Progress on $Z \longrightarrow \tau_{lep}\,\tau_{had}$ Polarization and Higgs CP Measurements

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tautau Analysis Working Group

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Measurement of the τ Polarization in $Z \longrightarrow \tau\tau$ Decays

Motivation

First measurement of the τ lepton polarization P_τ in Z boson decays at a hadron collider

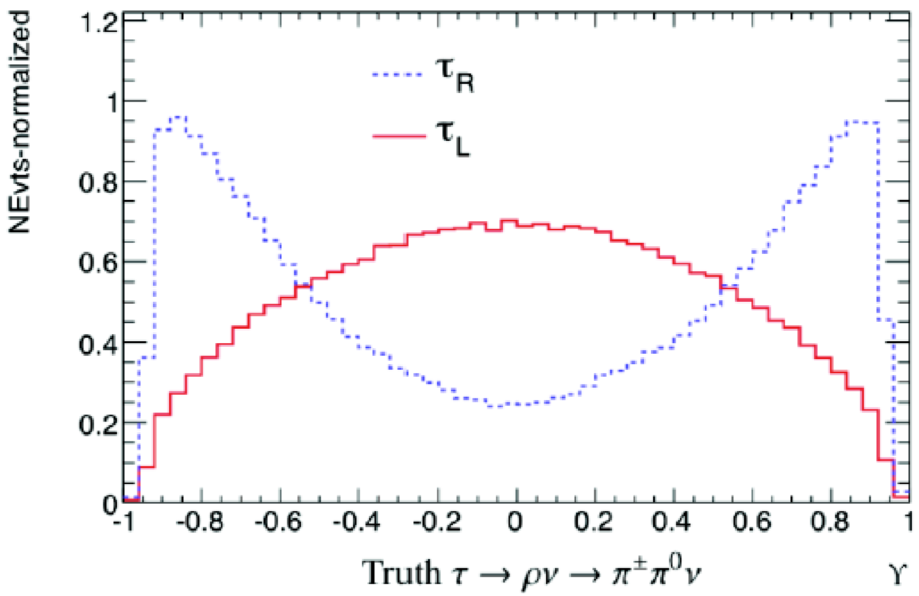
$$\mathcal{P}_\tau = \frac{N_R - N_L}{N_R + N_L}$$

measure polarization of hadronically decaying tau
$\tau \to \rho\nu \to \pi^\pm\pi^0\nu$
angle ψ between $\pi^\pm$ and ρ in ρ rest frame

$$\cos\psi = \frac{m_\rho}{\sqrt{m_\rho^2 - 4m_\pi^2}} \cdot \frac{E_{\pi^-} - E_{\pi^0}}{|\vec{p}_{\pi^-} + \vec{p}_{\pi^0}|}$$

$\Rightarrow$ Polarization observable Υ

$$\Upsilon = \frac{E_{\pi^-} - E_{\pi^0}}{E_{\pi^-} + E_{\pi^0}} = 2 \cdot \frac{p_T^{Trk}}{p_T^\tau} - 1$$



Motivation

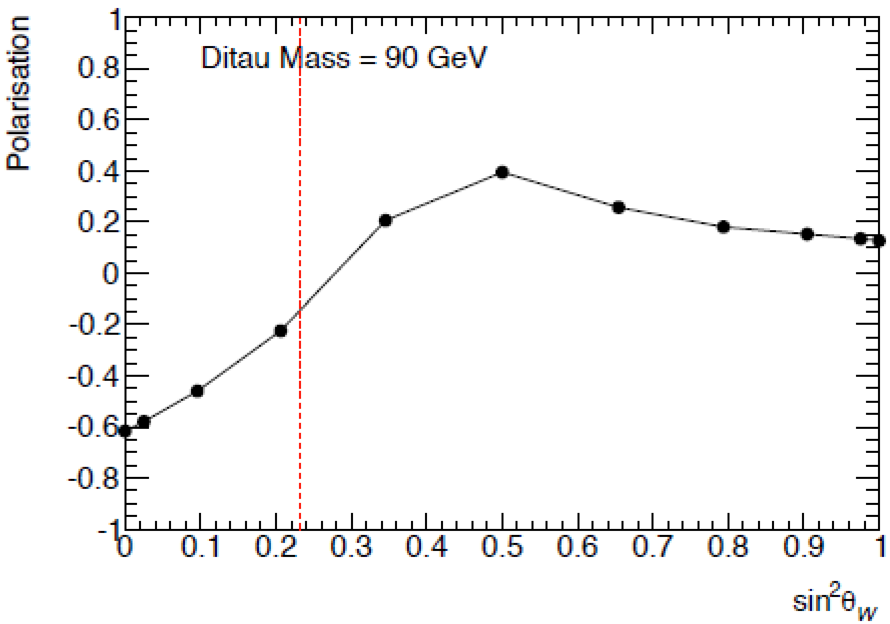
First measurement of effective Weinberg angle $\sin^2\theta_{W,eff}$ in 3rd generation lepton coupling at ATLAS

$$\mathcal{P}_f = -\frac{2 \cdot g_V^f g_A^f}{\left(g_V^f\right)^2 + \left(g_A^f\right)^2}$$

approximation $|g_V^\tau| \ll |g_A^\tau|$:

$$\mathcal{P}_\tau \approx -\frac{2 \cdot g_V^\tau}{g_A^\tau}$$

$$\mathcal{P}_\tau \approx -2\left(1 - 4\sin^2\theta_{W,eff}\right)$$



$\sin^2\theta_{W,eff}$ depends on generated mass spectrum

⟹ also provide acceptance (L&R) as function of mass

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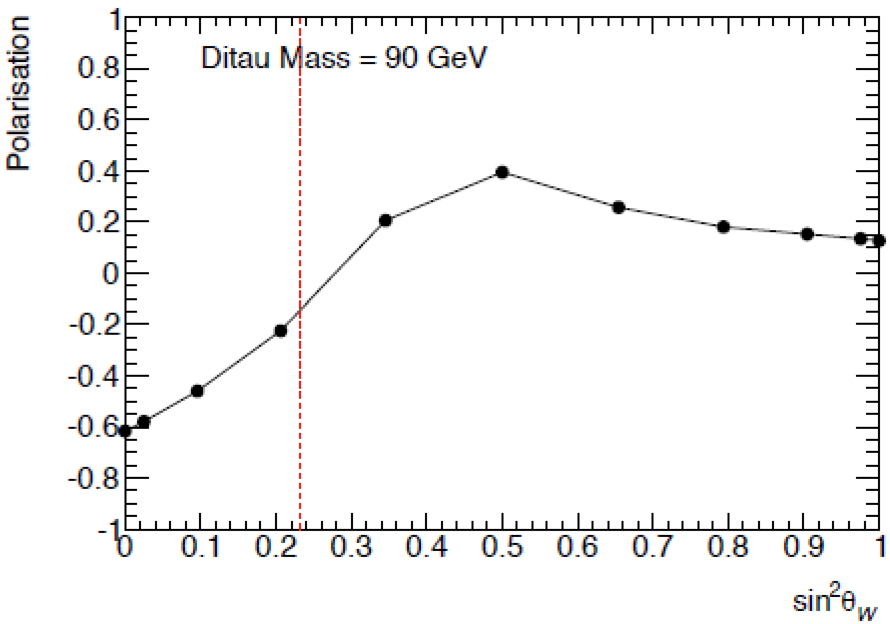


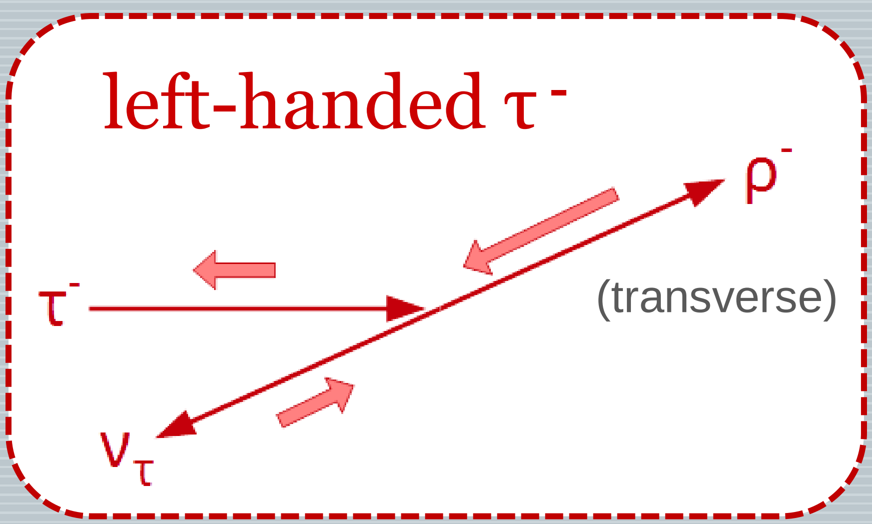
Preparation for Higgs CP analysis

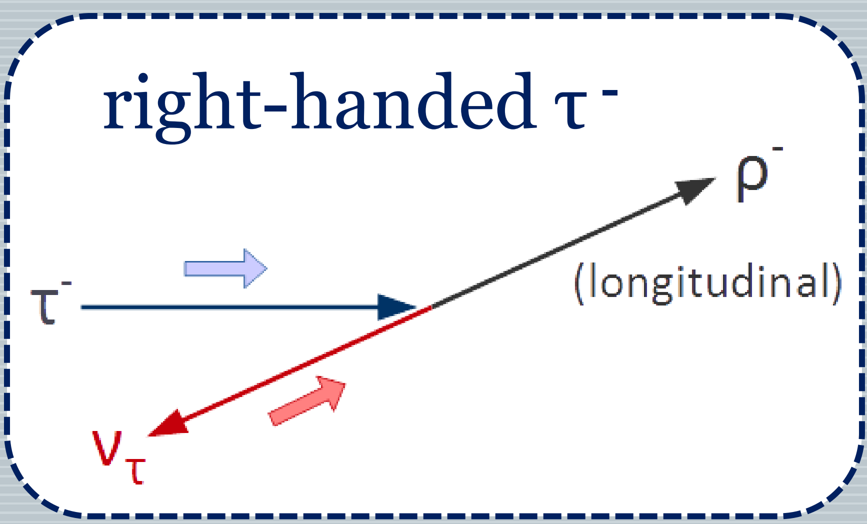
Polarization in the τ Decay

$$\tau^- \longrightarrow \rho^-\,\nu_\tau, \qquad \rho^- \longrightarrow \pi^-\,\pi^0$$

Charged Current couples to left-handed particles and right-handed anti-particles

Due to Lorentz boost: ρ in flight direction of τ preferred





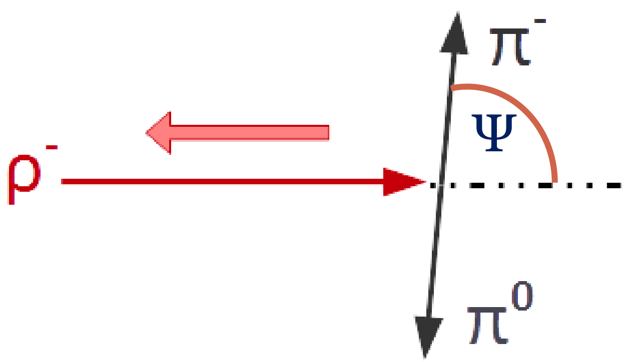
Polarization in the τ Decay

$$\tau^- \longrightarrow \rho^- \nu_\tau$$
$$\rho^- \longrightarrow \pi^- \pi^0$$

$$\cos\psi = \cancel{\frac{m_\rho}{\sqrt{m_\rho^2 - 4m_\pi^2}}} \cdot \frac{E_{\pi^-} - E_{\pi^0}}{|\vec{p}_{\pi^-} + \vec{p}_{\pi^0}|}$$

left-handed τ^-

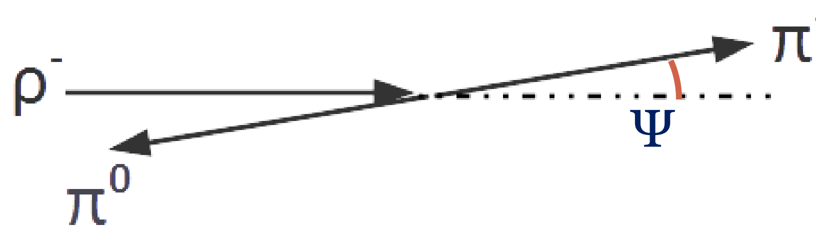
transverse ρ^-



$\Psi = 90°$

right-handed τ^-

longitudinal ρ^-



$\Psi = 0°, 180°$

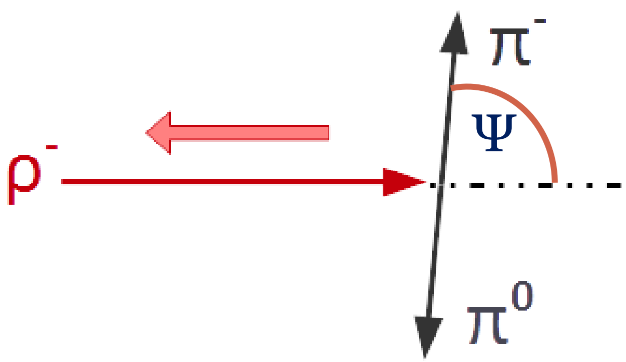
Conservation of angular momentum

Polarization in the τ Decay

Polarization Observable: $\Upsilon = \dfrac{E_{ch} - E_{\pi^0}}{E_{ch} + E_{\pi^0}} = \dfrac{2p_{\mathrm{T}}^{\mathrm{Trk}}}{E_{\mathrm{T}}} - 1$

left-handed τ^-

transverse ρ^-



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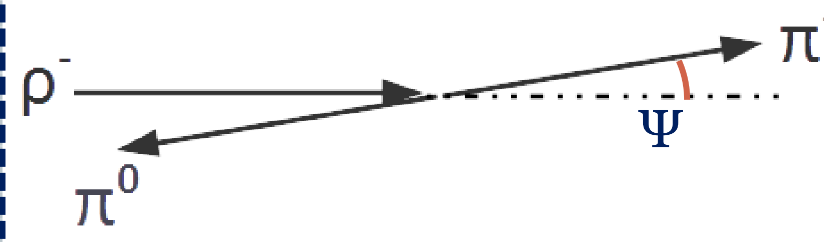
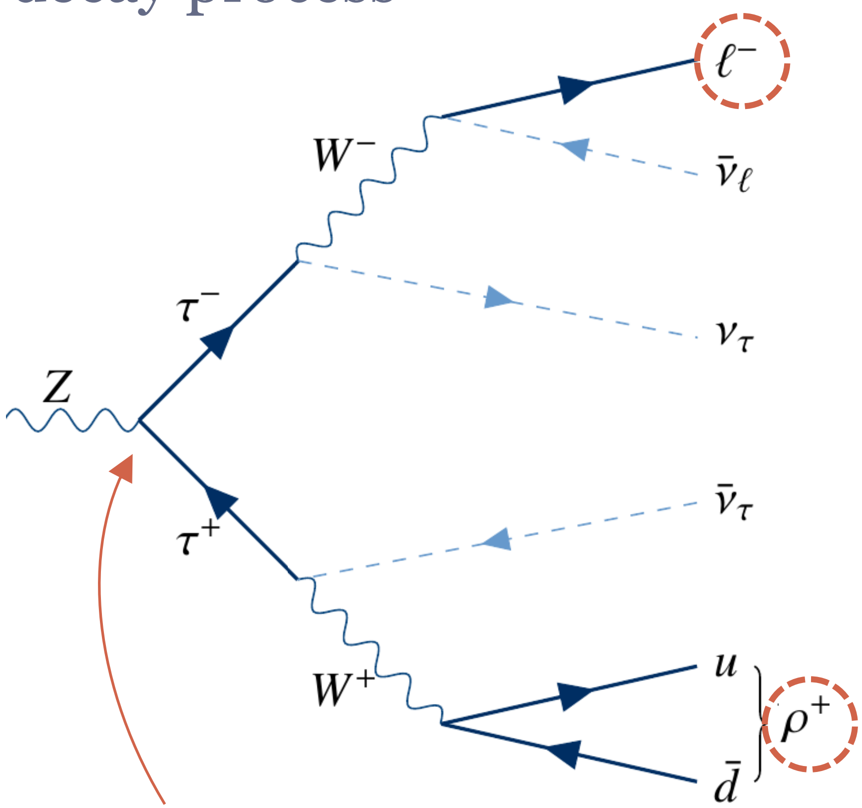


$\Psi = 0°, 180°$

Conservation of angular momentum

Event Selection

$Z \rightarrow \tau_{lep}\, \tau_{had}$ decay process



$\mathcal{BR}(Z \longrightarrow \tau\, \tau) = 3.37\ \%$

- exactly 1 isolated lepton
  - $p_T > 26$ GeV
  - single lepton trigger
- exactly 1 hadronic 1-prong τ
  - $p_T > 20$ GeV
  - tau ID efficiency ≈ 60 %
- lepton and τ opposite sign
- $m_T < 30$ GeV
- $\sum \Delta\varphi < 3.5$

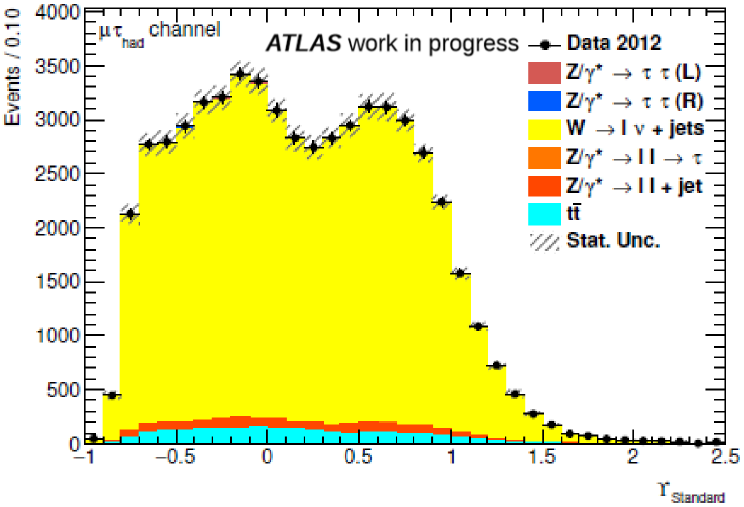
Background Estimates

Zll, ttbar: from MC

QCD: data driven estimate from SS-control region,
transfer from SS to OS region (ABCD method):
scale with OS/SS ratio from anti-isolated CR
(reversed both lepton isolation requirements)

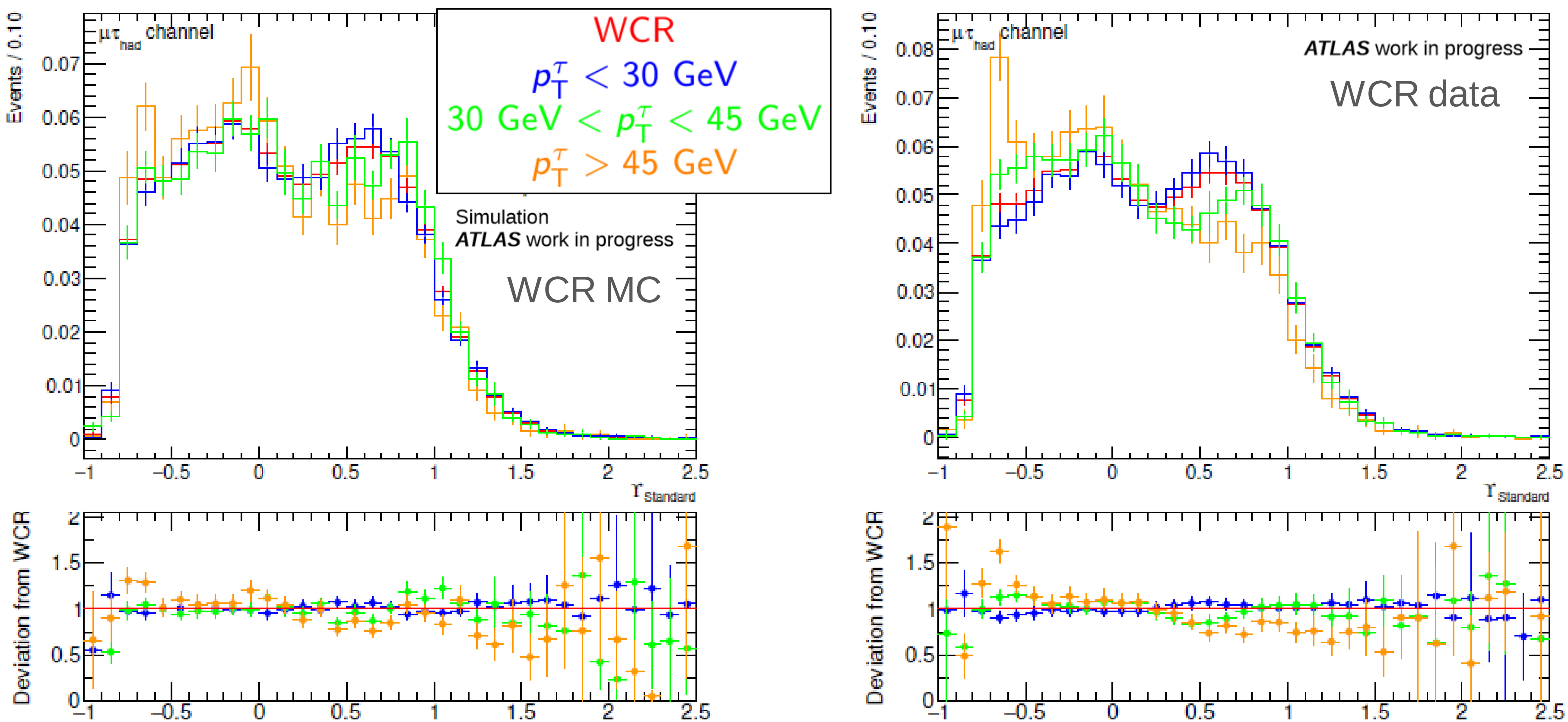
W+jets: data driven estimate from
W enriched control region
(m_T > 70 GeV , $\sum\Delta\varphi$ > 3.5):
- subtract non-W+jets MC backgrounds from data in OS WCR
- correct for slope in SR/WCR MC ratio
- transfer to SR: normalize to expected SR cross-section

⇨ systematic shape uncertainty



data driven W+jets estimate from opposite-sign WCR

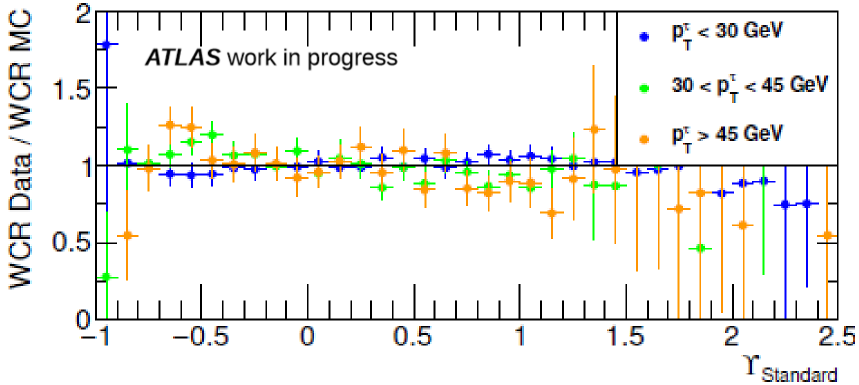
W+jets Υ Shape Dependence on p_T

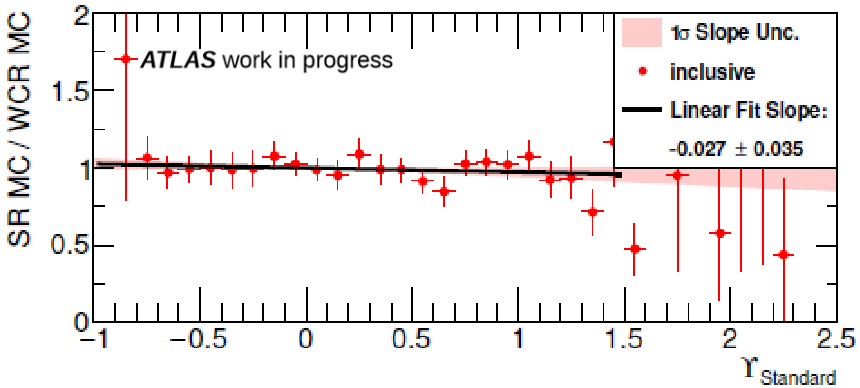


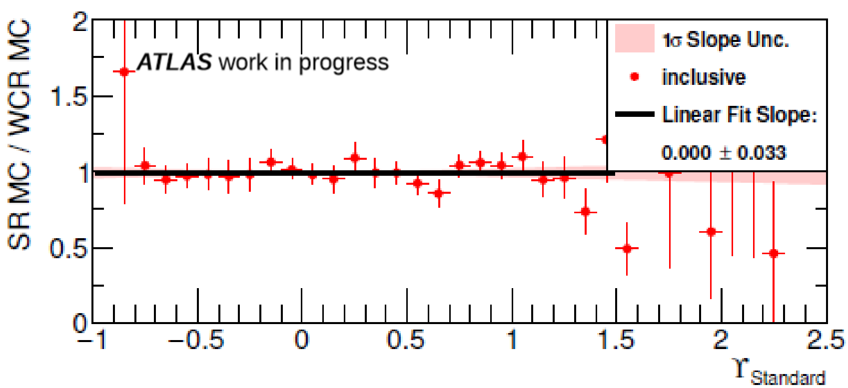
1. Υ shape varies in different bins of p_T
2. Shape variation stronger in W Control Region data

→ need reweighting for transfer from Control to Signal Region

Systematic Shape Uncertainty







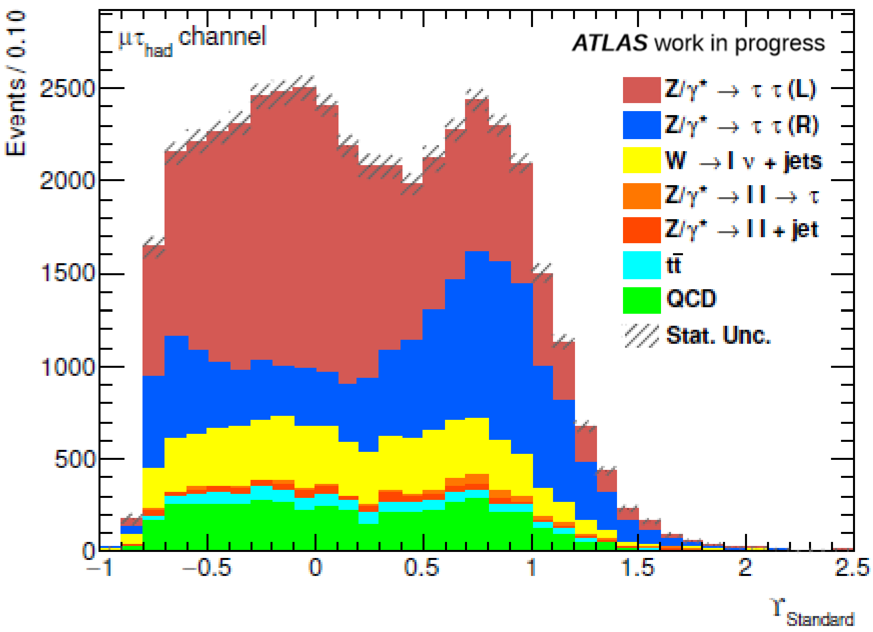
WCR data/WCR MC:
mismodeling of data is the same in different p_T bins
→ reweight inclusive distribution

Derive CR→SR ϒ reweighting from inclusive SR MC/WCR MC

weight ϒ shape of WCR data for transfer CR→SR with slope

Re-fit SR MC/WCR MC after reweighting
Systematic Shape Uncertainty:
UP: weight = 0.99198+0.06606 ϒ
DN: weight = 0.99198 - 0.06522 ϒ

Likelihood Fit & Systematics



Υ variable in signal region (blinded)

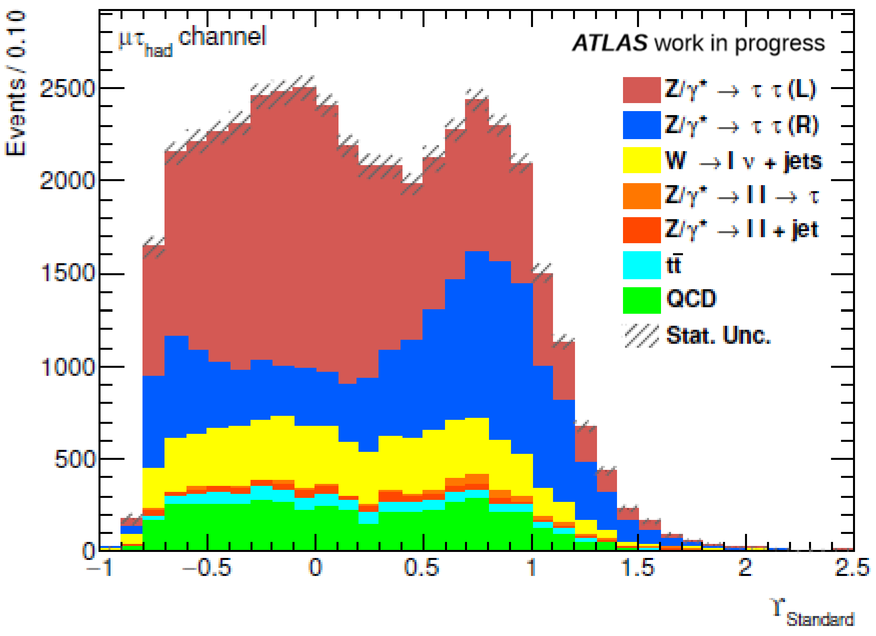
Binned Likelihood Fit:

- fit simultaneously in signal and control regions and in e-had and mu-had channels

Systematic Uncertainties:

- **τ energy scale** dominant
- include minor standard systematics to the fit
- MC uncertainties on Zττ templates
- shape uncertainty on W+jets

Likelihood Fit & Systematics



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Current Issues:

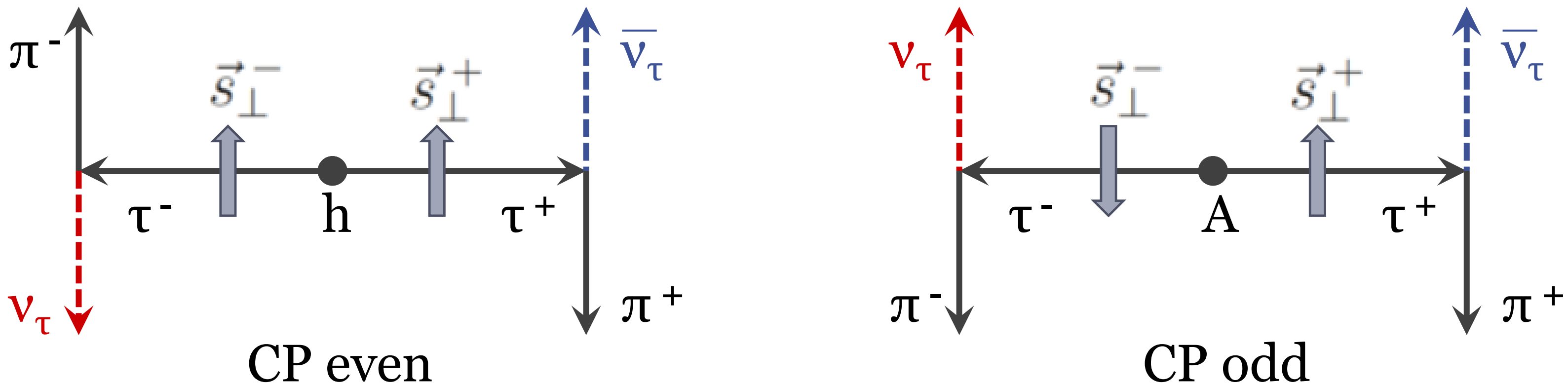
- TauSpinner and TAUOLA assign polarization incorrectly for Z+(≥ 1 jet), estimate uncertainty on polarization with TauSpinner/TAUOLA difficult
- have to estimate τ energy scale uncertainty separately for charged and neutral pion content

Higgs CP Measurements in $H \longrightarrow \tau\tau$ Decays

Motivation

- mixture of CP even and odd Higgs predicted by some BSM models
  ⟹ mixing angle φ_τ

- measure mixing using information on transverse τ spin correlations



  - reconstruct τ decay planes
  - determine angle φ^*_{CP} between the decay planes
  - measure differential cross-section as function of φ^*_{CP}
  - determine φ_τ from shift of cosine function

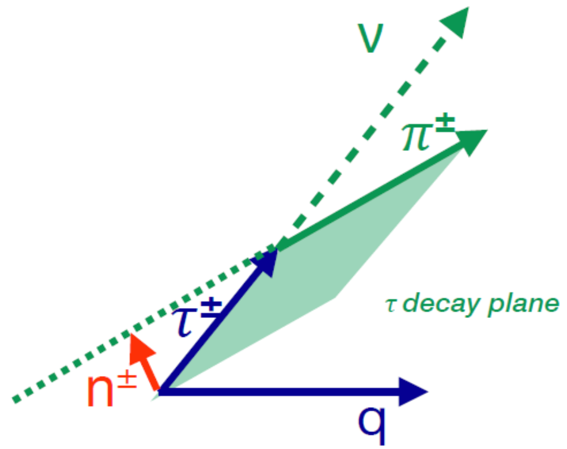
Combination of two Reconstruction Methods

Impact Parameter Method

multiple decay modes can be used, e.g.

$\tau \longrightarrow \pi^{\pm}\ \nu$ (1p0n)

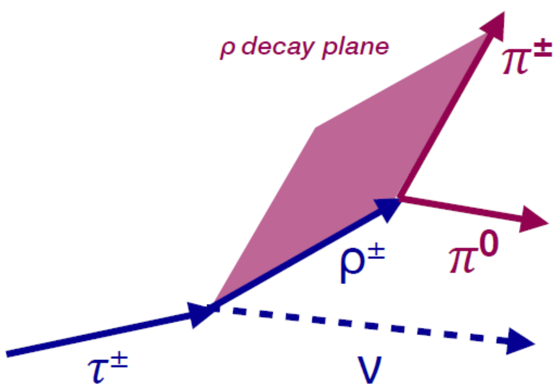
- reconstruction of $\tau^{\pm}$ decay plane
- using 3D impact parameter and primary vertex



ρ Decay Plane Method

$\tau \longrightarrow \rho^{\pm}\ \nu \longrightarrow \pi^{\pm}\ \nu$ (1p1n)

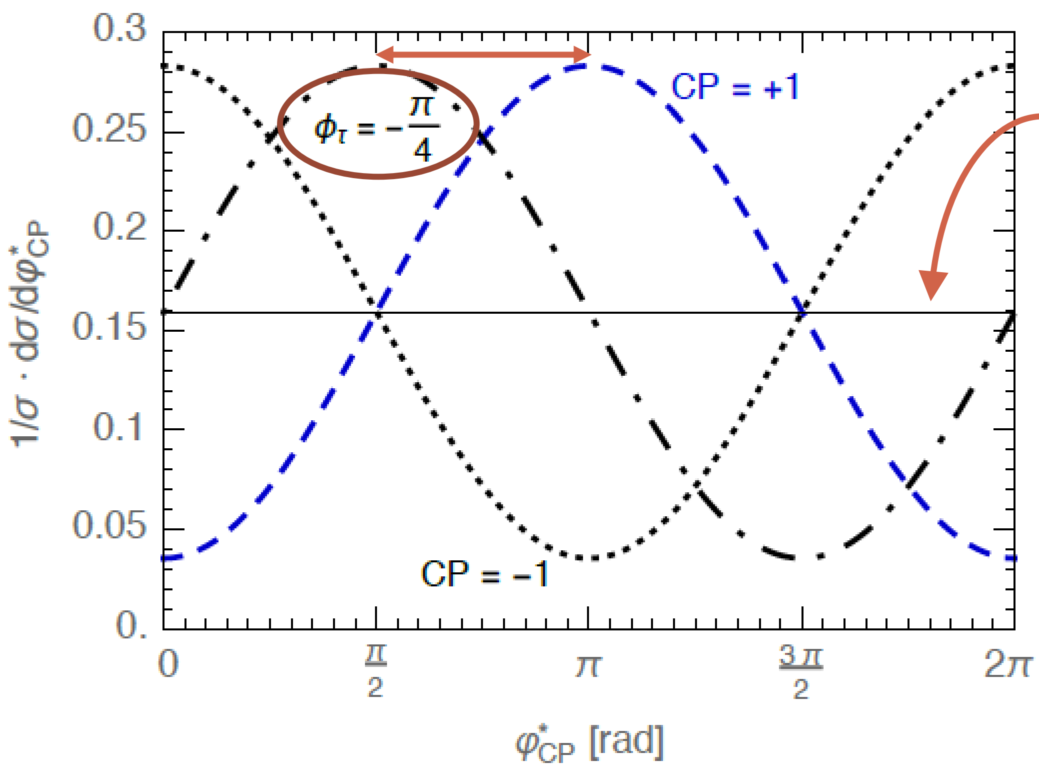
- reconstruction of $\rho^{\pm}$ decay plane
- using 4-vectors of $\pi^{\pm}$ and π^{0}



Use new Run-II decay mode classification & 4-mom reconstruction

Determination of φ_τ

- φ^*_{CP} : angle between the $\tau^\pm$ decay planes
- differential cross-section as function of φ^*_{CP}



$Z^*/\gamma^* \longrightarrow \tau\tau$

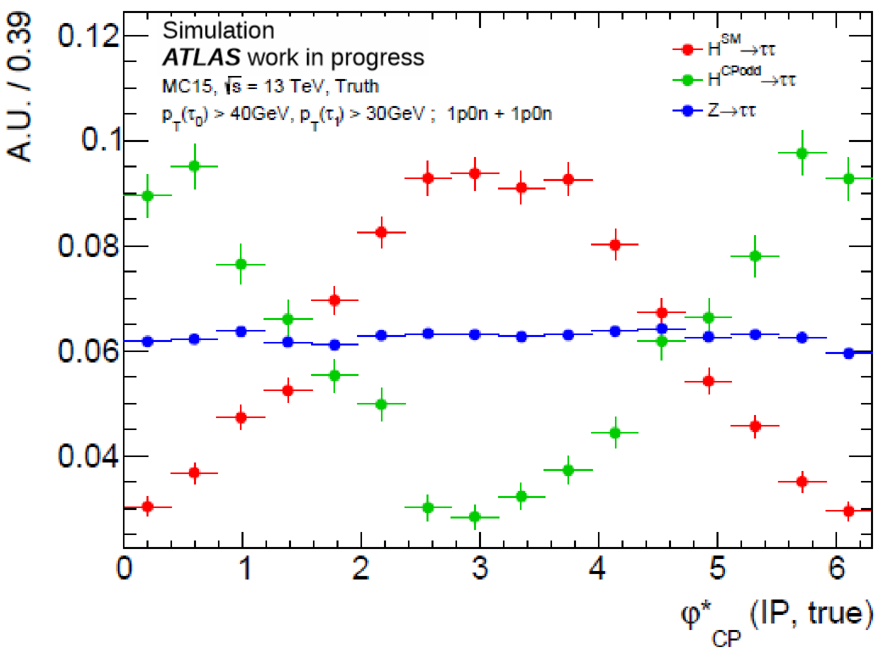
Calibration with $Z \longrightarrow \tau\tau$ (generate artificial cosine dependence)

- shift of peak in φ^*_{CP} spectrum
  ⇒ syst. uncertainty
- amplitude difference
  ⇒ estimate expected sensitivity

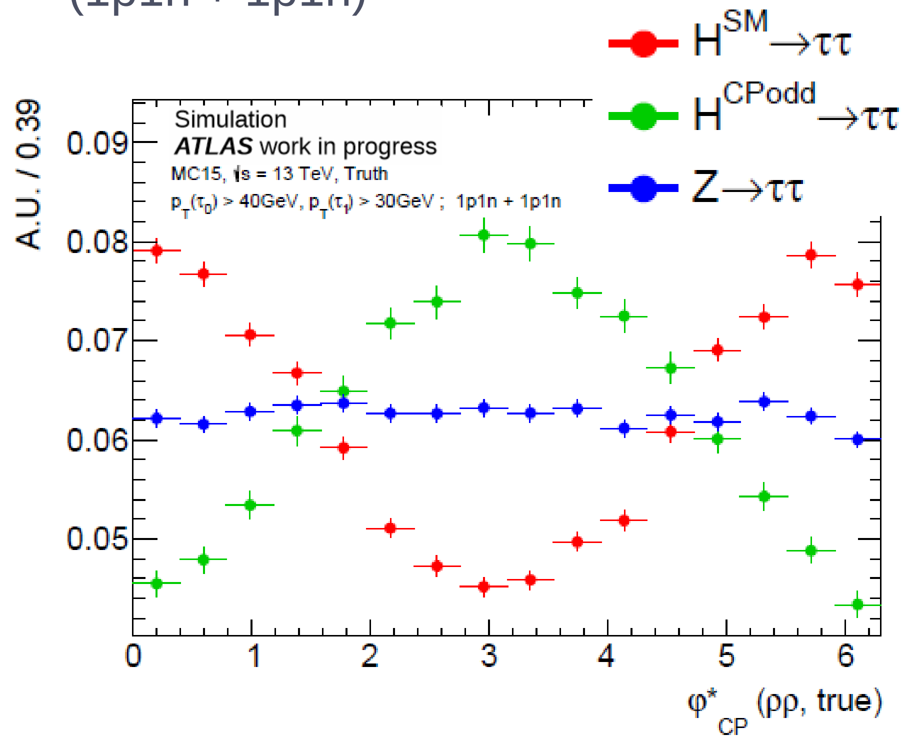
- mixing angle φ_τ from phase shift

φ^*_{CP} on Truth Level

impact parameter method
(1p0n + 1p0n)



ρ decay plane method
(1p1n + 1p1n)



- $Z \longrightarrow \tau\tau$: flat distribution
- $H \longrightarrow \tau\tau$: cos dependence

Summary & Outlook

- First τ polarization measurement in $Z \longrightarrow \tau\tau$ decays at a hadron collider & measurement of effective Weinberg angle in 3rd generation lepton coupling
  - Optimized data driven background estimates
  - Extracted systematic Υ shape uncertainty on W+jets background
  - Helps us to understand challenges for Run-II
- CP admixture in $H \longrightarrow \tau\tau$ can be extracted from Higgs decay by measuring the angle between the decay planes

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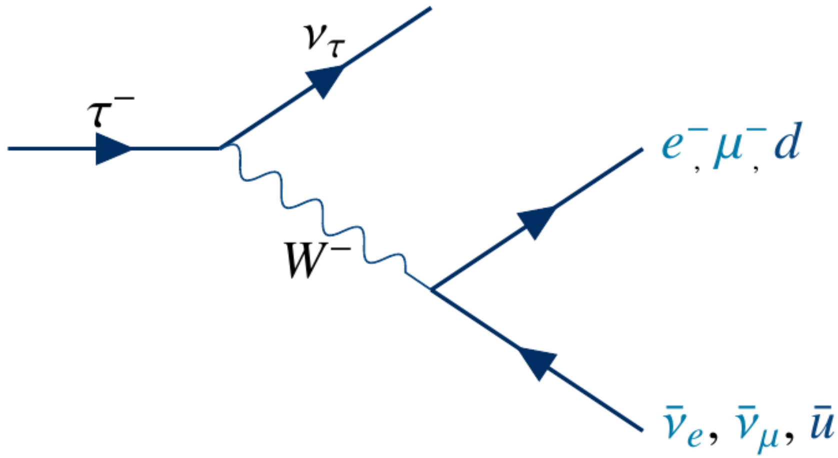
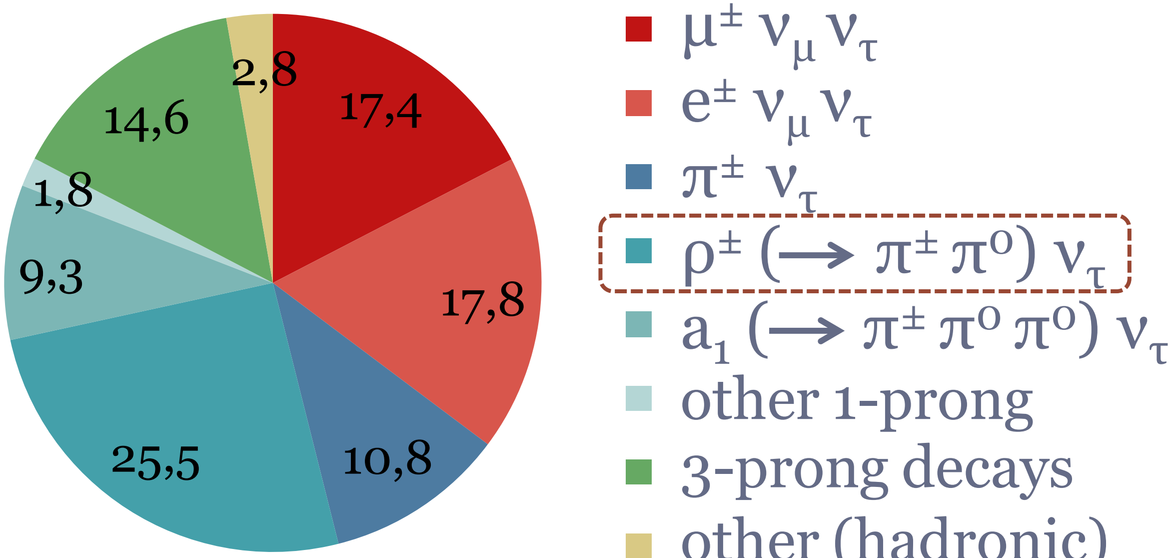
Thank you!

BACKUP

The τ Lepton

- heaviest lepton
  $m_\tau = 1777$ MeV
- extreme short lifetime
  of $290 \cdot 10^{-15}$ s
- decay length of 87 μm



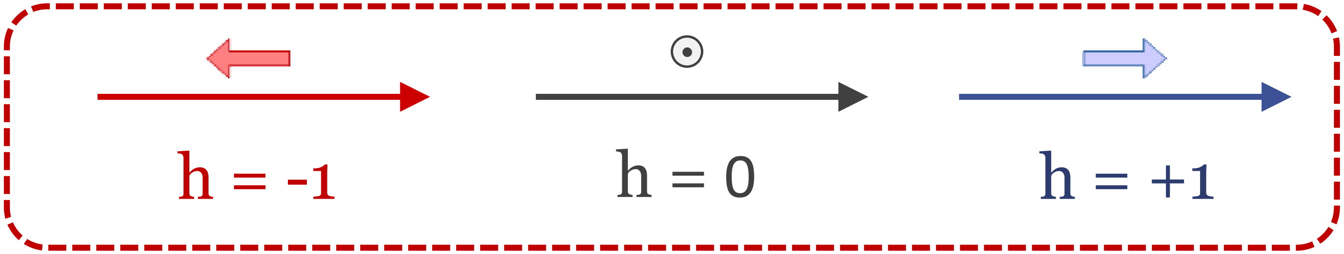


Quick Reminder on Polarization

Helicity: $$h = \frac{\vec{s} \cdot \vec{p}}{|\vec{s}||\vec{p}|}$$

left-handed: h = -1

right-handed: h = +1



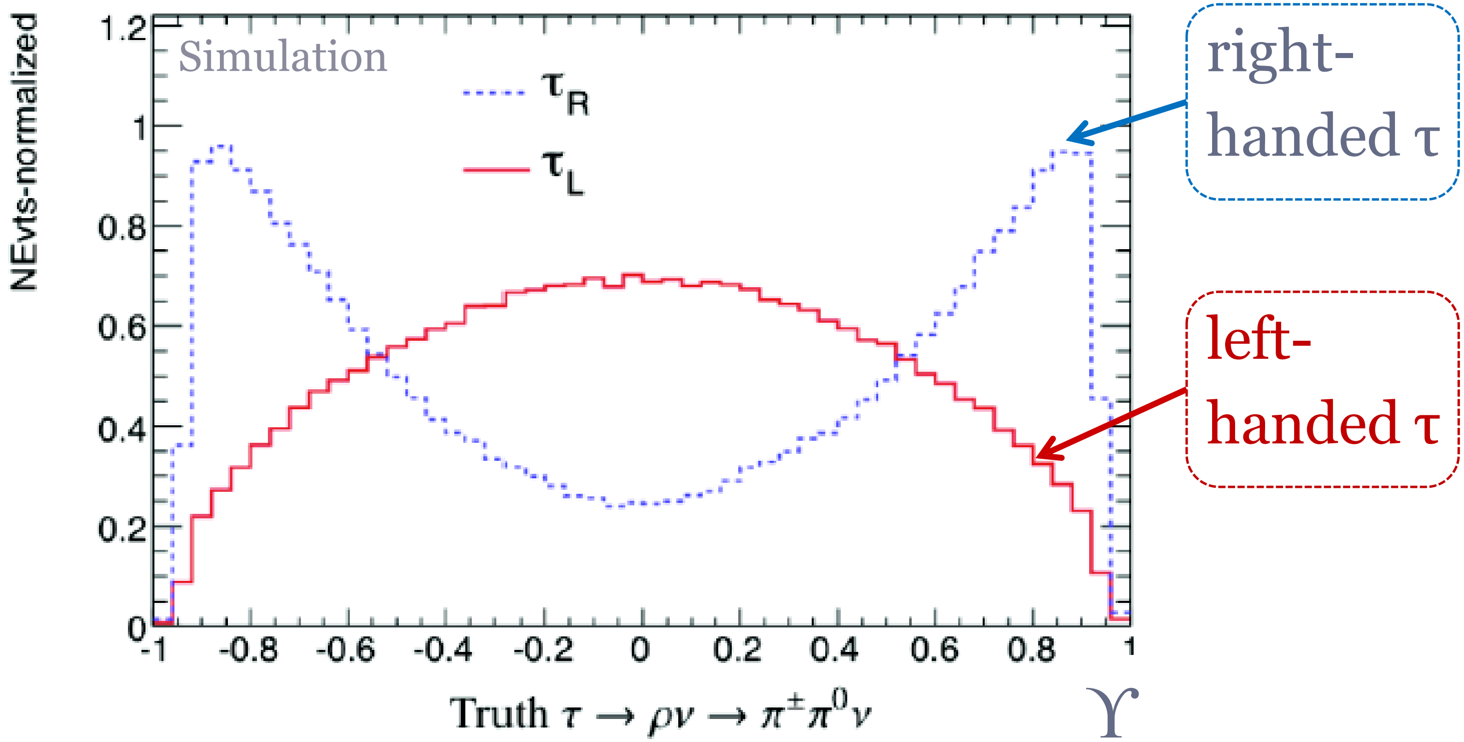
Polarization in a sample composed of right- and left-handed taus:

$$\boxed{\mathcal{P}_\tau = \frac{\sigma_\mathrm{R} - \sigma_\mathrm{L}}{\sigma_\mathrm{R} + \sigma_\mathrm{L}}}$$

Polarization Observable Υ

Upsilon: $$\Upsilon = \frac{E_{ch} - E_{\pi^0}}{E_{ch} + E_{\pi^0}} = \frac{2p_{\mathrm{T}}^{\mathrm{Trk}}}{E_{\mathrm{T}}} - 1$$

with $E_{\mathrm{T}}^{\pi^0} = E_{\mathrm{T}} - p_{\mathrm{T}}^{\mathrm{Trk}}$



Upsilon Calculation

$$P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \qquad \Upsilon = \frac{E_{ch} - E_{\pi^0}}{E_{ch} + E_{\pi^0}}$$

but: E_{π^0} not reconstructed

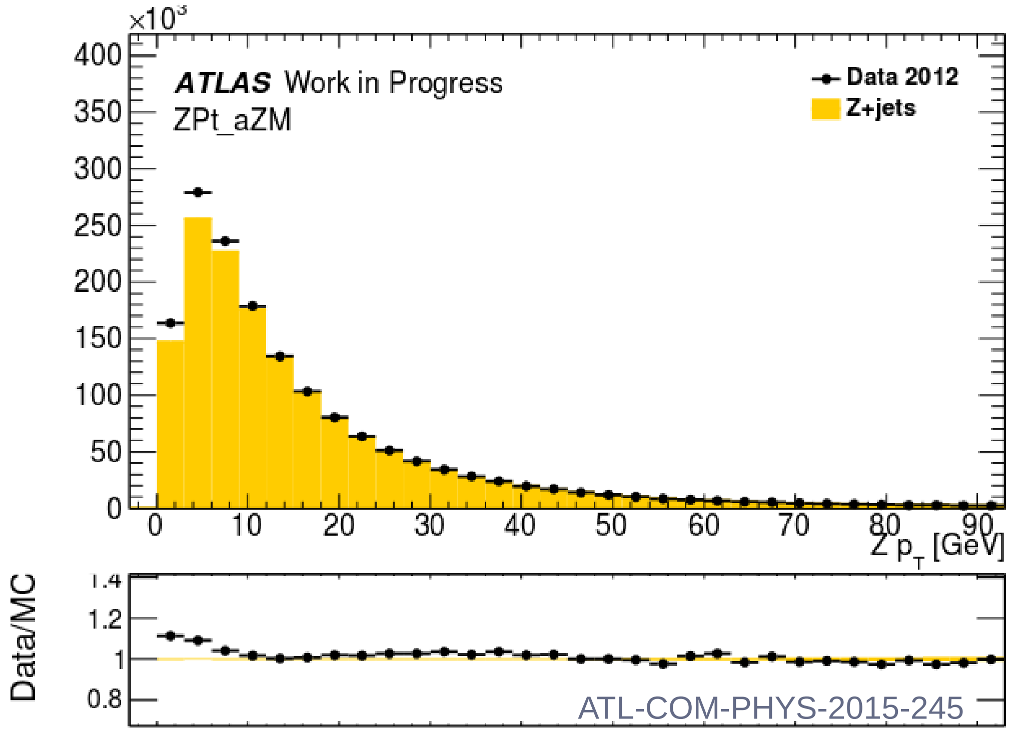
instead: total transverse calorimeter energy E_{T} (evtsel_tau_et)
transverse momentum of charged tracks $p_{\mathrm{T}}^{\mathrm{Trk}}$ (tau_leadTrkPt)

$$E_{\mathrm{T}}^{\pi^0} = E_{\mathrm{T}} - p_{\mathrm{T}}^{\mathrm{Trk}}$$

$$\Upsilon = \frac{p_{\mathrm{T}}^{\mathrm{Trk}} - \left(E_{\mathrm{T}} - p_{\mathrm{T}}^{\mathrm{Trk}}\right)}{p_{\mathrm{T}}^{\mathrm{Trk}} + \left(E_{\mathrm{T}} - p_{\mathrm{T}}^{\mathrm{Trk}}\right)} = \frac{2p_{\mathrm{T}}^{\mathrm{Trk}}}{E_{\mathrm{T}}} - 1$$

Modeling of Real Taus

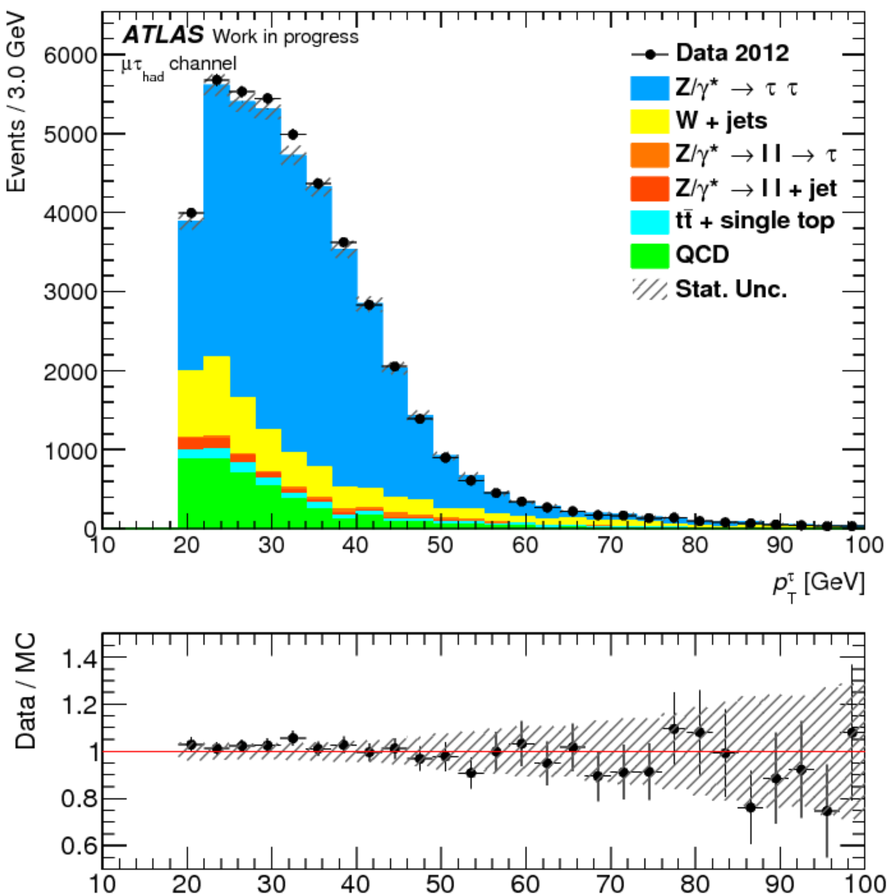
To improve the tau p_T modeling of signal MC: apply reweighting of Z boson p_T



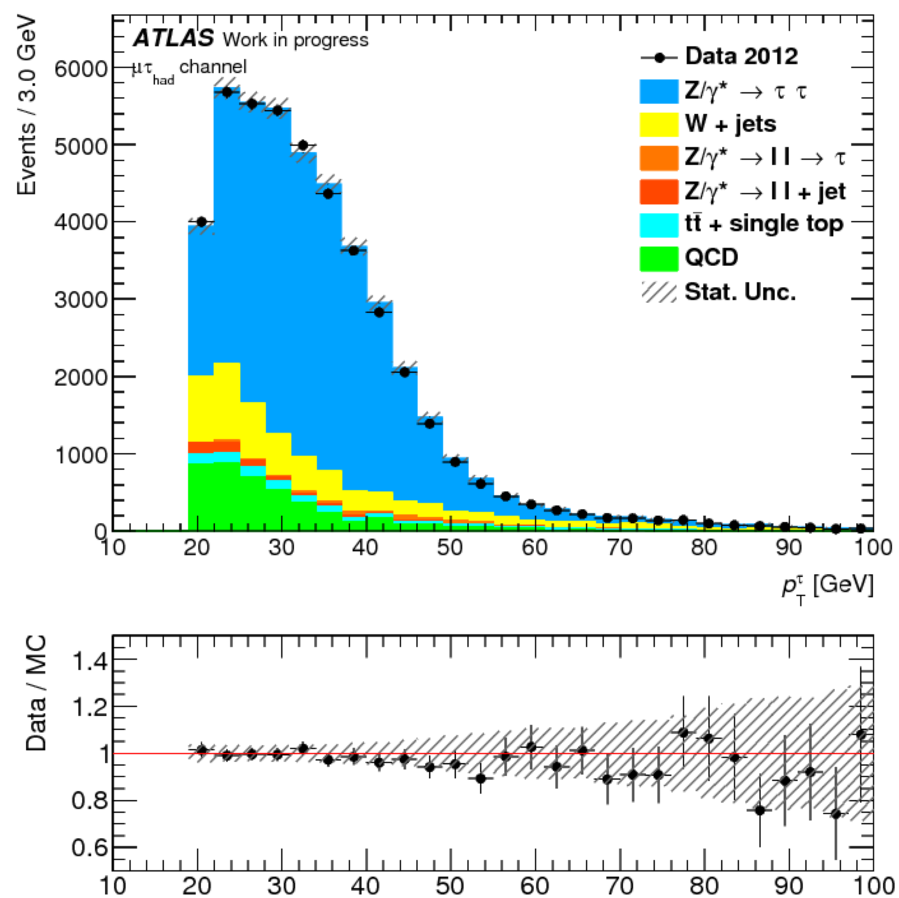
p_T^Z in $Z \to \mu\mu + \text{jets}$

Modeling of Real Taus

without Z p_T reweighting

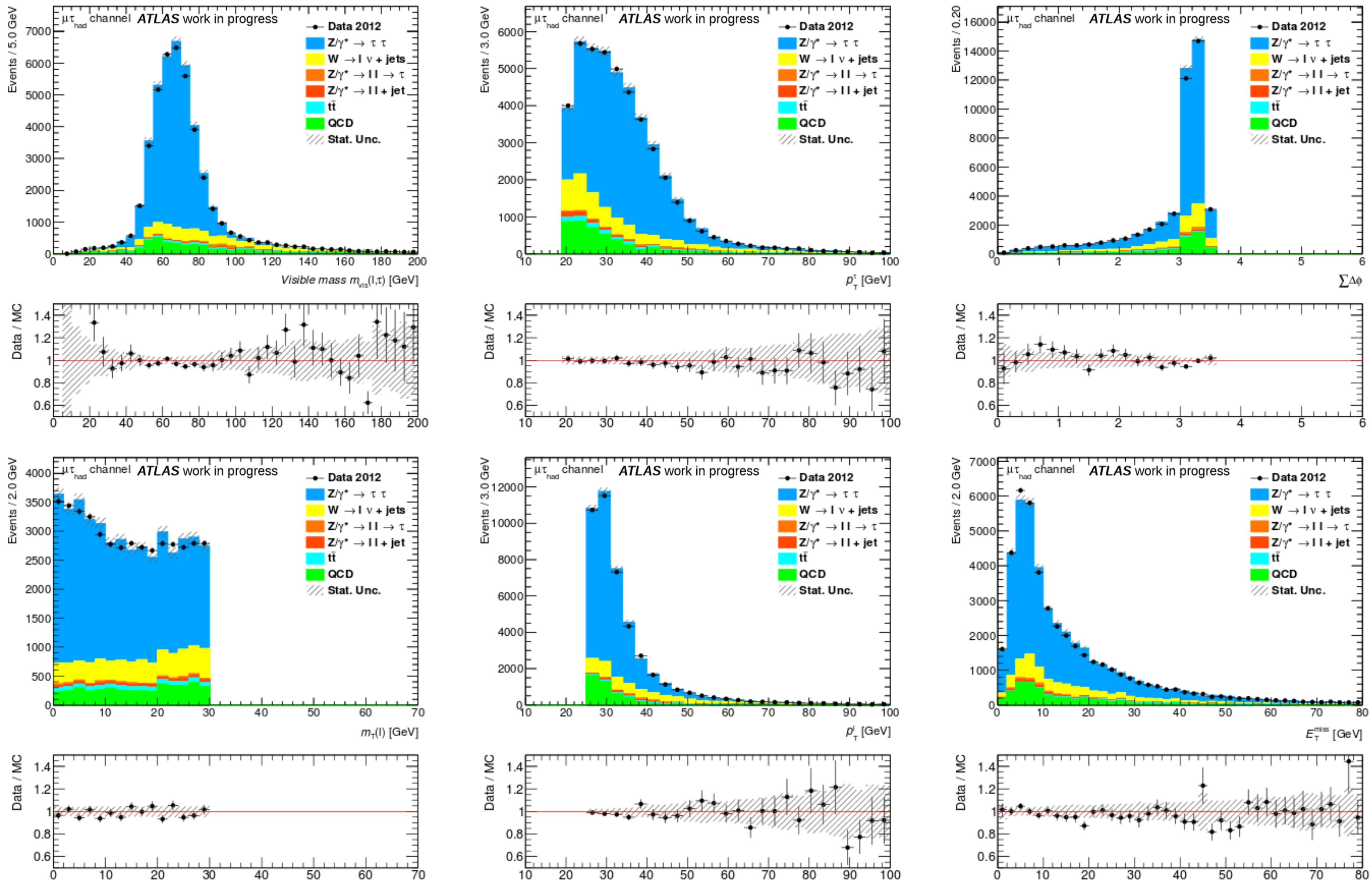


with Z p_T reweighting



→ improves modeling in low p_T region (high statistics)

Kinematic Modeling (muon channel)



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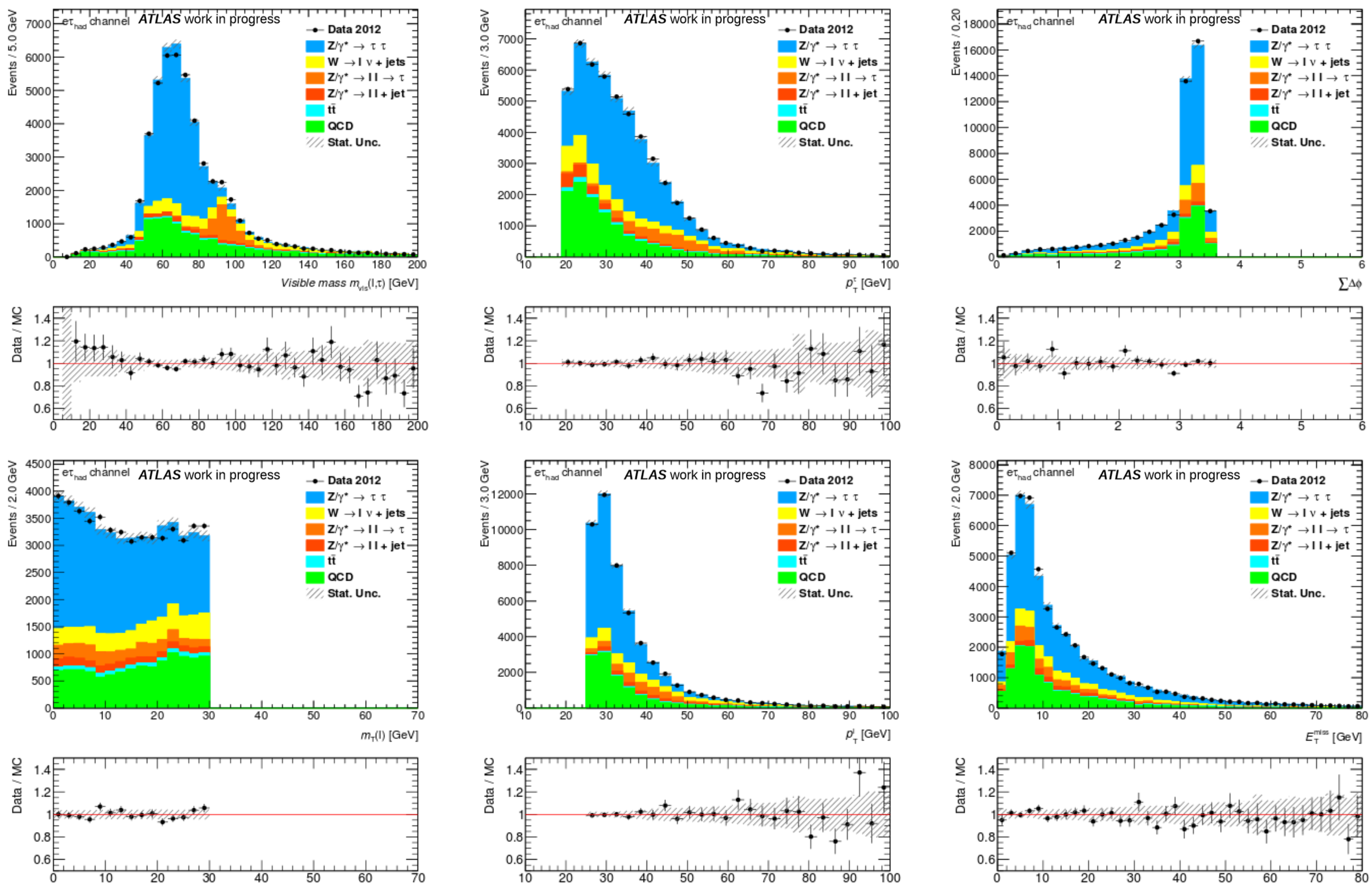
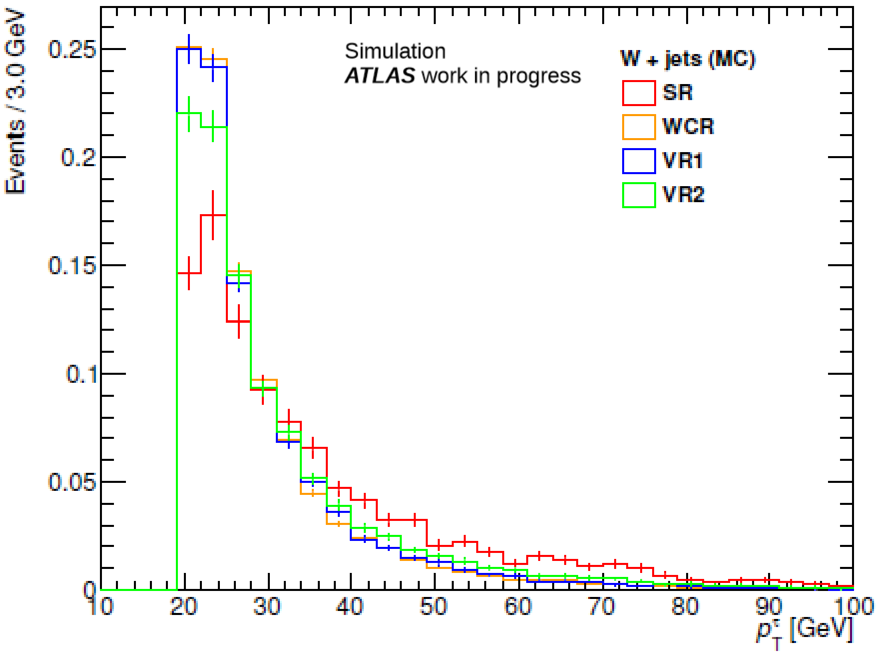
Kinematic Modeling (electron channel)



Study of ϒ Shape Variation in W+jets

Does ϒ shape depend on jet p_T ?

W+jets MC shows different tau p_T distributions in W Control Region and Signal Region



→ motivates studies of p_T binned ϒ distribution

→ extract systematic ϒ shape uncertainty

Validation Regions

Verify p_T dependence in Validation Regions - reminder:

WCR evtsel_transverseMass>70., evtsel_dPhiSum>3.5

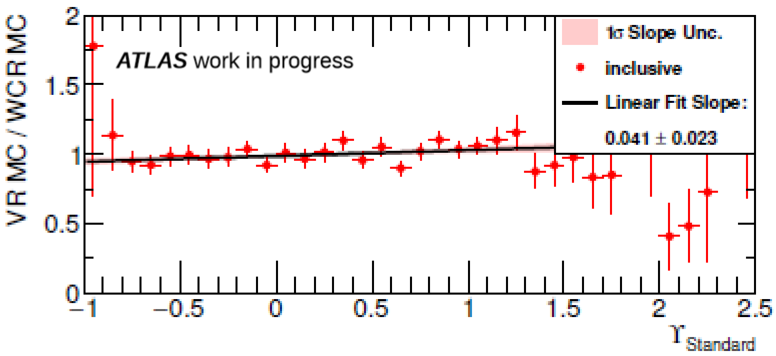
SR evtsel_transverseMass<30., evtsel_dPhiSum<3.5

Validation Regions - cuts like SR, except:

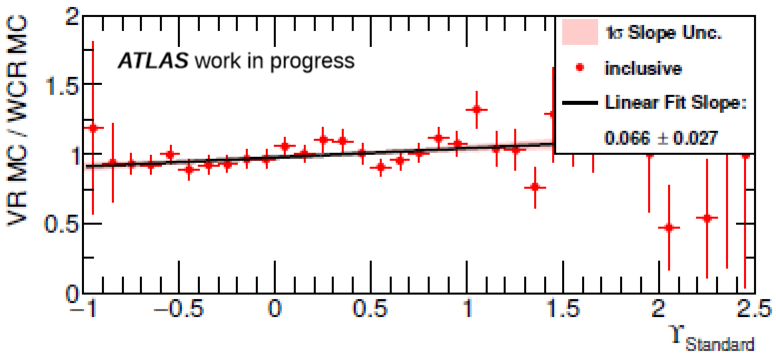
VR1 30.<evtsel_transverseMass<70., evtsel_dPhiSum>3.5

VR2 30.<evtsel_transverseMass<70., evtsel_dPhiSum<3.5

VR1



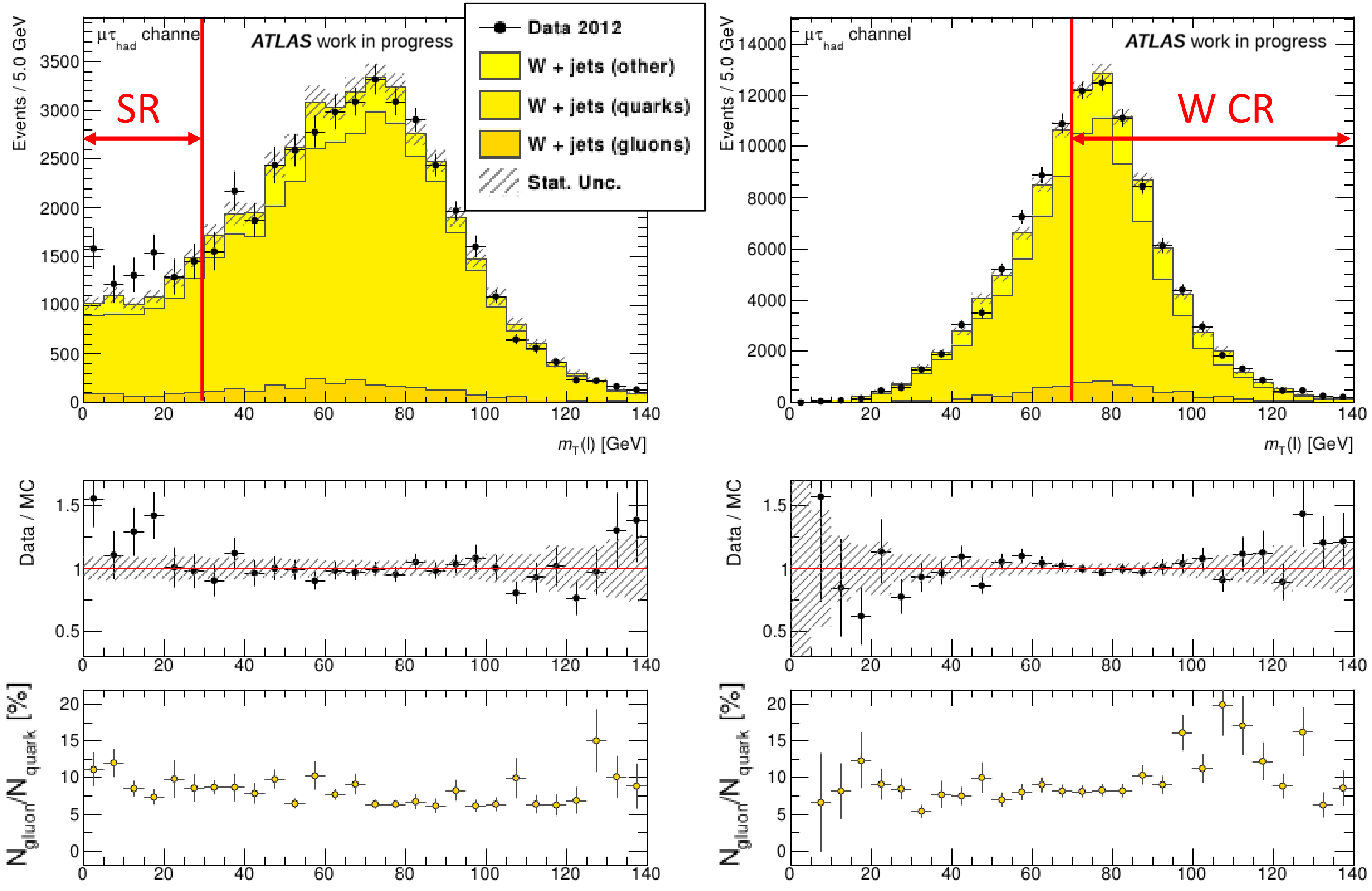
VR2



$\rightarrow \quad \approx 2\sigma$ deviation from 0

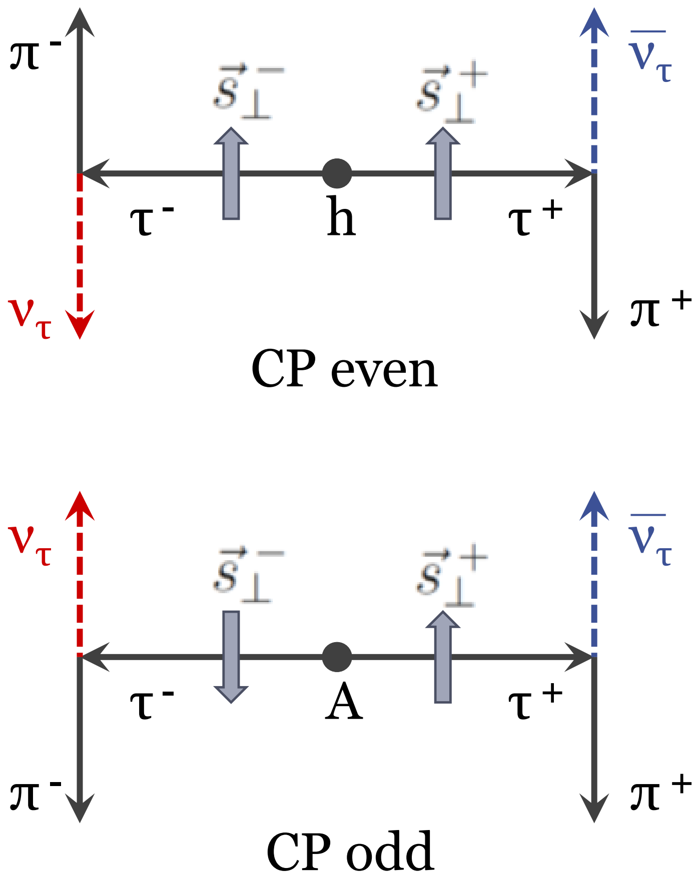
Study of Υ Shape Variation in W+jets

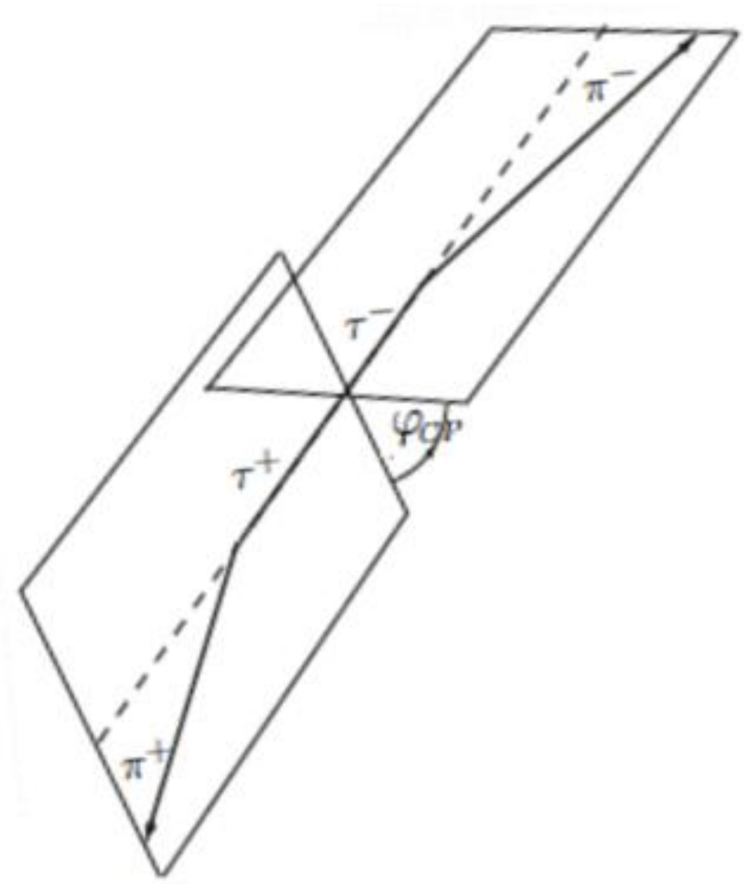
Does Υ shape depend on quark-gluon fraction?



$\sum \Delta\Phi < 3.5$ $\sum \Delta\Phi > 3.5$

Angle between Decay Planes





The ATLAS Detector