Handling of tau decays in simulation

Fernando Abudinén

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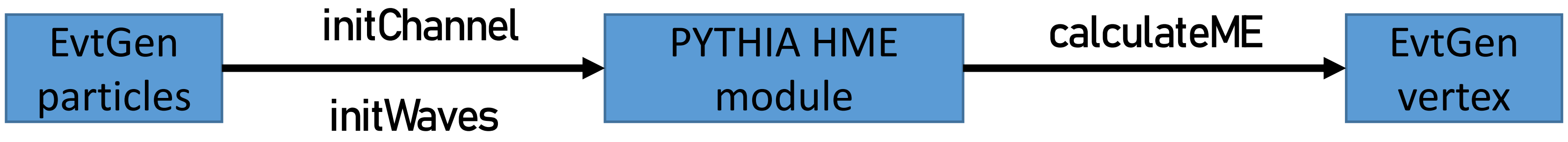
- Simulation: τ decay handling in B decays
- Analysis: search for $V \rightarrow \mu^{+}\mu^{-}$

THE UNIVERSITY OF WARWICK

Motivation

- Simulation of τ decays in EvtGen currently using TAUOLA
- Spin-state information of τ not propagated between EvtGen and TAUOLA:
  TAUOLA expects τ from a W, Z, γ or H boson, not from B
- Simulation of τ decays with spin-state propagation possible with PYTHIA using HME (helicity-matrix element) amplitude model.
- Currently available interface to HMEPYTHIA needs testing and development
- Propagation of τ spin information needed for analyses sensitive to τ polarization
- Moving to Pythia would facilitate event-level multithreading

The HME-PYTHIA interface



- Propagates decaying τ and daughters with 4-momenta to PYTHIA (as **HelicityParticles**)

$\Rightarrow$ Needs **initWaves** function in PYTHIA HME module to be made public

- Obtains amplitude for each spin state from the HME module (**calculateME** function)
- Propagates the amplitudes $\Rightarrow$ EvtGen then sums over all spin states
- Maximal event probability for loops obtained using **decayWeightMax**

Supported models

ID	Model	Example decay	Tested TAUOLA analogs
1521	Tau2Meson	$\tau^+ \to \pi^+\bar{\nu}_\tau$	TAUSCALARNU
1531	Tau2TwoLeptons	$\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$	TAULNUNU
1532	Tau2TwoMesonsViaVector	$\tau^+ \to \rho^+(\to \pi^+\pi^0)\bar{\nu}_\tau$	TAUVECTORNU
1533	Tau2TwoMesonsViaVectorScalar	$\tau^+ \to \pi^+\pi^-\bar{\nu}_\tau$	
1541	Tau2ThreePions	$\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$	TAUOLA 5 Curr Opt 0 or 1
1542	Tau2ThreeMesonsWithKaons	$\tau^+ \to K^+\pi^-\pi^+\bar{\nu}_\tau$	
1543	Tau2ThreeMesonsGeneric	$\tau^+ \to \pi^0\pi^0\pi^+\bar{\nu}_\tau$	TAUHADNU
1544	Tau2TwoPionsGamma	$\tau^+ \to \pi^0\pi^+\gamma\bar{\nu}_\tau$	
1551	Tau2FourPions	$\tau^+ \to \pi^+\pi^-\pi^+\pi^0\bar{\nu}_\tau$	
1561	Tau2FivePions	$\tau^+ \to \pi^+\pi^-\pi^+\pi^-\pi^+\bar{\nu}_\tau$	

$\Rightarrow$ Technically all working (some refinement in use of decayWeightMax needed for some)

Supported decays

- HME interface classifies decays according to the number of particles with more than 1 spin state.

- Maximally 3 particles with more than one spin state are supported.

  (Neutrinos have technically only one spin state)

- Since the mother is always a tau (2 states) we have the following cases:

a) One daughter has more than one state (tested for 2 or 3 states),

b) Two daughters have more than one state (not tested yet, probably not needed?)

Testing HME-PYTHIA

- Simulate decays with τ in EvtGen and check relevant distributions of observables
- Compare results obtained with PYTHIA and TAUOLA (when possible)
- Note: parent at rest, PHOTOS turned off, no B^0-$\bar{B}^0$ mixing

