Future e+e- electroweak measurements above the Z pole : W-pair threshold lineshape and W decay rates

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Precision for future e+e– colliders: targets and tools

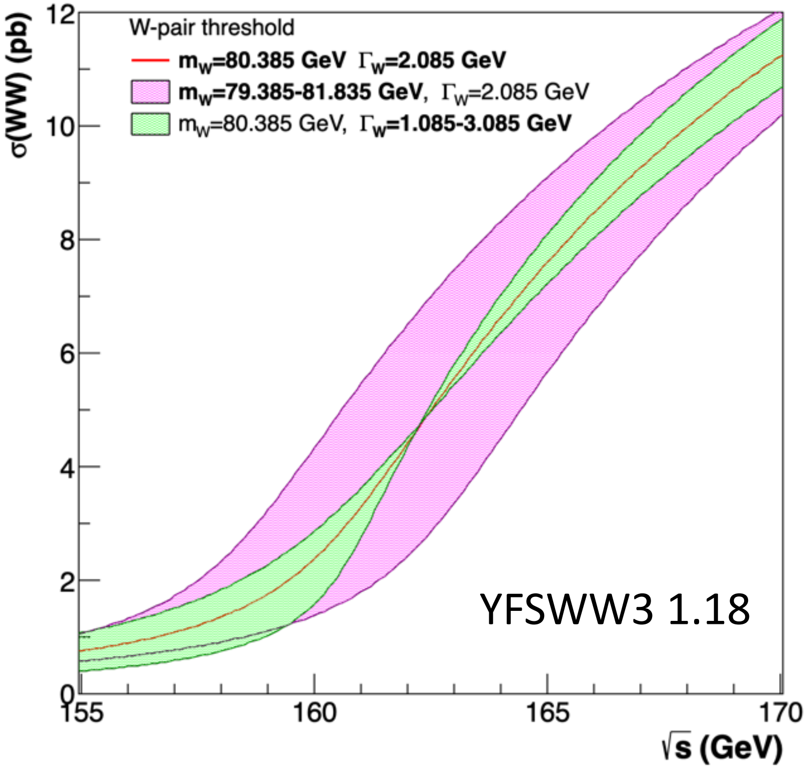
CERN June 10, 2022

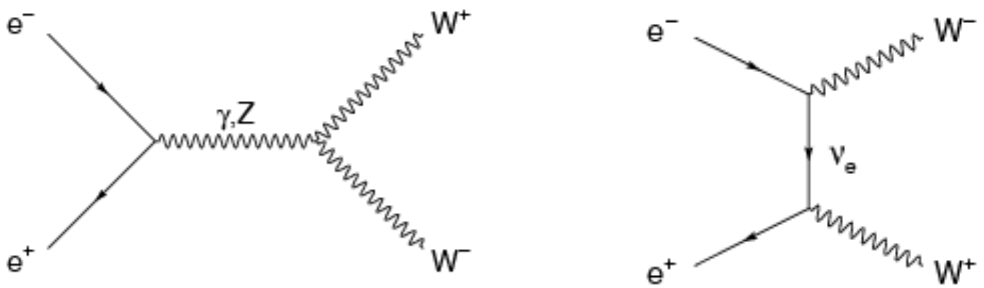
Outlook

- W-pair threshold production lineshape
  - single energy point (m_W)
  - two energy points (m_W, Γ_W), and more
- W decay branching fractions
  - leptonic and hadronic BRs (constraints on α_S and CKM unitarity)
  - direct CKM elements via flavor tagging (Rc, Vcs, Rb, Vub, Vcb)

- disclaimer : content is based on studies performed a while ago
- disclaimer : not a review of theory SotA / progress

The WW threshold lineshape and the W mass



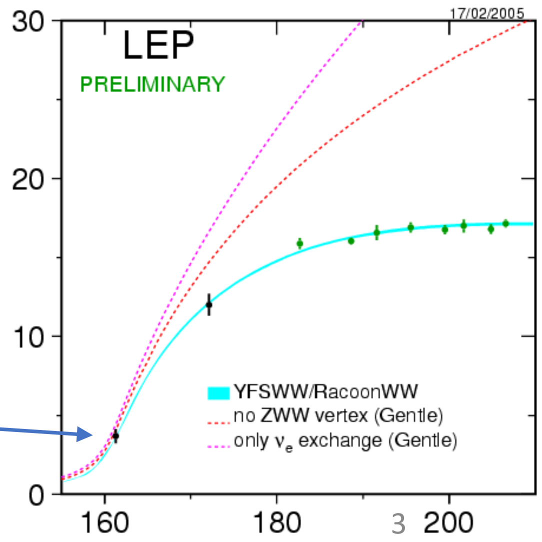


WW cross section rise $\beta = \sqrt{1 - 4m_W^2/s}$ driven by t-channel production

Extract the W mass inverting the m_W dependence

$$\sigma(m_W, E) \qquad\qquad m_W = \sigma^{-1}(E)$$

$$\Delta m_W = \left(\frac{d\sigma}{dm_W}\right)^{-1} \Delta\sigma$$



ALEPH [Phys.Lett.B 401 (1997) 347] with 10/pb $m_W = 80.14 \pm 0.34$ GeV

stat extrapolation to 10/ab $\Longrightarrow$ $\Delta m_W = 0.34$ MeV

The WW threshold : W mass uncertainties

$$\sigma = \left(\frac{N}{L} - \sigma_B\right)\frac{1}{\varepsilon}$$

$$\Delta m_W(stat) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \frac{\sqrt{\sigma}}{\sqrt{L}} \frac{1}{\sqrt{\varepsilon p}}$$

Statistical

$$\Delta\sigma_{WW} = \frac{\Delta\sigma_B}{\varepsilon}$$

$$\Delta m_W(B) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \left(\frac{\Delta\sigma_B}{\varepsilon} \oplus \Delta\sigma_{TH}\right)$$

Background and Theory

$$\Delta\sigma_{WW} = \sigma\left(\frac{\Delta\varepsilon}{\varepsilon} \oplus \frac{\Delta L}{L}\right)$$

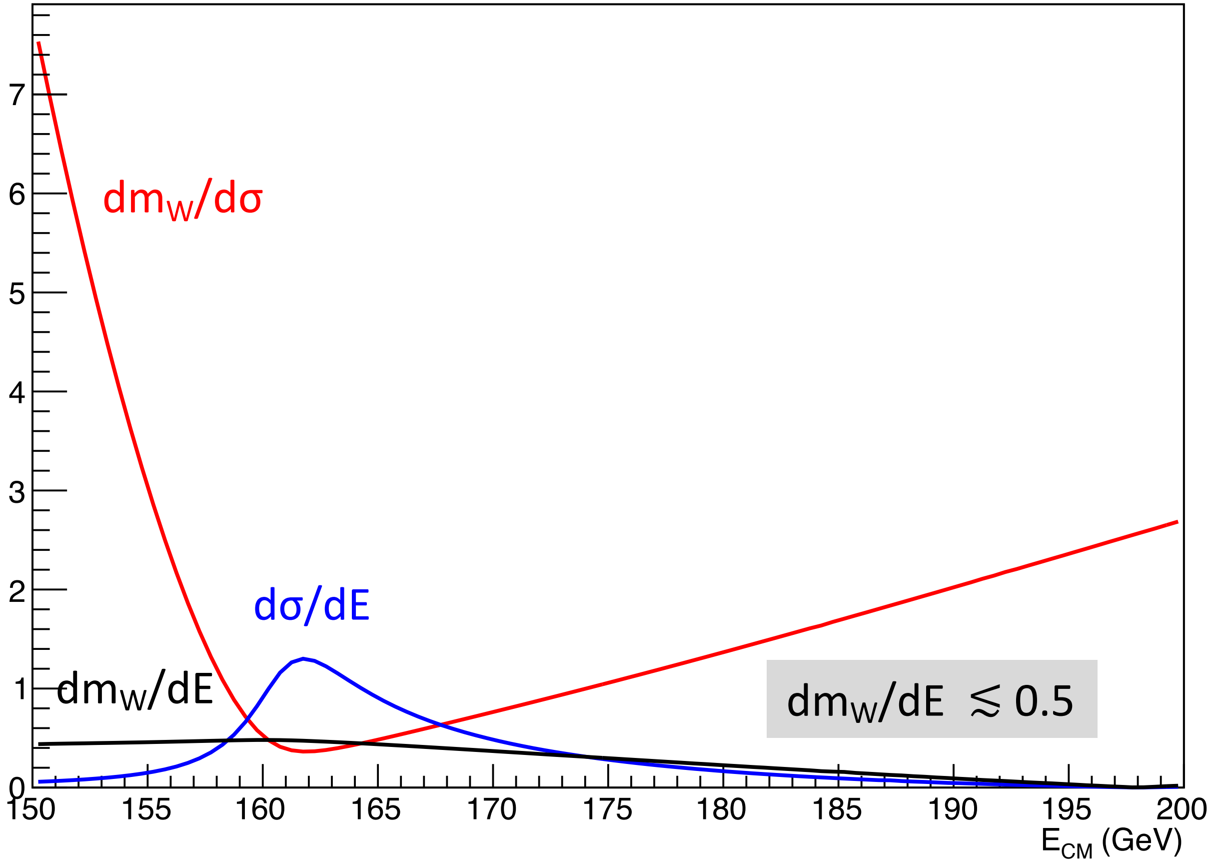
$$\Delta m_W(\varepsilon) = \sigma\left(\frac{d\sigma}{dm_W}\right)^{-1} \left(\frac{\Delta\varepsilon}{\varepsilon} + \frac{\Delta L}{L}\right)$$

