- Lepton Flavour Violating *Z* decays and FCNC in *b*-hadron decays implications on detector design.

- Proposal of benchmark modes for hadron particle identification detectors.

S. Monteil,
Université Blaise Pascal, Clermont,
LPC-IN2P3-CNRS.

Detector implications from FCNC and LFV processes at the *Z* pole

1) FCNC in *b*-hadron decays.

- The rare FCNC decays $b \rightarrow s\ \ell^+\ell^-$ are receiving increasing experimental and phenomenological interests:
  - good laboratory for new quark/lepton transitions operators.
  - possibly clean theoretical (QCD) uncertainties.
  - some signs of departures of the data w.r.t. the SM/QCD predictions.
  - also questioning lepton universality.

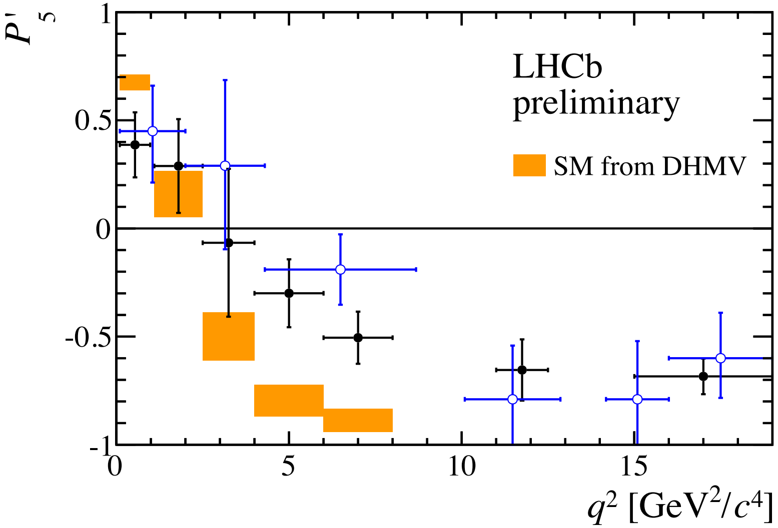
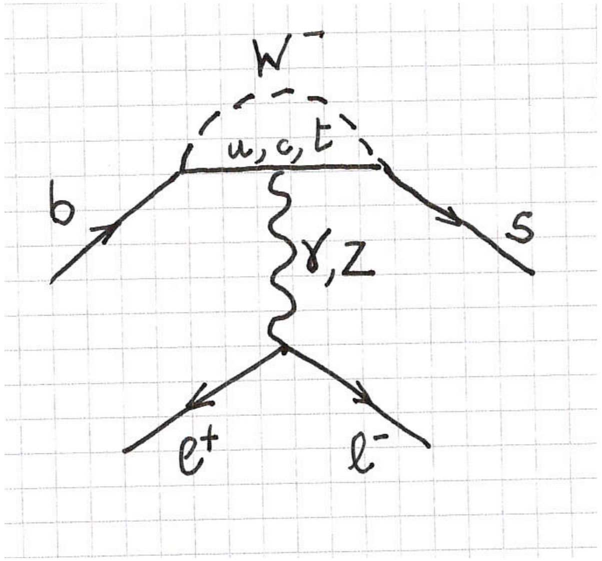


Figure 17: The observable P'_5 in bins of q^2. The shaded boxes show the SM prediction taken from Ref. [13]. The blue open markers show the result of the $1\,\mathrm{fb}^{-1}$ analysis from Ref. [7].



1) FCNC in *b*-hadron decays.

- Specific to FCC-*ee* : electron and tau final states
  - $B^0 \rightarrow K^{*0} \; e^+e^-$ has been explored in https://indico.cern.ch/event/403492/ . Bottomline: expect 100 times more events than Belle II.
  - $B^0 \rightarrow K^{*0} \; \tau^+\tau^-$ has been explored in https://indico.cern.ch/event/380986/. Bottomline: necessary to complete the picture and interesting per se since subjected to third family specific couplings. Experimental study an implications on vertexing reported in the following.
- Signal reconstruction: we want to infer the missing momentum of neutrinos. Makes use of partial reconstruction technique.
- Background study is required to address relevantly detector performance.

1) FCNC in *b*-hadron decays. $B^0 \to K^{*0}\ \tau^+\tau^-$.

