Flavour tagging in W decays @FCCee

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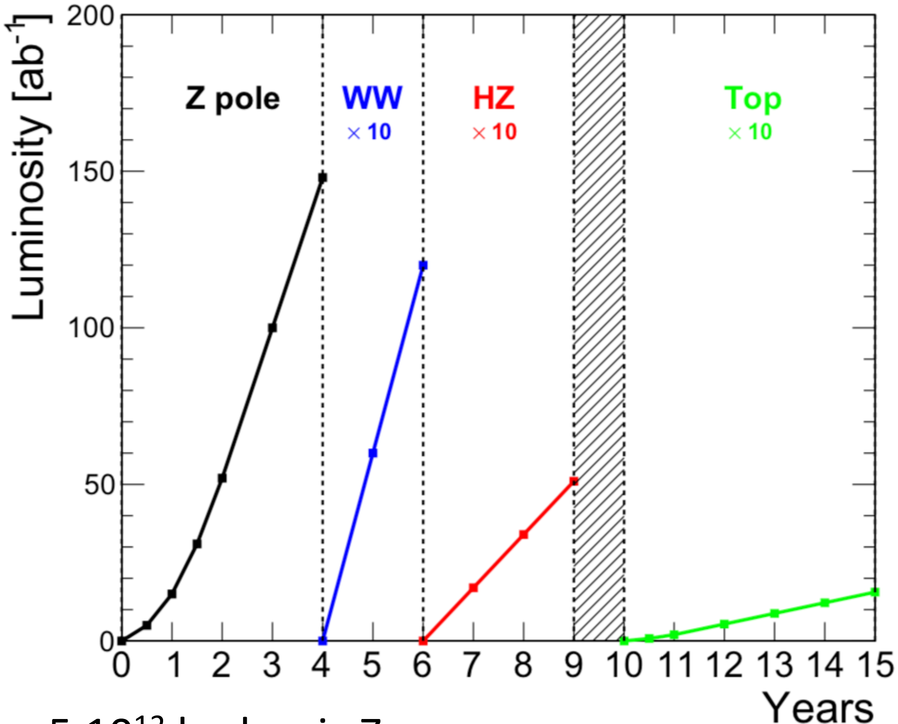
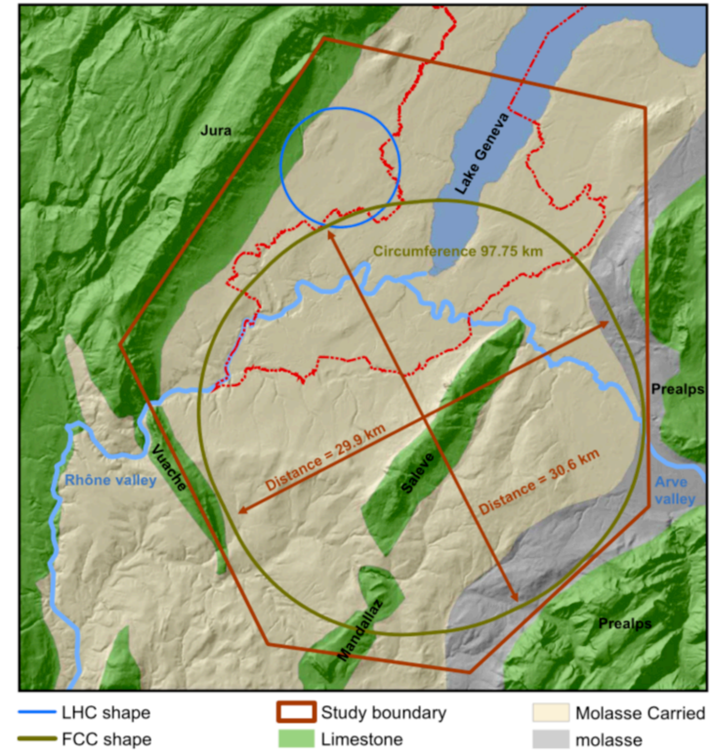
Snowmass2021 CKM Matrix

