Tau Reconstruction in CMS

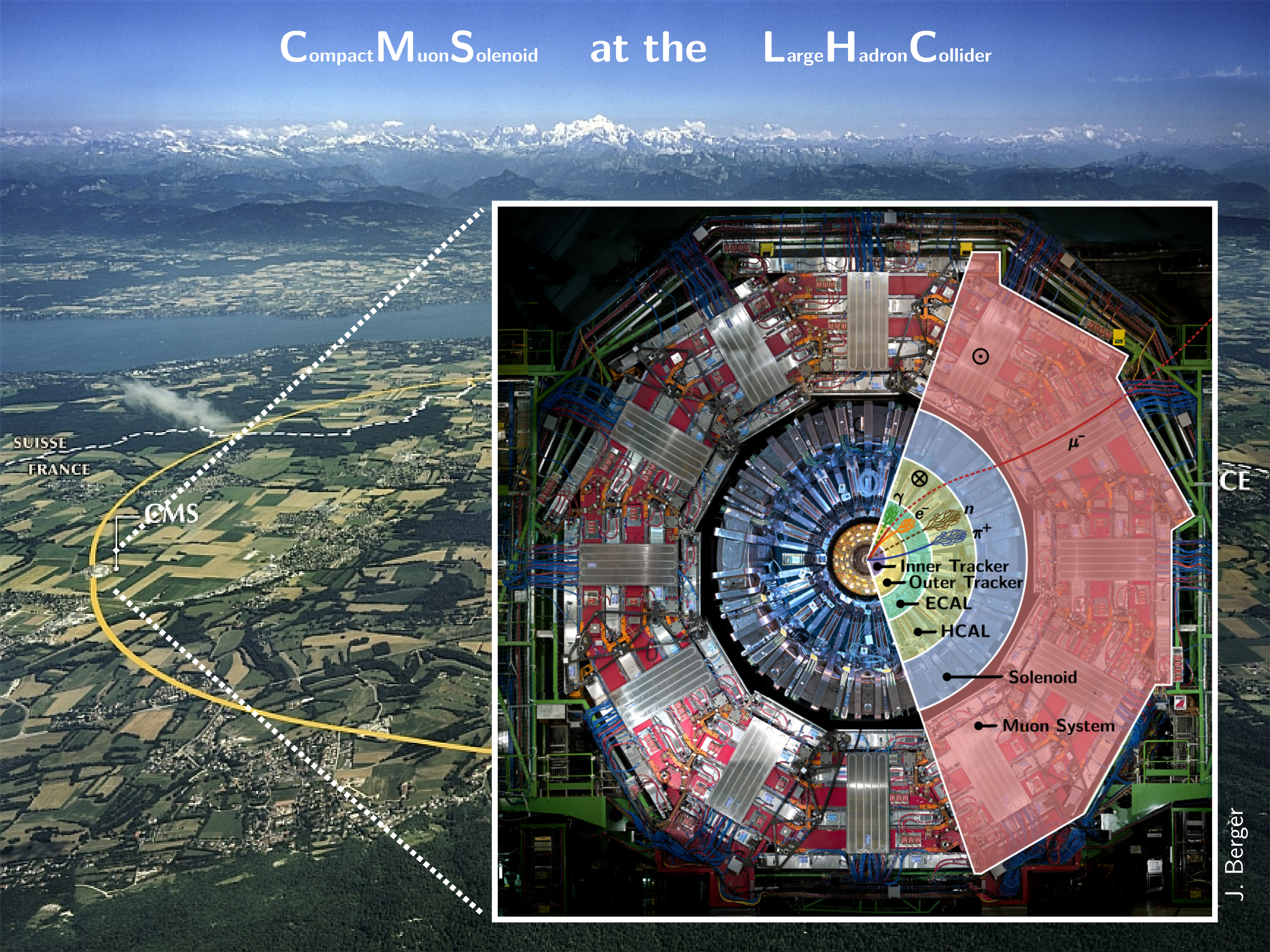
2018 CEPC Workshop, Beijing

Thomas Müller on behalf of the CMS Collaboration

III. Physikalisches Institut B

RWTH AACHEN UNIVERSITY

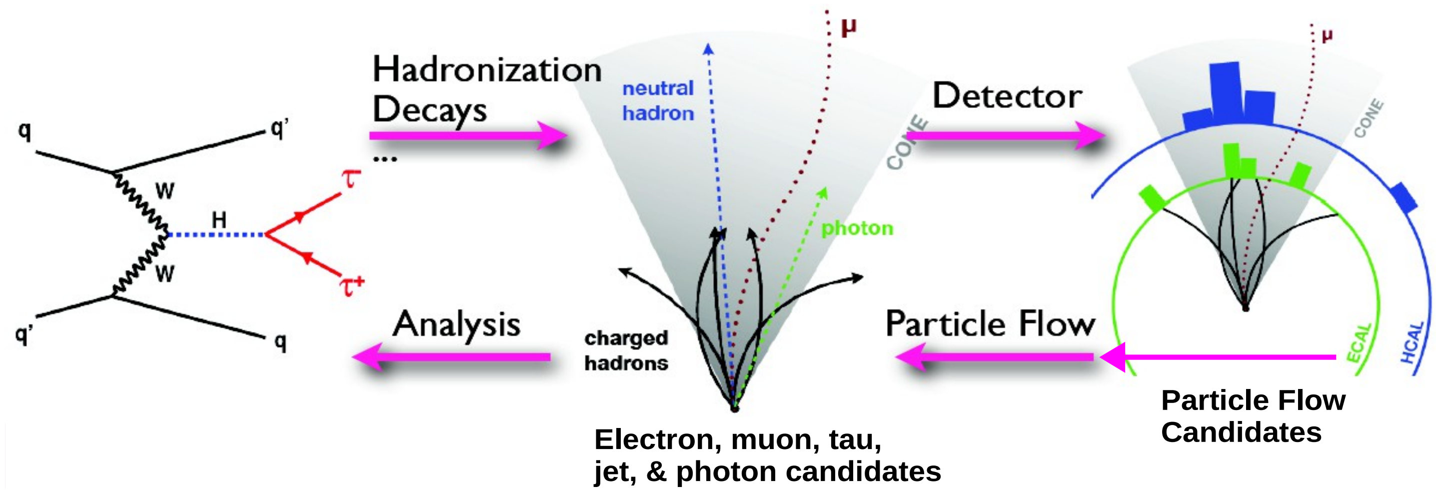
the Large Hadron Collider


Compact Muon Solenoid at the Large Hadron Collider
SUISSE
FRANCE
CMS
⊙
⊗
μ⁻
γ
e⁻
n
π⁺
Inner Tracker
Outer Tracker
ECAL
HCAL
Solenoid
Muon System
J. Berger

Particle Flow

CMS PRF-14/001

- Reconstruct physics objects from combined subdetector information
  - highly-segmented tracker
  - fine-grained ECAL
  - hermetic HCAL
  - strong magnetic field
  - excellent muon spectrometer

