International Master
Advanced Methods
in Particle Physics

Higgs boson properties and tau lepton identification at the $\sqrt{s} = 3$ TeV Muon Collider

Master's thesis defense

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Co-supervisor: prof. Maximiliano Sioli

30 September 2024

Outline

- Higgs boson properties
- The Muon Collider: a Higgs factory
- TauFinder: an algorithm for tau lepton reconstruction and identification
- TauFinder performance assessment and tau energy corrections
- $H \to \tau\tau$ identification at the 3 TeV Muon Collider
- $H \to \tau\tau$ cross section measurement
- Conclusions

Higgs physics

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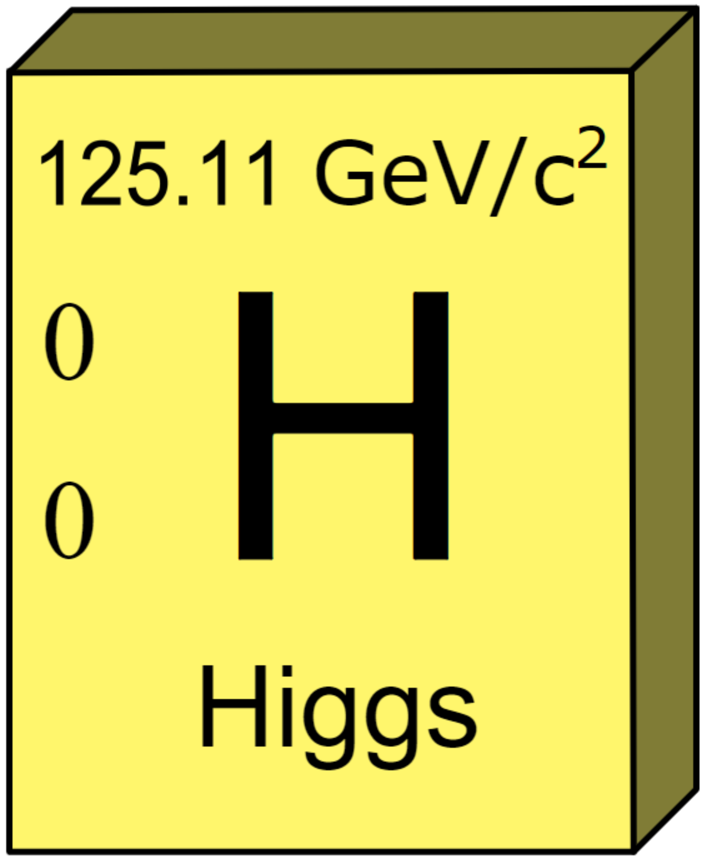
- Higgs boson: discovered in 2012
- Scalar particle, $m_H \sim 125\ GeV/c^2$
- Unstable ($\Gamma_H \sim 4$ MeV)
- Responsible for mass generation
- "**Higgs portal**": access to New Physics?
- Precision measurements of its parameters
- **Future colliders** to study its properties



The Muon Collider

- $\mu^+\mu^-$ collider
  - No initial state partons: clean environment, no PDFs
  - Low synchrotron radiation: high center-of-mass energies (Multi-TeV)
  - Challenges: beam-induced background, technology R&D

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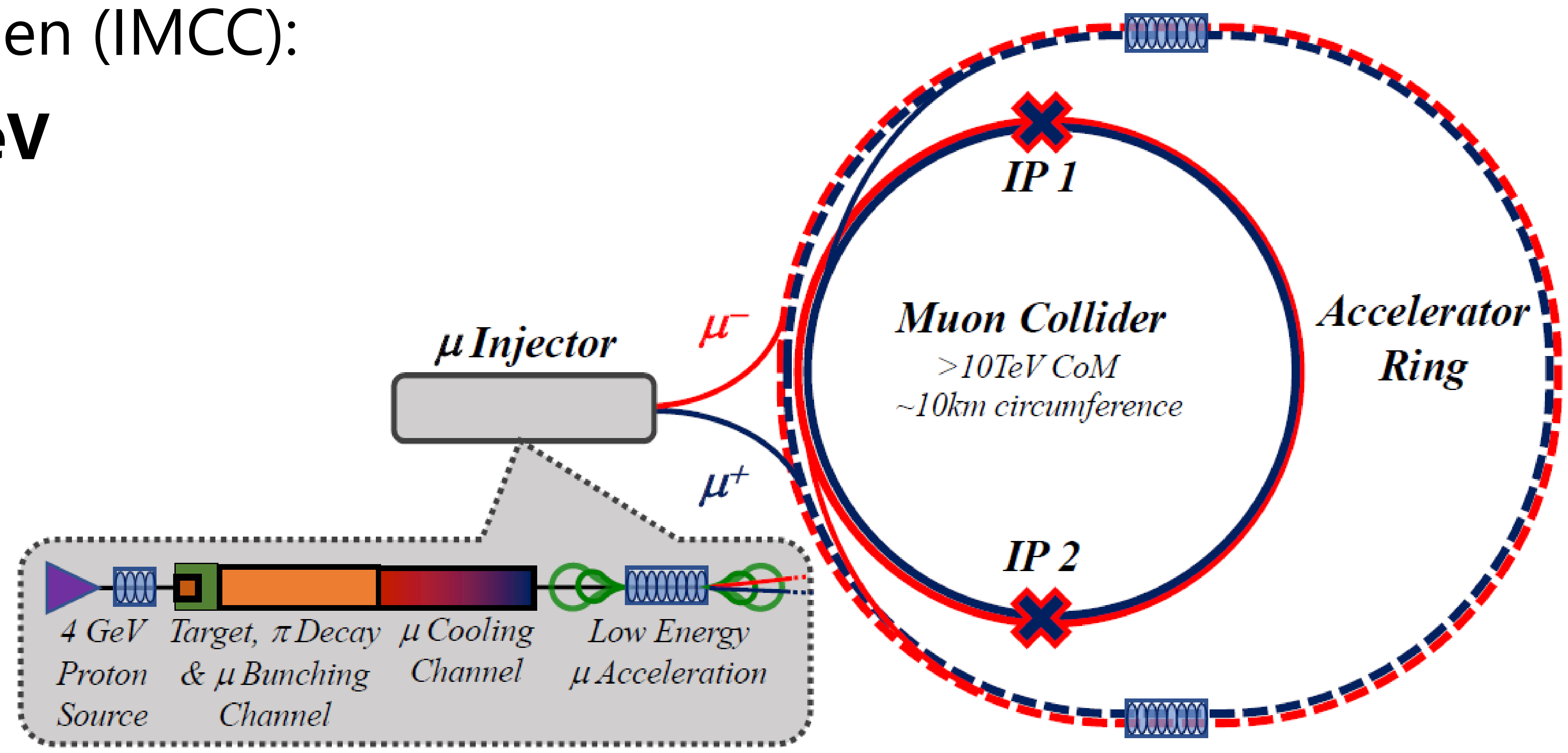
  - No initial state partons: clean environment, no PDFs
  - Low synchrotron radiation: high center-of-mass energies (Multi-TeV)
  - Challenges: beam-induced background, technology R&D
- Two stages foreseen (IMCC):
  $\sqrt{s}$ = **3 TeV**, **10 TeV**



[Eur. Phys. J. C 83, 864 (2023)]

Experimental apparatus

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- 4π detector + **nozzles** to shield BIB (soft, out-of-time particles)

hadronic calorimeter

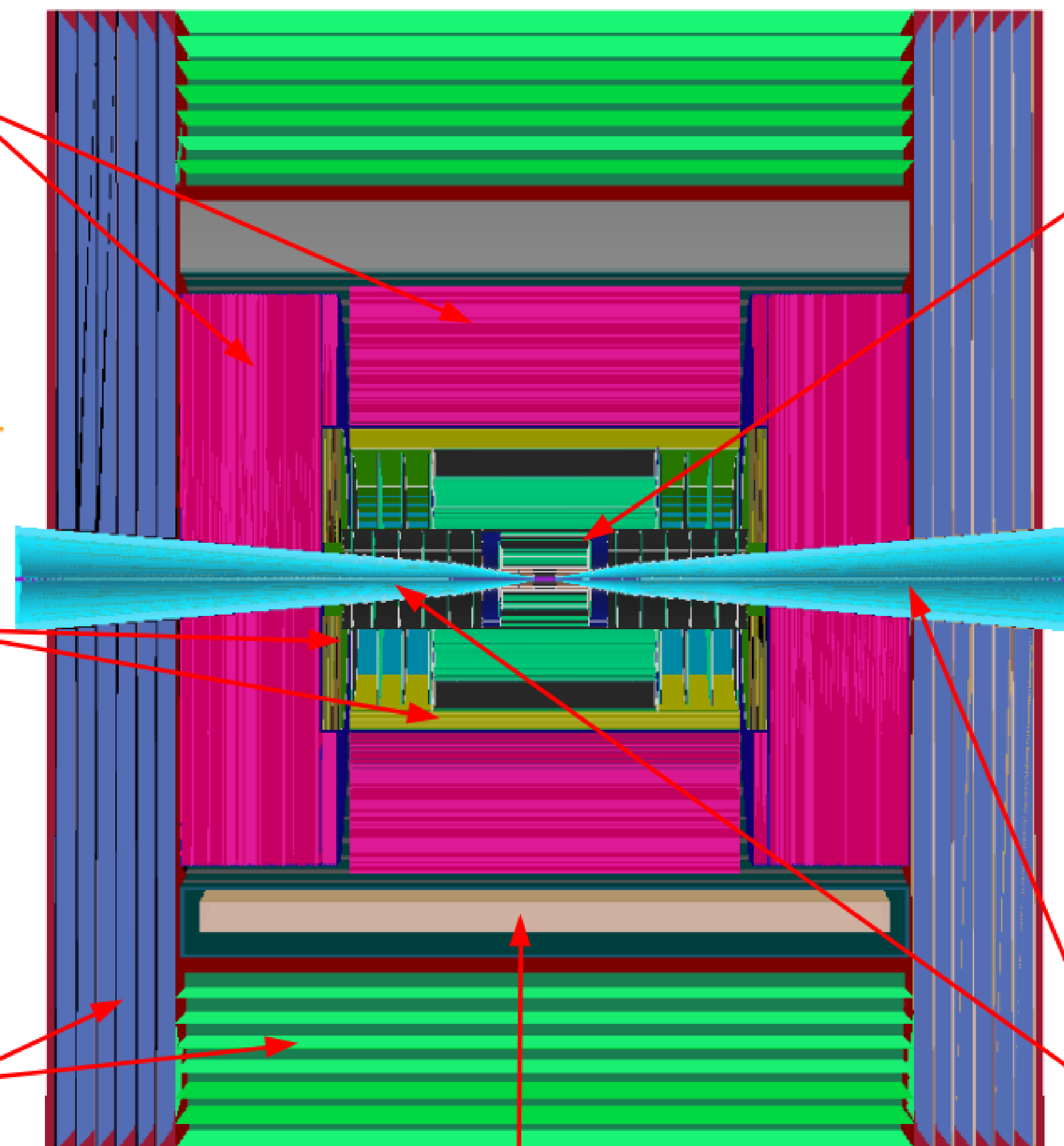
- 60 layers of 19-mm steel absorber + plastic scintillating tiles;
- 30x30 mm^2 cell size;
- 7.5 λ_I.

electromagnetic calorimeter

- 40 layers of 1.9-mm W absorber + silicon pad sensors;
- 5x5 mm^2 cell granularity;
- 22 X_0 + 1 λ_I.

muon detectors

- 7-barrel, 6-endcap RPC layers interleaved in the magnet's iron yoke;
- 30x30 mm^2 cell size.



superconducting solenoid (3.57T)

tracking system

- Vertex Detector:
  - double-sensor layers (4 barrel cylinders and 4+4 endcap disks);
  - 25x25 μm^2 pixel Si sensors.
- Inner Tracker:
  - 3 barrel layers and 7+7 endcap disks;
  - 50 μm x 1 mm macro-pixel Si sensors.
- Outer Tracker:
  - 3 barrel layers and 4+4 endcap disks;
  - 50 μm x 10 mm micro-strip Si sensors.

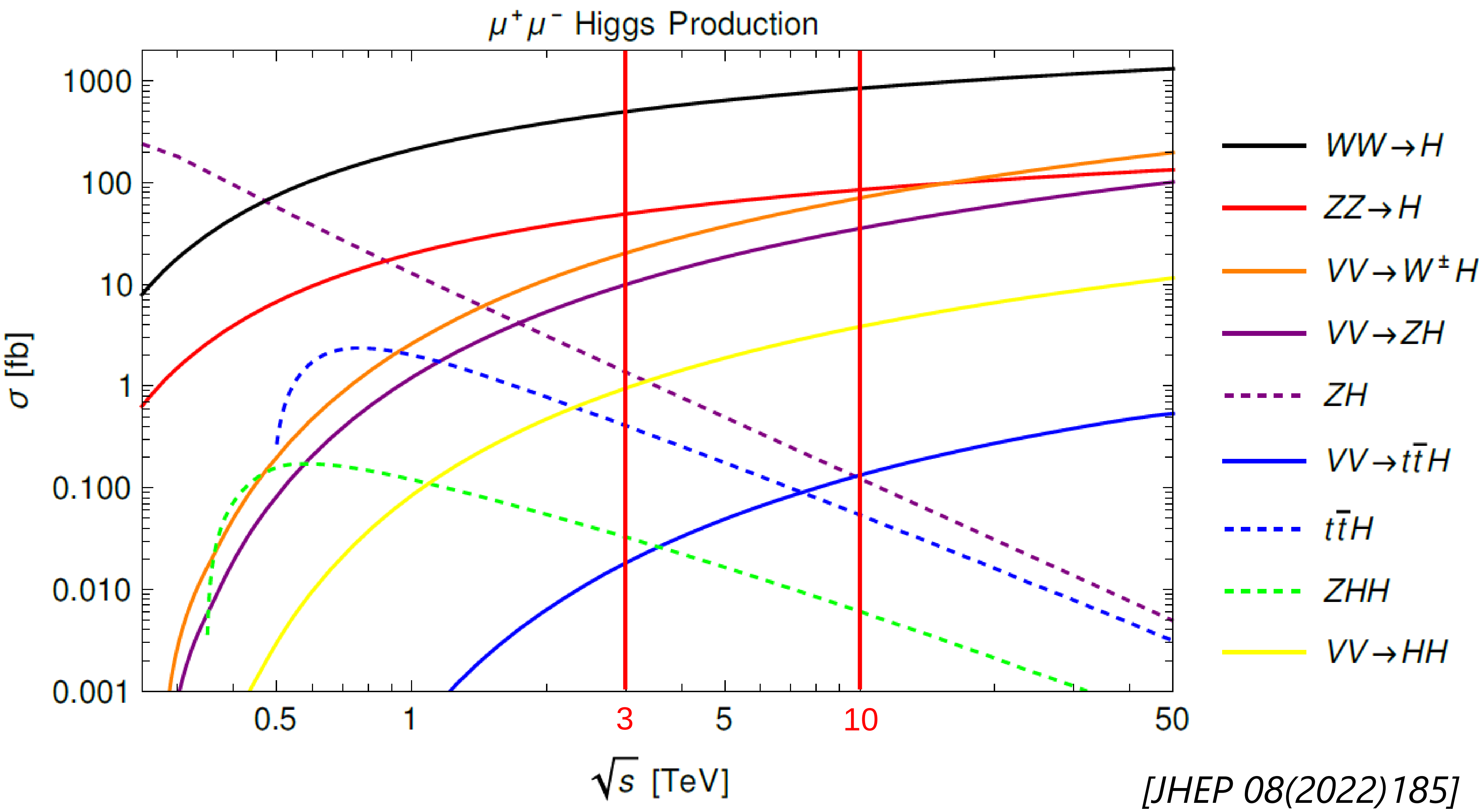
shielding nozzles

- Tungsten cones + borated polyethylene cladding.

