Flavours at FCC-*ee*:

A selection of Physics results and requirements on detectors

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Outline

- A word on the method for building the Flavours case.
- Executive Summary of the CDR results.
- Requirements to detectors w/ focus on hadronic PID.
- Plans for the next Phase of the study as conclusion.

1) Motivation and method: Flavour Physics case.

- Focus on the third generation Physics (but direct top).
- Start from the anticipated Flavour Physics landscape after Belle II and LHCb U1/2 experiments.
- Identify challenging flagship processes where FCC-*ee* is unique (in for a penny, in for a pound).
- Selection of modes which tells detector requirements.

Rare b-hadron decays — electroweak penguins

$$\begin{pmatrix}\nu_e\\ e\end{pmatrix} \quad \begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix} \quad \begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}$$

$$\begin{pmatrix}u\\ d\end{pmatrix} \quad \begin{pmatrix}c\\ s\end{pmatrix} \quad \begin{pmatrix}t\\ b\end{pmatrix}$$

Lepton Flavour Violating (LFV) *Z* decays

cLFV tau decays

CKM measurements —CPV in *B* mixings

LF universality tests w/ tau decays

2) Executive summary CDR — Flavours

https://cernbox.cern.ch/index.php/s/9ZuIudM8cUATaZD

The following slides can be taken and used from the above link.

A) Heavy Flavours Production — Comparisons

Working point	Lumi. / IP [10^{34} cm^{-2}.s^{-1}]	Total lumi. (2 IPs)	Run time	Physics goal
Z first phase	100	26 ab^{-1} /year	2	
Z second phase	200	52 ab^{-1} /year	2	150 ab^{-1}

Particle production (10^9)	B^0	B^-	B_s^0	Λ_b	$c\bar{c}$	$\tau^-\tau^+$
Belle II	27.5	27.5	n/a	n/a	65	45
FCC-*ee*	400	400	100	100	800	220

- Features:
  - ~15 times Belle II anticipated statistics.
  - All species of *b*-hadrons are produced.
  - Boost at the *Z*: topological reconstruction of the decays.
  - Effective flavour tagging efficiency can be expected at 10% level.

Note: the comparison with the LHCb experiment is more involved since the decay modes yields depend on trigger efficiency. Performance to be compared mode by mode.

B) CDR: Flavour anomalies - setting the scene

- The LHCb experiment measured a set of observables in electroweak penguin (EWP) transitions of a *b* quark, which are found in persistent and consistent tensions w.r.t. the Standard Model predictions.

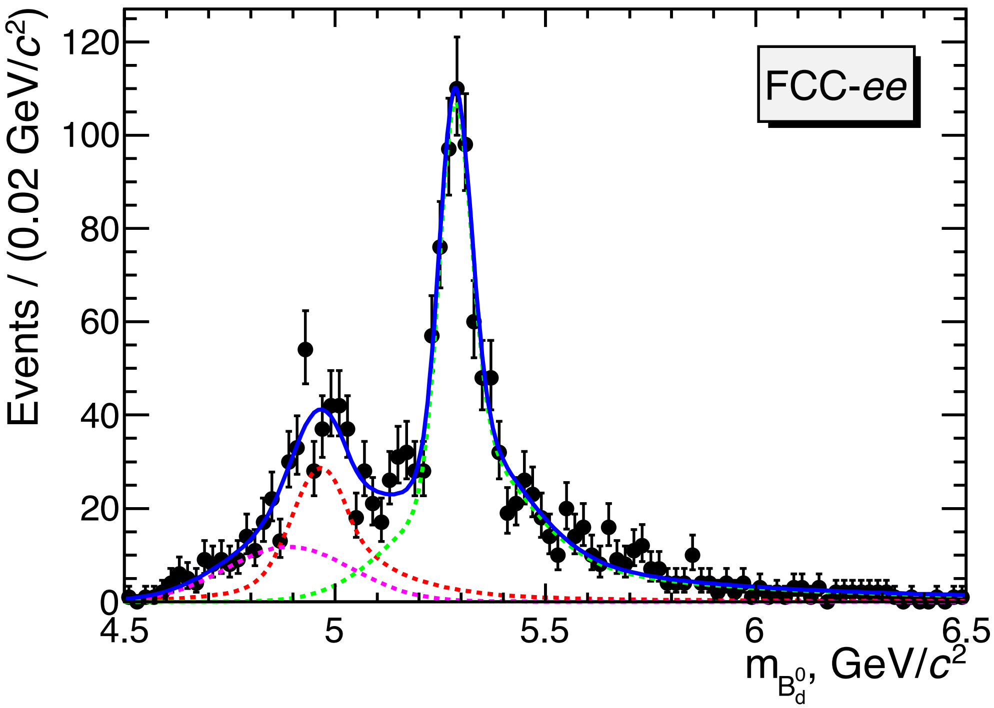
- In particular, the Lepton Flavour Universality in quark transitions is challenged. This is observed by comparing the rates of pairs of electrons and muons in the decays $B^0 \to K^{*0} \ell^+\ell^-$. FCC-*ee* shows a fantastic sensitivity to low q^2 *ee* final states.

- Should these current tensions be confirmed but even if they are not, the next laboratory to guide the relevant model of the effect comes from transitions as $b \to s\tau^+\tau^-$.

