|V_{cb}|: the WW threshold to fix at FCC-*ee* a longstanding question

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Outline of the presentation

- Motivations for V_{cb} w/ on-shell and boosted W:
  - State of the art
  - Anticipated CKM Flavour landscape in 204x
  - ECFA study
- The tools: jet flavour-tagging
- Asymptotic precision and critical systematics

1. Motivations

- The CKM element $|V_{cb}|$ as a corner stone of the test of the KM paradigm:

$$\mathcal{L}_{cc}^{\text{quarks}} = \frac{g}{2\sqrt{2}} W_\mu^\dagger \left[\sum_{ij} \bar{u}_i(q_2)\gamma^\mu(1-\gamma^5) V_{ij} d_j\right] + \text{h.c}$$

$$\begin{pmatrix} u \\ s \\ b \end{pmatrix}_{EW} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} u \\ s \\ b \end{pmatrix}_{MASS}$$

- It enters into fundamental SM parameters

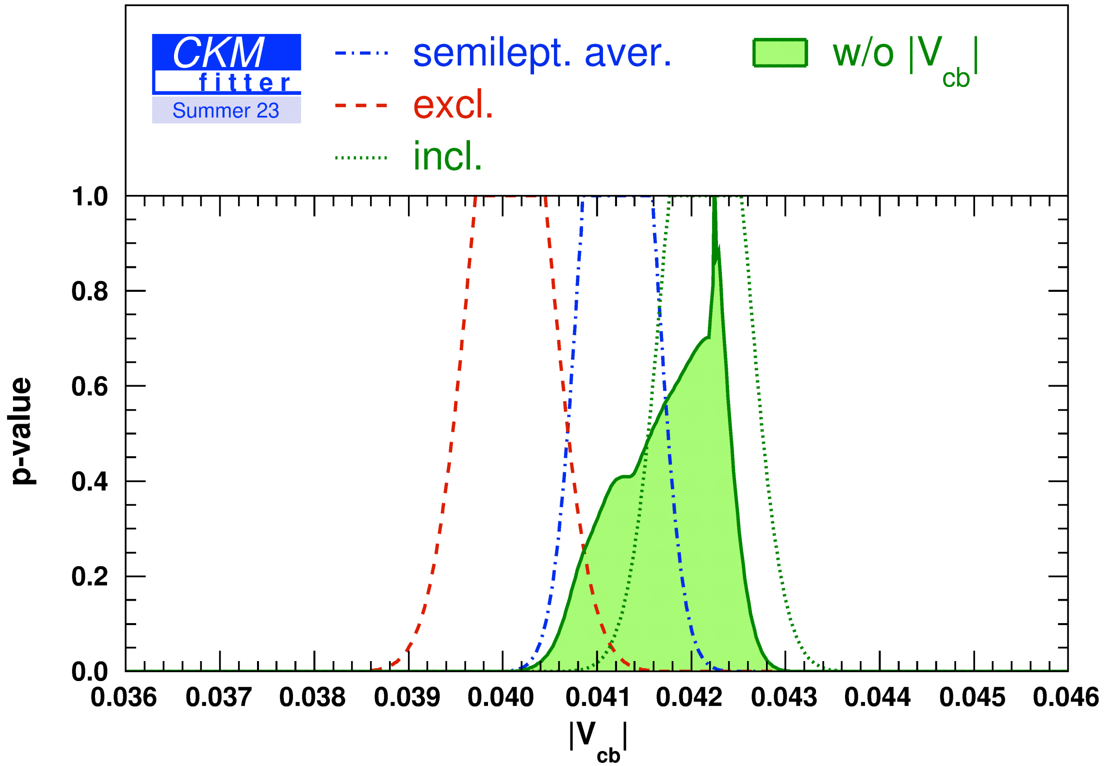
$$\lambda^2 = \frac{|V_{us}|^2}{|V_{ud}|^2 + |V_{us}|^2}, \quad A^2\lambda^4 = \frac{|V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2} \quad \text{and} \quad \bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

- and normalises the unitarity triangle:

$$\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} + \frac{V_{cd}V_{cb}^*}{V_{cd}V_{cb}^*} + \frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*} = 0.$$