Acceptance and Luminosity

$$\Delta m_W(E) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \left(\frac{d\sigma}{dE}\right)\Delta E \leq \frac{1}{2}\Delta E$$

Collision energy

The WW threshold W mass : beam energy



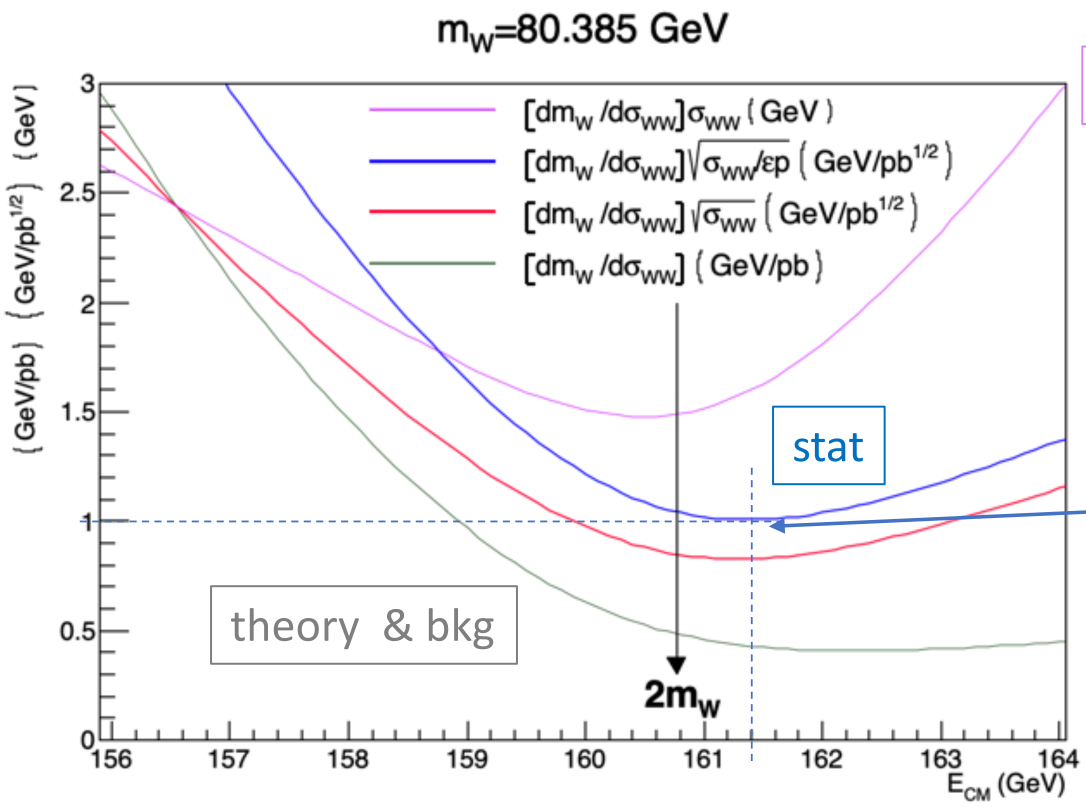
$$\Delta m_W(E) = \left(\frac{d\sigma}{dm_W}\right)^{-1}\left(\frac{d\sigma}{dE}\right)\Delta E \le \frac{1}{2}\Delta E$$

Uncertainty on beam energy $\Delta E_b = \frac{1}{2}\Delta E$ translates directly to m_W

$$\Delta E_b \cong \Delta m_W$$

Very limited variations of the dm_W/dE coefficient with E_{CM} in the threshold region

The WW threshold : W mass optimal E_{CM}



acceptance & lumi

stat uncertainty assuming event selection quality $Q=\sqrt{\varepsilon p}$ with fixed $\varepsilon=0.75$ and $\sigma_B=0.3$pb

Max stat sensitivity at E_{CM}~$2m_W$ + 0.6 GeV

$$\left[\left(\frac{d\sigma}{dm_W}\right)^{-1}\frac{\sqrt{\sigma}}{\sqrt{\varepsilon p}}\right]_{min} \cong 1\ \frac{GeV}{pb^{1/2}} = 1\ \frac{MeV}{ab^{1/2}}$$

With L=12/ab $\Longrightarrow$ Δm_W(stat) = 0.3 MeV

WW threshold : W mass precision requirements

Conditions to achieve Δm_W(syst)< Δm_W(stat) = 0.3 MeV
with a single point WW threshold measurement

$$\Delta m_W(B) = \left(\frac{d\sigma}{dm_W}\right)^{-1} \left(\frac{\Delta\sigma_B}{\varepsilon} \oplus \Delta\sigma_{TH}\right)$$

Background and Theory

$\Delta\sigma_{TH} <$ **1fb** $(\Delta\sigma_{TH}/\,\sigma_{TH} < 2\cdot 10^{-4})$
$\Delta\sigma_B/\varepsilon <$ **1fb** $(\Delta\sigma_B/\,\sigma_B < 4\cdot 10^{-3})$

$$\Delta m_W(\varepsilon) = \sigma\left(\frac{d\sigma}{dm_W}\right)^{-1}\left(\frac{\Delta\varepsilon}{\varepsilon} + \frac{\Delta L}{L}\right)$$

Acceptance and Luminosity

$\left(\frac{\Delta\varepsilon}{\varepsilon} \oplus \frac{\Delta L}{L}\right) < \mathbf{2\cdot 10^{-4}}$

$$\Delta m_W(E) = \left(\frac{d\sigma}{dm_W}\right)^{-1}\left(\frac{d\sigma}{dE}\right)\Delta E \le \frac{1}{2}\Delta E$$

Collision energy

$\Delta E_b < 0.3\ MeV$ $(\Delta E_b/\,E_b < 4\cdot 10^{-6})$

The WW threshold : background

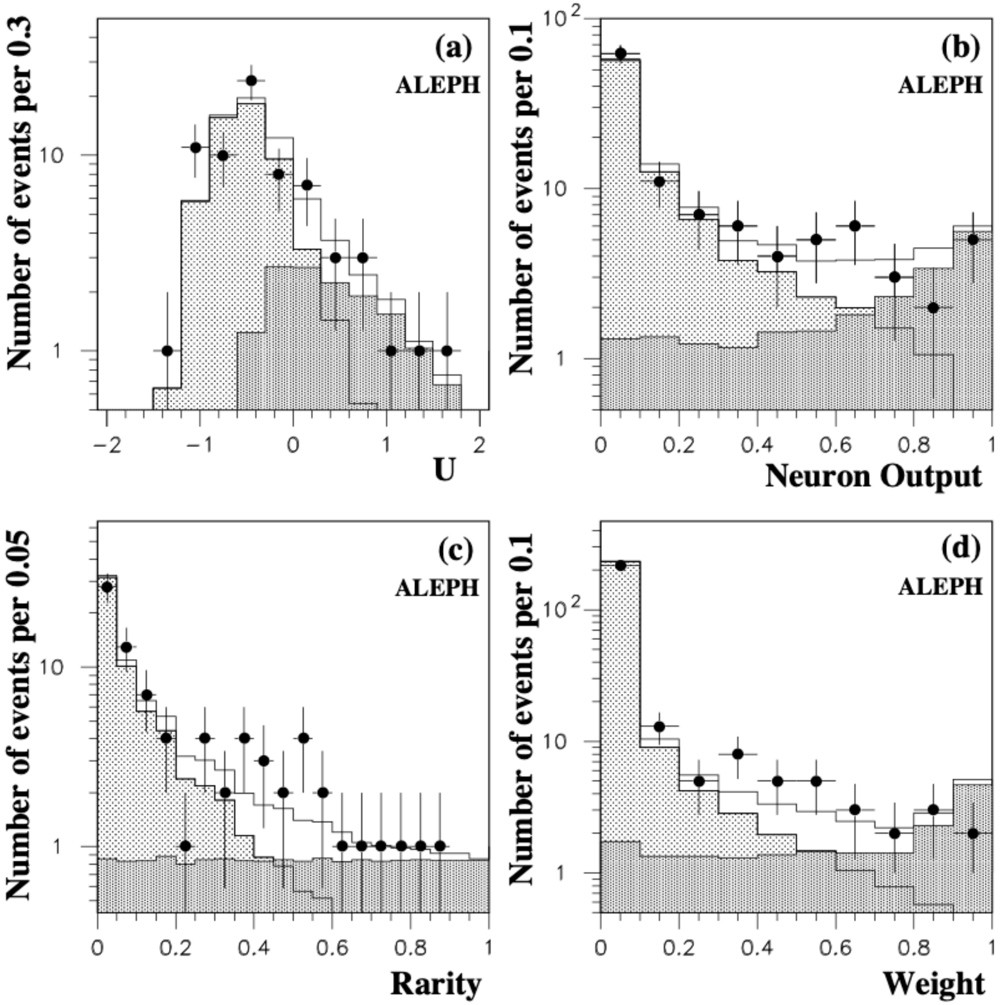
almost all bkg in the 4q channel

Selection	Expected signal	Expected background	Observed
$W^+W^- \to q\bar{q}q\bar{q}$	9.6 ± 1.0	3.44 ± 0.39	14
$W^+W^- \to q\bar{q}e\overline{\nu}_e$	3.89 ± 0.44	0.18 ± 0.27	3
$W^+W^- \to q\bar{q}\mu\overline{\nu}_\mu$	4.19 ± 0.46	0.27 ± 0.15	2
$W^+W^- \to q\bar{q}\tau\overline{\nu}_\tau$	2.32 ± 0.28	0.96 ± 0.34	7
$W^+W^- \to \ell^+\nu_\ell\ell'^-\overline{\nu}_{\ell'}$	2.58 ± 0.28	$0.19^{+0.12}_{-0.04}$	2
Combined	22.6 ± 2.4	5.0 ± 0.6	28

