EUROPEAN PHYSICAL SOCIETY HEP2015

FCC hh ee he

Precision Electroweak Measurements at the Future Circular e^+e^- Collider

Mogens Dam
Niels Bohr Institute
Copenhagen

On behalf of
the FCC-ee study group

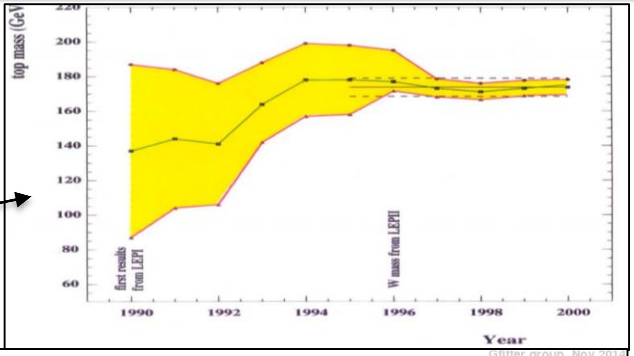
EPS-HEP 2015 – Vienna/Austria July 2015

Picture and slide layout, courtesy Jörg Wenninger

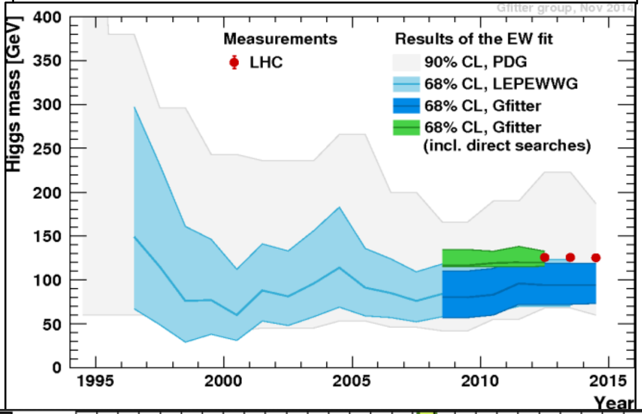
Electroweak Precision Tests (EWPT)

Historically EWPT have been instrumental in predicting/determining free parameters of the SM

- **1989-1995:**
  1. top mass predicted (LEP: mostly M_Z, Γ_Z)
  2. top quark discovered at predicted mass (Tevatron)

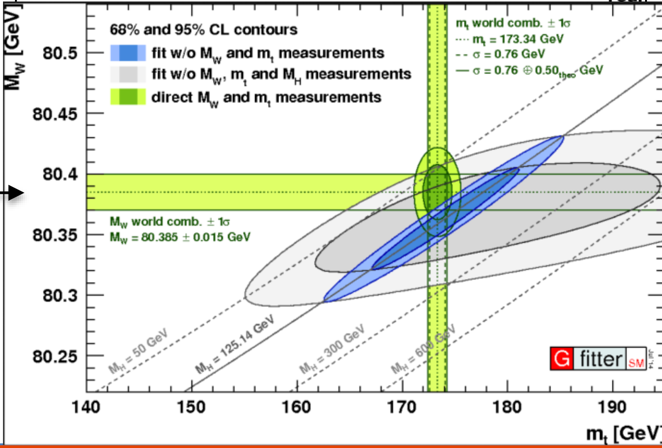


- **1995-2012:**
  1. Higgs boson mass constrained (LEP: H, M_Z etc; Tevatron: m_t, M_W)
  2. Higgs boson discovered with consistent mass (LHC)



Now, with the Higgs discovered, all SM particles are known

- There are no free knobs left to turn
- New target of EWPT: **BSM Physics**
  - Do all measurements show consistency?
  - Not known exactly how BSM physics would show up
    - ➢ Improve precision of all EW parameters!

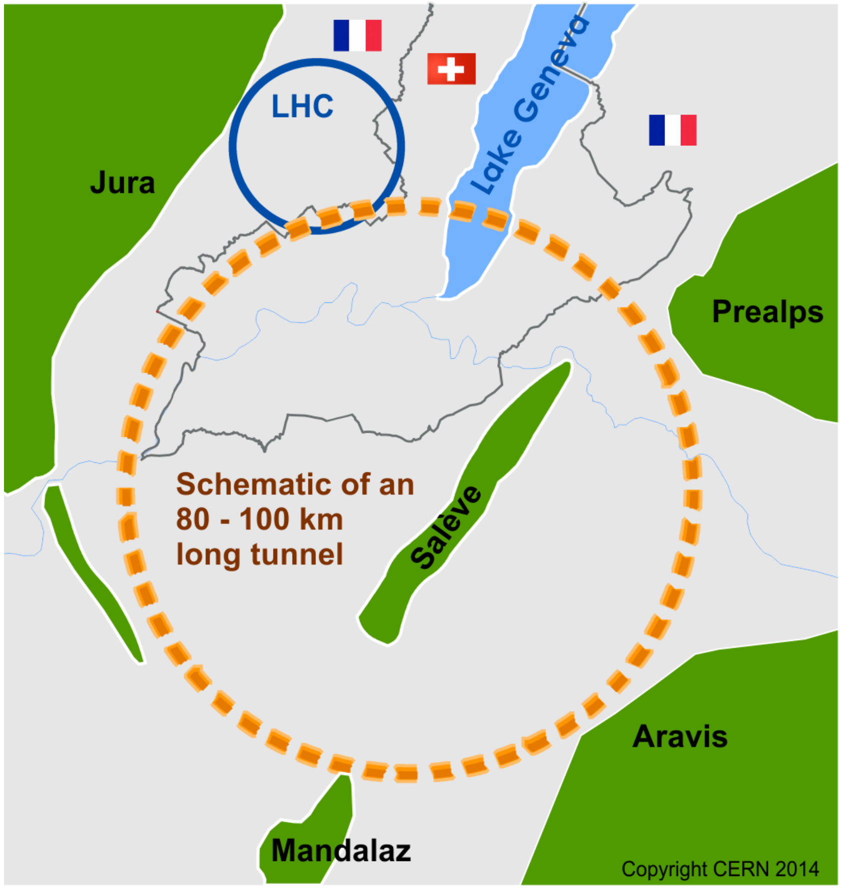


Future Circular Collider Study

With the discovery of the relatively light Higgs boson in 2012, it became clear that a high luminosity circular e^+e^- machine would constitute the optimal Higgs factory.

