Flavours Physics (rare decays, tau physics, CKM profile) at e^+e^- Higgs/top/EW/Flavour factories:

considerations on detector requirements

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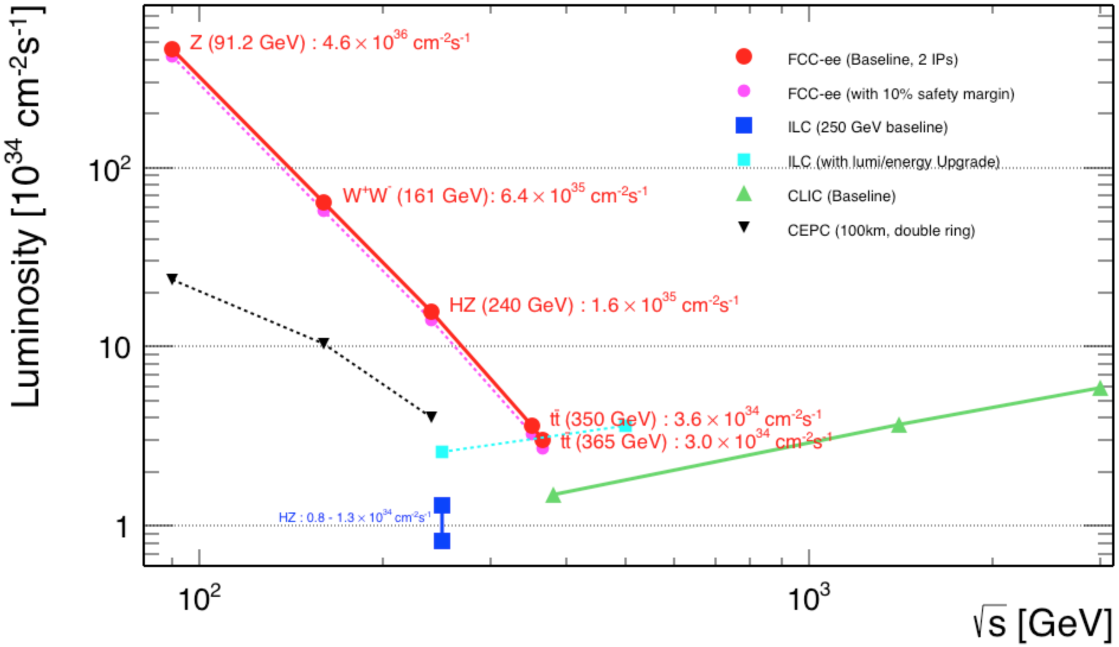
1. Flavours Physics. Experimental landscape 2040

- A rich program (approved and foreseen projects) in the next two decades.

- LHCb : 9/fb (still a lot to analyse)
- ATLAS & CMS: in operation, aims at 3000 /fb.
- Belle II: in operation, aims at 50 /ab.
- LHCb Upgrade 1: in operation, aims at 50 /fb.
- LHCb Upgrade 2: FTDR, not yet approved, aims at 300 /fb.
- Belle III: in discussion, aims at 250 /ab.
- Super Tau Charm Factory (STFC): close to threshold, aims at 20 /ab.

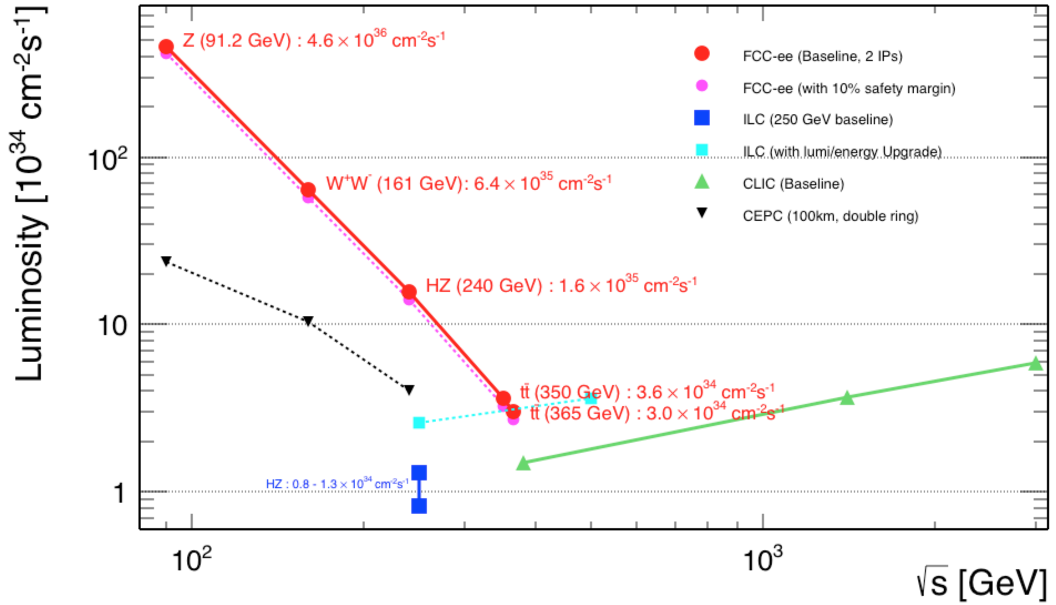
- Sharpening further the knowledge at the next machine?
  - Flavour Physics is about luminosity (no case to date w/ polarised beams).
  - You want at least 10 x Belle statistics $\Longleftrightarrow$ *e.g.* 5.10^{12} Z decays.
  - More is desirable! Circ. coll. are hence unique for this Physics.