- The available statistics and the capacity to fully reconstruct the decay even in the absence of the tauonic neutrinos at FCC-*ee* is beyond foreseeable competition. The reconstruction of the mode $B^0 \to K^{*0} \tau^+\tau^-$ has received a special attention in the FCC-*ee* context.

B) CDR: Rare decays & anomalies — $B^0 \to K^{*0}\ \tau^+\tau^-$.

- Topological reconstruction of the missing energy with meas. of the decay vertices.
- Background estimates from generic double-charmed decays at SM values w/ proxies (no meas. available).
- Vertex detector can be very close to the beam pipe. Considered ILD-like vertexing performance.
- Focus here on the charged-only three-prongs decays of the taus.

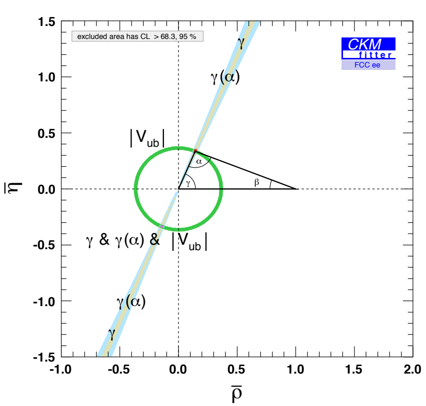


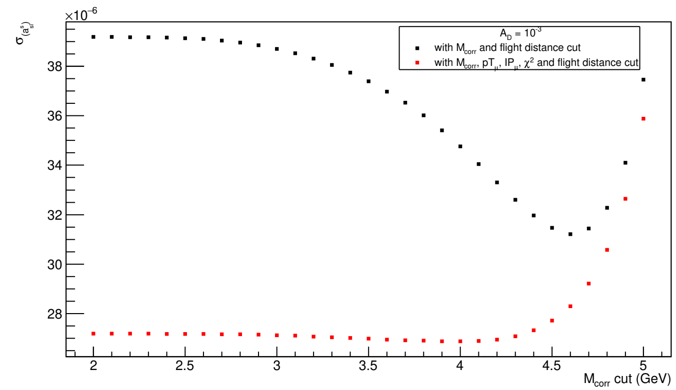
Bottomline: several thousands of decays can be reconstructed, if the branching fraction is at SM value. *O*(5%) precision on BF. Angular analyses can be performed [arXiv:1705.11106].

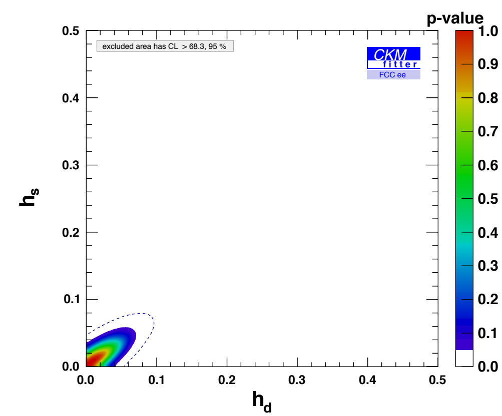
C) CDR: CKM and *CP* violation in quark mixings

- Expected precisions scaled with statistics and anticipated flavour tagging performance when necessary.
- First observation of *CP* violation in *B* mixing is at reach.
- A global analysis of BSM contributions in box mixing processes, assuming *Minimal Flavour Violation* pushes the BSM energy scale to 20 TeV.

Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-*ee*
CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	1.136 ± 0.004
$\lvert V_{ub}\rvert$ (precision)	5.9%	2.5%	6%	1%
Mixing-related inputs				
$\sin(2\beta)$	0.691 ± 0.017	0.691 ± 0.008	0.691 ± 0.009	0.691 ± 0.005
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	n/a	-3.65 ± 0.05	-3.65 ± 0.01
Δm_d (ps^{-1})	0.5065 ± 0.0020	same	same	same
Δm_s (ps^{-1})	17.757 ± 0.021	same	same	same
$a^d_{\rm fs}$ (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	-7 ± 2
$a^s_{\rm fs}$ (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	0.3 ± 2





