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

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IHEP

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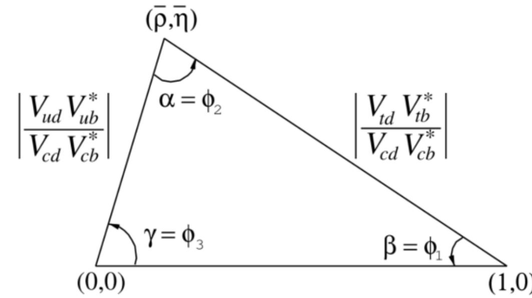
Introduction



- 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
future development of Lattice QCD

Future bottleneck
b-hadron decay
On-shell W decay

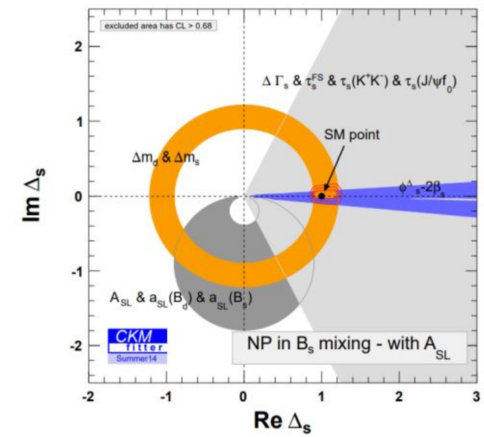
$$\sqrt{|\Delta_d|}-1=\frac{|V_{td}V_{tb}^*|-|V_{ud}V_{ub}^*+V_{cs}V_{cb}^*|}{|V_{td}V_{tb}^*|}$$

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

Deviation from unitarity of CKM matrix

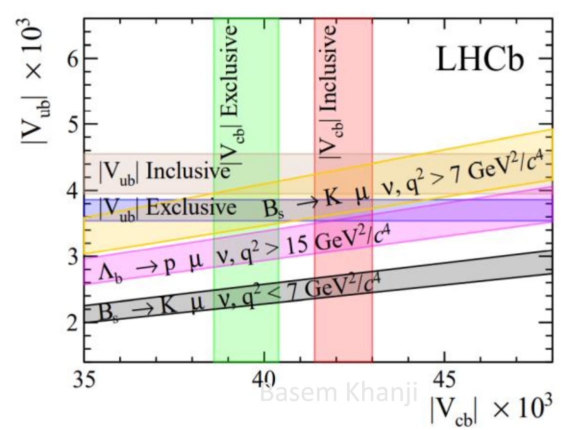
e.g. only minimum number of inputs: $f_{B_d}, B_{B_d}, \Delta m_d, |V_{ud}|, |V_{ub}|, |V_{cd}|, |V_{cb}|, \gamma$

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

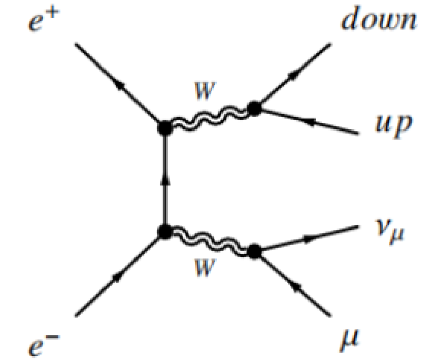


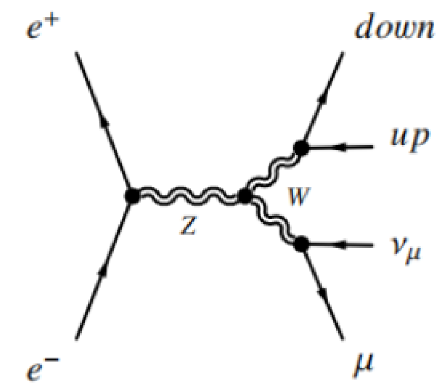
Phys.Rev. D91 (2015) 073007
More about this topic:
Phys. Rev. D 102, 056023 (2020)

- Significance of V_{cb} at EW energy scale
  - $|V_{cb}|$ via b-hadrons decays
    - non-perterbative QCD contribution
    - PDG report the value as 0.0410(14)
      - Larger than both Inclusive and exclusive analysis standalone, since they are in tension about p=1%
  - V_{cb} via W decay
    - Perturbatively QCD



Study Setup

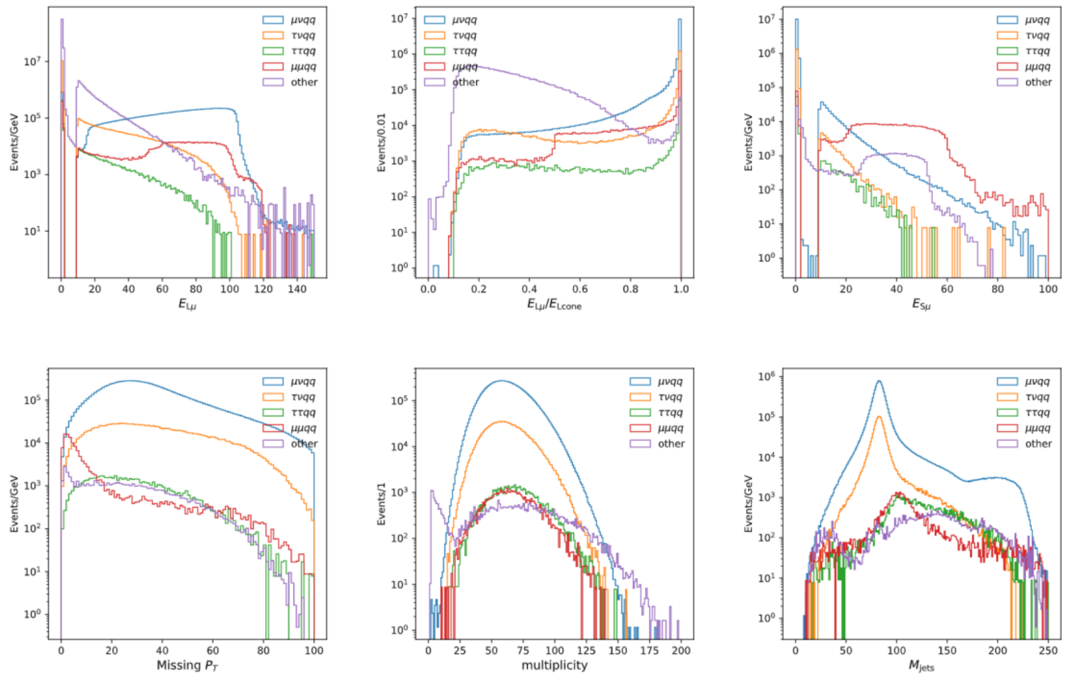




- Assumed:
  - Lumi. 5600 fb^{-1} $E = 240$ GeV
  - 13 million $\mu\nu qq$ and 11 thousand $\mu\nu cb$
- Study $\mu\nu W$ as first example
  - Cleanness of μ
  - Complementary analysis: $e\nu qq$ and $\tau\nu qq$ even $qqqq$
- Three signals measured simultaneously
  - $W \to cb, W \to c(s+d), W \to u(s+d)$
  - $W \to ub$ too tiny to access, fixed
- Besides V_{cb}
  - $\mathrm{R_W} = \mathrm{Br}(W \to qq)/\mathrm{Br}(W \to l\nu)$ unitarity test:
    - Total norm of first two rows
  - $W \to cb, W \to c(s+d), W \to u(s+d)$ unitarity test:
    - **each** norm of first two rows

Event selections

- Selection criteria are optimized for statistical uncertainty for $\mathrm{Br}(W \to cb)$



	$\mu\nu cb$	$\mu\nu ub$	$\mu\nu c(d/s)$	$\mu\nu u(d/s)$	$\mu 3\nu cb$	$\mu 3\nu c(d/s)$	$\mu 3\nu u(d/s)$
w.o. slections	11.3k	102	6.78M	6.78M	2.23k	1.18M	1.18M
$E_{L\mu} > 12\mathrm{GeV}$	10.6k	94	6.32M	6.32M	1.5k	834k	829k
$R_{L\mu} > 0.95$	9.23k	78	5.52M	5.53M	1.21k	710k	710k
$\cos(\theta_{L\mu})$	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	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)

Table 2: Event selections for signals. The number in the parenthesis are the uncertainties of the last two digits of the efficiencies arise from the statistics of Monte Carlo sample.

	$e3\nu qq$	$\tau_{\mathrm{had.}}3\nu qq$	$\tau\tau qq$	$\mu\mu qq$	other
w.o. slections	2.43M	8.79M	609k	1.25M	364.9M
$E_{L\mu} > 12\mathrm{GeV}$	37.3k	190k	118k	790k	13.6M
$R_{L\mu} > 0.95$	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
Eff.	0.000125	0.000964	0.011	0.00854	1.1e-05

Table 3: Event selections for backgrounds.

 Efficiencies differences under investigation. MC statistics? Cut bias?

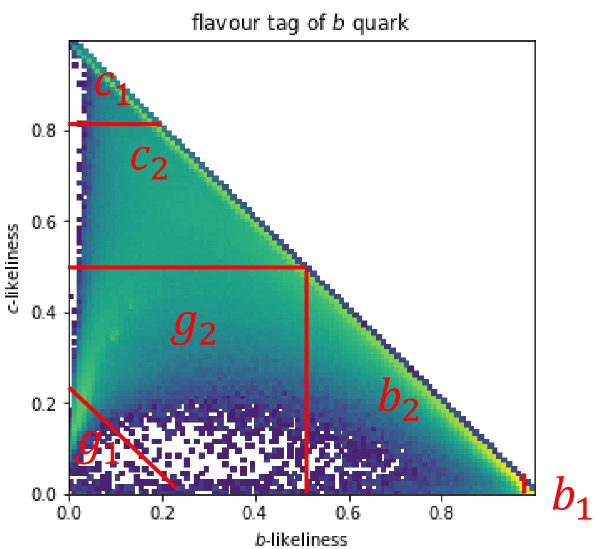
Jet flavour tagging

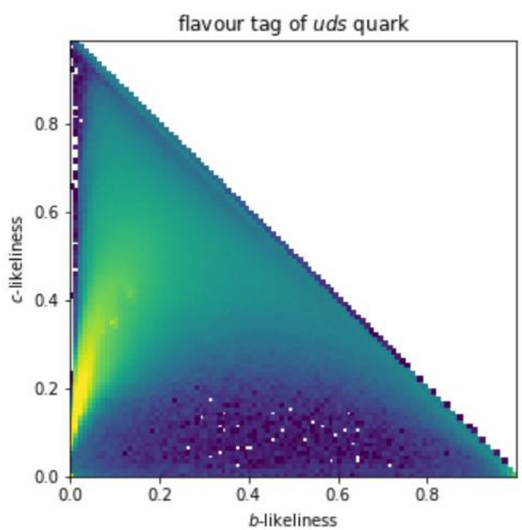
A first step to utilize differential information of flavour tagging of **two jets (four variables)**
Possible to cross-calibrate of the eff. between regions
Boundary between b1 and b2 (0.995): optimized for statistical error of $W \to cb$

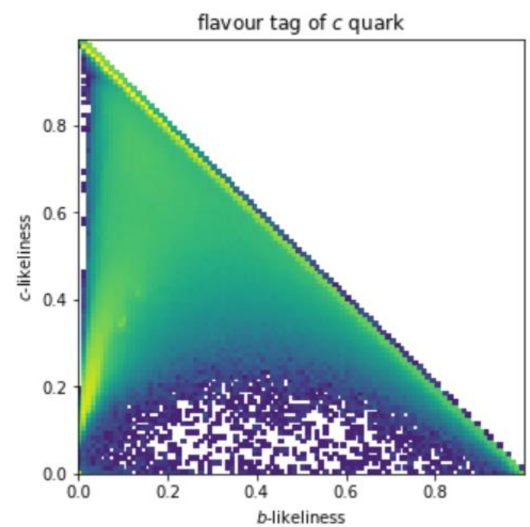
quark \ tag	b_1	b_2	c_1	c_2	g_1	g_2
b	0.47	0.378	0.0197	0.0965	0.00397	0.0315
c	0.00042	0.078	0.298	0.373	0.0682	0.182
uds	0.000104	0.00477	0.00145	0.054	0.538	0.401

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

Flavour tagging at Z-pole





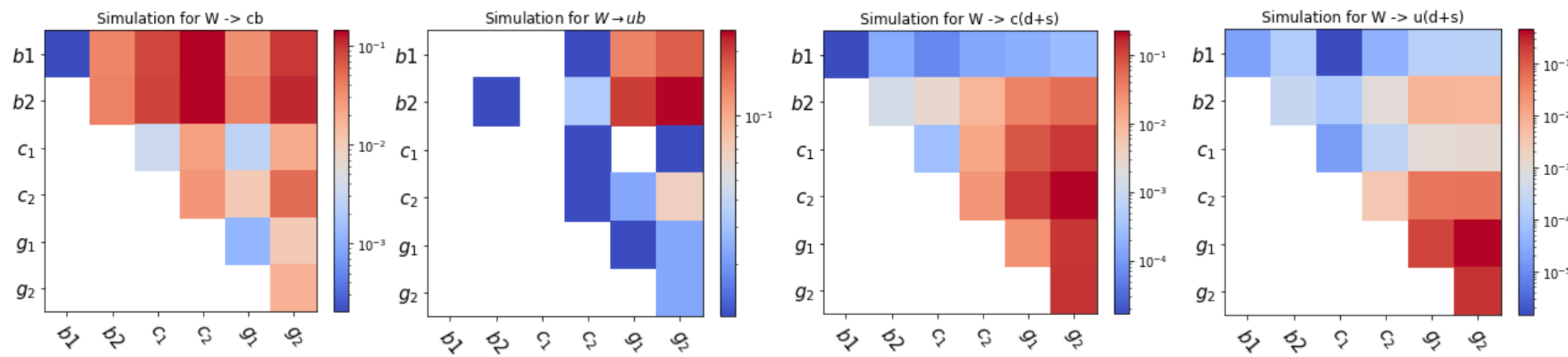


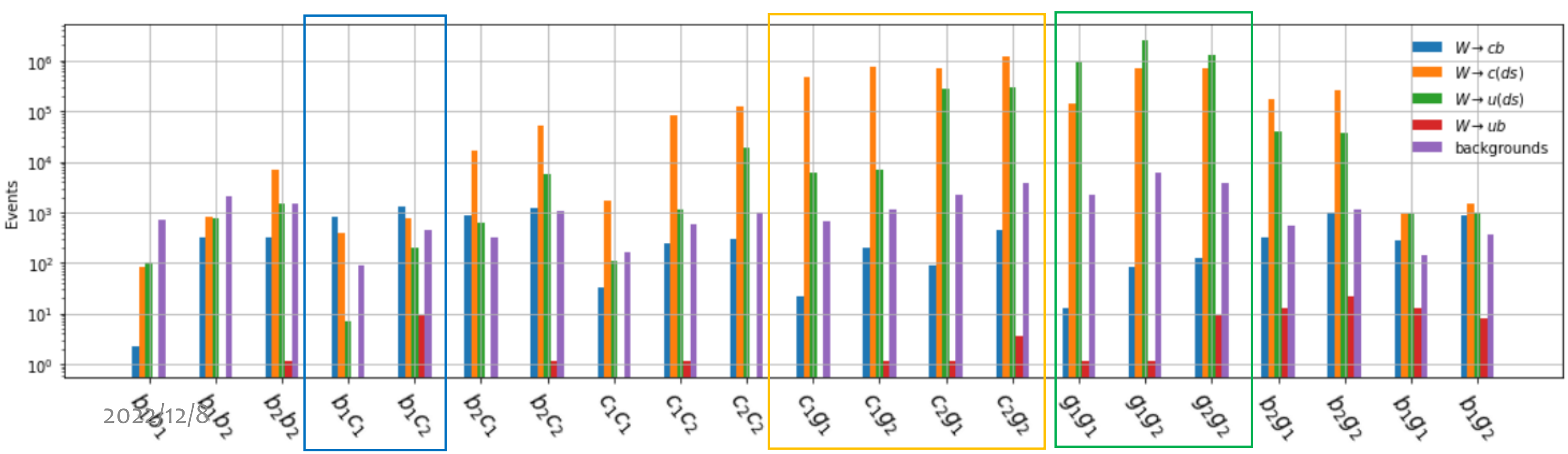
classify events into 21 categories

There are 21 flavour tag paring configurations.
Self-calibration nature for e.g. $W \to u(ds)$,

three unknown parameters $N_{u(ds)}$ $\mathrm{Eff}_{uds\to g_1}$ $\mathrm{Eff}_{uds\to g_2}$

correlation may be the problem





Extract the signal strength

- The χ^2 $-2\log(L(S_a)) = \sum_{i=1}^{21} \frac{(\sum_a S_a N_i^a + \text{bkg}_i - N_i^{\text{obs}})^2}{N_i^{\text{obs}}}$
  - Signal strengths S_a obtained by minimizing χ^2
  - the $\mu 2\nu(\leftarrow \tau)\nu qq$ has treated as signal
- Signal strengths for $W \to cb$ and $W \to c(ds)$ and $W \to u(ds)$:
  - statistical relative errors : 0.026, 5.9E-4, 5.8E-4
  - Correlation coef.

$$\begin{pmatrix} 1 & -0.077 & 0.020 \\ \cdots & 1 & -0.46 \\ \cdots & \cdots & 1 \end{pmatrix}$$

Result

- $|V_{cb}|$ by $\mu\nu qq$ and $\mu 2\nu(\leftarrow \tau)\nu qq$
  - relative statical uncertainty 1.3%
  - Half of either exclusive or inclusive analysis standalone result ~ 2%. one fourth of the combined result by PDG
  - Global fit good, but in tension….
  - Comparable to V_{cb} accuracy of 1% by the 3.6$\times 10^6$ $B_c \to \nu\tau$ decays from 1 Tera Z at the CEPC arXiv:2007.08234
  - At the FCC-ee by Marie-Helene Schune: 1.9%/1.5% level, aming at 0.4% with 100 million WW pairs above threshold

- The check of unitarity of CKM
  - $\frac{\sum_{j=bds}|V_{cj}|^2}{\sum_{j=bds}|V_{uj}|^2} = \frac{\sum S_j \mathrm{Br}(W_{\mathrm{cj}})}{\sum S_j \mathrm{Br}(W_{uj})}$
  - Statistical error: 0.1%
  - Systematics, need to take care of flavour tagging.
    - self-calibration from data? Correlation between jets? Enough data?

Systematics

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

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

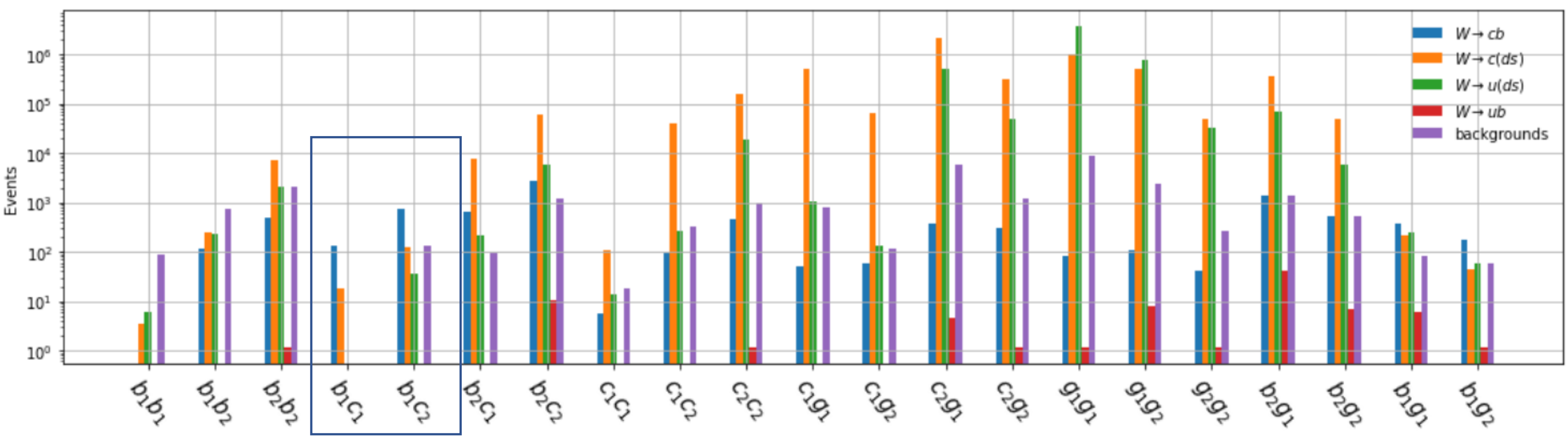
neglect the mass of quarks $C_{ij} = C$, where $C = G_F M_W^3 / (6\pi\sqrt{2})$.

	relative uncertainty	contribution to $\delta \ln |V_{cb}|$
Γ_W at CEPC	0.1%	0.05%
Γ_W assuming CKM unit.[dJ20]	0.06%	0.03%
$\alpha_s(W_W^2)$	$< 10^{-2}$	$< 10^{-3}$
$\mathrm{Br}(W \to qq)$	$< 10^{-3}$	$< 10^{-3}$
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 $|V_{cb}|$.

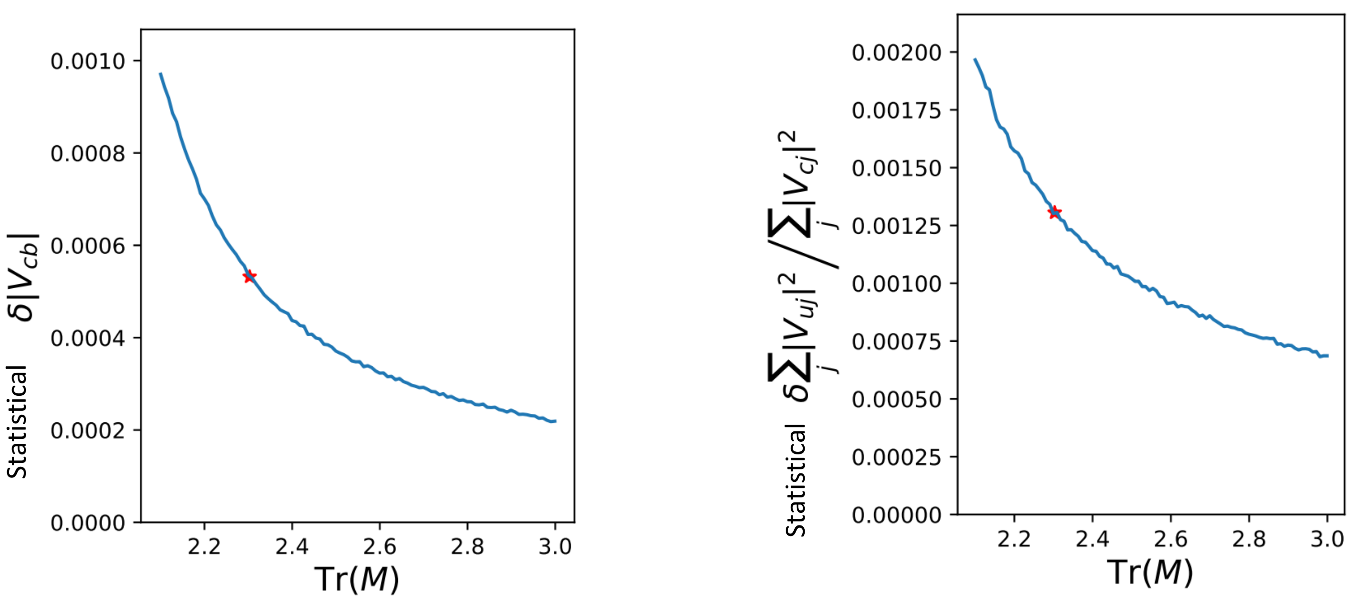
Extreame cut on b-likeliness

- Signal:
  - $b \to b_1, c \to c_{1,2}$ for signal, maybe calibrated from data
- Backgrounds:
  - $\mu\nu W, W \to \mathrm{c} + d/s$ and $\mathrm{ZZ} \to \mu\mu bb$
  - need to estimate the tag eff. $d/s \to b_1$ and $b \to c_1/c_2$
  - Which process this eff. dominate?
- Extreame cut on b-likeliness > 0.999
  - relax the requirement of relative systematical error of backgrounds
  - Relative statistical error for $S_{W\to cb}$: 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:
  - $N_{t_1 t_2} = \sum_{ij} N_{ij} M_{it_1} M_{jt_2} \,(2 - \delta_{t_1 t_2})$
- 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 tagging performance
- Extrapolation
  - Linear mix the baseline and `unit` matrix to obtain migration matrix with other trace



Questions still kept in mind and more?

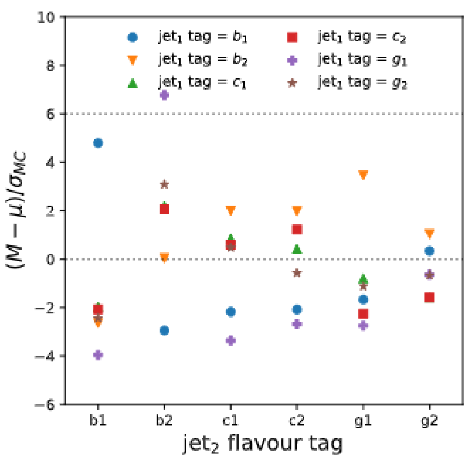
- $b \to b_1, c \to c_{1,2}$ for signal, possibly calibrated from data?
- How to check the MC tag eff. $d/s \to b_1$ and $b \to c_1/c_2$ with data?
- How much the full hadronic WW process contribute?
  - Considering 13 million semi-hadronic, 40 million full-hadronic.
  - Unlikely overwhelm the semi-hadronic
  - Jet confusion?
- Analysis beyond average flavour tagging eff?
  - E.g. binning with Pt?
- where analysis beyond jets level will lead us to?
- Other SM process contribution to $\mu\nu qq$ not via two on-shell WW decay, can be ignored, for the purpose of projecting future precision.

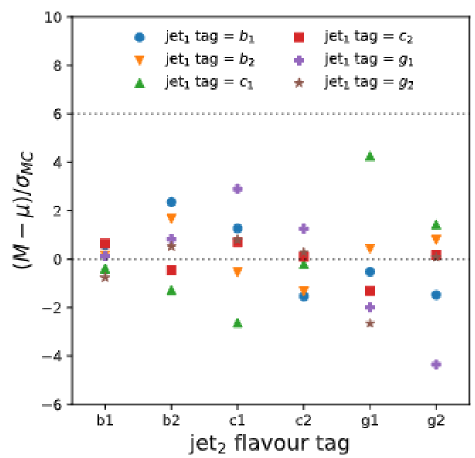
thanks

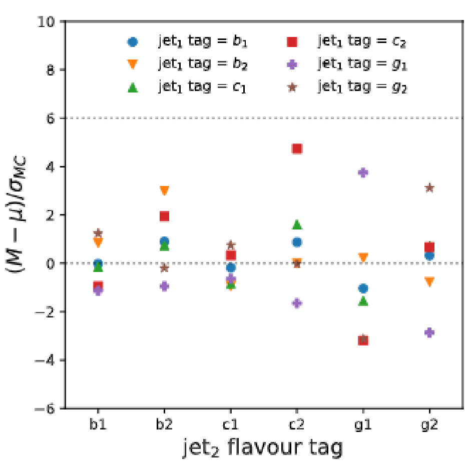
Study Setup

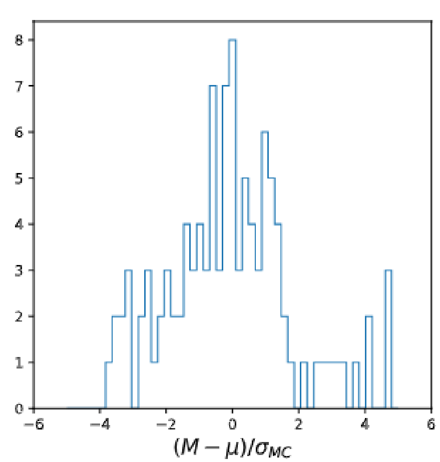
- Assumed:
  - Lumi. 5600 fb^{-1}
  - $E = 240$ GeV
- Study $\mu\nu W$ as first example
  - Cleanness of μ
  - Complementary analysis: $e\nu qq$ and $\tau\nu qq$ even $qqqq$
- Three signals measured simultaneously
  - $W \to cb, W \to c(s+d), W \to u(s+d)$
  - $W \to ub$ too tiny to access, fixed
- Besides V_{cb}
  - $\mathrm{R_W} = \mathrm{Br}(W \to qq)/\mathrm{Br}(W \to l\nu)$ leading to either α_s assuming unitary of CKM or inclusive unitarity check of the first two rows of CKM i.e. $\sum_{i=u,c;j=dsb}\left|V_{ij}\right|^2 = 2$
  - $W \to cb, W \to c(s+d), W \to u(s+d)$ leading to unitarity check of each of first two rows . $\sum_{j=dsb}\left|V_{uj}\right|^2 = \sum_{j=dsb}\left|V_{cj}\right|^2 = 1$

At z-pole correlations of flavour tagging between jet pair for selected events by jet mass









simple demonstration of the clibrtion at Z-pole

$$N_{ij} = \sum_{a=bb,cc,uds\times 2} C_{a,i,j} N_a M_{ai} M_{aj} (2-\delta_{ij})$$

$$\chi^2 = \sum_i \frac{(N_{ij}(M_{a,k}) - N_{\mathrm{obs},ij})^2}{N_{\mathrm{obs},ij}}$$

C=

```
[1.0048 0.9967 0.9867 0.9947 0.962  0.9969 0.9999 1.0124 1.0072 1.0817
 1.0099 1.0421 1.0156 0.8822 0.9901 1.0027 0.9537 0.98   0.68   0.8872
 1.0092]