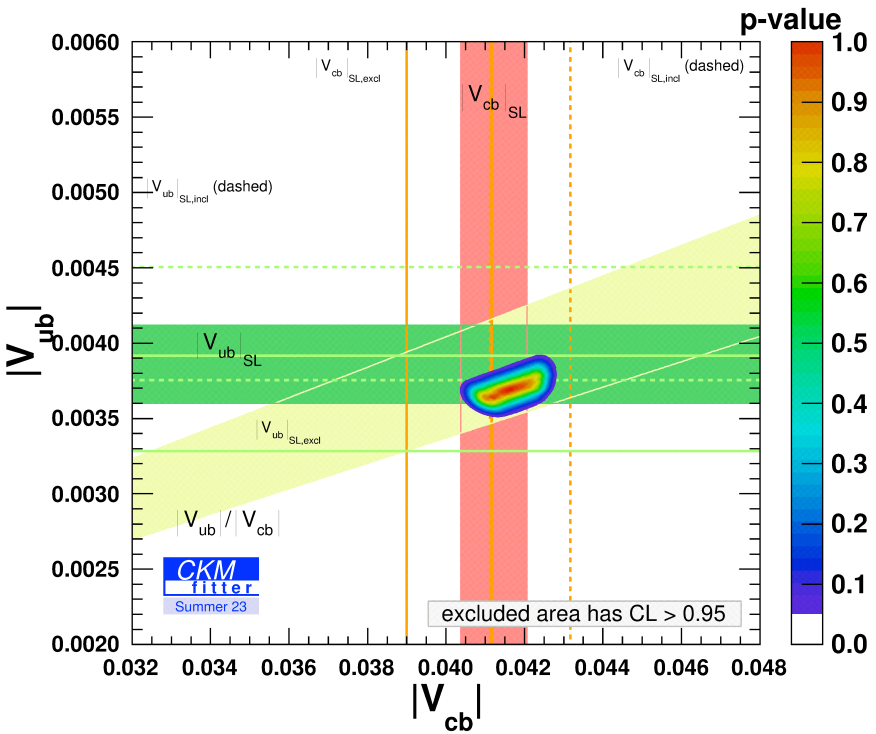
1. Motivations -State of the art

- $|V_{cb}|$ determination from $b \to c$ semileptonic transitions.
- Pioneered at CLEO and LEP, precision era at B-factories
- A longstanding tension between the exclusive (the final state particles but neutrino, are reconstructed) and inclusive (only the lepton).



1. Motivations -State of the art

- The tension between the exclusive and inclusive determination does exist as well for the $|V_{ub}|$ matrix element:



- These longstanding tensions in exclusive / inclusive determinations to be fixed hopefully!

1. Motivations - the CKM profile test in 204x

- At the horizon of the next electron collider, the knowledge of the CKM profile is expected to have been deeply revisited by LHCb and Belle II/III.
- The CKM angle γ can be known at the sub-degree precision; as will the angle β.
- One relevant figure of merit to devise the possible bottlenecks in precision that would alter the global interpretation of the CKM profile is a quasi-model-independent analysis of the BSM contributions in neutral kaon and beautiful-meson mixing phenomena.
- Bottomline: one needs the matrix element $|V_{cb}|$ at a much-higher precision than what semileptonic B decays can provide. The next couple of slides to justify the statement. $|V_{cb}|$ is the normalisation of the UT in the SM and beyond (in a large class of BSM models).

1. Motivations - the CKM profile test in 204x

- Model-independent approach to constrain BSM Physics in neutral meson mixing processes

$$\langle B_q | \mathcal{H}^{\rm SM+NP}_{\Delta B=2} | \bar{B}_q \rangle \equiv \langle B_q | \mathcal{H}^{\rm SM}_{\Delta B=2} | \bar{B}_q \rangle \times (\mathrm{Re}(\Delta_q) + i\,\mathrm{Im}(\Delta_q))$$

$$\mathrm{Re}(\Delta_q) + i\mathrm{Im}(\Delta_q) = r_q^2 e^{i2\theta_q} = 1 + h_q e^{i\sigma_q}$$

Soares & Wolfenstein, PRD 47, 1021 (1993)
Deshpande, Dutta & Oh, PRL77, 4499 (1996)
Silva & Wolfenstein, PRD 55, 5331 (1997)
Cohen et al., PRL78, 2300 (1997)
Grossman, Nir & Worah, PLB 407, 307 (1997)

Assumptions:

✓only the short distance part of the mixing processes might receive NP contributions.

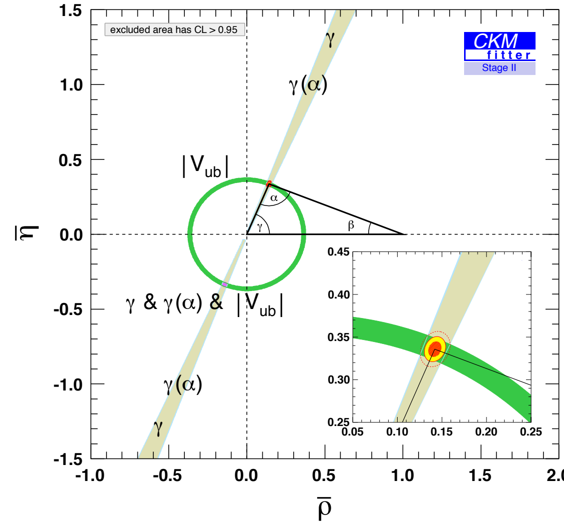
✓Unitary 3x3 CKM matrix (Flavour violation only from the Yukawas-MFV hypothesis).

✓ tree-level processes are not affected by NP (so-called SM4FC: $b \rightarrow f_i f_j f_k$ ($i \neq j \neq k$)). As a consequence, the quantities which do not receive NP contributions in that scenario are:

$$|V_{ud}|,\ |V_{us}|,\ |V_{ub}|,\ |V_{cb}|,\ B^+ \to \tau^+ \nu_\tau \text{ and } \gamma$$

1. Motivations - the CKM profile test in 204x

- The unitarity triangle: fixing CKM parameters w/ $|V_{ub}|$, $|V_{cb}|$ and gamma. This is the anticipated landscape after Belle II and LHCb Upgrade I.



