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From electroweak precision observables and flavours

8th FCC Physics Workshop

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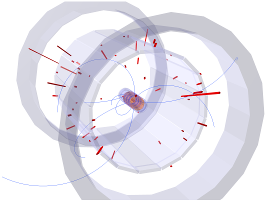
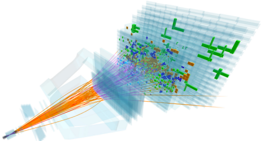
Flavours at FCC-ee

- Continuation of vibrant LHCb & Belle **flavour physics programme** with Z-pole statistics and boost

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



Belle



LHCb

- Additionally: defines stringent **detector requirements**
  → vertexing, tracking, calorimetry, particle-ID

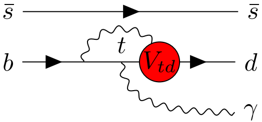
- E. g. vertexing requirements defined by modes with missing momentum $b \rightarrow s\tau\tau$
  + **new study in charm sector** $c \rightarrow u\nu\bar{\nu}$ [T. Hacheney tomorrow@2:40pm]

Today's outline:

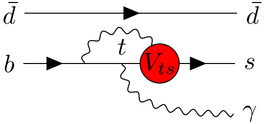
1. Academic exercise of rare, radiative FCNC $b \rightarrow (d, s)\gamma$ transitions to define **EM calorimetry resolution**
2. Flavours in a **global context** to measure EWPOs: $\{R_b, R_c, R_s\}$ and $\{A^b_{\mathrm{FB}}, A^s_{\mathrm{FB}}\}$

EM calorimetry requirements from radiative decays

- $b \to (d, s)\gamma$ probe NP in loop diagrams in addition to the photon dipole operator C_7
- However: $b \to d\gamma$ signal dominated by $b \to s\gamma$ background



$\boxed{B_s \to K^*\gamma}$



$\boxed{B_d \to K^*\gamma}$

→ $B_s \to K^*\gamma$ **not yet observed**, estimate event yield:

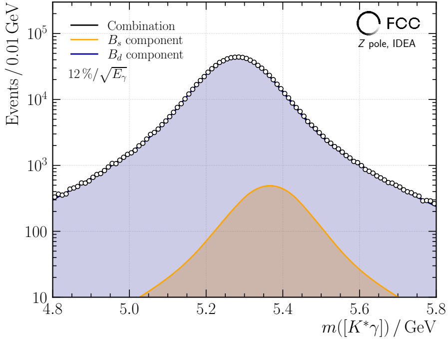
$$\frac{N_{B_d}}{N_{B_s}} \approx \frac{f_{b\to B_d}}{f_{b\to B_s}} \cdot \left|\frac{V_{ts}}{V_{td}}\right|^2 \approx 92$$

$$\to\ N_{B_d} \approx 30 \cdot 10^6 \quad \Rightarrow \quad N_{B_s} \approx 33 \cdot 10^4$$

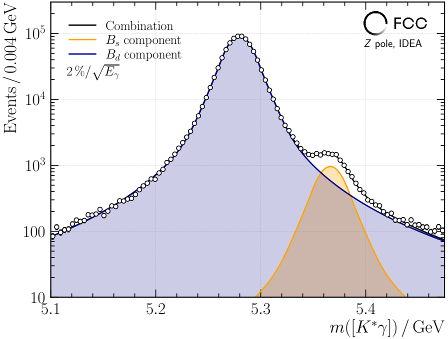
- Would allow to directly measure $\frac{F_{B_d \to K*}}{F_{B_s \to K*}} \left|\frac{V_{ts}}{V_{td}}\right|^2$, but depends on $\Delta m = m_{B_d} - m_{B_s} = 87\,\text{MeV}$ resolution
  → Limiting experimental factor: **EM calorimetry resolution**
  → **Goal:** Estimate precision of $\left|\frac{V_{td}}{V_{ts}}\right|$ as function of the stochastic term of EM energy resolution

EM calorimetry requirements from radiative decays

- Analysis based on 10^6 $B_d \to K^*\gamma$ events (simulated with `PYTHIA8` + `EvtGen` + default IDEA card)
- Emulate B_s signal by scaling B_d candidates
- Use $K^* \to K\pi$ from reconstructed particles, **smear photon momentum based on MC information**



IDEA baseline with $12\,\%/\sqrt{E_\gamma}$.

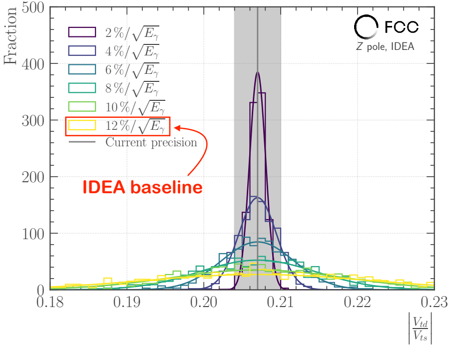


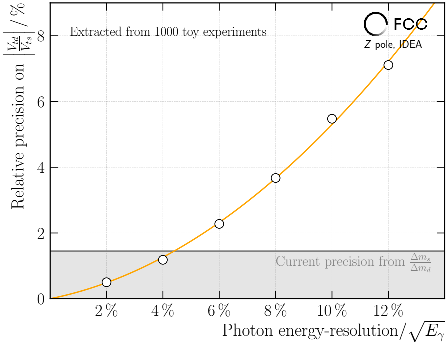
Scaled to $2\,\%/\sqrt{E_\gamma}$.