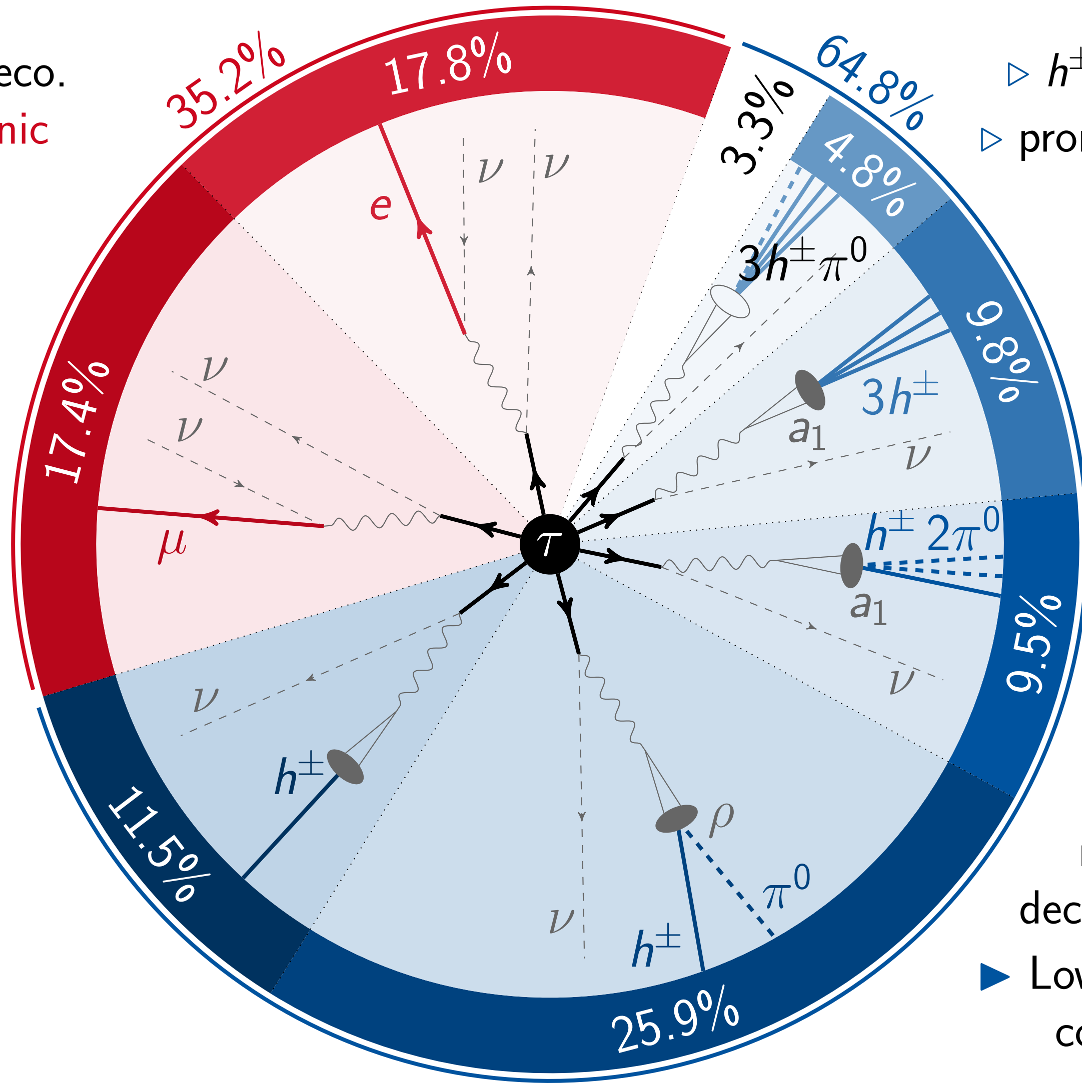


arXiv:1702.04685

- Reconstruct and identify 5 classes of particles:
  - electrons
  - photons
  - charged/neutral hadrons
  - muons
- Reconstruct and identify hadronic tau decays based on detailed information of jet constituents

Tau Decays in CMS

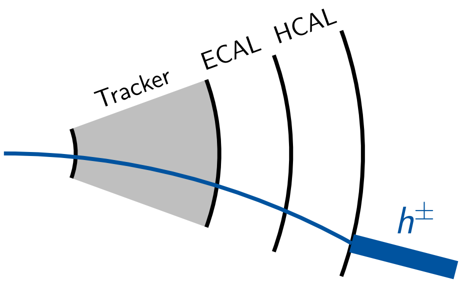
- Default e/μ reco. used for leptonic τ decays

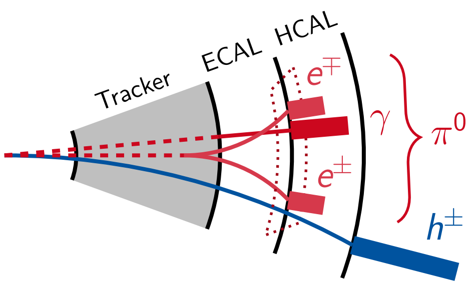


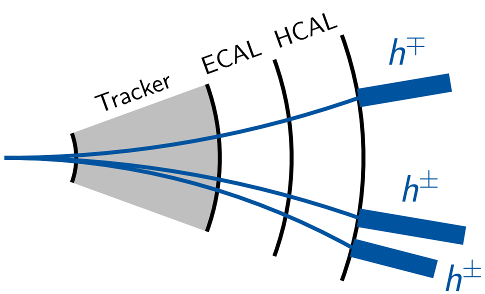
- ▷ $h^\pm$: charged pion/kaon
- ▷ prompt decays $\pi^0 \to \gamma\gamma$

- 5 main decay modes for hadronic τ decays are reconstructed
- Low particle multiplicity compared to QCD jets

Hadron Plus Strips Algorithm





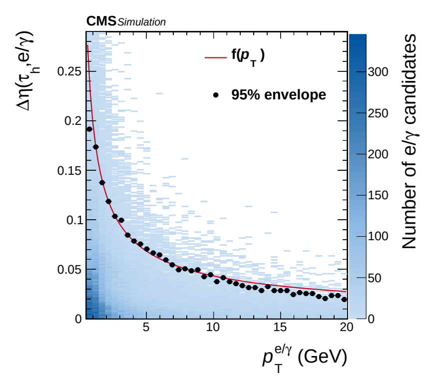


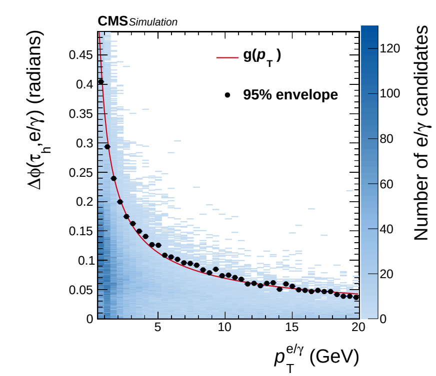
1. **Seeds**: particle-flow constituents ($e^\pm$, γ, $h^\pm$, h^0, $\mu^\pm$) of reconstructed anti-k_T jets with $R = 0.4$
   - Good tracks: $p_\mathrm{T} > 0.5\,\mathrm{GeV}$
   - Compatibility of tracks with a primary vertex (relaxed in x-y)

2. Identify all **possible combinations** for τ_h decay modes:
   - $\tau^\pm \rightarrow [1,3]h^\pm + [0-2]\pi^0 + \nu_\tau$

     $\pi^0 \rightarrow \gamma\gamma$

     $\gamma + \text{material} \rightarrow e^+e^-$
   - Signature of π^0 decays: activity in $\Delta\eta \times \Delta\varphi$ region (**strip**)

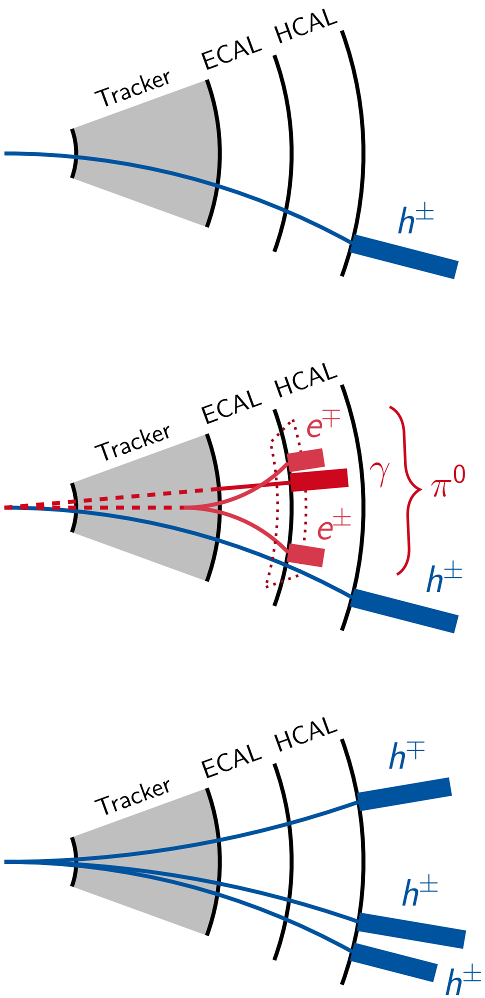




   - Signal cone size: $0.1 \geqslant R_\mathrm{sig} = \frac{3\,\mathrm{GeV}}{p_\mathrm{T}} \geqslant 0.05$

