Precision Electroweak Measurements at FCC-ee













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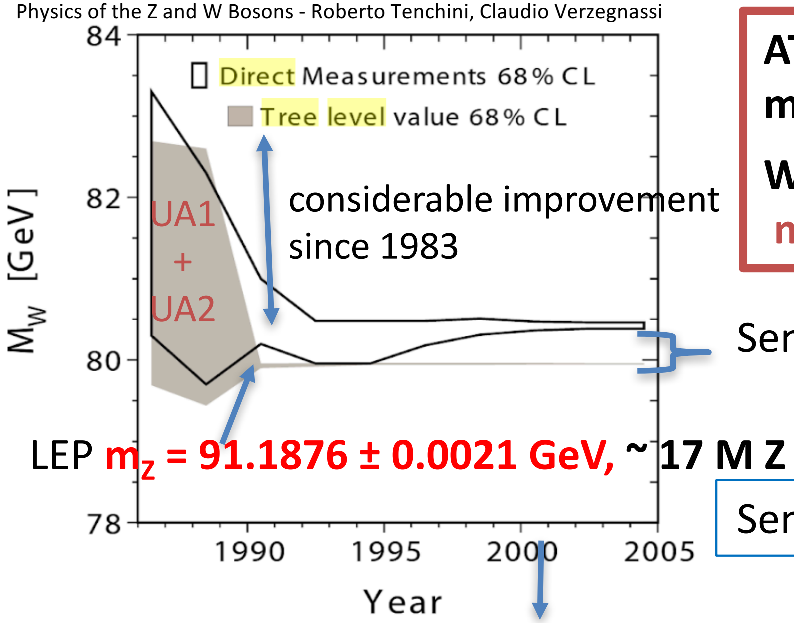
on behalf of the FCC-ee study group

Picture http://www.steptocity.com/place/fr/arènes-de-lutèce--1l24l550

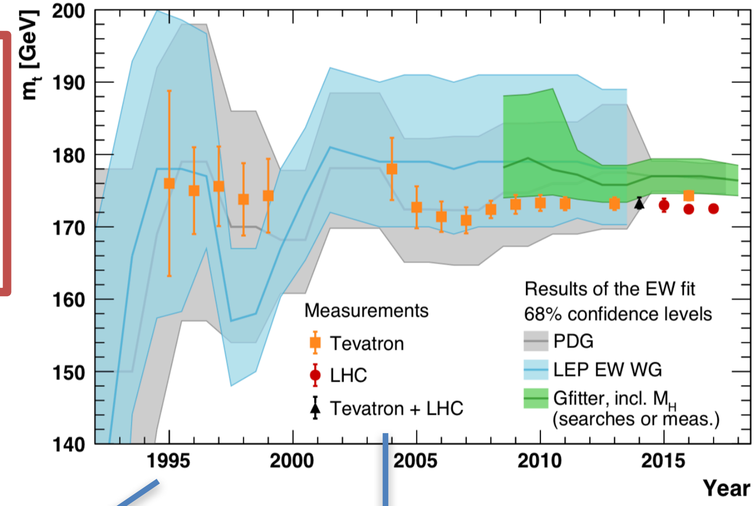
Evolution of the mass of some fundamental "bricks" of the SM with time



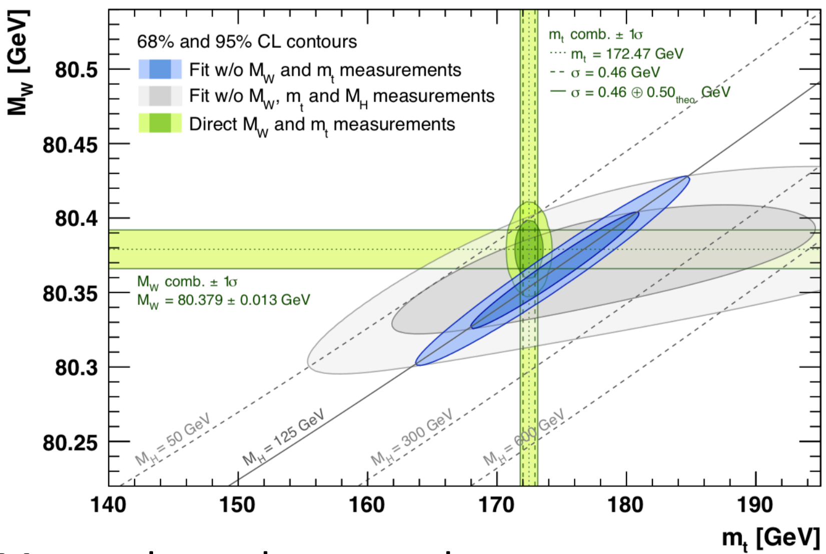
ATLAS 2018,
m_W = 80.370 ± 0.019 GeV
World average:
m_W = 80.379 ± 0.012 GeV

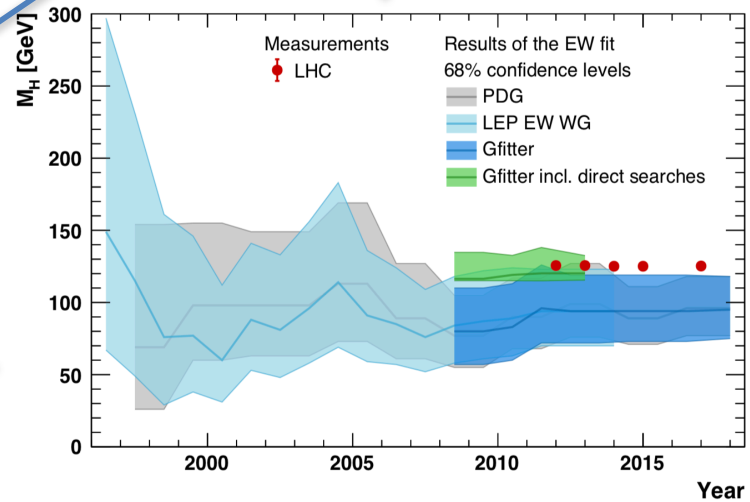
Sensitivity to EW loops

Sensitivity to new particles



https://arxiv.org/pdf/1803.01853.pdf

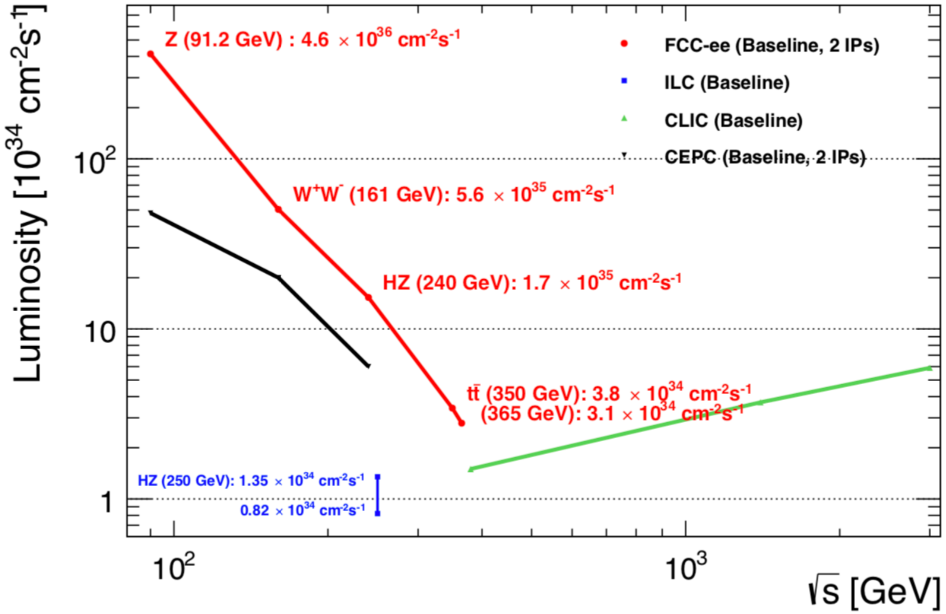




The SM complete, electroweak sector over-constrained

The global fit is one accurate test of the internal consistency of the SM to look for New Physics
→ exquisite precision in ew measurements & theoretical calculations

Baseline FCC-ee operation model (2 IPs)



Integrated luminosity goals for Z & W physics

- **150 ab^{-1} around the Z pole** (~100 at the pole)
- **10 ab^{-1} around the WW threshold**

(4 IPs investigated)

LEP 4 IPs:

- 0.6 fb^{-1} around the the Z pole
- 2.4 fb^{-1} around the WW threshold

Also important for WW physics!

