Edinburgh Royal Society - February 17th 2016 - Higgs-Maxwell Particle Physics Workshop

The FCC-ee project

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INFN Padova & CERN

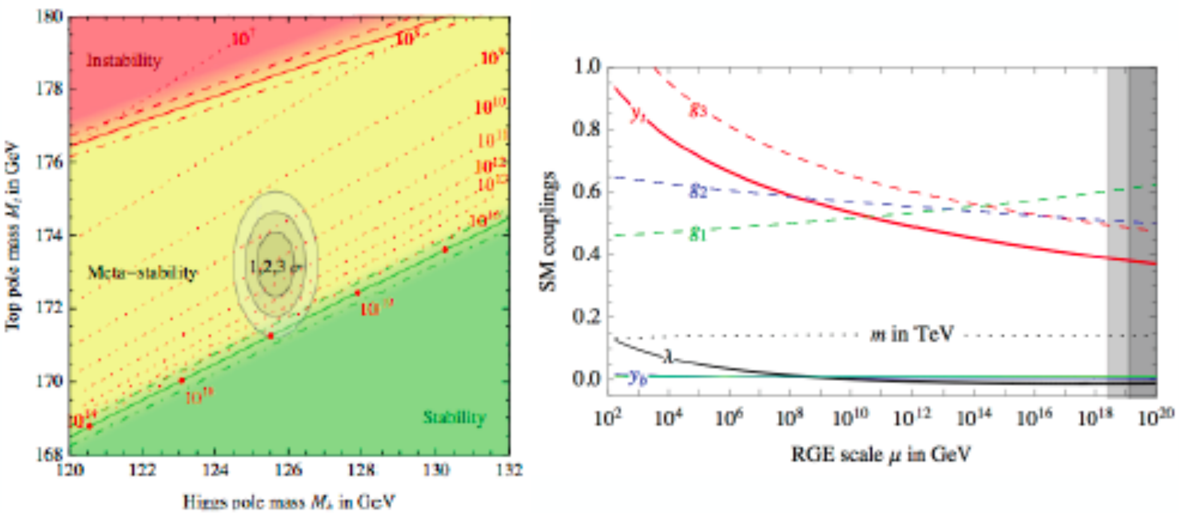
Outline

- Introduction
- Machines design and challenges
- Expected physics performances (Higgs, EWK, Top and New Physics searches)
- Organization of studies
- Conclusions

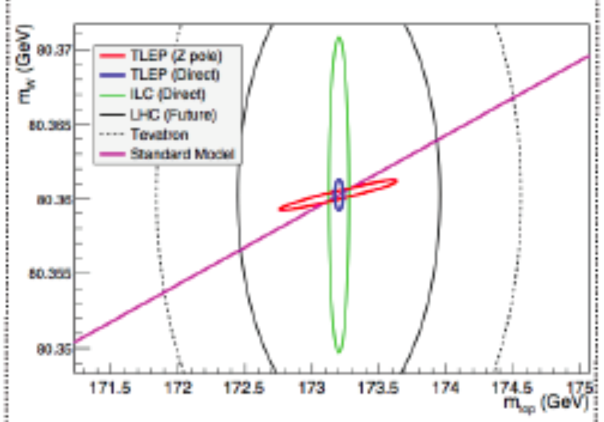
Physics Motivation

- (For the first time) The Standard Model is a consistent theory up to very high energies
  - all couplings remain perturbative
  - the standard model vacuum is however in a near-critical condition
  - the Higgs quartic coupling crosses zero below the Planck scale (suggest new physics or at least the study of λ)

[Buttazzo, Degrassi, Giardino, Giudice, Sala, Salvio, Strumia (JHEP'13)]



[TLEP Design Working Group (JHEP'14)]



More precision improves the picture

where is everybody? (Nima)

- There *must* be something beyond the Standard Theory (or totally different!)
- Experimental proofs such as:
  - Cosmological Dark Matter
  - Baryon Asymmetry of the Universe
  - non-zero (but very small) neutrino masses
- Plus, the small Higgs boson mass hints to crucial questions specific to the TeV scale that demand an answer and require exploration:
  - Hierarchy problem/Naturalness
  - EW dynamics above the symmetry breaking scale
- Which way to go?
  - Direct searches for new heavy particles —> Colliders with larger energies
  - Indirect search for effects of new physics on W,Z,H,top —> Colliders with unprecedented accuracy

LHC Run2 comes first

- 300 fb-1 at 14 TeV, first results in 2016

FIND A NEW HEAVY PARTICLE(S)

➡HL-LHC can study it

➡if m<1TeV and produced in e+e- collision CLIC is a good option

➡larger energies and luminosities needed to fully study the spectrum (FCC-hh)

FIND NO NEW PARTICLE, BUT HINTS FOR NON STANDARD HIGGS BEHAVIOR OR OTHER EXCESSES

➡HL-LHC can somewhat improve precision

➡Higgs and Z factories very interesting machines (FCC-ee)

➡push energy frontier to its limits (FCC-hh)

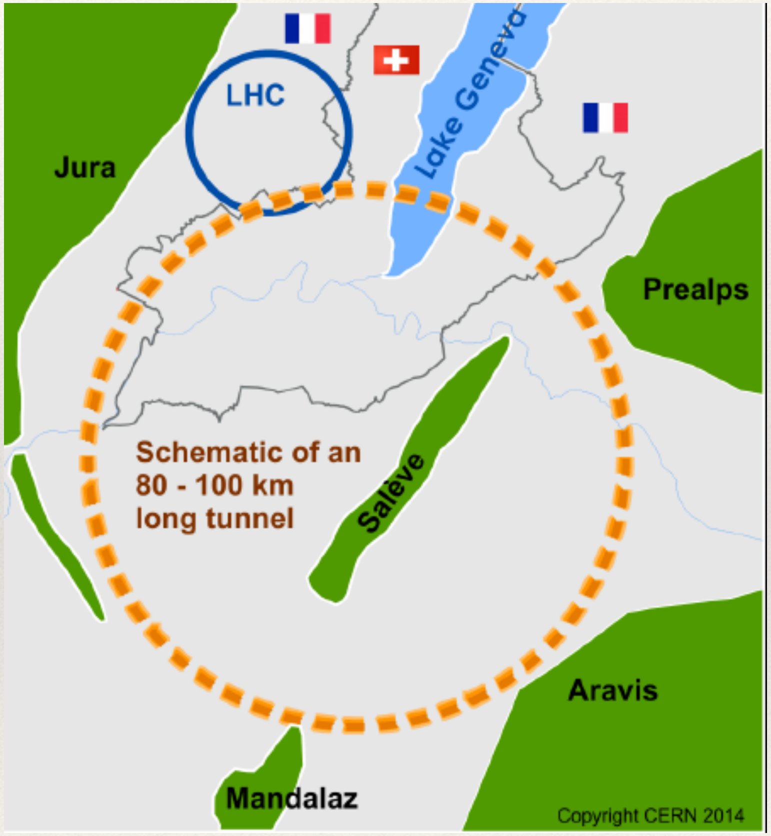
FIND NO NEW PARTICLE, STANDARD HIGGS PROPERTIES

➡push precision measurements to their limits (FCC-ee)

➡push energy frontier to its limits hoping the NP scale is reachable (FCC-hh)

the FCC project

- Build a 100 km tunnel in the Geneva region
- Ultimate goal: highest energy reach in pp collisions: 100 TeV
  - need time to develop the technology to get there
- First step: extreme precision circular e+e- collider
  - variable beam energy from 90-175 GeV
- Two complementary machines covering the largest phase space in the high energy frontier
  - a complete physics program for the next 50 years



FCC–ee physics requirements

A. Blondel,
J. Ellis ,
C. Grojean,
P. Janot,
et al.

- ***beam energy range from 35 GeV to ≈200 GeV***
- ***highest possible luminosities*** *at all working points*
- physics programs / energies:

  Z (45.5 GeV) Z pole, 'TeraZ' and high precision M_Z & Γ_Z

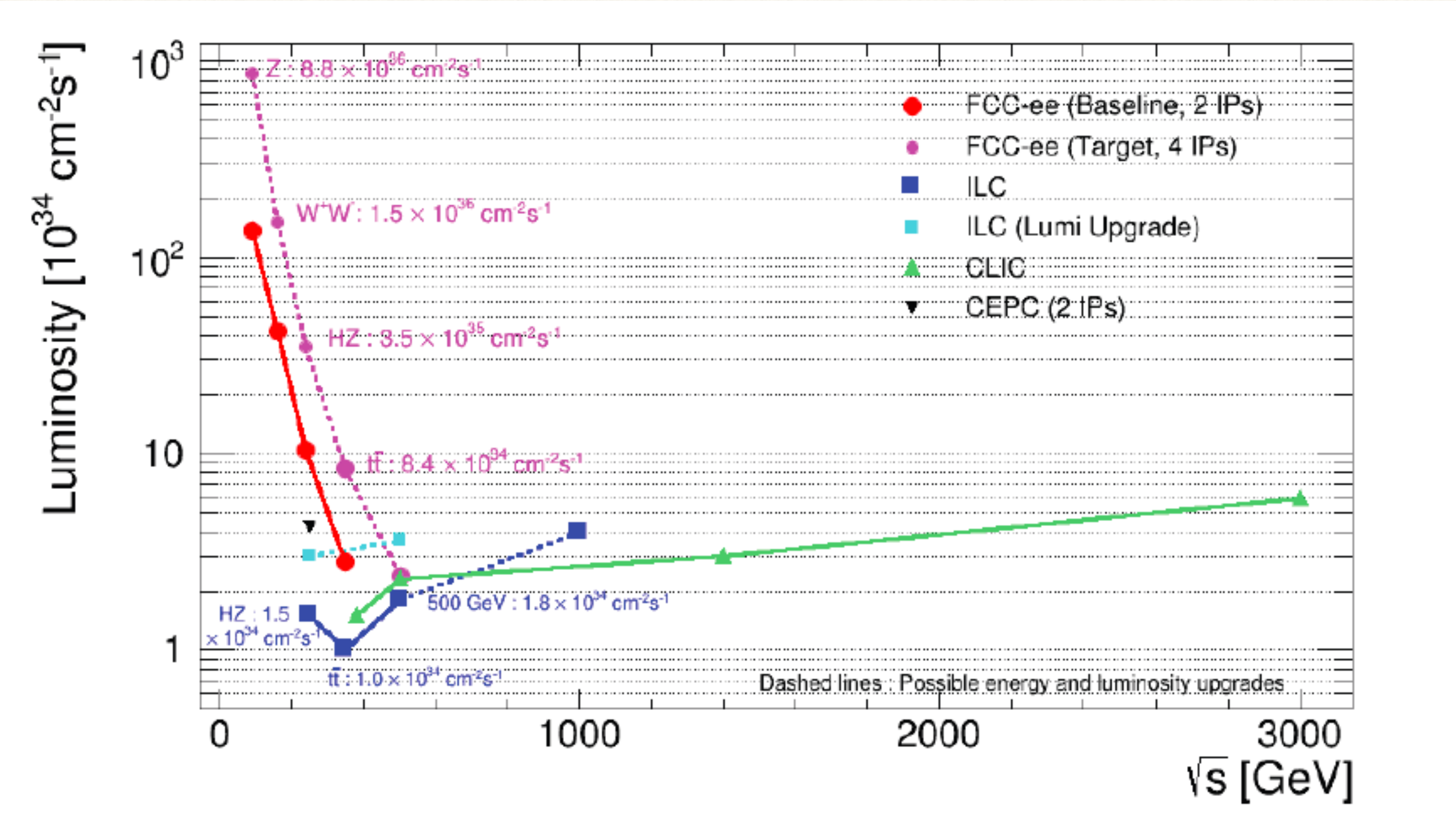
  W (80 GeV) W pair production threshold, high precision M_W

  H (120 GeV) ZH production (maximum rate of H's)

  t (175 GeV): $t\bar{t}$ threshold, H studies

  more (α_{QED} etc.)
- possibly *H* (63 GeV) direct *s*-channel production with **monochromatization**
- **some polarization up to ≥80 GeV** for beam energy calibration

FCC-ee: high luminosity from sqrt(s)=90-350GeV



Unprecedented precision: a challenge also to theory expectations

lepton collider parameters

parameter	FCC-ee			CEPC	LEP2
energy/beam [GeV]	**45**	**120**	**175**	**120**	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**70**	**5**	**1.3**	**2.0**	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	**100**			**103**	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5

FCC-ee: 2 separate rings

CEPC baseline: single beam pipe like LEP

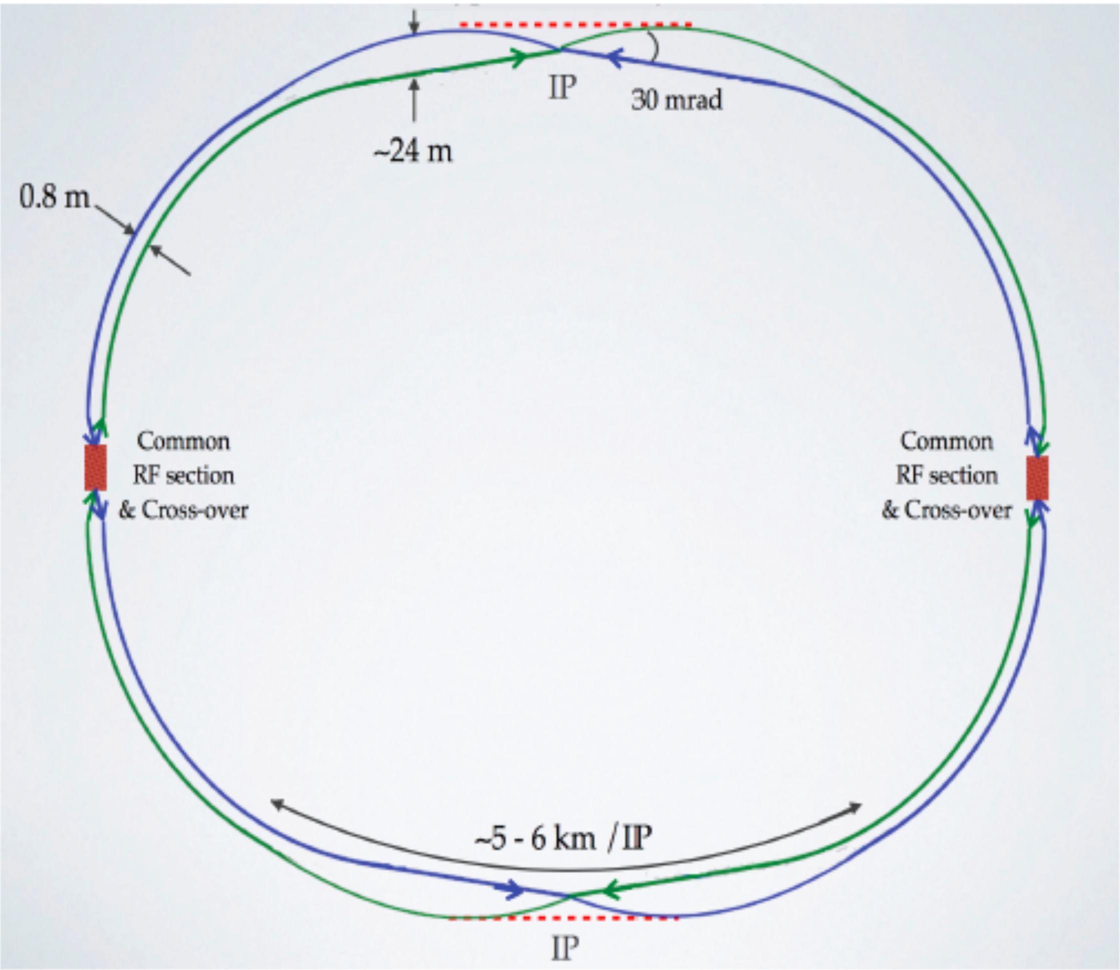
Selected FCC-ee beam parameters

Baseline design	LEP2	FCCee-Z	FCCee-W	FCCee-H	FCCee-t
Beam energy E_b [GeV]	104.5	45.5	80	120	175
Circumference [km]	26.7	100	100	[illegible]	[illegible]
Beam current [mA]	4	1450	152	[illegible]	[illegible]
SR power total [MW]	22	100	100	100	100
No. bunches/beam	4	90300	5192	770	78
No. e^- per bunch [10^{11}]	6	0.33	0.6	0.8	1.7
Horizontal emittance [nm]	48	0.09	0.27	[illegible]	[illegible]
Vertical emittance [pm]	250	1.0	1.0	[illegible]	[illegible]
β^*_x [m]	1.5	1	1	1	1
β^*_y [mm]	50	2	2	2	2
σ^*_x [µm]	270	9.5	16	25	36
σ^*_y [nm]	3500	45	45	51	72
L/IP [10^{34} cm^{-2}s^{-1}] (2 IPs)	0.0125	68	19	4.9	1.3
Beam lifetime [min] (2 IPs)	360	247	109	78	63

