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

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- Study of the rare heavy-flavoured decay $B^0 \to K^* \tau^+ \tau^-$ at FCC-*ee*
- Which one is not observed due to a weak SM prediction branching fraction $\mathcal{O}(10^{-7})$
- Electroweak penguin decay process
- Use of a specific channels : $\tau \to \pi\pi\pi\nu$ and $K^* \to K\pi$
- 10 particles in final states $(K, 7\pi, \nu, \bar{\nu})$
- 2 neutrinos which are not detected
- Goal : explore the feasability of the measurement and give the requirements on a detector to study $B^0 \to K^* \tau^+ \tau^-$

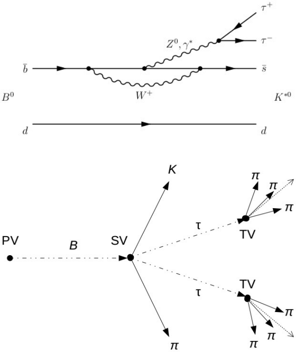


Figure – Quark-level transition and decay topology

To fully reconstruct the B invariant-mass we need :

- Momentum of all final particles (including neutrinos)
- The knowledge of the decay lengths together with the tau mass can be used to determine the missing coordinates
- We use energy-momentum conservation at tertiary (or τ decay) vertex with respect to τ direction

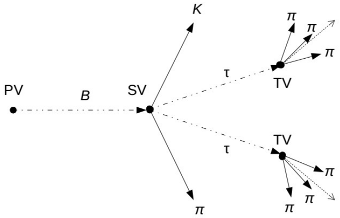


Figure – The dotted lines represent the non-reconstructed particles. The plain lines are the particles that can be reconstructed in the detector.

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

There is a quadratic ambiguity on each neutrinos momentum's !

$\rightarrow$ The ambiguities propagate to tau and B reconstruction

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

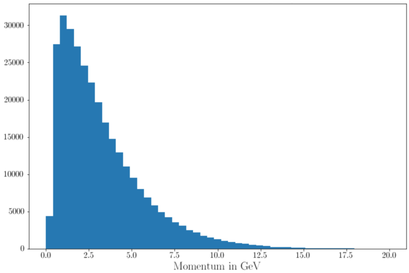
$\Rightarrow$ A selection rule is needed to choose the right possibility

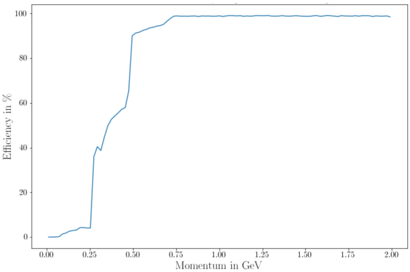
$\longrightarrow$ From the energy-momentum conservation for B decay, we have a condition between our 2 tau's and the K^* with respect to the B direction

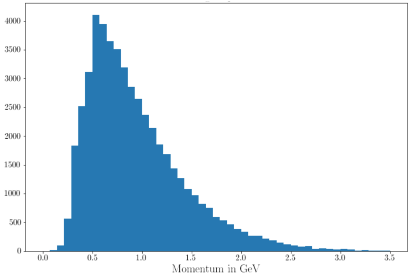
$$p_{\tau^+_-} = -\frac{\vec{p}^{\perp}_{K*}.\vec{e}_{\tau^+_-}}{1-(\vec{e}_{\tau^+_-}.\vec{e}_B)^2} - p_{\tau^-_+}.\frac{\vec{e}_{\tau^+_-}.\vec{e}_{\tau^-_+} - (\vec{e}_{\tau^+_-}.\vec{e}_B)(\vec{e}_{\tau^-_+}.\vec{e}_B)}{1-(\vec{e}_{\tau^+_-}.\vec{e}_B)^2}$$

Efficiency to reconstruct the final state tracks by combination

- 100000 events are generated (Pythia, EvtGen) for $B^0 \to K^* \tau^+ \tau^- \Rightarrow$ at least 100000 B^0 are expected
- Momentum resolution (FCC IDEA, Delphes) $\to$ not all the charged particles of the signal final state can be reconstructed
- The efficiency drops at low momenta
- Average momentum of the charge final state particles is modest because of the large multiplicity of the signal decay
- The minimum momentum of the pions from tau particles is less than a GeV

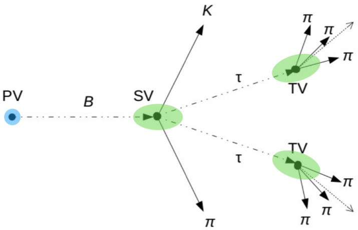






$\Rightarrow$ **almost 50% of B^0 reconstructed**

- No vertex resolution → use of a smearing to simulate a resolution effect on the vertices
- PV : 3D normal law of 3 μm width (conveniently)
- SV & TV → ellipsoid (decaying particle direction as reference) :
  - longitudinal
  - transverse
- Investigate those resolution impact on several quantities
- Fixed resolution taken with reference normal law



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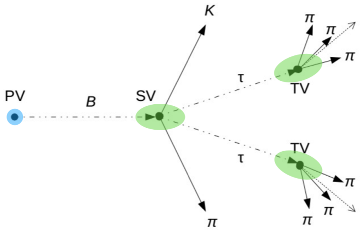
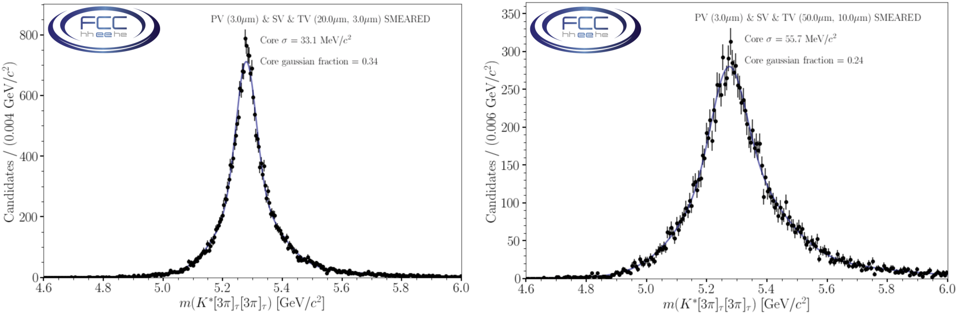


Observable

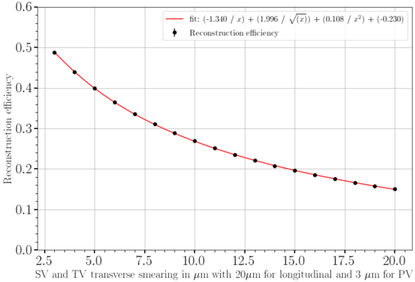
- B^0 invariant mass
- Fit : Opportunistic three-Gaussian function model
- Fit performed with zfit

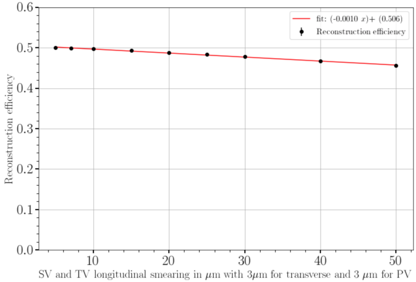
⇒ investigate vertices resolution impact on efficiencies, RMS and model

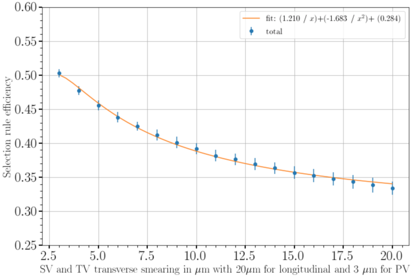


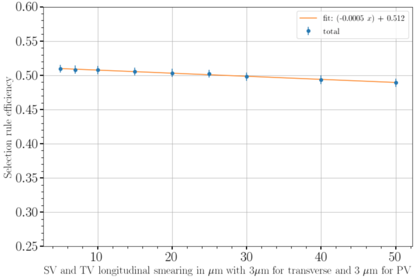
B^0 mass distribution for the correct solution with (left) 20/3 μm **resolution (asymptotic goal) and (right)** 50/10 μm **(less ambitious goal) $\Rightarrow$ vertex resolution is probably the most demanding requirement on the detector**

Reconstruction and selection rule efficiencies









Reconstruction efficiency

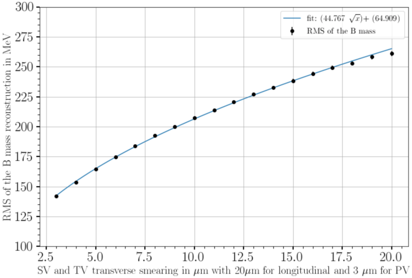
- Top left as function of transverse smearing and top right as function of longitudinal smearing
- Maximum of 50%
- Strong dependence with transverse smearing :
  - fall of 35%
  - fit with 4 free parameter
- Weak dependence with longitudinal smearing :
  - fall of 5%
  - linear fit
- 60 pseudo-experiments are used

