Reconstruction of m_{HH} in HH→ττττ Events with SVFit

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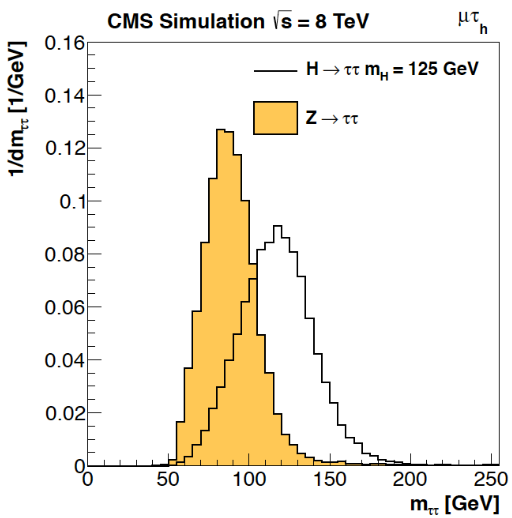
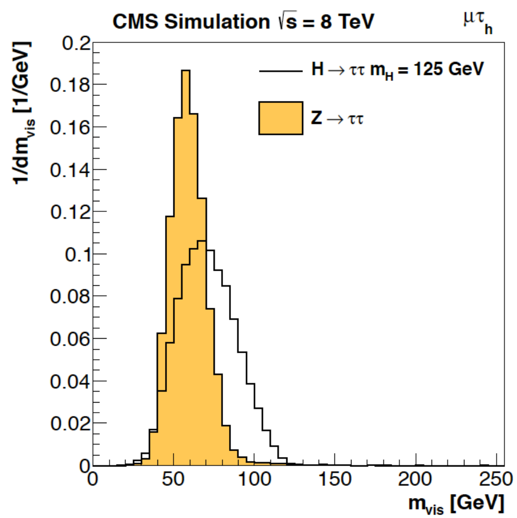
What is SVFit ?

Likelihood-based algorithm for reconstruction of the Higgs boson mass in $H \rightarrow \tau\tau$ events

Improves separation of $H \rightarrow \tau\tau$ signal from dominant irreducible $Z \rightarrow \tau\tau$ background





Phys. Rev. Lett. 106 (2011) 231801
J. Phys. Conf. Ser. 513 (2014) 022035
Nucl. Instrum. Meth. A 862 (2017) 54

Algorithm improved sensitivity of CMS SM $H \rightarrow \tau\tau$ analysis by 40% (equivalent to doubling luminosity)

ATLAS has developed similar algorithm ("Missing Mass Calculator")

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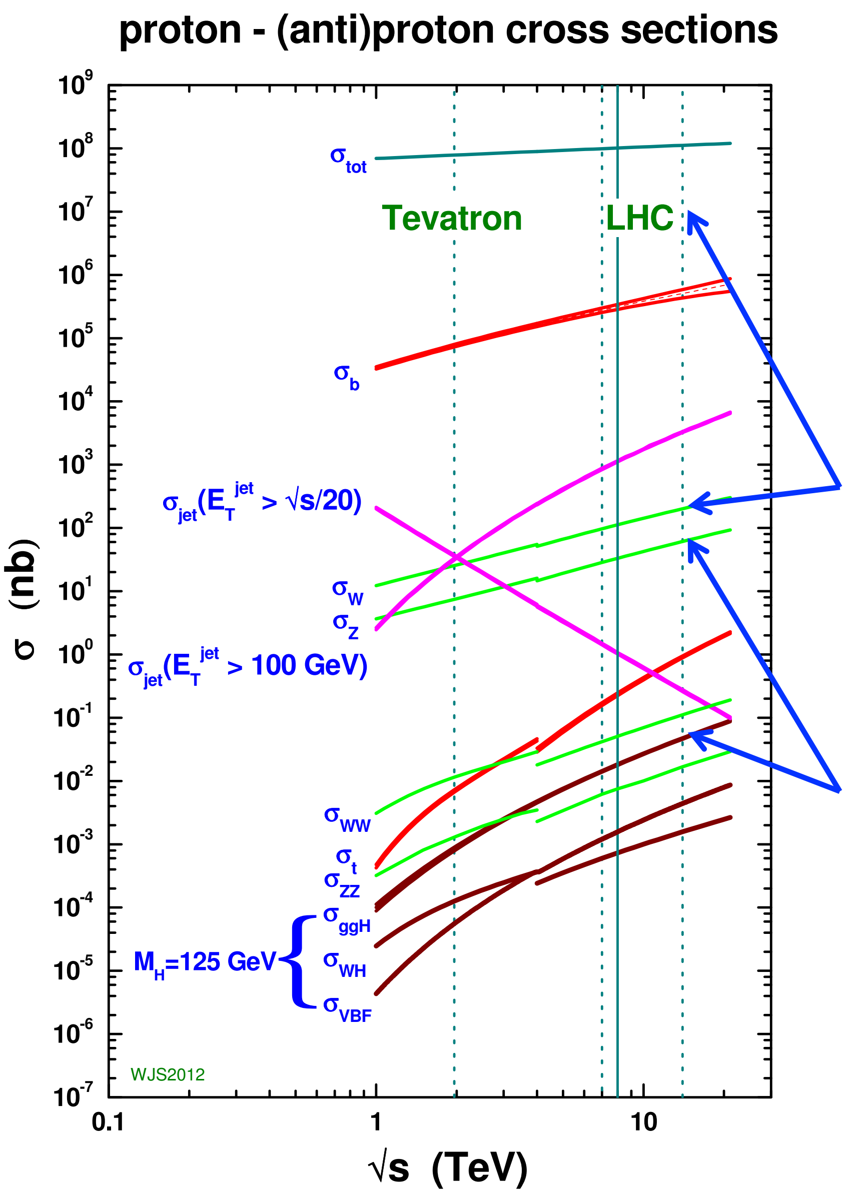
Motivation



http://www.hep.ph.ic.ac.uk/~wstirlin/plots/crosssections2012_v5.pdf

H→ττ signal buried underneath very large backgrounds!