Bunch crossing time down to 3 ns

Very strong vertical focussing

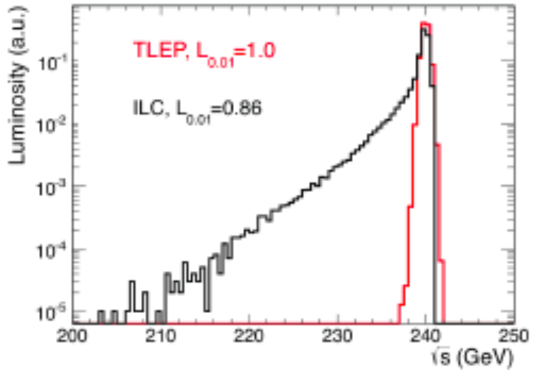
FCC-ee accelerator layout



Of particular importance for experiments

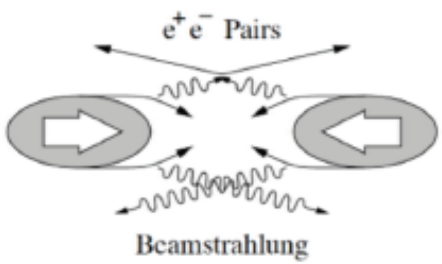
- 30 mrad beam crossing angle
  - Avoid parasitic crossings
- No bending of beams before crossing, only after
  - Minimize synchrotron radiation through interaction region
  - P_{SR} < 1 kW within 250 m from IP
  - E^{γ}_{crit} < 100 keV - minimize neutron production

FCC-ee experimental conditions



Sharp beam-energy profile

- Beams are circulating, *i.e.* have to be reusable after collision
  - Non-destructive focusing and collision
  - Beam-beam interactions have to be kept at a minimum



Low beamstrahlung background (study for √s = 90 GeV)

- On average 4000 e^+e^- pairs created per BX
- Carry total energy of ~1 TeV (400 x less that at ILC500)
- Vertex detector layer at R = 10 mm would receive a tolerable 1.5 hit / BX / cm^2

No underlying events; No pile-up

- Running conditions most "extreme" at Z peak:
  - **~100 kHz of Zs**
  - **~200 kHz** of small angle elastic e^+e^- (Bhabha) scattering - normalisation
  - Compare to **300 MHz** beam-crossing rate

Only 1:1000 bunch-crossings will have an interaction: **μ = 0.001**

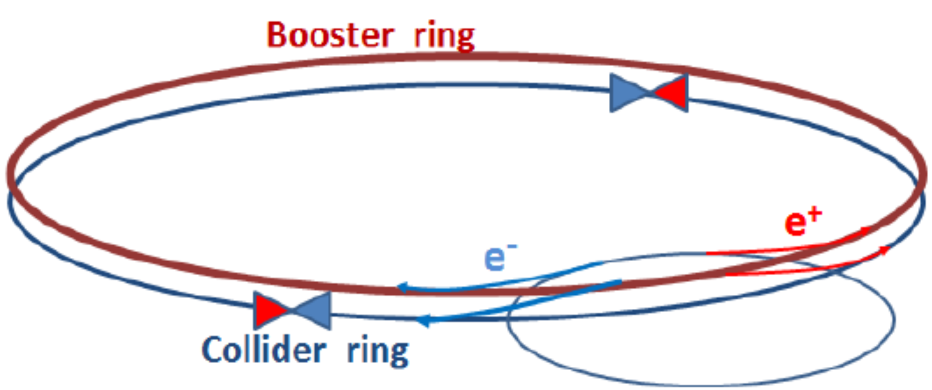
Beam lifetime & Top-Up Injection

Bhabha scattering cross section (σ~0.215 barn) implies a burn-off lifetime of ~20 min at 1e34 cm^{-2}Hz

Reminder, SuperKEKB is a demonstrator: τ~6min!

beside the collider ring(s), a booster of the same size (same tunnel) must provide beams for top-up injection to sustain the extremely high luminosity

- same size of RF system, but low power (~ MW)
- top up frequency ≈0.1 Hz
- booster injection energy ≈5-20 GeV
- bypass around the experiments



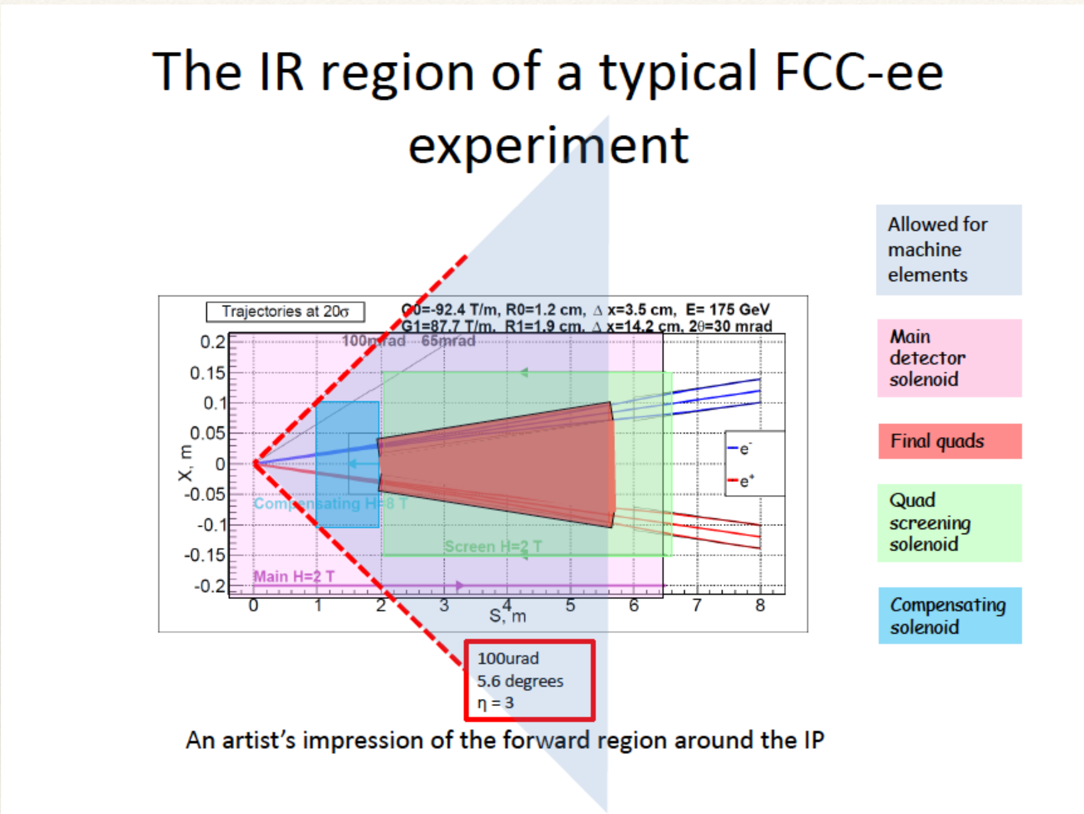
A. Blondel

Interaction region design

The Interaction Region is complicated

- Very strong focussing; low β* (2 mm)
  - Small distance between IP and first quadupole: L* ≈ 2 m
    - Final-focus magnets will be located inside the detector volume
- Beams cross at an angle of 30 mrad
  - Beams traverse detector volume at 15 mrad w.r.t. experimental B-field
    - Beam particles receive vertical kick; emittance blow-up
- Shielding/compensation needed
  a. Final-focus magnets need to be shielded from the main experimental solenoid
  b. Compensating magnets are needed in order to "undo" the effect of experimental B-field
- Small angle region is very busy
  - Need to understand backscattering of beamstrahlung and synchrotron radiation from heavy machine elements close to IP
  - Need to find space for instrumentation at small angles
    - Luminosity monitors,...

IR Region & first hardware piece of FCC-ee



3D printed prototype

Energy calibration

at *Z* and *W*: frequent resonant-depolarization measurements with non-colliding bunches

- ✓ much better resolution than at LEP, few tens of keV
- ✓ measurement of energy spread?
- ✓ extrapolation from average to individual IPs
- ✓ OR: injecting polarized beam

at higher energies, *H* and $t\bar{t}$:

- ✓ use physics measurements
- ✓ other? (laser back scattering / spectrometer?)
- ✓ OR: injecting polarized beam

A. Blondel, I. Koop, M. Koratzinos, N. Muchnoi, et al.

SR effects of LEP
high currents of KEKB and PEP-II
top-up of KEKB and PEP-II
crab waist of DAFNE
low β_y^* of SuperKEKB
***e+* source** of KEKB
cryo availability of LHC
spin gymnastics of RHIC (?)

F. Zimmermann

FCC-ee

individual parameters mostly relaxed compared with those in "demonstrator machines"

baseline **luminosity performance predicted w confidence**; further increases possible

optics footprint matched to the hadron collider layout

FCC-ee would bring the **tunnel**, the **infrastructure**, the **time** needed for high-field magnet production, and possibly also an even stronger **physics motivation** (and precise target energy) **for FCC-hh**

The Twin Frontiers of FCC-ee Physics

Precision Measurements

- Springboard for sensitivity to new physics
- Experimental issues:
  - Systematics
- Theoretical issues:
  - Higher-order QCD
  - Higher-order EW
  - Mixed QCD + EW

Heinemeyer, Freitas, Degrassi, Salvarezza, Soreq, Matsedonskyi, Riemann, Schwinn, De Curtis

Rare Decays

- Direct searches for new physics
- Many opportunities
- Z: 10^{13}
- b, c, τ: 10^{12}
- W: 10^{8}
- H: 10^{6}
- t: 10^{6}

Soreq, Nemevsek, Azzi, Strumia, Fischer

Very rich physics program

Appellation	*Tera-Z*	*Oku-W*	*Mega-Higgs*	*Mega-top*	
$\sqrt{s}$ (GeV)	90 (Z)	160 (WW)	240 (HZ)	350 ($t\bar{t}$)	350+ (WW→H)
Lumi [10^{34} cm^{-2}s^{-1}]	880	152	24	10	10
Lumi [ab^{-1}/yr]	88.0	15.2	3.5	1.0	1.0
Events/year	3.7×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2.5×10^{4}
Target # events	**(10^{12}) 10^{13}**	**10^{8}**	**2×10^{6}**	**10^{6} $t\bar{t}$**	
# years	(0.3) 2.5	1	3	0.5	3

∴ FCC-ee is the ultimate Z, W, Higgs, and top factory!

See arXiv:1308.6176, "First Look at the Physics Case of TLEP"
FCC-ee physics meetings, https://indico.cern.ch/category/5259/

Logically, divide the programme into two main parts:

a. Precision Higgs physics at $\sqrt{s}$ = 240 GeV
b. Precision electroweak physics at $\sqrt{s}$ = 90, 160, and 350 GeV

First let's study the Higgs!

Coupling	LHC Run1	LHC (300 fb^{-1})	LHC (1 ab^{-1})	HL-LHC
κ_W	15%	4-6%	3-5%	2-5%
κ_Z	20%	4-6%	3-5%	2-4%
κ_t	50%	14-15%	10-12%	7-10%
κ_b	40%	10-13%	6-10%	4-7%
κ_τ	25%	6-8%	4-6%	2-5%

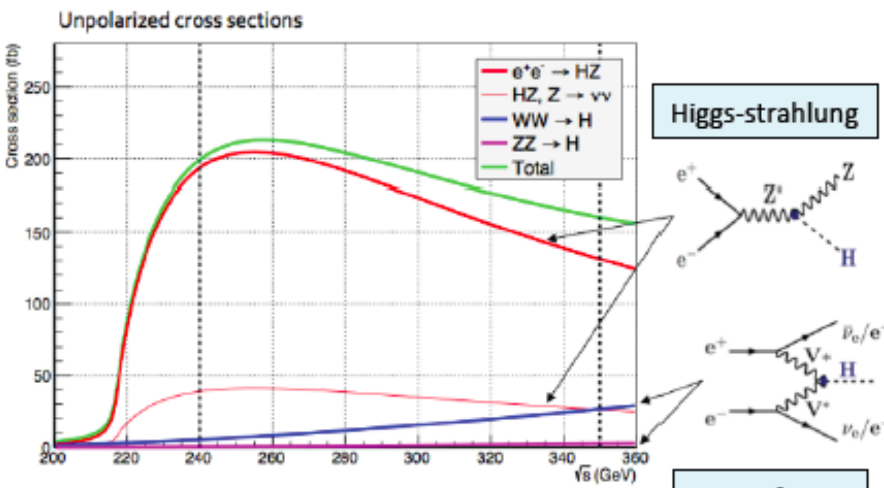
- The projections for the Higgs coupling at the HL-LHC bring a factor 1.5 to 2 on top of the Run2 (300 fb^{-1}). Limited by systematic uncertainties.
- The large statistics 3ab^{-1} allows sensitivity to H->μμ
  - measurement of the coupling to 10%
- is this precision *good enough* for a discovery?
  - **Need 1% precision on coupling for a 5σ discovery if Λ =1TeV**

Typically, expect deviations:

$\Delta\kappa/\kappa < \sim 5\,\% / \Lambda^2$

(with Λ in TeV)

Precision Higgs Physics @FCC-ee



Luminosity optimised running point(s)

- Collect 2M HZ events at √s = 240 GeV
- Plus 100k VV → H events at √s ≈ 350 GeV

m_H = 125 GeV

Decay	BR [%]	Unc. [%]
bb	57.7	3.3
ττ	6.32	5.7
cc	2.91	12.2
μμ	0.022	6.0
WW	21.5	4.3
gg	8.57	10.2
ZZ	2.64	4.3
γγ	0.23	5.0
Zγ	0.15	9.0
ΓH [MeV]	4.07	4.0