→ Complicated to even fit B_s signal yield with $12\,\%/\sqrt{E_\gamma}$ resolution + **no backgrounds** included + perfectly known signal-tail shapes

Extracting $\left|\frac{V_{td}}{V_{ts}}\right|$

- Pseudoexperiments with fixed shape parameters, but **floating signal yields** $\left(\rightarrow \text{floating } \left|\frac{V_{td}}{V_{ts}}\right|\right)$
- Extract precision of $\left|\frac{V_{td}}{V_{ts}}\right|$ from 1σ Gaussian fit as function of EM energy resolution





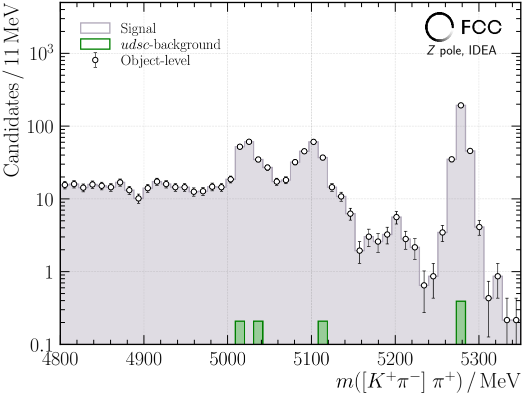
- In view of the consistency check, the precision on the determination from $\Delta m_s/\Delta m_d$ is indicated

→ Only for an EM resolution **below** $5\,\%/\sqrt{E_\gamma}$ comparative result w.r.t current precision

→ $\mathcal{O}(5\,\%/\sqrt{E_\gamma})$ well **in reach with crystals** [2312.07365]

Flavours in a global context

- Precision flavour programme is **key to probe NP effects** in the SM
- Also become important in the context of **electroweak precision observables:** R_b and A^b_{FB} [Ref.]
  → probe NP in radiative and vertex corrections involving top quarks



- **Background-free** hemisphere tag for R_b and A^b_{FB} possible at FCC-ee with exclusive tagger $\rightarrow \mathcal{O}\left(\sigma(R_b)/R_b\right) = \mathcal{O}\left(\sigma(A^b_{\mathrm{FB}})/A^b_{\mathrm{FB}}\right) = 0.01\,\%$
- Central role to achieve $\sigma_{\mathrm{stat.}} \approx \sigma_{\mathrm{syst.}}$
- Concept application for $R_{c,s}$ and $A^{c,s}_{\mathrm{FB}}$ more complicated, but ongoing

Measuring R_c with $\bar{D}^0 \to K^+\pi^-$ decays

- Double-tag equations from R_b measurement extended in case of R_c to benefit from excl. *b*-tagger:

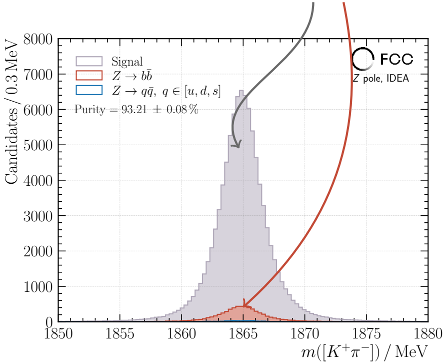
$$N^c_{\mathrm{ST}} = 2N_{Z\to\mathrm{had.}}\left(R_c\varepsilon^c_c + R_b\varepsilon^c_b + R_{uds}\varepsilon^c_{uds}\right)$$

$$N^c_{\mathrm{DT}} = N_{Z\to\mathrm{had.}}\left(R_c(\varepsilon^c_c)^2 C_c + R_b(\varepsilon^c_b)^2 C_b + R_{uds}(\varepsilon^c_{uds})^2 C_{uds}\right)$$

$$N^{cb}_{\mathrm{DT}} = N_{Z\to\mathrm{had.}}\left(R_c\varepsilon^c_c\varepsilon^b_c C_{cb} + R_b\varepsilon^b_b\varepsilon^c_b C_{bc} + R_{uds}\varepsilon^{uds}_{uds}\varepsilon^c_{uds} C_{udsc}\right)$$

- ε^j_i: *tag* flavour *j* of *quark*-flavour *i*

→ **Simultaneously** measure $\{R_c, \varepsilon^c_c, \varepsilon^c_b\}$, remaining inputs $\{R_b, \varepsilon^b_b\}$ from excl. *b*-tagger



Reconstruction results using `winter2023` samples:

→ $\varepsilon^c_c = 6.4 \cdot 10^{-3}$, $\varepsilon^c_b = 0.4 \cdot 10^{-3}$, $\varepsilon^c_{uds} = 1.5 \cdot 10^{-6}$

→ $\boxed{\sigma_{\mathrm{stat.}}(R_c) = 3 \cdot 10^{-5}}$

- Impact of ε^c_b significant for $\sigma_{\mathrm{syst.}}(R_c)$:

→ $\boxed{\sigma_{\mathrm{syst.}}(R_c, \text{from } \varepsilon^c_b) = 6.6 \cdot 10^{-5}}$

- Selection can be refined to remove *b* contamination

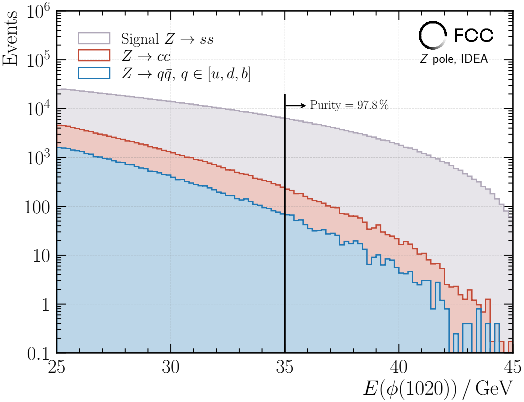
Commensurate $\sigma_{\mathrm{syst.}}$ and $\sigma_{\mathrm{stat.}}$ in reach

Measuring R_s with $\phi(1020) \to K^+K^-$ decays

- Multivariate s-tagger not capable to **suppress background efficiently** [2202.03285]
- Beam-like $|K^-\rangle = |\bar{u}s\rangle$ originating from interaction region suffer from u-quark **contamination**

→ $|\phi(1020)\rangle \approx |s\bar{s}\rangle$ meson possible candidate to measure R_s (A_{FB}^s requires charge tag!)