1. Flavours Physics ⟹ Luminosity



- Most interesting electroweak thresholds for Flavours: 10^5 *Z*/s , 10^4 *W*/h. In a very clean environment: no pile-up, controlled beam backgrounds, *E* and *p* constraints, w/o trigger loss.
- After two decades of B-factories, some LEP meas. still dominate (*e.g.* $b \to c\tau\nu$). Note that you do the LEP in a minute!

1. Flavours Physics ⟺ {Luminosity⊗Precision}



Attribute	$\Upsilon(4S)$	pp	Z^0
All hadron species		✓	✓
High boost		✓	✓
Enormous production cross-section		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)

Not only statistics at work.

Attention required to:

- Decay vertices,
- Invariant-masses,
- Missing energy,
- Long-lived particles, etc…

1. Flavours Physics $\Longleftrightarrow$ {Luminosity$\otimes$Precision}

- Motivation for this talk:

- The Flavour physics programme has been addressed at the first FLAV working group meeting: https://indico.cern.ch/event/1165192/

- It covers rare decays (focus on yesterday) but also CKM profile and tau physics (focus on net meetings).

- I will touch in this talk few of the important measurements in those two areas to question the required detector performances.

- Also suggest some analyses where a benchmark is desirable.

Outline

1. Circular e+e- colliders as the ultimate Flavours Factory
2. Tracking performance from the search for $Z \to \tau\mu$
3. Vertex performance from $B^0 \to K^{*0}\ \tau^+\tau^-$
4. V^0 tracking performance $B_s \to K_S K_S$, $B_0 \to K_S K_S K_S$
5. Calorimeter performance from $B_s \to \phi\gamma$, $B^0 \to (\pi^0\pi^0)$.
6. Jet flavour tagging from $|V_{cb}|$
7. Particle identification considerations
8. Conclusions

2. Tracking performance

- 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].

- $Z \to \tau\mu$ is likely unique to FCC-ee.

- 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. A lot of phenomenology to explore yet.

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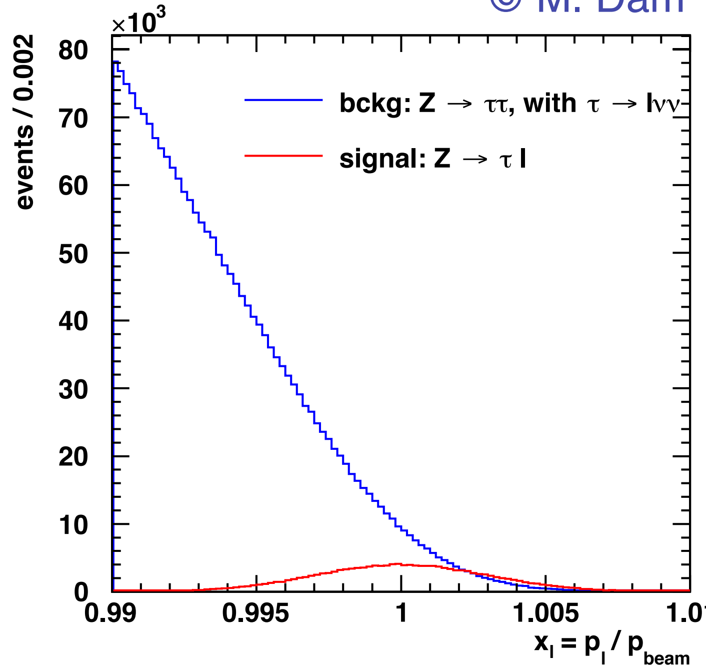

Bottomline for detector : the momentum resolution must be as good as the beam energy spread. This is close to state-of-the-art trackers used in simulation (CLD, IDEA).