Higgs decay modes

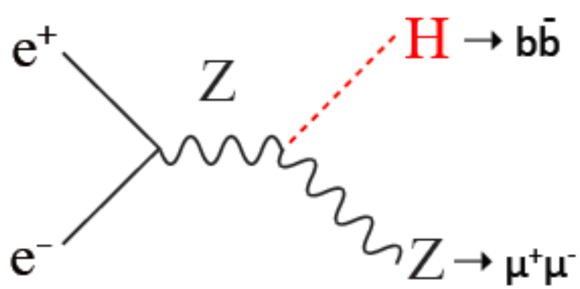
- Determine all Higgs couplings in a model-independent way
- Infer the Higgs total decay width
- Evaluate (or set limits on) Higgs invisible or exotic decays

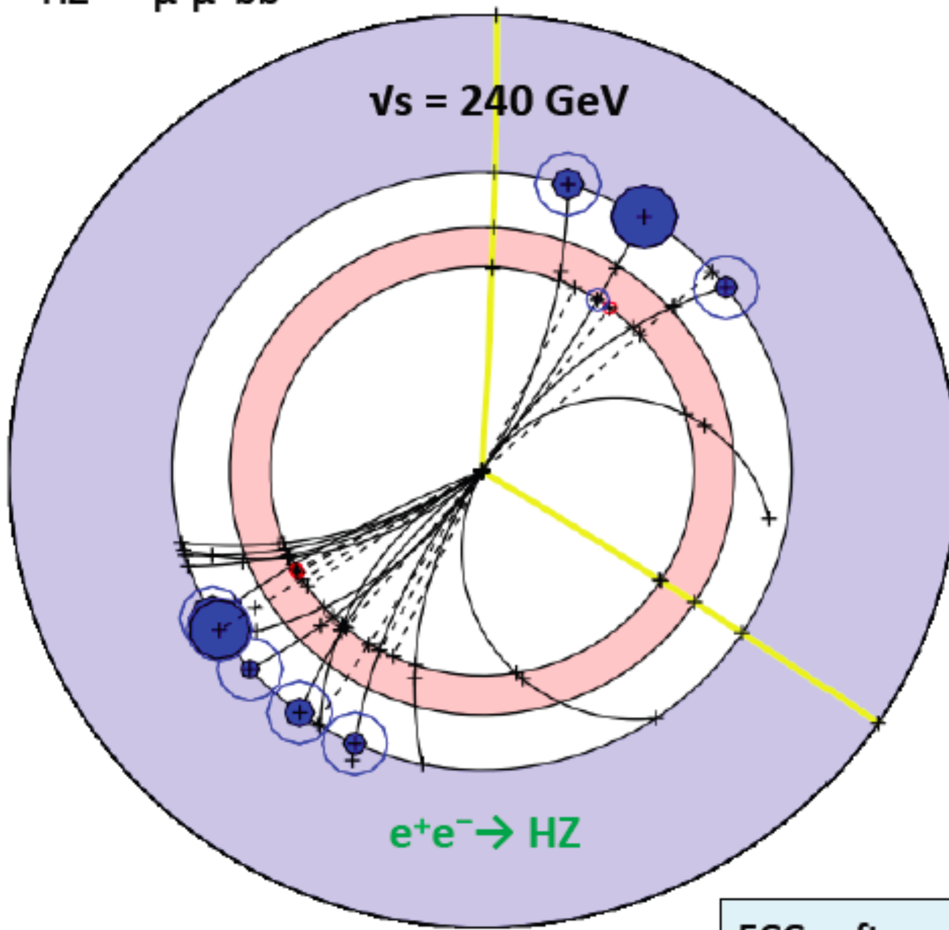
Measurement of σ(e^+e^- → H+X) × BR(H → YY) for Y = b, c, g, W, Z, γ, τ, μ, invisible

Precision Higgs Physics @ FCC-ee

Example of a Higgs boson event $e^+e^- \rightarrow HZ \rightarrow \mu^+\mu^- b\bar{b}$

- Tagged with $Z \rightarrow \mu^+\mu^-$
- Very clean signature





FCC software

Higgs Physics (1)

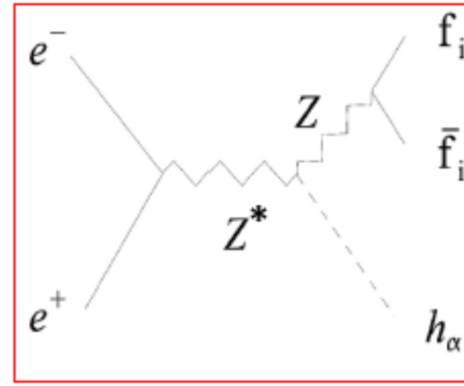
Recoil method unique to e^+e^- colliders

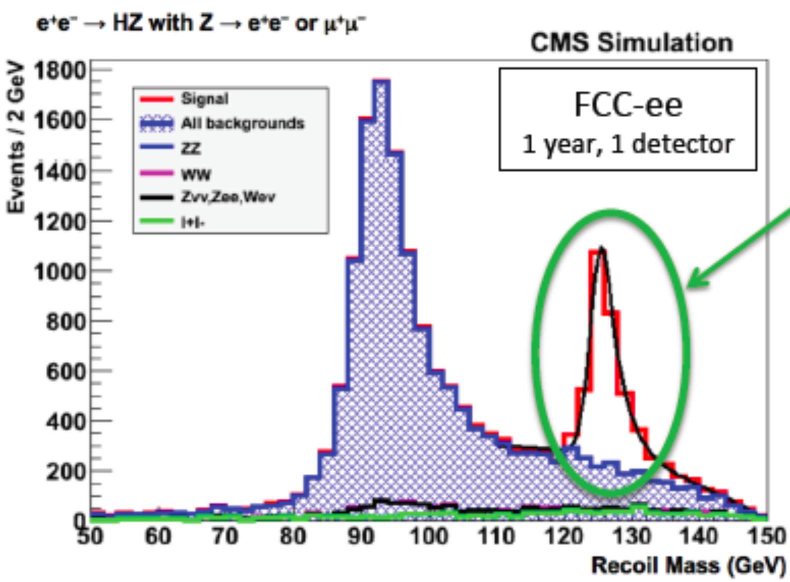
Tag Higgs boson in HZ event by the presence of a $Z \to e^+e^-, \mu^+\mu^-$

a. Select events with a lepton pair (e^+e^-, $\mu^+\mu^-$) with m_Z compatible mass
   - No requirement on Higgs decay
   - All Higgs decays also ***invisible*** will be selected

b. Apply energy-momentum conservation to determine "recoil mass"

$$m_{recoil}^2 = (\sqrt{s} - E_{ll})^2 - |p_{ll}|^2$$





c. Plot recoil mass distribution - resolution proportional to momentum resolution

d. From fit, determine number of HZ events, i.e. determine $\sigma_{HZ} \times BR(Z \to e^+e^-, \mu^+\mu^-)$

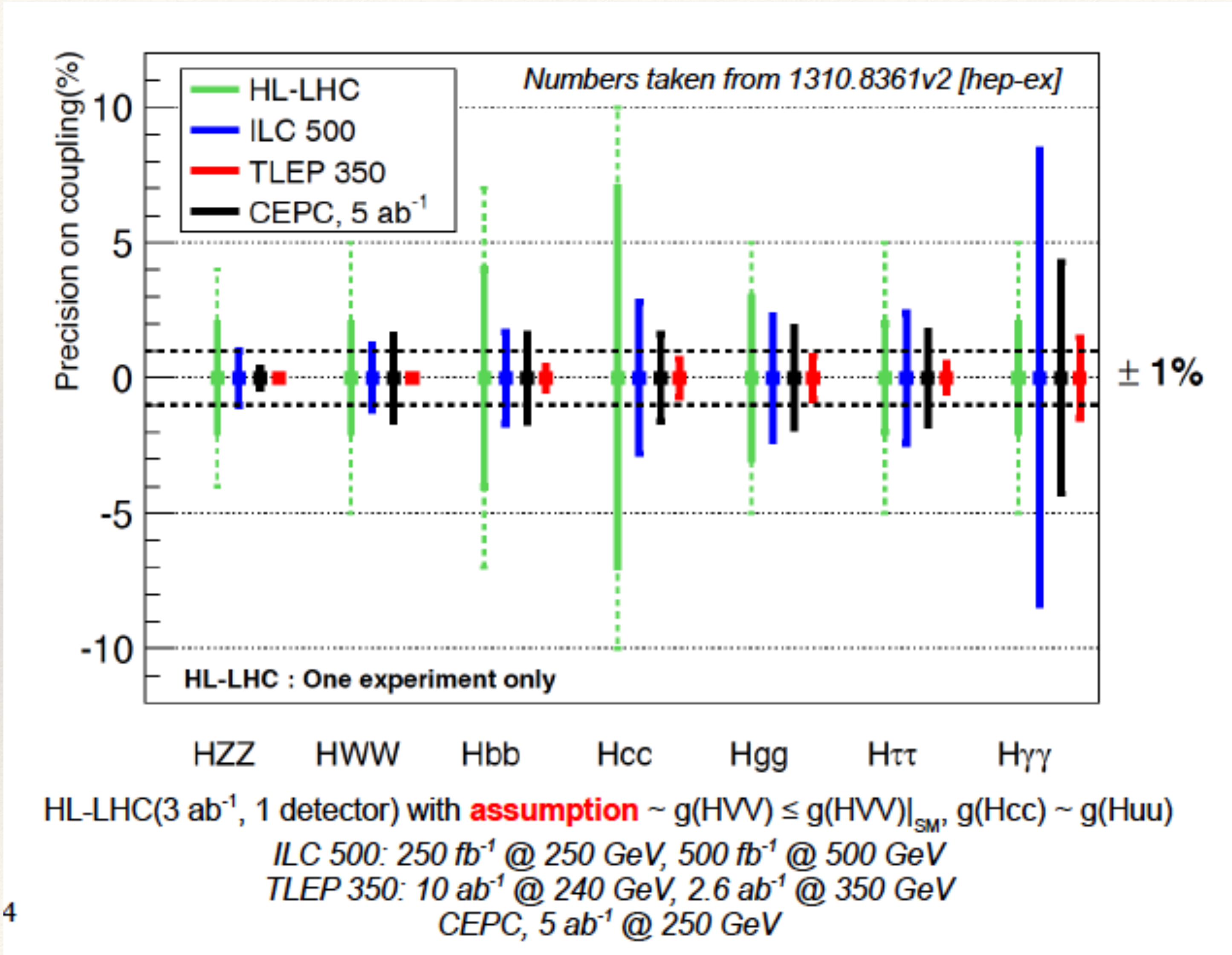
Full simulation studied, so far, using CMS detector

Summary of precisions

Coupling	HL-LHC	FCC-ee
κ_W	2-5%	0.19%
κ_Z	2-4%	0.15%
κ_b	4-7%	0.42%
κ_c	-	0.71%
κ_τ	2-5%	0.54%
κ_μ	~10%	6.2%
κ_γ	2-5%	1.5%
κ_g	3-5%	0.8%
$\kappa_{Z\gamma}$	~12%	?
BR_{inv}	~10-15%	0.25%
Γ_H	~50% ?	0.9%
κ_t	7-10%	13% (*)
κ_H	77%	80% (*)

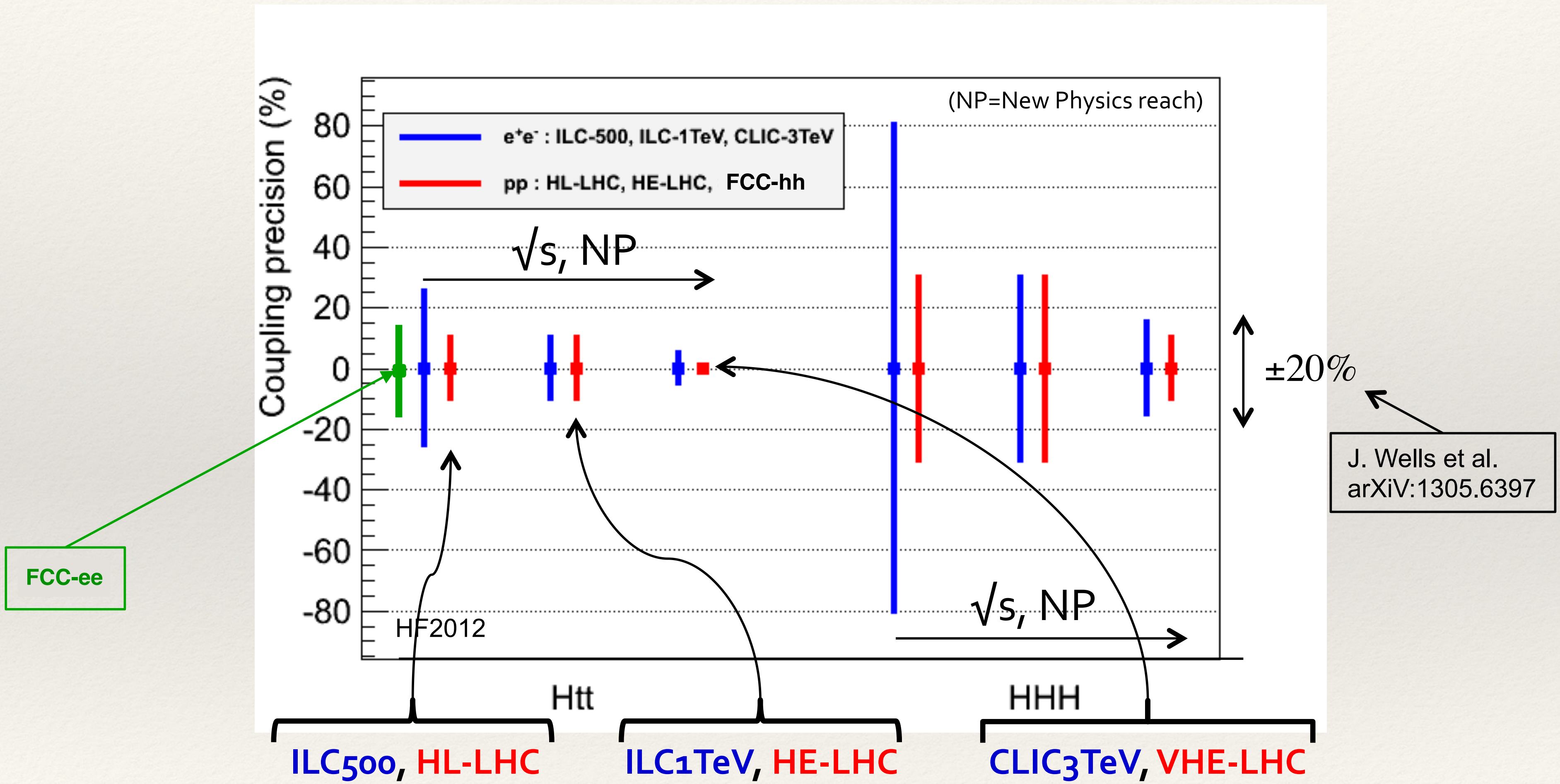
(*) indirect

Precision on Higgs couplings



FCC-hh

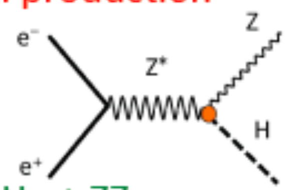
Higgs Physics @100TeV



Indirect determination of the Higgs total width

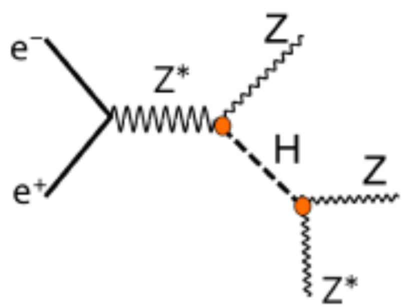
At √s=240 GeV

From the measurement of the total production cross section (slide 10)