- Knowing the CKM parameters, one can introduce the constraints of the *B* mixing observables depending on the NP complex number (here parameterised as Δ).

parameter	prediction in the presence of NP
Δm_q	$\lvert\Delta_q^{\mathrm{NP}}\rvert \times \Delta m_q^{\mathrm{SM}}$
2β	$2\beta^{\mathrm{SM}} + \Phi_d^{\mathrm{NP}}$
$2\beta_s$	$2\beta_s^{\mathrm{SM}} - \Phi_s^{\mathrm{NP}}$
2α	$2(\pi - \beta^{\mathrm{SM}} - \gamma) - \Phi_d^{\mathrm{NP}}$
$\Phi_{12,q} = \mathrm{Arg}[-\frac{M_{12,q}}{\Gamma_{12,q}}]$	$\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}}$
A_{SL}^q	$\frac{\Gamma_{12,q}}{M_{12,q}^{\mathrm{SM}}} \times \frac{\sin(\Phi_{12,q}^{\mathrm{SM}}+\Phi_q^{\mathrm{NP}})}{\lvert\Delta_q^{\mathrm{NP}}\rvert}$
$\Delta\Gamma_q$	$2\lvert\Gamma_{12,q}\rvert \times \cos(\Phi_{12,q}^{\mathrm{SM}} + \Phi_q^{\mathrm{NP}})$

1. Motivations - the CKM profile test in 204x

$$h \simeq 1.5 \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \frac{(4\pi)^2}{G_F \Lambda^2} \simeq \frac{|C_{ij}|^2}{|\lambda_{ij}^t|^2} \left(\frac{4.5\,\text{TeV}}{\Lambda} \right)^2,$$

$$\sigma = \arg\left(C_{ij}\, \lambda_{ij}^{t*}\right),$$

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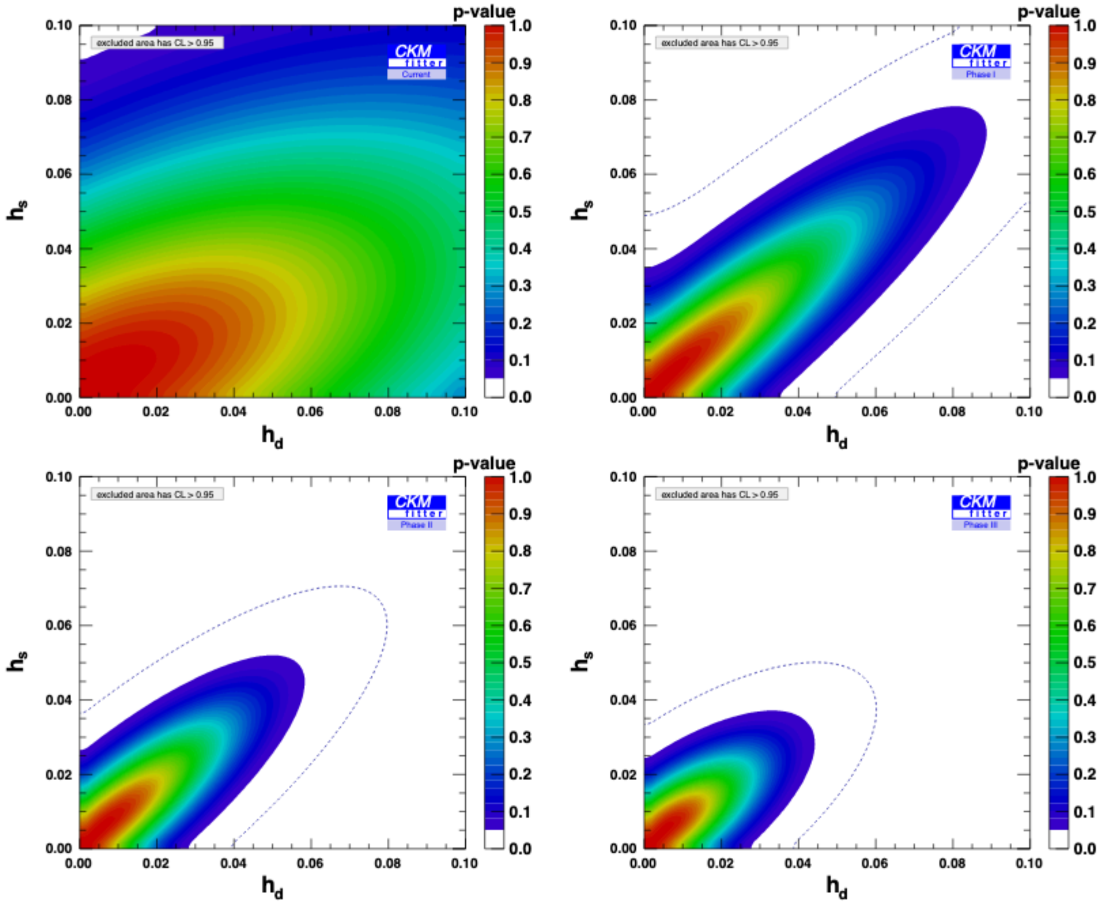

FIG. 2. Current (top left), Phase I (top right), Phase II (bottom left), and Phase III (bottom right) sensitivities to $h_d - h_s$ in B_d and B_s mixings, resulting from the data shown in Table I (where central values for the different inputs have been adjusted). The dotted curves show the 99.7% CL (3σ)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

