Input to Volume 1

1. should give a summary of event statistics and observable precisions.
2. Should also give implications for physics discovery potential
3. and should be consistent with volume 4.

IMPLEMENTATION AND RUN PLAN

"Ampere-class" machine

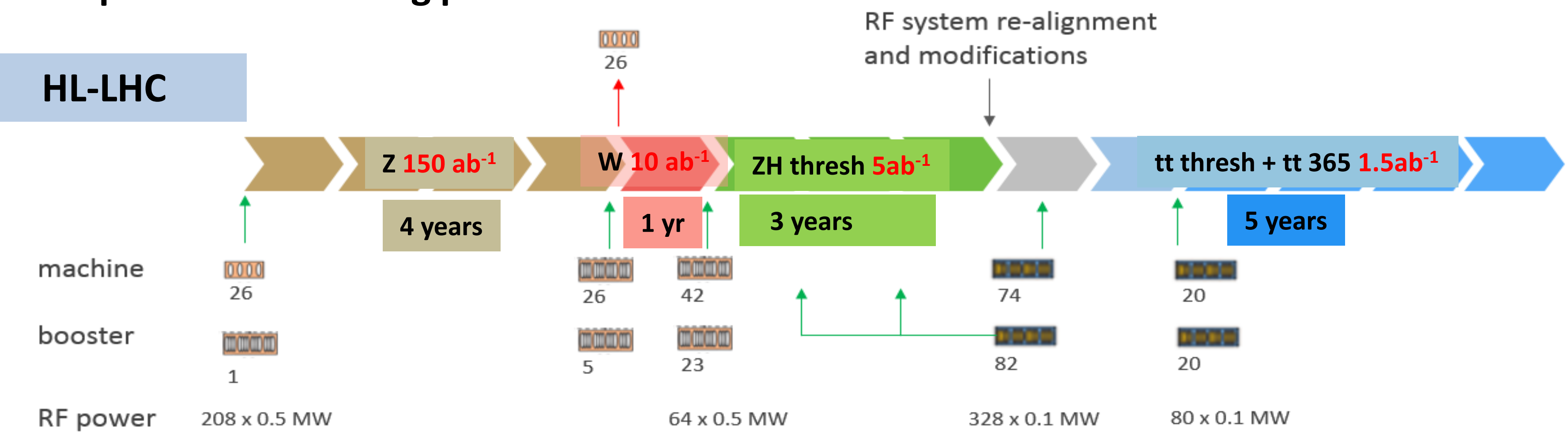
	V_tot (GV)	n_bunch	I_beam (mA)
Z	0.2	91500	1450
W	0.8	5260	152
H	3	780	30
t	10	81	6.6

"high gradient" machine

Three sets of RF cavities for FCCee & Booster:

- **Installation as LEP (≈30 CM/winter)**
- **high intensity (Z, FCC-hh): 400 MHz mono-cell cavities, ≈ 1MW source**
- **high energy (W, H, t): 400 MHz four-cell cavities, also for W machine**
- **booster and t machine complement: 800 MHz four-cell cavities**
- **Adaptable 100MW, 400MHz RF power distribution system +High effciency**

