Precision Electroweak Measurements at FCC-ee

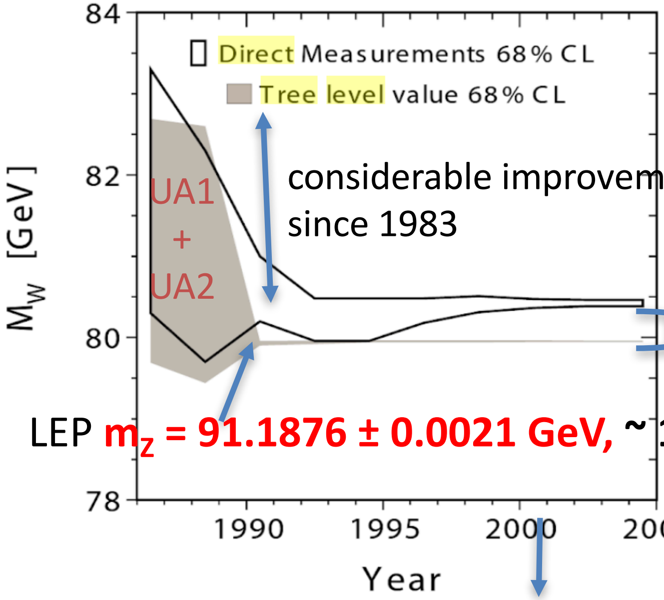
Elizabeth Locci
CEA-IRFU, Saclay

on behalf of the FCC-ee study group

Picture https://operasandcycling.com/gent-ghent-gand-gante/

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

Physics of the Z and W Bosons - Roberto Tenchini, Claudio Verzegnassi



UA1 + UA2

considerable improvement since 1983

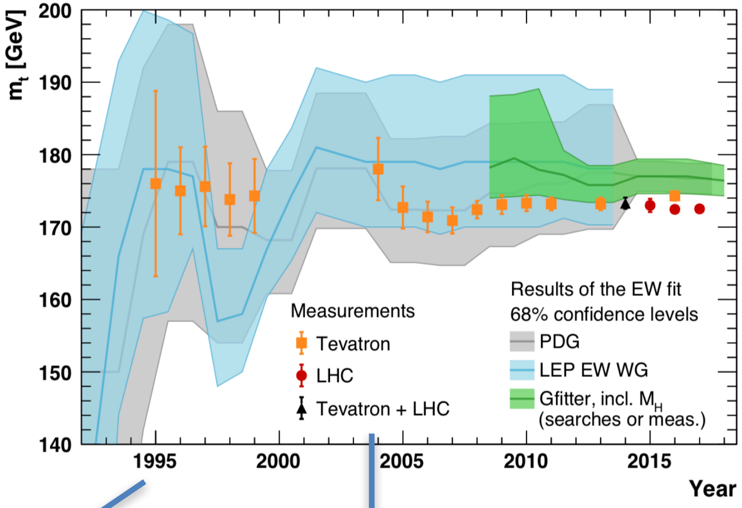
LEP m_Z = 91.1876 ± 0.0021 GeV, ~ 17 M Z