Principle of partial reconstruction technique:

- Reconstructing decay vertices and measuring distances: fixing two degrees of freedom. An additional constraint (*e.g.* mass of an intermediate resonance, here the tau mass) takes the remaining d.o.f.

- Invariant mass resolution is driven by the vertexing performance. The most important quantity in that respect is the secondary decay vertex (*B* meson given by the K^{*0}).

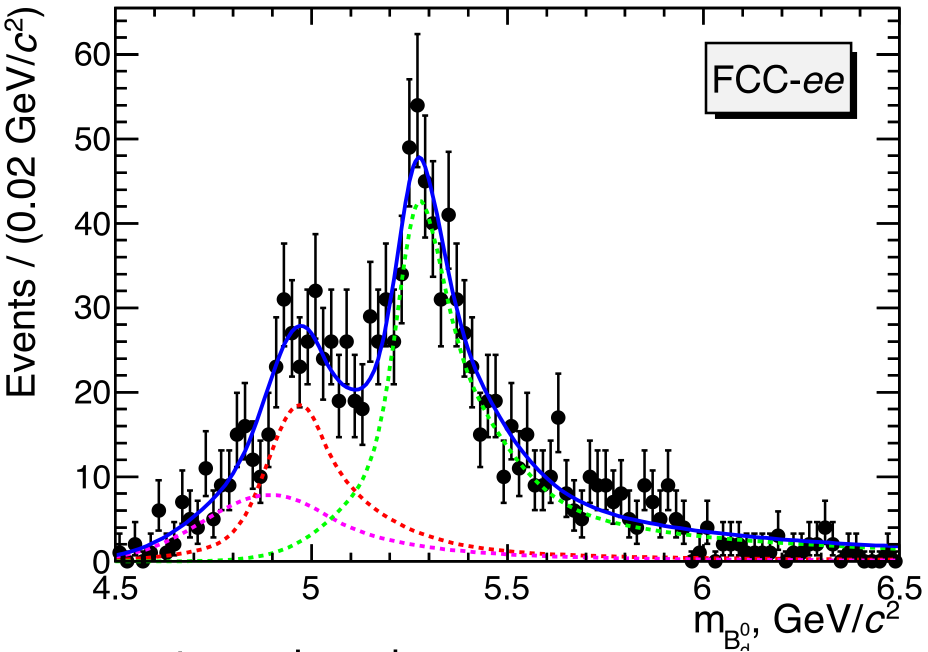
- Note: there is a further background killer: check the absence of calorimeter deposit in each of the neutrinos direction. This challenges simultaneously the granularity of the calorimetric apparatus and the angular resolution from partial reconstruction tracking. Not explored yet.

1) FCNC in *b*-hadron decays. $B^0 \to K^{*0}\ \tau^+\tau^-$.

- Backgrounds:

  (pink) $\bar{B}^0 \to D_s^+ \bar{K}^{*0} \tau^- \bar{\nu}_\tau$
  (red) $\bar{B}_s \to D_s^- D_s^+ K^{*0}$
  (signal in green).

