Study of a rare heavy-flavoured particle decay at FCC-*ee* including τ particles in the final state

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LPC Particules pLasmas Univers applicationS
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- Lepton Flavour Universality (LFU) : in the Standard Model (SM) charged leptons e, μ, τ are coupled identically to gauge bosons, any departure points towards Physics Beyond SM (BSM).
- Tensions w.r.t. LFU ($<5\sigma$) observed at LHCb and B-factories (BaBaR and BELLE) in particular $b \to s\ell\ell(\ell = e, \mu)$ with R_K, R_{K*}.
- Study of $b \to s\tau\tau$ ($m_\tau \sim 20 m_\mu$) transitions could allow to sort out LFUV models. Problem : measuring neutrinos !
- We need :
  - a clear experimental environment (like B-Factories),
  - boosted b-hadrons (like LHC) to measure their decay lengths.

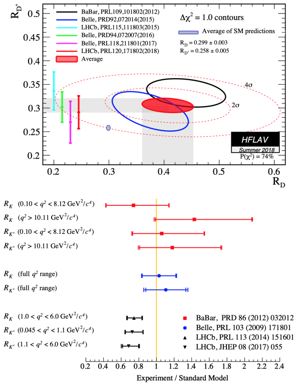

Figure – Experimental results [1] on R_D, R_{D*} [2] , R_K, R_{K*} [3, 4, 5, 6] and comparison to SM prediction. Some tensions appeared. A new measurement of R_K at LHCb gives $0.846^{+0.042}_{-0.039}(stat.)^{+0.013}_{-0.012}(syst.)$ and a tension of 3.1σ with the SM [7] is reported.

$\Rightarrow$ It looks like FCC-*ee* is the right candidate.

- In the SM the $b \to s\tau\tau$ proceed through an electroweak penguin diagram.
- Study of the rare heavy-flavoured decay $B^0 \to K^*\tau^+\tau^-$ at FCC-*ee*[8]. SM prediction : BR=$\mathcal{O}(10^{-7})$.
- Should the current level of the anomalies be the natural one some models do predict BR($B^0 \to K^*\tau\tau$) to be several orders of magnitudes larger [9].
- The study of $B^0 \to K^*\tau^+\tau^-$ decays is hence instrumental to sort out the possible BSM models.
- This decay is not observed yet (actual limit : $\mathcal{O}(10^{-3} - 10^{-4})$ [10]).

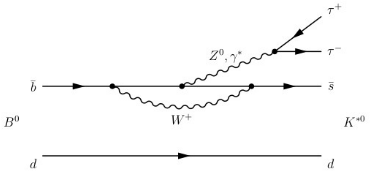

Figure – EW penguin quark-level transition

- The $B^0 \to K^*\tau\tau$ decay topology is covered by the tau decay processes.
- There is from 2 to 4 neutrinos (not detected) and at least 4 charged particles in the final state and one,two or three decay vertices.
- We focus on the 3-prongs tau decays ($\tau \to \pi\pi\pi\nu$) for which the decay vertex can be reconstructed in order to solve fully the kinematics.
- 10 particles in the final state ($K, 7\pi, \nu, \bar{\nu}$), 3 decay vertices and 2 undetected neutrinos.

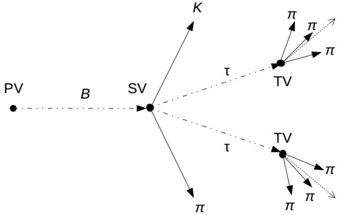

Figure – Decay topology

Goal : explore the feasability of the search for $B^0 \to K^*\tau^+\tau^-$ and give the corresponding detector requirements.

- The events used in this work are generated with Pythia [11] ($Z \to b\bar{b}$ and hadronisation) and EvtGen [12] (forcing the decay).
- 100000 events are generated for the decay thanks to the sw team Clement, Donal and Emmanuel.
- The reconstruction is performed with the FCC Analyses sw using Delphes [13] simulation (featuring the IDEA [14] detector).
- The simulated data yield reconstructed particle with the momentum resolution given by the IDEA drift chamber tracking system. One of the goal of the study is to address the required vertex reconstruction precision hence the vertex resolution is emulated.