ATLAS 2018,
m_W = 80.370 ± 0.019 GeV

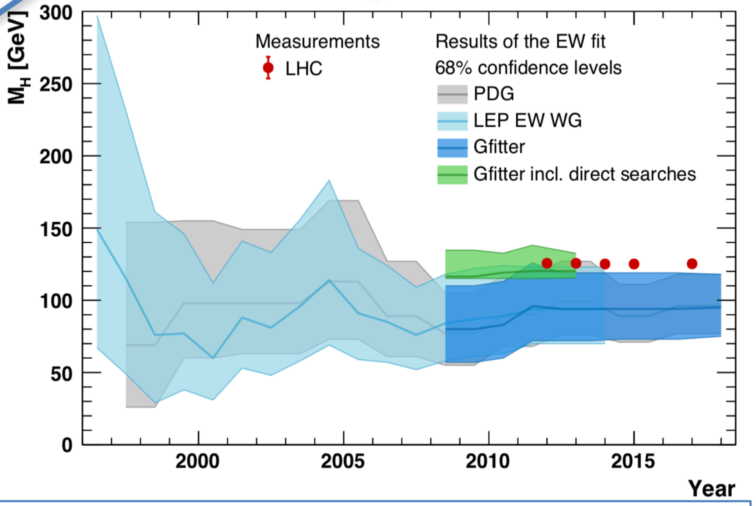
World average:
m_W = 80.379 ± 0.012 GeV

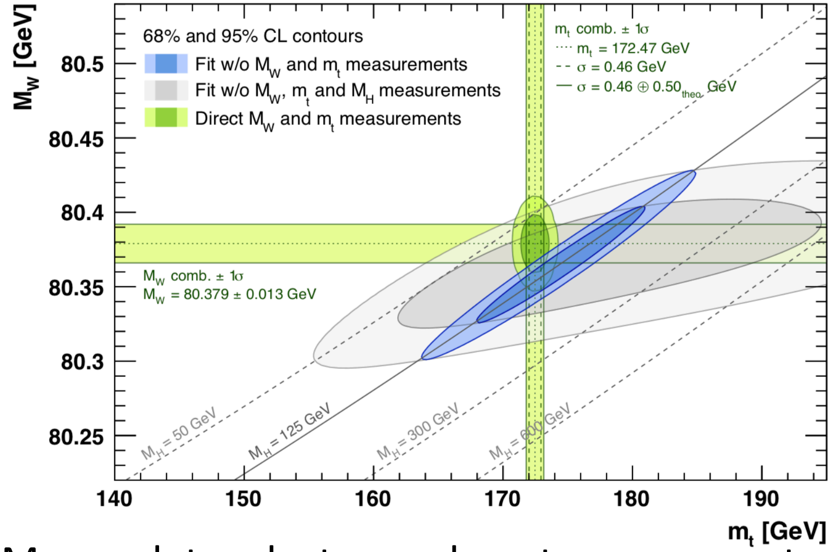
Sensitivity to EW loops

Sensitivity to new particles



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



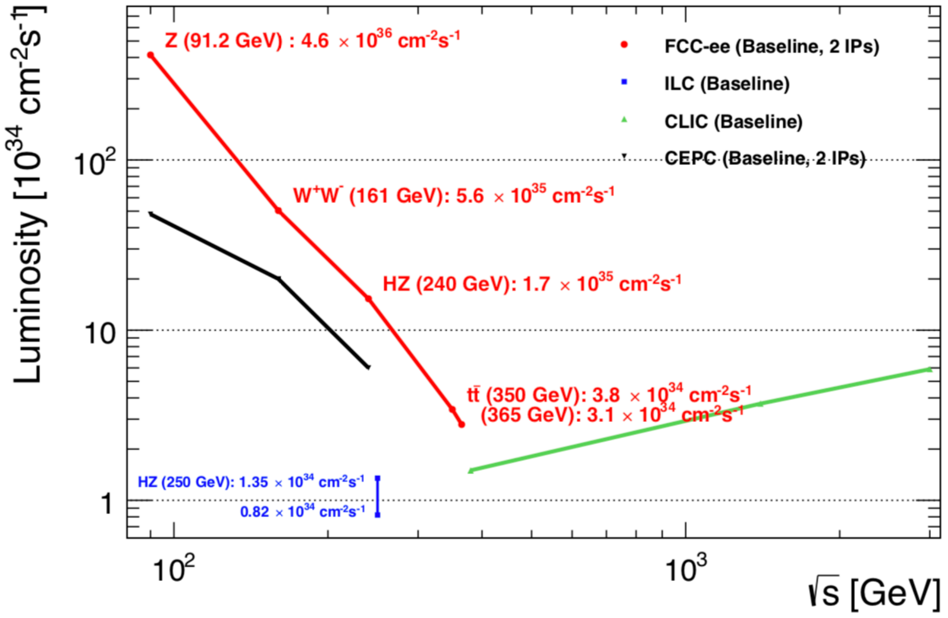


The SM complete, electroweak sector over-constrained

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

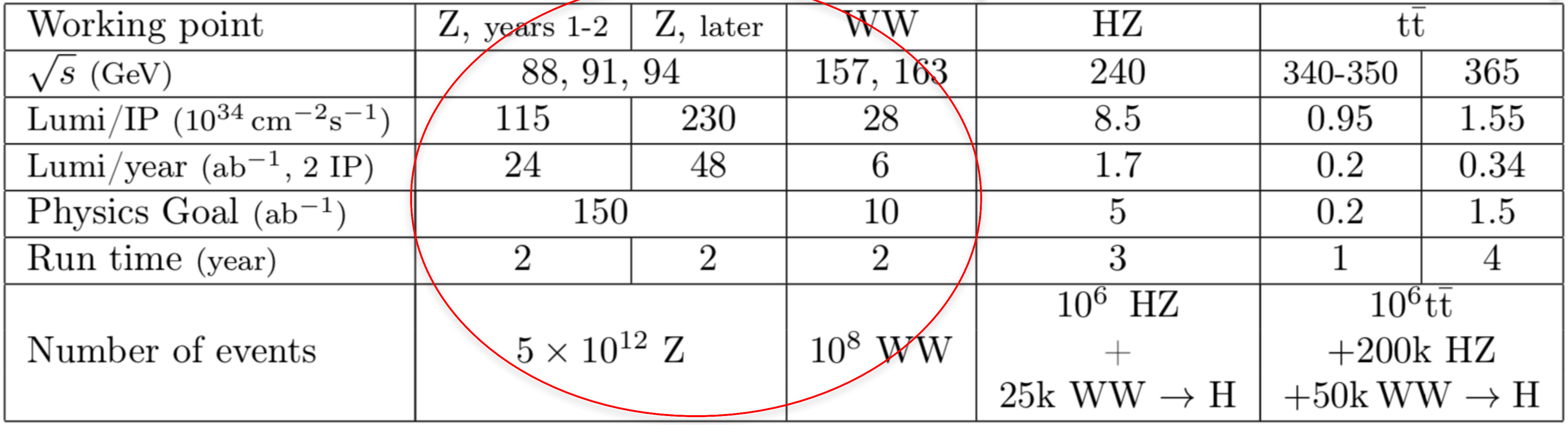
- **150 ab^{-1} around the Z pole** (~100 at the pole)
- **10 ab^{-1} around the WW threshold**

(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 ($10^{34}\,cm^{-2}s^{-1}$)	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 X 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)