$\sigma_{HZ} \propto g_{HZ}^2$

From a counting of HZ events with H → ZZ



Final state with three Zs.
Almost background free

- Measure σ_{HZ} x BR(H → ZZ)

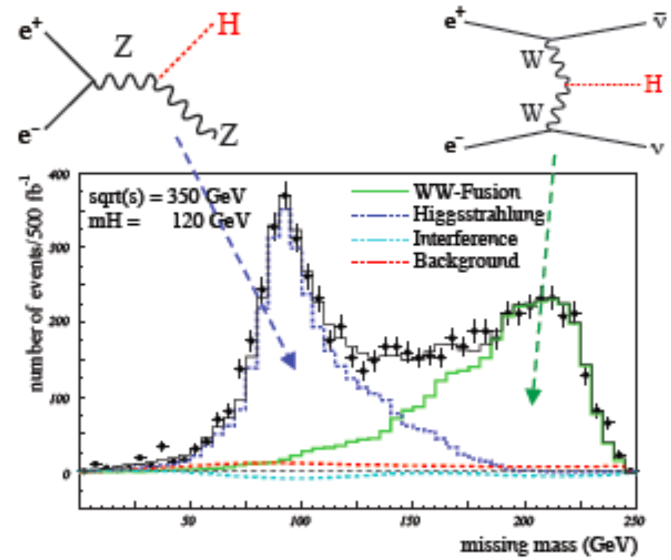
$\sigma_{HZ} \times BR(H \rightarrow ZZ) \propto g_{HZ}^4/\Gamma_H$

Infer Γ_H from combination of two measurements

$\Gamma_H \propto \sigma_{HZ} / BR(H \rightarrow ZZ)$

At √s ≥350 GeV

From counting of WW→H→bb events in bbνν final state



- Measure σ(WW →H→bb)
- Take BRs into WW and bb from 240 GeV run
- Infer the total width

$\Gamma_H \propto \sigma_{W\rightarrow W\rightarrow bb} / BR(H\rightarrow WW) \times BR(H\rightarrow bb)$

Pinning down the Standard Model

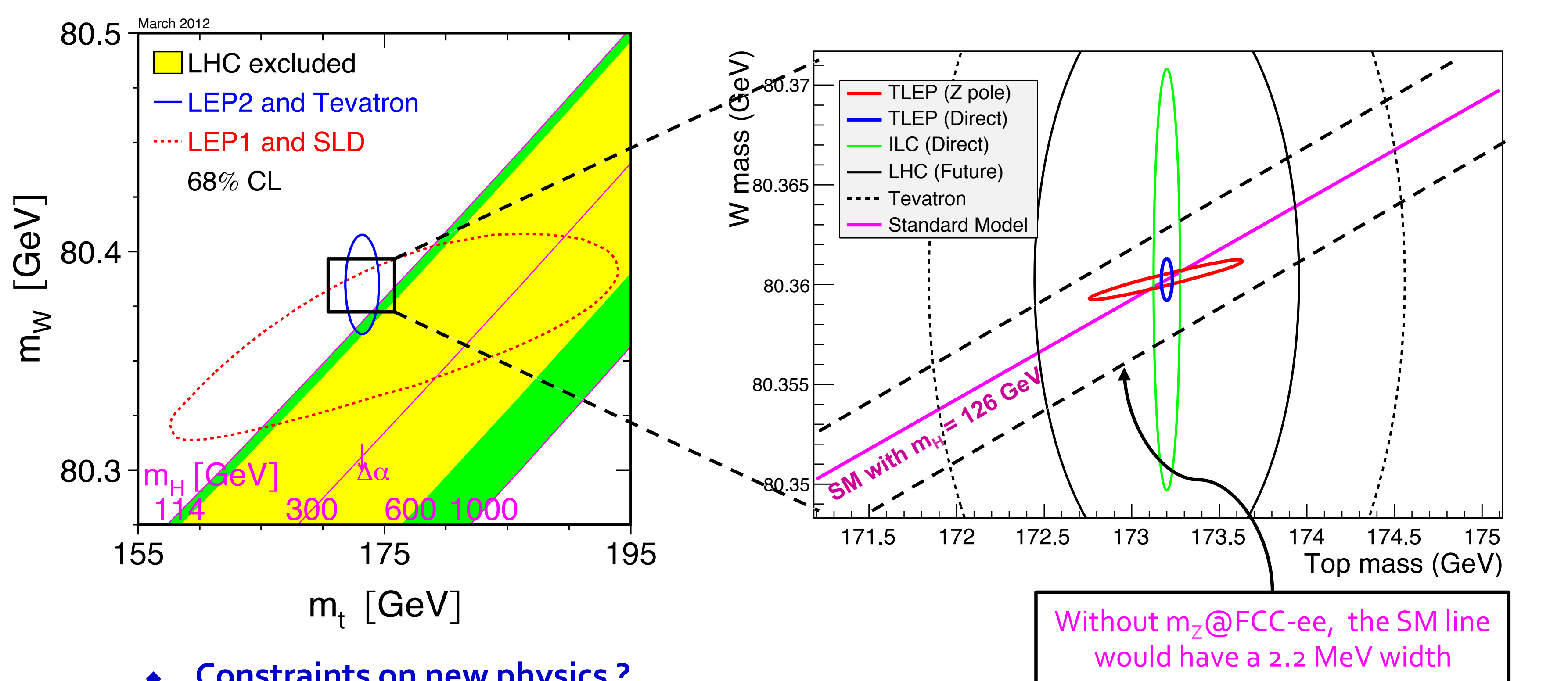
- **EWK fits** have shown their predicting power in the case of the Higgs mass: they could show the presence of new physics effects
  - theory needs to advance as well as the experiments to match the precision expected at the Fcc-ee
  - precision goals to be confirmed by complete studies

Quantity	Physics	Present precision	Measured from	Statistical uncertainty	Systematic uncertainty	Key	Challenge
m_Z (keV)	Input	91187500 ± 2100	Z Line shape scan	5 (6) keV	< 100 keV	E_{beam} calibration	QED corrections
Γ_Z (keV)	$\Delta\rho$ (not $\Delta\alpha_{had}$)	2495200 ± 2300	Z Line shape scan	8 (10) keV	< 100 keV	E_{beam} calibration	QED corrections
R_ℓ	α_s, δ_b	20.767 ± 0.025	Z Peak	0.00010 (12)	< 0.001	Statistics	QED corrections
N_ν	PMNS Unitarity, ...	2.984 ± 0.008	Z Peak	0.00008 (10)	< 0.004		Bhabha scat.
N_ν	... and sterile ν's	2.92 ± 0.05	$Z\gamma$, 161 GeV	0.0010 (12)	< 0.001	Statistics	
R_b	δ_b	0.21629 ± 0.00066	Z Peak	0.000003 (4)	< 0.000060	Statistics, small IP	Hemisphere correlations
A_{LR}	$\Delta\rho, \epsilon_3, \Delta\alpha_{had}$	0.1514 ± 0.0022	Z peak, polarized	0.000015 (18)	< 0.000015	4 bunch scheme, 2exp	Design experiment
m_W (MeV)	$\Delta\rho$, $\epsilon_3, \epsilon_2, \Delta\alpha_{had}$	80385 ± 15	WW threshold scan	0.3 (0.4)MeV	< 0.5 MeV	E_{beam}, Statistics	QED corrections
m_{top} (MeV)	Input	173200 ± 900	$t\bar{t}$ threshold scan	10 (12) MeV	< 10 MeV	Statistics	Theory interpretation

From arXiv:1308.6176

SM after FCC-ee

- In absence of New Physics the m_{top} vs m_W plot would look like this:



- **Constraints on new physics ?**

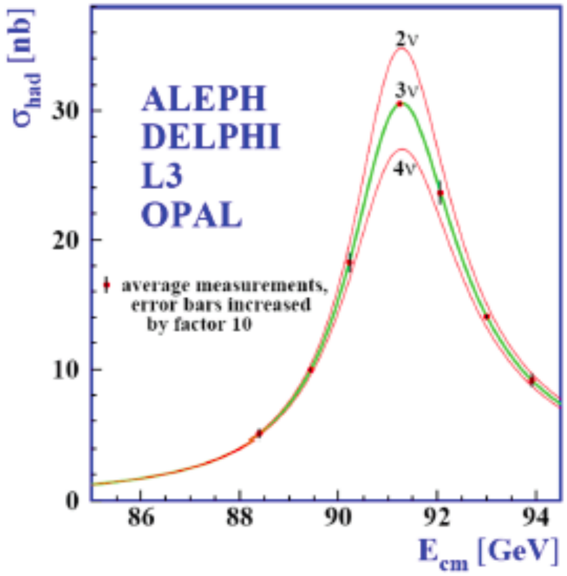
Precision EWK measurements (1)

Tera-Z: The Z line-shape measurement

Z = atomic clock of HEP
Christophe Grojean

- Repeat the LEP1 programme every few minutes
  - Remember, after 5 years at LEP

$$N_\nu = 2.984 \pm 0.008$$
$$\Gamma_Z = 2495.2 \pm 2.3 \text{ MeV}$$
$$m_Z = 91187.5 \pm 2.1 \text{ MeV}$$
$$R_l = 20.767 \pm 0.025$$
$$\alpha_s = 0.1190 \pm 0.0025$$



- Predicting accuracies with 300 times smaller statistical precision than at LEP is difficult
  - Conservatively use LEP experience for systematics
- Example: The uncertainty on E_{beam} (1.5 MeV) was the domninant uncertainty on m_Z, Γ_Z
  - Can we do significantly better at FCC-ee ?

Precision EWK measurements (2)

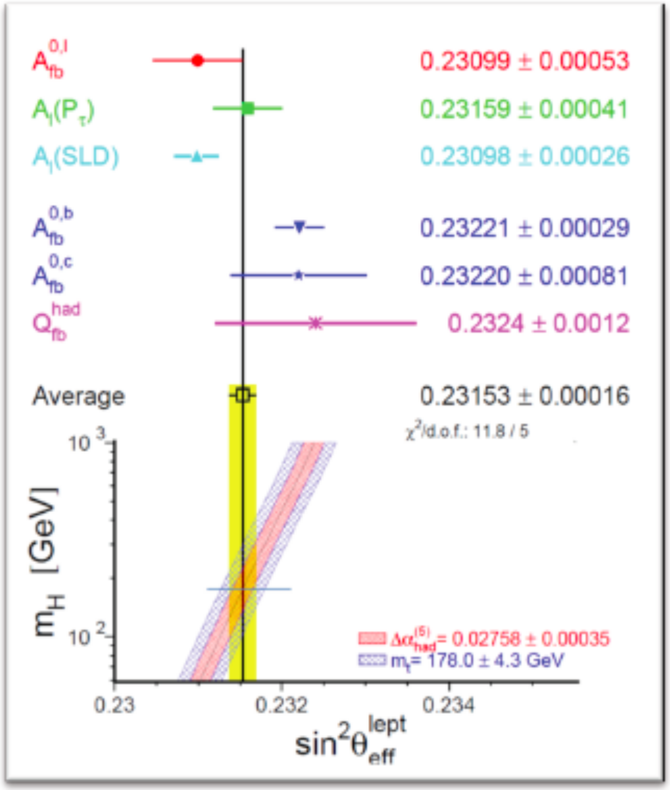
Asymmetries and $\sin^2\theta_W$

- LEP asymmetry measurements dominated by statistics
  - A_{FB}^{ll}, P_τ, A_{FB}^{bb}, A_{FB}^{cc}
- Large precision gain from $O(10^5)$ larger stats.

- Study of $A_{FB}^{\mu\mu}$ alone indicates factor 50 improvement compared to LEP
  - Matching uncertainties from stats. and beam energy syst. (assumed 100 keV)
- Study of $A_{FB}^{0,b}$ alone indicates gain of factor O(10)
- Potential of other asymmetries to be studied
  - e.g. P_τ

- Also, investigate A_{LR} with longitudinally polarized beam option
  - Beam energy calibration influenced by spin rotators?

- Still early days: much interesting work ahead …



Tera-Z: example of target accuracies

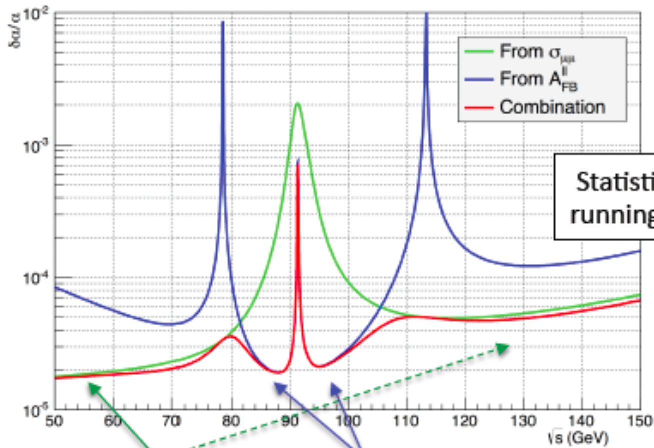
Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	QED corr.
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	g -> bb
N_ν	Peak	2.984 ± 0.008	0.00004	0.004	Lumi meast.
$A_{FB}^{\mu\mu}$	Peak	0.0171 ± 0.0010	0.000004	< 0.00001	E_{beam} meast.
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.000001	0.00015	New Physics
$1/\alpha_{QED}(M_Z)$	$A_{FB}^{\mu\mu}$ around peak	128.952 ± 0.015	0.004	0.002	EW corr.

Experimental uncertainties mostly of systematic origin

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

Direct α(QED) measurement

- Standard method involves extrapolation from $\alpha_{QED}(0)$ to $\alpha_{QED}(M_Z)$.
  - Error dominated by dispersion integral over hadronic xs (low energy res)
- Profit of large statistics: measuring α_{QED} directly close to the Z



Statistical uncertainty for one year of running at any centre-of-mass energy.

