Measurement of V_{cb} from $WW \to \mu\nu qq$ at the CEPC

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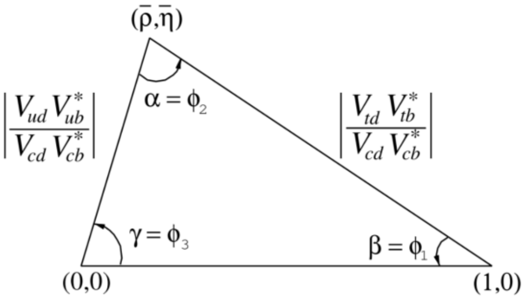
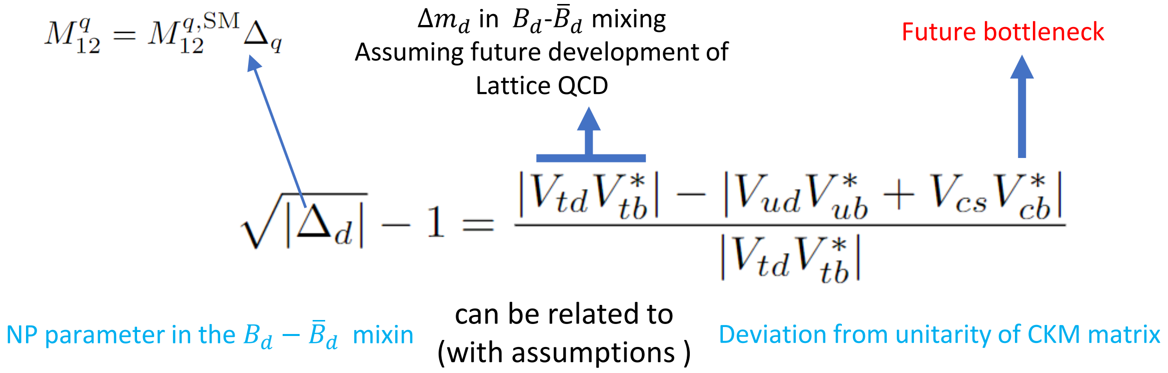
IHEP

March 24th, 2023

Introduction



- Significance of V_{cb}
  - The normalization of the unitarity triangle
  - New Physics study in B_s/B_d mixing



$$M_{12}^q = M_{12}^{q,\mathrm{SM}}\Delta_q$$

Δm_d in B_d-$\bar{B}_d$ mixing
Assuming future development of
Lattice QCD

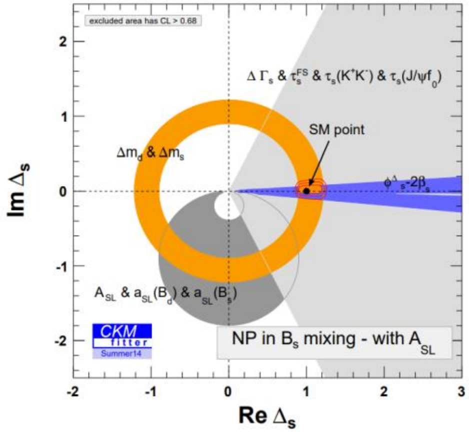
Future bottleneck

$$\sqrt{|\Delta_d|} - 1 = \frac{|V_{td}V_{tb}^*| - |V_{ud}V_{ub}^* + V_{cs}V_{cb}^*|}{|V_{td}V_{tb}^*|}$$

NP parameter in the $B_d - \bar{B}_d$ mixin

can be related to
(with assumptions)

Deviation from unitarity of CKM matrix

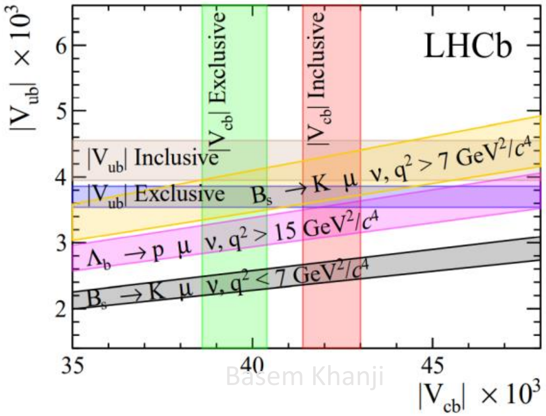


Phys.Rev. D91 (2015) 073007
More about this topic:
Phys. Rev. D 102,
056023 (2020)

