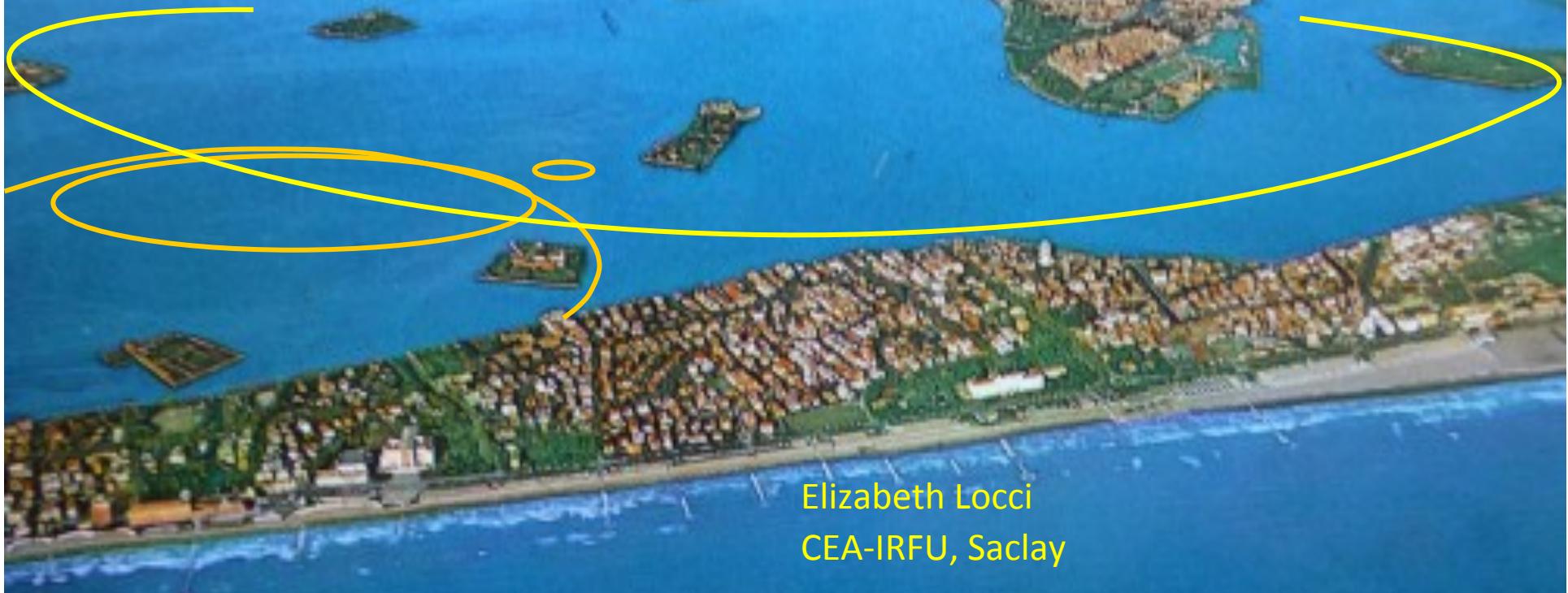




Precision Electroweak Measurements at FCC-ee (ILC, CLIC)

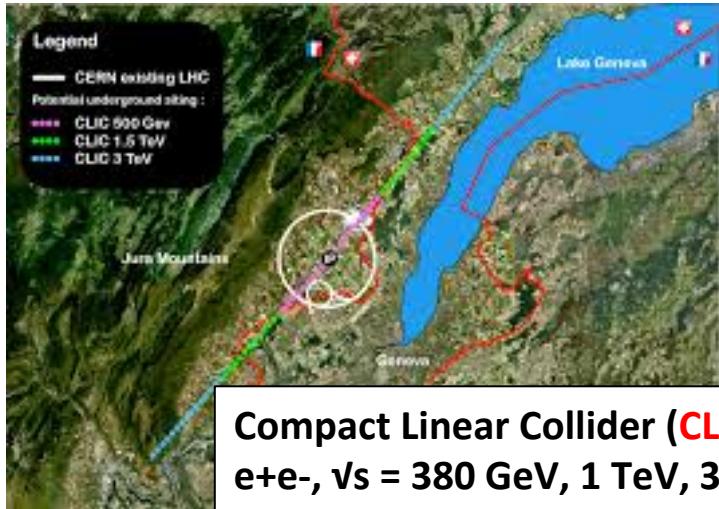


Elizabeth Locci
CEA-IRFU, Saclay

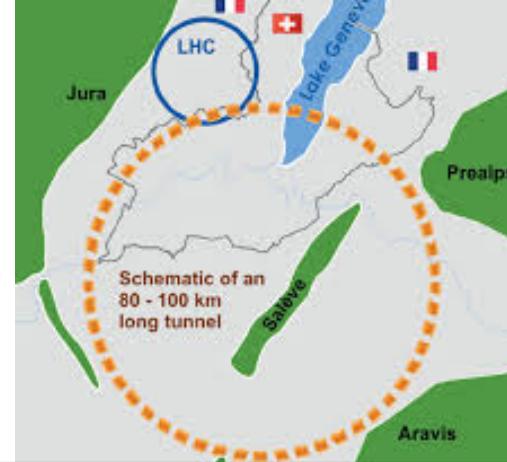
on behalf of the FCC-ee study group



High-energy e⁺e⁻ colliders



**Compact Linear Collider (CLIC): CERN e⁺e⁻, $\sqrt{s} = 380 \text{ GeV}, 1 \text{ TeV}, 3 \text{ TeV}$
Length = 11, 29, 50 km**



**Future Circular Collider (FCC): CERN e⁺e⁻, $\sqrt{s} = 90-350 \text{ GeV}$; pp, $\sqrt{s} \approx 100 \text{ TeV}$
Circumference = 97.5 km**



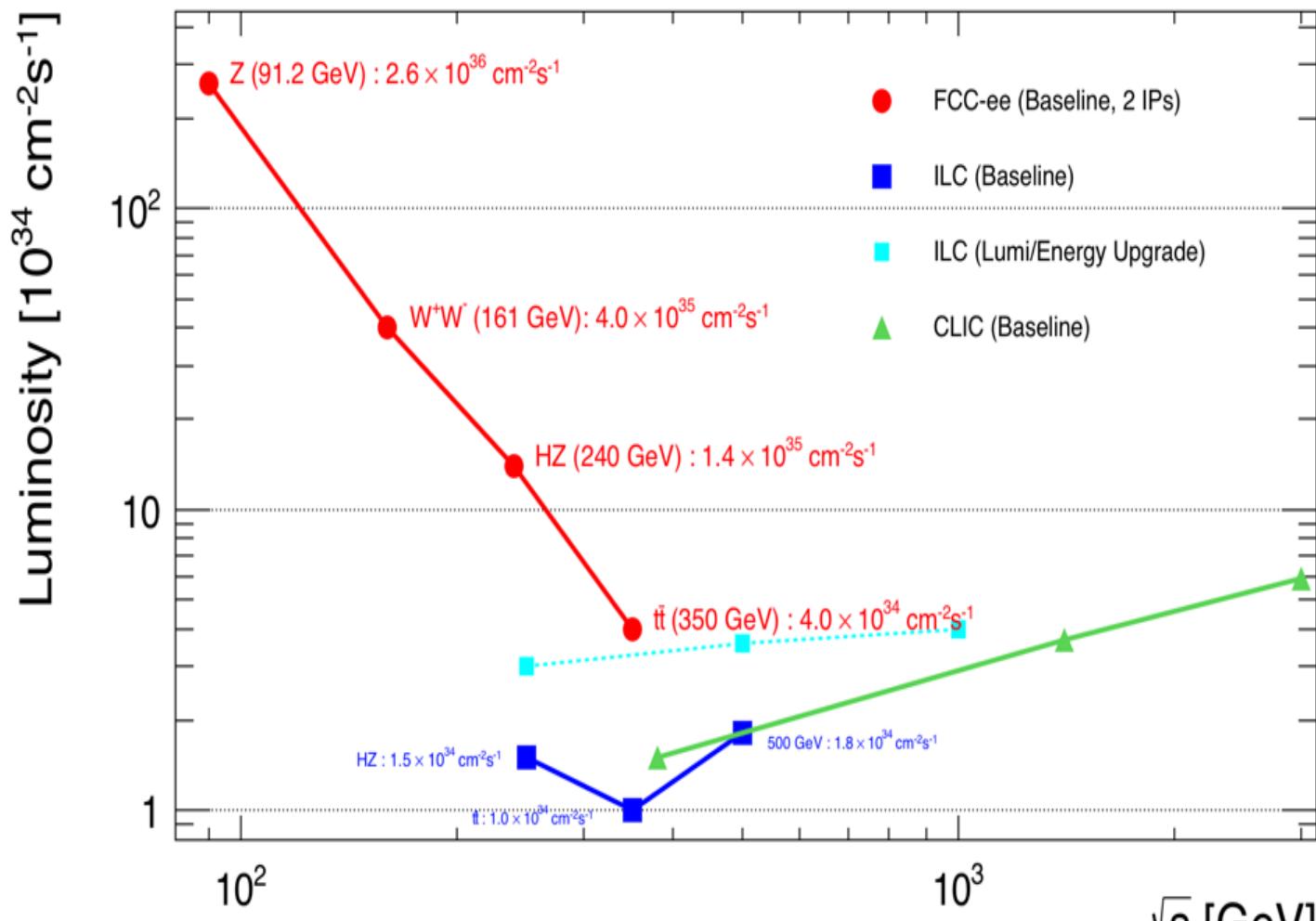
**International Linear Collider (ILC): Japan e⁺e⁻, $\sqrt{s} = 250, 350, 500 \text{ GeV}$ (1 TeV?)
Length = 31 km (50 km)**

**Circular Electron Positron Collider (CEPC): China e⁺e⁻, $\sqrt{s} = 90-250 \text{ GeV}$; SPPC pp
Length = 100 km**



Luminosity vs Energy

F. Zimmerman post-Berlin



Physics program: 88 to 370 GeV

Running scenarios

CLIC

Lucie Linssen- CERN seminar Jan.2017

Stage	\sqrt{s} (GeV)	\mathcal{L}_{int} (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

