Future Collider Studies at CERN

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7 August 2015

FCC
hh ee he

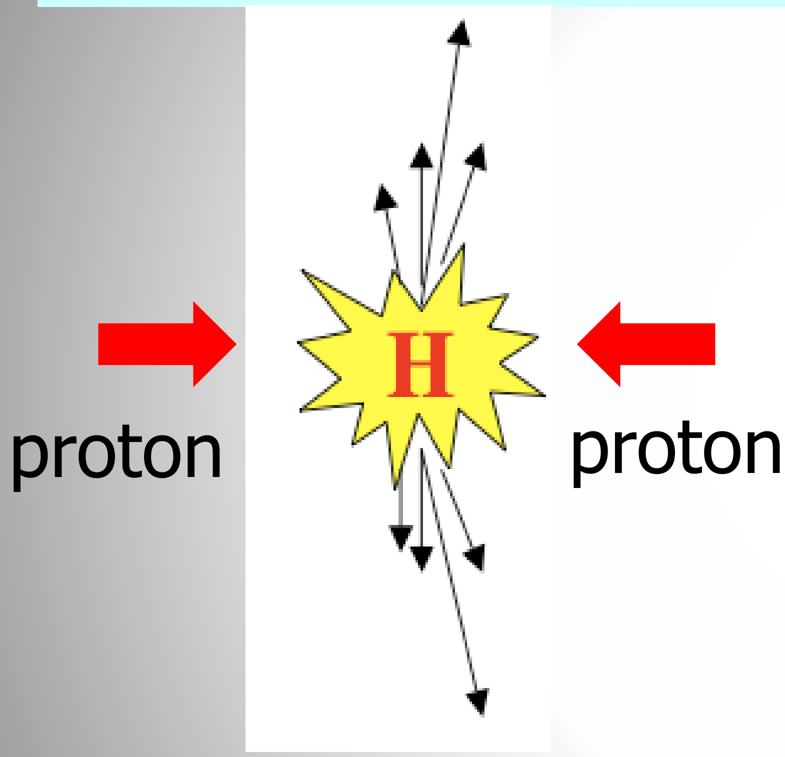
CLIC

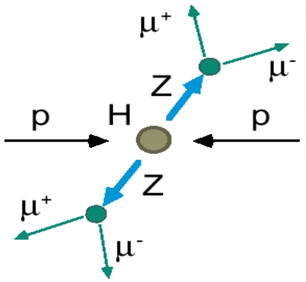
LISHEP2015
UEA - Universidade do Estado do Amazonas www.lishep.uerj.br
High Energy Physics Workshop
August 2 - 9, Manaus Amazonas
"On a River of Discovery"

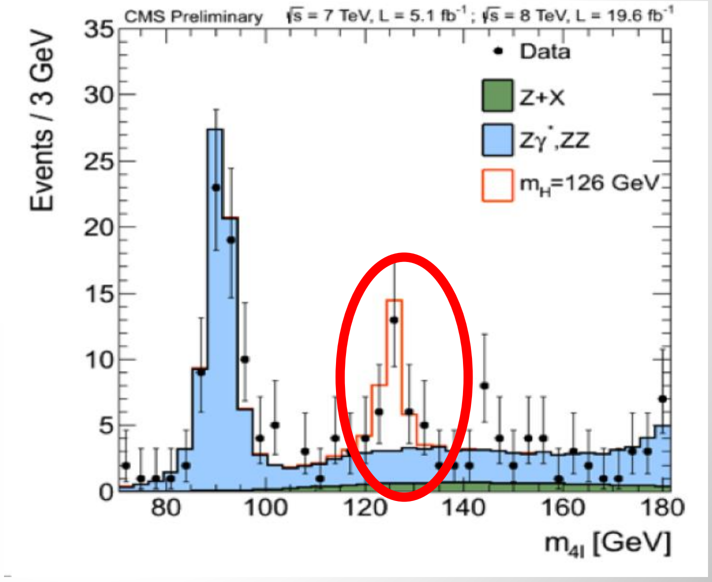
CERN

2012: A Milestone in Particle Physics

Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it





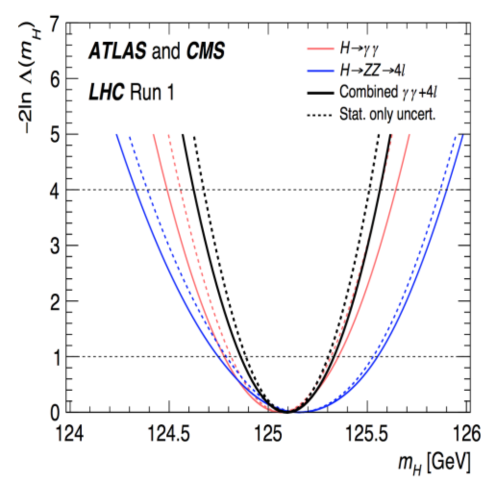


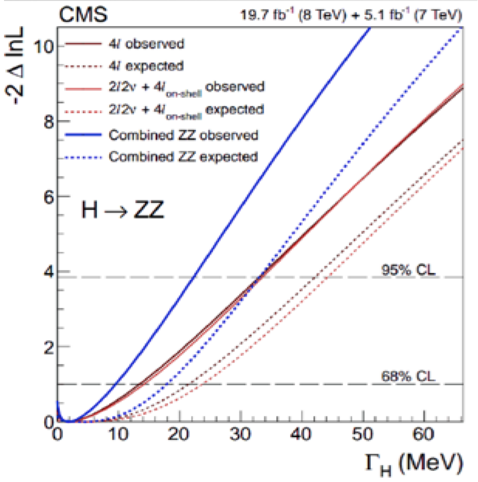
2013

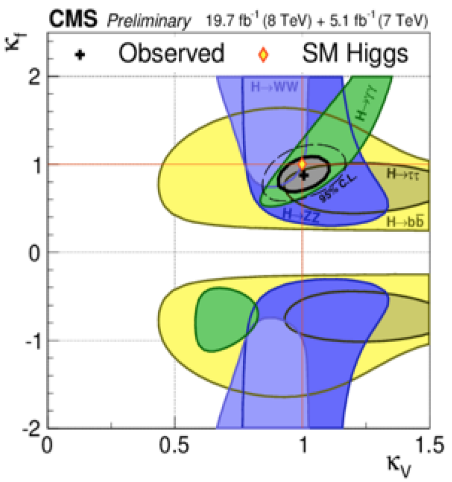
The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

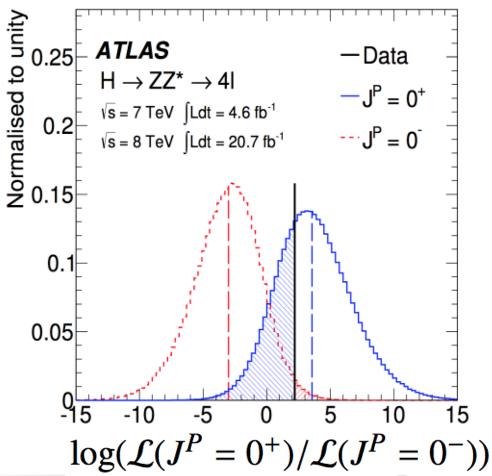
Brief Higgs Summary

We know already a lot on this Brand New Higgs Particle!!









Mass = CMS+ATLAS
125.09 ±0.21(stat)
±0.11(syst) GeV

Width =
A: < 24 MeV
C: < 22 MeV
(95%CL)

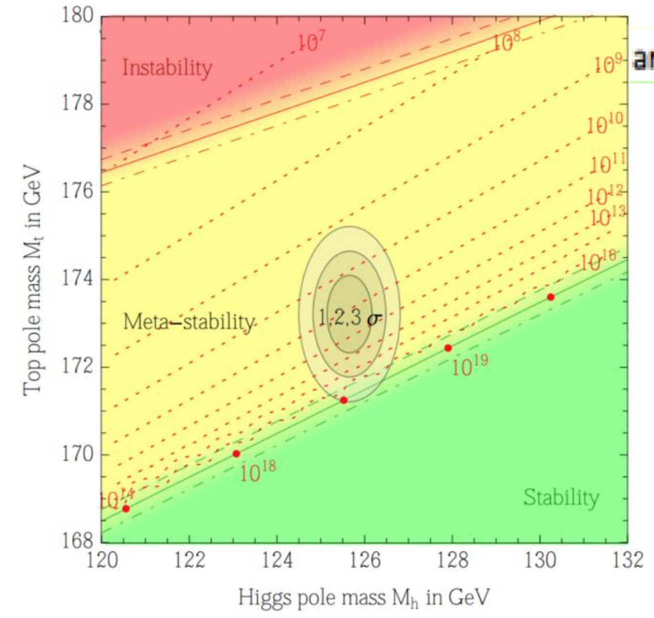
Couplings are within 20% of the SM values

Spin = $0^{+(+)}$ preferred over 0^-,1,2

SM-like behaviour for most properties, but continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production, other Higgses…

Consequences for our Universe?

Important SM parameter → stability of EW vacuum



arXiv:1205.6497

arXiv:1403.6535

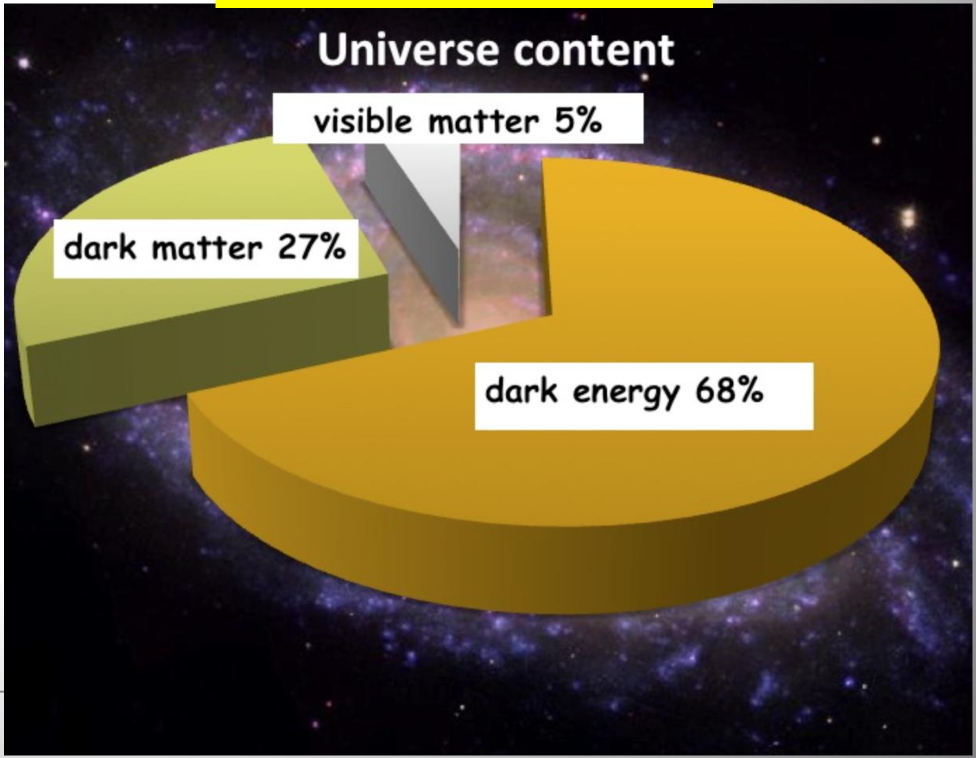
Precise measurements of the top quark and the Higgs mass:

New Physics inevitable?
But at which scale/energy?

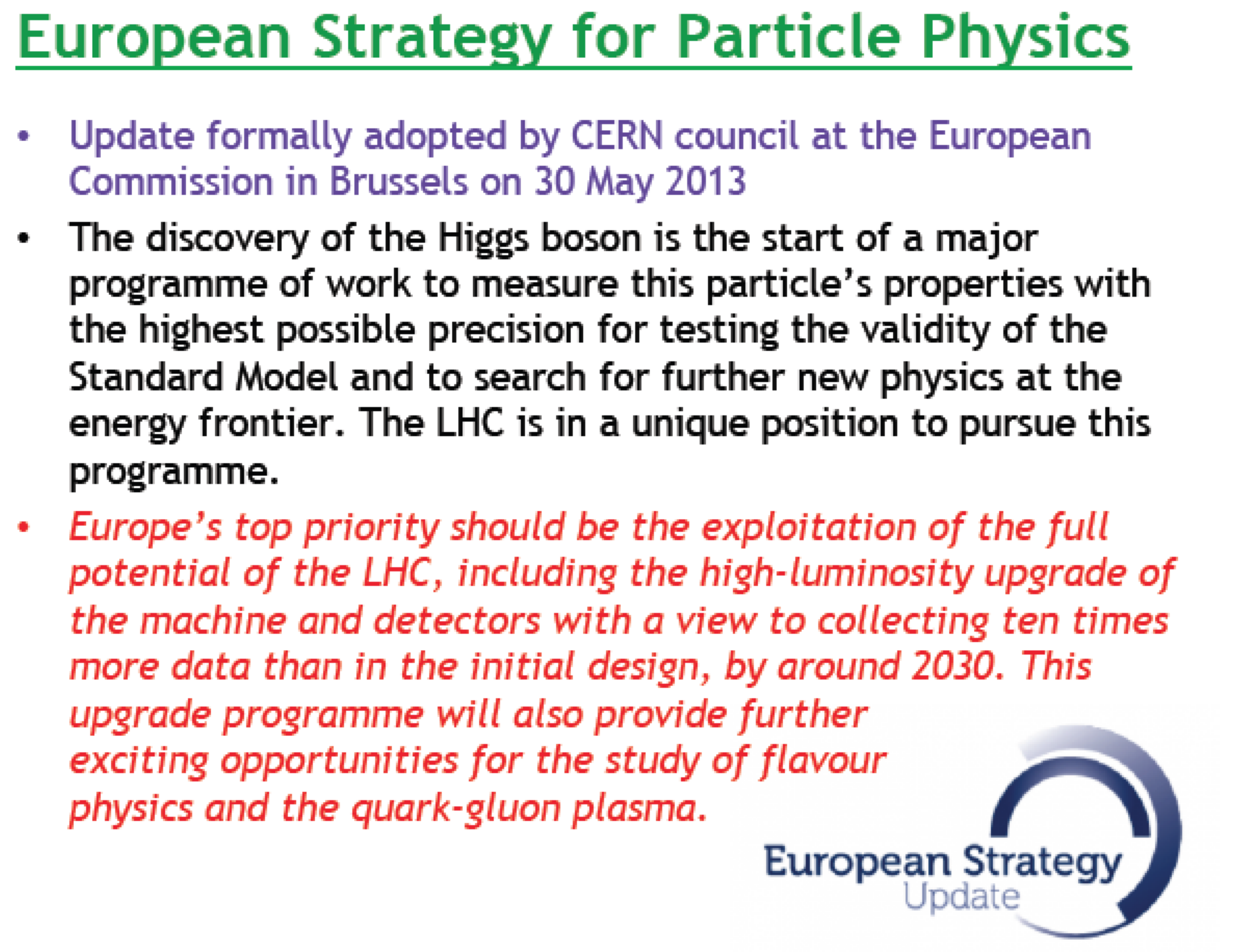
But Where Is Everybody?

N. Arkani-Hamed

We also know that:



Europe Strategy Group

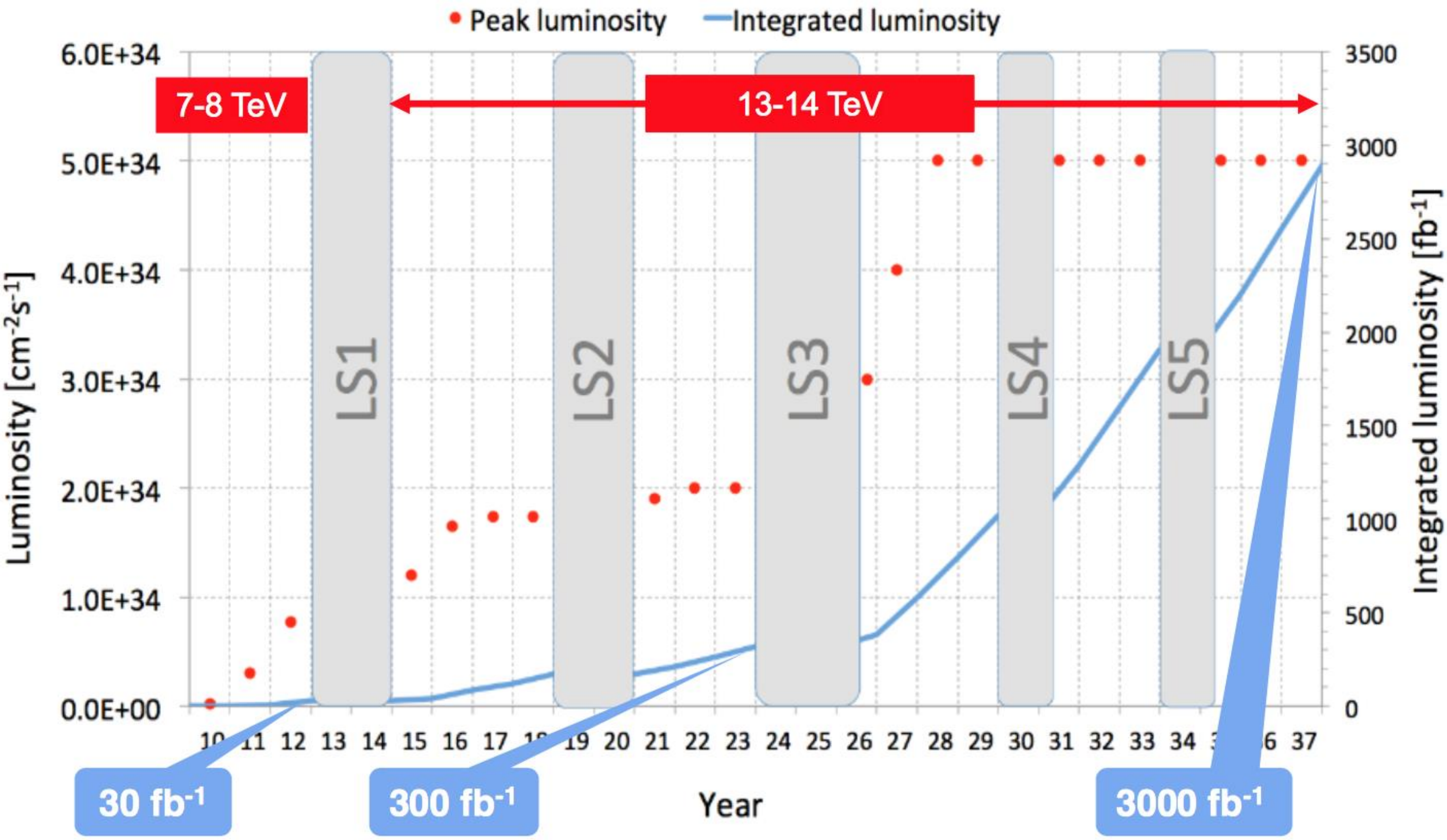


European Strategy for Particle Physics

- Update formally adopted by CERN council at the European Commission in Brussels on 30 May 2013
- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
- *Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.*

European Strategy
Update

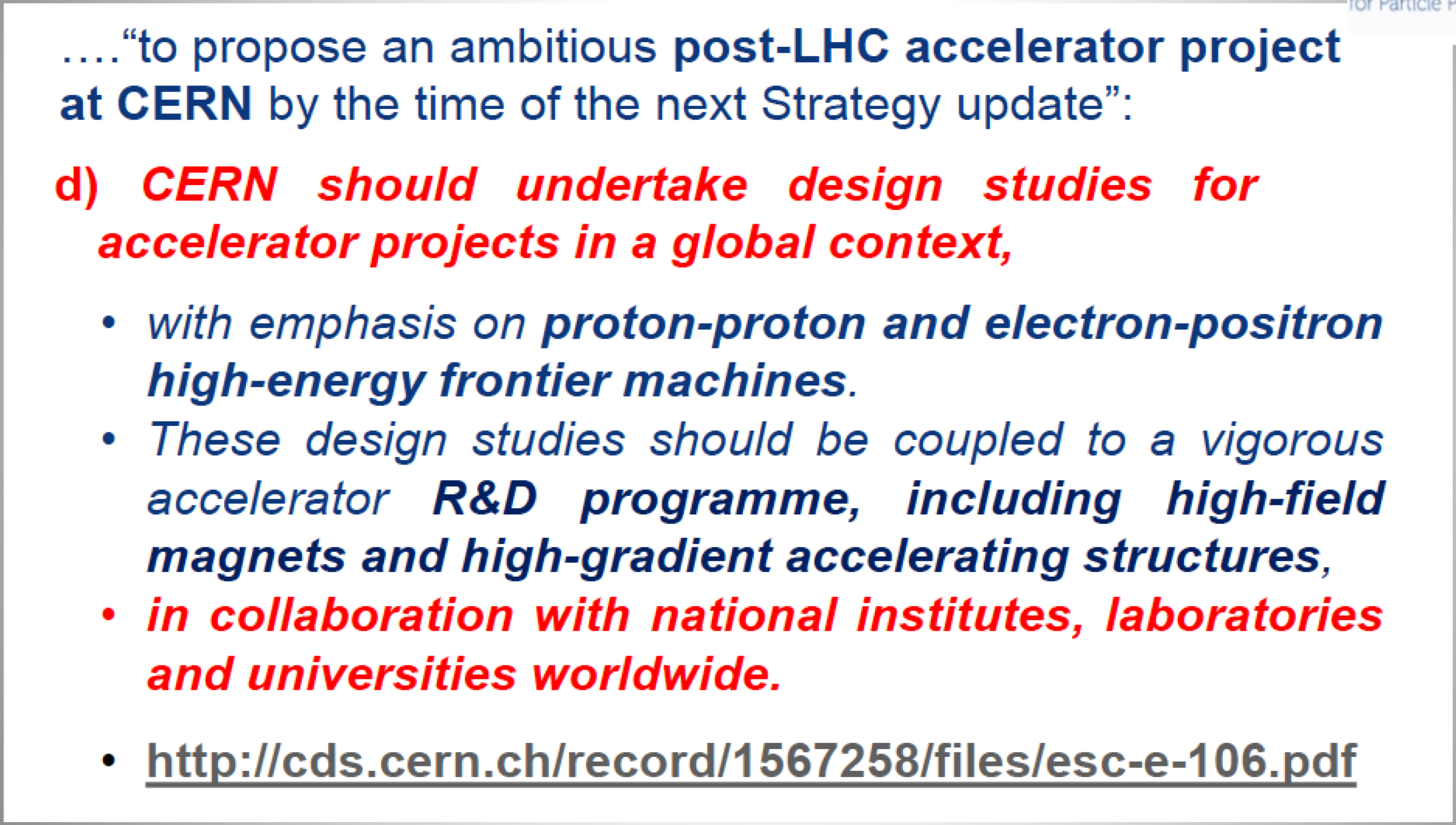
Long Term LHC Schedule



F. Bodry EPS Vienna, July 2015

Beyond the LHC…

From the European Strategy Group



….“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,***

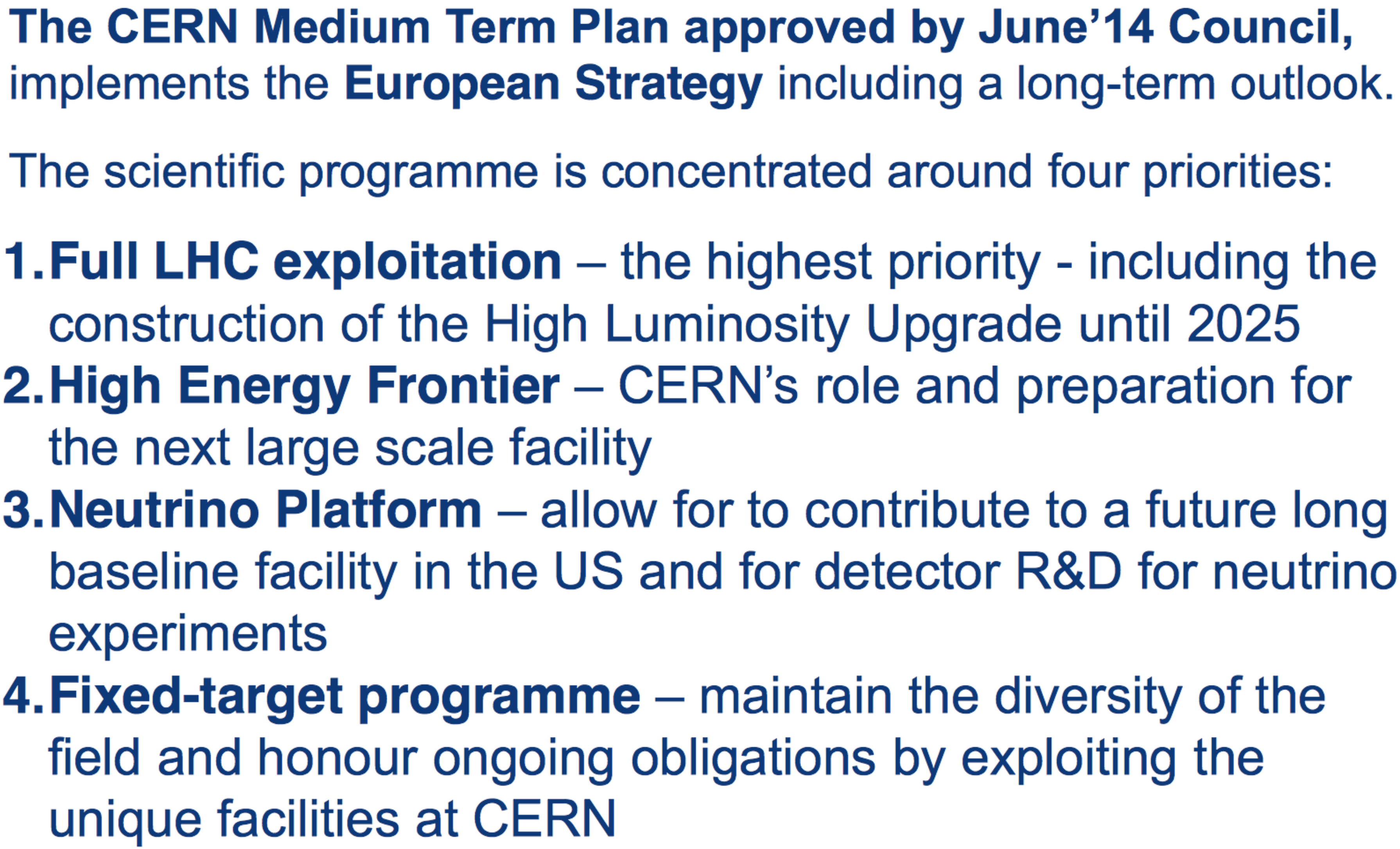
- *with emphasis on **proton-proton and electron-positron high-energy frontier machines**.*
- *These design studies should be coupled to a vigorous accelerator **R&D programme, including high-field magnets and high-gradient accelerating structures**,*
- ***in collaboration with national institutes, laboratories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

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

Similar recommendation from the Snowmass studies in the US

The CERN Roadmap

F. Bodry , March 2015



The CERN Medium Term Plan approved by June'14 Council, implements the **European Strategy** including a long-term outlook.