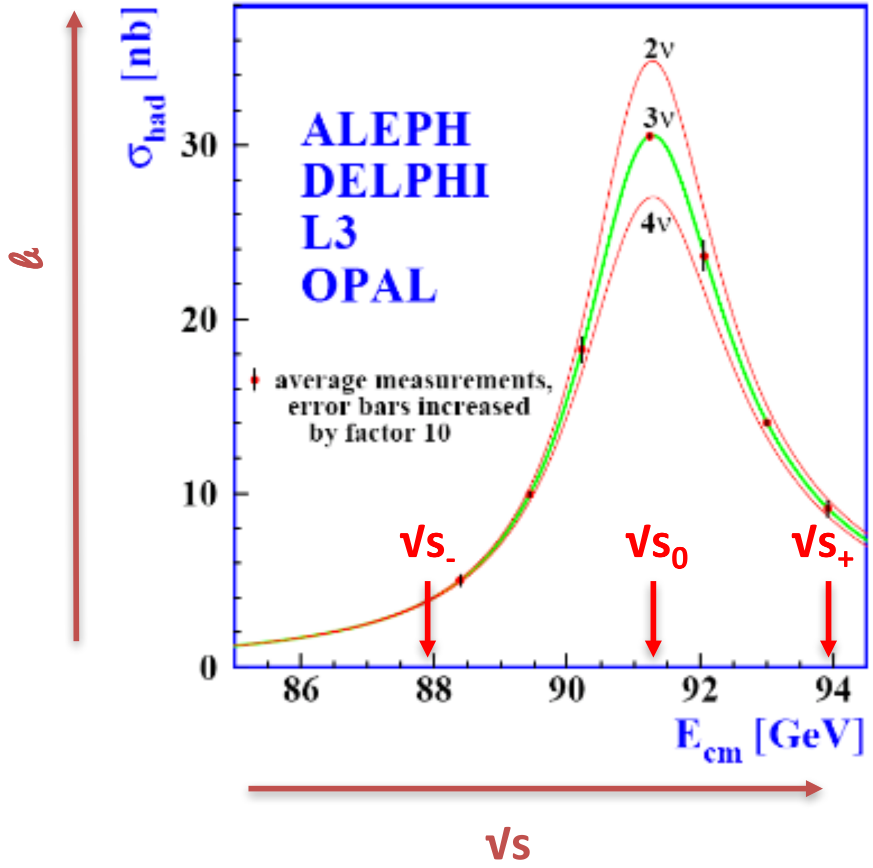
- R_b, R_c, $A_{FB}(bb)$, $A_{FB}(cc)$ (quark couplings)

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}

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 Δ√s ≈ 100 keV 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:

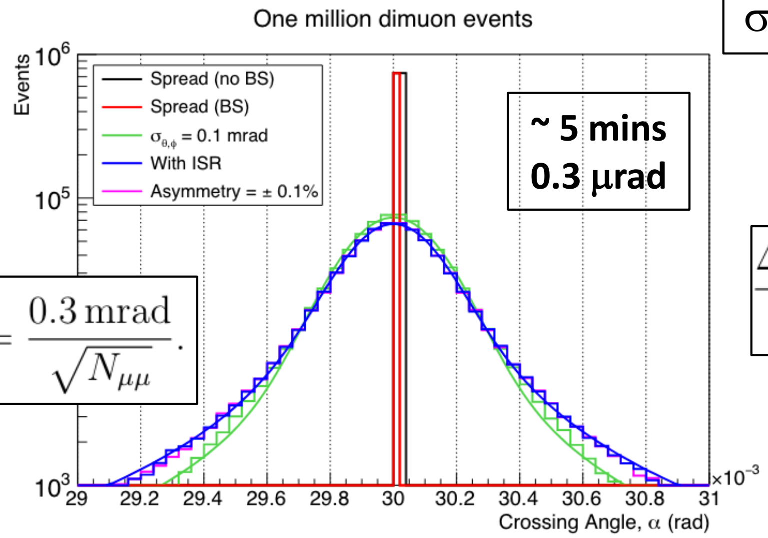
$$\alpha = 2 \arcsin \left[\frac{\sin(\varphi^- - \varphi^+) \sin\theta^+ \sin\theta^-}{\sin\varphi^- \sin\theta^- - \sin\varphi^+ \sin\theta^+} \right]$$

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

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

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

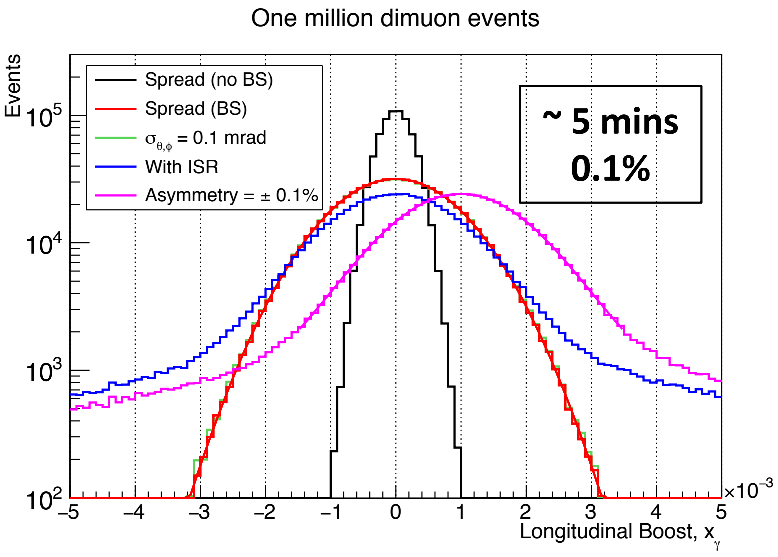
$\sigma_{\theta,\phi} \sim 100\ \mu$rad



~ 5 mins
0.3 μrad

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

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



~ 5 mins
0.1%

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

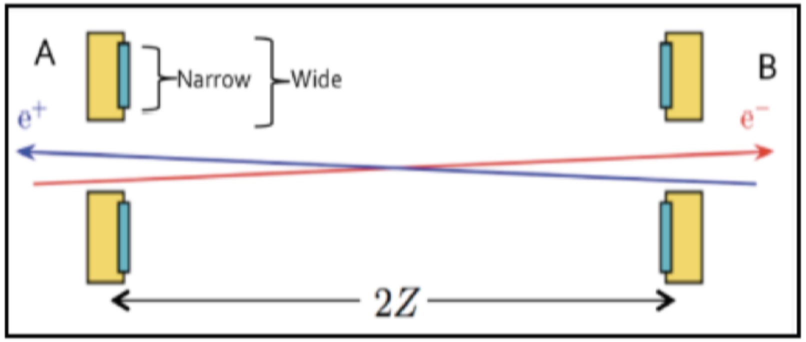
→ reduction **factor 8 in uncertainty** on number of light neutrino families, **N_ν*** **(ΔN_ν = 0.001)**

