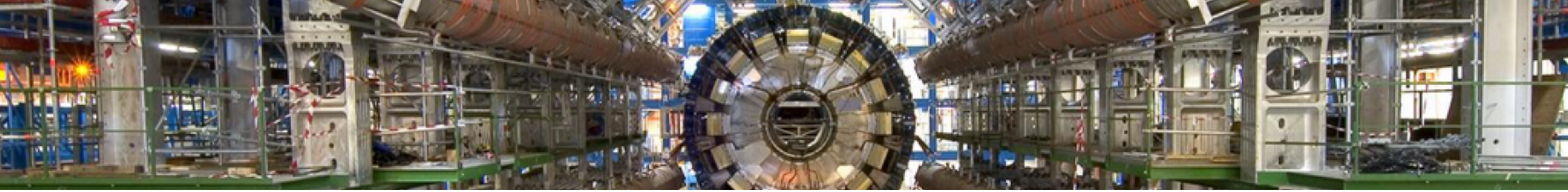


Deep learning approach to measurement of Higgs boson CP via $H \longrightarrow \tau\tau$ decays

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

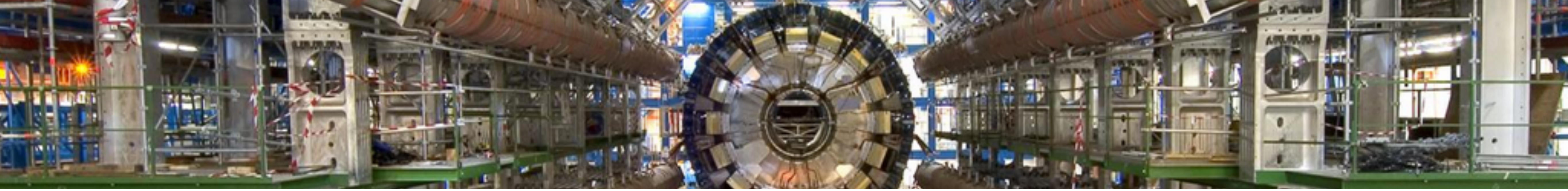
higgstools

Australian Government
Australian Research Council

THE UNIVERSITY OF MELBOURNE

ATLAS EXPERIMENT

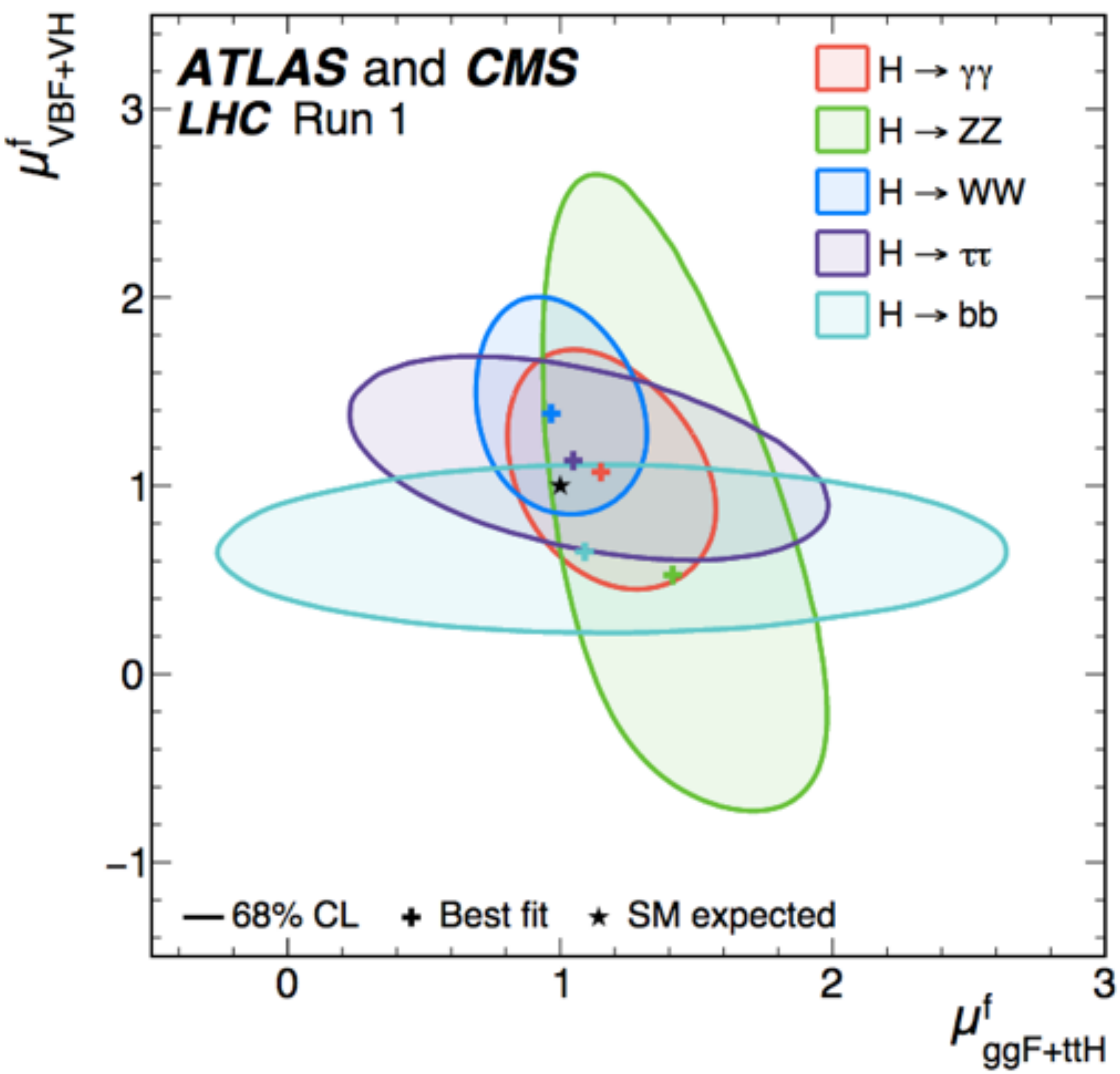
INSTYTUT FIZYKI JĄDROWEJ
IM. HENRYKA NIEWODNICZAŃSKIEGO
POLSKIEJ AKADEMII NAUK



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
$H \to \gamma\gamma$	$1.14^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$	5.0 (4.6)	5.6 (5.1)
$H \to ZZ$	$1.52^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$	7.6 (5.6)	7.0 (6.8)
$H \to WW$	$1.22^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$	6.8 (5.8)	4.8 (5.6)
$H \to \tau\tau$	$1.41^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$	4.4 (3.3)	3.4 (3.7)
$H \to bb$	$0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$	1.7 (2.7)	2.0 (2.5)
$H \to \mu\mu$	$-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$		
ttH production	$1.9^{+0.8}_{-0.7}$ $\left(^{+0.7}_{-0.7}\right)$	$2.9^{+1.0}_{-0.9}$ $\left(^{+0.9}_{-0.8}\right)$	2.7 (1.6)	3.6 (1.3)

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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

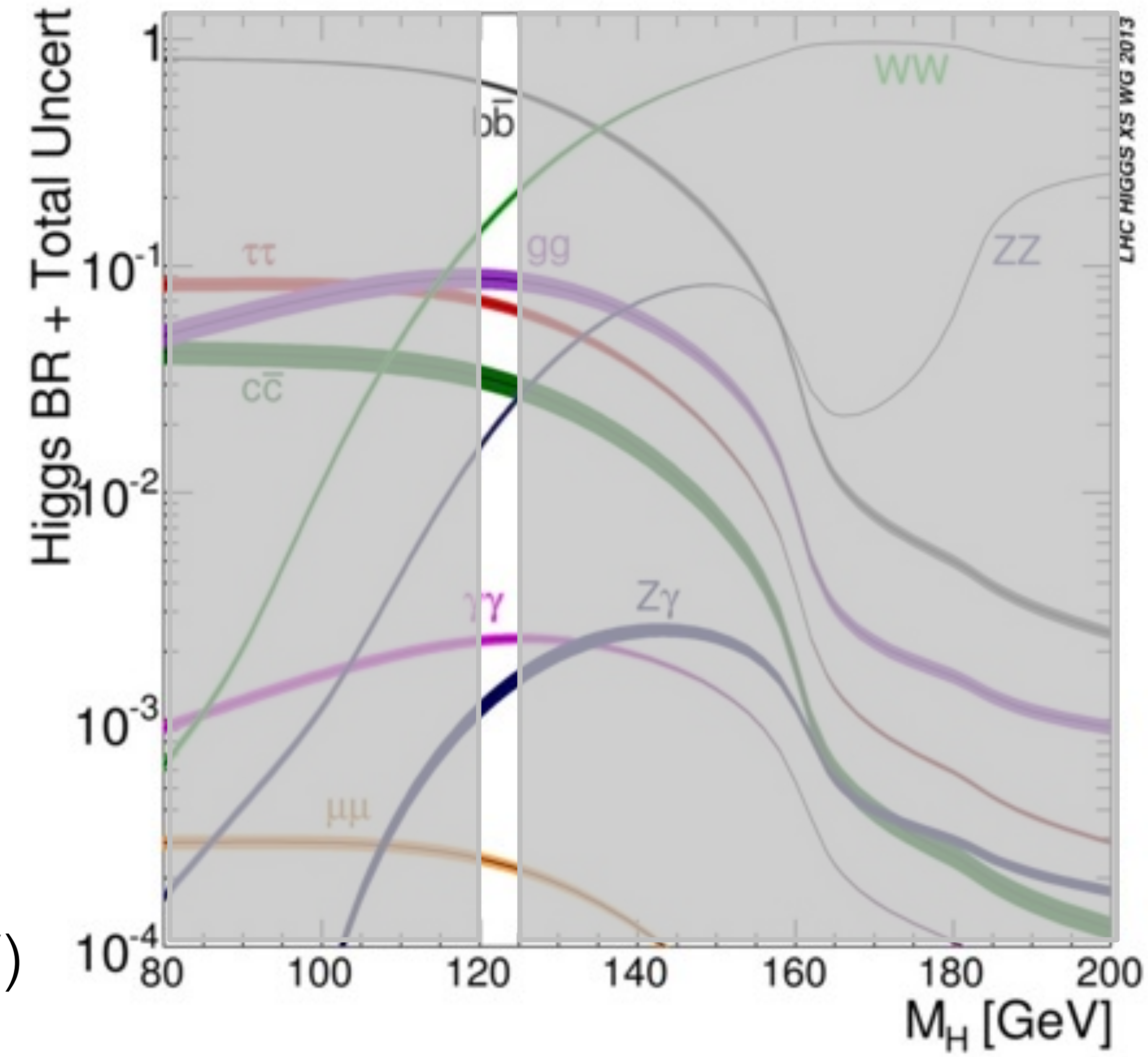
H⟶bb and **H⟶cc** are difficult measurements due to large backgrounds (Hbb has > 3.5σ [1708.03299](1708.03299))

H⟶ττ is a prime candidate for studying Yukawa couplings

- Large branching ratio
- Unique detector signature

Currently have evidence at 4.4σ with ATLAS (at 8 TeV) with > 5σ in combination with CMS

CMS claim discovery (8 TeV + 13 TeV).

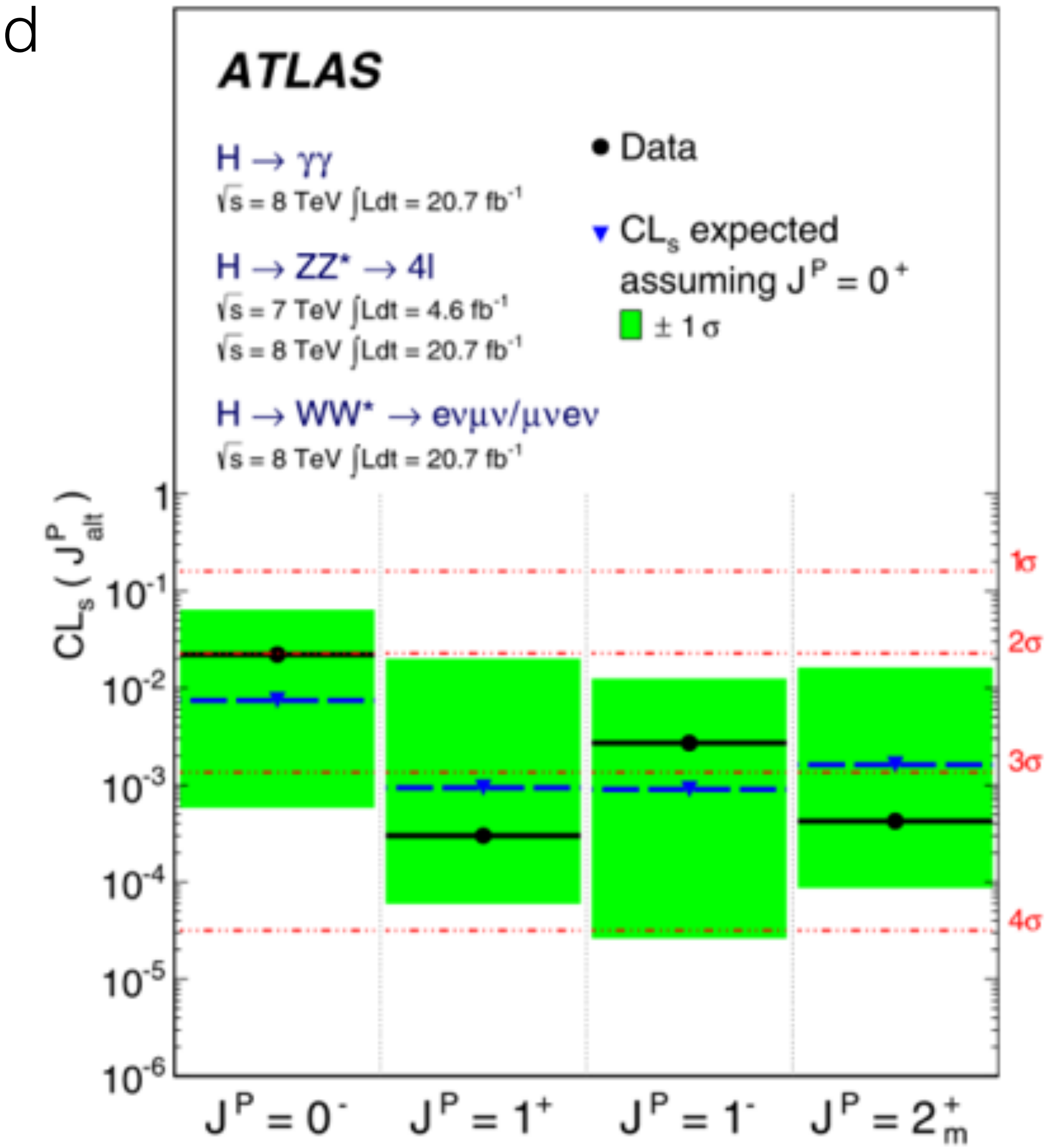


Coupling and Spin-CP

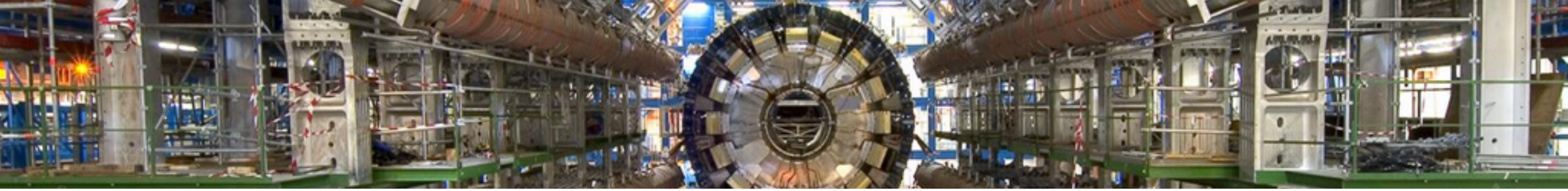
H⟶VV channels have claimed discovery and made measurements of coupling and CP properties

H⟶ττ is the first to measure the fermion coupling and will be first to measure 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 as accessible)
  - **H⟶ττ decay** allows measurement of **CP mixing**



arXiv:1307.1432

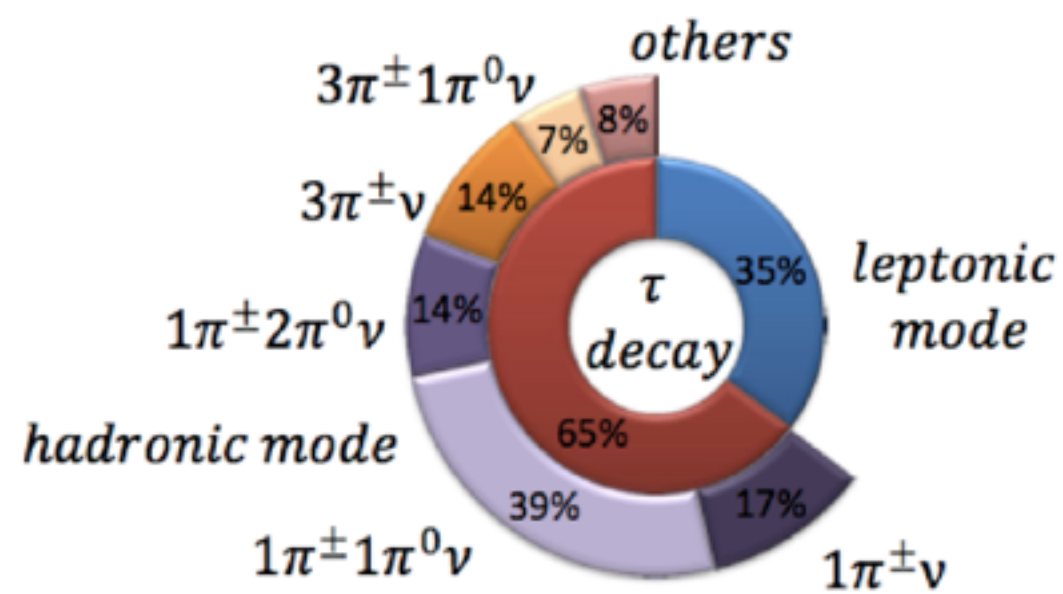


Part 1:

Tau Reconstruction

Tau Decays

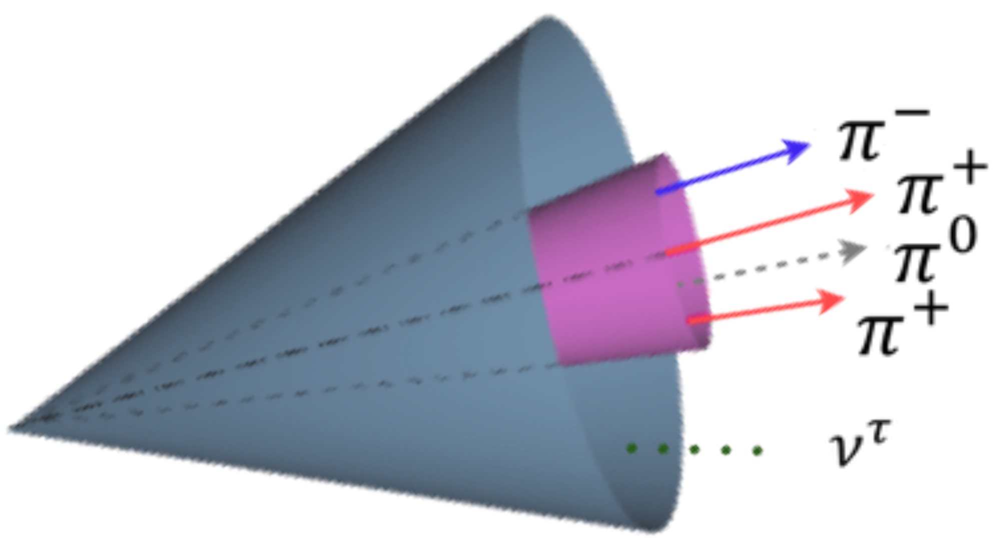
Tau leptons are not reconstructed directly by ATLAS, only the decay products (lepton or hadrons) are detected



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 (denoted with a p and n eg. 1p0n)



Reconstructed from jet candidates via anti-kT algorithm

Identification via BDT focussed on distinguishing vs QCD jets

Tau Reconstruction

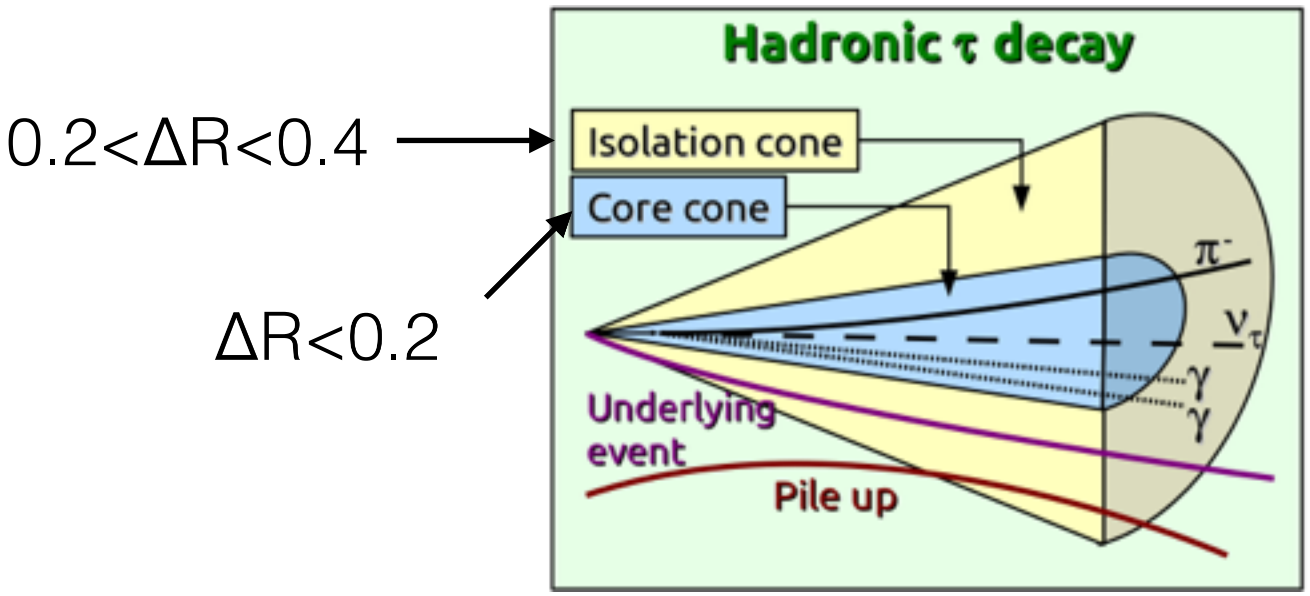
One key development for Run II is to allow for the tau substructure to be reconstructed.

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

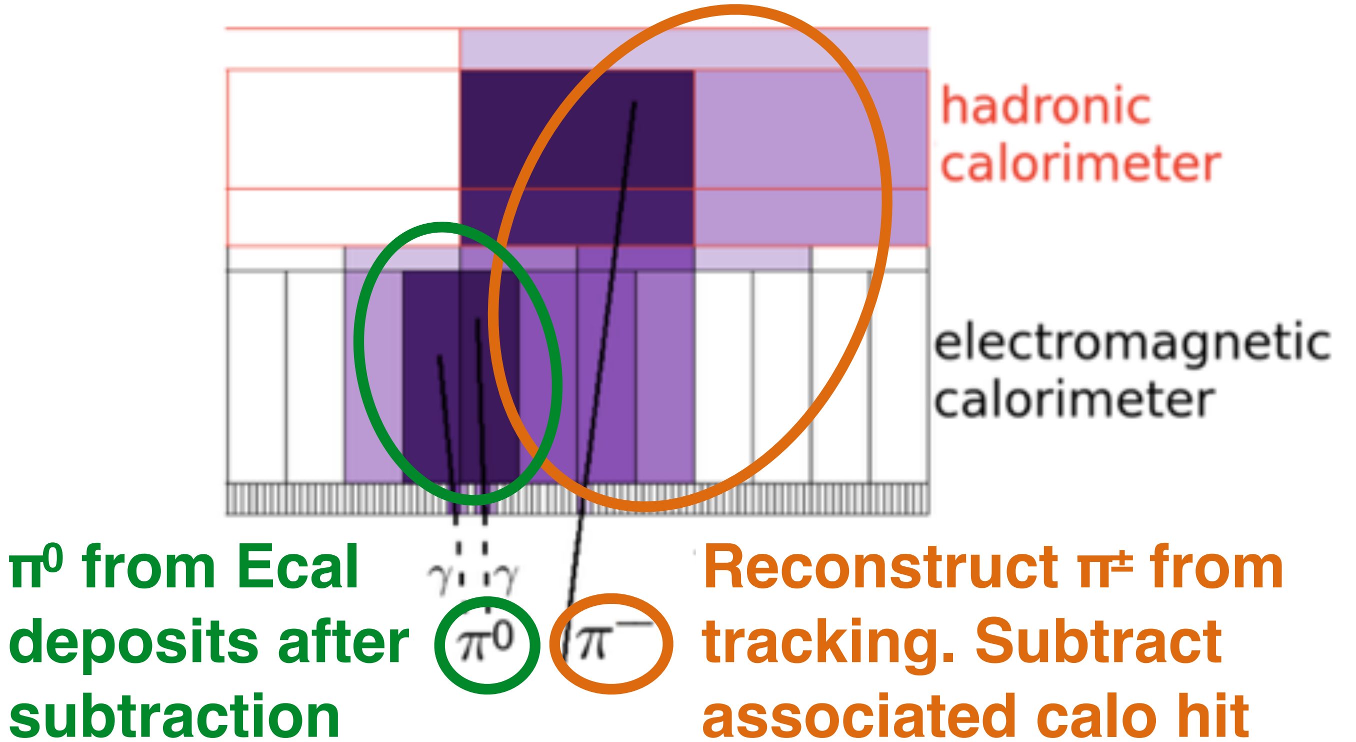
1. Charged hadrons reconstructed using track information
2. Calo deposits associated to the charged track are removed from the candidate
3. Neutrals pions are identified from the remaining calo deposits

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

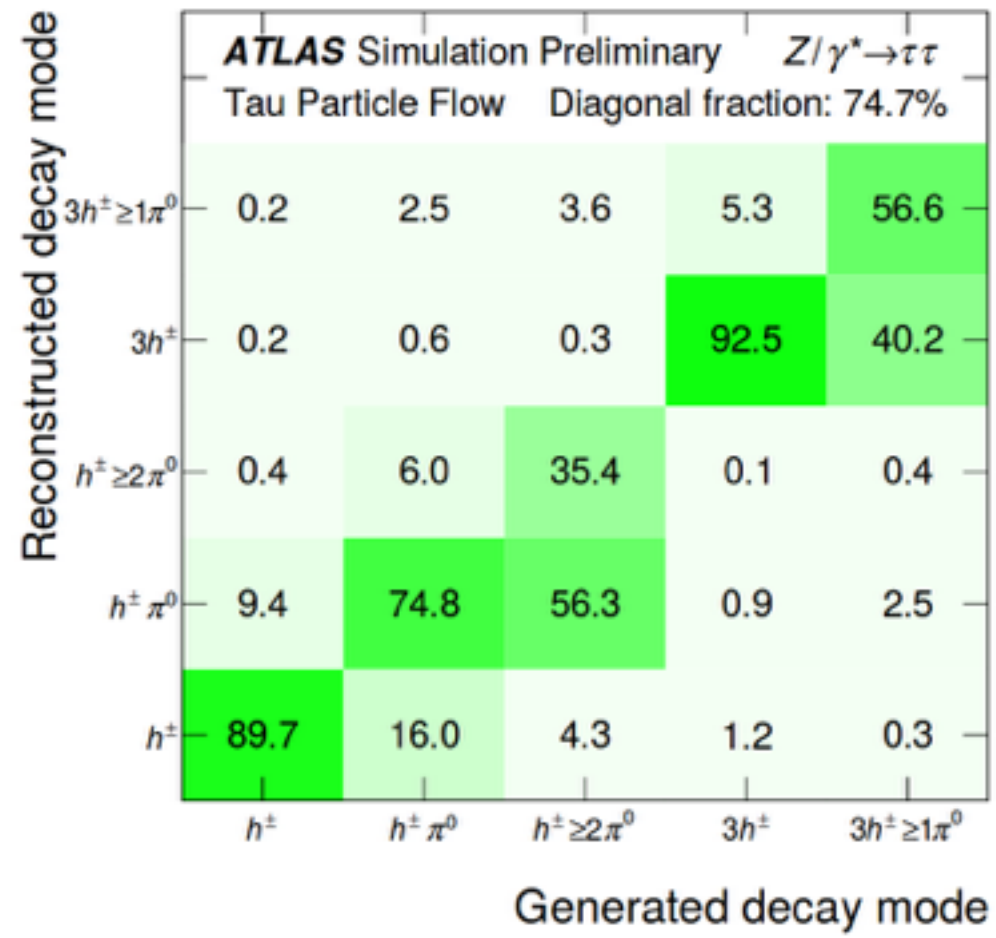
Result of new reconstruction allows for a substructure based 4-vector reconstruction, which with a better resolution. Intermediate masses can now be reconstructed.

Three BDTs are formed to separate decay modes:

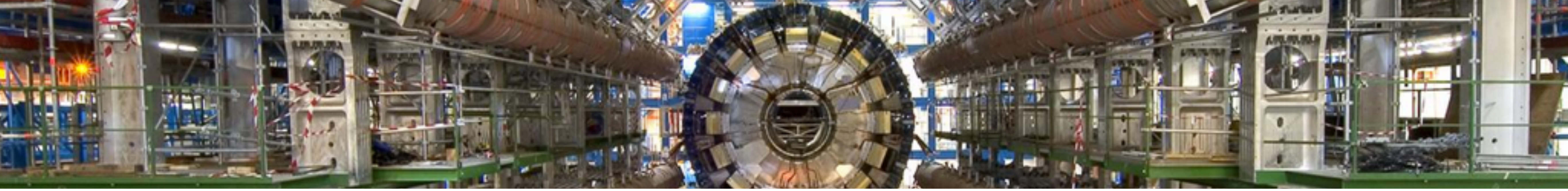
- 1p0n from 1p1n
- 1p1n from 1pXn (so far the most difficult)
- 3p0n from 3pXn

A five way classification is defined.

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



Eur. Phys. J C 76(5), 1-26



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.

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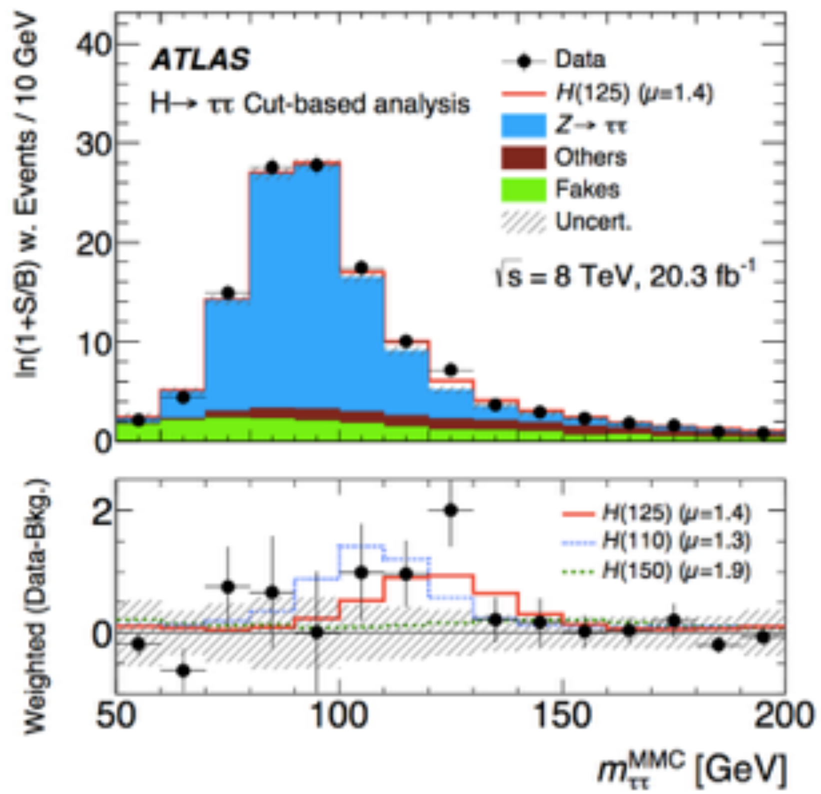
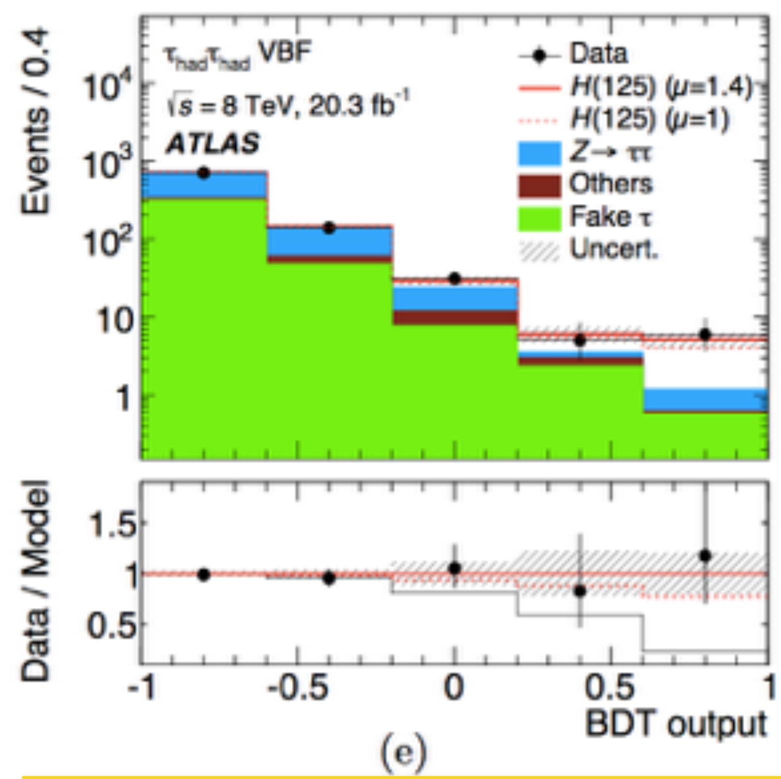
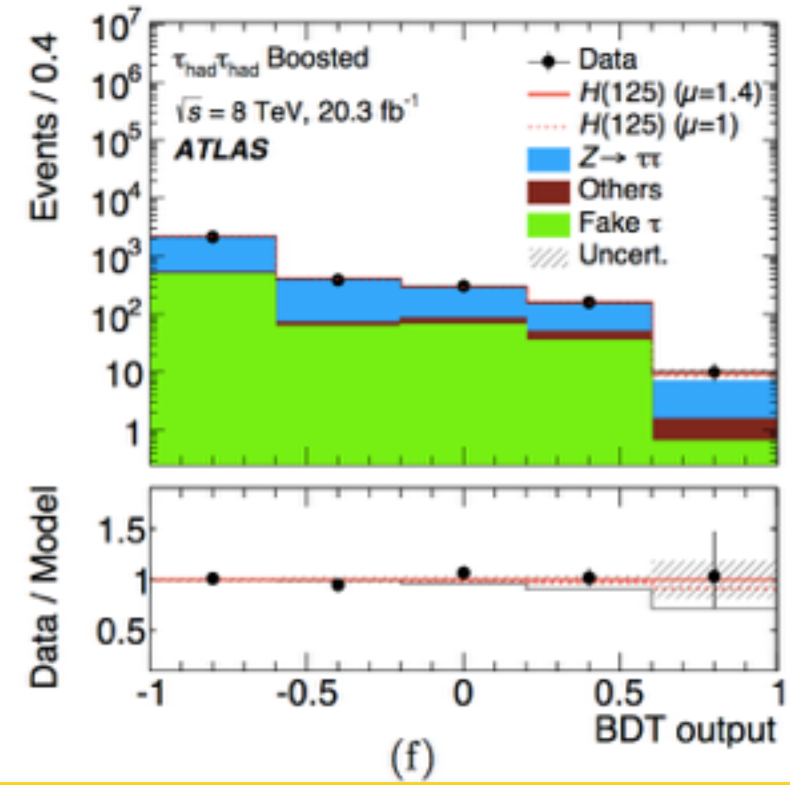






H⟶ττ process couple directly through Yukawa interaction, which allows for measurement of possible mixed CP states

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

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

where R is a rotation in the x-y plane

CP sensitive observable

CP of Higgs boson is **encoded in the tau-tau spin correlations**

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

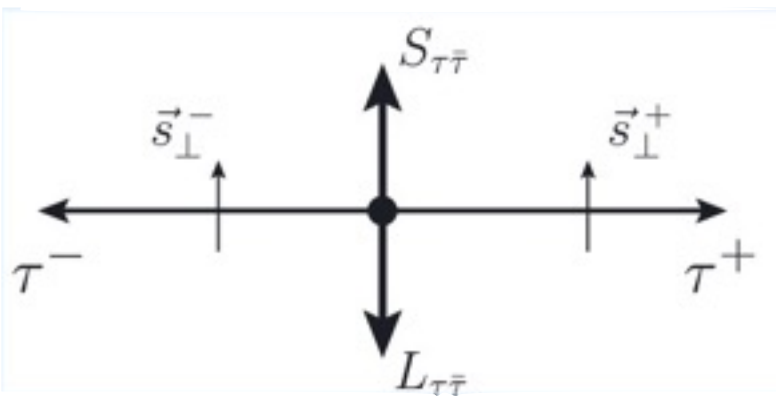
$$h^0$$

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

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

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

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



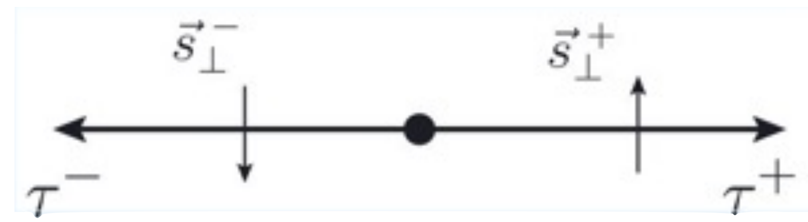
$$A^0$$

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

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h^0

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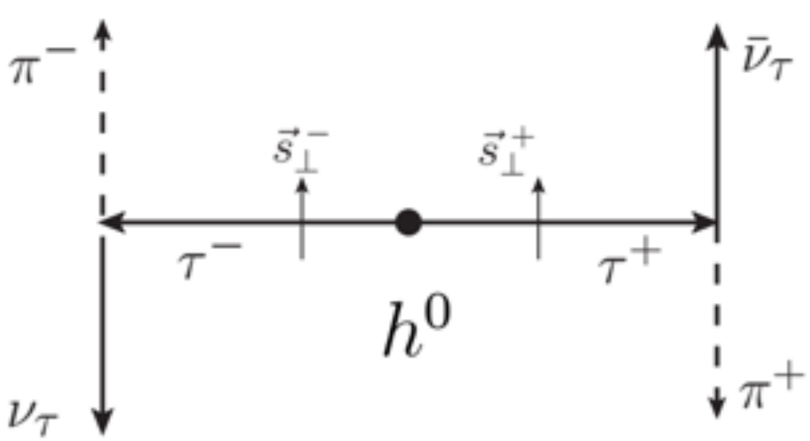
$$L_{\tau\bar{\tau}} = 1,\ S_{\tau\bar{\tau}} = 1$$



A^0

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

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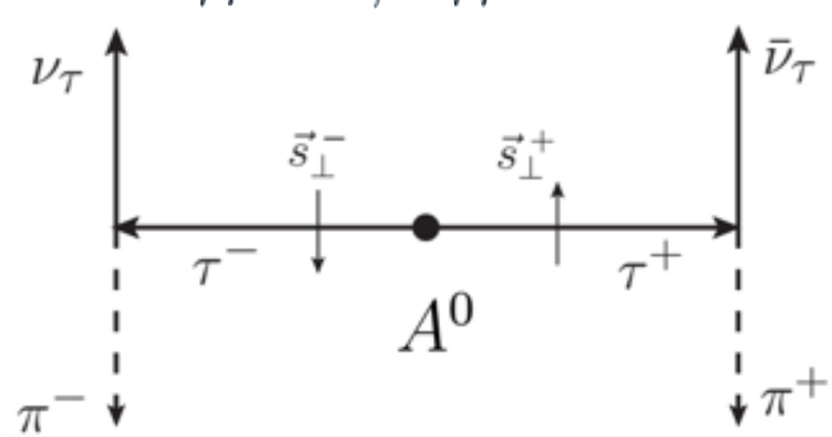


Tau Branching Ratios

category	decay mode	$\mathcal{B}$ [%]	nomenclature
hadronic 1-prong	$\tau^- \to \pi^- \nu_\tau$	**10.8**	1p0n
	$\tau^- \to K^- \nu_\tau$	0.7	1p0n
	$\tau^- \to \rho^-(\to \pi^-\pi^0)\nu_\tau$	**25.5**	1p1n
	$\tau^- \to K^{-\star}(\to K^-\pi^0)\nu_\tau$	0.4	1p1n
	$\tau^- \to a_1^-(\to \pi^-\pi^0\pi^0)\nu_\tau$	**9.3**	1pXn
	$\tau^- \to K^-\pi^0\pi^0\nu_\tau$	0.1	1pXn
	$\tau^- \to \pi^-\pi^0\pi^0\pi^0\nu_\tau$	1.1	1pXn
	$\tau^- \to hK^0_S \geq 0$ 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
	$\tau^- \to hhhK^0\nu_\tau$	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)

Our focus

Also used

Maybe Useful

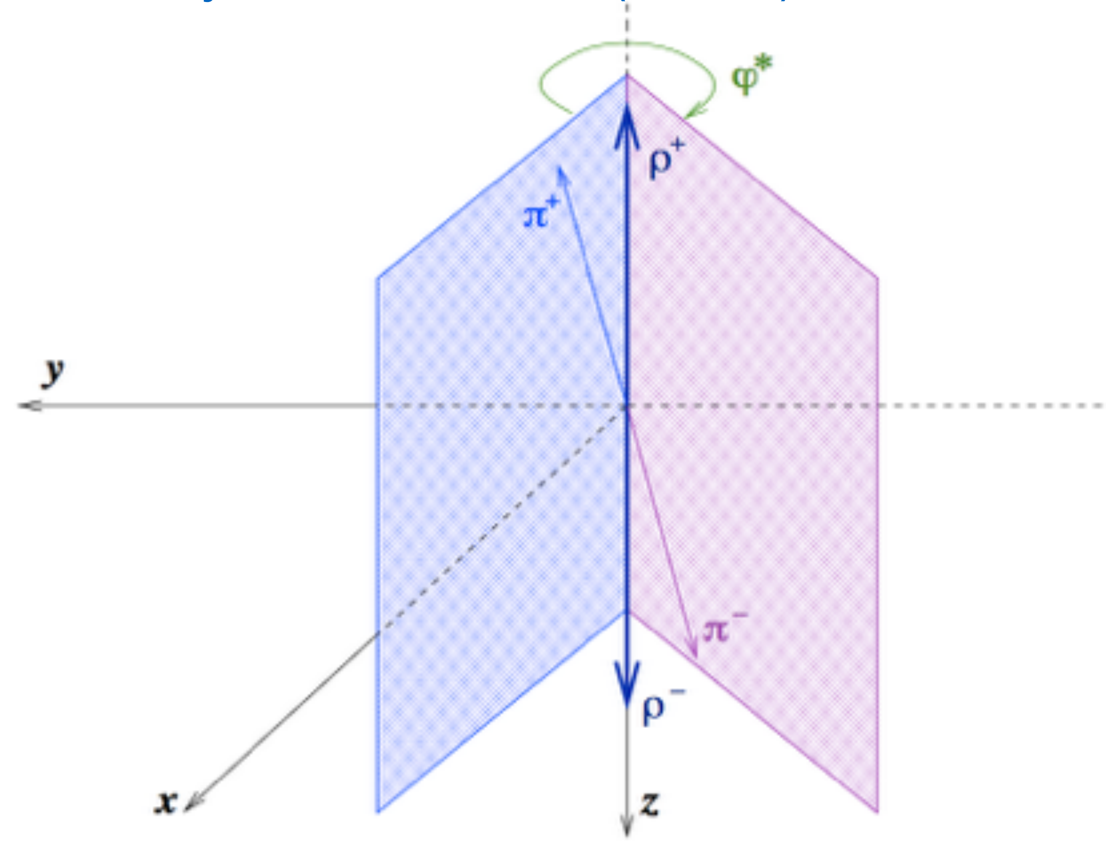
From 6% to 12% of $H\to\tau\tau$

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 $H \longrightarrow \tau\tau$ decays) as there is only one set of planes which can be defined.

Phys.Lett. B579 (2004) 157-164



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)

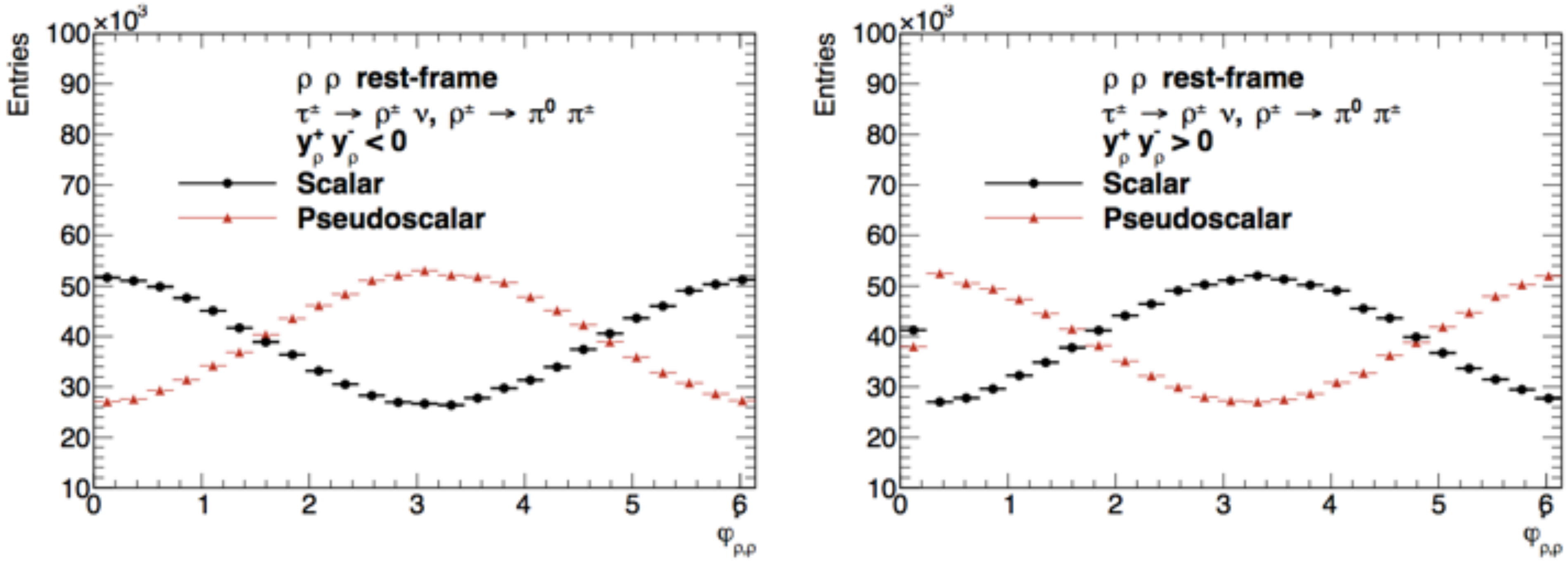
$$\tau^{\pm} \longrightarrow \rho^{\pm}\,\nu \longrightarrow \pi^0\pi^{\pm}\,\nu$$

$$\begin{aligned} \tau^{\pm} &\longrightarrow a_1\ \nu \\ &\longrightarrow \rho\ \ \pi^{\pm}\,\nu \\ &\longrightarrow \pi^{\pm}\pi^{\mp}\pi^{\pm}\,\nu \end{aligned}$$

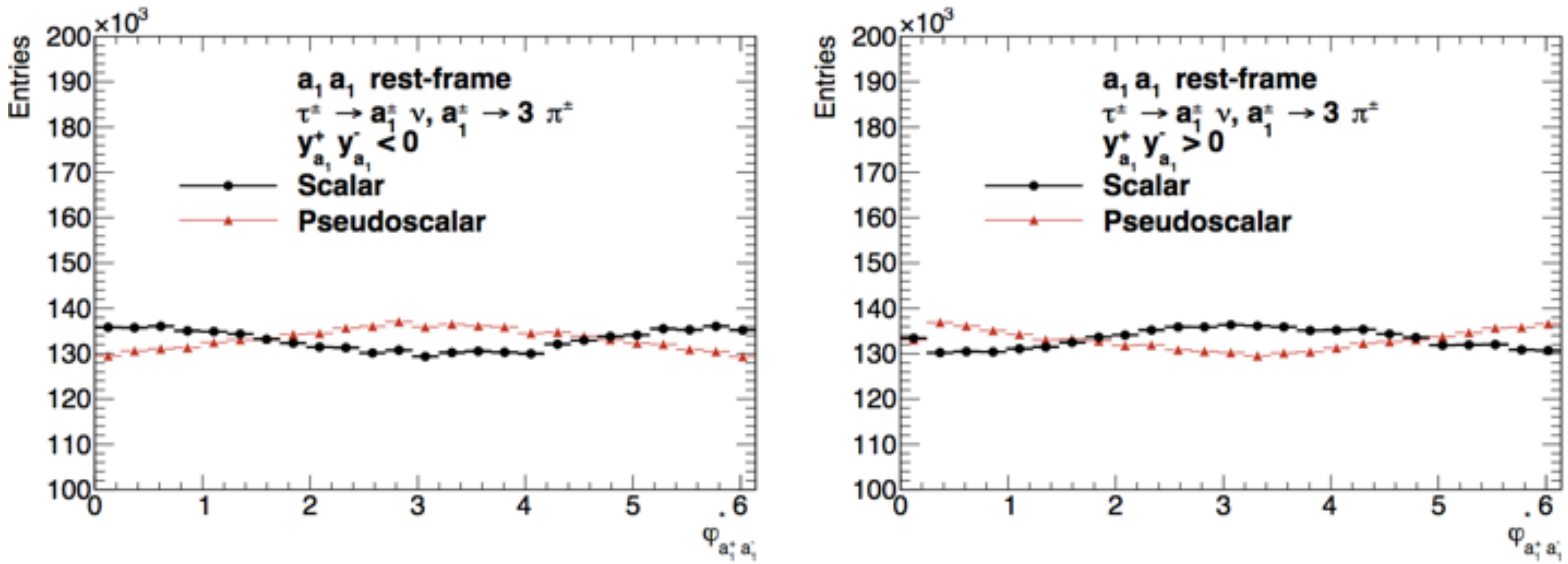
New: Substitute the neutral π in the above method with the neutral ρ, it further decays into $\pi^{\pm}\pi^{\mp}$ so another plane can be defined.

ρ-ρ vs a_1-a_1

(for a_1 small amplitude but many distributions)



[Phys. Rev. D 94, 093001 (2016)]



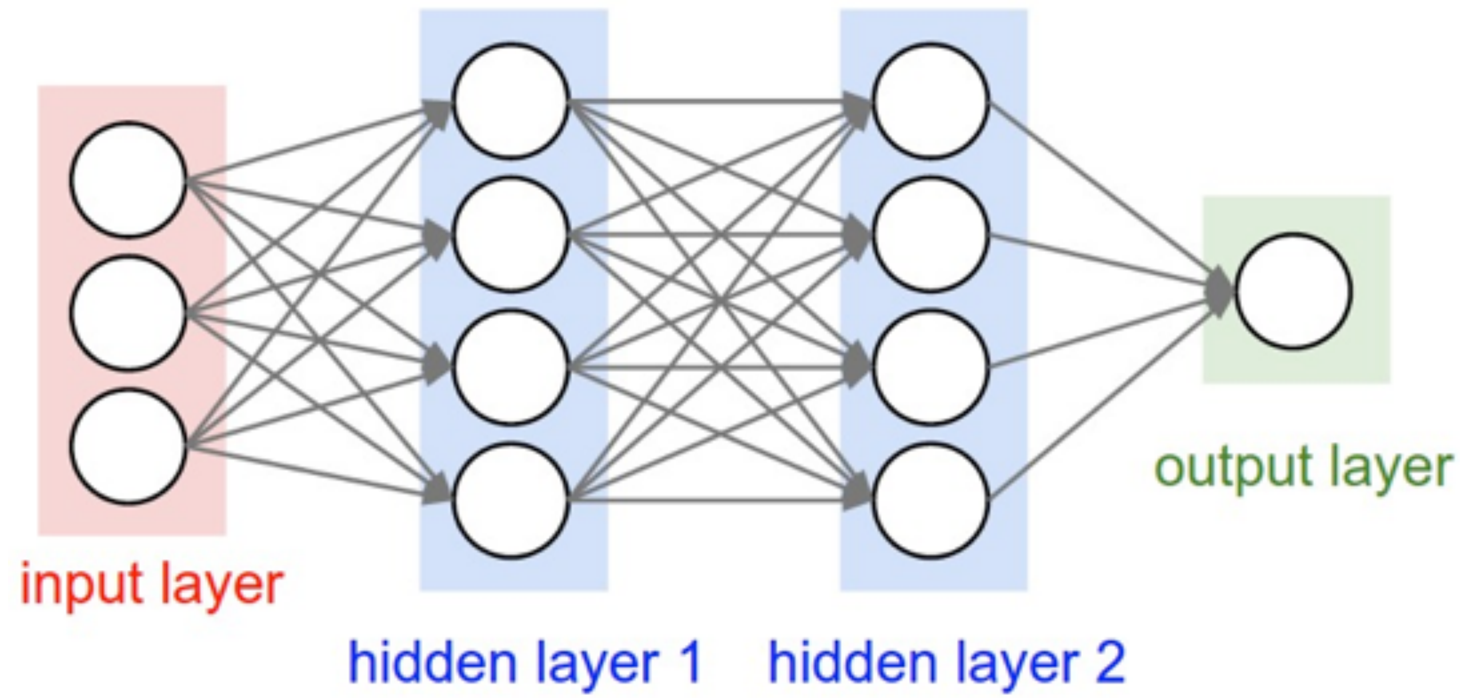
Note: Acoplanarity alone brings no CP sensitivity. One must use y variables which are ρ rest frame cosines of π^0 directions. We have to use this property of τ decay matrix element. Events are classified based on the sign of the product.

16 pairs of similar plots

Deep Learning NN

R. Józefowicz (Google (NY), now at Open AI (SFO)) E. Richter-Was and Z. Was developed neural network model with Tensorflow (Google project for various non-HEP applications). **Phys. Rev. D 94, 093001 (2016)**

NN approach found promising separation utilising the between scalar and pseudoscalar hypotheses.



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

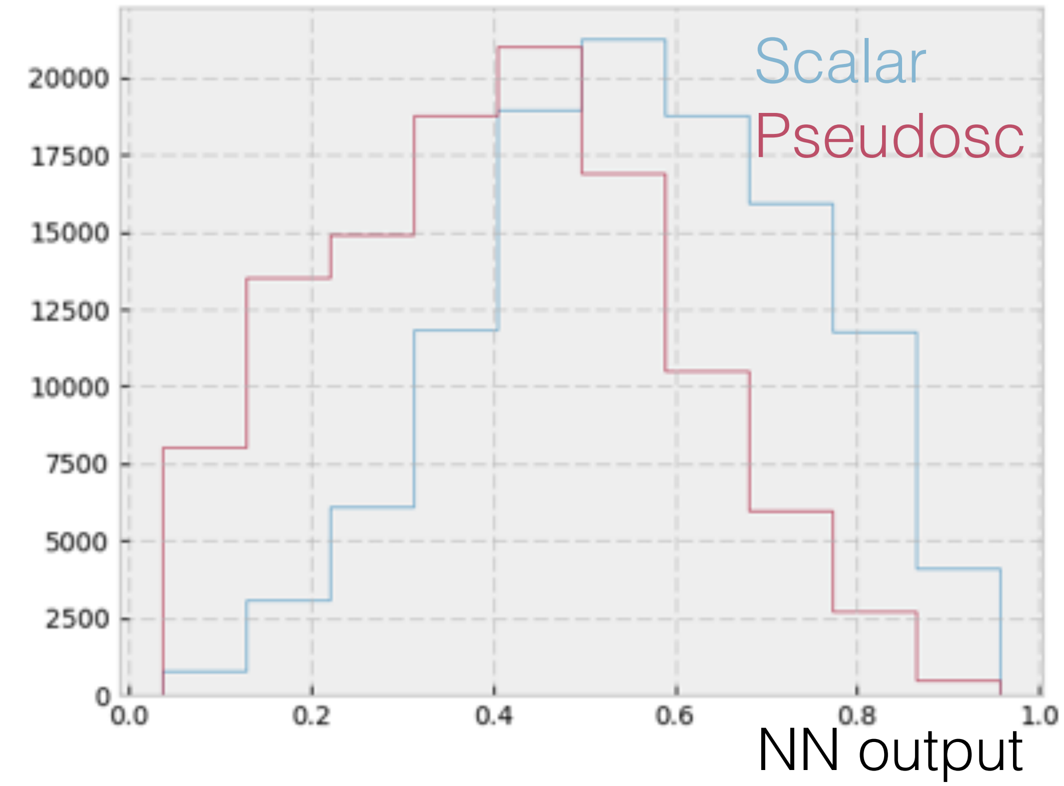
Three neural networks are trained (one for the decay modes of ρρ, ρa_1 and $a_1 a_1$) to separate the scalar and pseudoscalar hypotheses.

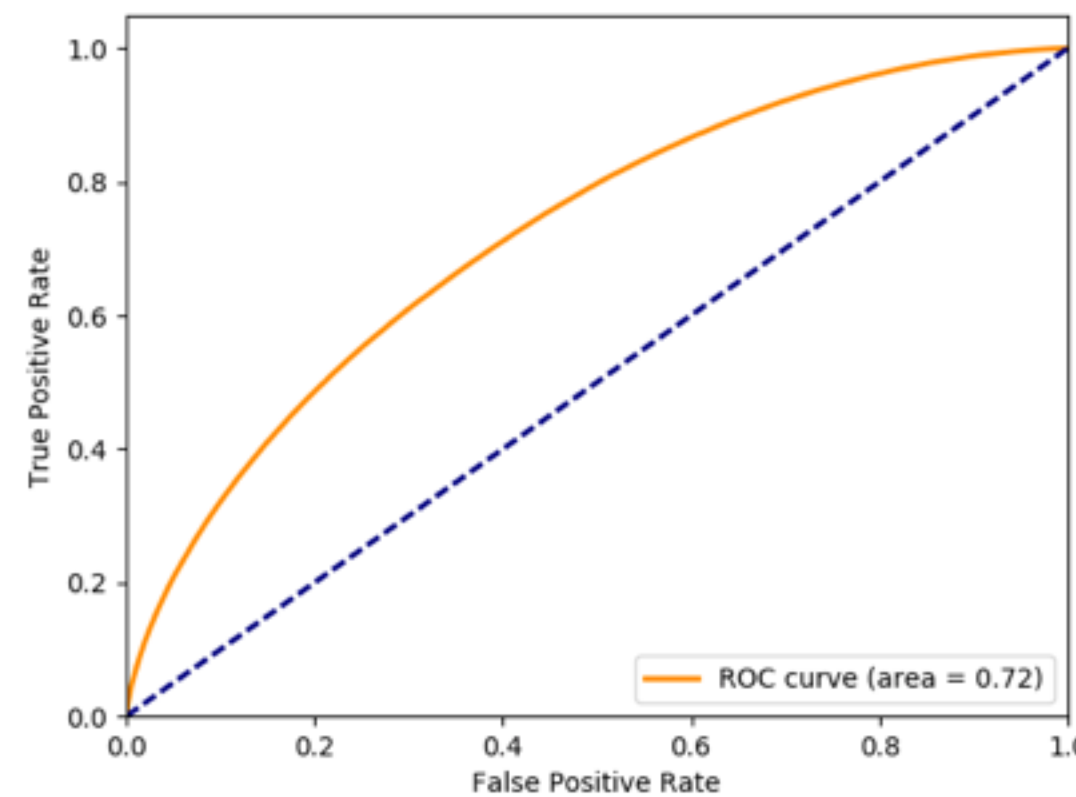
NN Input/Output

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, 4-vectors, mass, missing energy) are tested to best separate scalar and pseudoscalar events. 4-vectors are boosted into rest frame of visible products and rotated so one tau aligns along z axis.

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.





First results:

Area under ROC curve - A measure of separation

Features/variables [Phys. Rev. D 94, 093001 (2016)](https://doi.org/10.1103/PhysRevD.94.093001)	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

Limit of neural network approach of 0.782 (input all information including matrix elements) is same across three decay modes. Never reaches 1.0 due to overlap in distributions.

Results show a fair amount of separation, still fairly **weak for a_1-a_1 decay mode** though. No use of neutrino information 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.

This was the extent of the study, my work expanded on this (**arxiv:1706.07983**)

Artificial Neural Networks have spurred remarkable recent progress in image classification and speech recognition. But even though these are very useful tools based on well-known mathematical methods, **we actually understand surprisingly little of why certain models work and others don't**.
https://research.googleblog.com/2015/06/inceptionism-going-deeper-into-neural.html

Results depend on model assumptions. Models inspired with results. Fitting setup ⟶ biases. Our algorithms are far less elaborate than human eye/ brain. Problems known since times of Giuseppe Arcimboldo (1572 - 1593) at least.

NN brings no improvement for this…

Detector Response

Features				Exact ± (stat)	Smeared ± (stat) ± (syst)	[Phys. Rev. D 94, 093001 (2016)]
ϕ^*	4-vec	y_i	m_i			
				$a_1 - \rho$ Decays		
✓	✓	✓	✓	0.6035 ± 0.0005	$0.5923 \pm 0.0005 \pm 0.0002$	0.596
✓	✓	✓	-	0.5965 ± 0.0005	$0.5889 \pm 0.0005 \pm 0.0002$	-
✓	✓	-	✓	0.6037 ± 0.0005	$0.5933 \pm 0.0005 \pm 0.0003$	-
-	✓	-	-	0.5971 ± 0.0005	$0.5892 \pm 0.0005 \pm 0.0002$	0.590
✓	✓	-	-	0.5971 ± 0.0005	$0.5893 \pm 0.0005 \pm 0.0002$	0.594
✓	-	✓	✓	0.5927 ± 0.0005	$0.5847 \pm 0.0005 \pm 0.0002$	0.578
✓	-	✓	-	0.5819 ± 0.0005	$0.5746 \pm 0.0005 \pm 0.0002$	0.569
				$a_1 - a_1$ Decays		
✓	✓	✓	✓	0.5669 ± 0.0004	$0.5657 \pm 0.0004 \pm 0.0001$	0.573
✓	✓	✓	-	0.5596 ± 0.0004	$0.5599 \pm 0.0004 \pm 0.0001$	-
✓	✓	-	✓	0.5677 ± 0.0004	$0.5661 \pm 0.0004 \pm 0.0001$	-
-	✓	-	-	0.5654 ± 0.0004	$0.5641 \pm 0.0004 \pm 0.0001$	0.553
✓	✓	-	-	0.5623 ± 0.0004	$0.5615 \pm 0.0004 \pm 0.0001$	0.573
✓	-	✓	✓	0.5469 ± 0.0004	$0.5466 \pm 0.0004 \pm 0.0001$	0.548
✓	-	✓	-	0.5369 ± 0.0004	$0.5374 \pm 0.0004 \pm 0.0001$	0.536

From first results, networks were re-optimised and re-implemented with Keras (increased #epochs).

Detector effects included through simple Gaussian smearing of outgoing pion momenta.

Trained on smeared and unsmeared MC to test impact of detector response. No substantial loss.

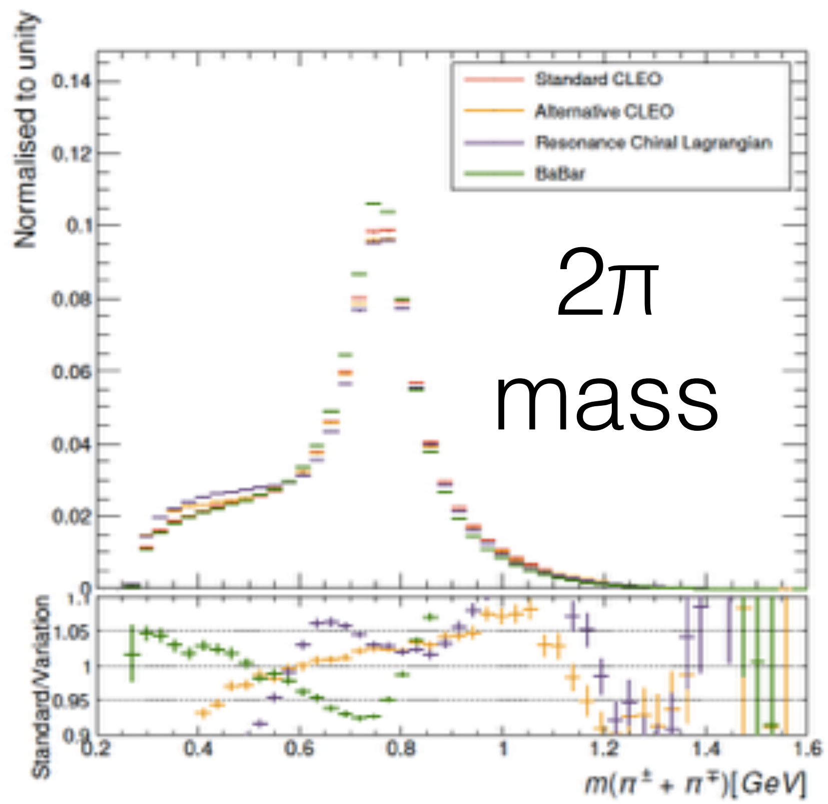
Theoretical Systematics

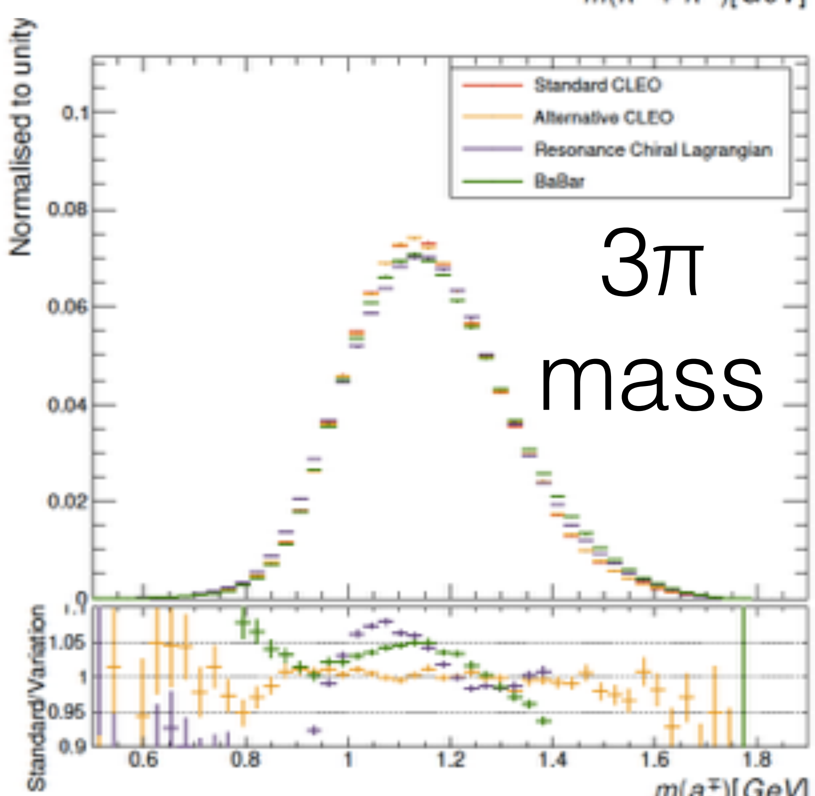
Modelling of tau decays dependent on parameterisation of vector currents. Variations are evaluated as systematics.

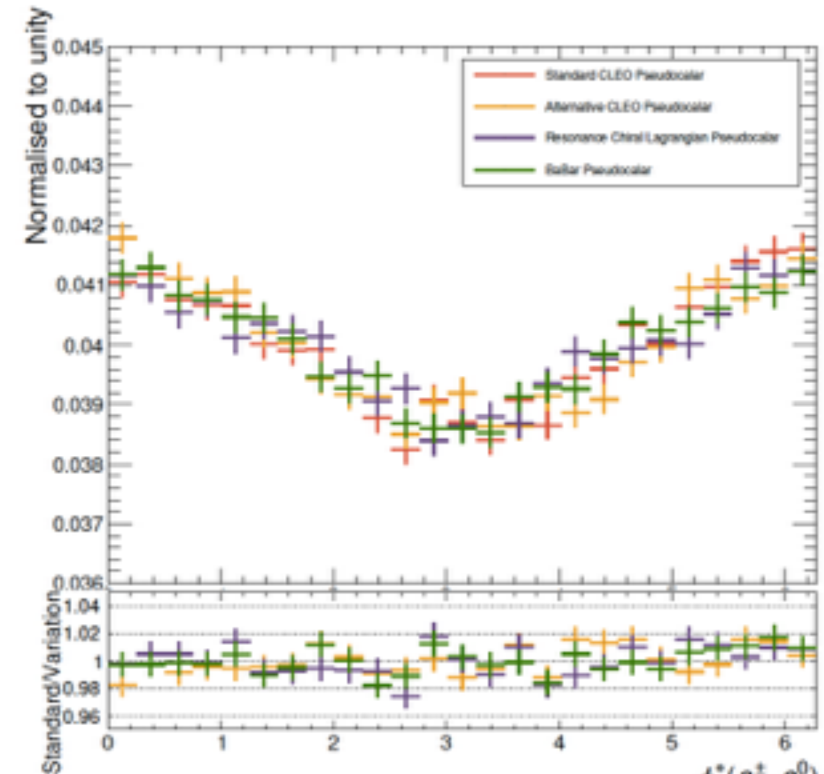
Available parameterisations:

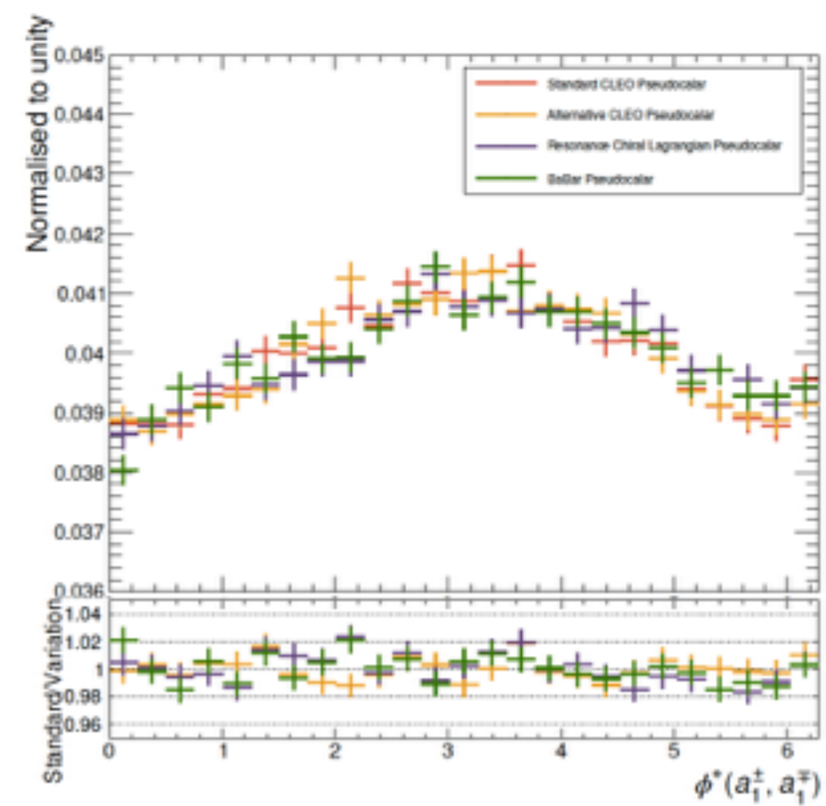
- CLEO - Standard in Tauola
- Resonance Chiral Lagrangian
- Alternative CLEO current (never fully published by collaboration)
- BaBar (also not published)

There are good reasons for the collaboration's hesitation.









Theoretical Systematics

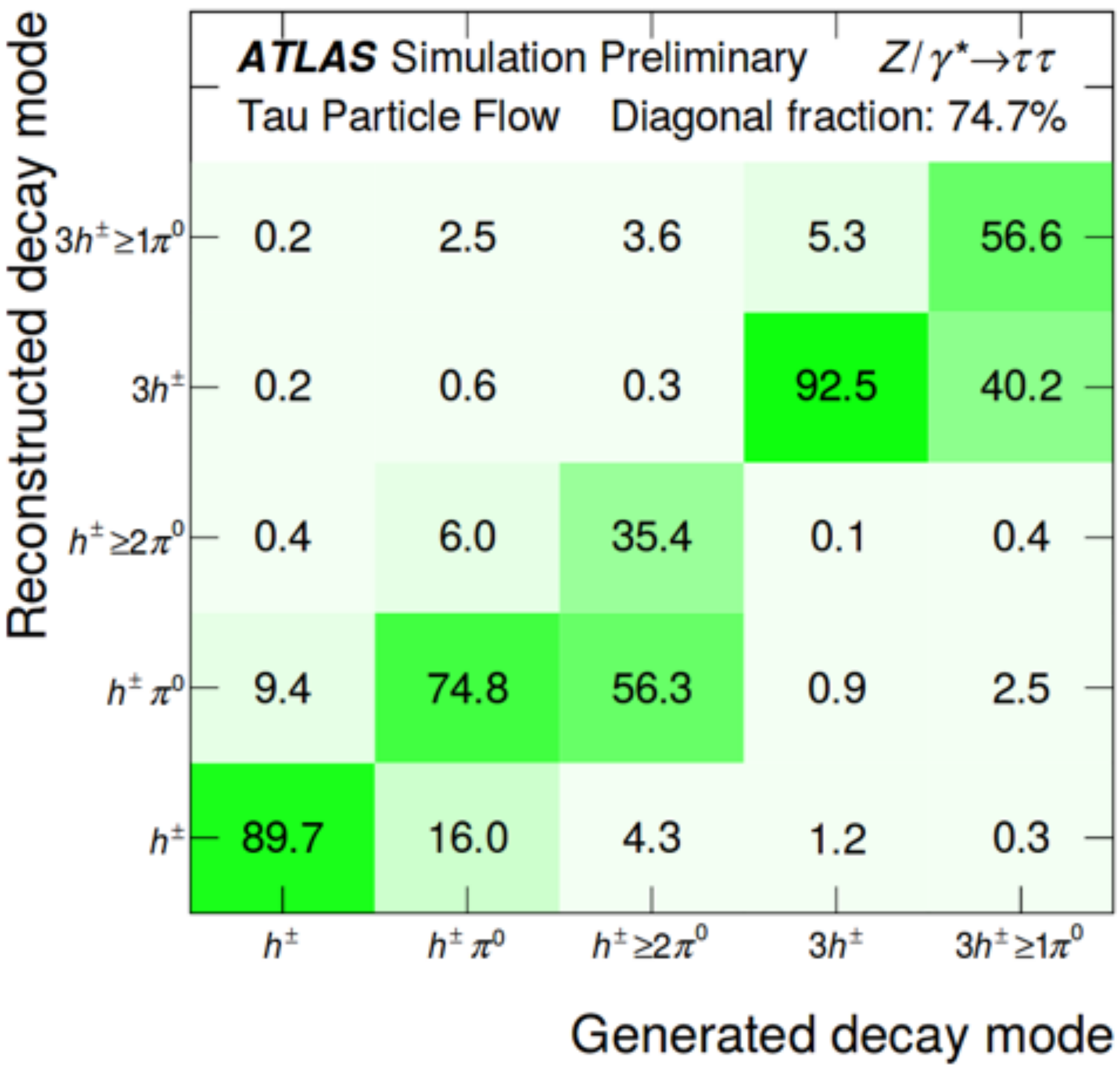
Features				STD	RχL	ALT	BBR
ϕ^*	4-vec	y_i	m_i				
$a_1 - \rho$ Decays							
✓	✓	✓	✓	0.604	0.604	0.603	0.603
✓	✓	✓	-	0.597	0.596	0.596	0.597
✓	✓	-	✓	0.604	0.604	0.604	0.604
-	✓	-	-	0.597	0.596	0.596	0.595
✓	✓	-	-	0.597	0.596	0.596	0.595
✓	-	✓	✓	0.593	0.593	0.593	0.593
✓	-	✓	-	0.582	0.579	0.580	0.578
$a_1 - a_1$ Decays							
✓	✓	✓	✓	0.567	0.563	0.564	0.564
✓	✓	✓	-	0.560	0.555	0.557	0.556
✓	✓	-	✓	0.568	0.564	0.566	0.566
-	✓	-	-	0.562	0.557	0.559	0.559
✓	✓	-	-	0.562	0.557	0.559	0.559
✓	-	✓	✓	0.547	0.546	0.547	0.545
✓	-	✓	-	0.537	0.534	0.535	0.533

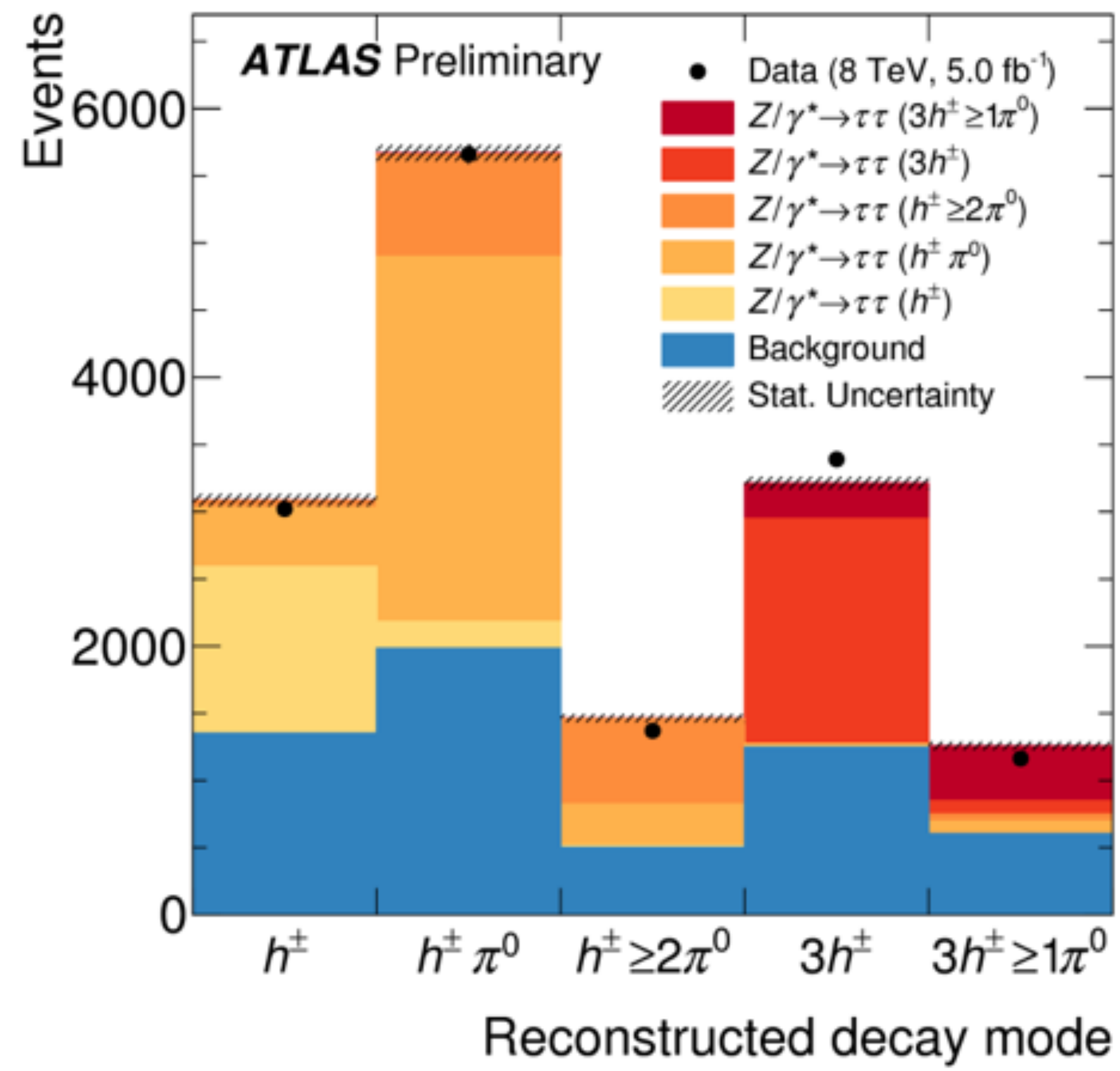
Variations not significant. Differences are within two standard deviations of the uncertainty due to smearing.

Substructure Reconstruction

Contamination between channels

[Eur. Phys. J C 76(5), 1-26]





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

Summary

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.

Paper ([**arxiv:1706.07983**]) is on arxiv and was recently (this week) accepted for publication in Physical Review D.

Potential future developments includes:

1. Inclusion of better discriminating variables - e.g. impact parameter
2. Inclusion of more decay modes - a_1 decaying to $\pi^{\pm}\pi^0\pi^0$
3. Investigation of effect of backgrounds
   - Is a 2D fit with second NN viable?
4. Investigation into how to practically utilise the NN
   - Implement fit and compare to standard approach

Brief Aside

Our Google ML expert R. Józefowicz tells that experience with NN in different context gives hints on how to improve algorithms.

In our example it was existence of longitudinal and transverse degrees of freedom which were mixed. Good example to develop ML. Not as good as DotA 2…

Elon Musk's 'Dota 2' Experiment is Disrupting Esports in a Big Way - No Playing Field

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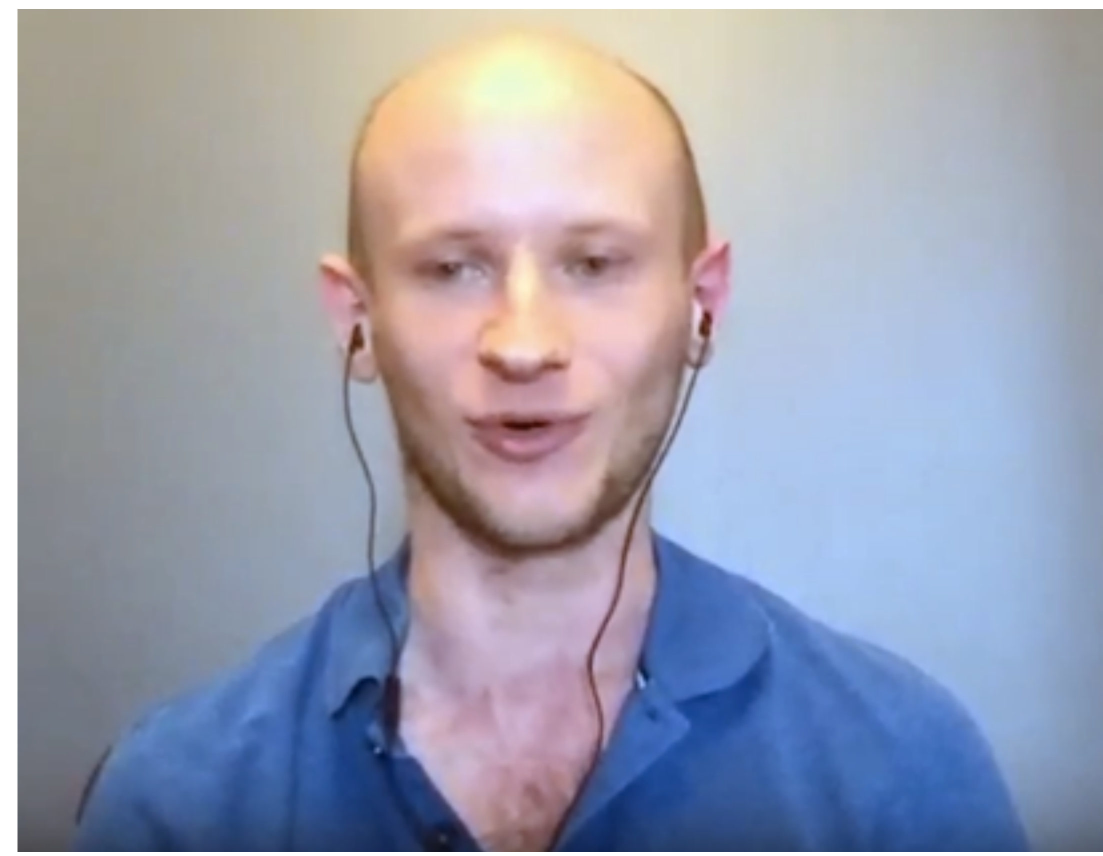
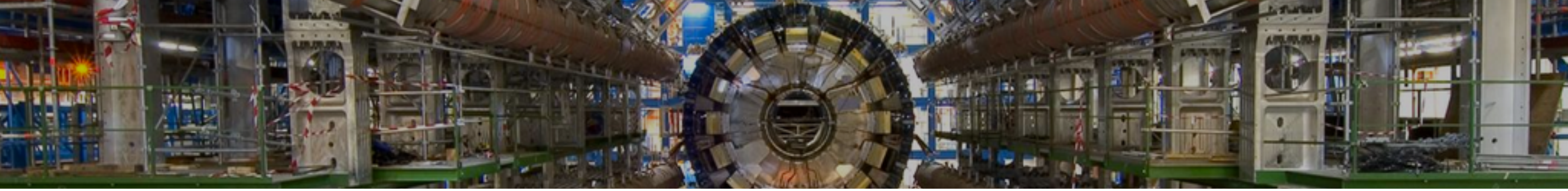




Backup

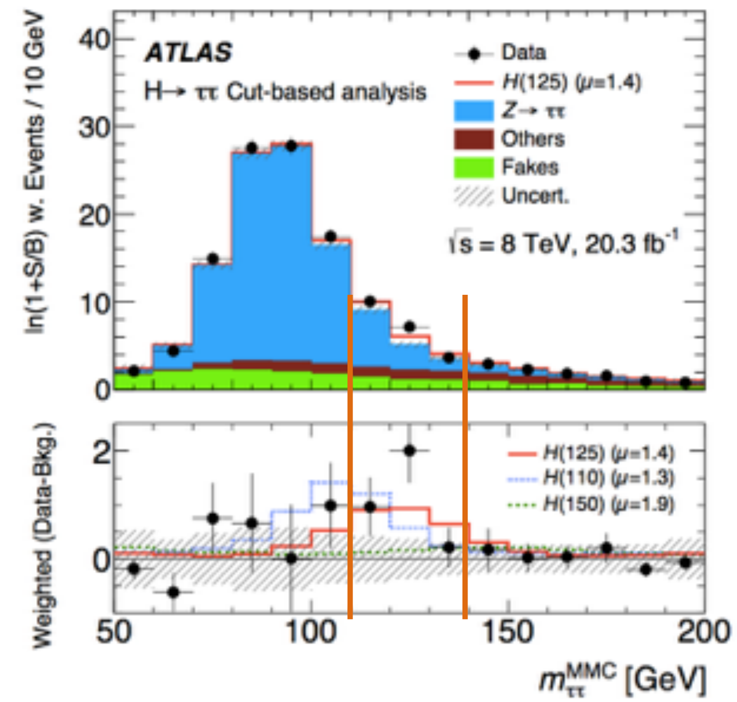
Z Background

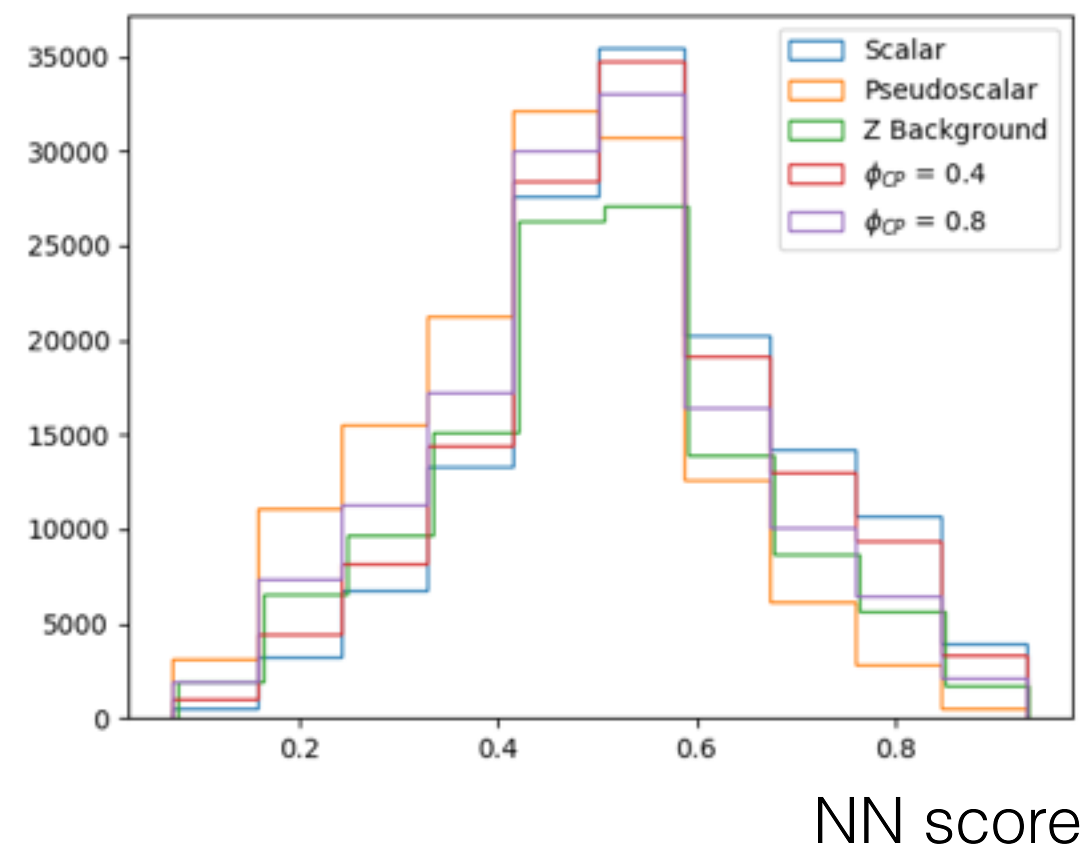
Largest background is from irreducible $Z \longrightarrow \tau\tau$ events. Ideally separation would based on mass but resolution of mass reconstruction (via MMC algorithm) is not sufficient for separation.

Checking NN response to Z events (in mass window 115-135 GeV) reveals that Z background is not flat wrt the NN score.

Would lose some power in the fit due to this large background.

Would like to try to separate these backgrounds as much as possible. Current proposal is to try to use a separate NN to help classify events in the mass window.



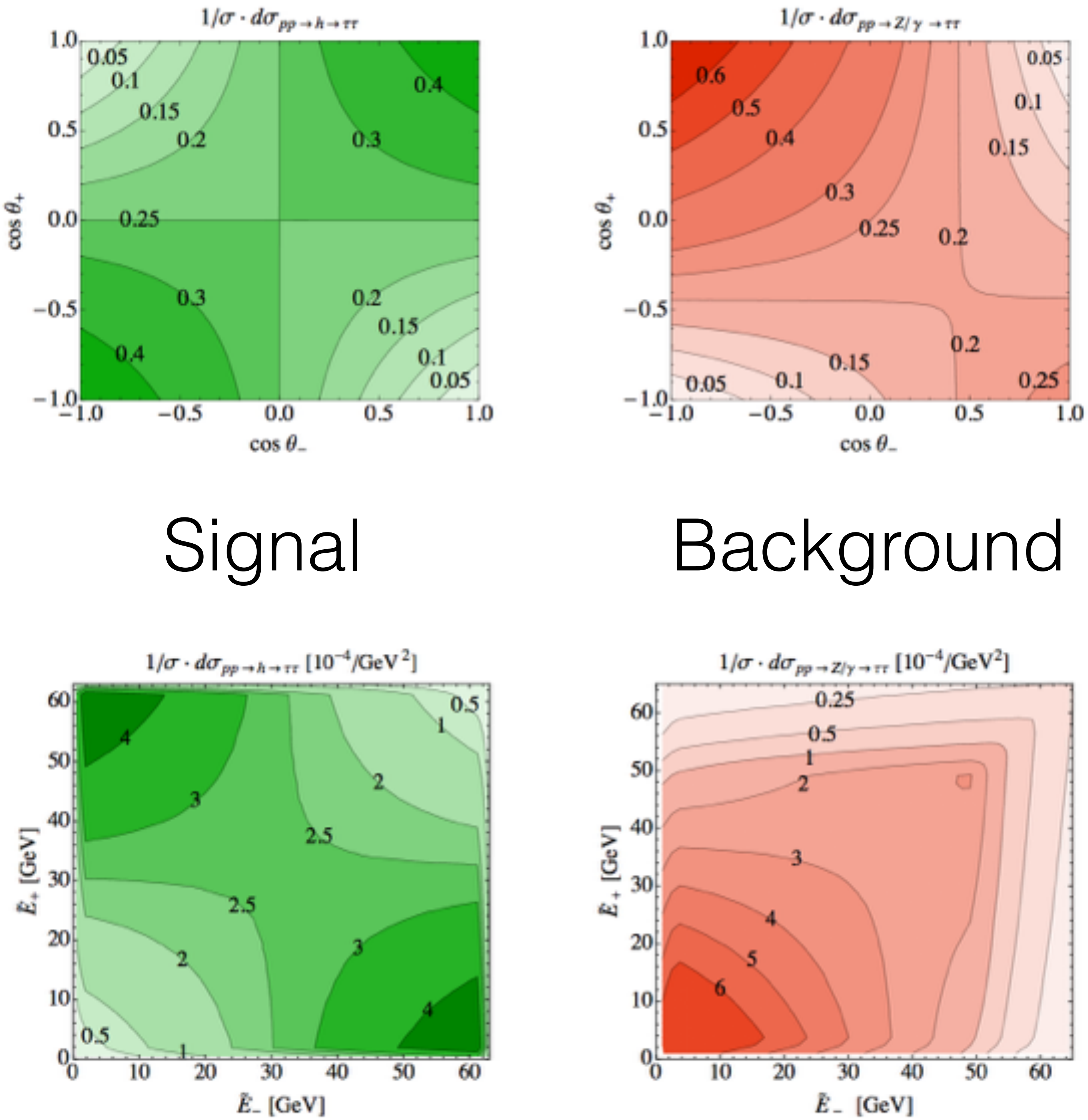


Z Background

Paper from Berge discusses the impact of Z background. Best discriminator of Z background is the mass of the boson (Z vs H) but we select events in the mass window. Need to look for more subtle effects - spin.

With the zero momentum frame (Z/H rest frame) you can use the polar angles in the zero momentum frame to separate the signal and background. This is related to the visible tau energy (which is more readily reconstructible).

These are induced from polarisation of Z. These effects are more complicated with respect to the H vs A.

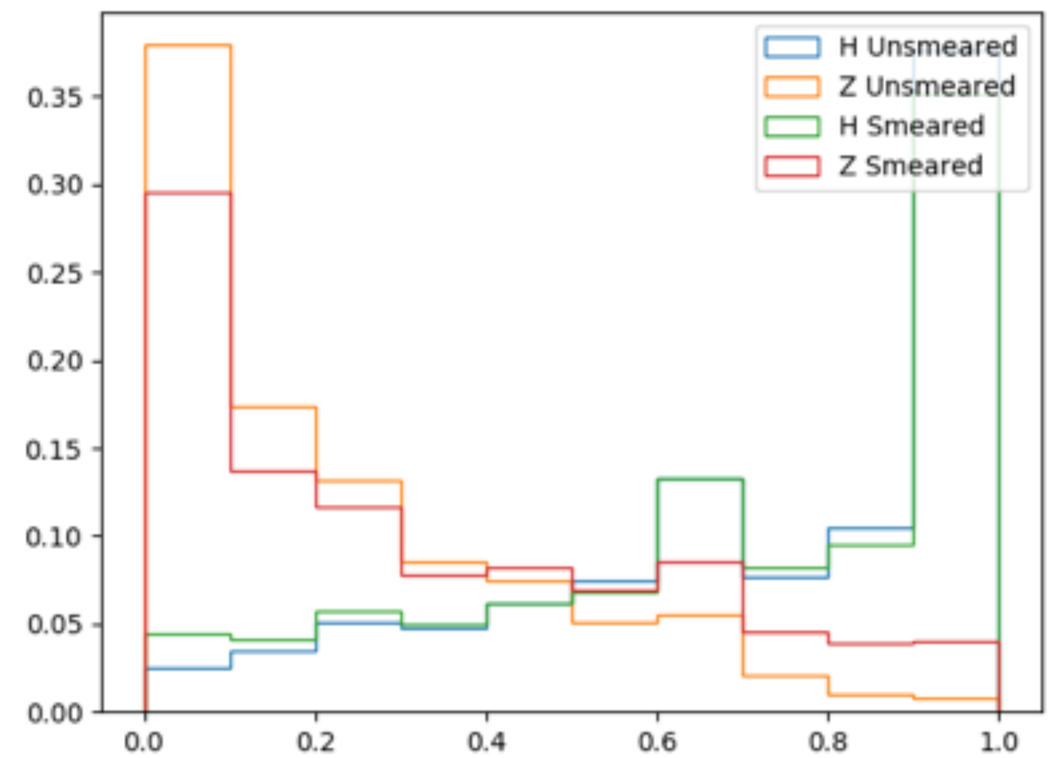


H vs Z NN

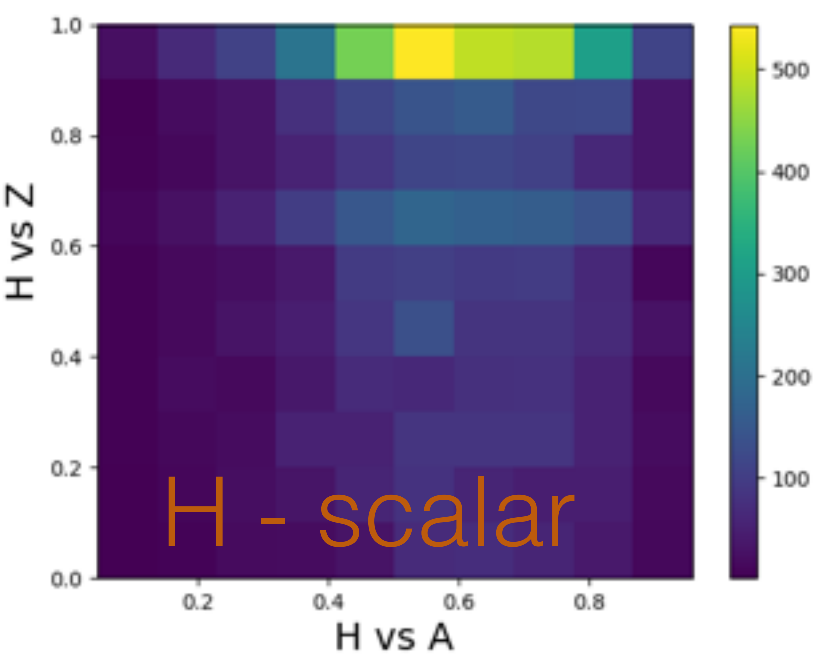
Focus will not be on discrimination based on mass separation (already established in Run 1 search). Instead need separation by other means.

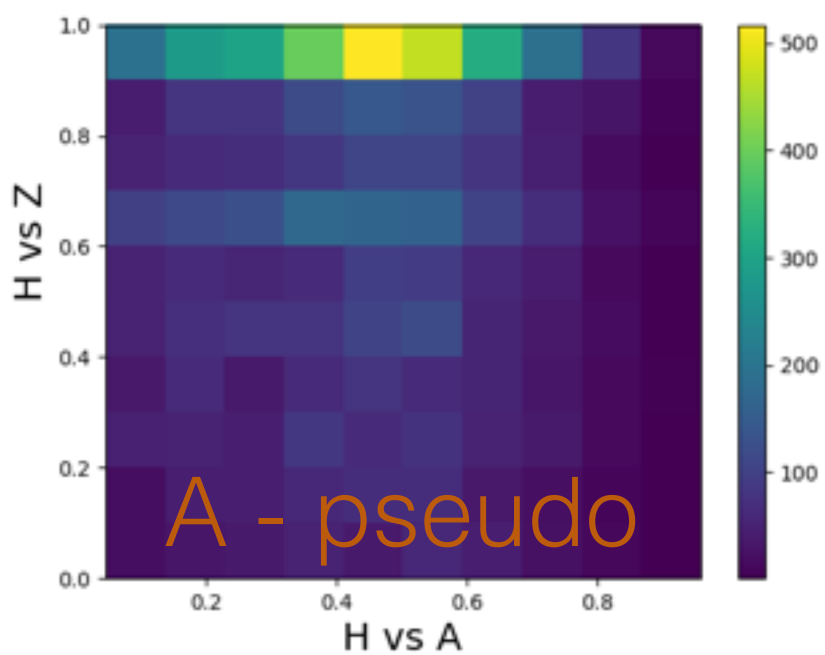
Since NN separating scalar and pseudoscalar was successful in identifying spin correlations largely from 4-vector inputs, as a first attempt try training NN based on this.

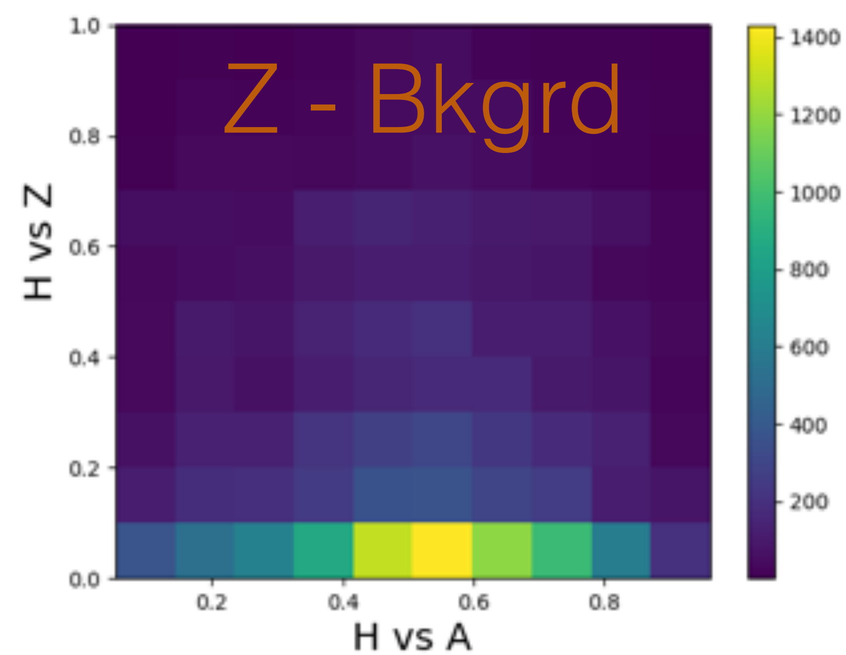
Still boosting into rest frame to avoid looking at production (which is targeted by cuts/MVA).



H vs Z NN score



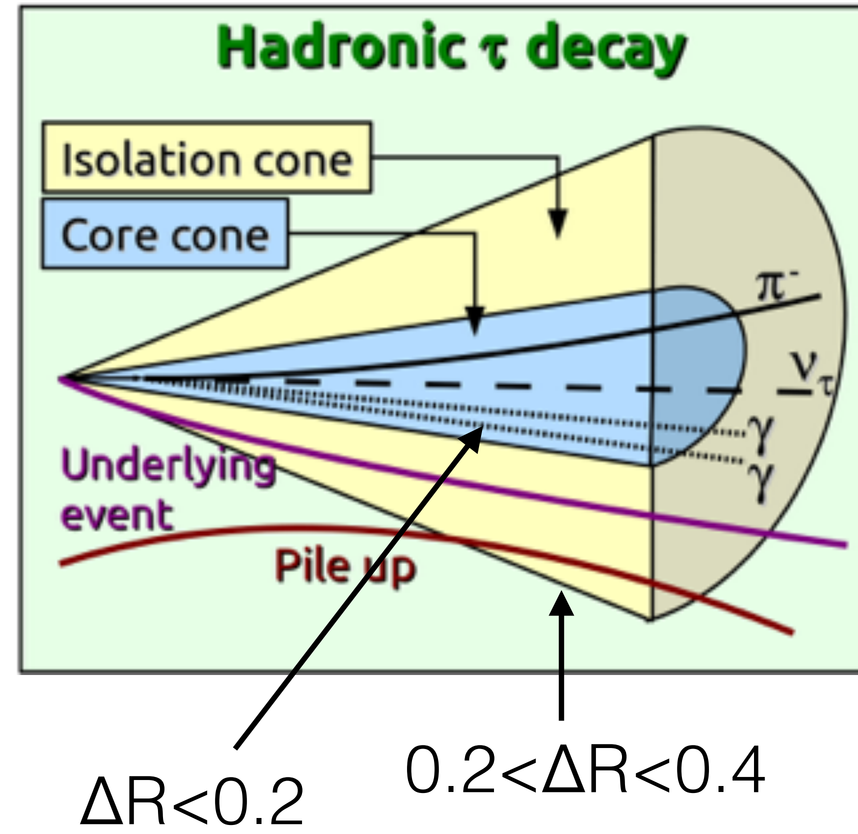




Tau Reco + ID

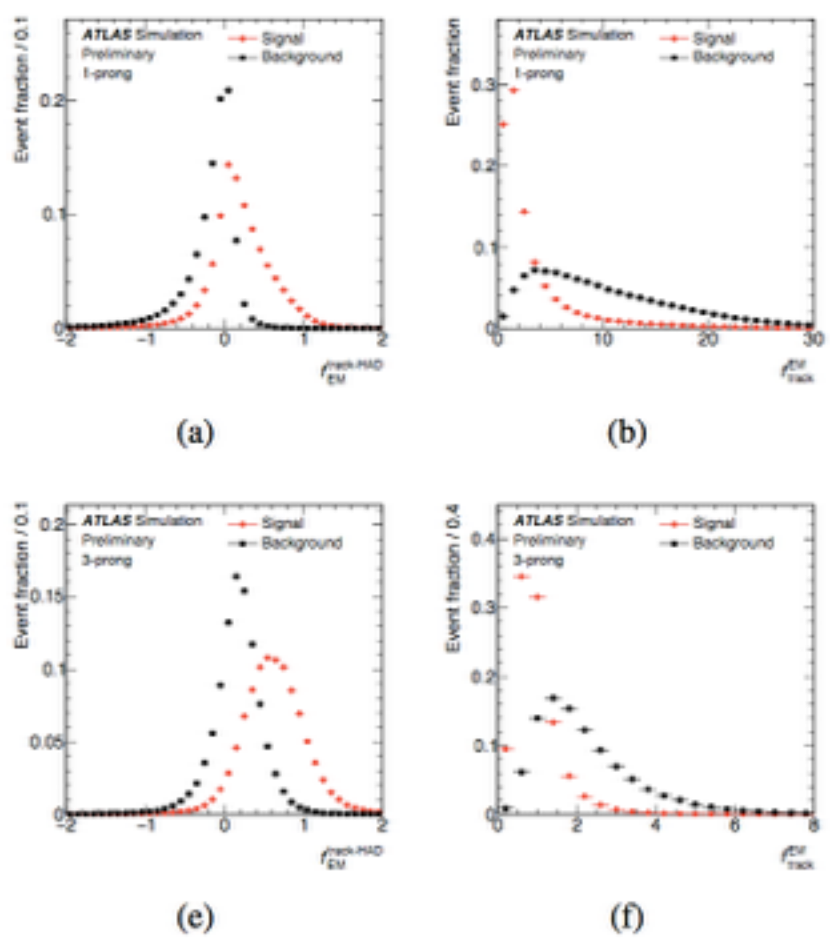
Tau-jets are reconstructed from jets reconstructed from anti-k_T jets with ΔR=0.4. Tracks are required to be contained within the core cone of ΔR<0.2.

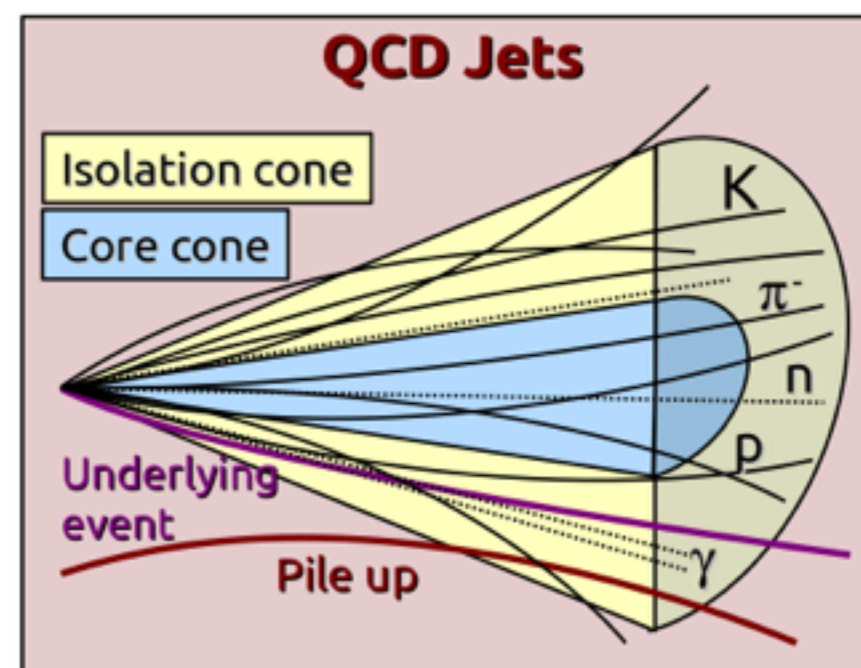
Identification is performed through a multivariate classifier. Three working points are defined for specific signal efficiencies of 40%, 60% and 70%.



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

Variable	Offline 1-track	Offline 3-track
f_{cent}	●	●
$f_{\text{leadtrack}}^{-1}$	●	●
$R_{\text{track}}^{0.2}$	●	●
$\lvert S_{\text{leadtrack}}\rvert$	●	
$f_{\text{iso}}^{\text{track}}$	●	
ΔR_{Max}		●
$S_{\text{T}}^{\text{flight}}$		●
m_{track}		●
$f_{\text{EM}}^{\text{track-HAD}}$	●	●
$f_{\text{track}}^{\text{EM}}$	●	●
$m_{\text{EM+track}}$	●	●
$p_{\text{T}}^{\text{EM+track}}/p_{\text{T}}$	●	●





Substructure Reconstruction

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

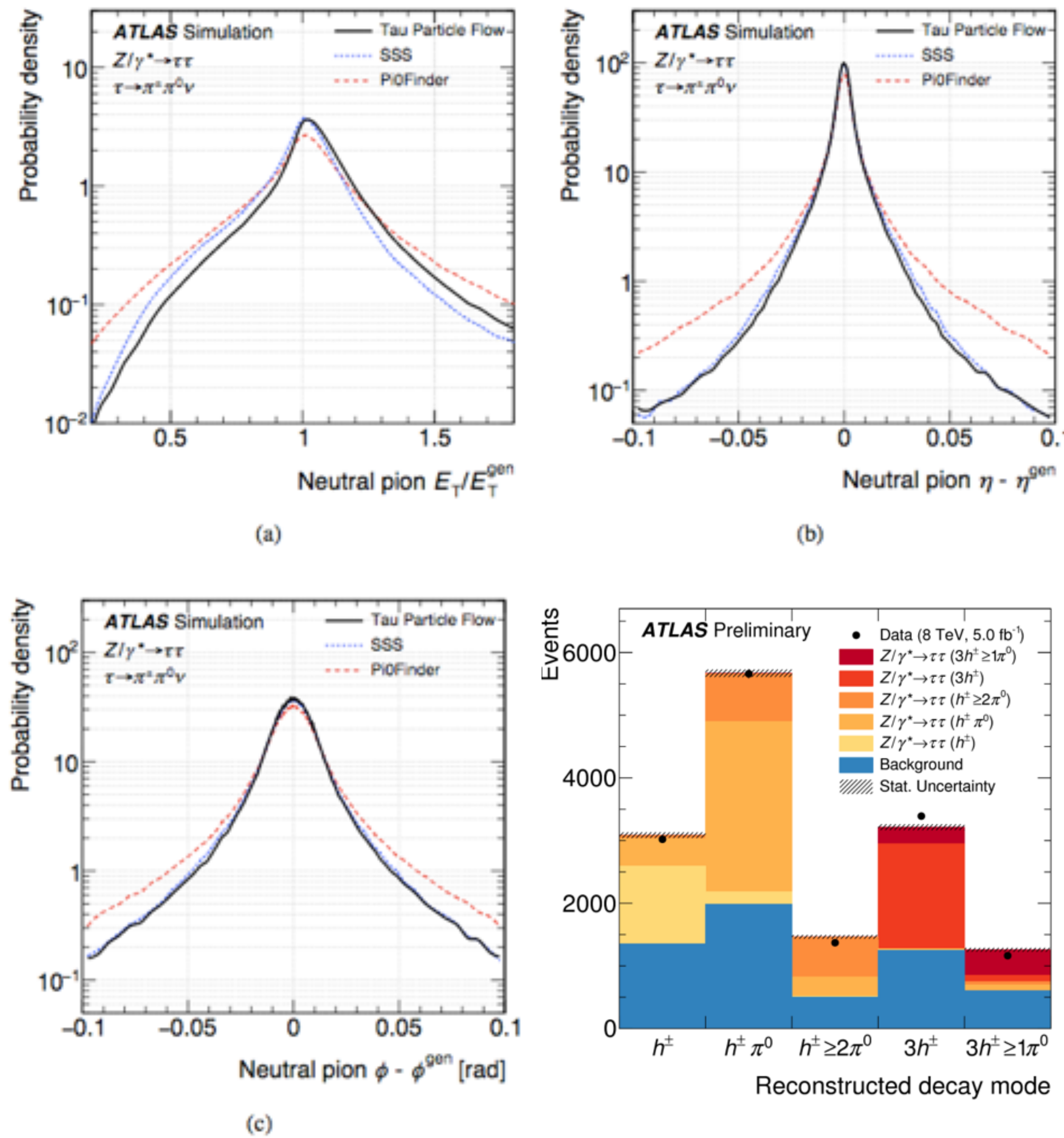
A particle flow approach is taken (rather than using only calo information). Charged hadrons reconstructed using track information, neutrals from calo deposits.

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.



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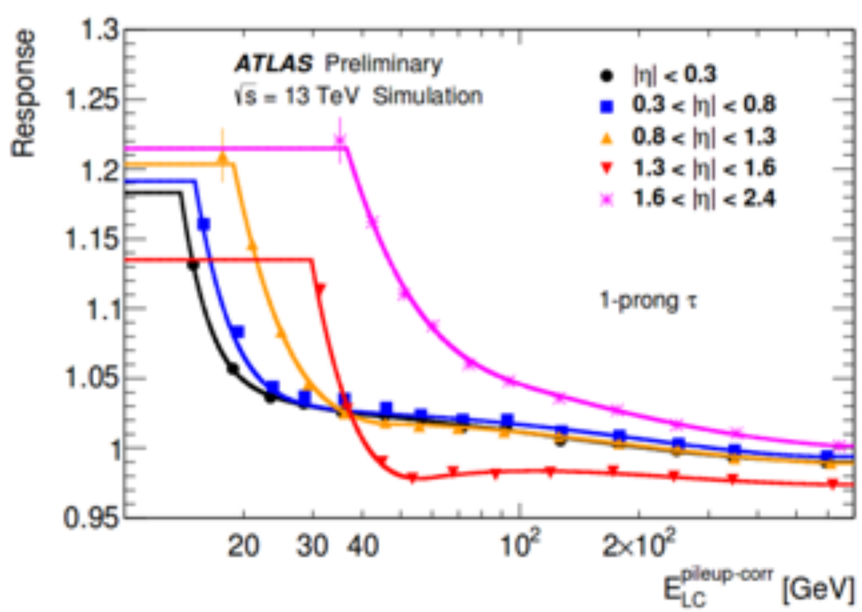
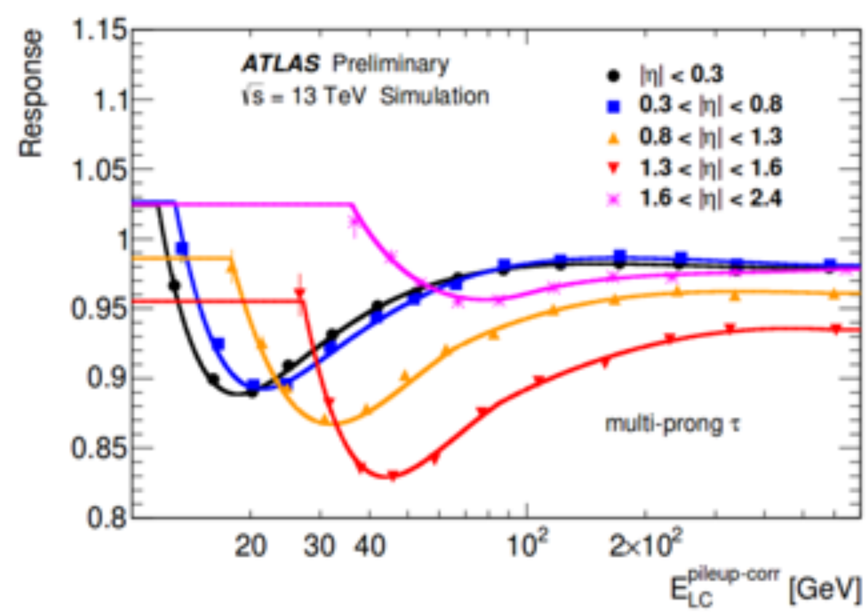
TES - Energy Calibration

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.





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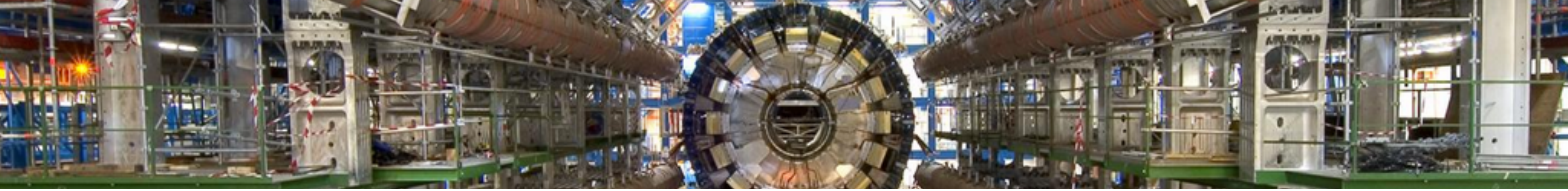


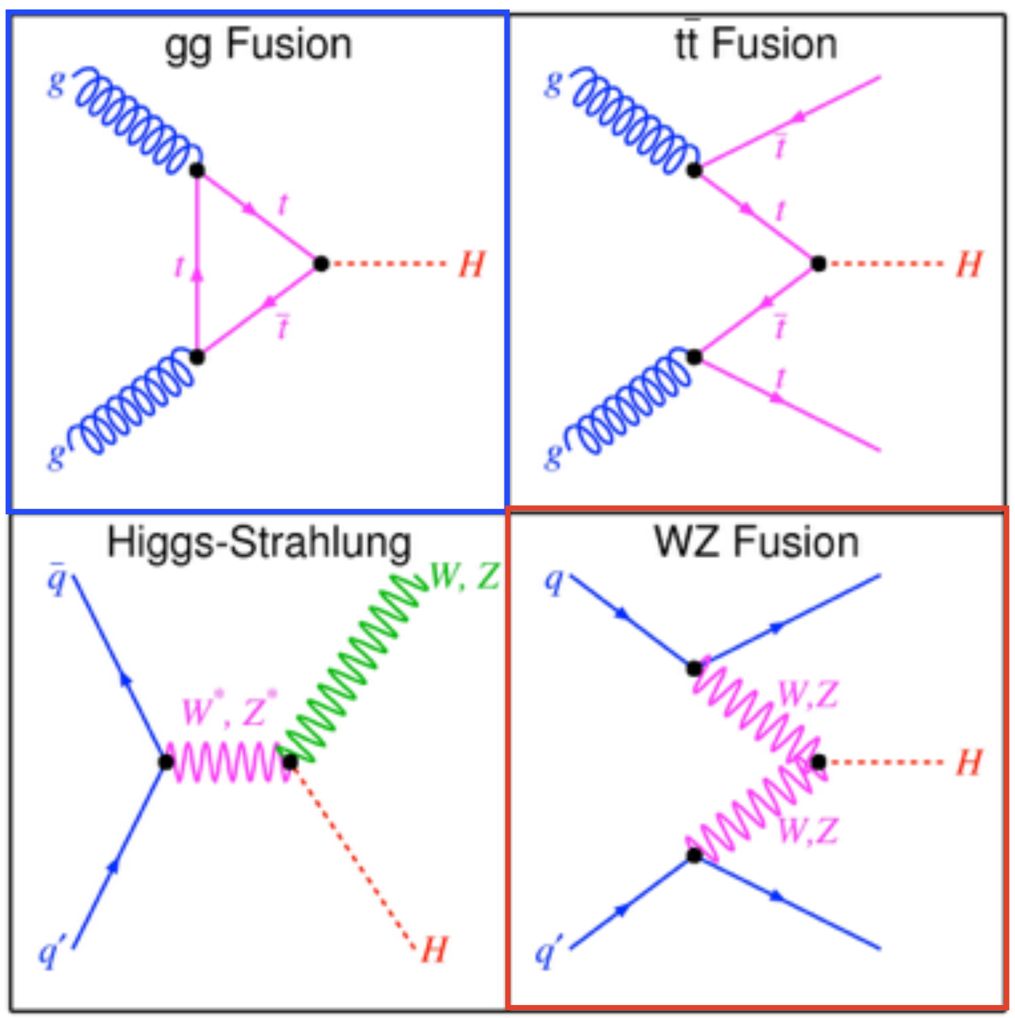
Part B:

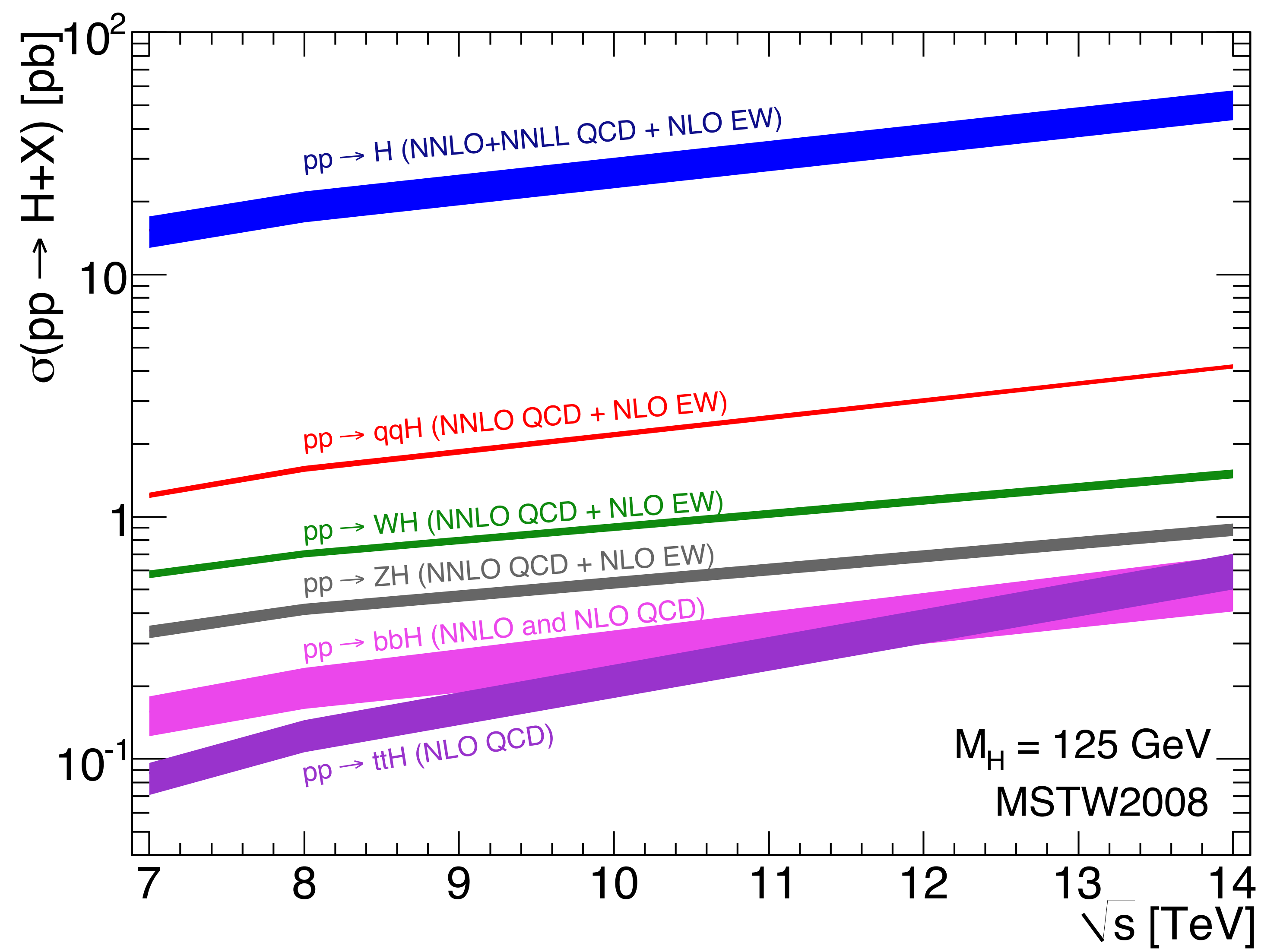
SM Coupling Analysis

H→ττ Signal

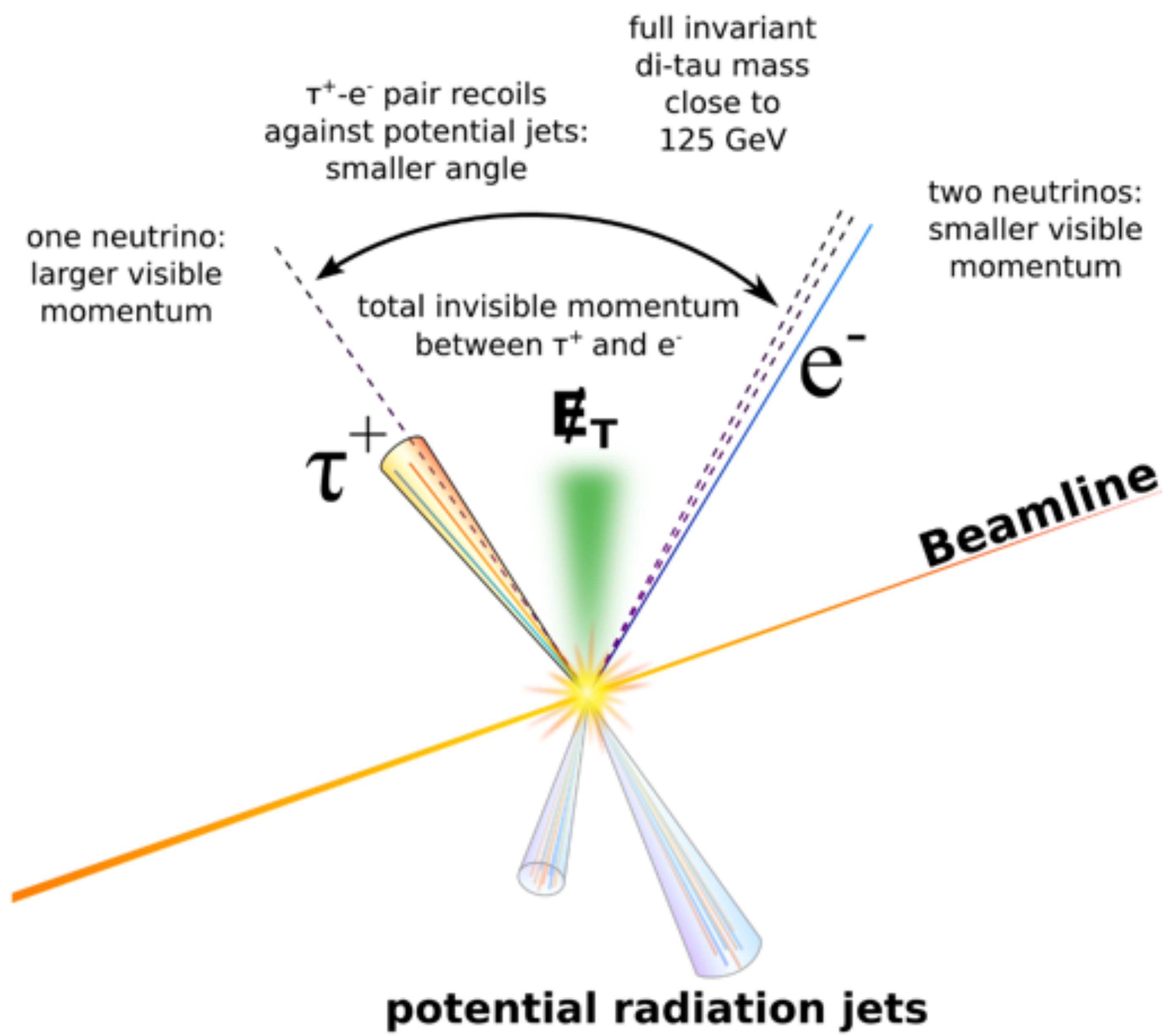
Leading two production modes are used in the main analysis

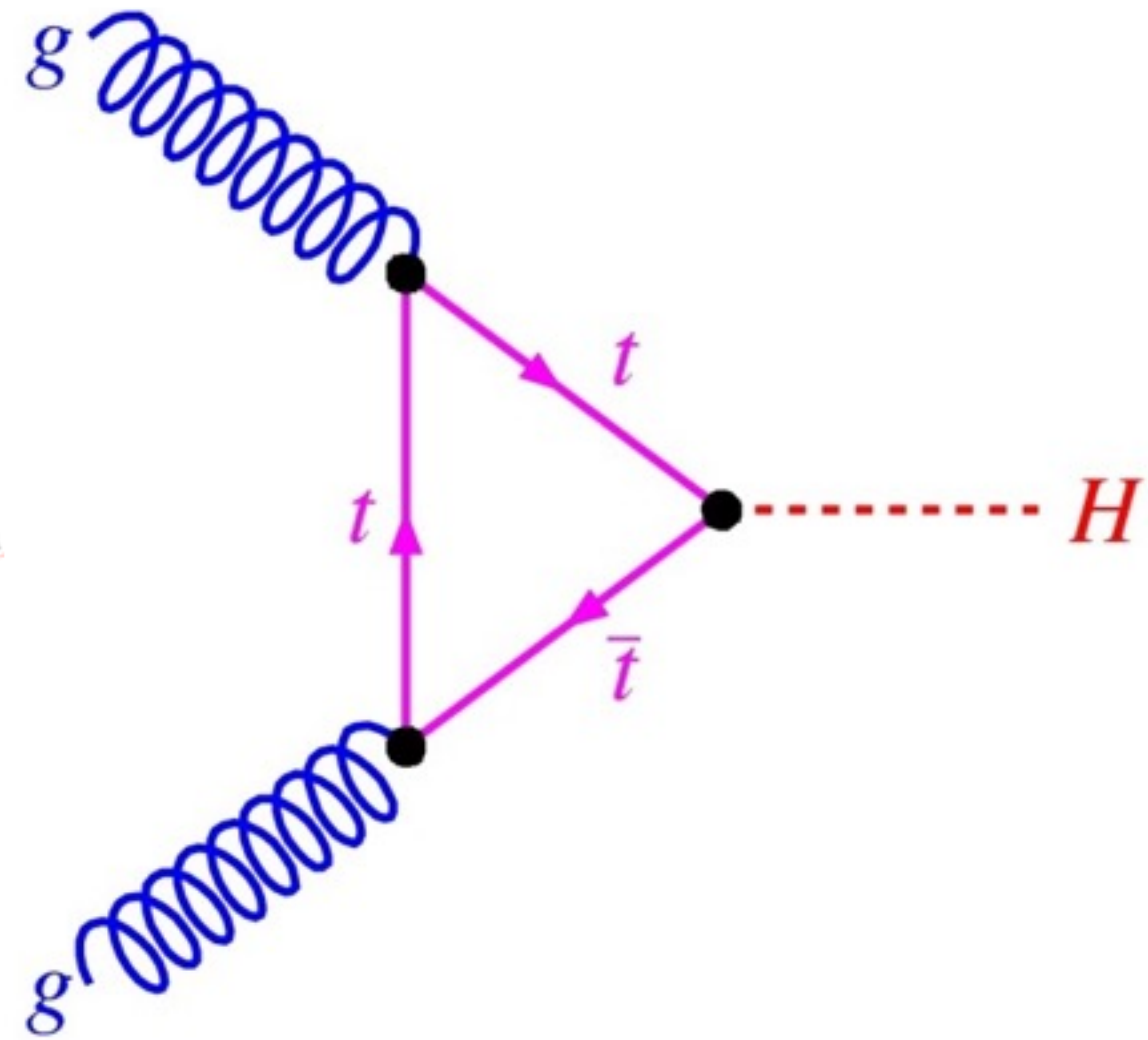
- Gluon-gluon fusion (ggF) and vector boson fusion (VBF)





Signal - ggF





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

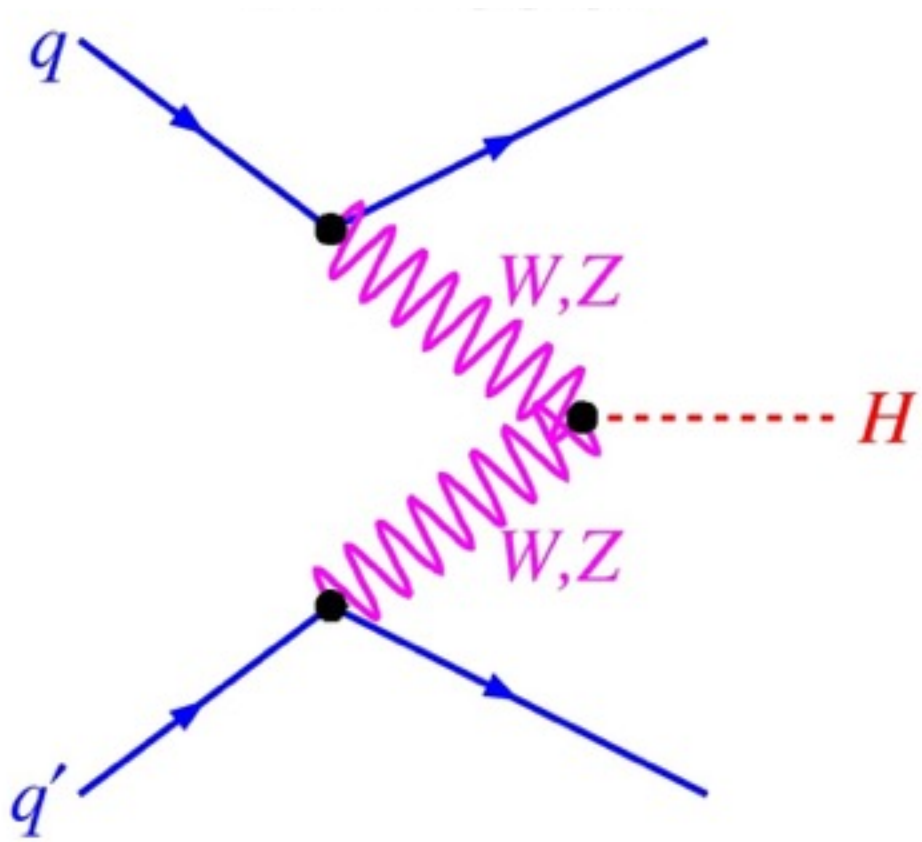
Topology characterised with **large boost in transverse plane recoiling off a jet**.

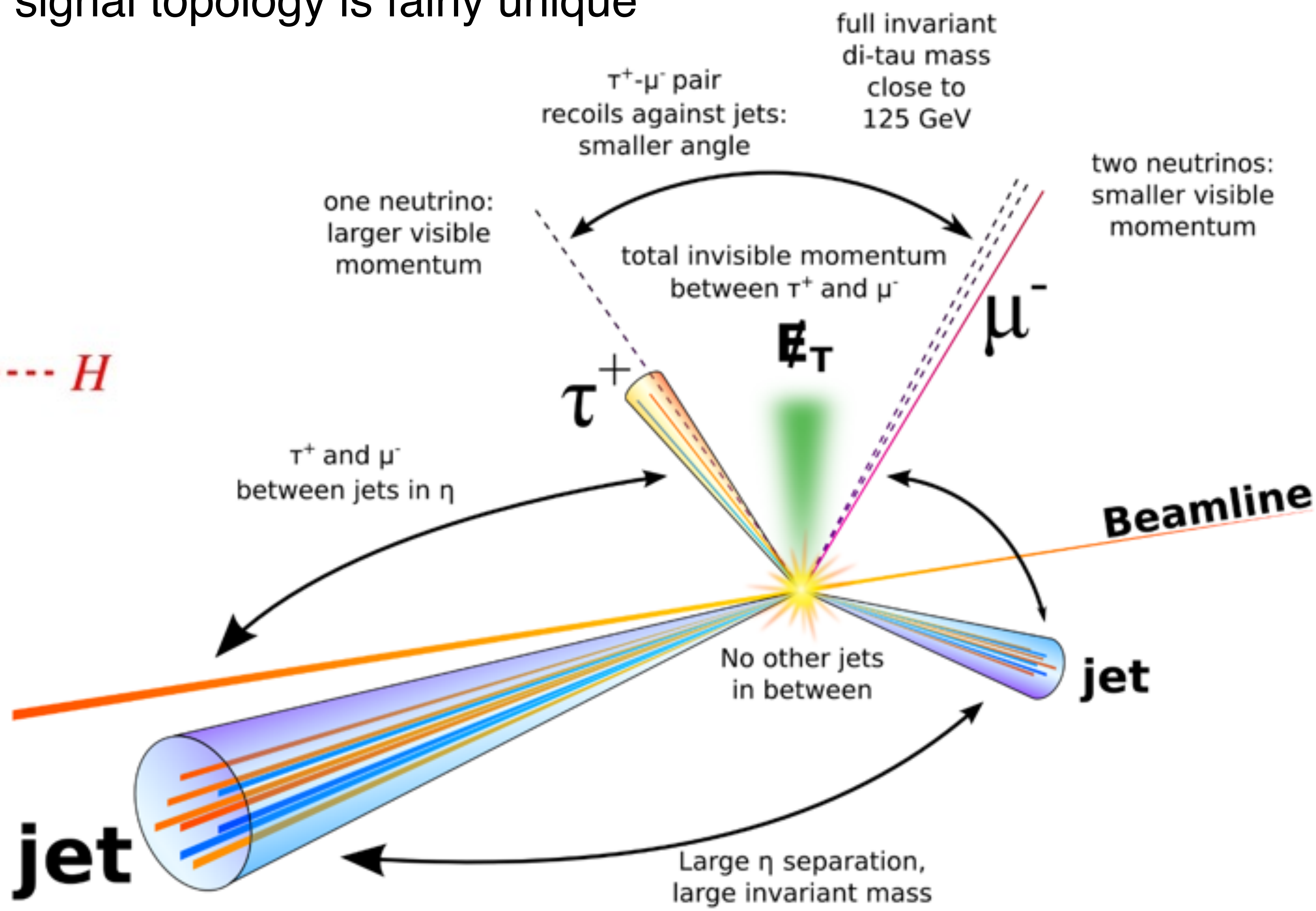
Topology lowers the x-sec used but allows for better discrimination from Z backgrounds.

Signal - VBF

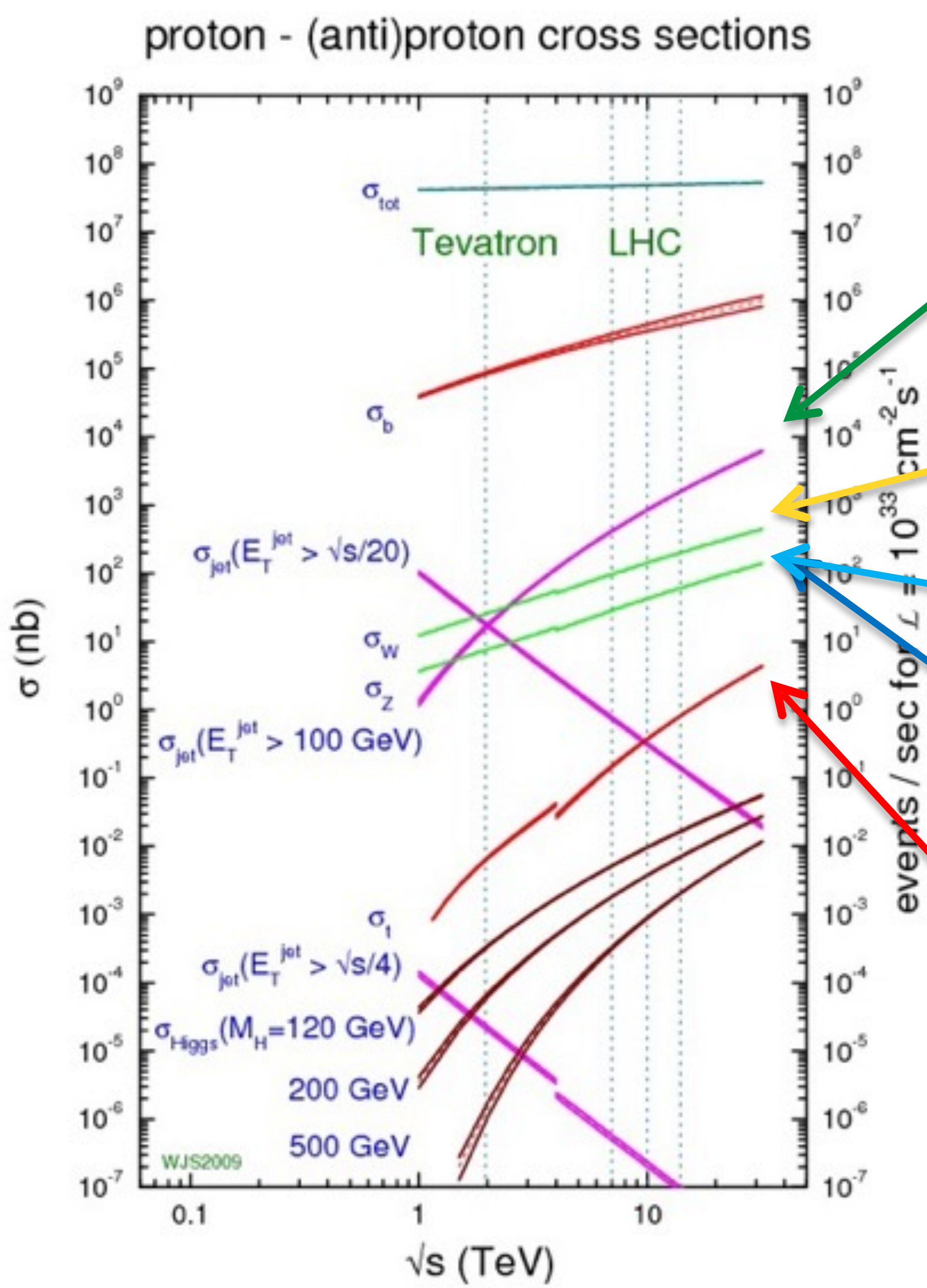
Vector Boson Fusion characterised by **two jets collimated along the beam**

Very sensitive channel as signal topology is fairly unique





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)**

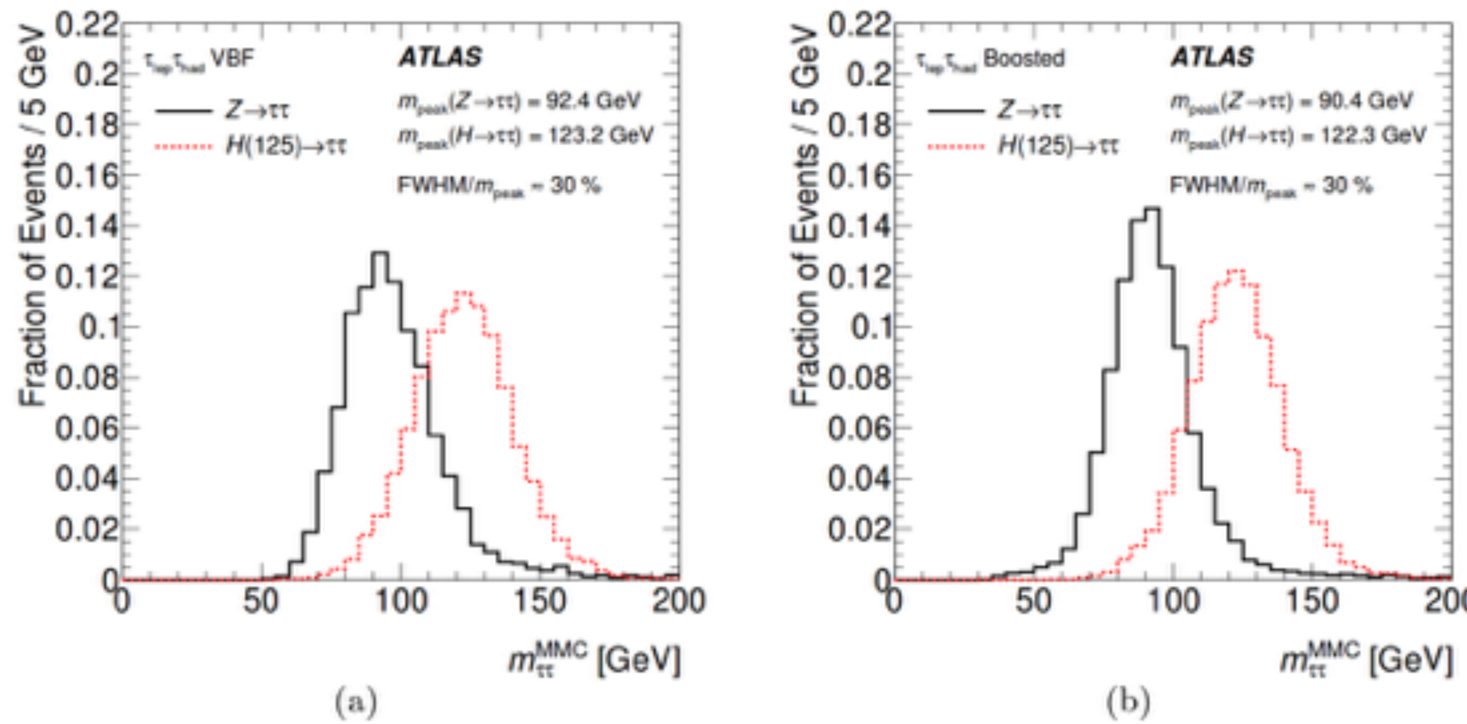
Best discriminator:

- **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

[arxiv:1501.04943](https://arxiv.org/abs/1501.04943)



(a) (b)

Reducible:

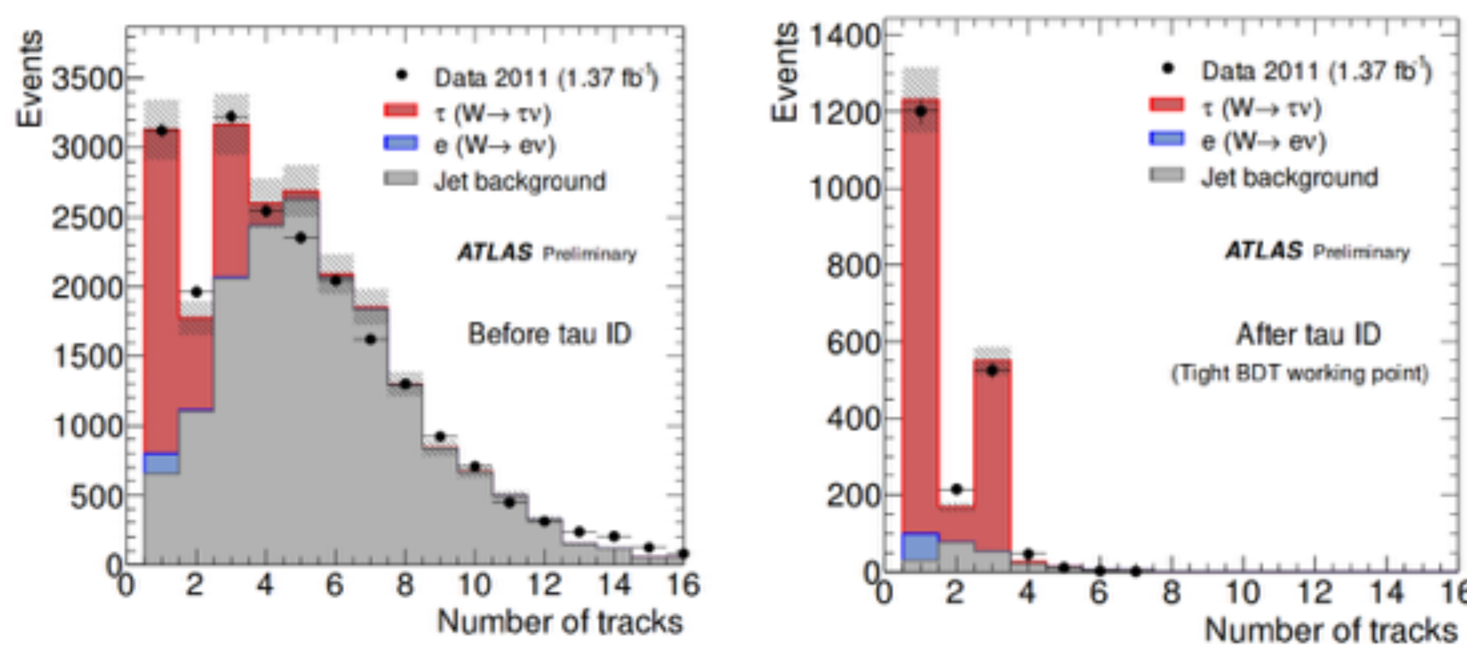
- Events with non-prompt final state (**processes where jet passes tau ID**)

Best discriminator:

- **Identification requirements** and topology

Modelling:

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



[arXiv:1412.7086](https://arxiv.org/abs/1412.7086)

Impact Parameter Method

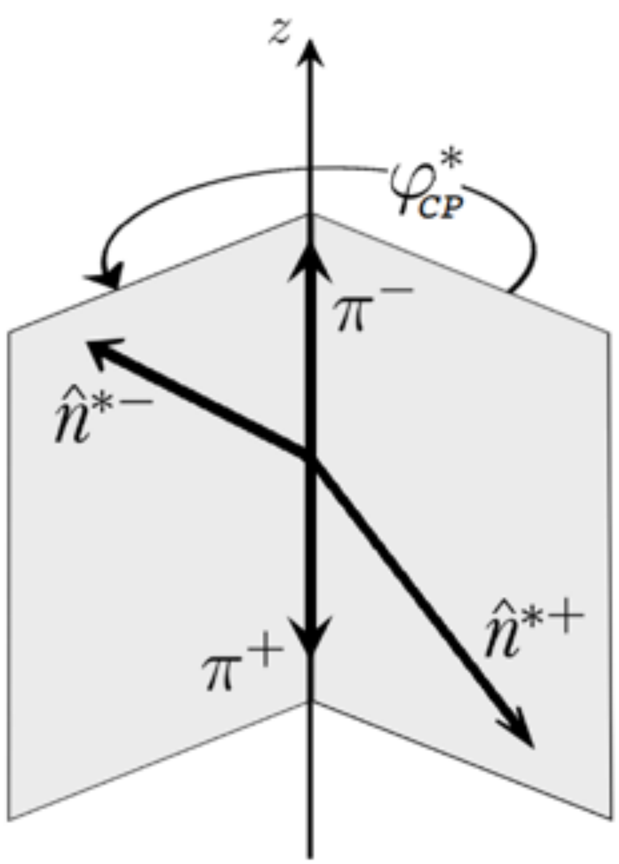
Method :

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

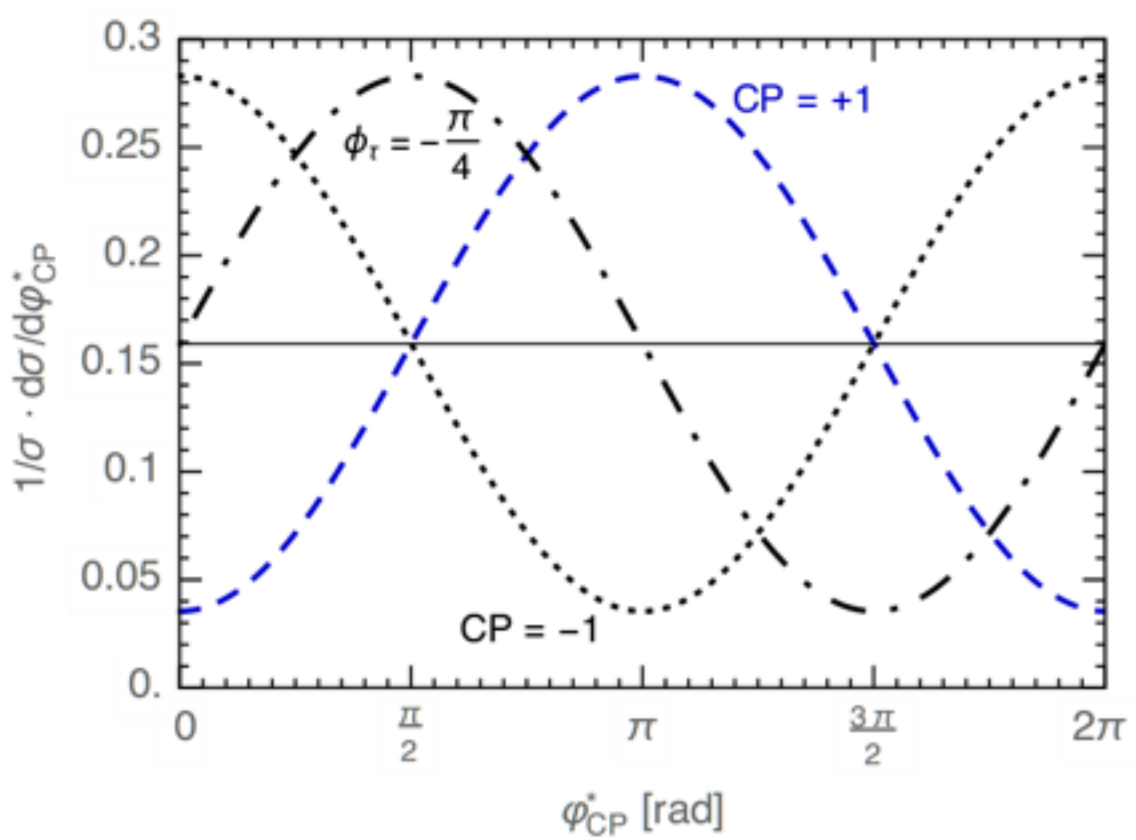
Pro : Can be used across **all decay modes**

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



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

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

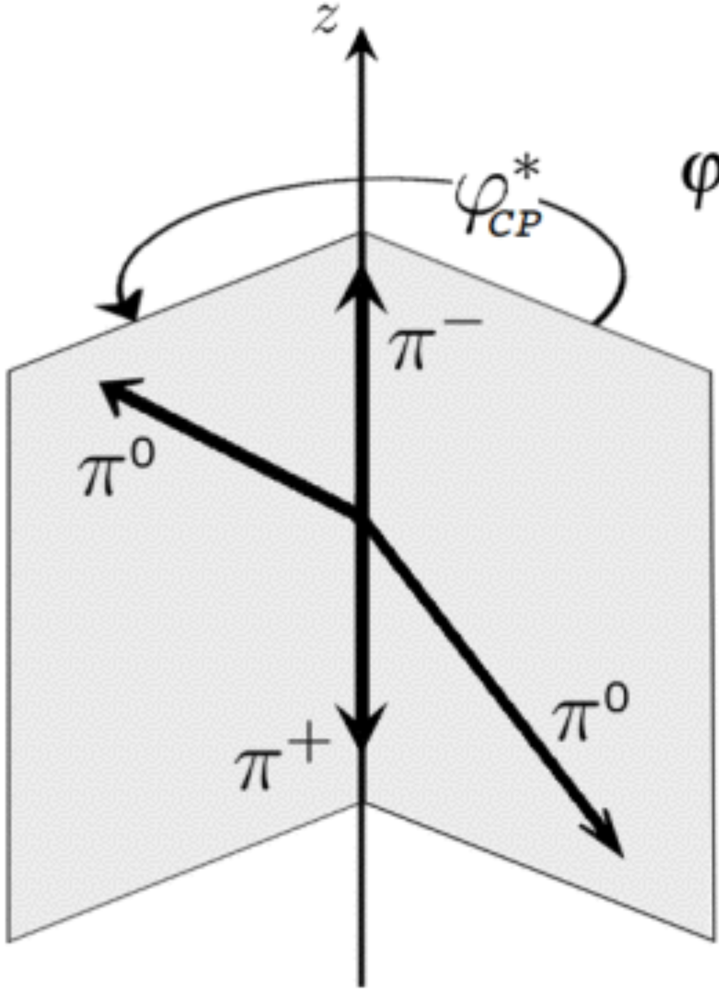
Observable for ρ decays

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**

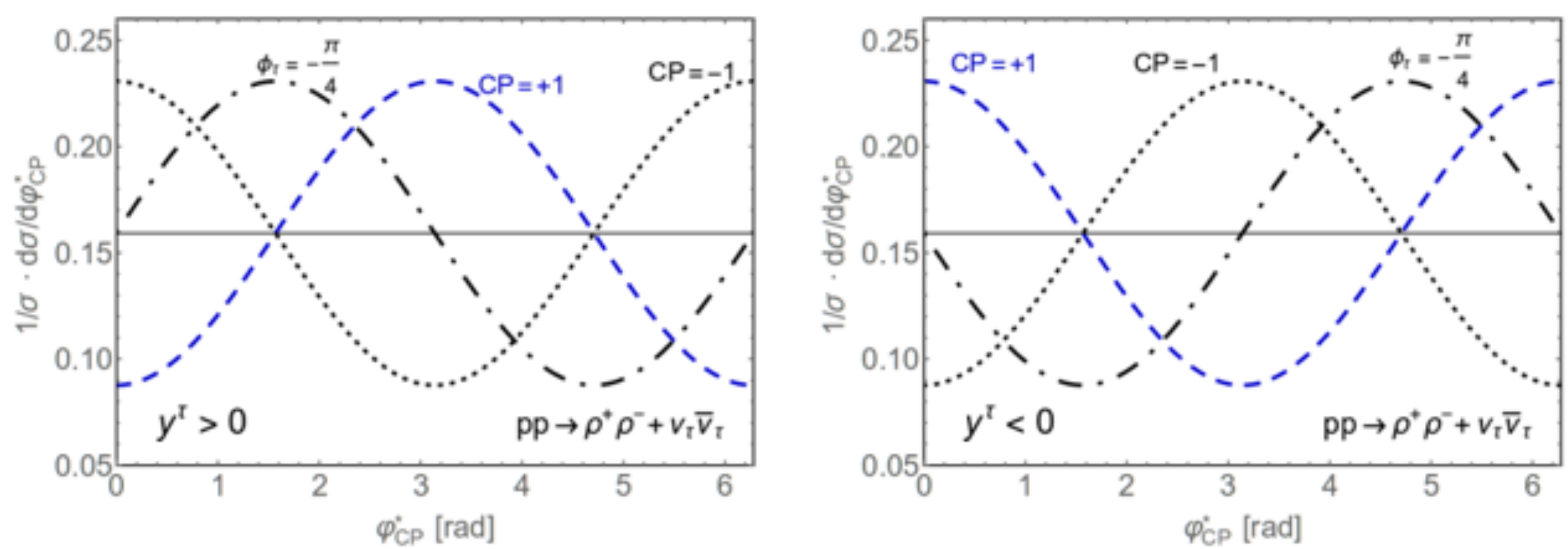


$$\varphi^*_{CP} = \begin{cases} \varphi^* & \text{if } \mathcal{O}^*_{CP} \geq 0\,, \\ 2\pi - \varphi^* & \text{if } \mathcal{O}^*_{CP} < 0\,, \end{cases}$$

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

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

[arxiv:1510.03850](https://arxiv.org/abs/1510.03850)



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- Prospects of constraining the Higgs CP nature in the tau decay channel at the LHC (S. Berge, W. Bernreuther, S. Kirchner) Phys. Rev. D92 (2015) : arxiv:1510.03850
- 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/