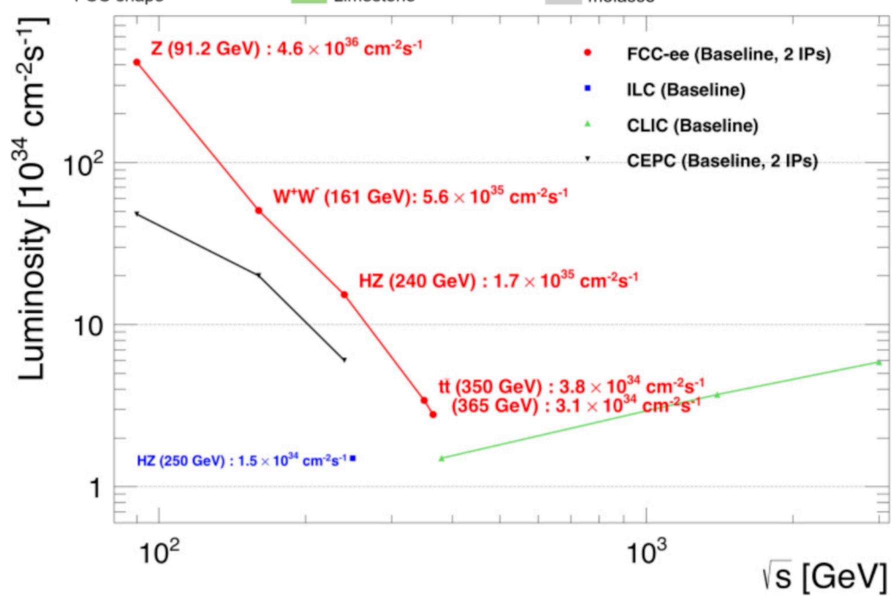
January 12th 2021

The FCC-ee



$5 \cdot 10^{12}$ hadronic Z
(10^5 LEP1)





W-pairs at FCCee : the OkuW

√s=162 GeV : L~3 10^{35} collect 12/ab
45-60 10^6 WW decays

$3 \cdot 10^5$ (LEP 161)

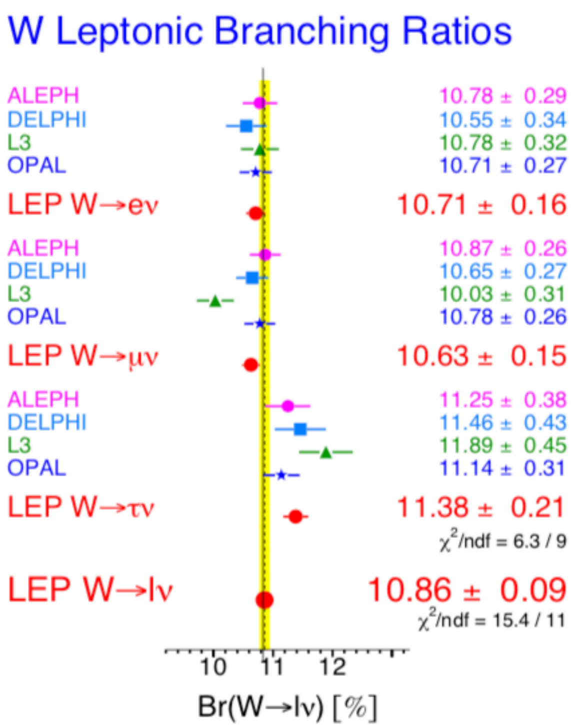
√s=240 GeV : L~0.7 10^{35} collect 5/ab
80 10^6 WW decays

$2 \cdot 10^3$ (LEP 200)

√s=365 GeV : L~ 10^{34} collect 1.65/ab
20 10^6 WW decays

In total → **300 10^6 W decays**

W decay BR



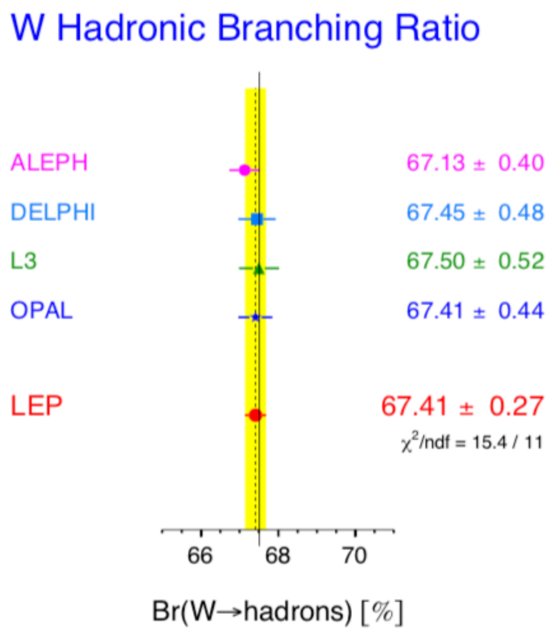
Lept universality test at 2% level

tau BR ~2.6 σ larger than e/mu

➔ *FCCee @ 3-4 10^{-4} level*

Table 3.1: Relative precision on the determination of the W decay branching ratios. Final combined results with LEP2 data are compared to the projected precision obtainable with FCC-ee.

