Feasibility study of $B^0 \to K^{*0}\tau\tau$ at FCC-*ee*

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- Third generation couplings in quark transitions are the less-well known.
- Specific models addressing the Flavour problem(s) often provide $b \to \tau$ enhancements or modifications w.r.t. the SM $\Rightarrow b \to s\tau\tau$ ($m_\tau \sim 20 m_\mu$) is a must do to sort out the BSM models [1, 2]. Problem : measuring the ν's.
- Study of the rare heavy-flavoured decay $B^0 \to K^* \tau^+ \tau^-$[3]. SM prediction : BR=$\mathcal{O}(10^{-7})$ $\to$ not observed yet (present limit : $\mathcal{O}(10^{-3} - 10^{-4})$ [4]).
- Work focused on the 3-prongs τ 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.

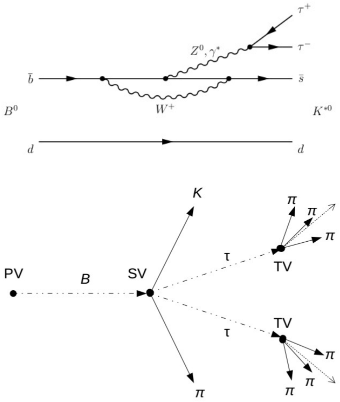


Figure – EW penguin quark-level transition and $B^0 \to K^{*0}\tau\tau$ with $\tau \to \pi\pi\pi\nu$ decay topology.

- The Future Circular Collider is a collider project at CERN as successor of HL-LHC.
- Circumference : about 91 km.
- FCC-*ee* is the first phase of the project with *ee* collision.
- 4 interaction points in the FCC-*ee* baseline and 4 data taking years at the Z pole $\to N_Z = 6 \times 10^{12}$.
- FCC-*ee* : combined clear experimental environment (like B-factories), boosted b hadrons (like *LHC*) and a high Z bosons statistic $\Rightarrow$ it looks like the right place to reconstruct the ν's and to study $B^0 \to K^{*0}\tau\tau$.

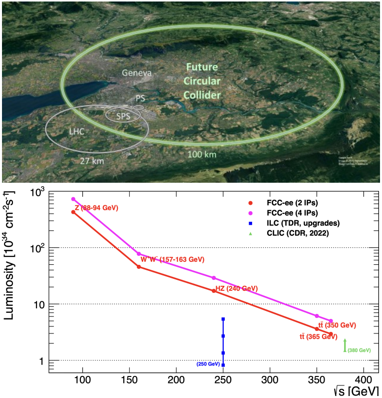


Figure – FCC plan and FCC-*ee* comparison in term of luminosity comparing to other projects.

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

- To fully reconstruct the kinematics of the decay $\rightarrow$ neutrinos momenta must be resolved.
- Enough constraints are available in order to determine the missing coordinates.
- Energy momentum conservation at τ decay vertex $\Rightarrow$ gives the neutrino momentum at the cost of a quadratic ambiguity :

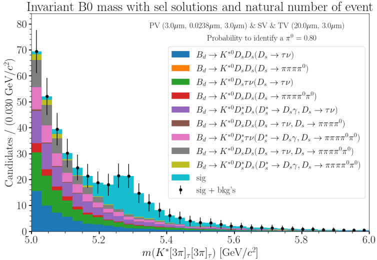
$$\begin{cases} p^{\perp}_{\nu_\tau} = -p^{\perp}_{\pi_t} \\ p^{\parallel}_{\nu_\tau} = \dfrac{((m^2_\tau - m^2_{\pi_t}) - 2p^{\perp,2}_{\pi_t})}{2(p^{\perp,2}_{\pi_t} + m^2_{\pi_t})} . p^{\parallel}_{\pi_t} \pm \dfrac{\sqrt{(m^2_\tau - m^2_{\pi_t})^2 - 4m^2_\tau p^{\perp,2}_{\pi_t}}}{2(p^{\perp,2}_{\pi_t}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

- A selection rule has to be build in order to solve the ambiguities.
- Practically energy-momentum conservation at the B decay vertex gives a condition between τ's and K^* :