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

From $A_{FB}^{\mu\mu}$ measurement
- Sensitivity best at points √s = 87.9 and 94.3 GeV
- Theoretical systs. largely cancel by "averaging" over 87.9 and 94.3 GeV points.
  - Higher order EW to be calculated (few x 10^{-4})
- Experimental systs. controlable; dominant contribution from knowledge of E_{BEAM}: **1 x 10^{-5}**

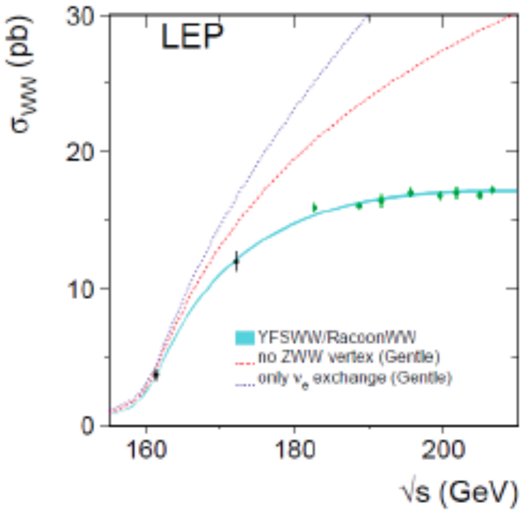
By running six months at each of 87.9 and 94.3 GeV points:
➢ Potential to reach a precision of : **$\delta\alpha/\alpha$ = 3 x 10^{-5}**

P. Janot

Oku-W physics program

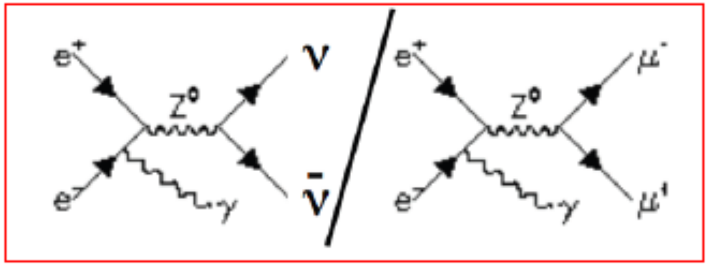
Oku-W: 10^8 WW events at production threshold

Measurement of the W mass with cross section at threshold



Measurement of the number of neutrinos (with single photon events)

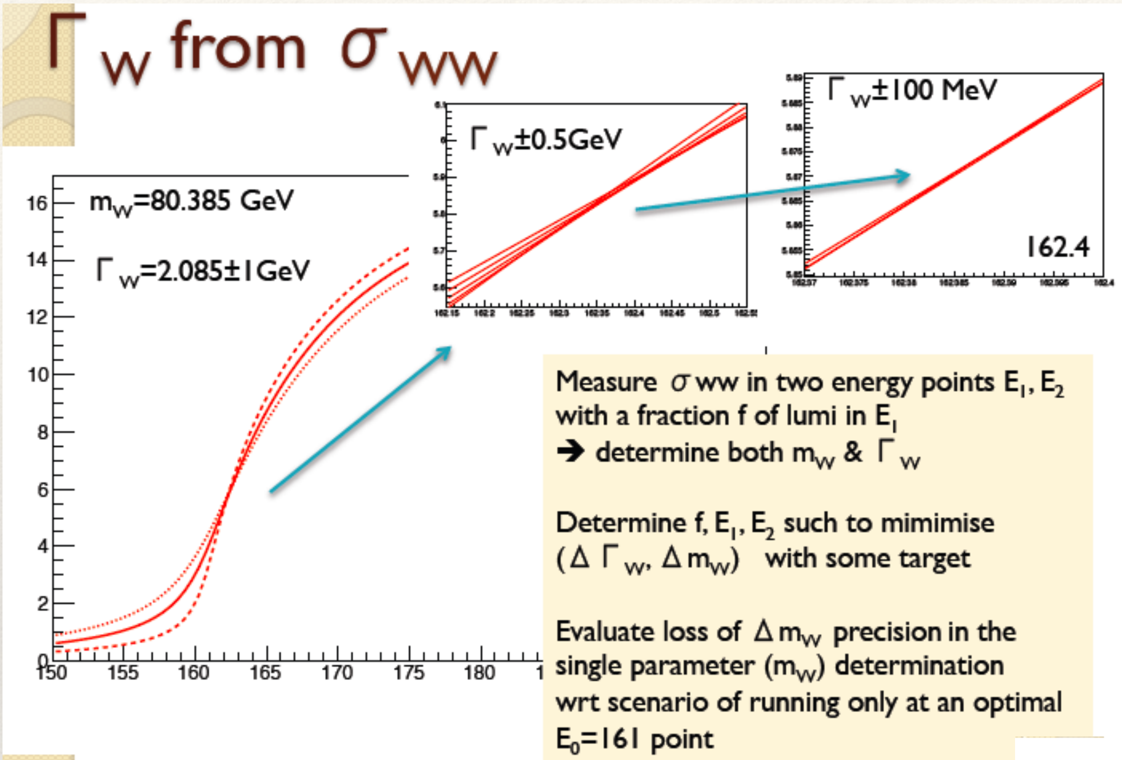
$N_\nu \sim \sigma(e^+e^- \to \nu\bar{\nu}\gamma) / 2\sigma(e^+e^- \to \mu^+\mu^-\gamma)$



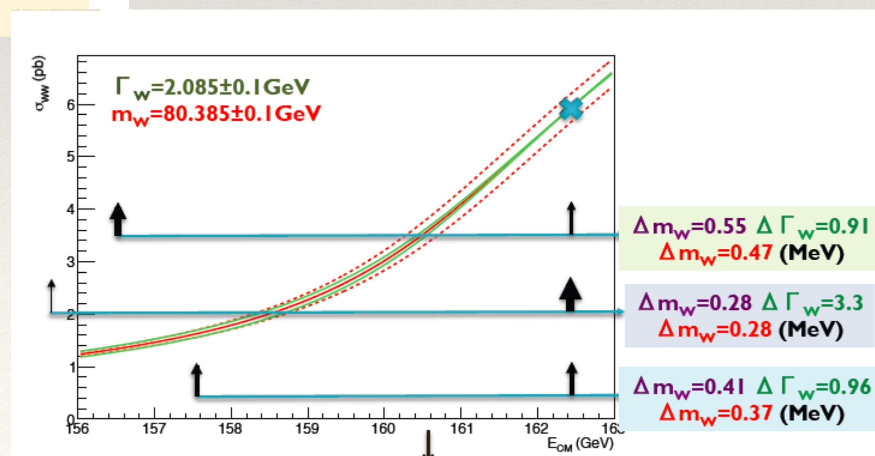
m_W to < 500 keV!

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	QED Corr.
N_ν	Radiative returns $e^+e^- \to \gamma Z, Z\nu\nu, ll$	2.92 ± 0.05 2.984 ± 0.008	0.001	< 0.001	?
$\alpha_s(m_W)$	$B_{had} = (\Gamma_{had}/\Gamma_{tot})_W$	B_{had} = 67.41 ± 0.27	0.00018	< 0.00015	CKM Matrix

m_W and Γ_W from threshold scan

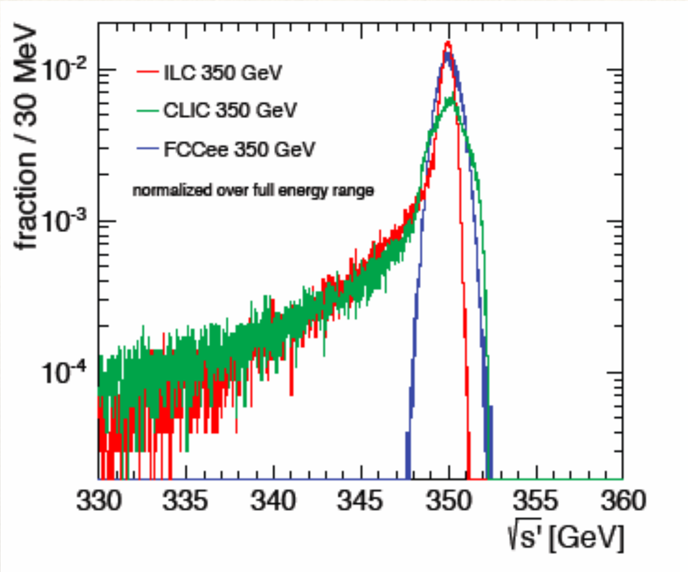


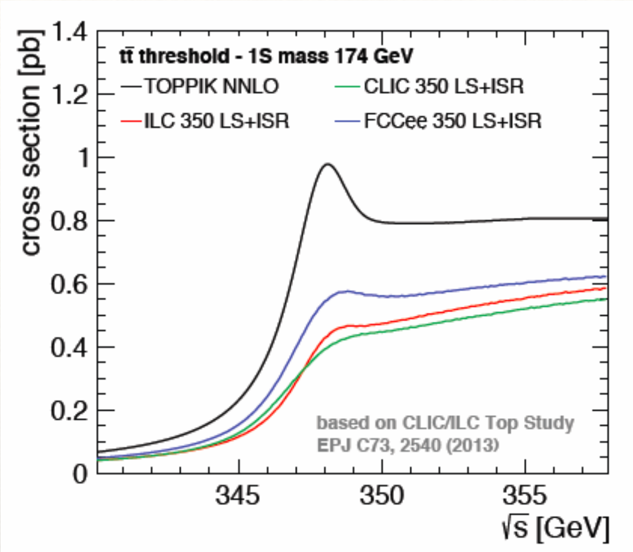
The interest in the σ_{WW} (E) lineshape could go beyond m_W and Γ_W

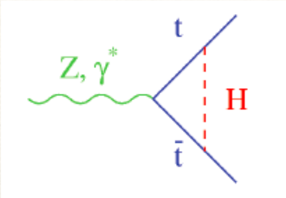


P. Azzurri

Precision top physics: mass







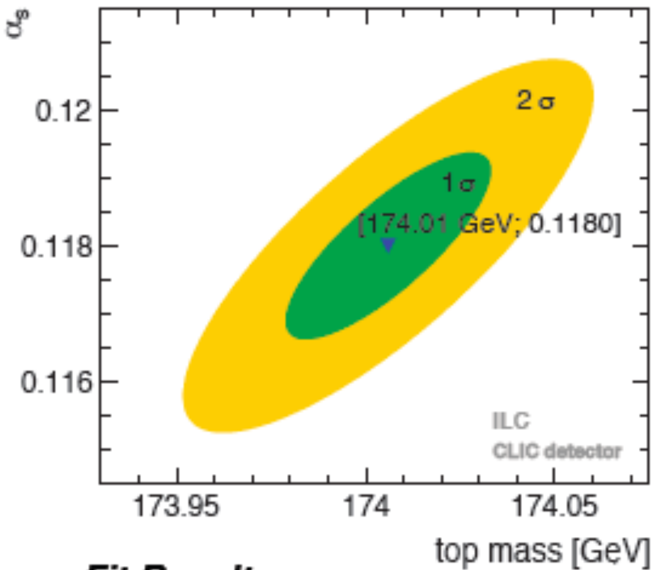
λ_{top} ~13% with indirect extraction from threshold scan.

To improve need higher energy or FCC-hh.

- Different luminosity spectra in different machines: no beamstrahlung tail for FCC-ee.
- Expected 1M top pairs produced

Observable	Measurement	Current precision	FCC-ee stat.	Possible syst.	Challenge
m_{top} (MeV)	Threshold scan	173200 ± 900	10	10	QCD (~40 MeV)
Γ_{top} (MeV)	Threshold scan	?	12	?	$\alpha_s(m_Z)$
λ_{top}	Threshold scan	m = 2.5 ± 1.05	13%	?	$\alpha_s(m_Z)$

1D fit with external input



- Additional possibilities:
  - With high precision external α_s the Top Yukawa coupling can be measured with ~ 7% (stat) precision
  - The top width can also be included in the fit - uncertainties (stat) ~ 30 MeV

arXiv:1310.0563

Fit Results

[MeV]	Δm	theory 1%/3%	Δα	theory 1%/3%
ILC - 2D Fit	27	5/9	0.0008	0.0009/0.0022
CLIC - 2D Fit	34	5/8	0.0009	0.0008/0.0022

[MeV]	Δm	theory 1%/3%	α_s
ILC - 1D Fit	**18**	18/55	21
CLIC - 1D Fit	22	18/56	20

EPJ C73, 2540 (2013)

Contribute from $\Delta\alpha_s$ of ~30MeV per 0.0007
In situ $\Delta\alpha_s$~0.0002 might reduce this by x3!

Perspectives for Top Physics at (I)LC
TOP2014, Cannes, October 2014

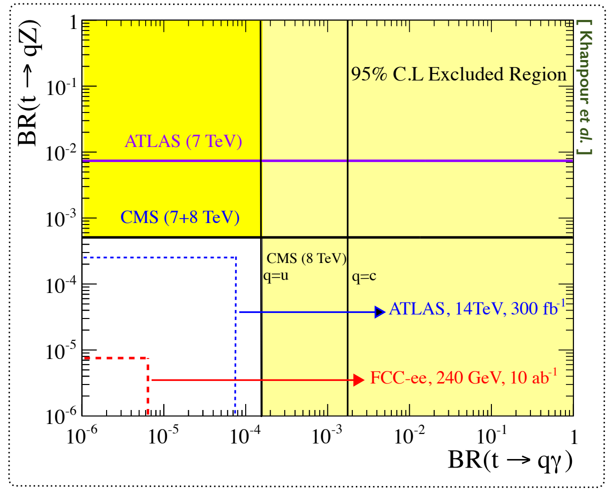
F. Simon

Precision top physics: FCNC & Rare-decays

- **rare decays and FCNC** are a real gold mine (i.e. t->Zq, γq, Zc). The improvements come from:
  - large statistic at 350GeV in pair production
  - can profit of single top production at 240 GeV
  - clean final states

✦ FCNC production of a top and a light quark

✤ At a center-of-mass energy of 240 GeV



✤ Gain of 1.5 order of magnitude w.r.t. LHC

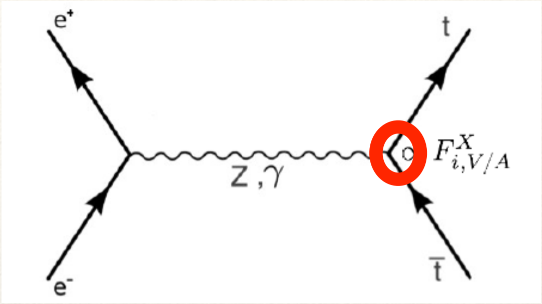
expectations from theory

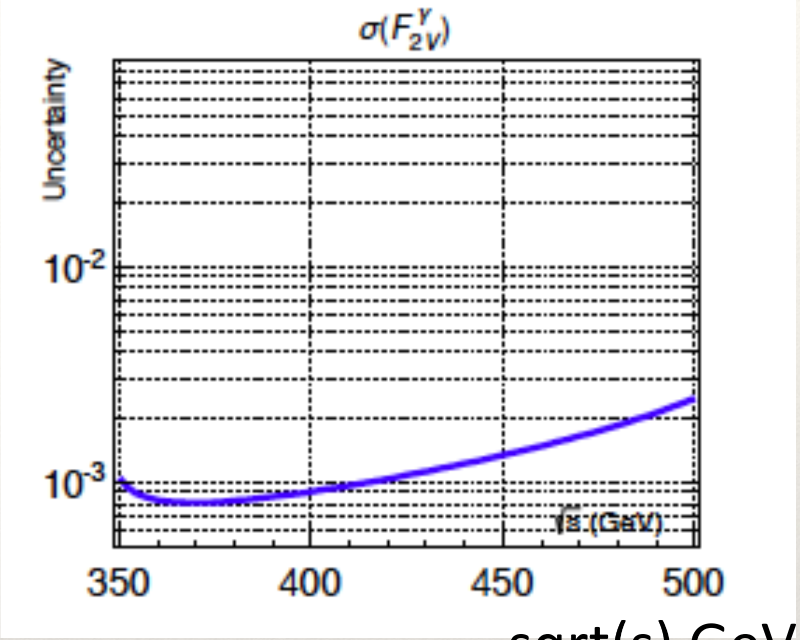
Process	SM	2HDM(FV)	2HDM(FC)	MSSM	RPV	RS
$t \to Zu$	7×10^{-17}	–	–	$\le 10^{-7}$	$\le 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\le 10^{-6}$	$\le 10^{-10}$	$\le 10^{-7}$	$\le 10^{-6}$	$\le 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\le 10^{-7}$	$\le 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\le 10^{-4}$	$\le 10^{-8}$	$\le 10^{-7}$	$\le 10^{-6}$	$\le 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\le 10^{-8}$	$\le 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\le 10^{-7}$	$\le 10^{-9}$	$\le 10^{-8}$	$\le 10^{-9}$	$\le 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\le 10^{-5}$	$\le 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\le 10^{-5}$	$\le 10^{-5}$	$\le 10^{-9}$	$\le 10^{-4}$

