Luminosity targets for FCC-ee

- **Outline**
  - Reminder: Expected luminosity as a function of $\sqrt{s}$
  - A very rich physics programme !
    - The Z pole scan, $\sqrt{s} \sim m_Z$ = 88-95 GeV ["90"]
    - The WW threshold scan, $\sqrt{s} \sim 2\, m_W \sim$ 160-170 GeV ["160"]
    - The Higgs factory, $\sqrt{s} \sim m_H+m_Z+25$ GeV ~ 220-240 GeV ["240"]
    - The top threshold scan, $\sqrt{s} \sim 2\, m_{top} \sim$ 340-370 GeV ["350"]
    - And also …
      - The Hee coupling and N_ν , $\sqrt{s} \sim m_H \sim$ 125 GeV
      - The EM coupling constant $\alpha_{QED}(m_Z)$, $\sqrt{s} = m_Z \pm 3.5$ GeV
      - The highest centre-of-mass energy, $\sqrt{s}$ = ?
    - And maybe more ?

Expected luminosity as a function of √s (1)

- From F. Zimmermann's presentation in Washington
  - Instantaneous luminosities / IP, expressed in 10^{34} $cm^{-2}s^{-1}$
    - B = Baseline, C = Crabbed-waist, 2/4 = number of IPs

√s (GeV)	B4	B2	C4	C2
90	21	27	215	277
160	10.4	13	38	38
240	5.3	7	8.7	11.0
350	1.5	1.9	2.1	2.6

- Note 1 : Luminosity increase at each IP for 2 IPs being challenged by Frank ?
- Note 2: Need official "working numbers", kept up-to-date (e.g., on the FCC-ee site)

Expected luminosity as a function of √s (2)

- Total integrated luminosity / year (10^7 seconds) in ab^{-1}
  - Summed over all IPs
    - B = Baseline, C = Crabbed-waist, 2/4 = number of IPs

√s (GeV)	B4	B2	C4	C2
90	8.4	5.4	86.0	55.4
160	4.16	2.6	15.2	7.6
240	2.12	1.4	3.48	2.20
350	0.60	0.38	0.84	0.52

➨ Up to twice more lumi with 4 IPs than with 2 IPs

Increase of the running time by a factor 2 with 2 IPs for the same physics

Expected luminosity as a function of √s (3)

- **Number of events / year**
  - Summed over all IPs

√s (GeV)	B4	B2	C4	C2	ILC programme	@FCC-ee
90 (Z)	3.6×10^{11}	2.3×10^{11}	3.7×10^{12}	2.4×10^{12}	10^{9} ?	1 day C4
160 (WW)	1.7×10^{7}	1.0×10^{7}	6.1×10^{7}	3.0×10^{7}	10^{5} ?	1 week C4
240 (HZ)	4.2×10^{5}	2.8×10^{5}	7.0×10^{5}	4.4×10^{5}	7×10^{4}	1 month C4
350 (tt)	3.0×10^{5}	1.9×10^{5}	4.2×10^{5}	2.6×10^{5}	1.4×10^{5}	4 months C4
350 (WW→H)	1.8×10^{4}	1.2×10^{4}	2.5×10^{4}	1.5×10^{4}	3.5×10^{4} @500 GeV	1.5 years C4

(2 years)

  - Do we need that much more luminosity at FCC-ee ? For what physics ?