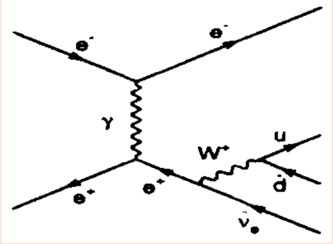
OPAL Phys. Lett. B 389 (1996) 416.

Phys.Lett.B 401 (1997) 347

purity ~95% achieved in the last bins



4-fermion-CC03 interference effects



positive & negative effects (10-50 fb) reported in the various channels, within the LEP analyses acceptance

WW threshold : acceptance

Syst unc at higher E_{CM} (207 GeV) on σ_{WW} (~16pb)

Source	uncertainty (fb)			
	$\ell\nu\ell\nu$	$\ell\nu$qq	qqqq	total
Tracking	4	19	31	54
Simulation of calorimeters	-	9	26	31
Hadronization models	-	27	8	35
Z peak $q\bar{q}$ fragmentation	-	-	20	20
Inter-W final state interaction	-	-	28	28
Background contamination	9	5	31	35
Lepton identification	1	2	-	3
Beam-related background	10	17	37	22
$\mathcal{O}(\alpha)$ corrections DPA	2	9	12	6
Luminosity	8	35	44	87
Simulation statistics	6	20	14	25
Total	17	57	87	126

ALEPH [Eur.Phys.J.C 38 (2004) 147]

Source	$\sigma_{WW}^{q\bar{q}q\bar{q}}$ (pb)	$\sigma_{WW}^{q\bar{q}l\nu}$ (pb)	$\sigma_{WW}^{l\nu l\nu}$ (pb)
Four-jet modelling	±0.051	±0.014	-
Background cross-sections	±0.009	±0.016	±0.006
Fragmentation	±0.045	±0.038	-
Final state interactions	±0.025	-	-
Radiative corrections	±0.008	±0.008	±0.002
Luminosity (theor)	±0.011	±0.010	±0.002
Luminosity (exp)	±0.045	±0.043	±0.011
Detector effects	±0.045	±0.053	±0.033
Monte Carlo statistics	±0.005	±0.014	±0.033

DELPHI [Eur.Phys.J.C 34 (2004) 127]

can roughly scale/4 for equivalent ε effects at threshold σ_{WW} (~4pb)

NP QCD effects have important impacts on both qqqq and qq$\ell\nu$

need improvements in fragmentation and hadronization modeling plus constraints from control data (Z→qq)

less worrisome than using jet properties for kin reco

WW threshold : W mass @ ILC

arXiv:1603.06016 & arXiv:1908.11299

ILC polarised collisions : enhance (x4) t-channel
WW production or suppress it to control background

Channel	Efficiency (%)	$\sigma^U_{\rm bkgd}$ (fb)	$A^B_{\rm LR}$	Eff. syst. (%)	Bkgd syst.	$A^B_{\rm LR}$ syst.
lvlv	87.5	10	0.15	0.1	free	0.025
qqlv	87.5	40	0.30	0.1	free	0.012
qqqq	83.5	200	0.48	0.1	free	0.005

Table 3: Experimental assumptions for the WW event selection near threshold using a polarized scan

$\sqrt{s}$ (GeV)	L ($\rm fb^{-1}$)	f	$\lambda_{e^-}\lambda_{e^+}$	N_{ll}	N_{lh}	N_{hh}	N_{RR}
160.6	4.348	0.7789	−+	2752	11279	12321	926968
		0.1704	+−	20	67	158	139932
		0.0254	++	2	19	27	6661
		0.0254	−−	21	100	102	8455
161.2	21.739	0.7789	−+	16096	67610	73538	4635245
		0.1704	+−	98	354	820	697141
		0.0254	++	37	134	130	33202
		0.0254	−−	145	574	622	42832
161.4	21.739	0.7789	−+	17334	72012	77991	4639495
		0.1704	+−	100	376	770	697459
		0.0254	++	28	104	133	33556
		0.0254	−−	135	553	661	42979
161.6	21.739	0.7789	−+	18364	76393	82169	4636591
		0.1704	+−	81	369	803	697851
		0.0254	++	43	135	174	33271
		0.0254	−−	146	618	681	42689
162.2	4.348	0.7789	−+	4159	17814	19145	927793
		0.1704	+−	16	62	173	138837
		0.0254	++	10	28	43	6633
		0.0254	−−	46	135	141	8463
170.0	26.087	0.7789	−+	63621	264869	270577	5560286
		0.1704	+−	244	957	1447	838233
		0.0254	++	106	451	466	40196
		0.0254	−−	508	2215	2282	50979

Table 1: Illustrative example of the numbers of events in each channel for the standard 100 $\rm fb^{-1}$ 6-point ILC scan with 4 helicity configurations. Columns give the center-of-mass energy, $\sqrt{s}$, the apportioned integrated luminosity, the fraction for each helicity configuration, $\lambda_{e^-}\lambda_{e^+}$, and the numbers of events observed in each channel.

with 100 fb−1

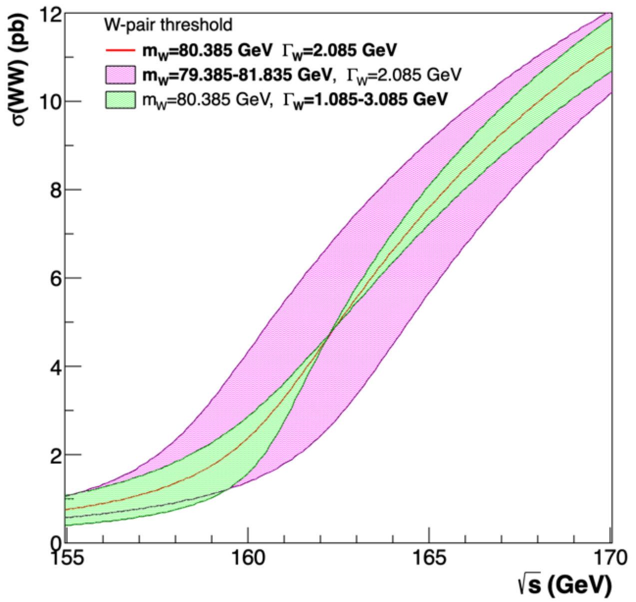
Fit type	Uncertainty source	ΔM_W [MeV]	ΔM_W (syst.) [MeV]
fixbkg	Background	3.20	2.30
fixpol	Polarization	3.73	1.27
fixeff	Efficiency	3.86	1.18
fixlum	Luminosity	3.76	0.78
fixALRB	$A^B_{\rm LR}$	3.86	0.80
fixall	Statistical	2.43	
	Systematic		3.10
standard	Total Error	3.94	

$$\Delta m_W(\text{MeV}) = 2.4\ (\text{stat}) \oplus 3.1\ (\text{syst}) \oplus 0.8\ (\sqrt{\text{s}}) \oplus \text{theory}$$

assumes $\Delta\varepsilon \sim 10^{-3}$ and $\Delta\sigma_B \sim$6 fb
additional impact of pol uncertainty