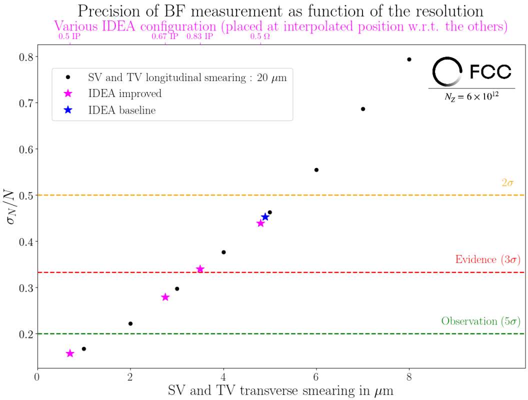
$$p_{\tau^+_-} = -\frac{\vec{p}^{\perp}_{K*} . \vec{e}_{\tau^+_-}}{1 - (\vec{e}_{\tau^+_-} . \vec{e}_B)^2} - p_{\tau^-_+} . \frac{\vec{e}_{\tau^+_-} . \vec{e}_{\tau^-_+} - (\vec{e}_{\tau^+_-} . \vec{e}_B)(\vec{e}_{\tau^-_+} . \vec{e}_B)}{1 - (\vec{e}_{\tau^+_-} . \vec{e}_B)^2}$$

- Method validated at MC truth level.

- Main backgrounds (similar final state to the signal) have been considered.
- XGBoost [5] selection applied in order to discriminate the backgrounds.
- Precision on the BF measurement extracted for several vertexing performance emulations from a fit to the reconstructed B^0 invariant mass.



Decay	BF (SM/meas.)	Intermediate decay	BF_had	Additional missing particles
Backgrounds $b \to c\bar{c}s$:				
$B^0 \to K^{*0} D_s D_s$	2.78×10^{-4}	$D_s \to \tau\nu$	5.79×10^{-10}	2ν
		$D_s \to \tau\nu, \pi\pi\pi\pi^0$	6.52×10^{-10}	ν , π^0
		$D_s \to \pi\pi\pi\pi^0$	7.35×10^{-10}	$2\pi^0$,
		$D_s \to \tau\nu, \pi\pi\pi\pi^0\pi^0$	5.47×10^{-9}	ν , $2\pi^0$
		$D_s \to \pi\pi\pi 2\pi^0$	5.17×10^{-8}	$4\pi^0$,
$B^0 \to K^{*0} D_s D_s^*$	8.78×10^{-4}	$D_s \to \tau\nu$	1.83×10^{-9}	2ν, γ/π^0
		$D_s \to \pi\pi\pi\pi^0\pi^0$	1.63×10^{-7}	$4\pi^0$, γ/π^0
Backgrounds $b \to c\tau\nu$:				
$B^0 \to K^{*0} D_s \tau\nu$	9.17×10^{-6}	$D_s \to \tau\nu$	3.59×10^{-10}	2ν
$B^0 \to K^{*0} D_s^* \tau\nu$	2.03×10^{-5}	$D_s \to \pi\pi\pi\pi^0\pi^0$	7.51×10^{-9}	ν, γ, $2\pi^0$



- Hint of the signal with the state-of-the-art vertex detector (IDEA[6]).
- Improvement of the Impact Parameters measurement or on luminosity can improve the picture.
- On the other hand, considering leptonic τ decays improve the statistic $\rightarrow$ requires other methods for the reconstruction.

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 [i].

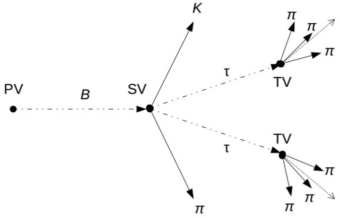


Figure – The dotted lines represent the non-reconstructed particles. The plain lines are the particles that can be reconstructed in the detector.

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

i. Another way to do this computation is given by [7].

There is a quadratic ambiguity on each neutrino momentum !

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

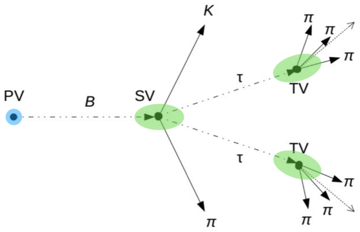
$\rightarrow$ 4 possibilities by taking all +/- combination for the two neutrinos

$\Rightarrow$ 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 :

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

- Signal and dominant backgrounds generated with Pythia [8] and EvtGen [9].
- Reconstruction is performed with the FCC Analyses sw using Delphes [10] simulation featuring the IDEA [6] detector.
- Particles reconstruted with IDEA momentum resolution.
- To investigate vertexing detector requirements → secondary vertexing resolution working points emulated along longitudinal and transverse directions to the decaying particles w.r.t. expectations and IDEA baseline.
- XGBoost [5] selection applied in order to discriminate the backgrounds.
- Precision on the BF measurement extracted for each working point via a fit to the reconstructed B^0 mass.