Decay mode relative precision	$B(W \to e\nu)$	$B(W \to \mu\nu)$	$B(W \to \tau\nu)$	$B(W \to qq)$
LEP2	1.5%	1.4%	1.8%	0.4%
FCC-ee	$3{\cdot}10^{-4}$	$3{\cdot}10^{-4}$	$4{\cdot}10^{-4}$	$1{\cdot}10^{-4}$



Scaling major syst uncertainties with data luminosity (as stat)

q/ l universality at 0.5%

➔ *FCCee @ 10^{-4} level*

For lept BR will need excellent control of **lepton id** and cross contaminations in signal channels (τ➔e,μ and e,μ channels)

Less stringent requirements for syst uncertainty control for hadr BR

Hadronic W BR

$$R_W = \frac{B_q}{1-B_q} = \left(1 + \frac{\alpha_S(m_W^2)}{\pi}\right) \sum_{i=u,c;j=d,s,b} |V_{ij}|^2.$$

$\rightarrow$ $\Delta\alpha_S$ (FCCee) $\approx(9\,\pi/2)\Delta B_q \approx\ 10^{-3}$

$$\left(1 + \frac{\alpha_s(M_W)}{\pi} + 1.409\frac{\alpha_s^2(M_W)}{\pi^2} - 12.77\frac{\alpha_s^3(M_W)}{\pi^3}\right)$$

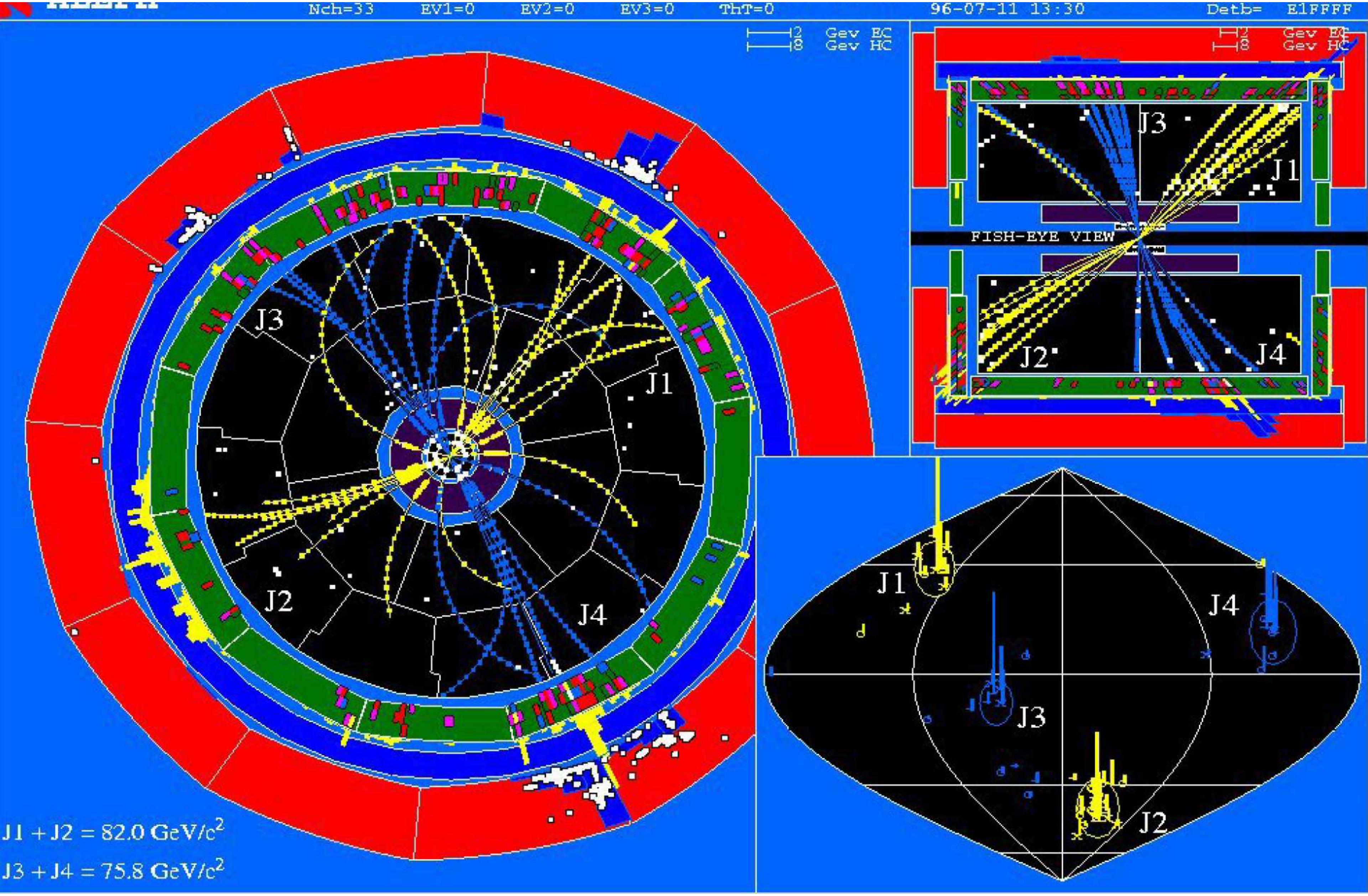
If the CKM unitarity is not assumed in the sum, and α_S $(m^2{}_W)$ is taken form other independent precision determinations, B_q and R_W measurements can be used in turn to provide a stringent test of CKM unitarity for the five lightest quarks

$$S_W = |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2$$

From LEP : $|V_{cs}| = 0.969 \pm 0.013$

Δ$|V_{cs}|$ (FCCee) $\rightarrow$ 2 10^{-4}

Flavor tagging can also allow to measure coupling to c & b-quarks (Vcs, Vcb,..) directly !



