

CKM determination from W decays with jet flavor tagging at CEPC

CEPC Physics and Detector Plenary Meeting

Zhao-Ling Zhang¹ Li-Bo Liao² Jia-Rong Li³ Jia-Bao Gong^{4,5} Wei-Min Song¹
Gang Li^{4,5}

¹College of Physics, Jilin University, Changchun, China

²Sun Yat-sen University, Guangzhou, China

³Tsinghua University, Beijing, China

⁴Institute of High Energy Physics, CAS, Beijing, China

⁵University of Chinese Academy of Sciences, Beijing, China

June 10, 2026

Outline

- 1 Motivation
- 2 Simulation samples and analysis setup
- 3 Event selection
- 4 Jet flavor tagging and fit
- 5 Results and uncertainties
- 6 Summary

Why measure CKM elements with hadronic W decays?

- The CKM matrix is the flavor-mixing matrix of the Standard Model.
- Precise determinations of $|V_{ij}|$ test CKM unitarity and probe possible new physics in charged-current interactions.
- Most existing measurements come from hadron decays and rely on non-perturbative hadronic inputs.
- Hadronic W decays provide a theoretically clean electroweak alternative.

Key relation

$$\text{BR}(W^- \rightarrow \bar{q}_i q_j) \approx \frac{1}{2} |V_{ij}|^2$$

Why CEPC?

- huge $W^+ W^-$ sample at $\sqrt{s} = 240$ GeV
- clean $e^+ e^-$ environment
- excellent tracking and flavor-tagging potential

Broader picture

This work explores whether CEPC can turn hadronic W branching fractions into precision CKM observables.

What kind of study is this? What is new?

- A **future sensitivity projection** for CEPC, not a measurement.
- Signal channel:

$$e^+e^- \rightarrow W^+W^- \rightarrow \mu\nu \bar{q}q$$

- Full chain included: detector simulation, event selection, ParticleNet flavor tagging, and simultaneous template fitting.
- The hadronic W decay is separated into ud , us , ub , cd , cs , and cb modes.
- The analysis targets $|V_{ud}|$, $|V_{us}|$, $|V_{cd}|$, $|V_{cs}|$, and $|V_{cb}|$ simultaneously.

Main novelty

Event-level flavor tagging makes direct CKM extraction from hadronic W decays realistic at CEPC.

Journal status

Current manuscript draft is prepared in the **EPJC** style.

How this compares with published results

- For $|V_{ud}|$ and $|V_{us}|$, low-energy measurements remain much more precise.
- For $|V_{cd}|$, $|V_{cs}|$, and $|V_{cb}|$, CEPC can provide competitive single-experiment sensitivities.
- The most closely related direct electroweak-boson measurements are:
 - LEP flavor-tagged determination of $|V_{cs}|$
 - ATLAS direct determination of $|V_{cb}|$
- The value of this study is therefore not only ultimate precision, but also **complementarity**: a clean electroweak-scale determination using on-shell W decays.

Plenary message

This analysis connects CEPC detector performance, ML-based flavor tagging, and a concrete precision-physics target.

Detector simulation and Monte Carlo setup

- $\sqrt{s} = 240$ GeV, integrated luminosity 21.6 ab^{-1} .
- Event generation: *WHIZARD*.
- Parton shower and hadronization: *PYTHIA*.
- Detector response: *DELPHES* with a dedicated CEPC detector card.
- ISR and bremsstrahlung effects are included.

Interpretation

This is a realistic fast-simulation study: detailed enough for detector-level sensitivity, but still computationally practical.

Signal topology

one isolated muon + missing momentum + two hadronic jets

Target hadronic modes

$\bar{u}d$, $\bar{u}s$, $\bar{u}b$, $\bar{c}d$, $\bar{c}s$, $\bar{c}b$

Why focus on the $\mu\nu\bar{q}q$ channel?

- The semileptonic channel gives a clean event topology.
- Compared with the $e\nu\bar{q}q$ channel, the muon channel is less affected by single- W and single- Z backgrounds.
- The isolated muon helps suppress purely hadronic and multi-jet backgrounds.
- The hadronic W can then be reconstructed with two jets and passed to the flavor-tagging stage.

Why not all channels yet?

This work is a first focused study. Additional semileptonic channels can be added later to improve the final sensitivity.

