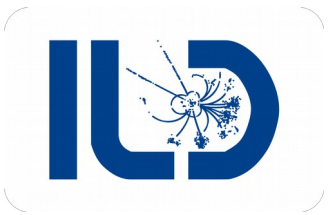
CKM Matrix Elements from W Decays

Ulrich Einhaus

3rd ECFA workshop on e^+e^- Higgs,
Top & ElectroWeak Factories
09.10.2024



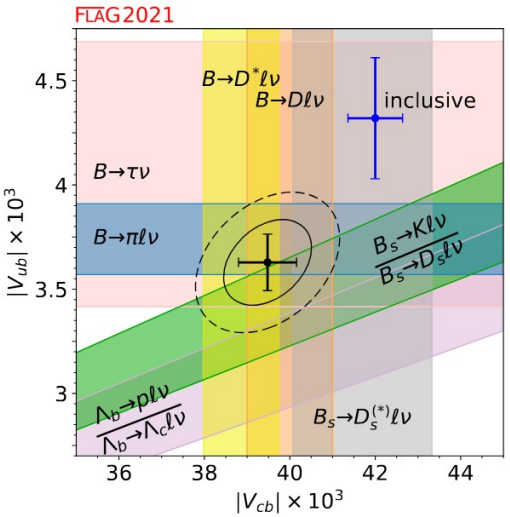
HELMHOLTZ

Motivation

- Target: determine CKM matrix elements with optimal precision
- Why do we want that?
  - New Physics can affect couplings at ‘low’ energies → deviations from SM expectation
  - Does the unitarity triangle actually close?
  - Specifically: tension between inclusive and exclusive measurements of V_{cb} at ~ 3 σ

$$|V_{cb}| \text{ from inclusive } B \text{ decays} \qquad (42.19 \pm 0.78) \times 10^{-3}$$
$$|V_{cb}| \text{ from exclusive } B,\ B_s \text{ and } \Lambda_b \text{ decays} \qquad (39.10 \pm 0.50) \times 10^{-3}$$

→ Focus topic WW-CKM, along with 2 more W-based focus topics (m_W, Wdiff) making use of large statistics at $E_{cm} \geq 2m_W$ at any future HTE factory



- Direct W decays allow to directly measure 6 ‘non-top’ elements
- See also 2-day meeting of flavour sub-group

CKM precision: status & outlook

- V_{cs} prospects to reach 0.2%
- V_{cb} already now systematically limited, reach possibly ~ 2% with HL-LHC
- Statistics at future HTE factory can allow for 1 order of magnitude higher precision

from study with FCC-ee:

$\lvert V_{ij}\rvert$	Current (PDG)		FCC-ee ($\delta_\epsilon = 1\%$)	FCC-ee ($\delta_\epsilon = 0.1\%$)
$\lvert V_{cs}\rvert$	0.975 ± 0.006	(0.6%)	0.36%	0.05%
$\lvert V_{cb}\rvert$	$(40.8 \pm 1.4) \times 10^{-3}$	(3.4%)	0.52%	0.16%

- For 10^8 W with perfect efficiency and no background:

$W^- \to$	$\bar{u}d$	$\bar{u}s$	$\bar{u}b$	$\bar{c}d$	$\bar{c}s$	$\bar{c}b$
BR	31.8%	1.7%	4.5×10^{-6}	1.7%	31.7%	5.9×10^{-4}
N_{ev}	64×10^6	3.4×10^6	900	3.4×10^6	63×10^6	118×10^3
$\delta^{\text{th}}_{V_{ij}}$	0.0063 %	0.027 %	1.7 %	0.027 %	0.0063 %	0.15 %

Method

- W branching fraction into quarks u_i + d_j directly proportional to $|V_{ij}|^2$
- Identify W events, simply tag and count decays into different quark combinations!
- Simply tag…? → crucial: high efficiency & purity & well-understood flavour tagger!
- Measuring CKM elements from B/D-meson decays suffers from significant non-perturbative hadronic contributions to the matrix element, not at $m_W >> \Lambda_{QCD}$
- Great prospects with perfect efficiency and no systematics, but what is realistic?

$W^- \to$	$\bar{u}d$	$\bar{u}s$	$\bar{u}b$	$\bar{c}d$	$\bar{c}s$	$\bar{c}b$
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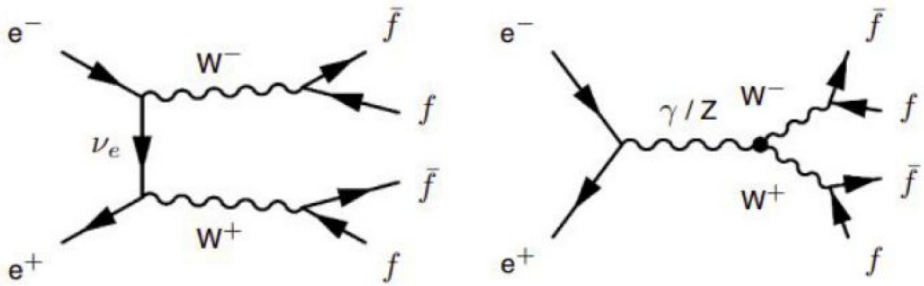
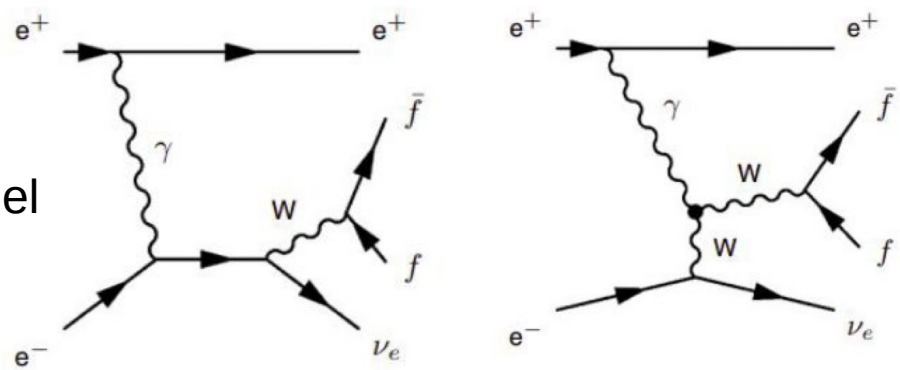
W Physics Working Points