Nch=33
EV1=0
EV2=0
EV3=0
ThT=0
96-07-11 13:30
Detb= E1FFFF
2 Gev EC
8 Gev HC
FISH-EYE VIEW
J1
J2
J3
J4
J1 + J2 = 82.0 GeV/c2
J3 + J4 = 75.8 GeV/c2

Hadronic W flavor tagging : cX cs

Charm (and strangeness) tagging at LEP2

DELPHI (161+172 GeV ~150 WW) *Phys. Lett. B* 439 (1998) 209

$$r^{(cs)} = \frac{\Gamma(W^+ \to c\bar{s})}{\Gamma(W^+ \to hadrons)} = 0.46^{+0.18}_{-0.14}(stat) \pm 0.07(syst) \qquad |V_{cs}| = 0.94^{+0.32}_{-0.26}(stat) \pm 0.13(syst)$$

Δ$|V_{cs}|$ (stat) FCCee → 3 10^{-4}

ALEPH 172-183GeV (~1K WW) *Phys. Lett. B* 465 (1999) 349

$$\mathrm{R_c^W} = \frac{|\mathrm{V_{cd}}|^2 + |\mathrm{V_{cs}}|^2 + |\mathrm{V_{cb}}|^2}{|\mathrm{V_{ud}}|^2 + |\mathrm{V_{us}}|^2 + |\mathrm{V_{ub}}|^2 + |\mathrm{V_{cd}}|^2 + |\mathrm{V_{cs}}|^2 + |\mathrm{V_{cb}}|^2}.$$

$$\mathrm{R_c^W} = 0.515 \pm 0.053. \qquad |\mathrm{V_{cs}}| = 1.00 \pm 0.11.$$

Δ$R_c{}^W$ (stat) FCCee → 1.5 10^{-4} **Δ** $|V_{cs}|$ (stat) FCCee → 3 10^{-4}

Hadronic W flavor tagging : cX cs

OPAL 183-189 GeV (4K WW) *Phys. Lett. B* 490 (2000) 71-86

$$R_c^W = 0.481 \pm 0.042\,(\text{stat.}) \pm 0.032\,(\text{syst.})$$

$$|V_{cs}| = 0.93 \pm 0.08\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \pm 0.004\ (\text{CKM}),$$

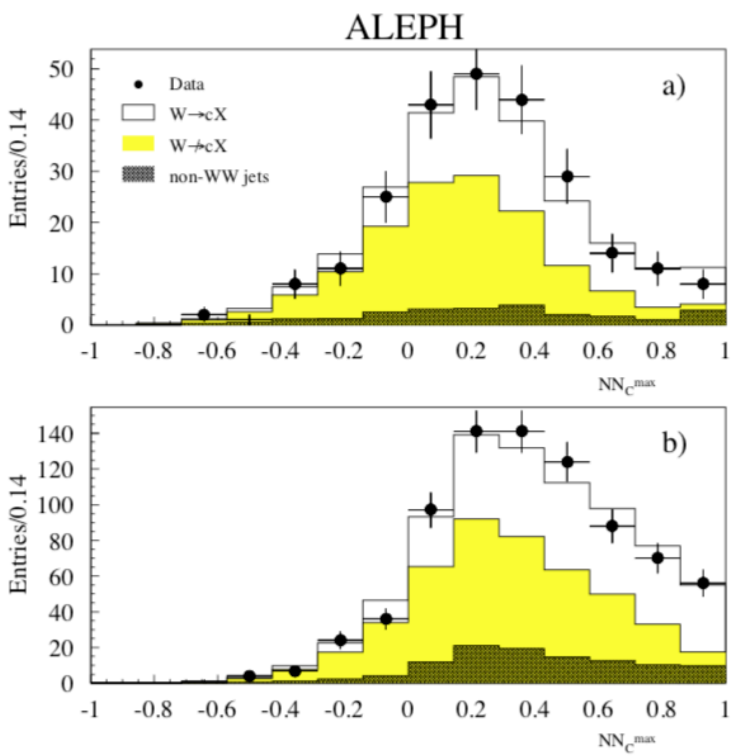
ΔR_c^W (stat) FCCee → 2 10^{-4} **Δ** $|V_{cs}|$ (stat) FCCee → 4 10^{-4}