Hadron Plus Strips Algorithm

CMS TAU-16/003



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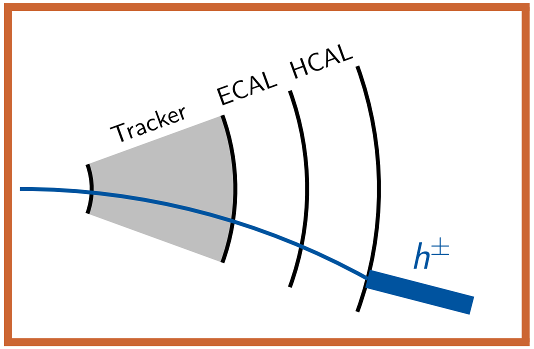
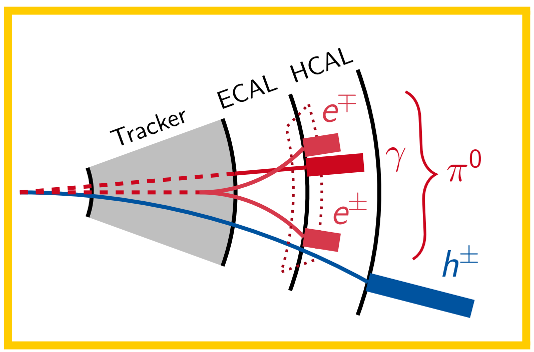
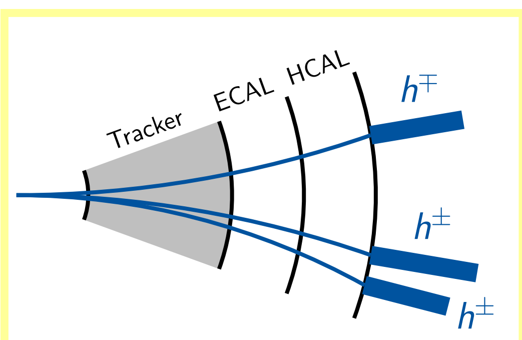
3. **Quality criteria**:
   - Charge of τ_h candidate is ± 1
   - Compatibility of τ_h mass with intermediate resonances: $\rho(770)$ and $a_1(1260)$

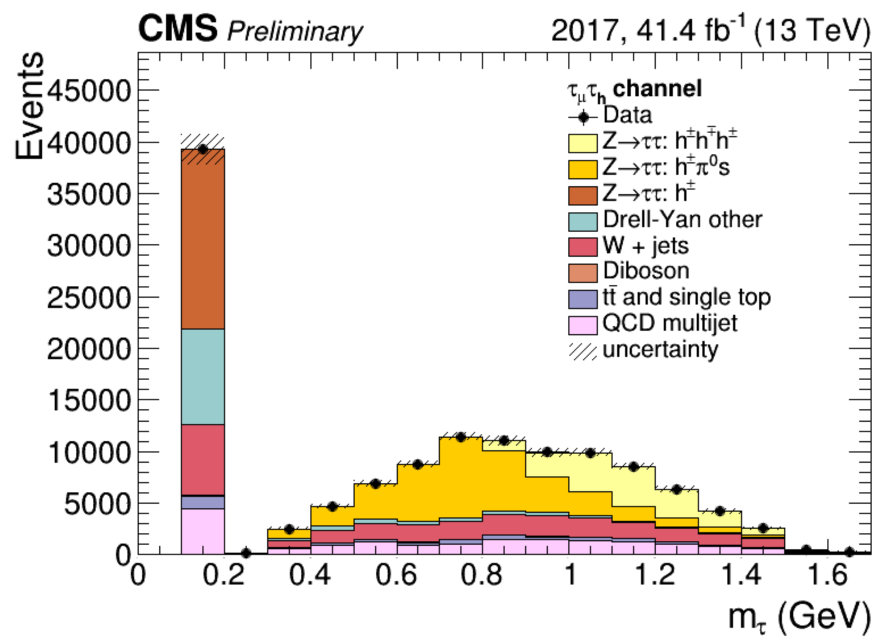
4. **Retain** τ_h candidate with **highest** $\boldsymbol{p_{\mathrm{T}}}$







- **Result**: reconstructed τ_h candidates with well defined decay modes

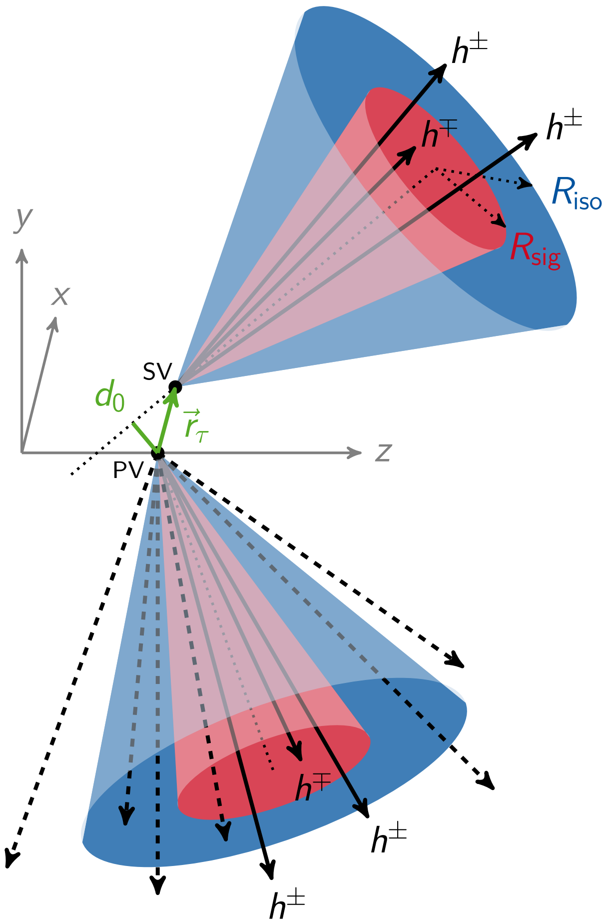


CMS DP-2018/026

- Next slides: identification of good τ_h candidates and corrections to simulation

Discrimination of τ_h Candidates against Jets

- τ leptons are produced and decay via **weak interaction**



- No color charge involved
  - ➜ Decays isolated from hadronic activity
- Long lifetime $\tau_\tau(50\,\text{GeV}) \approx 2.5\,\text{mm}$
  - ➜ Displaced tracks and decay vertices
- Small mass $m_\tau = 1.778\,\text{GeV}$
  - ➜ Low particle multiplicity

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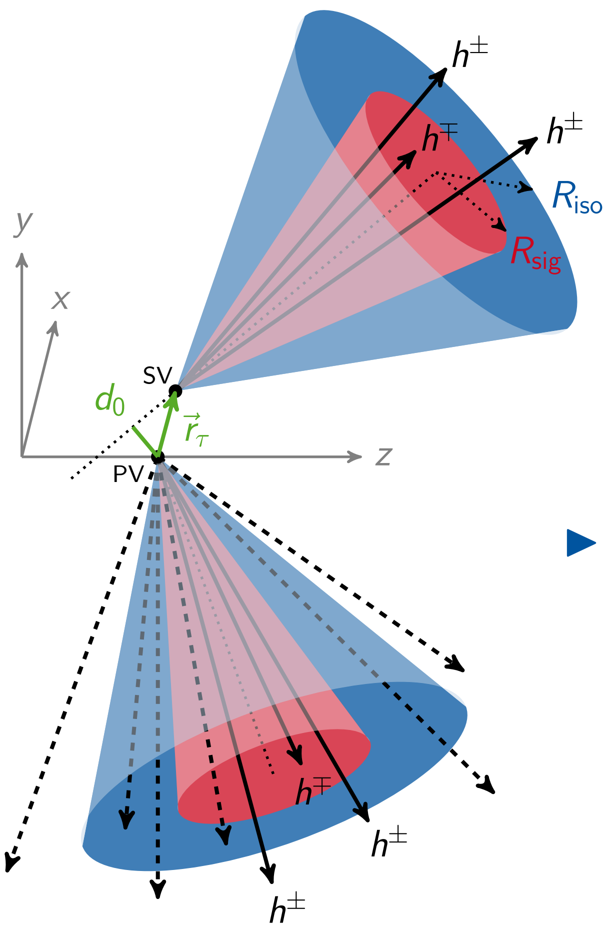