Simplified analysis. only minimum number of inputs: $f_{B_d}, B_{B_d}, \Delta m_d, |V_{ud}|, |V_{ub}|, |V_{cd}|, |V_{cb}|, \gamma$

$$\delta(\sqrt{|\Delta_d|}-1) = \frac{\delta f_{B_q}}{f_{B_q}} \oplus \frac{\delta \hat{B}_{B_d}}{2\hat{B}_{B_d}} \oplus \frac{\delta \Delta m_d}{2\Delta m_d} \oplus \frac{\delta|V_{ud}V_{ub}^*|\cos^2\alpha}{|V_{ud}V_{ub}^*|} \oplus \frac{\delta|V_{cd}V_{cb}^*|\cos^2\beta}{|V_{cd}V_{cb}^*|} \oplus \frac{\delta\gamma\sin\beta\sin\alpha}{\sin\gamma}$$

- Significance of V_{cb} at EW scale
  - $|V_{cb}|$ measured by b-hadrons decays
    - non-perturbative QCD contribution
    - Results show discrepancy between inclusive and exclusive analyses
  - V_{cb} by W decay
    - Perturbatively QCD
    - Normally b-hadrons decays is not sensitive to NP, what if the W boson decays?

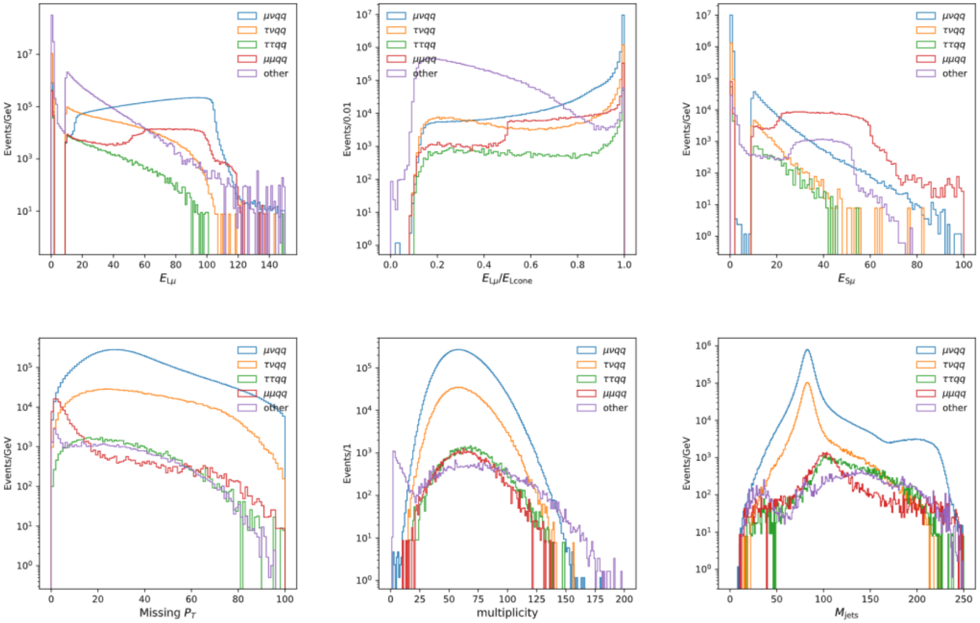


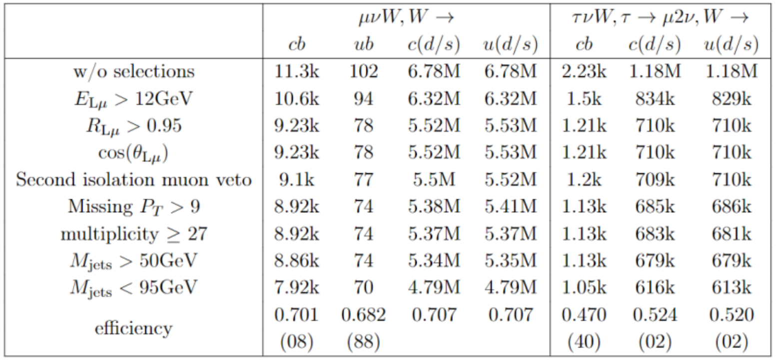
Study Setup

- Parameters in CDR:
  - Lumi. 5600 fb^{-1} $E = 240$ GeV
  - 11 thousand $\mu\nu cb$ in 13 million $\mu\nu qq$
- Study $\mu\nu W$ as first example
  - Cleanness of μ
  - Complementary analysis: $e\nu qq$ and $\tau\nu qq$ even $qqqq$
- We treat $\mu\nu qq$ and $\tau(\mu 2\nu)\nu qq$ as signal strength
- Three signals measured simultaneously
  - $W \to cb, W \to c(s+d), W \to u(s+d)$
  - $W \to ub$ too tiny to access, fixed to SM

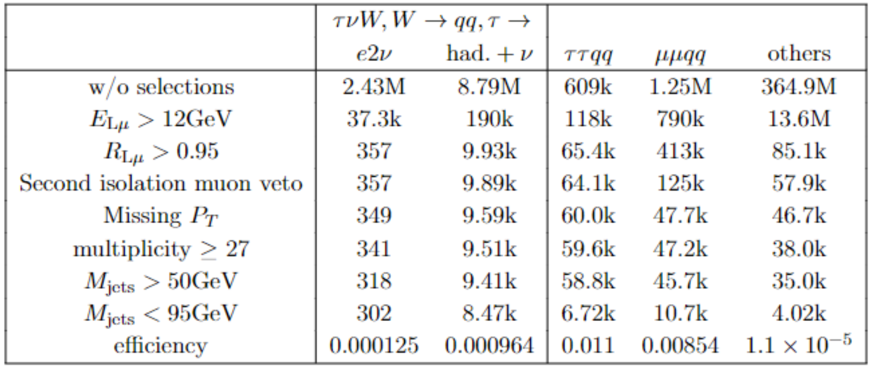
Event selections

- Selection criteria are optimized for statistical uncertainty for $\mathrm{Br}(W \to cb)$
- Purity > 99.5% at eff. of 70% for $W \to qq$





	$\mu\nu W, W \to$				$\tau\nu W, \tau \to \mu 2\nu, W \to$		
	cb	ub	$c(d/s)$	$u(d/s)$	cb	$c(d/s)$	$u(d/s)$
w/o selections	11.3k	102	6.78M	6.78M	2.23k	1.18M	1.18M
$E_{\mathrm{L}\mu} > 12\mathrm{GeV}$	10.6k	94	6.32M	6.32M	1.5k	834k	829k
$R_{\mathrm{L}\mu} > 0.95$	9.23k	78	5.52M	5.53M	1.21k	710k	710k
$\cos(\theta_{\mathrm{L}\mu})$	9.23k	78	5.52M	5.53M	1.21k	710k	710k
Second isolation muon veto	9.1k	77	5.5M	5.52M	1.2k	709k	710k
Missing $P_T > 9$	8.92k	74	5.38M	5.41M	1.13k	685k	686k
multiplicity ≥ 27	8.92k	74	5.37M	5.37M	1.13k	683k	681k
$M_{\mathrm{jets}} > 50\mathrm{GeV}$	8.86k	74	5.34M	5.35M	1.13k	679k	679k
$M_{\mathrm{jets}} < 95\mathrm{GeV}$	7.92k	70	4.79M	4.79M	1.05k	616k	613k
efficiency	0.701 (08)	0.682 (88)	0.707	0.707	0.470 (40)	0.524 (02)	0.520 (02)



	$\tau\nu W, W \to qq, \tau \to$				
	$e2\nu$	had. $+\,\nu$	$\tau\tau qq$	$\mu\mu qq$	others
w/o selections	2.43M	8.79M	609k	1.25M	364.9M
$E_{\mathrm{L}\mu} > 12\mathrm{GeV}$	37.3k	190k	118k	790k	13.6M
$R_{\mathrm{L}\mu} > 0.95$	357	9.93k	65.4k	413k	85.1k
Second isolation muon veto	357	9.89k	64.1k	125k	57.9k
Missing P_T	349	9.59k	60.0k	47.7k	46.7k
multiplicity ≥ 27	341	9.51k	59.6k	47.2k	38.0k
$M_{\mathrm{jets}} > 50\mathrm{GeV}$	318	9.41k	58.8k	45.7k	35.0k
$M_{\mathrm{jets}} < 95\mathrm{GeV}$	302	8.47k	6.72k	10.7k	4.02k
efficiency	0.000125	0.000964	0.011	0.00854	1.1×10^{-5}

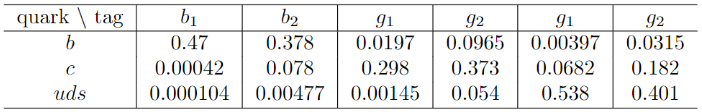
Table 3. Event selections for backgrounds.

Efficiencies differences under investigation. MC statistics? Cut bias?

Jet flavour tagging

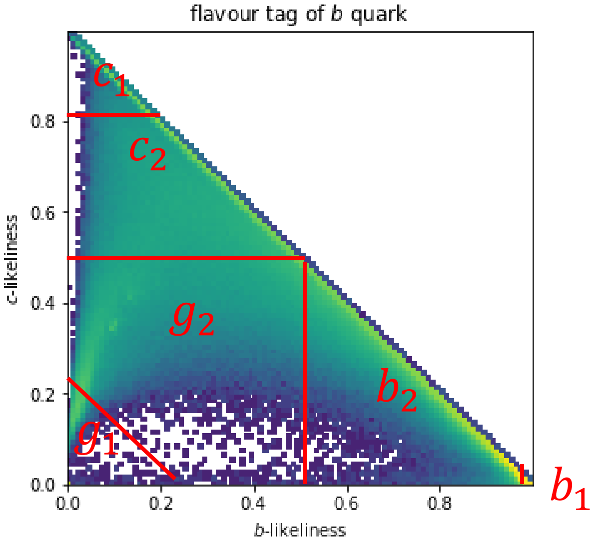
Boundary between b1 and b2 (0.995) which optimized for statistical error of $W \to cb$

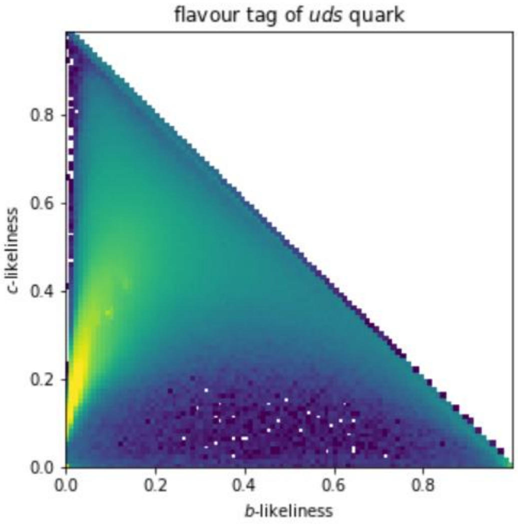
Flavour tagging at Z-pole

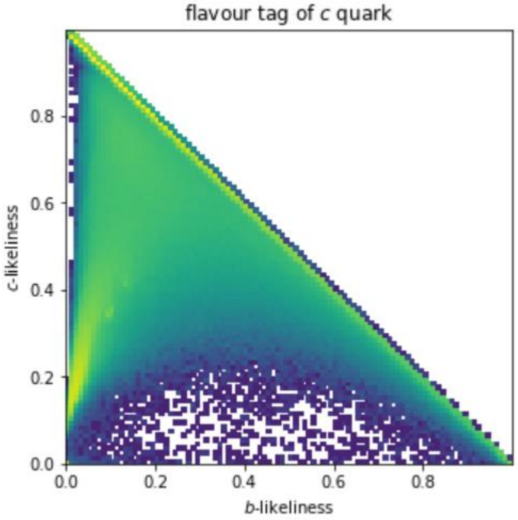


quark \ tag	b_1	b_2	g_1	g_2	g_1	g_2
b	0.47	0.378	0.0197	0.0965	0.00397	0.0315
c	0.00042	0.078	0.298	0.373	0.0682	0.182
uds	0.000104	0.00477	0.00145	0.054	0.538	0.401

Table 5: The flavour tag efficiencies at Z-pole with selected events.







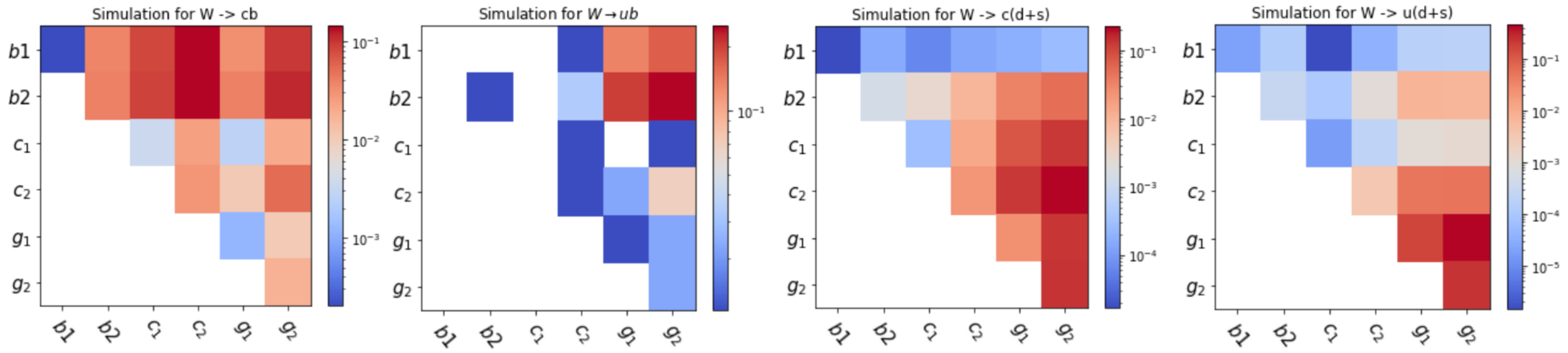
classify events into 21 categories

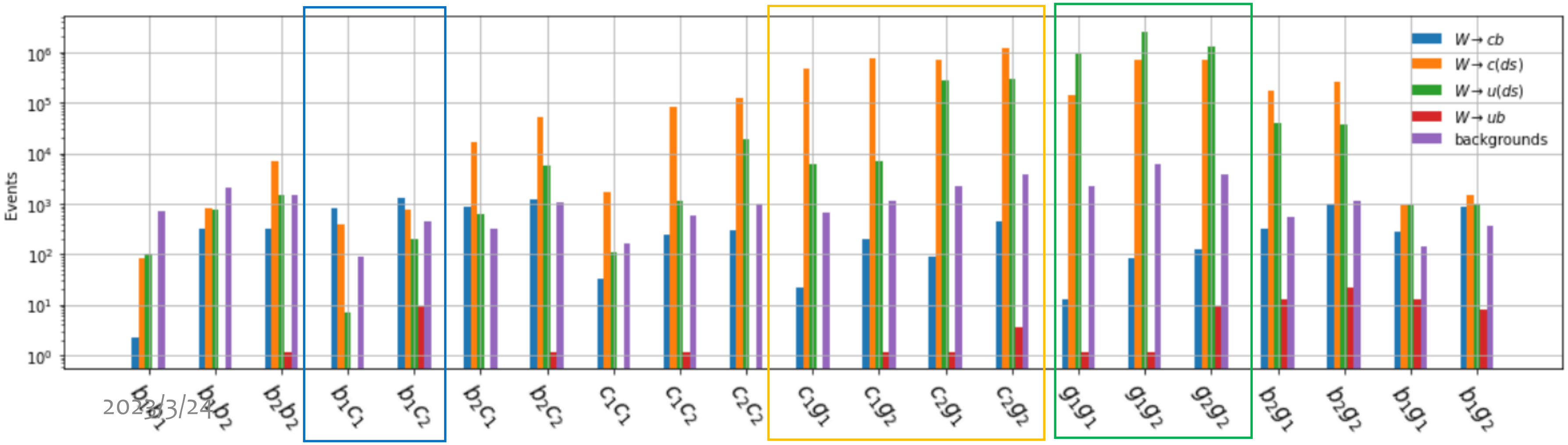
6 labels for a jets, and 21 combinations for di-jet.

Just an idea: Self-calibration is possible?

e.g. $W \to u(d+s)$,

- 3 main unknown parameters $N_{u(ds)}$, $\mathrm{Eff}_{uds\to g_1}$, and $\mathrm{Eff}_{uds\to g_2}$
- 3 observables: green bars in the green box





Statistics: Extraction of results

- The χ^2 $-2\log(L(S_a)) = \sum_{i=1}^{21} \frac{(\sum_a S_a N_i^a + \mathrm{bkg}_i - N_i^{\mathrm{obs}})^2}{N_i^{\mathrm{obs}}}$
  - Signal strengths for $W \to cb$ and $W \to c(ds)$ and $W \to u(ds)$
    - statistical errors: 0.026, 5.9E-4, 5.8E-4
    - Correlation coef. $\begin{pmatrix} 1 & -0.077 & 0.020 \\ \cdots & 1 & -0.46 \\ \cdots & \cdots & 1 \end{pmatrix}$
  - The ratio of $\mu\nu q_1 q_2$ to $\tau(\mu 2\nu)\nu q_1 q_2$ is assumed to be known
- $|V_{cb}|$
  - Relative statistical error: 1.3%
- The check of unitarity of CKM
  - $\frac{\sum_{j=bds}|V_{cj}|^2}{\sum_{j=bds}|V_{uj}|^2} = \frac{\sum S_{cj}\mathrm{Br}(W_{\mathrm{cj}})}{\sum S_{uj}\mathrm{Br}(W_{uj})}$
  - Statistical error: 0.1%
  - Systematics, need to take care of flavour tagging.

Statistics: comparison

- $|V_{cb}|$ by $\mu\nu qq$ and $\tau(\mu 2\nu)\nu qq$
  - relative statistical uncertainty 1.3%
  - Half of the exclusive and inclusive analysis by b-hadron, respectively.
  - Global fit result good
    - seems there is uncounted uncertainties in the measurements
  - Comparable to V_{cb} accuracy level of 1% by the 3.6× 10^6 $B_c \rightarrow \nu\tau$ decays from 1 Tera Z at the CEPC (arXiv:2007.08234)
  - At the FCC-*ee*, quick estimation by Marie-Helene Schune:
    - 1.9%/1.5%
    - aiming at 0.4% with 100 million WW pairs around threshold

Systematics

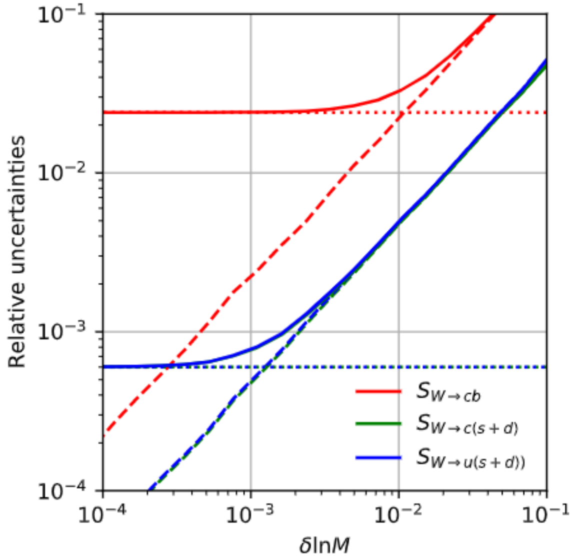
- $|V_{cb}|$ by $\mu\nu qq$ and $\tau(\mu 2\nu)\nu qq$
  - relative statical uncertainty 1.3%

$$|V_{bc}| = \sqrt{\frac{\Gamma_W R_{cb} \mathrm{Br}(W \to qq)}{\alpha_{\mathrm{QCD}} C_{cb}}} \qquad R_{bc} = \frac{\mathrm{Br}(W \to cb) S_{W \to cb}}{\sum_{\mathrm{hadronic}} \mathrm{Br}(a) S_a} \qquad c_{\mathrm{QCD}} = 1 + \sum_n c_n \alpha_s^n (M_W^2)$$

neglect the mass of quarks $C_{ij} = C$, where $C = G_F M_W^3 / (6\pi\sqrt{2})$.