The study of this machine, now forms part of the

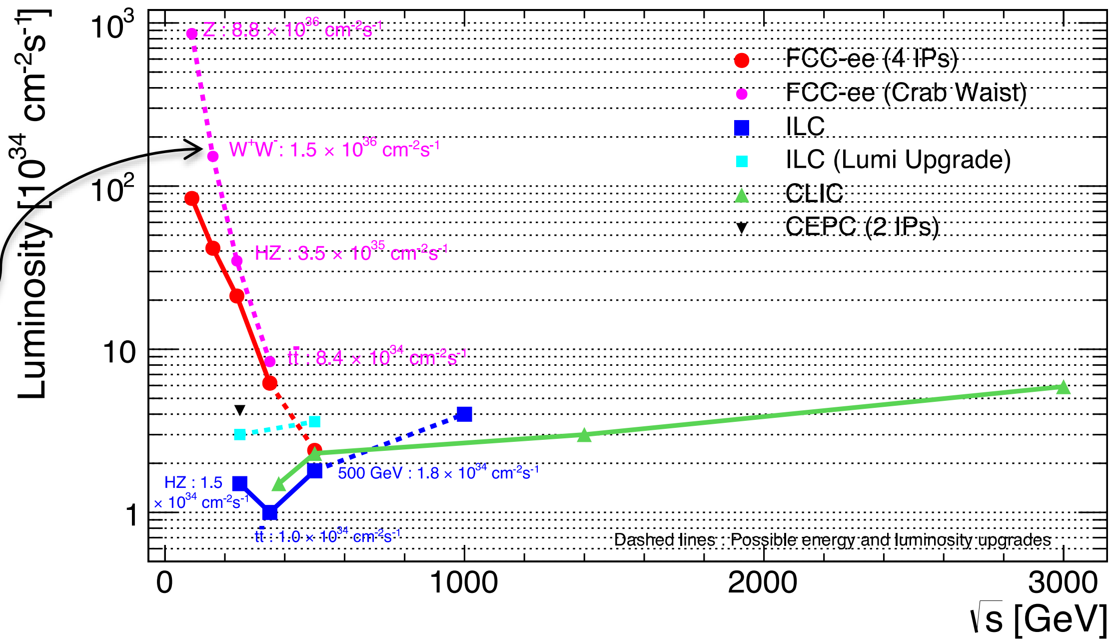
- **International FCC collaboration to study**
  - pp-collider (FCC-hh)
  - e^+e^- collider (FCC-ee)
  - p-e (FCC-he)
- 80-100 km infrastructure in Geneva area
- **Goal:** CDR and cost review by 2018 (ESU)



FCC-ee Program

Provide highest possible luminosity over a wide energy range by exploiting b-factory technologies:

- separate e^- and e^+ storage rings
- very strong focussing: β^*_y = 1mm
- top-up injection
- crab-waist crossing



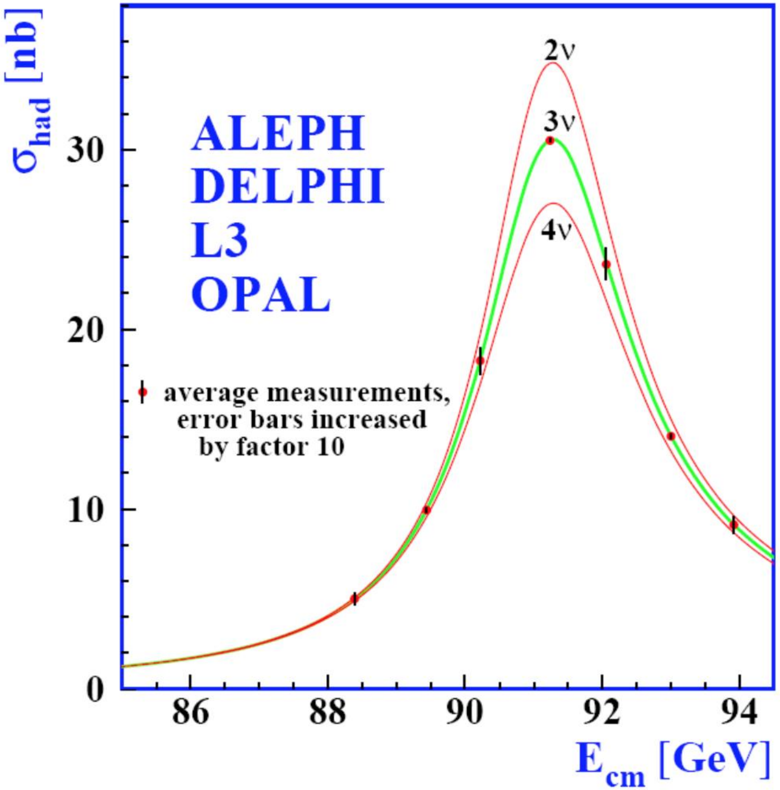
	Z	W	H	top
√s [GeV]	90	160	240	350
Physics Objective	10^{12} (10^{13}) Z	10^8 WW	2x10^6 HZ	10^6 ttbar

Higgs:
M.Klute's talk

top couplings:
P. Janot's talk

TeraZ: Z Resonance

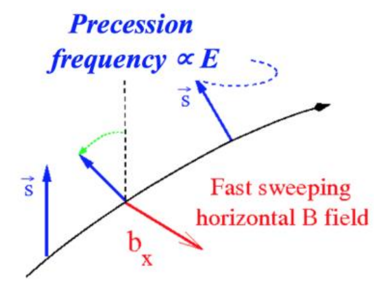
- High precision Z lineshape measurement by accumulating 10^{12} Z boson decays in an energy scan
- At LEP, reached precision O(2 MeV) on M_Z and Γ_Z. Gained experience on centre-of-mass energy determination with resonant depolarization
- At FCC-ee, potential to reach precision of <100 keV on M_Z and Γ_Z
- Improve measurement of branching ratios, e.g. R_l and R_b, and related $\alpha_s(M_Z)$ determination



Beam energy calibration via depolarization

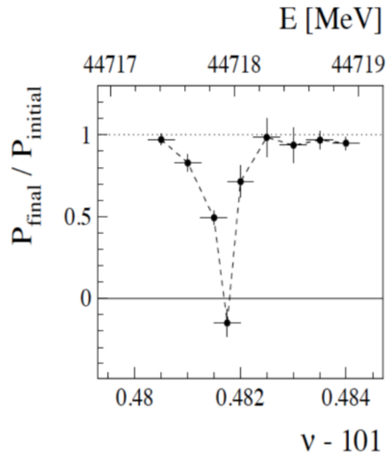
Resonant depolarization

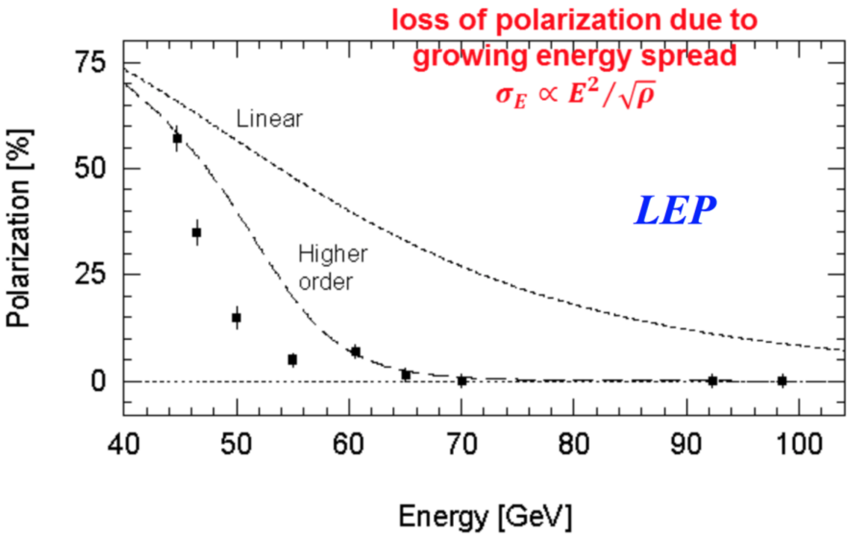
- use naturally occuring transverse beam polarization
- add fast oscillating horizontal B field to depolarize at Thomas precession frequency



Experience from LEP: Depolarization resonance very narrow: ~100 keV precision for each measurement

- However, final systematic uncertainty was 1.5 MeV due to transport from dedicated polarization runs
- At FCC-ee, continuous calibration with dedicated bunches: no transport uncertainty