The scientific programme is concentrated around four priorities:

1. **Full LHC exploitation** – the highest priority - including the construction of the High Luminosity Upgrade until 2025
2. **High Energy Frontier** – CERN's role and preparation for the next large scale facility
3. **Neutrino Platform** – allow for to contribute to a future long baseline facility in the US and for detector R&D for neutrino experiments
4. **Fixed-target programme** – maintain the diversity of the field and honour ongoing obligations by exploiting the unique facilities at CERN

The FCC Project

Future Circular Colliders: The return of studies for circular machines!

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh)
with possibility of e+-e- (FCC-ee) and p-e (FCC-he)

Future Circular Collider Study
Kick-off Meeting

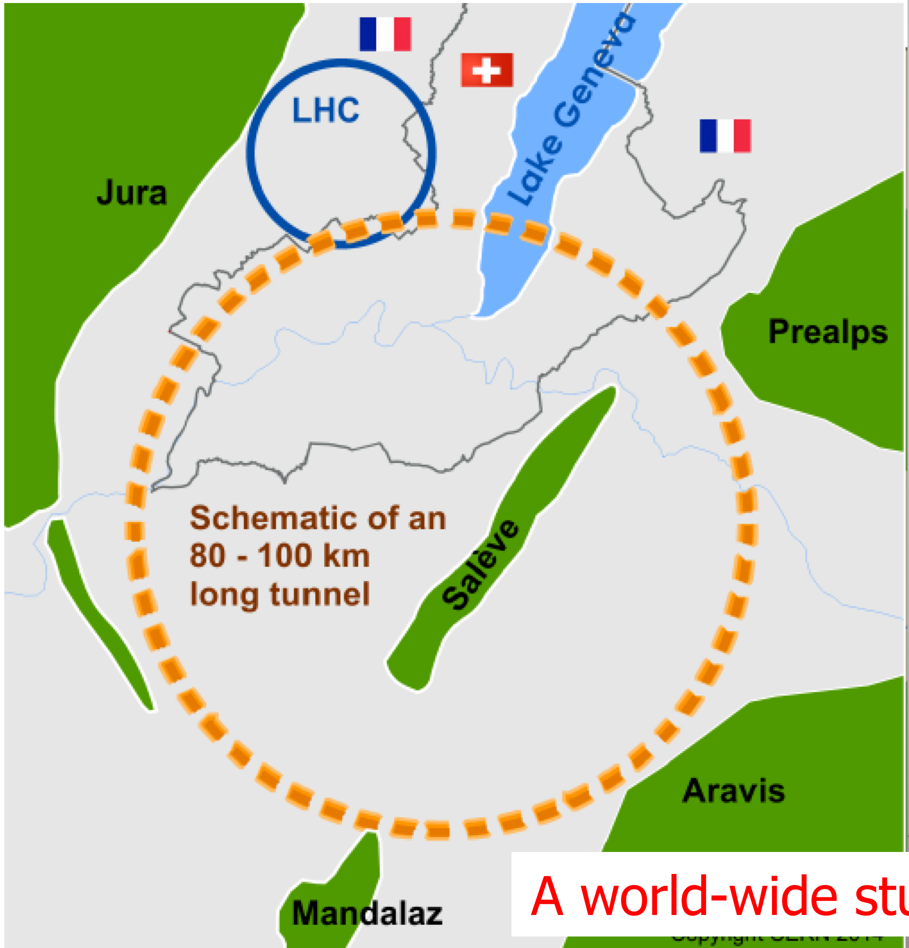
12-15 February 2014,
University of Geneva,
Switzerland

LOCAL ORGANIZING COMMITTEE
University of Geneva
C. Blanchard, A. Blondel,
C. Doglioni, G. Iacobucci,
M. Koratzinos
CERN
M. Benedikt, E. Delucinge,
J. Gutleber, D. Hudson,
C. Potter, F. Zimmermann

SCIENTIFIC ORGANIZING COMMITTEE
FCC Coordination Group
A. Ball, M. Benedikt, A. Blondel,
F. Bordry, L. Bottura, O. Brüning,
P. Collier, J. Ellis, F. Gianotti,
B. Goddard, P. Janot, E. Jensen,
J. M. Jimenez, M. Klein, P. Lebrun,
M. Mangano, D. Schulte,
F. Sonnemann, L. Tavian,
J. Wenninger, F. Zimmermann

UNIVERSITÉ DE GENÈVE

http://indico.cern.ch/e/fcc-kickoff



A world-wide study…

FCC
hh ee he

FCC Week 2015, Washington DC
23-27 March 2015

CERN

U.S. DEPARTMENT OF ENERGY

http://indico.cern.ch/event/340703/

In search of a 100 TeV pp collider….

A High Energy Proton-Proton Collider

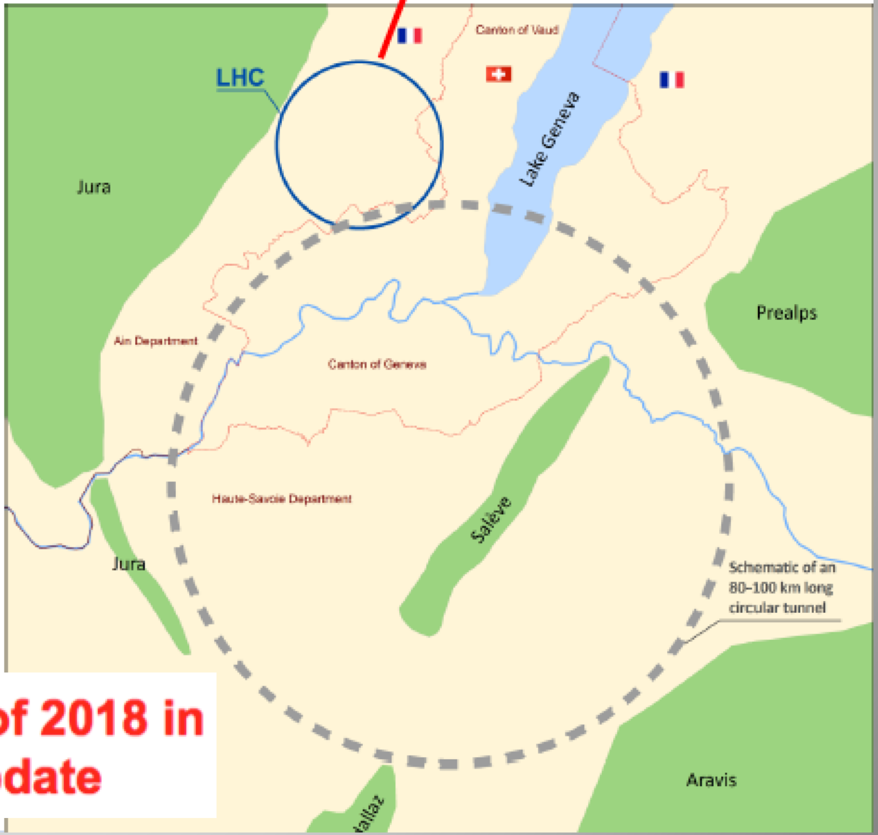
"Machine Options"

"High Energy LHC"

HE-LHC :33 TeV
with 20T magnets

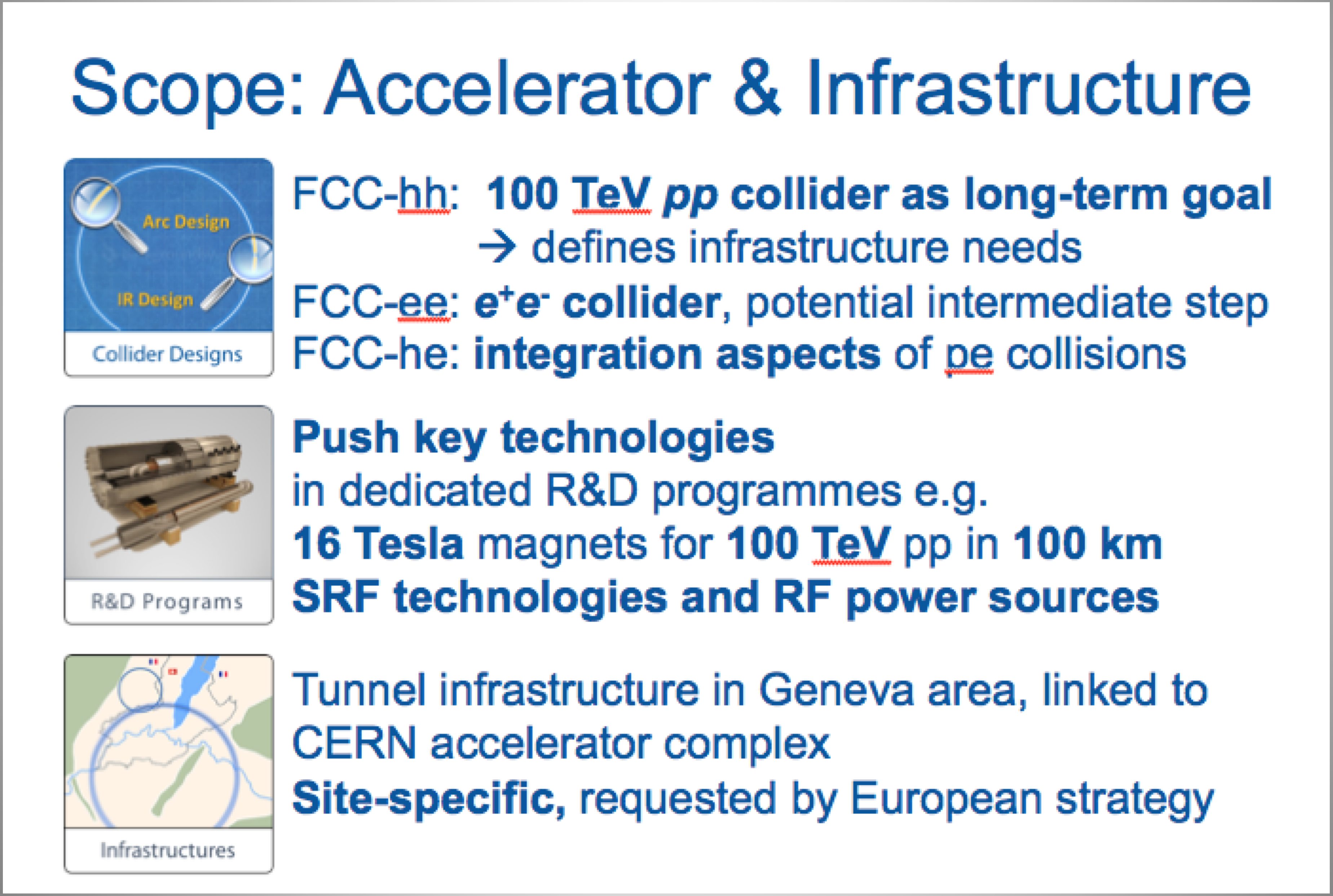
First studies on a new 80 km tunnel in the Geneva area

- 42 TeV with 8.3 T using present LHC dipoles
- 80 TeV with 16 T based on Nb_3Sn dipoles
- 100 TeV with 20 T based on HTS dipoles



Conceptual Design Report by end of 2018 in time for next European Strategy Update

The FCC Project



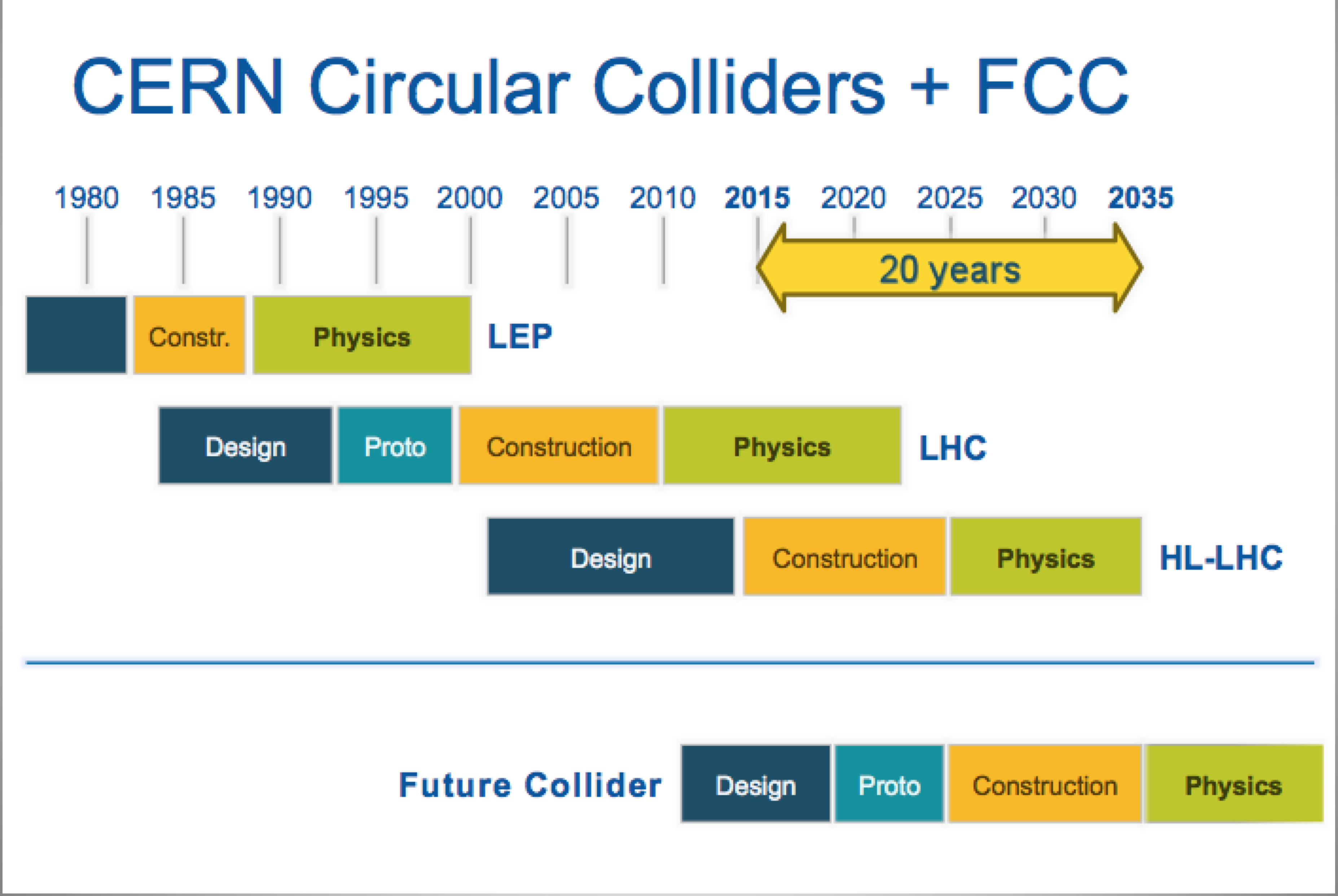
Scope: Accelerator & Infrastructure

FCC-hh: **100 TeV *pp* collider as long-term goal**
→ defines infrastructure needs
FCC-ee: **e^+e^- collider**, potential intermediate step
FCC-he: **integration aspects** of pe collisions

Push key technologies
in dedicated R&D programmes e.g.
16 Tesla magnets for **100 TeV** pp in **100 km**
SRF technologies and RF power sources

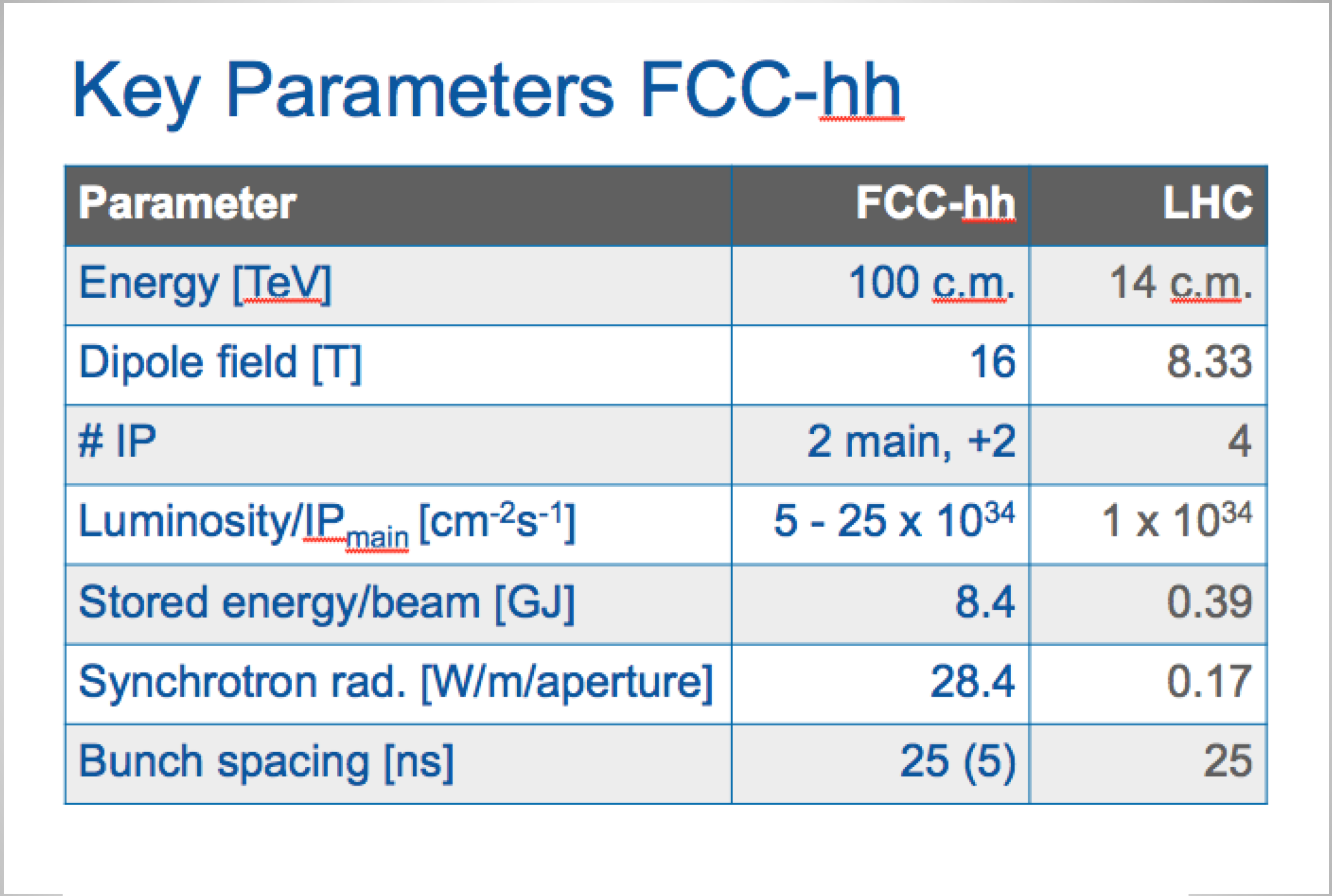
Tunnel infrastructure in Geneva area, linked to CERN accelerator complex
Site-specific, requested by European strategy

FCC Timeline



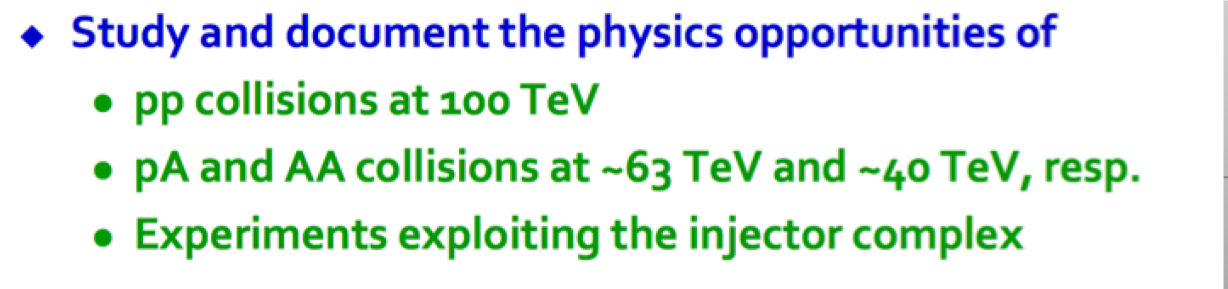
CERN Circular Colliders + FCC

The FCC-hh Project



Key Parameters FCC-hh

Parameter	FCC-hh	LHC
Energy [TeV]	100 c.m.	14 c.m.
Dipole field [T]	16	8.33
# IP	2 main, +2	4
Luminosity/IP$_{main}$ [cm^{-2}s^{-1}]	5 - 25 x 10^{34}	1 x 10^{34}
Stored energy/beam [GJ]	8.4	0.39
Synchrotron rad. [W/m/aperture]	28.4	0.17
Bunch spacing [ns]	25 (5)	25



- Study and document the physics opportunities of
  - pp collisions at 100 TeV
  - pA and AA collisions at ~63 TeV and ~40 TeV, resp.
  - Experiments exploiting the injector complex

The FCC-hh Project

FCC-hh Luminosity Goals

- **Two parameter sets for two operation phases:**

  - ☐ **phase 1 (baseline): 5 x 10^{34} cm^{-2}s^{-1} (peak),**
    250 fb^{-1}/year (averaged)
  - ☐ **phase 2 (ultimate): ~2.5 x 10^{35} cm^{-2}s^{-1} (peak),**
    1000 fb^{-1}/year (averaged)

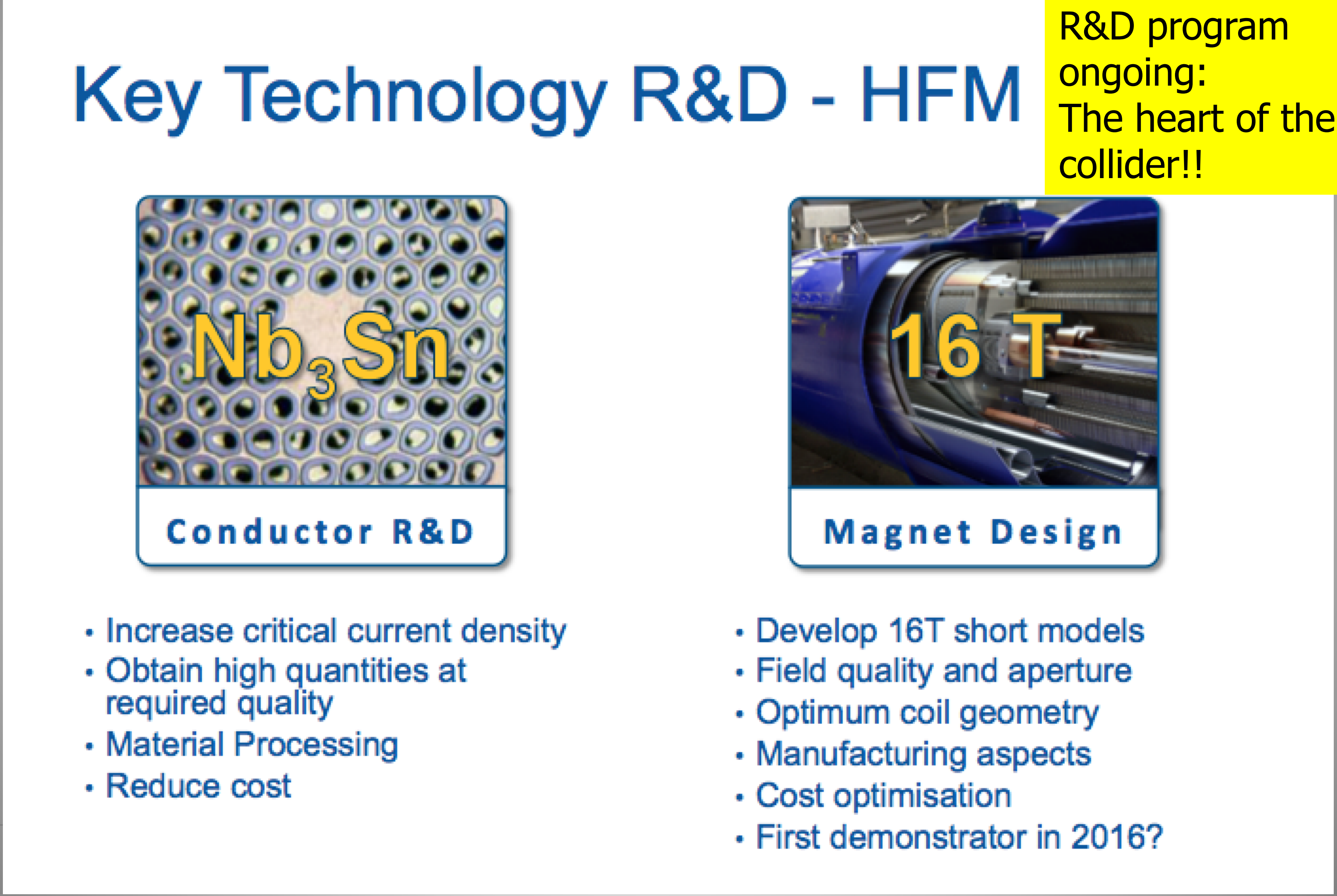
➔ total luminosity a few 10's of ab^{-1} over ~25 years of operation

OK for physics

See I. Hinchliffe et al. arXiv:1504.06108

The FCC Project: High Field Magnets

R&D program ongoing:
The heart of the collider!!