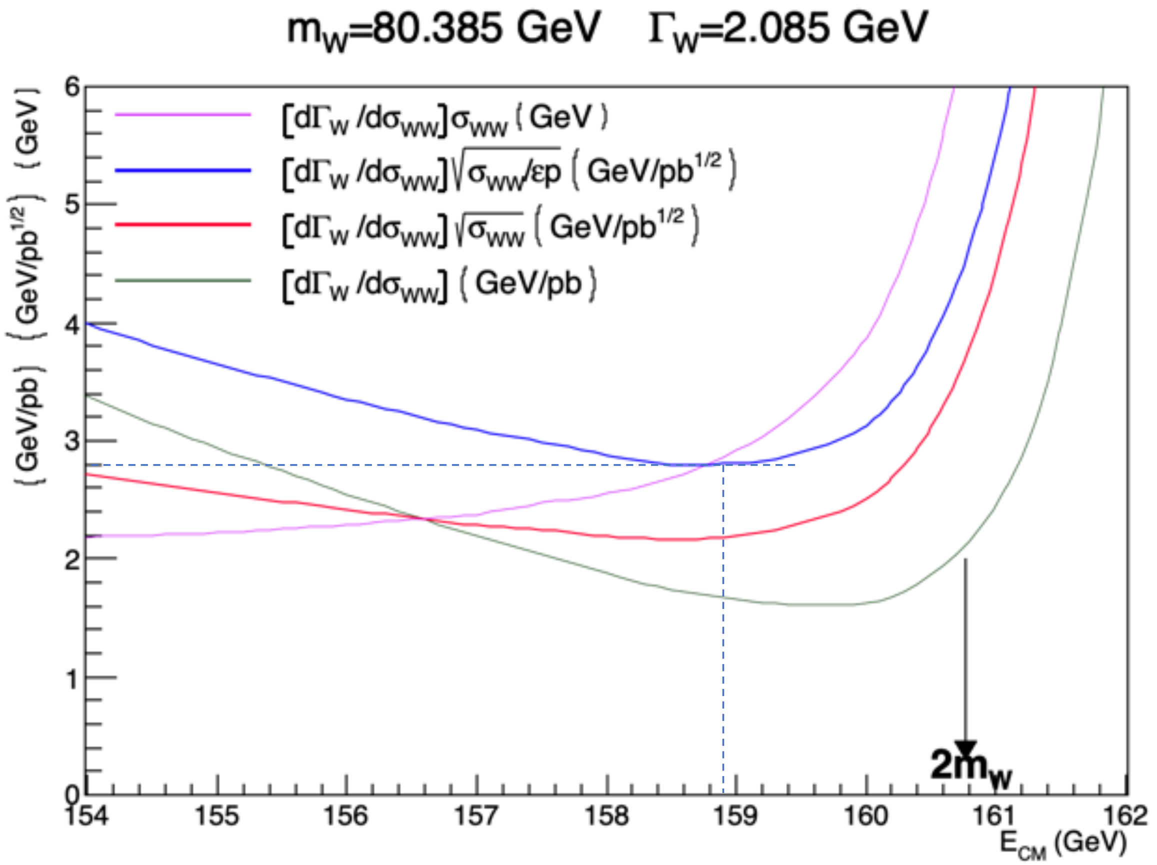
WW threshold : W mass and width

arXiv:1703.01626
arXiv:2107.04444



Max stat sensitivity at E_{CM}~ $2m_W$ - $\boldsymbol{\Gamma}_W$

$$\left[\left(\frac{d\sigma}{d\Gamma_W}\right)^{-1}\frac{\sqrt{\sigma}}{\sqrt{\varepsilon p}}\right]_{min} \cong 2.8\ \frac{GeV}{pb^{1/2}} = 2.8\ \frac{MeV}{ab^{1/2}}$$



WW threshold : W mass and width

With cross section $\sigma_1\sigma_2$ measurements at two energies E_1 E_2 : uncertainty propagation

$$\begin{cases}\sigma_1 = \sigma_{WW}(E_1, m_W, \Gamma_W)\\ \sigma_2 = \sigma_{WW}(E_2, m_W, \Gamma_W)\end{cases}$$

$$\begin{cases}\Delta\sigma_1 = a_1\Delta m + b_1\Delta\Gamma\\ \Delta\sigma_2 = a_2\Delta m + b_2\Delta\Gamma\end{cases}$$

$$a_1 = \frac{d\sigma_1}{dm} \qquad b_1 = \frac{d\sigma_1}{d\Gamma}$$

$$a_2 = \frac{d\sigma_2}{dm} \qquad b_2 = \frac{d\sigma_2}{d\Gamma}$$

$$\Delta m = -\frac{b_2\Delta\sigma_1 - b_1\Delta\sigma_2}{a_2b_1 - a_1b_2}$$

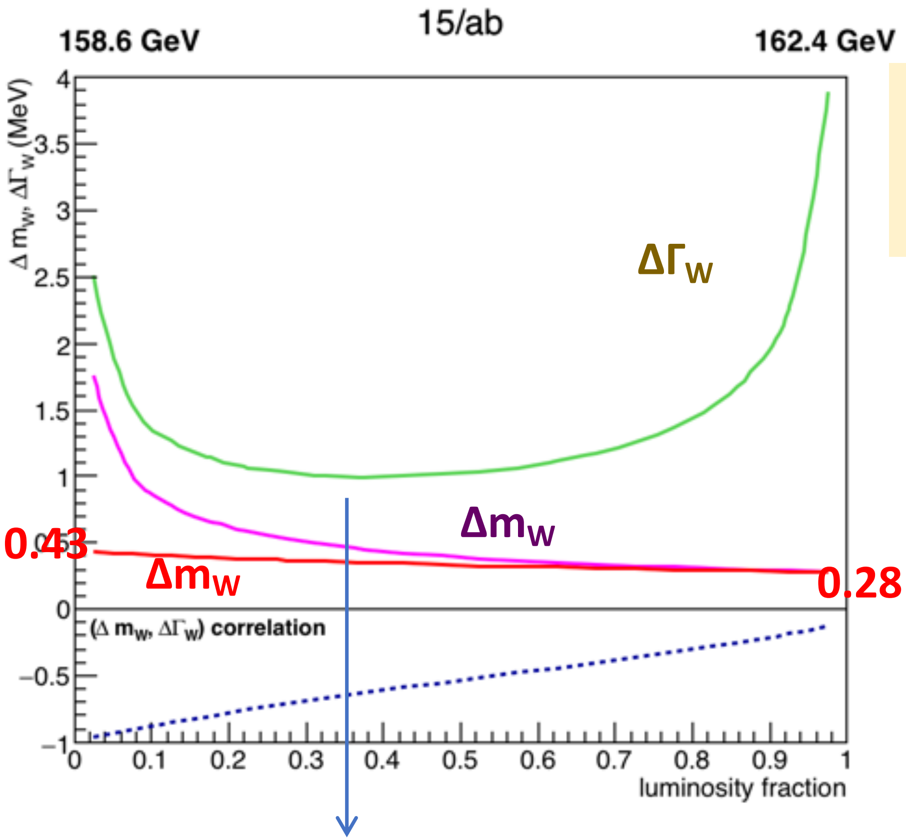
$$\Delta\Gamma = \frac{a_2\Delta\sigma_1 - a_1\Delta\sigma_2}{a_2b_1 - a_1b_2}$$

$\Delta m, \Delta\Gamma$ linear correlation with uncorrelated $\Delta\sigma_1$,$\Delta\sigma_2$

$$r = -\frac{1}{\Delta m\Delta\Gamma}\frac{a_2b_2\Delta\sigma_1^2 + a_1b_1\Delta\sigma_2^2}{\left(a_2b_1 - a_1b_2\right)^2}$$

WW threshold : W mass and width

Scans of possible E_1 E_2 data taking energies and luminosity fractions f (at the E_2 point)



