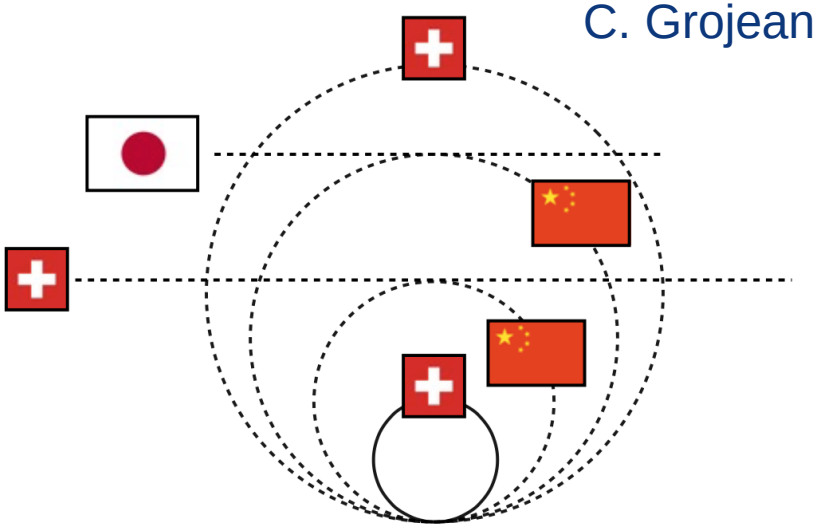
Overview of Future pp Collider Plans

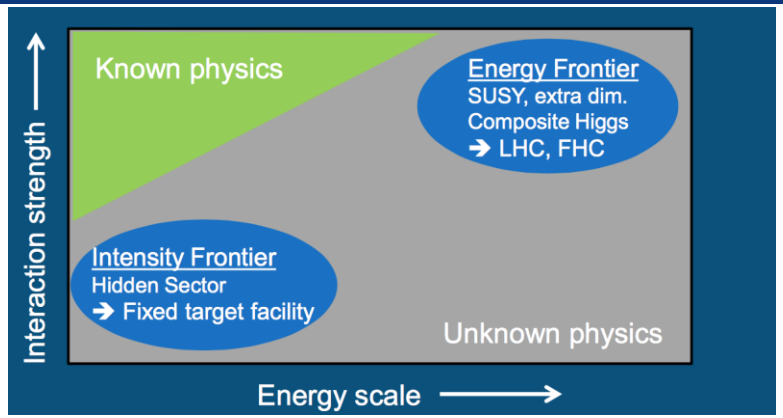
Albert De Roeck
CERN
17 June 2016

Contents: Future Colliders

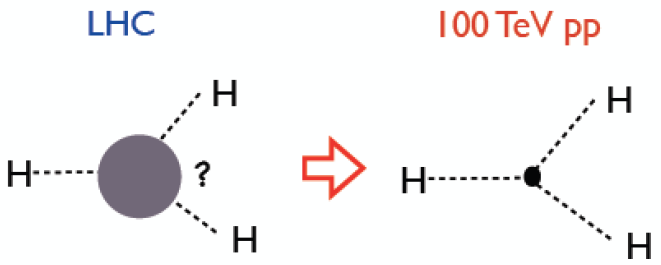
C. Grojean



Theorist view on future colliders



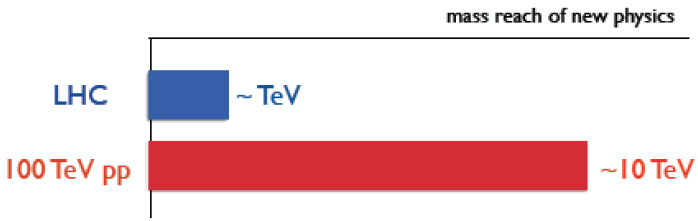
FCC-hh: THE machine for direct search at the higher energy scale.



Hadron colliders main themes:

The study of the Higgs Boson(s)

The search for massive new physics



Precision measurements

Hadron-Hadron Colliders Beyond the LHC at $\sqrt{s}$=14 TeV

FCC Project

High Energy LHC

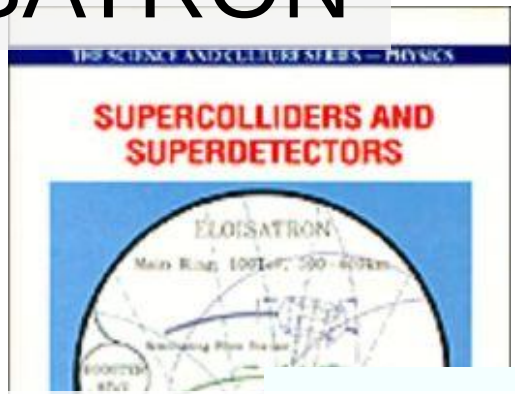
SppC

Thanks to M. Benedikt, M. Mangano, W. Riegler Y. Wang, F.Zimmerman,

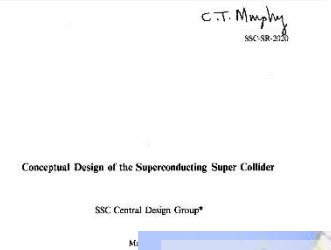
Previous studies in Italy (ELOISATRON 300km), USA (SSC 87km, VLHC 233km), Japan (TRISTAN-II 94km)

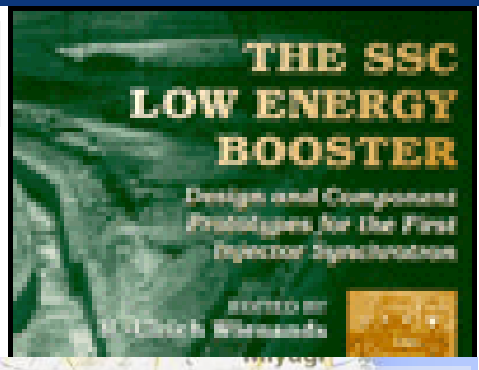
ex. ELOISATRON

Supercolliders Superdetectors: Proceedings of the 19th and 25th Workshops of the INFN Eloisatron



ex. SSC





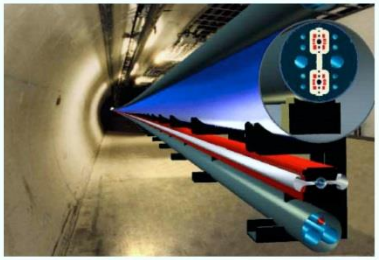
SSC C

ex. TRISTAN II

Many aspects of machine design and R&D non-site specific.
→ Exploit synergies with other projects and prev. studies

ex. VLHC

VLHC Design Study Group Collaboration
June 2001. 271 pp.
SLAC-R-591, SLAC-R-0591, SLAC-591, SLAC-0591, FERMILAB-TM-2149



http://www.vlhc.org/

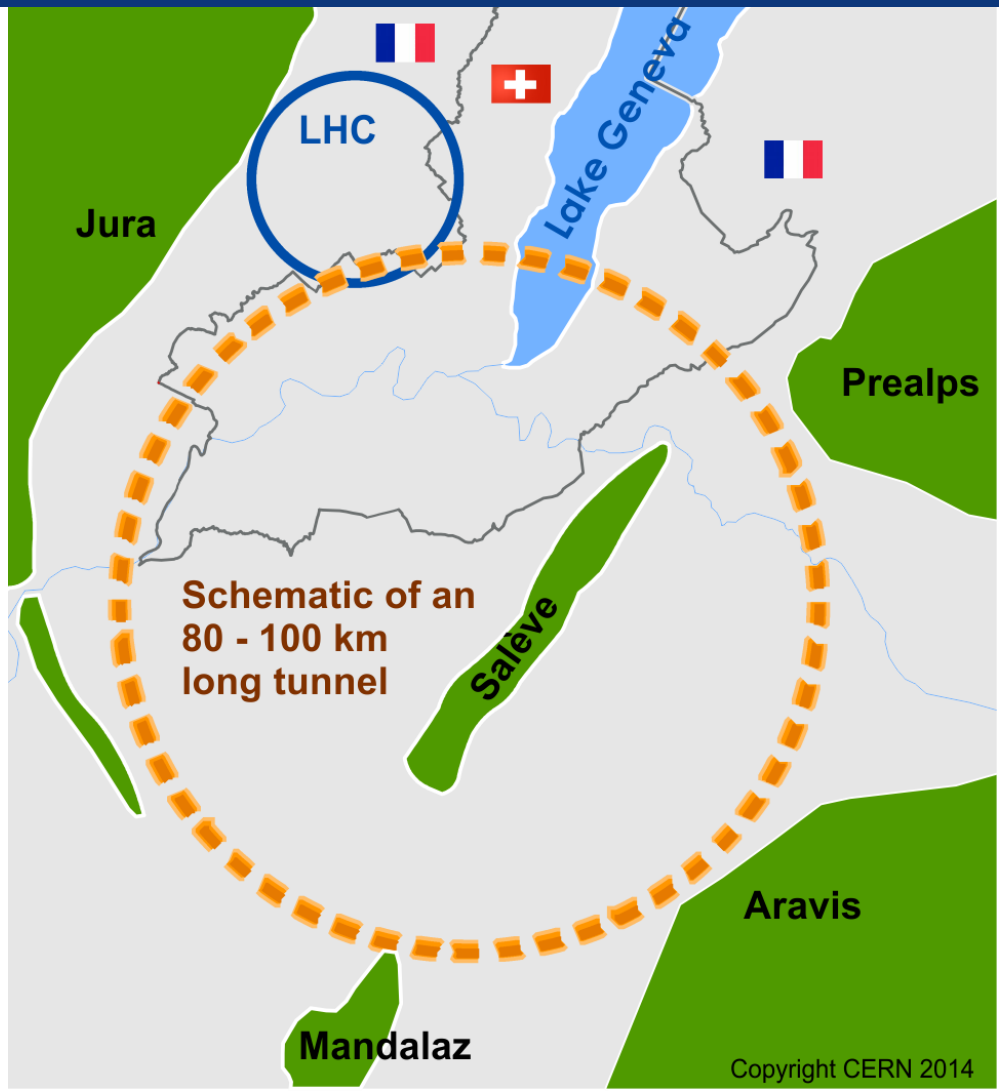
F. Takasaki

Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2018)

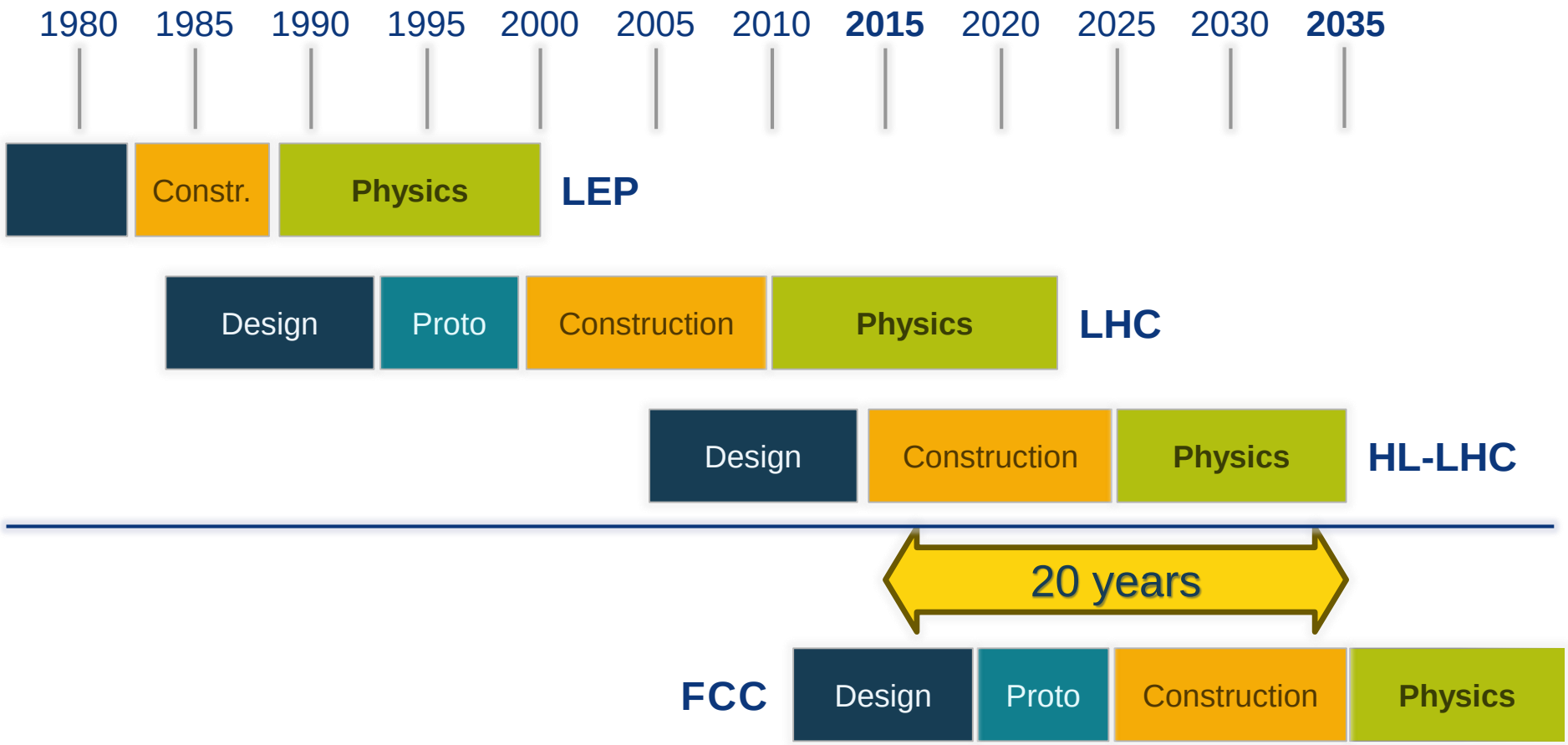
International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider *O(100) TeV* (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

  ~16 T ⇒ 100 TeV *pp* in 100 km
- **80-100 km tunnel infrastructure** in Geneva area
- **e^+e^- collider (*FCC-ee*)** as potential intermediate step
- ***p-e* (*FCC-he*) option**
- **HE-LHC** with *FCC-hh* technology



CERN Circular Colliders and FCC



Now is the right time to plan for the period 2035 – 2040

Goal of phase 1: CDR by end 2018 for next update of European Strategy

Key challenges for hadron colliders

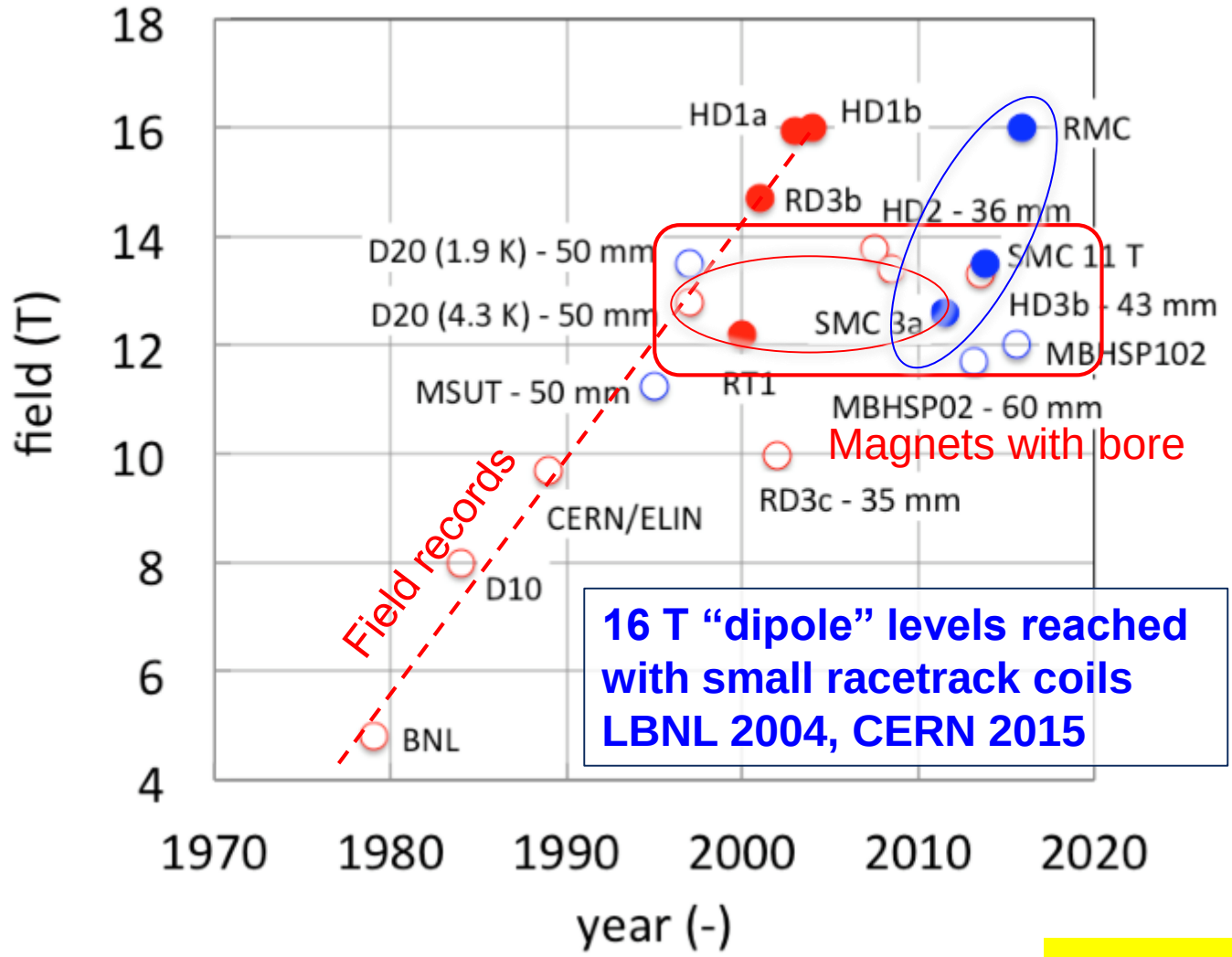
- **High energy**
  - ⇒ High field superconducting magnets
  - ⇒ Large tunnel infrastructures
- **High luminosity**
  - ⇒ Beam optics
  - ⇒ Beam current
  - ⇒ Synchrotron radiation to SC magnets
  - ⇒ IR shielding and element lifetime
- **High stored beam energy**
  - ⇒ Machine protection
  - ⇒ Beam handling
  - ⇒ Beam injection and dumping

No technical show stoppers so far!

Hadron Collider Parameters

parameter	FCC-hh		HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		>25	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotron rad. [W/m/beam]	30		3.6	(0.35) 0.18

CERN & EuroCirCol 16T Programs



LBNL HD1

CERN RMC

A small test coil at CERN reached 16T last fall

FCC-hh Luminosity Goals & Phases

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

  - **Phase 1 (baseline): 5 x 10^{34} $cm^{-2}s^{-1}$ (peak),**
    250 fb^{-1}/year (averaged) 25 nsec beam separation
    2500 fb^{-1} within 10 years (~HL LHC total luminosity)

  - **Phase 2 (ultimate): ~2.5 x 10^{35} $cm^{-2}s^{-1}$ (peak),**
    1000 fb^{-1}/year (averaged) 5 nsec beam separation?
    ➔ 15,000 fb^{-1} within 15 years

  - **Yielding total luminosity O(20,000) fb^{-1} over ~25 years of operation**

arXiv:1504.06108

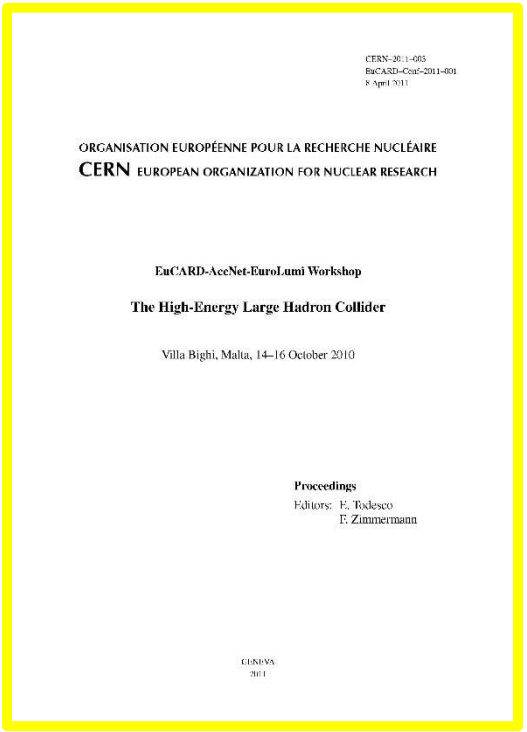
LUMINOSITY GOALS FOR A 100-TEV PP COLLIDER

Ian Hinchliffe[a*]; Ashutosh Kotwal[b†]; Michelangelo L. Mangano[c‡]; Chris Quigg[d§]; Lian-Tao Wang[e¶]

High-Energy LHC

FCC study continues effort on **high-field collider in LHC tunnel**

2010 EuCARD Workshop Malta;
Yellow Report CERN-2011-1


CERN-2011-003
EuCARD-Conf-2011-001
8 April 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

EuCARD-AccNet-EuroLumi Workshop

The High-Energy Large Hadron Collider

Villa Bighi, Malta, 14–16 October 2010

Proceedings
Editors: E. Todesco
F. Zimmermann

GENEVA
2011

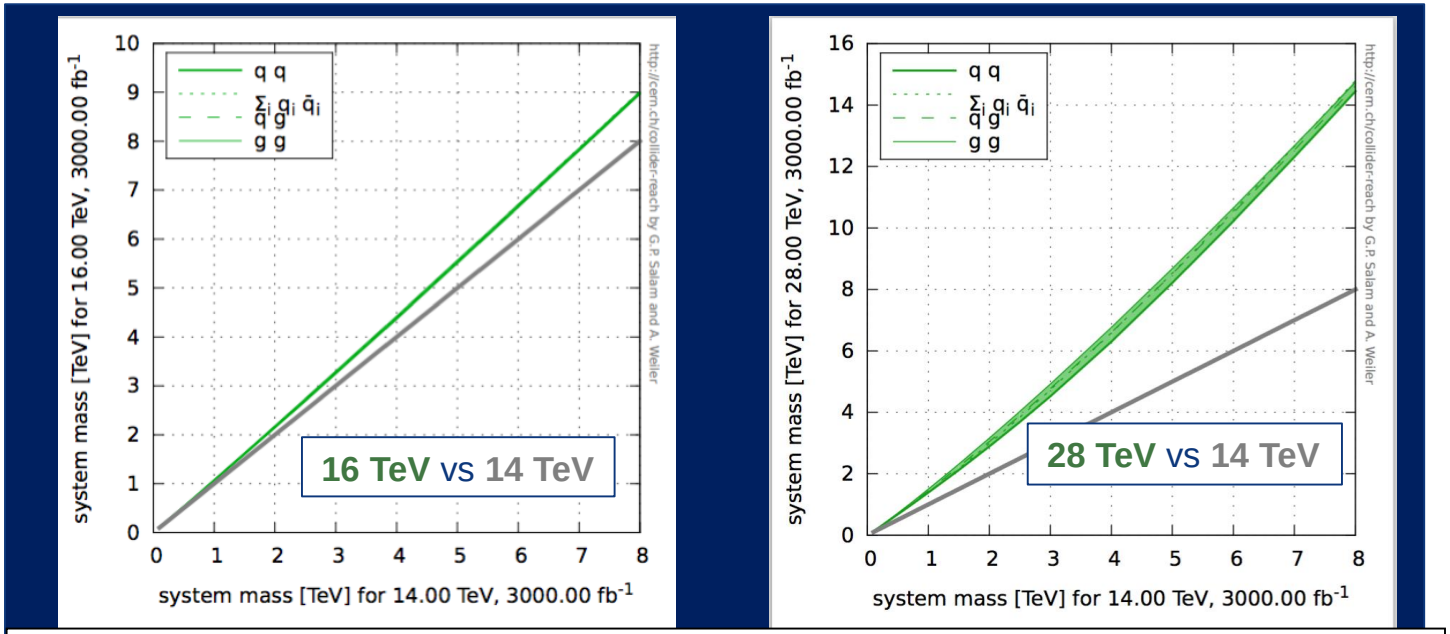
EuCARD-AccNet-EuroLumi Workshop: The High-Energy Large Hadron Collider - HE-LHC10, E. Todesco and F. Zimmermann (eds.), EuCARD-CON-2011-001; arXiv:1111.7188; CERN-2011-003 (2011)

- based on 16-T dipoles developed for FCC-hh
- extrapolation of other parts from the present (HL-)LHC and from FCC developments

CM Energy 25-28 TeV

High-Energy LHC

F. Gianotti
FCC meeting
Rome April 2016



Various options, with increasing amount of HW changes, technical challenges, cost, and physics reach

WG set up to explore technical feasibility of pushing LHC energy to:
1) design value: 14 TeV
2) ultimate value: 15 TeV (corresponding to max dipole field of 9 T)
3) beyond (e.g. by replacing 1/3 of dipoles with 11 T Nb_3Sn magnets)
→ Identify open risks, needed tests and technical developments, trade-off between energy and machine efficiency/availability
→ Report on 1) end 2016, 2) end 2017, 3) end 2018 (in time for ES)

HE-LHC (part of FCC study): ~16 T magnets in LHC tunnel (→ √s~ 30 TeV)
- ❑ uses existing tunnel and infrastructure; can be built at fixed budget
- ❑ strong physics case if new physics from LHC/HL-LHC
- ❑ powerful demonstration of the FCC-hh magnet technology

Science

China unveils plans for super-giant particle collider – the biggest and most powerful on Earth

By Hannah Osborne

October 29, 2015 10:06 GMT

This hit the news end if 2015!

What is all about??

China / Innovation

Hot Issues | Government | Society | Innovation | Education | Co

Photos

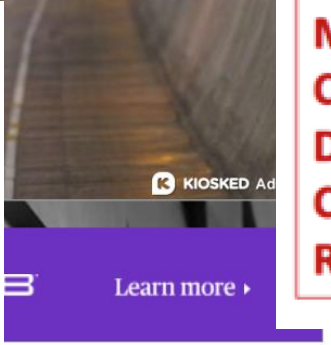
China plans world's most powerful particle collider

By Cheng Yingqi (China Daily)

Updated: 2015-10-29 07:49

Comments Print Mail Large Medium Small

The first phase of the project's construction is scheduled to begin between 2020 and 2025



Media is media
Chinese media is also media
Don't get too excited, nor panic
CEPC will not be easy and quick
R&D will come gradually

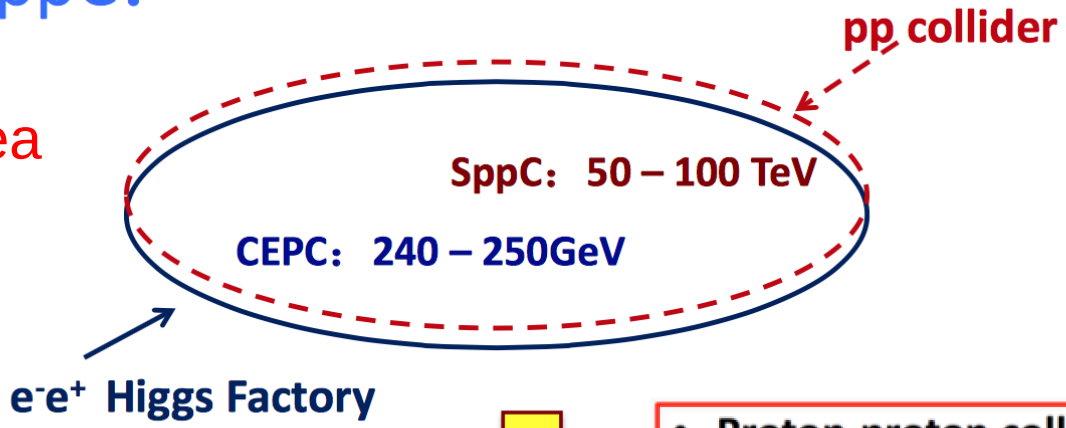
Y. Wang

China is set to build the biggest and most powerful particle collider on Earth, dwarfing the Large Hadron Collider at Cern. The super-giant particle collider will measure between 50 and 100km in circumference – double or quadruple that of the

The CEPC/SppC Design (China)

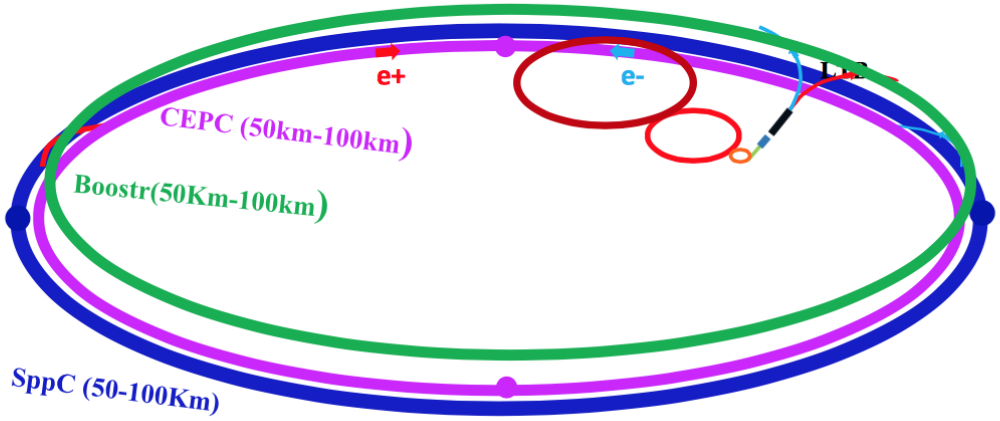
CEPC+SppC：

2012-2014: idea

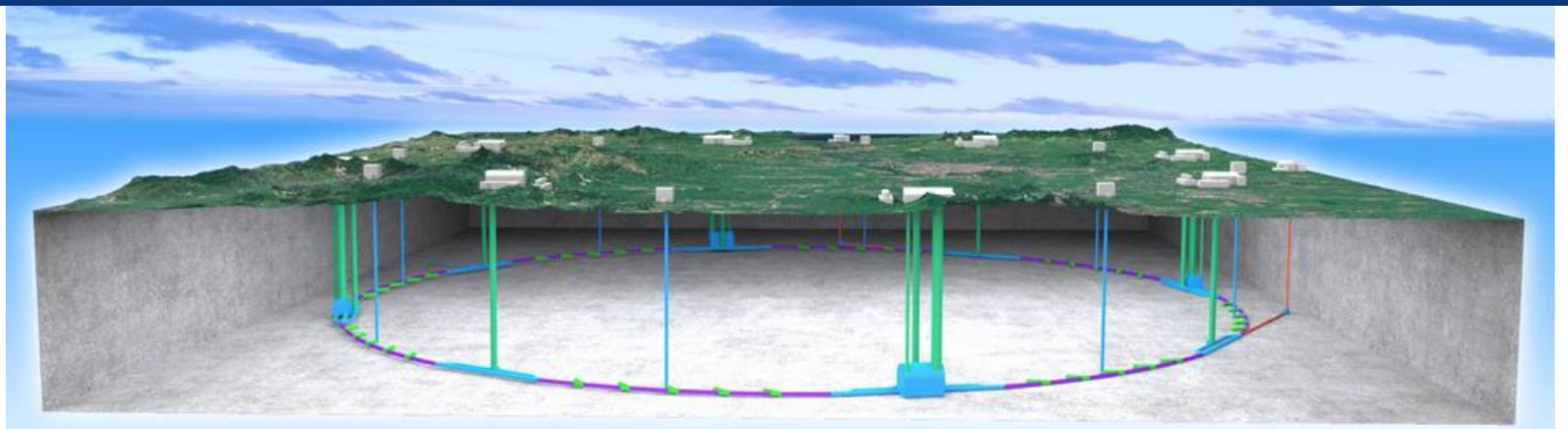


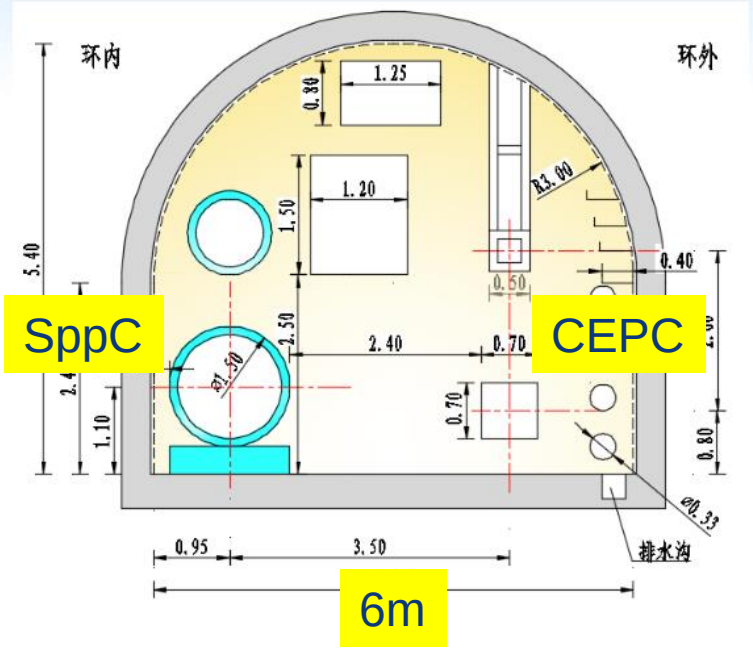
2015 pre-CDR

- Proton-proton collider(~100 TeV)
  - Directly search for new physics beyond SM
  - Precision test of SM
    - e.g., h^3 & h^4 couplings



The CEPC/SppC Civil Construction

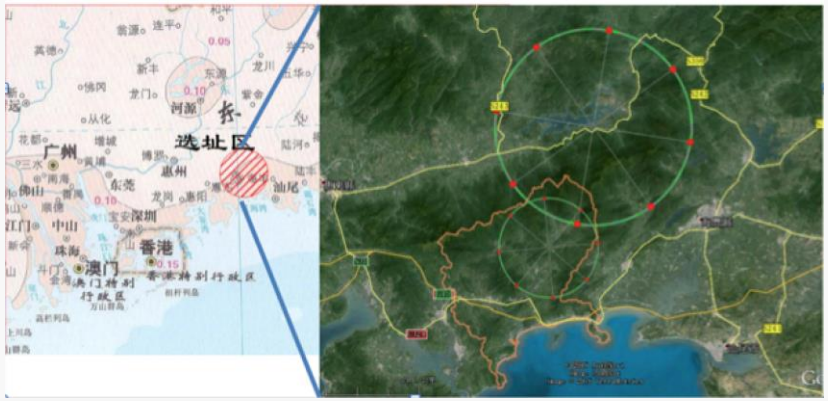




Site selection ongoing

Possibilities among others..

