(Heavy) Flavour Physics requirements on the detector design

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Outline

1. Vertexing (from FCNC *b*-hadron EW penguins)

2. Momentum resolution (from cLFV *Z* decays)

3. Charged particle identification p / K / π (from *CP*-violating weak phase measurements)

4. Calorimetry (from feelings)

Disclaimer: gathering ideas given in presentations here:

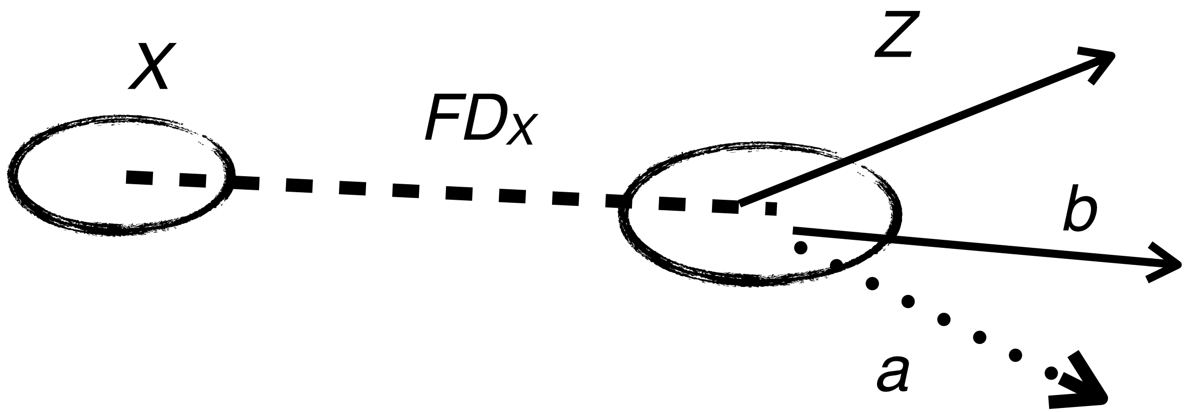
https://indico.cern.ch/event/438866/contributions/1084975/attachments/1258656/1859177/Monteil_FCC.pdf

https://indico.cern.ch/event/687191/

1) Vertexing — topological reconstruction

- One of the most demanding requirement for vertex detectors comes from the missing momentum reconstruction inferred from the decay flight distances.

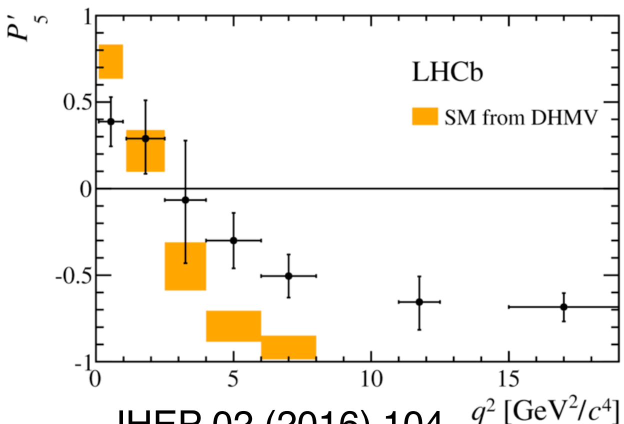
- Example: $X \to Y\,(\,Y \to [a]b\,)\,Z$ with *a* not reconstructed.



- Three momentum components to be searched for:
  - The measurement of *X* momentum direction fixes 2 d.o.f.
  - An additional constraint closes the system: m_Y or a tertiary vertex.
  - Usually, quadratic form of the constraints: solution up to an ambiguity.

1) Vertexing. Physics motivations in one slide.

- There are consistent and persistent departures in measurements of the FCNC decays $b \to s\ \ell^+\ell^-$ w.r.t. the SM predictions.



