# Measurement of $|V_{cb}|$ from $ee \to \ell\nu qq$ at the future $ee$ collider

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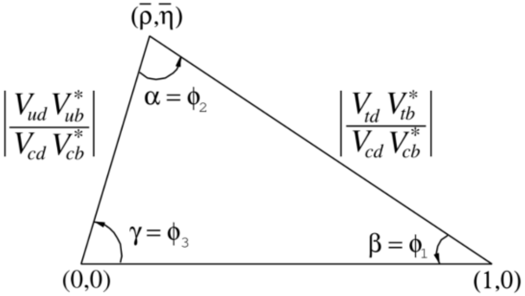
# Introduction

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



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

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

Future bottleneck

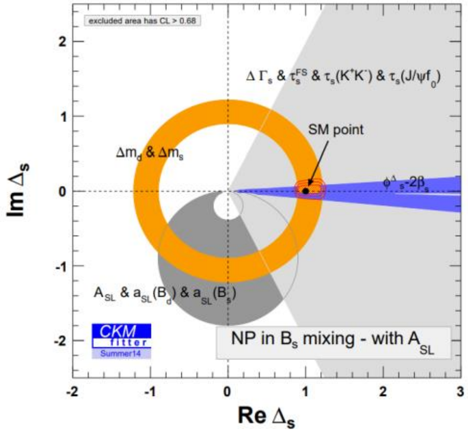
$$\sqrt{|\Delta_d|}-1=\frac{|V_{td}V_{tb}^*|-|V_{ud}V_{ub}^*+V_{cs}V_{cb}^*|}{|V_{td}V_{tb}^*|}$$

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

Deviation from unitarity of CKM matrix

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

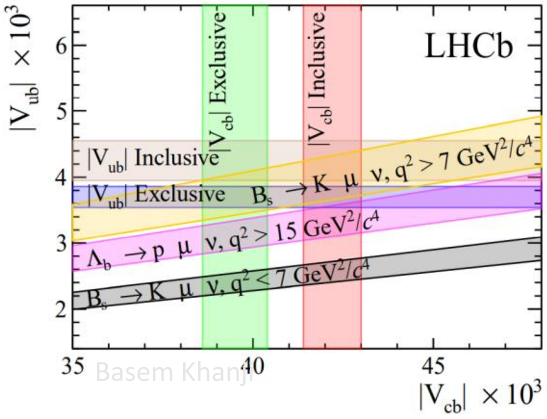
$$\delta(\sqrt{|\Delta_d|}-1)=\frac{\delta f_{B_q}}{f_{B_q}}\oplus\frac{\delta\hat{B}_{B_d}}{2\hat{B}_{B_d}}\oplus\frac{\delta\Delta m_d}{2\Delta m_d}\oplus\frac{\delta|V_{ud}V_{ub}^*|\cos^2\alpha}{|V_{ud}V_{ub}^*|}\oplus\frac{\delta|V_{cd}V_{cb}^*|\cos^2\beta}{|V_{cd}V_{cb}^*|}\oplus\frac{\delta\gamma\sin\beta\sin\alpha}{\sin\gamma}$$



Phys.Rev. D91 (2015) 073007

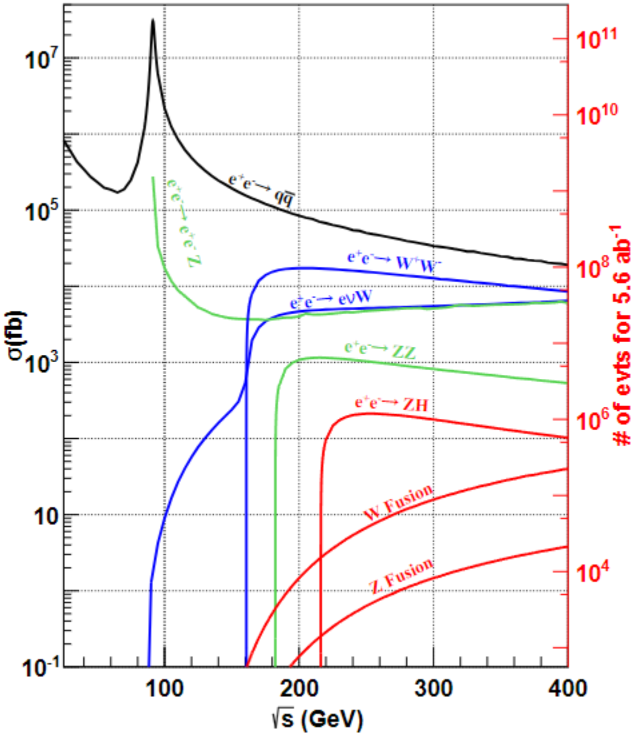
More about this topic: Phys. Rev. D 102, 056023 (2020)

- Significance of $|V_{cb}|$ at EW scale
  - $|V_{cb}|$ via $b$-hadron decays
    - non-perturbative QCD contribution
    - Results show discrepancy between inclusive and exclusive analyses
  - $|V_{cb}|$ via W decay
    - Perturbative QCD