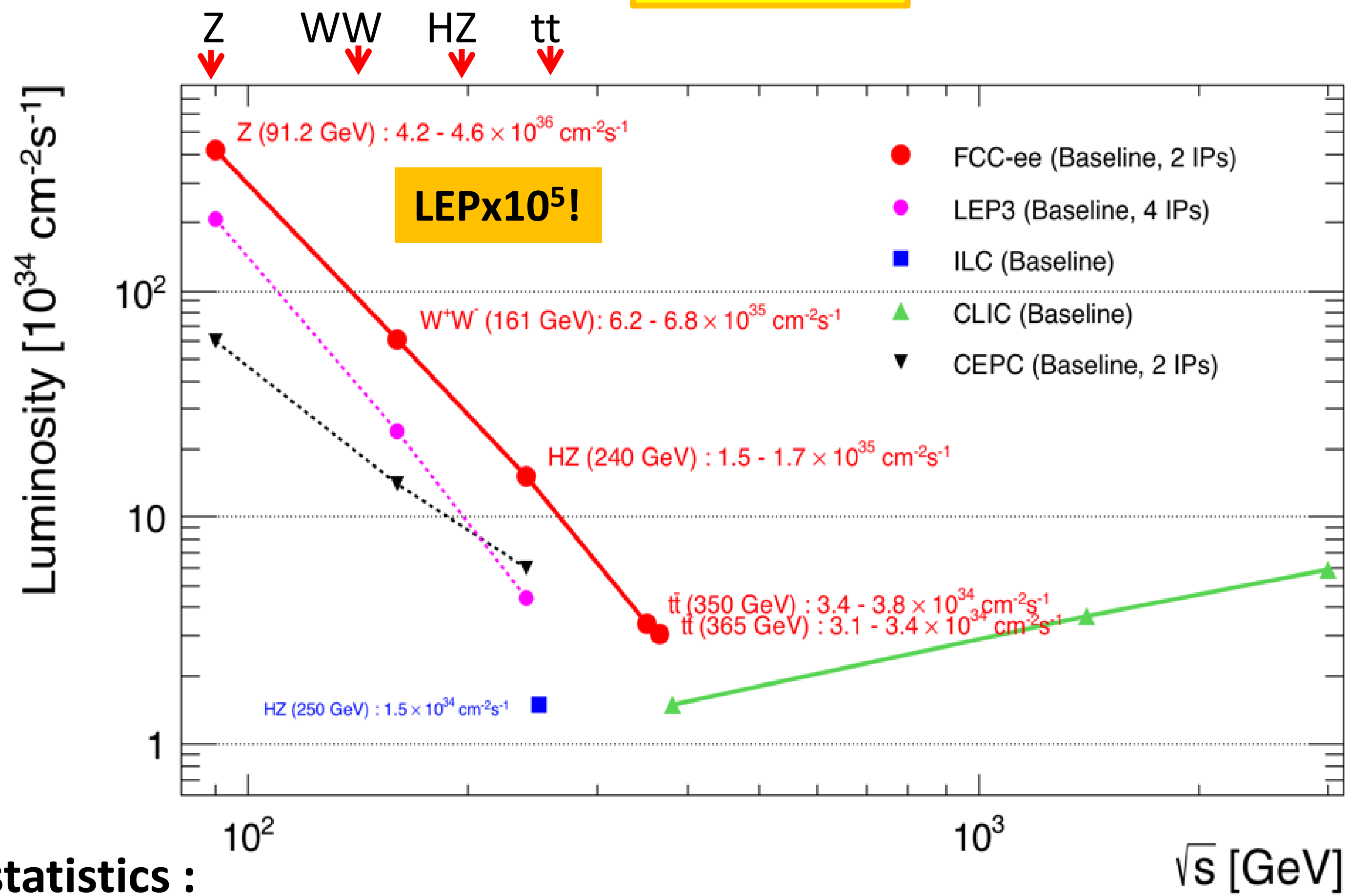
➔ Spreads the funding profile



indicative: total ~15 years

O(1/3) of the machine cost comes O(10) years after start

FCC-ee



Event statistics :

E_{CM} errors:

Z peak	**E_{cm} : 91 GeV**	**$5\ 10^{12}$ e+e- → Z**	**LEP x 10^5**	100 keV
WW threshold	**E_{cm} : 161 GeV**	**10^8 e+e- → WW**	**LEP x 2.10^3**	300 keV
ZH threshold	**E_{cm} : 240 GeV**	**10^6 e+e- → ZH**	**Never done**	1 MeV
$\overline{t}t$ threshold	**E_{cm} : 350 GeV**	**10^6 e+e- → $\overline{t}t$**	**Never done**	2 MeV

Great energy range for the heavy particles of the Standard Model.

FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could discover :

EXPLORE 10-100 TeV energy scale (and beyond) with Precision Measurements

-- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)
m_Z, m_W, m_{top} , $\sin^2 \theta_w^{eff}$, R_b , α_{QED} (m_z) α_s (m_z m_W m_τ), Higgs and top quark couplings

DISCOVER a violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
-- ex FCNC (Z --> $\mu\tau$, eτ) in 5 10^{12} Z decays and τ BR in 2 10^{11} Z→ τ τ
+ flavour physics (10^{12} bb events) (B→s τ τ etc..)

DISCOVER dark matter as «invisible decay» of H or Z (or in LHC loopholes)

DISCOVER very weakly coupled particle in 5-100 GeV energy scale
such as: Right-Handed neutrinos, Dark Photons etc…

+ an enormous amount of clean, unambiguous work on QCD (H→ gg) etc….