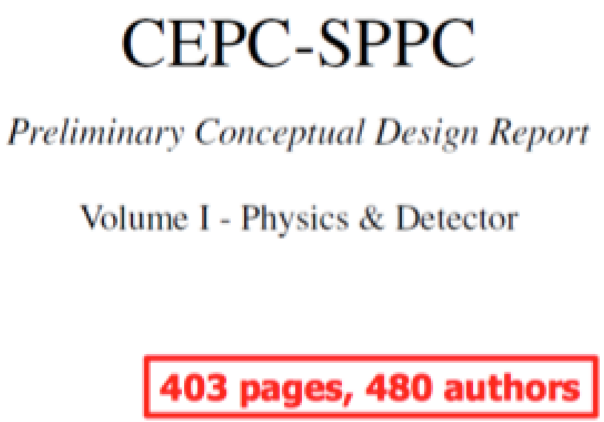
- Qinhuangdao (1 hr by train from Beijing)
- Close to Hong-Kong?...



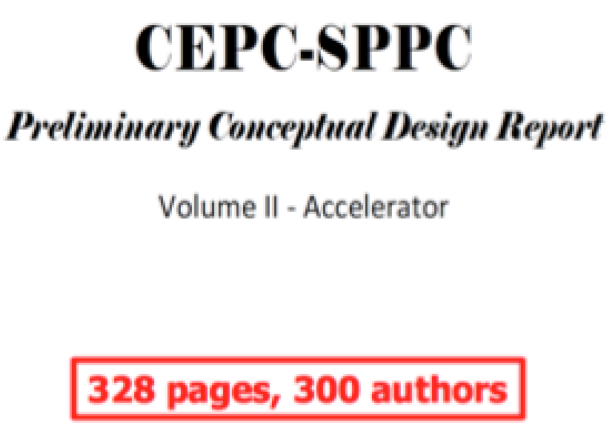
The SppC Pre-CDR

Can be downloaded from

http://cepc.ihep.ac.cn/preCDR/volume.html



403 pages, 480 authors



328 pages, 300 authors

- Limited international participation in the pre-CDR
  -> To built up confidence in the Chinese community
- Chinese government welcomes international collaboration
- Plan is to have this machine build owned by the International Community.
- An international advisory board has been installed last September.
- Substantial funding requests for R&D now in the pipeline…

Parameter choice for SPPC (Potential)

(F. Su et al)

Table 4. Parameter lists for LHC HL-LHC HE-LHC FCC-hh and SPPC.

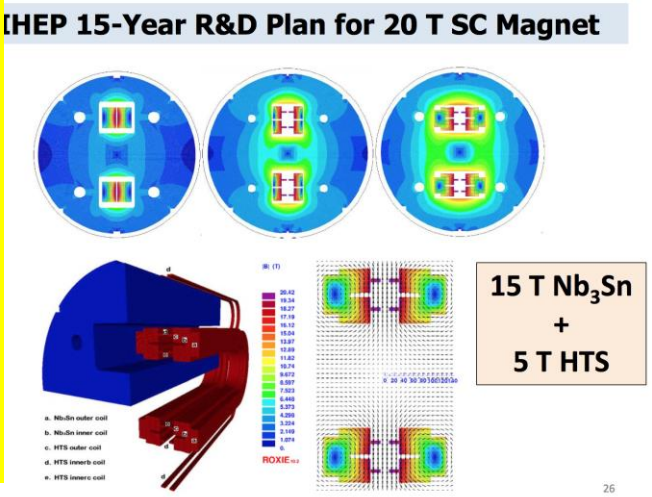
	LHC	HL-LHC	HE-LHC	FCC-hh	SPPC-Pre-CDR	SPPC-54.7Km	SPPC-100Km	SPPC-100Km	SPPC-78Km	
	Value									Unit
Main parameters and geometrical aspects										
Beam energy[E_0]	7	7	16.5	50	35.6	35.0	50.0	68.0	50.0	TeV
Circumference[C_0]	26.7	26.7	26.7	100(83)	54.7	54.7	100	100	78	km
Lorentz gamma[γ]	7463	7463	14392	53305	37942	37313	53305	72495	53305	
Dipole field[B]	8.33	8.33	20	16(20)	20	19.69	14.73	20.03	19.49	T
Dipole curvature radius[ρ]	2801	2801	2250	10416 (8333.3)	5928	5922.6	11315.9	11315.9	8549.8	m
Bunch filling factor[f_2]	0.78	0.78	0.63	0.79	0.8	0.8	0.8	0.8	0.8	
Arc filling factor[f_1]	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	
Total dipole magnet length [L_{Dipole}]	17599	17599	14062	65412 (52333)	37246	37213	71100	71100	53720	m
Arc length[L_{ARC}]	22476	22476	22476	83200 (66200)	47146	47105	90000	90000	68000	m
Total straight section length[L_{ss}]	4224	4224	4224	16800	7554	7595	10000	10000	10000	m
Energy gain factor in collider rings	15.6	15.6	13.5	15.2	17.0	16.67	17.5	17.5	17.5	
Injection energy [E_{inj}]	0.45	0.45	>1.0	3.3	2.1	2.1	2.9	3.9	2.9	TeV
Number of IPs[N_{IP}]	4	2	2	2	2	2	2	2	2	

Pre-CDR numbers

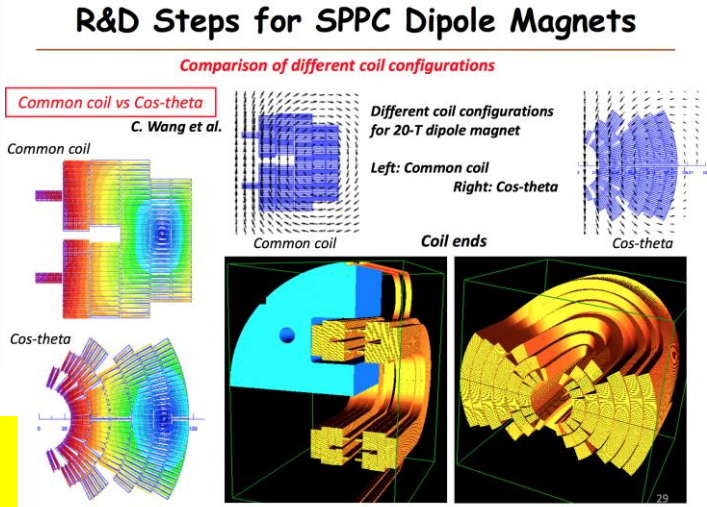
SppC Timeline (Present Ideas)

- CDR will be for a 54 km machine
- But 70-80 km machine being also studied (with 20T magnets -> 100 TeV)

- SppC planned for after CEPC
- Both could operate at the same time
- Detailed plan for developing 16-20T magnets



- **SppC** Y. Wang, FCC meeting April 2016
  - 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 -



Note added in proof on 15/6/2016 (Y. Wang):
CEPC/SPPC R&D funding request was not successful

Physics and Detectors for Hadron-Hadron Colliders

19

Physics Requirements (FCC-hh)

Higgs boson physics: 125 GeV object at 100 TeV can be highly boosted + need for optimal sensitivity to multi-Higgs and VBF processes.

- Precision tracking (momentum spectroscopy) and ECAL up to η=4
- Tracking and highly granular calorimetry for jets up to η=6.
- Sensitivity to low *pT* tracks vital for broad physics acceptance.

Searches require excellent performance at the highest energies.

- Calorimetry: hermetic and 1-2% constant term (shower containment needs 12 λ).
- Tracking: high momentum resolution ~10% at pT=10 TeV.

Pile-up for 30x10^34 and 25ns would reach ~1000 events/bunch crossing.

- Calorimeter granularity of $\Delta R \leq 0.05 \times 0.05$ or 0.025×0.025 to mitigate pile-up and measure jet substructure and boosted objects.
- Precision track association with primary vertex, timing for pileup rejection etc. …

Efficient b, c, τ -tagging despite intense radiation levels at low radii.