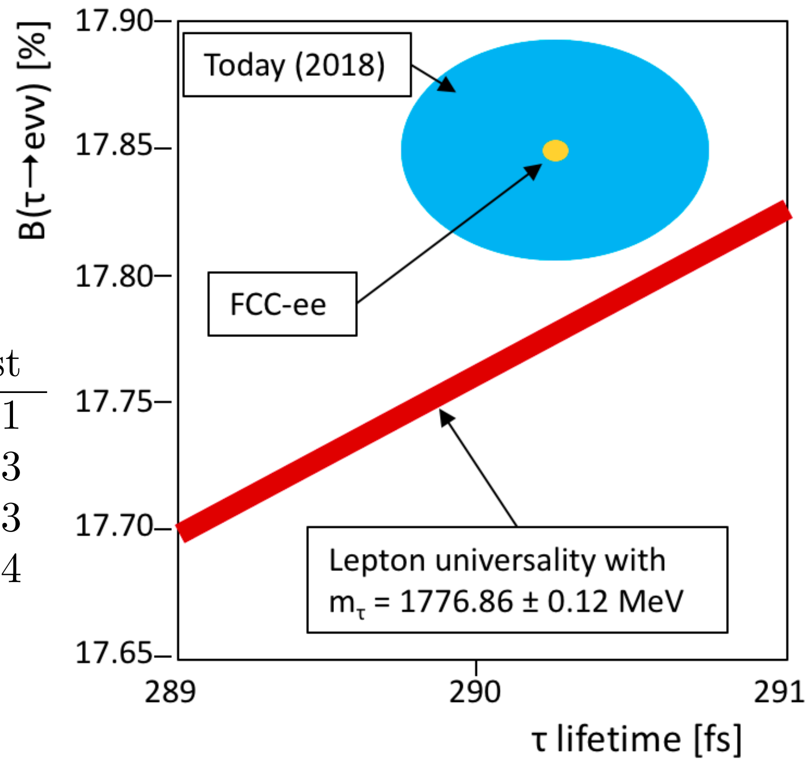


Bottomline: the constraints on BSM scale issued from *B*-mesons mixing observables with Minimal Flavour Violation $\Lambda_{\rm NP}(\Delta F = 2) > 20$ TeV

D) CDR: Tau decays and Lepton Flavour Universality

- Lifetime measurement in addition to branching fractions.
- Highly competitive Lepton Flavour Universality tests

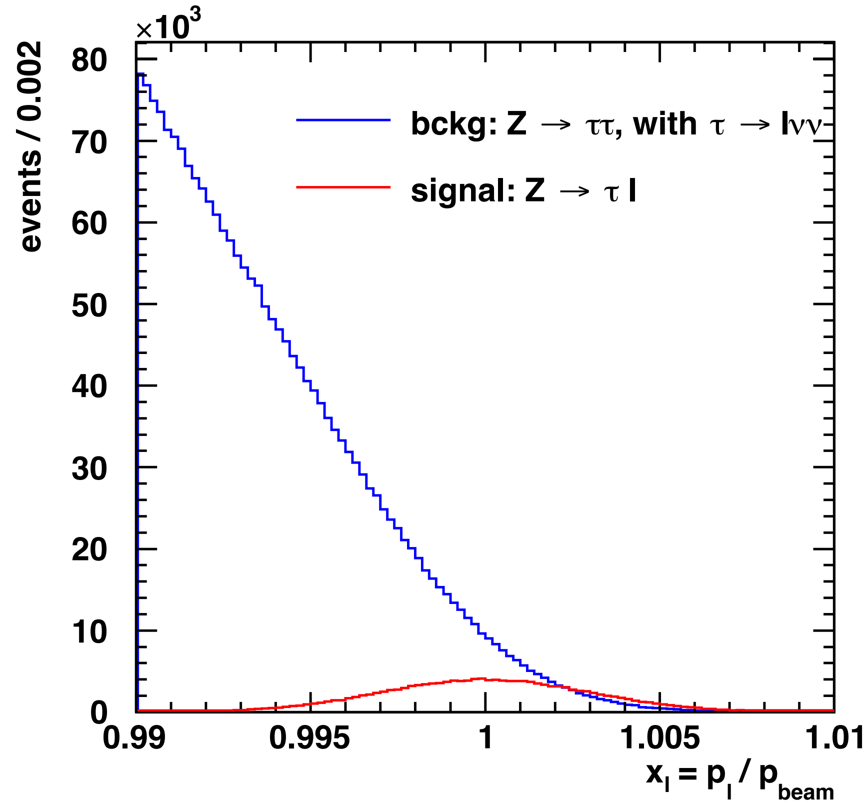
Observable / Property	Current WA	Stat.	Syst
Mass (MeV)	1776.86 ± 0.12	0.004	0.1
Branching fraction e (%)	17.82 ± 0.05	0.0001	0.003
Branching fraction μ (%)	17.39 ± 0.05	0.0001	0.003
Lifetime (fs)	290.3 ± 0.5	0.005	0.04



Bottomline: unprecedented statistics of boosted tau decay topologies.
Note: the systematic uncertainties projected here are scaled from LEP and ultra-conservative. Subjected to the cleverness of the experimentalists.

E) CDR: Lepton Flavour Violating-Z decays

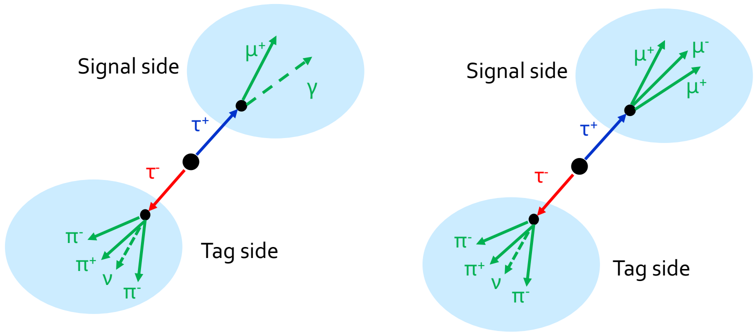
- Lepton Flavour-Violating Z decays in the SM with lepton mixing are typically < 10^{-50}.
- Any observation of such a decay would be an indisputable evidence for New Physics. FCC-*ee* exploration [JHEP 1504 (2015) 051].
- The dominant background is ($Z \to \tau\tau$), where one tau decays into a close to beam energy lepton. The search is limited by the momentum resolution.