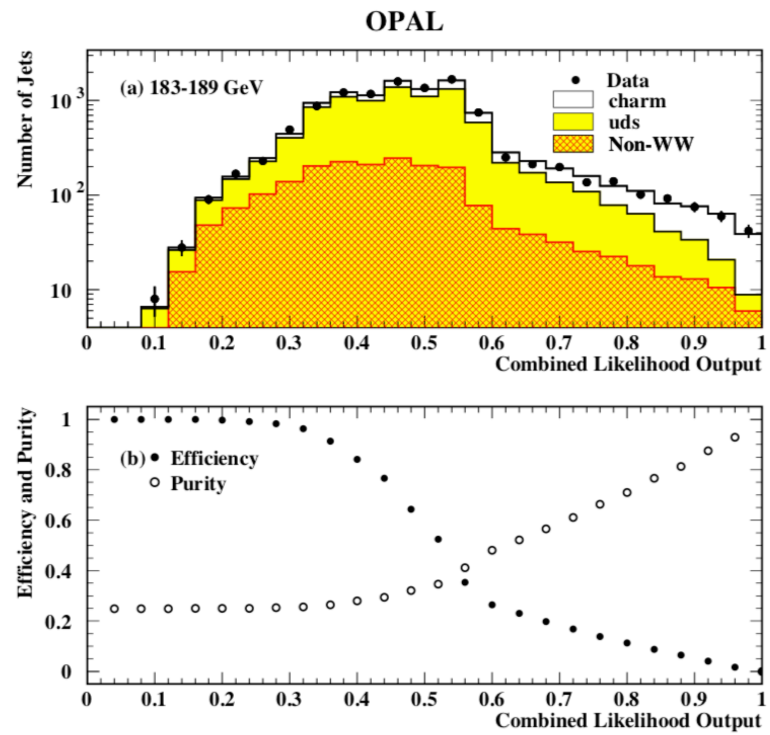
Table 2: Systematic errors on R_c^W.

Source	$\Delta R_c^W\ (10^{-2})$
Background normalization	0.2
Hadronization	2.9
Color reconnection	0.3
Calorimeter calibration	0.9
Tracking error	0.3
Impact parameter resolution	0.4
Mass of the W boson	0.4
Jet algorithm	0.4
Charm production	0.1
Charm fragmentation	0.3
Charm decay properties	0.9
Total Error	3.3

Source of Systematic Error	ΔR_c^W 183 GeV	189 GeV
Hadronisation Model	0.011	0.012
Centre–of–mass Energy	0.007	0.005
Mass of the W Boson	0.004	0.003
Charm Fragmentation Function	0.007	0.007
Background Cross-Section	0.006	0.005
Background Composition	0.010	0.009
Charm Hadron Fractions	0.006	0.007
Light Quark Composition	0.007	0.005
Vertex Reconstruction	0.016	0.017
Charm Hadron Lifetimes	0.003	0.002
Charm Decay Multiplicity	0.010	0.010
Lepton Identification	0.012	0.014
Lepton Energy Spectrum	0.003	0.003
Branching ratio $Br(c \to \ell)$	0.006	0.006
Total systematic error	0.032	0.032
Statistical error	0.090	0.047
Value of R_c^W	0.493	0.478

Hadronic W flavor tagging : cX cs



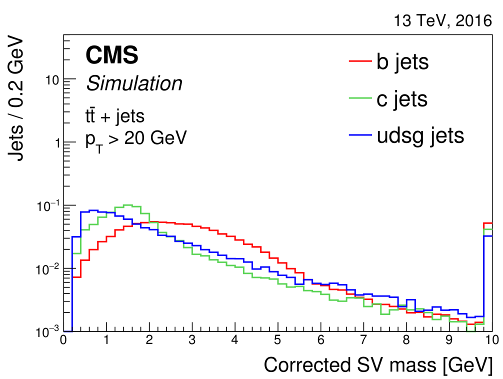


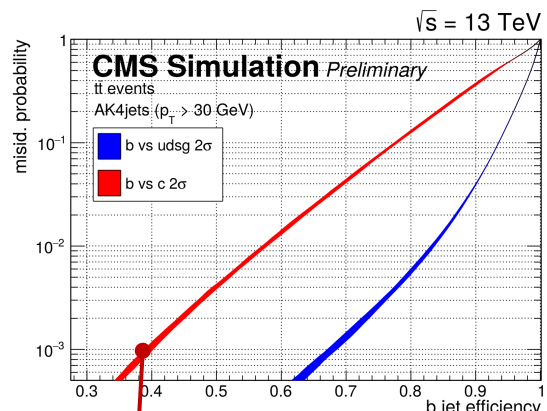
binned likelihood fits to the shape of the output distributions