New studies ongoing for the l+jets and all-hadronic channel

P. /

Top Electroweak Couplings





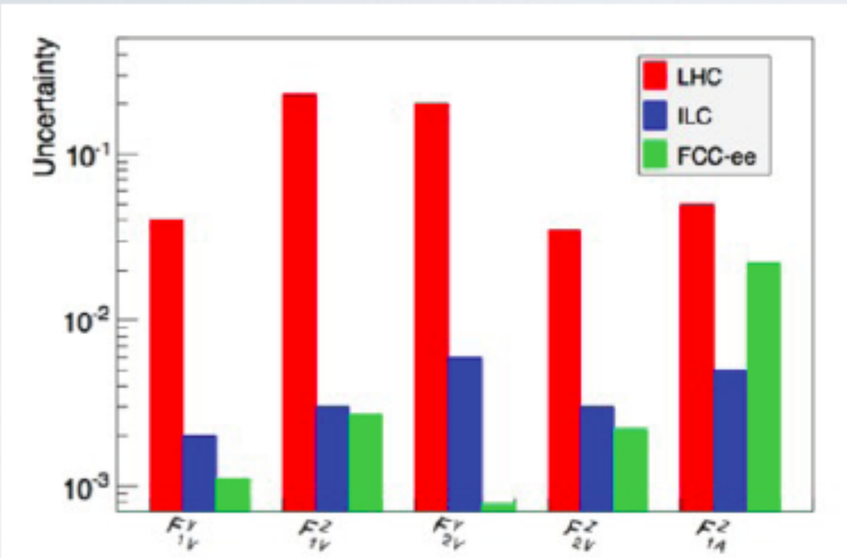
sqrt(s) GeV

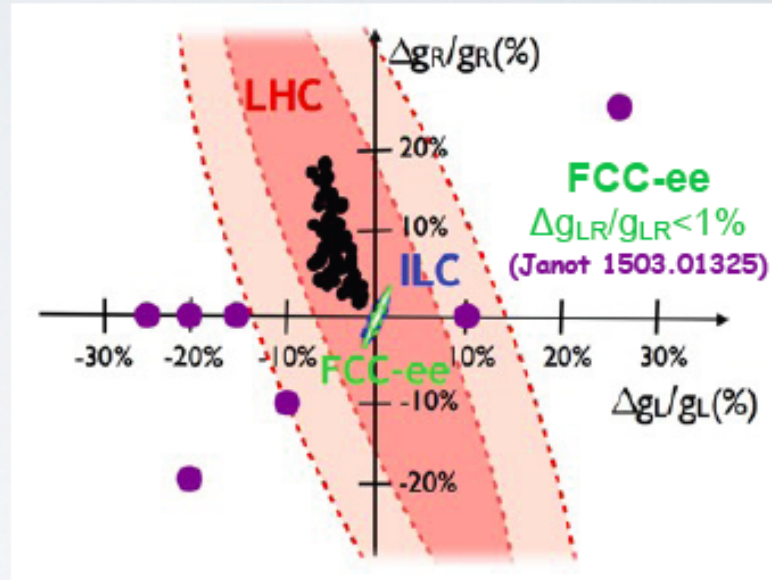
- Access the separate components from the ttZ and ttγ couplings and possible anomalous contributions from the top decay properties.
- Top polarization information is maximally transferred to its final state via the weak decay
  - **the lack of beam polarization is compensated by the final state polarization and by the larger statistics (1.6M top in 3 years)**
- Some optimal observable can be defined. In the case of tt->l+jets: the lepton polar angle and its reduced energy.
- main systematics comes from predicted event rate

- target precision at the per-mil level
- no need for high energy runs, far above the threshold (√s=365 optimal)

New Physics behind precision

Accuracy on Top Couplings



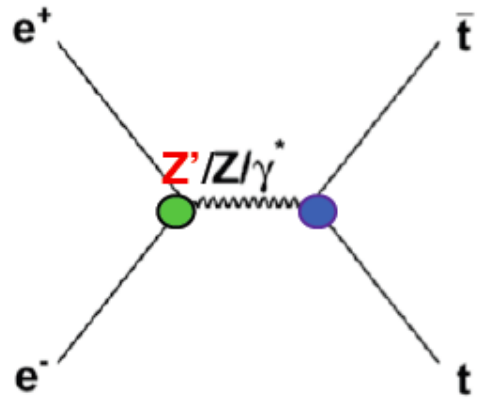


LHC (14 TeV, 300 fb^{-1})
ILC(500GeV, 500 fb^{-1}) with polarized beams
(ILC-TDR 1306.6352; Amjad et al. 1505.06020)
FCC-ee (360GeV, 2.6 ab^{-1}) from lepton angular and energy distributions
(Janot 1503.01325)

continuous(dashed): from angular and energy distributions of leptons (b-quarks)
(Janot, EPS HEP 2015, WhatNext White paper of CSN1)

total x-section predicted with a 2% precision
warning: large QCD corr. near threshold , possible underestimation of x-section error

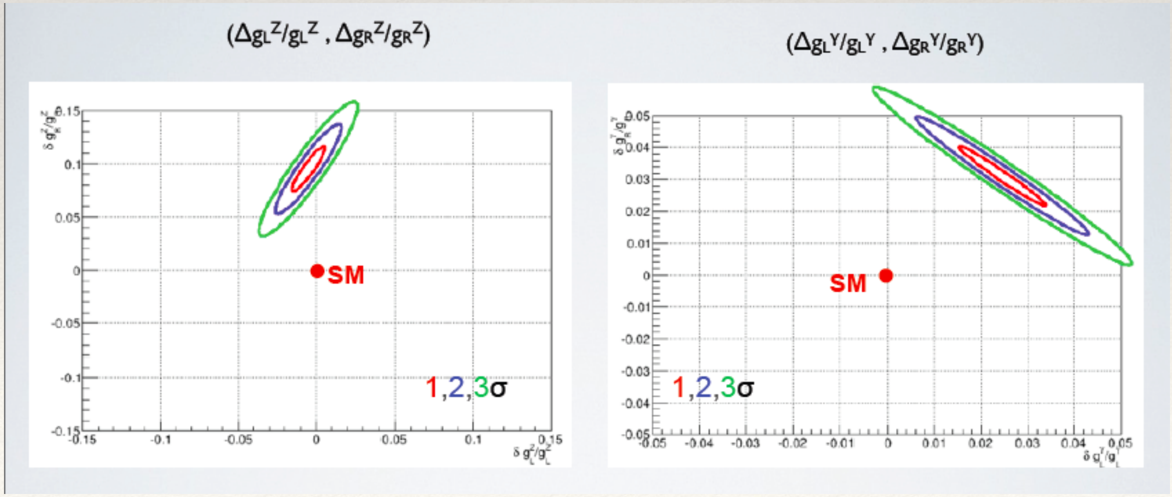
BSM potential: Composite Higgs model



The CHM modifications of the process arise via 3 effects:

- ☑ modification of the Zee coupling (negligible)
- ☑ modification of the Ztt coupling from: mixing between top and extra fermions (partial compositeness), mixing between Z and Z's
- ☑ the s-channel exchange of the new Z's (interference) - commonly neglected BUT can be very important also for large $M_{Z'}$

$e^+e^- \rightarrow$ tt production is one of the most prominent 6f process, **strong sensitivity also to new particles.** Asymmetries O(1)



S. De Curtis, S. Moretti

New physics searches with Tera-Z

Opportunities for direct searches for **new physics** through **rare decays**

- **10^{12} (10^{13}) Z, 10^{11} b, c or τ** : A fantastic potential that remains to be explored
- e.g. search for heavy "sterile" neutrino in Z decays

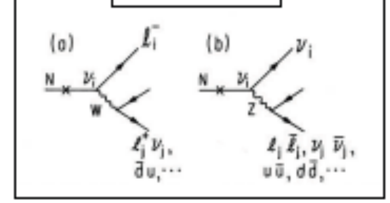
$$\nu_L = \nu \cos\theta + N \sin\theta$$

Light "normal" neutrino

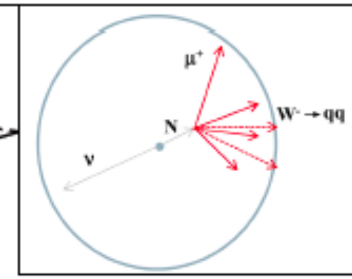
Heavy "sterile" neutrino

$Z \rightarrow N \nu_i$, with $N \rightarrow W^* l$ or $Z^* \nu_j$

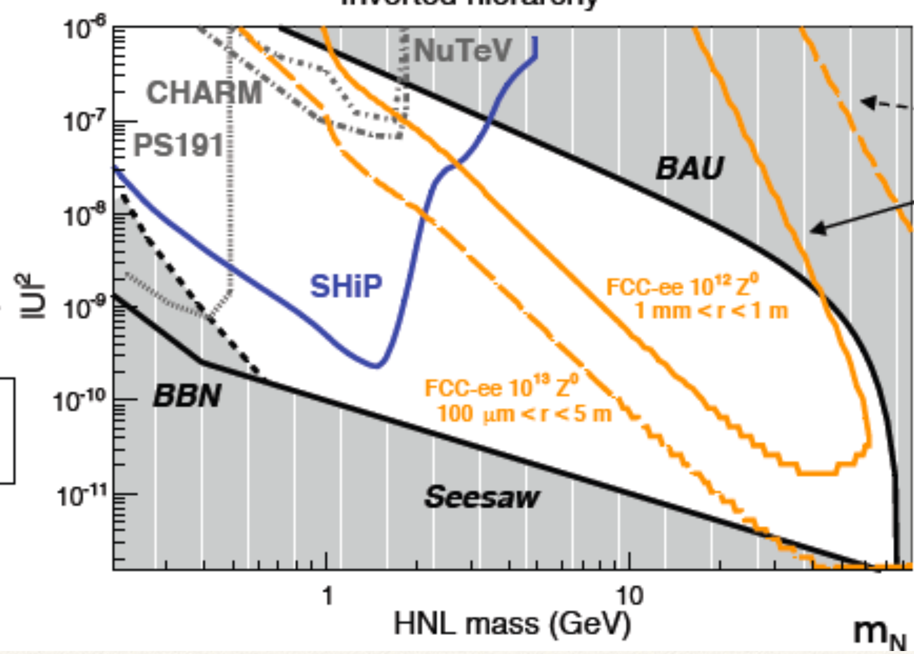
N decays



Signature: Detached vertex

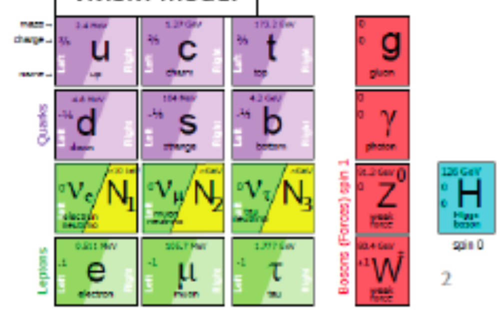


Inverted hierarchy



Mixing between N and ν

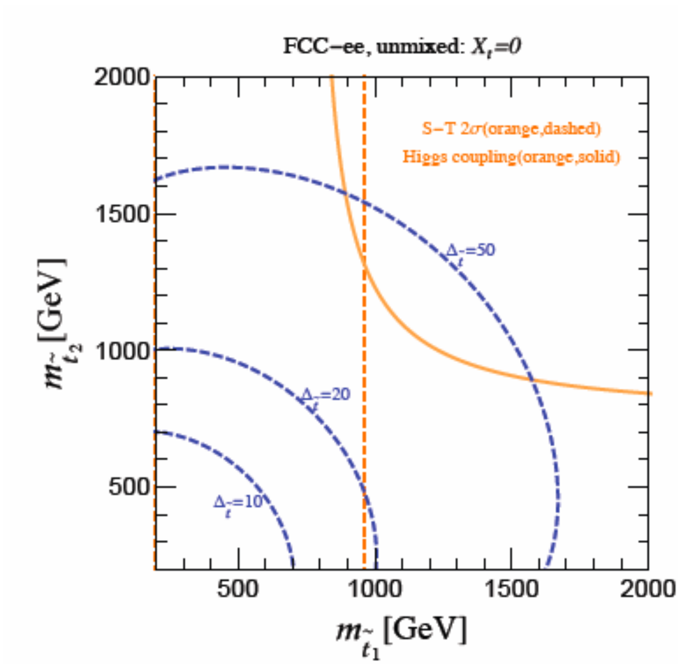
νMSM model

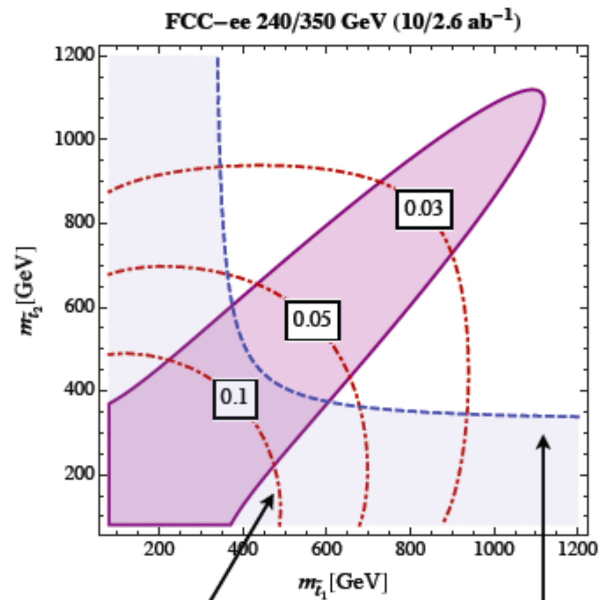


SUSY tests: from EWK & Higgs precision

Color naturalness & FCC-ee

Fan, Reece, Wang '14





Can exclude the 10% fine-tuned region and significantly constrain the 5% fine-tuned region