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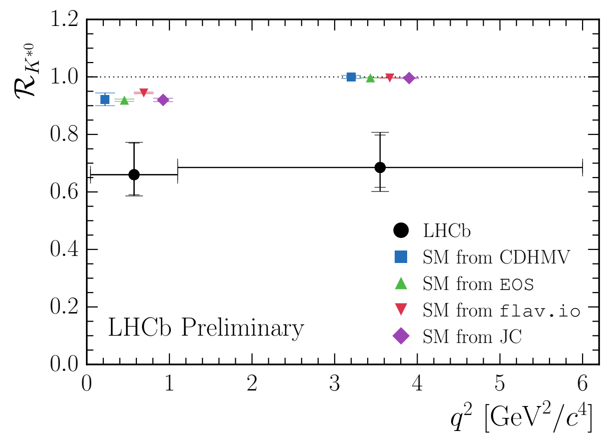
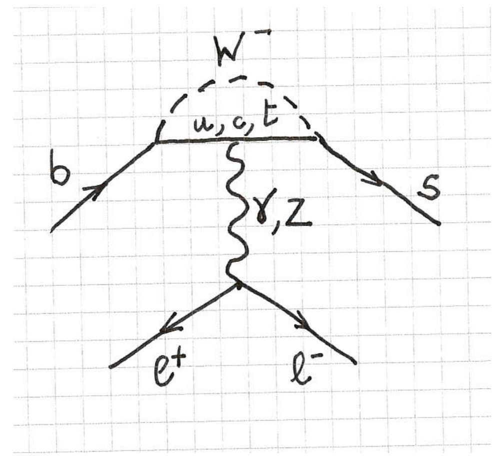




- In particular, Lepton Flavour Universality is challenged. Should anomalies be confirmed, modes with tau decays can prove to be invaluable to point towards the right model.

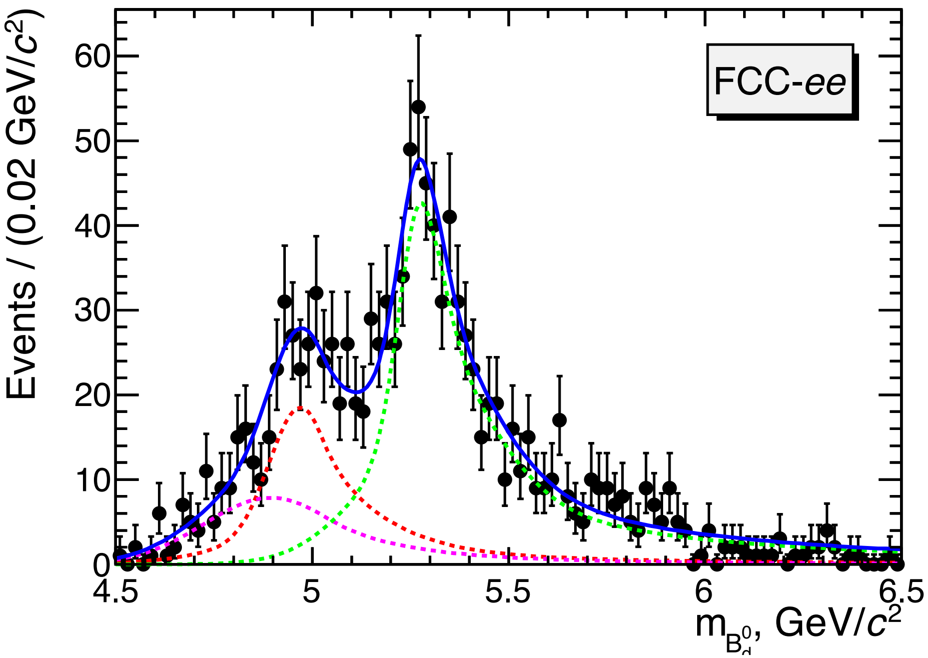
- $B^0 \to K^{*0}\ \tau^+\tau^-$ unique at FCC-*ee*. It has received a special attention in the FCC-*ee* context.

1) Vertexing. Reconstruction.

- 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).

