Tau ID and energy calibration at ATLAS and CMS

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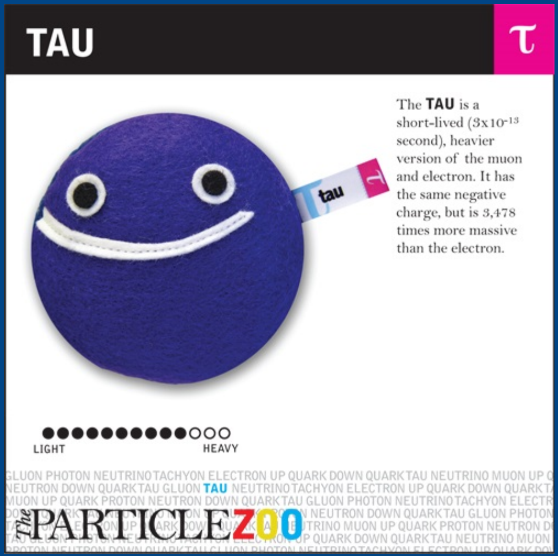


- TauID: Algorithm comparison ATLAS & CMS
- Tau energy calibration: ATLAS & CMS
- TauID and energy calibration performance with Run 2 data

Focus on LHC Run-2 and offline algorithms/performance

Why bother with hadronic τ leptons @LHC?

...even though it is easier to reconstruct e / μ?

- Higgs **Yukawa** couplings proportional to mass
  - higher rates than for electronic / muonic decays
- (Other) **lepton non-universality/**lepton flavor violation
  - measure ratios of leptonic decays or mixed decays
- Tau **polarisation** can be measured
- Enhancement of tau decays [wrt other fermions] in **BSM** scenarios
  - MSSM high tan-beta
  - Z'/W' with extended gauge groups
  - Leptoquarks coupling to a single generation of fermions

SM $H \to \tau\tau$

$HH \to bb\tau\tau$

LFV $H \to \mu\tau$

$B \to \tau\nu + X$

τ pol. $Z \to \tau\tau$

Higgs CP

MSSM $H \to \tau\tau$

$H^+ \to \tau\nu$

$Z' \to \tau\tau$ $W' \to \tau\nu$

$LQ \to b\tau$

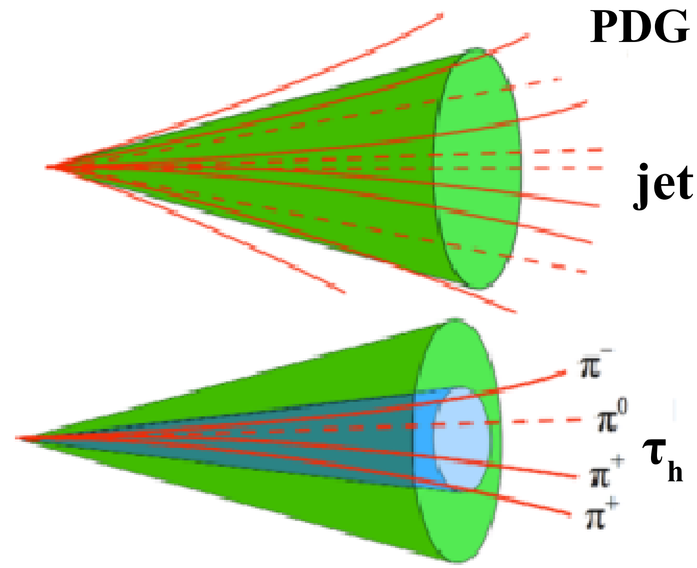
tau leptons: basic facts

- only lepton that can decay hadronically (65%)
- m_τ=1.78 GeV
- life time $3 \cdot 10^{-13}$ s
  - A 50-GeV-τ travels 3mm [expected]

Decay mode	Meson 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
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	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 modes with hadrons		3.2
All modes containing hadrons		64.8

PDG

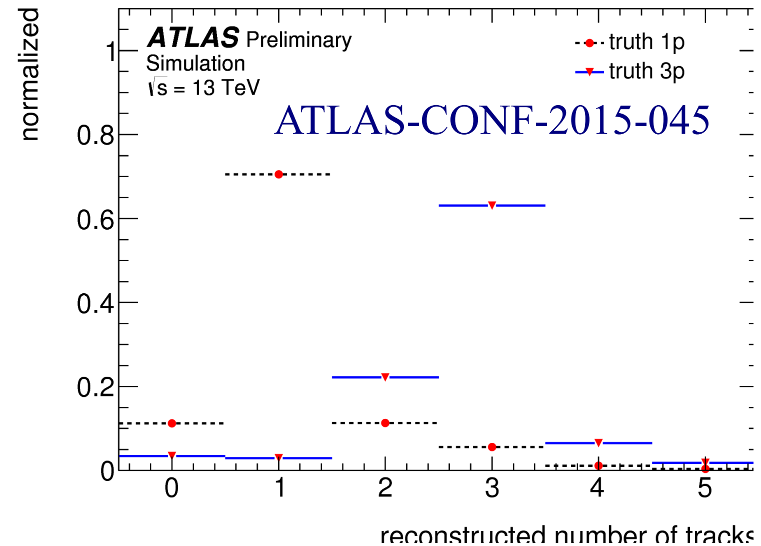
- **Hadronic τ decays are characterized by**
  - 1 or 3 charged hadrons [99.9%]
  - 0—2 neutral hadrons [99%]
  - finite travel length
    - impact parameter / secondary vertex
  - large EM component (via $\pi^0 \to \gamma\gamma$)
  - low visible mass $m_{vis} < m_\tau$



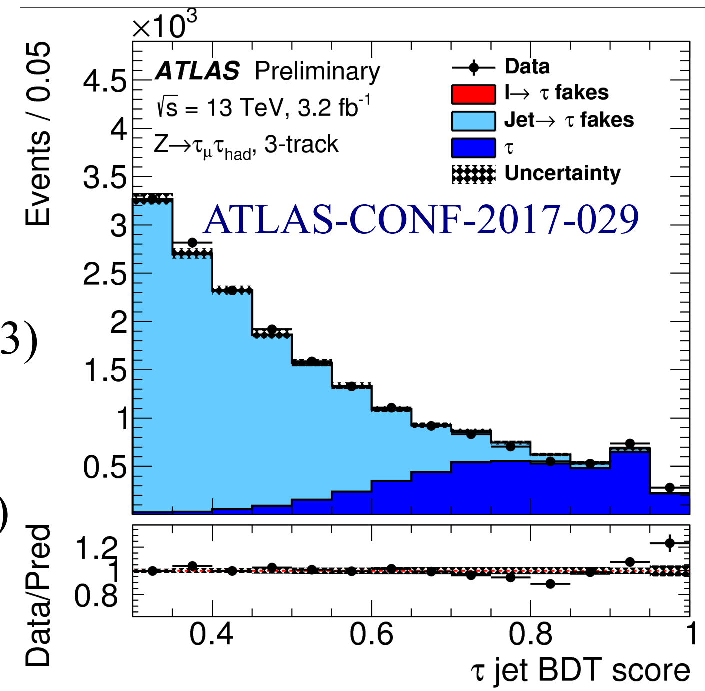
Main background:
- hadronic jets (rate!)
- electrons } for 1-track
- muons } for 1-track

TauID: ATLAS algorithm

- **seed: anti-k_T jets** (R=0.4) from clusters of **calo cells**, p_T>10 GeV, |η|<2.5
  - re-selection of dedicated tau primary vertex
  - tracks, p_T>1 GeV, R<0.2 within jet direction
    - **1 or 3 tracks** are required



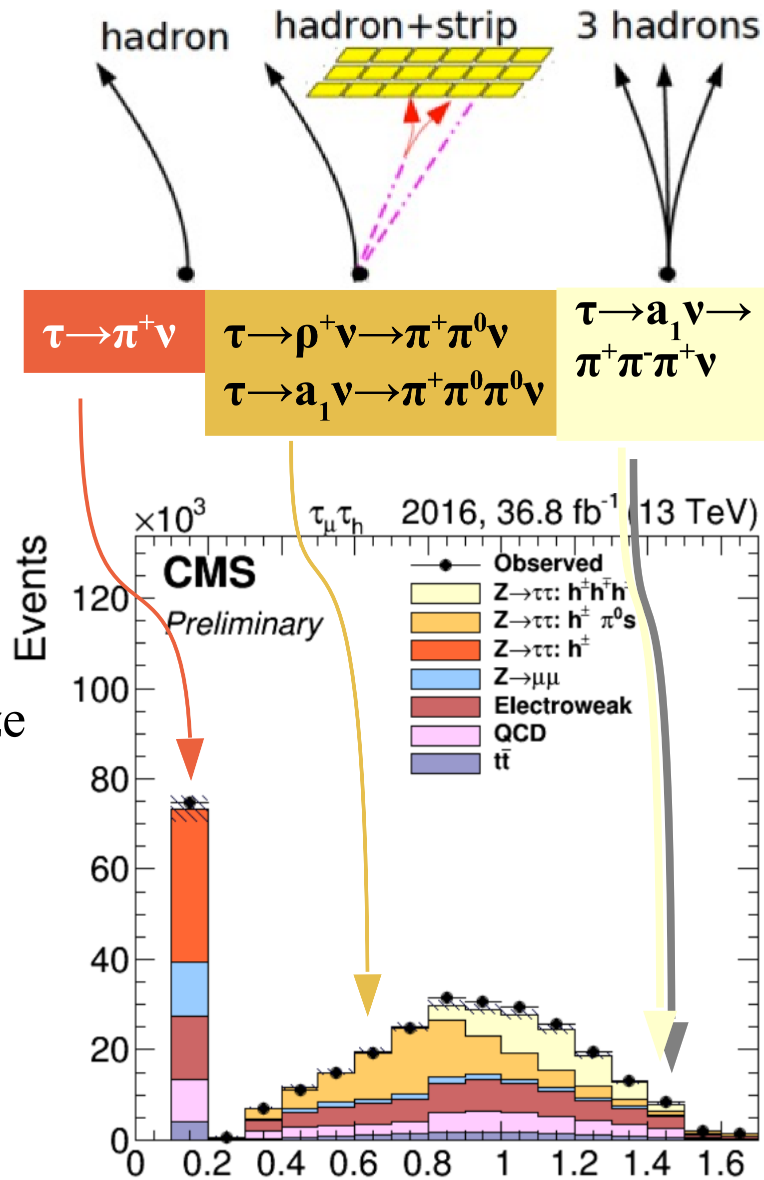
- **tau identification**
  - **BDT** discriminator versus hadronic jets
    - separately for 1- and 3-track candidates
    - 9 variables for 1-track, 10 for 3-track
      - collimation of tracks/calo cells
      - impact parameter (1-track) / secondary vertex (3)
      - visible mass
      - EM fraction of calorimeter deposits
      - (im)balance of calo/tracker measurements (E/p)



TauID: CMS algorithm

- **seed: anti-k_T jets** (R=0.4) of **particle flow** (PF) objects, p_T>14 GeV, |η|<2.5
  PF objects used for TauReco: $h^{\pm}$, γ, e

- ID step 1: **Decay mode identification**
  - Hadron-Plus-Strip algorithm
  - electrons and photons (p_T>0.5 GeV) in narrow strips form π^0 candidates
    - new in Run 2: p_T(e/γ)-dependent strip size
      Δφ=0.05-0.3, Δη=0.05-0.15
  - charged particles, p_T>0.5 GeV: π^+ candidates
  - π^+, $\pi^+\pi^0$, $\pi^+\pi^0\pi^0$, $\pi^+\pi^-\pi^+$ compatible with mass hypothesis (π^+,ρ, a_1) are kept



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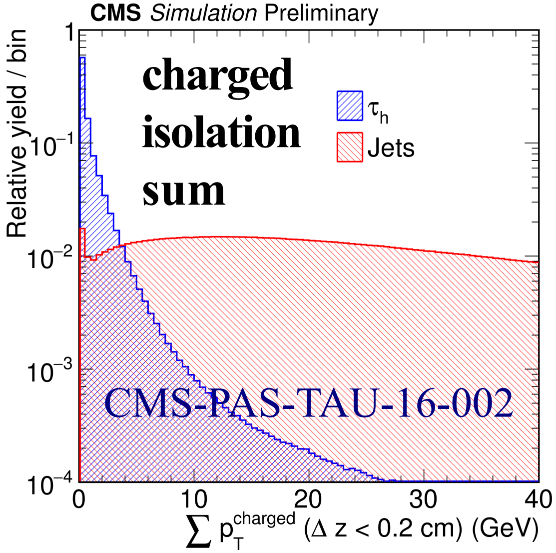
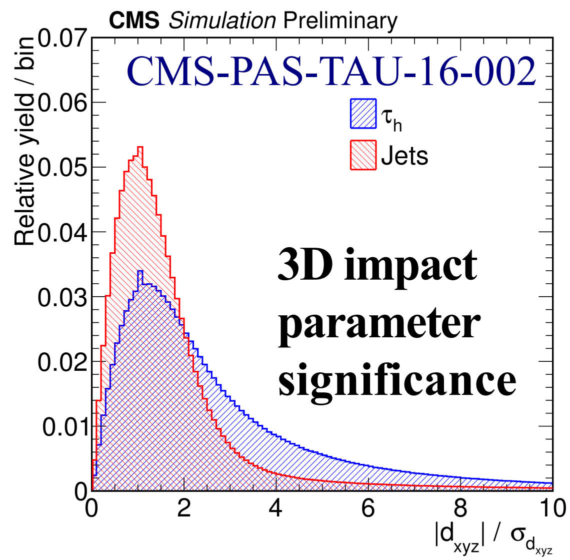
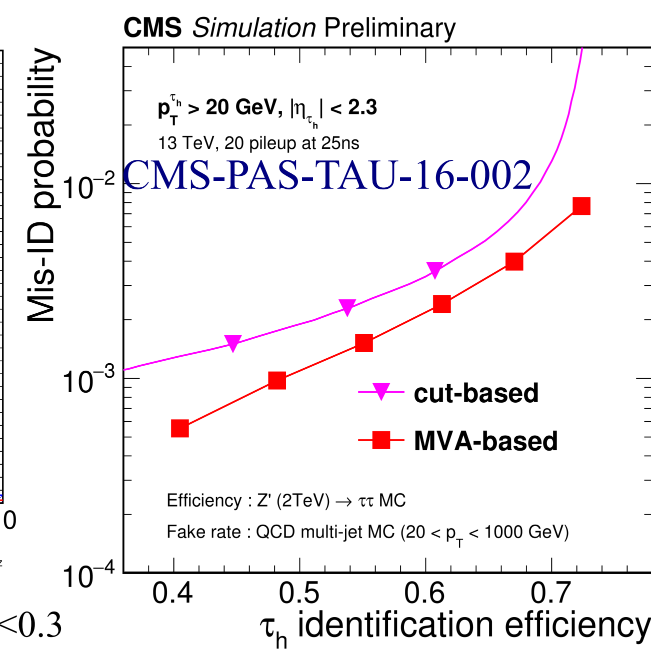
TauID: CMS algorithm

- ID step 2: **isolation** (+life time info)
  - **cut-based** isolation: selection cuts on
    - (pile-up corrected) p_T sum of charged/neutral particles in $\Delta R<0.5$*
    - p_T sum of e/γ, reco'ed in strips, outside p_T-dependent signal cone (0.05<ΔR<0.1)
  - **BDT-based** isolation: input variables
    - cut-based observables
    - shape (of e/γ wrt tau direction)
    - IP (leading track), flight distance
    - number of e/γ in signal & isolation cone







*alternatively, ΔR<0.3

TauID: Comparison ATLAS-CMS

- **Differences in TauID methodology**

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

*however, reco'ed for energy calibration of low-p_T τ_{had} – see next slides

**shrinking cone: $0.05<3/p_T[\text{GeV}]<0.1$

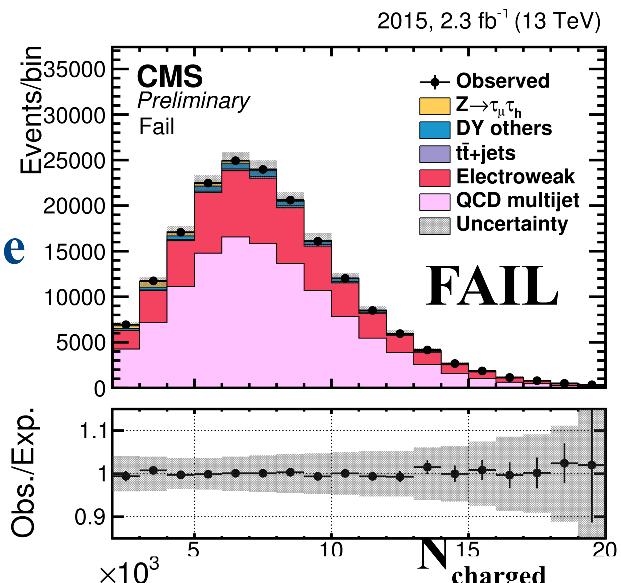
TauID: Performance

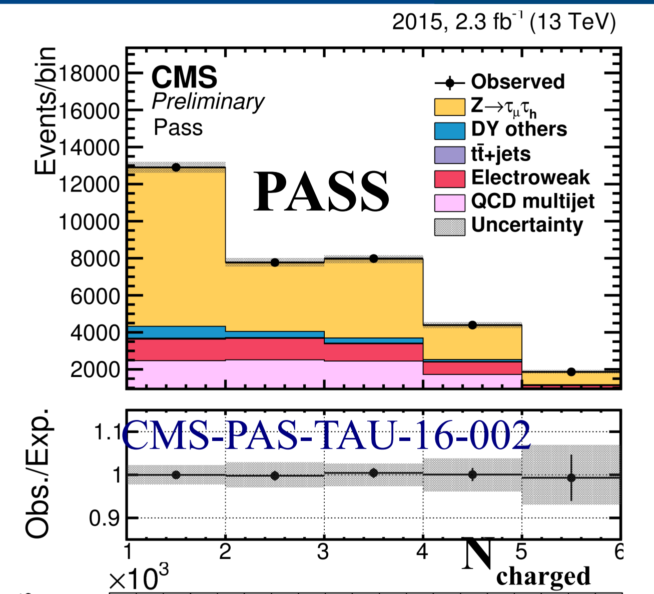
- $Z \to \tau\tau$: standard candle for tau measurements.
- Mostly: $\tau_\mu \tau_h$ **tag & probe**
  - ML fit to $m_{vis}(\mu,\tau)$ or $N_{charged}/N_{tracks}$ to extracts $\#\tau_{had}$ before/ after ID requirement

    => ratio = efficiency

Measured efficiencies agree with expectation from simulation within uncertainties.

- Complementary studies also in $W \to \tau\nu$ channel, and with $Z \to \mu\mu/\tau\tau$ ratios





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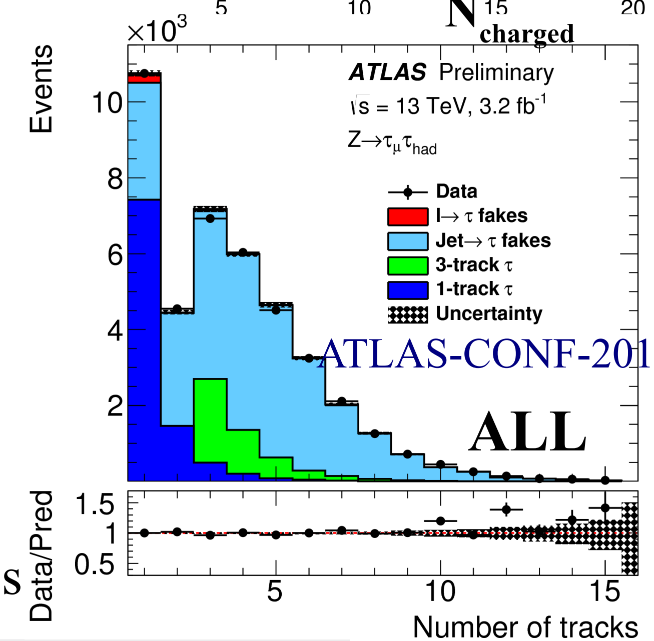
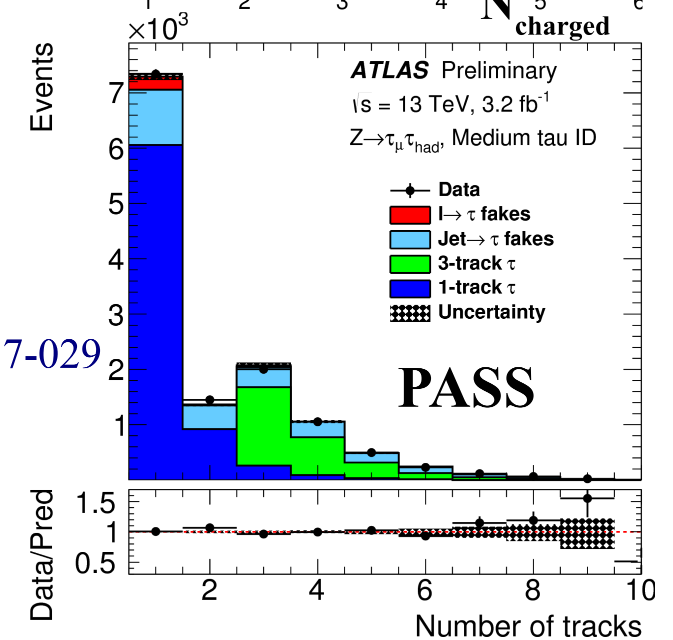
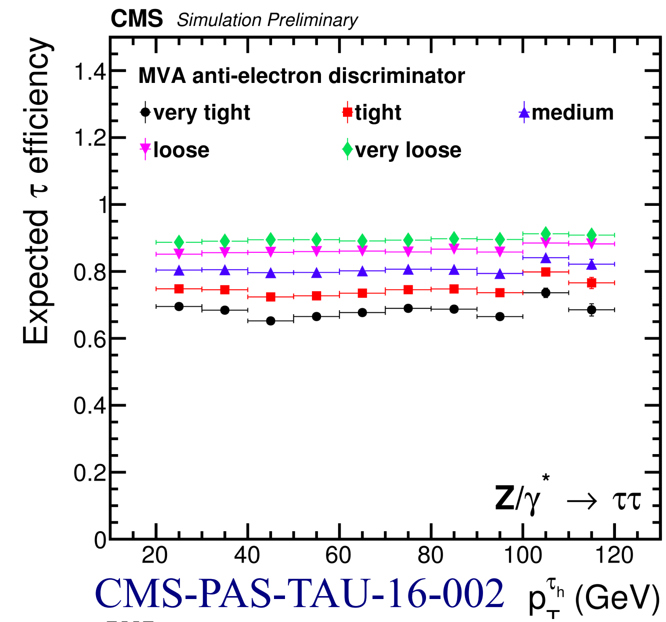




ATLAS-CONF-2017-029

Tau-versus-lepton discriminators

- τ_h **vs electron** discriminator
  - Depending on selection, e→τ_h background can be significant in the 1-track mode
  - CMS: BDT-based discriminator
    80% efficiency – reduce e misID to 10^{-2}–10^{-3}
  - ATLAS: dedicated WPs for inverted regular LLH-based electron ID
    [Run 1: dedicated τ-e BDT discriminator]



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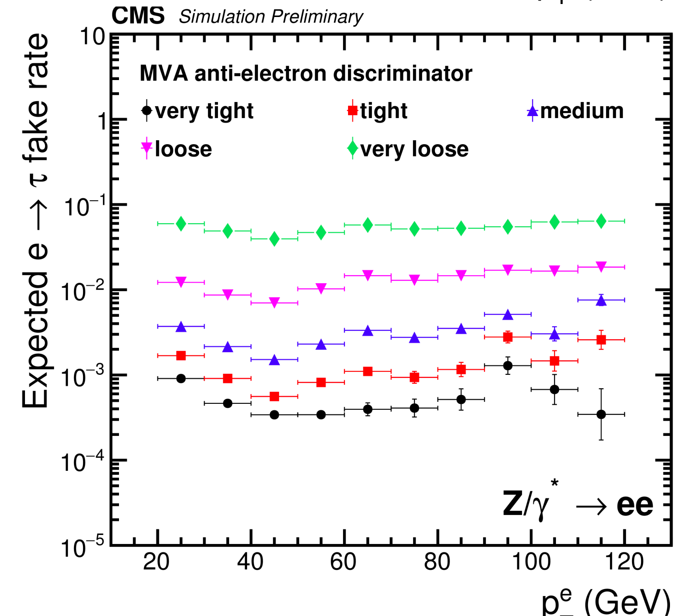


- τ_h **vs muon** discriminator
  - Slightly less relevant, efficiency 95%–100%
  - CMS: veto candidates if matching segments exist in the outer muon detector
  - ATLAS: no dedicated veto (overlap removal)
    [Run 1: dedicated muon veto]

TauID: Tau energy calibration, ATLAS

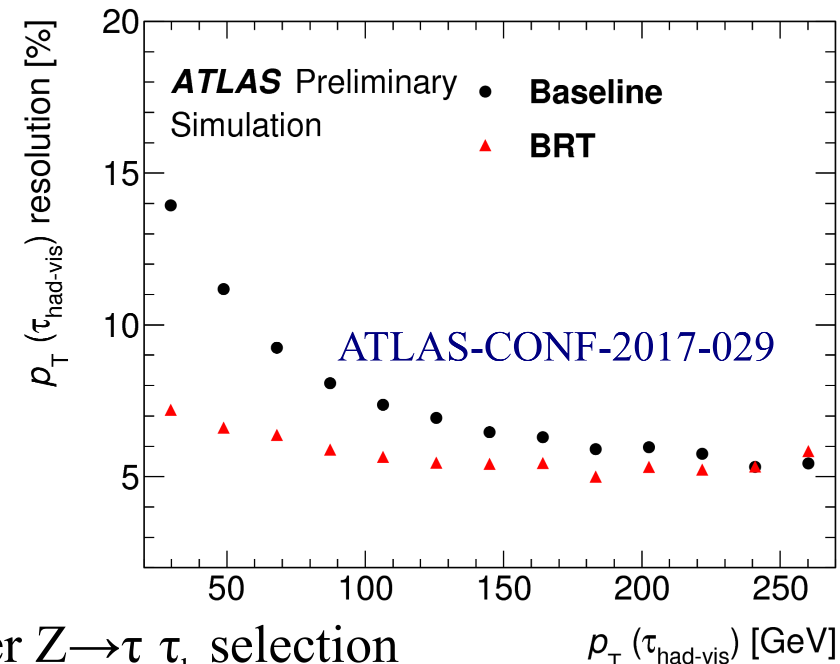
Two complementary methods

- **Calorimeter-based**
  - Input: LC-based calibration of topological calorimeter cell clusters

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

  - Corrections (from simulation): pile-up and detector response
  - Current ATLAS baseline

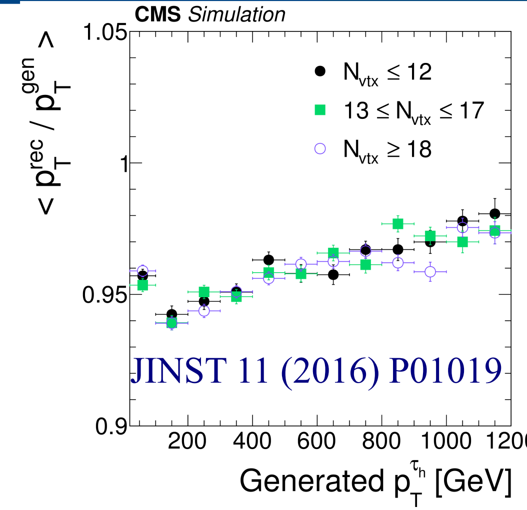
- **PF-based** (BRT)
  - Boosted Regression tree. Input:
    - Calorimeter quantities
    - Tracking quantities
    - Reconstructed h^+ and π^0 (PF)
  - Improves resolution for p_T<200 GeV



- Final data-based correction by fitting m_{vis} after $Z \rightarrow \tau_\mu \tau_h$ selection
  - Correct simulation to data (and hence away from the true response)

TauID: Tau energy calibration, CMS

- **PF inputs** are **already calibrated**
  - close to unity response & well-modeled



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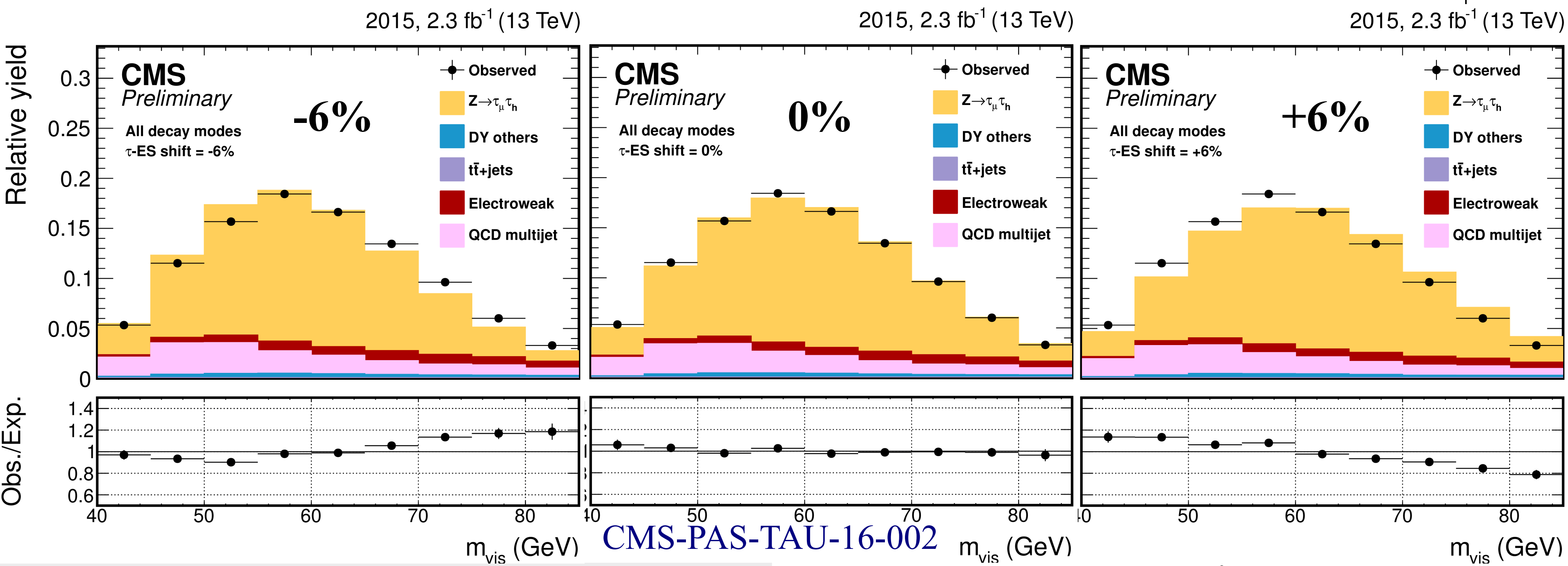
- Residual **data-to-sim correction**: In $Z \to \tau_\mu \tau_h$ events, fit m_{vis} or $m_{\tau h}$ for each decay mode* with shifted templates.
  - Shift: about ±1%, consistent with unity



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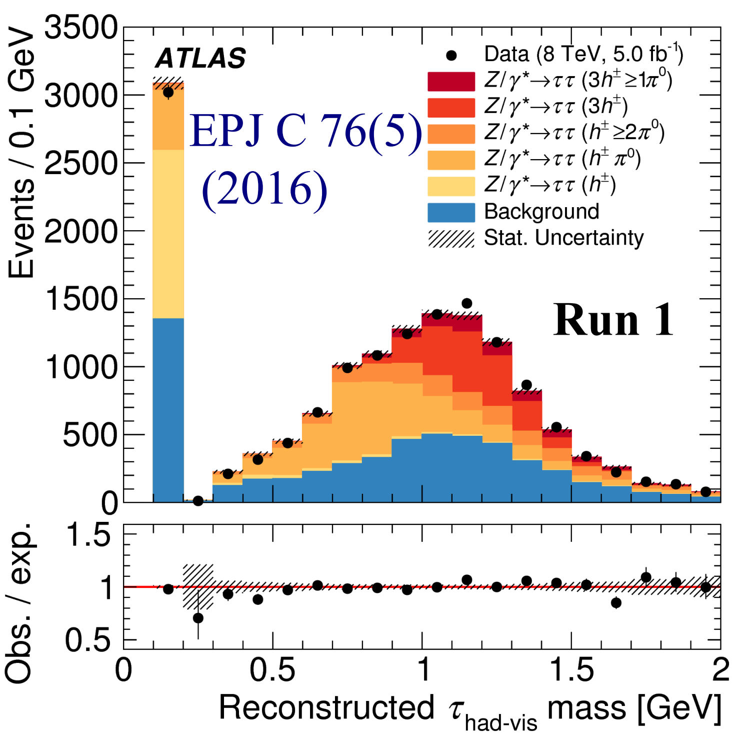
* $m_{\tau h}$ cannot be used for $1h^{+}0\pi^{0}$ mode

Tau energy calibration: Performance

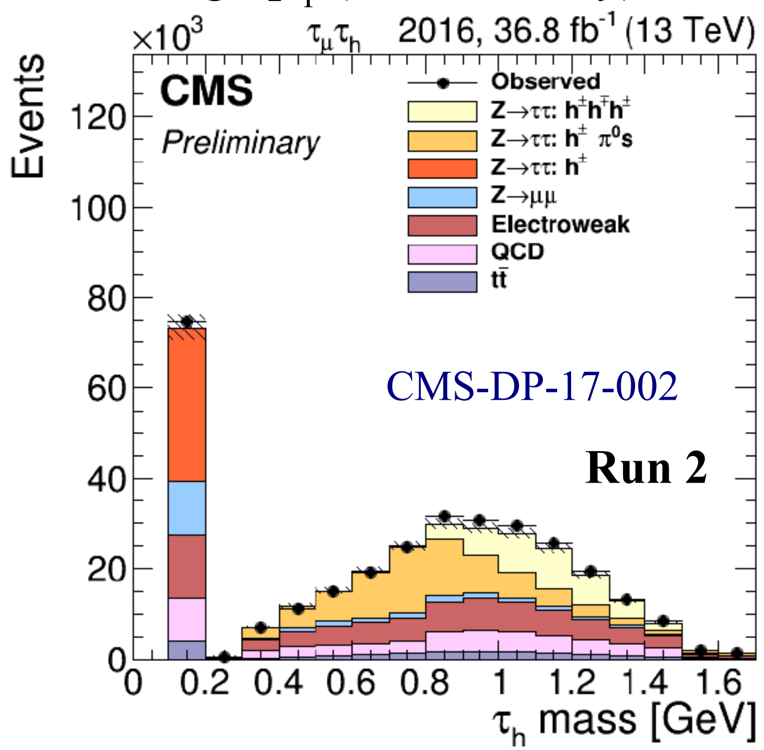
- Comparable quality of **τ_{had} mass reconstruction**

  [plots not 100% comparable – different ID requirements, e.g. mass window cuts.]

- **Resolution** definitions differ between ATLAS and CMS
  - Resolution in the ball park of 10% for both experiments
  - Calo-based calibration equally good or better for high p_T (ATLAS only)



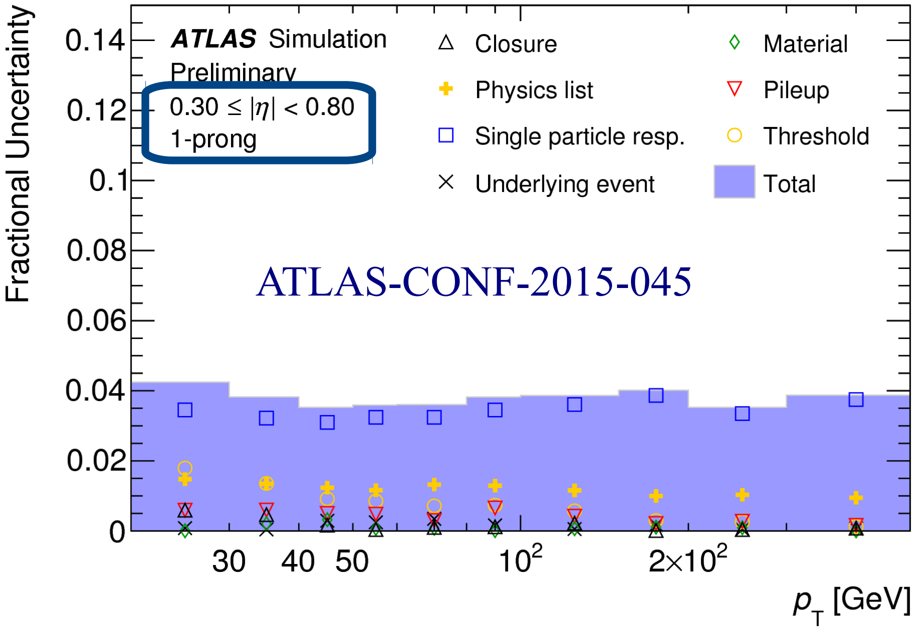
TauID WP: efficiency 55% / 40% for 1-/3-track



TauID WP: efficiency 55%
[wrt decay-mode finding]

Tau energy calibration: Systematics

- **ATLAS: Sim-based** evaluation (+data-based cross check)
  - MC: TES uncertainty **2% – 6%**, depending on p_T, η and #tracks
    – **absolute** scale uncertainty
  - Data-driven: **1% / 3%** for 1-/3-track
    – only account for **data/sim shifts**!

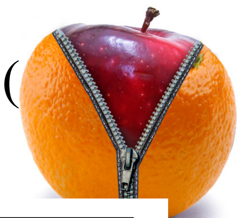


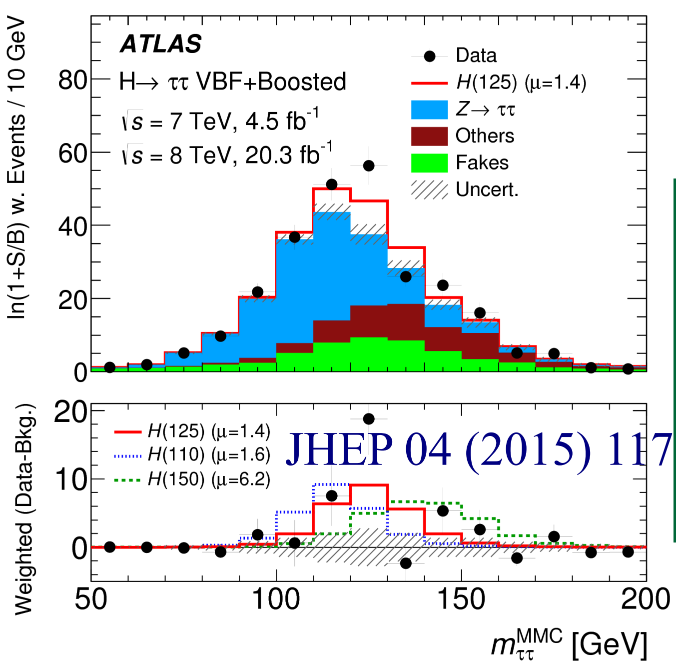
- **CMS**: Tag-and-probe analysis as described above (slide 10)
  - address uncertainties on **data/sim shift**
    <1% for $m_{\tau h}$ fit
    1-2% for m_{vis} (τ_h,μ) fit

Decay mode	Fit on m_{vis}	Fit on m_{τ_h}
All decay modes	$-1.0^{+1.1}_{-0.6}$	-
$h^\pm$	$+1.5^{+1.5}_{-1.8}$	-
$h^\pm\pi^0s$	$-1.5^{+0.8}_{-1.9}$	$-0.5^{+0.7}_{-0.9}$
$h^\pm h^\mp h^\pm$	$-1.0^{+2.3}_{-1.7}$	$+0.0^{+0.2}_{-0.4}$

CMS-PAS-TAU-16-002

Conclusions

- **Robust performance** of TauID at ATLAS and CMS
  - In spite of increasing pile-up, stable or improving performance
- Large **conceptual differences** between ATLAS and CMS
  - Calo-dominated versus PF (but recent introduction of TauPF by ATLAS)
- Comparison difficult ( -problem), but at the end of the(analysis) day, similar ratio true/misID in a realistic environment



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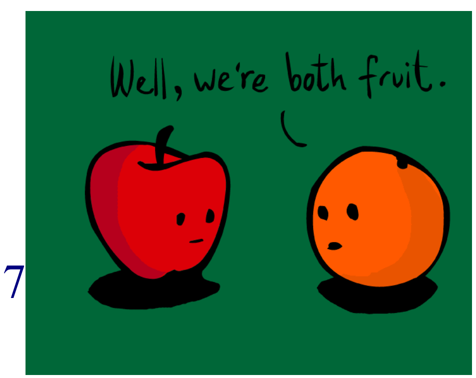

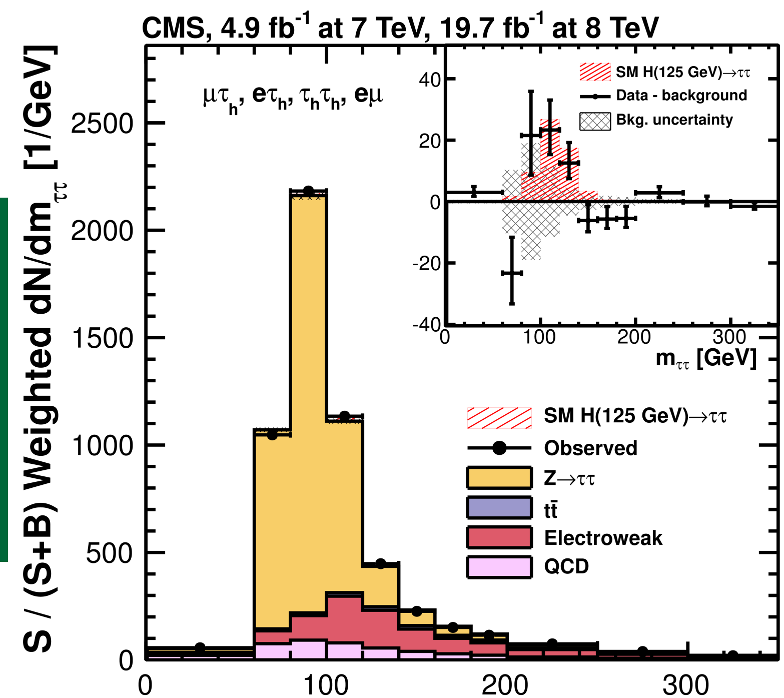

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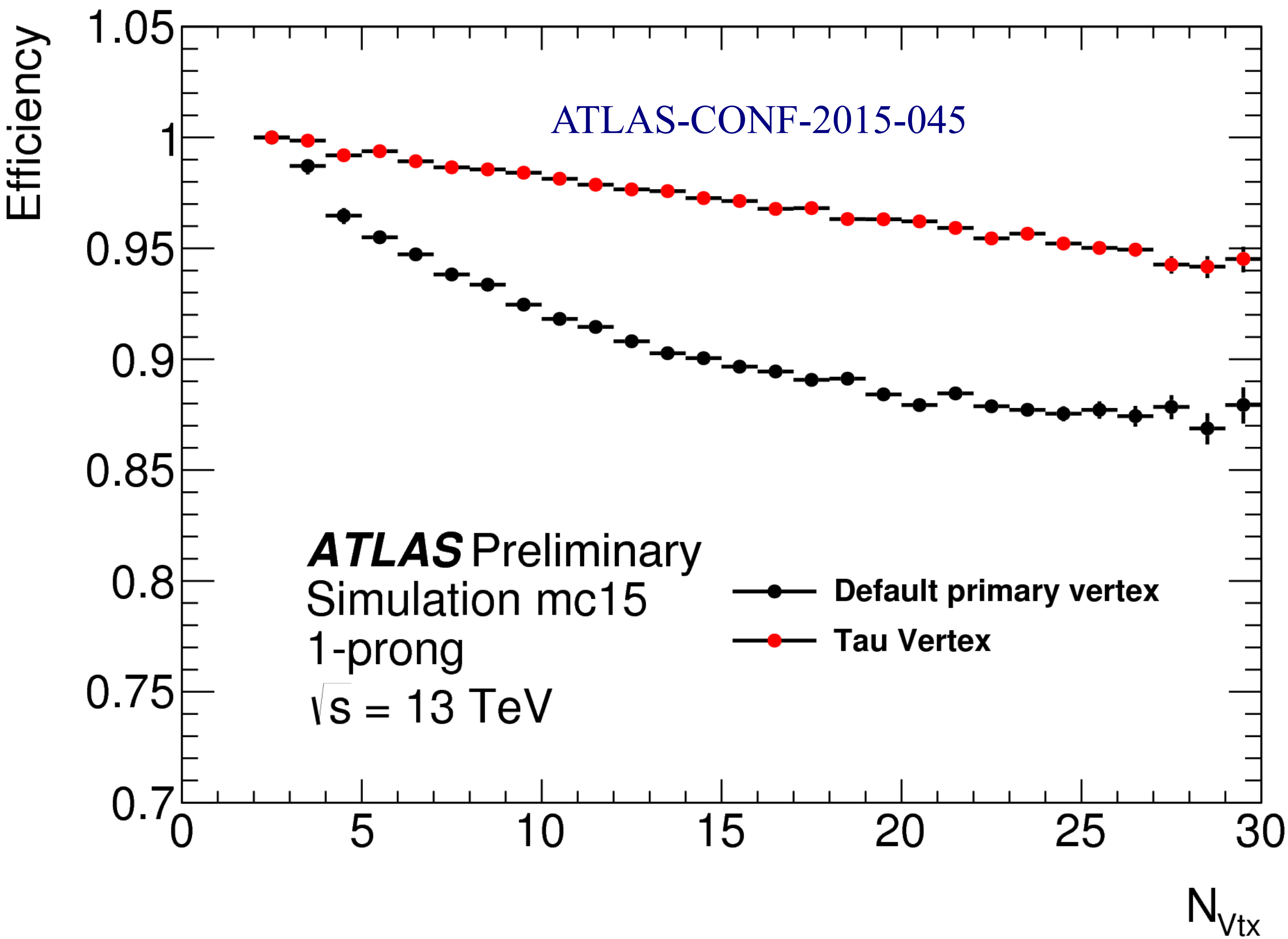
Backup slides



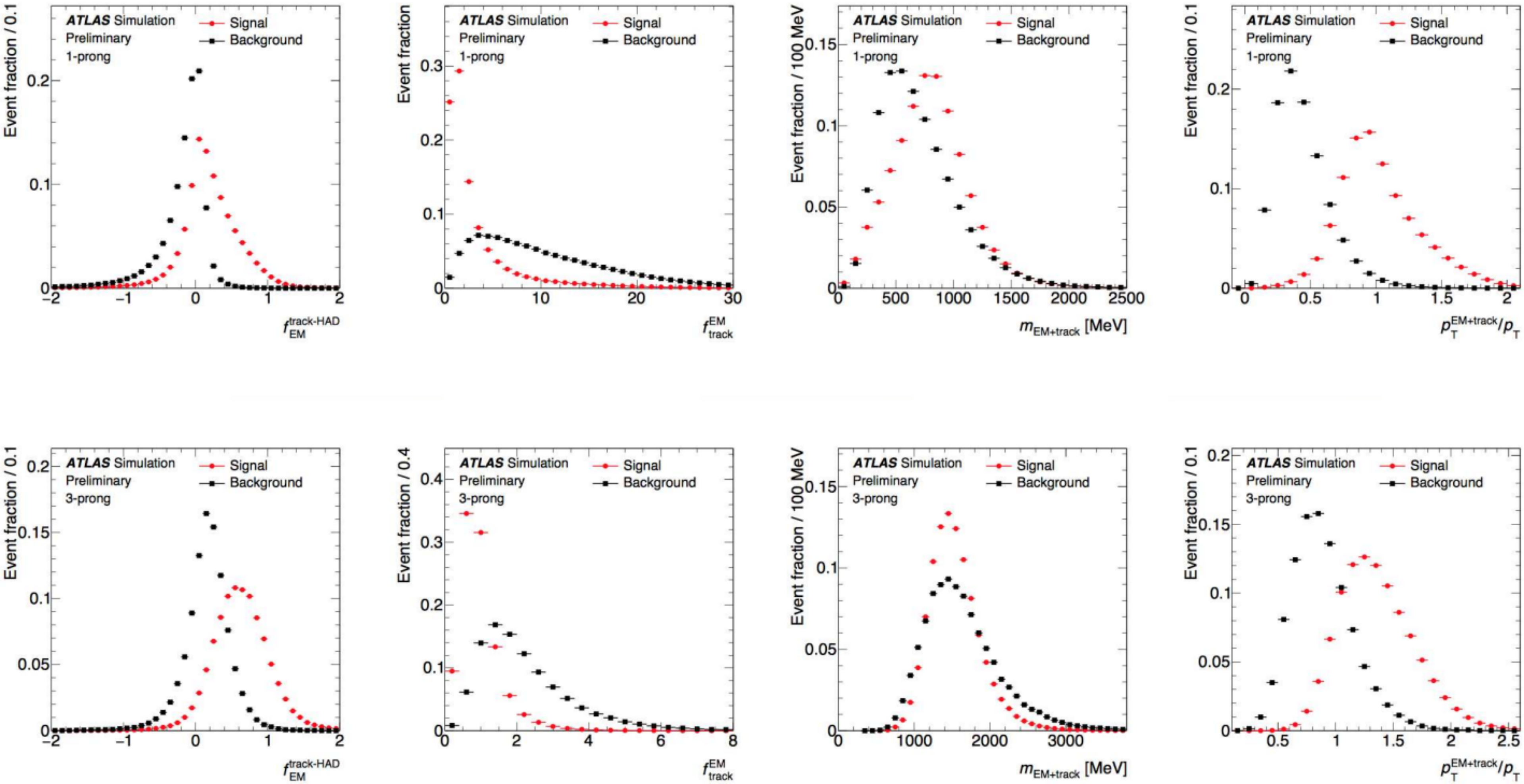
ATLAS-CONF-2015-045
Efficiency
1.05
1
0.95
0.9
0.85
0.8
0.75
0.7
0
5
10
15
20
25
30
N_{Vtx}
ATLAS Preliminary
Simulation mc15
1-prong
$\sqrt{s}$ = 13 TeV
Default primary vertex
Tau Vertex

ATLAS-CONF-2015-045

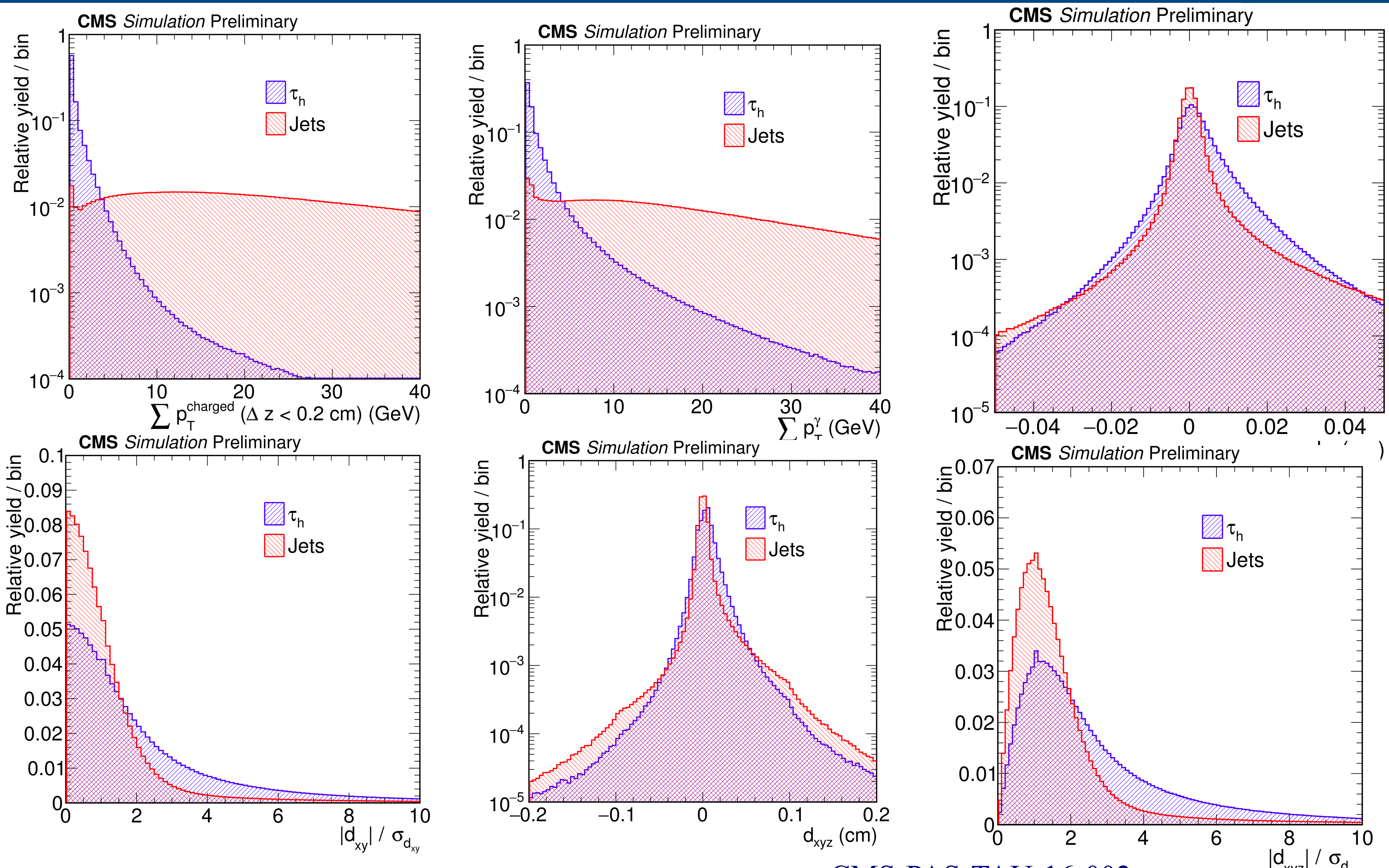
Variable	Offline	
	1-track	3-track
f_{cent}	●	●
$f^{-1}_{\mathrm{leadtrack}}$	●	●
	●	●
$\lvert S_{\mathrm{leadtrack}} \rvert$	●	
$f^{\mathrm{track}}_{\mathrm{iso}}$	●	
ΔR_{Max}		●
$S^{\mathrm{flight}}_{\mathrm{T}}$		●
m_{track}		●
$f^{\mathrm{track-HAD}}_{\mathrm{EM}}$	●	●
$f^{\mathrm{EM}}_{\mathrm{track}}$	●	●
$m_{\mathrm{EM+track}}$	●	●
$p^{\mathrm{EM+track}}_{\mathrm{T}}/p_{\mathrm{T}}$	●	●

(some) ATLAS BDT TauID input vars

ATLAS-CONF-2015-045



CMS BDT TauID input vars (1)



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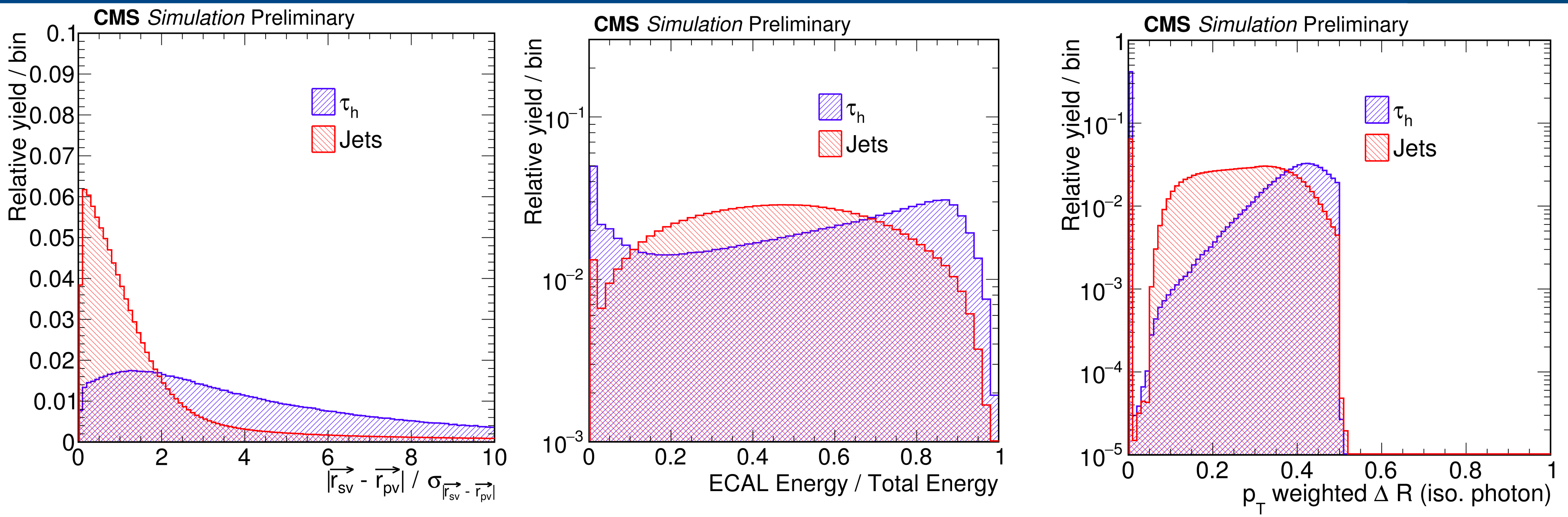
CMS BDT TauID input vars (2)



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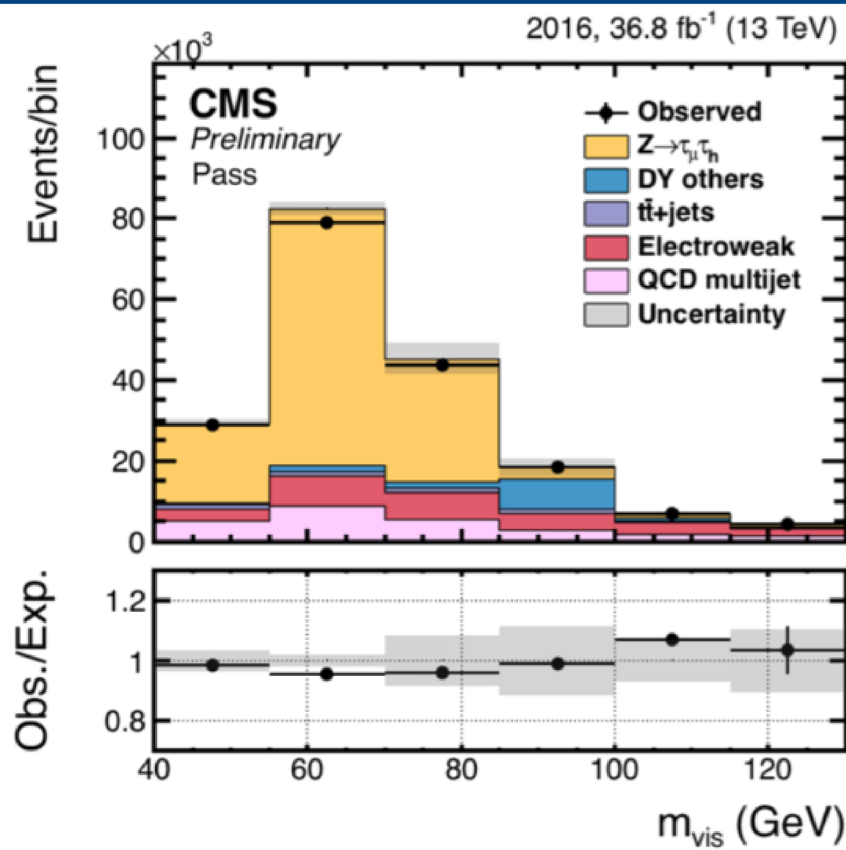

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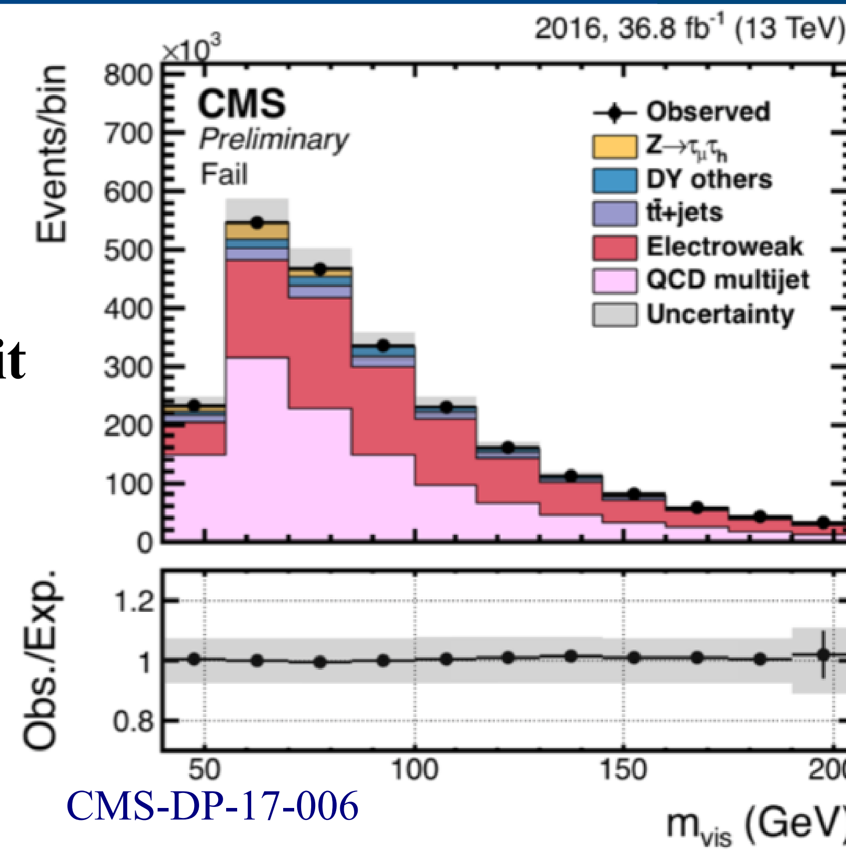

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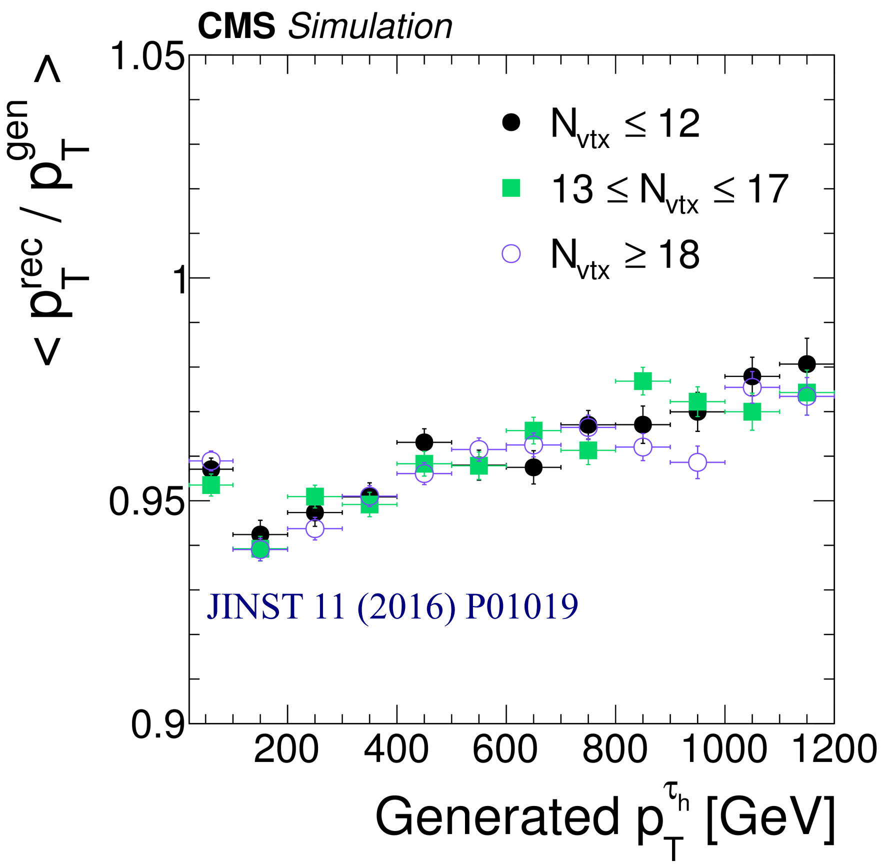
CMS Simulation
$N_{vtx} \leq 12$
$13 \leq N_{vtx} \leq 17$
$N_{vtx} \geq 18$
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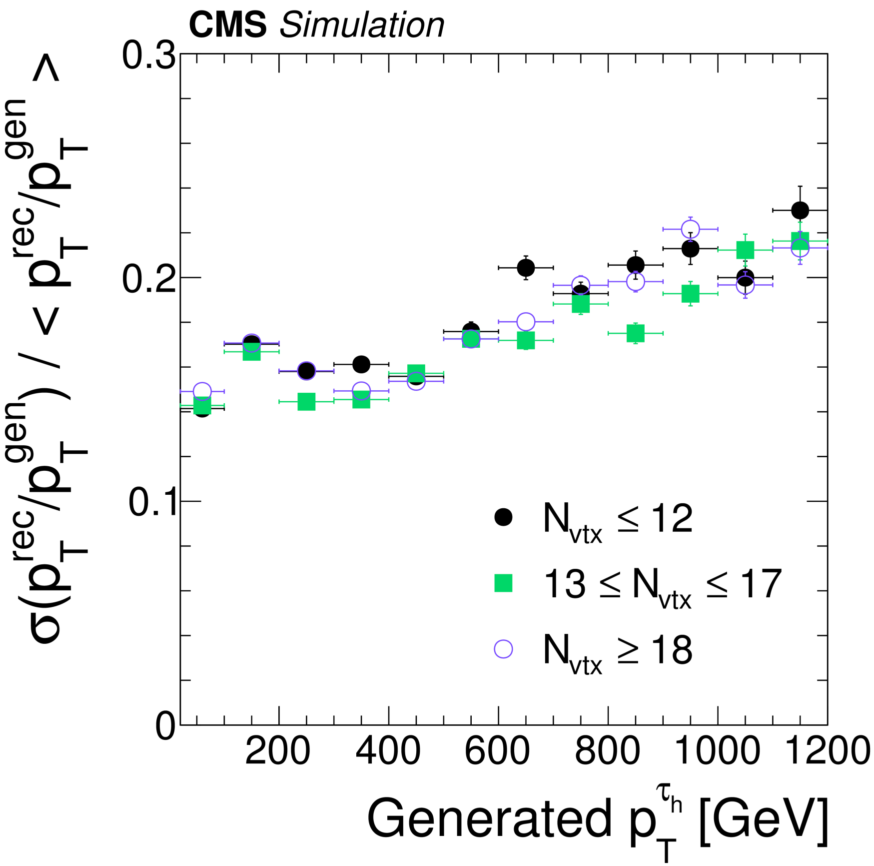
$< p_T^{rec} / p_T^{gen} >$
Generated $p_T^{\tau_h}$ [GeV]


CMS Simulation
$N_{vtx} \leq 12$
$13 \leq N_{vtx} \leq 17$
$N_{vtx} \geq 18$
$\sigma(p_T^{rec}/p_T^{gen}) / < p_T^{rec}/p_T^{gen} >$
Generated $p_T^{\tau_h}$ [GeV]

Data-driven TES corrections

CMS

Decay mode	Fit on m_{vis}	Fit on m_{τ_h}
All decay modes	$-1.0^{+1.1}_{-0.6}$	-
$h^{\pm}$	$+1.5^{+1.5}_{-1.8}$	-
$h^{\pm}\pi^{0}s$	$-1.5^{+0.8}_{-1.9}$	$-0.5^{+0.7}_{-0.9}$
$h^{\pm}h^{\mp}h^{\pm}$	$-1.0^{+2.3}_{-1.7}$	$+0.0^{+0.2}_{-0.4}$

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 $\tau_{\text{had-vis}}$ with one and three associated tracks, respectively. The corrections are applied to the momentum of $\tau_{\text{had-vis}}$ in simulation in order to yield agreement (on average) with data. The resulting m_{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 $\tau_{\text{had-vis}}$ with one and three associated tracks, respectively.

References

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TauPublicCollisionResults

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsPFT

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TAU/index.html

http://cms-results.web.cern.ch/cms-results/public-results/publications/TAU/index.html