Bottomline: With the expected tracking performance at FCC-*ee*, the current limits are pushed by three orders of magnitude.

$$\mathcal{B}(Z \to \tau^{\pm}\ell^{\mp}) < 10^{-9} \text{ @ } 95\% \text{ C.L.}$$

F) CDR: Lepton Flavour Violating-τ decays



Visible Z decays	3×10^{12}
$Z \to \tau^+\tau^-$	1.3×10^{11}
1 vs. 3 prongs	3.2×10^{10}
3 vs. 3 prong	2.8×10^{9}
1 vs. 5 prong	2.1×10^{8}
1 vs. 7 prong	< 67,000
1 vs 9 prong	?

- Benefits from the huge statistics and boosted topologies.
- Calorimetric performance as ILD.
- Main backgrounds are initial and final state radiative events.

Decay	Current bound	FCC-ee sensitivity
$\tau \to \mu\gamma$	4.4×10^{-8}	2×10^{-9}
$\tau \to 3\mu$	2×10^{-8}	10^{-10}

Bottomline: the current limits can be pushed by one to two orders of magnitude.

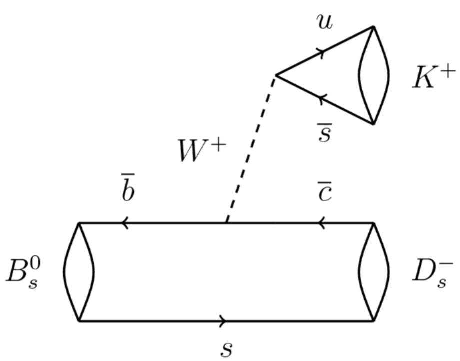
3) Hadron PID detector: p / K / π separation

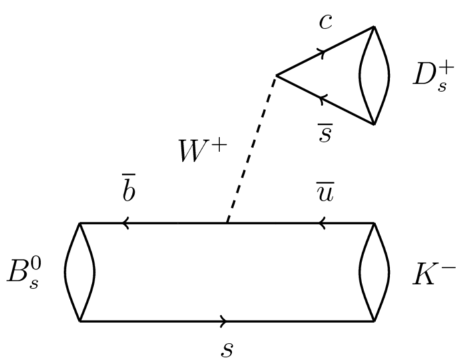
By a practical illustration:

- Pick a benchmark mode
- Check the momenta at work
- What is the separation w/o PID ?
- Check the tracking performance
- Add up all backgrounds.