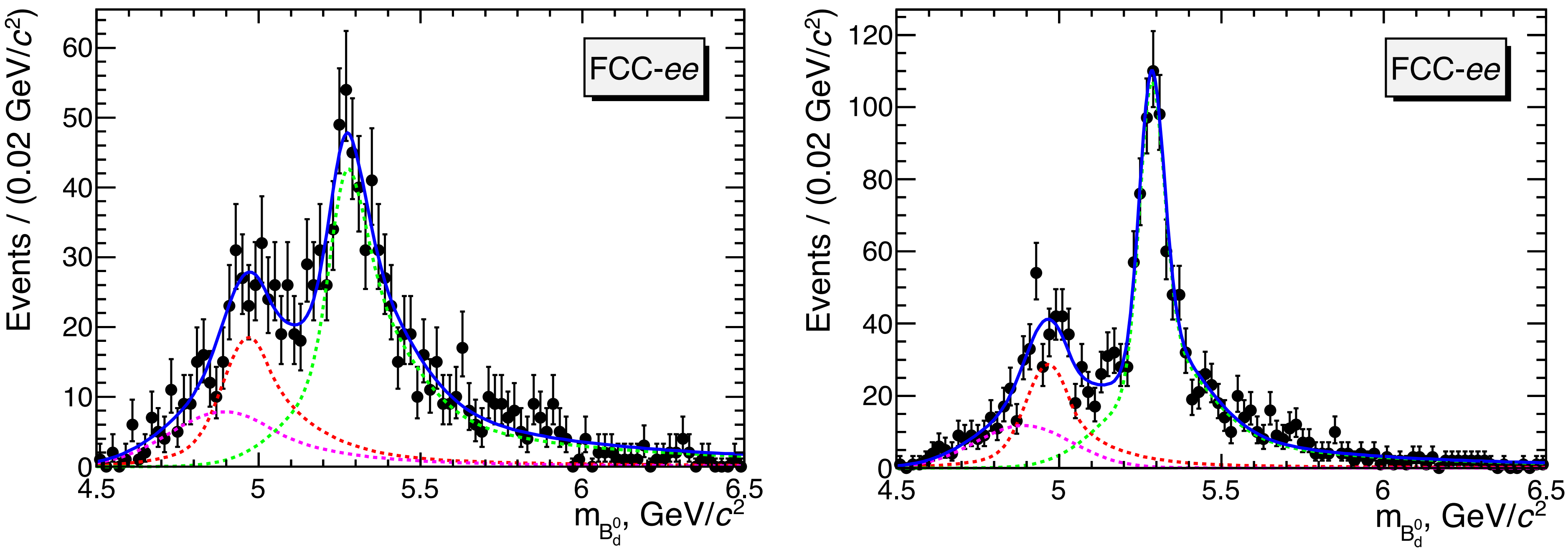
- Conditions: baseline luminosity, SM calculations of signal and background BF, vertexing and tracking performance as ILD detector. **Momentum** → 10 MeV, **Primary vertex** → 3 um, **SV** → 7 um, **TV** → 5 um



Few comments are in order:

- At baseline luminosity, 10^3 events of reconstructed signal. Angular analysis possible.
- With an ALEPH-like vertex detector performance, the signal peak can't be resolved.
- Another interesting and more challenging mode is $B_s \to \tau^+\tau^-$ (Marseille - tuples with the same parametric detector have been produced).

1) FCNC in *b*-hadron decays. $B^0 \to K^{*0}\ \tau^+\tau^-$.



- Conditions:
  - Baseline luminosity
  - The vertex detector can be placed as close as 2 cm from the beam
  - Left: vertexing performance as ILD.
  - Right: vertexing performance twice better than ILD.

2) Charged leptons FCNC Z decays

- Lepton Flavour-Violating Z decays in the SM with lepton mixing are typically

$$\mathcal{B}(Z \to e^{\pm}\mu^{\mp}) \sim \mathcal{B}(Z \to e^{\pm}\tau^{\mp}) \sim 10^{-54} \text{ and } \mathcal{B}(Z \to \mu^{\pm}\tau^{\mp}) \sim 4.10^{-60}$$

- Any observation of such a decay would be an indisputable evidence for New Physics.

- Current limits at the level of ~10^{-6} (from LEP and recently Atlas, *e.g.* [DELPHI, Z. Phys. C73 (1997) 243] [ATLAS, CERN-PH-EP-2014-195 (2014)])

- The FCC-*ee* high luminosity Z factory would allow to gain up to six orders of magnitude ... Complementary to the direct search for steriles.

- Explored with FCC-*ee* in mind in [De Romeri et al. JHEP 1504 (2015) 051]. It happens that the final states with taus are the most appealing.

2) Charged leptons FCNC Z decays

- There are actually three processes competing in the ball park we can address with a final state with a tau and a beam energy light lepton

  - The lepton Flavour-Violating Z decays
  - The SM $Z \to \tau^+\tau^-$
  - The SM $Z \to l^+l^-$ ($l \to W^*\nu$ and $W^* \to \tau\,\nu$)