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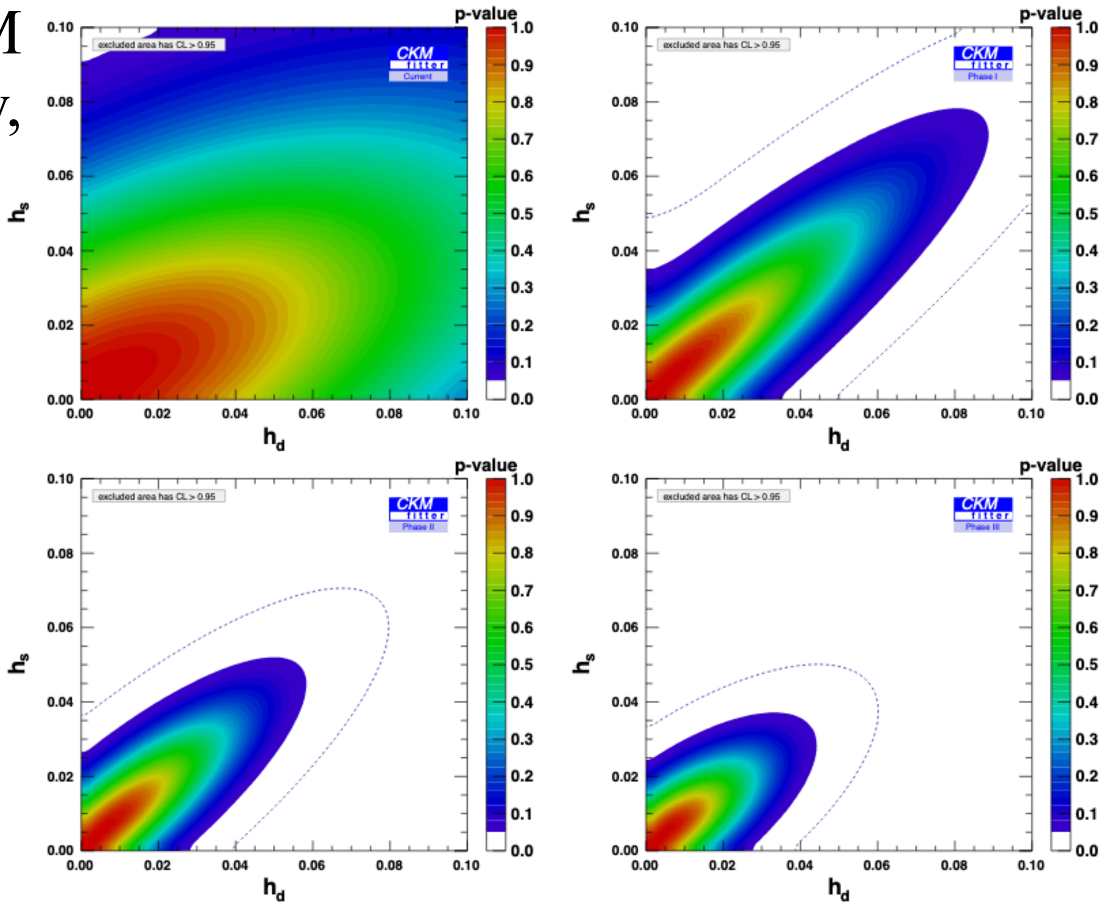
rescaled to SM — Now,



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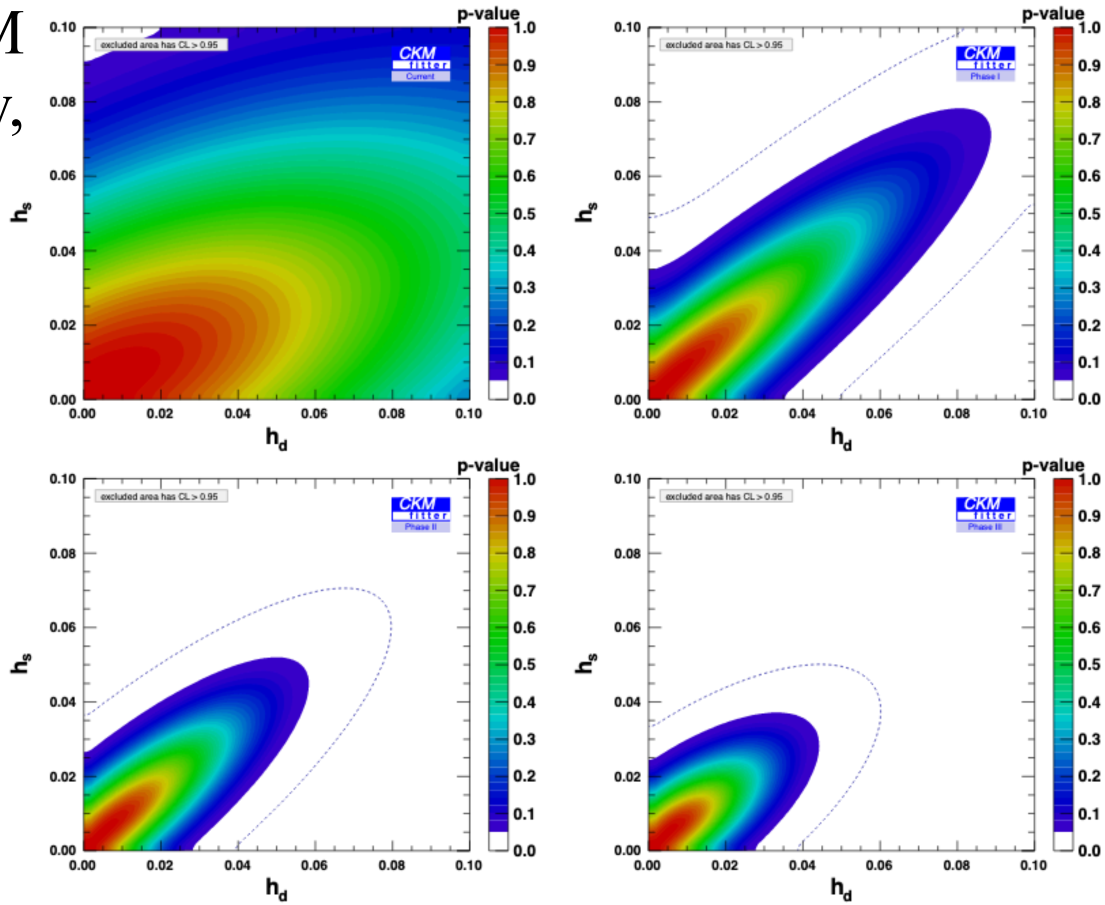
after LHCb-U1 and Belle II — 2030



