Flavours at FCC-*ee*.

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Outline of the talk

- Physics motivations for Flavours: Leptons and Quarks.
- Summary of the Physics Case identified so far.
- Two illustrations of the WG activity:
  - Lepton Flavour Violating *Z* decays
  - Installation of a typical *b*-hadron-related analysis: elements of the simulation of the signal.
- Conclusions.

Introduction: Scope of the Flavour Physics working

- Understand the experimental precision with which rare decays of *c*- and *b*-hadrons and CP violation in the heavy-quark sector could be measured with 10^{12} Z, as well as the potential sensitivity to new physics, and compare to the ultimate potential of the (soon to be) running LHCb upgrade and Belle II experiments. Examine the relevance of a dedicated PID (π / K / p separation) detector,

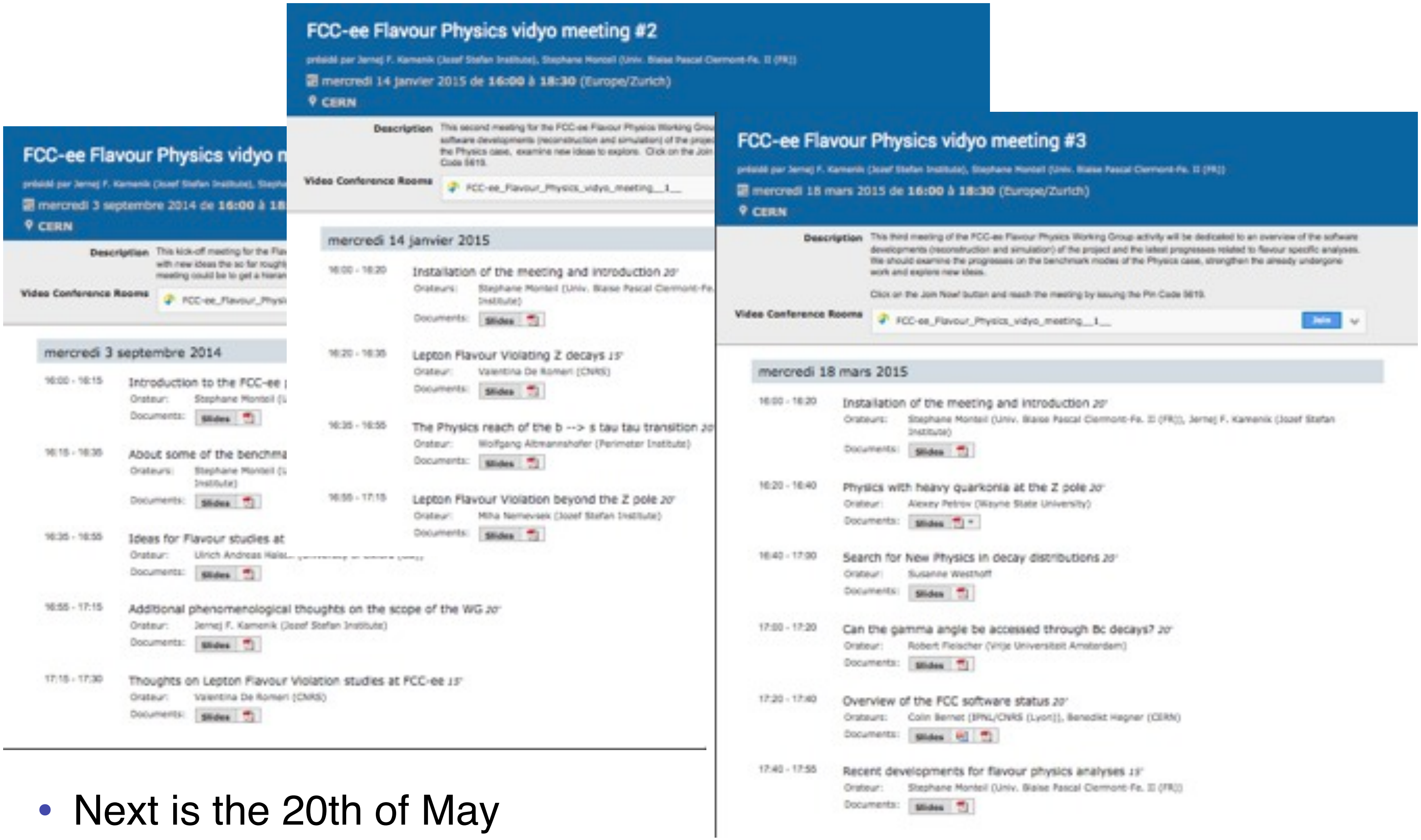
- The very same objective stands for the rare lepton decays.