- Validate performance from reconstructed $\phi(1020) \to K^+K^-$ mesons using `winter2023` samples



- Purity ≈ 98 % for $E(\phi(1020)) > 35$ GeV

→ $\varepsilon_s^s = 10^{-3}$, $\varepsilon_c^s = 2 \cdot 10^{-5}$, $\varepsilon_{udb}^s = 2 \cdot 10^{-6}$

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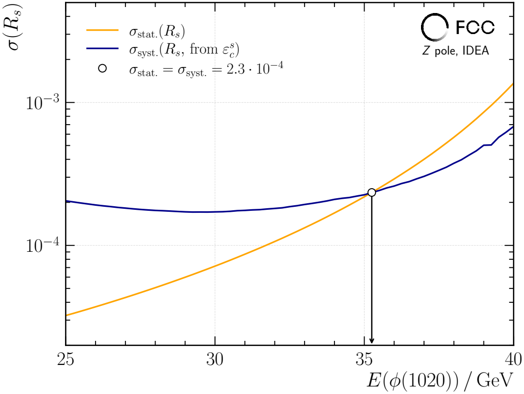

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→ $\varepsilon^s_s = 10^{-3}$, $\varepsilon^s_c = 2 \cdot 10^{-5}$, $\varepsilon^s_{udb} = 2 \cdot 10^{-6}$

- $Z \to c\bar{c}$ contribution significant for $\sigma_{\text{syst.}}(R_s)$

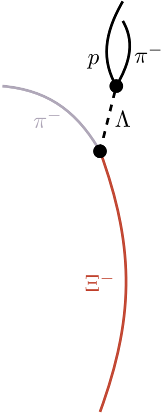
$$\mathcal{O}(\sigma(R_s)) = 3 \cdot 10^{-4} \text{ in reach}$$

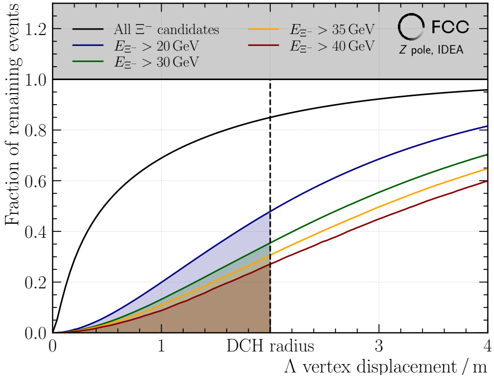
s-quark charge measurement

- A^{s}_{FB} relies on the charge tag of the s quark

→ Unambigious, pure charge tagger would vanish the systematics

→ Use **beam-like** ($E(\Xi^-) \gtrsim 35\,\text{GeV}$) $|\Xi^-\rangle = |ds\bar{s}\rangle$ in $\Xi^- \to \Lambda\pi^-$ decays
  - Complication: $\tau(\Xi^-) = 1.6 \cdot 10^{-10}\,\text{s} \Rightarrow \langle L(\Xi^-)\rangle = 1.2\,\text{m}$
  - Significant fraction of produced Ξ^- final-state particles **outside of tracking volume**





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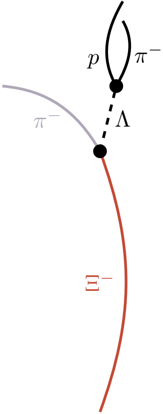
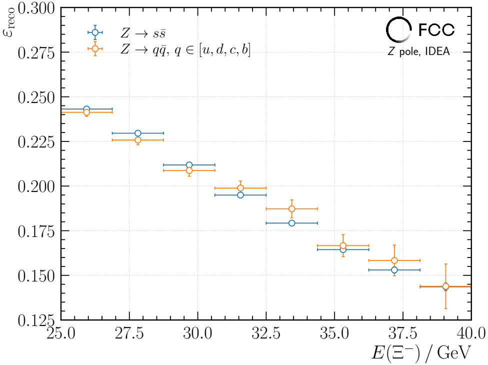
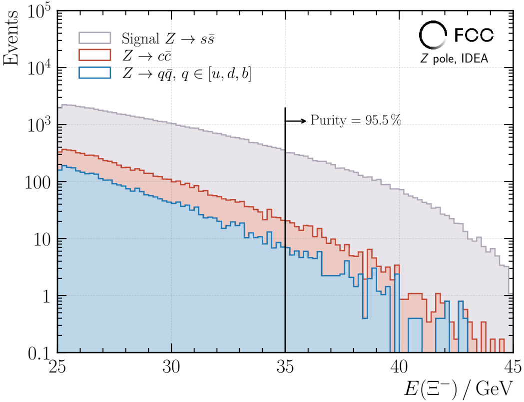
- For now: vertex Λ candidates with additional π^- track with $\mathcal{O}(\varepsilon_{\mathrm{reco}}) = 15\,\%$





A_{FB}^{s}: some numbers and outlook

- Purity above $> 95\,\%$ in reach for Ξ^- baryons



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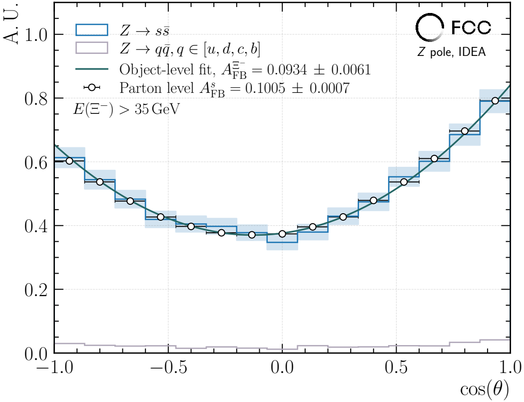
- Requires an **adequate correction** for detector acceptance effects

→ However: for $E(\Xi^-) > 35$ GeV **accurate approximation** of s-quark direction



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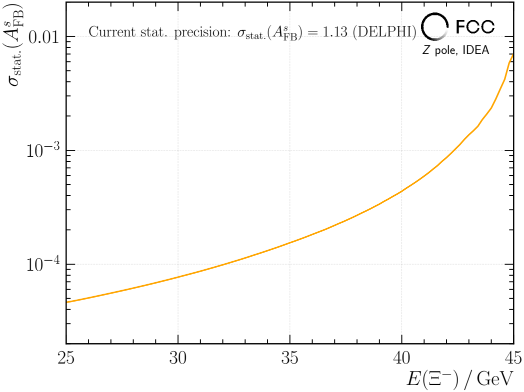