Tested τ-decay modes

$$\tau^+ \to e^+\nu_e\bar{\nu}_\tau$$

$$\tau^+ \to \pi^+\bar{\nu}_\tau$$

$$\tau^+ \to \pi^+\pi^-\pi^+\bar{\nu}_\tau$$

$$\tau^+ \to \rho^+\bar{\nu}_\tau$$

Tested B-decay modes

$$B^+ \to \tau^+\nu_\tau$$

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

$$B^0 \to D^{-*}\tau^+\nu_\tau$$

$$B^+ \to \bar{D}^0\,\tau^+\nu_\tau$$

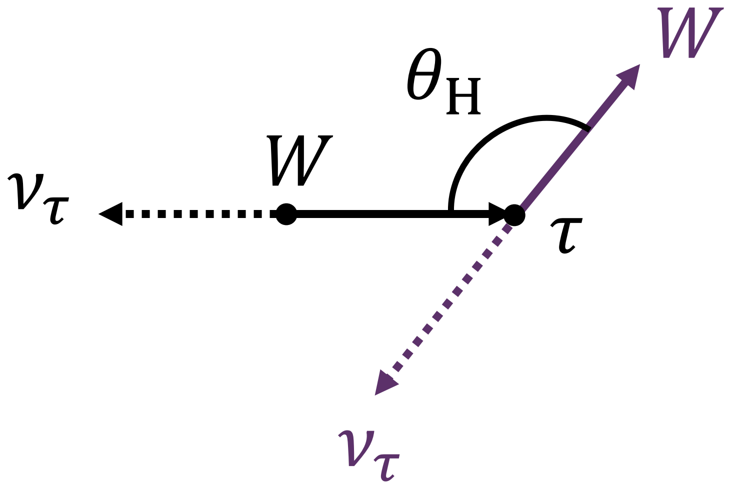
Tau polarization

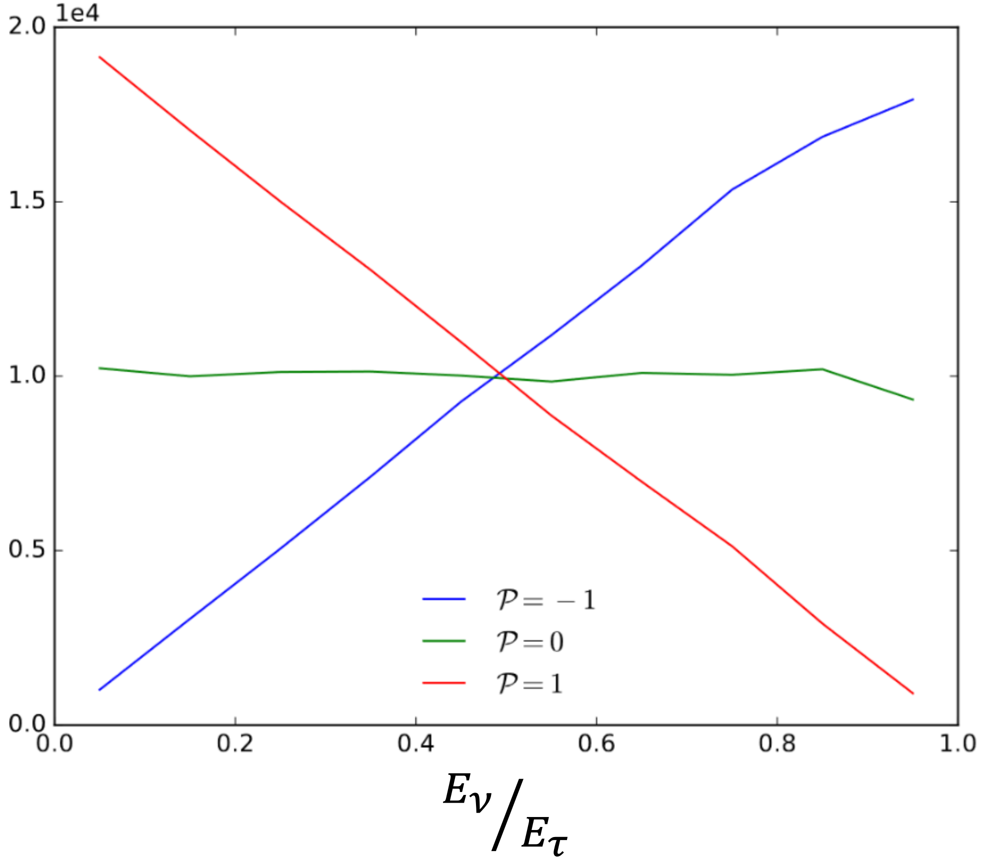
$$P = \frac{\Gamma^{+} - \Gamma^{-}}{\Gamma^{+} + \Gamma^{-}}$$

$\Gamma^{\pm}$: decay rate for τ helicity $\pm\,^{1}/_{2}$

Benchmark observables:

$^{E_\nu}/_{E_\tau}$, $\cos\theta_{\mathrm{H}}$

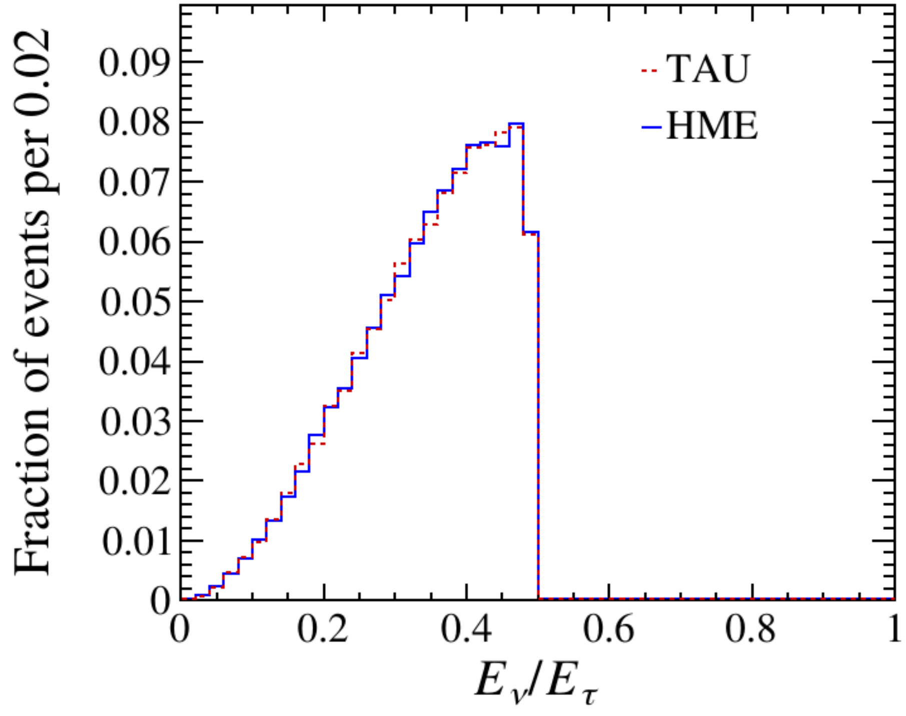




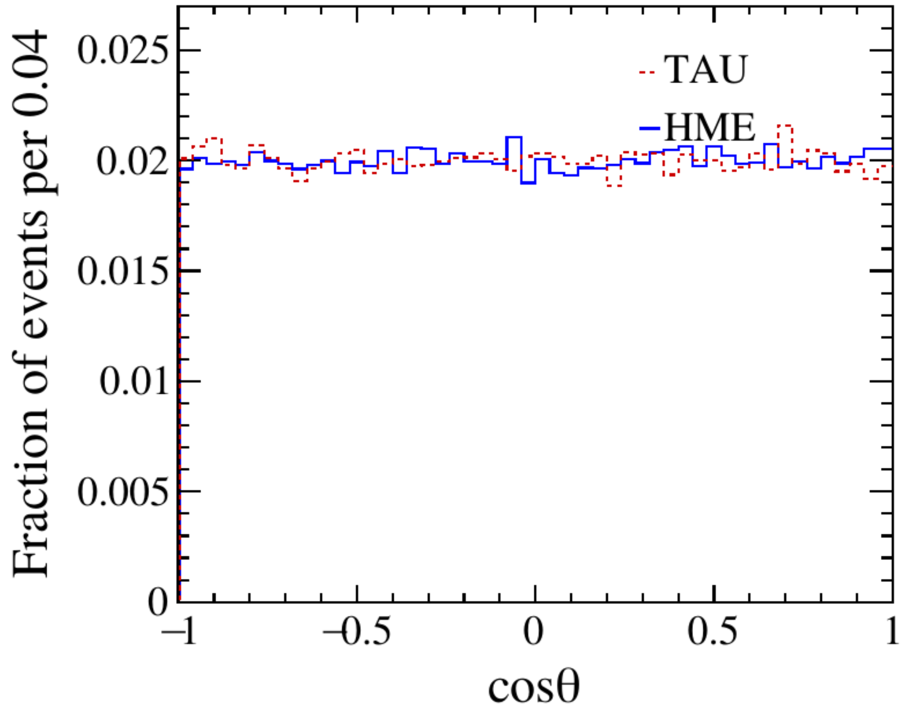
Single tau decays

Test HME and TAUOLA interfaces standalone with single τ decays

$\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$



$\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$

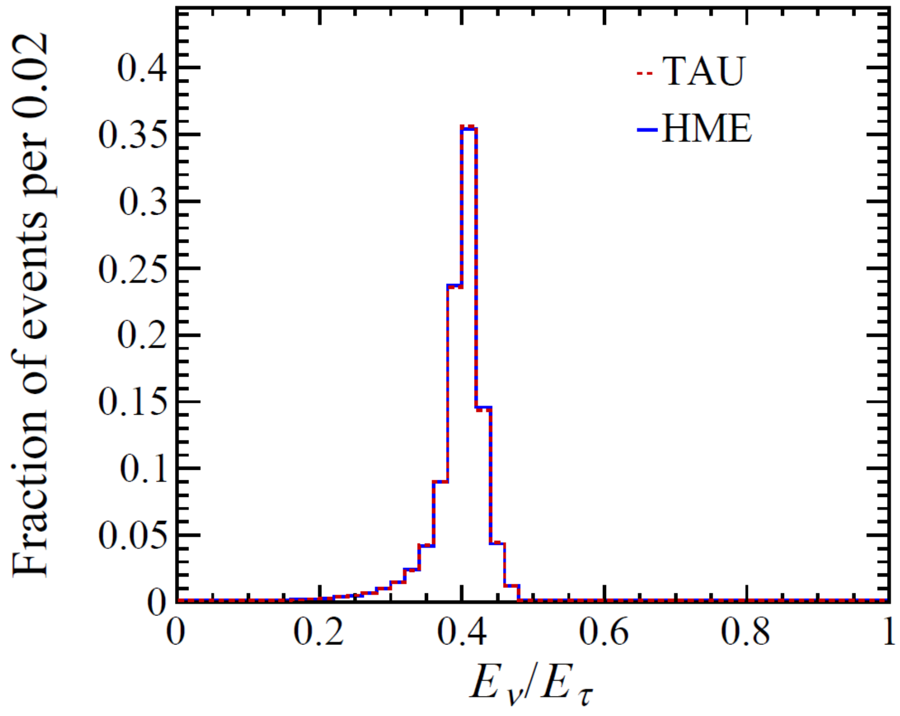


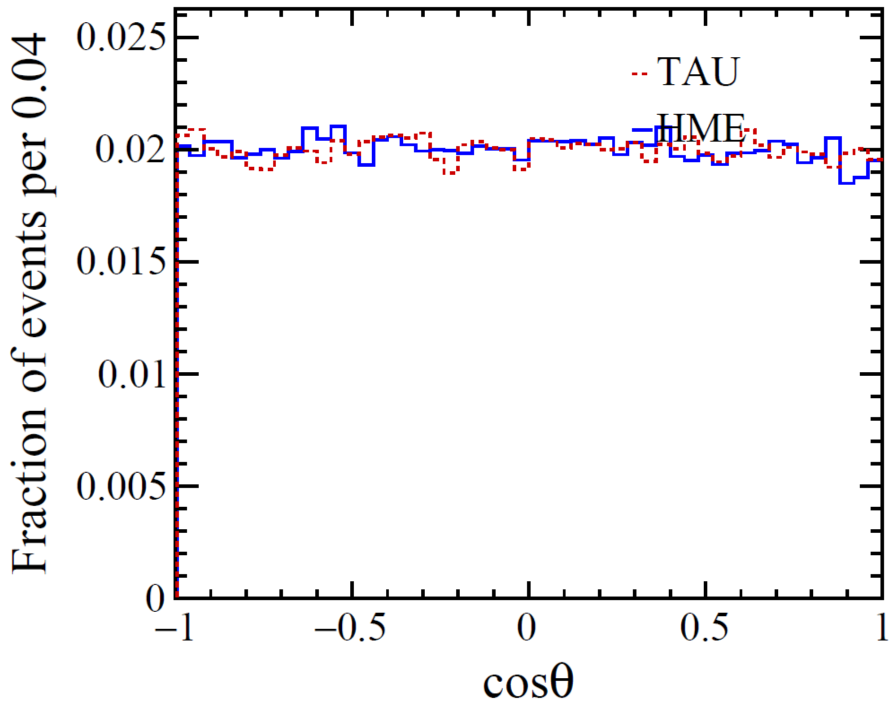
$\Rightarrow$ No visible difference between generators for single decays.

Single tau decays

Test HME and TAUOLA interfaces standalone with single τ decays

$$\tau^+ \rightarrow \rho^+ \bar{\nu}_\tau$$





$\Rightarrow$ No visible difference between generators for single decays.

Single tau decays

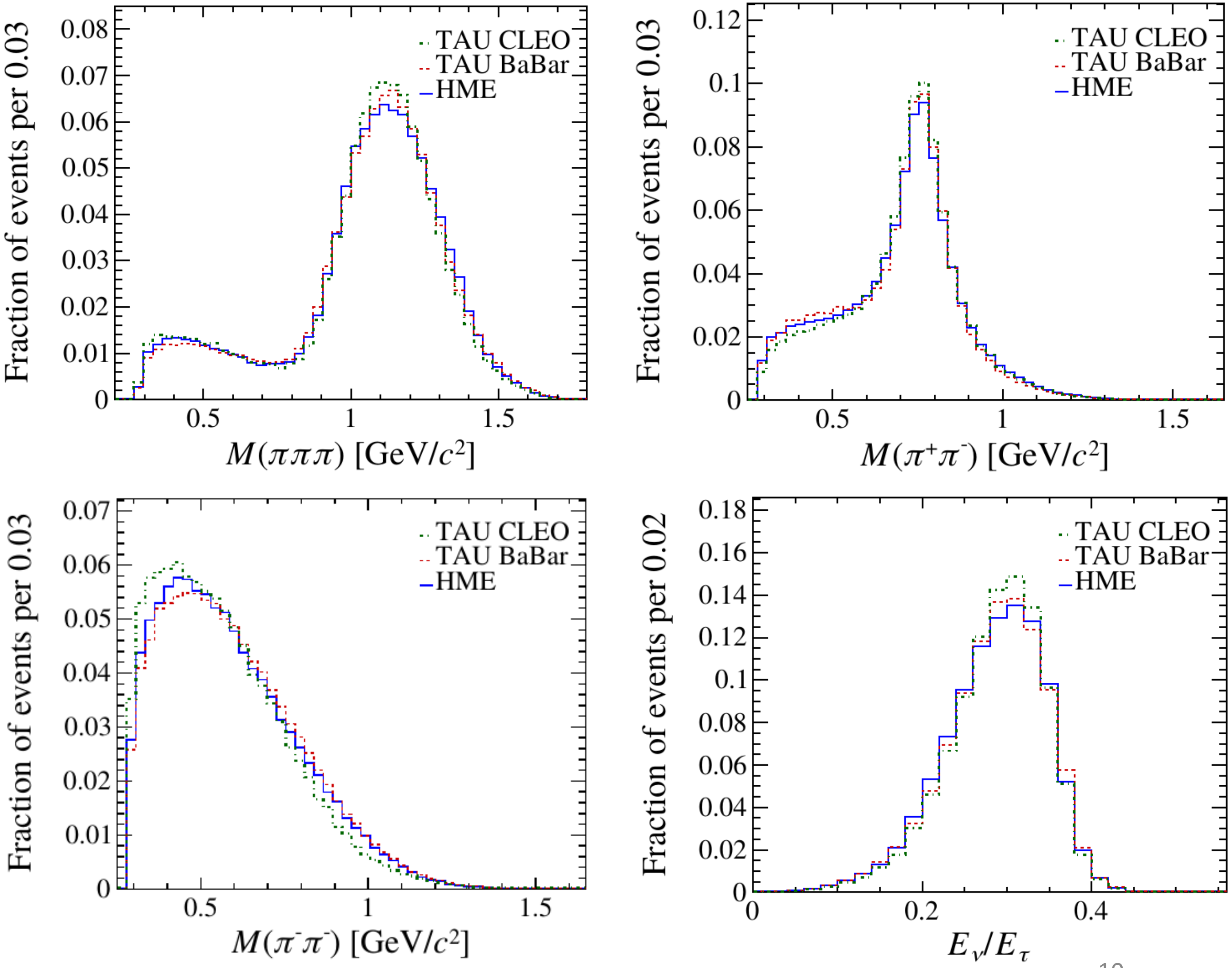
$\tau^+ \rightarrow \pi^+\pi^-\pi^+\bar{\nu}_\tau$

- Currently two available tunings for Dalitz structure: BaBar and CLEO.
- Both available in TAUOLA
- In PYTHIA should be CLEO

⇒ Apparently no big difference.

