Future Circular Colliders (FCC)

A long term vision for particle physics

By request from the organizers, cover, for FCC-ee:

- Distinctive features, prospects, and challenges
- Physics, Experiments, Accelerator

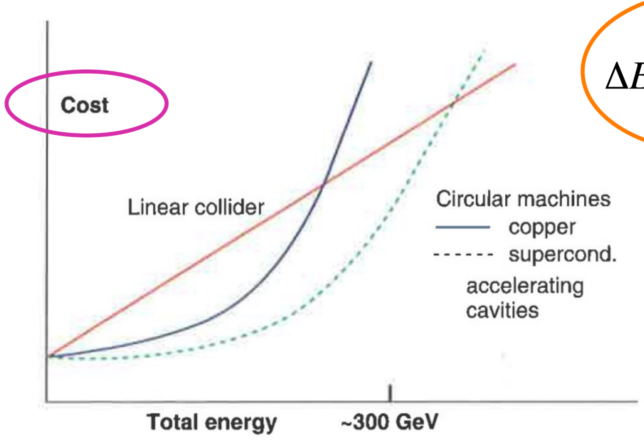
… in 30 minutes.

A selection of …

Distinctive features

Circular

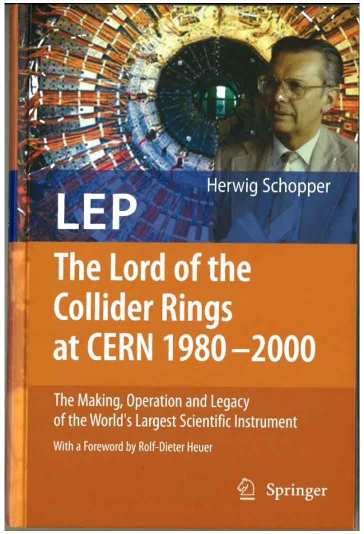
- **A few quotes and facts**
  - **"An e^+e^- storage ring in the range of a few hundred GeV in the centre-of-mass can be built with present technologies [...] would seem to be [...] the most useful project on the horizon"**
    - **Original LEP proposal (1976): 90 km for 400 GeV**
  - **Main obstacle to larger √s is synchrotron radiation**



$$\Delta E \propto \frac{1}{R}\left(\frac{E}{m}\right)^4$$

July 2012: m_H = 125 GeV

  - **"Up to a centre-of-mass energy of 350 GeV at least, a circular collider with superconducting accelerating cavities is the cheapest option"**



Author:
Herwig Schopper
(Former CERN DG)

Foreword:
Rolf Heuer
(Former CERN DG)

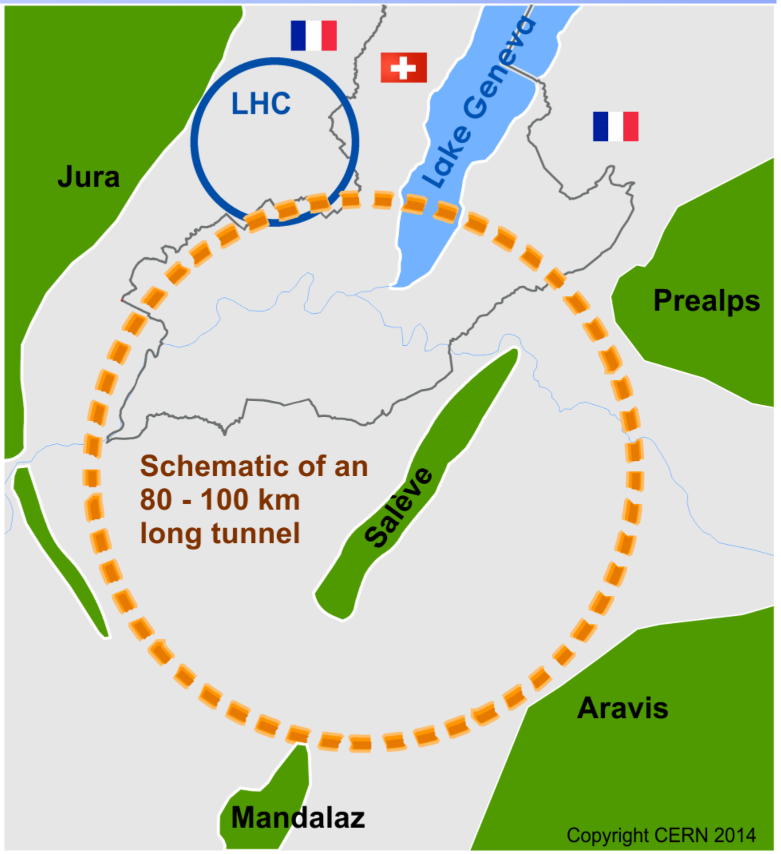
H. Schopper, private communication (2014)

Energy upgrade

- International FCC collaboration (CERN as host lab) to study
  - pp collider , 100 TeV (FCC-hh)
    - Ultimate goal, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

  - 80-100 km tunnel infrastructure in Geneva area
  - e^+e^- collider (FCC-ee) as a possible first step, with $\sqrt{s}$ from ~90 to ~400 GeV
  - p-e collider (FCC-eh) option



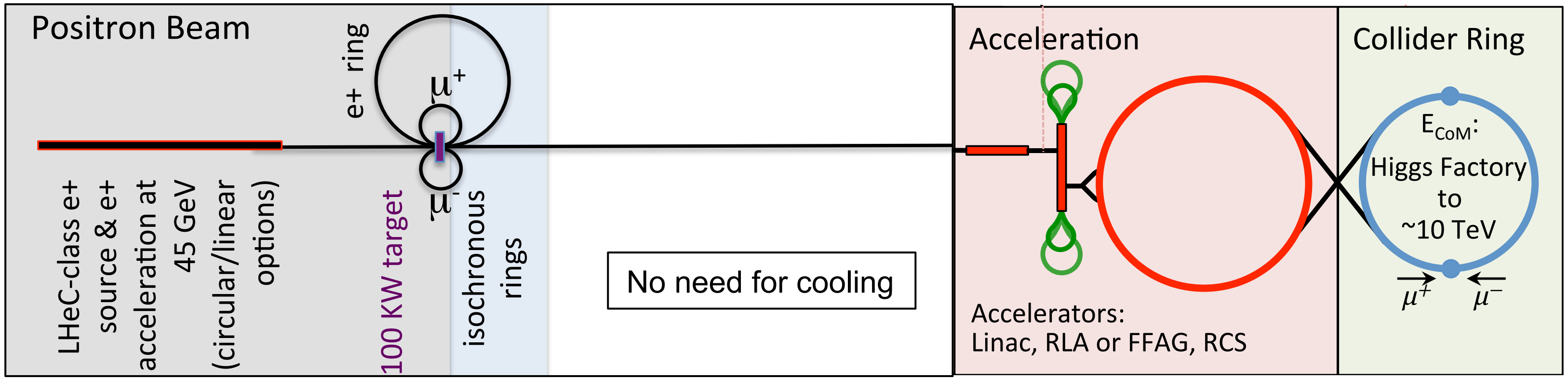
- The FCC-ee may serve as a spring board for the 100 TeV pp collider, bringing:
  - A large tunnel, most of the infrastructure, cryogenics, time, …
  - Additional physics motivations + performance goals for FCC-hh
  - The largest energy upgrade for e^+e^- projects on the market

M. Benedikt
F. Zimmermann

Energy upgrade (cont'd)

- **A very recent idea (2014) for muon colliders**

P. Raimondi



- **Intense e^+ beam with E = 45 GeV**
- **Non destructive target for $e^+e^- \rightarrow \mu^+\mu^-$**
- **Keep the e^+ beam in a ring**
- **Production at threshold ($\sqrt{s} \sim 2\, m_\mu$)**
  - **Quasi monochromatic muons, almost no need for cooling**
- **Fast acceleration and injection into moderately-sized circular ring(s)**
  - **See lecture from M. Palmer on Monday afternoon**
- **May be the best (only?) way to reach $\sqrt{s} > 3$ TeV with leptons**
  - **With the required luminosity**

Unique synergy with FCC-ee

50 years of experience

- FCC-ee exploits experience from past circular colliders

F. Zimmermann

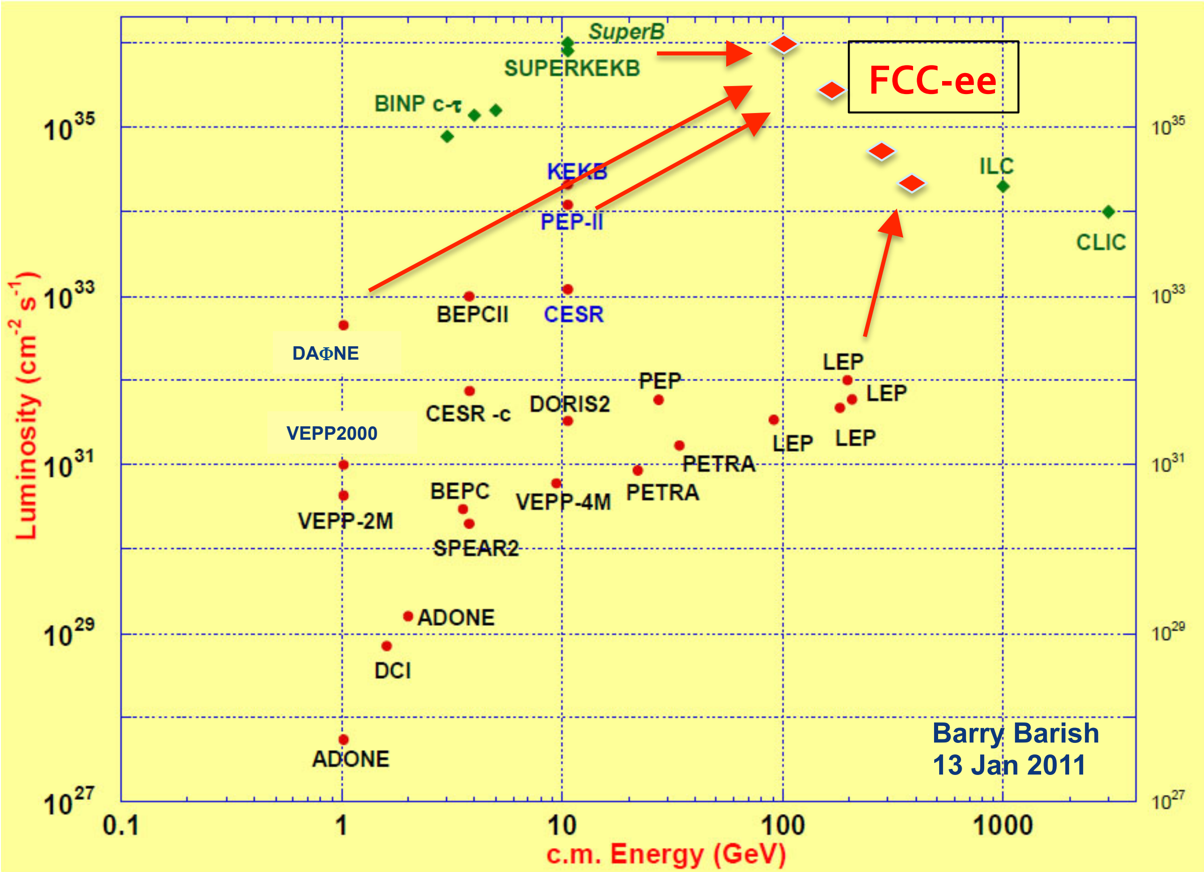
LEP
  high energy with SC RF
  control SR effects