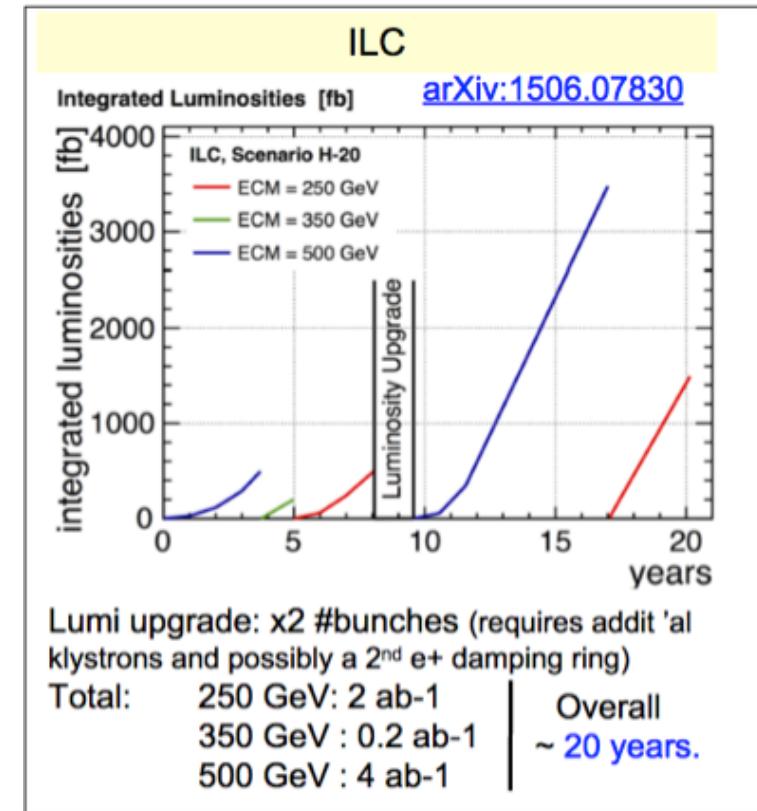
each 5 to 7 years of running

Dedicated to top mass threshold scan

FCC-ee

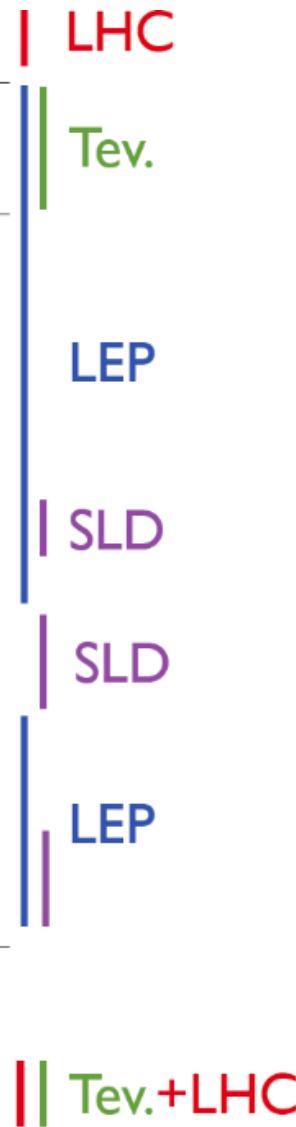
working point	luminosity/IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	geom. lumin.	luminosity/year	physics goal	run time [years]
Z first 2 years	65	69	17 ab ⁻¹ /year	150 ab ⁻¹	6
Z later	130	137	34 ab ⁻¹ /year		
W	20	30	5 ab ⁻¹ /year	8 - 10 ab ⁻¹	2
H	7	8	1.8 ab ⁻¹ /year	5 ab ⁻¹	3
top	2.0	2.1	0.5 ab ⁻¹ /year	1.5 ab ⁻¹	3

ILC



Inputs to EW fits

M_H [GeV] ^(o)	125.14 ± 0.24
M_W [GeV]	80.385 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ_{had}^0 [nb]	41.540 ± 0.037
R_ℓ^0	20.767 ± 0.025
$A_{FB}^{0,\ell}$	0.0171 ± 0.0010
$A_\ell^{(*)}$	0.1499 ± 0.0018
$\sin^2\theta_{\text{eff}}^\ell(Q_{\text{FB}})$	0.2324 ± 0.0012
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A_{FB}^{0,c}$	0.0707 ± 0.0035
$A_{FB}^{0,b}$	0.0992 ± 0.0016
R_c^0	0.1721 ± 0.0030
R_b^0	0.21629 ± 0.00066
\overline{m}_c [GeV]	$1.27^{+0.07}_{-0.11}$
\overline{m}_b [GeV]	$4.20^{+0.17}_{-0.07}$
m_t [GeV]	173.34 ± 0.76
$\Delta\alpha_{\text{had}}^{(5)}(M_Z^2)$	2757 ± 10



FCC-ee

expected to improve electroweak precision measurements by factors 20 to 50

Goals in JHEP 01 (2014) 164

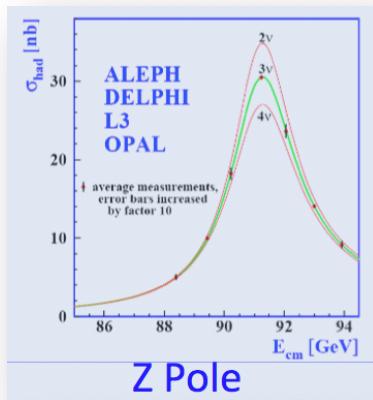
- ❖ Clean environment
- ❖ Very Large integrated luminosity (Z pole & WW threshold)
- ❖ c.m. energy precisely known (natural transverse polarization up to WW threshold)
100 keV achievable through resonant depolarization
- ❖ Narrow luminosity spectrum around nominal E_{CM}

Global Ewfit to
 $m_z, m_w, m_t, m_h, \alpha_s(m_z^2), G_F, \alpha_{\text{QED}}(m_z^2)$

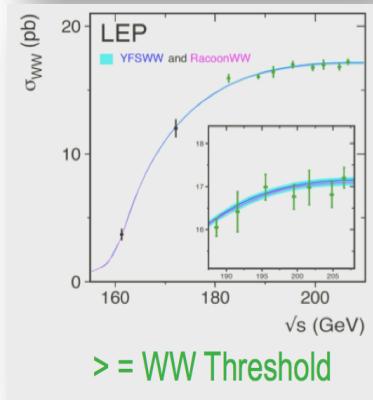
→ indirect search for NP up to 100 TeV achievable @ FCC-ee

well beyond the energy range accessible to direct searches

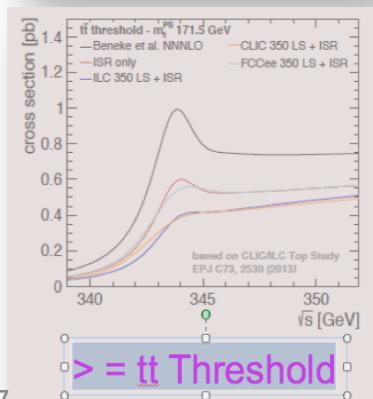
“Shopping” list



Z Pole



$>= \text{WW Threshold}$



$>= t\bar{t} \text{ Threshold}$

06/07/17

- ✓ **Z Mass & Width from line-shape**
- ✓ α_s from decay branching fractions
- ✓ **Number of neutrino species**
- ✓ $\sin^2\theta_W$ & α_{QED} from asymmetries

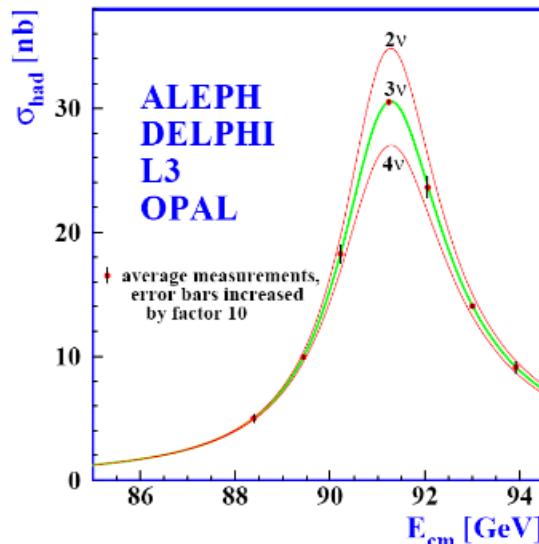
- ✓ **W Mass & Width from WW threshold scan**
- ✓ α_s from decay branching fractions
- ✓ **W Mass & Width from direct reconstruction**
- ✓ **W & WW cross-sections**
- ✓ **Constraints on gauge couplings**
- ✓ **Number of neutrino species from radiative Z events**

- ✓ **Top Mass from $t\bar{t}$ threshold scan**
- ✓ **Electroweak couplings of the top quark**

More in FCC week 2017 in Berlin

Tera Z

precision measurements @ the Z pole: Mass & Width



$L \approx 2 \cdot 10^{36} \rightarrow \approx 4 \cdot 10^{12} Z \text{ decays}$

Continuous E_{cm} calibration (resonant depolarization)
Z Mass & Width: 5 keV (stat) + 100 keV(syst)

Present relative theoretical uncertainty $\approx 10^{-4}$
(radiation function calculated up to $O(\alpha^3)$)
→ theoretical work to be done

Expected precision:

Z mass: $\Delta_{\text{rel}}(m_Z) \approx 10^{-6}$

Z width: $\Delta_{\text{rel}}(\Gamma_Z) \approx 5 \cdot 10^{-5}$

R_l (had/lep width): $\Delta_{\text{rel}}(R_l) \approx 5 \cdot 10^{-5} \rightarrow \Delta_{\text{rel}} \alpha_s(m_Z^2) \approx 2 \cdot 10^{-3}$

$\Delta N_\nu \approx 0.00008$ (0.0003) stat (syst) from lineshape

Gain factor w.r.t LEP

20

20

20

100 (stat), 20 (syst)

$\Delta R_b \approx 0.00001$ (0.00005-0.0002) stat (syst) *

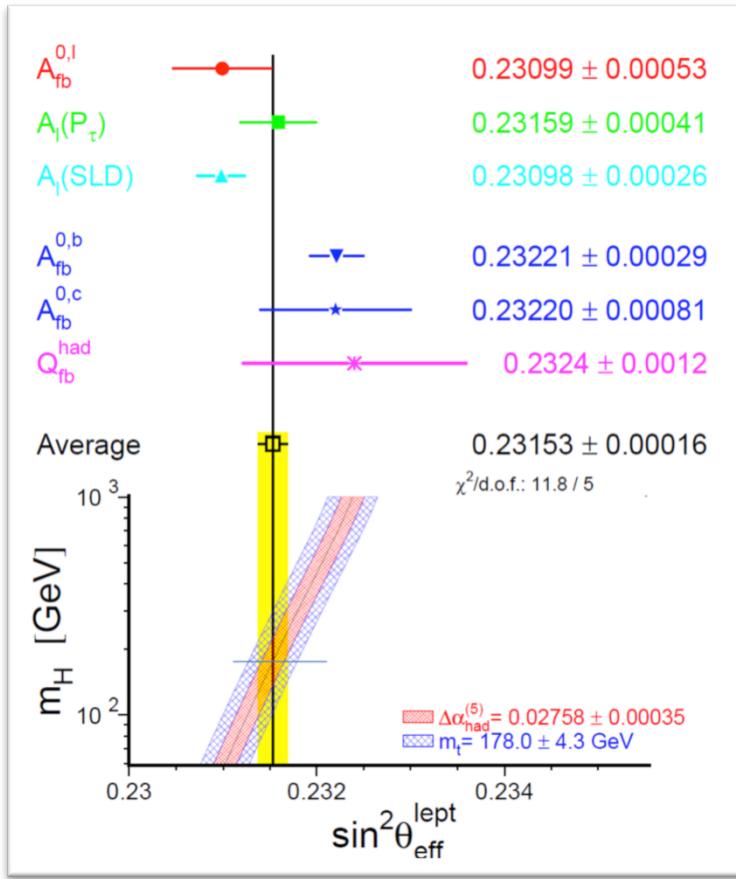
$\Delta R_c \approx 0.00003$ (0.0005) stat (syst) *

