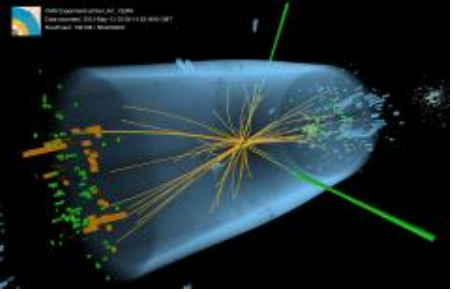


High Energy Proton-Proton Colliders

Swapan Chattopadhyay

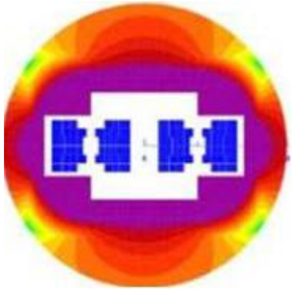
YEARS / ANS CERN

Fermilab

NIU

Xth Rencontres du Vietnam
Physics at LHC and Beyond
Quy Nhon, Vietnam

10-17 August , 2014



FCC
hh ee he

Acknowledgments

- **F. Zimmermann (CERN)**
- **P. Lebrun (CERN)**
- **M. Benedikt (CERN)**
- **D. Schulte (CERN)**
- **O. Bruning (CERN)**
- **Li Feng Yang (IHEP)**
- **V. Shiltsev FNAL)**

OUTLINE

- **Prelude**
- **Beyond LHC: HL-LHC, FCC, CepC, SppC**
- **Scenarios and parameters**
- **R&D elements**
- **Cost!!**
- **Alternative : reach “dark” sector via small experiments**
- **New paradigm of global Collaboration**

Sir Humphrey Davy

"Nothing tends so much to the advancement of knowledge as the application of a new instrument"

from

Elements of Chemical Philosophy (1812)

Accelerators are indeed grand instruments of science enabling advancement of knowledge of the universe in small- and large-scales

→ "Proton colliders" have been critical in advancing our knowledge of elementary particles and forces

Professor Victor F. Weisskopf

"When I think about how we got into this small-scale region, I must say that the most important contributors have been the machine innovators, designers and builders --- I am reminded of the voyage of Columbus. There were those hardy ship builders, who knew not how far or where to or for how long the ships had to sail, but that they should withstand all tests of the unknown sea. These are our accelerator and detector builders of today. Then we had those folks who simply jumped onto the ships and sailed away, landed at the first island they could reach and noted down everything they saw in great detail. These are our experimental physicists of the day. Finally there were those lazy fellows who stayed back in Madrid and told the expedition crew that they were going to land in India! These are today's theorists."