Key Technology R&D - HFM

Nb$_3$Sn

Conductor R&D

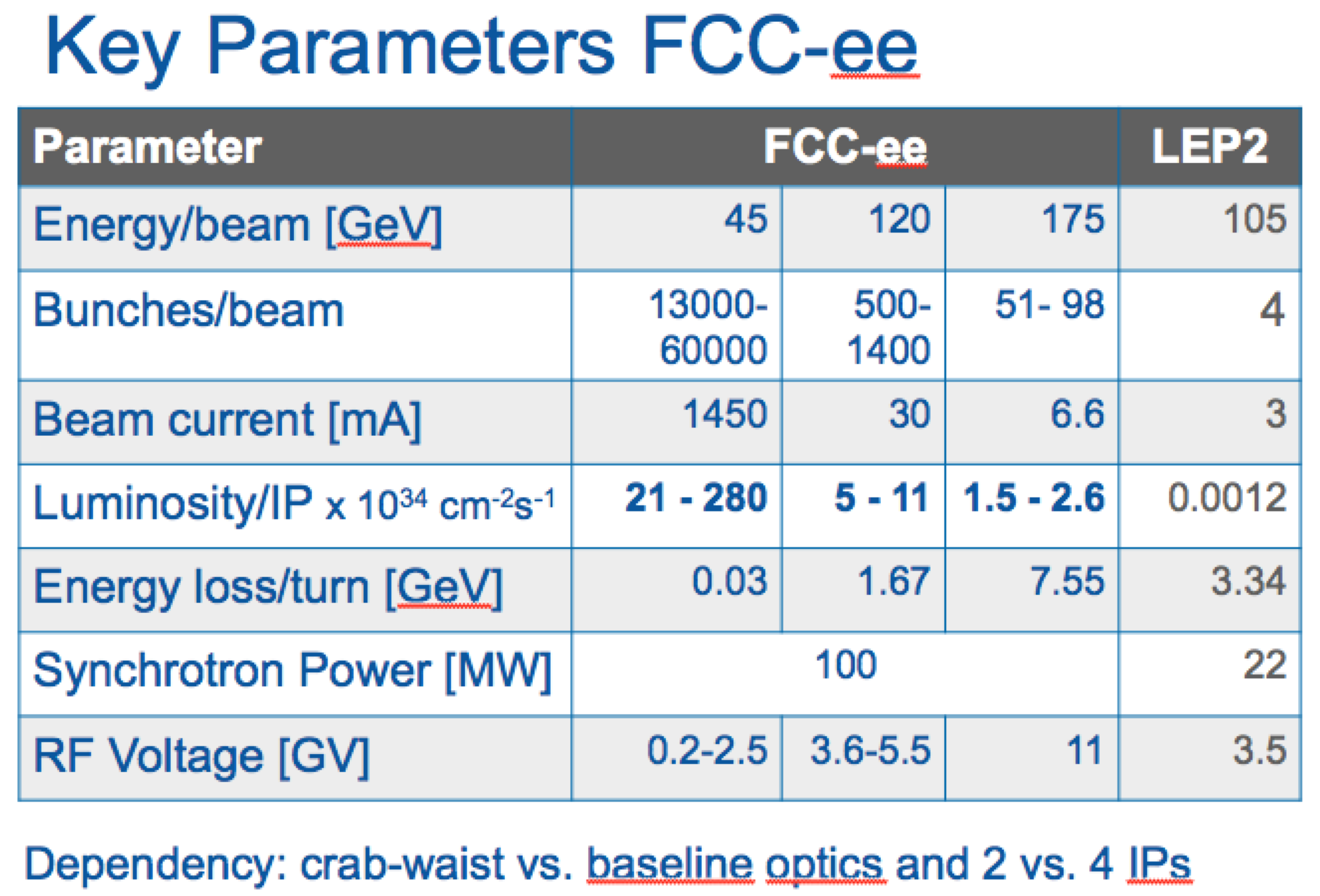
- Increase critical current density
- Obtain high quantities at required quality
- Material Processing
- Reduce cost

16 T

Magnet Design

- Develop 16T short models
- Field quality and aperture
- Optimum coil geometry
- Manufacturing aspects
- Cost optimisation
- First demonstrator in 2016?

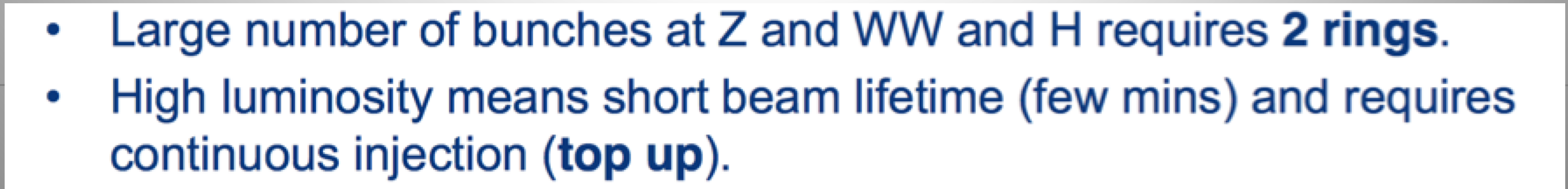
The FCC-ee Project



Key Parameters FCC-ee

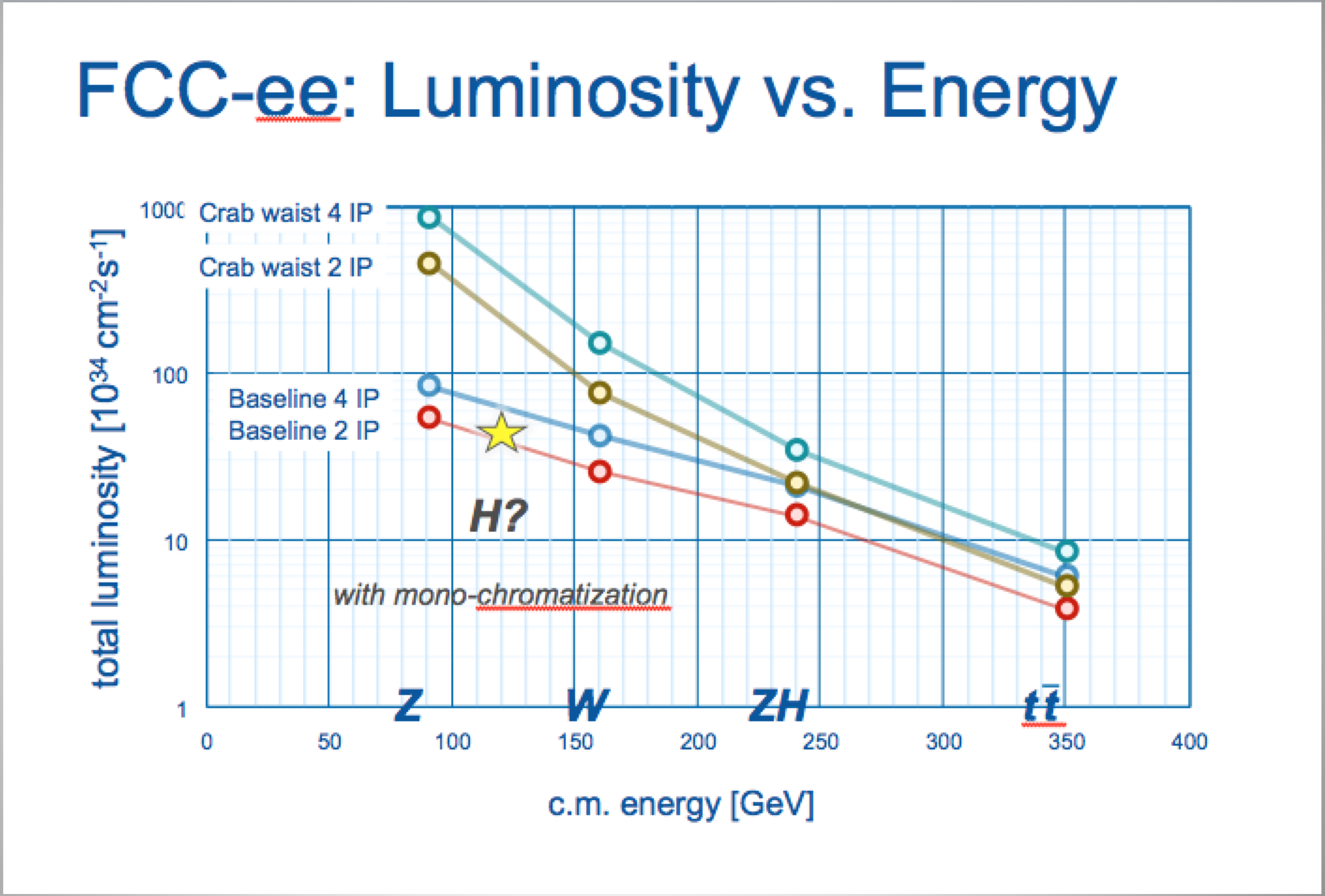
Parameter	FCC-ee			LEP2
Energy/beam [GeV]	45	120	175	105
Bunches/beam	13000- 60000	500- 1400	51- 98	4
Beam current [mA]	1450	30	6.6	3
Luminosity/IP x 10^{34} $cm^{-2}s^{-1}$	**21 - 280**	**5 - 11**	**1.5 - 2.6**	0.0012
Energy loss/turn [GeV]	0.03	1.67	7.55	3.34
Synchrotron Power [MW]	100			22
RF Voltage [GV]	0.2-2.5	3.6-5.5	11	3.5

Dependency: crab-waist vs. baseline optics and 2 vs. 4 IPs



- Large number of bunches at Z and WW and H requires **2 rings**.
- High luminosity means short beam lifetime (few mins) and requires continuous injection (**top up**).

The FCC-ee Project

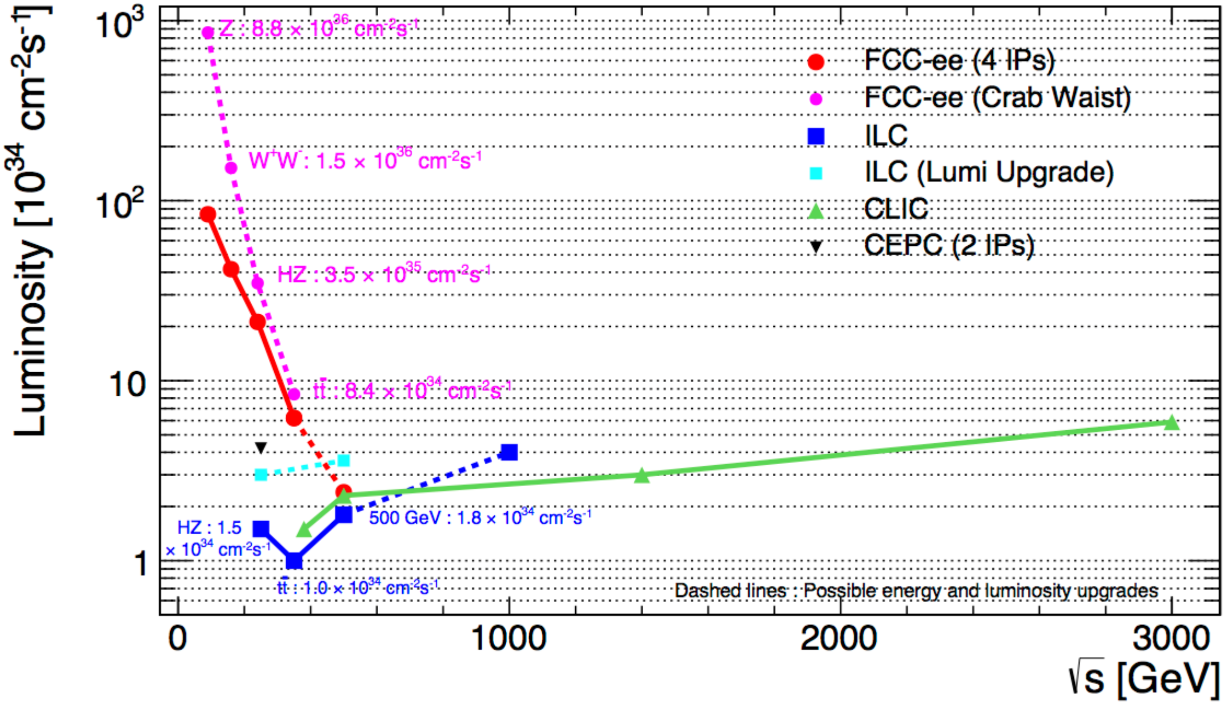


FCC-ee: Luminosity vs. Energy

Note: SuperKEKB will be an excellent "FCC-ee demonstrator"

FCC-ee Luminosity Targets

- **Target luminosities of e^+e^- projects**



LEP: 0.001 – 0.01, SLC: 0.0001

- **Within a few years at each centre-of-mass energy, FCC-ee would produce**
  - **Several trillions, up to 10^{13}, Z decays**
  - **Several Okus (10^8) W decays**
  - **Several millions Higgs and top decays**

The ultimate $e^+e^- \rightarrow$ Z, W, H and top factories and much more…

FCC International Collaboration

- 58 institutes
- 22 countries + EC

Status: July 30, 2015

FCC Next General Meeting

FCC Week 2016

Rome, 11 – 15 April 2016

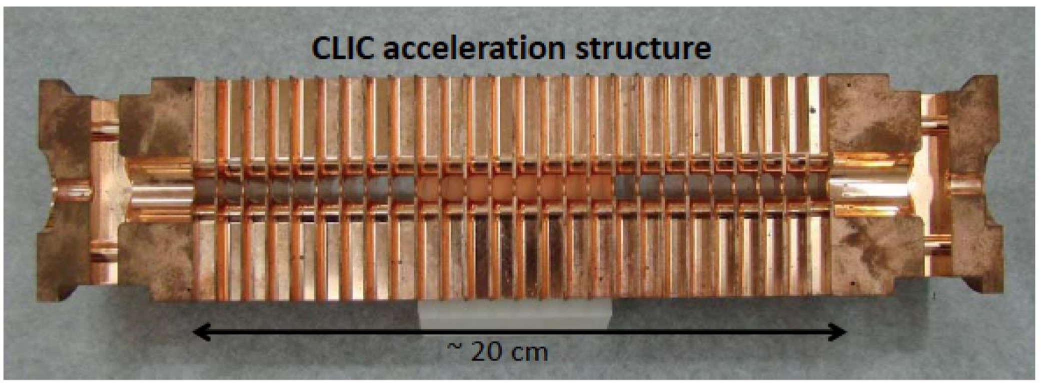
Linear e+e- Colliders

Electron-positron machines for high precision and possibly high energy (few TeV) …

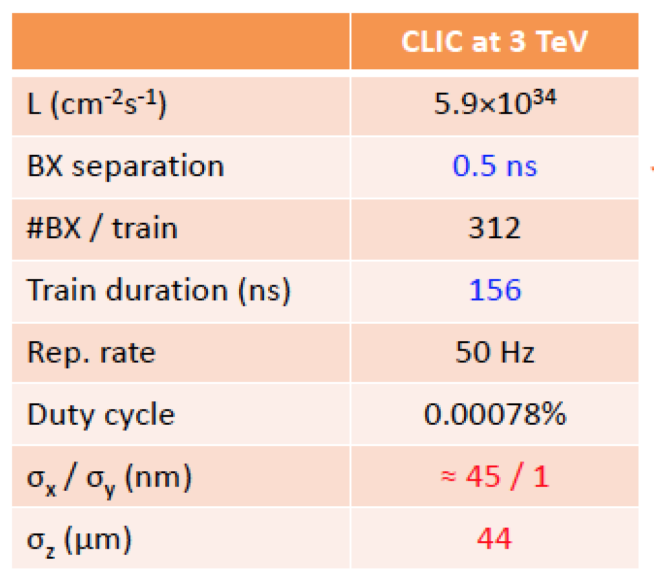
Studies and R&D work on linear colliders started in the '90's and they have achieved a very high level of maturity now…

CERN's Focus: The Compact Linear Collider CLIC

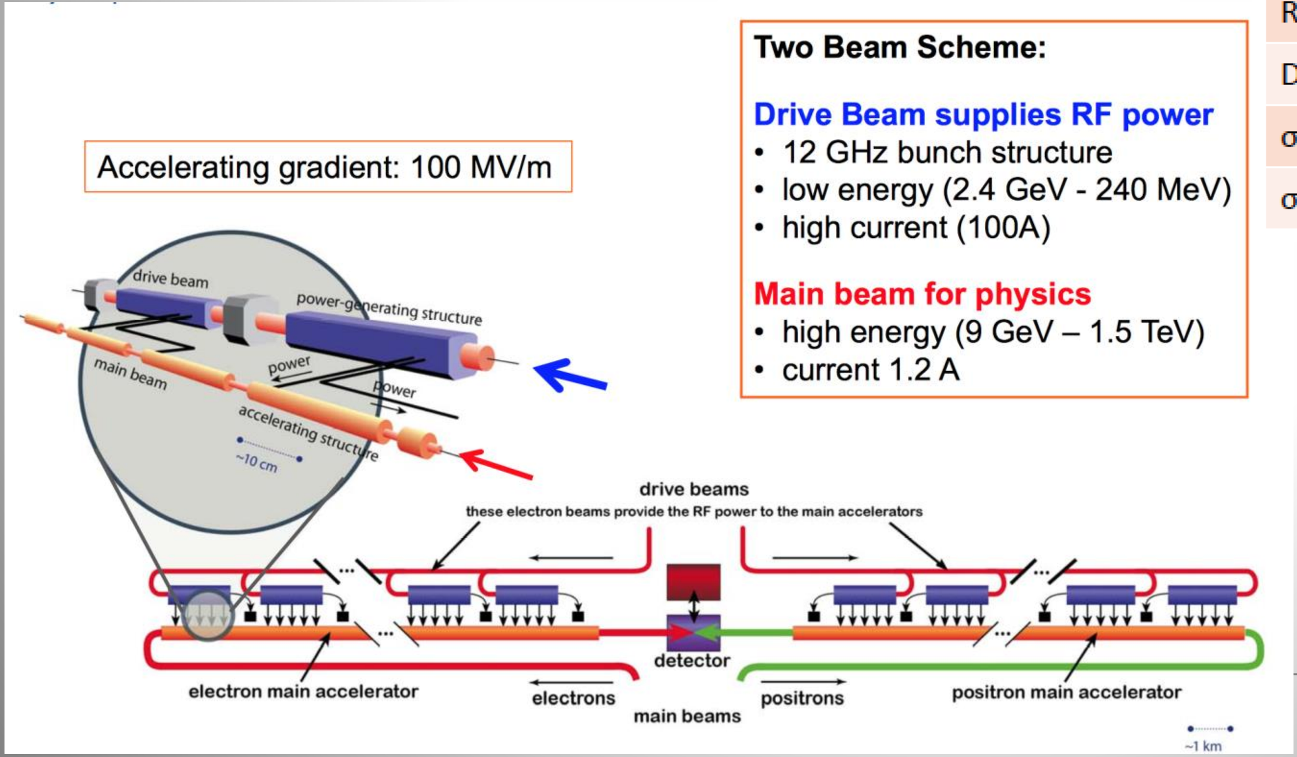
CLIC: Two Beam Acceleration



CLIC parameters



	CLIC at 3 TeV
L ($cm^{-2}s^{-1}$)	5.9×10^{34}
BX separation	0.5 ns
#BX / train	312
Train duration (ns)	156
Rep. rate	50 Hz
Duty cycle	0.00078%
σ_x / σ_y (nm)	≈ 45 / 1
σ_z (μm)	44



Accelerating gradient: 100 MV/m

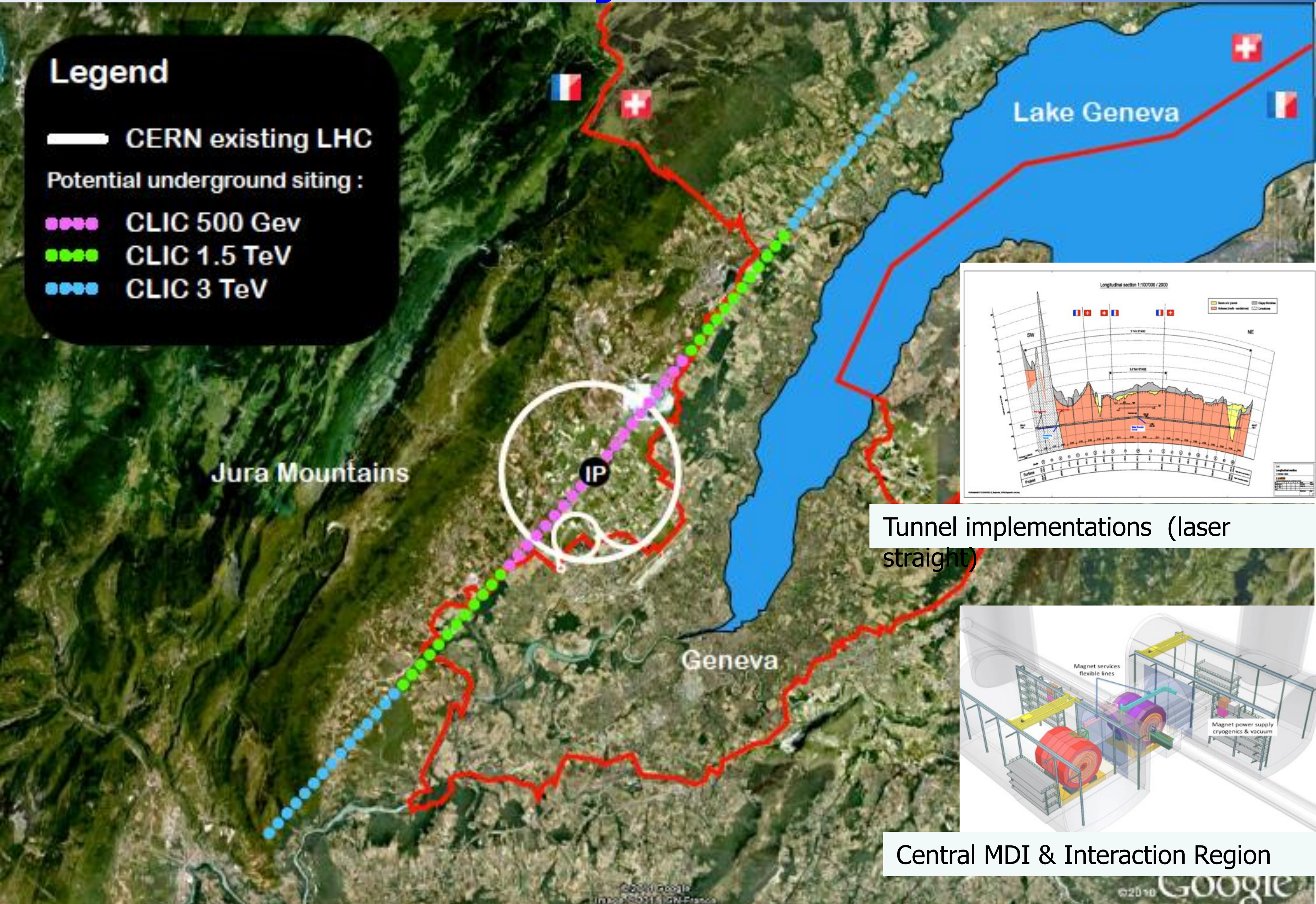
Two Beam Scheme:

Drive Beam supplies RF power
- 12 GHz bunch structure
- low energy (2.4 GeV - 240 MeV)
- high current (100A)

Main beam for physics
- high energy (9 GeV – 1.5 TeV)
- current 1.2 A

Parameters for √s
- •500 GeV
- •1.4 TeV
- •3 TeV

CLIC Layout @ CERN



Tunnel implementations (laser straight)

Central MDI & Interaction Region

CLIC accelerator collaboration

Collaboration to develop CLIC and to build and operate the CLIC test facility CTF3

http://clic-study.org/

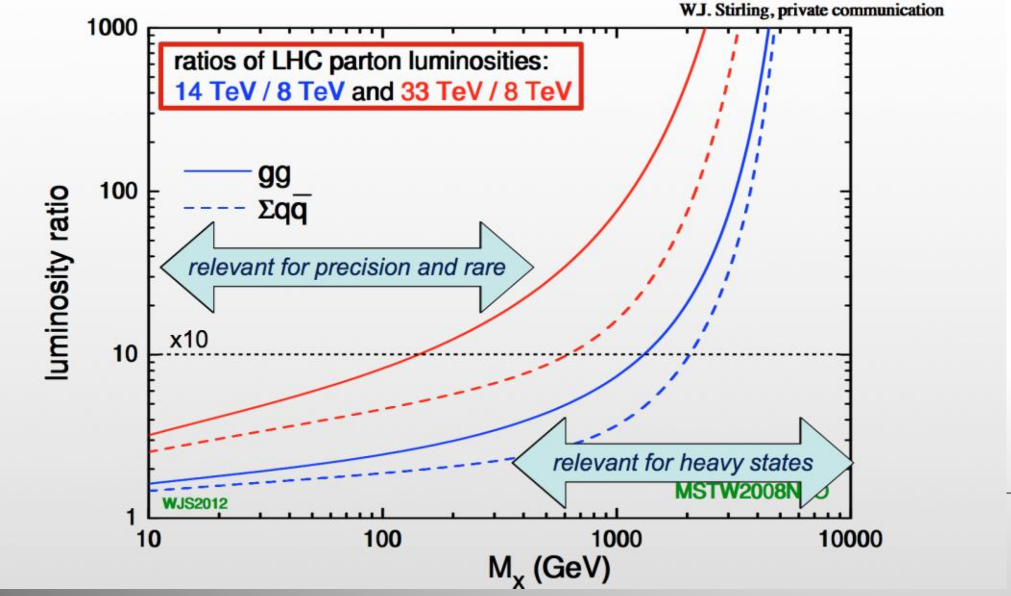
CLIC/CTF3: ~50 institutes

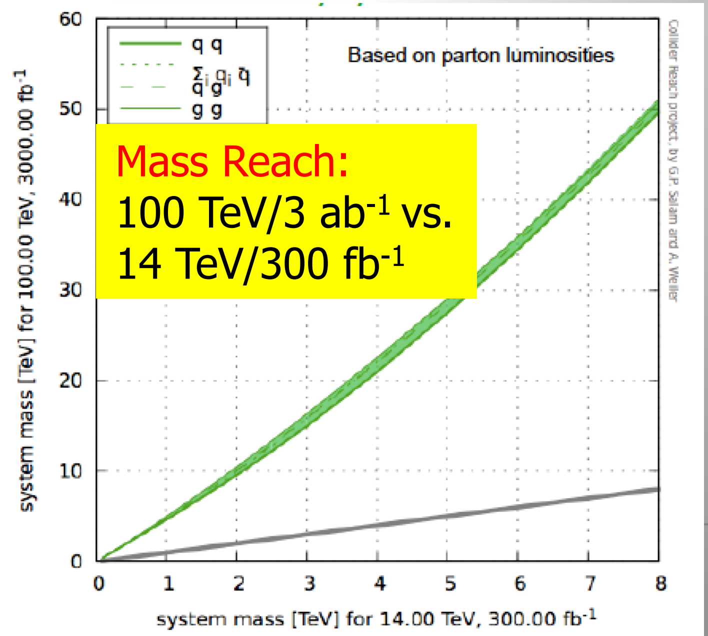
Physics Program: Key Topics

- Properties of the new Higgs boson, precise determination of its characteristics
- High mass reach for new particles and interactions
- Precision measurements
- Rare process

Studies in progress

-> However, no “no-loose theorem” known, as yet.



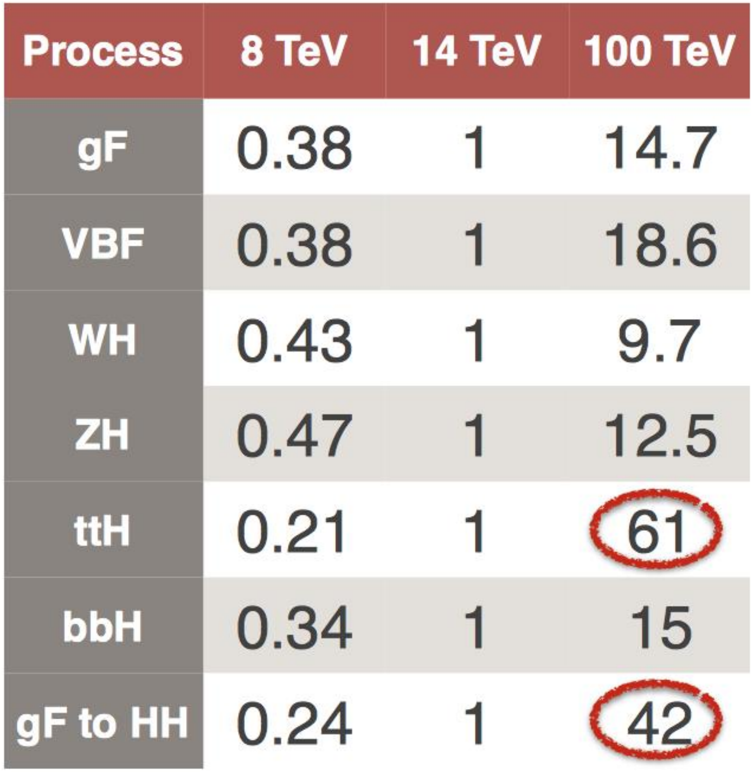


Mass Reach:
100 TeV/3 ab^{-1} vs.
14 TeV/300 fb^{-1}

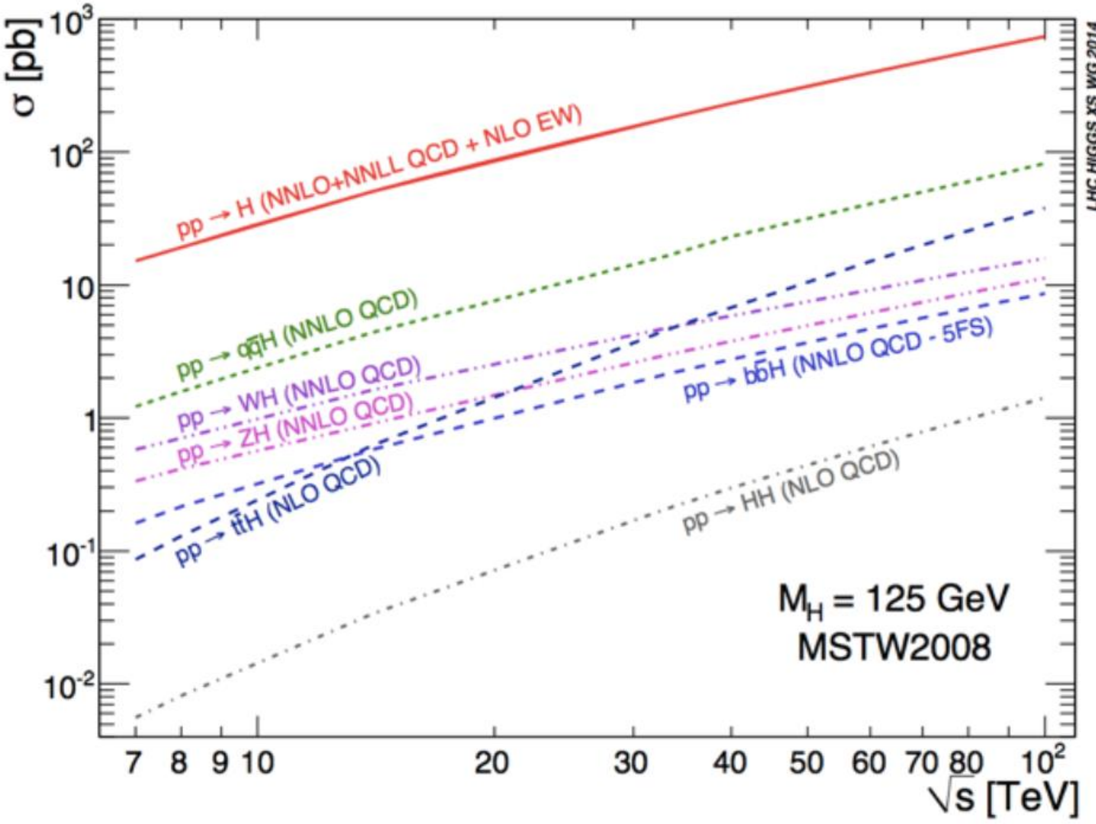
FCC-hh: Higgs

Relative cross section

M. Klute, March 2105



Process	8 TeV	14 TeV	100 TeV
gF	0.38	1	14.7
VBF	0.38	1	18.6
WH	0.43	1	9.7
ZH	0.47	1	12.5
ttH	0.21	1	61
bbH	0.34	1	15
gF to HH	0.24	1	42



Proton-proton Higgs datasets

LHC Run I

x300-600

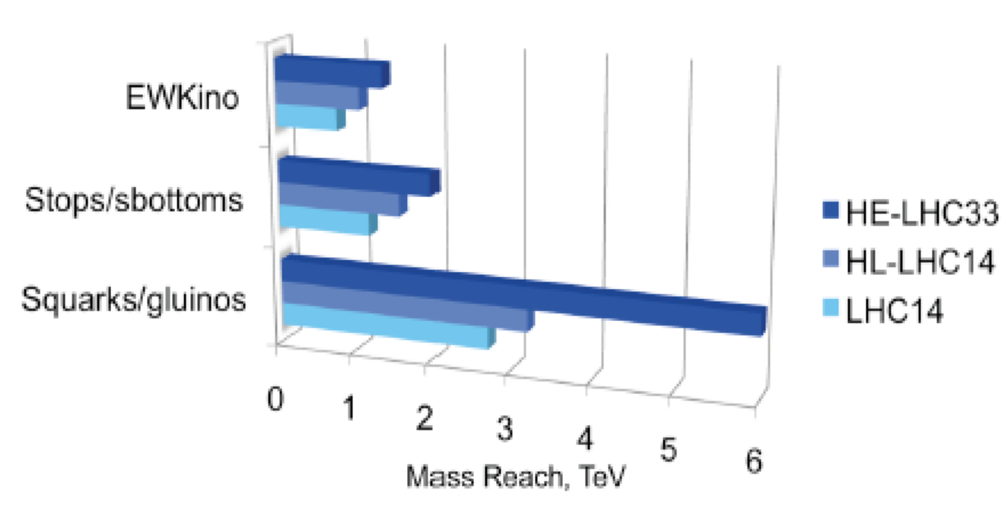
HL LHC

x10-400

FCC pp

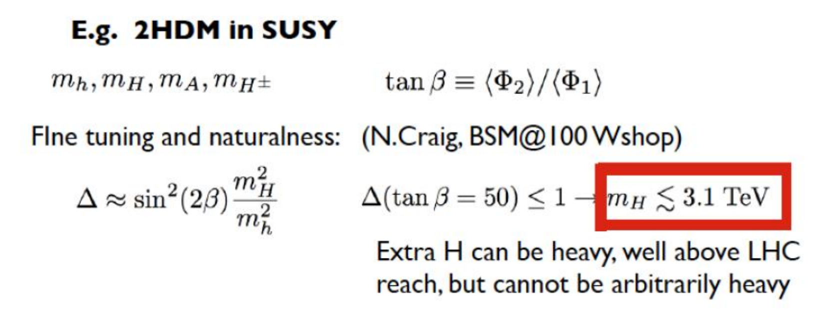
FCC-hh: Searches for New Particles

Searches for pair produced SUSY particles



FCC-hh

- -Reach sparticle masses search up to about 16 TeV for squarks of light quarks and 7 TeV for stops
- -Excited quarks probe the structure of quarks down to 4×10^{-21} m
- -Discovery of resonances up to masses of 40-50 TeV



E.g. 2HDM in SUSY

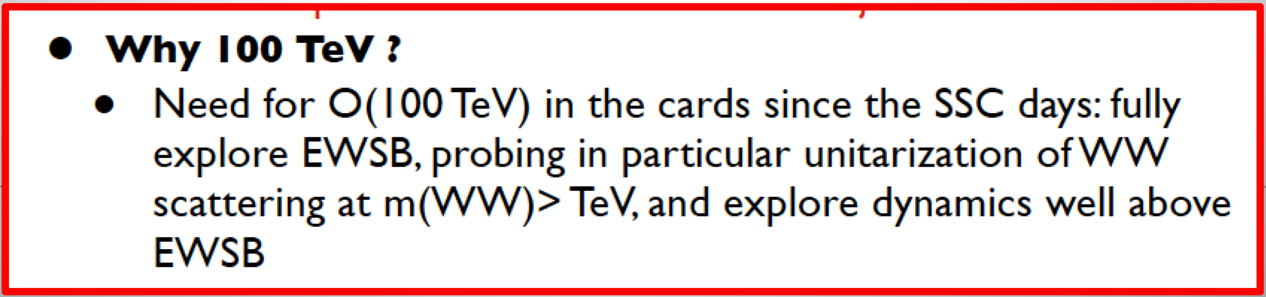
$m_h, m_H, m_A, m_{H^\pm}$ $\tan\beta \equiv \langle\Phi_2\rangle/\langle\Phi_1\rangle$

FIne tuning and naturalness: (N.Craig, BSM@100 Wshop)

$\Delta \approx \sin^2(2\beta)\frac{m_H^2}{m_h^2}$ $\Delta(\tan\beta = 50) \leq 1 \rightarrow \boxed{m_H \lesssim 3.1\ \text{TeV}}$

Extra H can be heavy, well above LHC reach, but cannot be arbitrarily heavy

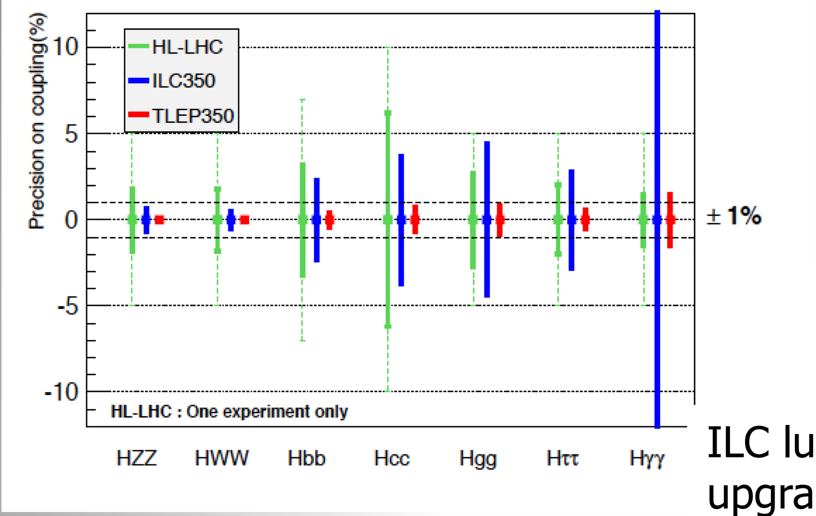
Upper limit for higher Higgs mass in 2HDM models?



- **Why 100 TeV ?**
  - Need for O(100 TeV) in the cards since the SSC days: fully explore EWSB, probing in particular unitarization of WW scattering at m(WW)> TeV, and explore dynamics well above EWSB

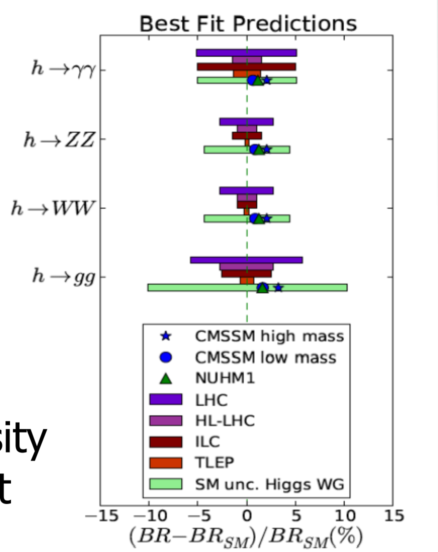
Physics at e+e- Colliders

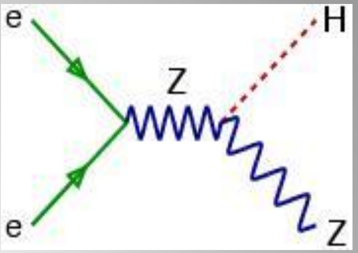
Higgs Boson Couplings



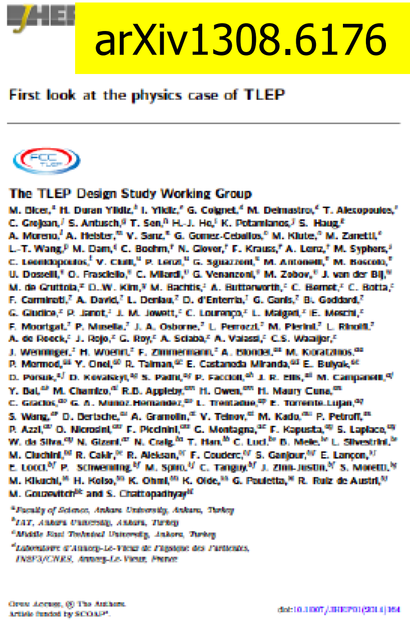
ILC luminosity upgrade not included

Higgs Boson decays





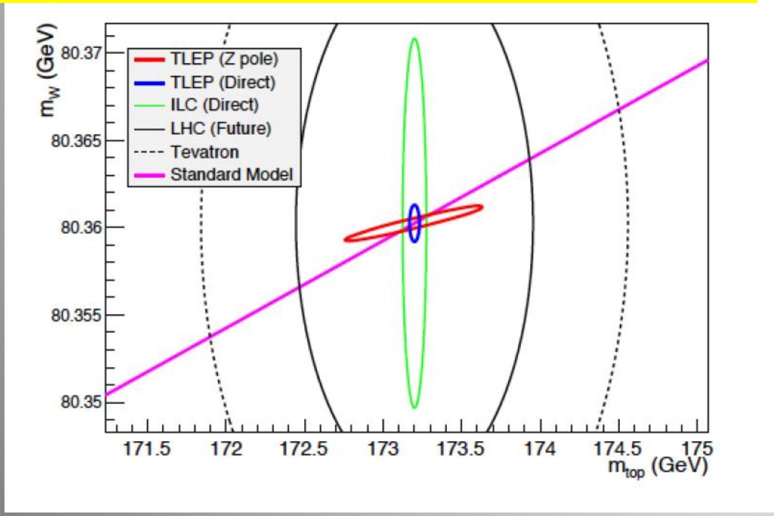
arXiv1308.6176



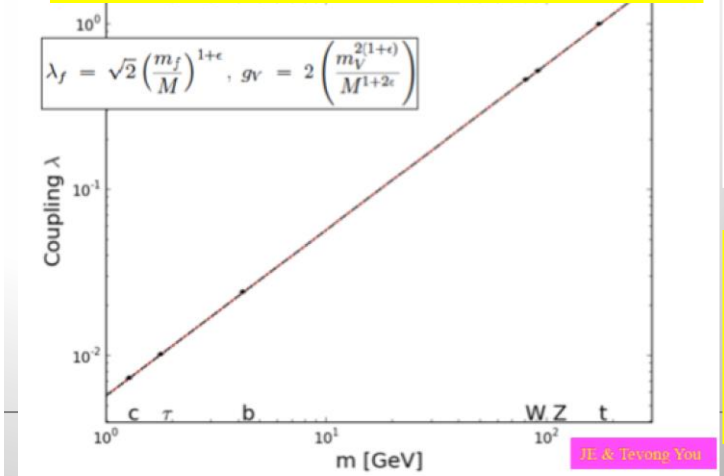
First look at the physics case of TLEP

The TLEP Design Study Working Group

Fit to all EWK precision measurements



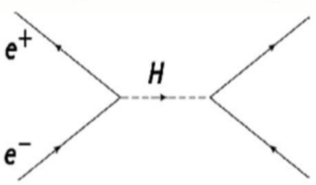
Higgs couplings vs particle mass



FCC-ee delivers very precise measurements

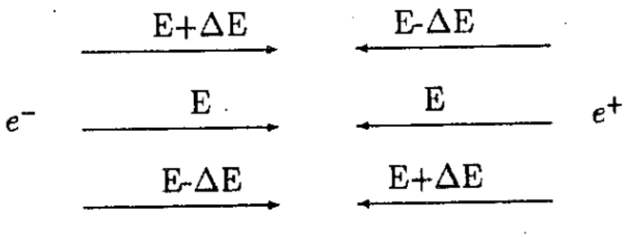
FCC-ee: Higgs Coupling to ee?

- **Unique to FCC-ee: couplings to the first generation of fermions**
  - Resonant production in the s channel : measure the electron Yukawa coupling



$\sqrt{s}$ = 125 GeV

D. d'Enterria, R. Aleksan



- FCC-ee: 10^4 events / year at the peak, but …
  - Huge background from Z, γ
  - $\Delta E_{beam} \sim 10\,\Gamma_H$
- Set upper limit on κ_e to ~2 × SM value

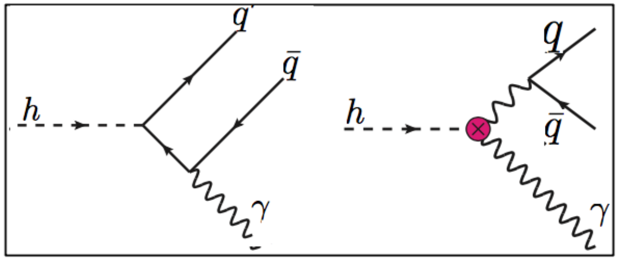
R&D and use of monochromators ?
Never tested … will reduce luminosity
Longitudinal polarization ?

