From Flavour Changing Neutral Currents at the *Z* pole and related friends

few thoughts on detector implications

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Disclaimers

- The question asked to this talk was how the search for Charged Lepton Flavour Violated Z decays (hence FCNC) processes could influence detector design.

- No actual physics reach experimental studies was performed yet. However, it is very likely that the reconstruction shares properties of other FCNC at the *Z* pole. Namely electroweak penguin b-hadron decays.

- In that respect, most of the quantitative material presented here comes from a collaboration with Andrii Semkiv (Clermont U. and TSN Kyiyv U.).

- Will also present other related (*CP* violation physics driven) benchmark modes.

Outline

Sketch some implications on detector designs implied by:

- Flavour changing charged leptons *Z* decays.
- FCNC in *b*-hadron decays.
- Few related benchmark modes (mostly *CP* violation driven)
- Summary.

1) 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.

1) Charged leptons FCNC *Z* decays - Backgrounds

- Signal event topology: one high energy track in one hemisphere, a tau decay in the other with 1, 3 or 5 prongs. This seems very clean experimental environment but keep in mind that we are chasing 10^{-13} sensitivity.

- Among the background sources, I examined:

  - $Z \to qq$ with low multiplicity.
  - $Z \to W^{*} \ell\nu$

- The latter (as a signal) is appealing *per se* as a SM candle and/or NP probe. [Durieux et al. arXiv:1512.03071]. The final state is the same as CLFV (with an additional neutrino) and the authors find a SM branching fraction of 1.4 10^{-8} ! Need to devise more than a counting experiment to make the most of the statistics.

- Give a rapid look at the former first.

1) Charged leptons FCNC Z decays - Backgrounds

- $Z \rightarrow qq$ can produce two signal-like topologies:

- Exclusive decay $Z \rightarrow \pi^+\pi^-$. this would directly challenge the CLFV decay $Z \rightarrow e\mu$.

- $Z \rightarrow$ *few* π with one unique high energy charged track in a single hemisphere (and few in the other hemisphere). Would mimic the CLFV decays $Z \rightarrow e\tau, \mu\tau$.

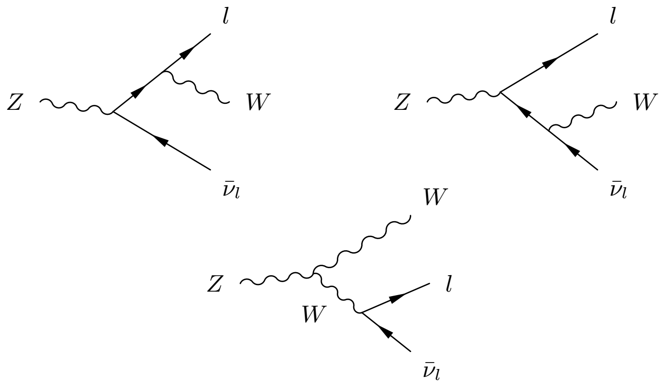
- Asked Pythia (8) about this: none of the first category in 20 M events. mis-identification as electron and muon are mitigated with a reasonable detector (already LEP-like) at few 10^{-4} .

- Few of the second category are found with the unique charged track in a single hemisphere w/ p larger than 40 GeV/c.

1) Charged leptons FCNC Z decays - Analysis

Come back to the $Z \rightarrow W^{*} \ell \nu$

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 (121 um horizontal, 250 nm vertical) 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.
- The question then becomes very similar to reconstruct final states with tau in hadronic Z decays, for which we (I) have a more educated view.

2) 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.