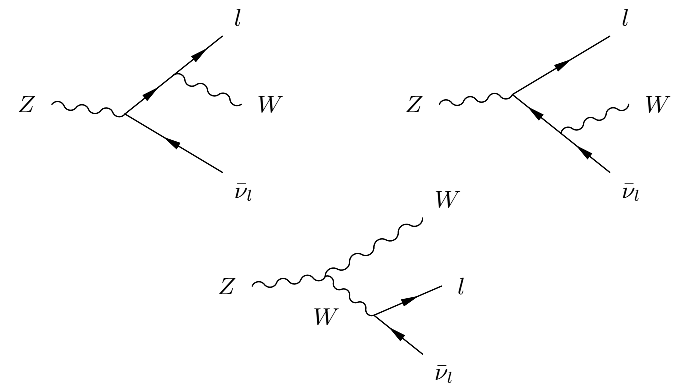
- Following Mogens Dam's study reported last week :

The SM process $Z \to \tau^+\tau^-$ provides a limit on LFV process which goes linearly with the momentum resolution. Which is asymptotically limited in turn by the beam energy spread (~ 30 MeV at 45 GeV, ~20 MeV at 90°). This makes the former limit pretty fundamental.

The latter process [Durieux et al. arXiv:1512.03071]. is interesting per se (NP enhancements) and can be distinguished from the two others by its kinematical properties: a partial reconstruction technique would make the job.

2) Charged leptons FCNC Z decays - Analysis

$Z \to W^{*} \ell \nu$



Same final state content as signal but one neutrino more. Idea to reconstruct the missing neutrino in signal.

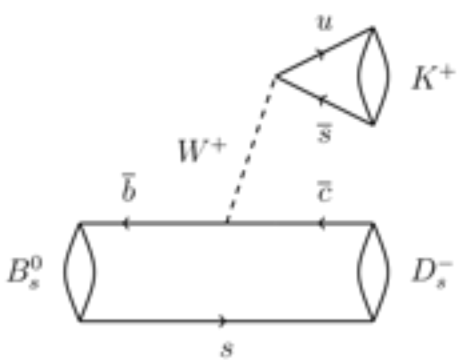
- The intercept of the light lepton momentum in one hemisphere with the beam spot defines in an invincible way the Z vertex.
- Search for hadronic decays of the tau leptons in three prongs, such that you can find the decay vertex.
- Makes use of the partial reconstruction technique to infer the neutrino momentum and hence reconstruct the Z mass.
- Additional mode to qualify the required vertexing perfomance.

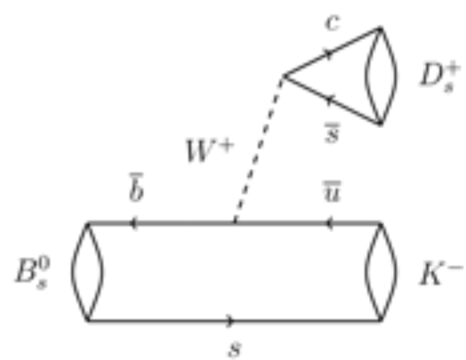
Two benchmarks for hadron PID detector

Benchmarks for hadron PID

1) *CP* violation studies: $B_s \to D_s K$:

- for Physics: measure simultaneously the phases γ (decay) and ϕ_s (mixing,B_s). No theoretical uncertainty plaguing the interpretation.



