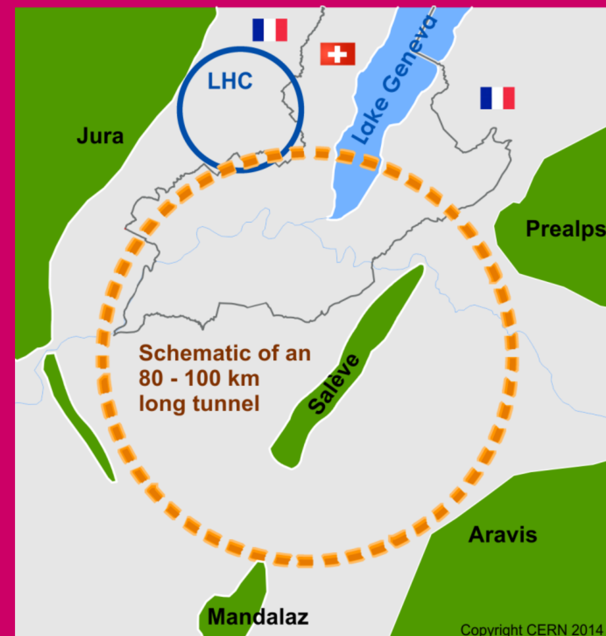
FCC - Future Circular Collider



Marek Taševský (FZÚ)

Shromáždění CZ HEP komunity, MFF UK 11/03/2014

Pouze základní fakta. Detaily na semináři ve FZÚ (27/02/2014)

Detailed talk from FZU seminar:

http://www.farm.particle.cz/twiki/bin/view/ATLAS/AtlasSeminars

Three main outcomes from LHC Run 1

We have consolidated the Standard Model with detailed studies at $\sqrt{s}$ = 7-8 TeV, which complement wealth of measurements at lower energy by previous/present machines
→ it works BEAUTIFULLY …

We have completed the Standard Model: Higgs boson discovery
(almost 100 years of theoretical and experimental efforts !)

We have NO evidence of new physics (yet …)

Note: the last point implies that, if new physics exists at the TeV scale and is discovered at $\sqrt{s}$ ~ 14 TeV in 2015++, its mass spectrum is quite heavy
→ it will likely require a lot of luminosity and energy to study it fully and in detail
→ implications on energy of future machines

The present paradox ….

On one hand:
the LHC results imply that the SM technically works up to scales much higher than the TeV scale, and current limits on new physics seriously challenge the simplest attempts (e.g. minimal SUSY) to fix its weaknesses

On the other hand:
there is strong evidence that the SM must be modified with the introduction of new particles and/or interactions at some E scale to address fundamental outstanding questions, e.g.:
naturalness, dark matter, matter/antimatter asymmetry, the flavour/family problems, unification of coupling constants, etc.

- Answers to some of the above (and other) questions expected at the ~TeV scale, whose study JUST started at the LHC → imperative necessity of exploring this scale as much as we can with the highest-E facility we have today
- Higgs sector (Higgs boson, EWSB mechanism): less known component (experimentally) of the SM → lot of work needed to e.g. understand if it is the minimal mechanism or something more complex

Future Circular Collider (FCC) Study

Summary: European Strategy Update 2013
Design studies and R&D at the energy frontier

….“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**

Kick-off by CERN DG

Why

- Push the energy frontier beyond LHC
- High Priority item within the European Strategy for Particle Physics
- Timely
  - lead times for R&D very long
  - LHC physics program for ~20 years
- Need for a project plan when LHC results indicate direction to go

What

- Technical/Conceptual Design Reports for linear e^+e^- Colliders exist: ILC/CLIC
  Japan interested in housing ILC
  Europe and CERN: participation in both endeavours will be continued
- Need to go beyond present energy frontier → circular high energy collider

How

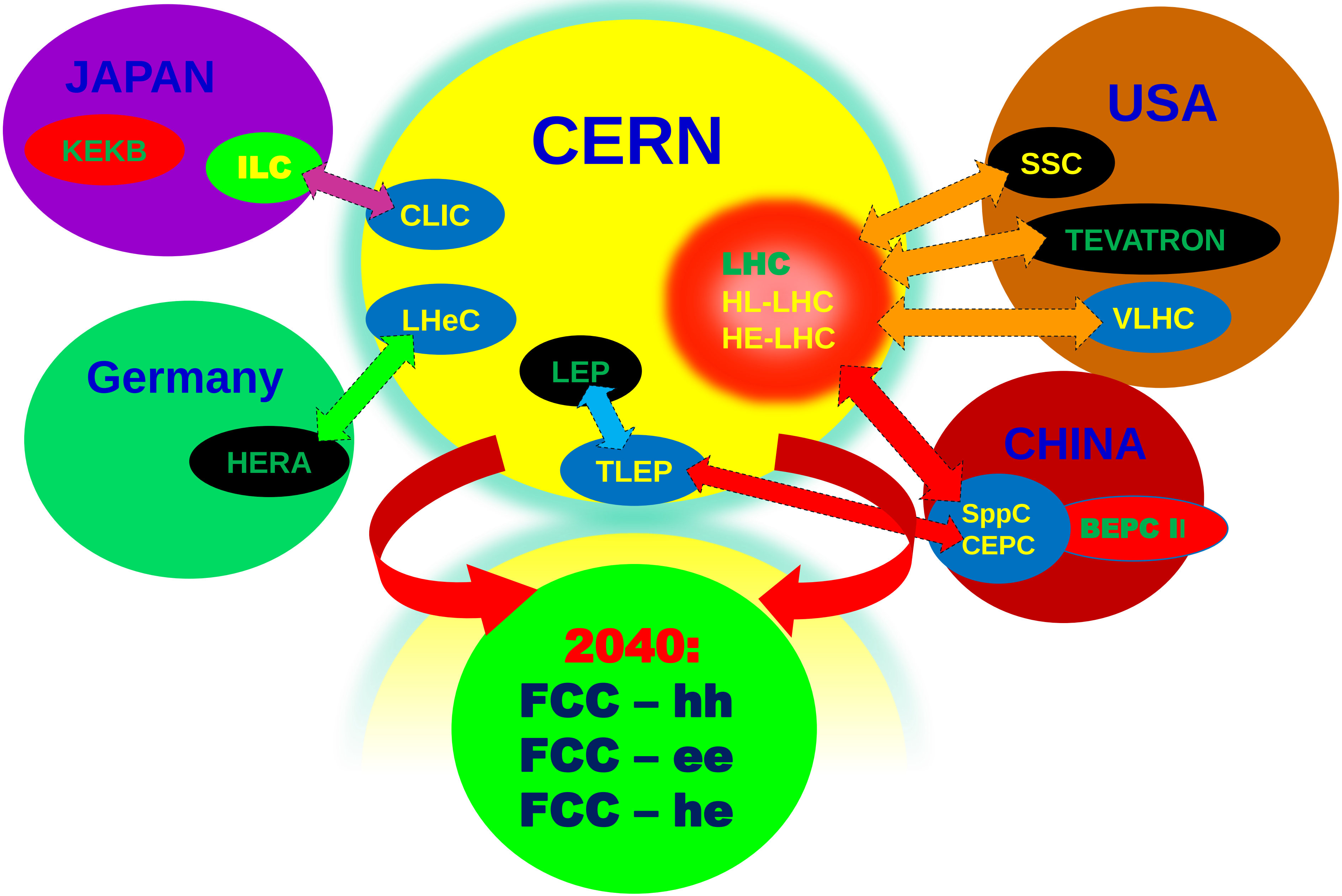
- Exploitation of **all options** for such a project (hh – ee – ep) **within one study**

- Global Collaboration for the **Study of Future Circular Colliders**
  (similar to the CLIC collaboration)
- Hosted by CERN

Scope

The main emphasis of the conceptual design study shall be the long-term goal of a hadron collider with a centre-of-mass energy of the order of 100 TeV in a new tunnel of 80-100 km circumference for the purposes of studying physics at the highest energies.
The conceptual design study shall also include a lepton collider and its detectors, as a potential intermediate step towards realization of the hadron facility. Potential synergies with linear collider detector designs should be considered.
Options for e-p scenarios and their impact on the infrastructure shall be examined at conceptual level.
The study shall include cost and energy optimisation, industrialisation aspects and provide implementation scenarios, including schedule and cost profiles.

Politics in the context



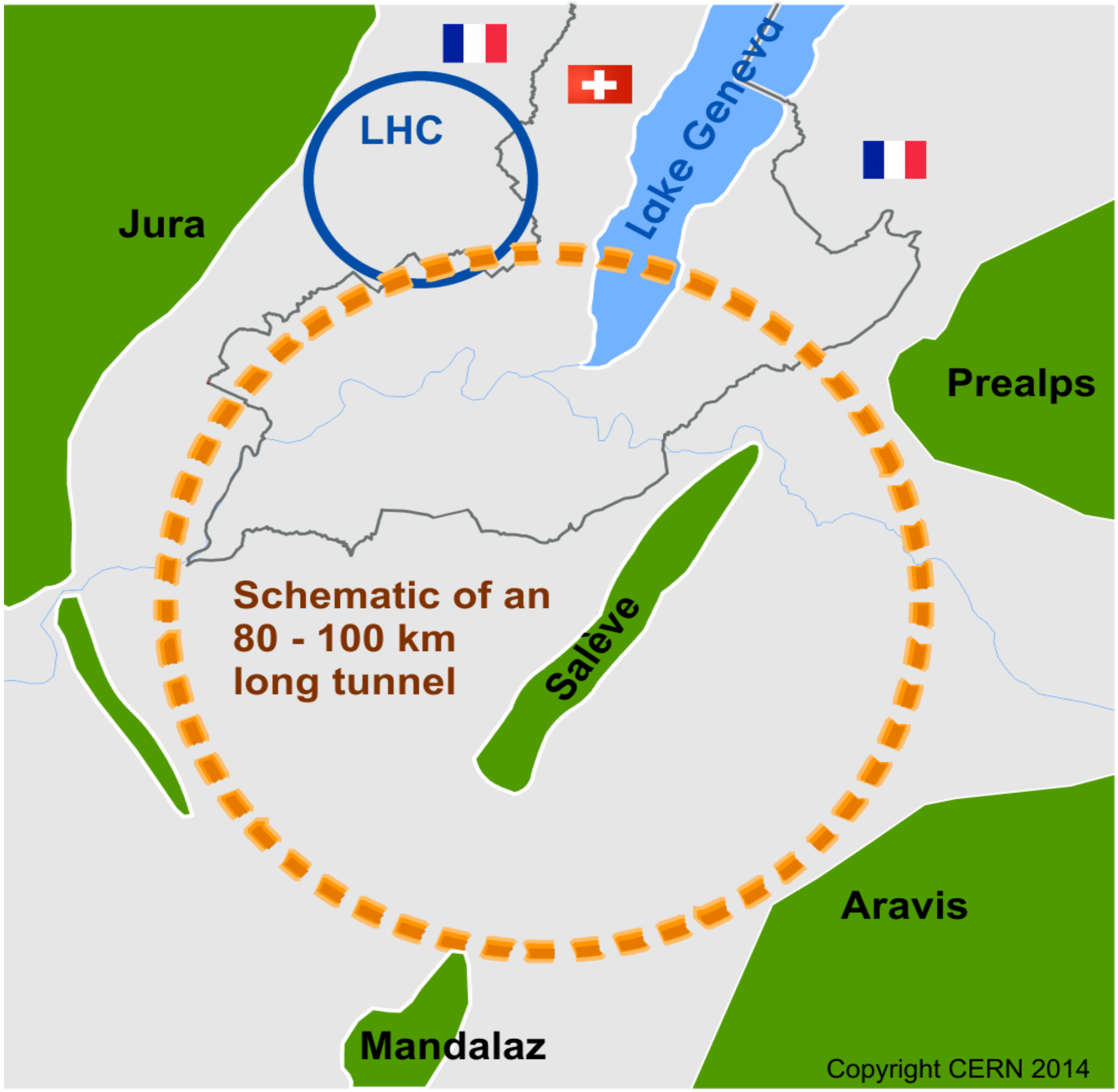
Future Circular Collider Study - SCOPE
CDR and cost review for the next ESU (2018)

Forming an international collaboration to study:

- ***pp*-collider (*FCC-hh*)** → defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

- ***e^+e^-* collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **80-100 km infrastructure** in Geneva area



FCC motivation: pushing energy frontier

High-energy hadron collider *FCC-hh* as long-term goal

- **Seems only approach to get to 100 TeV range** in the coming decades
- High energy and luminosity at affordable power consumption
- **Lead time design & construction > 20 years** (LHC study started 1983!)

  → Must start studying now to be ready for 2035/2040

Lepton collider *FCC-ee* as potential intermediate step

- Would provide/share **part of infrastructure**
- Important **precision measurements** indicating the energy scale at which new physics is expected
- Search for **new physics in rare decays of *Z, W, H, t*** and rare processes

Lepton-hadron collider *FCC-he* as option

- High precision **deep inelastic scattering and Higgs physics**

Most aspects of collider designs and R&D non-site specific.
Tunnel and site study in Geneva area as ESU requests.