NB Not only a «Higgs Factory», «Z factory» and «top» are important for 'discovery potential'

"First Look at the Physics Case of TLEP", JHEP 1401 (2014) 164

A sample of observables (more coming)

Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_Z (MeV)	Lineshape	91187.5 **± 2.1**	**0.005**	**< 0.1**	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 **± 2.3**	**0.008**	**< 0.1** *	QED / EW
R_l	Peak	20.767 **± 0.025**	**0.001**	**< 0.001**	Statistics
R_b	Peak	0.21629 **± 0.00066**	**0.000003**	**< 0.00006**	g → bb
N_ν	Peak	2.984 **± 0.008**	**0.00004**	**< 0.004**	Lumi meast
$\sin^2\theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 **± 0.00016**	**0.000003**	**<0.000005** *	Beam energy
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ (off-peak)	128.952 **± 0.014**	**0.004**	**< 0.004**	QED / EW
$\alpha_s(m_Z)$	R_l	0.1196 **± 0.0030**	**0.00001**	**<0.0002**	New Physics
m_W (MeV)	Threshold scan	80385 **± 15**	**0.6**	**< 0.6**	EW Corr.
Γ_W (MeV)	Threshold scan	2085 **± 42**	**1.5**	**<1.5**	EW Corr.
N_ν	$e^+e^- \to \gamma Z$, $Z \to \nu\nu$, ll	2.92 **± 0.05**	**0.001**	**< 0.001**	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 **± 0.27**	**0.00018**	**< 0.0001**	CKM Matrix
m_{top} (MeV)	Threshold scan	173340 **± 760 ± 500**	**20**	**<40**	QCD corr.
Γ_{top} (MeV)	Threshold scan	**?**	**40**	**<40**	QCD corr.
λ_{top}	Threshold scan	μ = 1.2 **± 0.3**	**0.08**	**< 0.05**	QCD corr.
ttZ couplings	√s = 365 GeV	**~30%**	**~2%**	**<2%**	QCD corr

* work to do: check if we cant improve

precisions on EW observables

qty	LEP	FCC-ee	stat (rel)	stat (abs)	syst (est)	
SUM(L)	808pb-1	150ab-1				
Z->qqbar	15.497 10^6	2.9 10^{12}				
Z-> ll (any)	1.724 10^6	3.2 10^{11}				
Z-> ll (one)		1.07 10^{11}				
Rl (all)		1.9 10^{-6}	1.9 10^{-6}	4 10^{-5}	25-100 10^{-5}	
$A_{FB}(\mu\mu)$				3 10^{-6}	9 10^{-6}	
Z-> bb $(62\%)^2$						
Rb			1.7 10^{-6}	3.5 10^{-7}		
m_Z	1.2 MeV			2.8 keV	100 keV	
Γ_Z	2 MeV			4.5 keV	100 keV	

the old values dated from Snowmass'13

	$A_{FB}^{\mu\mu}$ @ FCC-ee		A_{LR} @ ILC	A_{LR} @ FCC-ee
visible Z decays	10^{12}	visible Z decays	10^{9}	5.10^{10}
muon pairs	10^{11}	beam polarizatio n	90%	30%
$\Delta A_{FB}^{\mu\mu}$ (stat)	$3\ 10^{-6}$	ΔA_{LR} (stat)	$4.2\ 10^{-5}$	$4.5\ 10^{-5}$
$\Delta\ E_{cm}$ (MeV)	0.1		2.2	?
$\Delta A_{FB}^{\mu\mu}$ (E_{CM})	$9.2\ 10^{-6}$	ΔA_{LR} (E_{CM})	$4.1\ 10^{-5}$	
$\Delta A_{FB}^{\mu\mu}$	$1.0\ 10^{-5}$	ΔA_{LR}	$5.9\ 10^{-5}$	
$\Delta\sin^2\theta^{lept}_W$	$5.9\ 10^{-6}$		$7.5\ 10^{-6}$	$6\ 10^{-6}$ +?

All exceeds the theoretical precision from $\Delta\alpha(m_Z)$ (310^{-5}) or the comparison with m_W (500keV)

But this precision on $\Delta\sin^2\theta^{lept}_W$ can only be exploited at FCC-ee!