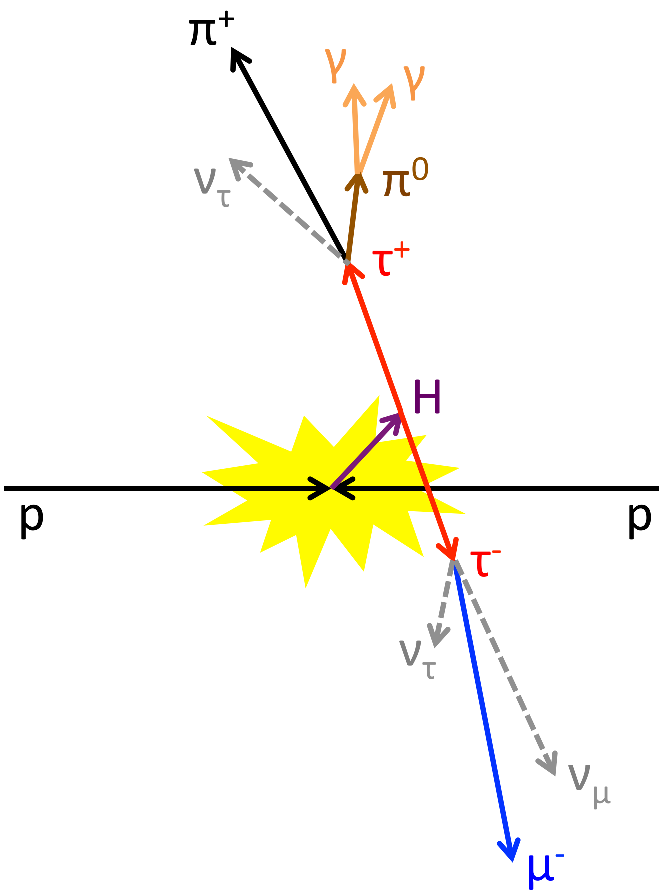
Two ingredients needed to find H→ττ signal:

1) Powerful τ identification needed to suppress reducible multijet and W+jets backgrounds

2) Good resolution on mass of ττ pair (m_H) needed to separate H→ττ signal from dominant irreducible Z→ττ background

The Task and its Solution

An H→ττ event

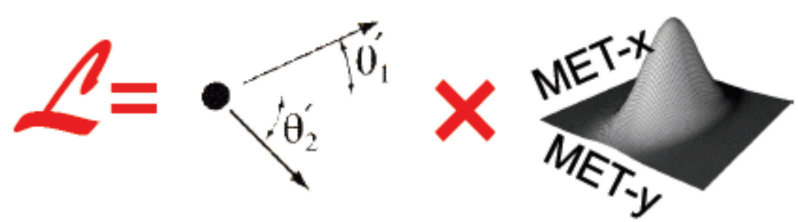


Reconstruction of m_H requires reconstruction of neutrinos produced in τ decays

Sum of neutrino momenta constrained by components E_x^{miss} and E_y^{miss} of reconstructed "missing transverse momentum"

SVFit algorithm based on likelihood approach, incorporates our knowledge on:

- τ decay kinematics
- Experimental resolution on E_x^{miss} and E_y^{miss}



Today's Presentation

Brief recap of τ decay properties

SVFit algorithm in CMS H→ττ analysis

- Parametrization of τ decay kinematics in SVfit
- The likelihood approach
  - Treatment of leptonic τ decays
  - Treatment of hadronic τ decays
  - Treatment of E_T^{miss}
- Resolution on m_H achieved in CMS SM H→ττ analysis

Extension of SVFit algorithm to HH→ττττ events

- Modifications to SVFit algorithm specific to HH→ττττ
  - Higgs mass constraint
  - Choice of $\tau^+\tau^-$ pairs for Higgs mass constraint
- Expected resolution on m_{HH}

Brief Recap of τ Decay Properties

Tau Decays

Mass m_τ= 1.78 GeV

Lifetime $c \bullet \tau$ = 87 μm

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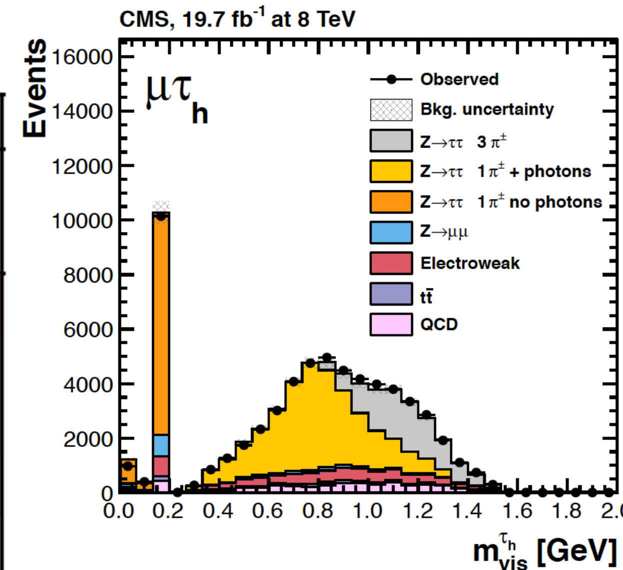
Decay Mode	Resonance	BR [%]
$\tau^- \rightarrow e^- \overline{\nu}_e \nu_\tau$		17.8
$\tau^- \rightarrow \mu^- \overline{\nu}_\mu \nu_\tau$		17.4
$\tau^- \rightarrow \pi^- \nu_\tau$	$\pi(140)$	11.6
$\tau^- \rightarrow \pi^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \rightarrow \pi^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	10.8
$\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \rightarrow \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$		4.8
Other hadronic modes		1.7
All hadronic modes		64.8

PDG



Electrons (muons) from $\tau \rightarrow e\nu\nu$ ($\tau \rightarrow \mu\nu\nu$) decays reconstructed by standard CMS electron (muon) reconstruction

Identification of hadronic τ decays in CMS ≅ reconstruction of $\pi^\pm$, $\rho^\pm$, $a_1^\pm$ signatures

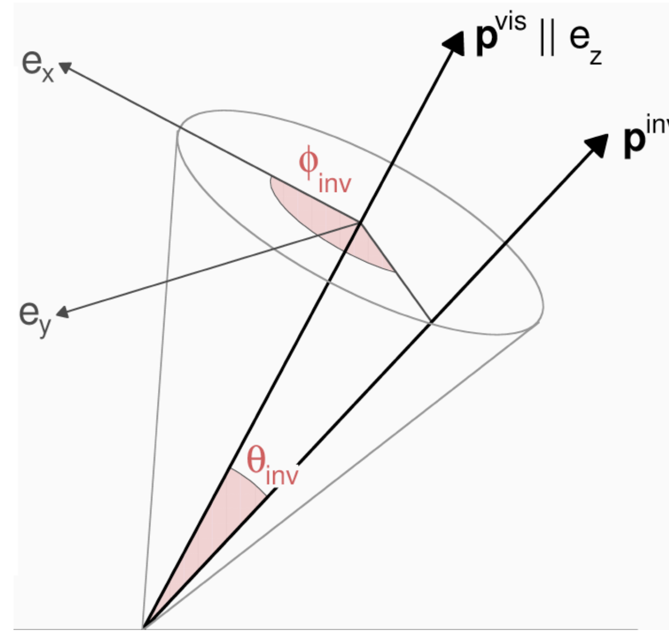
For the purpose of this talk: hadronic τ decays treated as 2-body decay into a hadronic system τ_h and a τ-neutrino