- W threshold
  - needed anyway for m_W
  - cross section ~ 5 pb
  - more interesting for CC
- Higgs (240-250 GeV)
  - needed anyway for H
  - cross section ~ 20 pb
  - more interesting for LC
- W(W) production profits greatly from polarisation

WW-channel



single-W channel

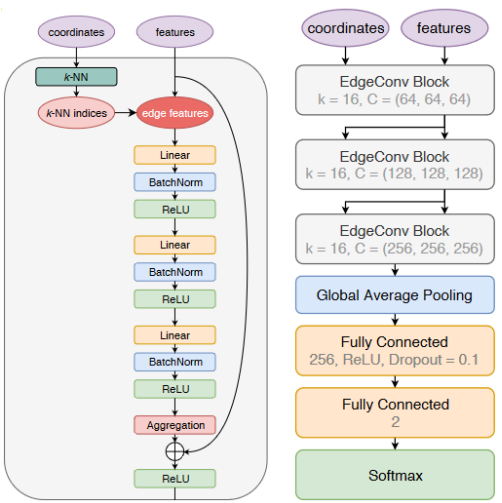


- Both CC and LC expect some 10^8 Ws
- Note: fully hadronic channel has colour reconnection!

Flavour Taggers

- Long-time (> 10 a) standard tool: LCFIPlus, now out-of-date with BDT and b/c/light tag
- A number of new flavour taggers have been developed, making use of neural networks and advanced machine learning
  - ParticleNet (ILD/CLD) [Meyer]
  - ParticleNet (IDEA) [Selvaggi e.a.]
  - ParticleNet (CEPC baseline) [Ruan e.a.]
  - Particle Transformer (ILD, IDEA) [Suehara]
  - Particle Transformer (CLD, Si-IDEA) [Aumiller e.a.]
- Adding strange-tag via PID (kaonID), possibly individual u- and d-tag via FSR

ParticleNet: https://arxiv.org/abs/1902.08570



- Systematic uncertainties on flavour taggers?
  → calibrate at Z-pole with double-tag method and 10^{12} events (FCC-ee) or some 10^{9} (LC)
  → limits to detector adaptions to center-of-mass energy?

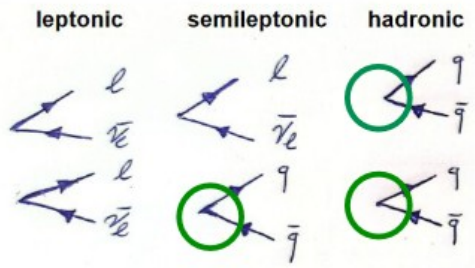
Study with ILD/CLD

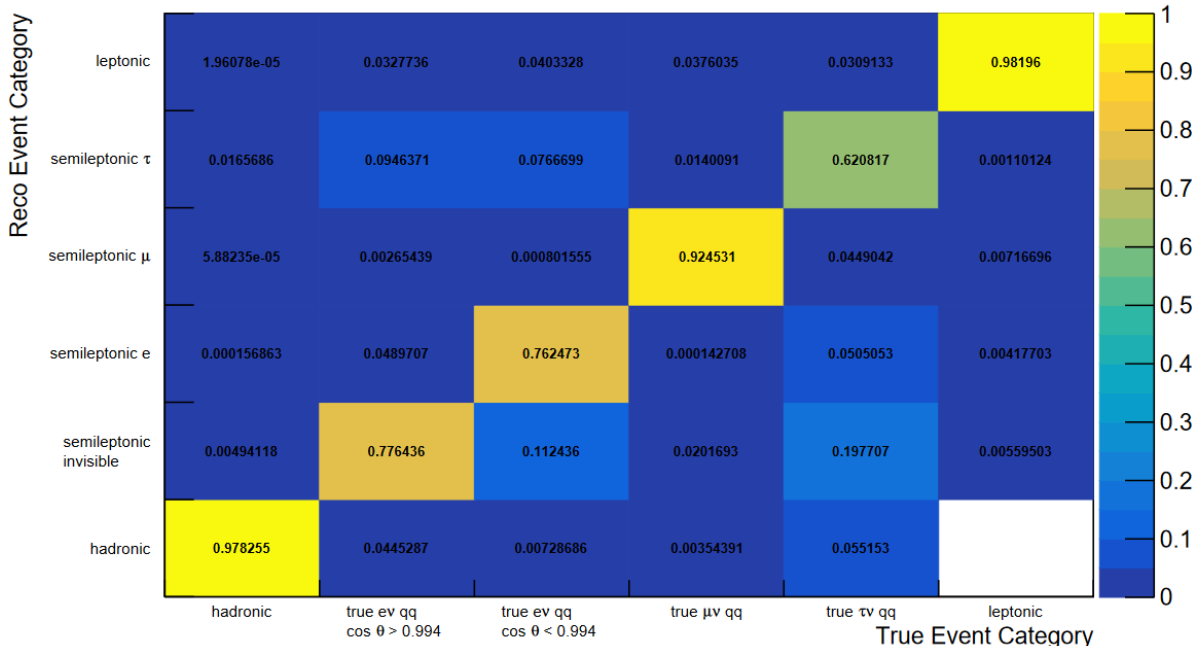
- Approach: full-sim incl. backgrounds, using 250 GeV MC production (ILC) of ~ 12 ab^{-1} (~ 6 times data from target luminosity)
- Goal: ILD post-processing of 250 GeV MC production (from DST to MiniDST) by adding new high-level-reco features, to provide easy-to-access analysis basis

  → Work in progress
- WW categorisation
- Flavour tagger, implementation in standard reco chain