- Examine the physics reach of lepton flavour violating processes and neutrino-related Physics unique to the FCC-*ee*.

- Have a platform to think of beyond standard observables.

- "What would like to do/see with/in 10^{12} / 10^{13} Z?" makes a nice playground to start with.

Flavours WG Meetings held on a bimonthly frequency



- Next is the 20th of May

Meetings held on a bimonthly frequency

- The meetings have been used so far to trigger flavour physics-related ideas to define the wished/necessary experimental studies of the design study.

- The initial Flavour case, built out of the highs and laws of current and anticipated Flavours programs was criticized and commented to establish the following quadriptych, in no particular order:

4) Lepton Flavour Violating processes.

- Direct LFV processes: $Z \to e\mu, e\tau, \tau\mu$. In terms of model constraints, this can be far richer than the current or foreseeable reach for $\mu \to e\gamma$ or $\tau \to \mu\gamma$ etc...
- Related to the large $\tau\tau$ production at the Z pole: $\tau \to e\gamma, \mu\gamma, eee, \mu\mu\mu$. both LFV and Majorana neutrino. In the latter case, possibly rich like-sign dilepton searches in *b*-hadron decays as well.

1) Any leptonic or semileptonic decay mode involving B_s, B_c or b-baryon, including electrons, in no particular order:

- $B_{d,s} \to ee, \mu\mu, \tau\tau$: if the second will be mostly covered by LHCb and CMS, the first can be searched for with a similar precision. The latter $B_s \to \tau\tau$ is most likely unique to FCC-*ee* and subjected to third family specific couplings.
- Leptonic decays in direct annihilation $B_{u,c} \to \mu\nu_\mu, \tau\nu_\tau$. The latter is a chance to get $|V_{cb}|$ with mild theoretical uncertainties.
- Radiative decays $B \to Xll$ ($s\tau\tau$ at first): rare FCNC complementing the B_d at B-factories.

- Note: if the baseline machine is to be confirmed with the crab-waist option, the flavours scope with 10^{13} Z is likely to improve dramatically. For instance, it should be possible to get $|V_{ub}|$ theory-free (well, strong isospin symmetry only ...) out of ratios of rare decays. Not mentioning that the large boost at the Z can be beneficial for classical methods.

Physics Case and benchmark modes

2) Any decay mode involving B_s, B_c or b-baryon with neutrals.

- $B_{d,s} \to \gamma\gamma$: theoretically difficult.
- $B_s \to K_S K_S$: CP violation studies. Also interesting for downstream tracking of V^0 in general.

3) Multibody (4 and more) hadronic b-hadron decays.

- $B_s \to \psi\eta'$ or $\eta_c\Phi$: flavour tagging required for weak mixing phase.
- $B_s \to D_s K$: PID definitely required to isolate the signal.
- Modes to be used to define the Particle Identification needs.

Starting with Leptons: LFV in rare Z-decays

- The Flavour Lepton Case as far as NP is concerned often goes through Lepton Flavour Violation(LFV) processes. An indisputable evidence for New Physics.

- Study specifically LFV decays of the Z boson to benefit for the pole statistics in the context of additional heavy neutral states (sterile neutrinos)

- Though LHCb and Belle II will be players in this game, the main contributors now and in the coming years will likely be low-energy LFV experiments: MEG, COMET...

- Address the complementarity with low-energy LFV experiments.

- Some illustration of obtained results.

LFV in rare Z-decays

- In the minimal SM (with massive neutrinos and PMNS mass mixing matrix), the LFV leptonic Z decays are beyond experimental reach

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

- Many NP models do foresee LFV Z decays: SUSY, Little Higgs etc...