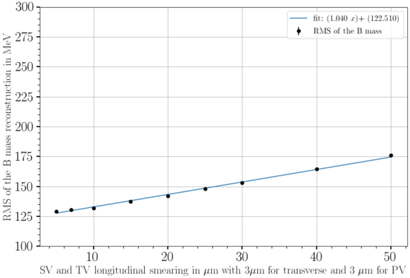
Selection rule efficiency

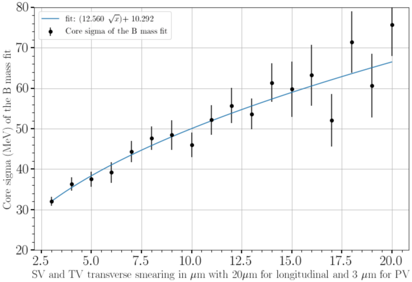
- Bottom left as function of transverse smearing and bottom right as function of longitudinal smearing
- Maximum of 50%
- Strong dependence with transverse smearing :
  - fall of 16%
  - fit with 3 free parameter
- Weak dependence with longitudinal smearing :
  - fall of 2%
  - linear fit
- Always a weak efficiency $\rightarrow$ use the truth right right solution in the following

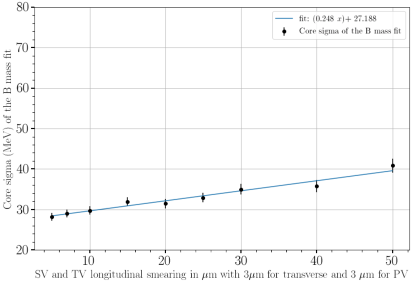
$\Rightarrow$ **transverse resolution has more impact than longitudinal resolution**

RMS and fit of the B^0 mass reconstruction









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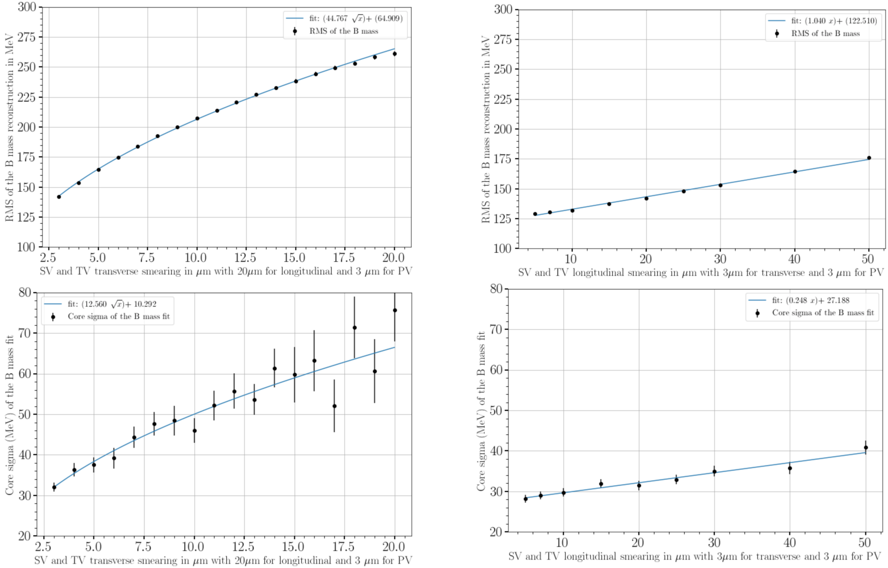


$\Rightarrow$ **transverse resolution is the key parameter !**

RMS

- Top left as function of transverse smearing and top right as function of longitudinal smearing
- RMS is a characteristic quantity of the distribution, in dependant to any fit
- Strong dependence with transverse smearing :
  - increase of 150 MeV
  - square root fit
- Weak dependence with longitudinal smearing :
  - increase of 50 MeV
  - linear fit

Core sigma

- Bottom left as function of transverse smearing and bottom right as function of longitudinal smearing
- Sigma of the narrower Gaussian of the model
- Strong dependence with transverse smearing :
  - increase of 50 MeV
  - square root fit
- Weak dependence with longitudinal smearing :
  - increase of 10 MeV
  - linear fit
- Big uncertainties because 10 pseudo-experiments are used

$\Rightarrow$ **transverse resolution is the key parameter !**

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

Configuration	Reconstruction efficiency (%)	Selection rule efficiency (%)	B^0 mass RMS (MeV)	Fit core sigma (MeV)
PV, SV, TV off	87.31 ± 0.15	93.56 ± 0.12	16.66 ± 0.06	4.23 ± 0.09
PV on / SV, TV off	87.31 ± 0.15	69.51 ± 0.22	16.66 ± 0.06	4.23 ± 0.09
PV, SV on / TV off	55.51 ± 0.22	56.13 ± 0.30	123.42 ± 0.52	25.75 ± 0.80
PV, TV on / SV off	57.23 ± 0.22	66.51 ± 0.28	112 ± 0.47	22.62 ± 0.60

- Secondary vertex → main driver of the overall performance
- Primary vertex → marginal impact

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

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

Where :