[PoS ICHEP2020 (2021) 826]

A Higgs factory

- The Muon Collider is a "**Higgs factory**"
  - Produce Higgs boson at a high rate w.r.t. backgrounds
  - Perform precision measurements of its parameters



[JHEP 08(2022)185]

Higgs couplings measurement

- Measure Higgs **couplings** to fermions through its decays

Decay mode	$\mathrm{BR} = \Gamma_i/\Gamma_H$
$H \to b\bar{b}$	58.2%
$H \to WW^*$	21.4%
$H \to gg$	8.19%
$H \to \tau^+\tau^-$	6.27%
$H \to c\bar{c}$	2.89%
$H \to ZZ^*$	2.62%
$H \to \gamma\gamma$	2.27×10^{-3}
$H \to Z\gamma$	1.53×10^{-3}
$H \to \mu^+\mu^-$	2.18×10^{-4}

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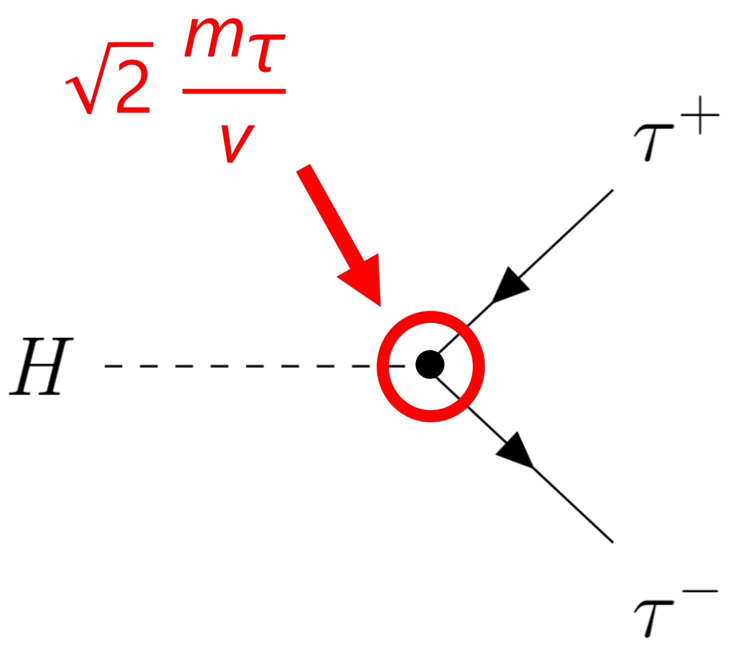
Coupling to τ leptons



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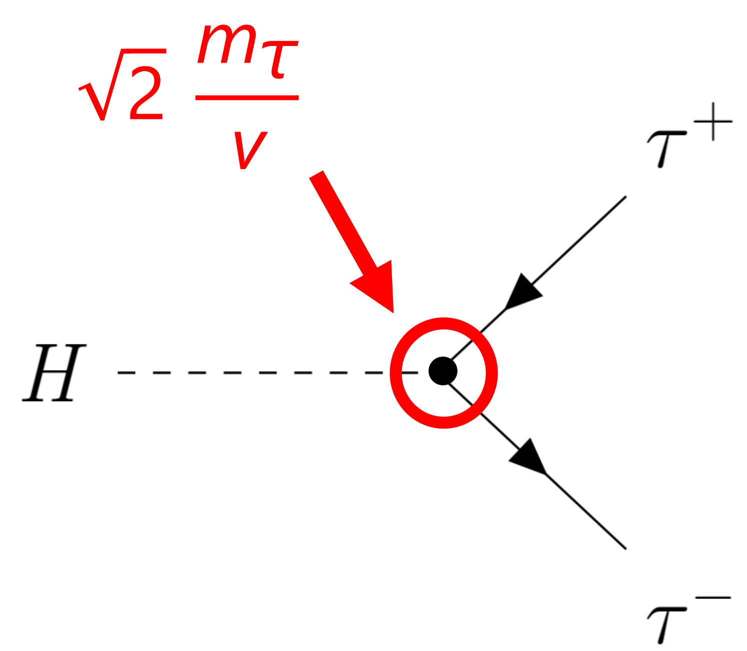
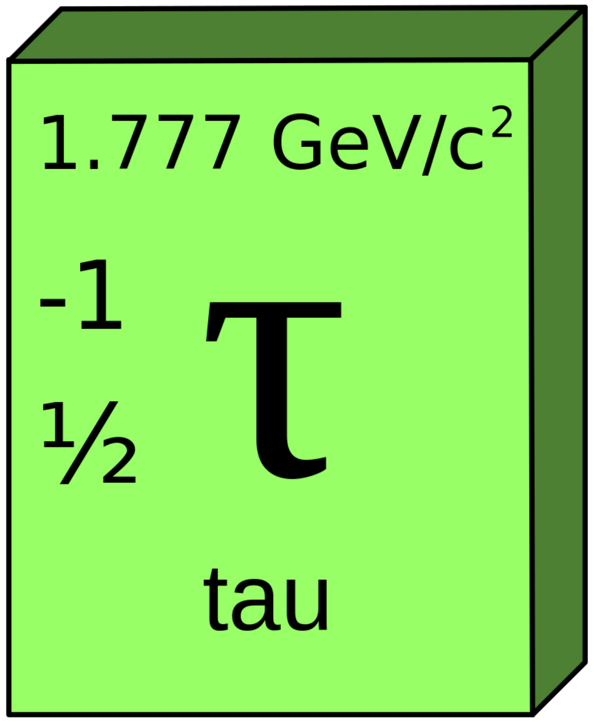


Goal of my thesis

Estimate the **statistical uncertainty** on $\boldsymbol{\sigma(H \to \tau\tau)}$ at the $\sqrt{s}$ = 3 TeV MuCol

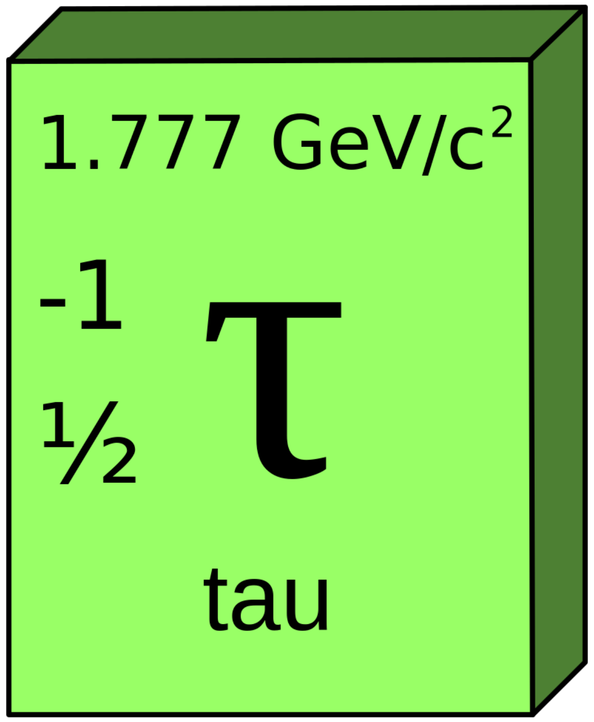
Tau lepton

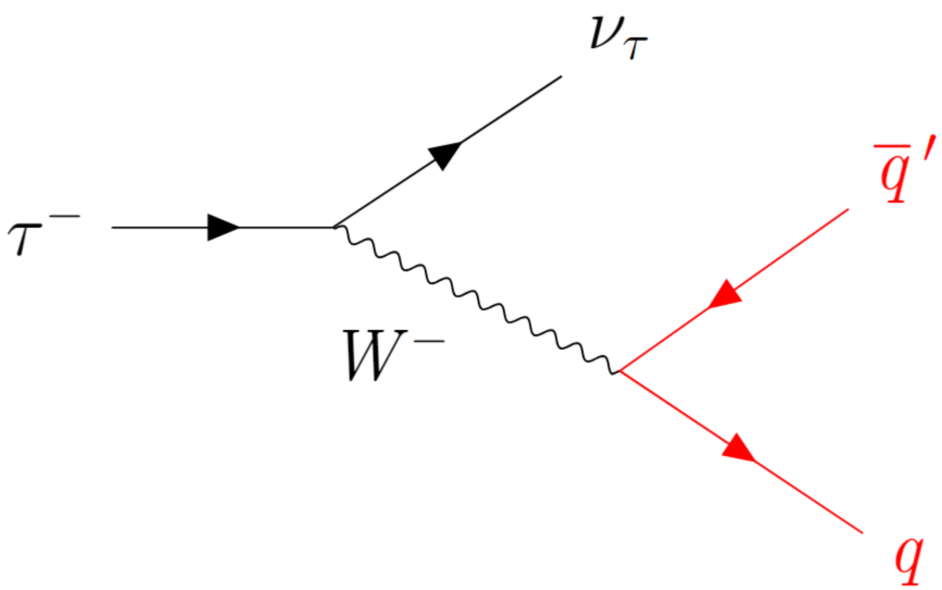
- 3rd generation fermion, m_τ = 1.777 GeV/c^2
- Unstable: τ = 2.9 × 10^{-13} s
- Decay length ~ 1 - 10 mm

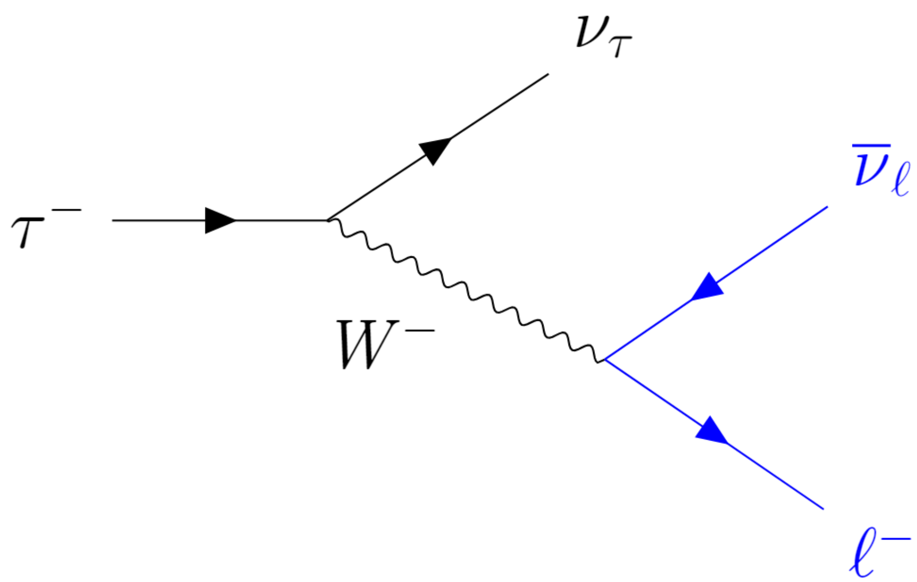


Tau lepton

- 3rd generation fermion, m_τ = 1.777 GeV/c^2
- Unstable: τ = 2.9 × 10^{-13} s
- Decay length ~ 1 - 10 mm
- Reconstructed from its **decay products**
  - $\boldsymbol{\nu_\tau}$ in the final state (missing transverse momentum)
  - **hadronic** (τ_h) or **leptonic** (τ_ℓ) final states







Tau lepton

- Hadronic decays: 1-prong (≈50%) or 3-prong (≈15%)

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

[JINST 17 (2022) P07023]

Particle Flow Algorithm

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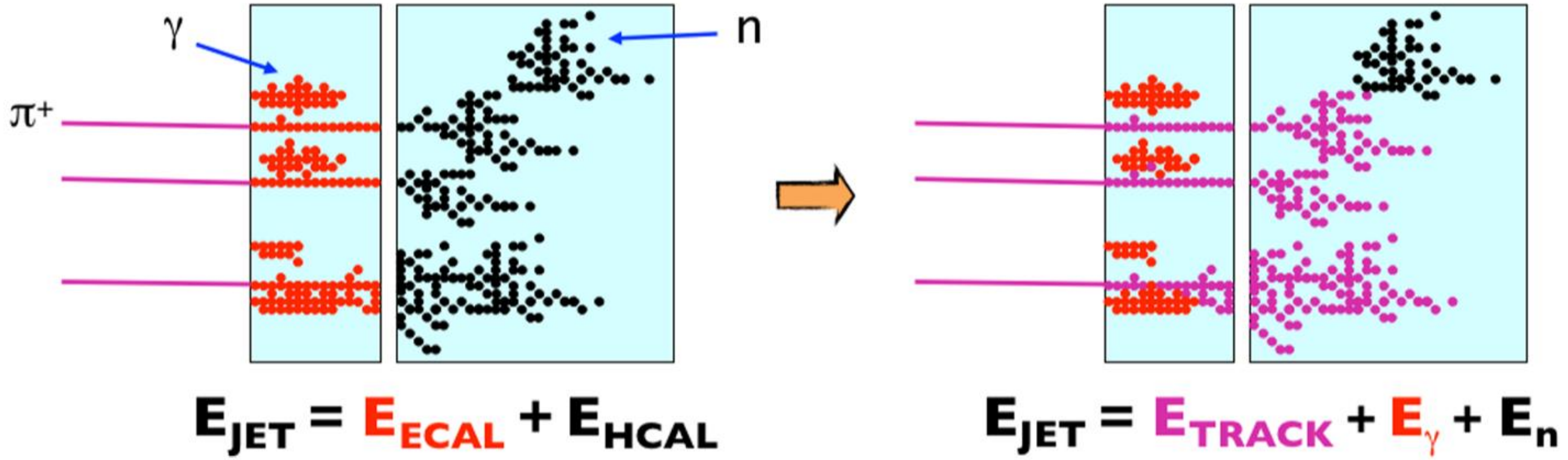
- Physics objects are reconstructed with **PandoraPFA** (Pandora Particle Flow Algorithm)



[arXiv:1308.4537]

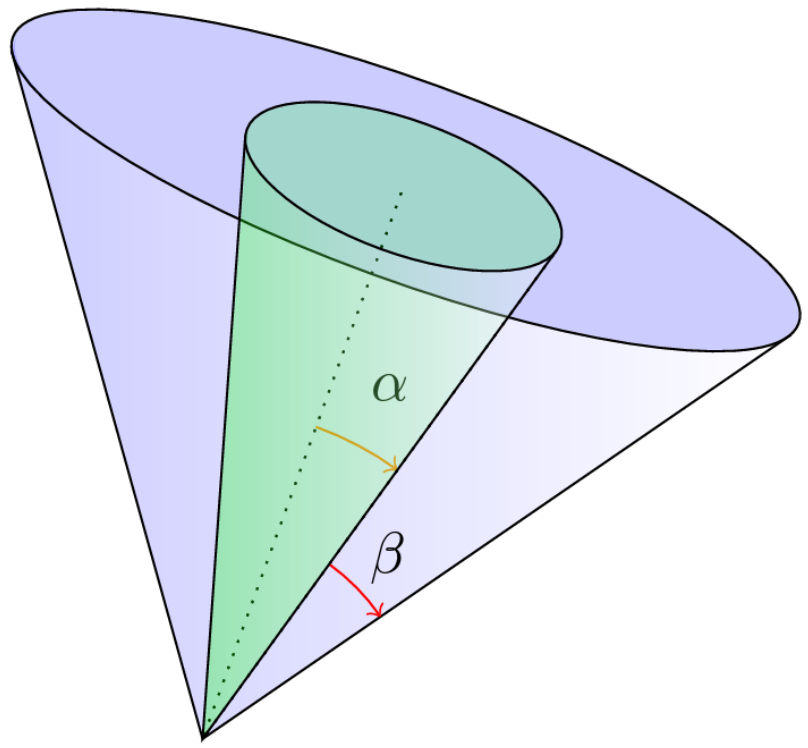
Tau leptons at the Muon Collider

- **TauFinder** algorithm for τ reconstruction and identification:

1) Define **τ seeds** - each charged particle, start from highest energy
2) **Charged particles** within the **search cone** (0.05 rad) are added to the τ candidate one at a time, adjusting the search cone
3) **Neutral particles** are added in the same way
4) Steps 1 to 3 are repeated until no particle is left out
5) All particles associated to one τ candidate are combined into a **reconstructed τ**
6) Check if a single τ was split into two τ candidates: combine all candidates whose angular separation is less than the opening angle of the search cone

Tau leptons at the Muon Collider

- Apply **selection cuts** to select "good" τ candidates
- Fixed quality cuts
  - Number of charged particles between 0 and 4
  - Number of charged + neutral particles below 10
  - Total charge equal to +1 or -1
- Reconstruction and isolation cuts
  - τ seed: $p_T > 5$ GeV/c
  - For each particle: $p_T > 1$ GeV/c
  - Energy in the **isolation cone** (+0.2 rad): $E_{iso} < 5$ GeV

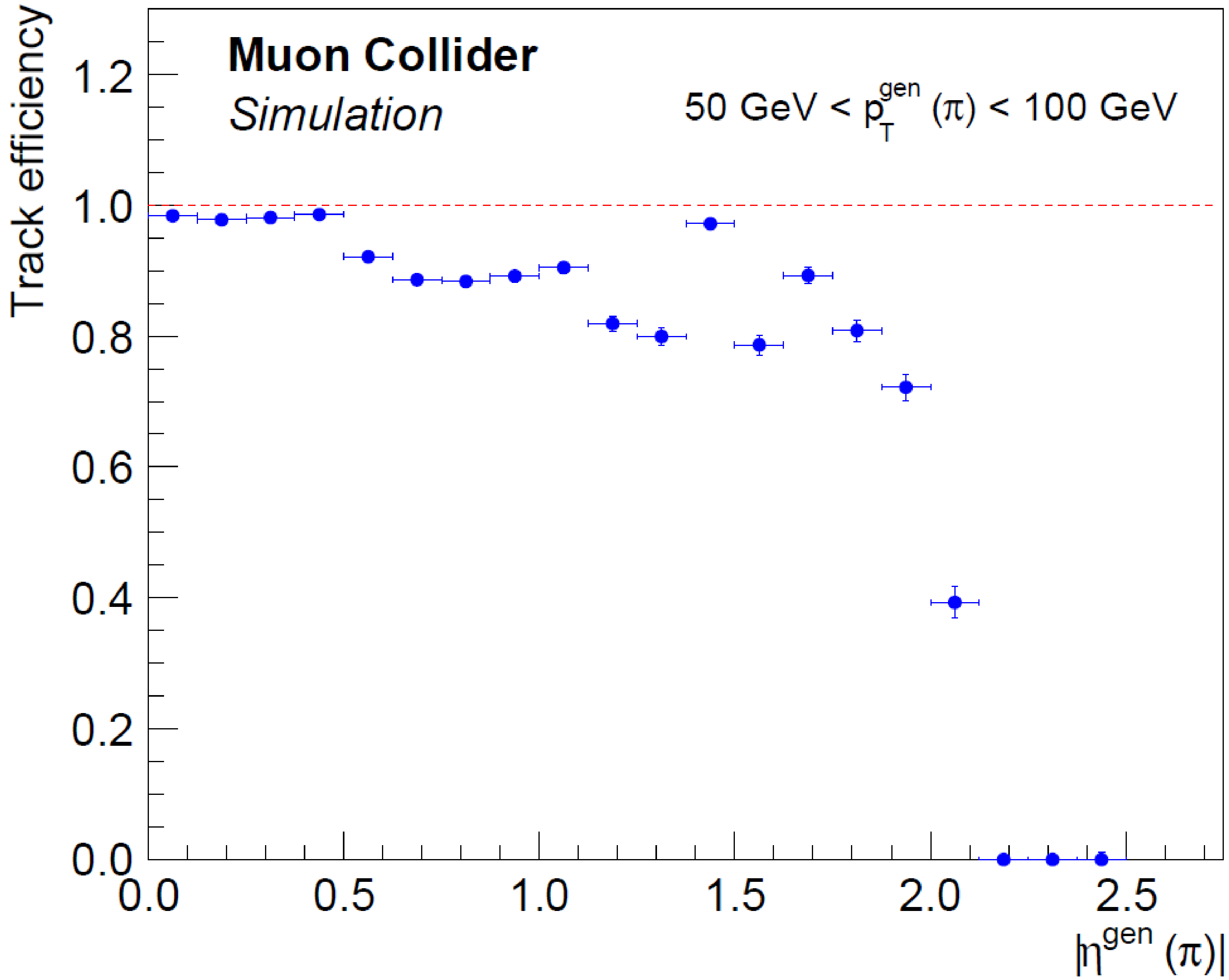


Tau leptons at the Muon Collider

- Focus on τ_h reconstruction and identification
- Muon Collider software v2.8 (Combinatorial Kalman Filter tracking + PandoraPFA reconstruction)
- "**Particle guns**" to estimate the efficiencies: simulation of a single particle in the detector + event reconstruction
- Plan to evaluate TauFinder performance:
  1) charged pion track efficiency (200k $\pi^{\pm}$ guns)
  2) charged pion reconstruction efficiency (200k $\pi^{\pm}$ guns)
  3) τ_h reconstruction efficiency (200k $\tau^{\pm}$ guns)
- Caveat: not including the beam-induced background in this analysis

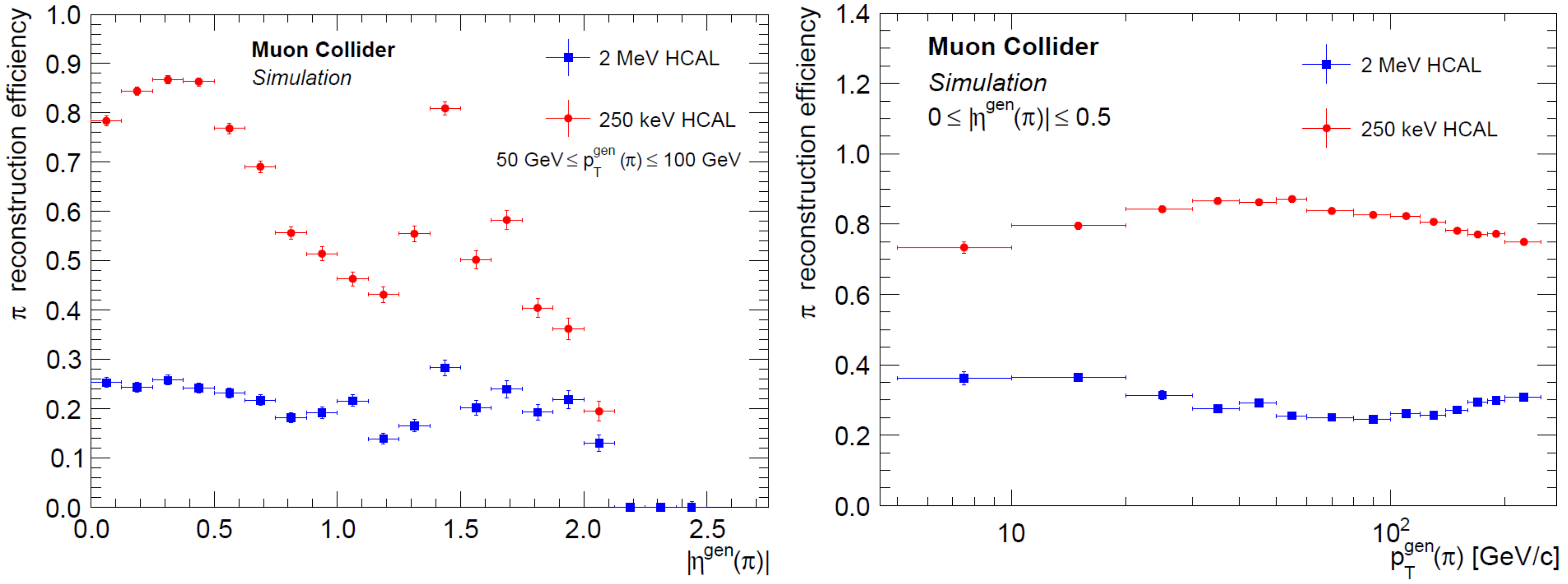
Charged pion tracking efficiency

- $\pi^{\pm}$ track efficiency performance (200k $\pi^{\pm}$ guns)
- Match the generated $\pi^{\pm}$ and the reco track : $\Delta R = \sqrt{\Delta\varphi^2 + \Delta\eta^2} \leq 0.1$



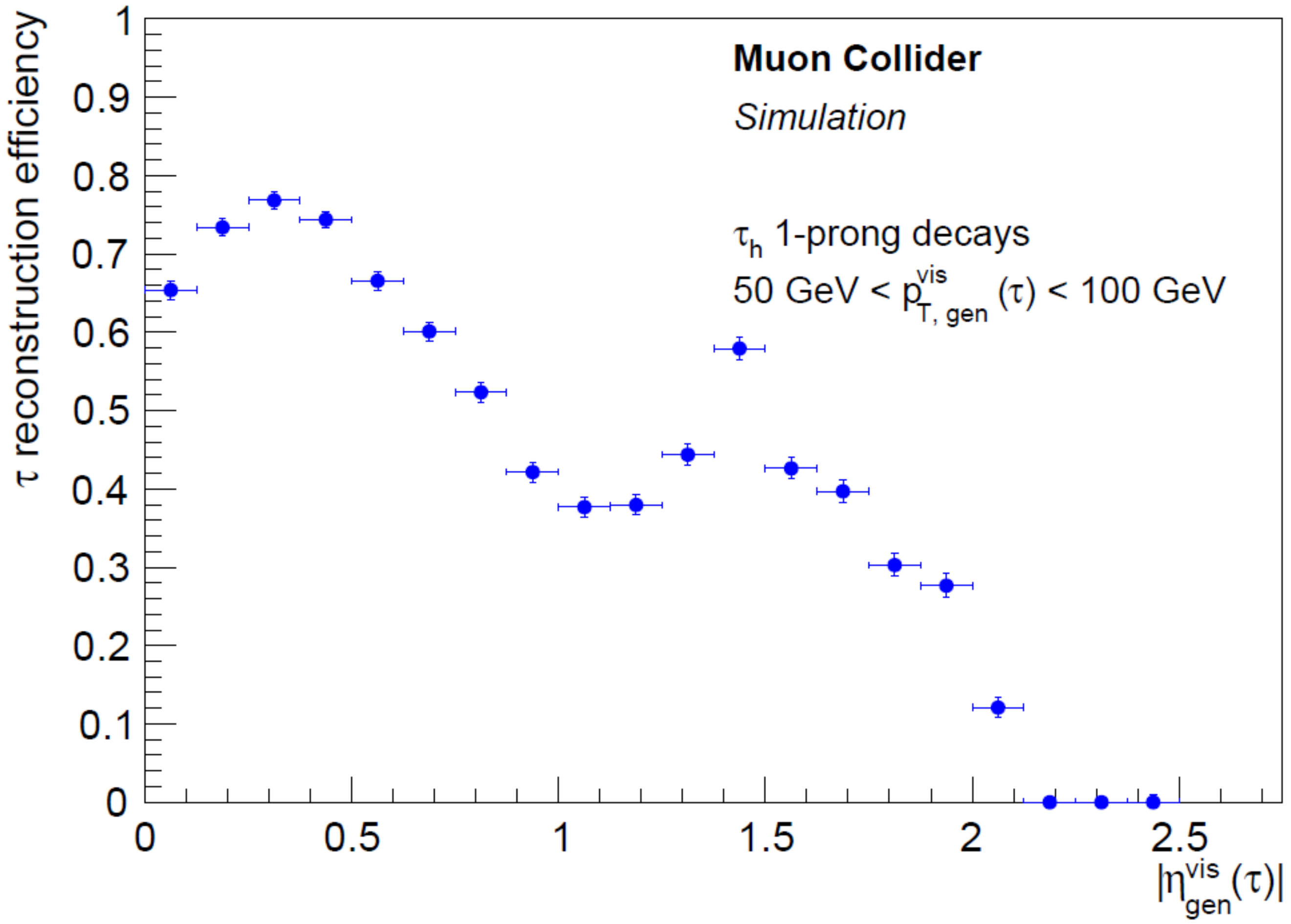
Charged pion reconstruction eff.

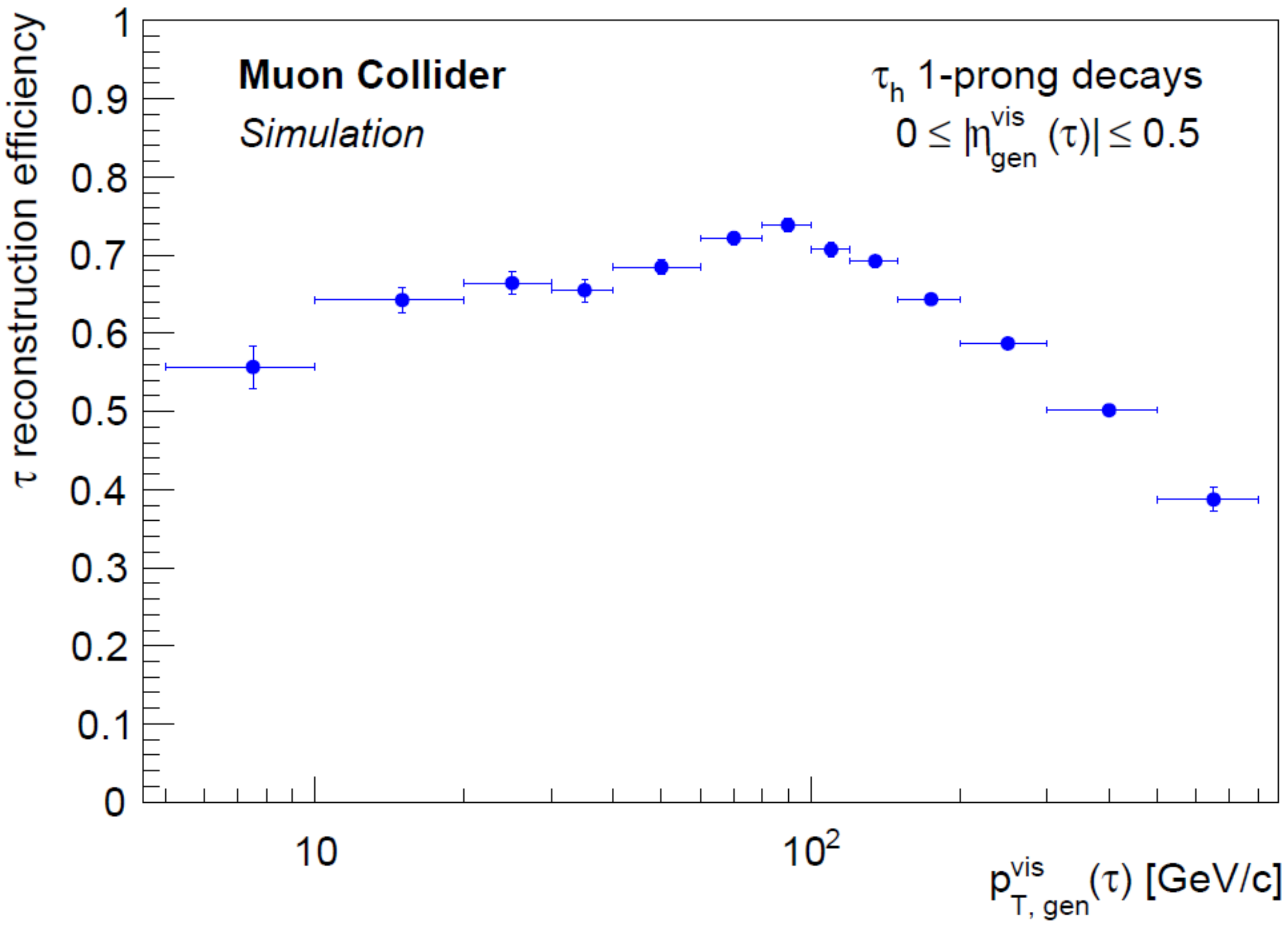
- $\pi^{\pm}$ reconstruction efficiency performance (200k $\pi^{\pm}$ guns)
- Study the best HCAL energy threshold configuration: 250 keV
- Match the generated and reconstructed $\pi^{\pm}$: $\Delta R \leq 0.1$, $\Delta p_T \leq 0.1\ p_T^{gen}$



Hadronic tau reconstruction eff.