Working point	Z, years 1-2	Z, later	WW	HZ	$t\bar{t}$	
$\sqrt{s}$ (GeV)	88, 91, 94		157, 163	240	340-350	365
Lumi/IP ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$)	115	230	28	8.5	0.95	1.55
Lumi/year (ab^{-1}, 2 IP)	24	48	6	1.7	0.2	0.34
Physics Goal (ab^{-1})	150		10	5	0.2	1.5
Run time (year)	2	2	2	3	1	4
Number of events	5×10^{12} Z		10^{8} WW	10^{6} HZ + 25k WW $\rightarrow$ H	$10^{6}\, t\bar{t}$ +200k HZ +50k WW $\rightarrow$ H	

EW Physics Observables at FCC-ee

TeraZ (5×10^{12} Z)

From data collected in a lineshape energy scan:

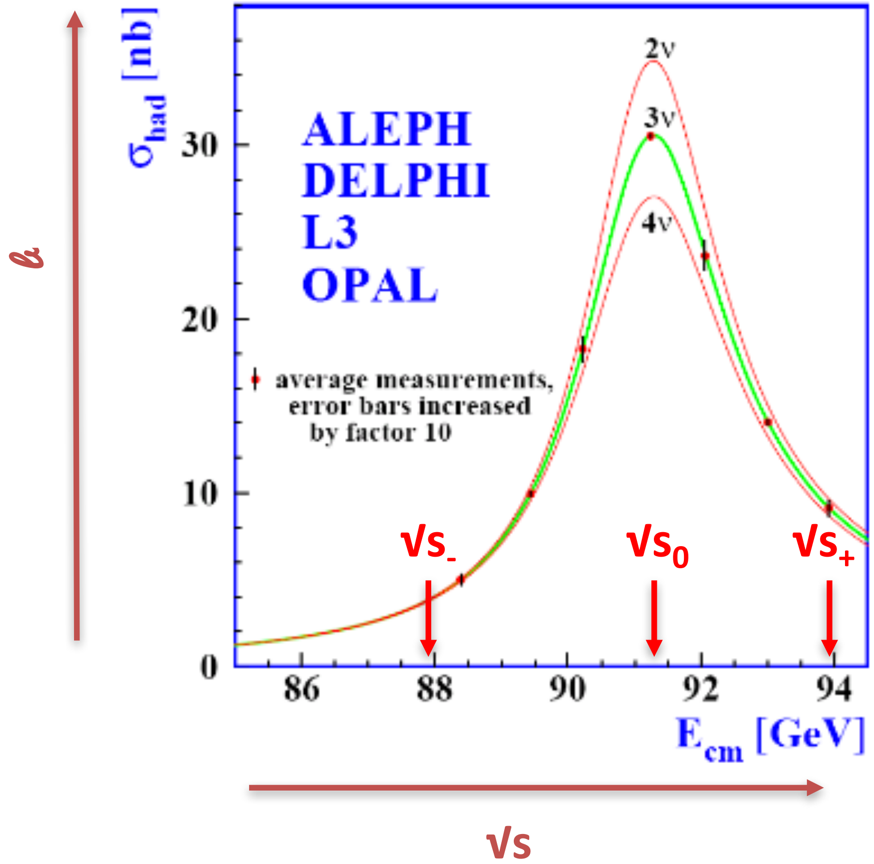
- Z mass (key for jump in precision for ewk fits)
- Z width (jump in sensitivity to ewk rad corr)
- R_l = hadronic/leptonic width ($\alpha_s(m^2_Z)$, lepton couplings, precise universality test)
- peak cross section (invisible width, N_ν)
- $A_{FB}(\mu\mu)$ ($\sin^2\theta_{eff}$, $\alpha_{QED}(m_Z^2)$, lepton couplings)
- Tau polarization ($\sin^2\theta_{eff}$, lepton couplings)
- R_b, R_c, $A_{FB}(bb)$, $A_{FB}(cc)$ (quark couplings)

OkuWW (10^8 WW)

From data collected around and above the WW threshold:

- W mass (key for jump in precision for ewk fits)
- W width (first precise direct meas)
- $R^W = \Gamma_{had}/\Gamma_{lept}$ ($\alpha_s(m^2_Z)$)
- Γ_e , Γ_μ , Γ_τ (precise universality test)
- Triple and Quartic Gauge couplings (jump in precision, especially for charged couplings)

I- Determination of Z mass and width



The exact choice of the off-peak energies for m_Z, Γ_Z is not as crucial at FCC-ee* as at LEP because of the huge statistics

But instead the **exact choice is crucial for $\alpha_{QED}(m_Z)$,**

which is driving the choice of:

$\sqrt{s}_-$ = 88 GeV & $\sqrt{s}_+$ = 94 GeV (slide 13)

* nevertheless ± 1 GeV (LEP) sub-optimal for Γ_Z

Most critical systematic uncertainties:

- **Center-of-mass energy and energy spread**
- **Luminosity**

Requirements on the detector are not crucial , nevertheless:

- the control of the acceptance over √s is important
- angular resolution < 0.1 mrad
- momentum resolution $\Delta p_T / p_T^2 < 4\ 10^{-5}$ GeV^{-1}

(See talk by Alain Blondel)

Beam energies and crossing angle *(FCC-ee Polarization and Center-of-mass Energy Calibration)*

Beams are transversely polarized below 165 GeV (Sokolov-Ternov effect)
and their **energies are continuously measured with resonant depolarization** on single non-colliding bunches

Around the Z pole $\Delta\sqrt{s} \approx$ 100 keV (40 keV point-to-point) is achievable → **$\Delta m_Z \approx$ 100 keV**

Beam crossing angle (**α = 30 mrad**) , energy spread (90 MeV) can be measured with
$e^+ e^- \to \mu^+ \mu^-$ events copiously produced at all energies. → **$\Delta\Gamma_Z \approx$ 25 keV**

From E-p conservation:

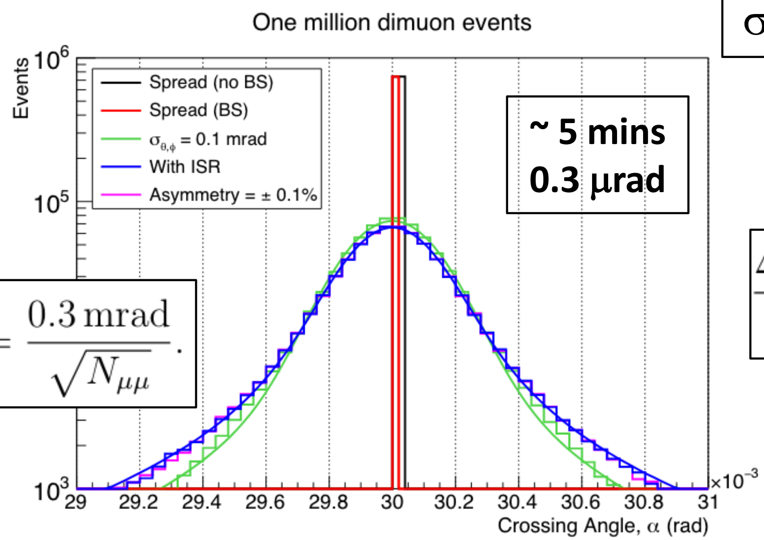
$$\alpha = 2 \arcsin \left[\frac{\sin(\varphi^- - \varphi^+) \sin\theta^+ \sin\theta^-}{\sin\varphi^- \sin\theta^- - \sin\varphi^+ \sin\theta^+} \right]$$

$$x_\gamma = -\frac{x_+ \cos\theta^+ + x_- \cos\theta^-}{\cos(\alpha/2) + |x_+ \cos\theta^+ + x_- \cos\theta^-|},$$

$$\text{with} \quad x_\pm = \frac{\mp \sin\theta^\mp \sin\varphi^\mp}{\sin\theta^+ \sin\varphi^+ - \sin\theta^- \sin\varphi^-}.$$

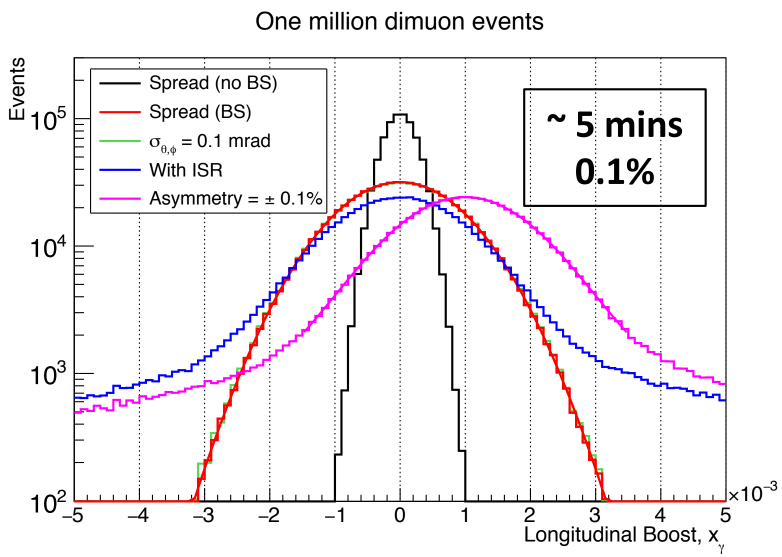
$$\sqrt{s} = 2\sqrt{E_{e^+} E_{e^-}} \cos{}^{\alpha}/_{2}$$

$\sigma_{\theta,\phi} \sim 100\ \mu$rad



$$\Delta\alpha = \frac{0.3\,\text{mrad}}{\sqrt{N_{\mu\mu}}}.$$

$$\frac{\Delta\sigma_{\sqrt{s}}}{\sigma_{\sqrt{s}}} = \frac{1}{\sqrt{N_{\mu\mu}}}$$



Measurement of luminosity

The reference process is **small angle Bhabha scattering**

Realistic goal for **theoretical uncertainty** from higher **order for low angle Bhabha** is **0.01%***
(Blondel, Jadach & al., arXiv:1812.01004) – **already at mid-road : 0.04 %**

Target $\Delta\mathcal{L}_{abs} \approx 0.0001$, $\Delta\mathcal{L} \approx 5\ 10^{-5}$ point-to-point

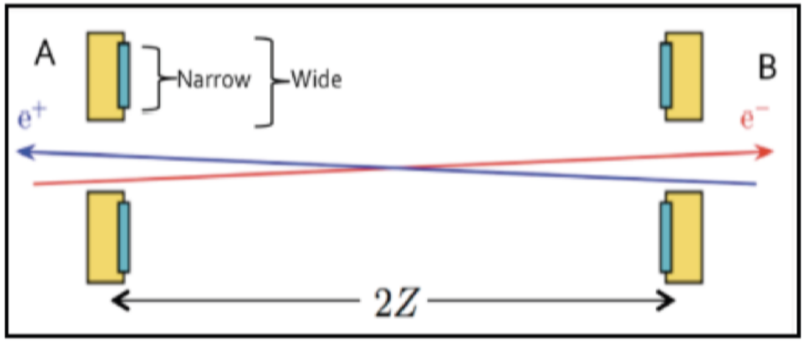
→ reduction **factor 8 in uncertainty** on number of light neutrino families, **N_ν*** **($\Delta N_\nu = 0.001$)**

* **0.01% uncertainty** also reachable with **1.4 ab^{-1} e^+e^- -> $\gamma\gamma$**, theory uncertainty already at this level

→ control of large angle Bhabha contamination

accuracy of **≈ 1 µm** required on luminometer internal radius

clever acceptance algorithms (a la lep), independent from beam spot position should be extended to beams with crossing angle.



** Measurement of N_ν with similar precision provided by $Z\gamma$, Z -> $\nu\nu$ (above the Z)
Systematics on γ selection, luminosity, etc cancel in the ratio

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

II- Partial widths ratios

$\mathbf{R_l} = \Gamma_l / \Gamma_{had} = \sigma_l / \sigma_{had}$ is a robust measurement, necessary input for a **precise measurement of lepton couplings** and ($\alpha_s(m_Z)$)

Exploiting FCC-ee potential requires an accurate control of acceptance, particularly for leptons

- acceptance uncertainties, subdominant at LEP, need factor 5 reduction to match **5.10^{-5} goal on R_l***

  *** corresponds to 0.00015 absolute uncertainty on $\alpha_s(m_Z^2)$**

- knowledge of boundaries, mechanical precisions, can be reached by exploiting 40 years of improvements in technology
- fiducial acceptance is asymmetric at FCC-ee :
  30 mrad X-angle causing a boost in transverse direction,
  which can be measured event by event for e^+e^-, $\mu^+\mu^-$

Z decays to individual quark flavours can be selected when the decay products can be efficiently tagged.

$Z \to b\bar{b}$

Measurement of b-tagging efficiency (ε_b) & R_b with double tagging

fraction of single tag: $F_1 = R_b(\varepsilon_b - \varepsilon_{uds}) + R_c(\varepsilon_c - \varepsilon_{uds}) + \varepsilon_{uds}$

fraction of double tag: $F_2 = R_b(C_b\varepsilon^2_b - \varepsilon^2_{uds}) + R_c(\varepsilon^2_c - \varepsilon^2_{uds}) + \varepsilon^2_{uds}$

$\longrightarrow \begin{cases} R_b = C_b F_1^2 / F_2 \\ \varepsilon_b = F_2 / C_b F_1 \end{cases}$

LHC detectors and current taggers can reach 3 x LEP b-tagging efficiency at same c and uds suppression in a harsher environment $\longrightarrow$ sizeable improvement expected at FCC-ee

- statistical uncertainty from double tag sample
- **systematic uncertainty from hemisphere correlations becomes dominating**
  FCC-ee projections conservatively consider reduction of that uncertainty from ≈ 0.1 % (LEP) **to ≈ 0.03 %**

Other sources such as gluon splitting and nasty sources of correlations can be studied with data @LHC

(e.g. momentum correlations, which can be suppressed by keeping b-tagging efficiency flat in momentum)

Improved measurement also in the charm sector

FCC-CDR presentation – R. Tenchini
https://indico.cern.ch/event/789349/

Expected precision on normalized partial widths

$$R_f = \sigma_f / \sigma_{had}$$

	Statistical uncertainty	Systematic uncertainty	improvement w.r.t. LEP
R_μ (R_ℓ)	10^{-6}	5×10^{-5}	20
R_τ	1.5×10^{-6}	10^{-4}	20
R_e	1.5×10^{-6}	3×10^{-4}	20
R_b	5×10^{-5}	3×10^{-4}	10
R_c	1.5×10^{-4}	15×10^{-4}	10

relative precisions

III- Asymmetries, τ polarization, couplings and $\sin^2\theta_{eff}$

Forward-backward asymmetry: $A_{FB}^{ff} = \dfrac{\sigma_F^{ff} - \sigma_B^{ff}}{\sigma_F^{ff} + \sigma_B^{ff}}$ unpolarized e beams

at the Z pole $A_{FB,\,0}^{ff} \approx \frac{3}{4}\, \mathcal{A}_e\, \mathcal{A}_f$ with $\mathcal{A}_f = \dfrac{2gVf\, gAf}{(gVf)2 + (gAf)2} = \dfrac{2gVf\,/\,gAf}{1 + (gVf\,/\,gAf)2}$, $\sin^2\theta_{eff} \equiv \frac{1}{4}\left(1 - \dfrac{g_{Ve}}{g_{Ae}}\right)$

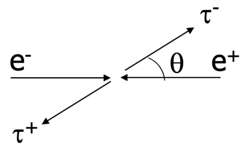
$A_{FB,\,0}^{\mu\mu} \approx (1 - 4\sin^2\theta_{eff})^2 \longrightarrow \Delta\sin^2\theta_{eff} \approx 5\ 10^{-6}$ (at least)

uncertainty driven by knowledge of √s (point to point energy uncertainties)

- **assumes muon-electron universality**

Tau polarization can reach similar precision without universality assumption

(rather measures e-τ universality)



$$A^{pol} = \frac{\sigma_{F,R} + \sigma_{B,R} - \sigma_{F,L} - \sigma_{B,L}}{\sigma_{tot}} = -\mathcal{A}_\tau$$

$$P_\tau(\cos\theta) = \frac{A_{pol}\,(1+\cos^2\theta) + 8/3\ AFBpol\ \cos\theta}{(1+\cos^2\theta) + 8/3\ AFB\ \cos\theta}$$

$$A_{FB}^{pol} = \frac{\sigma_{F,R} - \sigma_{B,R} - \sigma_{F,L} + \sigma_{B,L}}{\sigma_{tot}} = -3/4\,\mathcal{A}_e$$

it measures $\mathcal{A}_e$ & $\mathcal{A}_\tau$, which used as input to $A_{FB,\,0}^{\mu\mu}$ $\longrightarrow$ **e, μ, τ couplings separately**

(together with Γe, $\Gamma\mu$, $\Gamma\tau$)

- huge statistics $\longrightarrow$ improved knowledge of τ parameters (Br, decay modeling)
- use best decay channel, e.g. $\tau \to \rho\nu$ (very clean) $\longrightarrow$ detector performance for γ / π^0 mandatory

$\longrightarrow$ $\Delta\sin^2\theta_{eff} \approx 6\ 10^{-6}$

$A_{FB,\,0}^{bb}$, $A_{FB,\,0}^{cc}$ **provide input to quark couplings**

(together with Γ_b, Γ_c)

Expected precision on coupling ratio factors

FCC-CDR presentation – R. Tenchini
https://indico.cern.ch/event/789349/

$\mathcal{A}_f$

	Statistical uncertainty	Systematic uncertainty	improvement w.r.t. LEP
$\mathcal{A}_e$	$5. \times 10^{-5}$	$1. \times 10^{-4}$	50
$\mathcal{A}_\mu$	2.5×10^{-5}	1.5×10^{-4}	30
$\mathcal{A}_\tau$	$4. \times 10^{-5}$	$3. \times 10^{-4}$	15
$\mathcal{A}_b$	2×10^{-4}	30×10^{-4}	5
$\mathcal{A}_c$	3×10^{-4}	80×10^{-4}	4
$\sin^2\theta_{W,eff}$ (from muon FB)	10^{-7}	$5. \times 10^{-6}$	100
$\sin^2\theta_{W,eff}$ (from tau pol)	10^{-7}	6.6×10^{-6}	75

relative precisions but for $\sin^2\theta_{eff}$

Expected precision on vector and axial neutral couplings

fermion type	g_a	g_v
e	1.5×10^{-4}	2.5×10^{-4}
μ	2.5×10^{-5}	$2. \times 10^{-4}$
τ	0.5×10^{-4}	3.5×10^{-4}
b	1.5×10^{-3}	1×10^{-2}
c	2×10^{-3}	1×10^{-2}

1-2 orders of magnitudes improvement w.r.t LEP, depending on the fermion

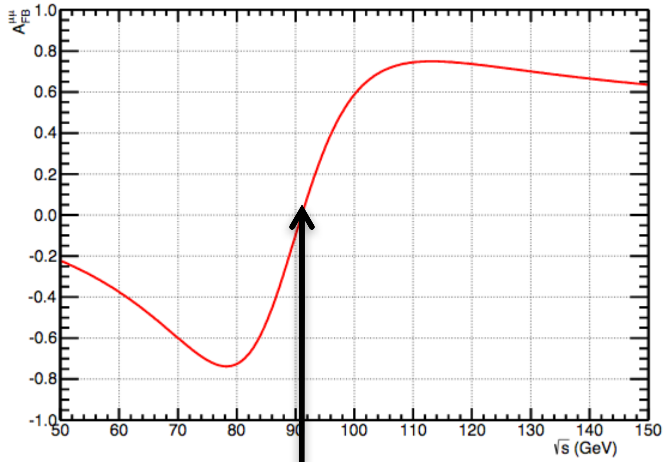
(still need to explore the potential for the measurement of the s quark coupling)

IV- e.m coupling: direct measurement of $\alpha_{QED}(m_Z^2)$

(Patrick Janot, JHEP (2016) 53 arXiv:1512.05544)

Now $\alpha_{QED}(M^2_Z)$ from the running of $\alpha \longrightarrow$ $\Delta\alpha/\alpha$ = **1.1 10^{-4}**

$$A_{FB}^{\mu\mu} = \frac{N_F^{\mu\mu} - N_B^{\mu\mu}}{N_F^{\mu\mu} + N_B^{\mu\mu}} \approx A_{FB,0}^{\mu\mu} + \alpha_{QED}(s)\,\frac{s - mZ^2}{2s}\, f(\sin^2\theta_{eff}) \longrightarrow \Delta\alpha_{QED} / \alpha_{QED} \approx \Delta A_{FB}^{\mu\mu} / A_{FB}^{\mu\mu}$$