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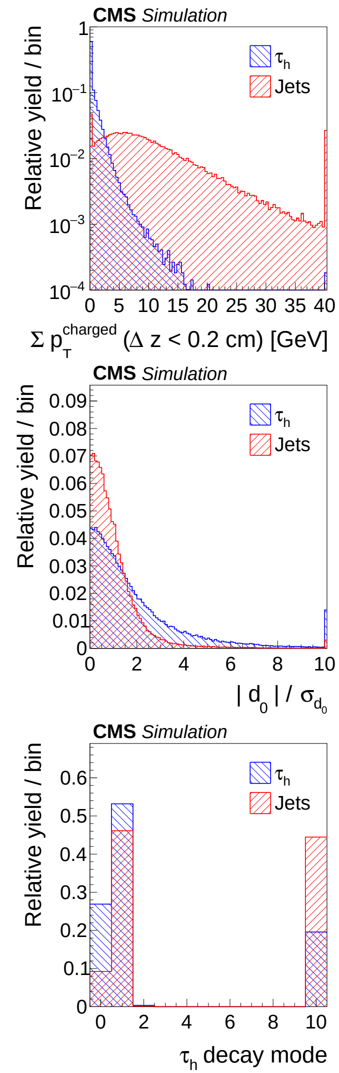
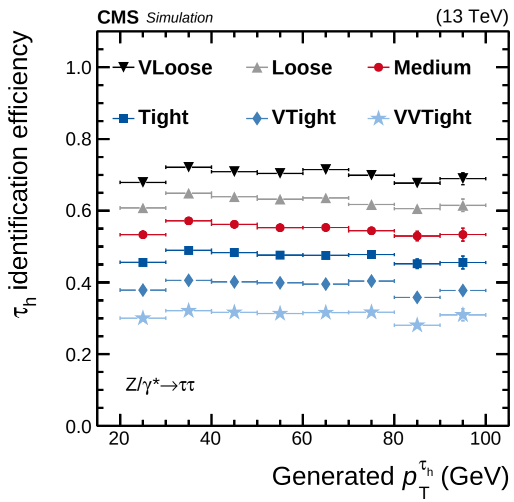
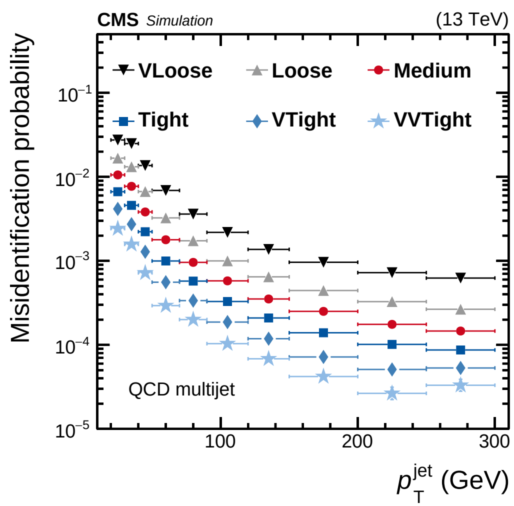
- MVA discrimination (BDT) based on
  - Charged/neutral isolation sums
  - Lifetime information (impact parameter, flight length)
  - Reconstructed τ_h decay mode
  - Particle multiplicities
  - Differential strip information



CMS TAU-14/001

Identification Performance in MC





- 6 MVA (+ 3 cut-based) working points provided
  - BDT thresholds adjusted as a function of p_T
  - Constant efficiencies from 30 to 70%
- Performance estimation in MC (w.r.t. relevant phase space)
  - Identification efficiency from $Z \to \tau\tau$ MC

$$\epsilon = \frac{\text{generated } \tau_h \,\&\, \text{reconstructed and good } \tau_h}{\text{generated } \tau_h}$$

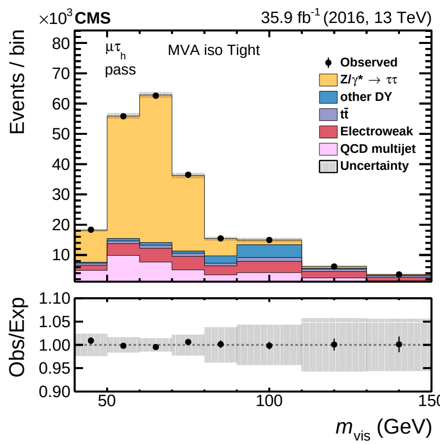
  - Misidentification probability from QCD multijet MC

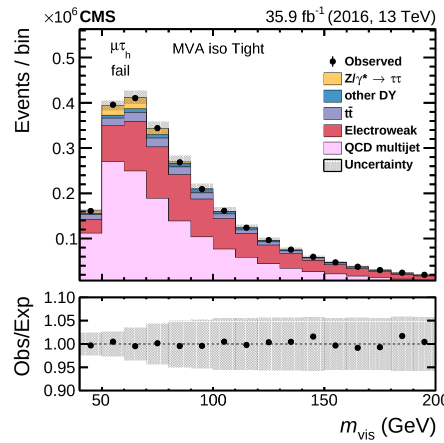
$$p = \frac{\text{generated } q/g \text{ jet} \,\&\, \text{reconstructed and good } \tau_h}{\text{generated } q/g \text{ jet}}$$

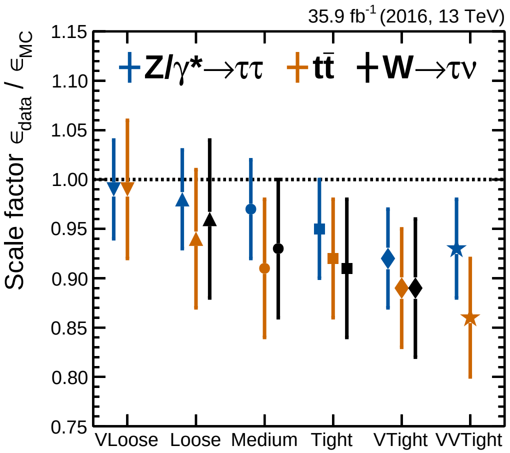
Identification Performance – Comparison of Data and MC

CMS TAU-16/003

- Measure efficiency in data with **Tag & Probe** method
  - Use $Z/\gamma* \to \tau\tau \to \mu\tau_h + 3\nu$ events
  - Tag events with good muon
  - Probe τ_h candidate matched to generator level τ
  - Probe τ_h candidate passes WP
  - Probe τ_h candidate fails WP







values from CMS TAU-16/003

- Scale factor obtained from simulataneous max. likelihood fit of signal+background to data in both categories

Identification Performance – Comparison of Data and MC

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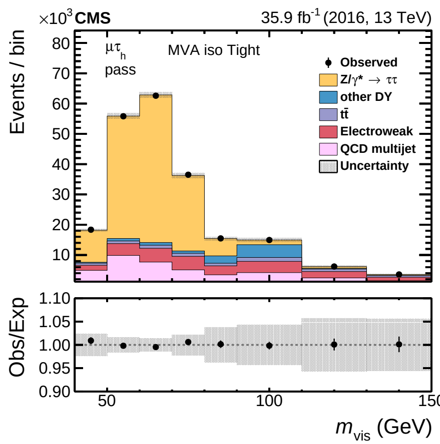

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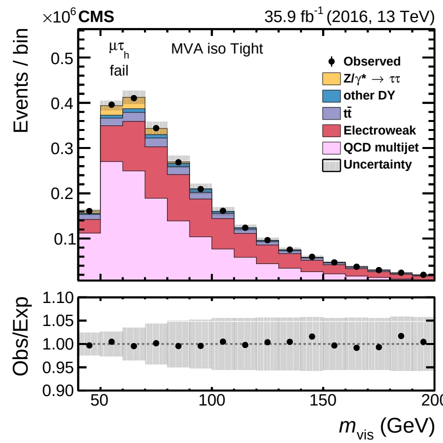

