CKM determination from W decays with jet flavor tagging at CEPC

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Outline

1. Motivation
2. Analysis setup
3. Jet flavor tagging
4. Results

Why measure CKM elements with W decays?

- The CKM matrix is the flavor-mixing matrix of the Standard Model.
- Precise measurements test CKM unitarity and probe new physics.
- Hadronic W decays provide a clean electroweak alternative to meson decays.
- The branching fraction is directly related to $|V_{ij}|^2$ with very small hadronic uncertainty.

Target elements in this study

$|V_{ud}|$, $|V_{us}|$, $|V_{cd}|$, $|V_{cs}|$, and $|V_{cb}|$

Key relation

$$\mathrm{BR}(W^- \to \bar{q}_i q_j) \propto |V_{ij}|^2$$

Why CEPC?

- large W^+W^- sample at $\sqrt{s} = 240$ GeV
- clean e^+e^- environment
- strong heavy- and light-flavor tagging capability

Dataset and signal topology

- Signal channel: $e^+e^- \to W^+W^- \to \mu\nu\bar{q}q$.
- Simulation at $\sqrt{s} = 240$ GeV with $21.6\,\mathrm{ab}^{-1}$.
- Signal channels considered: *ud*, *us*, *ub*, *cd*, *cs*, and *cb*.
- The *ub* mode is negligible and is fixed in the fit.
- Dominant backgrounds come from $2f$, ZZ, semileptonic WW, single-W/Z, and ZH processes.

Event picture

one isolated muon + missing momentum + two reconstructed jets

Simulation chain

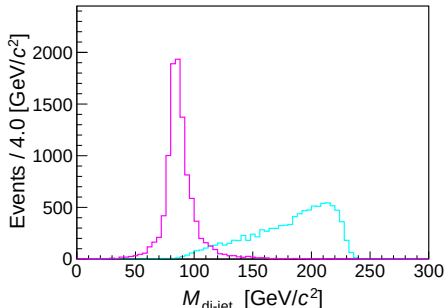
WHIZARD → PYTHIA → DELPHES

Main analysis handle

separate the hadronic W decay flavor with jet tagging and binned simultaneous fits

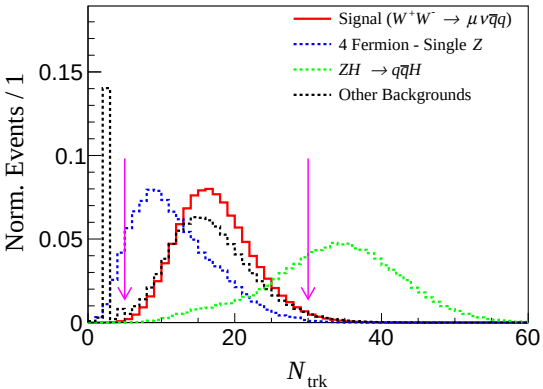
Event selection overview

- Preselection: $5 \leq N_{\mathrm{trk}} \leq 30$, $50 \leq \sum E_{\mathrm{trk}} \leq 200$ GeV, $P(\gamma_{\mathrm{lead}}) < 60$ GeV, and at least one lepton.
- Muon requirements: $N_{\mu} \geq 1$, $P(\mu_{\mathrm{lead}}) \geq 20$ GeV, $\sum P(\mu) \leq 100$ GeV.
- Kinematics: $80^{\circ} \leq \theta(\mu_{\mathrm{lead}}, \text{di-jet}) \leq 170^{\circ}$ and $E_{\mathrm{ratio}}(\mu_{\mathrm{lead}}) \geq 0.9$.
- Hadronic system: $50 \leq M_{\text{di-jet}} \leq 120$ GeV, $Y_{23} \leq 0.1$, $Y_{34} \leq 0.008$.
- Global cleanup: $|\cos\theta_{\mathrm{miss}}| < 0.9$, $U_{\mathrm{miss}} \leq 15$ GeV, and $\chi^2_{\mathrm{IP}} < 10$.

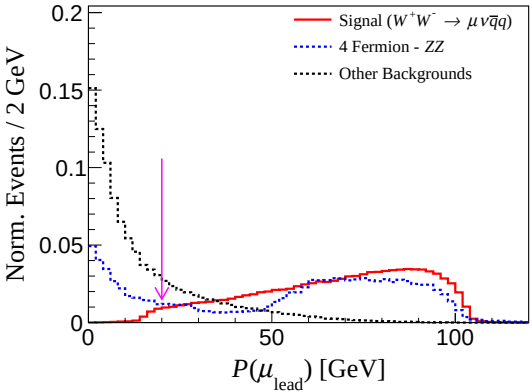


Removing the leading muon before clustering restores the hadronic W mass peak.