DAFNE
  high lumi w/ crab waist

***B-factories:* KEKB & PEP-II**
  high beam currents
  top-up injection
  double ring for e^+ & e^-
  e^+ source

SuperKEKB
  low β_y*

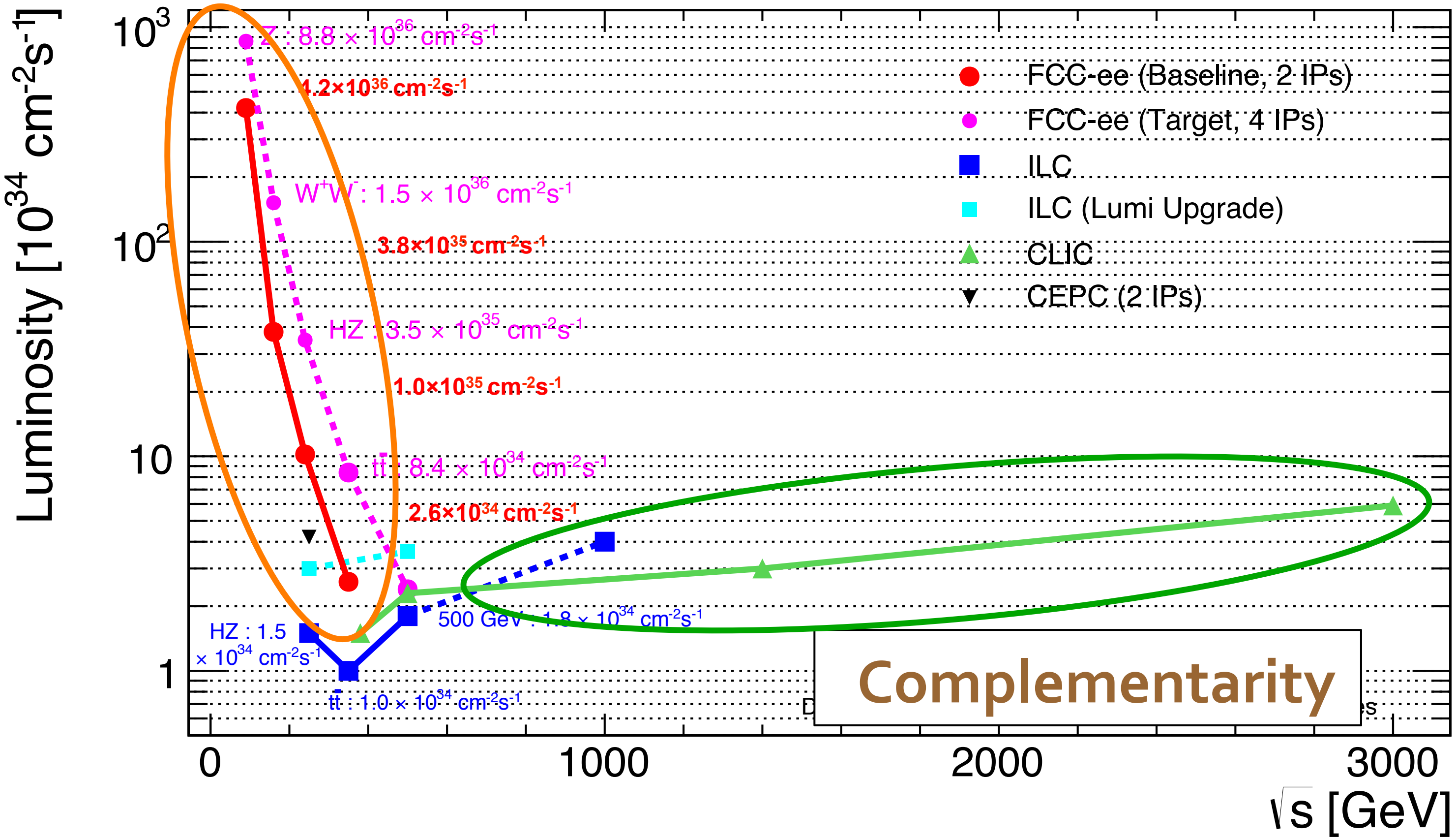
HERA, LEP, RHIC:
  spin gymnastics



- Combines successful ingredients
  - Towards extremely high luminosities at high centre-of-mass energies

Extremely high luminosities

- In the energy range from the Z pole to the top-pair threshold
  - (So-far) conservative baseline, with functioning optics and 2 IPs
    - Room for improvement with smaller β* and 4 IPs



Parameters

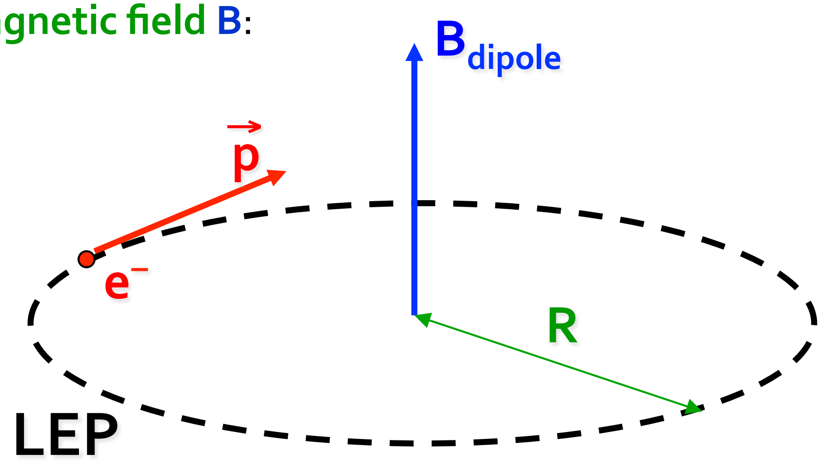
J. Wenninger et al.
FCC-ACC-SPC-003

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

Precise energy calibration with self polarization

- **Reminder: Measurement of the beam energy at LEP**
  - Ultra-precise measurement unique to circular colliders

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



L = 2πR = 27km

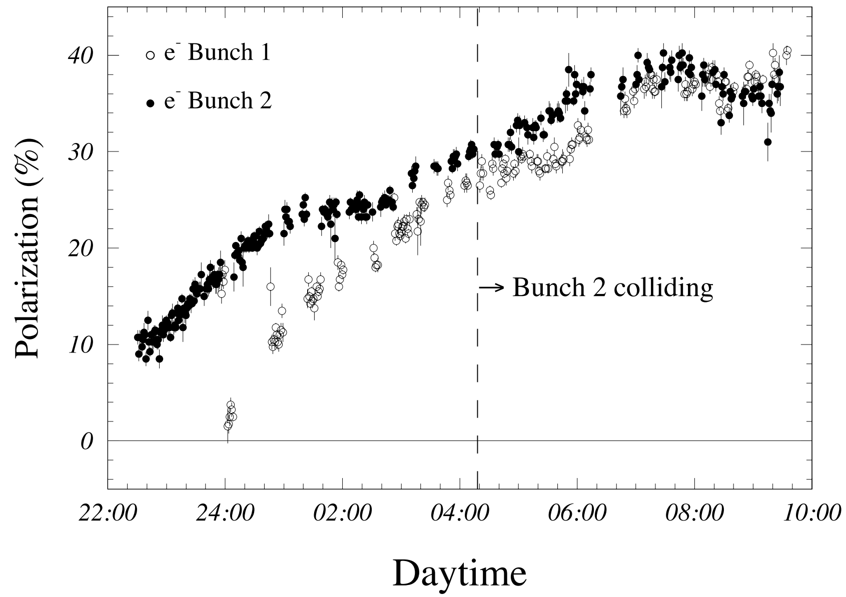
$E \sim p = e\,B\,R = (e/2\pi)\,B\,L$

In real life, B non uniform, ring not circular

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

To be measured

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



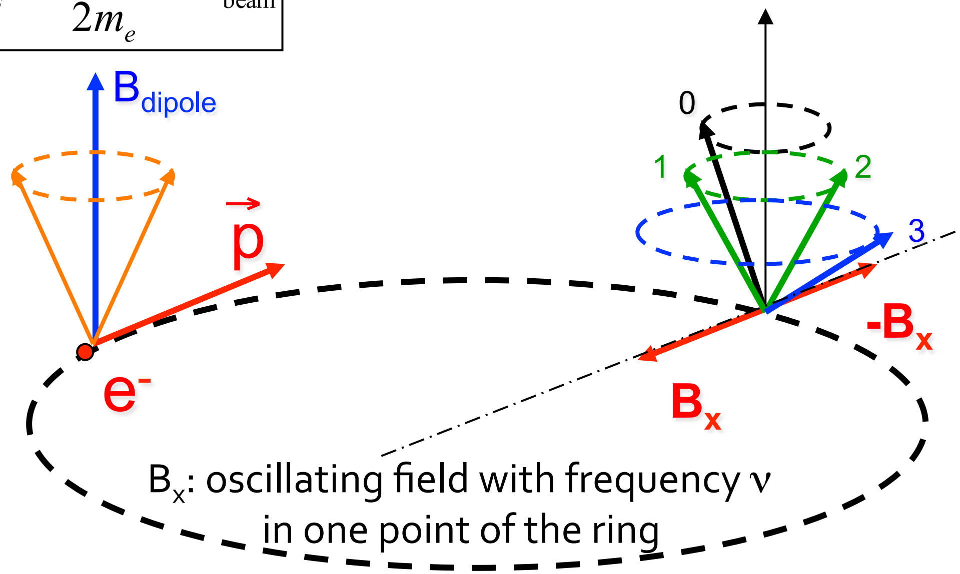
Slow process (especially at FCC-ee)

- P = 10% in 2.9h at 45 GeV (Z pole)
- P = 10% in 1.6h at 80 GeV (WW threshold)

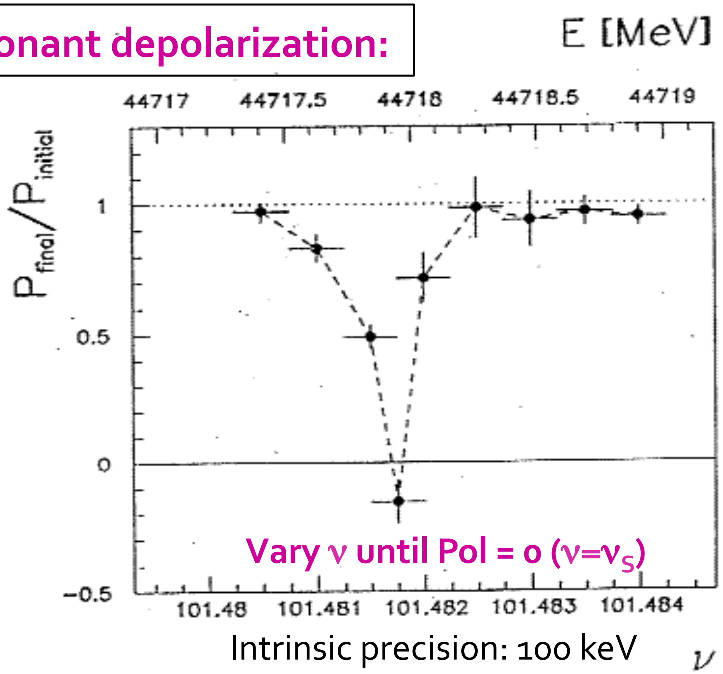
Precise energy calibration with self polarization