To fully reconstruct the kinematics of the decay (B invariant-mass observable for instance) we need :

- Momentum of all final particles including not detected neutrinos.
- The decay lengths (6 constraints) together with the tau mass (2 constraints) can be used to determine the missing coordinates (6 degrees of freedom).
- We use energy-momentum conservation at tertiary (or τ decay) vertex with respect to τ direction.

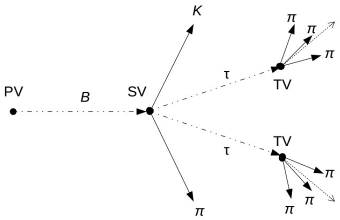

Figure – The dotted lines represent the non-reconstructed particles. The plain lines are the particles that can be reconstructed in the detector.

$$\begin{cases} p^{\perp}_{\nu_\tau} = -p^{\perp}_{\pi_t} \\ p^{\parallel}_{\nu_\tau} = \dfrac{((m^2_\tau - m^2_{\pi_t}) - 2p^{\perp,2}_{\pi_t})}{2(p^{\perp,2}_{\pi_t} + m^2_{\pi_t})}.p^{\parallel}_{\pi_t} \pm \dfrac{\sqrt{(m^2_\tau - m^2_{\pi_t})^2 - 4m^2_\tau p^{\perp,2}_{\pi_t}}}{2(p^{\perp,2}_{\pi_t} + m^2_{\pi_t})}.E_{\pi_t} \end{cases}$$

There is a quadratic ambiguity on each neutrino momentum !

$\rightarrow$ The ambiguities propagate to τ and B reconstructions

$\rightarrow$ 4 possibilities by taking all +/- combination for the two neutrinos

$\Rightarrow$ A selection rule is needed to choose the right possibility

$\longrightarrow$ From the energy-momentum conservation at the B decay vertex, we have a condition between the 2 taus and the K^* with respect to the B direction :

$$p_{\tau^+_-} = -\frac{\vec{p}^{\perp}_{K*}.\vec{e}_{\tau^+_-}}{1-(\vec{e}_{\tau^+_-}.\vec{e}_B)^2} - p_{\tau^-_+}.\frac{\vec{e}_{\tau^+_-}.\vec{e}_{\tau^-_+} - (\vec{e}_{\tau^+_-}.\vec{e}_B)(\vec{e}_{\tau^-_+}.\vec{e}_B)}{1-(\vec{e}_{\tau^+_-}.\vec{e}_B)^2}$$

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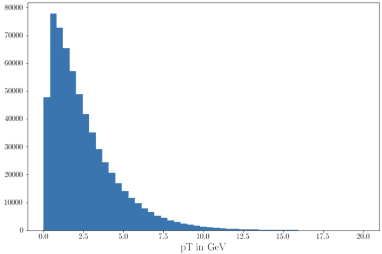
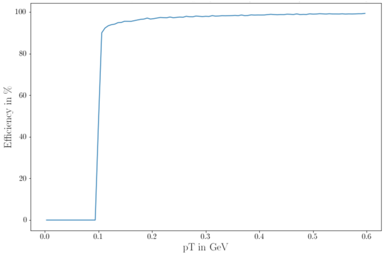
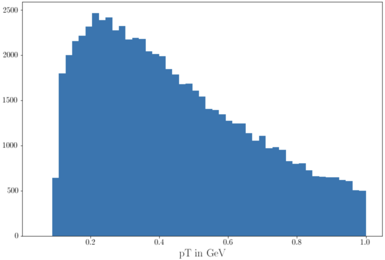
The name of the game is to measure as accurately as possible the decay vertices.

Efficiency to reconstruct the final state tracks by combination

- 100000 events are generated (Pythia, EvtGen) for $B^0 \to K^*\tau^+\tau^-$ $\Rightarrow$ there is 87000 events with the signal (hint ? Pythia hadronization fraction 0.435×2).
- Momentum resolution (FCC IDEA, Delphes) $\to$ not all the charged particles of the signal final state can be reconstructed.
- The efficiency drops at low transverse momentum.
- Average p_T of the charge final state particles is modest because of the large multiplicity of the signal decay.
- The minimum p_T of the signal tracks is on average less than half a GeV.