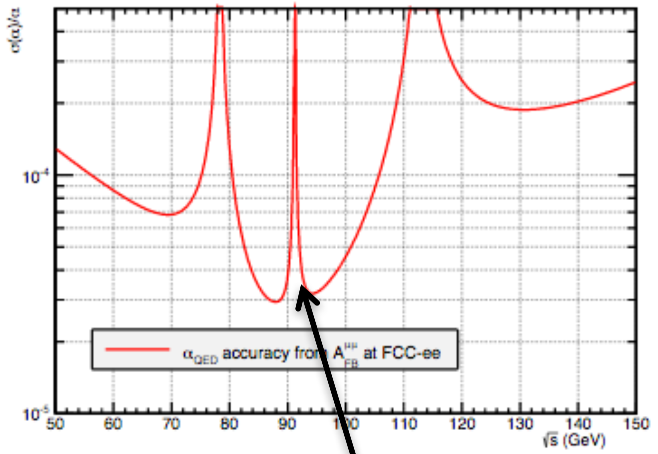
Z exchange dominant

→ no sensitivity to α_{QED}

$\Delta A_{FB}^{\mu\mu} / A_{FB}^{\mu}(s_-) < 0$

$\Delta A_{FB}^{\mu\mu} / A_{FB}^{\mu\mu}(s_+) > 0$

large cancellation of systematic uncertainties combining measurements below and above Z peak



$\sigma(\alpha)/\alpha$ for 1 year of running at any $\sqrt{s}$

Type	Source	Uncertainty
Experimental	E_{beam} calibration	1×10^{-5}
	E_{beam} spread	$< 10^{-7}$
	Acceptance and efficiency	negl.
	Charge inversion	negl.
	Backgrounds	negl.
Parametric	m_Z and Γ_Z	1×10^{-6}
	$\sin^2\theta_W$	5×10^{-6}
	G_F	5×10^{-7}
Theoretical	QED (ISR, FSR)	$< 10^{-6}$
	Missing EW higher orders, QED(IFI)	few 10^{-4}
	New physics in the running	0.0
Total (except missing EW higher orders)	Systematics	1.2×10^{-5}
	Statistics	3×10^{-5}

for **3 10^{-5} relative uncertainty on α_{QED}:**

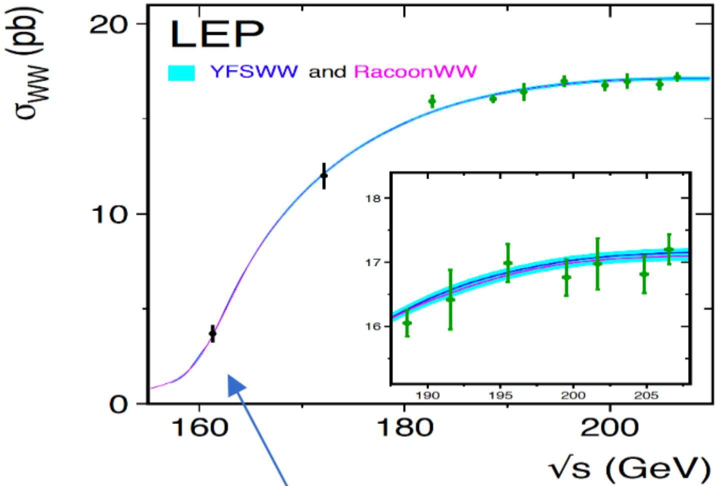
$\sqrt{s_-}$ = 87.9 GeV

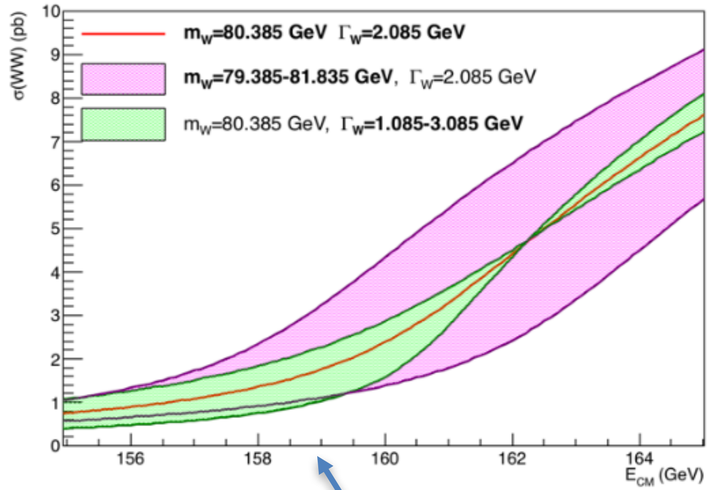
$\sqrt{s_+}$ = 94.3 GeV

work on EWK theoretical corrections required to reach **3 10^{-5}**

V- W mass and width from WW cross-section

(Paolo Azzurri)





At LEP2, √s = 161 GeV, 11 pb^{-1}

$m_W = 80.40 \pm 0.21$ GeV

Sensitivity to mass and width different at different √s

can **optimize m_W and Γ_W** by carefully choosing 2 √s

with **√s1 = 157.1 GeV**

√s2 = 162.6 GeV

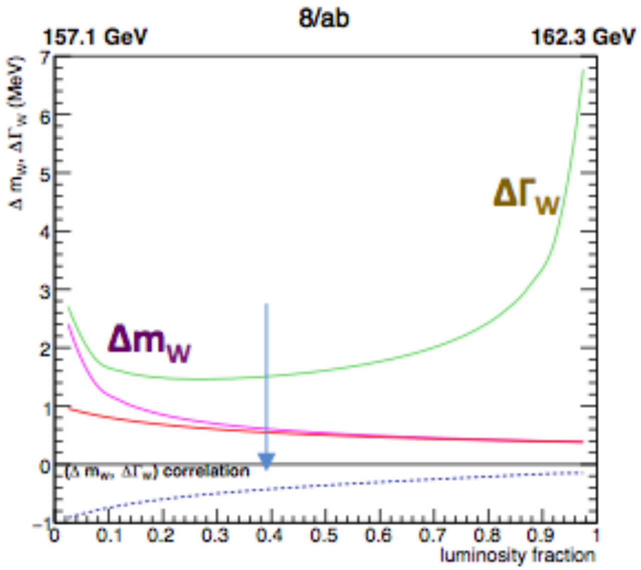
f = 0.4

ΔM_W = 0.4 MeV

$\Delta\Gamma_W$ = 1.2 MeV

Systematics control to:

- **ΔE_B < 0.35 MeV (4 10^{-6})**
- **$\Delta\varepsilon/\varepsilon$, $\Delta L/L$ < 2 10^{-4}**
- **$\Delta\sigma_B$ < 0.7 fb (2 10^{-3})**

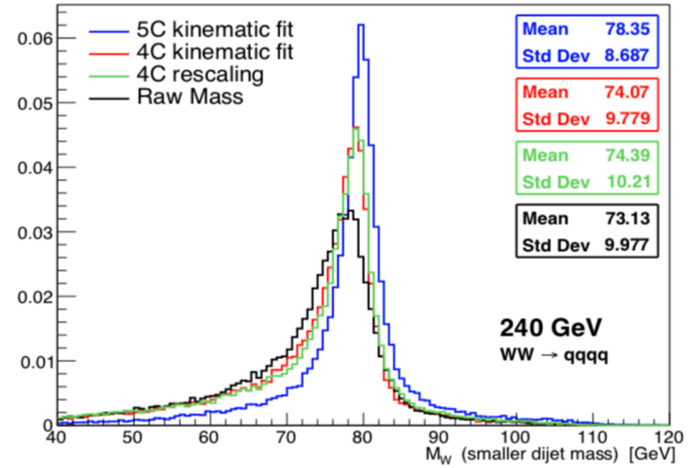


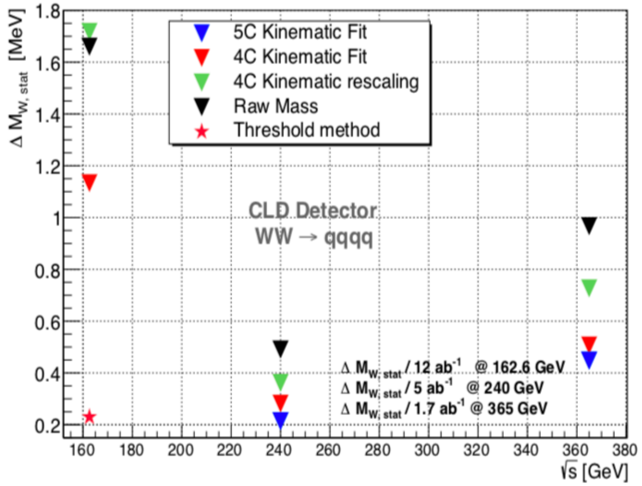
- same concept can be used to minimize the systematics (e.g. from background)
- √s known by resonant depolarization (available at ≈ 160 GeV)
- Luminosity from Bhabha (requirement similar to Z pole)

VI-1 W mass and width from direct reconstruction

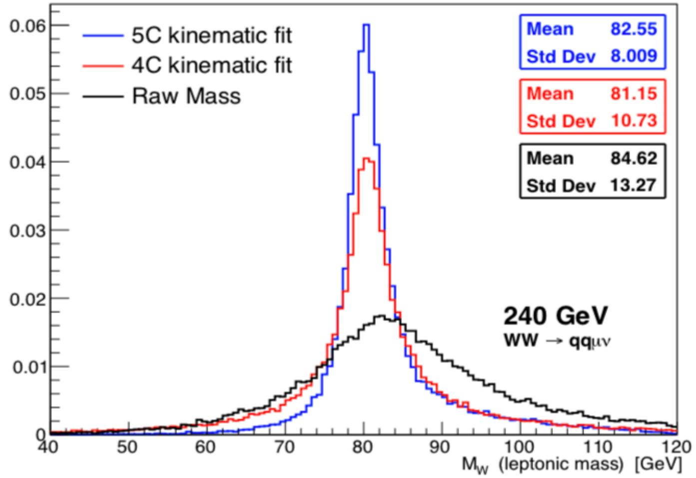
(Marina Béguin, Paolo Azzurri, E.L.)