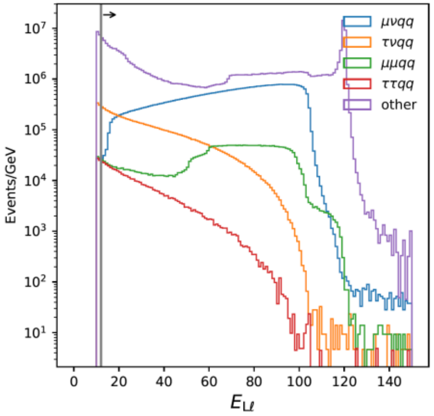
# History & Futrue

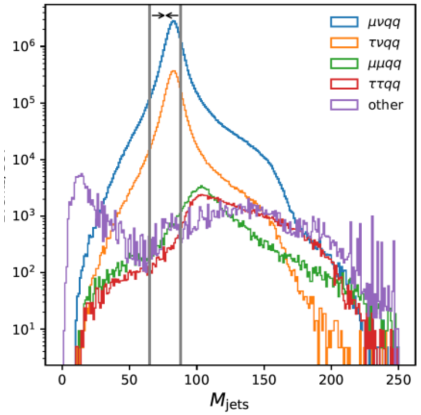
- LEP:
  - $\mathrm{Br}(\mathrm{W} \to \mathrm{qq})$ & $\mathrm{Br}(\mathrm{W} \to cs)$
- LHC:
  - $\mathrm{Br}(W \to qq)$
- Monte Carlo simulation
  - LHC: ~ 3% (Run 1 & Run 2 & Run 3)
  - Future HL-LHC Improve by a factor of 2
- Future ee-collider
  - Statistics & flavor tagging perofmrace & clean collision environment
- CEPC detector and luminosity as instance
  - Lumi. 20 ab$^{-1}$, $\sqrt{s}$=240 GeV
- $WW$ semi-hadronic
  - Analysis for $\mu\nu W$ and $e\mu W$
  - $\tau\nu W$ in which, the $\tau \to e/\mu$ was analyzed as side work of analysis of $\mu\nu W$ and $e\nu W$
- Three signals measured simultaneously
  - $W \to cb, W \to c(s+d), W \to u(s+d)$
  - $W \to ub$ too tiny to observed, fixed

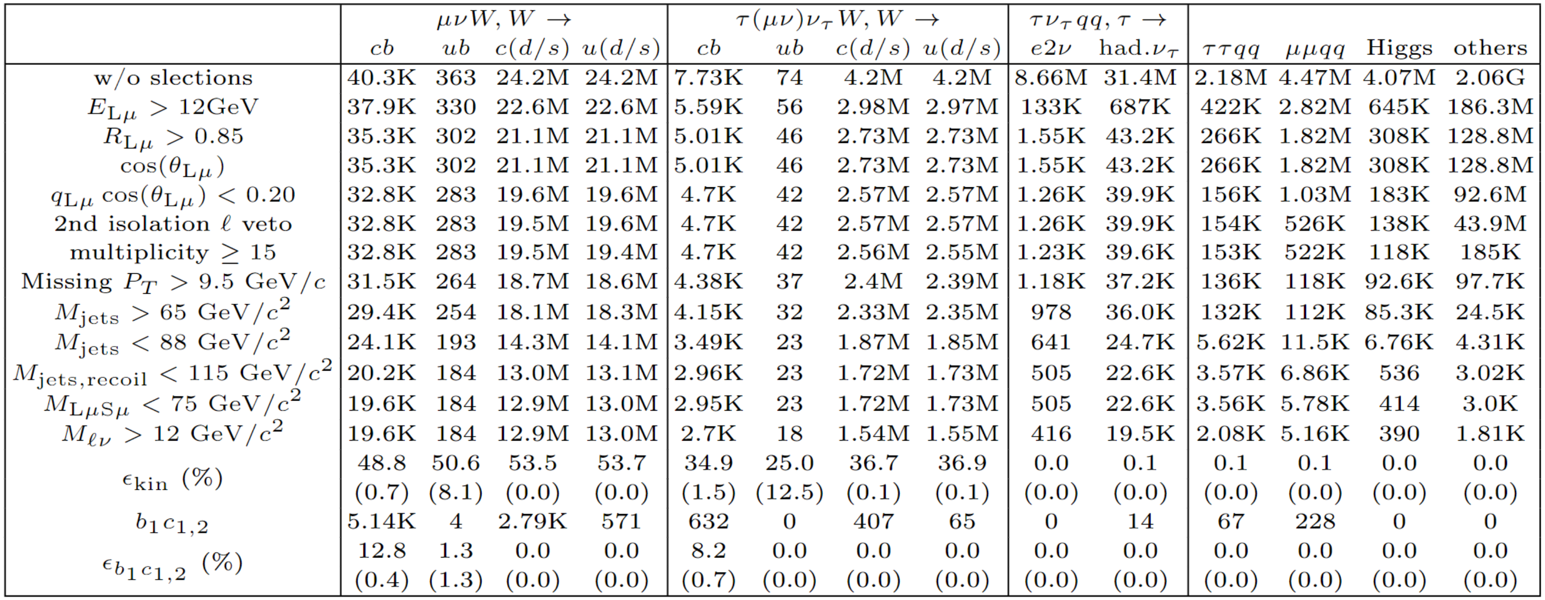


# Event selections ($\mu\nu qq$)

- Purity > 99.5% at Eff. 50% for $\mu\nu qq$ and 34% for $\tau(\mu 2\nu)\nu qq$
- Main backgrounds include:
  - $W \to c(d/s)$
  - $\mu\mu qq$



