Tau Polarization Update

María Cepeda for the Tau Polarization team

Tau Polarization Study using CLD Full Simulation

$$\mathcal{P}_\tau(\cos\theta_{\tau^-}) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta_{\tau^-}) + 2\mathcal{A}_e\cos\theta_{\tau^-}}{(1+\cos^2\theta_{\tau^-}) + \frac{8}{3}A^{\tau}_{FB}\cos\theta_{\tau^-}}$$

Working with full simulation (CLD) on a tau polarization sensitivity (SC request)

Focus on Atau

Prioritize Pion and Rho decay.

Two strategies for tau reconstruction:

- Simple, based on pandora ➔ this should have worked out of the box (but didn't)
- ML based (still in progress)

Today I will be giving an update on the analysis side

Not finished yet unfortunately: reporting today to show the status

Reminder: LEP

Combined LEP result: 0.1439 ± 0.0035 (stat) ±0.0026 (syst) (Z pole LEP+SLD paper, 2006)

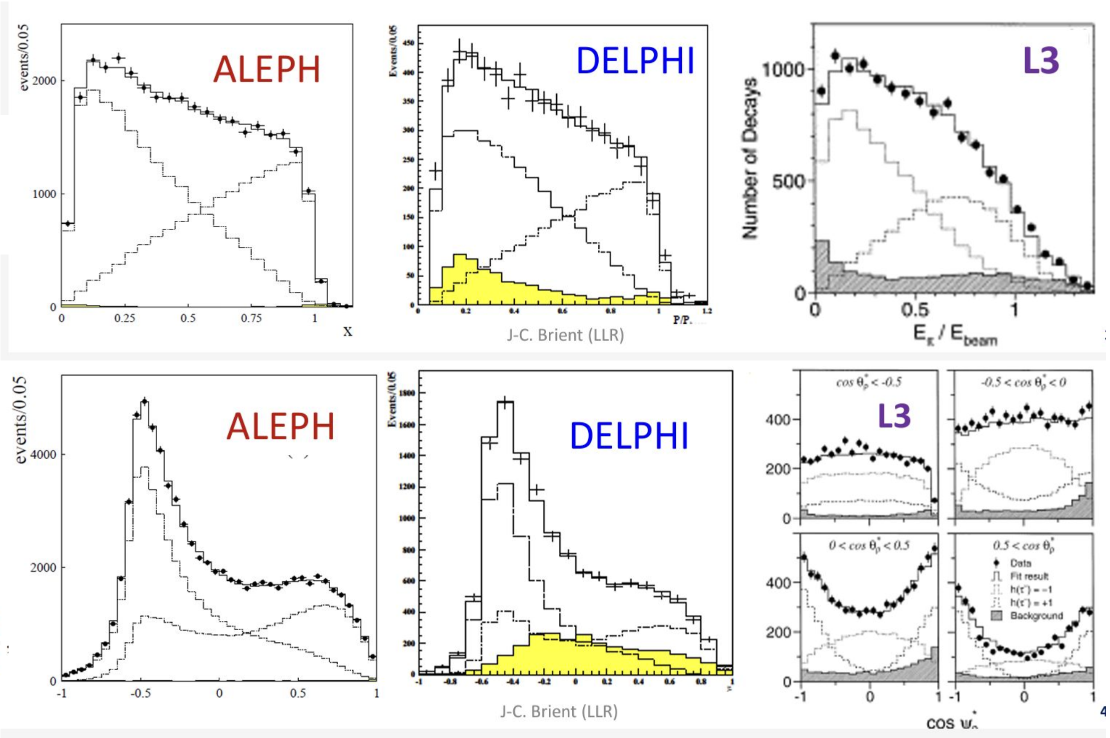
See J-C. Brient's presentation in Krakow Physics Workshop for a detailed discussion

$\tau \to \pi(k)\, \nu$

$$x_\pi = E_\pi / E_\tau$$

$\tau \to \rho(k^*)\, \nu$

$$\omega_\rho = \frac{W_+(\theta^*, \psi) - W_-(\theta^*, \psi)}{W_+(\theta^*, \psi) + W_-(\theta^*, \psi)}$$

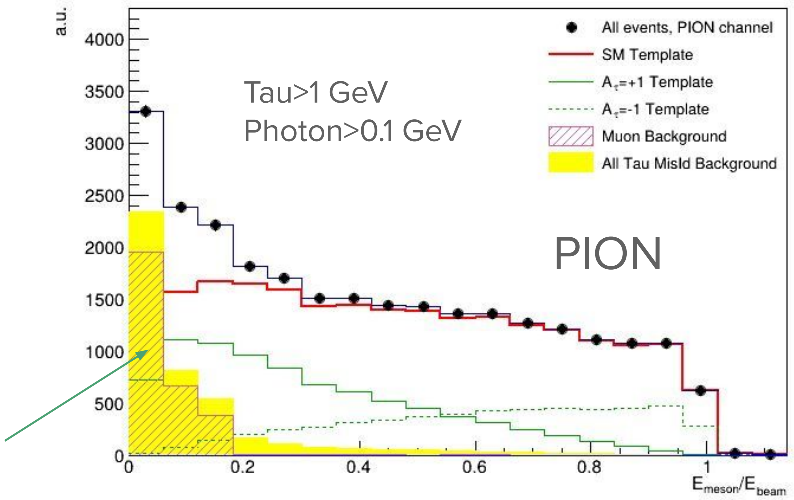


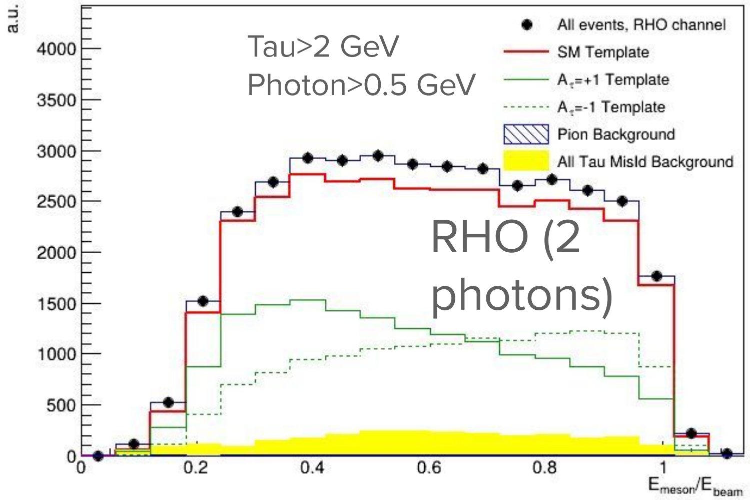
Effect of reconstruction on the templates?

Discrimination pion vs rho

Intro: where are we?

One of the useful observables (the simplest) for the study is E/Ebeam. In LEP, used as the final variable for the PION channel (not for the rho). This is how this looks now with **Pandora for CLD out of the box** and the simple tau reco for PION and RHO (with loose selection cuts).



