$B \to \tau^+\tau^-(\tau \to 3\pi\nu)$ decays in LHCb simulation

Generator Level Studies

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Introduction

Context :

- Preliminary result: $\mathcal{B}(B_s^0 \to \tau^+\tau^-) < 2.4\,(3.0) \times 10^{-3}$ [LHCb-CONF-2016-011]
  - using the hadronic decay $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$
  - limit obtained using EvtGen to decay the τs
  - result is model dependant
- For final result, study further the effects associated with the tau-decay modelling

This talk :

- Generator level comparison of $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ decays
- Spin correlation in $B \to \tau^+\tau^-$ decays

Outline

Some available $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ Monte Carlo models

EvtGen's TauHadNu:

- Theoretical model from Kuhn and Santamaria [1990] DOI:10.1007/BF01572024
- Tuned to CLEO results for $\tau^- \to \pi^-\pi^0\nu_\tau$ [1999] arxiv:hep-ex/9910046
- Used in LHCb (baseline for $B \to \tau^+\tau^-$ search so far)

Tauola (CLEO-tune):

- Combination of Breit-Wigner resonances
- Tuned to CLEO results for $\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$ [1999] arxiv:hep-ex/9902022
- Used in LHCb

Tauola (BaBar-tune):

- Resonance Chiral Lagrangian model [2013] arxiv:1310.1053
- Tuned to BaBar results for $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ [2013] arxiv:1301.7105
- Not yet released in LHCb simulation

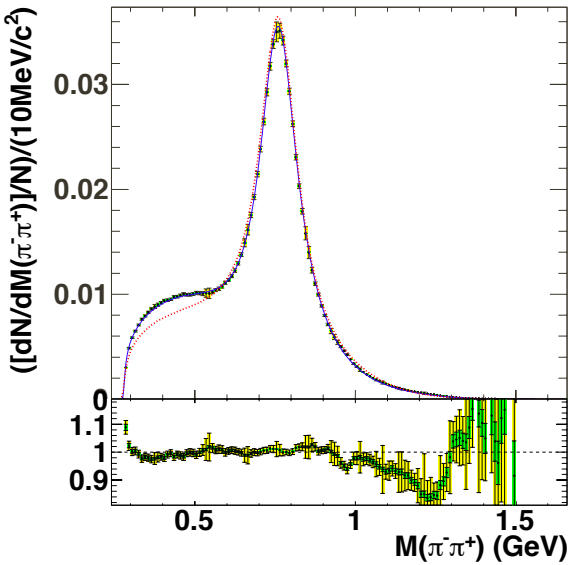
Tauola (CLEO Isospin Intricate-tune):

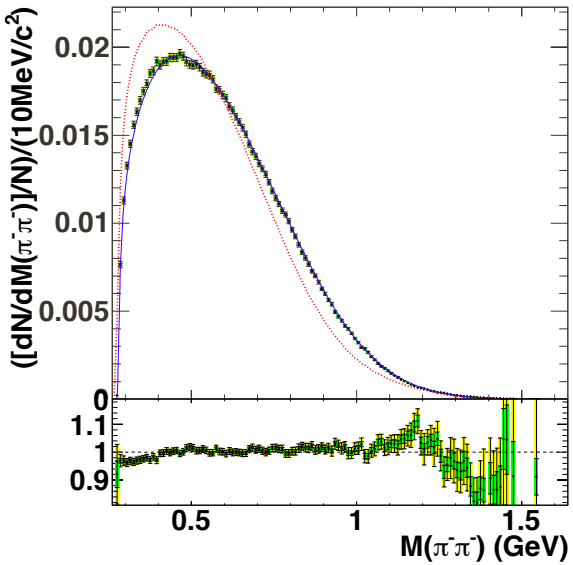
- CLEO-tune modified to account for isospin relations arxiv:1508.06424v1
- Hidden in Tauola ! (minor modifications of the fortran code needed)

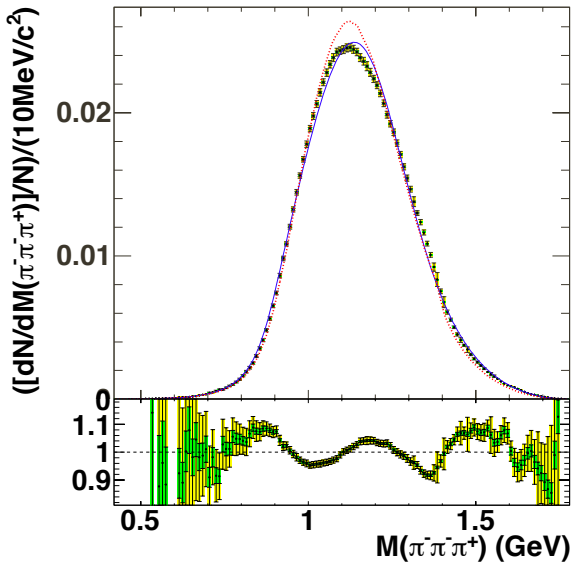
More models ▸ bonus slide 3

Tauola CLEO -VS- BaBar Tunes : comparison with experimental data

From arxiv:1310.1053







- Points: data from BaBar (arxiv:1301.7105)
- red dotted line : CLEO Tauola tune
- blue dotted line : Babar Tauola tune

Tests setup

- Local version of MC packages : Pythia8, Tauola, EvtGen
- Adapting examples given with the packages to generate $X \to \tau^+\tau^-$ decays
- Using Tauola with Pythia or with EvtGen

Pythia8

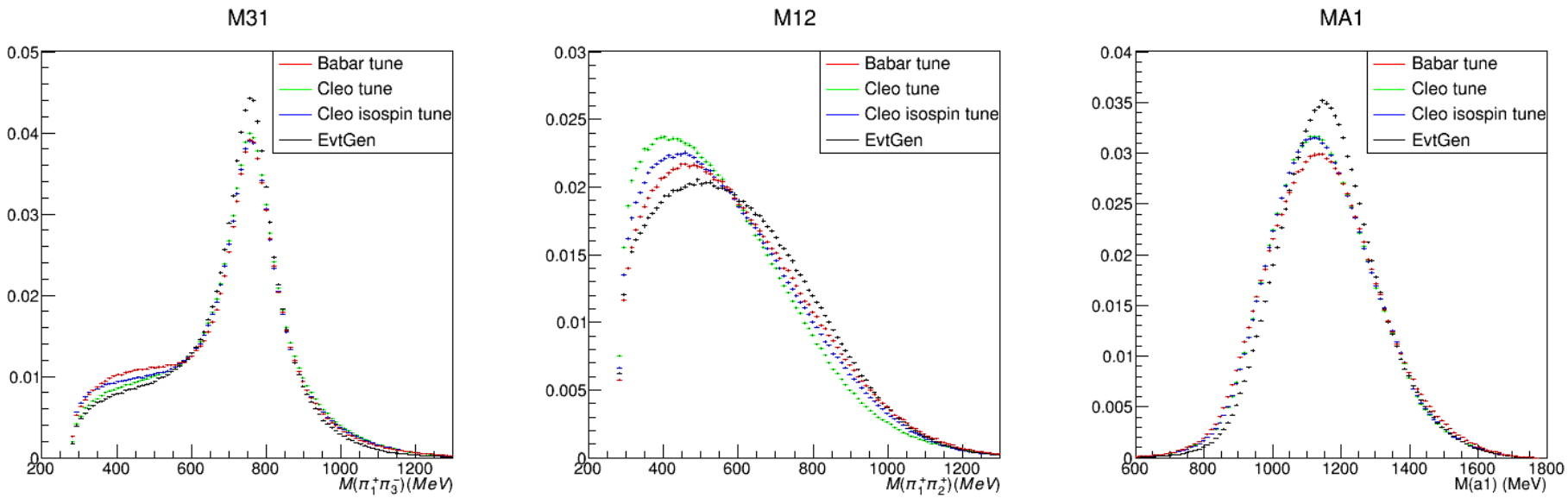
1. Pythia : $e^+e^- \to Z \to \tau^+\tau^-$
   - with $\sqrt{s} = 92GeV$
   - using WeakSingleBoson:ffbar2gmZ
2. τs decay with :
   - Pythia, or with
   - Tauola.

EvtGen

1. EvtGen : $\gamma^* \to \tau^+\tau^-$
   - *VLL* decay model
   - γ^* "at rest"
   - E_{γ^*} can be set to M_Z, M_B, ...
2. τs decay with :
   - EvtGen, or with
   - Tauola.

Generator level comparison of $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ distributions

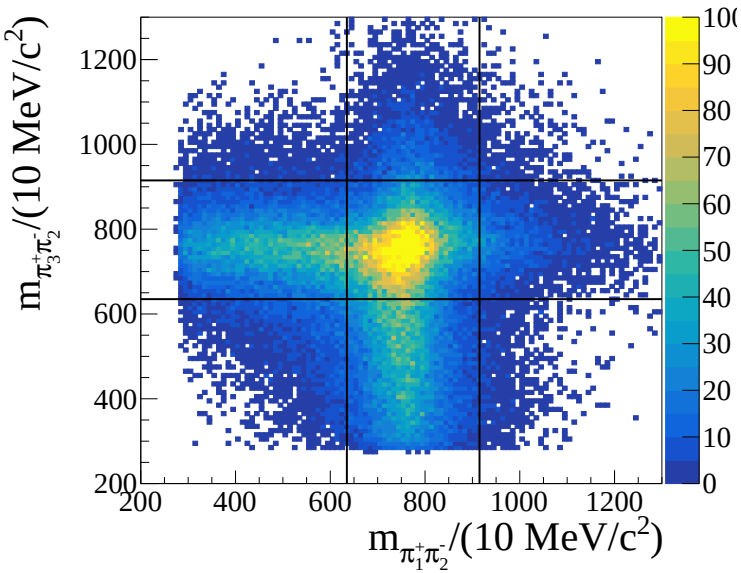
Using Tauola from EvtGen (using pythia gives completly consistent distributions) :



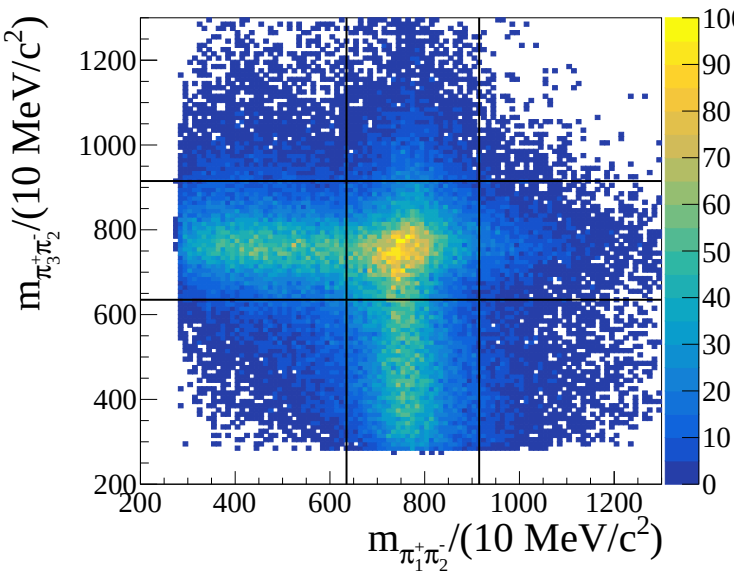
- Babar tune describes BaBar 1D mass distributions data correclty
- Cleo isospin intricate goes in the right direction but still differs from BaBar.

Effect on selection efficiency

EvtGen



Tauola (BaBar-tune)



Signal efficiencies computed at generator level ($\pm$ 0.1%) :

EvtGen	= 14.0%
Tauola Cleo-tune	= 10.9%
Tauola BaBar-tune	= 09.9%
Tauola Cleo-intricate	= 10.3%

Up to 10% effect among Tauola models

Event reweigthing

Reweighting the data event by event to simulate an other model :

Tauola :

- Use methods from the TauSpinner package provided with Tauola
- Compute the decay amplitudes for τ^+ and τ^- from the 4-momenta of their daughters
- Amplitudes can be computed for any Tauola tune

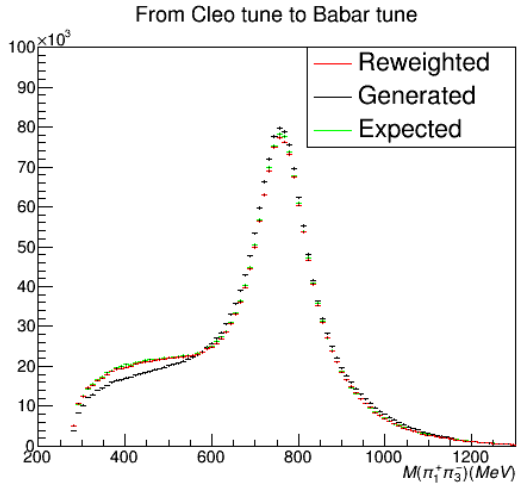
EvtGen :

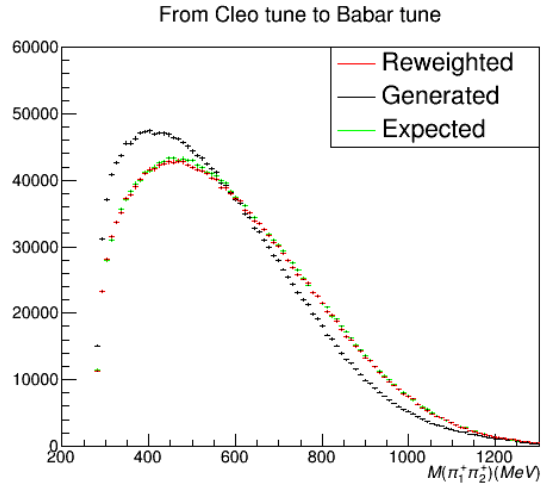
- Use the decayProb() method of EvtParticle for each τ
- Not available outside EvtGen
- Can not be recomputed easily a posteriori (as we know of at least)

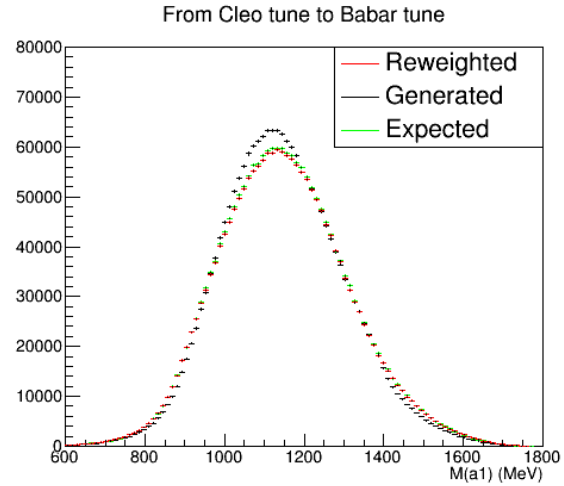
Reweighting :

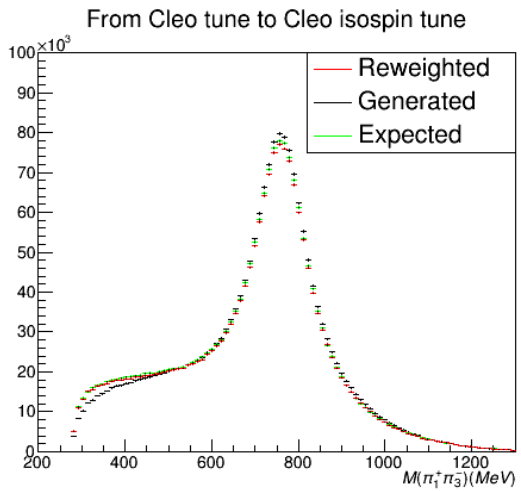
- $\omega^{\pm}_{gen}$: the amplitudes of the process used at generation
- $\omega^{\pm}_{new}$: the amplitudes of the process that we want to simulate
- $\omega = \frac{\omega^{+}_{new} \times \omega^{-}_{new}}{\omega^{+}_{gen} \times \omega^{-}_{gen}}$: the event weight

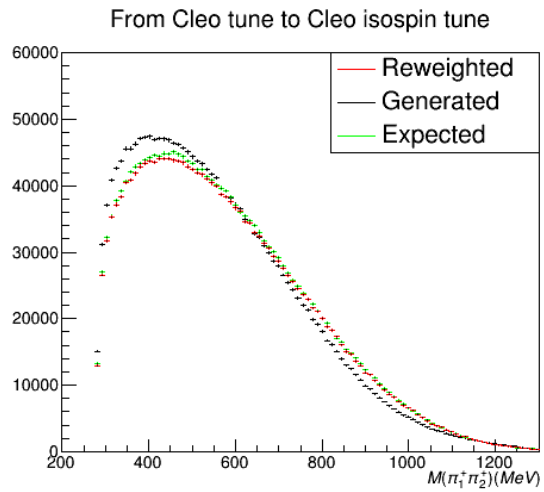
Reweighting from Tauola Cleo Tune

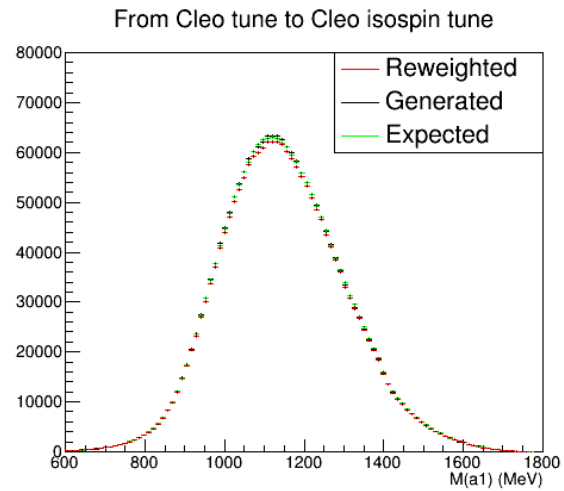












Perfect agreement !

Note: Reweighting from EvtGen still not fully understood ▸ bonus slide 4 - 7

Conclusion on $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ models

Many models on the market :

- Discussed in `arxiv:1508.06424v1` (Tauola authors)
- The BaBar-tune from Tauola is the one which seems to best match the data
- The hidden model implemented in Tauola using isospin relations seems more realistic than the simple Tauola Cleo-tune model

Reweighting :

- Data generated with any Tauola model can probably be reweighted to simulate an other Tauola model
- EvtGen weights not fully understood

Outline

Spin Correlation in Tauola

https://arxiv.org/pdf/1002.0543.pdf

- Tauola decays τs always in pair : $X \to \tau^+\tau^-$
- inputs: 4-momenta of X, τ^+ and τ^-
- decays both τs and computes a proba using the helicity density matrix R: $w = R.h^+.h^-/4$ where $h^{+,-}$ are the τs "polarimetric vectors" (?)
  NB : the "polarimetric vectors" are computed using the τs decay products

$H^0 \to \tau^+\tau^-$

$$R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$A^0 \to \tau^+\tau^-$

$$R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$Z/\gamma \to \tau^+\tau^-$

$$R = \begin{pmatrix} 1 & 0 & 0 & z \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ z & 0 & 0 & 1 \end{pmatrix}$$

where : $z = 2P_z(cos\beta, s) - 1$

- β : angle between the beam and the τ^+
- $\sqrt{s}$: CM energy

NB: longitunal polarisation only

Others

$$R = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$\to w = 0.25$ (!)

For generator level comparison see backup slides ▸ slide 11

Spin Correlation in B decays

From Aoife Bharucha and Jérôme Charles (Centre de Physique Théorique - Marseille)

They compute the R helicity density matrix for $B \to \tau^+\tau^-$
(following S. Jadach and Z. Was, Acta Phys. Polon. B **15** (1984) 1151)

General case : (pseudo)scalar state decaying into $\tau^+\tau^-$ through the interaction

$$\tau^+(k_S + k_P\gamma_5)\tau^-$$

where $k_{S,P}$ are complex couplings.

With $z = \frac{\beta k_S}{k_P}$ where $\beta = \sqrt{1-4m^2}$, they get :

$$R(z) = \begin{pmatrix} 1 & 0 & 0 & \frac{2Re(z)}{1+|z|^2} \\ 0 & \frac{-1+|z|^2}{1+|z|^2} & \frac{2Im(z)}{1+|z|^2} & 0 \\ 0 & -\frac{2Im(z)}{1+|z|^2} & \frac{-1+|z|^2}{1+|z|^2} & 0 \\ -\frac{2Re(z)}{1+|z|^2} & 0 & 0 & -1 \end{pmatrix}$$

$B \to \tau^+\tau^-$ case :

$$k_S = m_b(C_S - C_S^{'})\frac{m_{B_S}^2 f_{B_S}}{m_b + m_s} \; ; \; k_P = m_b(C_P - C_P^{'})\frac{m_{B_S}^2 f_{B_S}}{m_b + m_s} + 2m_\tau(C_{10} - C_{10}^{'})$$

- Standard Model (only $C_{10} \neq 0$) :

$$R_{SM} = R(z=0) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

- With BSM contributions, the coupling ratio z can take any value.
  As "extreme" (but reasonable) cases, they suggest : $z = 1, -1, i, -i$

$$R(z=1) = \begin{pmatrix} 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & -1 \end{pmatrix}$$

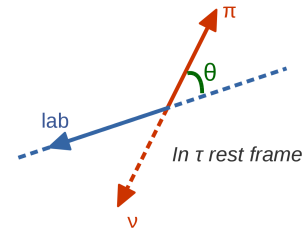
$$R(z=-1) = \begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & -1 \end{pmatrix}$$

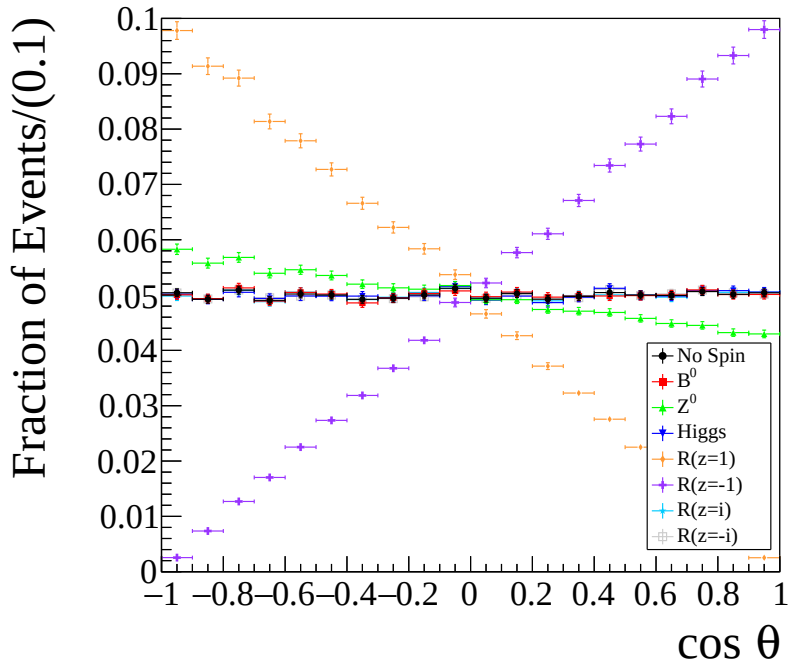
$$R(z=i) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$R(z=-i) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

Spin correlation with different helicity matrices

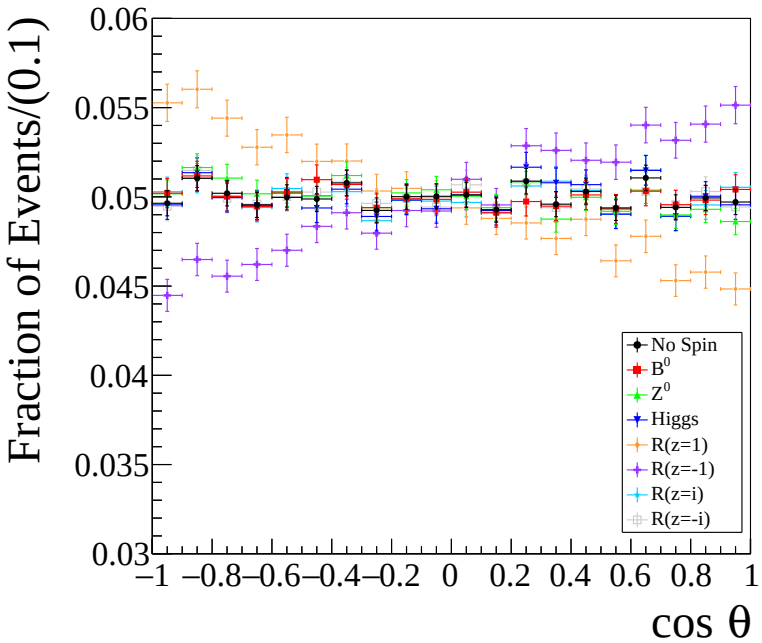
- Spin effects not easy to spot in $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ decays
- Using $\tau^+ \to \pi^+\overline{\nu}_\tau$ instead
- θ : angle beween the π^+ and the lab in the τ rest frame
- Comparing the $cos\theta$ distributions obtained by reweighting the events with the amplitude associated to the different helicity matrices :

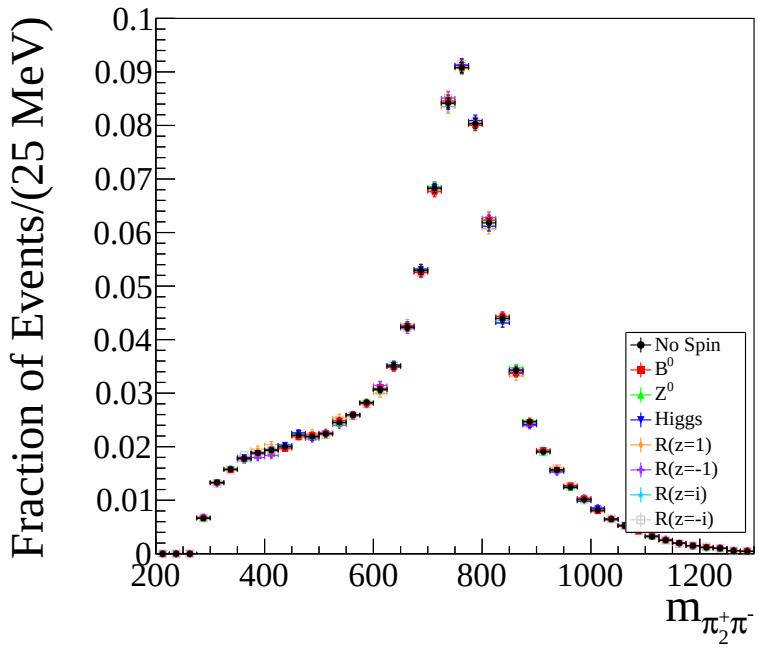




Note : $R(z)$ holds for a $\overline{B}$ event, $R^*(z)$ should be used for B

Effect of helicity matrices with $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ decays





- More angles to be looked at
- Visible effect on $cos(\theta)$ for $z = \pm 1$
- No visible effect on the mass distributions
- Effect on selection efficiency below 0.1%

Outline

Conclusion

Summary :

- Several models available for $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ decays
  - Tauola Babar-tune seems to be the one which best describes the 1D mass distributions
  - Tauola Cleo-intricate tune could also be a model worth looking at
- Proper helicity matrices for B decays (SM and BSM) have been computed
  ... Many thanks to Aoife and Jérôme !
  - Effect on mass distributions seems to be limited
  - Effect on angular variables seems small but can be visible on extreme cases.
    Is the analysis sensitive to such effects ?

Implementation in LHCb simulation :

- Modifications have been done to allow the use of the BaBar-tune and Cleo-intricate models. New samples should be generated soon
- Effects of spin correlation will be studied by reweighting sample produced without correlation

Backup:

Outline

4. $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ decay models
   - Used MC generator models
   - Model comparison
   - Monte Carlo reweighting

5. Spin correlation in $B \to \tau^+\tau^-$

$\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ models in Pythia 8 Nucl & Part Phys Proc 260 (2015) 5660

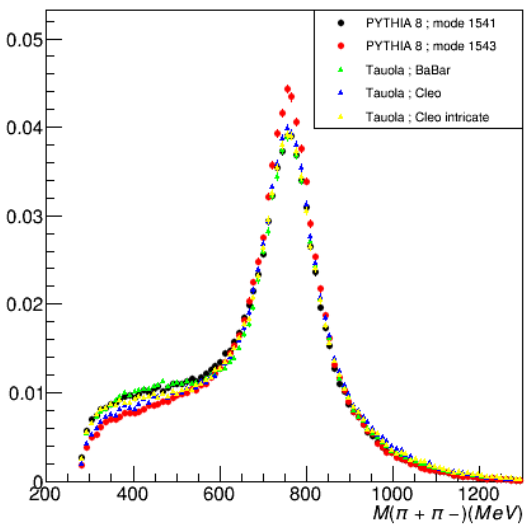
Pythia 8 (meMode 1541):

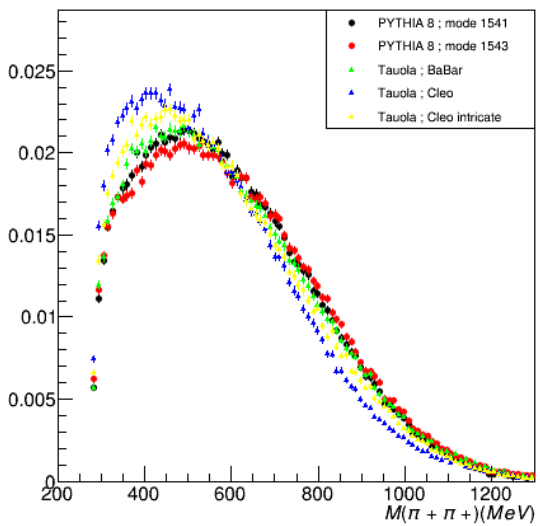
- Tuned to CLEO results for $\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$ [1999] arxiv:hep-ex/9902022

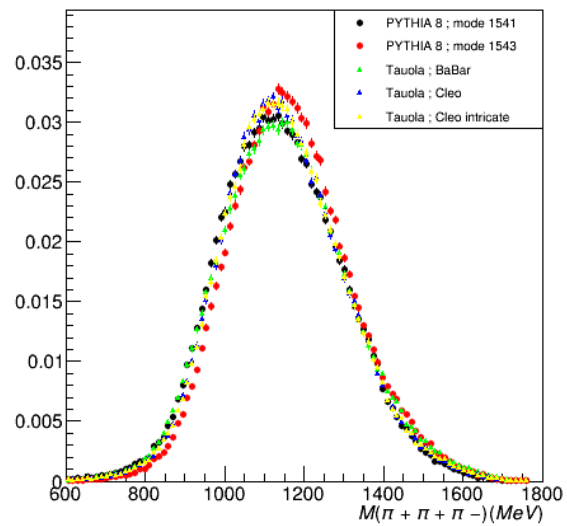
Pythia 8 (meMode 1543):

- General parametrisation of tau to 3 pseudoscalar mesons

R. Decker, et al., Z.Phys. C58 (1993)

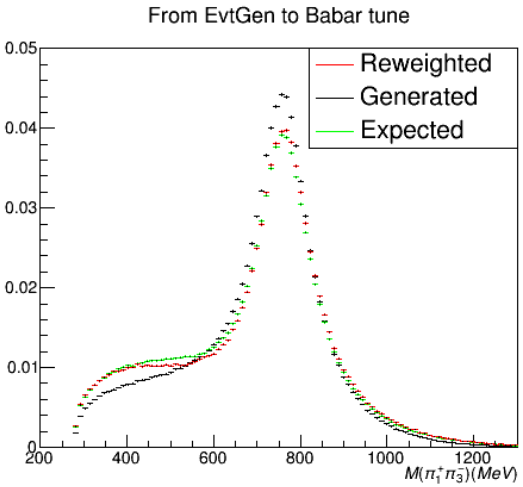


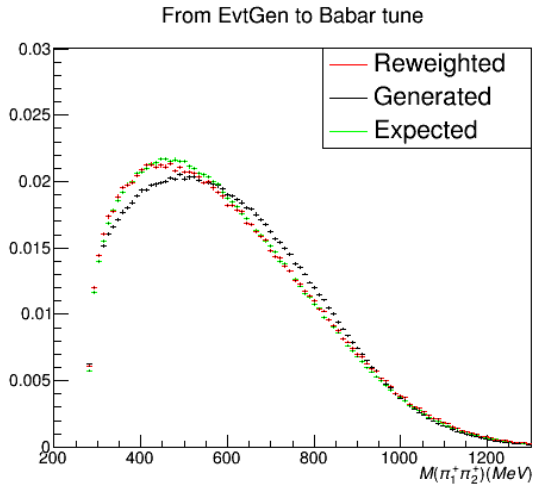


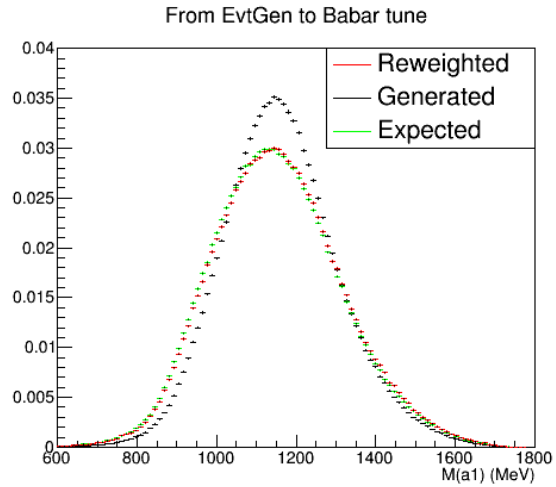


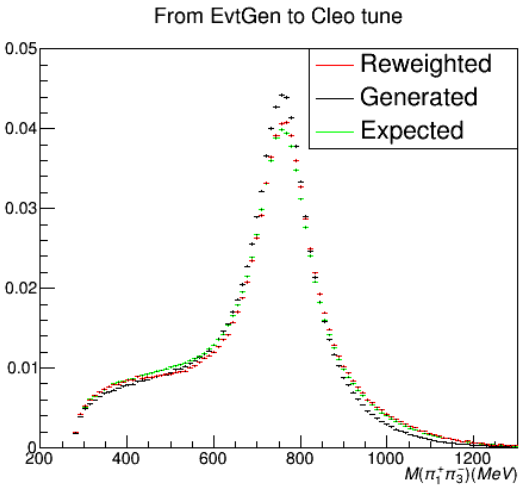
Back to available models ▸ slide 4

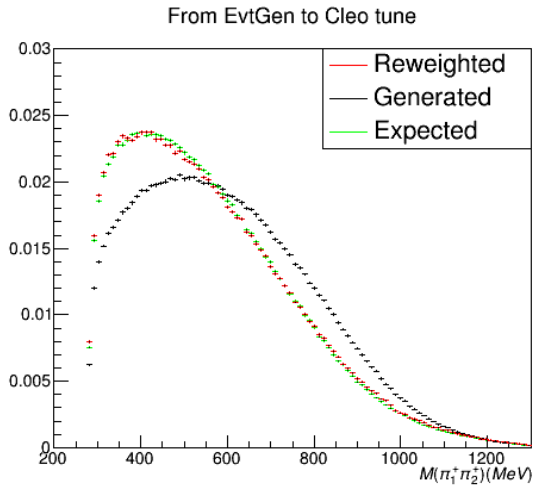
Starting From EvtGen

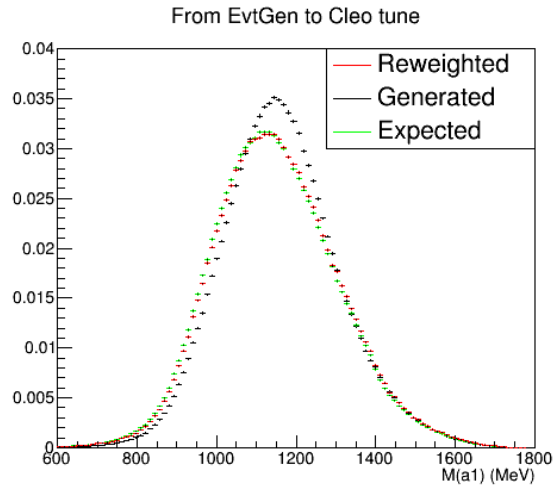








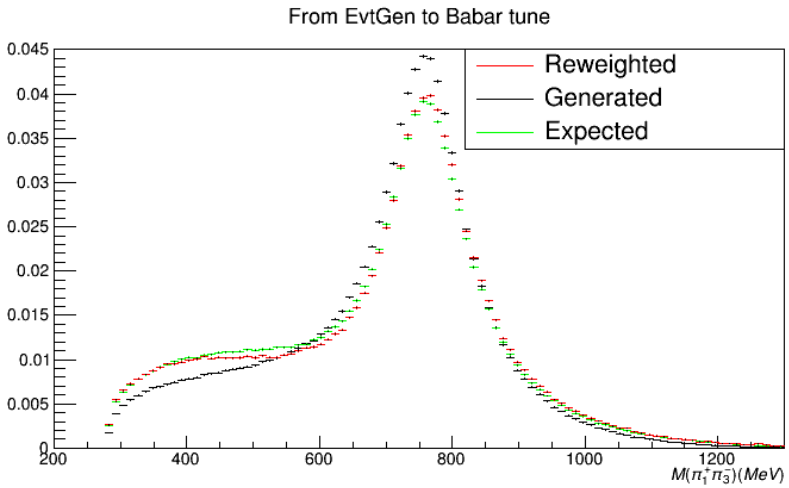


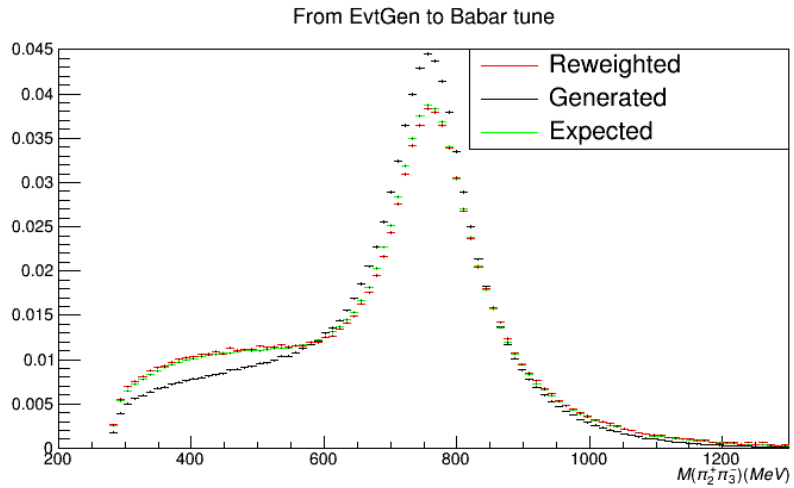


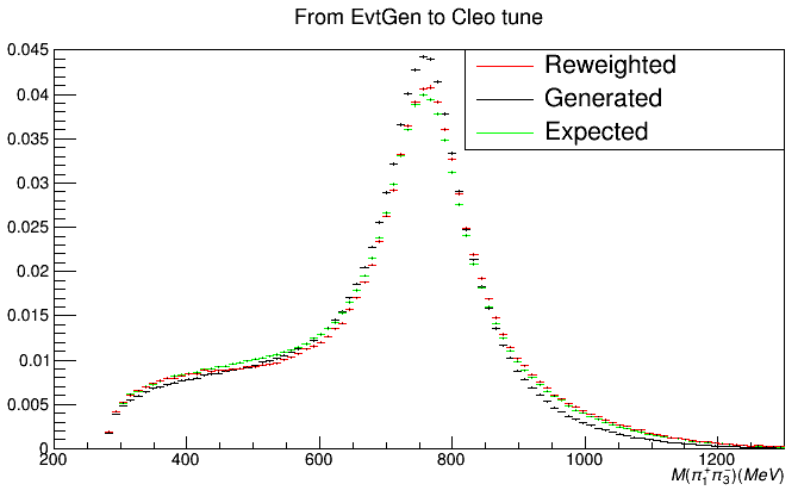
Something missing ?

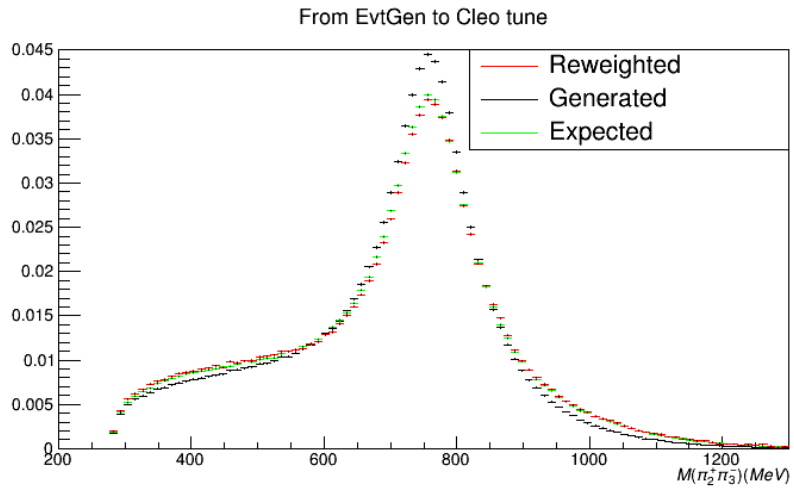
Back to reweighting from tauola ▸ slide 10

Starting From EvtGen : differences between $m(\pi_1^+\pi_3^-)$ and $m(\pi_2^+\pi_3^-)$!!!



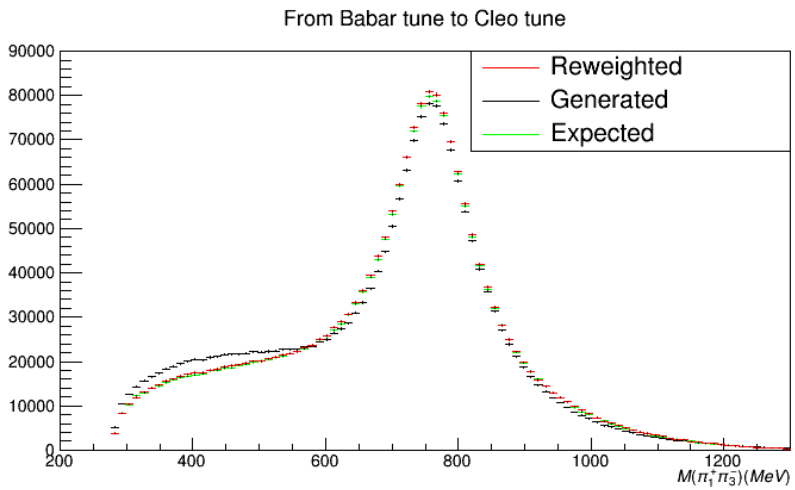


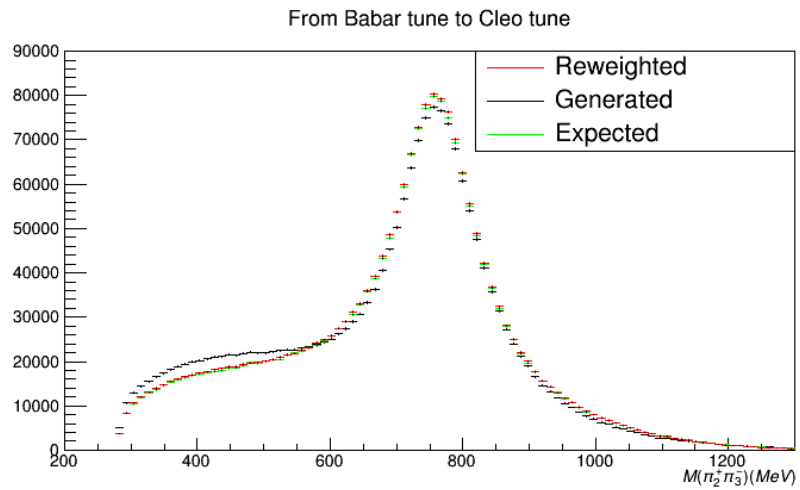


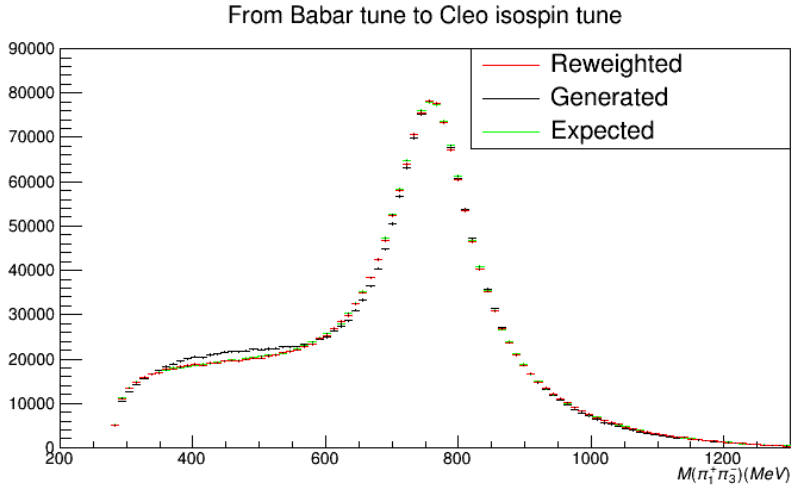


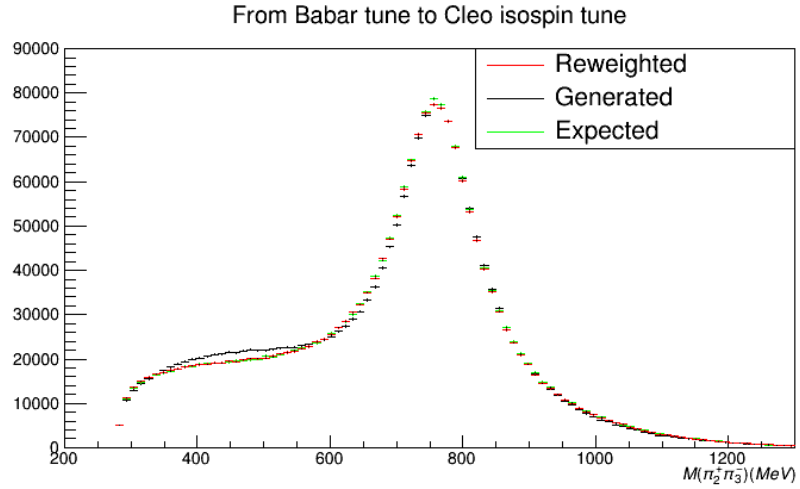
Back to reweighting from tauola ▸ slide 10

Starting From Tauola BaBar : agreement between $m(\pi_1^+\pi_3^-)$ and $m(\pi_2^+\pi_3^-)$





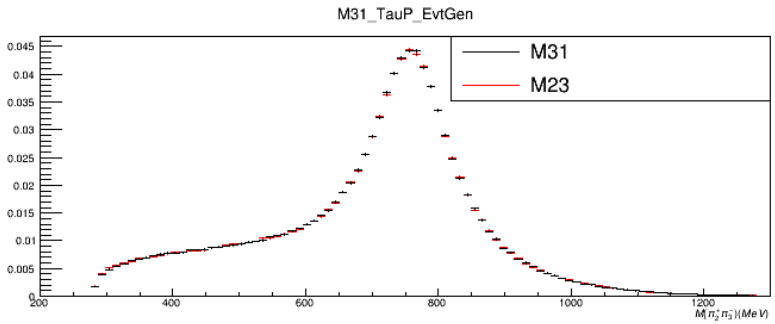


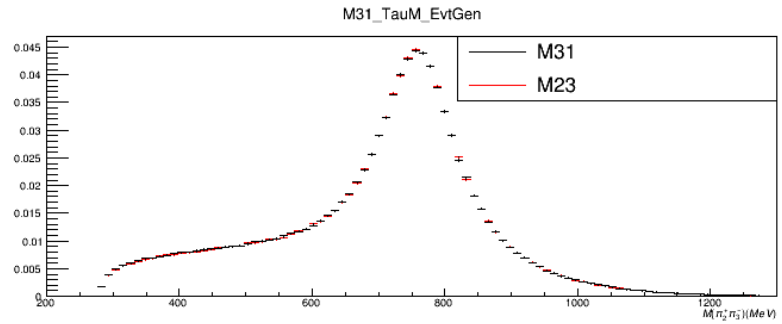


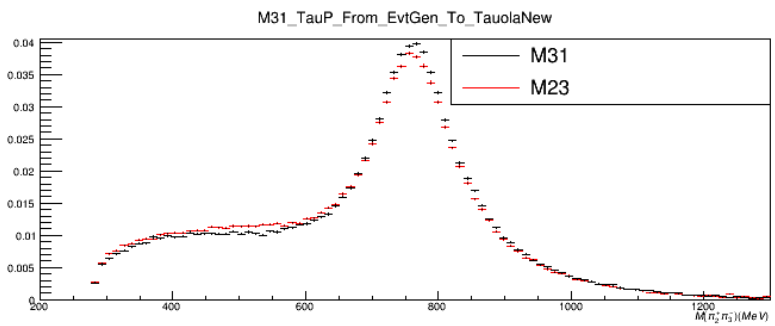
Back to reweighting from EvtGen ▸ slide 10

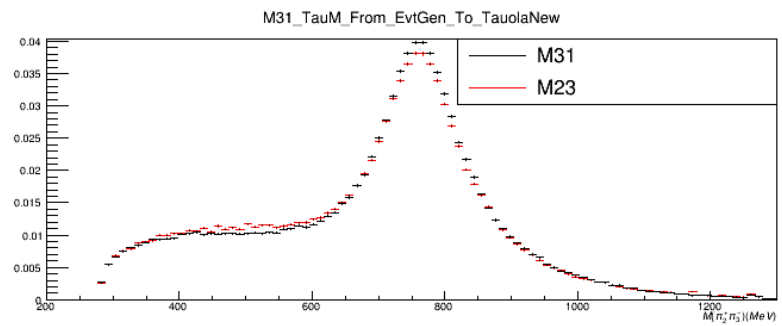
Starting From EvtGen : differences between $m(\pi_1^+\pi_3^-)$ and $m(\pi_2^+\pi_3^-)$!!!

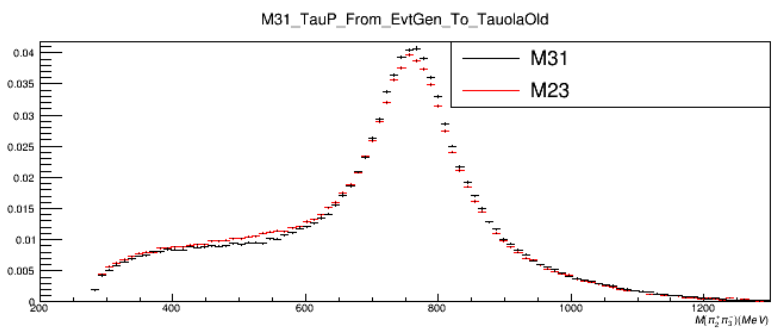
Distributions of $m(\pi_1^+\pi_3^-)$ and $m(\pi_2^+\pi_3^-)$ are compatible when generated by EvtGen but start to differ once the weights are applied.

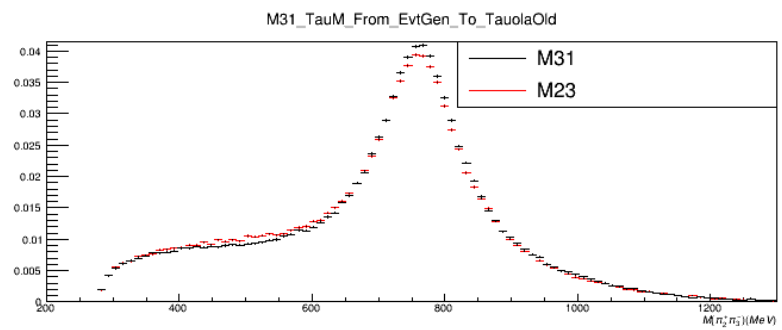












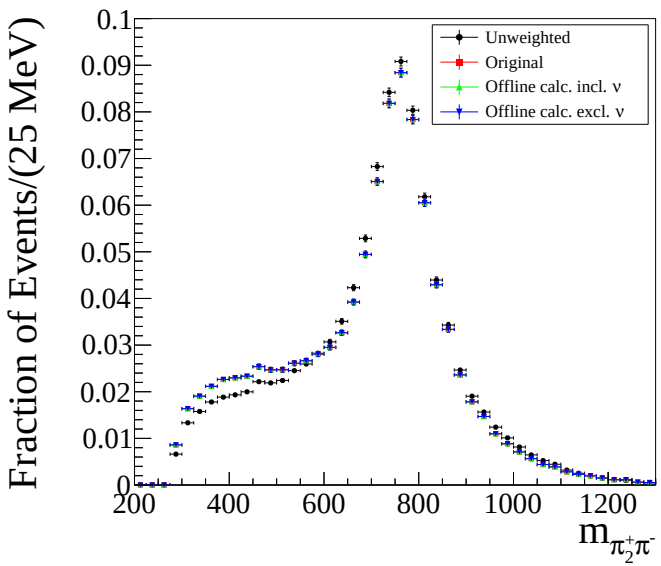
Back to reweighting from tauola ▸ slide 10

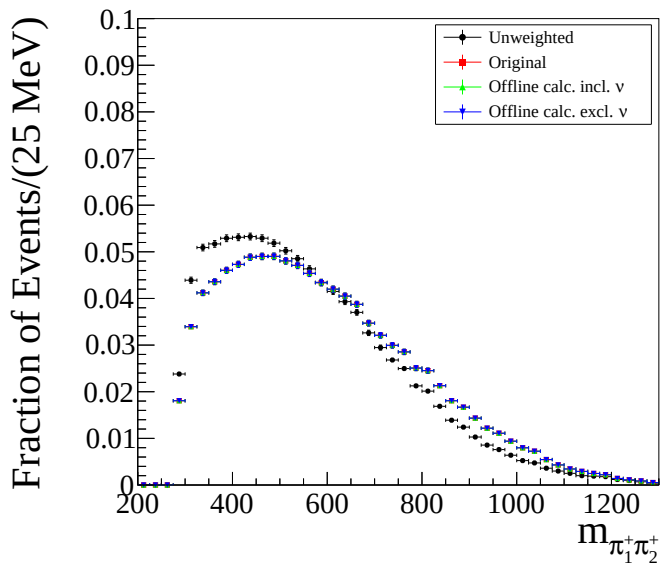
Reweighting using available variables

Further check : towards a more realistic way to compute the weights

- store the particles 4-momenta for each event
- recompute the weights "offline"

Example : reweighting from Tauola BaBar-tune to Tauola Cleo-tune





Conclusion : Reweighting can be applied on ntuple made from stripped data.

Outline

4. $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ decay models

5. Spin correlation in $B \to \tau^+\tau^-$
   - Modelling : current and new
   - Comparison

Spin Correlation in Pythia

$Z \to \tau^+\tau^-$

For electroweak processes, spin correlations are fully handled if the incoming fermions producing the γ, Z, or W are known. If the W is not produced from fermions or the fermions are unavailable, the τ-lepton is given a polarization of $\mathcal{P} = -1$, e.g. $H \to W \to \tau\nu_\tau$. For γ or Z hard processes not produced from fermions or with unavailable fermion information, the γ or Z is assumed to be unpolarized, e.g. $H \to ZZ \to 4\tau$.

$B \to \tau^+\tau^-$

The τ-lepton can also be produced from a variety of B and D meson decays. For these decays, the constituent quarks of the meson are approximated, and the spin correlations are calculated using an $f\bar{f}' \to W \to f\bar{f}'$ matrix element. For any τ-lepton from an unknown process, the τ-lepton is assumed to be unpolarized.

$\tau \to \pi\nu$

The slope of the energy distribution for pions from $\tau^- \to \nu_\tau\pi^-$ decays in the rest frame of the parent bosons is proportional to the average τ-lepton polarization. In Figure 1 this distribution, from Pythia simulation, is given for τ-leptons produced from electroweak and Higgs processes. Note the the opposite polarization of τ-leptons produced from a W and $H^\pm$, the unpolarized τ-leptons produced from neutral Higgses, and the slight polarization of τ-leptons produced from Z bosons at a pp collider.

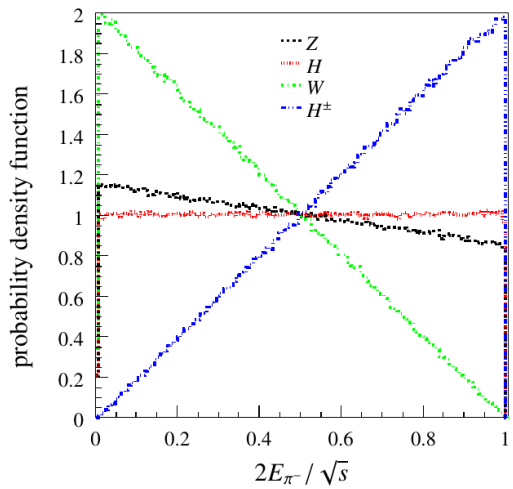


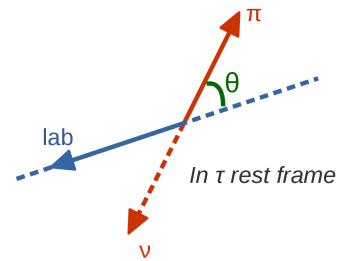
Figure 1: Distribution of the fractional energy of the pion from a $\tau^- \to \nu_\tau\pi^-$ decay in the rest frame of the producing boson. The τ-leptons are produced from Z (dashed black), H (dotted red), W (dash-dotted green), and $H^\pm$ (dash-dot-dotted blue) bosons.

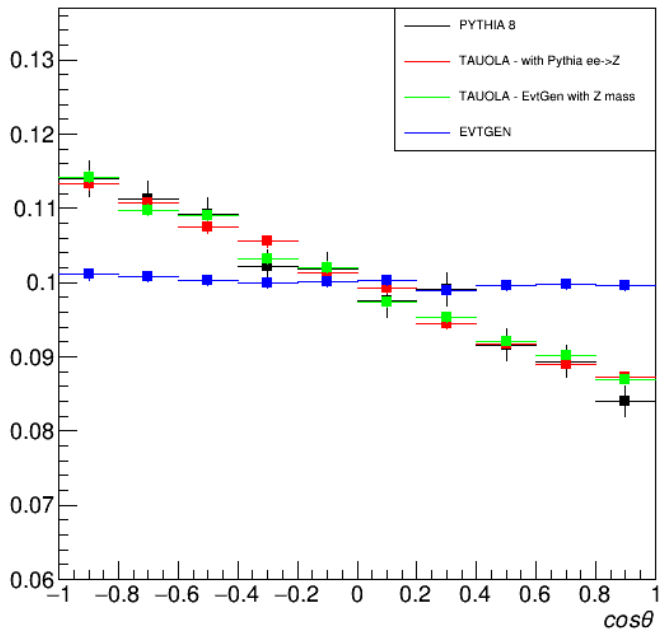
▸ slide 13

Spin correlation in $Z \to \tau^+\tau^-$ generated by Pythia, EvtGen and Tauola

- Spin effects not easy to spot in $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ decays
- Using $\tau^+ \to \pi^+\overline{\nu}_\tau$ instead
- θ : angle beween the π^+ and the lab in the τ rest frame

$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta} = \frac{1}{2}(1 + P_\tau cos\theta)$



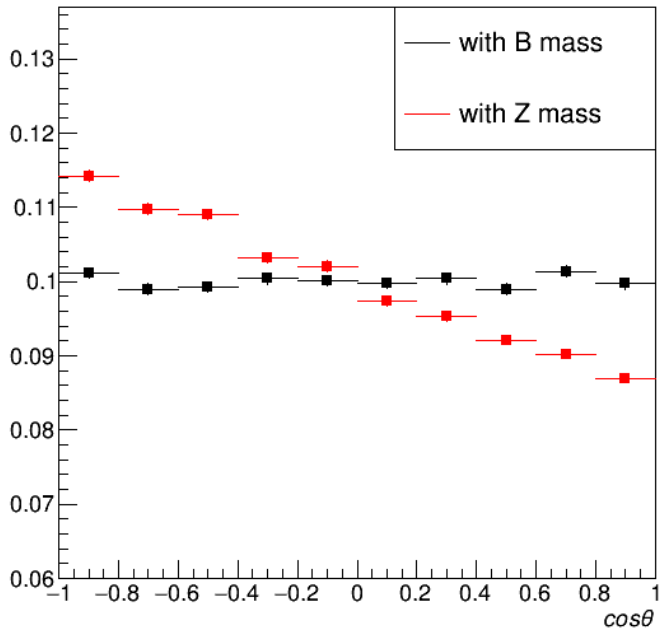


- No spin correlation observed w/ EvtGen ? (should be implemented in principle)

▸ slide 13

Spin correlation in $\gamma^* \to \tau^+\tau^-$ changing the CM Energy

1. Using EvtGen to generate $\gamma^* \to \tau^+\tau^-$
2. Setting either $E_{\gamma^*} = M_Z$ or $E_{\gamma^*} = M_B$

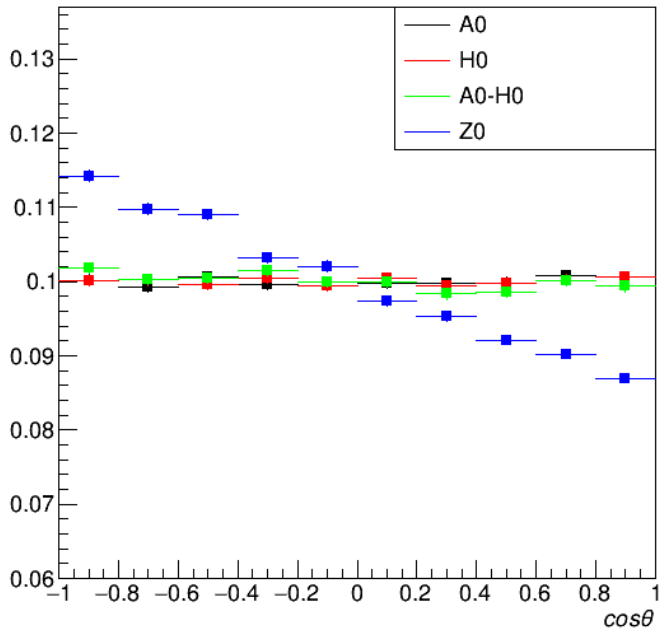


- NB : with $E_{\gamma^*} = M_Z$, $R_{0,3} = R_{3,0} = 0.149$ ($cos\beta = 0$ always - no incoming beams)
- with $E_{\gamma^*} = M_B$, $R_{0,3} = R_{3,0} = 0.000$

slide 13

Spin correlation in $X \to \tau^+\tau^-$ using different propagators in Tauola

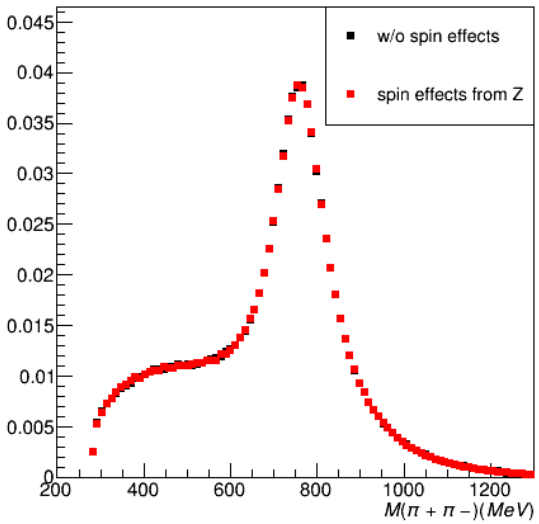
1. Use EvtGen to generate $\gamma^* \to \tau^+\tau^-$ with $E_{\gamma^*} = M_Z$
2. Change the mother PID to be a Z^0, a H^0 or a A^0
3. Let Tauola decay the τs

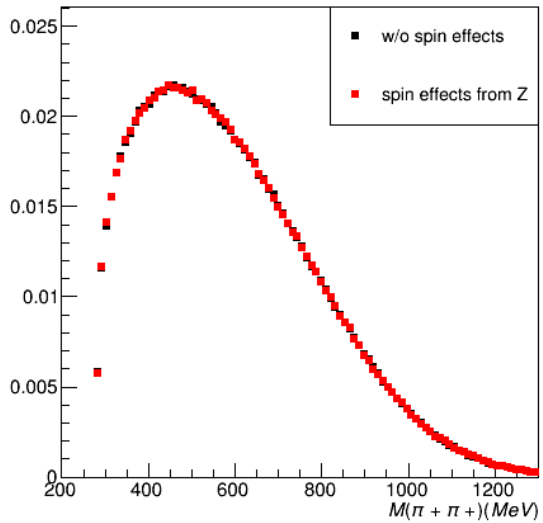


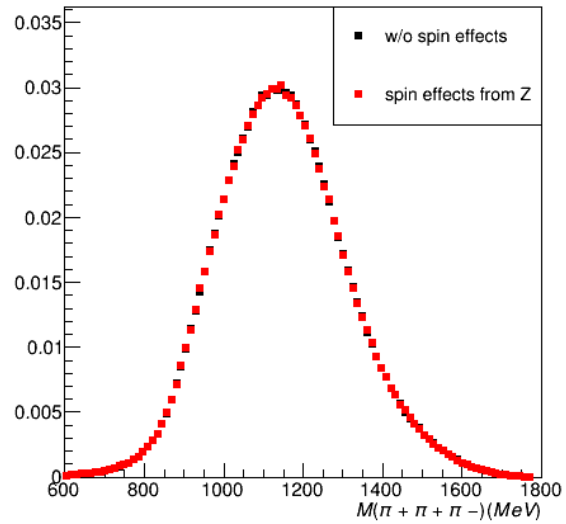
- NB: this is consistent with Pythia documentation ▸ slide 10

▸ slide 13

Spin effects on the inv. masses in the $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ mode







Signal efficiencies ($635 < m(\pi^+\pi^-) < 915$ (MeV) for both τs) :

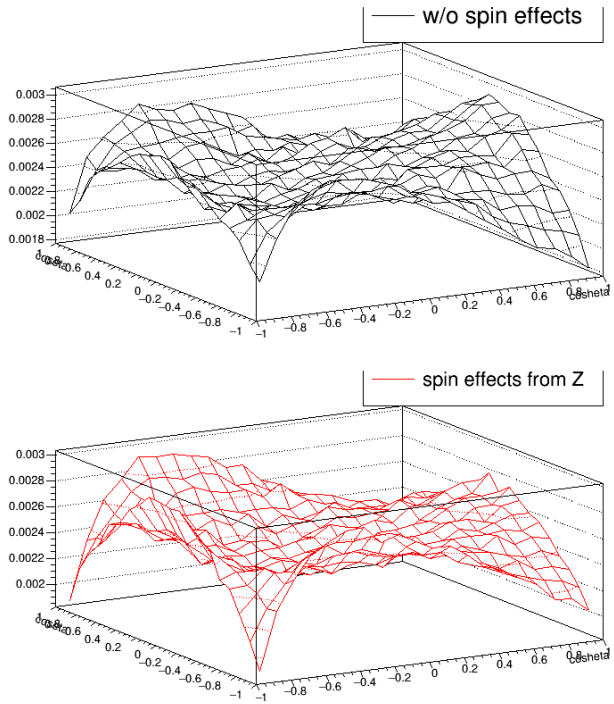
- EvtGen : $(14.38 \pm 0.11)\%$ (ref. point from current analysis)
- Tauola without spin effects : $(8.92 \pm 0.03)\%$
- Tauola with spin effects from Z^0 : $(8.98 \pm 0.03)\%$

No effects observed on the invariant mass distributions

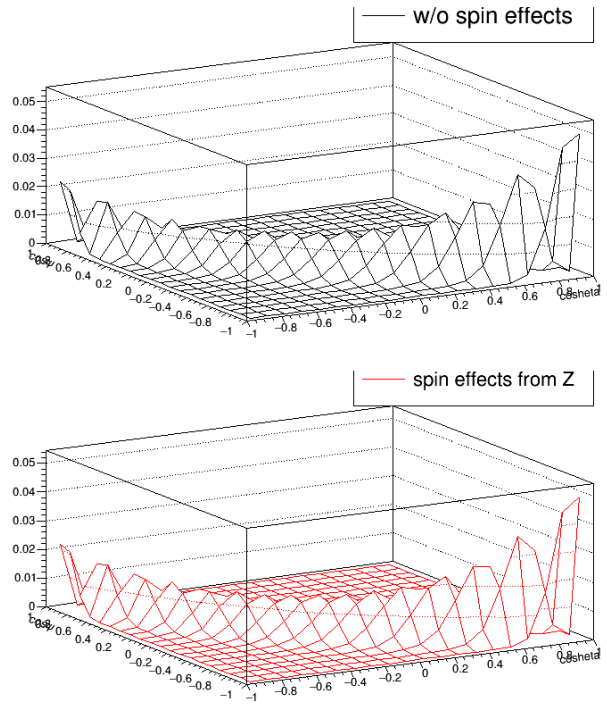
▸ slide 13

Spin effects on angular distributions in the $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ mode

$cos\beta - VS - cos\theta$



$cos\psi - VS - cos\theta$



where :

- θ : angle beween the $a1$ and the lab in the τ rest frame
- β : angle between the normal to the 3π plane and the lab in the $a1$ rest frame
- ψ : angle between the τ and the lab in the $a1$ rest frame

slide 13

Effect on selection efficiency

$B \to \tau^+\tau^-$ events selection requires : $635 \leq m(\pi^+\pi^-) \leq 915$ MeV (x4 !!)

Signal efficiencies computed at generator level ($\pm\ 0.1\%$) :

Effect of $\tau^+ \to \pi^+\pi^-\pi^+\overline{\nu}_\tau$ model

EvtGen	= 14.0%
Tauola Cleo-tune	= 10.9%
Tauola BaBar-tune	= 09.9%
Tauola Cleo-intricate	= 10.3%

Up to 10% effect among Tauola models

Effect of spin correlation

spin model No	= 10.9%
spin model B0	= 10.9%
spin model Z0	= 11.0%
spin model Higgs	= 10.9%
spin model R(z=1)	= 11.0%
spin model R(z=-1)	= 10.8%
spin model R(z=i)	= 10.9%
spin model R(z=-i)	= 10.9%

Very minor effect of spin correlation