However: LHCB $B \rightarrow \tau\tau$ analysis observes 20% difference in effcy. between CLEO and BaBar

PRL.118.251802



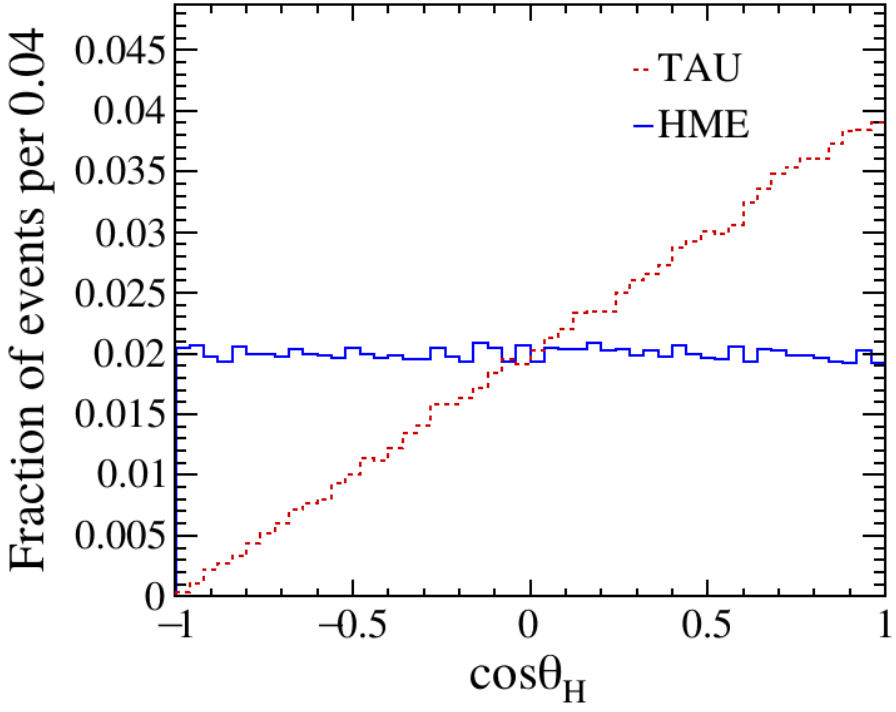
Taus from B

- Test τ decays inside a decay chain
- Start with simple case: $B^+ \to \tau^+(\to \pi^+\bar{\nu}_\tau)\,\nu_\tau$
- Expected $\cos\theta_\mathrm{H}$ distribution: $\sim(1+\cos\theta_\mathrm{H})$

$\Rightarrow$ Result with TAUOLA shows expected τ polarization, while result with HME is unpolarized.

- Hint: Pythia uses helicity basis while EvtGen uses spin basis (quantized along z direction)
- Check result by applying a basis rotation

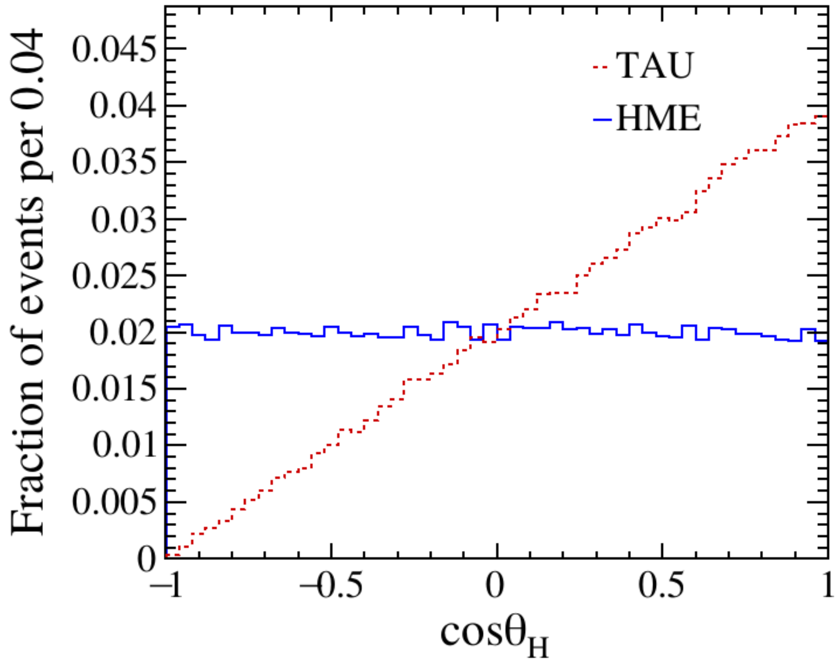
$B^+ \to \tau^+(\to \pi^+\bar{\nu}_\tau)\,\nu_\tau$



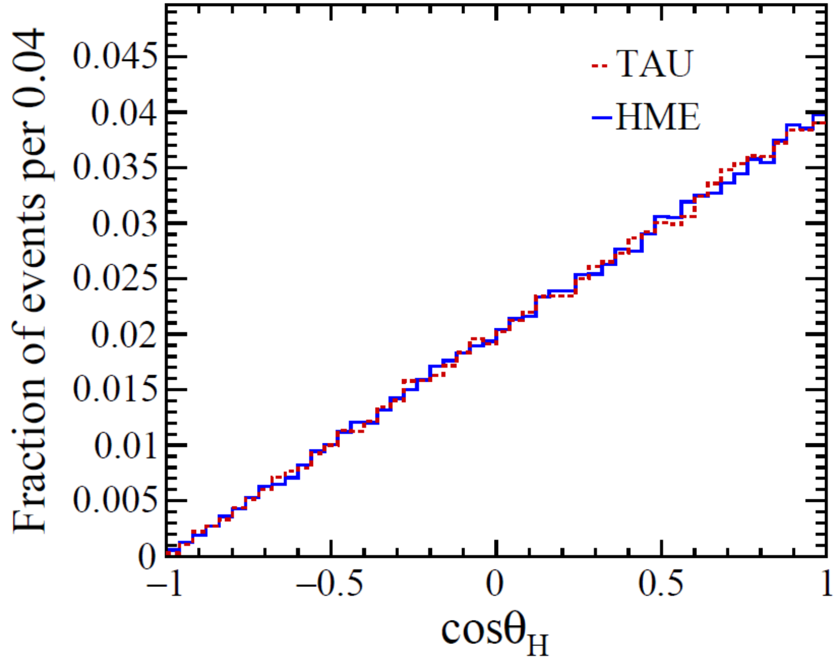
$$B^+ \to \tau^+(\to \pi^+\bar{\nu}_\tau)\,\nu_\tau$$

Apply a rotation using **rotateToHelicityBasis** (similar to the EvtGen **EvtHelAmp** module)