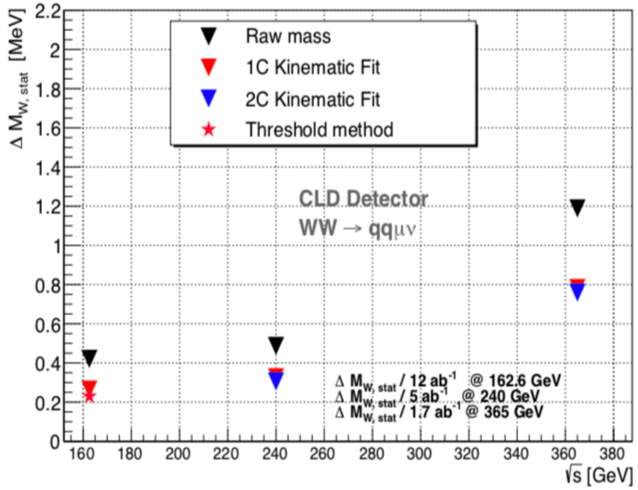
Fully hadronic channel





Semi-leptonic channel





@162.6, 240, 365 GeV

- **raw mass**
- 4C **jets momenta rescaling**
- **kinematic fit**

  4-momenta conservation

  (4C for fully had., 1C for semi lep.)

  \+ W mass equality

  (5C for fully had., 2C for semi lep.)

- **stat. uncertainty < 1 MeV**
- Statistics will help in reducing LEP systematics (e.g. fragmentation, jet mass)
- ΔE_{CM} ≈ **300 keV** @ 162.6 GeV
- Need to use Zγ & ZZ events to control E_B at √s > 200 GeV (no resonant depolarisation)

VI-2 W mass and width from direct reconstruction

(Marina Béguin, Paolo Azzurri, E.L.)

Fully hadronic channel

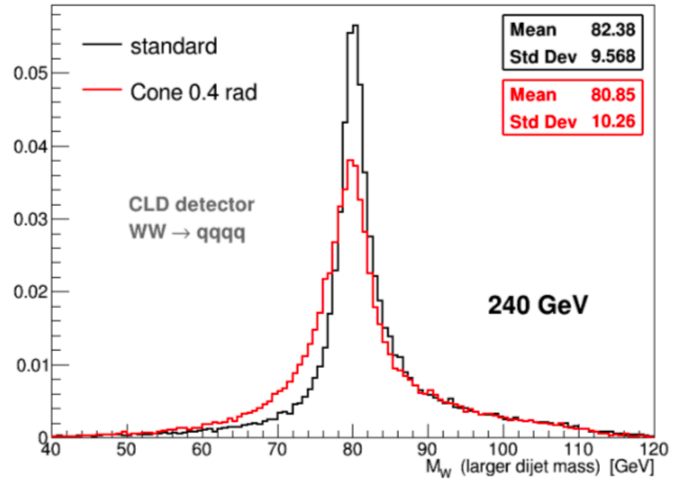
	σ_{M_W} MeV/c^2			σ_{Γ_W} MeV/c^2		
$\sqrt{s}$ GeV	162.6	240	365	162.6	240	365
Luminosity (ab^{-1})	12	5	1.7	12	5	1.7
Raw Mass	1.66	0.49	0.97	1.44	1.10	1.71
4C rescaling	1.72	0.36	0.73	1.53	0.77	1.48
4C fit	**1.14**	0.28	0.5	**1.1**	0.58	**0.95**
5C fit		**0.21**	**0.44**		**0.47**	1.02

Semi-leptonic channel

	σ_{M_W} MeV/c^2			σ_{Γ_W} MeV/c^2		
$\sqrt{s}$ GeV	162.6	240	365	162.6	240	365
Luminosity (ab^{-1})	12	5	1.7	12	5	1.7
Raw Mass	0.42	0.49	1.19	0.39	0.87	1.94
1C fit	**0.26**	0.33	0.78	**0.35**	**0.59**	**1.36**
2C fit		**0.31**	**0.75**		0.68	1.56

Largest sources of systematics in the hadronic channel @LEP2: FSI (CR & BEC)
Other sources are expected to be much reduced @FCC-ee, due to high statistics and better detectors.

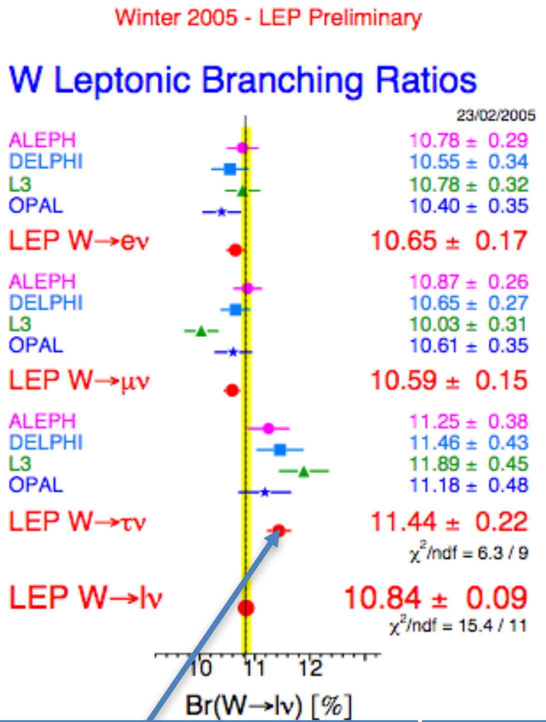
$\sqrt{s}$ [GeV]	162.6		240		365	
δM_{FSI} [MeV/c^2]	standard	cone	standard	cone	standard	cone
SKI	14.6	7.5	23.9	11.5	32.2	17.5
SKII	7.9	3.8	12.1	6.0	14.7	8.3
BEC	3.1	1.8	5.9	2.1	9.9	5.5

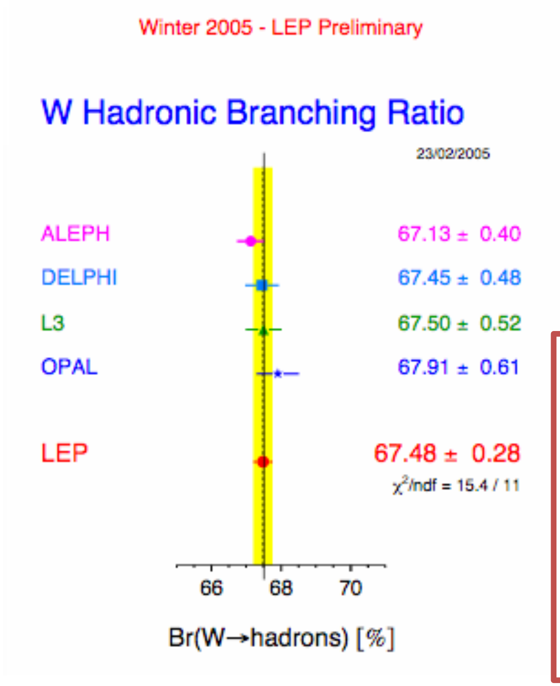


More in PhD thesis by Marina Béguin

Ultimate: simultaneous fit of WW, ZZ and Zγ
to extract m_W/m_Z with potential large cancellations of systematic uncertainties

VI- W decay Branching Fractions





$$\frac{B_q}{1-B_q} = 3\left(1+\frac{\alpha_s(m_W^2)}{\pi}\right)\sum_{i=u,c;j=d,s,b}|V_{ij}|^2$$

assuming CKM unitarity
$\Delta Br_{qq}/Br_{qq} = 10^{-4}$
→ $\Delta\alpha_s \approx 9\pi/2\ \Delta Br_{qq} \approx 0.0002$

with Br_{qq} & α_s (ind.) precisely measured
CKM unitarity tested at 10^{-4} level

Flavour tagging of jets
→ W coupling to b & c quarks (V_{cb}, V_{cs})

$Br_{\tau\nu} > Br_{e\nu}$, $Br_{\mu\nu}$ (2.8 σ)

@FCC-ee,
lepton universality test at 4 10^{-4} level

Also rare W decays can be probed at the level of 10^{-7} probability

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	$3\cdot10^{-4}$	$3\cdot10^{-4}$	$4\cdot10^{-4}$	$1\cdot10^{-4}$

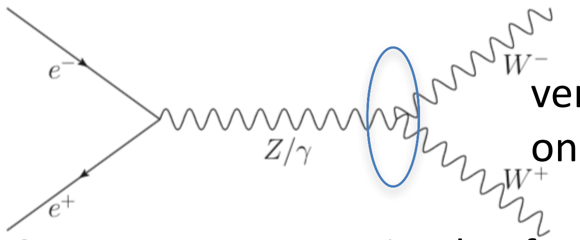
excellent control of jet reconstruction and lepton id are needed to control cross-contaminations in signal channel (τ -> e,μ ν)

("FCC-ee Physics, Experiments and Detectors")

VII- Probing the TGCs at high precision

(Jiayin Gu)

(also QGCs $WW\gamma\gamma$, $WWZ\gamma$ possible)



very important implications on BSM physics

@ LEP2,TGCs constrained at few % level

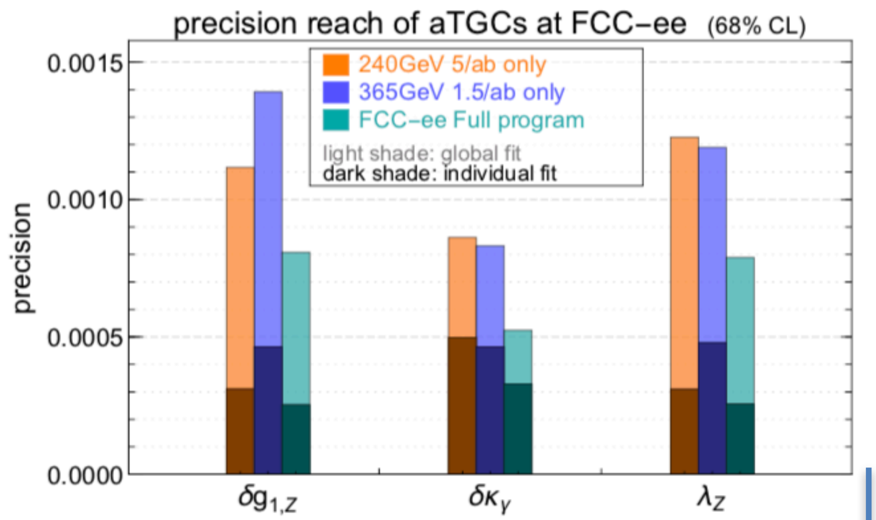
@FCC-ee, di-boson process will be measured @ 161, 240, 350, 365 GeV with much higher $\mathcal{L}$