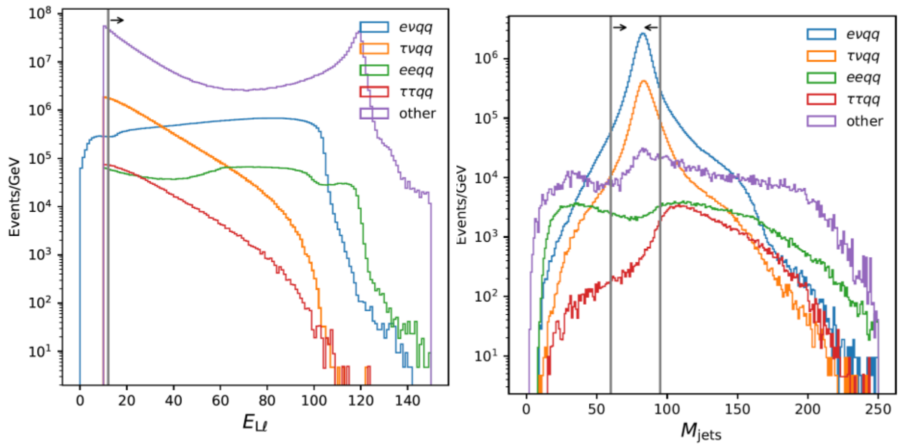


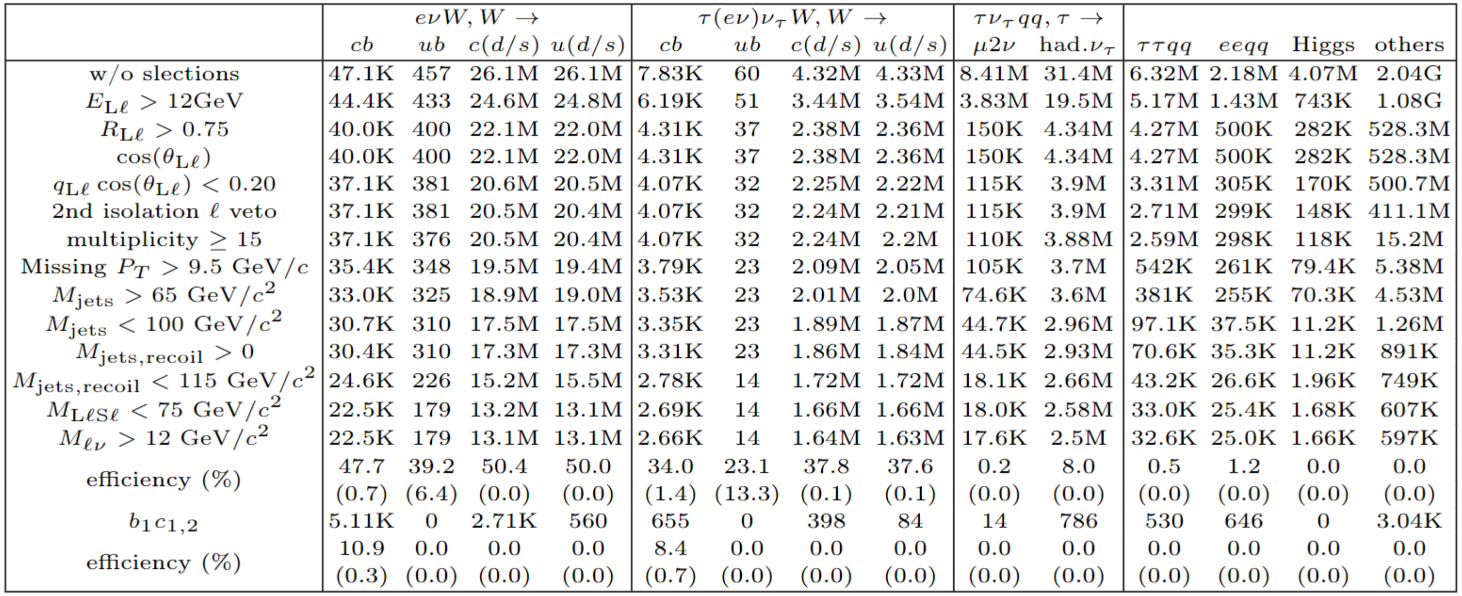


| | $\mu\nu W, W \to$ | | | | $\tau(\mu\nu)\nu_\tau W, W \to$ | | | | $\tau\nu_\tau qq, \tau \to$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $cb$ | $ub$ | $c(d/s)$ | $u(d/s)$ | $cb$ | $ub$ | $c(d/s)$ | $u(d/s)$ | $e2\nu$ | had.$\nu_\tau$ | $\tau\tau qq$ | $\mu\mu qq$ | Higgs | others |
| w/o slections | 40.3K | 363 | 24.2M | 24.2M | 7.73K | 74 | 4.2M | 4.2M | 8.66M | 31.4M | 2.18M | 4.47M | 4.07M | 2.06G |
| $E_{\rm L\mu} > 12$GeV | 37.9K | 330 | 22.6M | 22.6M | 5.59K | 56 | 2.98M | 2.97M | 133K | 687K | 422K | 2.82M | 645K | 186.3M |
| $R_{\rm L\mu} > 0.85$ | 35.3K | 302 | 21.1M | 21.1M | 5.01K | 46 | 2.73M | 2.73M | 1.55K | 43.2K | 266K | 1.82M | 308K | 128.8M |
| $\cos(\theta_{\rm L\mu})$ | 35.3K | 302 | 21.1M | 21.1M | 5.01K | 46 | 2.73M | 2.73M | 1.55K | 43.2K | 266K | 1.82M | 308K | 128.8M |
| $q_{\rm L\mu}\cos(\theta_{\rm L\mu}) < 0.20$ | 32.8K | 283 | 19.6M | 19.6M | 4.7K | 42 | 2.57M | 2.57M | 1.26K | 39.9K | 156K | 1.03M | 183K | 92.6M |
| 2nd isolation $\ell$ veto | 32.8K | 283 | 19.5M | 19.6M | 4.7K | 42 | 2.57M | 2.57M | 1.26K | 39.9K | 154K | 526K | 138K | 43.9M |
| multiplicity $\geq 15$ | 32.8K | 283 | 19.5M | 19.4M | 4.7K | 42 | 2.56M | 2.55M | 1.23K | 39.6K | 153K | 522K | 118K | 185K |
| Missing $P_T > 9.5$ GeV/$c$ | 31.5K | 264 | 18.7M | 18.6M | 4.38K | 37 | 2.4M | 2.39M | 1.18K | 37.2K | 136K | 118K | 92.6K | 97.7K |
| $M_{\rm jets} > 65$ GeV/$c^2$ | 29.4K | 254 | 18.1M | 18.3M | 4.15K | 32 | 2.33M | 2.35M | 978 | 36.0K | 132K | 112K | 85.3K | 24.5K |
| $M_{\rm jets} < 88$ GeV/$c^2$ | 24.1K | 193 | 14.3M | 14.1M | 3.49K | 23 | 1.87M | 1.85M | 641 | 24.7K | 5.62K | 11.5K | 6.76K | 4.31K |
| $M_{\rm jets,recoil} < 115$ GeV/$c^2$ | 20.2K | 184 | 13.0M | 13.1M | 2.96K | 23 | 1.72M | 1.73M | 505 | 22.6K | 3.57K | 6.86K | 536 | 3.02K |
| $M_{\rm L\mu S\mu} < 75$ GeV/$c^2$ | 19.6K | 184 | 12.9M | 13.0M | 2.95K | 23 | 1.72M | 1.73M | 505 | 22.6K | 3.56K | 5.78K | 414 | 3.0K |
| $M_{\ell\nu} > 12$ GeV/$c^2$ | 19.6K | 184 | 12.9M | 13.0M | 2.7K | 18 | 1.54M | 1.55M | 416 | 19.5K | 2.08K | 5.16K | 390 | 1.81K |
| $\epsilon_{\rm kin}$ (%) | 48.8 | 50.6 | 53.5 | 53.7 | 34.9 | 25.0 | 36.7 | 36.9 | 0.0 | 0.1 | 0.1 | 0.1 | 0.0 | 0.0 |
| | (0.7) | (8.1) | (0.0) | (0.0) | (1.5) | (12.5) | (0.1) | (0.1) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) |
| $b_1c_{1,2}$ | 5.14K | 4 | 2.79K | 571 | 632 | 0 | 407 | 65 | 0 | 14 | 67 | 228 | 0 | 0 |
| $\epsilon_{b_1c_{1,2}}$ (%) | 12.8 | 1.3 | 0.0 | 0.0 | 8.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | (0.4) | (1.3) | (0.0) | (0.0) | (0.7) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) |

# Event selections ($e\nu qq$)

- X-section increase by 15% by including $e\nu W$ process with kinematical cut on final-state electron
- Some cut adjusted compared to $\mu\nu qq$
- Noisy compared to $\mu\nu qq$
  - Additional backgrounds from $bb$ and $\tau(had.\nu)\nu qq$