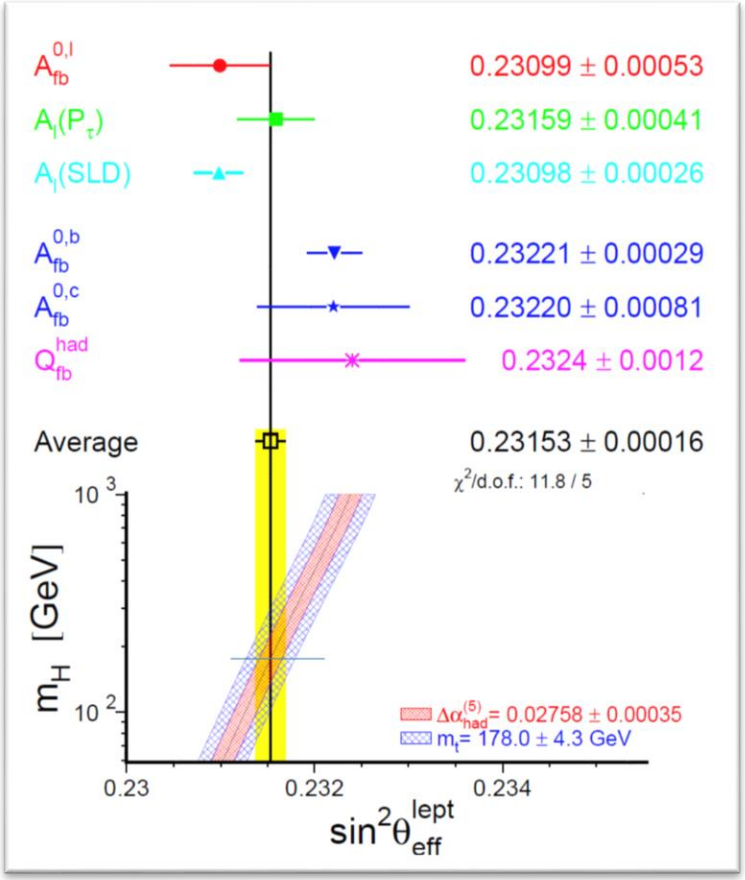
Scaling from LEP experience:

- Polarization expected up to the WW threshold

< 100 keV beam energy calibration at Z peak and at WW threshold

TeraZ: Asymmetries and $\sin^2\theta_W$

- Longstanding differences between different asymmetry measurements. Must be sorted out.
- LEP asymmetry measts. dominated by statistics
  - A_{FB}^{ll}, $A_l(P_\tau)$, A_{FB}^{bb}, A_{FB}^{cc}
- Large precision gain foreseen from $O(10^5)$ larger stats



- Study of $A_{FB}^{\mu\mu}$ alone indicates factor 50 improvement compared to LEP
  - Matching uncertainties from stats. and beam energy syst. (assumed 100 keV)
- Study of $A_{FB}^{0,b}$ alone indicates gain of factor O(10)
- Potential of other asymmetries to be studied
  - e.g. P_τ
- Also, investigate A_{LR} with long polarized beam option
  - Beam energy calibration influenced by spin rotators?

- Still early days: much work ahead …

OkuW: WW threshold scan

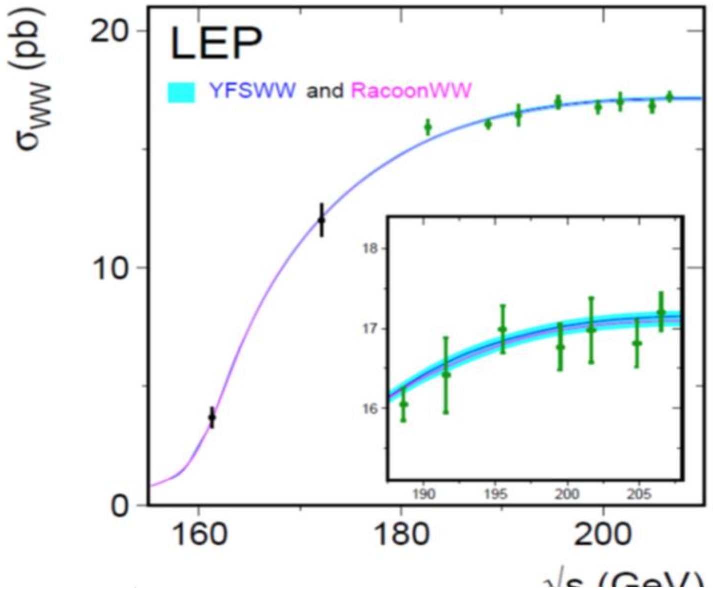
Precise W mass measurement from 10^8 events in WW threshold scan

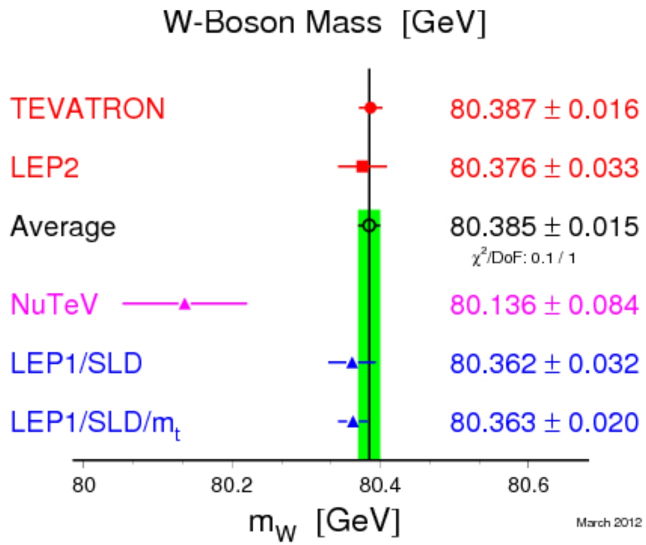
- Potential to reach 500 keV with precise E_{beam} determination via resonance depolarization at 80 GeV

Also revisit the LEP2 method of direct mass reconstruction

Precise measurement of branching fractions:

- R_e, R_μ, vs. R_τ : 3 σ diffence left over from LEP
- R_l, R_{had} : Extraction of $\alpha_s(M_W)$