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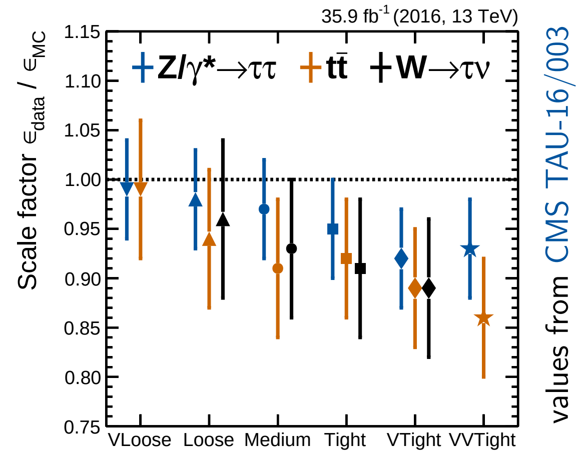
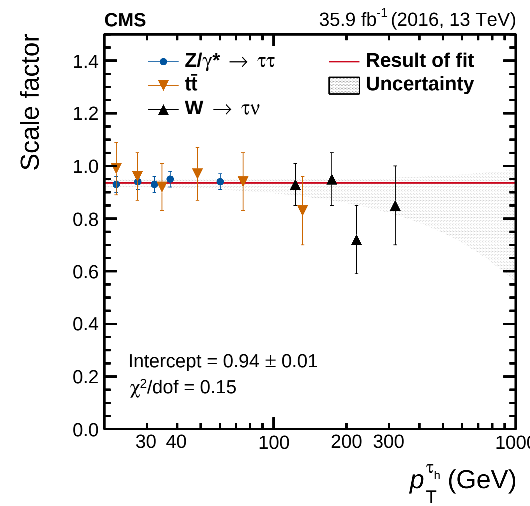


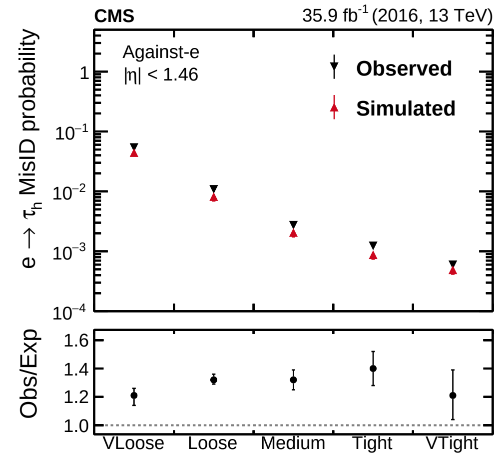
- **Similar measurements in $t\bar{t}$ and off-shell $W \to \tau\nu$ events**
  - Cover large range in p_T of τ_h candidate



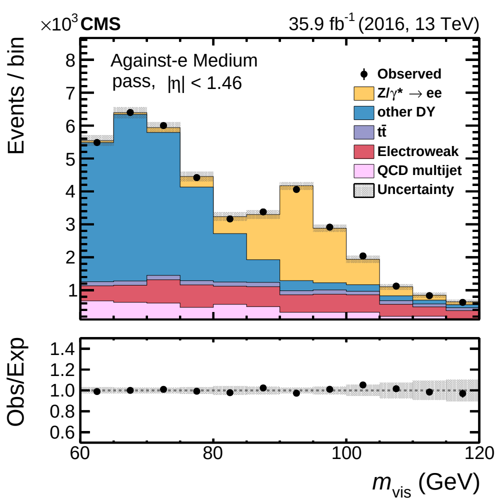
Discrimination of τ_h Candidates against Light Leptons

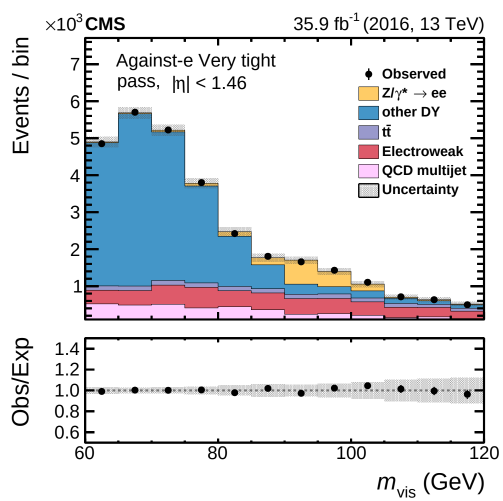
CMS TAU-16/003

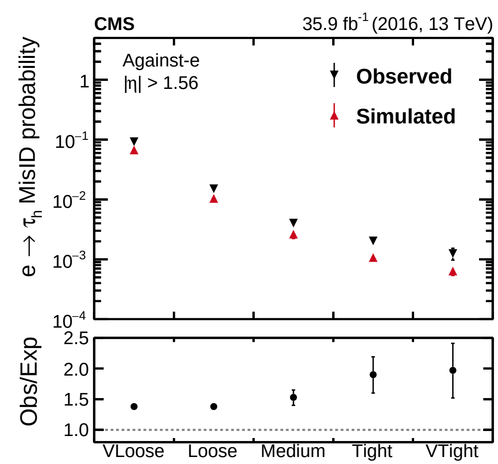
- Cut-based discriminator against **muons faking** τ_h
  - 2 working points
  - Misidentification probabilities smaller than 0.5%
- BDT discriminator against **electrons faking** τ_h
  - 5 working points
  - Efficiencies and scale factors measured via Tau & Probe