Benchmark mode: *CP* violation studies with $B_s \to D_s K$

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

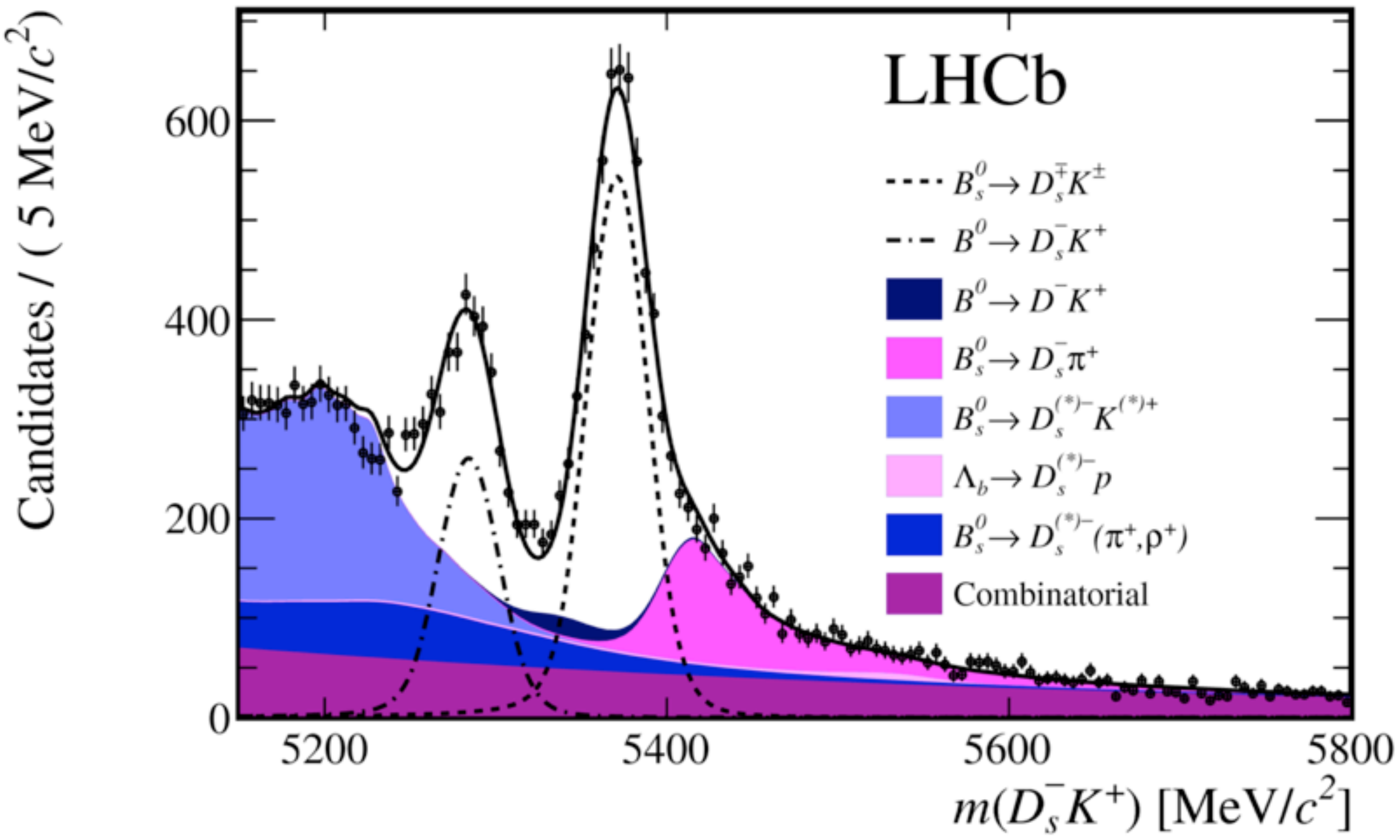




- for detectors: understand the needs of p / K / π separation. There is a competition of up-feeding and down-feeding contribution through mis-identification: $B_s \to D_s\pi$ and $\Lambda_b \to D_s p$. Serves also the purpose of quark flavour tagging.

CP violation studies: $B_s \to D_s K$:

LHCb-PAPER-2014-064
ArXiv:1412.7654

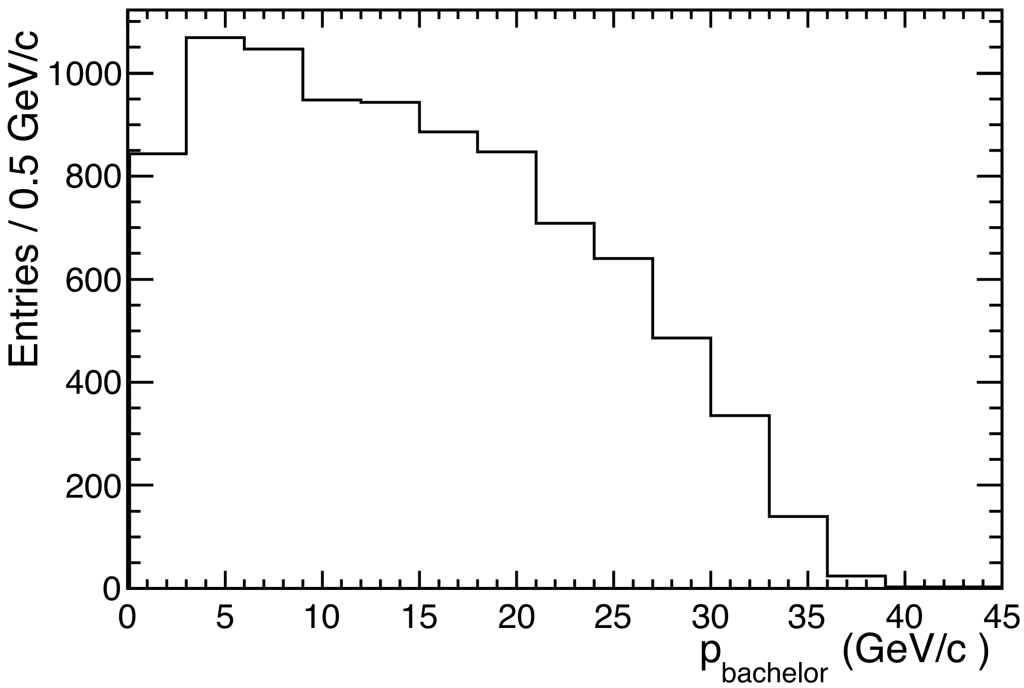


Note: this plot is obtained after PID cuts are applied ...

3) Hadron PID detector: *p / K / π* separation

• The discrimination acts on the bachelor particle *h* in $X_b \rightarrow D_s h$, *h* being *p / K / π* .

• Momentum of the *K* bachelor particle from 10 k $B_s \rightarrow D_s K$ simulated events (Pythia+ EvtGen).



• Since it is a Q2-body decay, one finds a hard spectrum of the bachelor particle (generally not representative of multibody *b*-hadron decays).