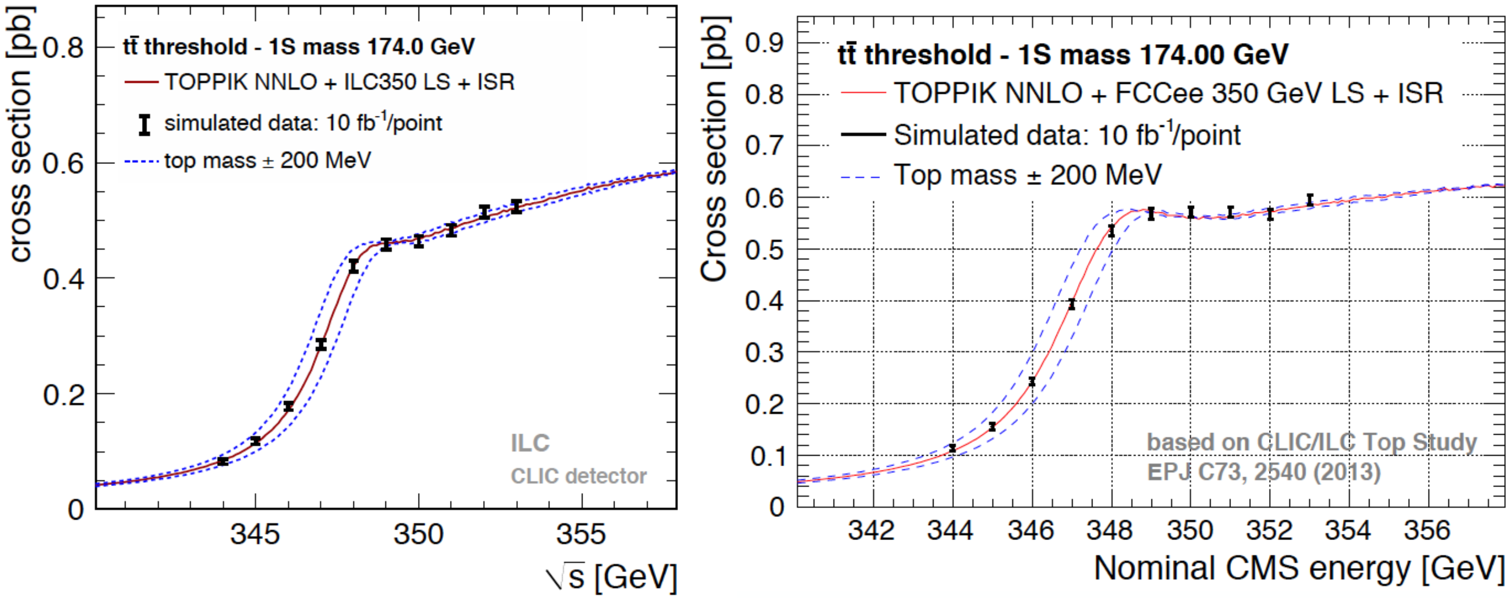




MegaTop: ttbar threshold scan

- Top mass measurement: Advantage of very low level of beamstrahlung
- Could potentially reach 10 MeV uncertainty (stat) on m_{top} (10^6 ttbar pairs)

- Comparing ILC and FCCee - assuming identical detector performance



Simulated data points - same integrated luminosity

NB: Assuming unpolarized beams - LC beams can be polarized, increasing cross-sections / reducing backgrounds

From Frank Simon, presentation at the 7th FCC-ee workshop, CERN, June 2014

Potential of $\alpha_{QED}(m_Z)$ measurement (1)

For exploitation of precision EW measurements, need precise knowledge of $\alpha_{QED}(m_Z)$

- Standard method involves extrapolation from $\alpha_{QED}(0)$ to $\alpha_{QED}(m_Z)$
  - Dispersion integral over hadronic cross section – low energy resonances: **$\delta\alpha/\alpha = 1.1 \times 10^{-4}$**

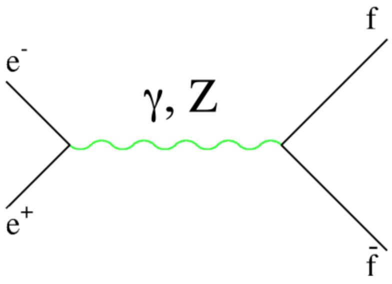
$$\alpha^{-1}_{QED}(m_Z) = 128.952 \pm 0.014$$

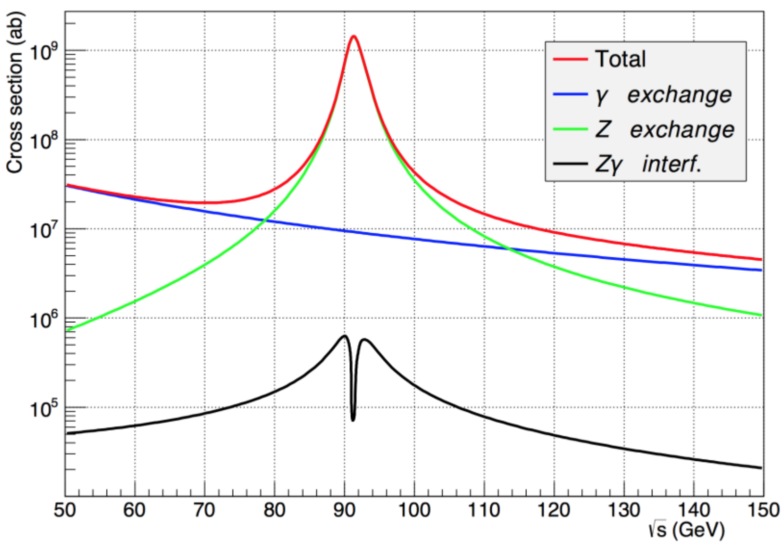
New idea: exploit large statistics of FCC-ee to measure $\alpha_{QED}(m_Z)$ directly **close to m_Z**

- Extrapolation error becomes negligible!

Two methods considered: Meast. of cross section, $\sigma(e^+e^- \to \mu^+\mu^-)$, and asymmetry, $A_{FB}^{\mu\mu}$

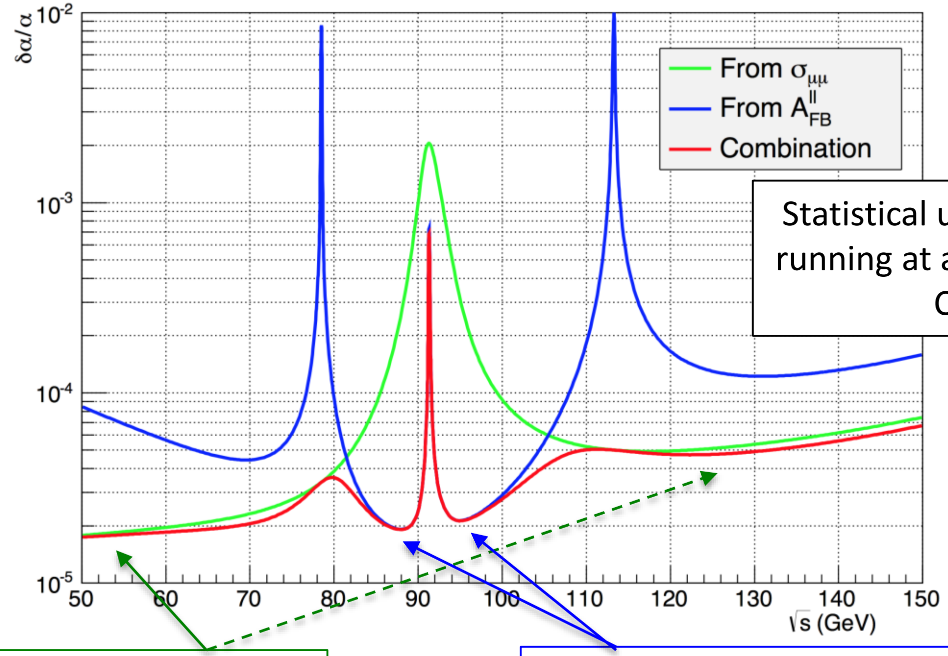
- γ exchange proportional to $\alpha^2_{QED}(\sqrt{s})$
- Z exchange independent of $\alpha_{QED}(\sqrt{s})$
- γZ interference proportional to $\alpha_{QED}(\sqrt{s})$





P. Janot: FCC-ee Physics Vidyo Meeting, June 29th 2015

Potential of $\alpha_{QED}(m_Z)$ measurement (2)



Statistical uncertainty for one year of running at any centre-of-mass energy. Crab-waiste, 4 IP.