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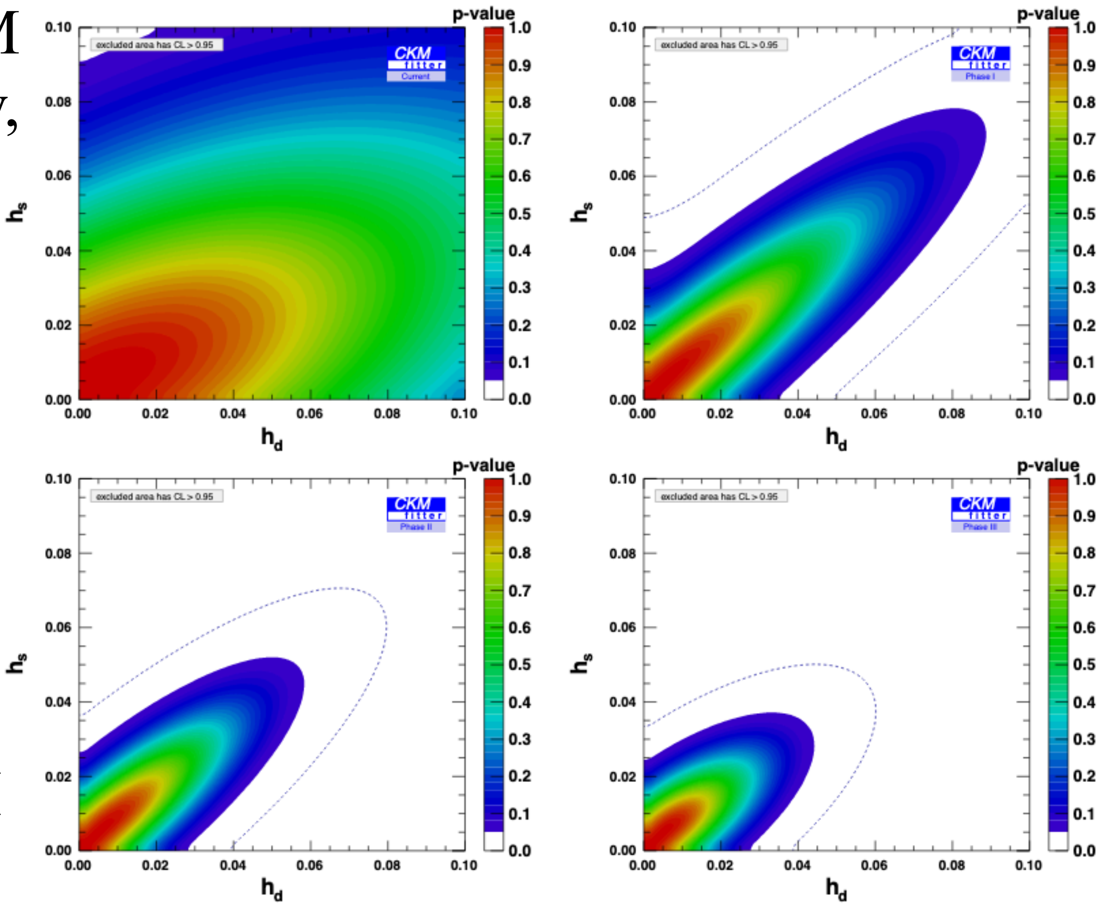
after LHCb U2 and Belle III — 2040