- Full analysis **lacks the proper analysis tools**
- All numbers presented rely on `PYTHIA8`'s hadronisation fraction for $s \to \{\phi(1020), \Xi^-\}$

$$\mathcal{O}(\sigma(A^s_{\mathrm{FB}})) = 1.5 \cdot 10^{-4} \text{ in reach}$$

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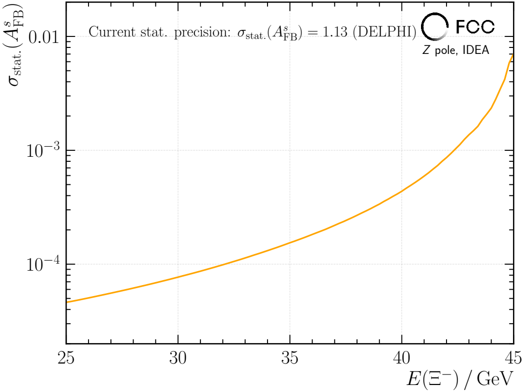

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$$\mathcal{O}(\sigma(A_{\mathrm{FB}}^{s})) = 1.5 \cdot 10^{-4} \text{ in reach}$$

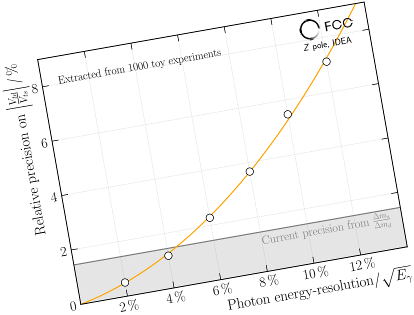
- Discussion of systematic uncertainties like QCD corrections to be done

→ Expected to be subdominant in **presence of energy cuts**

Conclusions & Outlook

- Flavour physics programme at FCC-ee opens up a multitude to probe NP effects

→ Defines stringent detector requirements, e. g. EM calorimetry resolution



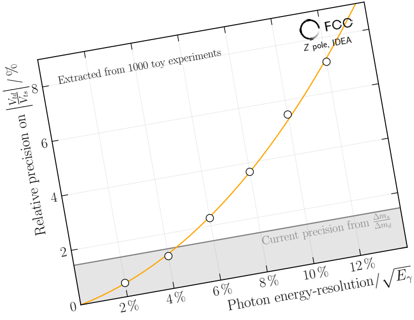
Conclusions & Outlook

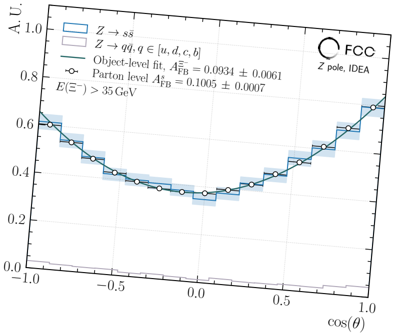
- Flavour physics programme at FCC-ee opens up a multitude to probe NP effects

→ Defines stringent detector requirements, e. g. EM calorimetry resolution

- Also allows to study EWPOs at a **new level of precision**

- Complement EWPOs in the charm sector with A_{FB}^{c} (but no showstoppers identified so far)



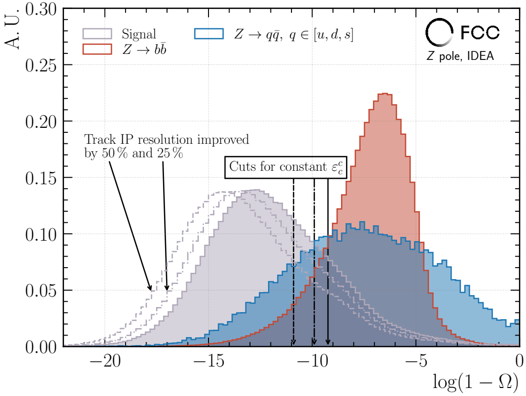


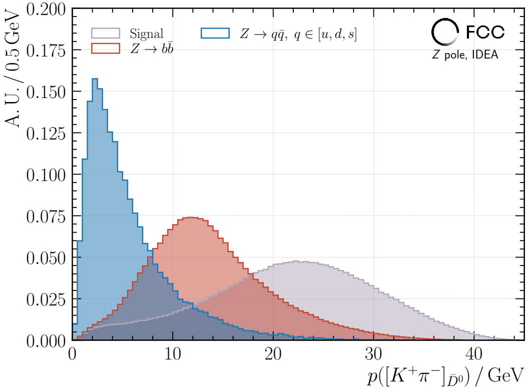
Backup

R_c: kinematic cuts in the phase space

- Simple cuts to suppress backgrounds from the most obvious processes

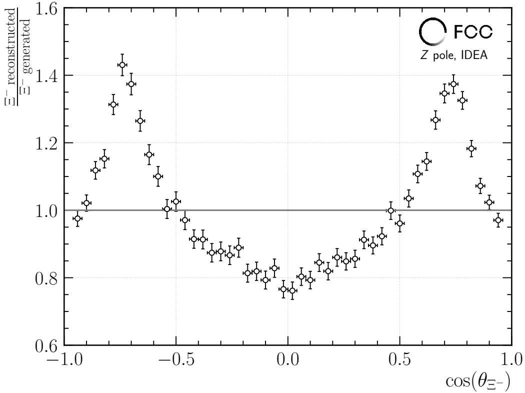
$$\rightarrow \ \mathrm{FD}(\bar{D}^0) < 3\,\mathrm{mm},\ d_0(K) < 1\,\mathrm{mm},\ N_{\mathrm{SL,hem.}} = 0,\ p(\bar{D}^0) > 16\,\mathrm{GeV},\ \Omega = \frac{\vec{f}\cdot\vec{p}(\bar{D}^0)}{|\vec{f}|\cdot|\vec{p}(\bar{D}^0)|} < -9$$

