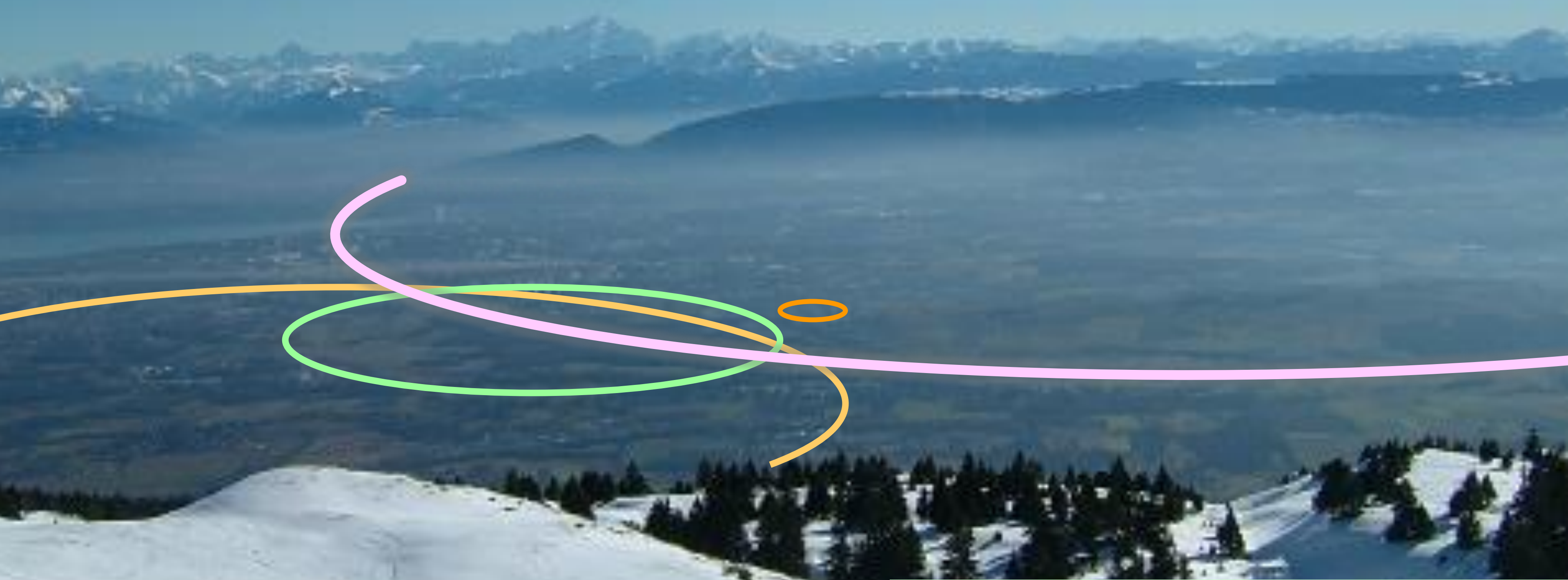
The FCC-ee study

Michael Koratzinos, UNIGE and CERN



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CERN

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Acknowledgements

- I would like to thank
  - the pioneers of the modern circular Higgs factory idea: **Roy Aleksan, Alain Blondel, John Ellis, Patrick Janot, Frank Zimmermann**

A. Blondel F. Zimmermann M. Koratzinos J. Ellis P. Janot R. Aleksan

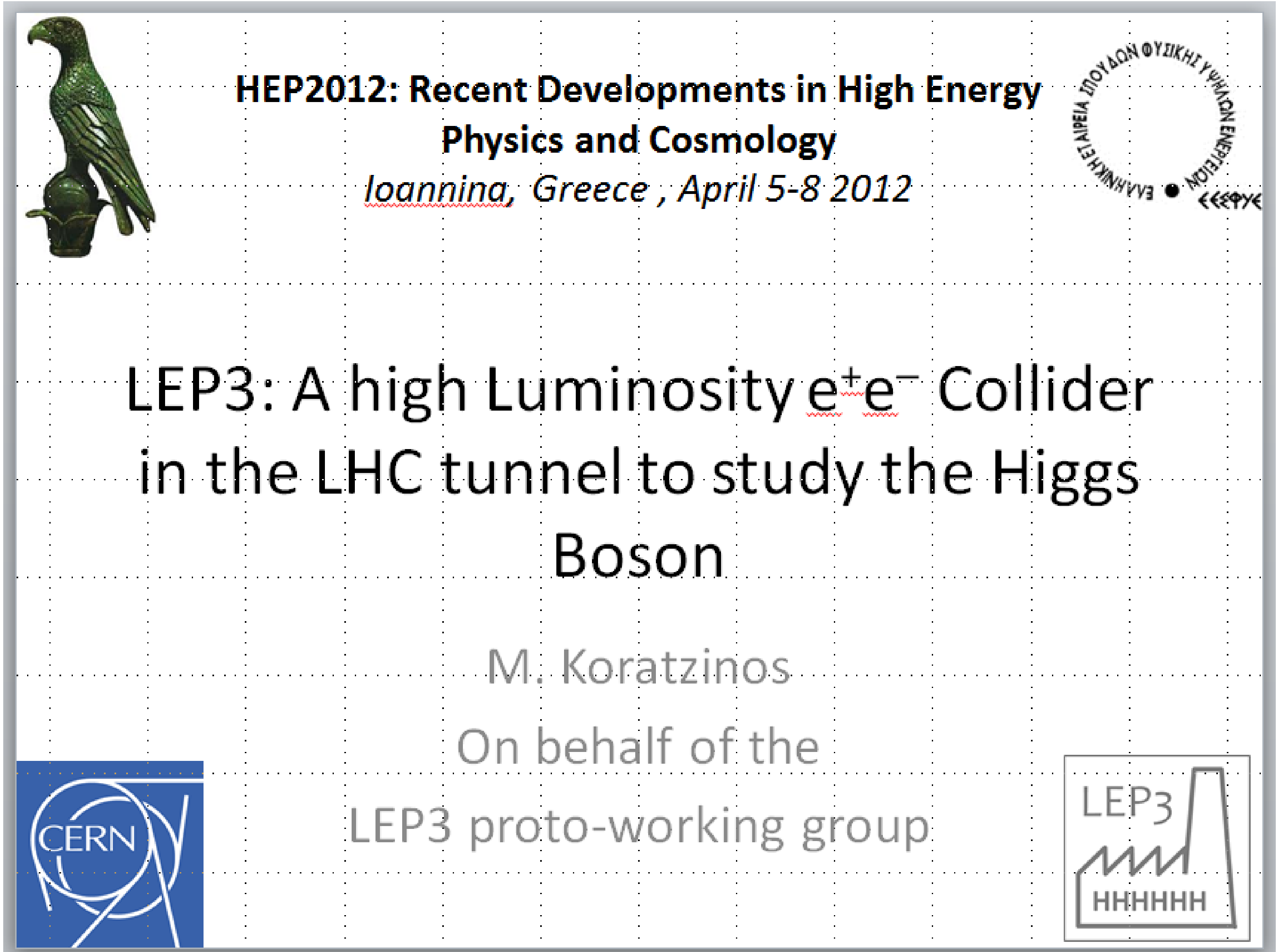
  - The whole FCC community
  - In particular A. Blondel, M. Benedikt, P. Janot, P. Lebrun, F. Zimmermann, J. Wenninger, A. Boghomyakov for the liberal use of material

Before I start…

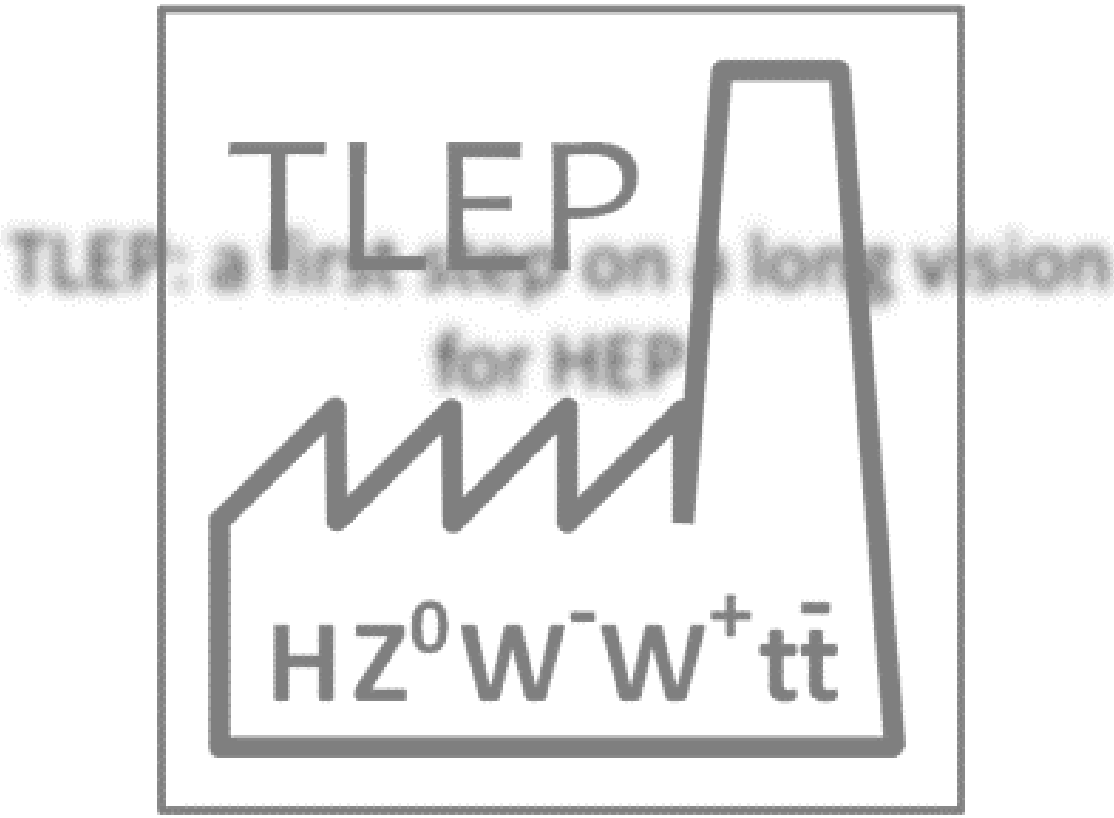
FCC-ee: "the project formally known as TLEP"

- This is a talk about the FCC-ee project.
- There are other excellent projects (both at CERN and world-wide) that might well be the ones that get the go-ahead: CLIC at CERN, the ILC in Japan, CEPC/SppC in China.
- I hope I have represented these projects accurately

You have heard it here first!



…and you have heard it again in Chios in 2013



What has changed since then?

- TLEP has become part of the official CERN study FCC – to produce a CDR circa 2018
- Much progress has been made in many areas (mainly accelerator design)
- The Chinese have launched their bid for a similar project (54 km circular collider) the CepC/SppC – pre-CDR released
- ILC: no change, in 'standby', awaiting a report by a committee set up by the Japanese government

The backdrop

- The Standard Model is complete, but it is not a complete theory
- Major problems:
  - What is the origin of lepton/baryon asymmetry?
  - What is the origin of dark matter?
  - What is the nature of neutrinos?
  - What is the solution to the hierarchy problem?
  - (plus even more profound questions)

Where is the new physics?

- The Higgs is light and SM-like
- No indication of new physics so far
- => the energy scale of new physics (Beyond the Standard Model) Λ has been pushed above ~few $\times$ 100GeV
- The new LHC run will extend this by a factor ~2
- A new project will be needed to push the Λ reach to O(10) to O(100)TeV
- (although there is no guarantee of discovery, the fine-tuning needed goes with the square of Λ, making the SM increasingly problematic)

Precision needed – Higgs sector

- New physics at an energy scale of 1 TeV would translate typically into deviations δg_{HXX} of the Higgs boson couplings to gauge bosons and fermions, g_{HXX}^{SM}, of up to 5% with respect to the Standard Model predictions, with a dependence that is inversely proportional to the square of the new energy scale Λ:

$$\frac{\delta g_{HXX}}{g_{HXX}^{SM}} \leq 5\% \times \left(\frac{1TeV}{\Lambda}\right)^2$$

Therefore the Higgs boson couplings need to be measured with a per-cent accuracy or better to be sensitive to 1 TeV new physics, and with a per-mil accuracy to be sensitive to multi-TeV new physics.

A possible strategy

1. A first step could require a facility that would measure the Z, W, top-quark and Higgs-boson properties with sufficient accuracy to provide sensitivity to new physics at a much higher energy scale.
2. The strategy could then be followed by a second step that would aim at discovering this new physics directly, via access to a much larger centre-of-mass energy than the LHC.
3. (The details of the optimal strategy for the next large facility can only be finalized once the results of the LHC run at 13-14 TeV are known.)

The FCC project answers points (1) and (2) above: a new circular tunnel can house a high-luminosity Z,W,t,H factory and later on a 100TeV collider

The brief history of FCC

The paper that revived the idea: arXiv:1112.2518 [hep-ex]

CERN-OPEN-2011-047
12 December 2011
Version 2.1

A High Luminosity e^+e^- Collider in the LHC tunnel to study the Higgs Boson

Alain Blondel[1], Frank Zimmermann[2]
[1]DPNC, University of Geneva, Switzerland; [2]CERN, Geneva, Switzerland

First international discussions: HF2012 at Fermilab:
http://indico.fnal.gov/conferenceDisplay.py?confId=5775

Following a recommendation of the European Strategy report, in Fall 2013 CERN Management set up the FCC project, with the main goal of preparing a Conceptual Design Report by the time of the next European strategy update (~2018)

FCC kick-off meeting took place on 12-15 February 2014 at University of Geneva
http://indico.cern.ch/event/282344/timetable/#20140212.detailed
Very successful, almost 350 participants, strong international interest

Links established with similar studies in China and in the US, already a series of successful workshops

European Strategy Update 2013

Extracts: Design studies and R&D at the energy frontier

(The committee urges CERN) ...“to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update”:

d) *CERN should undertake design studies for accelerator projects in a global context,*

- *with emphasis on **proton-proton and electron-positron high-energy frontier machines**.*
- *These design studies should be coupled to a vigorous accelerator **R&D programme, including high-field magnets and high-gradient accelerating structures**,*
- ***in collaboration with national institutes, laboratories and universities worldwide.***