- $\mathcal{N}_Z = 5 \times 10^{12}$ the expected number of Z produced
- $BR(Z \to b\bar{b}) = 0.1512$
- $f_d = 0.43$ the hadronisation term
- $BR(K^*\tau\tau) = 1.30 \times 10^{-7}$ the SM predicted branching fraction
- $BR(\tau \to \pi\pi\pi\nu) = 9.31 \times 10^{-2}$
- $BR(K^* \to K\pi) = 0.69$
- $\epsilon_{reco} = 0.25$ (0.5×0.5) for a smearing $3\,\mu m/20\,\mu m$

$$\Rightarrow \mathcal{N}_{K^*\tau\tau\to K7\pi 2\nu} \approx 130$$

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

- Signal event $B^0 \to K^* \tau^+ \tau^-$ necessary to validate reconstruction method and provides building blocks of the resolution performance
- Goal : showing that dominant backgrounds could be rejected
- The reconstruction leads to search the final state : $K7\pi$
- Relevant backgrounds are the ones with a similar final states

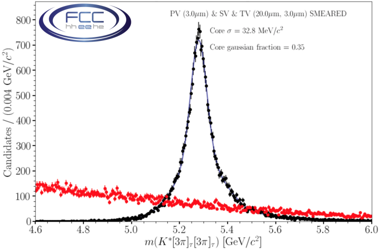
Next step $\Rightarrow$ build a table of the possible backgrounds with the visible BF and the list of additional missing particle (in addition of the two ν's) for each of them

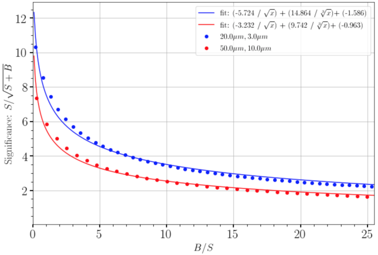
Decay	BF (SM/meas.)	Intermediate decay	Visible BF	Additional missing particles
Decay mode : $B^0 \to K^*\tau\tau$	1.30×10^{-7}	$\tau \to \pi\pi\pi\nu,\ K^* \to K\pi$	1.01×10^{-10}	
Backgrounds $b \to c\bar{c}s$: $B^0 \to K^{*0} D_s^{(*)} D_s^{(*)}$	1.6×10^{-3}	$D_s \to \tau\nu$ $D_s \to \tau\nu, \pi\pi\pi n\pi^0$ $D_s \to \pi\pi\pi n\pi^0$	3.64×10^{-9} 1.62×10^{-7} 7.21×10^{-6}	2ν, $(2\gamma/\pi^0)$ ν , $n\pi^0$, $(2\gamma/\pi^0)$ $2n\pi^0$, $(2\gamma/\pi^0)$
Backgrounds $b \to c\tau\nu$: $B_s \to K^{*0} D^{(*)}\tau\nu$	4.6×10^{-4}	$D \to \pi\pi\pi\pi^0$ $D^* \to D^0\pi, D\pi^0$ $D \to \pi\pi\pi\pi^0$ $D^0 \to 2\pi 2\pi\pi^0$	3.50×10^{-9} 2.14×10^{-9} 1.69×10^{-9}	ν, π^0 ν, $2\pi^0$ ν, $2\pi^0$, $2\pi^\pm$
$B^0 \to K^{*0} D_s^{(*)}\tau\nu$	3×10^{-5}	$D_s \to \tau\nu$ $D_s \to \pi\pi\pi n\pi^0$	1.23×10^{-9} 5.47×10^{-8}	2ν, (γ/π^0) ν, $n\pi^0$, (γ/π^0)

- Irreducible backgrounds are in red
- Most of these backgrounds are reducible with π^0 reconstruction in D decays
- Among them $B^0 \to K^{*0} D_s D_s$ with $D_s \to \pi\pi\pi n\pi^0$ is almost 10^5 times bigger than the signal must be considered first
- A priori irreducible backgrounds can be separated from signal by the topological method, thanks to the additional missing particle

Semileptonic background

- Backgrounds test with a semileptonic decay : $B^0 \rightarrow D^{*}\tau\nu$ (where D^{*} is perfectly reconstructed)
- Events available and quickly usable in our analysis as a proxy
- Clear separation of invariant mass distribution by topological method but long tails under signals
- How does vertex resolution act on the separation of the two : study of the significance of the signal peak comparing to the backgrounds for two resolution configuration
- Next step : realised the actual study in order with proper normalisation





Final goal : Simulation of the actual backgrounds and analysis of the events with the topological method

Conclusion

- Revisitation with a latest FCC sw of the proof of principle of the topological reconstruction
- Simulation of arbitrarily good vertex resolutions
- The transverse vertex resolution is the main driver of the overall performance
- The secondary vertex is the lever arm of the reconstruction
- Backgrounds are large (by order(s) of magnitude) w.r.t. signal

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Outlook

- Simulation of the main backgrounds
- Examine the selection rule
- Proof of principle of the measurement