W(W) channel categorisation

- Categorise W(W) decay channels: each event receives one ‘tag’
- → Overlap-free categories allow for easy combination of exclusive analyses of any W-related study
- Basis: number & flavour of leptons
- Refine with number of reco particles (n_{PFOs}), m_{inv}, E_{miss}, $p_{T,miss}$

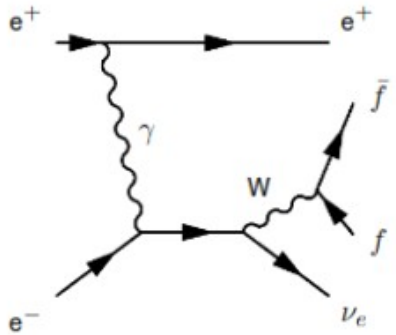


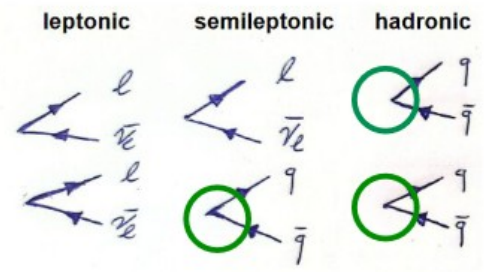


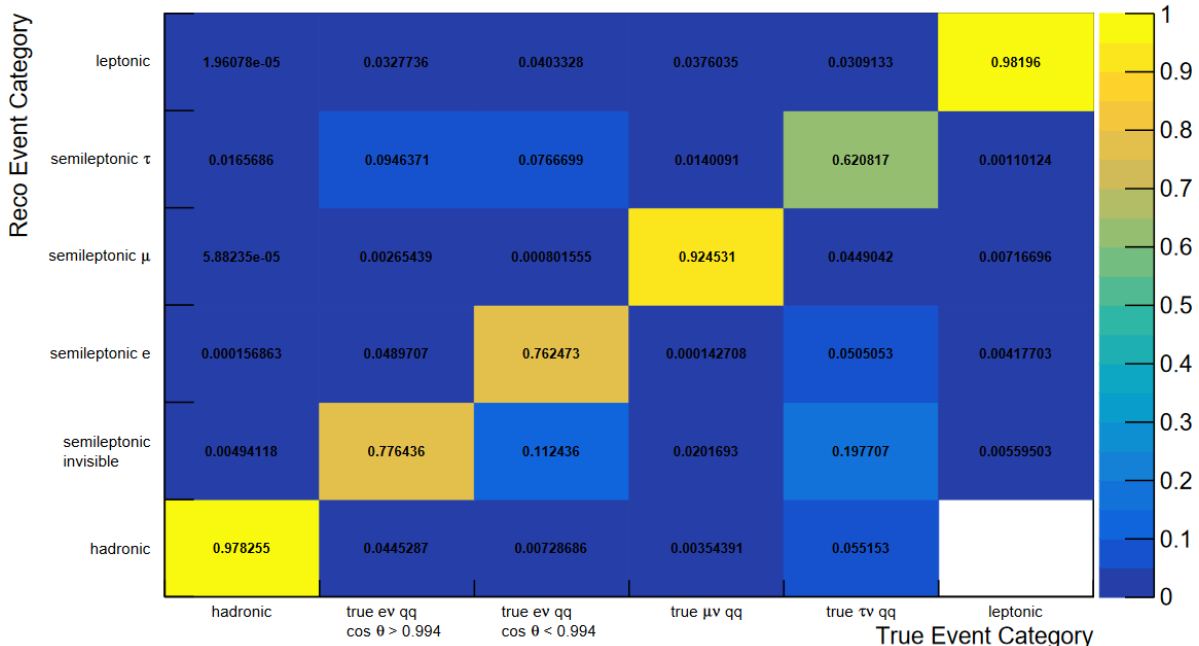
[A. Silva]

W(W) channel categorisation

- Good diagonality
  - hadronic & leptonic ~ 98% eff.
  - semilep. μ ~ 92% eff.
  - confusion at the edge of det. acc. in semilep e vis./invis. ~ 77 % eff. → invis. (cos θ > 0.994) mostly from t-channel contribution
  - some more confusion with semilep. τ ~ 62 % eff.
- Study: increase and understand electron detection efficiency at detector acceptance edge [L. Reichenbach]
- Potential study: τ tagger

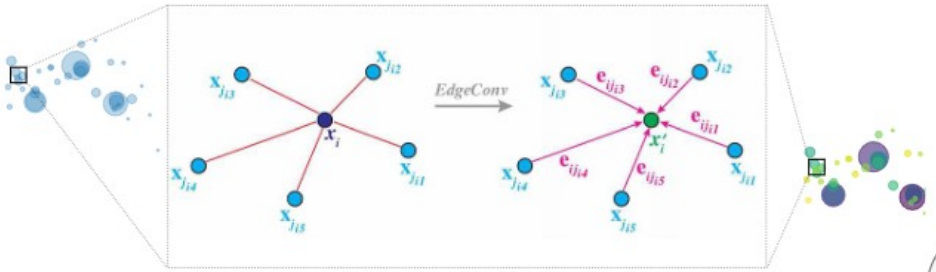






[A. Silva]

ParticleNet (ILD/CLD)



- treat jet as „particle cloud“
- input: **jet constituents**

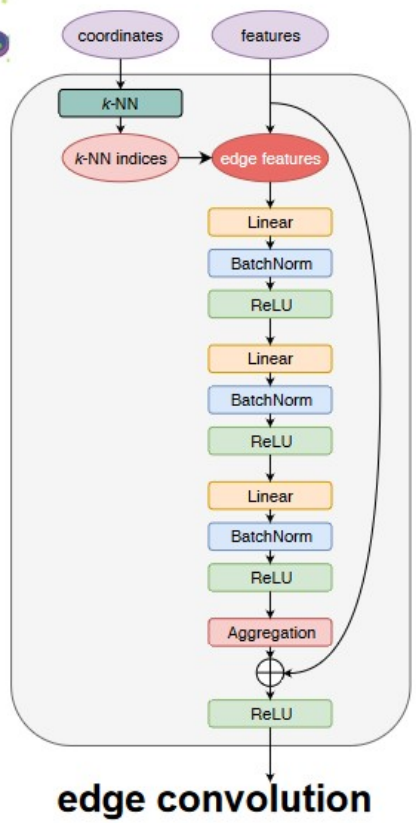
key building block: **edge convolution**