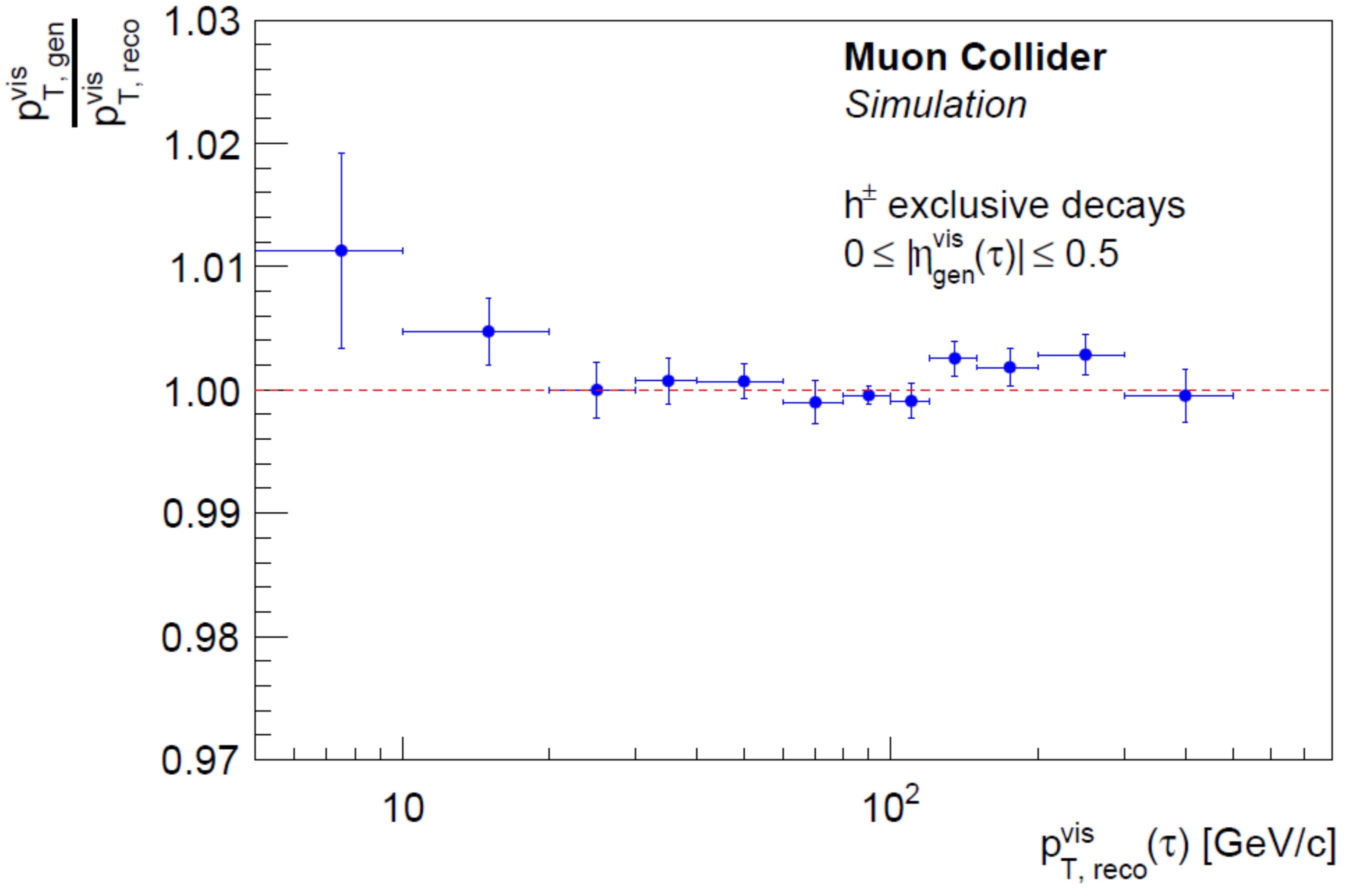
- τ_h reconstruction efficiency performance (200k $\tau^\pm$ guns)
- Match the generated and reconstructed $\tau^\pm$: $\Delta R \leq 0.1$

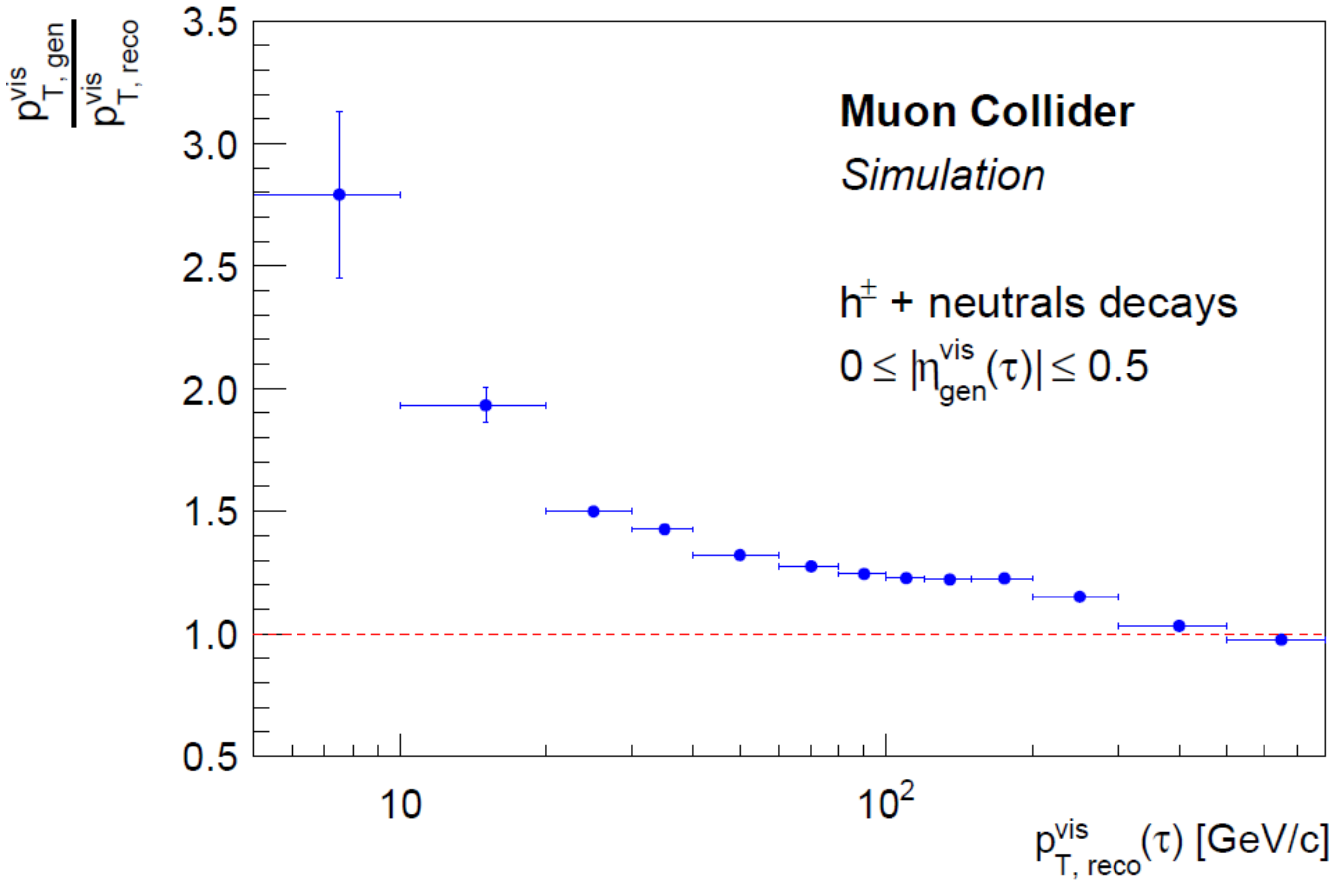




Tau energy corrections

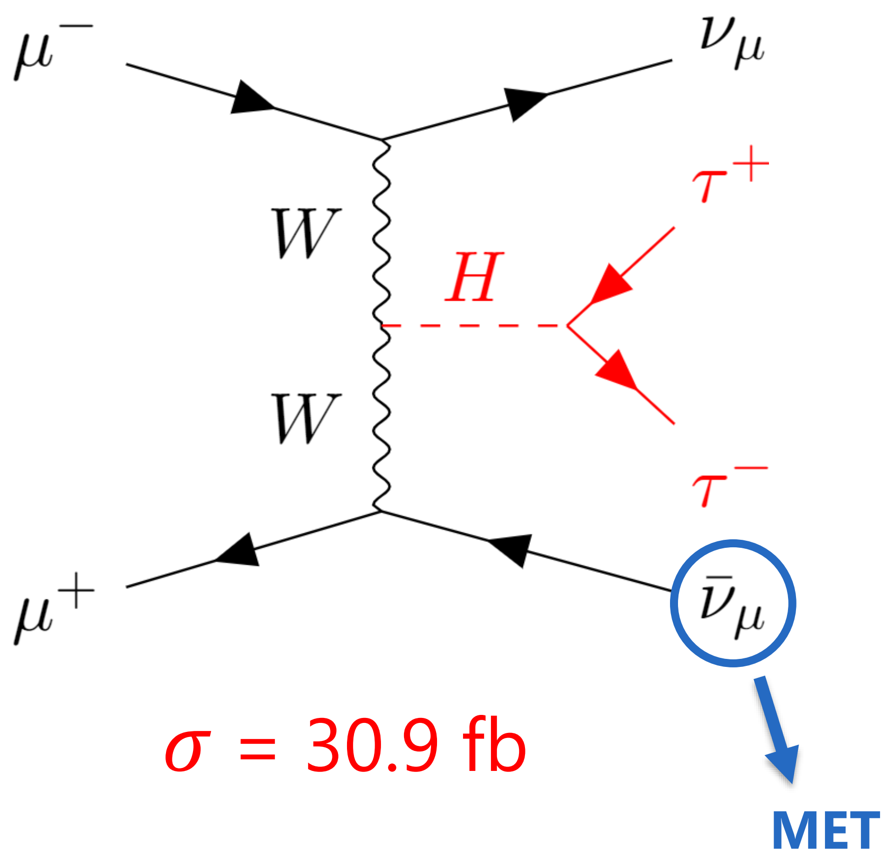
- Need to account for detector response
- Compute τ_h energy corrections for different decay modes





$H \to \tau\tau$ identification

- At 3 TeV, Higgs mainly produced via VBF (primarily *WW*)
- Need to discriminate signal



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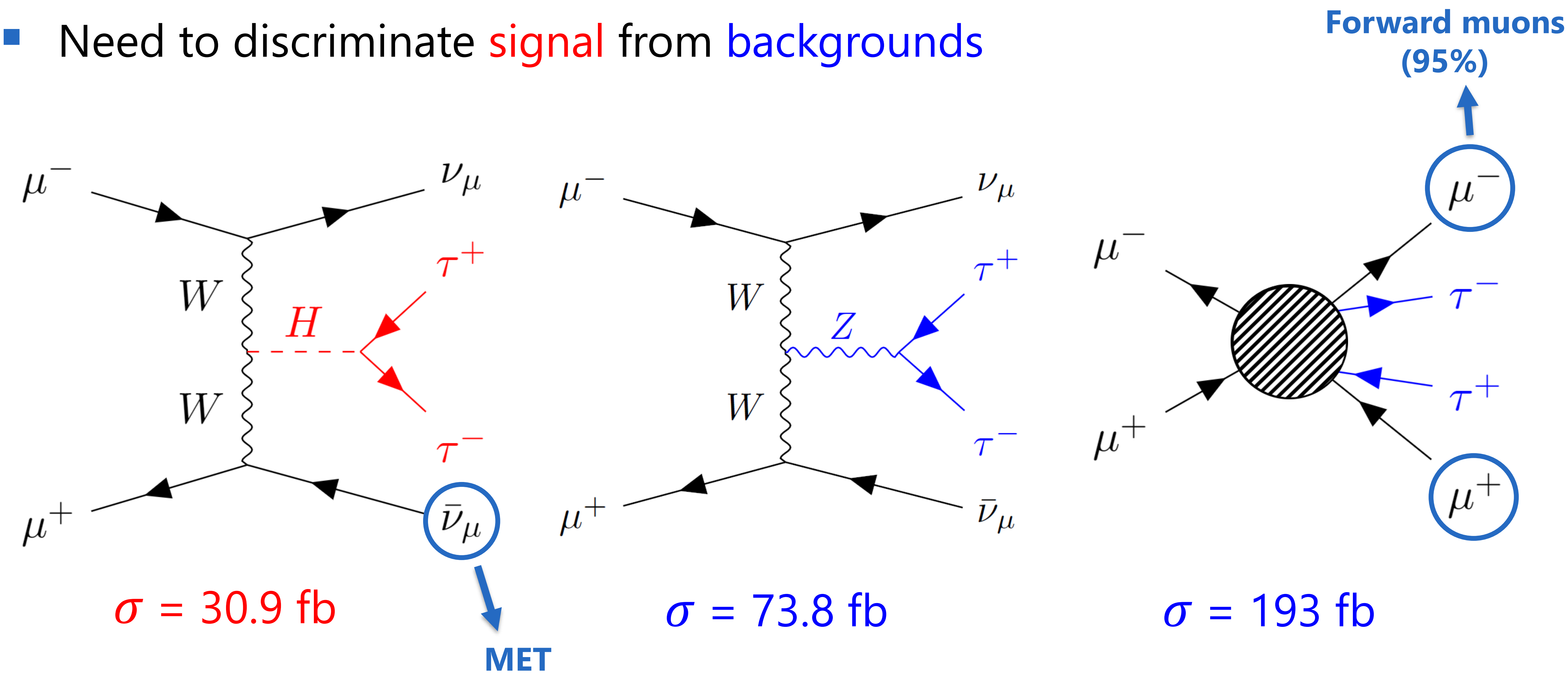