- Exclusive Higgs boson decays: measure the u/d quark Yukawa couplings with H → ργ

$$\frac{\mathrm{BR}_{h\to\rho\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma\left[(1.9\pm0.15)\kappa_\gamma - 0.24\bar{\kappa}_u - 0.12\bar{\kappa}_d\right]}{0.57\bar{\kappa}_b^2}\times 10^{-5}$$

- FCC-ee: 50 ± 15 H → ργ events for $\kappa_{u,d} = 1 \pm 1$
  - Limits $\kappa_{u,d}$ to be between [0,2] × SM value

Sensitivity through interference:

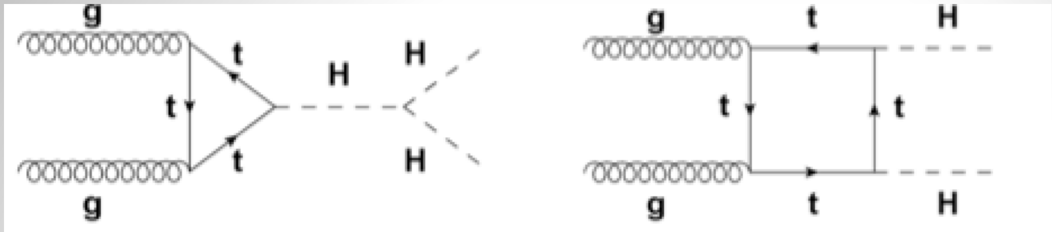


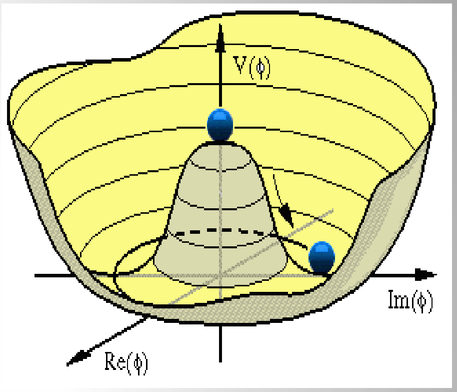
Y. Soreq

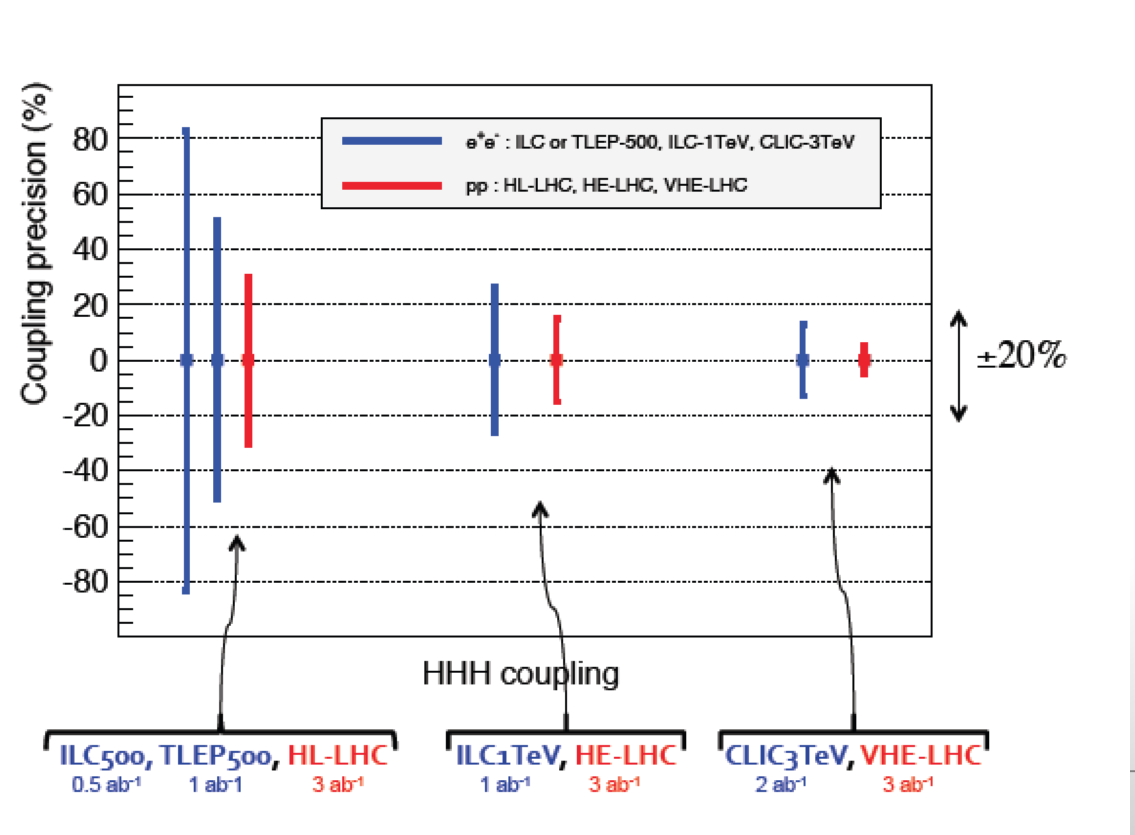
The Higgs Self Coupling!

A key measurement for our understanding of the Higgs field potential!

in pp





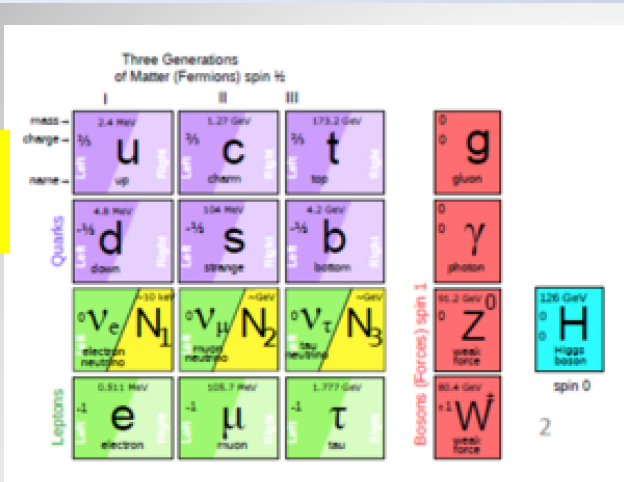


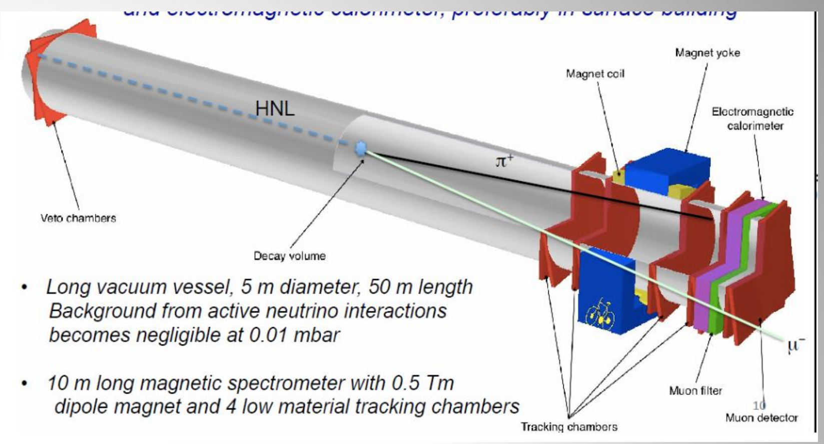
Difficult measurements!!: Evaluation till ongoing for HL-LHC sensitivity

e+e- machines with sufficient energy and FCC-hh can measure this process precisely

FCC-ee: Heavy Neutral Leptons

A. Blondel et al
arXiv:1411.5230





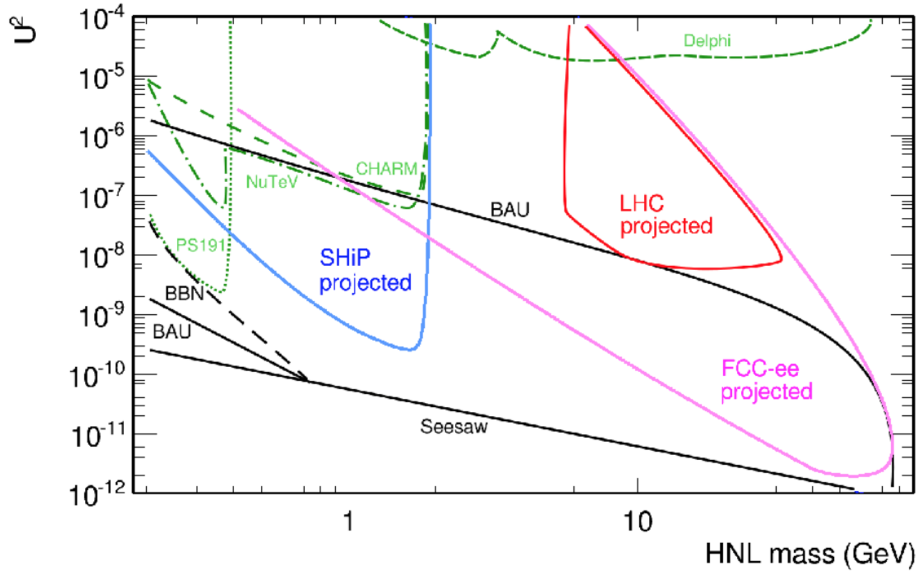
and electromagnetic calorimeter, preferably in surface building

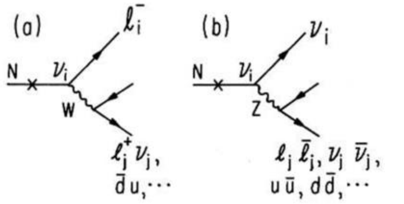
- *Long vacuum vessel, 5 m diameter, 50 m length Background from active neutrino interactions becomes negligible at 0.01 mbar*
- *10 m long magnetic spectrometer with 0.5 Tm dipole magnet and 4 low material tracking chambers*

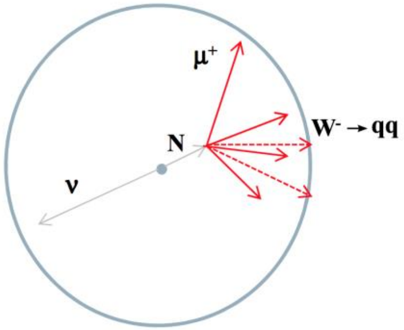
search $e^+ e^- \rightarrow \nu N$

Displaced vertices

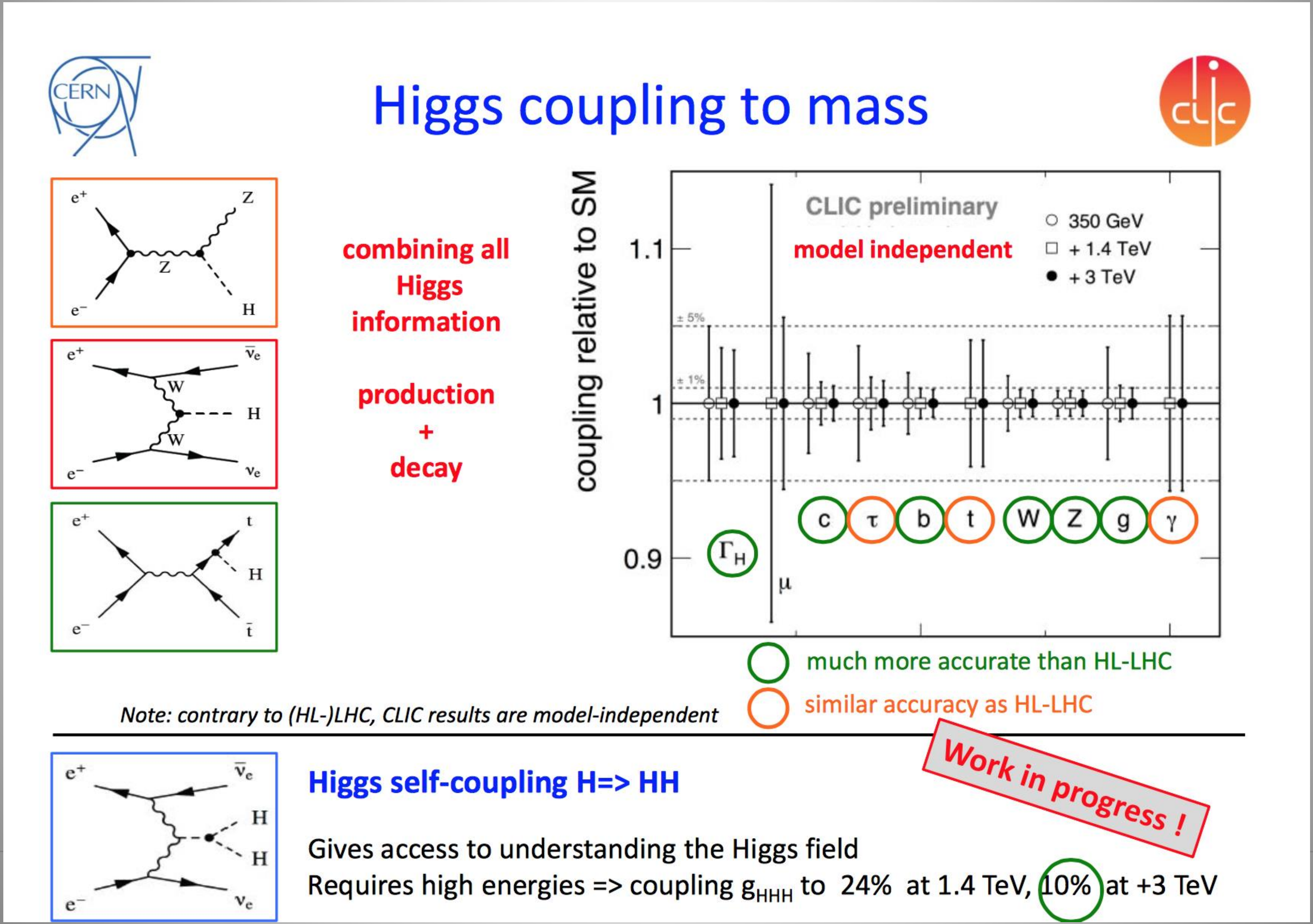
<u>Preliminary</u> projection for LHC (P. Mermod, very preliminary)







CLIC Higgs Studies



Higgs coupling to mass

combining all Higgs information

production + decay

CLIC preliminary

model independent

○ 350 GeV
□ + 1.4 TeV
● + 3 TeV

○ much more accurate than HL-LHC

○ similar accuracy as HL-LHC

Note: contrary to (HL-)LHC, CLIC results are model-independent

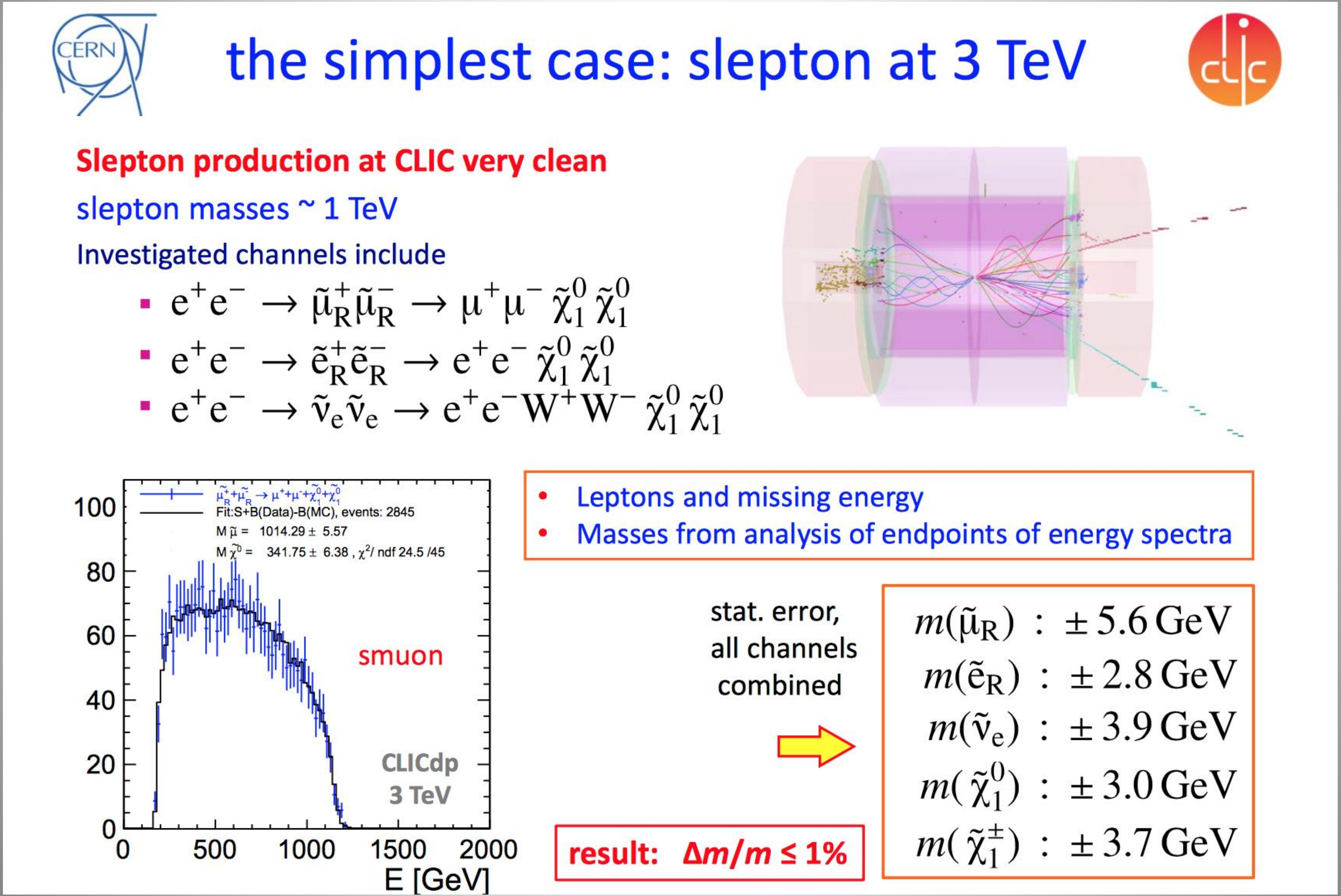
Work in progress !

Higgs self-coupling H=> HH

Gives access to understanding the Higgs field

Requires high energies => coupling g_{HHH} to 24% at 1.4 TeV, 10% at +3 TeV

CLIC SUSY Measurements



the simplest case: slepton at 3 TeV

Slepton production at CLIC very clean

slepton masses ~ 1 TeV

Investigated channels include

- $e^+e^- \rightarrow \tilde{\mu}_R^+\tilde{\mu}_R^- \rightarrow \mu^+\mu^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{e}_R^+\tilde{e}_R^- \rightarrow e^+e^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$
- $e^+e^- \rightarrow \tilde{\nu}_e\tilde{\nu}_e \rightarrow e^+e^-W^+W^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$

- Leptons and missing energy
- Masses from analysis of endpoints of energy spectra

stat. error,
all channels
combined

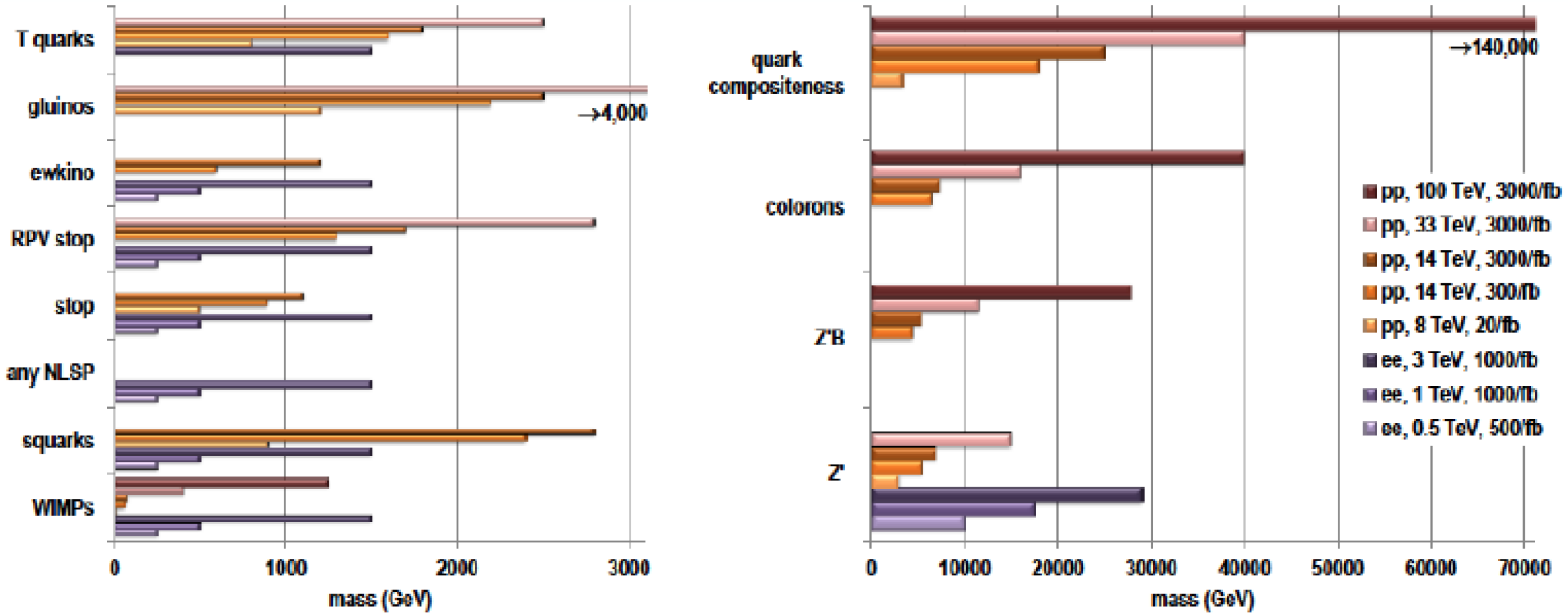
$m(\tilde{\mu}_R)$: ± 5.6 GeV
$m(\tilde{e}_R)$: ± 2.8 GeV
$m(\tilde{\nu}_e)$: ± 3.9 GeV
$m(\tilde{\chi}_1^0)$: ± 3.0 GeV
$m(\tilde{\chi}_1^\pm)$: ± 3.7 GeV

result: $\Delta m/m \leq 1\%$

Exotica Searches

Snowmass 2013 Study

Future colliders comparison

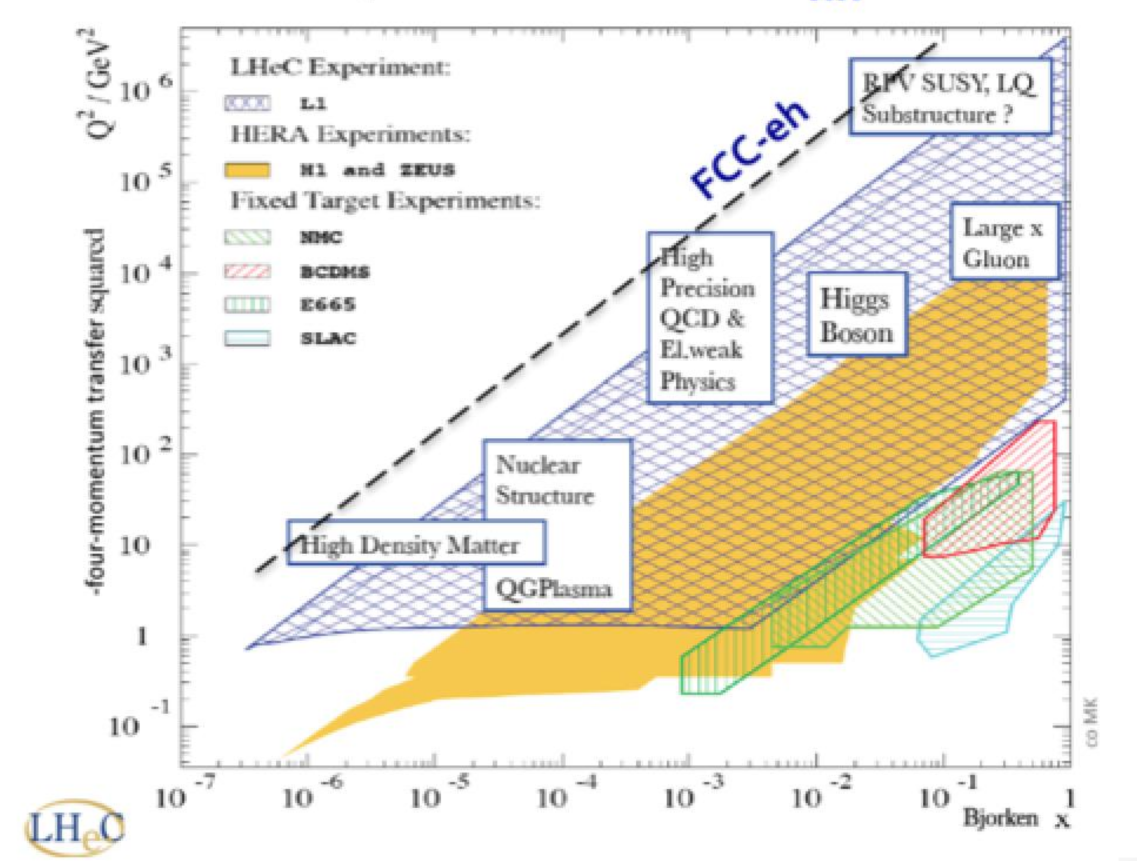


Energy Frontier Snowmass study (1311.0299)

Electron-Proton Collider

Always a useful complement to a hadron collider
eg via measurement parton distribution functions
....

FCC-hh + Energy Recovery
Linac for the electrons



Breaking of Factorisation

Free Quarks

Unconfined Color

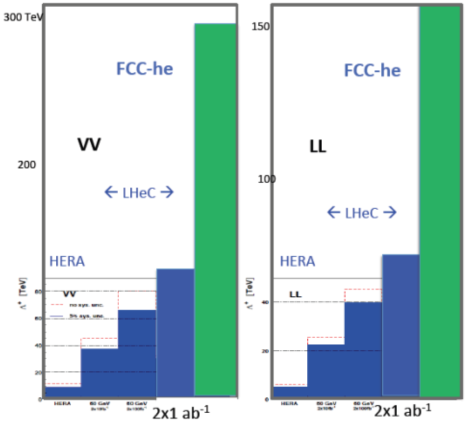
New kind of coloured matter

Quark substructure

New symmetry embedding QCD

QCD may break .. (Quigg DIS13)

Reach for CI (eeqq) at FCC-he

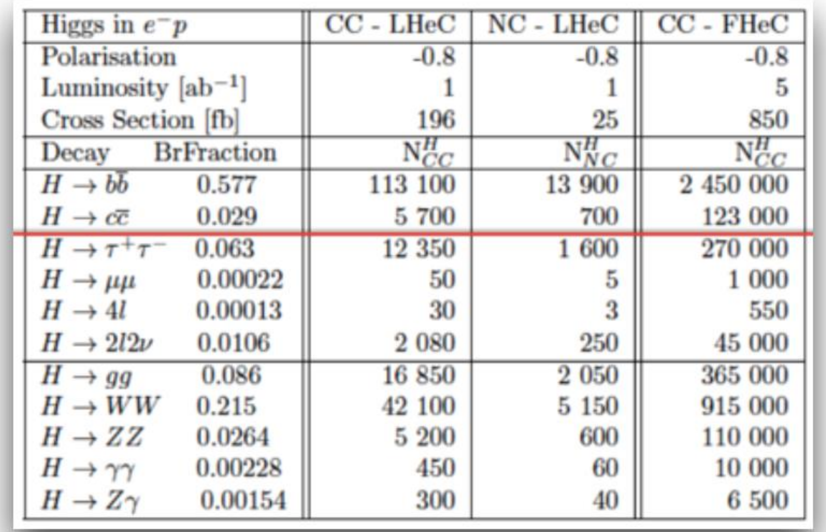


- Very preliminary scaling from LHeC
- Reach about O(100) TeV, expected to be competitive with FHC

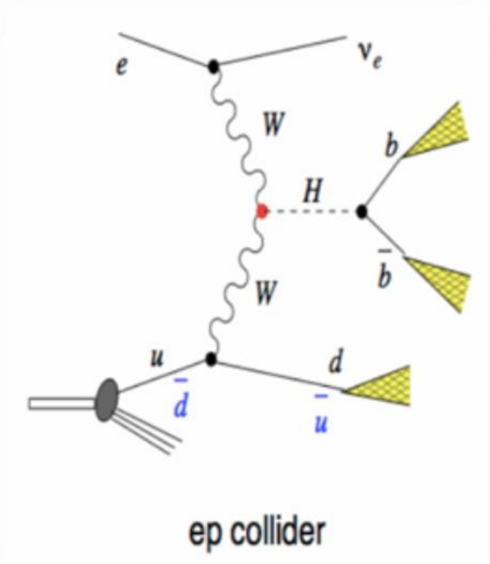
- Access to specific Higgs couplings
- Reach for new physics eg Leptoquarks, CIs…

Higgs at the LHeC/FCC-eh

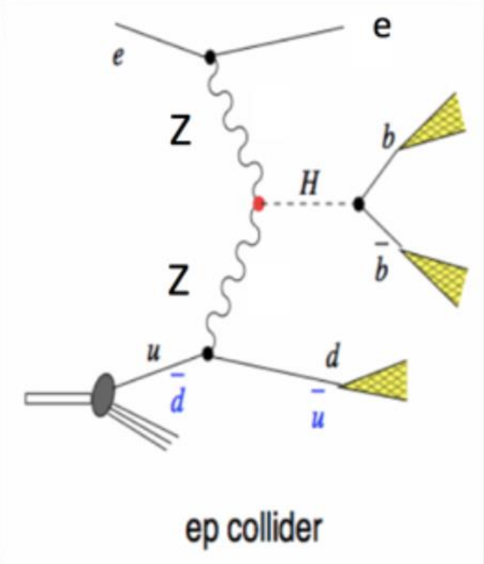
- ➡ FCC-ep can deliver PDFs for FCC-pp (Higgs) program
- ➡ Higgs studies in relatively clean environment
- ➡ Higgs precision κ_b measurement, < 1%
- ➡ Investigation potential of κ_c measurement using charm tagging



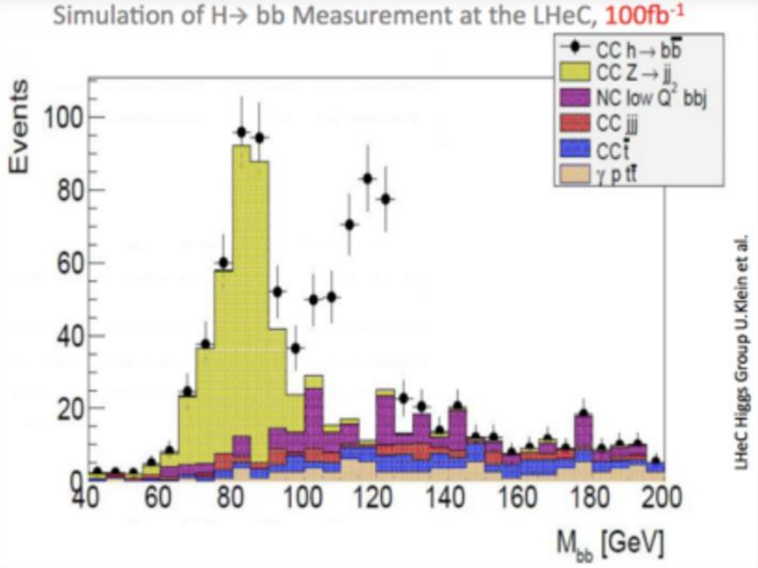
Higgs in e^-p		CC - LHeC	NC - LHeC	CC - FHeC
Polarisation		-0.8	-0.8	-0.8
Luminosity [ab^{-1}]		1	1	5
Cross Section [fb]		196	25	850
Decay	BrFraction	N^H_{CC}	N^H_{NC}	N^H_{CC}
$H \to b\bar{b}$	0.577	113 100	13 900	2 450 000
$H \to c\bar{c}$	0.029	5 700	700	123 000
$H \to \tau^+\tau^-$	0.063	12 350	1 600	270 000
$H \to \mu\mu$	0.00022	50	5	1 000
$H \to 4l$	0.00013	30	3	550
$H \to 2l2\nu$	0.0106	2 080	250	45 000
$H \to gg$	0.086	16 850	2 050	365 000
$H \to WW$	0.215	42 100	5 150	915 000
$H \to ZZ$	0.0264	5 200	600	110 000
$H \to \gamma\gamma$	0.00228	450	60	10 000
$H \to Z\gamma$	0.00154	300	40	6 500



ep collider



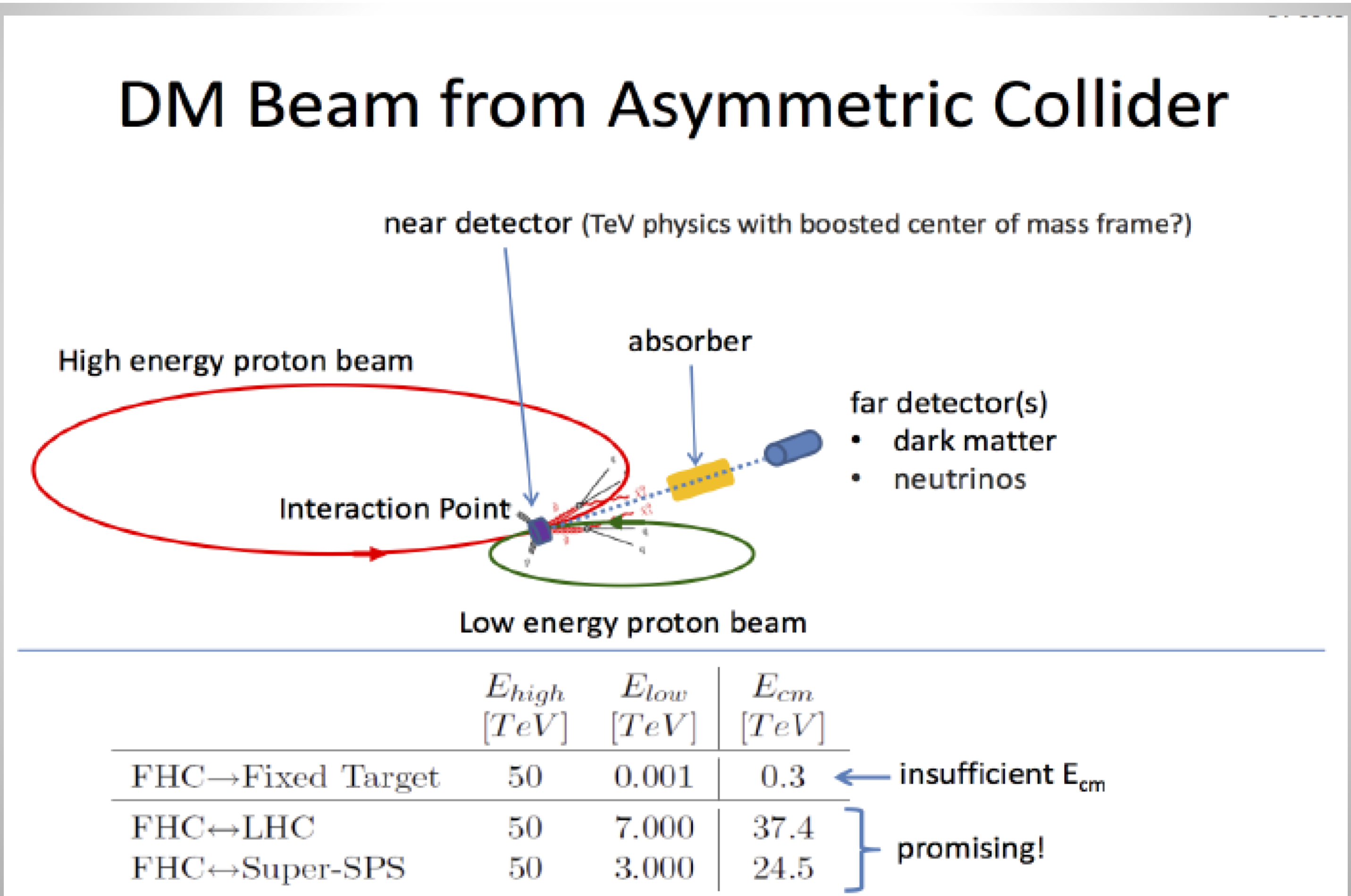
ep collider



Simulation of H→ bb Measurement at the LHeC, 100fb-1

Room for Blue Sky Thinking!

Example: If we produce Dark Matter particles candidates, can we be sure it is really DM? Check the interaction with matter in a detector!!



DM Beam from Asymmetric Collider

near detector (TeV physics with boosted center of mass frame?)

absorber

High energy proton beam

far detector(s)
- dark matter
- neutrinos

Interaction Point

Low energy proton beam

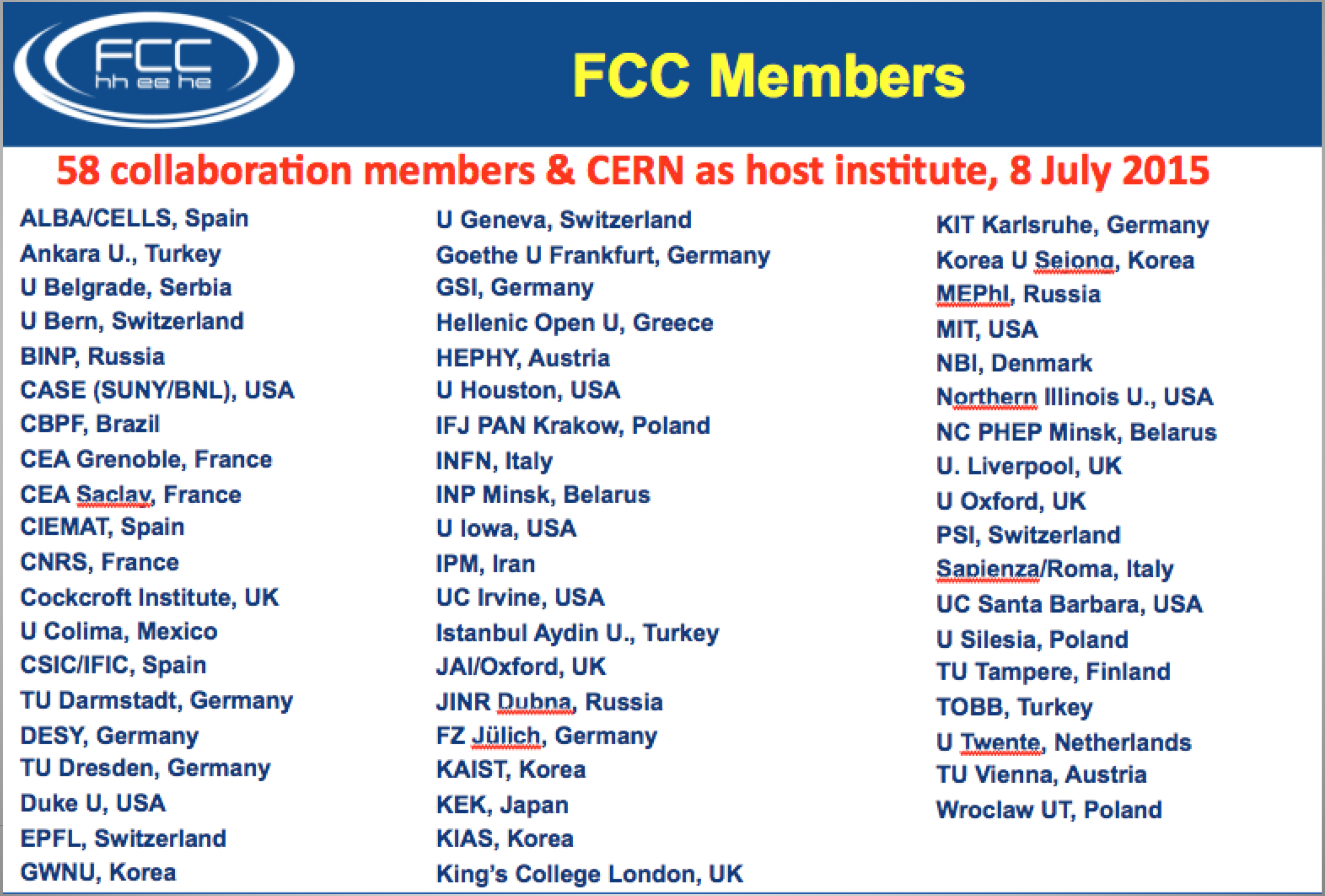
	E_{high} $[TeV]$	E_{low} $[TeV]$	E_{cm} $[TeV]$	
FHC→Fixed Target	50	0.001	0.3	← insufficient E_{cm}
FHC↔LHC	50	7.000	37.4	promising!
FHC↔Super-SPS	50	3.000	24.5	

Long timescales: Time to explore many new ideas!!

Summary

- In 2012 we found a Higgs Boson at the LHC. The next LHC run @ 13/14 TeV will hopefully reveal more.
- Study the Higgs in detail. (HE-)LHC will be able to do a lot but not everything we want…
- High energy pp colliders, at 100 TeV, will substantially extend the reach for new particles and interactions
- e+e- options for precision measurements (CLIC, FCC)
- A new collaboration on the FCC has formed, by the initiative of CERN, to study hh – ee – eh options.
- Lots of physics studies to be done, new ideas to be explored (TH+EXP). More contributors highly welcome
- The path towards new machines is long, and benefits for society (technology) will play an important role.

Summary



FCC Members

58 collaboration members & CERN as host institute, 8 July 2015

ALBA/CELLS, Spain
Ankara U., Turkey
U Belgrade, Serbia
U Bern, Switzerland
BINP, Russia
CASE (SUNY/BNL), USA
CBPF, Brazil
CEA Grenoble, France
CEA Saclay, 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
GWNU, Korea
U Geneva, Switzerland
Goethe U Frankfurt, Germany
GSI, Germany
Hellenic Open U, Greece
HEPHY, Austria
U Houston, USA
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
FZ Jülich, Germany
KAIST, Korea
KEK, Japan
KIAS, Korea
King's College London, UK
KIT Karlsruhe, Germany
Korea U Sejong, Korea
MEPhI, Russia
MIT, USA
NBI, Denmark
Northern Illinois U., USA
NC PHEP Minsk, Belarus
U. Liverpool, UK
U Oxford, UK
PSI, Switzerland
Sapienza/Roma, Italy
UC Santa Barbara, USA
U Silesia, Poland
TU Tampere, Finland
TOBB, Turkey
U Twente, Netherlands
TU Vienna, Austria
Wroclaw UT, Poland

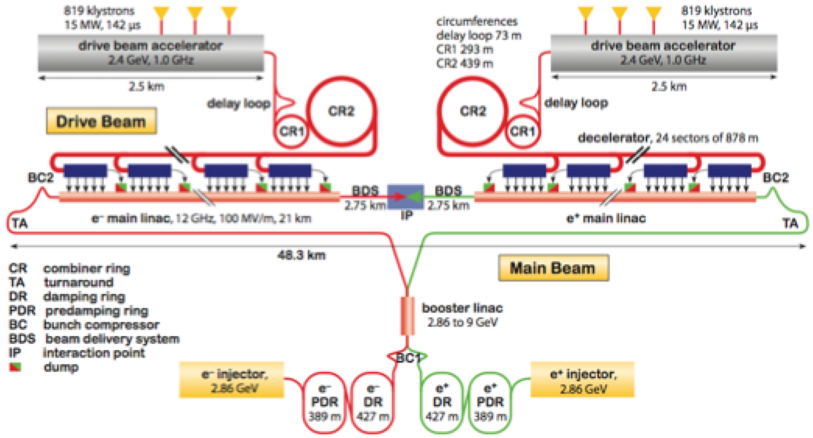
Summary

Compact Linear Collider (CLIC)

Main challenges:

- ❑ 100 MV/m accelerating gradient needed for compact (50 km) multi-TeV (up to 3 TeV) collider
- ❑ Keep RF breakdown rate small
- ❑ Short (156 ns) beam trains → bunch spacing 0.5 ns to maximize luminosity
- ❑ 2-beam acceleration (new concept): efficient RF power transfer from low-E high-intensity drive beam to (warm) accelerating structures for main beam
- ❑ Power consumption (600 MW at 3 TeV): reduction under investigation
- ❑ nm size beams; final focus
- ❑ Detectors: huge beamstrahlung (20 TeV per train in calorimeters at 3 TeV) → 1-10 ns time stamps needed

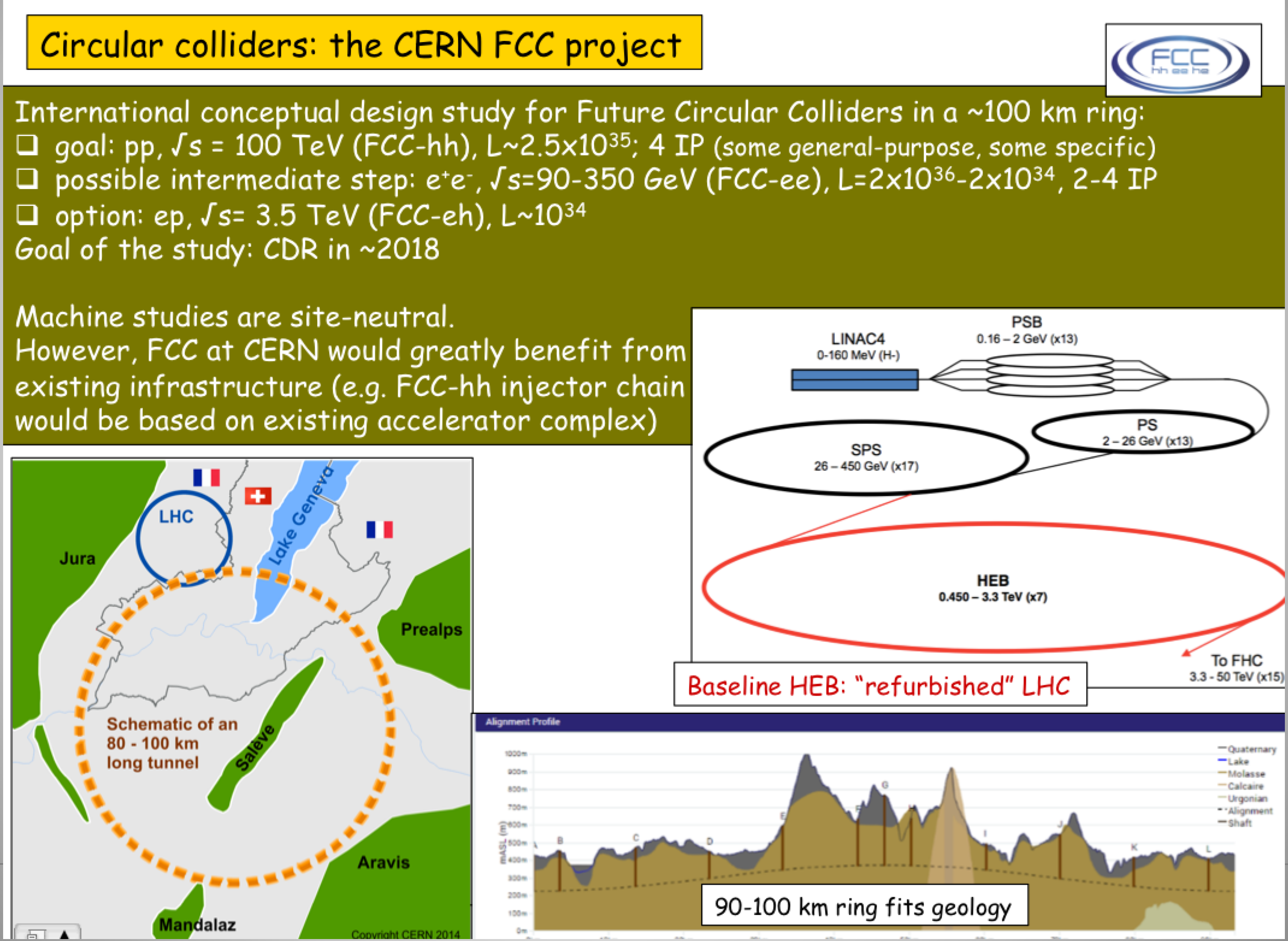
Conceptual Design Report end 2012



Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100

- ❑ Most recent operating scenario: start at √s=380 GeV for H and top physics
- ❑ If decision to proceed in ~ 2019 → construction could technically start ~2025, duration ~6 years for √s ~ 380 GeV (11 km Linac) → physics could start before 2035

Summary



Circular colliders: the CERN FCC project

International conceptual design study for Future Circular Colliders in a ~100 km ring:

- ❑ goal: pp, $\sqrt{s}$ = 100 TeV (FCC-hh), L~2.5x10^{35}; 4 IP (some general-purpose, some specific)
- ❑ possible intermediate step: e^+e^-, $\sqrt{s}$=90-350 GeV (FCC-ee), L=2x10^{36}-2x10^{34}, 2-4 IP
- ❑ option: ep, $\sqrt{s}$= 3.5 TeV (FCC-eh), L~10^{34}

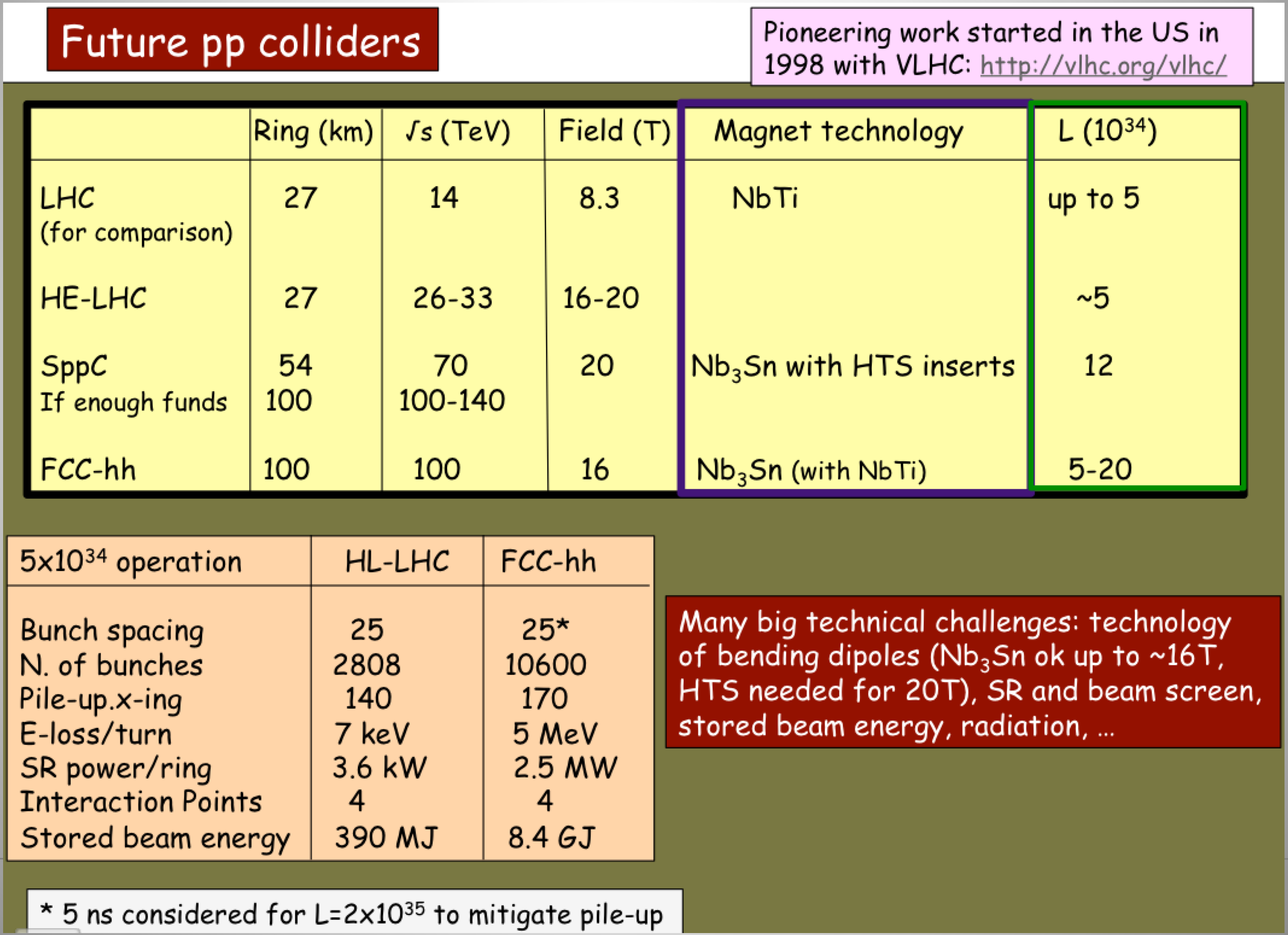
Goal of the study: CDR in ~2018

Machine studies are site-neutral.
However, FCC at CERN would greatly benefit from existing infrastructure (e.g. FCC-hh injector chain would be based on existing accelerator complex)

Baseline HEB: "refurbished" LHC

90-100 km ring fits geology

Summary



Future pp colliders

Pioneering work started in the US in 1998 with VLHC: http://vlhc.org/vlhc/

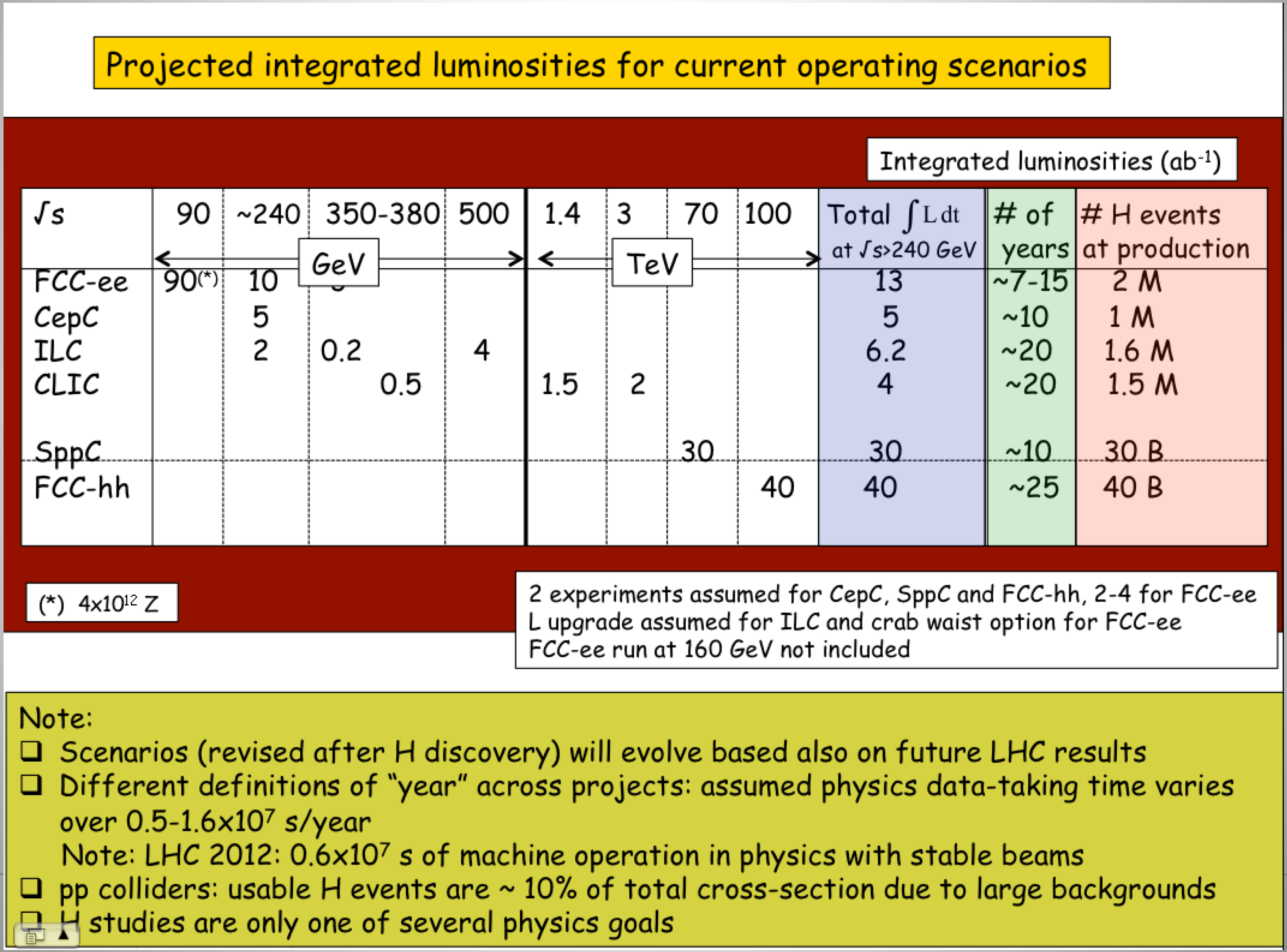
	Ring (km)	√s (TeV)	Field (T)	Magnet technology	L (10^{34})
LHC (for comparison)	27	14	8.3	NbTi	up to 5
HE-LHC	27	26-33	16-20		~5
SppC If enough funds	54 100	70 100-140	20	Nb_3Sn with HTS inserts	12
FCC-hh	100	100	16	Nb_3Sn (with NbTi)	5-20

5×10^{34} operation	HL-LHC	FCC-hh
Bunch spacing	25	25*
N. of bunches	2808	10600
Pile-up.x-ing	140	170
E-loss/turn	7 keV	5 MeV
SR power/ring	3.6 kW	2.5 MW
Interaction Points	4	4
Stored beam energy	390 MJ	8.4 GJ

Many big technical challenges: technology of bending dipoles (Nb_3Sn ok up to ~16T, HTS needed for 20T), SR and beam screen, stored beam energy, radiation, …

* 5 ns considered for $L=2\times10^{35}$ to mitigate pile-up

Summary



Projected integrated luminosities for current operating scenarios

Integrated luminosities (ab^{-1})

$\sqrt{s}$	90	~240	350-380	500	1.4	3	70	100	Total $\int L\,dt$ at $\sqrt{s}$>240 GeV	# of years	# H events at production
	GeV				TeV						
FCC-ee	90(*)	10	[illegible]						13	~7-15	2 M
CepC		5							5	~10	1 M
ILC		2	0.2	4					6.2	~20	1.6 M
CLIC			0.5		1.5	2			4	~20	1.5 M
SppC							30		30	~10	30 B
FCC-hh								40	40	~25	40 B

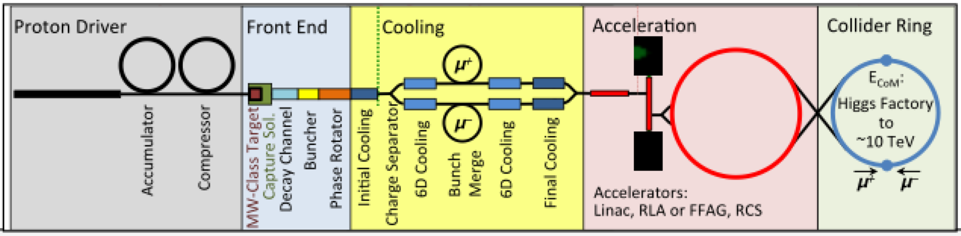
(*) $4x10^{12}$ Z

2 experiments assumed for CepC, SppC and FCC-hh, 2-4 for FCC-ee
L upgrade assumed for ILC and crab waist option for FCC-ee
FCC-ee run at 160 GeV not included

Note:
- ❑ Scenarios (revised after H discovery) will evolve based also on future LHC results
- ❑ Different definitions of "year" across projects: assumed physics data-taking time varies over 0.5-1.6x10^7 s/year
  Note: LHC 2012: 0.6x10^7 s of machine operation in physics with stable beams
- ❑ pp colliders: usable H events are ~ 10% of total cross-section due to large backgrounds
- ❑ H studies are only one of several physics goals

Summary

Muon colliders



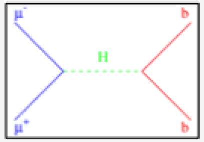
Synergies with neutrino factories

Main advantage compared to e^+e^- colliders: $m_\mu \sim 200\ m_e$

→ negligible SR → can reach multi-TeV with (compact !) circular colliders: 300 m ring for $\sqrt{s}$ = 125 GeV, 4.5 km for $\sqrt{s}$ = 3 TeV

→ negligible beamstrahlung → much smaller E spread

→ $\sigma(\mu\mu \to H) \sim 20$ pb (s-channel resonant production) → H factory

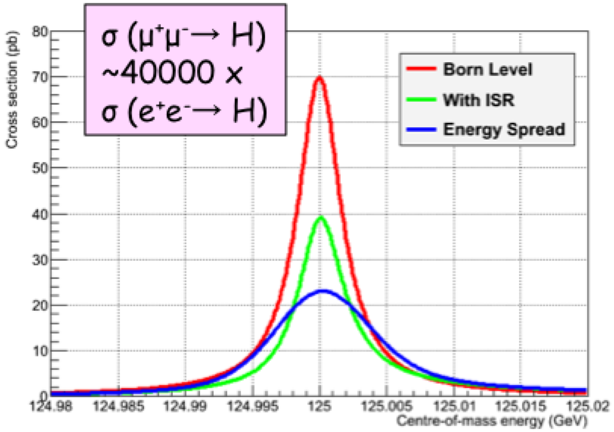


Main challenge: produce high-intensity, low E-spread beams:

☐ $m_\mu \sim 200\ m_e$ → SR damping does not work → novel cooling methods (dE/dx based) needed to reach beam energy spread of ~ 3×10^{-5} (for precise line shape studies) and high L

☐ $\tau_\mu \sim 2.2\ \mu s$ → production, collection, cooling, acceleration, collisions within ~ ms

Beam spread of ~ 3×10^{-5} would allow Γ_H measurement from line shape to 5% (0.2 MeV) → resolve (possible) resonances



$\sigma(\mu^+\mu^- \to H)$ ~40000 x $\sigma(e^+e^- \to H)$

However, with currently projected L (~10^{32}): ~ 20000 H/year → not competitive with e^+e^- colliders for coupling measurements (except Hμμ ~ 1%)

↓

More R&D needed to demonstrated feasibility, in particular cooling: linear systems (MICE at RAL), rings (recently re-ignited by C.Rubbia)

Summary

The H boson is not just … "yet another particle"

- ☐ Profoundly different from all elementary particles discovered so far
- ☐ Related to the most obscure sector of SM
- ☐ Linked to some of the deepest structural questions (flavour, naturalness, vacuum, ...)

Its discovery opens new paths of exploration, and a very broad and challenging experimental programme

Every problem of the SM originates from Higgs interactions

$$\mathcal{L} = \underset{\substack{\uparrow \\ \text{flavour}}}{\lambda H \psi \bar{\psi}} + \underset{\substack{\uparrow \\ \text{naturalness}}}{\mu^2} |H|^2 - \underset{\substack{\uparrow \\ \text{stability}}}{\lambda} |H|^4 - \underset{\substack{\uparrow \\ \text{C.C.}}}{V_0}$$

G.F. Giudice

- ☐ Precision measurements of couplings (as many generations as possible, loops, …)
- ☐ Forbidden and rare decays (e.g. H→ τμ)
  → flavour structure and source of fermion masses
- ☐ H potential (HH production, self-couplings):
  → EWSB mechanism (strong dynamics ?)
  → EW phase transition → baryogenesis ?
- ☐ Exotic decays (e.g. H→ E_T^{miss}) → new physics ?
- ☐ Other H properties (width, CP, …)
- ☐ Searches for additional H bosons

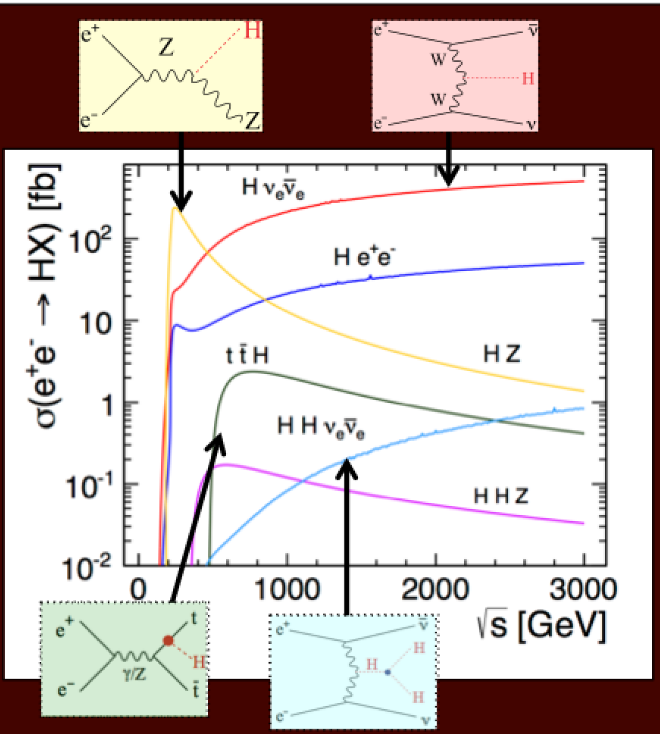
Impact of new physics on couplings:

$\Delta\kappa/\kappa \sim 5\%/\Lambda^2_{NP}$ (Λ_{NP} in TeV)

→ 0.1-1% exp. precision needed

Summary

e⁺e⁻ colliders

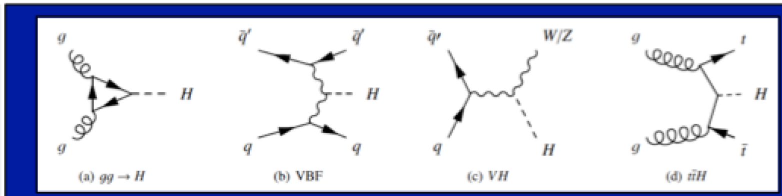


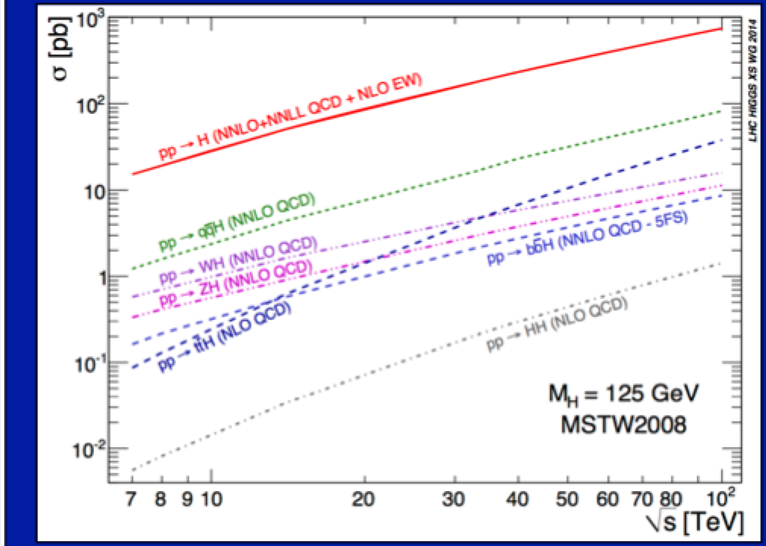
❑ Low backgrounds → all decay modes (hadronic, invisible, exotic) accessible

❑ Model-indep. coupling measurements: σ(HZ) and Γ_H from data (ZH → μμ/qq+X recoil, Hνν →bbνν)

❑ ttH and HH require √s ≥ 500 GeV

pp colliders



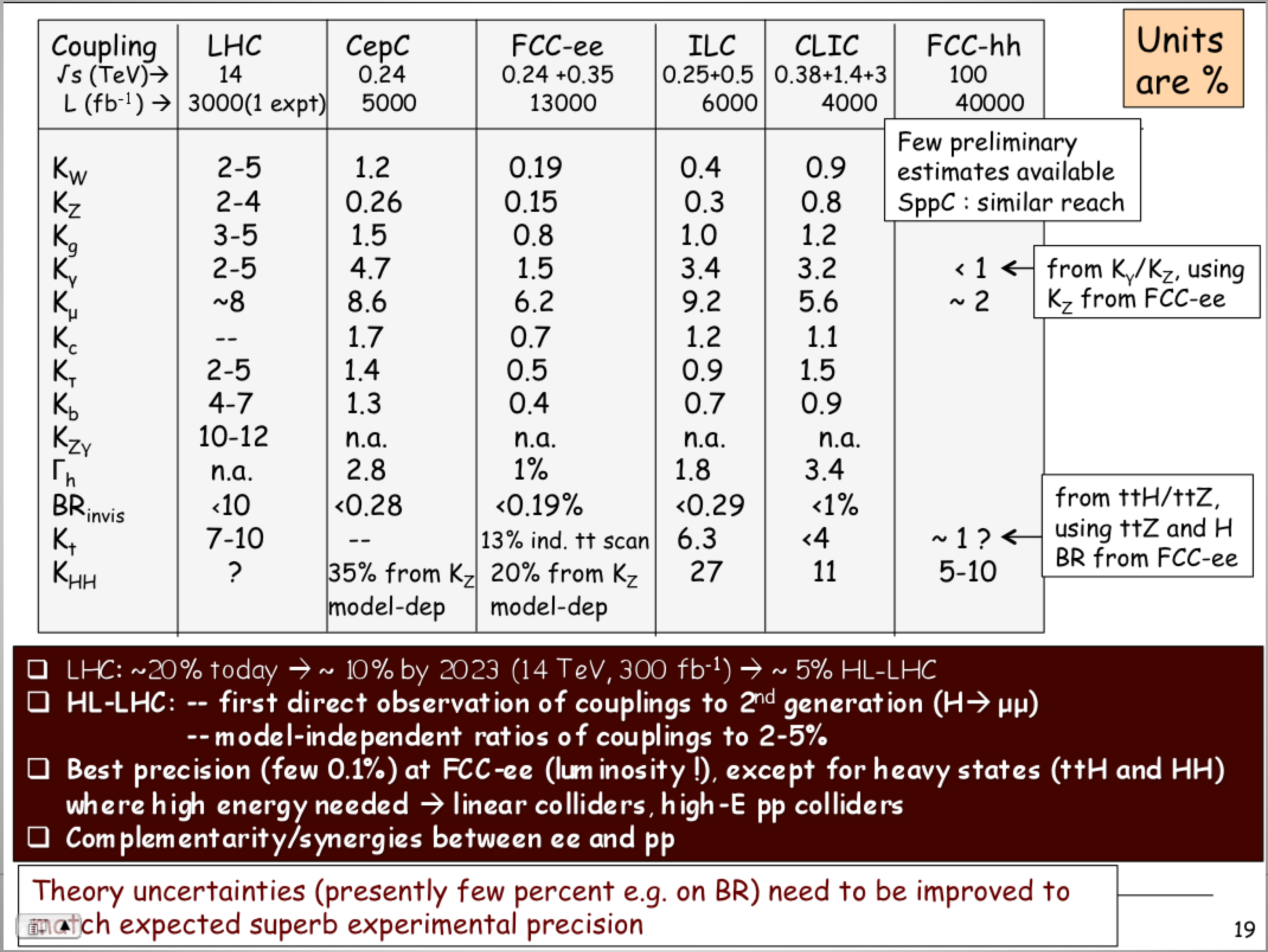


❑ High energy, huge cross-sections → optimal for (clean) rare decays and heavy final states (ttH, HH)

❑ Huge backgrounds → not all channels accessible

❑ Model-dep. coupling measurements: Γ_H and σ (H) from SM

Summary



Coupling $\sqrt{s}$ (TeV)→ L (fb^{-1}) →	LHC 14 3000(1 expt)	CepC 0.24 5000	FCC-ee 0.24 +0.35 13000	ILC 0.25+0.5 6000	CLIC 0.38+1.4+3 4000	FCC-hh 100 40000
K_W	2-5	1.2	0.19	0.4	0.9	
K_Z	2-4	0.26	0.15	0.3	0.8	
K_g	3-5	1.5	0.8	1.0	1.2	
K_γ	2-5	4.7	1.5	3.4	3.2	< 1
K_μ	~8	8.6	6.2	9.2	5.6	~ 2
K_c	--	1.7	0.7	1.2	1.1	
K_τ	2-5	1.4	0.5	0.9	1.5	
K_b	4-7	1.3	0.4	0.7	0.9	
$K_{Z\gamma}$	10-12	n.a.	n.a.	n.a.	n.a.	
Γ_h	n.a.	2.8	1%	1.8	3.4	
BR_{invis}	<10	<0.28	<0.19%	<0.29	<1%	
K_t	7-10	--	13% ind. tt scan	6.3	<4	~ 1 ?
K_{HH}	?	35% from K_Z model-dep	20% from K_Z model-dep	27	11	5-10

