



Stony Brook University



Tau Leptons at ATLAS

Quentin Buat (SBU) – May 20th, 2021

The Tau Lepton

- Predicted by Y-S Tsai in 1971
- <https://journals.aps.org/prd/pdf/10.1103/PhysRevD.4.2821>

Decay Correlations of Heavy Leptons in $e^+ + e^- \rightarrow l^+ + l^- \ast$

Yung-Su Tsai

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 22 July 1971)

Assuming that leptons heavier than muons exist in nature, we consider their decay modes and the correlations between the decay products of l^+ and l^- in the colliding-beam experiment: $e^+ + e^- \rightarrow l^+ + l^-$. Far above the threshold, the helicities of l^+ and l^- tend to be opposite to each other. Near the threshold the directions of spins of l^+ and l^- prefer to be parallel to each other, and the sum of the two spins prefers to be either parallel or anti-parallel to the direction of the incident electron. Because the parity conservation is violated maximally in the decays of l^+ and l^- , the angular distributions of decay products depend strongly on the spin orientation of the heavy leptons. Since the spins of l^+ and l^- are strongly correlated in the production, we found a strong correlation between the energy-angle distributions of the decay products of l^+ and l^- . The decay widths of l^- into channels $\nu_l \bar{\nu}_e e^-$, $\nu_l \bar{\nu}_\mu \mu^-$, $\nu_l \pi^-$, $\nu_l K^-$, $\nu_l \rho^-$, $\nu_l K^*$, $\nu_l A_1$, $\nu_l Q$, and $\nu_l +$ hadron continuum as functions of the mass of l^- are estimated.

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

M. L. Perl, G. S. Abrams, A. M. Boyarski, M. Breidenbach, D. D. Briggs, F. Bulos, W. Chinowsky, J. T. Dakin,[†] G. J. Feldman, C. E. Friedberg, D. Fryberger, G. Goldhaber, G. Hanson, F. B. Heile, B. Jean-Marie, J. A. Kadyk, R. R. Larsen, A. M. Litke, D. Lüke,[‡] B. A. Lulu, V. Lüth, D. Lyon, C. C. Morehouse, J. M. Paterson, F. M. Pierre,[§] T. P. Pun, P. A. Rapidis, B. Richter, B. Sadoulet, R. F. Schwitters, W. Tanenbaum, G. H. Trilling, F. Vannucci,^{||} J. S. Whitaker, F. C. Winkelmann, and J. E. Wiss

Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 18 August 1975)

We have found events of the form $e^+ + e^- \rightarrow e^\pm + \mu^\mp + \text{missing energy}$, in which no other charged particles or photons are detected. Most of these events are detected at or above a center-of-mass energy of 4 GeV. The missing-energy and missing-momentum spectra require that at least two additional particles be produced in each event. We have no conventional explanation for these events.

- Discovered in 1975 at SLAC by M. L. Perl et al.
- [PhysRevLett.35.1489](https://journals.aps.org/prl/pdf/10.1103/PhysRevLett.35.1489)

Since 1975...

- Wealth of measurements to characterise the tau lepton from electron colliders

- $m_\tau = 1.777 \text{ GeV}$, $c\tau = 87 \mu\text{m}$
- Only lepton with allowed hadronic decay modes in the SM



$$J = \frac{1}{2}$$

τ discovery paper was PERL 75. $e^+ e^- \rightarrow \tau^+ \tau^-$ cross-section threshold behavior and magnitude are consistent with pointlike spin-1/2 Dirac particle. BRANDELIK 78 ruled out pointlike spin-0 or spin-1 particle. FELDMAN 78 ruled out $J = 3/2$. KIRKBY 79 also ruled out $J=\text{integer}$, $J = 3/2$.

τ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	COMMENT
1776.86 ± 0.12 OUR AVERAGE				

τ MEAN LIFE

VALUE (10^{-15} s)	EVTS	DOCUMENT ID	TECN	COMMENT
290.3 ± 0.5 OUR AVERAGE				

τ^- DECAY MODES

τ^\pm modes are charge conjugates of the modes below. " h^\pm " stands for π^\pm or K^\pm . " ℓ " stands for e or μ . "Neutrals" stands for γ 's and/or π^0 's.

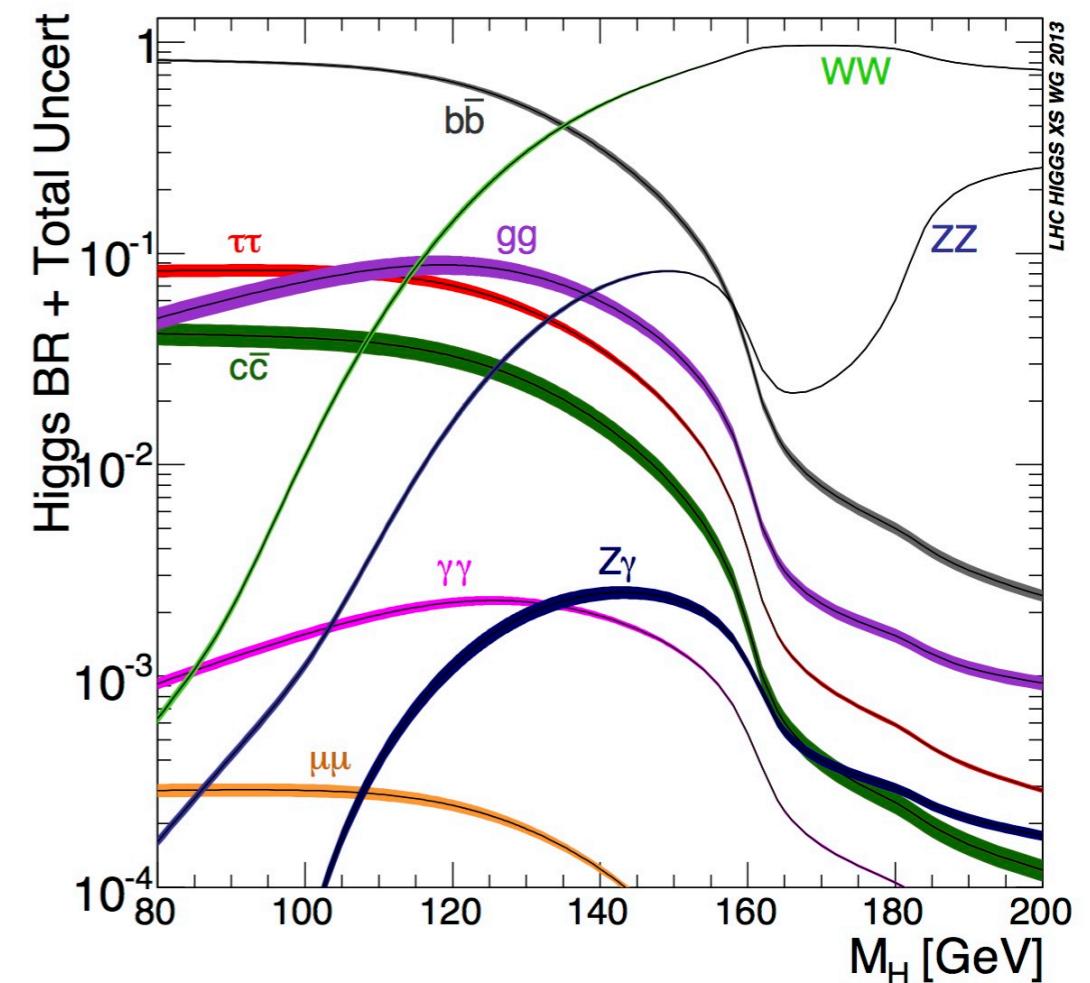
Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Modes with one charged particle		
Γ_1 particle $^- \geq 0$ neutrals $\geq 0 K^0 \nu_\tau$ ("1-prong")	(85.24 ± 0.06) %	
Γ_2 particle $^- \geq 0$ neutrals $\geq 0 K_L^0 \nu_\tau$	(84.58 ± 0.06) %	
Γ_3 $\mu^- \bar{\nu}_\mu \nu_\tau$	[a] (17.39 ± 0.04) %	
Γ_4 $\mu^- \bar{\nu}_\mu \nu_\tau \gamma$	[b] (3.67 ± 0.08) × 10 ⁻³	
Γ_5 $e^- \bar{\nu}_e \nu_\tau$	[a] (17.82 ± 0.04) %	
Γ_6 $e^- \bar{\nu}_e \nu_\tau \gamma$	[b] (1.83 ± 0.05) %	
Γ_7 $h^- \geq 0 K_L^0 \nu_\tau$	(12.03 ± 0.05) %	
Γ_8 $h^- \nu_\tau$	(11.51 ± 0.05) %	
Γ_9 $\pi^- \nu_\tau$	[a] (10.82 ± 0.05) %	
Γ_{10} $K^- \nu_\tau$	[a] (6.96 ± 0.10) × 10 ⁻³	
Γ_{11} $h^- \geq 1$ neutrals ν_τ	(37.01 ± 0.09) %	
Γ_{12} $h^- \geq 1 \pi^0 \nu_\tau$ (ex. K^0)	(36.51 ± 0.09) %	
Γ_{13} $h^- \geq 0$	(25.02 ± 0.09) %	
	± 0.09) %	
	± 3.2) × 10 ⁻³	
	± 0.15) × 10 ⁻³	
	± 0.09) %	
	± 0.10) %	
	± 0.10) %	

5+ pages of known decay modes

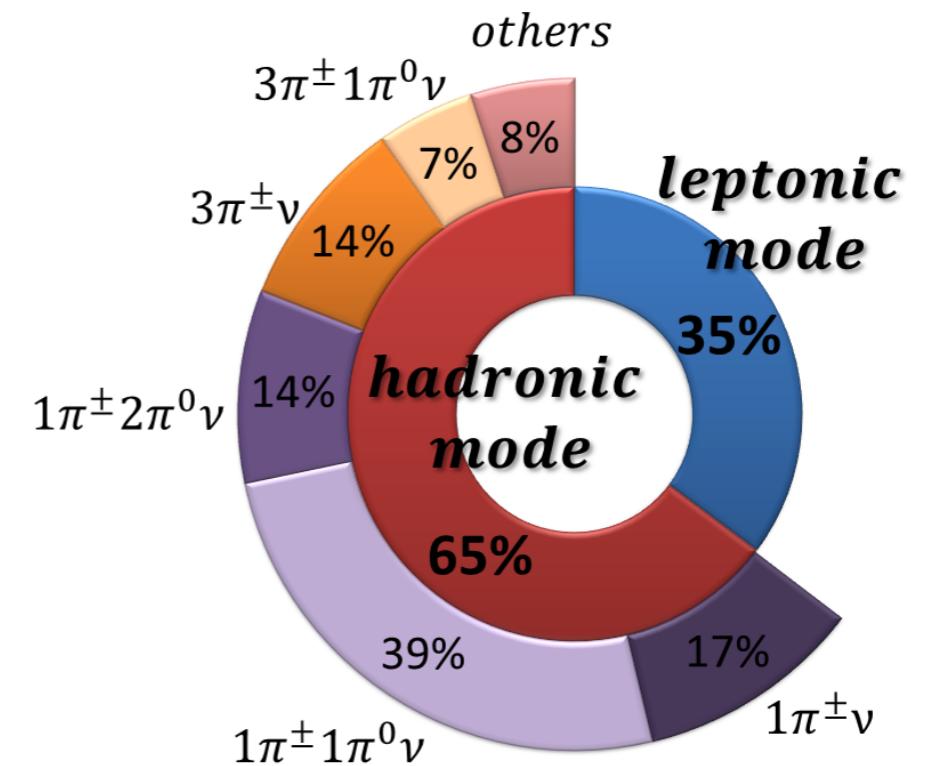
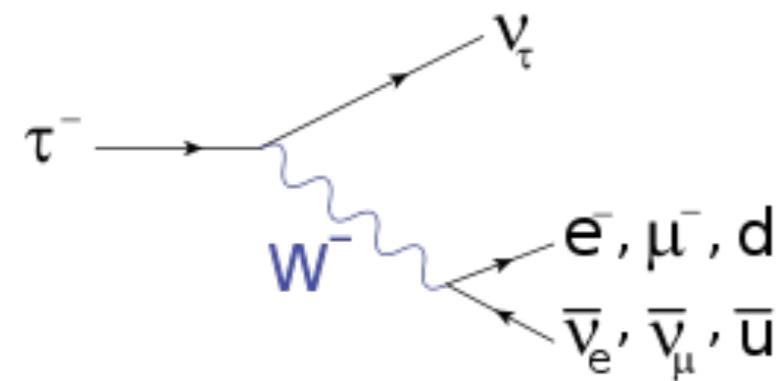
Γ_{21}	$\pi^- 2\pi^0 \nu_\tau$ (ex. K^0), scalar	< 9	$\times 10^{-3}$	CL=95%
Γ_{22}	$\pi^- 2\pi^0 \nu_\tau$ (ex. K^0), vector	< 7	$\times 10^{-3}$	CL=95%
Γ_{23}	$K^- 2\pi^0 \nu_\tau$ (ex. K^0)	[a] (6.5 ± 2.2) × 10 ⁻⁴		
Γ_{24}	$h^- \geq 3\pi^0 \nu_\tau$	(1.34 ± 0.07) %		
Γ_{25}	$h^- \geq 3\pi^0 \nu_\tau$ (ex. K^0)	(1.25 ± 0.07) %		
Γ_{26}	$h^- 3\pi^0 \nu_\tau$	(1.18 ± 0.07) %		
Γ_{27}	$\pi^- 3\pi^0 \nu_\tau$ (ex. K^0)	[a] (1.04 ± 0.07) %		
Γ_{28}	$K^- 3\pi^0 \nu_\tau$ (ex. K^0 , η)	[a] (4.8 ± 2.1) × 10 ⁻⁴		
Γ_{29}	$h^- 4\pi^0 \nu_\tau$ (ex. K^0)	(1.6 ± 0.4) × 10 ⁻³		
Γ_{30}	$h^- 4\pi^0 \nu_\tau$ (ex. K^0, η)	[a] (1.1 ± 0.4) × 10 ⁻³		
Γ_{31}	$a_1(1260) \nu_\tau \rightarrow \pi^- \gamma \nu_\tau$	(3.8 ± 1.5) × 10 ⁻⁴		
Γ_{32}	$K^- \geq 0 \pi^0 \geq 0 K^0 \geq 0 \gamma \nu_\tau$	(1.552 ± 0.029) %		
Γ_{33}	$K^- \geq 1 (\pi^0 \text{ or } K^0 \text{ or } \gamma) \nu_\tau$	(8.59 ± 0.28) × 10 ⁻³		

The Tau Lepton and the Higgs boson

- $m_\tau / m_\mu = 16.7$
 - $H \rightarrow \tau\tau$ branching ratio is 280x larger than $H \rightarrow \mu\mu$ BR
 - As a third generation object, many BSM scenarios favour large couplings to the tau lepton



Tau Lepton Decays

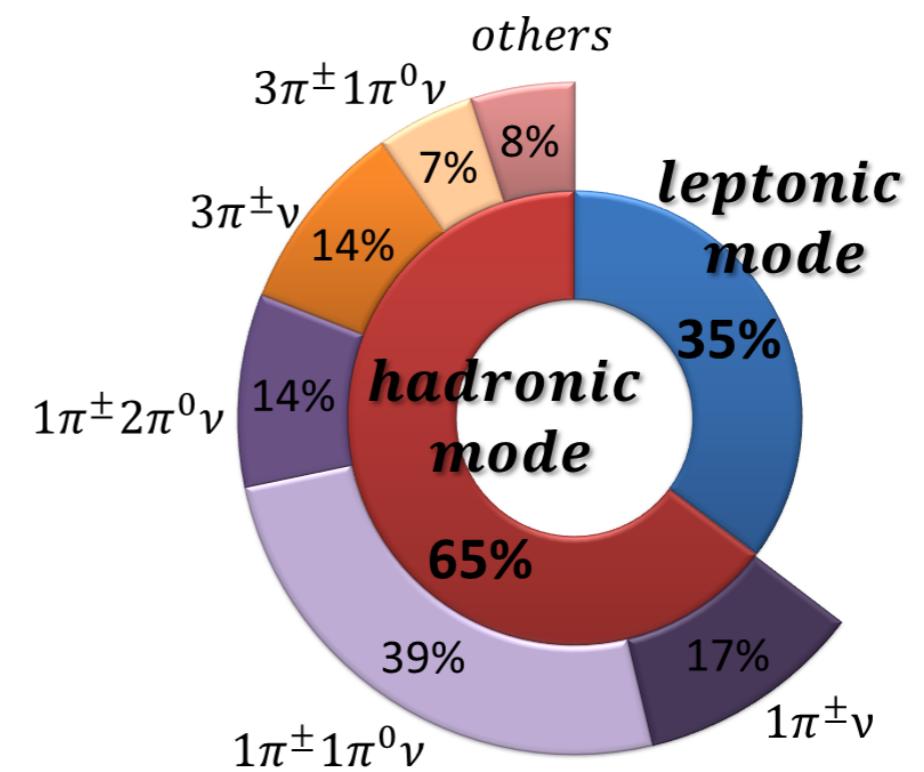


- $c\tau = 87 \text{ }\mu\text{m}$
- First active layer of ATLAS is at 33mm

Main decay modes

Why the hadronic decay modes?

- Branching fraction = 65%
- Only one neutrino
- Multi-body visible decays carry a lot of information about the parent particle



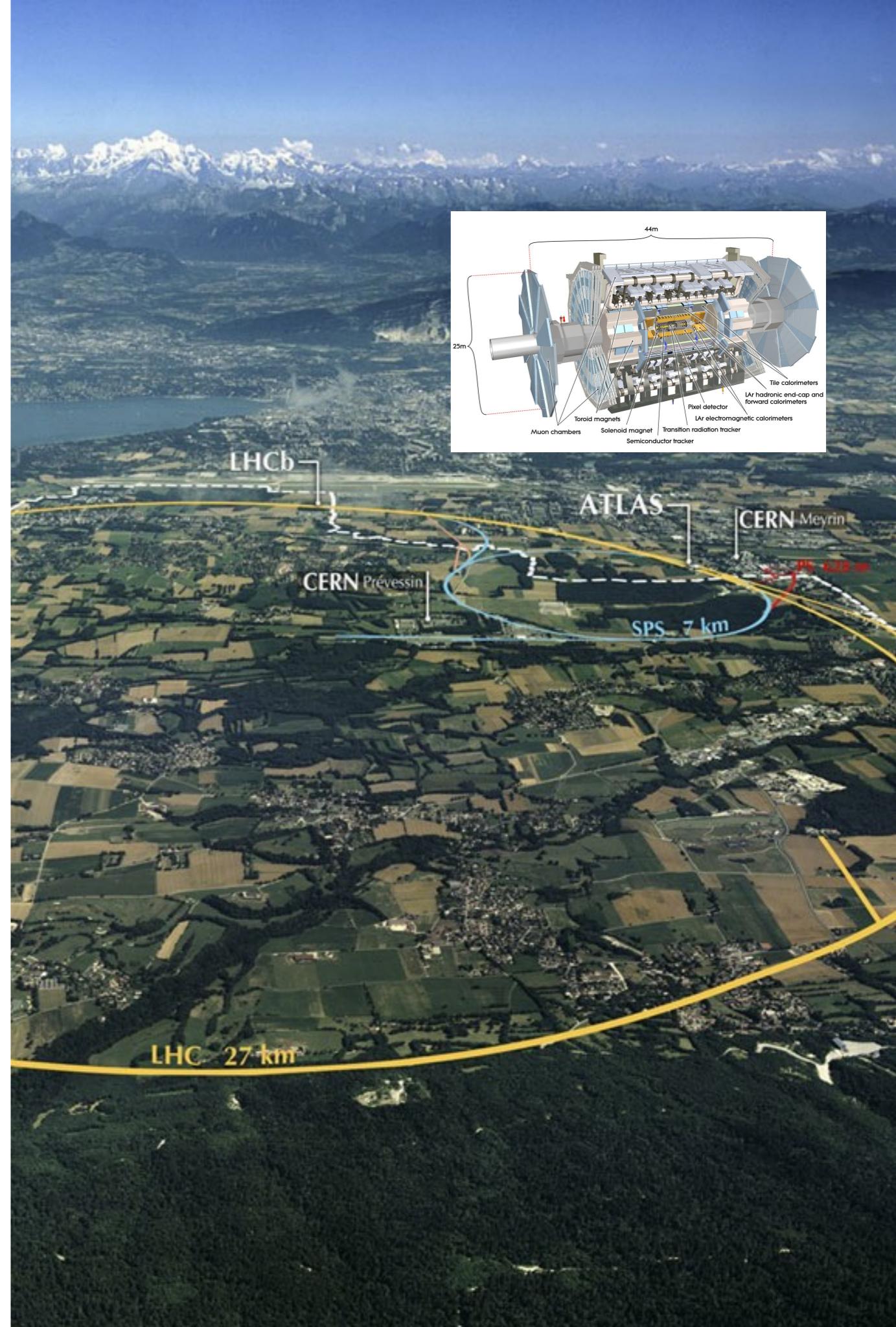
Main decay modes

Outline

- Hadronic tau lepton detection strategy
- Calibrating hadronic taus
- A powerful tool for the ATLAS physics program
- Triggering ATLAS with hadronic tau leptons

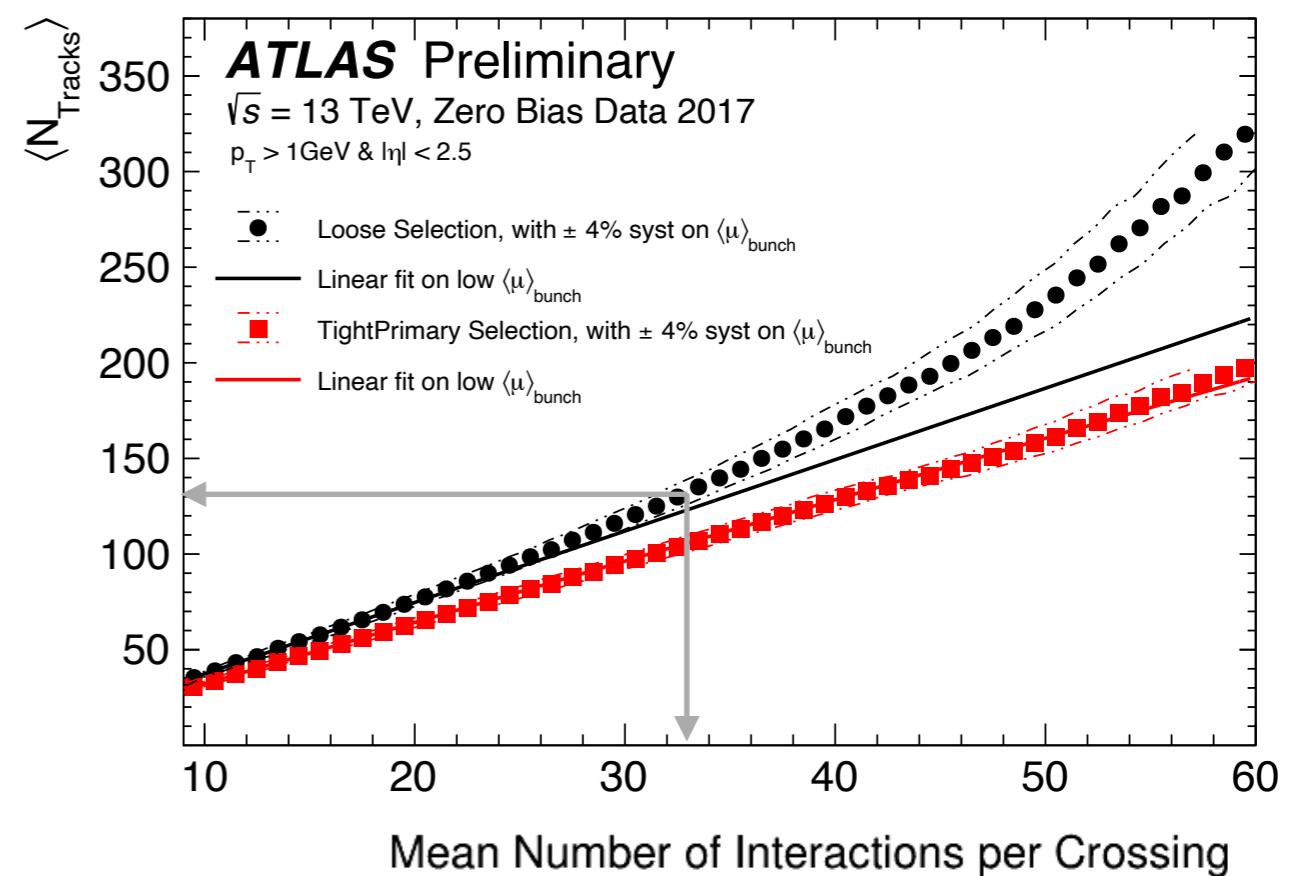
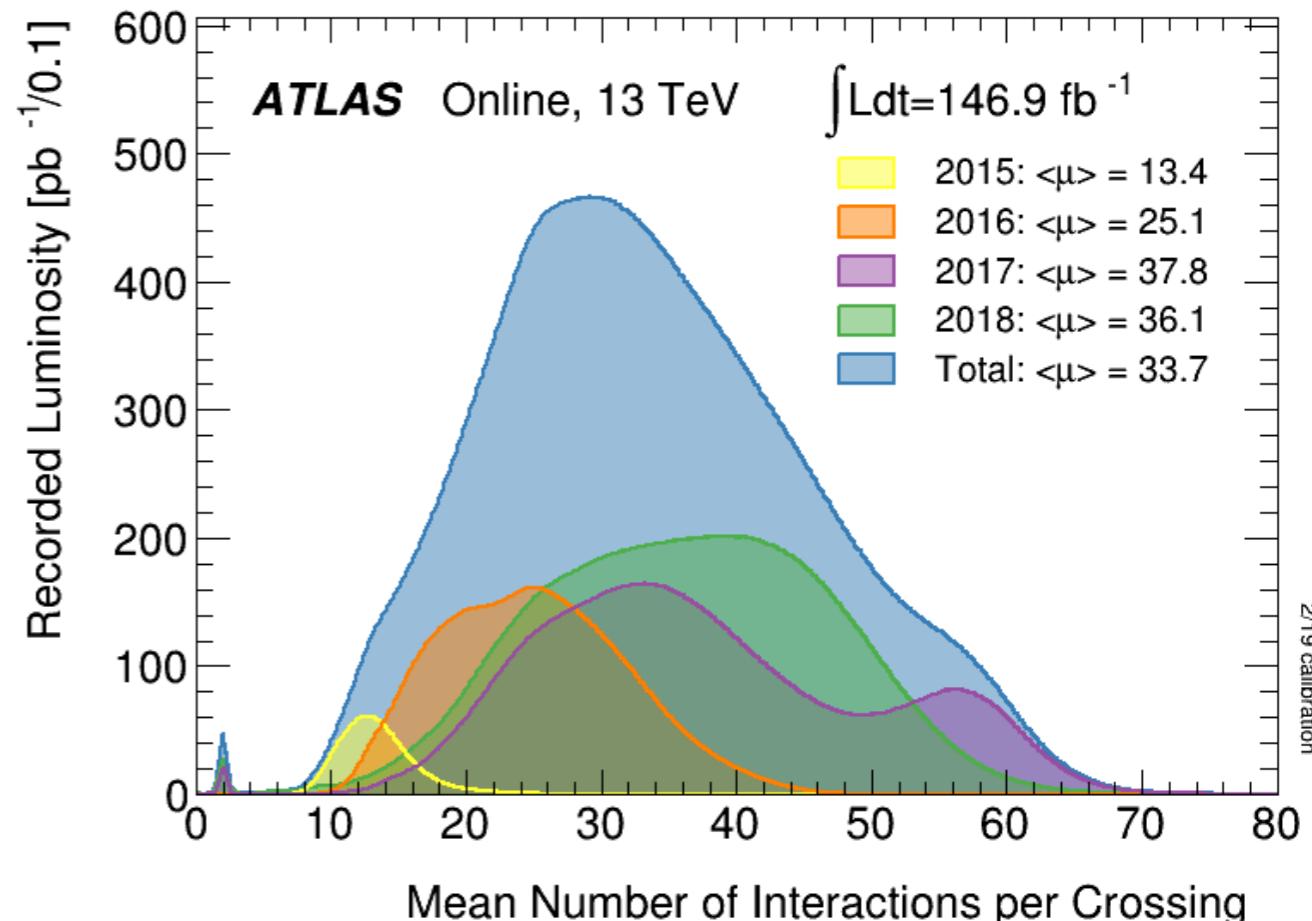
ATLAS And The LHC

- Hadron collider, started collecting data in 2010
- The dataset:
 - p-p collisions at $\sqrt{s} = 5, 7, 8, \textcolor{red}{13} \text{ TeV}$
 - Collisions with Pb and other heavy ions
- p-p collisions Run2 dataset
 - $\sqrt{s} = \textcolor{red}{13} \text{ TeV}$
 - $\sim 10^{11}$ protons per bunches
 - Up to 2556 bunches
 - For most of the data-taking, bunches were separated by 25 ns



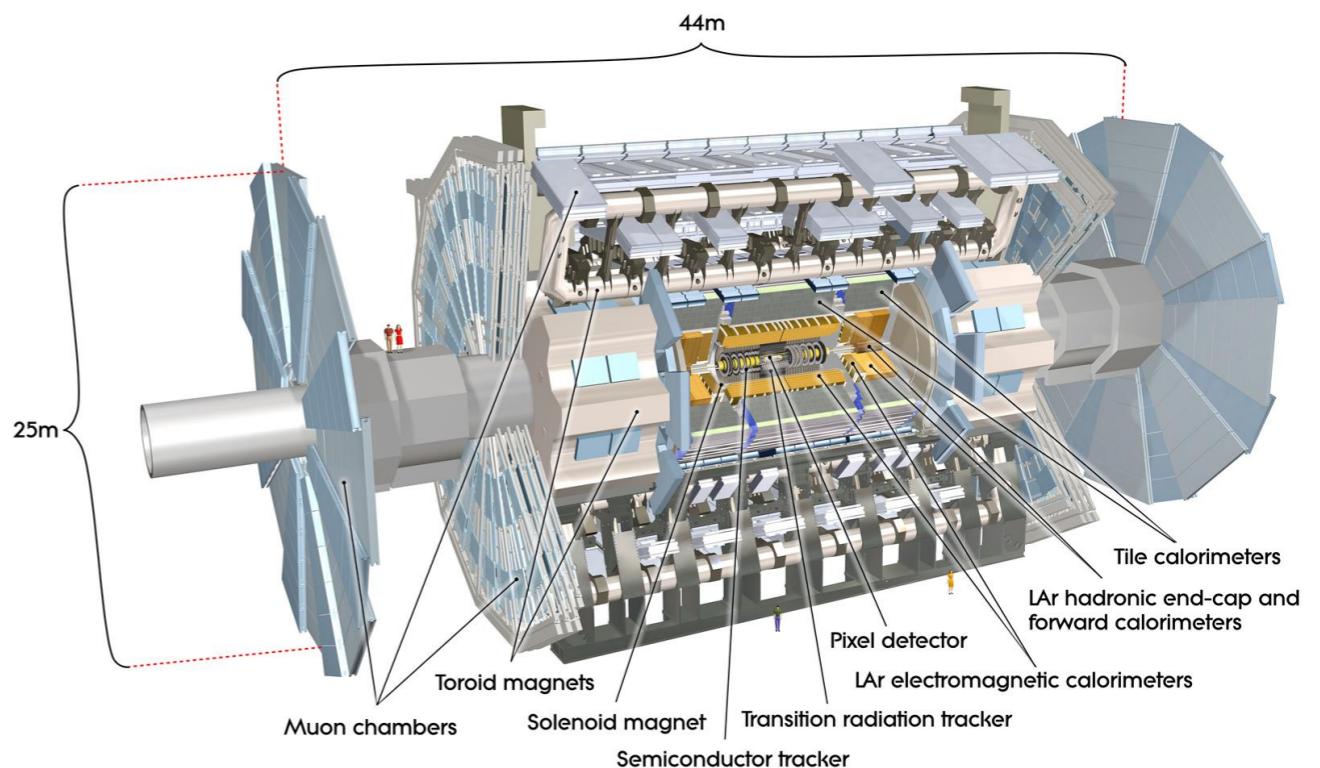
LHC Collision data

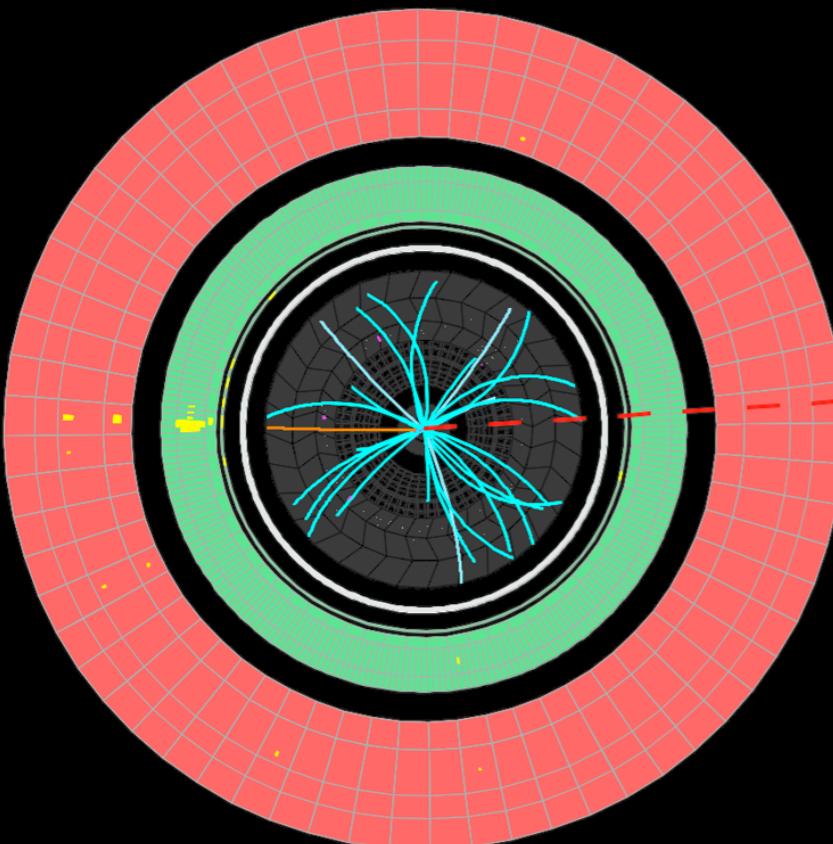
- Hadron collider, started collecting data in 2010
- The dataset:
 - p-p collisions at $\sqrt{s} = 5, 7, 8, \textcolor{red}{13} \text{ TeV}$
 - Collisions with Pb and other heavy ions
- Run2
 - $\sim 10^{11}$ protons per bunches
 - Up to 2556 bunches
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Tau reconstruction with ATLAS

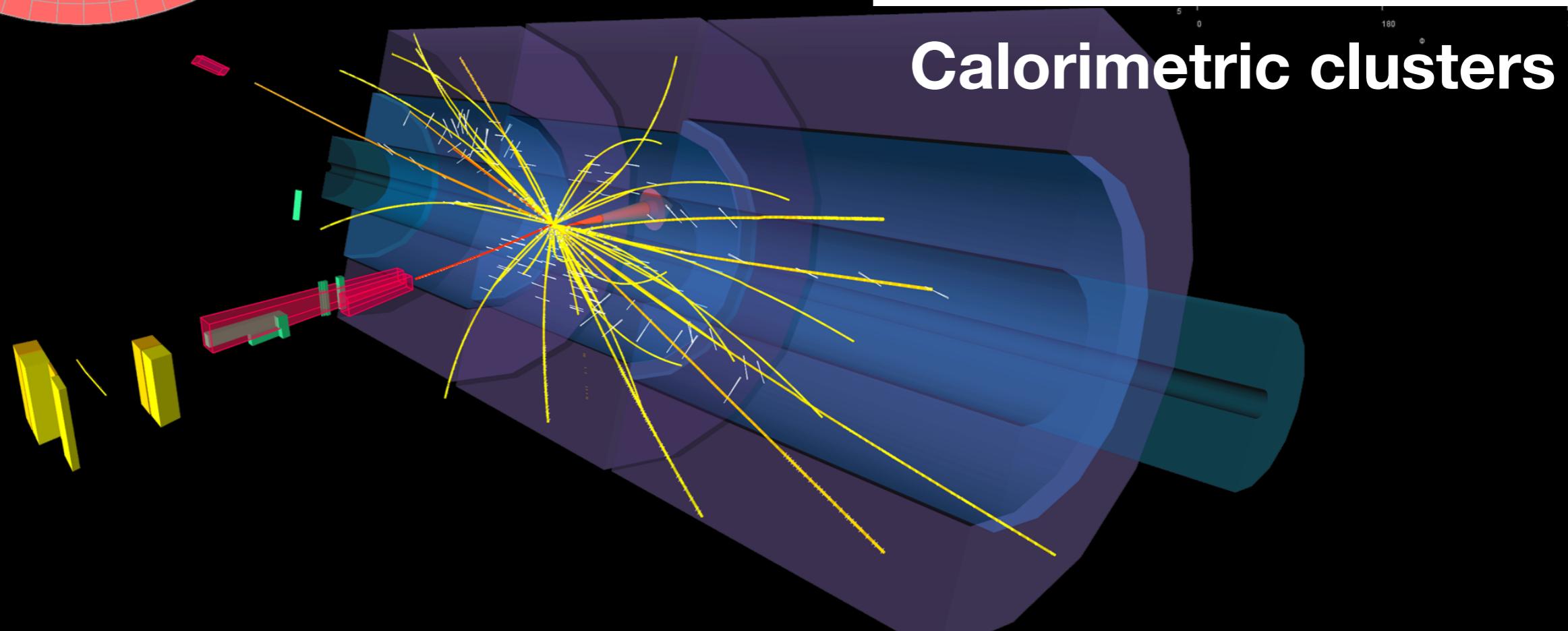
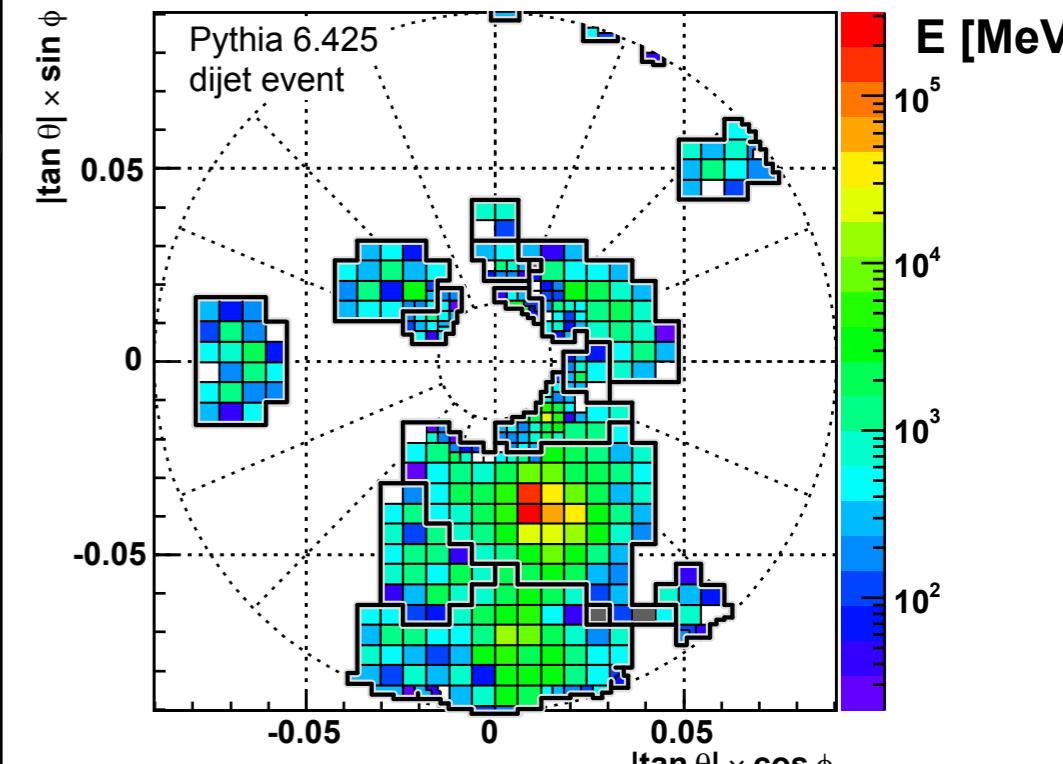
1. Collect information from the detector
2. Use it to measure relevant quantities (momentum, position, ...)





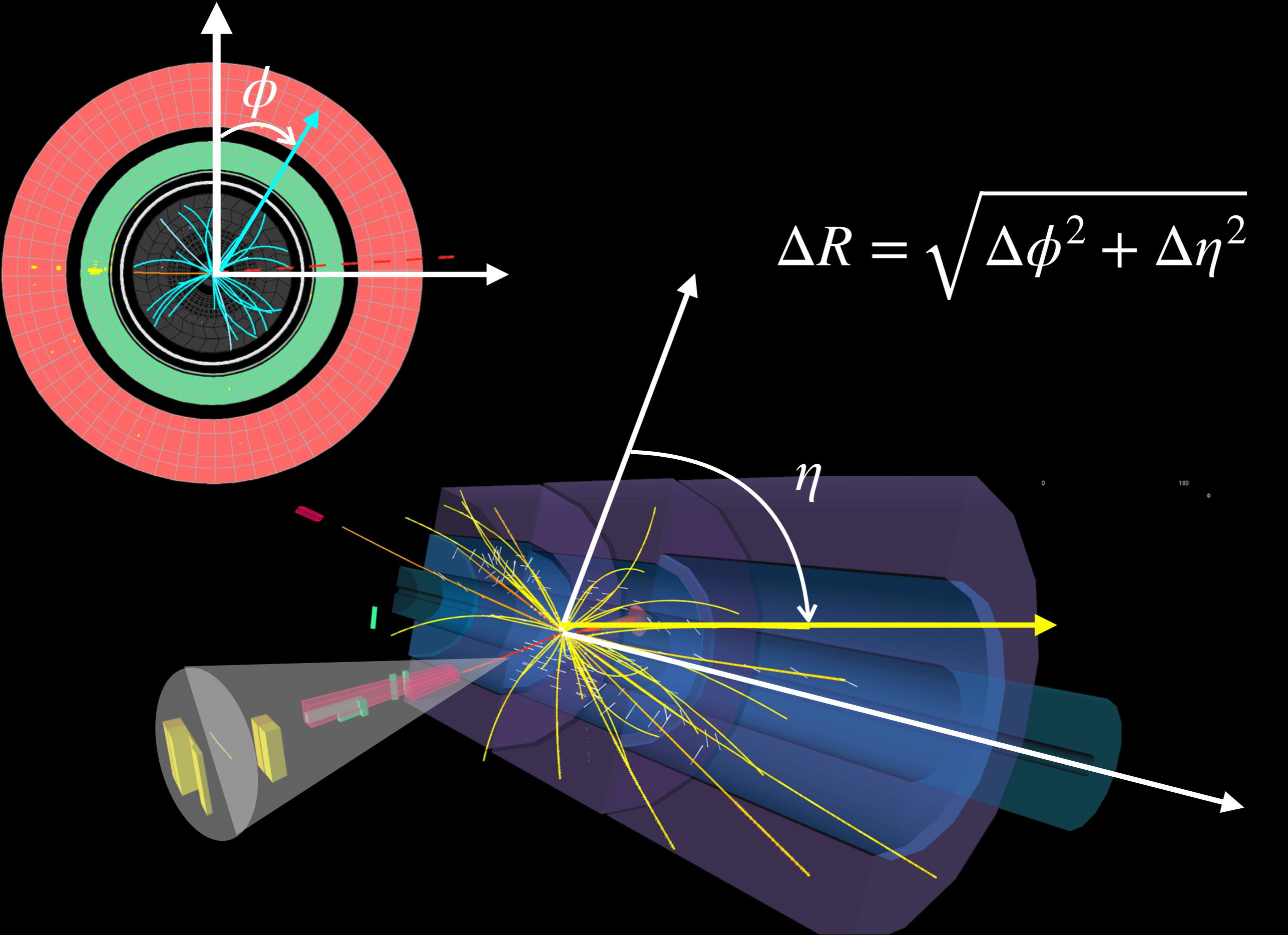
Run 155697, Event 6769403
Time 2010-05-24, 17:38 CEST

$W \rightarrow \tau \nu$ candidate in
7 TeV collisions

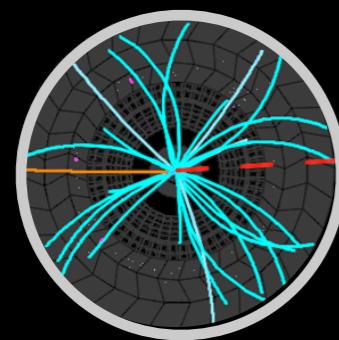


Calorimetric clusters

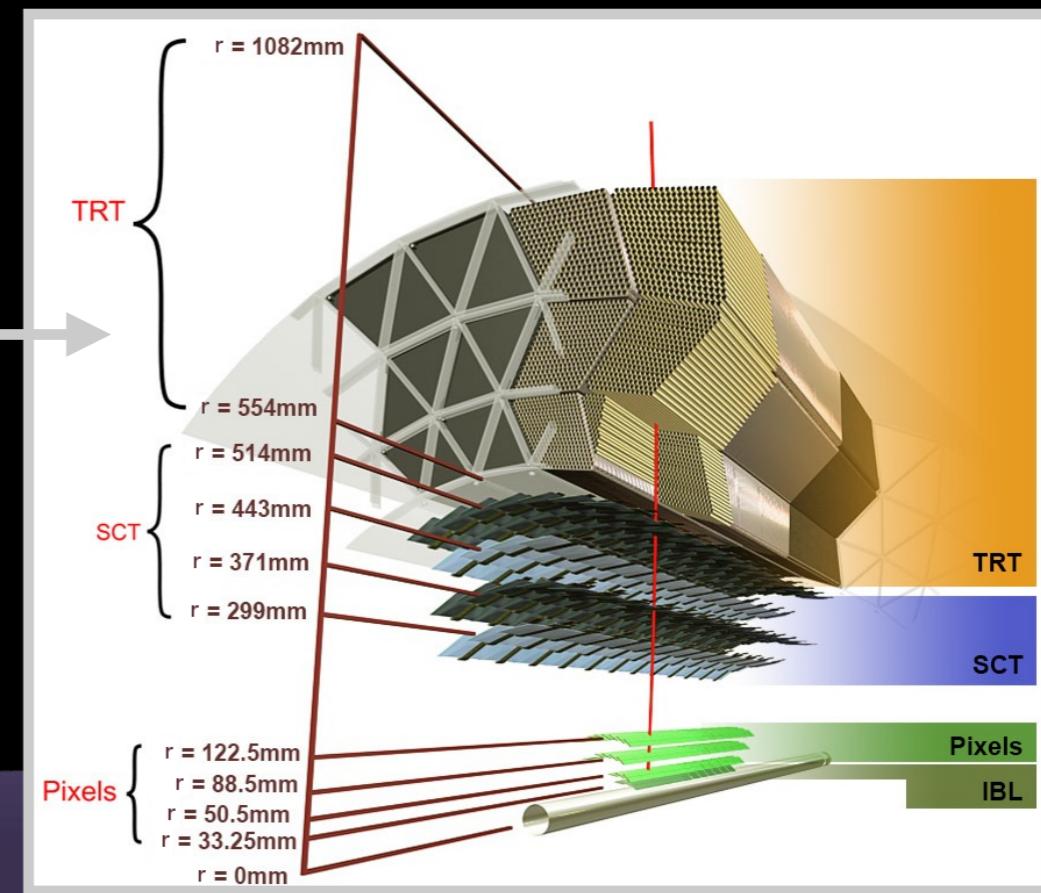
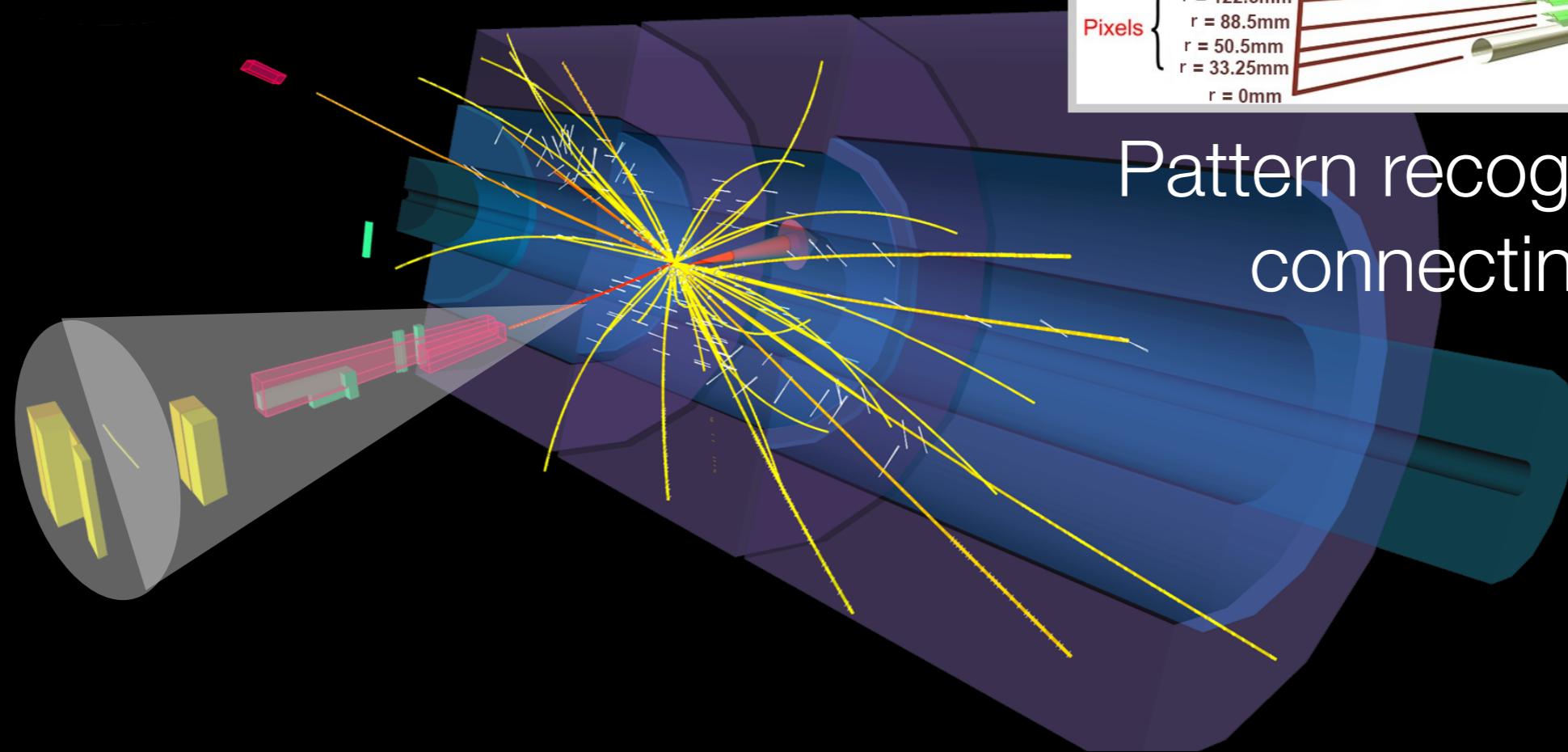
Collect information from the detector



Seeding: anti- k_T jet ($\Delta R=0.4$) algorithm on topological clusters

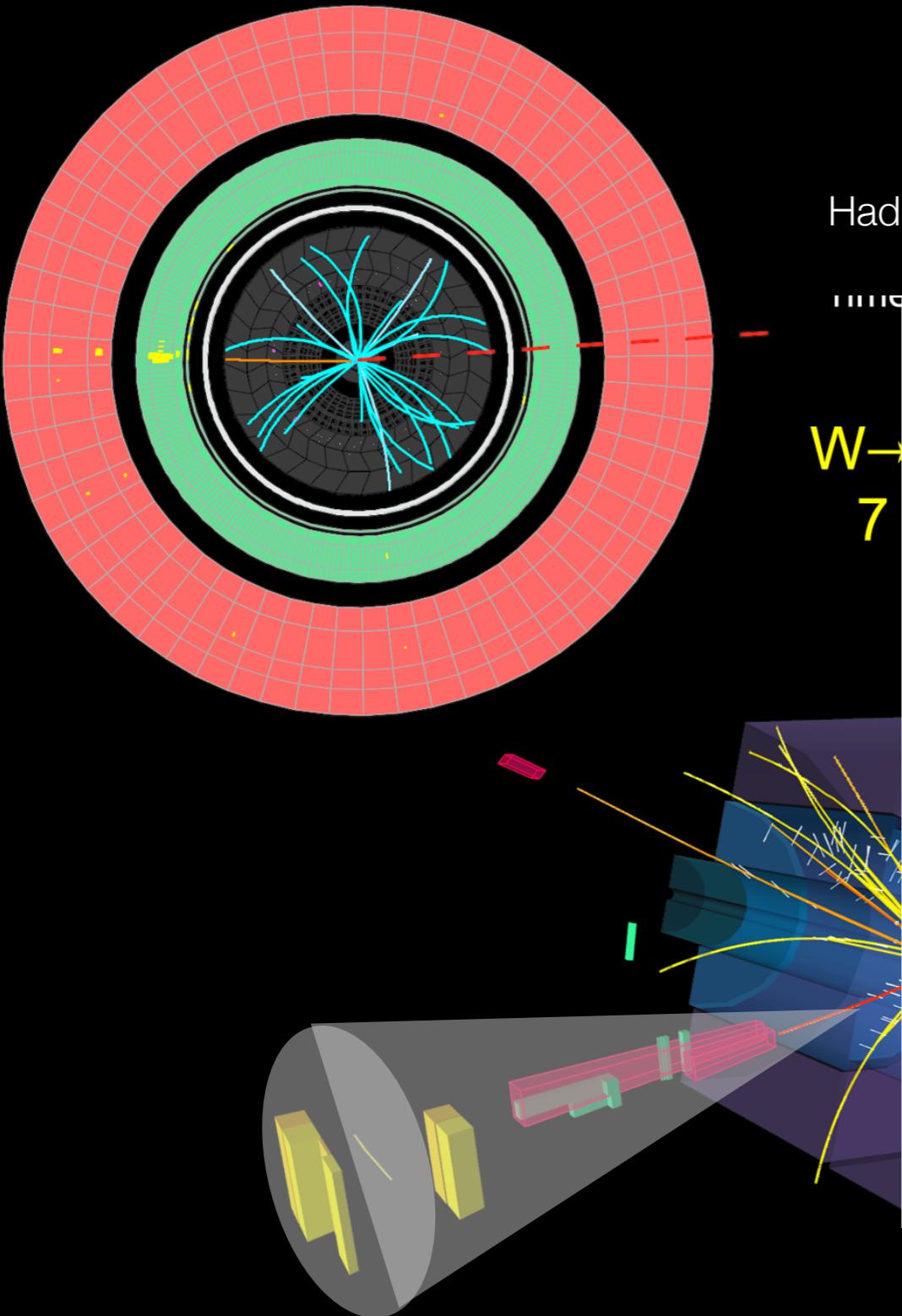


$W \rightarrow \tau \nu$ candidate in
7 TeV collisions

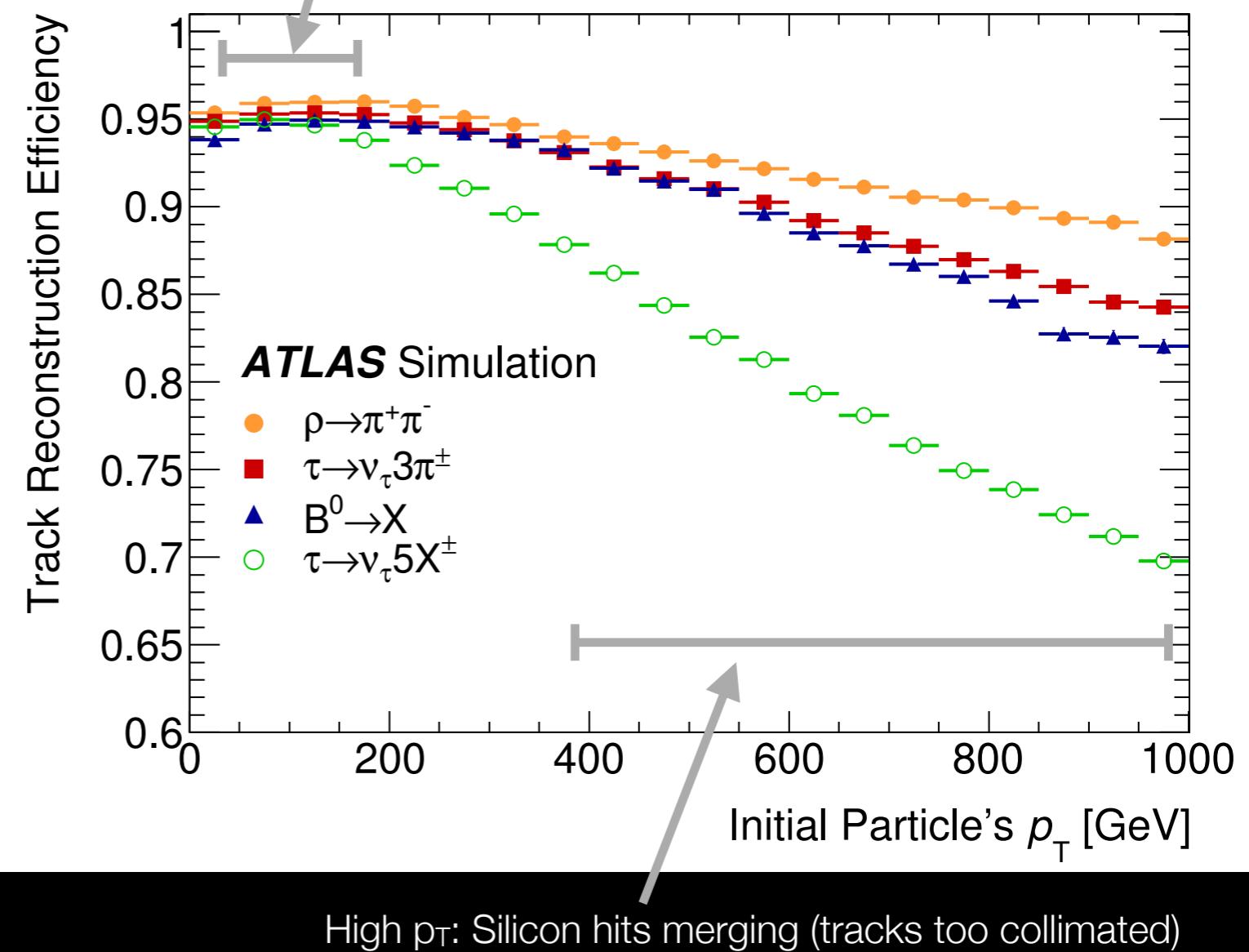


Pattern recognition alg.
connecting hits

Track reconstruction

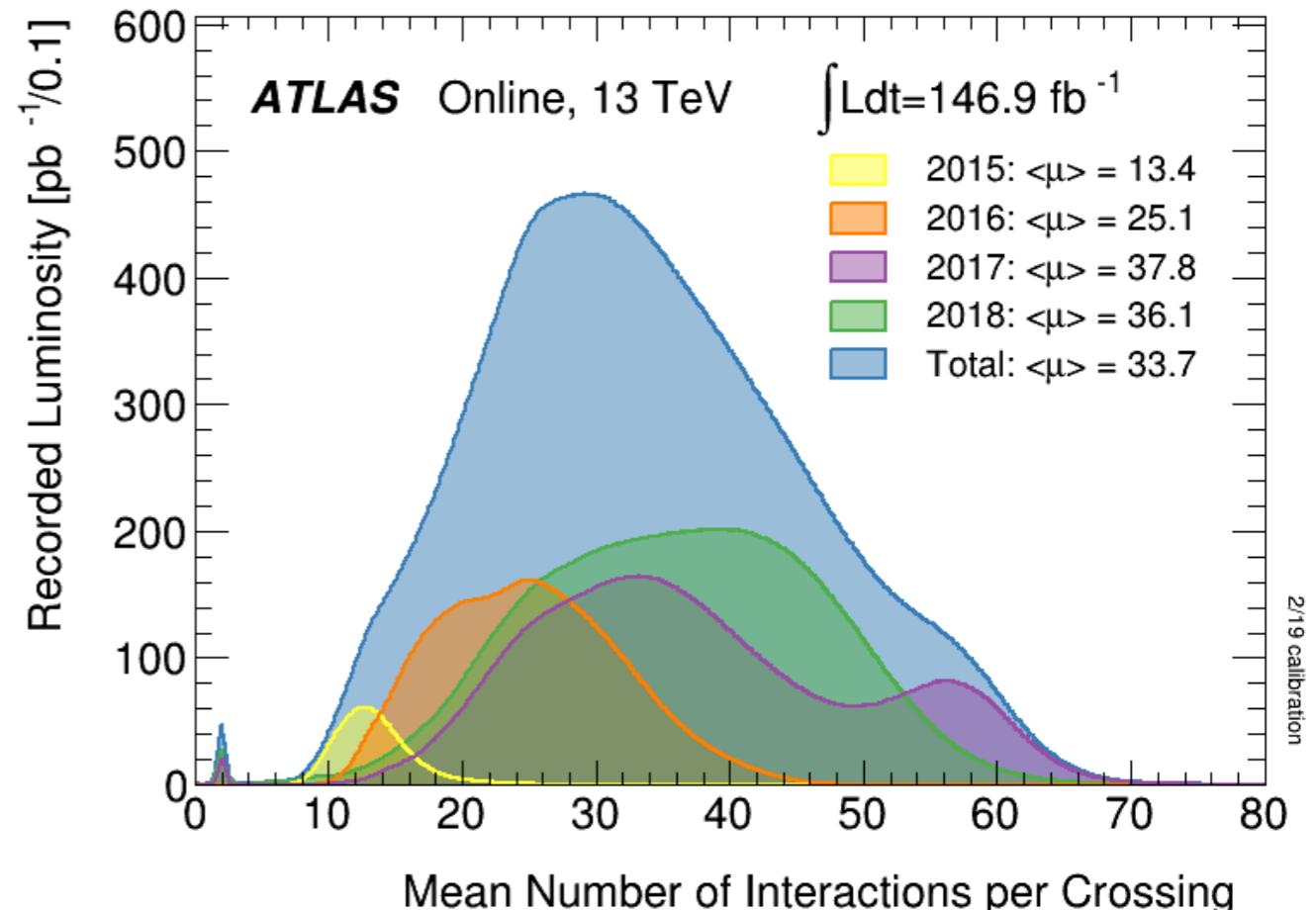


Hadronic interactions in the tracking material (5% loss)

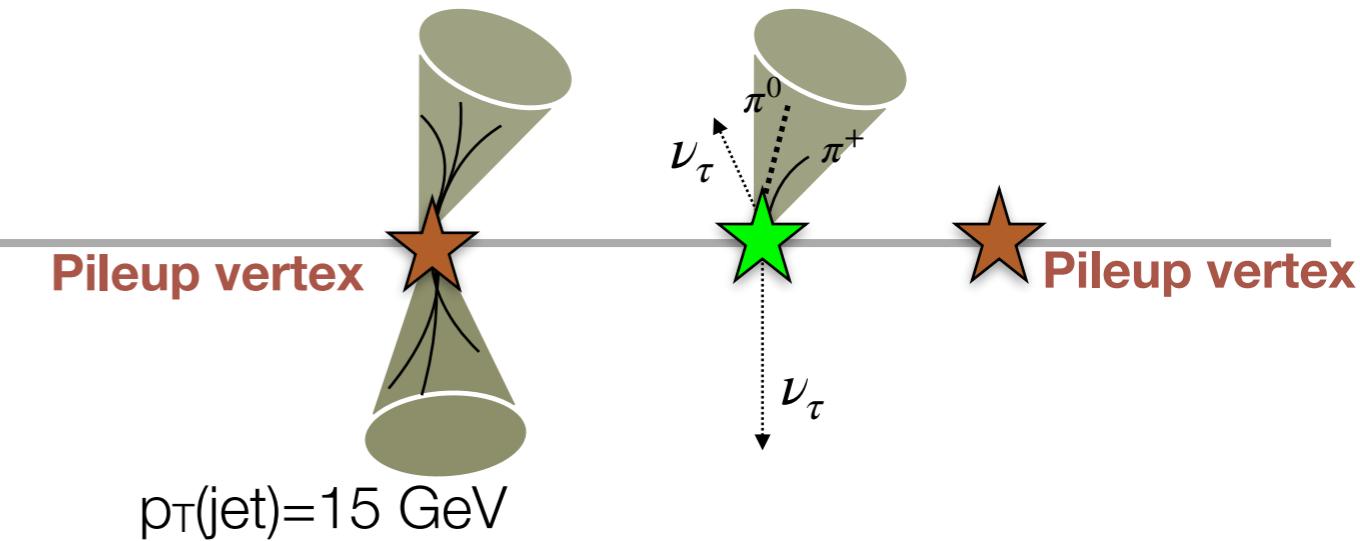


Finding the right vertex

- Pile-up interactions induce many vertices in addition to the expected vertex from the hard interaction
- Default: pick the vertex with the highest $\sum_{\text{all tracks}} p_T$
- Not necessarily suitable for events with tau leptons:
 - $W \rightarrow \tau\nu_\tau + 0 \text{ jets}$
 - Tau Vertex:** same definition as standard criteria but ONLY consider tracks in the tau cone

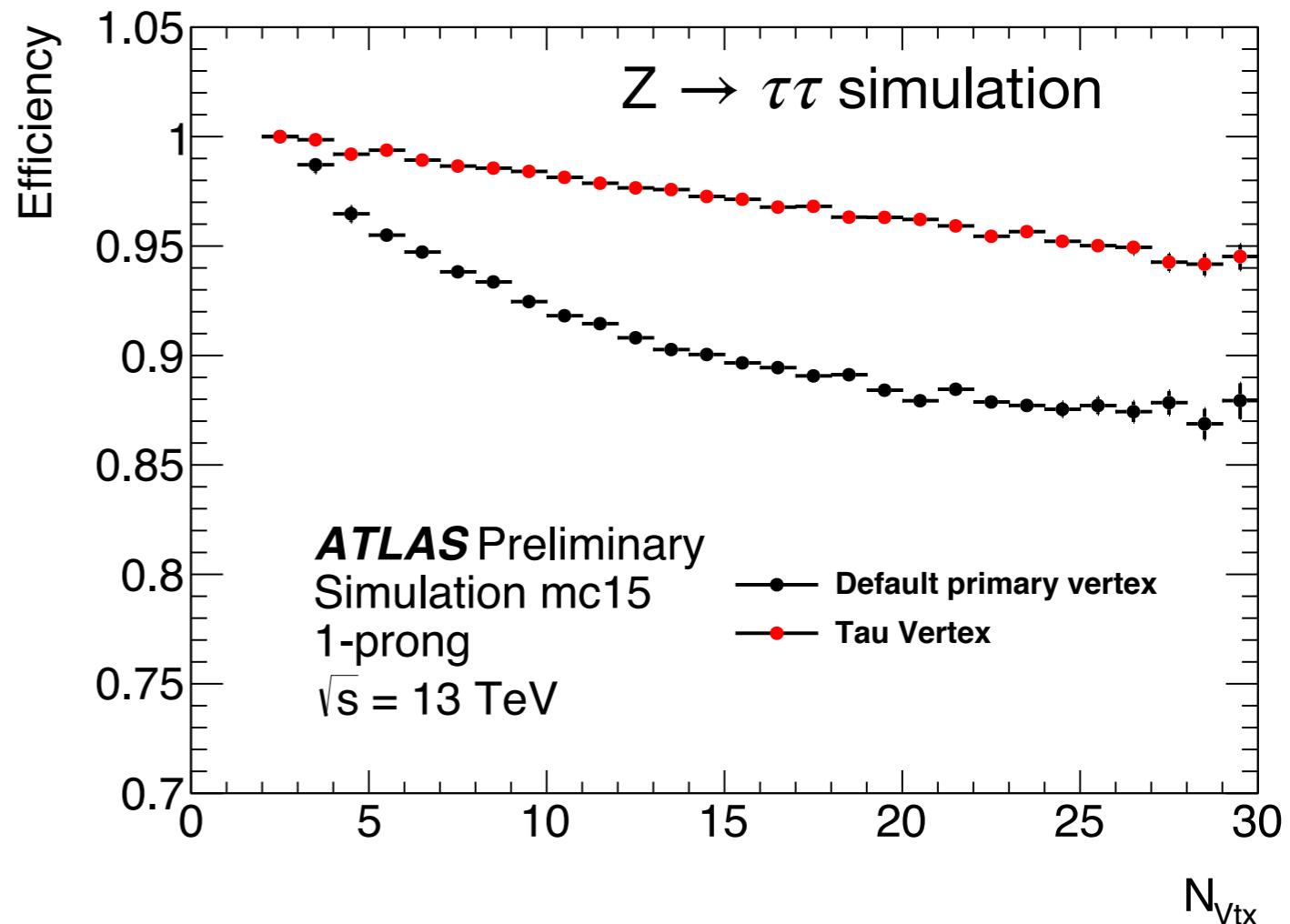


$p_T(\tau) = 40 \text{ GeV}$
 $p_T(\pi^+) = 15 \text{ GeV}$

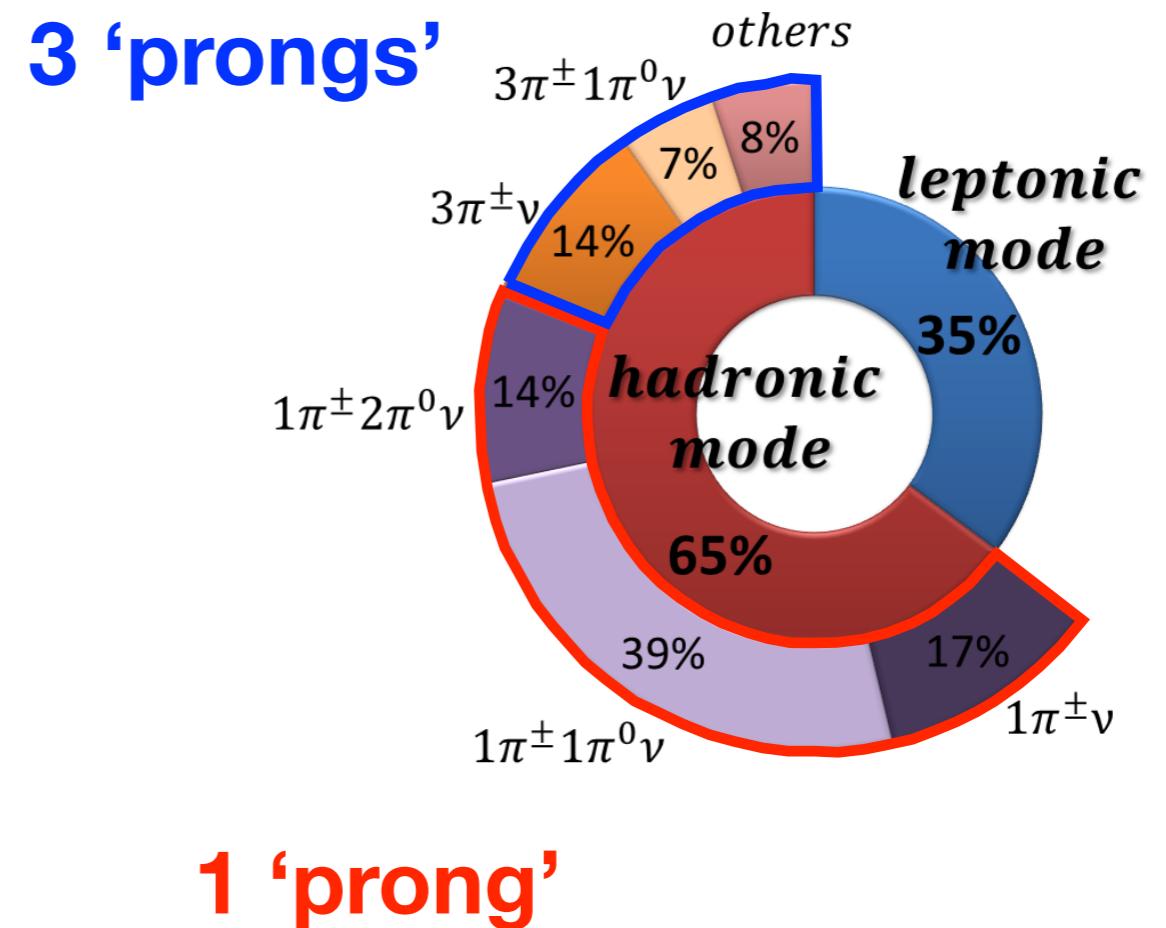
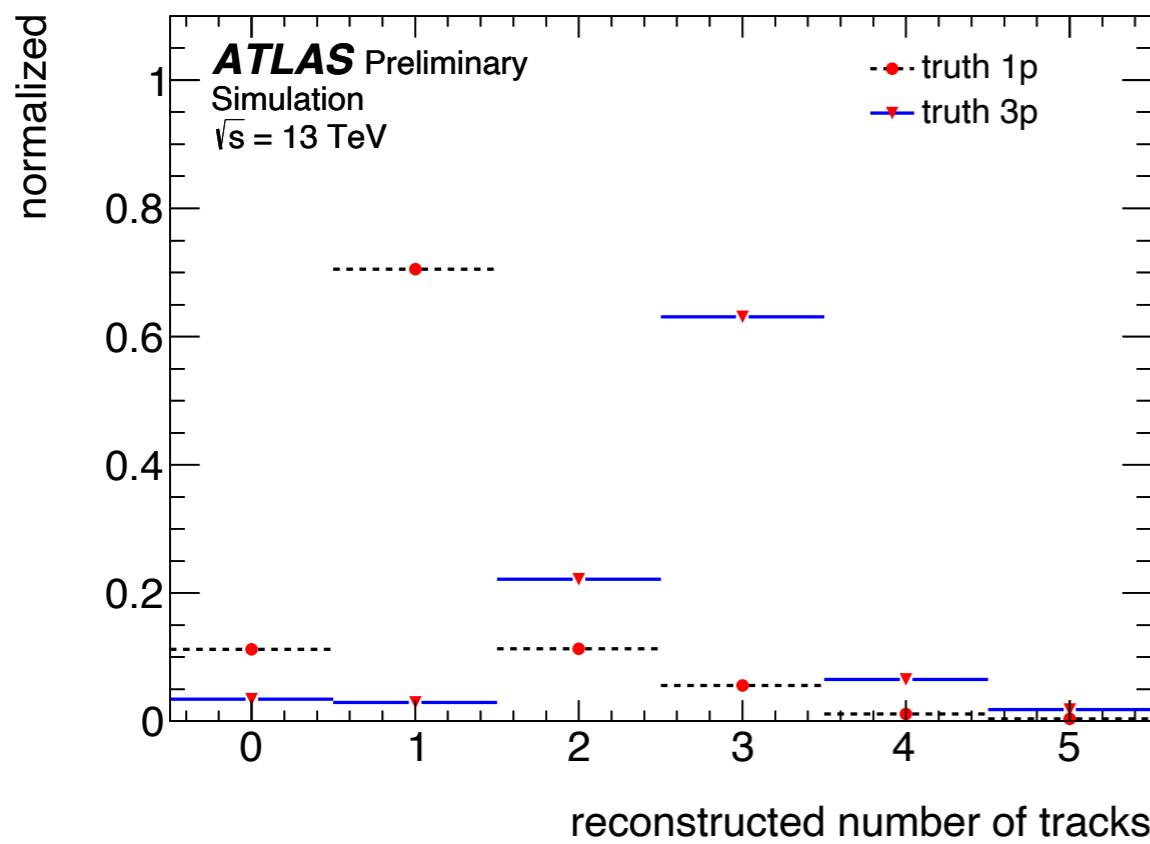


Finding the right vertex

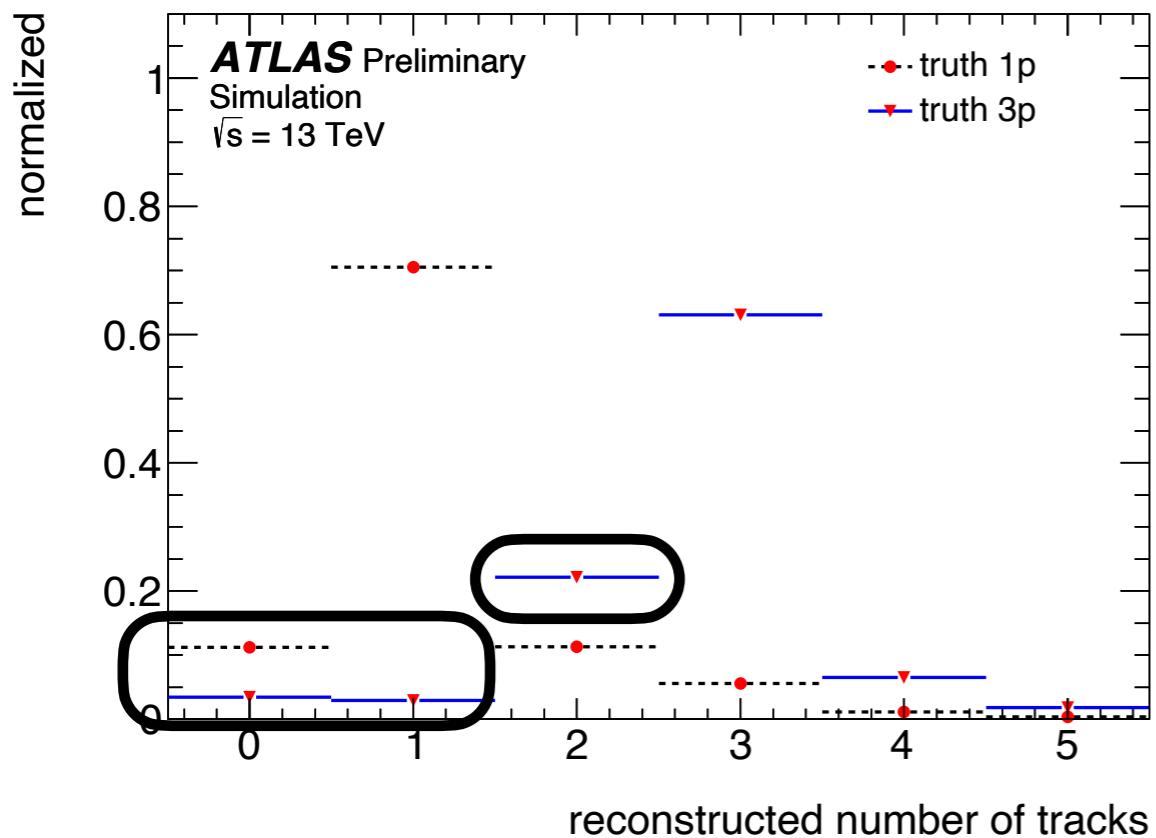
- Pile-up interactions induce many vertices in addition to the expected vertex from the hard interaction
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- Not necessarily suitable for events with tau leptons:
 - $W \rightarrow \tau\nu_\tau + 0 \text{ jets}$
- **Tau Vertex**: same definition as standard criteria but ONLY consider tracks in the tau cone



Track classification



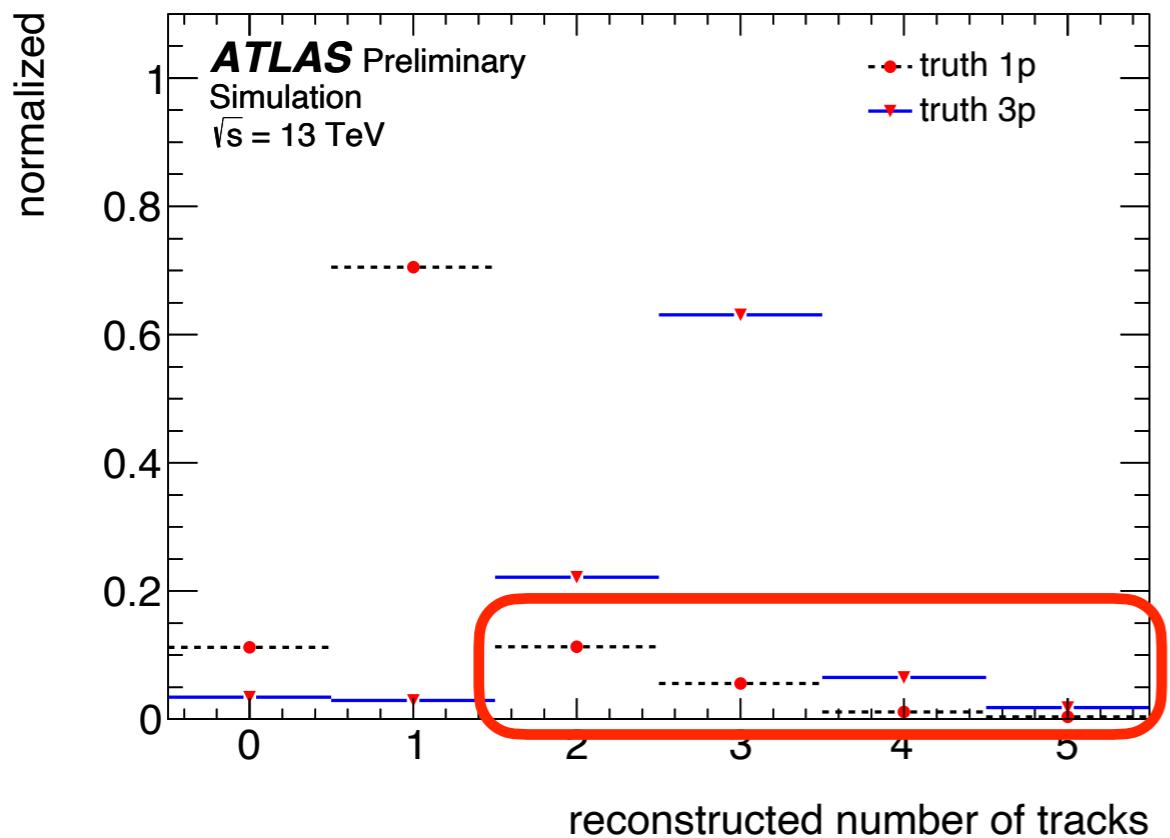
Track classification



Undercounting:

- Hadronic interactions
- Track quality criteria too tight
- Tracks too collimated to be distinguished

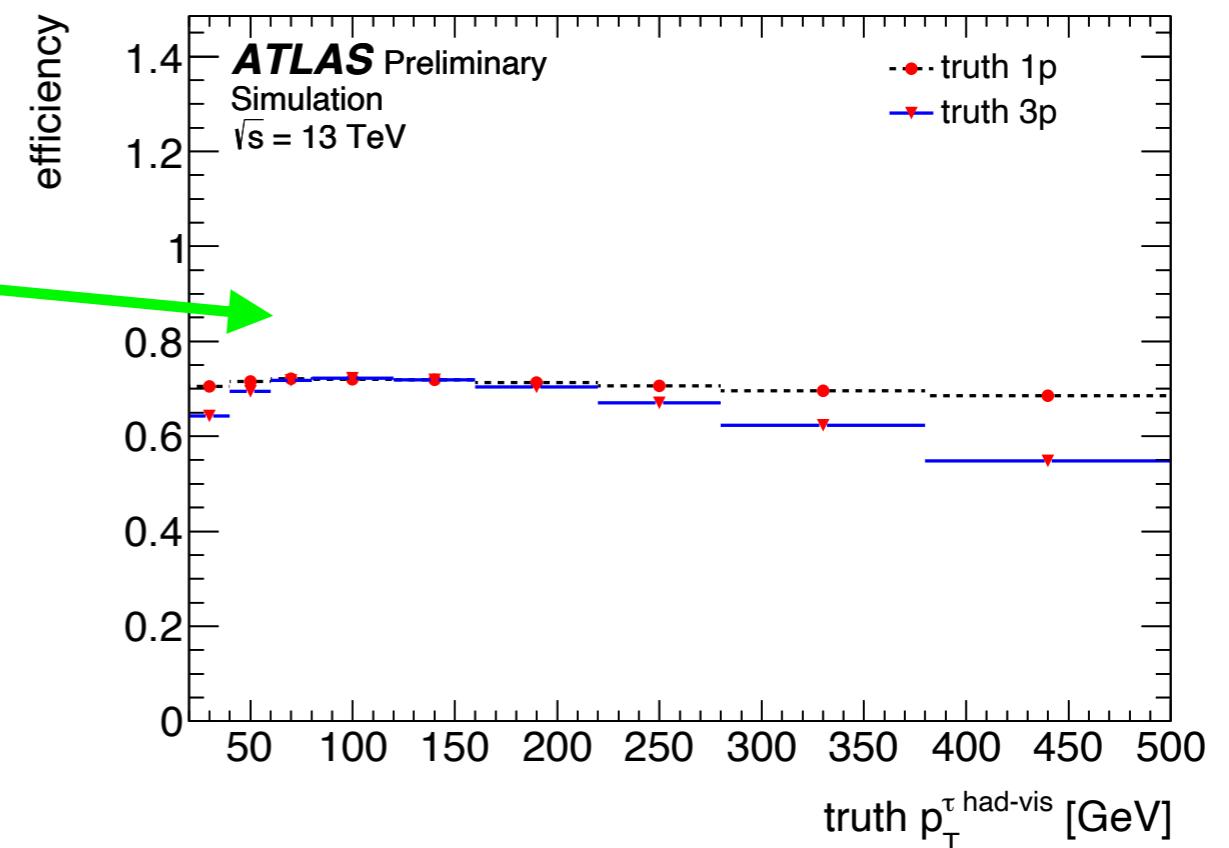
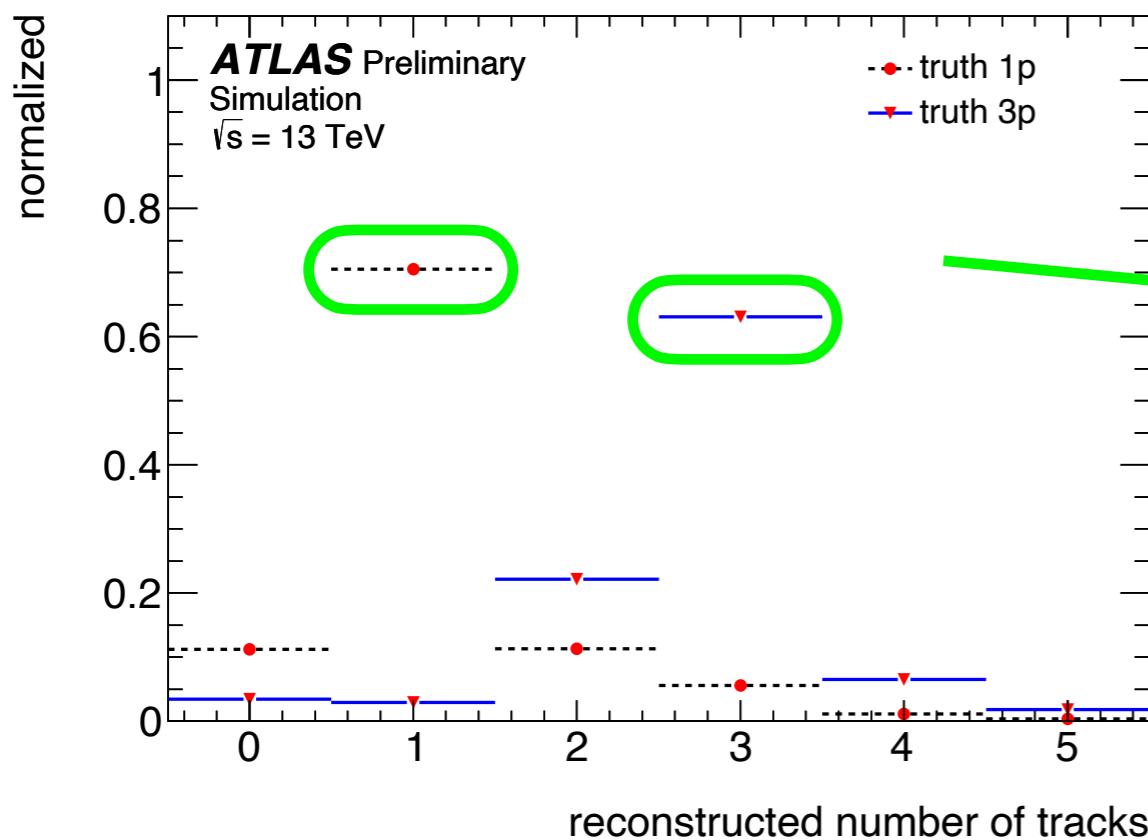
Track classification



Overcounting:

- Underlying Event or Pile-up tracks
- Photon conversion track
- Fake track (wrong association of hits)

Track classification



Correctly classified all the tracks in the tau cone

NB: Classification performances considerably improved since₂₀
beginning of run2 (unfortunately no public material to show)

Tau reconstruction with ATLAS

1. Collect information from the detector
2. Use it to measure relevant quantities (momentum, position, ...)

- Seed using topoclusters
 - Use reconstructed tracks to determine the correct vertex and recalibrate all the clusters w.r.t. to this vertex
 - Classify reconstructed tracks in the seeding cone
- At this **stage**:
- Set of tracks and clusters** that can be used to further characterise the tau

Tau reconstruction with ATLAS

1. Collect information from the detector
2. Use it to measure relevant quantities (momentum, position, ...)

Main ‘Tasks’

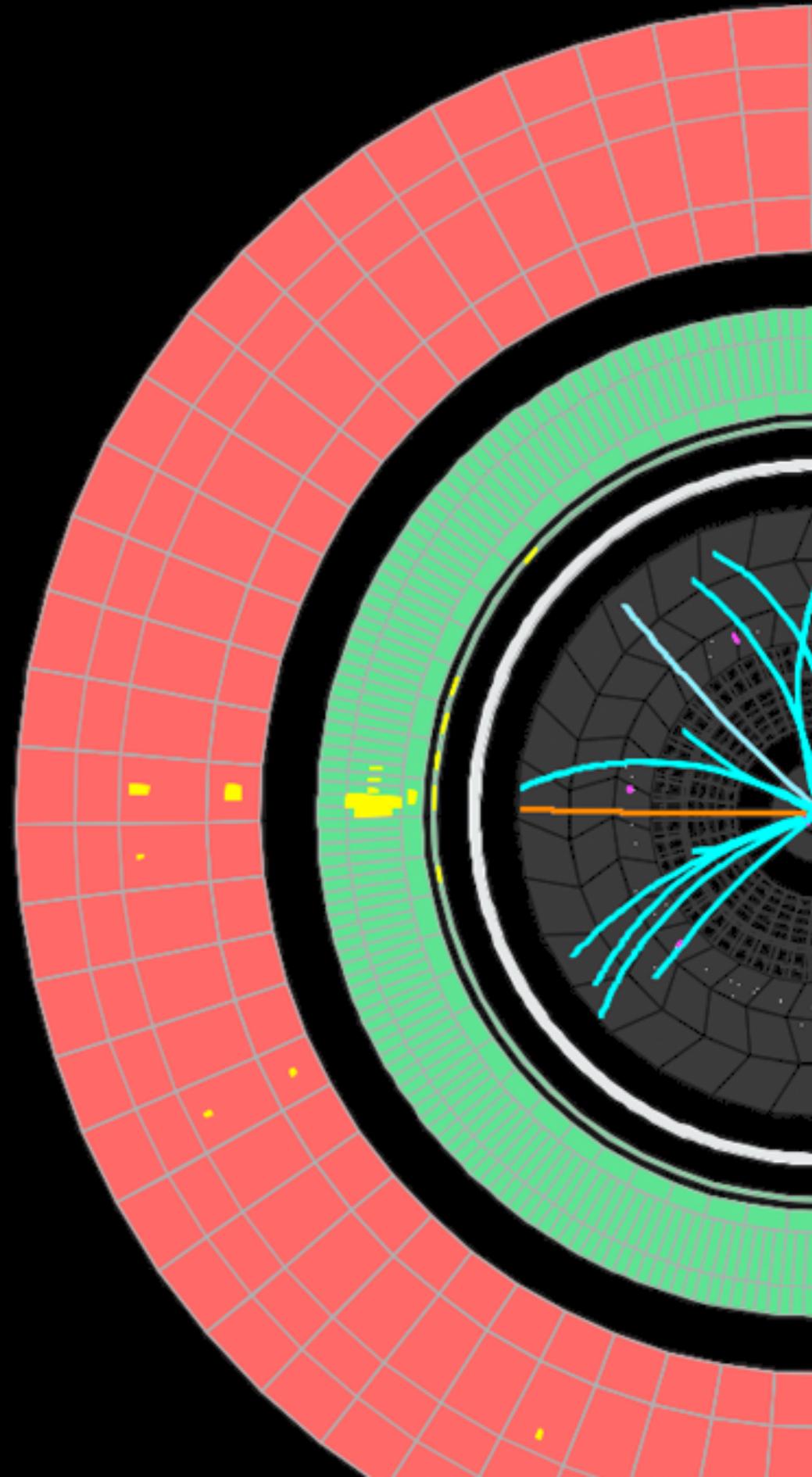
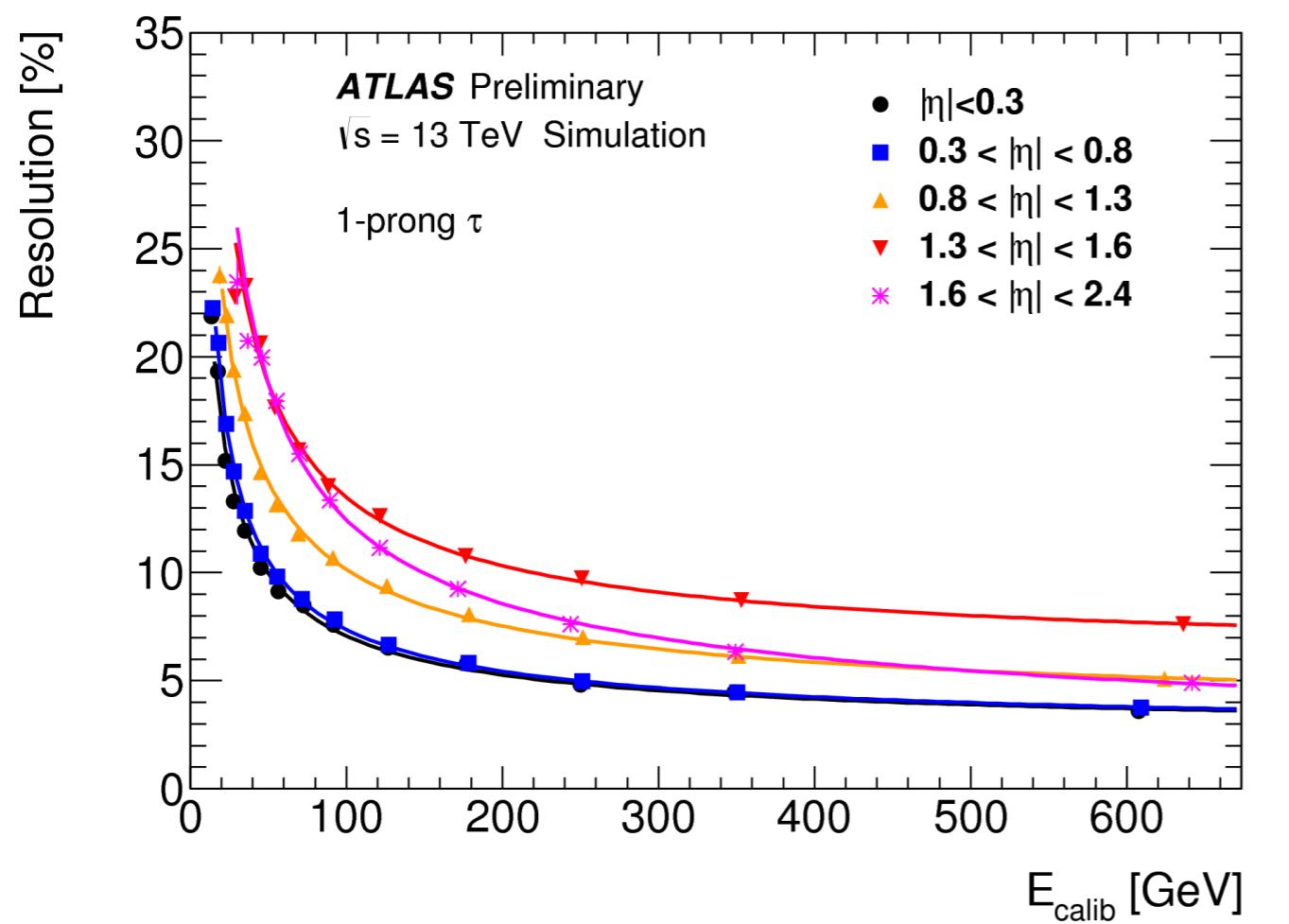
Tau Energy Scale

Individual pions finding

Rejecting jets

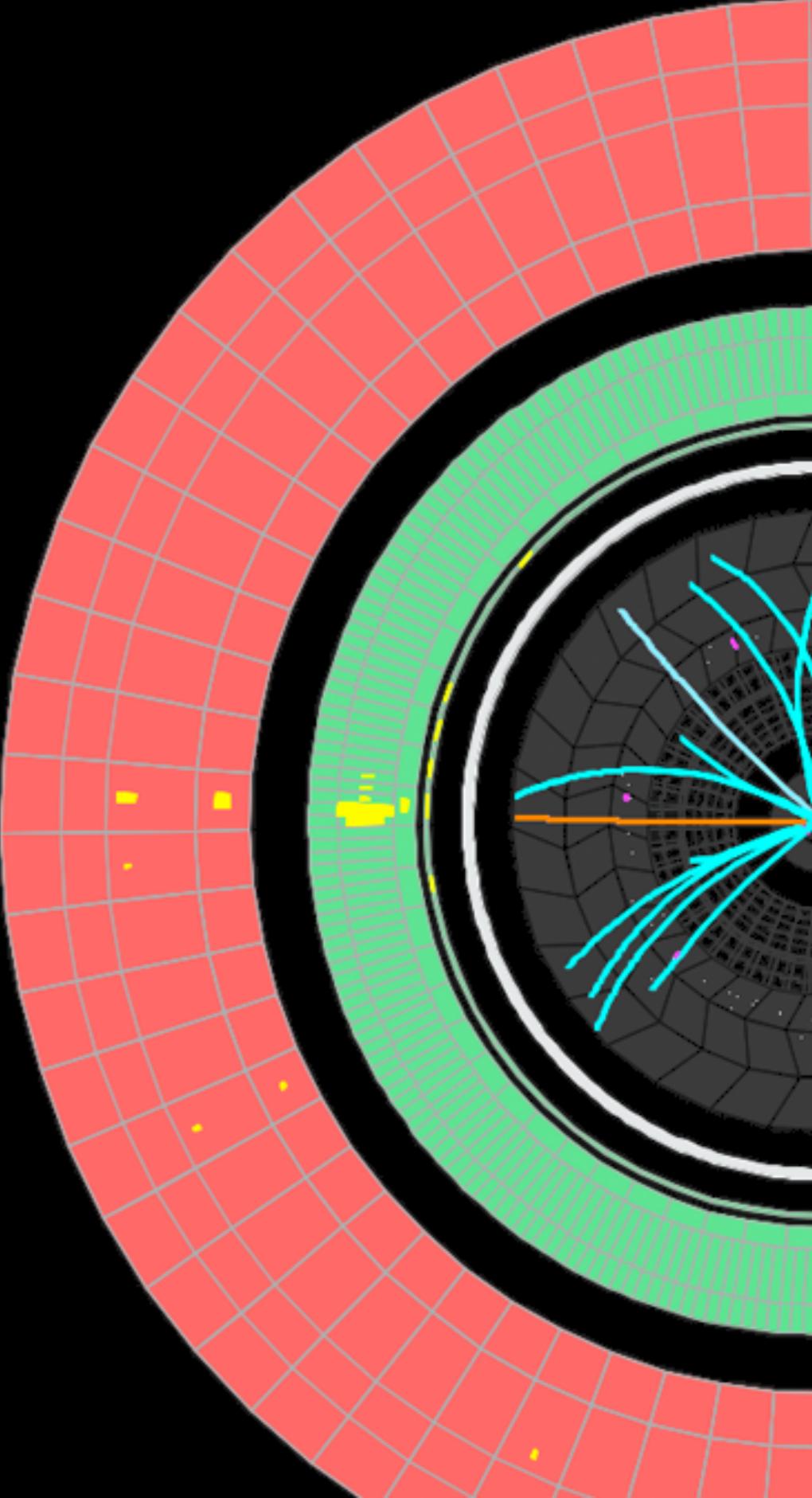
Tau Energy Scale

- Simple approach: use topo-clusters and calibrate with simulation
- Only relying on the calorimeters



Tau Particle Flow

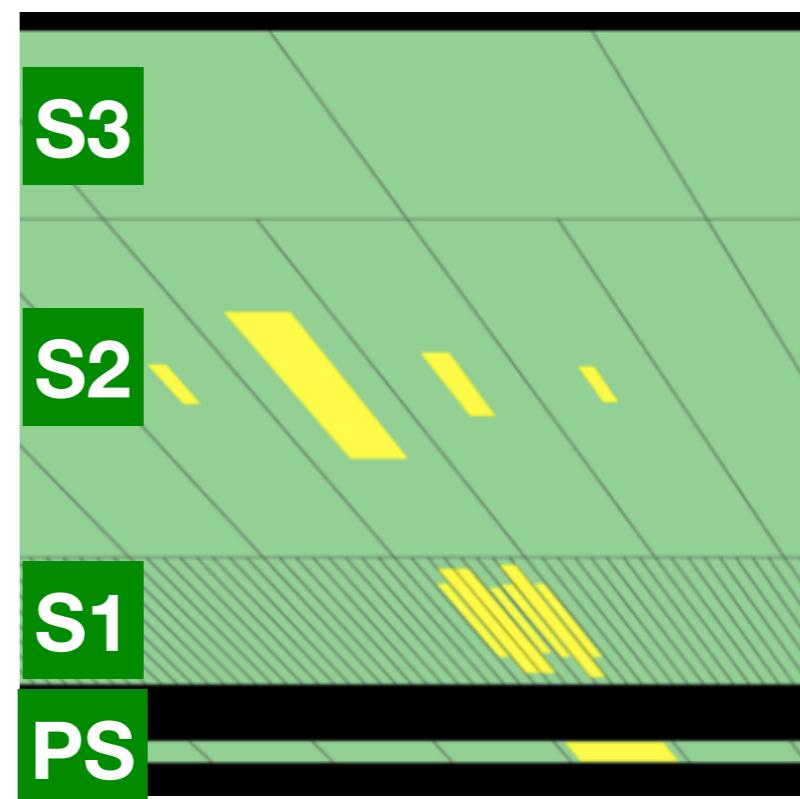
- At low p_T , the tracker is a better tool to estimate $p_T(\pi^+)$
- To use it, need to disentangle π^0 and π^+ deposits in the calorimeters
- The idea:
 - π^+ deposits in the HAD calorimeter
 - π^0 deposits contained to the ECAL (90% before S3)
- Very large hadronic shower-to-shower fluctuations complicate the exercise



Tau Particle Flow

- ECAL clusters tagged as potential **π^0 clusters**
- '**Shots**': As neutral pions can often be merged in single clusters, additional clustering algorithm to find maxima in the first layer of the ECAL

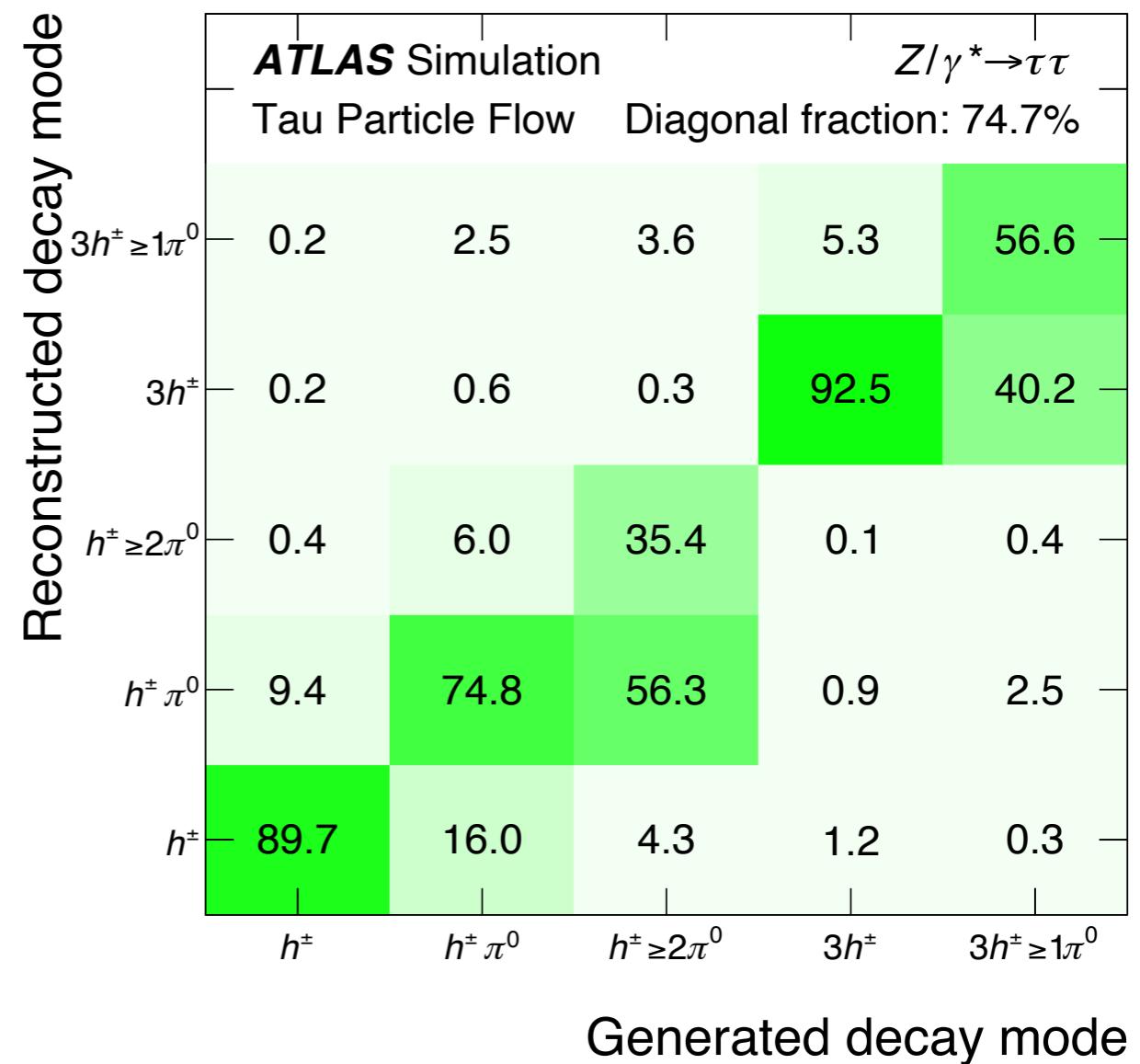
A view of the ECAL



Tau Particle Flow

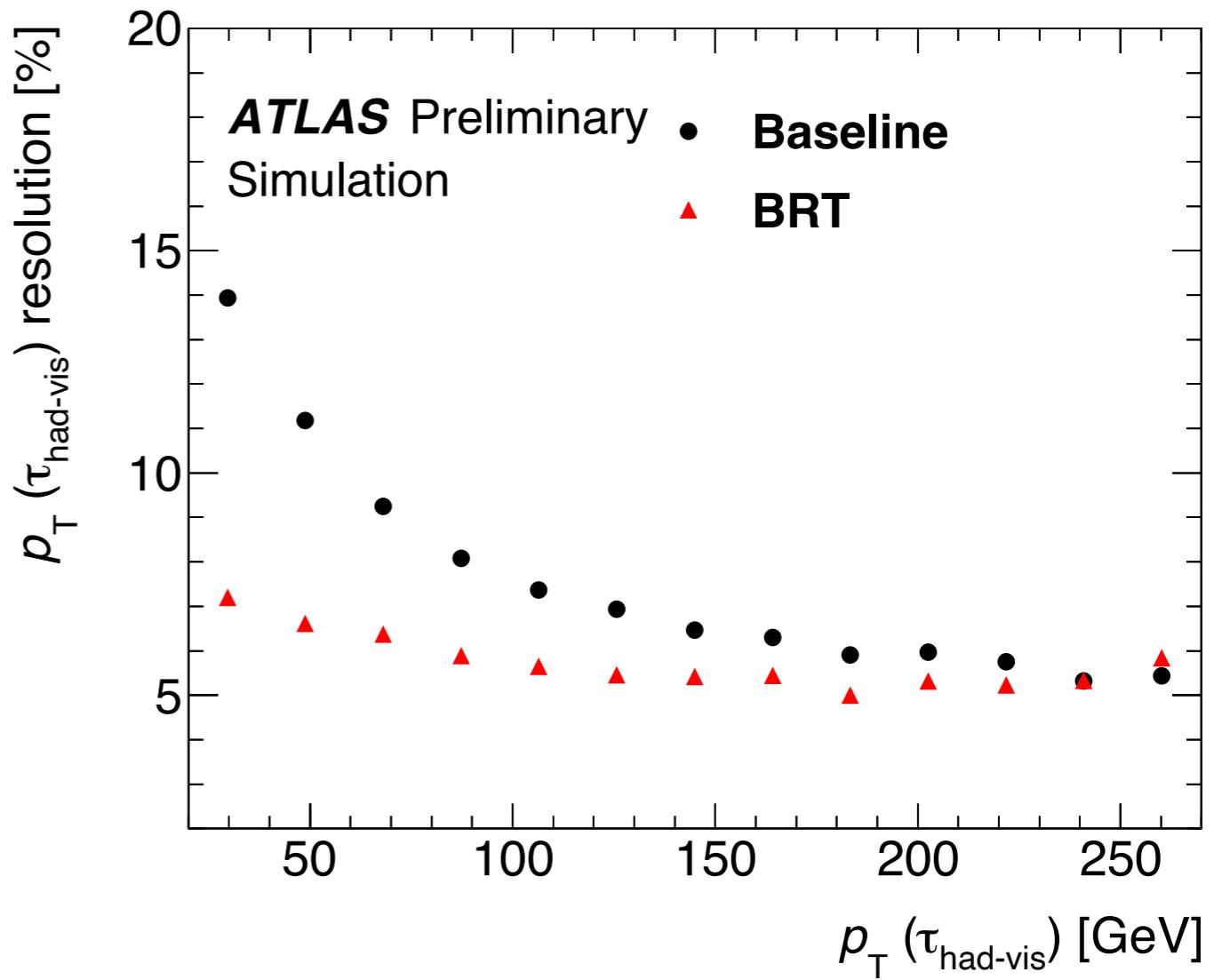
- ECAL clusters tagged as potential **π^0 clusters**
- '**Shots**': As neutral pions can often be merged in single clusters, additional clustering algorithm to find maxima in the first layer of the ECAL
- **Tracks, π^0 clusters and 'shots'** are then used in a series of BDTs to determine the decay modes

Works well to separate $0\pi^0$ vs $>0\pi^0$
Separating $1\pi^0$ vs $2\pi^0$ is difficult



Tau Energy Scale

- **Tracks, π^0 clusters and ‘shots’** are fed into a Boosted Regression Tree
- BRT setup to minimise the RMS of “estimated-truth”
- Sizeable improvement obtained over a very large range of p_T
- Largest gain at low p_T where we fully benefit from the tracking resolution



Object reconstruction with ATLAS

1. Collect information from the detectors
2. Combine them to measure relevant quantities of the studied deposit
3. Assess the performance in data and correct the simulations if necessary
correct it
4. Calibrate the detector response (in-situ calibration)

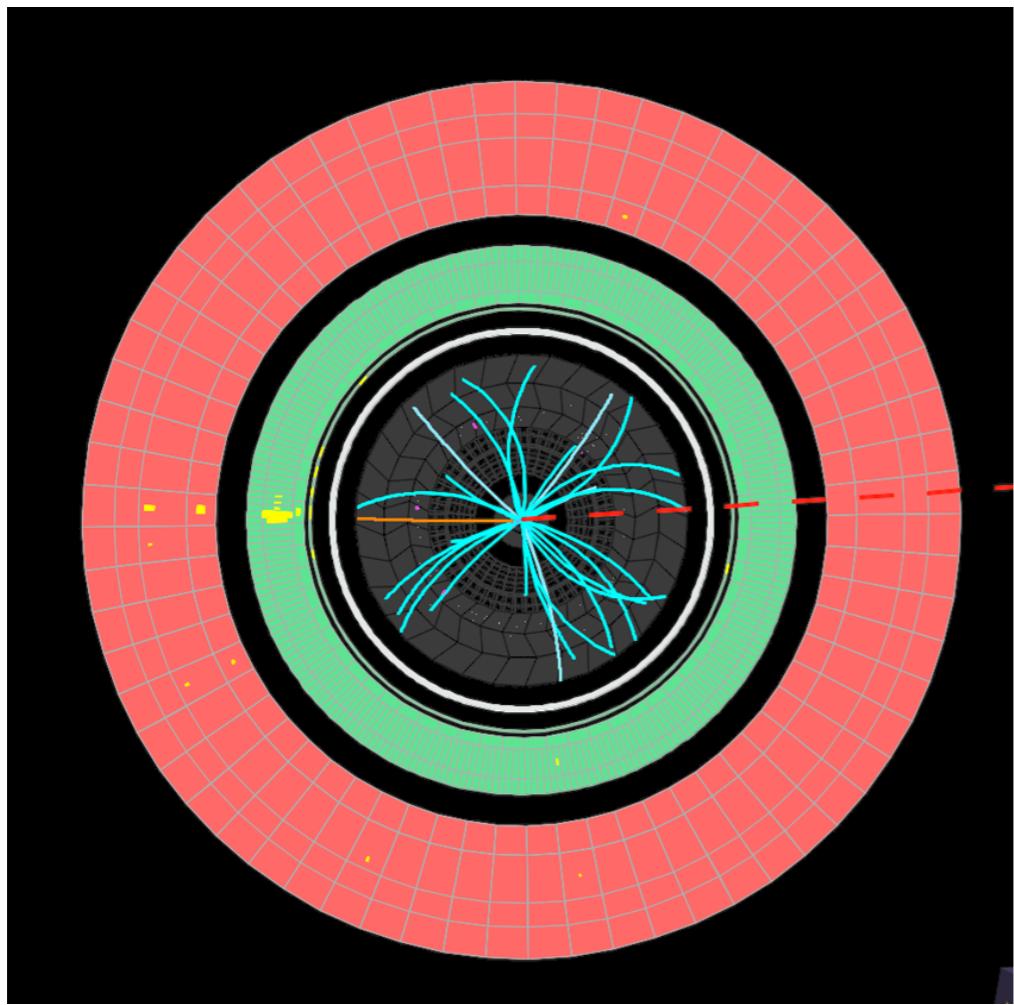
Main ‘Tasks’

Tau Energy Scale
Individual pions finding

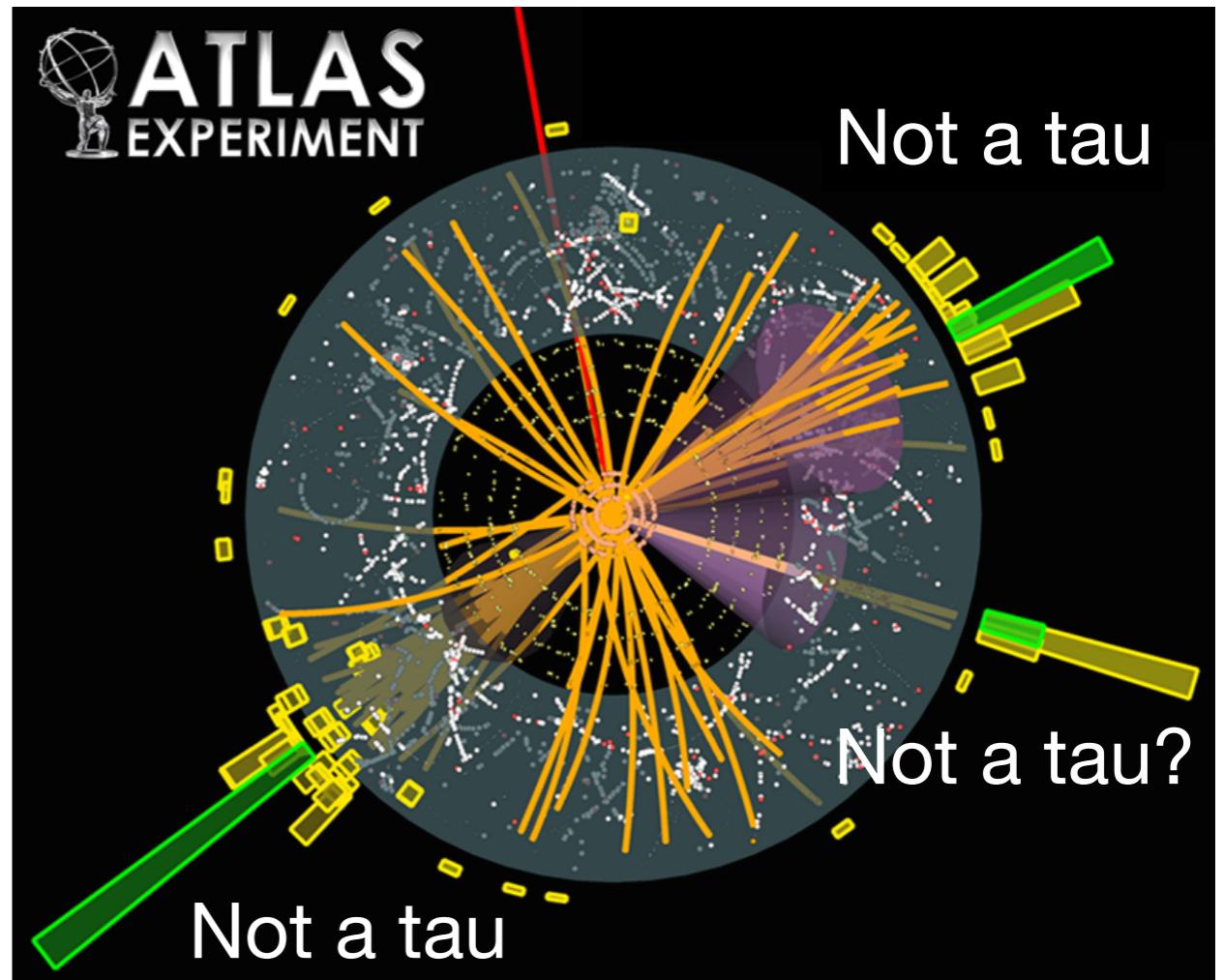
Rejecting jets

Rejecting jets

There is a hadronic tau lepton in this event



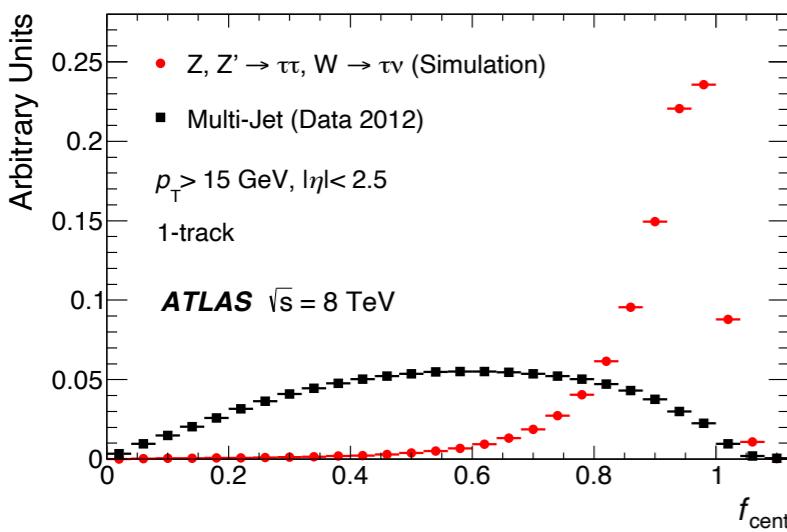
Not in this one



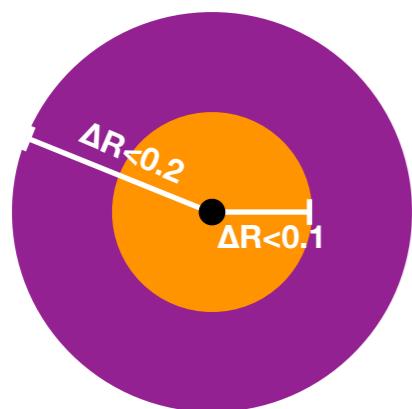
Hard to tell... and not only because event displays are hard to interpret

Rejecting jets

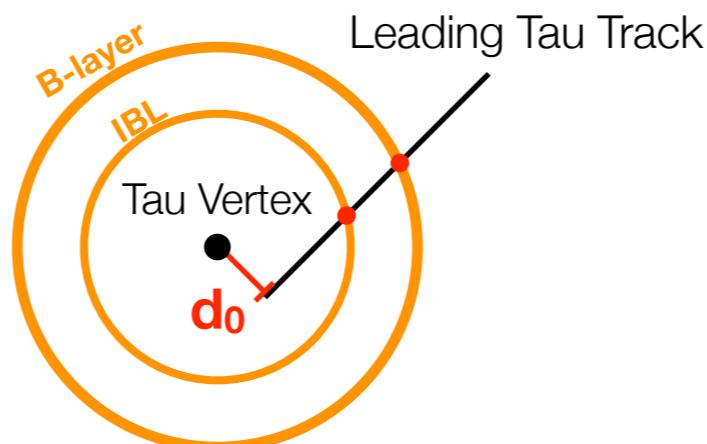
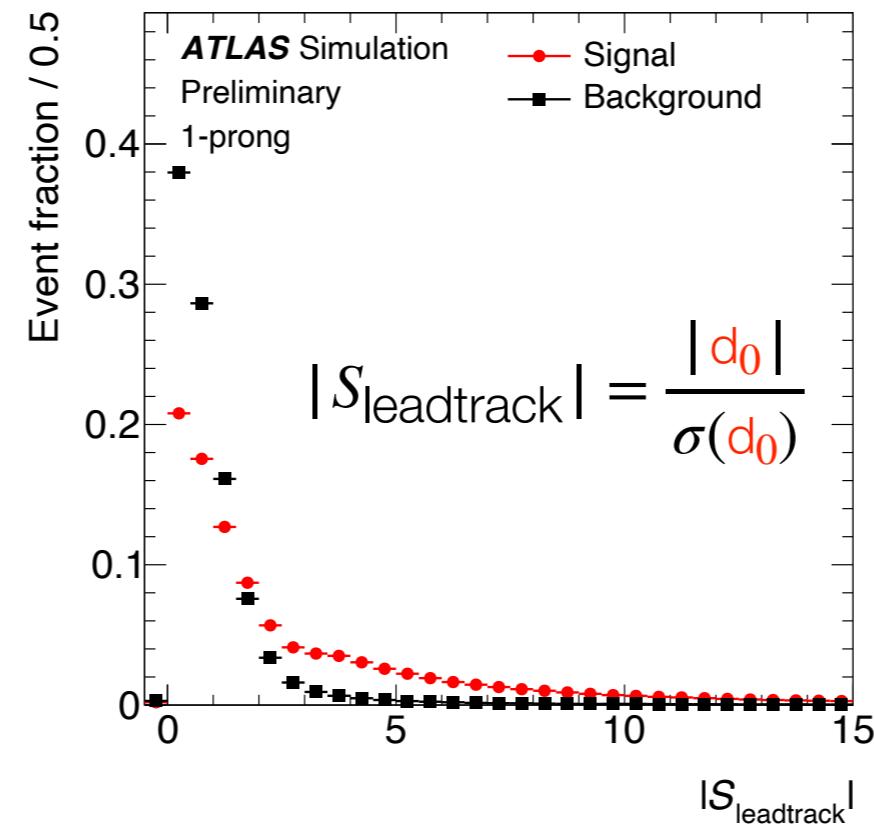
Only using the calorimeters



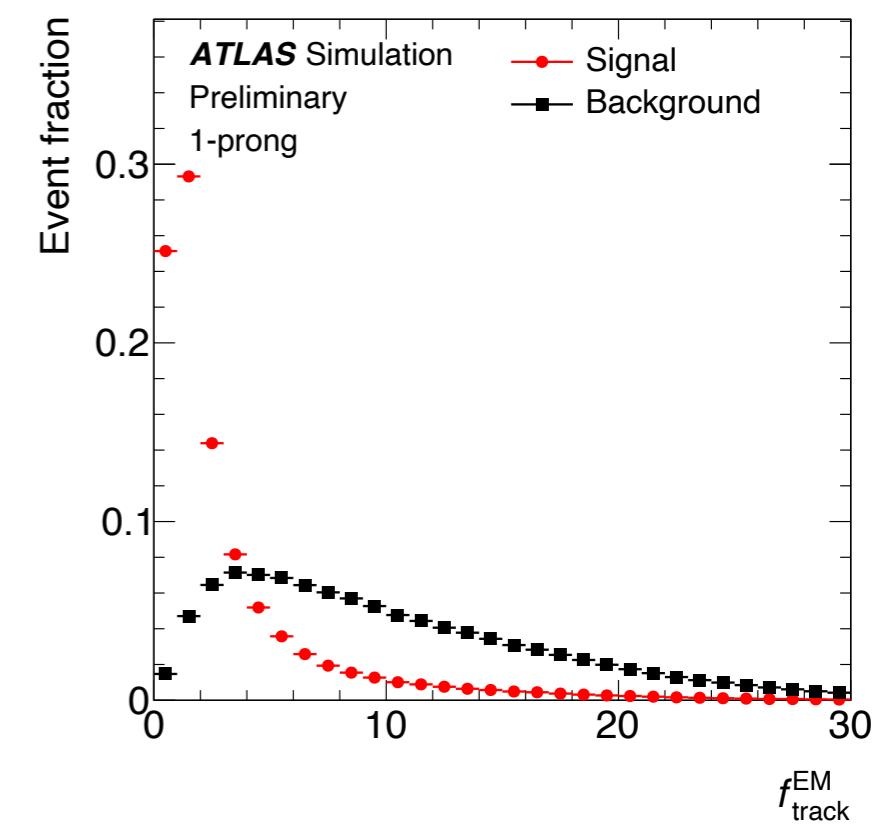
$$f_{cent} = \frac{E(\Delta R < 0.1)}{E(\Delta R < 0.2)}$$



Only using the tracker

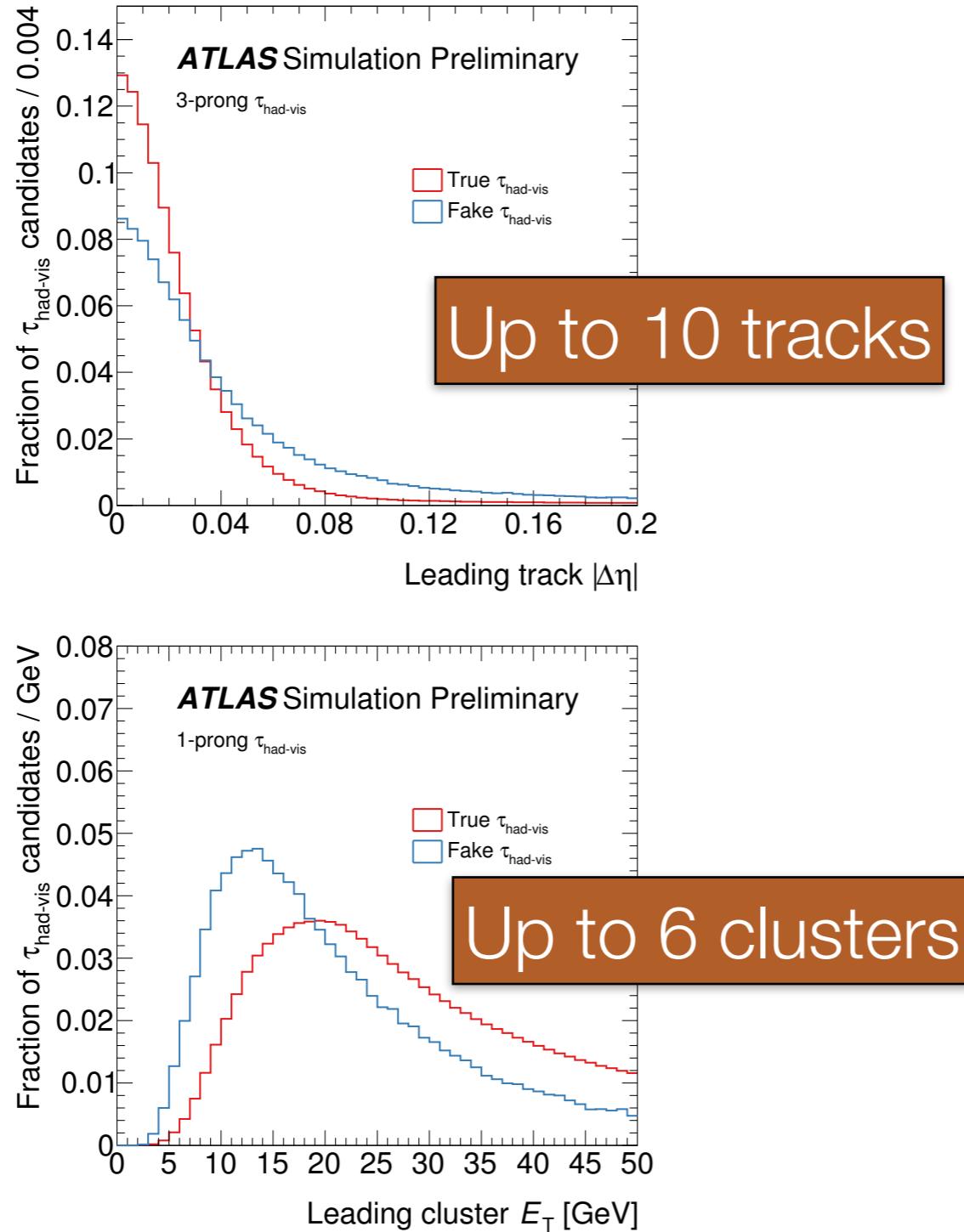


Combining the two



$$f_{\text{track}}^{\text{EM}} = \frac{\text{Energy deposited in ECAL}}{\text{Sum of track momenta}}$$

Rejecting jets

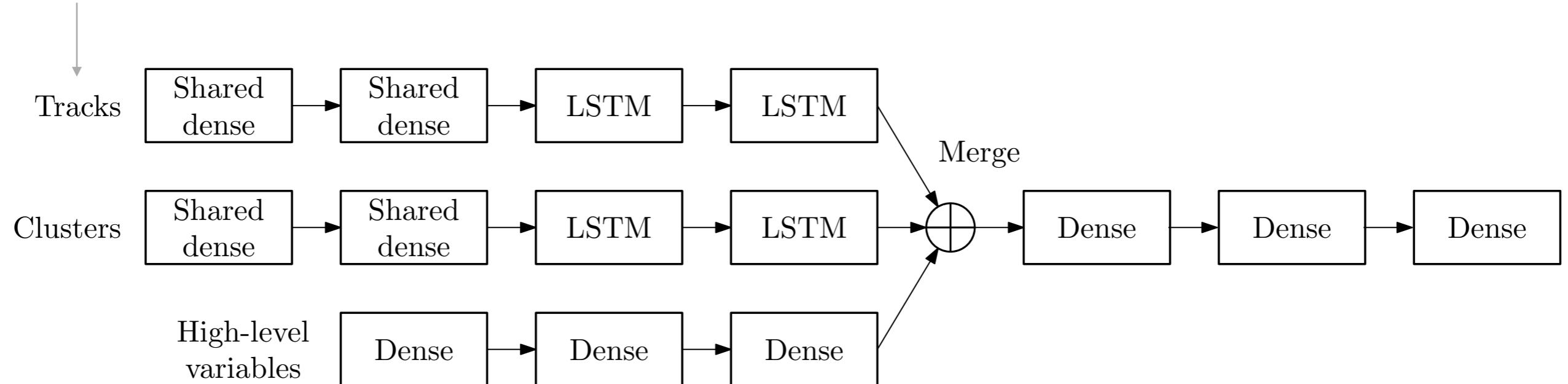


Observable	1-prong	3-prong
Track inputs	$p_T^{\text{seed jet}}$	•
	p_T^{track}	•
	$\Delta\eta^{\text{track}}$	•
	$\Delta\phi^{\text{track}}$	•
	$ d_0^{\text{track}} $	•
	$ z_0^{\text{track}} \sin \theta $	•
	$N_{\text{IBL hits}}$	•
	$N_{\text{Pixel hits}}$	•
	$N_{\text{SCT hits}}$	•
Cluster inputs	$p_T^{\text{jet seed}}$	•
	E_T^{cluster}	•
	$\Delta\eta^{\text{cluster}}$	•
	$\Delta\phi^{\text{cluster}}$	•
	λ_{cluster}	•
	$\langle \lambda_{\text{cluster}}^2 \rangle$	•
	$\langle r_{\text{cluster}}^2 \rangle$	•
High-level inputs	$p_T^{\text{uncalibrated}}$	•
	f_{cent}	•
	$f_{\text{leadtrack}}^{-1}$	•
	ΔR_{\max}	•
	$ S_{\text{leadtrack}} $	•
	$S_{\text{T}}^{\text{flight}}$	•
	f_{track}	•
	f_{iso}	•
	f_{EM}	•
	$f_{\text{track}}^{\text{EM+track}}$	•
	$p_T^{\text{EM+track}}/p_T$	•
	$m^{\text{EM+track}}$	•
	m^{track}	•

Rejecting jets

- Recurrent Neural Networks (LSTM units)
- Three independent branches for tracks, clusters and high-level variables

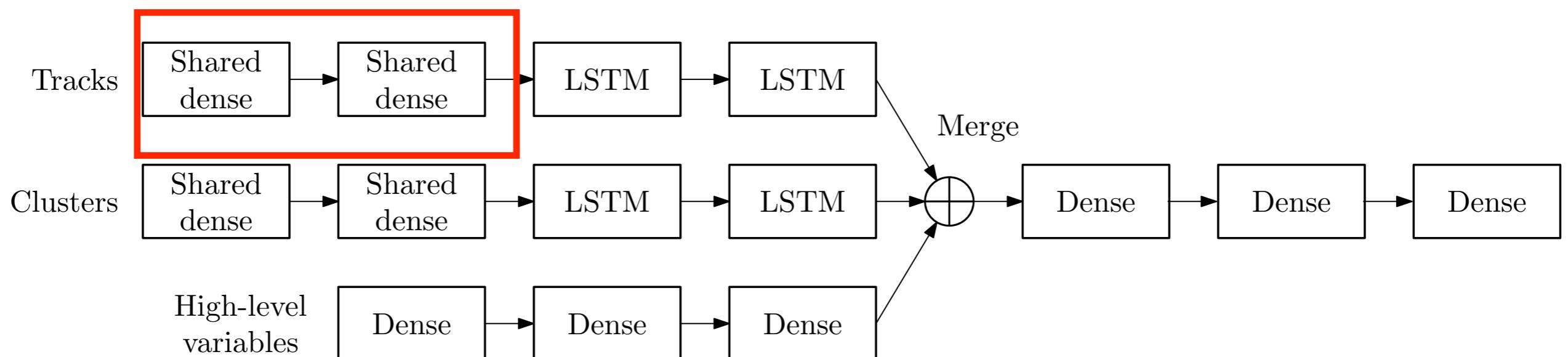
p_T -ordered



Rejecting jets

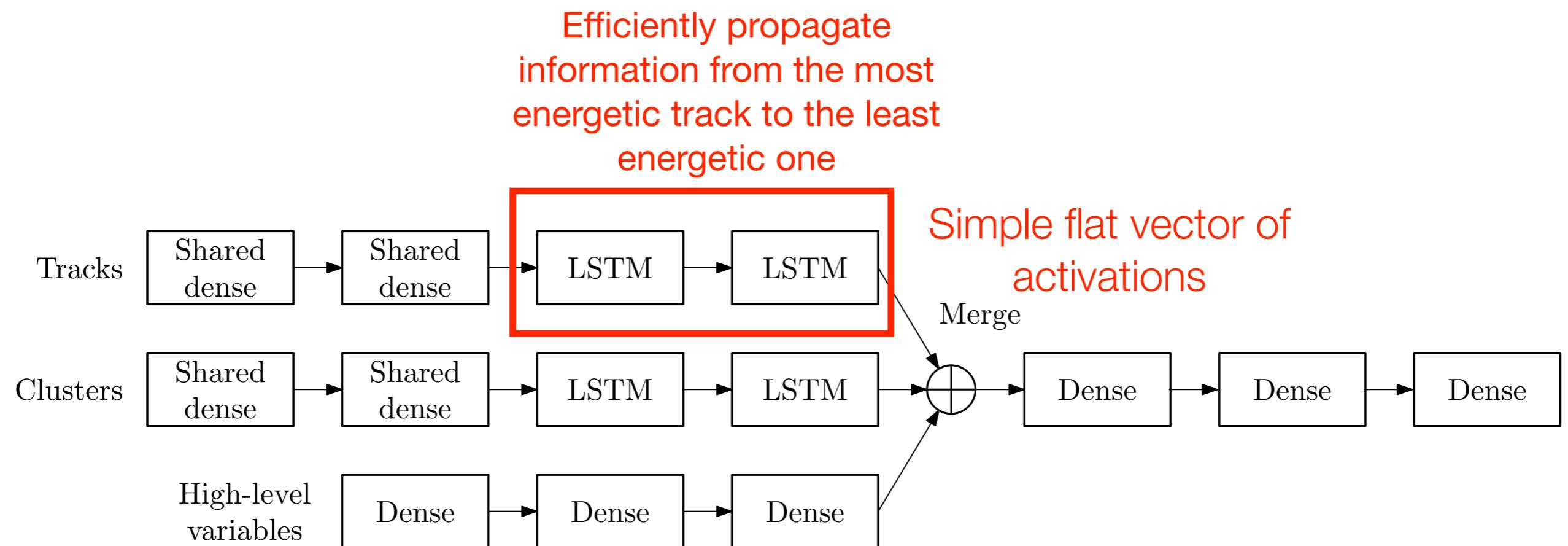
- Recurrent Neural Networks (LSTM units)
- Three independent branches for tracks, clusters and high-level variables

Weights are shared
among all tracks



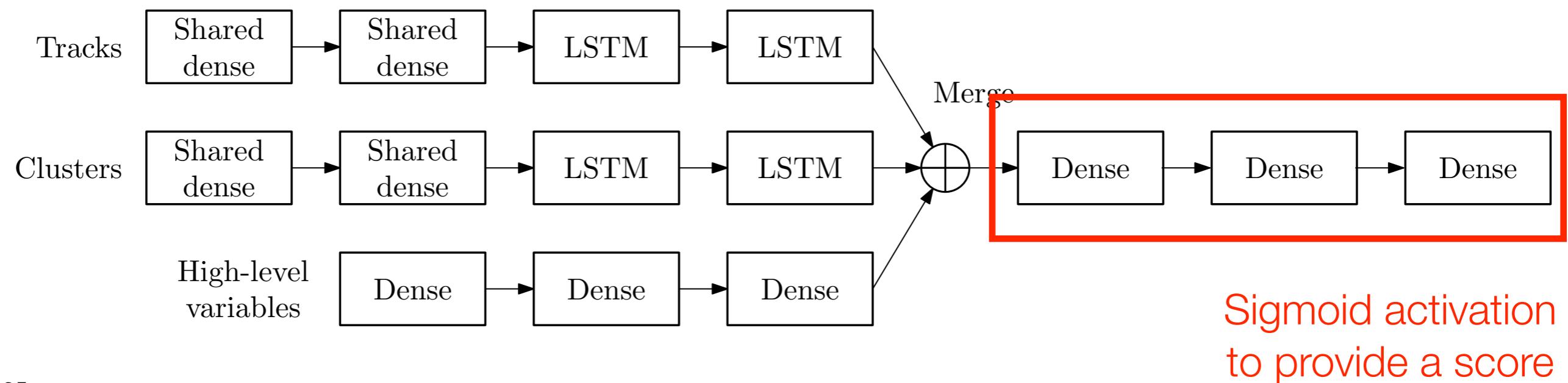
Rejecting jets

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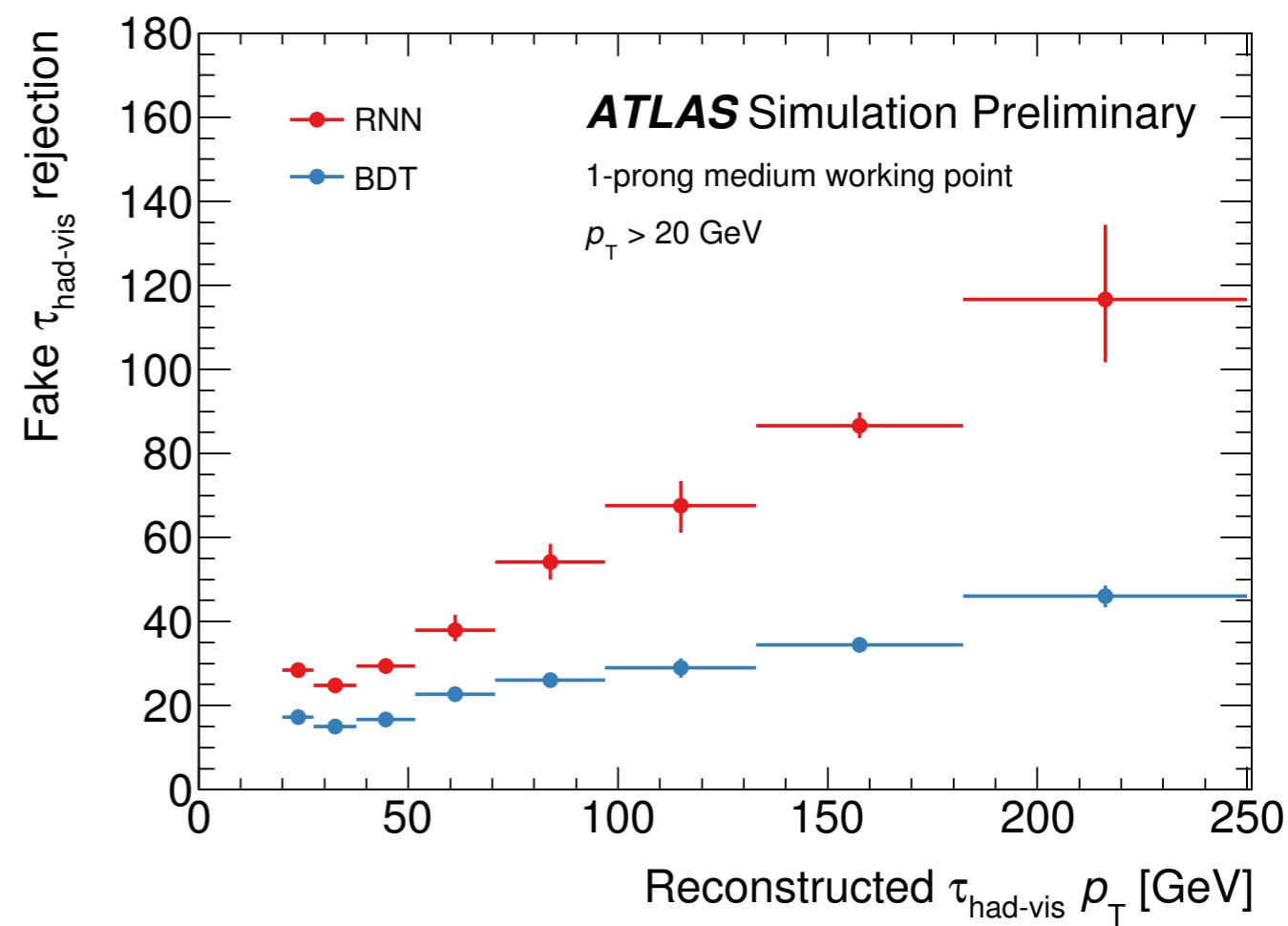
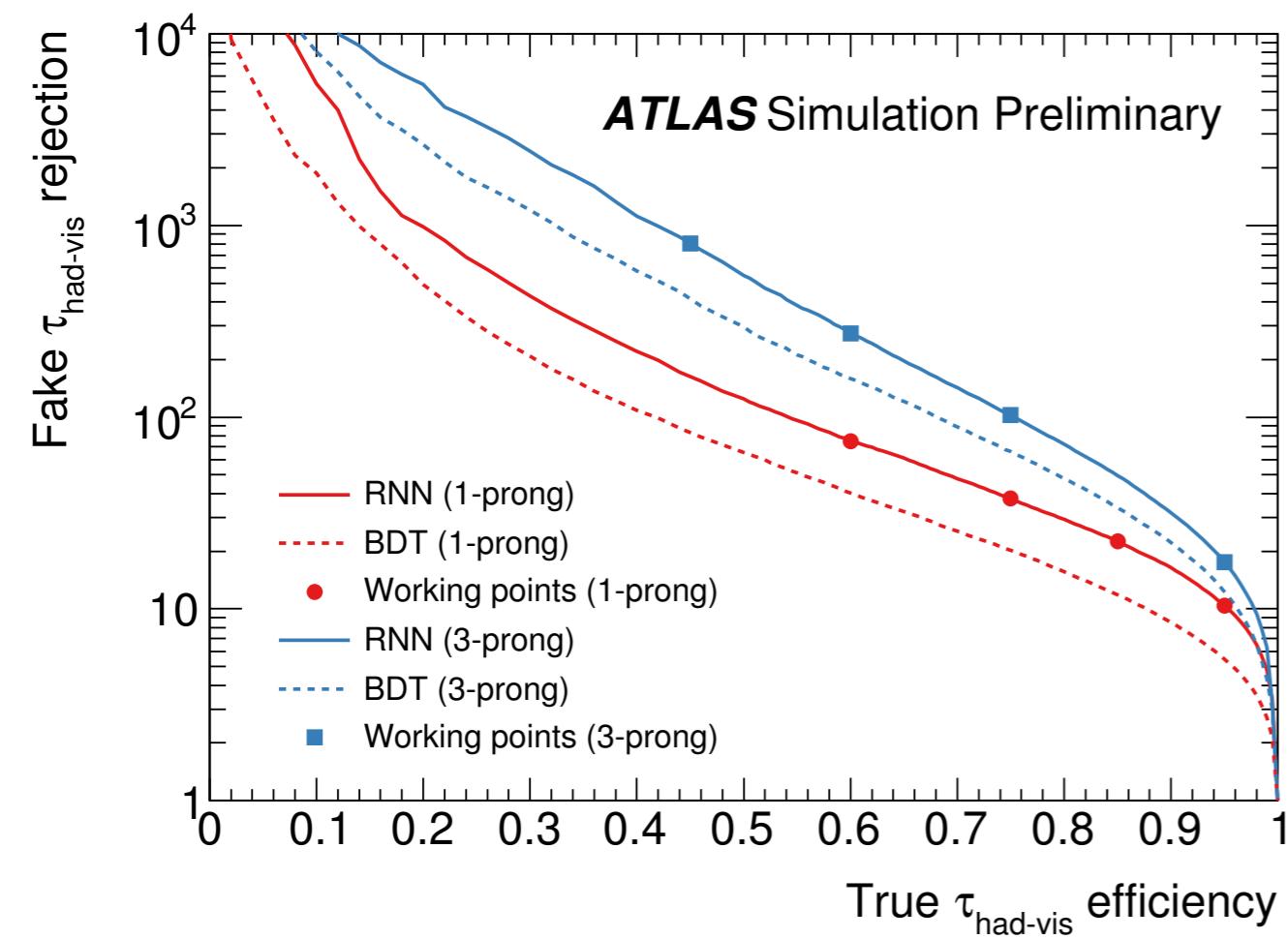


Rejecting jets

- Recurrent Neural Networks (LSTM units)
- Three independent branches for tracks, clusters and high-level variables



Rejecting jets



Outline

- Hadronic tau lepton detection strategy
 - >70% are found despite the challenging tracking conditions
 - Energy resolution at 5%
 - Very strong jet rejection thanks to deep learning techniques
- Calibrating hadronic taus
- A powerful tool for the ATLAS physics program
- Triggering ATLAS with hadronic tau leptons

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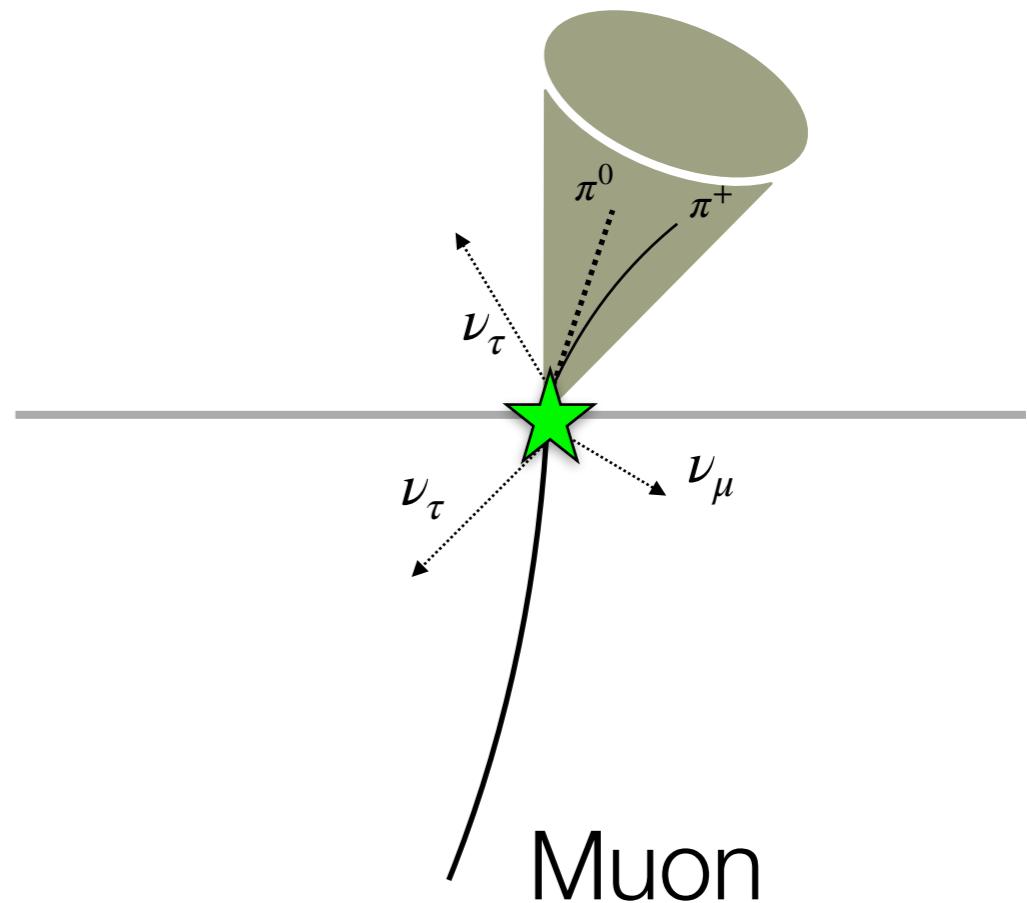
Standard Model candle: $Z \rightarrow \tau\tau \rightarrow \mu\tau_{\text{had}} (+ 3\nu)$

- Goal: select data events with a muon, characterise the τ_{had}

τ_{had}

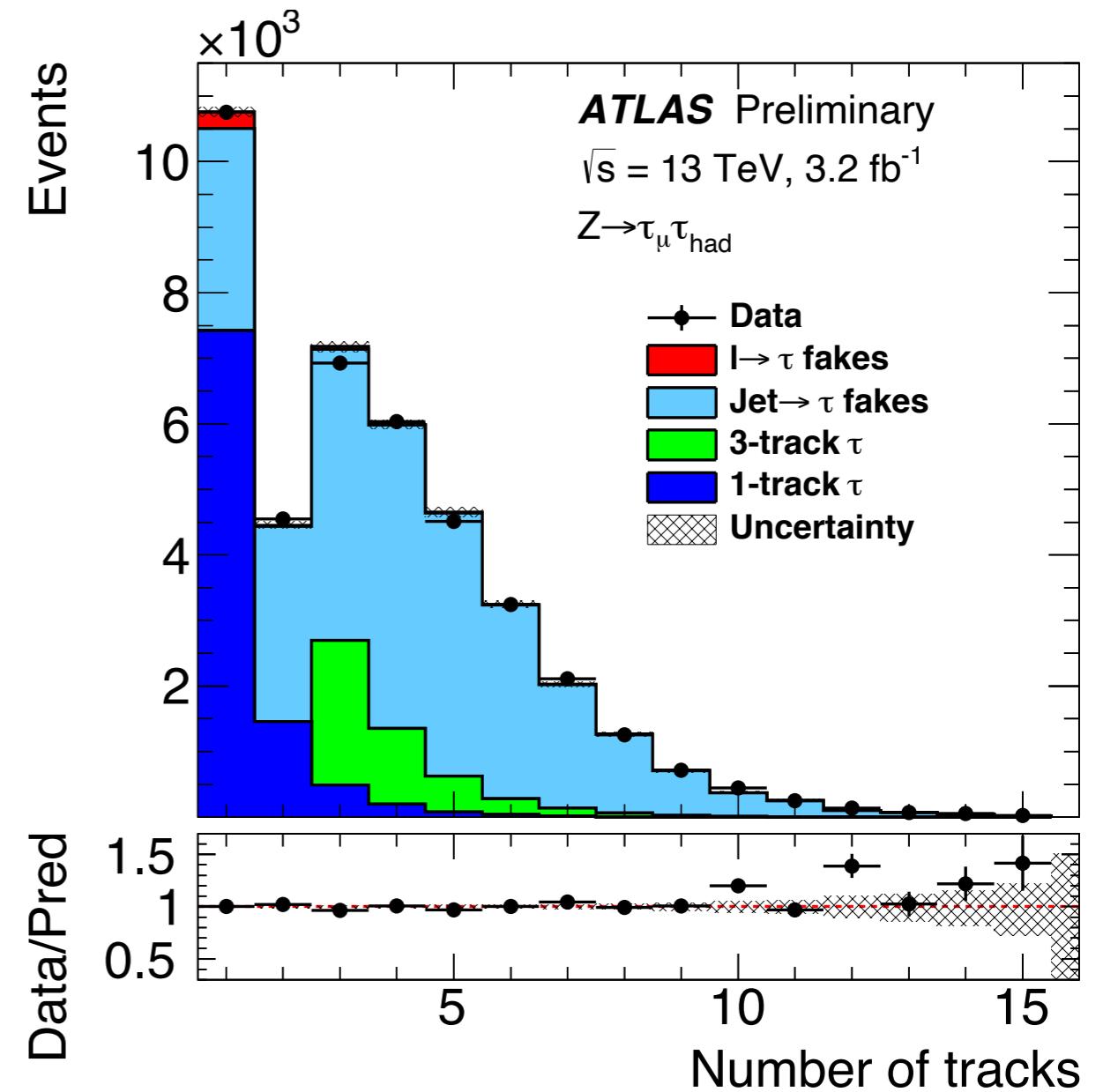
- Event selection:

- One single muon
- $m_T = \sqrt{2p_T^\mu \cdot E_T^{\text{miss}}(1 - \cos\Delta\phi(\mu, E_T^{\text{miss}}))} < 50 \text{ GeV}$
- $45 < m_{\text{vis}}(\mu, \tau_h) < 80 \text{ GeV}$
- Angular separation between E_T^{miss} and τ_h
- Veto b-tagged jets



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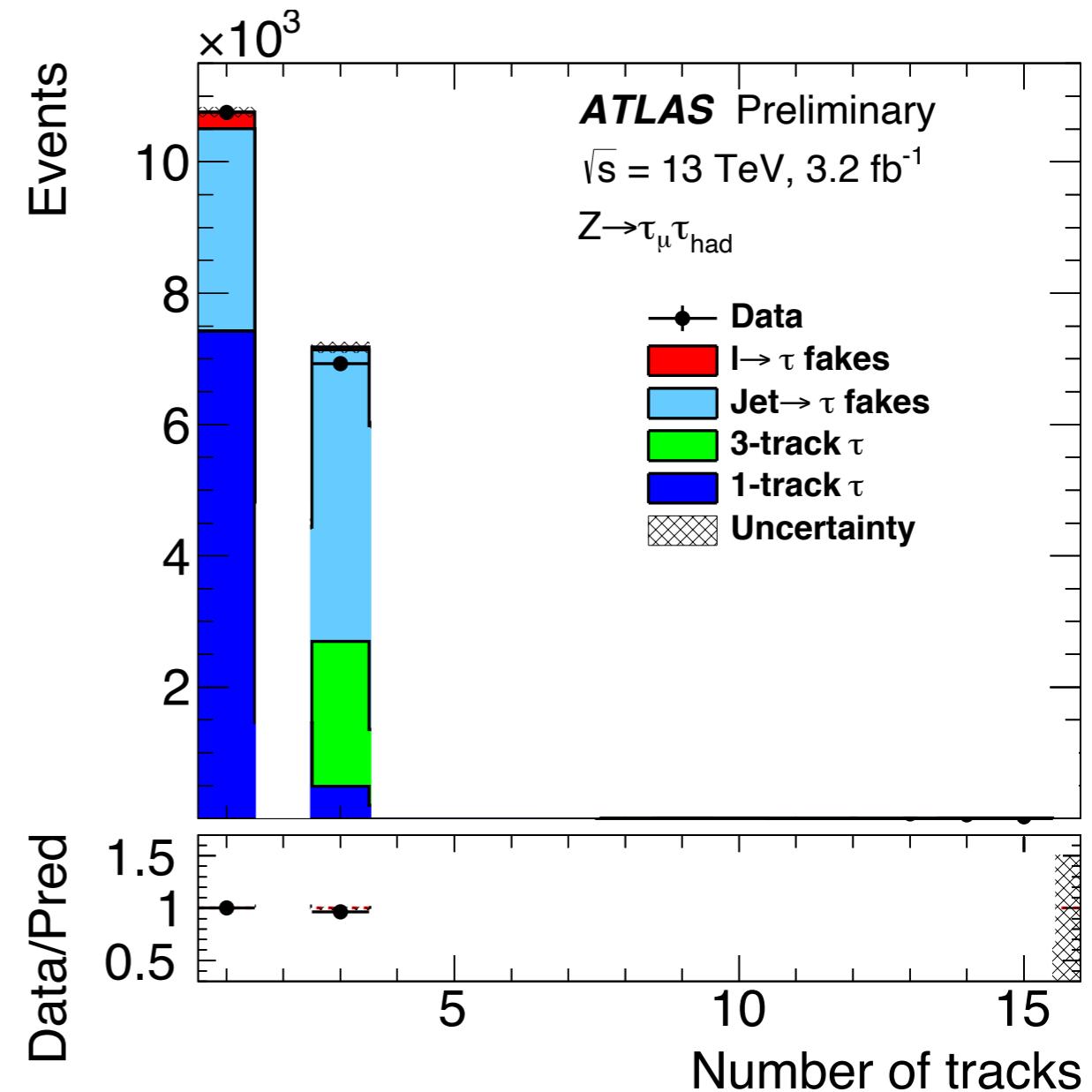
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Still overwhelmed with jet backgrounds

Standard Model candle: $Z \rightarrow \tau\tau \rightarrow \mu\tau_{\text{had}} (+ 3\nu)$

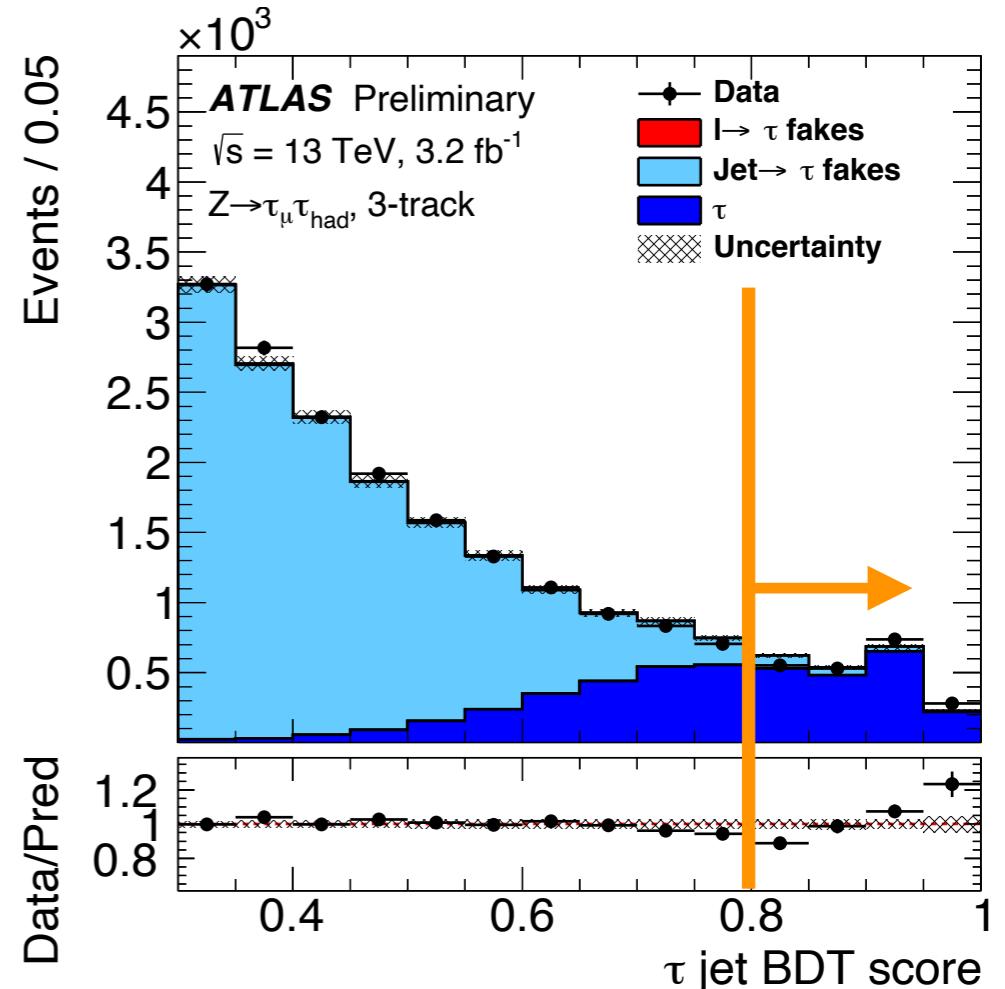
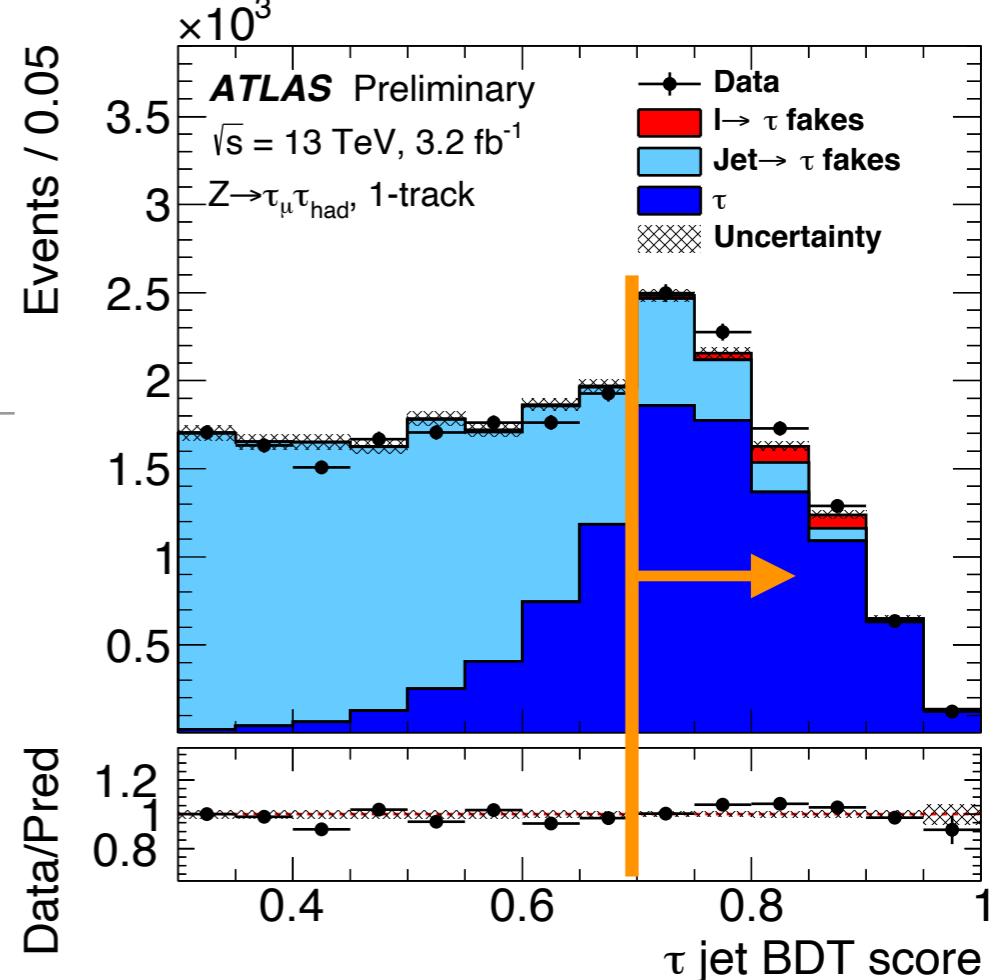
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 - Angular separation between E_T^{miss} and τ_h
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 - **N(tracks) = {1, 3}**



Track classifier behaviour
cannot be assessed in-situ

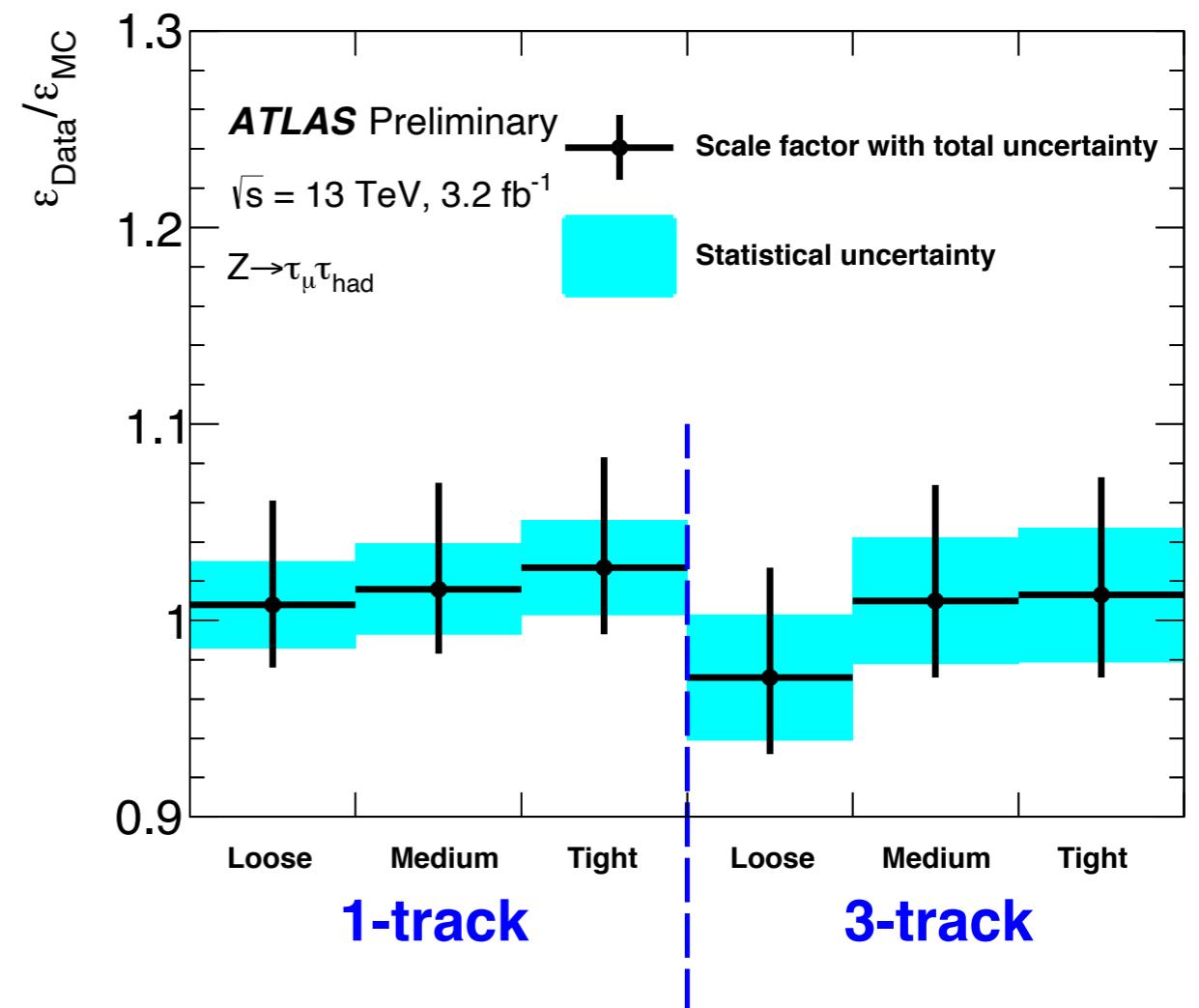
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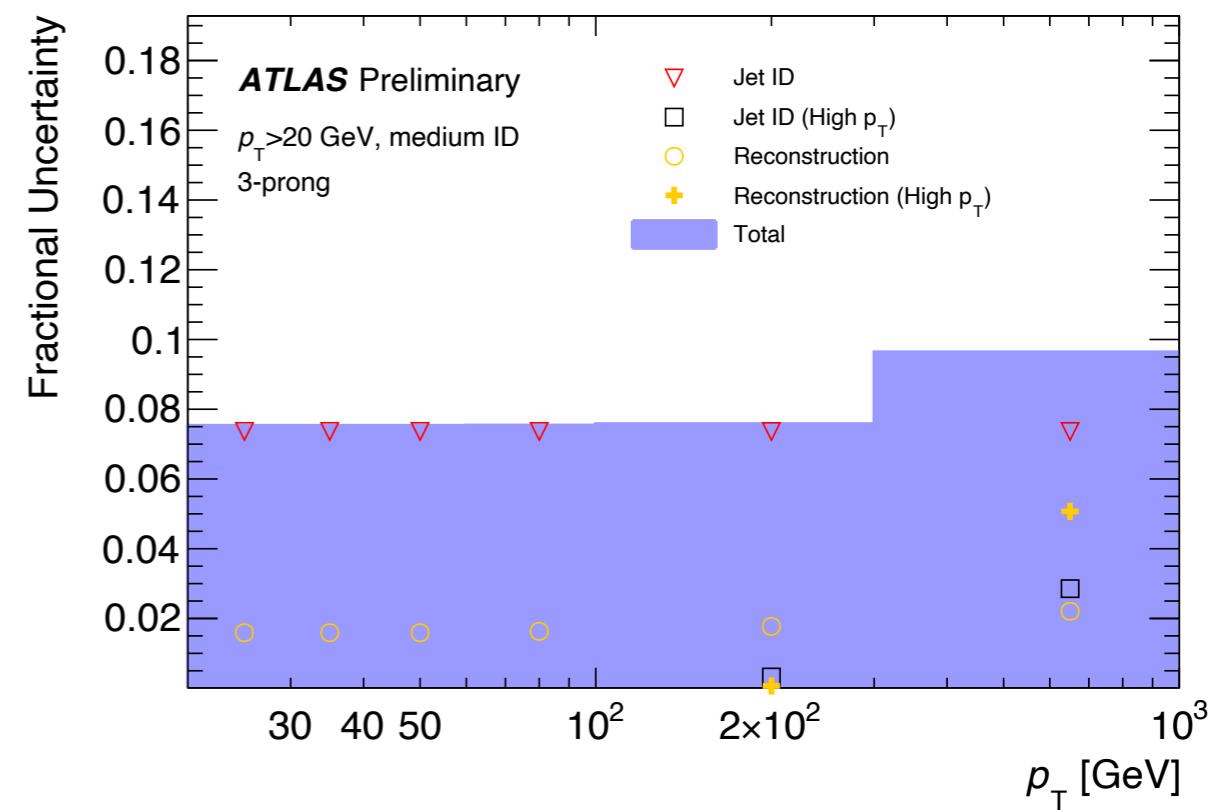
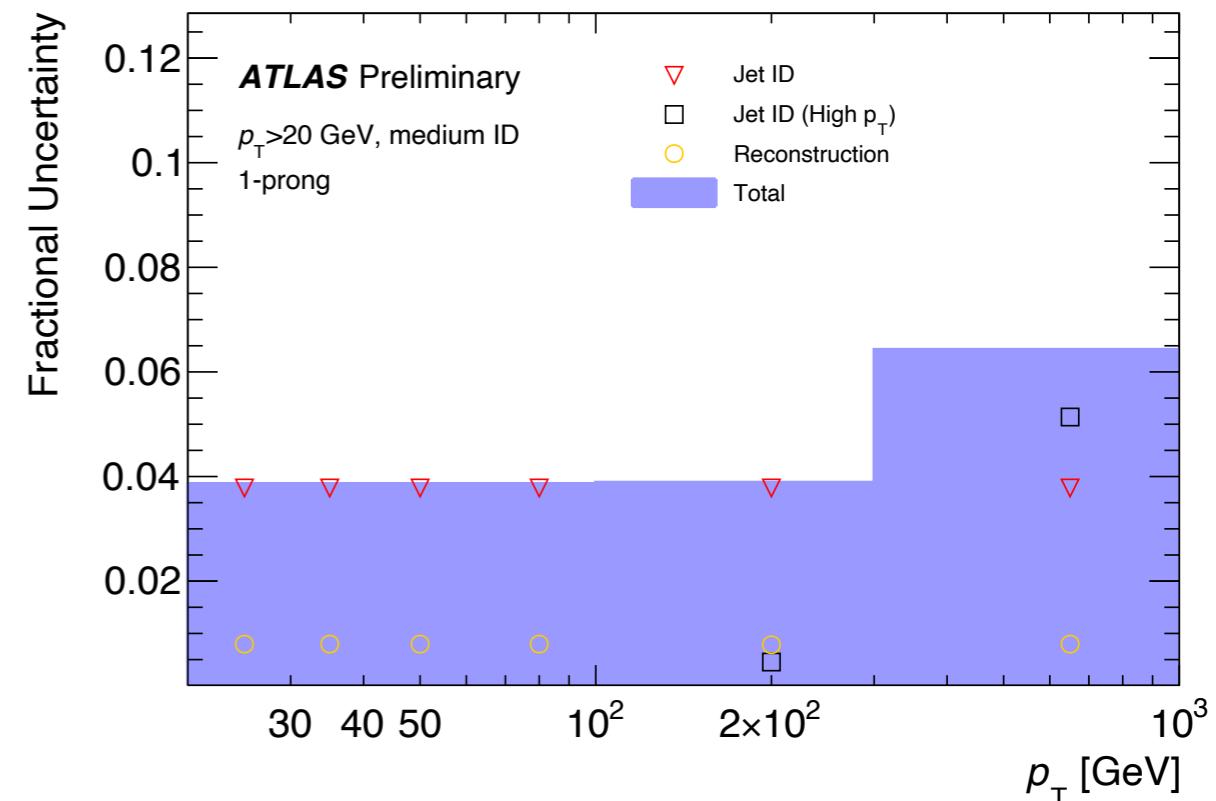
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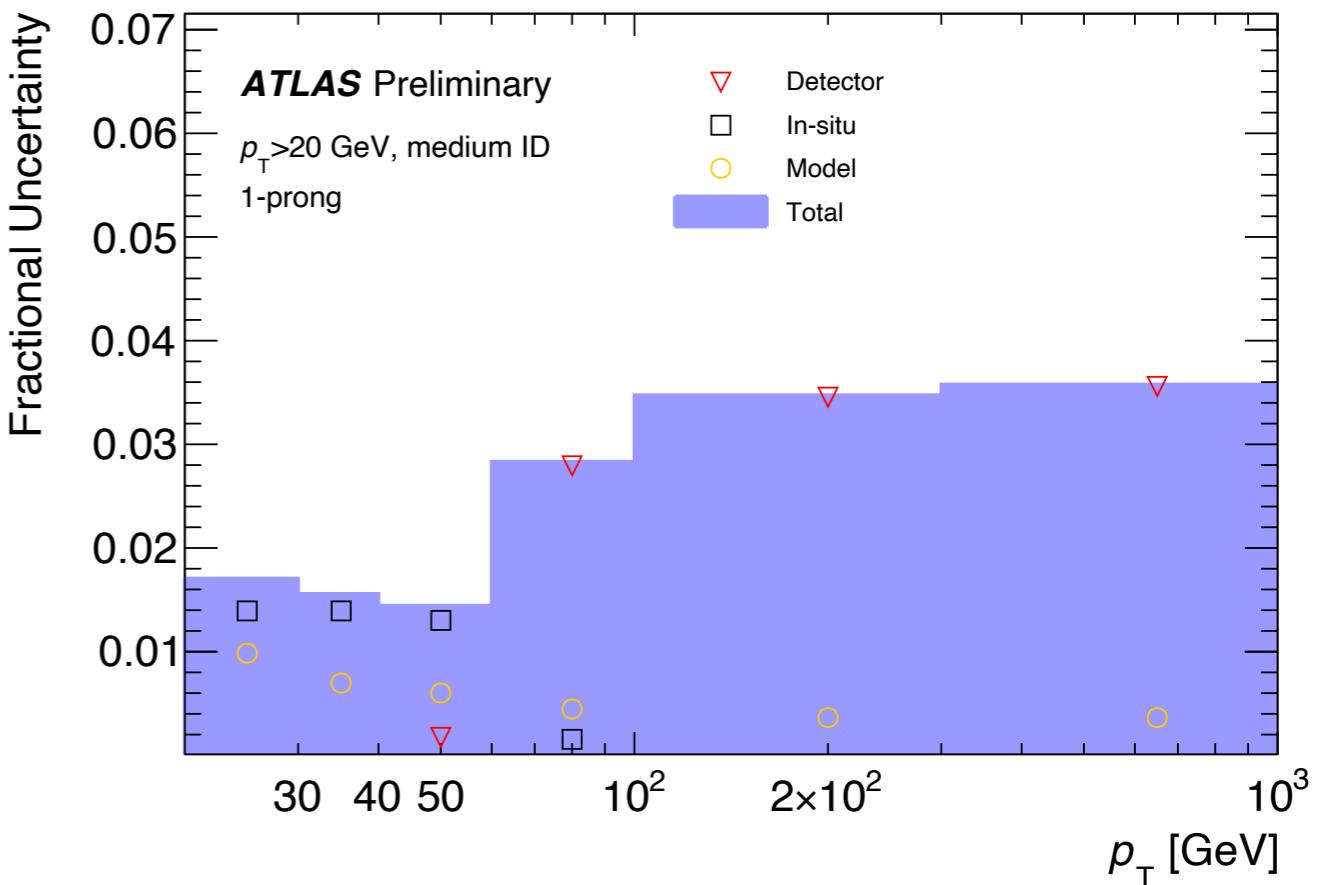
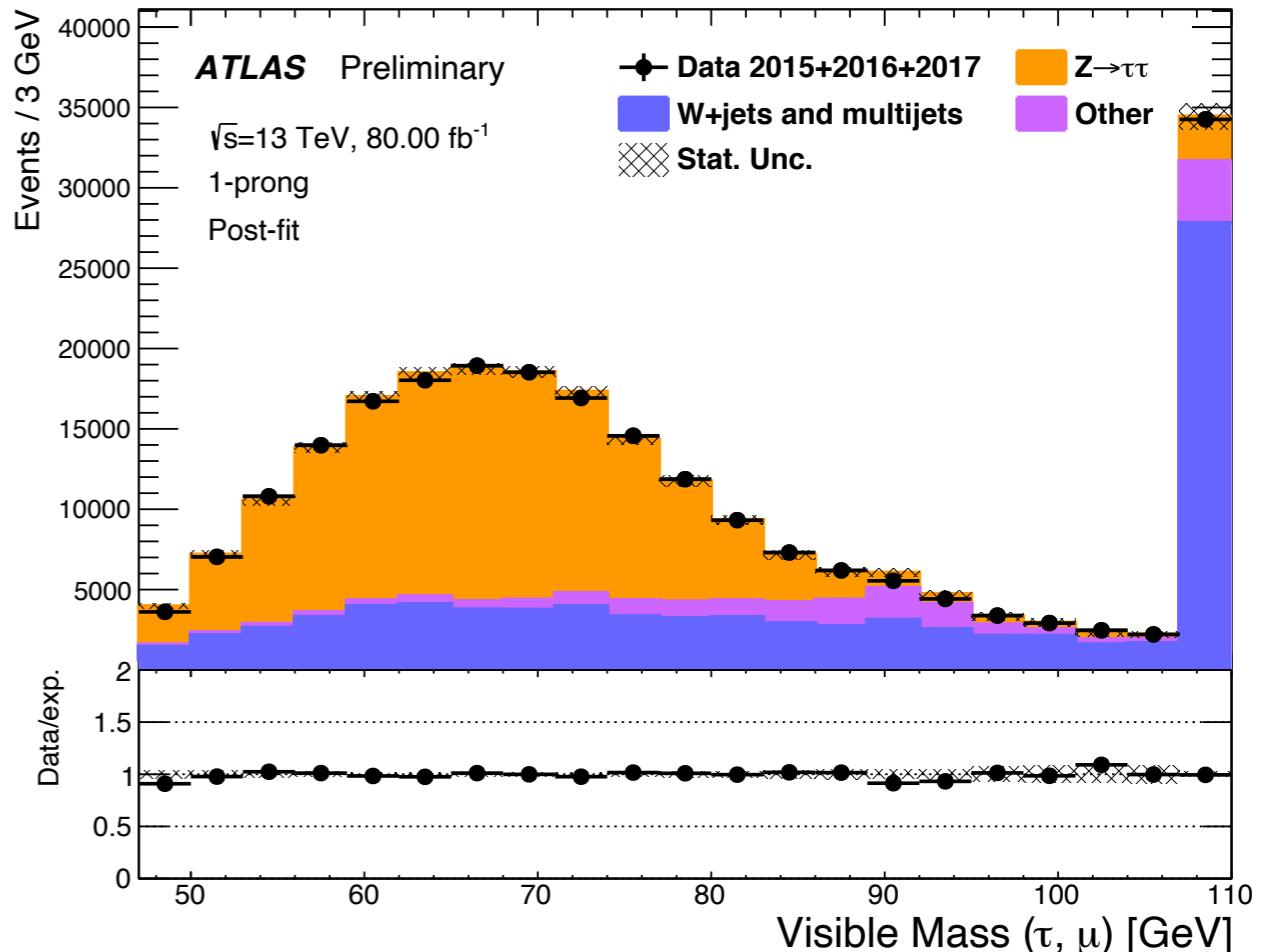
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NB: latest uncertainties are ~twice smaller

Tau Energy Scale

- Template fit of the visible mass to adjust α
- $\alpha(\text{Data} / \text{MC}) \sim 1\% (3\%)$ for 1p (3p) taus
- Uncertainties
 - In-situ measurement (sels, bkggs, ...)
 - Truth \longleftrightarrow Reconstruction in simulation (absolute scale)
 - Extrapolation of E/p measurement from single pions to taus as an ersatz for high p_T taus



Outline

- Hadronic tau lepton detection strategy
- Calibrating hadronic taus
 - Pure control sample selection challenging
 - Incomplete knowledge of the efficiency
 - The aspects we can measure known at the ~2-3% level
- A powerful tool for the ATLAS physics program
- Triggering ATLAS with hadronic tau leptons

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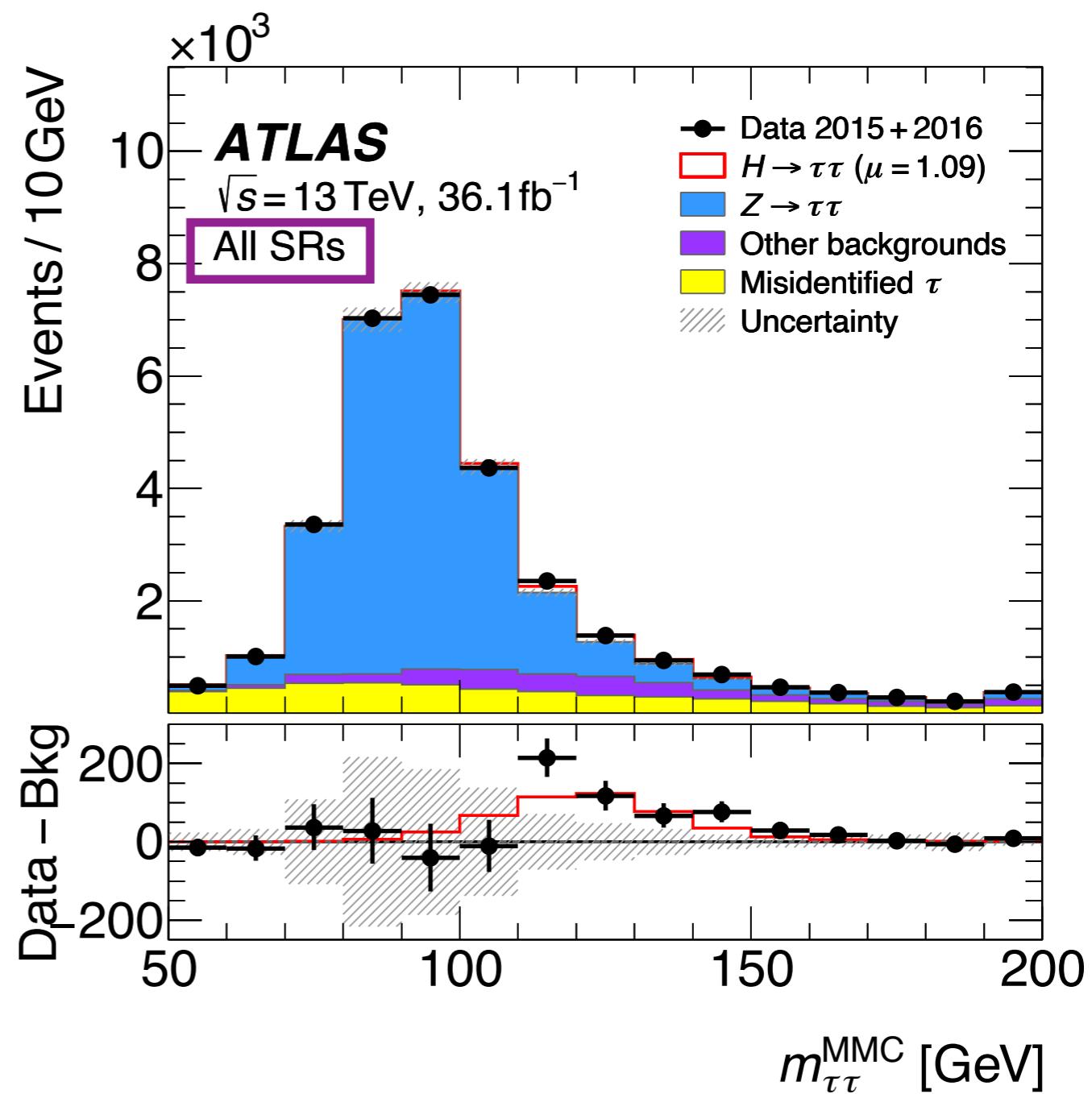
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Taus in Higgs physics: $H \rightarrow \tau\tau$ cross-section

Flagship ATLAS analysis
to be updated with full
Run2 dataset very soon!

Simultaneous fit on 13 signal
regions and 6 control regions

$Z \rightarrow \tau\tau$ norm. left floating in the fit:
uncertainty impacts extrapolation
from Z to Higgs



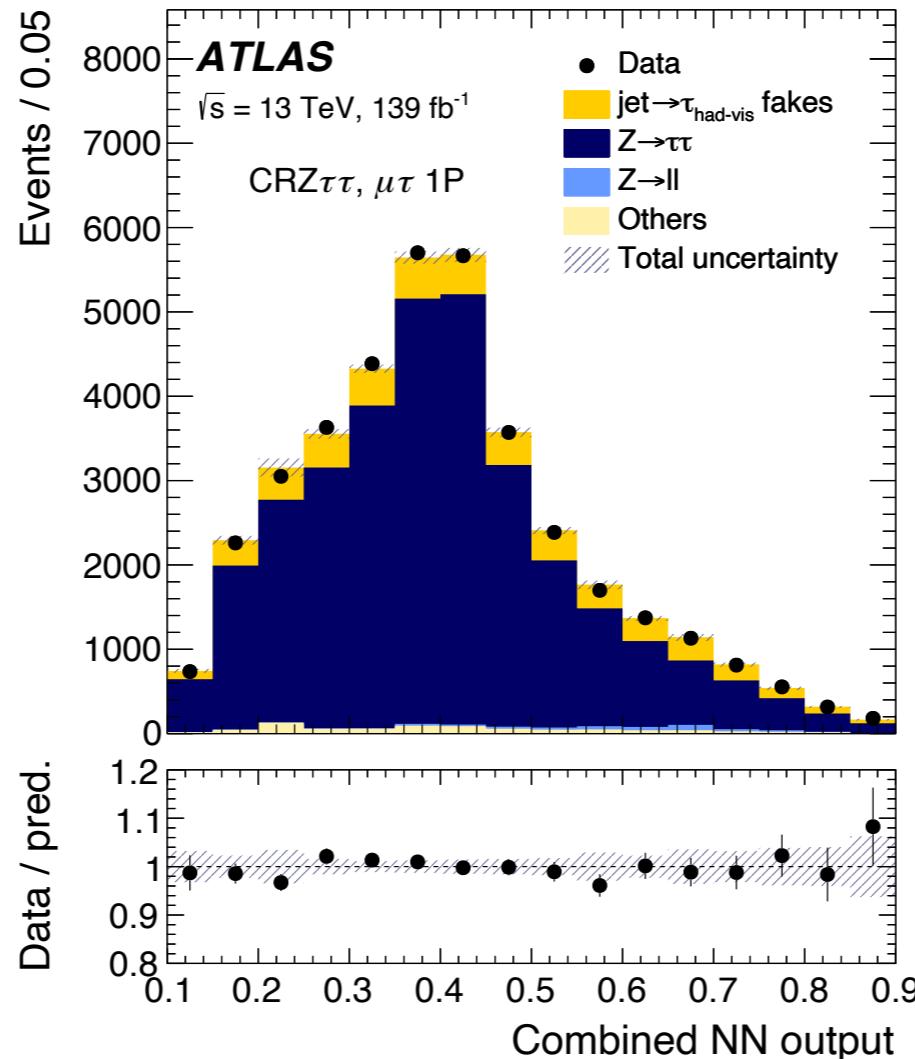
Taus in Higgs physics: $H \rightarrow \tau\tau$ cross-section

Source of uncertainty	Impact $\Delta\sigma/\sigma_{H \rightarrow \tau\tau}$ [%]	
	Observed	Expected
Theoretical uncert. in signal	+13.4 / -8.7	+12.0 / -7.8
Background statistics	+10.8 / -9.9	+10.1 / -9.7
Jets and E_T^{miss}	+11.2 / -9.1	+10.4 / -8.4
Background normalization	+6.3 / -4.4	+6.3 / -4.4
Misidentified τ	+4.5 / -4.2	+3.4 / -3.2
Theoretical uncert. in background	+4.6 / -3.6	+5.0 / -4.0
Hadronic τ decays	+4.4 / -2.9	+5.5 / -4.0
Flavor tagging	+3.4 / -3.4	+3.0 / -2.3
Luminosity	+3.3 / -2.4	+3.1 / -2.2
Electrons and muons	+1.2 / -0.9	+1.1 / -0.8
Total systematic uncert.	+23 / -20	+22 / -19
Data statistics	± 16	± 15
Total	+28 / -25	+27 / -24

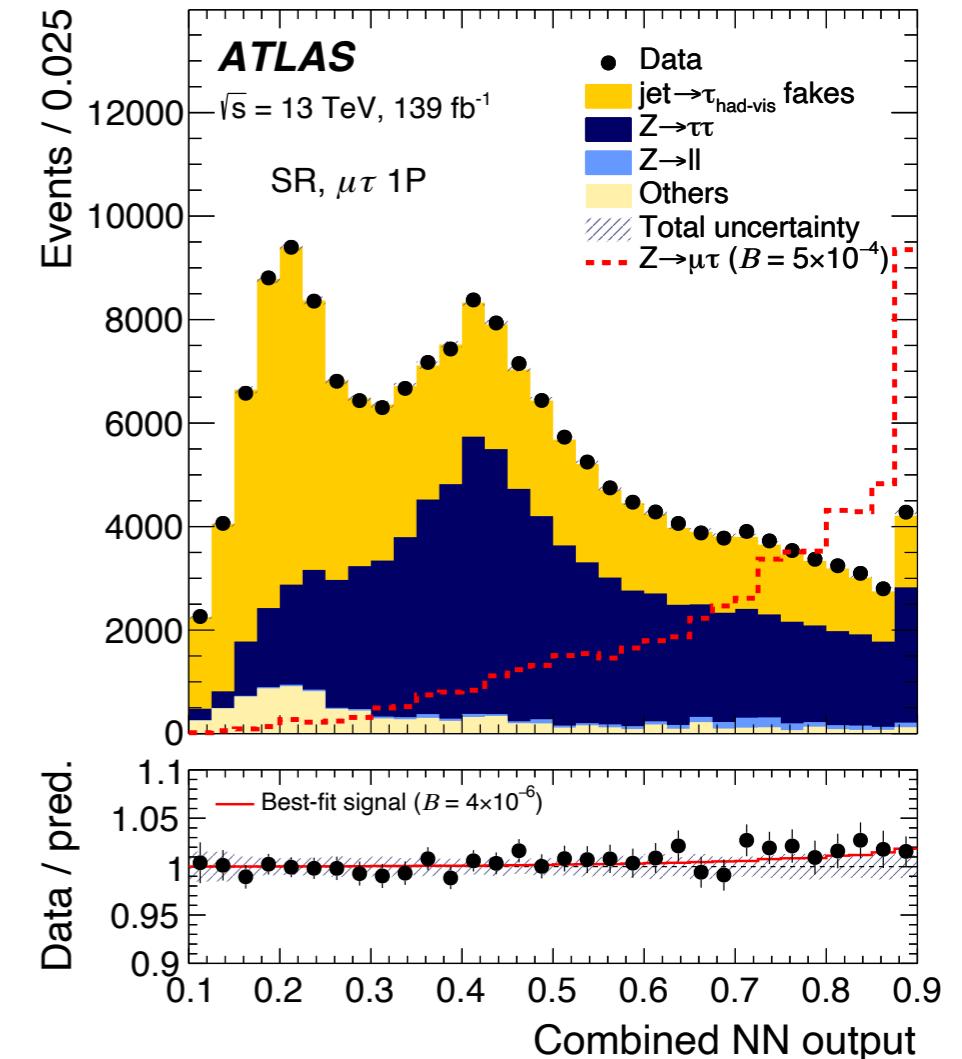
HL-LHC prospect: $\Delta\sigma/\sigma_{H \rightarrow \tau\tau} \approx 10\%$

Taus in Lepton Flavour Violation: $Z \rightarrow \mu\tau$, $Z \rightarrow e\tau$

$Z \rightarrow \tau\tau$ norm. left
floating in the fit



Large control
region with very
pure $Z \rightarrow \tau\tau$



Signal region
dominated by
 $W(\rightarrow \mu\tau) + \text{jets}$

$Z \rightarrow \mu\tau, Z \rightarrow e\tau$

- Hadronic tau uncertainty are the dominant source of systematics
- Important in-situ constraints from the control region

—●— Best-fit nuisance parameter
 —●— Best-fit normalisation factor
 Best-fit +1 σ impact
 Best-fit -1 σ impact

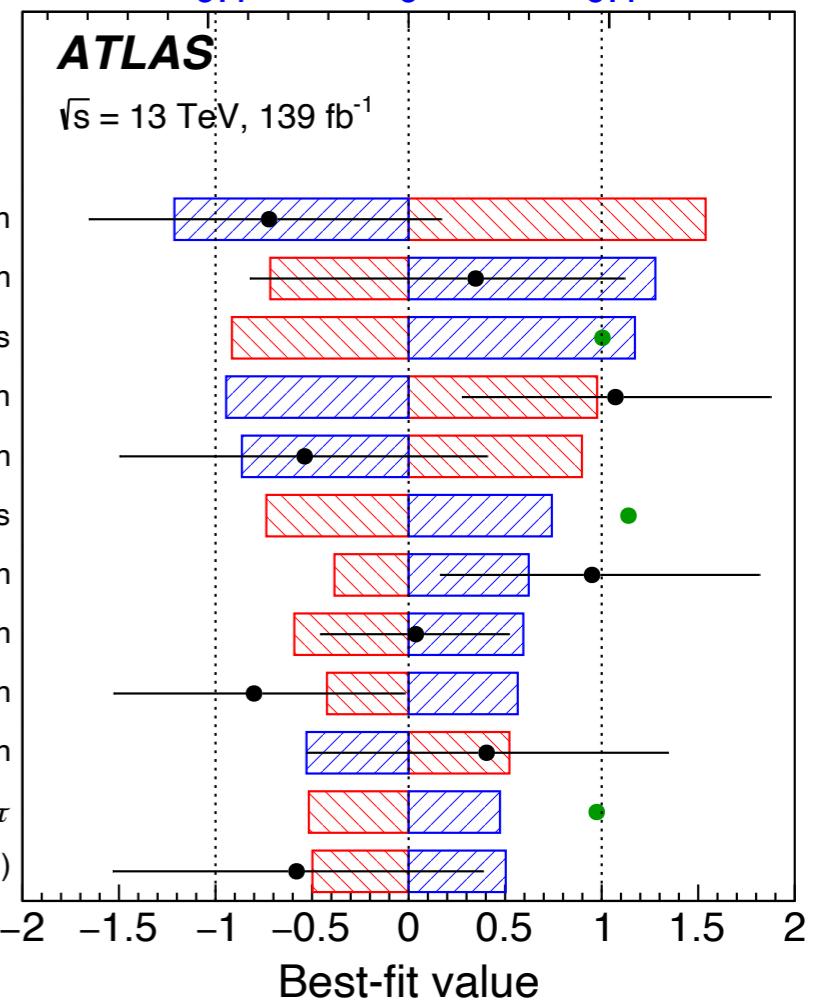
1P tau energy scale, in-situ exp., central region
 1P tau energy scale, in-situ fit, central region
 overall yield of 1P fakes
 3P tau energy scale, in-situ exp., central region
 1P tau energy scale, in-situ exp., forward region
 overall yield of 3P fakes
 1P tau energy scale, model, central region
 3P tau energy scale, in-situ fit, central region
 3P tau energy scale, model, central region
 3P tau energy scale, in-situ exp., forward region
 overall yield of $Z \rightarrow \tau\tau$
 1P fake factor (2nd p_T -bin 4th track- p_T -bin)

Best-fit impact on $B(Z \rightarrow \mu\tau)$

-0.1 0 0.1

ATLAS

$\sqrt{s} = 13 \text{ TeV}, 139 \text{ fb}^{-1}$



Source of uncertainty	Uncertainty on $B(Z \rightarrow \ell\tau)$ [$\times 10^{-6}$]	
	$e\tau$	$\mu\tau$
Statistical	± 3.5	± 2.8
Systematic	± 2.3	± 1.6
τ -leptons	± 1.9	± 1.5
Energy calibration	± 1.3	± 1.4
Jet rejection	± 0.3	± 0.3
Electron rejection	± 1.3	
Light leptons	± 0.4	± 0.1
E_T^{miss} , jets and flavour tagging	± 0.6	± 0.5
Z -boson modelling	± 0.7	± 0.3
Luminosity and other minor backgrounds	± 0.8	± 0.3
Total	± 4.1	± 3.2

The Unique Power of Hadronic Taus

- CP nature of the Higgs boson coupling

$$\mathcal{L} = g_{\tau\tau}(\cos(\phi_\tau)\bar{\tau}\tau + \sin(\phi_\tau)\bar{\tau}i\gamma_5\tau)h$$

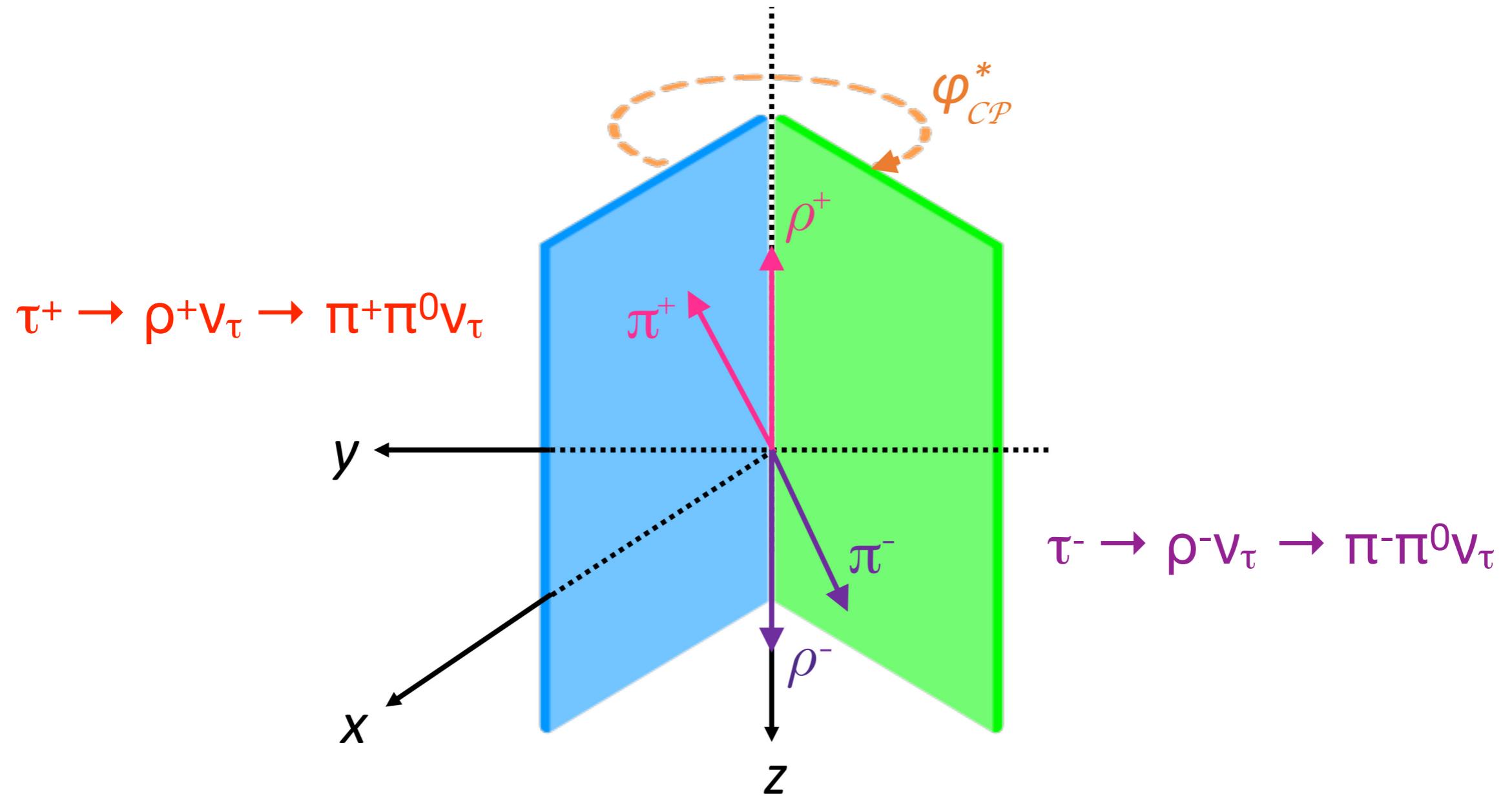
$\phi_\tau = 0 \rightarrow$ CP-even (SM)

$\phi_\tau = \frac{\pi}{2} \rightarrow$ CP-odd

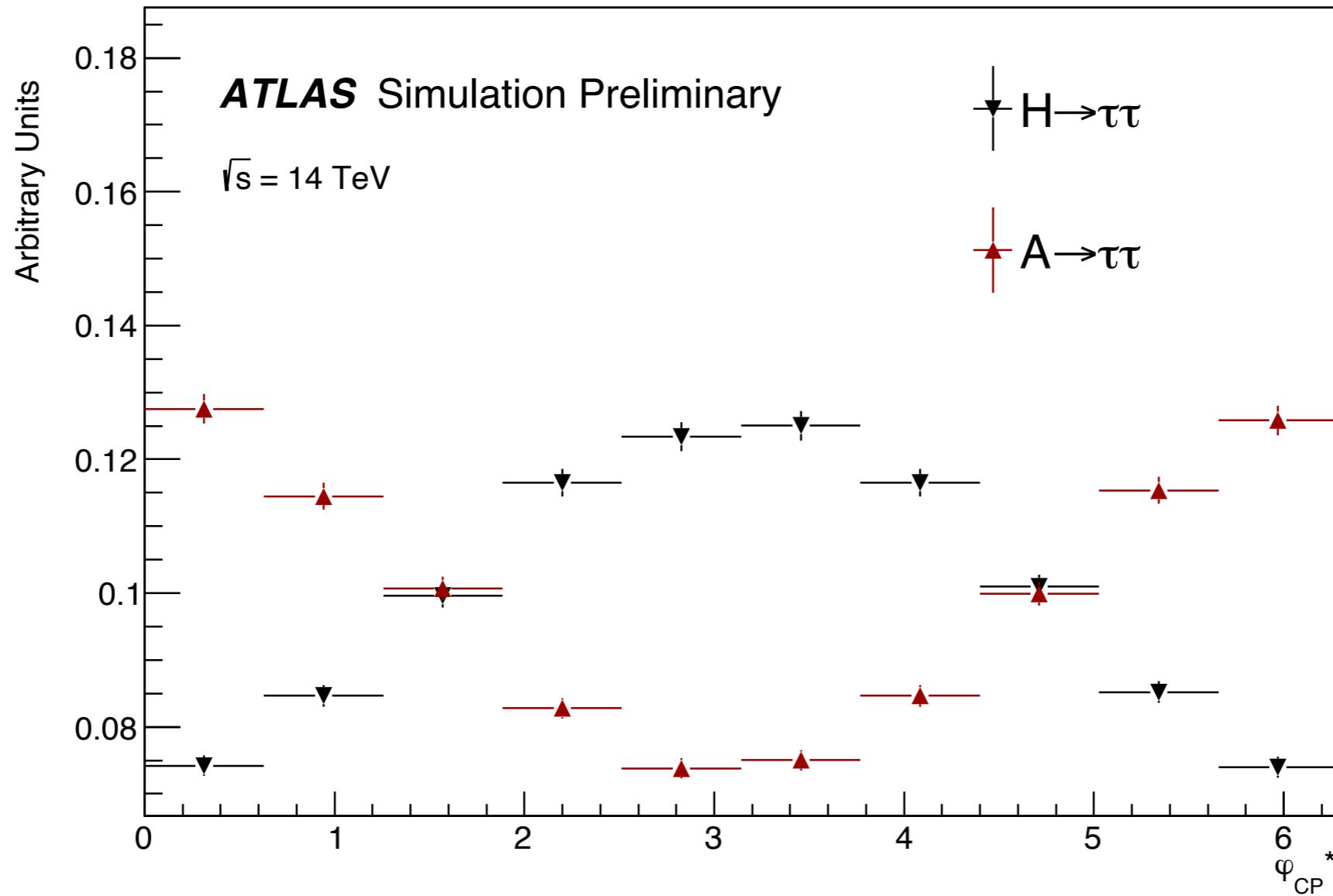
$\phi_\tau = \frac{\pi}{4} \rightarrow$ maximal CPV

- Yukawa couplings: CP-odd terms can be at the same order as CP-even terms (unlike bosonic ones)
- No significant changes on the predicted cross-sections
- Need observables carrying CP information of the parent particles
 - Tau leptons decay!

$H\tau\tau$ vertex properties



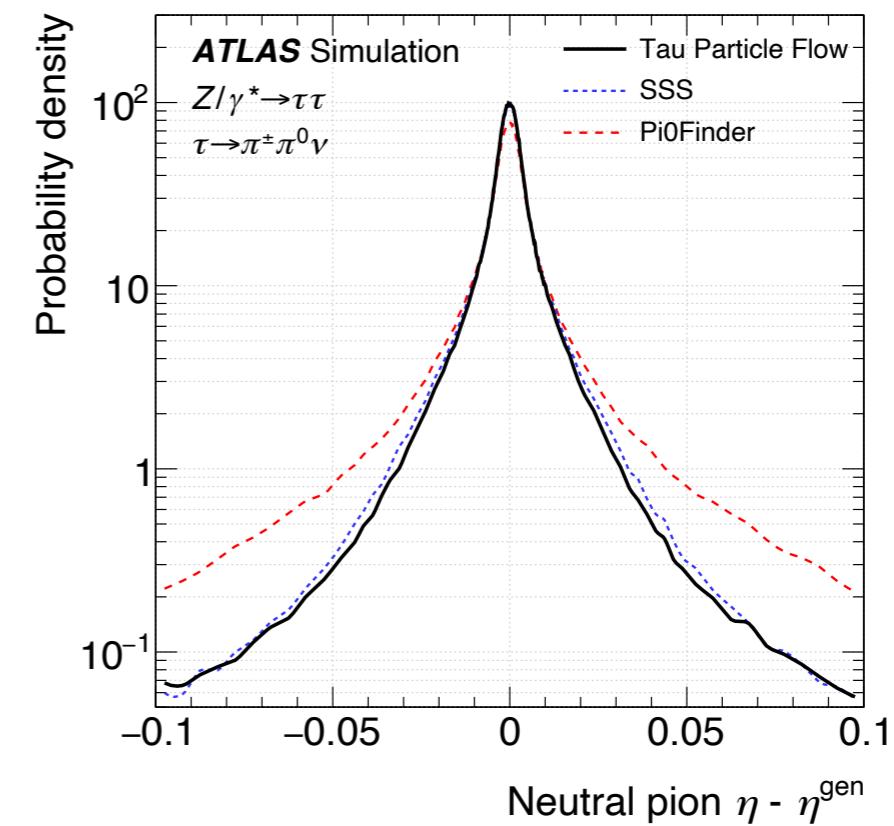
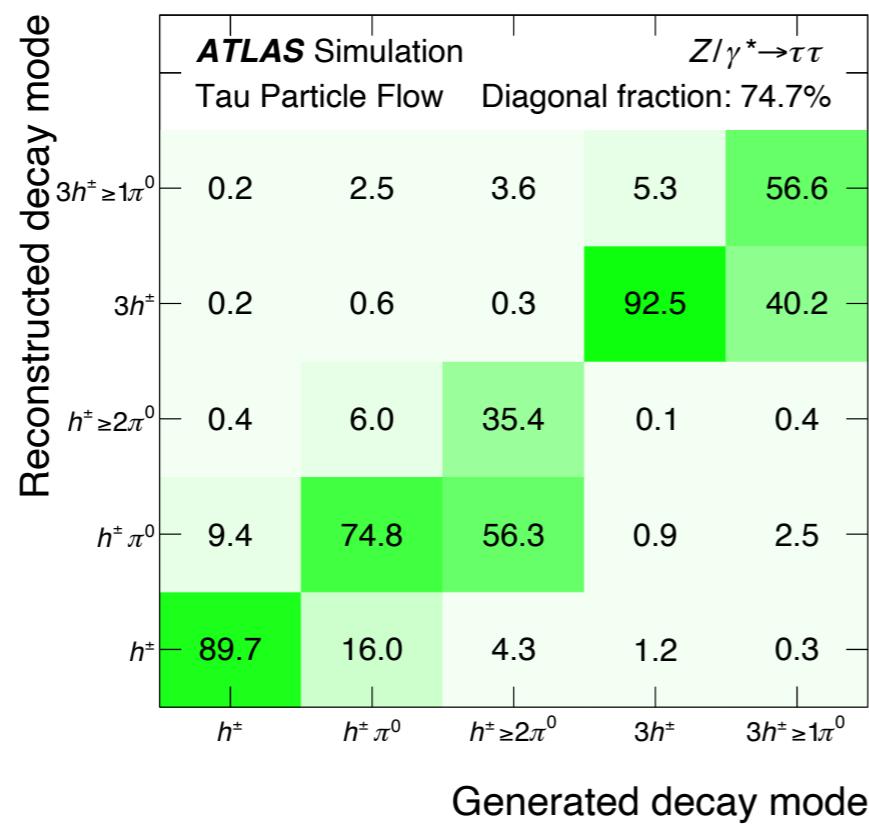
$H\tau\tau$ vertex properties



Constraint comes from shape differences in ϕ_{CP}^*

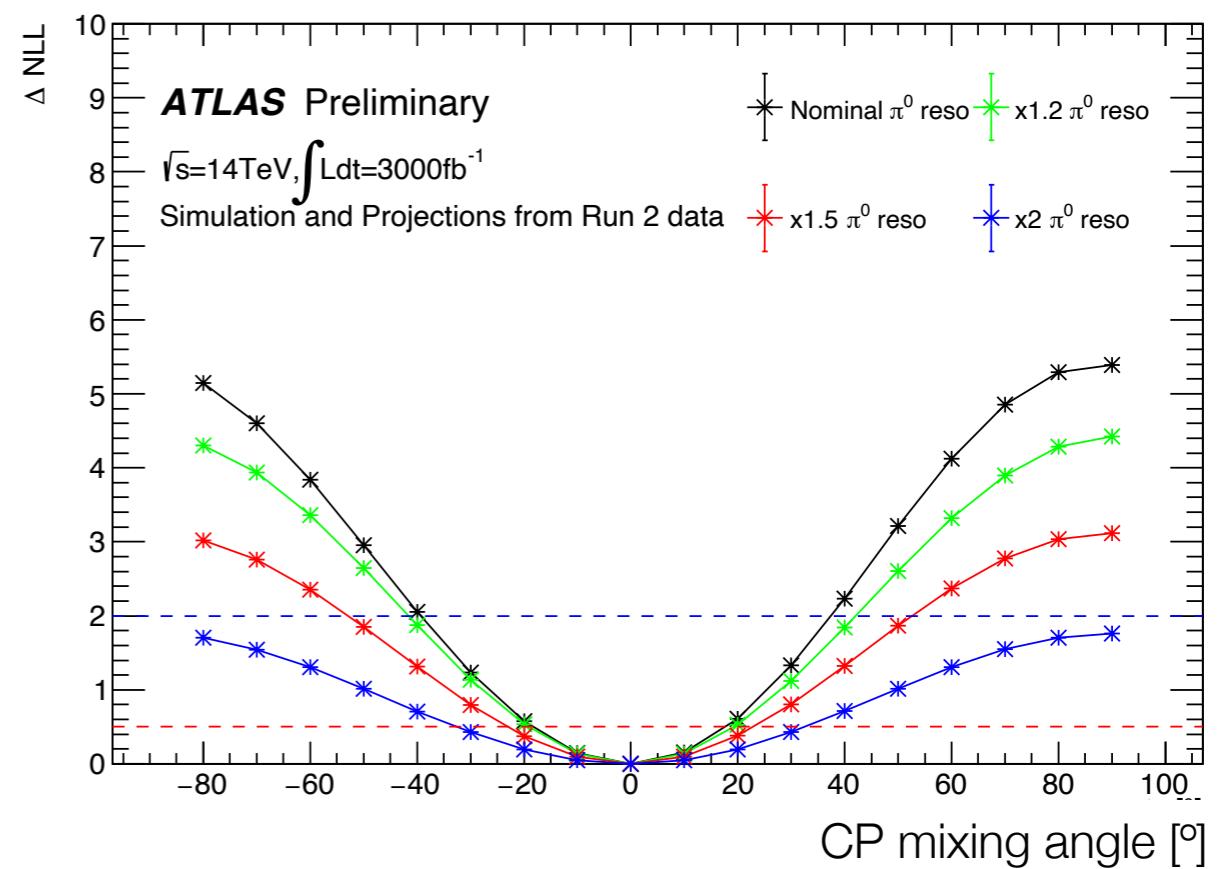
H $\tau\tau$ vertex properties

- Very challenging analysis
 - Selection of pure $\pi^+\pi^0-\pi^+\pi^0$ events
 - Reconstruction of the individual pions 4 momenta



H $\tau\tau$ vertex properties

- Projection: $\pm 18^\circ$ precision on the CP mixing-angle measurement
 - Precision on π^0 energy resolution has a large impact
 - $\pm 33^\circ$ if π^0 energy resolution twice larger than expected



Maximal CPV would be at $\pm 45^\circ$

Outline

- Hadronic tau lepton detection strategy
- Calibrating hadronic taus
- A powerful tool for the ATLAS physics program
 - Powered by excellent detection performance, discovered the Higgs boson with hadronic taus!
 - Continued work needed for future Higgs meas. and current precision searches
 - Hadronic tau decays offer unique opportunities for BSM searches through shape analyses
- Triggering ATLAS with hadronic tau leptons

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Why?

$X \rightarrow \tau\tau$	Visible Final State	BR (%)	Neutrinos in the event
Fully-leptonic	ee, $\mu\mu$, $e\mu$	13	4
Semi-leptonic	$e\tau_h$, $\mu\tau_h$	45	3
Fully-hadronic	$\tau_h\tau_h$	42	2

Light lepton triggers cover a large fraction of the ATLAS Physics program

Requires a dedicated tau trigger

87% of $X \rightarrow \tau\tau$ decays involve a hadronically-decaying tau lepton

The ATLAS Trigger System

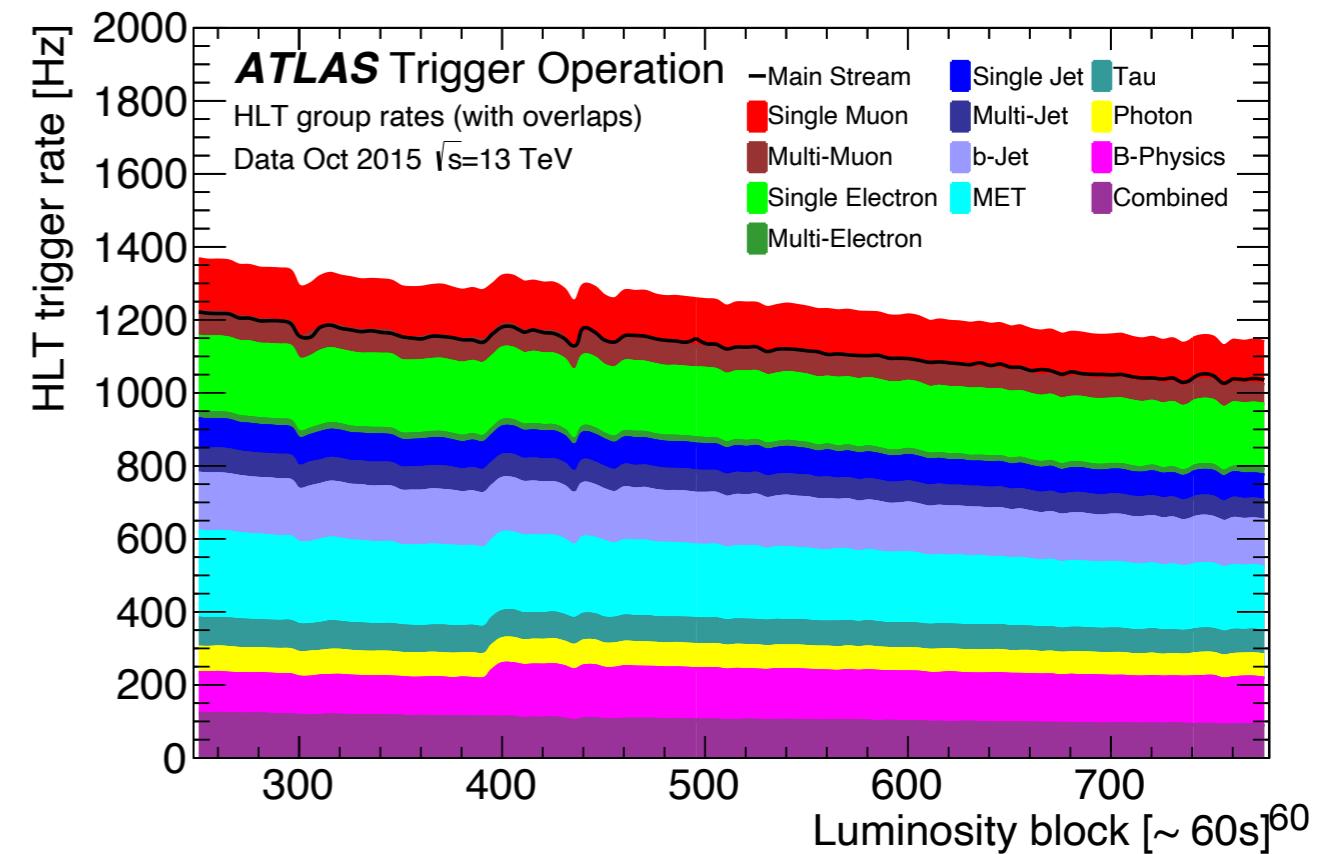
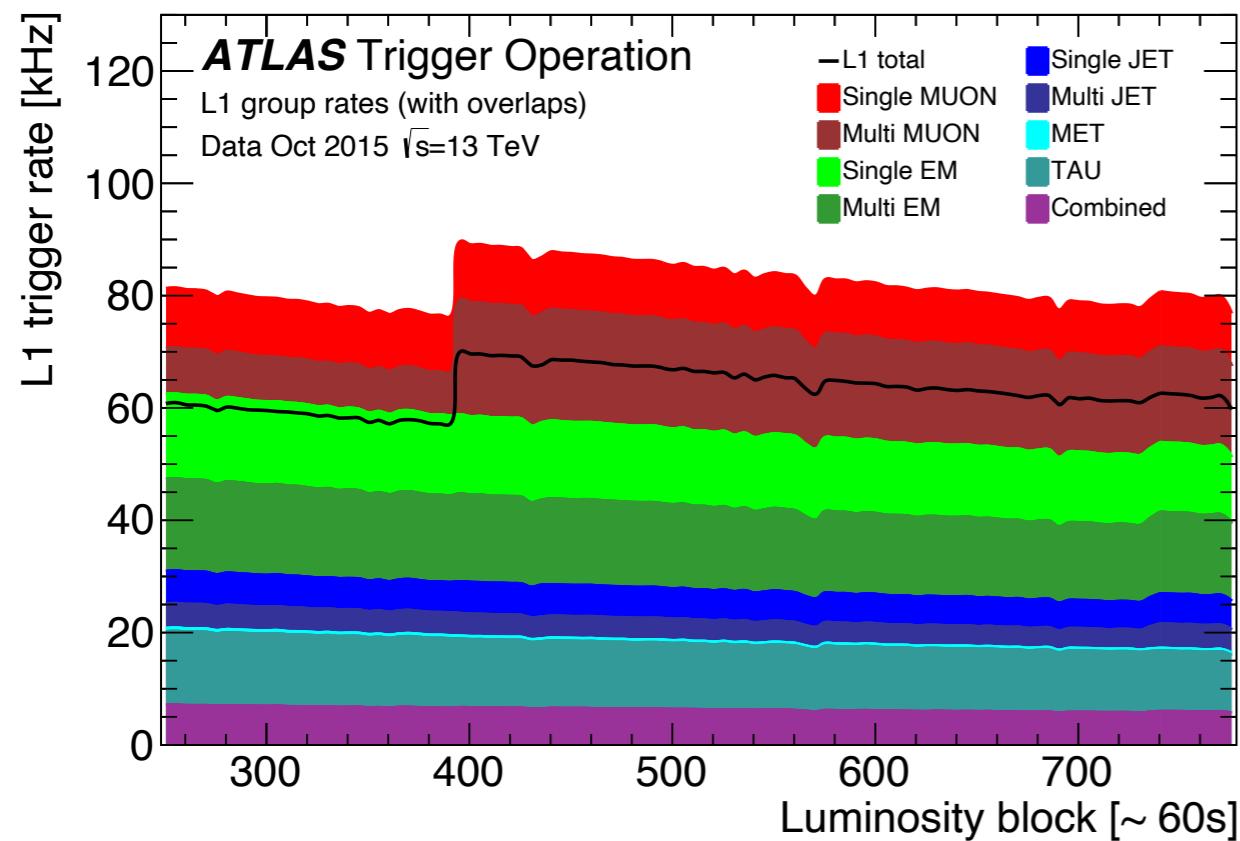
- 2-level system:
 - Level 1: hardware-based calorimeters and muon system
 - HLT: software-based, tracking in Rols
 - Record 1/40000 collisions

ATLAS Trigger key numbers

LHC bunch crossing rate 40 MHz

ATLAS L1 output rate 100 kHz

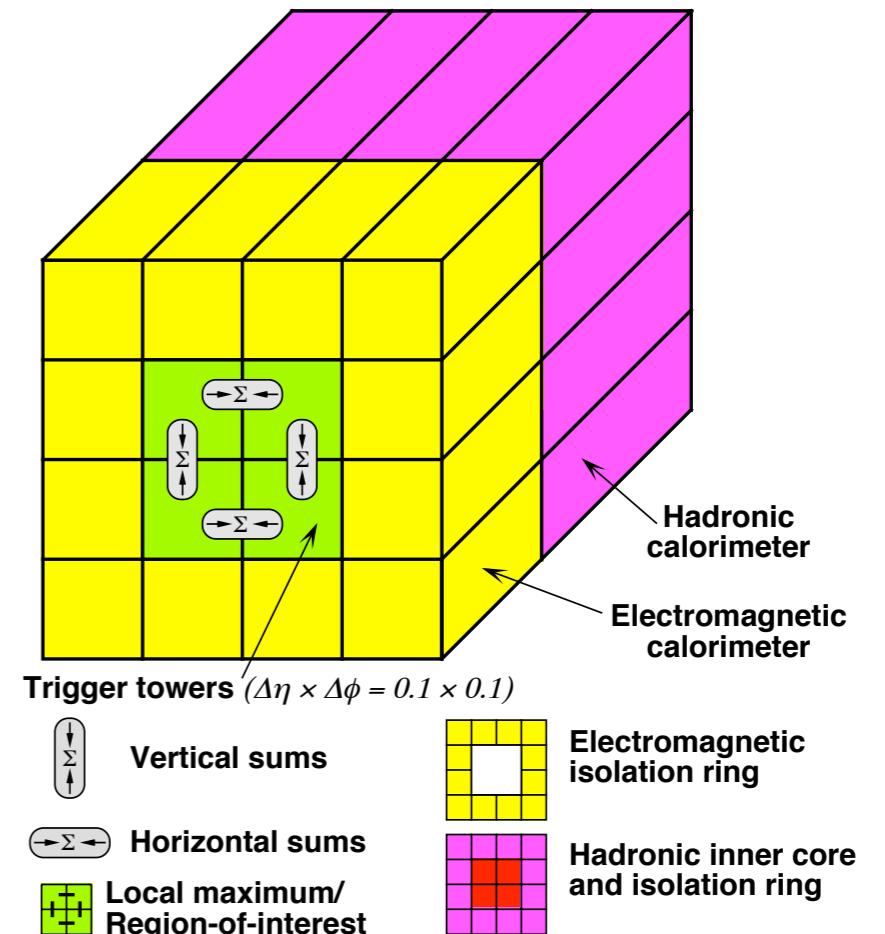
ATLAS HLT rate ~1 kHz



Tau Trigger Strategy

Level 1

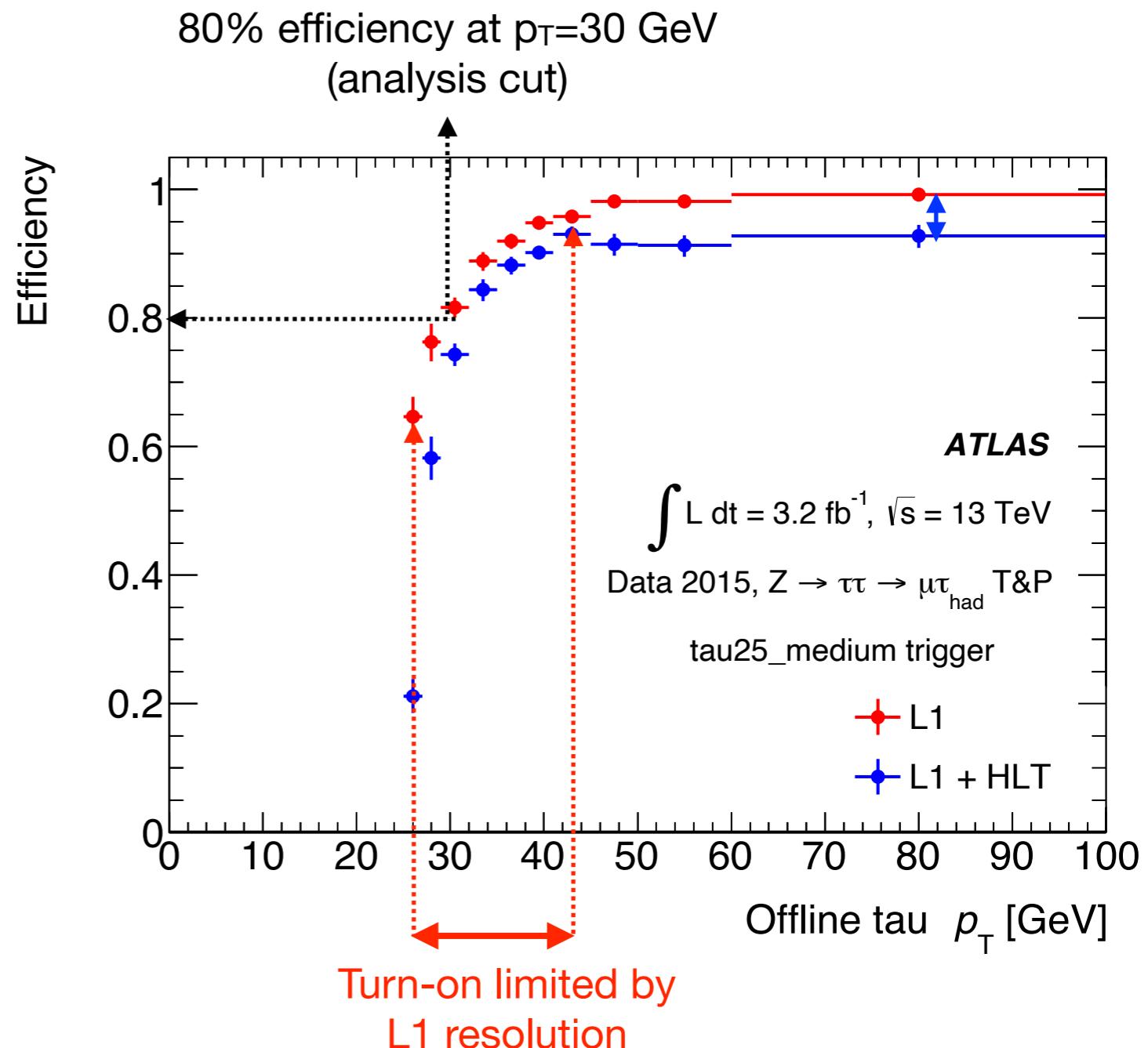
- Simple tau reconstruction:
 - No tracking
 - 2x2 calorimeter window (coarse granularity)
 - Isolation ring
- Event topology cuts to control the rates
 - $\Delta R(\tau_h, \tau_h) < 2.9$ and $p_T(j_0) > 25$
- ‘Acceptable’ rate: ~ 4 kHz



Tau Trigger Strategy

Level 1

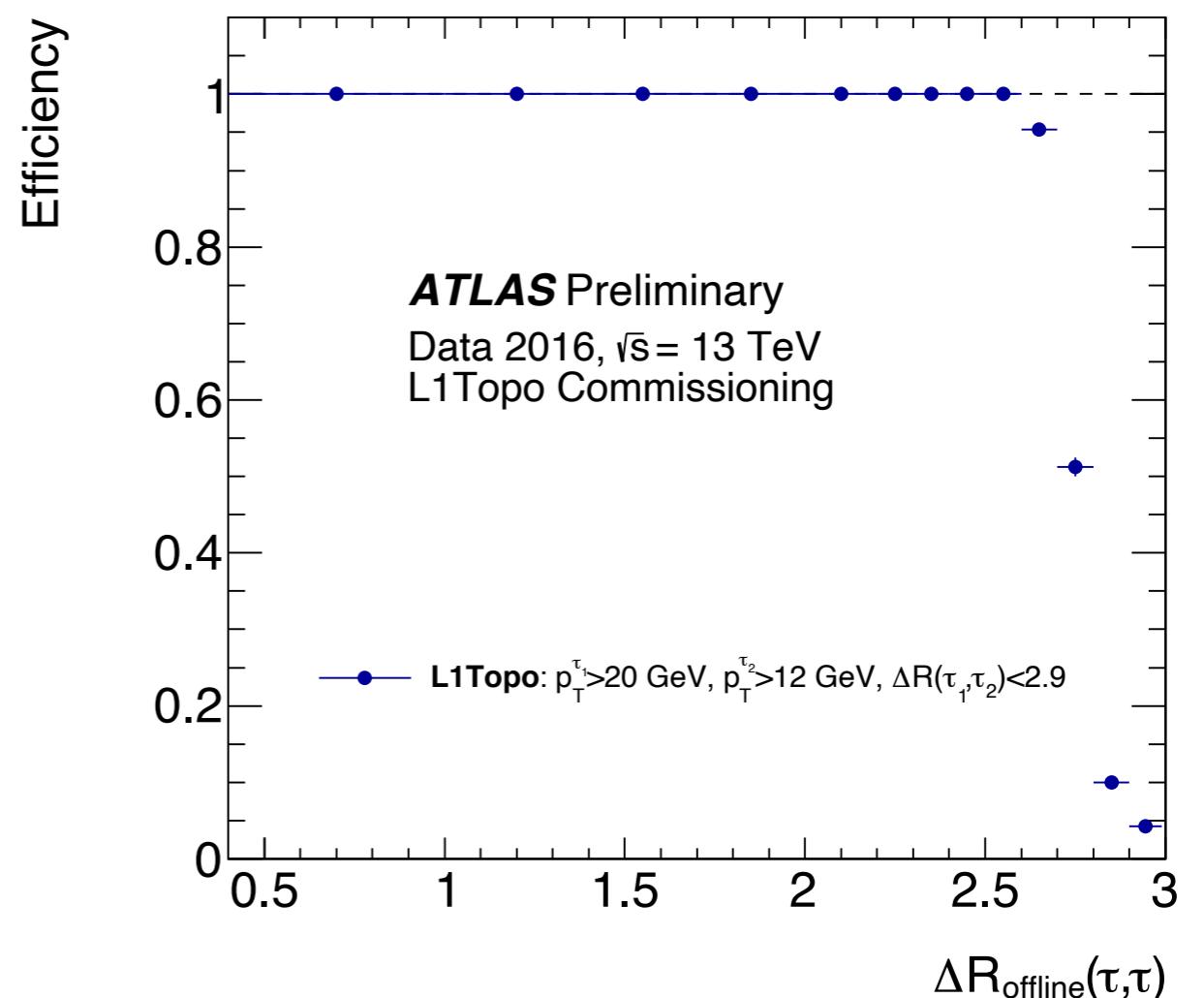
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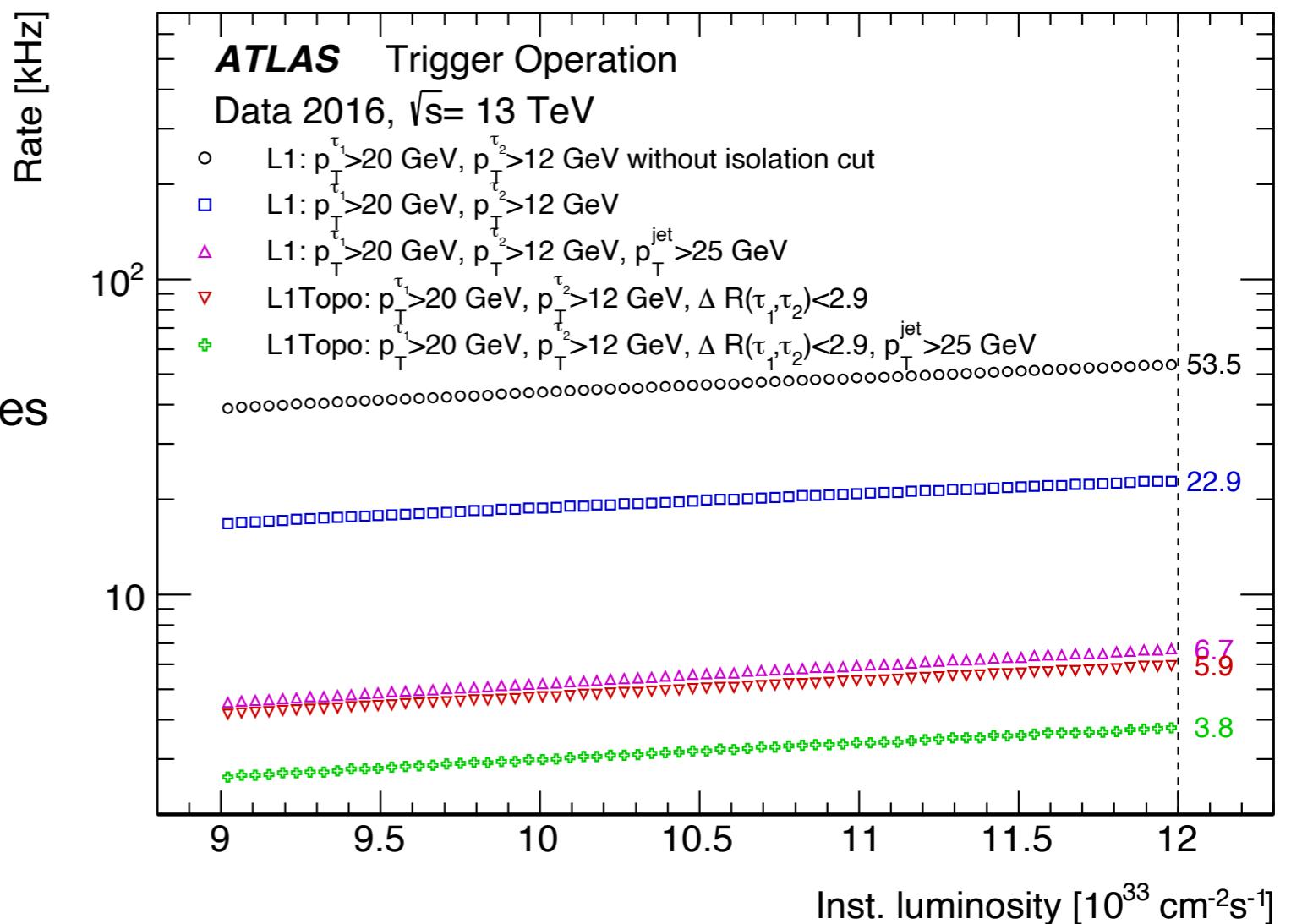
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Tau Trigger Rates

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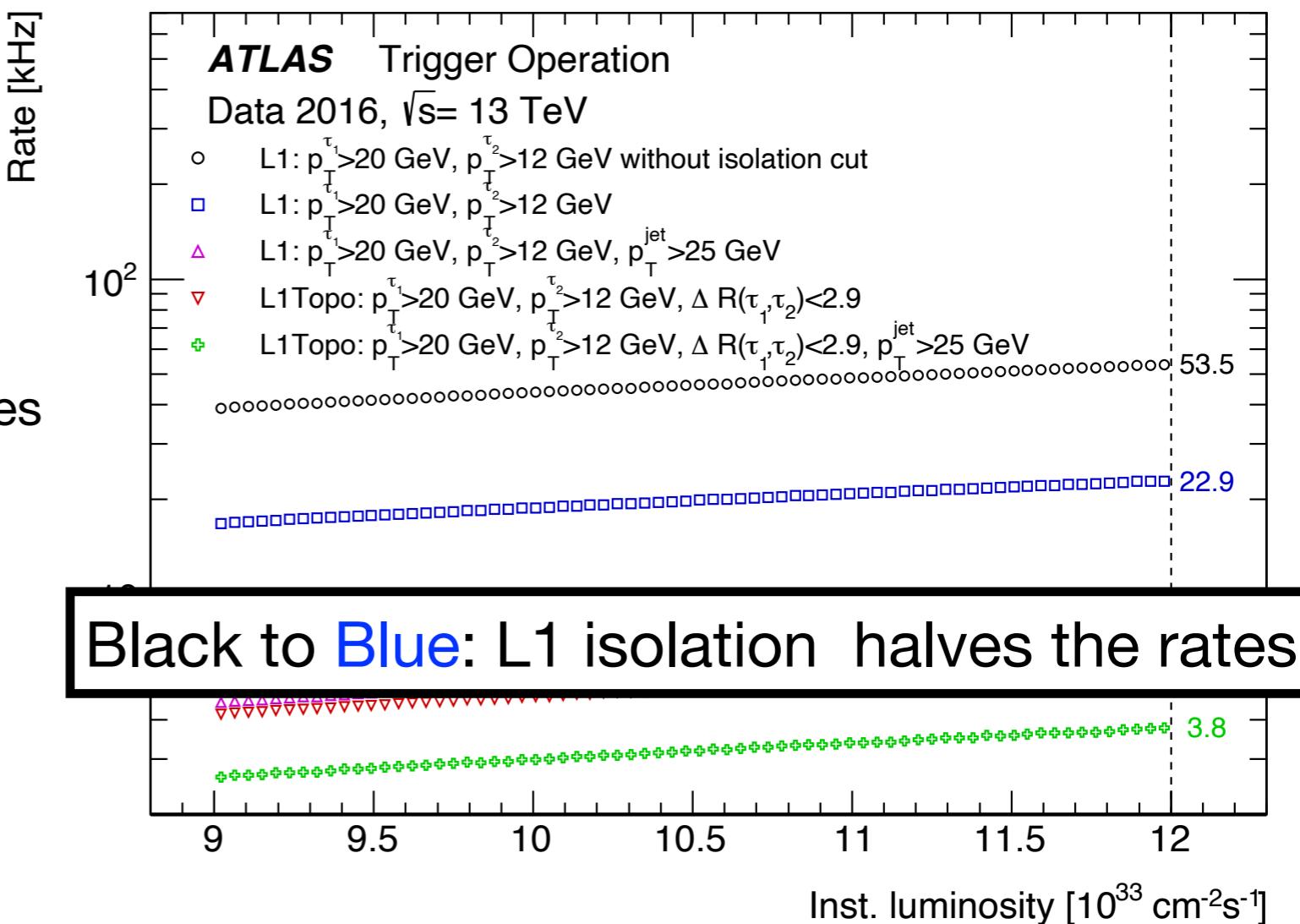
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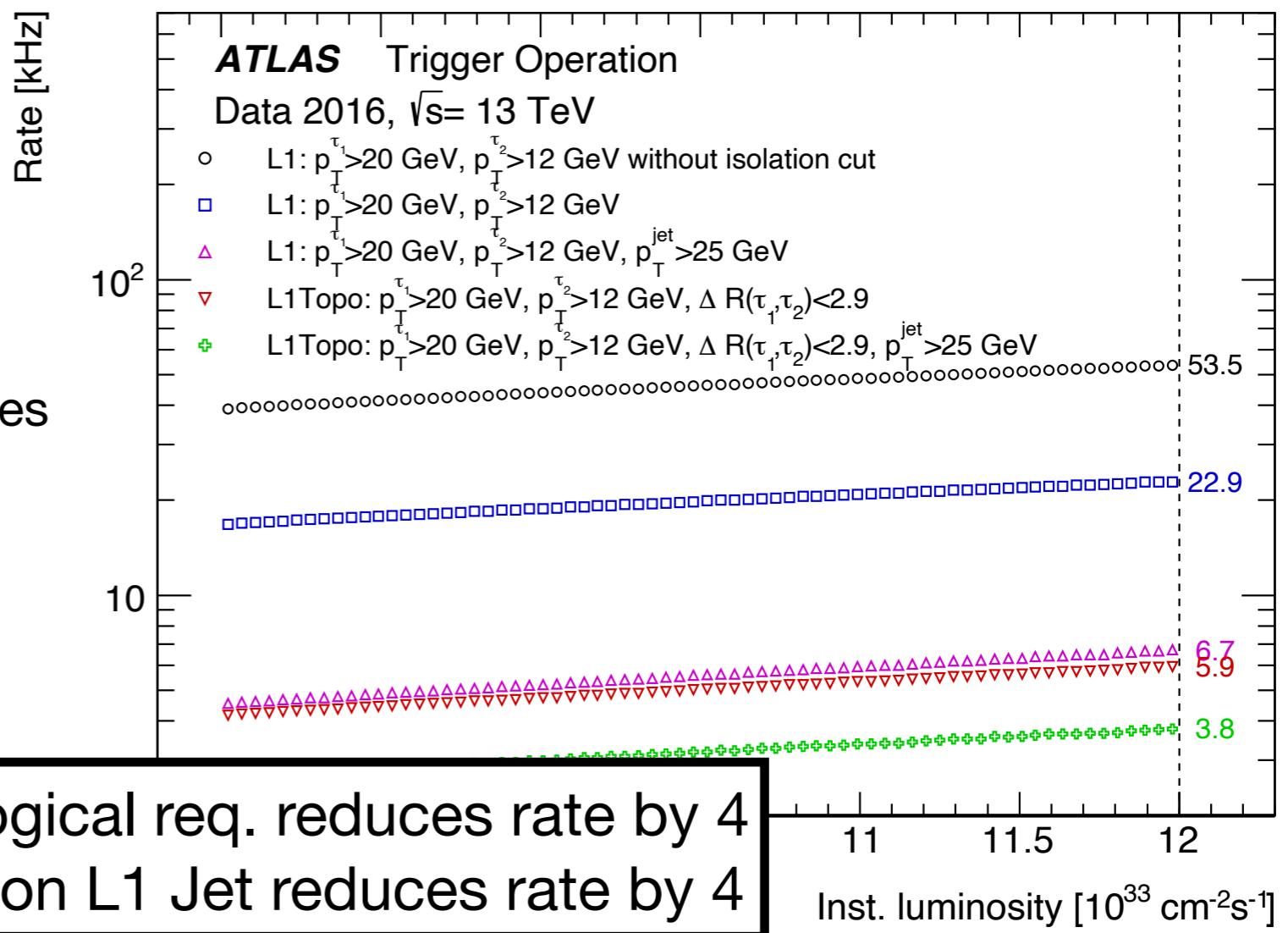
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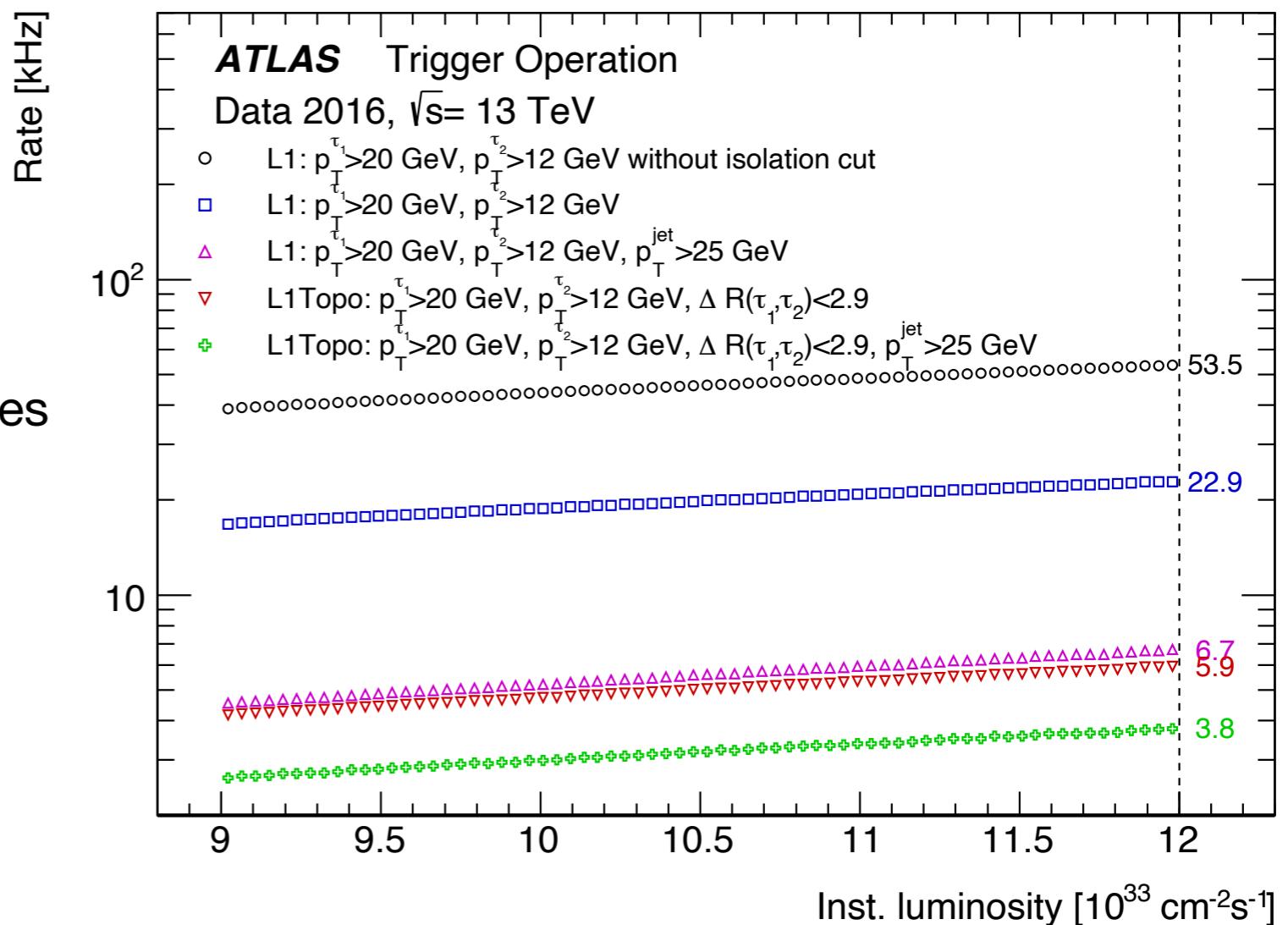


Blue to Red: topological req. reduces rate by 4
Blue to Pink: addition L1 Jet reduces rate by 4

Tau Trigger Rates

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Green: isol., topo, additional jet $\rightarrow 4$ kHz

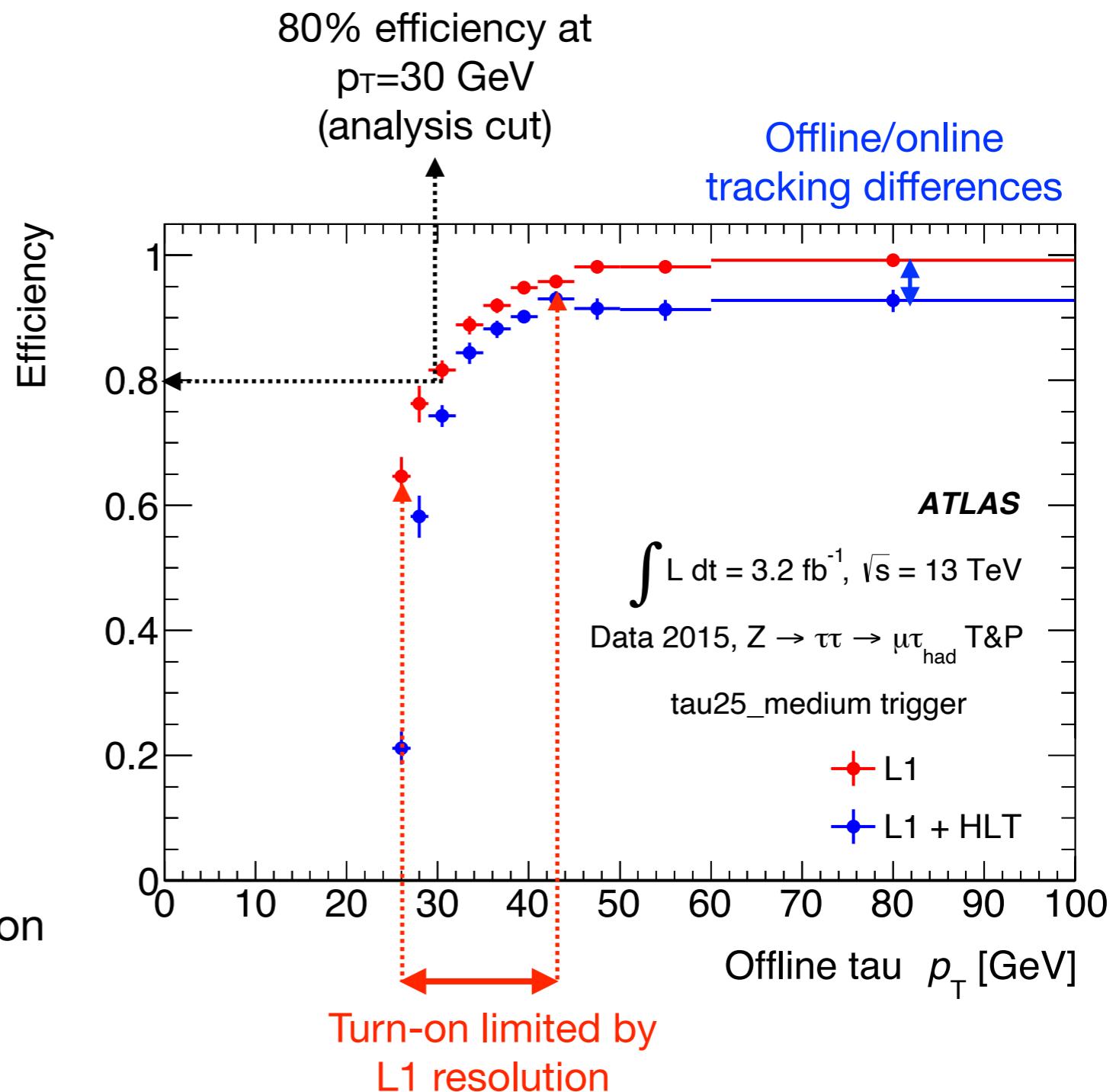
Tau Trigger Efficiency

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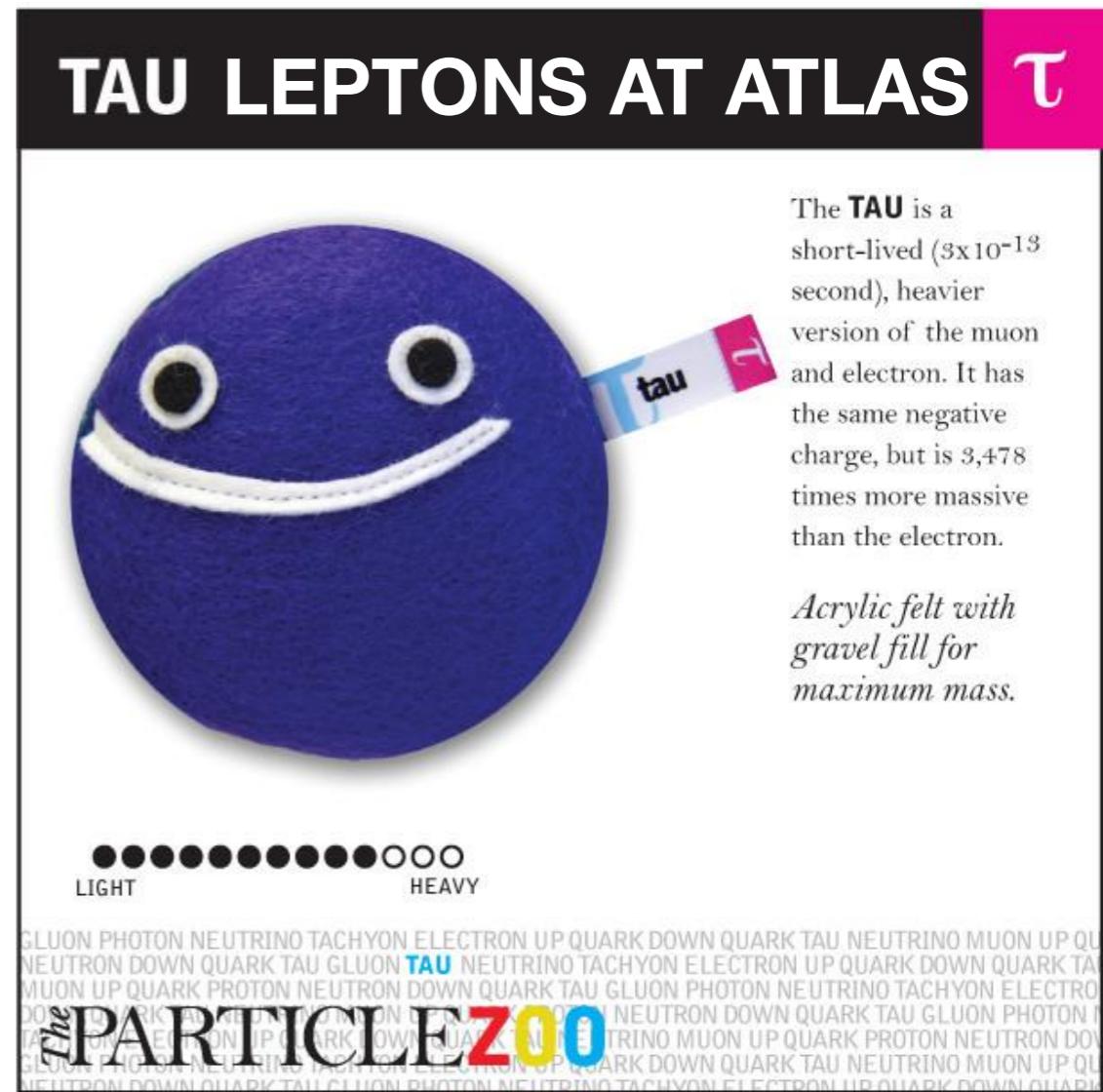
HLT

- Simplified version of offline reconstruction
 - Calo-based energy reconstruction
 - Simpler Track counting algorithm (poorer resolution)
- Same tau ID as offline



Conclusions

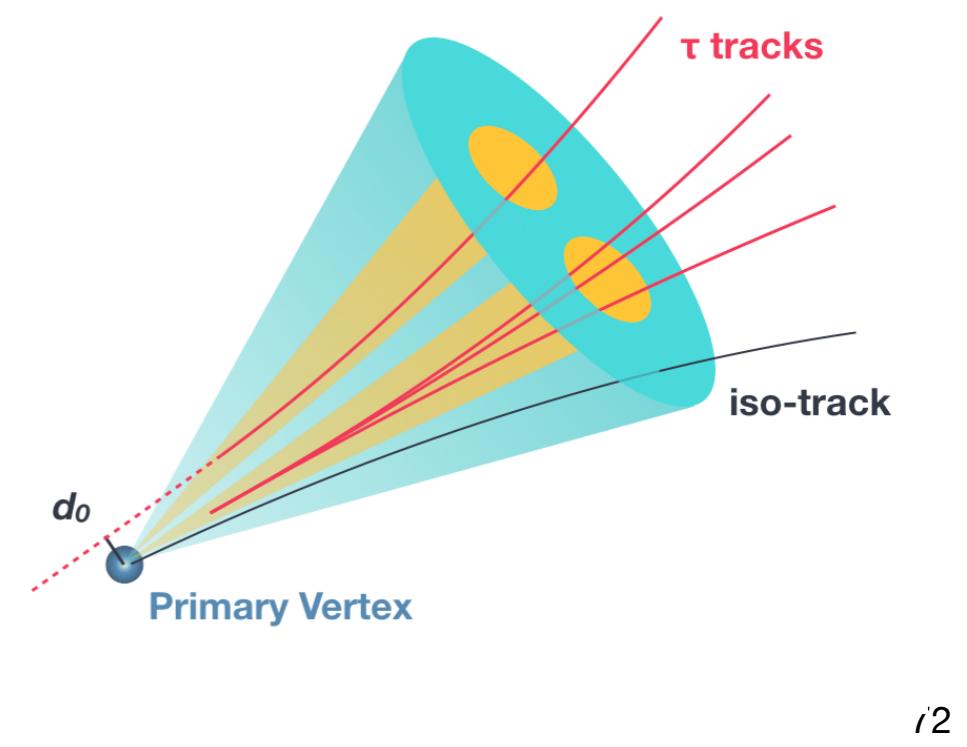
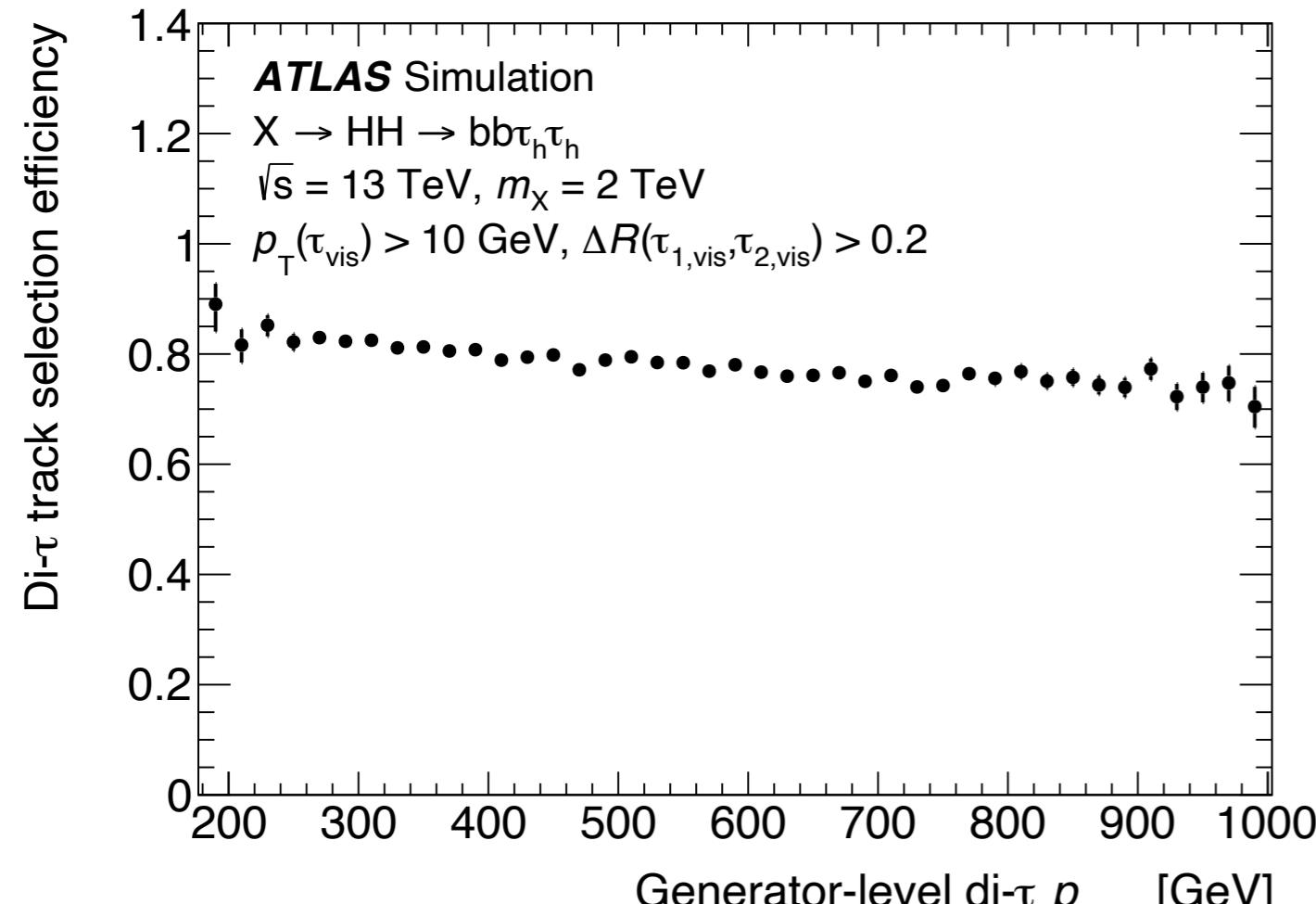
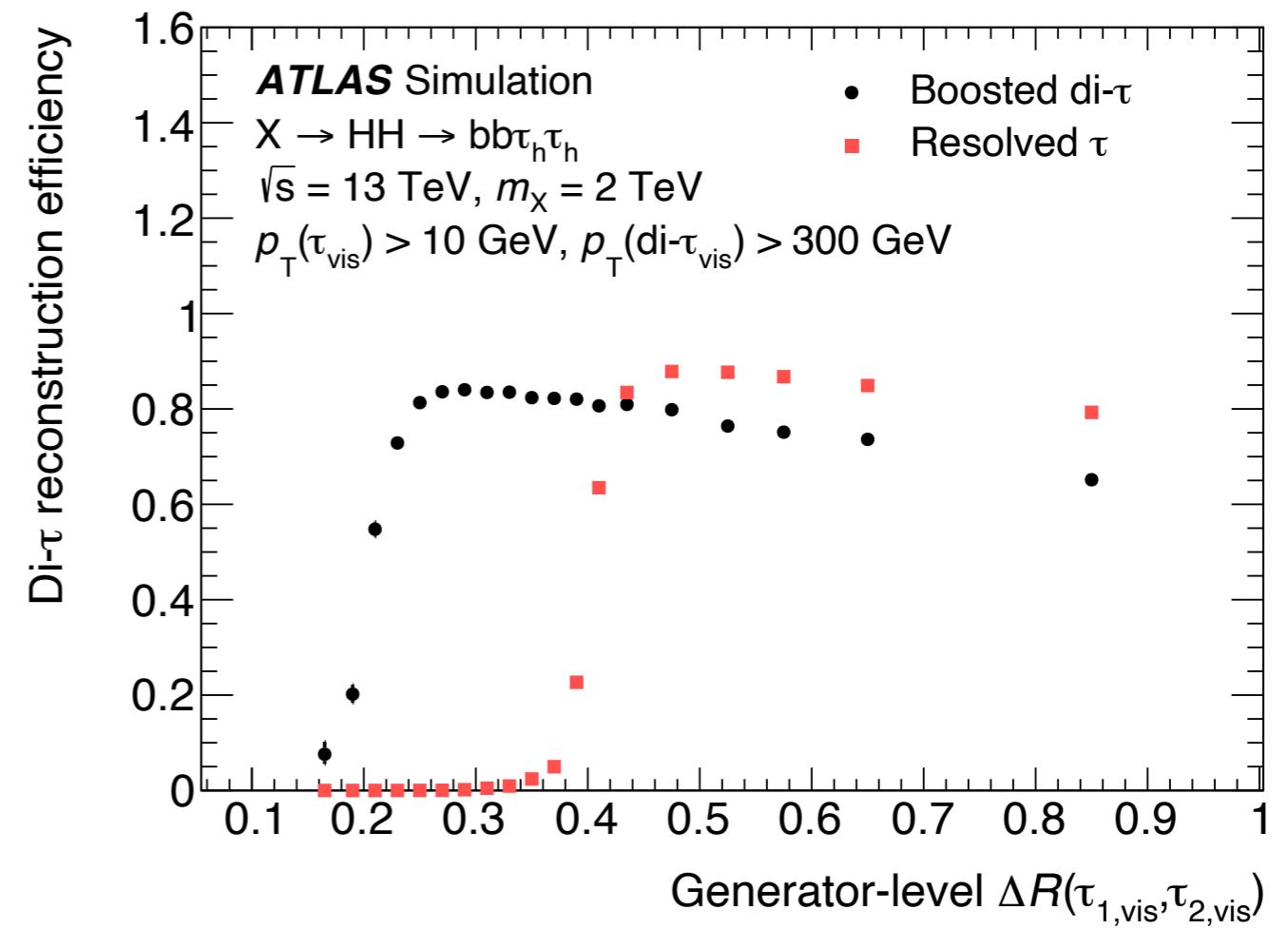
- Detecting hadronic tau leptons at the LHC is a challenging task!
 - Despite busy tracking environment, >70% of taus are detected
 - Triggering is even harder but critical for signatures without electrons or muons
 - Modern machine learning enable remarkable performance
- Tau reconstruction
 - Enables searches for unique BSM signatures
 - Further improvements key for ultimate precision on measurements



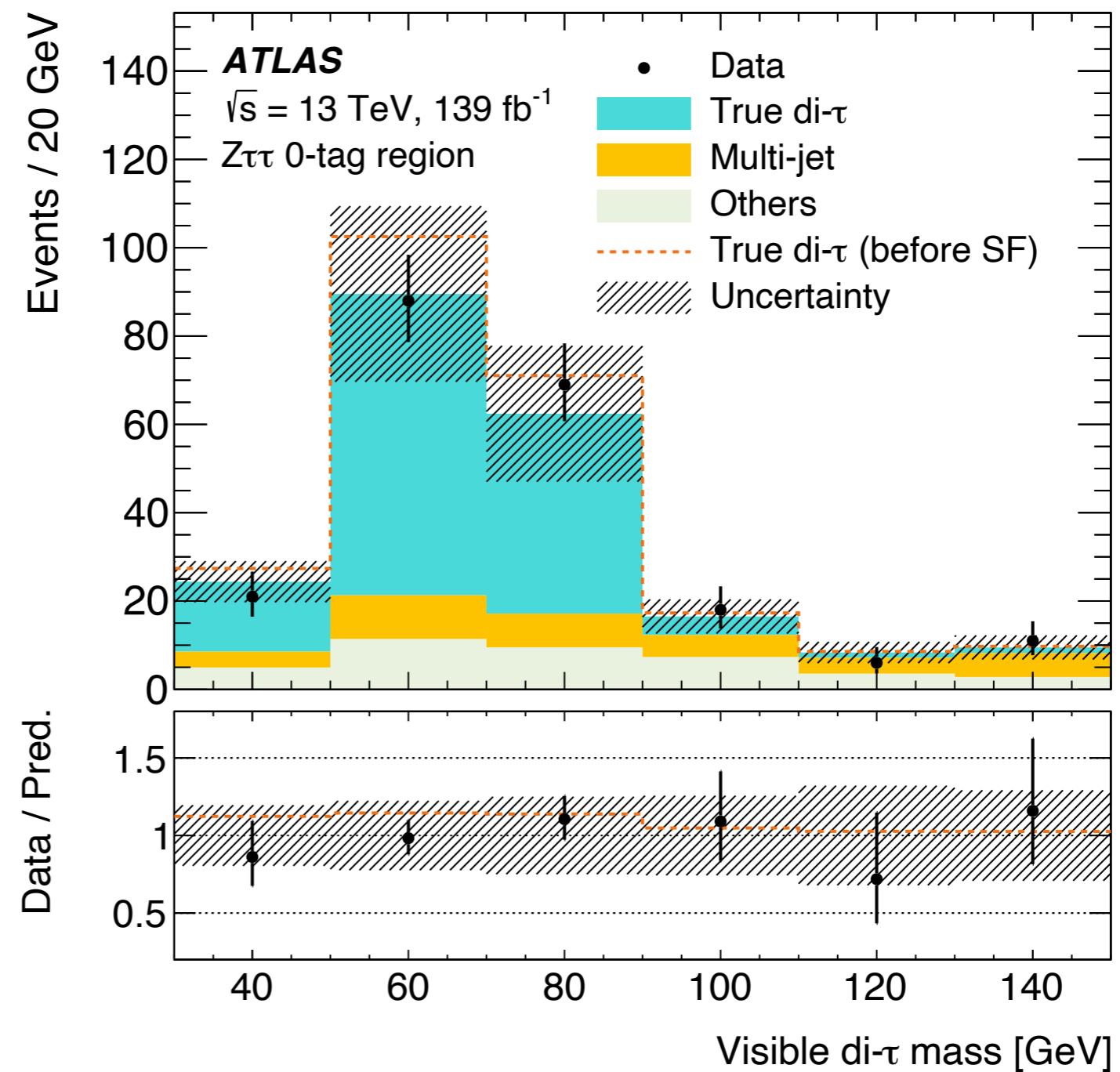
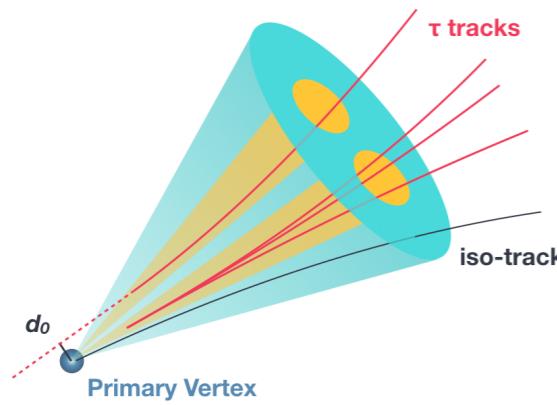
Additional material

Pushing to extreme phase spaces

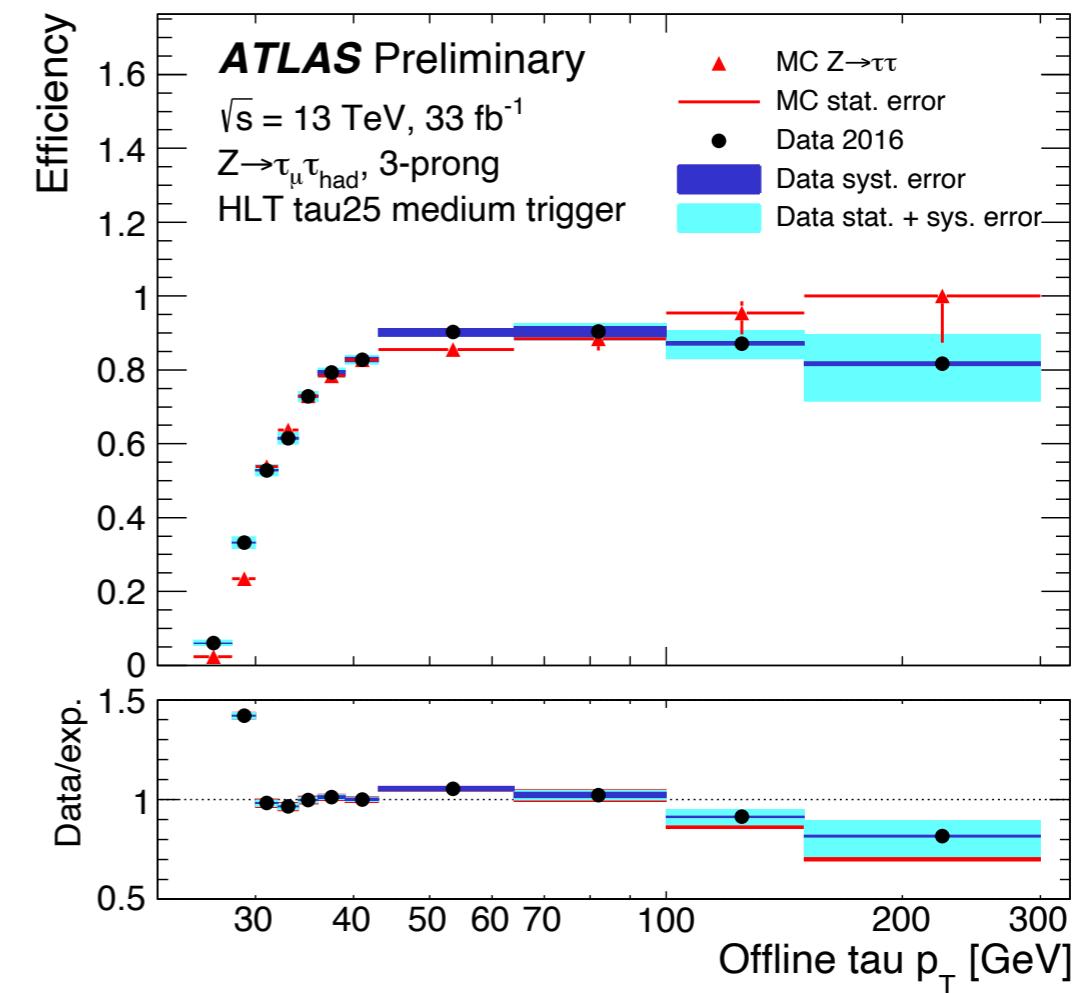
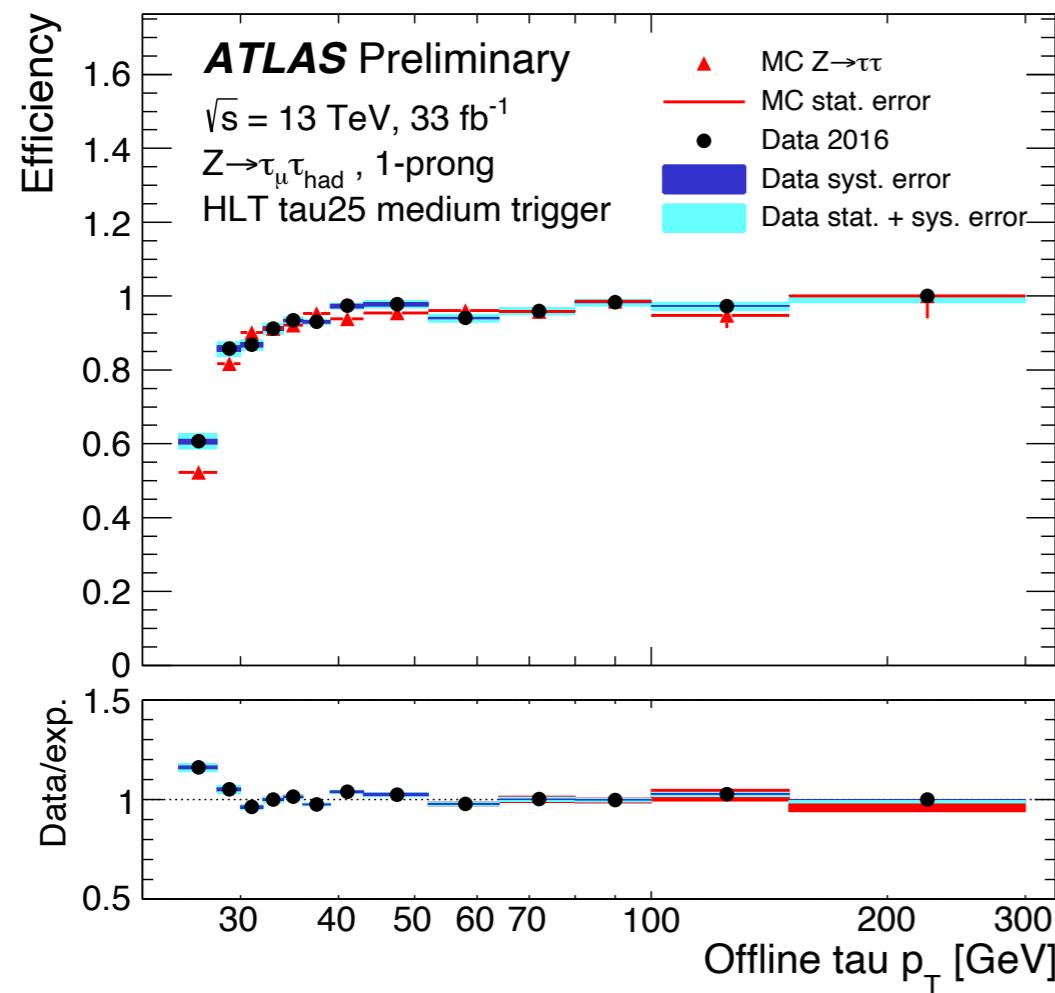
Boosted ditau



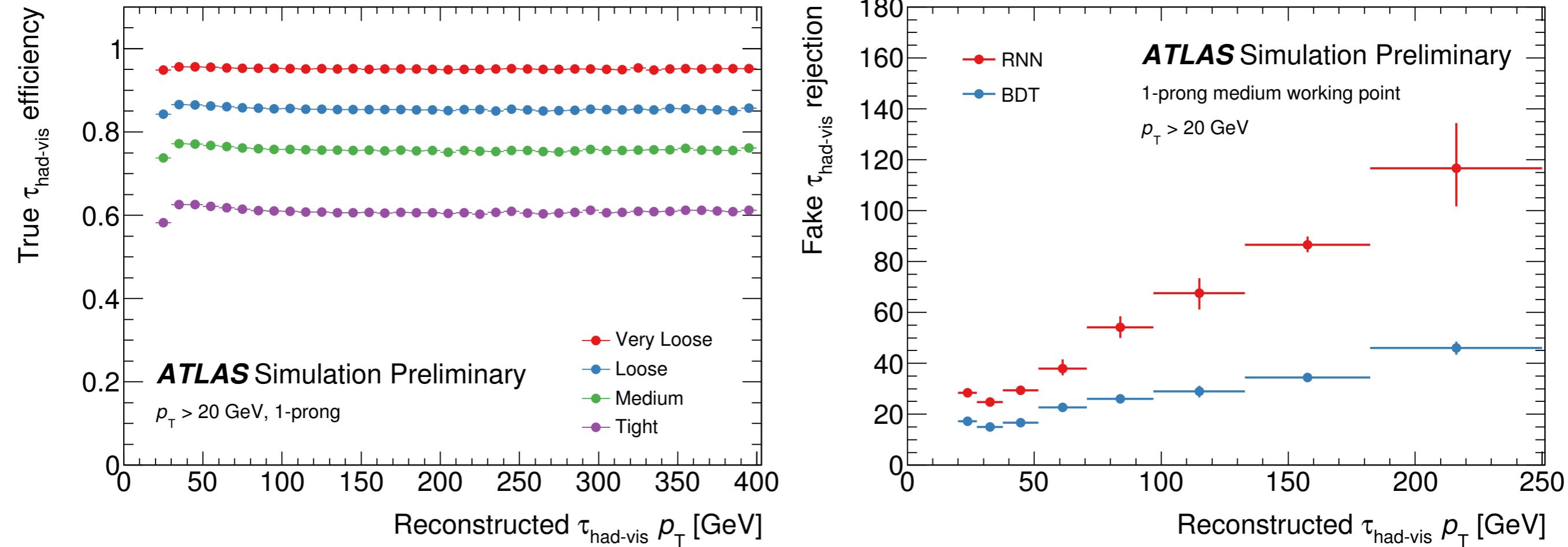
Boosted ditau



Tau Trigger Efficiency Measurement



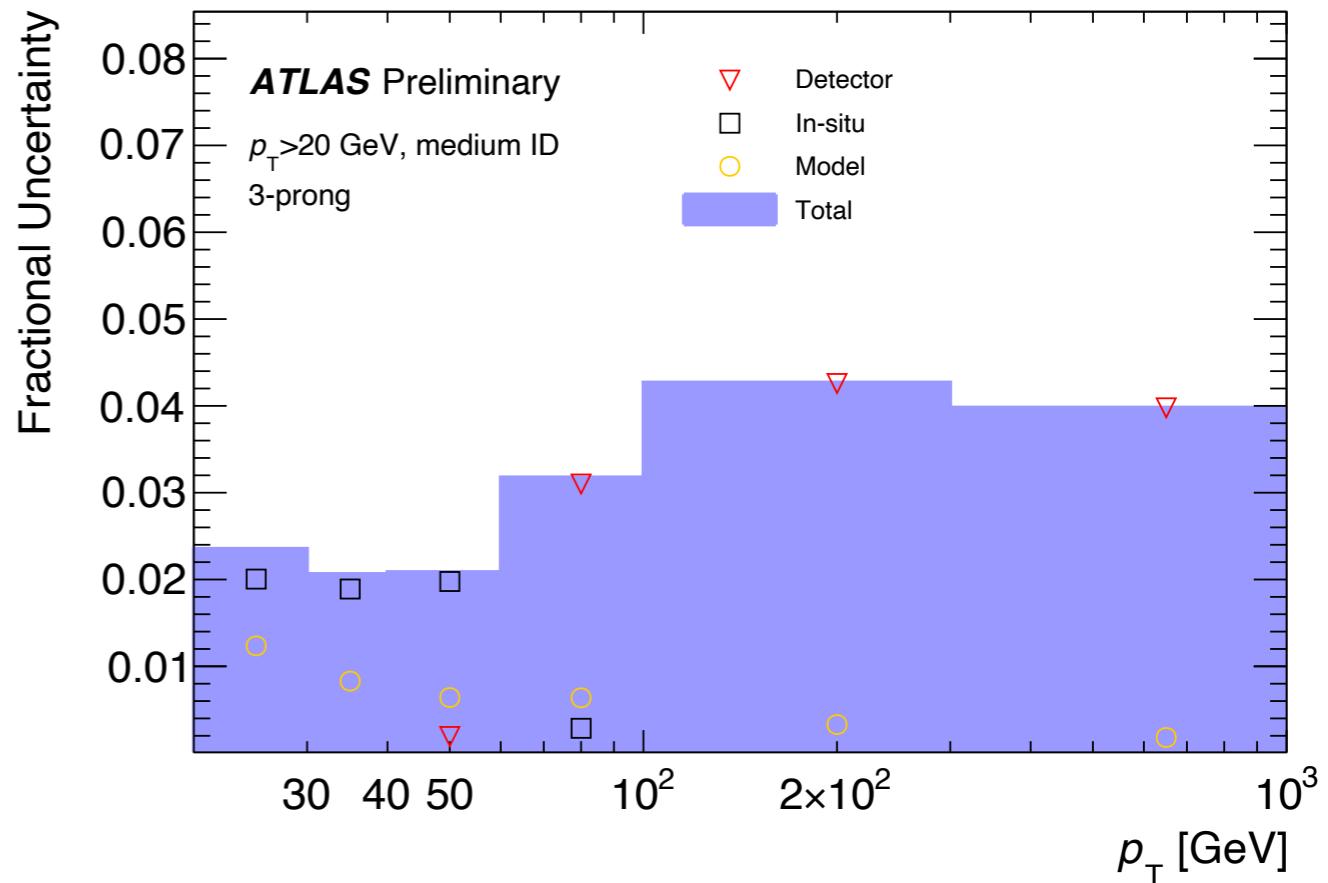
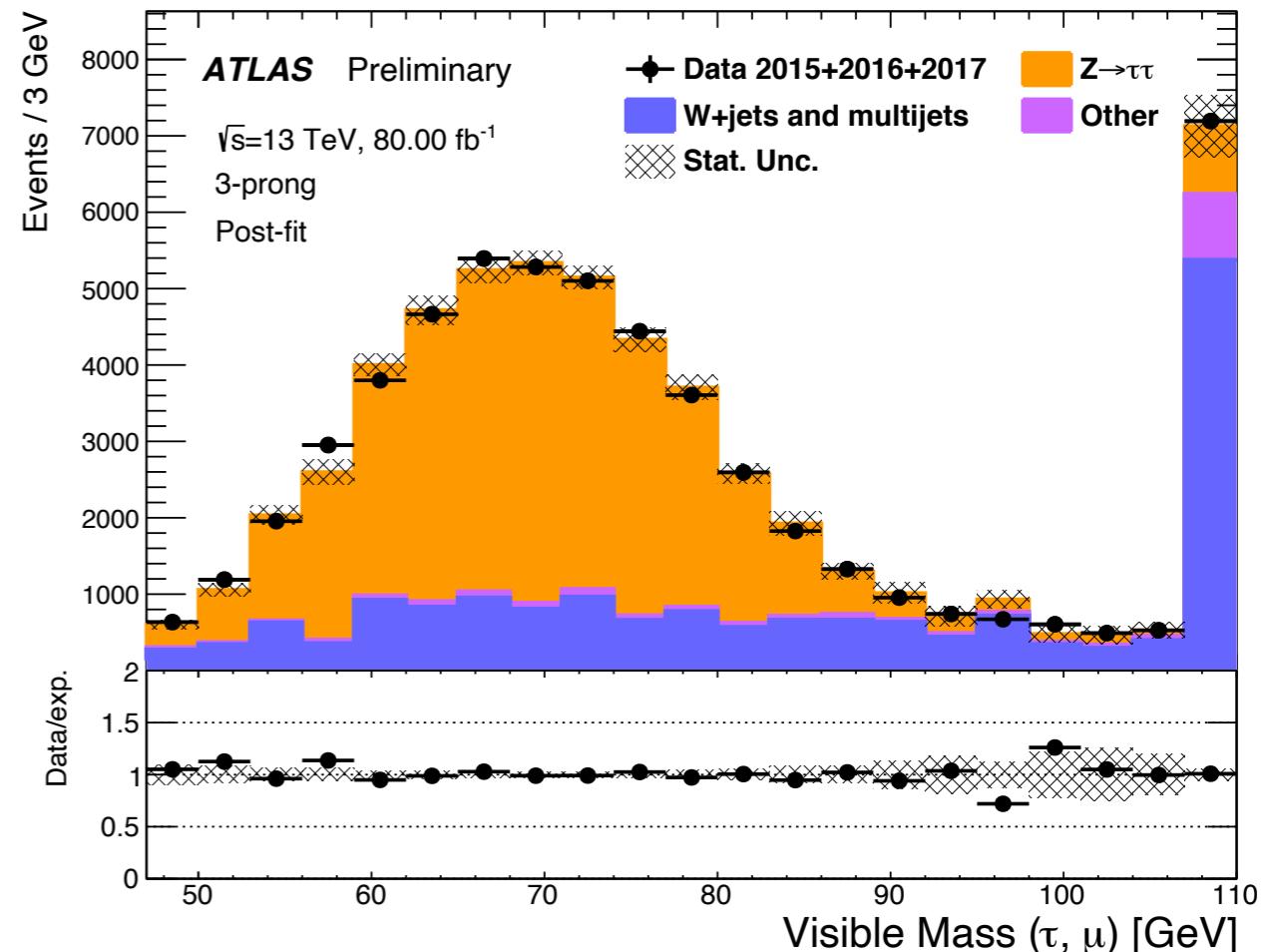
Rejecting jets



- Criteria ('cut') optimised for a flat efficiency vs $p_T(\tau)$ and $\langle \mu \rangle$.
- At fixed efficiency, RNN improves over BDT all across the $p_T(\tau)$ spectrum

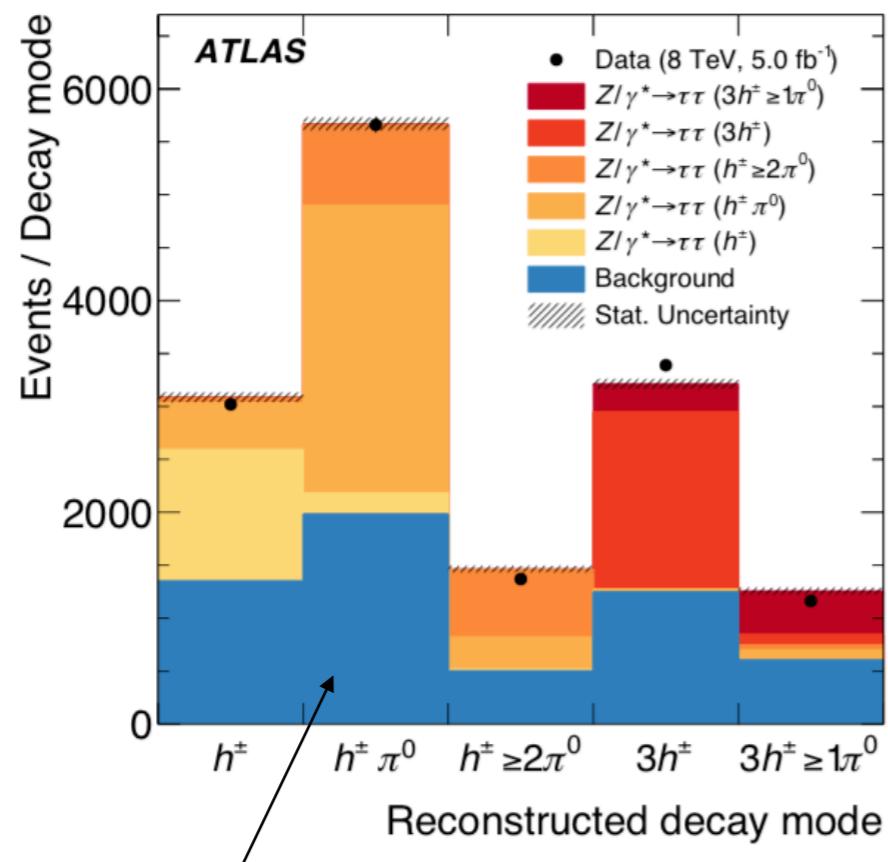
Tau Energy Scale

- Template fit of the visible mass to adjust α
- $\alpha(\text{Data} / \text{MC}) \sim 1\% (3\%)$ for 1p (3p) taus
- Uncertainties
 - In-situ measurement (sels, bkggs, ...)
 - Truth \longleftrightarrow Reconstruction in simulation (absolute scale)
 - Extrapolation of E/p measurement from single pions to taus as an ersatz for high p_T taus

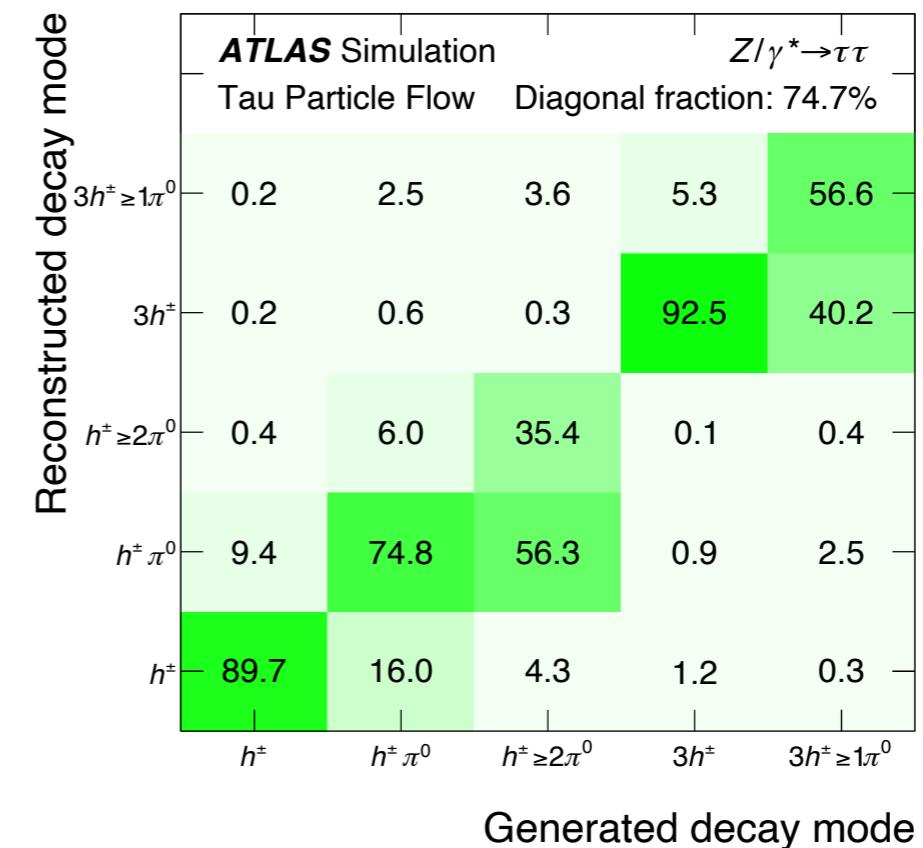


H $\tau\tau$ vertex properties

- Very challenging analysis
 - Selection of pure $\pi^+\pi^0-\pi^+\pi^0$ events
 - Reconstruction of the individual pions 4 momentums

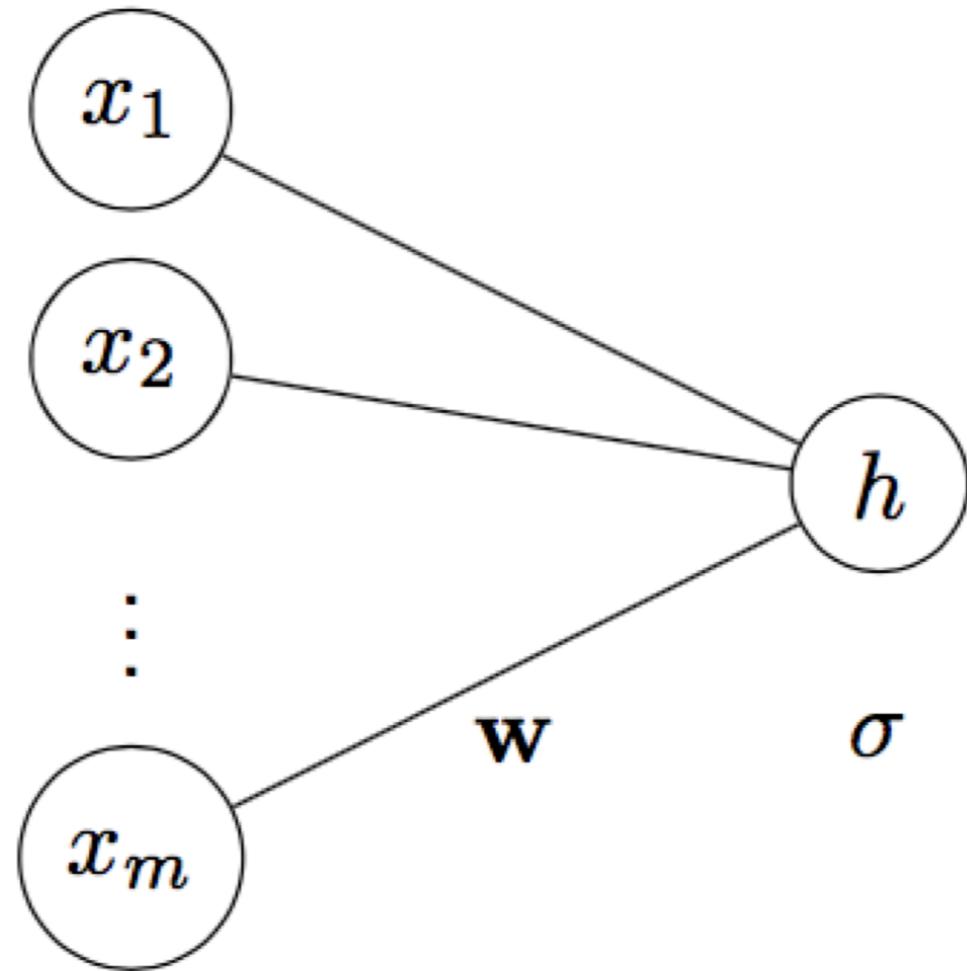


reconstructed $\pi^+\pi^0$ bin



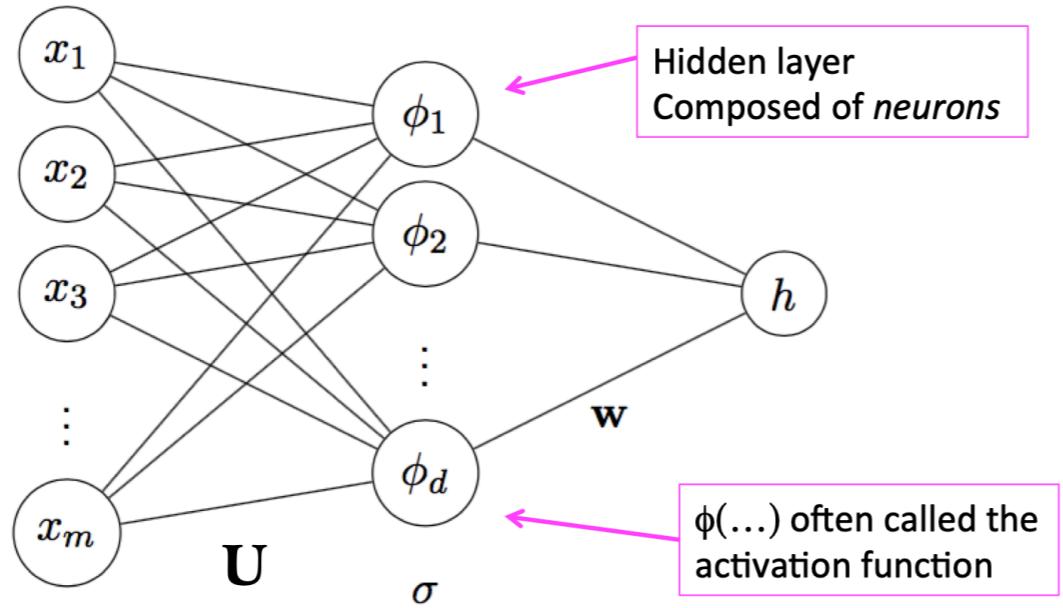
Logistic Regression

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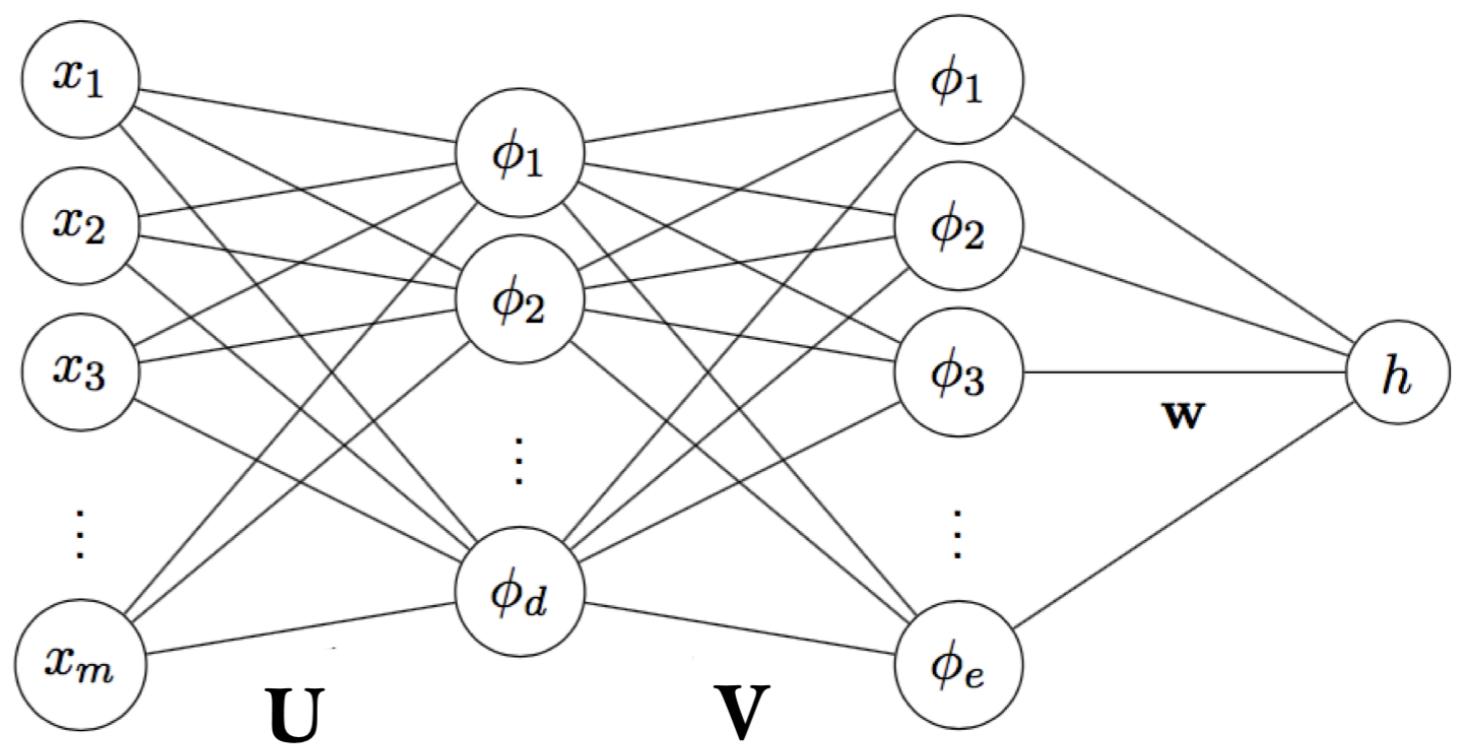
$$p(y = 1|\mathbf{x}) = \sigma(h(\mathbf{x}, \mathbf{w}))$$

$$= \frac{1}{1 + e^{-\mathbf{w}^T \mathbf{x}}}$$



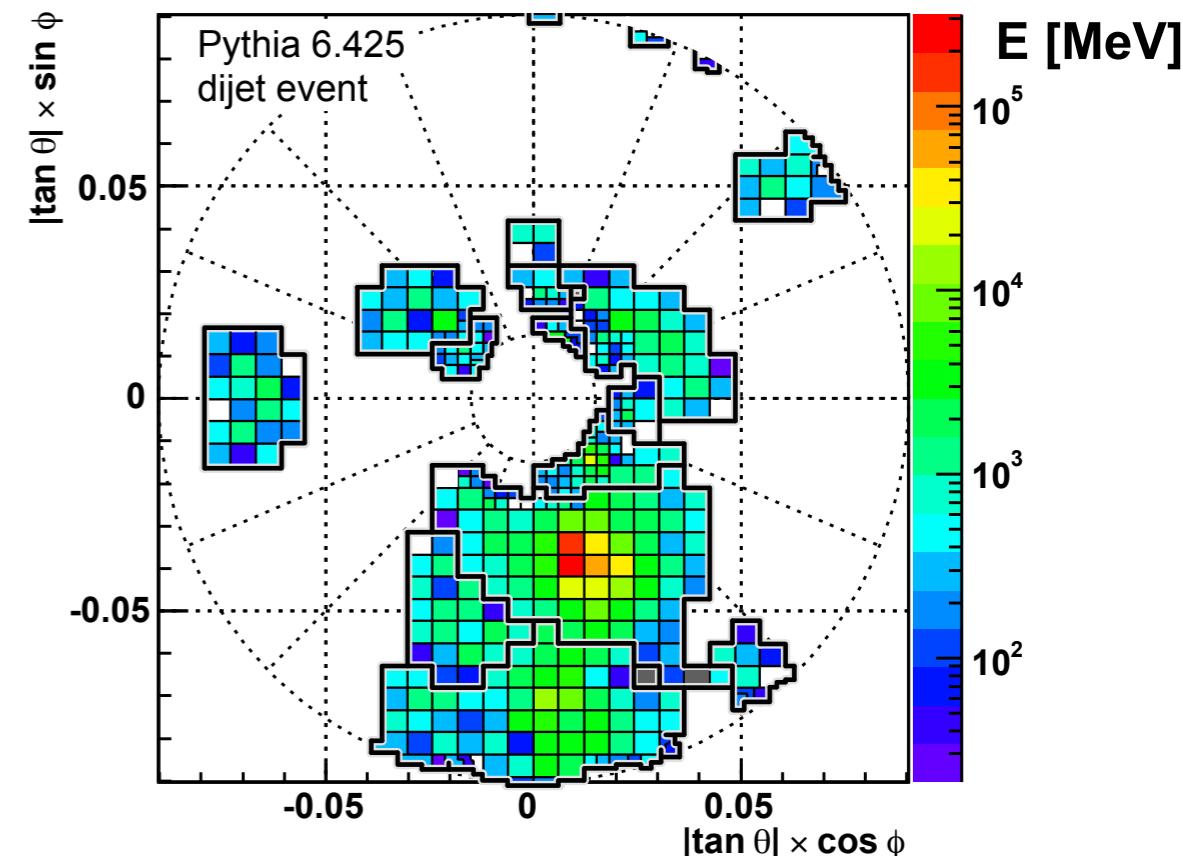
$$\phi(\mathbf{x}) = \sigma(\mathbf{U}\mathbf{x})$$

$$h(\mathbf{x}) = \mathbf{w}^T \phi(\mathbf{x})$$



Tau Particle Flow

- A low p_T , tracker is a better tool to estimate $p_T(\pi^+)$
- To use it, need to disentangle π^0 and π^+ deposits in the calorimeters
- Forming π^0 candidates
 - Clustering cells in the EM calorimeter
 - Extrapolate tracks to the HAD calorimeter and match them to the HAD clusters
 - Remove $E_{\pi^+}^{EM} = E_{\pi^+}^{trk} - E_{\pi^+}^{HAD}$ from the EM clusters
 - Discard clusters below 2 GeV (mostly pileup noise)



At this stage, large fraction
of π^+ remnants still in the
ECAL

Tau Particle Flow

- Dedicated MVA to identify the origin of the remaining clusters
- BDT using 12 variable characterising the topocluster (position in the detector and moments to characterise its shape)