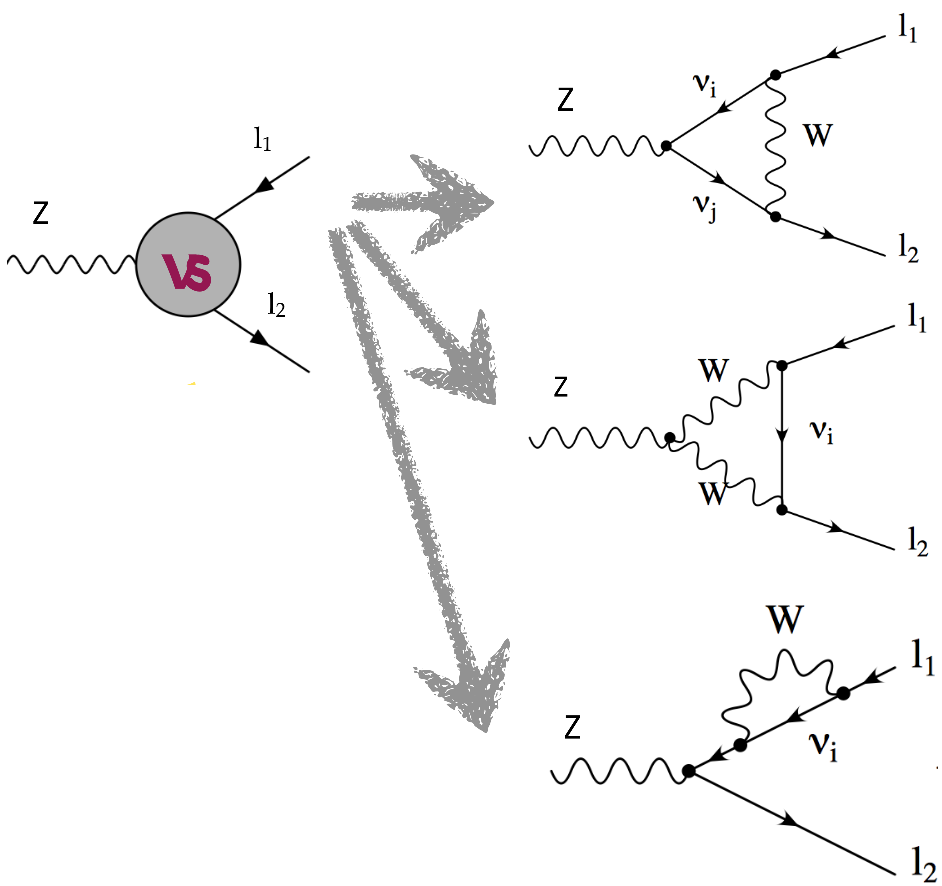
- The current experimental bounds:

$$\mathcal{B}(Z \to e^{\pm}\mu^{\mp}) < 7.5\ 10^{-7},$$
$$\mathcal{B}(Z \to e^{\pm}\tau^{\mp}) < 9.8\ 10^{-6},$$
$$\mathcal{B}(Z \to \mu^{\pm}\tau^{\mp}) < 1.2\ 10^{-5}.$$

- We could potentially go more than 5 orders of magnitude beyond.

- Illustration: study these decays in the context of additional sterile neutrinos and relate their constraints to other observables. arXiv:1412.6322 [hep-ph], V. De Romeri et al. to appear in JHEP.

LFV in rare Z-decays



Studies for the Giga-Z (Wilson, DESY-EFCA LC workshop (1998-1999), J. I. Illana and T. Riemann, Phys. Rev. D63 (2001) ... are revisited taking into account:

- θ_{13} and other neutrino data
- new contributions of sterile states are severely constrained:

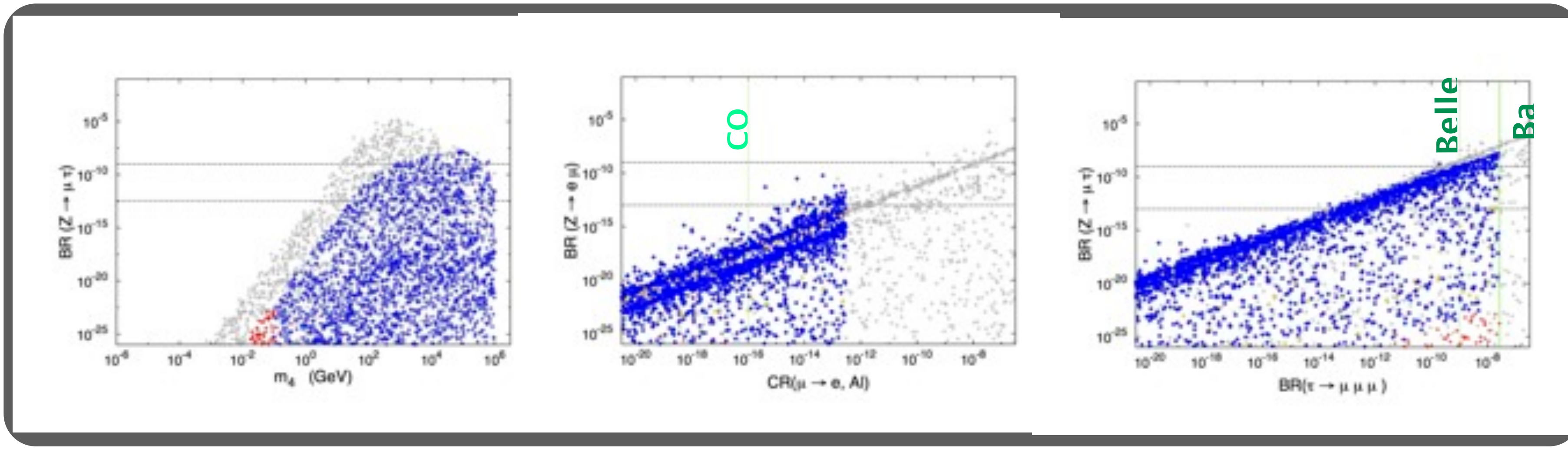
  - radiative decays (MEG)
  - 3-body decays
  - cosmology
  - neutrinoless double β decays
  - invisible Z-width

  ....

LFV in rare Z-decays: “3+1” toy model

3+1 model is a convenient ad-hoc extension; 4th state encodes contributions of arbitrary number of sterilevs

exp. excluded
cosmo X
cosmo OK



V. De Romeri et al.

- Steriles with mass above 80 GeV and mixings O(10^{-5}-10^{-4}) within FCCee reach.
- Low-energy experiment at work to probe the electron-muon sector
- FCC-*ee* provides the stringent constraint in tau-mu sectors.

Conclusion with LFV in rare Z-decays:

- Self-contained interest: unique constraints / measurements can be brought on LFV *Z* decays at FCC-*ee*.
- This study made in the context of additional sterile neutrino states by examining the complementarity of low- and high- energy experiments.
- If ever a LFV experiment finds a positive results, LFV *Z* decays should be an invaluable asset to qualify the result.
- Also complementarities within FCC-*ee*: see the next talk by Alain on the direct search for Heavy Neutrals.

Second illustration: *B* radiative (leptonic) decays

- The rare decays $b \to s\ \ell^+\ell^-$ 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.

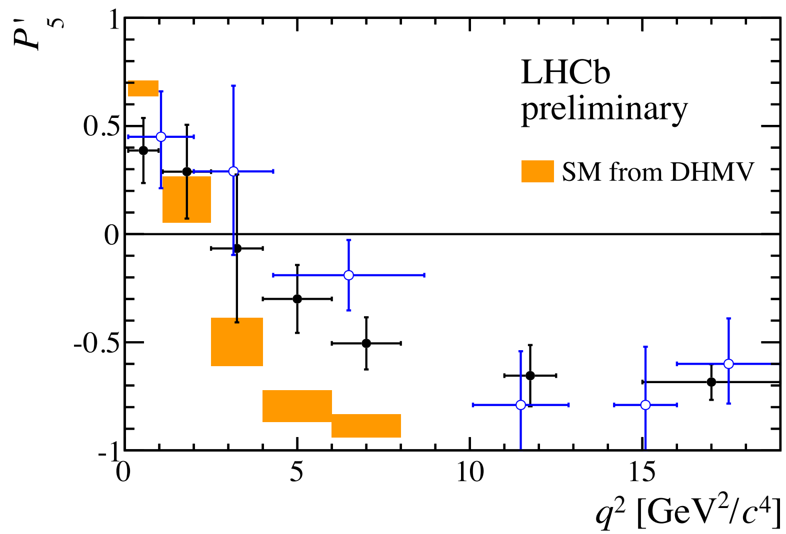


Figure 17: The observable P'_5 in bins of q^2. The shaded boxes show the SM prediction taken from Ref. [13]. The blue open markers show the result of the 1 fb^{-1} analysis from Ref. [7].

