Tau trigger and identification at CMS in Run-2

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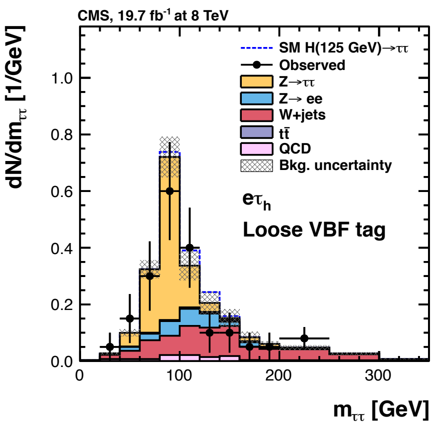
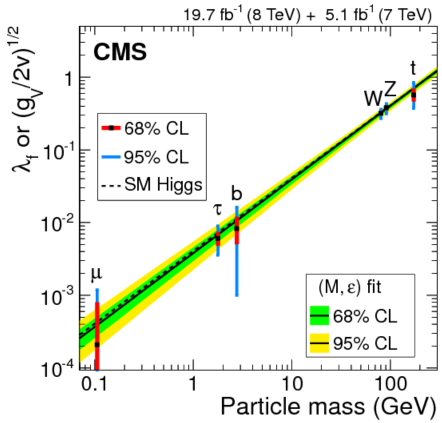
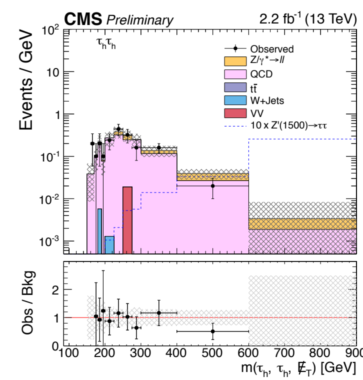
The 14th International Workshop on Tau Lepton Physics
IHEP – Beijing – China
21/09/16

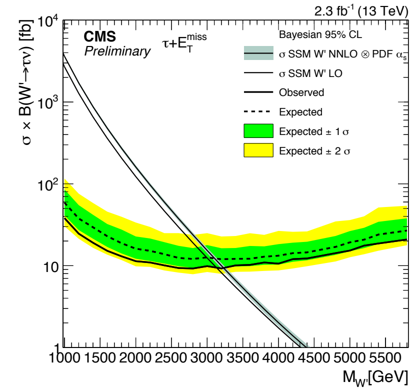
Taus @ CMS



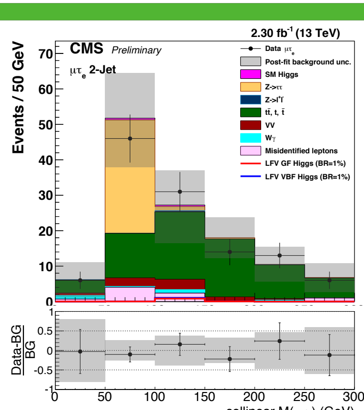


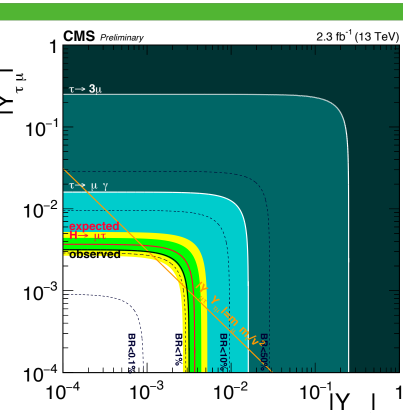
- **SM H→ττ (D. Zanzi, L. Dodd's talks)**
  - Only (current) access to H-lepton coupling
  - Provides best constraints on VBF



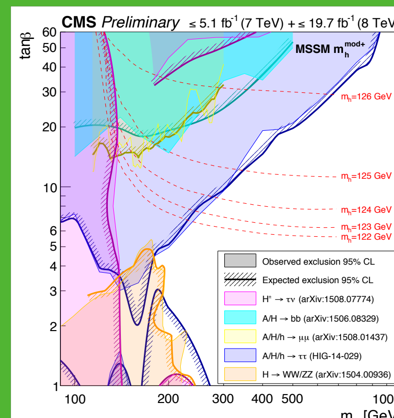


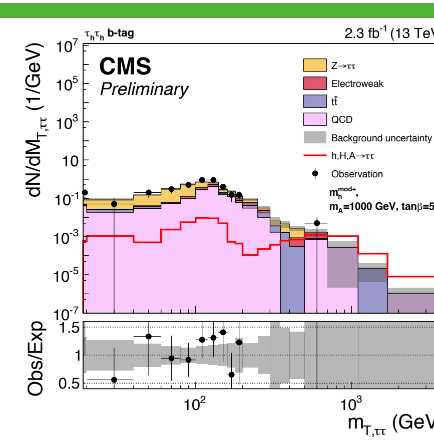
- **Exotic searches to τ's (Z. Mao's talk)**
  - Graviton, radion, Z', W'





- **LFV H→μτ (A. Nehrkorn's, K. De Bruyn's talks)**

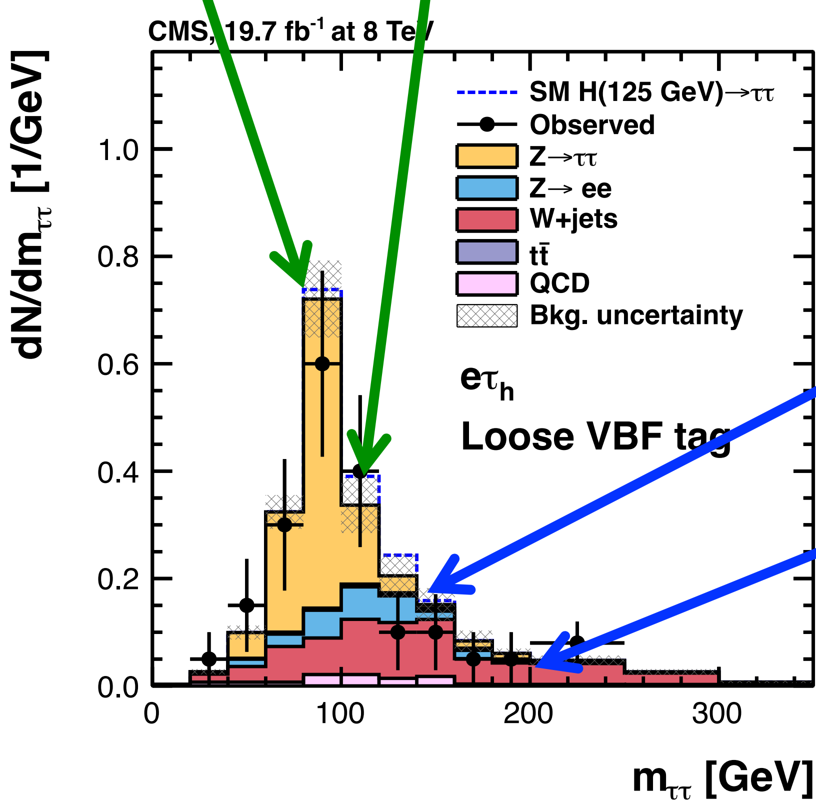




- **MSSM h,H,A→ττ / H→hh→ττbb / A→Zh→llττ / H$^{\pm}$→τν (L. Dodd's talks)**
  - Provides best constraints on extended scalar sector

Challenges in τ_h channels at CMS

Signal: reconstruction of genuine hadronic taus (τ_h)



Backgrounds:

Rejection of fake τ_h from electrons / muons

Rejection of fake τ_h from QCD jets

+ efficient trigger selection
+ rejection of pileup (LHC currently features up to ~40 collisions / bunch crossing)
+ reliable description of data using simulation

Overview

① Run II τ_h-trigger

- Phase-1 upgrade of L1 trigger: challenges & system overview
- L1 τ_h-algorithm: description and performance
- τ_h's at High Level Trigger (HLT)

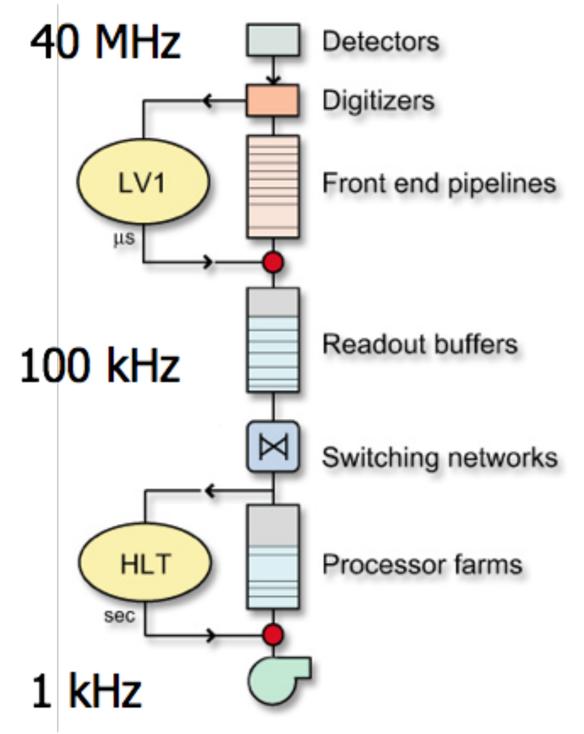
② Run II τ_h-identification

- Reconstruction based on Particle Flow algorithm
- Jet→τ_h discriminators
- Anti-electron discriminator
- Performance measured in Run-2 data

CMS trigger system

- Select interesting processes that have cross sections orders of magnitude lower than proton-proton cross section
- Cannot store all events (TB/s)
- Fast and efficient selection, adapted to interesting physics processes with scales between O(100) GeV to several TeV

→ Rate of events that enter the system (~40 MHz), driven by LHC luminosity

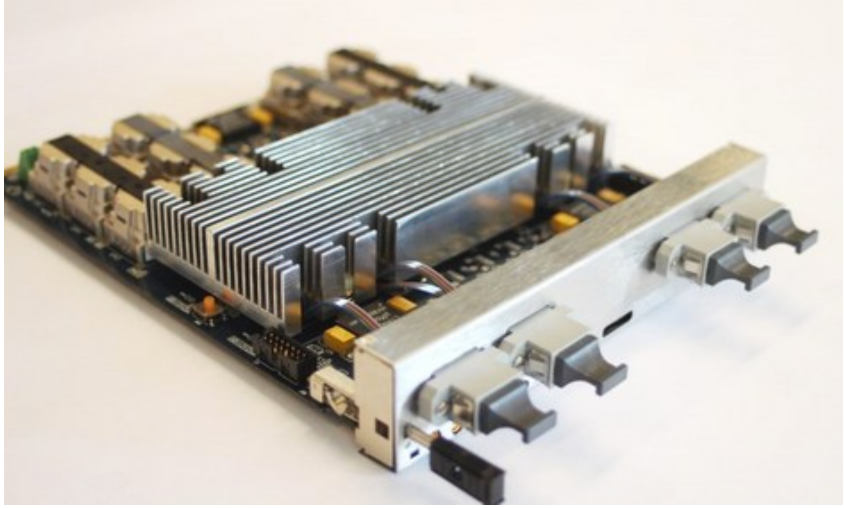


- Implementation in two levels
  - Level-1 (output rate 100 kHz): electronics-based, decision to keep/reject an event in few µs
  - High Level Trigger (output rate 1 kHz): CPU-based, advanced reconstruction of the objects, decisicion to be taken in O(0.2) s