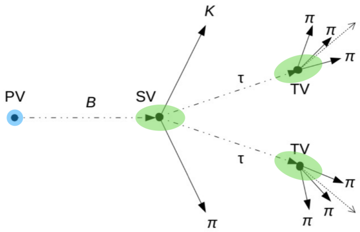






$\Rightarrow$ **about 88% of B^0 reconstructed**

- Vertex resolution is introduced by Gaussian smearings detailed in the following.
- PV : 3D normal law of 3 µm width (conservatively, does not limit the method).
- SV & TV → ellipsoidal (decaying particle direction as reference) :
    - longitudinal,
    - transverse.
- Investigate the impact of the resolution on several quantities.
- Two working points examined (longitudinal-transverse configuration).



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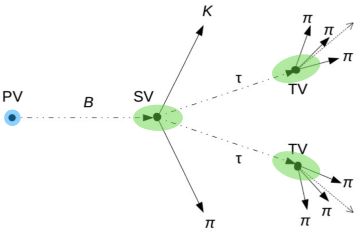
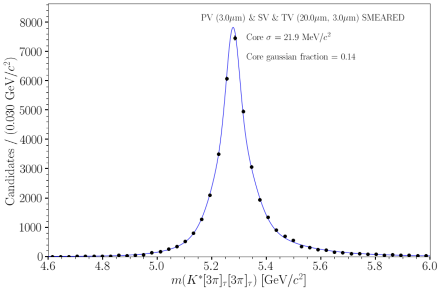


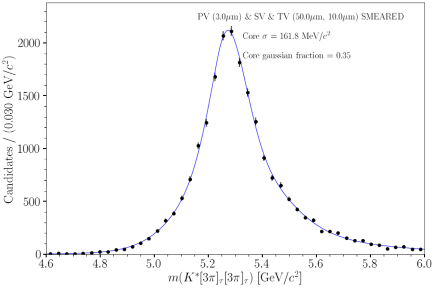
Observable

- B^0 invariant mass.
- Fit : two CrystalBall functions sharing the same Gaussian core and an additionnal Gaussian $\rightarrow$ opportunistic model.
- Fit performed with zfit.

$\Rightarrow$ **investigate vertices resolution impact on efficiencies and RMS.**

Configuration	Reconstruction efficiency	Selection rule efficiency	B^0 mass RMS (MeV)
3 µm (PV), 20 µm – 3 µm (L-T SV&TV)	0.5026 ± 0.0018	0.4959 ± 0.0025	125.58 ± 0.45
3 µm (PV), 50 µm – 10 µm (L-T SV&TV)	0.2760 ± 0.0016	0.3774 ± 0.0033	180.72 ± 0.89





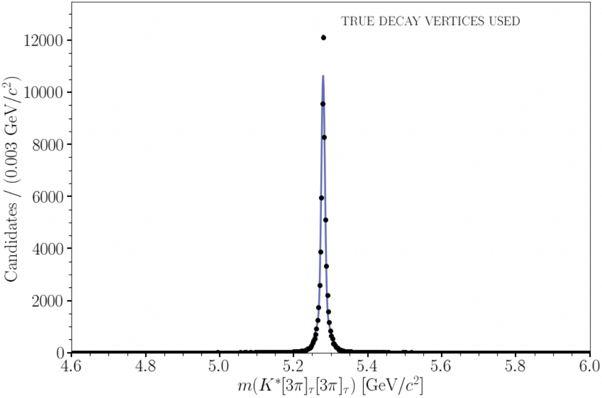
B^0 mass distribution for the correct solution with (left) 20/3 µm resolution (asymptotic goal) and (right) 50/10 µm (less ambitious goal) ⇒ the vertex resolution drives the feasibility of this measurement.

The fit model works fine but can't be used to interpret the performances.