* **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 Zγ , Z -> νν (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

$$\left.\begin{array}{ll} \text{fraction of single tag:} & F_1 = R_b\,(\varepsilon_b-\varepsilon_{uds}) + R_c\,(\varepsilon_c-\varepsilon_{uds}) + \varepsilon_{uds} \\ \text{fraction of double tag:} & F_2 = R_b\,(C_b\varepsilon^2_b-\varepsilon^2_{uds}) + R_c\,(\varepsilon^2_c-\varepsilon^2_{uds}) + \varepsilon^2_{uds} \end{array}\right\} \longrightarrow \left\{\begin{array}{l} R_b = C_b F_1^2 / F_2 \\ \varepsilon_b = F_2 / C_b F_1 \end{array}\right.$$

LHC detectors and current taggers can reach 3 x LEP b-tagging efficiency at same c and uds suppression in a harsher environment → 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

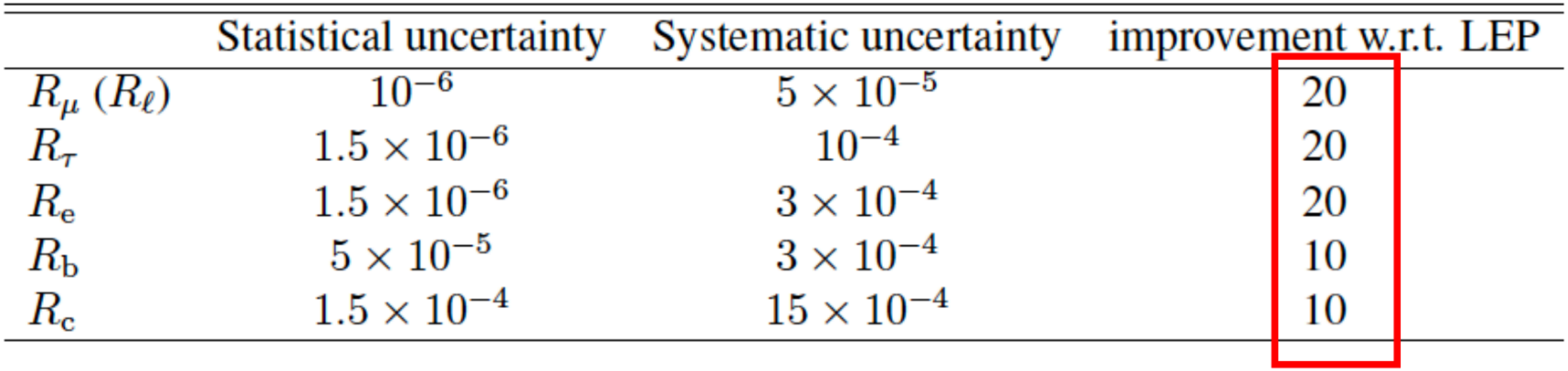
(e.g. momentum correlations, which can be suppressed by keeping b-tagging efficiency flat in momentum)

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: $A_{FB}^{ff} = \frac{\sigma_F^{ff} - \sigma_B^{ff}}{\sigma_F^{ff} + \sigma_B^{ff}}$ unpolarized e beams

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

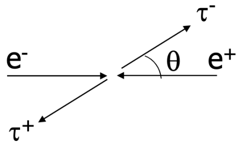
$A_{FB,\,0}^{\mu\mu} \approx (1 - 4\sin^2\theta_{eff})^2$ → $\Delta\sin^2\theta_{eff} \approx 5\;10^{-6}$ (at least)

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)



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

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

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

it measures $\mathcal{A}_e$ & $\mathcal{A}_t$, which used as input to $\mathbf{A_{FB,\,0}^{\mu\mu}}$ → **e, μ, τ couplings separately**
(together with Γe, $\Gamma\mu$, $\Gamma\tau$)

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

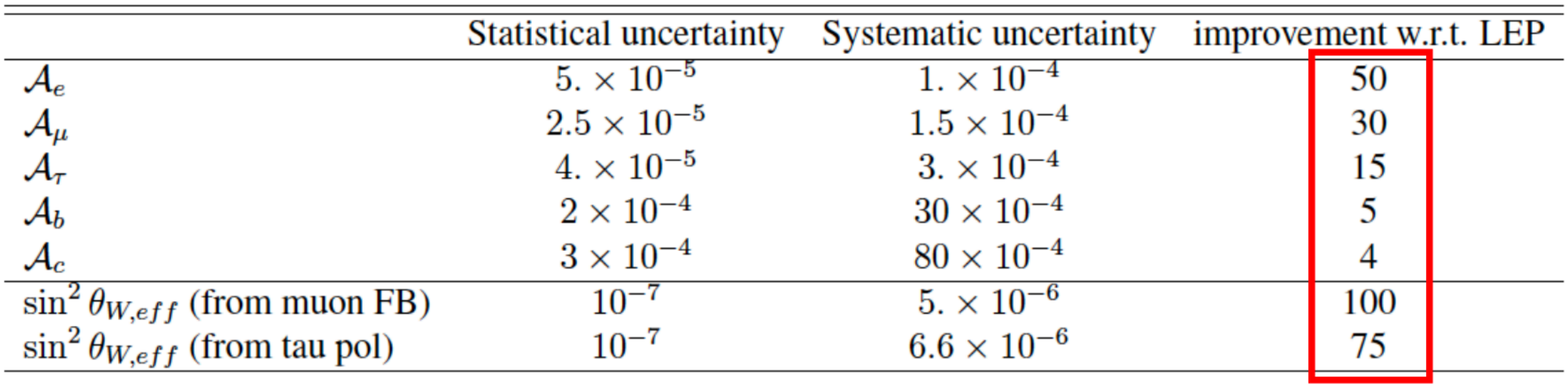
→ $\Delta\sin^2\theta_{eff} \approx 6\;10^{-6}$

