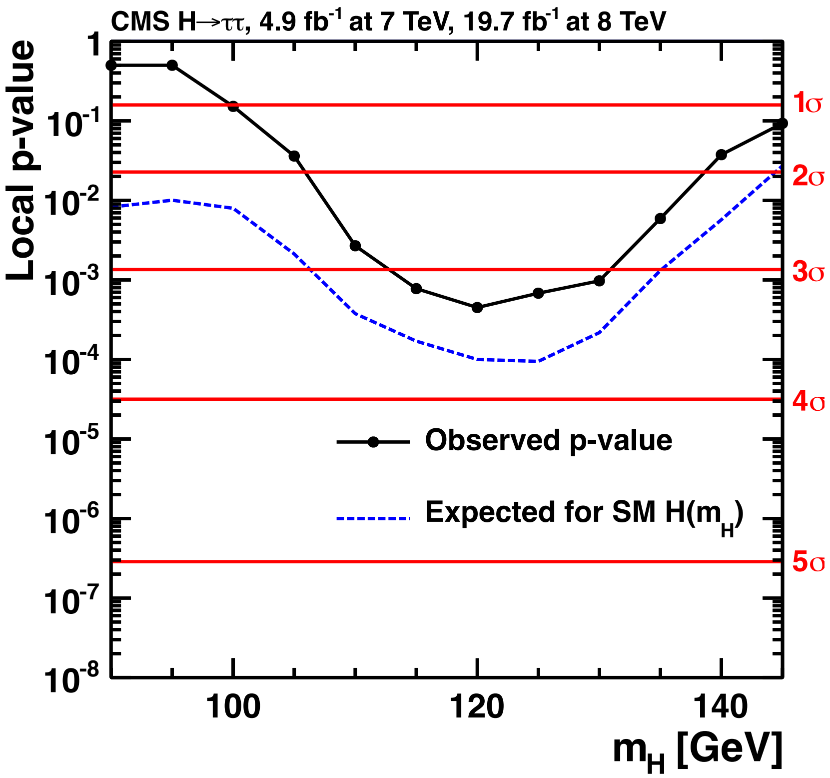




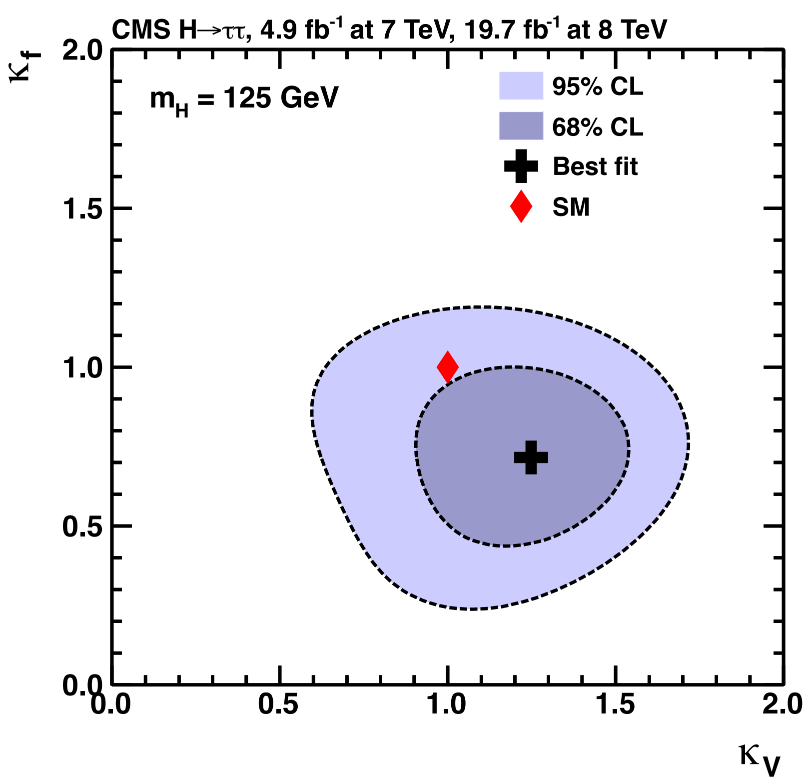
For 125 GeV Higgs: most competitive channels are $\mu\tau_h$ $e\tau_h$ and $\tau_h\tau_h$

1 jet and VBF categories are ~ equally powerful

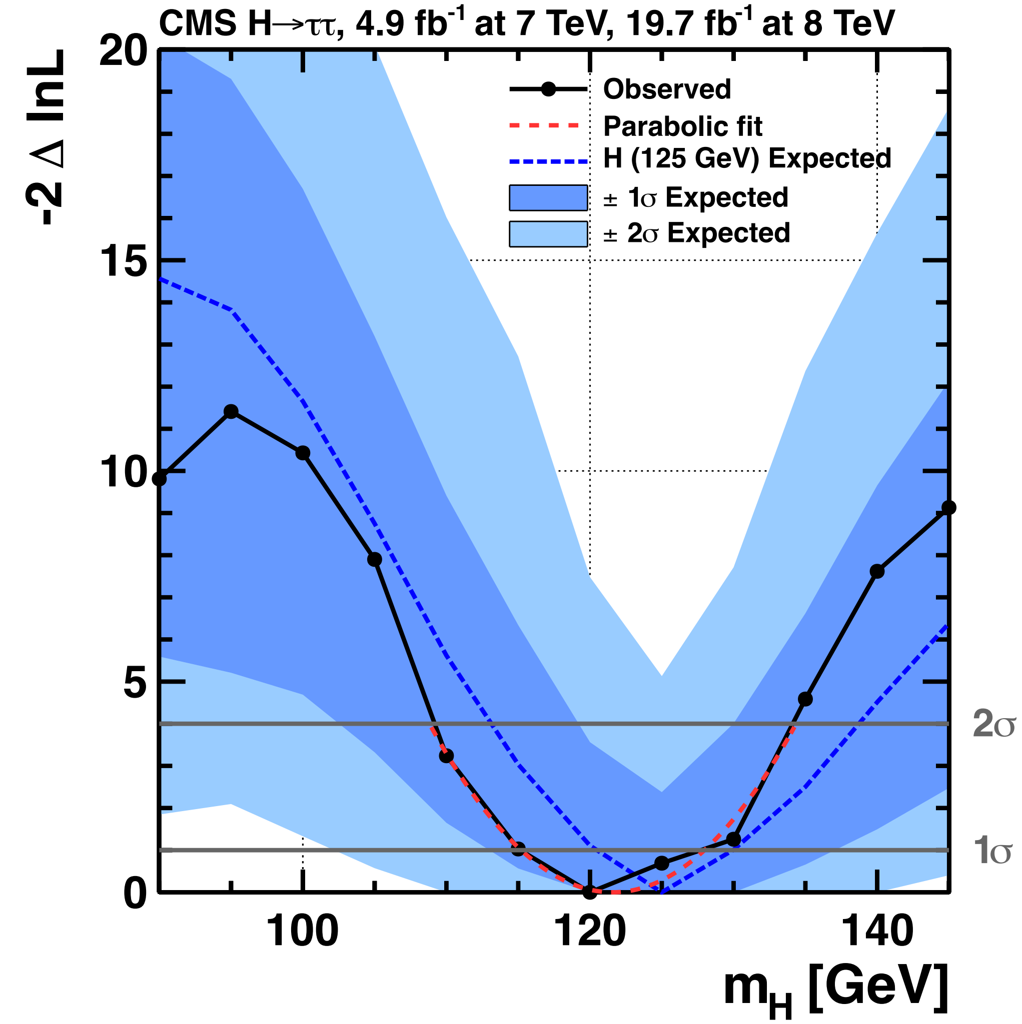
Interpretation of results



>3σ evidence for $H \rightarrow \tau\tau$ decays



Couplings to vector bosons and fermions consistent with SM H



Mass measurement yields best fit of 122 ± 7 GeV

Combination with ATLAS

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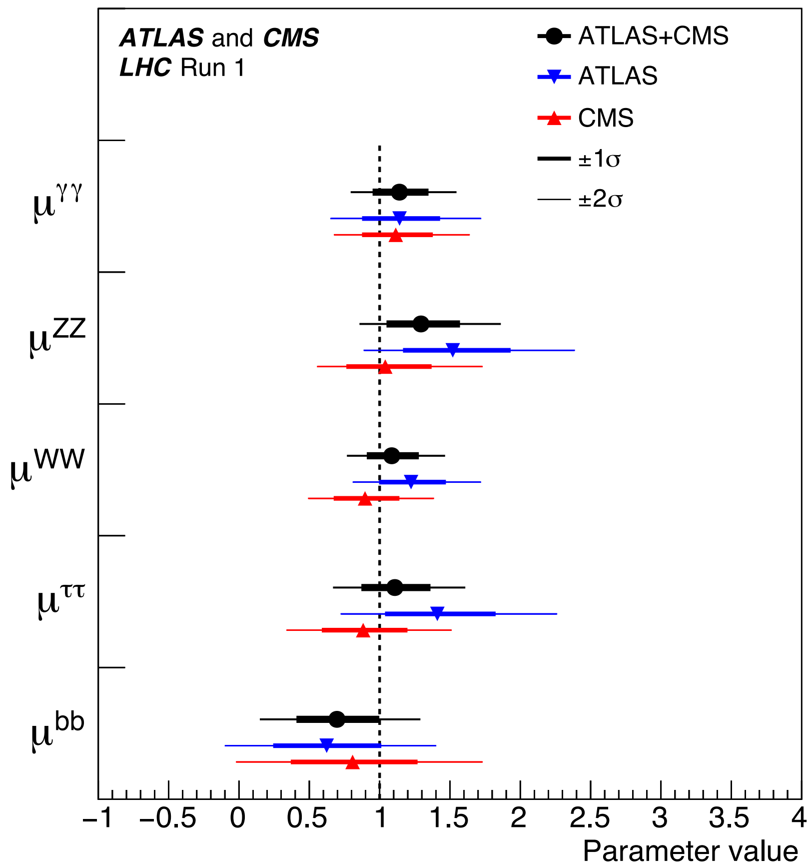
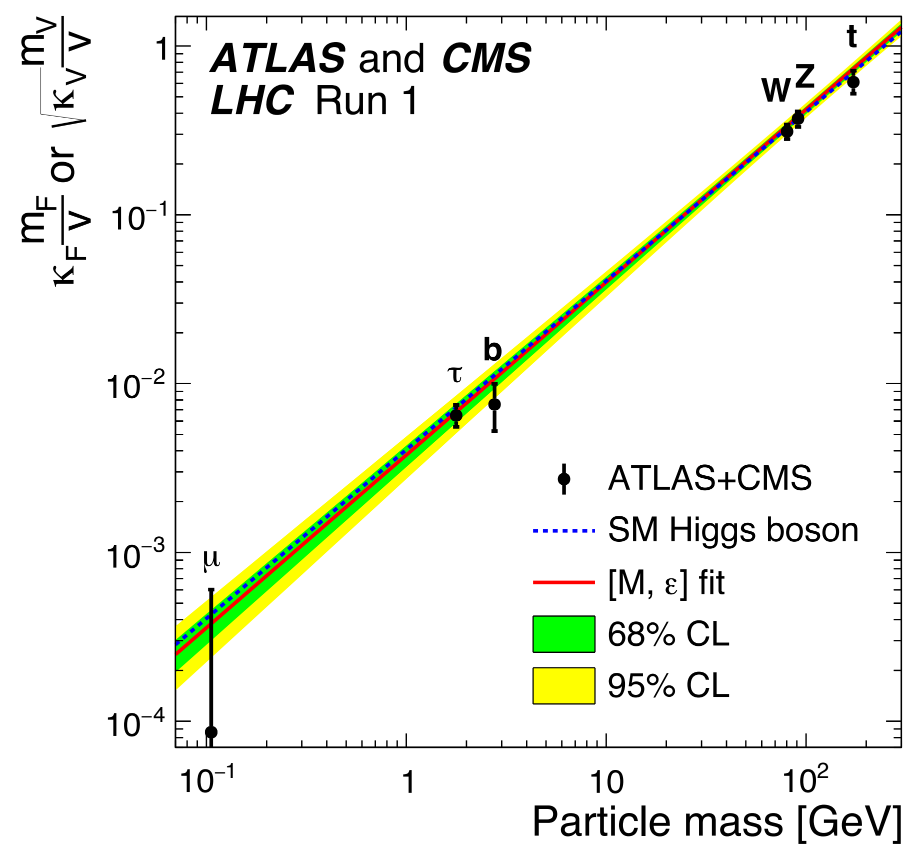




Production process	Measured significance (σ)	Expected significance (σ)
VBF	5.4	4.6
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
$H \to \tau\tau$	5.5	5.0
$H \to bb$	2.6	3.7