2. Tracking performance

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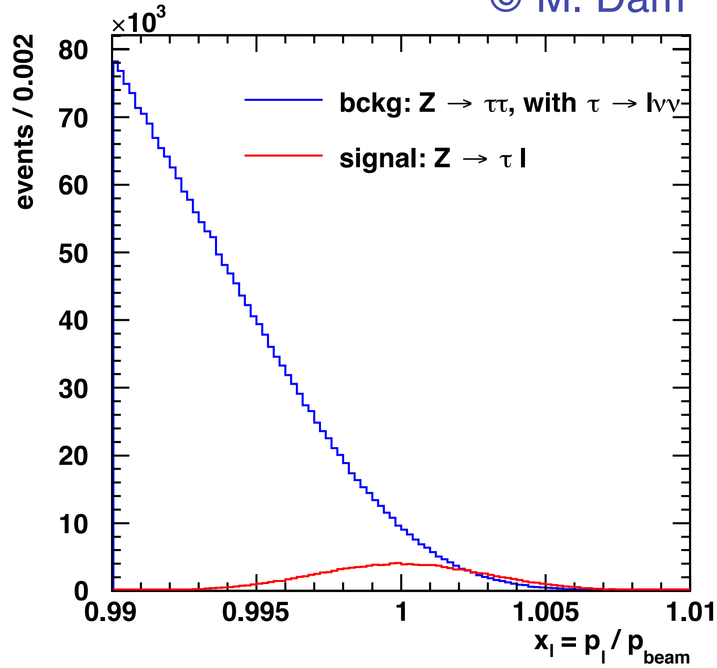
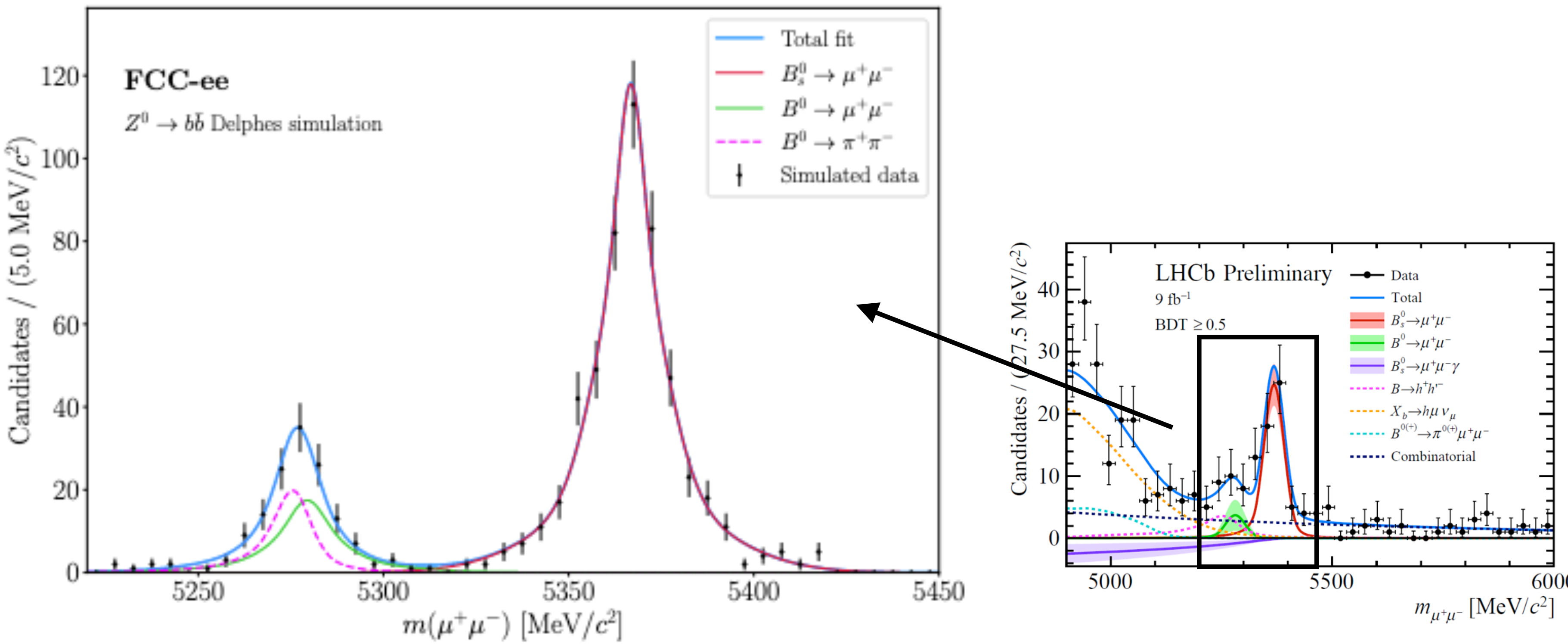


Bottomline for Physics: With the current tracking performance emulation at FCC-*ee* , the current limits are pushed by three orders of magnitude.