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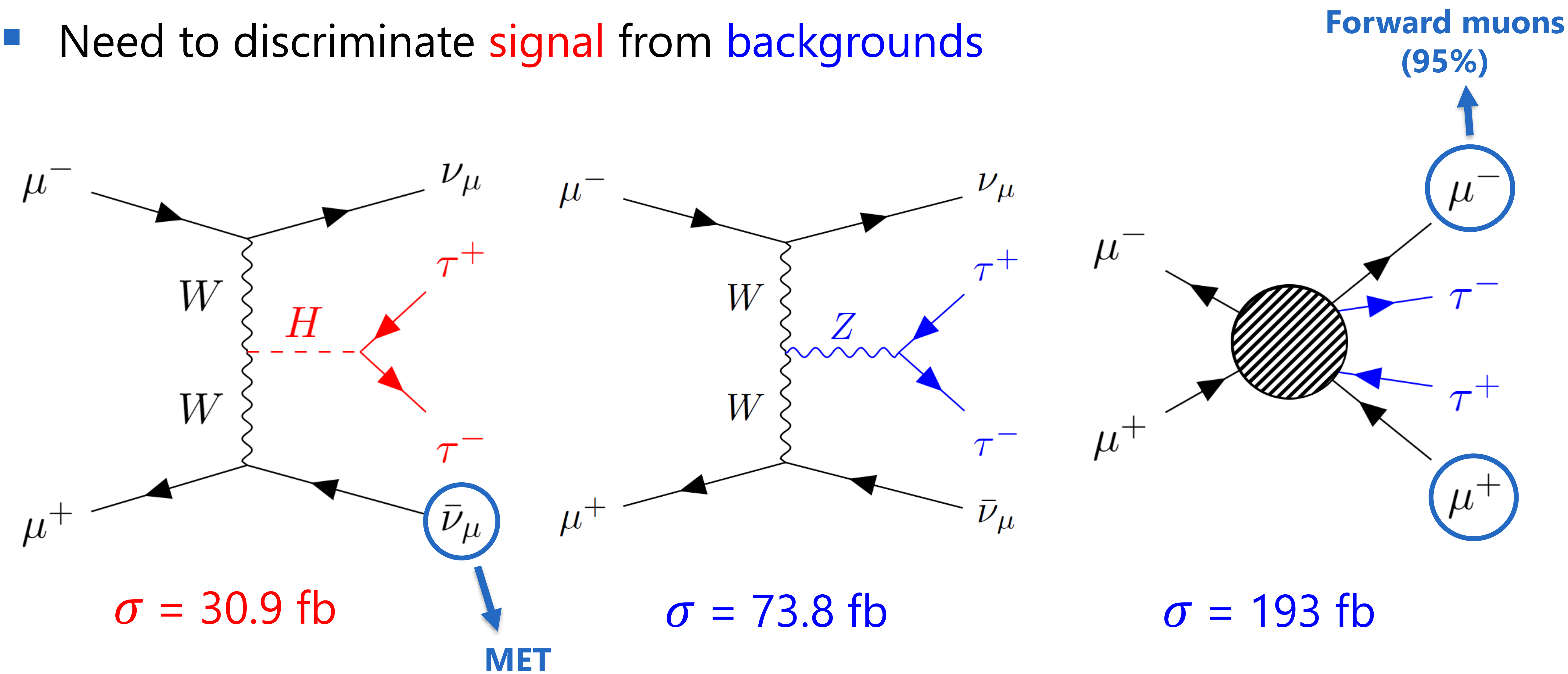

- Focus on the $\boldsymbol{\tau_h^+\tau_h^-}$ decay mode
- Search for **kinematic variables** with high discriminating power

$H \to \tau\tau$ identification

- Samples generation with MadGraph5 (300k events each)
- PYTHIA8 for showering, hadronization and τ decay
- Event selection: $\boldsymbol{p_T(\tau) > 20}$ **GeV/c** + **one** $\boldsymbol{\tau_h^+ \tau_h^-}$ **pair**

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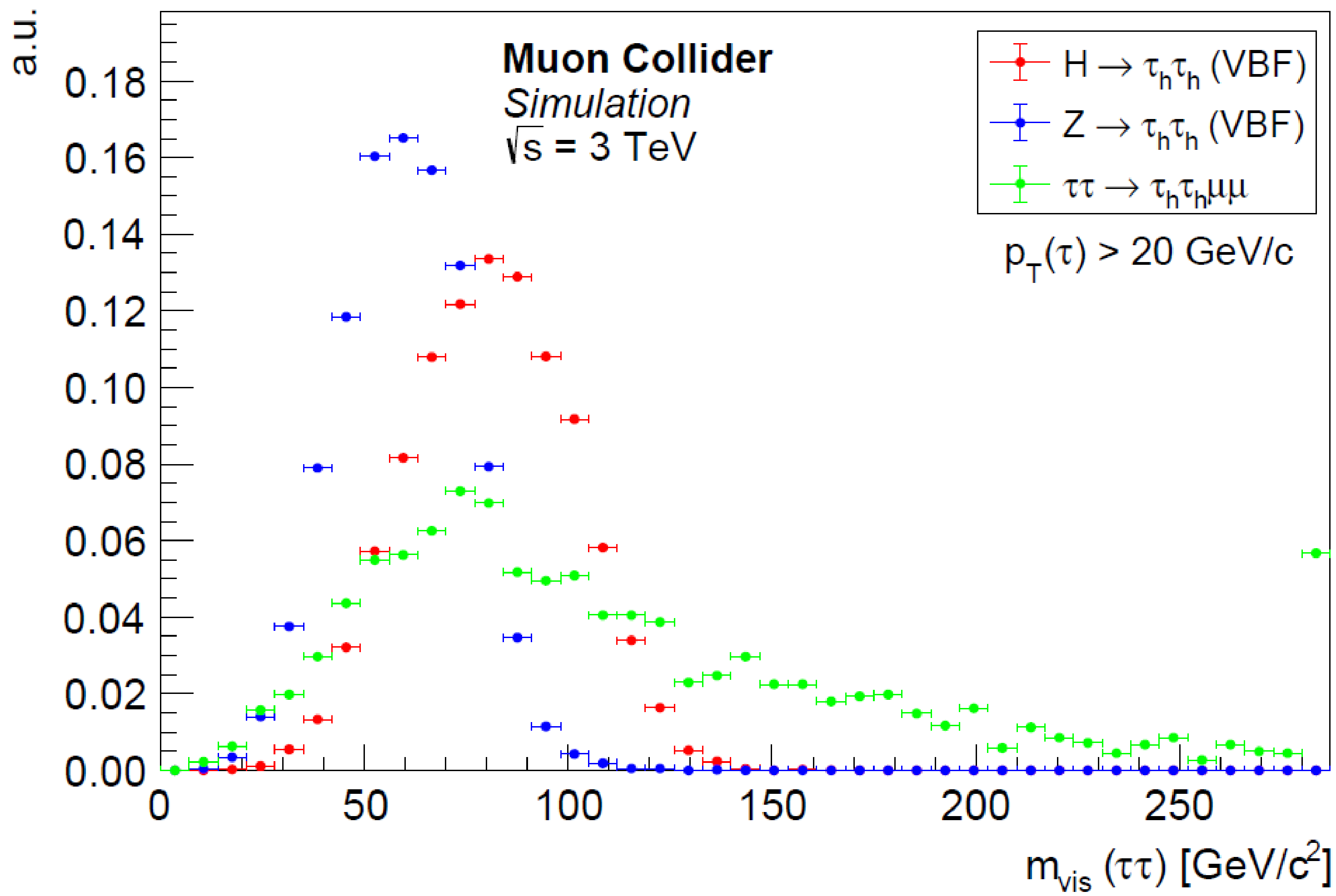
- PYTHIA8 for showering, hadronization and τ decay
- Event selection: $\boldsymbol{p_T(\tau) > 20}$ **GeV/c** + **one** $\boldsymbol{\tau_h^+\tau_h^-}$ **pair**
- Most significant variables: $m_{vis}(\tau\tau)$, $\Delta R(\tau\tau)$, $p_T(\tau\tau)$



$H \to \tau\tau$ cross section measurement

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- Classification with a Boosted Decision Tree (TMVA) to enhance signal-bkg discrimination
- Feed the $\tau_h^+\tau_h^-$ kinematical variables into the BDT (η, p_T, φ)

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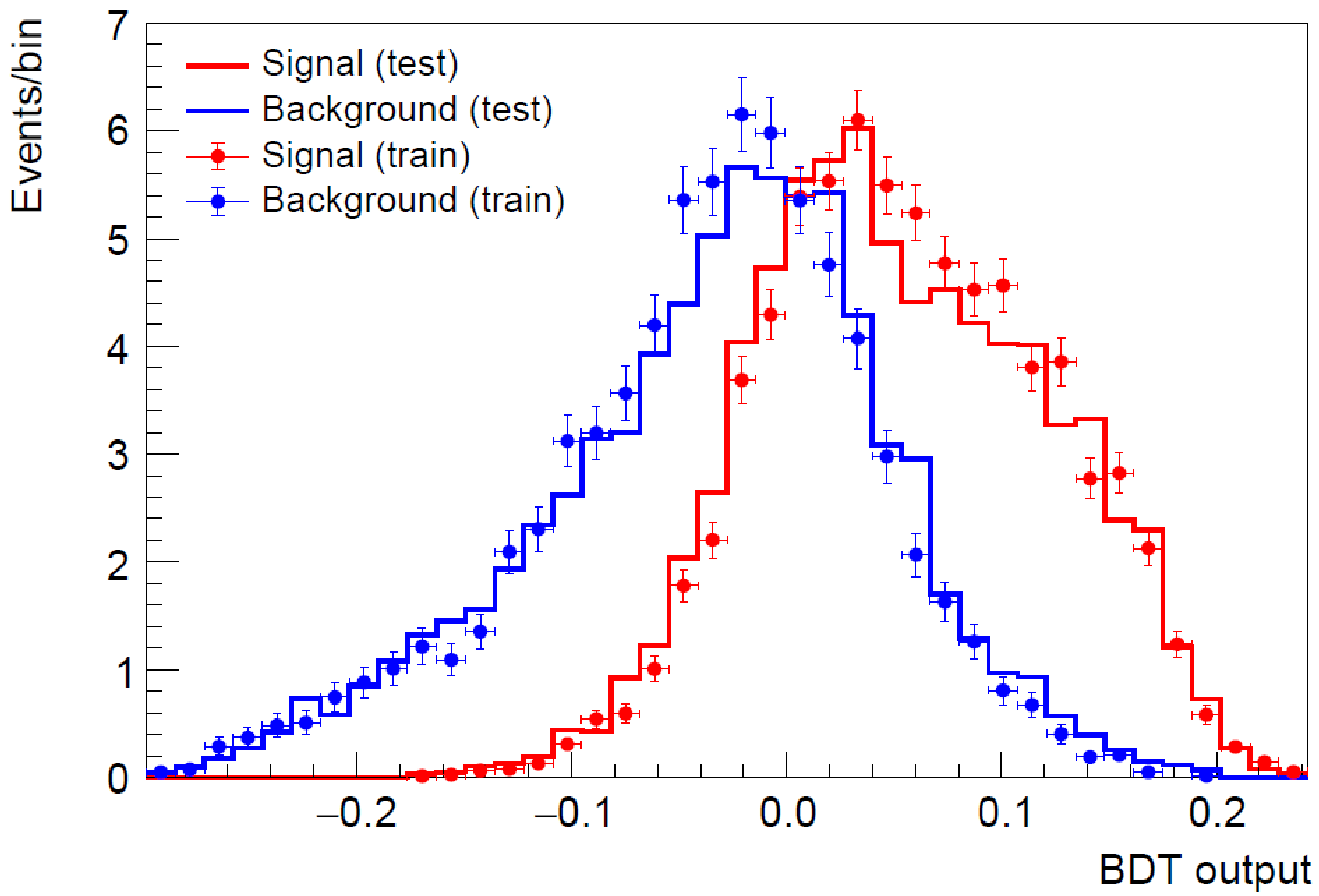

$H \rightarrow \tau\tau$ cross section measurement

IMAPP

- Normalize the BDT output distributions to the number of expected events at a 3 TeV Muon Collider ($\mathcal{L}$ =1 ab^{-1}):

$$N = \mathcal{L} \cdot \varepsilon \cdot \sigma$$

- Perform 100k MC **toy experiments** (bkg normalization floating)
- Perform a **histogram template fit** (signal + bkg distributions) for each toy experiment

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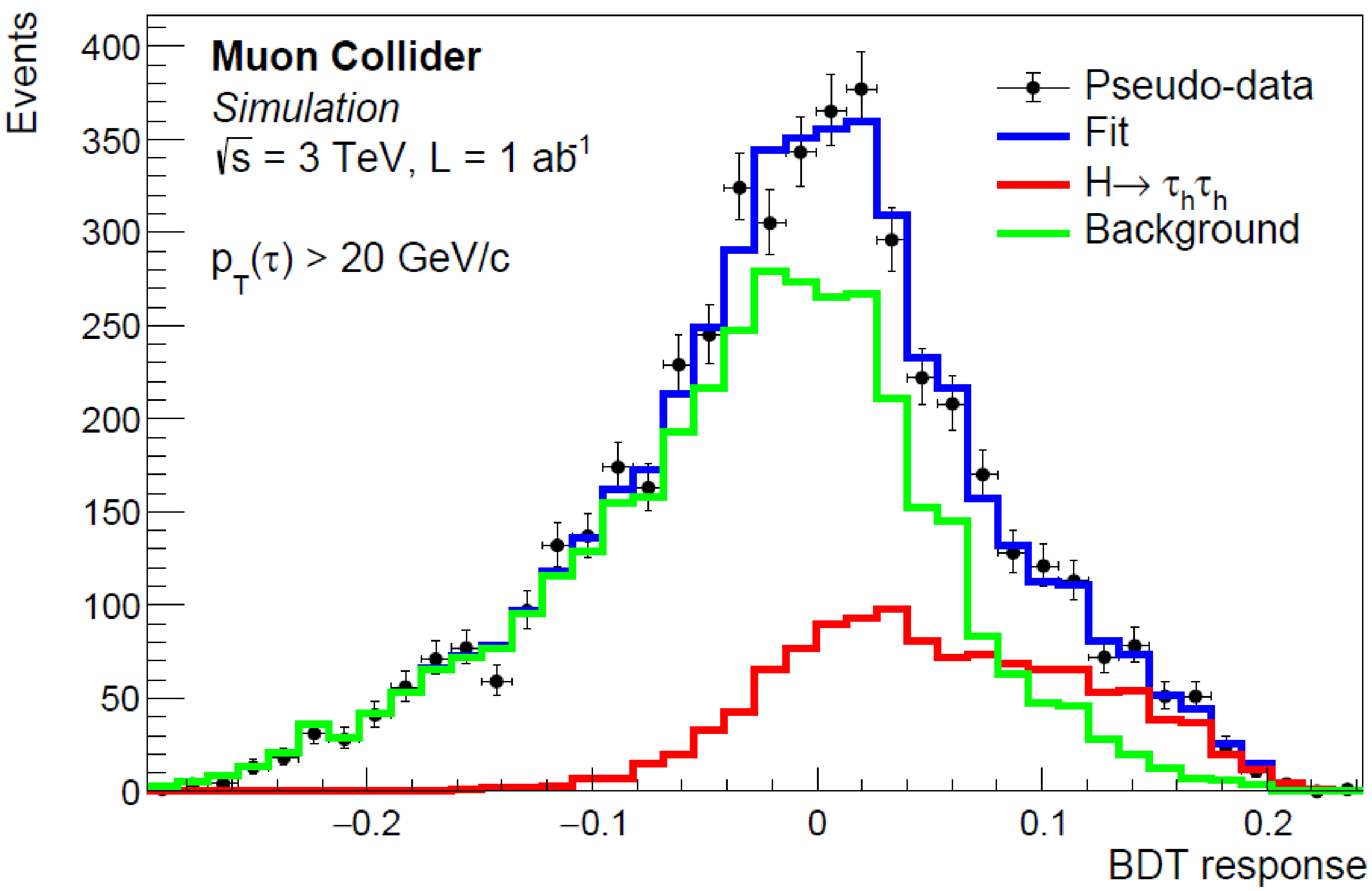
- Perform a **histogram template fit** (signal + bkg distributions) for each toy experiment
- Estimate the signal cross section as

$$\sigma(H \rightarrow \tau\tau) = \frac{N_S}{\mathcal{L} \cdot \varepsilon_S}$$

- Statistical uncertainty: $\boldsymbol{\Delta\sigma/\sigma(H \rightarrow \tau\tau) = \Delta N_s/N_s}$

$H \to \tau\tau$ cross section measurement



Process	ϵ	σ [fb]	N
$H \to \tau\tau$	0.04	30.9	1223
$Z \to \tau\tau$	0.03	73.8	2216
$\mu\mu \to \tau\tau\mu\mu$	0.007	193	1418

- Final result:

$$\Delta\sigma/\sigma(H \to \tau\tau) = 5.3\%$$

Conclusions

- The result obtained (5.3%) is **comparable** with the projection obtained with DELPHES for the MuCol (3.8%) *[JHEP 08(2022)185]*
- Sensitivity on $\boldsymbol{\kappa_\tau}$: CMS/ATLAS 8-9%, HL-LHC 1.9%, FCC 0.4%