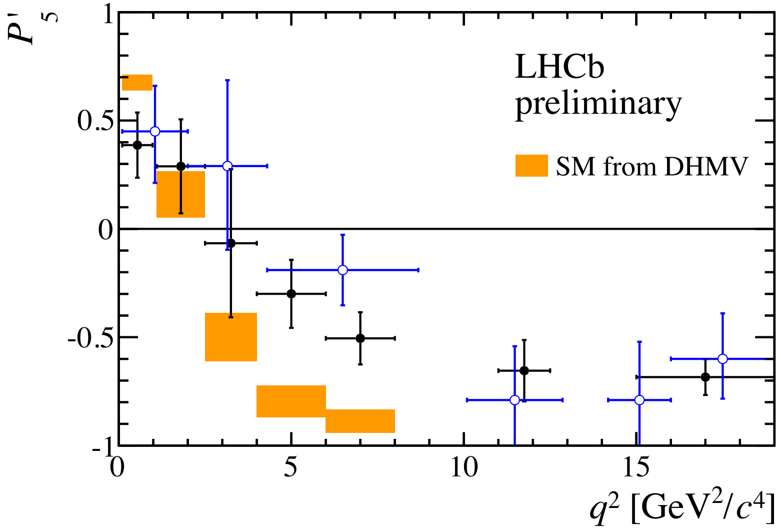
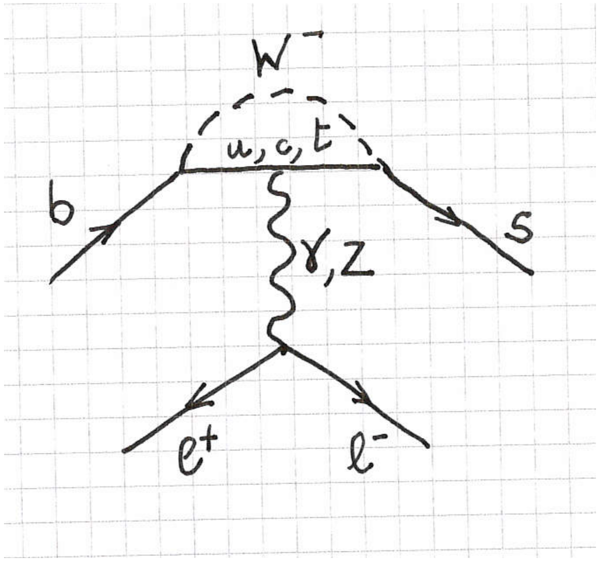


Figure 17: The observable P_5' in bins of q^2. The shaded boxes show the SM prediction taken from Ref. [13]. The blue open markers show the result of the $1\,\mathrm{fb}^{-1}$ analysis from Ref. [7].



2) 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 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. No a priori idea about the expected yields. Experimental study is required. Focus on this in the following.
- I'm giving here only the sketch of the study. See further information in the talk from Barbara Mele this week at the pheno session.
- 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.

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

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.

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

- Backgrounds:

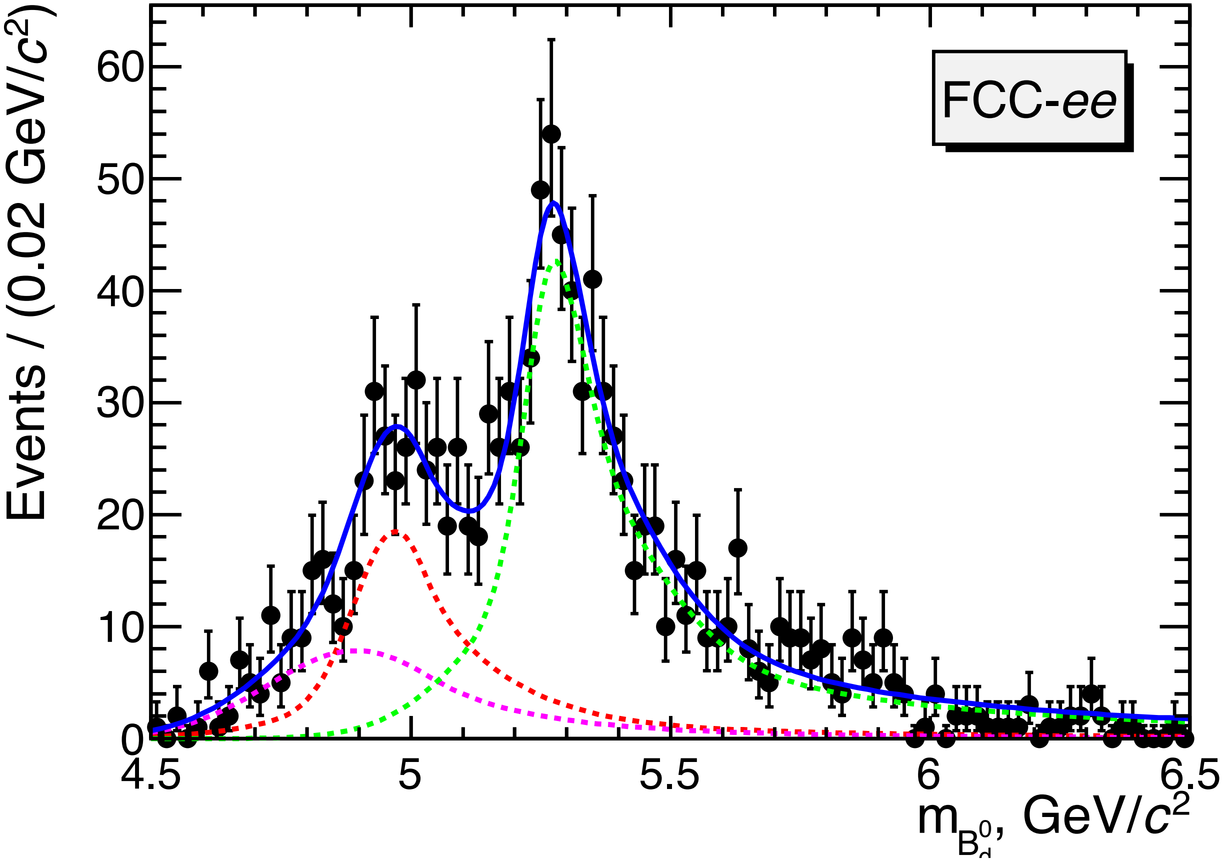
$$\bar{B}^0 \to D_s^+ \bar{K}^{*0} \tau^- \bar{\nu}_\tau$$