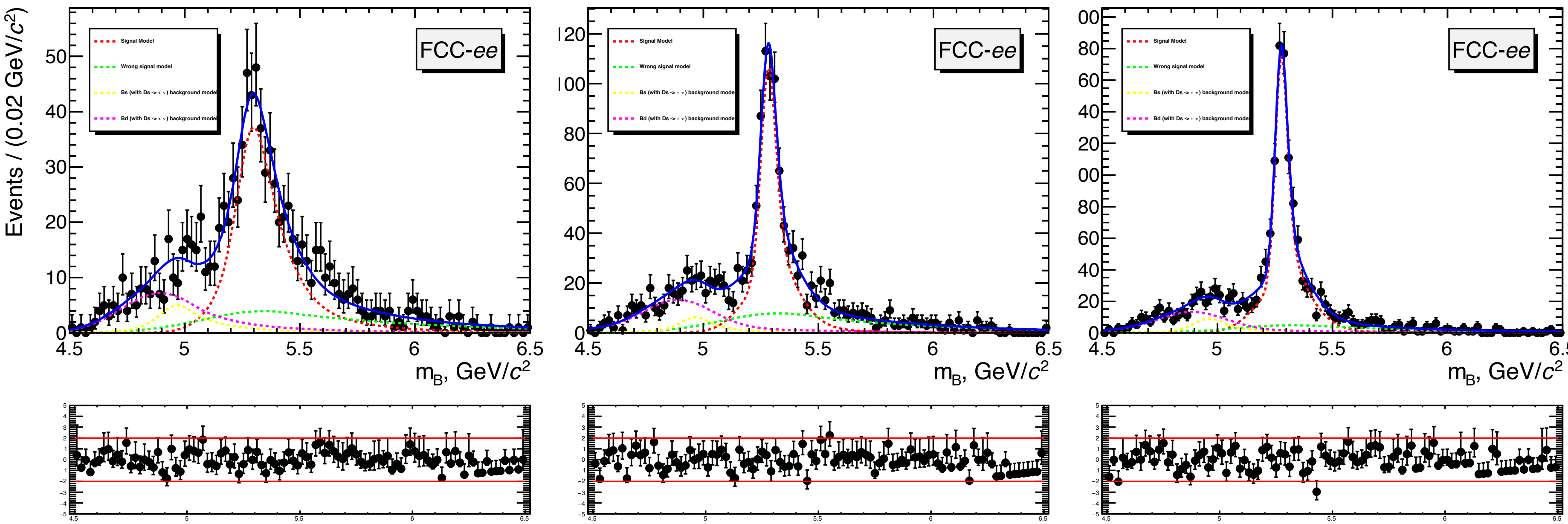
- Conditions: baseline luminosity, SM calculations of signal and background BF, vertexing and tracking performance as ILD detector. **Momentum** → 10 MeV, **Primary vertex** → 3 um, **SV** → 7 um, **TV** → 5 um



Few comments:

- At baseline luminosity, several 10^3 events of reconstructed signal. Angular éanalysis possible.
- With an ALEPH-like vertex detector performance, the signal peak can't be resolved.
- Another interesting and more challenging mode is $B_s \to \tau^+\tau^-$.

1) Vertexing. Performance of reconstruction (BF)



Performance / Conditions	ILD-like	ILD /2	ILD / 4
Efficiency of the identification of the correct solution (%)	42,3	52,6	62
Invariant mass resolution (core) [MeV/c^2]	42(1)	36(1)	27(1)

1) Vertexing. Outlook.

- The Physics perspectives are the sensitivity on the measurements of the branching fraction (differential in q^2) and the angular analysis of the decay.

- As soon as we go to angular observables, the angular resolution will provide additional constraints.

- This has been explored phenomenologically in arXiv:1705.11106.

- One needs to go to full simulation to provide sound figures on the BF and angular observable precisions.

2) Momentum resolution from cLFV *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) Momentum resolution from cLFV 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 here :

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.

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

2) Momentum resolution — Summary and one more

- cLFV *Z* decays studies requires to reach a momentum resolution at the level of the beam energy spread.