Point-to-point errors

	$A_{FB}^{\mu\mu}$ @ FCC-ee	$A_{FB}^{\mu\mu}$ @ FCC-ee 90% correlation	0.23 correlation (est. by M.K.)
visible Z decays	$2.8\ 10^{12}$		
muon pairs	$1.1\ 10^{11}$		
$\Delta A_{FB}^{\mu\mu}$ (stat)	$3\ 10^{-6}$		
$\Delta\ E_{cm}$ (MeV)	0.1	**0.01 ?**	**0.023**
$\Delta A_{FB}^{\mu\mu}$ (E_{CM})	$9.2\ 10^{-6}$	**$9.2\ 10^{-7}$?**	**$2.4\ 10^{-6}$**
$\Delta A_{FB}^{\mu\mu}$	$1.0\ 10^{-5}$	**$3\ 10^{-6}$?**	**$4\ 10^{-6}$**
$\Delta\sin^2\theta^{lept}_W$ (abs)	$5.9\ 10^{-6}$	**$1.8\ 10^{-6}$?**	**$2.2\ 10^{-6}$**

What matters for $A_{FB}^{\mu\mu}$ is the relative error between the Z peak point and the two off-peak points which determine the Z mass. Understanding the point-to-point errors in the energy calibration will be crucial. Presumably quite smaller.
This question has been touched on by M. Koratzinos, needs revisiting.

This would mlead to $\Delta\sin^2\theta^{lept}_W$ (abs) = **1.6 (stat) + 1.5-6(syst) 10^{-6}**

Uncertainty on Rl= Γ_{had} / Γ_{lepton} present LEP uncertainty : 20.767± 0.025 (rel 1.2 10^{-3})

1. statistically the error is dominated by that on the number of leptons

   take 10^{11} for one lepton type → DR/R = $10^{-5}/\sqrt{10}$ = 3 10^{-6}

   take three types and increase a bit for the electrons → ΔR/R = 2 10^{-6}

2. R=20.8 → ΔR = 4 10^{-5} 0.00004

3. systematic error due to lepton geometrical acceptance

   assume acceptance extends down to θ = 10 degrees

   → acceptance is given by $\int_{10}^{90} (1+\cos^2\theta)\, d\cos\theta/(4/3)$ = 0.977383856

   then assume that we have a precision on that angle of 50microns over 2m (2.5 10^{-5})

   the acceptance changes by 1.3 10^{-5}

   (the report gives 5 10^{-5} which corresponds to 200 um at 2m)

   this is a relative error

4. assuming this is an adequate number for the systematic error, we can compare with the present uncertainty of 20.767± 0.025 (rel 1.2 10^{-3})

taking error as 5 10^{-5} compared to LEP 1.2 10^{-3} gives an improvement by a **factor 25**
taking rel error as 1.3 10^{-5} would give factor 100.
I do not understand where **factor 8 in vol 5** comes from.

5. the uncertainty on α_s is such that
$\Delta\alpha_s = \pi.\ \Delta R/R$ = 1.6 10^{-4} or 4 10^{-5} if one takes 5 or 1.3 10^{-5}as relative uncertainty.

My take: the error is probably smaller than 5 10^{-5} relative (20.767±0.001) rather 1.3 10^{-5}

Uncertainty on $R_b = \Gamma_b/\Gamma_h$

best performance was obtained by SLD with 62% tagging efficiency at 97.8% purity

in 400'000 Z→ qq evts arxiv:0503005 obtained a precision of 0.216±0.001 (stat)

with 2.8 10^{12} Z→ qq, statistical error should be ±0.0000037(3.7 10^{-7} stat, absolute)

