CP in $H \to \tau\tau$ decays
1st Workshop
Oct 2019, DESY

Status update from DESY

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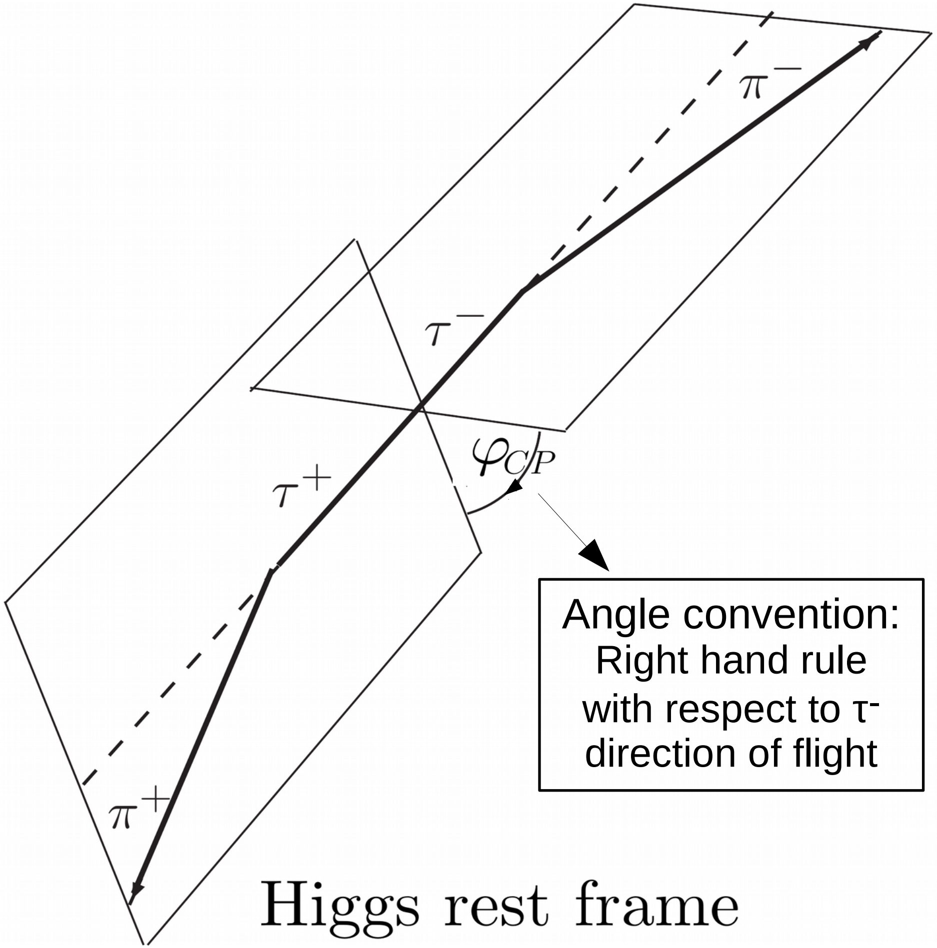
Deutsches Elektronen-Synchrotron - DESY

Achieved milestones

- Generator level studies in all channels
- Study of the $\mu\tau_h$ channel in 2017
  - Obtain good data/MC agreement
  - FF method, Embedded samples on the way
  - NN categorization to improve signal/bkg classification
- Datacard production → Combine setup almost ready

The acoplanarity angle

- To access the spin correlation we need to measure the angle between the τ decay planes
- Each plane is identified by 2 vectors:
  - One is the the momenta of the charged decay product ($\pi^{\pm}$,$\mu^{\pm}$,$e^{\pm}$,a_1)
  - The other is chosen depending on the decay channel:
    - 1 Prong: IP vector
    - 1 Prong + π^0s: momenta of the π^0s
    - 3 Prong: vector connecting PV and SV



CP angle at generator level

Boost reference vector $\hat{n}^{*\pm}$ in ZMF of charged decay products

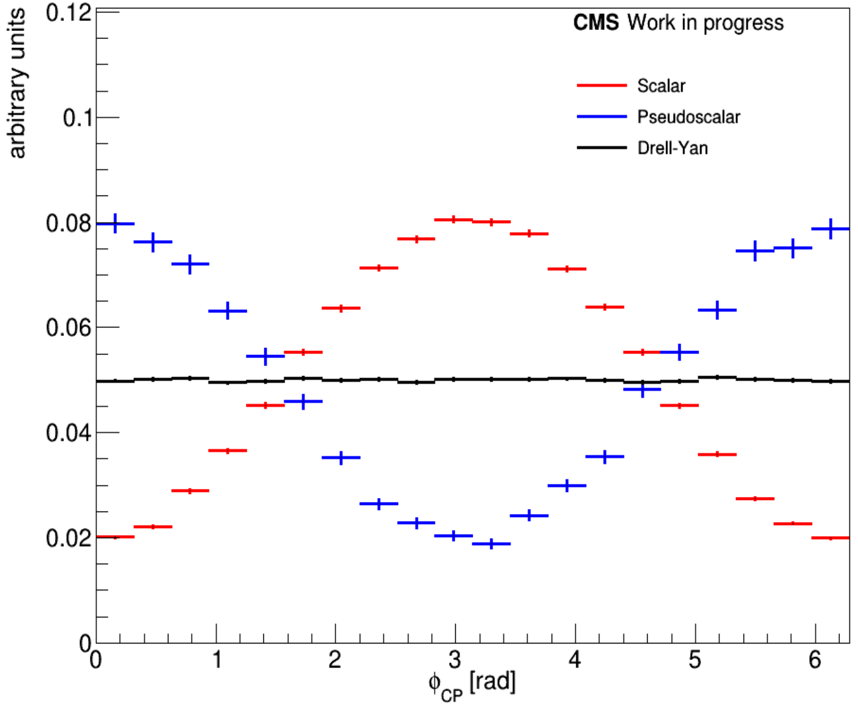
Use transverse components with respect to the prong momenta in that frame: $\hat{n}_{\perp}^{*\pm}$

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

$$O_{CP}^{*} = \hat{q}^{*-} \cdot (\hat{n}_{\perp}^{*+} \times \hat{n}_{\perp}^{*-})$$

$$\phi_{CP} = \begin{cases} \phi^{*} & if \;\; O_{CP}^{*} \geqslant 0 \\ 2\pi - \phi^{*} & if \;\; O_{CP}^{*} < 0 \end{cases}$$

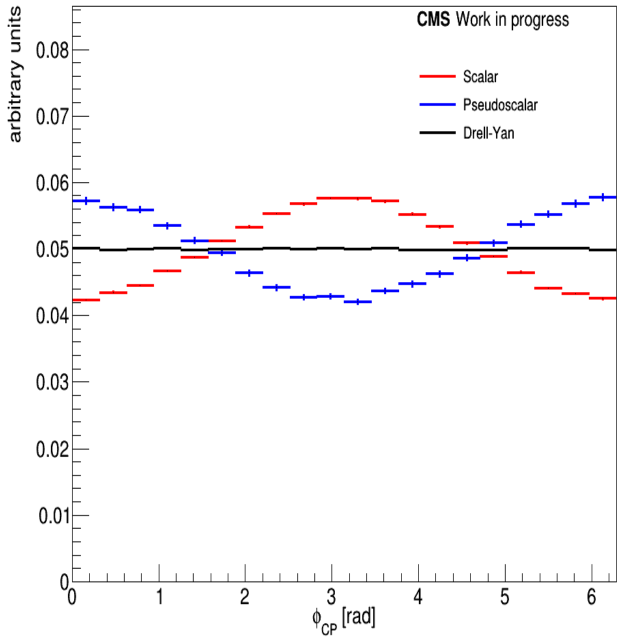
ππ - channel



No cuts are applied for these gen level studies
Results at reconstruction level will be shown later

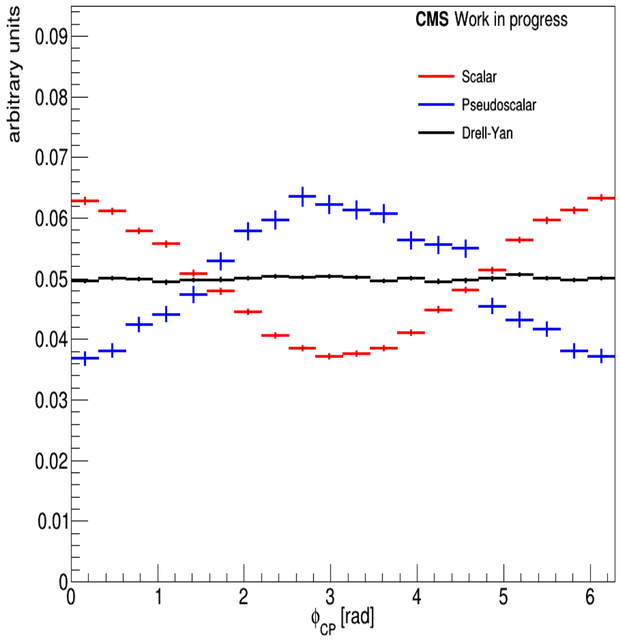
CP angle at generator level

ρ π - channel



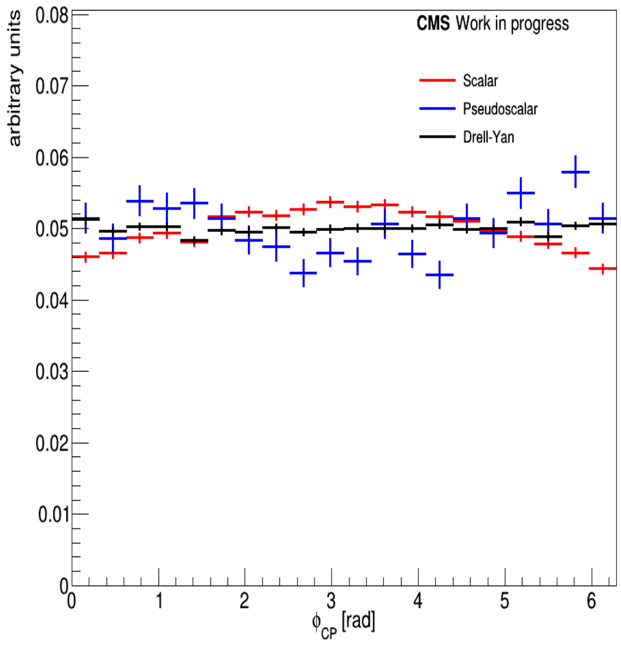
Competitive with ππ after categorization for ρ spin

μ π - channel



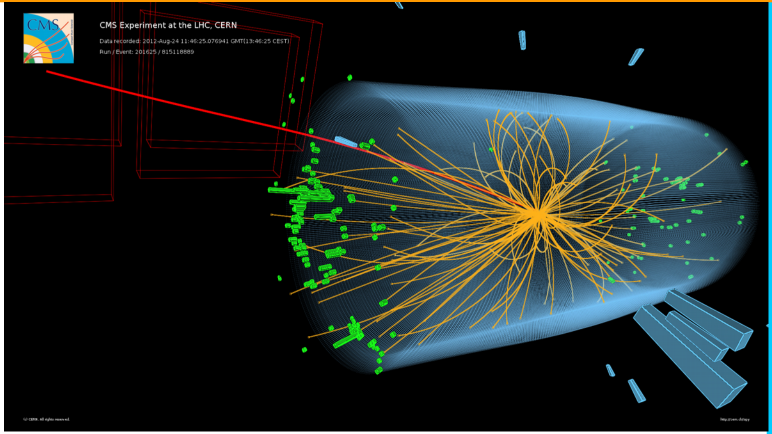
Note the shift in distribution due to two neutrinos

a_1π - channel



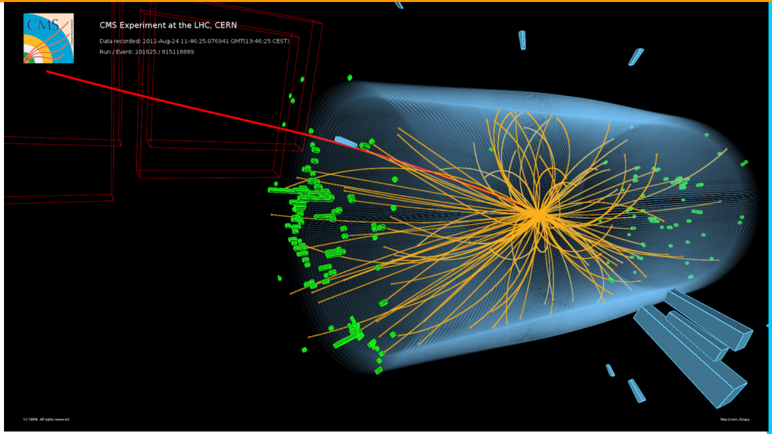
Without using the a_1 spin the sensitivity is lost

Reconstruction level



- Channel: $\mu\tau_h$
- Trigger: SingleMu24, SingleMu27 and Mu20Tau27
- Event selection:
  - Isolated μ with $p_T > 20$ GeV, $|\eta| < 2.1$
  - Hadronically decaying τ with $p_T > 30$ GeV, $|\eta| < 2.1$
  - $\Delta R > 0.5$ between muon and tau
  - Veto for other leptons with $p_T > 10$ GeV
  - Jets defined with $p_T > 30$ GeV
  - Tight wp for Tau Iso and against-mu discriminator, VLoose for against-ele

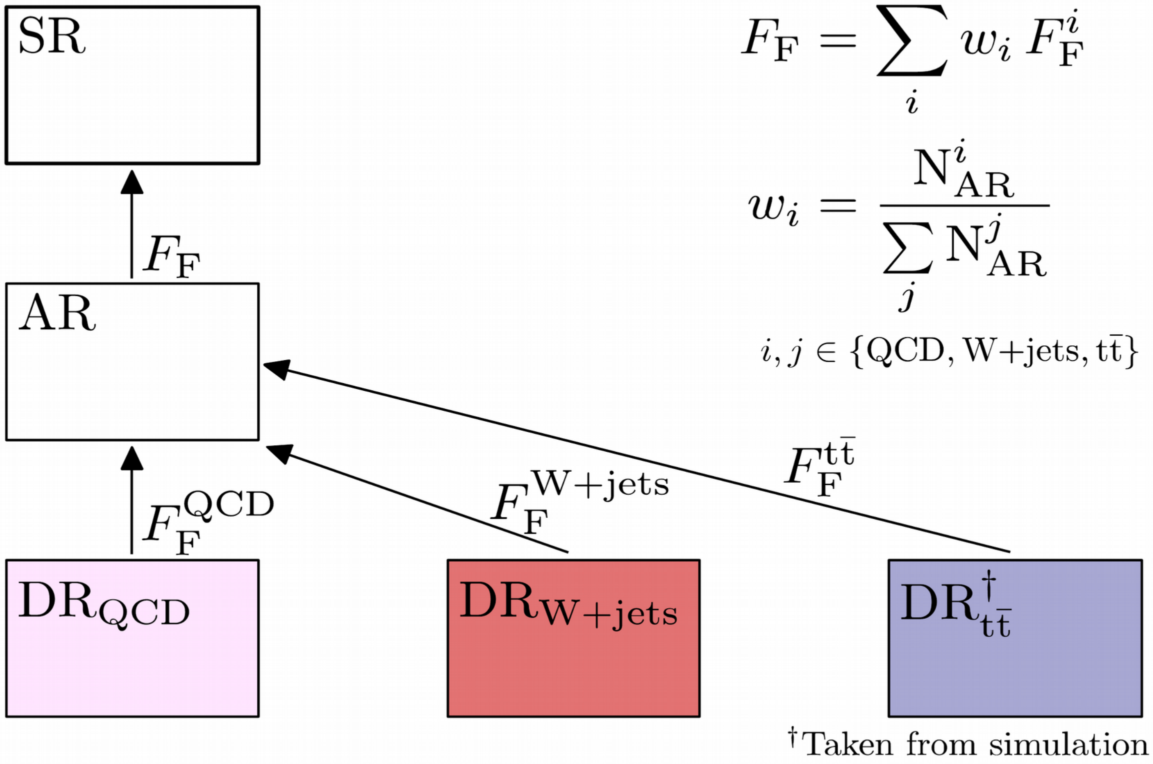
Reconstruction level



- Applied corrections:
  - PU reweighting
  - Trigger and lepton isolation efficiencies
  - Track efficiency
  - Tau ID flat SF
  - lep$\rightarrow\tau_h$ SF
  - Z and top pT reweighting
  - Recoil corrections and Type 1 corrected pfmet
  - Tau ES
  - Jet ES
  - Dilepton and extra lepton veto

Fake Factor method

- Data-driven method for background estimation with several contributions
- The phase space is divided into:
  - SR: signal region
  - AR: application region
  - DRs: determination regions
    - These regions have no cuts relative to the variable which separates AR and SR
- Each region is orthogonal to the others
- The method:
  - Weights for each processes are determined in their respective DRs
  - The weights are combined and applied in the AR to determine the bkg contribution in the SR