- Additional remarks on tracking:

  - *CP* violation program will be rich at FCC-*ee.* We can do with a significantly larger statistics the Belle II program (B^0 and B^+) plus the other weakly-decaying species (B_s , B_c and the *b*-baryons Λ_b, Ξ_b …)

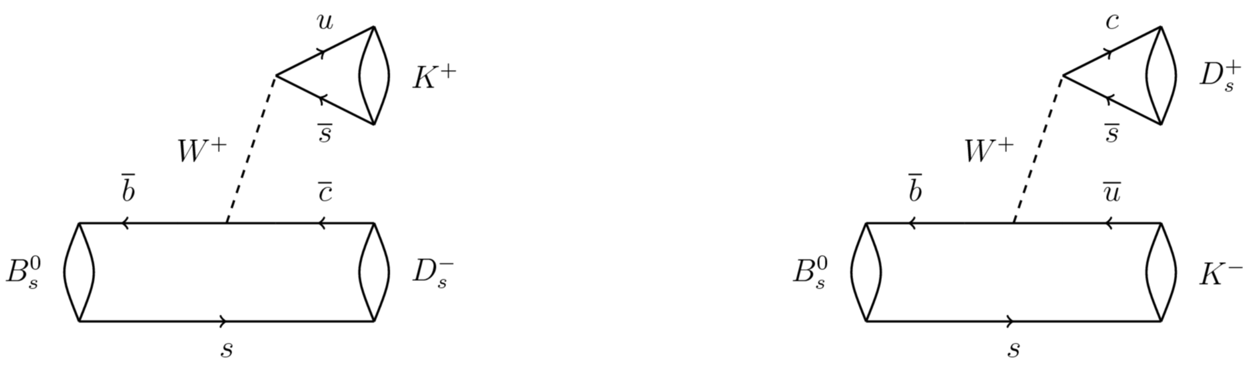
  - In many occurrences, one needs to select *CP* eigenstates with long-lived particles in the detector: K_S and Λ.

  - V^0 tracking capabilities is in order.