SVFit Algorithm
in CMS SM $H \rightarrow \tau\tau$ Analysis

Kinematics of τ Decays

Hadronic (leptonic) τ decays parametrized by 2 (3) variables:

- θ_{inv} } Decay angles in τ restframe
- ϕ_{inv}
- $m_{\nu\nu}$ (leptonic τ decays only)



N.B.: Momenta of neutrinos in laboratory frame are fully constrained by these variables

➔ 4 unknown variables in $\tau\tau \to \tau_h\tau_h$,
5 in $\tau\tau \to \ell\tau_h$,
6 in $\tau\tau \to \ell\ell$ events

Unknown variables constrained by 2 observables:

- $\Sigma p_x^\nu = E_x^{miss}$ } Reconstructed in laboratory frame with experimental resolution of O(10) GeV at the LHC
- $\Sigma p_y^\nu = E_y^{miss}$

➔ Problem of reconstructing m_H is underconstrained

The Likelihood Approach

m_H reconstructed by finding maximum of:

$$\frac{dL(M_{\tau\tau})}{dM_{\tau\tau}} = \int_{\Omega} \frac{df(\mathbf{x}_u|\mathbf{x}_m)}{d\mathbf{x}_u} \delta(M_{\tau\tau} - M_{\tau\tau}(\mathbf{x}_u, \mathbf{x}_m)) d\mathbf{x}_u$$

for a series of test mass hypotheses $M_{\tau\tau}$

x_u: unknown variables θ_{inv}, ϕ_{inv}, $m_{\nu\nu}$

x_m: measured observables E_x^{miss} and E_y^{miss}, momenta of visible τ decay products

Integral over likelihood function corresponds to taking an "average" over all possible kinematic confugurations x_u, weighted by their consistency with the observables x_m measured in the detector

Integral is computed numerically.

2 methods implemented in SVFit:

- Adaptive integration (VEGAS, part of GNU scientific library)
- Markov chain (custom implementation in SVfit)

Treatment of leptonic τ Decays

Matrix element for $\tau \rightarrow \ell\nu\nu$:

$$\frac{d\Gamma}{dx\ dm_{\nu\nu}} \sim \frac{m_{\nu\nu}}{4m_\tau^2}[(m_\tau^2+2m_{\nu\nu}^2)(m_\tau^2-m_{\nu\nu}^2)]$$

(with assumption that τ is unpolarized)

Physical region: $0 \leq x \leq 1$, $0 \leq m_{\nu\nu} \leq \sqrt{1-x}$

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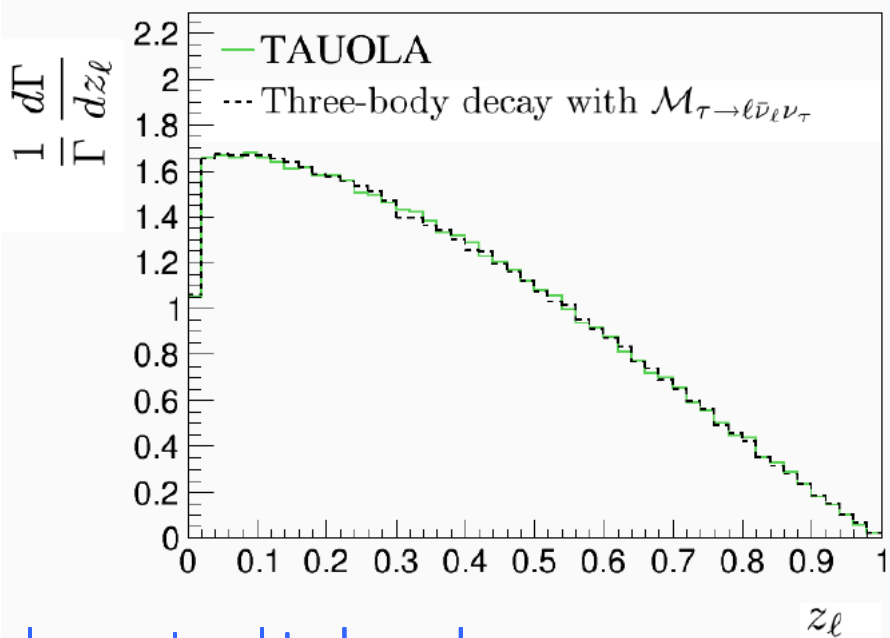
Implementation of likelihood for $\tau \rightarrow \ell\nu\nu$ decays validated by implementing ME in toy MC and comparing to τ decay library TAUOLA:

➔ toy MC agrees well with TAUOLA



NB.: Charged leptons produced in $\tau \rightarrow l\nu\nu$ decays tend to have low p_T

Treatment of hadronic τ Decays

Phase-space for 2-body decay:

$$\frac{d\Gamma}{dx} = \frac{1}{1 - \frac{m_{vis}^2}{m_\tau^2}}$$

Physical region: $\frac{m_{vis}}{m_\tau} \leq x \leq 1$

Implemented 2-body phase-space model for $\tau \rightarrow \tau_h \nu$ decays in toy MC and compared to TAUOLA

➔ Simple 2-body phase-space model represents good approximation to sum of all hadronic τ decay modes