Barrel



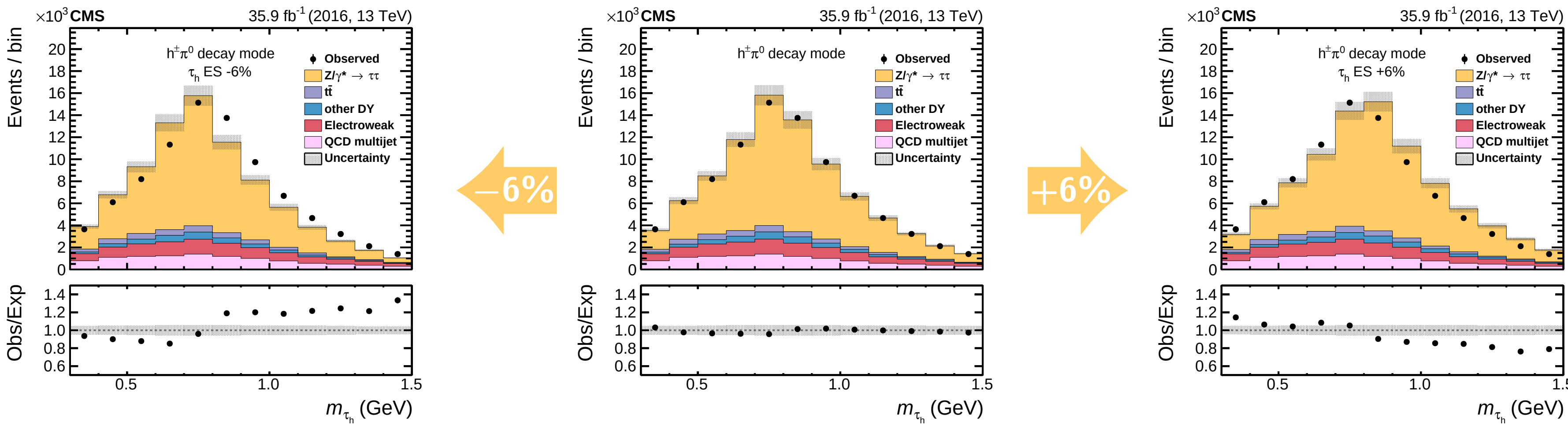


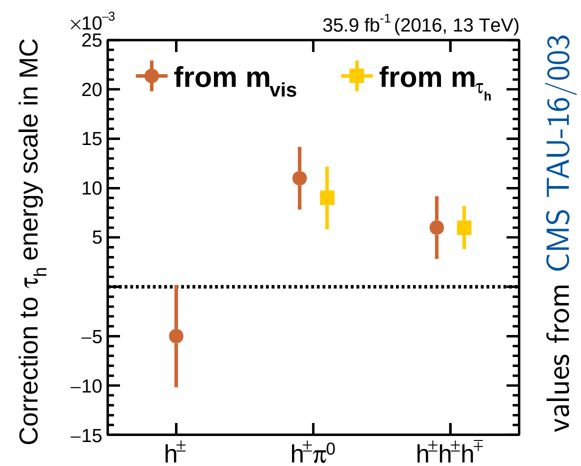


Endcap

Tau Energy Scale Corrections

CMS TAU-16/003

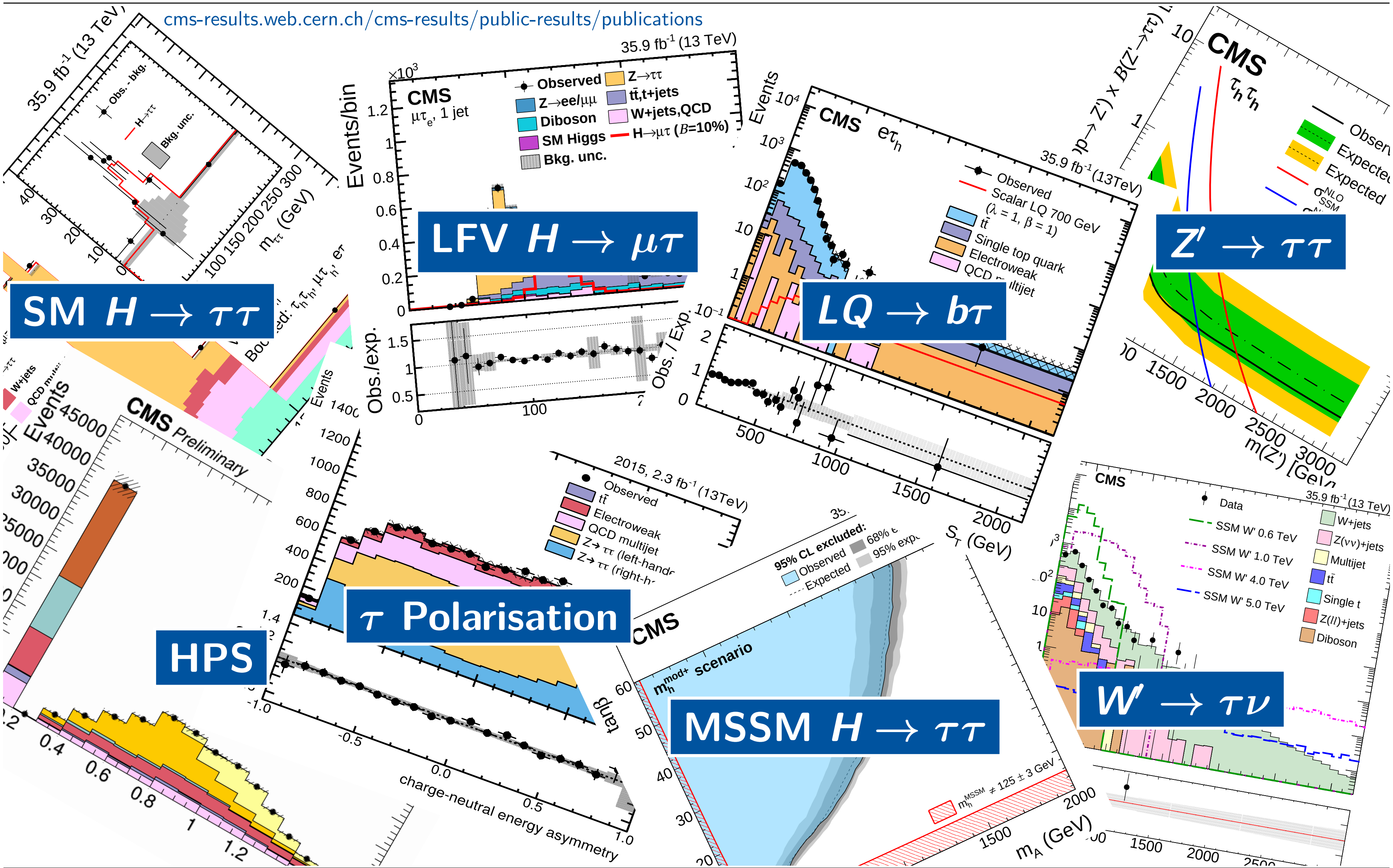




- τ_h energy scale = factor to scale four-momentum of τ_h
- Measure correction to MC from max. likelihood fit of mass templates to data
  - Visible $\mu + \tau_h$ mass for all τ_h decay modes separately
  - τ_h mass for $h^{\pm}\pi^0$ and $h^{\pm}h^{\pm}h^{\mp}$ decay modes
  - Corrections at 1% level observed

Application in Physics Analyses – Examples

cms-results.web.cern.ch/cms-results/public-results/publications



Conclusion

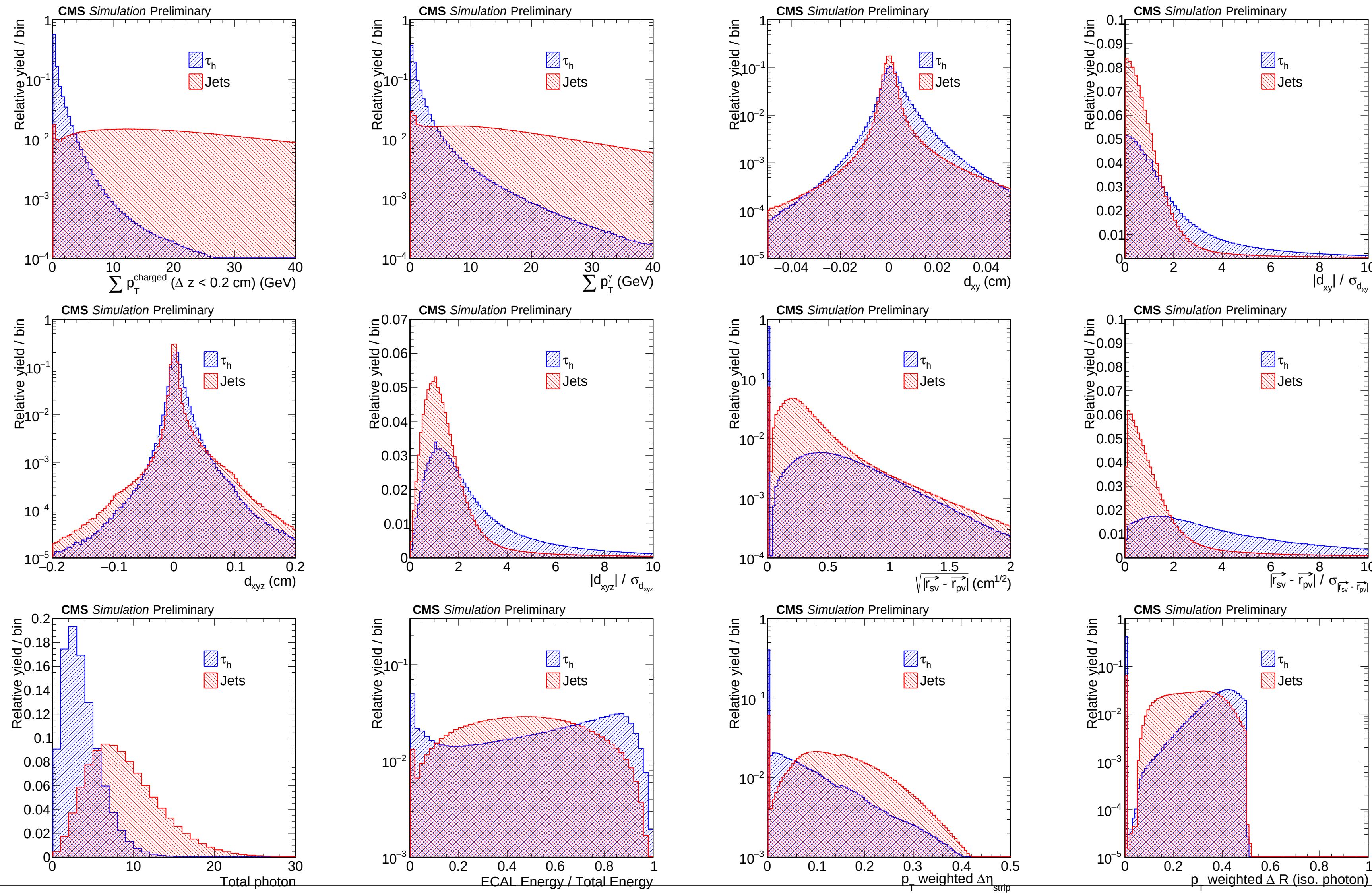
- ▷ Hadron+Strips τ_h reconstruction
- ▷ MVA discriminators for identification
- ▷ Measurement of scale factors and corrections from data

- Robust τ_h reconstruction and identification
- Good agreement between data and simulation
- Successfully used in numerous published analyses