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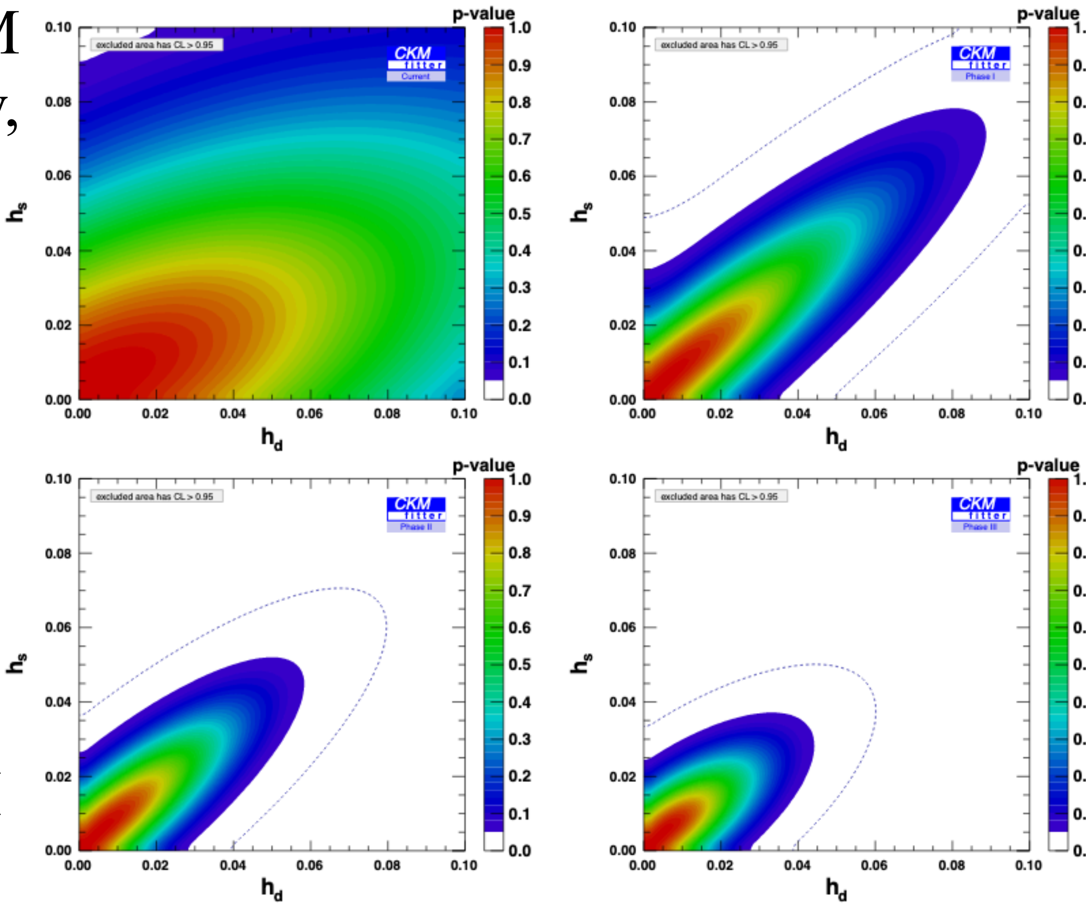
Vcb improved LQCD not



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1. Motivations - ECFA Study -

- A team has defined the methodology of the prospective study and some members will actually explore it: P. Koppenburg (Nikhef), SM, U. Einhaus (DESY, ILC), M. Selvaggi (CERN, FCC), P. Goldenzweig (KIT, BelleII), M. Bordone (CERN, TH), D. Marzocca (Trieste, TH), Z. Ligeti (Berkeley, TH). Contributions welcome!

- Preliminaries:
  - What is the ultimate precision on Vcb (and Vcs, and the other matrix elements! if possible) from Belle-II and LHCb? ILC / FCC-ee reach.
- From W decays:
  - Review of the state-of-the-art Flavour Tagging (FT) algorithms
  - Define FT calibration methods and related systematics.
  - Estimate the precision reachable in all accessible CKM matrix elements.
- Extra: What about *Z* pole: semileptonic, $B_c \to \tau\nu$? Assessing LQCD precision! Might be useful for *B* Physics and beyond …