$A_{FB,\,0}^{bb}$, $A_{FB,\,0}^{cc}$ 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/

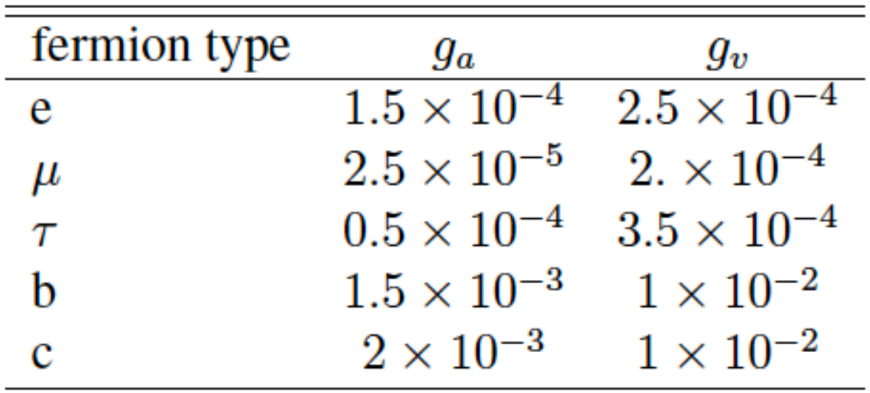
$\mathcal{A}_f$



	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

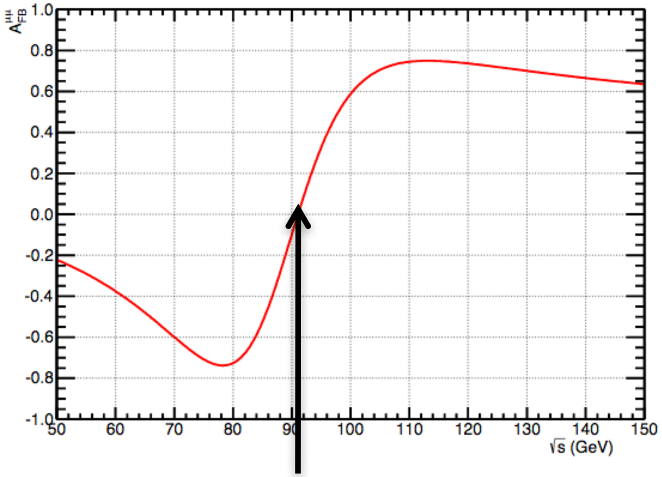
(still need to explore the potential for the measurement of the s quark coupling)

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 α ⟶ $\Delta\alpha/\alpha = 1.1\ 10^{-4}$

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



Z exchange dominant

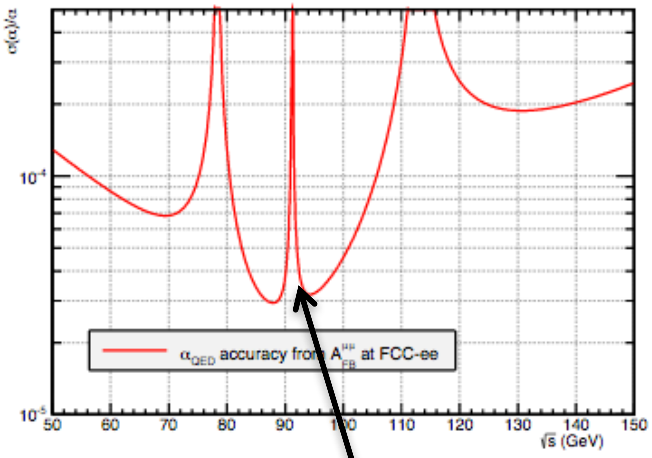
→ no sensitivity to α_{QED}

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

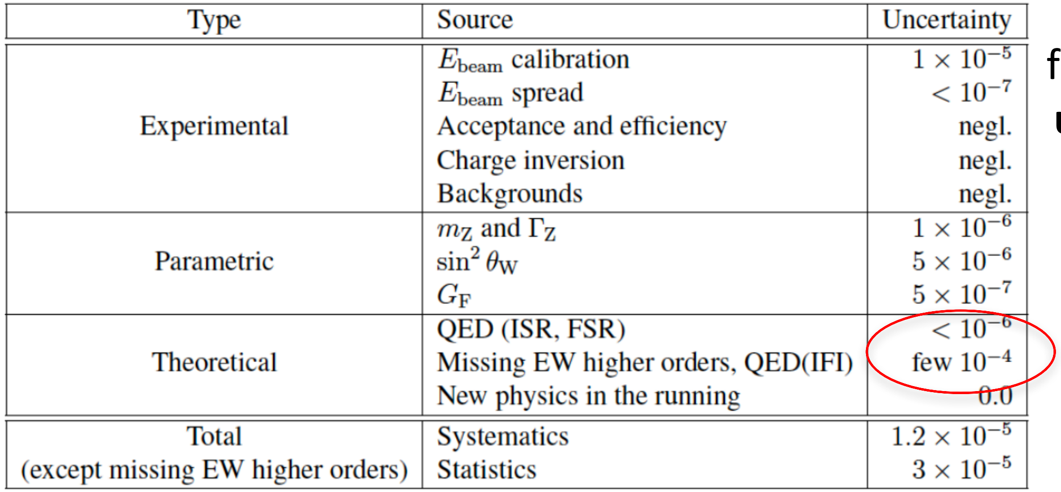
$\Delta A_{FB}^{\mu\mu} / A_{FB}^{\mu\mu}(s_+) > 0$

↓

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



$\sigma(\alpha)/\alpha$ for 1 year of running at any √s



Type	Source	Uncertainty
Experimental	$E_{\rm beam}$ calibration	1×10^{-5}
	$E_{\rm beam}$ 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