With 3 µm (PV), 20 µm – 3 µm (longitudinal-transverse for SV & TV) :

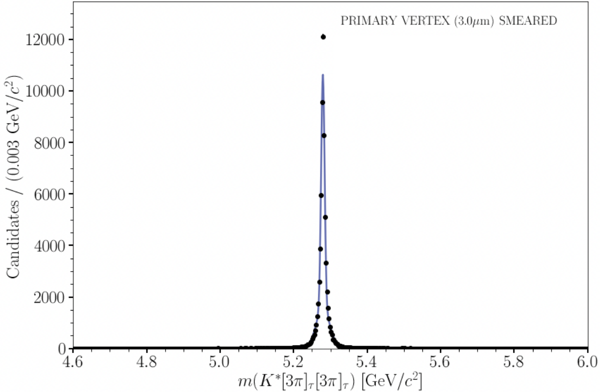
Configuration	Reconstruction efficiency	Selection rule efficiency
PV, SV, TV off	0.8982 ± 0.0011	0.9302 ± 0.0010
PV on / SV, TV off	0.8982 ± 0.0011	0.6970 ± 0.0017
PV, SV on / TV off	0.5641 ± 0.0018	0.5206 ± 0.0024
PV, TV, SV on	0.5002 ± 0.0018	0.4962 ± 0.0025

- When vertices are reconstructed without uncertainties we found the intrinsic performance for this decay.
- Secondary and tertiary vertices → main driver of the overall reconstruction performance.
- Primary vertex → marginal impact on reconstruction.
- Primary vertex → essential for the selection rule.
- If we managed to get these vertex performances reconstruction → reconstruction efficiency is about 50%.

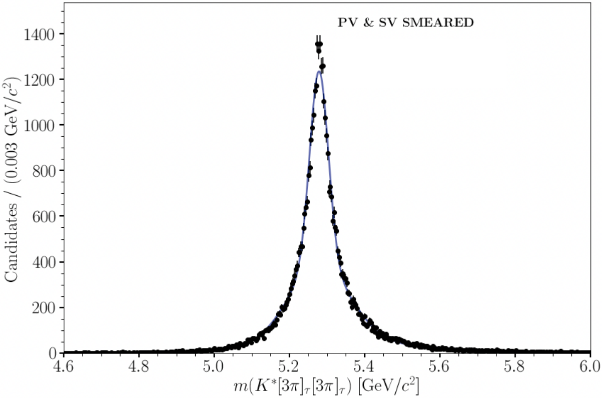


B^0 mass distribution for the correct solution with no vertex smearing.

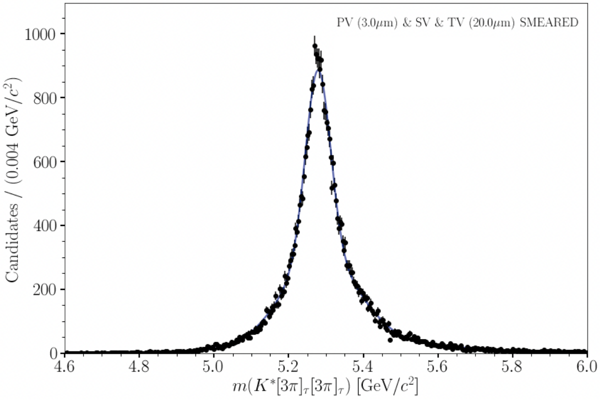
Vertices relative importance



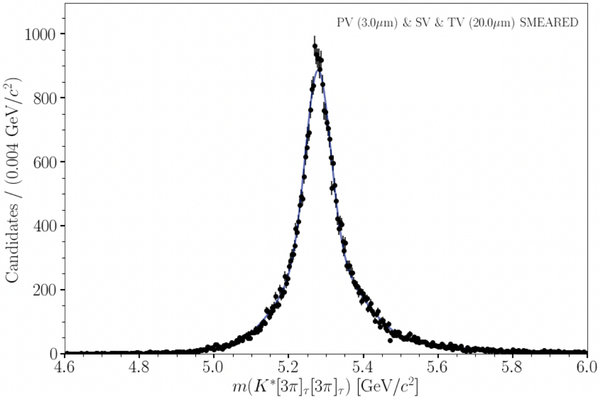
B^0 mass distribution for the correct solution with PV smeared.



B^0 mass distribution for the correct solution with PV and SV smeared.



B^0 mass distribution for the correct solution with all vertices smeared.



B^0 mass distribution for the correct solution with all vertices smeared.

Yield prediction :

$$\mathcal{N}_{K^*\tau\tau\to K\mathbf{7}\pi\mathbf{2}\nu} = \mathcal{N}_Z.BR(Z \to b\bar{b}).2f_d.BR(K^*\tau\tau).BR(\tau \to \pi\pi\pi\nu)^{\mathbf{2}}.BR(K^* \to K\pi).\epsilon_{reco}$$

$$\Rightarrow \mathcal{N}_{K^*\tau\tau\to K7\pi2\nu} \approx 215 \pm 30 \text{ (computation detailed in back-up).}$$

- Intermediate conclusion : reconstruction method has been validated with simulated signal events and provided the building blocks of the resolution performance.
- The next step is to identify the dominant backgrounds and quantify their contribution [15] in order to establish the feasibility of the measurement.
- Relevant backgrounds are the ones with a similar final states ($K7\pi$).
- Note : the 2 dominant backgrounds (in term of visible BF and number of additional missing particle) are generated (thanks to Emmanuel and Clement).

$\Rightarrow$ Build a table of the possible backgrounds with the visible BF and the list of additional missing particle (in addition of the two ν's) for each of them.

Decay	BF (SM/meas.)	Intermediate decay	Visible BF	Additional missing particles
Signal : $B^0 \to K^* \tau\tau$	1.30×10^{-7}	$\tau \to \pi\pi\pi\nu$, $K^* \to K\pi$	9.57×10^{-11}	
Backgrounds $b \to c\bar{c}s$:				
$B^0 \to K^{*0} D_s D_s$	2.15×10^{-4}	$D_s \to \tau\nu$ [i]	4.75×10^{-10}	2ν [ii]
		$D_s \to \tau\nu, \pi\pi\pi\pi^0$	1.74×10^{-9}	ν , π^0
		$D_s \to \pi\pi\pi\pi^0$ [i]	6.38×10^{-9}	$2\pi^0$,
		$D_s \to \pi\pi\pi 2\pi^0$ [iii iv]	1.04×10^{-6}	$4\pi^0$,
$B^0 \to K^{*0} D_s D_s^*$	6.8×10^{-4}	$D_s \to \tau\nu$	1.50×10^{-9}	2ν, γ/π^0
		$D_s \to \tau\nu, \pi\pi\pi\pi^0$	5.51×10^{-9}	ν , π^0, γ/π^0
		$D_s \to \pi\pi\pi\pi^0$ [iv]	2.02×10^{-8}	$2\pi^0$, γ/π^0
$B^0 \to K^{*0} D_s^* D_s^*$	7.05×10^{-4}	$D_s \to \tau\nu$	1.56×10^{-9}	2ν, $2\gamma/\pi^0$
		$D_s \to \tau\nu, \pi\pi\pi\pi^0$	5.71×10^{-9}	ν , π^0, $2\gamma/\pi^0$
		$D_s \to \pi\pi\pi\pi^0$ [iv]	2.09×10^{-8}	$2\pi^0$, $2\gamma/\pi^0$
Backgrounds $b \to c\tau\nu$:				
$B_s \to K^{*0} D\tau\nu$	1.44×10^{-4}	$D \to \pi\pi\pi\pi^0$	3.25×10^{-9}	ν, π^0
$B_s \to K^{*0} D^*\tau\nu$	3.16×10^{-4}	$D^* \to D^0\pi, D\pi^0$		
		$D \to \pi\pi\pi\pi^0$	2.18×10^{-9}	ν, $2\pi^0$
		$D^0 \to 2\pi 2\pi\pi^0$	1.74×10^{-9}	ν, $2\pi^0$, $2\pi^\pm$
$B^0 \to K^{*0} D_s\tau\nu$	9.40×10^{-6}	$D_s \to \tau\nu$	3.79×10^{-10}	2ν [ii]
		$D_s \to \pi\pi\pi\pi^0$	1.39×10^{-9}	ν, π^0
$B^0 \to K^{*0} D_s^*\tau\nu$	2.06×10^{-5}	$D_s \to \tau\nu$	8.31×10^{-10}	2ν, γ/π^0
		$D_s \to \pi\pi\pi\pi^0$	3.05×10^{-9}	ν, π^0, γ/π^0