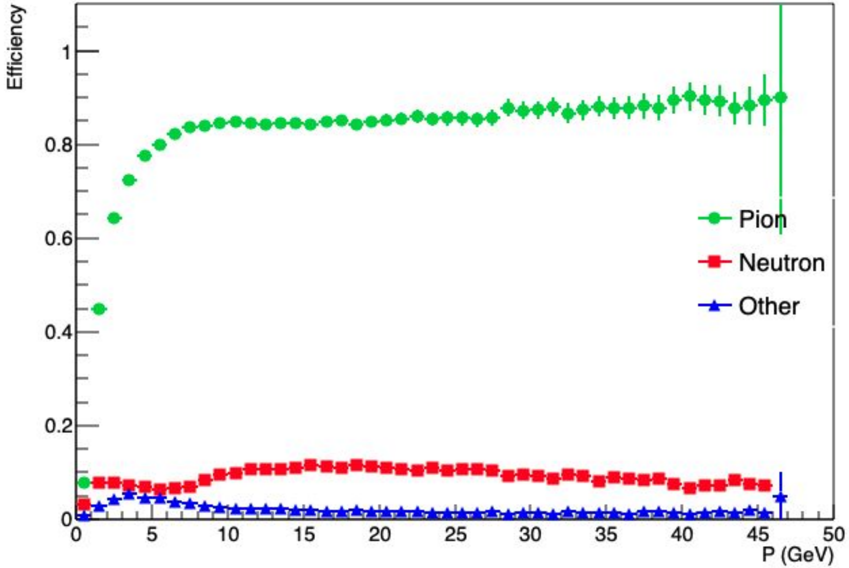


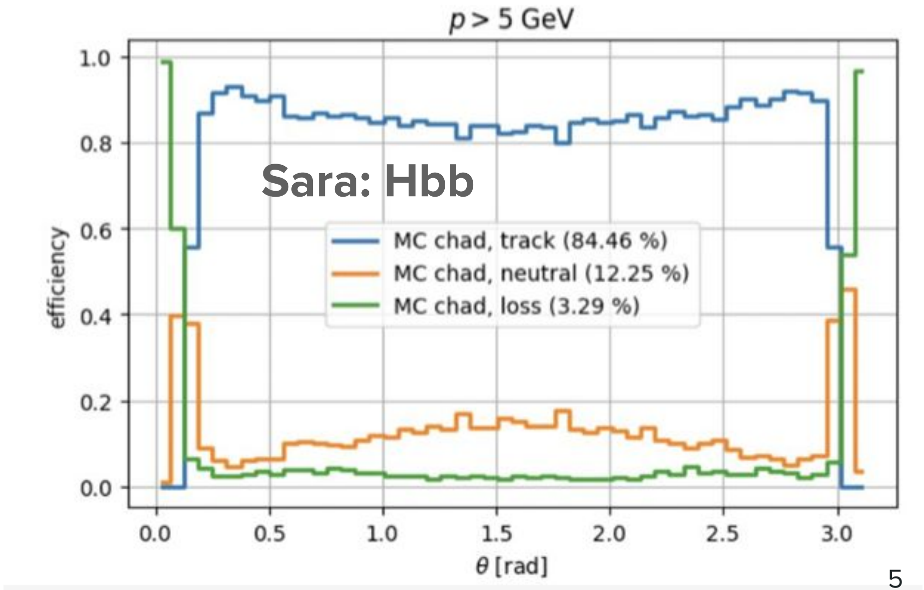
Note the selection here is quite loose on purpose to expose some of the issues
I'll explain the meaning of the templates later in this talk
Very poor MC stats here, less than 1 fb-1, we need to generate more events eventually

Reconstruction: Problems with pandora

In the last meeting we reported problems with pandora: low pion efficiency

Replicated & further studied by Sara Aumiller: report in Full Sim meeting

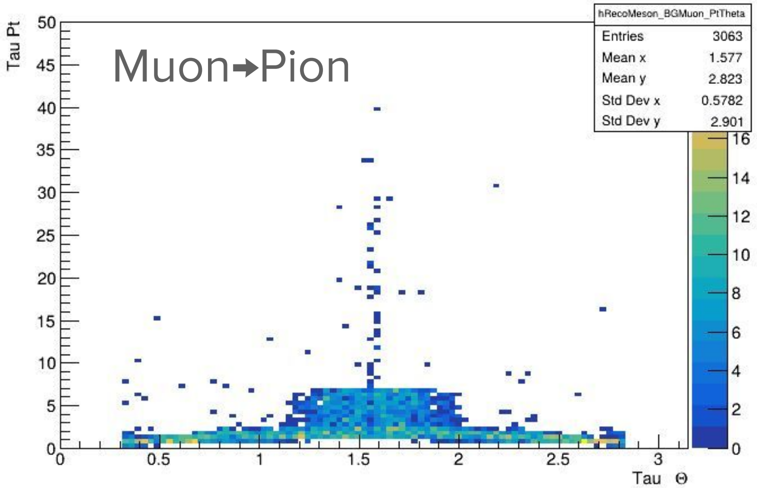


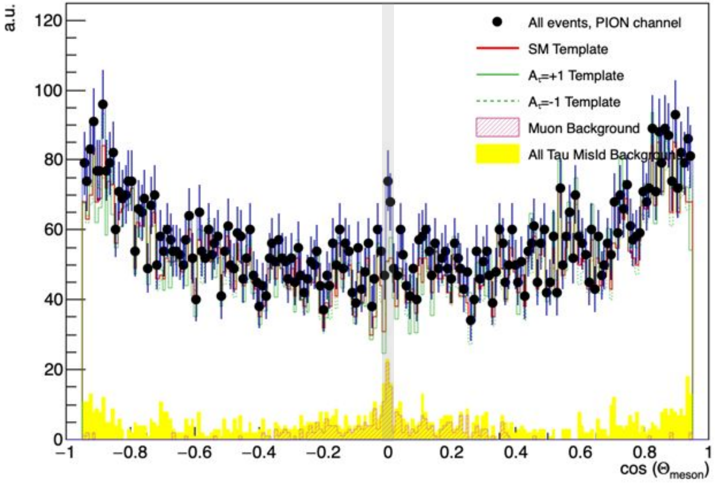


Further issues at low momentum: Muon Contamination

Three populations of Muon->Pion contamination

- **At high momentum,** concentrated at Theta~90º ➔ detector change? easily removed and not too problematic for analysis (very few events)
- **Below 2 GeV** ➔ seems like a detector limit. Starting the Taus at 2 GeV is reasonable
- **Between 2-7 GeV** ➔ what is happening here?. Problem for the Pion channel.
    - Difficult to debug without better documentation on Pandora. Ideally, remove these by improving reconstruction in Pandora, or adding a muon hits cut on top.
    - For now I can simply cut away these by P/Pt, but that cuts away an interesting part of the phasespace





Reconstruction: ML approach

Work in progress, following all the work done by Dolores et all

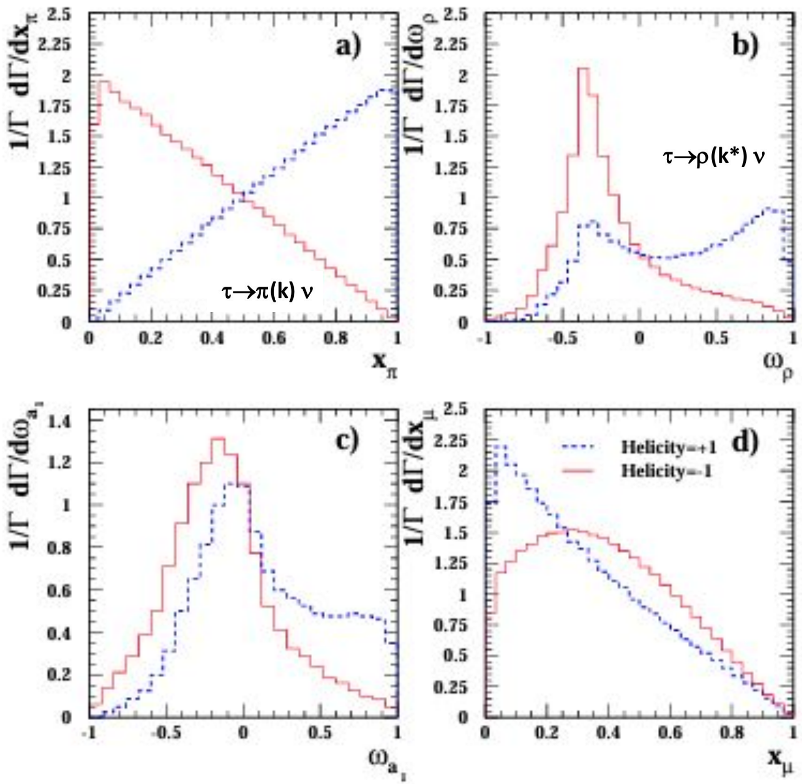
KIT (Jan Kieseler, Xunwu Zuo, Gregor Brodbek) joined the effort: focus on tau reconstruction using ML

Bachelor thesis for **Gregor Brodbek** :)

Timeline: November

Moving to the analysis side...

Shape of the polarization templates?



Z pole LEP+SLD paper: Physics Reports 427:257-454,2006

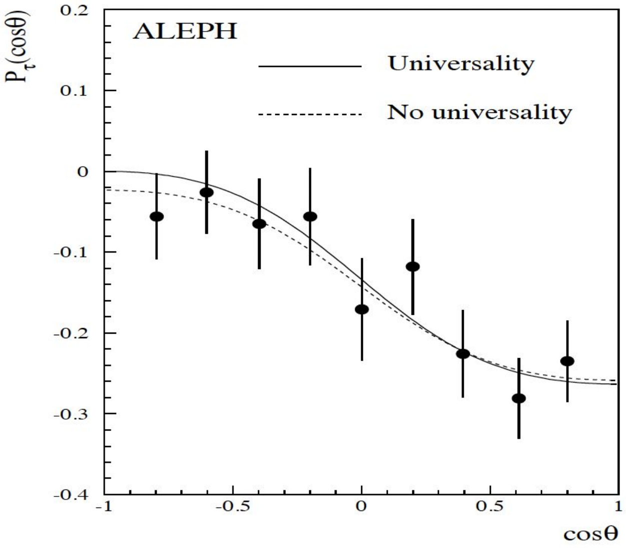
Figure 4.2: Monte Carlo simulated distributions of polarisation sensitive kinematic variables defined in the text for (a) $\tau \to \pi\nu$, (b) $\tau \to \rho\nu$, (c)$\tau \to a_1\nu$ and (d) $\tau \to \mu\nu\bar{\nu}$ decays for positive and negative helicity τ leptons excluding the effects of selection and detector response.

Dependence on cosTheta

$$\mathcal{P}_\tau\,(cos\theta) = -\frac{\mathcal{A}_\tau(1+cos^2\theta)+2\mathcal{A}_e cos\theta}{1+cos^2\theta+2\mathcal{A}_e\mathcal{A}_\tau cos\theta}$$

$$\mathcal{P}_\tau(total) = -\mathcal{A}_\tau$$

$$\mathcal{A}_\tau(SM) = \mathcal{A}_e(SM) = \frac{2g_v/g_a}{1+(g_v/g_a)^2} = -0.150$$



How to obtain the templates?

1) **Reweighting a single Pythia8 sample** taking into account the polarization dependence on cos Theta / Atau / Ae ➔ Details in backup (thanks to Juan for this!)

$$\frac{dN}{dz} \propto 1 + \alpha_R \mathcal{P}_\tau z$$

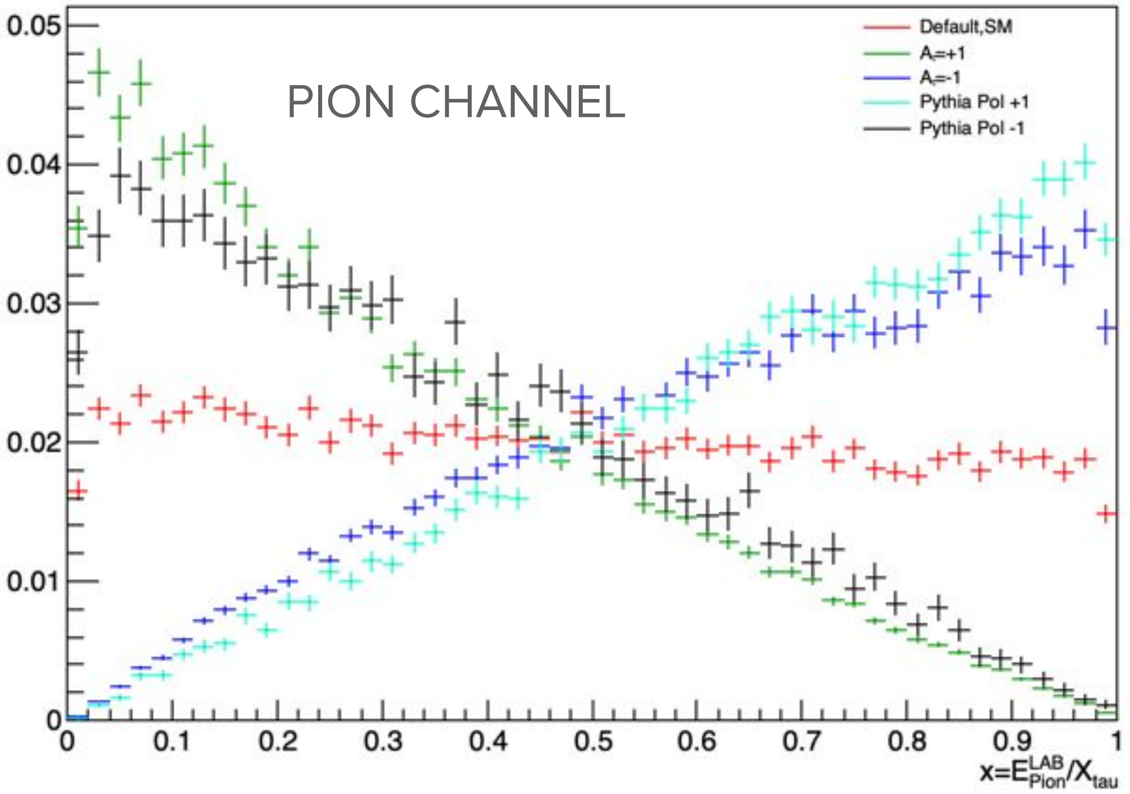
$$z = cos\theta_{\text{meson}}$$

$$\alpha_R = \begin{cases} 1 \text{ (scalar)} & \text{if } \tau^\pm \to \pi^\pm \nu \\ 0.56 & \text{if } \tau^\pm \to \pi^\pm \pi^0 (\rho) \nu \\ \approx 0.12 & \text{if } \tau^\pm \to \pi^\pm \pi^\mp \pi^\pm (a_1) \nu \end{cases}$$

$$w = \frac{1 + \alpha_R \mathcal{P}_{new} z}{1 + \alpha_R \mathcal{P}_\tau z}$$

2) **Directly generating new templates with Pythia8**
   a) Very simple to setup, but it implies having three very large ZTauTau samples (computationally complicated to do on my own)
   b) For now, using this approach as a validation of the reweighting technique

Reweighting vs samples with set Polarization?

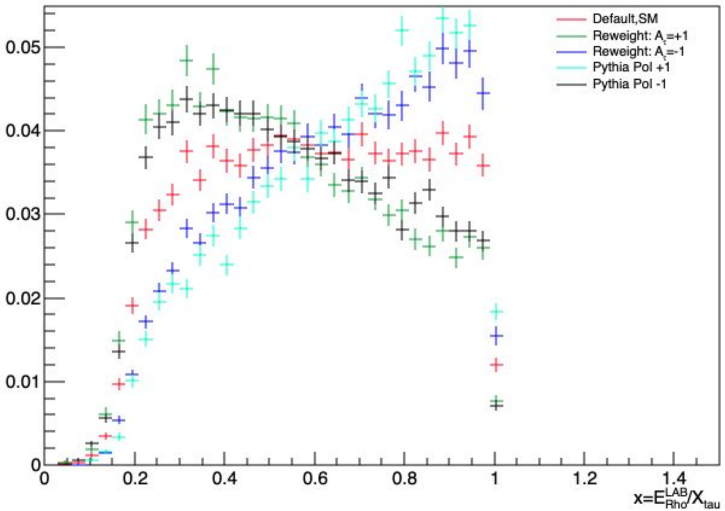


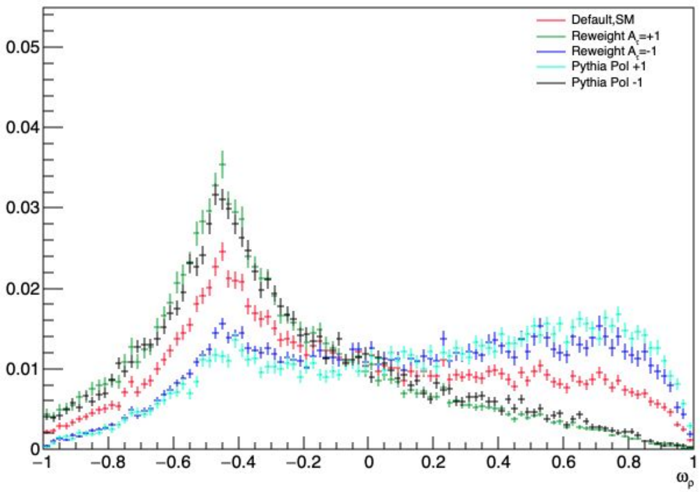
Generated some stats of new Pythia samples with P=+-1 -> compare with weighting method

The agreement is not perfect, particularly at at high / low E. Correlation effects between the two taus / cases far away from Z Peak / border effects ?

Good enough to start checking at reco level

Check for RHO (Gen LEVEL)



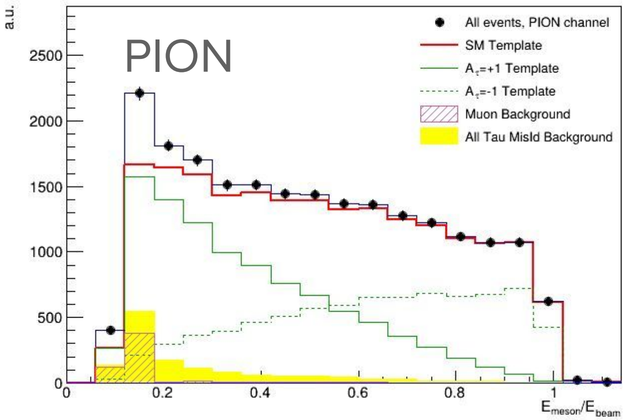


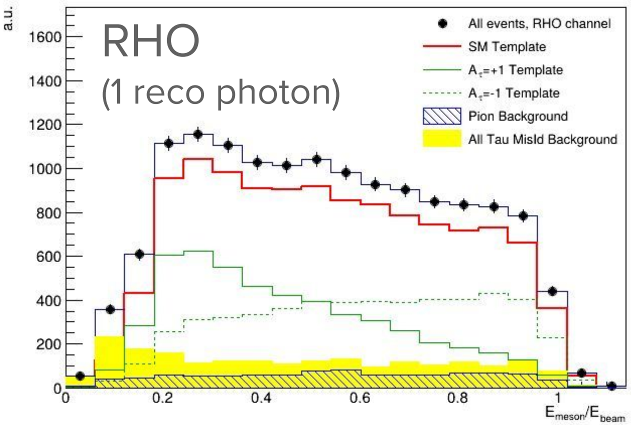
For RHO the optimal variable should be more advanced than just E/Ebeam, and the reweighting is also more complex (see in backup)

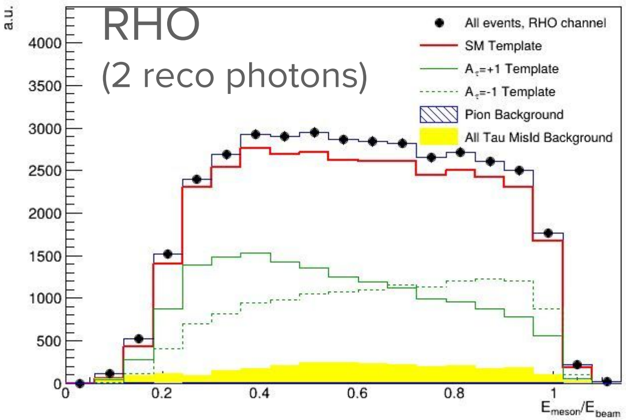
EG: The ω_p variable from ALEPH, which implies figuring out the tau direction. Easy at GEN level, for RECO level still some work to be done for this

For now, still using E/Ebeam, as the problems are more on the reconstruction / contamination side than the final variable.

At Reconstructed level: using PF Candidates





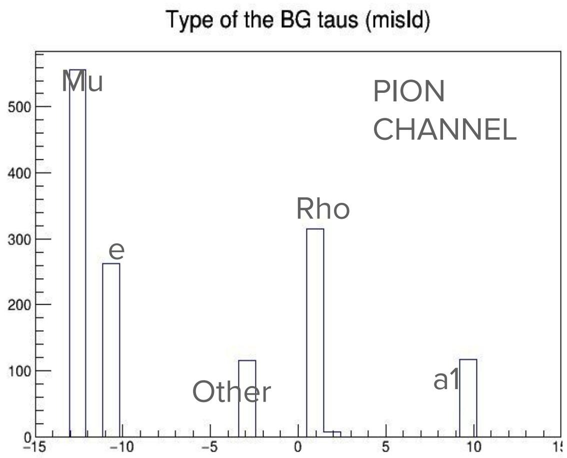


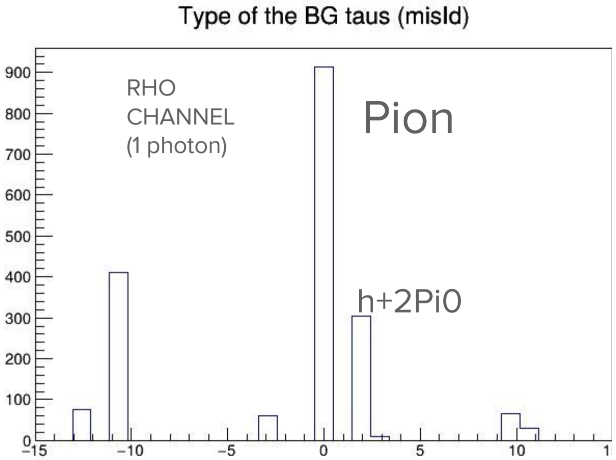
Reco cuts: Photon >0.1 GeV,
Pion P > 1 GeV (all Pions), DR=0.4
Lead Tau , Pion P > 5 GeV

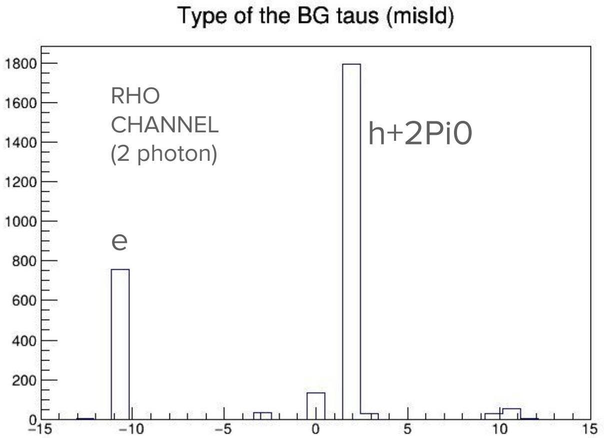
Reco cuts: Photon >0.5 GeV,
Pion P > 1 GeV (all Pions), DR=0.4
Lead Tau , Pion P > 2 GeV

Basis: ZTauTau selection, MuTau & ETau channels
S/B can be optimized further
For RHO this is not the best observable (WIP)
MC sample size: 605k events (equivalent to 0.401 fb-1)

Background sources ?

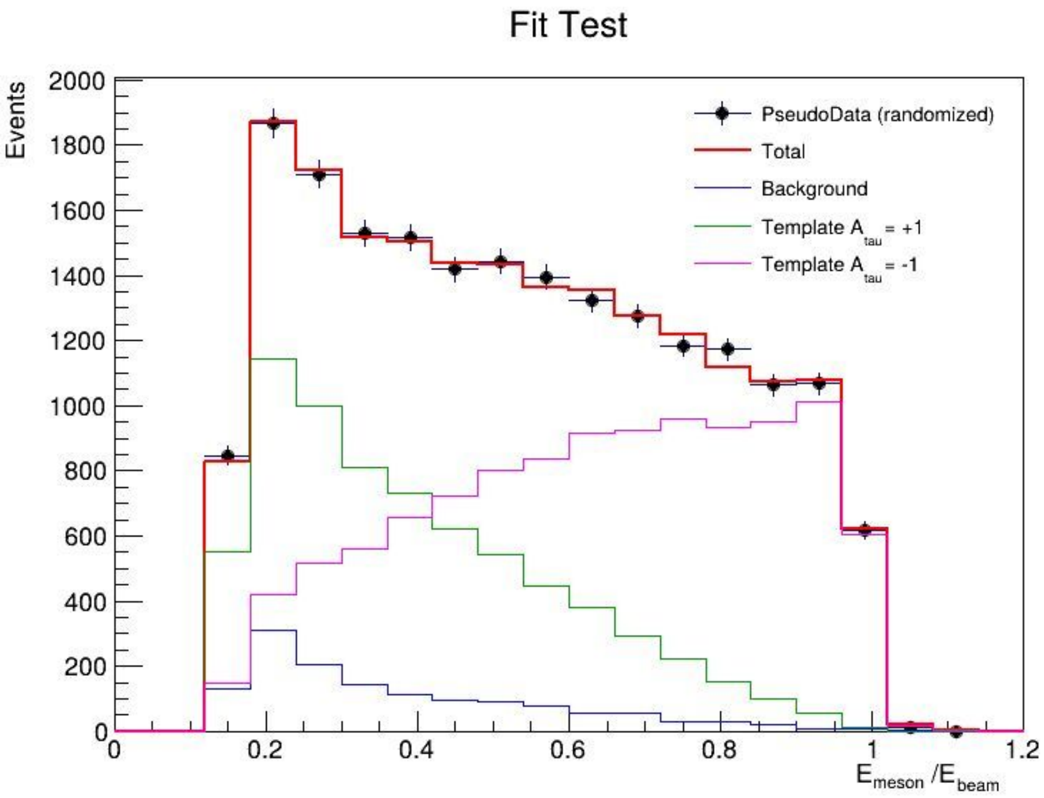






For pion channel: Muons/Rho/Ele
For Rho channel: Pions (only for cases with 1 photon, raise threshold?), electrons and other decays with several Pi0s
Electrons still to be investigated

Signal Extraction: WIP



Starting simple: Template fit to the sum of the two templates

$$N = p \cdot \mathcal{T}_{+1} + m \cdot \mathcal{T}_{-1}$$

$$N = p \cdot \mathcal{T}_{+1} + (1-p) \cdot \mathcal{T}_{-1}$$

Note: the input MC sample is rather small, 605k events, and this is only one channel
➔ Work in progress to do this fit more realistically
➔ Next, incorporate systematics.

Systematics

ALEPH

Systematics errors estimation as a function of the source of the uncertainties

Source	h	ρ	A_τ $3h$	$h2\pi^0$	e	μ	Incl. h
selection	-	0.01	-	-	0.14	0.02	0.08
tracking	0.06	-	0.22	-	-	0.10	-
ECAL scale	0.15	0.11	0.21	1.10	0.47	-	-
PID	0.15	0.06	0.04	0.01	0.07	0.07	0.18
misid.	0.05	-	-	-	0.08	0.03	0.05
photon	0.22	0.24	0.37	0.22	-	-	-
non-τ back.	0.19	0.08	0.05	0.18	0.54	0.67	0.15
τ BR	0.09	0.04	0.10	0.26	0.03	0.03	0.78
modelling	-	-	0.70	0.70	-	-	0.09
MC stat	0.30	0.26	0.49	0.63	0.61	0.63	0.26
TOTAL	0.49	0.38	1.00	1.52	0.96	0.93	0.87

Once the fit structure is finished (~end of this week), the next step is incorporating systematics.

Setup the fit to account for:

- Photons: energy scale (easy to change by a %), Identification (through modification of the background yield)
- Tracks: efficiency (to be addressed carefully since this is the main issue in pandora) / scale
- Muon->Pion normalization
- PID ➔ assumptions based on CLIC/LEP?

Note: non-tau background not considered here

These inputs need to come from the reconstruction study (in progress)

Conclusions

Progress over summer on template reweighting and setting up the analysis, but quite a lot of work to do still.

Reconstruction:

- Main backgrounds identified for Pion/Rho channel: work to do to mitigate them
- PandoraPF PID still problematic (charged particle identification) ➔ for now using it out of the box. Tuning of Pandora difficult without documentation
- Muon->Pion? What happens between 2 GeV and 7 GeV in Pandora?
- Work in progress towards a ML based tau reconstruction that ignores Pandora ➔ KIT joined the effort

Analysis level:

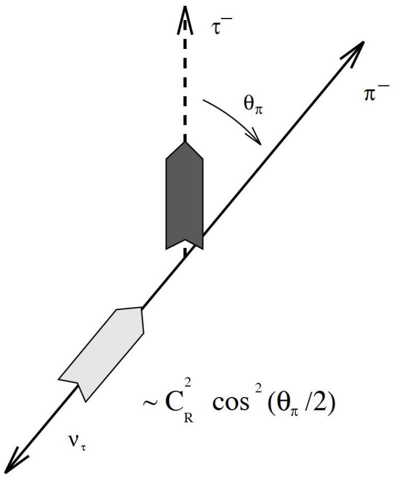
- Two avenues to obtain samples with +1/-1 polarization in place: reweighting SM pythia8 sample vs generating dedicated Pol=+1/-1 Pythia8 samples
- First analysis setup focusing on MuTau_h / ETau_h
- Preparing template fit (simple minuit based approach) to gauge sensitivity with a simplified model of systematics
- Reco level observable for RHO in progress still, for now using E/Ebeam for both pion and rho (not ideal)
- Statistics of the sample could be a problem

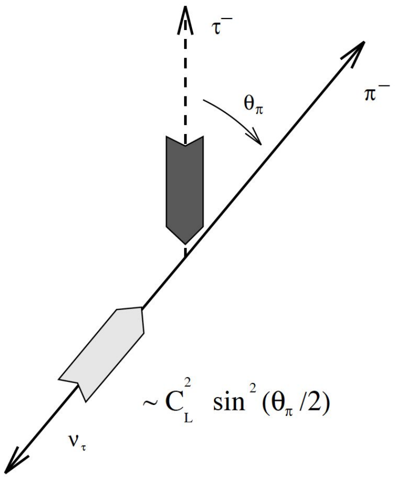
To be continued.

Does it make sense to show anything at ECFA? (not all the study, since it will not be ready in time)

Backup

Pions





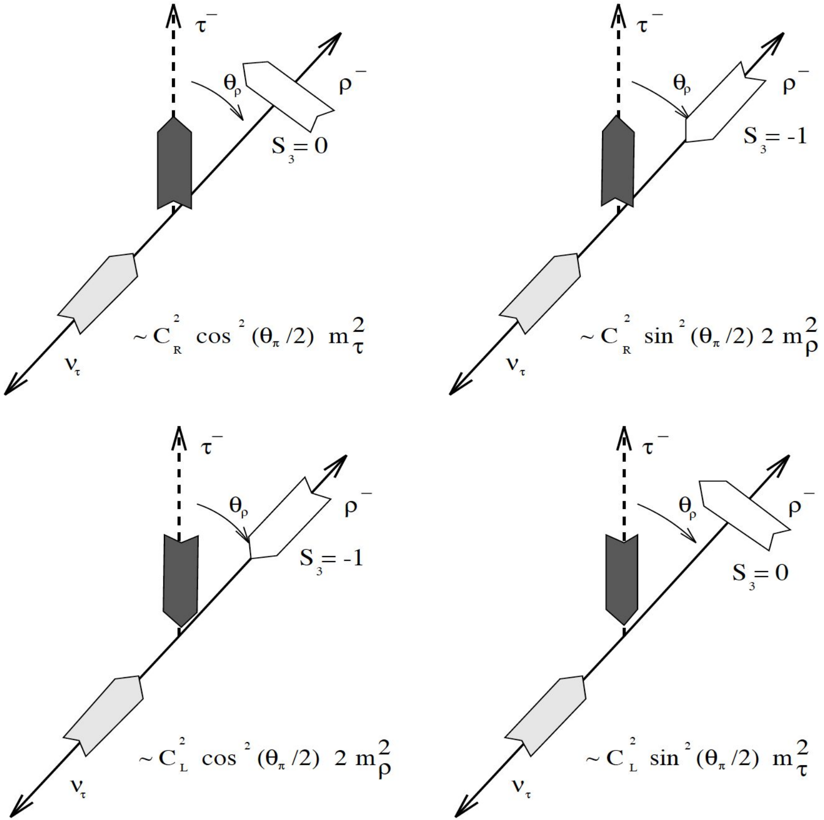
$$\frac{dN}{dz} \propto 1 + \mathcal{P}_\tau cos\theta_\pi$$

Ref: Juan Alcaraz, *TAU PHYSICS AT LEP, 1994*

Rho

$$\frac{dN}{dz} \propto 1 + \alpha_\rho \mathcal{P}_\tau cos\theta_\rho$$

$$\alpha_\rho = \frac{m_\tau^2 - 2m_\rho^2}{m_\tau^2 + 2m_\rho^2} = 0.56$$



Ref: Juan Alcaraz, *TAU PHYSICS AT LEP, 1994*

Weights?

$$\frac{dN}{dz} \propto 1 + \alpha_R \mathcal{P}_\tau z$$

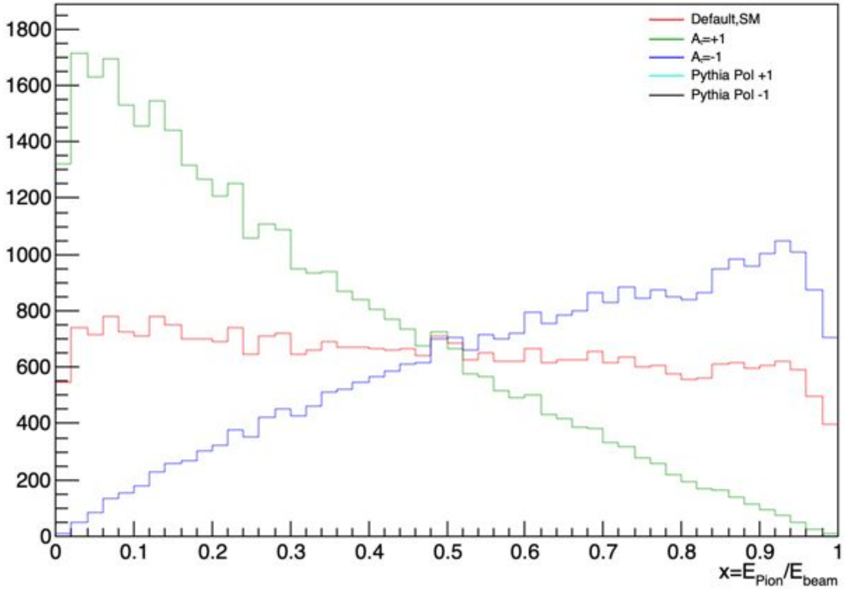
$$z = cos\theta_{\text{meson}}$$

$$\alpha_R = \begin{cases} 1 \text{ (scalar)} & \text{if } \tau^\pm \to \pi^\pm \nu \\ 0.56 & \text{if } \tau^\pm \to \pi^\pm \pi^0 (\rho) \nu \\ \approx 0.12 & \text{if } \tau^\pm \to \pi^\pm \pi^\mp \pi^\pm (a_1) \nu \end{cases}$$

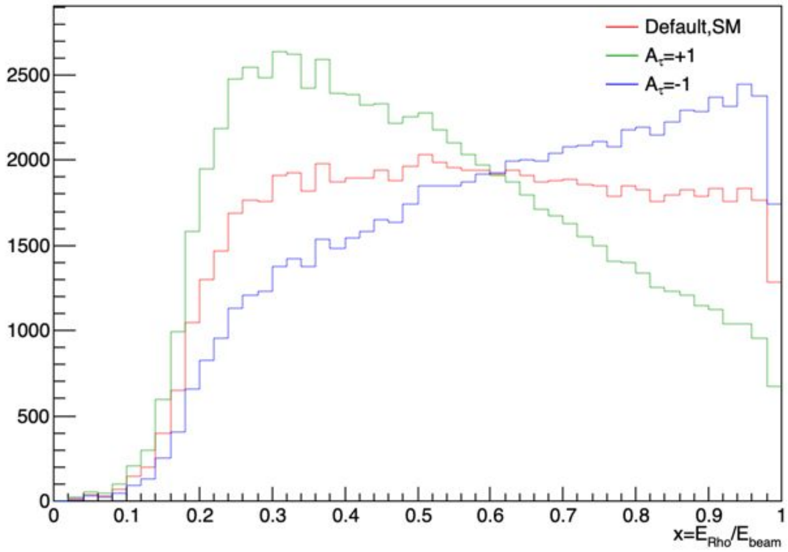
$$w = \frac{1 + \alpha_R \mathcal{P}_{new} z}{1 + \alpha_R \mathcal{P}_\tau z}$$

Reweighted samples (at gen level)

PION



RHO



Current implementation in Pythia8 of Tau Pol

Decays of *tau* leptons can be performed using helicity information from the *tau* production process and with the hadronic current of the *tau* decay modelled using form factors fit to data. The *tau* decay framework is largely based on the corresponding Herwig++ implementation [Gre07], with some input from Tauola [Jad90]. A short summary can be found in [Ilt12], while the complete writeup is in [Ilt14].

The decays of *tau* leptons are categorized as `correlated`, where a *tau* pair is produced from a single process, or `uncorrelated`, where only one *tau* is produced. Currently, internally supported *tau* production mechanisms include correlated decays from *gamma*, *Z^0*, *Z'^0*, *gamma^*/Z^0/Z'^0*, Higgs bosons (CP-even, odd, or mixed), and *t*-channel *gamma gamma → tau^+ tau^-*; and uncorrelated decays from *W^+-*, *W'^+-*, *B/D* hadrons, and charged Higgs bosons. For all mechanisms except *B/D* hadrons, both the full process, e.g. *q qbar → Z^0 → tau^+ tau^-*, as well as just the decay of the boson with a given initial helicity state, e.g. *Z^0 → tau^+ tau^-*, can be handled. The axial and vector couplings of the *Z'^0* and *W'^0* are set from the relevant parameters in New Gauge Boson Processes. Note that the CP of the various Higgs bosons can be set with the options `HiggsX:parity`, `HiggsX:etaParity`, and `HiggsX:phiParity` as described in Higgs Processes where `X` is either `H1`, `H2`, or `A3`. Any *tau* produced from a helicity shower can also be handled.

The *tau* polarization and *tau* decay correlation mechanism can be determined either using `internal` matrix elements or `external` SPINUP information provided in the event, e.g. via Les Houches Event Files (LHEF). The SPINUP digit is interpreted as the particle helicity state in the lab frame: *-1* and *1* are longitudinal and *0* is transverse. Other values are not valid. For internal determination any *tau* pair or single *tau* from the processes of the previous list can be handeled. For external determination of a single uncorrelated *tau*, its helicity state is set to its SPINUP information. When the SPINUP for the *tau* is not valid, e.g. when FSR is applied, the SPINUP for the first copy of that *tau* is used instead unless also invalid. While Pythia does not internally produce events with polarized beams, beam polarization for externally provided events is accounted for in *tau* decays when the beam SPINUP digits are set accordingly.

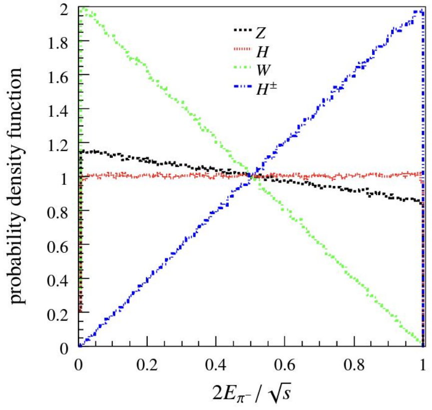


Figure 1: Distribution of the fractional energy of the pion from a $\tau^- \to \nu_\tau \pi^-$ decay in the rest frame of the producing boson. The τ-leptons are produced from Z (dashed black), H (dotted red), W (dash-dotted green), and $H^{\pm}$ (dash-dot-dotted blue) bosons.

hep-ph:1211.6730

How to change it?

`mode` **TauDecays:mode** (`default = `**`1`**; `minimum = 0`; `maximum = 5`)
Choice of *tau* decay model.
`option` **`0`** : old decay model, with isotropic decays.
`option` **`1`** : sophisticated decays where external and then internal determination is applied.
`option 2` : sophisticated decays as above, but now *tau*s with a mother `TauDecays:tauMother` are forced into an uncorrelated decay with a polarization set by `TauDecays:tauPolarization`.
`option 3` : sophisticated decays where all *tau*s, regardless of mother, are forced into an uncorrelated decay with a polarization set by `TauDecays:tauPolarization`.
`option` **`4`** : sophisticated decays where only internal determination is applied.
`option` **`5`** : sophisticated decays where only external (SPINUP) determination is applied.
Warning 1: options 2 and 3, to force a specific *tau* polarization, only affect the decay of the *tau*. The angular distribution of the *tau* itself, given by its production, is not modified by these options. If you want, e.g., a righthanded *W*, or a SUSY decay chain, the kinematics should be handled by the corresponding cross section class(es), supplemented by the resonance decay one(s). The options here could then still be used to ensure the correct polarization at the *tau* decay stage.
Warning 2: for options 1 through 5, if the polarization and correlation mechanism for the *tau* cannot be determined (internally or externally) then the default behaviour described above is applied.

`parm` **TauDecays:tauPolarization** (`default = `**`0`**; `minimum = -1.`; `maximum = 1.`)
Polarization of the *tau* when mode 2 or 3 of `TauDecays:mode` is selected. Note, this does not specific a helicity state, but rather a polarization probability.

➜ just a matter of adding to our Py8 card

! 5) Change Tau Pol
TauDecays:mode =3
TauDecays:tauPolarization =-1

(or TauDecays:tauPolarization =1)

This implies doing new samples, could be an issue if we need a lot of statistics

(Not clear to me if we need mode 2 or 3, to be tested further)

ω_ρ ?

Full formulas for the angles spelt out in this LEP thesis
https://cds.cern.ch/record/401680

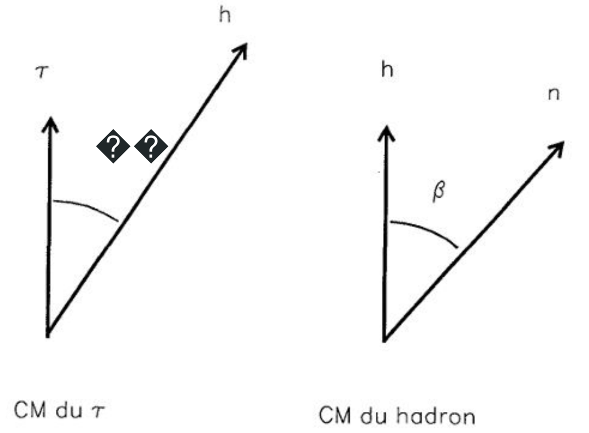


Figure 3.3: Définition des angles de désintégration du tau et du ρ (ou du a_1). Le vecteur $\vec{n}$ est, dans le cas du ρ, la direction du pion chargé et, dans le cas du a_1, la direction de la normale au plan des trois pions.

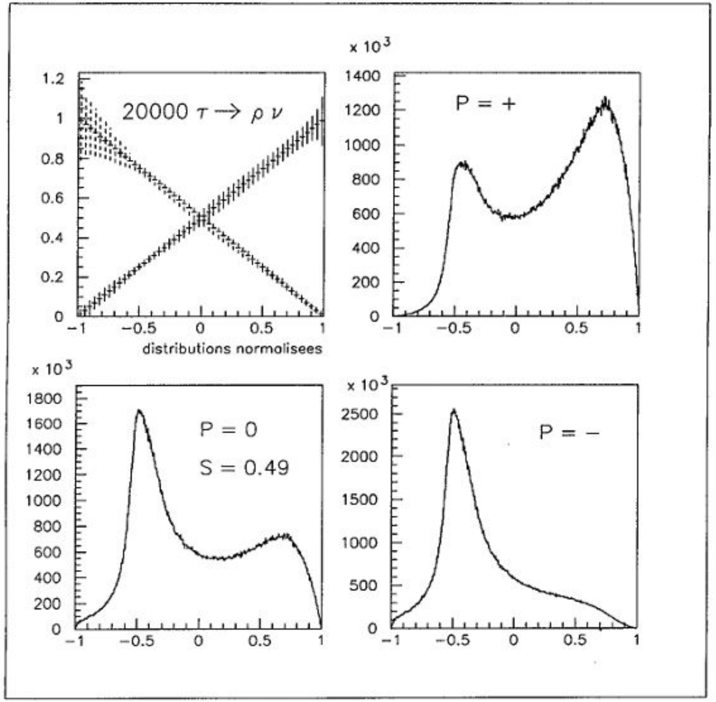


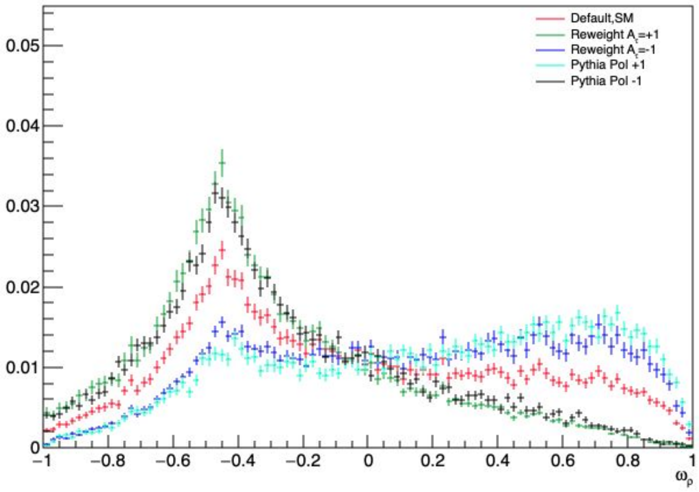
Figure 3.7: Distribution de la variable ω_ρ pour des événements totalement polarisés et pour une polarisation nulle. La distribution normalisée par la distribution à polarisation nulle est montrée pour les deux états d'hélicité. Les échelles sont en unités arbitraires.

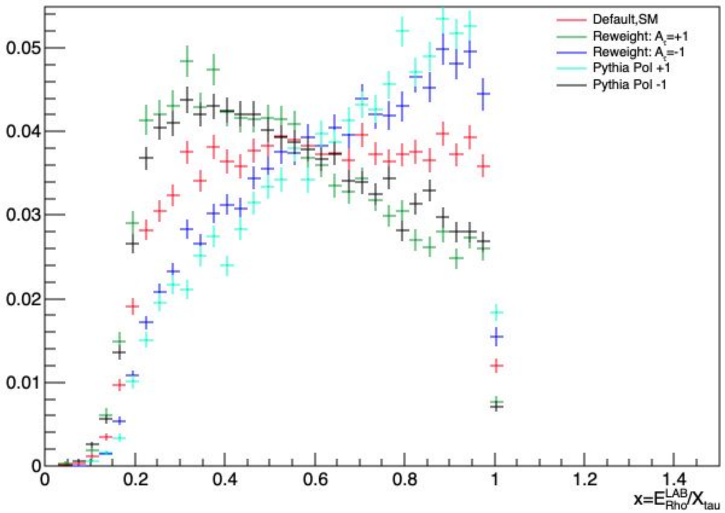
$$\cos\psi = \frac{x(m_\tau^2 + Q^2) - 2Q^2}{(m_\tau^2 - Q^2)\sqrt{x^2 - 4Q^2/s}}$$

$$x = 2\frac{E_h}{\sqrt{s}}.$$

$$\omega_\rho = \frac{\left(-2 + \frac{m_\tau^2}{Q^2} + 2\left(1 + \frac{m_\tau^2}{Q^2}\right)\frac{3\cos\psi - 1}{2}\frac{3\cos^2\beta - 1}{2}\right)\cos\theta + 3\sqrt{\frac{m_\tau^2}{Q^2}}\frac{3\cos^2\beta - 1}{2}\sin 2\psi\sin\theta}{2 + \frac{m_\tau^2}{Q^2} - 2\left(1 - \frac{m_\tau^2}{Q^2}\right)\frac{3\cos\psi - 1}{2}\frac{3\cos^2\beta - 1}{2}} \qquad (3.$$

At GEN level





$$\frac{d\Gamma}{dQ^2 d\cos\beta d\cos\theta} \propto \frac{(m_\tau{}^2 - Q^2)(Q^2 - 4m_\pi^2)}{\sqrt{Q^2}} \times$$

$$\{\frac{2}{3}[1 - P_\tau\cos\theta - \frac{m_\tau^2}{Q^2}(1 + P_\tau\cos\theta)] + \frac{m_\tau^2}{Q^2}(1 + P_\tau\cos\theta)$$

$$-\frac{2}{3}[(1 - P_\tau\cos\theta - \frac{m_\tau^2}{Q^2}(1 + P_\tau\cos\theta))\frac{3\cos^2\psi - 1}{2}$$

$$-\frac{3}{2}\sqrt{\frac{m_\tau^2}{Q^2}}P_\tau \sin 2\psi \sin\theta]\frac{3\cos^2\beta - 1}{2}\}$$

In this case the reweighting is done in a more complicated way, taking into account the dependence in Psi and Beta as well

Next: check how is this distorted at reco level (estimating the tau direction)

Z Selection

For now very simple, since we are only considering other tau decays as backgrounds

ZTauTau with one Tau decaying to muon/electron, the other hadronic.

- Muon or Electron P > 10 GeV
- Visible Hadronic Tau P = Meson P > 5 GeV
- |cos (Meson Theta)| < 0.95
- Meson: 1.565 < Theta < 1.575 (remove high P muons, only matters for pion channel)

LEP

Experiment	$\mathscr{A}_\tau$
ALEPH	$0.1451 \pm 0.0052 \pm 0.0029$
DELPHI	$0.1359 \pm 0.0079 \pm 0.0055$
L3	$0.1476 \pm 0.0088 \pm 0.0062$
OPAL	$0.1456 \pm 0.0076 \pm 0.0057$
LEP	$0.1439 \pm 0.0035 \pm 0.0026$