>5σ significance for H → ττ when combining ATLAS and CMS results from Run 1

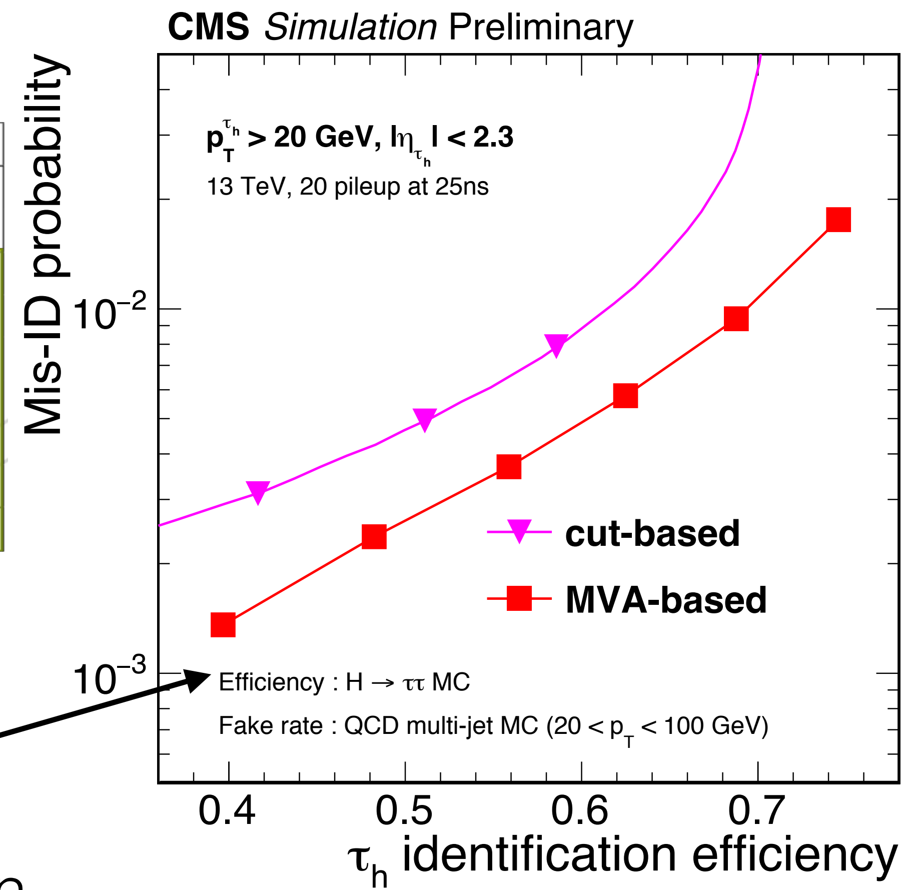
Tau ID in Run 2

CMS-PAS-TAU-16-002

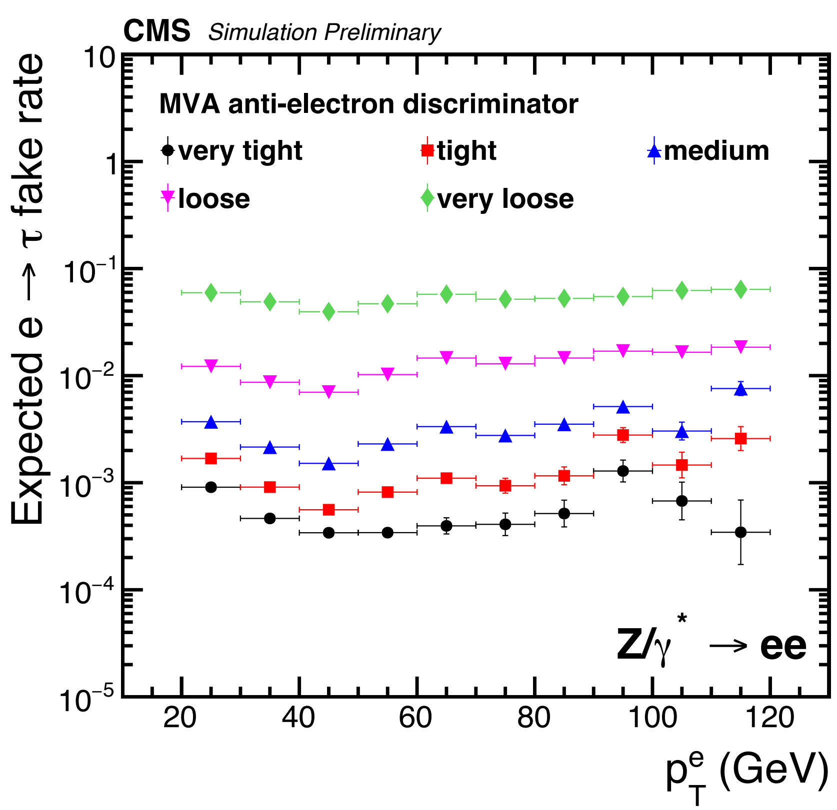
- As in Run 1 - reconstruct hadronic taus in different hadronic decay modes ("hadron plus strips" algorithm)

Decay Mode	Resonance	$\mathcal{B}$ [%]
$\tau^- \rightarrow e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \rightarrow \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \rightarrow h^- \nu_\tau$		11.5
$\tau^- \rightarrow h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	10.8
$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \rightarrow h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other hadronic modes		1.8
All hadronic modes		64.8

- New for Run 2 - **dynamic strip size** in 1 prong + pi0 reconstruction, changes as function of expected e/γ p_T



- **Multivariate isolation discriminator** retrained for Run 2, now includes information on dynamic strip size, significantly outperforms cut based discriminant



- New improved anti-electron discriminator, reduces number of electrons reconstructed as taus

Run 2 Higgs searches involving taus

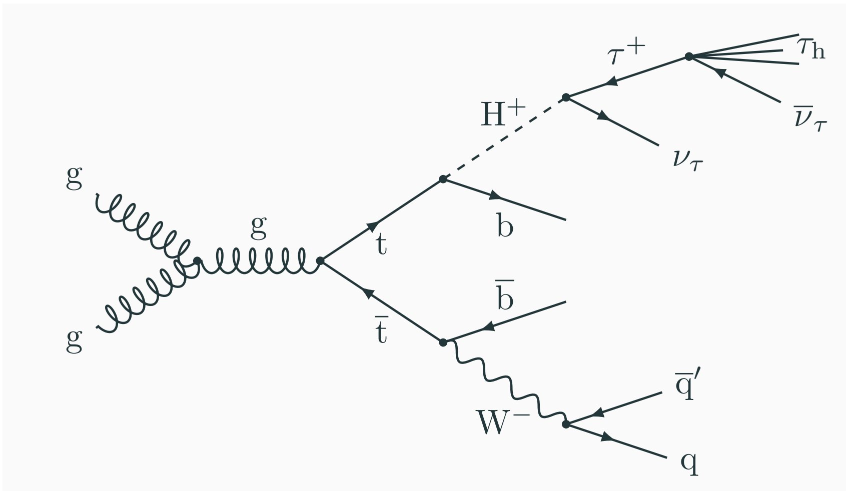
Gain in signal cross-section in going from 8 → 13 TeV much larger for heavier Higgs bosons → with early 13 TeV data focus was on BSM Higgs boson searches (in order of how recent):

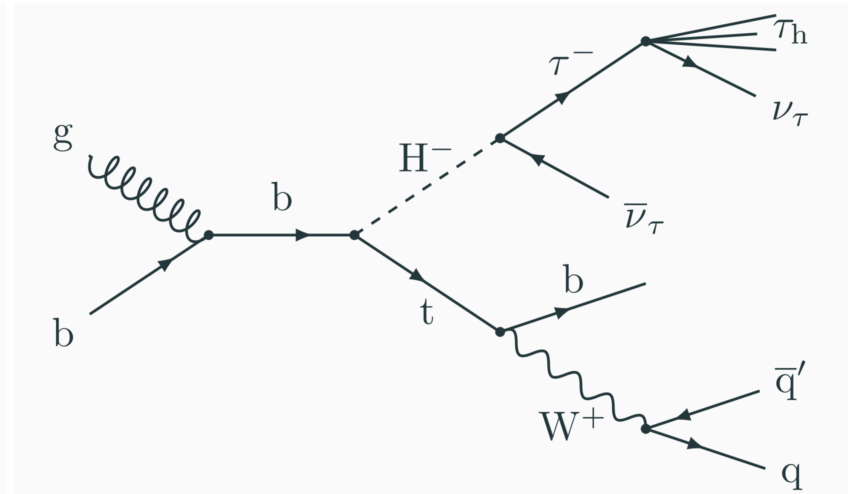
- **MSSM $\phi\to\tau\tau$** search on 12.9 fb^{-1} of 2016 data : CMS-PAS-HIG-16-037 - **new for this conference!** ← Later today
- **Charged Higgs $H^+\to\tau\nu$** search on 12.9 fb^{-1} of 2016 data: CMS-PAS-HIG-16-031 - released in early October for Charged Higgs 2016 conference - **more in the next slides**
- **$H\to hh\to\tau\tau bb$** resonant search on 12.9 fb^{-1} of 2016 data: CMS-PAS-HIG-16-029 - released for ICHEP ← Later today
- **$H\to hh\to\tau\tau bb$** non-resonant search on 12.9 fb^{-1} of 2016 data: CMS-PAS-HIG-16-028 - released for ICHEP ← Later today
- + some previous iterations on 2015 data
- **LFV $H\to\mu\tau$** on 2.3 fb^{-1} of 2015 data: CMS-PAS-HIG-16-005 ← Later this week

$H^+ \to \tau\nu$ Analysis at 13 TeV

CMS-PAS-HIG-16-031

$m_{H+} < m_t$





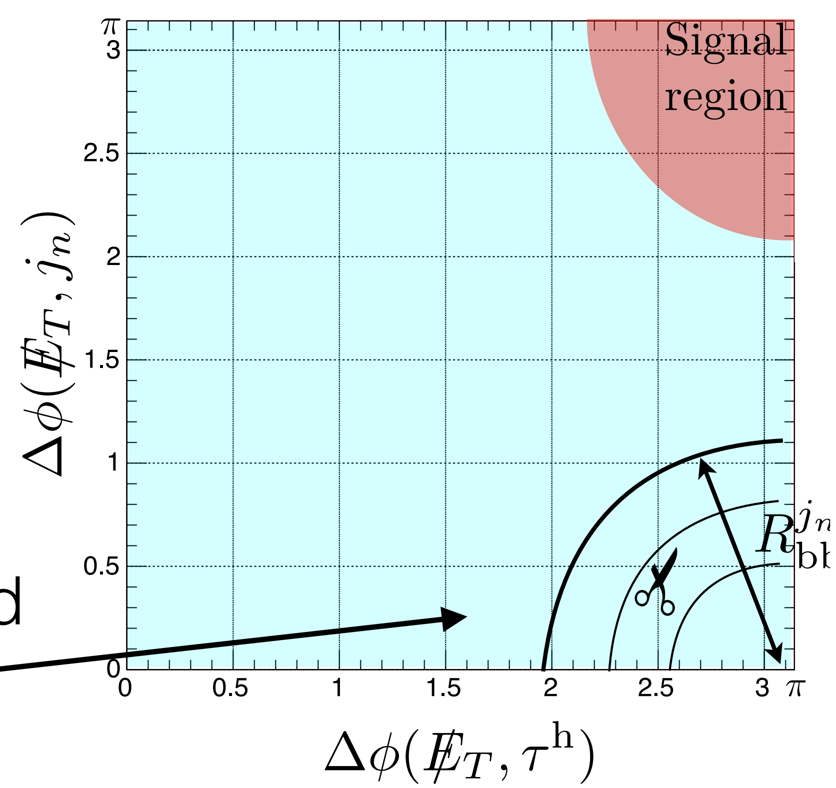
$m_{H+} > m_t$

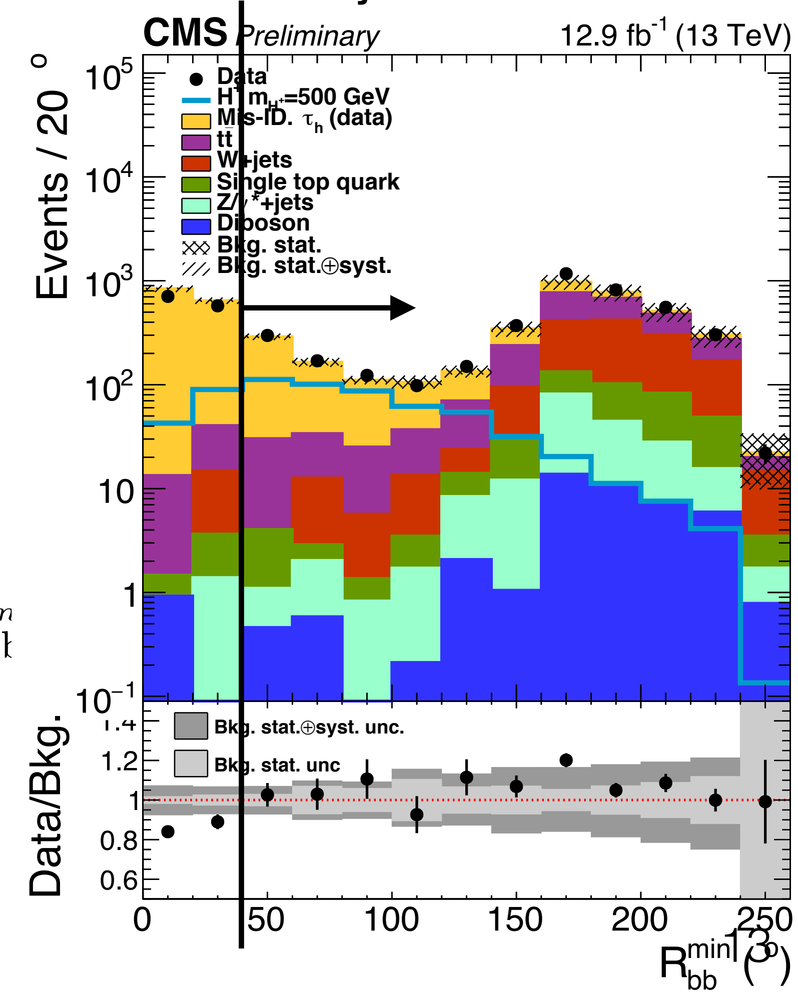
- Using **hadronic tau** final state for the H^+
- Cuts on missing E_T and tau p_T (cuts tuned separately for low and high mass search)
- For both topologies, **high jet multiplicities ->** select events with >= 3 jets and >=1 btag jet

- Additional cut on topological discriminator to reject multi jet events:

$$R_{bb}^{min} = \min_{j \in j_1..j_3} \sqrt{\Delta\phi(\not{E}_T, j)^2 + (\pi - \Delta\phi(\tau^h, \not{E}_T))^2}$$

Cut of R_{bb}^{min} > 40 degrees applied (i.e. outside of circle shown)

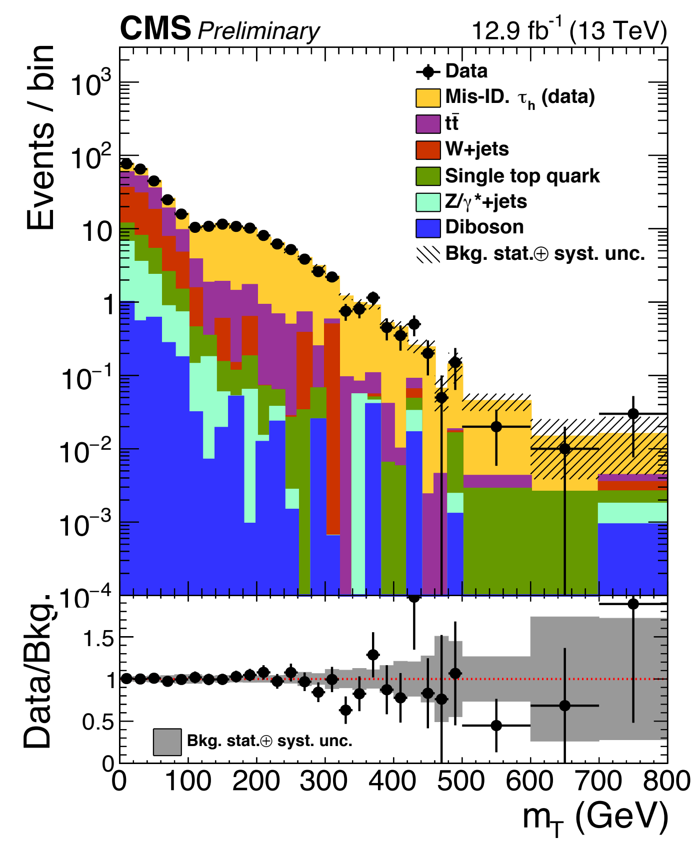




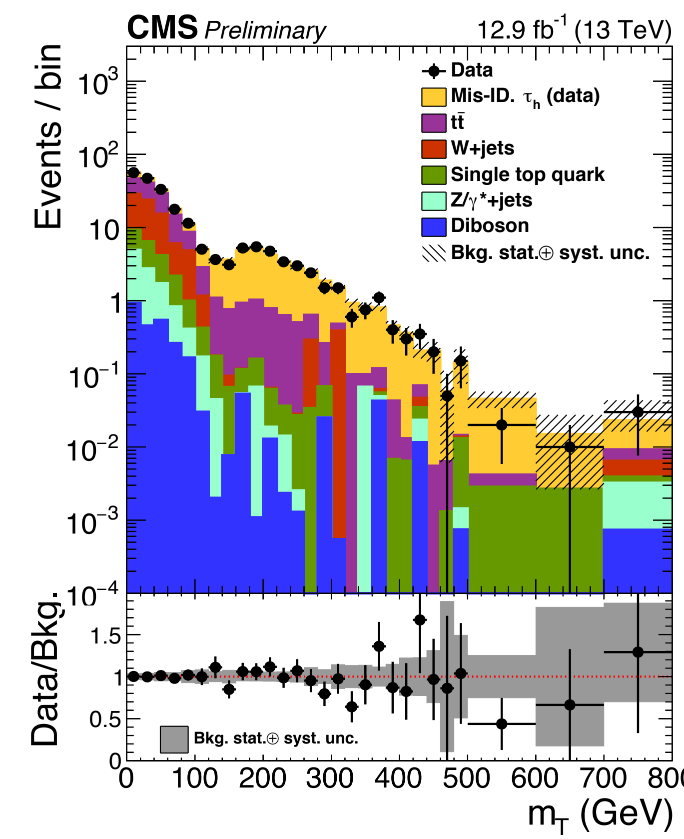
H+→τν Analysis at 13 TeV

- Transverse mass used as final discriminating variable:

$$m_{\mathrm{T}}^2 = 2 \cdot p_{\mathrm{T}}^{\tau^{\mathrm{h}}} |\vec{\not{E}}_T| \left(1 - \cos\Delta\phi(\not{E}_T, \tau^{\mathrm{h}})\right)$$



low mass



high mass

	Yields ($m_{\mathrm{H}^\pm} < mt - mb$)	Yields ($m_{\mathrm{H}^\pm} > mt - mb$)
EW	1454.3	1151.7
Top	1792.9	1318.4
Fake-τ^{h}	2564.4	1197.8
Tot	5811.6	3667.9
Data	6276	4179

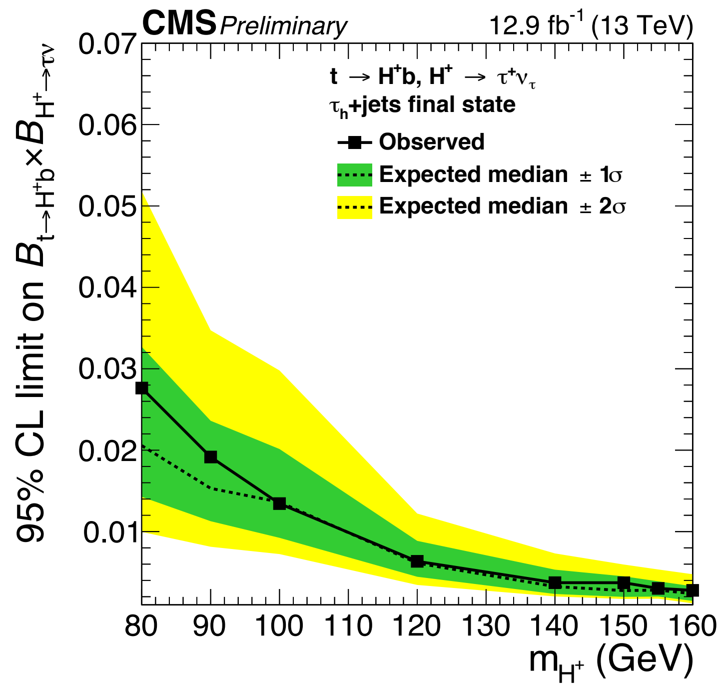
- Main backgrounds from fake taus - estimated from data using inverted tau selection
- EWK + tt genuine tau background taken from simulation

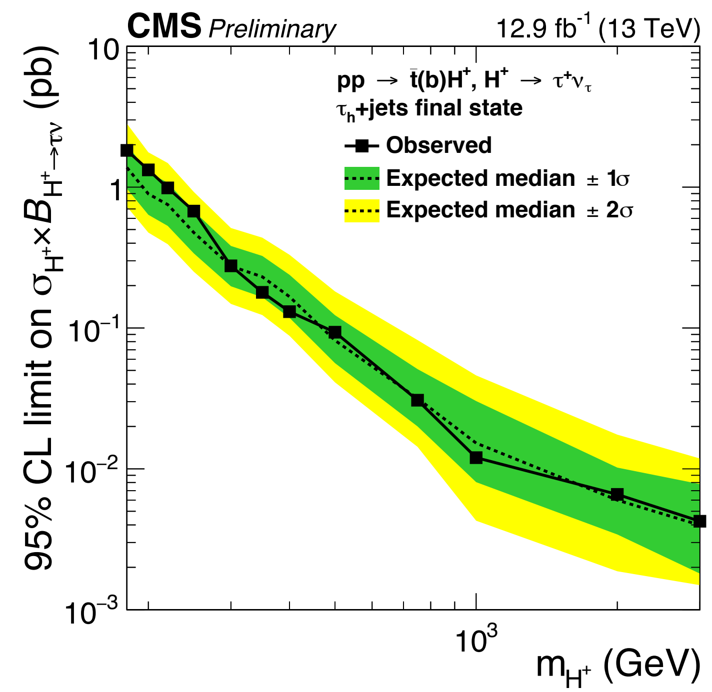
H+→τν results

- Limits on each production process for range of H+ masses:

low mass

Low mass limits set in range 80-160 GeV



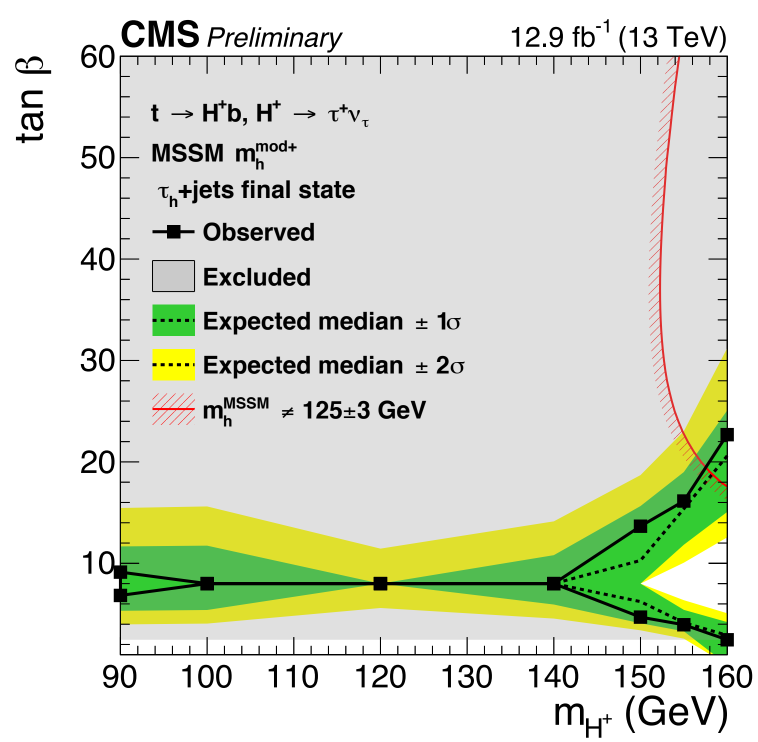


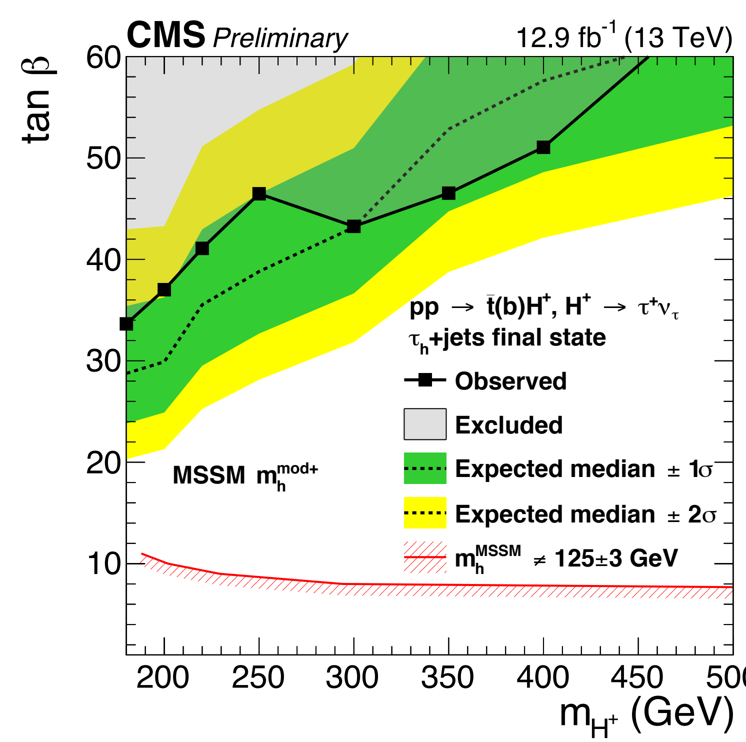
high mass

High mass limits in range 180 - 3 TeV

- Limits in **MSSM m_h^{mod+} benchmark scenario**:

low mass





high mass

Summary

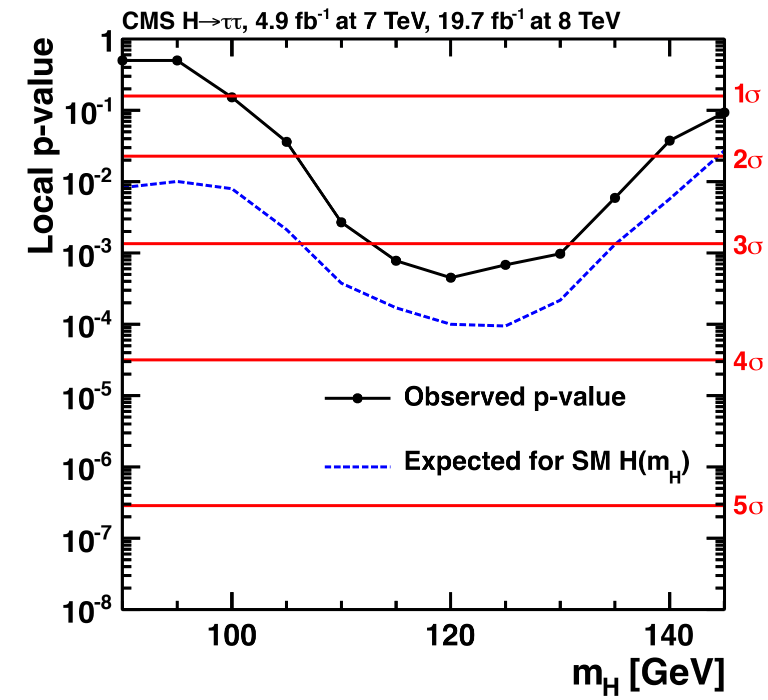
- SM $H \rightarrow \tau\tau$ has been seen at the level of 3σ in ATLAS and CMS alone and 5σ in combination using the Run 1 dataset.

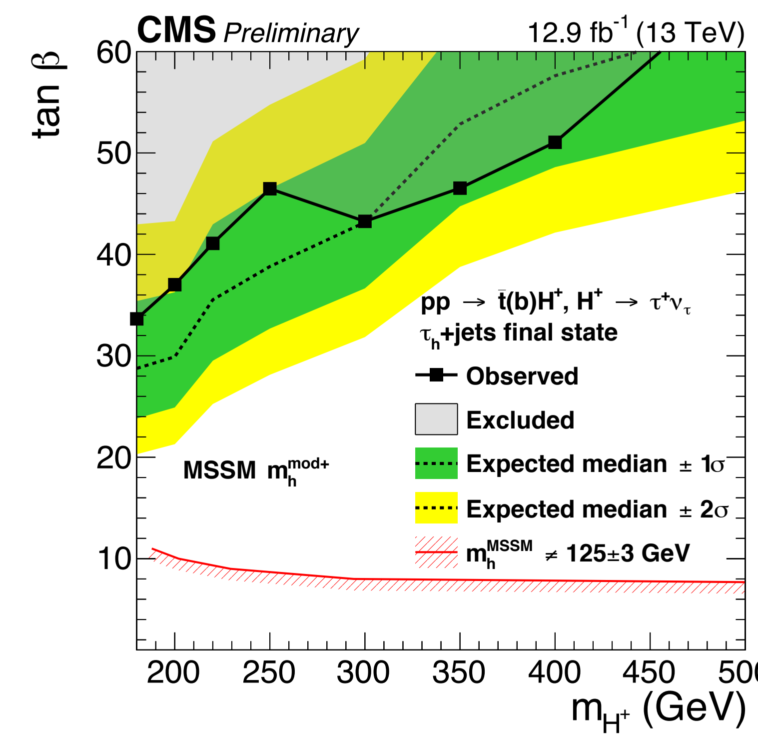
- Hadronic tau ID performance has generally been maintained and improved in Run 2 compared with Run 1

- Taus remain an important Higgs search channel in Run 2 and have a wide range of interesting BSM searches

- Many BSM $H \rightarrow \tau\tau$ results already released on Run 2 data, and show no evidence for additional Higgs bosons yet.

▸ **Watch this space! More coming soon with full 2016 dataset**





Backup

H->ττ in Run 1

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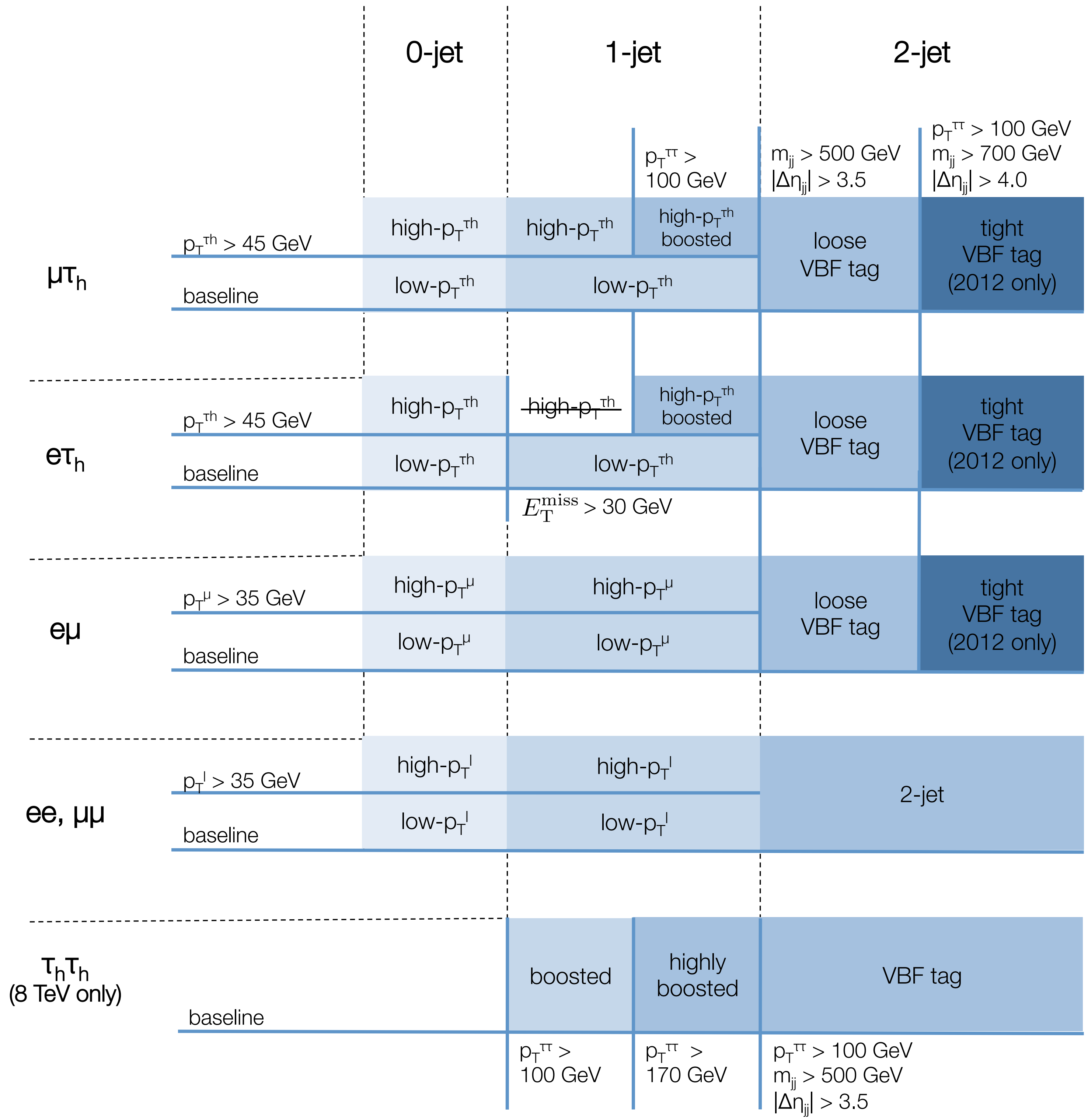

H->ττ in Run 1

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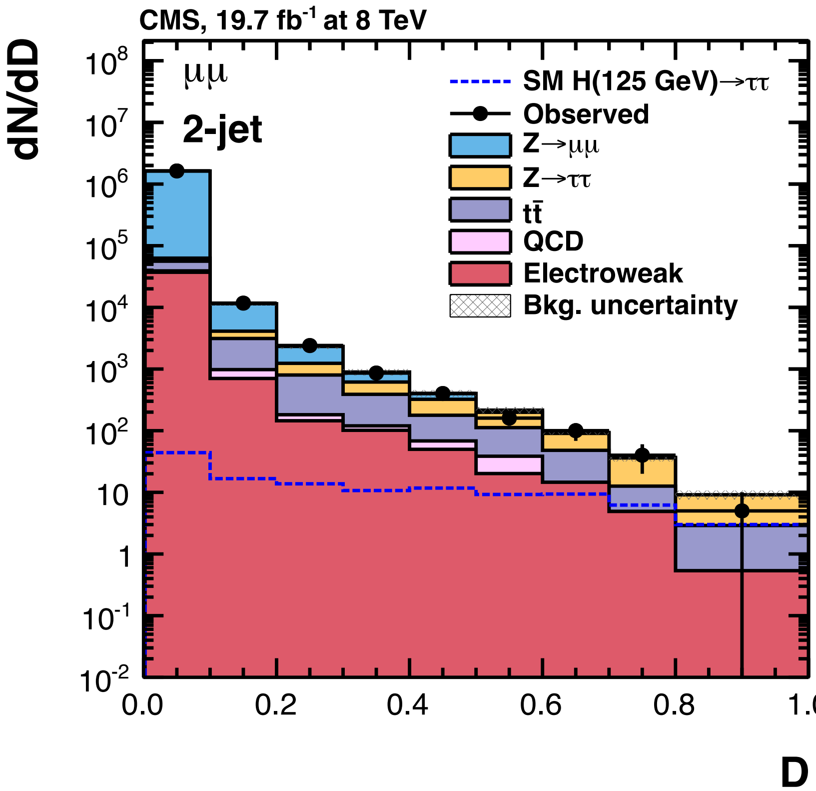
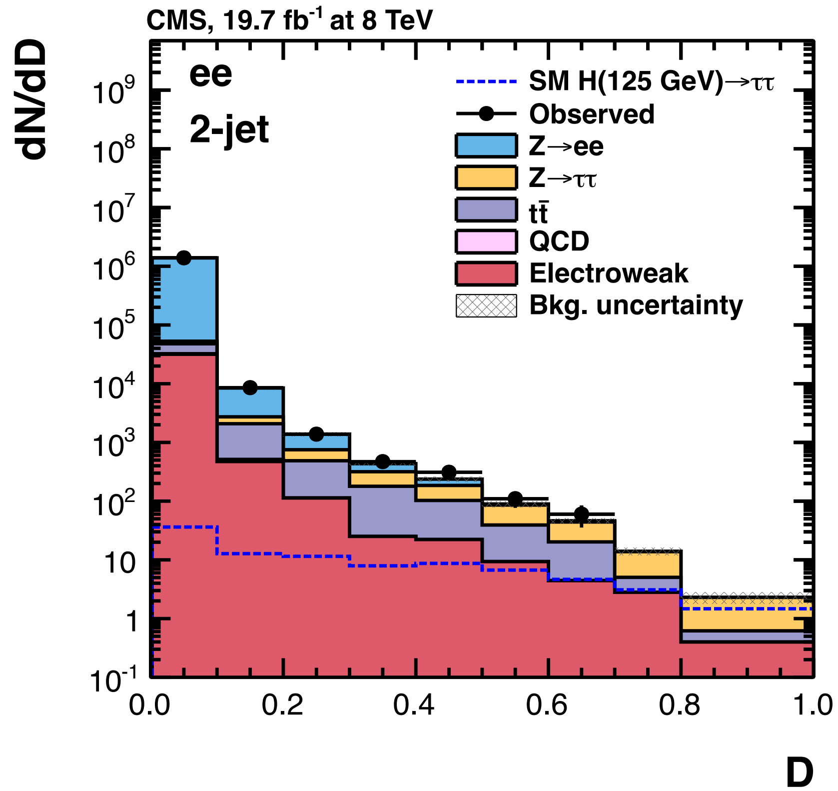
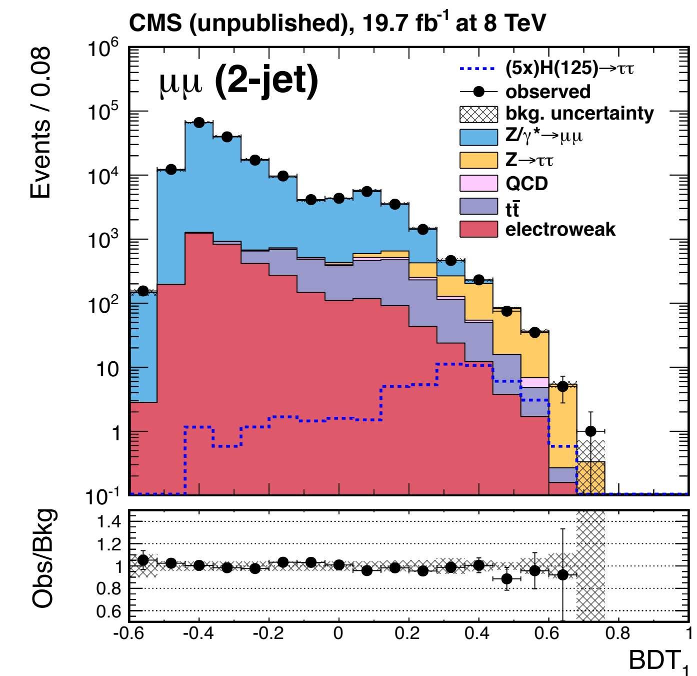
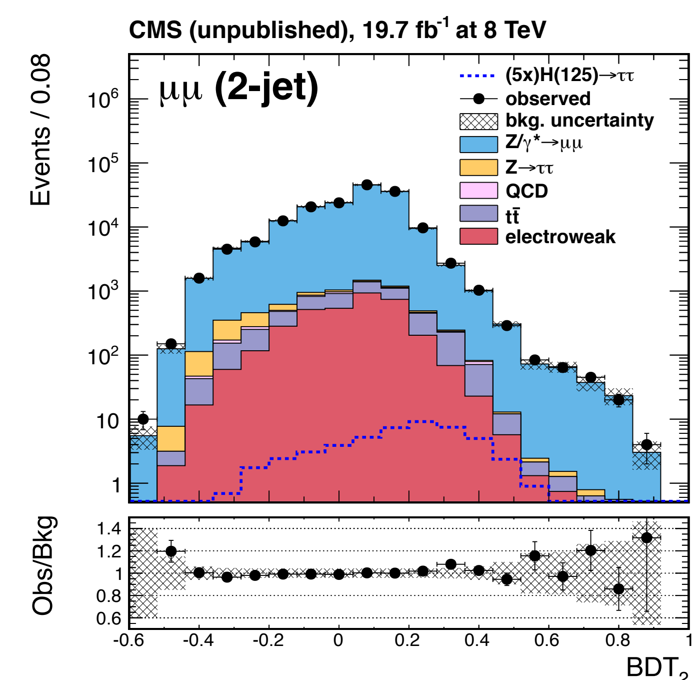






- BDT1 = Z->ττ vs Z->ll



- BDT2 = H->ττ vs Z->ττ

- BDT discriminant used in ee and μμ channels:

$$D = \int_{-\infty}^{B_1} \int_{-\infty}^{B_2} f_{\rm sig}(B_1', B_2')\, {\rm d}B_1'\, {\rm d}B_2'.$$

- i.e. probability for a signal event to have a value lower than B1 for the first BDT and B2 for the second BDT

H->ττ in Run 1

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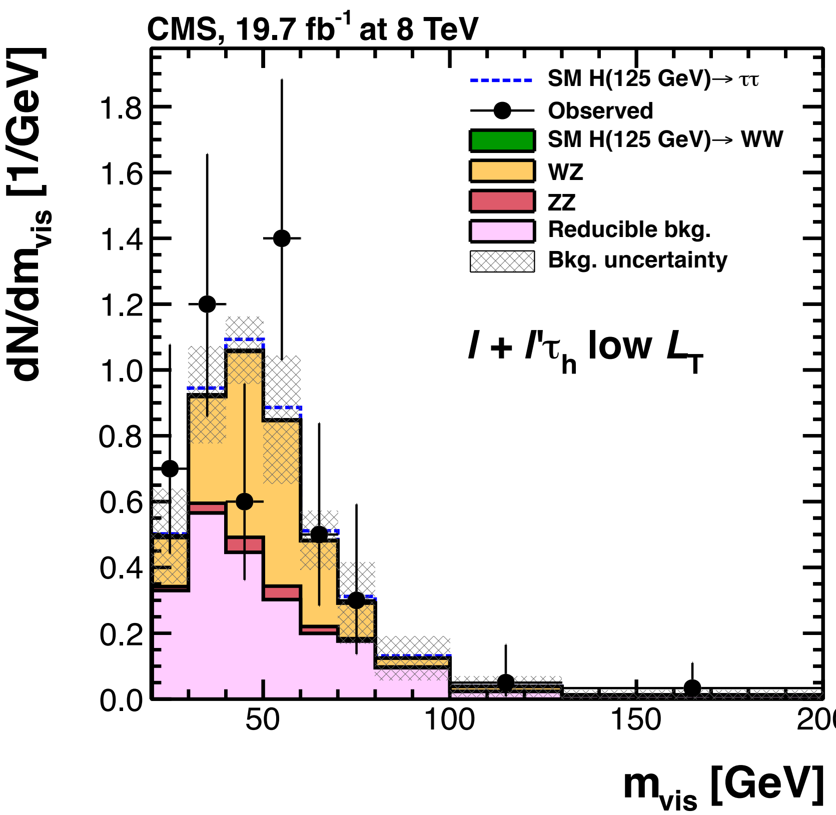

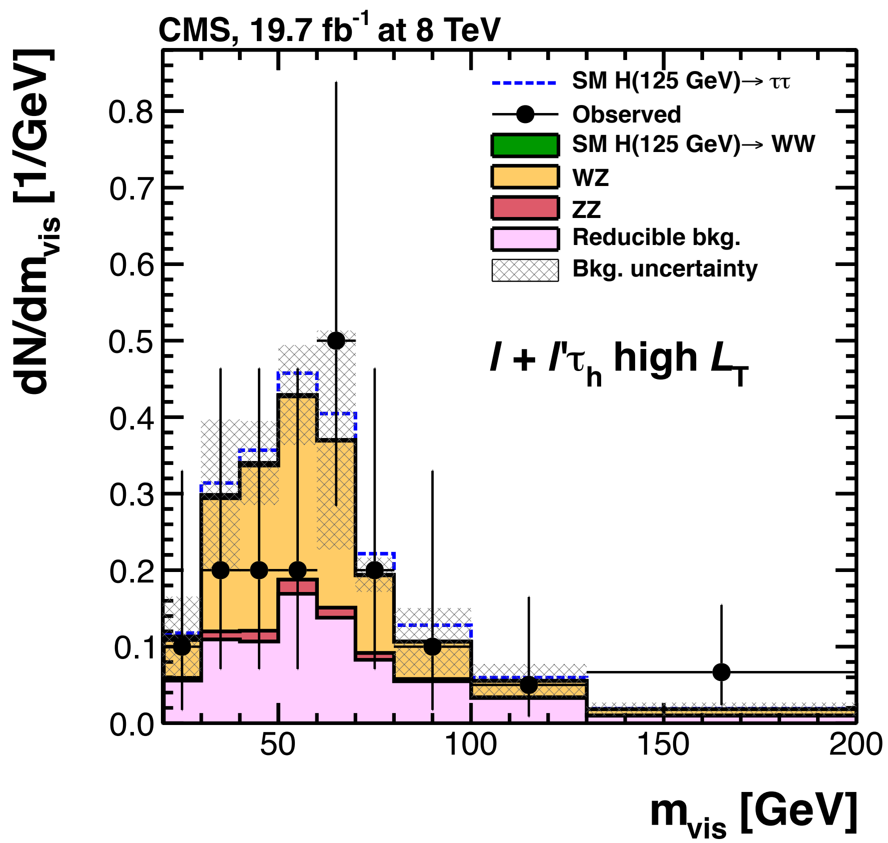

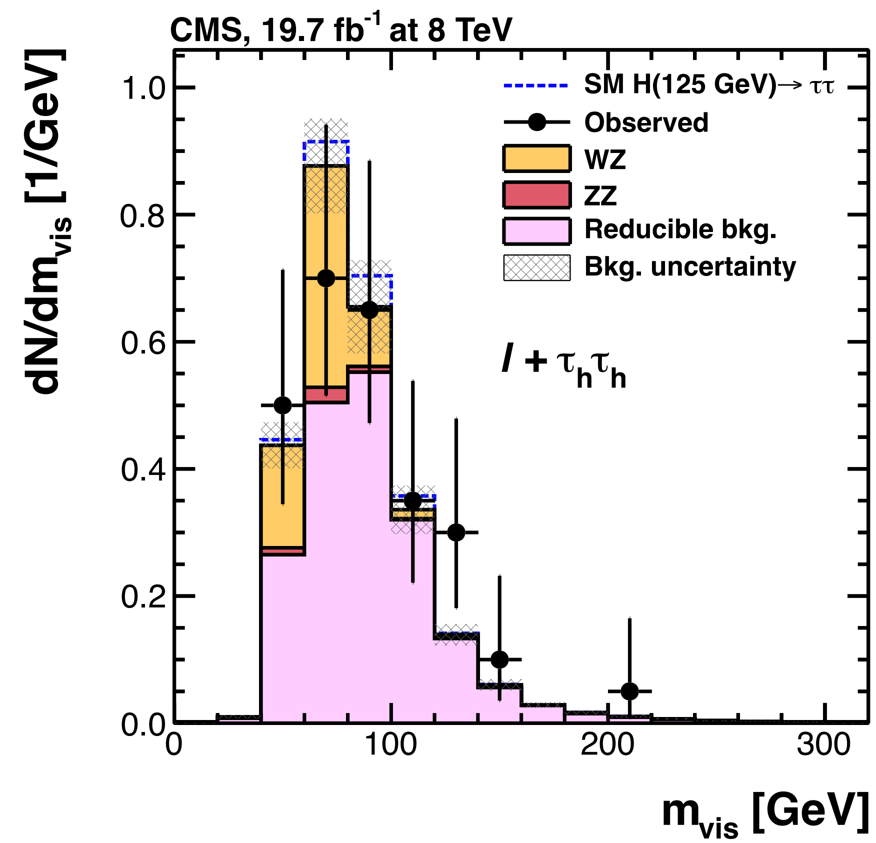

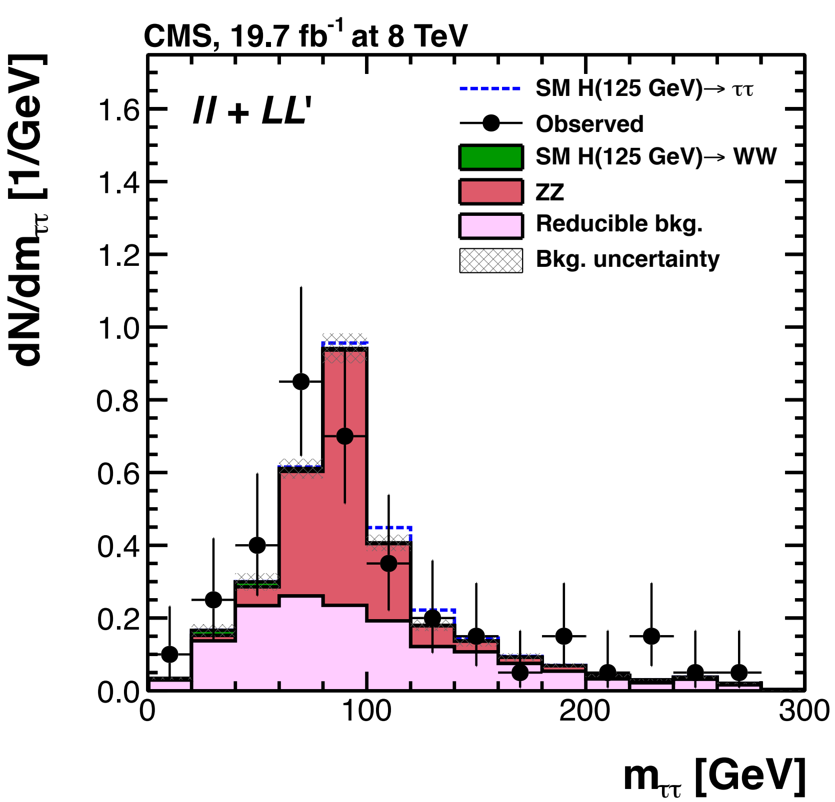

- WH and ZH channels in different tautau final states
- Use of L_T variable:
- for WH: $L_T = p_T^{l} + p_T^{l'} + p_T^{\tau h}$
- for ZH: $L_T = p_T^{L} + p_T^{L'}$

H->ττ in Run 1

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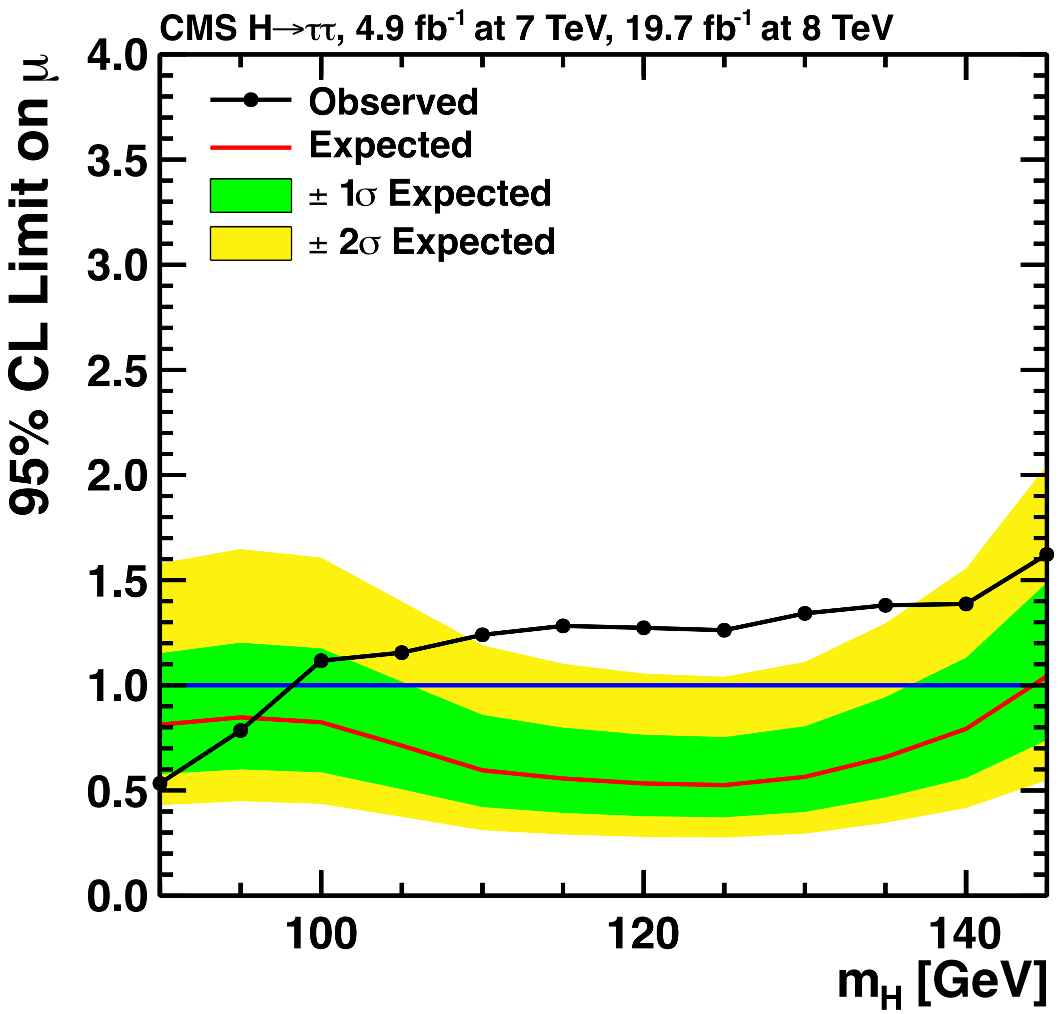