i. The generated backgrounds.
ii. Not totally irreducible due to additional missing neutrinos or lifetimes.
iii. Displayed one times but can be considered in place of each $D_s \to \pi\pi\pi\pi^0$.
iv. Additional missing particles takes some of the energy → reconstruction efficiency is small.

Data	Reconstruction 20 − 3	Reconstruction 50 − 10
Signal	0.5026 ± 0.0018	0.2760 ± 0.0016
$D_s \to \tau\nu$	0.6056 ± 0.0017	0.4943 ± 0.0018
$D_s \to \pi\pi\pi\pi^0$	0.0817 ± 0.0010	0.0694 ± 0.0009

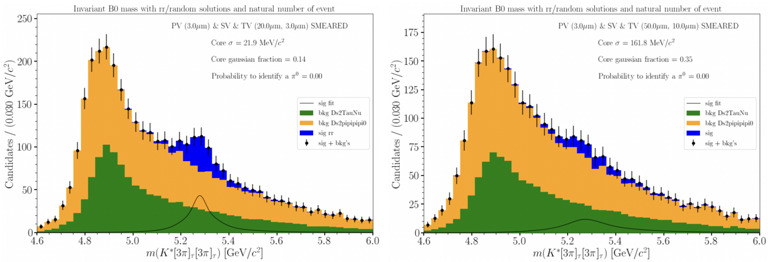


Figure – Stacked signal + backgrounds histograms with 20 − 3µm as smearing (left) and 50 − 10µm (right). The true solutions is taken for signal and a random one for backgrounds.

⇒ Clear peak with 20 − 3 but with MC truth solution selection.

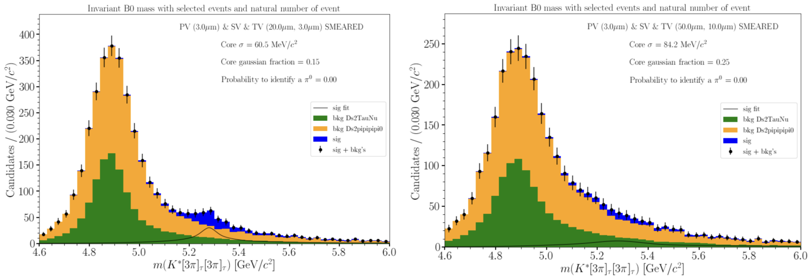


Figure – Stacked signal + backgrounds histograms with 20 − 3μm as smearing (left) and 50 − 10μm (right). The selected (by selection rule) solutions are taken for signal and backgrounds.

The peak remains when applying the selection rule. Note that the tails for backgrounds are reduced by the selection rule. ⇒ Selection rule help for backgrounds resolution !

$D_s \to \pi\pi\pi\pi^0$

- Backgrounds could be reducible.
- The calorimeter must allow the identification of the π^0's in the final state.
- With established performances : 50% of π^0 could be identified.
- If at least one π^0 is associated to a TV, the event will be rejected.
- It will remain $(1 - p_{id\ \pi^0})^2$ fraction of the initial bkg.