$\mathcal{L}_{SM} \xrightarrow{\text{BSM}} \mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$

Focus on CP-even dimension 6 operators

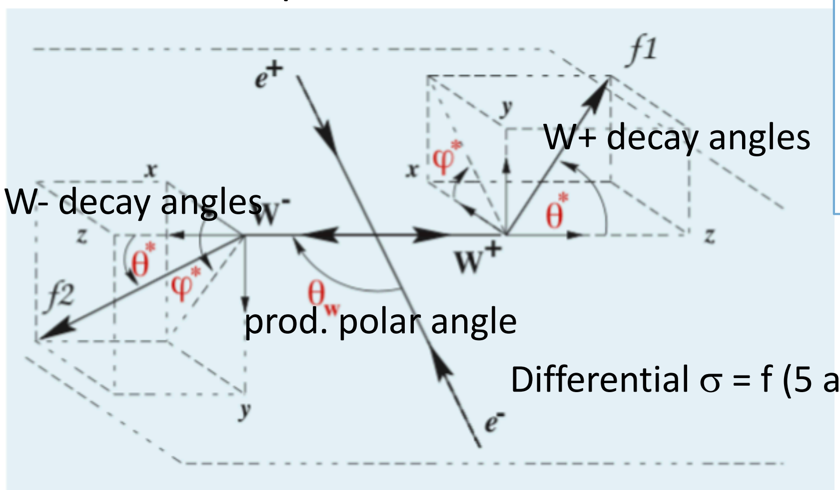
$\mathcal{L}_{TGC} = f\,(\delta g_1^Z, \delta\kappa_Z, \delta\kappa_\gamma, \lambda_Z, \lambda_\gamma)$

gauge invariance $\longrightarrow$ $\delta\kappa_Z = \delta g_1^Z - \tan^2(\theta_W)\,\delta\kappa_\gamma$, $\lambda_Z = \lambda_\gamma$



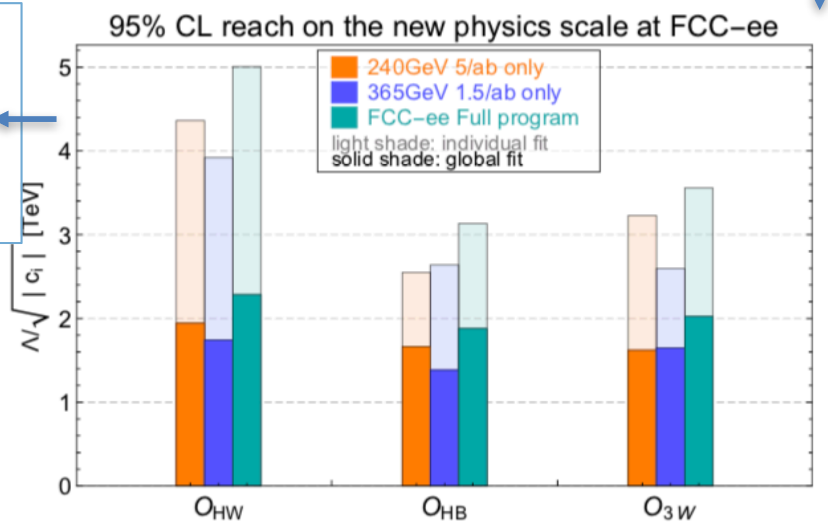
$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger\sigma^a(D^\nu H)W^a_{\mu\nu}$	$\delta g_{1,Z} = -m_Z^2\frac{c_{HW}}{\Lambda^2}$
$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger(D^\nu H)B_{\mu\nu}$	$\delta\kappa_\gamma = -m_W^2\left(\frac{c_{HW}}{\Lambda^2} + \frac{c_{HB}}{\Lambda^2}\right)$
$\mathcal{O}_{3W} = \frac{1}{3!}g\epsilon_{abc}W^{a\nu}_\mu W^b_{\nu\rho}W^{c\rho\mu}$	$\lambda_Z = -m_W^2\frac{c_{3W}}{\Lambda^2}$

In the semi-leptonic channel:



Differential σ = f (5 angles)

if $c_i \approx 1$, TGCs sensitive to Multi-TeV energy scale



Conclusions

FCC-ee has a considerable physics potential:

With **$5\ 10^{12}$ Z** around the Z pole and **10^{8} WW** at and above the W-pair production threshold a **large number of electroweak observables** (only a sample of them in this talk!) will be measured with **unprecedented statistical precision (1 to 2 order of magnitude w.r.t. present measurements).** **Large statistics also impacts systematic uncertainties: theory** (parametric uncertainties) **& detector** (data-based studies, trading with statistics)**!**

In order to fully exploit this potential,
the systematic uncertainty must match the statistical uncertainty

- The beam energy calibration is the dominant source of systematic uncertainty for a number of observables

  $\Delta E_{CM} \approx$ 100 keV @ the Z, 300 keV @ the WW threshold

  other effects (beam energy spread and asymmetry, etc..) under control at required level

- **Luminosity uncertainty** critical for all measurements related to cross-section

  absolute accuracy **$\approx 10^{-4}$** , **relative** (point to point) **$\approx 5\text{x}10^{-5}$**
  requires **precision** of construction and metrology at the level of **1μm** (internal radius)

- Also required: control of acceptance, lepton id, good γ/π^0 separation (granularity), flavour-tagging

Conclusions

A lot of interesting and challenging work both

- for experimentalists (new strategies & solutions). **A unique opportunity to develop creativity and skills in detection techniques, analysis!**
- for theorists (higher orders calculations; on the good track to match experimental uncertainties)

For more informations:

- **CDR (mainly Vol.2)**
- **"Your Questions answered" arXiv:1906.02693**
- A. Blondel et al., *Polarization and centre-of-mass energy calibration at FCC-ee*, **arXiv:1909.12245** [physics.acc-ph] , Sep 26, 2019.
- **talks @ FCC-week 2019 & EPS-HEP2019**

W & Z Observables

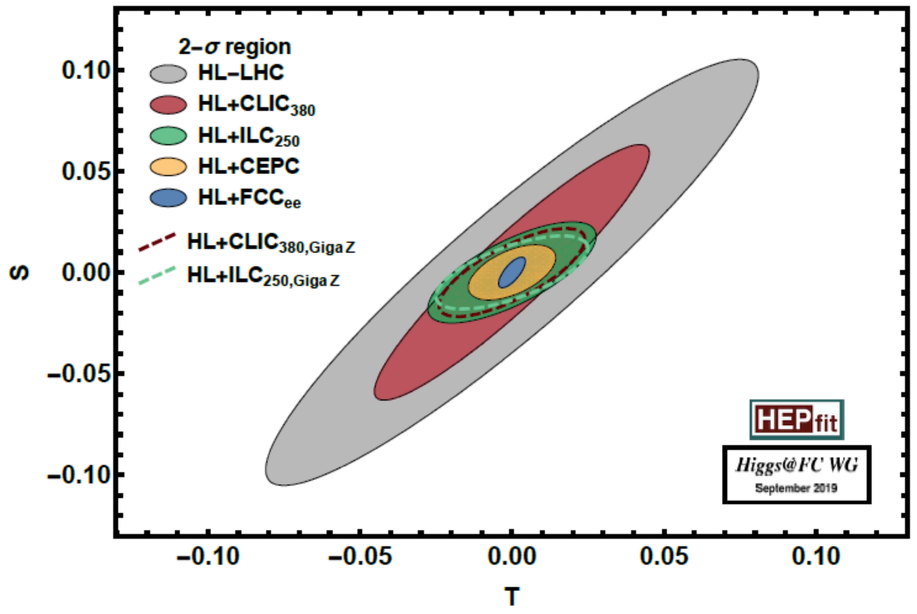
from CDR- Vol 1

Table 3.1: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions.

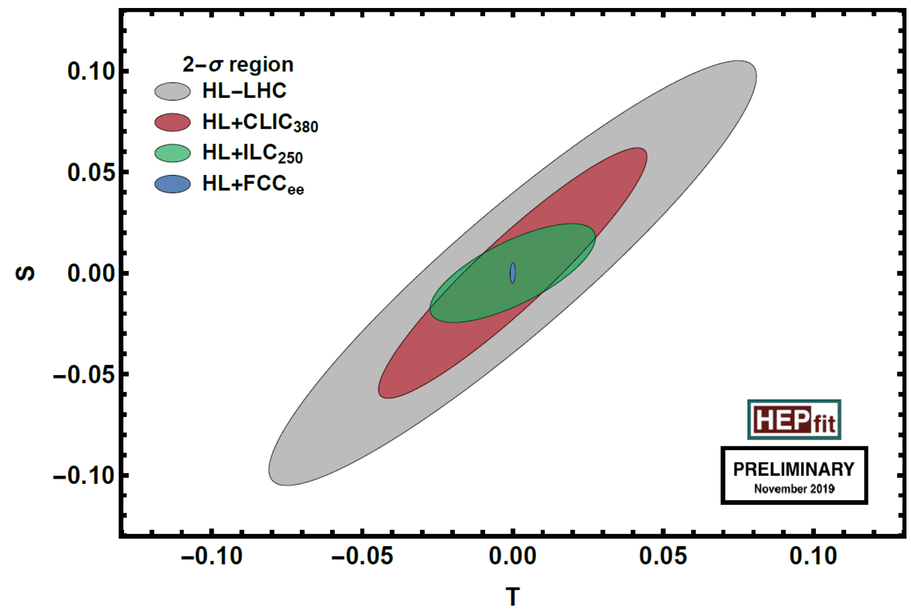
Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_Z (keV)	91186700 ± 2200	5	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2495200 ± 2300	8	~~100~~ 25	From Z line shape scan Beam energy calibration
R^Z_ℓ ($\times 10^3$)	20767 ± 25	0.06	0.2-1.0	ratio of hadrons to leptons acceptance for leptons
$\alpha_s(m_Z)$ ($\times 10^4$)	1196 ± 30	0.1	0.4-1.6	from R^Z_ℓ above [41]
R_b ($\times 10^6$)	216290 ± 660	0.3	<60	ratio of $b\bar{b}$ to hadrons stat. extrapol. from SLD [42]
σ^0_{had} ($\times 10^3$) (nb)	41541 ± 37	0.1	4	peak hadronic cross-section luminosity measurement
$N_\nu (\times 10^3)$	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta^{eff}_W (\times 10^6)$	231480 ± 160	3	~~2 - 5~~ 1-2	from $A^{\mu\mu}_{FB}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z)(\times 10^3)$	128952 ± 14	4	small	from $A^{\mu\mu}_{FB}$ off peak [32]
$A^b_{FB}, 0$ ($\times 10^4$)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge
$A^{pol,\tau}_{FB}$ ($\times 10^4$)	1498 ± 49	0.15	<2	τ polarisation and charge asymmetry τ decay physics
m_W (MeV)	80350 ± 15	0.6	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.5	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W)(\times 10^4)$	1170 ± 420	3	small	from R^W_ℓ [43]
$N_\nu (\times 10^3)$	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns

Expected uncertainty contours for S & T parameters

(courtesy Jorge de Blas)



present systematic errors estimates included (ESPP briefing book)

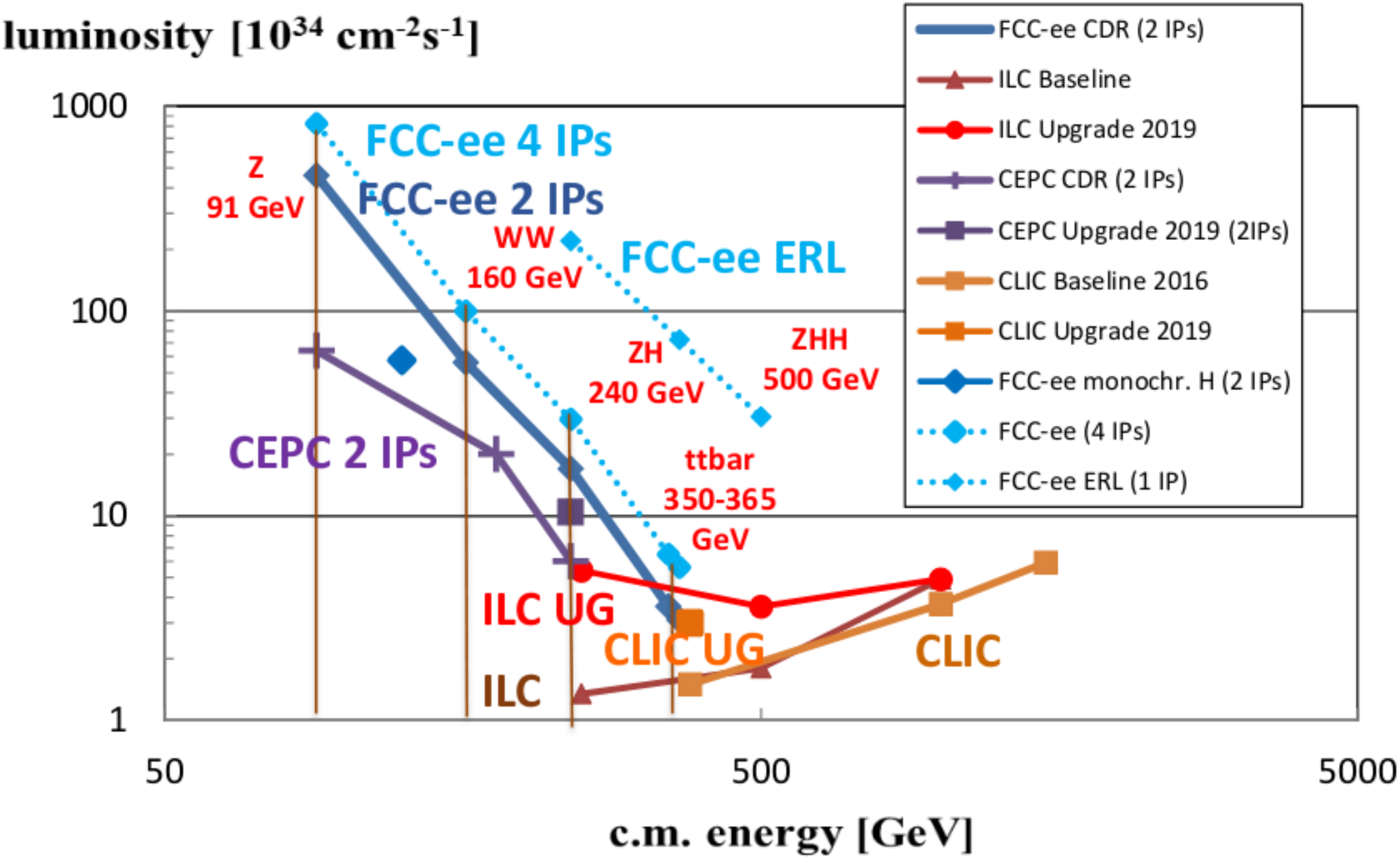


statistical & parametric uncertainties only

The true FCC-ee potential is better represented by using statistical & parametric uncertainties only, as **our next challenge is to improve both the experimental methods and theory calculations, so that systematics match the available statistics.**

SPARE SLIDES

2 or 4 Interaction Points?



FCC-ee design builds up on 50 years of experience with circular e^+e^- colliders:

- **LEP** (beam energy calibration)
- **SLC** (strong e+e- sources)
- **VEPP-4** (precise beam energy calibration)
- **KEKB & PEP-II B factories, BEPC-II** (separate bins for e^- and e^+)

→ larger number of bunches, continuous injection, mitigation of e-cloud effects, highest stored e current, crossing angle

- ΔΑΦΝΕ (crab-waist optics)
- **Super B factories** (strong focusing)

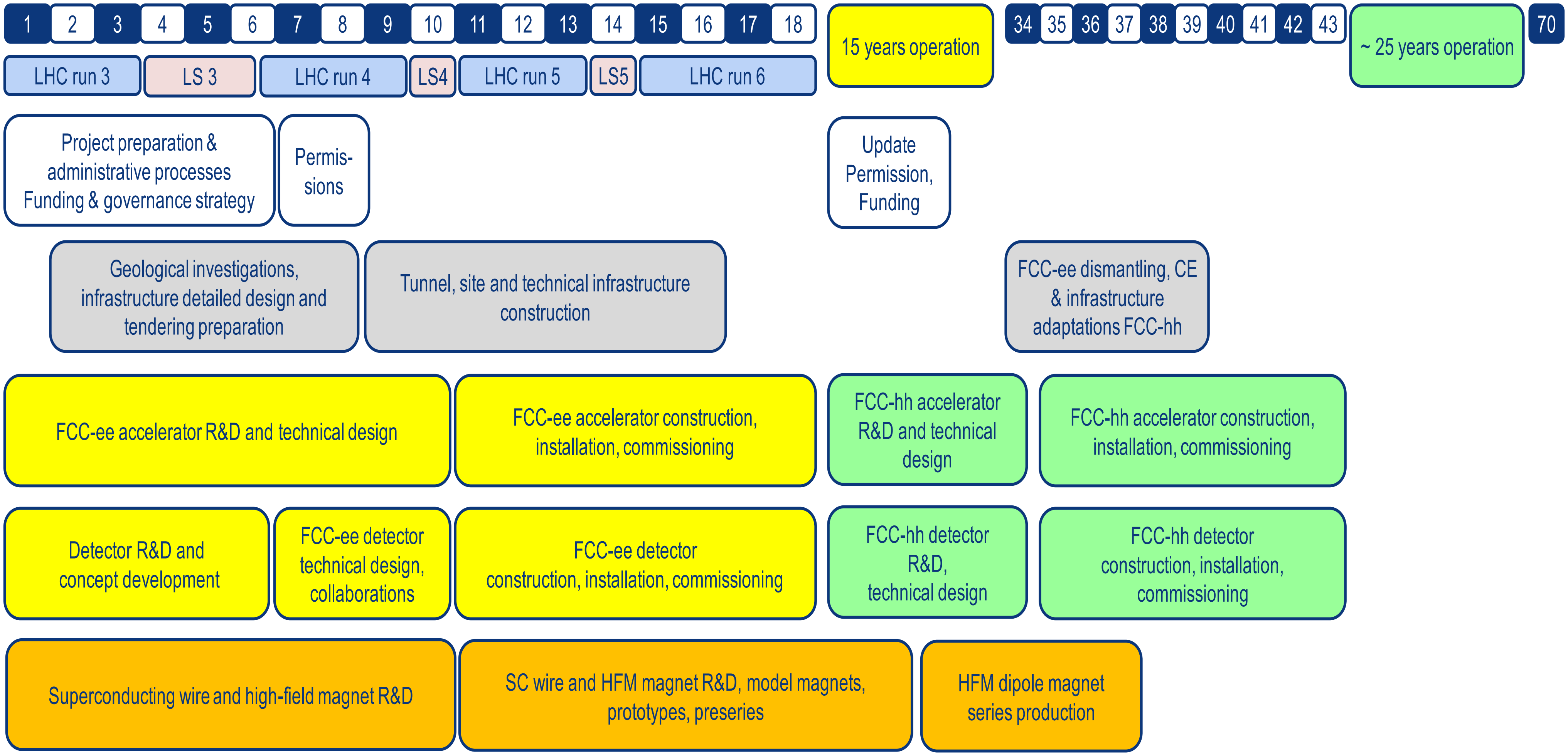
+ **recent, novel ingredients to reach extremely high luminosities at high energies**

FCC-ee can be built, with even better performance than originally thought & parameters much more robust

All technologies at hand

→ **FCC-ee can be built with the proposed luminosities now!**
as included in an integrated FCC programme

FCC integrated project technical schedule



- **FCC integrated project plan is fully integrated with HL-LHC exploitation**
- **provides for seamless further continuation of HEP in Europe.**

Circular vs Linear e^+e^- colliders

Circular	Linear
• Considerable amount of experience	• Extensive simulations and paper studies, but limited operational experience
• design luminosities are conservative estimates (always exceeded by factors 2 to 4)	• SLC reached half of design peak luminosity after 10 years • Larger than expected spot sizes @ SLC, FFTB, ATF2 (not entirely understood).
• Required positron production rates lower than those routinely achieved @ SLC and those expected.	• Required positron rates exceed present world record (factors 20 to 40). new scheme of high energy γ conversion @ILC -> issues of radiation & cooling.
• Low-emittance e-beams stored & maintained in storage rings for decades	• Extraction of low-emittance beam from a storage ring is needed (not standard mode) -> emittance increase

→ **Circular collider technology is reliable and relatively low-risk**

To polarize or not to polarize? (longitudinally)

- Transverse polarization enables accurate beam energy calibration with resonant depolarization (unique to circular colliders!)