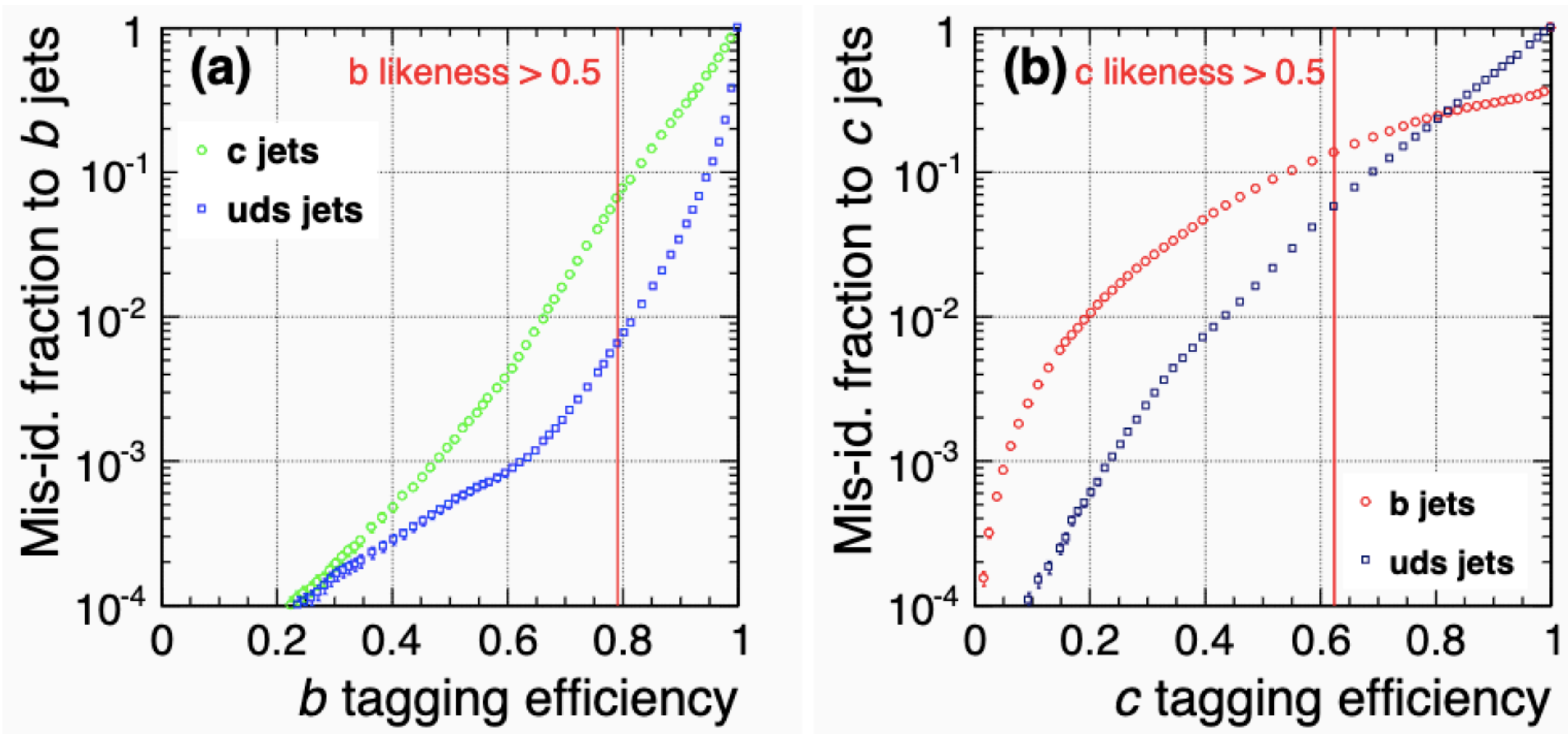
2. The tools

- Theory: none at WW threshold and beyond! Marginal correction to the B scale. Clean observable and hence becomes a benchmark to test the Lattice-QCD predictions.

- Experiment: this study can be a test bench for jet-flavour tagging algorithms. The latest (or close) performance of FCC-ee is tested today.

