τ reconstruction at the Muon Collider: Cross section measurement of the H→$\tau\tau$ process

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Summary

- Motivation
- TauFinder & Event selection
- Fit and Results
- Discussions

Motivation

Motivation: Estimate **physics performance** of tau reconstruction at a **muon collider** in a key reference channel

Goal:

1) Measure the statistical uncertainty on the cross section of the **H→$\tau\tau$** process at the **10 TeV CoM** Muon Collider
2) Improve TauFinder algorithm performance

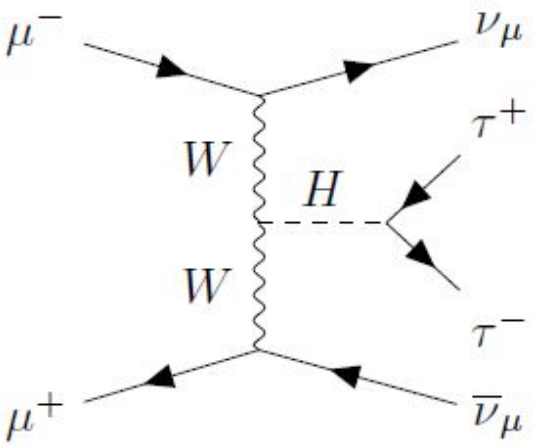


diagram of H→$\tau\tau$ signal process

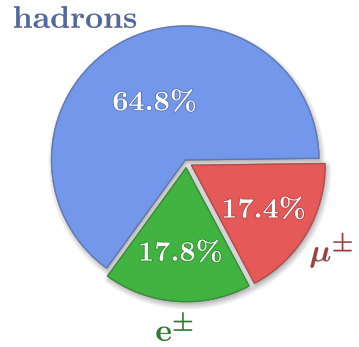
Simulation & TauFinder Algorithm

Samples generated with ***MadGraph*** for signal and backgrounds

Key4hep software framework : *GEANT4* and *MARLIN* to do simulation, digitisation and reconstruction with ***MAIA*** detector geometry

TauFinder identify τ´s from their decay products, reconstruct **hadronic** (τ_h: 1- and 3-prongs) and **leptonic** (electrons and muons) decays.
The analysis focuses on $\boldsymbol{\tau_h}$ **decay modes**

Study τ **kinematic variables** such as momentum, decay mode, angle …etc



Decay mode	Resonance	$\mathcal{B}$ (%)
Leptonic decays		35.2
$\tau^- \to e^- \overline{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$		17.4
Hadronic decays		64.8
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	25.9
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other		3.3

Decays of τ leptons and their branching fractions in percentage

Tau Identification Algorithm

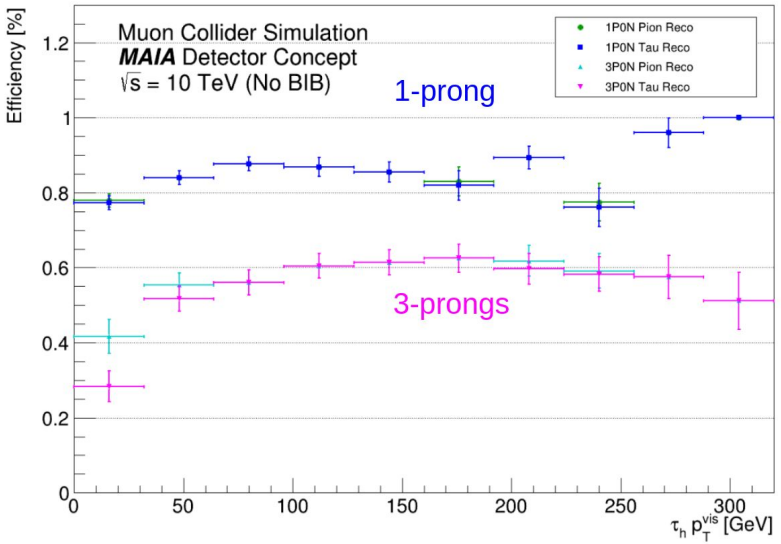
TauFinder algorithm (τ_h):

- Seeding: starts from highest-energy charged particles
- Cone: build *signal* and *isolation* cones
- Iteration: particles within the signal cone are added to tau candidate, repeat until no particle is left out,
- determine 4-momenta, merge split candidates

Taugun: ***15000*** τ *events generated,* $0 \leq \varphi \leq 2\pi$ *rad,* $10° \leq \theta \leq 170°$, $20 \leq p_T \leq 320$ *GeV/c*

Tau efficiency definition:

- Single $\pi^{\pm}$: $\frac{\#\ of\ Events\ with\ 1\ Reco\ \pi^{\pm}\ Matched\ with\ 1\ Unique\ MC\ \pi^{\pm}}{Total\ \#\ of\ Events\ with\ 1\ Unique\ MC\ \pi^{\pm}}$
- Triple $\pi^{\pm}$: $\frac{\#\ of\ Events\ with\ 3\ Reco\ \pi^{\pm}\ Each\ Matched\ with\ 1\ Unique\ MC\ \pi^{\pm}}{Total\ \#\ of\ Events\ with\ 3\ Unique\ MC\ \pi^{\pm}}$



Tau (τ_h) efficiency vs tau visible p_T

Electromagnetic fraction requirement

Issue: Many electrons reconstructed as pions

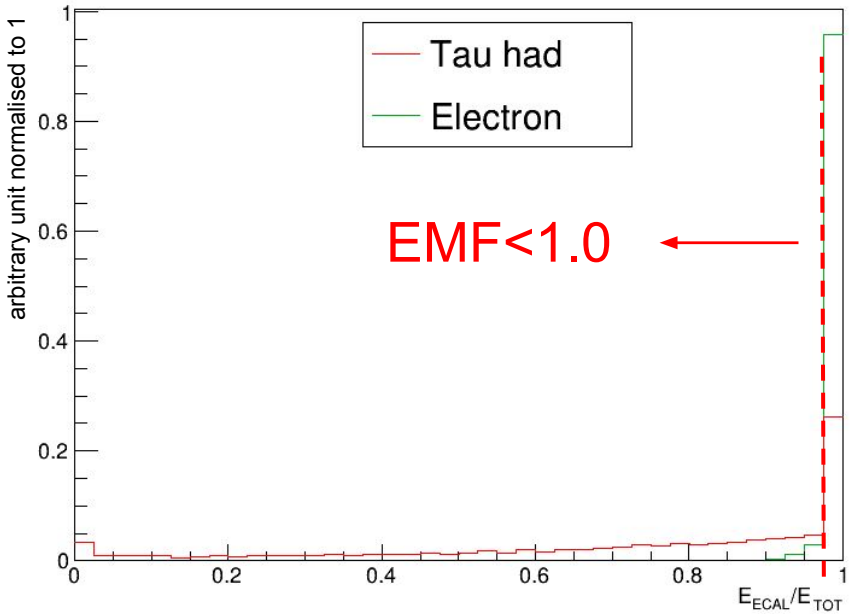
Study Electromagnetic Fraction (**EMF**) defined as:

$$EMF = \frac{E_{ECAL}}{E_{ECAL} + E_{HCAL}}$$

Observation:

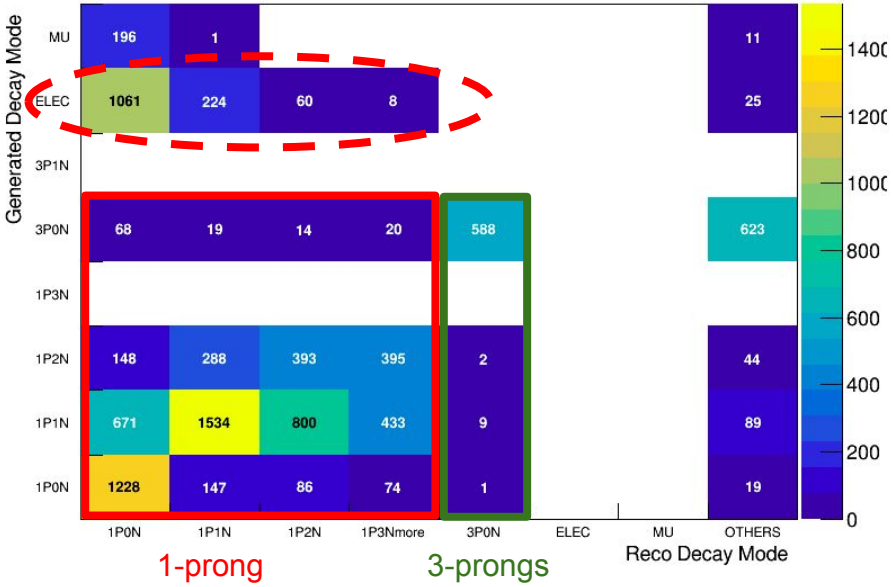
- **Electrons** → peak at EMF = 1
- ~20% reconstructed as **hadronic τ** candidates also at EMF = 1

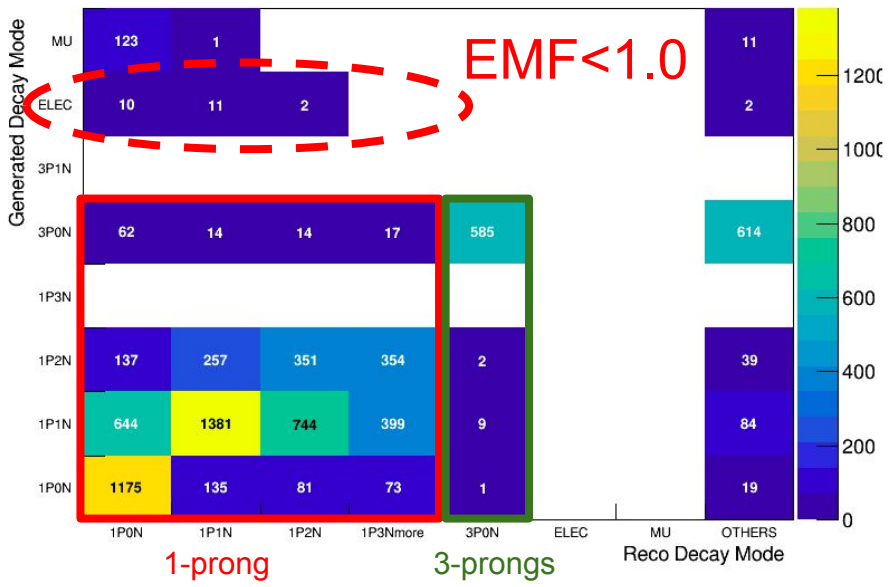
Solution: Apply requirement **EMF < 1.0**



Reconstructed τ_h vs e: EM Fraction (EMF)

Reco vs Gen: Electromagnetic fraction requirement





τ decay modes: Reconstructed vs gen-level before and after the EMF cut

- Removes most misclassified electron decays
- Improves hadronic τ purity
- Maintains high efficiency for genuine hadronic τ's

P.S: Cut on EMF<1 is a patch to remove misidentified electrons. Further improvements in the pion/electron ID are necessary.

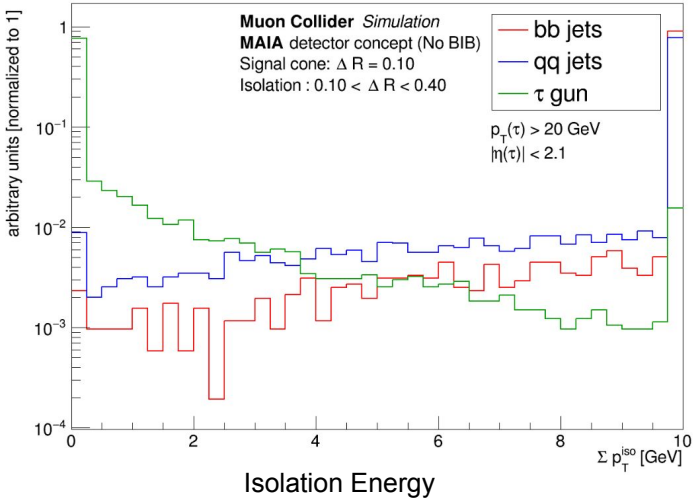
Tau mis-identification efficiency

15000 $\mu^+\mu^- \to Z\nu_\mu\bar{\nu}_\mu,\ Z \to q^+q^-$ **&** **15000** $\mu^+\mu^- \to Z\nu_\mu\bar{\nu}_\mu,\ Z \to b^+b^-$

We define the efficiency (a jet misidentified as a τ) as: $\varepsilon_{\text{Jets}} = \frac{N_\tau^{\text{reco}}}{N_{\text{jets}}}$

Kin. requirements: jets do not contains gen-level τs, p_T > 20 GeV, $|\eta|$<2.1; # of charged tracks != 2 & 4, M_{inv}< 3 GeV, # of reconstructed particles composing the τ_h candidate N_{PFOs}<8 (τ-Id), EMF<1.0

The number of jets (N_{jets}) is calculated with the number of quarks in the hepmc files passing the requirements p_T > 20GeV; $|\eta|$ < 2.1

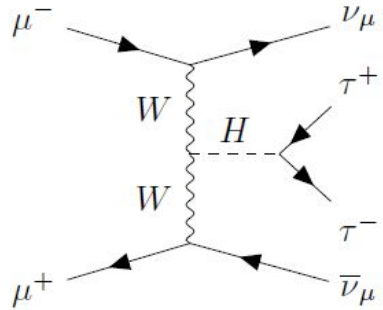


Isolation Energy

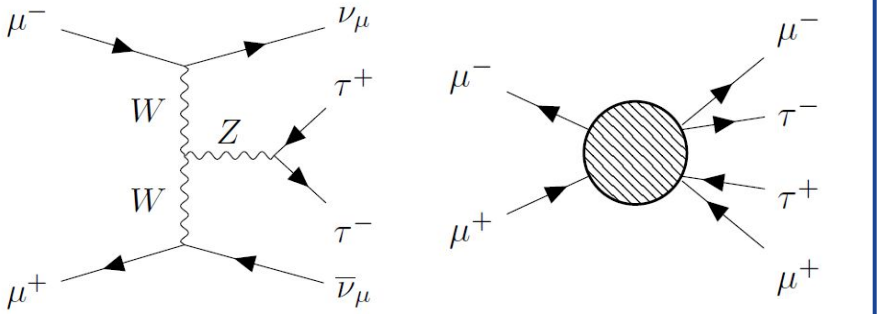
Physical objects	(u, s, d) jets	b-jets	τ_h
kinematics	13%	6%	69%
kin. + E_{iso} < 3 GeV	0.7%	0.1%	64%
kin. + E_{iso}/p_T^{lead} < 0.1	0.7%	0.1%	66%

Signal and Backgrounds samples

Signal: H → ττ



Backgrounds: Z → ττ, μμ → ττμμ



Process	Generated events	ϵ	σ[fb]	Expected events ($10\,\mathrm{ab}^{-1}$)
$\mu^+\mu^- \to H\nu_\mu\bar{\nu}_\mu,\ H \to \tau^+\tau^-$	100000	0.6	52.17	31302
$\mu^+\mu^- \to Z\nu_\mu\bar{\nu}_\mu,\ Z \to \tau^+\tau^-$	100000	0.04	127.4	50960
$\mu^+\mu^- \to \tau^+\tau^-\mu^+\mu^-$	100000	0.01	288.6	28860

ϵ after requirement: 2 reco τ_hs, opposite charges, p_T(reco)>20 GeV, EMF<1.0, $|\eta|$<2.1, E_{iso}<3GeV

σ given by MadGraph

Expected events: $N = \epsilon \cdot \sigma \cdot \mathscr{L}$ for a luminosity of 10 ab^{-1}

Event Selection

Signal:

- $H \rightarrow \tau\tau$

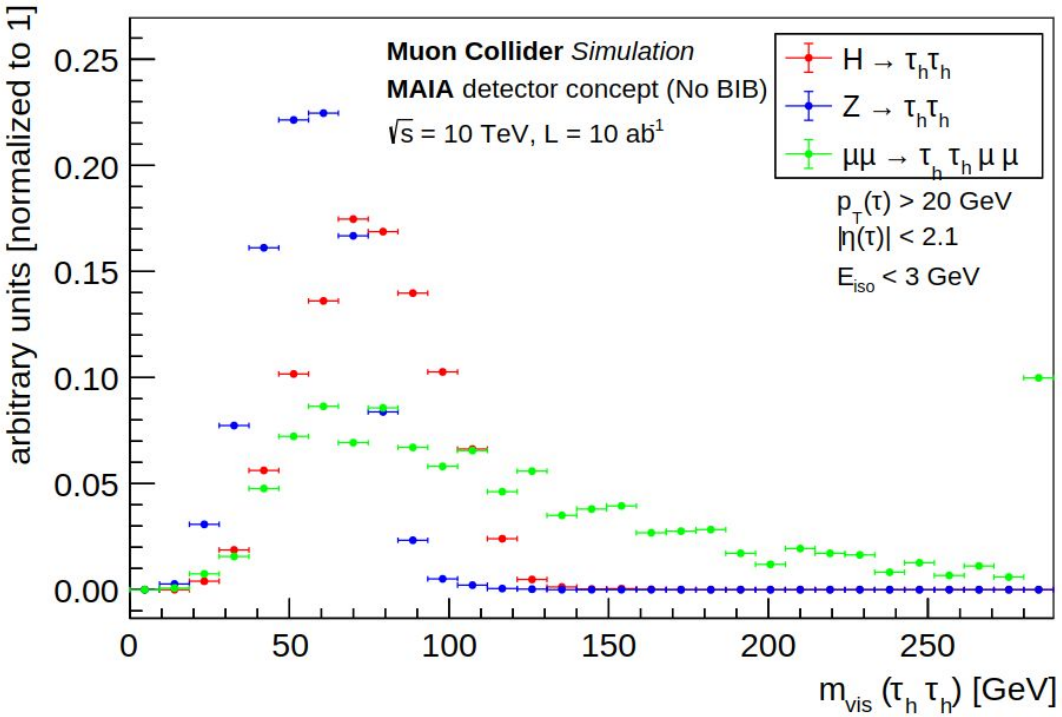
Backgrounds:

- $Z \rightarrow \tau\tau$
- $\mu\mu \rightarrow \tau\tau\mu\mu$

Require: 2 reconstructed τ_hs with opposite charges and with p_T(reco)>20GeV, EMF < 1.0, $|\eta|$<2.1, E_{iso}<3GeV

Visible invariant mass:

$$m_{vis} = \sqrt{E^2_{\tau^{pair}_{vis}} - P^2_{\tau^{pair}_{vis}}}$$



Visible invariant mass for hadronic τ decays for signal and background (distributions normalized to 1)

Fit procedure & results

Start from Signal (H) and Background (DY and $\mu\mu\tau\tau$); build PDFs (probability density function) templates; extract S and B from fit

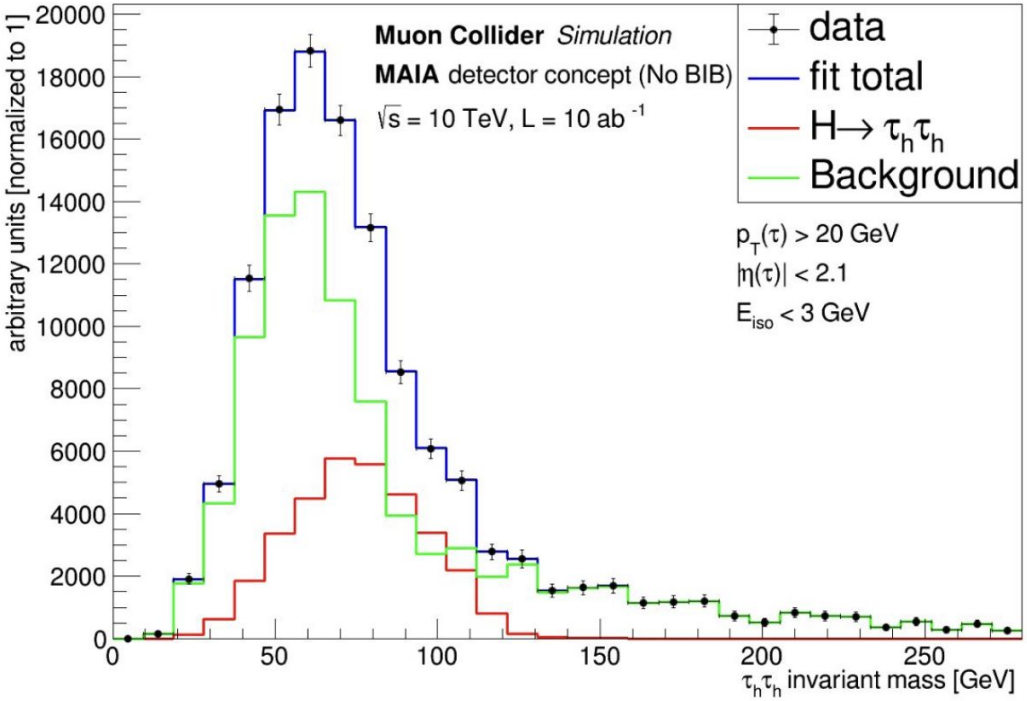
100 000 RooFit toy experiments → pseudo-data via Poisson fluctuations

Each toy: combined fit of signal + background → extract best estimates of event yields for N_{sig} & N_{bkg}

Extract cross section:

$\sigma(H \to \tau^+\tau^-) = \frac{N}{\epsilon L}$, *L* is Luminosity, ϵ is efficiency after cuts, *N* is signal event yield

We obtain: $\frac{\Delta\sigma}{\sigma} = 1.3\%$



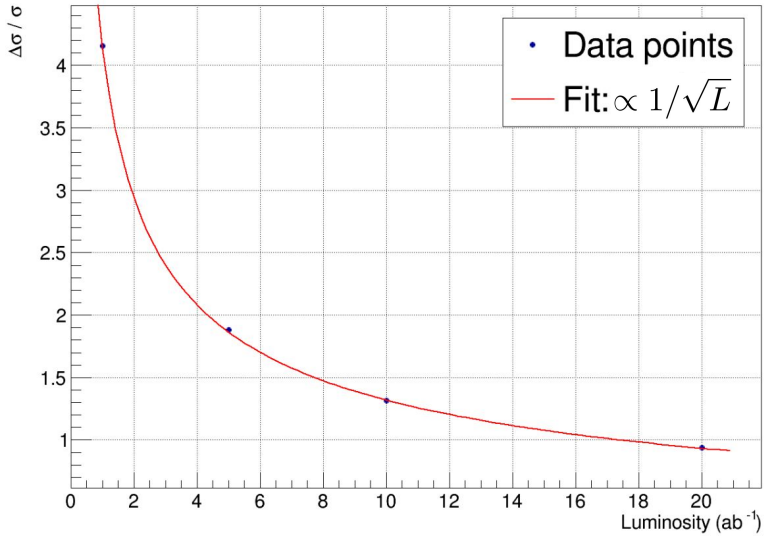
Visible invariant mass for hadronic τ decays for signal and background

Conclusions and Next Steps

Study sensitivity to Higgs boson properties at the future Muon Collider

Estimated the uncertainty on the cross section of the $H \to \tau\tau$ process at a **10 TeV** CoM Muon Collider using official detector reconstruction (TauFinder, Marlin) software framework:

⇒ **obtain: Δσ/σ=1.3% statistical uncertainty**



Results can be compared to:

- a previous study at **3 TeV** CoM that yielded **5.3%** statistical uncertainty (1 ab^{-1})
- sensitivity on κ_τ from **FCC** (**0.44%**) and **HL-LHC** (**1.9%**)

Current results can be improved. Further improvements can be done in: τ reconstruction and identification, TauFinder algorithm, electron and pion identification.

⇒ a document will be uploaded soon on the Cern server

Thank you for your attention