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

Tristan Miralles

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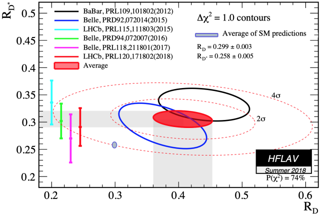
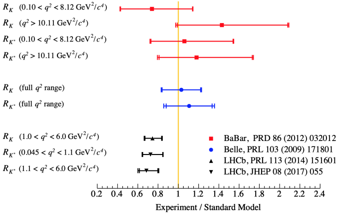
EUPI UNIVERSITÉ Clermont Auvergne
FUTURE CIRCULAR COLLIDER
LPC Particules pLasmas Univers applicationS
Laboratoire de Physique de Clermont

- 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 reported at LHCb and B-factories (BaBaR and BELLE) in particular $b \to s\ell\ell (\ell = e, \mu)$.
- Study of $b \to s\tau\tau$ ($m_\tau \sim 20 m_\mu$) transitions implying particles from third generations, it 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.





$\Rightarrow$ 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[1]. SM prediction : BR=$\mathcal{O}(10^{-7})$.
- Should the current level of the R_D, R_{D^*} anomalies be the natural one some models do predict BR($B^0 \to K^*\tau\tau$) to be several orders of magnitudes larger [2].
- 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 (present limit : $\mathcal{O}(10^{-3} - 10^{-4})$ [3]).

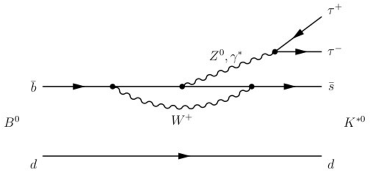


Figure – EW penguin quark-level transition

- The $B^0 \to K^*\tau\tau$ decay topology is driven 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.

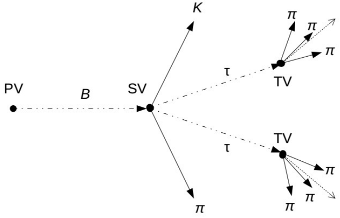


Figure – Decay topology

Goal : explore the feasibility 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 [4] ($Z \to b\bar{b}$ and hadronisation) and EvtGen [5] (forcing the decay to the best of its knowledge).
- 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 [6] simulation (featuring the IDEA [7] detector).
- The simulated data use particles reconstructed 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.
- Uproot is used in this analysis $\to$ thanks to Jim Pivarski for his reactivity with the development.

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].

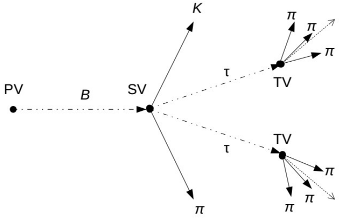


Figure – The dotted lines represent the non-reconstructed particles. The plain lines are the particles that can be reconstructed in the detector.

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

i. Another way to do this computation is given by [8].

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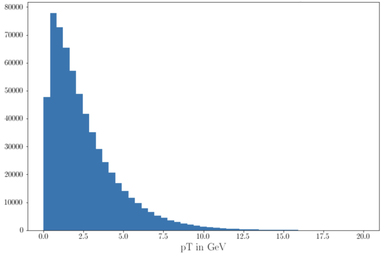
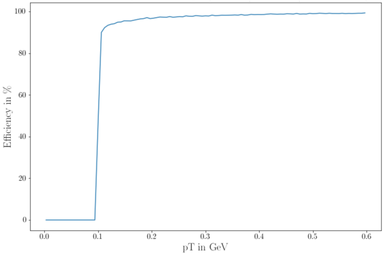
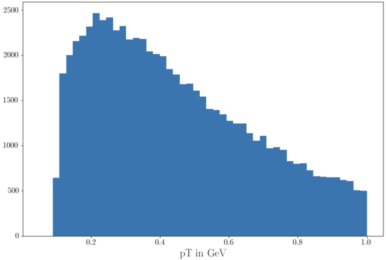
The name of the game is to measure as accurately as possible the decay vertices.