Including Z→qq Control Regions

Hadronic W flavor tagging : cb Xb

$|V_{cb}| = (41.0 \pm 1.4) \times 10^{-3}$ ➔ BR = 5.6 10^{-4} (1.7 10^5 W→cb @FCCee)
$|V_{ub}| = (3.82 \pm 0.24) \times 10^{-3}$ ➔ BR = 4.9 10^{-6} (1.5 10^3 W→ub @FCCee)

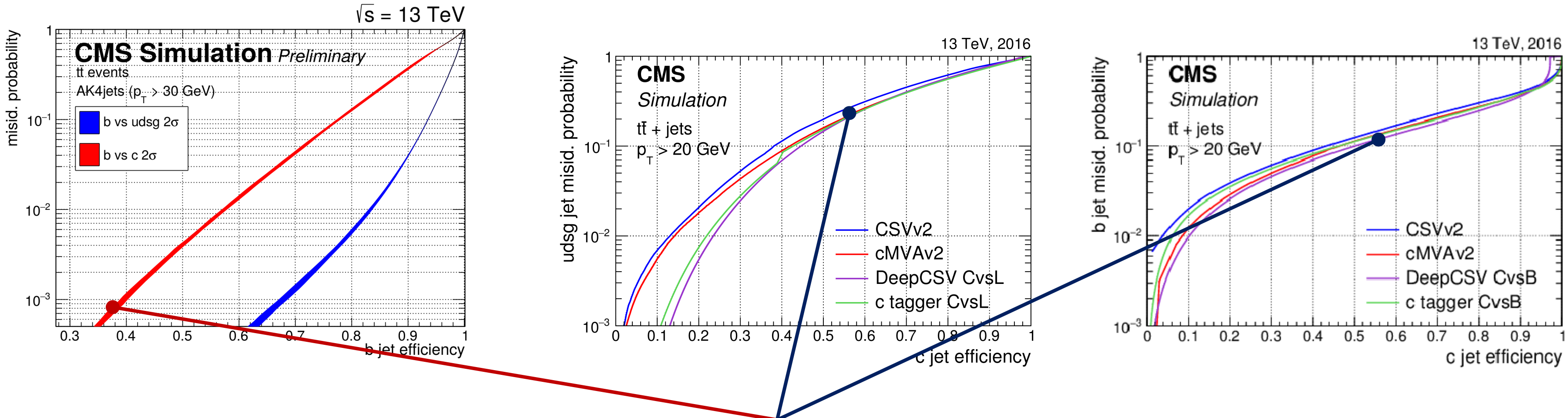




With $\boldsymbol{\varepsilon_b}$**=40% and** $\boldsymbol{\varepsilon_c}$**=$10^{-3}$** @FCCee: N(W→cs)≈100k N(W→bX)≈75k
Δ$R_b^{\,W}$ (stat)(FCCee) → 0.6% (rel) & **Δ** $|V_{cb}|$ (stat) (FCCee) → 0.3% (rel)

Hadronic W flavor tagging : cb Xb

$|V_{cb}| = (41.0 \pm 1.4) \times 10^{-3}$ ➔ BR = 5.6 10^{-4} (1.7 10^5 W→cb @FCCee)
$|V_{ub}| = (3.82 \pm 0.24) \times 10^{-3}$ ➔ BR = 4.9 10^{-6} (1.5 10^3 W→ub @FCCee)



First tag $\boldsymbol{\varepsilon_b}$**=40% and** $\boldsymbol{\varepsilon_c}$**=**$\mathbf{10^{-3}}$ $\boldsymbol{\varepsilon_{uds}}$**=**$\mathbf{10^{-5}}$ Second tag with $\boldsymbol{\varepsilon_c}$**=60% and** $\boldsymbol{\varepsilon_b}$**=0.1** $\boldsymbol{\varepsilon_{uds}}$**=0.2**
@FCCee: N(W→cs,cd)≈20k N(W→cb)≈50k ➔ direct **Δ** $|V_{cb}|$ (stat) (FCCee) → 0.2%(rel)

Similar conclusions on s19 here (**M.H.Schune FCC workshop Jan 2020**)
https://indico.cern.ch/event/838435/contributions/3635812/attachments/1971221/3279502/FCCee_17Jan2020_v2.pdf

Inverting second tag could also obtain **Δ** $|V_{ub}|$ (stat) (FCCee) → ~3-5%(rel)
(less interesting : ~1% from LHCb/Belle2/ FCCee Z)

From Stephane Monteil

Z pole

Particle specie at FCC-ee	B^0	B^+	B_s^0	Λ_b	B_c^+	$c\bar{c}$	$\tau^-\tau^+$
Yield ($\times 10^9$) [5.10^{12} Z]	310	310	75	65	$1.5^\dagger$	600	180