Main areas of FCC design study

Accelerators and infrastructure conceptual designs	Technologies R&D activities planning	Physics experiments detectors
Hadron collider conceptual design	High-field magnets	Hadron coll. physics experiments interface, integration
Lepton collider conceptual design	Superconducting RF systems	$e^+ e^-$ coll. physics experiments interface, integration
Hadron and lepton injectors	Cryogenics	e^- - p physics, experiments, Interface, integration
Safety, operation, energy management environmental aspects	Specific technologies	
Infrastructure	Planning	

FCC-hh parameters, challenges, R&D areas

Energy	**100 TeV c.m.**
Dipole field	**~ 16 T (Nb_3Sn), [20 T option HTS]**
Circumference	**~ 100 km**
#IPs	**2 main (tune shift) + 2**
Luminosity/IP_{main}	**$5x10^{34}$ $cm^{-2}s^{-1}$**
Stored beam energy	**8.2 GJ/beam**
Synchrotron radiation	**26 W/m/aperture** (filling fact. ~78% in arc)
Long. emit damping time	**0.5 h**
Bunch spacing	**25 ns [5 ns option]**
Bunch population (25 ns)	$1x10^{11}$ p
Transverse emittance	2.2 micron normalized
#bunches	10500
Beam-beam tune shift	0.01 (total)
β*	1.1 m (HL-LHC: 0.15 m)

FCC-hh **baseline 16T Nb_3Sn technology for ~100 TeV c.m. in ~100 km**

Develop Nb_3Sn-based 16 T dipole technology,

- with sufficient aperture (~40 mm) and
- accelerator features (field quality, protectability, cycled operation).
- In parallel conductor developments

Possible goal:

- **16T short dipole models by 2018 (America, Asia, Europe)**

In parallel HTS development targeting 20 T:

- HTS insert, generating *O*(5 T) additional field
- in large aperture *O*(100 mm, 15 T)

Possible goal:

demonstrate HTS/LTS 20 T technology in two steps

- a field record attempt to break the 20 T barrier (no aperture), and
- a 5 T insert, with sufficient aperture (40 mm) and accel. features

Optics and beam dynamics

- IR design, dynamic aperture studies, SC magnet field quality

Impedances, instabilities, feedbacks

- Beam-beam, e-cloud, resistive wall, feedback systems design

Synchrotron radiation damping

- controlled blow up, luminosity levelling, etc…

Energy in beam & magnets → dump, collimation, quench protection

- **Stored beam energy critical: 8 GJ/beam (0.4 GJ LHC)**
- Beam losses, radiation effects → collimation, shielding
- Synergies intensity frontier (**SNS, J-PARC, PSI, PIP, FRIB, ESS, FAIR**)

High synchrotron radiation load on beam pipe

- **Up to 26 W/m/aperture in arcs, total of ~5 MW for FCC-hh**
- (LHC has a total of 1W/m/aperture from different sources)
- Heat extraction: photon stop, beam screen temperature, cryo load,
- Synergies with **SSC,VLHC, LHC, light sources, SppC, …**

FCC-ee parameters, challenges, R&D areas

Design choice: max. synchrotron radiation power set to 50 MW/beam

- **Defines the maximum beam current at each energy**
- **4 physics operation points (energies) foreseen *Z, WW, H, ttbar***
- **Optimization at each operation point, mainly via bunch number and arc cell length**

Parameter	*Z*	*WW*	*H*	*ttbar*	*LEP2*
E/beam (GeV)	**45**	**80**	**120**	**175**	**105**
L (10^{34} cm^{-2}s^{-1})/IP	**28.0**	**12.0**	**5.9**	**1.8**	**0.012**
Bunches/beam	**16700**	**4490**	**1330**	**98**	**4**
I (mA)	1450	152	30	6.6	3
Bunch popul. [10^{11}]	1.8	0.7	0.47	1.40	4.2
Cell length [m]	300	100	50	50	79
Tune shift / IP	0.03	0.06	0.09	0.09	0.07

SC cavity R&D
- **Large Q_0 at high gradient and acceptable cryogenic power**
  - Recent results at 4 K with Nb_3Sn coating on Nb at Cornell
  - 800 °C ÷ 1400 °C heat treatment at JLAB
  - Beneficial effect of impurities observed at FNAL
- **Relevant for many other accelerator applications**

High efficiency RF power generation from grid to beam
- Power converter technology
- Klystron efficiencies beyond 65%, alternative RF sources as Solid State Power Amplifier or multi-beam IOT (inductive output tube), etc.
- **Relevant for all high power accelerators, intensity frontier (drivers):**
  J-PARC, SNS, νstorm, LBNE, XFEL, μcoll, ESS, MYRRHA, …

Overall RF system reliability → relevant for *FCC-hh* and *FCC-ee*

R&D Goal is optimization of overall efficiency, reliability and cost!
- Power source efficiency, low-loss high-gradient SC cavities, operation temperature vs. cryogenic load, total system cost and dimension.

Short beam lifetime from high luminosity (radiative Bhabha scattering)
- **Top-up injection** (single injector booster in collider tunnel)

Additional lifetime limit from beamstrahlung at top operation energy
- Flat beams (small vertical emittance, small vertical β* ~ 1 mm)
- Final focus with large (~2%) energy acceptance to reduce losses

Machine layout for high currents, large #bunches at *Z* pole, *WW*, *H*
- **Two ring layout and configuration of the RF system.**

Polarization for high precision energy calibration at *Z* pole and *WW* with long natural polarization times (*WW*: ~10 hours, *Z*: ~200 hours)

Important expertise available worldwide and potential synergies:
- **IR design, experimental insertions, machine detector interface, (transverse) polarization**
  RHIC, VEPP-2000, BEPC-II, SLC, LEP, *B*- and Super-*B* factories, CEPC, ILC, CLIC

FCC-he parameters, challenges, R&D areas

- **Design choice: beam parameters as available from *hh* and *ee***
  - Max. $e^{\pm}$ beam current at each energy determined by 50 MW SR limit.
  - **1 physics interaction point, optimization at each energy**

collider parameters	$e^{\pm}$ scenarios			protons
species	$e^{\pm}$ (polarized)	$e^{\pm}$	$e^{\pm}$	*p*
beam energy [GeV]	**80**	**120**	**175**	**50000**
luminosity [$10^{34}cm^{-2}s^{-1}$]	**2.3**	**1.2**	**0.15**	
bunch intensity [10^{11}]	0.7	0.46	1.4	1.0
#bunches per beam	4490	1360	98	10600
beam current [mA]	152	30	6.6	500
$\sigma_{x,y}$* [micron]	4.5, 2.3			

Integration aspects, machine detector interface
- Synchrotron radiation
- Large polar angle acceptance

IR optics & magnets with 3 beams
- Crossing scheme
- Detector integrated dipole, final SC quadrupoles, crab cavities,

Concurrent operation of $e^{\pm}h$ with *hh or/and* e^+e^- operation?

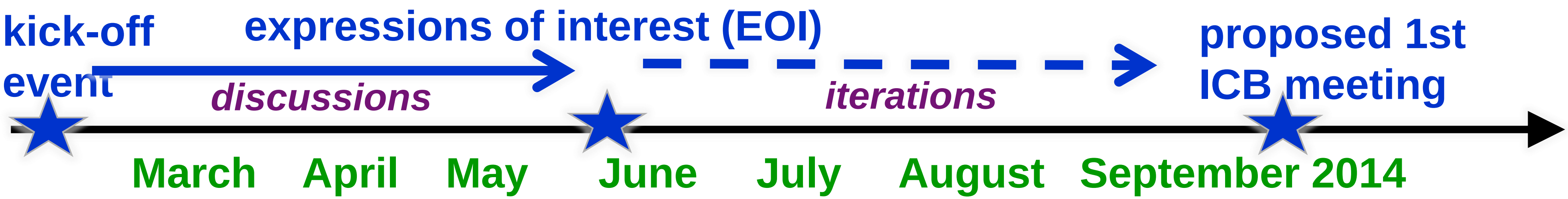
Relevant expertise available worldwide and potential synergies:
⇔ **HERA, eRHIC, MEIC, HIAF-EIC,…**

Alternative option for *eh* collisions in connection with *FCC-hh*:
- Potential reuse of an **energy recovery linac (ERL)** that is being **studied in the frame of the LHeC study.**

International collaboration process in 2014

Proposal for next steps:

- Suggestions and comments from international community and **discussion on study contents, organisation and resources**
- Invitation of non-committing **expressions of interest for contributions** from worldwide institutes **by end May 2014**
- Prepare for formation of **International Collaboration Board (ICB)**; proposed date first meeting **9-11 September 2014, to start FCC study**



Process can be moderated by preparation group (possibly extended – following EOI) until global collaboration is formed and an international team is put in place to conduct the further study

Process remains open, further joining possible …

FCC Kick-Off & Study Preparation Team

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

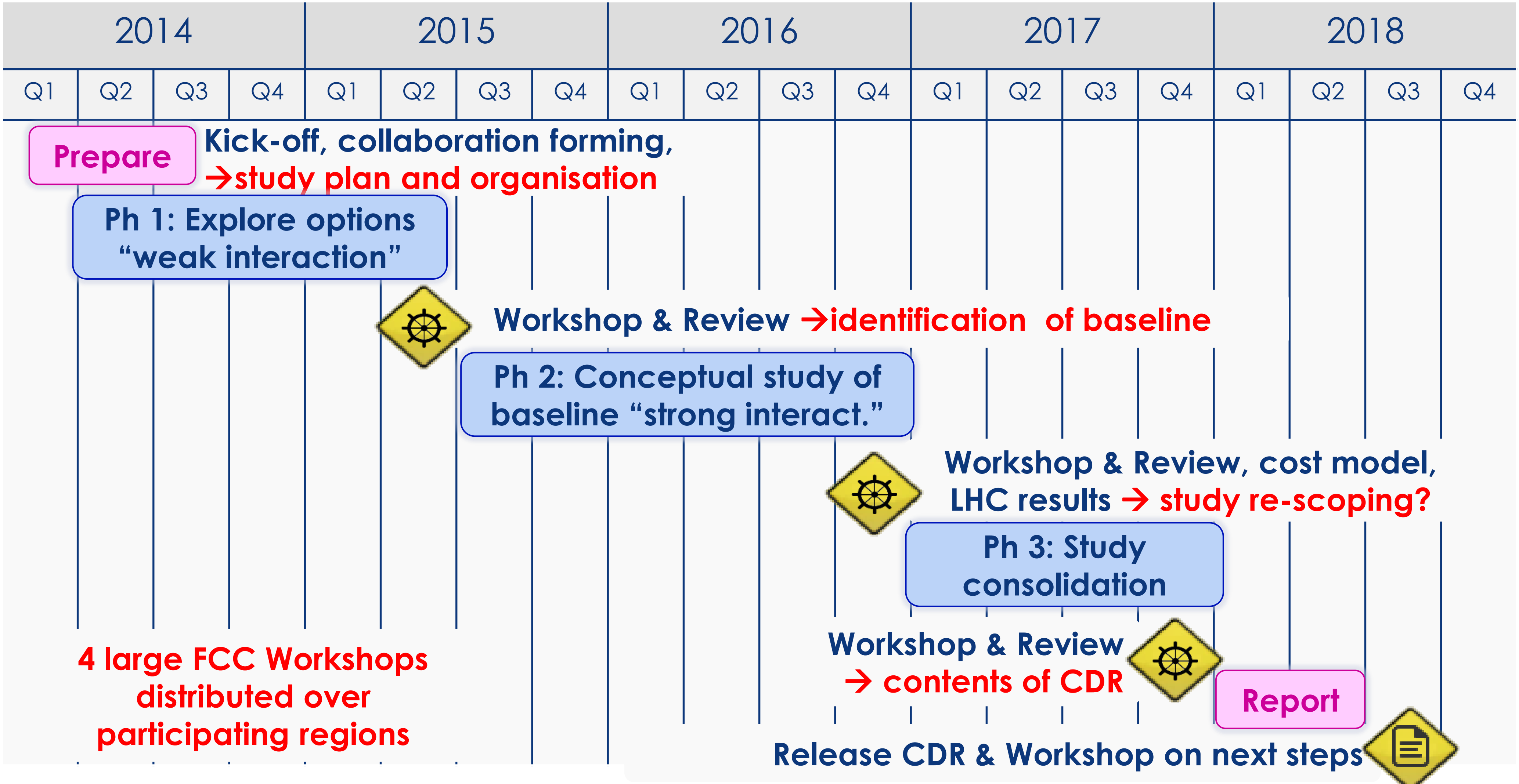
Hadron collider	Hadron injectors	e+ e- collider and injectors	Infrastructure, cost estimates	Technology	Physics and experiments
D. Schulte	**B. Goddard**	**J. Wenninger**	**P. Lebrun**	High Field Magnets **L. Bottura**	Hadrons **A. Ball, F. Gianotti, M. Mangano**
				Supercon-ducting RF **E. Jensen**	e+ e- **A. Blondel J. Ellis, P. Janot**
				Cryogenics **L. Tavian**	e- p **M. Klein**
				Specific Technologies **JM. Jimenez**	

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

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

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

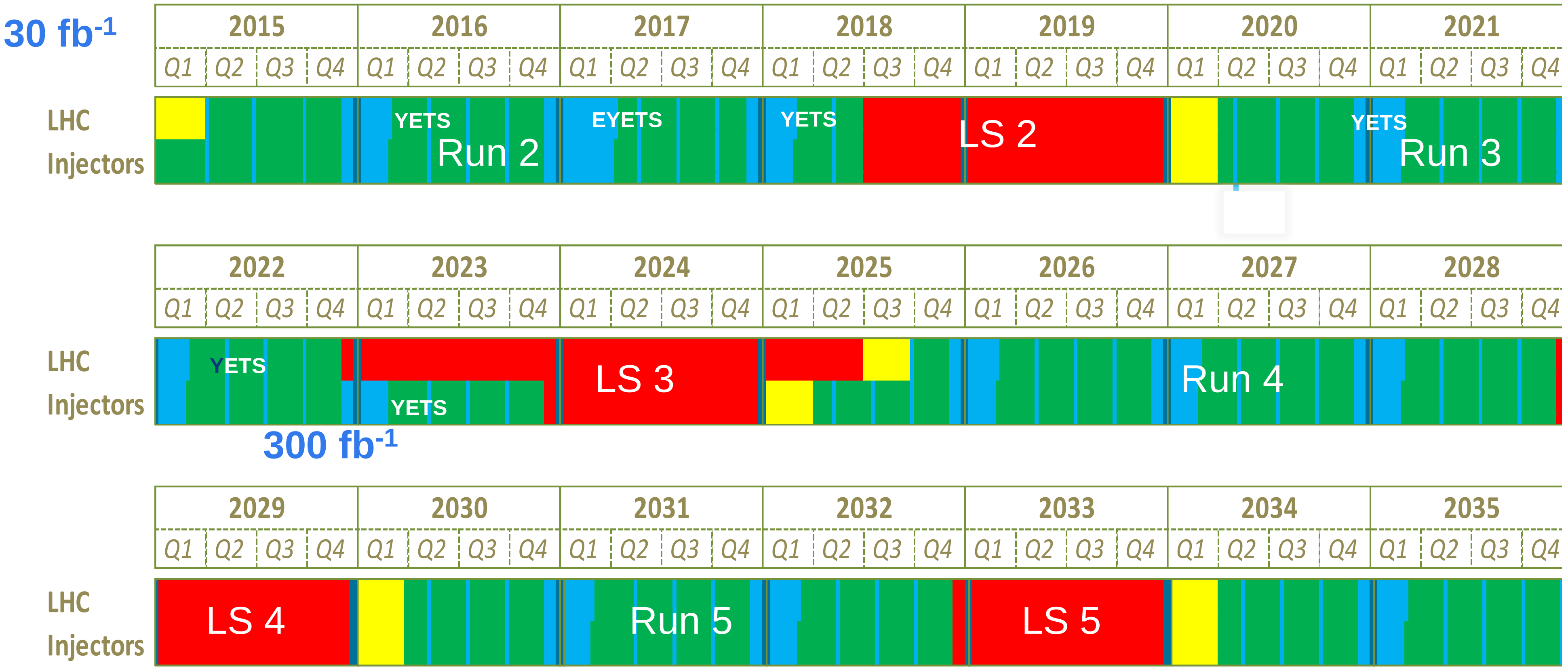
Proposal for FCC Study Time Line



LHC schedule beyond LS1

LS2 starting in 2018 (July) => 18 months + 3 months BC
LS3 LHC: starting in 2023 => 30 months + 3 months BC
Injectors: in 2024 => 13 months + 3 months BC

- Physics
- Shutdown
- Beam commissioning
- Technical stop



(Extended) Year End Technical Stop: (E)YETS

3'000 fb^{-1}

LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators (December 2013)