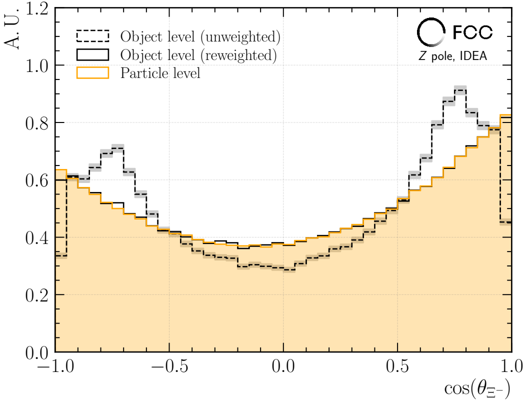




A_{FB}^{s}: correction for detector acceptance effects

- Angular acceptance given by volume infront of final-state decay particles





Exclusive reconstruction: included B^+ decay-modes

Mode	$\mathrm{Br}(B^+ \to XY)$ / %	$\mathrm{Br}(X \to \text{final state})$ / %		$\sum \mathrm{Br}$ / %
$J/\psi\ K^+$	0.102 ± 0.002	$J/\psi \to e^+e^-$ $J/\psi \to \mu^+\mu^-$	5.971 ± 0.032 5.961 ± 0.033	**0.012**
$\bar{D}^0\ \rho^+$ $\bar{D}^0\ \pi^+\pi^-\pi^+$ $\bar{D}^0\ \pi^+$ $[\bar{D}^0\pi^+]_{D^*(2010)^+}\ \pi^-\pi^-\pi^0$	1.340 ± 0.180 0.560 ± 0.210 0.468 ± 0.013 10.160 ± 4.740	$\bar{D}^0 \to K^+\pi^-\pi^0$ $\bar{D}^0 \to K^+\pi^-2\pi^0$ $\bar{D}^0 \to K^+2\pi^-\pi^+$ $\bar{D}^0 \to K^+2\pi^-\pi^+\pi^0$ $\bar{D}^0 \to K^+\pi^-$	14.400 ± 0.500 8.860 ± 0.230 8.220 ± 0.140 4.300 ± 0.400 3.947 ± 0.030	**0.545** **0.723** **0.909** **0.950**
$D^-\ \pi^+\pi^-$	0.107 ± 0.005	$D^+ \to K^-2\pi^+$ $D^+ \to K^-2\pi^+\pi^0$	9.380 ± 0.160 6.250 ± 0.180	**0.966**
$D_s^+\ \bar{D}^0$	0.900 ± 0.090	$D_s^+ \to [\pi^+\pi^-\pi^0]_\eta\ \pi^+\pi^0$ $D_s^+ \to [\pi^+\pi^-\pi^0]_\eta[\pi^+\pi^0]_{\rho^+}$ $D_s^+ \to K^+K^-\pi^+\pi^0$ $D_s^+ \to K^+K^-\pi^+$ $D_s^+ \to 2\pi^+\pi^-$ $D_s^+ \to K^+K^-2\pi^+\pi^-$ $D_s^+ \to 3\pi^+2\pi^-$	9.500 ± 0.500 8.900 ± 0.800 5.500 ± 0.240 5.380 ± 0.100 1.080 ± 0.040 0.860 ± 0.150 0.790 ± 0.080	**1.081**

Exclusive reconstruction: included B_d^0 decay-modes

Mode	$\mathrm{Br}(B^0 \to \text{final state})$ / %	$\sum \mathrm{Br}$ / %
$J/\psi\, K^+\pi^-$	0.014	**0.014**
$D^*(2010)^-\, \pi^+\pi^+\pi^-\pi^0$	0.473	**0.487**
$D^*(2010)^-\, \pi^+\pi^0$	0.403	**0.891**
$D^*(2010)^-\, \pi^+\pi^+\pi^-$	0.194	**1.084**
$D^-\, \pi^+\pi^+\pi^-$	0.094	**1.178**
$D^*(2010)^-\, \pi^+$	0.074	**1.252**
$D^*(2010)^-\, D_s^+$	0.069	**1.321**
$D^-\, \pi^+$	0.039	**1.360**
$D^-\, D_s^+$	0.036	**1.396**
$D^*(2010)^-\, D^0\, K^+$	0.026	**1.422**
$D^-\, D^0\, K^+$	0.007	**1.429**

Exclusive reconstruction: included B_s^0 decay-modes

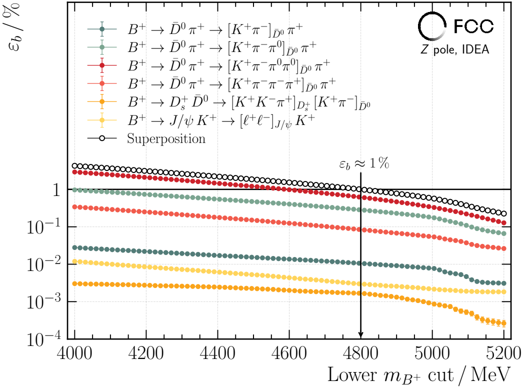
Mode	Br($B_s^0 \to$ final state) / %	$\sum$ Br / %
$D_s^- \, [\pi^+\pi^0]_{\rho^+}$	0.218	**0.218**
$D_s^- \, \pi^+\pi^+\pi^-$	0.195	**0.413**
$D^*(2010)^- \, \pi^+\pi^+\pi^-$	0.194	**0.607**
$D_s^- \, \pi^+$	0.095	**0.702**
$D_s^+ \, D_s^-$	0.045	**0.747**
$D^0 \, K^-\pi^+$	0.041	**0.789**

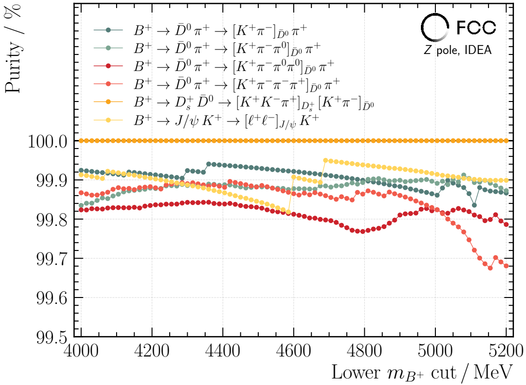
Exclusive reconstruction: included Λ_b^0 decay-modes