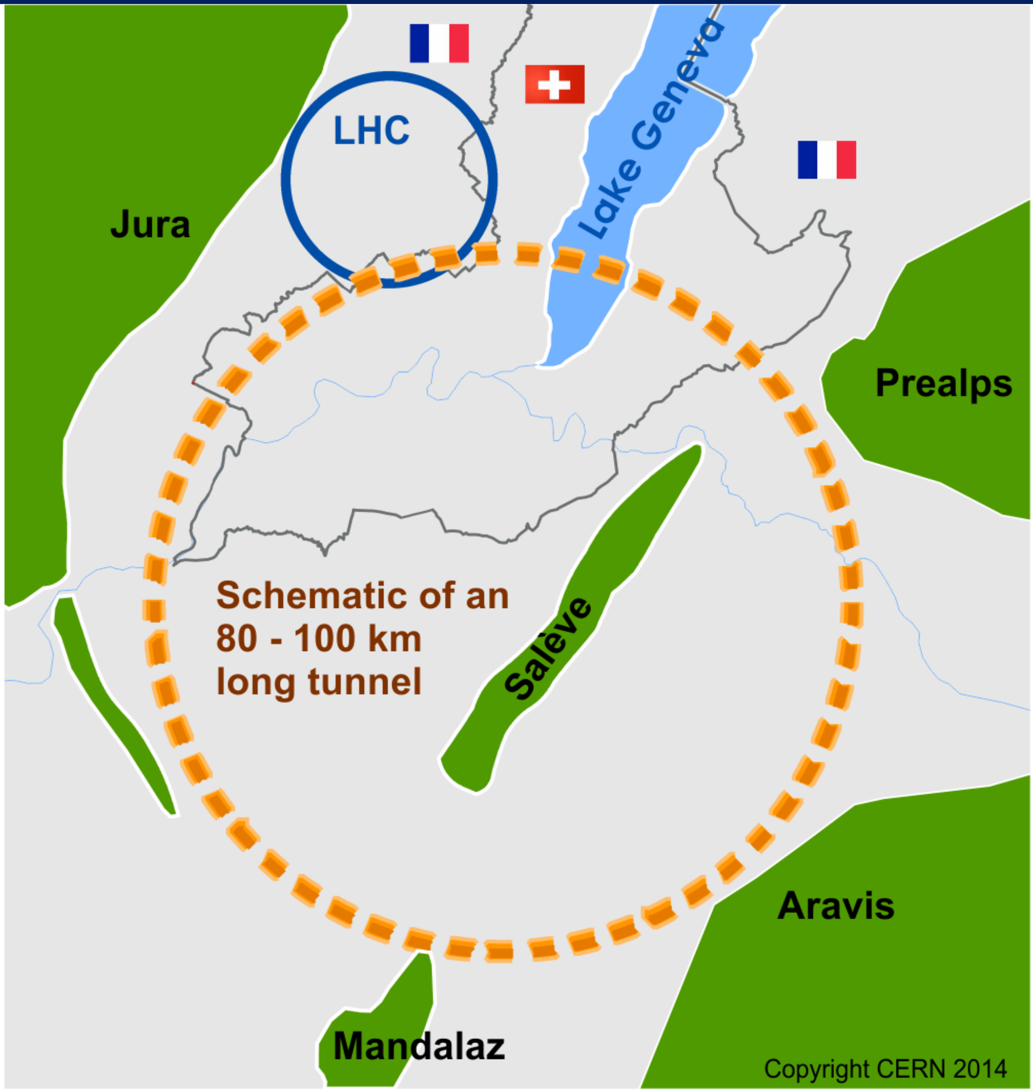
- **http://cds.cern.ch/record/1567258/files/esc-e-106.pdf**

Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Form an international collaboration to study:

- ***pp*-collider (*FCC-hh*)**
  → defining infrastructure requirements
- ***e^+e^-* collider (*FCC-ee*)** as potential intermediate step

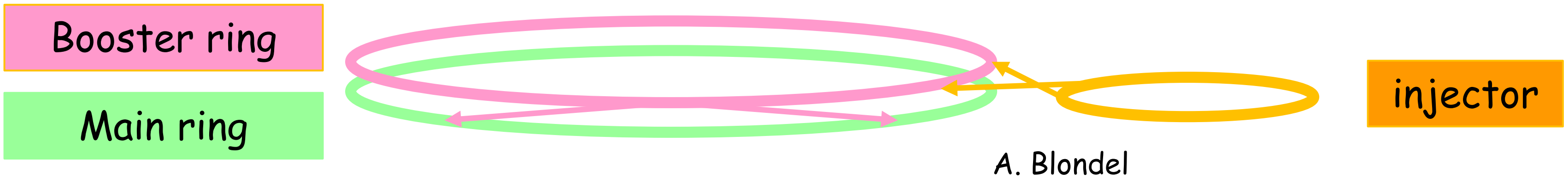
  → Study Z, W, H, top
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



The circular e+e- collider approach

For the high luminosities aimed at, the beam lifetimes due to natural physics processes (mainly radiative Bhabha scattering) are of the order of a few minutes – the accelerator is 'burning' the beams up very efficiently

A "top-up" scheme (*a la* B factories) is a must



- Booster ring the same size as main ring, tops up the main ring every ~O(10s)
- Main ring does not ramp up or down

- What kind of luminosities can be achieved?
- How big a ring needs to be?
- How much power will it consume?

Luminosity of a circular lepton collider

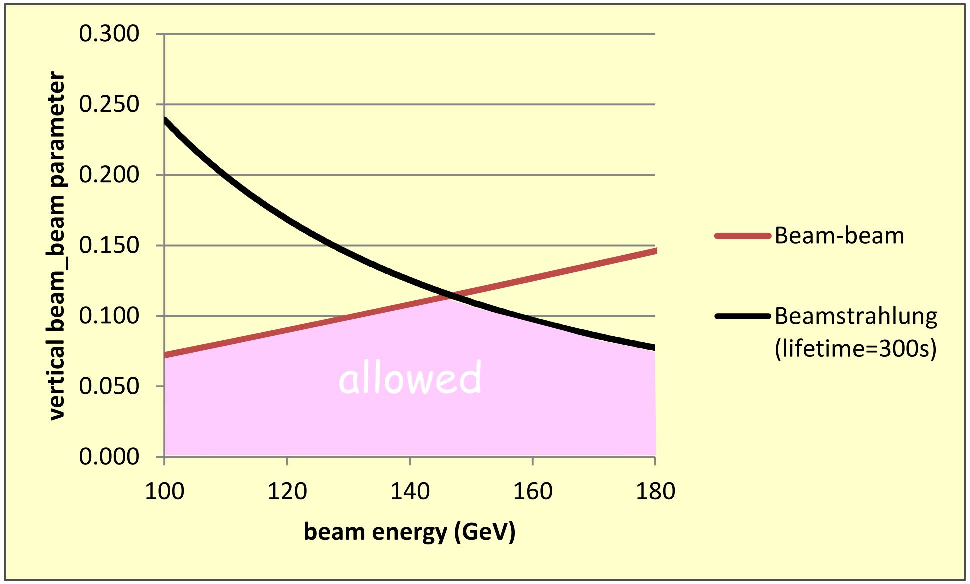
$$\mathcal{L} = const \times P_{tot} \frac{\rho}{{E_0}^3} \xi_y \frac{R_{hg}}{\beta_y^*}$$

The maximum luminosity is bound by the total power dissipated, the maximum achievable beam-beam parameter, the bending radius, the beam energy, the amount of vertical squeezing β_y^* , and the hourglass effect, a geometrical factor (which is a function of σ_z and β_y^*)

$$\mathcal{L} = 6.0 \times 10^{34} \left(\frac{P_{tot}}{50MW}\right)\left(\frac{\rho}{10km}\right)\left(\frac{120GeV}{E_0}\right)^3 \left(\frac{\xi_y}{0.1}\right)\left(\frac{R_{hg}}{0.83}\right)\left(\frac{1mm}{\beta_y^*}\right) cm^{-2}s^{-1}$$

Two limits for the beam-beam parameter

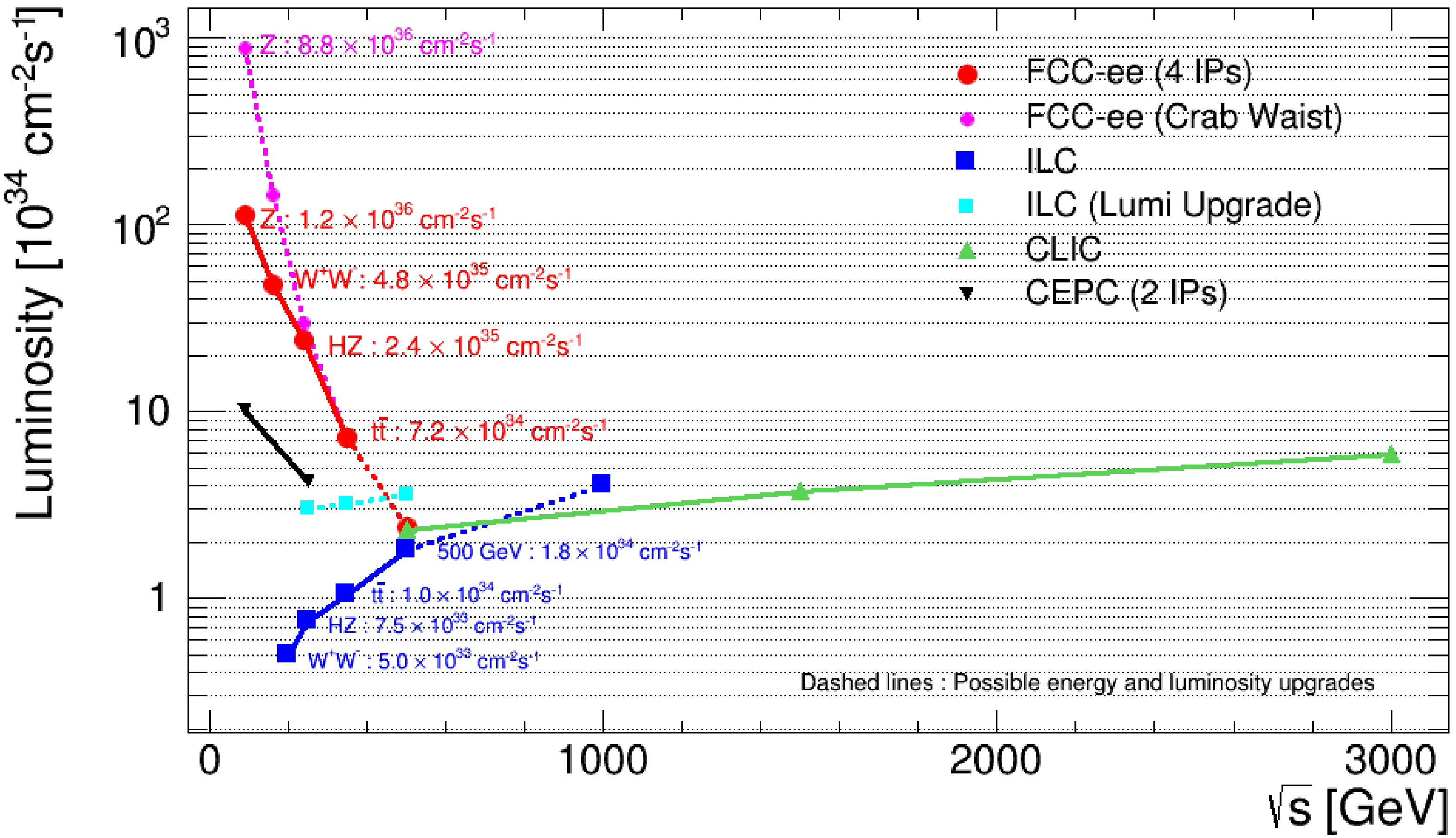
- At low energies the beam-beam parameter ξ saturates at the so-called beam-beam limit
- At high energies, the "beamstrahlung" limit arrives first



Parameters of FCC-ee-175

Beamstrahlung: is the synchrotron radiation emitted by an incoming electron in the collective electromagnetic field of the opposite bunch at an interaction point. The main effect at circular colliders at high energy is decreasing the beam lifetime.

Advertised luminosity of e+e- colliders



LEP1: 0.2×10^{32}
LEP2: 1.2×10^{32}

Linear colliders: energy reach
Circular colliders: high lumi for Z,W,t,H

Circular colliders: challenges

- Although the technology used is mature and used for 50 years…
- To squeeze the maximum possible luminosity there are a number of challenges:
  - Very small emittances although the rings are very large
  - Large momentum acceptance
  - The Interaction Region optics are complex
  - 100MW of SR power needs to be managed
  - Energy efficiency is important for responsible power management – currently the RF system has an efficiency (wall to beam) of 50% - we would like to have this figure increased
- Not to be underestimated the political and financial challenges for making the project a reality

Emittances

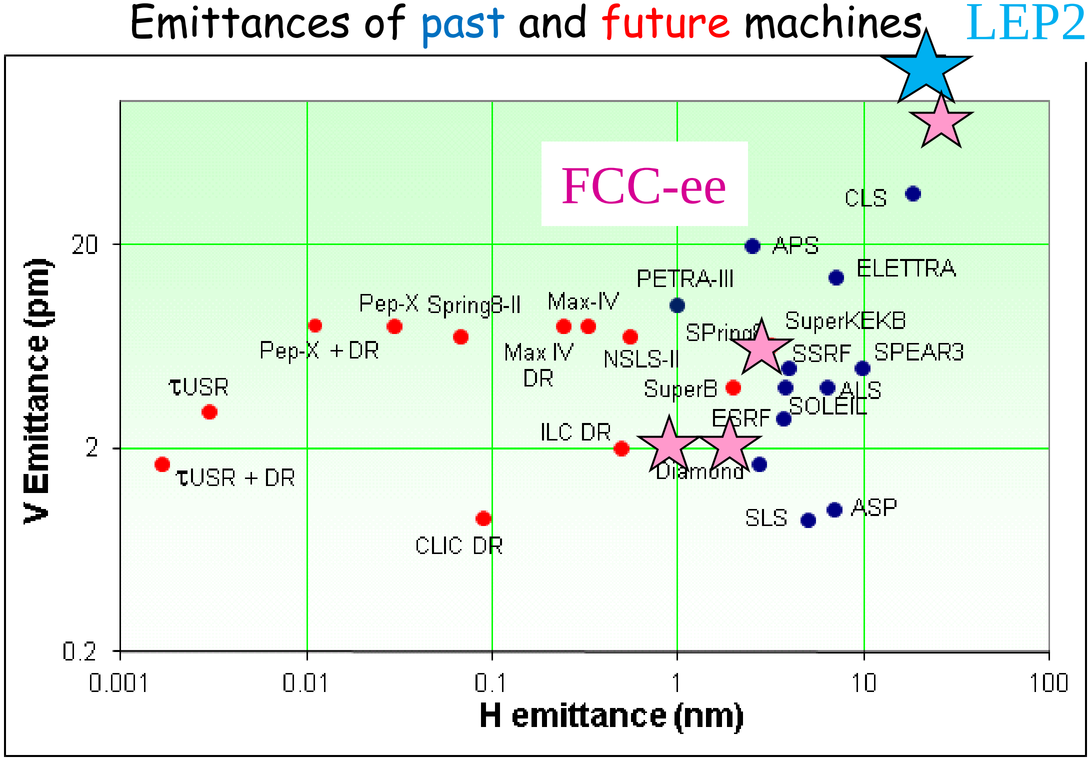
- Low emittances (especially vertical) is essential for delivering the luminosity promised and for mitigating the beamstrahlung problem
- FCC-ee is a very large machine, scaling of achievable emittances (mainly vertical) is not straightforward (Coupling, spurious vertical dispersion).
- Low emittances tend to be more difficult to achieve in colliders as compared to light sources or damping rings (beam-beam)

- FCC-ee parameters:
  - $\varepsilon_y/\varepsilon_x$ = 0.001 or 0.002,
  - $\varepsilon_y \geq \approx 2$ pm

  with a ring ~50-100 larger than a typical light source.