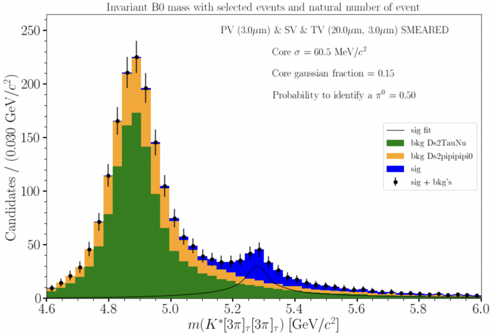


Figure – Stacked histograms 20 − 3 with 75% of $D_s \to \pi\pi\pi\pi^0$ rejected.

$D_s \to \pi\pi\pi\pi^0$

- Backgrounds could be reducible.
- The calorimeter must allow the identification of the π^0's in the final state.
- With more optimistic performances : 80% of π^0 could be identified.
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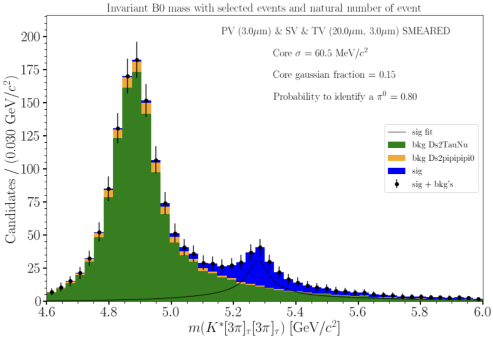

Figure – Stacked histograms 20 – 3 with 96% of $D_s \to \pi\pi\pi\pi^0$ rejected.

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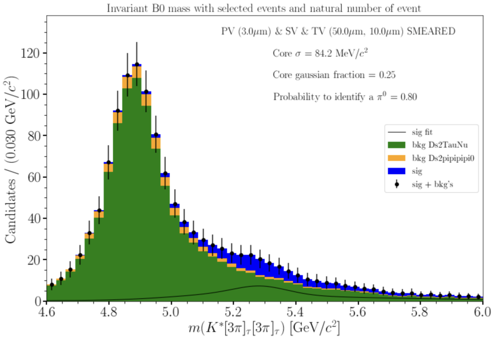

Figure – Stacked histograms 50 – 10 with 96% of $D_s \to \pi\pi\pi\pi^0$ rejected.

$\Rightarrow$ 75% of $D_s \to \pi\pi\pi\pi^0$ background could be rejected by a calorimeter with established performances. The measurement seems possible even with 50 – 10.

Conclusion

- Simulation of arbitrarily good vertex resolutions :
  - The transverse vertex resolution is the main driver of the overall performance (previous presentations),
  - Secondary and tertiary vertices are the lever arms of the reconstruction.
- Identification of the backgrounds : large (by order(s) of magnitude) w.r.t. signal
- The reconstruction and the selection rule allow to select signal with the emulated performance of the vertex detector.
- Further discrimination can be obtain to remove backgrounds in particular $D_s \to 3 - prongs$.

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Outlook

- Studying cuts to discriminate $D_s \rightarrow \tau\nu$ backgrounds (impact parameter, lifetime, ...).
- Introducing actual vertexing performance for the PV (selection rule).
- Several backgrounds to be added to for completeness.
- Find a better model to fit the distribution and interpret the performances.
- Confront this to actual vertexing performances.

The knowledge of the reconstruction efficiency allows us to compute the expected number of B^0 decays fully reconstructed at FCC-*ee* :

$$\mathcal{N}_{K^*\tau\tau\to K7\pi2\nu} = \mathcal{N}_Z.BR(Z \to b\bar{b}).2f_d.BR(K^*\tau\tau).BR(\tau \to \pi\pi\pi\nu)^2.BR(K^* \to K\pi).\epsilon_{reco}$$

Where :

- $\mathcal{N}_Z = 5 \times 10^{12}$ the expected number of Z produced,
- $BR(Z \to b\bar{b}) = 0.1512 \pm 0.0005$,
- $f_d = 0.407 \pm 0.007$ the hadronisation term,
- $BR(K^*\tau\tau) = 1.30 \times 10^{-7} \pm 10\%$ the SM predicted branching fraction,
- $BR(\tau \to \pi\pi\pi\nu) = 0.0931 \pm 0.0005$,
- $BR(K^* \to K\pi) = 0.69$,
- $\epsilon_{reco} = 0.4459$ $(0.8871 \pm 0.0011 \times 0.5026 \pm 0.0018)$ for a smearing $3\,\mu\text{m}/20\,\mu\text{m}$,

$$\Rightarrow \mathcal{N}_{K^*\tau\tau\to K7\pi2\nu} \approx 215 \pm 30.$$

Note : could be improved a bit by taking in addition other channels for τ : $\tau \to \pi\pi\pi\pi^0\nu$ for example $\to$ potential factor two.