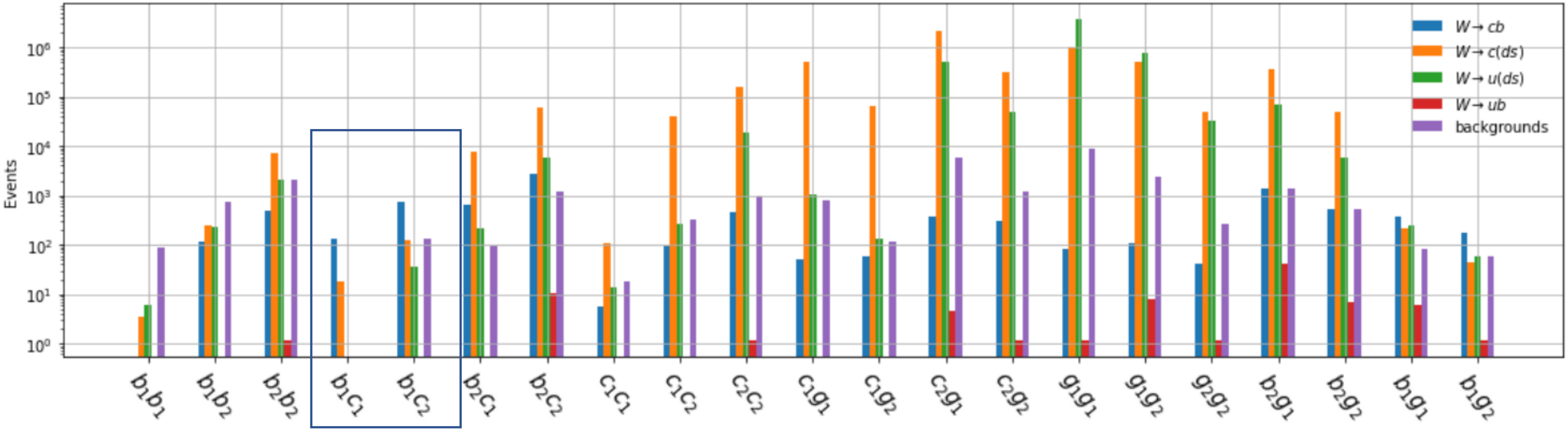
	relative uncertainty	contribution to $\delta \ln |V_{cb}|$
Γ_W at the CEPC [11]	0.1%	0.05%
Γ_W from W leptonic decay	0.1%	0.05%
Γ_W (current, CKM unit.)[4]	0.06%	0.03%
Γ_W (current, CKM exp.)[4]	$\sim 1.0\%$	$\sim 0.5\%$
$\alpha_s(W_W^2)$	$< 10^{-2}$	$< 10^{-3}$
$\mathrm{Br}(W \to qq)$	$< 10^{-3}$	$< 10^{-3}$
Events selections efficiencies	$< 10^{-3}$	$< 10^{-3}$
Flavour tag efficiencies	$??? \times 10^{-3}$	$??? \times 10^{-3}$
Statistics		1.3%
Total		$??? \times 10^{-2}$

Table 4. Uncertainties for $|V_{cb}|$.



Systematics: Extreme cut on b-likeliness

- Extreame cut on b-likeliness > 0.999
  - High purity sample of $W \rightarrow cb$
  - relax the requirement of ***relative*** systematical error of backgrounds
  - Relative statistical error for $S_{W\rightarrow cb}$: 3.1% (optimal one: 2.6%)



Extrapolation for flavour tagging performance

- Migration matrix M_{ij}
  - the i quark tagged as label j.
- mimic data with: $N_{t_1 t_2} = \sum_{ij} N_{ij} M_{it_1} M_{jt_2} \left(2 - \delta_{t_1 t_2}\right)$
- Trace of the migration matrix
  - $\mathrm{Tr}(M) = M_{bb_1} + M_{bb_2} + M_{cc_1} + M_{cc_2} + M_{uds,g_1} + M_{uds,g_2}$
  - characterizing the flavour tagging performance
- Extrapolation
  - Linear mix the baseline and `unit` matrix to obtain migration matrix with other trace

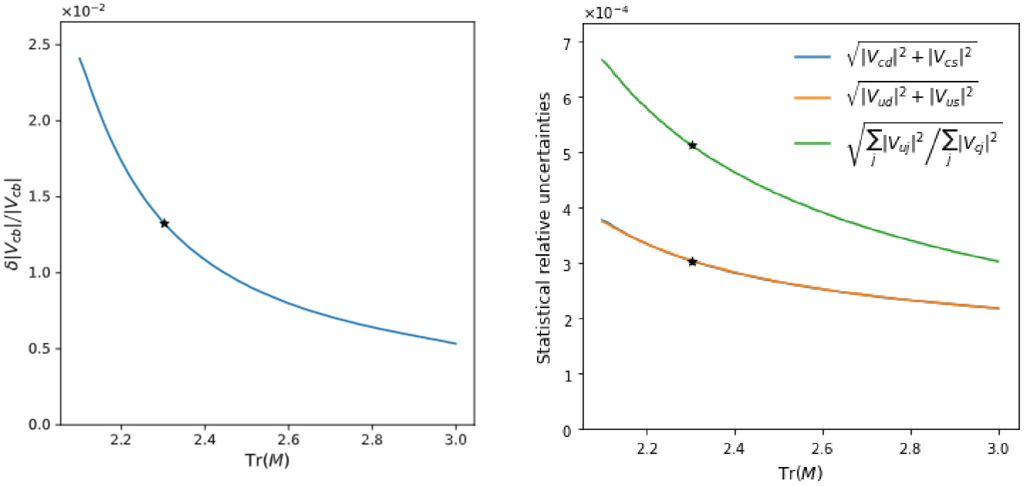


Figure 8. Left: the relative statistical uncertainties $|V_{cb}|$ vs. the trace of migraion matrix. Right: statistical precision of $W \to c(d+s)$, $W \to u(d+s)$ and unitarity test vs. the trace of migraion matrix. The stars mark the position of CEPC's baseline.

