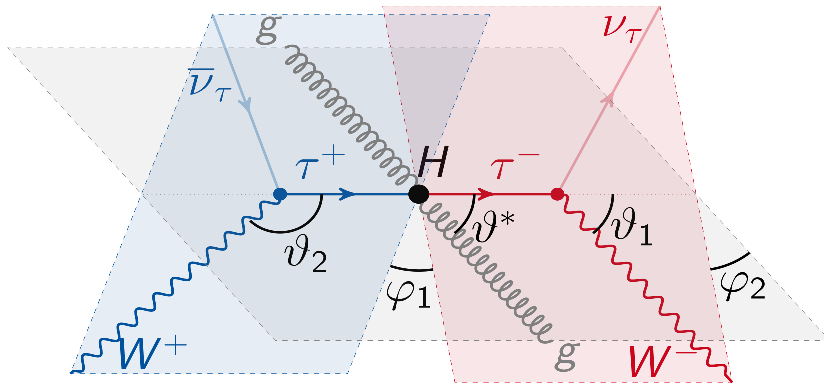


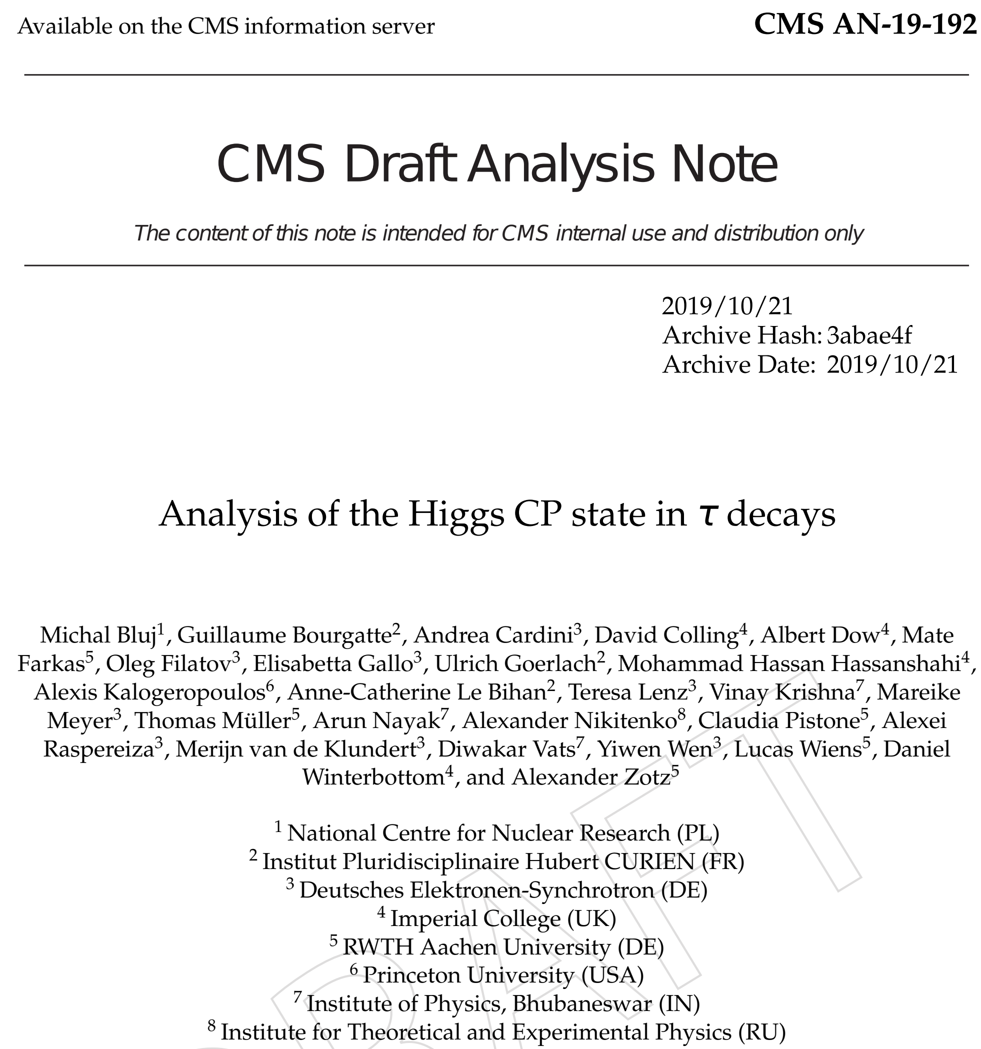
DESY Workshop – Higgs CP in Tau Decays

Summary

Thomas Müller on behalf of the $H \to \tau\tau$ Decay CP working group

Working Group and Previous Presentations

- **Previous presentations**:
  - Mohammad Hassan Hassanshahi, 20.05.2019, Tau POG: *Identification of ρ decay channel in the hadronic tau decay*
  - Mohammad Hassan Hassanshahi, 03.06.2019, Tau POG: *Identification of tau decay channels*
  - Merijn van de Klundert, 31.08.2019, Higgs PAG: *Higgs CP in tau decay: Status update*
  - Daniel Winterbottom, 03.10.2019, Higgs PAG: *Fake Factors for CP in decay*
- Working group meetings: indico.desy.de/indico/category/656
- AN-19-192 (work in progress)


Available on the CMS information server **CMS AN-19-192**

CMS Draft Analysis Note

The content of this note is intended for CMS internal use and distribution only

2019/10/21
Archive Hash: 3abae4f
Archive Date: 2019/10/21

Analysis of the Higgs CP state in τ decays

Michal Bluj[1], Guillaume Bourgatte[2], Andrea Cardini[3], David Colling[4], Albert Dow[4], Mate Farkas[5], Oleg Filatov[3], Elisabetta Gallo[3], Ulrich Goerlach[2], Mohammad Hassan Hassanshahi[4], Alexis Kalogeropoulos[6], Anne-Catherine Le Bihan[2], Teresa Lenz[3], Vinay Krishna[7], Mareike Meyer[3], Thomas Müller[5], Arun Nayak[7], Alexander Nikitenko[8], Claudia Pistone[5], Alexei Raspereiza[3], Merijn van de Klundert[3], Diwakar Vats[7], Yiwen Wen[3], Lucas Wiens[5], Daniel Winterbottom[4], and Alexander Zotz[5]

[1] National Centre for Nuclear Research (PL)
[2] Institut Pluridisciplinaire Hubert CURIEN (FR)
[3] Deutsches Elektronen-Synchrotron (DE)
[4] Imperial College (UK)
[5] RWTH Aachen University (DE)
[6] Princeton University (USA)
[7] Institute of Physics, Bhubaneswar (IN)
[8] Institute for Theoretical and Experimental Physics (RU)

Workshop Agenda

Thu 10/10

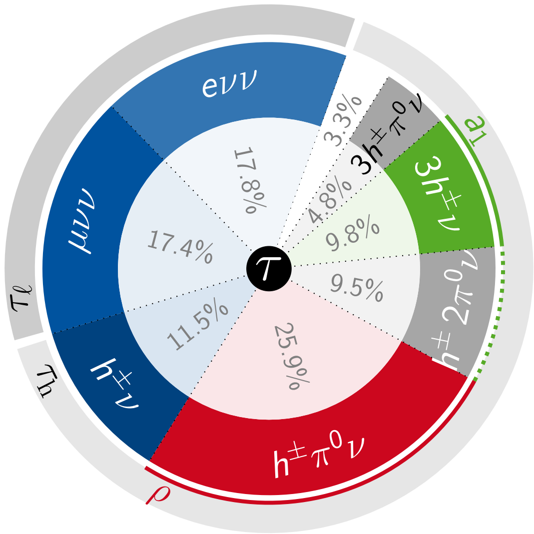
13:00 - 13:20	**Welcome, introduction**	*Dr. Merijn VAN DE KLUNDERT et al.*	*Seminar room 4b (first floor)*
13:20 - 13:50	**IoP Bhubaneswar**	*Mr. Aruna NAYAK et al.*	*Seminar room 4b (first floor)*
13:50 - 14:20	**RWTH Aachen**	*Dr. Thomas MÜLLER et al.*	*Seminar room 4b (first floor)*
14:20 - 14:50	**IPHC Strassbourg**	*Dr. Anne-Catherine LE BIHAN et al.*	*Seminar room 4b (first floor)*
14:50 - 15:10	**Coffee break**		*Seminar room 4b (first floor)*
15:10 - 15:40	**Imperial College**	*Prof. David COLLING et al.*	*Seminar room 4b (first floor)*
15:40 - 16:10	**DESY**	*Mr. Andrea CARDINI*	*Seminar room 4b (first floor)*
16:10 - 16:40	**Synchronisation**	*Michal BLUJ*	*Seminar room 4b (first floor)*
16:40 - 17:00	**Break (coffee/tea served outside seminar room)**		*Seminar room 4b (first floor)*
17:00 - 17:30	**Fake factors for tau decay modes**	*Mr. Daniel WINTERBOTTOM*	*Seminar room 4b (first floor)*