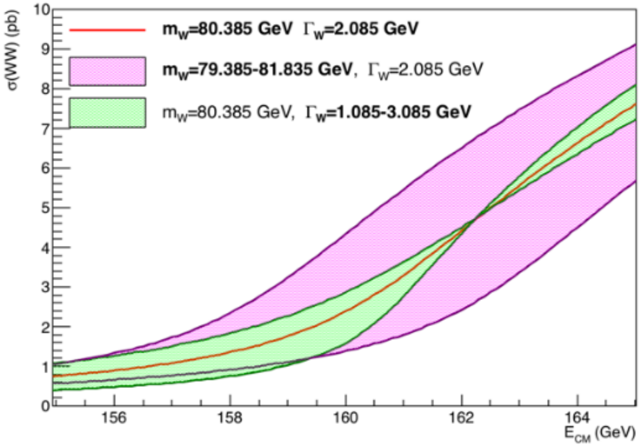
work on EWK theoretical corrections required to reach **$3\ 10^{-5}$** ⟶

V- W mass and width

More in Marina's talk

(Paolo Azzurri, Marina Béguin, E.L.)

from WW cross-section



@ $\sqrt{s_1}$ = 157.1 GeV, $\sqrt{s_2}$ = 162.3 GeV, f = 0.4

ΔM_W = 0.62 MeV (210 MeV @ LEP2)

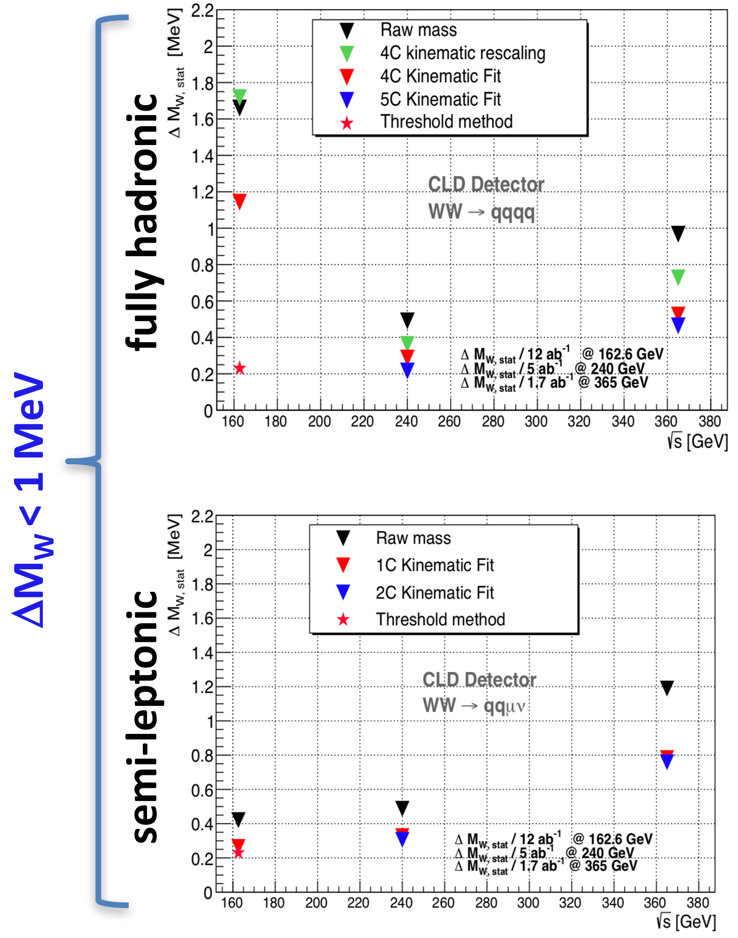
$\Delta\Gamma_W$ = 1.5 MeV

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})**

ℒ from Bhabha (requirement similar to Z pole)

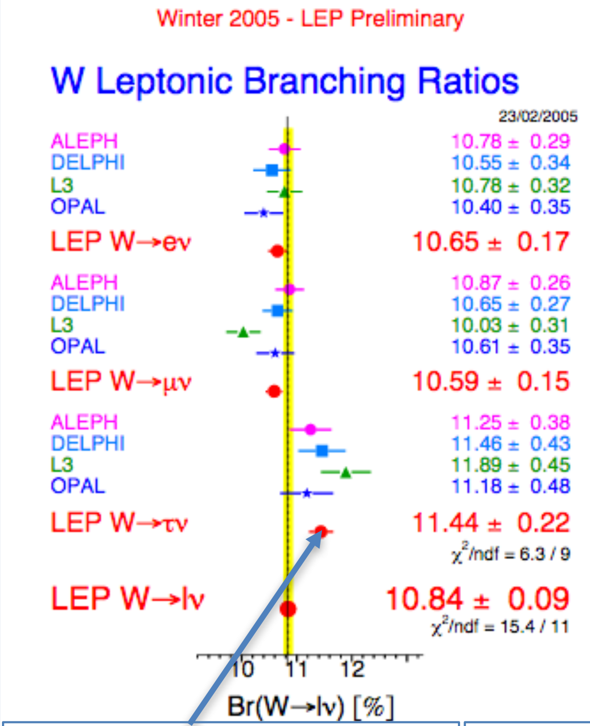
from WW direct reconstruction

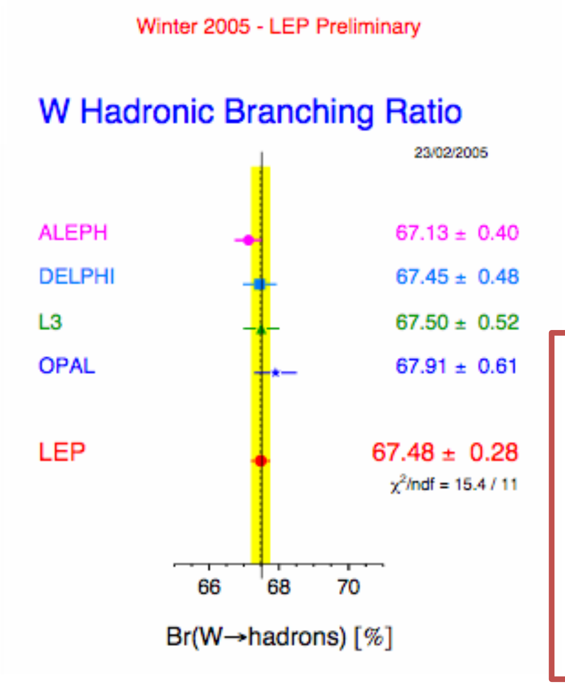


Stat.helps in reducing LEP syst.(fragmentation, jet mass...)