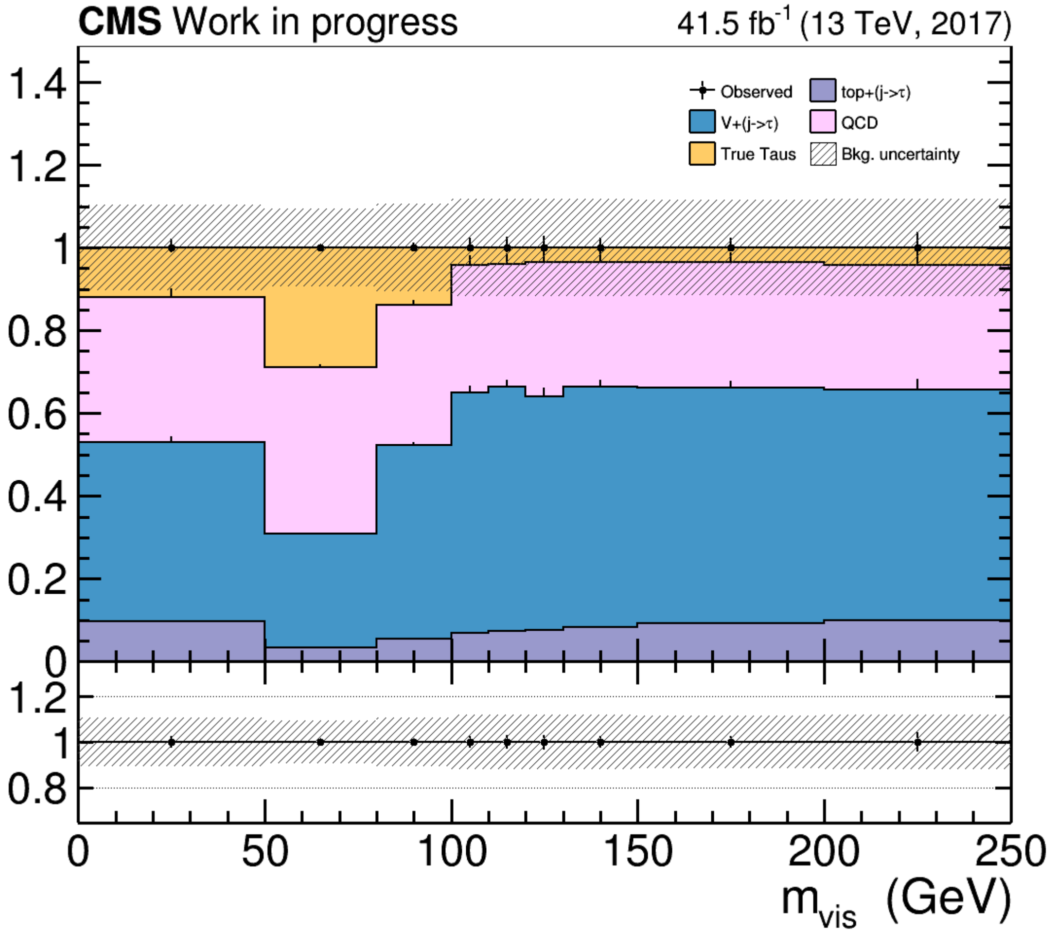
Weight calculation

- Inputs for weight calculation:
  - Tau pT
  - Tau decay mode
  - Number of jets
  - Visible mass
  - Transverse mass (mT)
  - Muon isolation

  } Already available

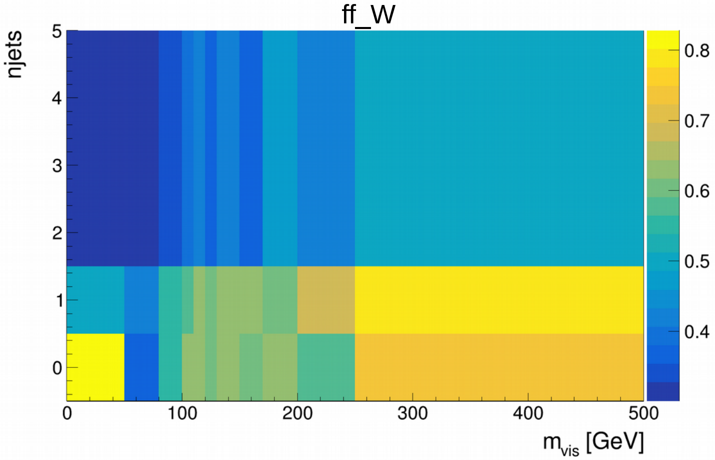
  - Fractions of QCD, Top, and W+jets events in anti-isolated region (!TightMVA2017v2 and VLooseMVA2017v2)
    - These fractions need to be computed by requiring that the reconstructed hadronic tau is a **jet at generator level**: genmatching==6
- Note: for a good method implementation the data/MC agreement should be good for these variables and the method **depends on the Tau Isolation discriminator**

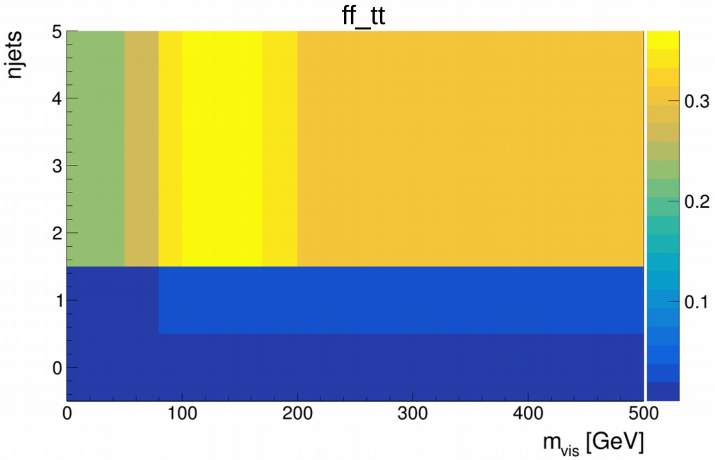
Anti-iso region



- QCD = data – (true taus + $V(j \rightarrow \tau_h)$ + $top(j \rightarrow \tau_h)$)
- Fake fractions are then renormalized to 1
- Actual fractions are computed as 2D distributions in njets and m_{vis}

Fractions of fakes

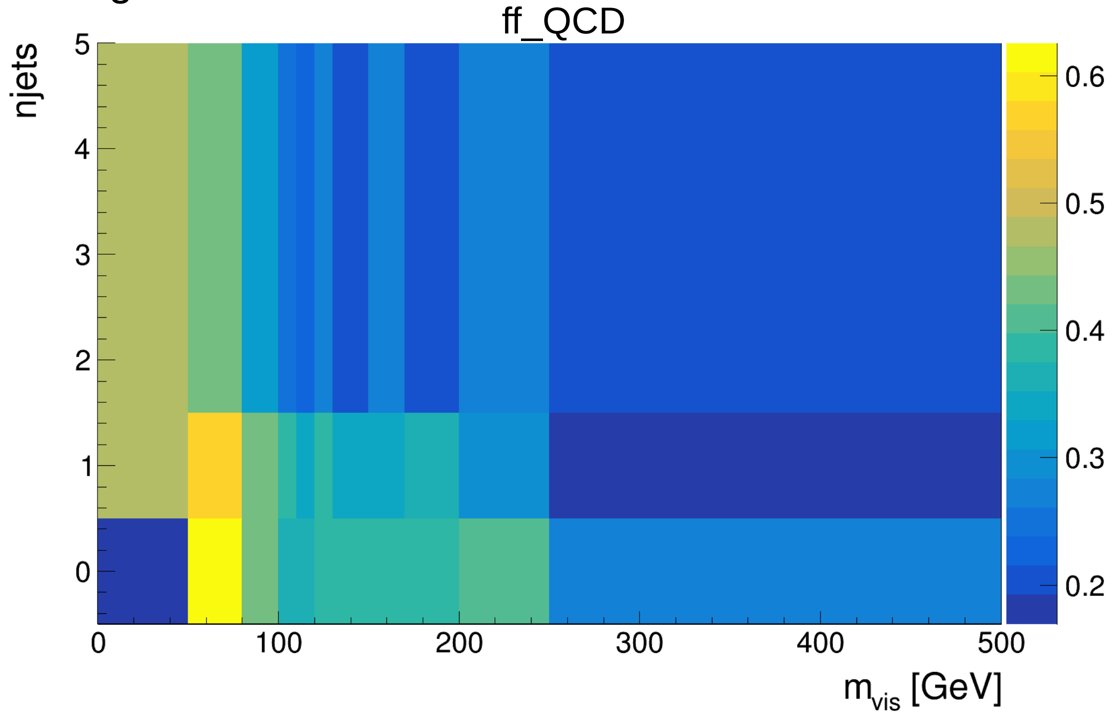




X axis: m_{vis} [0,50,80,100,110,120,130,150,170,200,250,2000]

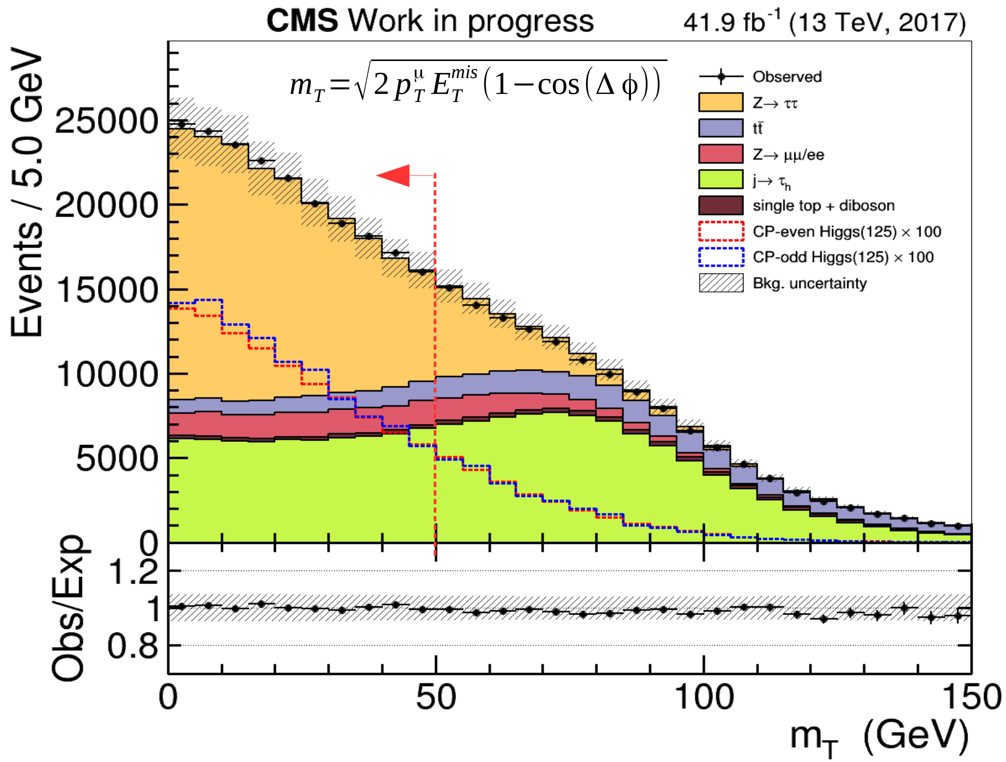
Y axis: njets [-0.5,0.5,1.5,15]

Z axis: bkg/data ratio



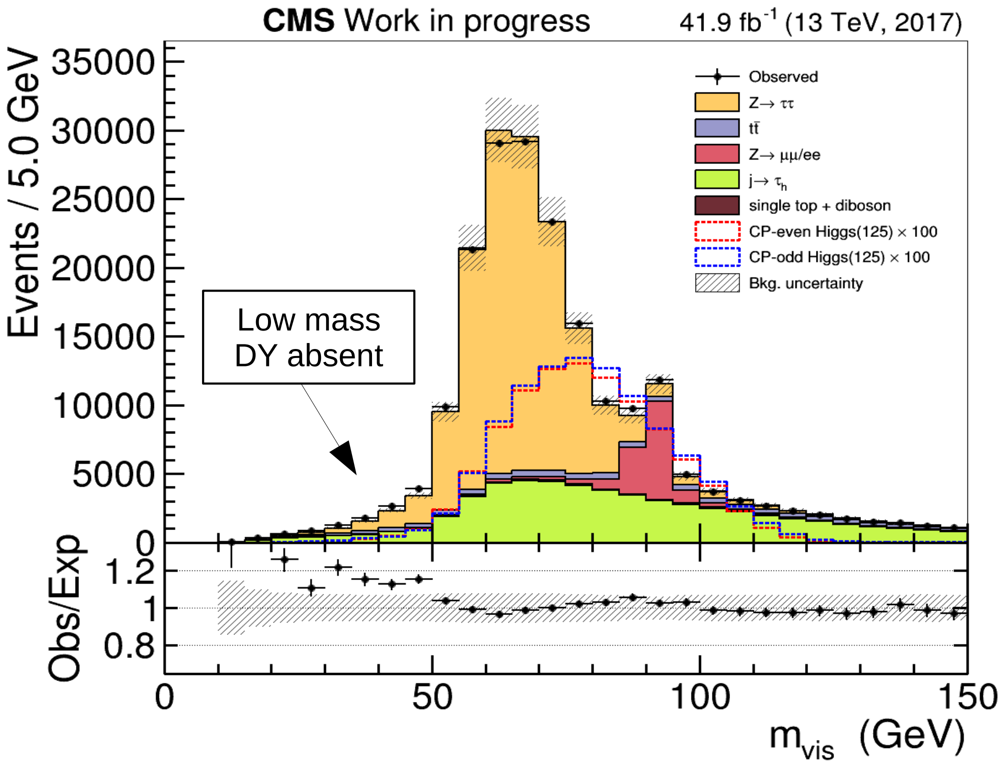
Inclusive selection region

Transverse mass



A cut on m_T is used to reduce the $j \rightarrow \tau_h$ bkg

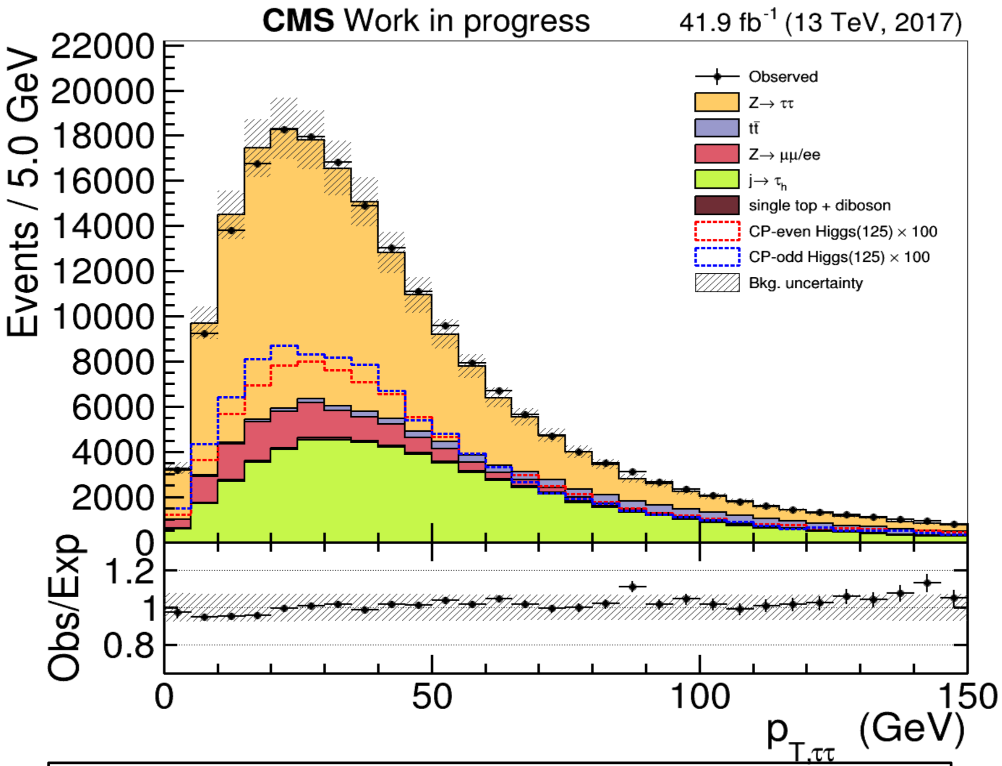
Visible mass



Both plots show a good data / MC agreement

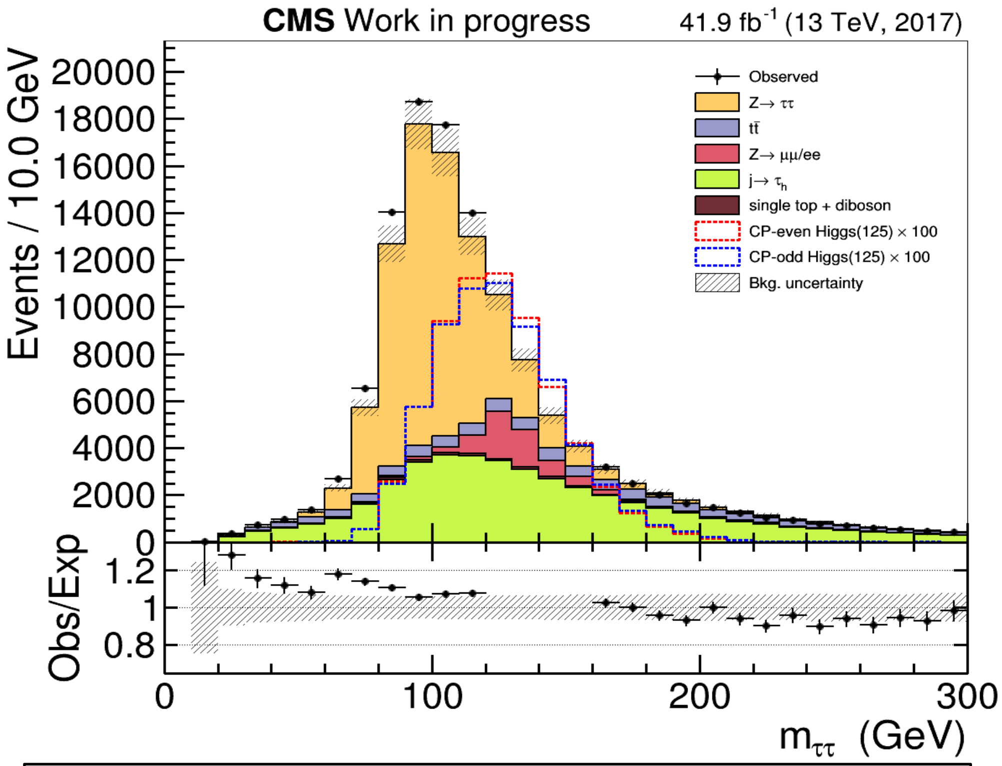
Inclusive selection region: ττ system

SVFit di-tau p_T



Good agreement over the whole range

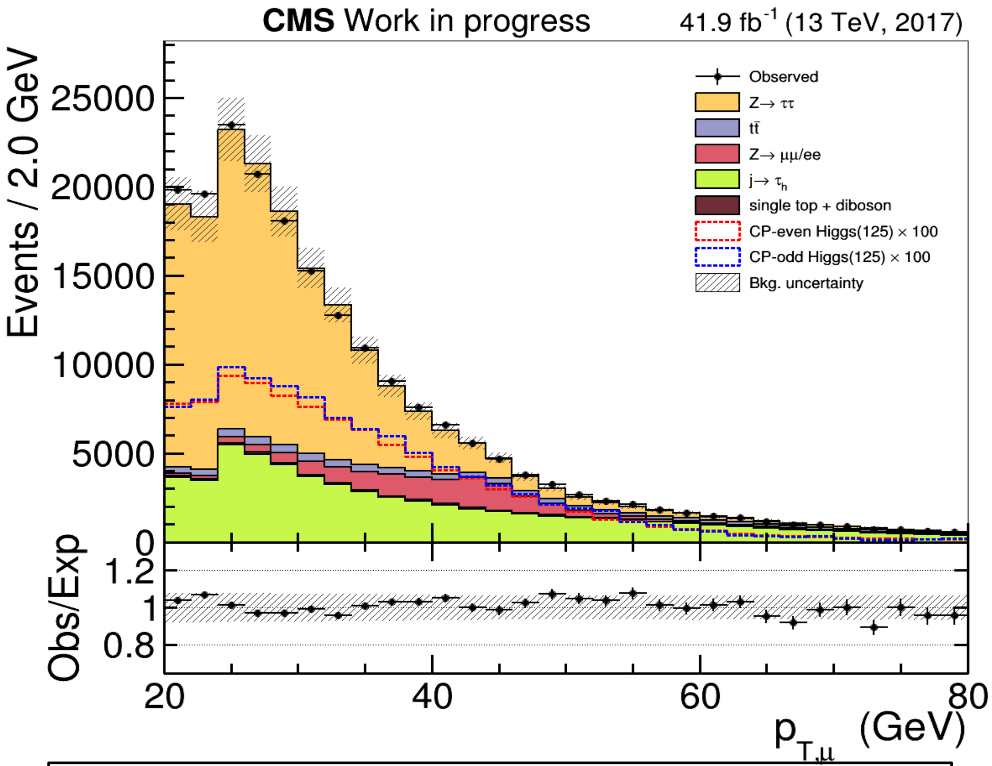
SVFit di-tau mass



Data blinded around the Higgs peak

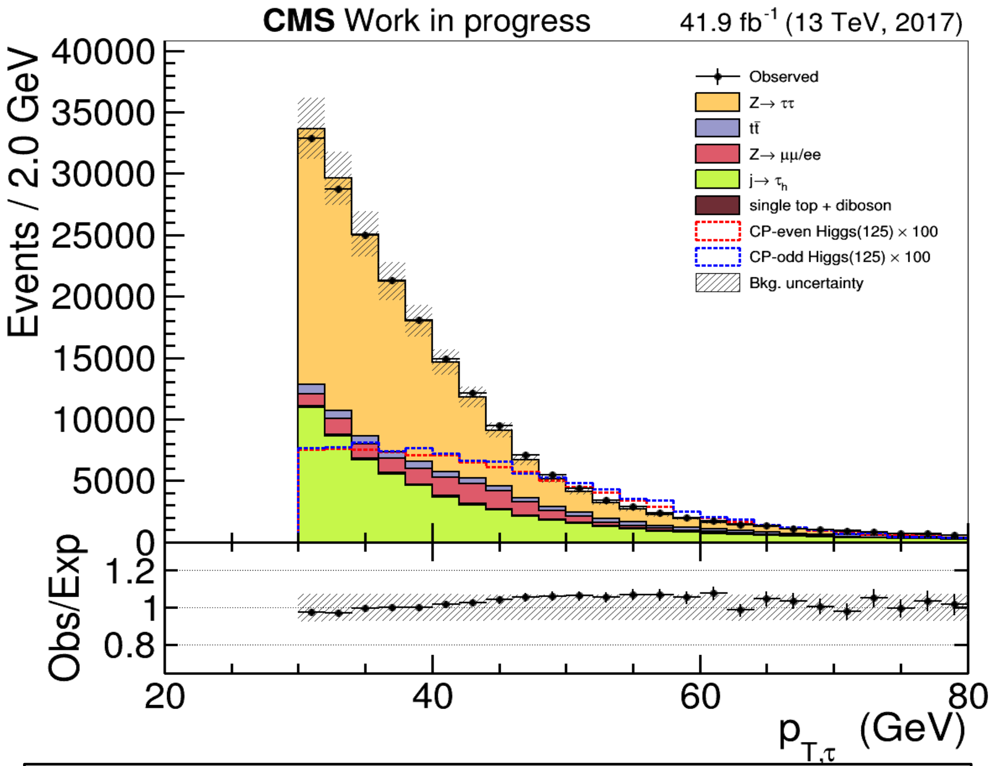
Inclusive selection region: leptons

Muon transverse momenta



Good muon reconstruction

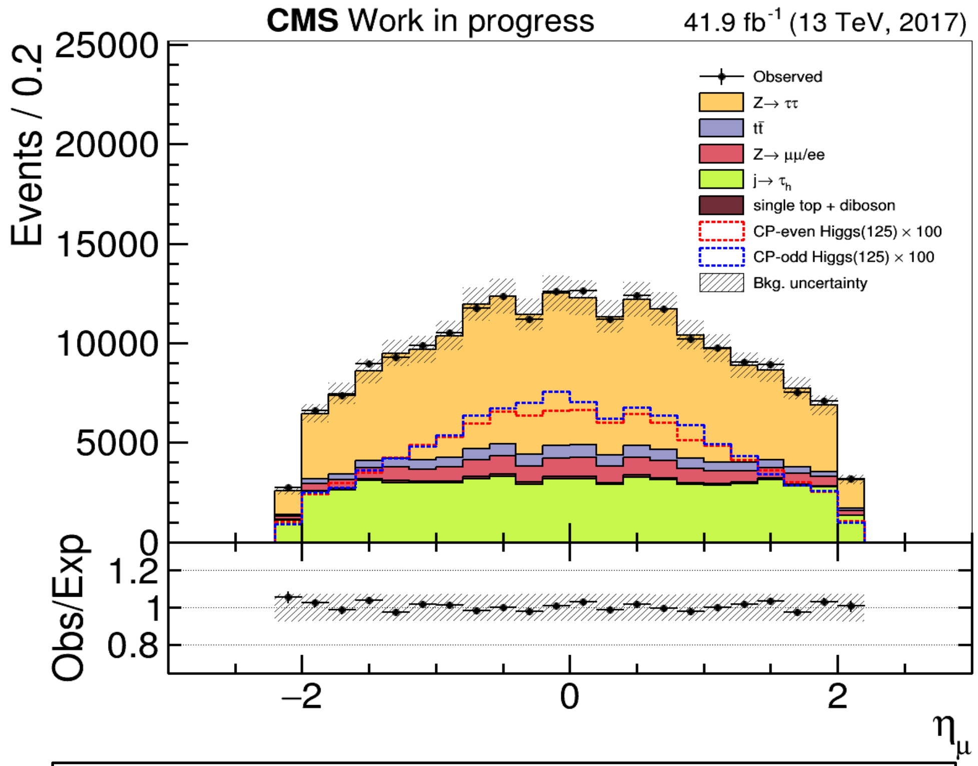
Tau transverse momenta



Small τ ES effect observed

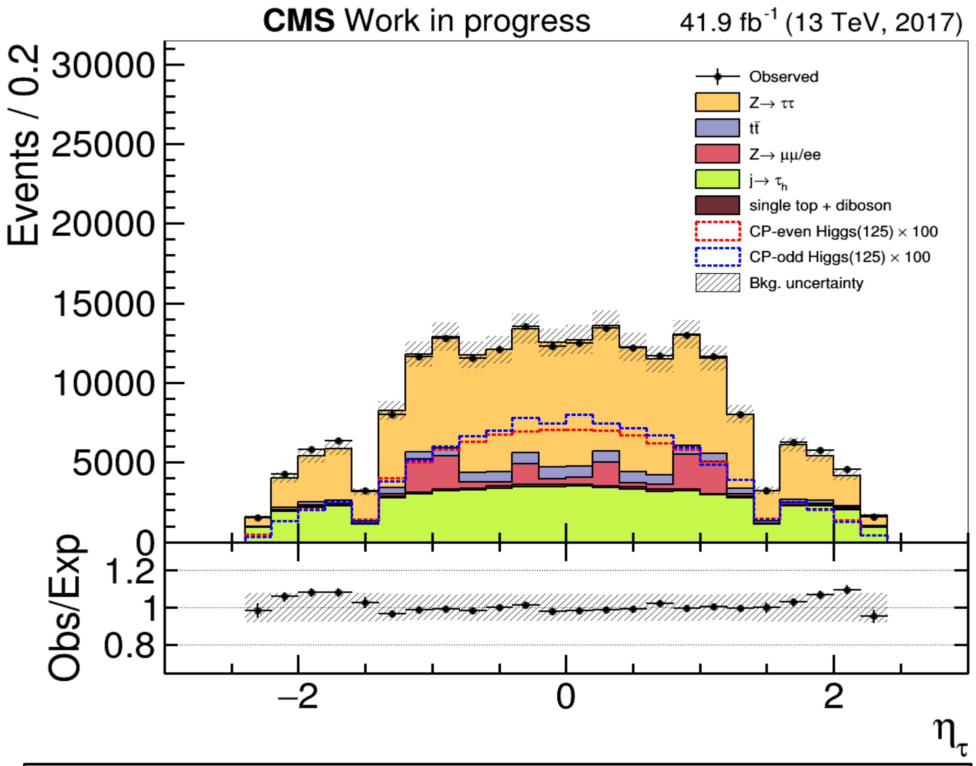
Inclusive selection region: leptons

Muon pseudorapidity



Good muon reconstruction

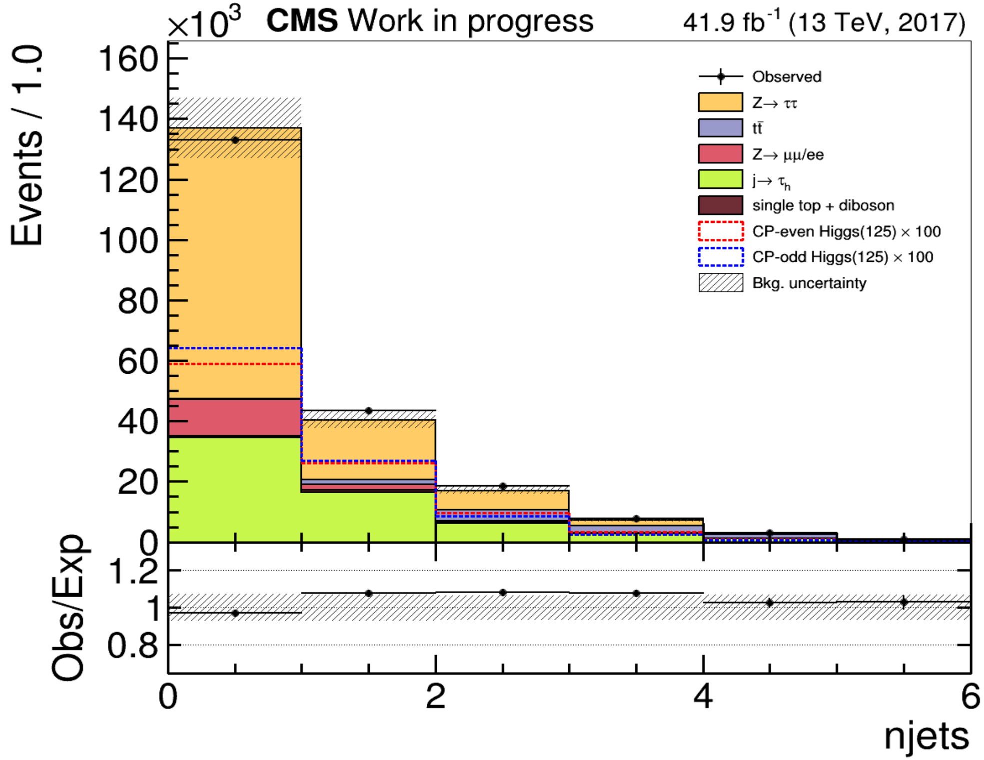
Tau pseudorapidity



Small deviation in EC-

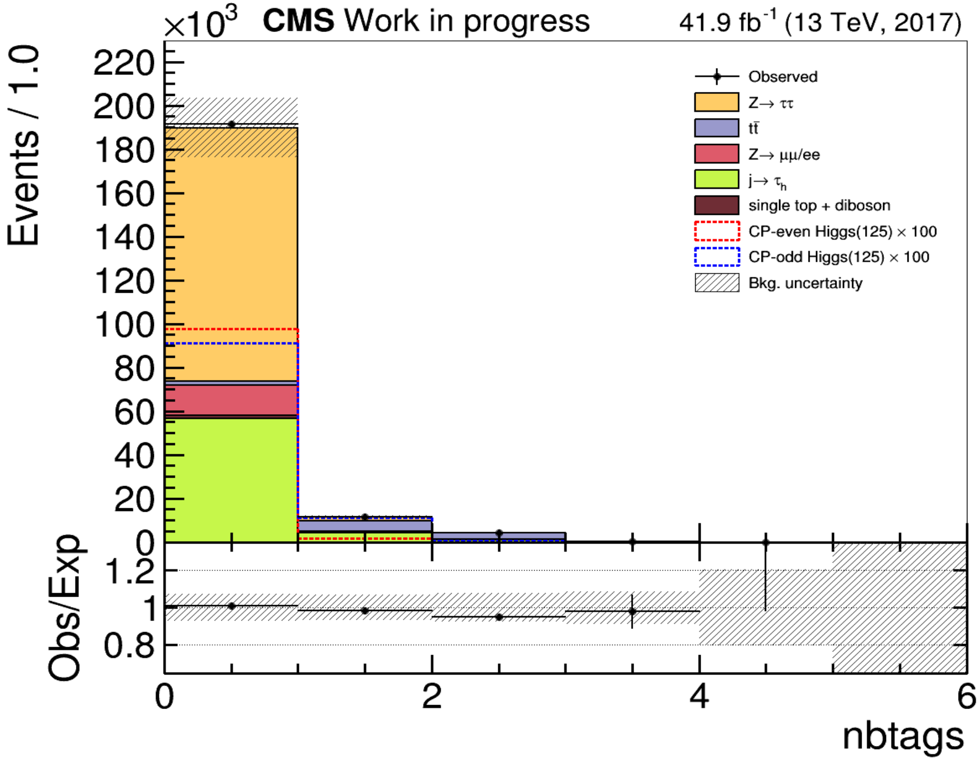
Inclusive selection region: jets

Number of jets



Jet counted with $p_T > 30$ GeV

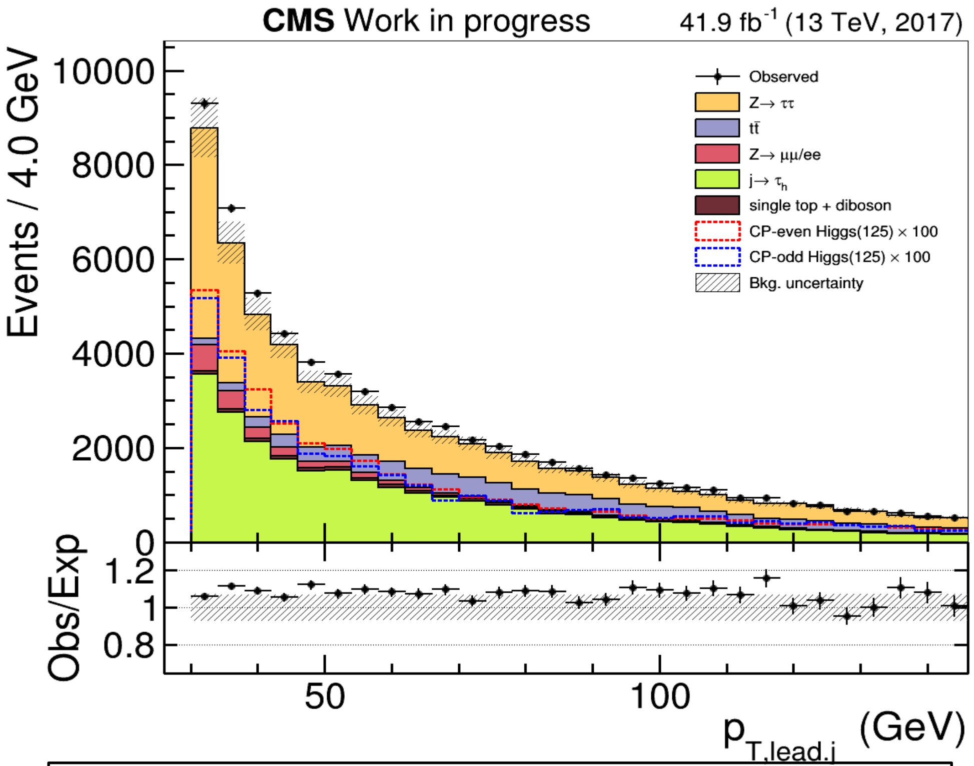
Number of b-jets



CP-odd contains b-associated production

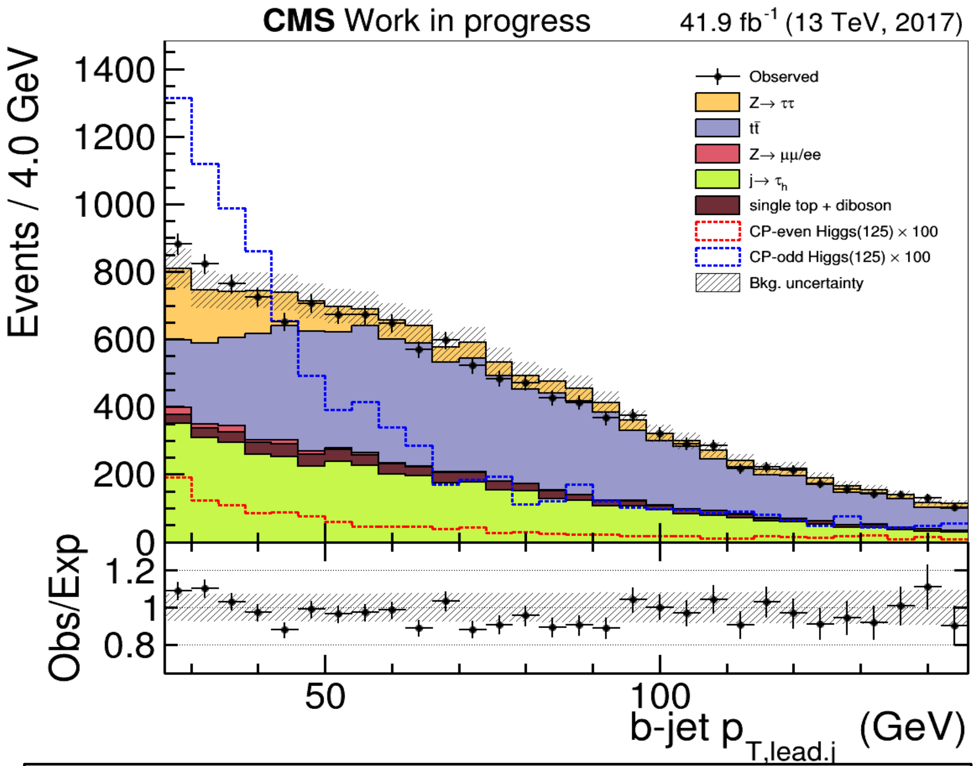
Inclusive selection region: jets

Leading jet p_T



Slight normalization problem

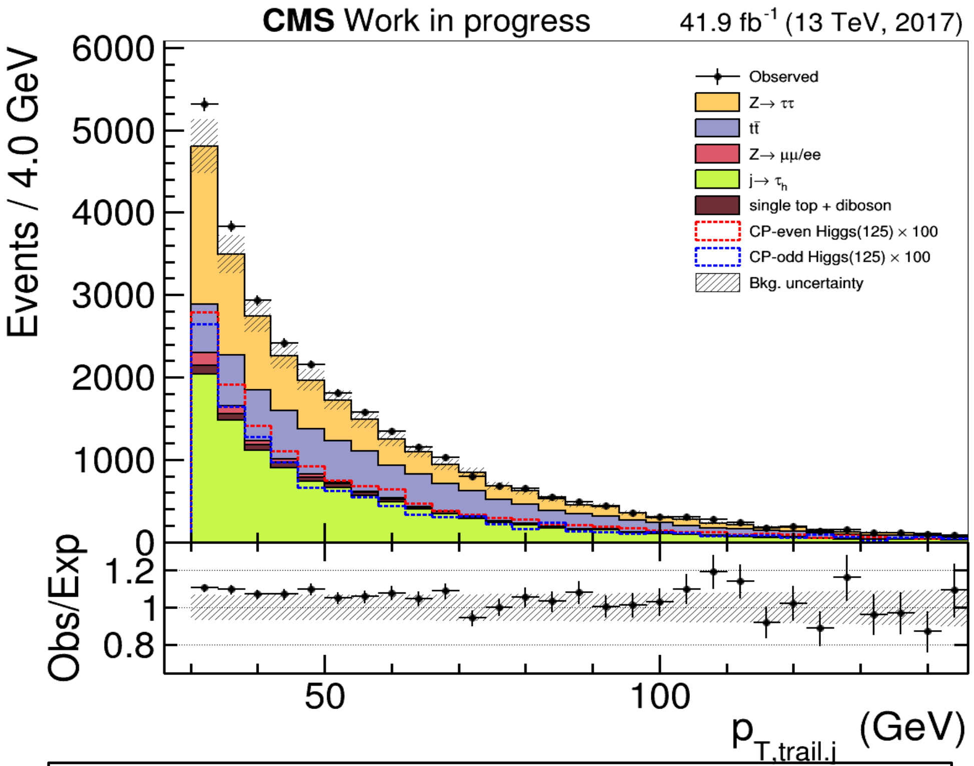
Leading b-jet p_T



CP-odd contains b-associated production

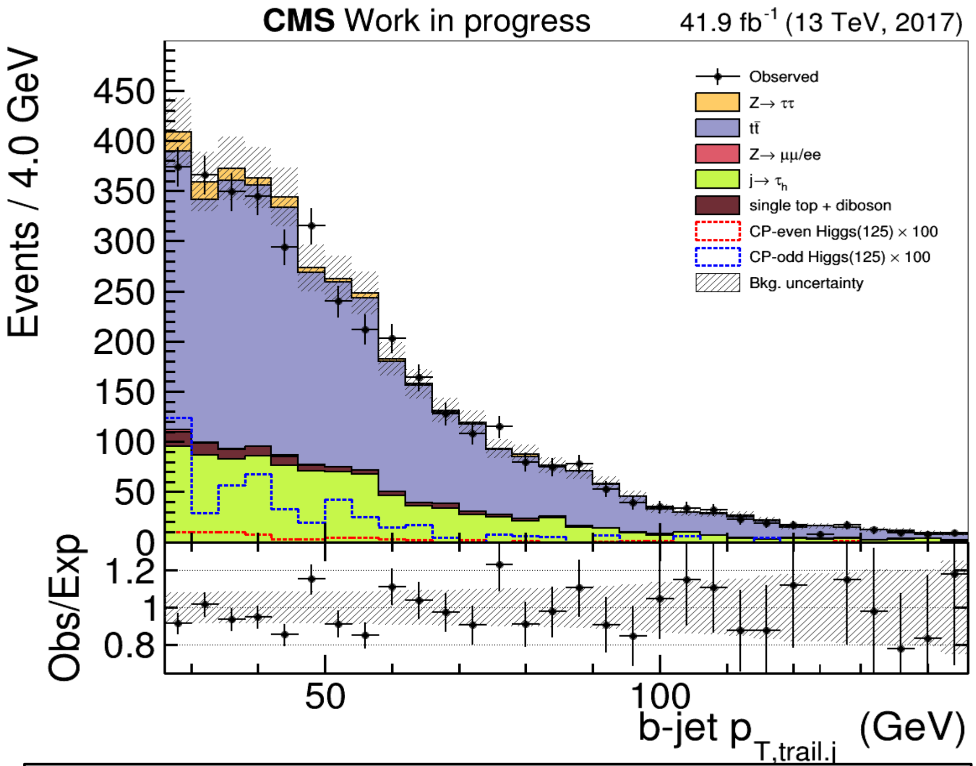
Inclusive selection region: jets

Sub-leading jet p_T



Slight normalization problem

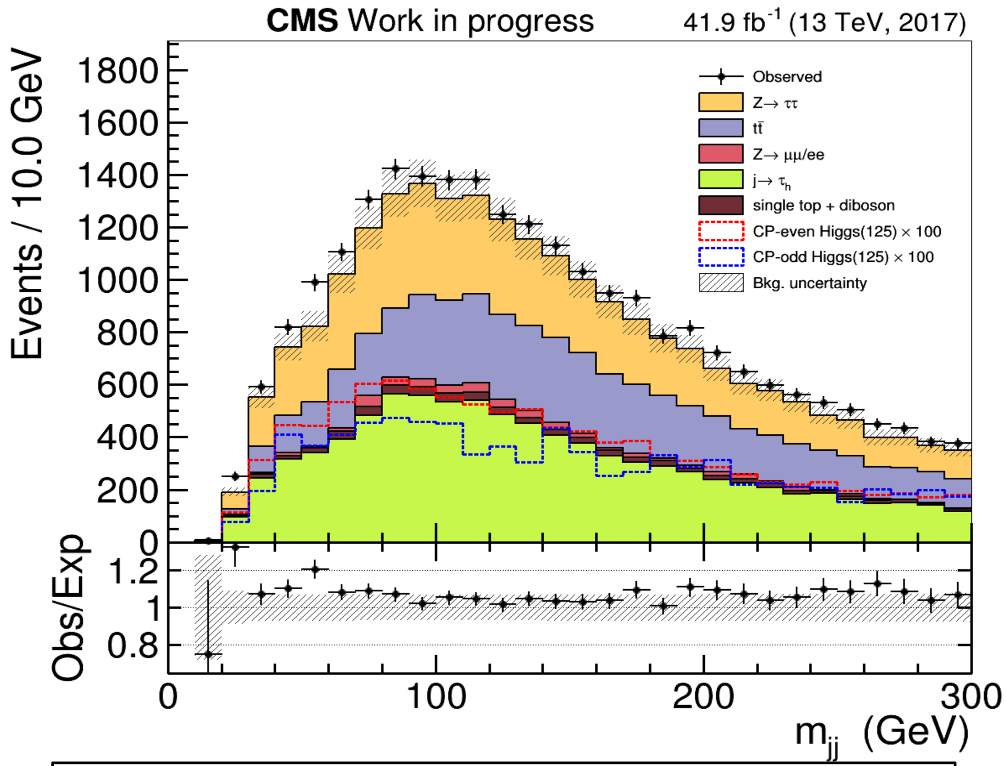
Sub-leading b-jet p_T



CP-odd contains b-associated production

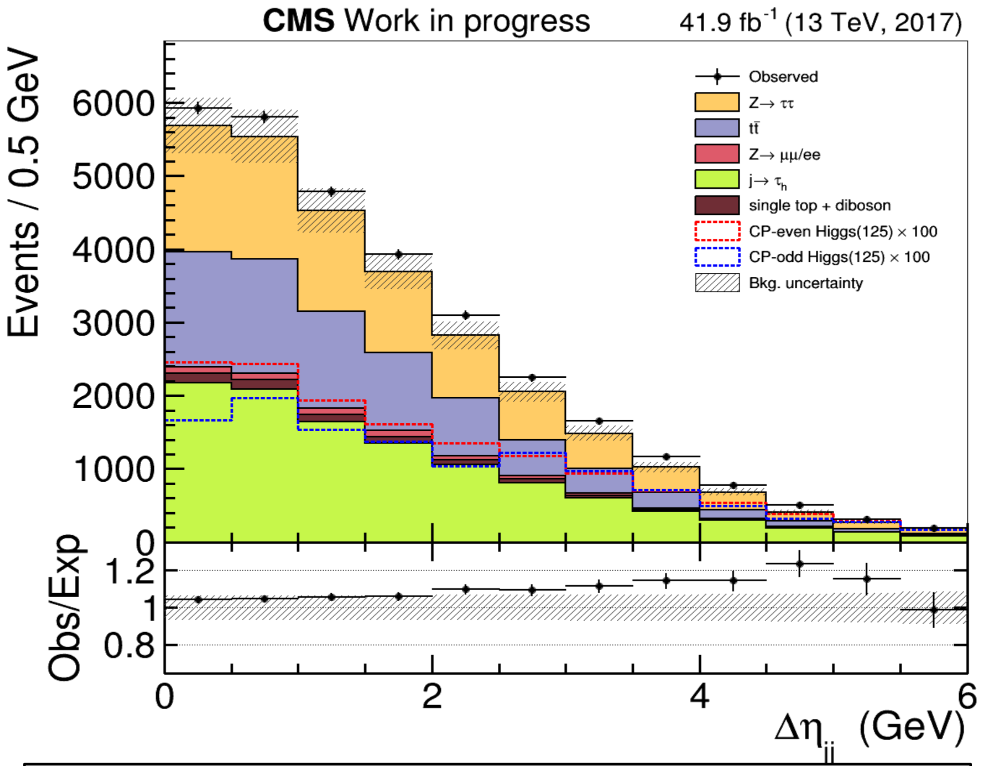
Inclusive selection region: jj system

Jet system mass



Slight normalization problem

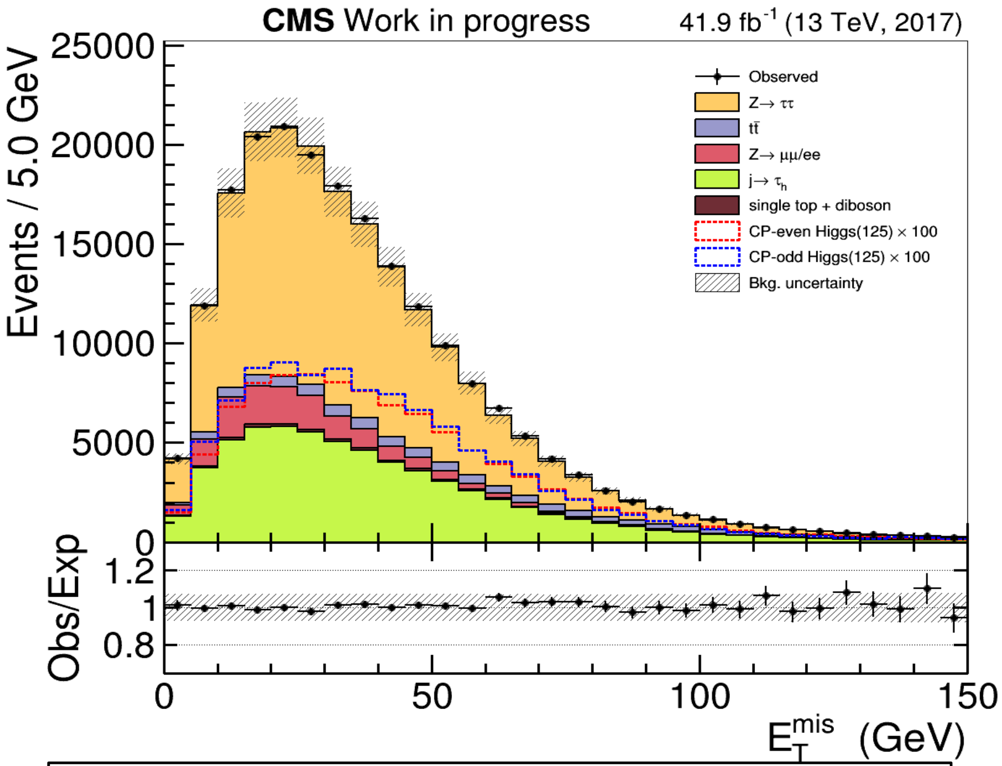
Jet eta separation



Slight normalization problem

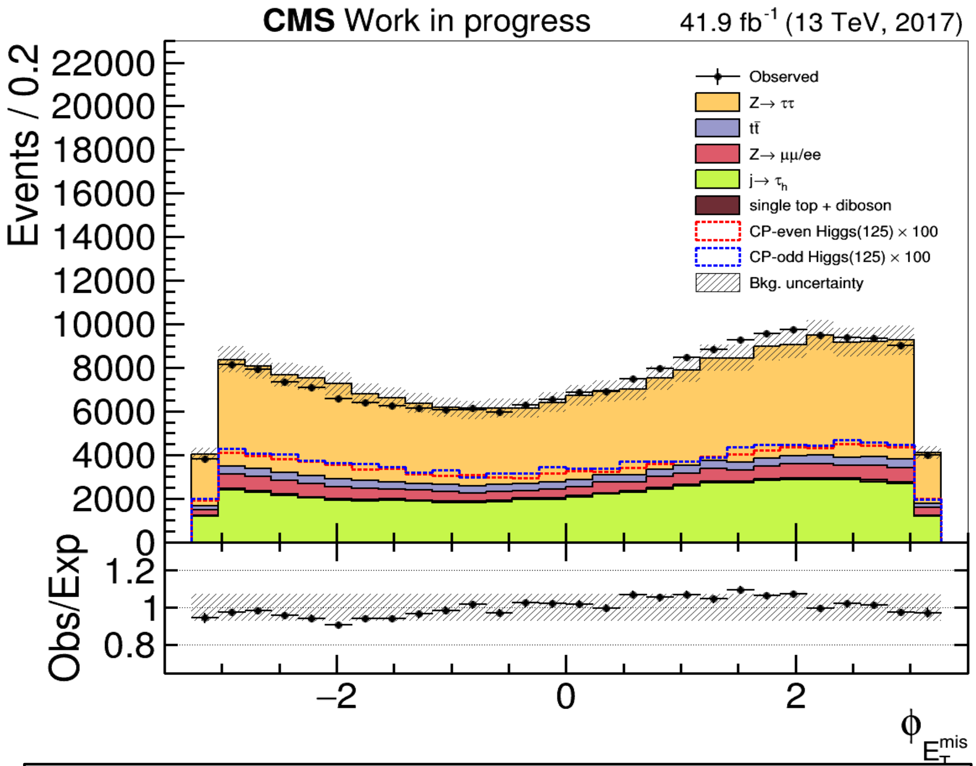
Inclusive selection region: met

Missing transverse energy



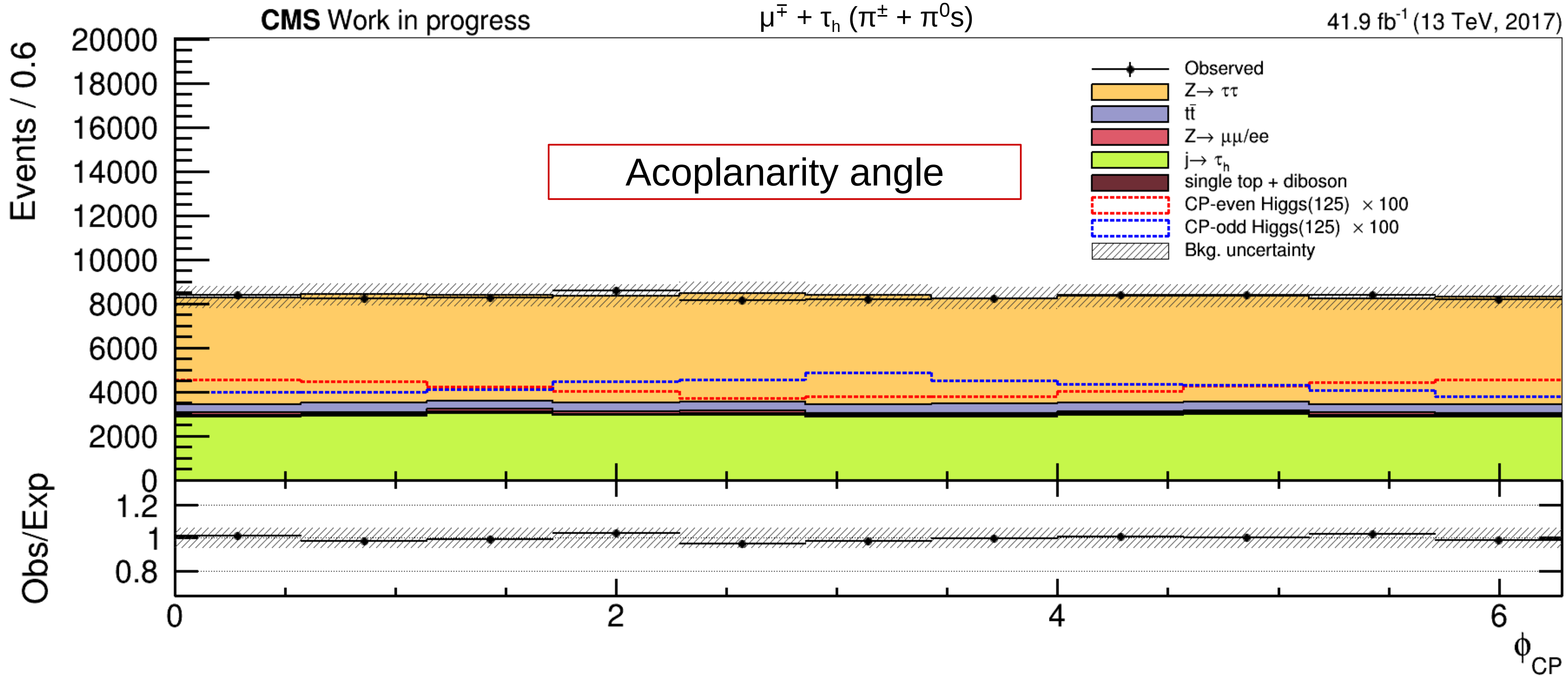
Good agreement after recoil corrections

Met φ



Curious modulation, similar to a phase shift

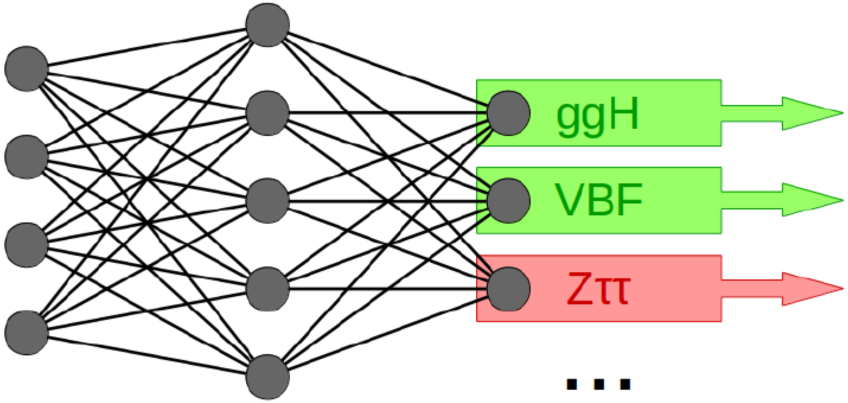
Inclusive selection region: φ_{CP}

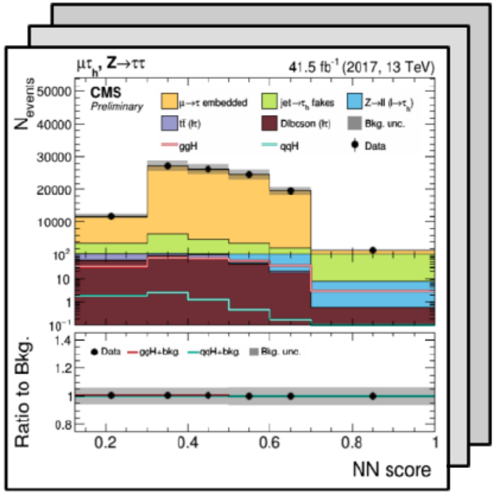


As expected, the backgrounds appear flat, while a modulation can be seen for the signal.

Signal / bkg separation

- To separate between the H → ττ signal and the bkg a Multi-class Neural Network is used (same as the one used for SM H → ττ analysis) [CMS-HIG-18-032]
- Current categories: ggH, qqH (VBF), Zττ, Zll, t t-bar, W+jets, QCD, misc.

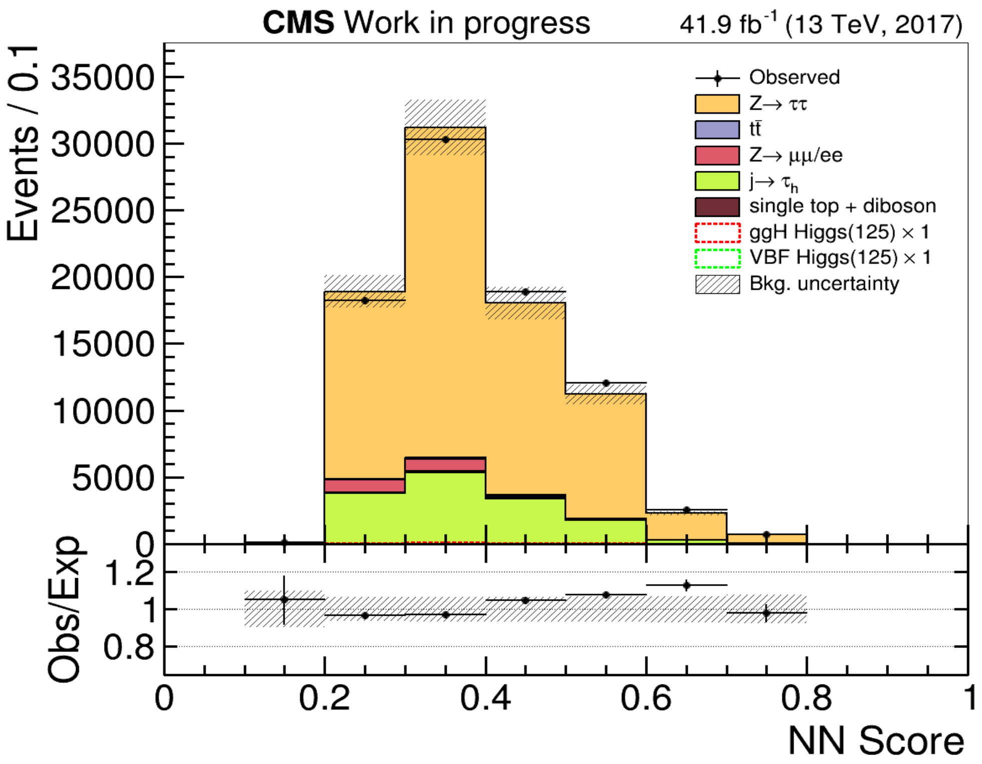




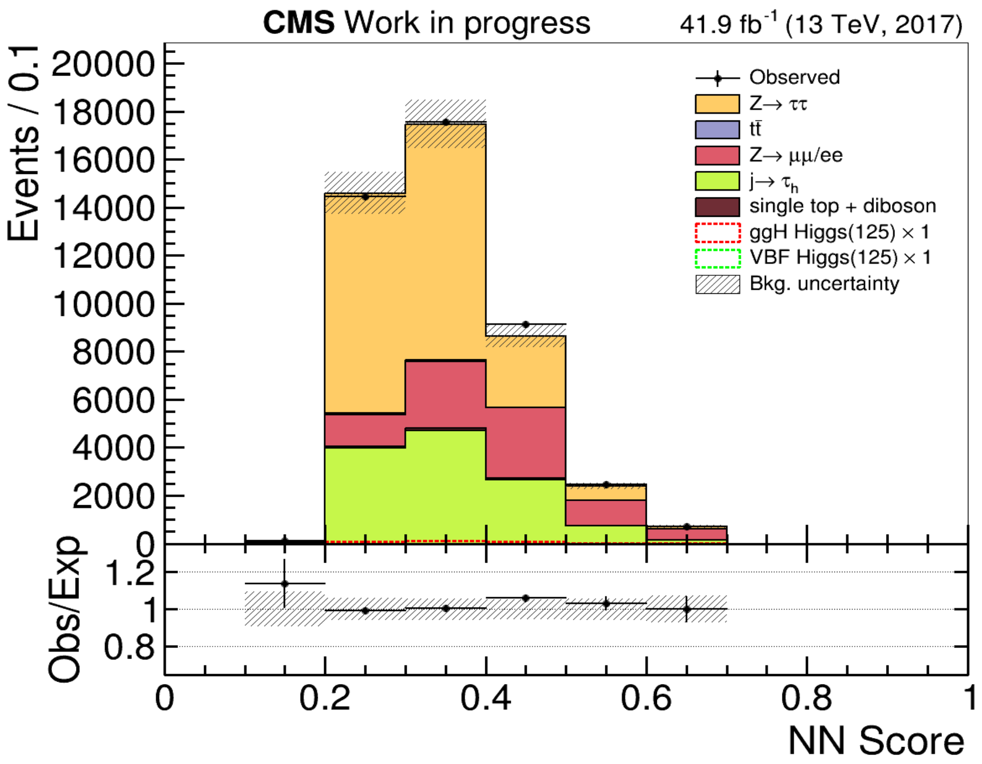
- Variable used: momenta of tau lepton, jets and b-jets, $m_{\tau\tau}$, $p_{T,\tau\tau}$, m_T, m_{jj}, $\Delta\eta_{jj}$, $p_{T,jj}$, njets and nbjets.

Bkg categories: Zττ and ZLL

Zττ category

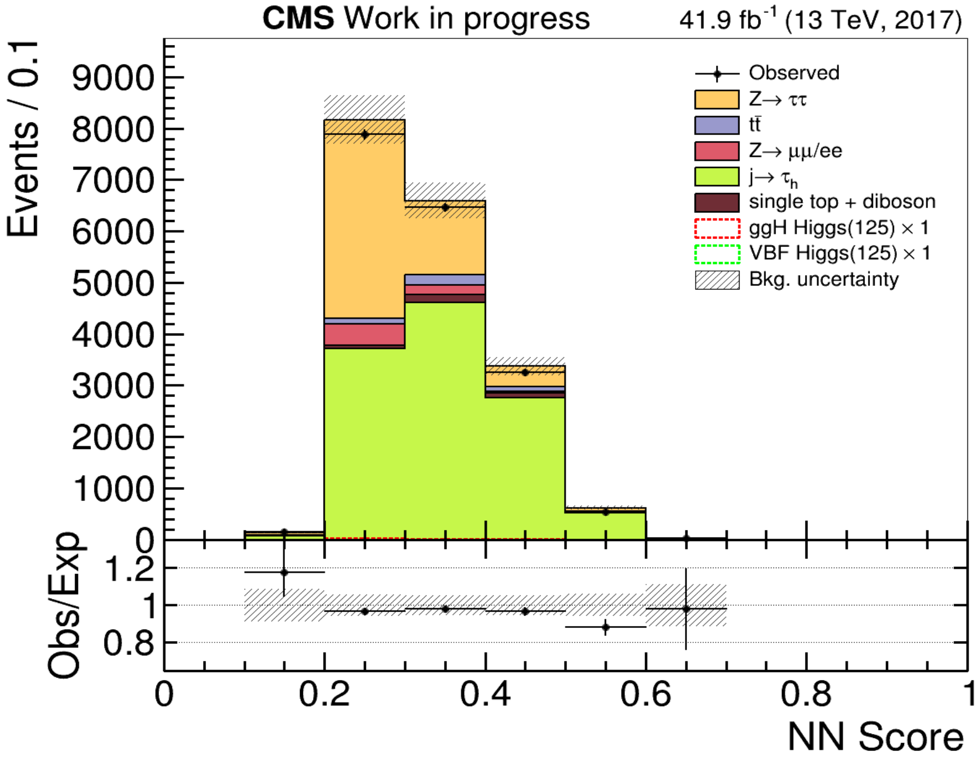


ZLL category

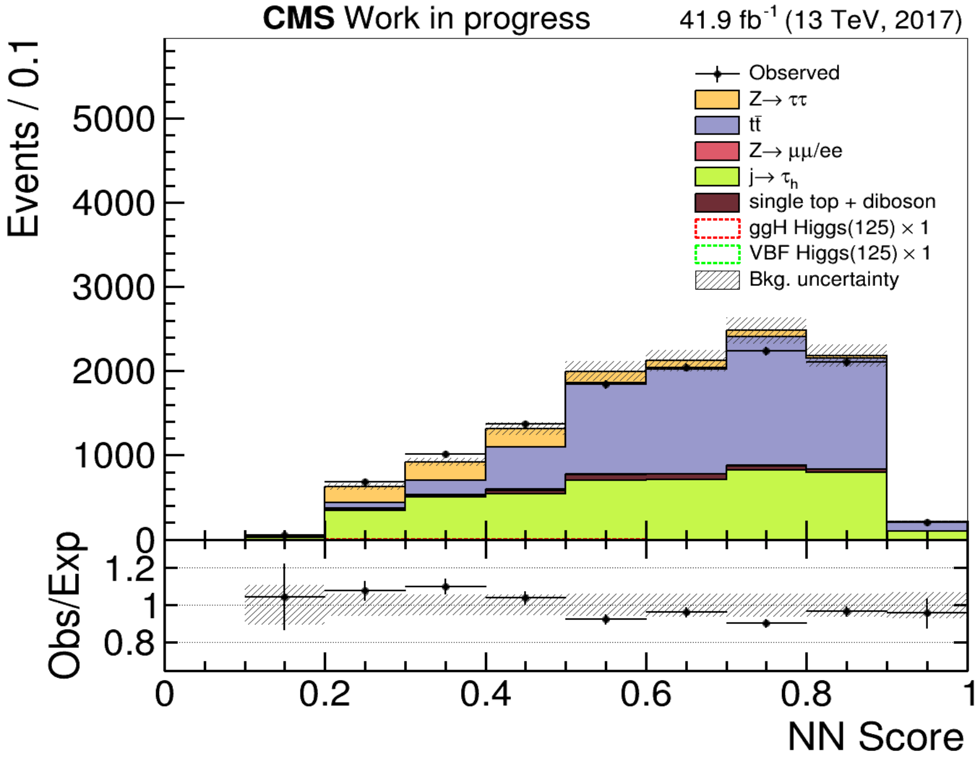


Bkg categories: W and top

W category

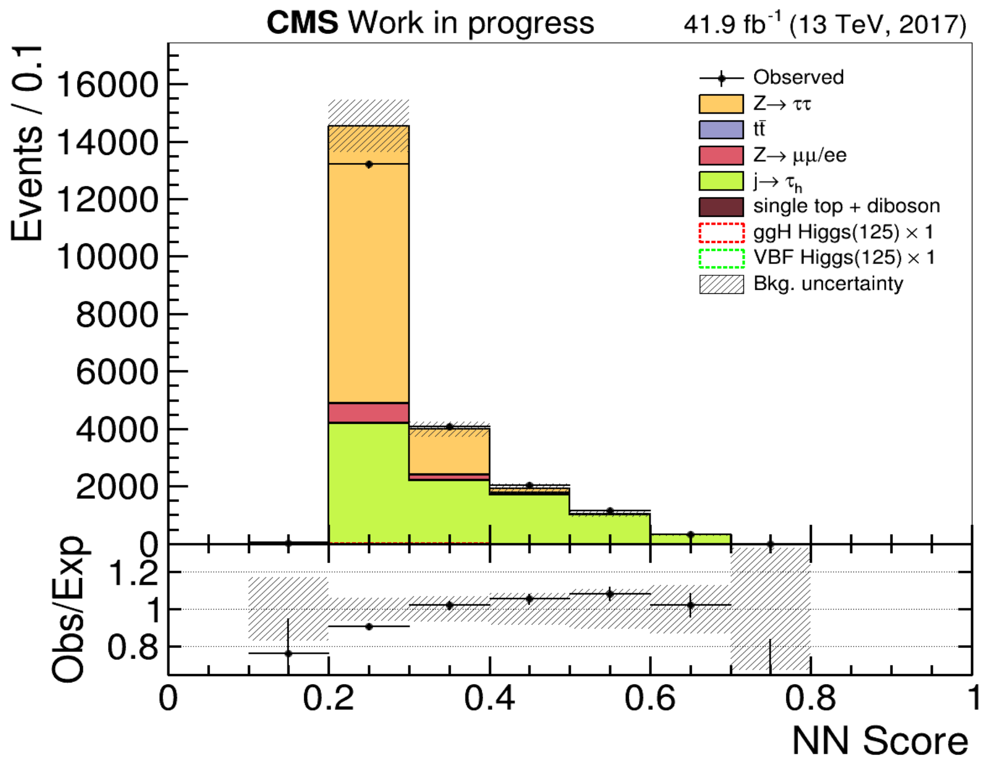


top category

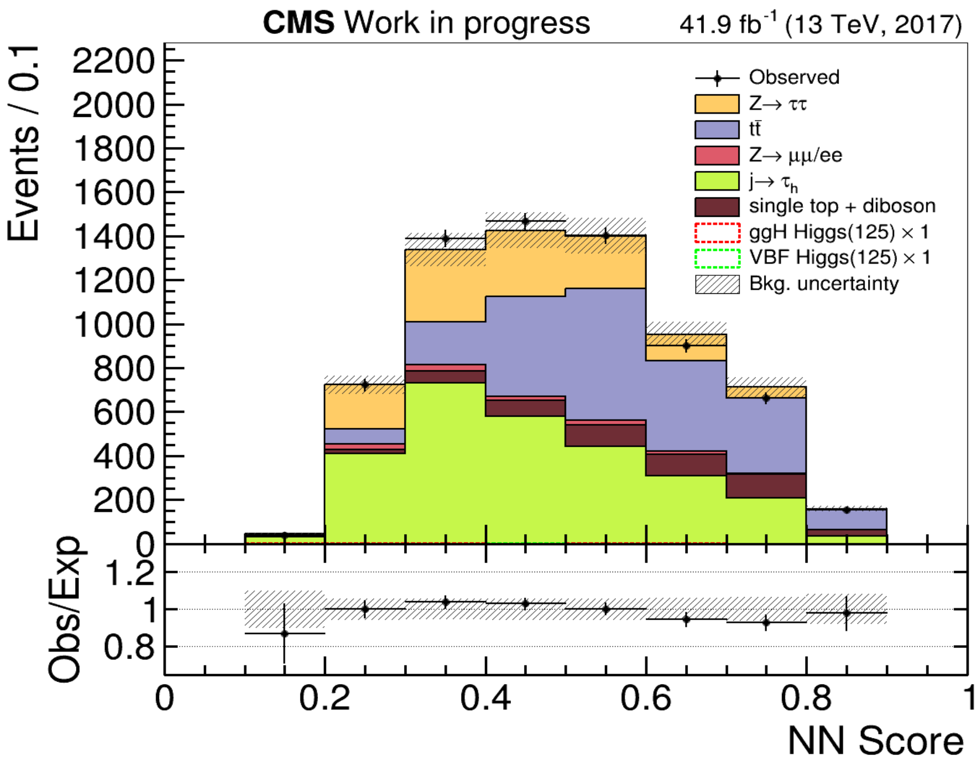


Bkg categories: same sign and misc.

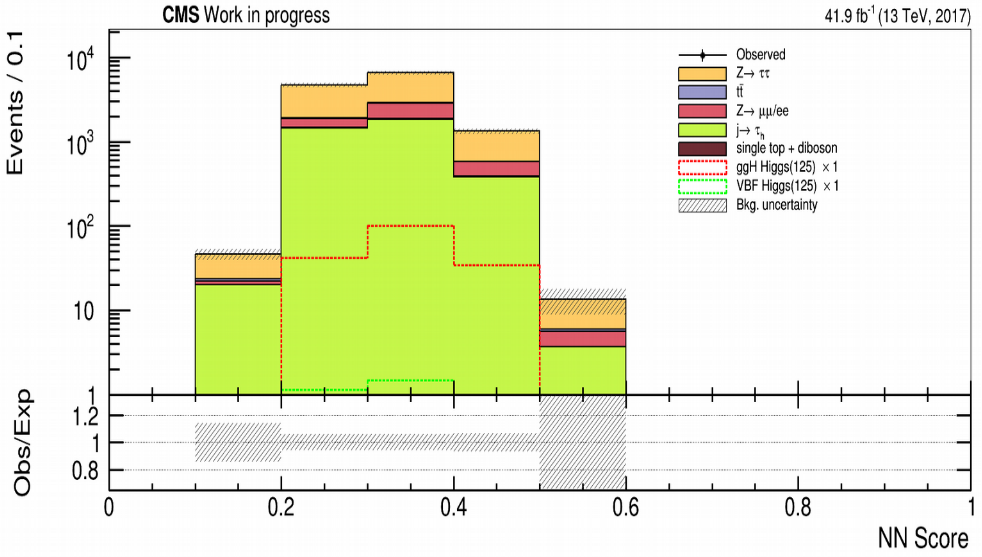
same sign category



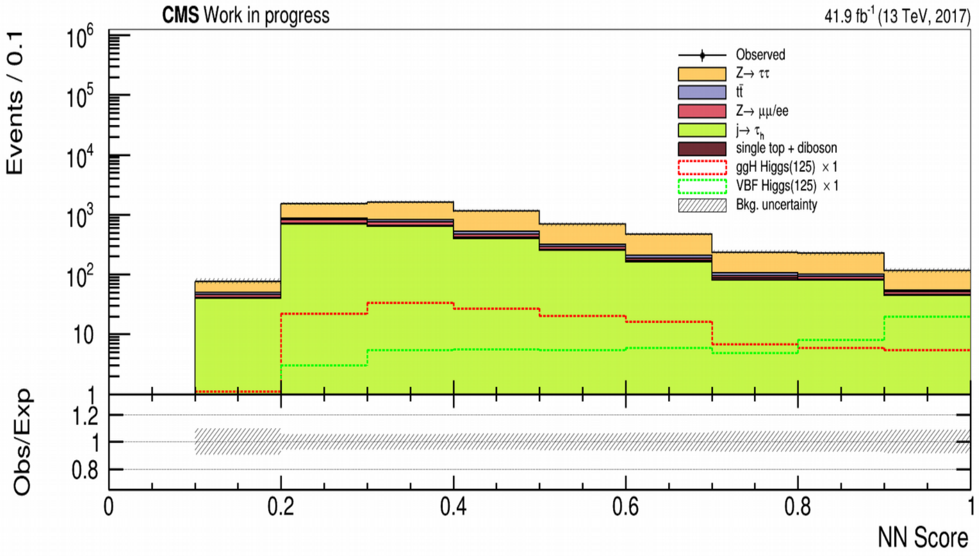
misc category



Signal categories: qqH and ggH

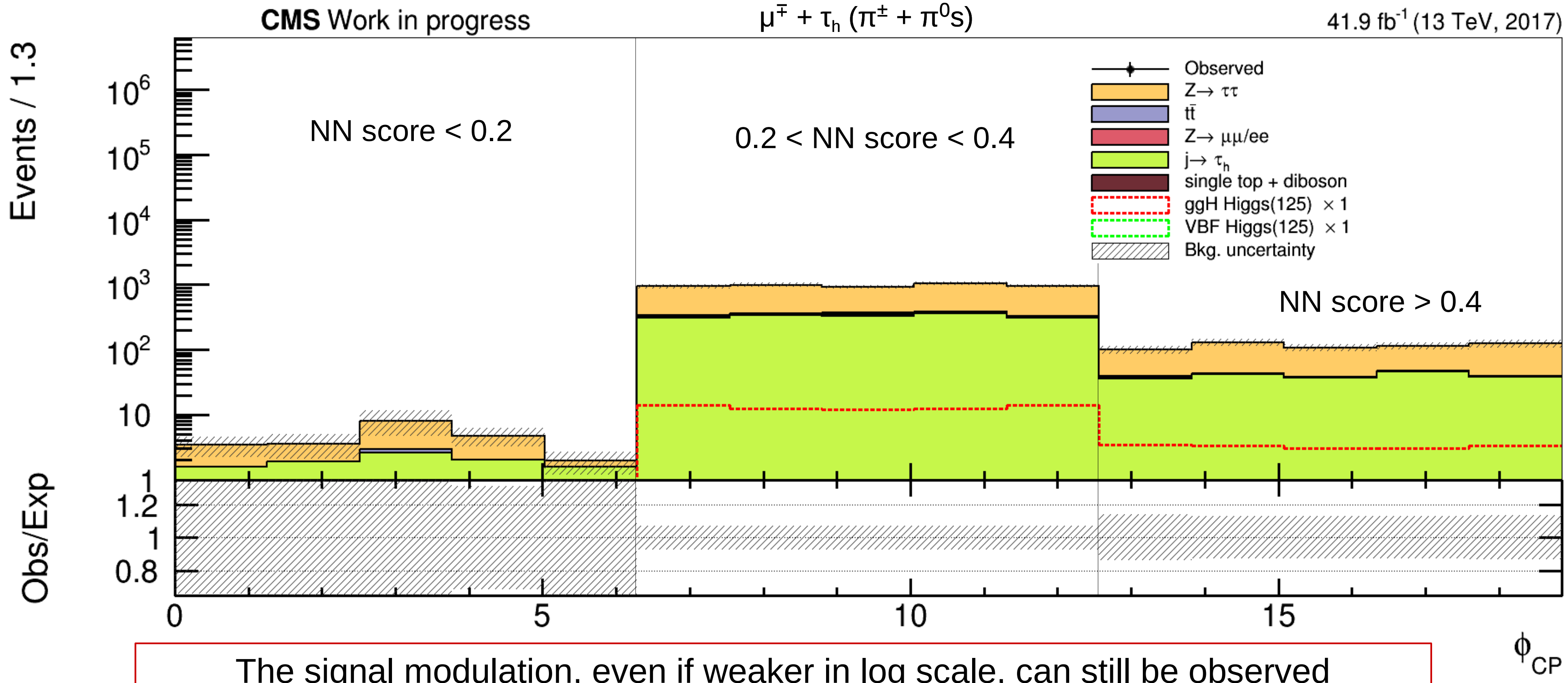


- Data blinded in signal categories
- VBF dominates at high NN score in qqH category



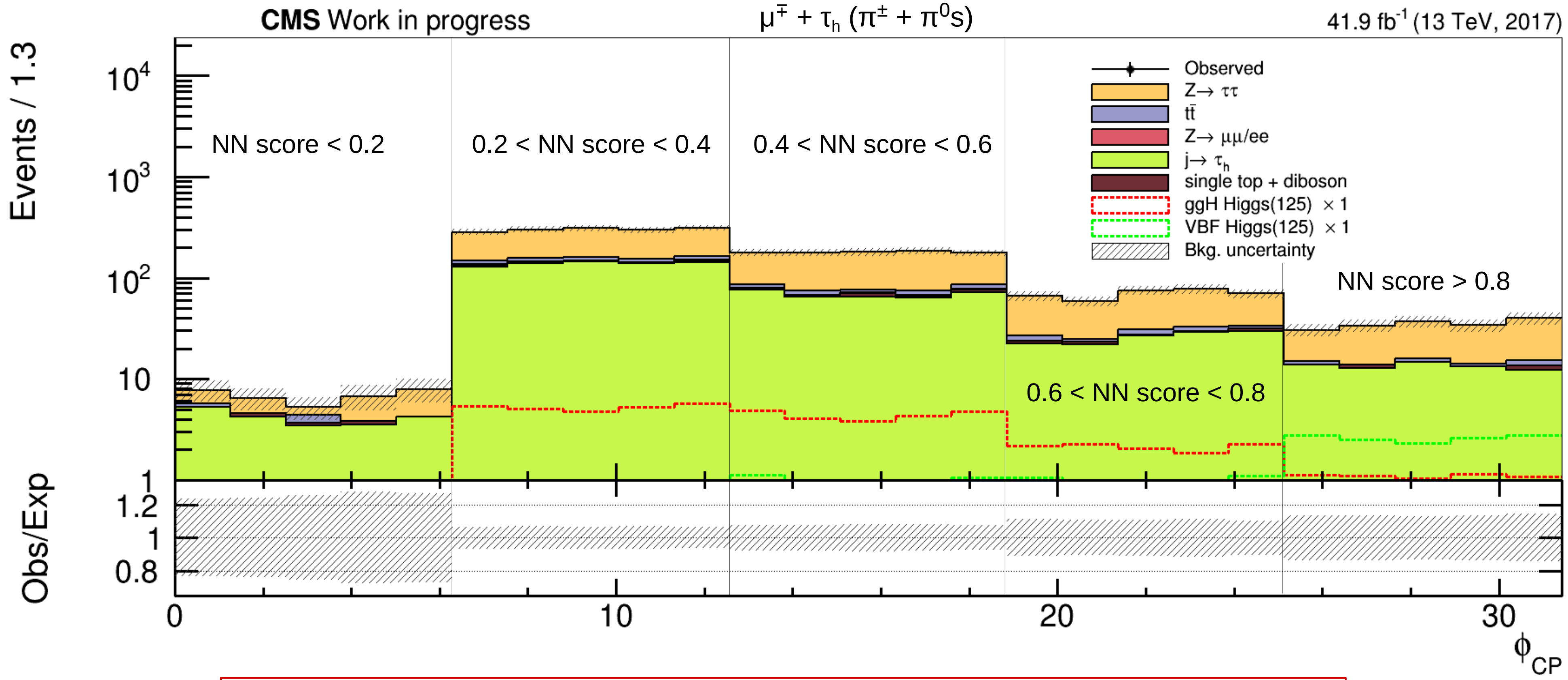
- Overall increase in signal purity at high NN score

Acoplanarity angle with ggH category



The signal modulation, even if weaker in log scale, can still be observed
Please note that the signal xsec is **not scaled**

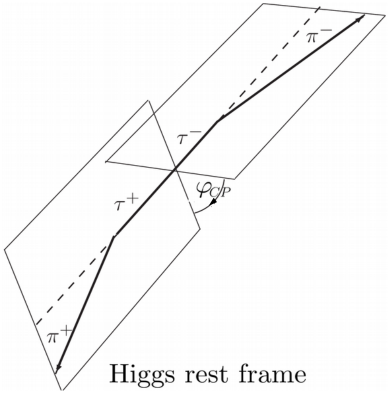
Acoplanarity angle with qqH category

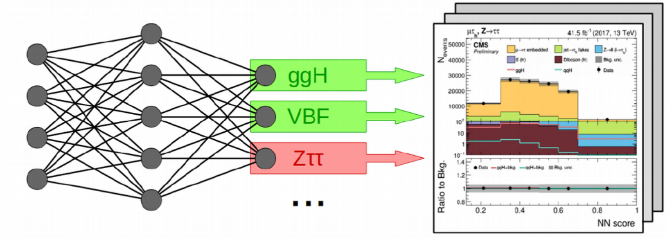


ggH and qqH samples appear to have the same modulation in φ_{CP}

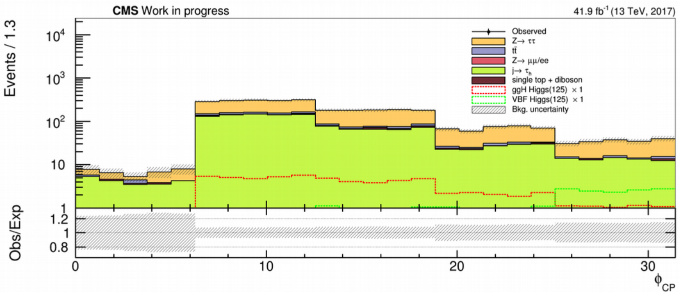
Prospects

- Oleg is currently working on extending our NTuple producer for 2016 and 2018
- The fit model for the extraction of the CP-mixing angle is close to be implemented
- FF method with DeepTau and new-DM MVA will be added





- The Neural Network will be optimized
- Tests for the use of CP observables will be made



- After obtaining a good signal/bkg separation the CP mixing angle will be measured with a combined fit in signal and bkg categories

CP measurement in $H \rightarrow \tau\tau$

Andrea Cardini

Look forward to the results with full Run 2 data!

Our collaboration

DESY: semileptonic channels ($\mu\tau_h$ for now)

Institute of Physics, Bhubaneswar: 1 Prong decays in $\tau_h\tau_h$ channel

IPHC Strasbourg: a_1a_1 channel

Imperial College: 1 Prong+π^0s decays in $\tau_h\tau_h$ channel

RWTH Aachen: ρ + 1 Prong channel

Our collaboration

DESY: Andrea Cardini – Oleg Filatov – Elisabetta Gallo – Teresa Lenz – Mareike Meyer – Alexei Raspereza – Merijn van de Klundert – Yiwen Wen

Institute of Physics, Bhubaneswar: Arun Nayak – Vinay Krishna – Diwakar Vats

IPHC Strassbourg: Anne-catherine Le Bihan – Guillaume Bourgatte

Imperial College: David Colling – Daniel Winterbottom – Albert Dow – Mohammad Hassan Hassanshahi

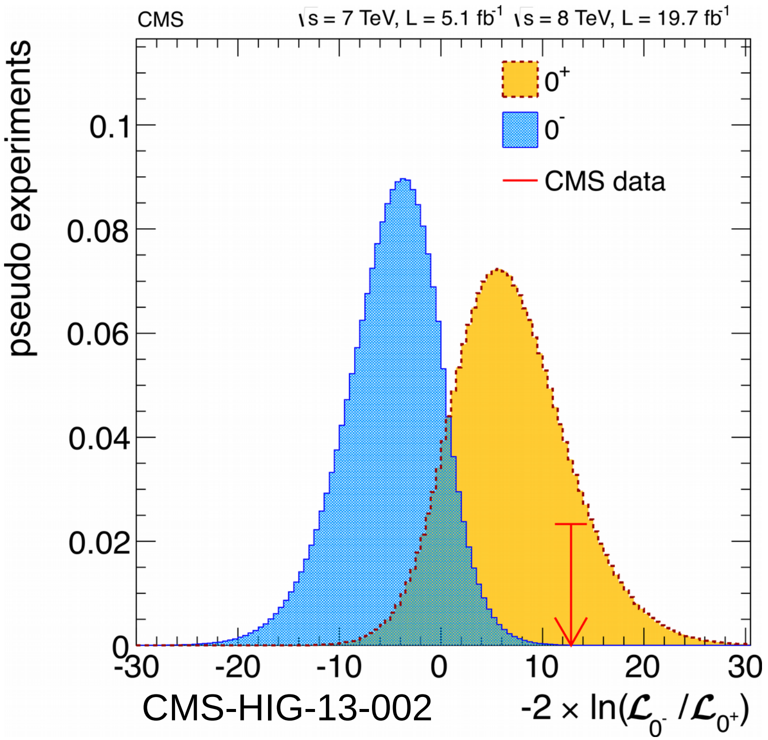
ITEP, Moscow: Sasha Nikitenko (also IC, London)

Princeton: Dan Marlow – Alexis Kalogeropoulos

RWTH Aachen: Thomas Mueller – Alexander Zotz – Lucas Wiens – Mate Farkas

Higgs CP nature

- The SM predicts only one Higgs boson, with spin-parity 0^+
- Run 1 constraints from H→VV excluded a pseudoscalar Higgs

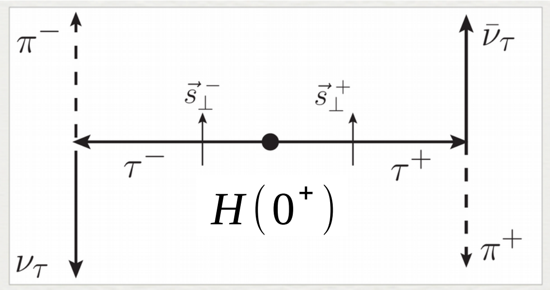


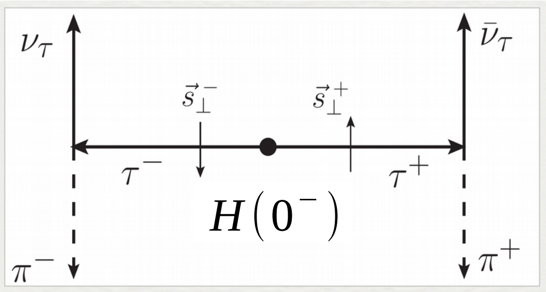
CMS-HIG-13-002

- The VBF H→4l + VBF H→ττ studies from Run2 [CMS-PAS-HIG-17-034] placed tight constraints on a CP-odd anomalous coupling in HVV
- However a CP-odd coupling in the Yukawa interactions is not excluded yet

The possibility of a small CP-mixing is still open and could appear in fermionic decays

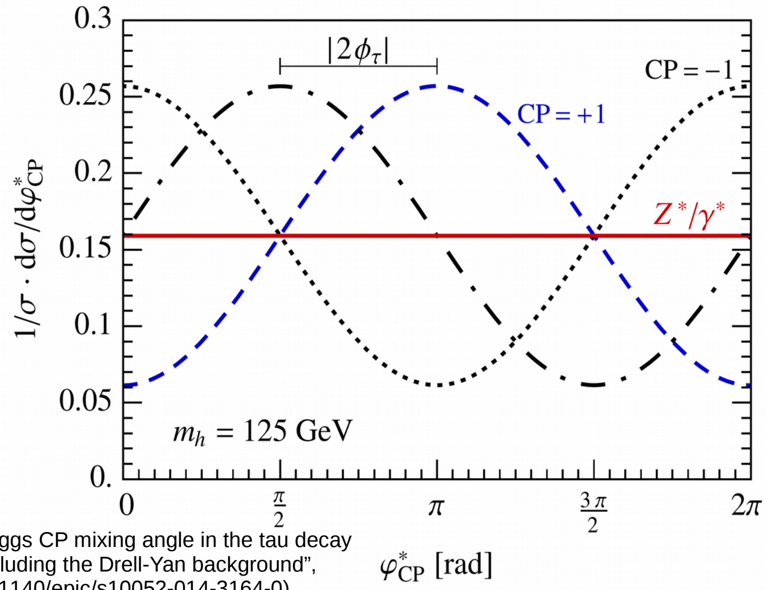
- CP-mixing may appear in the H→τ τ coupling at leading order:
  - $L_Y = -\frac{m_\tau}{v} k_\tau (\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i \gamma_5 \tau) h$
  - SM prediction: $\phi_\tau = 0 \rightarrow$ CP=+1
- To measure ϕ_τ we need to look at the spin correlation of tau decay products:





H→ τ τ cross section:

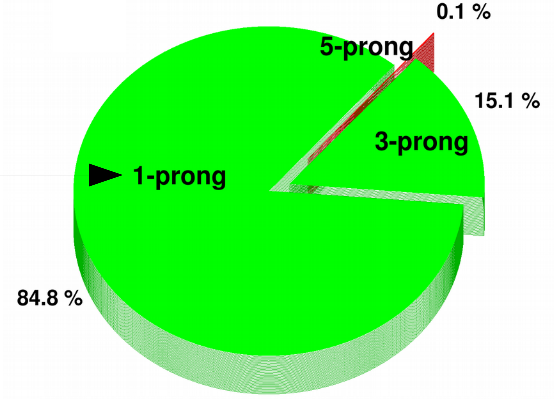
$$\frac{d\sigma}{d\varphi^*_{CP}} \propto -\cos(\varphi^*_{CP} - 2\phi_t)$$



"Determination of the Higgs CP mixing angle in the tau decay channels at the LHC including the Drell-Yan background", S. Berge et al. (doi: 10.1140/epjc/s10052-014-3164-0)

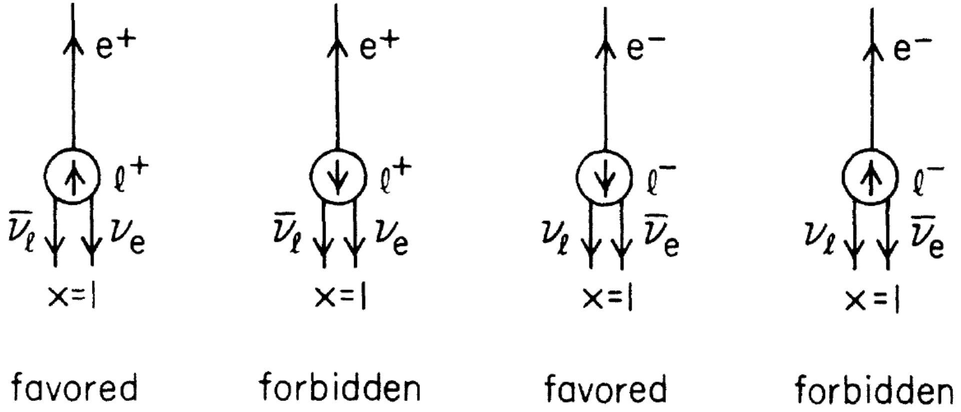
τ multi-body decays

Number of prongs
(charged decay products)



$$\tau \rightarrow l + \nu_l + \nu_\tau \,,$$
$$\tau \rightarrow \pi + \nu_\tau \,,$$
$$\tau \rightarrow \rho + \nu_\tau \rightarrow \pi + \pi^0 + \nu_\tau \,,$$
$$\tau \rightarrow a_1 + \nu_\tau \rightarrow \pi + 2\pi^0 + \nu_\tau \,,$$
$$\tau \rightarrow a_1^{L,T} + \nu_\tau \rightarrow 2\pi^\pm + \pi^\mp + \nu_\tau \,.$$

- Tau leptons have multiple decay channels
- 2-body decays allow for maximum sensitivity to spin correlation
- For multiple-body decays the spin correlation is partially diluted
- For hadronic decays, accounting for the spin of mesonic resonances recovers sensitivity



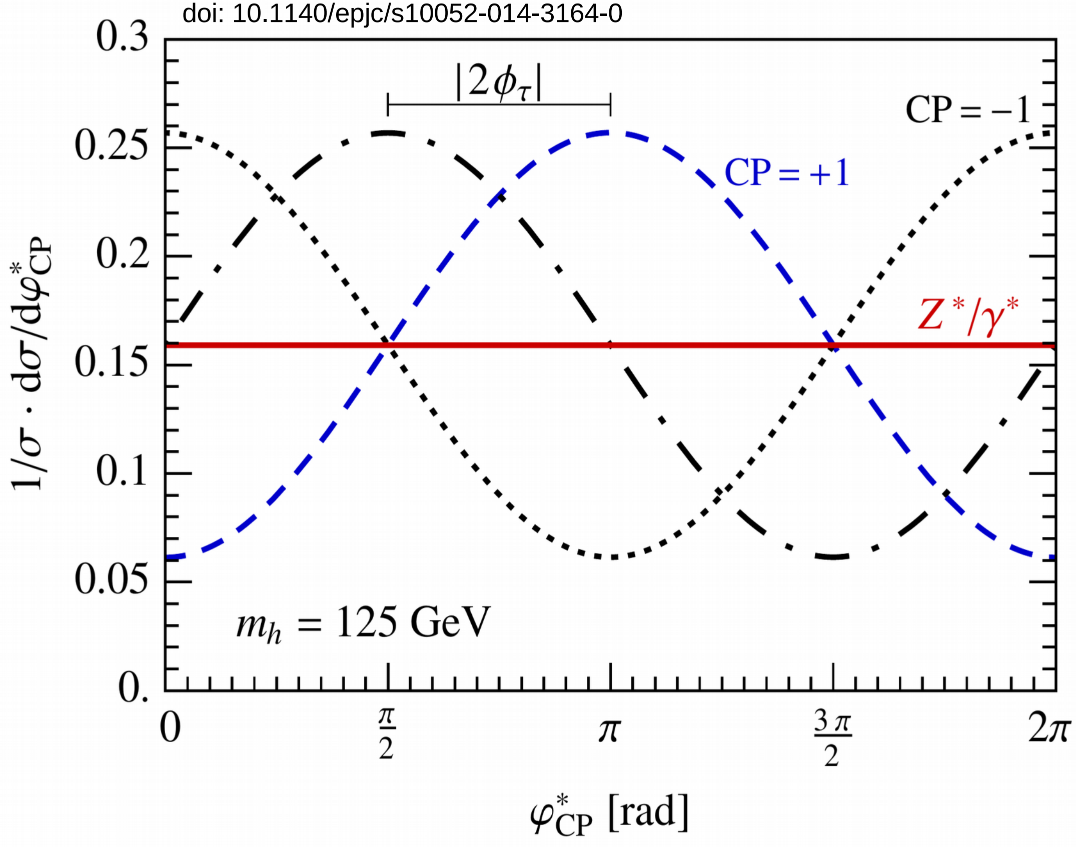
CP mixing angle

The mixing angle will appear as a phase shift with respect to the CP-even distribution

H→ τ τ cross section:

$$\frac{d\sigma}{d\varphi^*_{CP}} \propto -\cos\left(\varphi^*_{CP} - 2\phi_t\right)$$

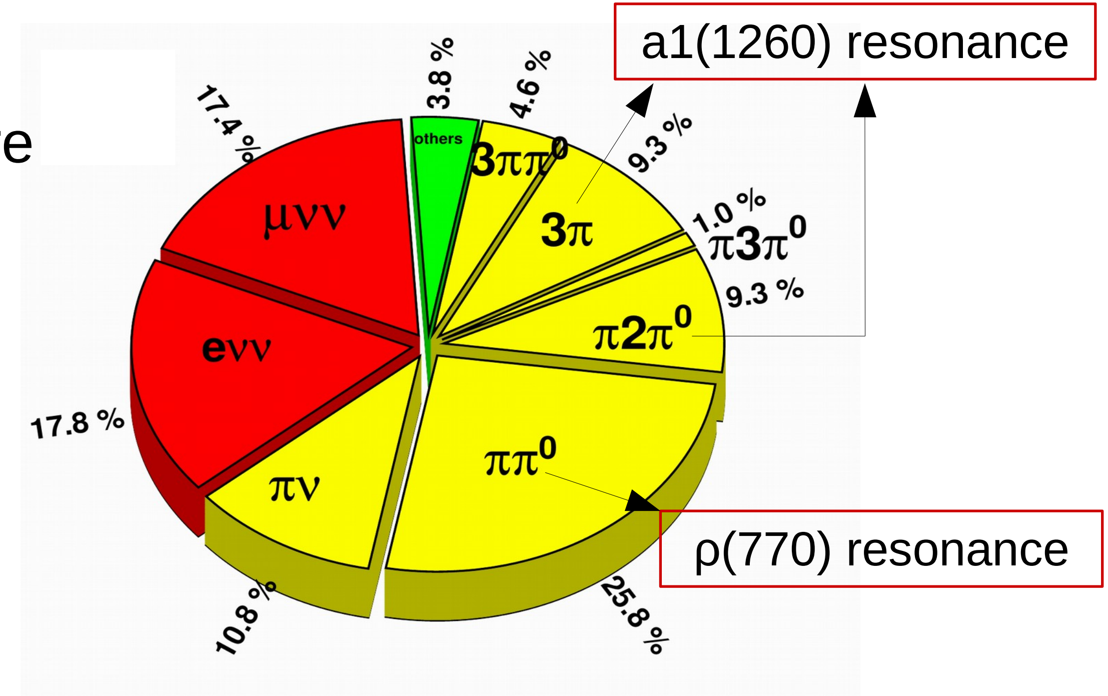
“Determination of the Higgs CP mixing angle in the tau decay channels at the LHC including the Drell-Yan background”, S. Berge et al.
doi: 10.1140/epjc/s10052-014-3164-0



τ hadronic decays

- Different decay channels need to be analyzed separately
- For hadronic decay channels there are mesonic resonances to be accounted for
- The spin of the intermediate resonance needs to be studied using a categorization

Main exclusive decay channels



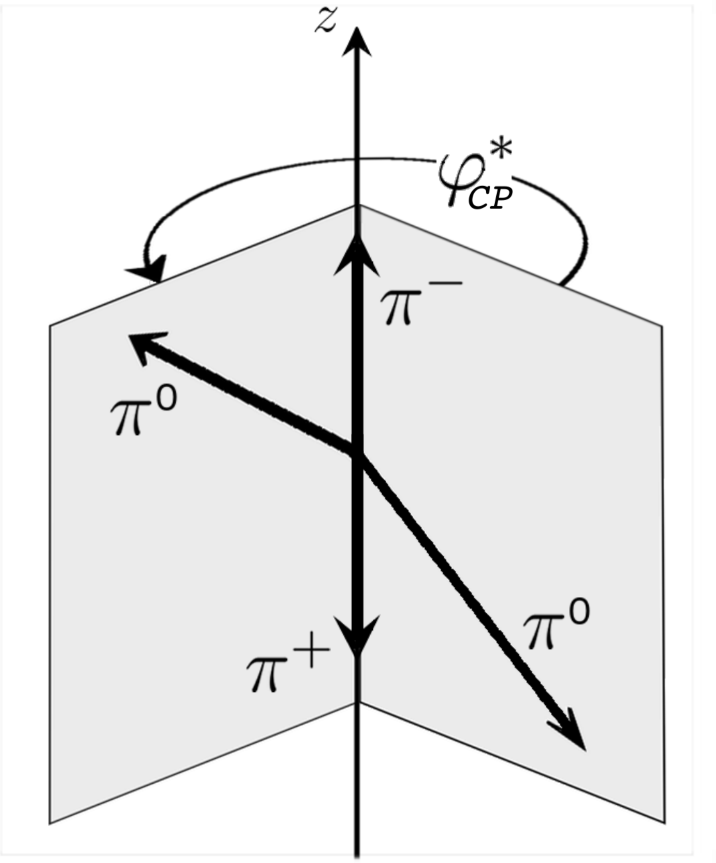
ρ resonance

- The 1 Prong + 1 π^0 channel is dominated by the ρ resonance
- Having a 2 body decay the spin correlation is retrieved by categorizing events with:

$$y^\tau > 0 \quad \text{or} \quad y^\tau < 0 \quad , \quad \text{where } y^\tau = y_-^\tau y_+^\tau$$

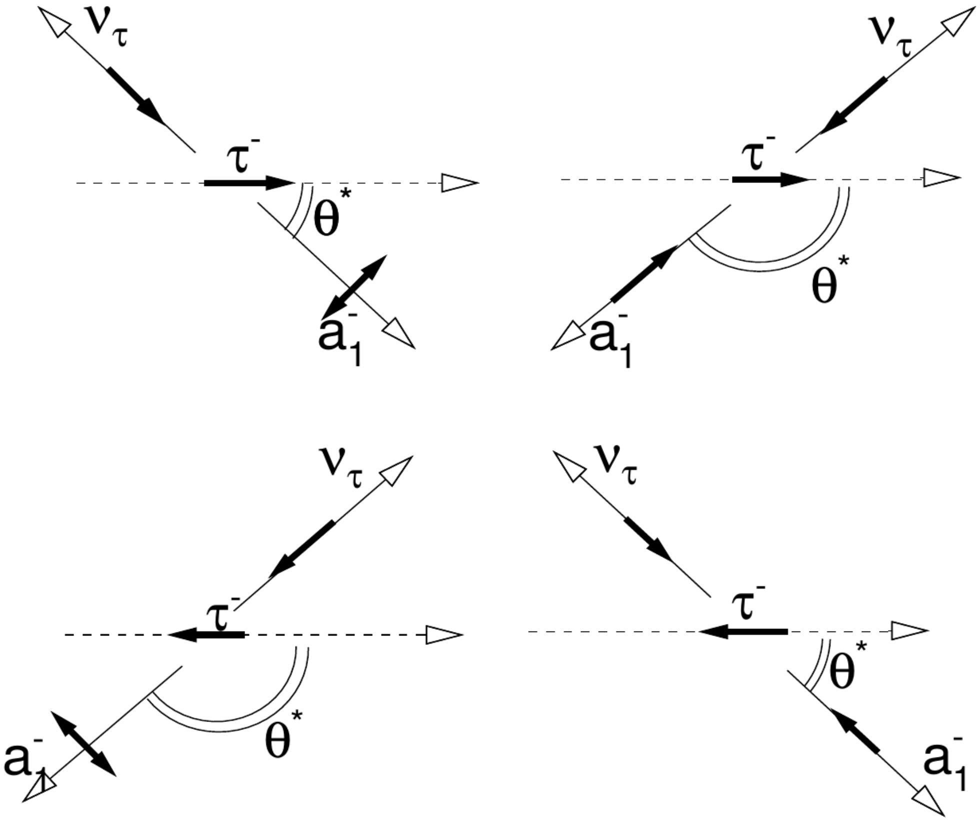
$$y_+^\tau = \frac{(E_{\pi^+} - E_{\pi^0})}{(E_{\pi^+} + E_{\pi^0})} \qquad y_-^\tau = \frac{(E_{\pi^-} - E_{\pi^0})}{(E_{\pi^-} + E_{\pi^0})}$$

- The two categories will show a phase shift of π w.r.t. one another

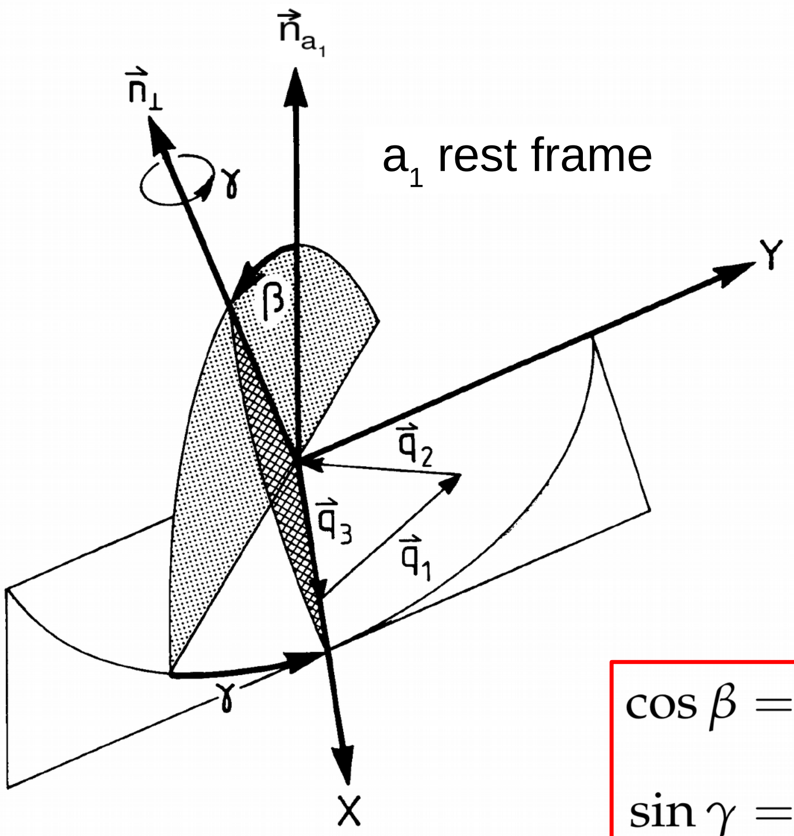


3 Prong channel

- The 3-prong channel is dominated by the a_1 resonance
- However the a_1 meson has spin 1 ⇒ L and T polarization have opposite spin correlation with the τ
- A categorization based on the a_1 polarization may be needed to study the spin correlation

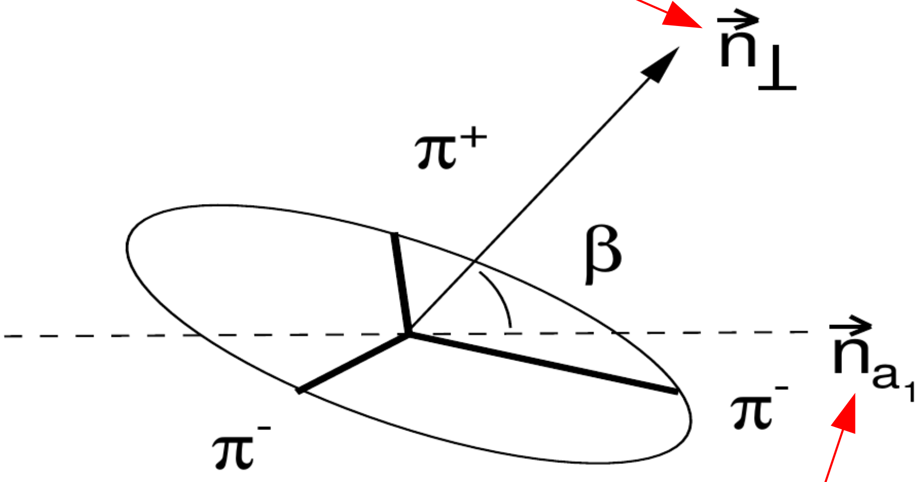


$a_1 \rightarrow 3\pi$



a_1 rest frame

normal to the π decay plane in the a_1 f.o.r. (it coincides with the a_1 spin)



direction of motion of a_1

$$\cos\beta = \vec{n}_\perp \vec{n}_{a_1}$$

$$\sin\gamma = \frac{(\vec{n}_\perp \times \vec{n}_{a_1})\vec{q}_3}{|\vec{n}_\perp \times \vec{n}_{a_1}|}$$

Polarization measurement

$$cos\beta = \frac{\vec{p}_3(\vec{p}_1 \times \vec{p}_2)}{|\vec{p}_{3\pi}|T}$$

where:

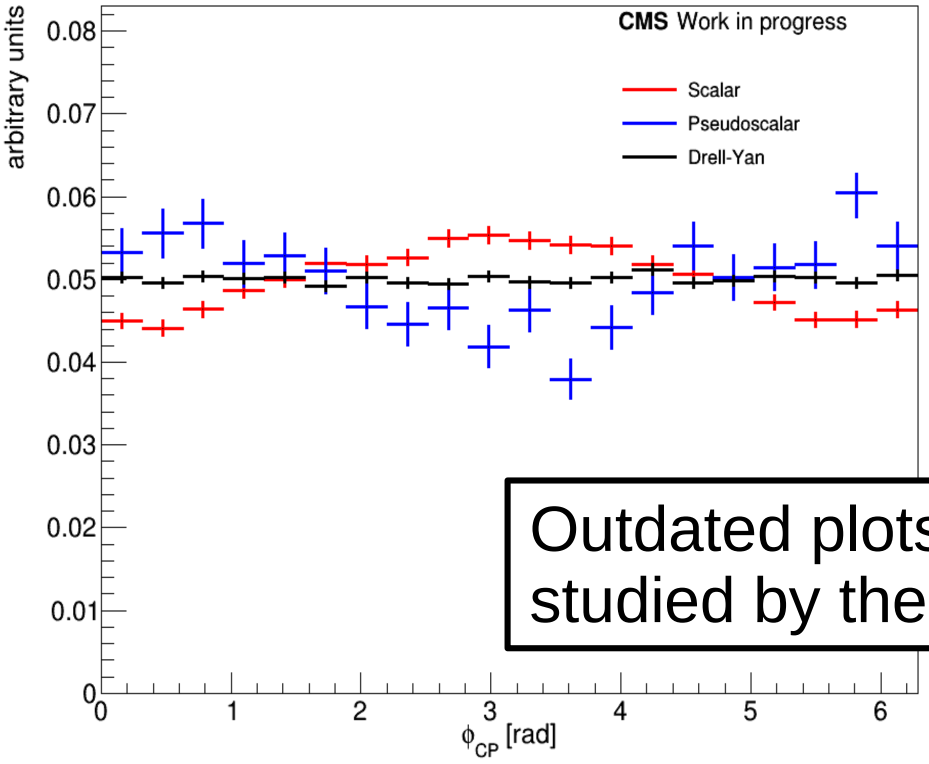
$$T = \frac{1}{2}\sqrt{-\lambda(B_1, B_2, B_3)}$$

$$\lambda(B_1, B_2, B_3) = B_1^2 + B_2^2 + B_3^2 - 2B_1B_2 - 2B_1B_3 - 2B_2B_3$$

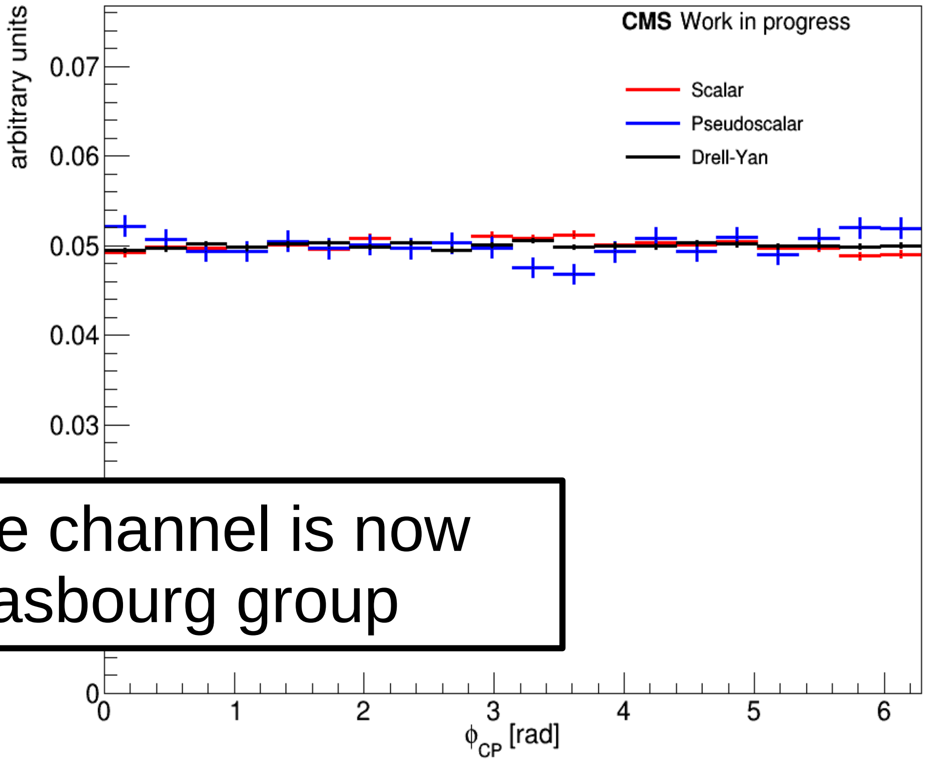
$$B_i = \frac{(E_iE_{3\pi} - \vec{p}_{3\pi}\vec{p}_i)^2 - Q^2m_\pi^2}{Q^2}$$

3 Prong channel

Tau 1 decay mode: $\tau^{\pm} \rightarrow a_1$ transv. pol.
Tau 2 decay mode: $\tau^{\pm} \rightarrow \pi^{\pm}$



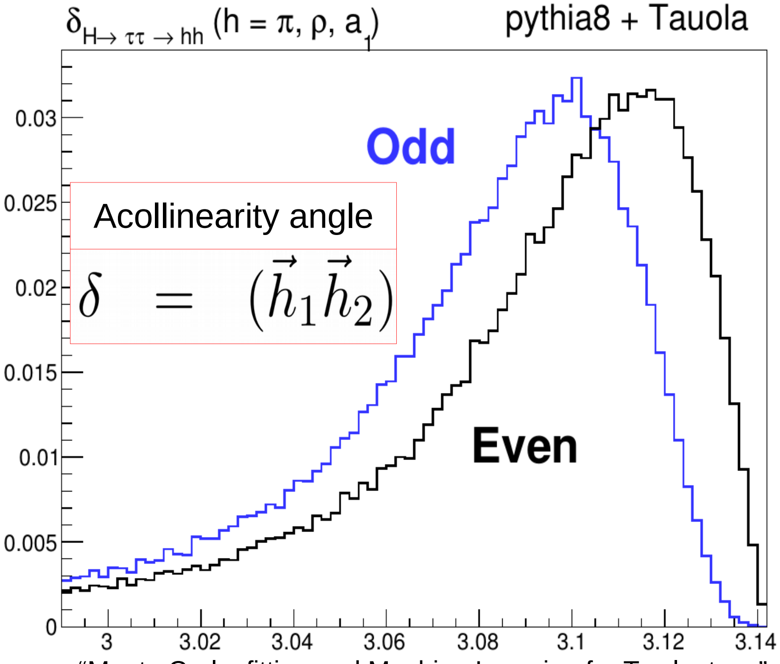
Tau 1 decay mode: $\tau^{\pm} \rightarrow a_1$ long. pol.
Tau 2 decay mode: $\tau^{\pm} \rightarrow \pi^{\pm} + \pi^{0}$



Outdated plots, the channel is now studied by the Strasbourg group

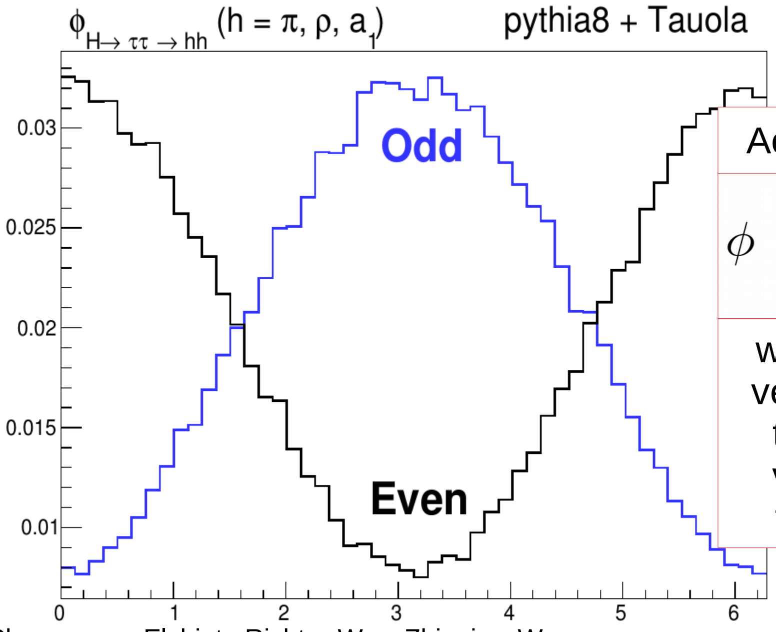
Polarimetric vectors

- The polarimetric vector are computed by a routine in TauSpinner (which is part of the TAUOLA tool)
- Using these vectors it is possible to define define 2 interesting observables:



Acollinearity angle

$$\delta = (\vec{h}_1 \vec{h}_2)$$



Acoplanarity angle

$$\phi = \frac{\vec{k}_1 \times \vec{k}_2}{|\vec{k}_1 \times \vec{k}_2|}$$

with k normalized vector products of the polarimetric vectors and tau flight directions

“Monte Carlo, fitting and Machine Learning for Tau leptons”, Vladimir Cherepanov, Elzbieta Richter-Was, Zbigniew Was, doi: 10.21468/SciPostPhysProc.1.018

Samples used: bkg

- /WjetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14_ext1-v2/MINIAODSIM
- /WJetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM
- /W1JetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v3/MINIAODSIM
- /W2JetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v4/MINIAODSIM
- /W3JetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM
- /W4JetsToLNu_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM

- /DYJetsToLL_M-5to50_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM
- /DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017RECOSIMstep_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM
- /DYJetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017RECOSIMstep_12Apr2018_94X_mc2017_realistic_v14_ext1-v1/MINIAODSIM
- /DY1JetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14_ext1-v1/MINIAODSIM
- /DY2JetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM
- /DY2JetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14_ext1-v1/MINIAODSIM
- /DY3JetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM
- /DY3JetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14_ext1-v1/MINIAODSIM
- /DY4JetsToLL_M-50_TuneCP5_13TeV-madgraphMLM-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM

- /WW_TuneCP5_13TeV-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM
- /WZ_TuneCP5_13TeV-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM
- /ZZ_TuneCP5_13TeV-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM

- /TTToSemiLeptonic_TuneCP5_13TeV-powheg-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v2/MINIAODSIM
- /TTTo2L2Nu_TuneCP5_13TeV-powheg-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM
- /TTToHadronic_TuneCP5_13TeV-powheg-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM

- /ST_tW_top_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM
- /ST_tW_antitop_5f_inclusiveDecays_TuneCP5_13TeV-powheg-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM
- /ST_t-channel_top_4f_inclusiveDecays_TuneCP5_13TeV-powhegV2-madspin-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_new_pmx_94X_mc2017_realistic_v14-v1/MINIAODSIM
- /ST_t-channel_antitop_4f_inclusiveDecays_TuneCP5_13TeV-powhegV2-madspin-pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM

Samples used: data and signals

- Data:
  - /SingleMuon/Run2017F-31Mar2018-v1/MINIAOD
  - /SingleMuon/Run2017E-31Mar2018-v1/MINIAOD
  - /SingleMuon/Run2017D-31Mar2018-v1/MINIAOD
  - /SingleMuon/Run2017C-31Mar2018-v1/MINIAOD
  - /SingleMuon/Run2017B-31Mar2018-v1/MINIAOD
- Signal
  - /SUSYGluGluToHToTauTau_M-120_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM
  - /SUSYGluGluToHToTauTau_M-130_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM
  - /SUSYGluGluToBBHToTauTau_M-120_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM
  - /SUSYGluGluToBBHToTauTau_M-130_TuneCP5_13TeV-pythia8/RunIIAutumn18MiniAOD-102X_upgrade2018_realistic_v15-v2/MINIAODSIM
  - /GluGluHToTauTau_M125_13TeV_powheg_pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM
  - /GluGluHToTauTau_M125_13TeV_powheg_pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14_ext1-v1/MINIAODSIM
  - /VBFHToTauTau_M125_13TeV_powheg_pythia8/RunIIFall17MiniAODv2-PU2017_12Apr2018_94X_mc2017_realistic_v14-v1/MINIAODSIM

Systematics

- Bin-by-bin MC statistical uncertainty
- 3% lumi uncertainty
- 3% Muon reconstruction
- Bkg normalization uncertainty:
  - T T-bar: 7%
  - DY: 6%
  - VV and Single Top: 15%
  - Fakes: 15%