- **Very challenging target for a ring of this size!**

Emittances of past and future machines

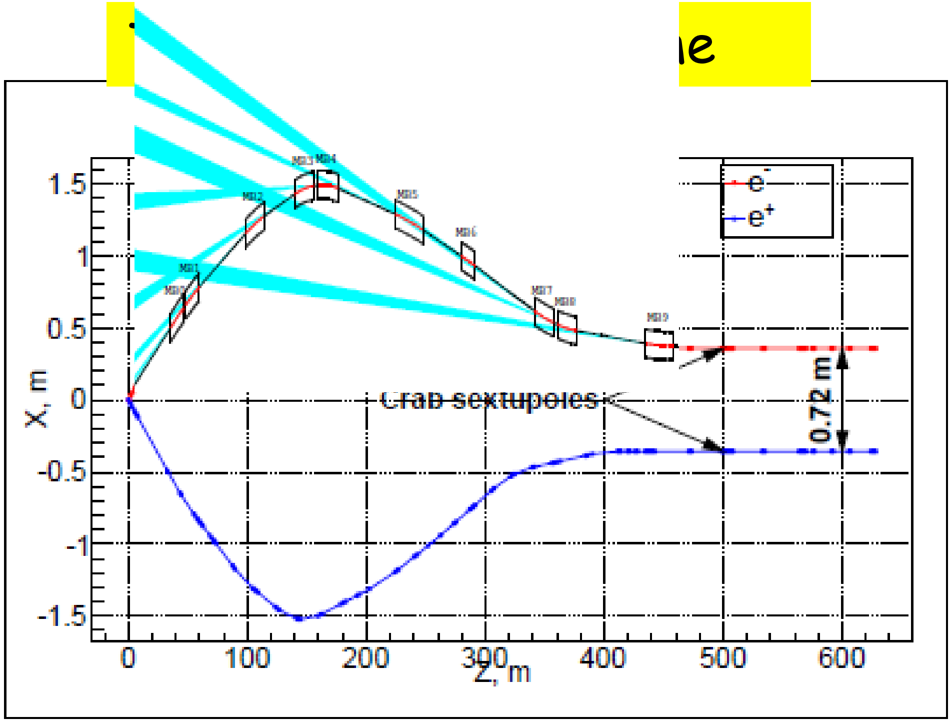


R. Bartolini, DIAMOND

The interaction region

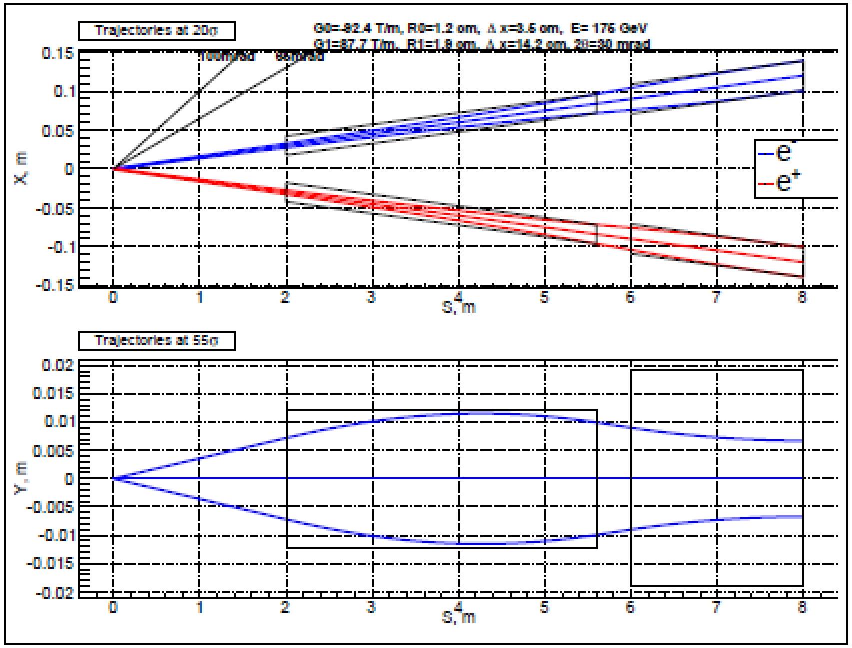
Beams cross at the IP with an angle of 30mrad
Interaction region optical elements are 1.2kms long

Synchrotron radiation fans

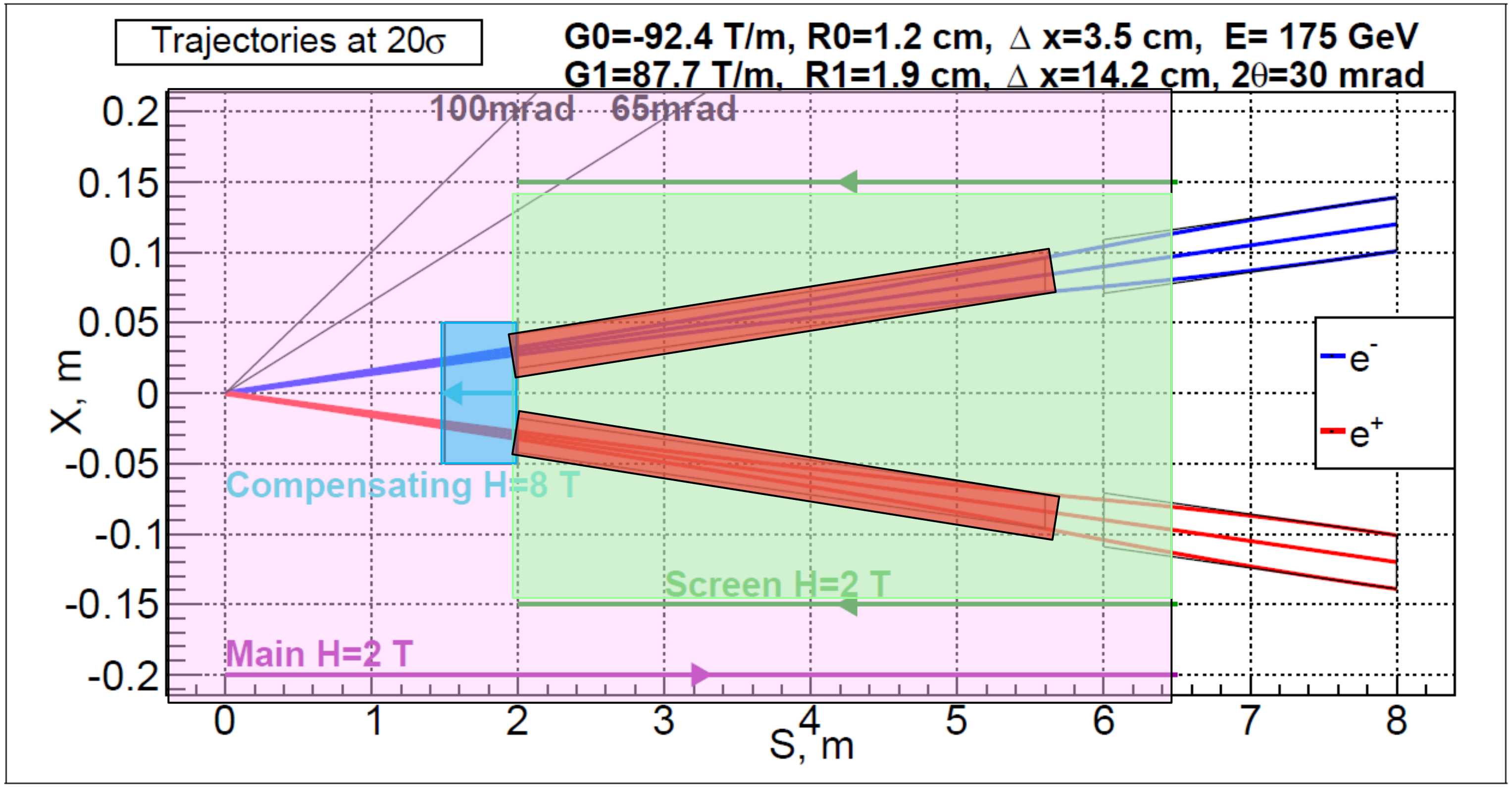


Energy loss $\Delta U = 0.1$ GeV

Bare apertures at the IR. Note that last focusing quadruple is 2m from the IR



A zoom close to the IR: main, compensating and screening solenoids



Final quads

Main detector solenoid

Quad screening solenoid

Compensating solenoid

Siting study 93 km perimeter
PRELIMINARY

Alignment | **Shaft Tools**

Choose alignment option

93km quasi-circular ▼

Tunnel depth at centre: 286mASL

Gradient Parameters

Azimuth (°): -15

Slope Angle x-x(%): .3

Slope Angle y-y(%): 0

CALCULATE

Alignment centre

X: 2498923 Y: 1106695

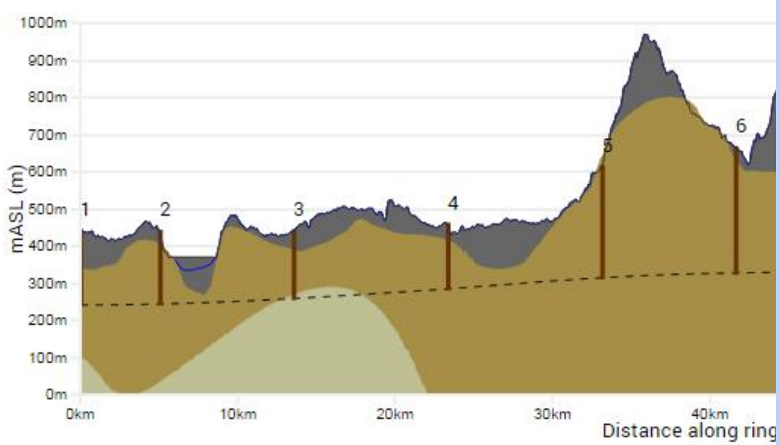
LHC Intersection	IP 1	IP 2
Angle	1°	-1°
Depth	542m	542m

Alignment Location

Geology Intersected by Shafts | **Shaft Depths**

	Shaft Depth (m)				Geology (m)		
Shaft	Actual	Min	Mean	Max	Moraine	Molasse	Calcaire
1	200	195	197	200	92	108	0
2	196	143	181	211	34	162	0
3	183	175	184	194	53	121	9
4	174	146	166	178	44	130	0
5	299	286	311	350	0	325	0
6	336	325	339	350	35	302	0
7	374	349	377	412	119	256	0
8	337	318	341	366	44	56	237
9	155	131	145	167	94	61	0
10	315	305	320	336	46	269	0
11	203	199	202	204	122	81	0
12	239	229	238	243	58	181	0
Total	3014	2801	3001	3211	741	2052	247

Alignment Profile



First look at geology: Tool exists

Preliminary conclusions:

- 93 km tunnel fits geological situation well
- 100 km tunnel seems also compatible with geological considerations
- The LHC could be used as an injector

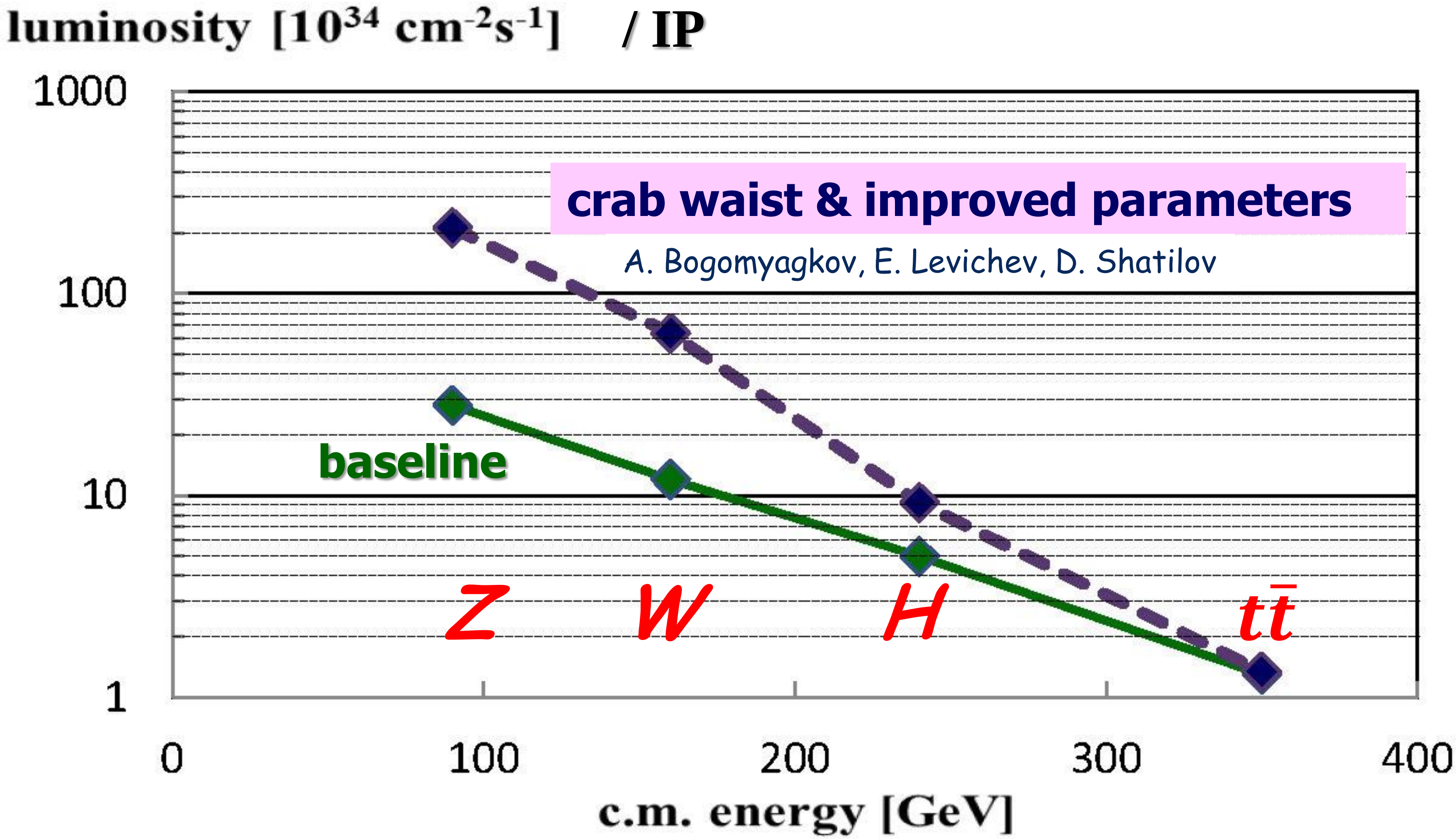
J. Osborne & C. Cook

Main baseline parameters

- This is work in progress and rapidly evolving

Parameter	Z	W	H	t	LEP2
E (GeV)	45	80	120	175	104
I (mA)	1400	152	30	7	4
No. bunches	16’700	4’490	1’330	98	4
Power (MW/beam)	50	50	50	50	11
E loss/turn (GeV)	0.03	0.33	1.67	7.55	3.34
Total RF voltage(GV)	2.5	4	5.5	11	3.5
$\beta^*_{x/y}$ (mm)	500 / 1	500 / 1	500 / 1	1000 / 1	1500 / 50
ε_x (nm)	29	3.3	1	2	30-50
ε_y (pm)	60	7	2	2	~250
ξ_y	0.03	0.06	0.09	0.09	0.07
L (10^{34} $cm^{-2}s^{-1}$)	**28**	**12**	**6.0**	**1.8**	**0.012**
Number of IPs	4	4	4	4	4
Lumi lifetime (mins)	213	52	21	24	310

FCC-ee luminosity vs energy



The crab waist approach looks very promising and might well become our baseline approach

Statistics

A possible physics programme:

- two years at the Z pole (of which one year with the design luminosity and resonant depolarization for energy calibration, and one year with longitudinal polarization at reduced luminosity)
- one or two years at the WW threshold with periodic returns at the Z peak for detector calibration, and with resonant depolarization
- five years at 240 GeV as a Higgs factory with periodic returns at the Z peak
- and five years at the $t\bar{t}$ threshold with periodic returns at the Z.

ECM (GeV)	Luminosity per IP	Statistics – 4 IPs
350	1.8×10^{34} cm^{-2}s^{-1}	10^6 $t\bar{t}$ pairs
240	5.9×10^{34} cm^{-2}s^{-1}	$2\ 10^6$ ZH events
160	1.2×10^{35} cm^{-2}s^{-1}	10^8 WW pairs
90	$2.8\ 10^{35}$ cm^{-2}s^{-1}	10^{12} Z decays

If only two experiments, reduce statistics by 35% (and not 50%, due to higher beam-beam parameter)

A real Z, W, H, t factory!

The physics case of FCC-ee

Physics case published: JHEP01 (2014) 164

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First look at the physics case of TLEP

The TLEP Design Study Working Group

M. Bicer,[a] H. Duran Yildiz,[b] I. Yildiz,[c] G. Coignet,[d] M. Delmastro,[d] T. Alexopoulos,[e] C. Grojean,[f] S. Antusch,[g] T. Sen,[h] H.-J. He,[i] K. Potamianos,[j] S. Haug,[k] A. Moreno,[l] A. Heister,[m] V. Sanz,[n] G. Gomez-Ceballos,[o] M. Klute,[o] M. Zanetti,[o] L.-T. Wang,[p] M. Dam,[q] C. Boehm,[r] N. Glover,[r] F. Krauss,[r] A. Lenz,[r] M. Syphers,[s] C. Leonidopoulos,[t] V. Ciulli,[u] P. Lenzi,[u] G. Sguazzoni,[u] M. Antonelli,[v] M. Boscolo,[v] U. Dosselli,[v] O. Frasciello,[v] C. Milardi,[v] G. Venanzoni,[v] M. Zobov,[v] J. van der Bij,[w] M. de Gruttola,[x] D.-W. Kim,[y] M. Bachtis,[z] A. Butterworth,[z] C. Bernet,[z] C. Botta,[z] F. Carminati,[z] A. David,[z] L. Deniau,[z] D. d'Enterria,[z] G. Ganis,[z] B. Goddard,[z] G. Giudice,[z] P. Janot,[z] J. M. Jowett,[z] C. Lourenço,[z] L. Malgeri,[z] E. Meschi,[z] F. Moortgat,[z] P. Musella,[z] J. A. Osborne,[z] L. Perrozzi,[z] M. Pierini,[z] L. Rinolfi,[z] A. de Roeck,[z] J. Rojo,[z] G. Roy,[z] A. Sciabà,[z] A. Valassi,[z] C.S. Waaijer,[z] J. Wenninger,[z] H. Woehri,[z] F. Zimmermann,[z] A. Blondel,[aa] M. Koratzinos,[aa] P. Mermod,[aa] Y. Onel,[ab] R. Talman,[ac] E. Castaneda Miranda,[ad] E. Bulyak,[ae] D. Porsuk,[af] D. Kovalskyi,[ag] S. Padhi,[ag] P. Faccioli,[ah] J. R. Ellis,[ai] M. Campanelli,[aj] Y. Bai,[ak] M. Chamizo,[al] R.B. Appleby,[am] H. Owen,[am] H. Maury Cuna,[an] C. Gracios,[ao] G. A. Munoz-Hernandez,[ao] L. Trentadue,[ap] E. Torrente-Lujan,[aq] S. Wang,[ar] D. Bertsche,[as] A. Gramolin,[at] V. Telnov,[at] M. Kado,[au] P. Petroff,[au] P. Azzi,[av] O. Nicrosini,[aw] F. Piccinini,[aw] G. Montagna,[ax] F. Kapusta,[ay] S. Laplace,[ay] W. da Silva,[ay] N. Gizani,[az] N. Craig,[ba] T. Han,[bb] C. Luci,[bc] B. Mele,[bc] L. Silvestrini,[bc] M. Ciuchini,[bd] R. Cakir,[be] R. Aleksan,[bf] F. Couderc,[bf] S. Ganjour,[bf] E. Lançon,[bf] E. Locci,[bf] P. Schwemling,[bf] M. Spiro,[bf] C. Tanguy,[bf] J. Zinn-Justin,[bf] S. Moretti,[bg] M. Kikuchi,[bh] H. Koiso,[bh] K. Ohmi,[bh] K. Oide,[bh] G. Pauletta,[bi] R. Ruiz de Austri,[bj] M. Gouzevitch[bk] and S. Chattopadhyay[bl]

JHEP01(2014)164

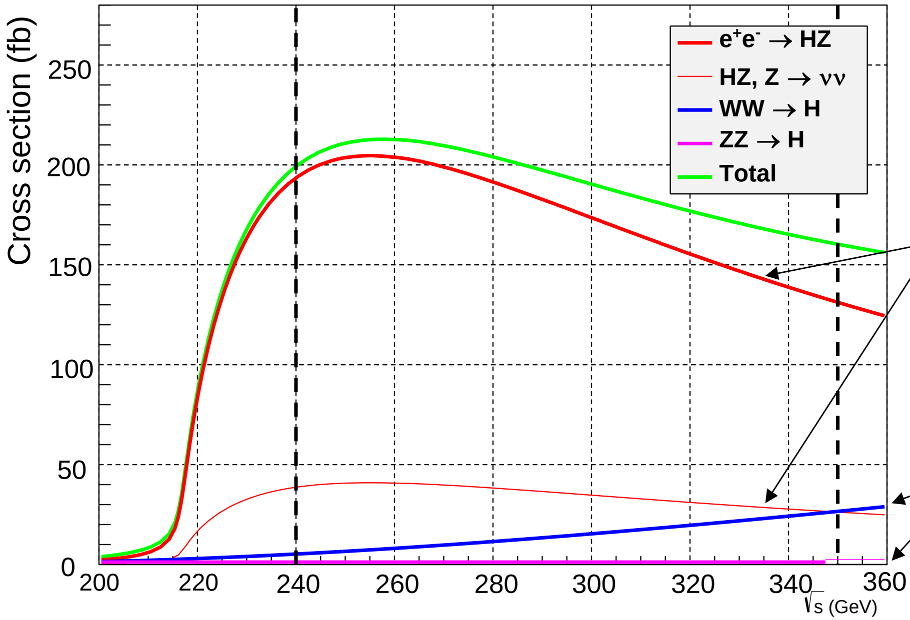
- **Precision measurements**
  - **Model independent Higgs properties**
    - ➔ **Couplings (0.1%), Γ_H (1%), m_H (8 MeV)**
    - ➔ **Dark matter (invisible width – 0.1%)**
    - ➔ **Exploration of new physics with couplings to Higgs boson up to 10 TeV**
  - **Precise mass measurements**
    - ➔ **m_Z (< 0.1 MeV), m_W (< 0.5 MeV)**
    - ➔ **m_{top} (~10 MeV)**
  - **Electroweak observables, α_S, …**
    - ➔ **Exploration of new physics with EW couplings up to 100 TeV**
- **So far , CMS simulations or "just" paper studies**
- **New ideas have appeared in recent workshops, e.g.,**
  - **Higher luminosity with crab waist**
  - **Smaller energy spread with monochromators**
  - **Sensitivity to very small couplings**
    - ➔ **Higgs couplings to 1^{st} generation**
    - ➔ **Sterile neutrinos**

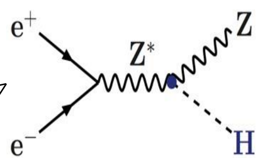
- **It is only the tip of the iceberg**
  - **Thinking out of the box needed until 2018 at least**

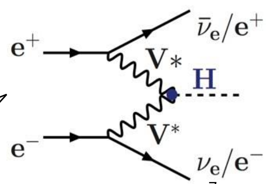
P. Janot

Higgs cross sections and expected events

Unpolarized cross sections

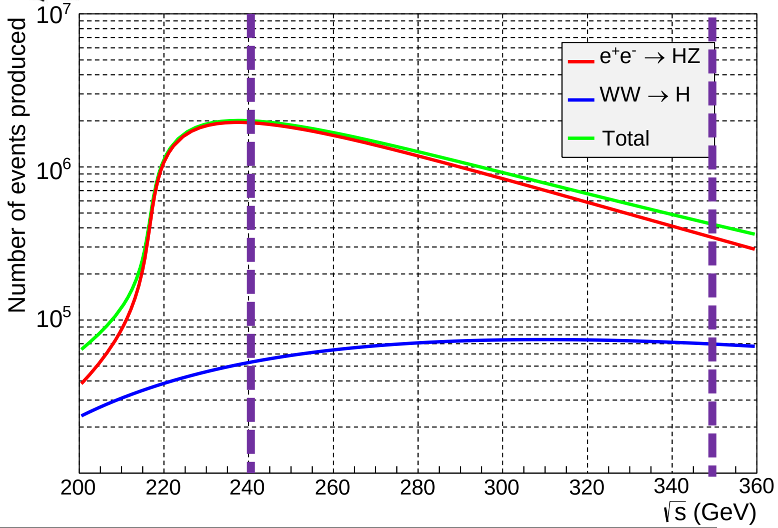






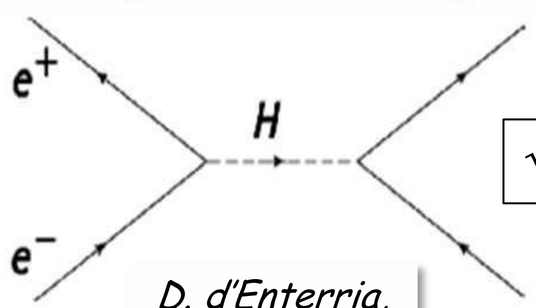
Cross sections for Higgstrahlung and vector boson fusion processes

Xross sections combined with the FCC-ee luminosity profile – five years and for 4 experiments



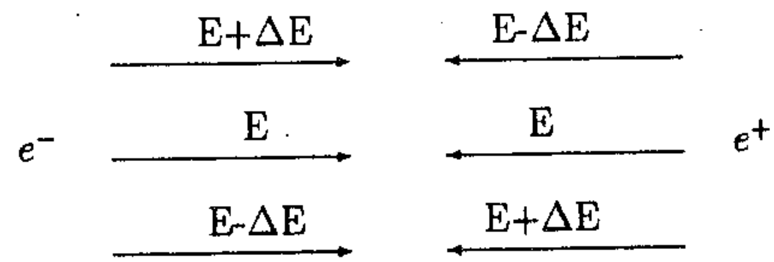
Higgs couplings to the first generation

- Is it s crazy idea to measure directly the Yukawa couplings to electrons (resonant production in the s channel)? The coupling is very small, but the FCC-ee has very high luminosity



D. d'Enterria, R. Aleksan

$\sqrt{s}$ = 125 GeV



Monochromatization technique - principle

- An immediate problem we encounter: the beam energy spread is ~10 times larger than the Higgs width – for this idea to work a "monochromatization technique" should be used
- FCC-ee: 10^4 events / year at the peak, but …
  - Huge background from Z, γ , need to follow the tides, …
  - Can set upper limit on κ_e to ~2 × SM value

Difficult but exciting

Opportunities in Higgs physics, ILC, CLIC, FCC-ee

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)		CLIC		
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
BR_{inv}	0.9%	$< 0.9\%$	$< 0.9\%$	0.4%	0.19%	$< 0.19\%$			

F. Lediberder

- Higgs couplings, width, branching fraction to exotics. Statistical errors only, model independent fit
- Need to reduce theoretical uncertainties to match

Opportunities in EW precision physics

- Electroweak precision measurements made at LEP with 10^7 Z decays, together with accurate W and top-quark mass measurements from the Tevatron, are sensitive to weakly-coupled new physics at a scale up to ~3 TeV.
- To increase this sensitivity by a factor of 10 to 30 TeV, an improvement in precision by two orders of magnitude is needed, i.e., an increase in statistics by four orders of magnitude to at least 10^{11} Z decays.
- At the same time, the current precision of the W and top-quark mass measurements needs to be improved by at least one order of magnitude, i.e., to better than 1 MeV and 50 MeV respectively, in order to match the increased Z-pole measurement sensitivity.
- These experimental endeavours might well be possible at the FCC-ee.

Opportunities in EW precision physics

Observable	Measurement	Current precision	TLEP stat.	Possible syst.	Challenge
m_Z (MeV)	Lineshape	91187.5 ± 2.1	0.005	< 0.1	QED corr.
Γ_Z (MeV)	Lineshape	2495.2 ± 2.3	0.008	< 0.1	QED corr.
R_l	Peak	20.767 ± 0.025	0.0001	< 0.001	Statistics
R_b	Peak	0.21629 ± 0.00066	0.000003	< 0.00006	$g \rightarrow bb$
N_ν	Peak	2.984 ± 0.008	0.00004	< 0.004	Lumi meas.
$\alpha_s(m_Z)$	R_l	0.1190 ± 0.0025	0.00001	0.0001	New Physics
m_W (MeV)	Threshold scan	80385 ± 15	0.3	< 0.5	QED Corr.
N_ν	Radiative returns $e^+e^- \rightarrow \gamma Z, Z \rightarrow \nu\nu, ll$	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	< 0.0001	CKM Matrix
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	μ = 2.5 ± 1.05	13%	?	$\alpha_s(m_Z)$

Systematic errors dominate!

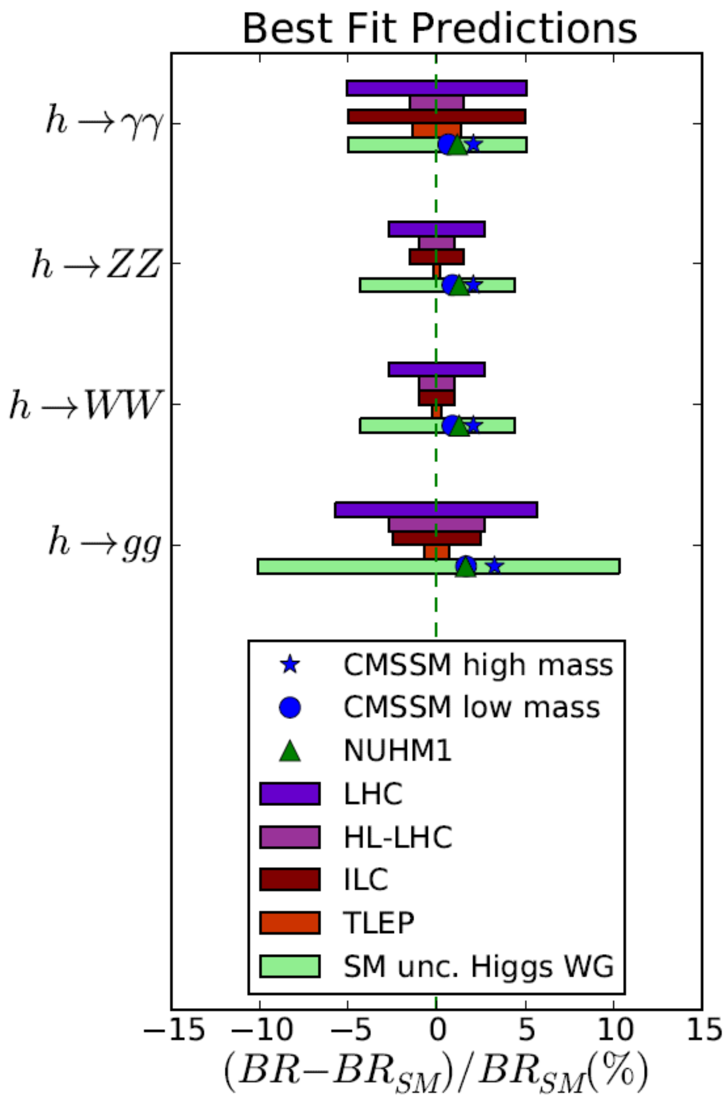
Based on LEP experience – much work ahead.

Polarization at FCC-ee

- Transverse polarization essential for the accurate measurement of lineshape parameters – using the resonant depolarization technique which gives an instantaneous error of ~100keV
- At LEP transverse polarization was used at the Z but not the W
- We aim for a large improvement at FCC-ee:
  - Depolarization measurement of non-colliding bunches every few minutes – most systematic errors of LEP disappear
  - It is expected that polarization will be observable at the WW threshold, making a huge improvement of the measurement of the W mass
  - (However, polarization times at the FCC-ee are very long: need the use of polarization wigglers)
- Longitudinal polarization at the Z is very valuable for the measurement of A_{LR} and $A^{f}_{FB.Pol}$, but is not straight forward to achieve with colliding beams (contrary to linear colliders).

$$\sigma_E \propto \frac{E^2}{\sqrt{\rho}}$$

SUSY and accuracies



Do we have the accuracy needed to see deviations from SM predictions? In the plot on the left we see the predictions of three SUSY models compared to the accuracy of the LHC, HL-LHC, ILC and TLEP. The theory uncertainty is also shown

Only TLEP can really probe the accuracy of those models

Note that theoretical uncertainties are currently larger than the deviations of susy models and larger than the FCC-ee projected accuracy. Substantial theoretical effort is needed to reduce the uncertainties in the theoretical calculations of the Higgs properties

The physics case - conclusions

The FCC-ee would provide

i. per-mil precision in measurements of Higgs couplings,
ii. unique precision in measurements of Electroweak Symmetry-Breaking parameters and the strong coupling constant,
iii. a measurement of the Z invisible width equivalent to better than 0.001 of a conventional neutrino species, and
iv. a unique search programme for rare Z, W, Higgs, and top decays.

The FCC project – namely the combination of FCC-ee and FCC-hh offers, for a great cost effectiveness, the best precision and the best search reach of all options presently on the market.

JHEP 01 (2014) 164

The first experiment proto-collaboration

Elizabeth Locci (elizabeth.locci@cern.ch) Draft : 01/02/2015

ASAHEL
(A Simple Apparatus for High Energy LEP)

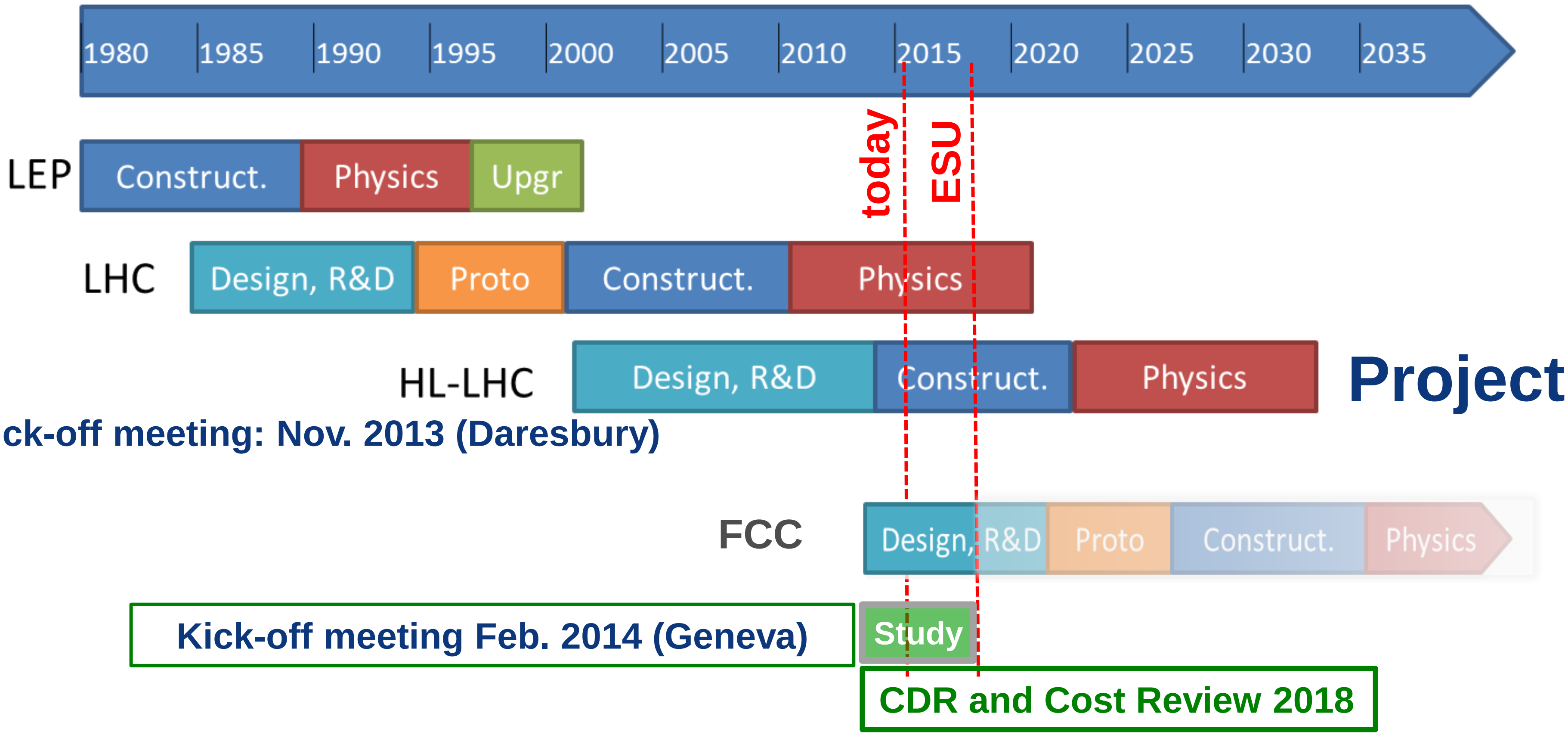
Proposal

Authors, Institutes

Abstract

The TLEP Design Study Working Group published "Fist Look at the TLEP Physics Case" in December 2013. TLEP, a 90-400 GeV high-luminosity, high precision, e^+e^- machine, is now part of the Future Circular Collider (FCC) design study, as a possible first step (named FCC-ee) towards a high-energy proton-proton collider (named FCC-hh).

CERN and FCC timelines



- LHC and HL-LHC operation until ~2035
- Must start now developing FCC concepts to be ready in time

FCC Kick-off Meeting
University of Geneva
12-15 February 2014

~340 participants

First FCC Week

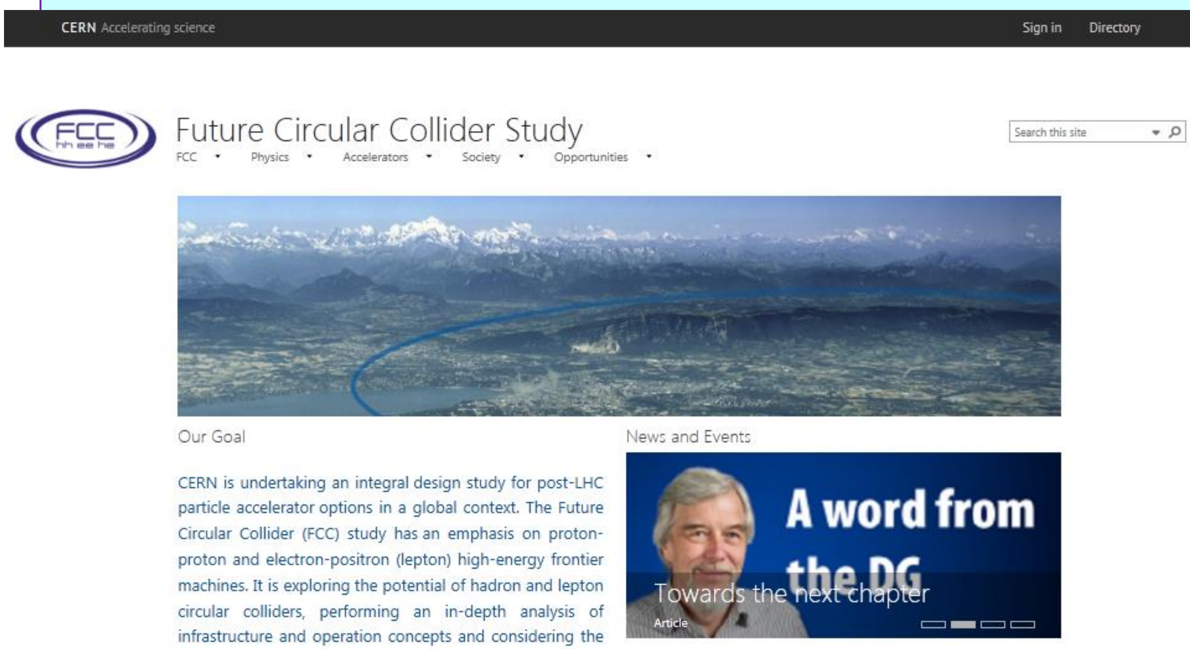
Conference

Washington DC
23-27 March 2015

http://cern.ch/fccw2015

Join us!

- This programme stretches way into the future (provided that it gets the go-ahead)
- But you can help shape the future today by joining in one or more of the working groups



Public site: http://cern.ch/fcc
FCC collaboration site: http://cern.ch/fcc/collaboration
Indico site: http://indico.cern.ch/category/5153/

Conclusions

- The FCC project offers unique opportunities to further explore Nature…
  - …by increasing the Energy frontier (through the 100TeV hadron collider)
  - …and by changing the game of precision physics by offering unprecedented statistics at an E_{CM} of 90 GeV (Z), 160 GeV (W), 240 GeV (ZH) and 350 GeV (tt) (with a high luminosity e+e- collider)

Is history repeating itself…?

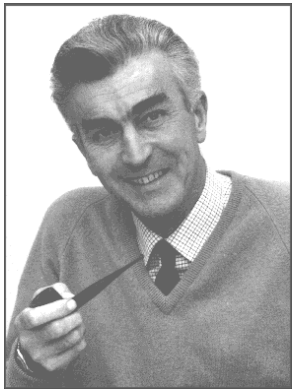
When **Lady Margaret Thatcher** visited CERN in 1982, she asked the then CERN Director-General **Herwig Schopper** ***how big would the next tunnel after LEP be.***

Margaret Thatcher,
British PM 1979-90

Dr. Schopper's answer was ***there would be no bigger tunnel at CERN***.

Herwig Schopper
CERN DG 1981-88
built LEP

Lady Thatcher replied that she had obtained ***exactly the same answer from Sir John Adams when the SPS was built 10 years earlier***, and therefore she did not believe him.



John Adams
CERN DG 1960-61 & 1971-75
built PS & SPS

Was lady Thatcher right?

Herwig Schopper, private communication, 2013; curtesy F. Zimmermann

End

Thank you

BACKUP SLIDES

FCC-ee baseline parameters including crab waist (c.w.)

parameter	LEP2	FCC-ee				
		Z	Z (c.w.)	W	H	t
E_{beam} [GeV]	104	45	45	80	120	175
circumference [km]	26.7	100	100	100	100	100
current [mA]	3.0	1450	1431	152	30	6.6
$P_{SR,tot}$ [MW]	22	100	100	100	100	100
no. bunches	4	16700	29791	4490	1360	98
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4
ε_x [nm]	22	29	0.14	3.3	0.94	2
ε_y [pm]	250	60	1	1	2	2
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0
β^*_y [mm]	50	1	1	1	1	1
σ^*_y [nm]	3500	250	32	84	44	45
$\sigma_{z,SR}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16
$\sigma_{z,tot}$ [mm] (w beamstr.)	11.5	2.56	5.9	1.49	1.17	1.49
hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73
L/IP [10^{34} cm^{-2}s^{-1}]	0.01	28	212	12	6	1.7
τ_{beam} [min]	434	298	39	73	29	21

Ph. Lebrun

FCC study

MoU status on 21 January 2015

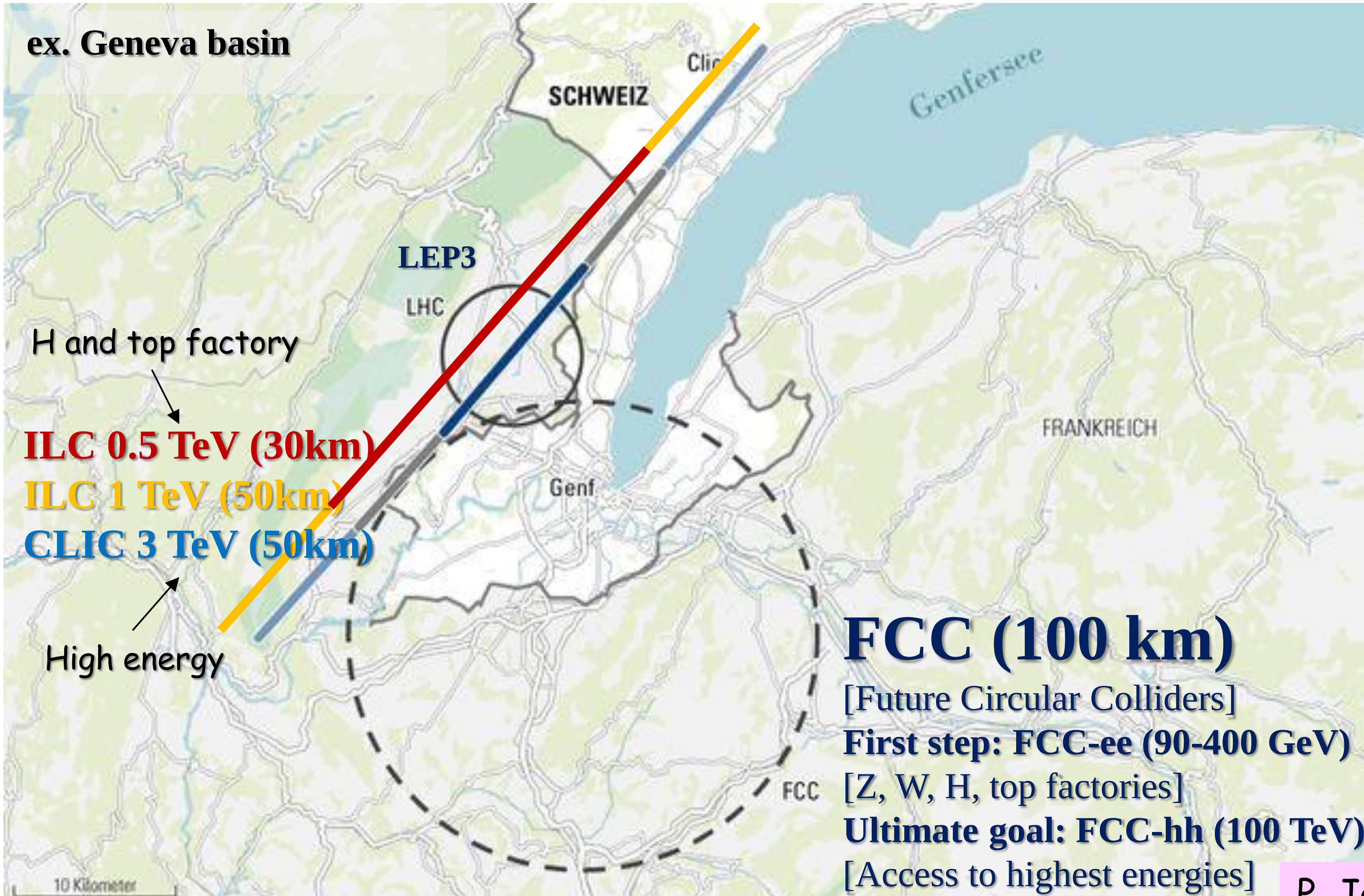
43 collaboration members

ALBA/CELLS, Spain
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CIEMAT, Spain
CNRS, France
Cockcroft Institute, UK
U Colima, Mexico
CSIC/IFIC, Spain
TU Darmstadt, Germany
DESY, Germany
TU Dresden, Germany
Duke U, USA

EPFL, Switzerland
Gangneung-Wonju Nat. U., Korea
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
Hellenic Open U, Greece
HEPHY, Austria
IFJ PAN Krakow, Poland
INFN, Italy
INP Minsk, Belarus
U Iowa, USA
IPM, Iran
UC Irvine, USA
Istanbul Aydin U., Turkey

JAI/Oxford, UK
JINR Dubna, Russia
KEK, Japan
KIAS, Korea
King’s College London, UK
Korea U Sejong, Korea
MEPhI, Russia
Northern Illinois U., USA
NC PHEP Minsk, Belarus
PSI, Switzerland
Sapienza/Roma, Italy
UC Santa Barbara, USA
U Silesia, Poland
TU Tampere, Finland

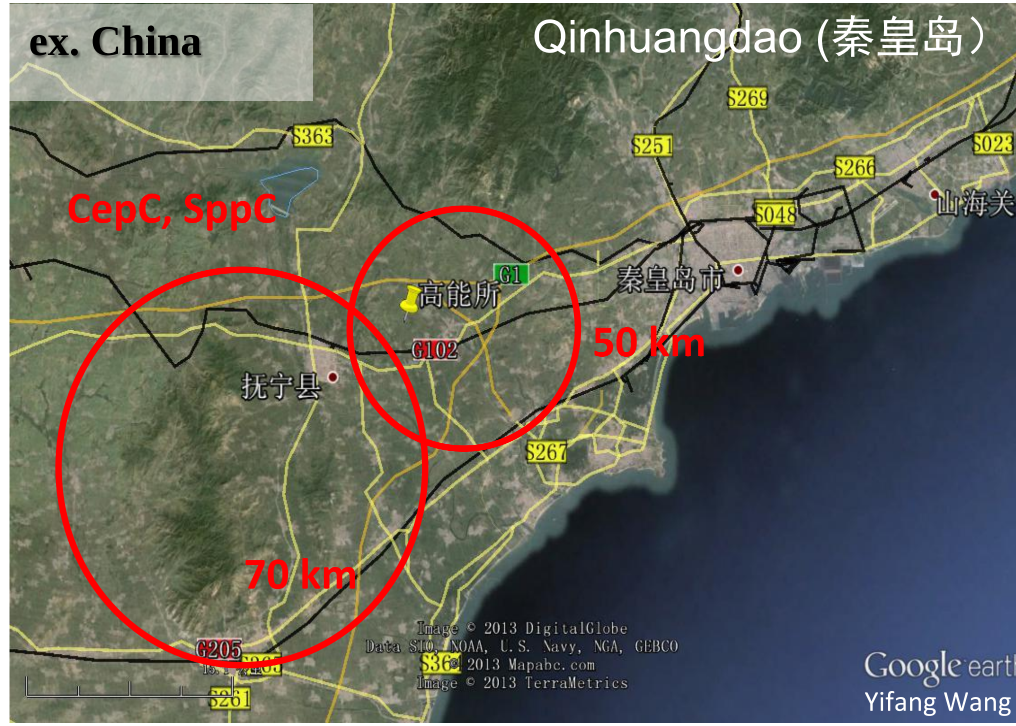
e^+e^- colliders (1)



P. Janot

e^+e^- colliders (2)

- Europe / Asia

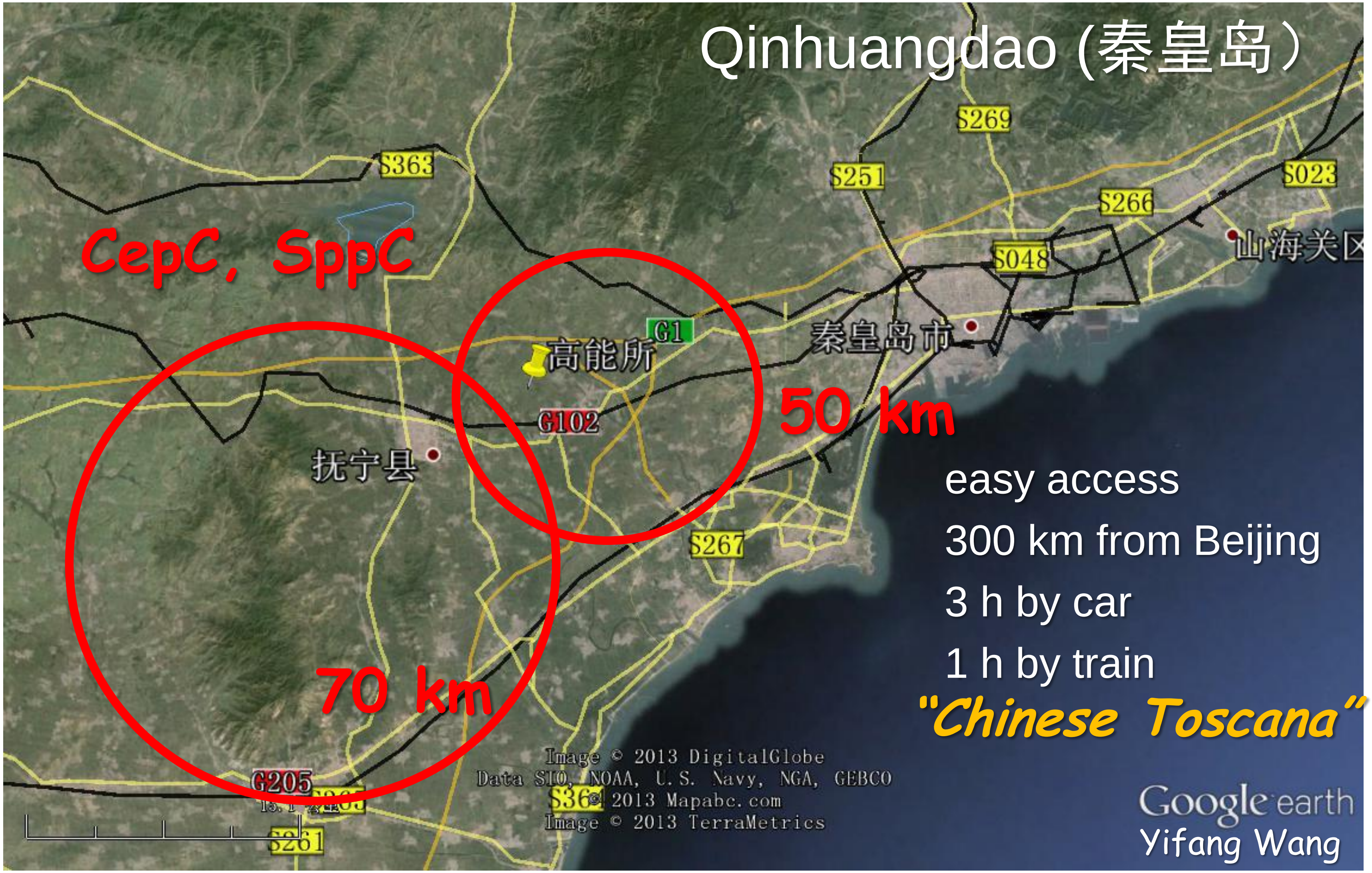


CepC: e^+e^- collisions at 240 GeV (Higgs factory, first step)
SppC: pp collisions at 50-70 TeV (Highest energies)

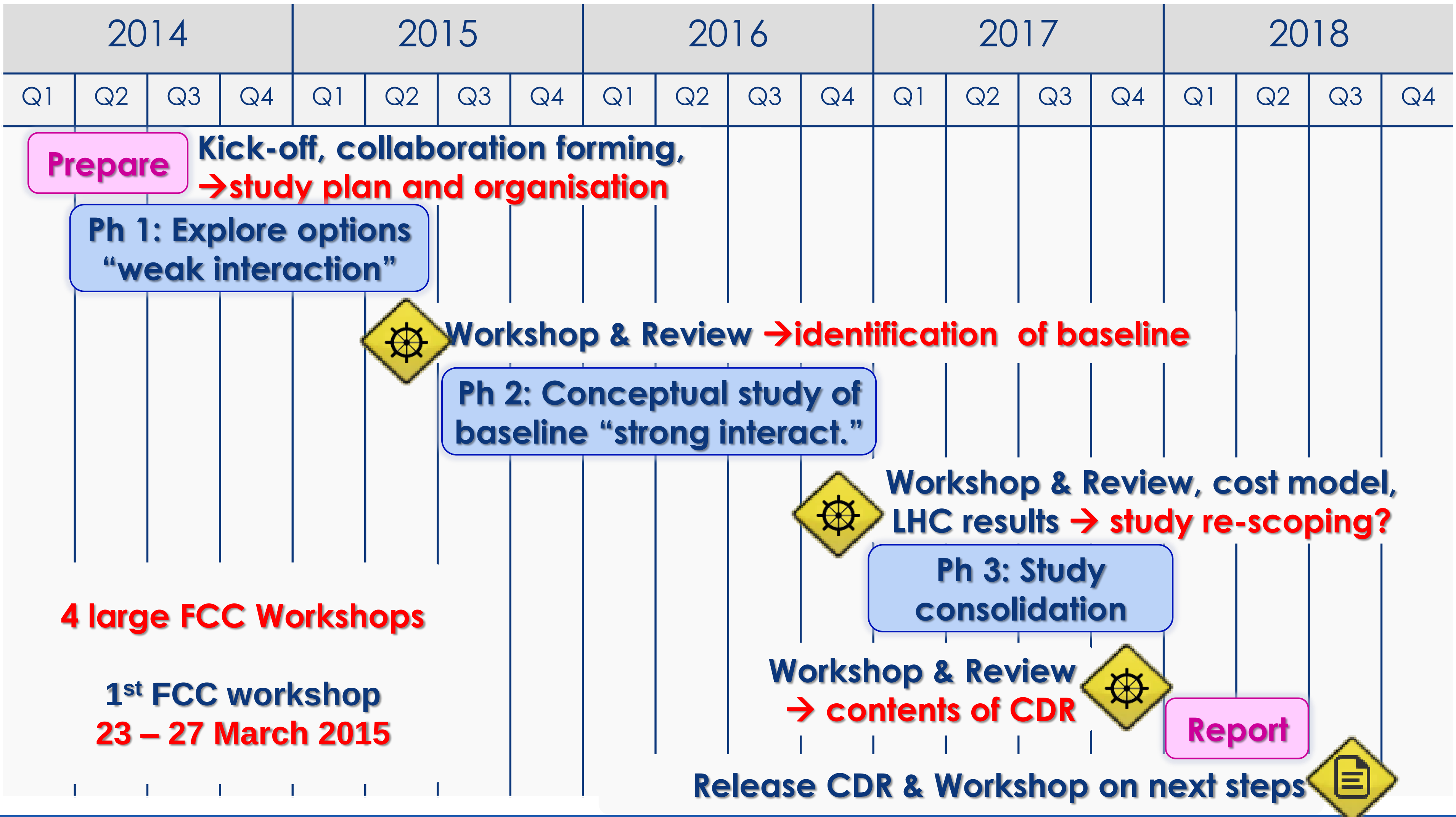
P. Janot

CepC/SppC study (CAS-IHEP), CepC pCDR

Feb. 2015, e^+e^- collisions ~2028; *pp* collisions ~2042



FCC work plan study phase



The Twin Frontiers of **FCC-ee** Physics

Precision Measurements	Rare Decays
• Springboard for sensitivity to new physics • Experimental issues: – Systematics • Theoretical issues: – Higher-order QCD – Higher-order EW – Mixed QCD + EW	• Direct searches for new physics • Many opportunities • Z: 10^{13} • b, c, τ: 10^{12} • W: 10^{8} • H: 10^{6} • t: 10^{6}

J. Ellis

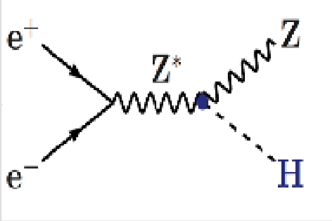
Physics capabilities - example

Main strength is the capability to study all known particles (W, Z, Higgs, top, …) with very high precision. For example: repeat the whole of the LEP physics programme in a few minutes. Also sensitivity to very rare phenomena (very small couplings).

This represents a formidable challenge to theory: with statistical errors reduced by a factor of as much as 100 compared to LEP, theory needs to follow…

Example: **invisible widths**:

- Higgs BR_{exotic} measured to 0.16% (4 IPs)
- Z invisible width (ΔN_ν from LEP 0.008):
  - Z lineshape: N_ν measured to 0.0001 (stat)$\pm$0.004(syst)
  - tagged Z (1 year at ECM 160GeV plus data from 240 and 359GeV) ΔN_ν =0.0008
  - Dedicated run at 105 GeV: ΔN_ν =0.0004



2 10^6 ZH events in 5 years

«A tagged Higgs beam».

$$N_\nu = \frac{\dfrac{\gamma Z(inv)}{\gamma Z \to ee,\mu\mu}}{\dfrac{\Gamma_\nu}{\Gamma_{e,\mu}}(SM)}$$

The physics case – the experimentalist's point of view

Fabiola Gianotti

- "Regardless of the (outcome of the LHC), […] the directions for future high-Energy colliders are clear:
  - highest precision → to probe E scales potentially up to O(100) TeV and smallest couplings (e+e- collider)
  - highest energy → to explore directly new territories and get crucial information to interpret results from indirect probes (pp collider)"
- This calls for an approach similar to the LEP-LHC approach: a new tunnel than can host a variety of circular colliders (pp, ee, ep, …)

The view of a theoretical physicist

Nima Arkani-Hamed

In my view, the scientific questions at stake in our field today are the most difficult + profound ones we have faced since the 1930's

The scale of our vision and ambition – both theoretically + experimentally – must be commensurate with the ... tasks at hand

Clearly, how to proceed will depend on first LHC13 results.

But in every scenario I can imagine, we will need the 100 TeV pp machine

* Circular e^+e^- machine Higgs Factory plays very important, complementary role

Looking for $\frac{h^\dagger h (h Q b^c)}{\Lambda^2}$, $\frac{(h^\dagger D_\mu h)^2}{\Lambda^2}$, ...

* Tera-Z particularly exciting + powerful probe!

Global fit for Higgs boson couplings - detailed

	Model-independent fit			Constrained fit	
Coupling	TLEP-240	TLEP	ILC	TLEP	ILC
g_{HZZ}	0.16%	0.15% (0.18%)	0.9%	0.05% (0.06%)	0.31%
g_{HWW}	0.85%	0.19% (0.23%)	0.5%	0.09% (0.11%)	0.25%
g_{Hbb}	0.88%	0.42% (0.52%)	2.4%	0.19% (0.23%)	0.85%
g_{Hcc}	1.0%	0.71% (0.87%)	3.8%	0.68% (0.84%)	3.5%
g_{Hgg}	1.1%	0.80% (0.98%)	4.4%	0.79% (0.97%)	4.4%
$g_{H\tau\tau}$	0.94%	0.54% (0.66%)	2.9%	0.49% (0.60%)	2.6%
$g_{H\mu\mu}$	6.4%	6.2% (7.6%)	45%	6.2% (7.6%)	45%
$g_{H\gamma\gamma}$	1.7%	1.5% (1.8%)	14.5%	1.4% (1.7%)	14.5%
BR_{exo}	0.48%	0.45% (0.55%)	2.9%	0.16% (0.20%)	0.9%

FCC Coordination Team

Future Circular Colliders - Conceptual Design Study
Study coordination, M. Benedikt, F. Zimmermann

Hadron collider
D. Schulte

Hadron injectors
B. Goddard

e+ e- collider and injectors
J. Wenninger

Infrastructure, cost estimates
P. Lebrun

e- p option
Integration aspects **O. Brüning**

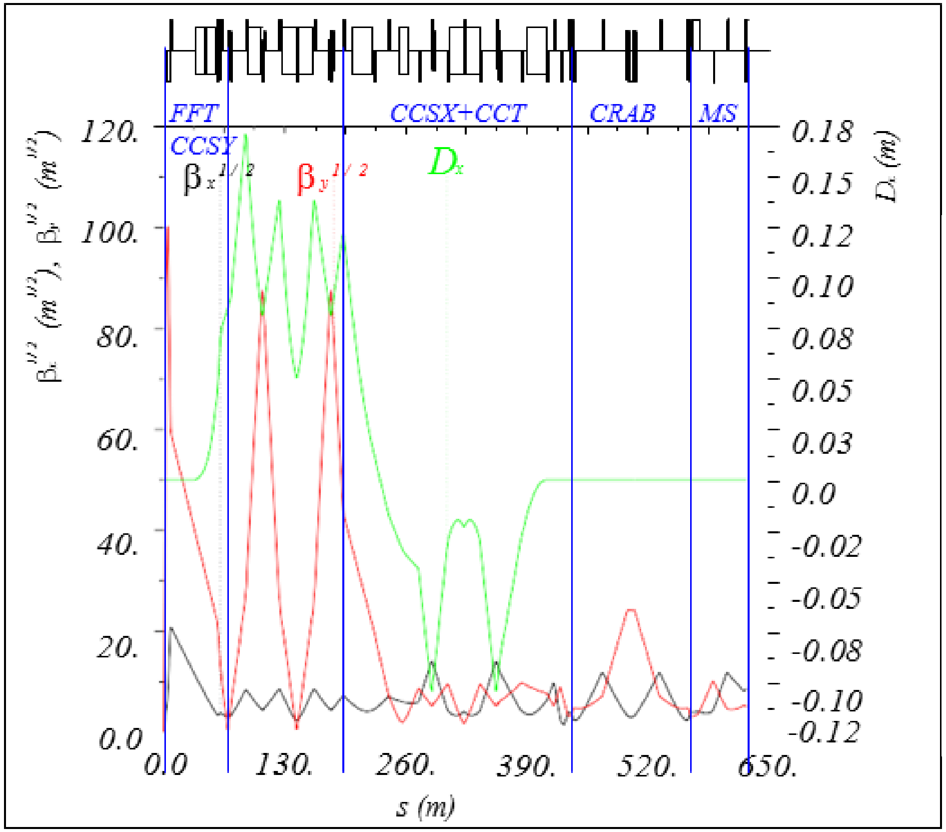
Operation aspects,
energy efficiency, safety, environment **P. Collier**

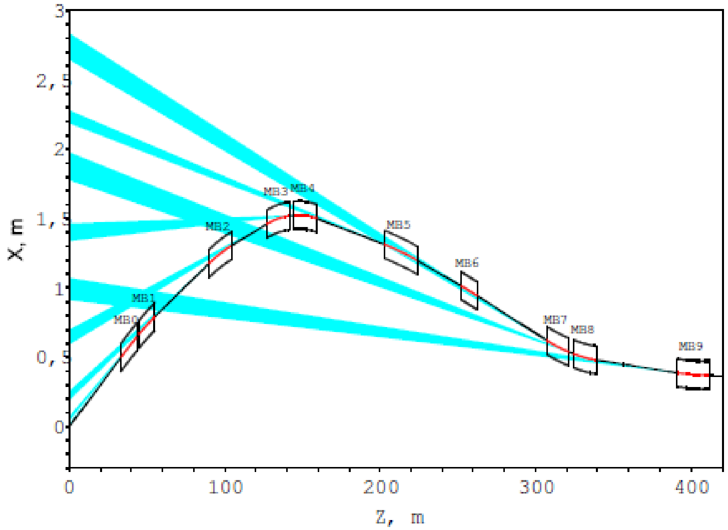
Technology
- High Field Magnets **L. Bottura**
- Supercon-ducting RF **E. Jensen**
- Cryogenics **L. Tavian**
- Specific Technologies **JM. Jimenez**

Physics and experiments
- Hadrons **A. Ball, F. Gianotti, M. Mangano**
- e+ e- **A. Blondel J. Ellis, P. Janot**
- e- p **M. Klein**

Planning (Implementation roadmap, financial planning, reporting)
F. Sonnemann, J. Gutleber

Optical functions and radiation fans – crab waist scheme

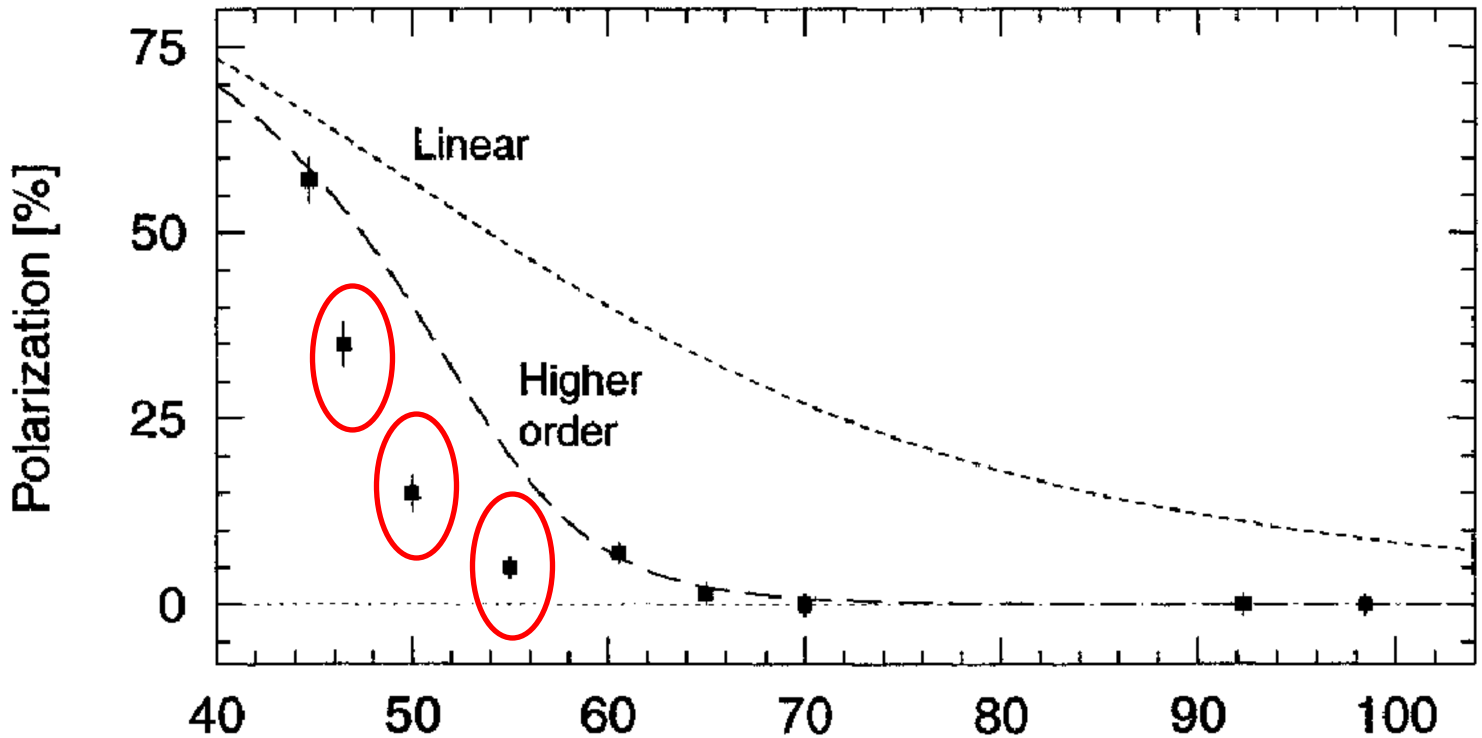




Polarization measurements from LEP

Polarization was seen up to 60GeV – extrapolation to different ring diameters

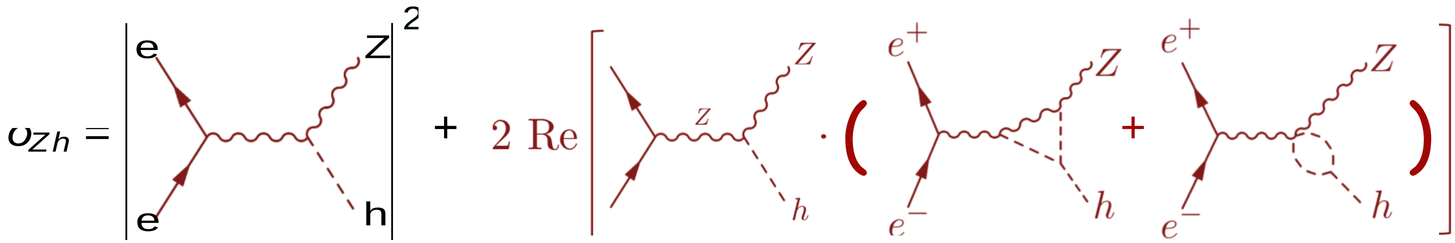
: Not optimized



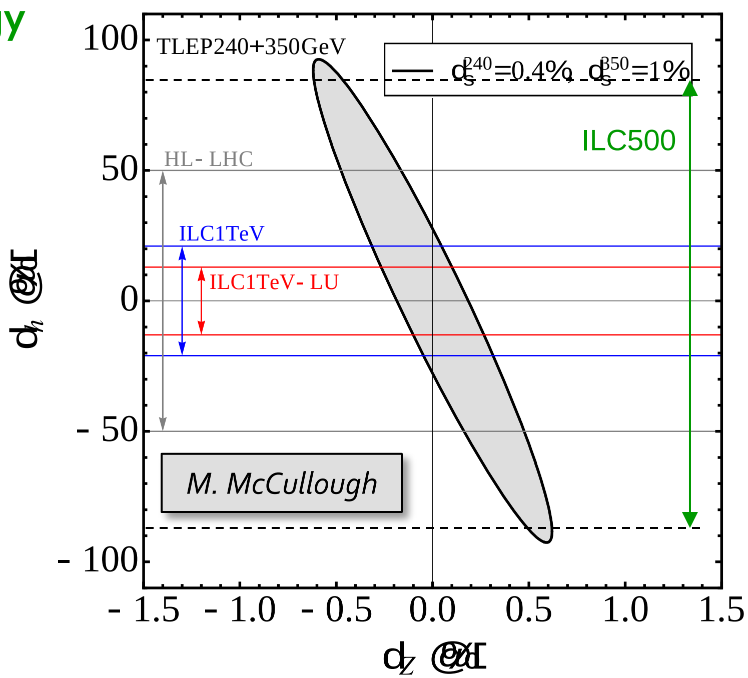
CEPC	47.6	59.5	71.4	83.2	95.1	107.0	118.9
TLEP	55.5	69.4	83.2	97.1	111.0	124.9	138.7

Opportunities in Higgs physics – HHH coupling

- **Unique indirect sensitivity to HHH coupling through the interference term**



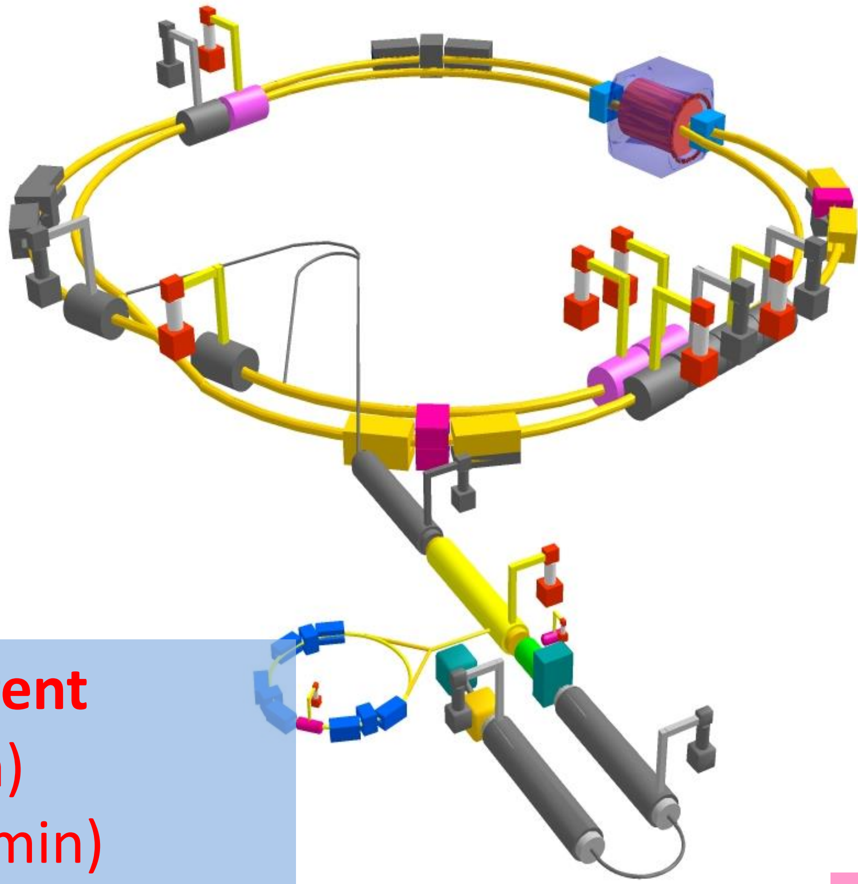
- Tiny effect, but visible thanks to the extraordinary precision on Zh cross section
  - Effect dependent on the centre-of-mass energy
    - ➔ Precision similar to ILC500 (80%)
    - ➔ Reduced to 30% for SM g_{ZZH}



- Comment from N. Arkani-Hamed (HF2014)
  - New physics causing a deviation to the HHH coupling with respect to the standard model would also cause a much larger deviation to the ZZH coupling… (from model building ?)
- Direct double Higgs production FCC-hh
  - Opportunity for better precision (~10% ?)
    - ➔ See Michelangelo's presentation

SuperKEKB = *FCC-ee* demonstrator

beam commissioning will start in early 2015



F. Zimmermann

top up injection at high current

β_y^* =300 μm (FCC-ee: 1 mm)

lifetime 5 min (FCC-ee: ≥20 min)

$\varepsilon_y/\varepsilon_x$ =0.25% (similar to FCC-ee)

off momentum acceptance (±1.5%, similar to FCC-ee)

***e*⁺ production rate** (2.5x10^{12}/s, FCC-ee: <1.5x10^{12}/s (*Z* cr.waist)

***SuperKEKB* goes beyond *FCC-ee*, testing all concepts**

The hadron collider: FCC-hh

The name of the game of a hadron machine is **energy reach.**

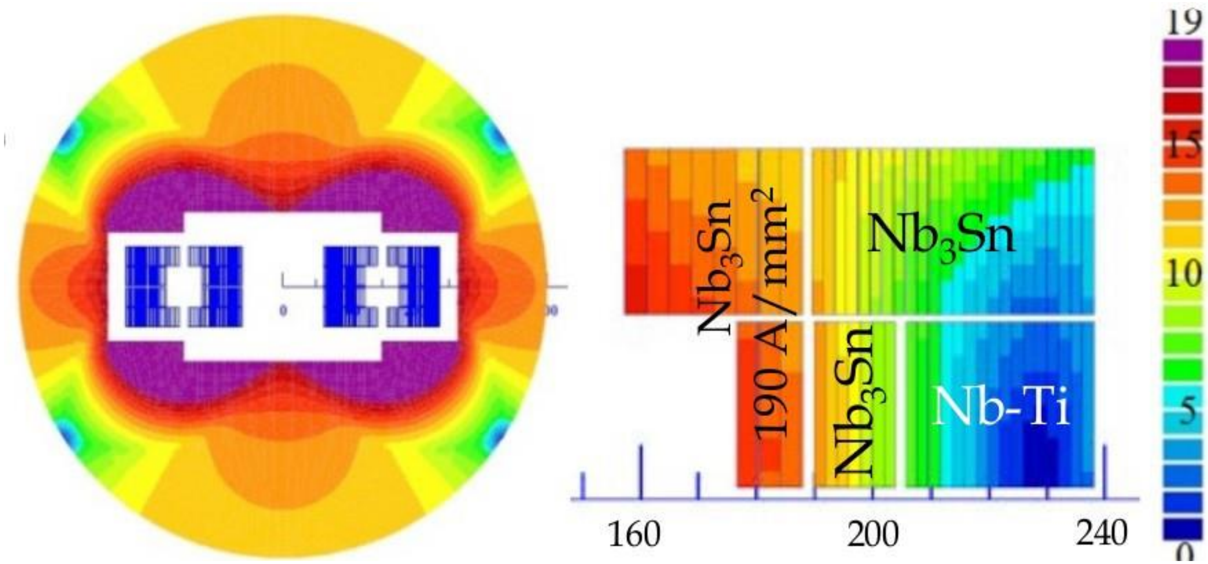
$$E \propto B_{dipole} \times \rho_{bending}$$