$B^+ \to \tau\nu$

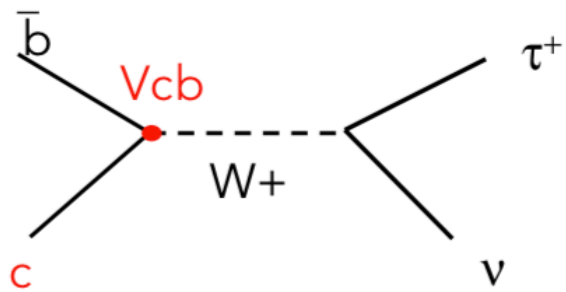
Observable / Experiments	Current W/A	Belle II (50 /ab)	LHCb-U1 (23/fb)	FCC-ee
CKM inputs				
γ (uncert., rad)	$1.296^{+0.087}_{-0.101}$	1.136 ± 0.026	1.136 ± 0.025	1.136 ± 0.004
$\lvert V_{ub}\rvert$ (precision)	5.9%	2.5%	6%	1%
Mixing-related inputs				
$\sin(2\beta)$	0.691 ± 0.017	0.691 ± 0.008	0.691 ± 0.009	0.691 ± 0.005
ϕ_s (uncert. rad 10^{-2})	-1.5 ± 3.5	n/a	-3.65 ± 0.05	-3.65 ± 0.01
Δm_d (ps^{-1})	0.5065 ± 0.0020	same	same	same
Δm_s (ps^{-1})	17.757 ± 0.021	same	same	same
$a_{\rm fs}^d$ (10^{-4}, precision)	23 ± 26	-7 ± 15	-7 ± 15	-7 ± 2
$a_{\rm fs}^s$ (10^{-4}, precision)	-48 ± 48	n/a	0.3 ± 15	0.3 ± 2

See recent review *New physics in B meson mixing: future sensitivity and limitations* arXiv:2006.04824 Phys. Rev. D 102, 056023 (2020)

« identify the measurement of |Vcb| as one of the key ingredients in which progress beyond current expectations is necessary to maximize future sensitivity .»

From M.H.Schune FCC workshop Jan 2020

V_{cb} from $B_c \to \tau\nu$



$$\Gamma_{SM}(P^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi}|V_{Qq}|^2 f_P^2 M_P m_\ell^2 (1 - \frac{m_\ell^2}{M_P^2})^2$$

with NP : $$\Gamma_{H^\pm}(P^+ \to \ell^+\nu_\ell) = \Gamma_{SM}(P^+ \to \ell^+\nu_\ell) \times \left(1 - \frac{\tan^2\beta}{M_H^2} M_P^2\right)^2$$

Large missing energy
Use of the other hemisphere

About 20 10^6 $B_c \to \tau\nu$ with $\tau \to e/\mu\nu$ produced

1% precision should be achievable

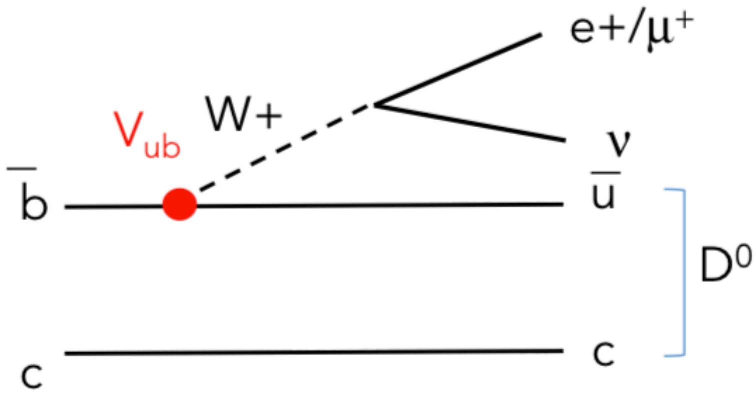
$$\frac{N_{B_c}}{N_{B_u}} = \frac{f(b \to B_c)}{f(b \to B_u)} \left|\frac{V_{cb}}{V_{ub}}\right|^2 \left(\frac{f_{B_c}}{f_{B_u}}\right)^2 \frac{m_{B_c}}{m_{B_u}} \frac{\tau_{B_c}}{\tau_{B_u}} \frac{(1 - \frac{m_\tau^2}{m_{B_c}^2})^2}{(1 - \frac{m_\tau^2}{m_{B_u}^2})^2} \sim 1$$

	B_u	B_c
Mass	~5280 MeV	~6275 MeV
Lifetime	~1.5 ps	~0.5 ps

⇒ discrimination should be possible

Analysis of $B_c \to \tau\nu_\tau$ at CEPC
arXiv:2007.08234

From M.H.Schune FCC workshop Jan 2020



But $B_u \to \bar{D}^0 \ell\nu$ and DCS D^0 decay

$$\frac{BR(B_c \to D^0 \ell^+ \nu)}{BR(B_u \to \overline{D^0} \ell^+ \nu)} \sim .0092$$

Number kindly provided by Sebastien Descotes-Genon)

$$\frac{\mathrm{N(B_c)}}{\mathrm{N(B_u)}} = \frac{1.5}{600} \frac{3.9\ 10^{-2}}{1.5\ 10^{-4}} \times .0092 \sim .006$$

	B_u	B_c
Mass	~5280 MeV	~6275 MeV
Lifetime	~1.5 ps	~0.5 ps

⇒ some discrimination.
Studies to be performed (need a factor ~ 200)

Conclusions

- 200M Hadronic W decays at FCCee will offer a great opportunity for **precise direct CKM measurements**
  - B_q => test of unitarity at 10^{-4} level for $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2$
  - Direct measurements of R_c and $|V_{cs}|$ with charm- (and s-) tagging, also at ~ 10^{-4} level stat : what will be syst limitations ?
  - Direct measurements of R_b and $|V_{cb}|$ with b- (and charm-) tagging at few 10^{-3} level stat . Maybe also $|V_{ub}|$ at 5% (less interesting)
  - Looking forward to more detailed studies for a better understanding of these measurements

arXiv:2006.04824

	Central values	Uncertainties: Current [18]	Phase I	Phase II	Phase III	Reference Phases I–III
$\|V_{ud}\|$	0.97437	± 0.00021	id	id	id	[18]
$\|V_{us}\| f_+^{K\to\pi}(0)$	0.2177	± 0.0004	id	id	id	[18]
$\|V_{cd}\|$	0.2248	± 0.0043	± 0.003	id	id	[19, 20]
$\|V_{cs}\|$	0.9735	± 0.0094	id	id	id	[18–20]
Δm_d [ps^{-1}]	0.5065	± 0.0019	id	id	id	[17]
Δm_s [ps^{-1}]	17.757	± 0.021	id	id	id	[17]
$\|V_{cb}\|_{\rm SL} \times 10^3$	42.26	± 0.58	± 0.60	± 0.44	id	[21]
$\|V_{cb}\|_{W\to cb} \times 10^3$		—	—	—	± 0.17	[22–24]
$\|V_{ub}\|_{\rm SL} \times 10^3$	3.56	± 0.22	± 0.042	± 0.032	id	[21]
$\|V_{ub}/V_{cb}\|$ (from Λ_b)	0.0842	± 0.0050	± 0.0025	± 0.0008	id	[25]
$\mathcal{B}(B\to\tau\nu)\times 10^4$	0.83	± 0.24	± 0.04	± 0.02	± 0.009	[21, 22]
$\mathcal{B}(B\to\mu\nu)\times 10^6$	0.37	—	± 0.03	± 0.02	id	[21]
$\sin 2\beta$	0.680	± 0.017	± 0.005	± 0.002	± 0.0008	[21, 22, 25]
α [°] (mod 180°)	91.9	± 4.4	± 0.6	id	id	[21]
γ [°] (mod 180°)	66.7	± 5.6	± 1	± 0.25	± 0.20	[21, 22, 25]
β_s [rad]	-0.035	± 0.021	± 0.014	± 0.004	± 0.002	[22, 25]
$A_{\rm SL}^d \times 10^4$	-6	± 19	± 5	± 2	± 0.25	[14, 17, 22, 26]
$A_{\rm SL}^s \times 10^5$	3	± 300	± 70	± 30	± 2.5	[14, 17, 22, 26]
$\bar m_t$ [GeV]	165.30	± 0.32	id	id	± 0.020	[18, 22]
$\alpha_s(m_Z)$	0.1185	± 0.0011	id	id	± 0.00003	[18, 22]
$f_+^{K\to\pi}(0)$	0.9681	± 0.0026	± 0.0012	id	id	[25]
f_K [GeV]	0.1552	± 0.0006	± 0.0005	id	id	[25]
f_{B_s} [GeV]	0.2315	± 0.0020	± 0.0011	id	id	[25]
B_{B_s}	1.219	± 0.034	± 0.010	± 0.007	id	[25]
f_{B_s}/f_{B_d}	1.204	± 0.007	± 0.005	id	id	[25]
B_{B_s}/B_{B_d}	1.054	± 0.019	± 0.005	± 0.003	id	[25]
$\tilde B_{B_s}/\tilde B_{B_d}$	1.02	± 0.05	± 0.013	id	id	[25, 27, 28]
$\tilde B_{B_s}$	0.98	± 0.12	± 0.035	id	id	[25, 27, 28]
η_B	0.5522	± 0.0022	id	id	id	[29]

- Phase I: LHCb 50/fb, Belle II 50/ab (late 2020s);
- Phase II: LHCb 300/fb, Belle II 250/ab (late 2030s);
- Phase III: Phase II + FCC-ee (5×10^{12} Z decays).