- 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 $\int$Bdl)

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



Resonant depolarization:



Intrinsic precision: 100 keV

- LEP was colliding 4 bunches of e^+ and e^-
  - Specific calibration runs were needed: extrapolation error ~ 2.2 MeV
- FCC-ee will have 10,000's of bunches.
  - Use ~100 "single" bunches to measure E_{BEAM} with resonant depolarization
    - ➨ Each measurement gives 100 keV precision, with no extrapolation uncertainty

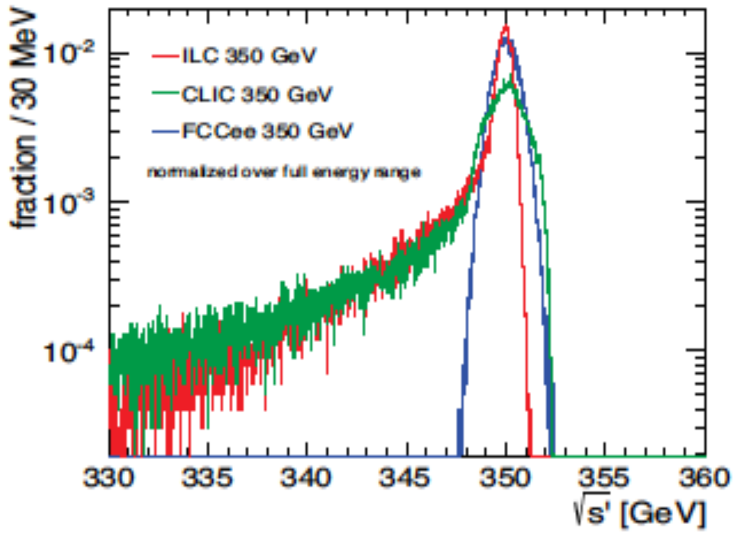
Experimental conditions

- **A few specificities with respect to linear colliders**
  - Two to four interaction points
  - Bunch crossing time from 2.5 – 7.5 ns (Z) up to 4 μs (top)
  - No pile-up interactions (< 0.001 / bunch crossing)
  - Beamstrahlung is mild for experiments

E. Perez

	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

F. Simon



- Much smaller background in the detectors
- Better centre-of-mass energy definition
  - ➨ Beam energy spread < 0.1% at all √s
- High luminosity reached with 30 mrad crossing angle and strong focusing ("crab-waist")
  - Last focusing quadrupole "inside" the detector : L* ~ 2 m
  - Experiment magnetic field needs to be compensated / shielded
    - ➨ Shielding & compensating solenoids up to 1m from the interaction point

European Strategy statement

- **In 2013, the European Strategy group said**

e) There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded.

- **The FCC-ee complies best with this statement**
  - **Unprecedented and largest luminosities from 90 to 400 GeV**
    - **To study the properties of the $Z^{(*)}$, $W^{(*)}$, H, and top particles**
    - **With close-to-ideal experimental conditions**
  - **Unrivaled precision for the measurement of the beam energy**
    - **See in a few slides for the motivation**
  - **Energy upgrade (FCC-hh) up to 100 TeV**
    - **Required by the negative results from LHC searches**
      - ➨ **No new physics below 1 TeV (so far)**

(*) Linear colliders don't have a design for these energies

A selection of …

Challenges

Foreword

- **The FCC-ee is designed to be the ultimate Z, W, H, and top factories**
  - It is a project in its infancy: less than three years old
    - Lots of progress were made in the past two years
      - ➨ Technology is ready – on paper
  - This machine has still many technological challenges to solve
    - A high-power (200 MW), high-gradient (10 MV/m), 2 km-long, RF system
    - Loads of synchrotron radiation (100 MW) to deal with
    - A booster (for top up injection), and a double ring for e^+ and e^-
    - An optics with very low β^*, and large momentum acceptance
    - An intense positron source
    - Transverse polarization for beam energy measurement
    - Up to four experiments to serve
    - … and much more
  - It is supported by 50 years of experience and progress with e^+e^- circular machines
    - Most of the above challenges are being addressed at SuperKEKB (starting 2015)
      - ➨ FCC-ee will have to build on this experience

RF system

- **Very broad range of operation parameters**
  - **ΔE_{SR} from 34 MeV to 7.55 GeV**
  - **Accelerating gradient from 0.2 to 10 GV**
  - **Total current from 6.6 mA to 1.45 A**

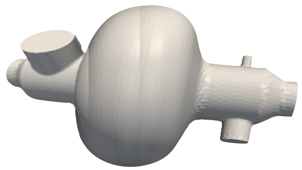
O. Brunner, A. Butterworth, R. Calaga

"Ampere-class" machines

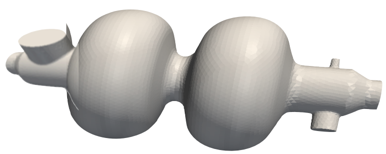
	V_{total} GV	$n_{bunches}$	I_{beam} mA	ΔE/turn GeV
FCC-hh	0.032		500	
Z	0.4/0.2	30000/90000	1450	0.034
W	0.8	5162	152	0.33
H	5.5	770	30	1.67
t	10	78	6.6	7.55

"high gradient" machines

- **No well-adapted single RF system solution**
  - **Start with 400 MHz single-cell Nb/Cu cavities @ 4.5K for Z and WW**



  - **Add 800 MHz multi-cell bulk Nb cavities @ 2K for the higher energies**



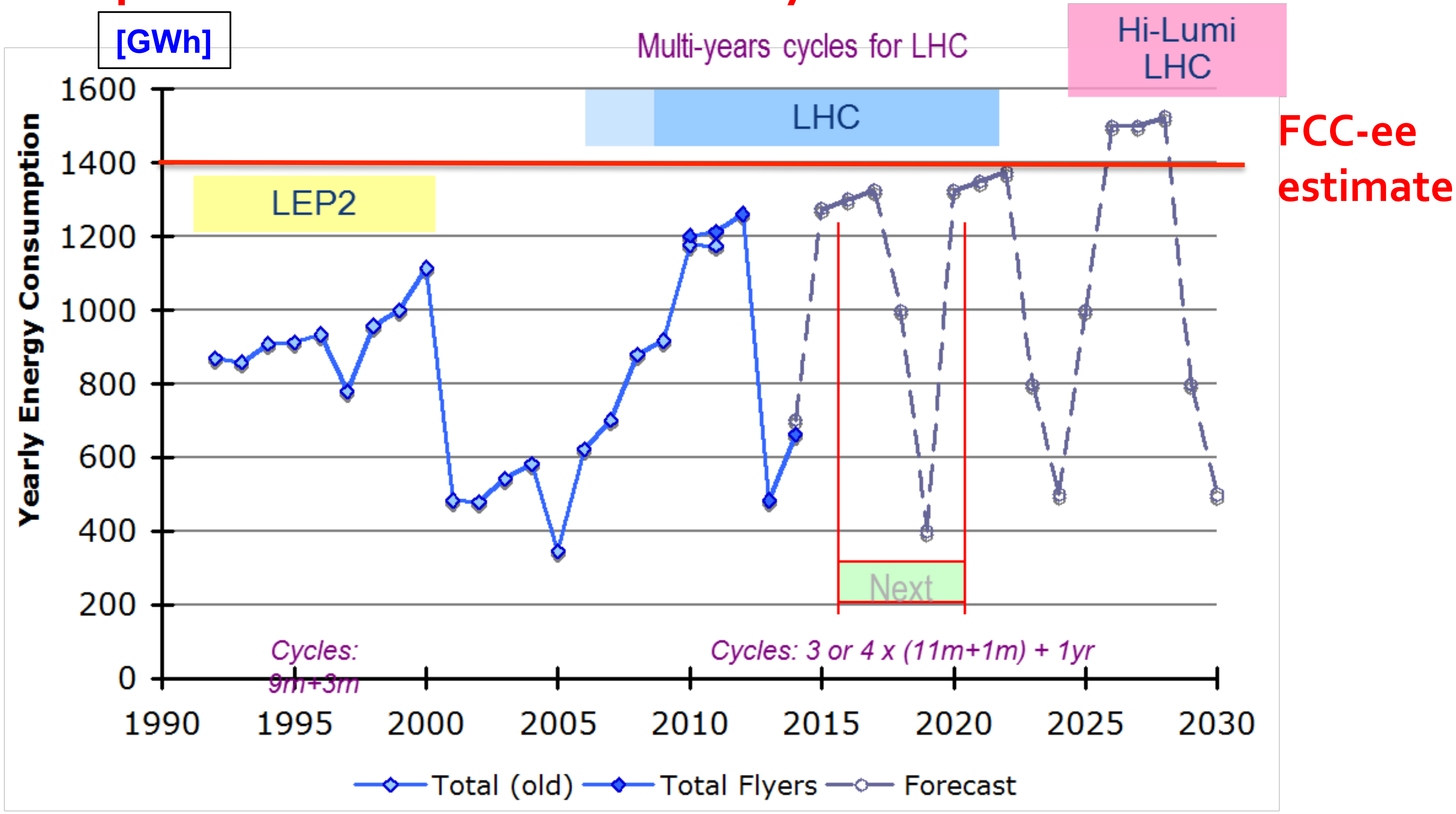
RF power source efficiency …

- The RF system needs to compensate for 100 MW SR losses
  - Corresponds to 200 MW with 50% efficient RF power sources (klystrons)
    - Reminder: Klystron efficiency was ~ 55% at LEP2
  - Recent breakthrough (2014) in klystron theory
    - Three methods applied together promise more than 90% efficiency
      - "Congregated bunch" — V.A. Kochetova (1981)
      - "Bunch core oscillations" — A. Yu. Baikov et al. (2014)
      - "BAC" — I. A. Guzilov et al. (2013)
  - Just started an international collaboration "HEIKA"
    - CERN, ESS, SLAC, CEA, MFUA, Lancaster U., Thales, L3, CPI, VDBT
      - Now designing, building, and testing prototypes
  - Simulation and first hardware tests extremely encouraging

- Projected FCC-ee total power from 275 MW (Z) to 364 MW (top)
  - … to be compared to 237 MW used by CERN in 1998
    - The total RF power accounts for half of it (with 70% efficiency)