(pink)

$$\bar{B}_s \to D_s^- D_s^+ K^{*0}$$

(red)

(signal in green).



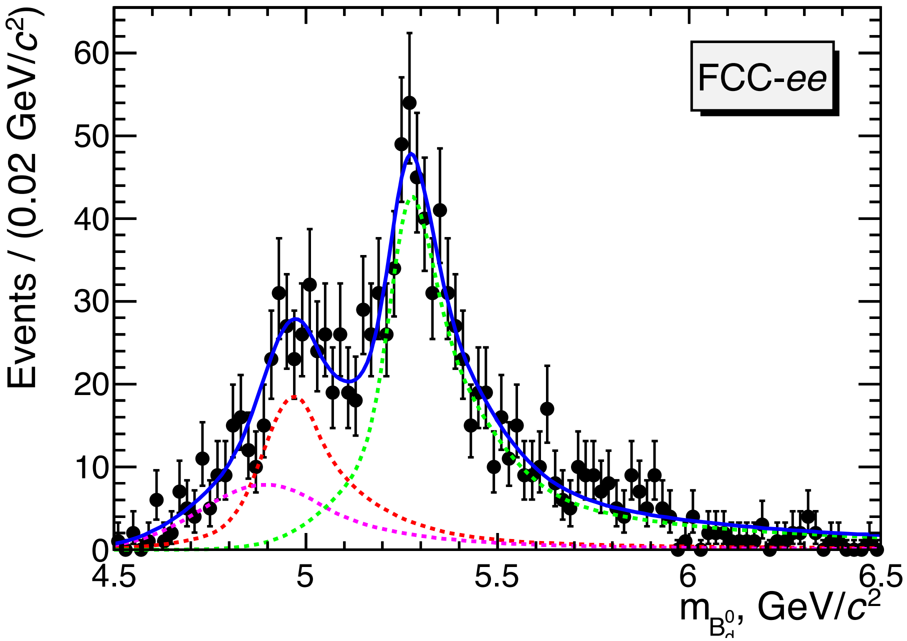
- Conditions: target luminosity, SM calculations of signal and background BF, vertexing and tracking performance as ILD detector. **Momentum** → 10 MeV, **Primary vertex** → 3 um, **SV** → 7 um, **TV** → 5 um

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

Few comments are in order:

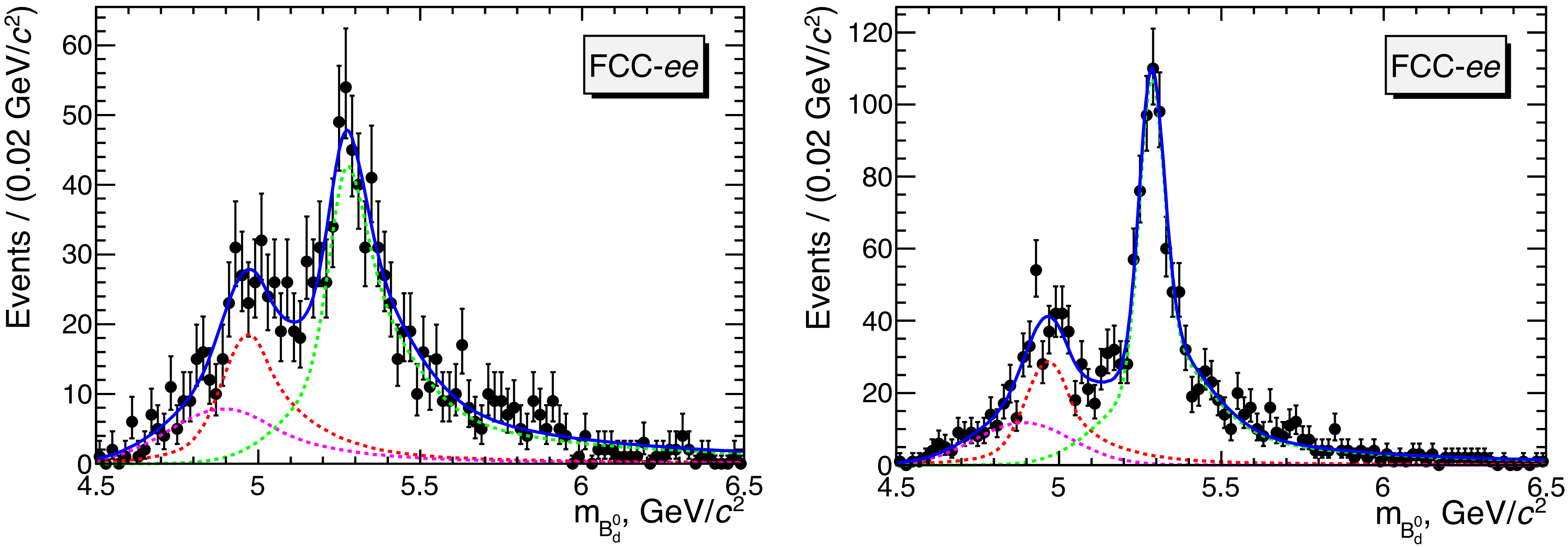
- At target luminosity, we can expect about 10^3 events of reconstructed signal. A handful at Belle II experiment. Angular analysis possible. And more w/ polarization.

- With an ALEPH-like vertex detector performance, the signal peak can't be resolved.



This mode can serve as a benchmark for partial reconstruction techniques and hence vertexing. Another interesting and more challenging mode is $B^0 \rightarrow \tau^+\tau^-$. Work has started (Marseille).

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



- Conditions:
  - Target luminosity
  - Left: vertexing performance as ILD.
  - Right: vertexing performance twice better than ILD.

2) 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.

3) Other (related) benchmark modes for detector studies

- $B_s \rightarrow D_s K$:
  - 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: $B^0 \rightarrow D_s\pi$ and $\Lambda_b \rightarrow D_s\, p$. Serves also the purpose of quark flavour tagging.
- Speaking of large tracking system: the V^0 tracking can be studied with the decays $B_s \rightarrow K_S K_S$. CP violation studies.

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 (focus of this talk).

- Calorimetry constraints are as well brought by these FCNC processes:

  - tracking π^0 from tau decays (in jets).
  - tracking missing energy (in jets).

- Those vertexing and calorimetric constraints are likely adding up to Higgs and EWPT demands.

- *CP*-violating observables demand in addition to study:
  - PID separation π / K / p relevance. A benchmark mode is identified.
  - efficient V0 (K^0_S / Λ) tracking.

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 100 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.

Charged leptons FCNC *Z* decays

e - mu mis-identifications:

- it seems to me this cannot possibly drive the detector design.
  - Actually, electron identification hits the limit the charge exchange at the entrance of the calorimeter.

$$\pi^- p \rightarrow n\pi^0,\ \pi^+ n \rightarrow p\pi^0$$

  - muon mis-identification is limited by punch-through hadrons and decays in flight.

$$K^+, \pi^+ \rightarrow \mu^+ \nu_\mu$$

- Any reasonable detector (already LEP-like) do mitigate these two effects at the level of 10^{-4}. The design question would then transport to tau reconstruction.