3-10

6

Tera Z

precision measurements @ the Z pole: Asymmetries



FCC-ee could give the final word to long-standing differences between asymmetries:

LEP measurements:

$A_{FB}^{||}, A_l(P_\tau), A_{FB}^{cc}, A_{FB}^{bb}$

were dominated by statistics

→ large gain expected from $\times O(15)$

Expected precision:

$\Delta A_b \approx 0.00002 (0.0004) \text{ stat (syst)} ^*$

$\Delta A_c \approx 0.00003 (0.0004) \text{ stat (syst)} ^*$

from τ polarisation:

$\Delta A_e \approx 0.00005 (0.0001) \text{ stat (syst)}$

$\Delta A_\tau \approx 0.00004 (0.0003) \text{ stat (syst)}$

Gain factor w.r.t LEP

5

8

30

10

from $A_{FB}(\mu\mu)$: $\Delta \sin^2 \theta_{eff} \approx 0.000006$

Gain factor w.r.t LEP ≈ 40

also $A_{FB}(ee), A_{FB}(\tau\tau)$

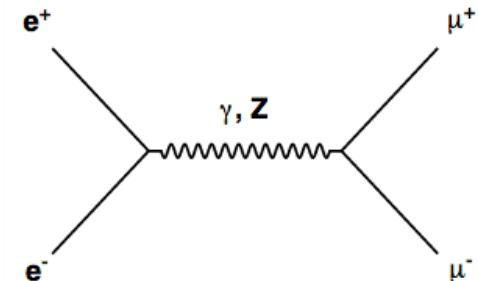
* work in progress

Tera Z

direct measurement of $\alpha_{\text{QED}}(m^2_Z)$ (1)

(Patrick Janot, arXiv:1512:05544, JHEP 2016(2) 1)

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



rather get α_{QED} directly @ the Z pole from a self-normalized quantity, the forward-backward asymmetry

$$A_{\text{FB}}^{\mu\mu} = \frac{\sigma_{\mu\mu}^{\text{F}} - \sigma_{\mu\mu}^{\text{B}}}{\sigma_{\mu\mu}^{\text{F}} + \sigma_{\mu\mu}^{\text{B}}}$$

uncertainties on efficiency, acceptance, luminosity cancel

$$A_{\text{FB}}^{\mu\mu} \approx A_{\text{FB},0}^{\mu\mu} + C^{\text{ste}} * \alpha_{\text{QED}} * (s - m^2_Z) / m^2_Z$$

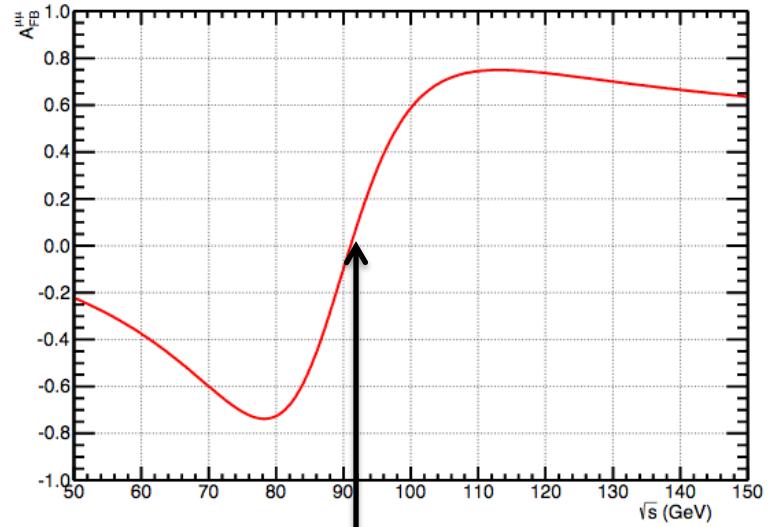
$$\Delta\alpha_{\text{QED}} / \alpha_{\text{QED}} \approx \Delta A_{\text{FB}}^{\mu\mu} / A_{\text{FB}}^{\mu\mu}$$

$$\frac{\Delta\alpha_0}{\alpha_0} \simeq 0.528 \frac{\Delta A_{\text{FB}}}{A_{\text{FB}}} (s_-) + 0.563 \frac{\Delta A_{\text{FB}}}{A_{\text{FB}}} (s_+)$$

$$\alpha_0 = \alpha_{\text{QED}}(m^2_Z)$$

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

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



Z exchange dominant

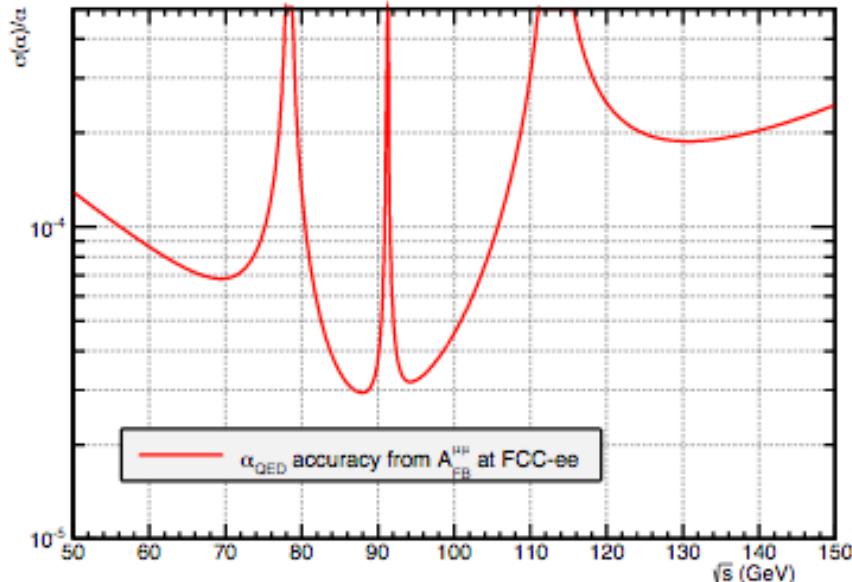
→ no sensitivity to α_{QED}

Tera Z

direct measurement of $\alpha_{\text{QED}}(m_Z^2)$ (2)

(Patrick Janot, arXiv:1512:05544, JHEP 2016(2) 1)

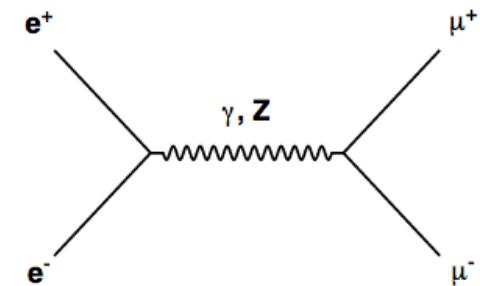
$\sigma(\alpha)/\alpha$ for a year of running @ any \sqrt{s} :



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, IFI)	$< 10^{-6}$
	Missing EW higher orders	$\text{few } 10^{-4}$
	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 statistical uncertainty on α_{QED} :
optimal: $\sqrt{s_-} = 87.9$ GeV & $\sqrt{s_+} = 94.3$ GeV

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



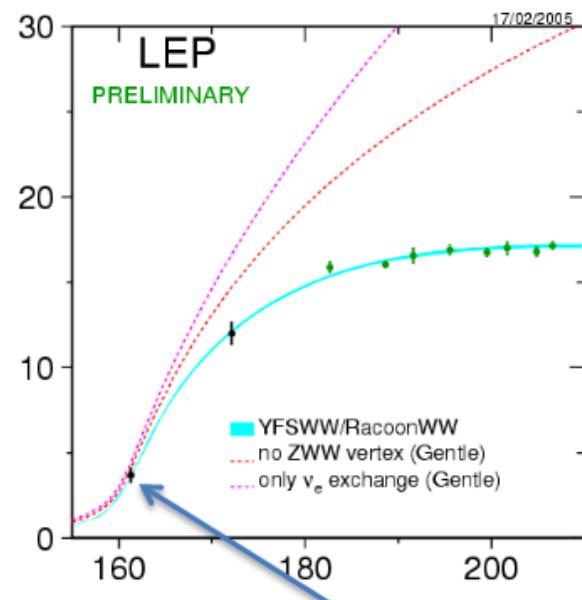
Oku W

WW threshold scan: W mass & Width from WW cross-section (1)

At FCC-ee:

$\text{@ } \sqrt{s} = 161 \text{ GeV}, L \approx 4 \cdot 10^{35}, 8 \text{ ab}^{-1} \rightarrow \approx 30 \cdot 10^6 \text{ WW decays}$

$\text{@ } \sqrt{s} = 240 \text{ GeV}, L \approx 0.9 \cdot 10^{35}, 5 \text{ ab}^{-1} \rightarrow \approx 80 \cdot 10^6 \text{ WW decays}$