CERN

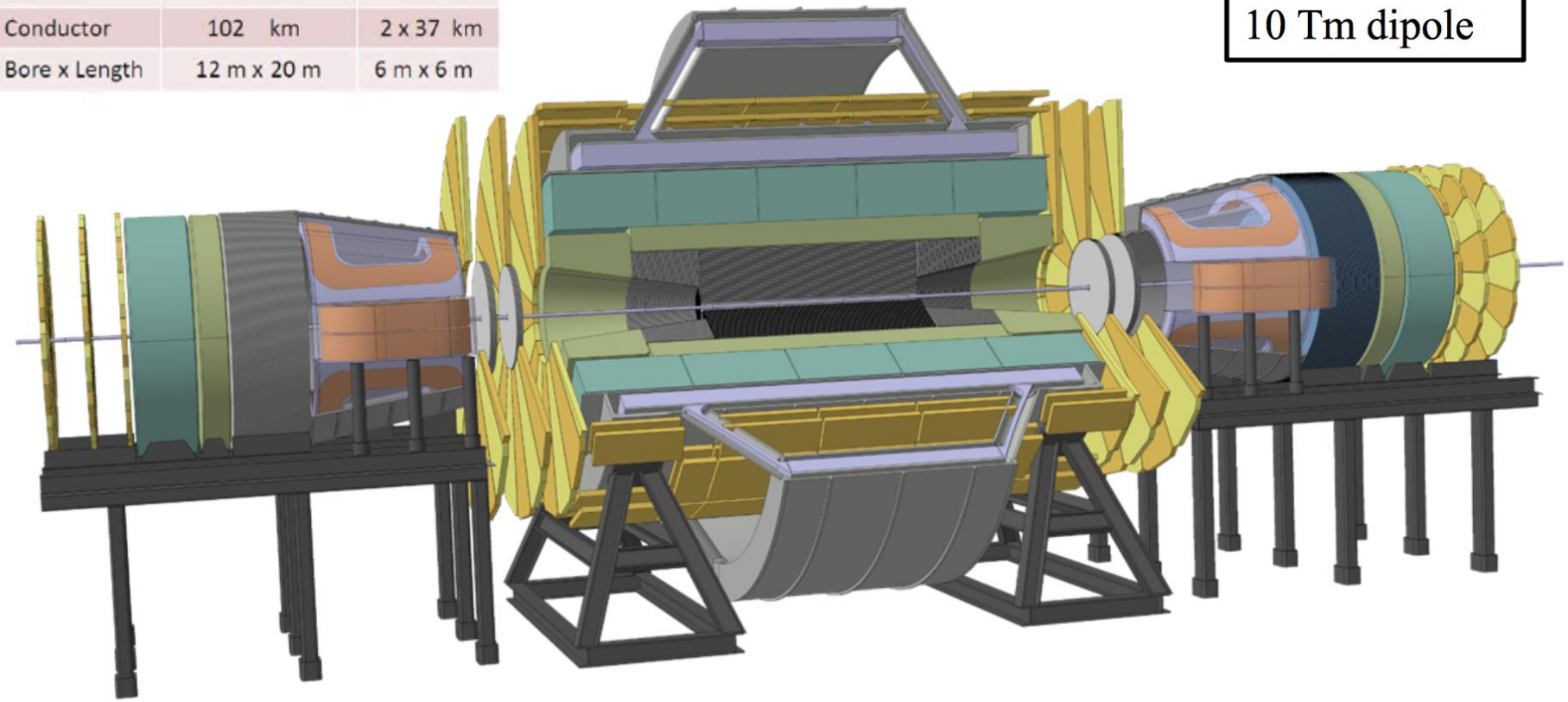
e-mail-list:fcc-experiments-hadron@cern.ch
Contact: Werner.Riegler@cern.ch

Baseline FCC-hh Detector

	Twin Solenoid	Dipole
Stored energy	53 GJ	2 x 1.5 GJ
Total mass	6 kt	0.5 kt
Peak field	6.5 T	6.0 T
Current	80 kA	20 kA
Conductor	102 km	2 x 37 km
Bore x Length	12 m x 20 m	6 m x 6 m

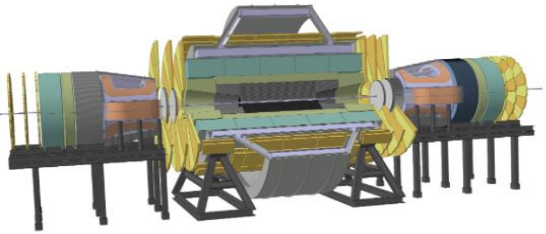
King Size Detector!
Diameter 27m
Length 60m

Twin solenoid
6 Tesla
12m bore
10 Tm dipole



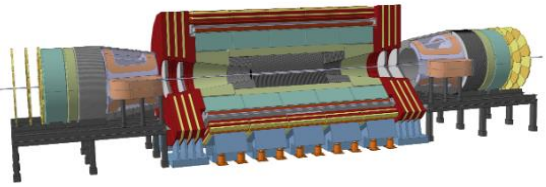
But magnet system would cost close to 0.7 BCHF!! Reasonable?

Follow-up Ideas for a FCC-hh Detector

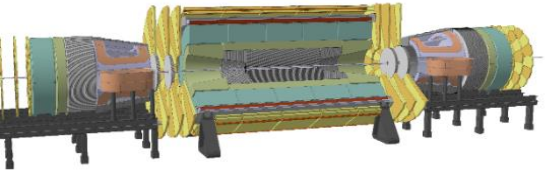


Twin solenoid with dipoles (min. shaft diameter 27.5m)

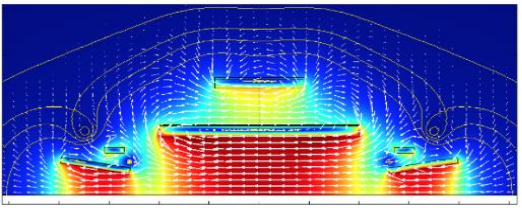
Cheaper/simpler systems?
Reduce dimensions/field of magnet system?



Partially shielded solenoid with dipoles



Unshielded solenoid with dipoles (min. shaft diameter 16.3m, if rotated under ground)

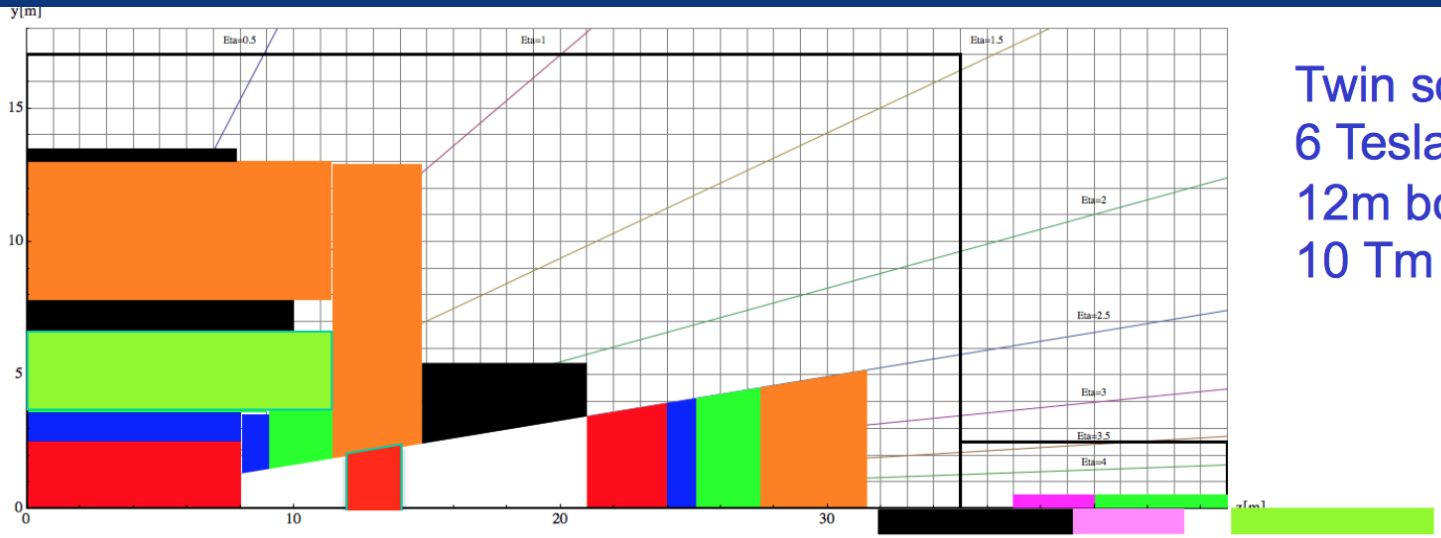


Twin solenoid with balanced conical solenoid

Unshielded solenoid with balanced conical solenoid

Herman Ten Kate, Matthias Mentink

Layout of a FCC-hh Detector



Twin solenoid
6 Tesla
12m bore
10 Tm dipole

Barrel:

Tracker available space:
R=2.1cm to R=2.5m, L=8m

EMCAL available space:
R=2.5m to R= 3.6m → dR= 1.1m

HCAL available space:
R= 3.6m to R=6.0m → dR=2.4m

Coil+Cryostat:
R= 6m to R= 7.825 → dR = 1.575m, L=10.1m

Muon available space:
R= 7.825m to R= 13m → dR = 5.175m
Revision of outer radius is ongoing.