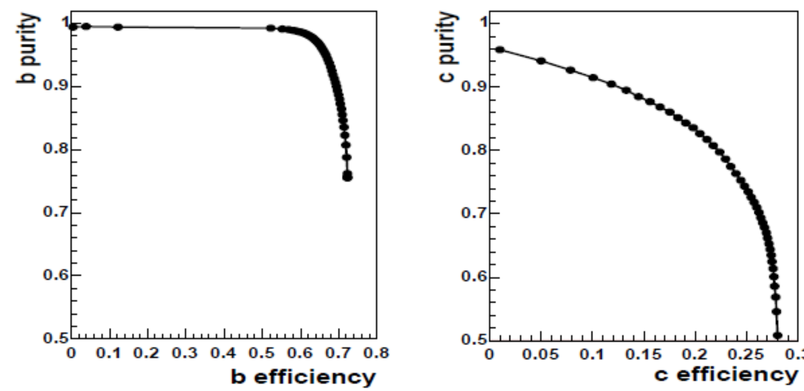
SLAC–PUB–9941
February, 2005

Measurement of the branching ratios of the Z^0 into heavy quarks*

Koya Abe,[23] Kenji Abe,[14] T. Abe,[20] I. Adam,[20] H. Akimoto,[20] D. Aston,[20] K.G. Baird,[10] C. Baltay,[29] H.R. Band,[28] T.L. Barklow,[20] J.M. Bauer,[11] G. Bellodi,[16] R. Berger,[20] G. Blaylock,[10] J.R. Bogart,[20] G.R. Bower,[20] J.E. Brau,[15] M. Breidenbach,[20] W.M. Bugg,[22] D. Burke,[20] T.H. Burnett,[27] P.N. Burrows,[16] A. Calcaterra,[7] R. Cassell,[20] A. Chou,[20] H.O. Cohn,[22] J.A. Coller,[3] M.R. Convery,[20] V. Cook,[27] R.F. Cowan,[12] G. Crawford,[20] C.J.S. Damerell,[18] M. Daoudi,[20] N. de Groot,[18] R. de Sangro,[7] D.N. Dong,[12] M. Doser,[20] R. Dubois, I. Erofeeva,[13] V. Eschenburg,[11] E. Etzion,[28] S. Fahey,[4] D. Falciai,[7] J.P. Fernandez,[25] K. Flood,[10] R. Frey,[15] E.L. Hart,[22] K. Hasuko,[23] S.S. Hertzbach,[10] M.E. Huffer,[20] X. Huynh,[20] M. Iwasaki,[15] D.J. Jackson,[18] P. Jacques,[19] J.A. Jaros,[20] Z.Y. Jiang,[20] A.S. Johnson,[20] J.R. Johnson,[28] R. Kajikawa,[14] M. Kalelkar,[19] H.J. Kang,[19] R.R. Kofler,[10] R.S. Kroeger,[11] M. Langston,[15] D.W.G. Leith,[20] V. Lia,[12] C. Lin,[10] G. Mancinelli,[19] S. Manly,[29] G. Mantovani,[17] T.W. Markiewicz,[20] T. Maruyama,[20] A.K. McKemey,[2] R. Messner,[20] K.C. Moffeit,[20] T.B. Moore,[29] M. Morii,[20] D. Muller,[20] V. Murzin,[13] S. Narita,[23] U. Nauenberg,[4] H. Neal,[29] G. Nesom,[16] N. Oishi,[14] D. Onoprienko,[22] L.S. Osborne,[12] R.S. Panvini,[26] C.H. Park,[21] I. Peruzzi,[7] M. Piccolo,[7] L. Piemontese,[6] R.J. Plano,[19] R. Prepost,[28] C.Y. Prescott,[20] B.N. Ratcliff,[20] J. Reidy,[11] P.L. Reinertsen,[25] L.S. Rochester,[20] P.C. Rowson,[20] J.J. Russell,[20] O.H. Saxton,[20] T. Schalk,[25] B.A. Schumm,[25] J. Schwiening,[20] V.V. Serbo,[20] G. Shapiro,[9] N.B. Sinev,[15] J.A. Snyder,[29] H. Staengle,[5] A. Stahl,[20] P. Stamer,[19] H. Steiner,[9] D. Su,[20] F. Suekane,[23] A. Sugiyama,[14] A. Suzuki,[14] M. Swartz,[8] F.E. Taylor,[12] J. Thom,[20] E. Torrence,[12] T. Usher,[20] J. Va'vra,[20] R. Verdier,[12] D.L. Wagner,[4] A.P. Waite,[20] S. Walston,[15] A.W. Weidemann,[22] E.R. Weiss,[27] J.S. Whitaker,[3] S.H. Williams,[20] S. Willocq,[10] R.J. Wilson,[5] W.J. Wisniewski,[20] J.L. Wittlin,[10] M. Woods,[20] T.R. Wright,[28] R.K. Yamamoto,[12] J. Yashima,[23] S.J. Yellin,[24] C.C. Young,[20] H. Yuta.[1]

(The SLD Collaboration)

Figure 5: Purity vs. efficiency for hemispheres in (a) charm and (b) bottom events, as the selection neural network cut is varied.



we can certainly do better than that…

and we have 0.7 10^7 times more events.