Efficiency to reconstruct the final state tracks by combination

- 100000 events are generated (Pythia, EvtGen) for $B^0 \to K^* \tau^+ \tau^-$.
- 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.

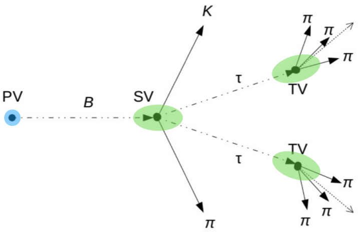






$\Rightarrow$ **about 77% of B^0 reconstructed**

- 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 $\rightarrow$ 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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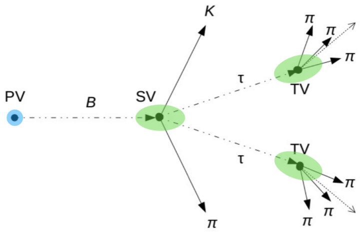
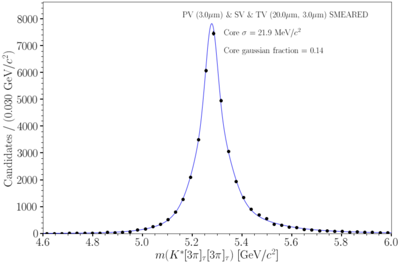


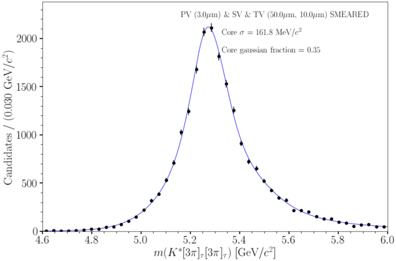
Observable

- 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) : **asymptotic goal**	0.5026 ± 0.0018	0.4959 ± 0.0025	125.58 ± 0.45
3 µm (PV), 50 µm – 10 µm (L-T SV&TV) : **less ambitious goal**	0.2760 ± 0.0016	0.3774 ± 0.0033	180.72 ± 0.89





From $B \to K^*\tau\tau$, Liverpool FCC Physics Workshop 2022

- The vertex resolution drives the feasibility of this measurement.
- Secondary and tertiary vertices are the main driver of the reconstruction.
- Primary vertex resolution has an impact on the selection rule.

Configuration	Reconstruction efficiency	Selection rule purity	B^0 mass RMS (MeV)
3 µm (PV), 20 µm − 3 µm (L-T SV&TV) : **asymptotic goal**	0.5026 ± 0.0018	0.4959 ± 0.0025	125.58 ± 0.45
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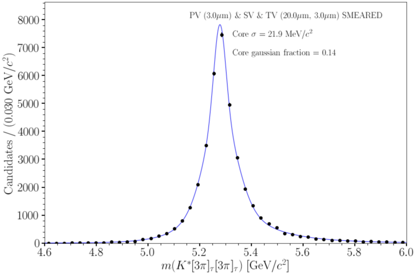
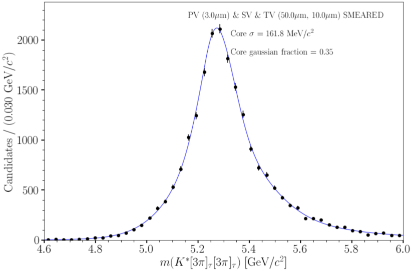




Yield prediction :

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

$$\Rightarrow \mathcal{N}_{K^*\tau\tau\to K7\pi2\nu} \approx 185 \pm 24 \text{ (computation detailed in back-up).}$$

- 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 [9] in order to establish the feasibility of the measurement.
- Relevant backgrounds are the ones with a similar final state ($K7\pi$).
- Note : 6 dominant backgrounds (in term of visible BF and number of additional missing particle) are generated .