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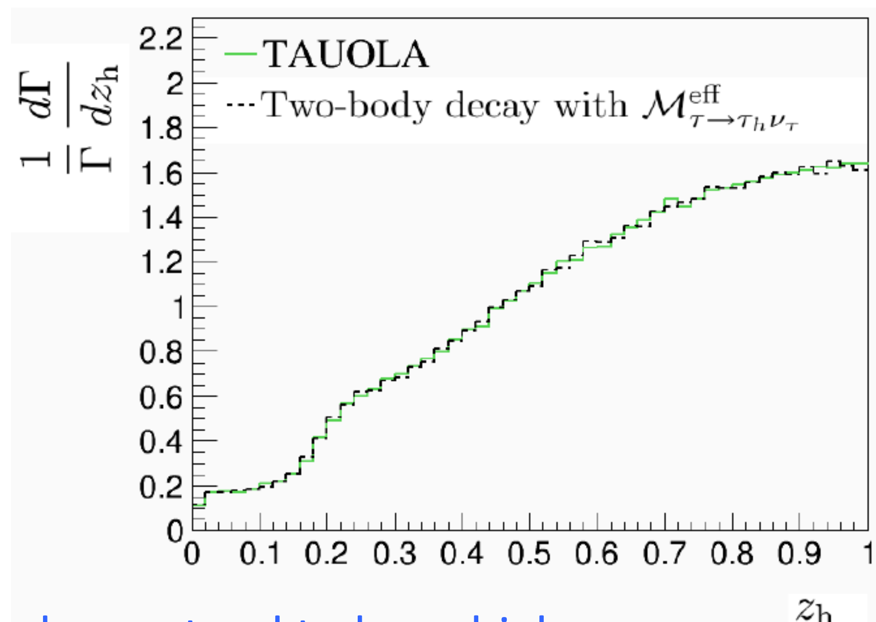

NB.: Hadronic system produced in $\tau \rightarrow \tau_h \nu$ decays tend to have high p_T

Treatment of E_T^{miss}

Momentum sum of neutrinos produced in τ decays required to be equal to components E_x^{miss} and E_y^{miss} of reconstructed "missing transverse momentum"

Experimental resolution on E_x^{miss} and E_y^{miss} modelled by two-dimensional normal distribution

$$L(\vec{E}_T^{miss} | \sum_i \vec{p}_T^{\nu\ i}) = \frac{1}{\sqrt{2\pi|\mathbf{V}|}} e^{\frac{1}{2}(\vec{E}_T^{miss} - \sum_i \vec{p}_T^{\nu\ i})^T \mathbf{V}^{-1} (\vec{E}_T^{miss} - \sum_i \vec{p}_T^{\nu\ i})}$$

τ-neutrino momentum $p_T^{\nu} = p_T^{\nu}(\theta, \phi, m_{\nu\nu})$

Covariance matrix V represents E_T^{miss} resolution expected for a given event.
It is computed event-by-event by summing resolutions,
obtained by MC simulation, for individual particles (e, γ, μ, τ_h, and jets)
reconstructed in the event by the CMS particle-flow algorithm.

CMS SM H→ττ Analysis (Run 1)

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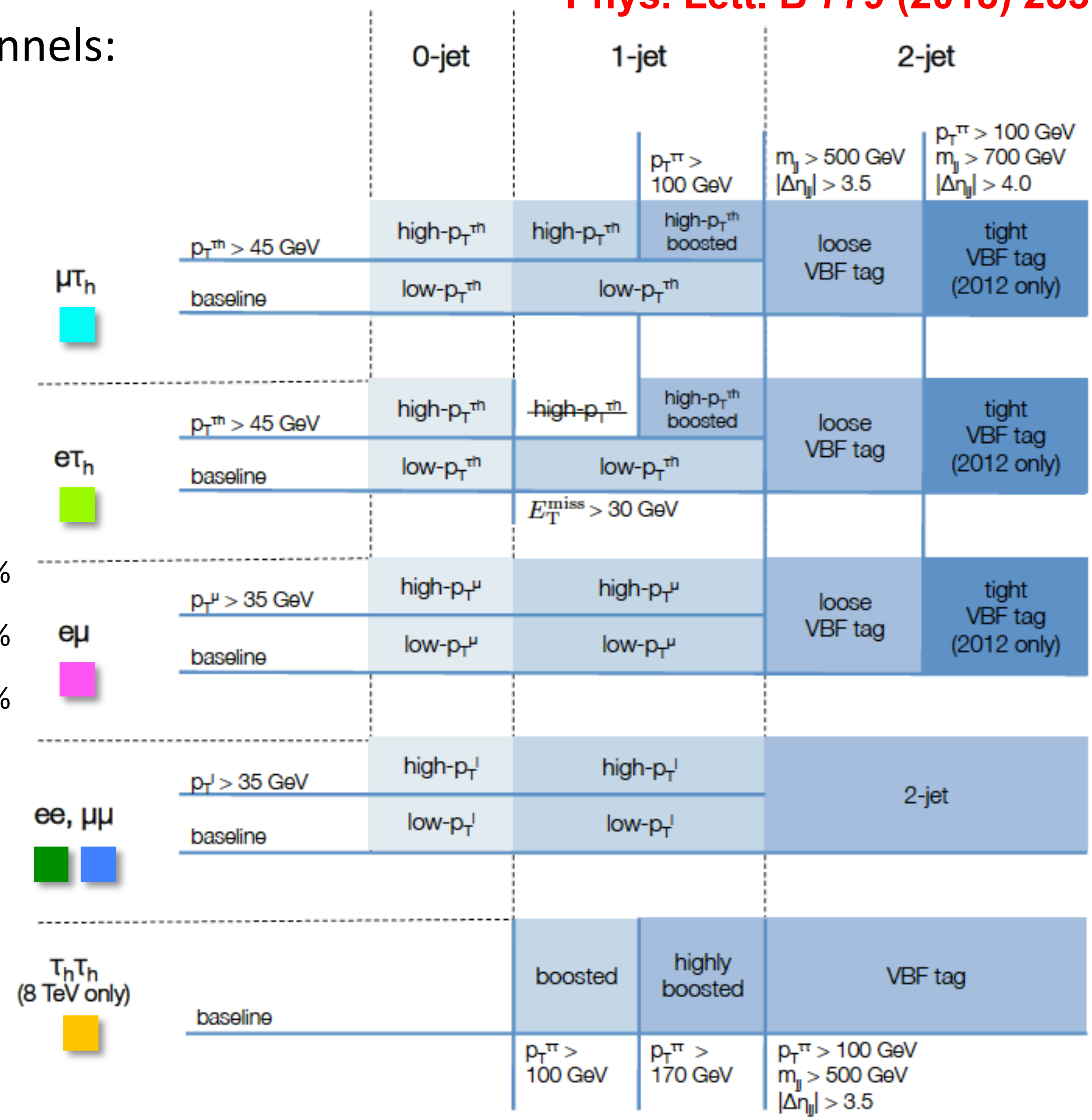
Events analyzed in 6 decay channels:

$\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$, $\tau_e\tau_\mu$, $\tau_e\tau_e$, $\tau_\mu\tau_\mu$