	96			97-98		
R_b	0.21432	±	0.00289	0.21624	±	0.00104
ϵ_b(data)(%)	56.63	±	0.67	62.01	±	0.24
ϵ_b(MC)(%)	56.91	±	0.08	61.78	±	0.03
Π_b (%)	97.8	±	0.4	97.9	±	0.1
ϵ_c(MC)(%)	1.24	±	0.02	1.19	±	0.01
ϵ_{uds}(MC)(%)	0.113	±	0.006	0.134	±	0.003
$C_b - 1$(MC)	0.0067	±	0.0015	-0.00012	±	0.00049
$C_c - 1$(MC)	0.16	±	0.26	0.30	±	0.12
N events	29996			191770		
N single tag	3315			20738		
N double tag	2091			16048		

Table 1: R_b result and tagging performance parameters. Π_b is the hemisphere b-tag purity. All errors are statistical only.

from this I expect a statistical error of

Rb= 0.216xxxxx ± 0.00000037 …. (3.7 10^{-7})

Uncertainty on A_{FB}^{b}

AFBb (ALEPH) = 0.1010 ± 0.0025 ± 0.0012

using 4 10^{6} hadronic Z decays

Ab(SLD) = 0.923 ± 0.020

using 400000 hadronic Z decays

rescaled to FCC-ee (2.8 10^{12} hadronic Zs) → 0.000006 (6 10^{-6})

A sample of observables (more coming)

Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_Z (MeV)	Lineshape	91187.5 **± 2.1**	**0.005**	**< 0.1**	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 **± 2.3**	**0.008**	**< 0.1** *	QED / EW
R_l	Peak	20.767 **± 0.025**	**0.001**	**< 0.001**	Statistics
R_b	Peak	0.21629 **± 0.00066**	**0.000003**	**< 0.00006**	$g \to bb$
N_ν	Peak	2.984 **± 0.008**	**0.00004**	**< 0.004**	Lumi meast
$\sin^2\theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 **± 0.00016**	**0.000003**	**<0.000005** *	Beam energy
$1/\alpha_{QED}(m_Z)$	$A_{FB}^{\mu\mu}$ (off-peak)	128.952 **± 0.014**	**0.004**	**< 0.004**	QED / EW
$\alpha_s(m_Z)$	R_l	0.1196 **± 0.0030**	**0.00001**	**<0.0002**	New Physics
m_W (MeV)	Threshold scan	80385 **± 15**	**0.6**	**< 0.6**	EW Corr.
Γ_W (MeV)	Threshold scan	2085 **± 42**	**1.5**	**<1.5**	EW Corr.
N_ν	$e^+e^- \to \gamma Z, Z \to \nu\nu, ll$	2.92 **± 0.05**	**0.001**	**< 0.001**	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 **± 0.27**	**0.00018**	**< 0.0001**	CKM Matrix
m_{top} (MeV)	Threshold scan	173340 **± 760 ± 500**	**20**	**<40**	QCD corr.
Γ_{top} (MeV)	Threshold scan	**?**	**40**	**<40**	QCD corr.
λ_{top}	Threshold scan	μ = 1.2 **± 0.3**	**0.08**	**< 0.05**	QCD corr.
ttZ couplings	$\sqrt{s}$ = 365 GeV	**~30%**	**~2%**	**<2%**	QCD corr

* work to do: check if we cant improve

A sample of observables (more coming)

Observable	Measurement	Current precision	FCC-ee **stat.**	**Possible syst.**	Challenge
m_Z (MeV)	Lineshape	91187.5 **± 2.1**	**0.0028**	**0.1**	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 **± 2.3**	**0.0045**	**0.02-0.1**	QED / EW
R_l	Peak	20.767 **± 0.025**	**0.00004**	**0.00025-0.00100**	Statistics
R_b	Peak	0.21629 **± 0.00066**	**0.0000003**	**< 0.00006**	g → bb
N_ν	Peak	2.984 **± 0.008**	**0.00004**	**0.001**	Lumi meast
$\sin^2\theta_W^{eff}$	$A_{FB}^{\mu\mu}$ (peak)	0.23148 **± 0.00016**	**0.000002**	**0.00000(2-5)**	Beam energy
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N_ν	$e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, ll$	2.92 **± 0.05**	**0.0008**	**<0.0004**	?
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ttZ couplings	√s = 365 GeV	**~30%**	**~2%**	**<2%**	QCD corr

* work to do: check if we cant improve

1. The statistical errors give a good estimate of the potential of the facility
Also they set proper targets for systematics both experimentally and theoretically.

2. They are fairly straightforward and I would welcome some cross-check.