$\Rightarrow$ **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.**

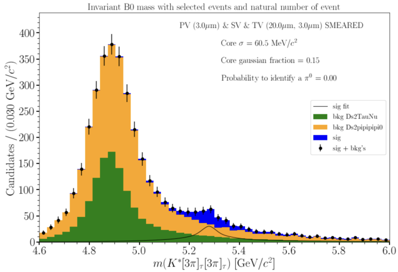
Backgrounds identification

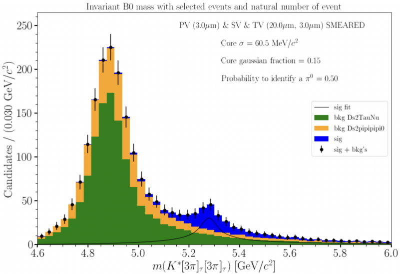
Decay	BF (SM/meas.)	Intermediate decay	BF_had	Additional missing particles
Signal : $B^0 \to K^*\tau\tau$	1.30×10^{-7}	$\tau \to \pi\pi\pi\nu$, $K^* \to K\pi$	9.57×10^{-11}	
Backgrounds $b \to c\bar{c}s$:				
$B^0 \to K^{*0} D_s D_s$	2.15×10^{-4}	$D_s \to \tau\nu$ [ii]	4.75×10^{-10}	2ν [iii]
		$D_s \to \tau\nu, \pi\pi\pi\pi^0$ [ii]	1.74×10^{-9}	ν , π^0
		$D_s \to \pi\pi\pi\pi^0$ [ii]	6.38×10^{-9}	$2\pi^0$,
		$D_s \to \pi\pi\pi 2\pi^0$ [ii] [iv] [v]	8.23×10^{-8}	$4\pi^0$,
$B^0 \to K^{*0} D_s D_s^*$	6.8×10^{-4}	$D_s \to \tau\nu$ [ii]	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
		$D_s \to \pi\pi\pi\pi^0$	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, $2\gamma/\pi^0$
		$D_s \to \pi\pi\pi\pi^0$	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}	$D \to \pi\pi\pi^0$	3.25×10^{-9}	ν, π^0
$B_s \to K^{*0} D^*\tau\nu$	3.16×10^{-4}	$D^* \to D^0\pi, D\pi^0$		
		$D \to \pi\pi\pi^0$	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}	$D_s \to \tau\nu$ [ii]	3.79×10^{-10}	2ν [iii]
		$D_s \to \pi\pi\pi\pi^0$	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

ii. The generated backgrounds.
iii. Not totally irreducible due to additional missing neutrinos or lifetimes.
iv. Displayed one times but can be considered in place of each $D_s \to \pi\pi\pi\pi^0$.
v. Background with the biggest BF, very dangerous if not killed by the reconstruction.

From $B \to K^*\tau\tau$, Liverpool FCC Physics Workshop 2022

- The selection rule is used to choose the +/- solutions.
- $B^0 \to K^{*0} D_s D_s (D_s \to \pi\pi\pi\pi^0)$ is cut by both reconstruction method and a conservative (ALEPH like) π^0 identification
- $B^0 \to K^{*0} D_s D_s (D_s \to \tau\nu)$ is dominant (at least now, no way to limit it).
- The measurement seemed possible with the two working points.





Signal and backgrounds reconstruction efficiencies.