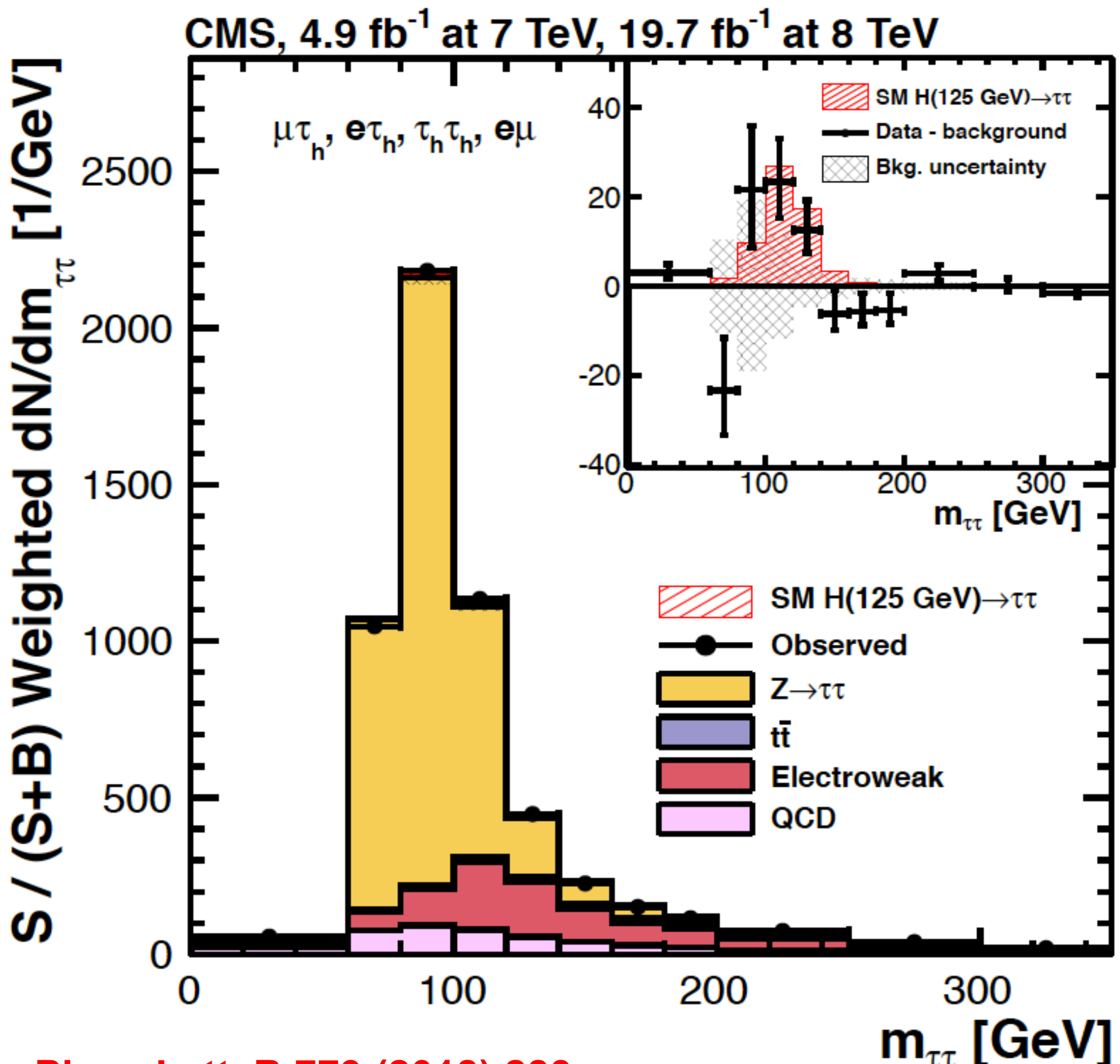
and different event categories, targeting gluon fusion and vector boson fusion (VBF) production

	BR
$\tau_h\tau_h$	42.0%
$e\tau_h$	23.1%
$\mu\tau_h$	22.6%
$e\mu$	6.2%
$\mu\mu$	3.0%
ee	3.1%



Performance in CMS SM H→ττ Analysis

All decay channel added, events in different decay channels and categories weighted by S/(S+B)



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Extension of SVfit Algorithm to $H \rightarrow \tau\tau\tau\tau$ Events

Modified SVFit Algorithm for HH→ττττ

$$\frac{dL(M_{\tau\tau})}{dM_{\tau\tau}} = \int_{\Omega} \frac{df(\mathbf{x}_u|\mathbf{x}_m)}{d\mathbf{x}_u} \delta(M_{\tau\tau} - M_{\tau\tau}(\mathbf{x}_u, \mathbf{x}_m)) d\mathbf{x}_u$$

1) Integration over x_u extended by integration over unknown variables θ_{inv}, ϕ_{inv}, $m_{\nu\nu}$ for 3rd and 4th τ lepton

2) Mass constraints added (by adding suitable δ-functions to integrand), which enforce that mass of each $\tau^+\tau^-$ pair is equal to m_H=125 GeV

➔ Used to search for unknown resonances X decaying to pairs of SM Higgs bosons, each subsequently decaying to $\tau^+\tau^-$

NB.: Charge of τ lepton equals charge of its visible decay products (e, μ, or τ_h)

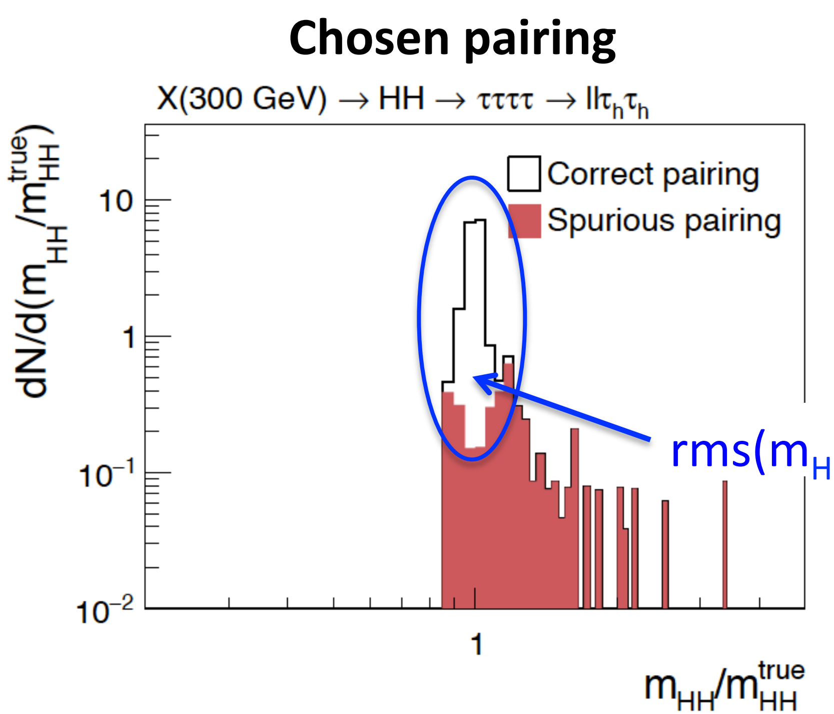
3) Two-fold ambiguity for building $\tau^+\tau^-$ pairs in HH→ττττ events resolved by choosing pair that yields maximal $\frac{dL(M_{\tau\tau})}{dM_{\tau\tau}}$ (for any $M_{\tau\tau}$)