The European Strategy for Particle Physics
Update 2013

c) *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.*

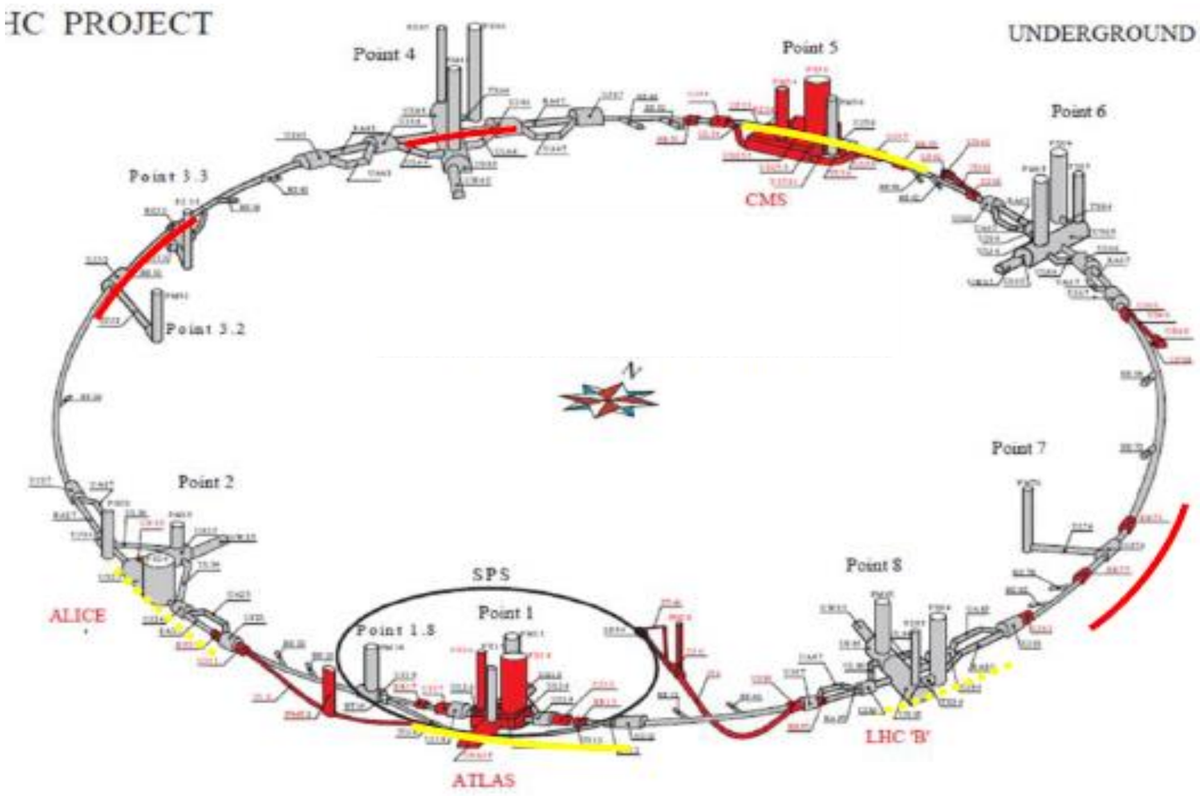
HL-LHC from a study to a PROJECT

300 fb^{-1} → 3000 fb^{-1}

including LHC injectors upgrade **LIU** (Linac 4, Booster 2GeV, PS and SPS upgrade)

The HL-LHC Project

- **Obtain about 3 - 4 fb^{-1}/day (40% stable beams)**
- **About 250 to 300 fb^{-1}/year**



- New IR-quads Nb_3Sn (inner triplets)
- New 11 T Nb_3Sn (short) dipoles
- Collimation upgrade
- Cryogenics upgrade
- Crab Cavities
- Cold powering
- Machine protection
- …

Major intervention on more than 1.2 km of the LHC

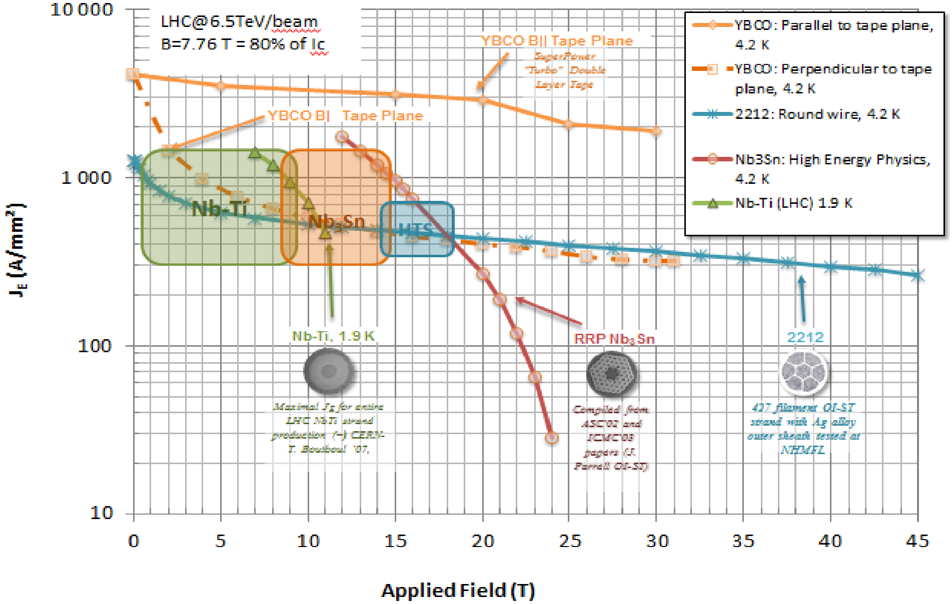
Project leadership: L. Rossi and O. Brüning

"to propose an ambitious **post-LHC accelerator project at CERN** by the time of the next Strategy update"

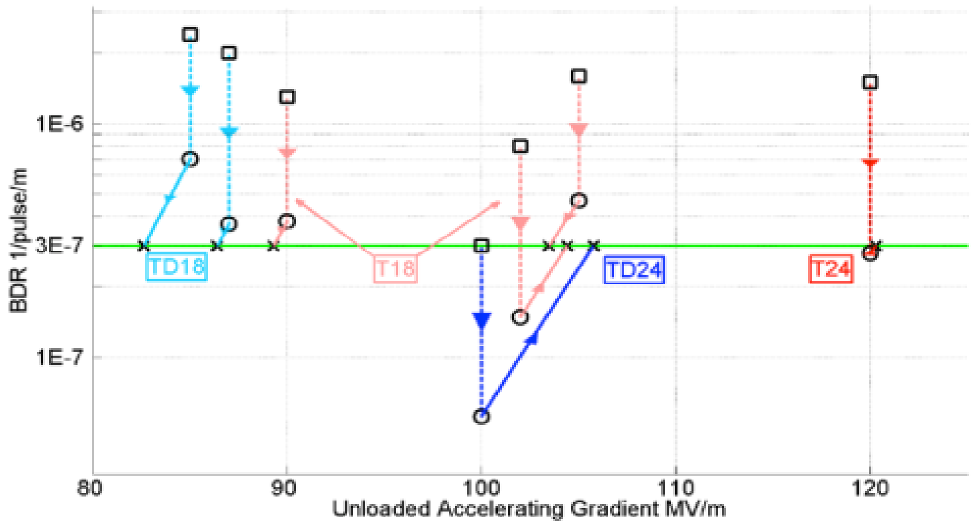
d) *CERN should undertake design studies for accelerator projects in a global context,*

*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.***

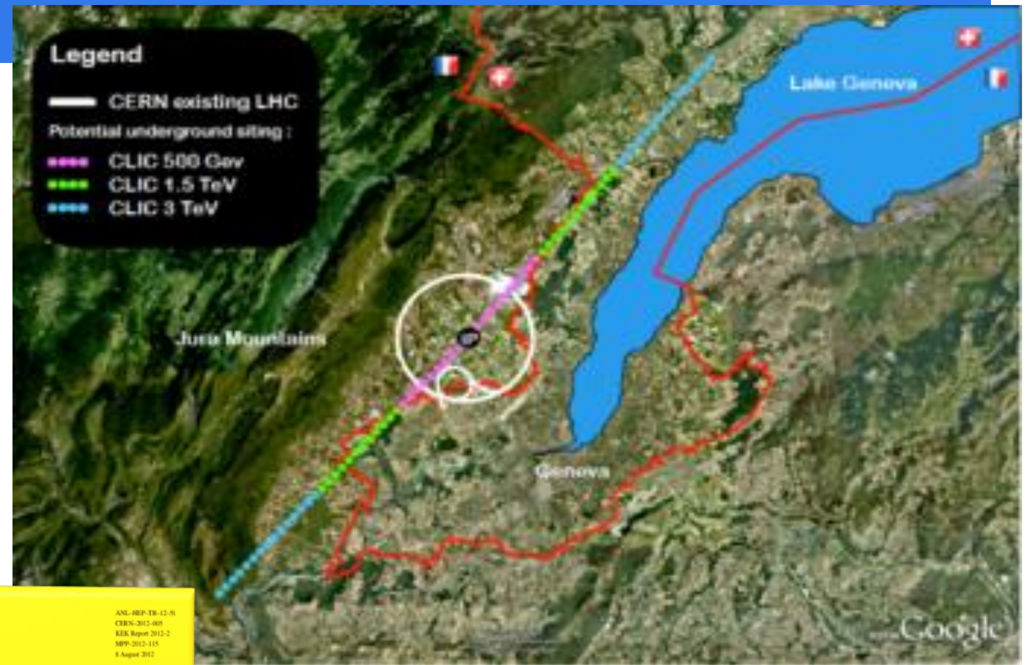
HFM - FCC



HGA - CLIC

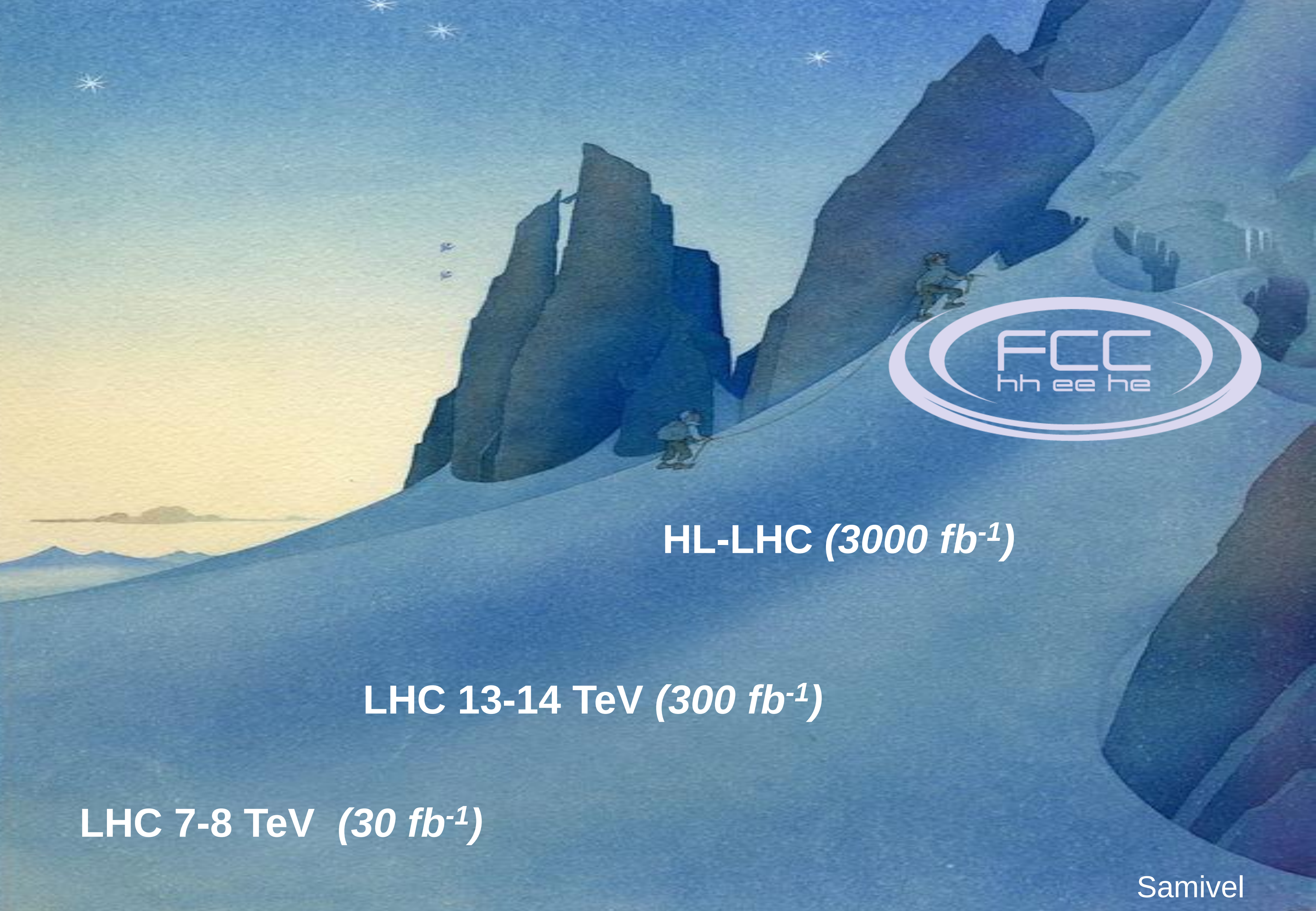


“CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and ***electron- positron high-energy frontier machines.****”*



Highest possible energy e^+e^- with CLIC (CDR 2012)

Multi-lateral collaboration


FCC
hh ee he
HL-LHC (3000 fb-1)
LHC 13-14 TeV (300 fb-1)
LHC 7-8 TeV (30 fb-1)
Samivel

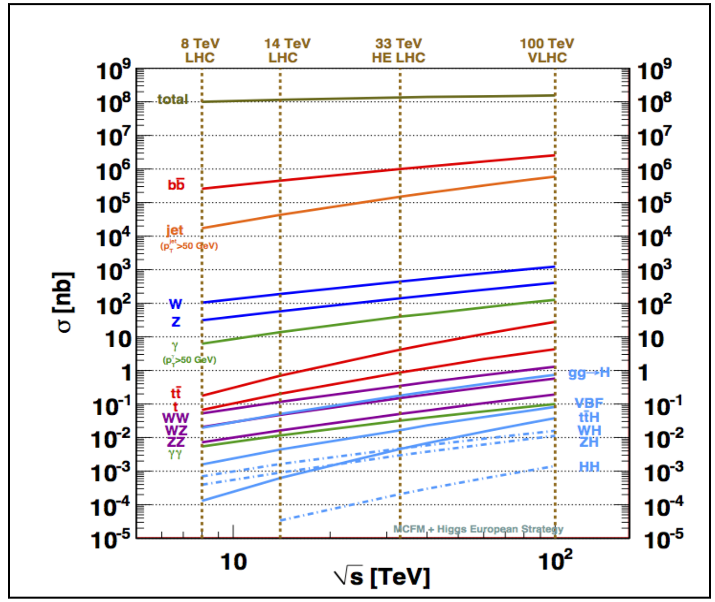
The HEP landscape after LHC (C. Grojean)

My key message

M. Mangano @ ASPEN14

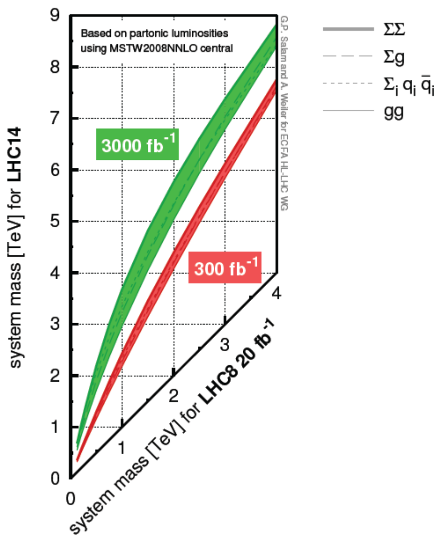
- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)

This simply implies that, more than for the past 30 years, future HEP progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

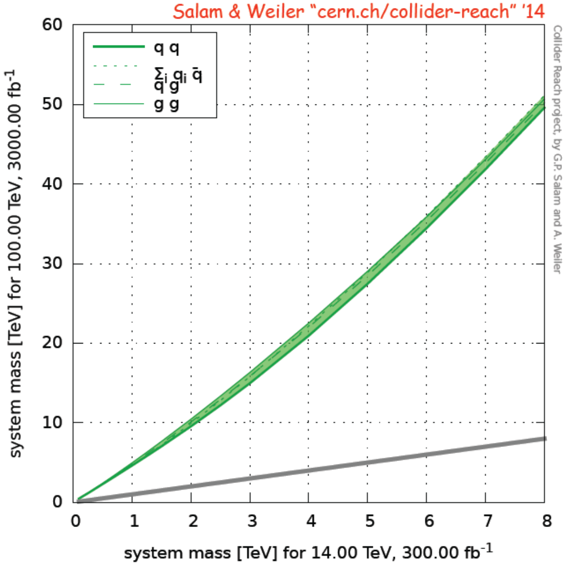


The benefit of being energetic

Direct exploration of an unexplored energy territory



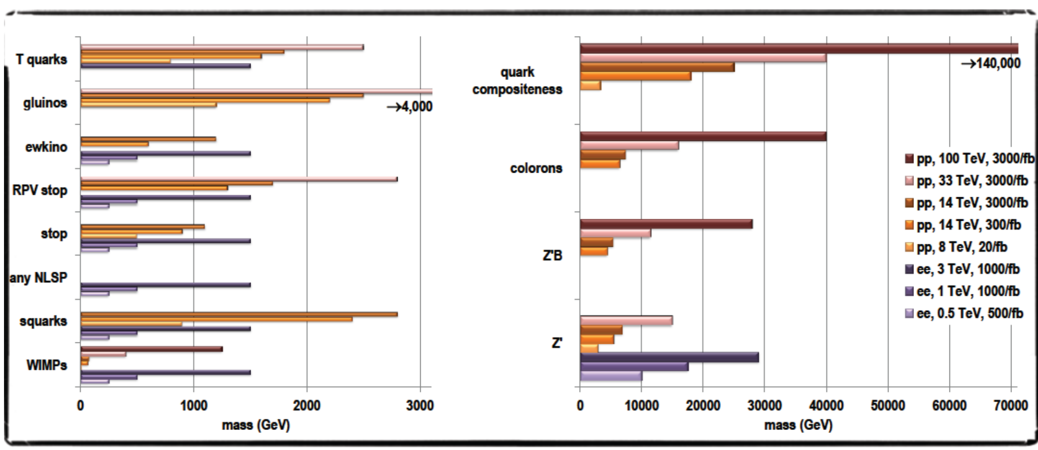
LHC14/LHC8:
mass reach x O(2)



VHE-LHC100/LHC14:
mass reach x O(5)

The benefit of being energetic

Direct exploration of an unexplored energy territory



Energy Frontier Snowmass Study '13

Naturalness. EW vacuum : question of precision (C. Grojean)

A Higgs: Now what? What's next?

1 Higgs properties

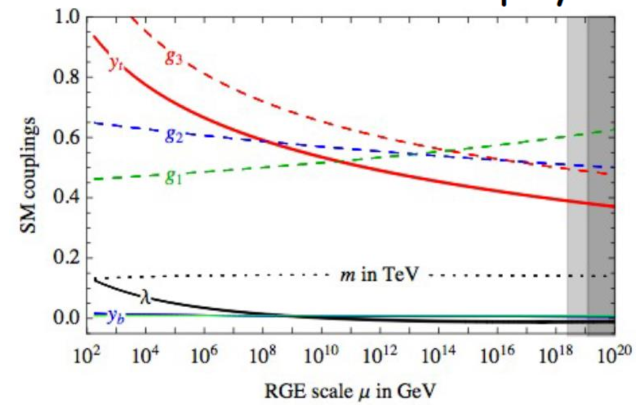
J^{PC}

Important & nice to see progresses but "this question carries a similar potential for surprise as a football game between Brazil and Tonga" Resonaances

2 Higgs couplings

3 BSM implications

Can we live without new physics?



Can the SM (without new physics) be valid up to M_{Pl} and remain weakly coupled?

Higgs couplings measurement projections

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

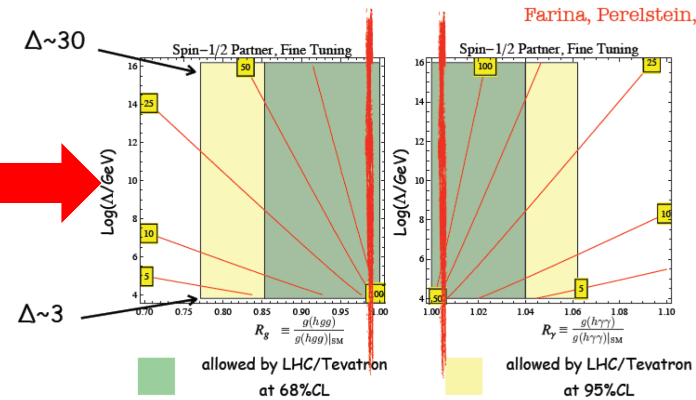
Rich experimental program of (sub)percent precision

Higgs couplings = test of Naturalness?

simple toy model: a single spin-½ top partner

deviations in the couplings ⇔ amount of fine-tuning $\Delta = \delta m_H^2 / m_H^2$

Farina, Perelstein, Rey-Le Noisier, '13



Λ cutoff scale of log. divergences to the Higgs mass

High scale models ($\Lambda \sim 10^{16}$GeV) come with a generic fine-tuning O(1/30)

Increasing the couplings measurement to 1% precision will raise the fine-tuning to O(1/400)

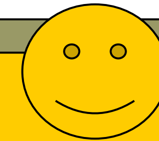
Summary

- In line with the **European Strategy**, CERN is launching a **5-year international design study** for Future Circular Colliders; unique road up to 100 TeV energy scale
- **Worldwide collaboration in all areas** - physics, experiments and accelerators – **is essential** to bring this study to fruition (and to arrive at a CDR by 2018)
- Need to present (additional) **benefits to society** from the very beginning of the study (examples: SC technologies)
- **FCC R&D areas** e.g. **SC high-field magnets** and **SC RF** are **of general interest & relevant for many other applications**
- Need to have **excellent communication and outreach** accompanying the study
- **Significant R&D investments have been made** over last decade(s), e.g. in the framework of LHC and HL-LHC; **further continuation will ensure efficient use of past investments**. Interconnect with other projects/studies

BACKUP SLIDES

Physics case: two scenarios

One of the main goals of
the Conceptual Design Report (~ 2018)
→ will be studied in detail in the years to come …
→ see also M.Mangano's talk



- ❑ LHC and/or HL-LHC find new physics:
  the heavier part of the spectrum may not be fully accessible at $\sqrt{s}$ ~ 14 TeV
  → strong case for a 100 TeV pp collider: complete the spectrum and measure it in some detail
- ❑ LHC and/or HL-LHC find indications for the scale of new physics being in the 10-50 TeV region (e.g. from dijet angular distributions → Λ Compositeness)
  → strong case for a 100 TeV pp collider: directly probe the scale of new physics

LHC and HL-LHC find NO new physics nor indications of the next E scale:

- ❑ several Higgs-related questions (naturalness, HH production, $V_L V_L$ scattering) may require high-E machines (higher than a 1 TeV ILC)
- ❑ a significant step in energy, made possible by strong technology progress (from which society also benefits), is the only way to look directly for the scale of new physics

Although there is no theoretical/experimental preference today for new physics in the 10-50 TeV region, the outstanding questions are major and crucial, and we must address them. This requires concerted efforts of all possible approaches: intensity-frontier precision experiments, astroparticle experiments, dedicated searches, neutrino physics, high-E colliders, …

Physics landscape and opportunities for pp colliders at 100 TeV (M. Mangano)

pp at 100 TeV opens three windows:

➥ Access to new particles in the few→30 TeV mass range, beyond LHC reach

➥ Immense rates for phenomena in the sub-TeV mass range ⇒

increased precision w.r.t. LHC

➥ Access to very rare processes in the sub-TeV mass range ⇒

search for stealth phenomena, invisible at the LHC

Topics for the forthcoming studies

- Extend to 100 TeV discovery-reach studies for high-mass objects (SUSY, Z'/W', new fermions, etc.etc.)
- Assess precision reach for Higgs and EWSB studies:
  - H couplings
  - WW scattering at masses >> TeV
  - Higgs-pair production dynamics and H self-couplings
  - compare indirect sensitivity of precise measurements in e^+e^- with direct sensitivity to high-mass states at 100 TeV (⇒ Rattazzi at BSM@100 TeV wshop)
- Study limiting systematics:
  - define priorities for development of theoretical modeling tools
  - define programme of ancillary measurements to reduce theoretical/ experimental systematics (e.g. PDF measurements, validation of MC generators, validation of higher-order calculations)
- Examine prospects for improved measurements of SM quantities: W/ Z/, top, b: fundamental EW parameters ($\sin^2\theta_W$, m_W, m_{top}), rare decays
- Identify new scenarios and opportunities specific to 100 TeV

The Twin Frontiers of FCC-ee Physics

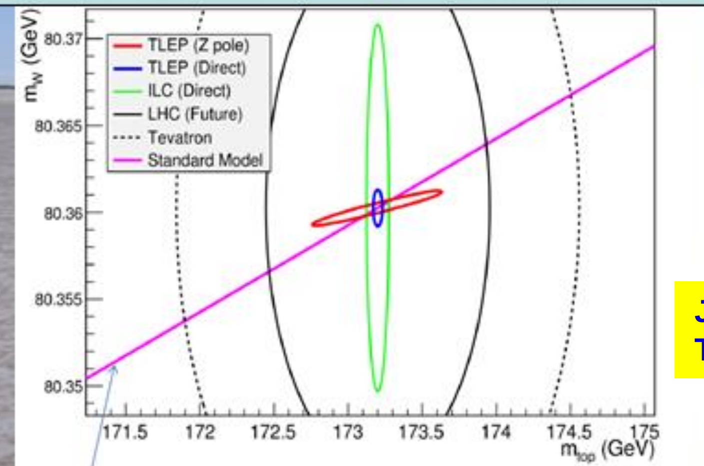
Precision Measurements

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

Rare Decays

- Direct searches for new physics
- Many opportunities
- Z: 10^{12}
- b, c, τ: 10^{11}
- W: 10^{8}
- H: 10^{6}
- t: 10^{6}

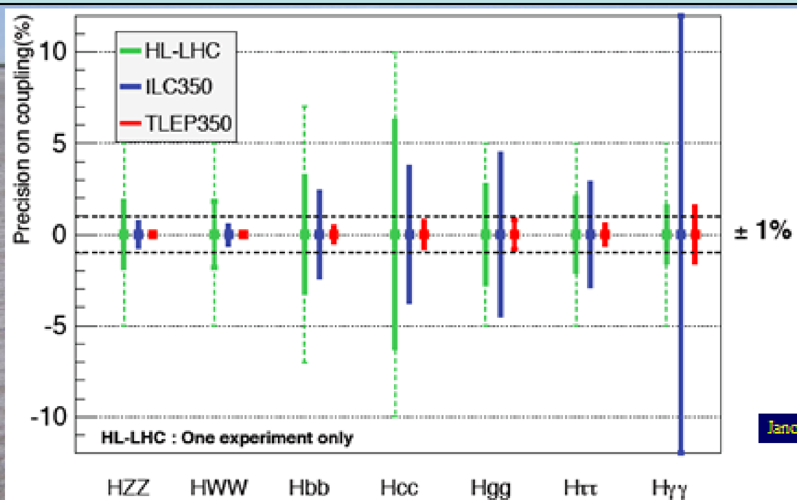
TLEP Measurements of m_t & M_W



NB without TLEP the SM line would have a 2.2 MeV width

J. Ellis
TLEP = FCC-ee

Possible Future Higgs Measurements



What else is there?

Supersymmetry

- Successful prediction for Higgs mass
  - Should be < 130 GeV in simple models
- Successful predictions for couplings
  - Should be within few % of SM values
- Naturalness, GUTs, string, … (???)

Among the main targets for the coming months: identify experimental challenges, in particular those requiring new concepts and detector R&D

The two main goals
- ❑ Higgs boson measurements beyond HL-LHC (and any e^+e^- collider)
- ❑ exploration of energy frontier

are quite different in terms of machine and detector requirements

Exploration of E-frontier → look for heavy objects up to m ~30-50 TeV, including high-mass $V_L V_L$ scattering:
- ❑ requires as much integrated luminosity as possible (cross-section goes like 1/s)
- → may require operating at higher pile-up than HL-LHC (~140 events/x-ing)
- ❑ events are mainly central → "ATLAS/CMS-like" geometry is ok
- ❑ main experimental challenges: good muon momentum resolution up to ~ 50 TeV; size of detector to contain up to ~ 50 TeV showers; forward jet tagging; pile-up

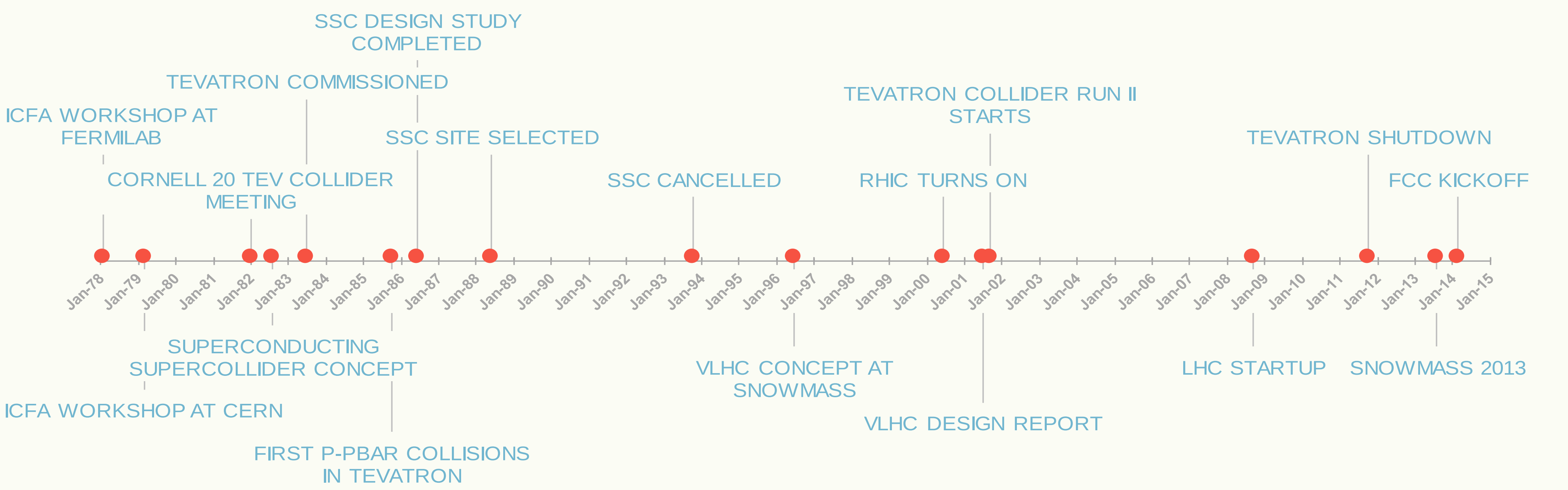
Precise measurements of Higgs boson:
- ❑ would benefit from moderate pile-up
- ❑ light object → production becomes flatter in rapidity with increasing $\sqrt{s}$
- ❑ main experimental challenges: larger acceptance for precision physics than ATLAS/CMS → tracking/B-field and good EM granularity down to $|\eta|$~4-5; forward jet tagging; pile-up

→ more in D.Fournier's talk

USA: Collider Activities – Selected Milestones

PROTON COLLIDER ACTIVITIES IN THE US

TIMELINE



SSC main facts:

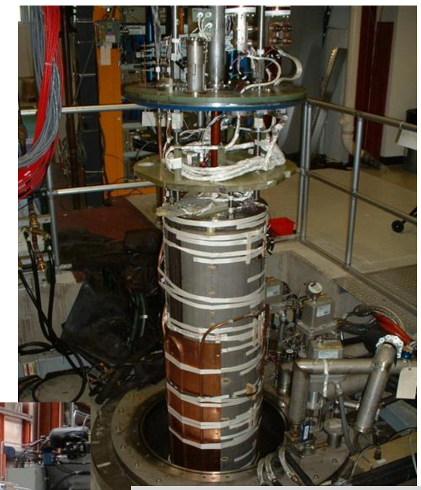
87 km, 20 TeV + 20 TeV proton-proton, $\mathcal{L}$ ~10^{33} cm^{-2} sec^{-1}

- 1982: emerged from Snowmass study
- 1986: design study complete
- 1988: Texas site selected and construction began
- 1993: Project terminated after spending $2B
- Seventeen shafts were sunk and 23 km (14.6 mi) of tunnel were bored

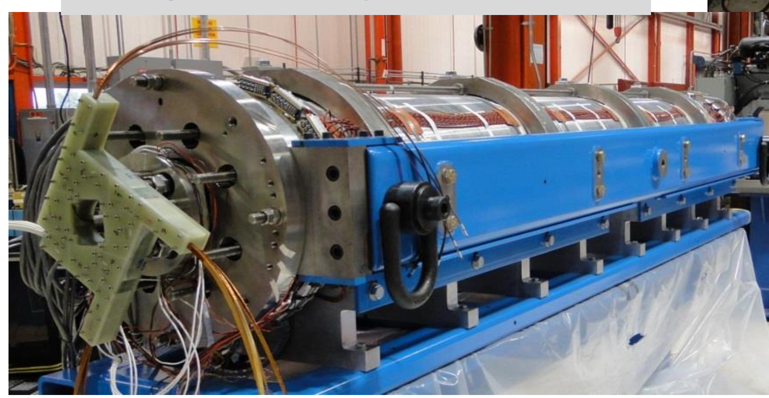
Circumference	87 km
Energy per beam	20 TeV
Magnetic field	6.6 T
Injection energy	2 TeV
Luminosity	10^{33} cm^{-2} sec^{-1}
N_{dipole} (long/shrt)	7956/504

USA: Technology for Future Colliders

- US has developed and nurtured a very strong high-field magnet R&D program through DOE/HEP
  - Nb_3Sn conductor development program
  - High-field magnet program for developing accelerator magnets
- High Field Magnet and LARP programs have brought Nb_3Sn accelerator magnet technology to the deployment stage for HiLumi
- Nb_3Sn development lays the groundwork for 15T Dipoles
- Active R&D is underway to extend reach beyond 15 T with HTS
- Extensive development of SCRF technology and capabilities over the last decade, required for e+e- collider concepts


11T Dipole

Long Quadrupole LQS



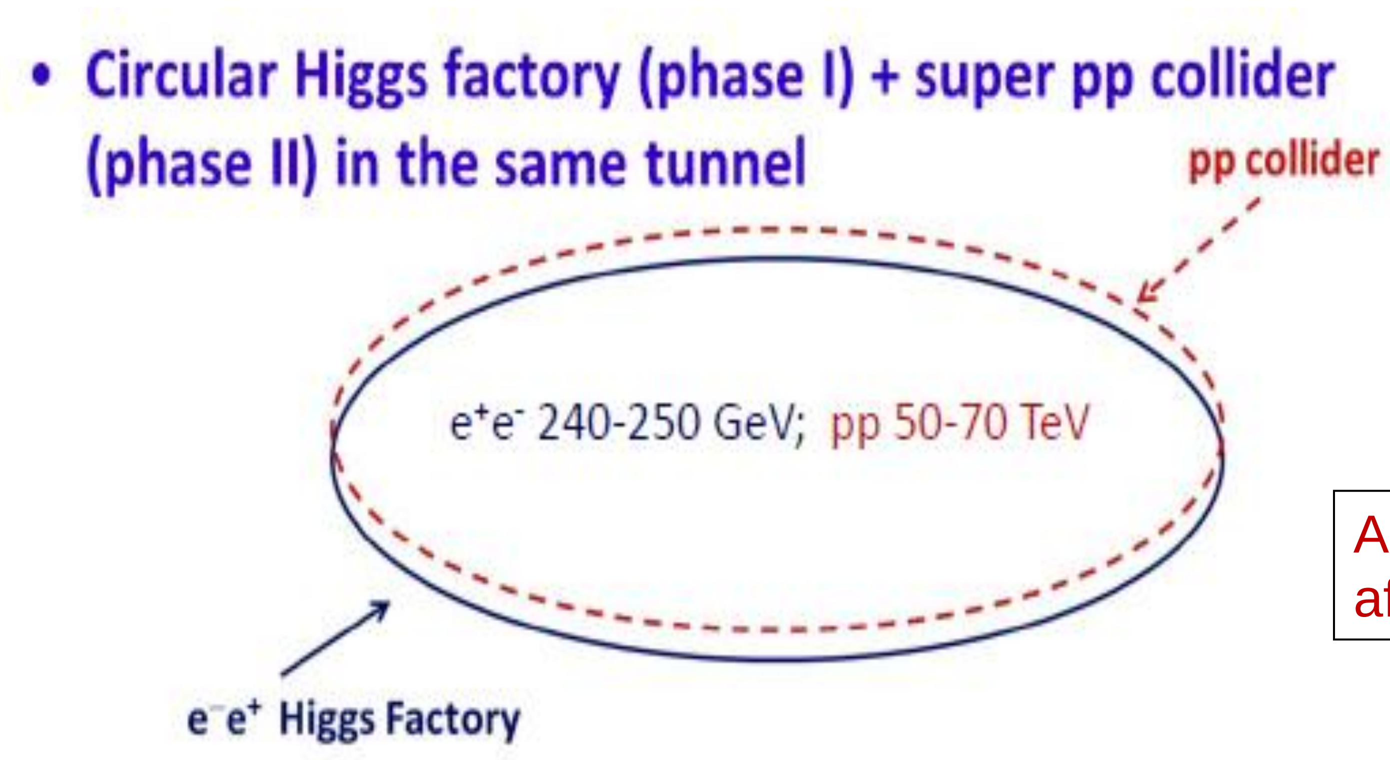

Americas 9-cell cavities

Fermilab

China: CEPC+SppC

Yifang Wang, IHEP Beijing

- For about 8 years, we have been talking about "What can be done after BEPCII in China"
- Thanks to the discovery of the low mass Higgs boson, and stimulated by ideas of Circular Higgs Factories in the world, CEPC+SppC configuration was proposed in Sep. 2012



A 50-70 km tunnel is very affordable in China NOW

China

In Practice

- A circular Higgs factory fits our strategic needs in terms of
  - Science (great & definite physics)
  - Timing (after BEPCII)
  - Technological feasibility (experience at BEPC/BEPCII and other machines in the world),
  - Manpower reality (our hands are free after ~2020)
  - Economical scale (although slightly too high)
- The risk of no-new-physics is complement by a pp collider in the same tunnel
  - A definite path to the future
- A unique position for China to contribute at this moment:
  - Economical growth ➔ new funding to the community
  - Large & young population ➔ new blood to the community
  - Affordable tunnel & infrastructure
  - If no new project, no new resources ➔ It is a pity if we miss it

Site

- Preliminary selected: Qinhuangdao (秦皇岛)
- Strong support by the local government

Timeline (dream)

- **CPEC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15
      - **Pre-CDR by the end of 2014 for R&D funding req**
    - R&D: 2016-2020
    - Engineering Design: 2015-2020
  - Construction: 2021-2027
  - Data taking: 2028-2035
- **SppC**
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-2020
    - R&D: 2020-2030
    - Engineering Design: 2030-2035
  - Construction: 2035-2042
  - Data taking: 2042 -

Main parameters of CEPC at 50km

Bean Energy	GeV	120	Circumference	km	50
Number of IP		2	L_0/IP (10^{34})	$cm^{-2}s^{-1}$	2.62
No. of Higgs/year/IP		1E+05	Power(wall)	MW	200
e+ polarization		0	e- polarization		0

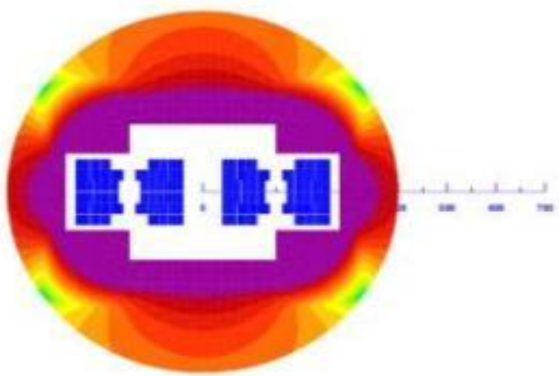
Main parameters of SppC	SppC-1	SppC-2
Beam energy (TeV)	25	45
Circumference (km)	49.78	69.88
Number of IPs	2	2
B_0 (T)	12	19.24
Luminosity /IP ($10^{35}cm^{-2}s^{-1}$)	2.15	2.85

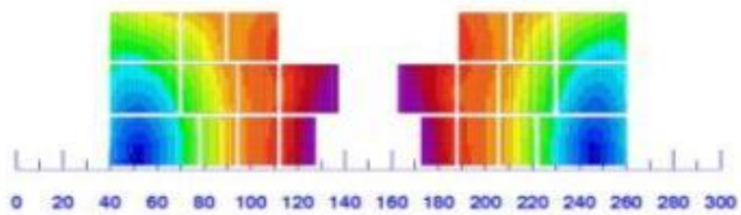
Summary

- **It is difficult**
- **But it is very exciting**
- **Even if it is not in China, it is still very beneficial to our field and to the Chinese HEP & Science community**
- **We fully support a global effort**
- **Let's us work for our dream**

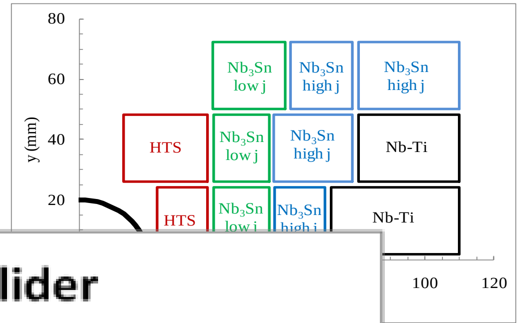
Malta Workshop: **HE-LHC @ 33 TeV c.o.m.**

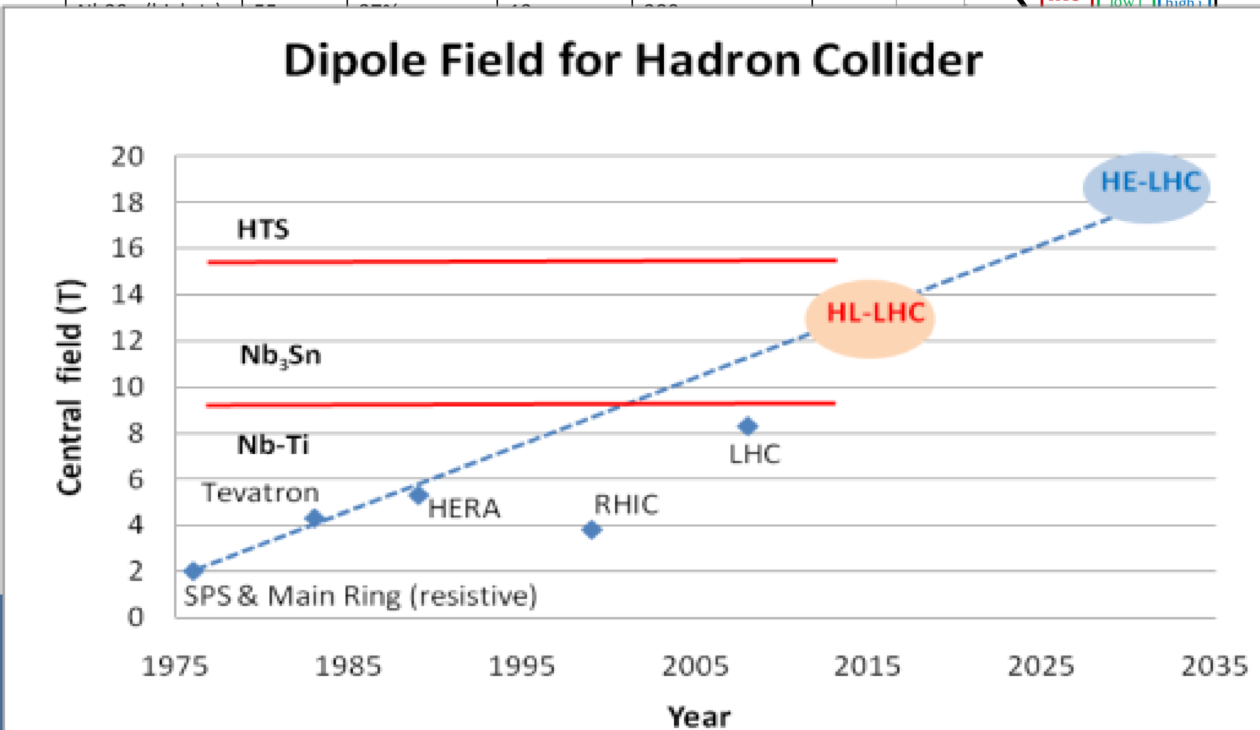
14-16 October 2010





Material	N. turns	Coil fraction	Peak field	$J_{overall}$ (A/mm^2)
Nb-Ti	41	27%	8	380





Magnet design (20 T): very challenging but not impossible.

300 mm inter-beam

Multiple powering in the same magnet (and more sectioning for energy)

Work for 4 years to assess HTS for 2X20T to open the way to 16.5 T/beam .

Otherwise limit field to 15.5 T for 2x13 TeV

Higher INJ energy is desirable (2xSPS)

…n screen at 60 K.

…g time.

…g $2x10^{34}$ appears reasonable.

…**dling for INJ & beam dump**: new …room for LHC kickers.

Possible FCC Study Phases

Phase 1: Explore options, now – spring 2015:

- Investigate **different options** in all technical areas, **taking a broad view**
- **Deliverables: description and comparison of options with relative merits/cost**
- **FCC workshop to converge to common baseline with small number of options**
- **Proposed WS date 23 – 27 March 2015** (presently no known collisions…)
- Followed by review ~2 months later, begin June 2015

Phase 2: Conceptual design: spring 2015 – autumn 2016

- Conceptual study of baseline and remaining options with iterations between all areas
- Deliverable: description of baseline with first cost model, identification of critical areas, cost drivers, performance limitations
- FCC workshop to discuss conceptual design, performance and cost figures
- Proposed date autumn 2016.
- Followed by review 2 months later to take into account LHC results and do re-scoping of study for phase 3

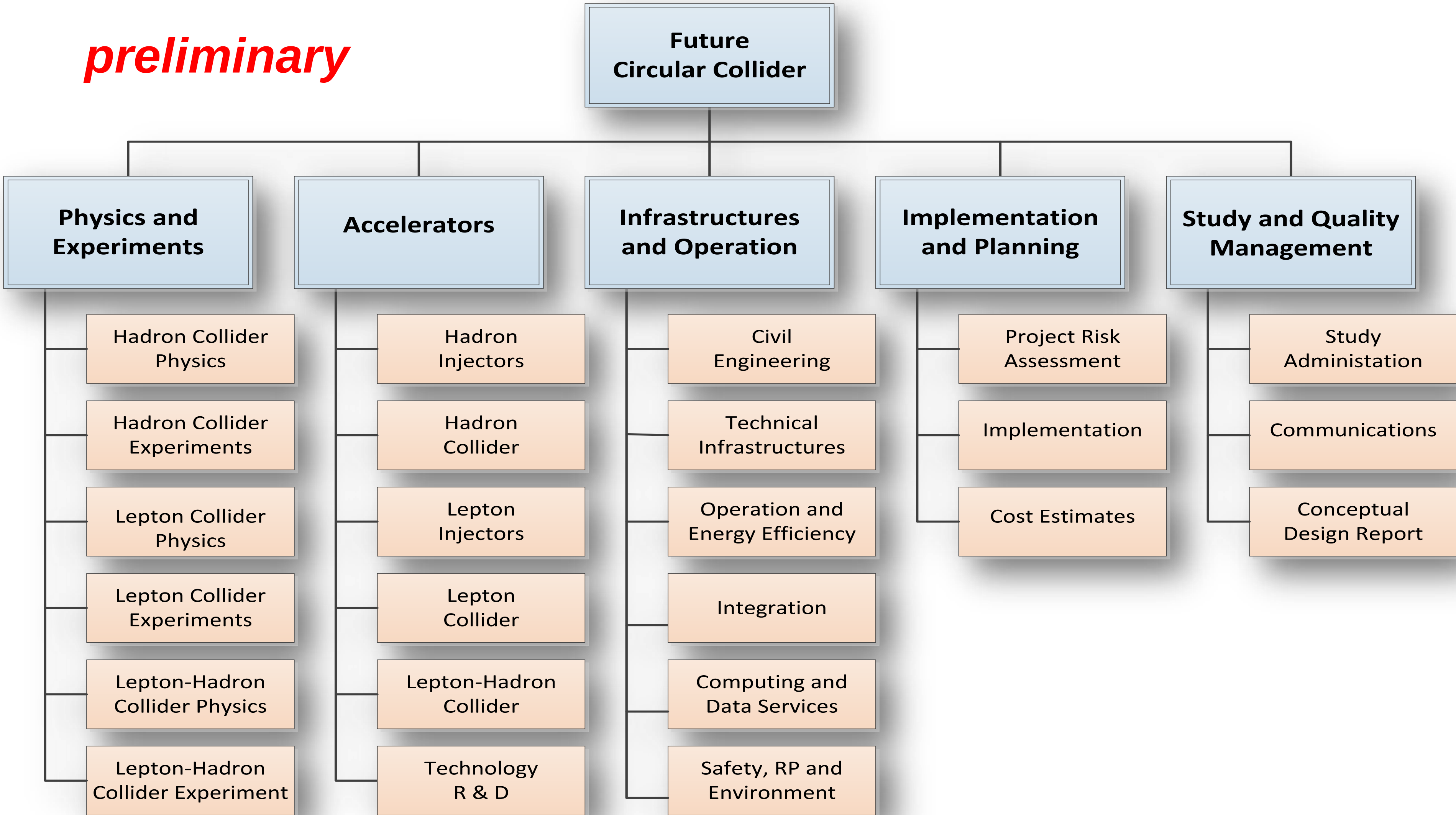
Phase 3: Study consolidation: winter 2016 – winter 2017

- Detailed conceptual design of re-scoped baseline
- Deliverables: description of re-scoped baseline with cost model, identification of critical areas, cost drivers, performance limitations, planning for further R&D activities
- FCC workshop to discuss conceptual design, performance and cost figures and contents for CDR editing.
- Proposed date autumn 2017.
- Followed by review 2 months later to confirm CDR contents

Phase4: Editing conceptual design report: winter 2017 – summer 2018

Proposal for FCC WBS top level

preliminary

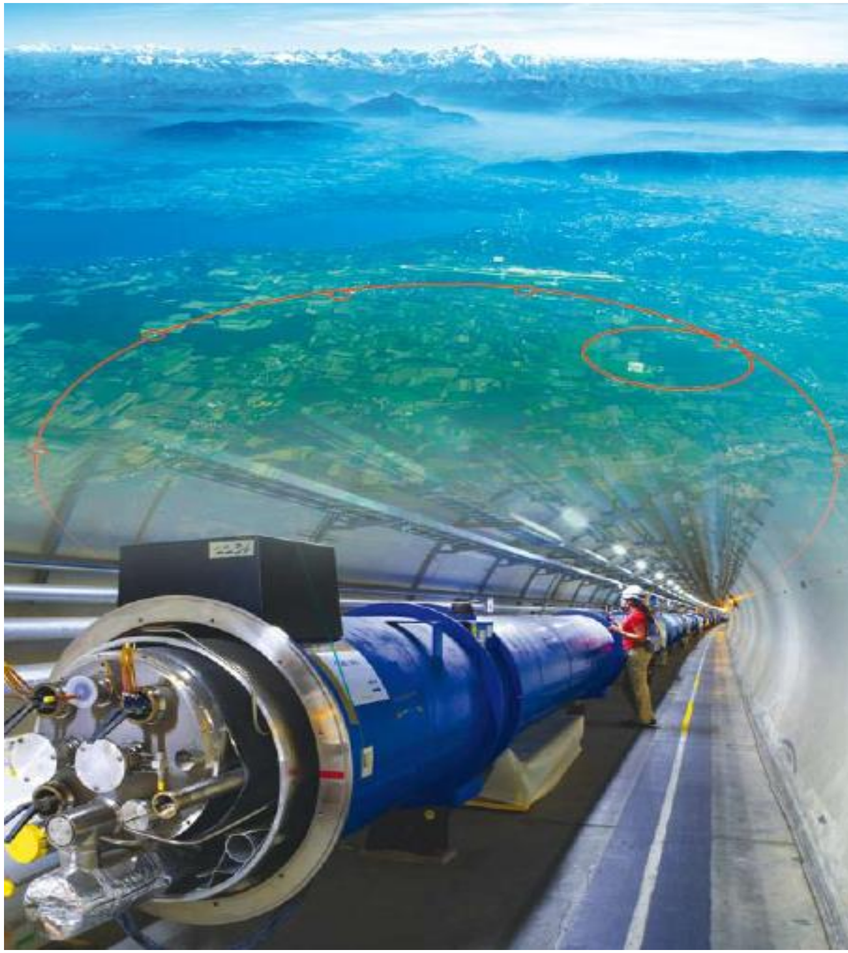


LHC (Large Hadron Collider)

14 TeV proton-proton accelerator-collider built in the LEP tunnel

Lead-Lead (Lead-proton) collisions

1983 : First studies for the LHC project
1988 : First magnet model (feasibility)
1994 : Approval of the LHC by the CERN Council
1996-1999 : Series production industrialisation
1998 : Declaration of Public Utility & Start of civil engineering
1998-2000: Placement of the main production contracts
2004 : Start of the LHC installation
2005-2007: Magnets Installation in the tunnel
2006-2008: Hardware commissioning
2008-2009: Beam commissioning and repair
2009-2035: Physics exploitation



FCC EU Design Study (DS) Proposal

Horizon2020 call – design study, deadline 02.09.2014

Prepare proposal parallel to FCC collaboration setup

Goals fo EU DS: conceptual design, prototypes, cost estimates, …

From FP7 HiLumi LHC DS → positive experience:

- **5-6 work packages as sub-set of FCC study**
- **~10-15 beneficiaries** (signatories of the contract with EC)

Time line

March	April	May	June	July	August	September 2014
kick-off event	*discussions*	**input from interested partners, end of May**	**complete draft proposal, end of June**	*iteration, agreements, signatures*		**submission of EU FCC DS proposal, 2 Sept.**

Non-EU partners can join as beneficiary – signatory with or w/o EC contribution (**contractual commitment**) **or as associated partner – non-signatory** (in-kind contribution with own funding, no contractual commitment)

- ❑ Work started in November 2013
- ❑ > 200 people subscribed to the FCC-hh mailing list, but small number (~30) active so far at tiny fraction of their time

Only few very preliminary ideas shown here …

Hope for a strong international collaboration in the FCC-hh studies !

- ❑ We are benefitting from previous studies: e.g. SSC and VLHC efforts in the US (and Snowmass 2001 and 2013)
- ❑ Links established with similar activities in the world (e.g. cross attendance of workshops) → will be pursued and intensified

China:

- ❑ Future High-Energy Circular Colliders WS, Bejing, 16-17 December 2013: http://indico.ihep.ac.cn/conferenceDisplay.py?confId=3813
- ❑ 1st CFHEP (= Center for Future High Energy Physics) Symposium on Circular Collider Physics, Beijing, 23-25 February 2014: http://cfhep.ihep.ac.cn

US:

- ❑ Physics at a 100 TeV Collider, SLAC, 23-25 April 2014: https://indico.fnal.gov/conferenceDisplay.py?confId=7633
- ❑ Next steps in the Energy Frontier: Hadron Colliders, FNAL, 28-31 July 2014

Full exploitation of the LHC → HL-LHC ($\sqrt{s}$ ~ 14 TeV, 3000 fb^{-1}) is a MUST
Europe's top priority, according to the European Strategy

HL-LHC potential in a nutshell

- Higgs couplings (assuming SM Γ_H):
  -- 2-5% in most cases, 10% for rare processes (H→ μμ, ttH → ttγγ)
  -- access for first time to 2nd generation fermions through (rare) H → μμ decay
  -- direct access for first time to top Yukawa coupling through (rare) ttH → ttγγ
  -- may measure Higgs self couplings to 30% ?
- Extend reach for stop quarks (naturalness !) up to m ~ 1.5 TeV
- Extend mass reach for singly-produced particles by 1-2 TeV compared to design LHC (300 fb^{-1}) → push energy frontier close to ~10 TeV

→ significant step forward in the knowledge of the Higgs boson
(though not competitive with ultimate reach of FCC-ee, ILC, CLIC)
→ detailed exploration of the TeV scale

Detector/Magnets for pp collisions at 100 TeV

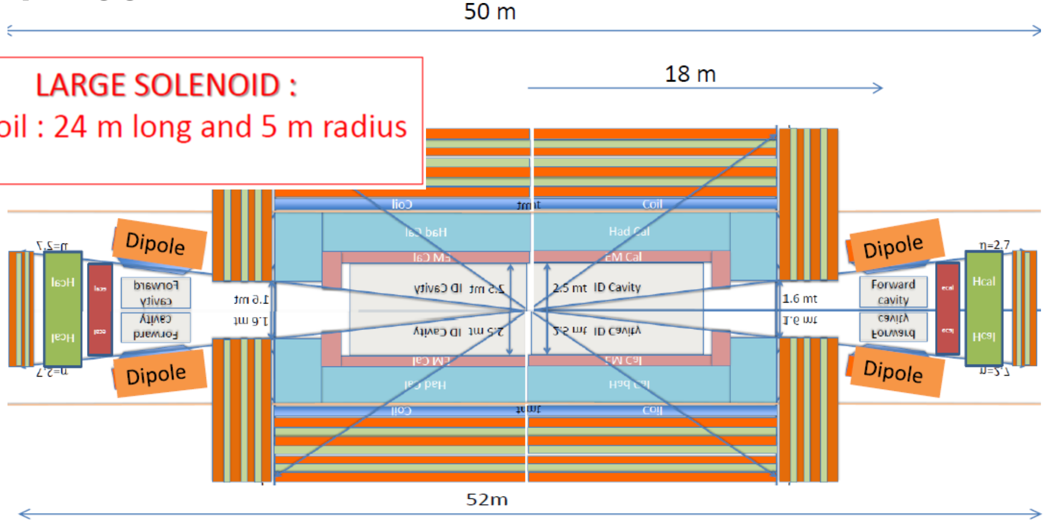
1) High masses
2) VV scattering
3) Boosted jets
4) Higgs channels

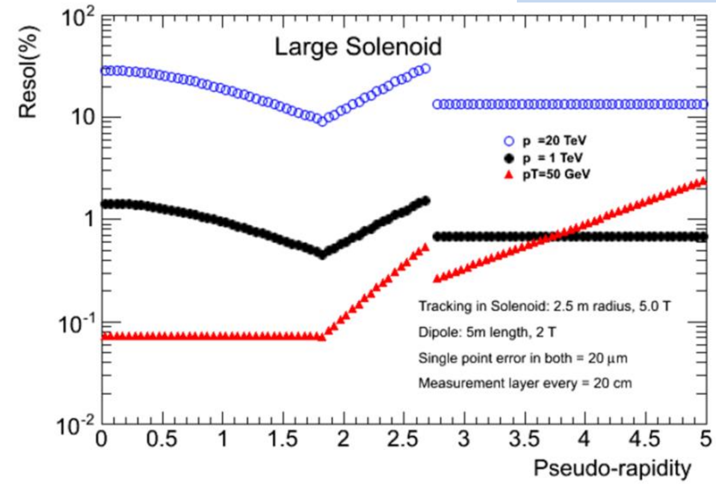
Driving req's:

- Increase central bending power (muons)
- Extend coverage of tracking in B–field (up to ~η=5?)
- Increase thickness of calorimeters
- Move EC calorimeters away from collision point