- With our previous exploration we seen that several B^0 have not flying (with $FD = 0$).

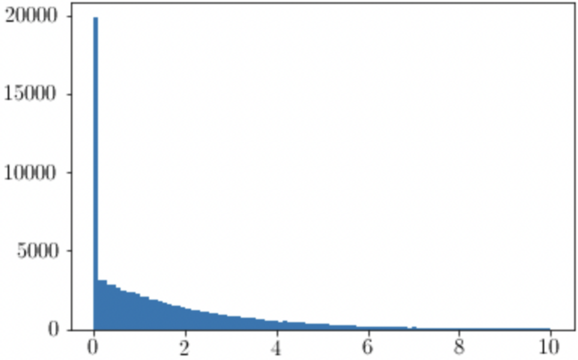
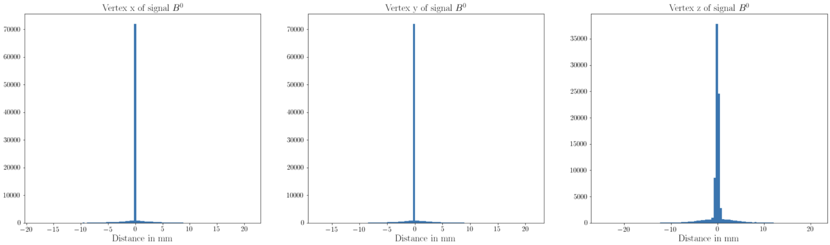


Figure – B^0 flight distance distribution in mm

$\Rightarrow$ Solved : there is $B^0 - \bar{B}^0$ mixing and the production vertex gives to the second particles is the decay vertex of the system (at SV).

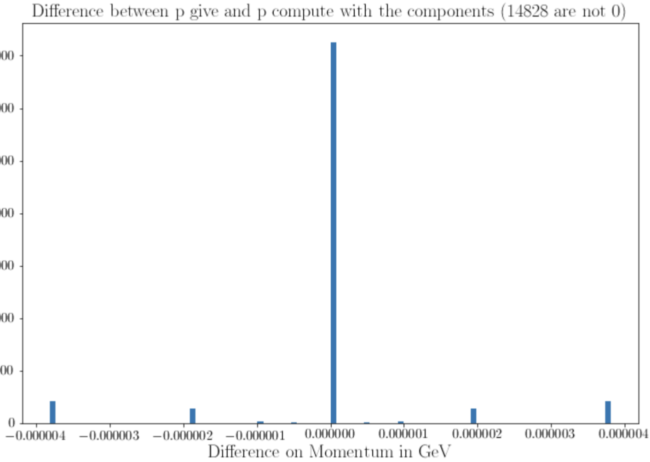
- We are expecting a gaussian distribution for the PV position which are milimetric on z (beam direction), and smaller (μ or n-metric) on x and y.
- In fact we have these regimes but each of them come with a centimetric regime in addition.



$\Rightarrow$ Solved : the PV of $B^0 - \bar{B}^0$ mixing system is fixed at the SV. We take the authentic PV as PV for each event.

- There is some bad mass attribution in our RP data (K with a π mass for example) $\rightarrow$ we modified that.
- There is some charged 0 $\pi^{\pm}$ or $K^{\pm}$ in our RP data $\rightarrow$ we cut them for the $\pi^{\pm}$ or $K^{\pm}$ reconstructions.

- By computing $\sqrt{p_x^2 + p_y^2 + p_z^2} - p$ for signal B^0, π and k we seen that a rounding are in the game (B^0 as example below).



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