Tau Performance at Hadron Colliders

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The $\tau$ Lepton

- Anticipated by theory in 1971
- Discovered in 1975 using the Mark-I detector (SLAC-LBL Magnetic Detector) at the SLAC $e^+e^-$ collider SPEAR
- Now a stepping-stone taking us beyond the Standard Model
- Not only for precision measurements on the SM Higgs, but also searches for additional Higgs bosons, $Z'$, graviton, SUSY particles, leptoquarkS, etc.

Evidence for Anomalous Lepton Production in $e^+e^-$ Annihilation

M. L. Perl et al., PRL 35 (1975) 1489

Yung-Su Tsai, PRD 4 (1971) 2821
Some $\tau$ Lepton Properties

- Only lepton heavy enough to decay both hadronically and leptonically

### Tau Lepton Decay

<table>
<thead>
<tr>
<th>Decay modes</th>
<th>TAUOLA-CLEO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau \rightarrow e\nu e\nu_\tau$</td>
<td>17.8 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \mu\nu\mu\nu_\tau$</td>
<td>17.4 %</td>
</tr>
<tr>
<td>$\tau \rightarrow h^\pm neutr.\nu_\tau$</td>
<td>49.5 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^\pm \nu_\tau$</td>
<td>11.1 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^0\nu_\tau$</td>
<td>25.4 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^0\pi^\pm\nu_\tau$</td>
<td>9.19 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^0\pi^0\pi^\pm\nu_\tau$</td>
<td>1.08 %</td>
</tr>
<tr>
<td>$\tau \rightarrow K^\pm neutr.\nu_\tau$</td>
<td>1.56 %</td>
</tr>
<tr>
<td>$\tau \rightarrow h^0h^0h^\pm neutr.\nu_\tau$</td>
<td>14.57 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^\pm\pi^\pm\pi^\pm\nu_\tau$</td>
<td>8.98 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^0\pi^0\pi^\pm\nu_\tau$</td>
<td>4.30 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^0\pi^0\pi^\pm\pi^\pm\nu_\tau$</td>
<td>0.50 %</td>
</tr>
<tr>
<td>$\tau \rightarrow \pi^0\pi^0\pi^0\pi^0\pi^\pm\pi^\pm\nu_\tau$</td>
<td>0.11 %</td>
</tr>
<tr>
<td>$\tau \rightarrow K_S^0 X^\pm\nu_\tau$</td>
<td>0.90 %</td>
</tr>
<tr>
<td>$\tau \rightarrow (\pi^0)\pi^\pm\pi^\pm\pi^\pm\pi^\pm\pi^\pm\nu_\tau$</td>
<td>0.10 %</td>
</tr>
<tr>
<td>other modes with K</td>
<td>1.30 %</td>
</tr>
<tr>
<td>others</td>
<td>0.03 %</td>
</tr>
</tbody>
</table>

### Tau Lepton Characteristics

- Mass: $m_\tau \approx 1776.86 \pm 0.12$ MeV
- Proper lifetime: $cT \approx 87 \mu$m
- Hadronic decays (~65% of the time) collection of charged & neutral pions / kaons (well-collimated, if boosted)
- Leading pion direction reproduces the parent $\tau$ direction well
- Presence of one or more neutrinos among the decay daughters (low visible mass $m_{vis} < m_\tau$)

- With this lifetime, decay vertices can be resolved in the central tracking detectors of collider experiments (e.g., silicon trackers of ATLAS and CMS)
The Large Hadron Collider (LHC) at CERN

- The world’s highest-energy particle collider, just outside of Geneva, CH

Proton-proton collider

27 km in circumference

14 TeV design CME

Run-I:
7 TeV CME running in 2011
8 TeV CME running in 2012

Run-II
13 TeV CME running from 2015-2018

Currently in a long shutdown (LS2)

Home to four major experiments
Major experiments at the LHC

- Inner tracking detector and both calorimeters are critical for taus
...and Some of Their Results Using \( \tau \) Leptons

\[ \text{arXiv:1809.10733} \]

\[ \text{ATLAS-CONF-2018-043} \]

\[ \text{JHEP 09 (2018) 007} \]

\[ \text{JHEP 01 (2018) 055} \]
Tau Leptons in Collider Experiments

- Generally, reconstructed as narrow calorimetric showers with a low track multiplicity
- “one-prong” vs. “three-prong”
- Transverse visible energy of τ leptons from a few GeV all the way up to ~100s of GeV (e.g., Z’)
- Sizable fake-rate, as opposed to electron, muon or jet identification
- Note: One cannot really separate leptonically-decaying taus from electrons or muons; “tau reconstruction” means hadronic decays

ATLAS CSC Book
The Real Challenge

**Tau**

1. Narrow & collimated
2. 1 or 3 tracks
3. High fraction of energy deposited in EM calo when neutral pions present ($\pi^0 \rightarrow \gamma \gamma$)
4. Isolation region with low activity
5. Leading track carries most of the $\tau$ momentum

**Jet**

1. Wide
2. Many tracks
3. High fraction of energy deposited in HAD calo
4. Busy isolation region
5. Jet momentum spread over tracks

- Must distinguish hadronically decaying tau leptons from jets (these originate from processes that have very large cross-sections)
Tau Reconstruction
CMS Particle Flow

- CMS uses a holistic approach

- Reconstruct and calibrate all stable particles in the event (Particle Flow—“PFlow”)

- Combine $e$, $\gamma$, $\mu$, neutral and charged hadrons to build high-level objects in a consistent way

- PFlow is able to resolve tau decay products and to reconstruct the surrounding particles to determine isolation
CMS Reconstruction

- Anti-$k_T$ jets (distance parameter of $R=0.4$) with PFlow constituents ($h^\pm, e^\pm, \gamma$)
- Charged hadrons with $p_T>0.5$ GeV inside a cone of variable radius $R=3/p_T$

- Neutral pions decay into two photons
  - Reconstruction from conversions, bremsstrahlung
- $e^\pm, \gamma$ with $p_T>1$ GeV clustered into “calorimeter strips”
  - The barycentre of these strips is required to be inside of $R_{\text{sig}}$

$R_{\text{iso}}$ for isolation purposes
$R=0.5$
($R=0.3$ for top like analyses)

$R_{\text{sig}}$, variable size, collect charged hadrons
$R=0.05-0.1$

$dz < 0.2$

(Atlas EM Calorimeter shown)
CMS Dynamic Strip Reconstruction

- Strip size depends on the $p_T$ of the strip and $e^{\pm}/\gamma$
  (dynamic; $\Delta\phi=0.05-0.3, \Delta\eta=0.05-0.15$)
- Iterative merging of $e^{\pm}/\gamma$
- Taus can be boosted (appear collimated) but with low $p_T$ conversions and bremsstrahlung (both effects need to be taken into account)

Simulated $\tau_h$ decays

$\Delta\eta \times \Delta\phi$ window size:

$\Delta\eta = f(p_T^{e/\gamma}) + f(p_T^{\text{strip}})$

$\Delta\phi = g(p_T^{e/\gamma}) + g(p_T^{\text{strip}})$

$p_T$ of the second-highest $e^{\pm}/\gamma$ deposition
Reconstruction of all possible decay modes

\[ \tau \rightarrow \pi^{\pm}\nu \]  
\( \rho(770) \) resonance

\[ \tau \rightarrow \pi^{\pm}\pi^{\pm}\pi^{0}\nu \] (1 \( h^\pm \), 1 strip)  
0.3 \( \Delta m_\tau \) \( < m_\tau \) \( < 1.3 \sqrt{p_\tau/100} + \Delta m_\tau \)

\[ \tau \rightarrow \pi^{\pm}\pi^{\pm}\pi^{0}\nu \] (1 \( h^\pm \), 2 strips)  
0.4 \( \Delta m_\tau \) \( < m_\tau \) \( < 1.2 \sqrt{p_\tau/100} + \Delta m_\tau \)

\[ \tau \rightarrow \pi^{\pm}\pi^{\pm}\pi^{0}\nu \] (1 \( h^\pm \), 1 strip)  
0.8 \( < m_\tau \) \( < 1.5 \)

\[ \tau \rightarrow \pi^{\pm}\pi^{\pm}\pi^{0}\nu \] (1 \( h^\pm \), 2 strips)  
0.8 \( < m_\tau \) \( < 1.5 \)

\( (*) \) \( \Delta m_\tau \) related to the additional \( e^\pm/\gamma \) added to strips

\[ \sum^+_{\pi^+\pi^0}, \sum^+\pi^0\pi^0, \sum^+\pi^0\tau^+\tau^-\tau^- \] compatible with a mass hypothesis (\( \pi^\pm, \rho, a_1 \)) are kept

A candidate that passes the mass selection criteria with the highest \( p_\tau \) is retained as a tau candidate.
**ATLAS Algorithm**

- Anti-$k_T$ jets ($R=0.4$) from calorimeter cells
- 1 or 3 tracks ($p_T>1$ GeV)
- Fixed isolation cone $0.2 < \Delta R < 0.4$
- Track selection done using a BDT with over a dozen input variables
- Primary vertex calculated using the selected tau tracks (inner cone)

---

(*) Efficiency to assign the correct number of tracks
Syst. uncertainty 2-5%

(*) Efficiency to assign the correct vertex vs number of vertices
Discrimination Against Jets and Identification Performance
Discrimination Against Jets: CMS

- From isolation:
  - Cut on the $p_T$-sum of the charged and neutral particles in $R_{iso}$
  - Cut on the $p_T$-sum of $e^\pm/\gamma$ in strips but outside $R_{sig}$

\[
l_T = \sum_{d_z < 0.2 \text{ cm}} p_T^{\text{charged}} + \max \left( 0, \sum_{d_z > 0.2 \text{ cm}} p_T^\gamma - \Delta \beta \sum_{d_z > 0.2 \text{ cm}} p_T^{\text{charged}} \right)
\]

\[p_{T, \text{strip, outer}} = \sum_{\Delta R > R_{sig}} p_T^{e/\gamma} < 0.1 p_T^{\tau_h}\]

(*) Subtraction of pile-up photons
$\Delta \beta = 0.2$ (Run 2)

- MVA: Boosted Decision Tree (BDT) with 23 input variables

- Isolation sums
- Distributions and multiplicities of particles inside/outside the cone:
  - number of photons in tau, photons $p_T$ outside signal cone etc.
- Lifetime-related:
  - flight length (significance), secondary vertex, impact parameter vector
- Tau quantities:
  - $p_T^{\tau}, |p_T^{\tau}|$, decay mode(DM), energy ratios etc.
- 2017 training strategy improvements:
  - added Gottfried-Jackson angle for 3 prong decay mode
  - $p_T$ cut-off for photons is increased

Flight length significance 3-prongs

Misidentification probability

$\tau_h$ reco+ID efficiency: $H \rightarrow \tau\tau$

Misidentification probability: QCD multijet ($20 < p_T < 100$ GeV)
Discrimination Against Jets: ATLAS

- BDT trained separately for 1- or 3-track candidates
- Variables pertaining to:
  - Collimation of calorimeter cells, tracks
  - E/p fraction
  - secondary vertex, impact parameter
- Stable efficiency at high $p_T$

<table>
<thead>
<tr>
<th>Variable</th>
<th>Offline 1-track</th>
<th>Offline 3-track</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{cent}$</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>$f_{leadtrack}$</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>$</td>
<td>S_{leadtrack}</td>
<td>$</td>
</tr>
<tr>
<td>$f_{iso}$</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>$\Delta R_{Max}$</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>$S_{flight}$</td>
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<td>●</td>
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<tr>
<td>$m_{track}$</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>$f_{EM-HAD}$</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>$f_{EM}$</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>$m_{EM+track}$</td>
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<td>●</td>
</tr>
<tr>
<td>$p_T^{EM+track}$/p_T</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>

ATLAS Preliminary Simulation

$\sqrt{s} = 13$ TeV

truth 3-prong

Inverse Background Efficiency

$\rho > 20$ GeV, $|\eta| < 2.5$

1-track $\tau_{had-vis}$

3-track $\tau_{had-vis}$

Signal Efficiency

ATL-PHYS-PUB-2015-045
ATLAS and CMS Identification Performances

- Tag-and-probe used on $Z \rightarrow \tau\mu\tau_h$ events

- ATLAS: fit to Ntracks
  - Uncertainty of 4-10% depending on 1- or 3-track candidate and $p_T$

- CMS: fit to the visible mass, $m_{\text{vis}}(\mu,\tau)$
  - Scale factor uncertainties $\sim 3%$
  - Momentum dependence checked in $tt$ and $W \rightarrow \tau\nu$ events
  - Complementary method with $Z \rightarrow \mu\mu / Z \rightarrow \tau\tau$ ratio (cancellation of systematics)
Identification per Decay Mode

- Key ingredients for tau spin observables and CP violation in the Higgs-tau Yukawa coupling...

ATLAS Tau Particle Flow: Dedicated BDT for decay mode separation
Discrimination Against $e$ and $\mu$
Discrimination Against Electrons and Muons

- Electrons can mimic $\tau \rightarrow \pi^\pm n\pi^0\nu$
- ATLAS:
  - 1-track candidates discarded if matched to electrons (a very loose working point of a dedicated BDT)
  - $\sim 95\%$ efficiency; mis-ID $\sim 0.5\%-2.5\%$
- CMS:
  - Several BDTs, working point optimized vs $p_T$
  - $\sim 95\%$ efficiency; mis-ID $\sim 0.1\%-1\%$

- Muons can mimic $\tau \rightarrow \pi^\pm \nu$
- ATLAS:
  - overlap removal
- CMS:
  - veto candidates if matching segments exist in the outer muon detector
  - $\tau$ efficiency to survive 95-100%
  - mis-ID probability: $3.4 \times 10^{-3} - 1.4 \times 10^{-3}$ (CMS)
Discrimination Validation

- Tag and probe in $Z \rightarrow \ell \ell$ events
- ATLAS: ratios of events that pass the discriminators in data and simulation
- CMS: fit of $m_{\text{vis}}(l, \tau)$

Data-to-simulation scale factors derived, close to $\sim 1$ in the barrel
Tau Energy Scale
CMS Energy Scale

- Tau building blocks are already calibrated thanks to PFlow
- Residual corrections derived from $m(\tau)$ and $m_{\text{vis}}(\tau, \mu)$ distributions, sensitive to energy scale
- A fit is performed independently for each decay mode
- Templates shifted in steps of 0.1% energy scale between -6% and +6%

(*) Response vs $p_T$ for PFlow taus

(*) $m(\tau)$ can’t be used for $h^\pm$ mode (pion mass is constant)
ATLAS Energy Scale

- Taus need to be calibrated; two approaches:
  - Baseline (calorimeter-based):
    - Uses topo-cluster calibration with local weighting (LC) pile-up corrections
    - Correction from simulation (R)

\[ E_{\text{calib}} = \frac{E_{\text{LC}} - E_{\text{pileup}}}{R \left( E_{\text{LC}} - E_{\text{pileup}}, |\eta|, n_p \right)} \]

- Particle flow method (boosted regression tree; BRT):
  - Tau particle flow (TPF): reconstruction of \( \pi^\pm \) and \( \pi^0 \)
    (cluster variables from clusters not attached to \( \pi^\pm \) used in dedicated BDT)

- BDT regression targeting an interpolation between \( p_T^{\text{LC}} \) and \( p_T^{\text{TPF}} \)

\[ p_T^{\text{interp}} = f_x \times p_T^{\text{LC}} + (1 - f_x) \times p_T^{\text{TPF}}. \]

- \( p_T^{\text{TPF}} \) resolution < \( p_T^{\text{LC}} \) resolution below 250 GeV

ATLAS-CONF-2017-029

EPJC 76 (2016) 295
Energy Scale Corrections

- **ATLAS**: final corrections from a fit to $m_{\text{vis}}(\mu, \tau)$ in $Z \rightarrow \tau \mu \tau_h$

- **CMS**: residual correction to the reconstructed energy in simulation [%]

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>$m_{\tau_h}$</th>
<th>$m_{\text{vis}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h^\pm$</td>
<td></td>
<td>$-0.5 \pm 0.5$</td>
</tr>
<tr>
<td>$h^\pm \pi^0$</td>
<td>$0.9 \pm 0.3$</td>
<td>$1.1 \pm 0.3$</td>
</tr>
<tr>
<td>$h^\pm h^\mp$</td>
<td>$0.6 \pm 0.2$</td>
<td>$0.6 \pm 0.3$</td>
</tr>
</tbody>
</table>

→ shifts measured in data below % level
Conclusions and Outlook

- Both ATLAS and CMS use different approaches to tau lepton identification
  - ATLAS uses calorimeter-based reconstruction
  - CMS uses particle-flow (however ATLAS is exploring this as well)

- The LHC experiments have an excellent understanding of their detectors, the algorithms used, as well as the necessary calibrations

- With an eye toward the CepC, will mention what ATLAS and CMS have in common
  - Taus decays are very complicated: note the use of multi-variate techniques
  - It is important to have calorimeters with fine granularity
  - Note the use of $Z \rightarrow \tau\tau$ as a ‘standard candle’ in these experiments
  - Helpful to provide multiple working points (e.g., “loose”, “medium” and “tight”)

- The identification algorithms are robust, perform well, and have helped to deliver extremely impressive and ground-breaking results at the energy frontier
Back-up Slides
ATLAS LAr Calorimeter

Segmentation in (eta, phi)
Segmentation in depth, 3 layers:
   Strips, Middle, Back
   Strips highly segmented:
      good rejection π⁰/γ
24 X₀ in total
Presampler up to |eta| = 1.8

Energy resolution:

\[
\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E}} \oplus 0.7\%
\]
Tau Performance at the HL-LHC

HL-LHC: 140-200 pile-up events per bunch crossing ($\times$ 5 LHC)
Instantaneous luminosity: $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ ($\times$ 2-3 LHC)

→ upgrades needed in terms of radiation hardness, granularity and bandwidth

**ATLAS:** new all silicon tracker (ITk), new readout electronics for calos...
**CMS:** tracker and forward calorimeter to be replaced (HGCAL)...

High granularity → excellent track reconstruction & PFlow
Lower material budget → less secondaries
Timing layers → pile-up mitigation
Extended coverage at high $\eta$ → tau ID at high $\eta$ !
ATLAS Preliminary
Simulation mc15
1-prong
\( \sqrt{s} = 13 \) TeV

Efficiency

\( N_{\text{vtx}} \)
<table>
<thead>
<tr>
<th>Variable</th>
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<tr>
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<td>$f_{\text{cent}}$</td>
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<td>$f_{\text{leadtrack}}^{-1}$</td>
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<td>$\Delta R_{\text{Max}}$</td>
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<td>$f_{\text{track-HAD}}$</td>
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<tr>
<td>$f_{\text{EM}}$</td>
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<td>$f_{\text{track}}$</td>
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</tr>
<tr>
<td>$m_{\text{EM+track}}$</td>
<td>●</td>
<td>●</td>
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<tr>
<td>$p_{\text{T}}^\text{EM+track}/p_T$</td>
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</tbody>
</table>
ATLAS BDT TauID Input Variables (some of them)
CMS BDT TauID Input Variables
CMS BDT TauID Input Variables (con’t)
CMS-DP-17-006
Data-driven TES Corrections

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Fit on $m_{\text{vis}}$</th>
<th>Fit on $m_{\tau_h}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All decay modes</td>
<td>$-1.0^{+1.1}_{-0.6}$</td>
<td>-</td>
</tr>
<tr>
<td>$h^\pm$</td>
<td>$+1.5^{+1.5}_{-1.8}$</td>
<td>-</td>
</tr>
<tr>
<td>$h^\pm \pi^0 s$</td>
<td>$-1.5^{+0.8}_{-1.9}$</td>
<td>$-0.5^{+0.7}_{-0.9}$</td>
</tr>
<tr>
<td>$h^\pm h^\mp h^\pm$</td>
<td>$-1.0^{+2.3}_{-1.7}$</td>
<td>$0.0^{+0.2}_{-0.4}$</td>
</tr>
</tbody>
</table>

ATLAS

For the baseline tau energy calibration, the measured TES shift factor is $\alpha = -0.7\% \pm 0.8\%$ (stat) $\pm 1.2\%$ (syst) and $\alpha = -3.6\% \pm 1.2\%$ (stat) $\pm 3.0\%$ (syst) for $\tau_{\text{had}}$ with one and three associated tracks, respectively. The corrections are applied to the momentum of $\tau_{\text{had}}$ in simulation in order to yield agreement (on average) with data. The resulting $m_{\text{vis}}$ distribution for data and simulation is shown in Figure 14 after applying the TES correction. For the BRT tau energy calibration, the measured TES shift factor is $\alpha = 0.95\% \pm 0.9\%$ (stat) $\pm 1.7\%$ (syst) and $\alpha = -3.1\% \pm 1.1\%$ (stat) $\pm 1.6\%$ (syst) for $\tau_{\text{had}}$ with one and three associated tracks, respectively.
**L1**: EM and hadronic towers with $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, core region 2x2 towers

**HLT**: calibrated topo-clusters in $\Delta R < 0.2$ around L1
Fast-tracking followed by HLT-tracking similar to offline
Same BDT against jets than offline, pile-up corrected input variables, lifetime variables computed w.r.t. beamspot

(*) Efficiency vs $p_T$

(*) Efficiency vs $N$ vertices

(*) Efficiency measured in $tt$ to derive efficiency at high $p_T$
**CMS Tau Trigger**

- L1 clusters built around local maxima, shape templates

- **Pixel tracks and vertices** in $0.2 < \Delta R < 0.4$
  - charged isolation $< 1.85$ GeV
- Regional tracking + **PFlow**
- Static strip size reconstruction, shrinking signal cone reconstruction
  - inclusive sizes vs offline
- **Charged isolation** combined or not with **photon isolation** to define WP

---

Refined level-1 algorithm since start of 13 TeV data taking!

HLT decision has to be made in 150 ms!
**Comparison of ATLAS and CMS**

- **Differences in TauID methodology**

<table>
<thead>
<tr>
<th></th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed jet: cluster of...</td>
<td>calorimeter cells</td>
<td>particles (PF) – used: $h^+, e, \gamma$</td>
</tr>
<tr>
<td>explicit $\pi^0$ reconstruction</td>
<td>no*</td>
<td>yes</td>
</tr>
<tr>
<td>ID steps</td>
<td>1 (+minimal reco step)</td>
<td>2 (decay mode; iso+rest)</td>
</tr>
<tr>
<td>$\tau$(had) mass</td>
<td>set to 0*</td>
<td>reconstructed and used</td>
</tr>
<tr>
<td>Signal cone, R=</td>
<td>0.2</td>
<td>0.05-0.1**</td>
</tr>
<tr>
<td>Isolation cone (charged), R=</td>
<td>0.2-0.4</td>
<td>0.0-0.5 (excl. signal constituents)</td>
</tr>
<tr>
<td>$h^+$ / tracks $p_T$ cut</td>
<td>1.0</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*however, reco'ed for energy calibration of low-$p_T \tau$ had – see next slides

**shrinking cone: $0.05 < p_T [GeV] < 0.1$**
ATLAS Track BDT Training Details

- R21 training performed on mc16 Gamma → ττ sample
- Final variable set:
  - jetSeedPt
  - trackEta
  - $z_0 \sin \theta$ wrt TJVA
  - rConvII
  - dRJetSeedAxis
  - $d_0$
  - qOoverP
  - numberOfInnermostPixelLayerHits
  - numberOfPixelSharedHits
  - numberOfSCTSharedHits
  - eProbabilityHT
  - nPixHits
  - nSiHits