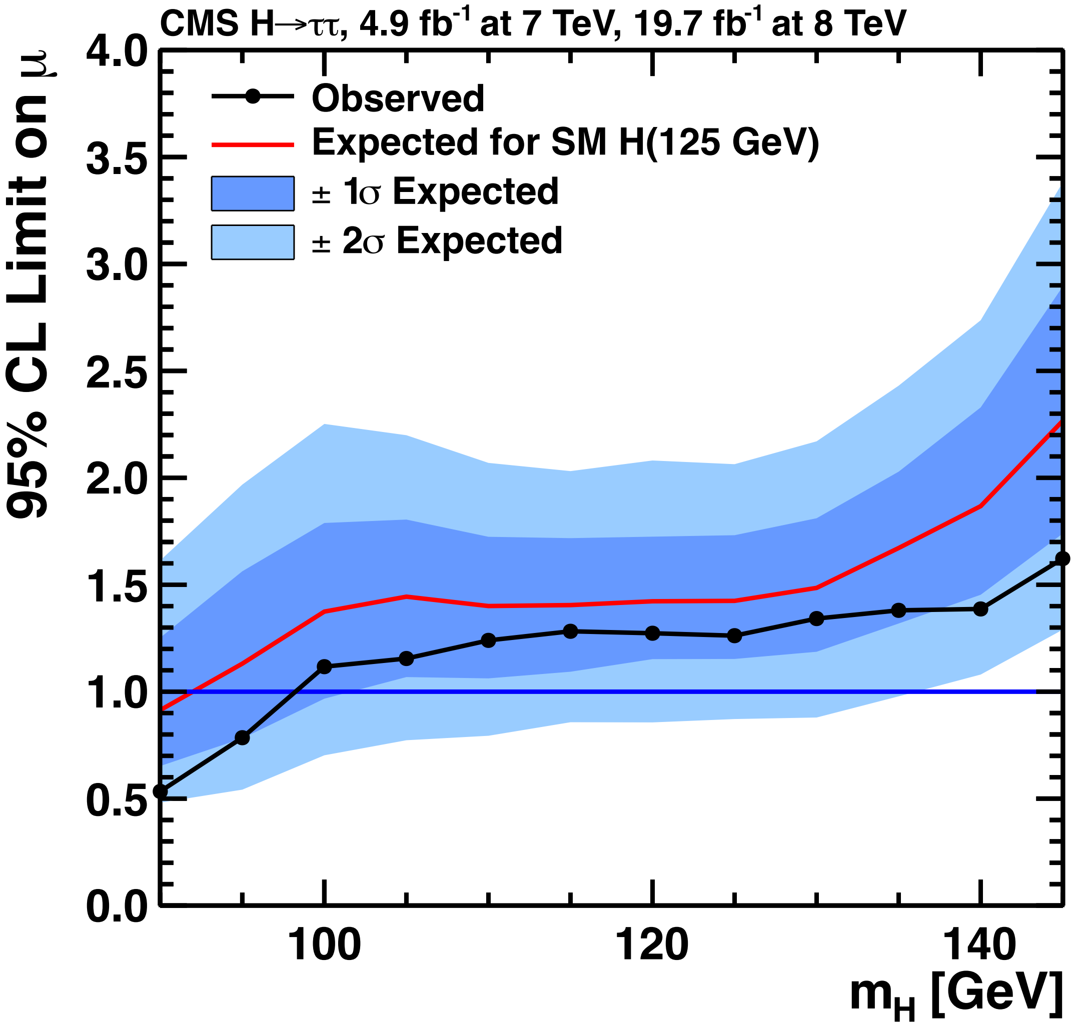

- SM(125) signal injected

H->ττ in Run 1

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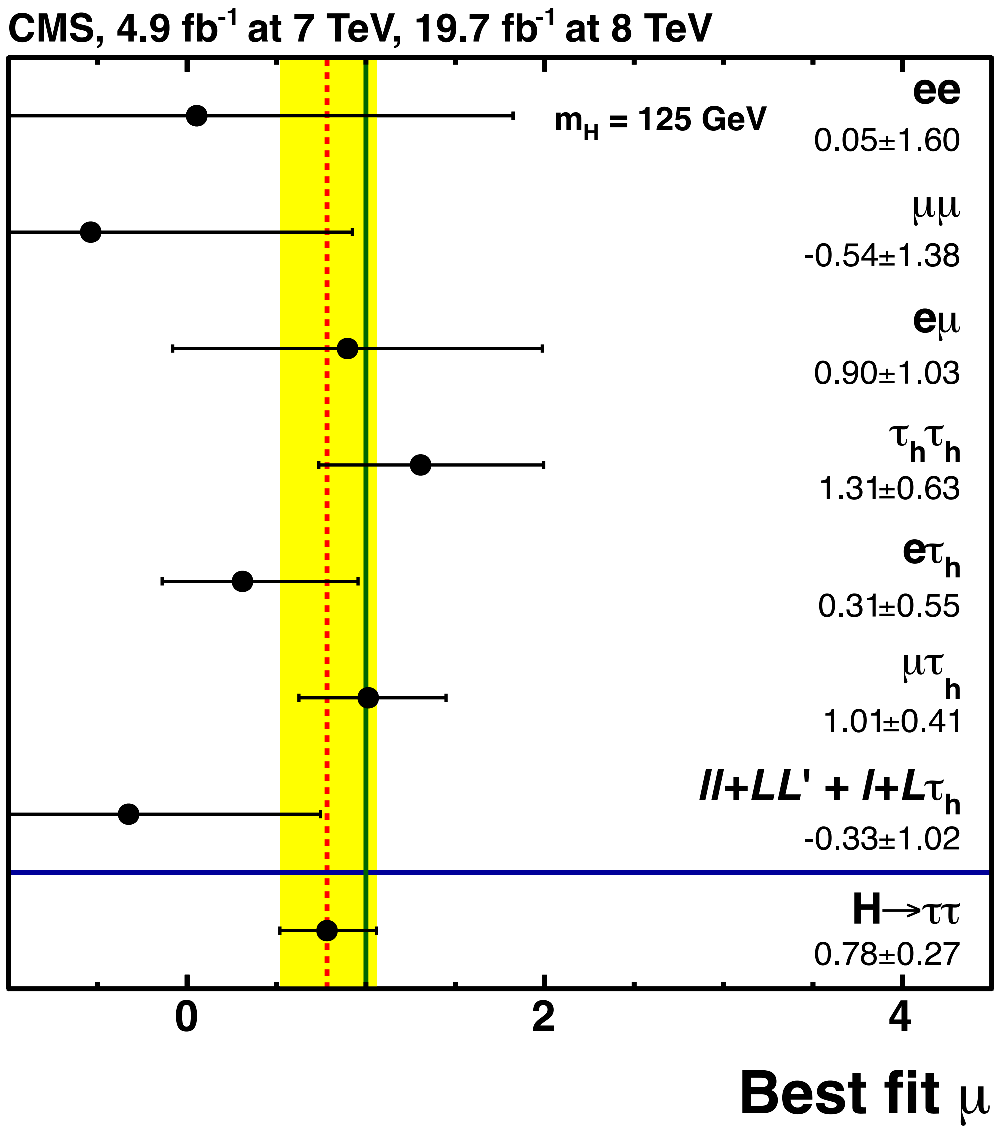