Data	Reconstruction 20 − 3	Reconstruction 50 − 10
$B^0 \to K^{*0}\tau\tau(\tau \to \pi\pi\pi\nu)$	0.5005 ± 0.0018	0.2718 ± 0.0016
$B^0 \to K^{*0}D_sD_s(D_s \to \tau\nu)$	0.6038 ± 0.0017	0.4948 ± 0.0018
$B^0 \to K^{*0}D_sD_s(D_s \to \pi\pi\pi\pi^0)$	0.0822 ± 0.0010	0.0695 ± 0.0009
$B^0 \to K^{*0}D_sD_s(D_s \to \pi\pi\pi\pi^0, \tau\nu)$	0.2228 ± 0.0015	0.1831 ± 0.0014
$B^0 \to K^{*0}D_sD_s(D_s \to \pi\pi\pi\pi^0\pi^0)$	0.6677 ± 0.0017	0.4906 ± 0.0018
$B^0 \to K^{*0}D_s\tau\nu(D_s \to \tau\nu)$	0.5543 ± 0.0018	0.3696 ± 0.0017
$B^0 \to K^{*0}D_s^*D_s(D_s^* \to D_s\gamma, D_s \to \tau\nu)$	0.6068 ± 0.0017	0.4967 ± 0.0014

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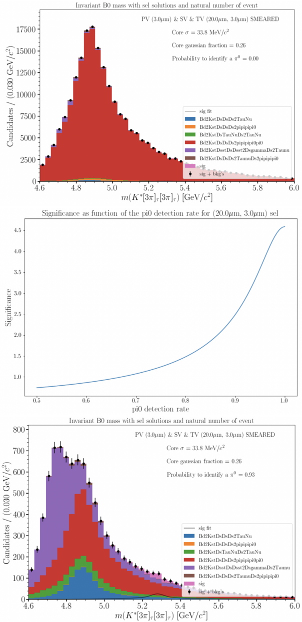
The elephant in the room

- We initially thought that $D_s \to \pi\pi\pi\pi^0\pi^0$ would be massively cut by the reconstruction method.
- A nasty kinematical conspiracy makes this decay very resembling to the signal one. A more educated simulation of this D_s decay (so far Phase Space) is in order.
- Its BF is several orders of magnitude over the signal, it becomes the background to fight against.

How to deal with $B^0 \to K^{*0}D_sD_s(D_s \to \pi\pi\pi\pi^0\pi^0)$?

- Work in progress.
- Without any action, $D_s \to \pi\pi\pi\pi^0\pi^0$ is overwhelming.
- The capability to identify the two π^0's from one D_s allows to reduce this background.
- The probability for an event to survive is : $(1-\epsilon_{\pi^0}^2)^2$, ϵ_{π^0} is the probability to identify one π^0.
- Significance $S/\sqrt{S+B}$ as function of ϵ_{π^0} is 3 at $\epsilon_{\pi^0} = 0.93$.
- The D_s decay proceeds with $\eta\rho, \eta\pi\pi^0, \omega\pi\pi^0 \Rightarrow$ possibility to veto the η and ω masses, only with one π^0.



- Work in progress : towards a selection.
- Use the kinematical properties of the charged particles of the decay.
- Use impact parameters and decay lengthes (D_s lifetime larger than τ lifetime).
- Use mass vetoes of intermediate particles of the decay (η, ω ...).
- Use of the missing energy of the hemisphere to which the candidate decay belongs (more missing energy with the decay with ν).

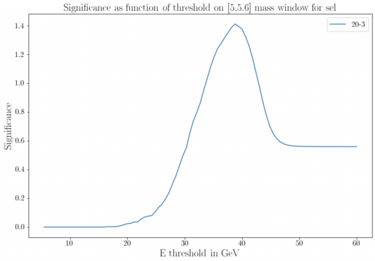


Figure – Significance as function of threshold on E in decay hemisphere (thrust).

Conclusion

- Simulation of arbitrarily good vertex resolutions (previous presentations) :
  - The transverse vertex resolution is the main driver of the overall performance,
  - 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 backgrounds with $D_s \to \pi\pi\pi\pi^0\pi^0$ mimic $\tau \to \pi\pi\pi\nu$. It is possible to reduce it at an acceptable level though (wip).

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Outlook

- Introducing actual vertexing performance for the PV (selection rule).
- Introduce a selection (the topological reconstruction would not make it alone).
- Produce the precision of the measurement as a function of the resolution.
- Analysis close to completion (we have all the tools) but this work is done in a background of other activities.