3) Particle identification: *p / K / π* separation

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

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

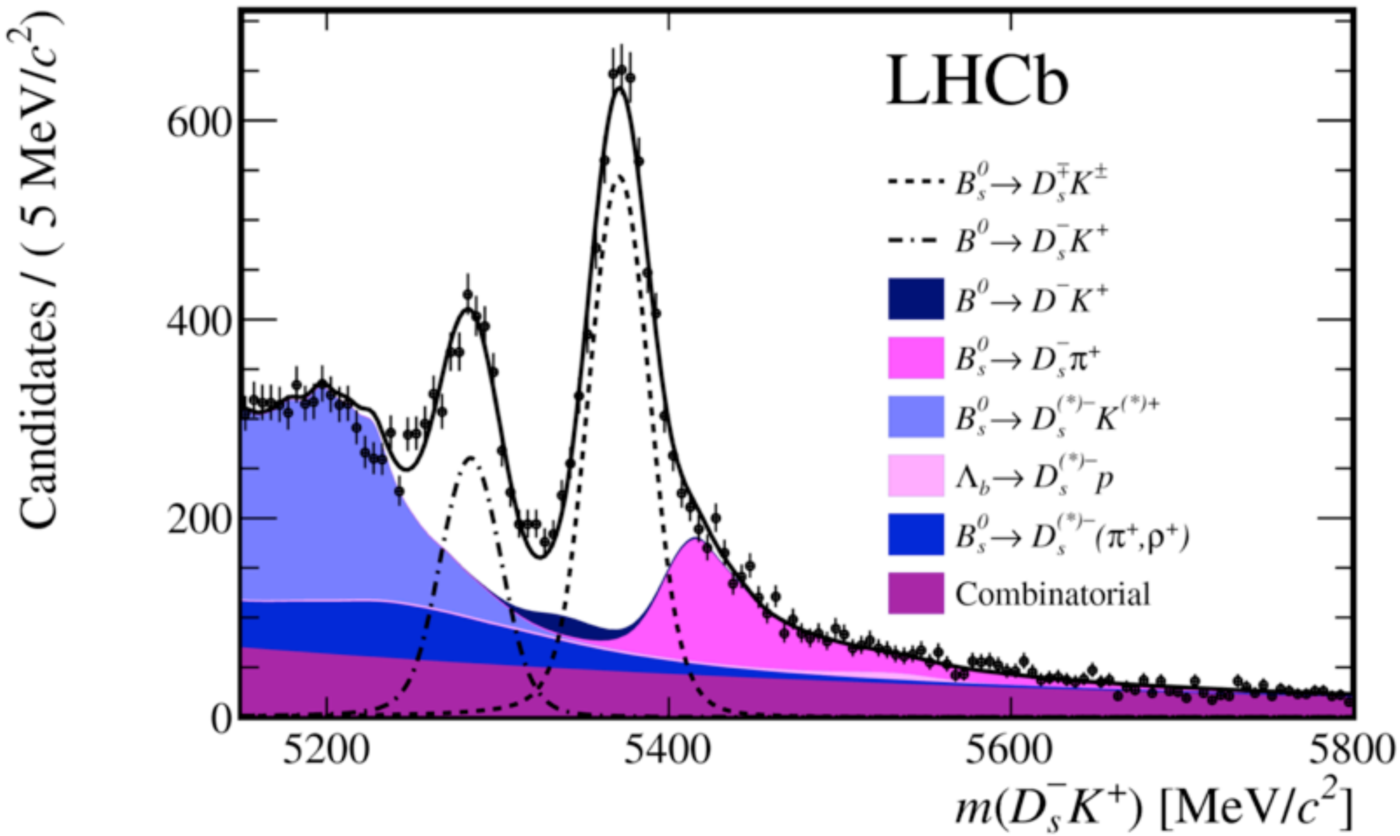


- for detectors: understand the needs of *p / K / π* separation. This mode is interesting since there is a competition of up-feeding and down-feeding contribution through for instance mis-identification: $B_s \rightarrow D_s\pi$ and $\Lambda_b \rightarrow D_s p$. At some point , it will be useful as well to determine the quark flavour tagging effciency *(e.g.* same side kaon).

3) Particle identification: *p* / *K* / *π* separation

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

LHCb-PAPER-2014-064
ArXiv:1412.7654

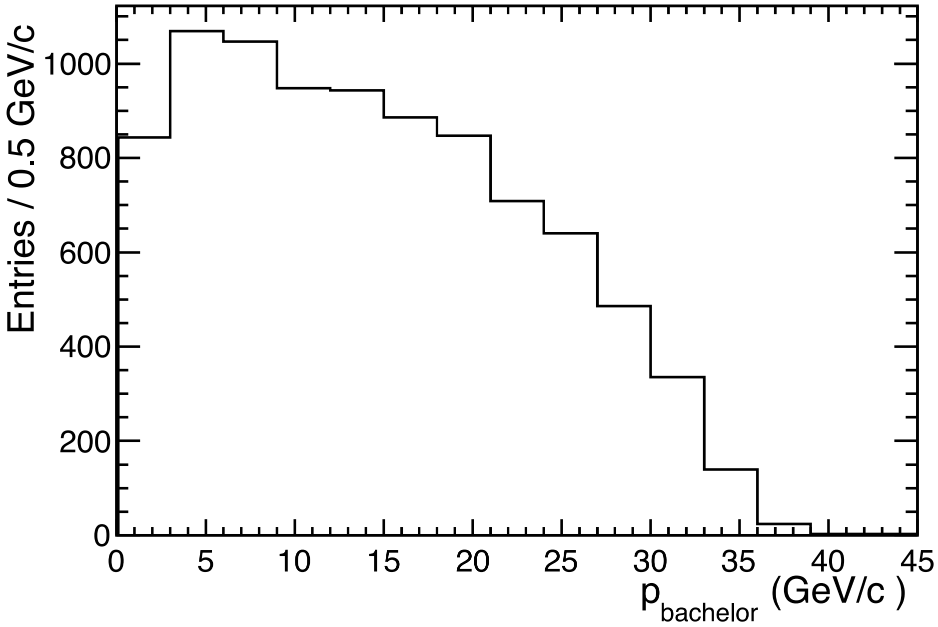


Note: this plot is obtained after PID cuts are applied ...