2. Tracking performance — Application

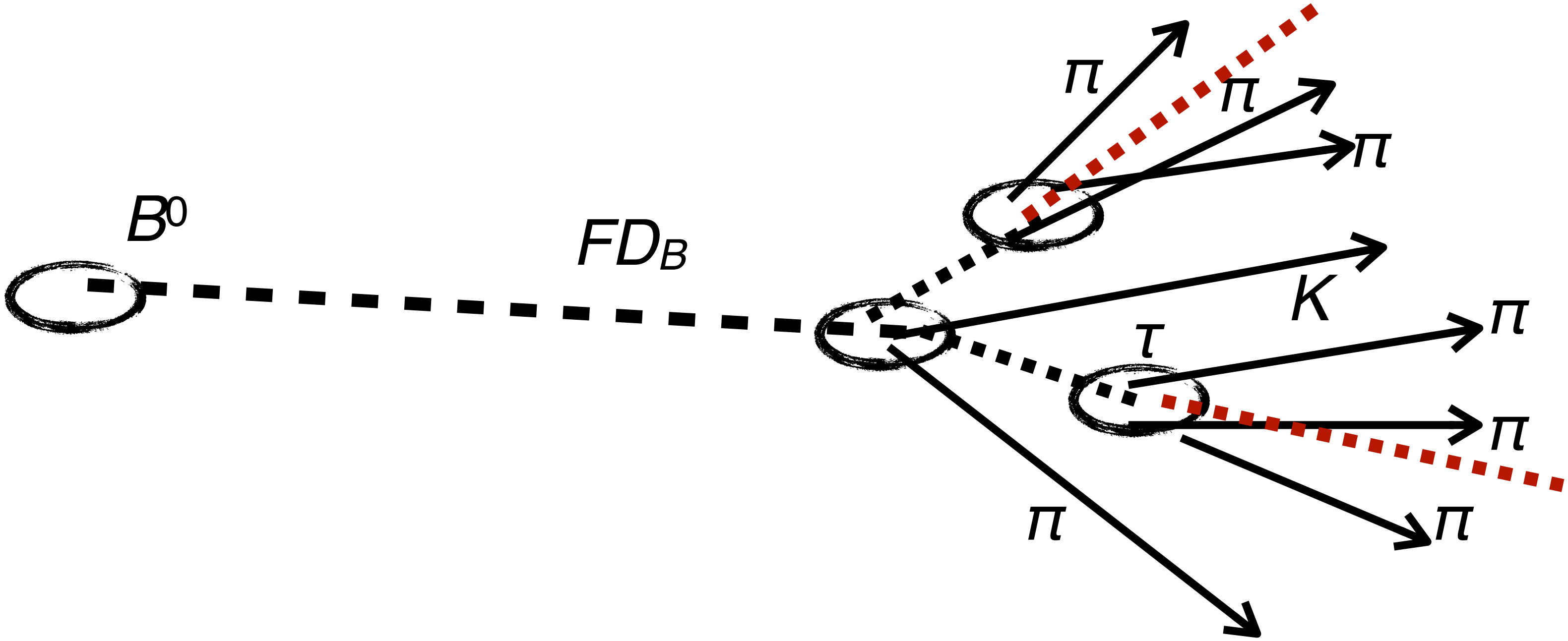
Invariant-mass resolution as it is in the current state of IDEA fast simulation:



For heavy-flavoured charged track modes, “perfect” separation of Bd and Bs spectra. Performance set !

3. Vertex performance: $B^0 \to K^{*0}\ \tau^+\tau^-$

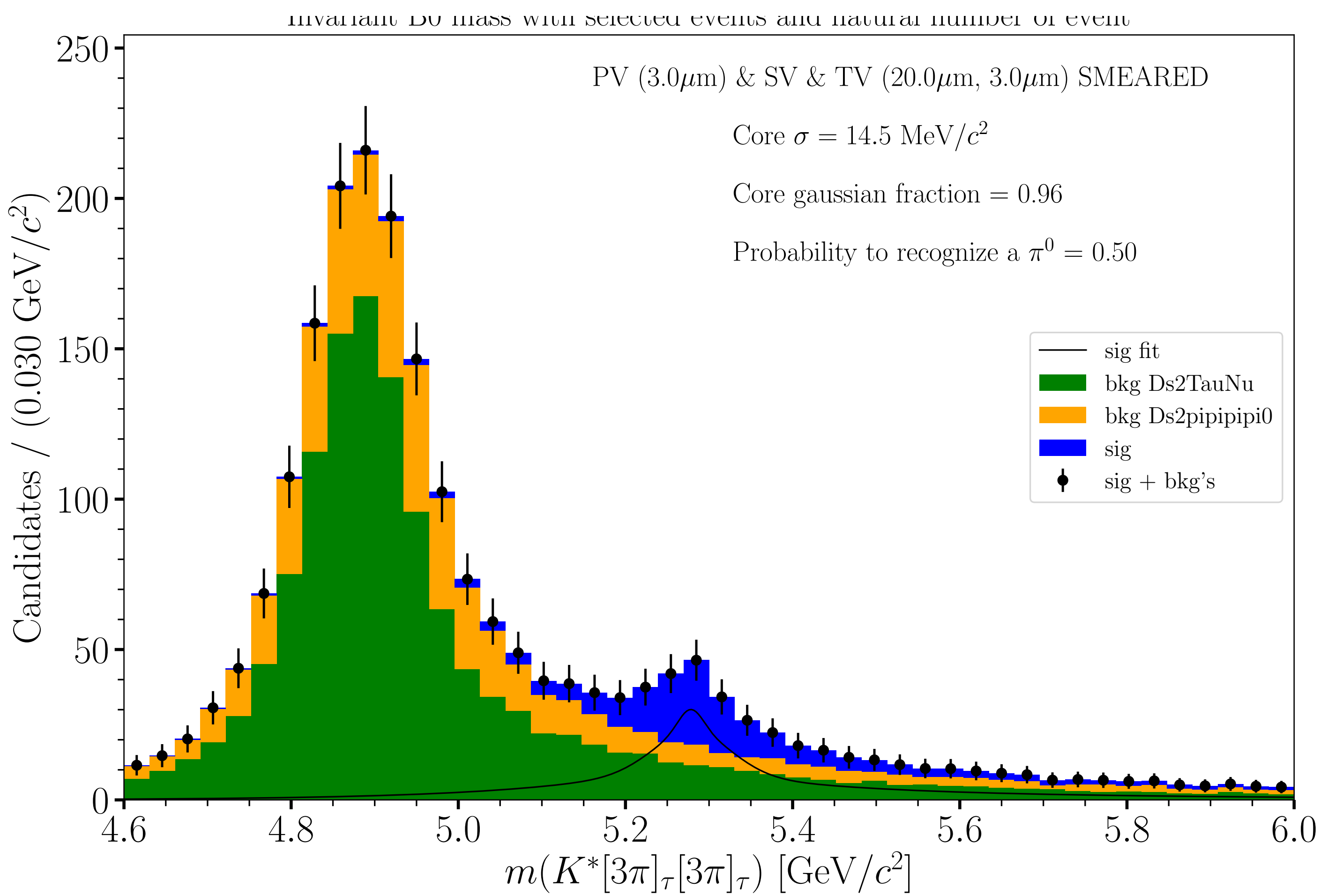
- $B^0 \to K^{*0}\ \tau^+\tau^-$: some vertices indeed.