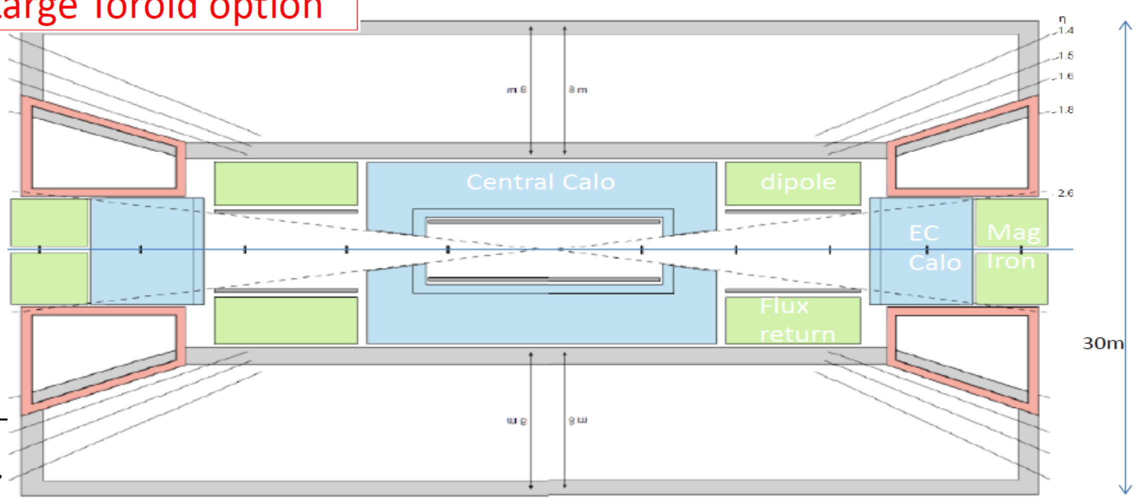
CMS:
12% at 1 TeV

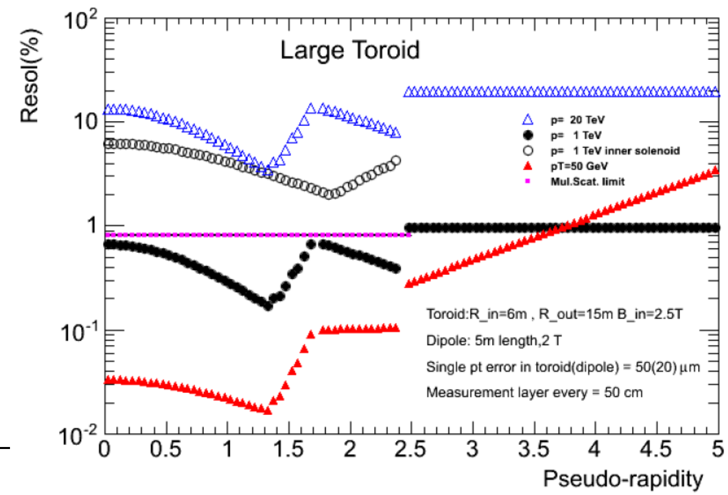
LARGE SOLENOID :
coil : 24 m long and 5 m radius





Large Toroid option

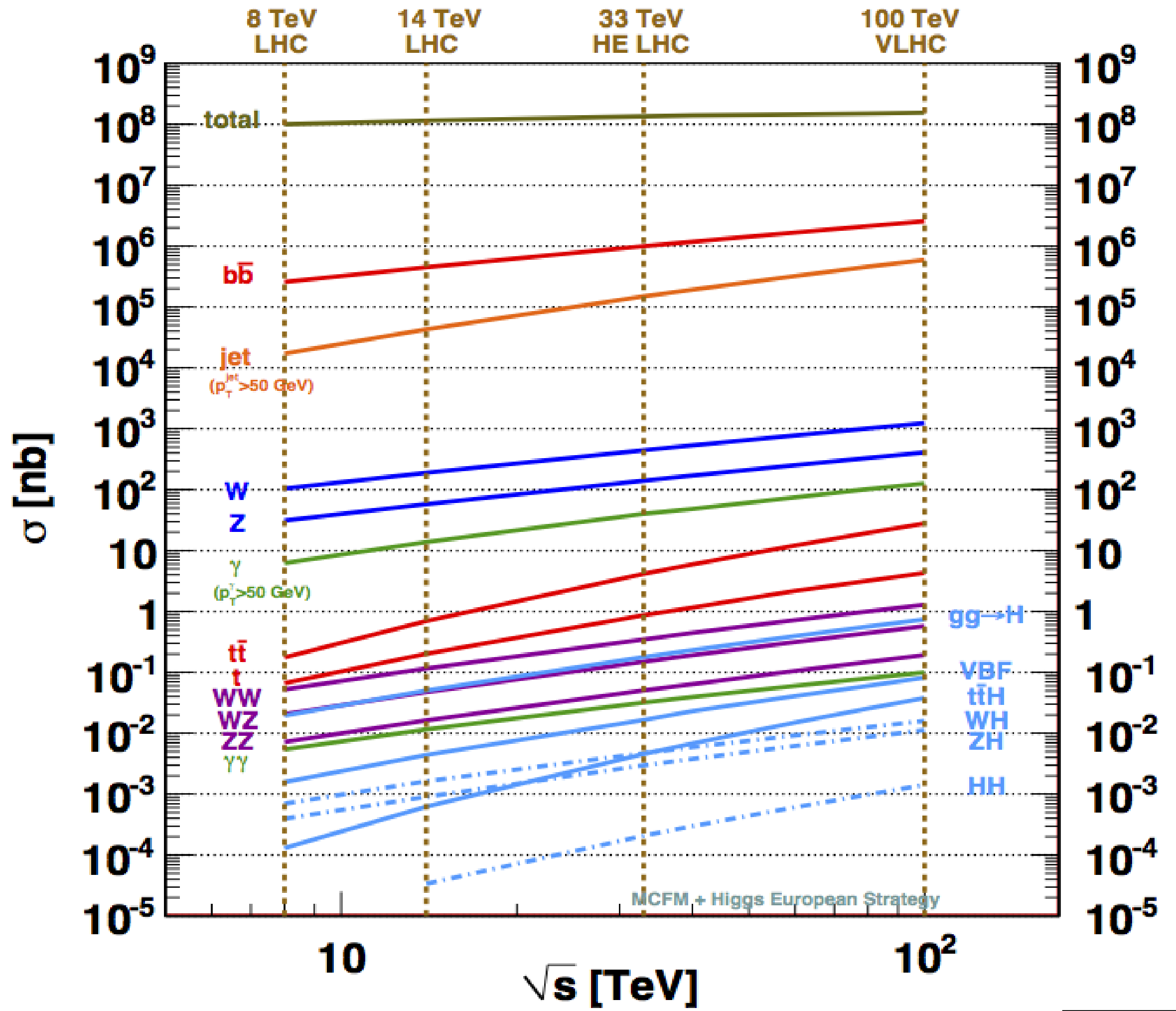




F.

Cross sections vs $\sqrt{s}$

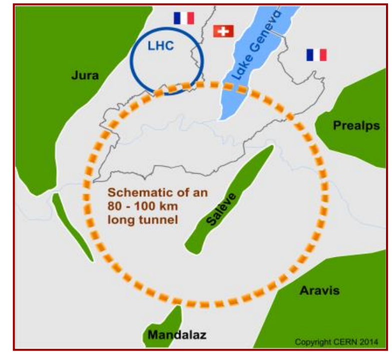
Snowmass report: arXiv:1310.5189



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

Cross-sections close to mass reach:
σ (q*) ~ 10^{-2} fb M ~ 50 TeV
σ (Z' → ee) ~ 4×10^{-3} fb M ~ 30 TeV

Physics case for a ~ 100 TeV pp collider



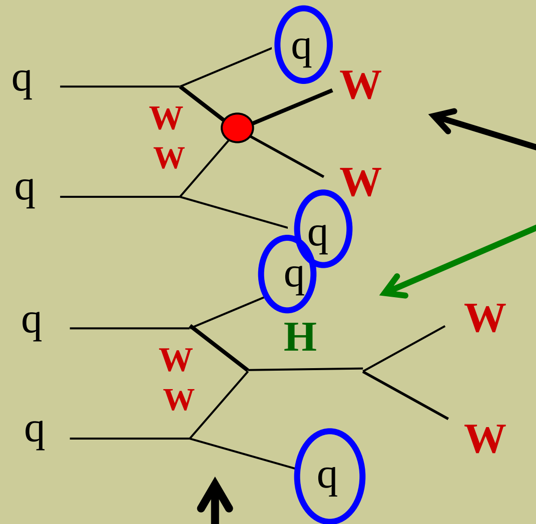
One of the main goals of the Conceptual Design Report (~ 2018)
→ will be studied in detail in the years to come …
→ see also M.Mangano's talk

Note:
-- Nb_3Sn ok up to 16 T
-- 20 T needs HTS

Studies will be made vs √s:
- ❑ comparison with HE-LHC
- ❑ if cost forces machine staging

	Ring (km)	Magnets (T)	√s (TeV)
LHC	27	8.3	14
HE-LHC	27	16-20	26-33
"SSC-like" (not attractive, not considered)	80	8.3	42
FCC-hh	80 100	20 16	100 100

Forward jet tagging: crucial for both low-mass (Higgs) and high-mass (VV scattering)

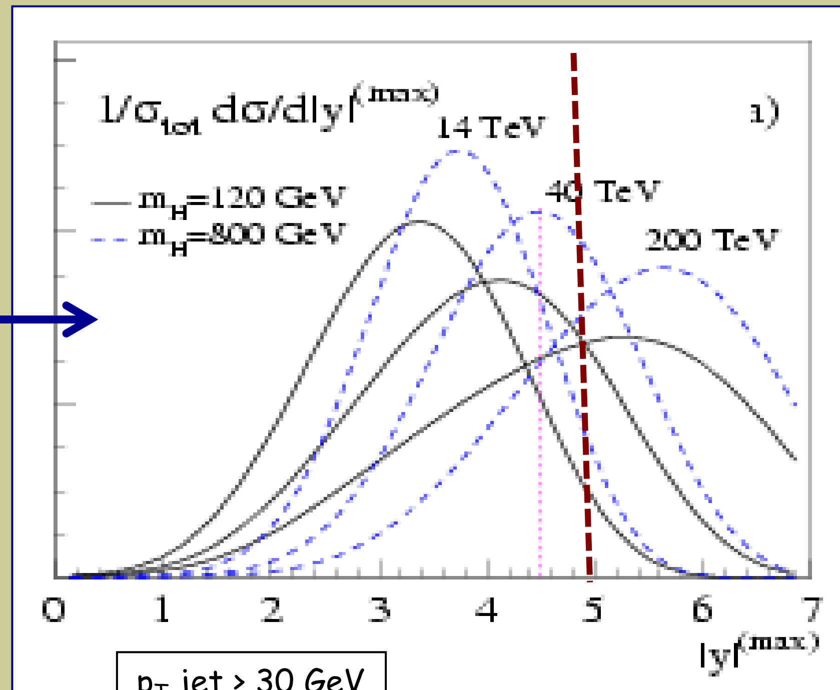


This process violates unitarity: $\sigma \sim E^2$ at $m_{WW} \sim$ TeV
(divergent cross section → unphysical)
if this process does not exist

Important to verify that H (125) accomplishes this task
→ a crucial "closure test" of the SM
Complete elucidation of EWSB: cross section measurements and searches for resonances
→ Likely requires high-E machine beyond HL-LHC and ILC

In addition: VBF Higgs production:
- ~10% of cross-section,
- information on couplings

Maximum jet rapidity vs √s for
VBF "Higgs" production
(from Snowmass 2001 US VLHC study: hep-ph/0201227)



ATLAS and CMS calorimeter coverage: |η|< 5
100 TeV detectors need to extend to |η| ≥ 6
→ pile-up is a big challenge !!

Work outline - I

2	**Physics and experiments**
2.1	**Hadron collider physics**
2.1.1	**Exploration of EW Symmetry Breaking**
2.1.1.1	High-mass WW scattering, high mass HH production
2.1.1.2	Rare Higgs production/decays and precision studies of Higgs properties
2.1.1.3	Additional BSM Higgs bosons: discovery reach and precision physics programme
2.1.1.4	New handles on the study of non-SM EWSB dynamics
2.1.2	**Exploration of BSM phenomena**
2.1.2.1	Discovery reach for various scenarios
2.1.2.2	Theoretical implications of discovery/non-discovery of BSM scenarios
2.1.3	**Continued exploration of SM particles**
2.1.3.1	Physics of the top quark
2.1.3.2	Physics of the bottom quark
2.1.3.3	Physics of the tau lepton
2.1.3.4	W/Z physics
2.1.3.5	QCD dynamics
2.1.4	**Opportunities other than pp physics**
2.1.4.1	Heavy Ion Collisions
2.1.4.2	Fixed target experiments
2.1.4.3	Smaller-size experiments for dedicated purposes
2.1.5	**Theoretical tools for the study of 100 TeV collisions**
2.1.5.1	Parton Distribution Function
2.1.5.2	MC generators
2.1.5.3	N^nLO calculations

Main physics goals

High-precision studies may require dedicated experiments

FCC-hh may be a very versatile facility
→ room for ideas for experiments of different type (collider, fixed target), size and scope (precise measurements, dedicated searches, ..)

More in Michelangelo's talk

Work outline - II

2.2	**Hadron collider experiments**
2.2.1	**Detector performance**
2.2.1.1	Rapidity coverage for tracking, leptons, jets
2.2.1.2	Forward tracking and b-tag vs pile-up density
2.2.1.3	Electromagnetic calorimeter: dynamic range, forward granularity
2.2.1.4	Forward jet tagging
2.2.1.5	Muon resolution in the O(10 TeV) region
2.2.1.6	Optimisation of the bunch spacing (trigger and readout vs pile-up)
2.2.2	**Technical systems**
2.2.2.1	Technologies that require R&D
2.2.2.2	Detector technologies
2.2.2.3	Radiation effects
2.2.2.4	Shielding
2.2.2.5	ECAL
2.2.2.6	HCAL
2.2.2.7	Magnet system
2.2.2.8	Muon detection
2.2.2.9	Inner detector
2.2.2.10	Tracking
2.2.2.11	Trigger system
2.2.2.12	Data acquisition, detector controls and detector safety
2.2.3	**Detector machine Interface**
2.2.3.1	L*, TAS, TAN locations and specifications
2.2.3.2	Bunch structure, luminous region and crossing angle
2.2.3.3	Beam pipe and vacuum design
2.2.3.4	Fluencies, shielding, dose rates, activation, and radiological dose minimization
2.2.3.5	Physics and detector protection instrumentation in the long straight section

Performance requirements and experimental challenges

Detectors layout, R&D and technologies
→ synergies with FCC-ee, ILC and CLIC being established

Detector-machine interface issues

More in D. Fournier's talk and Friday afternoon's parallel session

Future organization

→ more discussion in Friday's parallel session

In the coming months: continue with one working group (plus already-existing HI group):
- ❑ at this early stage we benefit from discussions in one forum
- ❑ we want to give opportunity to more people from all over the world to join and give their input before defining a WG structure and assigning coordination roles

Meetings: typically every two weeks (possibly with alternating emphasis on detector and physics) at a fixed time slot

In a few months: set up a WG structure (approximately mapping the WBS), starting with macro-groups and increasing granularity with time

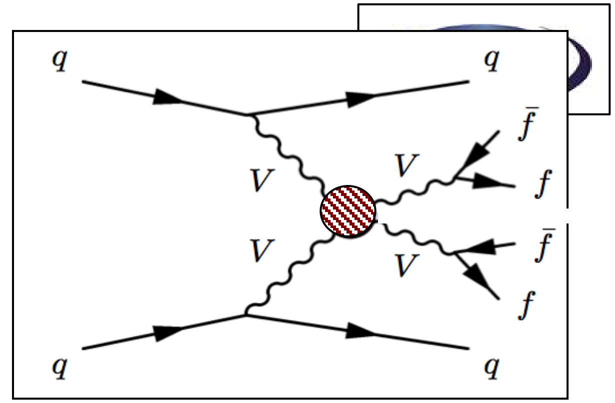
Note: intellectually very-stimulating activity:
- ❑ establishing the physics potential
- ❑ conceiving challenging experiments at a cha
- ❑ developing/improving (new) detector techno

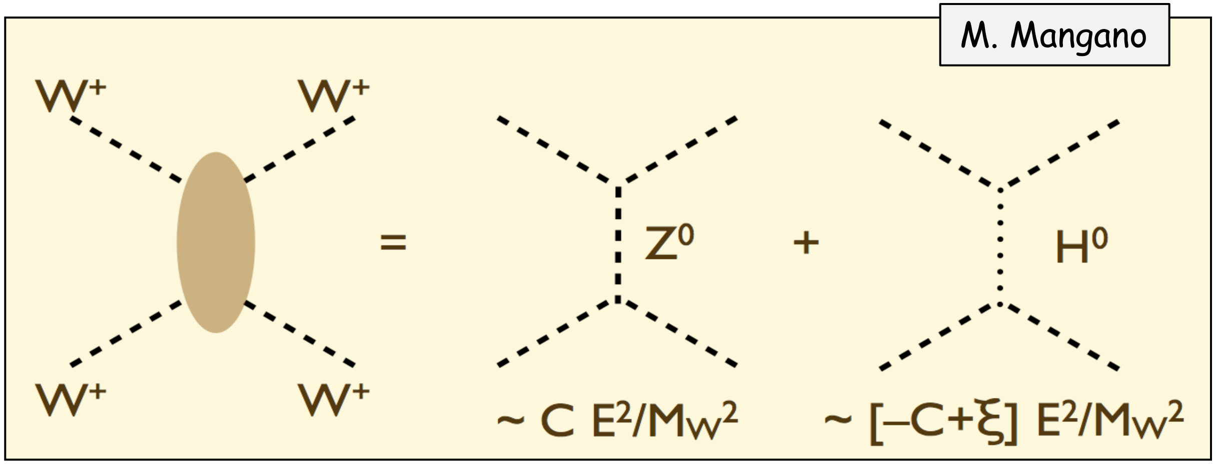
→ hope to attract many (young) people

- ❑ Meeting page: http://indico.cern.ch/category/5258/
- ❑ Mailing list: fcc-experiments-hadron@cern.

PLEASE JOIN !

Vector-Boson (V=W, Z) Scattering at large m_{VV} → insight into EWSB dynamics





First process (Z exchange) becomes unphysical ($\sigma \sim E^2$) at $m_{WW} \sim$ TeV if no Higgs, i.e. if second process (H exchange) does not exists. In the SM with Higgs: $\xi = 0$

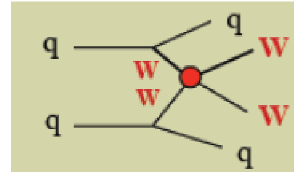
CRUCIAL "CLOSURE TEST" of the SM:

- ❑ Verify that Higgs boson accomplishes the job of canceling the divergences
- ❑ Does it accomplish it fully or partially ? I.e. is $\xi = 0$ or $\xi \neq 0$?

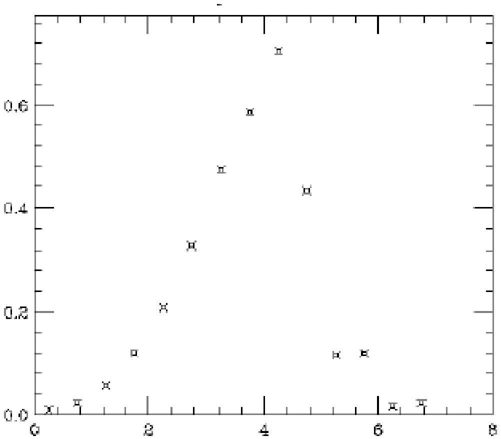
If $\xi \neq 0$ → new physics (resonant and/or non-resonant deviations) → important to study as many final states as possible (WW, WZ, ZZ) to constrain the new (strong) dynamics

Requires energy and luminosity → first studies possible with design LHC, but HL-LHC 3000 fb^{-1} needed for sensitive measurements of SM cross section or else more complete understanding of new dynamics

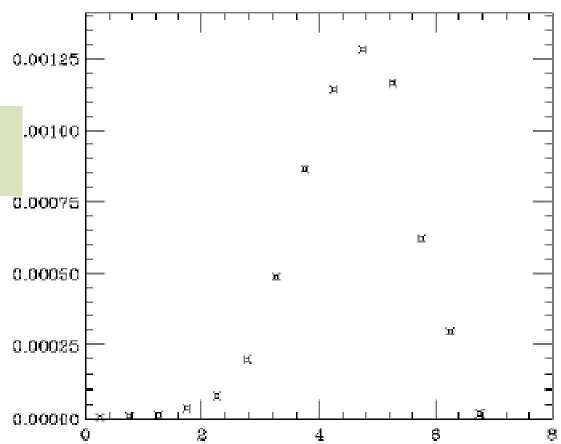
VBF jets acceptance



Max η of forward jets



WW by VBF M_{WW}>1 TeV



HH by VBF M_{HH} > 1 TeV

VBF measurement up to eta=6 desirable (means coverage beyond 6…)

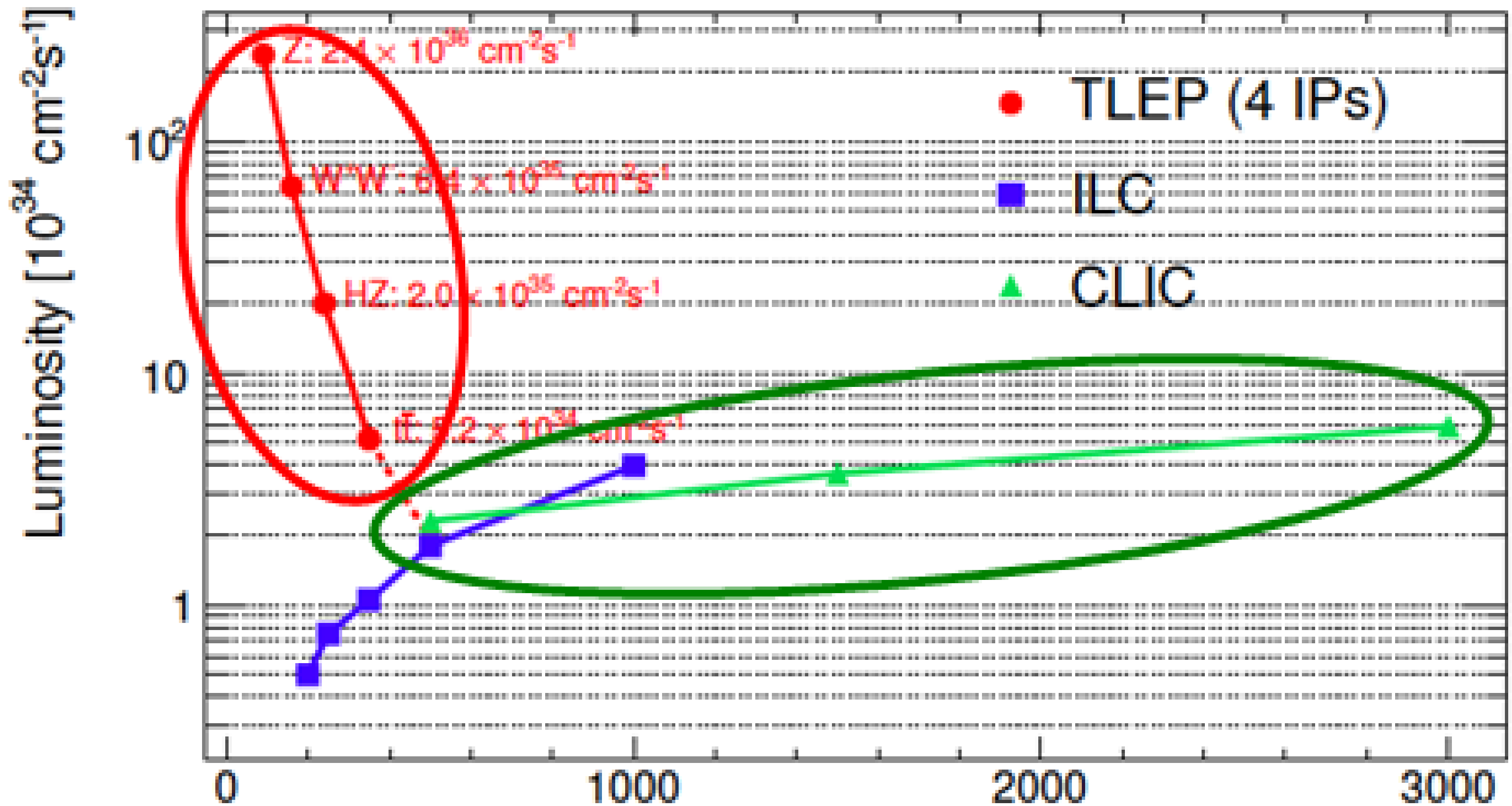
ETmiss ?? No investigation so far

To gain 1 η unit, an EC calo of fixed Inner Radius needs to be moved 2.7 times further away from the collision point (from ~5m in present expts to ~15m)

High density(W) desirable –inner part at least- to limit transverse size of particle showers

Fast response mandatory. 5ns bc would be an asset if detector speed can follow…

Projected e^+e^- Colliders: Luminosity vs Energy



TLEP physics study group: arXiv:1308.6176

Detectors for pp collisions at 100 TeV
Driving requirements

(1) Discovery of « high-mass » phenomena at the « Lσ »limit

- From « Drell-Yan » Limit m(Z') ~ 30 TeV

Z'→μμ : muon spectrometer (resolution,acceptance)

Z'→ee : EMcal (thickness, resolution-constant term- ,dynamic range,..)

- From QCD: q* Limit m(q*) ~ 50 TeV

  -jet resolution, linearity

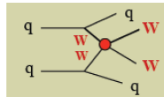
-SUSY

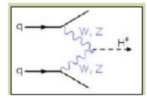
  -complex signatures ETmiss, jets, leptons, taus,...

-Many other scenarios (monopoles,...) not to be forgotten

(2) Study of VV scattering by « VBF mechanism »

- **Is H playing its role?**





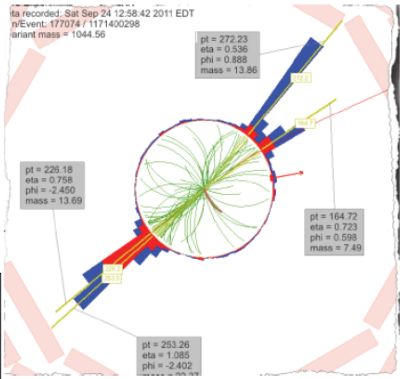
- **Are there « high mass » resonances in WW,ZZ,HH,..?**

- VBF jets between η~2 and η~6
  need to be well measured and separated from pile-up
- muons (and electrons) around ~1 TeV pT
  need to be triggered, identified, precisely measured
- Boosted jets ? To supply leptonic final states

(3) Boosted Jets (M.Pierini –see talk on friday)

- Recognizing if a high-PT jet is a QCD jet (quark,gluon) or a W or a Z or a H
  would greatly enhance the physics potential (WW-scat, New resonances,.)
- With PT of ~1 TeV pileup should not be the isssue...
- Part of ILC/CLIC program ; some trials in CMS : JME 13-006, EXO-12-021,..

For FCC-100 TeV
- Simulated RS->VV
- Jet pruning
- Discriminating variables:
  -jet mass
  -SubJettiness
- Very preliminary results,..Ongoing effort



CMS VV_jet candidate

Detector Aspects:
-is the « track-only » sub-structure good-enough?
-Can Particle-Flow work (at and above ~1 TeV)?
(require high granularity calorimeter)

(4) More on the Higgs Boson(s)

- As many decay modes as possible
  - -γγ, Zγ : EMcal resolution & acceptance
  - -ZZ* →4l : acceptance , particle ID
  - -WW→llνν :acceptance, ETmiss
  - -ττ , bb :high performance tracking, secondary vertices
  - -μμ :luminosity, acceptance
- As many production modes as possible
  - ggF,
  - WH,ZH :large boost,
  - VBF : forward jet tagging (again)
  - ttH : complex final state

Examples:
ttH : x 60 (from LHC 14)
HH : x 42

- Di-Higgs production: HE machines like 100TeV pp
  are « the places» where to measure λ
  promising final states: bbγγ , bbττ,.

$$M_H^2 = \lambda v^2$$

$$g_{hhh} \equiv 3\lambda v = \frac{3M_H^2}{v}$$

Science & Technology Facilities Council

Cultural, Economic and Societal Impacts of big science projects

John Womersley

Chief Executive
Science and Technology Facilities Council

10 February 2014

Science & Technology Facilities Council

how can we sell a project like a future circular collider?

☑ Science case

Convince me that this project is scientifically excellent

☑ Project Plan

Convince me that you know what you are doing: scope, costs and schedule are under control

☑ "Business case"

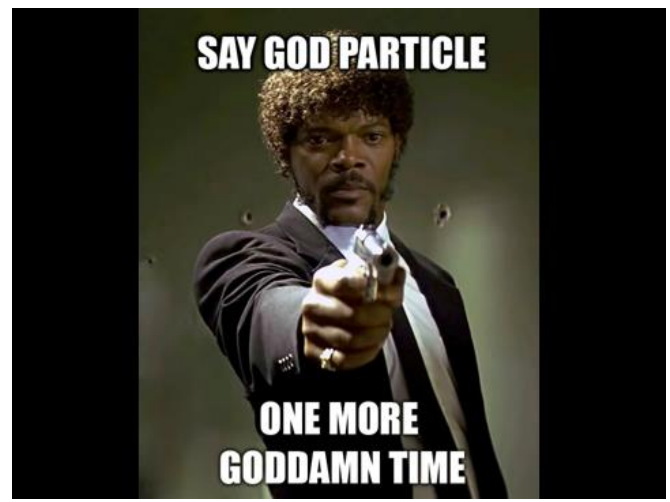
Convince me that this is a good use of public money

We need

Positive environment for science

Project-specific benefits

Personal connections with policymakers



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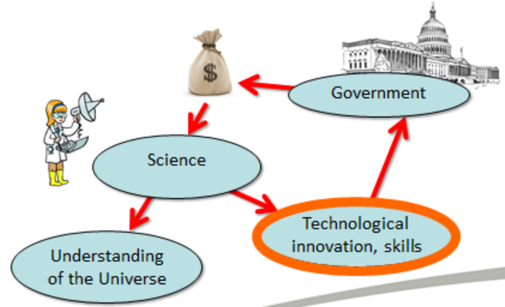
We need

Positive environment for science
Project-specific benefits
Personal connections with policymake

Why do governments support science?



Balance sheet

- 20 year investment in Tevatron ~ $4B
- Students $4B
- Magnets and MRI $5-10B } ~ $50B total
- Computing $40B

Very rough calculation – but confirms our gut feeling that investment in fundamental science pays off

I think there is an opportunity for someone to repeat this exercise more rigorously

cf. STFC study of SRS Impact

http://www.stfc.ac.uk/2428.aspx

Science & Technology Facilities Council

We need

Positive environment for science
Project-specific benefits
Personal connections with policymakers

George Osborne
UK Finance Minister