… and FCC-ee energy consumption

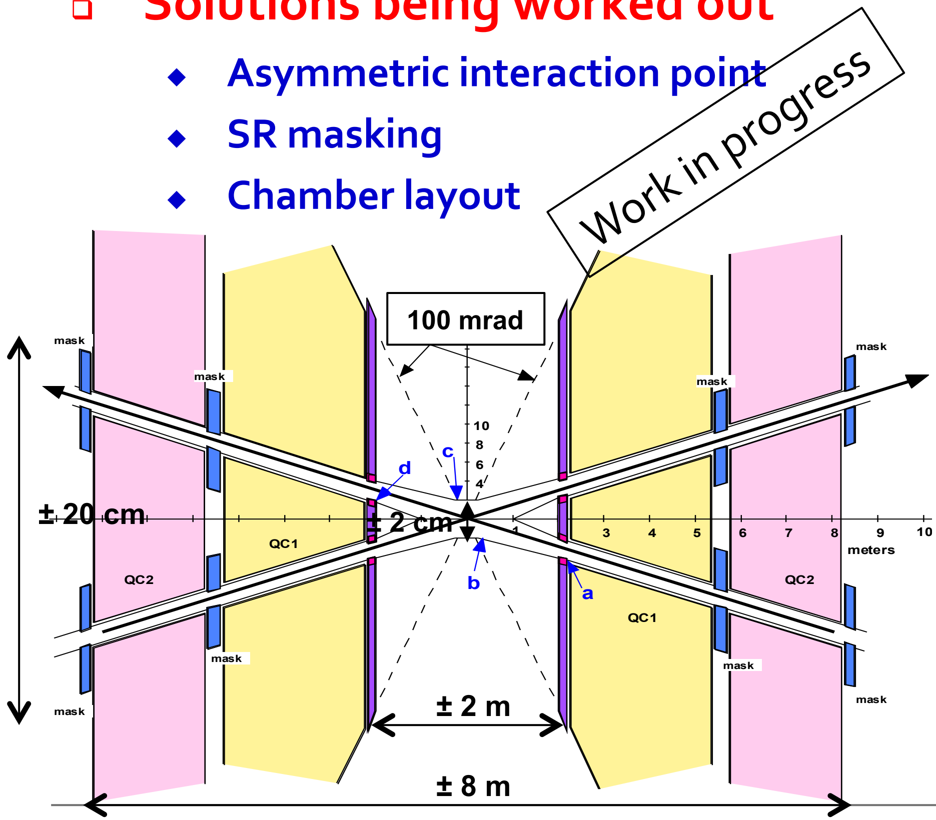
- Compared to recent CERN history

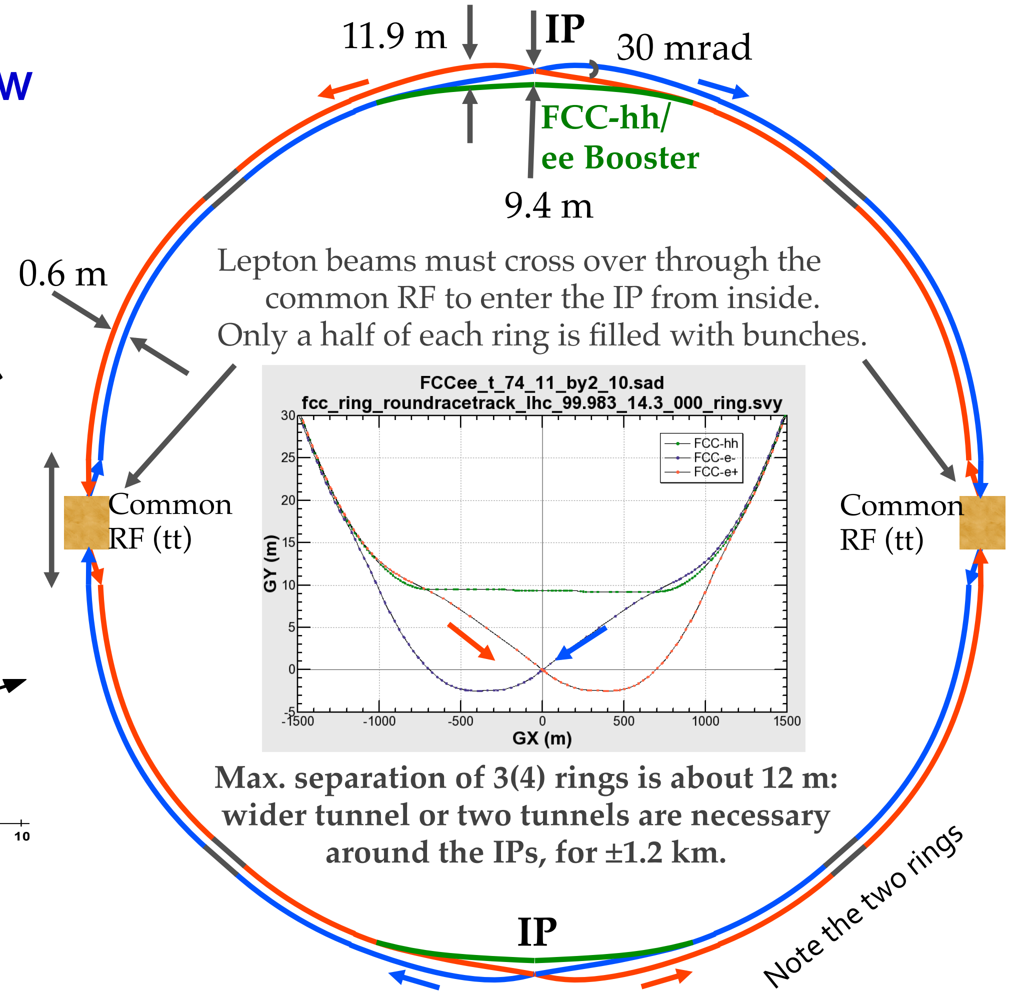


S. Claudet - CERN Procurement Strategy 3rd Energy Workshop 29-30 October 2015

Synchrotron radiation and MDI optimization

- **Design choices**
  - Synchrotron radiation power : 100 MW
  - Common layout with FCC-hh
  - ΔE_{SR} = 7.55 GeV / turn @ 175 GeV
- **Solutions being worked out**
  - Asymmetric interaction point
  - SR masking
  - Chamber layout

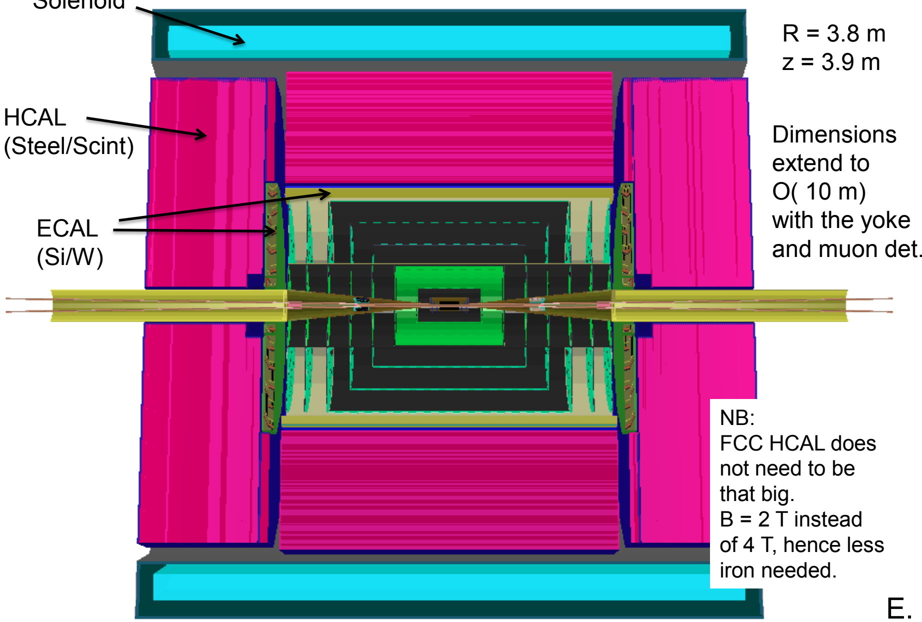




FCC-ee 1, FCC-ee 2,
FCC-ee booster (FCC-hh footprint)

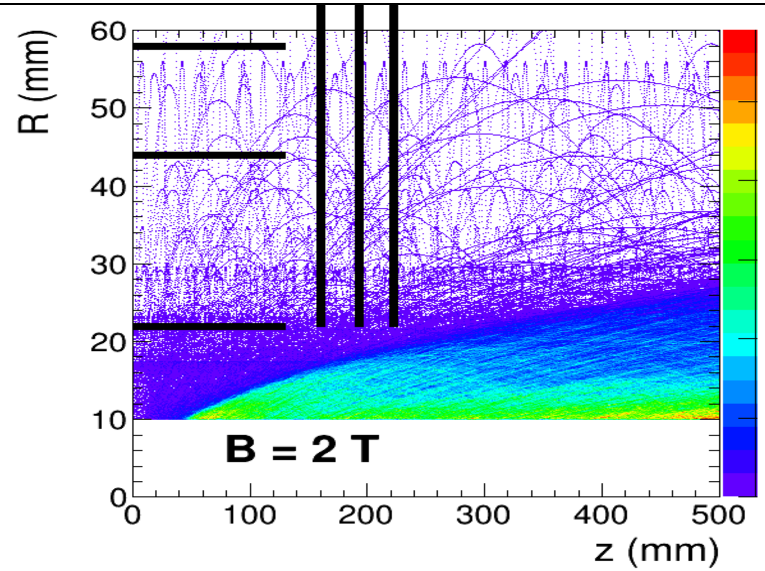
Detector design

- "To study properties with unprecedented precision"
  - Challenging, but ILC and CLIC detector characteristics are adequate
    - The control of systematic uncertainties will be of paramount importance
      - ➨ Possible at the FCC-ee with regular high-statistics runs at the Z pole
- Started to adapt CLIC detector design to FCC-ee



E. Perez

Beamstrahlung simulation: VTX can live at ~2cm from IP



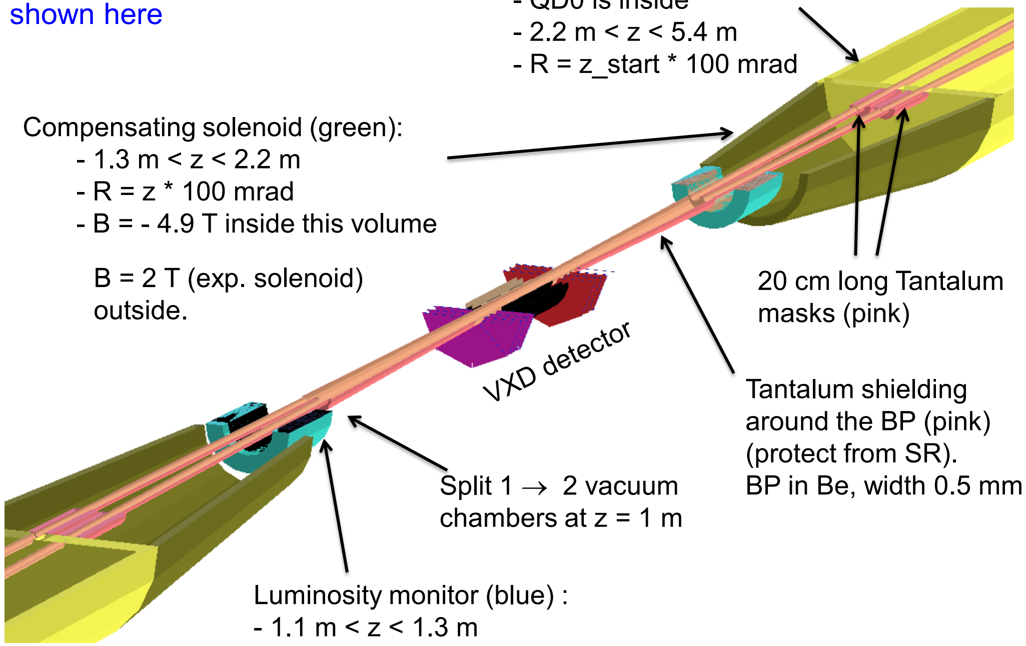
Synchrotron radiation effects being studied