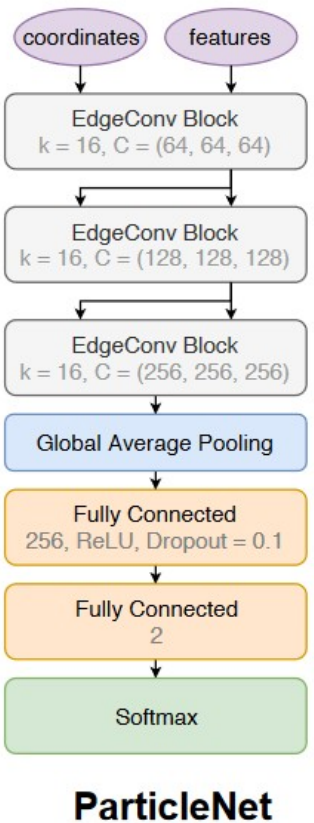
- particle cloud: graph, each point: vertex, connections between each point & k nearest neighboring points: edges
- learn an „**edge feature**“ for each pair:

$$e_{ij} = \mathrm{MLP}(x_i, x_j)$$

- **MLP**: parameters **shared among all edges**
- **aggregation** of edge features: $x_i' = \mathrm{mean}_j\, e_{ij}$

arXiv:1902.08570, *Pushing the Limit of Jet Tagging With Graph Neural Networks*, Huilin Qu, talk at ML4Jets2021, July 7, 2021





from https://agenda.infn.it/event/34841/contributions/207748/

Used features

[M. Meyer, UE]

adapted from https://agenda.infn.it/event/34841/contributions/207748/

jet constituents: coordinates

$\Delta\eta, \Delta\Phi$

jet constituents: features

$\Delta\eta, \Delta\Phi, \eta$

$\log(p_T)$, $\log(E)$, $\log(p_T/p_T^{jet})$, $\log(E/E^{jet})$, $\vec{p}^{track} \cdot \vec{p}^{jet}/p^{jet}$

ΔR

q

isElectron, isMuon, isChargedHadron, isNeutralHadron, isPhoton

impact parameter & significances

impact parameter tag probabilities

track used in PV?

lepton related variables

pid variables → now including CPID: {e, μ, π, K, p} scores

$E_{HCAL}/E_{HCAL+ECAL}$

χ2/ndf

34 39 input features

secondary vertices: coordinates

$\Delta\eta, \Delta\Phi$

secondary vertices: features

$\Delta\eta, \Delta\Phi$

$\log(p_T)$, E_{SV}/E_{jet}, E_{SV}

η

m_{SV}

$N_{tracks\ in\ SV}$

χ2/ndf

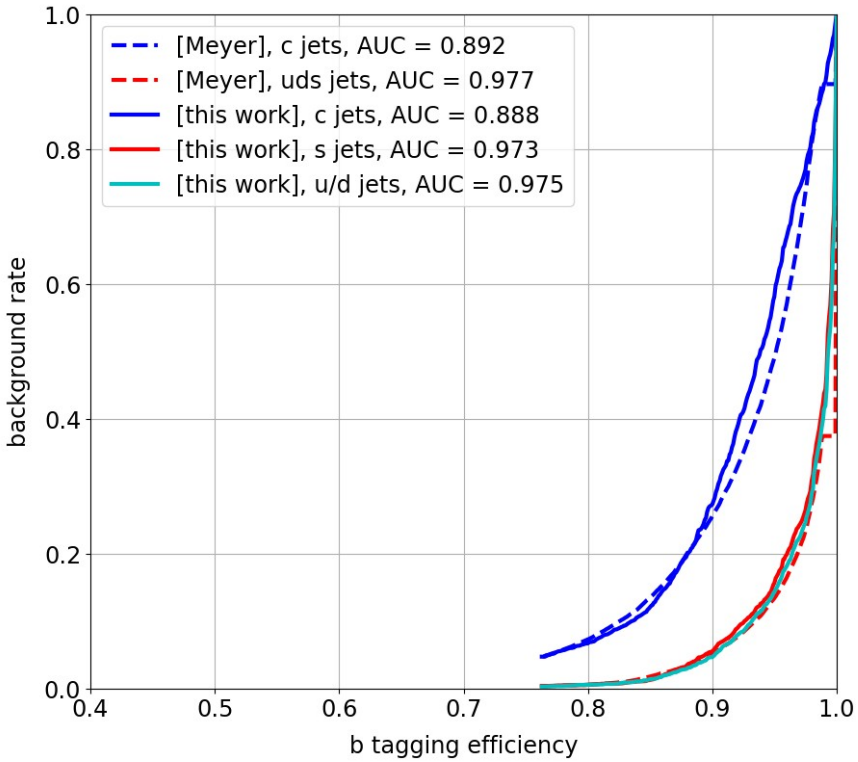
impact parameters &significances

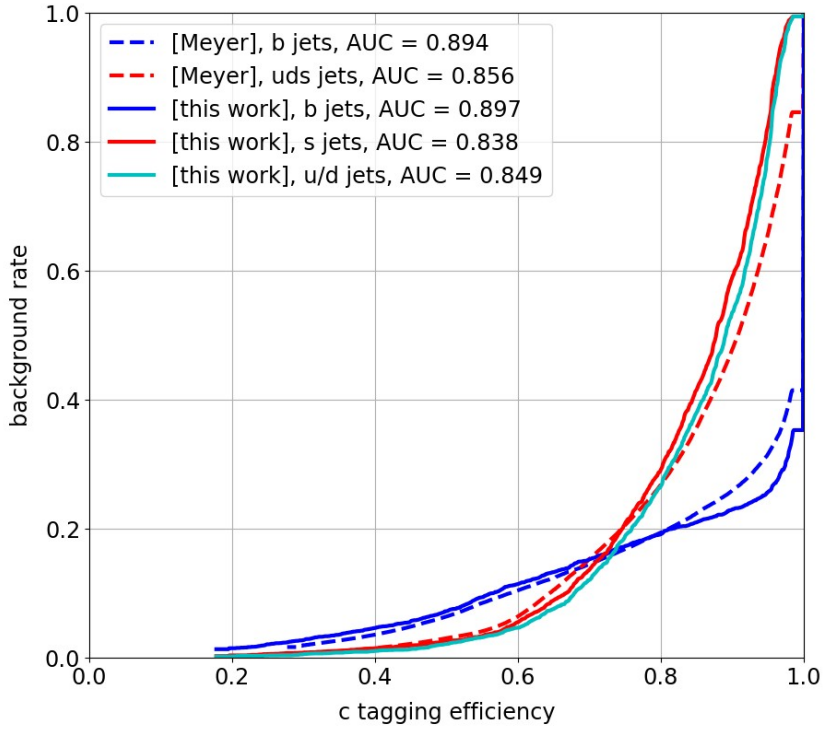
$\cos(\text{flight direction}_{SV}, \vec{p}_{SV})$

14 input features

2 SVs & all jet constituents considered, no ordering of inputs
output classes: b, c, light
→ b, c, s, u/d

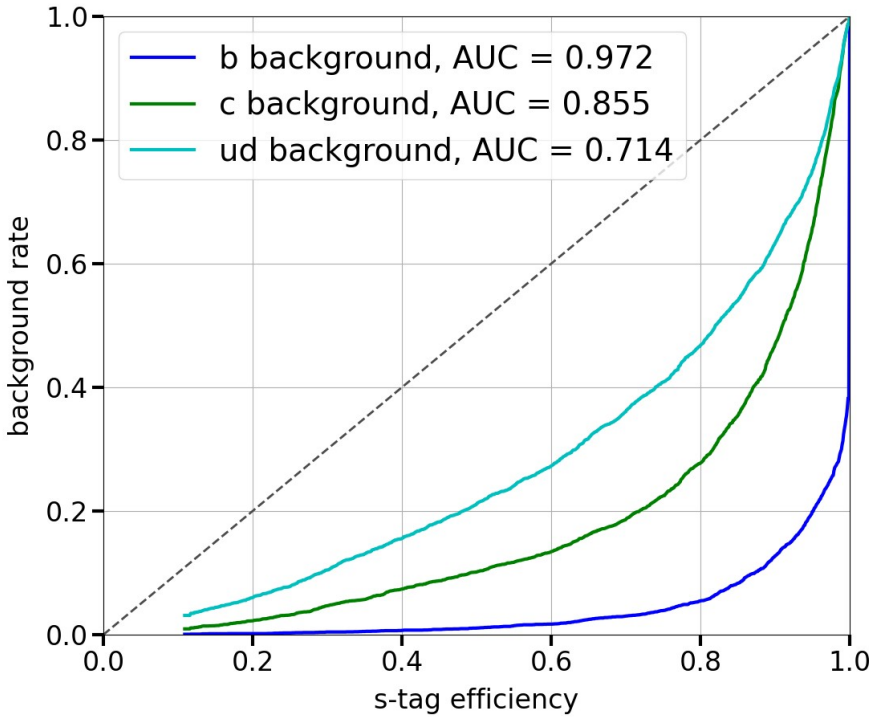
Comparison with ‘best of’ training by M. Meyer

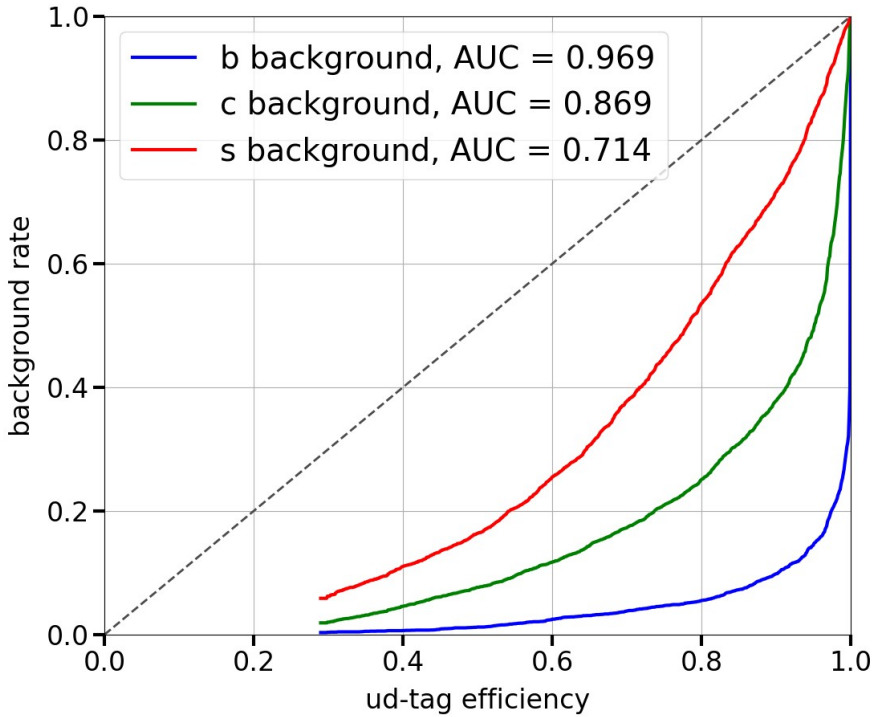




very similar performance, overall slightly worse → space for CNN parameter improvements

ROC Curves of strange and u/d tagging

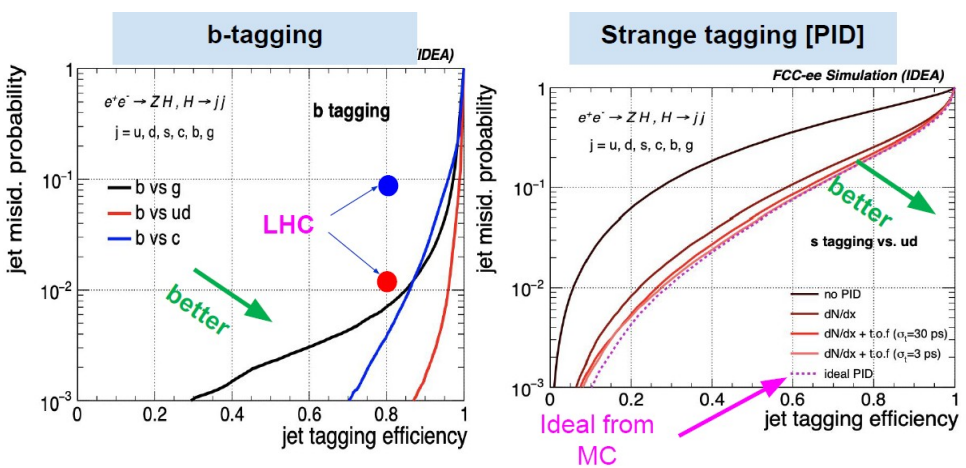




Study with FCC-ee

→ D. Marzocca, M.Szewc, M.Tammaro: https://arxiv.org/abs/2405.08880

- Assessment of prospects with given systematics, starting from quarks from the W decays at the parton level, using 3×10^8 Ws at the W threshold
- Background: only 2q (+2j) considered
- Showing measurement estimates in dependence of parton-to-flavour-tag systematics
- Focus on V_{cb} and V_{cs}



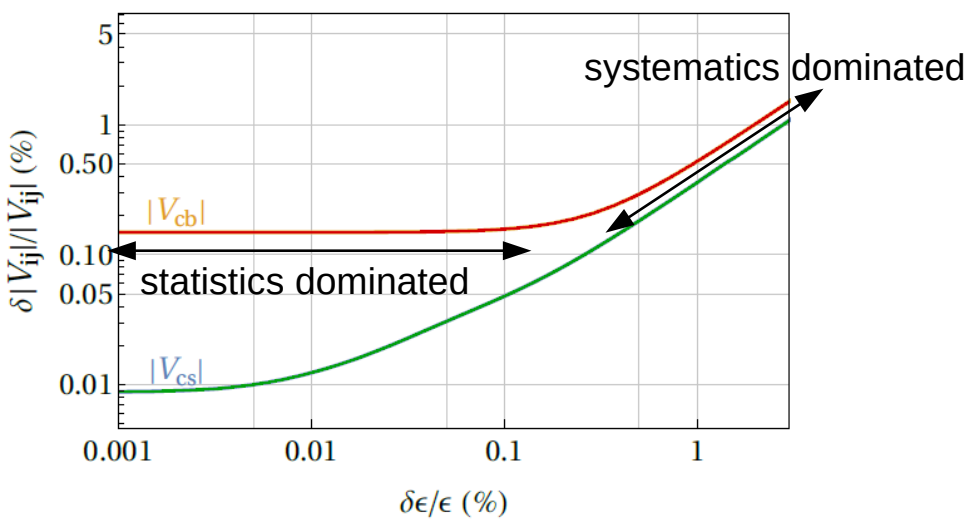
EPJ C 82 646 (2022)

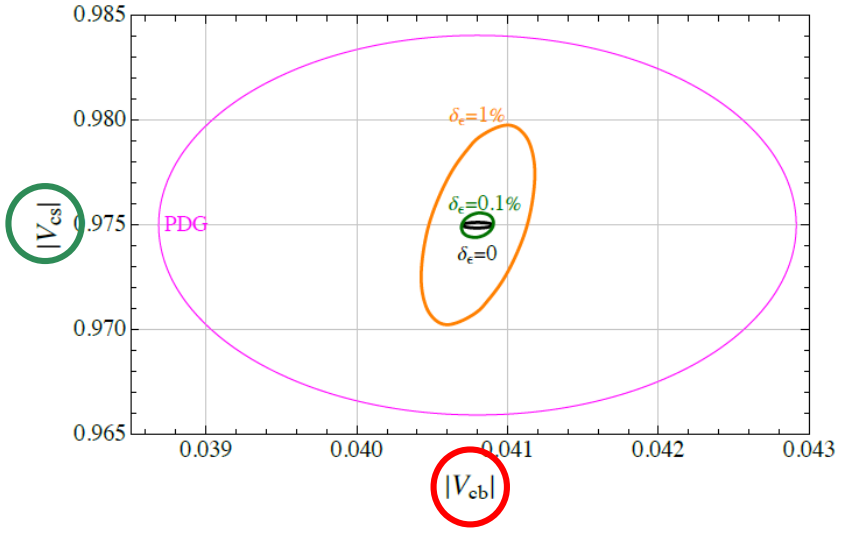
ParticleNet (IDEA) flavour tag working points used:

	b	s	c	u	d	g
ϵ_β^b	0.8	0.0001	0.003	0.0005	0.0005	0.007
ϵ_β^c	0.02	0.008	0.8	0.01	0.01	0.01
ϵ_β^s	0.01	0.9	0.1	0.3	0.3	0.2

Study with FCC-ee

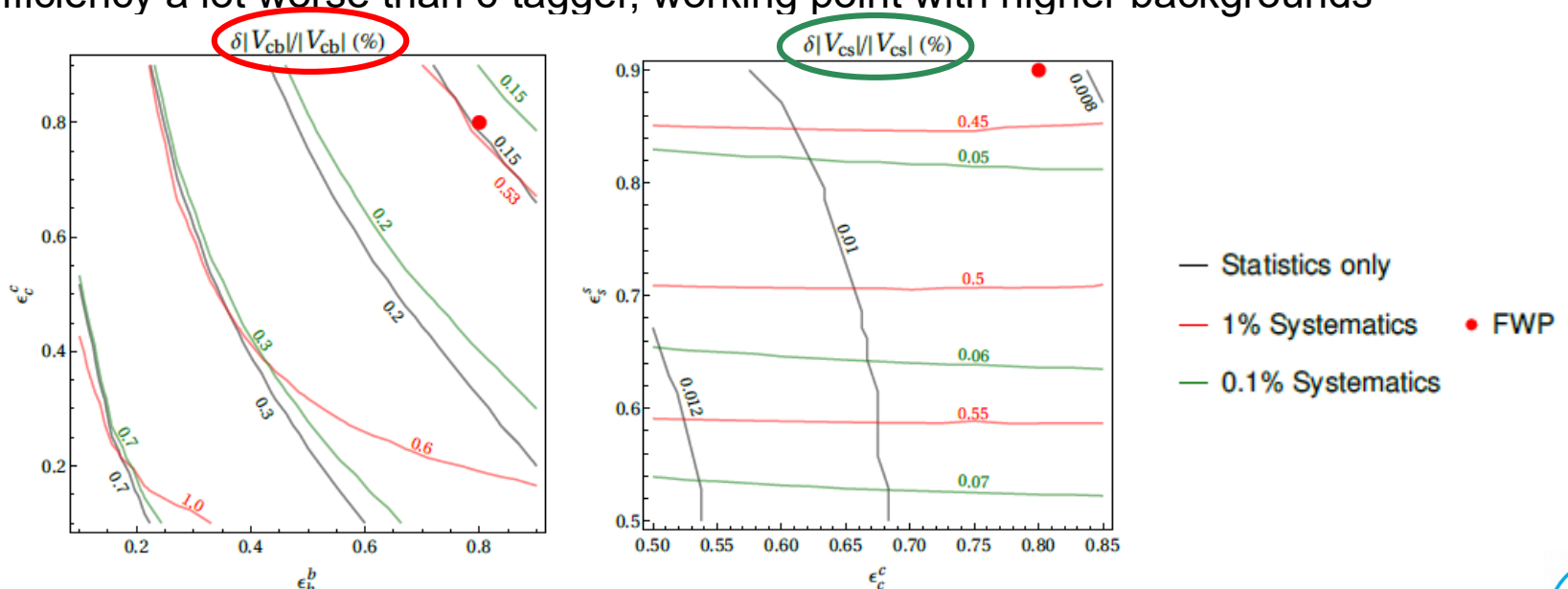
- Achievable uncertainties on V_{cb} and V_{cs}, depending on systematics uncertainties
- V_{cs} would profit from systematics below 0.01%
- V_{cb} stronger limited through statistics, flat below 0.1% systematics





Study with FCC-ee

- Systematic impact assessment:
- For V_{cb}, both c- and b-tagger uncertainties are of somparable impact
  - fewer b-jets than c-jets, but b-tagger has higher purity working point than c-tagger
- For V_{cs}, the uncertainty is dominated by the contribution from the s-tagger
  - efficiency a lot worse than c-tagger, working point with higher backgrounds



Study with CEPC

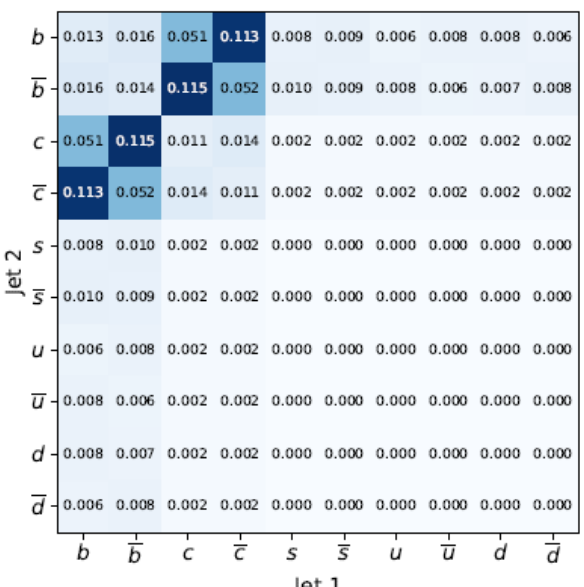
→ H. Liang, L. Li, Y. Zhu, X. Shen, M. Ruan: https://arxiv.org/abs/2406.01675

- Approach: full-sim with CEPC-baseline detector (ILD-like) at 240 GeV
- Focus on V_{cb} in semileptonic channel WW → lvcb
- Extrapolation to running scenarios for various future HTE factories
- Uncertainty assessment: theoretical uncertainties ~ 0.1%,
  flavour taggers dominating at ~ 2% → need for excellent calibration!
- Backgrounds: WW(other), 2f, 4f, Higgs
  → one conclusion: 2f is least important background

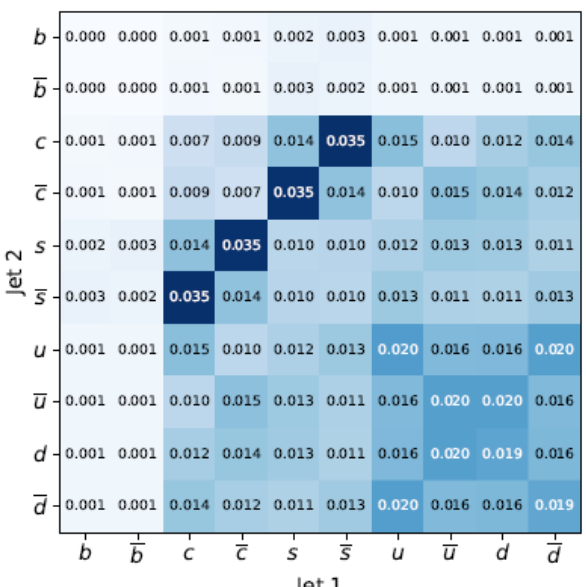
Flavour Tagger: ParticleNet (CEPC)

- 5 quarks + 5 anti-quarks → 10x10 confusion matrix for 2 tagged jets
- Use jet scores in BDT to identify cb-decays