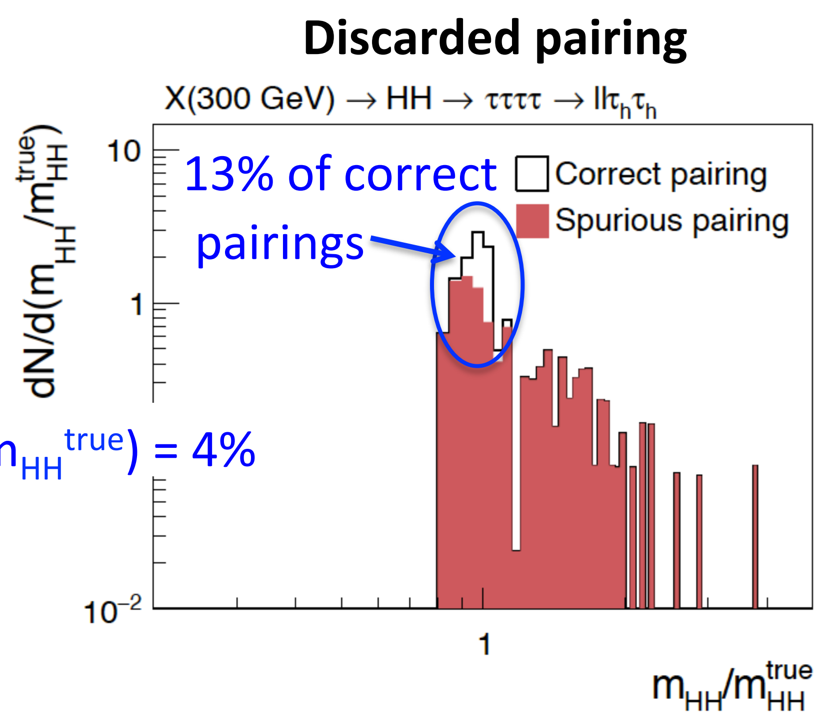
Expected Resolution on m_{HH}

Private work

Mass resolution studied on generator level, using simulated $X \rightarrow HH \rightarrow \tau\tau\tau\tau$ events with resonances X of different mass m_X = 300, 500, and 800 GeV.

Experimental resolution on energy of τ_h taken from **Nucl. Instrum. Meth. A 862 (2017) 54**
Resolution on E_x^{miss} and E_y^{miss} assumed to be 10 GeV

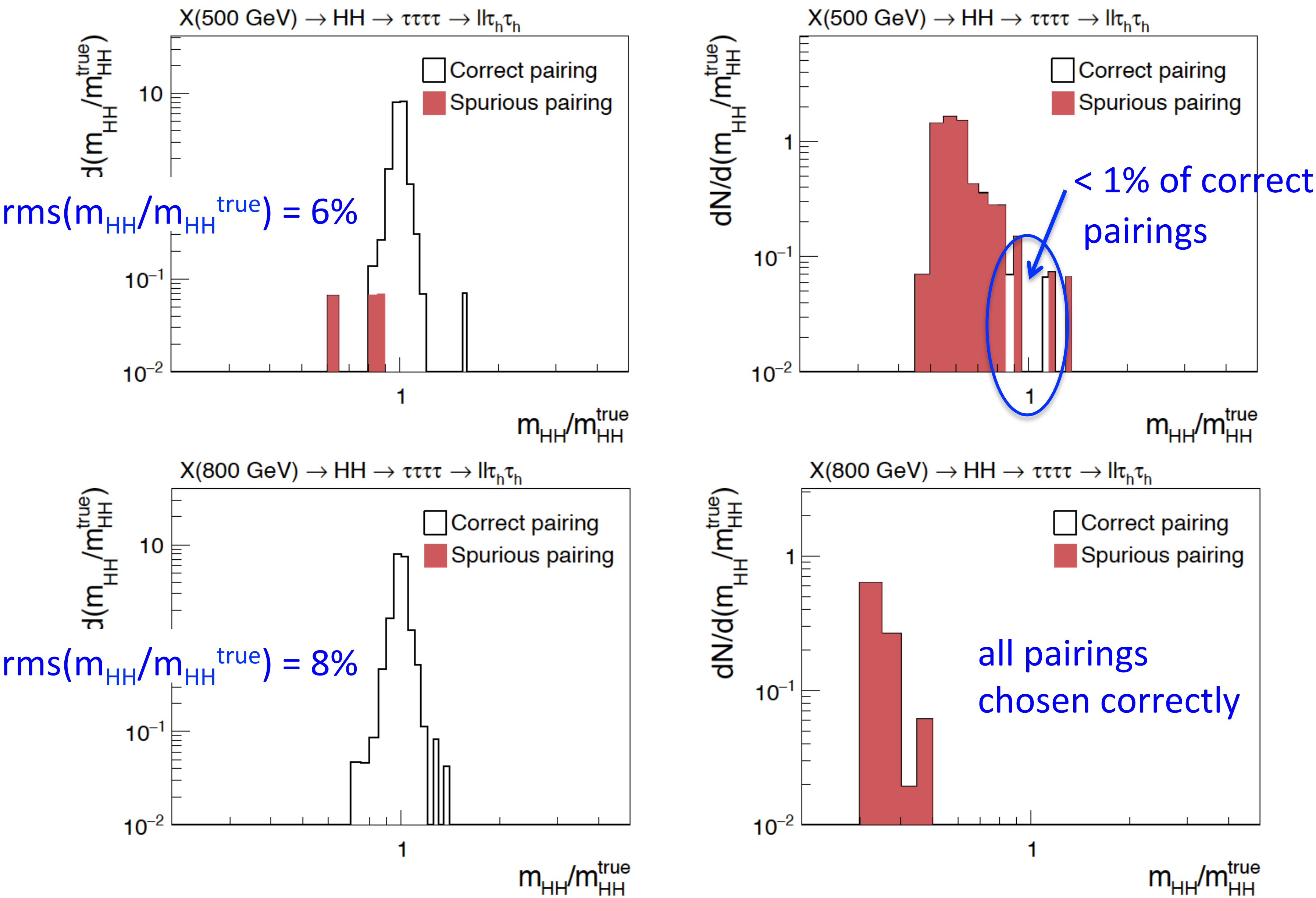




➔ Algorithm achieves resolution of 4% if correct pairing is chosen. Unfortunately, algorithm chooses wrong pairing for 13% of signal events, which degrades resolution to 22%