Mode	$\mathrm{Br}(\Lambda_b^0 \to XY)$ / %	$\mathrm{Br}(X \to \text{final state})$ / %		$\sum \mathrm{Br}$ / %
$\Lambda_b^0 \to \Lambda_c^+ \pi^+ \pi^- \pi^-$	0.760 ± 0.110	$\Lambda_c^+ \to p K^- \pi^+$	6.280 ± 0.320	**0.082**
		$\Lambda_c^+ \to p K^- \pi^+ \pi^0$	4.460 ± 0.300	

Increasing the tagging efficiency

- For R_b, also partially reconstructed candidates are b-taggers
- Releasing the B^+-mass constraint significantly increases ε_b





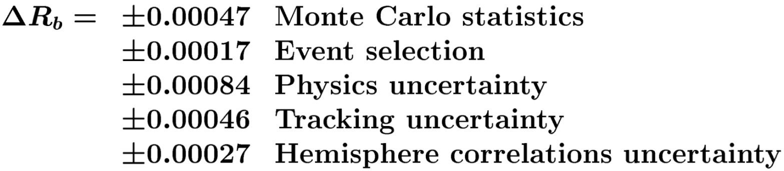
Quantitative summary

B^+ decay-mode	$\varepsilon_{\text{reco}}$ / %	Purity / %	B^+ signal width / MeV
$\bar{D}^0\pi^+ \to [K^+\pi^-]_{\bar{D}^0}\pi^+$	77.17 ± 2.99	99.93 ± 0.11	7.0
$\bar{D}^0\pi^+ \to [K^+\pi^-\pi^0]_{\bar{D}^0}\pi^+$	64.89 ± 1.41	99.89 ± 0.09	32.8
$\bar{D}^0\pi^+ \to [K^+\pi^-\pi^0\pi^0]_{\bar{D}^0}\pi^+$	49.95 ± 2.68	99.81 ± 0.07	35.1
$\bar{D}^0\pi^+ \to [K^+\pi^-\pi^-\pi^+]_{\bar{D}^0}\pi^+$	72.63 ± 6.90	99.73 ± 0.27	9.7
$D_s^+\bar{D}^0 \to [K^+K^-\pi^+]_{D_s^+}[K^+\pi^-]_{\bar{D}^0}$	78.57 ± 22.39	100.00	5.6
$J/\psi K^+ \to [\ell^+\ell^-]_{J/\psi}K^+$	85.87 ± 4.13	99.90 ± 0.24	7.4

b-quark partial-decay width ratio

R_b: systematic uncertainties from ALEPH

- Systematic uncertainties enter where quantities have been estimated from MC simulations: ε_{udsc}, ΔC_q
- For ε_{udsc}, predictions depend on assumed impact parameter resolution and efficiency for vertex-detector hits to be associated to a track
- Physical parameters that enter the calculation of ε_{udsc}

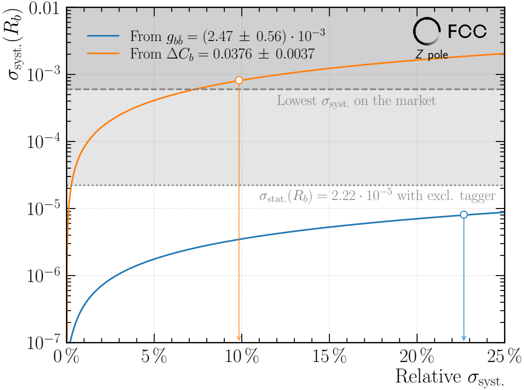


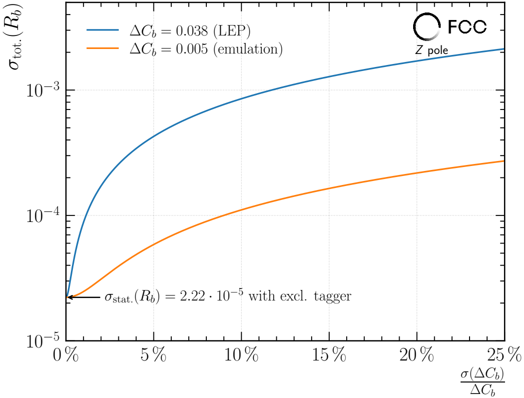
$$
\begin{aligned}
\Delta R_b = \; & \pm 0.00047 \quad \textbf{Monte Carlo statistics} \\
& \pm 0.00017 \quad \textbf{Event selection} \\
& \pm 0.00084 \quad \textbf{Physics uncertainty} \\
& \pm 0.00046 \quad \textbf{Tracking uncertainty} \\
& \pm 0.00027 \quad \textbf{Hemisphere correlations uncertainty}
\end{aligned}
$$

R_b: systematic uncertainties comparison

- Gluon splitting rate $g_{b\bar{b}} = 0.002\,47(56)$ as source of $\sigma_{\text{syst.}}(R_b)$ negligible compared to ΔC_b

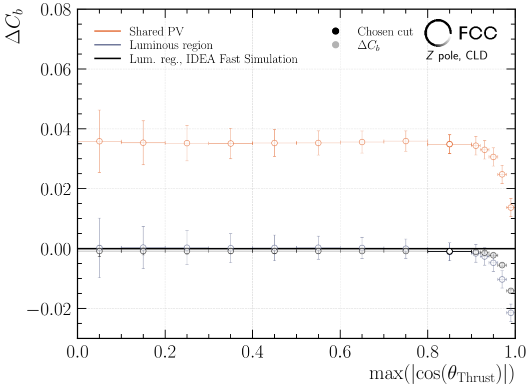
$$N_b = 2N_Z \left(R_b \varepsilon_{b_{1,2}}^{Z\to b\bar{b}} \varepsilon_{E_B}^{Z\to b\bar{b}} + (1 - R_b) g_{b\bar{b}} \varepsilon_{udsc_{1,2}}^{g\to b\bar{b}} \varepsilon_{E_B}^{g\to b\bar{b}} \right)$$