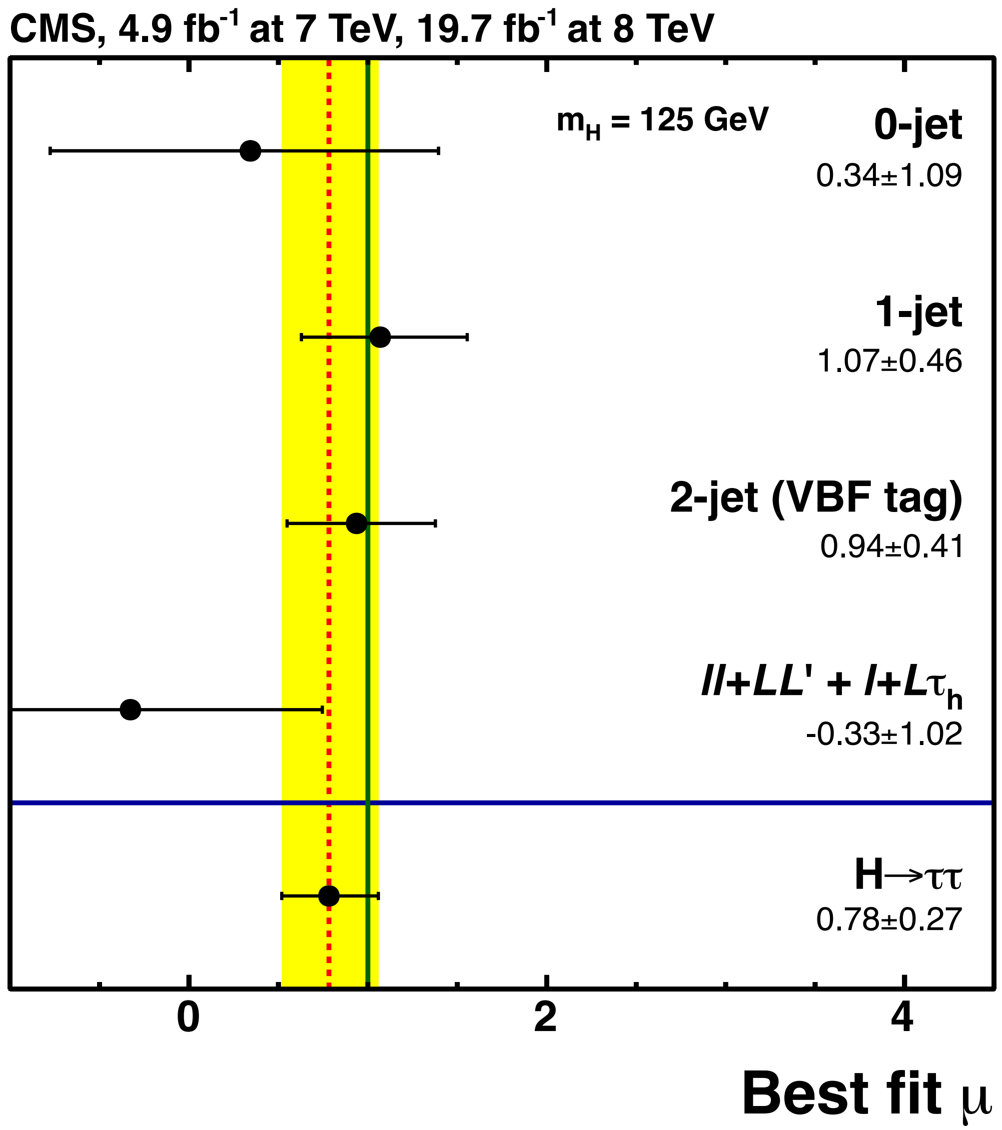

H->ττ in Run 1

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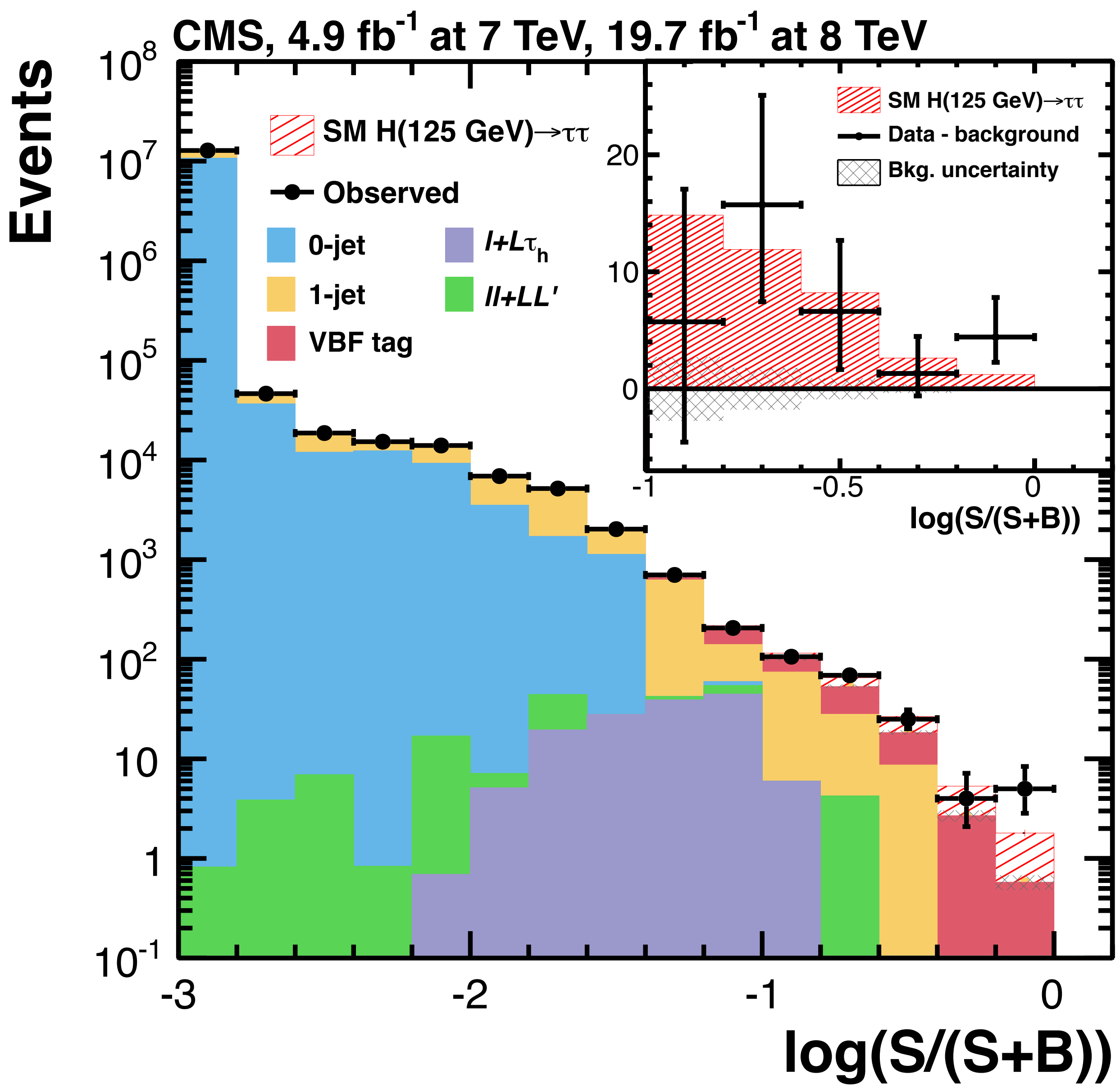
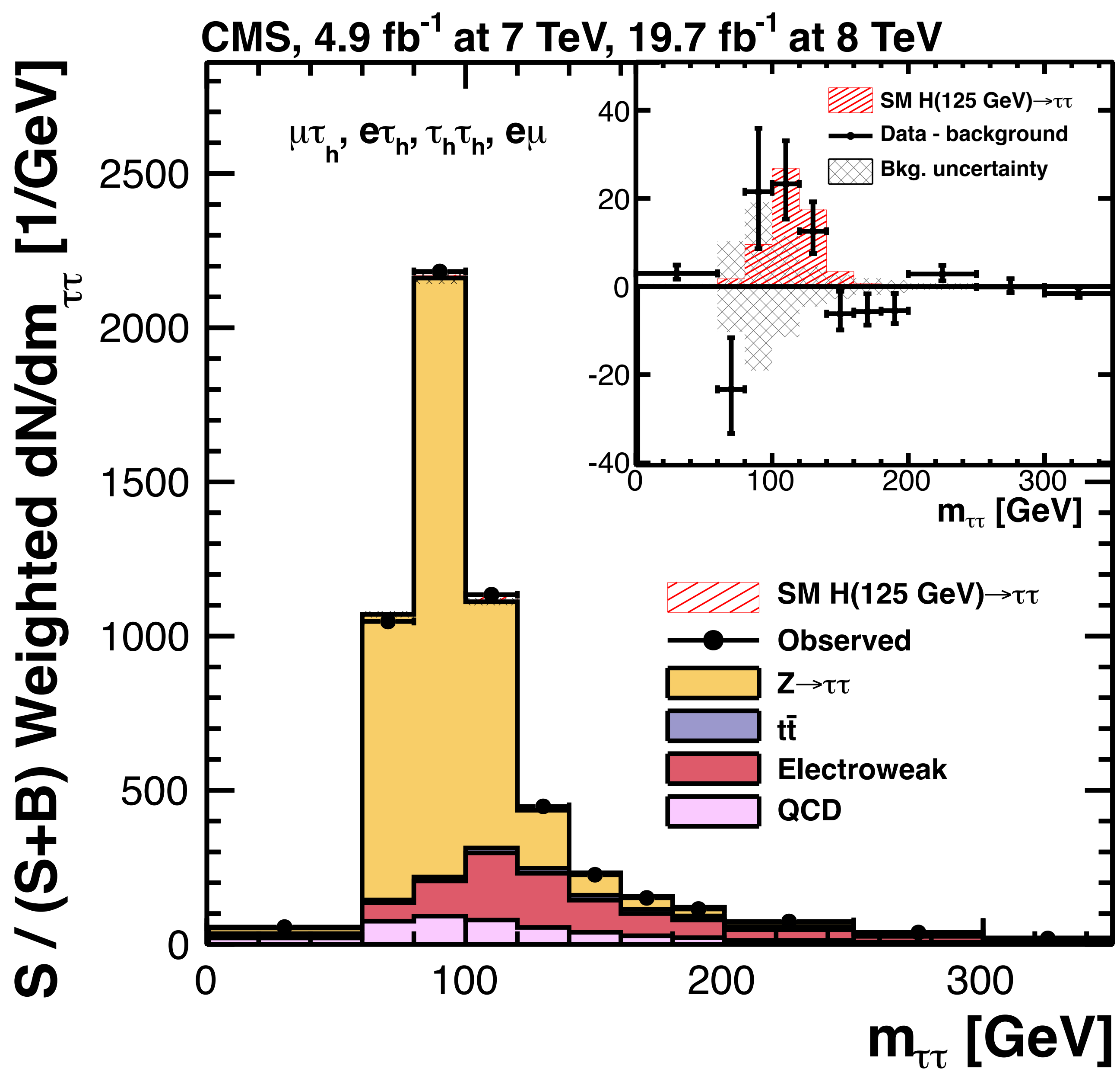
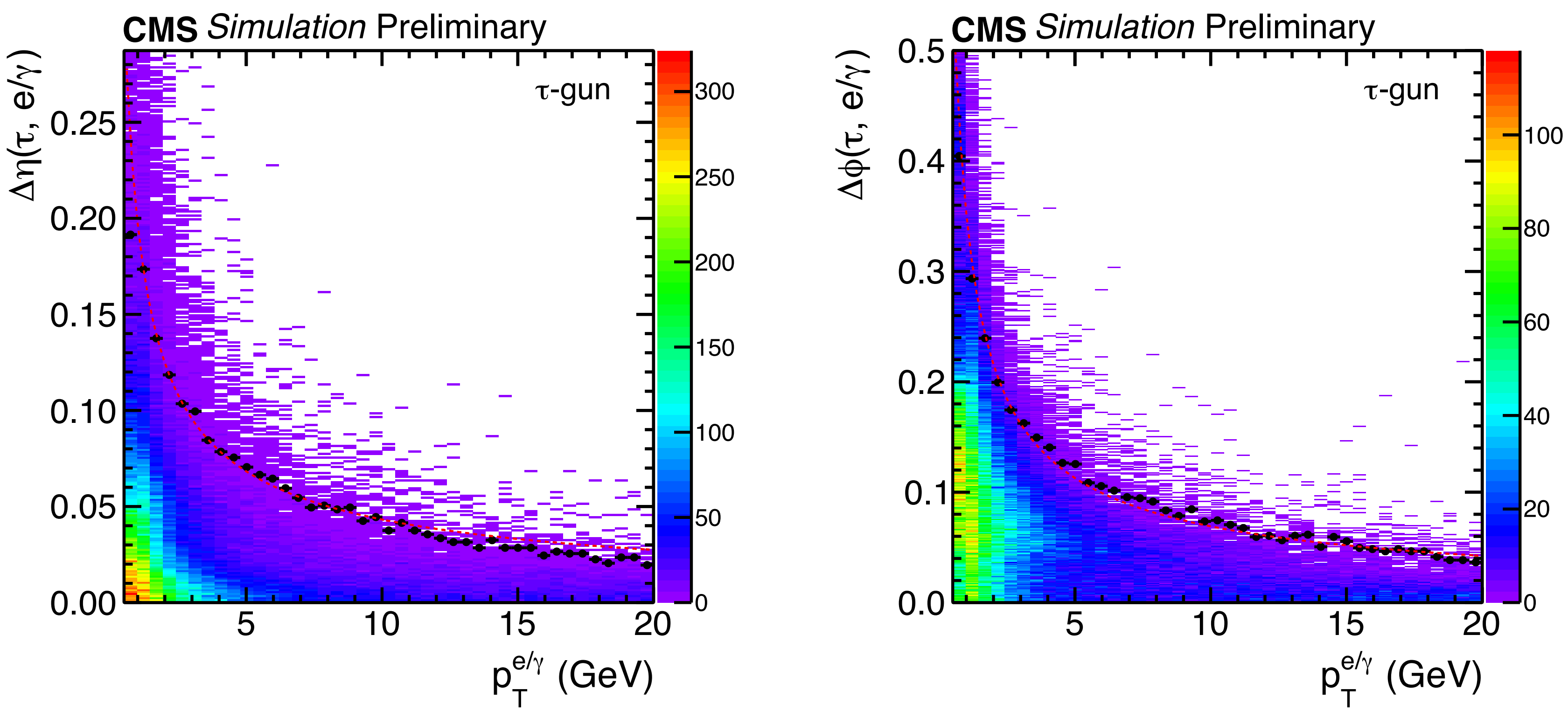




Dynamic strip reconstruction



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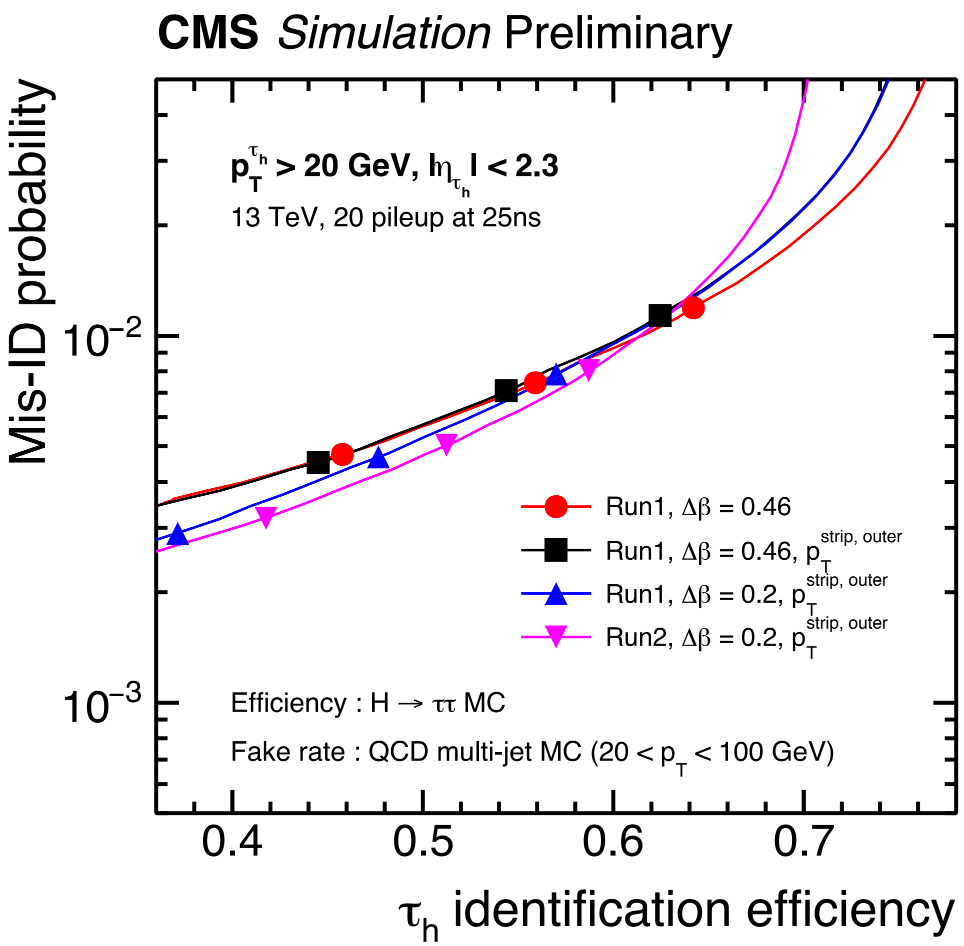
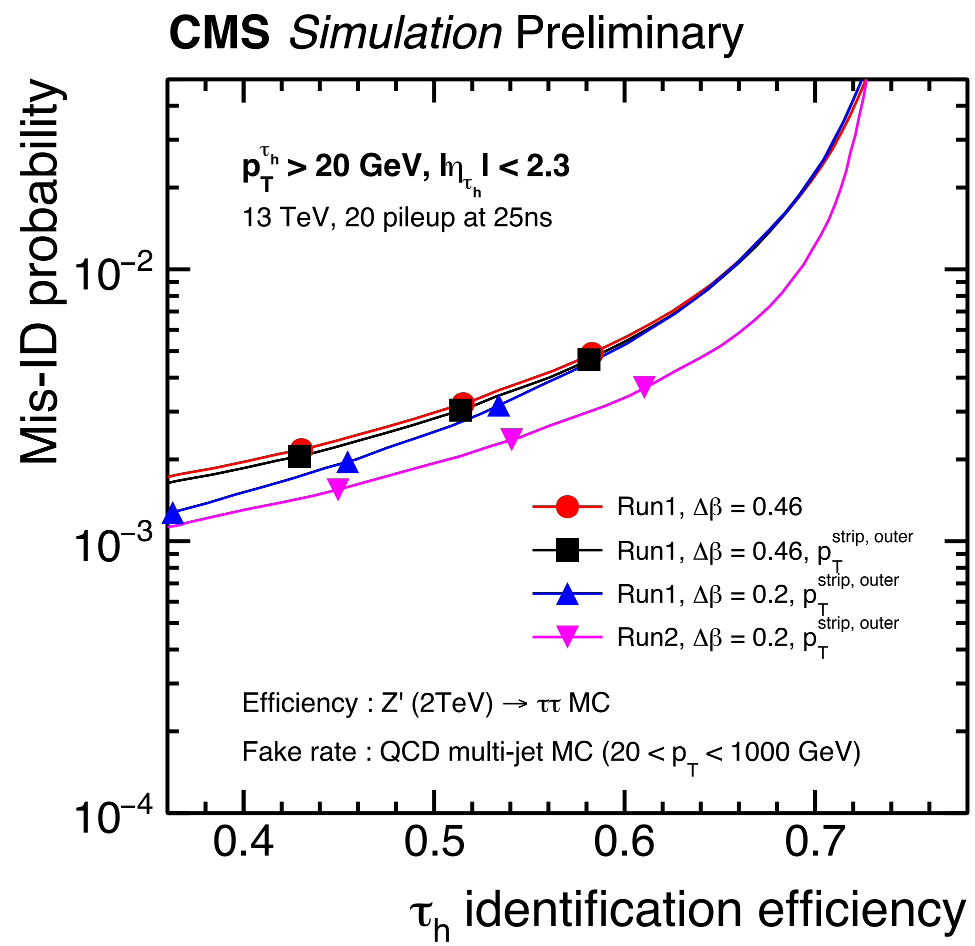
After Run-1, additional studies were performed in order to optimize the strip size. In practice, there were cases where τ_h decay products contributed to the isolation, such as:

- A charged pion from τ_h decay experiences nuclear interaction with tracker material and produces several secondary particles with low p_T. This ends up with low p_T electrons and photons that go outside strip window. This will affect the isolation of the τ_h, although it is part of the τ_h decay product.
- Photons from $\pi^0 \to \gamma\gamma$ have a large probability to convert to an e^+e^- pair and, after multiple conversion and bremsstrahlung, electrons and photons may go outside the fixed size window. This will also affect the isolation.