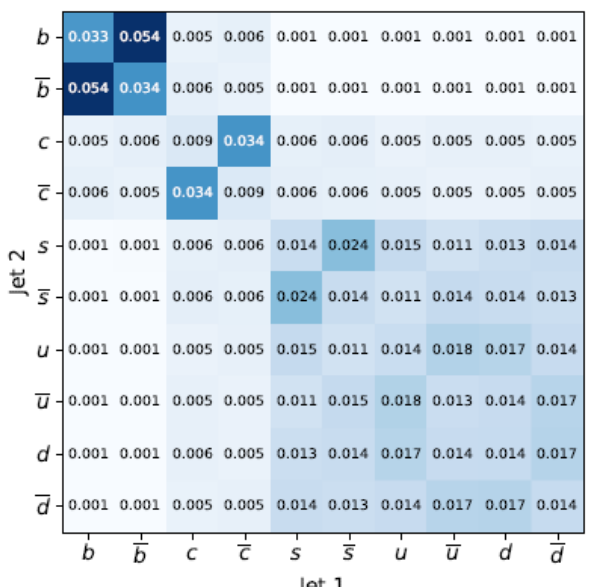
signal: W → μνcb



bkg: other W decays



bkg: other

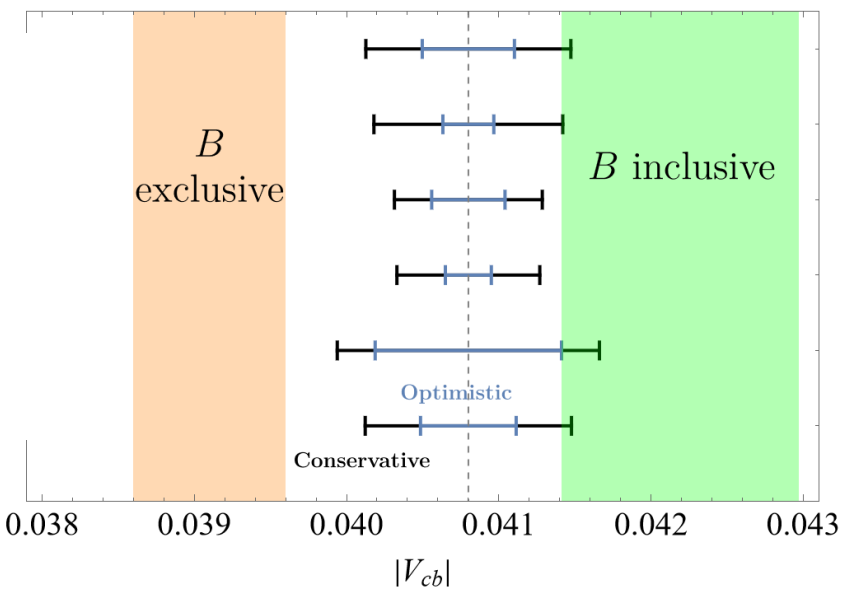


Study with CEPC

- Results, depending on running scenarios for various future HTE factories
- Combined statistical uncertainty on V_{cb} with sl (e, μ) channels;
  plot includes optimistic (0.2%) and conservative (1.5%) scenario on systematics

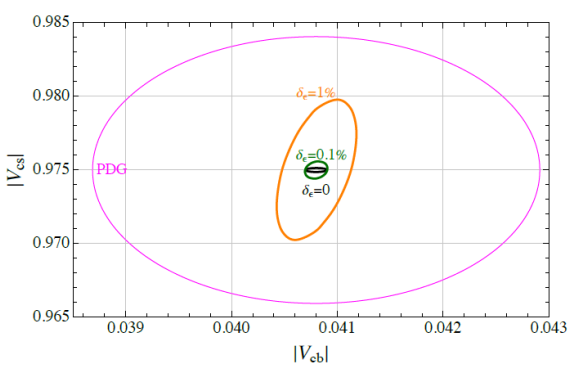
plot: Lingfeng Li

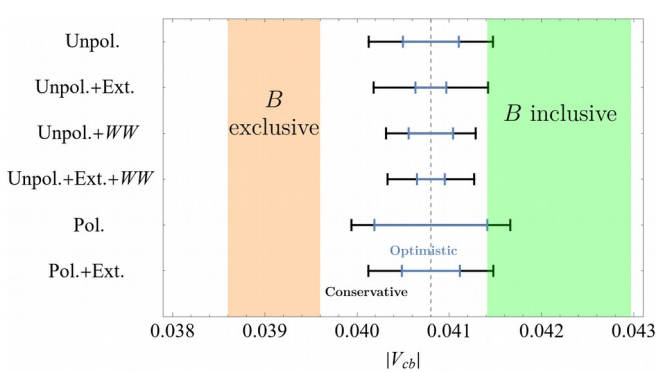
Unpolarized, Baseline (5 ab^{-1})	0.72%
Unpolarized, Extended (20 ab^{-1})	0.36%
Unpolarized, Baseline + WW	0.58%
Unpolarized, Extended + WW	0.34%
Polarized, Baseline (0.5 ab^{-1})	1.5%
Polarized, Extended (2 ab^{-1})	0.75%

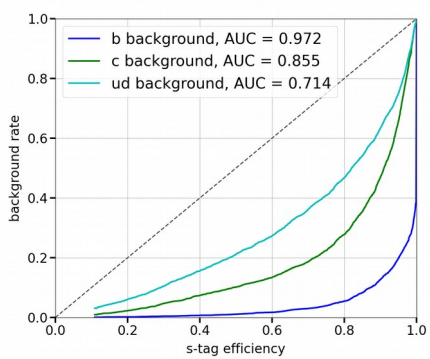


Outlook & Conclusions

- CKM matrix elements great opportunity for e+e- precision physics
- Focus on V_{cs} and V_{cb}, where HL-LHC and Belle II are limited already/soon, and standing tension in V_{cb} at 3 σ
- Studies ongoing, first papers are out – prospects of 1 order of magnitude or more in enhanced precision, resolve tension
- Discussions ongoing how to continue, expand and refine results
- Critical: systematics, in particular of the flavour taggers
- Also: great ongoing progress in theory, in particular LQCD!







CEPC study: cross check jet tagging in Z vs. H

plots from M. Ruan