Vertexing requirements from (flavour) physics

FCC week 2024 — San Francisco

Lars Röhrig[1,2], Kevin Kröninger[1], Romain Madar[2], Stéphane Monteil[2]

12/06/2024

[1]Department of Physics – TU Dortmund University
[2]Laboratoire de Physique de Clermont – Université Clermont-Auvergne

Disclaimer: this presentation has been prepared in accordance with the FCC PED Flavour group conveners

Introduction I

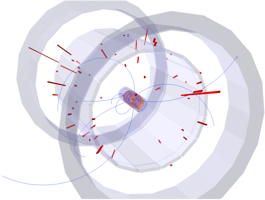
- Z pole offers **unrivalled precision** and a variety of possibilities for EWPO & flavour physics (+ synergies!)

\+ About **15 times** more $B^{0,+}$ mesons compared to Belle II

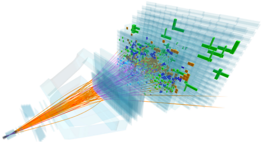
\+ b-quark boost $\langle\beta\gamma\rangle \approx 6$ allows for ultra-clean selection

$\rightarrow$ Unique flavour-physics environment: combining the **best of two worlds**

	Belle	LHC(b)	FCC-ee
All hadron species		✓	✓
Boost		✓	✓
High production σ		✓	
Negligible trigger losses	✓		✓
Low backgrounds	✓		✓
Initial energy constraint	✓		(✓)



Belle



LHCb

© S. Monteil & G. Wilkinson [2106.01259], S. Cunliffe [1708.09423]

Introduction II

- Flavour physics defines **variety of detector requirements**: vertexing, tracking, calorimetry, particle-ID

$\rightarrow$ Vertexing requirements defined by modes with **missing momentum** (ν('s)) in the final state

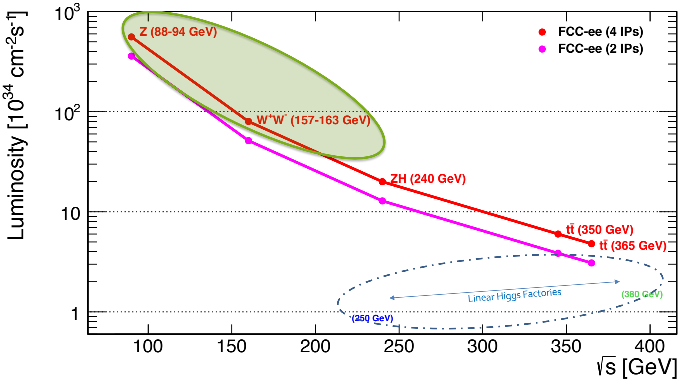
- Of highest interest are modes with τ leptons: heaviest lepton $\rightarrow 3^{\text{rd}}$ gen. couplings exp. less well known
- Here: detector requirements from $b \rightarrow s\tau^+\tau^-$, $b \rightarrow s\nu\bar{\nu}$, timing + interplay of (EWPO $\otimes$ flavours)

Introduction II

- Flavour physics defines **variety of detector requirements**: vertexing, tracking, calorimetry, particle-ID

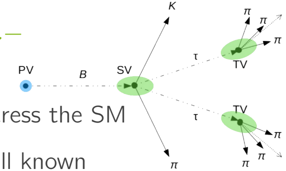
$\rightarrow$ Vertexing requirements defined by modes with **missing momentum** (ν('s)) in the final state

- Of highest interest are modes with τ leptons: heaviest lepton $\rightarrow 3^{rd}$ gen. couplings exp. less well known
- Here: detector requirements from $b \rightarrow s\tau^+\tau^-$, $b \rightarrow s\nu\bar{\nu}$, timing + interplay of (EWPO $\otimes$ flavours)



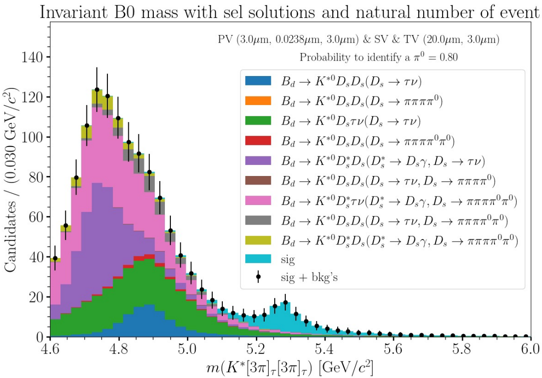
- Not to be forgotten: $\sim 3 \cdot 10^8$ WW pairs to access $|V_{cb}|$ and $|V_{cs}|$ of the **CKM matrix**

Vertex requirements: setting the stage with $b \to s\tau^+\tau^-$



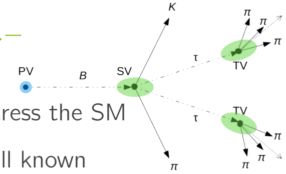
- **EW penguin transitions** of b quark in the SM very rare → good laboratory to stress the SM
- Third generation transitions in $B^0 \to K^*\tau^+\tau^-$ couplings experimentally less well known

→ Feasibility depends on neutrino reconstruction ✓ → depends on **vertex precision**



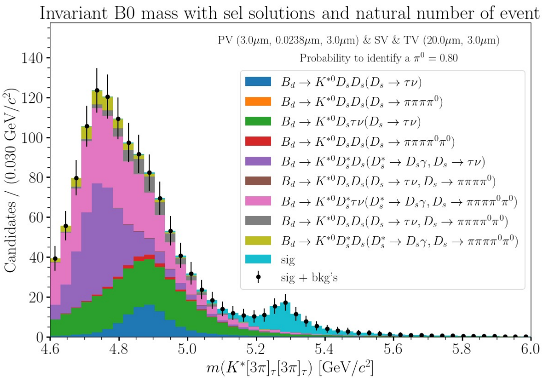
© T. Miralles & S. Monteil Ref.

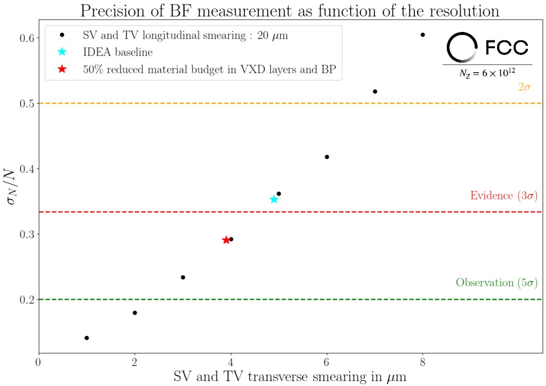
Vertex requirements: setting the stage with $b \to s\tau^+\tau^-$



- **EW penguin transitions** of b quark in the SM very rare $\to$ good laboratory to stress the SM
- Third generation transitions in $\boxed{B^0 \to K^*\tau^+\tau^-}$ couplings experimentally less well known

$\to$ Feasibility depends on neutrino reconstruction ✓ $\to$ depends on **vertex precision**





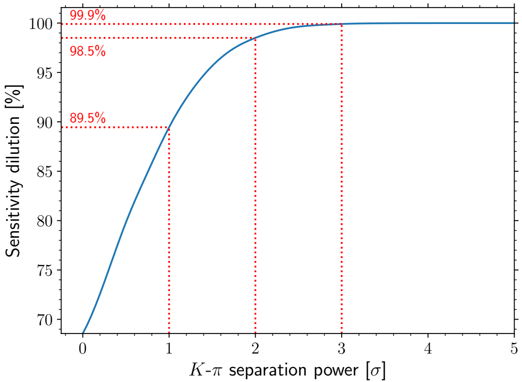
$\to$ $\boxed{\text{Transverse vertex resolution of } \mathcal{O}(5\,\mu\text{m}) \text{ required}}$ (limited by the **material budget of the beampipe**)

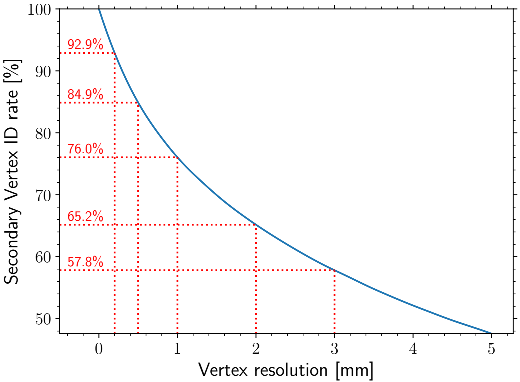
Vertex requirements: $b \to s\nu\bar{\nu}$

- Effective-operator coupling to 3rd generation **poorer constrained**, e. g. in ν_τ

$\to$ $\boxed{B^0 \to K^*\nu\bar{\nu}}$ experimentally cleaner than $B^0 \to K^*\tau^+\tau^-$ (+ theoretically immune to c-quark loops)

- Particle-ID (2σ K/π separation) + SV resolution $\left(\mathcal{O}(10^{-1}\,\text{mm})\right)$ not limiting! **. . . but**





$\to$ Systematic uncertainties significant **if no improvement** on b-fragmentation functions

© Y. Amhis et. al [2309.11353]

Vertex requirements from and for $R_{D^{(*)}}$

- $R_{D^{(*)}} = \frac{\text{Br}(\bar{B}\to\bar{D}^{(*)}\tau^+\nu_\tau)}{\text{Br}(\bar{B}\to\bar{D}^{(*)}\ell^+\nu_\ell)}$ recently raised 3.2σ combined LFU **discrepancy with SM prediction**

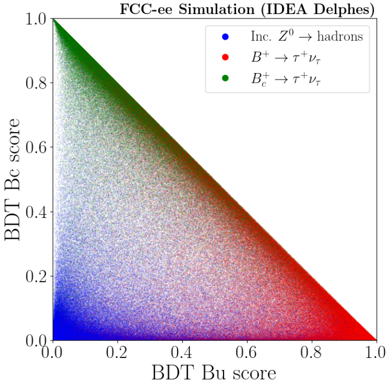
$\rightarrow$ $\boxed{B_c^+ \to [2\pi^+\pi^-\bar{\nu}_\tau]_{\tau^+}\nu_\tau}$ same **quark-level process**, but theoretically simpler + clean probe for $|V_{cb}|$

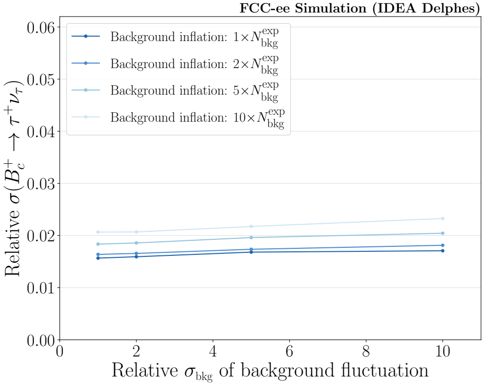
Vertex requirements from and for $R_{D^{(*)}}$

- $R_{D^{(*)}} = \frac{\text{Br}(\bar{B}\to\bar{D}^{(*)}\tau^+\nu_\tau)}{\text{Br}(\bar{B}\to\bar{D}^{(*)}\ell^+\nu_\ell)}$ recently raised 3.2σ combined LFU **discrepancy with SM prediction**

$\rightarrow$ $\boxed{B_c^+ \rightarrow [2\pi^+\pi^-\bar{\nu}_\tau]_{\tau^+}\nu_\tau}$ same **quark-level process**, but theoretically simpler + clean probe for $|V_{cb}|$

- Large missing momentum at Z pole: overcomes $\sqrt{s}\otimes$ pile-up (LHCb) + $\not{B_c^+}$ (Belle) limitations





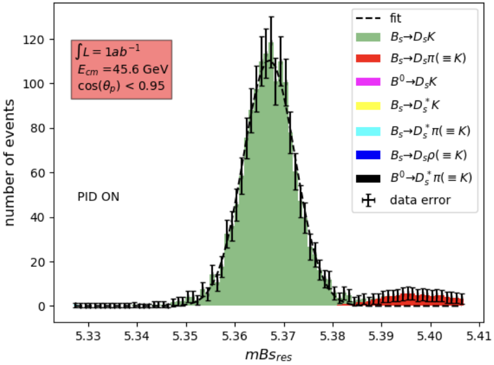
- So far: vertex MC-seeded, but imperfection ($\rightarrow$ background inflation) has negligible impact on Br & $|V_{ub}|$

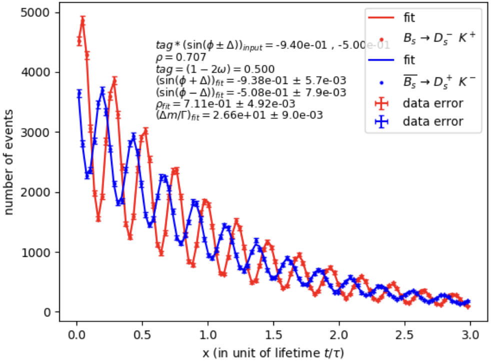
$\rightarrow$ However: $|V_{cb}|$ only possible with improvement on hadronisation fraction $f(\bar{b}\rightarrow B_c^+)$

© X. Zuo et. al [2305.02998]

Vertex requirements from decay time

- Probes of the CP sector of the SM from $B_s \to D_s^- K^+$ time-dependent CP asymmetry





© R. Aleksan et. al [2107.02002]

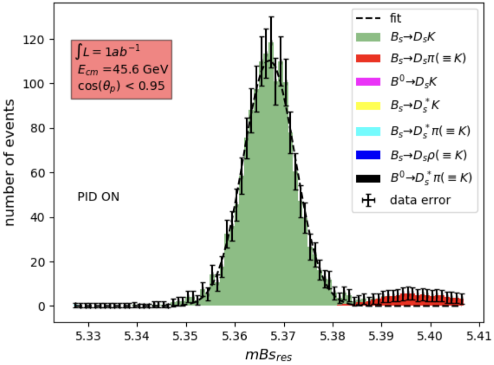
Vertex requirements from decay time

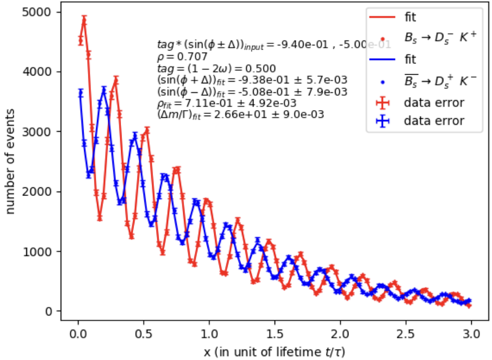
- Probes of the *CP* sector of the SM from $B_s \to D_s^- K^+$ time-dependent *CP* asymmetry
- Experimental precision relies on **wrong-tagging efficiency** of inital flavour (b or $\bar{b}$), $\sigma_{\text{syst.}}$ sources:

$\to$ PV and B_s decay-vertex position

  - Fully charged: $\mathcal{O}(20\,\mu\text{m})$
  - Including neutrals in $B_s \to [K^+K^-]_\phi K_S$: $\mathcal{O}(70\,\mu\text{m})$

$\to$ IDEA baseline **sufficient to derive CKM phase Φ_s** with 0.5 % precision at SM level

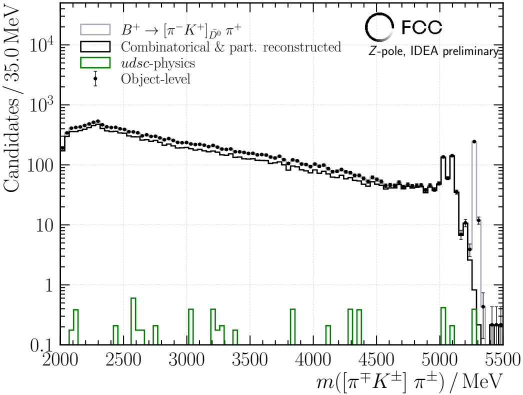




© R. Aleksan et. al [2107.02002]

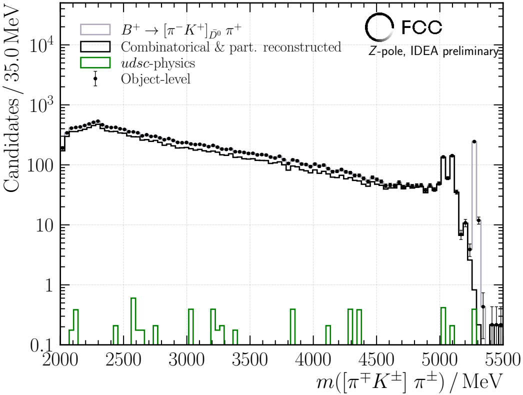
A word on synergies and next steps

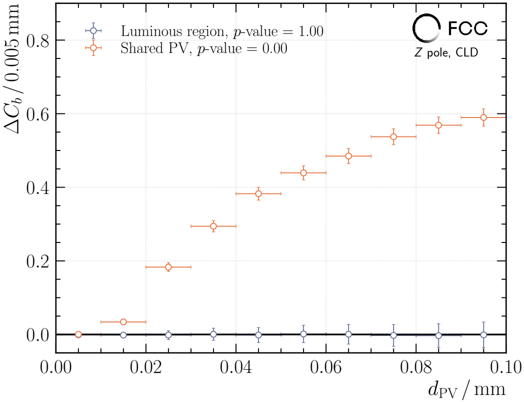
- **EWPO meets flavour:** Excl. b-hadron reconstruction explored for R_b → **ultra-pure tagger** $\geq 99.8\,\%$



A word on synergies and next steps

- **EWPO meets flavour:** Excl. b-hadron reconstruction explored for $R_b \rightarrow$ **ultra-pure tagger** $\geq 99.8\,\%$
- Hemisphere correlation ΔC_b main source of $\sigma_{\text{syst.}}$ from **PV determination**, options:
  1. PV vertex determination would need precision improvement
  2. Overcome PV bias by selecting tracks outside the luminous region





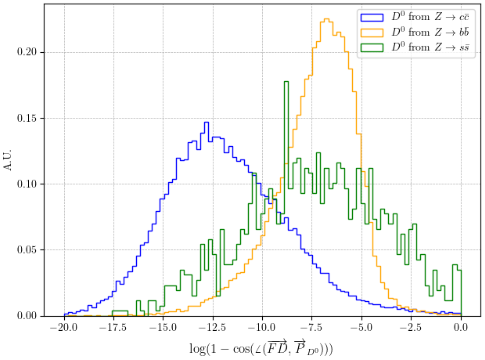
$\rightarrow$ Reduce $\mathcal{O}(\sigma_{\text{syst.}}) \approx \mathcal{O}(\sigma_{\text{stat.}}) \approx 2 \cdot 10^{-5}$ confirmed ✓

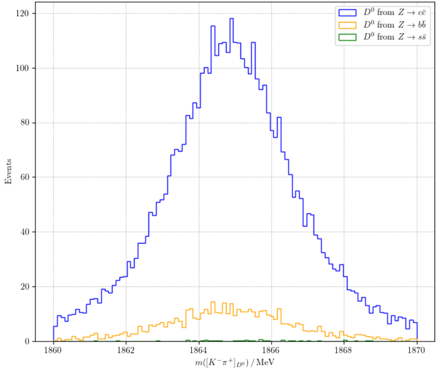
A word on synergies and next steps: R_c

- Application to R_c with c-meson decays, **main hurdle:** b-quark contamination ε_c^b from $X_b \to X_c h$:

$$R_c = \frac{(f_{\text{single-tagged}} - 2R_b\varepsilon_c^b)^2}{4(f_{\text{double-tagged}} - (\varepsilon_c^b)^2 R_b)}$$

$\rightarrow$ WIP: measure ε_c^b to $\mathcal{O}(10^{-5})$ level + **improved impact parameter resolution** might help discrimination





- So far: $\sigma_{\text{stat.}} = \mathcal{O}(10^{-5})$, $\sigma_{\text{syst.}}$ again the name of the game! (to be evaluated)

Conclusions

- Z pole and WW threshold at FCC-ee: the place to continue the flavour-physics programme (boost + high-stat)
- Flavour-physics programme asks for the most demanding vertexing requirements

$\rightarrow$ $b \rightarrow s\tau^+\tau^-$ defines them: evidence with $\mathcal{O}(5\,\mu\text{m})$

- If enough statistics could be gathered, angular analyses could be possible
- CP violation studies with π^0 modes appealing $\Rightarrow$ requires an EM calorimeter with $\lesssim \mathcal{O}(0.03)/\sqrt{E}$

$\rightarrow$ Next limitation: statistical precision!