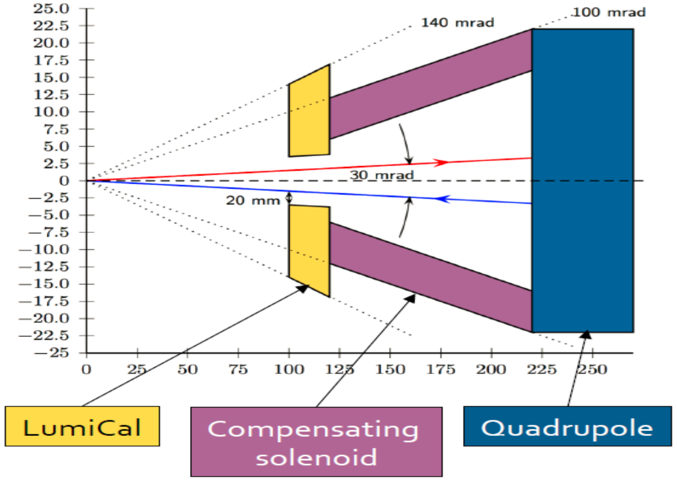
- Started to work also on specific FCC-ee detector design: first conclusions within a year

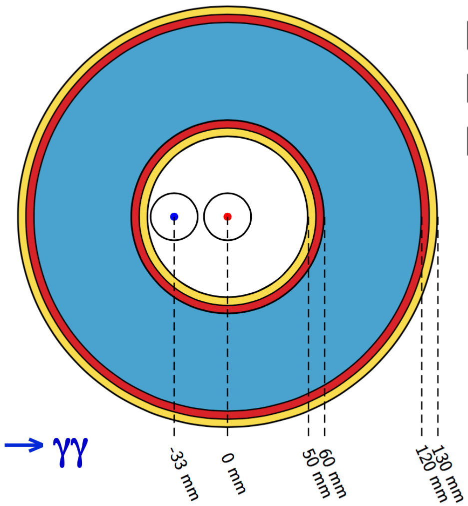
Detector design (cont'd)

- **Trying to squeeze in the luminosity calorimeter**
  - **Usually measure luminosity with well-known low-angle QED process $e^+e^- \rightarrow e^+e^-$**

Implemented for the simulations shown here







Narrow acceptance
Wide acceptance: 5 mm
leakage region: 5 mm

Narrow acceptance
- θ_{min} = 54.5 mrad
- θ_{max} = 109 mrad
- σ = 30.2 nb

Front face at z = 1.1m

4/12/2016

M. Dam

- **Control of geometry will be crucial**
  - **Also envision to use large angle process $e^+e^- \rightarrow \gamma\gamma$**

A selection of …

Physics Prospects

Lumi / year and typical running scenario

- **Assumptions**
  - 160 days of physics / year (LEP, LHC)
  - Beam availability 65% with top-up injection (PEP2, KEKB)
  - Conservative baseline with 2 experiments / Target with 4 experiments
- **Integrated luminosities and number of events**

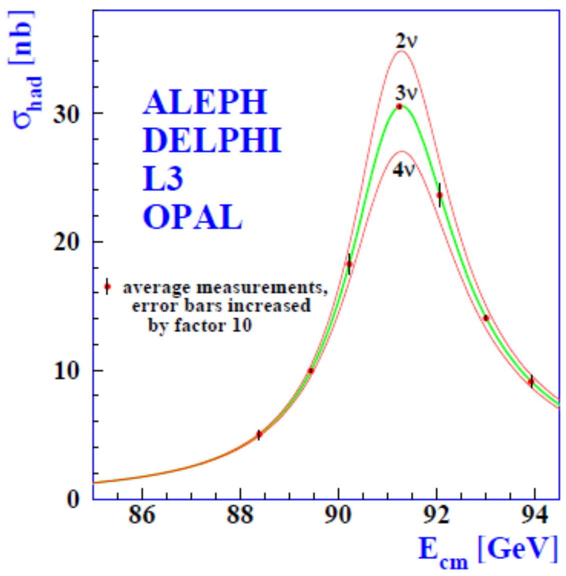
Mode	Lumi / year	# years	# events	Remark
Z (88-94)	40-80 ab^{-1}	3-5	Up to 10^{13} Z	>10^5 LEP
WW (161)	4-15 ab^{-1}	1-2	Up to 10^8 WW	~10^4 LEP
HZ (240)	1-3.5 ab^{-1}	3-5	1-2 × 10^6 HZ	~10 ILC
$t\bar{t}$ (350-370)	0.25-1 ab^{-1}	3-5	1-2 × 10^6 $t\bar{t}$	~ ILC / CLIC
H (125)	2 ab^{-1}	?	500 H / year	Preliminary (*)

(*) Work in progress, needs monochromatization, $\sqrt{s}$ spread ~ 6 MeV possible

- Predicting accuracies with 300 times smaller statistical precision than at LEP is difficult
  - Conservatively used LEP experience for systematic uncertainties
    - ➨ This is just the start.

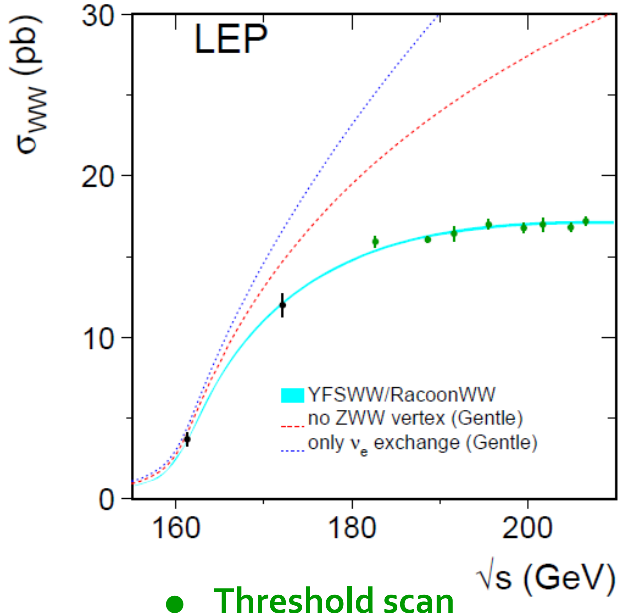
Precision electroweak measurements

Z resonance: TeraZ

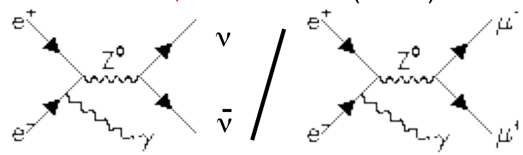


- Lineshape
  - Exquisite E_{beam} (unique!)
  - m_Z, Γ_Z to < 100 keV (2.2 MeV)
- Asymmetries
  - $\sin^2\theta_W$ to 6×10^{-6} (1.6×10^{-4})
  - $\alpha_{QED}(m_Z)$ to 3×10^{-5} (1.5×10^{-4})
- Branching ratios, R_l, R_b
  - $\alpha_S(m_Z)$ to 0.0002 (0.002)

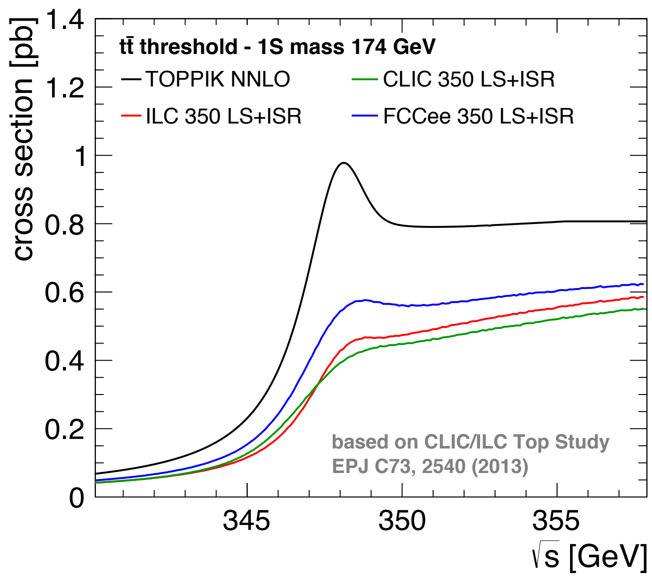
WW threshold scan: OkuW



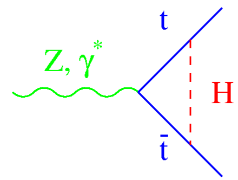
- Threshold scan
  - m_W to 500 keV (15 MeV)
- Branching ratios R_l, R_{had}
  - $\alpha_S(m_W)$ to 0.0002
- Radiative returns $e^+e^-\rightarrow\gamma Z$
  - N_ν to 0.0004 (0.008)



tt threshold scan: MegaTops

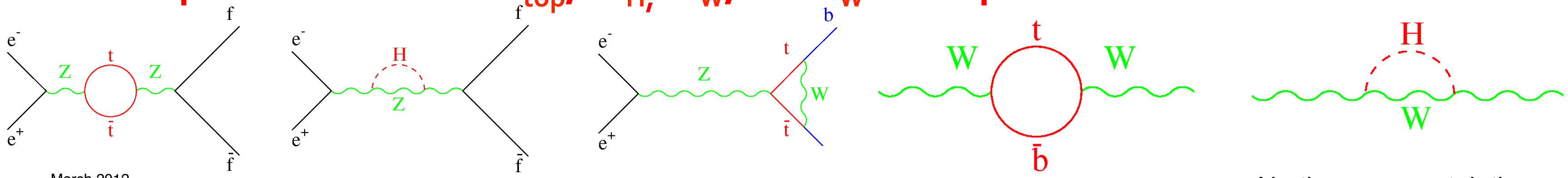


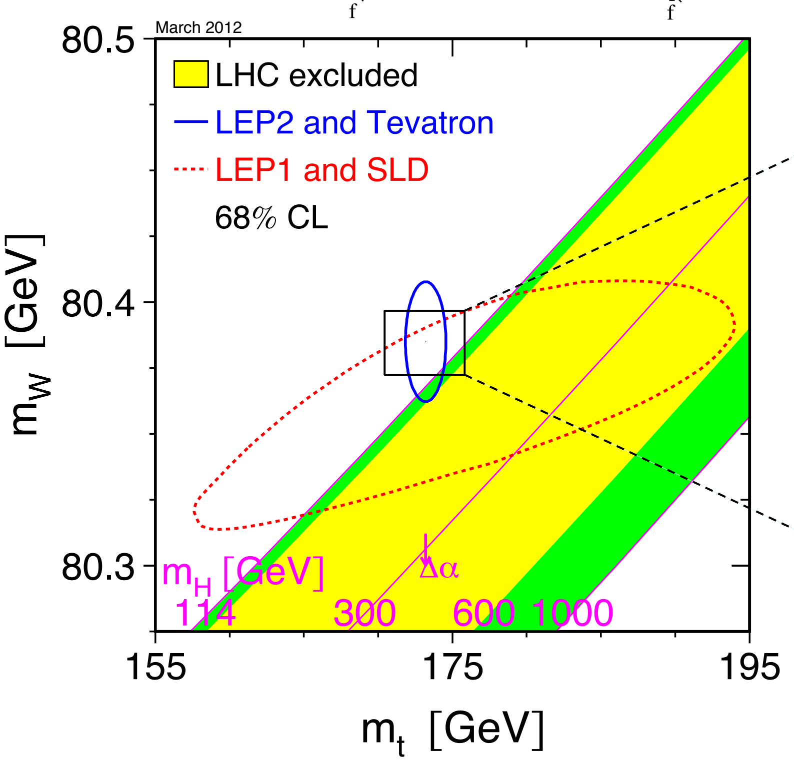
- Threshold scan
  - m_{top} to 10 MeV (500 MeV)
  - λ_{top} to 13%
  - Top EW couplings to 1%

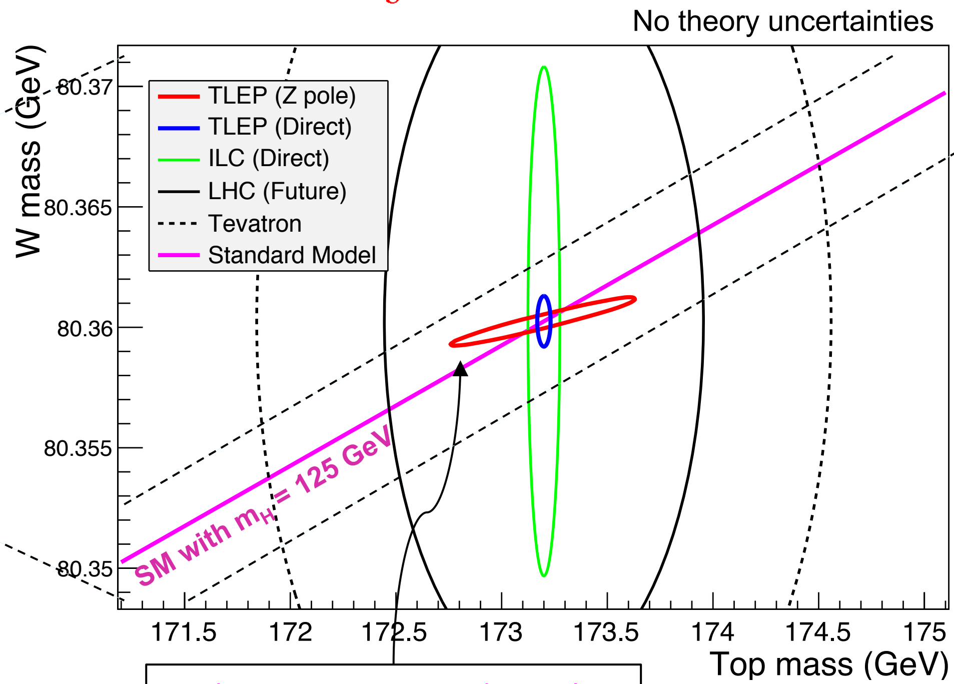


Combination of all precision EW measurements

- FCC-ee precision allows m_{top}, m_{H}, m_{W}, $\sin^2\theta_W$ to be predicted in the SM







Without m_Z@FCC-ee, the SM line would have a 2.2 MeV width

- With m_{top}, m_W, m_H known, the Standard Model has nowhere to go
  - New physics discovery potential … or constraints on new physics ?

arXiv:1308.6173

Theory uncertainties

- The predictions of m_{top}, m_{W}, m_{H}, $\sin^2\theta_W$ have theory uncertainties (in SM)
  - Which may in turn cancel the sensitivity to new physics
- For m_W and $\sin^2\theta_W$ today, these uncertainties are as follows

$$M_W = 80.3593 \pm 0.0056_{m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{had}} \pm 0.0017_{\alpha_S} \pm 0.0002_{M_H} \pm 0.0040_{theo} = 80.359 \pm 0.011_{tot}$$

Exp: 0.015

$$\sin^2\theta^{\ell}_{eff} = 0.231496 \pm 0.000030_{m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{had}} \pm 0.000010_{\alpha_S} \pm 0.000002_{M_H} \pm 0.000047_{theo} = 0.23150 \pm 0.00010_{tot}$$

Exp: 0.00014

- Parametric uncertainties and missing higher orders in theoretical calculations:
  - Are of the same order
  - Smaller than experimental uncertainties

S. Heinemeyer

Theory uncertainties

- **Most of the parametric uncertainties will reduce adequately at FCC-ee**
  - **New generation of theoretical calculations is necessary to gain a factor 10 in precision**
    - **To match the precision of the direct FCC-ee measurements**

$$
\begin{aligned}
M_W &= 80.3593 \pm 0.0001_{m_t} \pm 0.0001_{M_Z} \pm 0.0003_{\Delta\alpha_{had}} \\
&\quad \pm 0.0002_{\alpha_S} \pm 0.0000_{M_H} \pm 0.0040_{theo} \\
&= 80.359 \pm 0.005_{tot}
\end{aligned}
$$

Exp: 0.0005

$$
\begin{aligned}
\sin^2\theta^{\ell}_{eff} &= 0.231496 \pm 0.000001_{m_t} \pm 0.000001_{M_Z} \pm 0.000008_{\Delta\alpha_{had}} \\
&\quad \pm 0.000001_{\alpha_S} \pm 0.000000_{M_H} \pm 0.000047_{theo} \\
&= 0.23150 \pm 0.00006_{tot}
\end{aligned}
$$

Exp: 0.000006

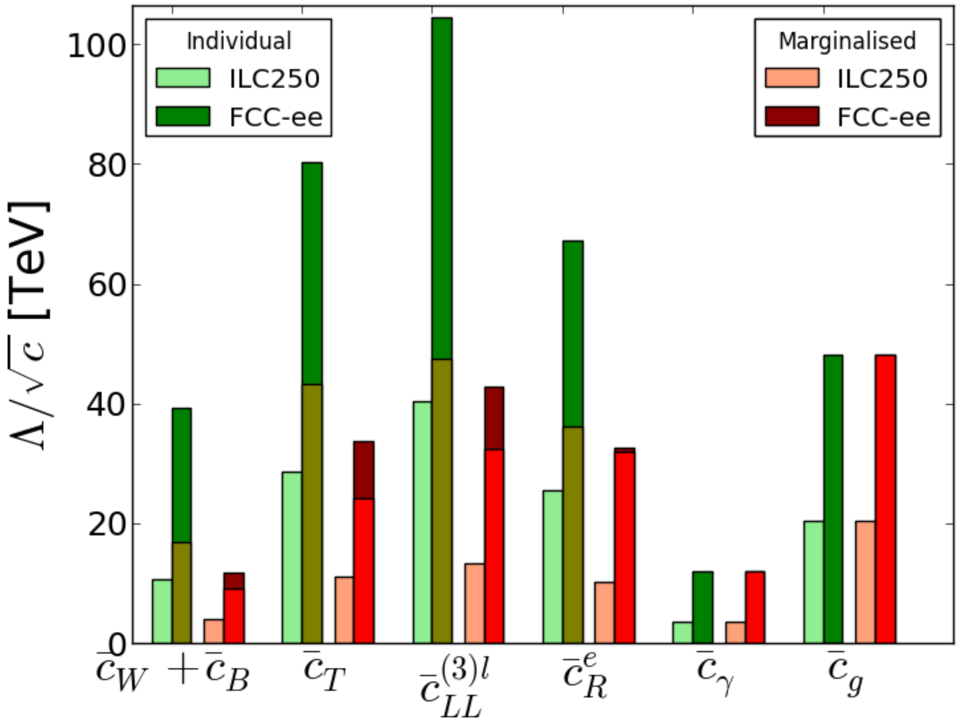
  - **Will require calculations up to three or four loops to gain an order of magnitude**
    - **Might need a new paradigm in the actual computing methods**
      - ➨ **Lot of interesting work for future generations of theorists**

Generic constraints on new physics

- **Higher-dimensional operators as relic of new physics ?**

  - **Possible corrections to the standard model**

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



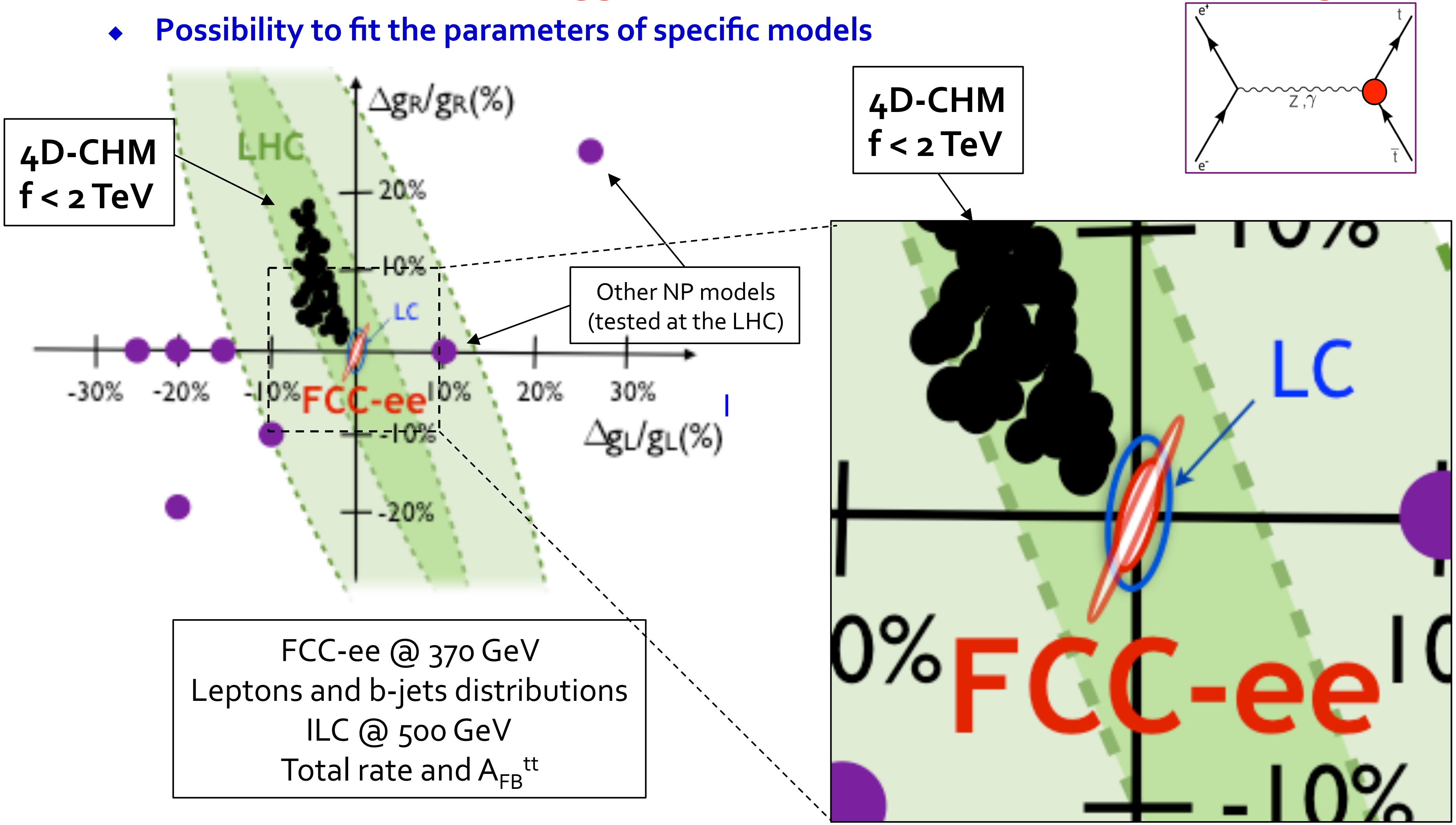
In green: one operator at a time
In red: all operators together
ILC sensitivity vanishes w/o Z and WW runs

J. Ellis, T. You, arXiv:1510:04561

After FCC-ee: Λ_{NP} > 100 TeV ?