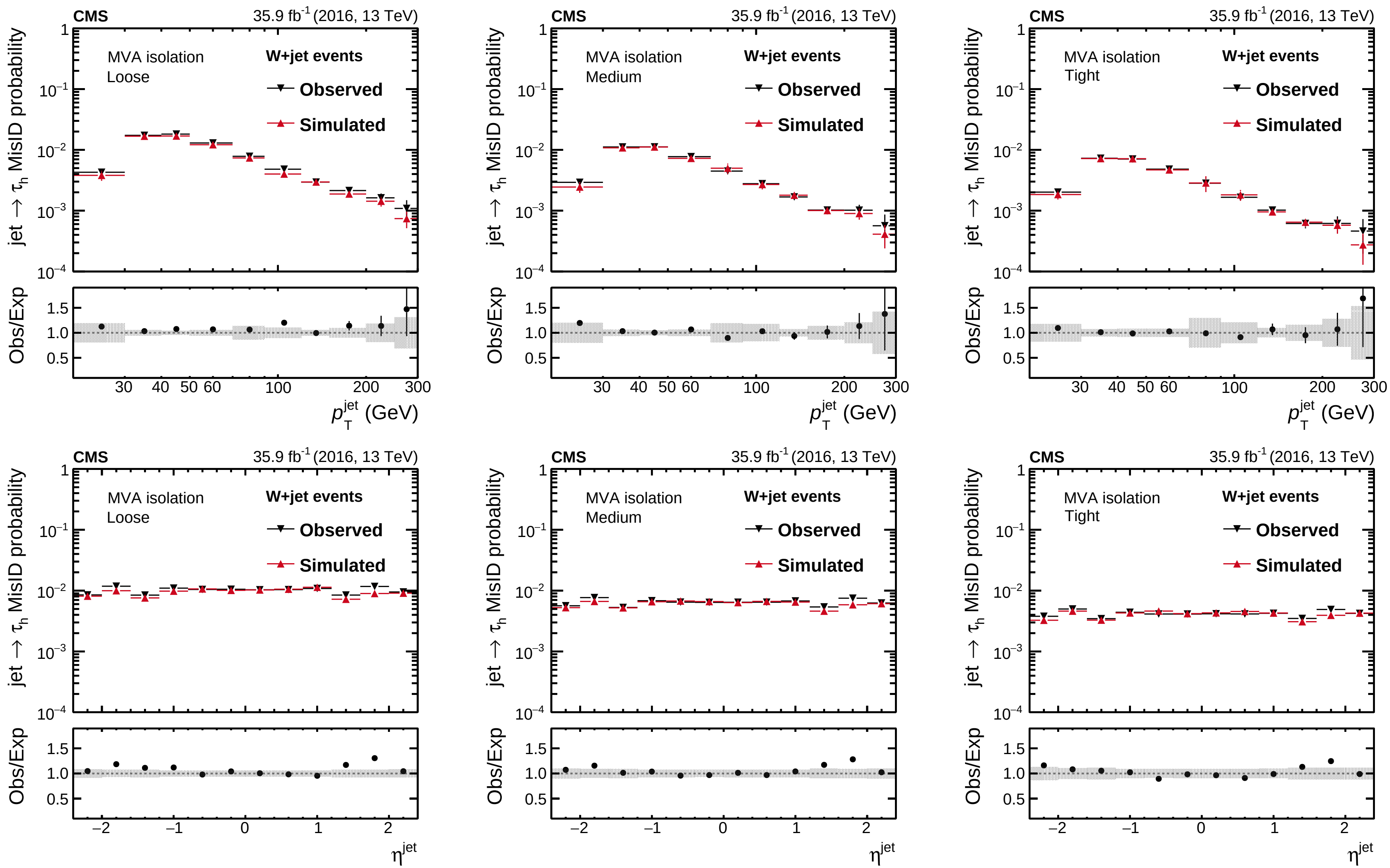
Additional Material

BDT Inputs for Discrimination against Jets

CMS PAS TAU-16/002

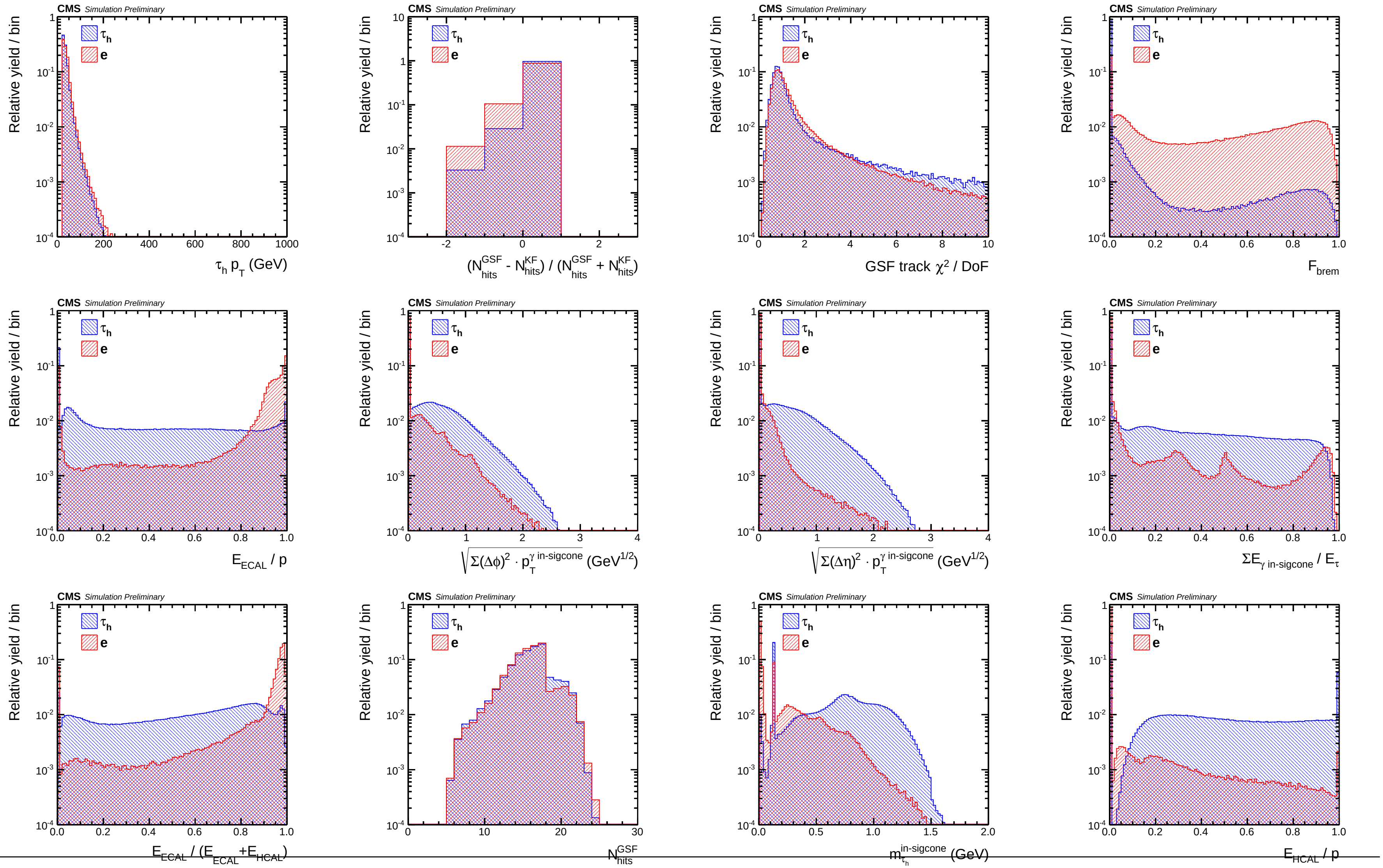


Jet $\rightarrow \tau_h$ Misidentification Probabilities in Data



BDT Inputs for Discrimination against Electrons

CMS PAS TAU-16/002



Discrimination of τ_h Candidates against Muons

CMS TAU-16/003

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  - 2 working points
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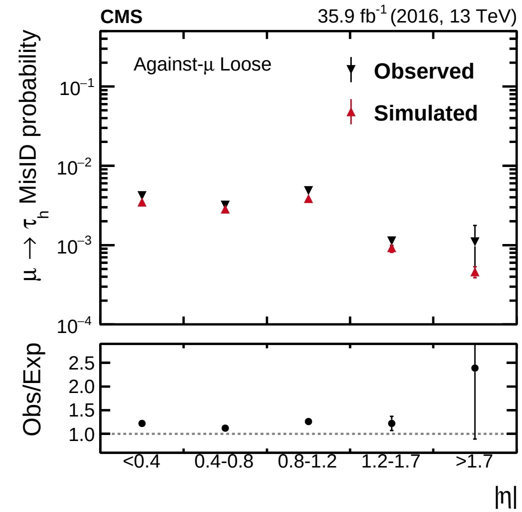
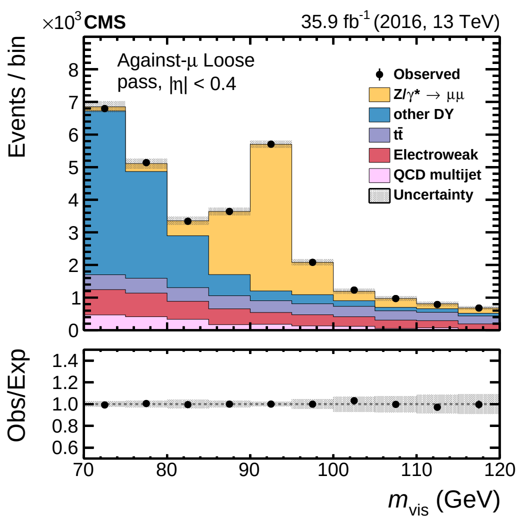
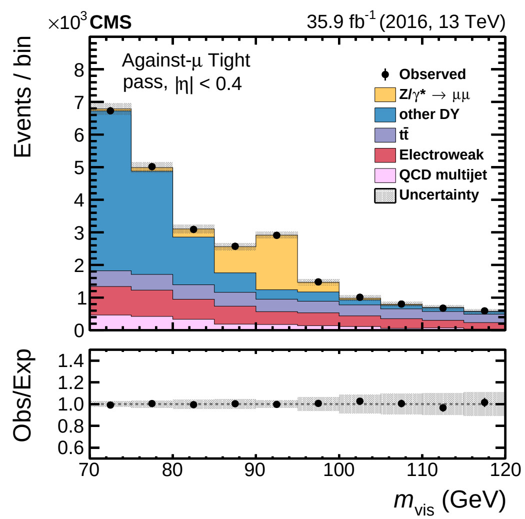
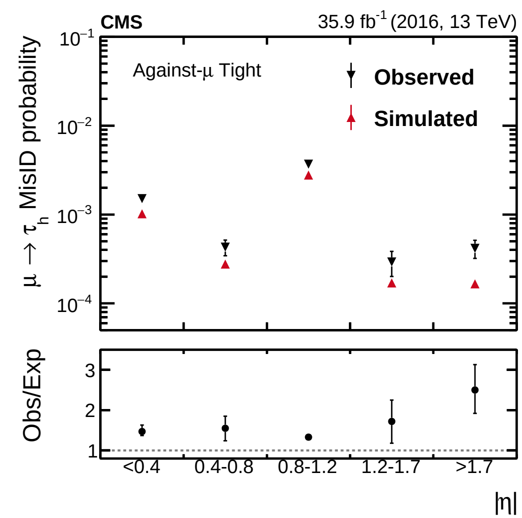
  - Efficiencies and scale factors measured via Tag & Probe



Loose WP







Tight WP

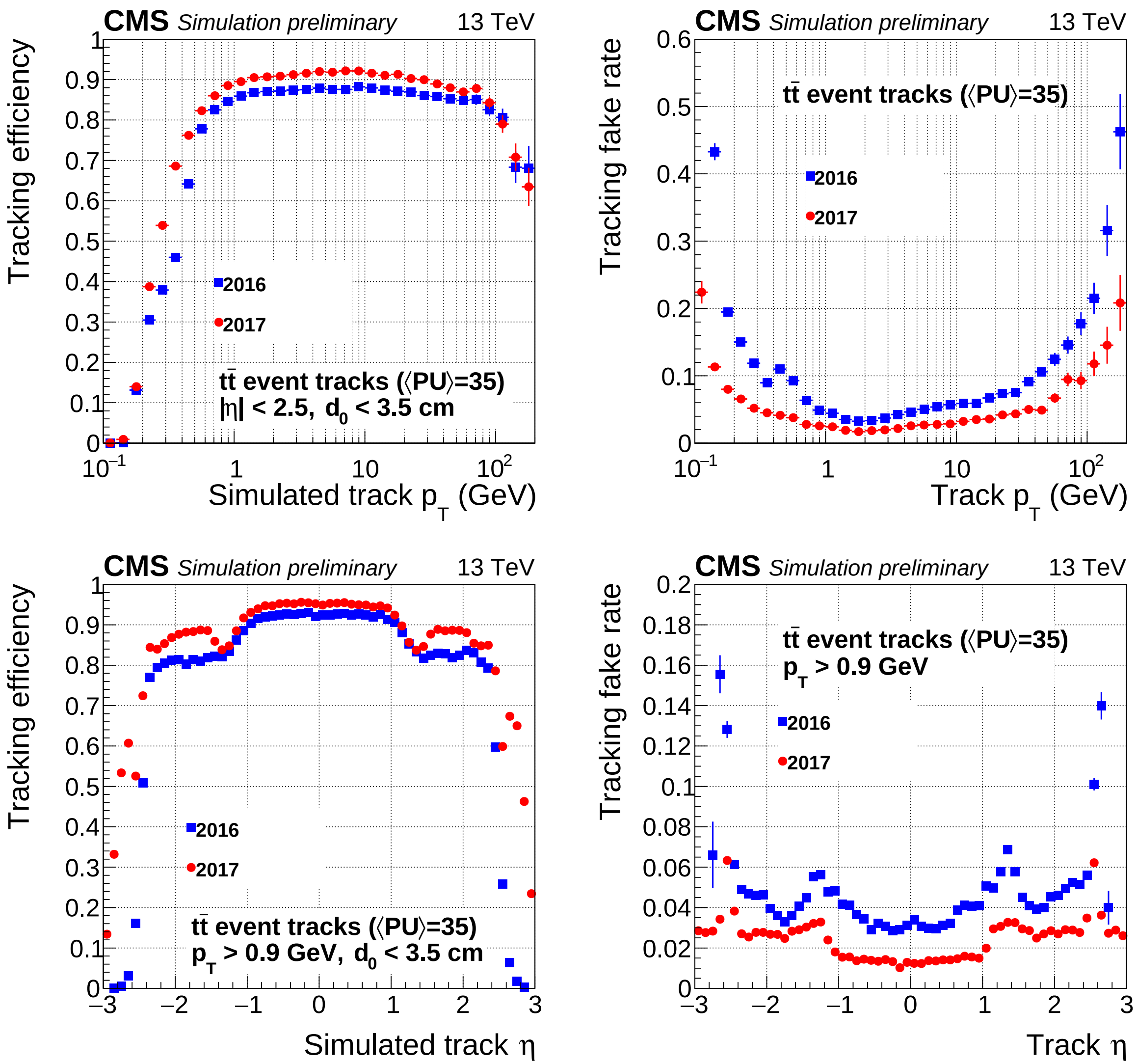
Some CMS Numbers

CMS PRF-14/001

- Solenoid
  - Superconducting coil, 3.8 T inside, 2 T outside
  - 12.5 m length, 3.15 m inner radius
- Tracker
  - Silicon strips and pixels, 1.20 m outer radius, 4-3 + 11-10 layers