  The precision could be affected by longitudinal polarization

- Longitudinal polarization would lead to a loss of luminosity (factor 50)
- For Z, W, t (produced and decaying via parity violating weak interactions), longitudinal polarization brings no information that could not be obtained otherwise

Costs

Construction costs

- **4 GCHF** **FCC-ee collider & injector**
- **17 GCHF** **FCC-hh collider & injector** (9.4 GCHF for the magnets)
- **7.6 GCHF** **FCC-ee common civil engineering & technical infrastructure**

Operation costs

- **27 TWh** **for 14 years of FCC-ee research program -> 1.9 TWh/year**
  (1.2 for CERN today, 1.4 for HL-LHC))

→ **Price of the FCC-ee Higgs Boson = 255 euros** (<< CLIC & ILC)

Detectors & Beam Background

$\mathcal{L}$ @ FCC-ee > 10^6 x $\mathcal{L}$ @ LEP (Z pole)

but

- spread over a large number of bunches (16,640 vs 4) -> similar bunch intensities
- asymmetric design of IP -> similar synchrotron radiation -> negligible related background

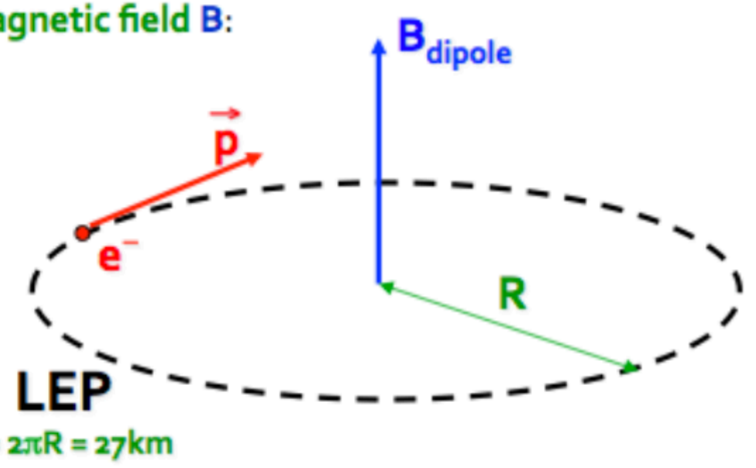
Detailed simulations

e.g vertex detector occupancy < 10^{-5} @ Z pole, a few 10^{-4} @365GeV

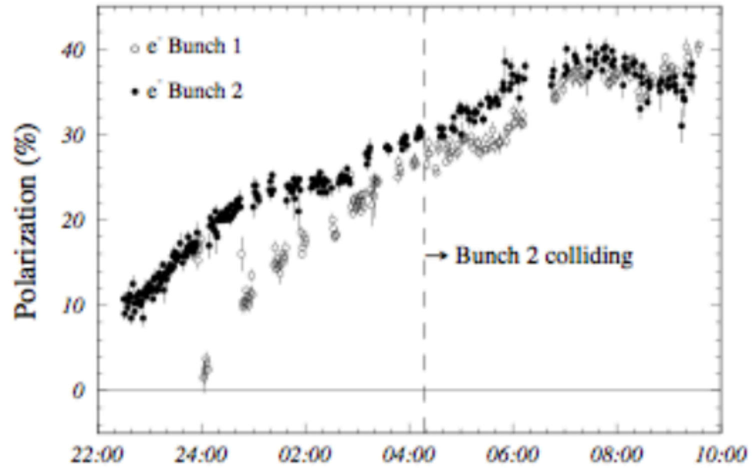
- **negligible background**
- **detectors satisfying the requirements are feasible**

Beam polarization & Resonant depolarization

Electron with momentum **p** in a uniform vertical magnetic field **B**:

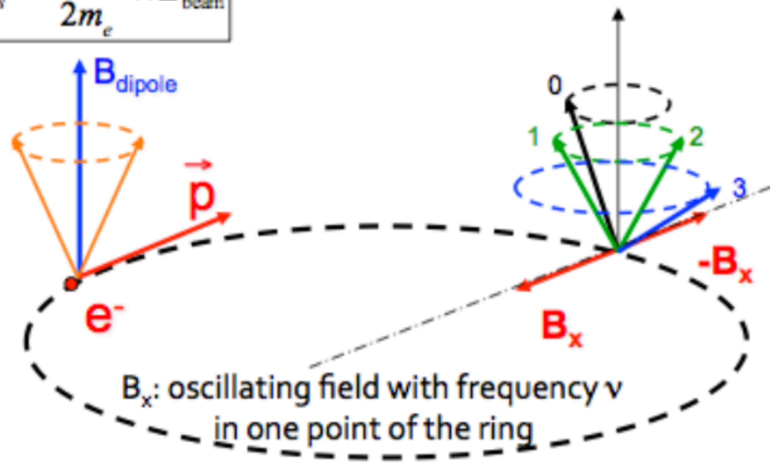


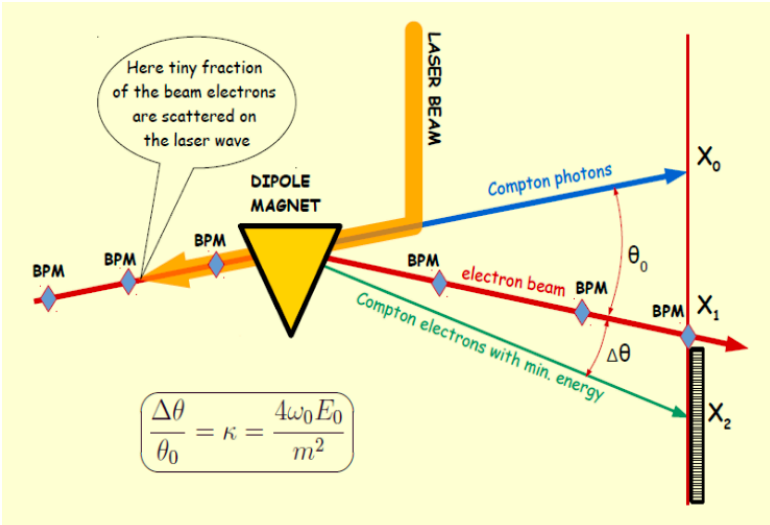
The electrons get transversally polarized (i.e., their spin tends to align with **B**)



- The spin precesses around B with a frequency proportional to B (Larmor precession)
  - Hence, the number of revolutions ν_S for each LEP turn is proportional to BL (or ∫Bdl)

$$\nu_s = \frac{g_e - 2}{2m_e} \times E_{beam}$$



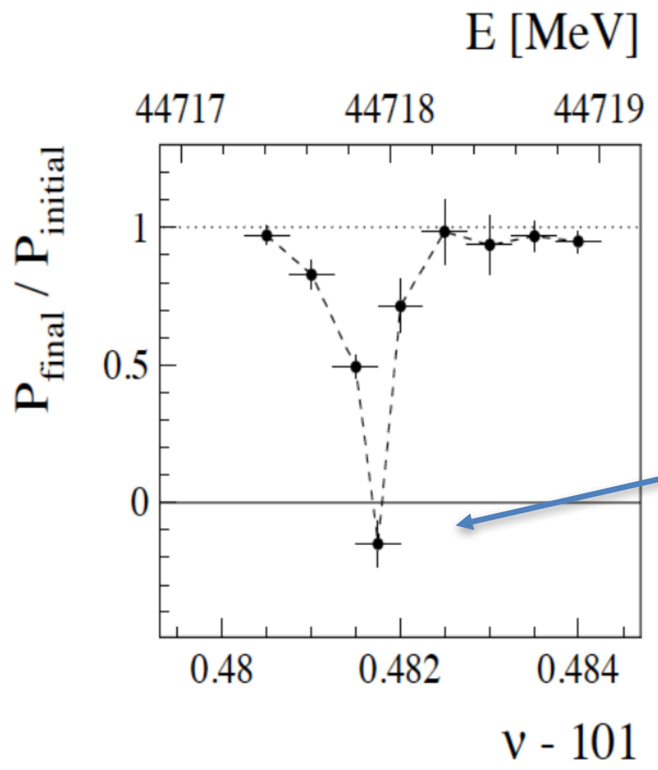


Beam polarization & Resonant depolarization

The spin precession (f_{sp}) frequency is determined by resonant depolarization

$f_{sp} = \nu f_{rev}$

$$\nu = a_e \gamma = \frac{g_e - 2}{2} \frac{E_{\mathrm{Beam}}}{m_e c^2} = \frac{E_{\mathrm{Beam}}}{0.4406486(1)}$$



Resonant depolarization is produced by exciting the beam with an oscillating magnetic field generated by a vertical kicker magnet (field in the horizontal plane)

If the frequency of the resulting spin kick is in phase with the spin precession, a resonance condition occurs. The electron spins are coherently swept away from the vertical direction, and polarization disappears