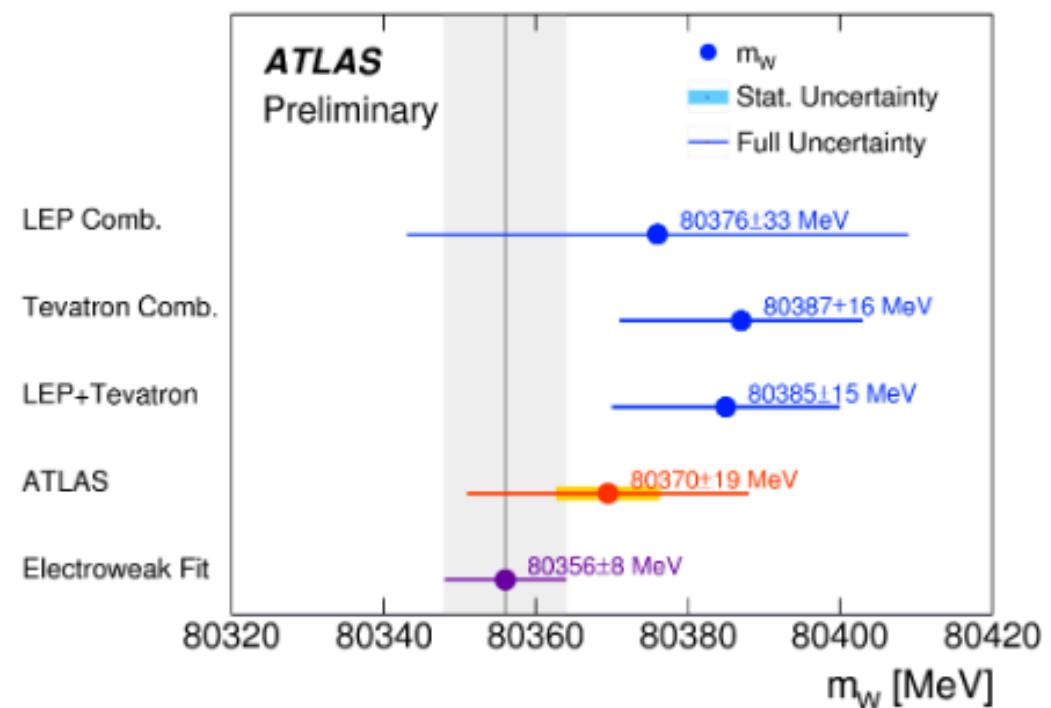
At LEP2 $\sqrt{s}=161 \text{ GeV} \sigma=4 \text{ pb}$

$\epsilon=0.75, \sigma_B=300 \text{ fb}$

$p=0.9 : \epsilon p \approx 0.68 (@161)$

$\rightarrow m_W = 80.40 \pm 0.21 \text{ GeV}$

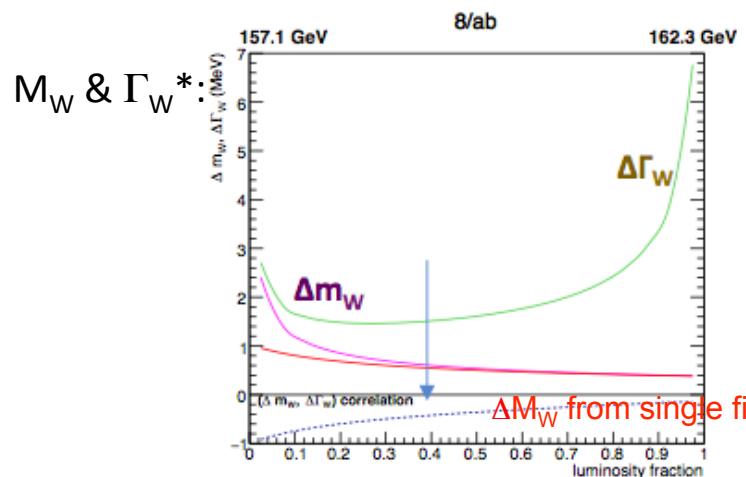
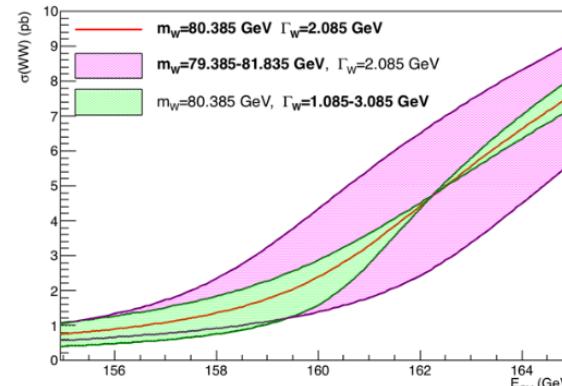
with $11/\text{pb}$ @ $E_{\text{CM}}=161 \text{ GeV}$



Oku W

WW threshold scan: W mass & width from cross-section (2)

Sensitivity to mass & width is different for different \sqrt{s}



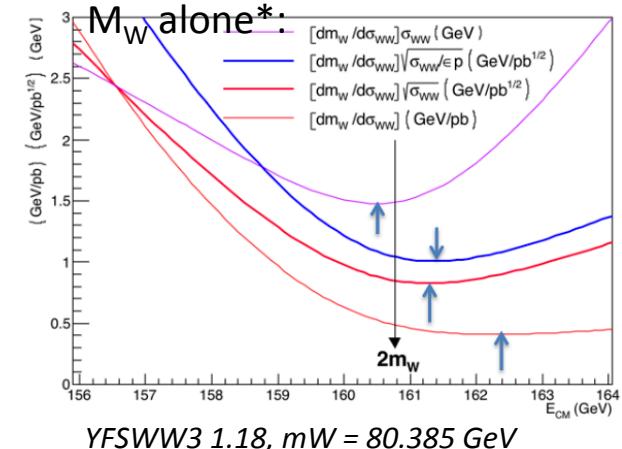
with $E_1 = 157.1$ GeV $E_2 = 162.3$ GeV $f = 0.4$
 $\Delta m_W = 0.62$ $\Delta \Gamma_W = 1.5$ $\Delta M_W = 0.56$ (MeV)

also M_W from direct reconstruction: $\Delta M_W = 0.5$ (1?) MeV stat (syst)

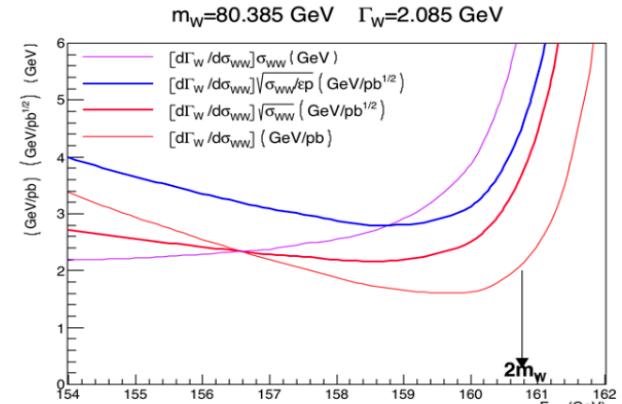
max stat sensitivity
 $\text{@ } \sqrt{s} \approx 2 M_W + 600 \text{ MeV}$

statistical precision:
 $350 \text{ MeV} @ L = 11 \text{ pb}^{-1}$
 $400 \text{ keV} @ L = 8 \text{ ab}^{-1}$

systematics controlled to:
 $\Delta E_{beam} < 400 \text{ keV} (5 \cdot 10^{-6})$
 $\Delta \varepsilon / \varepsilon, \Delta L / L < 10^{-4}$
 $\Delta \sigma_B < 0.7 \text{ fb} (2 \cdot 10^{-3})$



M_W alone*:



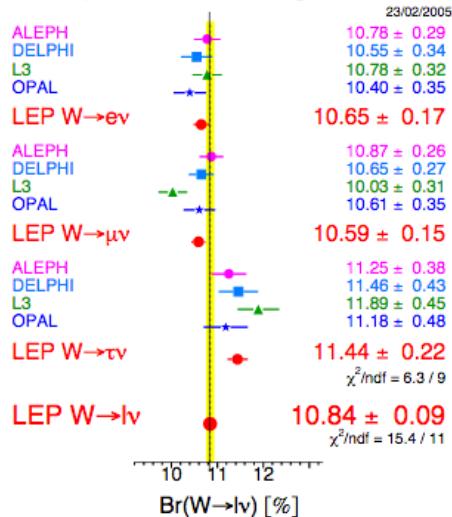
* assume ε, p, σ_B from LEP

Oku W

WW threshold scan: decay branching fractions

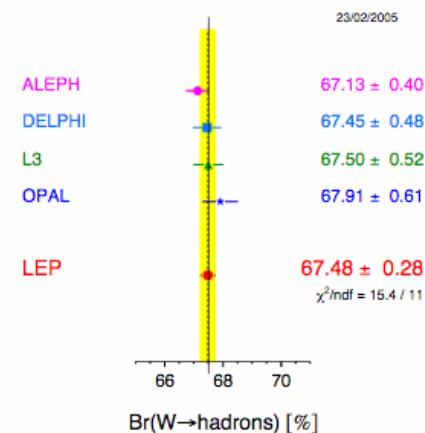
Winter 2005 - LEP Preliminary

W Leptonic Branching Ratios



Winter 2005 - LEP Preliminary

W Hadronic Branching Ratio



Lepton universality test at the 2% level
 $\text{Br}(\tau) > \text{Br}(e, \mu)$ at 2.7σ

At FCC-ee: $\Delta_{\text{rel}} \text{Br}(e\nu, \mu\nu, \tau\nu) \approx 4 \cdot 10^{-4}$

Beware: channel cross-contamination
 → better control of lepton id

l/l universality test at the 0.6% level

$$\Delta_{\text{rel}} \text{Br}(q\bar{q}) \approx 10^{-4}$$

$$\downarrow$$

$$\Delta_{\text{rel}} \alpha_s(m^2_W) \approx (9\pi/2) \Delta_{\text{rel}} \text{Br}(q\bar{q}) \approx 10^{-3}$$

$$\rightarrow \Delta \alpha_s(m^2_W) \approx \pm 0.0001$$

Gain factor w.r.t LEP ≈ 40 (10 w.r.t. today !!!)

also coupling to c & b quarks (V_{cb} , V_{cb} , ...) with flavor tagging *

* work in progress

Oku W

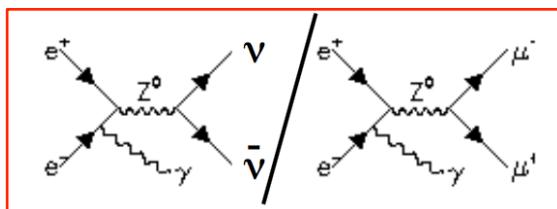
Neutrino counting

- @ LEP $N_\nu = 2.984 \pm 0.008$ from Z-line shape
 2σ “low” \rightarrow non-unitarity of the PMNS matrix?

dominated by statistical uncertainty on normalization to small angle Bhabha cross-section ± 0.0046 on N_ν

Possible improvement @ FCC-ee (*slide 7*)
by precisely measuring luminosity with $e^+e^- \rightarrow \gamma\gamma$

Another method:

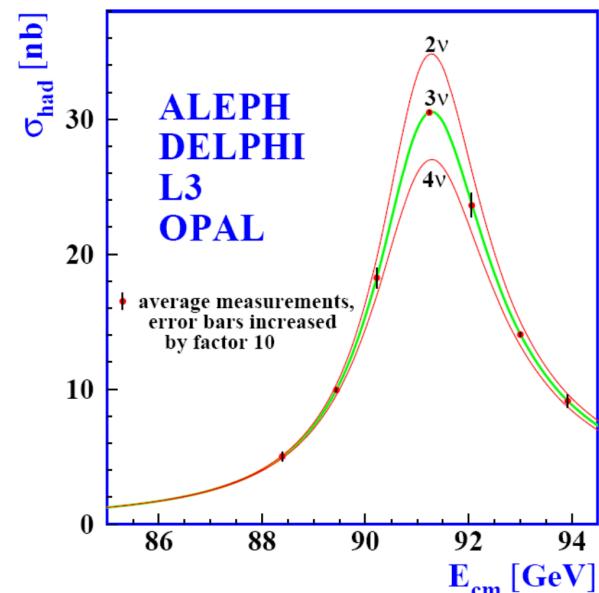


$$N_\nu = \frac{\gamma Z(\text{inv})}{\gamma Z \rightarrow ee, \mu\mu} \frac{\Gamma_\nu}{\Gamma e, \mu} (\text{SM})$$

above the Z pole radiative return to Z lead to a clean sample of γ -tagged Zs
Systematics on γ selection, luminosity, etc cancel in the ratio

After 5 years of running @ the WW threshold: $\Delta N_\nu \approx 0.001$

Gain factor w.r.t LEP ≈ 10

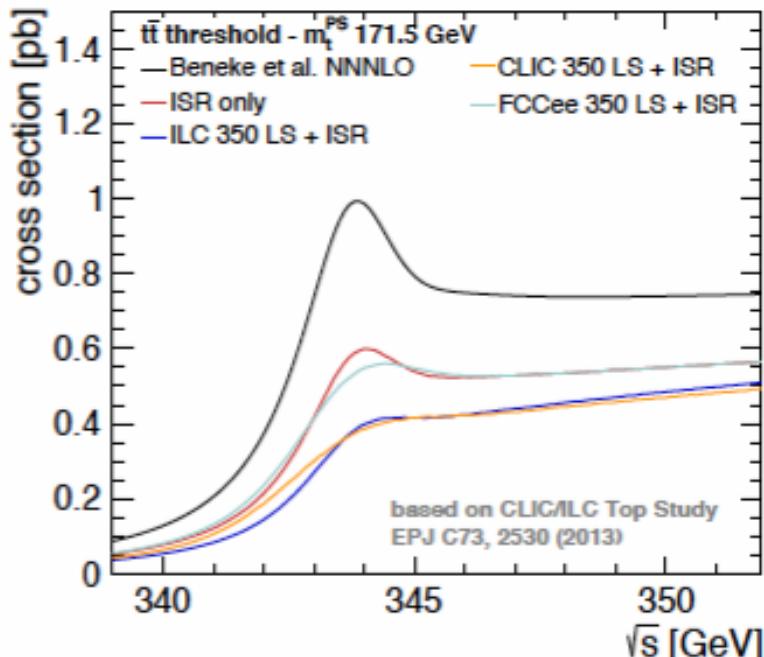


Mega Top

$t\bar{t}$ threshold scan: top mass

Cross-section shape strongly depends on t-quark mass, width, α_s , Y_t

t-quark mass from threshold scan

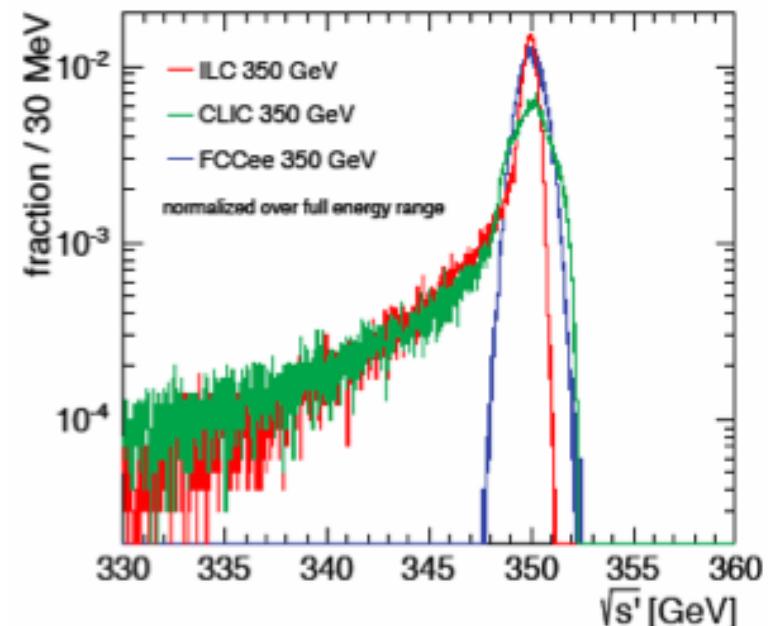


F. Simon arXiv:1611:03399 (2016)

$200 \text{ fb}^{-1} \rightarrow \Delta m_t \approx 10 \text{ MeV (stat)}$

The threshold shape is affected by ISR & beam energy spread

FCC-ee has a very steep beam profile
→ enhanced size of the top sample



Experimental systematic uncertainty:
 E_{beam} (few MeV) & E_{beam} spread → $\Delta m_t < 5 \text{ MeV}$
 $\Delta \alpha_s$ (@FCC-ee) ≈ 0.0002 → $\Delta m_t < 20 \text{ MeV}$

Theory systematic uncertainty:
 $1S/\text{PS} \rightarrow \overline{\text{MS}}@\text{4loop} \rightarrow \Delta m_t \approx 10 \text{ MeV}$
other scale uncertainties under study

@ ILC & CLIC

also above threshold: top mass

Direct reconstruction

K.Seidl & al. Eur. Phys. J. C73 (2013)

in continuum @ all energies above threshold

100 fb⁻¹ @ 500 GeV → Δm_t ≈ 80 MeV (stat)

Significant theory uncertainties when converting to a particular mass scheme

Radiative events

P.Gomis @ ECFA LC Workshop 2016

@ √s >> threshold, there is still sensitivity to t̄t threshold in radiative events
(rate of energetic ISR γ & FSR g strongly depends on m_t)

500 fb⁻¹ @ 380 GeV → Δm_t ≈ 100 MeV (stat)

3.5 ab⁻¹ @ 1 TeV → Δm_t ≈ 388 MeV (stat)

using ISR

well defined theoretical scheme

Other considered methods

- b-jet energy distribution
- event shape analysis

F.Franceschini @ TopLC'2016

A. Hoang @ TopLC'2016

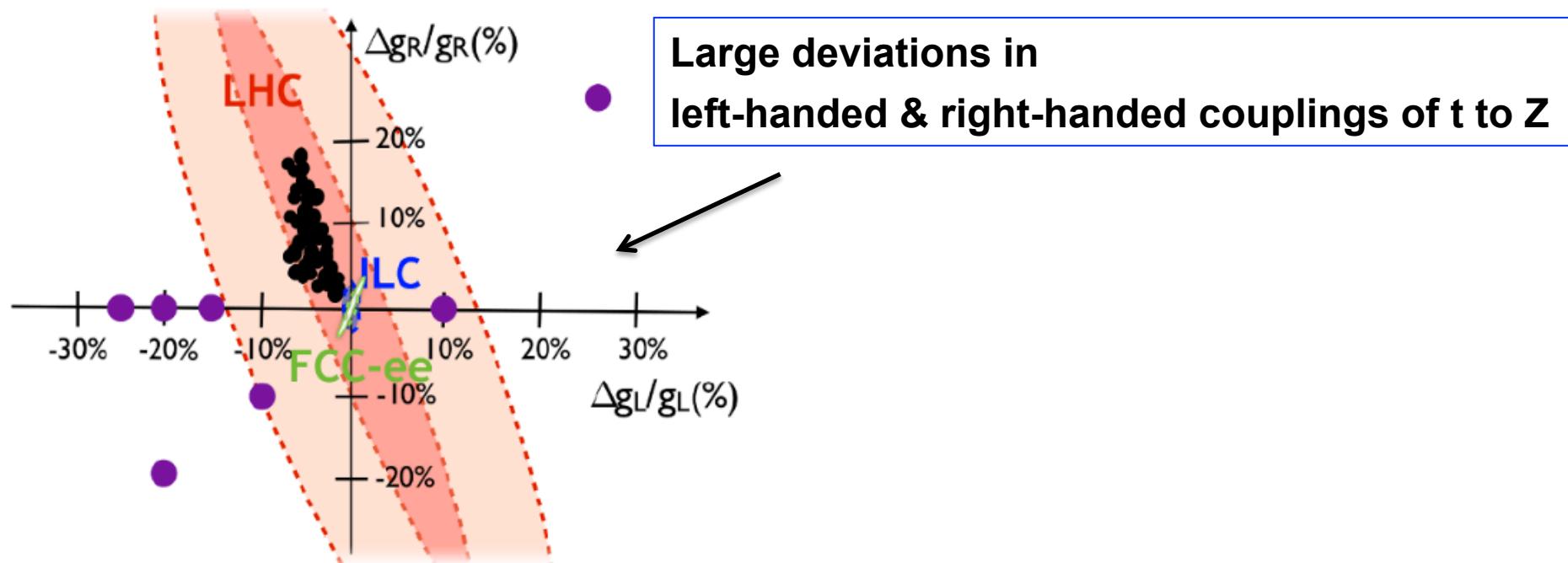
Mega Top

$t\bar{t}$ threshold scan: electroweak couplings of the top quark (1)

Couplings of the top quark to Z & γ
are very sensitive to effects from massive unknown particles