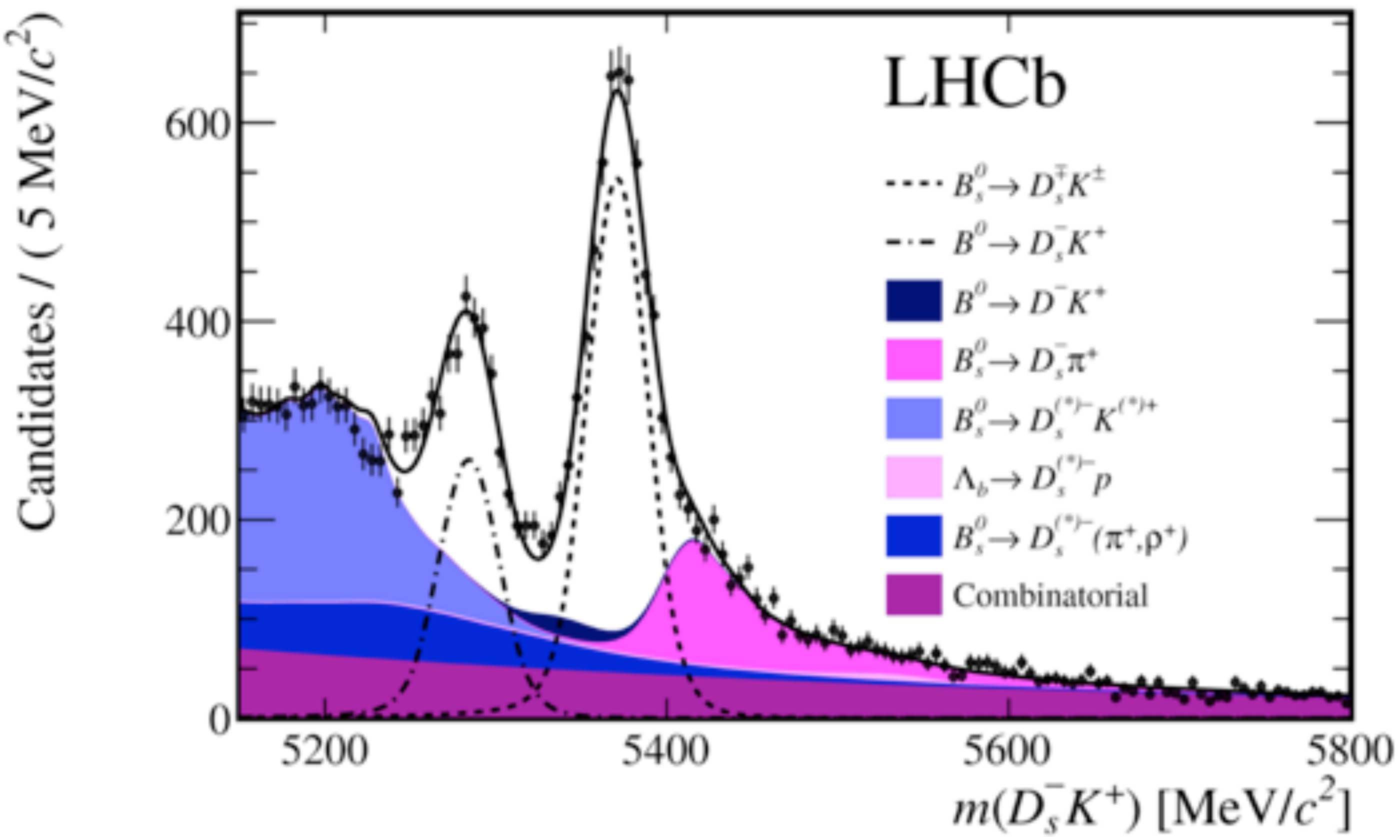


- for detectors: understand the needs of p / K / π separation. There is a competition of up-feeding and down-feeding contribution through mis-identification: $B^0 \to D_s\pi$ and $\Lambda_b \to D_s\, p$. Serves also the purpose of quark flavour tagging.

Benchmarks for hadron PID

1) *CP* violation studies: $B_s \to D_s K$:

LHCb-PAPER-2014-064
ArXiv:1412.7654



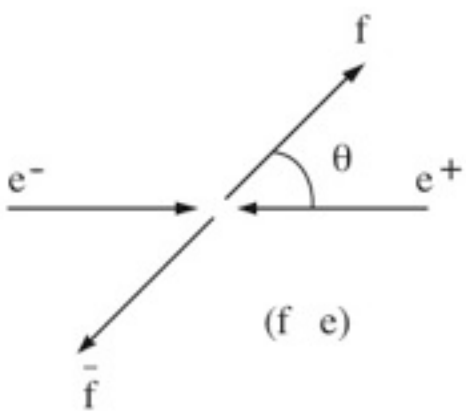
Benchmarks for hadron PID

1) *CP* violation studies: $B_s \rightarrow D_s K$:

- The backgrounds do consist of *b*-hadron decays. You don't do this Physics without a powerful Hadron Identification Performance.
- Toy studies (up to the γ angle determination) can be performed in a stand-alone way to educate the first view of on the subject. In particular, the interplay between invariant mass resolution (momentum) and PID requirements. Someone identified for the job.
- I missed time to produce actual momentum distributions of the hadrons in these decays. Will do for the next iteration.