Selection variables I

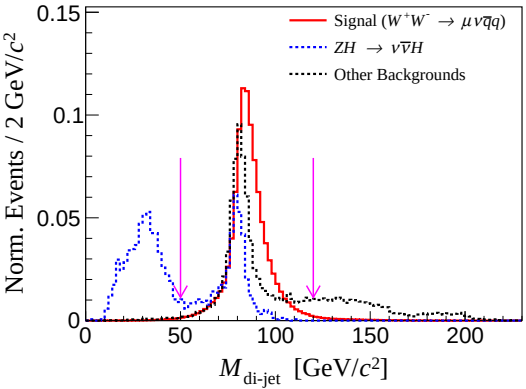


Charged-track multiplicity cleanly rejects low-multiplicity leptonic events.

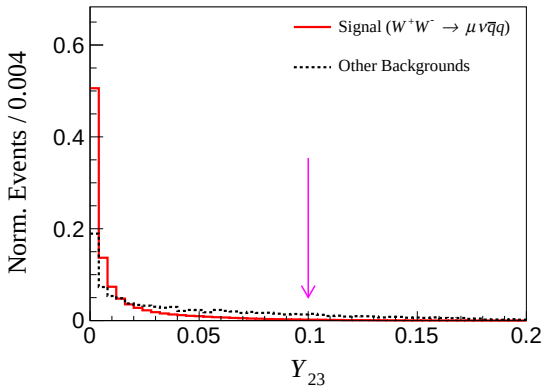


The leading-muon momentum suppresses soft and non-prompt muons.

Selection variables II



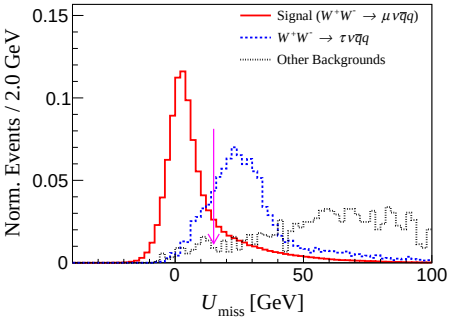
The di-jet mass selects the hadronic W resonance.



The jet-resolution variable rejects residual multi-jet topologies.

Selection variable III

- The missing-momentum direction suppresses ISR-dominated and forward-peaked events.
- The missing-mass proxy $U_{\text{miss}} = E_{\text{miss}} - P_{\text{miss}}$ rejects multi-neutrino backgrounds.
- The final impact-parameter requirement removes cosmic-ray and decay-in-flight contamination.
- After the full selection, the background contamination is reduced to a very small level.



Residual background

Dominated by $W^+W^- \to \tau\nu\bar{q}q$ with small ZZ and ZH contributions.

Selection cutflow

Selection criterion	$\mu\nu\bar{c}s$	$q\bar{q}$	ZZ	$\tau\nu\bar{q}q$	ZH
Total events	25,257,744	1,168,708,160	9,668,592	57,499,848	4,399,256
$N_{\text{jet}} = 2$	100.0%	99.9%	100.0%	100.0%	93.1%
$5 \leq N_{\text{trk}} \leq 30$	99.0%	94.9%	97.6%	99.6%	47.8%
$N_{\ell} \geq 1$	98.9%	24.3%	54.5%	45.2%	32.3%
$50 \leq \sum E_{\text{trk}} \leq 200$ GeV	97.8%	19.2%	44.7%	42.0%	31.0%
$P(\gamma_{\text{lead}}) \leq 60$ GeV	97.4%	15.5%	43.2%	41.8%	30.9%
$N_{\mu} \geq 1$	97.4%	6.6%	36.7%	19.4%	16.8%
$P(\mu_{\text{lead}}) \geq 20$ GeV	95.1%	1.2%	27.7%	9.8%	5.0%
$\sum P(\mu) \leq 100$ GeV	90.5%	1.2%	10.0%	9.8%	5.0%
$80^{\circ} \leq \theta(\mu_{\text{lead}}, \text{di-jet}) \leq 170^{\circ}$	82.9%	0.2%	3.1%	8.5%	3.3%
$E_{\text{ratio}}(\mu_{\text{lead}}) \geq 0.9$	79.7%	$< 0.1\%$	1.8%	8.2%	2.3%
$50 \leq M_{\text{di-jet}} \leq 120$ GeV	77.8%	$< 0.1\%$	1.0%	7.9%	0.8%
$Y_{23} \leq 0.1$	76.6%	$< 0.1\%$	0.9%	6.5%	0.6%
$Y_{34} \leq 0.008$	73.8%	$< 0.1\%$	0.8%	5.8%	0.4%
$\lvert \cos\theta_{\text{miss}} \rvert \leq 0.9$	68.4%	0.0%	0.1%	4.4%	0.4%
$U_{\text{miss}} \leq 15$ GeV	54.1%	0.0%	$< 0.1\%$	0.8%	$< 0.1\%$
$\chi^2_{\text{IP}} \leq 10$	53.8%	0.0%	$< 0.1\%$	0.2%	$< 0.1\%$
Final expected yields	13,588,666	0	3,846	115,000	1,225