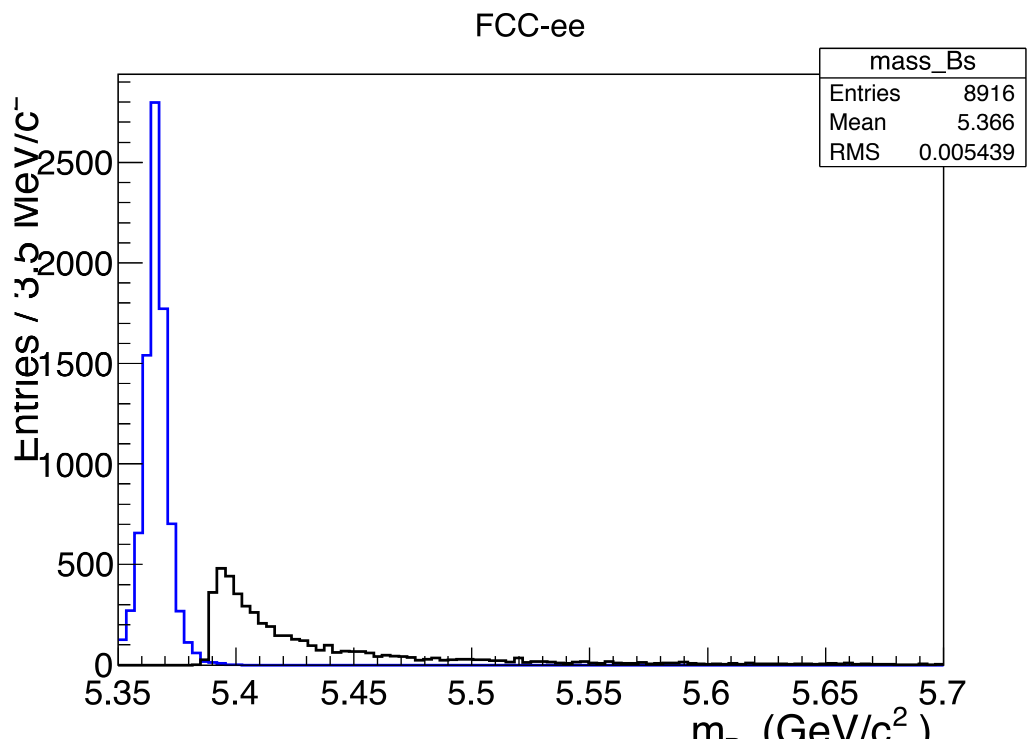
3) Hadron PID detector: p / K / π separation

- Reconstruct 10k events of $B_s \to D_s K$ *and* $B_s \to D_s \pi$ both under the hypothesis of $D_s K$ final state.

- The momentum resolution was emulated following ILD performance:

$$\frac{\sigma p_\perp}{p_\perp^2} = 2 \times 10^{-5} + \frac{10^-3}{p_\perp \sin\theta}.$$

2014 J. Phys.: Conf. Ser. 513 022011



- Not to the conclusion yet but remarkable that the most natural misidentification is defeated w/o PID specific detector.

3) Hadron PID detector: *p / K / π* separation

The momentum resolution was emulated following ILD performance, but now with the natural proportions of all the possible backgrounds:

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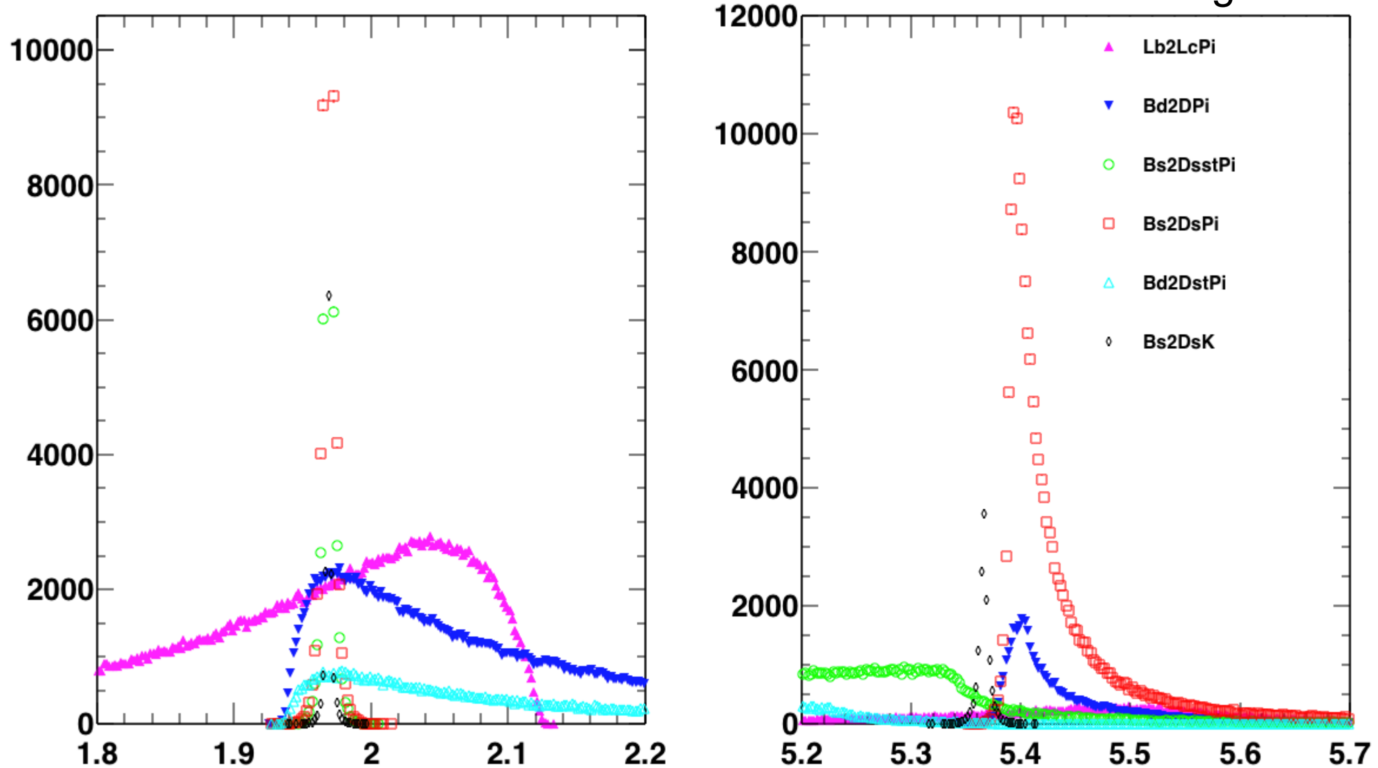
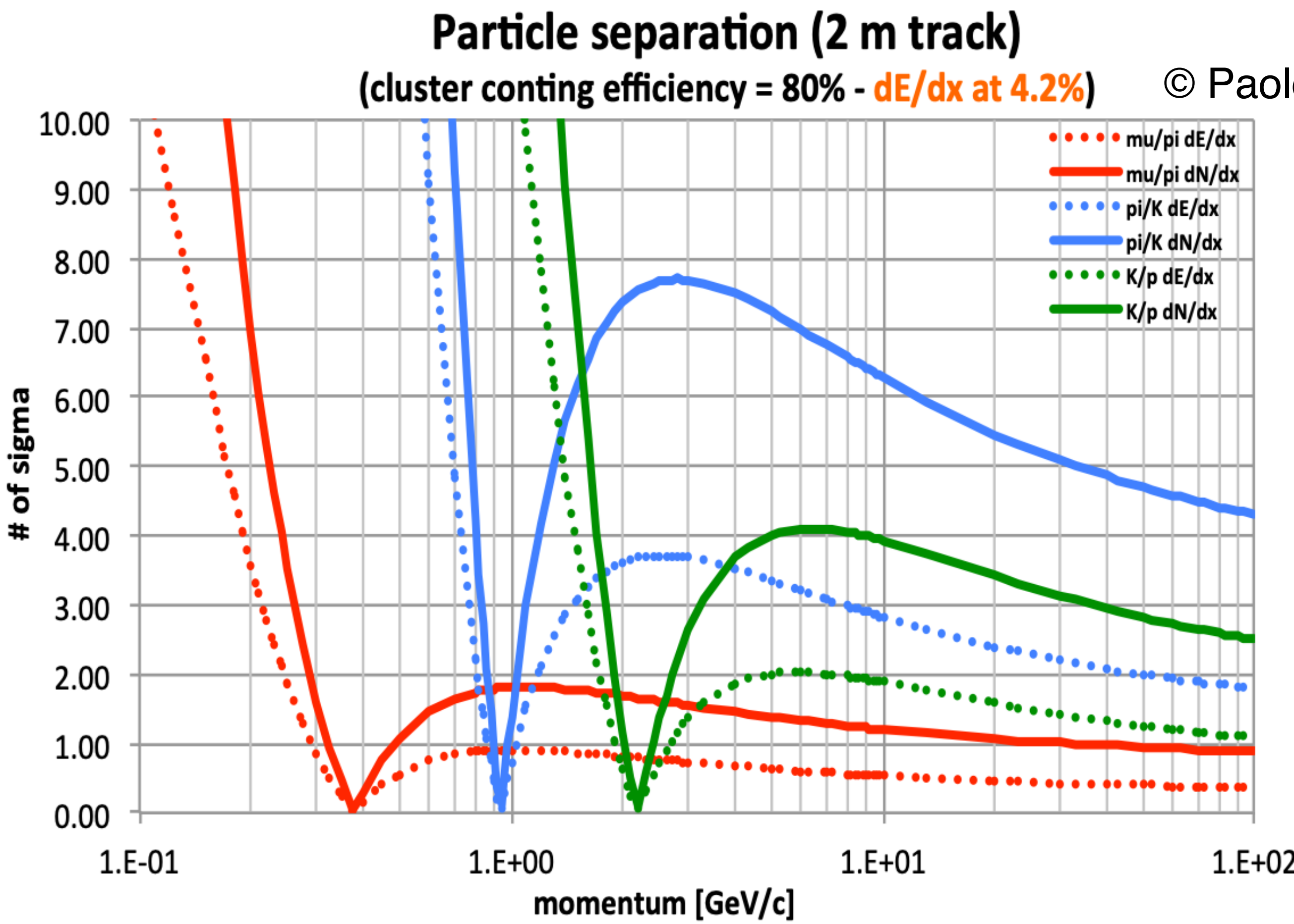


- Most toxic backgrounds are partially reconstructed *$B_s 2D^*_s Pi$*
- Hadron PID required to clear up the figure.

3) Hadron PID detector: p / K / π separation

A natural option is dE/dx measurements in the tracker



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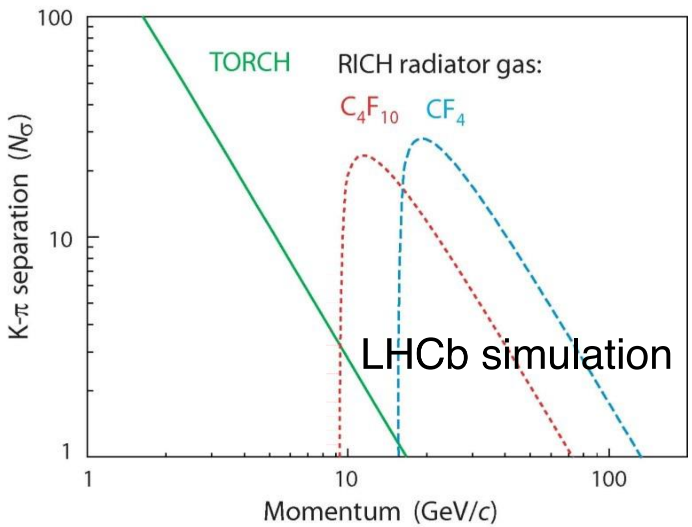
- If performance is confirmed, that's a good candidate.

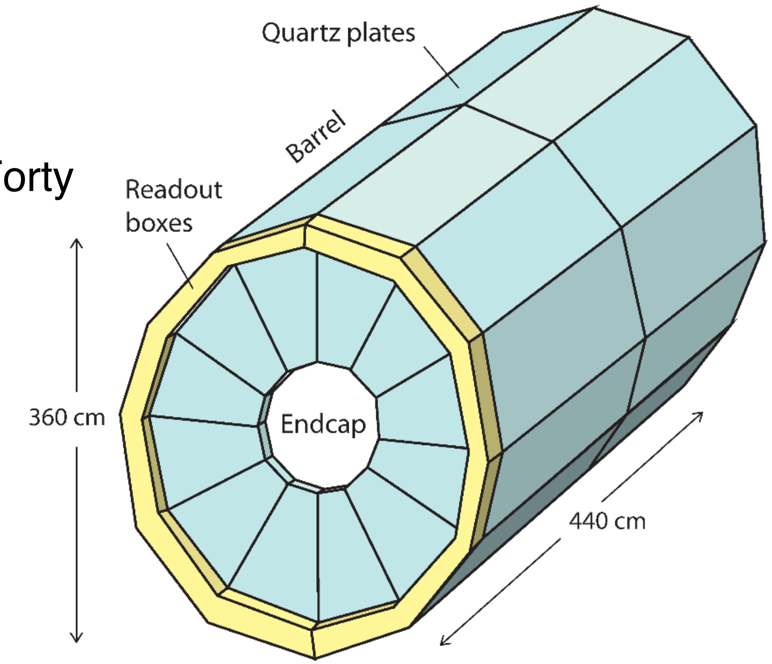
3) Hadron PID detector: p / K / π separation

Other options were envisaged: the TORCH technology (mixes RICH and TOF information as an example

Isolated tracks (TOF only)



© Roger Forty



- The momentum range for good separation is more modest, but redundancy might prove useful. Compromise to be found with the amount of material (8% of X^0) in front of the calorimeter.

4) Plans for the short term: detector concepts.

- How Flavour Physics can help to exercise the detector concepts?

- Topological reconstruction (full kinematical solution) à la $B^0 \to K^{*0}\ \tau^+\tau^-$: demanding vertexing performance.

- Tau Physics (standard Branching Fractions per se or in view of the tau polarisation optimal measurement): History (and intuition) tells us that current best precision for modes with π^0 were highly dependent on the calorimeter design / performances. Transverse and longitudinal segmentation are in order. Extends to electrons / gammas in jets / b-hadron decays

- LFV Z decays search poses demanding tracking requirements.

- The quark flavour program relies for a significant part on Hadronic Particle Identification. A canonical mode to benchmark PID detector concepts can be $B_s \to D_s K$. Exploratory study was engaged showing the necessity of PID. To be continued with actual detectors.

5) Summary

- Exploration phase for Flavour Physics was successful / promising:
  - FCC-*ee* can compete favourably with each of the ultimate precisions of LHCb and Belle II experiments.
  - There are processes for which FCC-*ee* is unique. The explored subjects in the CDR will benefit of full simulations of different detector concepts and should be reviewed in the light of realistic detector performance.
  - 5 10^{12} Z decays are needed (most of the measurements reported here are statistically limited).

- The initial case can be strengthened with additional flagship studies (*e.g.* $B_s \to \tau^+\tau^-$, $B^+_c \to \tau^+\nu_\tau$, etc…) with full simulation and the consolidation of the CKM profile(s).

- Flavour Physics defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements. The next phase of the program should entangle the Physics performance and detector concepts.

5) References as a conclusion:

- CDR(s):
  - https://fcc-cdr.web.cern.ch
- FAQs about FCC:
  - https://arxiv.org/pdf/1906.02693.pdf
- Join the Study (a model):
  - https://www.cern.ch/fcc-ee (then *join us* item and provide your preferences)
  - A successful approach in Flavours has been to gather small groups of experimentalists and theoreticians targeting at a paper. The unique opportunities offered by FCC-*ee* can trigger new ideas / new areas of thinking to be applied to current programs.
- Software is up as Clément advertised ! Hands-on tutorials available here:
  - https://indico.cern.ch/event/839794/
- Rapid (EvtGEn + param. detectors) study also possible. Get in touch!