- Six momentum components to be searched for:
  - B^0 momentum direction from $K\pi$ fixes 2 d.o.f.
  - τ momenta direction fixes 4 d.o.f.
  - Mass of the τ provides 2 additional constraints
  - Since both tau legs provide quadratic equations, one ends up w/ 4 solutions.
  - Yet, the system is over-constrained and in principle fully solvable.

3. Vertex performance: $B^0 \rightarrow K^{*0}\ \tau^+\tau^-$

- $B^0 \rightarrow K^{*0}\ \tau^+\tau^-$: a couple of backgrounds that an adequate vertexing can discriminate.



3. Vertex performance: $B^0 \to K^{*0}\ \tau^+\tau^-$

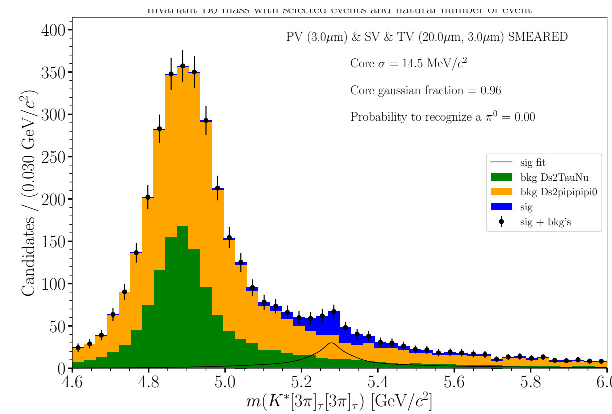
- $B^0 \to K^{*0}\ \tau^+\tau^-$: executive summary

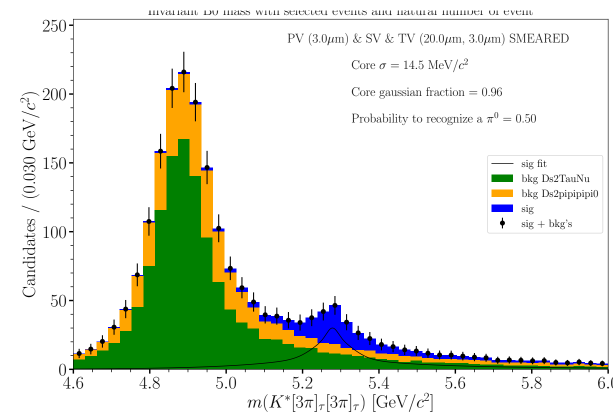
- IDEA Delphes card for *p* resolution. Vertexing performance from smearing: allows to assess the required performance.

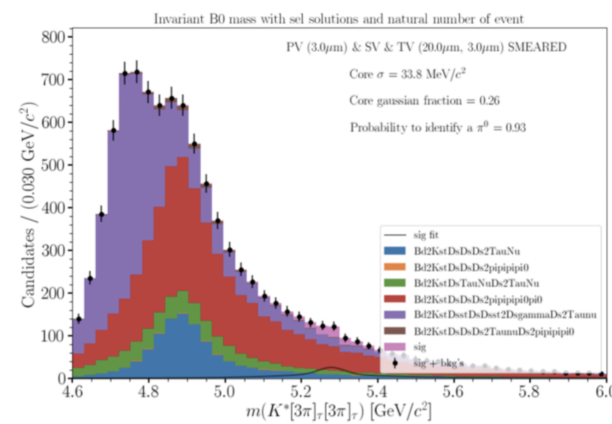
- Study w/ background has started. Initial look promising [O(200) events at SM value]. Some overwhelming backgrounds (with several pi0 discovered.

- A selection is in order.

- Outlook: attempt at a “comprehensive" bkg estimate (getting to it). The topological method won’t be enough (selection required). Actual vertex detector geometries to be assessed as a function of the precision.







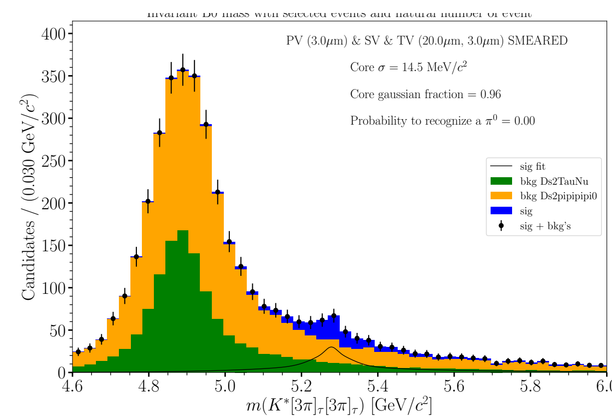
3. Vertex performance: $B^0 \to K^{*0}\ \tau^+\tau^-$