EW precision and Higgs data probe TeV-stops

Indirect BSM constraints: EFT fits

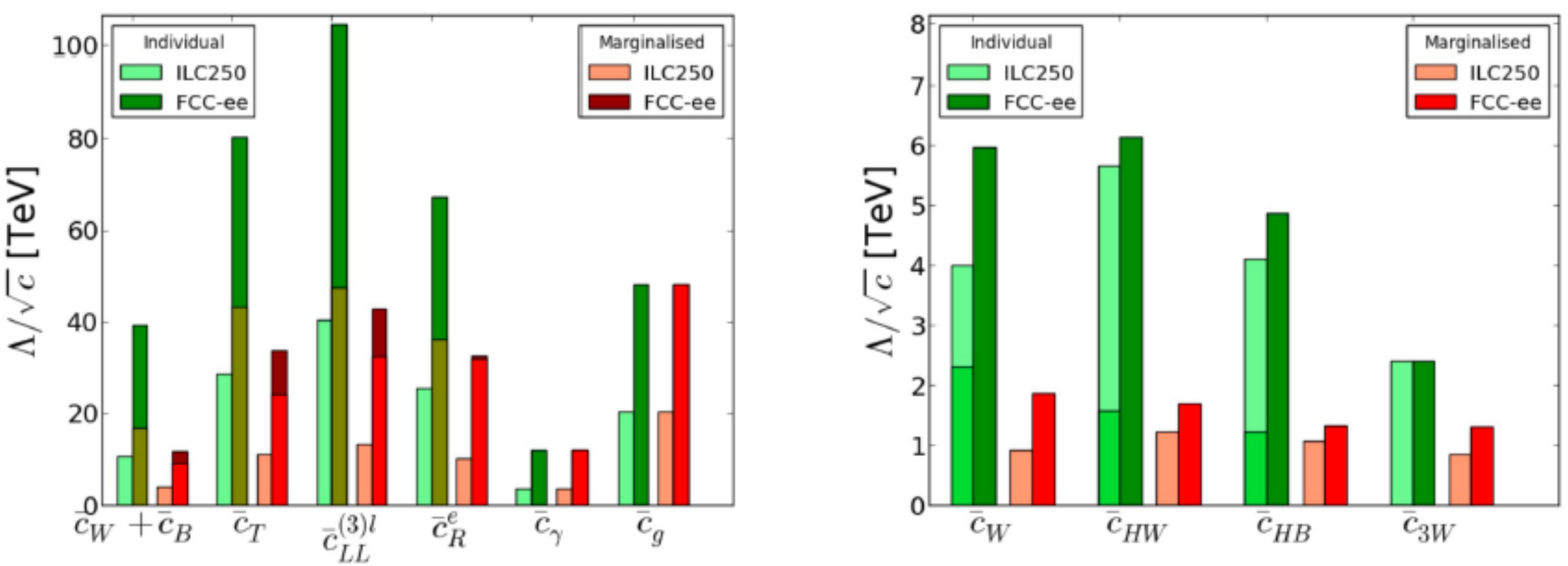


Figure 9: *Summary of the reaches for the dimension-6 operator coefficients with TeV scale sensitivity, when switched on individually (green) and when marginalised (red), from projected precision measurements at the ILC250 (lighter shades) and FCC-ee (darker shades). The left plot shows the operators that are most strongly constrained by EWPTs and Higgs physics, where the different shades of dark green and dark red represent the effects of EWPT theoretical uncertainties at FCC-ee. The right plot is constrained by Higgs physics and TGCs, and the different shades of light green demonstrate the improved sensitivity when TGCs are added at ILC250.*

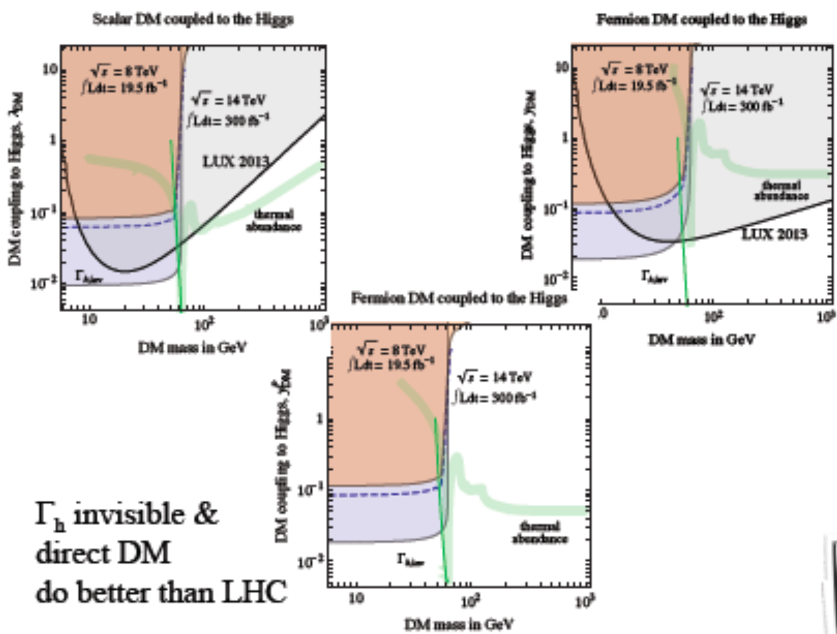
Ellis & You '15

DM potential at FCC-ee

- In traditional WIMP models, DM carries SM(weak) charges
- Other models where FCC-ee can be particularly relevant: SM neutral DM+light mediators (could be the Higgs itself)

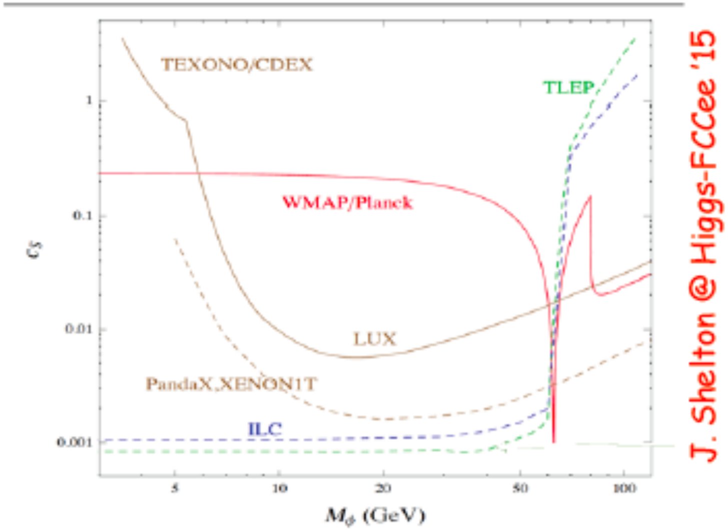
Higgs portal: $\mathcal{L} = -hJ_h\,, \quad J_h = \frac{1}{\sqrt{2}}\left[\sum_f y_f \bar{f} f + \bar{\psi}_{\rm DM}(y_{\rm DM} + i y^P_{\rm DM}\gamma_5)\psi_{\rm DM} + \frac{\lambda_{\rm DM} v}{2} s^2_{\rm DM}\right]$ y, y^P, λ arbitrary couplings

current LHC bounds



Γ_h invisible & direct DM do better than LHC

future bounds



Γ_Z and Γ_h invisible are the most efficient way to explore SM-mediated DM at colliders

P. A

De Simone, Giudice, Strumia '14

FCC-ee Study group organization

- Physics studies: A. Blondel, P. Janot (Exp); J. Ellis, C. Grojean (Th)
  - Study the properties of the Higgs and other particles with unprecedented precision

EW Physics (Z pole)
R. Tenchini, F. Piccinini
S. Heinmeyer, A. Freitas

Diboson physics, m_W
R. Tenchini, F. Piccinini
S. Heinmeyer, A. Freitas

Higgs Properties
M. Klute, K. Peters
S. Heinmeyer, A. Freitas

Top Quark Physics
P. Azzi, F. Blekman
S. Heinmeyer, A. Freitas

QCD and $\gamma\gamma$ Physics
D. d'Enterria
P.Skands

Flavour Physics
S. Monteil
J. Kamenik

New Physics
M. Pierini, C. Rogan
M. McCullough

- Develop the necessary tools — Understand the experimental conditions

Offline Software
C. Bernet, B. Hegner
C. Helsens

Online
C. Leonidopoulos,
E. Perez

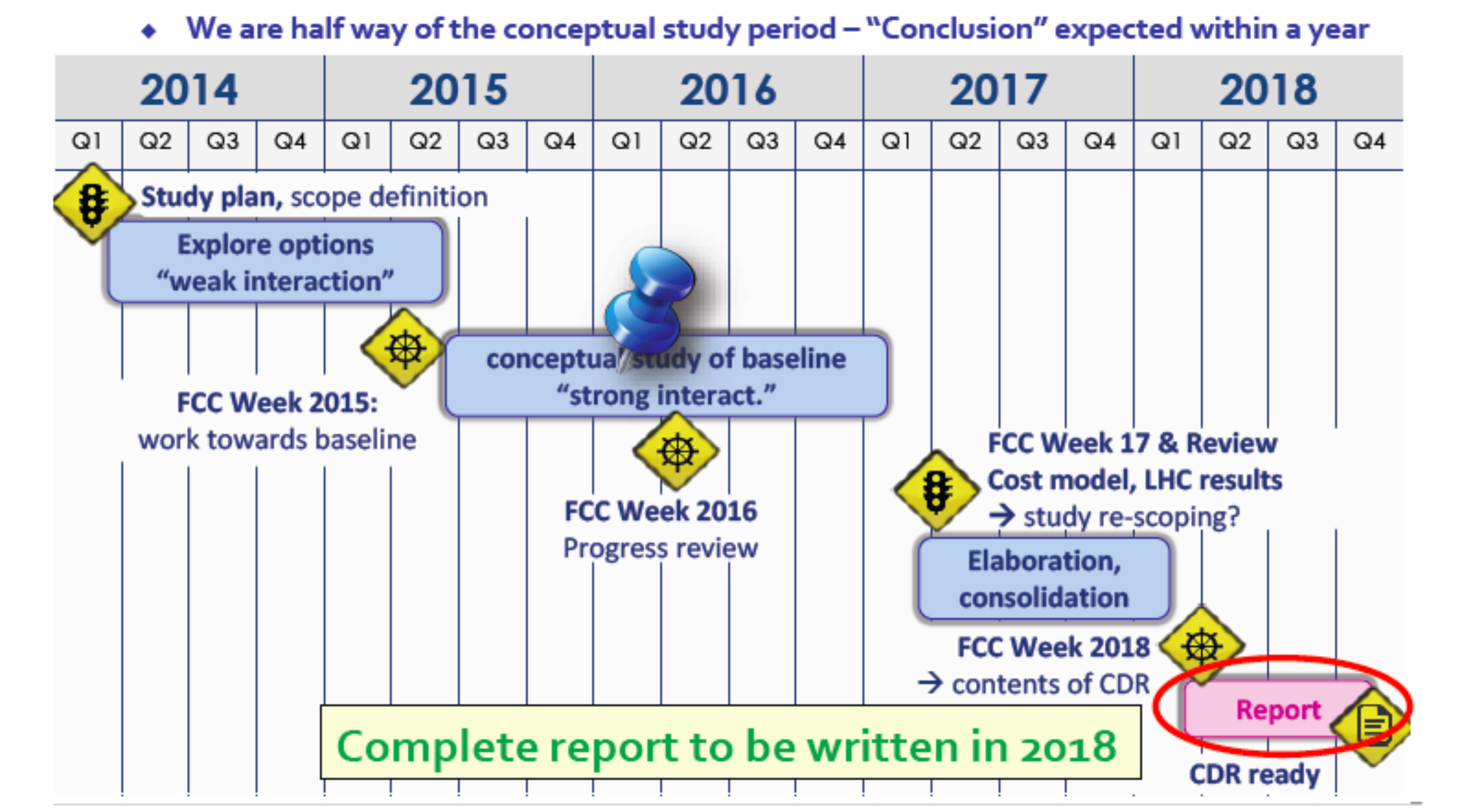
MDI
N. Bacchetta,
M. Boscolo

- Set constraints on the possible detector designs to match statistical precision

Detector Designs
A. Cattai, M. Dam,
G. Rolandi

FCC-ee studies time line

- **FCC-ee studies are part of the FCC design study time-line**
  - now half-way through the conceptual design period. « Conclusion » expected within a year.



Conclusions

- The physics potential of the FCC project, in its complete form, allows:
  - *unprecedented precision measurements* at very large integrated luminosity and a clean environment with FCC-ee
  - *unprecedented reach* for precision on rare and (hopefully) new processes at higher energy with FCC-hh
  - If no new physics is found in Run2 of the LHC this program would allow to push further the boundaries of our knowledge
- To achieve this immense physics program there are extreme accelerator, detector, reconstruction and theory challenges to be studied and overcome in the next 30 years.
  - *a quite active and enthusiast community. Lots of new developments in the last year. Need to keep the momentum!*

FCC Week 2016

Rome, 11-15 April 2016

http://cern.ch/fccw2016

REGISTER HERE TO FOLLOW FCC-ee ACTIVITIES

https://cern.ch/fcc-ee

IEEE CSC Council on Superconductivity

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CERN

Reminder FCC-ee physics program

See arXiv:1308.6176, "First Look at the Physics Case of TLEP"
FCC-ee physics meetings, https://indico.cern.ch/cetegory/5259/

A very rich physics menu!

- Core physics programme
  - The Z pole scan, $\sqrt{s}$=88-95 GeV
    - m_Z, Γ_Z to < 100 keV, $\sin^2\theta_W$ to 5×10^{-6}, $\alpha_{QED}(m_Z)$ to 2×10^{-5}, $\alpha_s(m_Z)$ to 2×10^{-4}, …
    - Rare decays/process searches and flavour physics with up to 10^{13} Z decays
  - The WW threshold scan, $\sqrt{s}$=160-165 GeV
    - m_W to 300 keV, $\alpha_s(m_Z)$ to 2×10^{-4}, …
  - The Higgs factory, $\sqrt{s}$=240 GeV and above
    - Improve HL-LHC precision on Higgs couplings by an order of magnitude
    - Measure the Higgs width to better to 1%, and BR_{invis} to 0.1%
  - The top threshold scan, $\sqrt{s}$=340-350 GeV
    - m_{top} to 10-20 MeV
  - Set constraints on new physics scale to 100 (10) TeV if weakly (Higgs) coupled
    - Possibly discover very-weakly-coupled new physics through rare processes

Well matched to FCC-hh discovery range

- And also…
  - Top electroweak couplings at $\sqrt{s}$=365-370 GeV (as part of the top threshold scan)
  - The Hee coupling at $\sqrt{s}$=120 GeV
  - The highest centre-of-mass energy $\sqrt{s}$=500 GeV (physics case?)

Run plan (in preparation)

- We are preparing a written document for the FCC-ee run plan
  - With the target luminosities and 4 IPs, the run plan is as follows
    - Number of events expected per year of running

$\sqrt{s}$ (GeV)	90 (Z)	160 (WW)	240 (Higgs)	350 (tt)	365 top EW couplings
Lumi (ab^{-1}/yr)	86.0	15.2	3.5	1.0	1.0
Events/year	3.7×10^{12}	6.1×10^{7}	7.0×10^{5}	4.2×10^{5}	2×10^{6}

    - Number of years needed to finish the program

1 year = 10^7 s

# years	2.5	1	3	0.5	3

    - The FCC-ee core programme can be finished in about 10 years
      - m_Z to 100 keV, α_{QED} to 3×10^{-5}, α_S to 0.0001, $\sin^2\theta_W$ to 6×10^{-4}
      - m_W to 0.5 MeV
      - Higgs couplings/width to sub per cent, top EW couplings to per cent
      - ...
  - These precisions (i.e., these luminosities) are needed for the new physics sensitivity
    - The conservative baseline parameters are a first giant step on this way.

Detector Requirements

The FCC-ee physics programme is very broad.
With multiple IPs (up to 4) there is room for different design emphasis.
One could think of at least two major options:

- **Precision physics** & **new physics searches**

Higgs Precision Physics

Excellent energy/momentum resolution for e, μ, jet

- Z tagging via μμ, ee
- Possibility to use Z → qq tag for for several h final states (h → invisible)
- Rare Higgs decay modes: μμ, γγ, ZZ, invisible

Excellent flavour tagging:

- Separation of Higgs to bb, cc, gg

M. Dams et al.

EW Precision Physics

Extremely precise definition of **fiducial volumes** for signal and normalization.
This includes

- geometry: precise borders, no cracks
- momentum/energy: no bias

New Physics Searches

Detached vertices over a large lifetime range

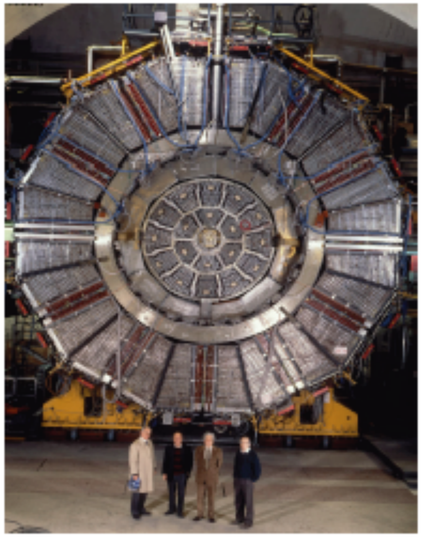
- Large radius tracking volume
- Excellent primary/secondary vertex resolution and flavour tagging

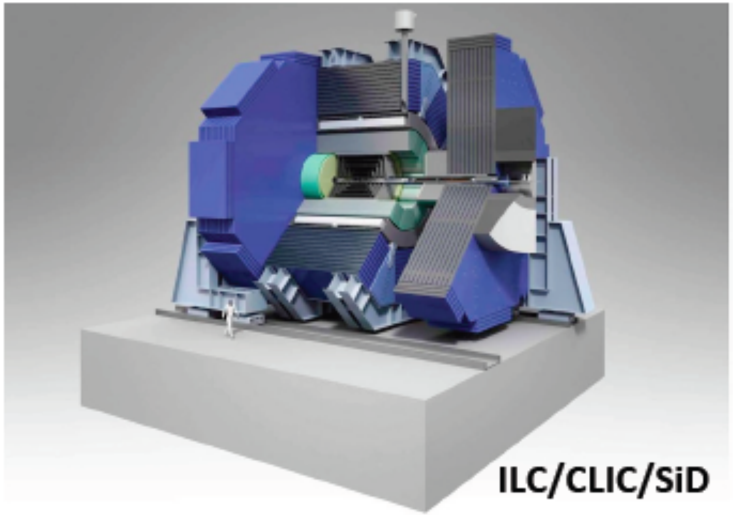
No escaping particles: Hermiticity

Detectors for FCC-ee

We know today how to build a detector for e^+e^- precision physics

- Experience with LEP detectors and 20-years R&D with ILC/CLIC detectors





Detectors must have the ability to collect 100 kHz of Z decays, with 100% efficiency

… and be able to repeat the whole LEP1 programme in about two minutes.

Inspiration should come from LHC detector upgrades and DAQ systems.

Physics differences between linear collider and FCC-ee case

- Lower maximum energy – 400 vs. 1000 GeV
  - Momentum resolution, energy resolution, calorimeter depth
- Higher statistics: matching systematics – have to under acceptance to better than $1/\sqrt{N}$

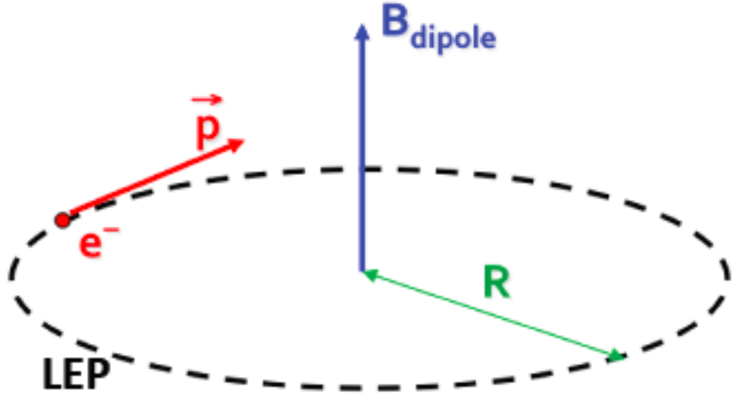
Technical differences between linear collider and FCC-ee case

- Extremely high physics rate – 100 kHz Zs: DAQ
- Continuous running (no bunching of beams): cooling issues
- Machine Detector Interface

Measurement of the beam energy at LEP

- **Ultra-precise measurement unique to circular colliders (crucial for m_Z, Γ_Z)**

Electron with momentum **p** in uniform vertical magnetic fiend **B**



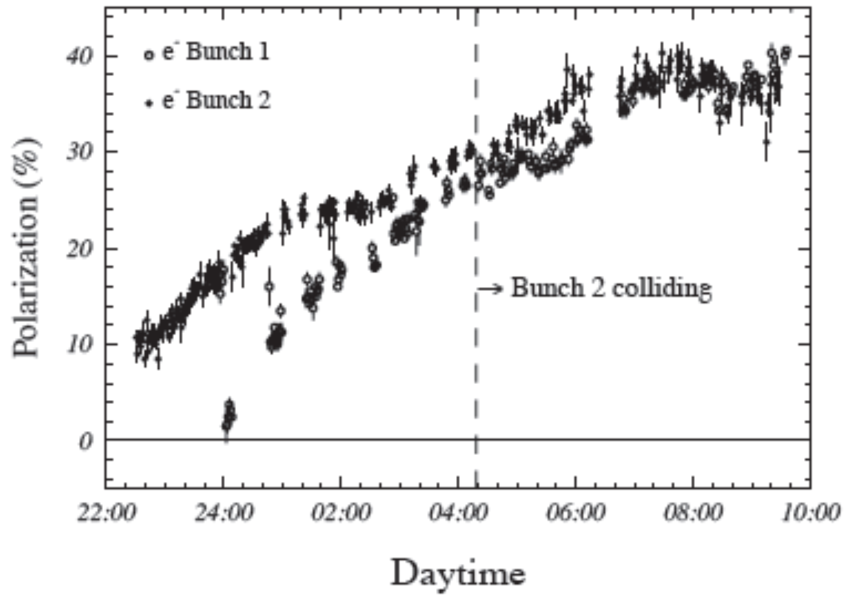
$E \simeq p = eBR = (e/2\pi)\, BL$

In real life, B non-uniform, LEP ring not circular

$$E = \frac{e}{2\pi} \oint_{\text{LEP}} B\,\mathrm{d}l$$

To be measured

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



Slow process (~1 hour to get 10% polarization)

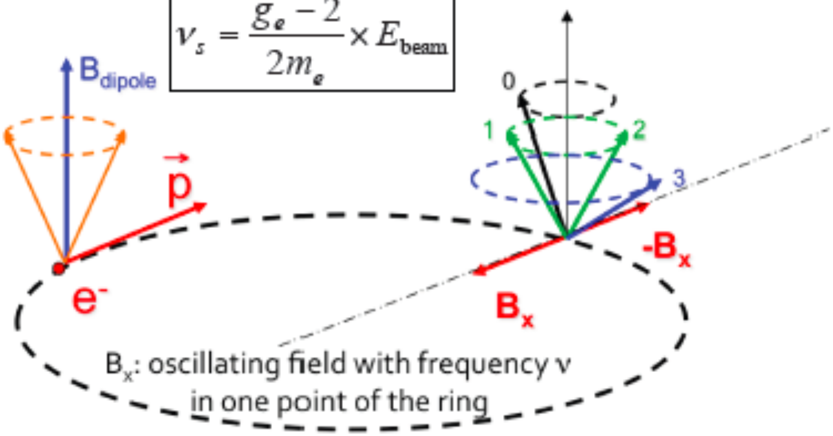
NB. Polarization can be maintained in collisions (was tried only once at LEP)

Precision electroweak physics at FCC-ee (3)

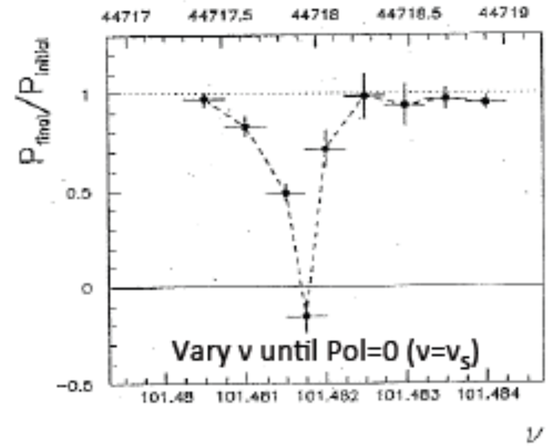
Measurement of the beam energy at LEP (cont'd)

- **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 $\oint$ BdL)

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



Resonant depolarization



Intrinsic precision of the method: ΔE_{beam} < 100 keV !

- **However, m_Z and Γ_Z measured at LEP with a precision of 2.2 MeV**
  - Extrapolation uncertainty from measurement performed w/o collisions

Measurement of the beam energy at FCC-ee

- **LEP was colliding 4 bunches of e^+ and e^-; FCC-ee will have 10.000's of bunches.**
- **Use ~100 "single" bunches to measure E_{beam} with resonant depolarization**
  - Measure E_{beam} directly in physics runs
  - Each measurement gives 100 keV precision; no extrapolation uncertainty

m_Z to < 100 keV

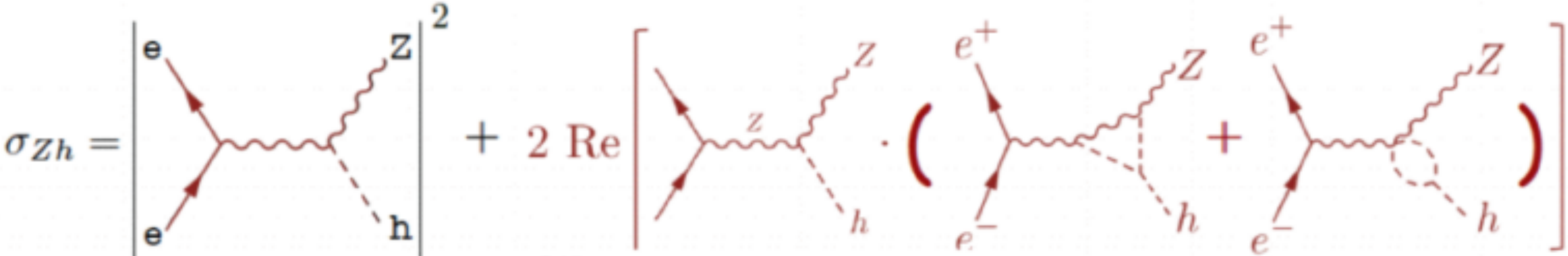
FCC-ee

Expected deviations from benchmark models

- if new physics scale at 1TeV

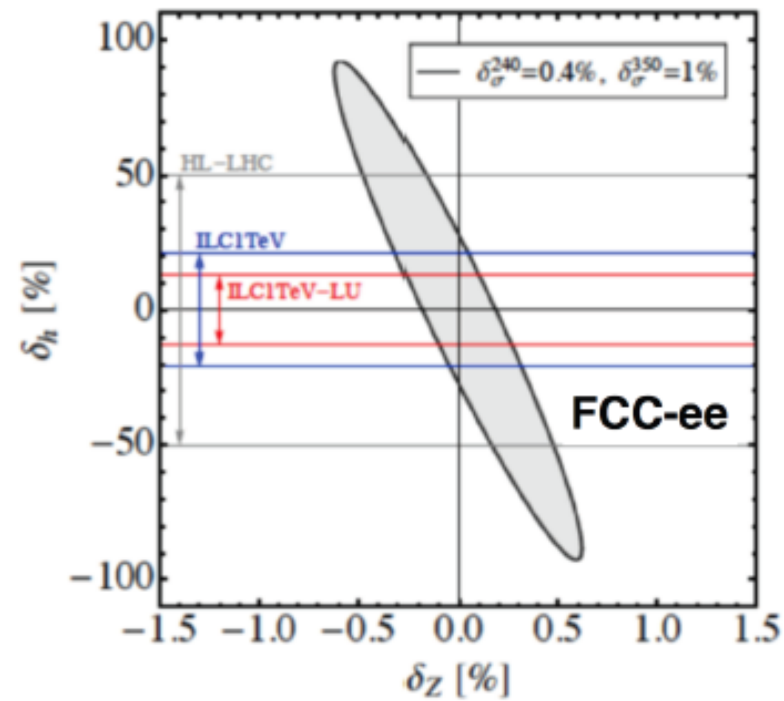
	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Higgs self-coupling through loop corrections



$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- Very large datasets at high energy allow extreme precision g_{ZH} measurements
- Indirect and model-dependent probe of Higgs self-coupling
- Note, the time axis is missing from the plot



Matthew McCullough

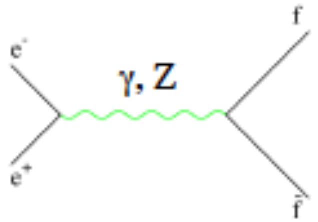
arxiv:1312.3322

Accessing SM input parameters

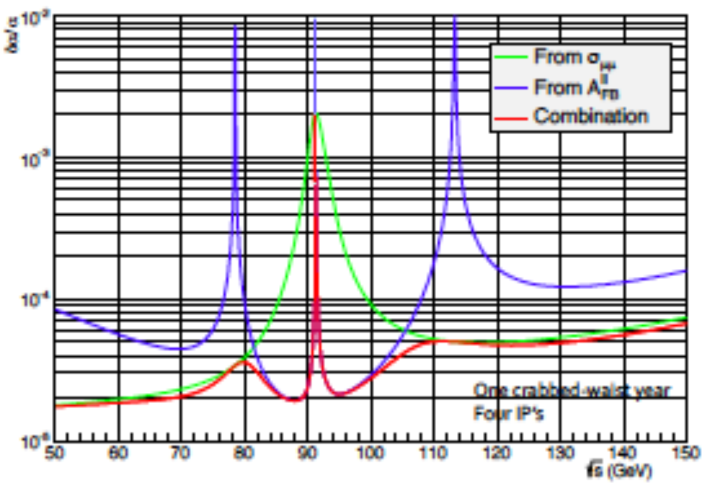
$\alpha_{QED}(m_Z)$

Janot '15

measure $\sigma(e^+e^- \to \mu^+\mu^-)$ and $A_{FB}^{\mu\mu}$ at (a) judicious $\sqrt{s}$



The γ exchange term is proportional to $\alpha^2_{QED}(\sqrt{s})$
The Z exchange term is proportional to G^2_F, hence independent of α_{QED}
The γZ interference is proportional to $\alpha_{QED}(\sqrt{s}) \times G_F$



By running six months at each of 88 and 95 GeV points:
➢ Could potentially reach a precision of : $\delta\alpha/\alpha = 2 \times 10^{-5}$

$\alpha_{QCD}(m_Z)$

Dam @ EPS'15

$$R_l = \Gamma_{had}/\Gamma_l$$

LEP measurements with
(1) new N³LO results
(2) improved m_{top}
(3) m_{Higgs}

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

stat. limited

TLEP statistics

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