- Electromagnetic calorimeter
  - Lead tungstate ($PbWO_4$) crystals, ~25 radiation lengths
  - Barrel: $2.2 \times 2.2\,\mathrm{cm}^2$ (2.2 cm Molière radius), equivalent to $\Delta\eta \times \Delta\varphi = 0.0174 \times 0.0174$
  - Endcap: $2.9 \times 2.9\,\mathrm{cm}^2$
  - Energy resolution: $\frac{\sigma_E}{E} = \frac{2.8\,\%}{\sqrt{E/\mathrm{GeV}}} \oplus \frac{12\,\%}{E/\mathrm{GeV}} \oplus 0.3\,\%$
- Hadronic calorimeter
  - Brass absorber + plastic scintillator tiles, ~6-10 radiation lengths
  - $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$ to 0.17×0.17
  - Energy resolution: $\frac{\sigma_E}{E} = \frac{110\,\%}{\sqrt{E/\mathrm{GeV}}} \oplus 9\,\%$
- Muon system
  - DTs (barrel), CSCs (endcal), RPCs (everywhere)
  - Tracker dominates momentum measurement up to $p_{\mathrm{T}} \approx 200\,\mathrm{GeV}$

Tracking Performance

TrackingPOGPerformance2017MC



Tracking Performance

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