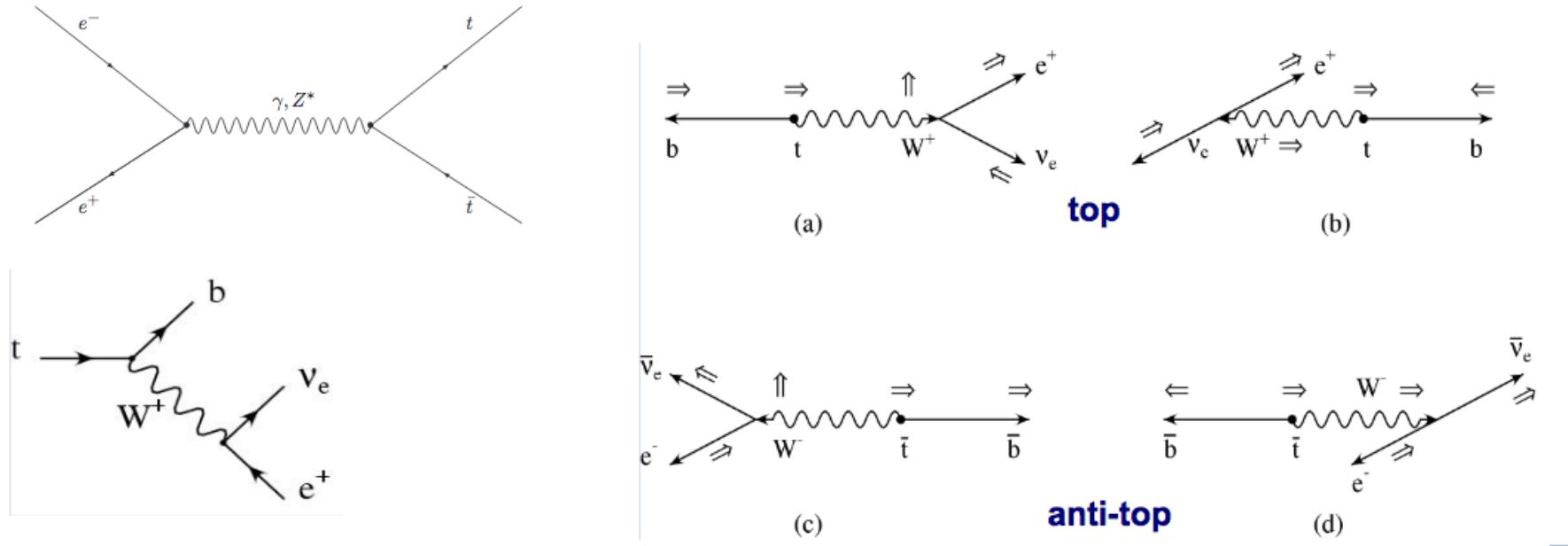
→ NP discovery beyond machine energy-scale or constraints to SM extensions

e.g. composite Higgs models



Mega Top

$t\bar{t}$ threshold scan: electroweak couplings of the top quark (2)



Large stat & final state polarization ($\text{Br}(t \rightarrow Wb) = 100\%$)

→ left & right couplings of the t-quark can be extracted with
no need for initial state polarization

use **lv q-q b-b** final states

sensitivity to t electroweak couplings from **lepton angular & energy distributions**

Mega Top

$t\bar{t}$ threshold scan: electroweak couplings of the top quark (2)

parametrisation of the $t\bar{t}X$ vertex ($X = \gamma, Z$):

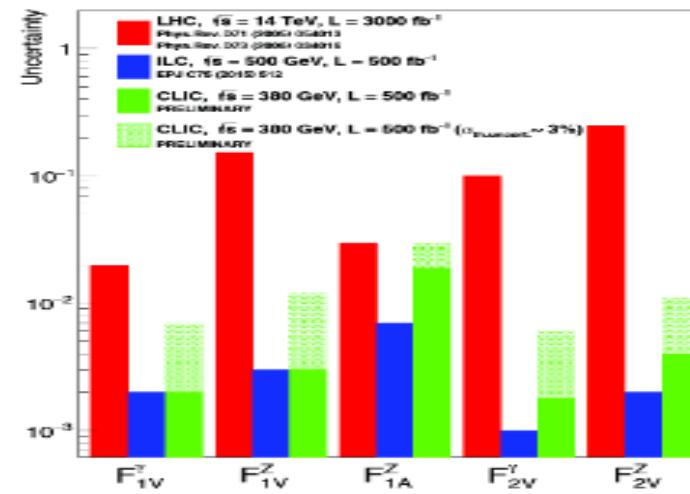
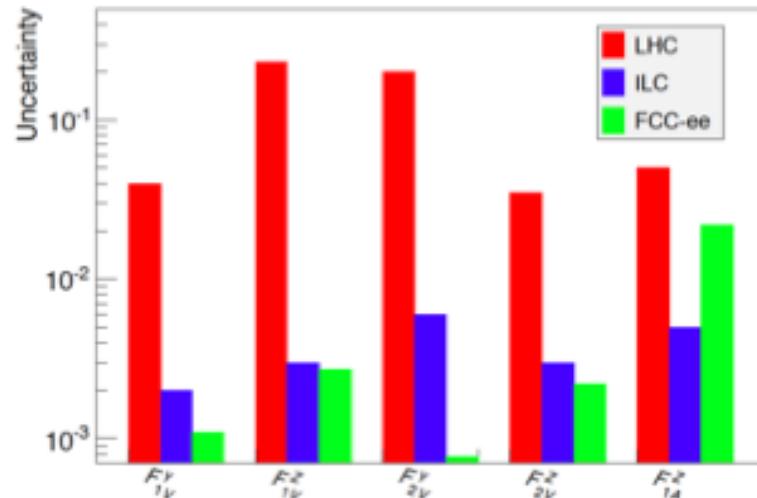
$$\Gamma_\mu^{t\bar{t}X}(k^2, q, \bar{q}) = ie \left\{ \gamma_\mu \left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2) \right) - \frac{\sigma_{\mu\nu}}{2m_t} (q + \bar{q})^\nu \left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2) \right) \right\}$$

in SM at tree level: $F_{1V}^{\gamma,SM} = \frac{2}{3}$, $F_{1A}^{\gamma,SM} = 0$, $F_{1V}^{Z,SM} = \frac{1}{4s_w c_w} \left(1 - \frac{8}{3} s_w^2 \right)$, $F_{1A}^{Z,SM} = -\frac{1}{4s_w c_w}$, $F_{2A,V}^X = 0$

$$g_L^Z = F_{1V}^Z - F_{1A}^Z, \quad g_R^Z = F_{1V}^Z + F_{1A}^Z$$

for the 6 CP conserving form factors:

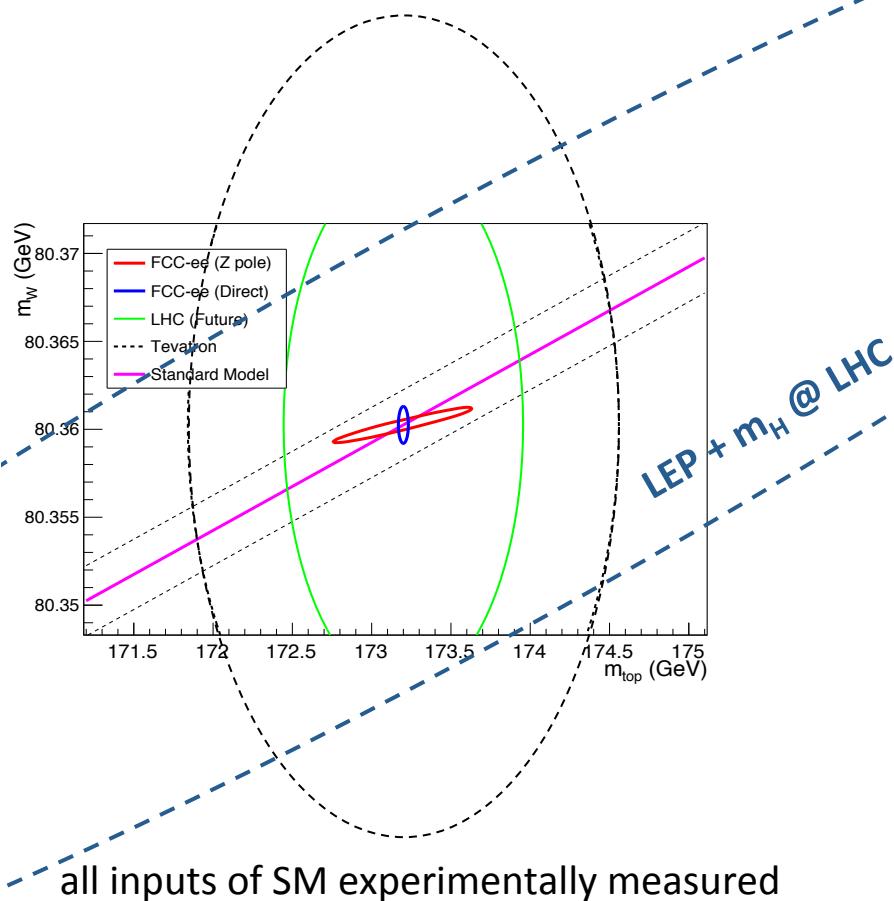
Optimal $\sqrt{s} = 365 - 370$ GeV No initial state polarization!



FCC-ee expected relative statistical precision $\approx 10^{-2} - 10^{-3}$

Conclusion:

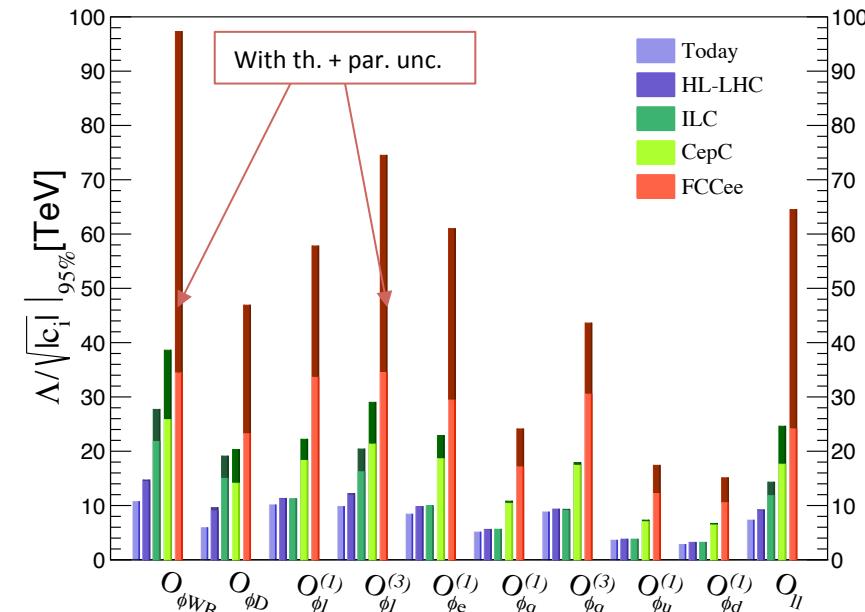
Global ewk fit and sensitivity to new physics



- any observable sensitive to ew radiative corrections unambiguously predicted
- any deviation from measurements reveals new weakly interacting particles

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

Jorge de Blas
LHC 2017



10 operators contributing to ew precision observables in the chosen basis
fit to ewpd, 1 operator at a time generated by NP

LEP limit: $\Lambda_{\text{NP}} > 10 \text{ TeV}$

FCC limit: $\Lambda_{\text{NP}} > 100 \text{ TeV} ?$

and also:

Direct discoveries from:

- ✓ rare decays
- ✓ flavor physics
- ✓ top decays
- ✓ very weakly coupled particles
- ✓

**giving access to New Physics
hardly accessible to hadron colliders**



perhaps



surprising



even striking discoveries!

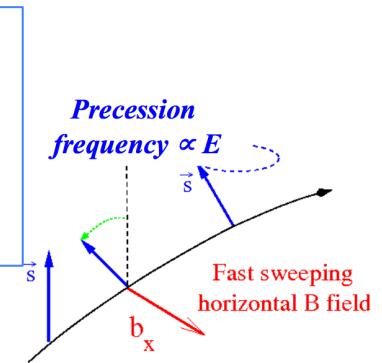
backup

E_{CM} calibration

Resonant depolarisation: a key ingredient!

- @ WW threshold beam transverse polarization occurs naturally (10% is enough)
- @ Z pole use wigglers at the beginning of fills to shorten the polarization time
- not available @ $E_{beam} > 90$ GeV (due to increased energy spread $\propto E^2$)
but for H & top, $ee \rightarrow Zg$ or $ee \rightarrow ZZ$, WW can be used ($\Delta E_{CM} \approx 5$ MeV)

add fast oscillating B field to depolarize the bunch, the depolarization frequency corresponds to $\langle E_{beam} \rangle$. Beam polarization measured by laser polarimeters.



- @ LEP

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

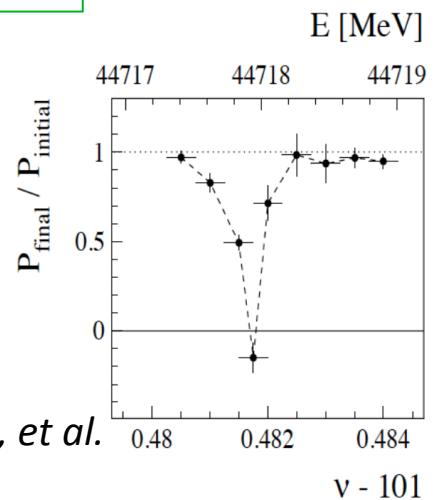
But final systematic uncertainty was 1.5 MeV due to transport from dedicated polarization runs to the physics runs.

- @ FCC-ee

continuous calibration with dedicated bunches → no transport uncertainty

→ $\Delta E_{beam} \ll 100$ keV @ Z pole & WW threshold

$\Delta M_Z, \Delta \Gamma_Z \approx 0.1$ MeV ; $\Delta M_W \approx 0.5$ MeV



"EPOL" working group on polarization and beam energy:

J.Wenninger, E.Gianfelice, D.Barber, W.Hillert, A.Bogomyagkov, K.Oide, A.Blondel, et al.
arxiv:1506.00933

Tera Z

precision measurements @ the Z pole: Asymmetries (b1)

$Z \rightarrow ff$: 3 observables from the direction and decay of outgoing fermion:

$$A_f = \frac{2g_{Vf}g_{Af}}{(g_{Vf})^2 + (g_{Af})^2}$$

$$\sin^2 \theta_{eff}^{l\bar{l}} \equiv \frac{1}{4} \left(1 - \frac{g_{Vl}}{g_{Al}} \right)$$

$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_{tot}} = \frac{3}{4} A_e A_f \quad \text{Can measure for } e, \mu, \tau, c, b$$

$$A_{pol} = \frac{\sigma_{F,R} + \sigma_{B,R} - \sigma_{F,L} - \sigma_{B,L}}{\sigma_{tot}} = -A_f \quad \text{Can measure with } \tau' \text{'s}$$

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

+ 2 observables with polarisation* of the initial state:

$$A_{LR} = \frac{\sigma_l - \sigma_r}{\sigma_{tot}} = A_e$$

$$A_{FB}^{pol} = \frac{\sigma_{F,l} - \sigma_{B,l} - \sigma_{F,r} + \sigma_{B,r}}{\sigma_{tot}} = \frac{3}{4} A_f$$

* not mandatory, as no significant gain and loss of luminosity

Tera Z

direct measurement of $\alpha_{\text{QED}}(m_Z^2)$ (b1)

(Patrick Janot, arXiv:1512:05544, JHEP 2016(2) 1)

Now $\alpha_{\text{QED}}(M_Z^2)$ from the running of α :

$$\alpha_{\text{QED}}(m_Z^2) = \frac{\alpha_{\text{QED}}(0)}{1 - \Delta\alpha_\ell(m_Z^2) - \Delta\alpha_{\text{had}}^{(5)}(m_Z^2)}.$$

@ FCC-ee: direct measurement at M_Z :

$$\sigma_{\mu\mu} = G + Z + I$$

$$G = \alpha_{\text{QED}}^2(s), \quad Z = G_F^2, \quad I = \alpha_{\text{QED}}(s) \times G_F$$

$$G = \frac{c_\gamma^2}{s},$$

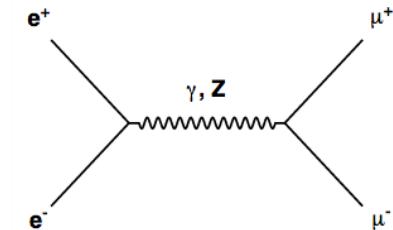
$$Z = \frac{c_Z^2(v^2 + a^2)^2 \times s}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2},$$

$$I = \frac{2c_\gamma c_Z v^2 \times (s - m_Z^2)}{(s - m_Z^2)^2 + m_Z^2 \Gamma_Z^2},$$

$$c_\gamma = \sqrt{\frac{4\pi}{3}} \alpha_{\text{QED}}(s), \quad c_Z = \sqrt{\frac{4\pi}{3}} \frac{m_Z^2}{2\pi} \frac{G_F}{\sqrt{2}}, \quad a = -\frac{1}{2}, \quad v = a \times (1 - 4 \sin^2 \theta_W),$$

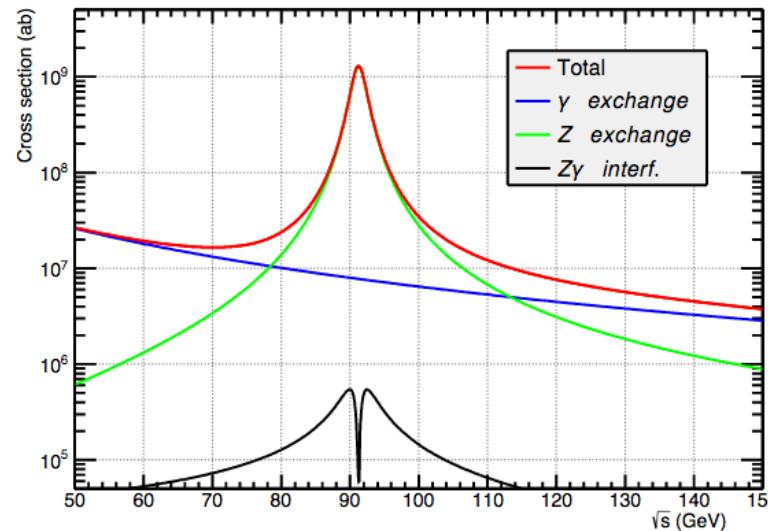
$$\Delta\sigma_{\mu\mu} = \frac{\Delta\alpha}{\alpha} (I + 2G) \rightarrow$$

$$\frac{\Delta\alpha}{\alpha} \simeq \frac{\Delta\sigma_{\mu\mu}}{2G} \simeq \frac{1}{2} \frac{\Delta\sigma_{\mu\mu}}{\sigma_{\mu\mu}} \left(1 + \frac{Z}{G} \right)$$



$$\Delta\alpha_{\text{had}}^{(5)}(m_Z^2) = \frac{\alpha m_Z^2}{3\pi} \int_{4m_\pi^2}^\infty \frac{R_\gamma(s)}{s(m_Z^2 - s)} ds, = (275.7 \pm 1.0) \times 10^{-4},$$

$$\rightarrow \alpha_{\text{QED}}^{-1}(m_Z^2) = 128.952 \pm 0.014, \rightarrow \boxed{\Delta\alpha/\alpha = 1.1 \cdot 10^{-4}}$$



$$\Delta\alpha \approx 2 \cdot 10^{-5}$$

with $N_{\mu\mu} > 10^9$

Tera Z

direct measurement of $\alpha_{\text{QED}}(m_Z^2)$ (b2)

(Patrick Janot, arXiv:1512:05544, JHEP 2016(2) 1)

$$A_{\text{FB}}^{\mu\mu} = \frac{\sigma_{\mu\mu}^{\text{F}} - \sigma_{\mu\mu}^{\text{B}}}{\sigma_{\mu\mu}^{\text{F}} + \sigma_{\mu\mu}^{\text{B}}}$$

uncertainties on efficiency, acceptance, luminosity cancel

$$\frac{d\sigma_{\mu\mu}}{d\cos\theta}(s) \propto G_1(s) \times (1 + \cos^2\theta) + G_3(s) \times 2\cos\theta,$$

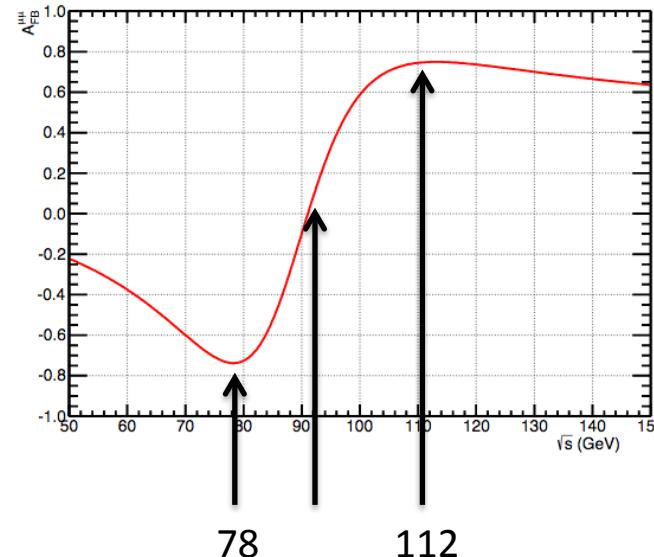
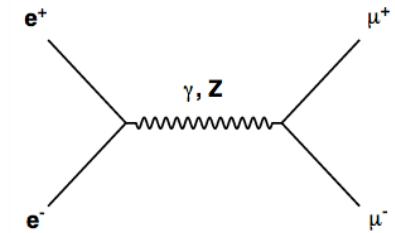
$$G_1(s) = \mathcal{G} + \mathcal{I} + \mathcal{Z}$$

$$G_3(s) = \frac{a^2}{v^2} \left\{ \mathcal{I} + \frac{4v^4/a^4}{(1+v^2/a^2)^2} \mathcal{Z} \right\}$$