Event picture

prompt muon + one neutrino + one hadronic W

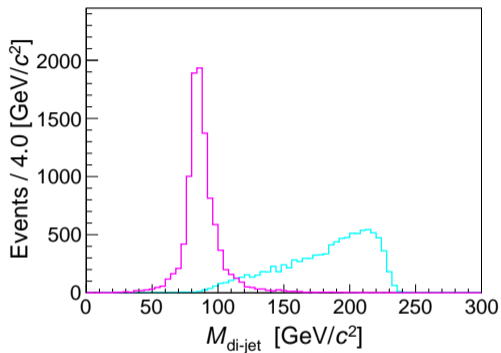
Signal and background samples

Process category	Cross section (fb)	Expected events
$W^+ W^- \rightarrow \mu\nu\bar{u}d$	1173.02	25,337,232
$W^+ W^- \rightarrow \mu\nu\bar{u}s$	62.71	1,354,536
$W^+ W^- \rightarrow \mu\nu\bar{c}d$	62.71	1,354,536
$W^+ W^- \rightarrow \mu\nu\bar{c}s$	1169.34	25,257,744
$W^+ W^- \rightarrow \mu\nu\bar{c}b$	2.18	47,088
two-fermion backgrounds	—	3.09×10^9
ZZ backgrounds	—	1.20×10^7
semileptonic WW backgrounds	—	1.12×10^8
single- W/Z backgrounds	—	8.53×10^7
ZH backgrounds	—	4.40×10^6

The ub mode is generated but excluded from the fit because its expected yield is negligible.

Event reconstruction and hadronic W reconstruction

- All visible particles are clustered into exactly two jets with the $ee-k_t$ algorithm.
- The leading muon candidate is removed before jet clustering.
- This significantly improves the di-jet mass resolution.
- The reconstructed di-jet mass is then used to identify the hadronic W candidate.



Technical point

Removing the signal muon before clustering is essential for recovering the hadronic W peak.

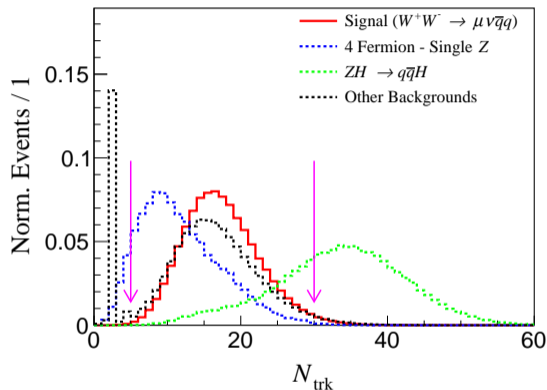
Selection overview

- Preselection: track multiplicity, visible energy, photon veto, and at least one lepton.
 - Muon selection: at least one muon, hard leading muon, muon isolation, and recoil-angle requirement.
 - Hadronic system: di-jet mass window and jet-resolution variables.
 - Global cleanup: missing-momentum direction, missing-mass proxy, and impact-parameter consistency.
- $5 \leq N_{\text{trk}} \leq 30$
 - $50 \leq \sum E_{\text{trk}} \leq 200 \text{ GeV}$
 - $P(\mu_{\text{lead}}) \geq 20 \text{ GeV}$
 - $50 \leq M_{\text{di-jet}} \leq 120 \text{ GeV}$
 - $Y_{23} \leq 0.1, Y_{34} \leq 0.008$
 - $U_{\text{miss}} \leq 15 \text{ GeV}$

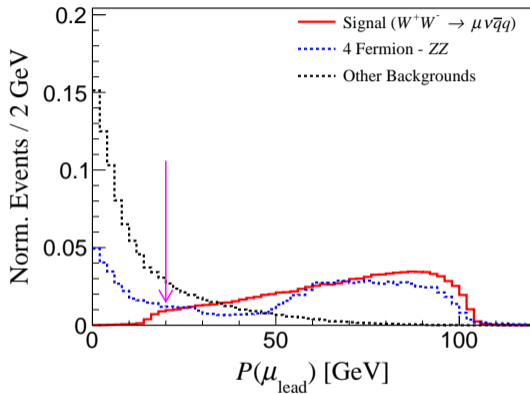
Goal

Keep a clean $\mu\nu\bar{q}q$ topology while reducing huge $2f$ and multi-fermion backgrounds.