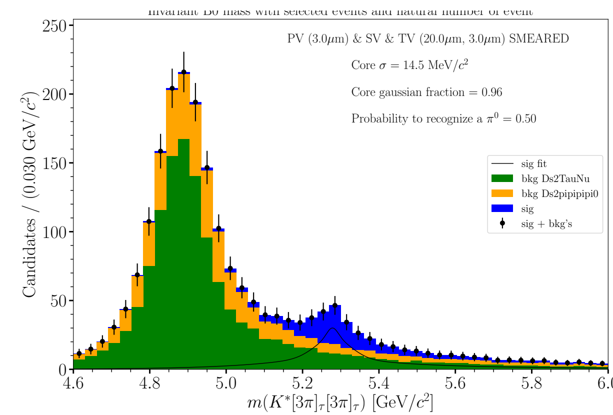
- $B^0 \to K^{*0}\ \tau^+\tau^-$: executive summary

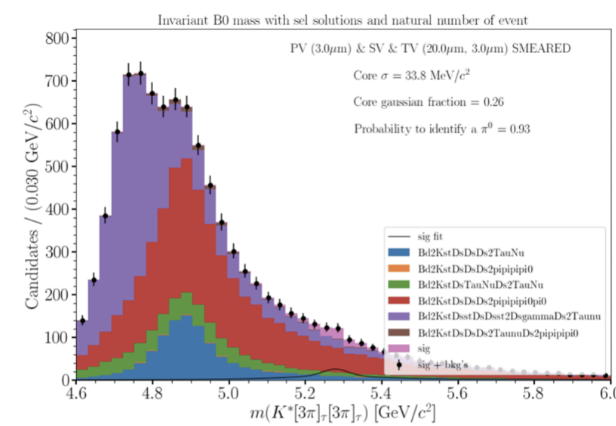
- We'll provide the precision on BF as a function of the vertex resolutions (transverse and longitudinal). Target: January 2023.

- Most demanding requirement to vertex detector to my knowledge. Anticipated likely outcome: have to go beyond state-of-the art.

- Outlook: check the performance improvement as a function of:
  — curvature of the Si
  — distance of the first layer to IP
  — pixel pitch
  — beam transverse disks
  — etc..







5. Calorimetry

The span of relevant observables including photons and neutral pions to understand further the *CP* symmetry breaking is large.

- A comprehensive program of *CP* violation must include the study of modes w/ π^0, *e.g.* $B^0 \to \pi^0\pi^0$, $B^0 \to \pi^+\pi^0\pi^-\pi^0$, … critical to measure the CKM alpha angle as an example (word of caution: theory limitation).
- High resolution at low energy is the key here. Aim at 3%/sqrt(E) — or better!
- Other calorimetry cases were discussed earlier: https://indico.cern.ch/event/1186057/
- Radiative decays following $b \to s\gamma$, provide the same requirements. Critical for some charm studies as well. Volunteers welcome !

5. Calorimetry — Application

- Towards a degree alpha measurement : a study to get started.

- The alpha angle can be measured through an isospin analysis from $B^{0,+-} \rightarrow (\pi\pi)^{+-/00}$. The knowledge of parameter S^{00} , that can be accessed from time-dependent studies, allows to lift degeneracies among solutions.

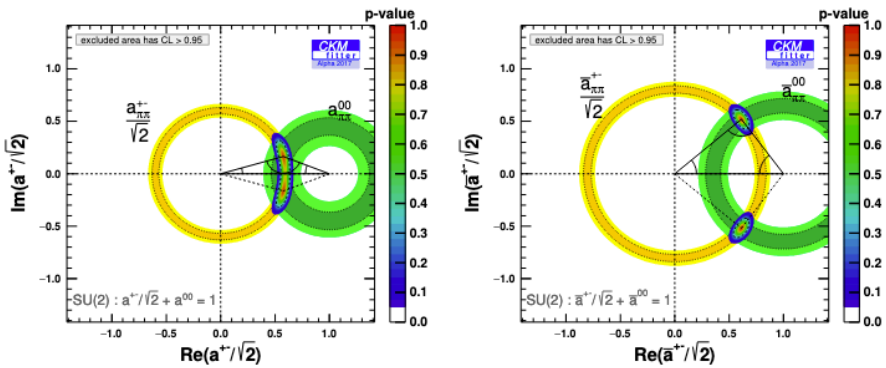


Figure 4: *Constraint on the reduced amplitude $a^{+-} = A^{+-}/A^{+0}$ in the complex plane for the $B \to \pi\pi$ (left) and $\bar{B} \to \pi\pi$ systems (right). The individual constraint from the $B^0(\bar{B}^0) \to \pi^+\pi^-$ observables and from the $B^0(\bar{B}^0) \to \pi^0\pi^0$ observables are indicated by the yellow and green circular areas, respectively. The corresponding isospin triangular relations $a^{00} + a^{+-}/\sqrt{2} = 1$ (and CP conjugate) are represented by the black triangles.*

- Accessible through Dalitz decays of the π^0 in $B^0 \rightarrow (\pi^0\pi^0)$. Vertex is there. Statistics too [O(10k)]. A possible case study for EM calo. design.