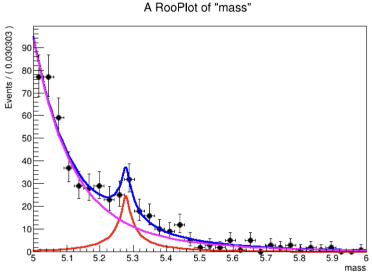


Figure – Vertexing performances emulation and mass fit example.

- The relevant backgrounds are the ones with a similar final state than the signal ($K7\pi$).
- Several possible modes in $b \to c\bar{c}s$ and $b \to c\tau\nu$ transitions [ii] but often not observed to date $\Rightarrow$ guesstimate of the branching fraction from phase space computation and use of analogies.
- Determination of the dominant backgrounds for the measurement by building per track efficiencies from already generated ones.

Decay	BF (SM/meas.)	Intermediate decay	BF_had	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 $b \to c\bar{c}s$:				
$B^0 \to K^{*0}D_sD_s$	2.78×10^{-4}	$D_s \to \tau\nu$	5.79×10^{-10}	2ν
		$D_s \to \tau\nu, \pi\pi\pi\pi^0$	6.52×10^{-10}	ν , π^0
		$D_s \to \pi\pi\pi\pi^0$	7.35×10^{-10}	$2\pi^0$,
		$D_s \to \tau\nu, \pi\pi\pi\pi^0\pi^0$	5.47×10^{-9}	ν , $2\pi^0$
		$D_s \to \pi\pi\pi 2\pi^0$	5.17×10^{-8}	$4\pi^0$,
$B^0 \to K^{*0}D_sD_s^*$	8.78×10^{-4}	$D_s \to \tau\nu$	1.83×10^{-9}	2ν, γ/π^0
		$D_s \to \pi\pi\pi\pi^0\pi^0$	1.63×10^{-7}	$4\pi^0$, γ/π^0
Backgrounds $b \to c\tau\nu$:				
$B^0 \to K^{*0}D_s\tau\nu$	9.17×10^{-6}	$D_s \to \tau\nu$	3.59×10^{-10}	2ν
$B^0 \to K^{*0}D_s^*\tau\nu$	2.03×10^{-5}	$D_s \to \pi\pi\pi\pi^0\pi^0$	7.51×10^{-9}	$\nu, \gamma, 2\pi^0$

ii. **More details on backgrounds choices in appendix.**

Extended background table

Decay	BF (SM/meas.)	Intermediate decay	BF_had	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 $b \to c\bar{c}s$:				
$B^0 \to K^{*0} D_s D_s$	2.78×10^{-4}	$D_s \to \tau\nu$	5.79×10^{-10}	2ν
		$D_s \to \tau\nu, \pi\pi\pi\pi^0$ iii	6.52×10^{-10}	ν , π^0
		$D_s \to \pi\pi\pi\pi^0$ iii	7.35×10^{-10}	$2\pi^0$,
		$D_s \to \tau\nu, \pi\pi\pi\pi^0\pi^0$	5.47×10^{-9}	ν , $2\pi^0$
		$D_s \to \pi\pi\pi 2\pi^0$ iii	5.17×10^{-8}	$4\pi^0$,
$B^0 \to K^{*0} D_s D_s^*$	8.78×10^{-4}	$D_s \to \tau\nu$	1.83×10^{-9}	2ν, γ/π^0
		$D_s \to \tau\nu, \pi\pi\pi\pi^0$	2.06×10^{-9}	ν , π^0, γ/π^0
		$D_s \to \pi\pi\pi\pi^0$	2.32×10^{-9}	$2\pi^0$, γ/π^0
		$D_s \to \pi\pi\pi\pi^0\pi^0$	1.63×10^{-7}	$4\pi^0$, γ/π^0
$B^0 \to K^{*0} D_s^* D_s^*$	9.10×10^{-4}	$D_s \to \tau\nu$	1.90×10^{-9}	2ν, $2\gamma/\pi^0$
		$D_s \to \tau\nu, \pi\pi\pi\pi^0$	2.14×10^{-9}	ν , π^0, $2\gamma/\pi^0$
		$D_s \to \pi\pi\pi\pi^0$	2.41×10^{-9}	$2\pi^0$, $2\gamma/\pi^0$
Backgrounds $b \to c\tau\nu$:				
$B_s \to K^{*0} D\tau\nu$	7.27×10^{-5}	$D \to \pi\pi\pi\pi^0$	1.65×10^{-9}	ν, π^0
$B_s \to K^{*0} D^*\tau\nu$	2.03×10^{-4}	$D^* \to D^0\pi, D\pi^0$		
		$D \to \pi\pi\pi\pi^0$	1.12×10^{-9}	ν, $2\pi^0$
		$D^0 \to 2\pi 2\pi\pi^0$	8.98×10^{-10}	ν, $2\pi^0$, $2\pi^\pm$
$B^0 \to K^{*0} D_s\tau\nu$	9.17×10^{-6}	$D_s \to \tau\nu$	3.68×10^{-10}	2ν
		$D_s \to \pi\pi\pi\pi^0$	4.15×10^{-10}	ν, π^0
$B^0 \to K^{*0} D_s^*\tau\nu$	2.03×10^{-5}	$D_s \to \tau\nu$	8.07×10^{-10}	2ν, γ/π^0
		$D_s \to \pi\pi\pi\pi^0$	9.09×10^{-10}	ν, π^0, γ/π^0
		$D_s \to \pi\pi\pi\pi^0\pi^0$	7.51×10^{-9}	ν, γ, $2\pi^0$

iii. $D_s \to 3\pi n\pi^0$ modes involves η/ω intermediate states (see appendix).

- $B^0 \to K^{*0} D_s D_s$ from analogy game :

$$BF(B^0 \to K^{*0} D_s D_s) = BF(B^0 \to D D_s) \times \frac{BF(B^0 \to D_s \pi K^0)}{BF(B^0 \to D\pi)}$$

  where $B^0 \to D D_s$ is the equivalent mode without $s\bar{s}$ from vaccum, $B^0 \to D\pi$ is the equivalent mode without $s\bar{s}$ from vaccum and with $W \to \bar{u}d$, $B^0 \to D_s \pi K^0$ is the equivalent mode with $W \to \bar{u}d$.
- $B^0 \to K^{*0} D_s^* D_s$ and $B^0 \to K^{*0} D_s^* D_s^*$ w.r.t. $B^0 \to K^{*0} D_s D_s$ from $B_s^0 \to D_s^{(*)} D_s^{(*)}$ hierarchy.
- $B^0 \to K^{*0} D_s^{(*)} \tau\nu$ from analogy via phase space computation[7] :

$$BF(B^0 \to K^{*0} D_s^{(*)} \tau\nu) = BF(B^+ \to K D_s^{(*)} \ell\nu) \times \frac{PS(B^0 \to K^{*0} D_s^{(*)} \tau\nu)}{PS(B^+ \to K D_s^{(*)} \ell\nu)}$$

  where PS denotes the Phase Space computed numerricaly (three body decay hypothesis used conservatively) and $B^+ \to K D_s^{(*)} \ell\nu$ is a reference mode with a known BF.
- $B^0 \to K^{*0} D_s \tau\nu$ and $B^0 \to K^{*0} D_s^* \tau\nu$ w.r.t $B^0 \to K^{*0} D_s^{(*)} \tau\nu$ from $B^0 \to D^{(*)} \ell\nu$ hierarchy.

- $B_s^0 \to K^{*0} D^{(*)} \tau\nu$ from analogy via phase space computation[7] :

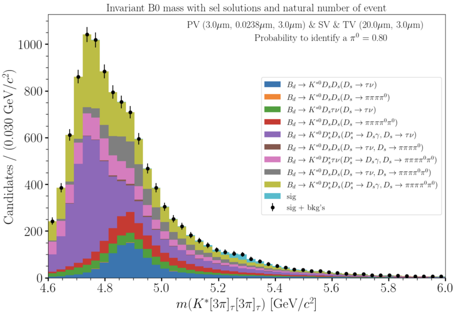
$$BF(B_s^0 \to K^{*0} D^{(*)} \tau\nu) = BF(B_s^0 \to D_{s1} \mu\nu) \times \frac{PS(B_s^0 \to K^{*0} D^{(*)} \tau\nu)}{PS(B_s^0 \to D_{s1} \mu\nu)}$$

  where PS denotes the Phase Space computed numerricaly (three body decay hypothesis used conservatively) and $B_s^0 \to D_{s1} \mu\nu$ is a reference mode with a known BF.
- $B_s^0 \to K^{*0} D \tau\nu$ and $B_s^0 \to K^{*0} D^{*} \tau\nu$ w.r.t. $B_s^0 \to K^{*0} D^{(*)} \tau\nu$ from $B^0 \to D^{(*)} \ell\nu$ hierarchy.

- $B^0 \to K^{*0} D_s D_s$ with the two D_s deacying as $D_s \to \tau\nu$, $D_s \to \pi\pi\pi\pi^0$ and $D_s \to \pi\pi\pi\pi^0\pi^0$ already generated.
- $B^0 \to K^{*0} D_s^* D_s$ with the two D_s deacying as $D_s \to \tau\nu$ already generated.
- $B^0 \to K^{*0} D_s D_s$ with both $D_s \to \tau\nu$ and $D_s \to \pi\pi\pi\pi^0$ already generated.
- Construction of a "per track" efficiency by taking the square root of the reconstruction efficiency of the four first modes $\Rightarrow \epsilon(D_s \to \tau\nu)$, $\epsilon(D_s^* \to \tau\nu)$, $\epsilon(D_s \to \pi\pi\pi\pi^0)$ and $\epsilon(D_s \to \pi\pi\pi\pi^0\pi^0)$.
- Cross check : $\epsilon(D_s \to \tau\nu) \times \epsilon(D_s \to \pi\pi\pi\pi^0) \simeq \epsilon(B^0 \to K^{*0} D_s D_s, D_s \to \tau\nu, D_s \to \pi\pi\pi\pi^0)$.
- Construction of an $\epsilon(*) = \epsilon(D_s^* \to \tau\nu)/\epsilon(D_s \to \tau\nu)$.
- Computation of an estimated efficiency for the possible background from these per track efficiencies.
- Ranking of the backgrounds via $BF \times \epsilon$.
- Choice of the biggest one for each type of specific topology.

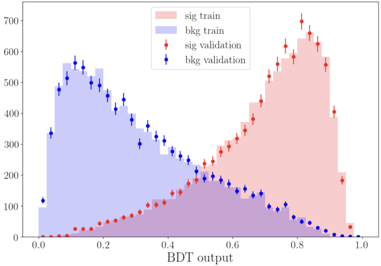
- Several kinematics variables has been save for each events (like momentum or intermediate mass).
- Among them several discriminatives variables have been found [iv].
- The preselection has been built with these variables.
- The plot displays the result after preselection → the picture show a first improvement.
- The MVA can be trained against the backgrounds on the [5,5.6] GeV mass window.

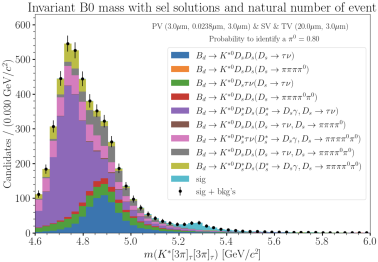
Variable	Cut
$m^2_{2\pi\,min}$ & $m^2_{2\pi\,max}$	<0.3 & <0.5 GeV
p_{K^*}	<1GeV
$p_{3\pi}$	<1GeV
$p_{\pi\,max}$	<0.25GeV
$p_{\pi\,min}$	<0.2GeV
FD_B	<0.3mm
FD_τ	>4mm
$m_{3\pi}$	<0.750GeV
$m_{2\pi\,max}$	<0.5GeV
$m_{2\pi\,min}$	>1GeV



iv. Example of discriminative variables in appendix.

- Training dataset generated with signal and the collection of available backgrounds.
- The backgrounds are considered in natural proportion (after the preselection).
- 50/50 split train/validation.
- Previous variables are given as inputs as well as the reconstructed p_τ of each τ candidate.
- XGB parameters optimised on AUC.
- Overtraining plot in order to check the validity of the training $\rightarrow$ OK.
- Use of the MVA [v] to perform the selection (cut at 0.5 on the BDT output).





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