Second illustration: *B* radiative (tauonic) decays

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  - 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.
- The tau lepton final state is unexplored so far but is necessary to complete the landscape, whatever the NP scenario is there or ruled out.
- See a nice first phenomenological exploration of this decay by W. Altmanshoffer here: https://indico.cern.ch/event/359433/contribution/0/material/slides/0.pdf
- Experimentally, aim at:
  - measuring the branching fraction,
  - studying the angular distributions.

Second illustration: *B* radiative (tauonic) decays

- Experimentally, aim at:

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  - measuring the branching fraction,
  - studying the angular distributions.

- The latter requires the reconstruction of a particle decay in absence of the explicit reconstruction of one or several particles of the decay chain.

- Means: the partial reconstruction technique makes use of the vertices experimental information. The transition $b \to s\tau^+\tau^-$ can be fully solvable in the exclusive $B^0 \to K^{*0}\,\tau^+\tau^-$, if one tau vertex can be reconstructed.

- Counting the degrees of freedom:
  - *B* flight distance $\to$ 2 d.o.f., τ flight distances $\to$ 4 d.o.f., τ masses $\to$ 2 d.o.f.
  - Saturate the constraints to determine the six missing neutrinos momentum coordinates.

Second illustration: *B* radiative (tauonic) decays

- The transition $B^0 \to K^{*0}\,\tau^+\tau^-$ can be fully solved. In equations:

$$\vec{0} = \vec{p}^{\perp}_{\tau+} + \vec{p}^{\perp}_{\tau-} + \vec{p}^{\perp}_{\pi K} \qquad (5)$$

Here:

$$p^{\parallel}_{\tau+} = \vec{p}_{\tau+}\vec{e}_B = p_{\tau+}(\vec{e}_{\tau+}\vec{e}_B)$$

$$\vec{p}^{\perp}_{\tau+} = \vec{p}_{\tau+} - \vec{p}^{\parallel}_{\tau+} = p_{\tau+}\vec{e}_{\tau+} - p^{\parallel}_{\tau+}\vec{e}_B = p_{\tau+}[\vec{e}_{\tau+} - (\vec{e}_{\tau+}\vec{e}_B)\vec{e}_B]$$

And the same for $p^{\parallel}_{\tau-}$, $\vec{p}^{\perp}_{\tau-}$, $p^{\parallel}_{\pi K}$ and $\vec{p}^{\perp}_{\pi K}$. Rewrite the equation (5):

$$\vec{0} = p_{\tau+}[\vec{e}_{\tau+} - (\vec{e}_{\tau+}\vec{e}_B)\vec{e}_B] + p_{\tau-}[\vec{e}_{\tau-} - (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B] + \vec{p}^{\perp}_{\pi K} \qquad (6)$$

Multiplying both sides of this equation by $[\vec{e}_{\tau-} + (\vec{e}_{\tau+}\vec{e}_B)\vec{e}_B]$, we get:

$$\begin{aligned} p_{\tau-}[\vec{e}_{\tau-} - (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B][\vec{e}_{\tau-} + (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B] = \\ = -\{\vec{p}^{\perp}_{\pi K} + p_{\tau+}[\vec{e}_{\tau+} - (\vec{e}_{\tau+}\vec{e}_B)\vec{e}_B]\}[\vec{e}_{\tau-} + (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B] \end{aligned} \qquad (7)$$

Or, taking into account that $e^2_{\tau+} = e^2_{\tau-} = e^2_B = 1$:

$$\begin{aligned} p_{\tau-}[1 - (\vec{e}_{\tau+}\vec{e}_{\tau-})^2] = -p_{\tau+}[\vec{e}_{\tau+}\vec{e}_{\tau-} - (\vec{e}_{\tau+}\vec{e}_B)(\vec{e}_{\tau-}\vec{e}_B)] - \\ -\vec{p}^{\perp}_{\pi K}[\vec{e}_{\tau-} + (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B] \end{aligned} \qquad (8)$$

Thus,

$$\begin{aligned} p_{\tau-} = -\frac{\vec{e}_{\tau+}\vec{e}_{\tau-} - (\vec{e}_{\tau+}\vec{e}_B)(\vec{e}_{\tau-}\vec{e}_B)}{1 - (\vec{e}_{\tau+}\vec{e}_{\tau-})^2}p_{\tau+} - \\ -\frac{\vec{p}^{\perp}_{\pi K}[\vec{e}_{\tau-} + (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B]}{1 - (\vec{e}_{\tau+}\vec{e}_{\tau-})^2} \end{aligned} \qquad (9)$$

So, we have:

$$p_{\tau-} = Ap_{\tau+} + B \qquad (10)$$

Here

$$A = -\frac{\vec{e}_{\tau+}\vec{e}_{\tau-} - (\vec{e}_{\tau+}\vec{e}_B)(\vec{e}_{\tau-}\vec{e}_B)}{1 - (\vec{e}_{\tau+}\vec{e}_{\tau-})^2}$$

and

$$B = -\frac{\vec{p}^{\perp}_{\pi K}[\vec{e}_{\tau-} + (\vec{e}_{\tau-}\vec{e}_B)\vec{e}_B]}{1 - (\vec{e}_{\tau+}\vec{e}_{\tau-})^2}$$

0.2 Tertiary vertex 1

Energy and momenta conservation:

$$\sqrt{m^2_{\tau+} + p^2_{\tau+}} = E_{\pi 1} + p_{\nu 1} \qquad (11)$$

$$\vec{p}_{\tau+} = \vec{p}_{\pi 1} + \vec{p}_{\nu 1} \qquad (12)$$

Here $E_{\pi 1}$ and $\vec{p}_{\pi 1}$ are summary energy and momenta of all pions respectively and $\vec{p}_{\nu 1}$ is the neutrino momentum. Rewrite the equation (12):

$$p_{\tau+} = p^{\parallel}_{\pi 1} + p^{\parallel}_{\nu 1} \qquad (13)$$

$$\vec{0} = \vec{p}^{\perp}_{\pi 1} + \vec{p}^{\perp}_{\nu 1} \qquad (14)$$

Squaring both sides of the equations (11) and (13):

$$m^2_{\tau+} + p^2_{\tau+} = E^2_{\pi 1} + p^2_{\nu 1} + 2E_{\pi 1}p_{\nu 1} \qquad (15)$$

$$p^2_{\tau+} = p^{\parallel 2}_{\pi 1} + p^{\parallel 2}_{\nu 1} + 2p^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1} \qquad (16)$$

Subtracting (16) from (15) we get:

$$m^2_{\tau+} = E^2_{\pi 1} - p^{\parallel 2}_{\pi 1} + p^{\perp 2}_{\nu 1} + 2(E_{\pi 1}p_{\nu 1} - p^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1}) \qquad (17)$$

Now let's take into account that $p^{\perp 2}_{\pi 1} = p^{\perp 2}_{\nu 1}$ (from (14)):

$$m^2_{\tau+} = E^2_{\pi 1} - p^{\parallel 2}_{\pi 1} + p^{\perp 2}_{\pi 1} + 2(E_{\pi 1}p_{\nu 1} - p^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1}) \qquad (18)$$

Rearrange equation (18), taking into account that $p_{\nu 1} = \sqrt{p^{\perp 2}_{\nu 1} + p^{\parallel 2}_{\nu 1}}$

$$m^2_{\tau+} - E^2_{\pi 1} + p^{\parallel 2}_{\pi 1} - p^{\perp 2}_{\pi 1} + 2p^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1} = 2E_{\pi 1}\sqrt{p^{\perp 2}_{\nu 1} + p^{\parallel 2}_{\nu 1}} \qquad (19)$$

Denoting $2C = m^2_{\tau+} - E^2_{\pi 1} + p^{\parallel 2}_{\pi 1} - p^{\perp 2}_{\pi 1}$, taking into account that $p^{\perp 2}_{\nu 1} = p^{\perp 2}_{\pi 1}$ and squaring both sides of the equation (19), we get:

$$p^{\parallel 2}_{\pi 1}p^{\parallel 2}_{\nu 1} + C^2 + 2Cp^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1} = E^2_{\pi 1}(p^{\perp 2}_{\pi 1} + p^{\parallel 2}_{\nu 1}) \qquad (20)$$

Rearranging equation (20):

$$(E^2_{\pi 1} - p^{\parallel 2}_{\pi 1})p^{\parallel 2}_{\nu 1} - 2Cp^{\parallel}_{\pi 1}p^{\parallel}_{\nu 1} + E^2_{\pi 1}p^{\perp 2}_{\pi 1} - C^2 = 0 \qquad (21)$$

The only unknown quantity in this equation is $p^{\parallel}_{\nu 1}$. Solving this quadratic equation yields:

$$p_{\nu 1} = \alpha_1 \pm \beta_1 \qquad (22)$$

Here:

$$\alpha_1 = \frac{Cp^{\parallel}_{\pi 1}}{E^2_{\pi 1} - p^{\parallel 2}_{\pi 1}}$$

$$\beta_1 = \frac{E_{\pi 1}\sqrt{p^{\perp 2}_{\pi 1}p^{\parallel 2}_{\pi 1} + C^2 - E^2_{\pi 1}p^{\perp 2}_{\pi 1}}}{E^2_{\pi 1} - p^{\parallel 2}_{\pi 1}}$$

Now we can use this expression in equation (15) to find the value of $p_{\tau+}$ and then find the value of p_B using equations (10) and (3)

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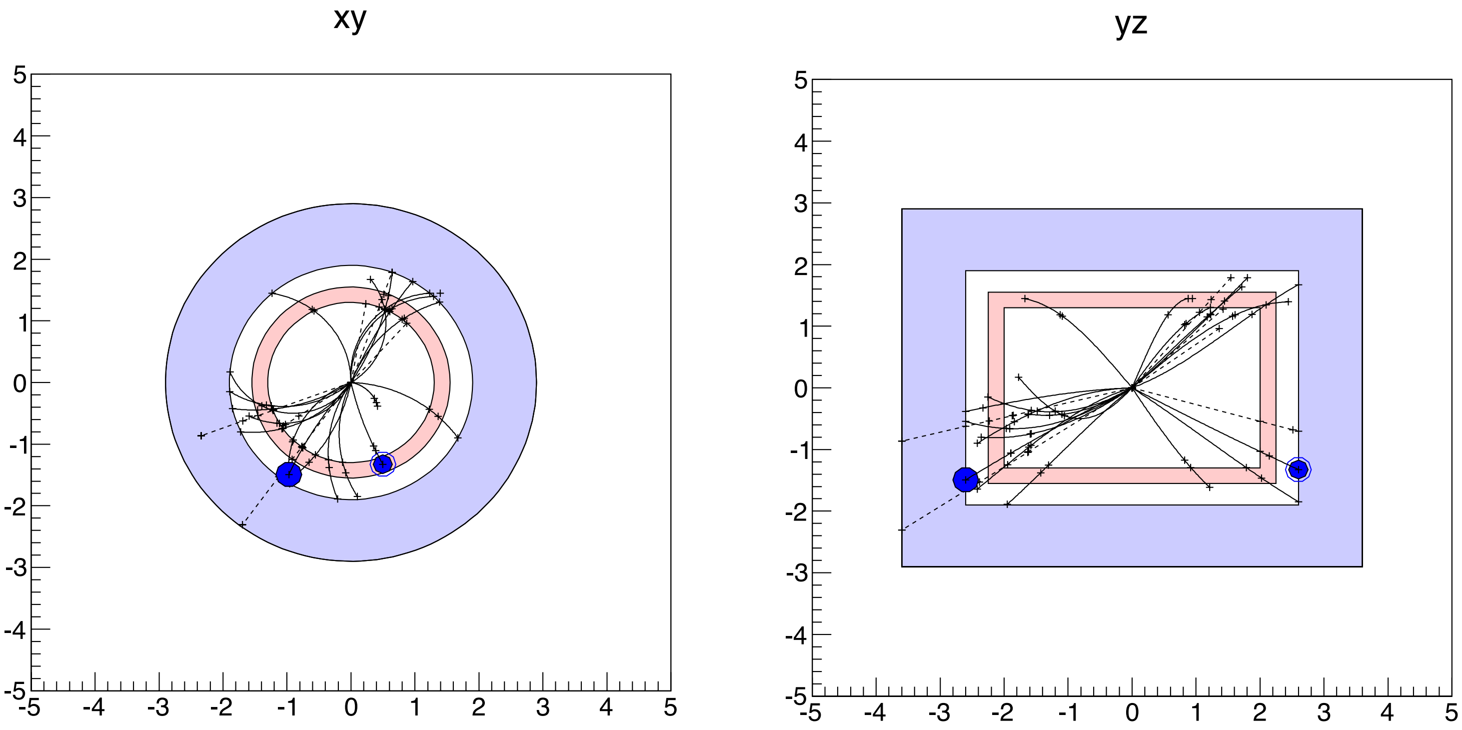
- Nothing complicated but quite ... cumbersome.