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- **Margins of improvement** in τ reconstruction and $H \rightarrow \tau\tau$ analysis
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  - Find the best TauFinder working point
  - Include other decay channels ($\tau_h \tau_\ell$, $\tau_e \tau_\mu$)

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- **Caveats:**
  - The BIB was not included in the analysis
  - Events with "fake" τ(s) were neglected

Summary

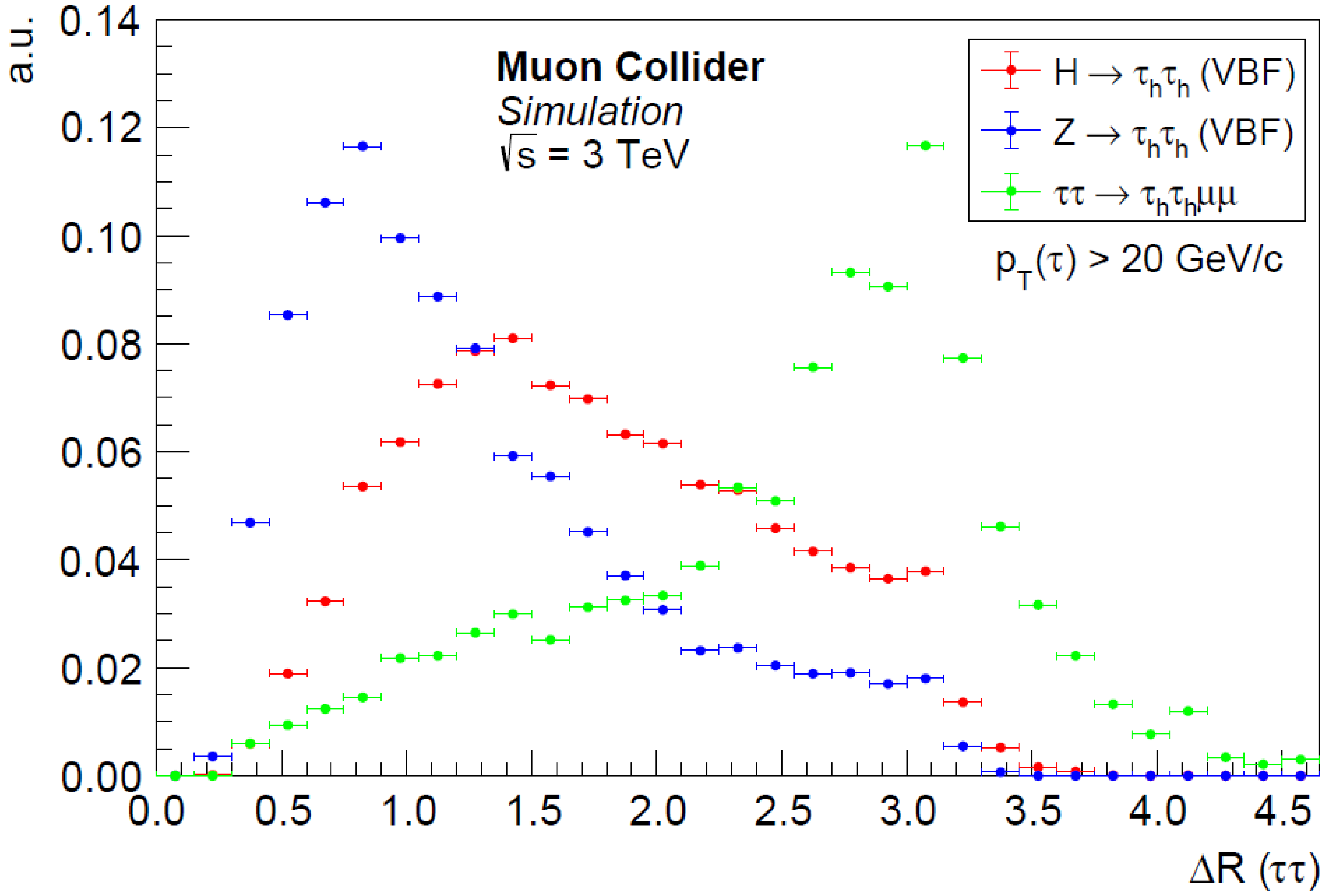
- The Higgs sector is crucial, and the MuCol is suited to study it
- Measure $\sigma(H \to \tau\tau)$ to measure the Higgs coupling to τ leptons
- Studied $\pi^{\pm}$ and $\tau^{\pm}$ tracking and reconstruction performance
- Computed τ energy corrections
- Performed $H \to \tau_h \tau_h$ signal-background discrimination with a BDT
- Histogram template fit with Monte Carlo toy experiments
- Estimated $\Delta\sigma/\sigma(H \to \tau\tau) = 5.3\%$

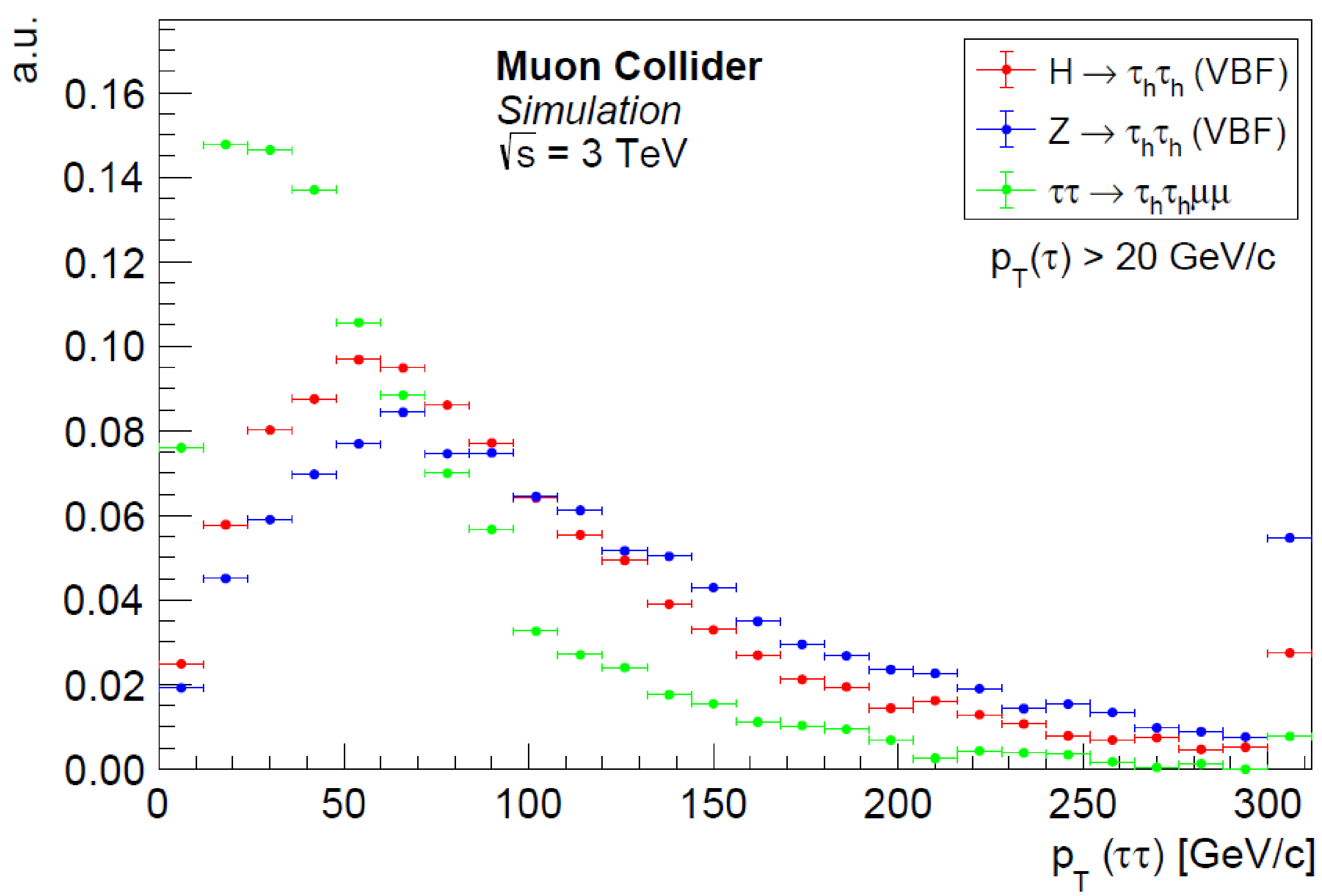
Acknowledgements

A heartful thanks to my supervisors for their support, and to PhD students Giacomo Da Molin and Giovanni Marozzo for their guidance. Thanks also to all members of LIP and of the Muon Collider collaboration for their help, and to the EU project “MuCol HORIZON-INFRA-2022-DEV-01-01” for the financial support.

BACKUP

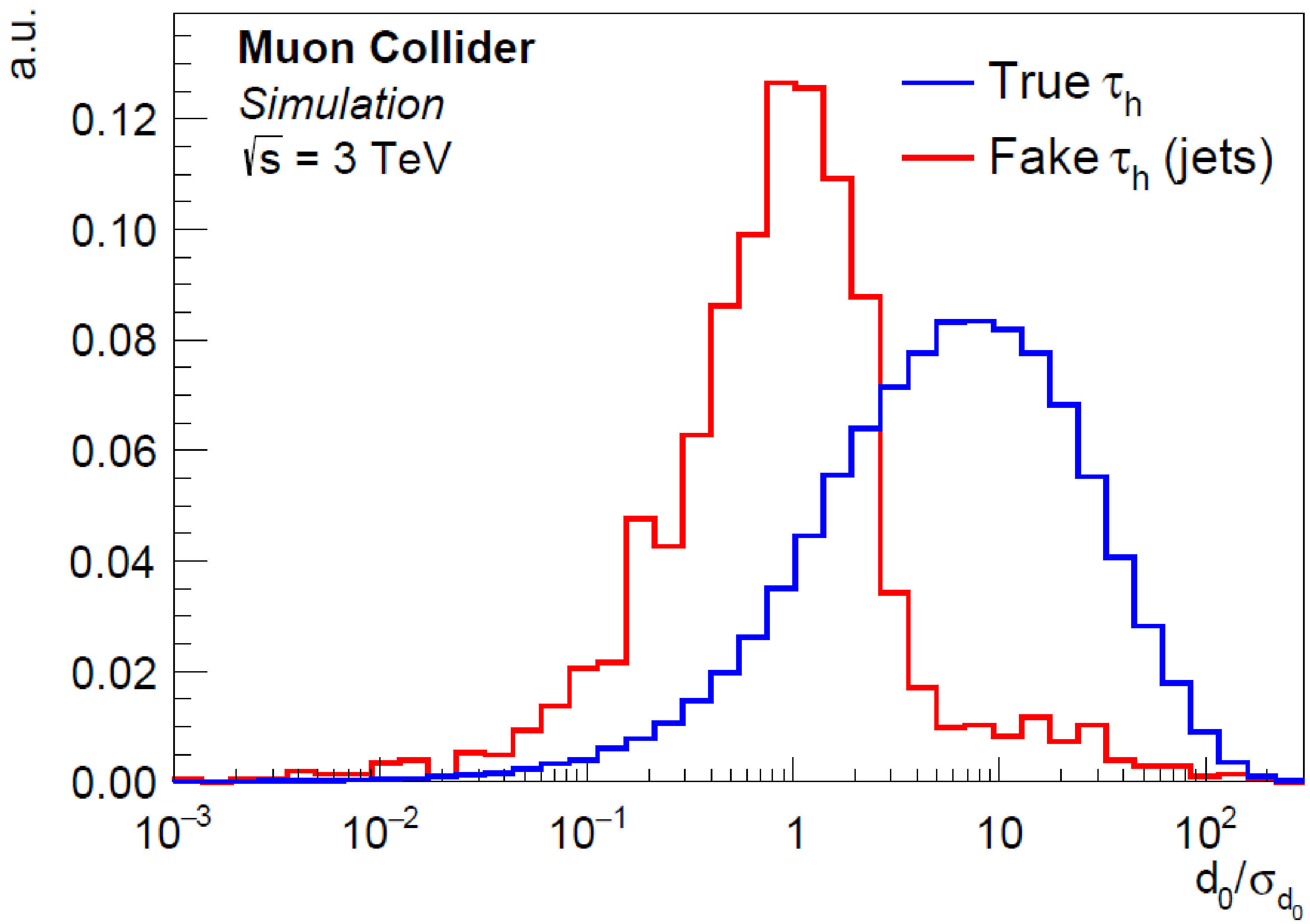
Kinematic variables





TauFinder misidentification

Physics object	Misidentification rate
Light-flavored jets (u, d, s)	5.8%
b-jets	3.9%
Electrons	2.8%



Higgs production at MuCol

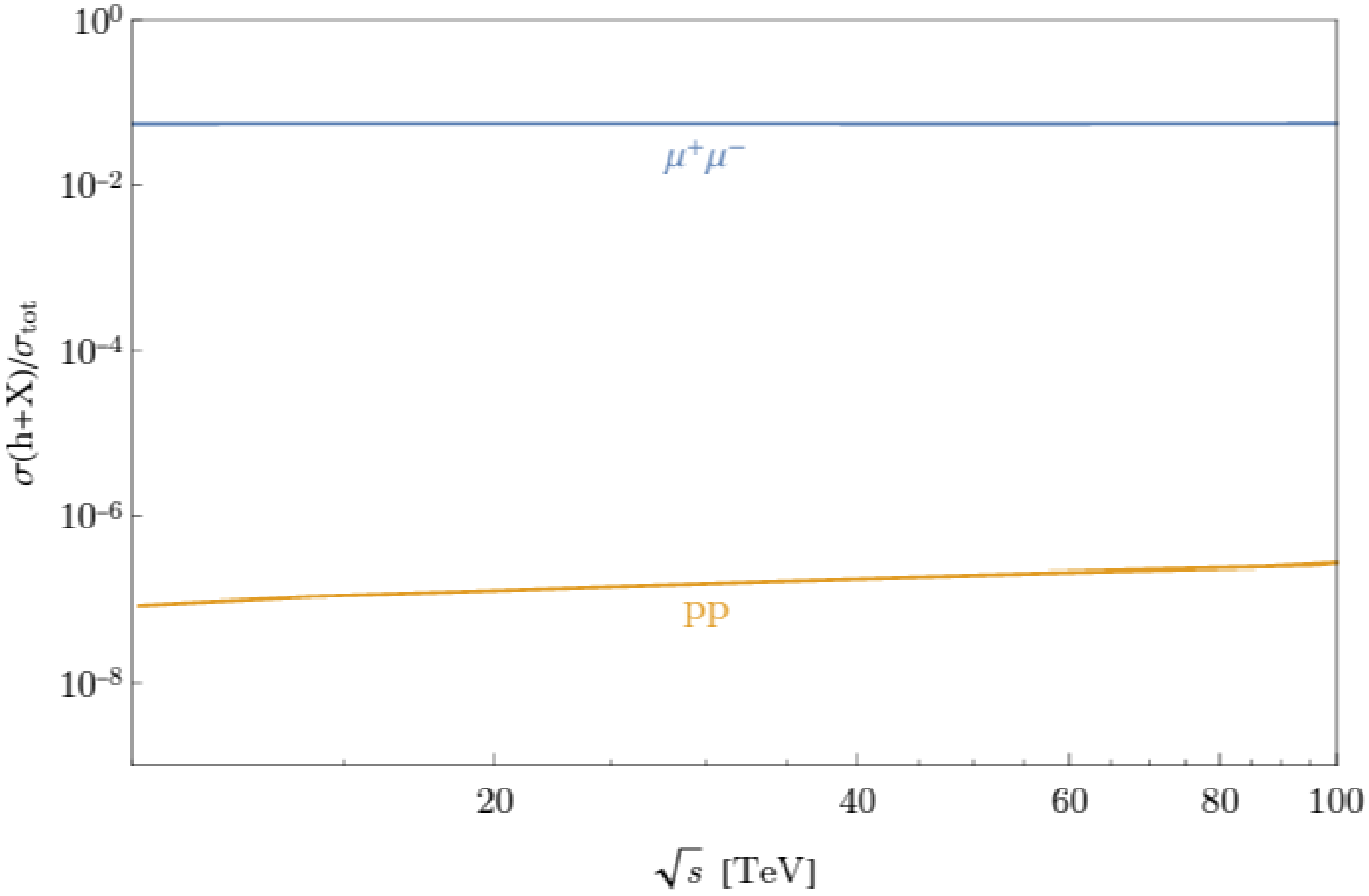


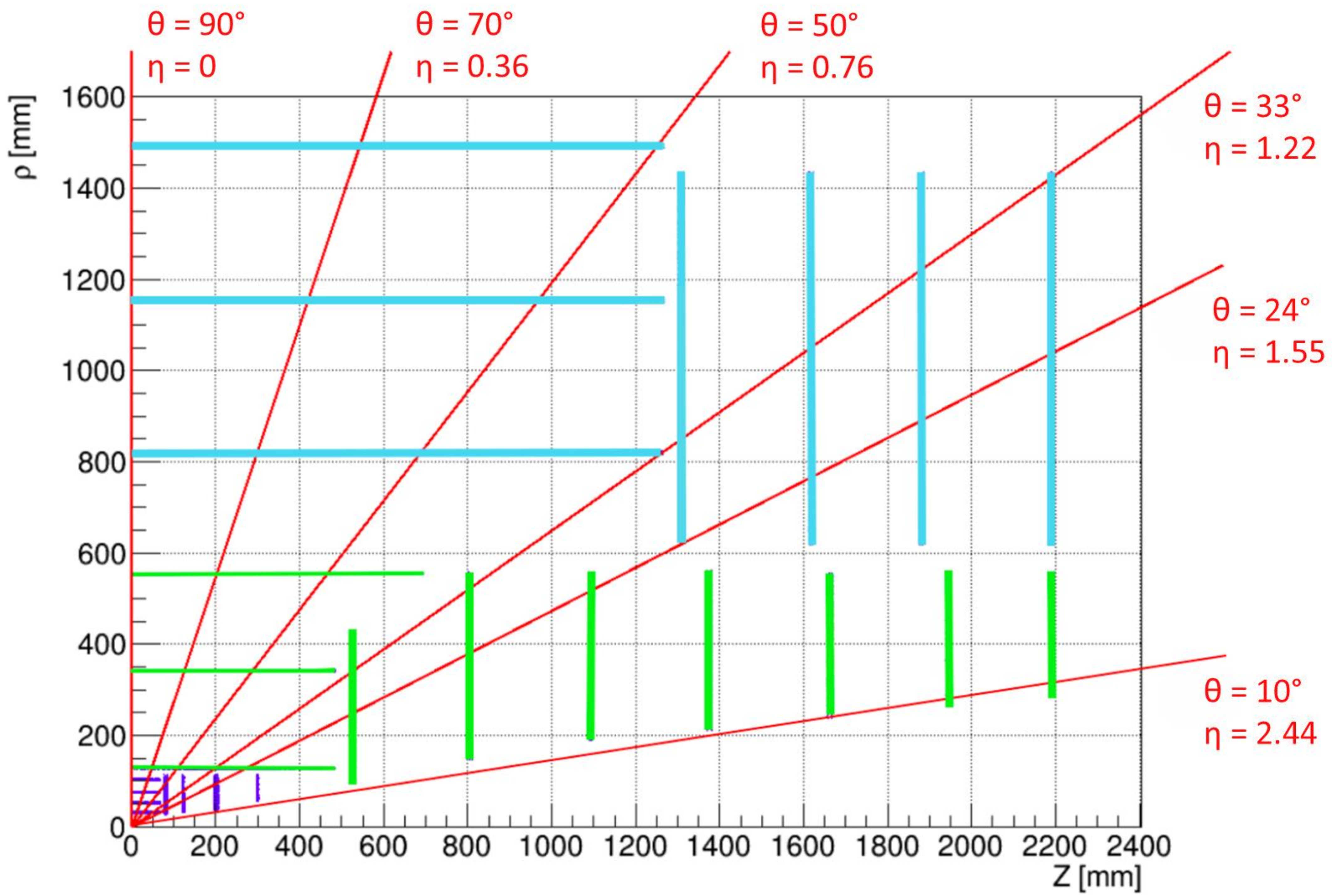
Figure 4: Higgs production cross section $\sigma(h+X)$ as a fraction of a representative "total" cross section σ_{tot} for $\mu^+\mu^-$ and pp colliders. For $\mu^+\mu^-$ colliders, we compute Higgs production using the LO cross section for $\mu^+\mu^- \to h + \nu\bar{\nu}$, while the "total" cross section σ_{tot} is taken to be the rate for single electroweak boson production, which is dominated by VBF production of W, Z, h, γ at these energies. For pp colliders we take the Higgs production cross section to be the N3LO cross section for $gg \to h$ [50] presented in [51], while the "total" cross section σ_{tot} is taken to be the $pp \to b\bar{b}$ cross section computed by MCFM [52].

[Rep. Prog. Phys. 85 084201]

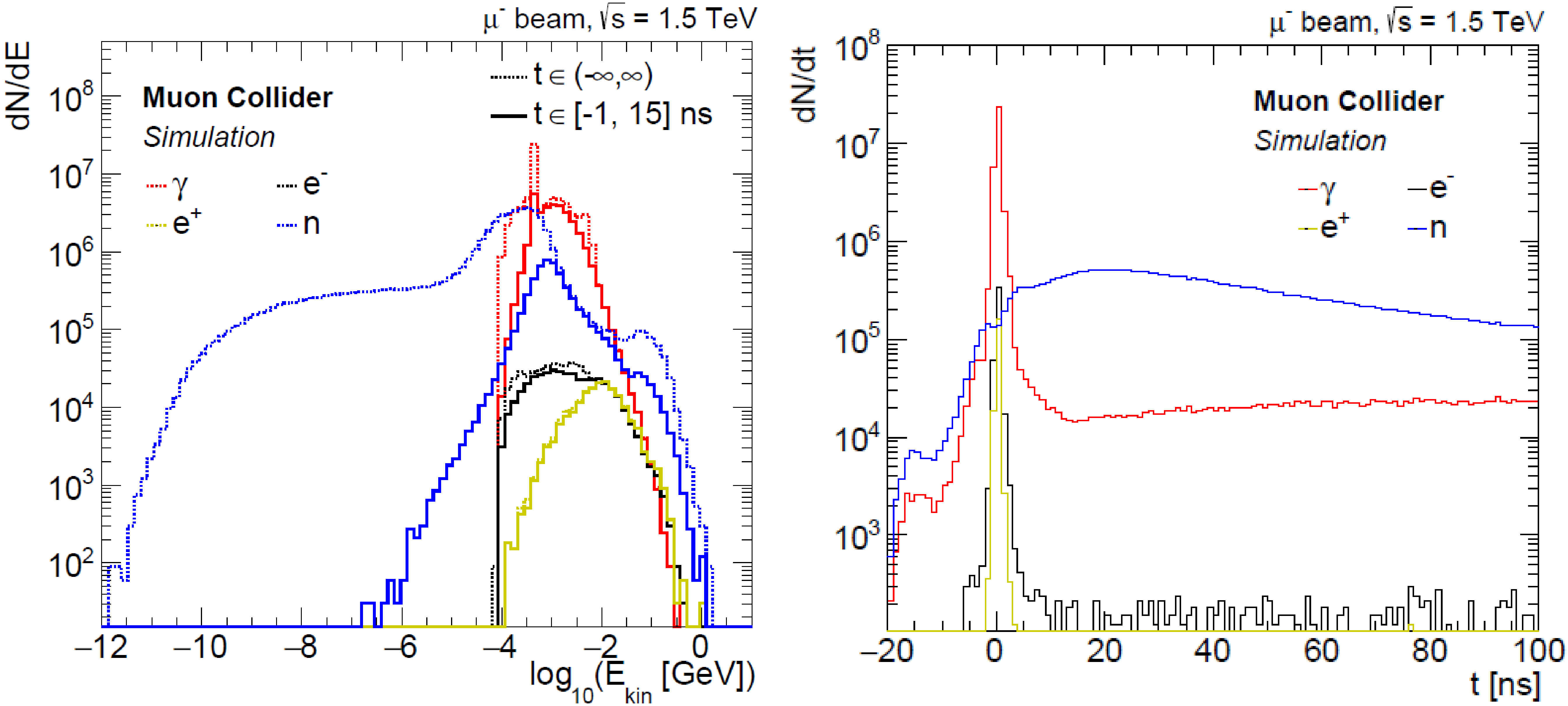
Muon Collider parameters

Parameter	Symbol	unit	Scenario 1	
			Stage 1	Stage 2
Centre-of-mass energy	E_{cm}	TeV	3	10
Target integrated luminosity	$\int \mathcal{L}_{\mathrm{target}}$	ab^{-1}	1	10
Estimated luminosity	$\mathcal{L}_{\mathrm{estimated}}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	2.1	21
Collider circumference	C_{coll}	km	4.5	10
Collider arc peak field	B_{arc}	T	11	16
Luminosity lifetime	N_{turn}	turns	1039	1558
Muons/bunch	N	10^{12}	2.2	1.8
Repetition rate	f_{r}	Hz	5	5
Beam power	P_{coll}	MW	5.3	14.4
RMS longitudinal emittance	$\varepsilon_{\parallel}$	eVs	0.025	0.025
Norm. RMS transverse emittance	$\varepsilon_{\perp}$	µm	25	25
IP bunch length	σ_z	mm	5	1.5
IP betafunction	β	mm	5	1.5
IP beam size	σ	µm	3	0.9
Protons on target/bunch	N_{p}	10^{14}	5	5
Protons energy on target	E_{p}	GeV	5	5

Tracking system

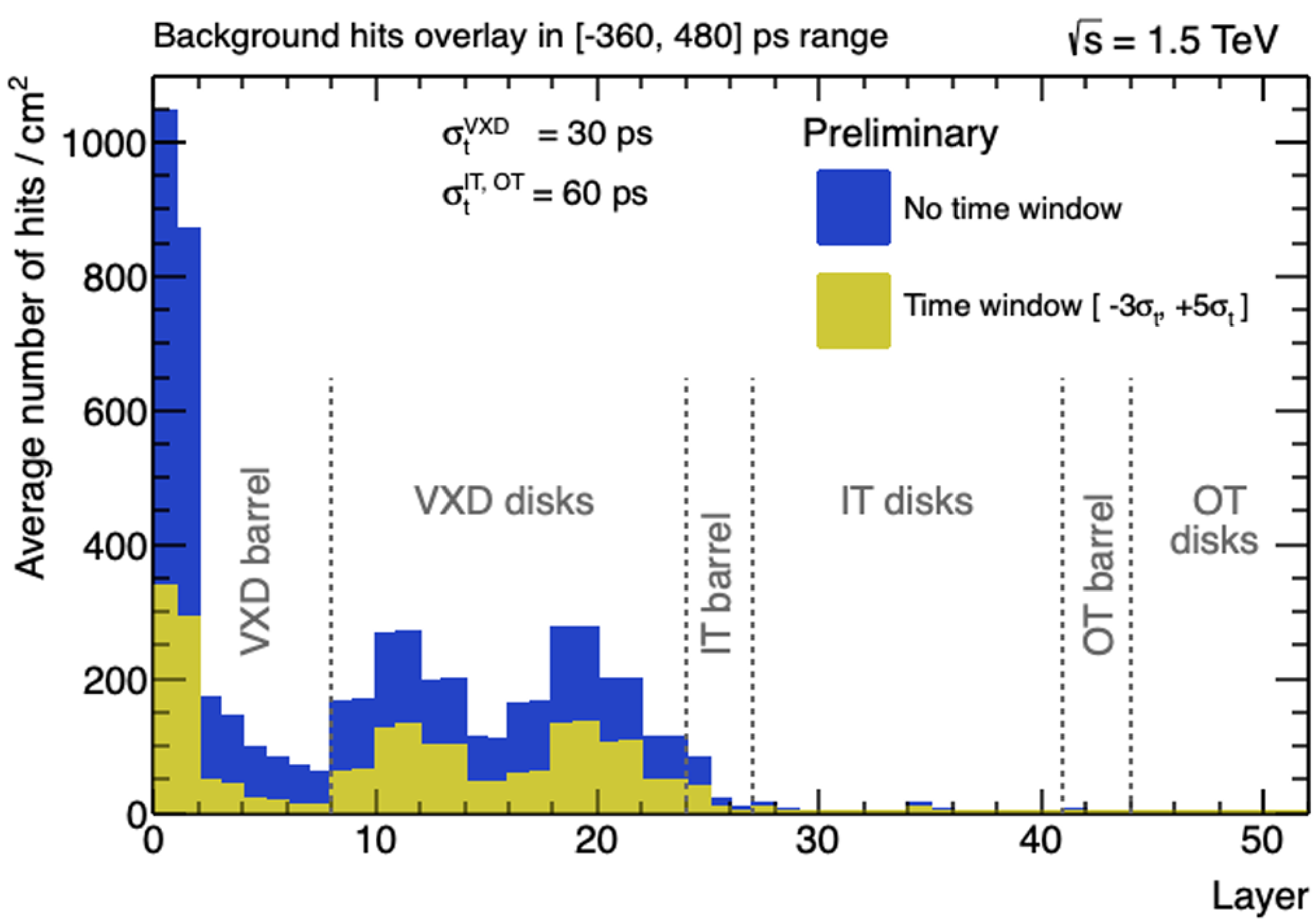


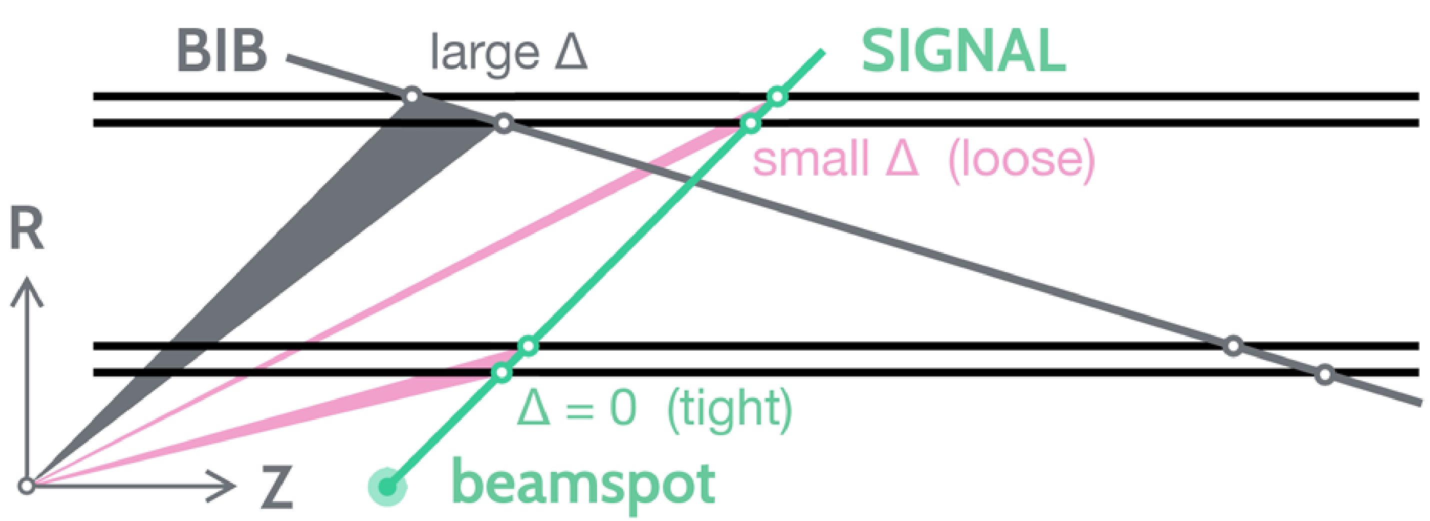
Beam-Induced Background



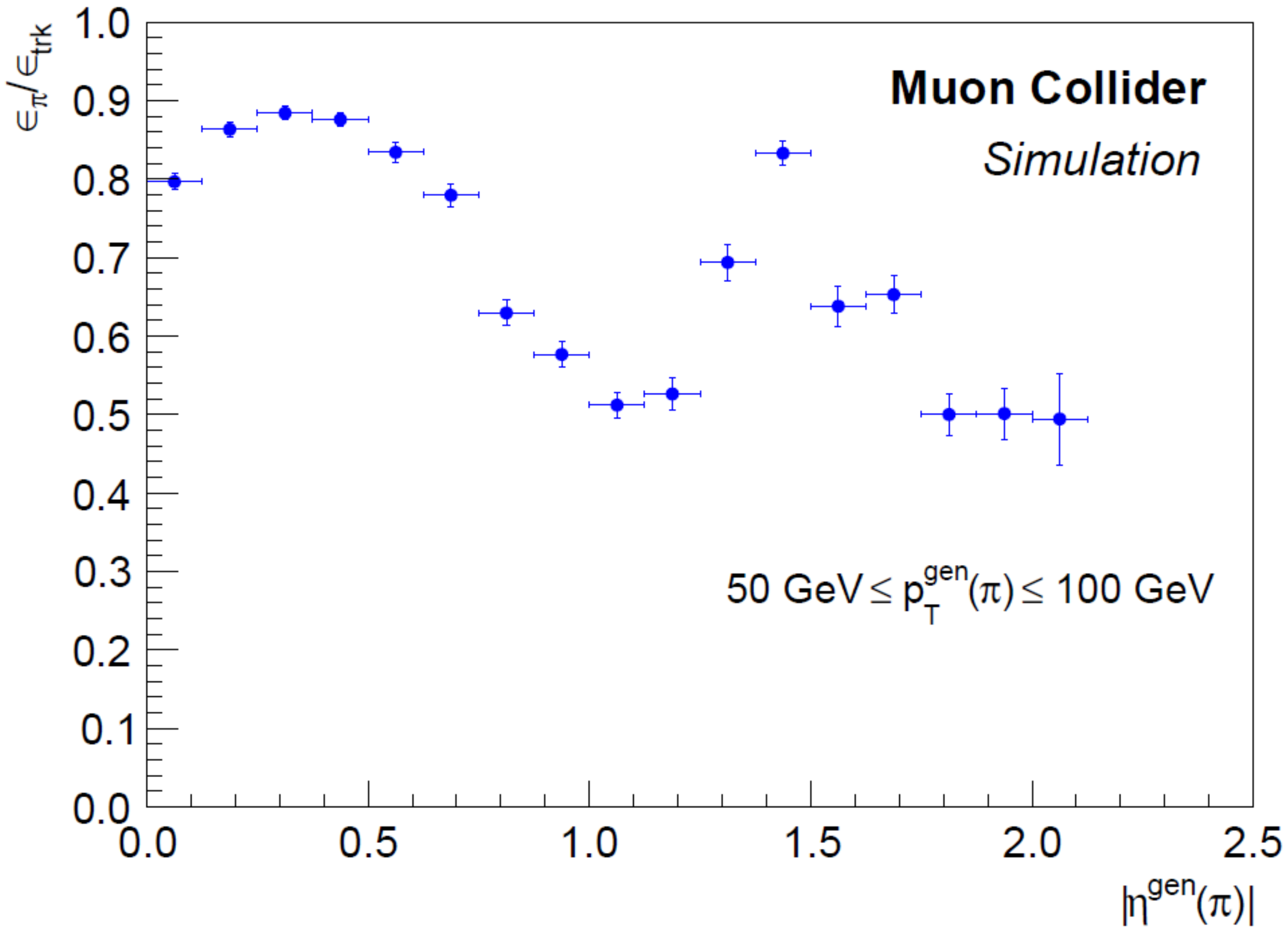
[Eur. Phys. J. C 83, 864 (2023)]

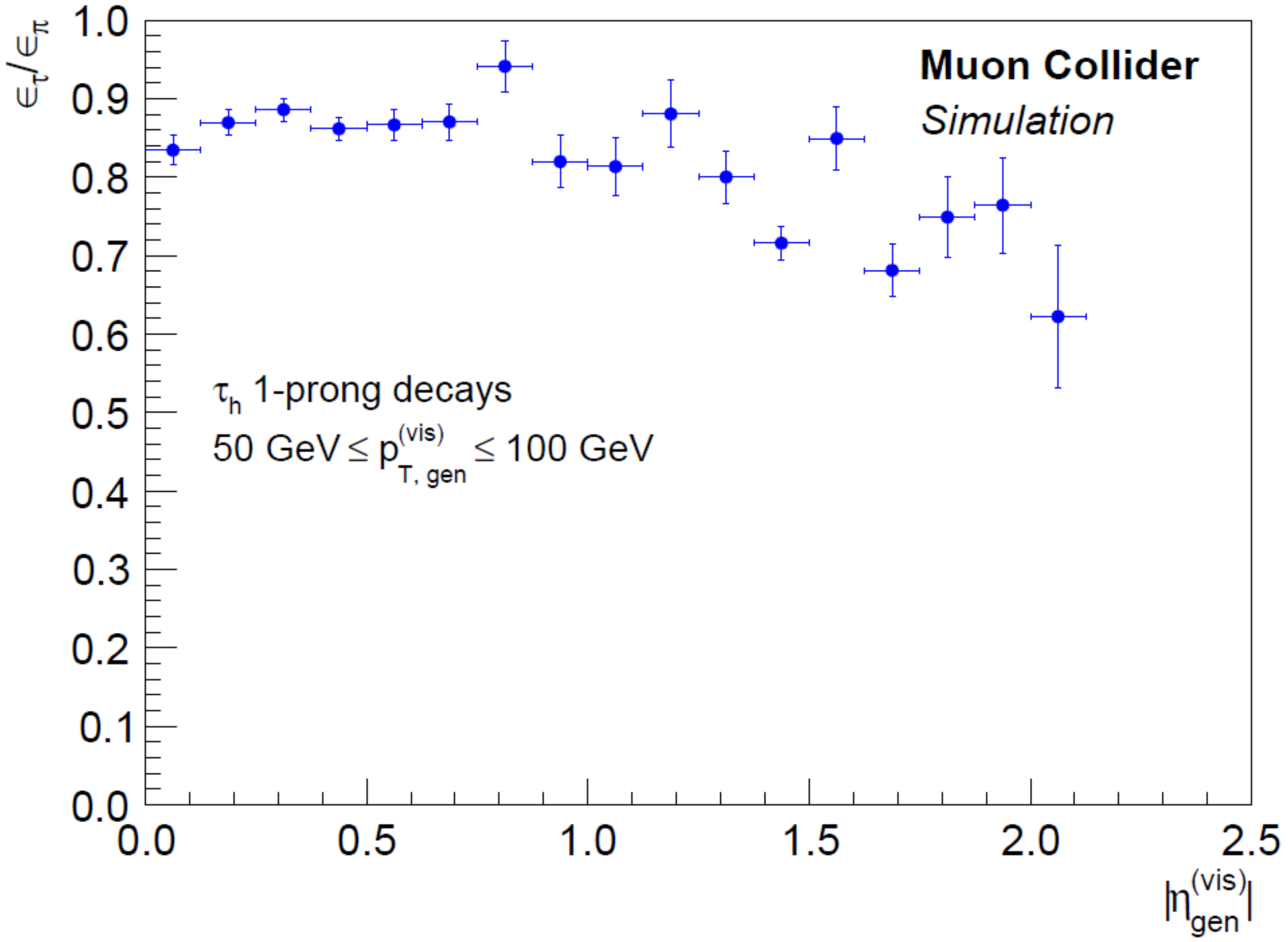
BIB in the tracker



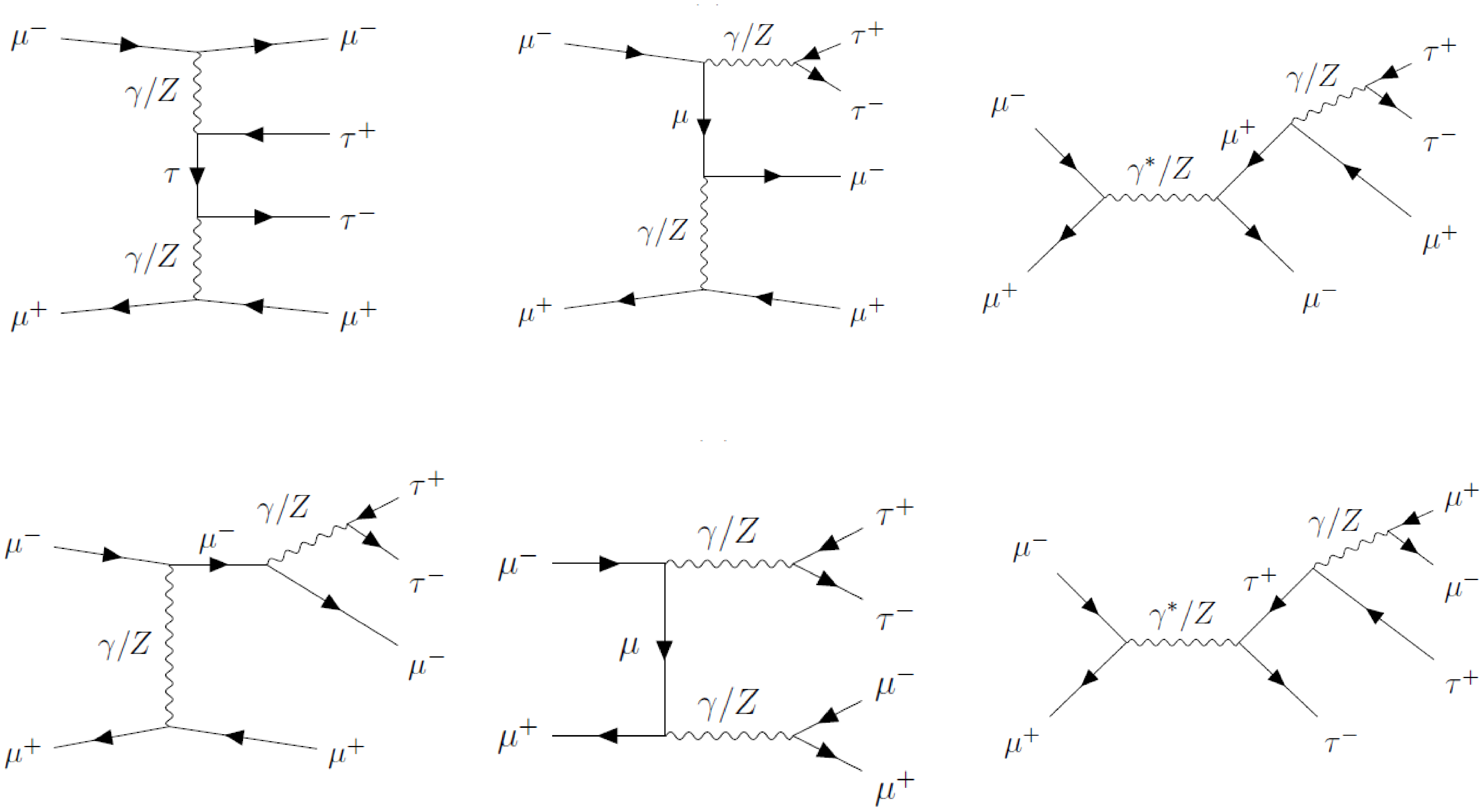


Efficiencies ratios

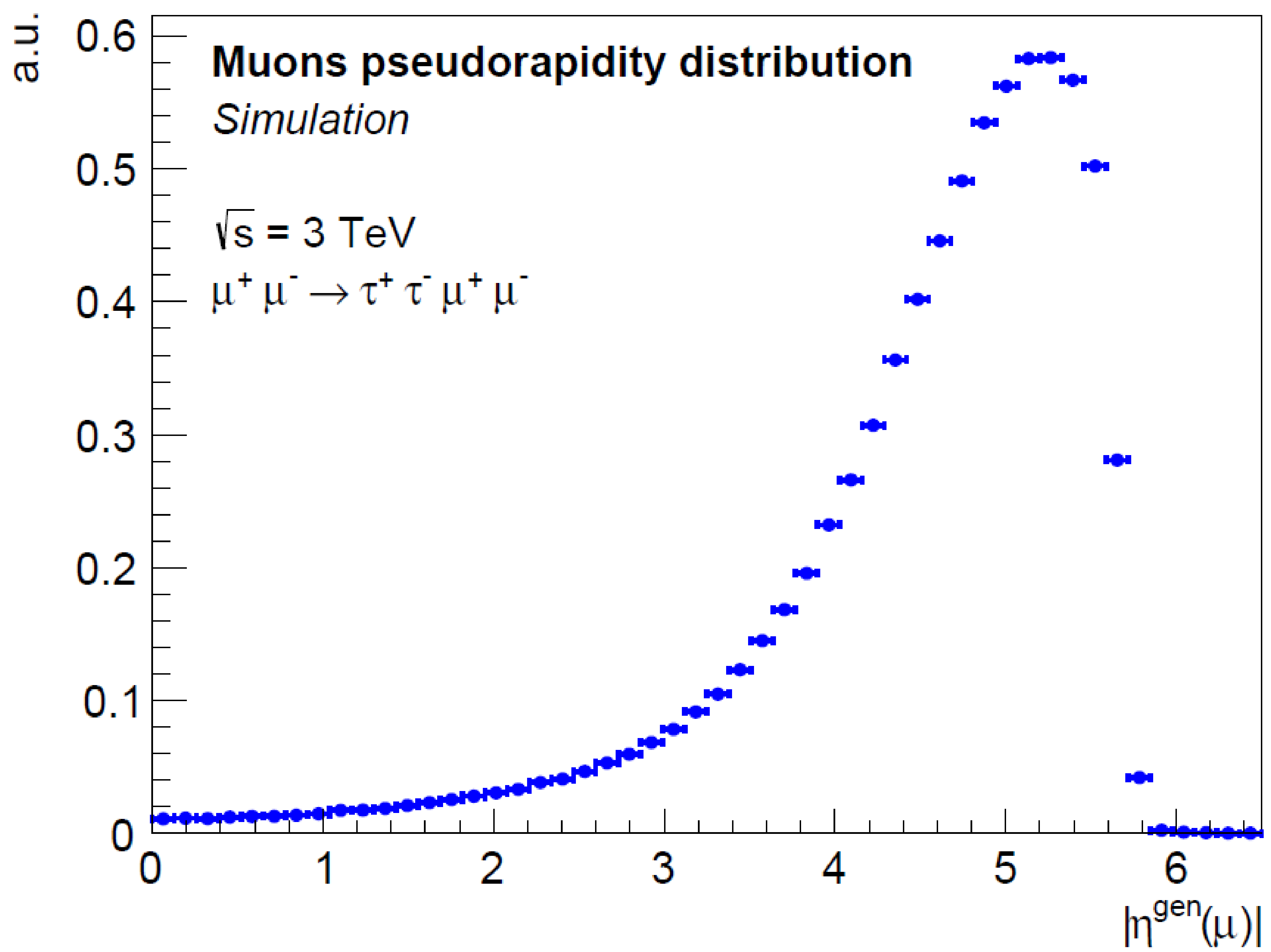




$\mu\mu \rightarrow \tau\tau\mu\mu$ processes



$\mu\mu \rightarrow \tau\tau\mu\mu$ pseudorapidity



τ transverse momentum