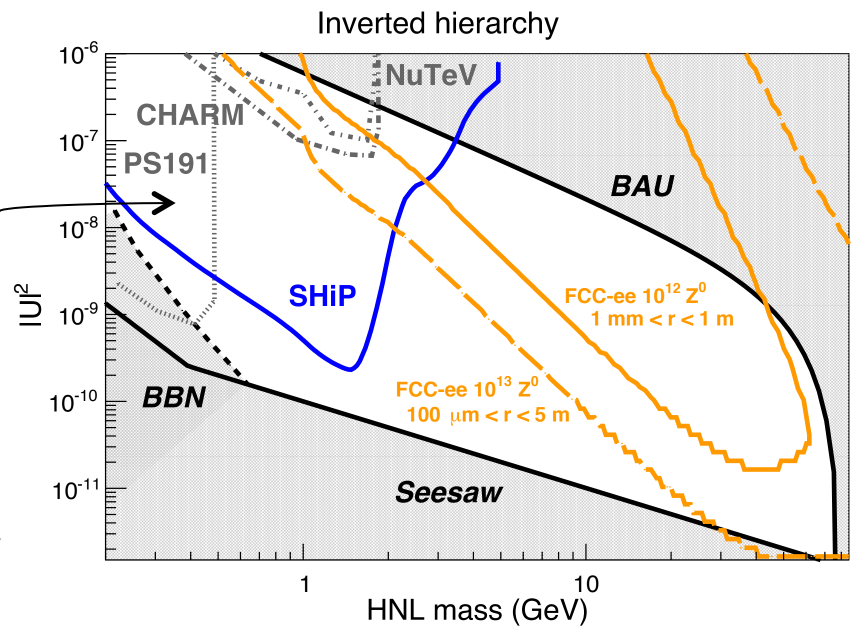
The Z pole

- **Lineshape**
  - m_Z and Γ_Z measurements limited to ~50 keV by the E_{beam} measurement
    - 5×10^{10} Z suffice to reach this statistical precision
      - ➨ A few weeks in the first C4 year with 20% of the RF power.
      - ➨ Polarization is mandatory: implies learning precise tuning of the accelerator
- **Asymmetries**
  - $A^{FB}_{\mu\mu}$ limited to 5×10^{-6} by the E_{beam} measurement
    - 10^{12} Z suffice to reach this statistical precision (= 3 B4 years with full RF power)
      - ➨ Can be done in the first C4 year with 20% of the RF power.
- **Search for rare processes**
  - Ex: RH neutrino search needs at least 10^{13} Z
    - ➨ 2.5 years of C4 with full RF needed

      Or 4 years of C2

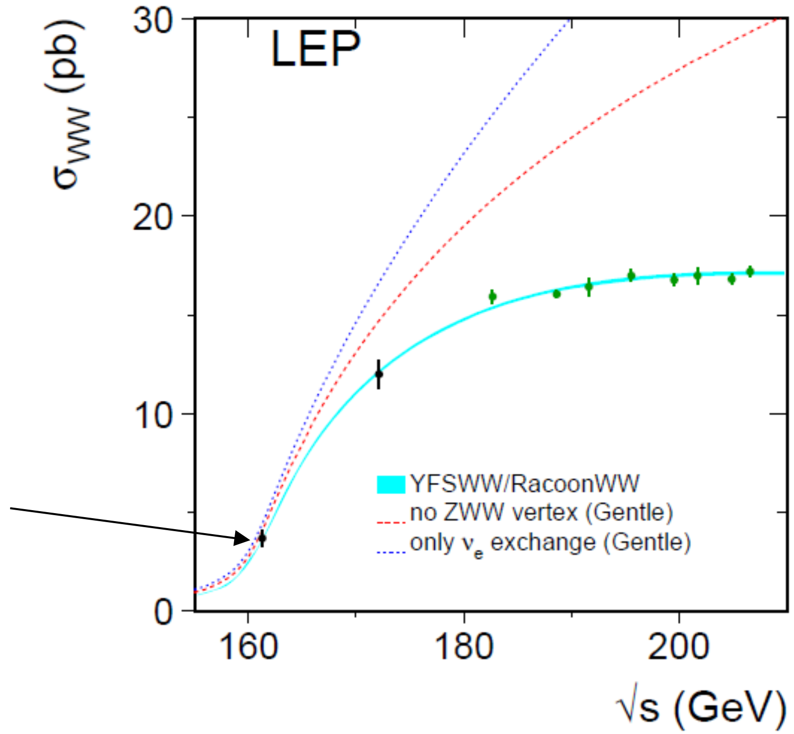
      Or 25 years of B4

      Or 40 years of B2
  - Towards major discovery(ies)
    - or definitive exclusion in the 20-80 GeV range



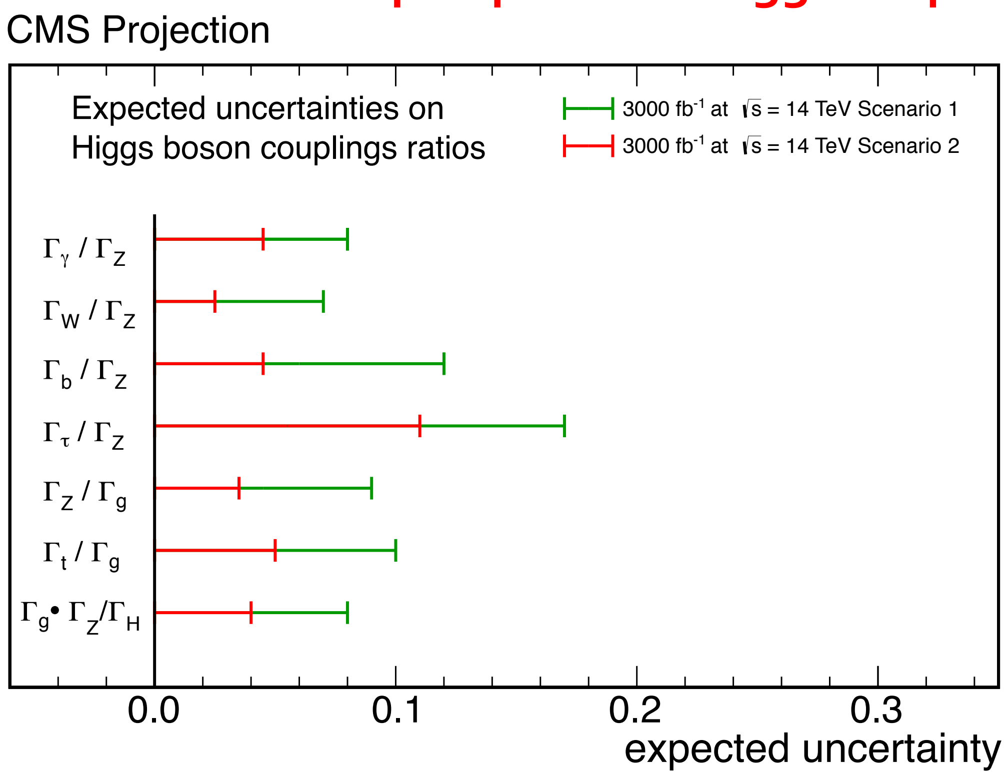
The WW threshold

- W mass measurement @ threshold
  - σ_{WW} measurement limited to 2×10^{-4} (?) by luminosity measurement accuracy
    - Translates to an uncertainty of 300 keV on the W mass
  - About 5×10^{7} W at threshold suffice to reach this statistical precision.
    - Can be done in one C4 year with full RF power
      - Or two C2 years
      - Or three B4 years
      - Or five B2 years



The Higgs factory (1)

- **Reminder: HL-LHC prospects for Higgs coupling ratios**



- **As soon as a lepton collider is turned on, the HZZ coupling is "fixed" from σ_{HZ}**
  - **Model-independent coupling precision vary from 2% (HWW) to 10% (H$\tau\tau$)**

- **Need a meaningful step after HL-LHC ➔ improve by at least one order of magnitude**

The Higgs factory (2)

- **Reminder: TLEP prospects**
  - At 240 GeV: 2 million HZ events; At 350 GeV: 70,000 WW -> H events
    - ~Same running time at 240 and 350 GeV
    - CMS detector simulation: conservative projections

	Model-independent fit			HL-LHC
Coupling	TLEP-240	TLEP		
g_{HZZ}	0.16%	**0.15%**	(0.18%)	–
g_{HWW}	0.85%	**0.19%**	(0.23%)	2-4%
g_{Hbb}	0.88%	**0.42%**	(0.52%)	3-6%
g_{Hcc}	1.0%	**0.71%**	(0.87%)	–
g_{Hgg}	1.1%	**0.80%**	(0.98%)	2-5%
$g_{\mathrm{H}\tau\tau}$	0.94%	**0.54%**	(0.66%)	6-9%
$g_{\mathrm{H}\mu\mu}$	6.4%	**6.2%**	(7.6%)	~10%
$g_{\mathrm{H}\gamma\gamma}$	1.7%	**1.5%**	(1.8%)	3-5%
BR_{inv}	0.1%	0.1%		10%

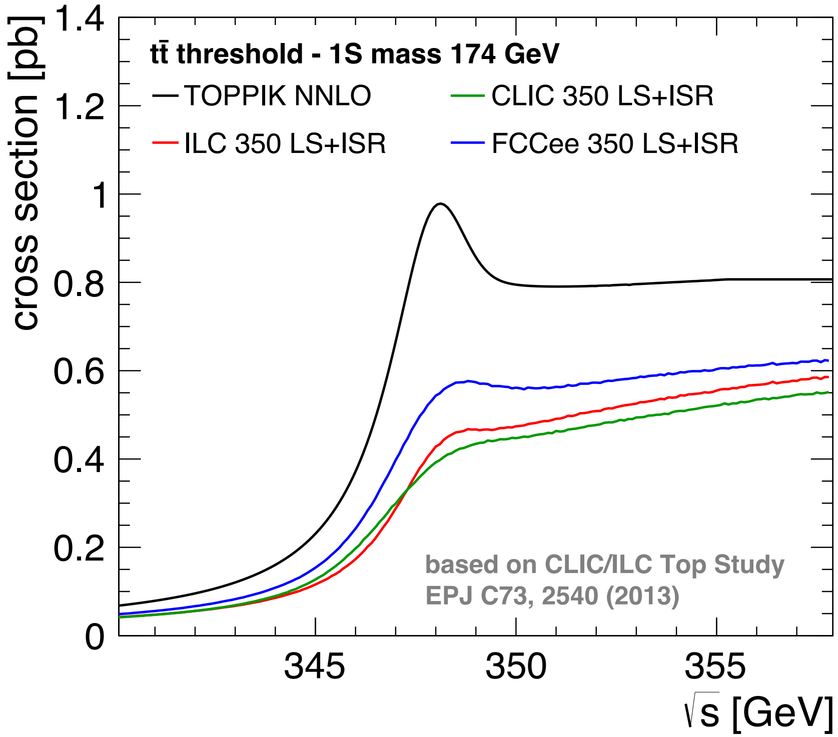
  - About an order of magnitude improvement for FCC-ee over the "constrained" HL-LHC
    - 2 million HZ events and 70,000 WW -> H events are about the right amount

The Higgs factory (3)

- **To get two million HZ events at 240 GeV, one needs**
  - Three years in the C4 configuration
    - Or five years in the C2 configuration
    - Or five years in the B4 configuration (TLEP paper)
    - Or seven years in the B2 configuration
  - Complemented by five years in the B4 configuration at 350 GeV
    - Or eight years in the B2 configuration
      - ➨ Required to optimally measure the total Higgs width and the HWW coupling
        Which in turns fixes all couplings in a model-independent manner
  - NB: These measurements are not limited by experimental systematic uncertainties
    - The more luminosity the better
      - ➨ Provided that theory calculations match the experimental precision.

The top threshold

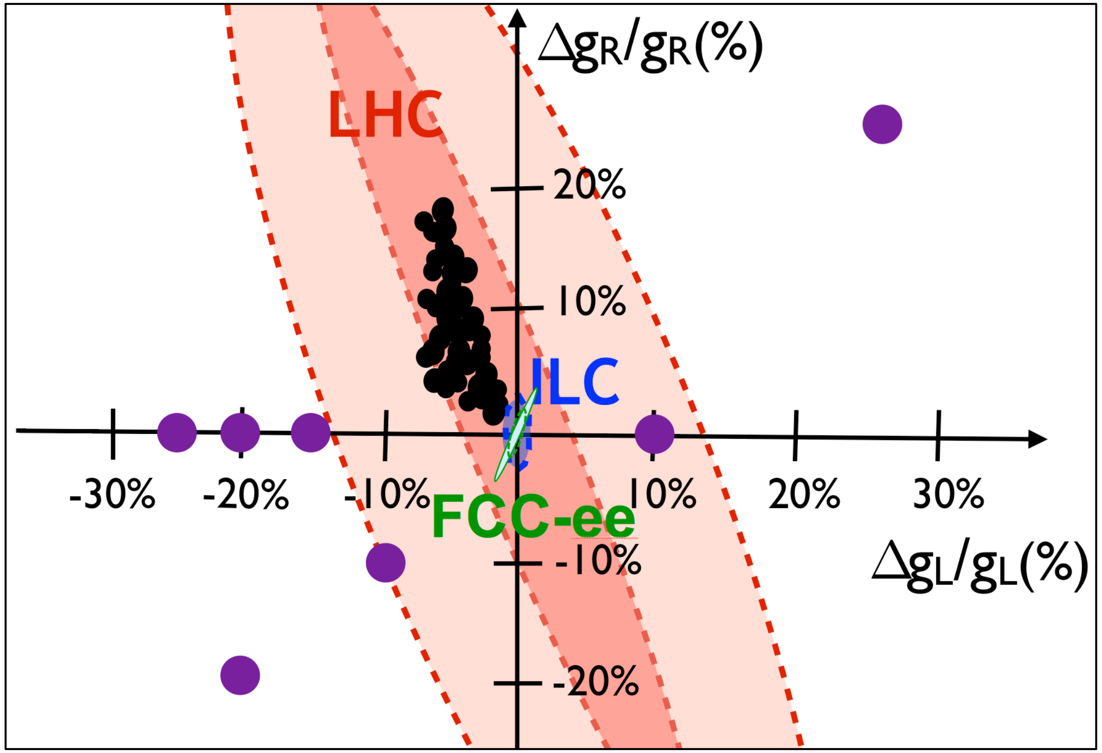
- **Scan the top threshold**
  - **With several energy points from 340 to 350 GeV**



- **A year in the B4 configuration is more than enough to reach a 15 MeV statistical accuracy on the top quark mass.**

The top electroweak couplings

- **Need to go above the top threshold**
  - Typically 365-370 GeV is almost optimal for all practical purposes
    - FCC-ee projections for the ttZ couplings
      - ➨ With four (six) years at 365 GeV in the B4 (B2) configuration



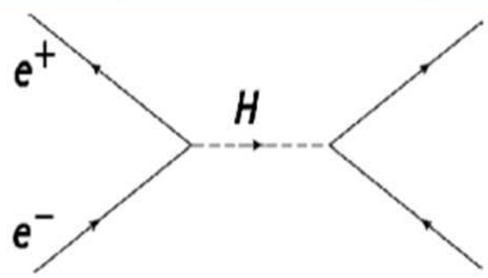
- Large improvement wrt (HL)-LHC – Separation from composite Higgs models ~ ILC.

Beyond the core programme…

- **Still under evaluation**
  - **The next four slides are very preliminary**
    - **The 4^{th} is even very vague**

The Hee coupling at √s = 125 GeV

- **The Hee coupling through resonant production in the s channel**

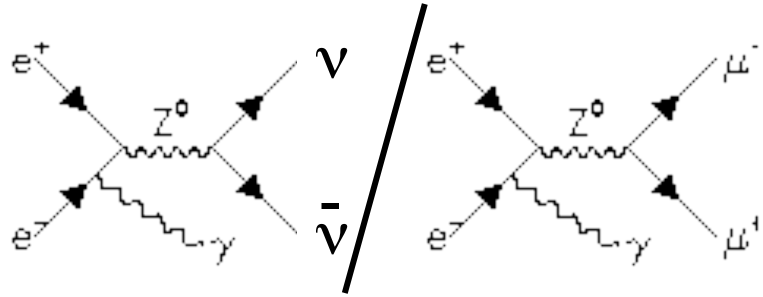


- With the use of mono-chromators ($\delta\sqrt{s}$ ~ 5 MeV)
  - Provided that they do not reduce the luminosity (!)
    - ➨ Can set an upper limit on κ_e to ~2 × SM value with 10 ab^{-1}
- In the C4 configuration, about 40 ab^{-1} are expected every year
  - Reach SM sensitivity within a year in the C4 configuration
    - ➨ Within 2 years in the C2 configuration
    - ➨ Within 8 years in the B4 configuration
    - ➨ Within 12 years in the B2 configuration
  - Could benefit from more running

Measurement of Γ_Z^{inv} at $\sqrt{s}$ = 125 GeV

- **The run at 125 GeV is also optimal for the Z invisible width measurement**
  - **Or equivalently, the "number of neutrinos" N_ν**

$$N_\nu \sim \sigma(e^+e^- \to \nu\bar{\nu}\gamma) / 2\sigma(e^+e^- \to \mu^+\mu^-\gamma)$$



- **About 0.8 billion ννγ events expected per year at $\sqrt{s}$ ~ 125 GeV (in the C4 config.)**
  - **Statistical precision on N_ν ~ 0.0003**

    Factor 25 improvement over today's precision : 0.008
  - **Possible systematic uncertainty < 0.0001**

    Could benefit from more running

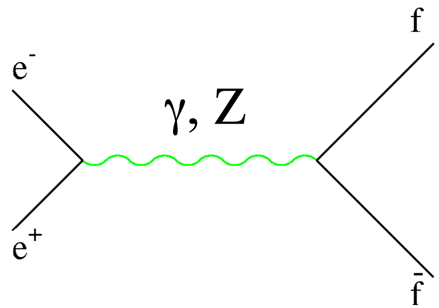
Measurement of $\alpha_{QED}(m_Z)$

- **Uncertainty dominant in the interpretation of precision measurements**
  - Limits severely the potential for new physics exploration at the FCC-ee
    - Would require this uncertainty to be reduced by at least a factor 5
  - Use the FCC-ee to measure $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ and $A_{FB}^{\mu\mu}$
    - γ exchange proportional to $\alpha^2_{QED}(\sqrt{s})$
    - Z exchange independent of α_{QED}
    - γZ interference proportional to $\alpha_{QED}(\sqrt{s})$
      - ➨ The run at the Z pole is of course not well suited to this measurement !

        Just below or just above the Z pole ? One or several points ?
      - ➨ And then use theory to extrapolate from $\alpha_{QED}(\sqrt{s})$ to $\alpha_{QED}(m_Z)$

        Not affected by e^+e^- resonances at small energies

        Theoretical error becomes negligible

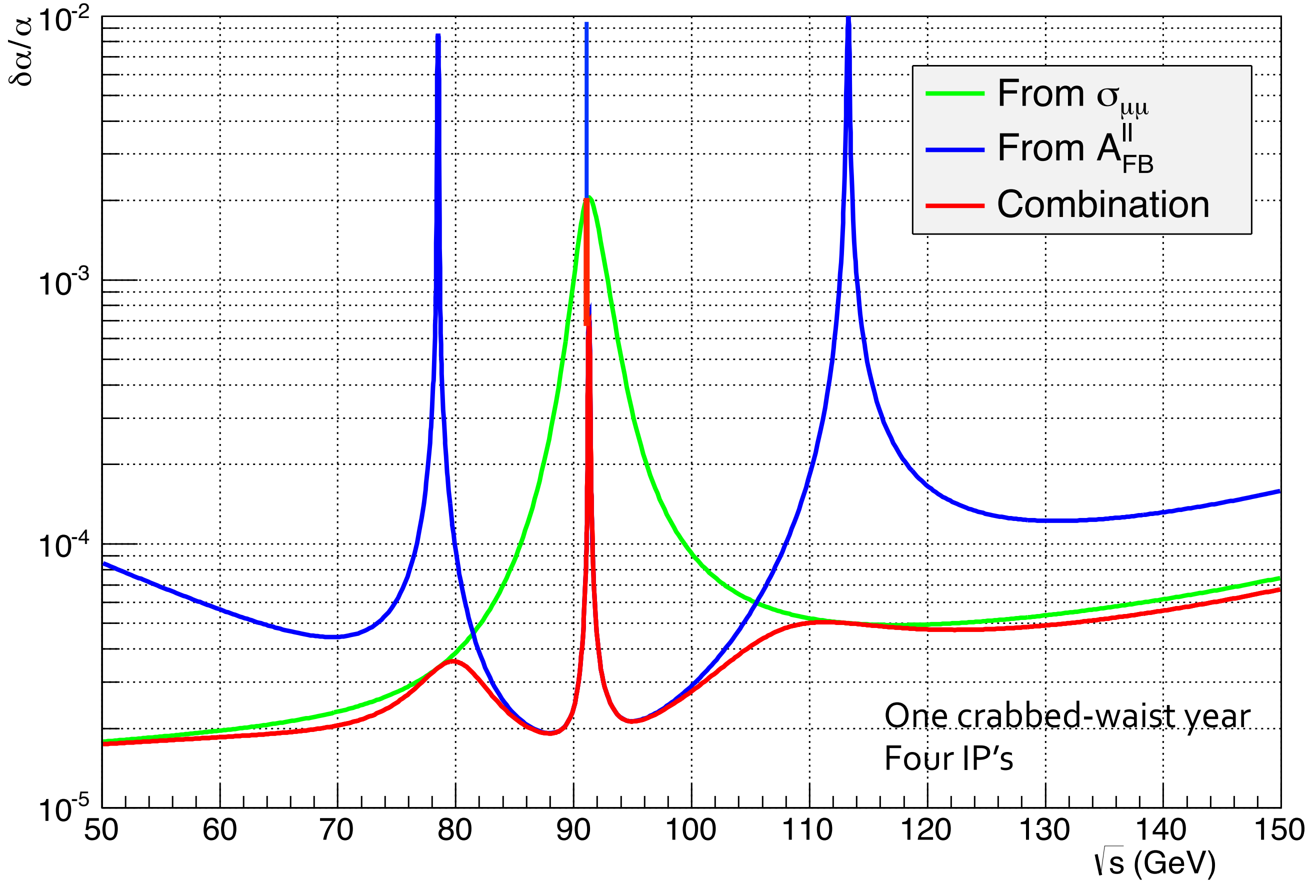


  - Challenge is that current uncertainty is ~ 10^{-4}
    - To be reduced to 2×10^{-5} or better

$$\alpha^{-1}_{QED}(m_Z) = 128.952 \pm 0.014$$

Measurement of $\alpha_{QED}(m_Z)$

- Combination of cross section ($\mu\mu$) and A_{FB} ($\mu\mu$ and $\tau\tau$), in a year (CW, 4IPs)



- Get to 2×10^{-5} at $\sqrt{s} \le 70$ GeV (cross section) and 88 / 95 GeV (forward-backward asym.)
  - Absolute cross section measurement more difficult + exotic $\sqrt{s}$: priority is to A_{FB}

The highest centre-of-mass energy ?

- **It is important to determine the ultimate √s reachable at the FCC-ee**
  - **Definition of "ultimate √s"**
    - **Manageable beam lifetime (> 10 s)**
    - **Manageable RF length**
    - **Integrated luminosity comparable to that of ILC at the same √s**
      - ➨ **Frank had inferred two years ago that $\sqrt{s}_{ult.}$ ~ 500 GeV for four IPs**
  - **If time and money allow, it might be useful to spend few years (typically three) there**
    - **Physics case still unclear – to be studied.**

Summary : the FCC-ee physics programme (1)

- Time needed (in years) at each centre-of-mass energy with full RF power

	$\sqrt{s}$	C4	C2	B4	B2
$N_Z = 10^{(12)13}$	90	(<1) 2.5	(<1) 4	(2.5) 25	(4) 40
	160	1	2	3	5
	240	3	5	5	7
	340-370	4	6	5	7
	Beyond the core programme, under study				
	88 / 95 (α_{QED})	1	1.5	10	15
	125	1	1.5	8	12
	Highest ?	3 ?	5 ?	3 ?	5 ?
	Commissioning	2	2	2	2
	TOTAL	(9) 10.5 (17.5)	(14) 17 (27)	(15.5) 38 (61?)	(24) 59 (93?)

- Only B4 an B2 configurations are used at and above 350 GeV

Summary : the FCC-ee physics programme (2)

- **The baseline design with 4 IPs allows a powerful baseline programme**
  - With all relevant precision measurements in about 15 years
    - … and already 10^{12} Z decays!

- **The crabbed-waist scheme reduces the needed time to ~10 years (4 IP)**
  - AND, most of all, renders possible exciting / crucial aspects of the physics programme
    - High-luminosity run (+ 1-2 years) at the Z peak, up to 10^{13} Z decays
      - ➨ Look for rare processes, maybe the shortest way to discovery ?
    - One year devoted to the measurement of α_{QED}
      - ➨ Just below/above the Z peak, crucial for new physics interpretation
    - And, perhaps, the possibility to measure the Hee coupling at $\sqrt{s}$ = 125 GeV

- **The option with only 2 IPs has an impact on the time needed**
  - Typically increased by 50% for the same physics outcome
    - We ought to leave open the possibility of 4 IPs

- **Forthcoming work will refine the present estimates**
  - E.g., what relevance for higher energies ?