Luminosity is (to first order) less of a problem – simply run at a tolerable **pileup.**

To go to 100 TeV from the current 14 TeV of the LHC we need to increase the diameter by a factor of ~3-4 and the field from 8 T to 16-20 T

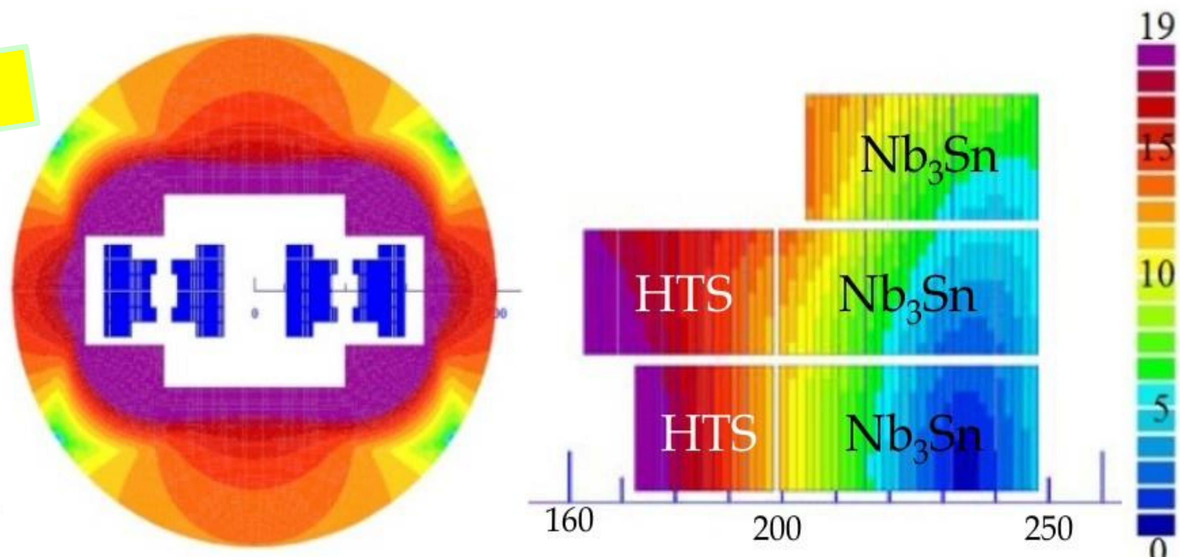
High field dipole magnets

15 T with Nb3Sn and Nb-Ti (preliminary, project goal 16 T)



Quench protection!

20 T with HTS and Nb3Sn

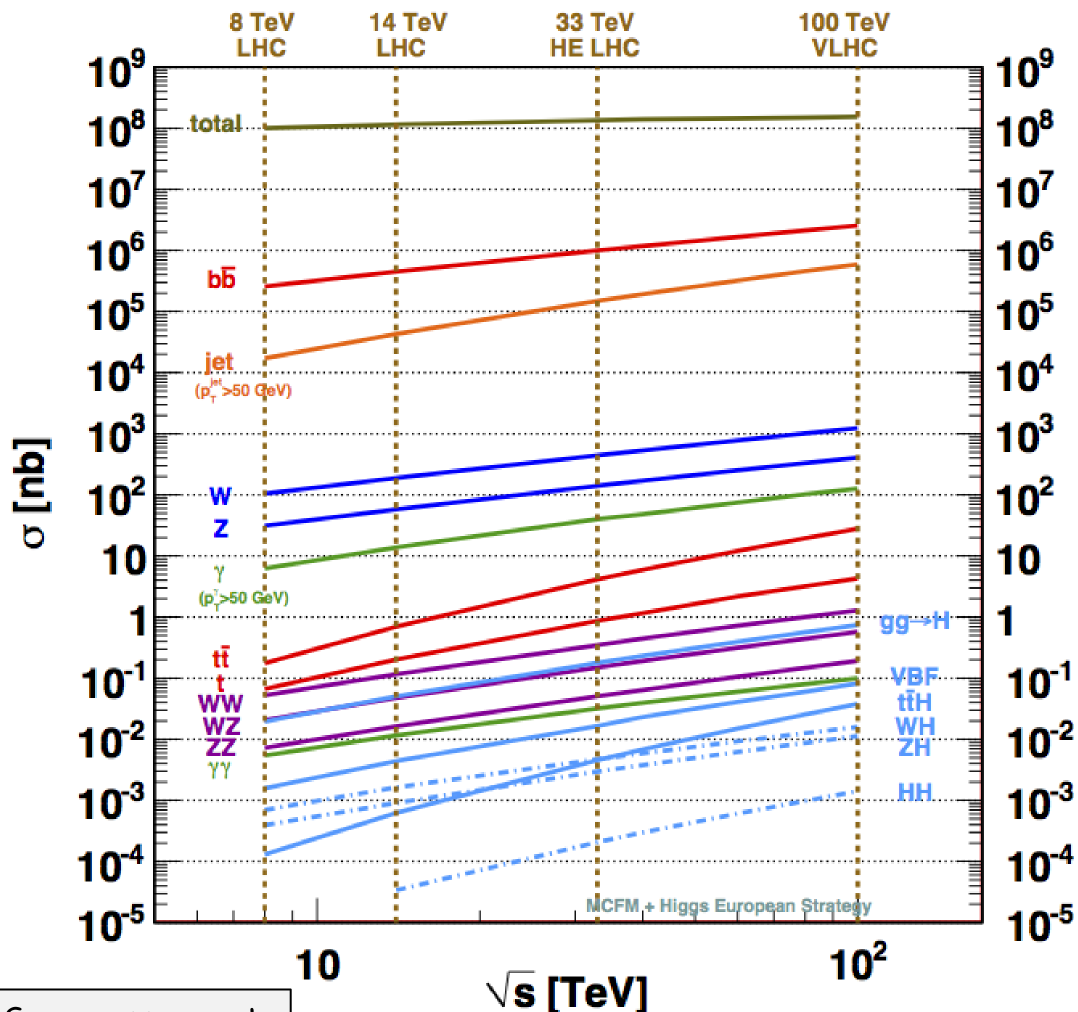


L. Rossi, E. Todesco, `Conceptual design of 20 T dipoles for High-Energy LHC', CERN Yellow Report 2011-003 13-9 (2011)

FCC-hh: main parameters

Parameter	LHC	HL-LHC	FCC-hh
c.m. energy [TeV]	14	14	100
dipole magnet field [T]	8.33	8.33	16 (20)
circumference [km]	27	27	100 (83)
luminosity [1034 cm-2s-1]	1	5	5 [→20?]
bunch spacing [ns]	25	25	25(5)
events / bunch crossing	27	135	170 (34)
bunch population [10[11]]	1		
norm. transverse emitt. [mm]	3		
IP beta-function [m] 0.55	0		
IP beam size [mm]	1		
synchrotron rad. [W/m/aperture]	0		
critical energy [keV]	0		
total syncrotronrad. power [MW]	0		
Total energy stored (beam) [GJ]	0		
Total energy stored (magnets) [GJ]	9		

Cross sections vs √s



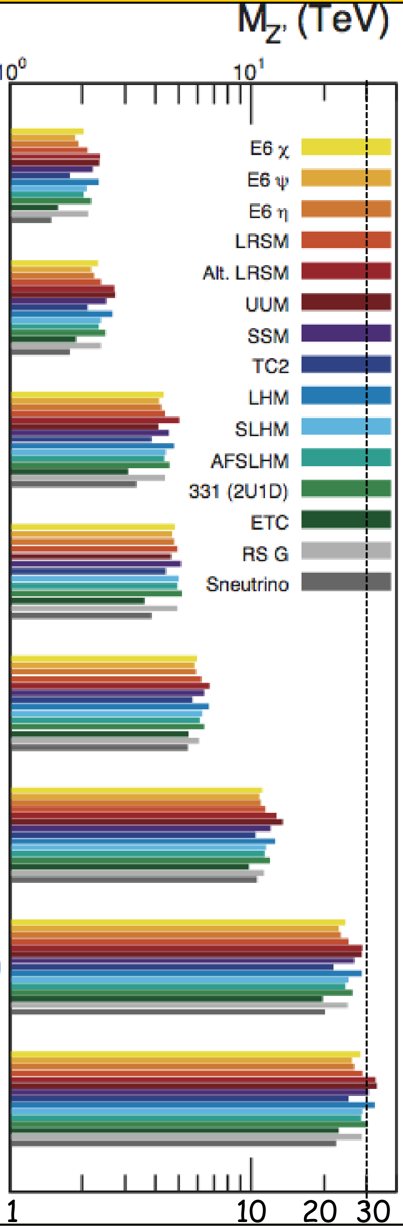
Snowmass report:
arXiv:1310.5189

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	~10^3

→ With 10000/fb at √s=100 TeV expect: 10^{12} top, 10^{10} Higgs bosons, 10^8 m=1 TeV stop pairs, …

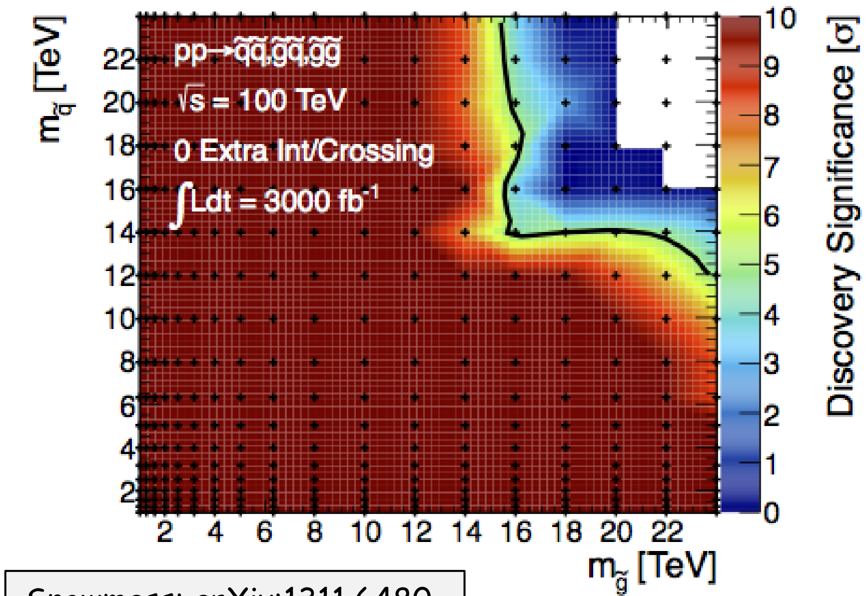
A 100 TeV pp collider is the instrument to explore the O(10 TeV) E-scale directly

Z'



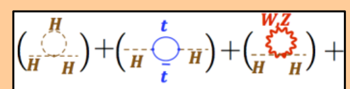
Snowmass report: arXiv:1309.1688

Discovery of squarks and gluinos: up to ~ 15 TeV



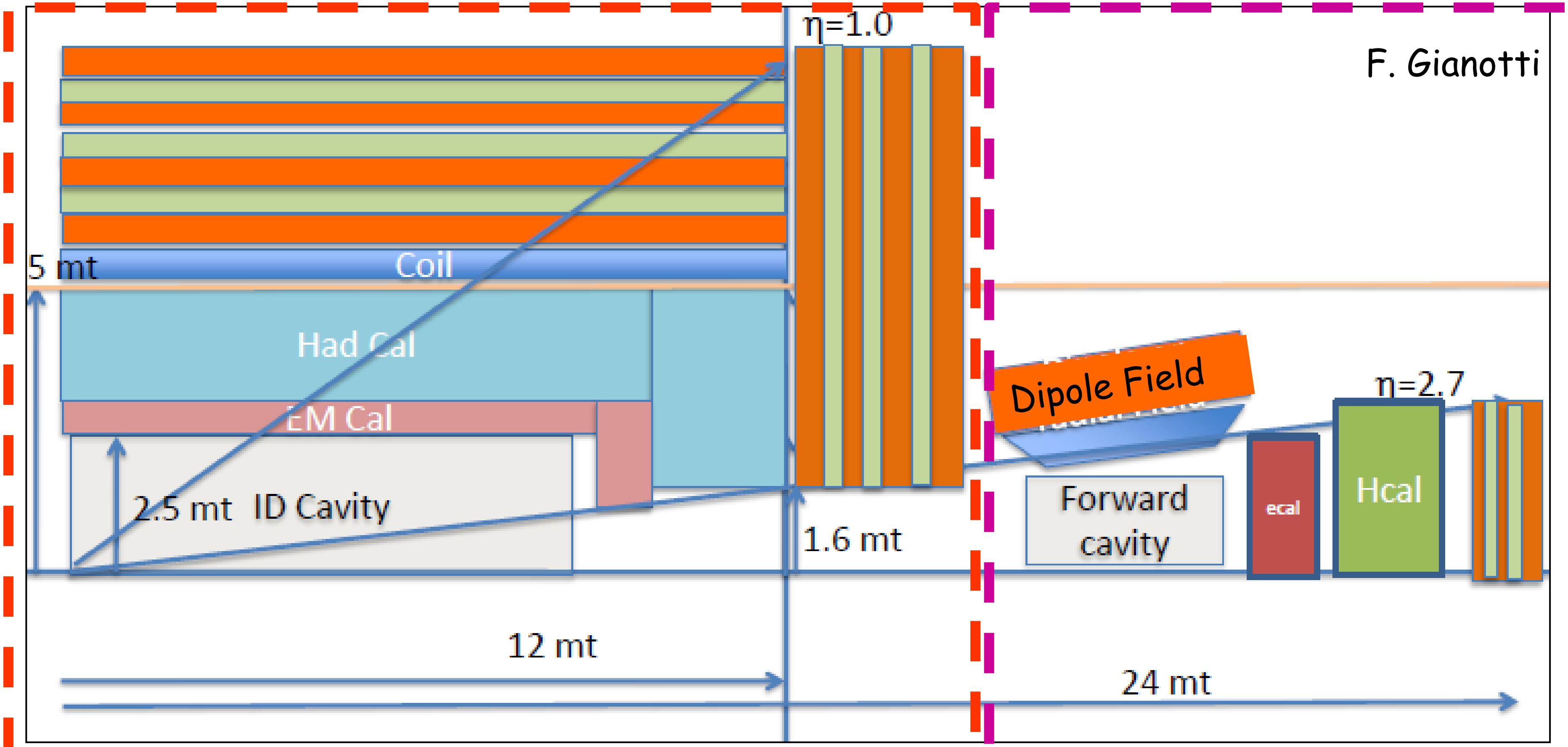
Snowmass: arXiv:1311.6480

The naturalness problem:

$\Delta M_H^2 \sim$  $\cdots \sim \Lambda^2$

- ❑ Only Higgs and nothing else at ~O(1 TeV)
  → 10^{-2} fine-tuning
- ❑ Only Higgs and nothing else at ~O(10 TeV)
  → 10^{-4} fine-tuning

First ideas about detector layout: a-la CMS + LHCb



- Need BL^2 ~10 x ATLAS/CMS to achieve 10% muon momentum resolution at 10-20 TeV
- Solenoid: B=5T, R_{in}=5-6m, L=24m → size is x2 CMS. Stored energy: ~ 50 GJ
- > 5000 m^3 of Fe in return joke → alternative: thin (twin) lower-B solenoid at larger R to capture return flux of main solenoid
- Forward dipole à la LHCb: B~10 Tm
- Calorimetry: ≥ 12 λ for shower containment; W takes less space but requires 50ns integration for slow neutrons; speed advantageous for 5ns option (→ Si active medium ?)