EW precision tests at the FCC-ee

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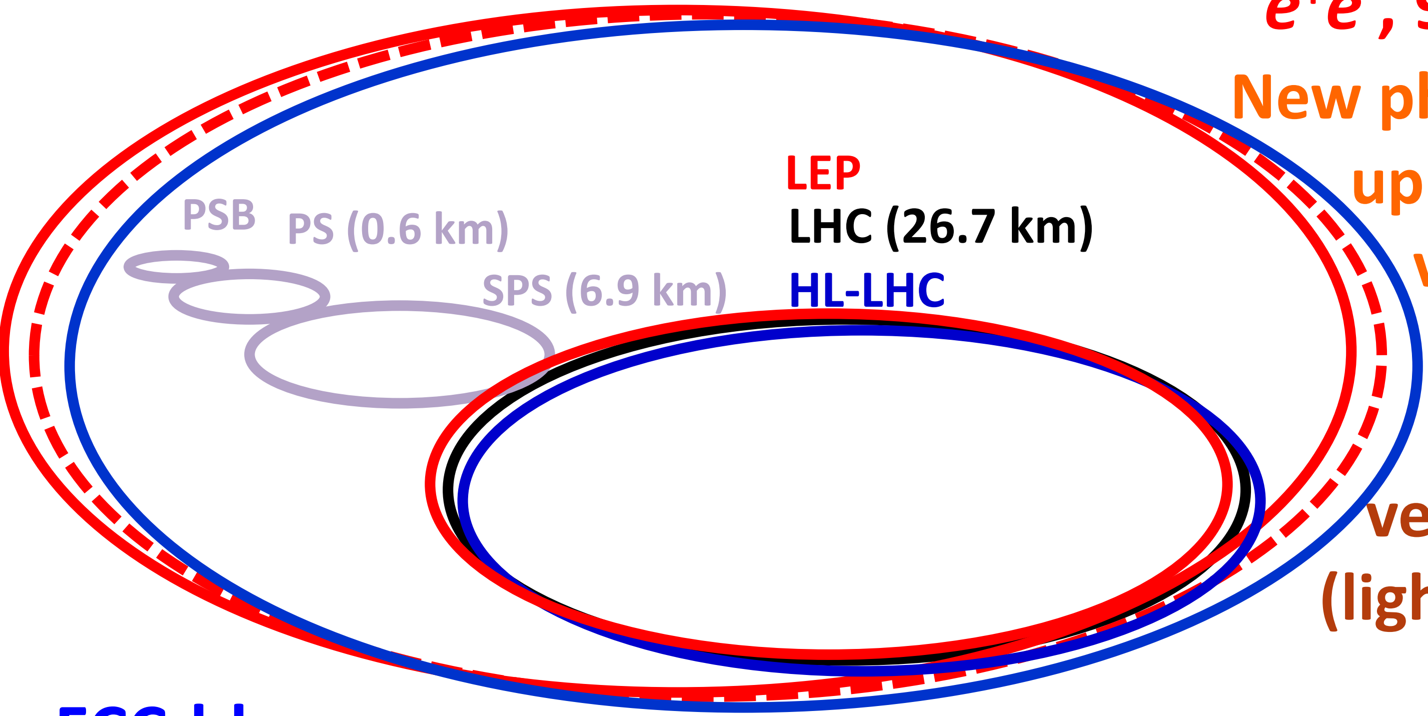
On behalf of
the FCC-ee study group

The FCC: a long-term strategy for HEP



FCC-ee (100 km,
***e^+e^-*, 90-400 GeV)**

New physics discovery
up to 100 TeV
via its quantum
effects
rare processes
very weak coupling
(light new physics)”

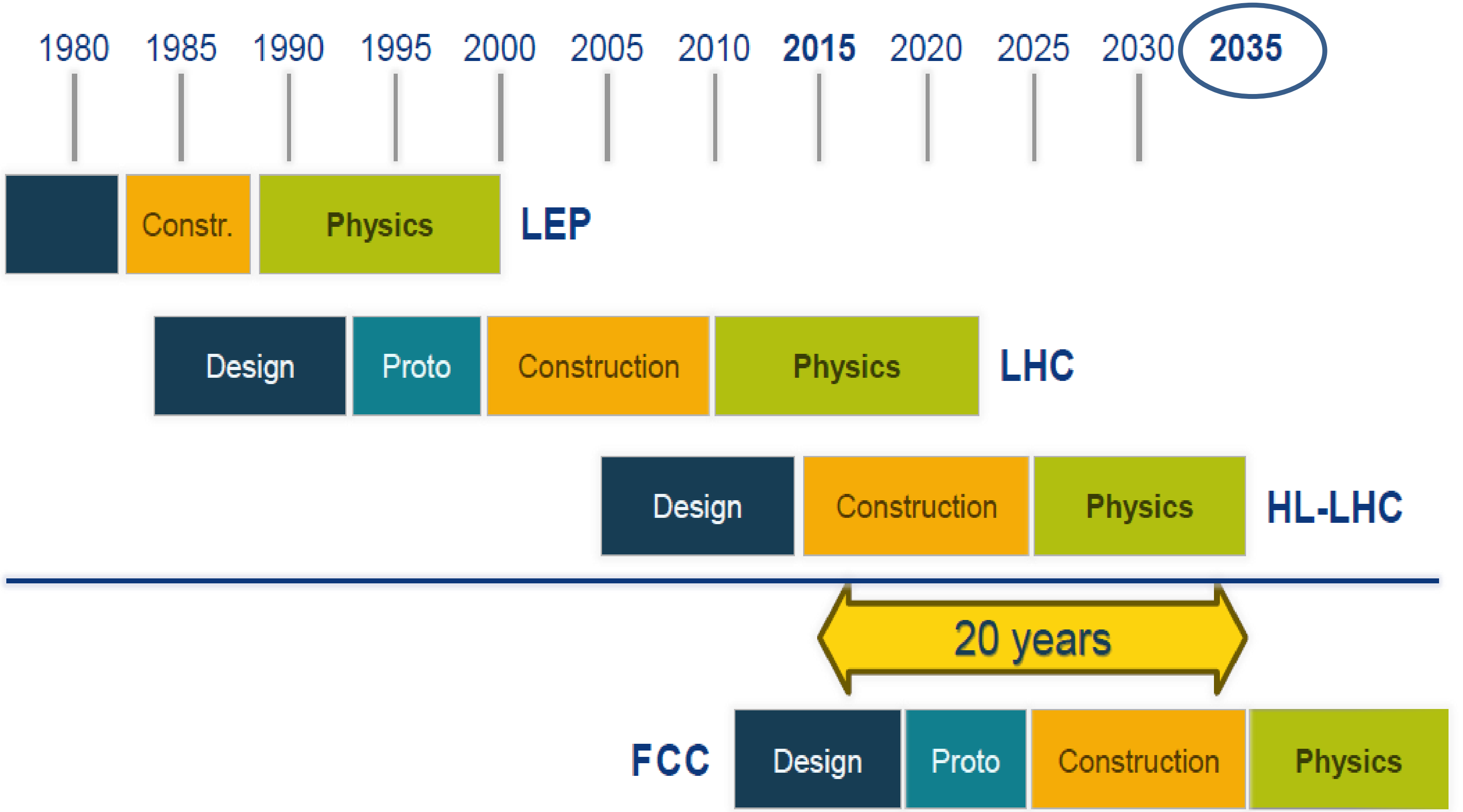
FCC-hh
(*pp*, 100 TeV)

Direct exploration of heavy new physics
(up to 20-30 TeV)

& ***$e^\pm$* (120 GeV)–*p* (7, 16 & 50 TeV)** collisions FCC-eh)

≥60 years of *e^+e^-*, *pp*, *ep/A* physics at highest energies

CERN Circular Colliders and FCC



1980 1985 1990 1995 2000 2005 2010 **2015** 2020 2025 2030 **2035**

Constr. | Physics | **LEP**

Design | Proto | Construction | Physics | **LHC**

Design | Construction | Physics | **HL-LHC**

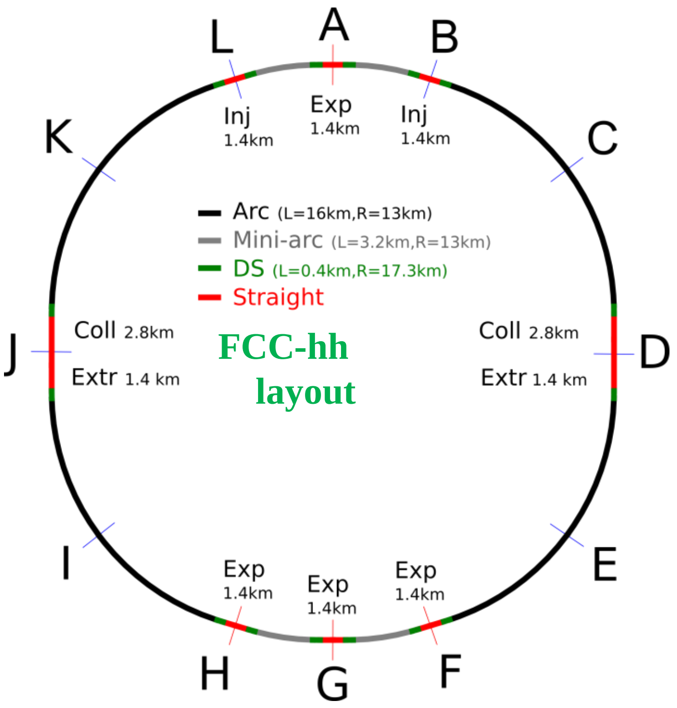
20 years

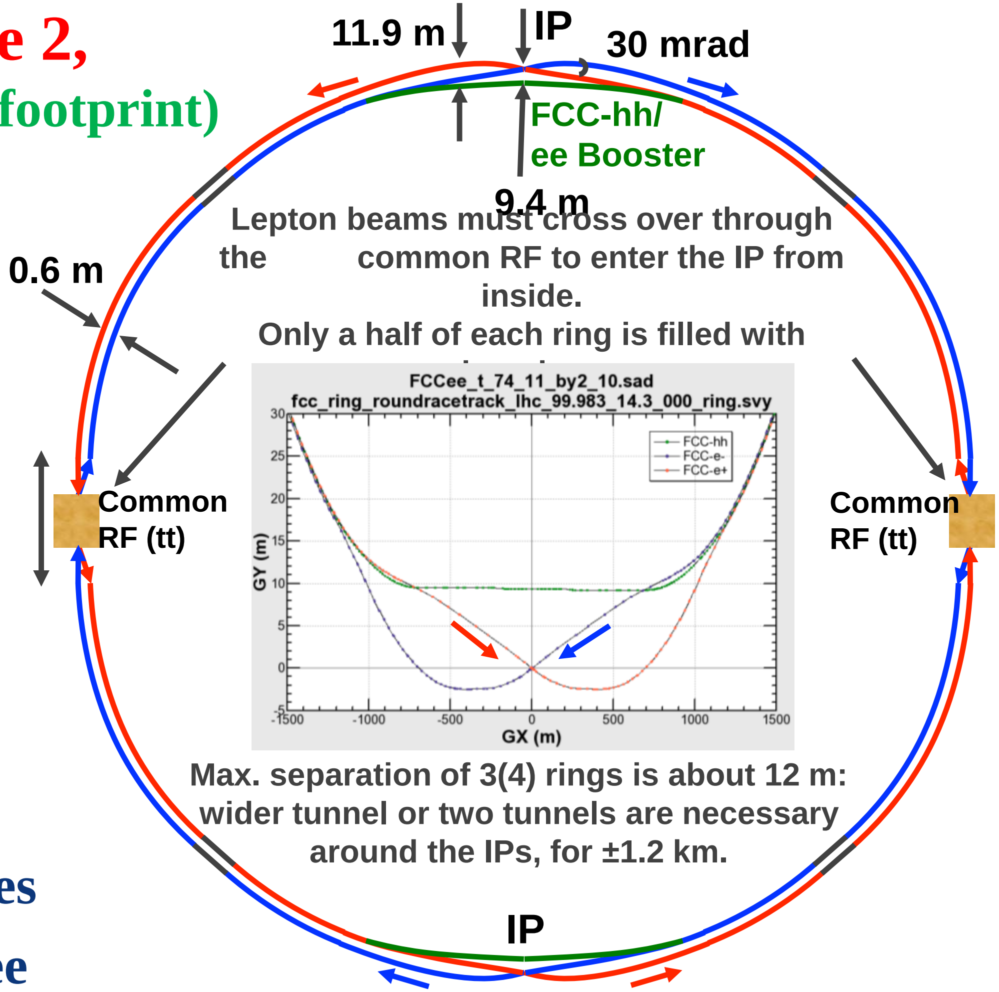
FCC | Design | Proto | Construction | Physics

(FCC-ee)

common layouts for hh & ee

FCC-ee 1, FCC-ee 2,
FCC-ee booster (FCC-hh footprint)





Lepton beams must cross over through the common RF to enter the IP from inside.

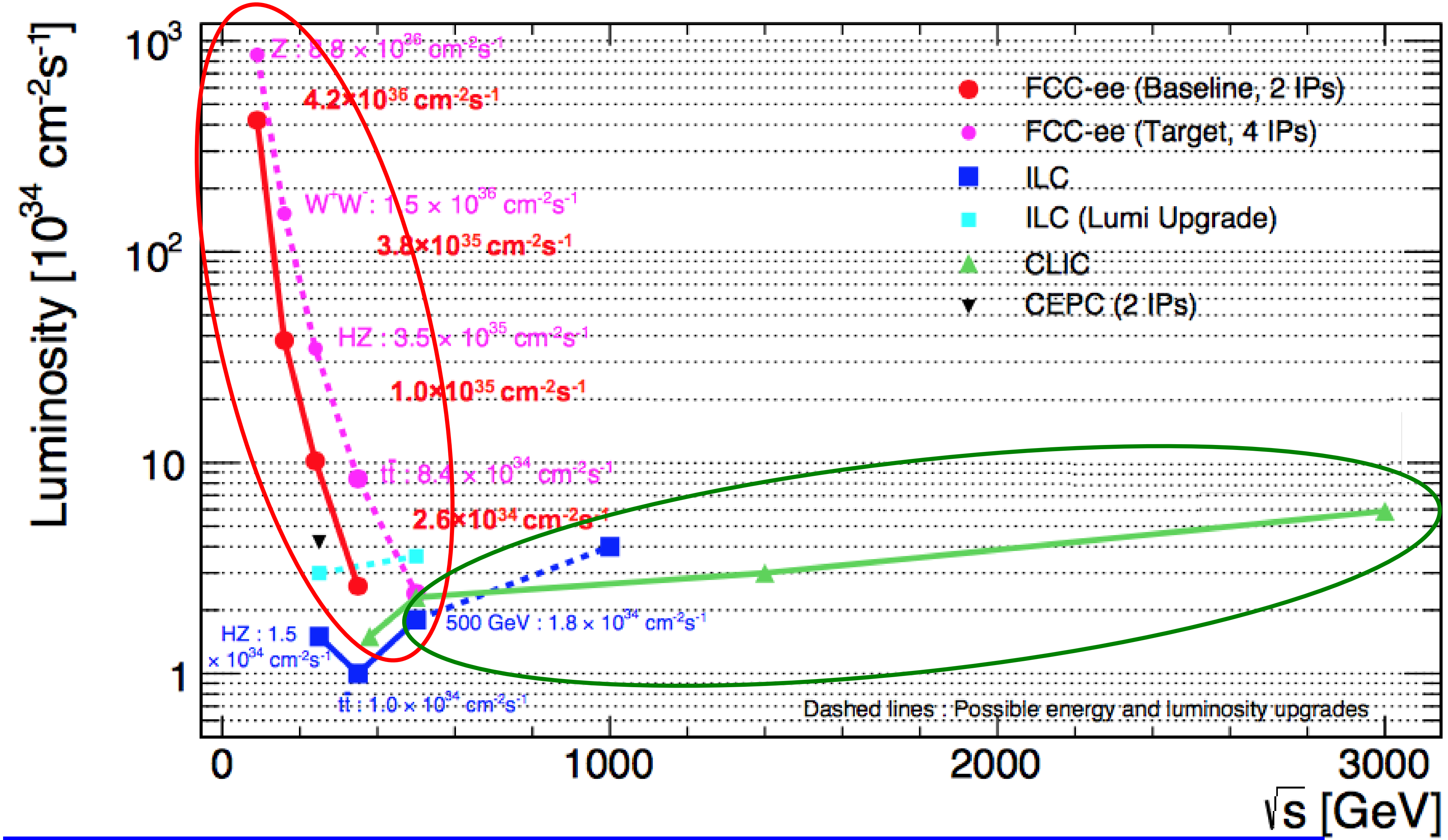
Only a half of each ring is filled with

Max. separation of 3(4) rings is about 12 m: wider tunnel or two tunnels are necessary around the IPs, for ±1.2 km.

- 2 main IPs in A, G for both machines
- asymmetric IR optic/geometry for ee to limit synchrotron radiation to detector

lepton collider parameters

parameter	**FCC-ee**					**LEP2**
physics working point	**Z**		**WW**	**ZH**	**tt_{bar}**	
energy/beam [GeV]	**45.6**		**80**	**120**	**175**	105
bunches/beam	**30180**	91500	**5260**	**780**	**81**	4
bunch spacing [ns]	**7.5**	2.5	**50**	**400**	**4000**	22000
bunch population [10^{11}]	**1.0**	0.33	**0.6**	**0.8**	**1.7**	4.2
beam current [mA]	**1450**	1450	**152**	**30**	**6.6**	3
luminosity/IP x 10^{34}cm^{-2}s^{-1}	**210**	90	**19**	**5.1**	**1.3**	0.0012
energy loss/turn [GeV]	**0.03**	0.03	**0.33**	**1.67**	**7.55**	3.34
synchrotron power [MW]	**100**					22
RF voltage [GV]	**0.4**	0.2	**0.8**	**3.0**	**10**	3.5
rms cm *E* spread SR [%]	**0.03**	0.03	**0.05**	**0.07**	**0.10**	0.11
rms cm *E* spread SR+BS [%]	**0.15**	0.06	**0.07**	**0.08**	**0.12**	0.11



- “baseline” is based on a conservative optics with 2 Ips

all efforts are developed to reach the target

- overlap linear and circular machines

Circ: High luminosity, experimental environment (2 to 4 IP), E_{CM} calibration

Linear: higher energy reach, longitudinal beam polarization

FCC-ee PHYSICS PROGRAM

- Z and W Electroweak physics ($5x10^{12}$Z, 10^8 WW)
  - precision energy calibration (100 KeV) → m_Z, Γ_Z, m_W, $\sin^2\theta_W^{eff}$
  - possibly precision measurement of $\alpha_{QED}(m_Z)$, $\alpha_S(m_Z)$
  - high luminosity search for rare Z decays
  - neutrino counting and search for RH neutrinos
- Tera Z is also a Flavour Factory (boosted and tagged b, c, τ)

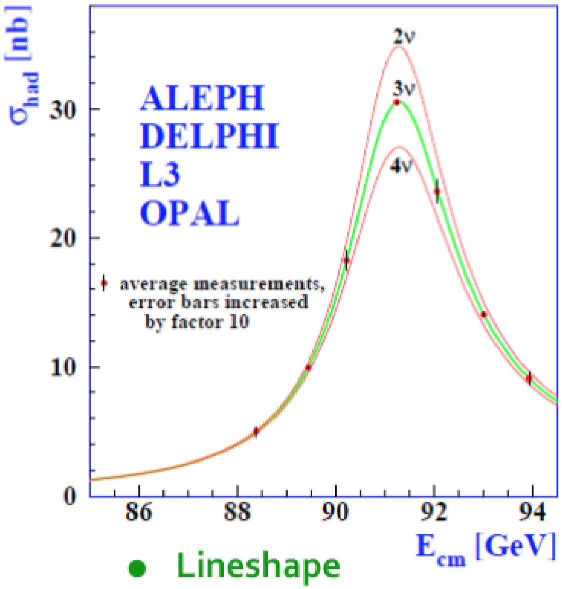
- Higgs Physics at E_{CM}= 240 GeV (ZH) and 350 GeV, 2 10^6 ZH events
  - unique determination of ZH coupling and H width,
  - all fermion and boson couplings (except HHH)
  - rare decays

- top quark physics at 350 -370 GeV (ses talk by Freya Blekman)
  - top quark mass (essential for precision EW tests) to exp. precision of 10 MeV
  - top quark couplings (no need for beam polarization)

- investigating run at E_{CM}= m_H to determine Hee coupling

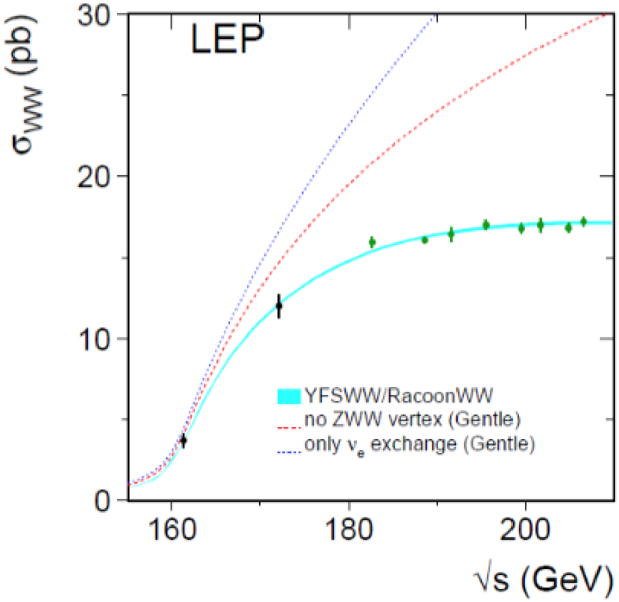
FCC-ee physics: High –precision W, Z, top

Z resonance: TeraZ



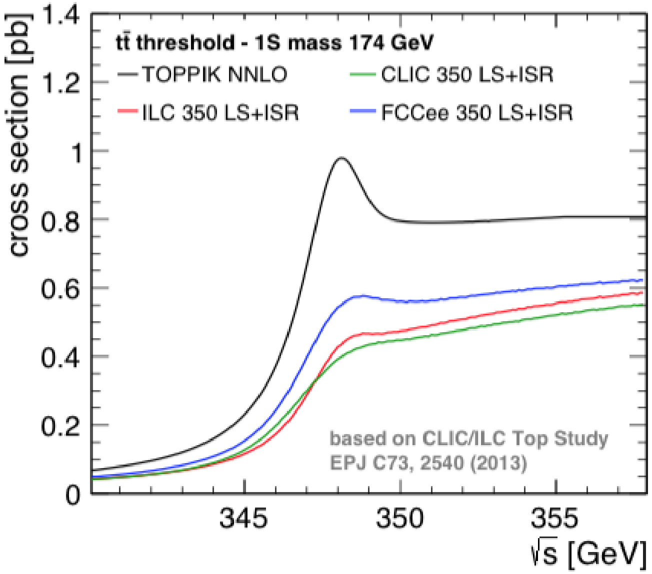
- Lineshape
  - ➨ Exquisite E_{beam} (unique!)
  - ➨ m_Z, Γ_Z to < 100 keV (2.2 MeV)
- Asymmetries
  - ➨ $\sin^2\theta_W$ to 6×10^{-6} (1.6×10^{-4})
  - ➨ $\alpha_{QED}(m_Z)$ to 3×10^{-5} (1.5×10^{-4})
- Branching ratios, R_l, R_b
  - ➨ $\alpha_S(m_Z)$ to 0.0002 (0.002)

WW threshold scan: OkuW

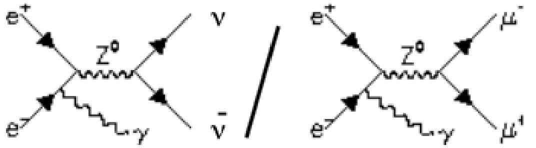


- Threshold scan
  - ➨ m_W to 500 keV (15 MeV)
- Branching ratios R_l, R_{had}
  - ➨ $\alpha_S(m_W)$ to 0.0002
- Radiative returns $e^+e^-\rightarrow\gamma Z$
  - ➨ N_ν to 0.0004 (0.008)

tt threshold scan: MegaTops



- Threshold scan
  - ➨ m_{top} to 10 MeV (500 MeV)
  - ➨ λ_{top} to 13%
  - ➨ EW couplings to 1%

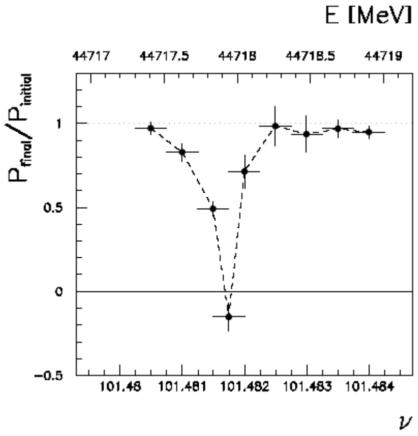


■ Mostly thanks to: (i) huge stats, (ii) threshold scans with E_{beam} ~ 0.1 MeV

Beam polarization and E-calibration @ FCC-ee

Precise meast of E_{beam} by resonant depolarization

~100 keV each time the meas is made *LEP →*



At LEP transverse polarization was achieved routinely at Z peak.

instrumental in 10^{-3} measurement of the Z width in 1993
led to prediction of top quark mass (179+- 20 GeV) in Mar'94

At LEP beam energy spread destroyed polarization above 61 GeV

$\sigma_E \propto E^2/\sqrt{\rho}$ → *At TLEP transverse polarization up to at least 81 GeV (WW threshold)*
to go to higher energies requires spin rotators and siberian snake

FCC-ee: use 'single' bunches to measure the beam energy continuously

→*no interpolation errors due to tides, ground motion or trains etc…*

<< 100 keV beam energy calibration around Z peak and W pair threshold.

Δm_Z ~0.1 MeV, $\Delta\Gamma_Z$ ~0.1 MeV, Δm_W ~ 0.5 MeV

A Sample of Essential Quantities:

X	Physics	Present precision		TLEP stat Syst Precision	TLEP key	Challenge
M_Z MeV/c2	**Input**	91187.5 ±2.1	Z Line shape scan	**0.005 MeV** **<±0.1 MeV**	E_cal	QED corrections
Γ_Z MeV/c2	**$\Delta\rho$ (T)** **(no $\Delta\alpha$!)**	2495.2 ±2.3	Z Line shape scan	**0.008 MeV** **<±0.1 MeV**	E_cal	QED corrections
R_ℓ	α_s , δ_b	20.767 ± 0.025	Z Peak	**0.0001** **± 0.002** **- 0.0002**	Statistics	QED corrections
N_ν	**Unitarity of PMNS, sterile ν's**	2.984 ±0.008	Z Peak Z+γ(161 GeV)	**0.00008** **±0.004** **0.0004-0.001**	->lumi meast Statistics	**QED corrections to Bhabha scat.**
R_b	δ_b	0.21629 ±0.00066	Z Peak	**0.000003** **±0.000020 - 60**	Statistics, small IP	Hemisphere correlations
M_W MeV/c2	**$\Delta\rho$, ε_3 , ε_2, $\Delta\alpha$** **(T, S, U)**	80385 ± 15	Threshold (161 GeV)	**0.3 MeV** **<1 MeV**	E_cal & Statistics	QED corections
m_{top} MeV/c2	**Input**	173200 ± 900	Threshold scan	**10 MeV**	E_cal & Statistics	Theory limit at 100 MeV?

Physics of μ+ μ- asymmetry: $\sin^2\theta^{lept}_W$ and α_{QED}

Unwanted error

$$\sin^2\theta_W^{eff}\cos^2\theta_W^{eff} = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\,M_Z^2}\,\frac{1}{1+\Delta\rho}\,\frac{1}{1-\frac{\varepsilon_3}{\cos^2\theta_W}}$$

Physics discoveries

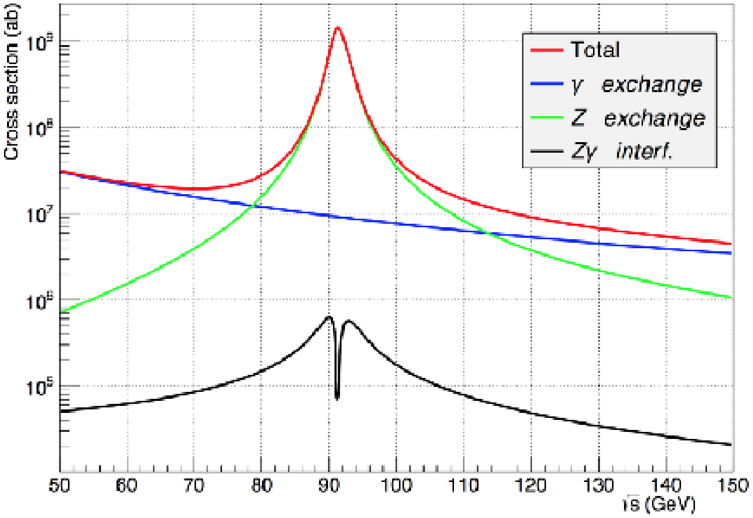
Uncertainties in m_{top}, $\Delta\alpha(m_z)$, m_H, etc....

$\Delta\sin^2\theta^{lept}_W$ ~ $\Delta\alpha(m_z)/3 = 10^{-5}$ have to reduce $\Delta\alpha(m_z)$

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

- Extrapolation error becomes negligible!

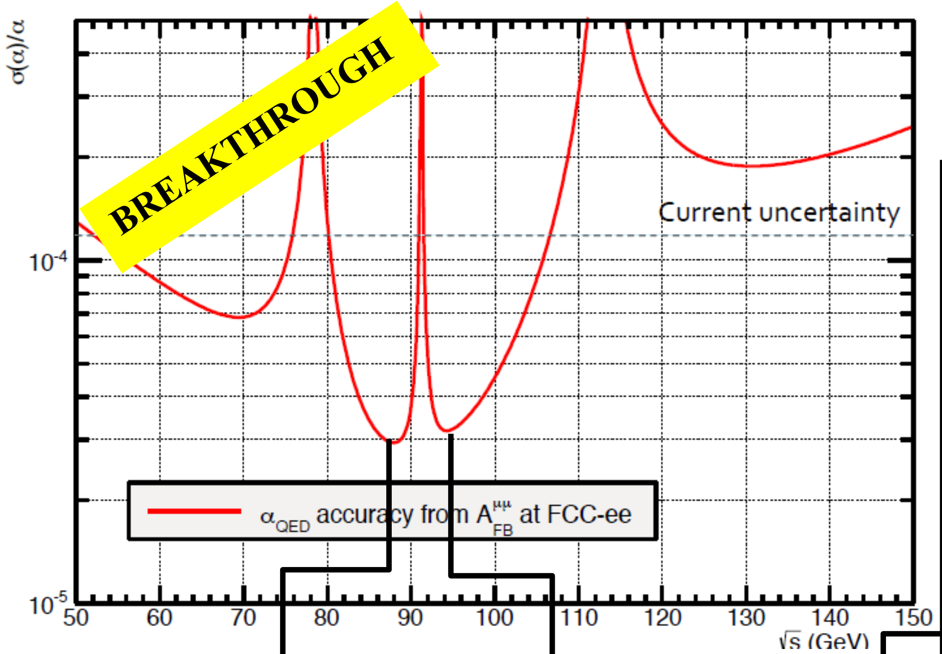
P. Janot: FCC-ee Physics Vidyo Meeting, June 29th 2015



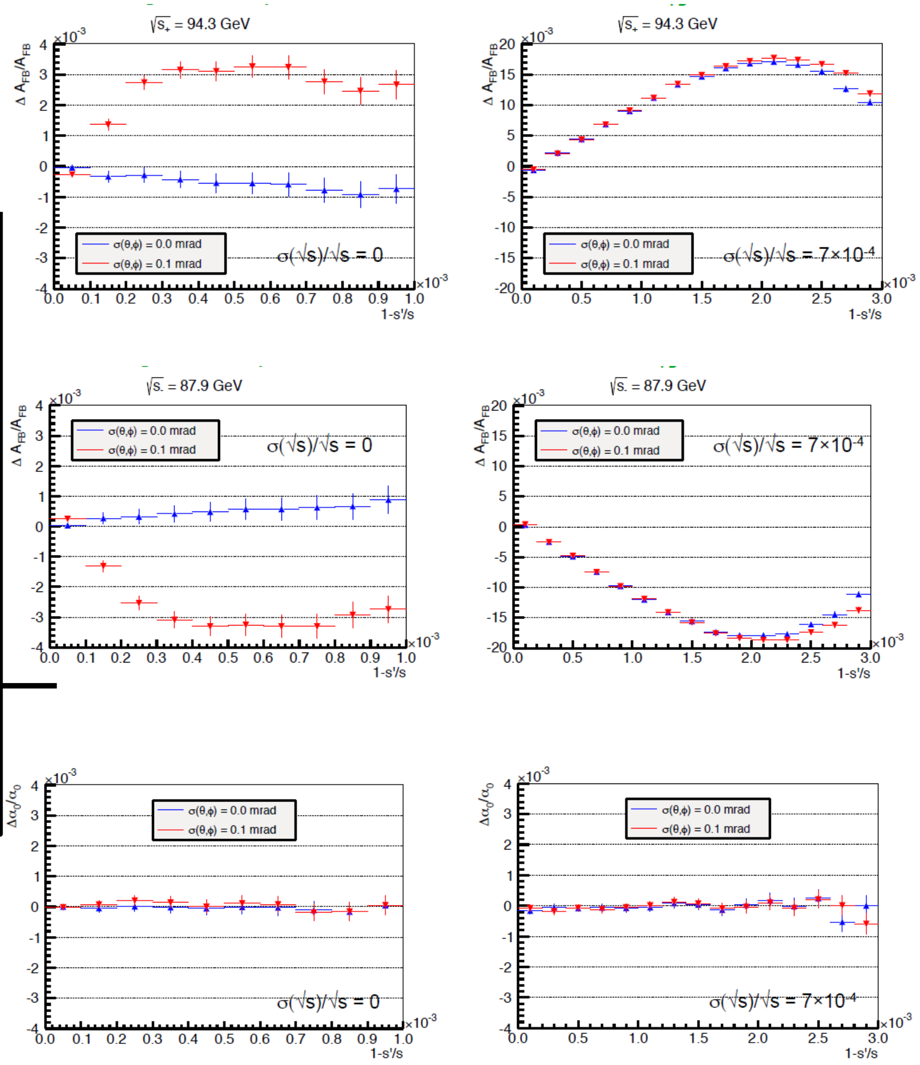
Use different sensitivity vs √s
nice Z lineshape scan
measure both within the same environment

@ M_Z
A_{FB} to extract $\sin^2\theta^{lept}_W$
@M_Z +3 GeV M_Z -3 GeV to extract $\alpha_{QED}(M_Z)$

Precise detrmination of α_{QED} form A_{FB}



Angular resolution **Beam energy spread**

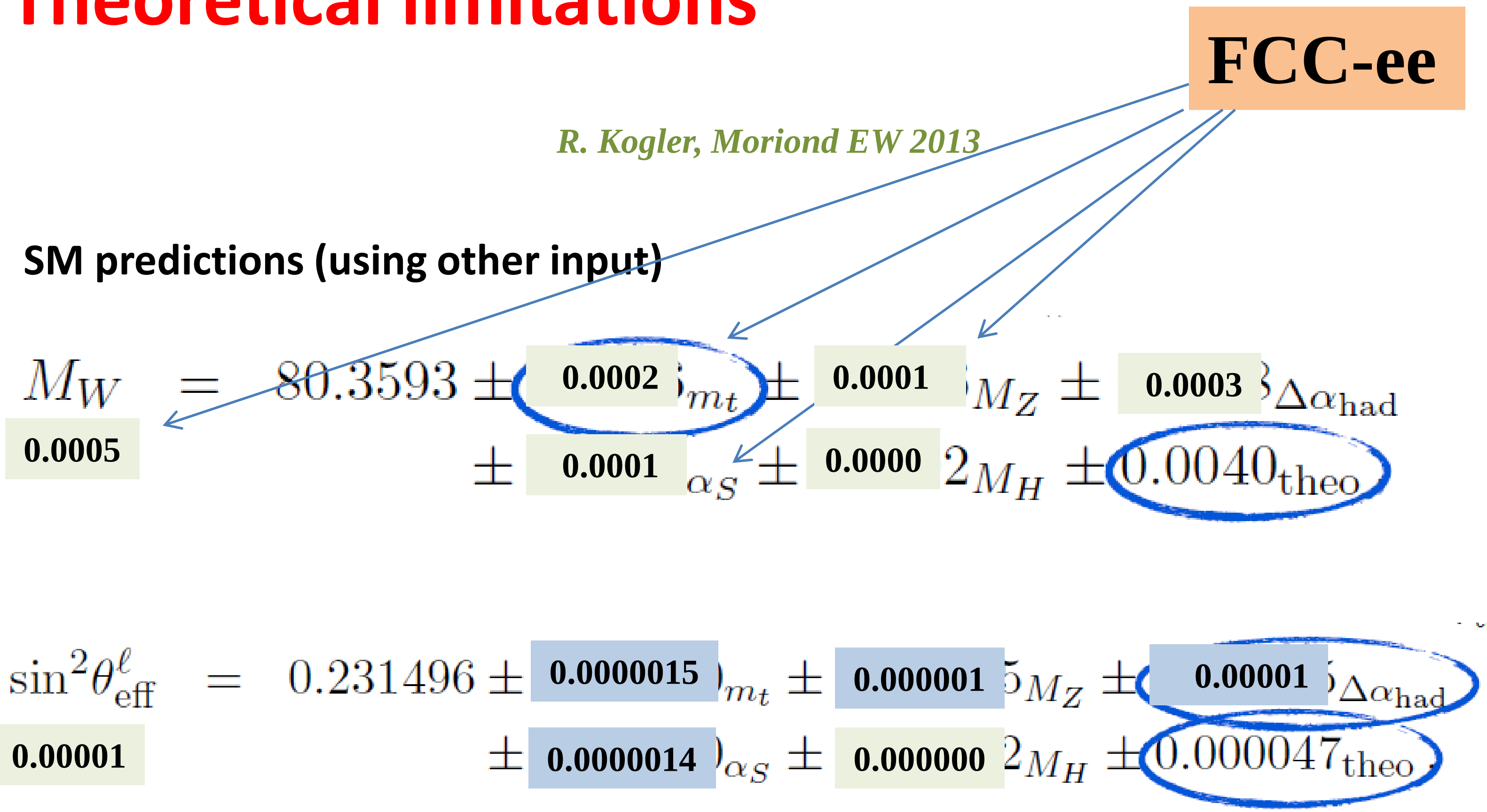


$A_{FB}^{\mu\mu}$ at $\sqrt{s}$-=87.9 GeV $\sqrt{s}$+=94.3 GeV

error cancellation of +3 vs -3 points.

- Total bias on $\alpha_{QED}(m_Z^2)$ of the order of 8×10^{-6}

Theoretical limitations



FCC-ee

R. Kogler, Moriond EW 2013

SM predictions (using other input)

$$M_W = 80.3593 \pm \mathbf{0.0002}_{m_t} \pm \mathbf{0.0001}_{M_Z} \pm \mathbf{0.0003}_{\Delta\alpha_{had}} \pm \mathbf{0.0001}_{\alpha_S} \pm \mathbf{0.0000}\,2_{M_H} \pm 0.0040_{theo}$$

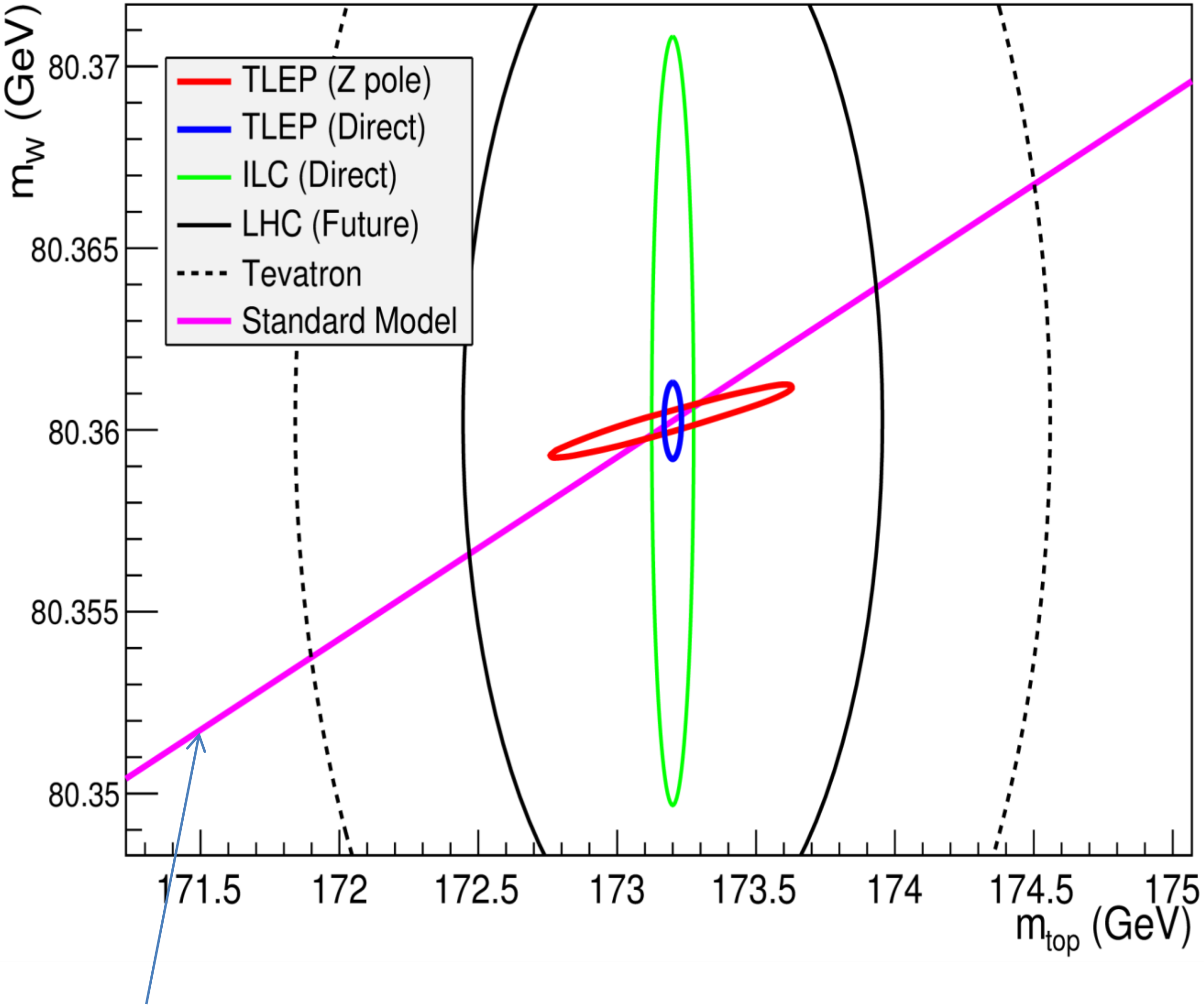
0.0005

$$\sin^2\theta^{\ell}_{eff} = 0.231496 \pm \mathbf{0.0000015}_{m_t} \pm \mathbf{0.000001}\,5_{M_Z} \pm \mathbf{0.00001}\,5_{\Delta\alpha_{had}} \pm \mathbf{0.0000014}_{\alpha_S} \pm \mathbf{0.000000}\,2_{M_H} \pm 0.000047_{theo}$$

0.00001

Experimental errors at FCC-ee will be 20-100 times smaller than the present errors.
BUT can be typically 10 -30 times smaller than present level of theory errors
Will require significant theoretical effort and additional measurements!

Radiative correction workshop 13-14 July 2015 stressed the need for 3 loop calculations for the future!



NB width of this line : Z mass error. Without FCC-ee its 2.2 MeV!

in other words .... $\Delta(\Delta\rho) = \pm 10^{-5}$ + several tests of same precision

New physics reach

sensitive to heavy new physics up to 100 TeV

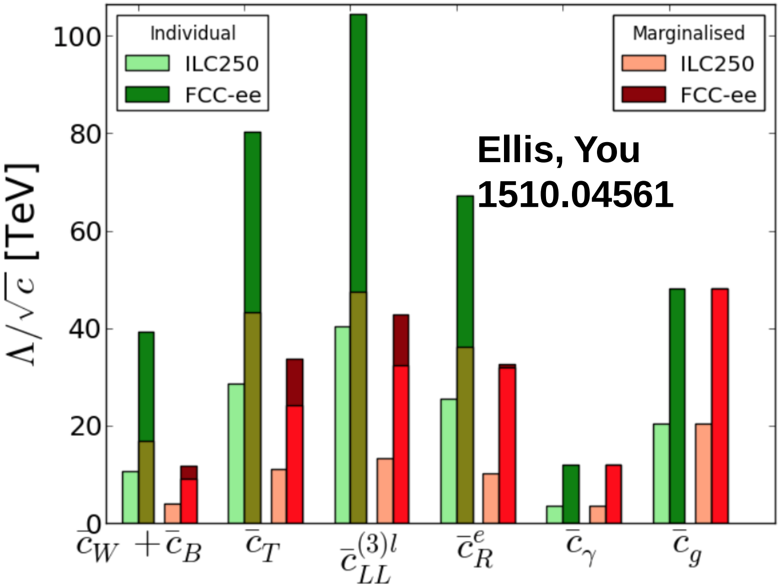
Effective lagrangian Dim-6 operators

$$\frac{1}{2}\frac{(\bar{c}_W+\bar{c}_B)}{m_W^2}(\mathcal{O}_W+\mathcal{O}_B)+\frac{\bar{c}_T}{v^2}\mathcal{O}_T+\frac{\bar{c}_{LL}^{(3)l}}{v^2}\mathcal{O}_{LL}^{(3)l}+\frac{\bar{c}_R^e}{v^2}\mathcal{O}_R^e\,,$$

$$\frac{1}{2}\frac{(\bar{c}_W-\bar{c}_B)}{m_W^2}(\mathcal{O}_W-\mathcal{O}_B)+\frac{\bar{c}_{HW}}{m_W^2}\mathcal{O}_{HW}+\frac{\bar{c}_{HB}}{m_W^2}\mathcal{O}_{HB}+\frac{\bar{c}_g}{m_W^2}\mathcal{O}_g+\frac{\bar{c}_\gamma}{m_W^2}\mathcal{O}_\gamma$$

$$+\frac{\bar{c}_H}{v^2}\mathcal{O}_H+\frac{\bar{c}_f}{v^2}\mathcal{O}_f\,.$$

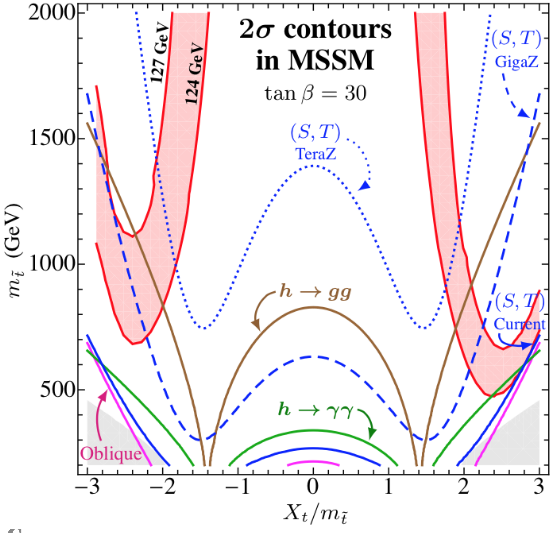
$$\bar{c}_i=c_i\frac{M^2}{\Lambda^2}\,,$$



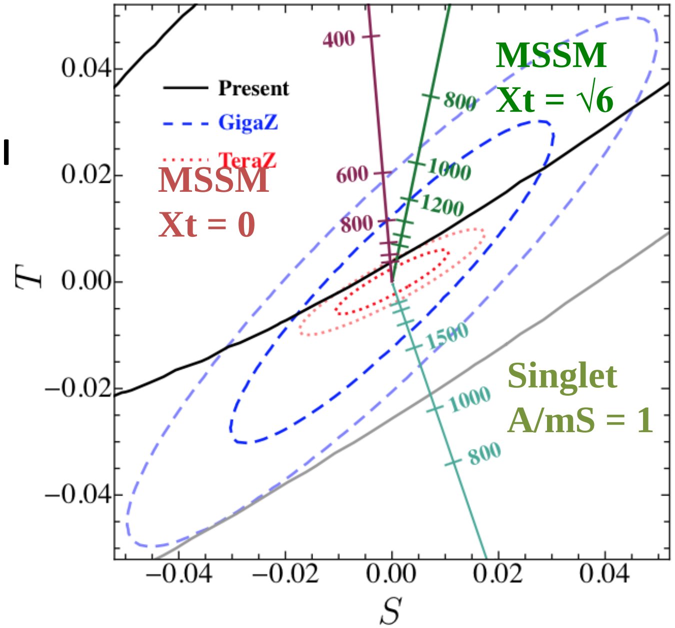
Ellis, You 1510.04561

Model examples:

MSSM , heavy gauge singlet that couples to the SM via a Higgs portal



Henning et al 1404.1058



Conclusion

lesson from past experience:

Precision EW tests allowed to predict mass of particles before discovery(Top, Higgs) and excluded new physics up to (100 GeV)

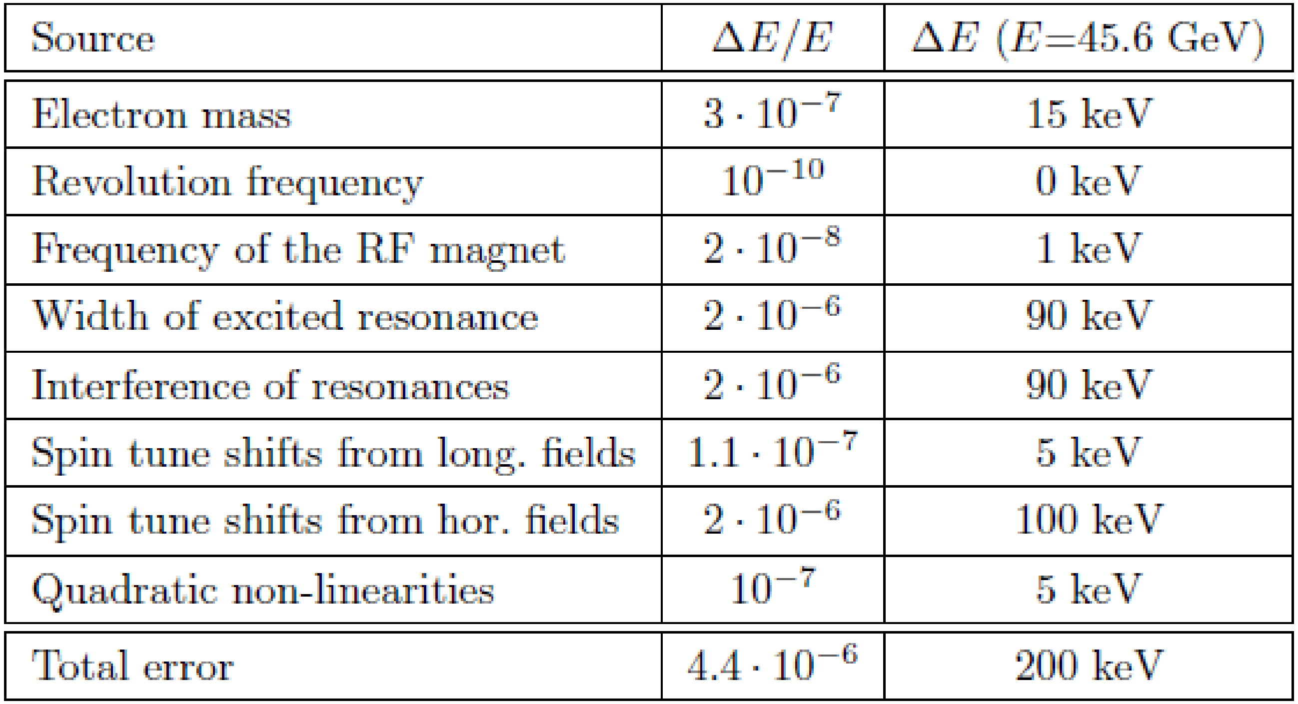
FCC-ee will allow sensitivity to new physics up to 100 TeV
Through its effect in quantum corrections

FCC-ee offers a broad, coherent program of EW precision measts on 'all fronts'.
Transverse polarization is critical for Z and W masses, Z width. (unique feature of circular colliders)

No physics case could be found for longitudinal polarization or Ecm larger than 37 GeV at the FCC-ee: AFB @ large luminosities over-compensate, and the FCC-hh is better suited for higher energy

Resonant depolarization accuracy at TLEP/FCCee – extrapolation

Per beam, not ECM



Source	$\Delta E/E$	ΔE (E=45.6 GeV)	**Correlated/Z mass**	**Uncorrelated / Z width**
Electron mass	$3 \cdot 10^{-7}$	15 keV	**15keV**	**0keV**
Revolution frequency	10^{-10}	0 keV	**0keV**	**0keV**
Frequency of the RF magnet	$2 \cdot 10^{-8}$	1 keV	**1keV**	**0keV**
Width of excited resonance	$2 \cdot 10^{-6}$	90 keV	**1keV**	**1keV**
Interference of resonances	$2 \cdot 10^{-6}$	90 keV	**9keV**	**9keV**
Spin tune shifts from long. fields	$1.1 \cdot 10^{-7}$	5 keV	**5keV**	**5keV**
Spin tune shifts from hor. fields	$2 \cdot 10^{-6}$	100 keV	**3keV**	**1keV**
Quadratic non-linearities	10^{-7}	5 keV	**5keV**	**5keV**
Total error	$4.4 \cdot 10^{-6}$	200 keV	**~20keV**	**~12keV**
IP specific errors			**~40keV**	**~20keV**
total			**~45keV**	**~23keV**

- Statistical errors are divided by sqrt(10,000) - negligible
- This is a zeroth order working hypothesis
- The table should eventually also include effects that were negligible at the time of LEP

Extracting physics from $\sin^2\theta^{lept}_W$

1. Direct comparison with m_Z

$$\sin^2\theta_W^{eff}\cos^2\theta_W^{eff} = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\,m_Z^2}\;\frac{1}{1+\Delta\rho}\;\frac{1}{1-\frac{\varepsilon_3}{\cos^2\theta_W}}$$

Uncertainties in m_{top} , $\Delta\alpha(m_z)$, m_H , etc….

$\Delta\sin^2\theta^{lept}_W$ ~ $\Delta\alpha(m_z)$ /3 = 10^{-5} if we can reduce $\Delta\alpha(m_z)$ (see P. Janot idea)

2. Comparison with m_w/m_Z

Compare above formula with similar one:

$$\sin^2\theta_W\cos^2\theta_W = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F\,m_Z^2}\cdot \qquad - \frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + 2\,\frac{\cos^2\theta_W}{\sin^2\theta_W}\varepsilon_3 + \frac{c^2-s^2}{s^2}\varepsilon_2 \quad)$$

Where it can be seen that $\Delta\alpha(m_z)$ cancels in the relation.
The limiting error is the error on m_W.
For Δm_W= 0.5 MeV this corresponds to $\Delta\sin^2\theta^{lept}_W = 10^{-5}$

The main players

Inputs:

$G_F = 1.1663787(6) \times 10^{-5}$ /GeV^2	from muon life time	**6 10^{-7}**
$M_Z = 91.1876 \pm 0.0021$ GeV	Z line shape	**2 10^{-5}**
$\alpha = 1/137.035999074(44)$	electron g-2	**3 10^{-10}**

EW observables sensitive to new physics:

$M_W = 80.385 \pm 0.015$	LEP, Tevatron	**2 10^{-4}**
$\sin^2\theta_W^{eff} = 0.23153 \pm 0.00016$	WA Z pole asymmetries	**7 10^{-4}**
+ Γ Rb etc...		

Nuisance parameters:

$\alpha(M_Z) = 1/127.944(14)$	**hadronic corrections** to running alpha	**1.1 10^{-4}**
$\alpha_S(M_Z) = 0.1187(17)$	strong coupling constant	**1.7 10^{-3}**
m_{top} = 173.34 ± 0.76 GeV	from LHC+Tevatron combination	**4 10^{-3}**

m_H = 125.09±0.21 (stat.)±0.11 (syst.) GeV/c^2 (CMS+ATLAS)	**2 10^{-3}**

EWRCs

relations to the well measured

$G_F\ m_Z\ \alpha_{QED}$

$\Delta\rho$: $\equiv \varepsilon_1$

$$\Gamma_\ell = (1+\Delta\rho)\frac{G_F\ M_Z^3}{24\pi\sqrt{2}}\left(1+\left(\frac{g_{V\ell}}{g_{A\ell}}\right)^2\right)\left(1+\frac{3}{4}\frac{\alpha}{\pi}\right)$$

ε_3

$$\sin^2\theta_W^{eff}\cos^2\theta_W^{eff} = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\ G_F\ M_Z^2}\ \frac{1}{1+\Delta\rho}\ \frac{1}{1-\frac{\varepsilon_3}{\cos^2\theta_W}}$$

δ_{vb}

$$\Gamma_b = (1+\delta_{vb})\ \Gamma_d\ \left(1-\underset{\alpha\, m_b^2/M_Z^2}{\text{mass corrections}}\right)$$

ε_2

$$M_W^2 = \frac{\pi\alpha(M_Z^2)}{\sqrt{2}\ G_F \sin^2\theta_W^{eff.}}\cdot\frac{1}{(1-\varepsilon_3+\varepsilon_2)}$$

$\sin^2\theta_W^{eff}$ is defined from

$$\sin^2\theta_W^{eff} = \frac{1}{4}\left(1-\underbrace{\frac{g_{V\ell}}{g_{A\ell}}}\right) = \sin^2\theta_{W\,lept}^{eff}$$

obtained from asymmetries at the Z.

also

Δr

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\,G_F}\cdot\frac{1}{\left(1-\frac{M_W^2}{M_Z^2}\right)}\ \frac{1}{(1-\Delta r)}$$

$$\Delta r = \Delta\alpha - \frac{\cos^2\theta_W}{\sin^2\theta_W}\Delta\rho + 2\frac{\cos^2\theta_W}{\sin^2\theta_W}\varepsilon_3 + \frac{c^2-s^2}{s^2}\varepsilon_2$$

at first order:

$\Delta\rho = \alpha/\pi\ \ (m_{top}/m_Z)^2$

$- \alpha/4\pi\ \ \log (m_h/m_Z)^2$

$\varepsilon_3 = \cos^2\theta_W\ \alpha/9\pi\ \ \log(m_h/m_Z)^2$

$\delta_{vb} = 20/13\ \alpha/\pi\ \ (m_{top}/m_Z)^2$

complete formulae at 2d order
including strong corrections
are available in fitting codes

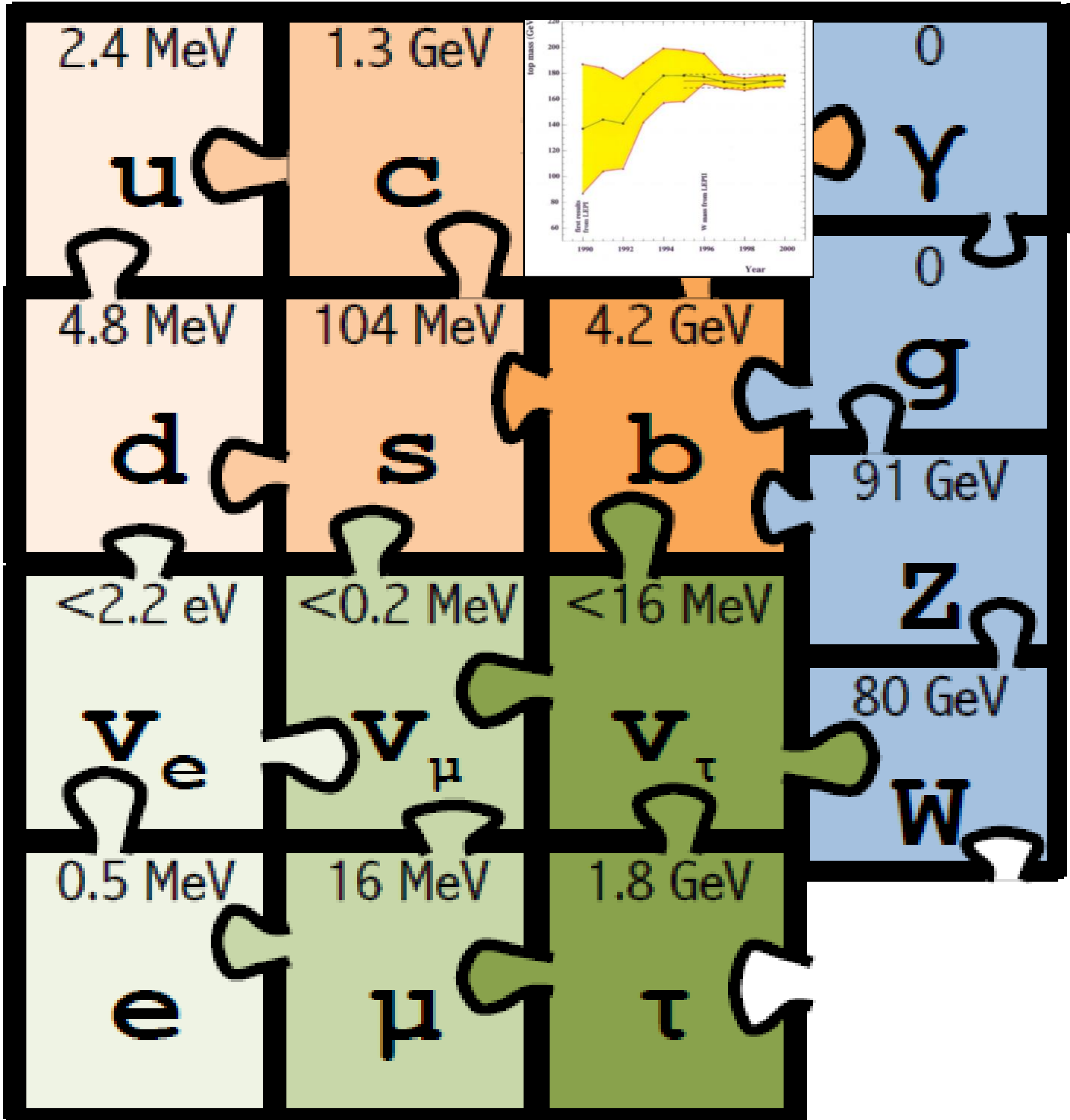
e.g. ZFITTER , GFITTER

1989
1995

Quarks

Leptons

Bosons



c) Sfyrla

1995
2012

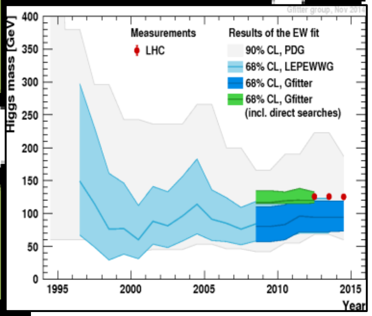
Quarks

Leptons

Bosons

2.4 MeV u	1.3 GeV c	170 GeV t	0 γ
4.8 MeV d	104 MeV s	4.2 GeV b	0 g
<2.2 eV ν_e	<0.2 MeV ν_μ	<16 MeV ν_τ	91 GeV Z
0.5 MeV e	16 MeV μ	1.8 GeV τ	80 GeV W

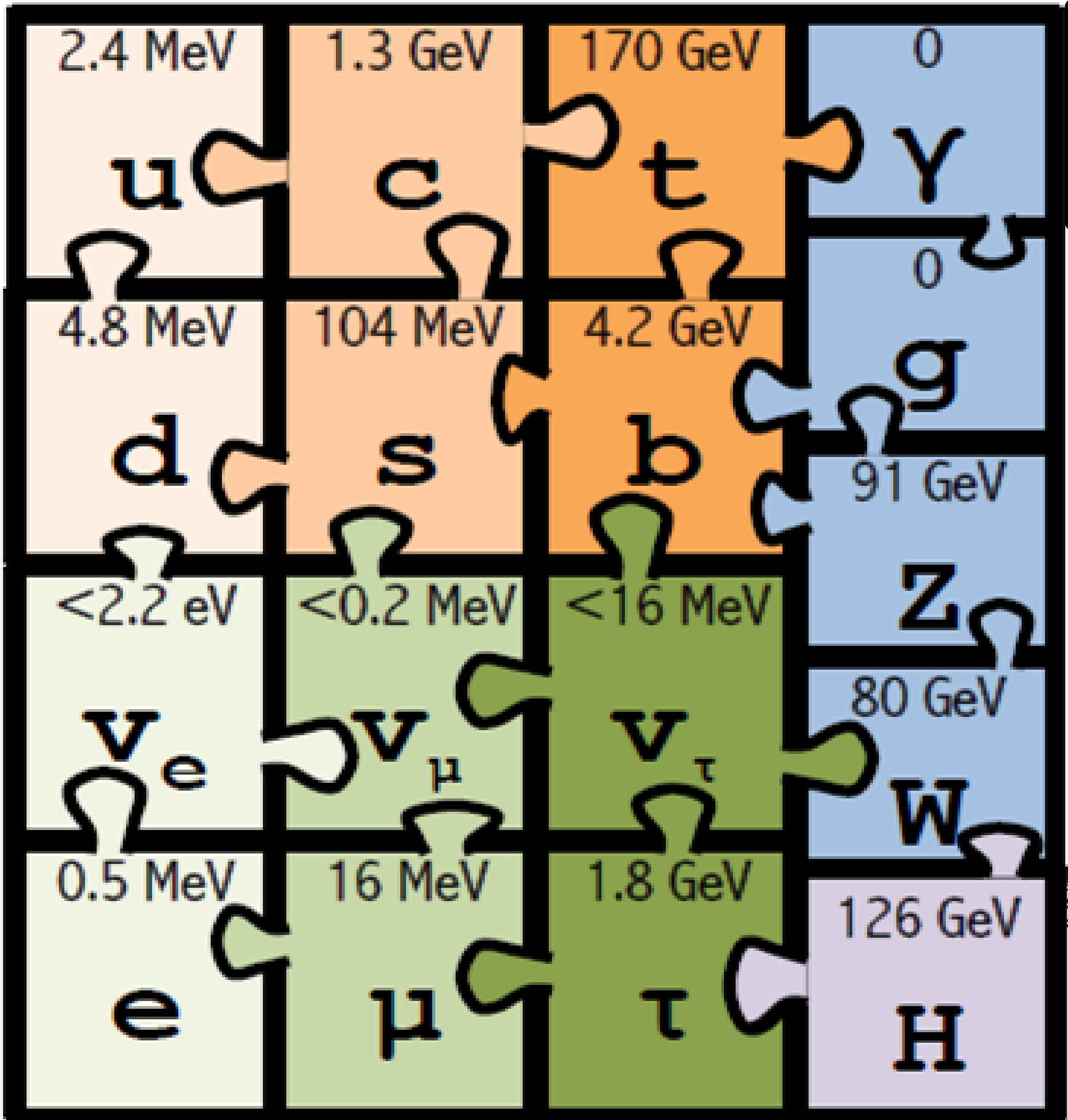
(c) Sfyrla



2012
now

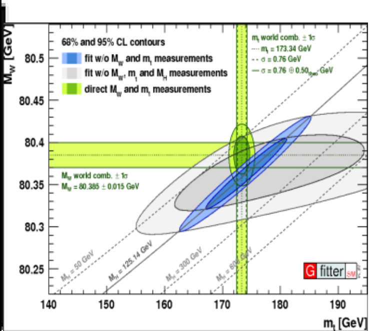
Quarks

Leptons



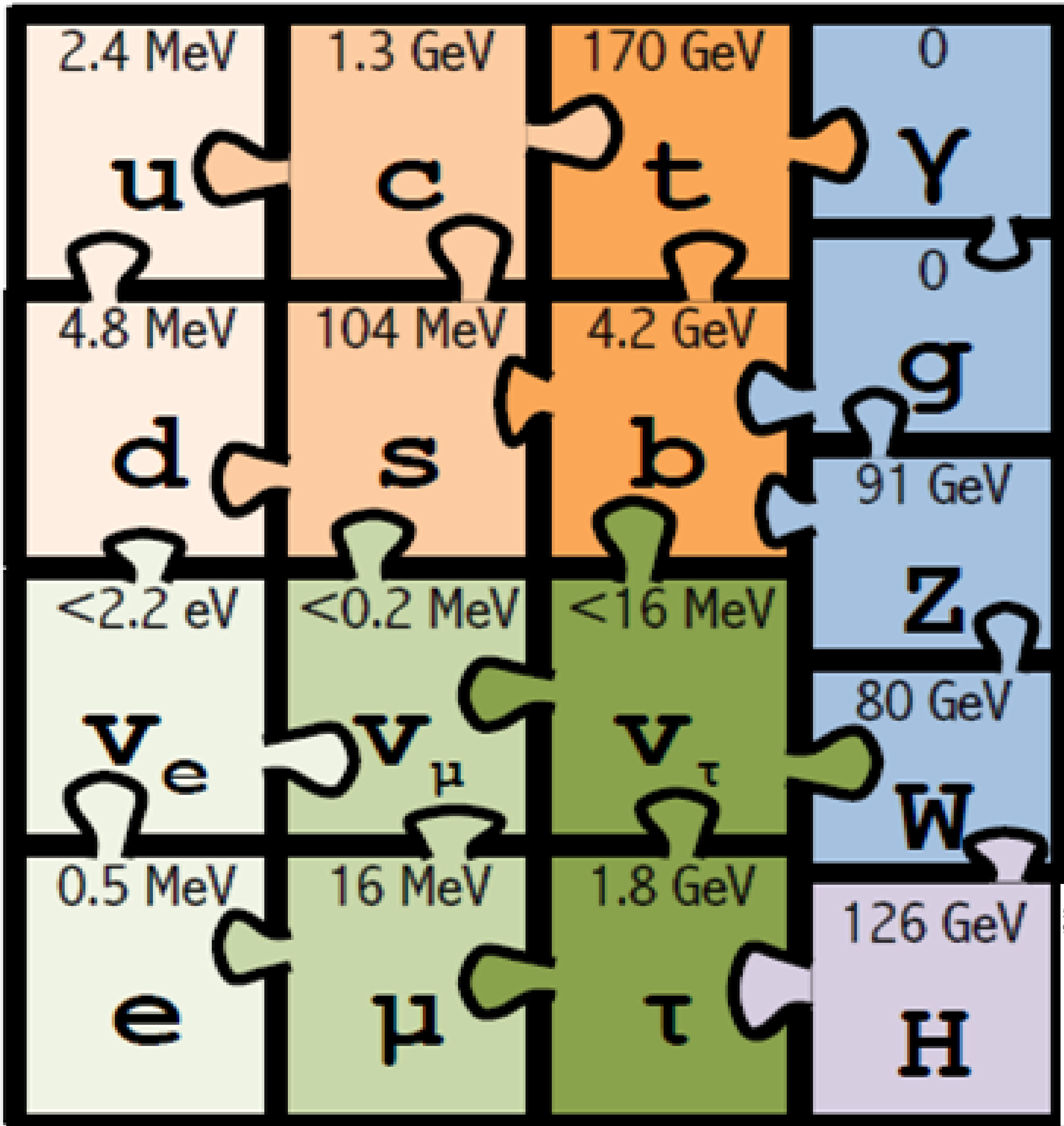
(c) Sfyrla

Bosons



2035

20xx



Quarks

2.4 MeV u

1.3 GeV c

170 GeV t

4.8 MeV d

104 MeV s

4.2 GeV b

Leptons

<2.2 eV ν_e

<0.2 MeV ν_μ

<16 MeV ν_τ

0.5 MeV e

16 MeV μ

1.8 GeV τ

Bosons

0 γ

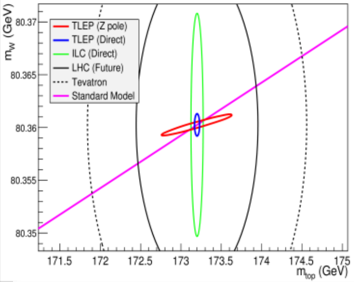
0 g

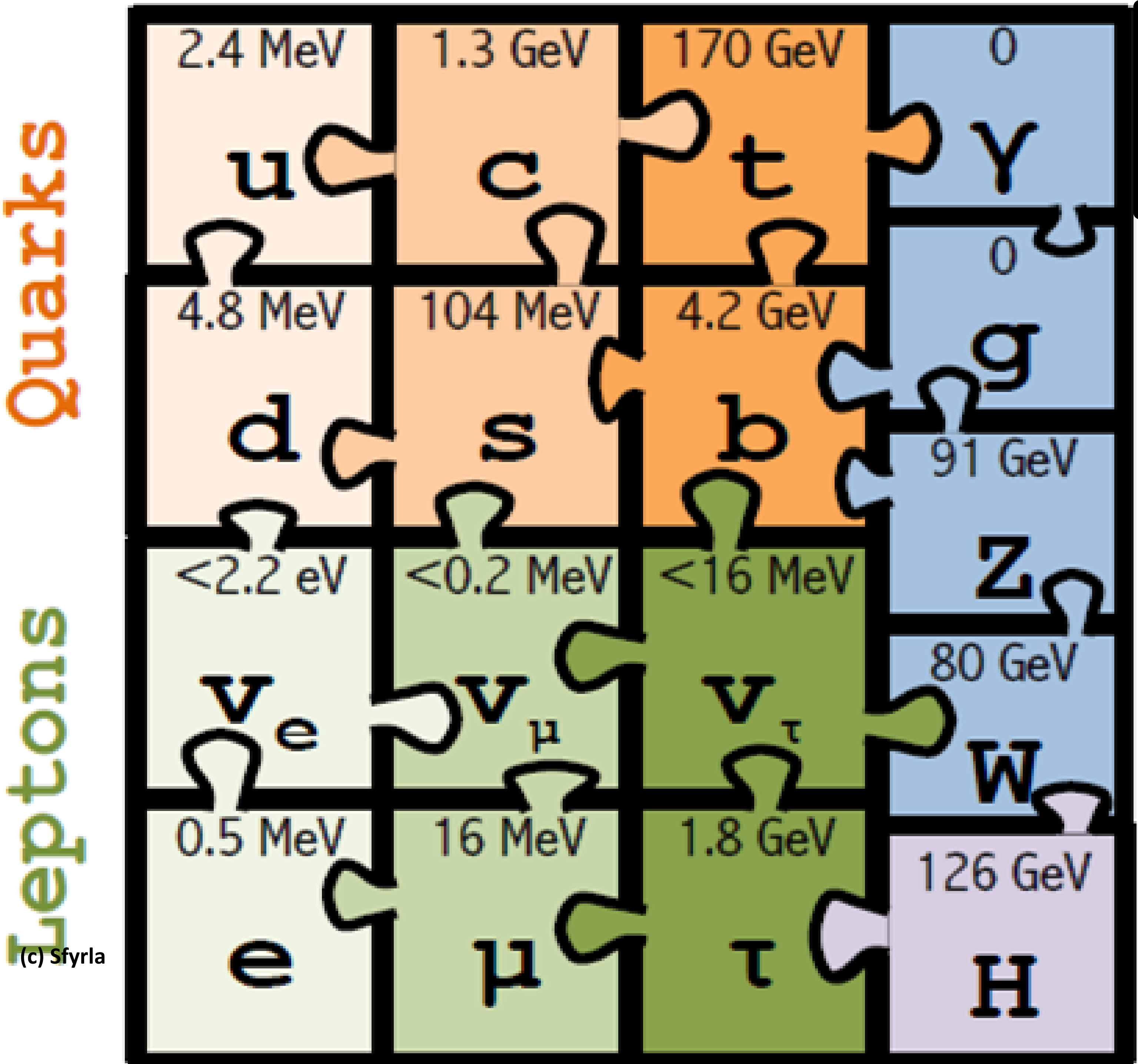
91 GeV Z

80 GeV W

126 GeV H

(c) Sfyrla

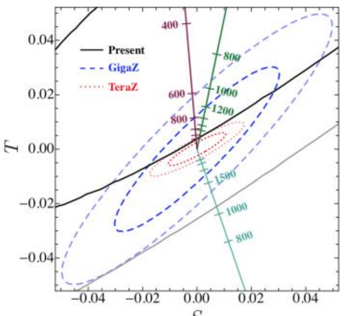




(c) Sfyrla

2035

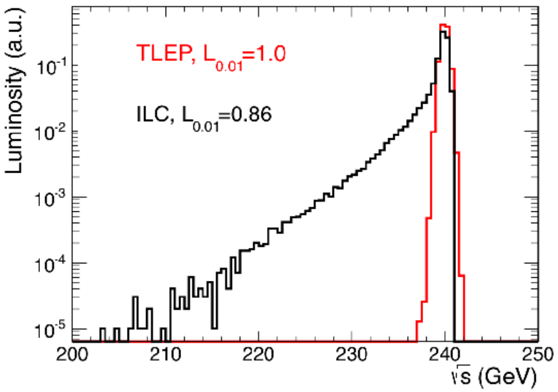
20xx

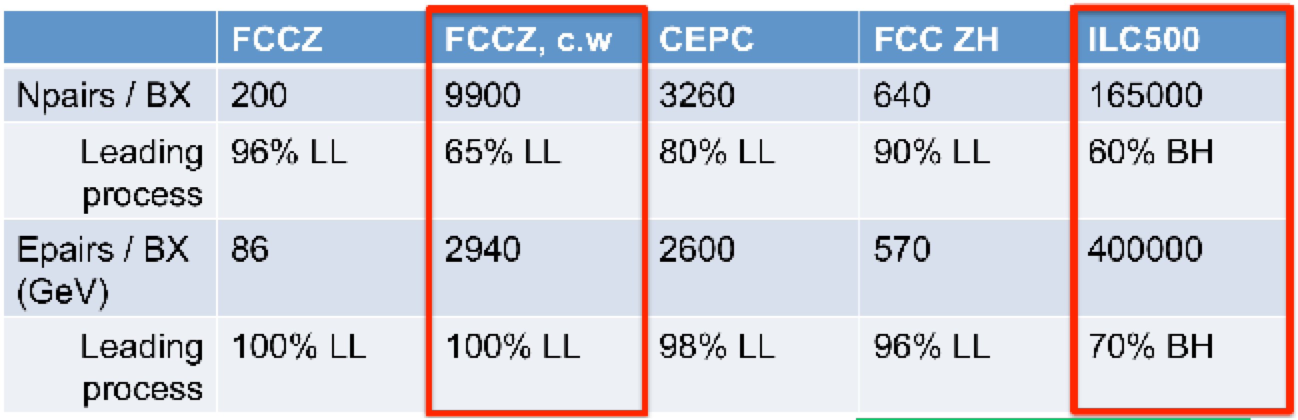


Picture and slide layout,
courtesy Jörg Wenninger

Experimental conditions

- **2-4 IPs L^*~2m**
- **bunch crossing spacing from 2-5 ns (Z) up to 3μs (top)**
- **no pile-up (<0.001 at FCC-Z/CrabWaist)**
- **beamstrahlung is mild for experiments**





	FCCZ	FCCZ, c.w	CEPC	FCC ZH	ILC500
Npairs / BX	200	9900	3260	640	165000
Leading process	96% LL	65% LL	80% LL	90% LL	60% BH
Epairs / BX (GeV)	86	2940	2600	570	400000
Leading process	100% LL	100% LL	98% LL	96% LL	70% BH

E. Perez,
C. Leonidopoulos

- **Beam energy calibration for Z and W running**
- **IR design with crossing angle is not trivial**

➔ a challenging magnet design issue.

Input from Physics to the accelerator design

0. Nobody complains that the luminosity is too high (the more you get, the more you want)

no pile up, even at the Z: at most 1ev /300bx

1. Do we need polarized beams?

-1- transverse polarization:

continuous beam Energy calibration with resonant depolarization
central to the precision measurements of m_Z , m_W , Γ_Z
requires 'single bunches' and calibration of both e+ and e-
a priori doable up to W energies -- workarounds exist above (e.g. γZ events)
large ring with small emittance excellent. Saw-tooth smaller than LEP for Z
need wigglers (or else inject polarized e- and e+) to polarize 'singles';
simulations ongoing (E. Gianfelice, M. Koratzinos, I.Kopp)

-2- longitudinal polarization requires spin rotators and is very difficult at high energies
-- We recently found that it is not necessary to extract top couplings (Janot)
-- improves Z peak measurements *if loss in luminosity is not too strong*
but brings no information that is not otherwise accessible

2. What energies are necessary?

-- in addition to Z, W, H and top listed the following are being considered
-- e+e- → H(125.2) (requires monochromatization A. Faus) (under study)
-- e+e- at top threshold + ~20 GeV for top couplings (E_max up to 180 -185 GeV)
-- no obvious case for going to 500 GeV