From $\sigma_{\mu\mu}$ measurement

- Sensitivity best ”far” away from Z peak, particularly at the low side
- Systematics (normalisation) probably a killer

From $A_{FB}^{\mu\mu}$ measurement

- Sensitivity best at 88 and 95 GeV
- Experimental systs. looks controlable; further studies needed
- Theoretical systs. to large degree cancel by ”averaging” over 88 and 95 GeV point

By running six months at each of 88 and 95 GeV points:

➢ Could potentially reach a precision of : **$\delta\alpha/\alpha = 2 \times 10^{-5}$**

Strong coupling constant, $\alpha_s(m_Z)$

At LEP, a precise $\alpha_s(m_Z)$ measurement was derived from the Z decay ratio $R_l = \Gamma_{had}/\Gamma_l$.
Reinterpreting this measurement in light of: i) new N_3LO calculations; ii) improved m_{top}; and iii) knowledge of the m_{Higgs}, the uncertainty is now something like:

$$\delta\,(\alpha_s(m_Z))_{LEP} = \pm\, 0.0038\ (\text{exp.}) \pm 0.0002\ (\text{others})$$

R_l measurement was statistics dominated: Foresee a factor ≥25 improvement at FCC-ee.
From the Z-pole, therefore a resonable experimental target is

$$\delta\,(\alpha_s(m_Z))_{FCC\text{-}ee} = \pm\, 0.00015$$

Similarly, from the WW threshold, $\alpha_s(m_W)$ can be derived from the high stats measurement of $B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$

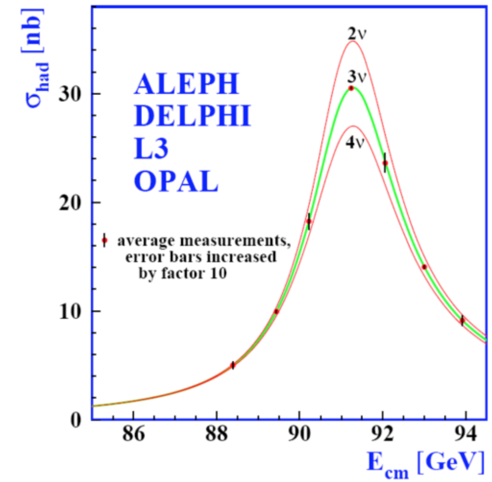
$$\delta\,(\alpha_s(m_W))_{FCC\text{-}ee} = \pm\, 0.00015$$

Combining the two above, a realistic target precision would be

$$\delta\,(\alpha_s(m_Z))_{FCC\text{-}ee} = \pm\, 0.0001$$

Neutrino counting

At the end of LEP: $N_\nu = 2.984 \pm 0.008$ 2σ “low”



Could this be pointing to non-unitarity of the PMNS matrix?

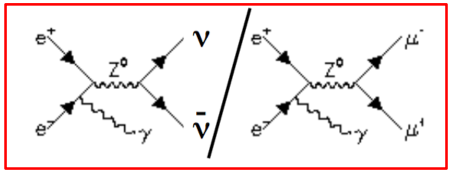
Determined from the Z line-shape scan:

- Dominated by the theoretical uncertainty on normalization, i.e. on small angle Bhabha cross section ($\oplus$0.0046 on N_ν).
- Unlikely to be improved substantially.

Alternate method:

Given the very high luminosity, the following measurement can be performed

$$N_\nu = \frac{\dfrac{\gamma Z(inv)}{\gamma Z \to ee, \mu\mu}}{\dfrac{\Gamma_\nu}{\Gamma e, \mu}\,(SM)}$$



Common γ tag allows cancellations of systematics due to photon selection, luminosity, etc.
Theory uncertainty on Γ_ν/Γ_e (SM) is very small.

During one years running at WW threshold ($3\text{x}10^7$ γZ(inv) evts) .... $\Delta N_\nu = 0.0011$

Adding 5 yrs of data at 240 and 350 GeV .... $\Delta N_\nu = 0.0008$

An interesting point is 125 GeV allowing in one year....................................... $\Delta N_\nu = 0.0004$

- Point suggested in order to measure e^+e^- -> H process directly; see M. Klute’s talk

Selected set of FCC-ee precision observables

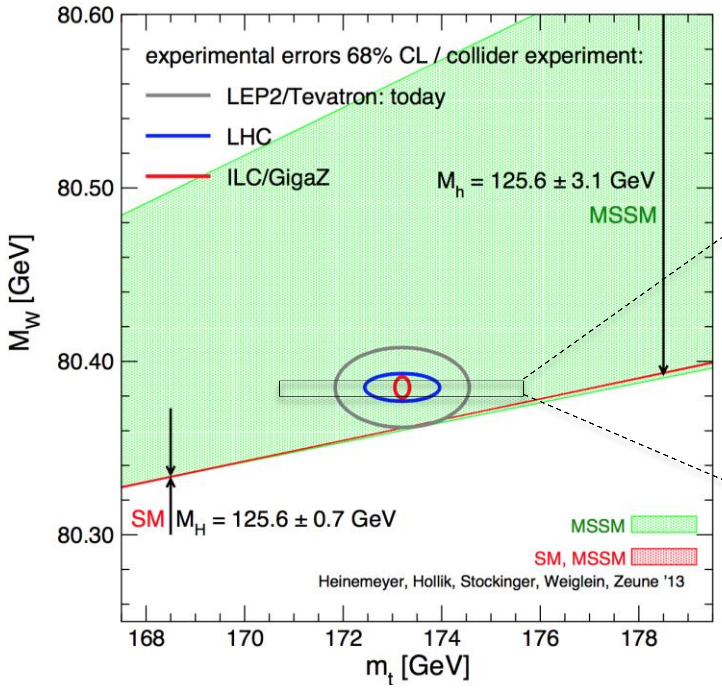
Experimental uncertainties mostly of systematic origin

- So far, mostly conservatively estimated based on LEP experience
- Work ahead to establish more solid numbers

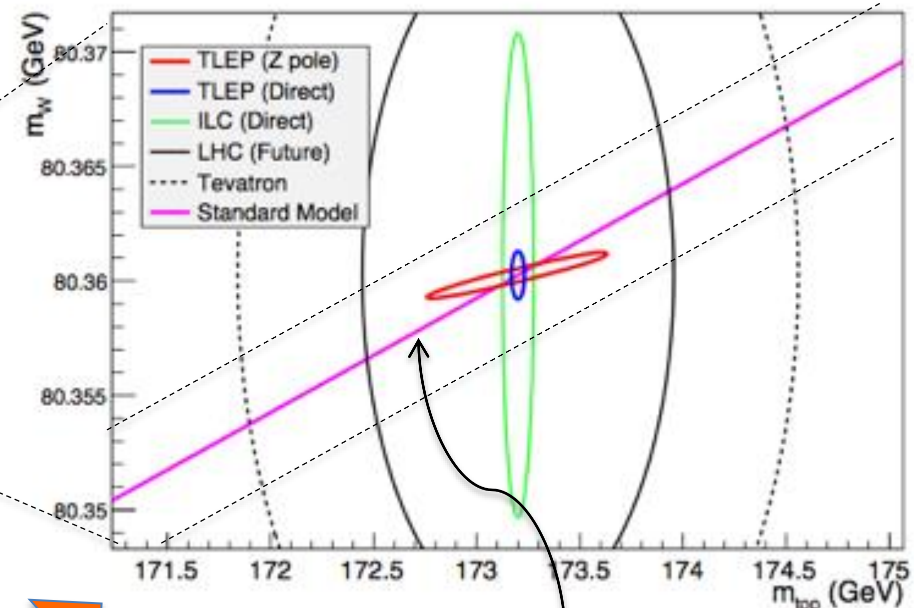
Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	g -> bb
N_ν	Peak	2.984 ± 0.008	0.00004	0.004	Lumi meast.
$A_{FB}^{\mu\mu}$	Peak	0.0171 ± 0.0010	0.000004	<0.00001	E_{beam} meast.
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.000001	0.00015	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 1	QED corr.
N_ν	Radiative return e^+e^- -> $\gamma Z(inv)$	2.92 ± 0.05 2.984 ± 0.008	0.0008	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	0.00015	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)