CMS L1 trigger in 2016

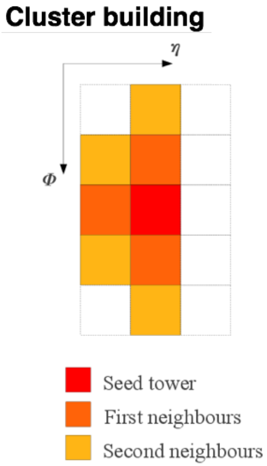
- **Complete replacement of L1 trigger system (hardware, software)**
- **Upgrade commissioned this past year**
- **Brand new architecture**

- **The key conceptual changes to the L1 calorimeter trigger are**
  - ***Streaming data from single event* into one FPGA**
  - ***Dynamic clustering* of energy deposits**
  - ***Pile-up subtraction* @ L1**



The MP7 card on which runs the L1 calorimetric object algorithms (including τ_h)

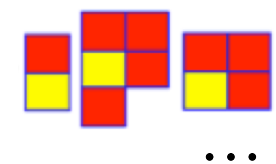
The L1 τ_h-algorithm (1/2)



Dynamic clustering of "trigger towers" (TT)

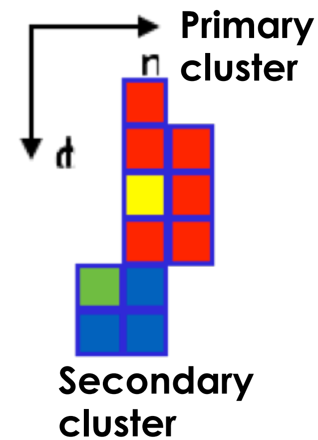
- ECAL + HCAL energies
- Designed to **capture the τ-footprint**
- Improved energy containment/ resolution
- Minimized effect of pileup

Cluster shapes:



Merging

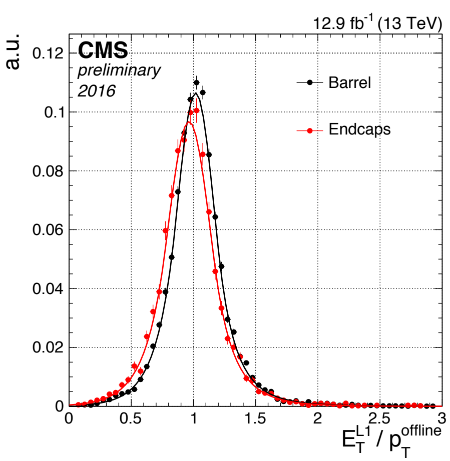
- Merging neighboring clusters (~15%)
- Capture $h^{\pm}\pi^0$'s (1-prong + π^0's) decays



Energy calibration

- Improved energy response and resolution → sharp turn-ons
- Function of E_T, pseudorapidity, merging and electromagnetic fraction

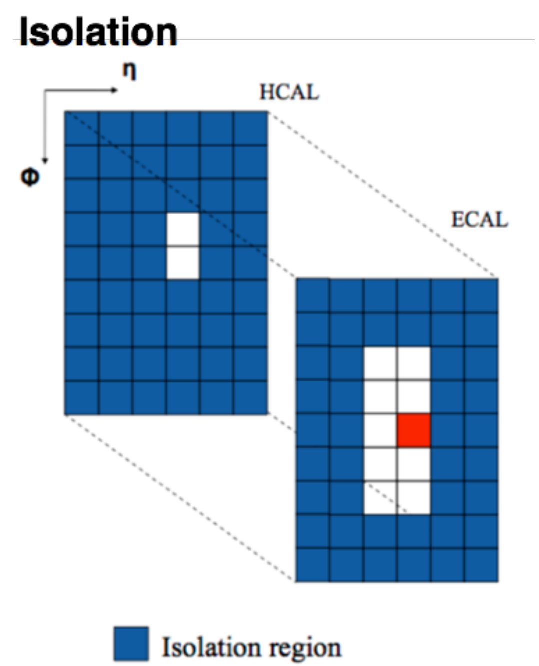
Energy response and resolution



The L1 τ_h-algorithm (2/2)

Isolation

- Isolation energy: E_T(6x9 TT)-E_T(τ-clusters)
- Sums of ECAL and HCAL energies
- Cut: isolation energy requirement function of p_T, pileup and pseudorapidity $\eta=-\ln[\tan(\theta/2)]$
- Isolation energy cut relaxed as function of p_T



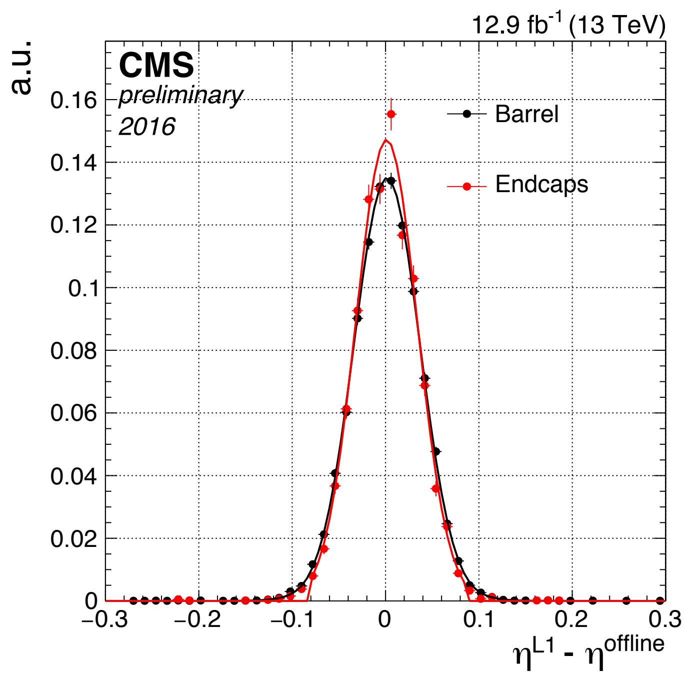
- **Allows control of the rate, increases τ_h-purity**
- **Enables pileup resilient selection of τ_h at L1**

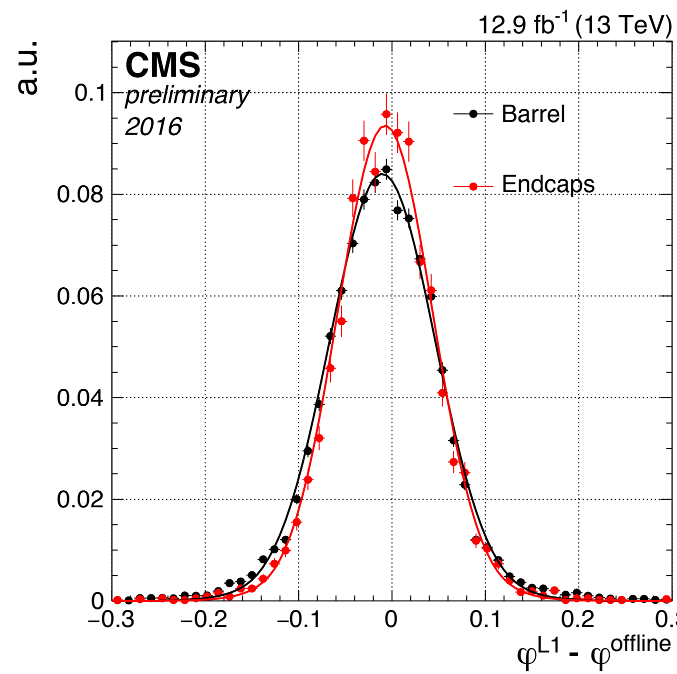
→ Keep low p_T thresholds to efficiently select physics events: $H\rightarrow\tau\tau\rightarrow\tau_h\tau_h$ $H\rightarrow\tau\tau\rightarrow e\tau_h$, etc.

L1 τ_h-trigger performance in data (1/3)

- **Measurements based on ~ 12.9 fb^{-1} of 2016 data, using the Tag & Probe technique on μ+τ events selected by a single-μ trigger**

- **Resolution in position <0.1 in both η and ϕ directions**

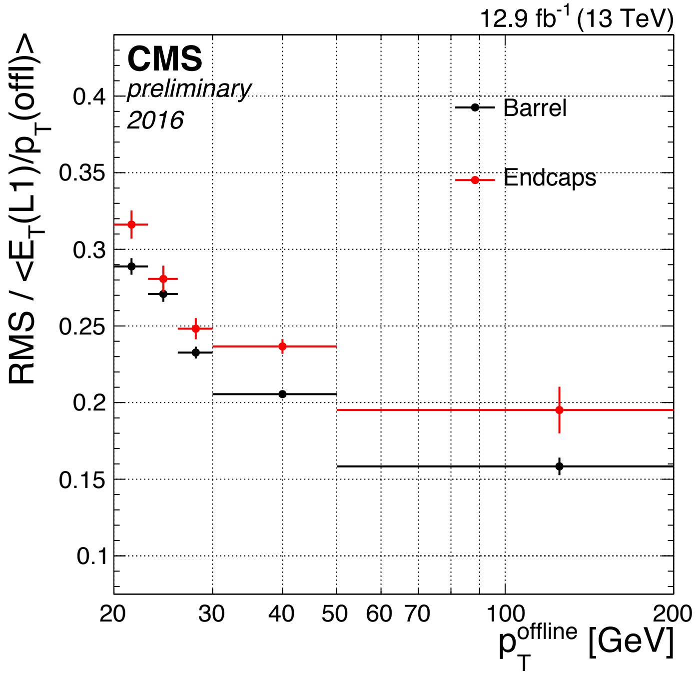


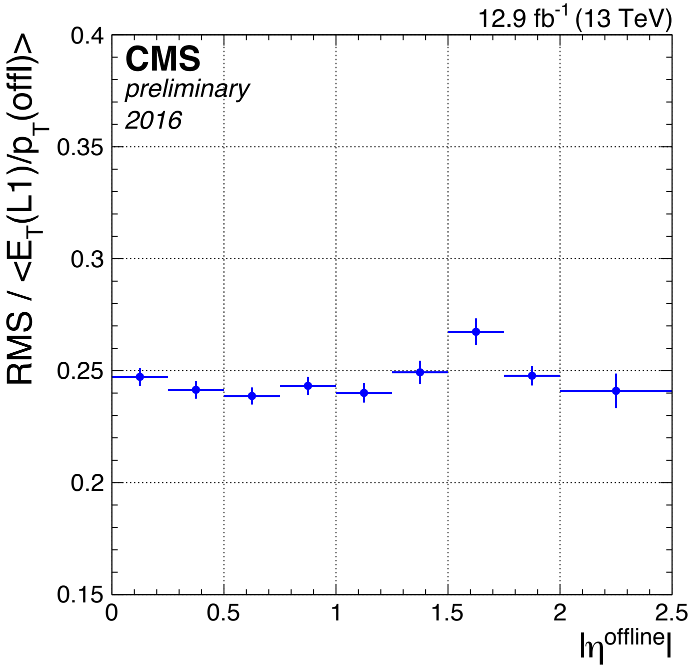


L1 τ_h-trigger performance in data (2/3)