$$A_{\text{FB}}^{\mu\mu}(s) = \frac{3}{4} \frac{G_3(s)}{G_1(s)},$$

$$A_{\text{FB}}^{\mu\mu} = A_{\text{FB},0}^{\mu\mu} + \frac{3}{4} \frac{a^2}{v^2} \frac{\mathcal{I}}{\mathcal{G} + \mathcal{Z}}.$$

$$A_{\text{FB},0}^{\mu\mu} = (3/4) \times 4v^2a^2/(a^2 + v^2)^2 \simeq 0.016$$



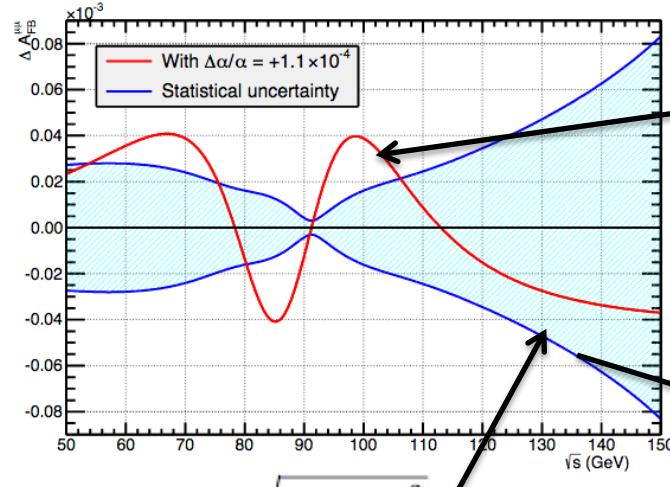
A_{FB} insensitive to α in these 3 points

$$\Delta A_{\text{FB}}^{\mu\mu} = \frac{\Delta\alpha}{\alpha} \times \frac{3}{4} \frac{a^2}{v^2} \frac{\mathcal{I}(\mathcal{Z} - \mathcal{G})}{(\mathcal{G} + \mathcal{Z})^2} = \left(A_{\text{FB}}^{\mu\mu} - A_{\text{FB},0}^{\mu\mu} \right) \times \frac{\mathcal{Z} - \mathcal{G}}{\mathcal{Z} + \mathcal{G}} \times \frac{\Delta\alpha}{\alpha}$$

Tera Z

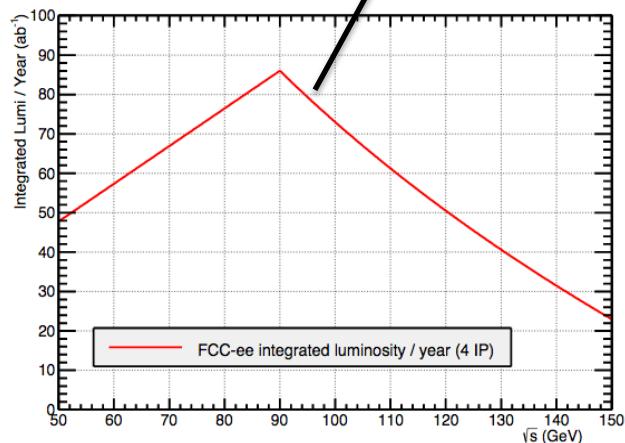
direct measurement of $\alpha_{\text{QED}}(m_Z^2)$ (b3)

(Patrick Janot, arXiv:1512:05544, JHEP 2016(2) 1)



$$\sigma(A_{\text{FB}}^{\mu\mu}) = \sqrt{\frac{1 - A_{\text{FB}}^{\mu\mu} 2}{\mathcal{L} \sigma_{\mu\mu}}}$$

statistical accuracy



06/07/17

$$\frac{\Delta\alpha}{\alpha} = \frac{\Delta A_{\text{FB}}^{\mu\mu}}{A_{\text{FB}}^{\mu\mu} - A_{\text{FB},0}^{\mu\mu}} \times \frac{\mathcal{Z} + \mathcal{G}}{\mathcal{Z} - \mathcal{G}} \simeq \frac{\Delta A_{\text{FB}}^{\mu\mu}}{A_{\text{FB}}^{\mu\mu}} \times \frac{\mathcal{Z} + \mathcal{G}}{\mathcal{Z} - \mathcal{G}},$$

sets the minimum accuracy of A_{FB} to start improving α accuracy

off the Z peak

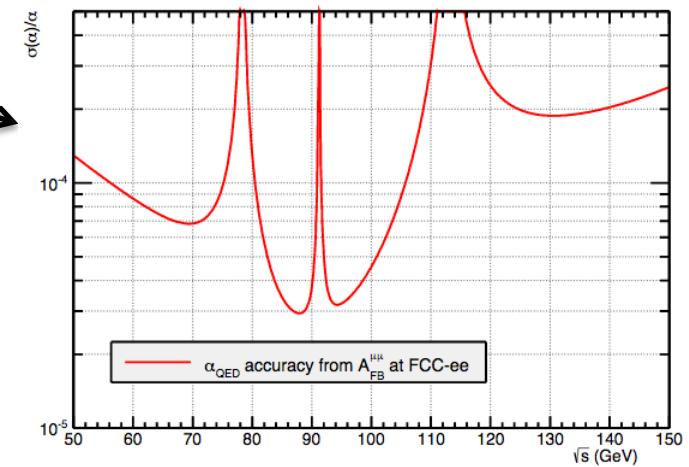
$$\frac{1}{\alpha_0} = \frac{1}{\alpha_{\pm}} + \beta \log \frac{s_{\pm}}{m_Z^2},$$

$$\beta_0 = \sum_f Q_f^2 / 3\pi, \quad (f = e, \mu, \tau, d, u, s, c, b)$$

$$\frac{1}{\alpha_0} = \frac{1}{2} \left(\frac{1 - \xi}{\alpha_-} + \frac{1 + \xi}{\alpha_+} \right)$$

$$\xi = \frac{\log s_- s_+ / m_Z^4}{\log s_- / s_+} \simeq 0.045,$$

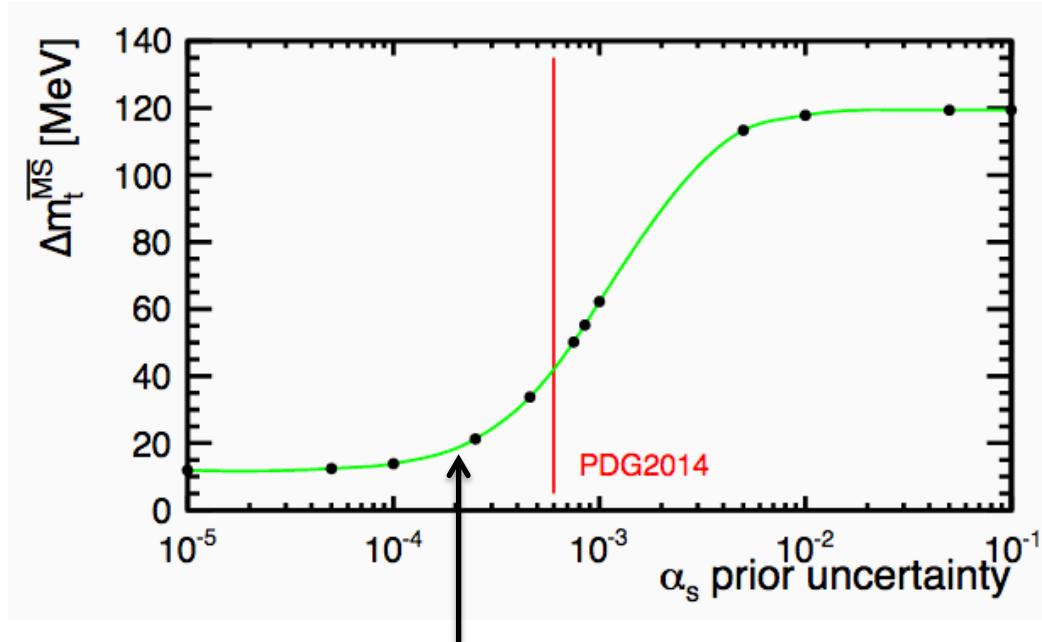
can also use ee, ττ



removes model dependence & theory uncertainty

Mega Top

$t\bar{t}$ threshold scan: top mass (b1)



M. Perello & M. Vos

conservative upper limit
from expected precision on α_s @FCC-ee
uncertainty on line shape &
parametric uncertainty in mass conversion
added in quadrature

Experimental systematic uncertainty:
 E_{beam} (few MeV) & E_{beam} spread $\rightarrow \Delta m_t < 5$ MeV
 $\Delta \alpha_s(@FCC-ee) \approx 2 \cdot 10^{-4} \rightarrow \Delta m_t < 20$ MeV

Theory systematic uncertainty:
1S/PS $\rightarrow \overline{\text{MS}}$ @4loop $\rightarrow \Delta m_t \approx 10$ MeV
other scale uncertainties under study

Summary table

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	$g \rightarrow bb$
N_v	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_v	Radiative return $e^+e^- \rightarrow \gamma Z(\text{inv})$	2.92 ± 0.05 2.984 ± 0.008	0.0008	< 0.001	?
$\alpha_s(m_w)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_w$	$B_{had} = 67.41 \pm 0.27$	0.00018	0.00015	CKM Matrix
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~ 40 MeV)

Global ewk fit and sensitivity to new physics

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$$

Jorge de Blas
LHCPh 2017

- 2 bosonic interactions: $\mathcal{O}_{\phi D} = |\phi^\dagger D^\mu \phi|^2$, $\mathcal{O}_{\phi WB} = (\phi^\dagger \sigma_a \phi) W_{\mu\nu}^a B^{\mu\nu}$

giving rise to tree level contributions to S & T parameters

$$\alpha_{\text{em}} S = 4 \sin \theta_W \cos \theta_W c_{\phi WB} v^2 / \Lambda^2 , \quad \alpha_{\text{em}} T = -c_{\phi D} v^2 / (2 \Lambda^2)$$

- 7 fermionic currents: $\mathcal{O}_{\phi\psi}^{(1)} = (\phi^\dagger \overset{\leftrightarrow}{D}^\mu \phi) (\bar{\psi} \gamma_\mu \psi)$ ($\psi = l, e, q, u, d$)
and $\mathcal{O}_{\phi F}^{(3)} = (\phi^\dagger \sigma_a \overset{\leftrightarrow}{D}^\mu \phi) (\bar{F} \gamma_\mu \sigma_a F)$ ($F = l, q$)

inducing corrections to the neutral and charged current vertices

- 1 four-lepton operator: $\mathcal{O}_{ll} = (\bar{l} \gamma_\mu l) (\bar{l} \gamma^\mu l)$
modifying the amplitude the amplitude of muon decay (used to extract G_F)