Generally better by factor ≥ 25

Standard Model has no free knobs left to turn:
=> Any deviations between measurements would point to New Physics



If theory uncertainties match exp'tal uncertainties



Without MZ@FCC-ee, the SM line would have a 2.2 MeV width

Presence of New Physics could dramatically change this picture

Sensitivity to New Physics

- Higher-dimensional operators as relic of new physics ?
  - Possible corrections to the Standard Model Lagrangian

$$L_{\text{eff}} = \sum_n \frac{c_n v^2}{\Lambda^2} O_n$$

$$\mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$$

$$\mathcal{O}_{LL}^{(3)\,l} = (\bar{L}_L \sigma^a \gamma^\mu L_L)\,(\bar{L}_L \sigma^a \gamma_\mu L_L)$$

$$\mathcal{O}_W = \frac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D}^\mu H\right) D^\nu W^a_{\mu\nu}$$

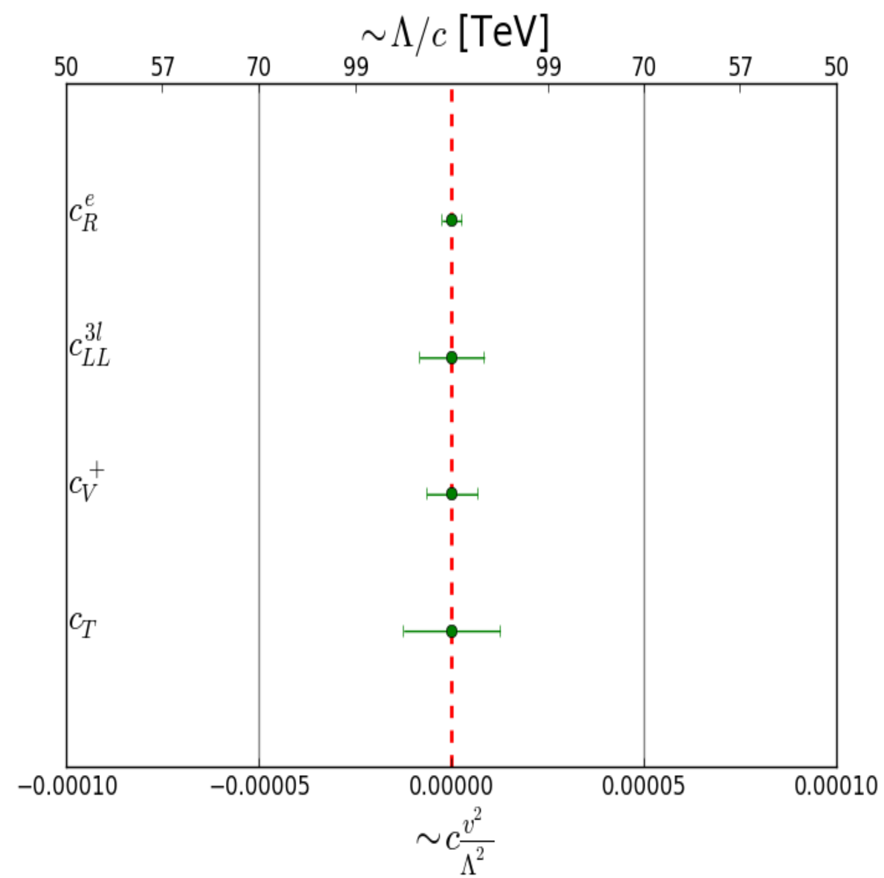
$$\mathcal{O}_B = \frac{ig'}{2}\left(H^\dagger \overleftrightarrow{D}^\mu H\right) \partial^\nu B_{\mu\nu}$$

$$\mathcal{O}_T = \frac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$

LEP constraints: Λ_{NP} > 10 TeV

After FCC-ee: Λ_{NP} > 100 TeV ?

Sensitivity to
Weakly-coupled NP



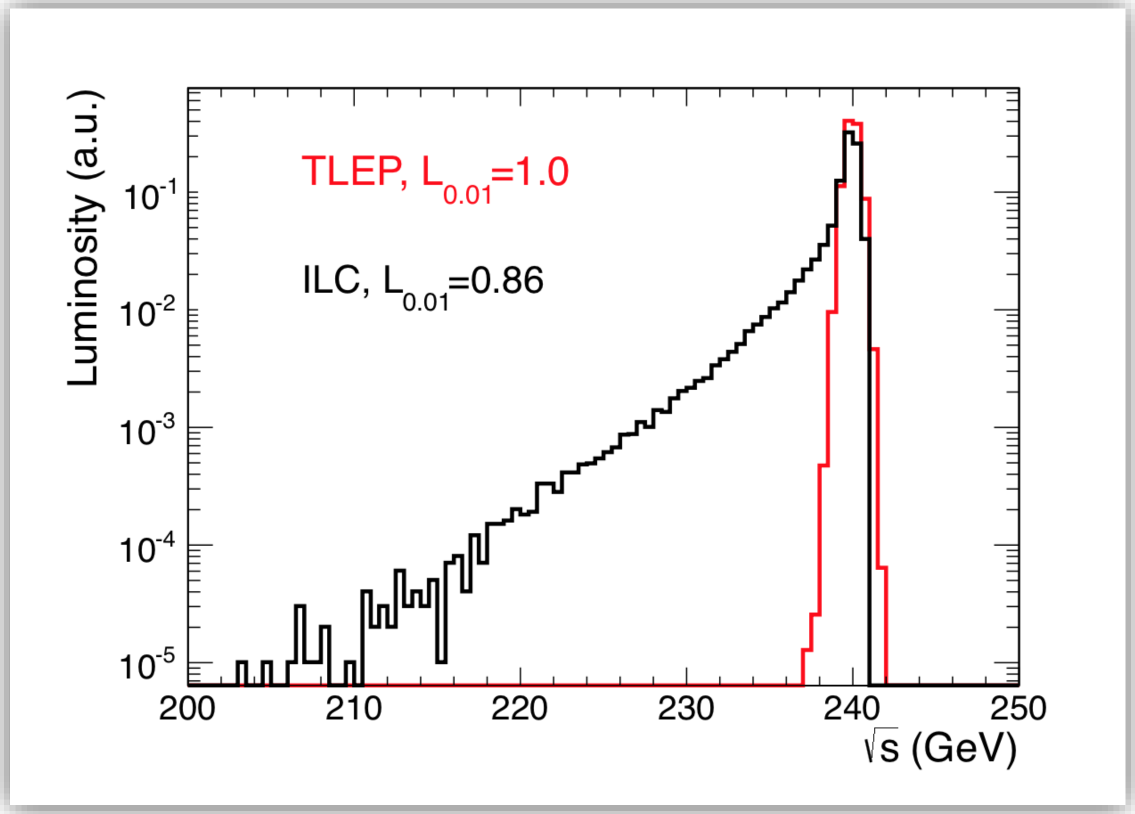
J. Ellis, T. You, see e.g. [8th FCC-ee Workshop, Paris, Oct. 2014](#)