Naïvely, these decay products can be integrated as part of the signal by suitably widening the strip size. On the contrary, if the τ_h has a large p_T the decay product tend to be boosted in the τ_h flight direction. In this case, a smaller strip size than that considered in Run-1 [30] can reduce background contributions in the strip while accounting for all τ_h decay products.

Cut based isolation improvements





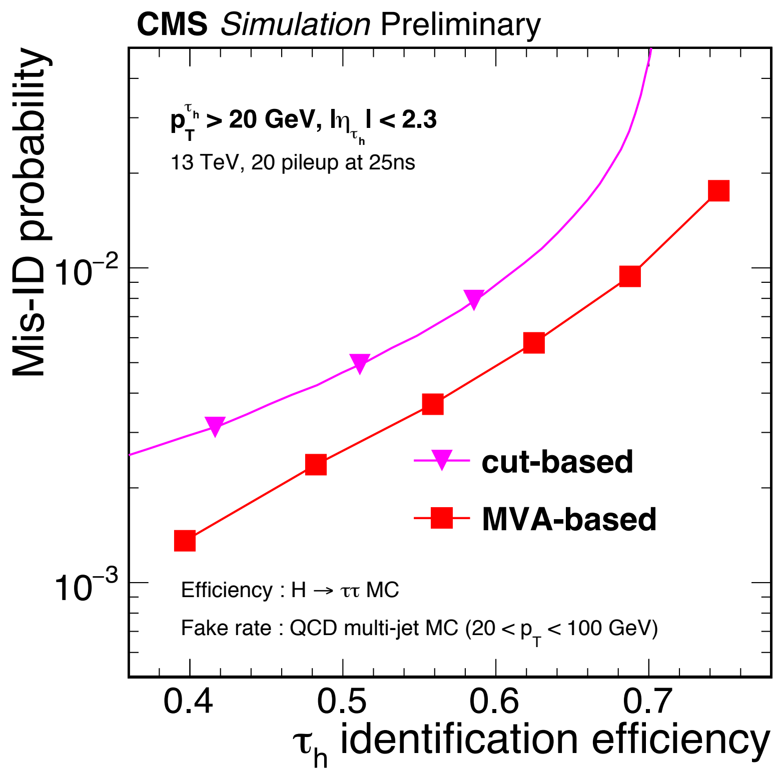
CMS-PAS-TAU-16-002

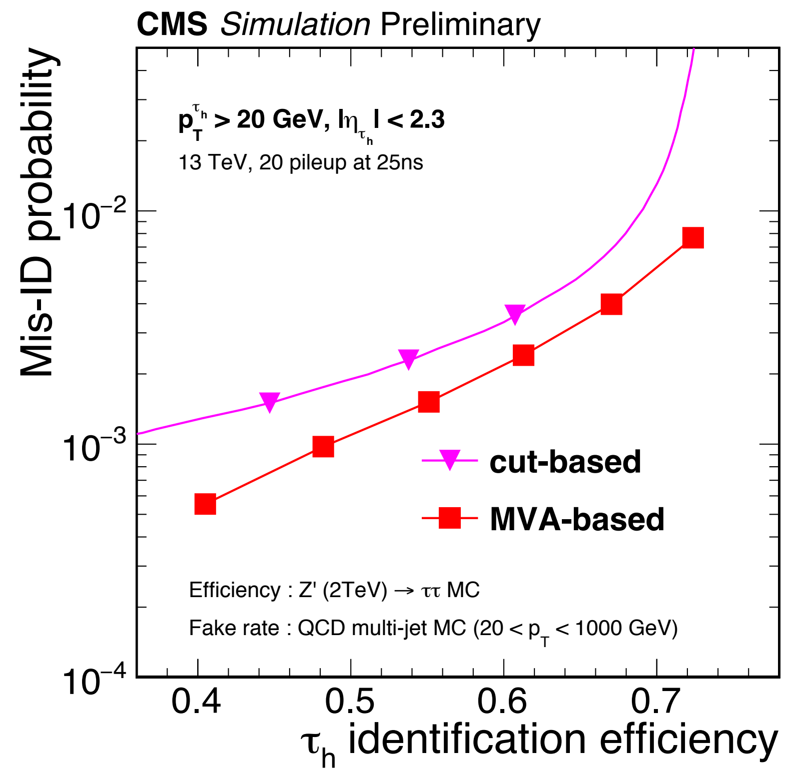
Run 2 vs Run 1: Δβ retuned, additional cut on $p_T^{\text{strip, outer}}$ added

Gain in signal efficiency especially for high p_T taus (Z' signal)

MVA isolation improvements

CMS-PAS-TAU-16-002





In addition to the variables used in Run-1, a few more variables have been included in Run-2:

- Shape variables: $p_T^{\text{strip, outer}}$ (Eq. 5) and p_T-weighted ΔR, $\Delta\eta$ and $\Delta\phi$ (with respect to the τ_h axis) of photons and electrons in strips inside or outside of signal cone,
- τ-lifetime information: the signed impact parameter of the leading track of the τ_h candidate, and its significance,
- Multiplicity: the total number of photon and electron candidates ($p_T > 0.5\,\text{GeV}$) in signal and isolation cones.

e->tau fakerate improvements

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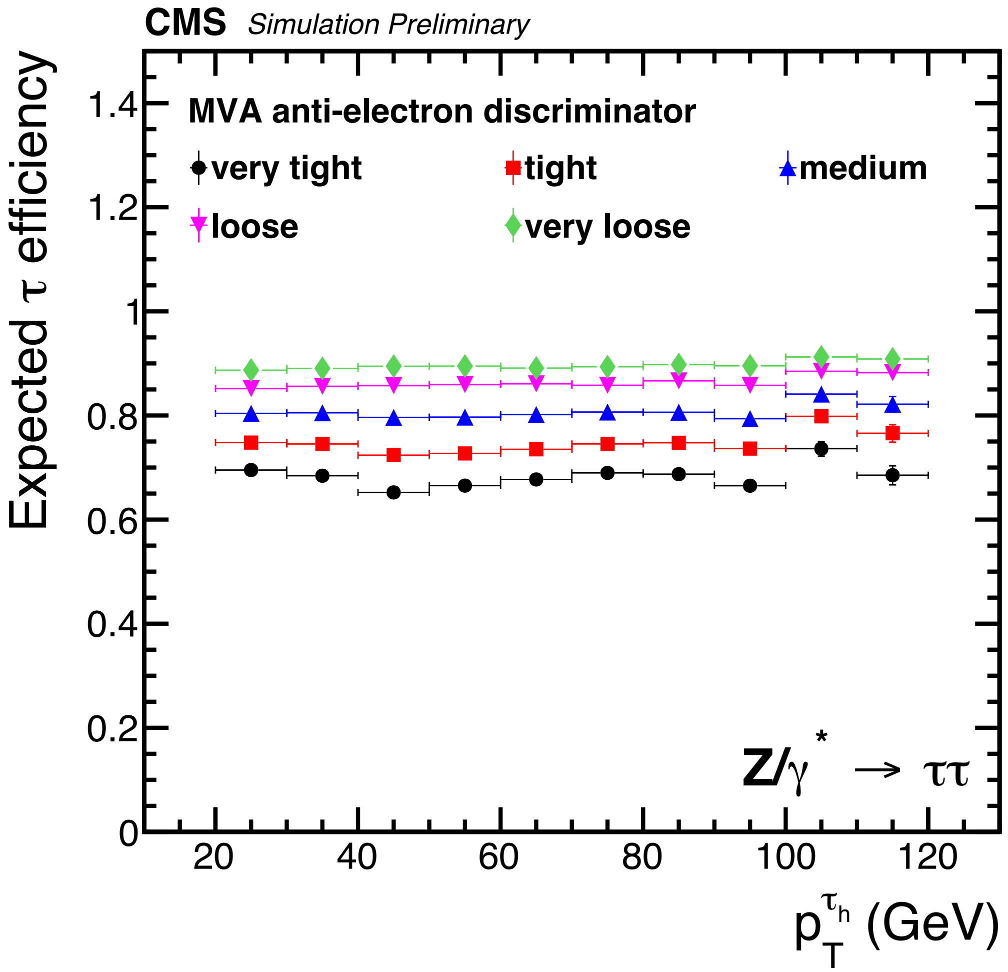

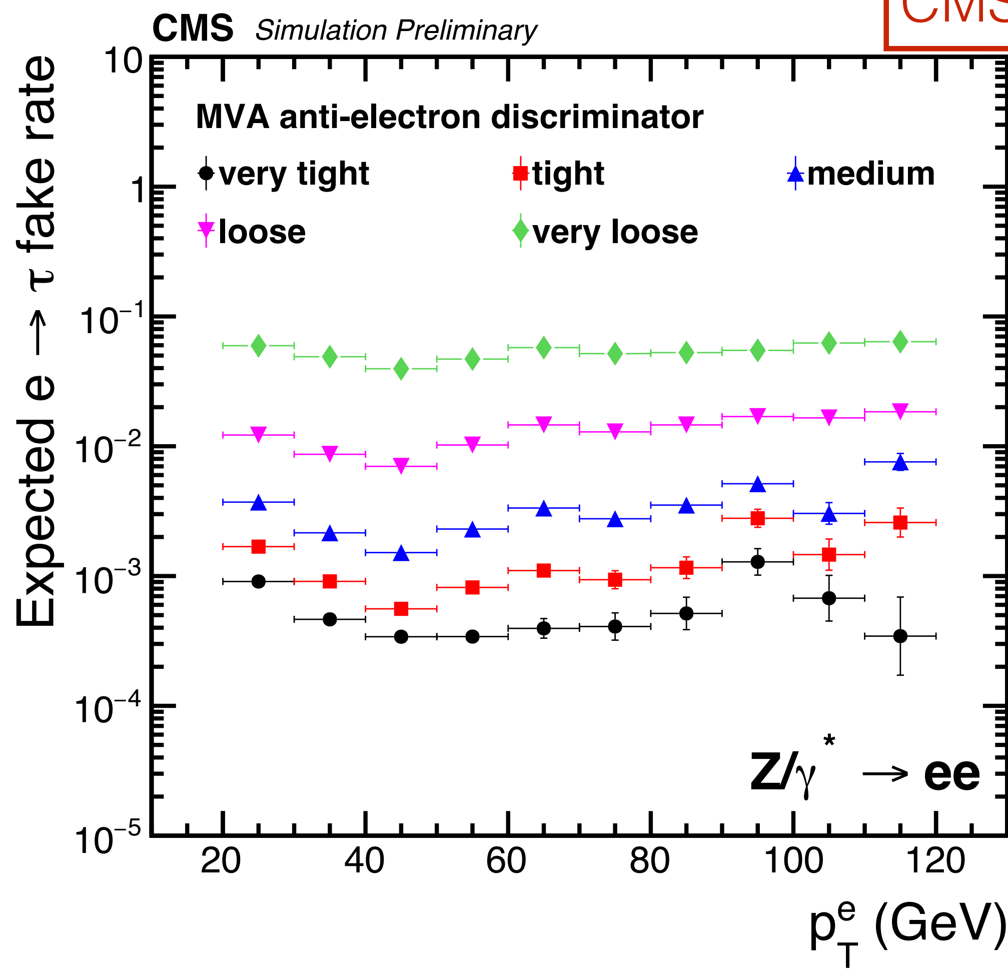

- Same variables as in Run 1 plus:
  - the number of photons in any of the strips associated with the τ_h candidate;
  - the p_T-weighted root-mean-square of the distances in η and ϕ between all photons included in any strip and the leading track of the τ_h candidate;
  - the fraction of τ_h energy carried by photons.