No basis rotation



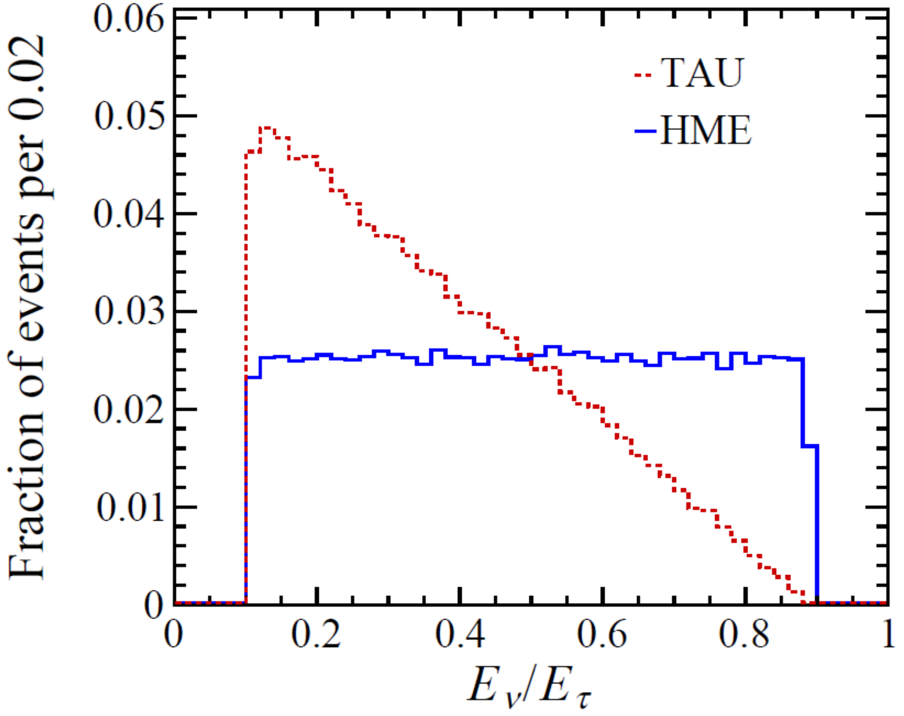
With basis rotation



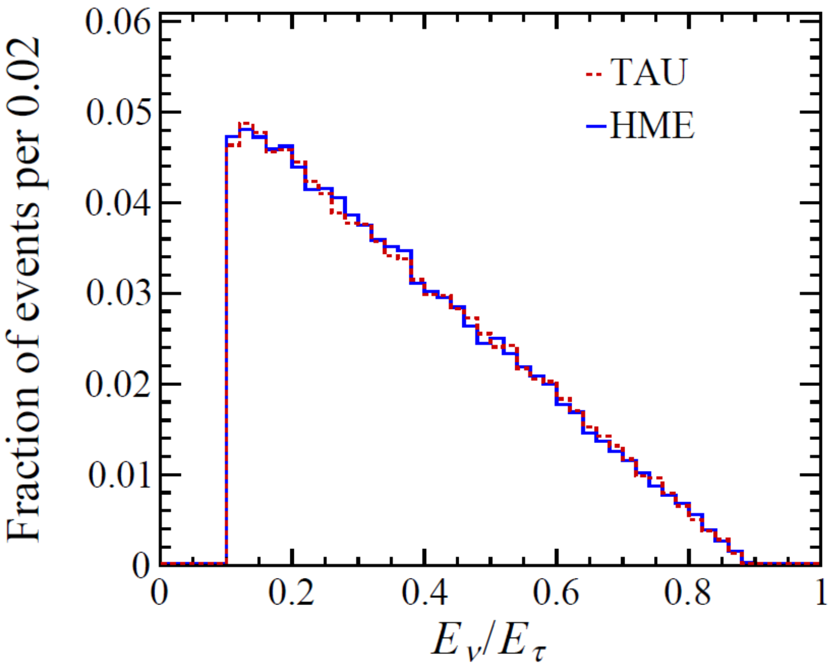
$\Rightarrow$ Check the neutrino

$$B^+ \rightarrow \tau^+(\rightarrow \pi^+\bar{\nu}_\tau)\,\nu_\tau$$

No basis rotation



With basis rotation

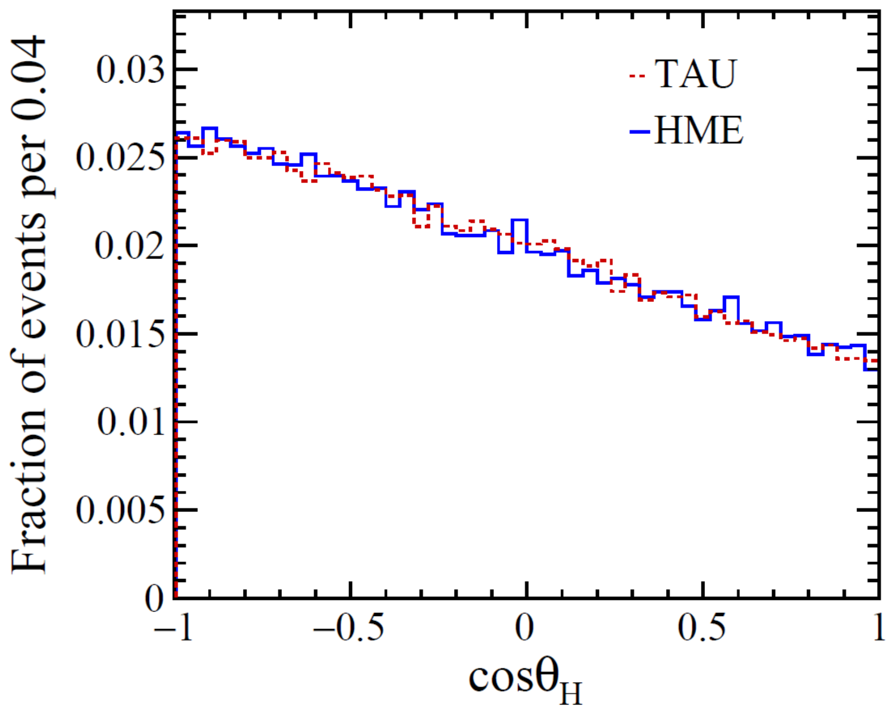


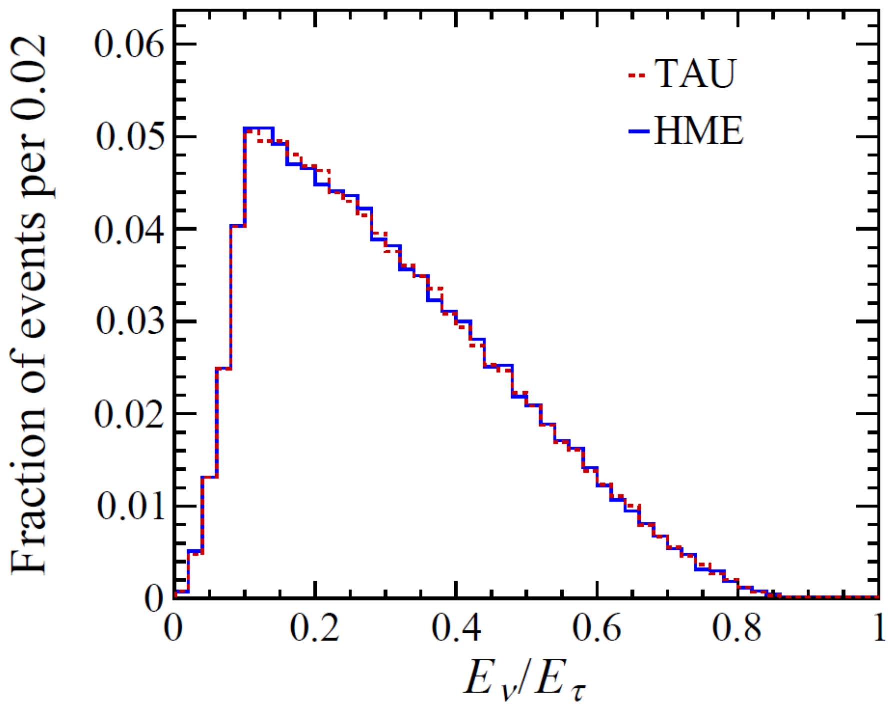
$\Rightarrow$ Results look good after rotation