Expected Resolution on m_{HH}

Private work



Summary

- SVFit algorithm used for reconstructing m_H in H→ττ events has been extended to reconstruct m_{HH} in HH→ττττ events

- Algorithm achieves resolution on m_{HH} of 7-22% relative to true mass of H boson pair

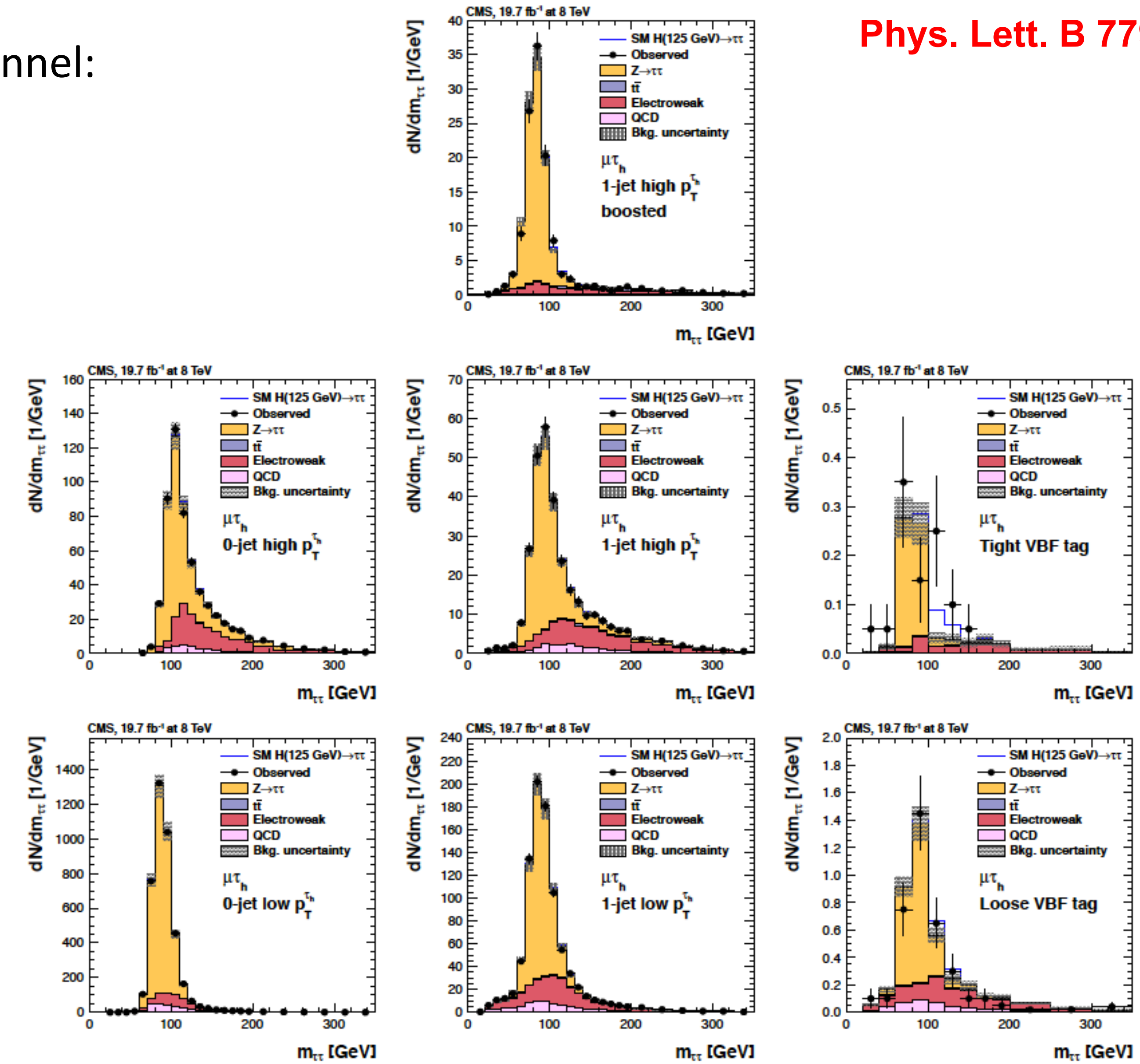
- Resolution for H boson pairs of low mass limited by fact that algorithm chooses wrong pairing of τ leptons in 13% of signal events
  ➔ Room for improvement: In case correct pairing is chosen for all events, resolution improves to 4-8%

- I expect that this algorithm will be useful for improving sensitivity of HH→ττττ channel at the LHC

Backup

Performance in CMS SM H→ττ Analysis

$\mu\tau_h$ decay channel:



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Performance in CMS SM H→ττ Analysis

$e\tau_h$ decay channel:

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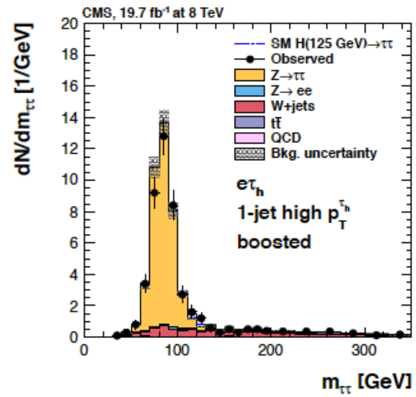