Fri 11/10

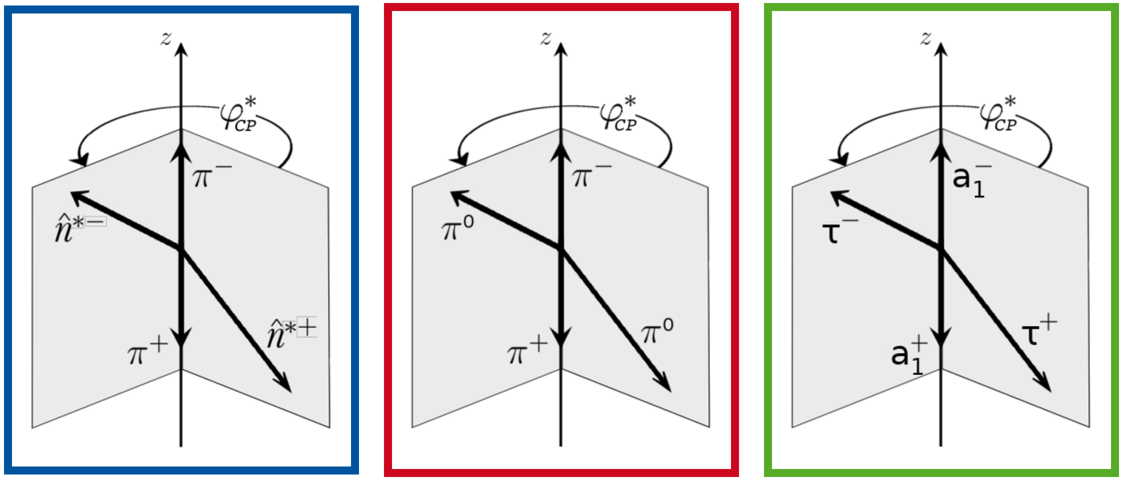
09:00 - 09:30	**CombineHarvester**	*Mr. Albert DOW*	*Seminar room 4b (first floor)*
09:30 - 10:00	**Tau selection**	*Mr. Mohammad Hassan HASSANSHAHI*	*Seminar room 4b (first floor)*
10:00 - 10:30	**Event categorisation**	*Dr. Merijn VAN DE KLUNDERT*	*Seminar room 4b (first floor)*
10:30 - 10:50	**Coffee break**		*Seminar room 4b (first floor)*
10:50 - 11:20	**Vertex estimates**	*Mr. Aruna NAYAK*	*Seminar room 4b (first floor)*
11:20 - 11:40	**IP vector methods**	*Mr. Lucas WIENS*	*Seminar room 4b (first floor)*
11:40 - 12:00	**Monte Carlo production**	*Mr. Daniel WINTERBOTTOM*	*Seminar room 4b (first floor)*
12:00 - 13:00	**Lunch break**		*Seminar room 4b (first floor)*
13:00 - 15:00	**Paper roadmap and workshop summary**	*Prof. David COLLING*	*Seminar room 4b (first floor)*
15:00 - 15:30	**Coffee and tea break**		*Seminar room 4b (first floor)*

▶ indico.desy.de/indico/event/23344

Analysis Overview

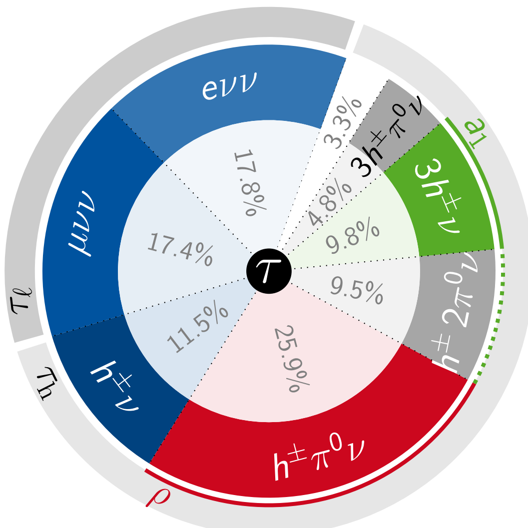


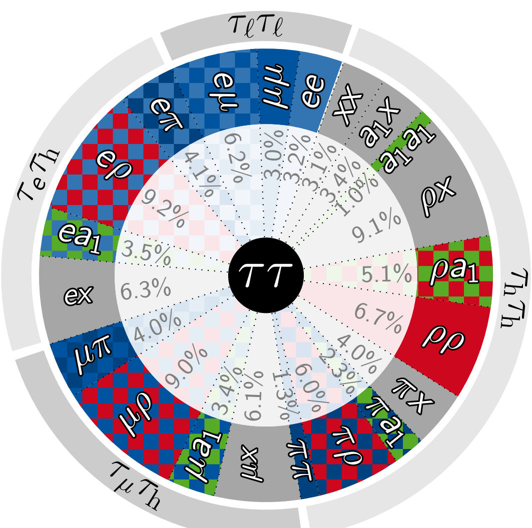
- Decay-mode dependent τ decay plane reconstruction:



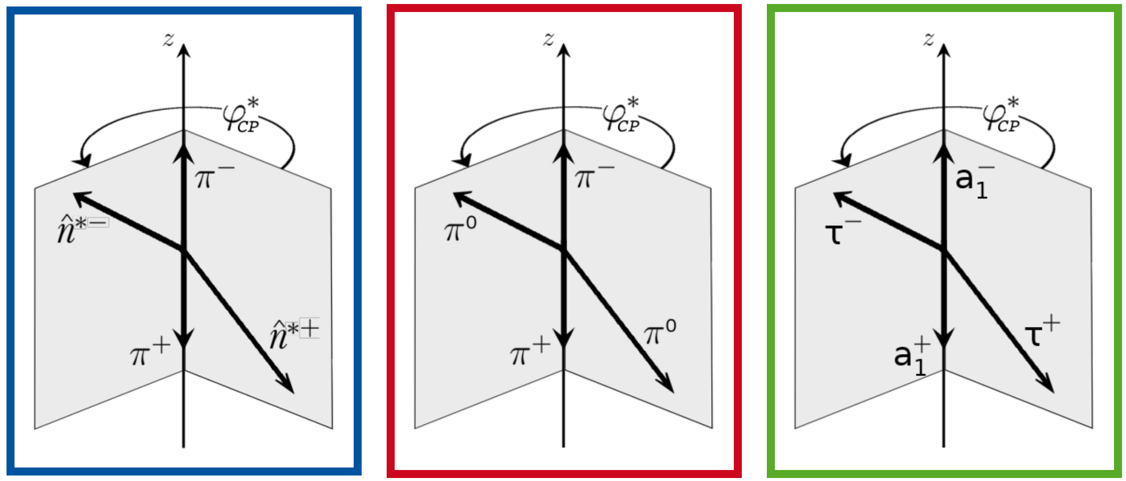
- Combinations of "pure" methods in various di-τ final states
  - Comparisons of sensitivities still ongoing
  - Plan to use promising methods also for $a_1^{\pm} \to \pi^{\pm} 2\pi^0$ channels

Analysis Overview



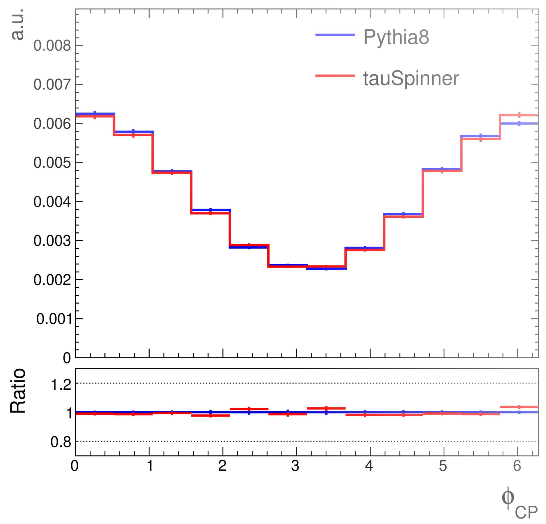


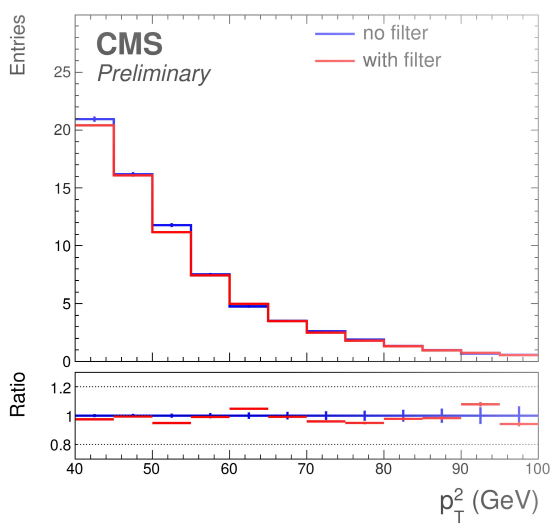
- ▶ Decay-mode dependent τ decay plane reconstruction:



- ▶ Combinations of "pure" methods in various di-τ final states
  - ▷ Comparisons of sensitivities still ongoing
  - ▷ Plan to use promising methods also for $a_1^{\pm} \to \pi^{\pm} 2\pi^0$ channels
- ▶ **Final states covered in this analysis**:
  - ▷ IPHC Strasbourg: $a_1 a_1$
  - ▷ IC London: $\rho\rho$, ρa_1, $a_1 a_1$
  - ▷ RWTH Aachen, NCBJ Warsaw: $\mu\rho$, $\pi\rho$, ($e\rho$)
  - ▷ DESY Hamburg: $\mu\rho$, $\mu\pi$, ($e\rho$, $e\pi$)
  - ▷ IOPB Bhubaneswar: $\pi\pi$, $\rho\rho$, $\pi\rho$ (sharing framework with DESY)
  - ▷ All analyses are set up to cross check other groups

Monte Carlo Samples for Signal

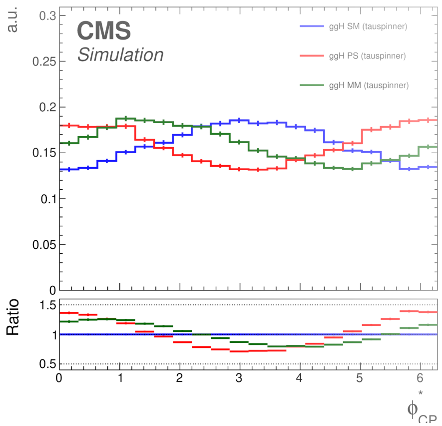




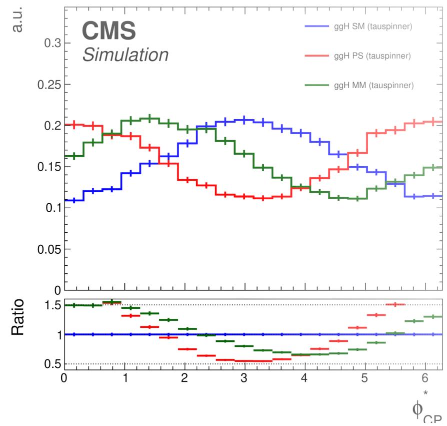
- Signal templates for arbitrary CP mixing angle are constructed as superposition from 3 samples
  - CP even, CP odd plus contribution form interference or any other CP mixing angle
- **Use TauSpinner to reweight from one to another scenario**
  - Request unpolarised samples (to avoid large weights)
  - TauSpinner reweighting yields same distribution as Pythia8 simulation of τ decays
  - **Advantage**: only one signal sample (per production mode) needed ➜ larger statistics possible
- **Submitted requests**
  - NLO POWHEG, unpolarised τ decays
  - 20M ggH (with) + 0.5M (without gen. filter) per year
  - 20M VBF (with) + 0.5M (without gen. filter) per year
  - 9M=4M+3M+2M VH=ZH+W^+H+W^-H (with) + 0.3M (without gen. filter) per year
  - Low priority currently, hope for 2018 samples in block 1

Tau Decay Mode MVAs

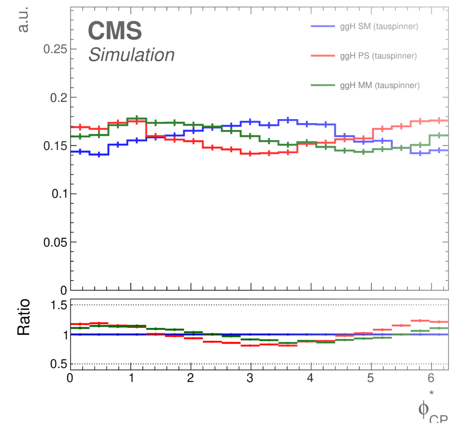
▷ HPS decay mode 1



▷ Identified real ρ



▷ Identified fake ρ

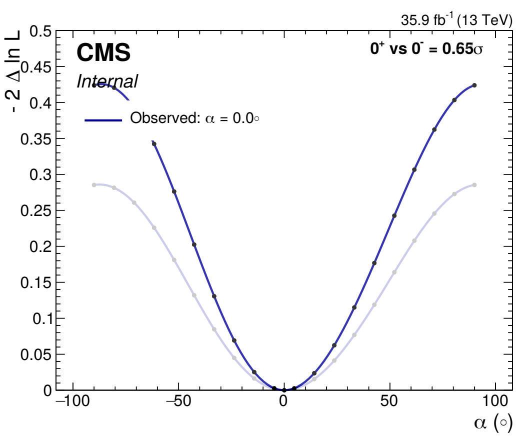


▷ Efficiency:

	$\tau^\pm \to \pi^\pm$	$\tau^\pm \to \rho^\pm \to \pi^\pm\pi^0$	$\tau^\pm \to a_1^\pm \to \pi^\pm 2\pi^0$
Reco-based	89%	74%	-
MVA-based	86%	84%	42%
Gain	-3%	10%	42%

▷ Purity:

	$\tau^\pm \to \pi^\pm$	$\tau^\pm \to \rho^\pm \to \pi^\pm\pi^0$	$\tau^\pm \to a_1^\pm \to \pi^\pm 2\pi^0$
Reco-based	56%	57%	-
MVA-based	75%	71%	59%
Gain	19%	14%	59%

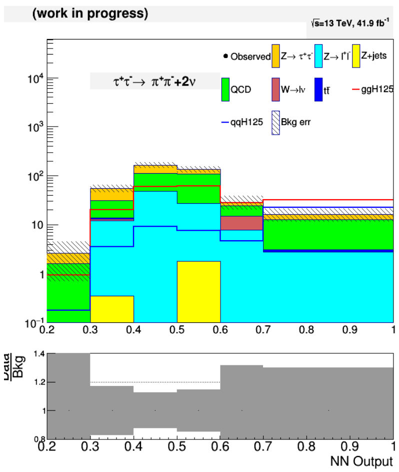


- Above: MVA to improve identification of 1-prong DMs
- Similar MVA for 3-prong decay modes available
- 22% gain in combination of $\rho\rho$+$a_1\rho$ categories
  - ▷ Fit "fake" events in separate categories
- Will be included in all sub-analyses soon (together with deepTauID)

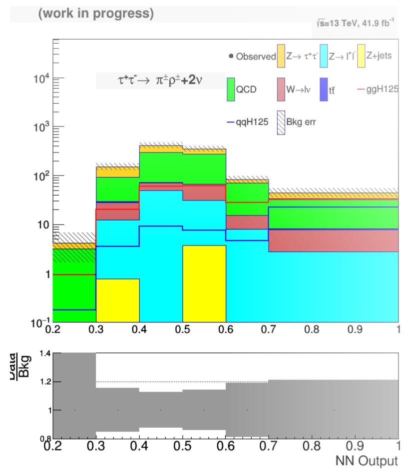
DNN for Signal vs. Background Separation

Vinay Krishna, Andrea Cardini

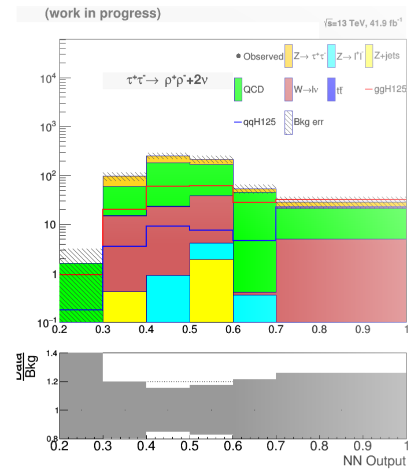
▷ $\pi\pi$



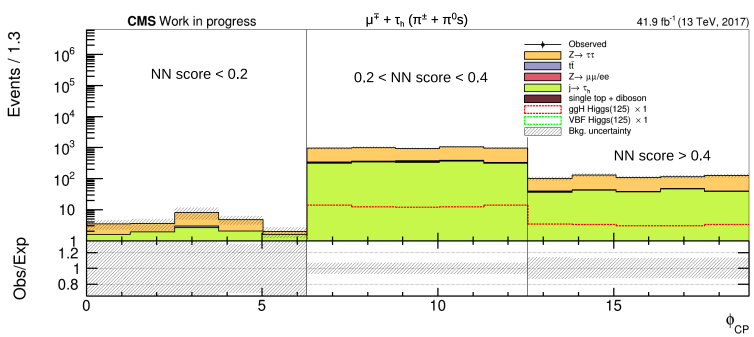
▷ $\rho\pi$



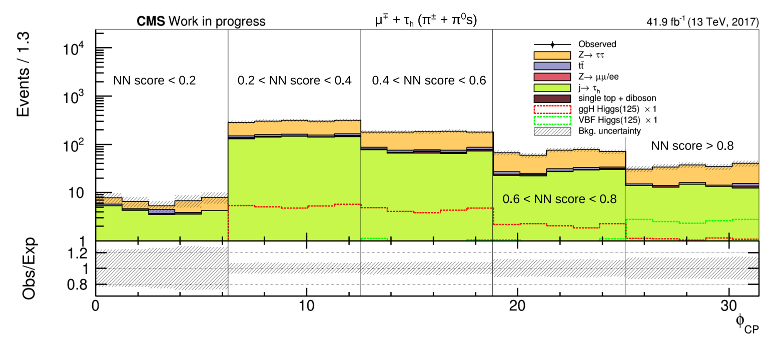
▷ $\rho\rho$



▷ $\mu\rho$ (ggH)



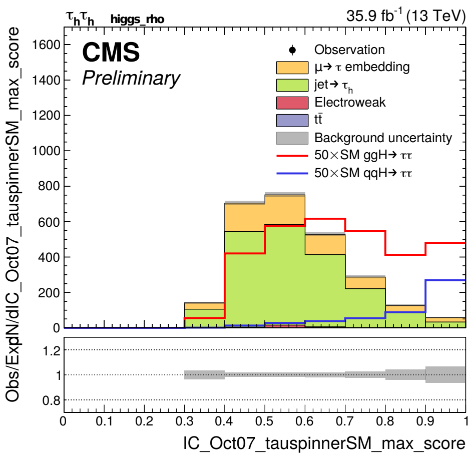
▷ $\mu\rho$ (qqH)



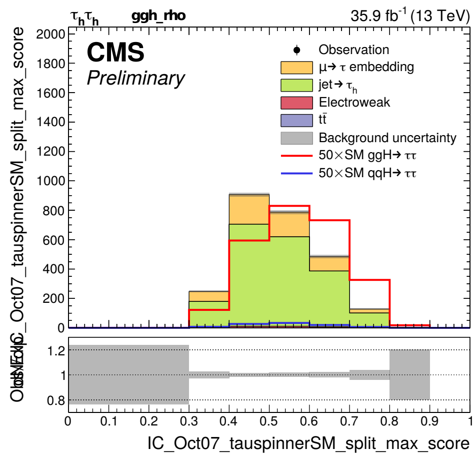
- DESY/IOPB trained multi-class **neural networks** similar to CMS-HIG-18-032 to categorise signal and background processes
- ggH and VBF signal are treated by separate classes

BDT for Signal vs. Background Separation (1)

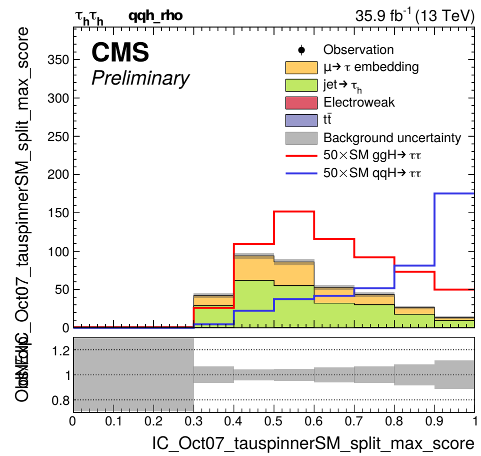
▷ Combined ggH/qqH class

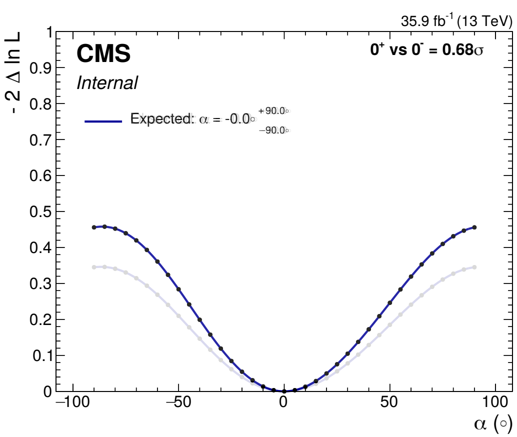


▷ Separate ggH class



▷ Separate qqH class



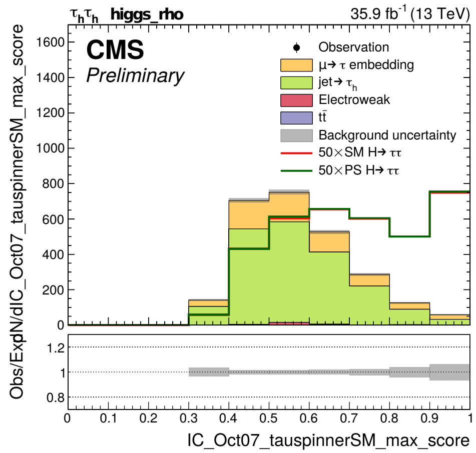


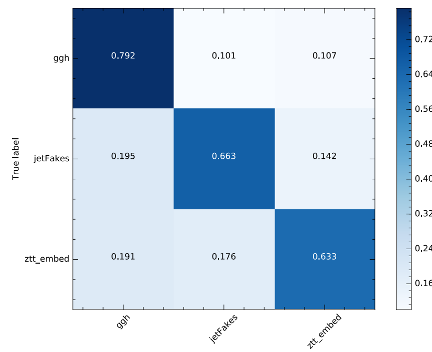
- IC trained multi-class **BDTs** to categorise signal and background processes
- Combined ggH/qqH class provides 15-25% better sensitivity compared to separated classes
- All sub-analysis will implement MVA categorisation soon
  - Still need to converge on the actual method, e.g. BDT vs. DNN

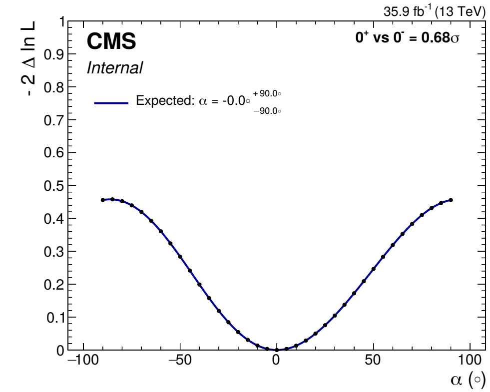
BDT for Signal vs. Background Separation (2)

Albert Dow

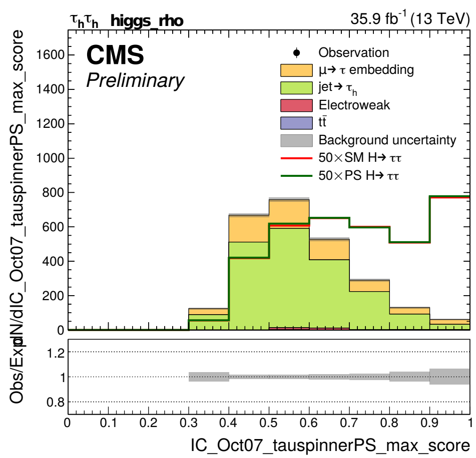
Train on CP even sig.

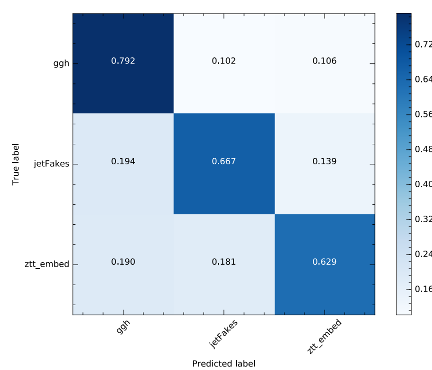


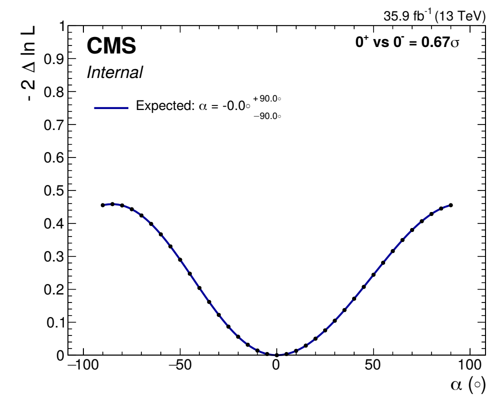




Train on CP odd sig.





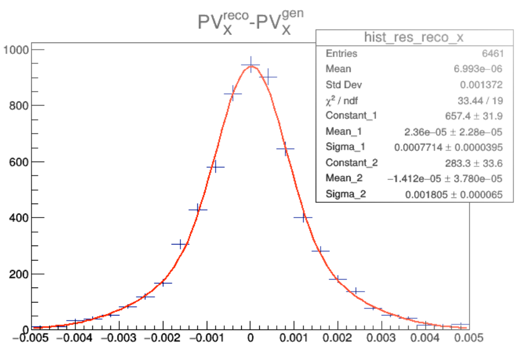


- Signal vs. background training not sensitive to differences between CP even/odd

Primary Vertex Reconstruction (1)

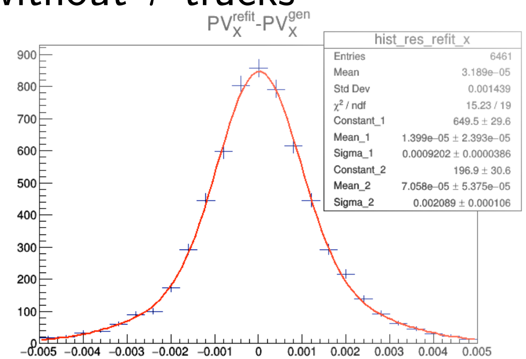
Arun Nayak, Diwakar Vats, Lucas Wiens

▷ Nominal PV



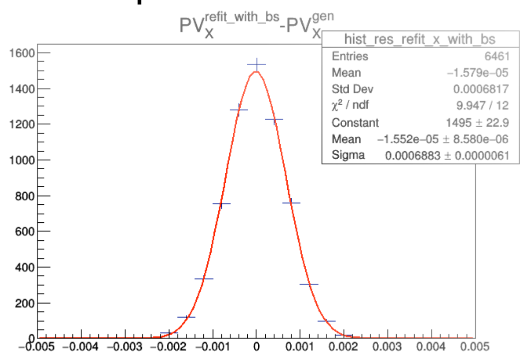
▷ $\sigma_{1/2} = 7.7/18\,\mu$m

▷ Refitted PV without τ tracks



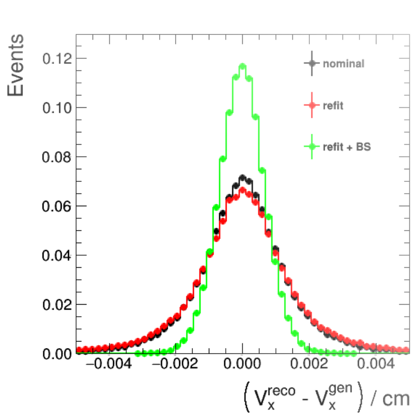
▷ $\sigma_{1/2} = 9.2/21\,\mu$m

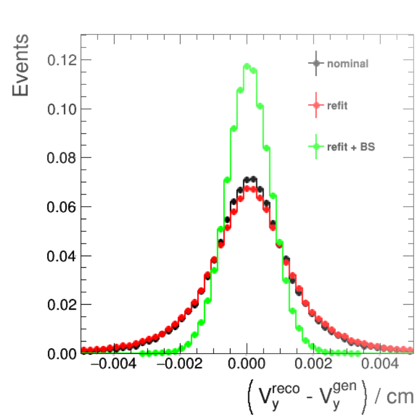
▷ Refitted PV including beams spot constraint

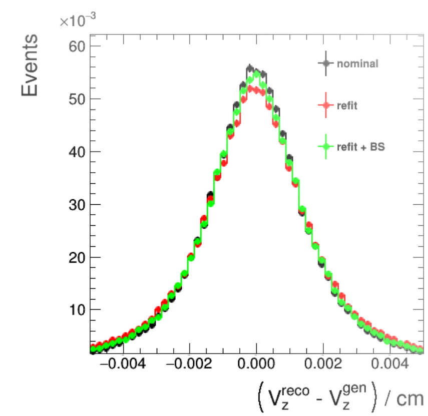


▷ $\sigma = 6.8\,\mu$m

- Slight reduction in resolution when removing high-p_{T} τ tracks
- Strong constraint from beam spot in transversal plane removes long tails



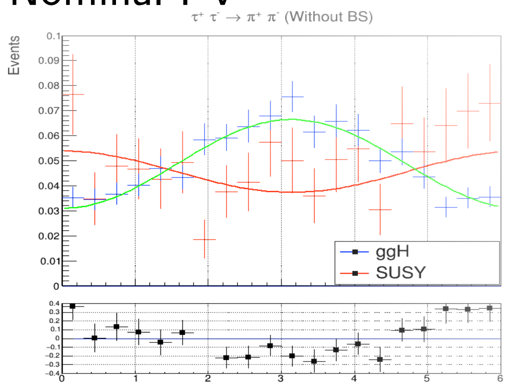




Arun Nayak, Vinay Krishna, Lucas Wiens

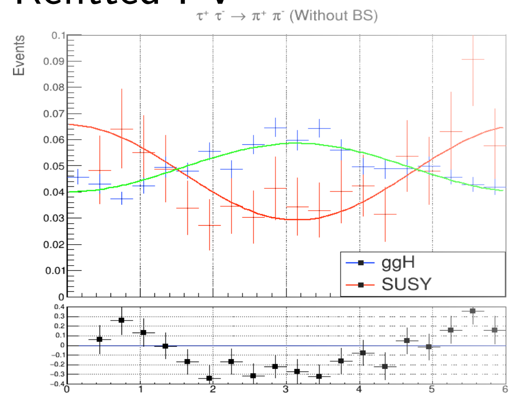
Primary Vertex Reconstruction (2)

▷ Nominal PV



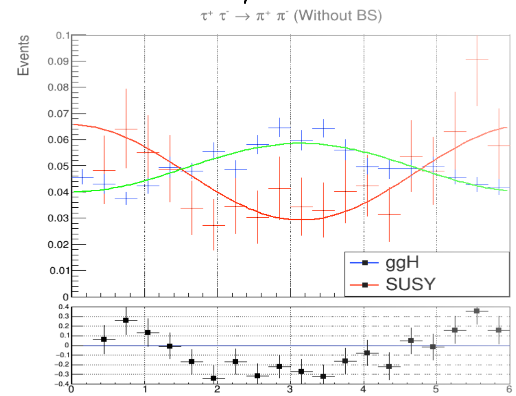
▷ $\left(\frac{a}{b}\right)_{\text{even/odd}} = -0.36/0.18$

▷ Refitted PV



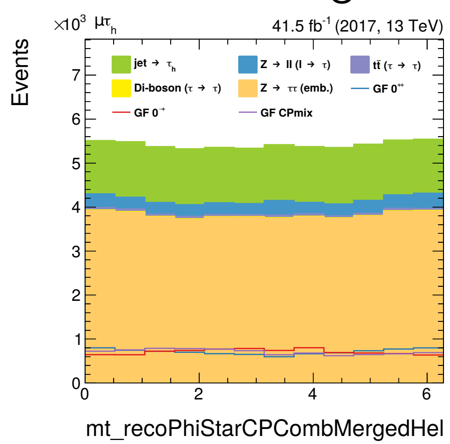
▷ $\left(\frac{a}{b}\right)_{\text{even/odd}} = -0.22/0.38$

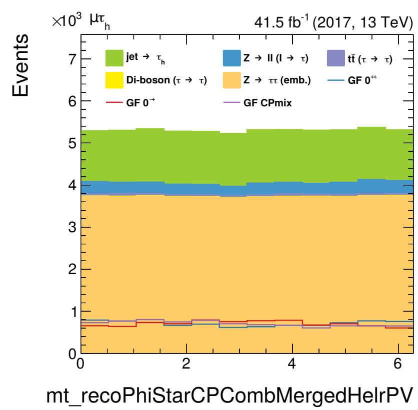
▷ Refitted PV, BS constraint

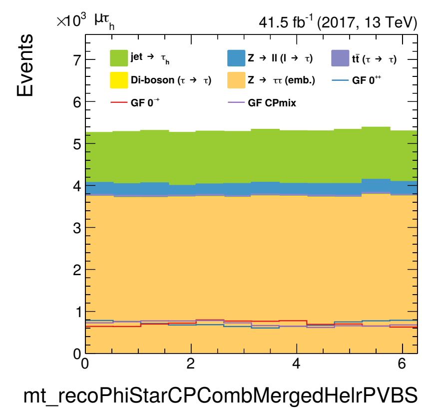


▷ $\left(\frac{a}{b}\right)_{\text{even/odd}} = -0.21/0.51$

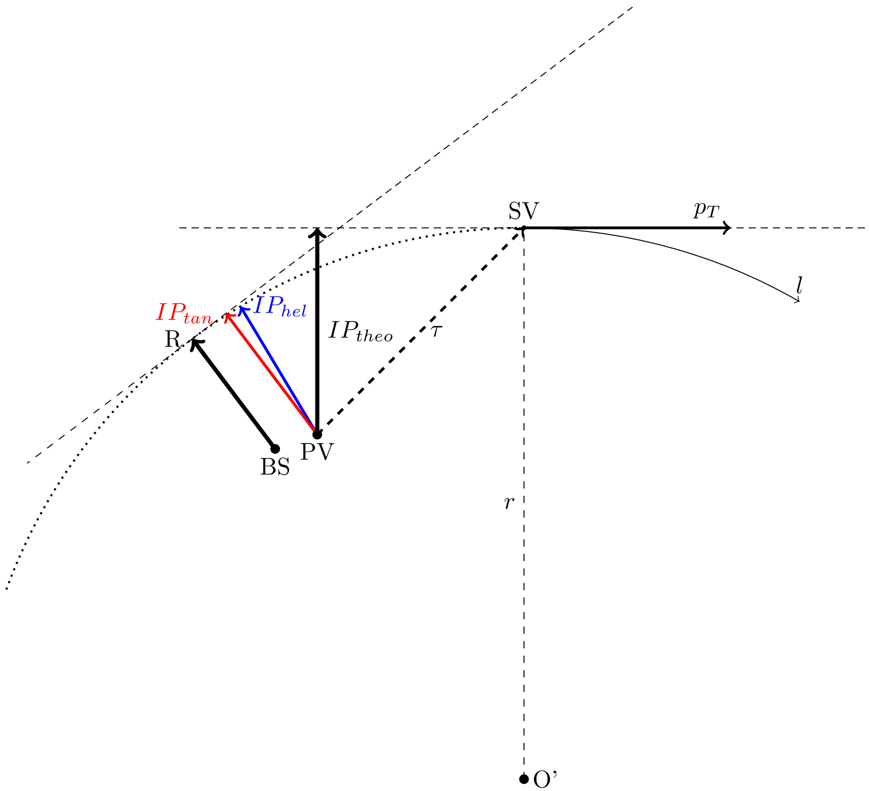
- Separation of pure CP states improves (fit function $a \cdot \cos\varphi^*_{\text{CP}} + b$)
- Removes bias in background distribution, which becomes flat after refitting

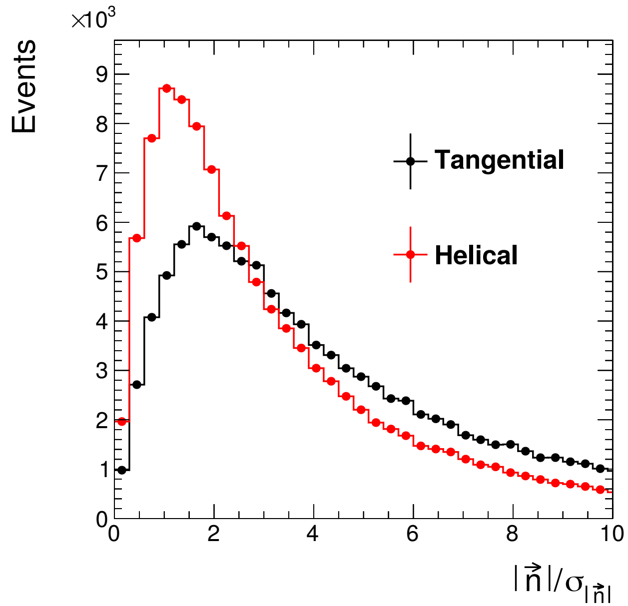






Impact Parameter Reconstruction (1)





- ▷ Tangent: $\Sigma_{\vec{n}} = J_{\text{tan}} \cdot \Sigma_{\text{PV}} \cdot J^T_{\text{tan}}$
- ▷ Helix:

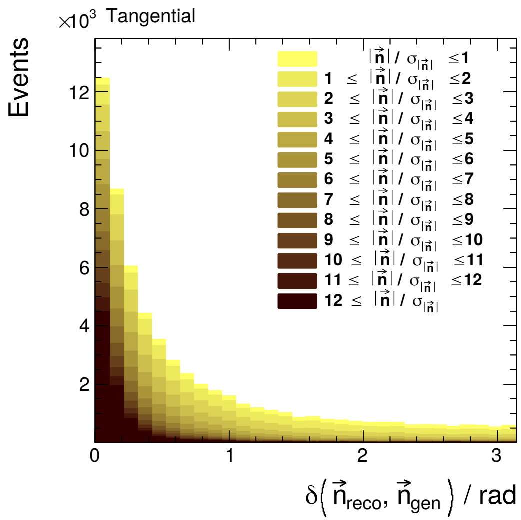
$$\Sigma_{\vec{n}} = J_{\text{hel}} \cdot \begin{pmatrix} \Sigma_{\text{track}} & 0 \\ 0 & \Sigma_{\text{PV}} \end{pmatrix} \cdot J^T_{\text{hel}}$$

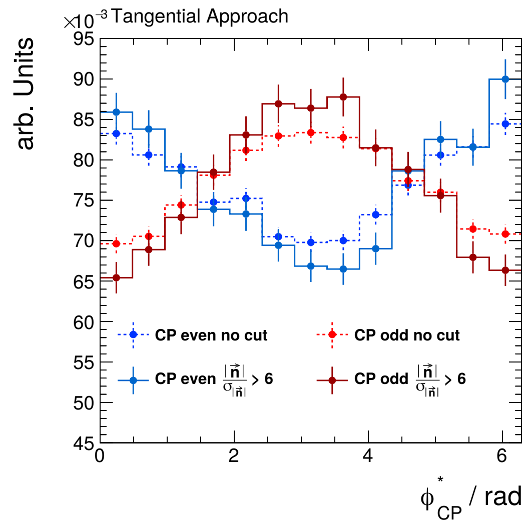
- ▶ Taking into account curvature of tracks does not change the impact parameter vector magnitude/direction significantly
- ▶ Full helical approach allows to include full PV and track uncertainties in impact parameter significance ➜ track uncertainties not negligible

Impact Parameter Reconstruction (2)

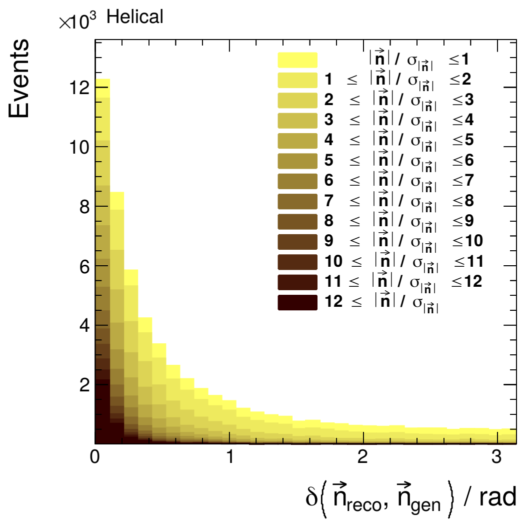
Lucas Wiens

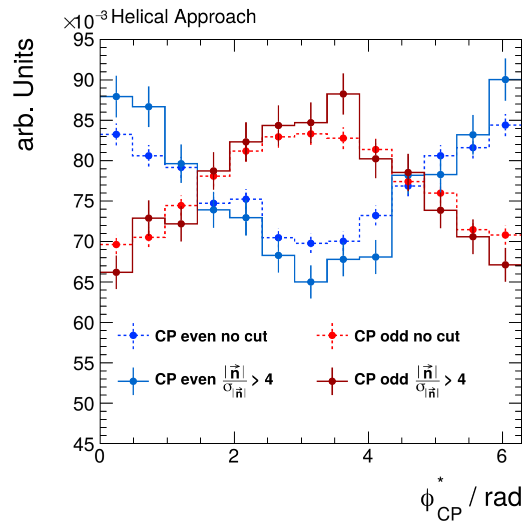
Tangent to track





Track helix

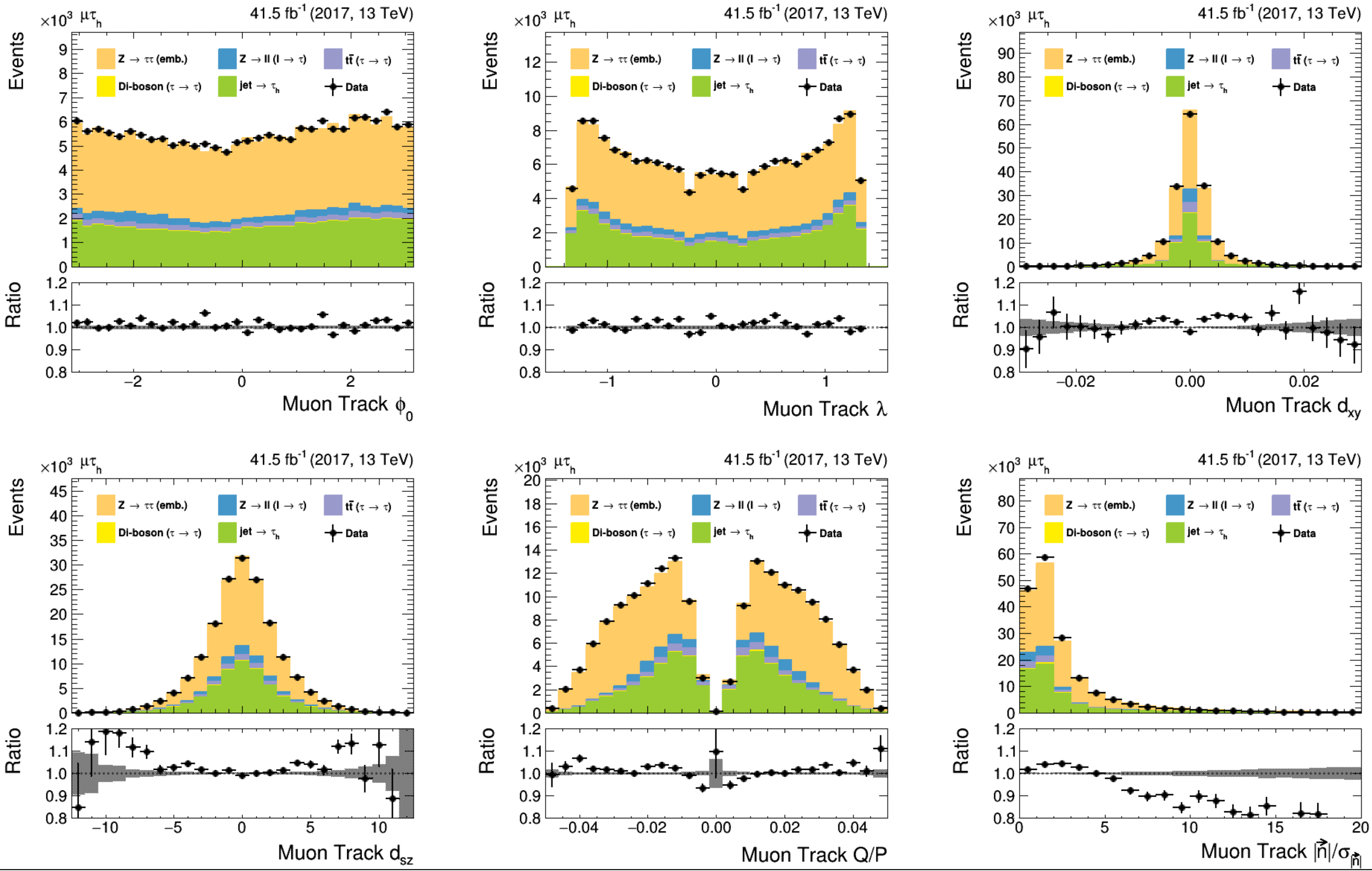




- Cuts on IP significance allow to select events with good IP vector direction reconstruction
- Increased separation in φ^*_{CP} distribution
- Cuts still to be optimised (e.g. for categorisation)

Track Parameters – Data/MC Agreement

Alexander Zotz

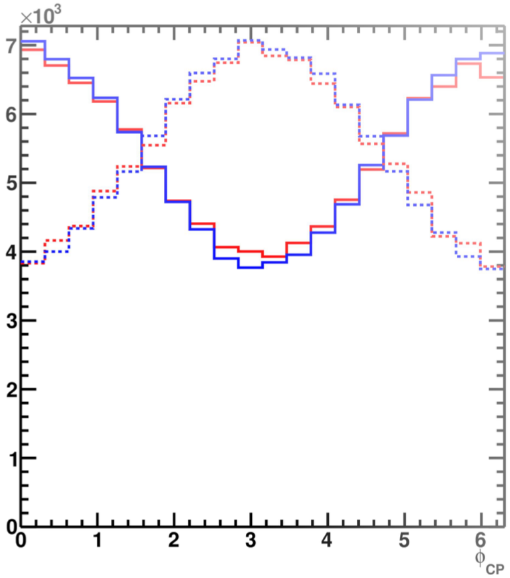


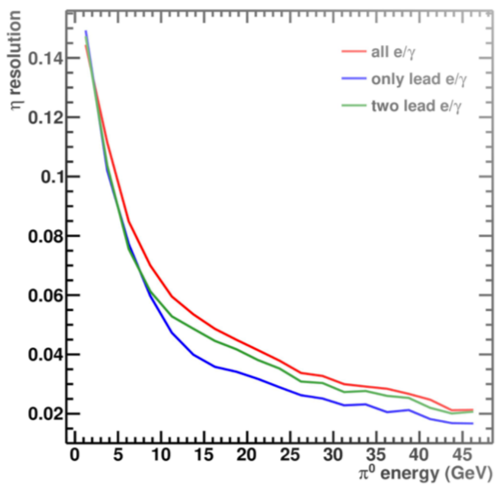
Impact Parameter – Calibration of Simulation

- **Two main sources of disagreement between data and MC**:
  - PV vertex resolution in data, embedding and MC
    - To be corrected by smearing (separate for embedding and MC)
    - Generated PV in embedding set to nominal PV in $Z \to \mu\mu$ events from data
      ➜ resolution plots biased
  - Simulation of track parameters (mainly d_{xy} and d_{sz}, but also q/p)
    - Check impact of momentum correction (mainly for taus) on q/p helix parameter
    - Transverse/longitudinal impact parameters to be corrected by calibration
    - General idea from ML HTT analysis: e.g. talk by Mareike Meyer
- DESY and RWTH groups plan to study this

Decay Plane Method for $\rho^{\pm} \rightarrow \pi^{\pm}\pi^{0}$ Decays

Mohammad Hassanshahi





- HPS: η and ϕ are weighted average over photons in strip
- Leading photon: Leading photon η and ϕ (together with strip energy) provides better separation
  - For high-energy π^0's leading photon has better angular distribution
  - For low-energy π^0's IC plans to use more complicated approaches (e.g. MVA regression)
- Additional plans to work on separate energy corrections for charged and neutral pions

Polarimetric Vector Method

- Polarimetric vector, $\vec{h}$, is a good estimate for the τ spin, $\vec{S}$, direction: $d\Gamma \sim 1 + \vec{h} \cdot \vec{S}$

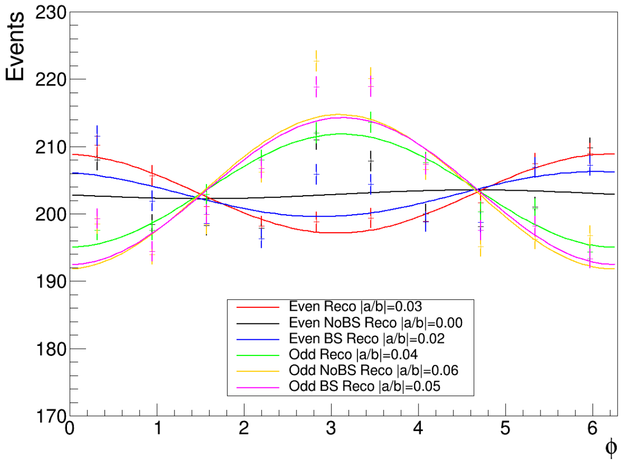
$$\tau^{\pm} \rightarrow \pi^{\pm} \nu : \vec{h} = -\vec{n}_{\pi}$$

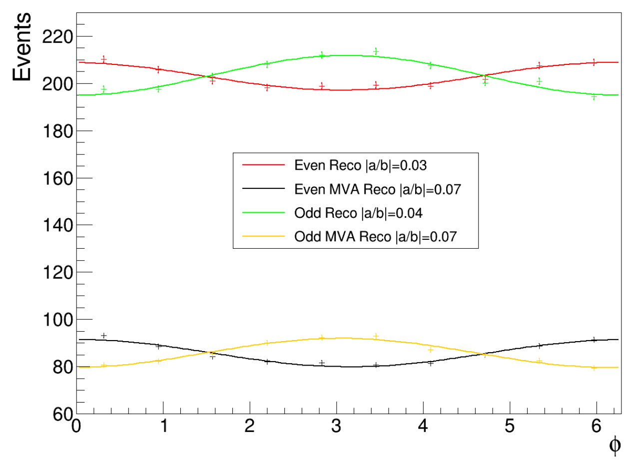
$$\tau^{\pm} \rightarrow \rho^{\pm} \nu \rightarrow \pi^{\pm} \pi^{0} \nu : \vec{h} = m_{\tau} \frac{2(qN)\vec{q} - q^{2}\vec{N}}{2(qN)(qP) - q^{2}(NP)}$$

$m_{\tau}: \tau$ mass

$q: \pi^{\pm} - \pi^{0}$, $N: \nu = \tau^{\pm} - \pi^{\pm} - \pi^{0}$, $P: \tau^{\pm}$ } 4-vectors

  - More complicated definition for a_1 decay, see e.g. Phys. Rev. D61 (2000) 012002
    - Requires knowledge of the τ momentum
    - Possibility for full event reconstruction with τ SV from 3-prong decays

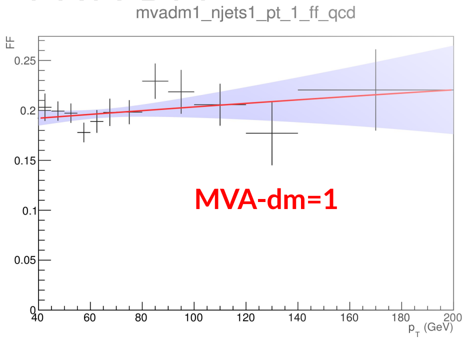


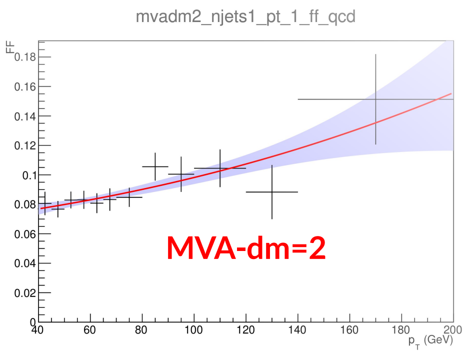


- Analysis fully set up ➜ Promising results, details still to be cross checked
- Sensitivity to be compared with other a_1 methods (together with IC), e.g.
  - IP method with leading charged pion track
  - Decay plane spanned by τ flight direction (from SV) and $a_1 = \sum \pi^{\pm}$ momentum

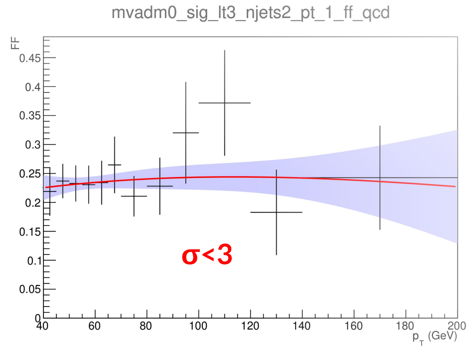
Fake Factors

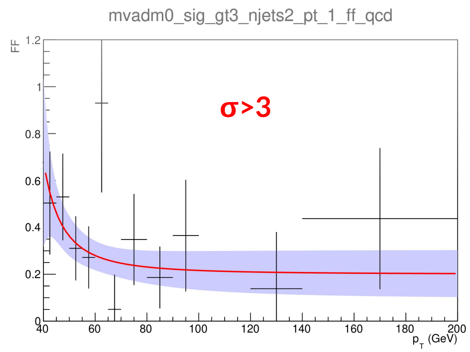
▷ Dependence on τ MVA DM



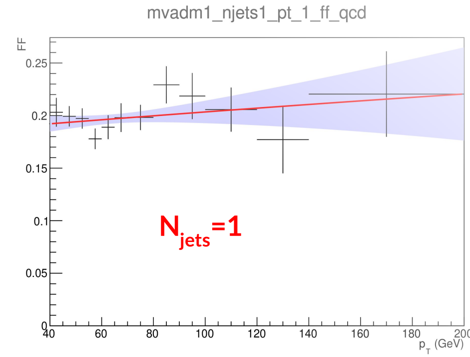


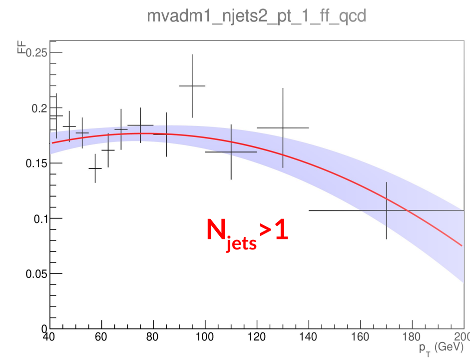
▷ Dependence on IP significance





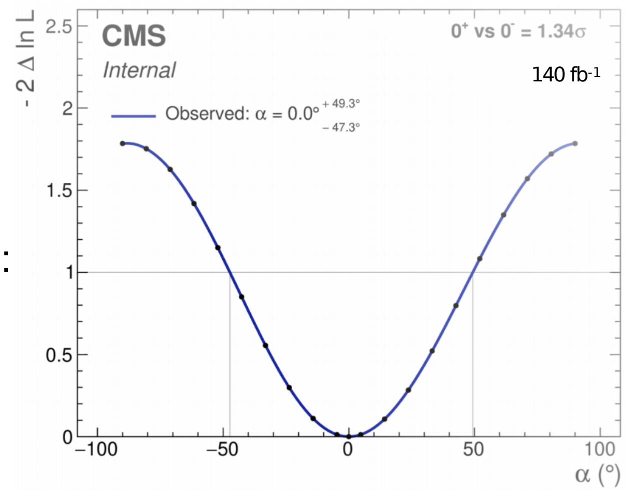
▷ Dependence on jet multiplicity





- Fake factors depends on CP-relevant quantities
- Needed to (re-) measure them separately for all categories in CP analysis
- IC started with measurement in ρ categories
  - Update needed after final analysis is set up

- **Measurement of Yukawa couplings to τ leptons**
  - Analysis is completely orthogonal to ggH initial state CP analysis (focus on top Yukawa couplings)
  - One CP parameter (mixing angle α_τ)
  - Two free signal scaling μ_{ggH} and μ_{qqH} parameter (times $\mu_{\tau\tau} = 1$ to be more precise)
  - CP even scaling: $a_1\, a_1 - a_1\, a_3$
  - CP odd scaling: $a_3\, a_3 - a_1\, a_3$
  - Scaling for maximum mixing ($\alpha_\tau = \frac{\pi}{4}$): $2\, a_1\, a_3$
  - $a_1 = \sqrt{\mu_{\tau\tau}} \cos\alpha_\tau,\ a_3 = \sqrt{\mu_{\tau\tau}} \sin\alpha_\tau$



- **Projection from 2016 samples to full run 2 dataset**:
  - Only $\rho\rho$ and $a_1\rho$ categories
  - No deepTauID included so far
  - Improvement from more categories/final states expected
  - Sensitivity to exclude $\alpha_\tau > \frac{\pi}{4}$ at 68% CL feasible

- Combine (Harvester) setup for CMSSW_10_2_13:

  github.com/albertdow/CombineHarvester/tree/HTTCPDecays18- dev/HTTSMCPDecays18

- Physics model:

  github.com/albertdow/CombineHarvester/blob/HTTCPDecays18-dev/ CombinePdfs/python/CPMixtureDecays.py

Synchronisation

- **Current status**:
  - Most analyses can produce control plots with reasonable data-MC agreement
  - Analyses roughly synchronised w.r.t. published (SM) HTT analysis
- **Ntuple-level sychronisation plans**:
  - Add CP-relevant quantities to SM HTT-based synchronisation
    - MVA DMs, IPs, PV, SV, charged/neutral momenta
    - TauSpinner weights, scale factors, event weights
  - Synchronisation samples for CMSSW version $\geqslant$ 10_2_16
    - /VBFHToTauTau_M125_13TeV_powheg_pythia8/RunIISummer16MiniAODv3-PUMoriond17_94X_mcRun2_asymptotic_v3-v2/MINIAODSIM
    - /VBFHToTauTau_M125_13TeV_powheg_pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_new_pmx_94X_mc2017_realistic_v14-v1/MINIAODSIM
    - /VBFHToTauTau_M125_13TeV_powheg_pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15_ext1-v1/MINIAODSIM
  - Techniques to be included
    - deepTauID, MVA DMs
    - PV refitting
    - PUPPI MET, DeepFlavour
- Twiki: twiki.cern.ch/twiki/bin/viewauth/CMS/HiggsCPinTauDecaysSync

Publication Plans

- **Final goal**: paper for/after Moriond 2020
  - First (CMS) measurement of CP properties in τ Yukawa couplings
  - Paper about different methods to reconstruct decay planes
  - Analysis will be based on SM HTT analysis but diverge starting from categorisation on

- **Preliminary timeline**:
  - Write AN until end of November
  - Ask for CADI line before Christmas
  - (Pre-) approval in February
  - PAS for Moriond 2020 (March 2020)

Conclusion and Outlook

- All sub-analyses/frameworks well set up for at least one channel and data of one year
- Synchonisation will start as soon as possible
- Groups working towards analysis set up from full run-2 data up to likelihood scans
- Most promising channels well covered (only electron channels not looked at so far)
- This will be included:
  - deepTauID and τ decay mode MVA
  - PV vertex refit without τ tracks
  - Helical reconstruction of impact parameter (uncertainty)
- This still needs to be studied and decided:
  - PUPPI MET (to be discussed with HWW group)
  - Beam spot constraint (bias on background shape?)
  - Which MVA method to separate signal from background?
  - DY MC vs. Embedding ➜ **how exactly are spins simulated in embedding?**
- **Some links**:
  - Minutes: e-group mail
  - Mailing list: HiggsCPinTauDecays-CMS@cern.ch
  - Working group meetings: indico.desy.de/indico/category/656 (Mondays, 13h)
  - Analysis twiki: twiki.cern.ch/twiki/bin/view/CMS/HiggsCPinTauDecays