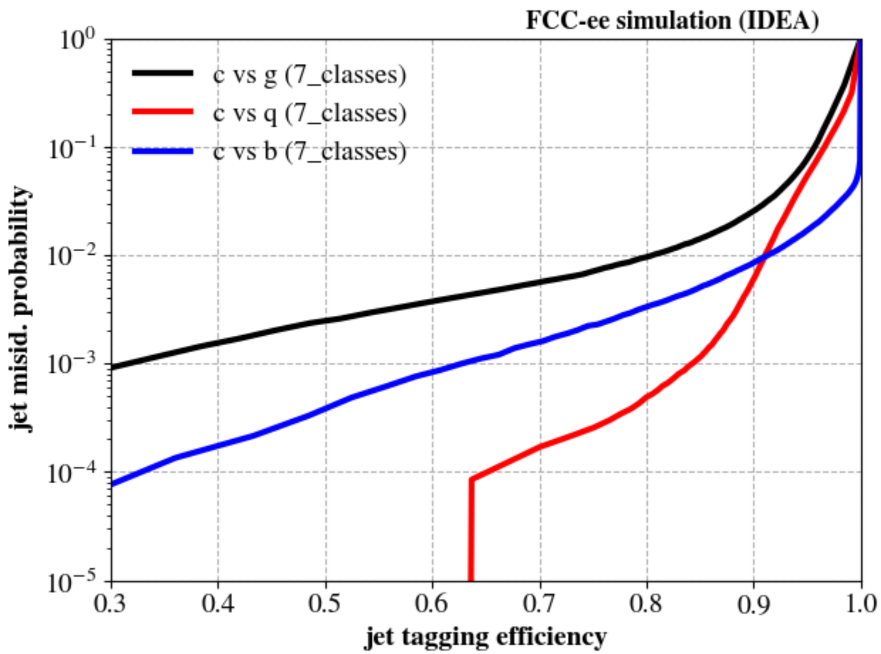
2. The tools: flavour tagging

- 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, HKU

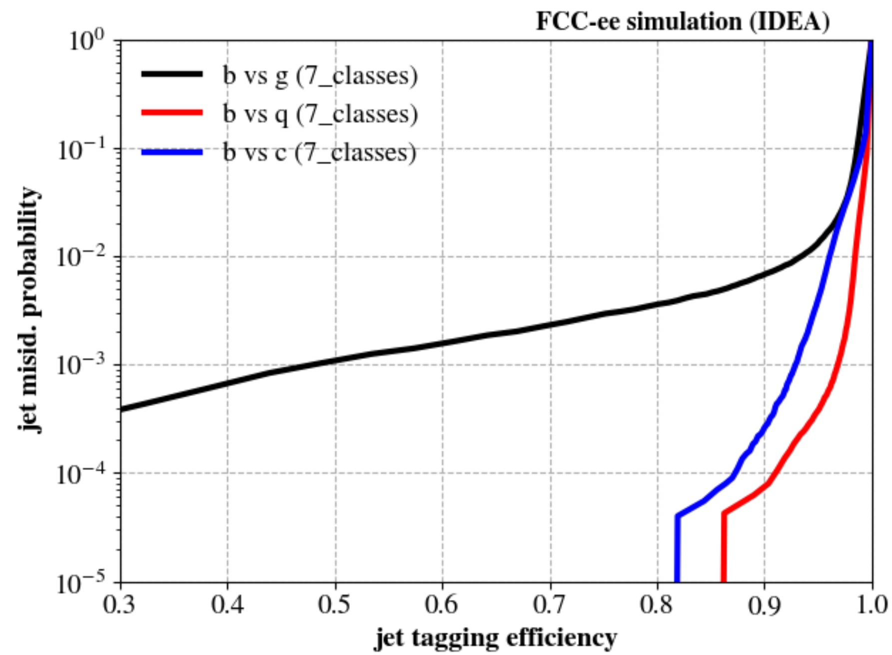


2. The tools: flavour tagging at FCC-ee

- Jet flavour tagging performance as presented by Michele Selvaggi in London



c-tag

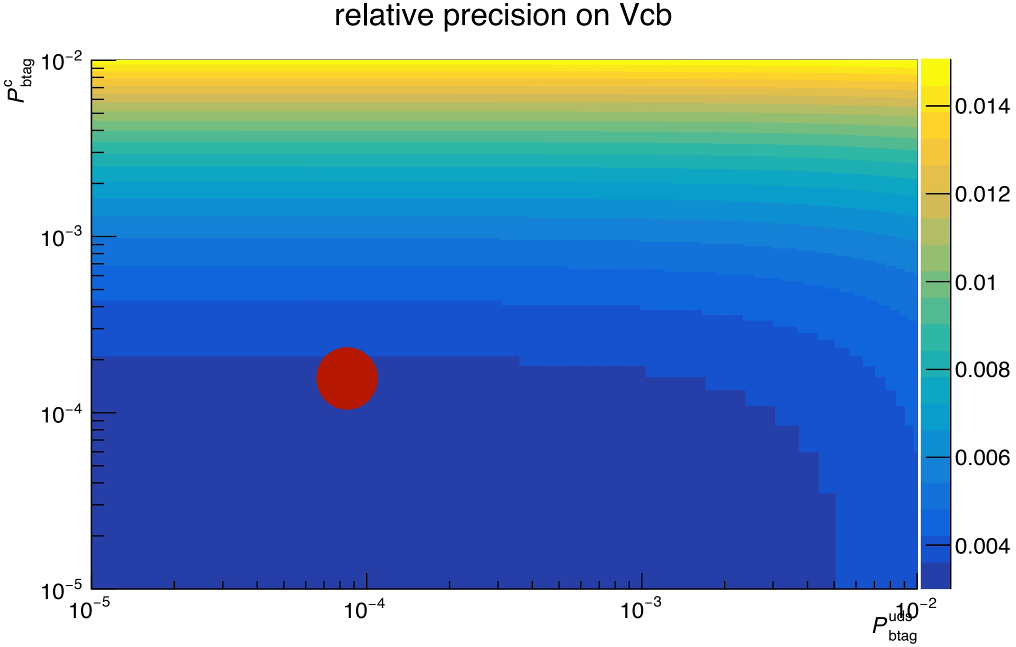


b-tag

3. Precision on $|V_{cb}|$

- Jet tagging performance supposed as in the ILD@ILC reference
- Consider $N_{WW} = 10^8$; count the signal and background.

Eff. \ Flav.	*b*	*c*	*uds*
b-tag	0.25		
c-tag	0.10	0.50	0.02

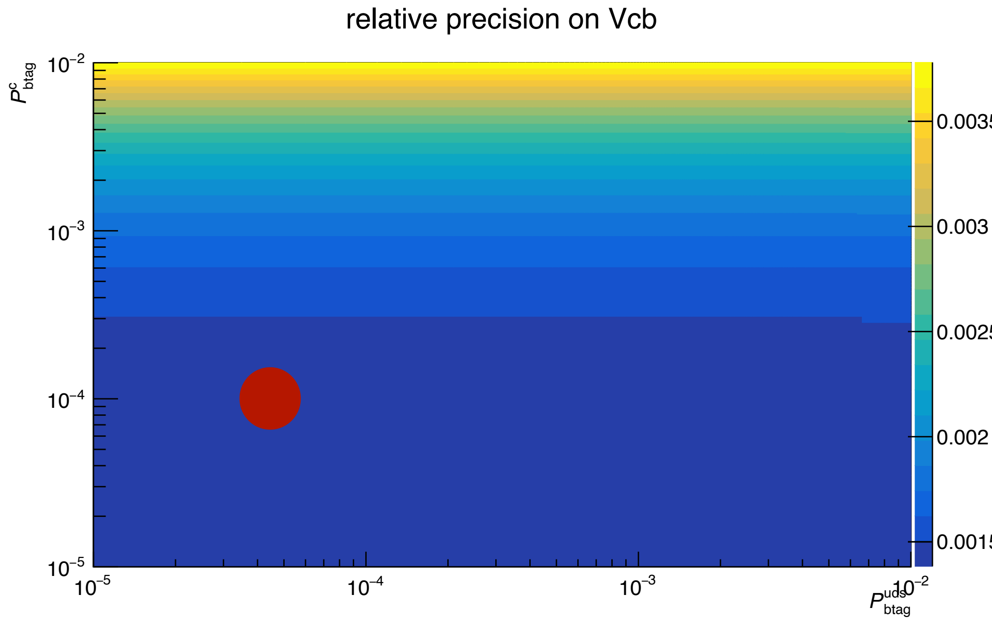


- $|V_{cb}|$ measurement precision is at the level of 0.4%

3. Precision on $|V_{cb}|$

- Jet tagging performance supposed as in the ILD@ILC reference
- Consider $N_{WW} = 10^8$; count the signal and background.

Eff. \	b	c	uds
b-tag	0.87		
c-tag	1	0.65	0.0001



- $|V_{cb}|$ measurement precision is 0.15 %, one order of magnitude better than the current precision and close to the asymptotic precision.
- Jet-tagging efficiencies shall be determined from data at Z-pole

4. Conclusions

- Longstanding tension between the exclusive and inclusive determination of the $|V_{cb}|$ matrix element.

- The WW threshold and beyond provides an invincible precision, useful to constrain further the CKM profile and the related BSM constraints, otherwise limited.

- The $|V_{cb}|$ determination with on-shell and boosted W can serve as a benchmark for Lattice-QCD calculations used at the Z pole. Definitely useful for B physics but also beyond.

- Calibrating the jet favour tagging performances will be the measurement challenge.