3) Particle identification: $p / K / \pi$ separation

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

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

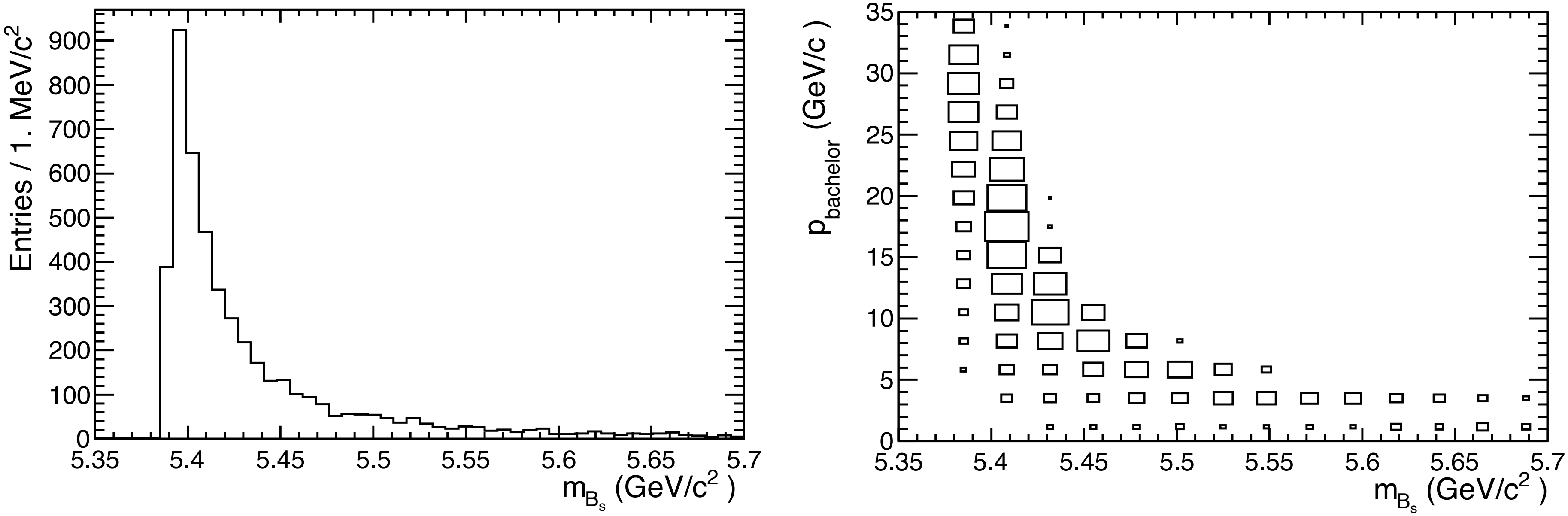


- Since it is a Q2-body decay, one finds a hard spectrum of the bachelor particle (generally not representative of *b*-hadron decays).

3) Particle identification: p / K / π separation

- The discrimination acts on the bachelor particle h in $X_b \rightarrow D_s h$, h being p / K / π . 10 k of $B_s \rightarrow D_s\pi$ were generated to

- reconstruct $B_s \rightarrow D_s\pi$ as $B_s \rightarrow D_s K$. Correlate the invariant mass with the Bachelor particle momentum.



- The harder is the momentum, the higher is the cross-feeding probability.

3) Particle identification: *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.

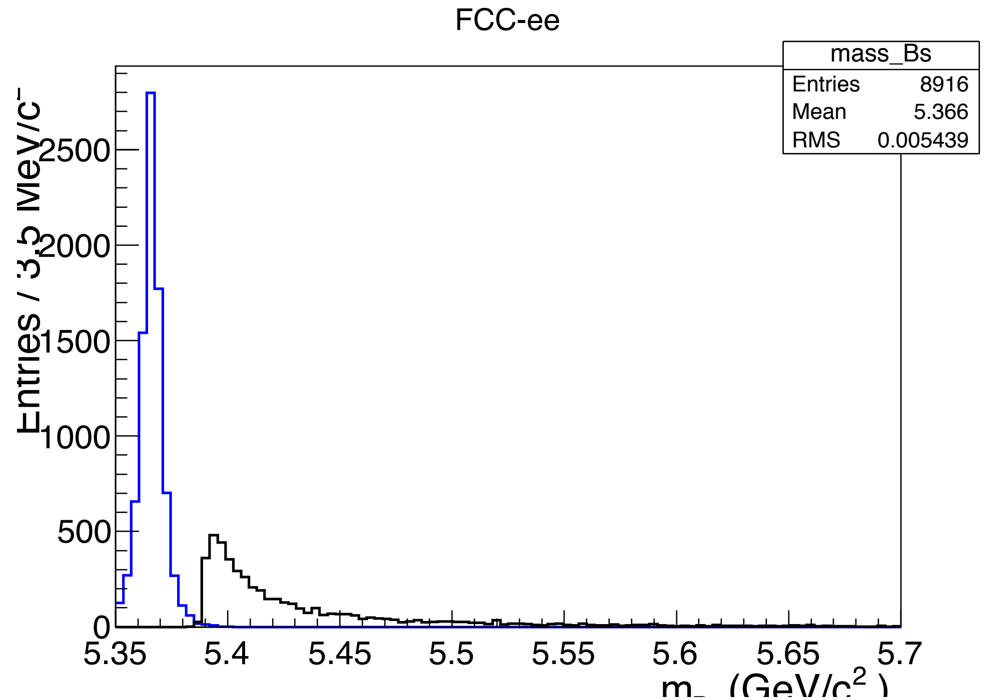
- The momentum resolution was emulated following ILD performance:

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

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

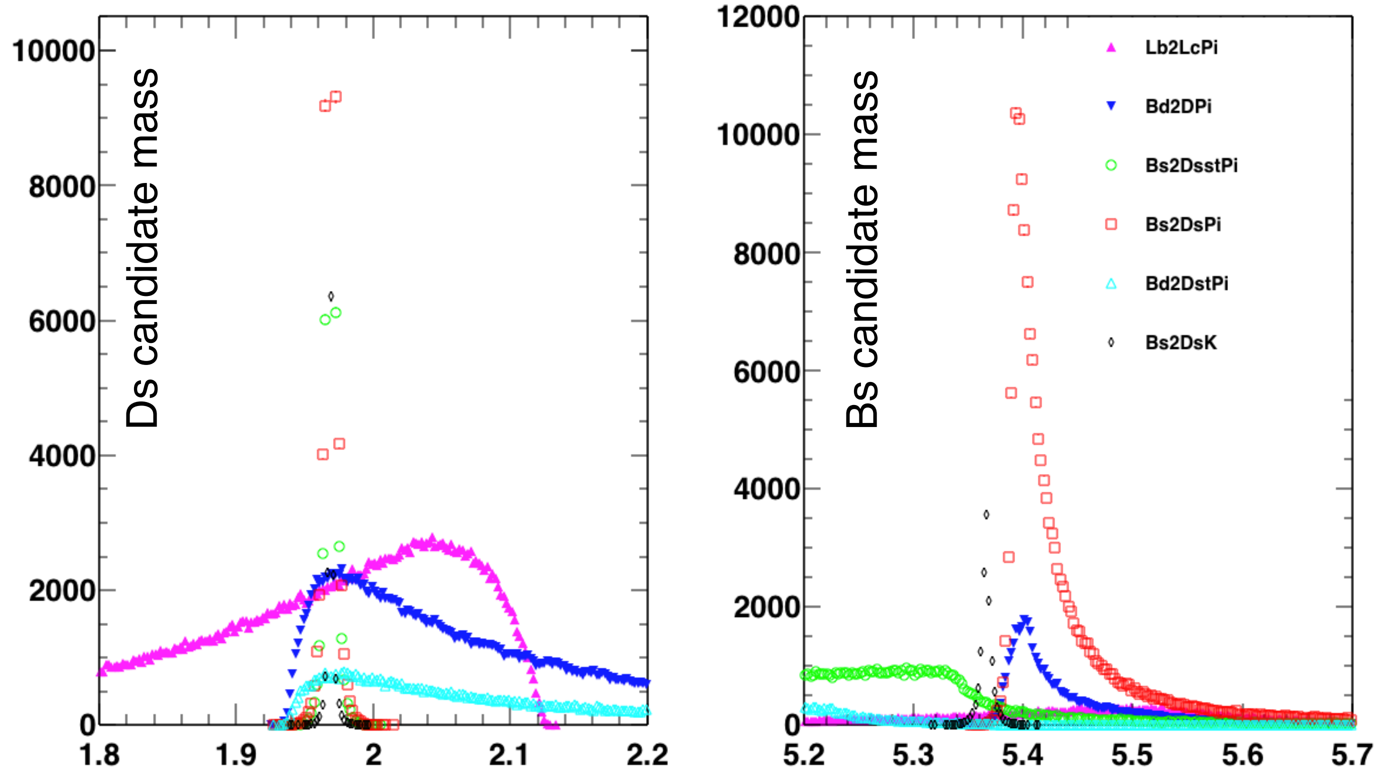
- Fantastic separation of the two components but that is not the end of the story.

- The other backgrounds from partially reconstructed events must be accounted for.



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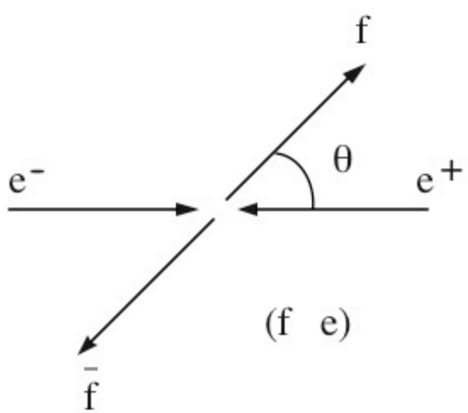
- Most toxic backgrounds are partially reconstructed $B_s 2D^*_s Pi$
- Hadron PID required to clear up the figure.

3) Particle identification: *p* / *K* / *π* separation

A further comment of the necessity of hadronic PID beyond the Flavour Physics program.

- The measurement of the forward-backward asymmetry of the *b* quark in *Z* decays is primarily meant for *Ab* determination, since muons must 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.

3) Particle identification: p / K / π separation

A further comment of the necessity of hadronic PID beyond the Flavour Physics program.

- Limitations of LEP-like measurements of $A_{FB}(b)$:
  - mixing dilution with lepton tags (and jet charge).
  - 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.

3) Particle identification: p / K / π separation

A further comment of the necessity of hadronic PID beyond the Flavour Physics program.

- Limitations of LEP-like measurements of $A_{FB}(b)$:
  - mixing dilution with lepton tags.
  - purity of the sample.
  - QCD corrections (gluon radiations).

- Hadron PID required for at least correct mass assignment of the hypothesis and get rid of cross-feeds.
- 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 (to be studied but should reduce the QCD corrections by selecting clean topologies).
- Many other use cases from exclusive reconstructions.

4) Calorimetry — generalities

The Flavour (tau and *b*-hadron Physics) constraints are mostly inline with the standard needs of the (Particle) Energy Flow requirements:

- Tracking π^0 in jets or tau decays.
- Identify neutral hadrons in jets.
- Identify electrons in jets.
- For rare LFV processes, separate muons and electrons.
- Identify missing energy position in jets (*e.g. B2Kvv*)

In turn, the requirements follow:

- High transverse granularity.
- Fine longitudinal segmentation.
- The farer the better.
- The lighter (in front) the better.

5) Conclusions (1)

1. Vertexing from FCNC *b*-hadron EW penguins

- Topological reconstruction (w/ missing neutrinos) is very demanding for the vertexing: EW penguin transition $B^0 \to K^{*0}\ \tau^+\tau^-$ (unique to FCC-*ee*) used as a benchmark.
- ILD performance makes the job for this one. But the more resolved the better.

2. Momentum resolution from LFV *Z* decays and *CP* studies

- Aiming at hitting the beam energy spread @ 45 GeV.
- V^0 tracking is mandatory for *CP* violation studies

5) Conclusions (2)

3. Charged particle identification *p / K / π*

- It is mandatory at least for the Flavour Physics program. More stringent requirements in the momentum range than Belle II.
- Hadronic PID beneficial beyond the Flavour case.
- We'll hear next of several appealing approaches.

4.Calorimetry

- High transverse granularity
- Longitudinal granularity is in order (calorimeter tracking).