FCC-ee Outlook

- Extremely rich physics program: The FCC-ee will enable very high precision measurements of electroweak observables at the Z pole, at the WW threshold, and at the ttbar threshold
- Exploration of the physics potential is ongoing
- New exciting ideas are appearing at a steady pace
- An important program of precision calculations will be necessary to match the experimental potential
- Many opportunities to contribute!
- Join us at http://cern.ch/FCC-ee

Backup…

Beam Energy Spread

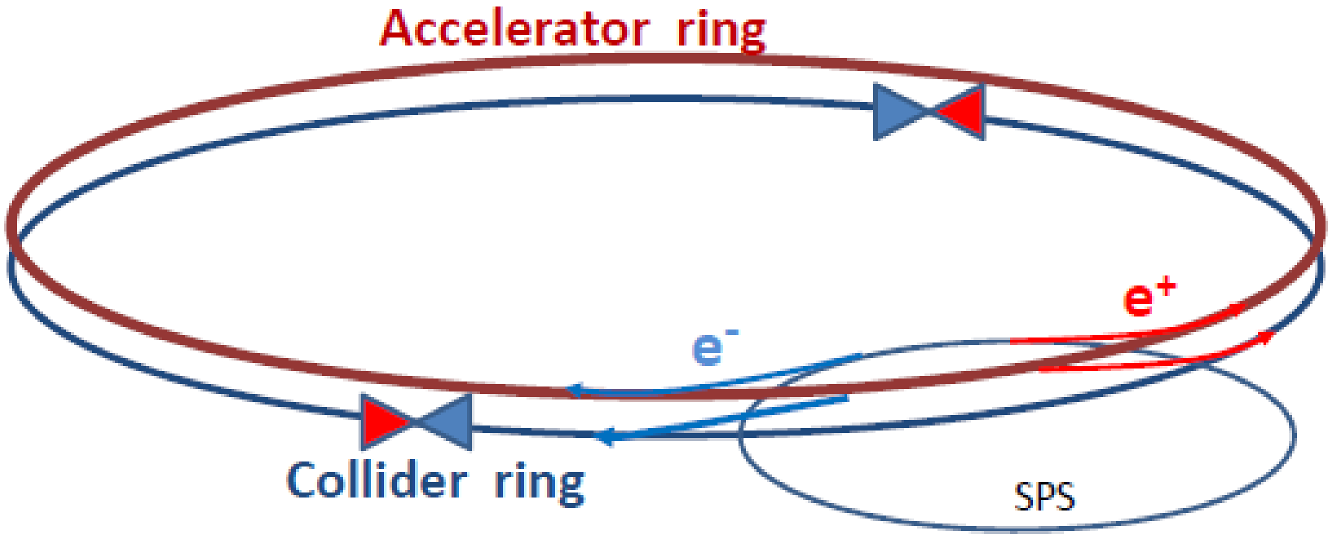


Non-destructive focusing and collision of beams:
- Center-of-mass energy spread by construction modest

How to increase luminosity w.r.t. LEP

Employ B-factory design to gain factor ~500 w.r.t. LEP:
Low vertical emittance combined small value of β^*_y (very strong focussing in vertical plane):

- Electrons and positrons have a much higher chance of interacting
- ➢ Very short beam lifetimes (few minutes)
- ➢ Top-up injection: feed beam continuously with an ancillary accelerator



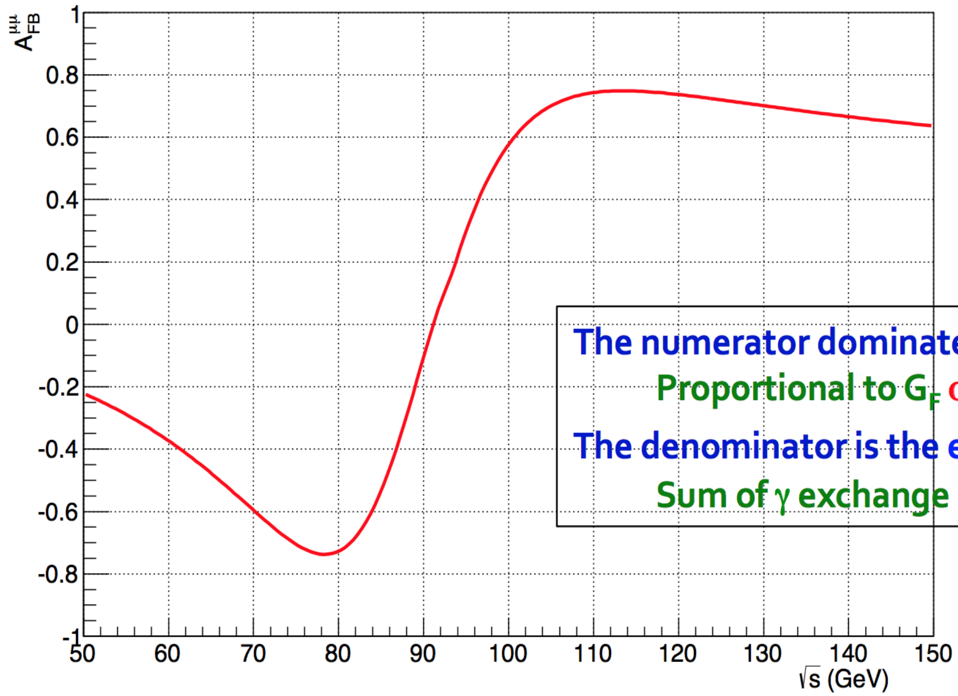
Two separate beam pipes for e^+ and e^- to avoid collisions away from IPs

Hence, a total of three beam pipes

The forward-backward asymmetry $A_{FB}^{\mu\mu}$

- **A measurement potentially free of theory error**
  - Self normalized
  - Lots of uncertainties cancel in the ratio
    - Including experimental uncertainties

$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu\mu} - N_B^{\mu\mu}}{N_F^{\mu\mu} + N_B^{\mu\mu}}$$



The numerator dominated by interference term

Proportional to $G_F\, \alpha_{QED}(s)$ [Except at the Z peak]

The denominator is the $e^+e^- \to \mu^+\mu^-$ cross section

Sum of γ exchange ($\sim\alpha^2_{QED}(s)$) and Z exchange ($\sim G_F^2$)

Sensitivity of $A_{FB}^{\mu\mu}$ to α_{QED} (1)

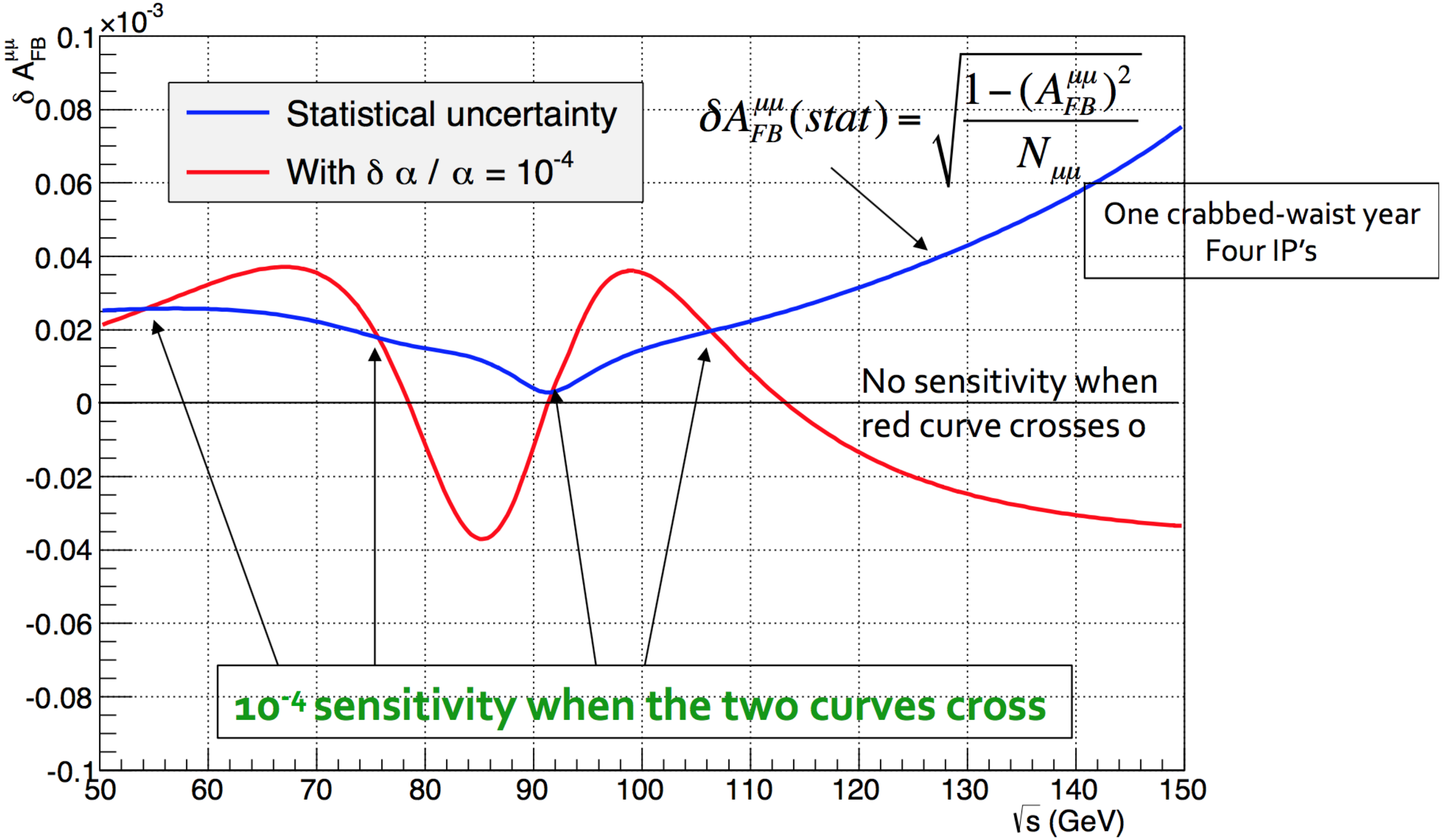
- Assume we can measure $A_{FB}^{\mu\mu}$ with a precision $\delta A_{FB}^{\mu\mu}$ at a given $\sqrt{s}$
  - The asymmetry can be parameterized as a function of α_{QED} as follows

$$A_{FB}^{\mu\mu}(\alpha) \propto \frac{\frac{\alpha}{\alpha_0} I(\alpha_0)}{z + \frac{\alpha^2}{\alpha_0^2}\gamma(\alpha_0)}$$

    - Where I, z, and γ are the interference and the Z/γ exchange terms ($\alpha = \alpha_0$)
  - Hence $$\delta A_{FB}^{\mu\mu} \propto \frac{I(z-\gamma)}{\sigma_{\mu\mu}^2}\frac{\delta\alpha}{\alpha}$$ or $$\frac{\delta A_{FB}^{\mu\mu}}{A_{FB}^{\mu\mu}} = \frac{z-\gamma}{\sigma_{\mu\mu}}\frac{\delta\alpha}{\alpha}$$
  - No dependence on α_{QED} when Z and γ exchange are equal
    - i.e., when the interference is maximal : $\sqrt{s}$ = 78 GeV and $\sqrt{s}$ = 114 GeV
  - No dependence on α_{QED} when the interference term / the asymmetry vanishes
    - i.e., at the Z pole : $\sqrt{s} = m_Z$
  - Relative sign of δA_{FB} and $\delta\alpha$ changes at these three values of $\sqrt{s}$
    - Important remark when it comes to evaluate systematic uncertainties (see later)

Sensitivity of $A_{FB}^{\mu\mu}$ to α_{QED} (2)

- **Sensitivity quite dependent on √s**



- **Best just above and just below the Z pole**

Potential of $\alpha_{QED}(m_Z)$ measurement

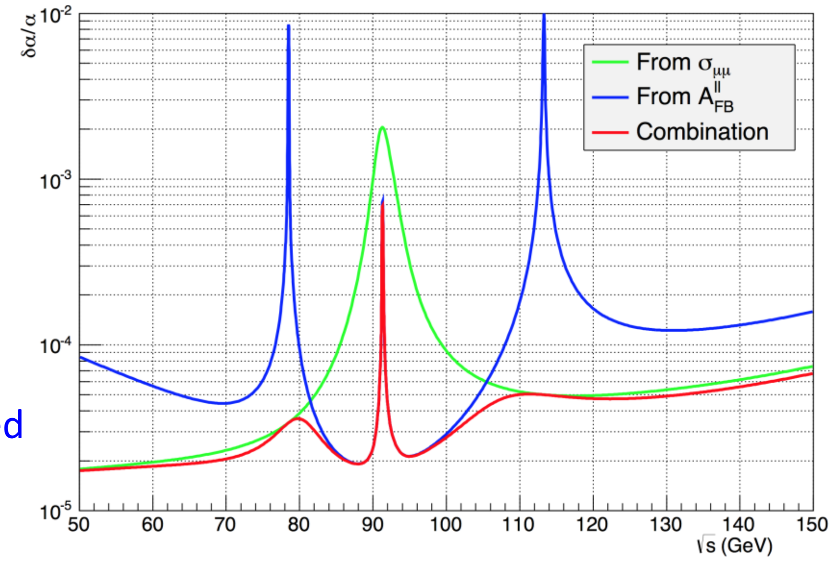
For exploitation of precision EW measurements, need precise knowledge of $\alpha_{QED}(m_Z)$

- Standard method involves extrapolation from $\alpha_{QED}(0)$ to $\alpha_{QED}(m_Z)$
  - Dispersion integral over hadronic cross section – low energy resonances: **$\delta\alpha/\alpha = 1.1 \times 10^{-4}$**
- New idea: exploit large statistics of FCC-ee to measure $\alpha_{QED}(m_Z)$ directly close to m_Z
  - Avoid extrapolation error!

Two methods considered:

i. From $\sigma_{\mu\mu}$
   - Sensitivity best "far" away from Z peak, particularly at the low side
   - Systematics (normalisation) probably a killer

ii. From $A_{FB}^{\mu\mu}$
   - Sensitivity best at 88 and 95 GeV
   - Experimental systs. looks controlable, but need further study
   - Theoretical systs. to large degree cancel by "averaging" over 88 and 95 GeV point



Statistical uncertainty for one year of running at any centre-of-mass energy. Crab-waiste, 4 IP.

P. Janot

By running six months at each of 88 and 95 GeV points:

- Could potentially reach a precision of **2×10^{-5}**