[1.0256 1.2518 1.0365 0.9478 0.9878 0.9275 1.0338 0.9977 0.9917 1.0082
 1.0025 0.9936 0.9994 1.0232 1.0039 1.0021 0.998  1.001  0.9661 0.9754
 0.9999]
[0.9988 1.2378 0.9981 1.199  0.9283 1.0253 1.4116 0.9888 1.0486 0.993
 0.9954 0.9264 1.091  0.9925 0.9988 1.0767 0.9896 1.0026 1.0055 0.9942
 1.0075]
```

```
normalized to 10 million Z boson
                   bb                       cc                       lightx2
signal mean: [0.9999315462613185 0.9999642961814725 1.0000400331912618]
signal  std: [0.000912530662729489 0.0005429807359446 49 0.00048048747392434 1]
```

$$\delta \ln M = \begin{pmatrix} 0.839 & 2.82 & 1.91e+02 & 38.0 & 1.44e+03 & 95.1 \\ -5.98e+03 & 75.7 & 1.8 & 1.78 & 1.18e+02 & 32.6 \\ -1.5e+05 & 2.84e+02 & 8.83e+02 & 23.2 & 0.645 & 1.74 \end{pmatrix} \times 10^{-3}$$

$$M = \begin{pmatrix} 0.47 & 0.378 & 0.0197 & 0.0965 & 0.00397 & 0.0315 \\ 0.00042 & 0.078 & 0.298 & 0.373 & 0.0682 & 0.182 \\ 0.000104 & 0.00477 & 0.00145 & 0.054 & 0.538 & 0.401 \end{pmatrix}$$

M_extracted_mean/M_truth*

```
[[0.9998958945189709 1.0000364428728372 1.004587776020042
  1.000912119409266  0.9729958565307091 0.9988633138169138]
 [0.6251331324126443 0.9982743612709353 0.9997646647958848
  1.0000002464824151 1.0035699665385738 1.0006498410427873]
 [1.6958956944595756 1.0318445873901592 0.9855574069054088
  1.0021931172458023 0.9943371806922174 1.0067934426955516]]
```