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Thanks for your attention !

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

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

Where :

- $\mathcal{N}_Z = 5\times 10^{12}$ the expected number of Z produced,
- $BR(Z\to b\bar{b}) = 0.1512 \pm 0.0005$,
- $f_d = 0.407 \pm 0.007$ the hadronisation term,
- $BR(K^*\tau\tau) = 1.30\times 10^{-7} \pm 10\%$ the SM predicted branching fraction,
- $BR(\tau\to\pi\pi\pi\nu) = 0.0931 \pm 0.0005$,
- $BR(K^*\to K\pi) = 0.69$,
- $\epsilon_{reco} = 0.3860$ $(0.7712 \pm 0.0013 \times 0.5005 \pm 0.0018)$ for a smearing $3\,\mu\mathrm{m}/20\,\mu\mathrm{m}$,

$$\Rightarrow \mathcal{N}_{K^*\tau\tau\to K7\pi 2\nu} \approx 185 \pm 24.$$

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.

Data	Reconstruction 20 − 3	Reconstruction 50 − 10
Signal	0.5026 ± 0.0018	0.2760 ± 0.0016
$B^0 \to K^{*0} D_s D_s (D_s \to \tau\nu)$	0.6056 ± 0.0017	0.4943 ± 0.0018
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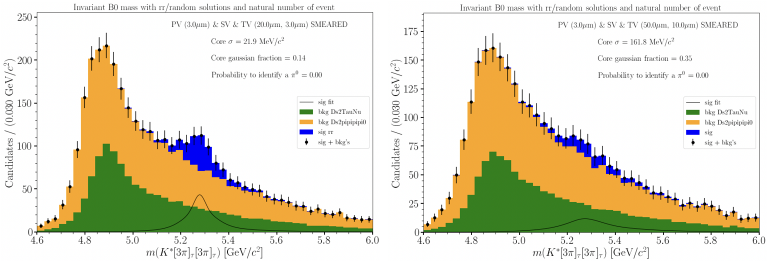

Figure – Stacked signal + backgrounds histograms with 20 − 3μm as smearing (left) and 50 − 10μm (right). The true solutions is taken for signal and a random one for backgrounds.

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

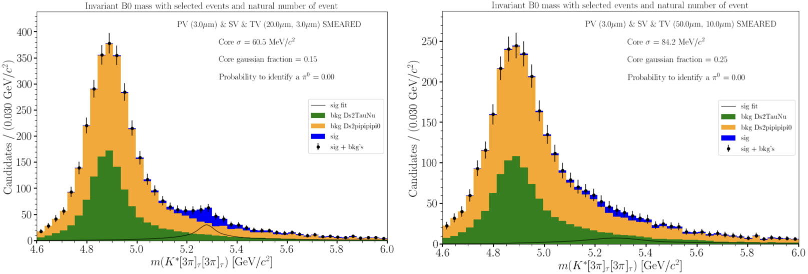

Figure – Stacked signal + backgrounds histograms with 20 − 3µm as smearing (left) and 50 − 10µm (right). The selected (by selection rule) solutions are taken for signal and backgrounds.

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 (ALEPH) : 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.

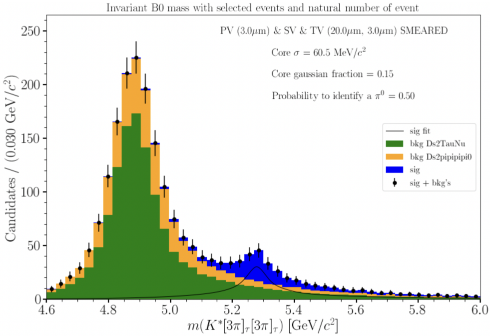

Figure – Stacked histograms 20 – 3 with 75% of $D_s \to \pi\pi\pi\pi^0$ rejected.

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

- 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.
- 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.