- **$\Delta\sqrt{s}$ ≈ 300 keV** @ 162.6 GeV
- Need to use Zγ & ZZ events to control √s at √s > 200 GeV (no resonant depolarization) or/and measure mW @ threshold to determine √s above threshold

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

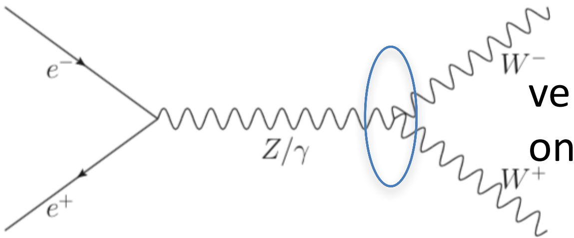
excellent control of jet reconstruction and lepton id are needed to control cross-contaminations in signal channel (τ -> e,μ ν)

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

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

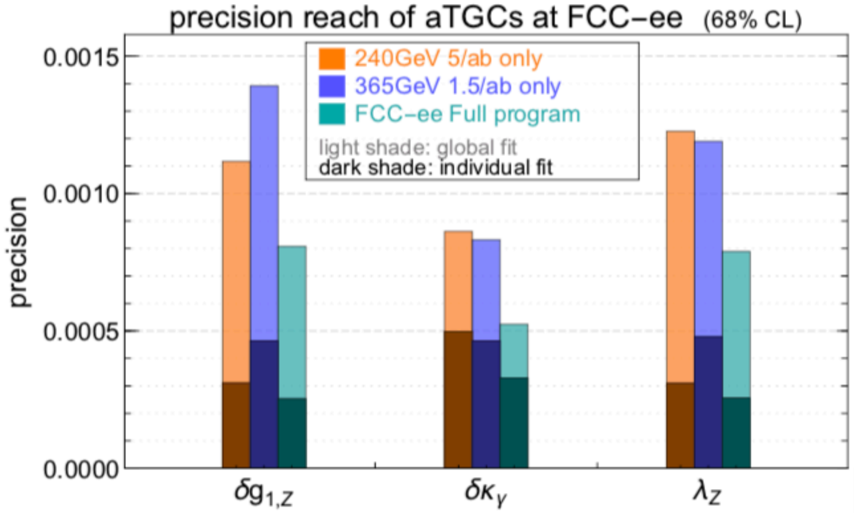
@ 161, 240, 350, 365 GeV with much higher $\mathcal{L}$

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

Focus on CP-even dimension 6 operators

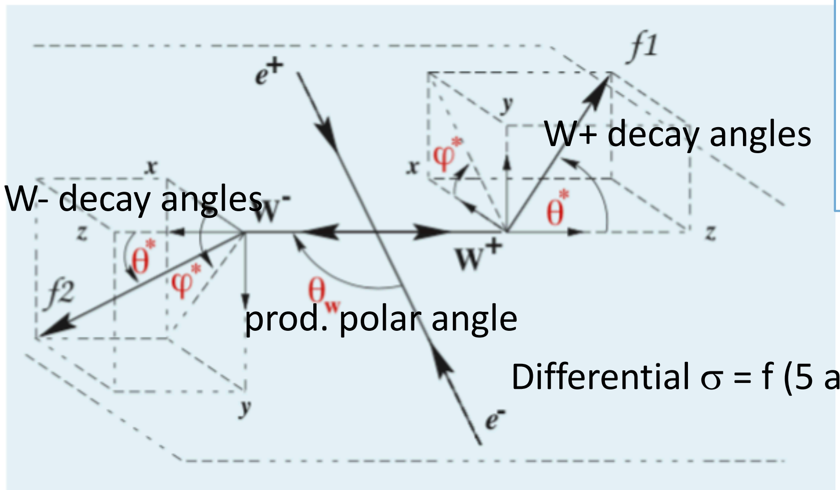
$\mathcal{L}_{TGC} = f\,(\delta g_1^Z, \delta\kappa_Z, \delta\kappa_\gamma, \lambda_Z, \lambda_\gamma)$

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



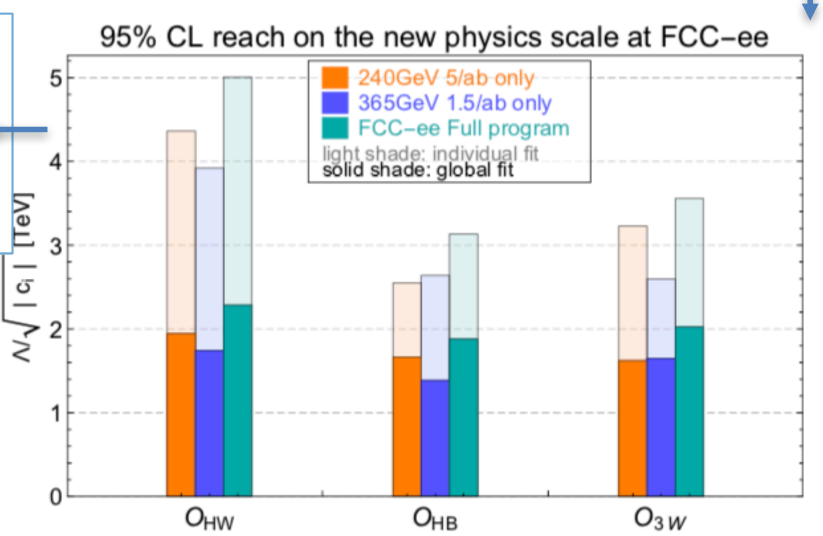
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu} \qquad \delta g_{1,Z} = -m_Z^2 \frac{c_{HW}}{\Lambda^2}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \qquad \delta\kappa_\gamma = -m_W^2 \left(\frac{c_{HW}}{\Lambda^2} + \frac{c_{HB}}{\Lambda^2}\right)$$
$$\mathcal{O}_{3W}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