Endcap:

EMCAL available space:
z=8m to z= 9.1m → dz= 1.1m

HCAL available space:
z= 9.1m to z=11.5m → dz=2.4m

Muon available space:
z= 11.5m to z= 14.8m → dz = 3.3m

Forward:

Dipole:
z= 14.8m to z= 21m → dz=6.2m

FTracker available space:
z=21m to R=24m, L=3m

FEMCAL available space:
Z=24m to z= 25.1m → dz= 1.1m

FHCAL available space:
z= 25.1m to z=27.5m → dz=2.4m

FMuon available space:
z= 27.5m to z=31.5m → dz=4m

Physics Prospects

arXiv:1606.00947

Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

~ 115 authors

- **Volume 1: SM processes** (238 pages)
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages)
- **Volume 3: beyond the Standard Model phenomena** (189 pages)
- **Volume 4: physics with heavy ions** (56 pages)
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)

Many detailed detector studies needed by the next European strategy update still to be done

Baseline detector in simulation software now available

A list with useful links in the backup

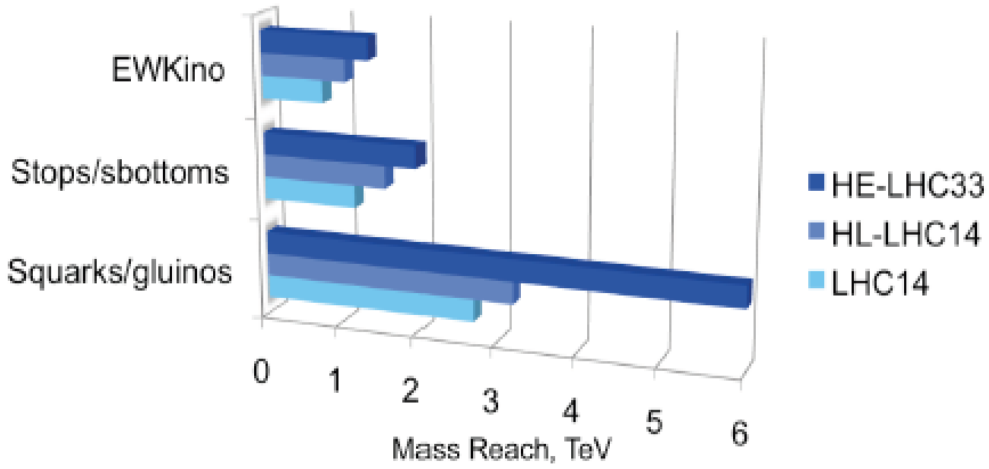
Physics Opportunities of a 100 TeV Proton-Proton Collider

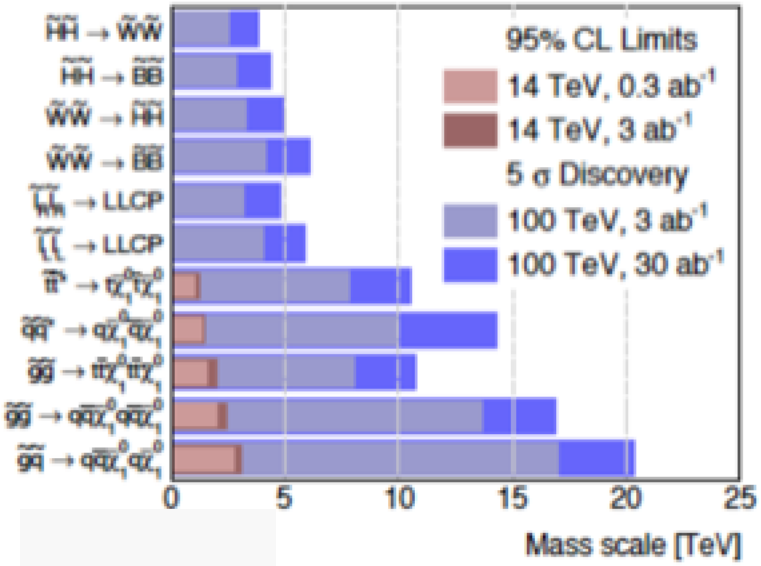
Nima Arkani-Hamed[a], Tao Han[b], Michelangelo Mangano[c], Lian-Tao Wang[d]

A recent review paper arXiv:1511.06495

Searches for New Physics

Searches for pair produced SUSY particles





FCC-hh

-Reach sparticle masses search up to about 20 TeV for gluinos and 10 TeV for stops for 30 ab^{-1}

-Excited quarks probe the structure of quarks down to $4x10^{-21}$ m

-Discovery of resonances up to masses of about 40-50 TeV

- Break through the neutrino-wall in dark matter searches

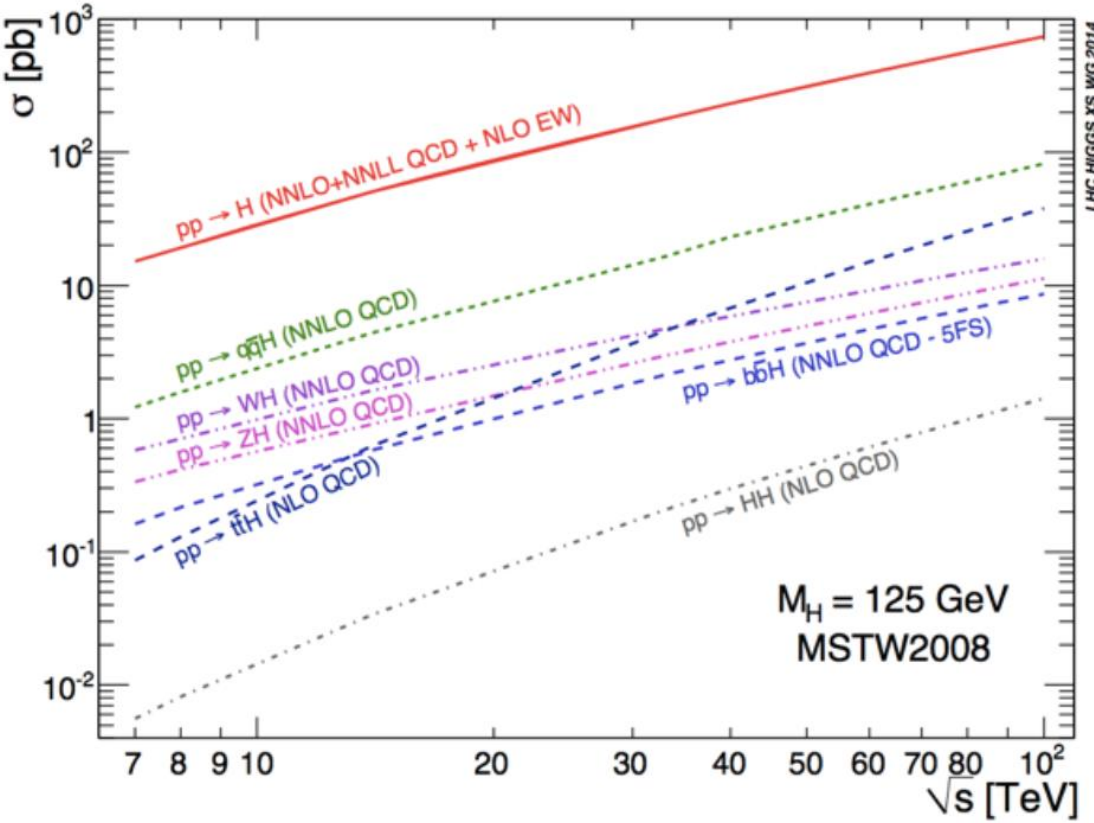
A very huge discovery potential

Plenty of Higgs Bosons at the FCC-hh

Relative cross section

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

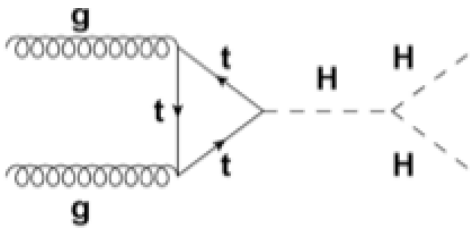
M. Klute, EPS 2105

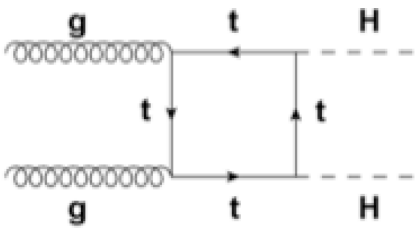


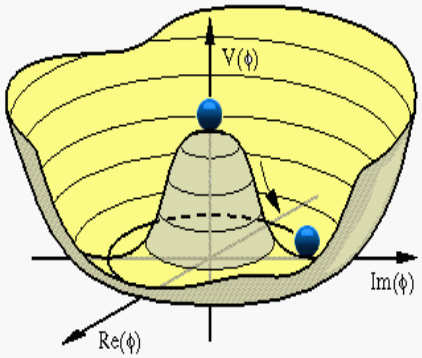
Proton-proton Higgs datasets — **LHC Run I** → x300-600 → **HL LHC** → x10-400 → **FCC pp**