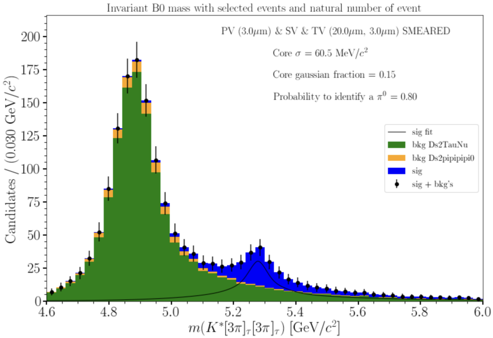

Figure – Stacked histograms 20 – 3 with 96% of $D_s \to \pi\pi\pi\pi^0$ rejected.

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

- 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.
- If at least one π^0 is associated to a TV, the event will be rejected.
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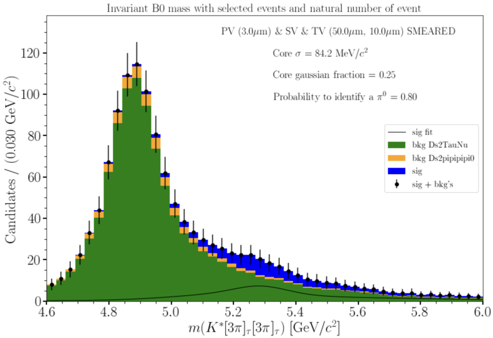


Figure – Stacked histograms $50 - 10$ with 96% of $D_s \to \pi\pi\pi\pi^0$ rejected.

$\Rightarrow$ 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 $50 - 10$.

How $D_s \to \pi\pi\pi^0\pi^0$ mimic $\tau \to \pi\pi\pi\nu$

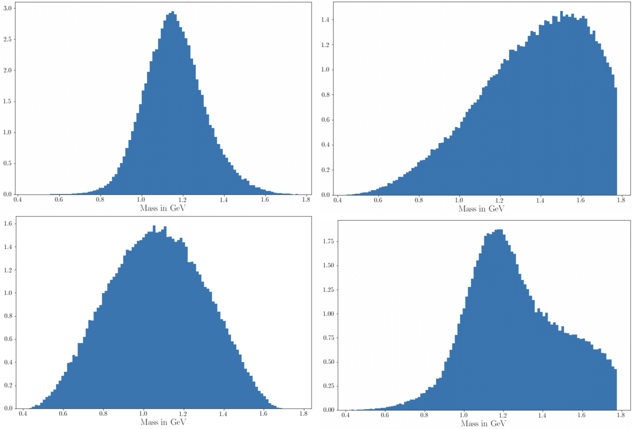


Figure – From top left to bottom right, mass distribution (area normalized to 1) of the 3-pions system from $\tau \to \pi\pi\pi\nu$, $D_s \to \pi\pi\pi\pi^0$, $D_s \to \pi\pi\pi^0\pi^0$ and $D_s \to \pi\pi\pi\pi^0$, $D_s \to \tau\nu$. $D_s \to \pi\pi\pi\pi^0$ candidates peaks clearly over the $\tau \to \pi\pi\pi\nu$ candidates, this is why so much events is killed by the reconstruction. Concerning $D_s \to \pi\pi\pi^0\pi^0$ the second missing π^0 lead the distribution to peak close to the $\tau \to \pi\pi\pi\nu$ candidates, this is why the reconstruction doesn't kill it. $\tau \to \pi\pi\pi\nu$ is narrower than $D_s \to \pi\pi\pi^0\pi^0$. Using the reconstruction of one η or ω could be a way to kill this background.

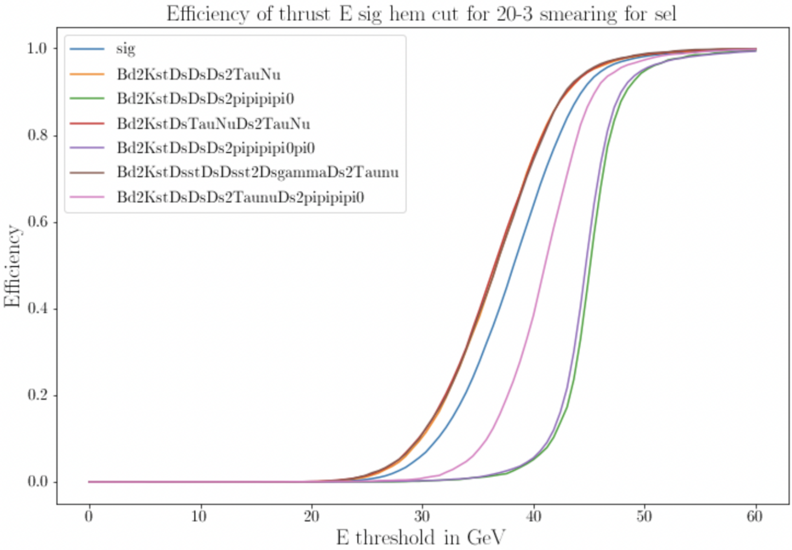


Figure – Efficiency of the cut on E in decay hemisphere (thrust).

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

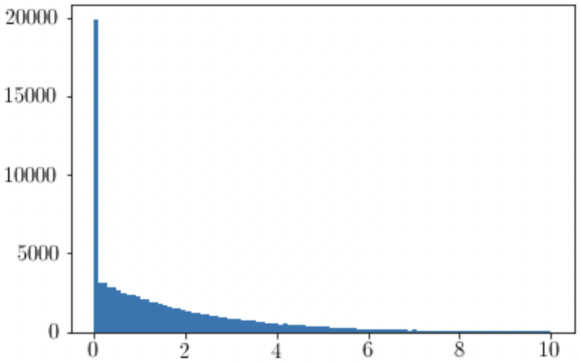
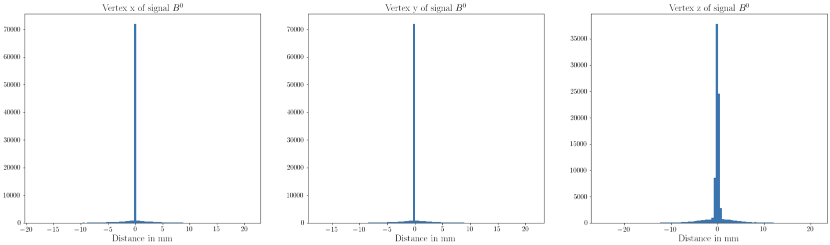


Figure – B^0 flight distance distribution in mm

$\Rightarrow$ 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).

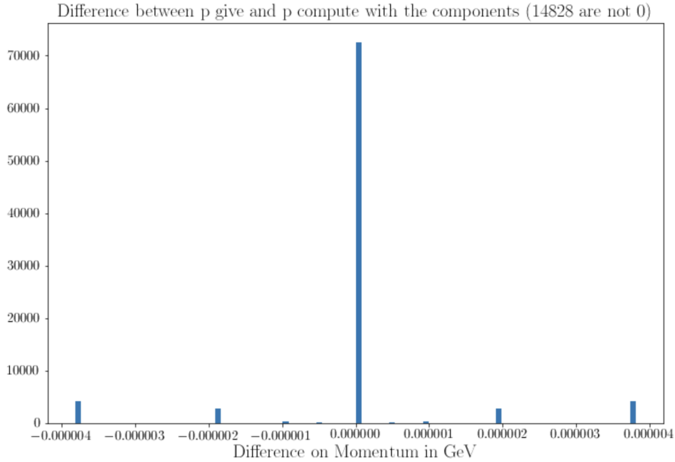
- We are expecting a gaussian distribution for the PV position which are milimetric on z (beam direction), and smaller (μ or n-metric) on x and y.
- In fact we have these regimes but each of them come with a centimetric regime in addition.



$\Rightarrow$ 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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