$\Rightarrow$ Check now when τ daughter not spin-0

$B^+ \rightarrow \tau^+(\rightarrow \mu^+\nu_\mu\bar{\nu}_\tau)\,\nu_\tau$

$\Rightarrow$ (2×2 states) after rotation



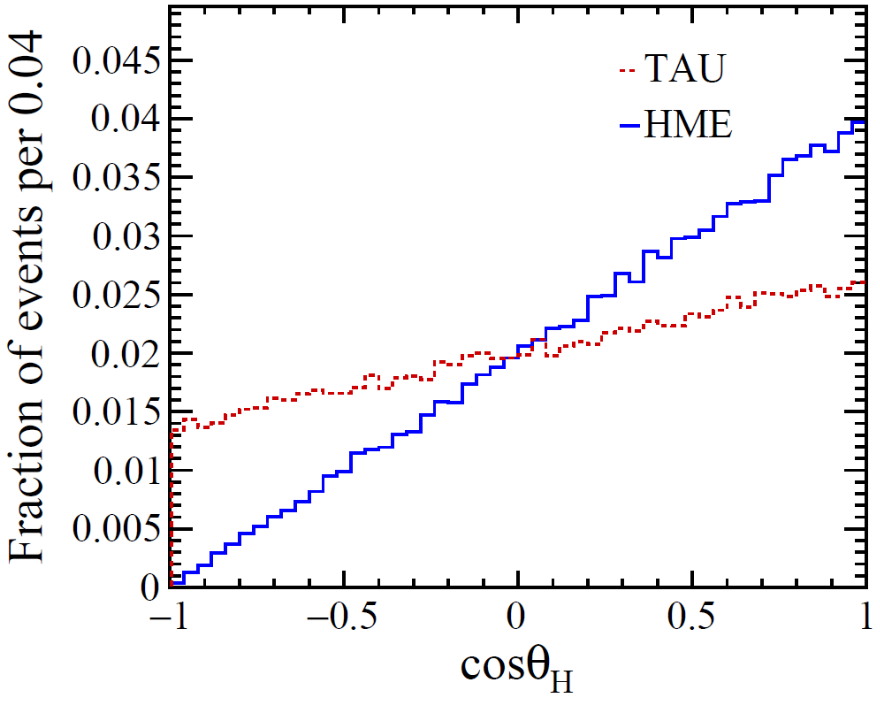


$\Rightarrow$ Results look good
$\Rightarrow$ Similar results with an electron
$\Rightarrow$ Similarly good agreement for 3 pion model (as shown previously)

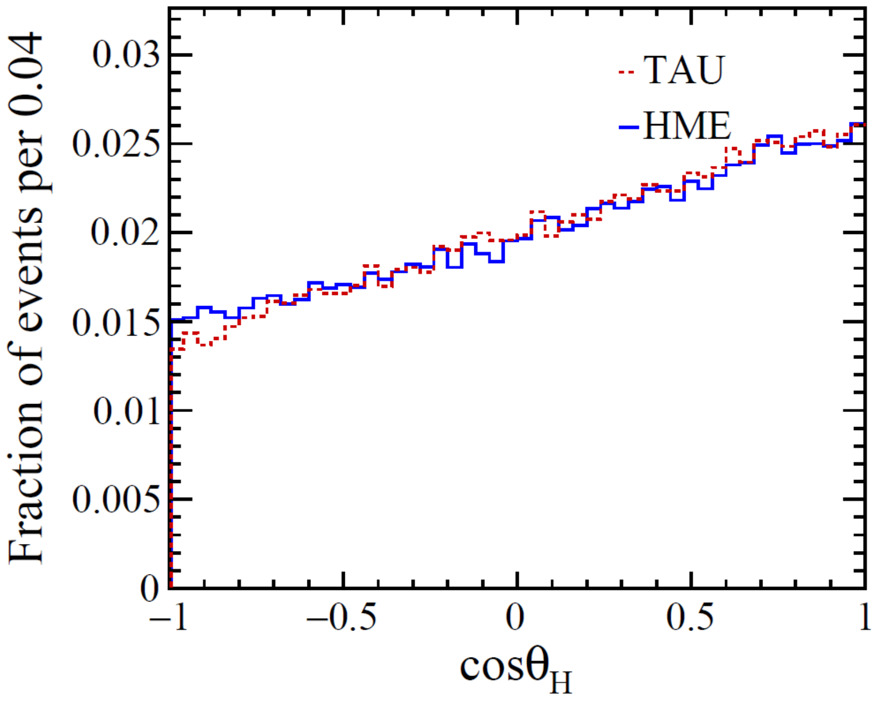
$B^+ \rightarrow \tau^+(\rightarrow \rho^+\bar{\nu}_\tau)\,\nu_\tau$

2×3 states: it seems that PYTHIA HME indices are permuted if the daughter has more helicity states than the mother (using Tau2Meson model)

No permutation



With permutation



$\Rightarrow$ Results look in good agreement with TAUOLA after permutation + rotation.

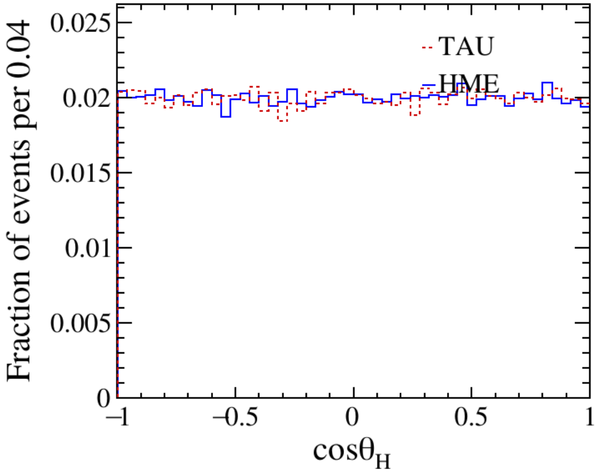
Taus in other B decays

Check $B^0 \rightarrow \tau^+\tau^-$, both $\tau \rightarrow \pi\bar{\nu}_\tau$

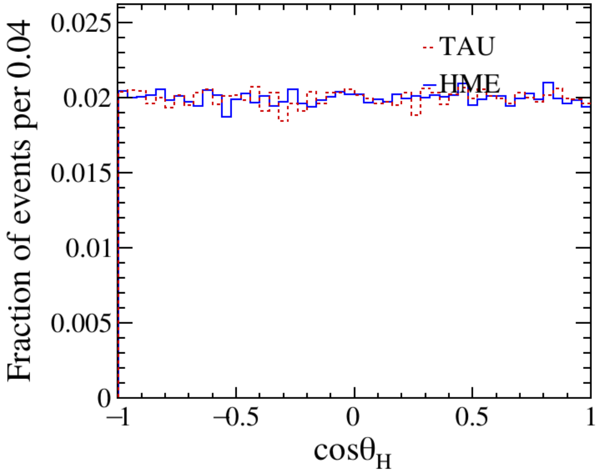
Expected spin correlation between the 2 taus

No rotation

τ_1

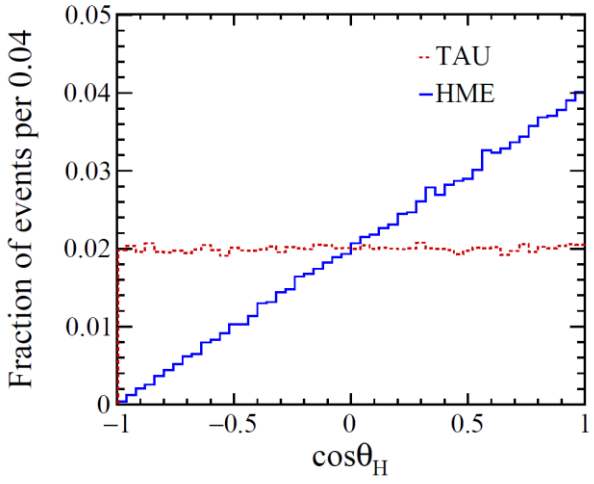


τ_2

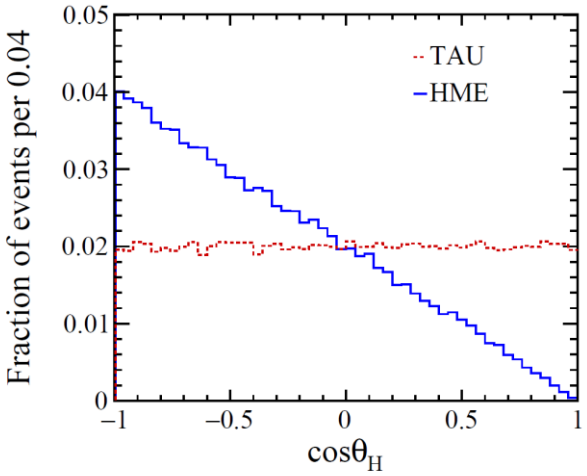


With rotation

τ_1



τ_2



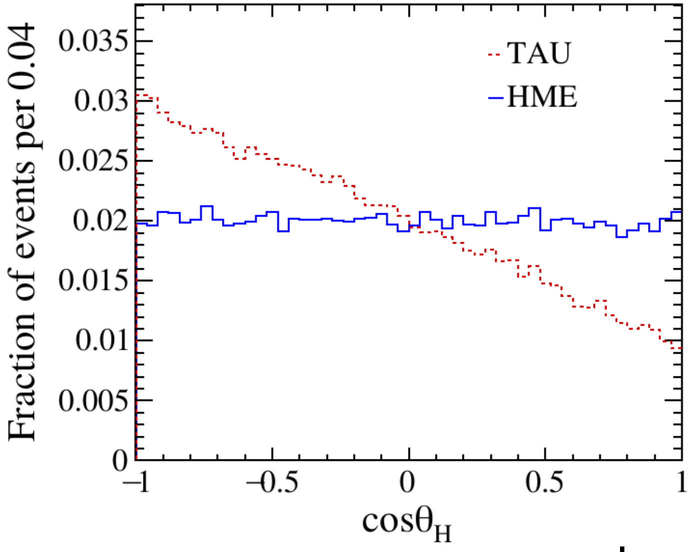
$\Rightarrow$ Need to compare with expectations, but HME shows expected correlation.

Semileptonic decays

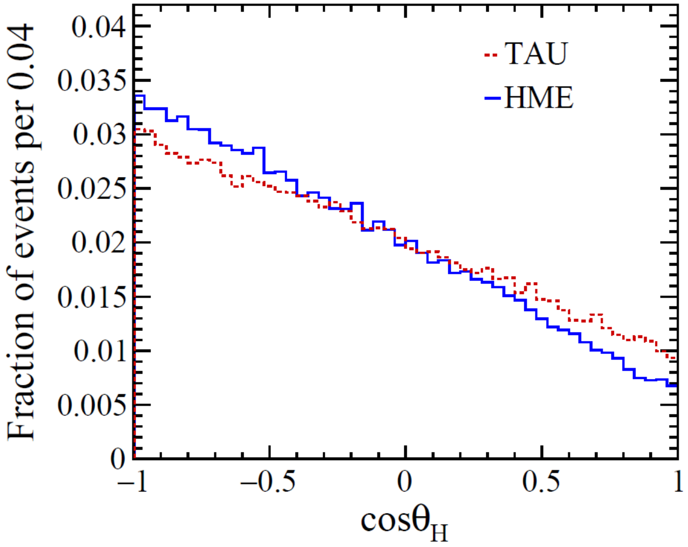
$B^0 \rightarrow D^{-*}\tau^+\nu_\tau$

Using ISGW2 generator for B decays

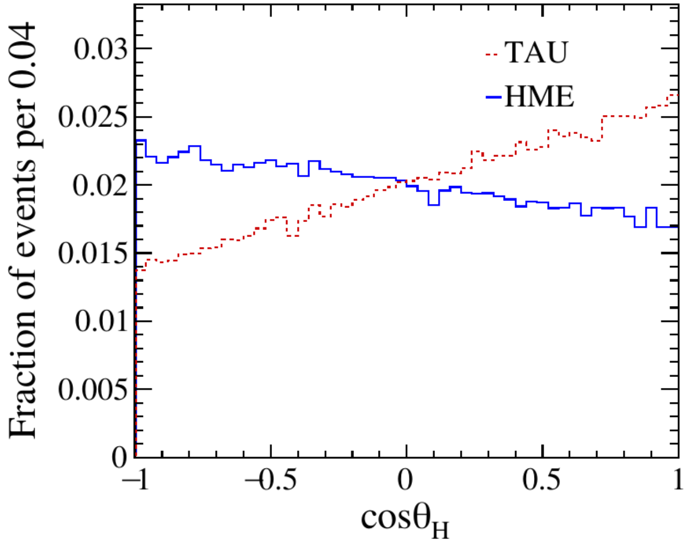
No rotation

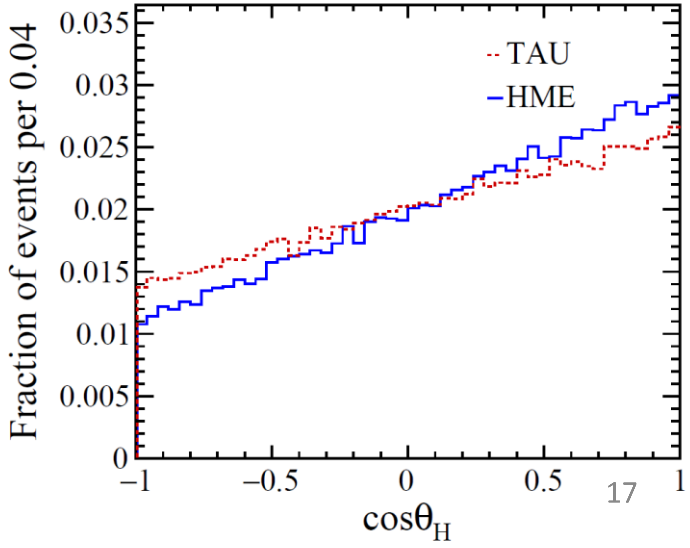


With rotation



$B^+ \rightarrow \overline{D}^0\, \tau^+\nu_\tau$

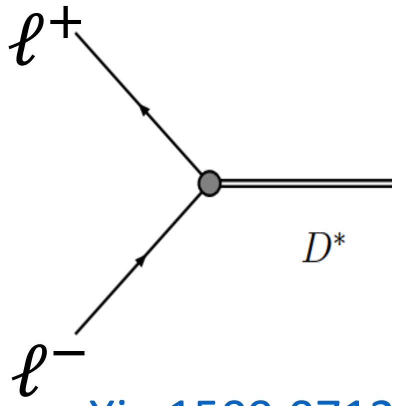




$\Rightarrow$ Results look similar but further understanding of discrepancies needed.

Search for $V \rightarrow \mu^+\mu^-$

Goal



- Perform a dedicated search for $D^{*0} \to \mu^+\mu^-$ in $B^+ \to \mu^+\mu^-\pi^+$decays

$\Rightarrow$ Extend the search then to $B^{*0}_{(s)} \to \mu^+\mu^-$ in $B^+_c \to \mu^+\mu^-\pi^+$decays

arXiv:1509.07123

Motivation

- Decays of heavy-flavored vector mesons into lepton pairs predicted to have very small branching fractions in the SM, for instance $\mathcal{B}(D^{*0} \to \mu^+\mu^-) \lesssim 10^{-11}$.
- D^{*0} and $B^{*0}_{(s)}$ mesons decay via strong or EM int. (unlike D^0 and B^0)

$\Rightarrow$ Probe for several effective operators

$\Rightarrow$ Not helicity suppressed

- Can be searched through analysis of $B^+_{(c)} \to \mu^+\mu^-\pi^+$decays

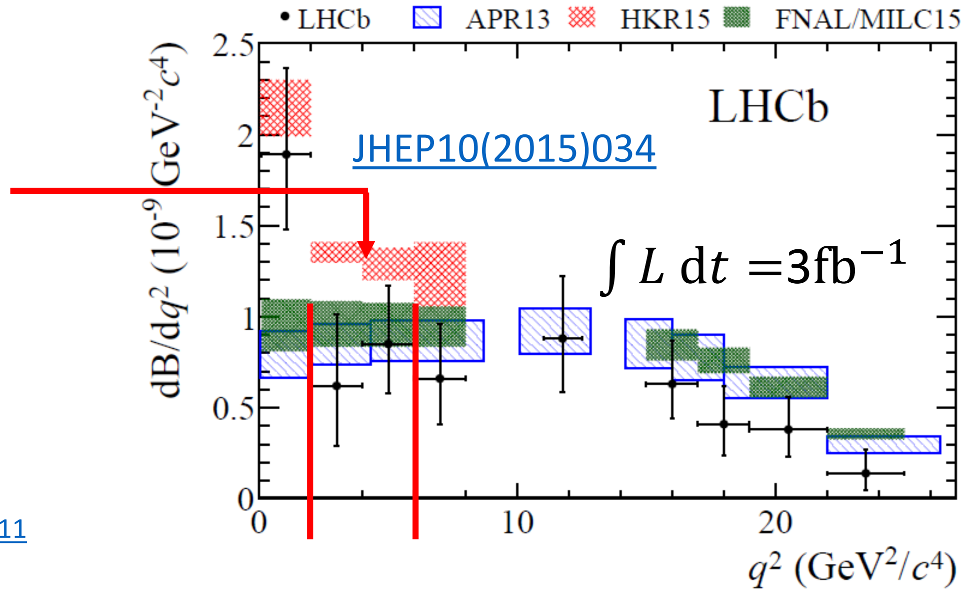
$\Rightarrow$ Exploit displaced vertex signature to reject background

Expected precision

- Limit looking at previous measurements of $d\mathcal{B}(B^+ \to \mu^+\mu^-\pi^+)/dq^2$ at LHCb:

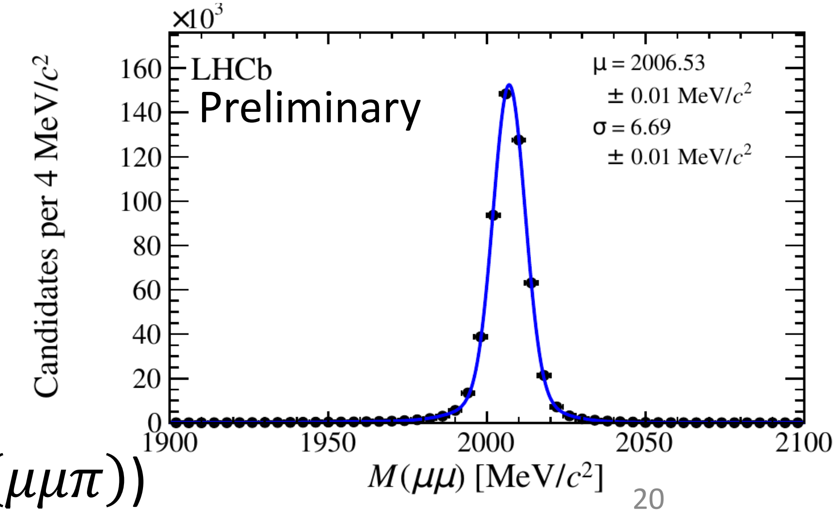
Assume that $\mathcal{B}(B^- \to [\mu^+\mu^-]_{D^{*0}}\,\pi^-)$ less than half the signal in the two bins around $M^2_{D^{*0}}$

$$\Rightarrow \mathcal{B}(D^{*0} \to \mu^+\mu^-) = \frac{\mathcal{B}(B^-\to[\mu^+\mu^-]_{D^{*0}}\,\pi^-)}{\mathcal{B}(B^-\to D^{*0}\pi^-)} \lesssim 3\cdot 10^{-7}$$



$\Rightarrow$ Expect at least ten times higher sensitivity with a dedicated search in 9fb^{-1} (world record is $\lesssim 10^{-6}$) epjconf/201921202011

Status



- Started from analysis tools and selection for $B^+ \to \mu^+\mu^-\pi^+$

$\Rightarrow$ Processed data and MC applying mass constraint to B^+ candidates

$\Rightarrow$ Developing fit model using $M(\mu\mu)$ (and possibly unconstrained $M(\mu\mu\pi)$)

Summary

Handling of tau simulation:

- HME-PYTHIA interface working in all tested cases
- Simulation with HME mirrors results with TAUOLA in simple benchmark cases
- Effect of basis rotation needs understanding in more complex cases
- Some technical issues to be ironed out (probmax handling, initialization)

Analysis:

- Processed full collision data and simulation samples
- Preparation of fit model ongoing