- This can be generalized even to decays where the secondary vertex is NOT reconstructed. Thinking of $B^0_s \to \tau^+\tau^-$ for instance.

Second illustration: *B* radiative (tauonic) decays

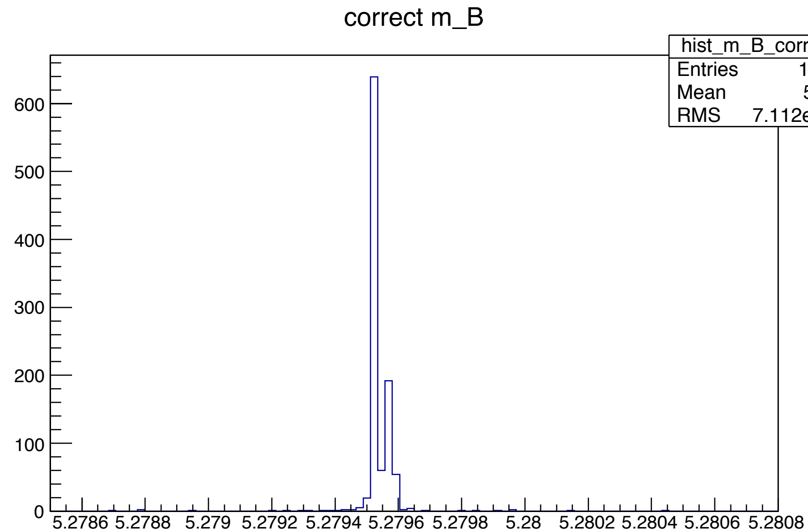
- We generated at the *Z* pole within FCC software interfaced with the EvtGen generator the decay $B^0 \to K^{0*}\tau^+\tau^-$

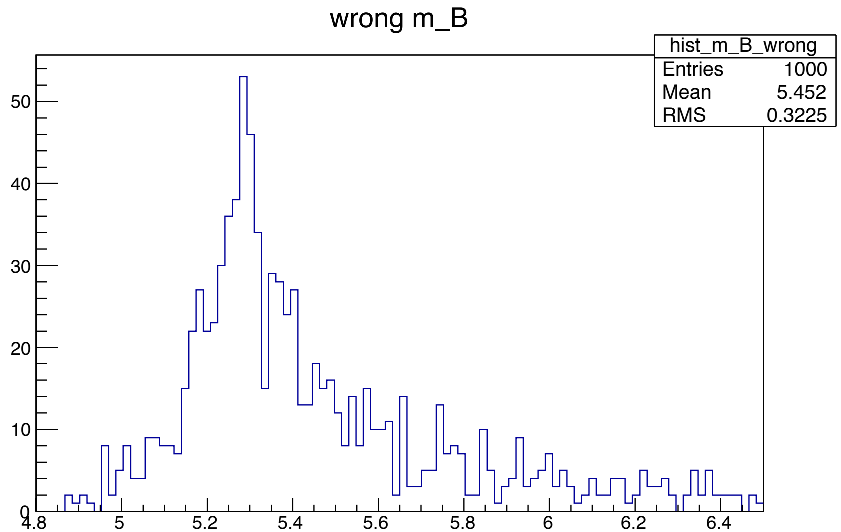
- Generation in pictures: the detector is CMS-like. Note that the *B* field is set at 1 T. Warm thanks to the FCC software team.



Second illustration: *B* radiative (tauonic) decays

- Commissioning the partial reconstruction. It works!





- Next step will be to smear the vertex distances with relevant detector resolutions and figure out the performance of the partial reconstruction in this use case in presence of backgrounds.

- The anticipated excellent vertexing at FCC-*ee* experiments, the clean experimental environment and the large boost at the *Z* pole should be invaluable arguments for these techniques.

Summary

- Within the Flavours working group, we start to gather small experimentalists / theoreticians teams on the benchmark modes.
- We reported the installation of the elements (phenomenological and experimental) of two analyses for the design study.
- Use also this WG as a platform for thinking beyond standard observables. Please get in touch with us if you're interested to join.
- A distribution list is set up. You're very welcome to join it : *fcc-ee-FlavourPhysics@cern.ch*
- A twiki page is gathering the progresses: *https://twiki.cern.ch/twiki/bin/viewauth/FCC/FCCeeFlavourPhysics*