Di-Higgs Production: Prospects

Higgs selfcouplings: $pp \rightarrow HH$







$HH \rightarrow b\bar{b}\gamma\gamma$	Barr,Dolan,Englert,Lima, Spannowsky JHEP 1502 (2015) 016	Contino, Azatov, Panico, Son arXiv:1502.00539	He, Ren Yao arXiv:1506.03302
$FCC_{@100TeV}$ 3/ab	30~40%	30%	15%
$FCC_{@100TeV}$ 30/ab	10%	10%	5%
$S/\sqrt{B}$	8.4	15.2	16.5
Details	✓ λ_{HHH} modification only ✓ $c \rightarrow b$ & $j \rightarrow \gamma$ included ✓ Background systematics ○ $b\bar{b}\gamma\gamma$ not matched ✓ $m_{\gamma\gamma} = 125 \pm 1$ GeV	✓ Full EFT approach ○ No $c \rightarrow b$ & $j \rightarrow \gamma$ ✓ Marginalized ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 5$ GeV ✓ Jet /W_{had} veto	✓ λ_{HHH} modification only ✓ $c \rightarrow b$ & $j \rightarrow \gamma$ included ○ No marginalization ✓ $b\bar{b}\gamma\gamma$ matched ✓ $m_{\gamma\gamma} = 125 \pm 3$ GeV

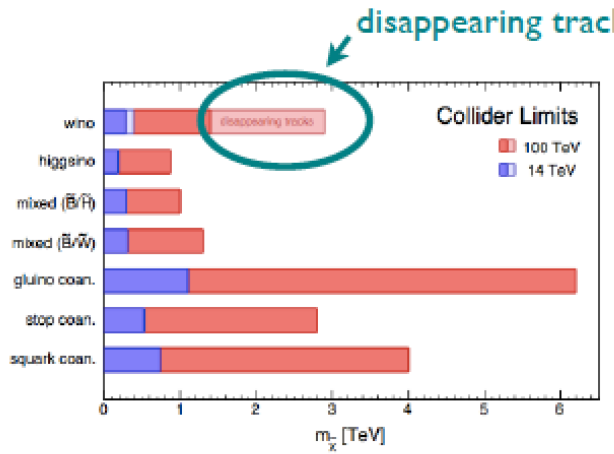
Work in progress to compare studies, harmonize performance assumptions, optimize, etc
⇒ ideal benchmarking framework

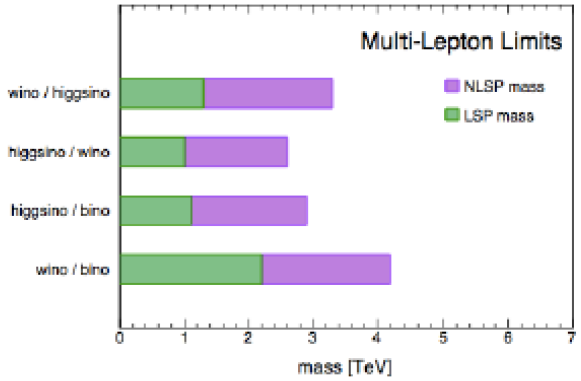
Dark Matter Studies at the FCC-hh

Dark Matter Searches within SUSY Scenarios

WIMP searches at colliders

L.Wang @ FCC week





Collider reach for neutralino DM

$$M_{\mathrm{WIMP}} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

Electroweakino cascades

100 TeV pp collider will probe TeV WIMP very well.

FCC-hh: More Topics Under Study

- Precision measurements in EWK, top, Higgs, QCD…
- EWK radiation of W's and opportunities
- New high mass scalar resonance sensitivity
- Production of exotic coloured states
- Flavor physics opportunities
- Quadruple Higgs production and quartic couplings
- EW interactions at multi-TeV (eg WW scattering)
- Coloured and neutral naturalness
- Composite Higgs, twin-Higgs… models
- Heavy Leptons and Leptoquarks
- Heavy Ion program
- …

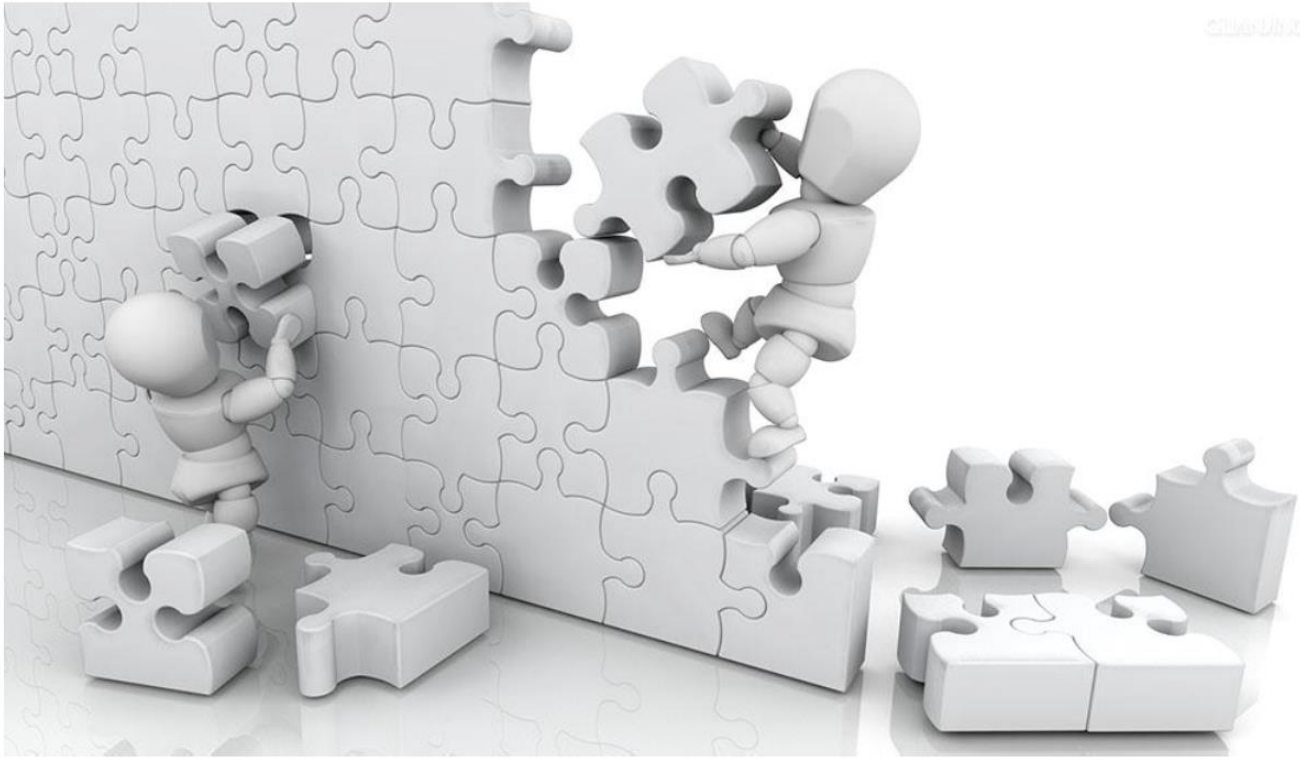
Lots of opportunities for studies

Future Hadron Colliders: Summary

- FCC-hadron collider design is being developed as option for future flagship project at CERN for the world-wide high energy physics community.
  - Goal is to have CDR ready by end 2018 for European strategy update. No show stoppers so far
  - **https://indico.cern.ch/category/5153/**
- A High Energy LHC scenario is studied (again)
- SppC in China is moving to a CDR phase
  - Detailed magnet R&D program ramping up
- Detailed physics studies for pp at 100 TeV in progress. Interested people welcome!

A new particle, say at 750 GeV, would be a game changer!

All workers on colliders unite!



To follow FCC-hh physics activities

- Register with the FCC-hh mailing list for announcements:
  - http://simba3.web.cern.ch/simba3/SelfSubscription.aspx?groupName=fcc-experiments-hadron
- Check agendas and contents of previous events at the following indico categories:
  - *Informal meetings of all **physics** subgroups (SM, Higgs, BSM):*
    - https://indico.cern.ch/category/6067/
  - *Workshops*
    - https://indico.cern.ch/category/6071/
  - *Physics with injectors:*
    - https://indico.cern.ch/category/6070/
  - *Heavy ion physics:*
    - https://indico.cern.ch/category/6068/
  - *Detector subgroup:*
    - https://indico.cern.ch/category/6069/
  - *Detector magnets subgroup:*
    - https://indico.cern.ch/category/6244/
  - *Software group (common with FCC-ee and FCC-eh):*
    - https://indico.cern.ch/category/5666/