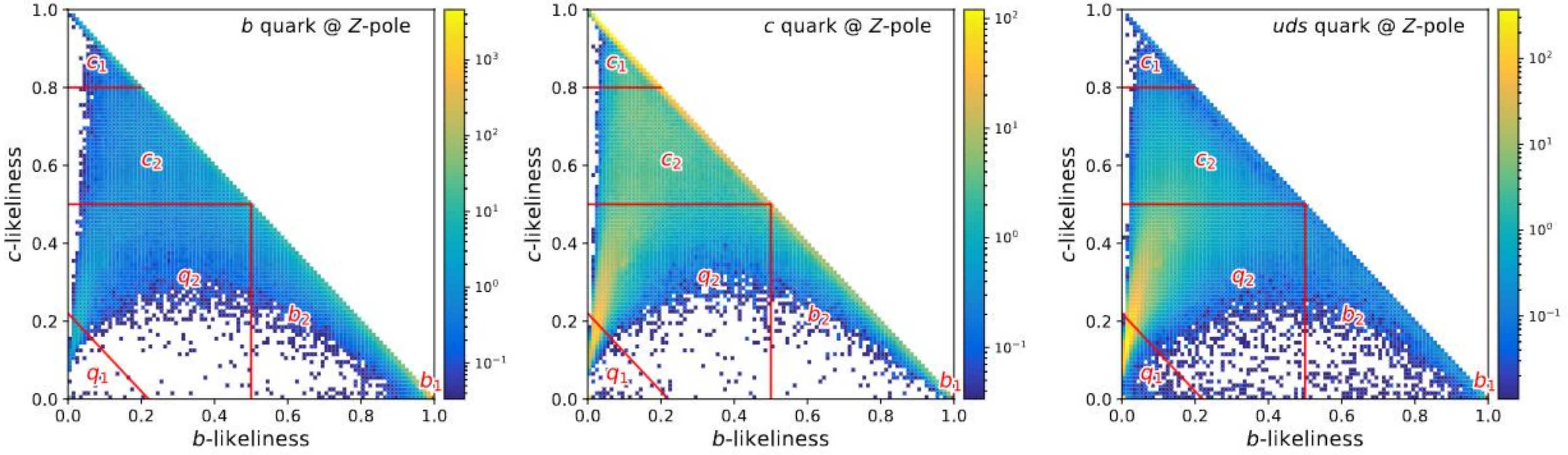




| | $e\nu W, W \rightarrow$ | | | | $\tau(e\nu)\nu_\tau W, W \rightarrow$ | | | | $\tau\nu_\tau qq, \tau \rightarrow$ | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $cb$ | $ub$ | $c(d/s)$ | $u(d/s)$ | $cb$ | $ub$ | $c(d/s)$ | $u(d/s)$ | $\mu 2\nu$ | had.$\nu_\tau$ | $\tau\tau qq$ | $eeqq$ | Higgs | others |
| w/o slections | 47.1K | 457 | 26.1M | 26.1M | 7.83K | 60 | 4.32M | 4.33M | 8.41M | 31.4M | 6.32M | 2.18M | 4.07M | 2.04G |
| $E_{\text{L}\ell} > 12\text{GeV}$ | 44.4K | 433 | 24.6M | 24.8M | 6.19K | 51 | 3.44M | 3.54M | 3.83M | 19.5M | 5.17M | 1.43M | 743K | 1.08G |
| $R_{\text{L}\ell} > 0.75$ | 40.0K | 400 | 22.1M | 22.0M | 4.31K | 37 | 2.38M | 2.36M | 150K | 4.34M | 4.27M | 500K | 282K | 528.3M |
| $\cos(\theta_{\text{L}\ell})$ | 40.0K | 400 | 22.1M | 22.0M | 4.31K | 37 | 2.38M | 2.36M | 150K | 4.34M | 4.27M | 500K | 282K | 528.3M |
| $q_{\text{L}\ell}\cos(\theta_{\text{L}\ell}) < 0.20$ | 37.1K | 381 | 20.6M | 20.5M | 4.07K | 32 | 2.25M | 2.22M | 115K | 3.9M | 3.31M | 305K | 170K | 500.7M |
| 2nd isolation $\ell$ veto | 37.1K | 381 | 20.5M | 20.4M | 4.07K | 32 | 2.24M | 2.21M | 115K | 3.9M | 2.71M | 299K | 148K | 411.1M |
| multiplicity $\geq 15$ | 37.1K | 376 | 20.5M | 20.4M | 4.07K | 32 | 2.24M | 2.2M | 110K | 3.88M | 2.59M | 298K | 118K | 15.2M |
| Missing $P_T > 9.5$ GeV/$c$ | 35.4K | 348 | 19.5M | 19.4M | 3.79K | 23 | 2.09M | 2.05M | 105K | 3.7M | 542K | 261K | 79.4K | 5.38M |
| $M_{\text{jets}} > 65$ GeV/$c^2$ | 33.0K | 325 | 18.9M | 19.0M | 3.53K | 23 | 2.01M | 2.0M | 74.6K | 3.6M | 381K | 255K | 70.3K | 4.53M |
| $M_{\text{jets}} < 100$ GeV/$c^2$ | 30.7K | 310 | 17.5M | 17.5M | 3.35K | 23 | 1.89M | 1.87M | 44.7K | 2.96M | 97.1K | 37.5K | 11.2K | 1.26M |
| $M_{\text{jets,recoil}} > 0$ | 30.4K | 310 | 17.3M | 17.3M | 3.31K | 23 | 1.86M | 1.84M | 44.5K | 2.93M | 70.6K | 35.3K | 11.2K | 891K |
| $M_{\text{jets,recoil}} < 115$ GeV/$c^2$ | 24.6K | 226 | 15.2M | 15.5M | 2.78K | 14 | 1.72M | 1.72M | 18.1K | 2.66M | 43.2K | 26.6K | 1.96K | 749K |
| $M_{\text{L}\ell\text{S}\ell} < 75$ GeV/$c^2$ | 22.5K | 179 | 13.2M | 13.1M | 2.69K | 14 | 1.66M | 1.66M | 18.0K | 2.58M | 33.0K | 25.4K | 1.68K | 607K |
| $M_{\ell\nu} > 12$ GeV/$c^2$ | 22.5K | 179 | 13.1M | 13.1M | 2.66K | 14 | 1.64M | 1.63M | 17.6K | 2.5M | 32.6K | 25.0K | 1.66K | 597K |
| efficiency (%) | 47.7 | 39.2 | 50.4 | 50.0 | 34.0 | 23.1 | 37.8 | 37.6 | 0.2 | 8.0 | 0.5 | 1.2 | 0.0 | 0.0 |
| | (0.7) | (6.4) | (0.0) | (0.0) | (1.4) | (13.3) | (0.1) | (0.1) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) |
| $b_1 c_{1,2}$ | 5.11K | 0 | 2.71K | 560 | 655 | 0 | 398 | 84 | 14 | 786 | 530 | 646 | 0 | 3.04K |
| efficiency (%) | 10.9 | 0.0 | 0.0 | 0.0 | 8.4 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| | (0.3) | (0.0) | (0.0) | (0.0) | (0.7) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) | (0.0) |

# Flavor tagging

- LCFIPlus used at the CEPC
- Trained using Z-pole sample

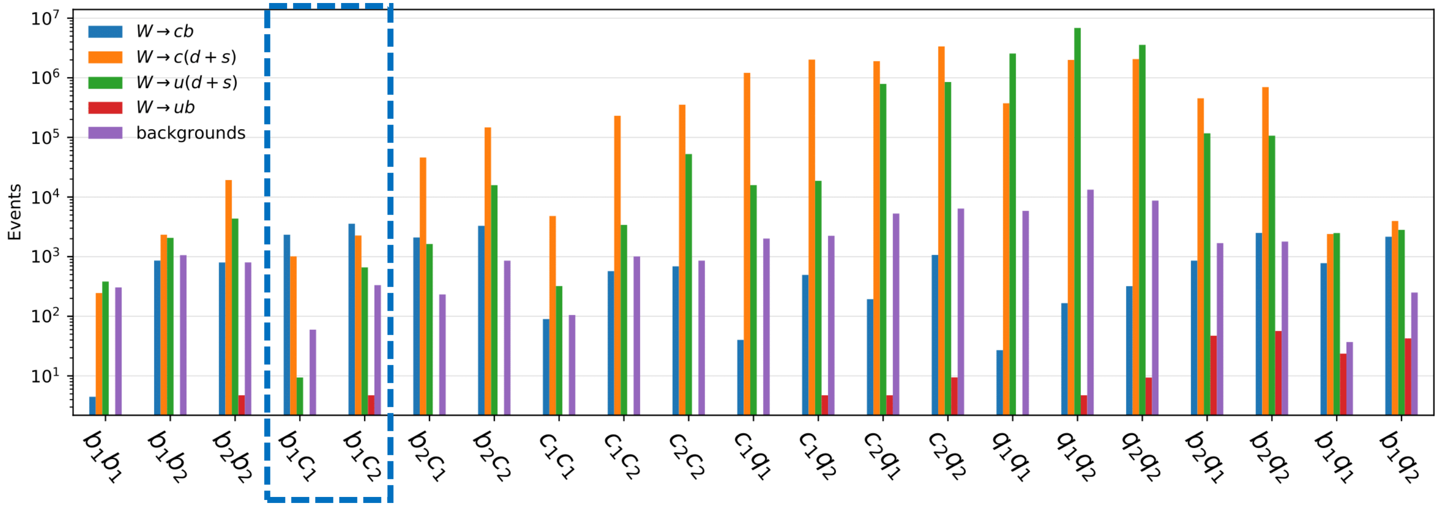


| quark \ tag | $b_1$ | $b_2$ | $c_1$ | $c_2$ | $q_1$ | $q_2$ |
|---|---|---|---|---|---|---|
| $b$ | 0.47 | 0.378 | 0.0197 | 0.0965 | 0.00397 | 0.0315 |
| $c$ | 0.00042 | 0.078 | 0.298 | 0.373 | 0.0682 | 0.182 |
| $uds$ | 0.000104 | 0.00477 | 0.00145 | 0.054 | 0.538 | 0.401 |

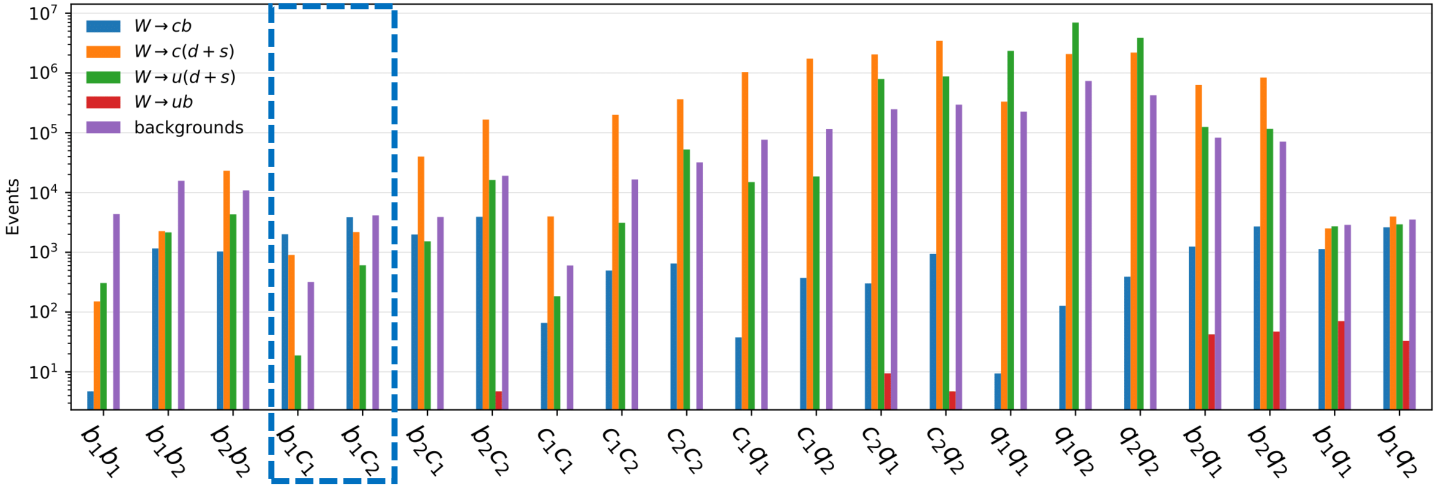
# classify events into 21 categories

6 tags for a jet, and 21 tag combinations for an event (di-jet).

$\mu\nu qq$



$e\nu qq$



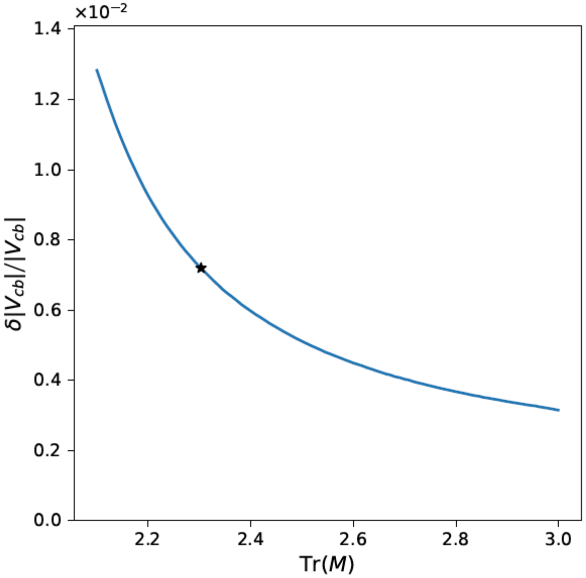
LCFIPlus performs excellent for jets from W boson decay

# Extract the signal strength

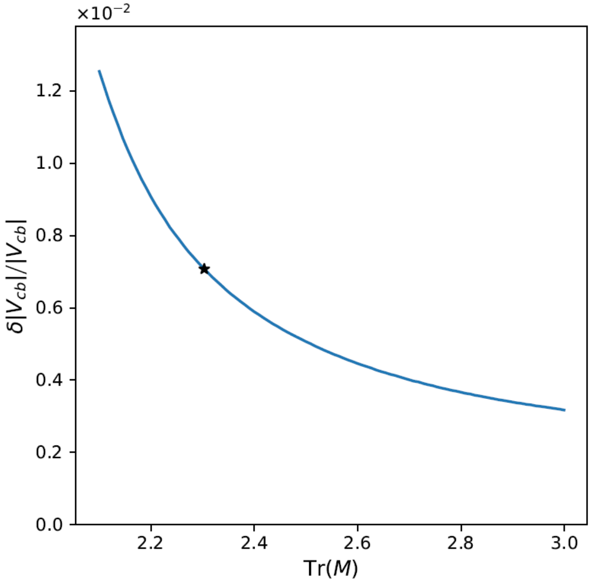
- The $\chi^2$ $$-2\log(L(S_a)) = \sum_{i=1}^{21} \frac{(\sum_a S_a N_i^a + \mathrm{bkg}_i - N_i^{\mathrm{obs}})^2}{N_i^{\mathrm{obs}}}$$
  - Signal strengths for $W \to cb$ and $W \to c(ds)$ and $W \to u(ds)$
  - The ratio of $\mu\nu q_1 q_2$ to $\tau(\mu 2\nu)\nu q_1 q_2$ is assumed to be known
- $\mu\nu qq$
  - Statistical (relative) error: 1.5%, 3.4E-4, 3.4E-4
  - Correlation coef. $\begin{pmatrix} 1 & -0.077 & 0.020 \\ \cdots & 1 & -0.46 \\ \cdots & \cdots & 1 \end{pmatrix}$
  - $|V_{cb}|$ Statistical error: 0.75%
- $e\nu qq$
  - statistical (relative) error: 1.7%, 3.7E-4, 3.7E-4
  - Correlation coef. $\begin{pmatrix} 1 & -0.076 & 0.021 \\ \cdots & 1 & -0.47 \\ \cdots & \cdots & 1 \end{pmatrix}$
  - $|V_{cb}|$ Statistical error: 0.85%

# Extrapolation for flavor tagging performance

- Trace of the confusion matrix
  - $\mathrm{Tr}(M) = (M_{bb_1} + M_{bb_2}) + (M_{cc_1} + M_{cc_2}) + (M_{uds,q_1} + M_{uds,q_2})$
  - $M_{ij}$ the $i$ quark tagged as label $j$.
- Extrapolation
  - Scale the non-diagonal elements



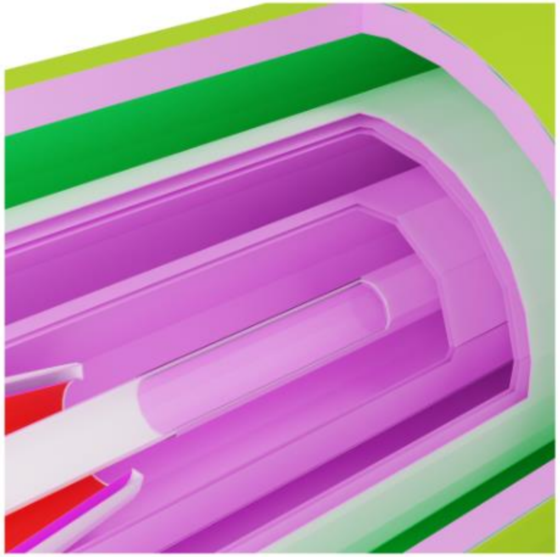
$evqq$

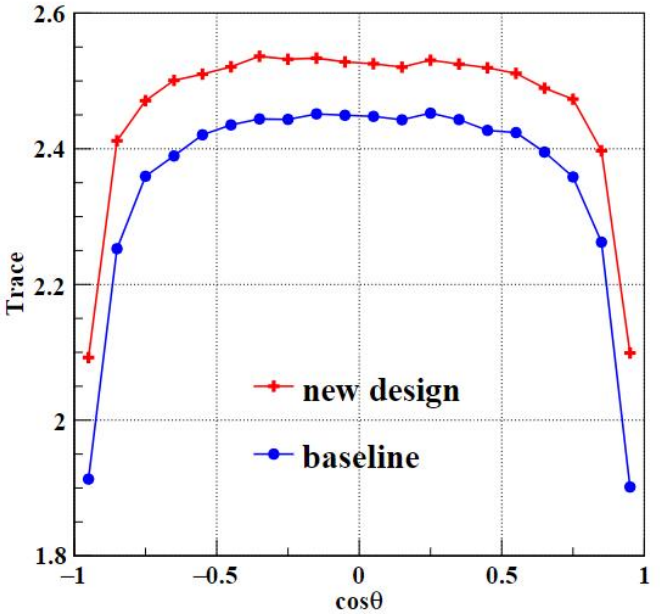


$\mu vqq$

# A conceptual design of VTX: Vin-B

- Conceptual design
  - Put the innermost layer of the VTX into the beam-pipe
    - Reduce the radius of innermost layer of the VTX:  from 16mm to 8 mm
  - We simplify the support structure
- Trace  improved by 0.1, Vcb by 20%





# Discussions on theory & systematics

$$|V_{cb}|^2 \simeq \sum_{f=d,s,b} (|V_{uf}|^2 + |V_{cf}|^2) R_{cb} \qquad R_{cb} = \mathrm{Br}(W \to bc)/\mathrm{Br}(W \to qq)$$

- Theory
  - We exam the uncertainties from $M_W$, $m_t$, calculation are negligible, if the unitarity of CKM matrix is imposed
- Systematics
  - Uncertainties from kinematic selection & WW boson yields are mostly canceled in calculation of $R_{cb}$
  - For the signal
    - $b \to b_1$ & $c \to c_{1,2}$ can be measured from Z-pole data
  - For the backgrounds:
    - $W \to u(d/s)$
      - $uds \to b_1$ is not feasible to be measured from Z-pole data

# Conclusion

- $e\nu qq$ and $\mu\nu qq$
  - 0.75% and 0.85% @ 20 $\mathrm{ab}^{-1}$ 240GeV
  - (current best: 2% for inclusively and exclusive, respectively)
- Conceptual VTX design are exam
  - 20% improvement in Vcb
- Outlook:
  - Further development of flavor tagging algorithm is required
  - Simulation at WW threshold is ongoing

thanks