Selection variables I

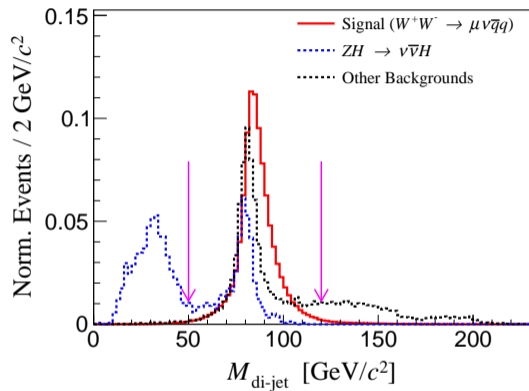


Charged-track multiplicity suppresses low-multiplicity leptonic backgrounds.

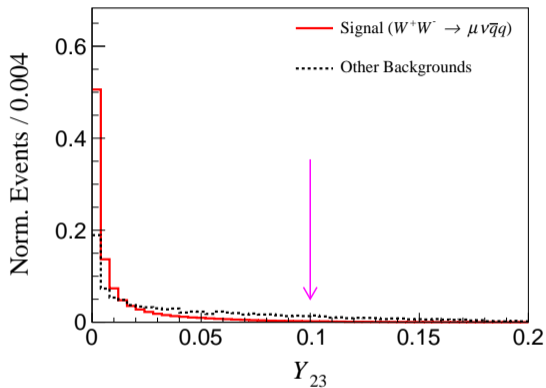


The leading-muon momentum rejects soft and non-prompt muons.

Selection variables II



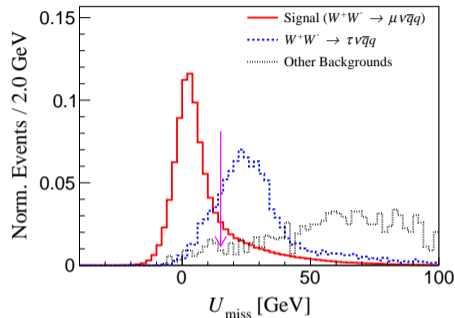
The di-jet mass window selects the hadronic W resonance.



Y_{23} removes residual multi-jet topologies with hard radiation.

Selection variable III

- $|\cos \theta_{\text{miss}}|$ suppresses forward ISR-dominated topologies.
- $U_{\text{miss}} = E_{\text{miss}} - P_{\text{miss}}$ rejects events with multiple missing particles.
- The final impact-parameter requirement removes non-collision contamination.
- After the full selection, the surviving background is very small.



Residual background

Dominated by $W^+W^- \rightarrow \tau\nu\bar{q}q$, 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%
$ \cos \theta_{\text{miss}} \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%
$\chi_{\text{IP}}^2 \leq 10$	53.8%	0.0%	< 0.1%	0.2%	< 0.1%
Final expected yields	13,588,666	0	3,846	115,000	1,225

Background composition before and after selection

Before selection	
Category	Events
Signal ($\mu\nu\bar{q}q$)	53,351,568
Two-fermion	3,090,157,920
ZZ	12,020,184
W^+W^- (τ/e channels)	111,614,328
single- W/Z	85,253,256
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	0
ZZ	3,846
W^+W^- (τ/e channels)	115,000
single- W/Z	negligible
ZH	1,225
Total background	120,071

The final sample is highly pure; the dominant residual background is $W^+W^- \rightarrow \tau\nu\bar{q}q$.

Final signal yields after the full selection

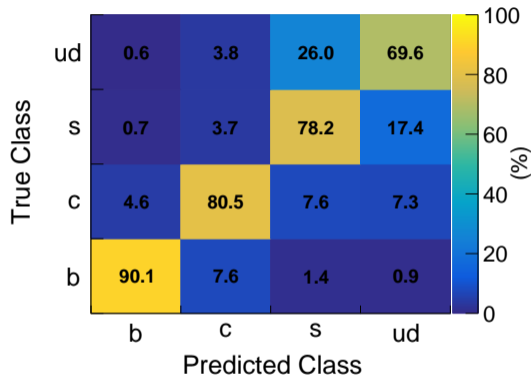
Signal channel	Efficiency (%)	Expected yield
$W^+ W^- \rightarrow \mu\nu\bar{u}d$	58.2	14,746,269
$W^+ W^- \rightarrow \mu\nu\bar{u}s$	56.4	763,958
$W^+ W^- \rightarrow \mu\nu\bar{c}d$	55.2	747,704
$W^+ W^- \rightarrow \mu\nu\bar{c}s$	53.8	13,588,666
$W^+ W^- \rightarrow \mu\nu\bar{c}b$	44.7	21,048
$W^+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

Take-away

The selection keeps more than 50% efficiency for the light and charm channels while reducing the background to a very low level.

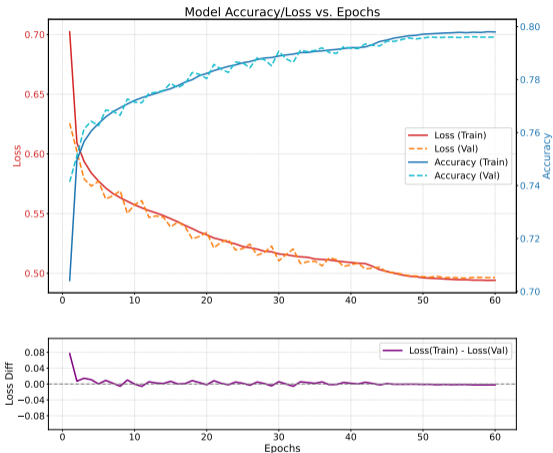
ParticleNet flavor tagger

- Four output classes: b , c , s , and merged ud .
- The u and d jets are merged because they are experimentally difficult to separate.
- Lightweight architecture: three EdgeConv blocks with 8 nearest neighbors.
- Training sample: one million events per class.
- Training: 60 epochs, Adam optimizer.
- Validation accuracy reaches 79.6%.



Training stability

- Stable convergence of training and validation curves.
- No strong sign of overfitting.
- Best performance is reached after about 50 epochs.
- The remaining challenge is mainly physics separation, especially *s* versus *ud*.



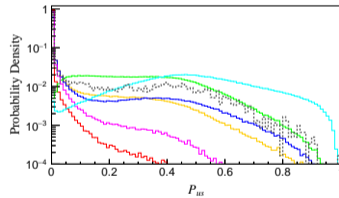
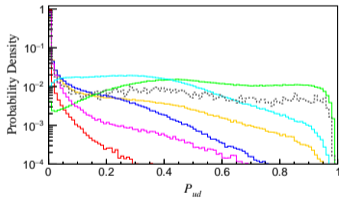
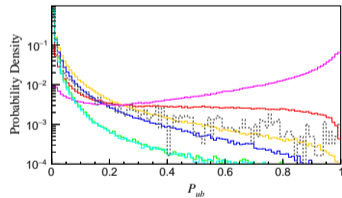
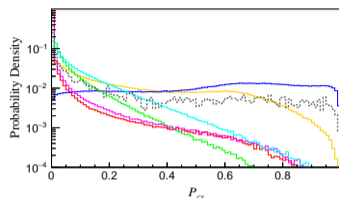
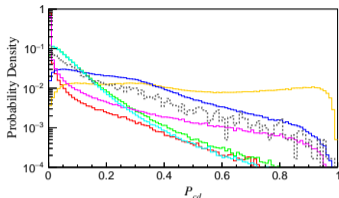
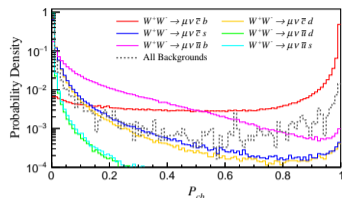
Event-level flavor discriminants

- For each event, the two jet-tag outputs are combined into an event-level flavor discriminant.
- The six signal hypotheses are P_{cb} , P_{cd} , P_{cs} , P_{ub} , P_{ud} , and P_{us} .
- Jet-order ambiguity is removed by symmetrization.
- Large values indicate a good match to the target flavor assignment.
- Background and mismatched flavor combinations accumulate at lower values.
- These templates are the core inputs to the simultaneous fit.

Definition

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

Event-level discriminant shapes



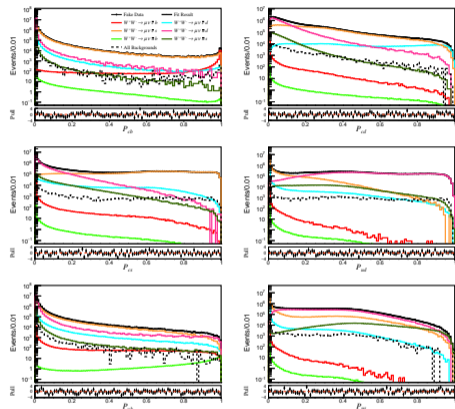
The signal hypothesis is concentrated at high discriminant values, while background populates the lower-discriminant region.

Simultaneous binned fit

- A binned extended maximum-likelihood fit is used because the selected sample is very large.
- Free parameters: N_{cb} , N_{cd} , N_{cs} , N_{ud} , and N_{us} .
- The ub mode and the total residual background are fixed.
- Fitted yields are converted into branching fractions and then into CKM elements.

Fit content

The six event-level flavor discriminants are fitted simultaneously.



Fitted signal 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%

- ud and cs benefit from very large statistics.
- cb remains the statistically most difficult channel.

The fitted yields are consistent with the input expectations.

From fitted yields to CKM elements

Branching fraction extraction

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

CKM extraction

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

- The conversion is clean because the leading QCD and electroweak corrections are flavor independent to a very good approximation.
- The quoted result assumes CKM unitarity in the normalization.

Where does the statistical error come from?

- The statistical error comes directly from the simultaneous fit.
- Once the fitted yield uncertainty δN_{ij} is known, the CKM statistical error follows as

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

- So the channels with the largest yields, ud and cs , have the smallest statistical errors.
- The most difficult channel is still cb because of its low yield.

Statistical precision

- $|V_{ud}|$: 0.01%
- $|V_{us}|$: 0.20%
- $|V_{cd}|$: 0.18%
- $|V_{cs}|$: 0.01%
- $|V_{cb}|$: 0.59%

Where does the systematic error come from?

- In this study, the quoted systematic error comes from detector resolution effects.
- We vary the tracking, vertexing, and calorimeter resolutions in Delphes by $\pm 10\%$.
- The resulting common detector-related uncertainty is about 0.82%.
- This already dominates the total error for most channels.

Not yet included in the quoted total

Parton-shower / hadronization modeling and flavor-tag calibration will be important in a full analysis, but are not yet included here.

Projected precision on CKM elements

CKM element	Stat.	Syst.	Total
$ V_{ud} $	0.01%	0.82%	0.83%
$ V_{us} $	0.20%	0.82%	0.84%
$ V_{cd} $	0.18%	0.82%	0.84%
$ V_{cs} $	0.01%	0.82%	0.83%
$ V_{cb} $	0.59%	0.82%	1.02%

Take-away

For $|V_{cb}|$, statistics still matter. For the other channels, the present sensitivity is already mainly limited by detector-related systematics.

How do we compare with existing results?

CKM element	CEPC total	PDG avg.	Representative result
$ 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%

Take-away

For $|V_{ud}|$ and $|V_{us}|$, CEPC will mainly provide an independent electroweak-scale cross-check. For $|V_{cd}|$, $|V_{cs}|$, and $|V_{cb}|$, the sensitivity is already quite competitive.

What remains for a full precision analysis

- Calibrate flavor-tagging efficiencies and mistag rates with realistic control samples.
- Estimate parton-shower and hadronization uncertainties with generator comparisons.
- Refine the detector-related uncertainty evaluation beyond the current common 0.82% treatment.
- Extend to additional semileptonic channels and possibly other tagging strategies.

Why this is useful for the collaboration

The study highlights where detector performance, flavor-tag calibration, and physics analysis need to meet.

Summary

- In this work, we studied direct CKM measurements from semileptonic W decays at CEPC with realistic fast simulation.
- The full analysis chain is already in place: event selection, ParticleNet flavor tagging, and a simultaneous fit to event-level flavor discriminants.
- The projected precision is at the level of 0.83–1.02% for the five CKM elements considered here.
- The most interesting channels are $|V_{cd}|$, $|V_{cs}|$, and $|V_{cb}|$, where CEPC can give competitive and complementary information.
- So the main message is that direct CKM measurements from hadronic W decays are a realistic part of the CEPC physics program.

Thank you!