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 the Z cross-section

  absolute accuracy **$\approx 10^{-4}$** , **relative** (point to point) **$\approx 10^{-5}$**
  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**
- **FCC-ee Polarization and Center-of-mass Energy Calibration (soon out)**
- **talks @ FCC-week 2019**

W & Z Observables

from CDR- Vol 1

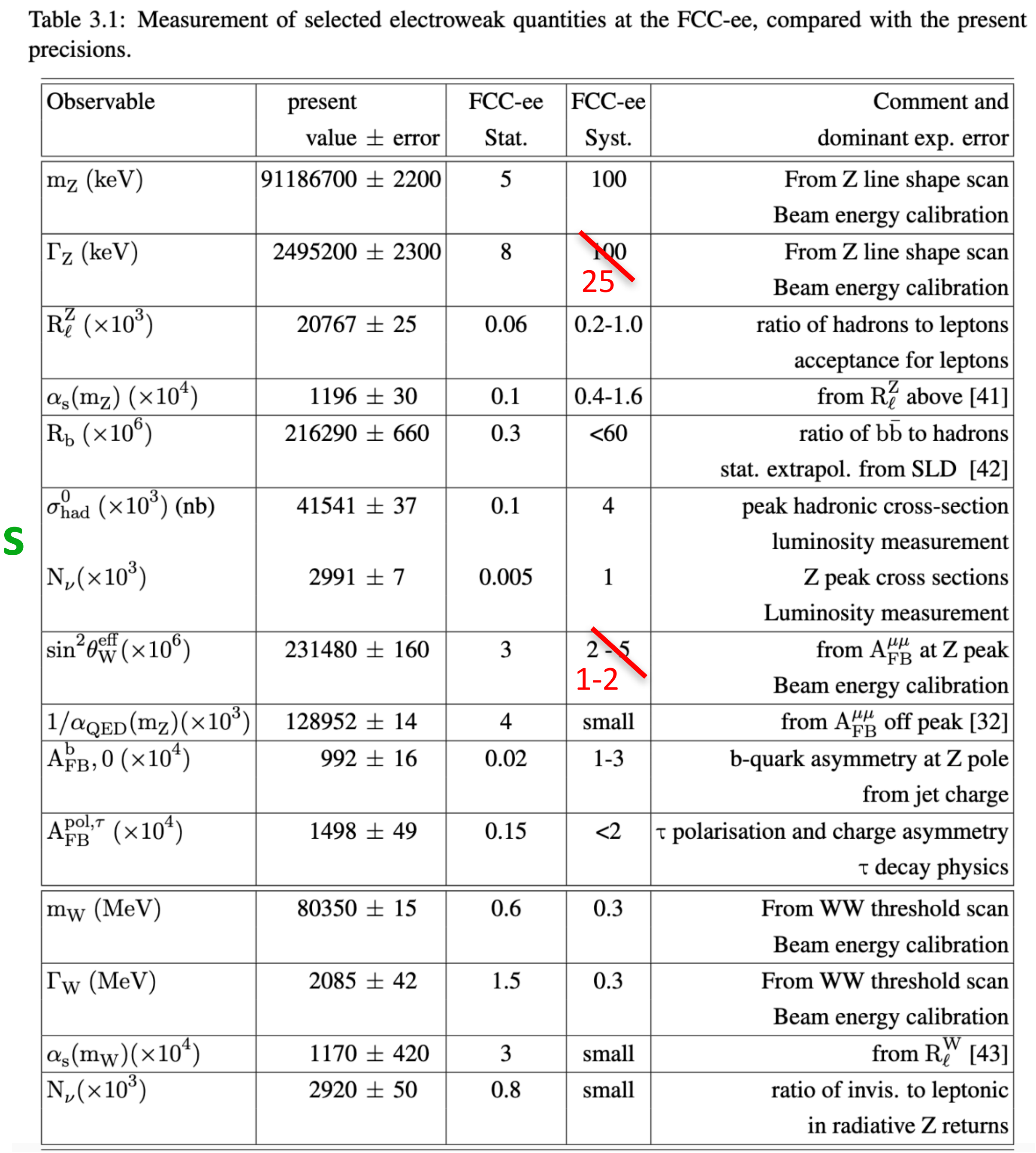


Table 3.1: Measurement of selected electroweak quantities at the FCC-ee, compared with the present precisions.

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_ℓ^Z ($\times 10^3$)	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_ℓ^Z 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_{had}^0 ($\times 10^3$) (nb)	41541 ± 37	0.1	4	peak hadronic cross-section luminosity measurement
N_ν($\times 10^3$)	2991 ± 7	0.005	1	Z peak cross sections Luminosity measurement
$\sin^2\theta_W^{eff}$($\times 10^6$)	231480 ± 160	3	~~2 - 5~~ 1-2	from $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z)$($\times 10^3$)	128952 ± 14	4	small	from $A_{FB}^{\mu\mu}$ off peak [32]
$A_{FB}^b, 0$ ($\times 10^4$)	992 ± 16	0.02	1-3	b-quark asymmetry at Z pole from jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	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_ℓ^W [43]
N_ν($\times 10^3$)	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns