Flavours (and opportunities) at FCC-ee

3rd ECFA Workshop — Paris

Lars Röhrig[1,2], Kevin Kröninger[1], Stéphane Monteil[2], Dominik Mitzel[1]

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

Flavour-physics programme at FCC-ee

- FCC-ee Tera-Z programme provides **unique opportunities** for flavour physics

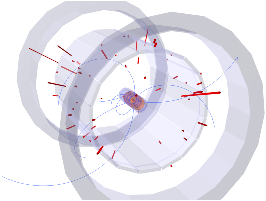
\+ About 15 times more B^0 and B^+ mesons compared to Belle II

\+ Quark boost at $\sqrt{s} = 91\,\text{GeV}$: topological reconstruction of the decays

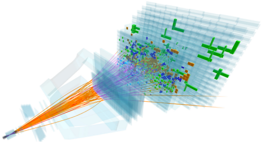
- But flavours drive the **detector requirements**: vertexing, tracking, calorimetry, particle-ID

- Vertexing requirements driven by modes with missing energy in the FS

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



Belle

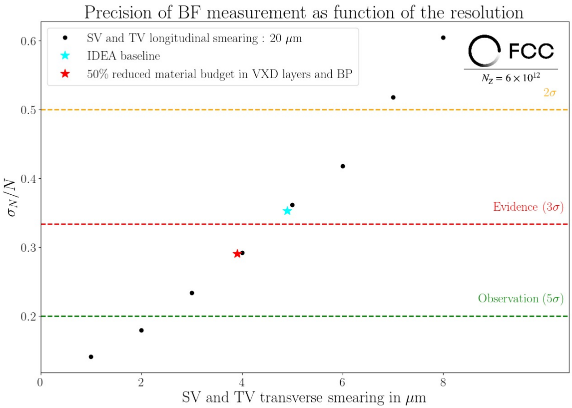


LHCb

Disclaimer: All presented results have been obtained with the IDEA detector concept

Flavour-physics programme at FCC-ee

- **Beauty physics:** selected studies at hand ($b \to s\tau^+\tau^-$, $b \to s\nu\bar{\nu}$, $b \to \tau\nu$, CP sector)
- Stringent (transverse) vertex-resolution requirements from $B_d^0 \to K^*\tau^+\tau^-$: $\mathcal{O}(5\,\mu\text{m})$



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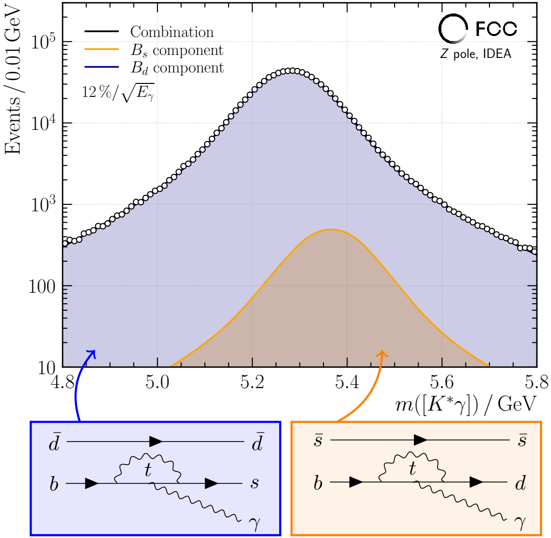
- Radiative quark transition separation $b \to s/d\gamma$ requires **ECAL resolution** well below $10\,\%/\sqrt{E_\gamma}$



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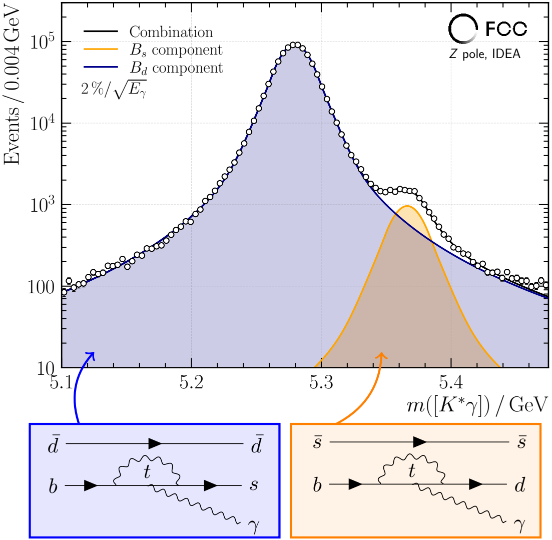

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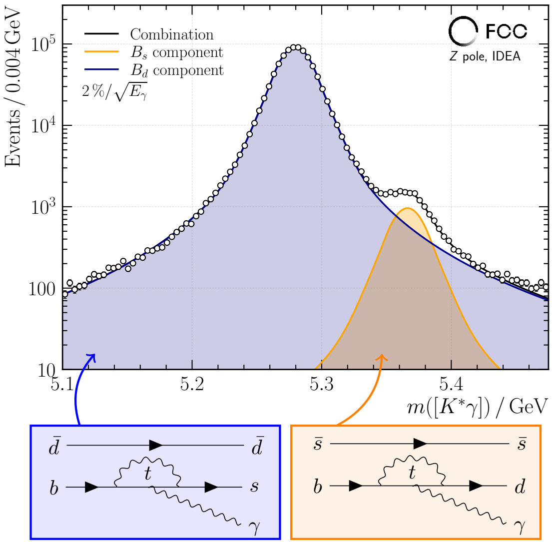
- **Charm physics:** studies ramping up (e. g. $c \to u\nu\bar{\nu}$, $D^0 \to \pi^0\pi^0$)

$\to$ Detector requirements to be defined (if any)

- NP potential in $D^0 \to \rho/\phi\gamma$ requires exquisite π^0/γ separation



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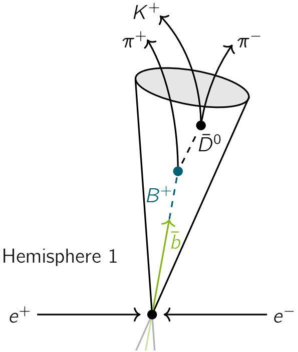
New synergies at the horizon

- Z-pole statistics allow to go **beyond established concepts**

→ E. g.: b-tagging for **EWPO** measurements for $R_b = \frac{\Gamma(Z\to b\bar{b})}{\Gamma(Z\to \text{hadrons})}$ and A^b_{FB}

- Usual approach: use b-hadron specific kinematic properties in MVA (SV masses, flight distances, etc.)

- **New hemisphere tag:** Exclusively reconstructed b-hadron of the event



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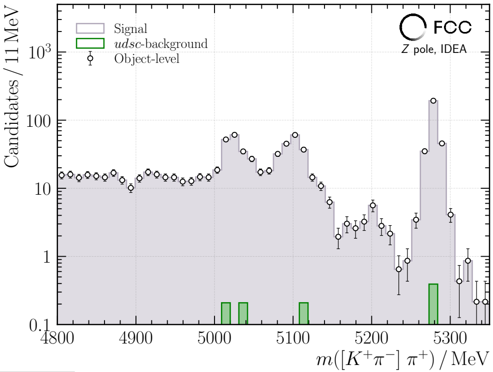

Here in the $B^+ \to \bar{D}^0\pi^+$ channel

+ 5/200 more **representative** b-hadron decay modes validated ✓

Unique opportunities for R_b

Account for $\sim 80\,\%$ of $\sigma_{\text{syst.}}(R_b)$

- Measurement of R_b based on **double-tag** of b-hemispheres:

$$N_1 = 2N_Z \cdot (R_b \varepsilon_b + (1 - R_b)\varepsilon_{udsc})$$

$$N_2 = N_Z \cdot (R_b \varepsilon_b^b \, \Delta C_b + (1 - R_b)\varepsilon_{udsc}^{udsc} \, \Delta C_{udsc})$$

- Implications of $100\,\%$ purity:
  - $\varepsilon_{udsc} = \varepsilon_{udsc}^{udsc} = 0\,\% \Rightarrow$ significant $\sigma_{\text{syst.}}(R_b)$ redux
  - $\varepsilon_b \approx 1\,\% \Rightarrow$ $\sigma_{\text{stat.}}(R_b) = 2 \cdot 10^{-5}$

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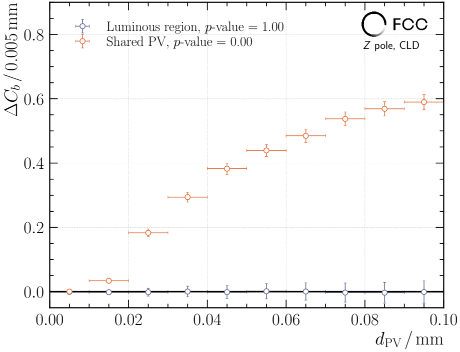
- Remaining, leading systematic uncertainty: **correlation of hemispheres** ΔC_b (biased from shared event PV)

→ Alternative track selection outside luminous region:
$\sigma(\Delta C_b)/\Delta C_b = 10\,\%$ for $\sigma_{\text{syst.}}(R_b) \approx \sigma_{\text{stat.}}(R_b)$



d_{PV} quantifies PV fit uncertainty

. . . and A^b_{FB}

- In addition to R_b, A^b_{FB} needs a **charge- and direction tag** of the b-hemisphere

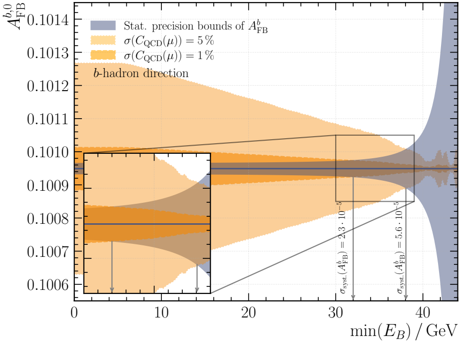
- Implications of 100 % purity:
  $\rightarrow$ Leading $\sigma_{\mathrm{syst.}}(A^b_{\mathrm{FB}})$: b-quark direction distortion from gluon radiations

- Reconstructed b-hadron provides everything:
  - **Charge-unambigious** hemisphere tag (B^+ and Λ^0_b decays $\rightarrow$ no mixing dilution)
  - b-quark direction estimate from $\vec{p}_{B^+}$ and $\vec{p}_{\Lambda^0_b}$
  - Handle on **QCD corrections** via b-hadron energy

$\rightarrow$ With $\sigma(C_{\mathrm{QCD}})/C_{\mathrm{QCD}} = 5\,\%$:

$$\sigma_{\mathrm{stat.}}(A^b_{\mathrm{FB}}) = \sigma_{\mathrm{syst.}}(A^b_{\mathrm{FB}}) = 5.6 \cdot 10^{-5}$$

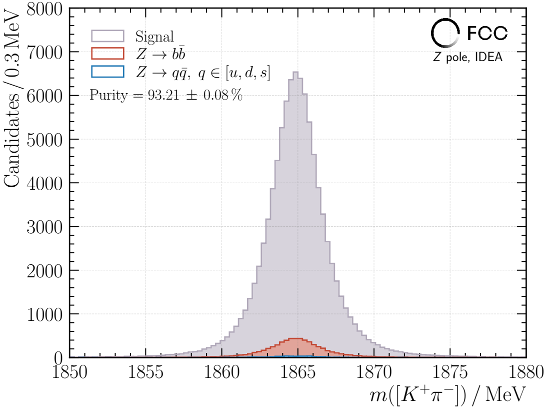
- Even more: $\sin^2(\theta_{\mathrm{W}})$ measurement at the 0.002 % level



Outlook for exclusive tagger

Charm:

- $D^{0,+}_{(s)}$ decays with sufficiently high **branching ratios**
- However: c-tag contamination from $b \to c$
- $\sigma_{\text{stat.}}(R_c) = 3 \cdot 10^{-5}$



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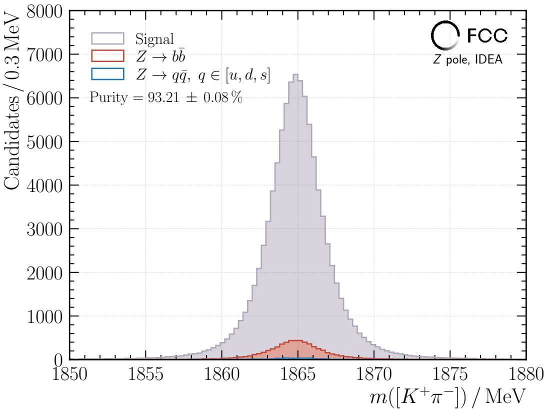
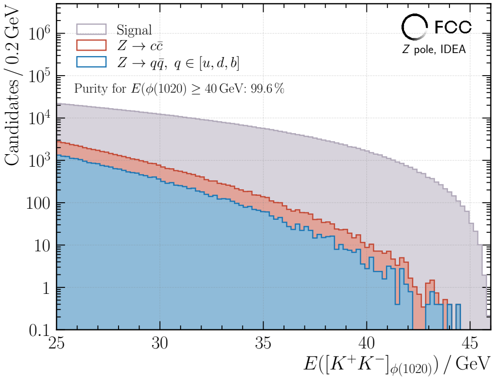


Strange:

- **Beam-like** s-hadrons (require excellent PID):
  - R_s: $\phi \to K^+K^- \to$ $\sigma_{\text{stat.}}(R_s) = 2 \cdot 10^{-5}$



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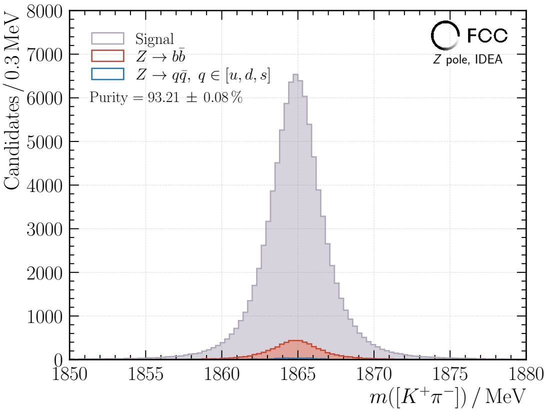
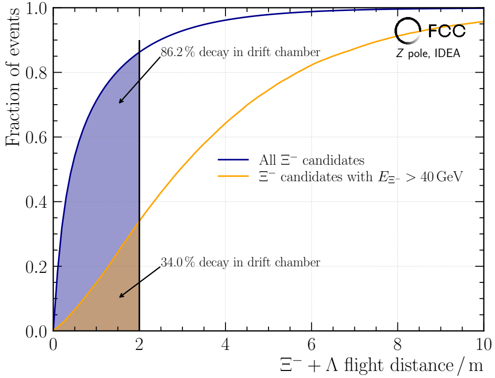


Strange:

- **Beam-like** s-hadrons (require excellent PID):
  - R_s: $\phi \to K^+K^- \to \boxed{\sigma_{\text{stat.}}(R_s) = 2 \cdot 10^{-5}}$
  - A^s_{FB}: $\Xi^- \to \Lambda\pi^-$ (challenging reco. due to Ξ^- lifetime) $\to \boxed{\sigma_{\text{stat.}}(A^s_{\text{FB}}) = 2 \cdot 10^{-4}}$



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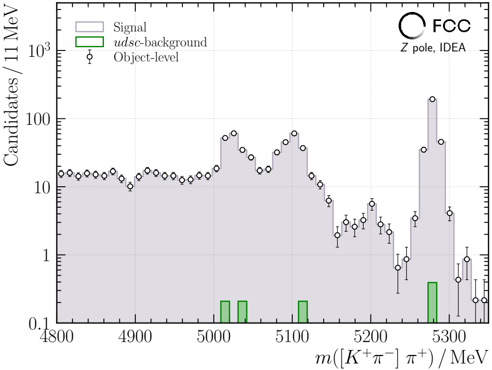
Conclusions

- Potentially exciting times for a rich flavour-physics programme at FCC-ee
- Unique opportunities for rare/radiative/ν modes in the b- and c-sectors
- $6 \cdot 10^{12}$ Z-decays even allow to go beyond established concepts (see, e. g. EWPOs)



Lab activities (TU Dortmund University):

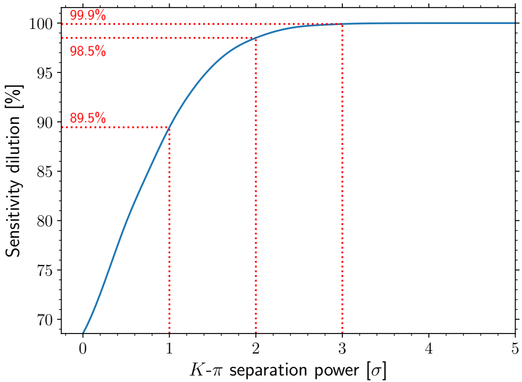
- Just started activities on charm with a student
- Possibly in collaboration with BNL

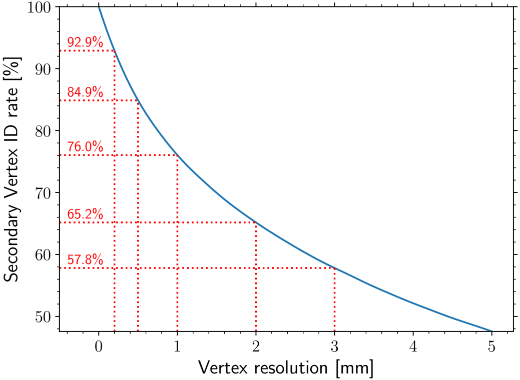
Vertex requirements: $b \to s\nu\bar{\nu}$

- 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

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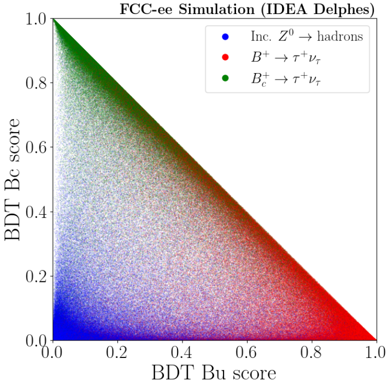
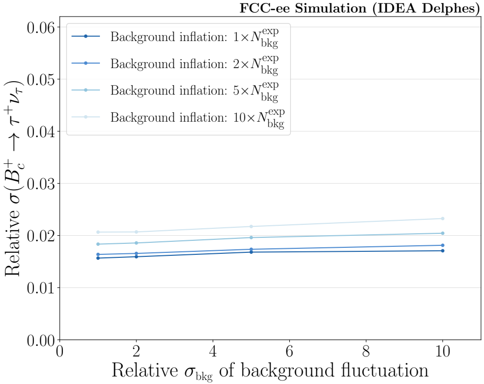
Vertex requirements from and for $R_{D^{(*)}}$

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

$\rightarrow$ $B_c^+ \rightarrow [2\pi^+\pi^-\bar{\nu}_\tau]_{\tau^+}\nu_\tau$ 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 & $|V_{ub}|$

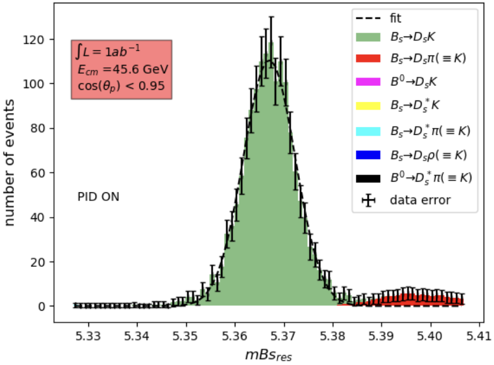
$\rightarrow$ However: $|V_{cb}|$ only possible with improvement on hadronisation fraction $f(\bar{b} \rightarrow B_c^+)$

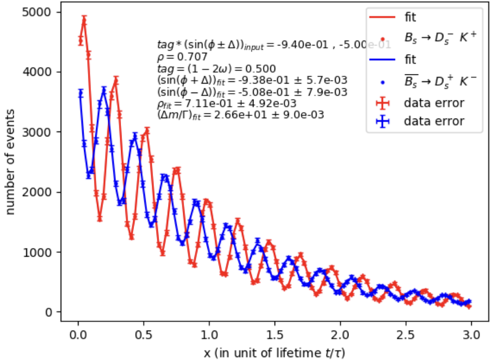
Vertex requirements from decay time

- 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:

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

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





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