Specific sensitivity to new physics

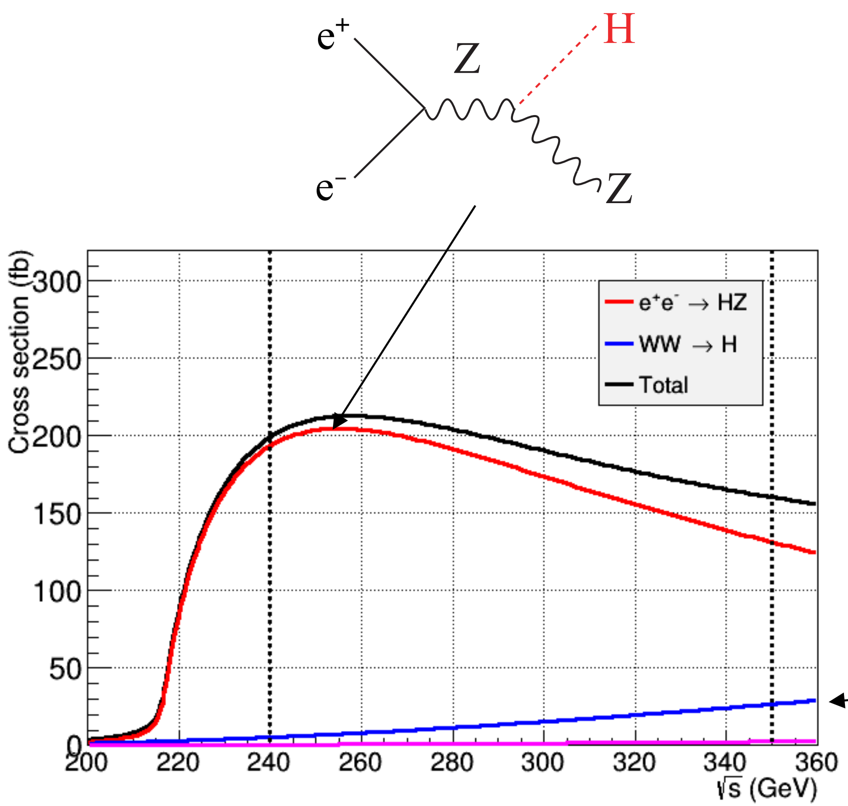
- **For example, composite Higgs models would modify top EW couplings**
  - **Possibility to fit the parameters of specific models**

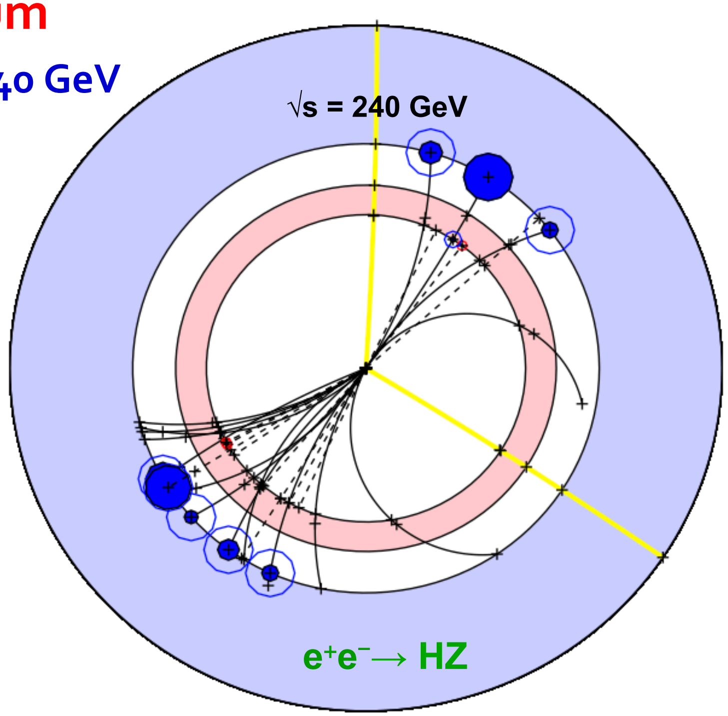


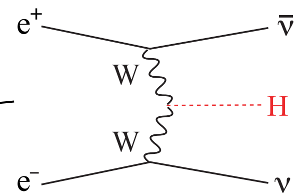
arXiv:1503.01325, arXiv:1510.09056

Precision Higgs physics

- **Production cross section ~ 200 fb at maximum**
  - **Between 400,000 and 1,500,000 events / year @ 240 GeV**
    - **Higgs boson tagged by a Z and recoil mass**







- **Model-independent precision measurements of mass, couplings, width, inv. width**

Higgs measurements: Summary

- **From M. Klute, LCWS'15**

Uncertainties	HL-LHC*	μ-	CLIC	ILC**	CEPC	FCC-ee
m_H [MeV]	40	0.06	40	30	5.5	8
Γ_H [MeV]	-	0.17	0.16	0.16	0.12	0.04
g_{HZZ} [%]	2.0	-	1.0	0.6	0.25	0.15
g_{HWW} [%]	2.0	2.2	1.0	0.8	1.2	0.2
g_{Hbb} [%]	4.0	2.3	1.0	1.5	1.3	0.4
$g_{H\tau\tau}$ [%]	2.0	5	2.0	1.9	1.4	0.5
$g_{H\gamma\gamma}$ [%]	2.0	10	6.0	7.8	4.7	1.5
g_{Hcc} [%]	-	-	2.0	2.7	1.7	0.7
g_{Hgg} [%]	3.0	-	2.0	2.3	1.5	0.8
g_{Htt} [%]	4.0	-	4.5	18	-	13 ***
$g_{H\mu\mu}$ [%]	4.0	2.1	8.0	20	8.6	6.2
g_{HHH} [%]	30	-	24	-	-	80 ***

= best potential

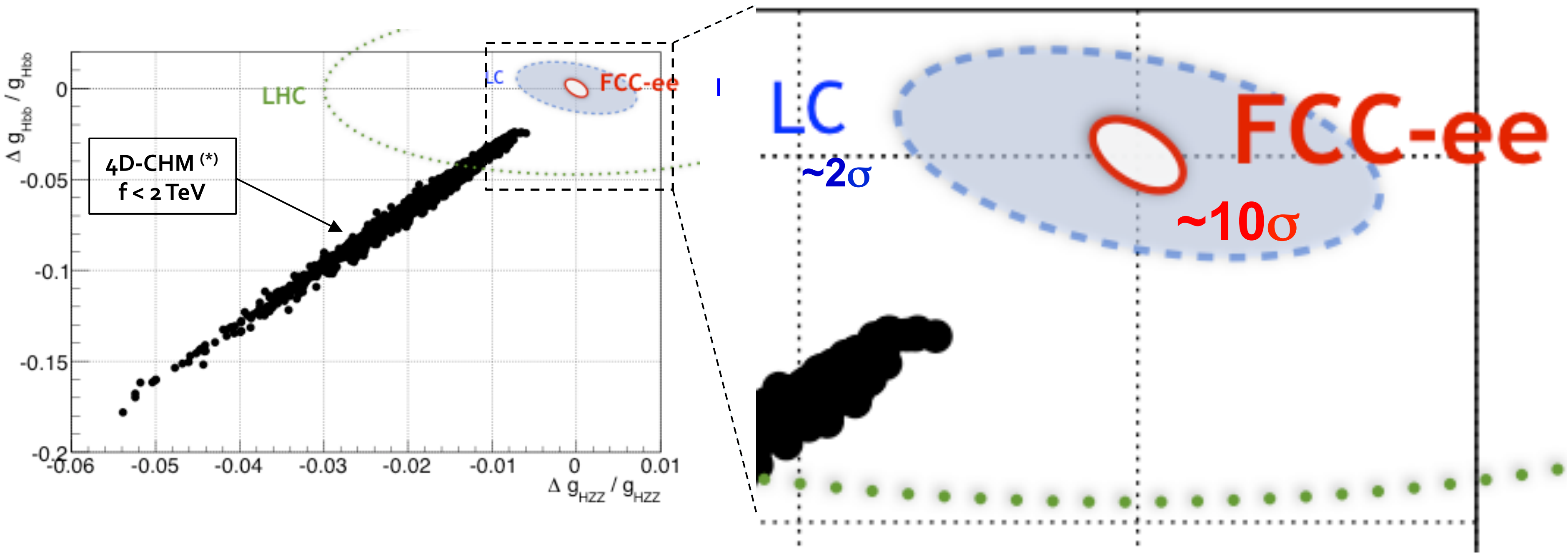
Synergy with FCC-hh

* Estimate for two HL-LHC experiments
** ILC lumi upgrade improves precision by factor 2
*** Indirect

For ~10y operation. Lots of "!,*,?"
Every number comes with her own story.

Sensitivity to new physics: Discovery potential

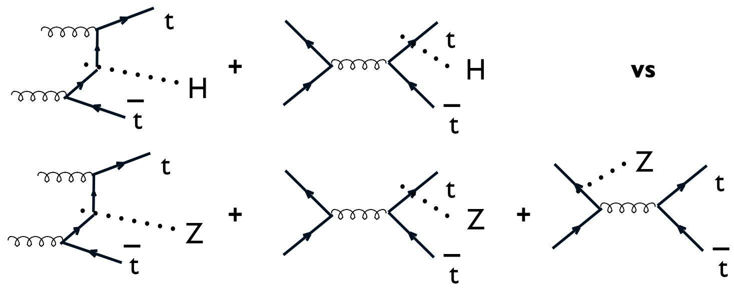
- **Higgs couplings are affected by new physics**
  - Example: Effect on κ_Z and κ_b for 4D-Higgs Composite Models



  - Generically, FCC-ee precision gives access to new physics coupled to the Higgs sector
    - Up to scales of ~ 10 TeV

Synergy with FCC-hh for Htt, HHH, Hμμ

- With 30 ab^{-1} at FCC-hh (See lecture of L.T. Wang)
  - 10^9 gg → ttH events, 5×10^7 gg → HH events, 5×10^8 gg → H → μμ
    - Statistical precision won't be much of a problem, even after selection
    - Systematic uncertainties will dominate, but can be drastically reduced with ratios
      - ➨ Normalize to the precise measurements made at the FCC-ee
  - Example: Infer Htt coupling from the measurement of σ(ttH) / σ(ttZ)
    - Very similar production, gg dominant
    - Most theory uncertainty cancel
    - 1% precision possible on σ(ttH) / σ(ttZ)
    - σ(ttZ) and Higgs BR's from FCC-ee



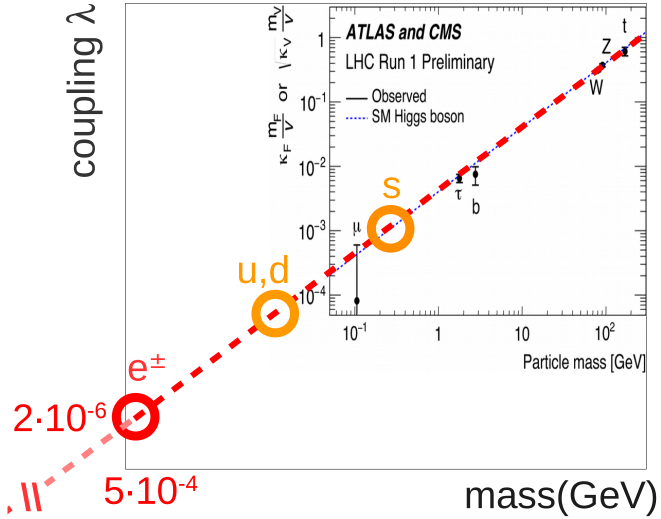
- Achievable precisions

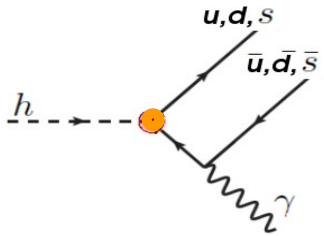
Collider	HL-LHC	LC 500 GeV	LC 1-3TeV	FCC-ee+hh
g_{Htt}	4%	7-14%	2-4%	**<1%**
g_{HHH}	50%	30-80%	10-15%	**<5%**
$g_{H\mu\mu}$	4%	10-20%	8%	**<1%**

  - The combination of FCC-ee and FCC-hh will be "invincible"

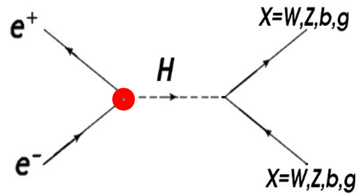
Coupling to the first generation of fermions

- **Small !**



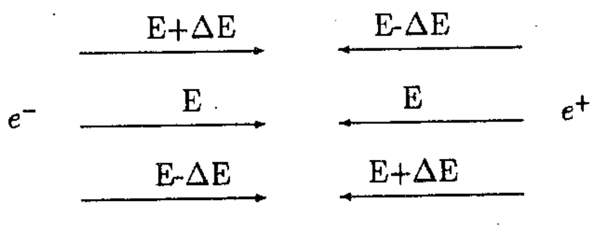


Exclusive decays
e.g., $H \rightarrow \rho\gamma$

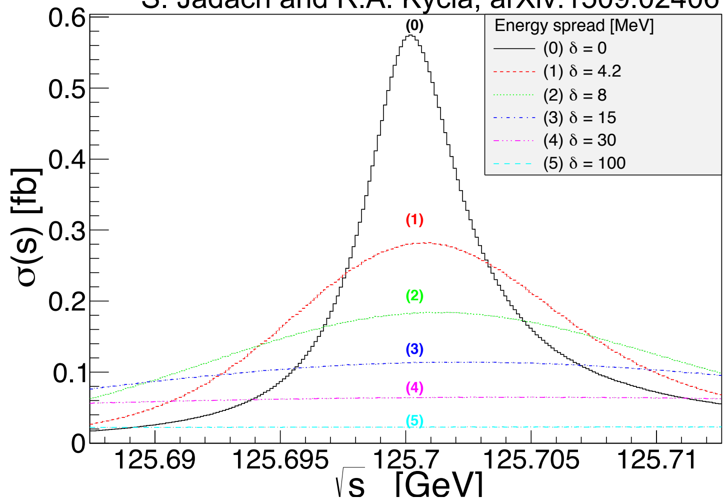


$e^+e^- \rightarrow H$
$\sqrt{s}$ = 125 GeV

- **Opportunities open with the huge FCC-ee luminosities**
  - **$\sqrt{s}$ mono-chromatization down to 6 MeV feasible**



S. Jadach and R.A. Kycia, arXiv:1509.02406

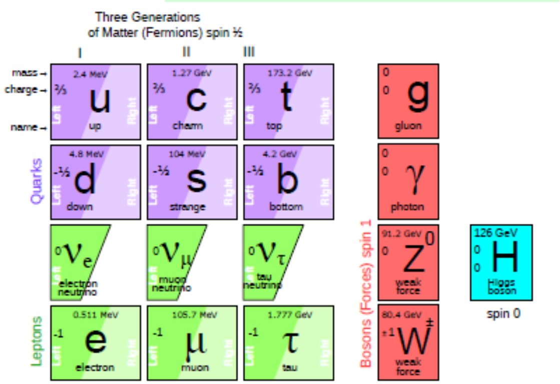


- **Work in progress to increase luminosity**
  - ➨ **Huge backgrounds from $e^+e^- \rightarrow Z, \gamma$**
- **Sensitive to g_{Hee} ~ 2 × SM value**

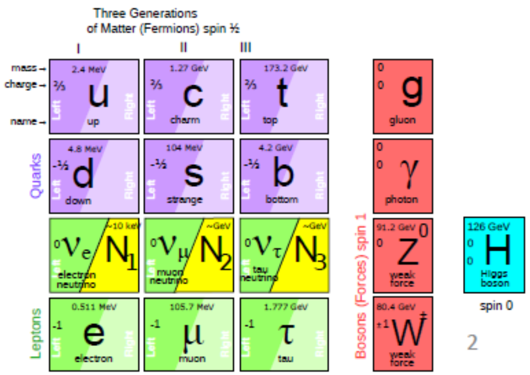
FCC-ee specific discovery potential

- **EXPLORE the 10-100 TeV energy scale with precision measurements**
- **DISCOVER that SM does not fit**
  - Then extra weakly-coupled particles exist
  - Understand the underlying physics through effects via loops
- **DISCOVER a violation of flavour conservation**
  - Examples: $Z \rightarrow \tau\mu$ in 10^{13} Z decays; or $t \rightarrow cZ$, cH at $\sqrt{s}$ = 240 or 350 GeV
  - Also a lot of flavour physics in 10^{12} bb events
- **DISCOVER dark matter as invisible decays of Higgs or Z**
- **DISCOVER very weakly coupled particles in the 5-100 GeV mass range**
  - Such as right-handed neutrinos, dark photons, …

Synergy with FCC-hh

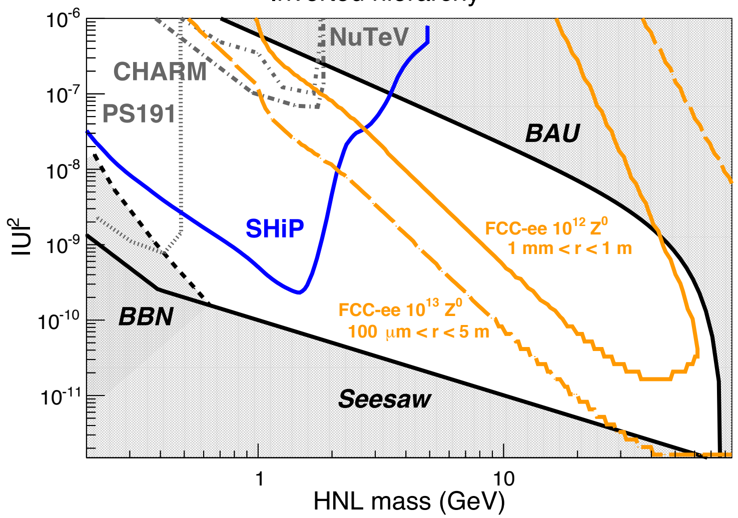


The νMSM, M. Shaposhnickov



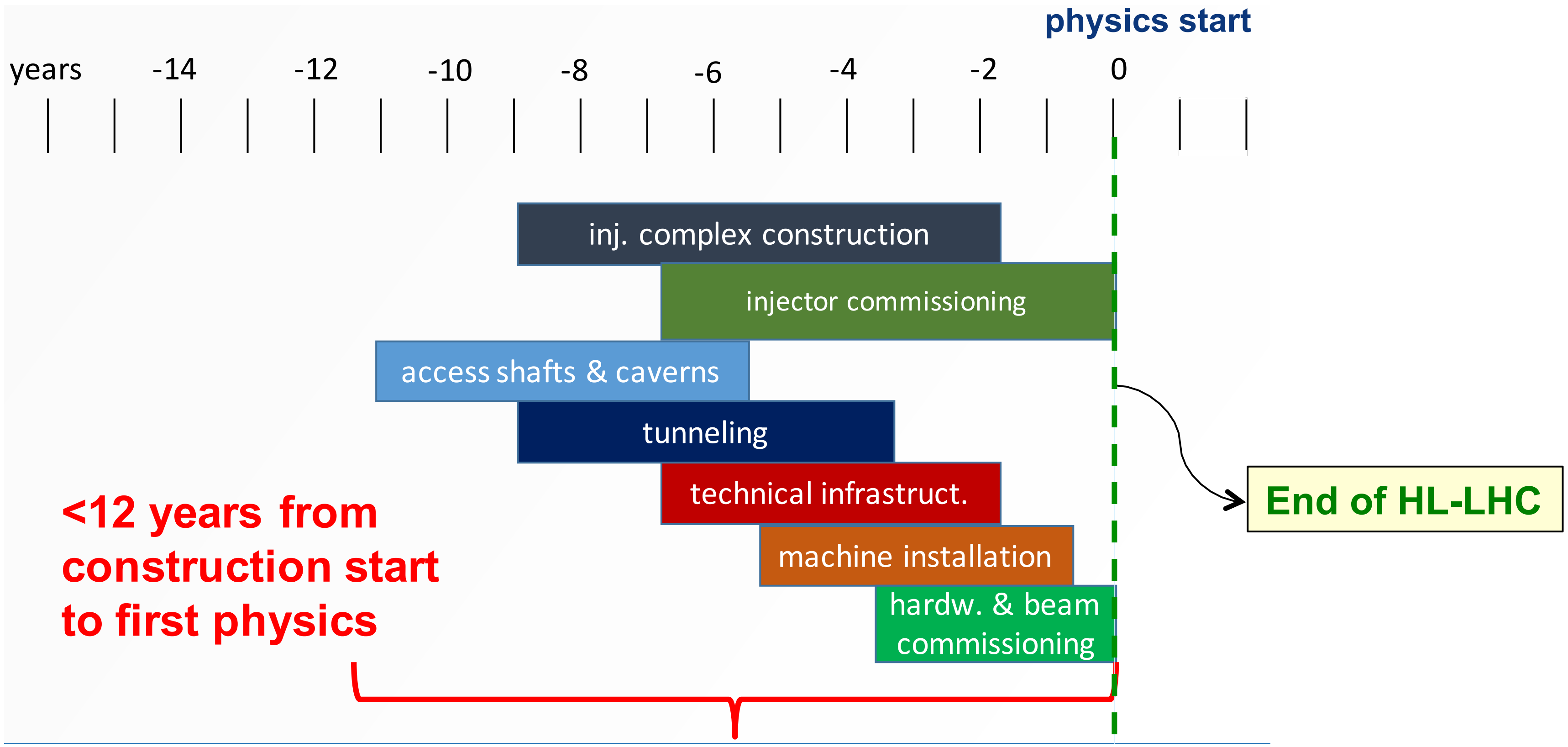
Inverted hierarchy

N. Serra



Tentative timeline (based on LEP experience)

- Possible in parallel with HL-LHC running



F. Zimmermann

- Dismantle the LHC and replace it with the FCC-hh injector
  - In parallel with the FCC-ee physics run (10 to 15 years)

Summary

- FCC-ee successfully combines several concepts
  - Invented and demonstrated in the last 20 years (LEP2 + flavour factories)
- FCC-ee offers extremely large luminosities
  - In the energy range from the Z to the top-pair threshold and beyond
    - Combined with precise beam energy calibration at the Z and the WW threshold
- FCC-ee technology is ready
  - Ongoing R&D aims at further optimizing cost and energy efficiency
  - Optics fullfils all requirements, matched to the FCC-hh footprint
  - Baseline luminosity is predicted with confidence, more is coming
- FCC-ee provides superb new physics discovery potential
  - To potentially very high scales (up to ~100 TeV)
  - To potentially very small couplings (sterile neutrinos, dark matter, ...)
- FCC-ee may serve as a great spring board for the FCC-hh 100 TeV collider
  - Bringing a large tunnel, infrastructure, cryogenics, time, physics & performance goals
- Physics absolutely needs an e^+e^- collider at the EW scale
  - FCC-ee + hh is a most powerful combination for the Energy Frontier