Units are %

Few preliminary estimates available
SppC : similar reach

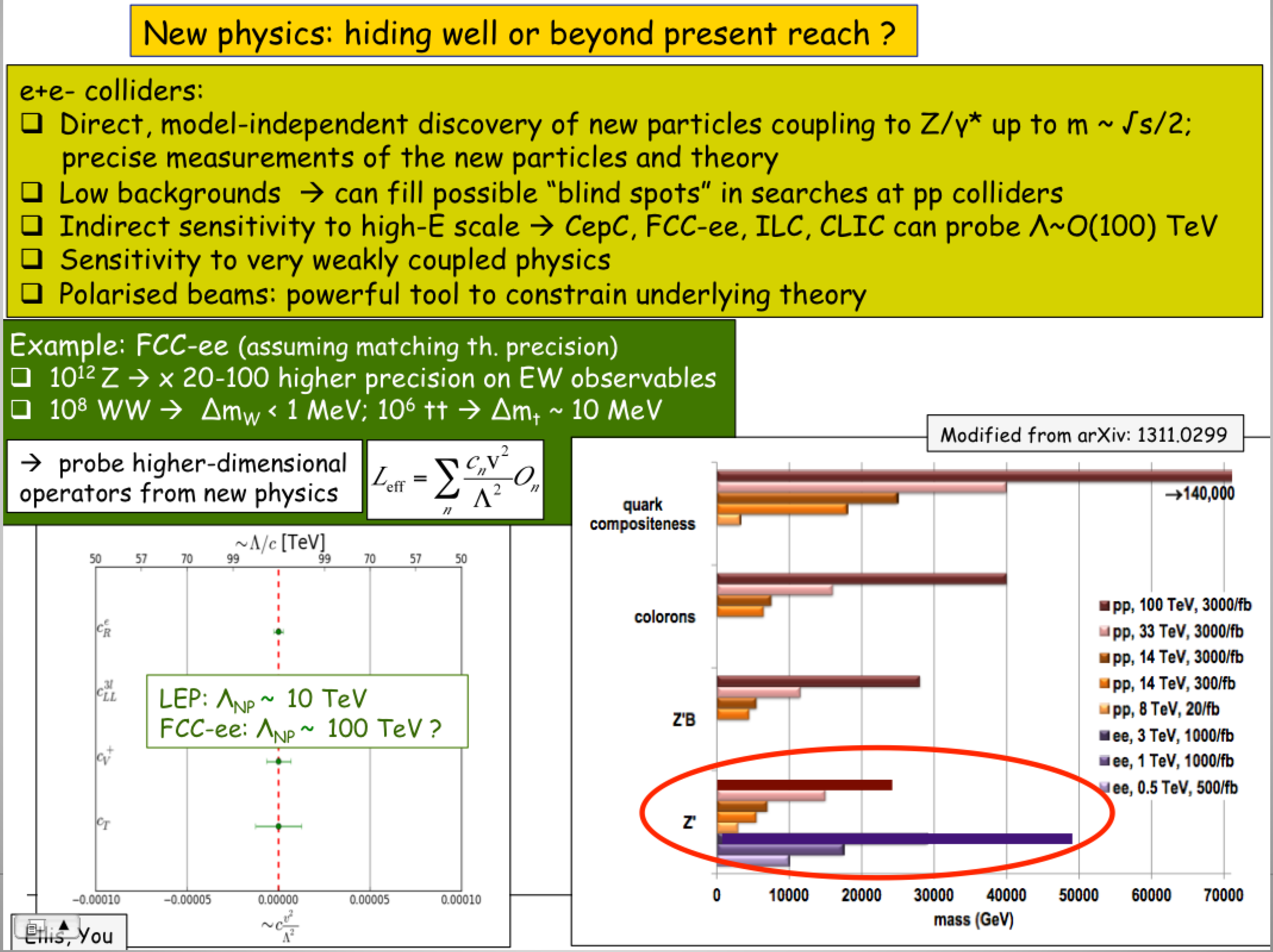
from K_γ/K_Z, using K_Z from FCC-ee

from ttH/ttZ, using ttZ and H BR from FCC-ee

- ☐ LHC: ~20% today → ~ 10% by 2023 (14 TeV, 300 fb^{-1}) → ~ 5% HL-LHC
- ☐ HL-LHC: -- first direct observation of couplings to 2nd generation (H→ μμ)
  -- model-independent ratios of couplings to 2-5%
- ☐ Best precision (few 0.1%) at FCC-ee (luminosity !), except for heavy states (ttH and HH) where high energy needed → linear colliders, high-E pp colliders
- ☐ Complementarity/synergies between ee and pp

Theory uncertainties (presently few percent e.g. on BR) need to be improved to match expected superb experimental precision

Summary



New physics: hiding well or beyond present reach ?

e+e- colliders:

- ❑ Direct, model-independent discovery of new particles coupling to Z/γ* up to m ~ √s/2; precise measurements of the new particles and theory
- ❑ Low backgrounds → can fill possible "blind spots" in searches at pp colliders
- ❑ Indirect sensitivity to high-E scale → CepC, FCC-ee, ILC, CLIC can probe Λ~O(100) TeV
- ❑ Sensitivity to very weakly coupled physics
- ❑ Polarised beams: powerful tool to constrain underlying theory

Example: FCC-ee (assuming matching th. precision)

- ❑ 10^{12} Z → x 20-100 higher precision on EW observables
- ❑ 10^8 WW → Δm_W < 1 MeV; 10^6 tt → Δm_t ~ 10 MeV

→ probe higher-dimensional operators from new physics

$$L_{\text{eff}} = \sum_n \frac{c_n v^2}{\Lambda^2} O_n$$

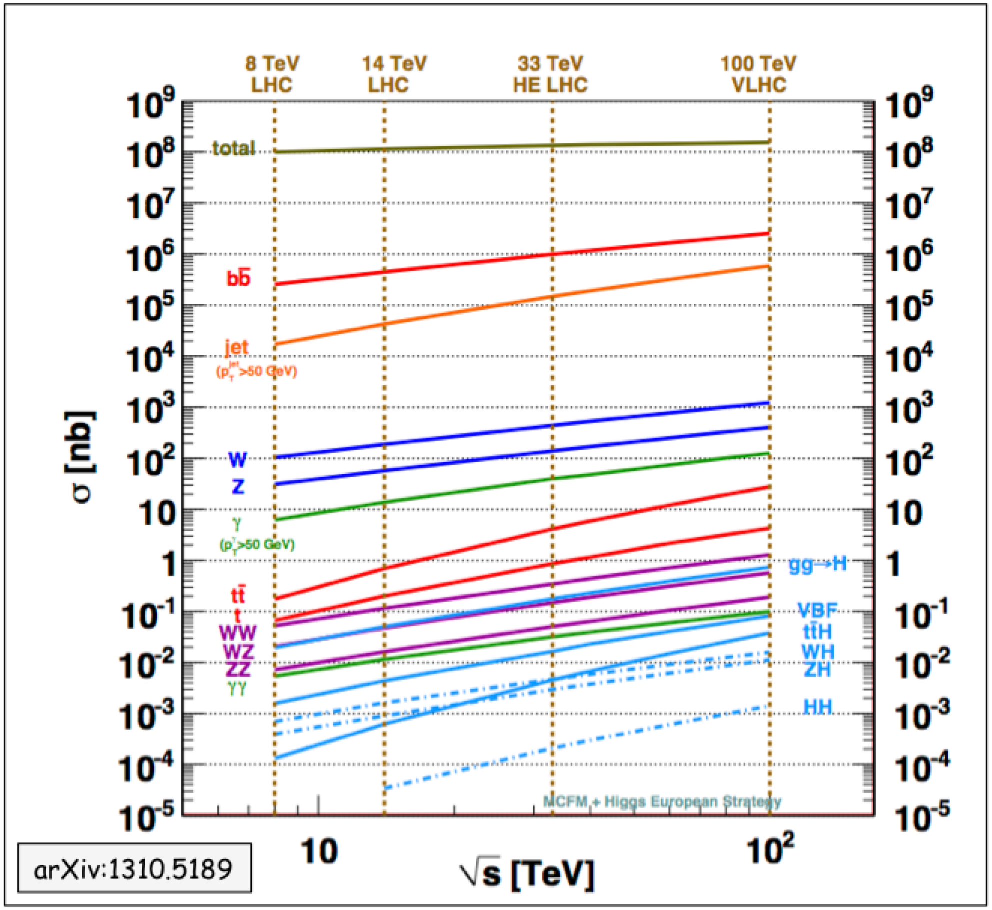
LEP: Λ_{NP} ~ 10 TeV
FCC-ee: Λ_{NP} ~ 100 TeV ?

Modified from arXiv: 1311.0299

Ellis, You

Summary

Hadron colliders: direct exploration of the "energy frontier"



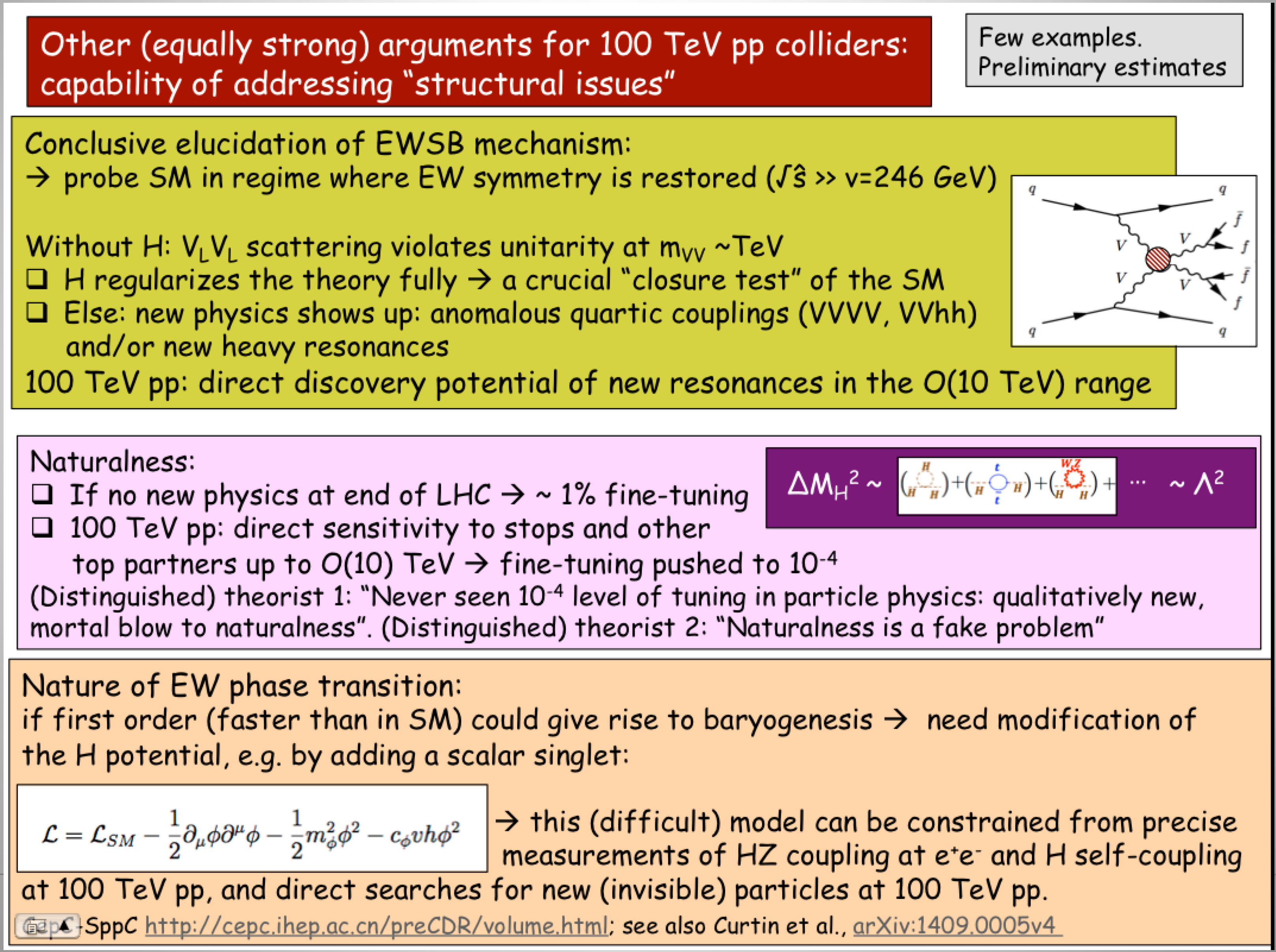
arXiv:1310.5189

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)	$\sim10^3$

With 40/ab at √s=100 TeV expect: $\sim10^{12}$ top, 10^{10} H bosons, 10^5 m=8 TeV gluino pairs, …

If new (heavy) physics discovered at the LHC → completion of spectrum is a "no-lose" argument for future ~ 100 TeV pp collider: extend discovery potential up to m~50 TeV

Summary



Other (equally strong) arguments for 100 TeV pp colliders: capability of addressing "structural issues"

Few examples. Preliminary estimates

Conclusive elucidation of EWSB mechanism:

→ probe SM in regime where EW symmetry is restored ($\sqrt{\hat{s}} >> v=246$ GeV)

Without H: V_LV_L scattering violates unitarity at m_{VV} ~TeV

- ☐ H regularizes the theory fully → a crucial "closure test" of the SM
- ☐ Else: new physics shows up: anomalous quartic couplings (VVVV, VVhh) and/or new heavy resonances

100 TeV pp: direct discovery potential of new resonances in the O(10 TeV) range

Naturalness:

- ☐ If no new physics at end of LHC → ~ 1% fine-tuning
- ☐ 100 TeV pp: direct sensitivity to stops and other top partners up to O(10) TeV → fine-tuning pushed to 10^{-4}

$\Delta M_H^2 \sim$ ( )+( )+( )+ ··· $\sim \Lambda^2$

(Distinguished) theorist 1: "Never seen 10^{-4} level of tuning in particle physics: qualitatively new, mortal blow to naturalness". (Distinguished) theorist 2: "Naturalness is a fake problem"

Nature of EW phase transition:

if first order (faster than in SM) could give rise to baryogenesis → need modification of the H potential, e.g. by adding a scalar singlet:

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - c_\phi v h \phi^2$$

→ this (difficult) model can be constrained from precise measurements of HZ coupling at e^+e^- and H self-coupling at 100 TeV pp, and direct searches for new (invisible) particles at 100 TeV pp.

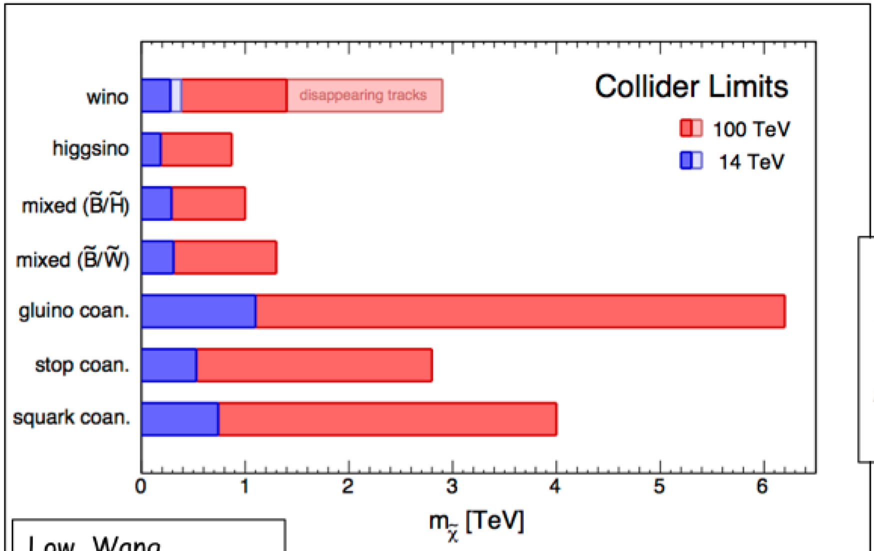
CepC-SppC http://cepc.ihep.ac.cn/preCDR/volume.html; see also Curtin et al., arXiv:1409.0005v4

Summary

Conclusive searches of TeV-scale WIMP dark matter ?

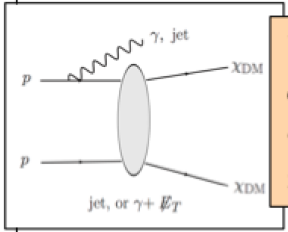
From relic abundance:

$$M_{\rm DM} \lesssim 1.8\ {\rm TeV}\left(\frac{g_{\rm eff}^2}{0.3}\right)$$



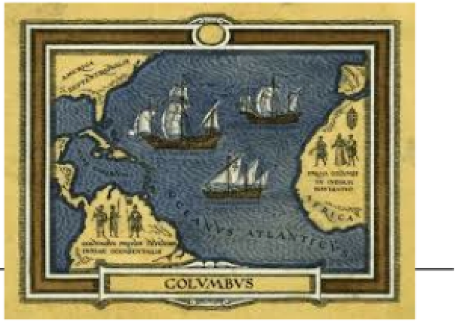
Low, Wang
arXiv:1404.0682v2

DM candidates from generic EW multiplets (direct pair production or from 1-step decays of nearly-degenerate heavier states)

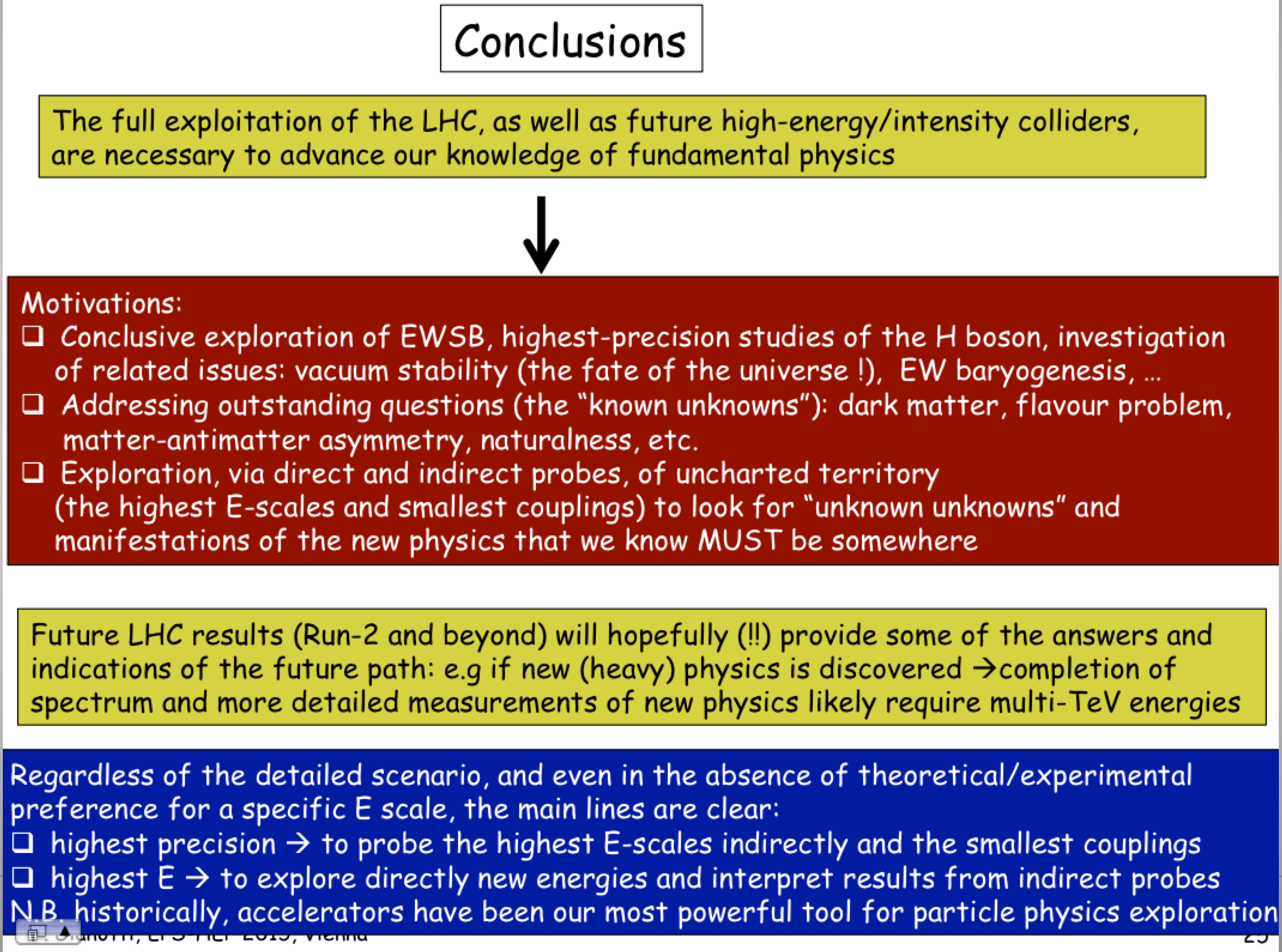


Note: challenging experimental signatures (mainly based on ISR mono-object)

… and of course exploration of unknown territory …



Summary



Conclusions

The full exploitation of the LHC, as well as future high-energy/intensity colliders, are necessary to advance our knowledge of fundamental physics

↓

Motivations:

- ❑ Conclusive exploration of EWSB, highest-precision studies of the H boson, investigation of related issues: vacuum stability (the fate of the universe !), EW baryogenesis, …
- ❑ Addressing outstanding questions (the "known unknowns"): dark matter, flavour problem, matter-antimatter asymmetry, naturalness, etc.
- ❑ Exploration, via direct and indirect probes, of uncharted territory (the highest E-scales and smallest couplings) to look for "unknown unknowns" and manifestations of the new physics that we know MUST be somewhere

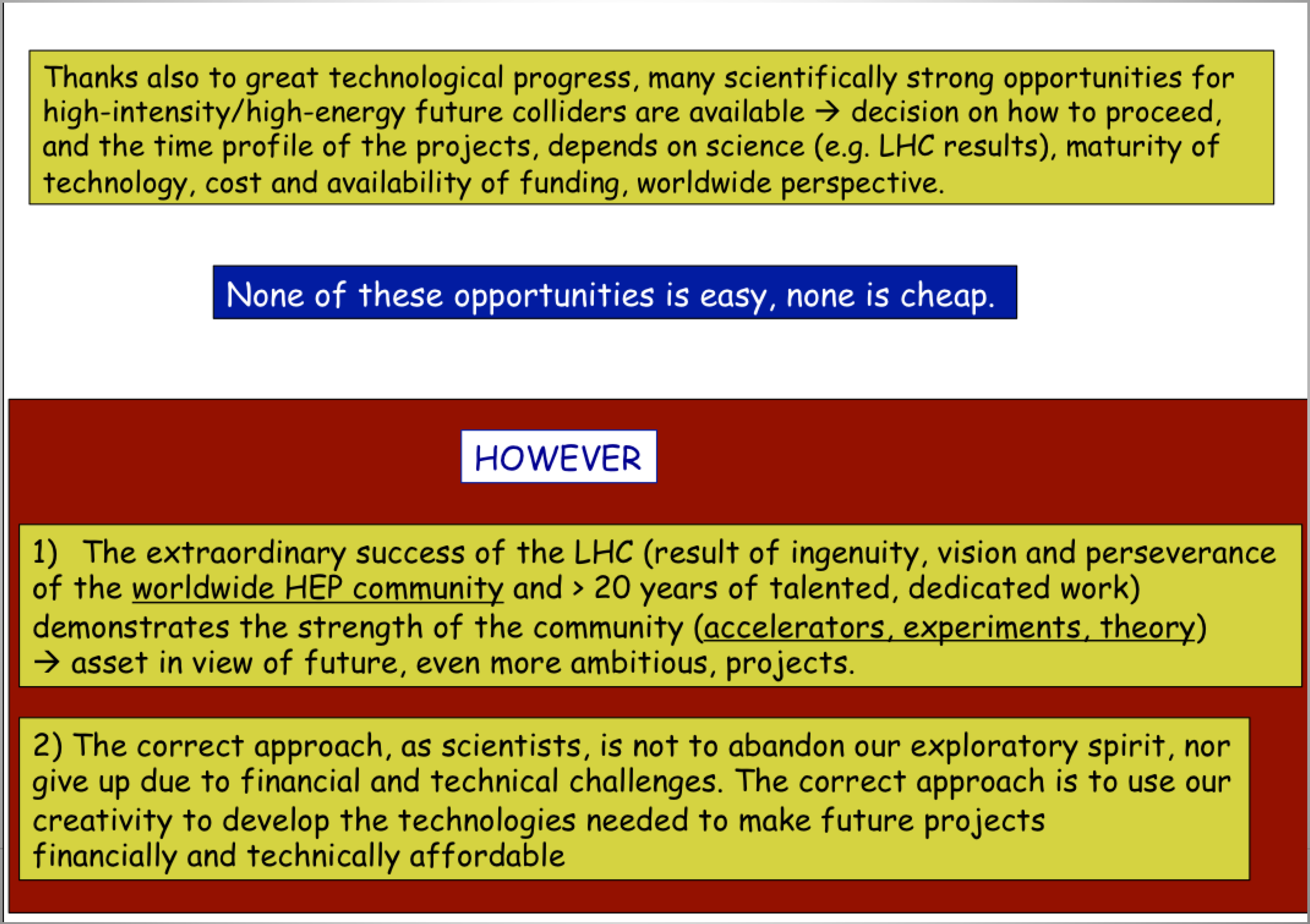
Future LHC results (Run-2 and beyond) will hopefully (!!) provide some of the answers and indications of the future path: e.g if new (heavy) physics is discovered → completion of spectrum and more detailed measurements of new physics likely require multi-TeV energies

Regardless of the detailed scenario, and even in the absence of theoretical/experimental preference for a specific E scale, the main lines are clear:

- ❑ highest precision → to probe the highest E-scales indirectly and the smallest couplings
- ❑ highest E → to explore directly new energies and interpret results from indirect probes

N.B. historically, accelerators have been our most powerful tool for particle physics exploration

Summary



Thanks also to great technological progress, many scientifically strong opportunities for high-intensity/high-energy future colliders are available → decision on how to proceed, and the time profile of the projects, depends on science (e.g. LHC results), maturity of technology, cost and availability of funding, worldwide perspective.

None of these opportunities is easy, none is cheap.

HOWEVER

1) The extraordinary success of the LHC (result of ingenuity, vision and perseverance of the worldwide HEP community and > 20 years of talented, dedicated work) demonstrates the strength of the community (accelerators, experiments, theory) → asset in view of future, even more ambitious, projects.

2) The correct approach, as scientists, is not to abandon our exploratory spirit, nor give up due to financial and technical challenges. The correct approach is to use our creativity to develop the technologies needed to make future projects financially and technically affordable