2) *b*-flavour asymmetry at the *Z* pole:

- The measurement of the forward-backward asymmetry of the *b* quark in *Z* decays is primarily meant for *Ab* determination, since muons will drive the determination of $\sin^2\theta_W$.



$$\frac{d\sigma^f}{d\cos\theta} = \sigma^f_{\rm tot} \cdot [\frac{3}{8}(1+\cos^2\theta) + A^{f\bar{f}}_{\rm FB}\cos\theta]$$

$$A^{f\bar{f}}_{\rm FB} = \frac{N_F - N_B}{N_F + N_B} \text{ with } N_F = \int_0^1 \frac{d\sigma_{f\bar{f}}}{d\cos\theta} \cdot d\cos\theta$$

$$A^{f\bar{f}}_{\rm FB} \propto A_e \cdot A_f \propto \frac{g^e_V g^e_A}{(g^e_V)^2 + (g^e_A)^2} \cdot \frac{g^f_V g^f_A}{(g^f_V)^2 + (g^f_A)^2}$$

- Explore exclusive *b*-hadron decays reconstruction to benefit of the *Z* pole statistics.

Benchmarks for hadron PID

2) *b*-flavour asymmetry at the *Z* pole:

- Limitations of LEP-like measurements of A_{FB}(b):
  - mixing dilution with lepton tags.
  - purity of the sample.
  - QCD corrections (gluon radiations).
- Exclusive reconstruction of hadronic B^+ *or* Λ_b decays, *e.g.*
  - $B^- \to D^0\pi^-, D^0\pi^-\pi^+\pi^-$ [10^{-2}] followed by $D^0 \to K^-\pi^+, K^-\pi^+\pi^+\pi^-$, $K_S^0\pi^+\pi^-$ [15.10^{-2}]
  - $\Lambda_b \to \Lambda_c\pi^+, \Lambda_c\pi^+\pi^-\pi^-$ [10^{-2}] followed by $\Lambda_c \to p\,K^-\pi^+$ [$7.\ 10^{-2}$]
- Can expect several 10^9 of them.

2) *b*-flavour asymmetry at the *Z* pole:

- Limitations of LEP-like measurements of $A_{FB}(b)$:
  - mixing dilution with lepton tags.
  - purity of the sample.
  - QCD corrections (gluon radiations).
- The two former limitations are overcome. On top of that, get the direction of the *b*-hadron, in addition to the thrust of the event.
- Hadron PID required for at least correct mass assignment of the hypothesis.
- The idea requires to be polished (if ever judged relevant) but this could bring a benchmark outside of flavour physics.

Summary

- CLFV *Z* decays and *b*-hadron electroweak penguin decays do bring similar detector constrains / requests in terms of vertexing through the partial reconstruction of τ leptons. CLFV *Z* decays require asymptotic momentum resolution.
- Calorimetry constraints are as well brought by these FCNC processes (not evoked in this talk):
  - tracking π^0 from tau decays (in jets).
  - tracking missing energy (in jets).
- Proposals for two benchmark physics processes (one for CP violation, the other EWPT) for qualifying the hadron PID performance.

Sketch of an adequate detector for Flavours at *Z* pole

- Vertex detector with a secondary vertex resolution at or better than ~ 3 µm in the three dimensions, hence in *z*. Certainly serves all purposes.

- Tracking system: large TPC or whatever but large. Well suited for direct search of Heavy Neutral Leptons as well. Momentum resolution at the level of the beam energy spread limit (~30 MeV at 45 GeV).

- If the tracking system is large, modest magnetic field is good.

- Efficient downstream (w.r.t. the vertex locator) tracking: V0.

- PID detector: ideally a Time of Flight / Cerenkov embedded in a PreShower for photon tracking.

- Finely granular electromagnetic calorimeter for tau decays reconstruction. Also serves all purpose.

1) FCNC in *b*-hadron decays. $B^0 \rightarrow K^{*0}\ \tau^+\tau^-$.

A further consideration:

- τ decays into one additional neutral pions brings an additional 30% statistics w.r.t. the fully charged 3 prongs. More than an actual doubling of the statistics for both τ.

- The detector requirement is here to track π^0 within a jet in the calorimeter.

- It seems to me that a high-granularity calorimeter such as *e.g*. the Si-W from Calice coll. is just designed for this.

- This is not only about EM granularity. Interplay in between the tracking volume and ECAL granularity. All modes discussed here would benefit of a large tracking volume.