Background categories before and after selection

Before selection

Category	Events
Signal ($\mu\nu\bar{q}q$)	53,351,568
Two-fermion ($q\bar{q}, \ell\ell, \nu\nu$)	3,090,157,920
ZZ	12,020,184
W^+W^- ($\tau\nu\bar{q}q, e\nu\bar{q}q$)	111,614,328
single-Z	9,971,856
single-W	75,281,400
ZH	4,399,256
Total background	3,303,444,944

After full selection

Category	Events
Signal ($\mu\nu\bar{q}q$)	29,867,852
Two-fermion ($q\bar{q}, \ell\ell, \nu\nu$)	0
ZZ	3,846
W^+W^- ($\tau\nu\bar{q}q, e\nu\bar{q}q$)	115,000
single-Z	negligible
single-W	negligible
ZH	1,225
Total background	120,071

The surviving background is dominated by $W^+W^- \to \tau\nu\bar{q}q$, with smaller ZZ and ZH contributions.

Final signal yields after the full selection

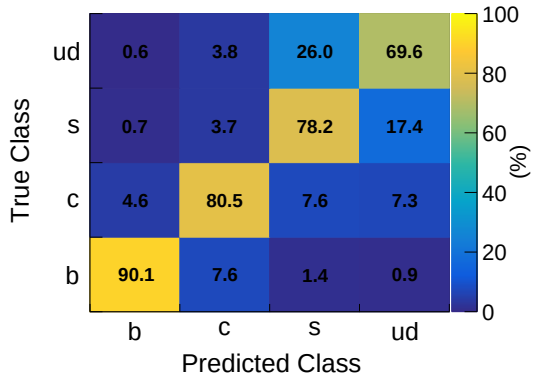
Signal channel	Efficiency (%)	Expected yield
$W^+W^- \to \mu\nu\bar{u}d$	58.2	14,746,269
$W^+W^- \to \mu\nu\bar{u}s$	56.4	763,958
$W^+W^- \to \mu\nu\bar{c}d$	55.2	747,704
$W^+W^- \to \mu\nu\bar{c}s$	53.8	13,588,666
$W^+W^- \to \mu\nu\bar{c}b$	44.7	21,048
$W^+W^- \to \mu\nu\bar{u}b$	48.0	207

Takeaway

The selection keeps more than 50% efficiency for the light and charm channels while strongly suppressing the background.

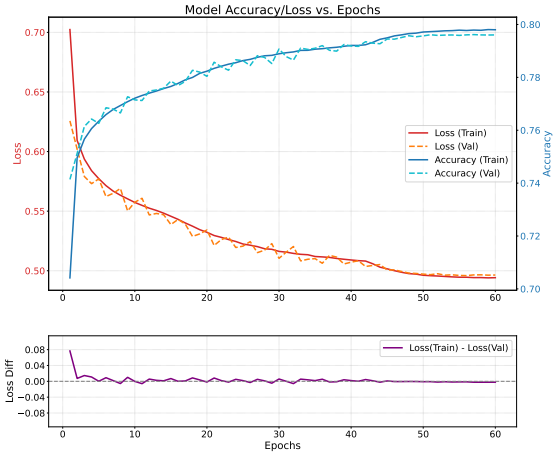
ParticleNet flavor tagger

- Four output classes: b, c, s, and ud.
- The u and d jets are merged because they are experimentally difficult to separate.
- Lightweight architecture: three EdgeConv blocks, 8 nearest neighbors, and a final dense layer.
- Trained with 1M events per class for 60 epochs using Adam.
- Validation accuracy reaches 79.6%.
- The largest residual confusion is between s and ud jets.



Training stability

- Training and validation curves converge smoothly.
- No visible sign of overfitting.
- Best performance is reached after about 50 epochs.



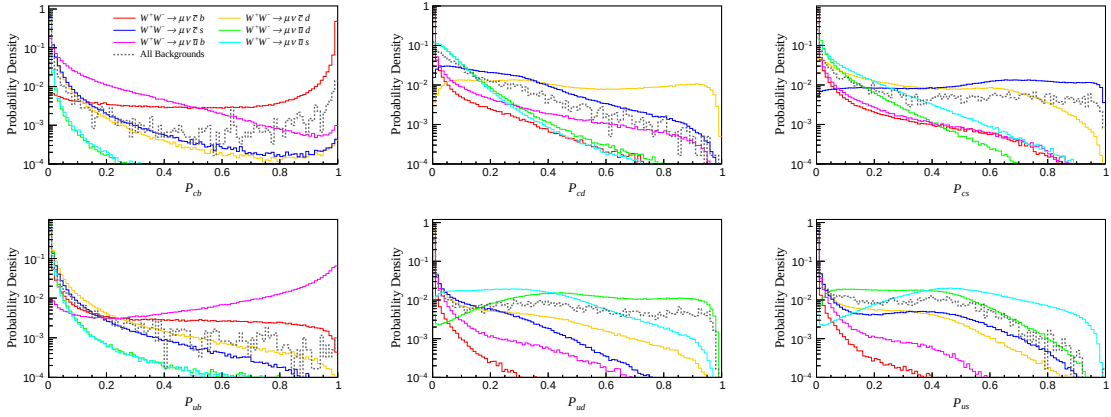
Event-level flavor discriminants

- For each jet pair, the two ParticleNet outputs are combined into an event-level discriminant.
- The six discriminants correspond to the signal hypotheses P_{cb}, P_{cd}, P_{cs}, P_{ub}, P_{ud}, and P_{us}.
- Values near unity indicate a good match to the target flavor assignment.
- Background and mismatched flavor combinations populate smaller values.

$$P_{ij} = \frac{P_1(i)P_2(j)+P_2(i)P_1(j)}{\sum_{h_1,h_2\in\{b,c,s,ud\}}[P_1(h_1)P_2(h_2)+P_2(h_1)P_1(h_2)]}$$

The symmetrized numerator removes the jet-order ambiguity.

Event-level discriminant shapes



The signal hypothesis is concentrated at large discriminant values, while backgrounds populate the low-discriminant region.

From fitted yields to branching fractions

- The fitted signal yields are converted into branching fractions using the channel efficiency.
- The *ub* contribution is fixed because its expected yield is negligible.
- The extracted branching fractions provide the direct input for the CKM determination.

Physics point

The conversion is clean because the flavor-independent QCD and electroweak corrections largely cancel in the ratio.

Branching fraction

$$\mathrm{BR}(W^- \to \bar{q}_i q_j) = \frac{N_{ij}}{\varepsilon_{ij} \cdot N_{W^+W^- \to \mu\nu\bar{q}q}}$$

From branching fractions to CKM elements

- Under CKM unitarity, the hadronic W branching fraction gives a direct handle on $|V_{ij}|$.
- The simultaneous fit result is translated channel by channel into the CKM elements.

CKM relation

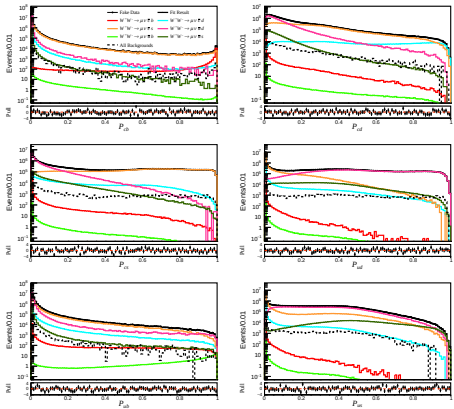
$$|V_{ij}| \approx \sqrt{\frac{2N_{ij}}{\varepsilon_{ij} \cdot N_{W^+W^- \to \mu\nu\bar{q}q}}}$$

Interpretation

This gives an electroweak determination of CKM elements without hadronic form-factor uncertainties.

Binned simultaneous fit and CKM extraction

- Event-level flavor discriminants are built from the two jet-tag outputs.
- A binned simultaneous fit is performed for the six hypotheses P_{cb}, P_{cd}, P_{cs}, P_{ub}, P_{ud}, and P_{us}.
- The selected sample is large, so a binned extended maximum-likelihood fit is used.
- The *ub* contribution and the residual background are fixed.
- Fitted yields agree well with the input expectations.



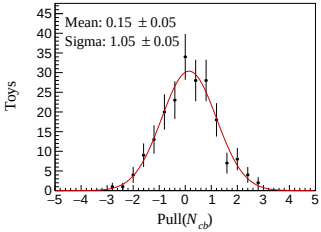
Fitted yields

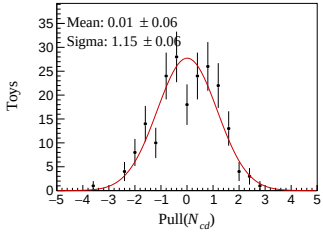
Yield	Initial	Fitted	Uncertainty	Rel. unc.
N_{cb}	2.10×10^4	2.12×10^4	2.50×10^2	1.18%
N_{cd}	7.48×10^5	7.45×10^5	2.66×10^3	0.36%
N_{cs}	1.36×10^7	1.36×10^7	3.22×10^3	0.02%
N_{ud}	1.47×10^7	1.48×10^7	3.40×10^3	0.02%
N_{us}	7.64×10^5	7.61×10^5	3.09×10^3	0.41%

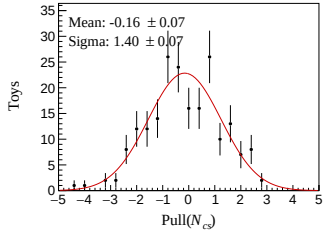
The fitted yields are consistent with the input expectations.

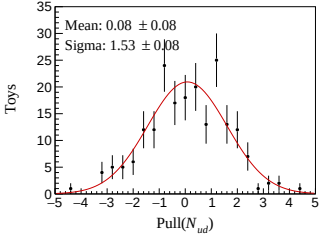
- The pull study is shown on the next slide.
- High-yield channels dominate the statistical precision.

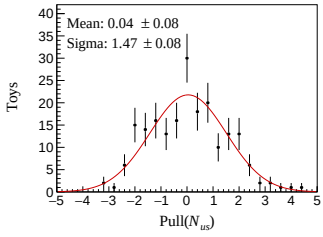
Pull validation











Pull means are compatible with zero and the widths are close to unity.

Statistical uncertainty

- Statistical uncertainties come directly from the binned simultaneous fit.
- For each channel, the relative statistical uncertainty on $|V_{ij}|$ follows

$$\frac{\delta|V_{ij}|}{|V_{ij}|} = \frac{1}{2}\frac{\delta N_{ij}}{N_{ij}}.$$

- The relative yield uncertainties range from 0.02% to 1.18% for the fitted channels.
- The smallest statistical errors come from the high-yield *ud* and *cs* modes.

Systematic uncertainty

- Detector resolution effects are evaluated by varying the track, vertex, and calorimeter resolutions by $\pm 10\%$.
- The common detector-related uncertainty is 0.82% and dominates the quoted total precision.
- Parton-shower and hadronization modeling are important for a full analysis, but are not included in the quoted total here.
- Flavor-tag calibration and external unitarity input are also treated as future or interpretation-level uncertainties.

Quoted total uncertainty

$$\sigma_{\mathrm{tot}} = \sqrt{\sigma_{\mathrm{stat}}^2 + \sigma_{\mathrm{syst}}^2}$$

Main message

The quoted total uncertainty is dominated by detector-driven systematics rather than by statistics.

Projected precision on CKM elements

CKM element	CEPC total	PDG avg.	Benchmark
$\|V_{ud}\|$	0.83%	0.03%	PIBETA: 0.28%
$\|V_{us}\|$	0.84%	0.38%	KLOE: 0.18%
$\|V_{cd}\|$	0.84%	1.81%	BESIII: 3.4%
$\|V_{cs}\|$	0.83%	0.62%	BESIII: 1.7%
$\|V_{cb}\|$	1.02%	2.92%	Belle-based: 1.5%

- The CEPC is competitive for $|V_{cd}|$, $|V_{cs}|$, and $|V_{cb}|$.
- It provides an independent electroweak determination for all five CKM elements.

Summary

- We studied direct CKM measurements from semileptonic W decays at the CEPC.
- A clean event selection and ParticleNet-based jet flavor tagging provide strong flavor separation.
- A binned simultaneous fit yields projected precisions of 0.83–1.02% for the five CKM elements studied.
- The CEPC can provide competitive and complementary CKM measurements in a clean electroweak environment.
- **Current Status:** The manuscript draft has been prepared.
- **Next Steps:** Investigate the pull width issue and check the Toy MC generation.

Thank you!