VTX: Vin-B

- New design: Vin-B (**V**ertex **in b**eampipe tube)
  - Most inner layer inside the beampipe tube
  - Reduce the inner and middle layers of VTX
  - Remove supports structure of VTX
    - Self-support of silicon sensitive volume
- 20% improvement for V_{cb}

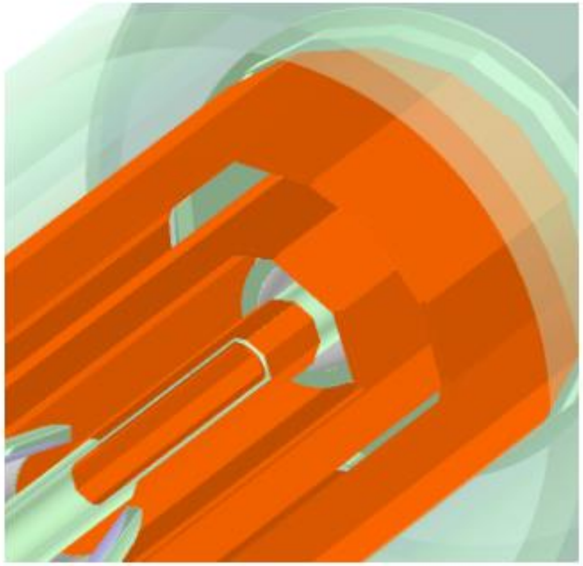
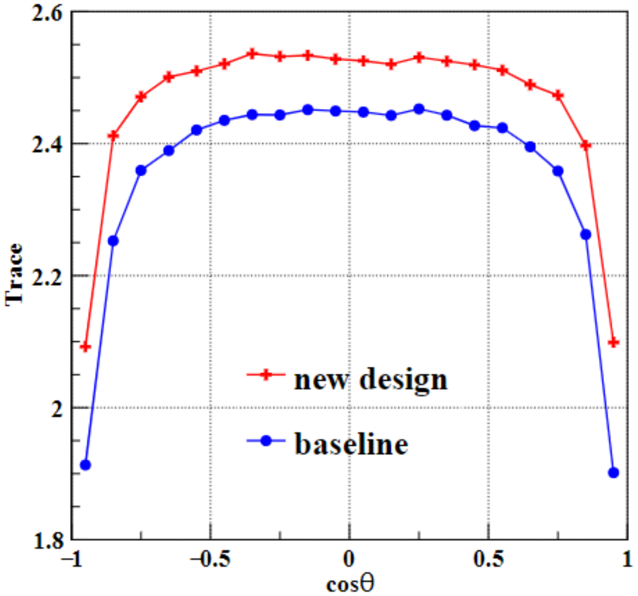


Figure 9. The new design of the VXD.



Numbers summarized

V_{cb} relative statistical uncertainty	V_{uds} or V_{cds} relative statistical uncertainty	detector	channels	luminosity	comments
1.3%	0.03%	baseline	$\mu\nu qq+$ $\tau(\mu 2\nu)\nu qq$	CDR 5.6 iab	Full simulation
0.85%	0.019%	baseline	$l\nu qq$	CDR	Assume e the the same as mu. Tauon has a penalty in eff. of 80% (1)
0.71%	0.016%	baseline	$\mu\nu qq+$ $\tau(\mu 2\nu)\nu qq$	Snowmass 2022 20 iab	Cuts unchanged. we found optimal cuts not changed with changs of lumi. (2)
0.45%	0.010%	baseline	$l\nu qq$	Snowmass 2022	(1)+(2)
0.36%	0.0092%	Vin-B	$l\nu qq$	Snowmass 2022	Improved by 20% for Vcb and by 8% for Vuds/Vcds
2%			Inc. and exc. B decay respectively		PDG2020/PDG2022

$$V_{cds} = \sqrt{|V_{cs}|^2 + |V_{cd}|^2}$$

V_{uds} is similar

Questions still kept in mind

- Tag efficiencies for $b \rightarrow b_1, c \rightarrow c_{1,2}$ for signal, possibly calibrated from data?
- How much the full hadronic WW process contribute?
  - Considering 13 million semi-hadronic, 40 million full-hadronic.
  - Unlikely surpass the semi-hadronic
  - Jet confusion?
- Analysis beyond average flavour tagging eff.?
  - E.g. data binning with Pt?