- Measurements based on ~ 12.9 fb^{-1} of 2016 data, using the Tag & Probe technique on $\mu+\tau$ events selected by a single-μ trigger

- **Resolution in energy as function of p_T and position in η**



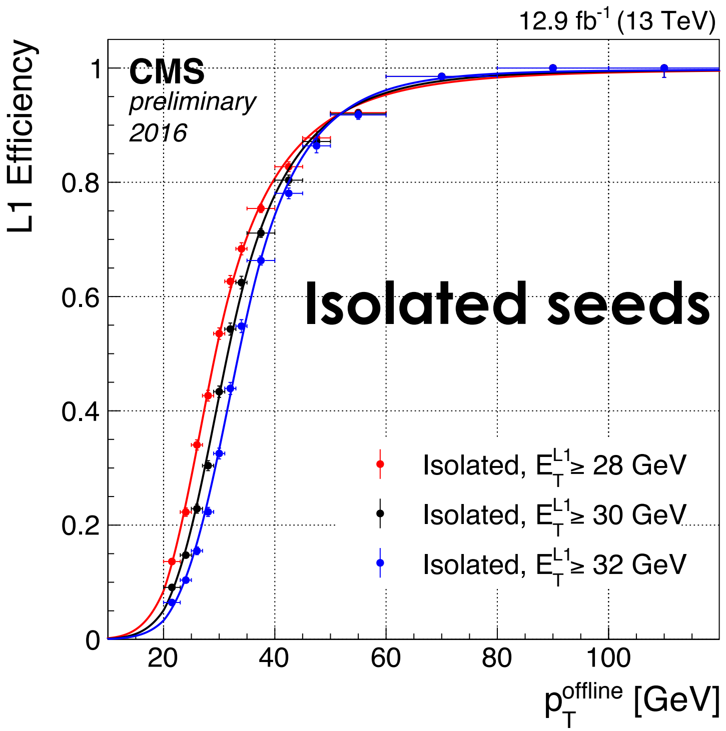


- **Resolution in energy improves with p_T**
- **Resolution in energy ~ stable with η**

L1 τ_h-trigger performance in data (3/3)

- Measurements based on ~ 12.9 fb^{-1} of 2016 data, using the Tag & Probe technique on $\mu+\tau$ events selected by a single-μ trigger

- **Turn-ons: L1 τ-trigger efficiency w.r.t. offline selection as function of $p_{T,}$ for L1 E_T thresholds of 28, 30 and 32 GeV**

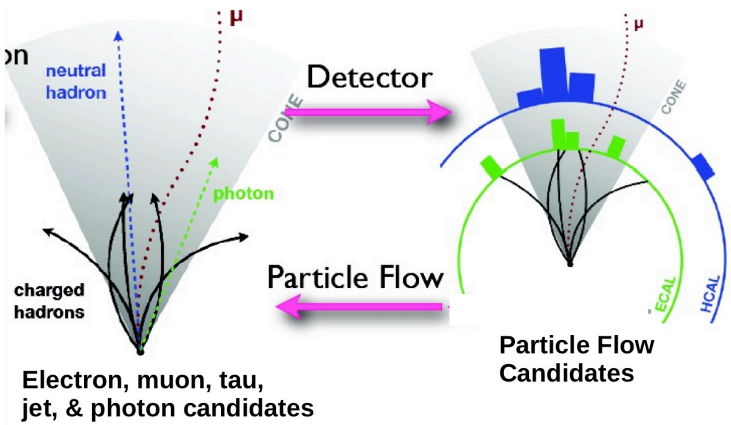


- **In spite of increasing LHC lumi*, thresholds for L1 di-τ_h-iso maintained in the 28-32 GeV range throughout 2016**
- → **Large improvement over Run-1 where we relied on jet triggers**

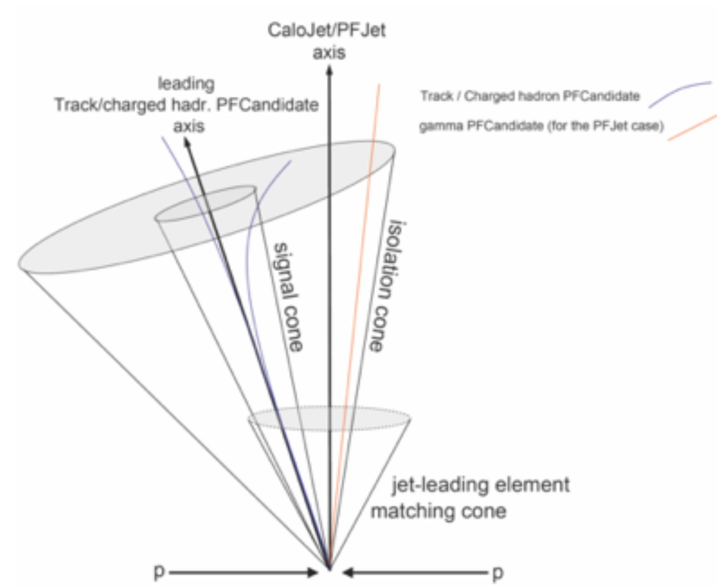
- **Also: definition of $\mu+\tau_h$, $e+\tau_h$, τ_h+MET triggers @ L1**
- → **Possible to design many more algorithms thanks to the flexibility of the system**

* Now inst. luminosity up to ~1.3 x 10^{34} $cm^{-2}.s^{-1}$

HLT τ_h-trigger: description



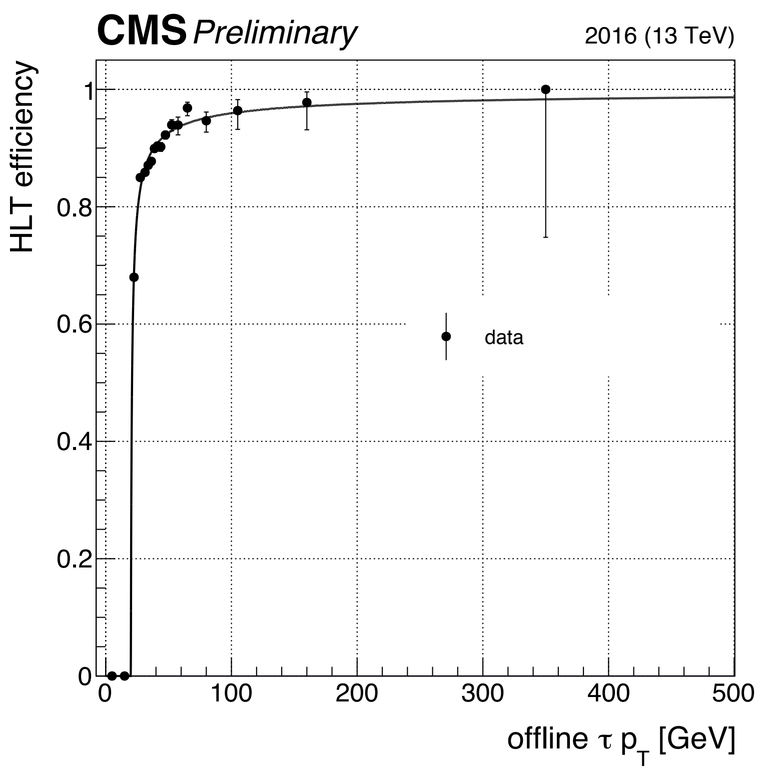
- **Particle Flow**
  - ***Global* event reconstruction**
  - **Optimal combination of information from CMS subdetectors**
  - **Tracking/magnetic field integral are key ingredients**
  - **Separation between neutral and charged hadrons**
  - → **List of stable particles (e/μ/γ/hadrons)**
  - → **Combines them to build jets, τ's, MET**



- **HLT τ_h-reconstruction: based on PF@HLT**
  - **τ_h are isolated jets**
  - **Track-based isolation (PU resilient)**

HLT τ_h-trigger performance in Run-2 data

- **HLT τ-trigger performance measured in 2016 data with respect to an offline selection, and using the Tag & Probe technique in events triggered by a single-μ trigger**

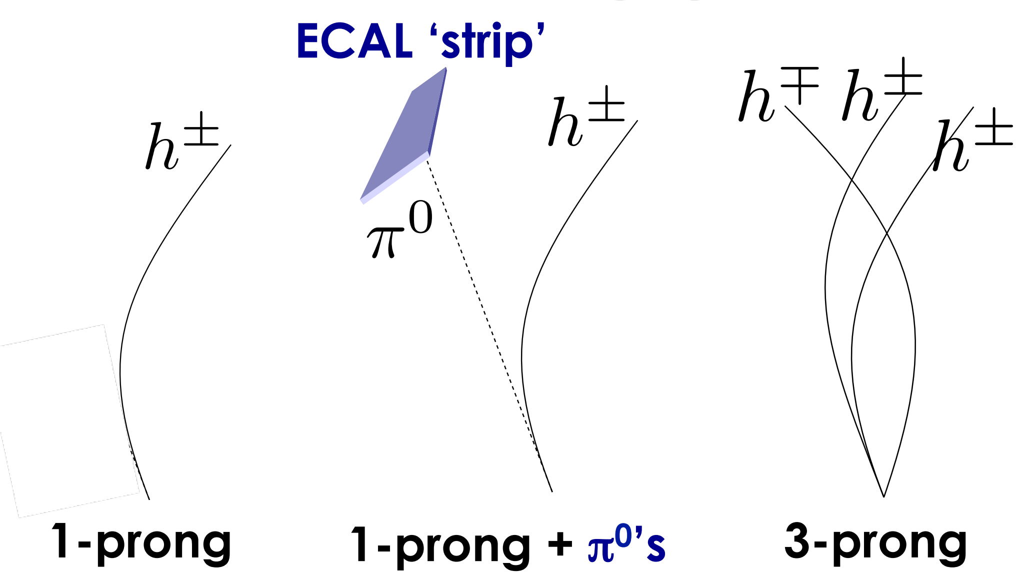


- **High Level Trigger efficiency of the τ_h-leg in $\mu+\tau_h$ events selected as in the $H\to\tau\tau\to\mu\tau_h$ analysis**

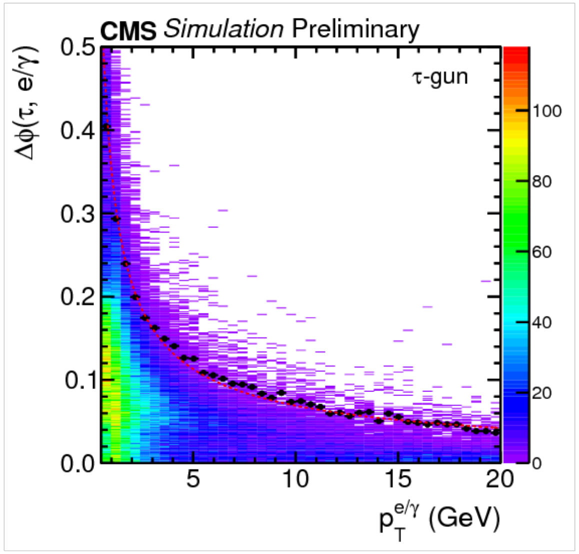
τ_h reconstruction

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

- **τ_h reconstruction @ CMS:** ***Hadron Plus Strips* (HPS) algorithm**
  - **τ_h build from combination of Particle Flow $\pi^\pm$ and $\pi^0 \to \gamma\gamma$ candidates (strips)**
  - **Reconstruction of different decay modes**



- **Essentially same algorithm as Run-1**
- **New: dynamic strip size in 1-prong + π^0's reconstruction, function of expected e/γ p_T**



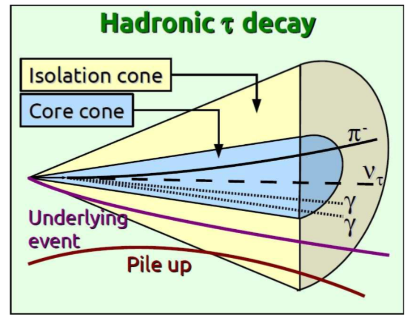
Jet→τ_h rejection: isolation

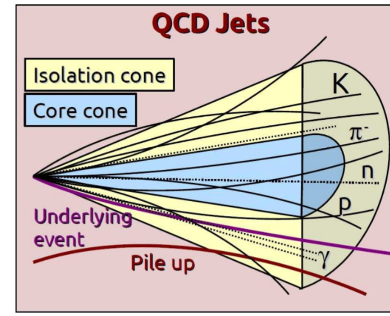
- Main handle in τ_h discrimination against QCD jets: **isolation**

Cut based discriminant

based on energies of PF particles in isolation cone

$$I_\tau = \sum_{\mathrm{charged},\Delta z<0.2\,\mathrm{cm}} p_\mathrm{T} + \max\left\{0, \sum_\gamma p_\mathrm{T} - \Delta\beta\right\}$$

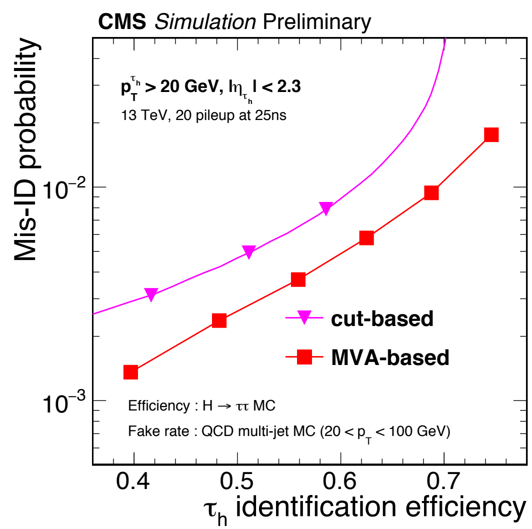


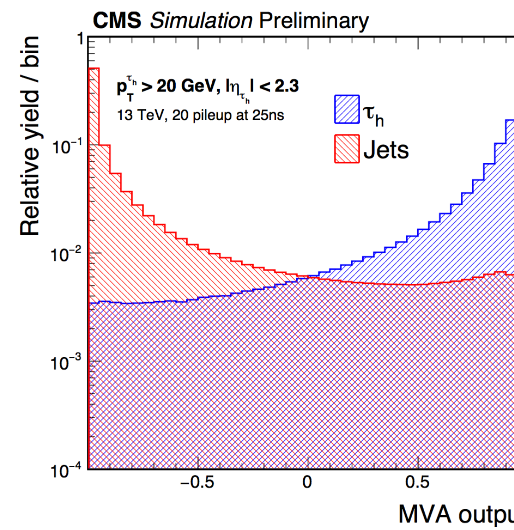


MVA discriminant w/ τ_h lifetime information

- Charged and neutral energies in isolation cone
- Reconstructed decay mode type
- Transverse impact parameter + significance
- Distance between PV and SV + significance
- Shape variables
- e/γ multiplicity

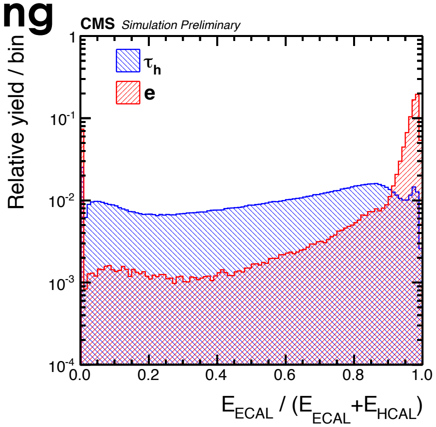
MVA: ~50% better background rejection at same signal efficiency

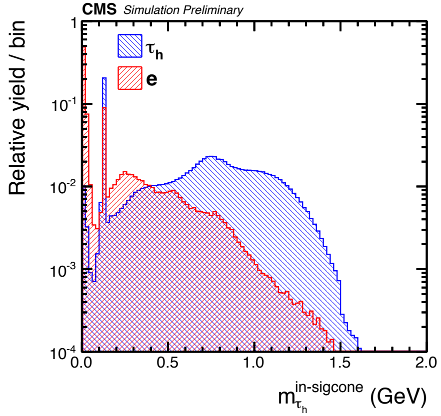




$e \rightarrow \tau_h$ rejection

- **Electrons can fake 1-prong + π^0 if:**
  - **e track + deposit compatible w/ τ_h's prong**
  - **Brem. γ(s) mimick $\pi^0 \rightarrow \gamma\gamma$ (strip)**

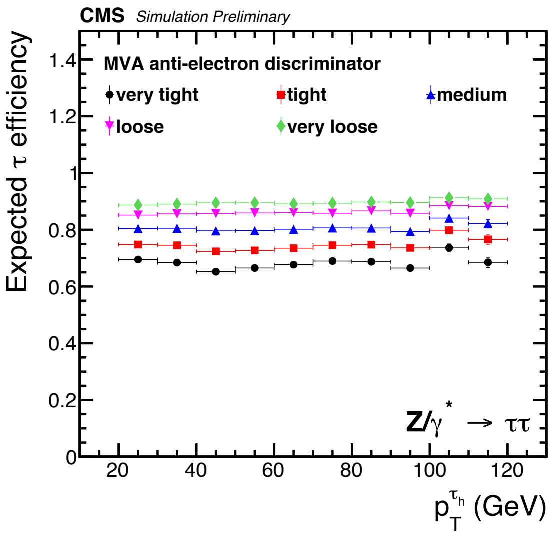




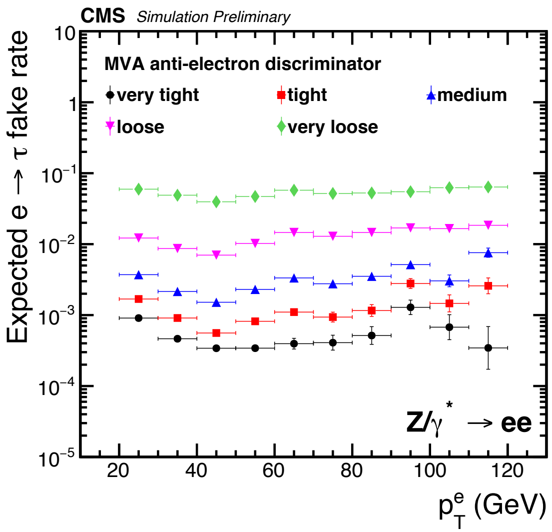
MVA-based discriminant

- **Fractions of energy in HCAL and ECAL**
- **Photon multiplicity**
- **Energy-weighted difference in η/ϕ position between leading track and strips**
- **Visible mass of particles in signal cone**

Several working points defined



Fake rates between 10^{-1} and 10^{-4}



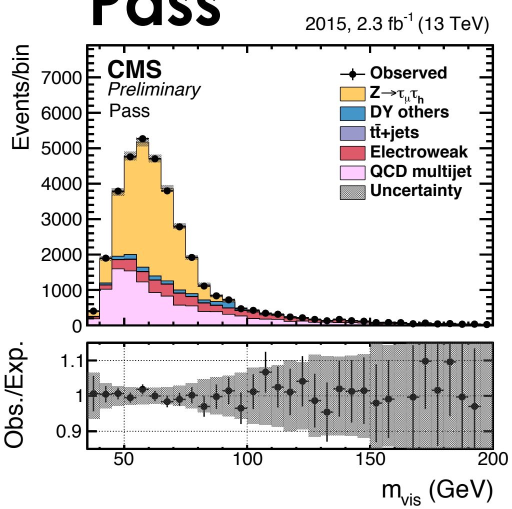
τ_h-ID efficiency in Run-2 data

- Three data-driven methods used to measure **τ-ID efficiency**

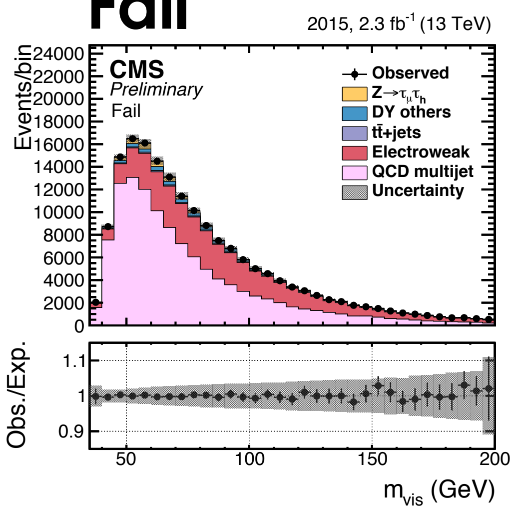
① **Tag & Probe on Z→μτ data**
② **Measurement of the Z→ττ/Z→μμ ratio**
} **Complementary methods (different systematics)**

③ **Measurement in W*→τν events** → **High p_T**

Pass



Fail

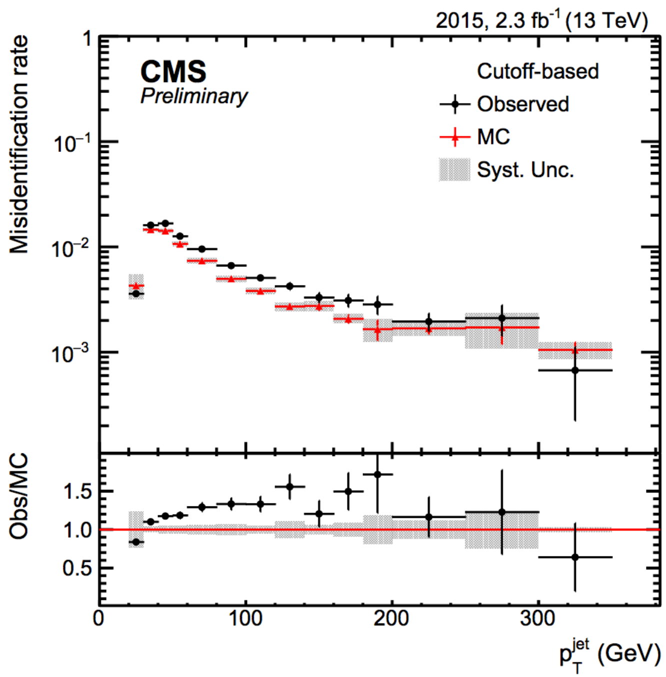


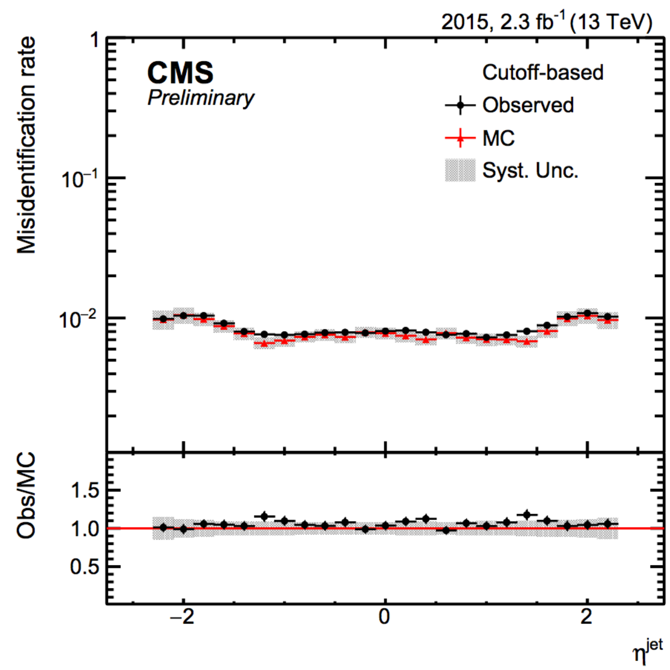
Discriminant	Data/MC scale factor (m_{vis})
MVA Very Loose	1.00 ± 0.06
MVA Loose	1.00 ± 0.06
MVA Medium	1.01 ± 0.06
MVA Tight	1.00 ± 0.06
Cut-based Loose	0.98 ± 0.06
Cut-based Medium	0.98 ± 0.06
Cut-based Tight	0.97 ± 0.06

- **Simulation gives a good description of data** (SFs are compatible within unity)
- **The three methods give compatible results** (SFs are compatible within uncertainties of ~ 6%)

jet→τ_h fake rate in Run-2 data

- **Measured in W→$\mu\nu$ + jets data (dominated by jet→τ_h fakes)**
  - **Dedicated selection for fakes**
  - **Real τ_h contribution subtracted based on MC**





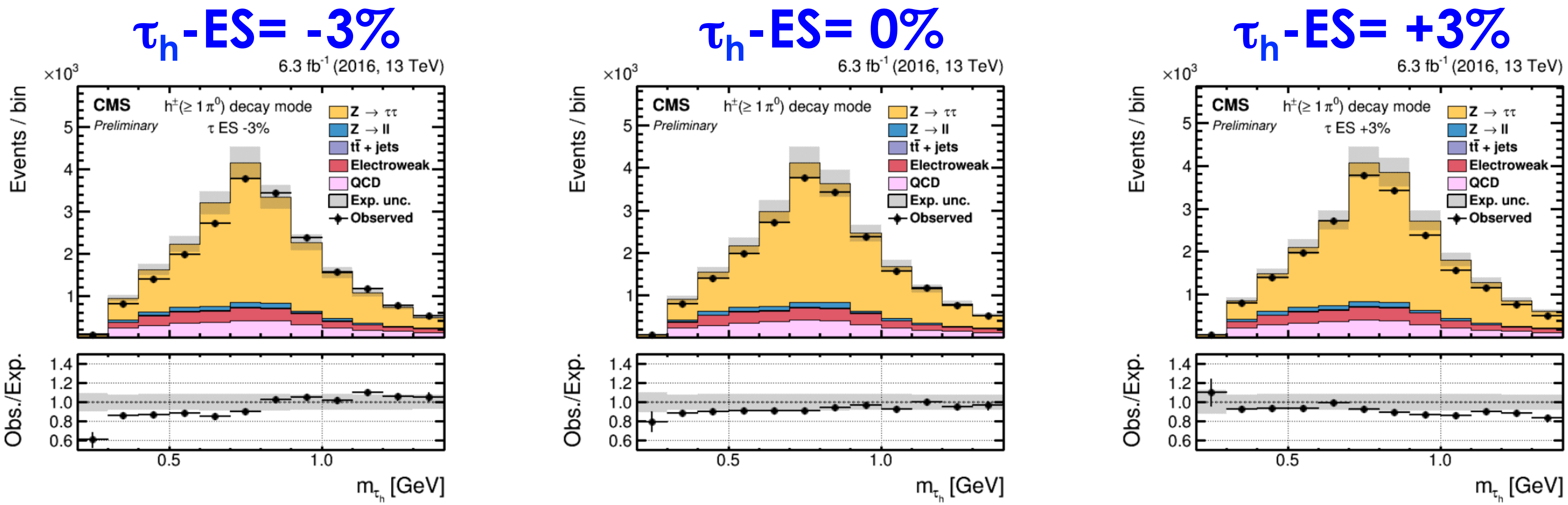
- **Fake rates at the level of a few % (low p_T) and less than 1% (high p_T)**
- **Fake rate higher in data than in MC → likely due to hadronization/UE tune in MC**

τ_h-energy scale in Run-2 data

- **τ_h-ES (= correction on energy scale for simulation)**
  - **Using Tag & Probe in $Z \rightarrow \mu\tau_h$ data**
  - **Data fitted using τ_h-ES-shifted MC templates**

Fit variables:

- **1-prong: fit of the $m_{vis}(\mu\tau_h)$**
- **1-prong + π^0's, 3-prong: $m_{vis}(\tau_h)$**



- **Measured for different τ_h reconstructed decay modes**

Decay mode	τ_h-ES [%]
1-prong	+0.0 ± 1.1
1-prong + π^0's	+1.0 ± 0.4
3-prong	-0.1 ± 0.2

Summary

- Exciting developments at CMS in LHC Run-2

  - L1 trigger upgrade
  → Substantial changes in architecture and algorithms
  → Maintains high efficiency to τ_h thanks to isolation and PU subtraction

  - Improvements in τ_h reconstruction and identification
  → Changes to better reconstruct 1-prong + π^0's decays
  → Re-training of anti-e/μ and MVA-isolation discriminants

- Full appraisal of τ_h performance in Run-2 data

LHC already delivered >31 fb^{-1} this year!

More improvements and nice results with τ_h's to come in the next years ☺

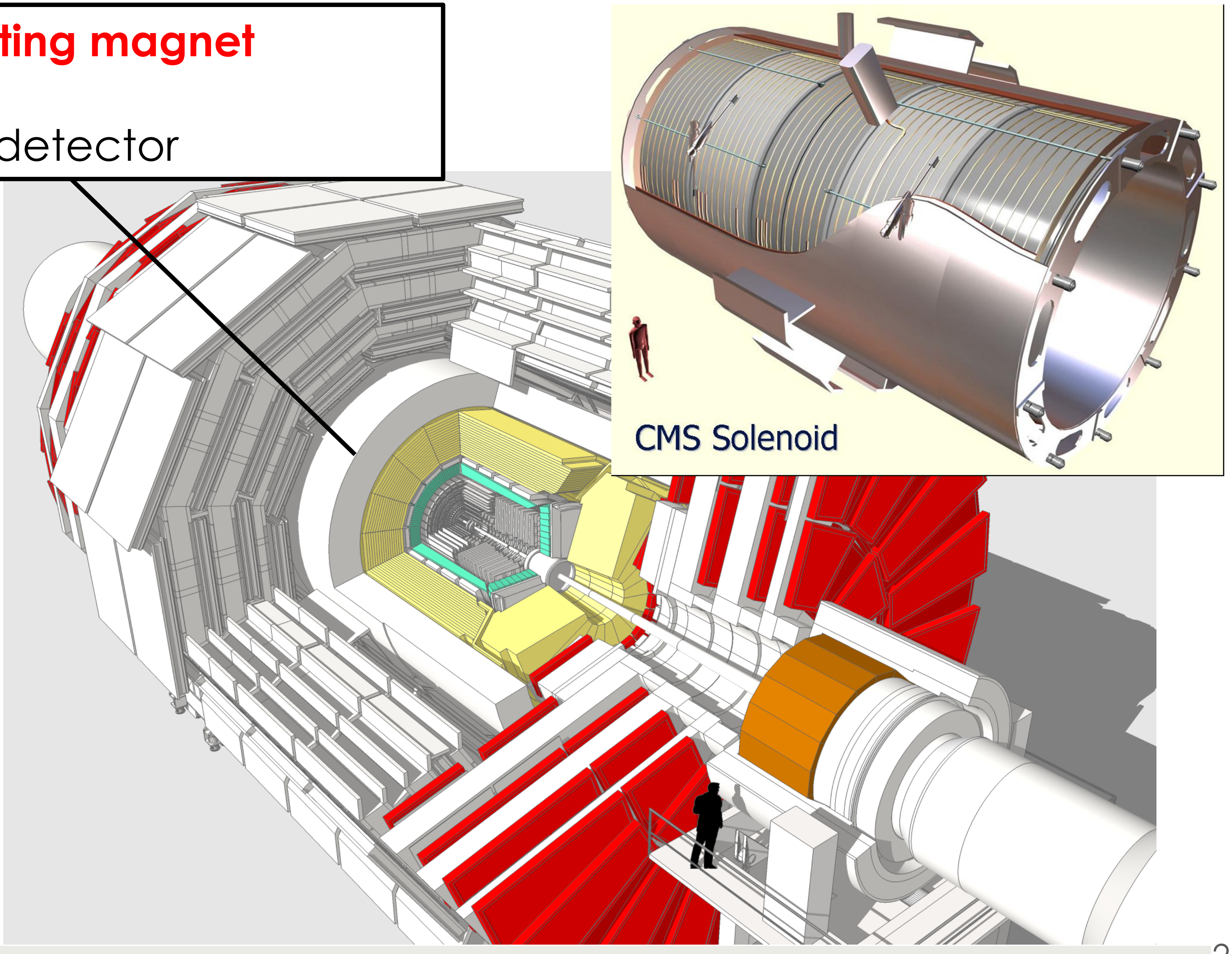
Backup

References

- **L1 trigger, and in particular taus:**
  - CMS-DP-2015-009
  - JINST 11 (2016) 02, C02008
  - CERN-LHCC-2013-011, CMS-TDR-12 (2013)
  - CMS-DP-2016-044
  - CMS-DP-2016-021
- **HLT tau trigger performance in 2016 data**
  - CMS-DP-2016-056
- **Tau reconstruction & ID in Run-1 and Run-2**
  - **Run-1:** JINST 11 (2016) P01019
  - **Run-2:**
    - CMS-PAS-TAU-16-002
    - **Update of tau energy scale & muon fake rate:** CMS DP-16-040
    - **Preliminary performance:** CMS-DP-2016-015, CMS-DP-2016-019

The CMS detector

Superconducting magnet
Field: 3.8 T
→ Compact detector

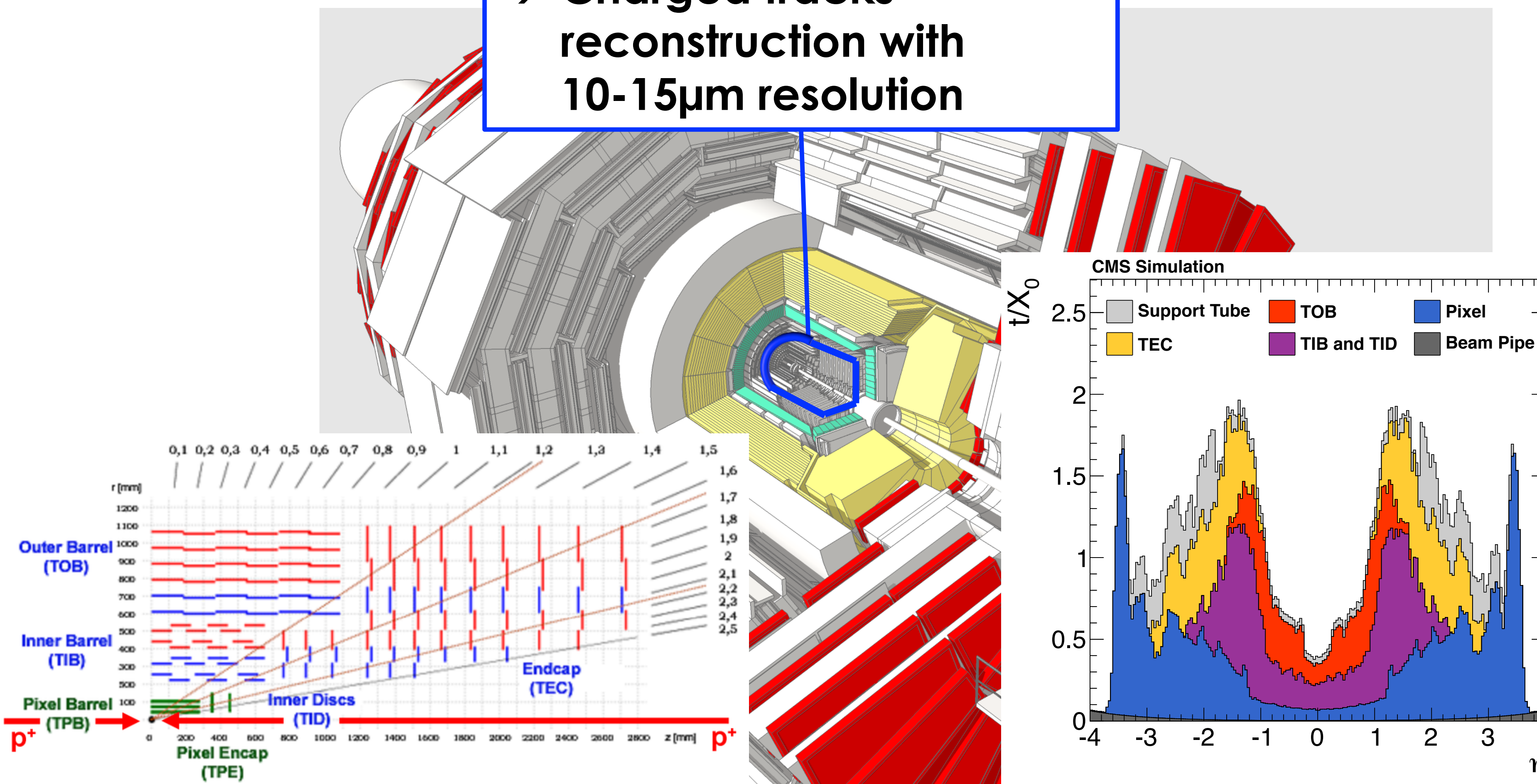


The CMS detector

Inner Tracker

'Pixels' & silicon strips

→ **Charged tracks reconstruction with 10-15μm resolution**



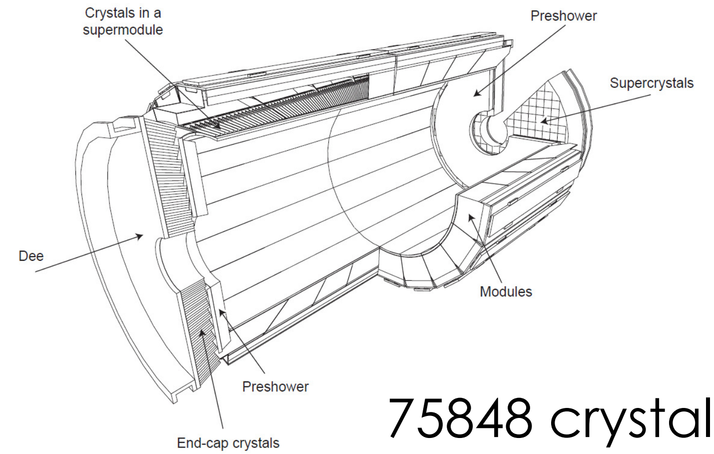
The CMS detector

Electromagnetic Calorimeter

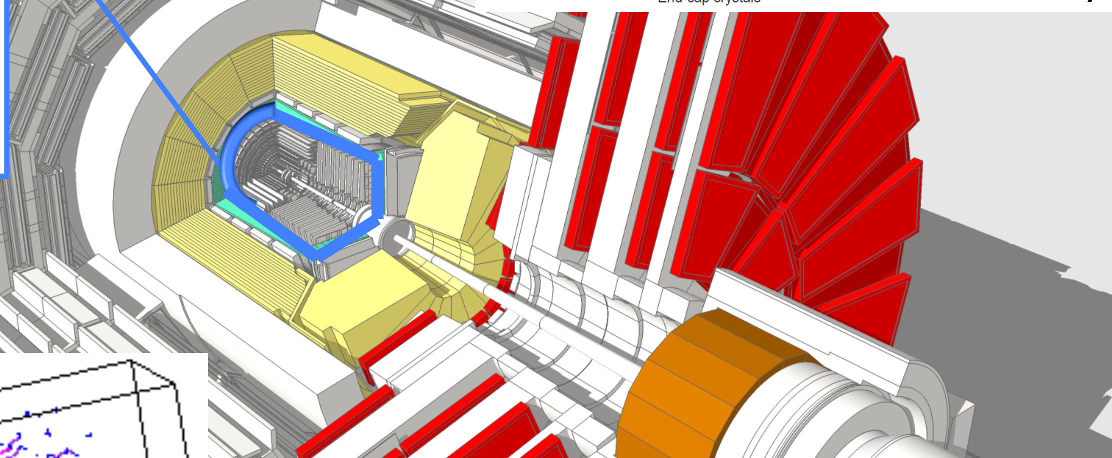
homogeneous calorimeter, scintillating crystals ($PbWO_4$)

→ **Electron/photon reconstruction**

→ **Excellent energy and position resolution**

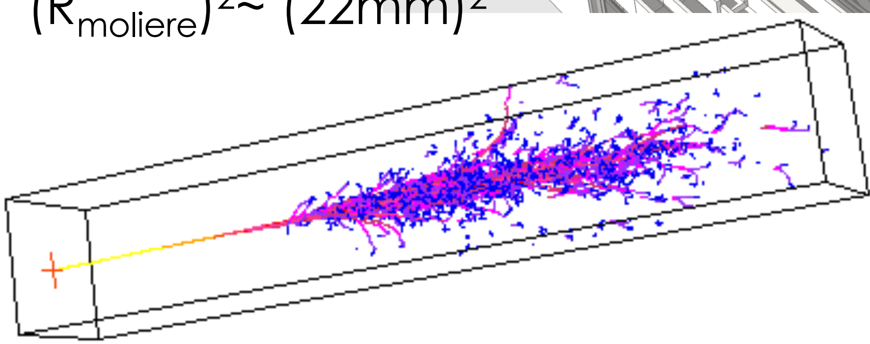


75848 crystals

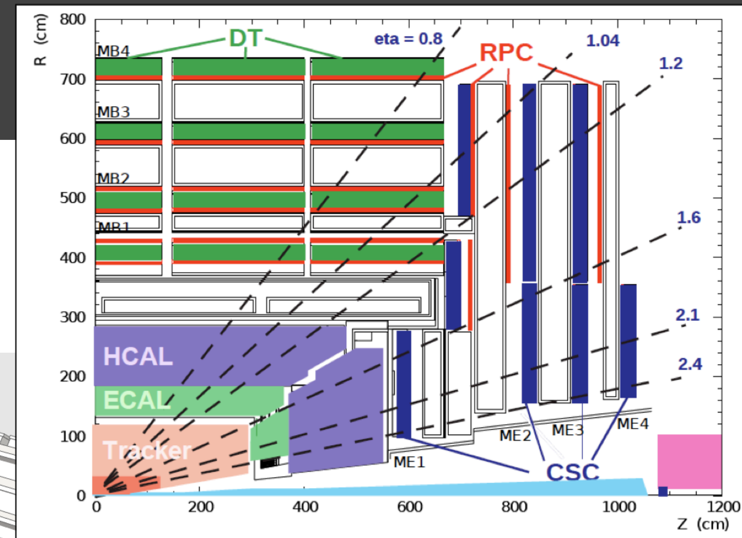


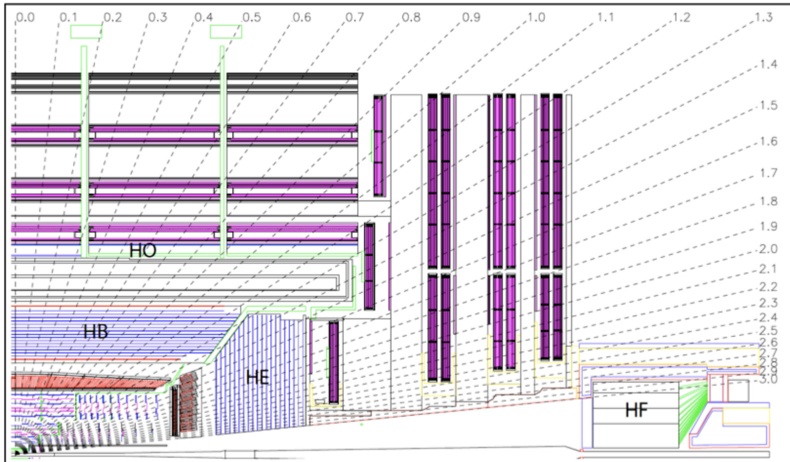
$26\ X_0 \sim 23$ cm

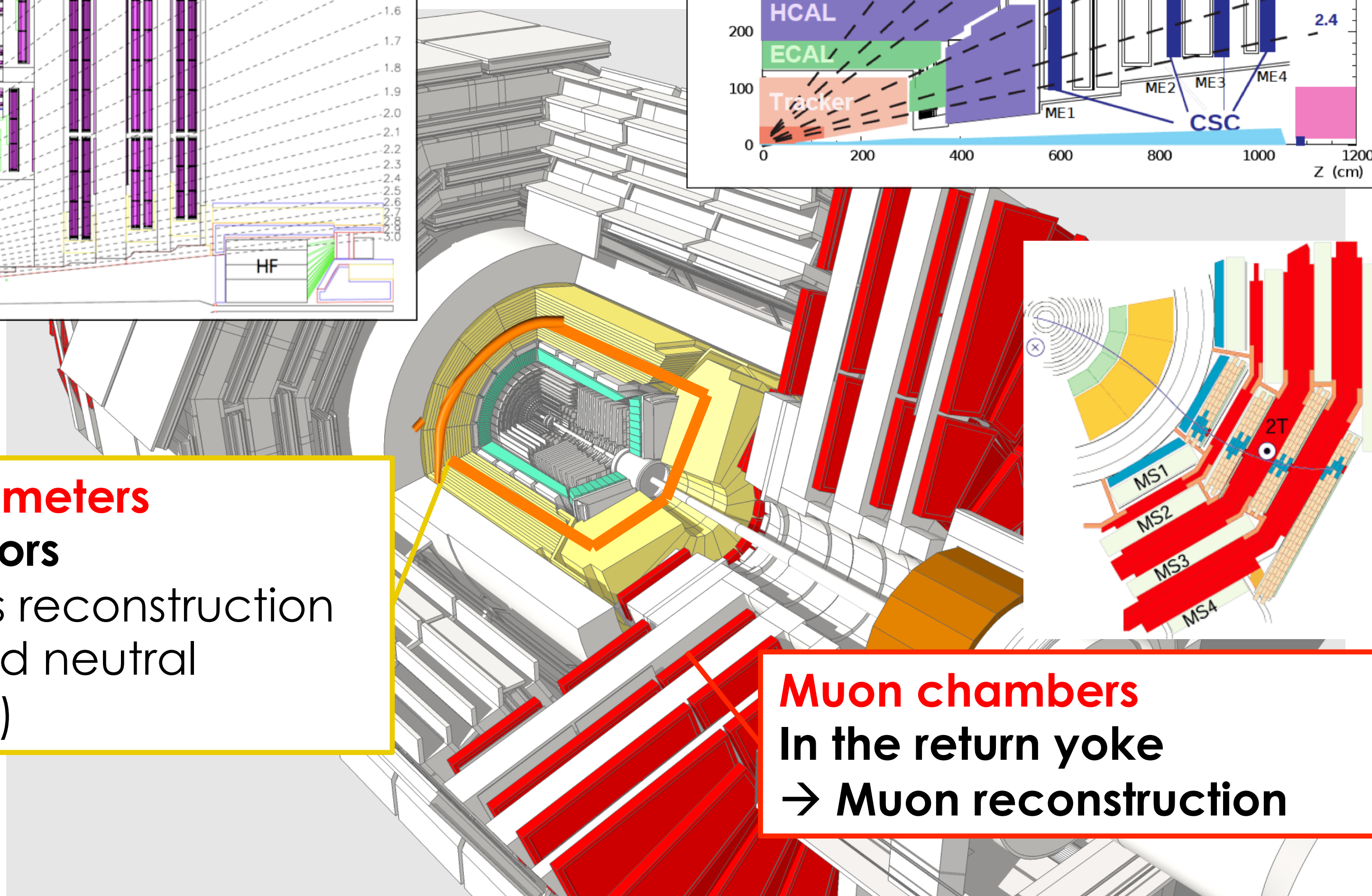
$(R_{moliere})^2 \sim (22\text{mm})^2$



The CMS detector







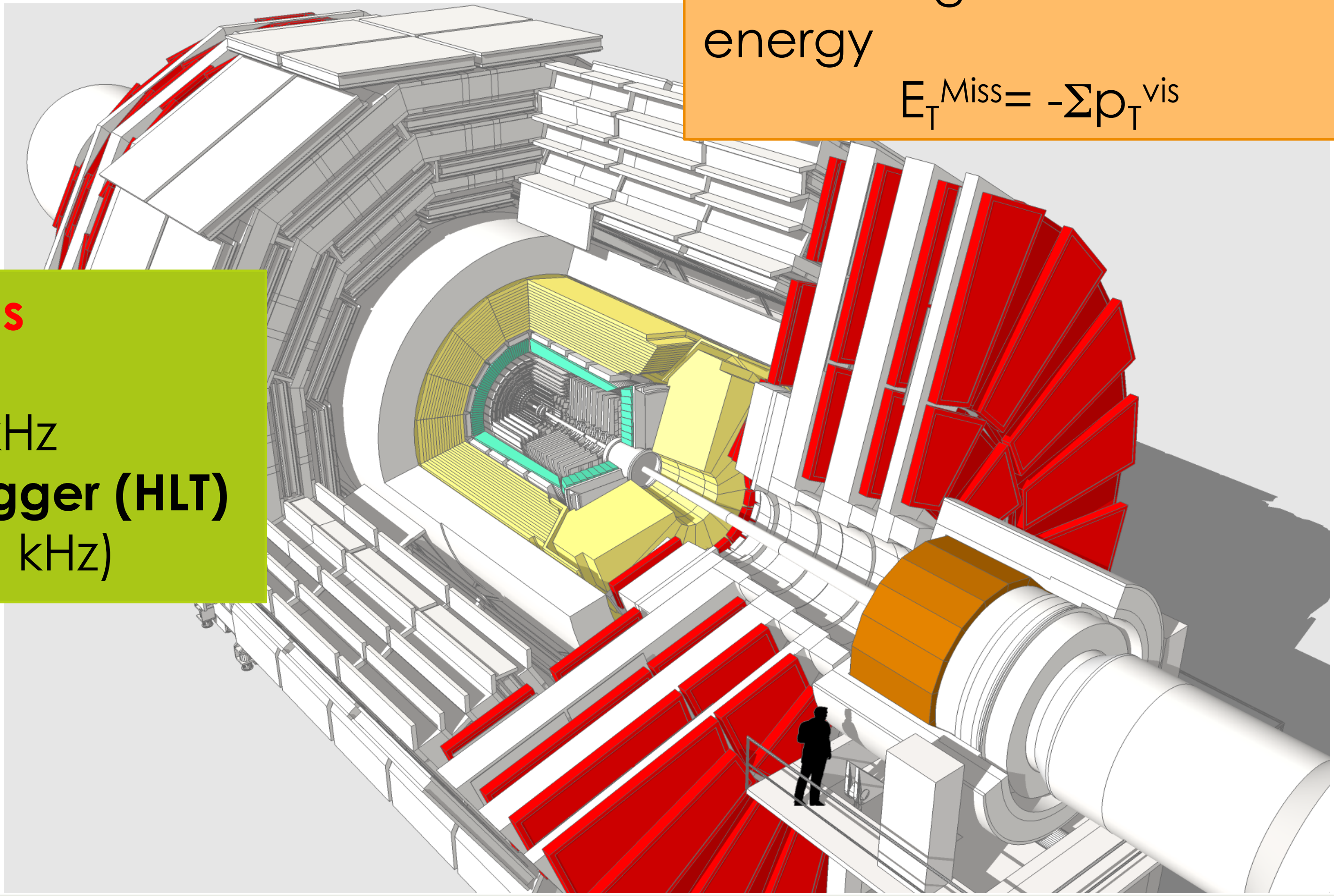
Hadronic calorimeters
plastic scintillators
→ Hadronic jets reconstruction (charged and neutral components)

Muon chambers
In the return yoke
→ Muon reconstruction

The CMS detector

Compact and hermetic detector: measurement of the missing transverse energy

$E_T^{Miss} = -\Sigma p_T^{vis}$



2 trigger levels

Level 1 (L1)

40 MHz→100kHz

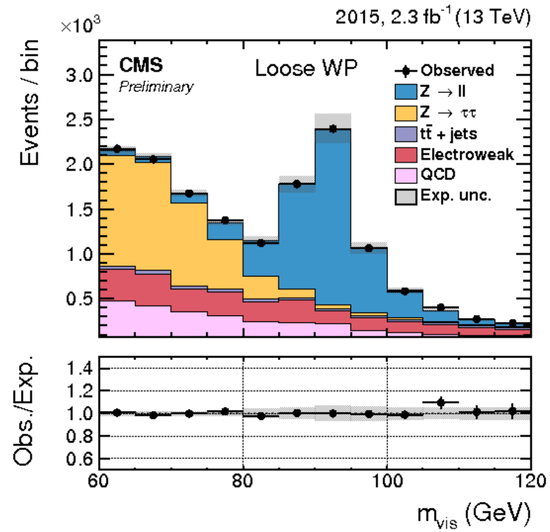
High Level Trigger (HLT)

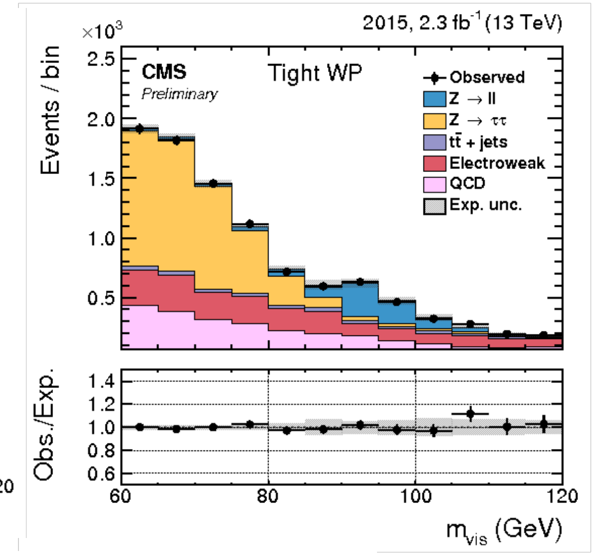
100 kHz→ O(1 kHz)

Topics not discussed (1/2)

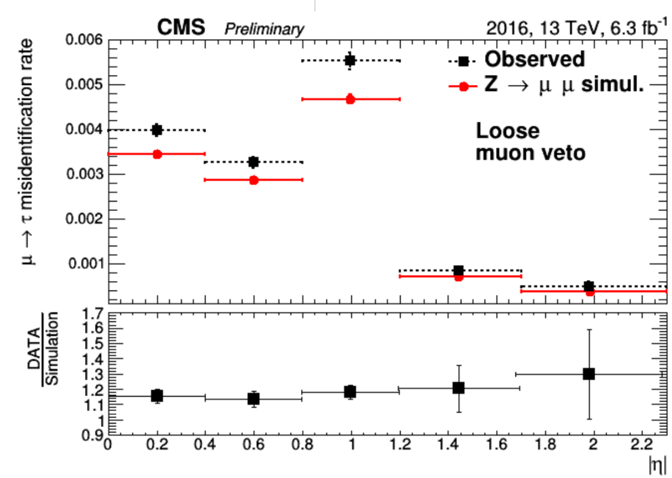
- **Tau-charge mis-identification**: **(0.22 ± 0.05)%** **(CMS TAU-16-002)**

- **Electron to tau fake rate**
  - **Measured for different WPs**
  - **Ref: CMS TAU-16-002**



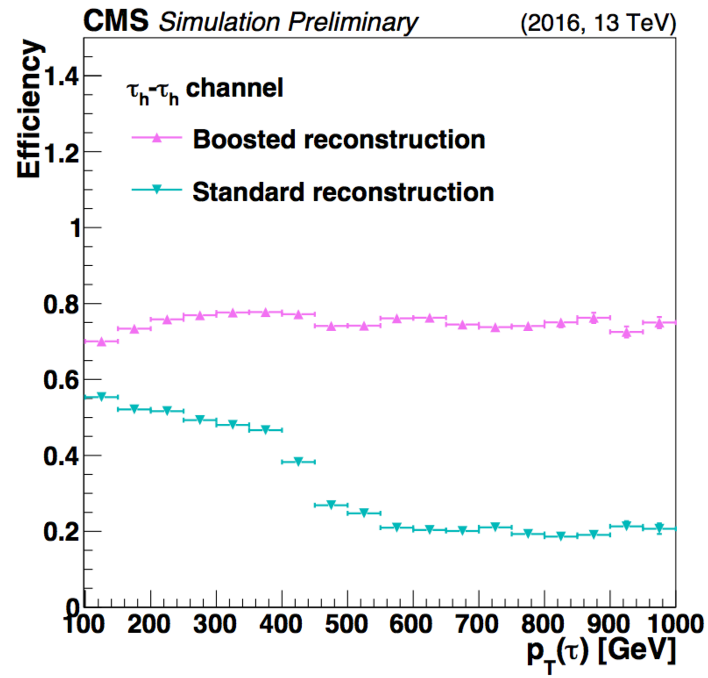


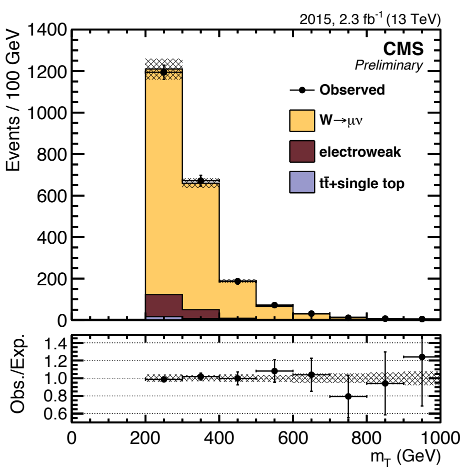
- **Muon to tau fake rate**
  - **Measured for different WPs**
  - **Ref: CMS DP-16-040**

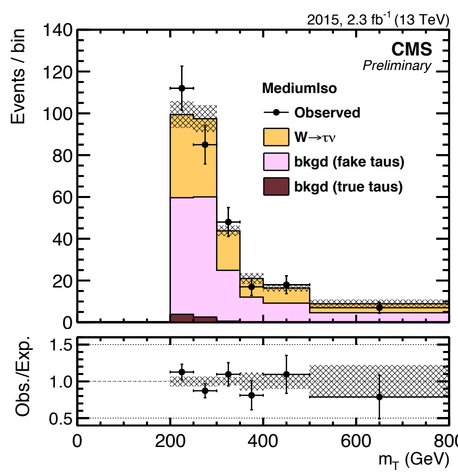


Topics not discussed (2/2)

- **Tau identification in boosted topologies**
  - **Ref: CMS-DP-2016-038**
- **Tau identification efficiency from W*→τν events**
  - **Ref: CMS TAU-16-002**
  - **Use highly virtual W* events to measure the tau ID efficiency at very high p_T (>100 GeV)**

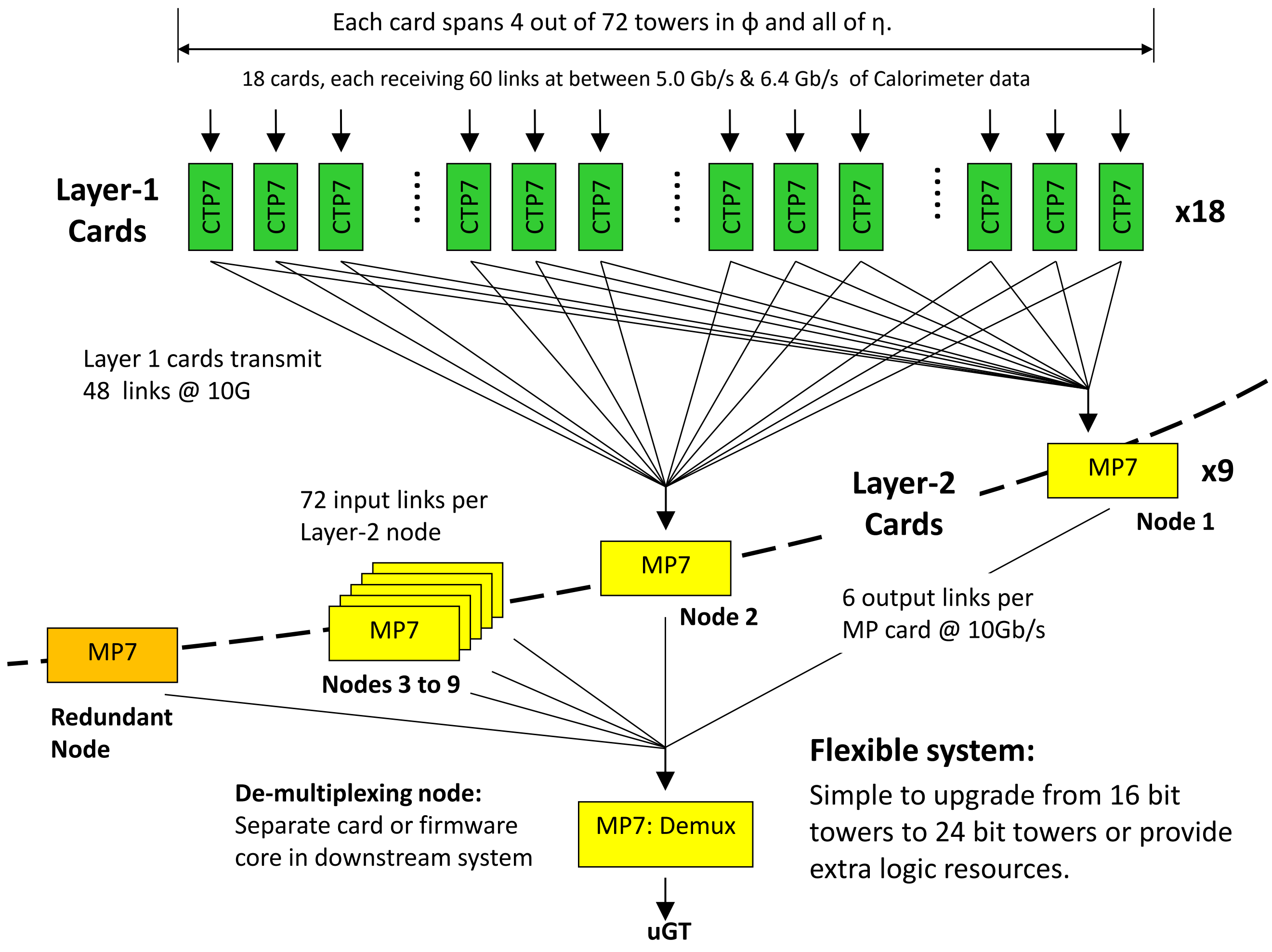






Isolation discriminant		τ id SF	r (W norm.)	correlation
Isolation-sum $\Delta R = 0.5$	Loose	0.94 ± 0.21	1.01 ± 0.05	-0.18
	Medium	0.91 ± 0.19	1.01 ± 0.05	-0.19
	Tight	0.83 ± 0.20	1.01 ± 0.05	-0.17
MVA-based $\Delta R = 0.5$	Loose	0.96 ± 0.17	1.01 ± 0.05	-0.22
	Medium	0.95 ± 0.15	1.01 ± 0.05	-0.25
	Tight	0.94 ± 0.15	1.01 ± 0.05	-0.27
	Very Tight	0.94 ± 0.14	1.01 ± 0.05	-0.27

Ttrigger time multiplexing



Flexible system:

Simple to upgrade from 16 bit towers to 24 bit towers or provide extra logic resources.

Details on *Hadron Plus Strips (HPS)*

- **Reconstruction seeded by jets with p_T>14 GeV built using anti-kT algorithm**
- **Clustering of the photons and electrons inside the jet into strips:**
  - **Minimum p_T of e/γ that enter strips: 0.5 GeV**
  - **Construction of strips is an iterative process**
  - **Minimum p_T of strips: 2.5 GeV**
  - **Size of strip dynamically enlarged in particular to account for magnetic drift of e^+e^- pairs**
- **τ_h = combination of strips and charged hadrons (p_T) inside jet**
  - **Build τ_h kinematics from visible decay products**
  - **Test hypothesis: 1-prong, 1-prong + pi0, 1-prong + 2pi0, 3-prong, etc.**
  - **Check if pass visible mass criteria (specific to each decay mode) that depend on the τ_h p_T , and if it passes charge requirements.**