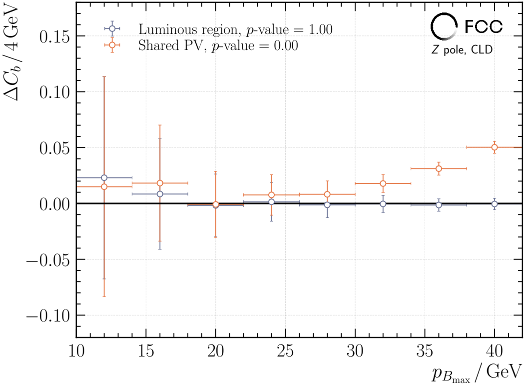




R_b: systematic uncertaintes

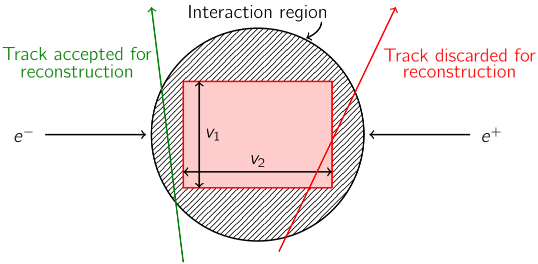
- PV reconstruction main source of $\Delta C_b \neq 0$
- However: detector acceptance effects + gluon splitting studied as well

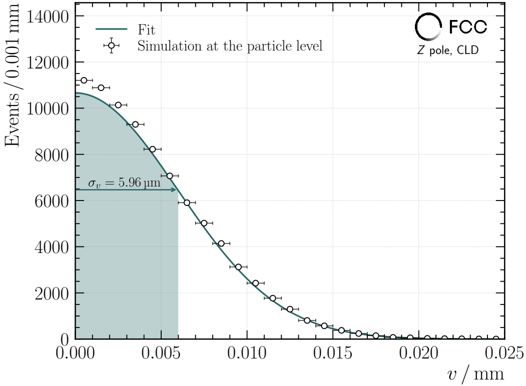




Luminous region selection

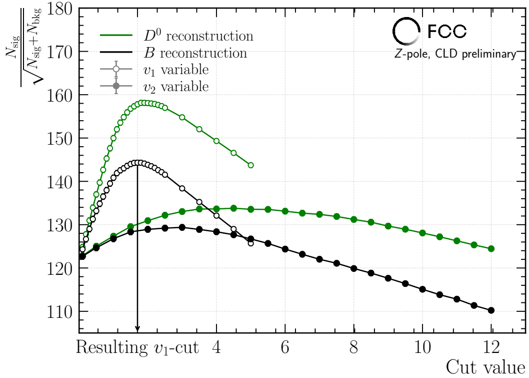
- Selection of tracks outside of luminous region to overcome PV limitations
- Maximise $v_1 = d_0/\sqrt{\sigma_{d_0}^2 + \sigma_v^2}$ and $v_2 = z_0/\sqrt{\sigma_{z_0}^2 + \sigma_v^2}$ w.r.t. specific FOM

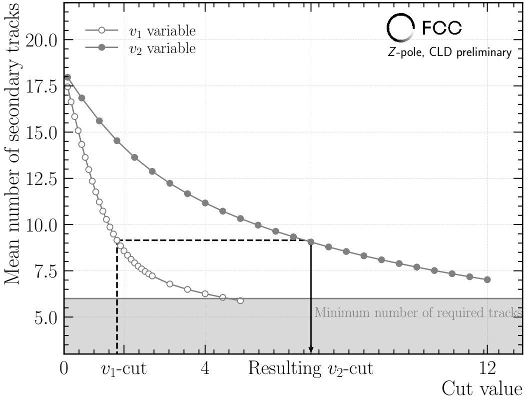




Luminous region selection: FOMs

- Evaluate $\bar{D}^0$ and B^+ significance + mean number of secondary tracks



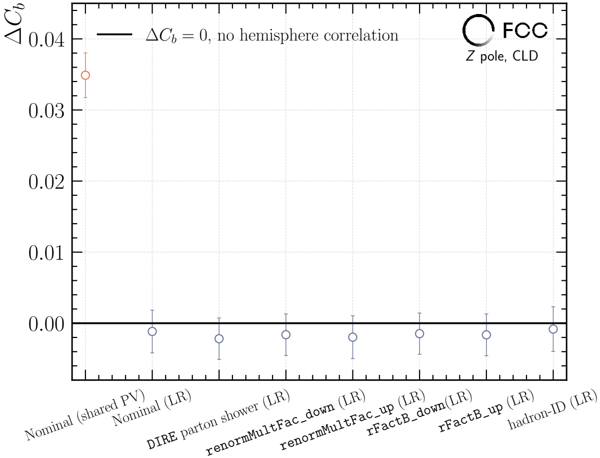


→ $v_1 \leq 3$ & $v_2 \leq 8$

ΔC_b: systematic uncertainties

- First investigation of systematic uncertainties for ΔC_b
- Varying inputs: `DIRE` parton shower, renormalisation scale, *b* fragmentation, track ID

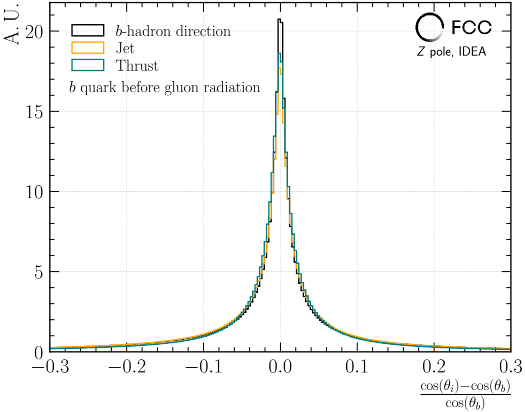
→ No significant impact on ΔC_b

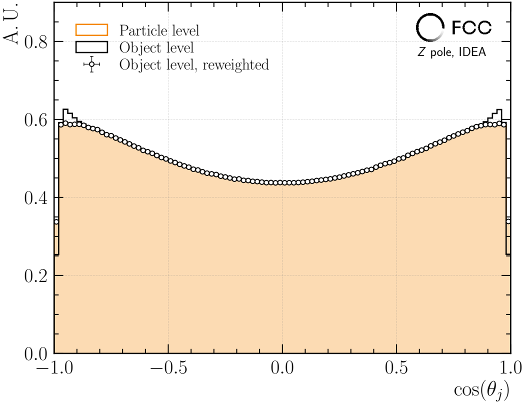


b-quark forward-backward asymmetry

Different *b*-quark direction estimators

- Usual choices at LEP: thrust-axis
- Existing study @FCC-ee: *b*-quark direction from *b*-tagged jets
- Taking into account jet-reconstruction efficiency effects