Δm_W =0.45 MeV , $\Delta\Gamma_W$=1 MeV (r=-0.6)
Δm_W=0.35 MeV

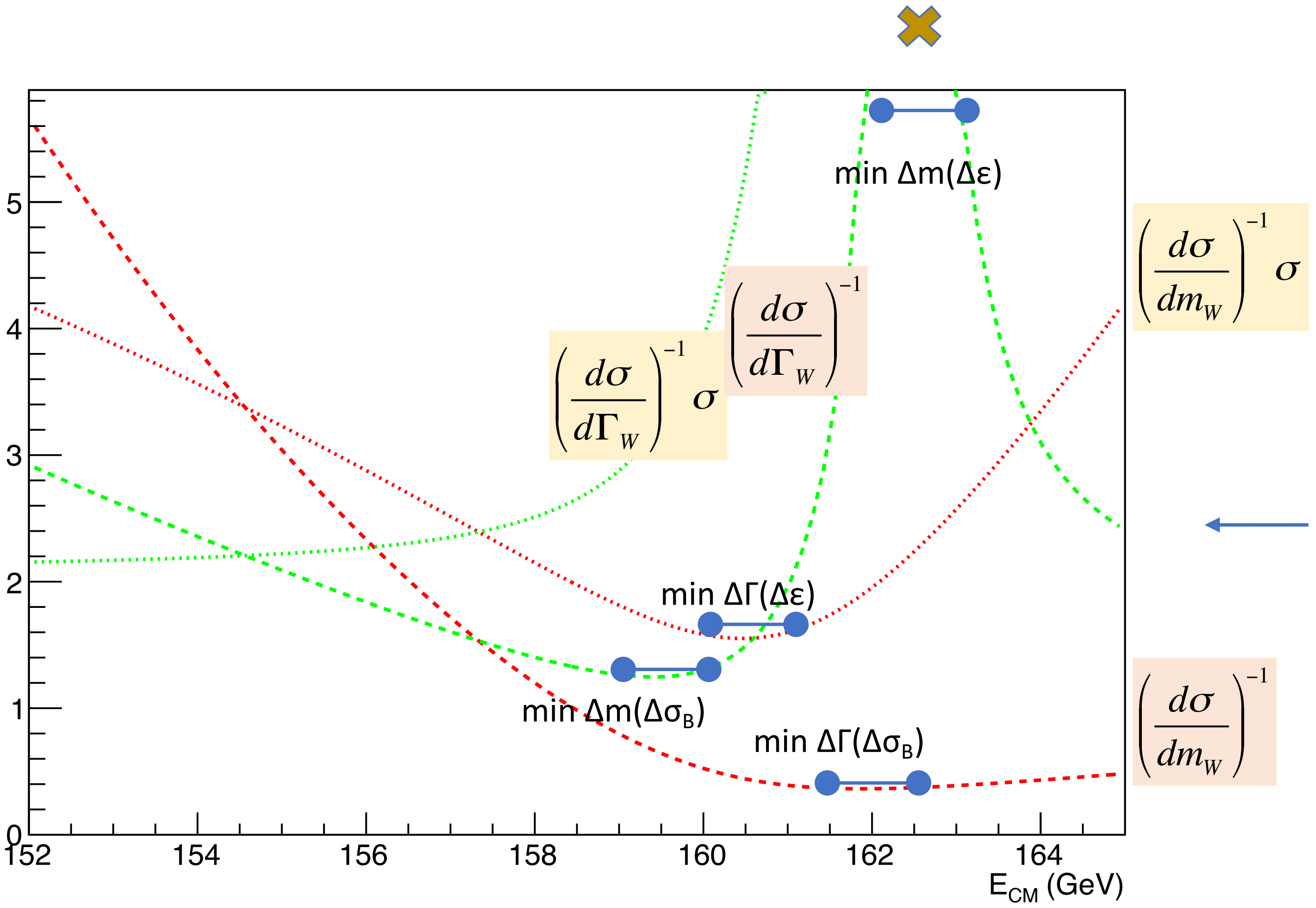
A -minimum of $\Delta\Gamma_W$=0.91 MeV with Δm_W=0.55 MeV
taking data at E_1=**156.6** GeV E_2=**162.4** GeV f=**0.25**
yields Δm_W=**0.47 MeV** (as single par)

B- minimum of Δm_W=0.28 MeV $\Delta\Gamma_W$=3.3 MeV with
E_1=**155.5** GeV E_2=**162.4** GeV f=**0.95**
yields Δm_W=**0.28 MeV** (as single par)

C- minimum of $\Delta\Gamma_W$=0.96 MeV +Δm_W=0.41 MeV with
E_1=**157.5** GeV E_2=**162.4** GeV f=**0.45**
yields and Δm_W=**0.37 MeV** (as single par)

Δm_W , $\Delta\Gamma_W$: error on W mass and width from fitting both
Δm_W : error on W mass from fitting only m_W

WW threshold : W mass and width



optimal E points with limiting correlated systs

Scans of (E_1, E_2, f) data taking **assuming limiting syst uncertainties**, either Δε+ΔL or $\Delta\sigma_B$+ $\Delta\sigma_{TH}$

More complex situation, depends very much on the correlation of uncertainties between the energy points (that can be quite large)

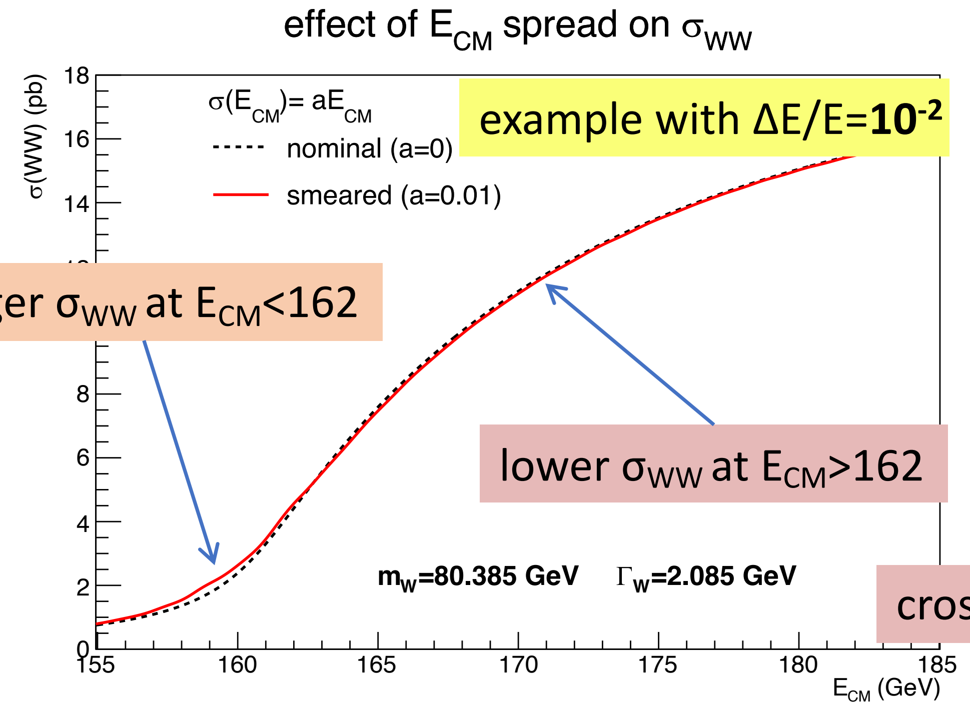
Correlated syst can cancel taking data at different E_{CM} points where the relevant differential factors are equal (around their minima)

>2 energy points will be beneficial to reduce the impact of (correlated) systematic uncertainties careful choice of additional points recommended

partially explored in Eur. Phys. J. C 80 no. 1, (2020) 66

WW threshold : energy spread effects

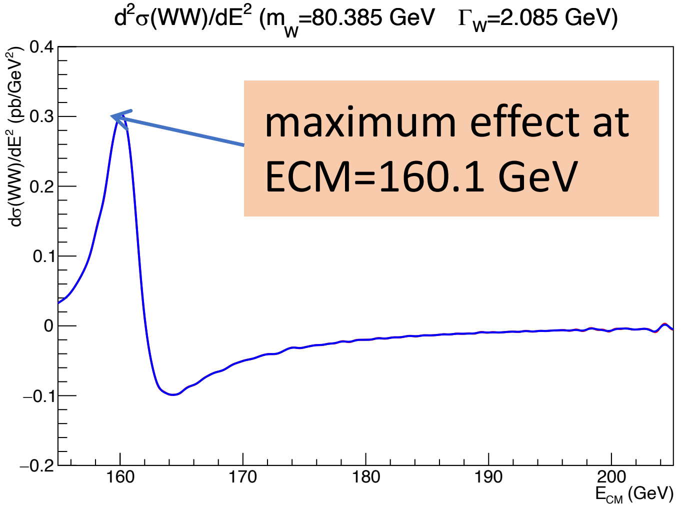
arXiv:1909.12245



example with $\Delta E/E=$**10^{-2}**

larger σ_{WW} at $E_{CM}<162$

lower σ_{WW} at $E_{CM}>162$



maximum effect at ECM=160.1 GeV

crossing point near the $d\sigma_{WW}/\Gamma_W=0$ point

Optimal m_W & Γ_W points @E_{CM}=**157.3 & 162.6** GeV

➔ $\Delta\sigma_{WW}$ = +(0.24-1.3) fb & = -(0.18-1.0) fb

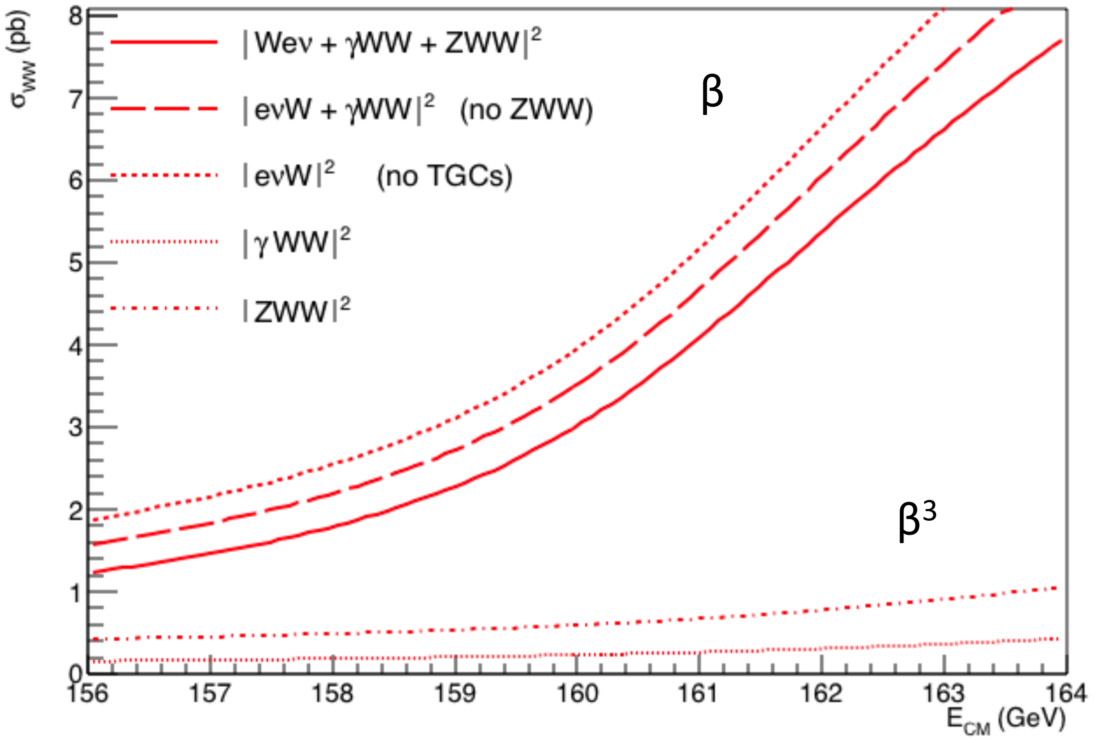
➔ **Δm_W = -(0.09-0.48) MeV**

➔ **$\Delta\Gamma_W$ = +(0.6-3.3) MeV**

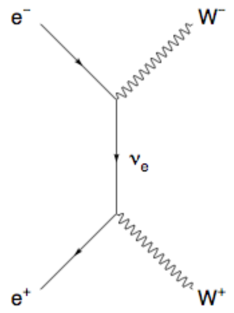
$\sigma(E_{CM})$=**(0.47-1.10) 10^{-3}** E_{CM}

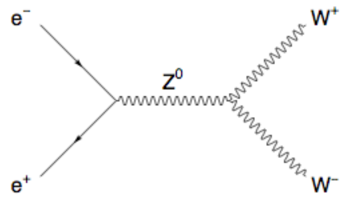
Maximum effects are at the level of Δm_W(stat) and 2x $\Delta\Gamma_W$ (stat) so that control on the beam energy RMS <50% is required to avoid additional syst contributions from this source

TGCs at threshold

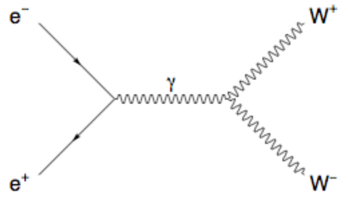


Weν





WWZ



WWγ

SU(2)⊗U(1) Gauge Cancellations

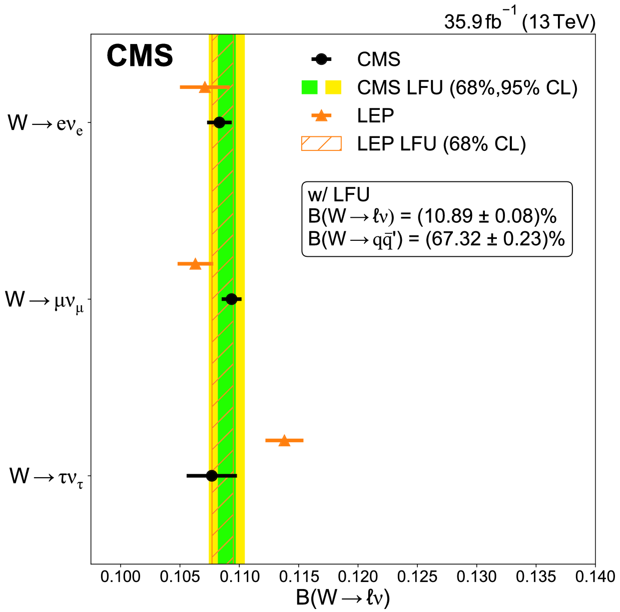
without TGCs
σ_{WW} +40% @157GeV +25%@162GeV

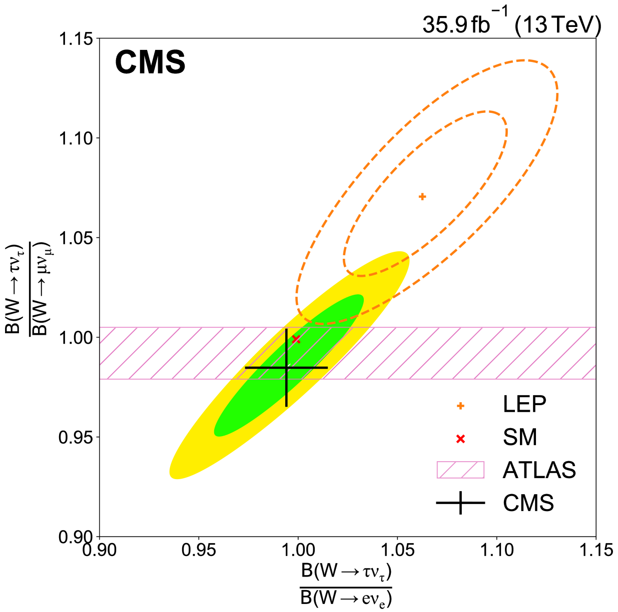
W decay branching fractions

LEP arXiv:1302.3415

	CMS	LEP
$\mathcal{B}(W \to e\overline{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\ \%$
$\mathcal{B}(W \to q\overline{q}')$	$(67.46 \pm 0.04 \pm 0.28)\%$	—
Assuming LFU		
$\mathcal{B}(W \to \ell\overline{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to q\overline{q}')$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$

LEP2 W→$\tau\nu$ 2.6σ larger than eν+$\mu\nu$ average : unconfirmed by more precise recent ATLAS & CMS measurements





CMS arXiv:2201.07861 ATLAS arXiv:2007.14040

Current W BR relative precisions
eν(1%) $\mu\nu$ (1%) $\tau\nu$(2%) qq(0.3%)

	CMS	LEP	ATLAS	LHCb	CDF	D0
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010	0.980 ± 0.012	0.991 ± 0.012	0.886 ± 0.121
$R_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	—	—	—	—
$R_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013	—	—	—
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	—	—	—	—

$\alpha_S(m_W^2)$	$\|V_{cs}\|$	$\sum_{ij}\|V_{ij}\|^2$
0.095 ± 0.033	0.967 ± 0.011	1.984 ± 0.021 height

BR(W→qq') derived determinations

W decay branching fractions: extrapolations

FCCee: 12/ab@162 + 5/ab@240 ~ 120M WW decays

ILC : 2/ab @250 GeV, 1/ab with enhanced WW (~40M)

arXiv:1908.11299

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	$3{\cdot}10^{-4}$	$3{\cdot}10^{-4}$	$4{\cdot}10^{-4}$	$1{\cdot}10^{-4}$

Event selections	B_e	B_μ	B_τ	R_μ	R_τ
All 10	4.2	4.1	5.2	6.1	7.5
9 (not fully-hadronic)	5.9	5.7	6.4	6.1	7.5
9 (not tau-semileptonic)	4.6	4.6	7.8	6.1	10.8
8 (not f-h and not τ-semileptonic)	8.3	8.4	7.8	6.1	12.8
7 (not f-h and not τ-sl and not di-τ)	9.0	9.1	10.6	6.1	16.7

Table 4: Statistical uncertainties, expressed as relative errors in units of 10^{-4} for the leptonic branching fractions of the W boson (B_e, B_μ and B_τ) and the ratios of branching fractions $R_\mu = B_\mu/B_e$, $R_\tau = B_\tau/B_e$. The lines of the table refer to different choices of the included event selections. The values assume ILC measurements at $\sqrt{s} = 250$ GeV using the 45% of the 2 ab^{-1} integrated luminosity with enhanced $e^-_L e^+_R$ collisions, with the same efficiencies and the same background cross sections as in the OPAL measurement [44]. The uncertainties given for R_μ, R_τ are from a separate fit using the (B_e, R_μ and R_τ) parametrization.

Scaling major syst uncertainties with luminosity (as data stat)

Lept universality tests at *3-4 10^{-4} level*

q/ l universality test *10^{-4} level*

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

$\Delta R_W^\ell = 9\,\Delta B_q \sim 10^{-3}$

stringent test of CKM unitarity in the first two rows

alternatively

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

W decay branching fractions : systematics

Table 8. W branching ratio systematic error breakdown in units of 10^{-4}

Source	uncertainty			
	$e\nu$	$\mu\nu$	$\tau\nu$	qq
Tracking	2.6	3.8	3.9	3.2
Simulation of calorimeters	1.6	2.4	2.0	5.9
Hadronization models	2.8	2.8	0.7	0.4
Z peak $q\bar{q}$ fragmentation	0.5	0.5	0.5	1.6
Inter-W final state interaction	1.9	1.9	1.9	5.7
Background contamination	1.9	2.4	2.6	6.4
Lepton identification	7.7	5.5	11.2	0.5
Beam-related background	2.5	1.4	15.4	10.2
$\mathcal{O}(\alpha)$ corrections DPA	0.4	1.1	3.1	1.7
Luminosity	0.8	0.5	0.3	1.5
Simulation statistics	1.0	0.7	1.4	1.4
Total	9.6	8.5	20.2	15.2

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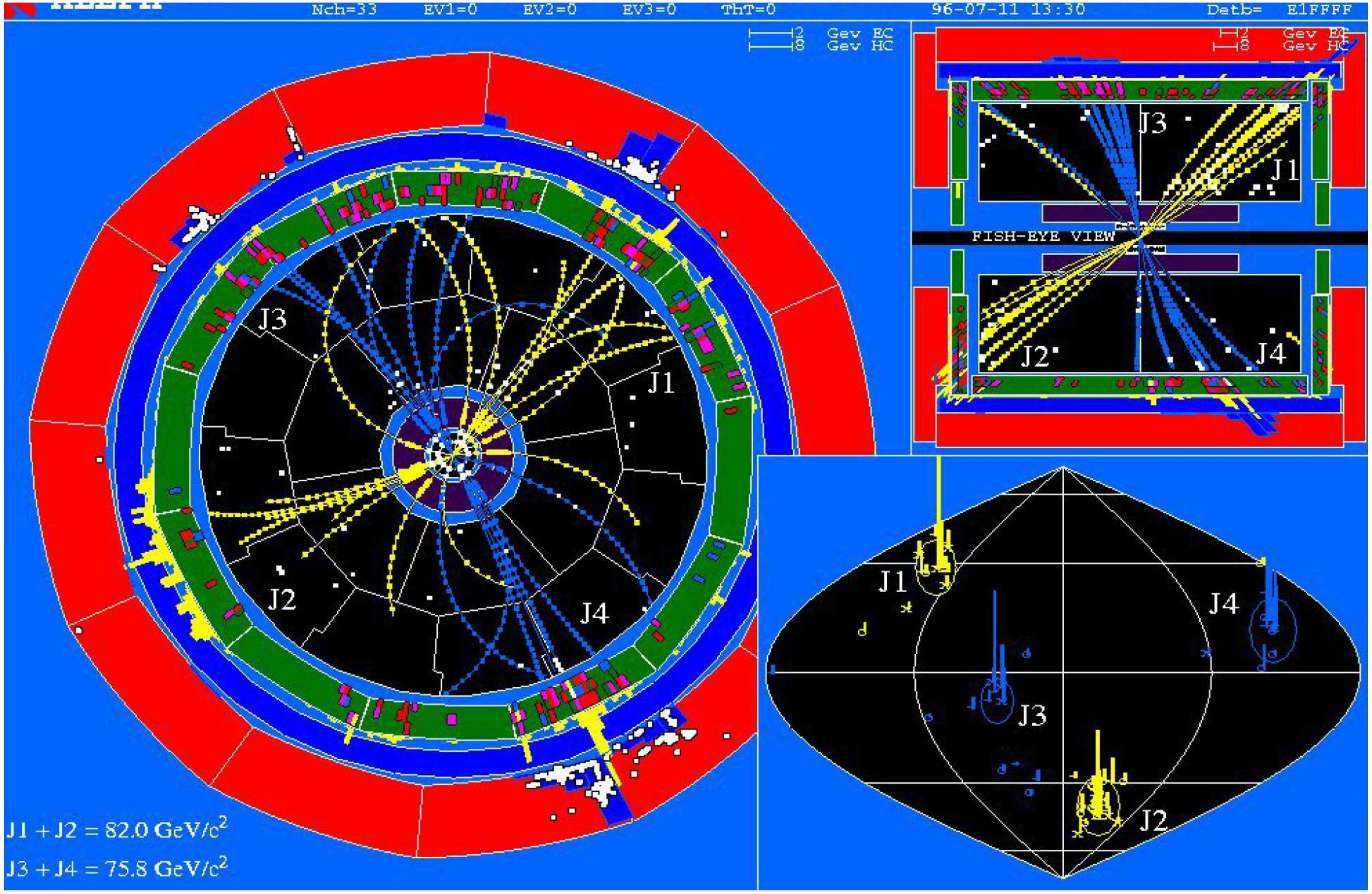
For lept BR will need excellent control of **lepton id** and cross contaminations in signal channels ($\tau \rightarrow e,\mu$ and e,μ channels)

Less stringent requirements for syst uncertainty control for hadr BR

Hadronic W decays flavor tagging



Hadronic W flavor tagging : cX & cs

Charm (+strange) tagging. Done with LEP2 data. Stat extrapolations to (FCCee) 120M WW datasets

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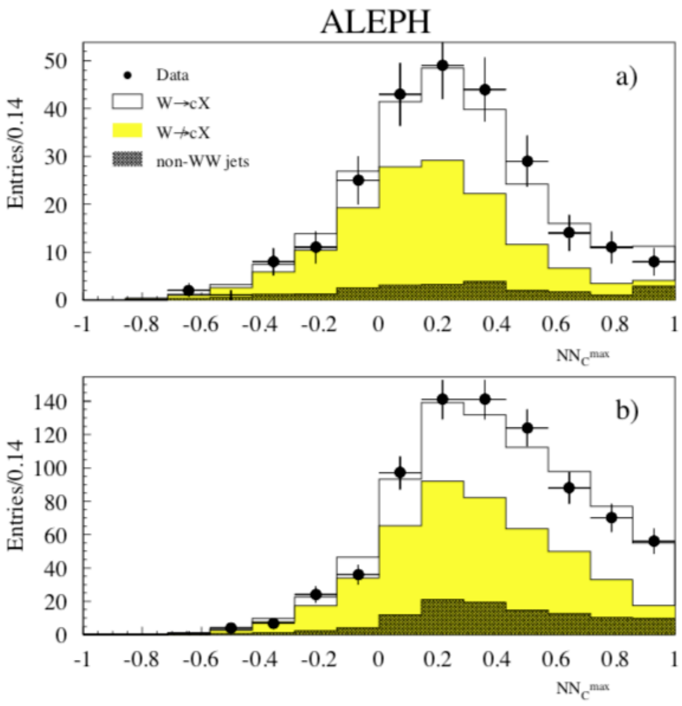
ΔR_c^W (stat) FCCee → 2 10^{-4}



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

Table 2: Systematic errors on R_c^W.

Source	ΔR_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

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$\Delta|V_{cs}|$ (stat) FCCee → 3 10^{-4}

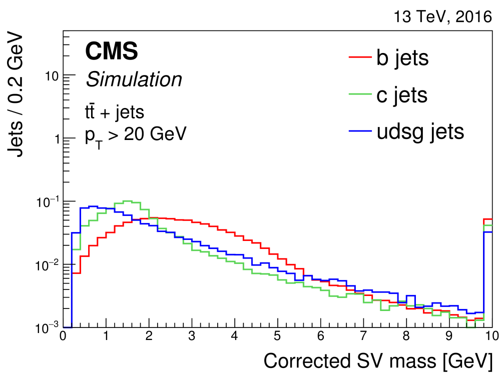
Source of Systematic Error	ΔR_c^W 183 GeV	189 GeV
Hadronisation Model	0.011	0.012
Centre–of–mass Energy	0.007	0.005
Mass of the W Boson	0.004	0.003
Charm Fragmentation Function	0.007	0.007
Background Cross-Section	0.006	0.005
Background Composition	0.010	0.009
Charm Hadron Fractions	0.006	0.007
Light 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

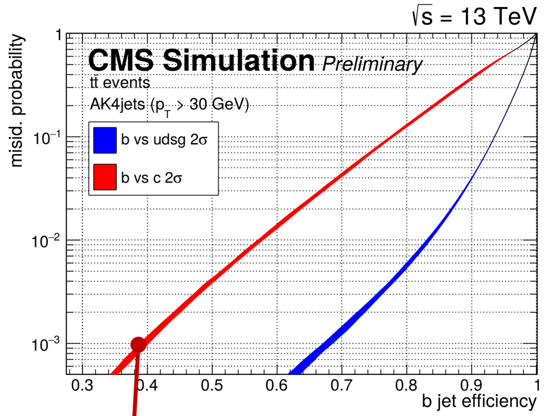
challenging syst effects

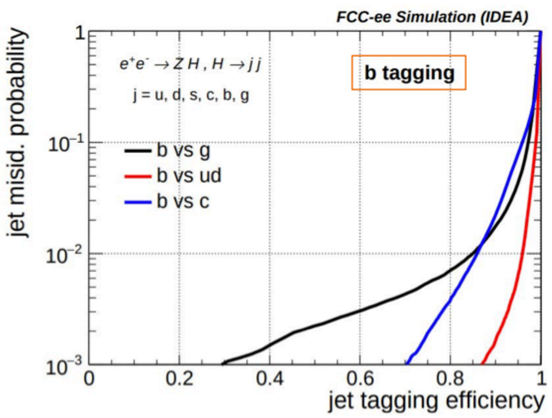
Hadronic W flavor tagging : bX, bc, bu

Very small B($W\to$bX). Not possible with LEP data.

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





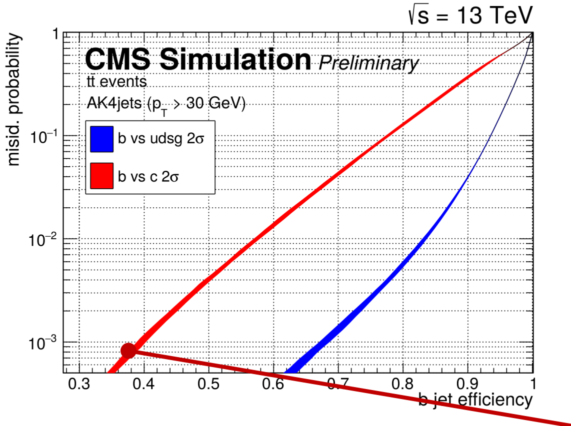


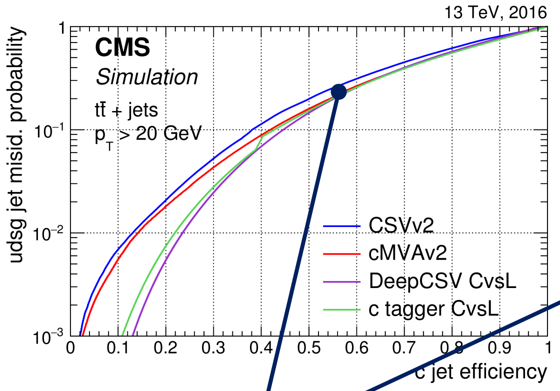
With $\boldsymbol{\varepsilon_b}$**=40% and** $\boldsymbol{\varepsilon_c}$**=$10^{-3}$** @FCCee: N(W→cs)≈100k N(W→bX)≈75k
Δ$R_b^{\,W}$ (stat)(FCCee) → 0.6% (rel) & **Δ** $|V_{cb}|$ (stat) (FCCee) → 0.3% (rel)

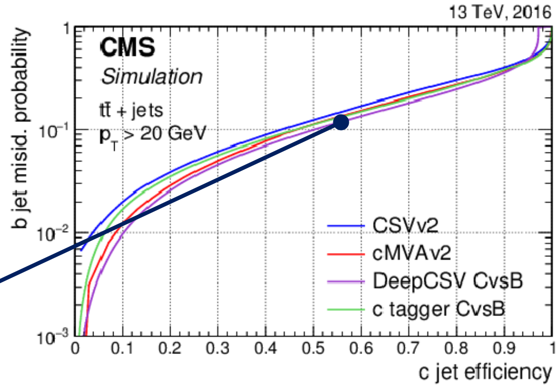
Hadronic W flavor tagging : bX, bc, bu

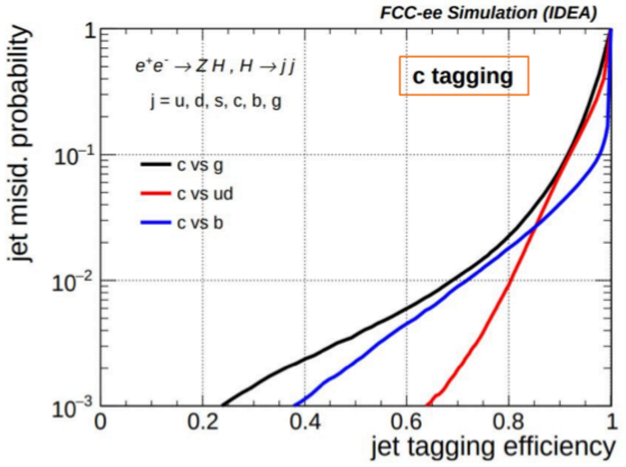
$|V_{cb}| = (41.0 \pm 1.4) \times 10^{-3}$ ➔ BR = 5.6 10^{-4} (1.7 10^5 W→cb @FCCee)

$|V_{ub}| = (3.82 \pm 0.24) \times 10^{-3}$ ➔ BR = 4.9 10^{-6} (1.5 10^3 W→ub @FCCee)







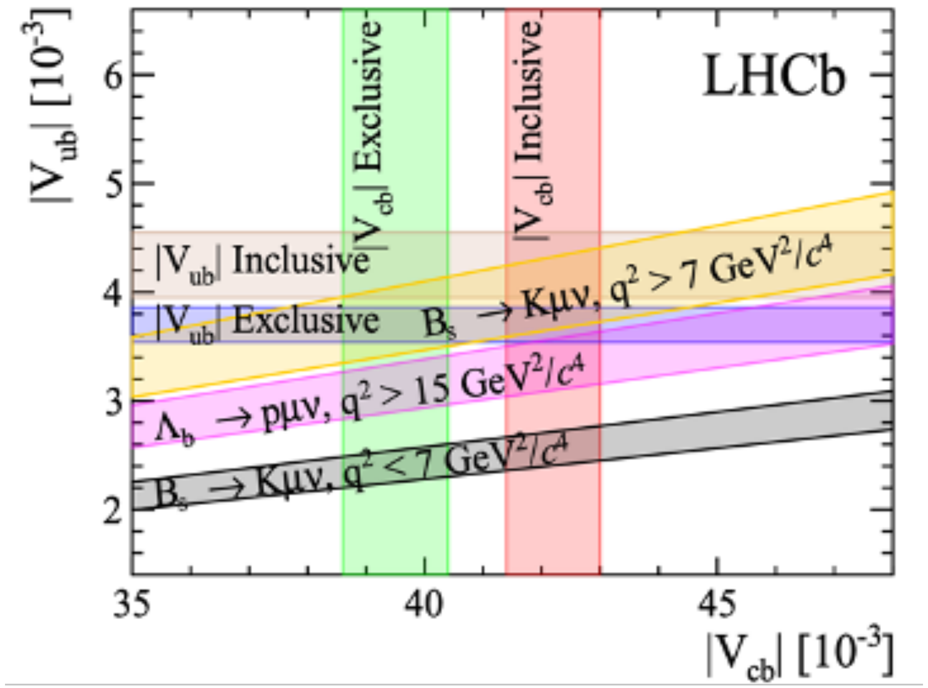


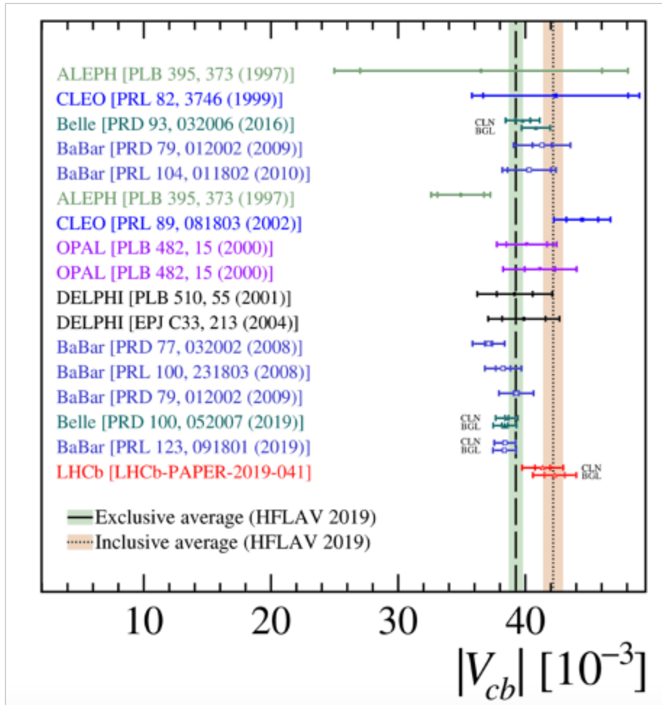
First tag $\boldsymbol{\varepsilon_b}$**=40% and** $\boldsymbol{\varepsilon_c}$**=$10^{-3}$** $\boldsymbol{\varepsilon_{uds}}$**=$10^{-5}$** Second tag with $\boldsymbol{\varepsilon_c}$**=60% and** $\boldsymbol{\varepsilon_b}$**=0.1** $\boldsymbol{\varepsilon_{uds}}$**=0.2**
@FCCee: N(W→cs,cd)≈20k N(W→cb)≈50k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

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

Hadronic W flavor tagging : bX, bc, bu

Current situation with |Vcb| and |Vub|





Projections with 120M WW

Δ$R_b^{\,W}$ (rel) ≃ 0.6% **stat**

Δ $|V_{ub}|$ (rel) ≃ 3-5% **stat**

Δ $|V_{cb}|$ (rel) ≃ 0.2% **stat**

Summary

- WW threshold data can provide both m_W and Γ_W with unprecedented precision
  - optimal data taking at E_{CM}= $2m_w$+1.5 GeV (**Γ_W-insensitive**) and E_{CM} =$2m_w$- Γ_W (**off shell**) yileds with 12/ab stat precision Δm_W =0.5 MeV and $\Delta\Gamma_W$=1.2 MeV, some challenges from syst uncertainties (acceptance control at few 10^{-4} level)
  - interest of additional E_{CM} points for syst control and investigate other lineshape properties
  - threshold data can be used for other measurements as direct N_ν from radiative Z, single V ($We\nu$, Zee), …
- Large W-pair data at threshold and above will provide precise W decay BRs
  - Lepton universality and lepton/quark universality tests at the 10^{-4} level, similar precision on CKM matrix unitarity in first two rows, also $\Delta\alpha_S(m_W)$ at 10^{-3}.
  - Flavor tagging of hadronic W decays will offer a great opportunity for **precise direct CKM measurements** e.g. $|V_{cb}|$ with b- and c-tagging at few 10^{-3} rel precision level (can be tried also with LHC data)