5. Jet Flavour tagging from $|V_{cb}|$

Bottlenecks in the interpretation of CKM profile meas. identified (true already for LHCb U2) (2006.04824): $|V_{cb}|$ (normalisation matters) and QCD mixing parameters (not only decay constants and bag factors from LQCD; eta parameters as well).

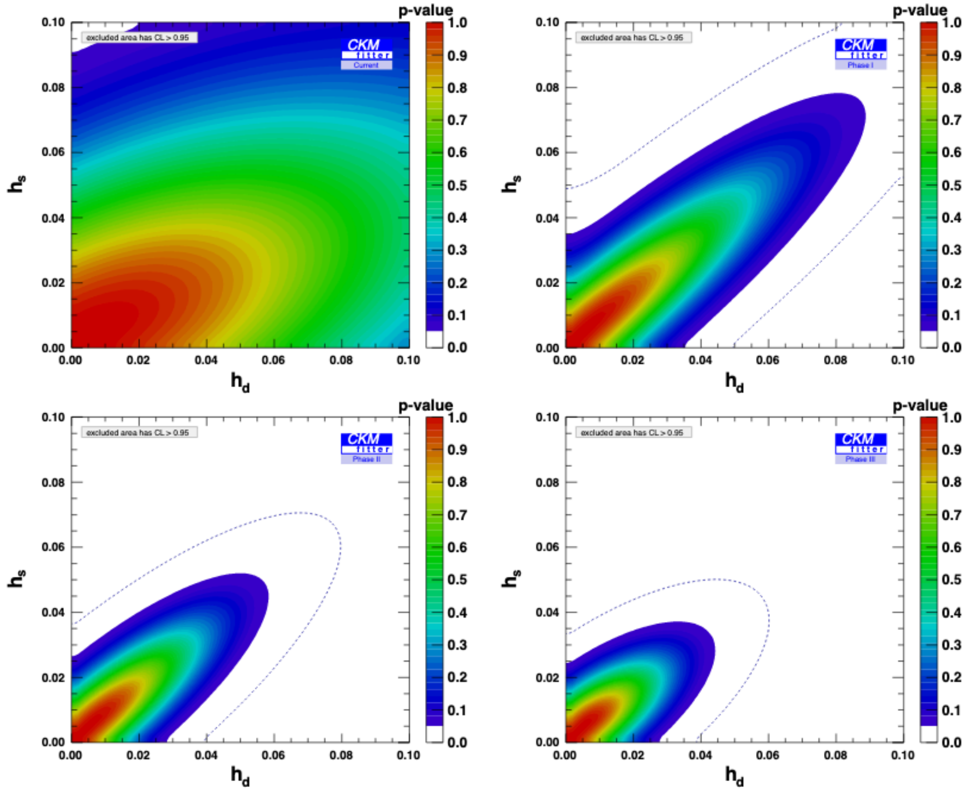


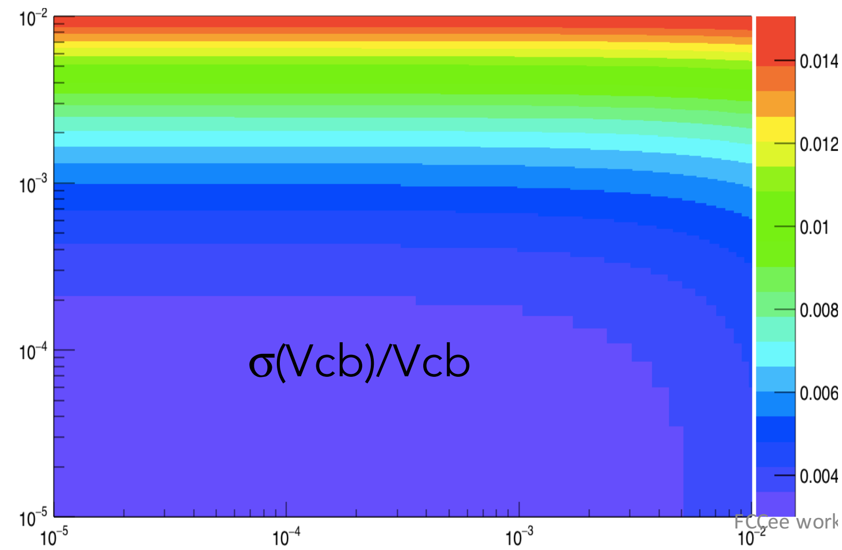
FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ) contours.

5. Jet Flavour tagging from $|V_{cb}|$

- $|V_{cb}|$ measurement: the WW threshold. First look here.

Eff. \ *q*-jet	*b*-jet	*c*-jet	*uds*-jet
b-tag	25 %		
c-tag	10 %	50 %	2 %

- Numbers picked from *Tracking and Vertexing at Future Linear Colliders: Applications in Flavour Tagging* — Tomohiko Tanabe. ILD@ILC. IAS Program on High Energy Physics 2017, HKUST



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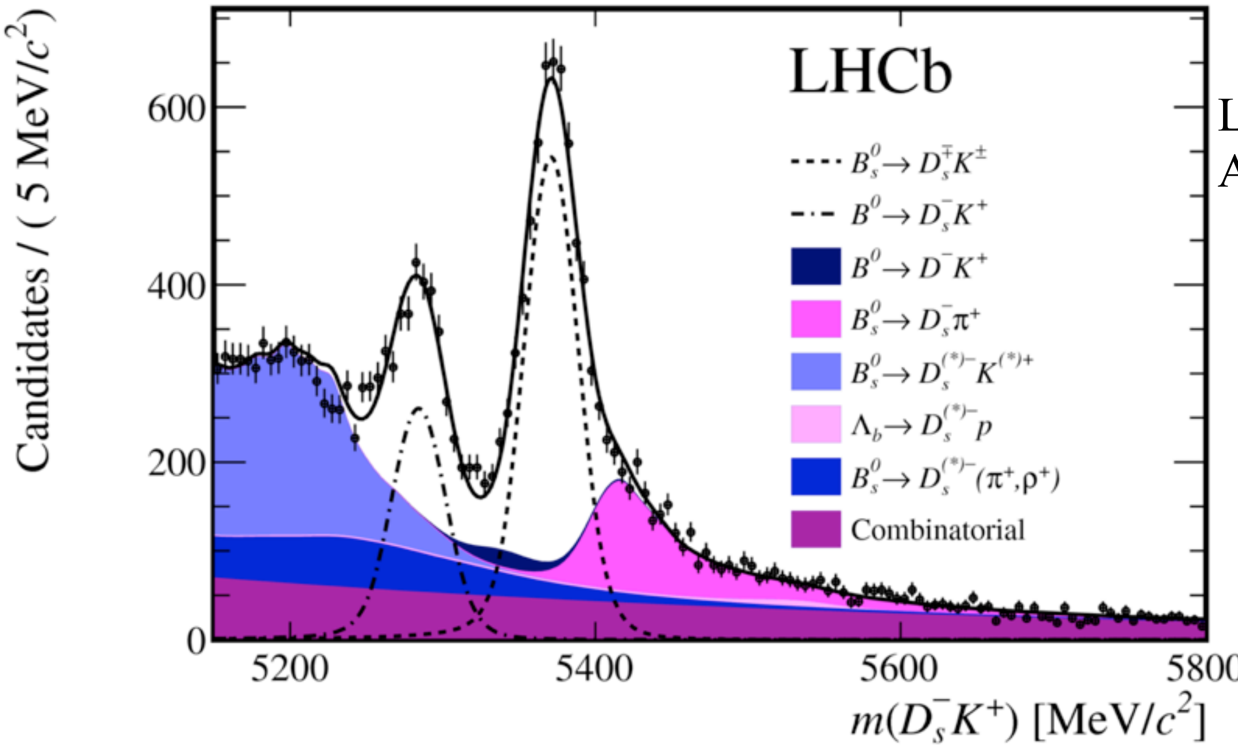
- With these state-of-the-art inputs, precision on $|V_{cb}|$ improves from 1.9% (current) to 0.4%. Ultimate statistical precision is $O(10^{-4})$.

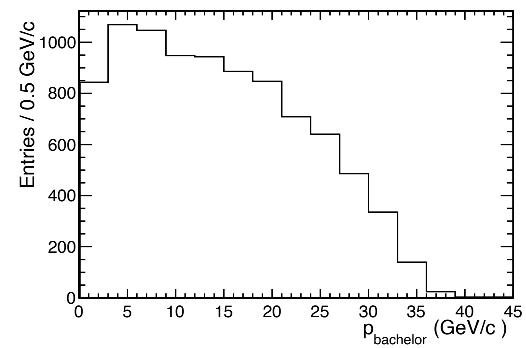
- Actual study in order. A driver for the *b*- and *c*-jet tagging performance.
- Volunteers welcome !

7) Particle identification

No successful Flavour experiment with a powerful particle identification. *CP* violation studies: $B_s \to D_s K$



LHCb-PAPER-2014-064
ArXiv:1412.7654



Bachelor mom. at FCC-ee.

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

7) Particle identification

No successful Flavour experiment with a powerful particle identification (Selection, flavour (q / barq) tagging).

- Cluster counting in a drift chamber dN/dx (IDEA) seems a possible ultimate particle identification when supplemented with a Time of Flight for mip blind window. Simulation performance to be backed up w/ actual particles.

- Novel ideas to fit a Cerenkov detector in front of the calorimeter (see *e.g.* talk from Martin Tat in WG3 parallel)

CP violation studies: $B_s \rightarrow D_s K$ is only one example of the benchmarks one can imagine. Alternative modes / Volunteers welcome.

8) Outlook

- Flavour Physics defines shared (vertexing, tracking, calorimetry) and specific (hadronic PID) detector requirements. The feasibility study entangles the Physics performance and detector concepts. Flavour physics places most demanding requirements for vertexing and calorimetry, that are not pushed forward yet in the ECFA studies.

- The FCC feasibility study on the other hand will be used to systematically address the physics case while placing requirements on the detectors. Hadron particle identification deserves a special treatment and Flavour physics is at the heart of it.

- All studies at the Z pole shown above are made for 5.10^{12} Z decays. Most of flavour observables will remain statistically limited. More would be desirable ! The machine study from two IPs to four IPs is positive and would bring about a factor 2 (1.7) in integrated luminosity.

- Four experiments can as well allow for different experiment designs, including a flavour-oriented concept. Engage and reach out to make this plan happening. A lot of challenging and elegant work.