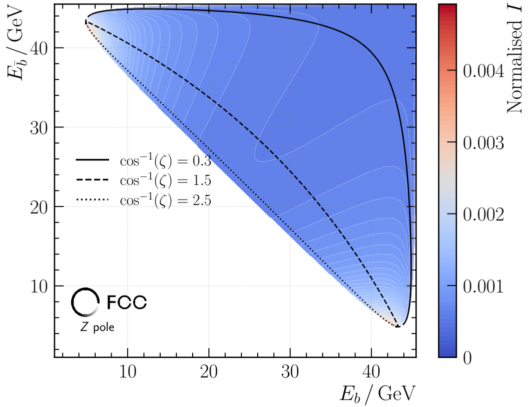


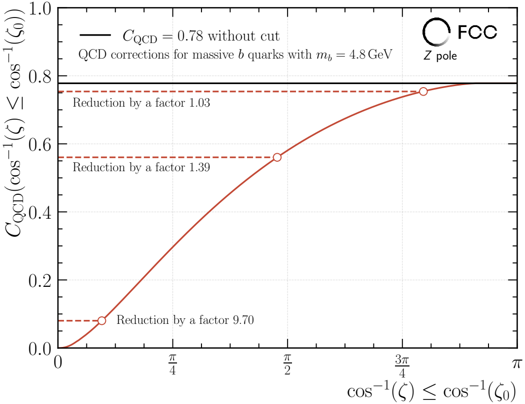
Calculations of C_{QCD} for jet-jet acollinearity

- C_{QCD} as function of acollinearity $\cos(\zeta(x,\bar{x})) = \frac{x\bar{x}+\mu^2+2(1-x-\bar{x})}{\sqrt{x^2-\mu^2}\sqrt{\bar{x}^2-\mu^2}}$ with $x = 2E_b/\sqrt{s}$ and $\mu = 2m_b/\sqrt{s}$

$$C_{\mathrm{QCD}} \approx \int_{x_{\mathrm{min}}}^{x_{\mathrm{max}}} \int_{\bar{x}_{\mathrm{min}}(x)}^{\bar{x}_{\mathrm{max}}(x)} \frac{2\bar{x}^2(1-\cos(\zeta(x,\bar{x})))}{3(1-x)(1-\bar{x})}\,\mathrm{d}\bar{x}\,\mathrm{d}x\,,$$

$$I(x,\bar{x}) = \frac{(x^2+\bar{x}^2)\cdot(1-\cos(\zeta(x,\bar{x})))}{3(1-x)(1-\bar{x})}$$





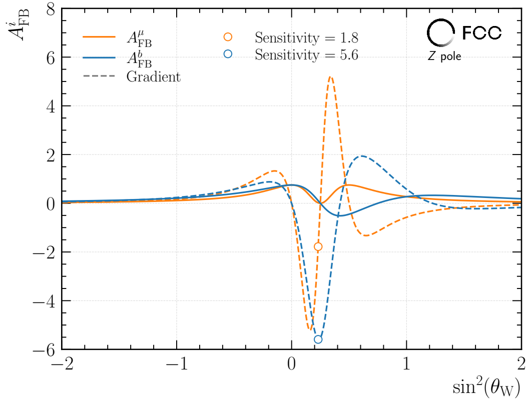
Impact on SM parameters: weak mixing angle

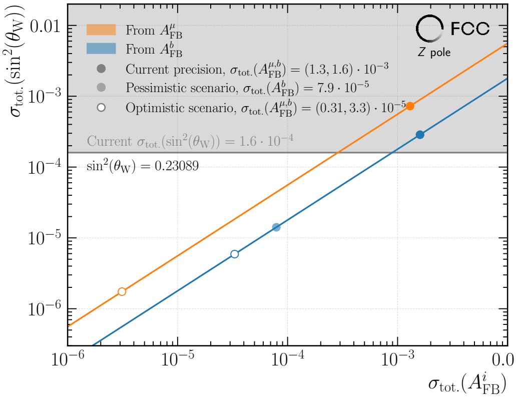
- Precision of A^b_{FB} impacts precision of $\sin^2(\theta_{\mathrm{W}})$

$$A_{\mathrm{FB}} = \frac{3}{4} A_e A_b\,, \quad \text{with} \quad A_f = \frac{2 v_f a_f}{v_f^2 + a_f^2}\,,$$

$$a_f = T_f\,, \quad \text{and} \quad v_f = T_f - 2 Q_f \sin^2(\theta_{\mathrm{W}})$$

→ 3× more sensitivity from A^b_{FB} to $\sin^2(\theta_{\mathrm{W}})$ than from A^μ_{FB} (fractional charge)





Impact on SM parameters: top-quark mass

- Precision of m_t from top-quark loops in Z propagator and $\sin^2(\theta_W^{\text{eff.}}) = \xi \sin^2(\theta_W)$ and $\xi = 1 + \Delta\rho \cot^2(\theta_W)$

$$\Delta\rho = 3x_t + 3x_t^2(19 - \pi^2)\,, \quad \text{and} \quad x_t = \frac{G_F m_t^2}{8\sqrt{2}\pi^2}$$

- In addition: account for vertex corrections with top quarks

$$\Delta\tau = -2x_t - \frac{G_F m_Z^2}{6\sqrt{2}\pi^2} \cdot (1 - \cos(\theta_W)) \ln\left(\frac{m_t}{m_W}\right) - 2x_t^2 \cdot \left(2 - \frac{\pi^2}{3}\right),$$

$$\Rightarrow \quad v_f \rightarrow \bar{v}_f = \sqrt{\rho_f}\left(T_f - \frac{2Q_f \sin^2(\theta_W^{\text{eff.}})}{1 + \Delta\tau}\right),$$

$$\Rightarrow \quad a_f \rightarrow \bar{a}_f = \sqrt{\rho_f}\, T_f\,, \quad \text{with} \quad \rho_f = \frac{(1 + \Delta\tau)^2}{1 - \Delta\rho}$$