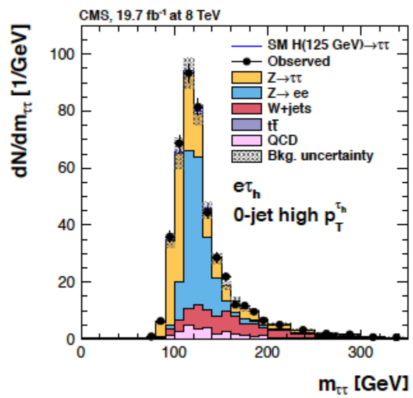

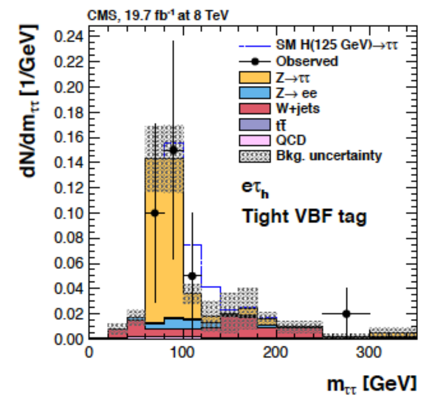

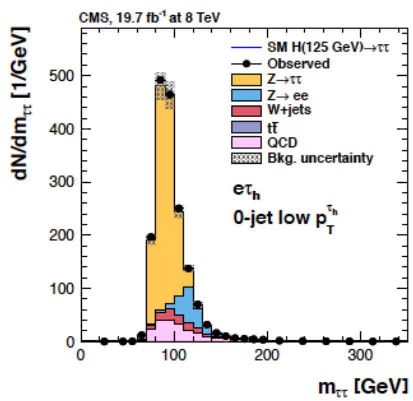

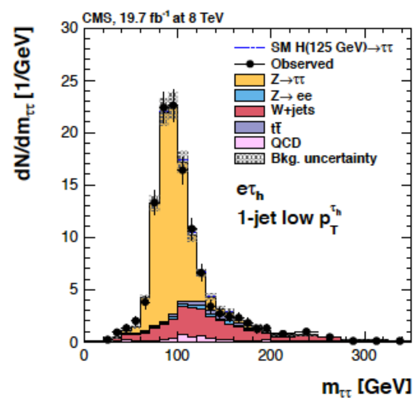

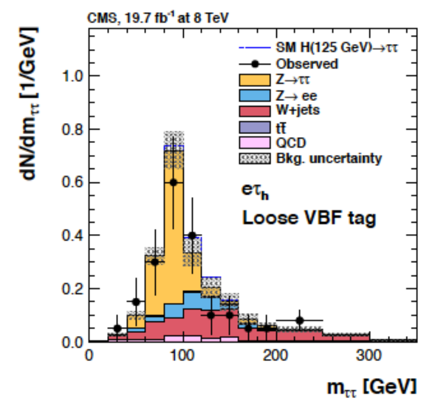

Performance in CMS SM H→ττ Analysis

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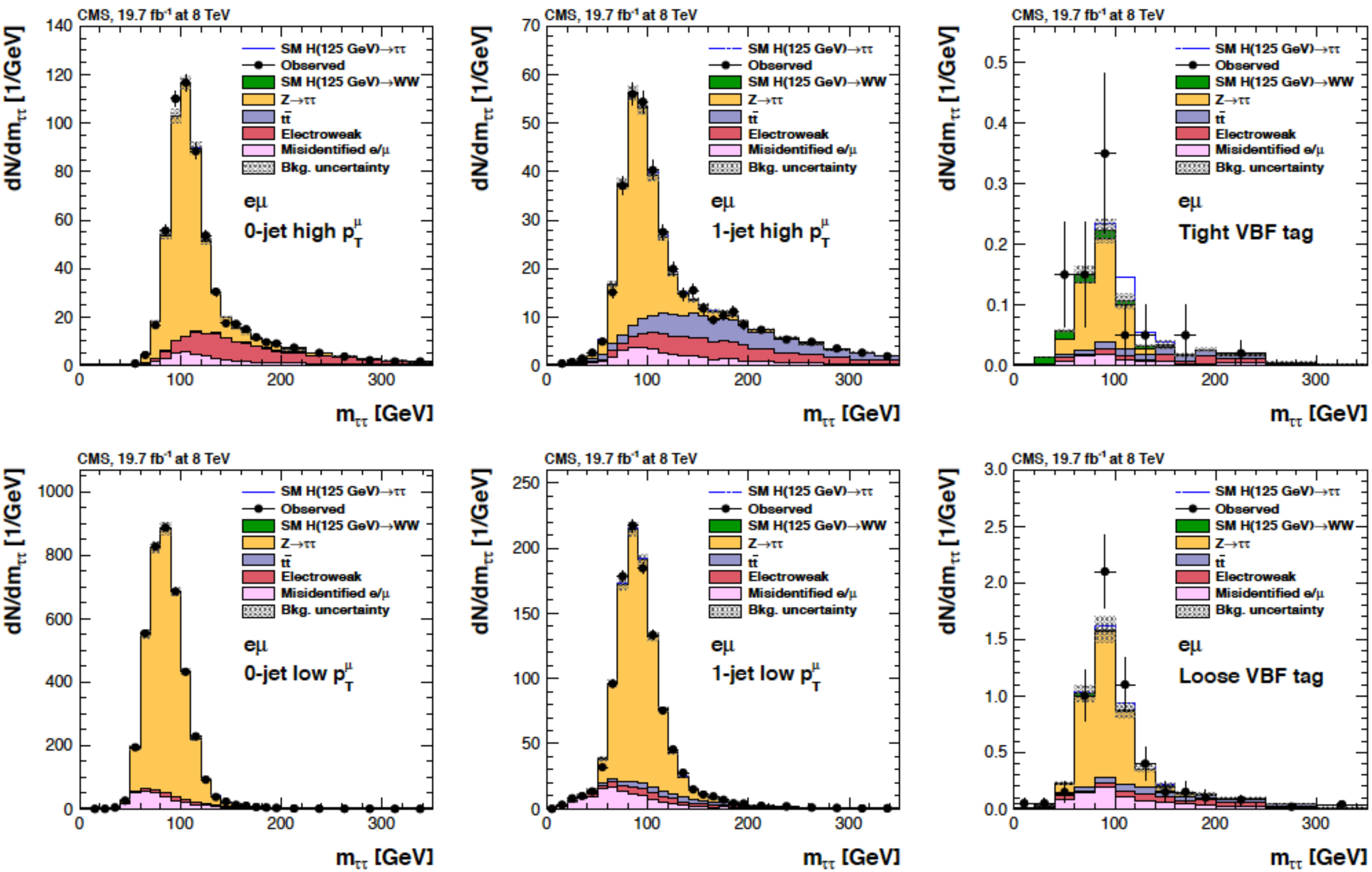
eμ decay channel:



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$\tau_h\tau_h$ decay channel: