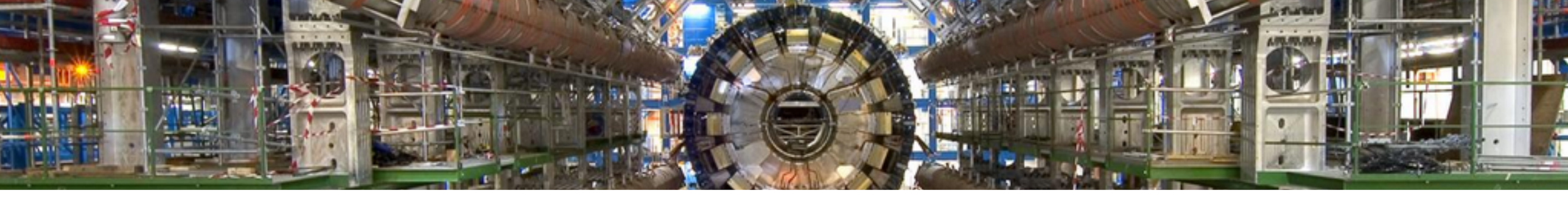

Measurements of Higgs boson properties via $H \rightarrow \tau\tau$ decays

Brian Le

E. Barberio, E. Richter-Was (Jagiellonian), Z. Was (IFJ-PAN), D. Zanzi

(supported in part by European Union under the Grant Agreement PITNGA2012316704 (HiggsTools)
and the Australian Research Council)

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

higgstools

Australian Government
Australian Research Council

THE UNIVERSITY OF MELBOURNE

ATLAS EXPERIMENT

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POLSKIEJ AKADEMII NAUK

Outline

Introduction: Higgs and Taus

Part 1: Tau Reconstruction

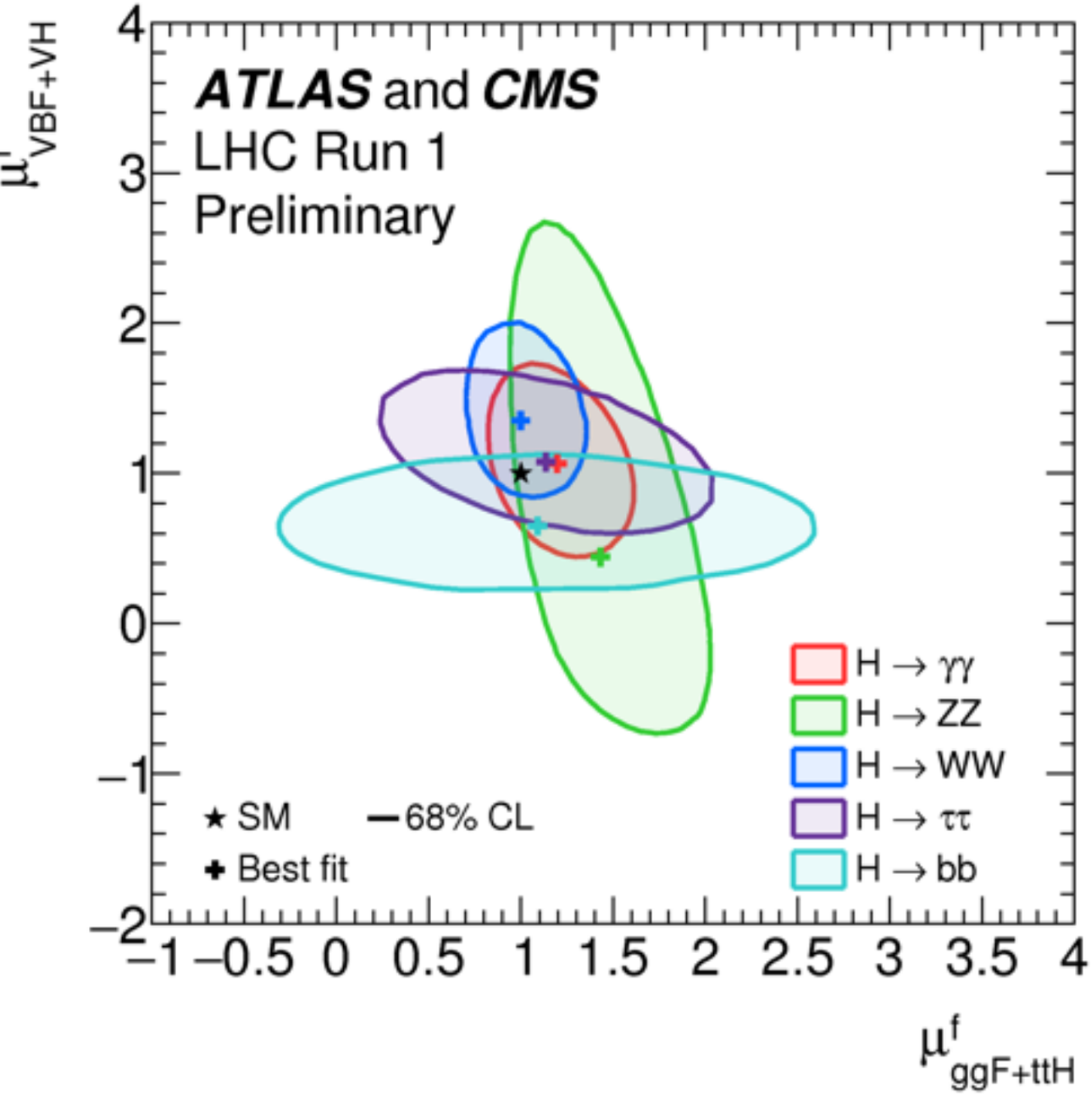
Part 2: Higgs CP Measurement

Conclusion

Introduction:

Higgs and Taus

What Higgs couplings are measured?



Channel	Signal strength [μ] from results in this paper (Section 5.2)		Signal significance [σ]	
	ATLAS	CMS	ATLAS	CMS
$H \to \gamma\gamma$	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$	5.0	5.6
	$(^{+0.26}_{-0.24})$	$(^{+0.24}_{-0.22})$	(4.6)	(5.1)
$H \to ZZ \to 4\ell$	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$	6.6	7.0
	$(^{+0.33}_{-0.27})$	$(^{+0.31}_{-0.26})$	(5.5)	(6.8)
$H \to WW$	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$	6.8	4.8
	$(^{+0.21}_{-0.20})$	$(^{+0.23}_{-0.20})$	(5.8)	(5.6)
$H \to \tau\tau$	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$	4.4	3.4
	$(^{+0.37}_{-0.33})$	$(^{+0.31}_{-0.29})$	(3.3)	(3.7)
$H \to bb$	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	1.7	2.0
	$(^{+0.39}_{-0.37})$	$(^{+0.45}_{-0.43})$	(2.7)	(2.5)
$H \to \mu\mu$	-0.7 ± 3.6	0.8 ± 3.5		
	(± 3.6)	(± 3.5)		
ttH production	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	2.7	3.6
	$(^{+0.72}_{-0.66})$	$(^{+0.88}_{-0.80})$	(1.6)	(1.3)

ATLAS-CONF-2015-044

What's left to measure?

H⟶ff (Yukawa) couplings are yet to be measured to the same extent as H⟶VV couplings.

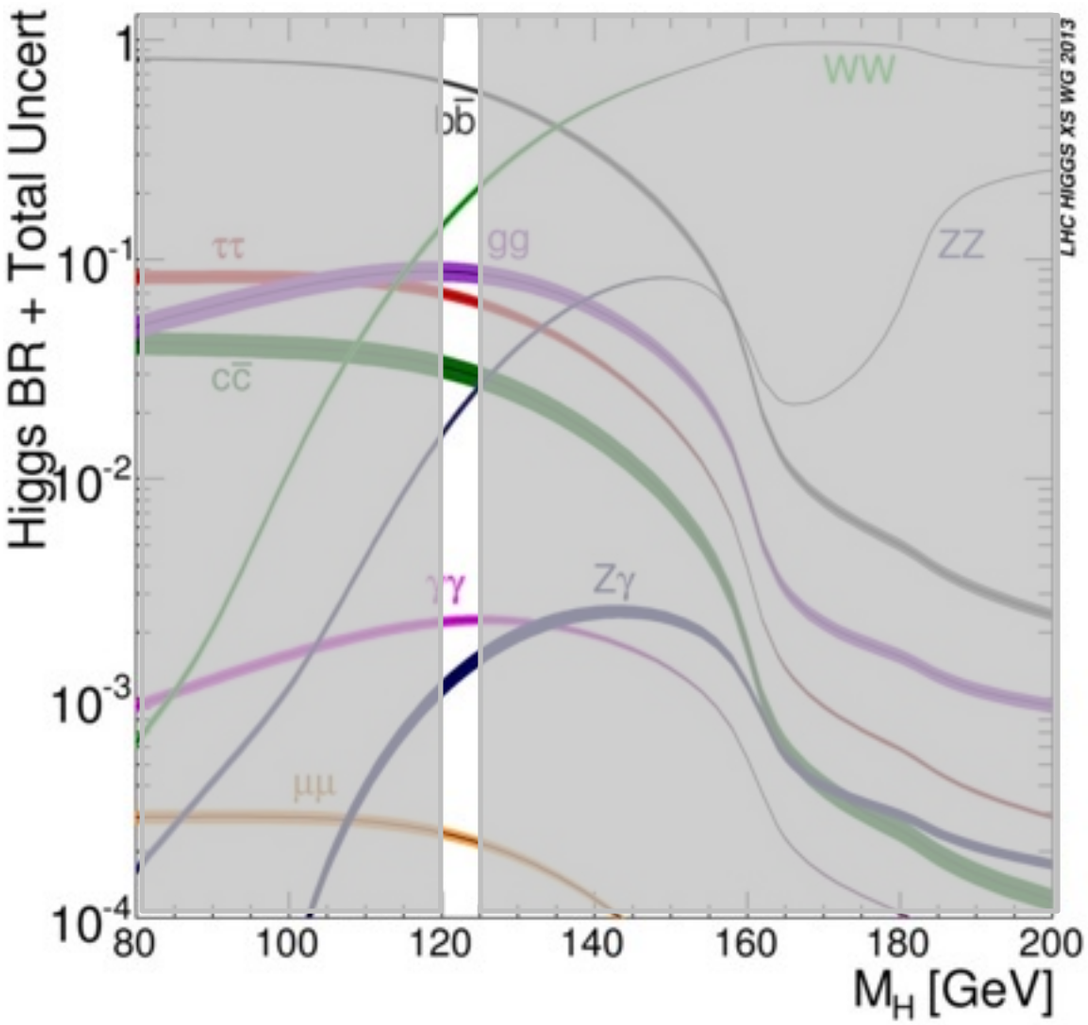
H⟶μμ and **H⟶ee** have very low x-sec

H⟶bb and **H⟶cc** are difficult measurements due to large backgrounds

H⟶ττ is the prime candidate for studying Yukawa couplings

- Large branching ratio
- Unique detector signature

Currently have evidence at 4.4σ with ATLAS

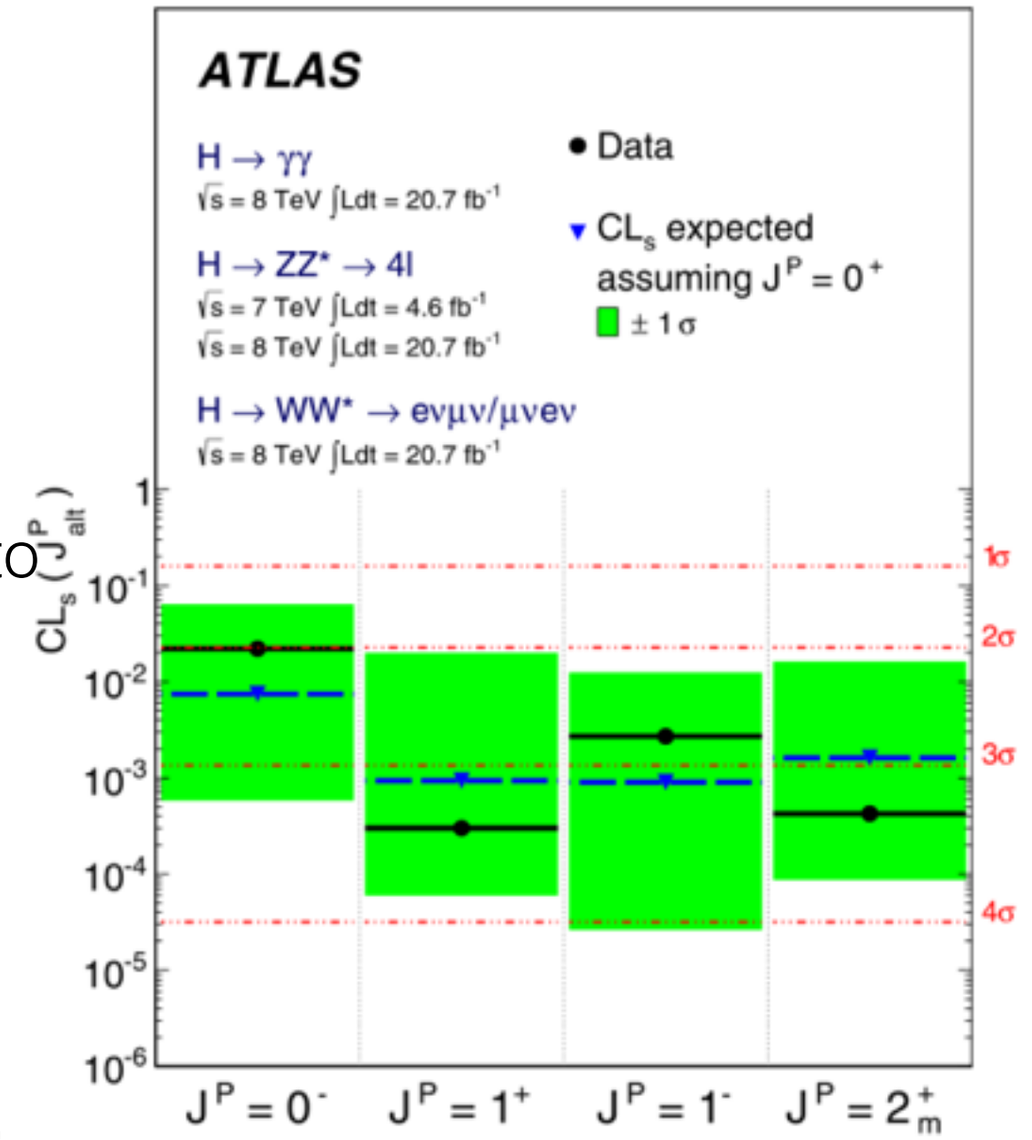


Coupling and Spin-CP

H⟶VV channels have claimed discovery and made measurements of coupling and CP properties - still no direct measurements to fermions

H⟶ττ will be the first to measure the coupling and CP properties in fermionic decays

- **First Yukawa coupling measurement** for a fundamental scalar
- **H⟶ττ decay** is sensitive to tree level couplings to **CP-odd Higgs boson**
  - Pure states already excluded by H⟶VV measurements (but mixed states not accessible)
  - **H⟶ττ decay** allows measurement of **CP mixing**



arXiv:1307.1432

Part 1:

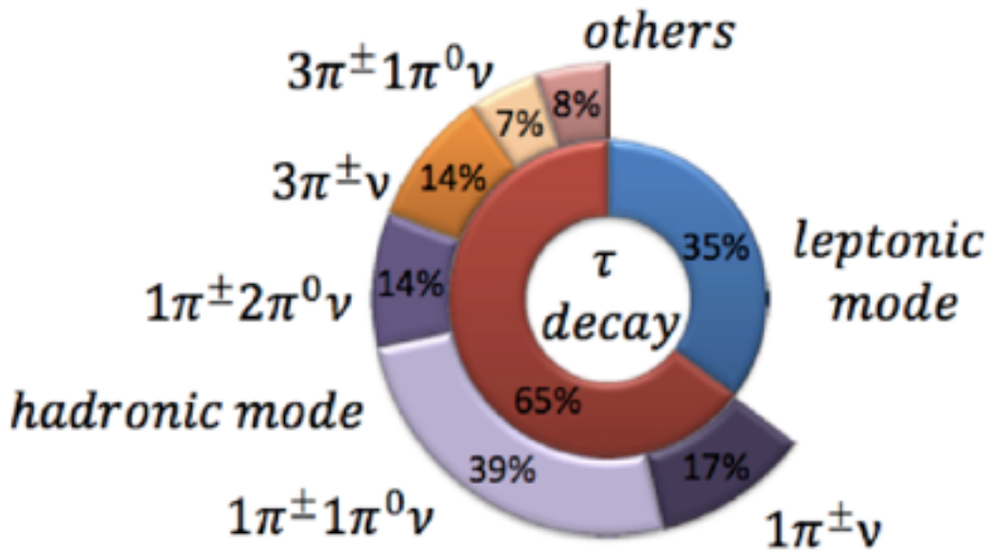
Tau Reconstruction

Tau Decays

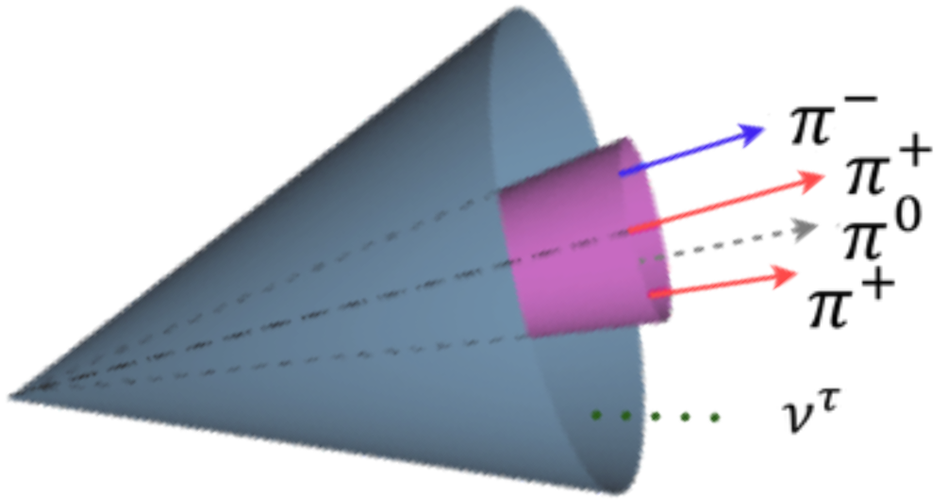
Tau leptons are not reconstructed directly by ATLAS, only the decay products (lepton or hadrons) are detected

Decays to leptons are indistinguishable to prompt leptons

Tau-jet or τ_{had} candidates typically are:



- Highly collimated “jet”
- Odd number of charged tracks (“prongs”) with neutral pions



Reconstructed from jet candidates via anti-kT algorithm

Identification via BDT focussed on distinguishing vs QCD jets

Tau Reconstruction

One key development for Run II is to allow for the tau substructure to be reconstructed.

A particle flow approach is taken (rather than using only calo information):

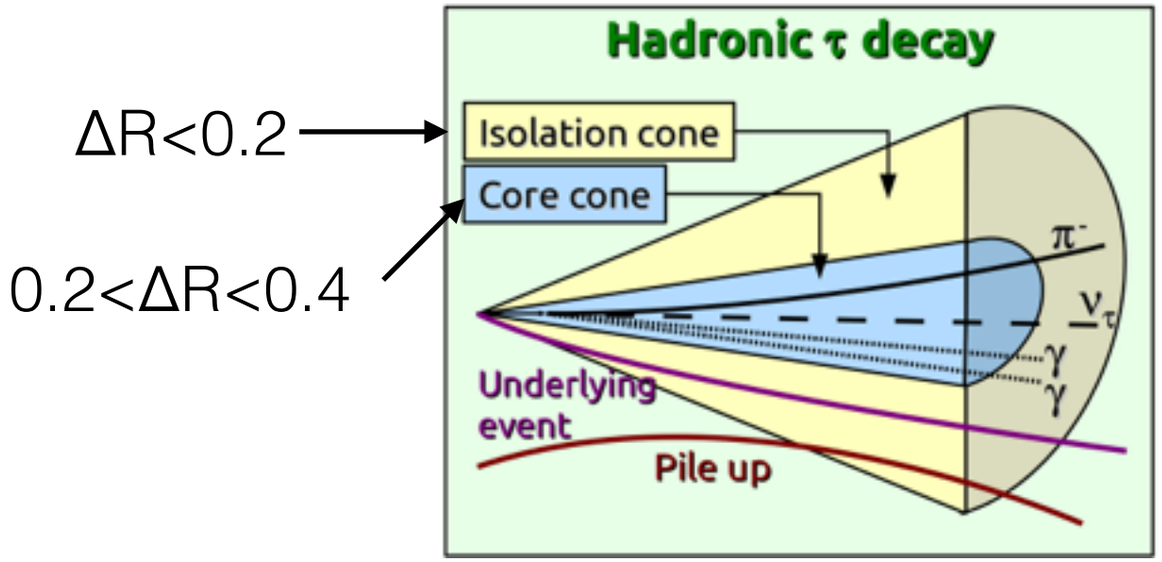
1. Charged hadrons reconstructed using track information

2. Calo deposits associated to the charged track are removed from the candidate

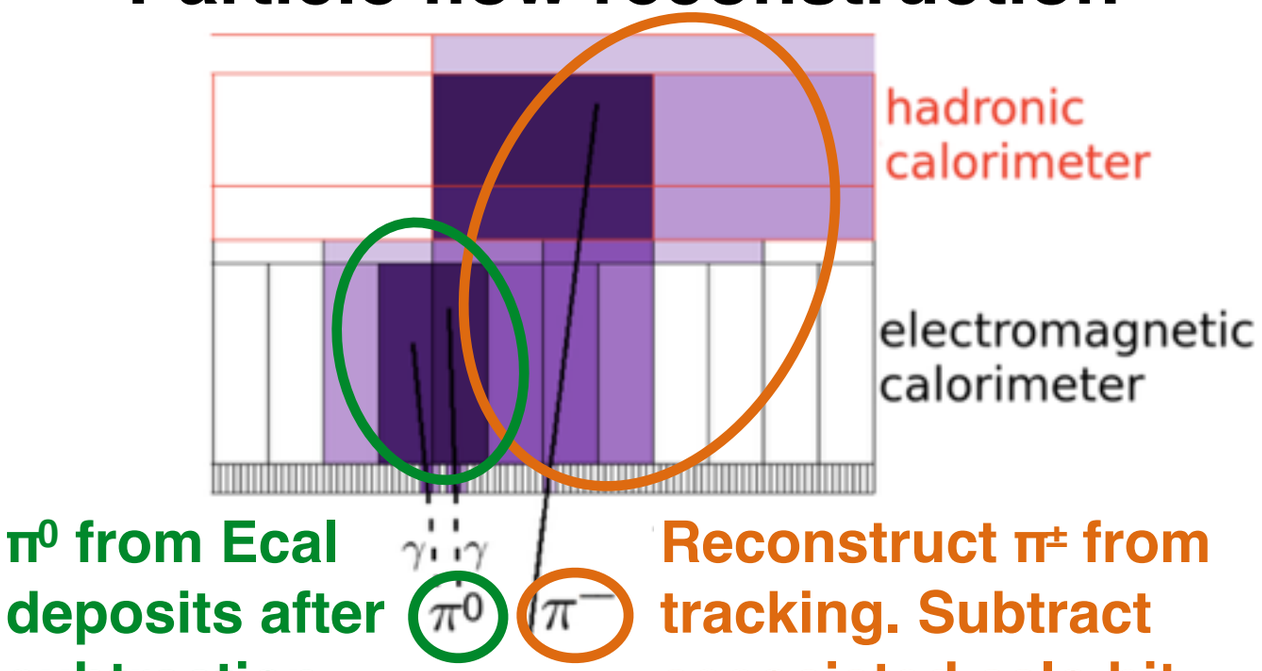
3. Neutrals pions are identified from the remaining calo deposits

Combining calo and tracking information allows for a more detailed and accurate reconstruction.

Calo-based reconstruction



Particle flow reconstruction



LHCP 2016 Poster - B. Winter

Substructure and Decay Classification

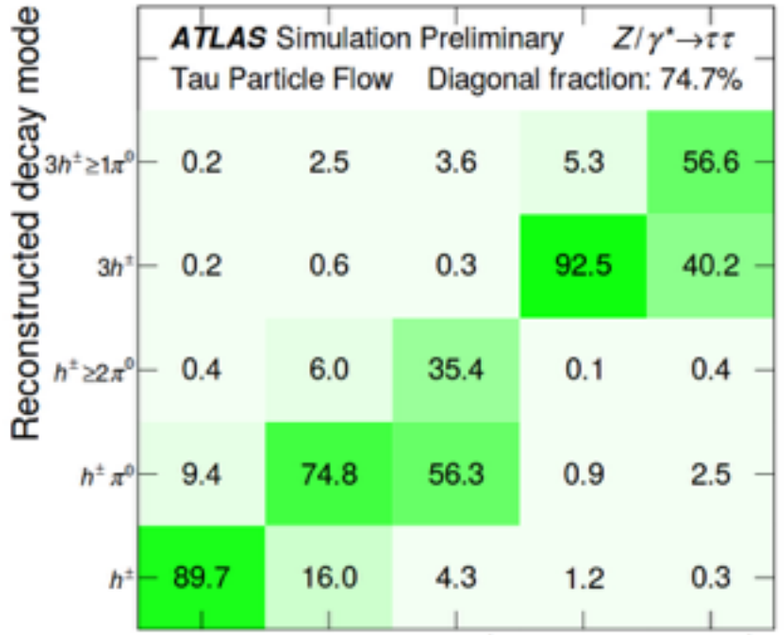
Result of new reconstruction allows for a substructure based 4-vector reconstruction, which with a better resolution. Intermediate masses can now be reconstructed.

Three BDTs are formed to separate decay modes:

- 1p0n from 1p1n
- 1p1n from 1pXn (so far the most difficult)
- 3p0n from 3pXn

A five way classification is defined.

Both classification and subtructure reconstruction will be critical in forming the structure of the CP measurement. Each decay mode has unique challenges associated.



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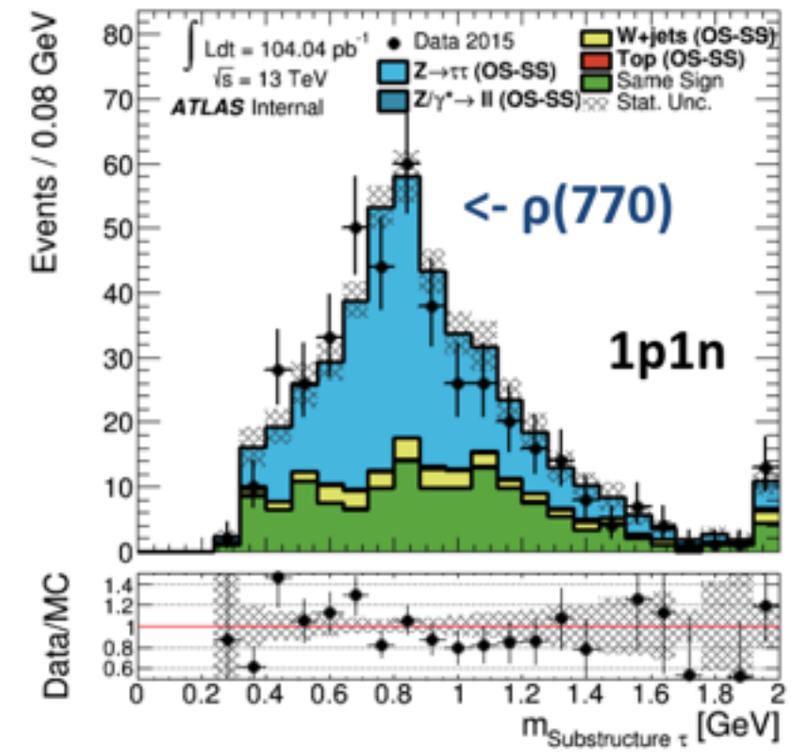


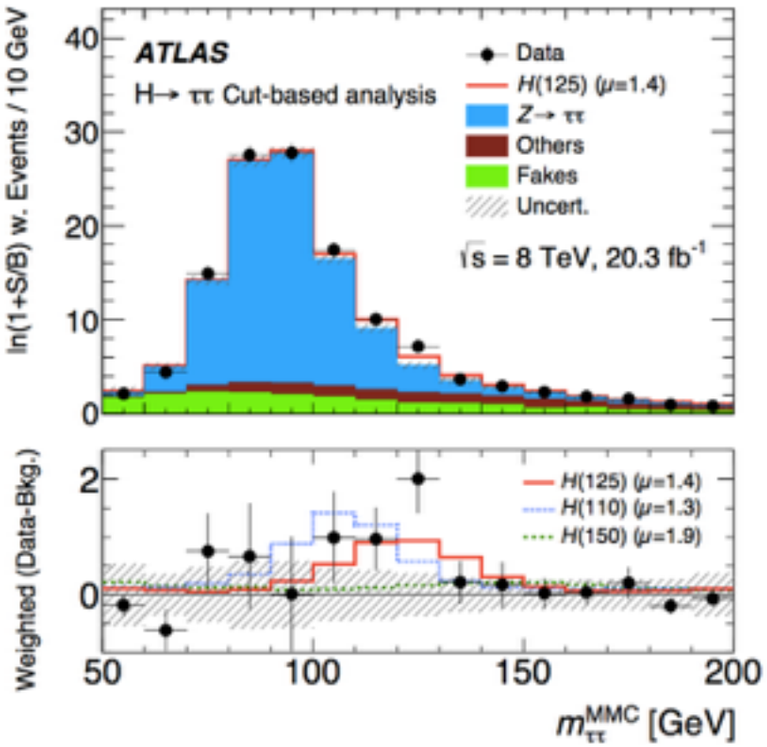
Part 2:

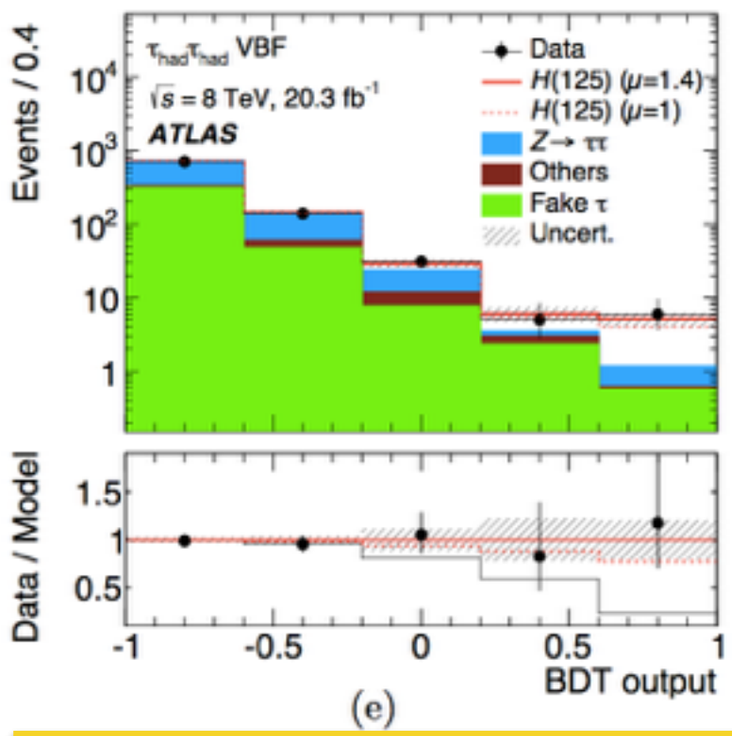
Higgs CP Measurement

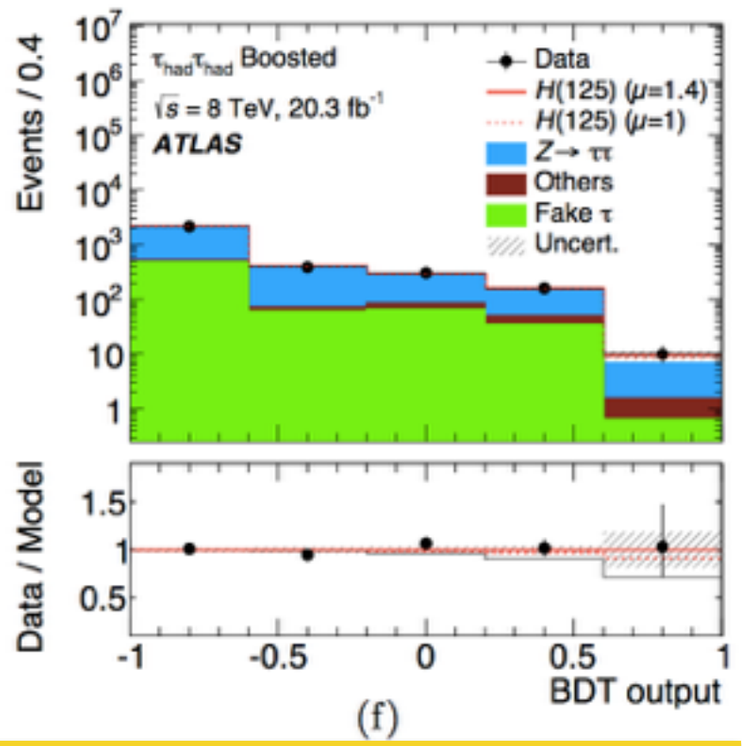
Higgs CP Measurement

Search strategy for SM coupling analysis (background estimation, event selection) can be recycled for the CP measurement. Only the fully hadronic decays are used as they provide the strongest sensitivity.

arXiv:1501.04943







H⟶ττ process couple directly through Yukawa interaction, which allows for measurement of possible mixed CP states

$$\mathcal{L}_Y^{tau} = -g_\tau \left(\cos\phi_\tau \cdot \bar{\tau}\tau + \sin\phi_\tau \cdot \bar{\tau} i\gamma_5 \tau\right) h$$

$$\Gamma(h_{mix} \to \tau^+\tau^-) \sim 1 - s_\parallel^{\tau^+} s_\parallel^{\tau^-} + s_\perp^{\tau^+} R(2\phi_\tau)\ s_\perp^{\tau^-}$$

where R is a rotation in the x-y plane

CP sensitive observable

CP of Higgs boson is **encoded in the tau-tau polarisation**

- **Angle between decay planes** is **best observable** to measure this

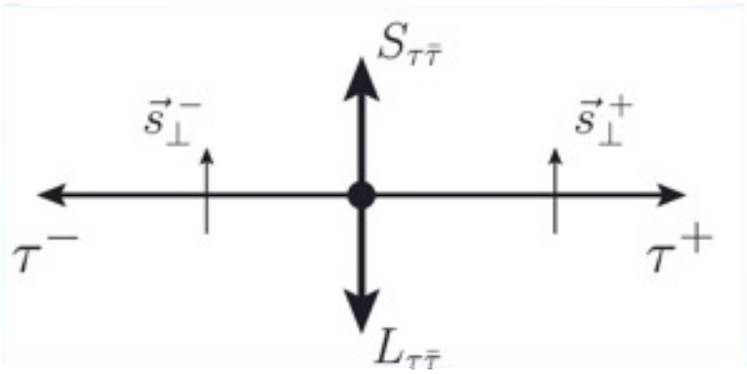
$$h^0$$

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

$$\mathcal{L}_{h^0\tau\tau} = -g_\tau \cdot \bar{\tau}\tau h$$

$$J^{PC} = 0^{++}$$

$$L_{\tau\bar{\tau}} = 1,\ S_{\tau\bar{\tau}} = 1$$



$$A^0$$

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

$$\mathcal{L}_{A^0} = -g_\tau \cdot \bar{\tau} i\gamma_5 \tau h$$

$$J^{PC} = 0^{-+}$$

$$L_{\tau\bar{\tau}} = 0,\ S_{\tau\bar{\tau}} = 0$$

CP sensitive observable

CP of Higgs boson is **encoded in the tau-tau polarisation**

- **Angle between decay planes** is **best observable** to measure this

$$h^0$$

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

$$\mathcal{L}_{h^0\tau\tau} = -g_\tau \cdot \bar{\tau}\tau h$$

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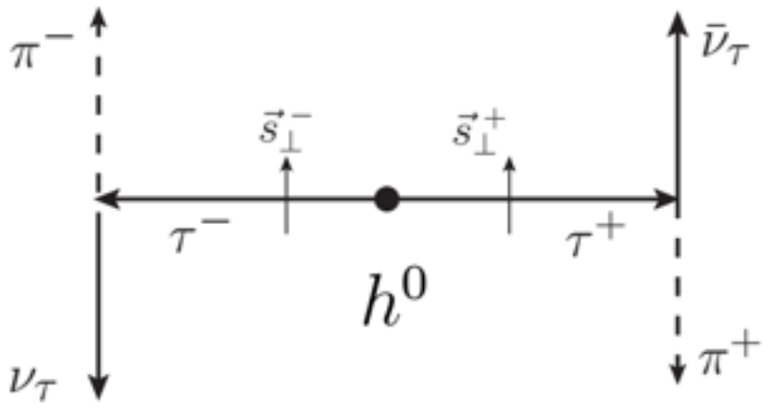

$$A^0$$

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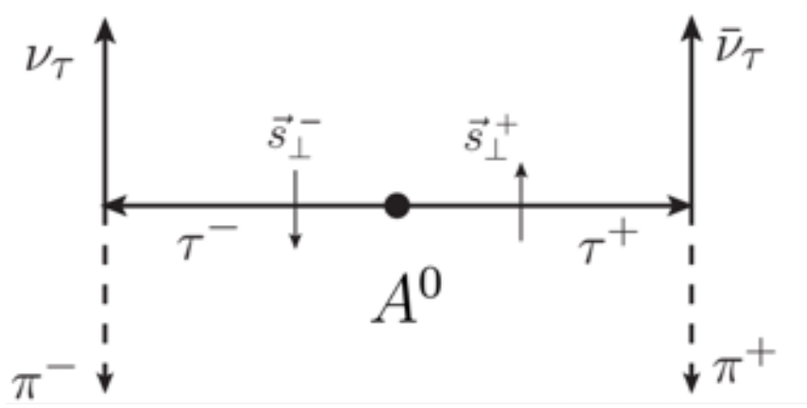
$$J^{PC} = 0^{-+}$$

$$L_{\tau\bar{\tau}} = 0,\ S_{\tau\bar{\tau}} = 0$$



Tau Branching Ratios

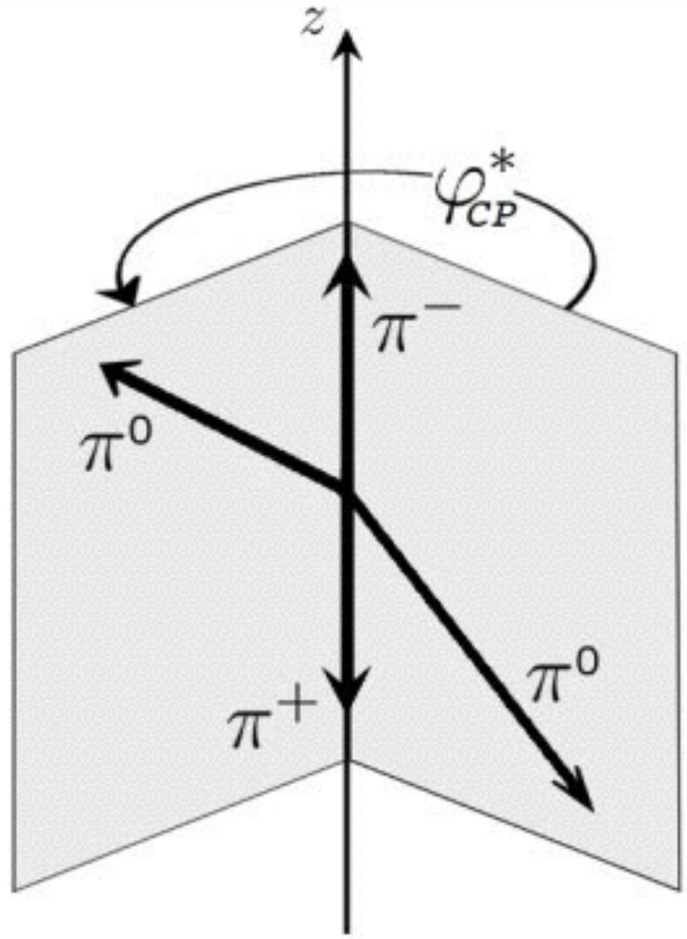
category	decay mode	$\mathcal{B}$ [%]	nomenclature
hadronic 1-prong	$\tau^- \to \pi^- \nu_\tau$	**10.8**	1p0n
Our focus	$\tau^- \to K^- \nu_\tau$	0.7	1p0n
	$\tau^- \to \rho^-(\to \pi^- \pi^0)\nu_\tau$	**25.5**	1p1n
Also used	$\tau^- \to K^{-\star}(\to K^- \pi^0)\nu_\tau$	0.4	1p1n
	$\tau^- \to a_1^-(\to \pi^- \pi^0 \pi^0)\nu_\tau$	**9.3**	1pXn
Maybe Useful	$\tau^- \to K^- \pi^0 \pi^0 \nu_\tau$	0.1	1pXn
	$\tau^- \to \pi^- \pi^0 \pi^0 \pi^0 \nu_\tau$	1.1	1pXn
	$\tau^- \to h K^0_S \geq 0$ neutrals ν_τ	0.9	1pXk
hadronic 3-prong	$\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau$ (mostly via a_1^-)	**9.3**	3p0n
	$\tau^- \to \pi^- \pi^- \pi^+ \pi^0 \nu_\tau$	**4.6**	3pXn
	$\tau^- \to hhh K^0 \nu_\tau$	0.2	3pXk
hadronic ≥5-prong	$\tau^- \to \geq 5h \geq 0$ neutrals ν_τ	0.1	(none)
leptonic	$\tau^- \to e^- \nu_\tau \nu_e$	17.8	(none)
	$\tau^- \to \mu^- \nu_\tau \nu_\mu$	17.4	(none)

From 6% to 12% of $H \to \tau\tau$

Observable for ρ decays

Method :

Use **secondary decay products** component to **form the decay plane**. Only well defined for single decay mode (6.5% of all H⟶$\tau\tau$ decays) as there is only one set of planes which can be defined.



$\tau^{\pm} \longrightarrow \rho^{\pm}\, \nu \longrightarrow \pi^0\pi^{\pm}\, \nu$

Provides strongest observable for ρ decays of di-tau system. Want to extend method to decays with intermediate a_1 resonance (three charged π final state)

$\tau^{\pm} \longrightarrow a_1\, \nu$

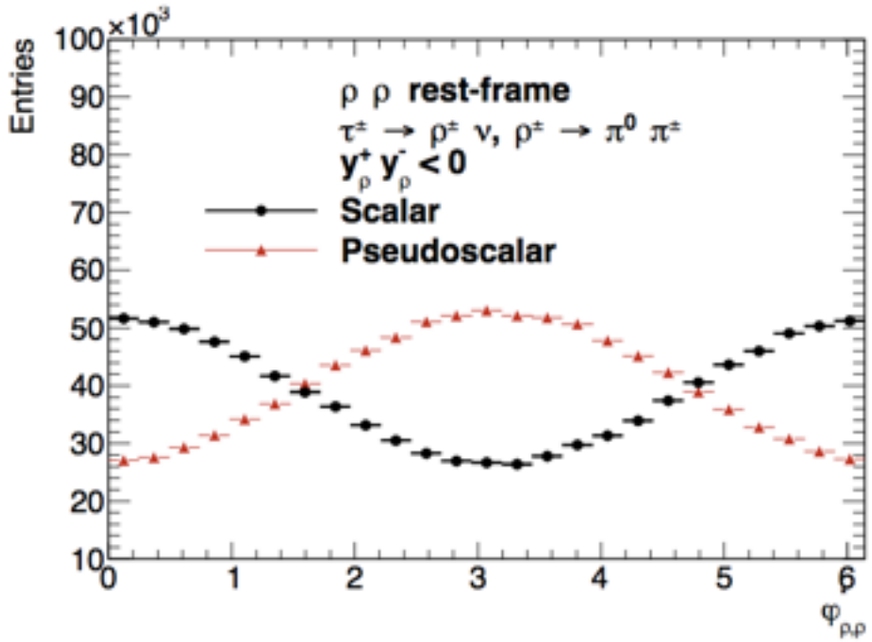
$\longrightarrow \rho\, \pi^{\pm}\, \nu$

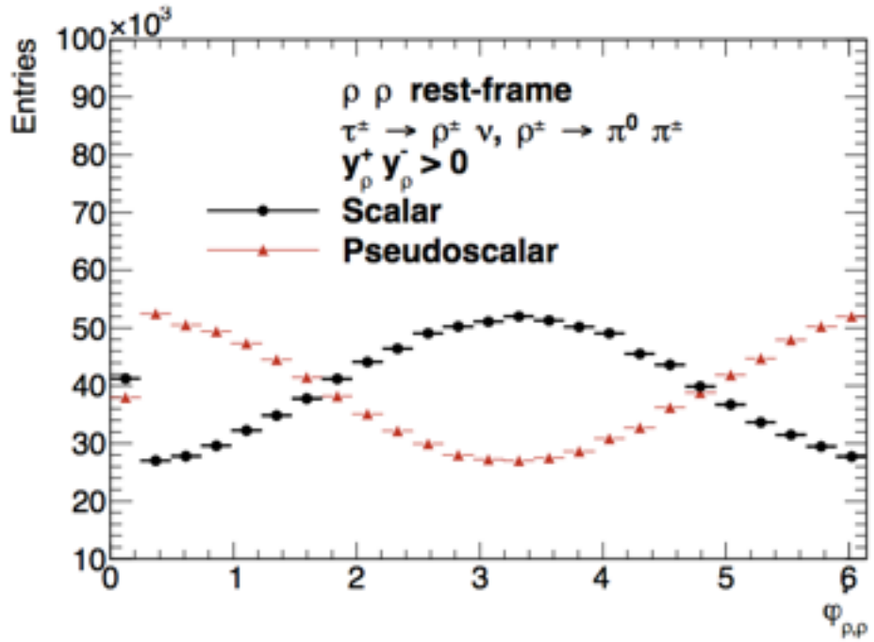
$\longrightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}\, \nu$

New: Substitute the neutral π in the above method with the neutral ρ, it further decays into $\pi^{\pm}\pi^{\mp}$ so another plane can be defined.

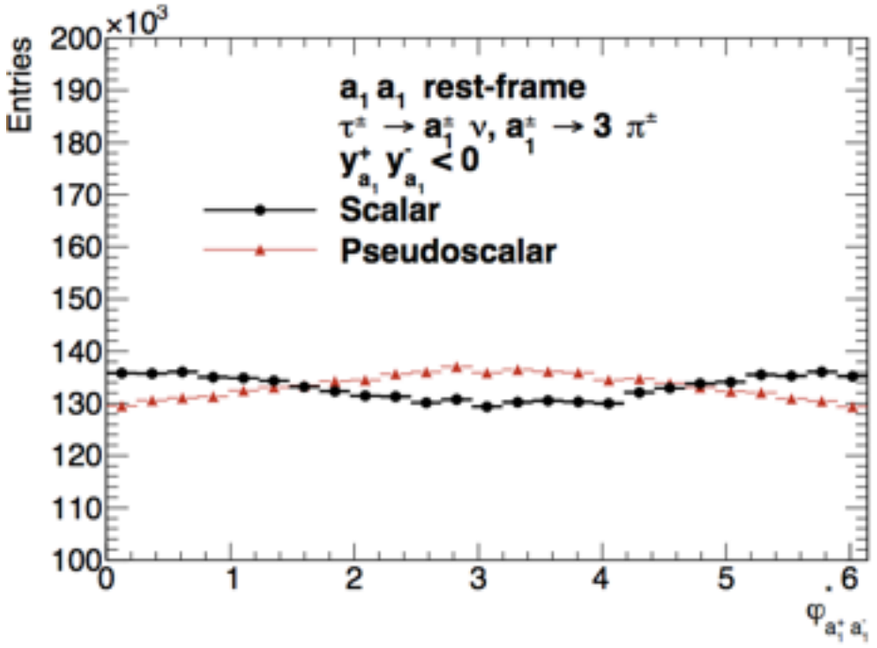
ρ-ρ vs a_1-a_1

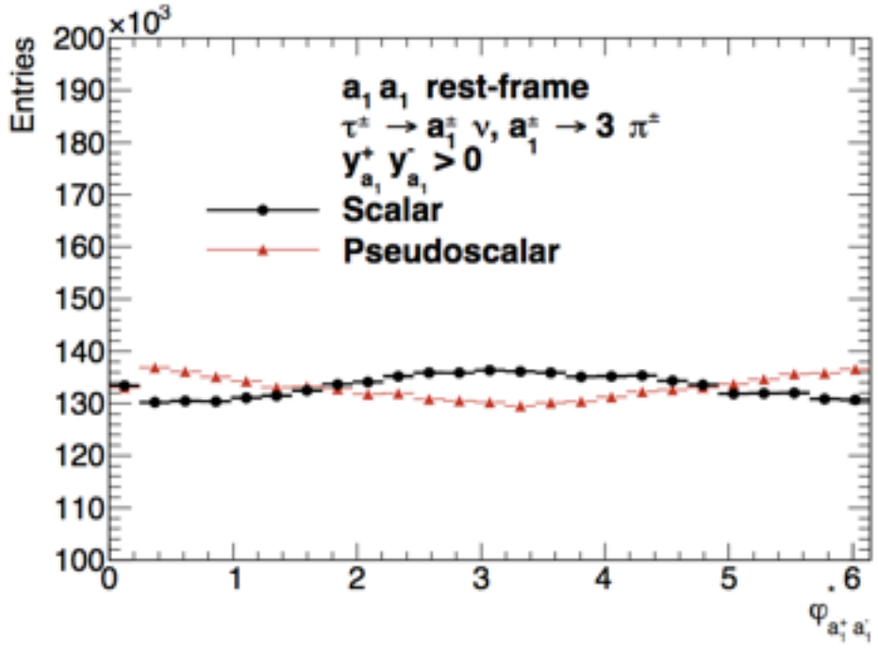
(for a_1 small amplitude but many distributions)





arxiv:1608.02609





Note:
Acoplanarity alone brings no CP sensitivity. One must use y variables which are ρ rest frame cosines of π^0 directions.

We have to use this property of τ decay matrix element. Events are classified based on the sign of the product.

16 pairs of similar plots

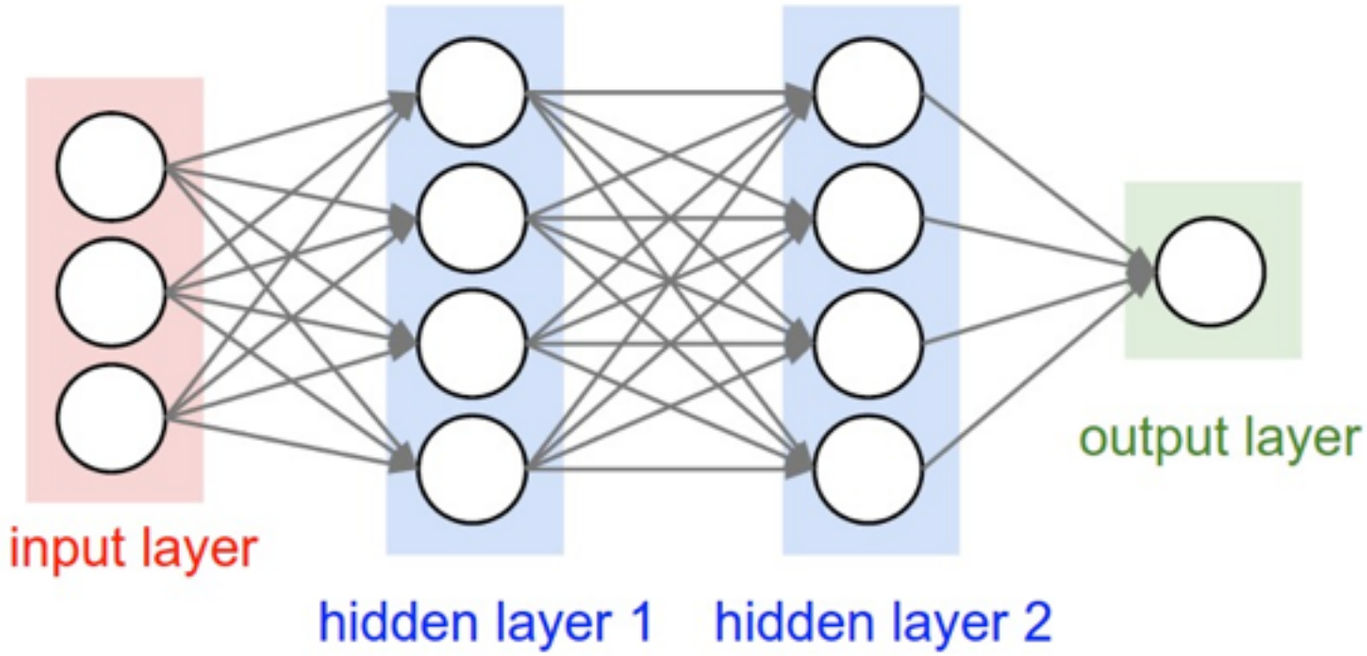
Deep Learning NN

R. Józefowicz (Google (NY), now at Open AI (SFO)) developed neural network model with Tensorflow (Google project for various non-HEP applications).

Z. Was and E. Richter-Was found promising separation utilising the neural network between scalar and pseudoscalar.

Why a neural network?

- Problem is very multidimensional (a_1-a_1 can have 16 possible acoplanar angles and 8 y variables)
- Separation amplitudes are small for each individual acoplanar angle
- NN allows for non-linear connections between all variables



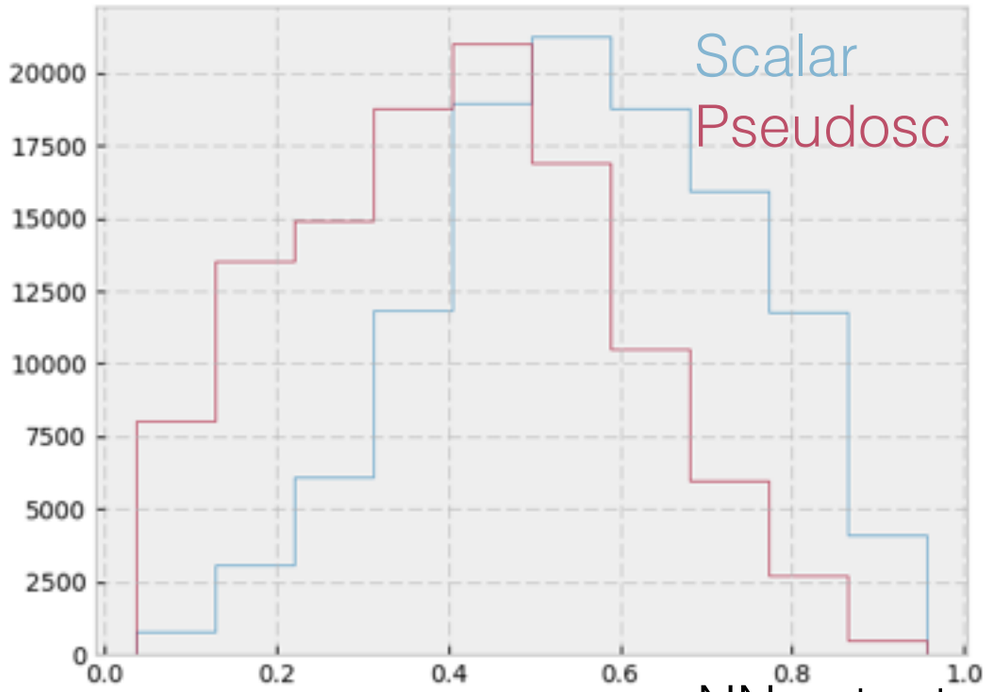
Three neural networks are trained (one for the decay modes of ρρ, ρa_1 and a_1a_1) to separate the scalar and pseudoscalar hypotheses.

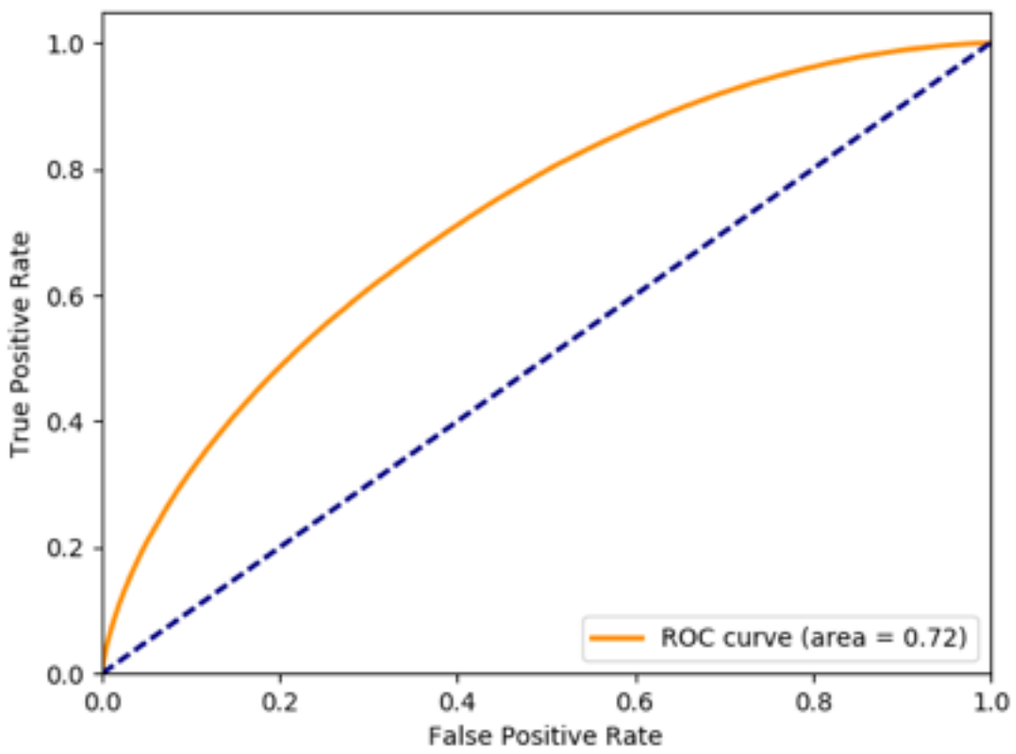
NN Input/Output

Input samples of Pythia generated H⟶$\tau\tau$ (τ decays simulated with TAUOLA) and weights for scalar and pseudoscalar angles generated with TauSpinner. Only τ decaying to hadronic final state used.

Various combinations of input features (acoplanar angles, y variables, mass, missing energy) are tested to best separate scalar and pseudoscalar events.

Predicted NN output is then assessed for its separation power. The measure of separation power is the area under the ROC curve ∈ [0.5, 1]. Area of 0.5 represents no separation and area of 1 represents perfect separation.





Preliminary results:

Area under ROC curve - A measure of separation

Features/variables	Decay mode: $\rho^{\pm} - \rho^{\mp}$ $\rho^{\pm} \to \pi^0 \pi^{\pm}$	Decay mode: $a_1^{\pm} - \rho^{\mp}$ $a_1^{\pm} \to \rho^0 \pi^{\mp}$, $\rho^0 \to \pi^+ \pi^-$ $\rho^{\mp} \to \pi^0 \pi^{\mp}$	Decay mode: $a_1^{\pm} - a_1^{\mp}$ $a_1^{\pm} \to \rho^0 \pi^{\pm}$, $\rho^0 \to \pi^+ \pi^-$
True classification	0.782	0.782	0.782
$\varphi^*_{i,k}$	0.500	0.500	0.500
$\varphi^*_{i,k}$ and y_i, y_k	0.624	0.569	0.536
4-vectors	0.638	0.590	0.557
$\varphi^*_{i,k}$, 4-vectors	0.638	0.594	0.573
$\varphi^*_{i,k}, y_i, y_k$ and m_i^2, m_k^2	0.626	0.578	0.548
$\varphi^*_{i,k}, y_i, y_k, m_i^2, m_k^2$ and 4-vectors	0.639	0.596	0.573

arxiv:1608.02609

Limit of neural network approach of 0.782 (input all information including matrix elements) is same across three decay modes due to overlap in distributions.

Results show a fair amount of separation, still fairly **weak for a_1 decay mode** though.

Seemingly **most important class of input are the 4-vectors**. Would indicate the neural network can “learn” important features such as y and mass within the model.

Latest results:

Partial use of neutrinos via E_T^{miss}

		Base selections $p_T(\tau) > 20$ GeV			Hard selections: $p_T(H) > 100$ GeV, $p_T(\tau) > 40$ GeV		
		ρ-ρ	**ρ-a_1**	**a_1-a_1**	**ρ-ρ**	**ρ-a_1**	**a_1-a_1**
φ^*, y	**NO E_T^{miss}**	0.652	0.581	0.540	0.648	0.590	0.542
φ^*, y, m	**NO E_T^{miss}**	0.652	0.593	0.551	0.646	0.603	0.557
φ^*, 4-vec	**NO E_T^{miss}**	0.660	0.600	0.569	0.656	0.610	0.569
φ^*, y	**+ E_T^{miss}**	0.662	0.594	0.537	0.655	0.599	0.541
φ^*, y, m	**+ E_T^{miss}**	0.669	0.611	0.586	0.661	0.618	0.593
φ^*, 4-vec	**+ E_T^{miss}**	0.720	0.674	0.648	0.710	0.677	0.650

Addition of neutrino information provide some orthogonal information to visible components of tau decay. Simple use of E_T^{miss} was to circumvent approximations which lead to solving quartics. **Strong gains using E_T^{miss} show NN can learn important orthogonal information.**

Also tested is using harder selections which are kinematically closer to events in the boosted category. **Results are largely compatible with base selections.**

Detector Smearing

		No Smearing			Smearing		
		ρ-ρ	ρ-a_1	a_1-a_1	ρ-ρ	ρ-a_1	a_1-a_1
φ^*, y	NO E_T^{miss}	0.652	0.581	0.540	0.632	0.581	0.538
φ^*, y, m		0.652	0.593	0.551	0.630	0.593	0.531
φ^*, 4-vec		0.660	0.600	0.569	0.623	0.600	0.533
φ^*, y	+ E_T^{miss}	0.662	0.594	0.537	0.629	0.577	0.536
φ^*, y, m		0.669	0.611	0.586	0.631	0.588	0.533
φ^*, 4-vec		0.720	0.674	0.648	0.613	0.602	0.524

Large improvement in separation may look promising but in the end needs to be evaluated with more realistic simulation (accounting for detector effects).

Applied simple Gaussian smearing to charged and neutral pions (sourcing resolutions from public ATLAS notes) as well as E_T^{miss} (set to resolution to 2 GeV) and re-evaluated trained NN on smeared MC.

Strong losses using mass and E_T^{miss}, overall use of NN is still viable as separation still present. Use of E_T^{miss} becomes apparently very problematic - need to find way to recover loss.

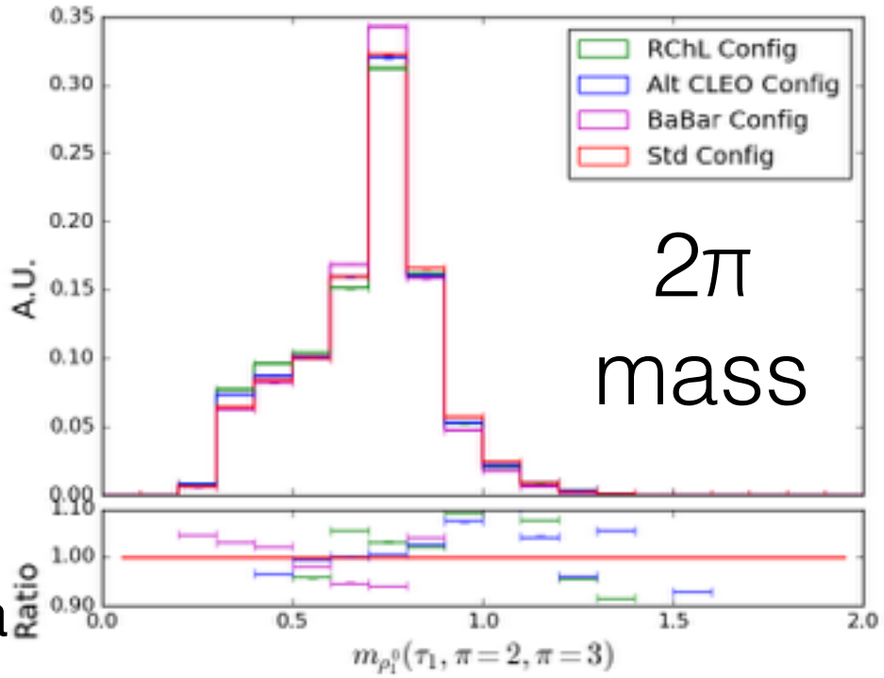
Theoretical Systematics

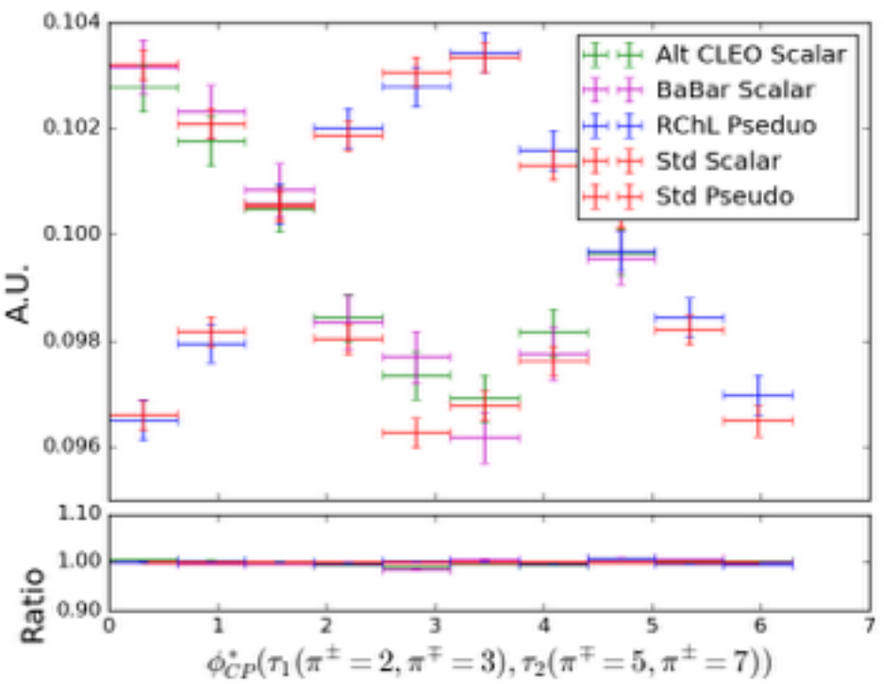
Modelling of tau decays dependent on parameterisation of vector currents. Variations are evaluated as systematics.

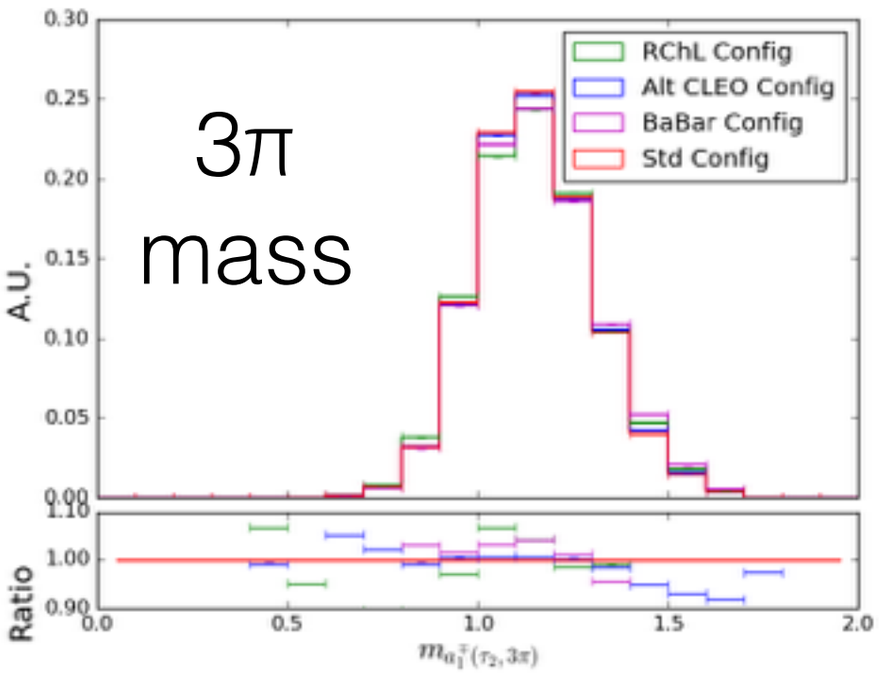
Available parameterisations:

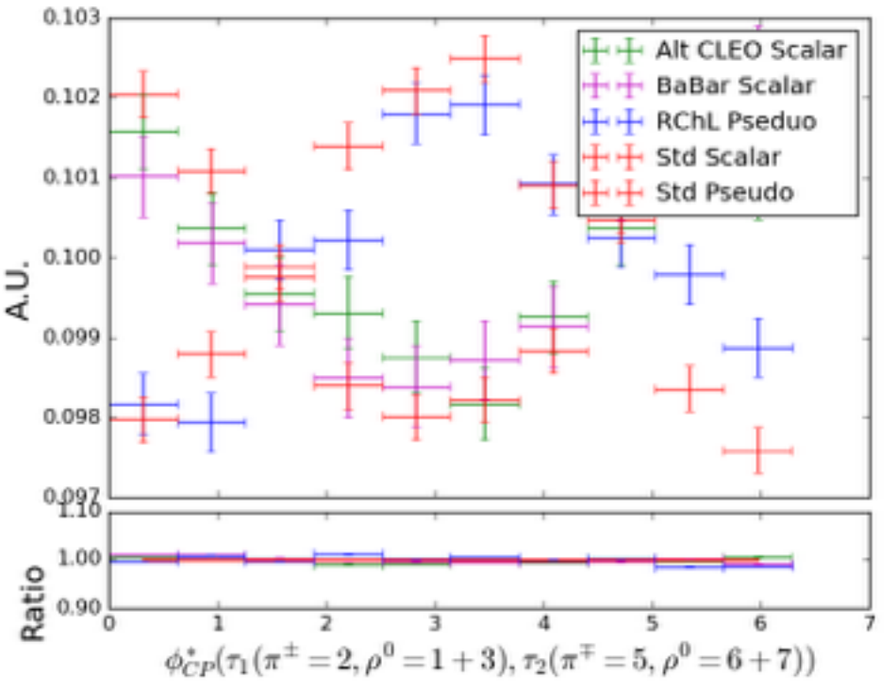
- CLEO - Standard in Tauola
- Resonance Chiral Lagrangian
- Alternative CLEO current (never fully published by collaboration)
- BaBar (also not published)

There are good reasons for the collaboration's hesitation.









Theoretical Systematics

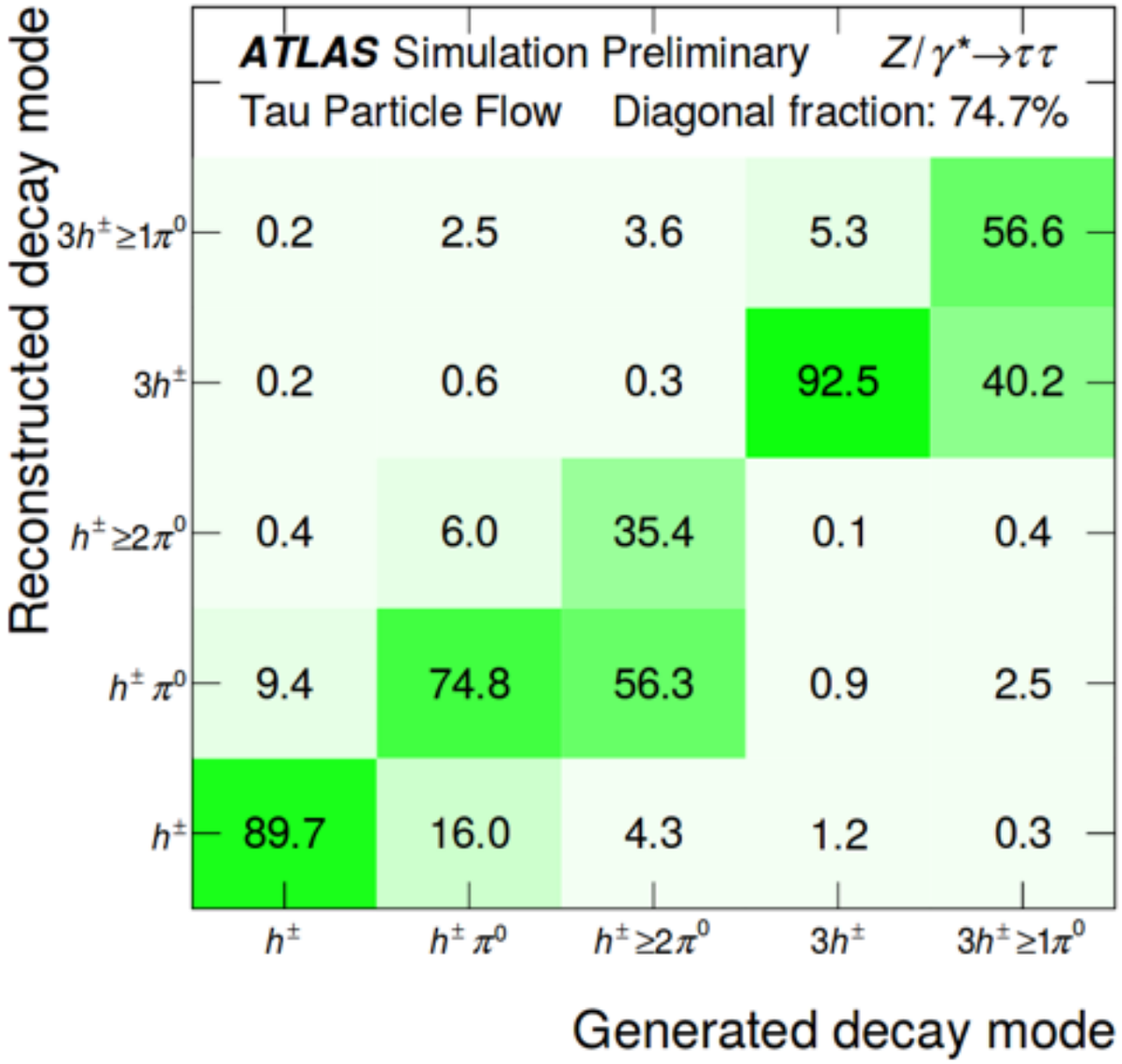
	CLEO	RChL	Alt. CLEO	BaBar
φ^*, y	0.540	0.538	0.537	0.536
φ^*, y, m	0.551	0.550	0.549	0.549
φ^*, 4-vec	0.569	0.566	0.565	0.564
φ^*, y, E_T^{miss}	0.537	0.535	0.534	0.534
φ^*, y, m, E_T^{miss}	0.586	0.584	0.582	0.581
φ^*, 4-vec, E_T^{miss}	0.648	0.643	0.641	0.638

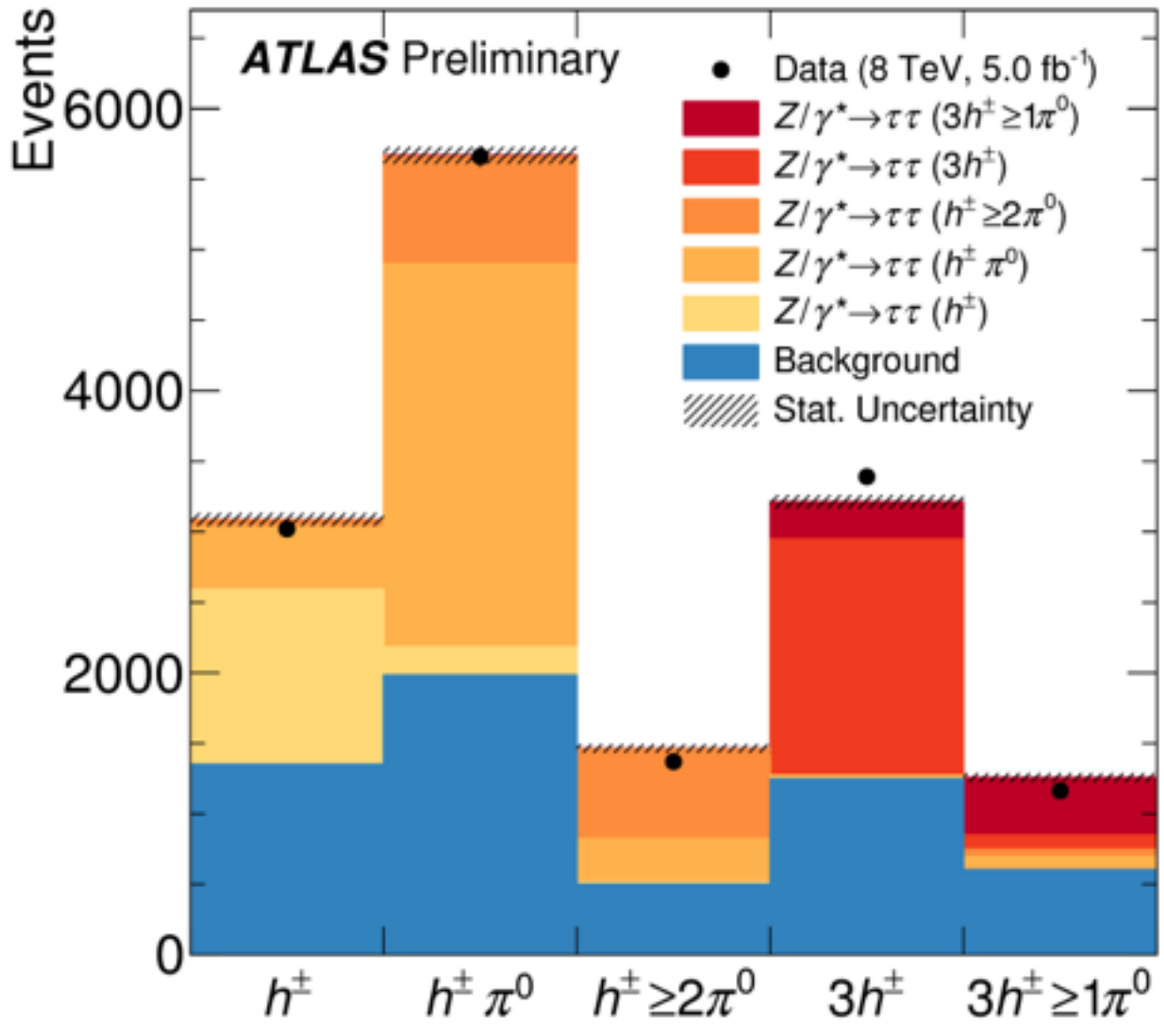
Variations not significant. Differences well covered by smearing.

Substructure Reconstruction

Contamination between channels

ATL-COM-PHYS-2015-214





Contamination between channels results in loss in sensitivity.
Misclassification of #π^0 results in incorrect calculations of φ^*

Summary

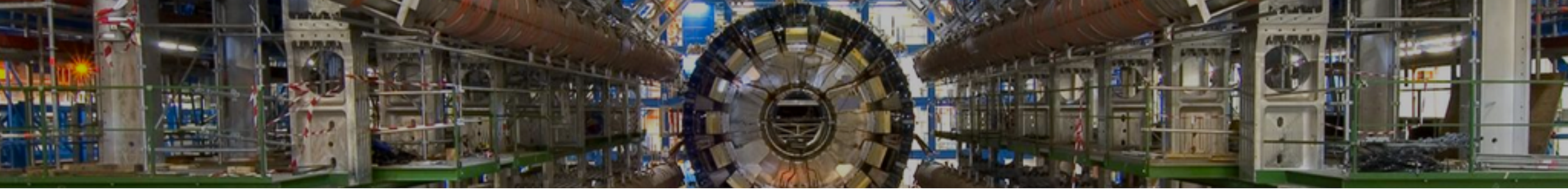
Precision Higgs measurement era yielding exciting prospects. H→ττ decays offer a rich vein of new measurements for Higgs CP enabled by new developments in τ reconstruction.

Neural network approach can be utilised to optimise the CP measurement of the Higgs boson decaying in the H→ττ decay mode. Inclusion of a_1 decay mode may prove invaluable to recovering lost sensitivity.

Plenty of work still to come in terms of validation, optimisation and building more experimentally realisable model.

Future work includes:

1. Inclusion of more decay modes
2. Investigation of effect of backgrounds
3. Investigation into how to practically utilise the NN



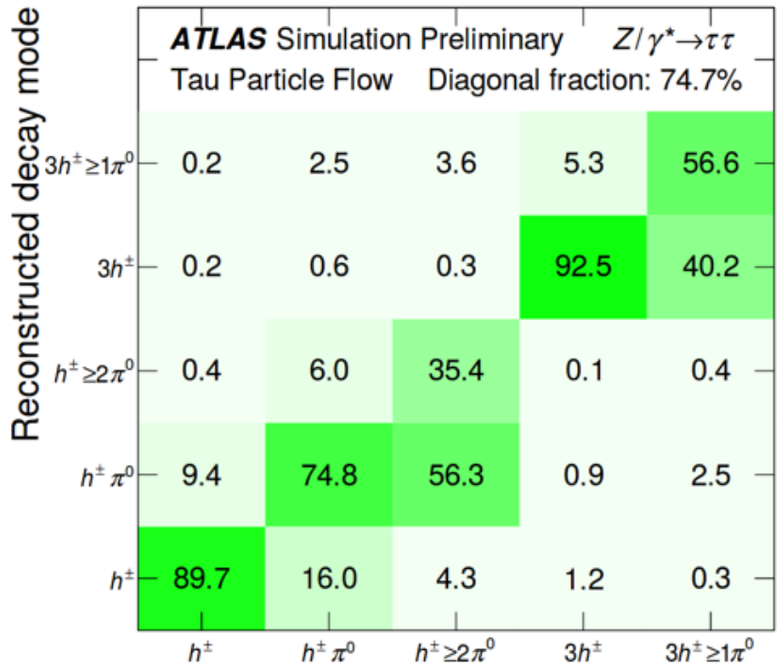
Backup

Taus for Run II

For Run II, tau reconstruction has been updated to account for:

- New centre-of-mass energy (13 TeV)
- Higher instantaneous luminosity
- New pileup conditions
- Addition of IBL (extra layer in the tracking)

New additions are the decay mode classification and substructure reconstruction. Very important for measurement of Higgs CP.



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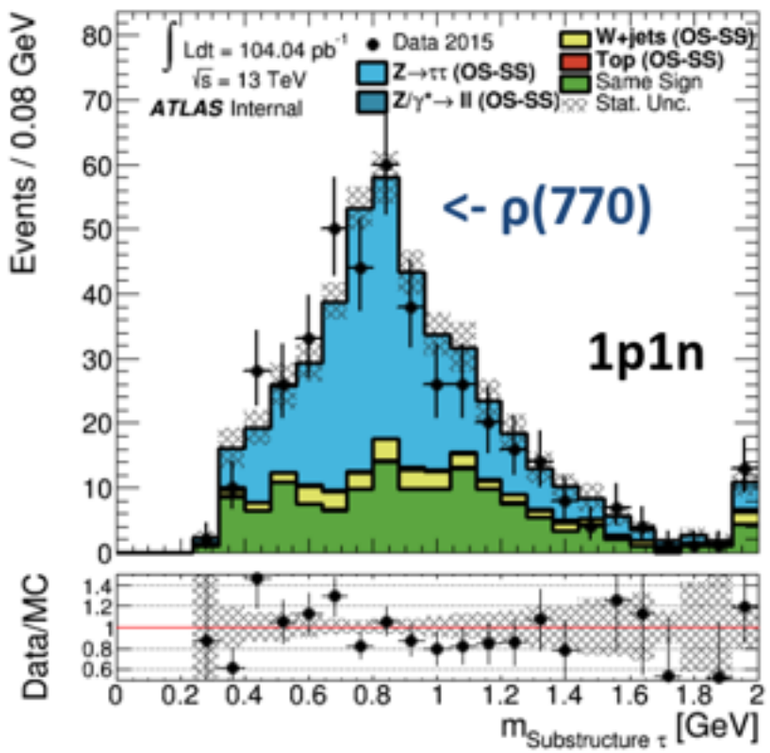
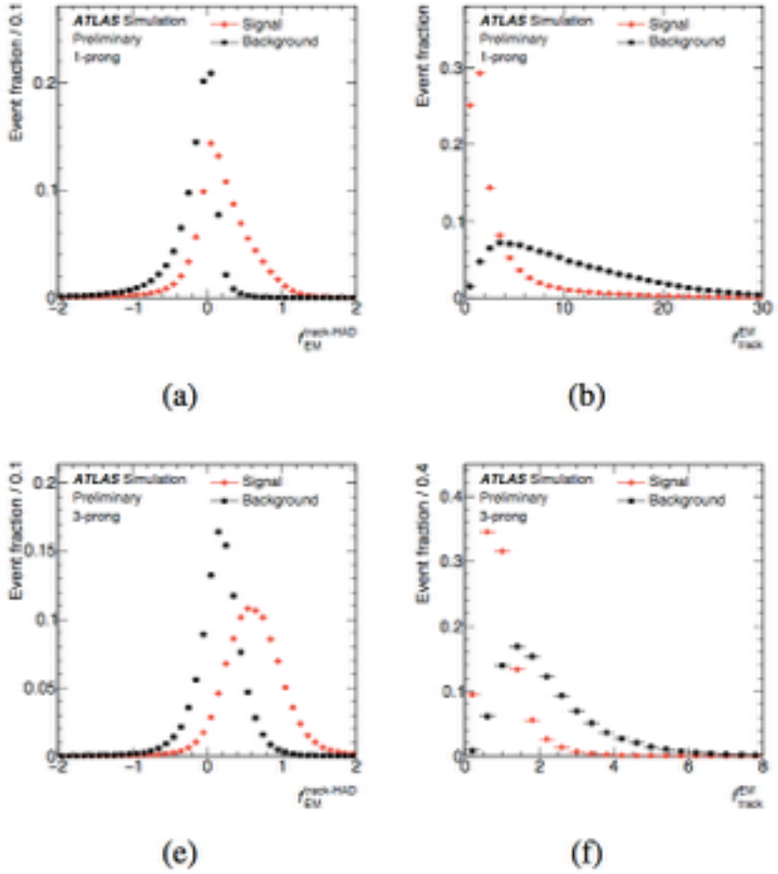


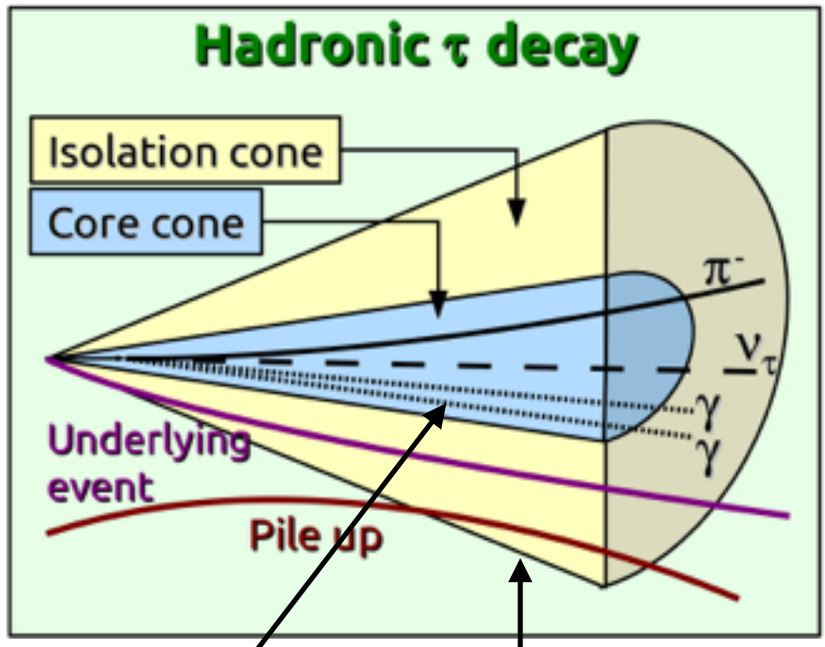
Tau Reco + ID

Tau-jets are reconstructed from jets reconstructed from anti-k_T jets with $\Delta R=0.4$. Tracks are required to be contained within the core cone of $\Delta R<0.2$.

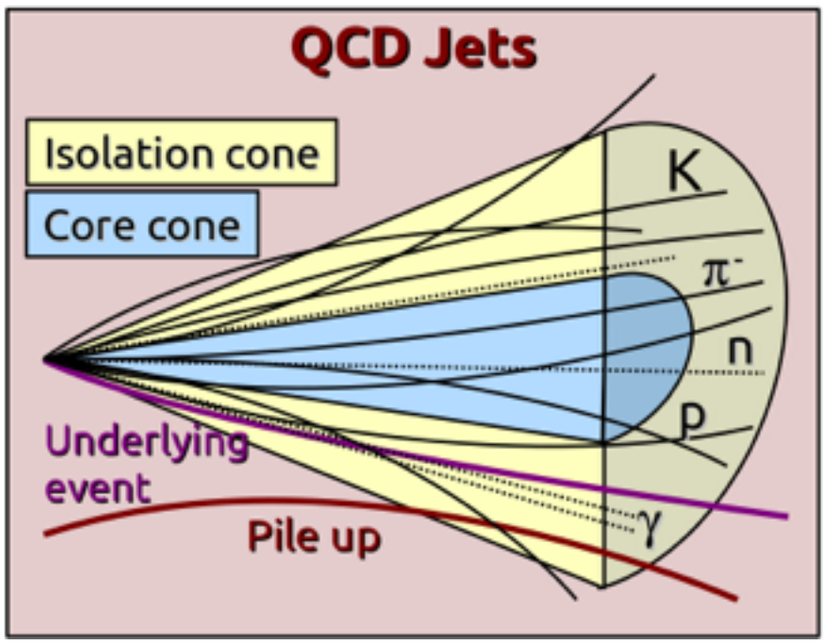
Identification is performed through a multivariate classifier. Three working points are defined for specific signal efficiencies of 40%, 60% and 70%.

Variable	Offline 1-track	Offline 3-track
f_{cent}	•	•
$f^{-1}_{\text{leadtrack}}$	•	•
$R^{0.2}_{\text{track}}$	•	•
$\lvert S_{\text{leadtrack}}\rvert$	•	
$f^{\text{track}}_{\text{iso}}$	•	
ΔR_{Max}		•
$S^{\text{flight}}_{\text{T}}$		•
m_{track}		•
$f^{\text{track-HAD}}_{\text{EM}}$	•	•
$f^{\text{EM}}_{\text{track}}$	•	•
$m_{\text{EM+track}}$	•	•
$p^{\text{EM+track}}_{\text{T}}/p_{\text{T}}$	•	•





$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$



Substructure Reconstruction

One key development for Run II is to allow for the tau substructure to be reconstructed.

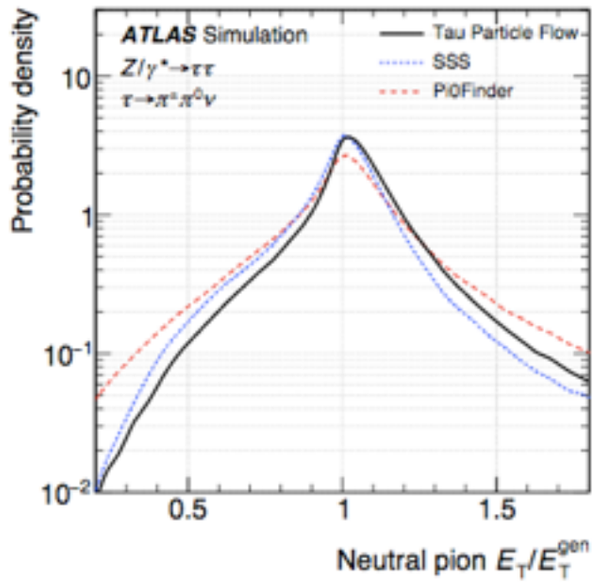
A particle flow approach is taken (rather than using only calo information). Charged hadrons reconstructed using track information, neutrals from calo deposits.

Leads to better four momenta-resolution and allows for classification of tau decay.

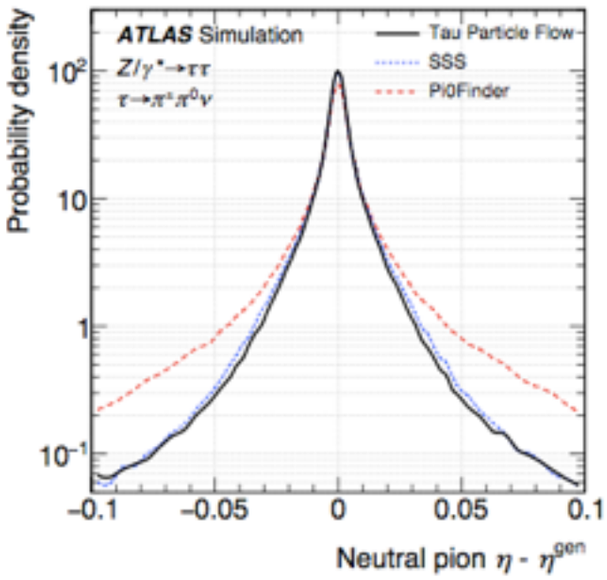
Three BDTs are formed to separate decay modes:

- 1p0n from 1p1n
- 1p1n from 1pXn (so far the most difficult)
- 3p0n from 3pXn

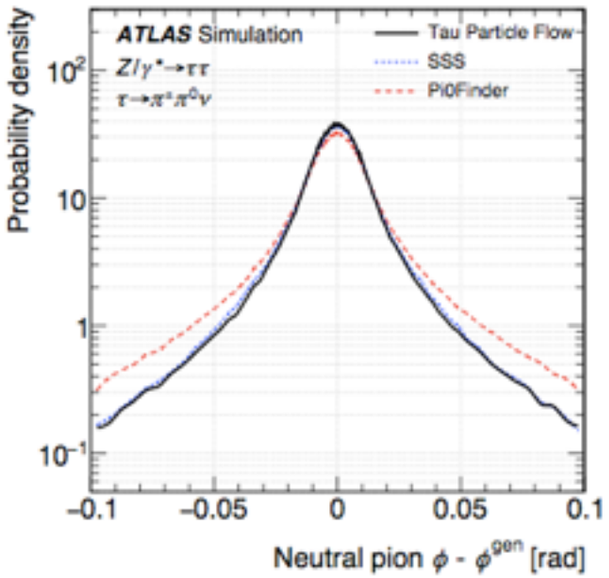
A five way classification is defined and will be critical in forming the structure of the CP measurement.



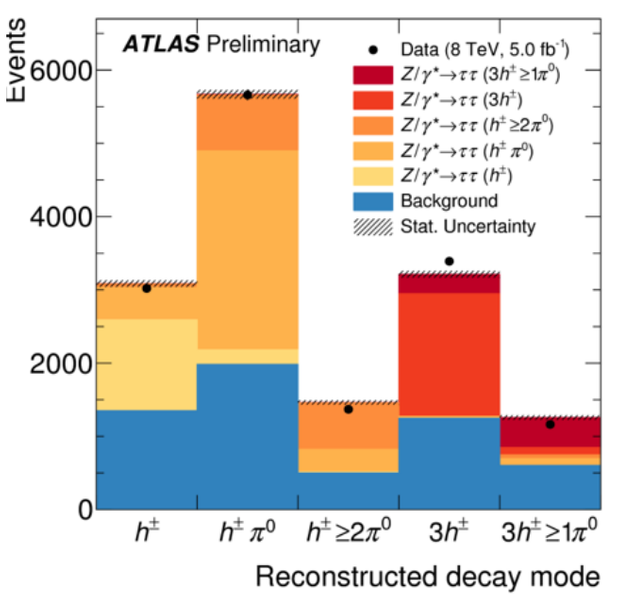
(a)



(b)



(c)



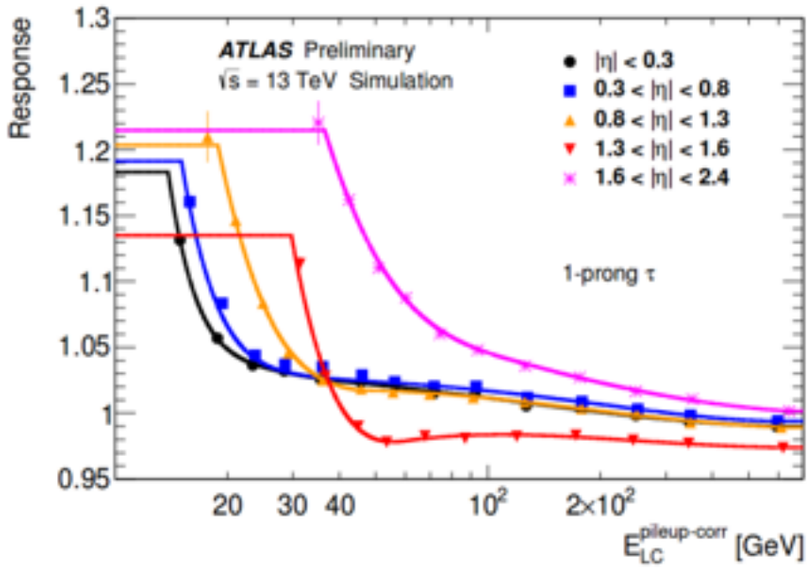
[ATL-COM-PHYS-2015-214]

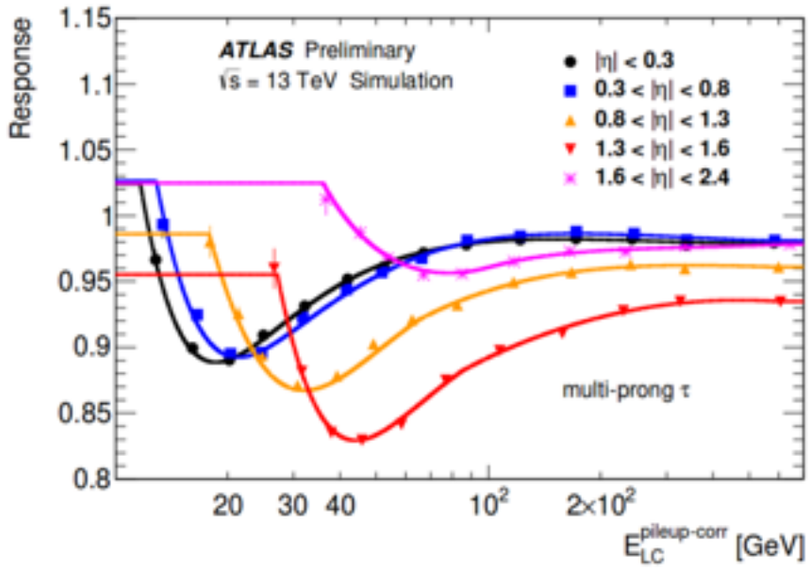
TES - Energy Calibration

Energy is calibrated using Local Hadron Calibration (LC) prior to reconstruction which accounts for several detector effects

Typical jets contain a different mixture of EM (neutral π^0) and hadronic components so tau-jets require a more specific calibration

This is called the Tau Energy Scale (TES). The p_T is corrected through calibration curves binned in prong, η as a function of p_T corrected.





[ATL-COM-PHYS-2015-928]

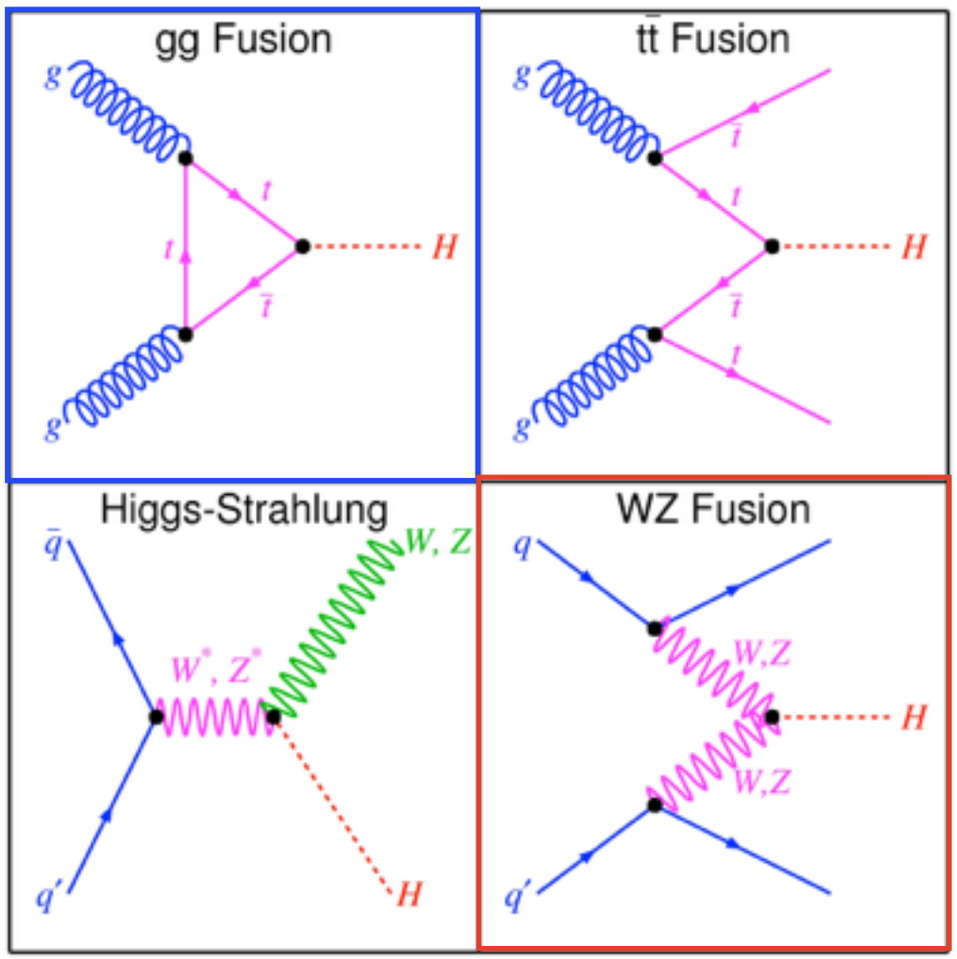
Part B:

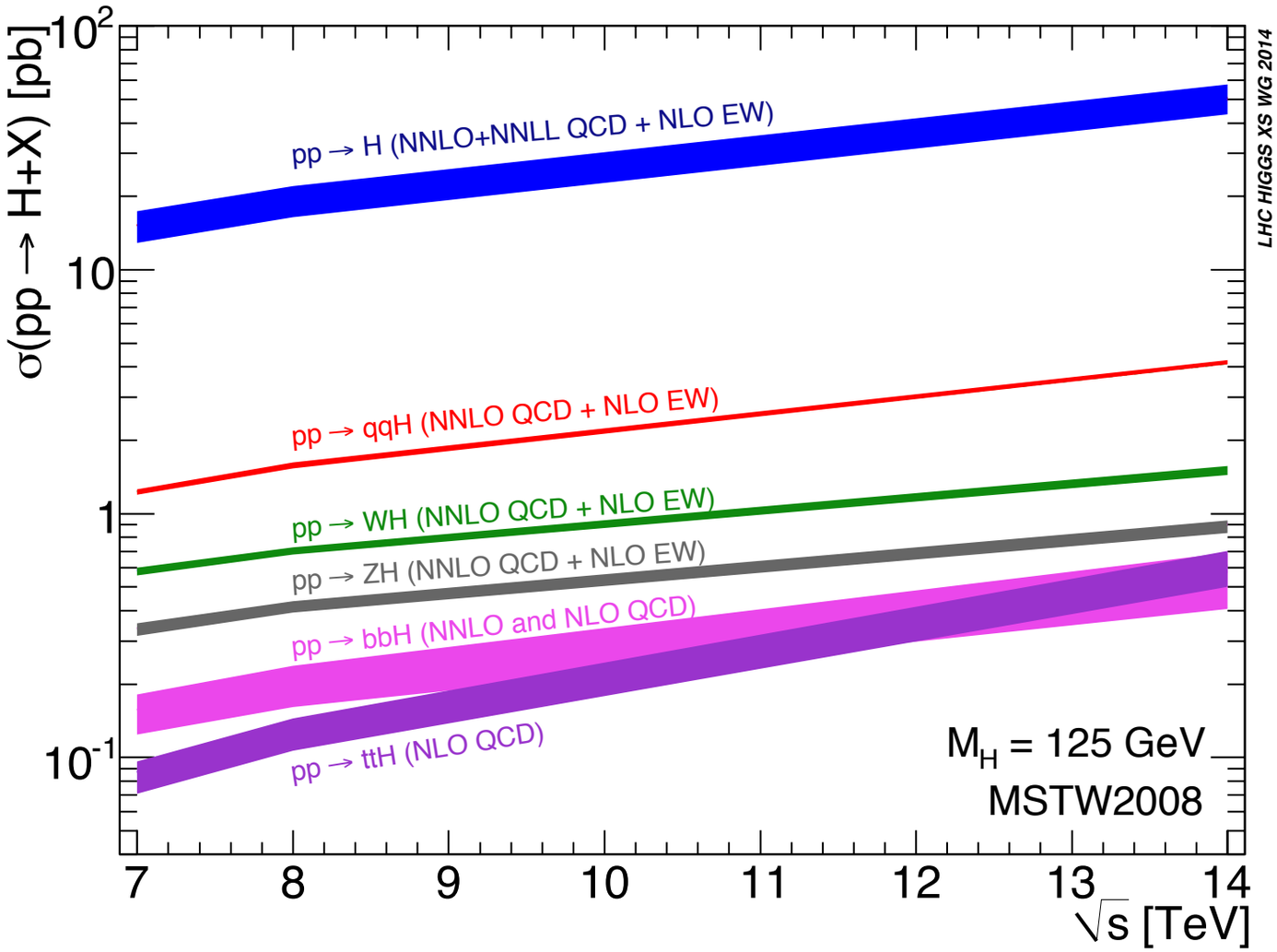
SM Coupling Analysis

H⟶ττ Signal

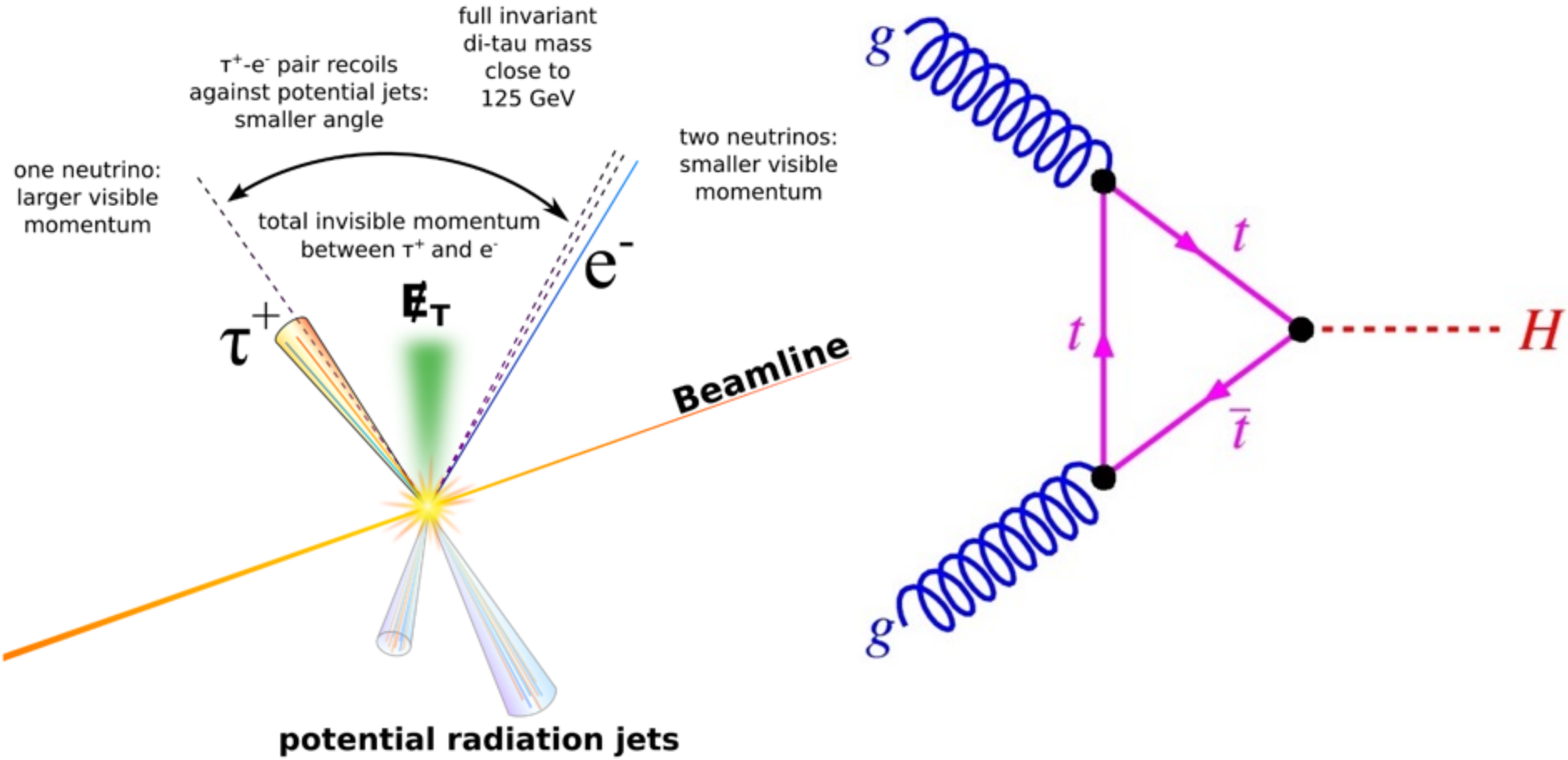
Leading two production modes are used in the main analysis

- Gluon-gluon fusion (ggF) and vector boson fusion (VBF)





Signal - ggF



Gluon-gluon fusion contains the **largest cross-section**.

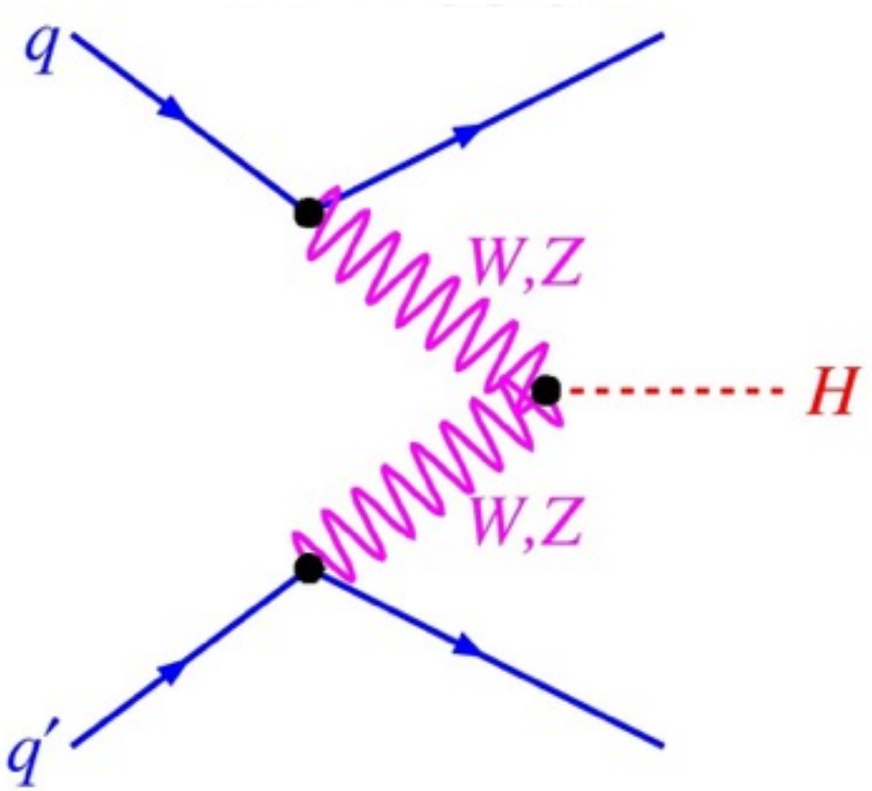
Topology characterised with **large boost in transverse plane recoiling off a jet**.

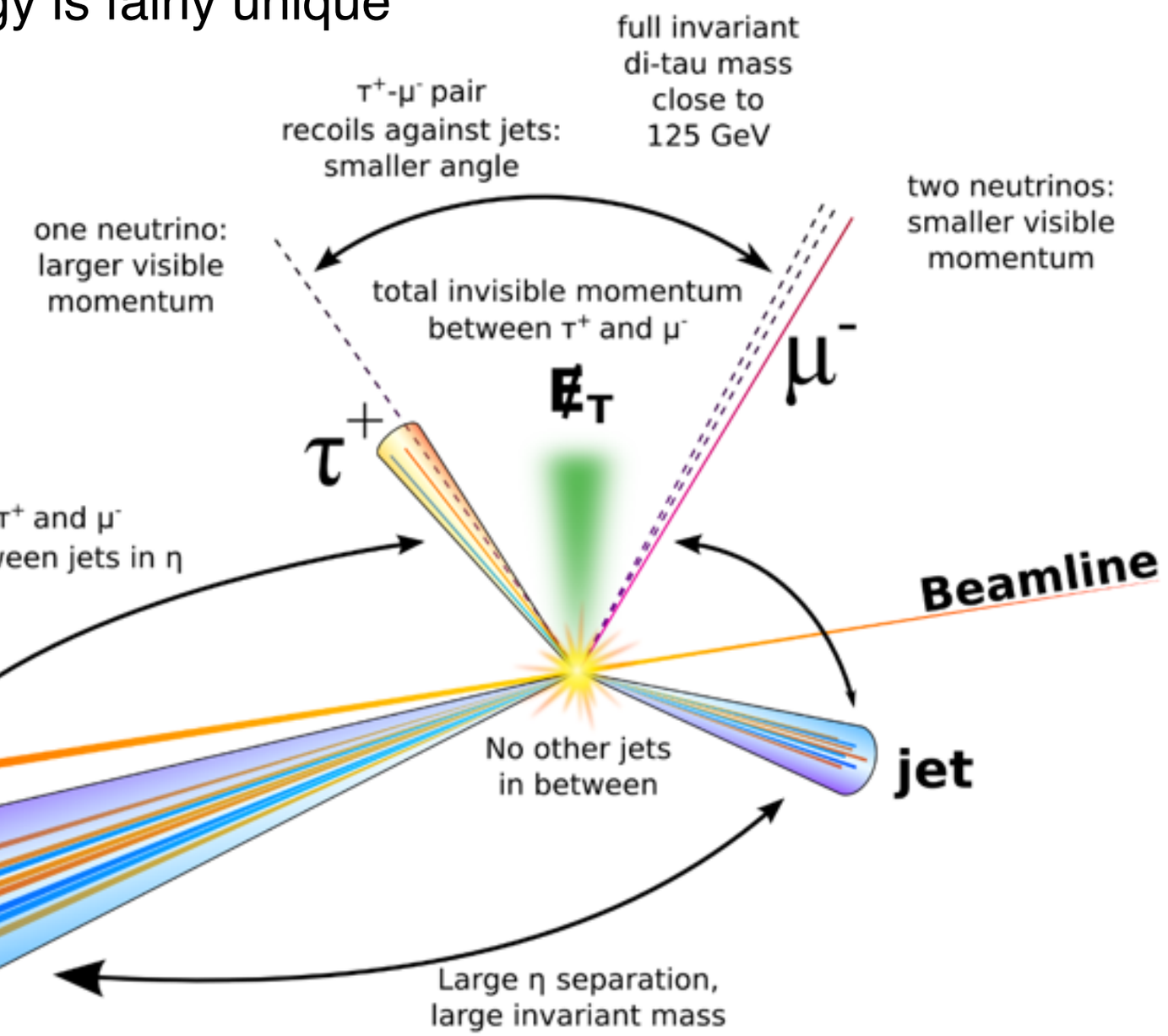
Topology lowers the x-sec used but allows for better discrimination from Z backgrounds.

Signal - VBF

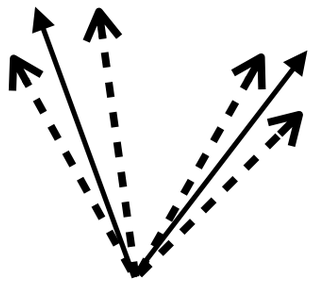
Vector Boson Fusion characterised by **two jets collimated along the beam**

Very sensitive channel as signal topology is fairly unique



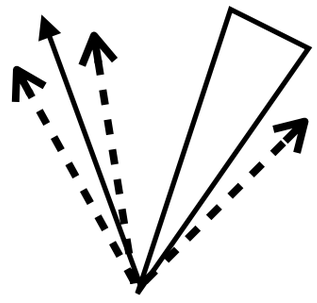


Channels



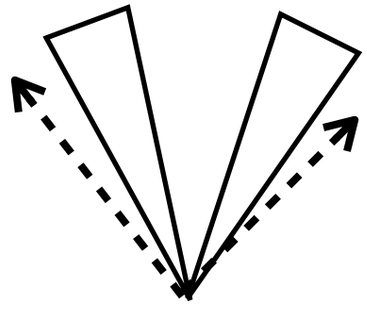
LL (fully leptonic)

- Combination of di-lepton and single lepton triggers
- Isolated leptons
- Veto events with hadronic tau decays
- Large Z background



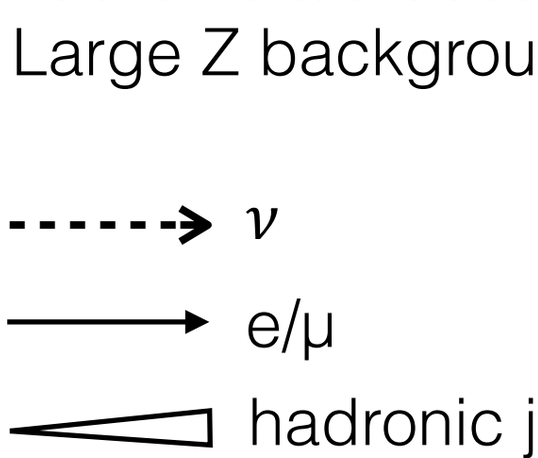
LH (semi-leptonic)

- Single lepton triggers
- Veto events with b-tagged jets
- Isolated lepton
- Tau with medium ID working point
- Dominant backgrounds from processes with jets passing tau ID and Z⟶ττ



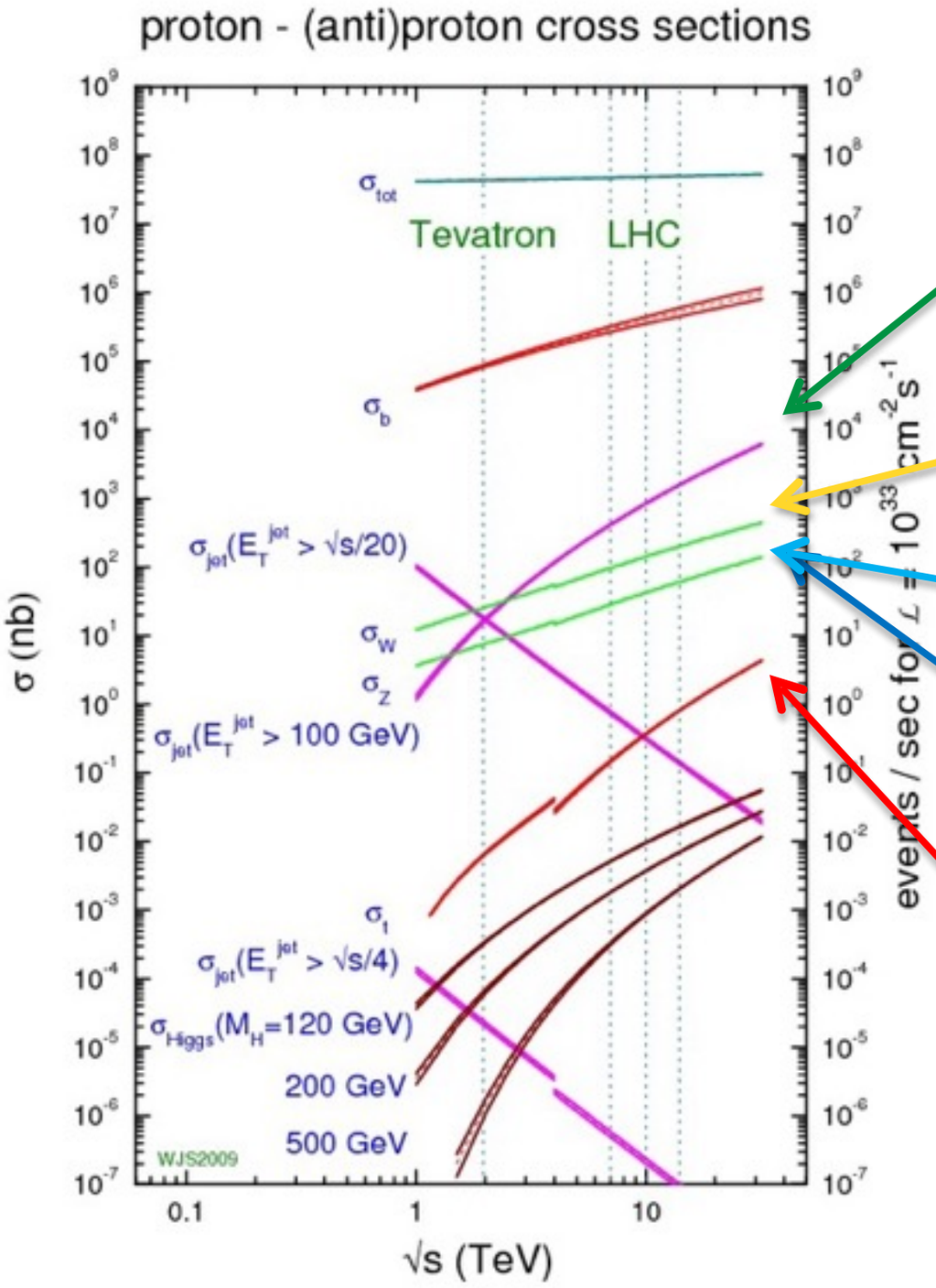
HH (fully hadronic)

- Di-tau (hadronic) triggers
- Both tau candidates passing medium ID working point
- Veto events with leptons
- Dominant background from Z⟶ττ and di-jet



Note: Each channel contains two categories enriched with ggF and VBF signals. MVA was used for final Run I result.

Backgrounds



Multijet production increases with higher energy. Jets can be misreconstructed as taus

W+jet production also very large cross-section

Z⟶ll important background for LL and LH (through lepton mis-id)

Z⟶ττ is largest irreducible background

Top backgrounds also important as there is a large multiplicity final state. Important for LL and LH channels only.

Backgrounds

Irreducible:

- Events with **identical prompt final state (Ztt)**

Best discriminator:

- **Mass of boson** decaying to tau pair
- Kinematics of the decay products

Modelling:

- Had a data-driven method in Run I
- Z⟶μμ events in data combined with tau-simulation

Reducible:

- Events with non-prompt final state (**processes where jet passes tau ID**)

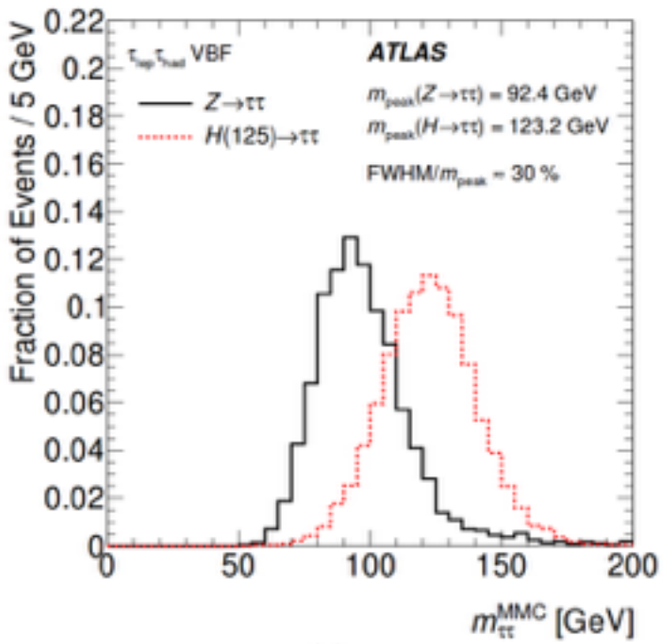
Best discriminator:

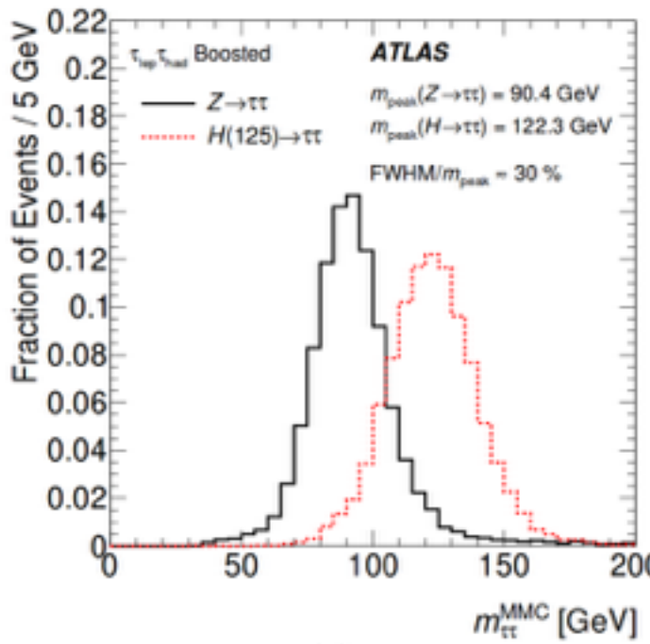
- **Identification requirements** and topology

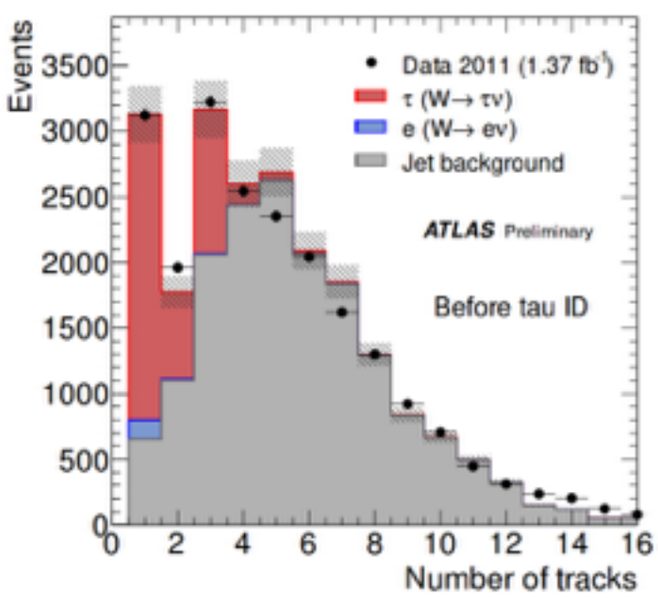
Modelling:

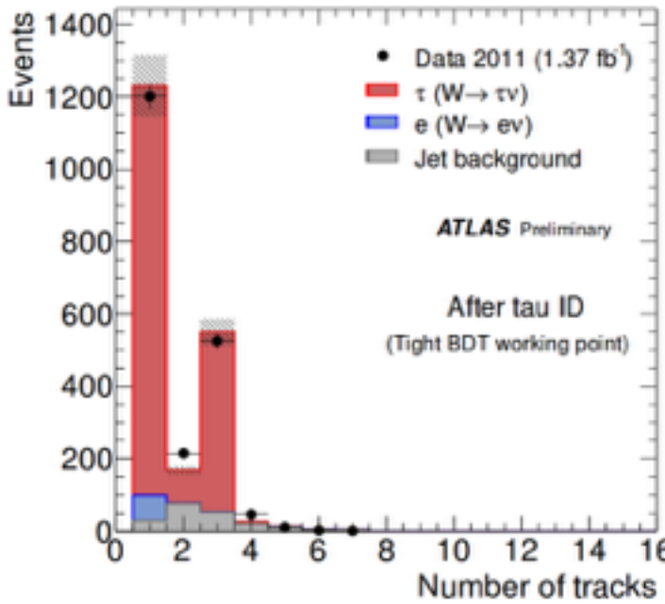
- Uses data-driven methods (varies from channel to channel based on composition of background).

arxiv:1501.04943









arXiv:1412.7086

Impact Parameter Method

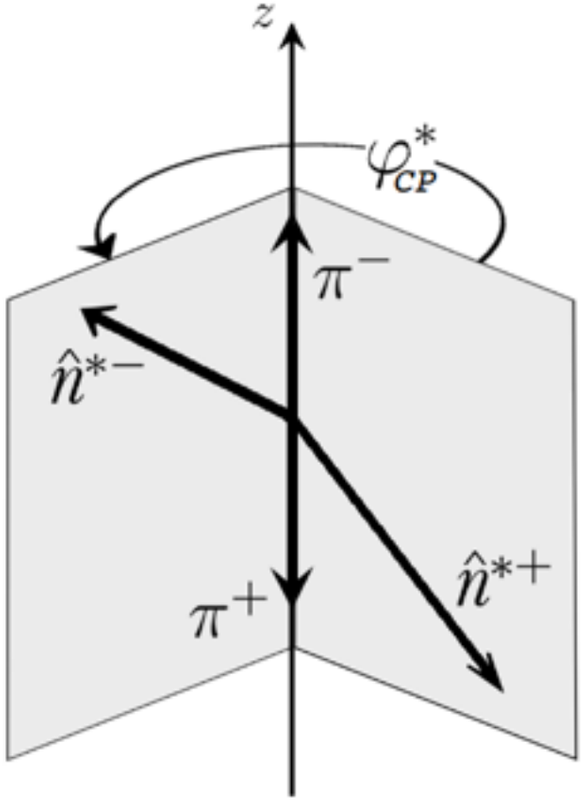
Method :

Approximate the **decay plane** with **impact parameter and the momenta vector**

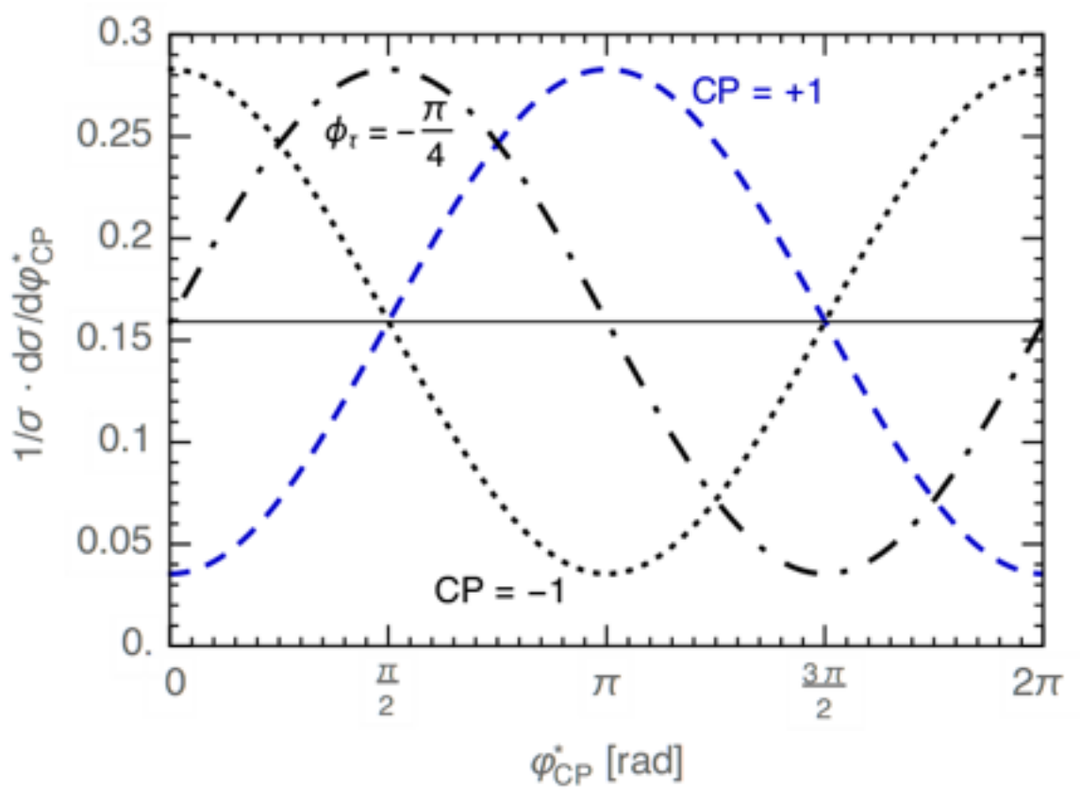
Pro : Can be used across **all decay modes**

Con : Highly dependent on the **resolution of the impact parameter**

$$\varphi^*_{CP} = \begin{cases} \varphi^* & \text{if } \mathcal{O}^*_{CP} \geq 0\,, \\ 2\pi - \varphi^* & \text{if } \mathcal{O}^*_{CP} < 0\,, \end{cases}$$



arxiv:1510.03850



$$\varphi^* = \arccos(\hat{\mathbf{n}}^{*+}_{\perp} \cdot \hat{\mathbf{n}}^{*-}_{\perp})\,,$$

$$\mathcal{O}^*_{CP} = \hat{\mathbf{q}}^*_{-} \cdot (\hat{\mathbf{n}}^{*+}_{\perp} \times \hat{\mathbf{n}}^{*-}_{\perp})\,,$$

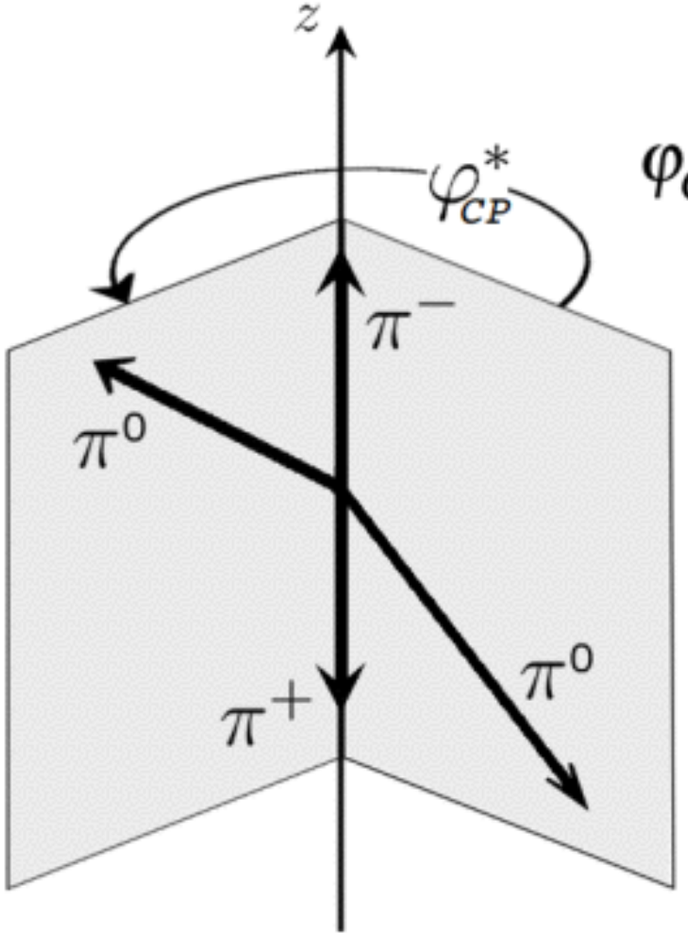
Observable for ρ decays

Method :

Use **vector of charged and neutral** component to **form decay plane**

Pro : Better performance than relying on impact parameter

Con : Only useful for **single decay mode**

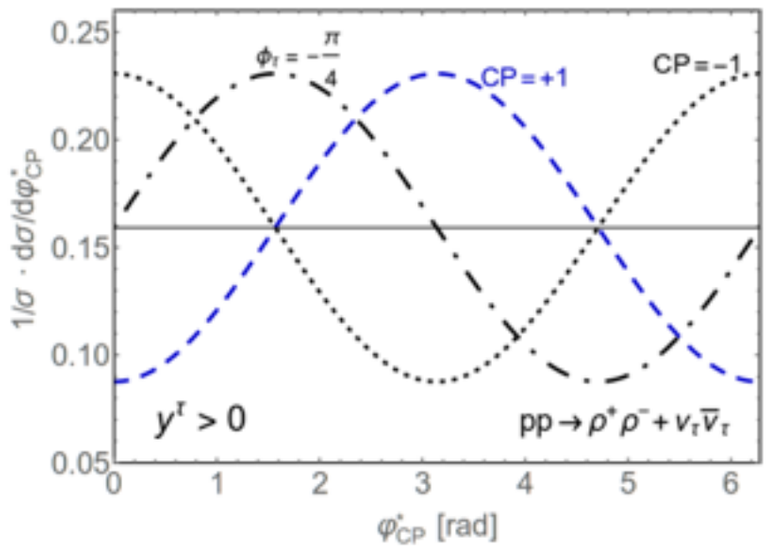


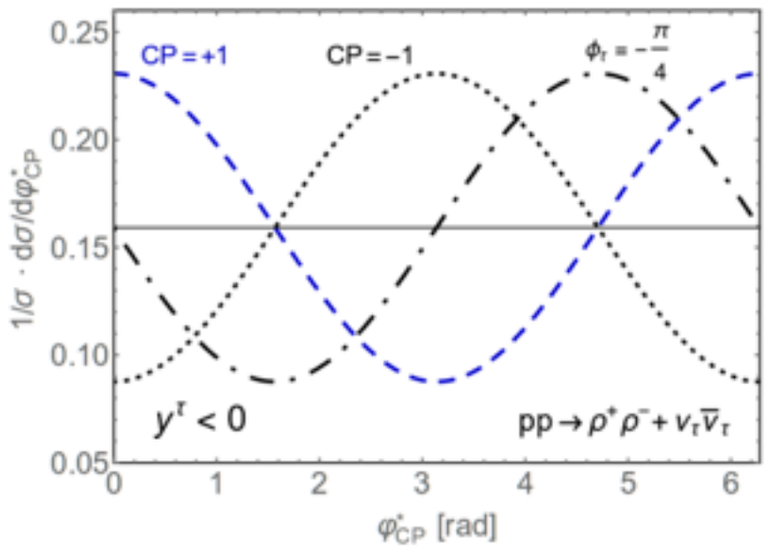
$$\varphi^*_{CP} = \begin{cases} \varphi^* & \text{if } \mathcal{O}^*_{CP} \geq 0, \\ 2\pi - \varphi^* & \text{if } \mathcal{O}^*_{CP} < 0, \end{cases}$$

$$\varphi^* = \arccos\left(\hat{\mathbf{q}}^{*0+}_{\perp} \cdot \hat{\mathbf{q}}^{*0-}_{\perp}\right)$$

$$\mathcal{O}^* = \hat{\mathbf{q}}^{*-} \cdot \left(\hat{\mathbf{q}}^{*0+}_{\perp} \times \hat{\mathbf{q}}^{*0-}_{\perp}\right)$$

arxiv:1510.03850





Our NN

Inputs are chosen from the following set:

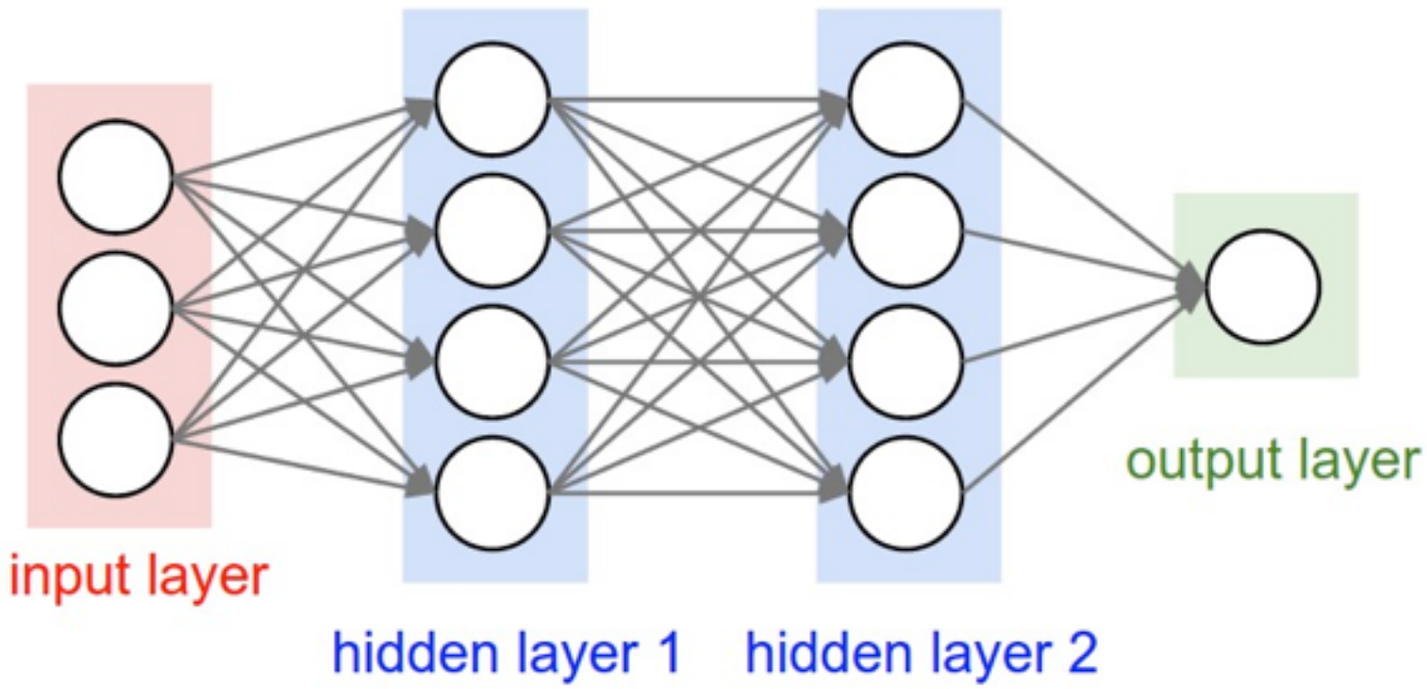
- Acoplanarity angles between particle i and j (φ^*_{ij})
- 4-vectors of visible decay products
- Fractional energy difference between charged and neutral components (y_i, y_j)
- Reconstructed intermediate resonance

Combinations of these sets were tested in order to determine an optimal set of inputs. Inputs were also boosted into the reconstructed visible decay product frame. Our model was built with 6 hidden layers of 300 nodes. Final layer extracted through a sigmoid function.

Three separate networks were trained, one for each combination of intermediate decay mode:

- $\rho\rho$, ρa_1 and $a_1 a_1$

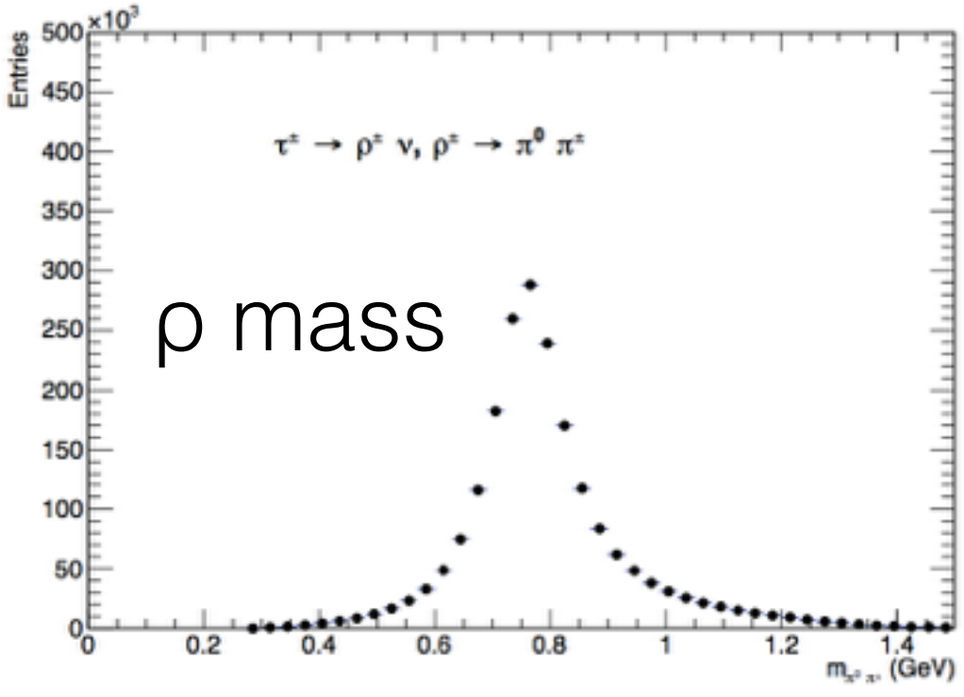
Still room for improvement in neural network, exploring possibility of including neutrino momenta information.



Mass distribution

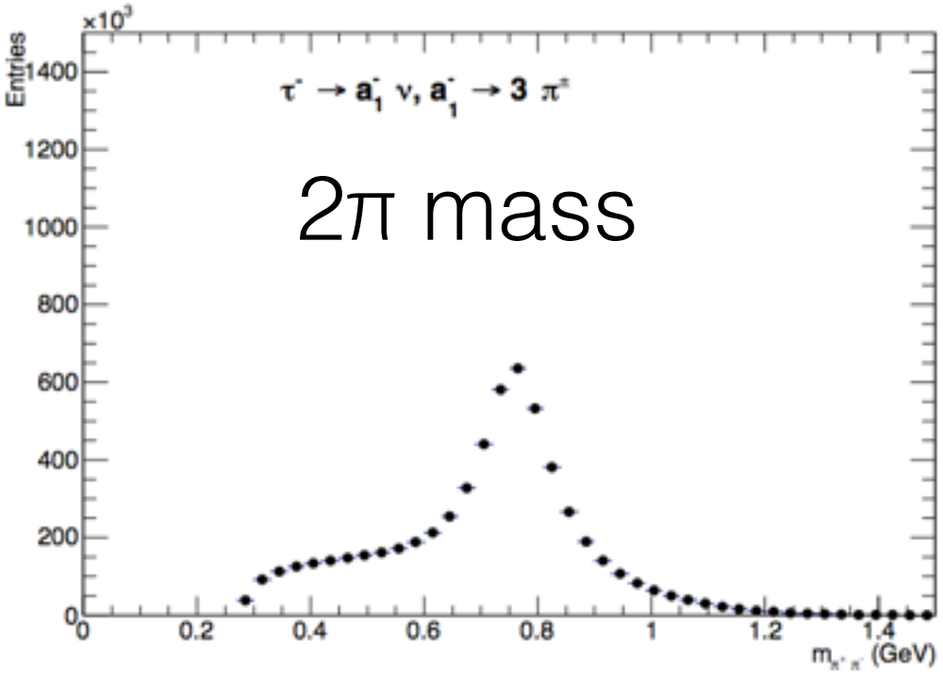
τ⟶ρν decay

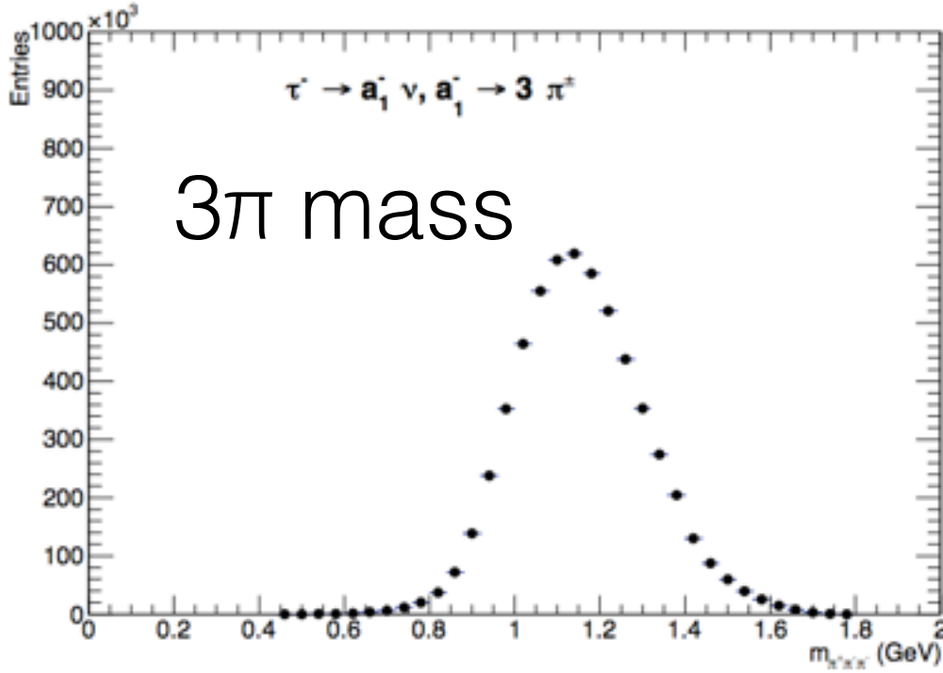
Unique possibility for ρ



τ⟶a_1(⟶ρπ)ν decay

Two interfering cascades ⟶ th. unc. for spin sensitivity





Matrix Element Weights

Create weights to apply to SM events with specific mixing
New event = SM event * weight

$$weight = \frac{|ME_{new}|^2}{|ME_{old}|^2}$$

$$|ME|^2 = R_{ij} h^i h^j$$

where h^i and h^j are for each tau decay

$$R_{ij} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos(\phi) & sin(\phi) & 0 \\ 0 & -sin(\phi) & cos(\phi) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

For spin 0 decay with scalar (phi=0) and pseudoscalar(phi=180) or even mixed state

References

- Potential for optimizing Higgs boson CP measurement in H to tau tau decay at LHC and ML techniques (R. Józefowicz, E. Richter-Was, Z. Was) Phys. Rev. D 94 (2016): arxiv:1608.02609 ← Cutting edge tools of Google used (and cross-checked)
- Probing the CP nature of the Higgs boson at linear colliders with τ spin correlations; the case of mixed scalar–pseudoscalar couplings (K. Desch, A. Imhof, Z. Was, M. Worek) Eur. Phys. J. C29 (2003): arxiv:0307331
- Measuring Higgs parity with τ⟶ρν decays (G. R. Bower, T. Pierzchala, Z. Was, M. Worek) Phys. Lett. B543 (2002) : arxiv:0204292

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- Reconstruction of hadronic decay products of tau leptons with the ATLAS experiment (ATLAS collaboration) Eur. Phys. J C 76(5) (2016): arxiv:1512.05955
- Tensorflow (low-level neural network training software): https://www.tensorflow.org/
- Keras (high-level interface for Tensorflow and Theano): https://keras.io/