from

" The Structure of Matter and Elementary Particles " **CERN (1978)**

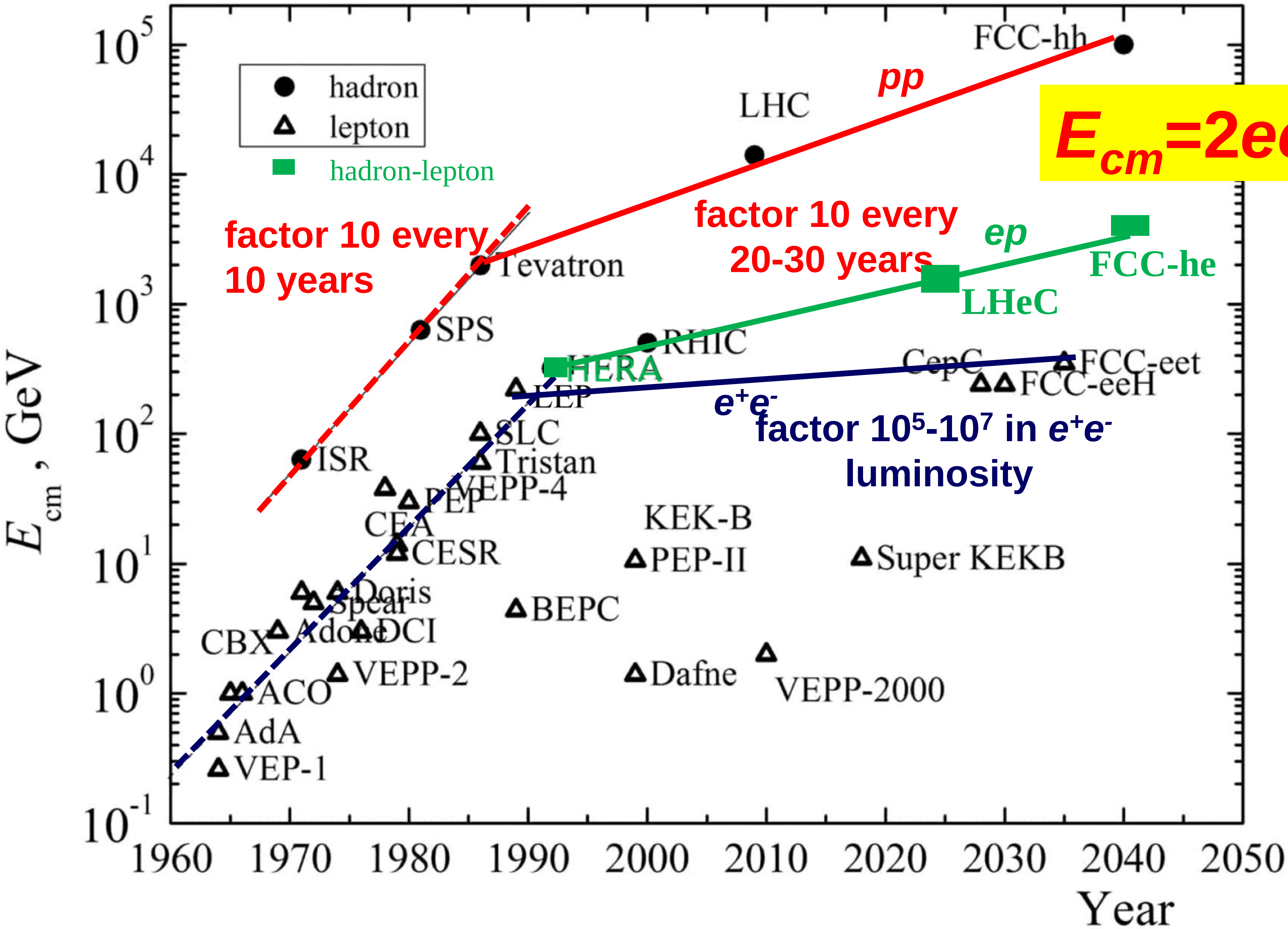
While it was very kind and gracious of an accomplished "theorist" such as Professor Weisskopf to pay tribute to the accelerator and detector physicists and engineers, he was slightly off the mark when it comes to hadron coilliders !!

- SppS @ CERN → "W and Z Bosons" found in 1983 but predicted by Sheldon, Glashow and Salam in 1970's in their "electro-weak unification" model;

- Tevatron @ Fermilab → the "top" quark found in 1990 but long predicted by the theorists in the Standard model (Gellmann et al 1960s);

- LHC @ CERN → the "Brout – Englert - Higgs" Boson found in 2012, predicted 1960s.

collider c.m. energy vs. year



$E_{cm}=2ec(B\rho)$

Courtesy V. Shiltsev,

Future h-h Colliders: "Phase-Space"

- "Interesting Physics"
  - 10 -100 TeV
  - decent luminosity

- "Live within our means":
  - < few x 10 B$
  - < few x 10 km
  - < few x 10 MW (beam power, ~ few x 100MW total)

Realistic Hadron Colliders on the horizon and for future

(ca 2030 and beyond)

- High-Luminosity LHC (x5 design L) @ 14 TeV in c.m.

- 100 TeV hh (FCC/CERN and SppC/CAS-IHEP)

European Strategy Update on Particle Physics

Exploit the full potential of the LHC

European Strategy
for Particle Physics

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} by 2035
including LHC injectors upgrade **LIU**
(Linac 4, Booster 2GeV, PS and SPS upgrade)

Already heard Talk

by

Oliver Bruning

on

“HL-LHC “at CERN

20-100 TeV –scale Hadron Colliders

Previous studies (1984-):

Italy: ELOISATRON around the island of Sicily;
USA : SSC (much more than a study, 1984-1992), VLHC (1992-)
Japan: TRISTAN-II (1983)

Current serious studies (2013-):

CERN: FCC in Europe (and US?)
CAS-IHEP : SppC in China (and US?)

FCC
hh ee he

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

>340 participants

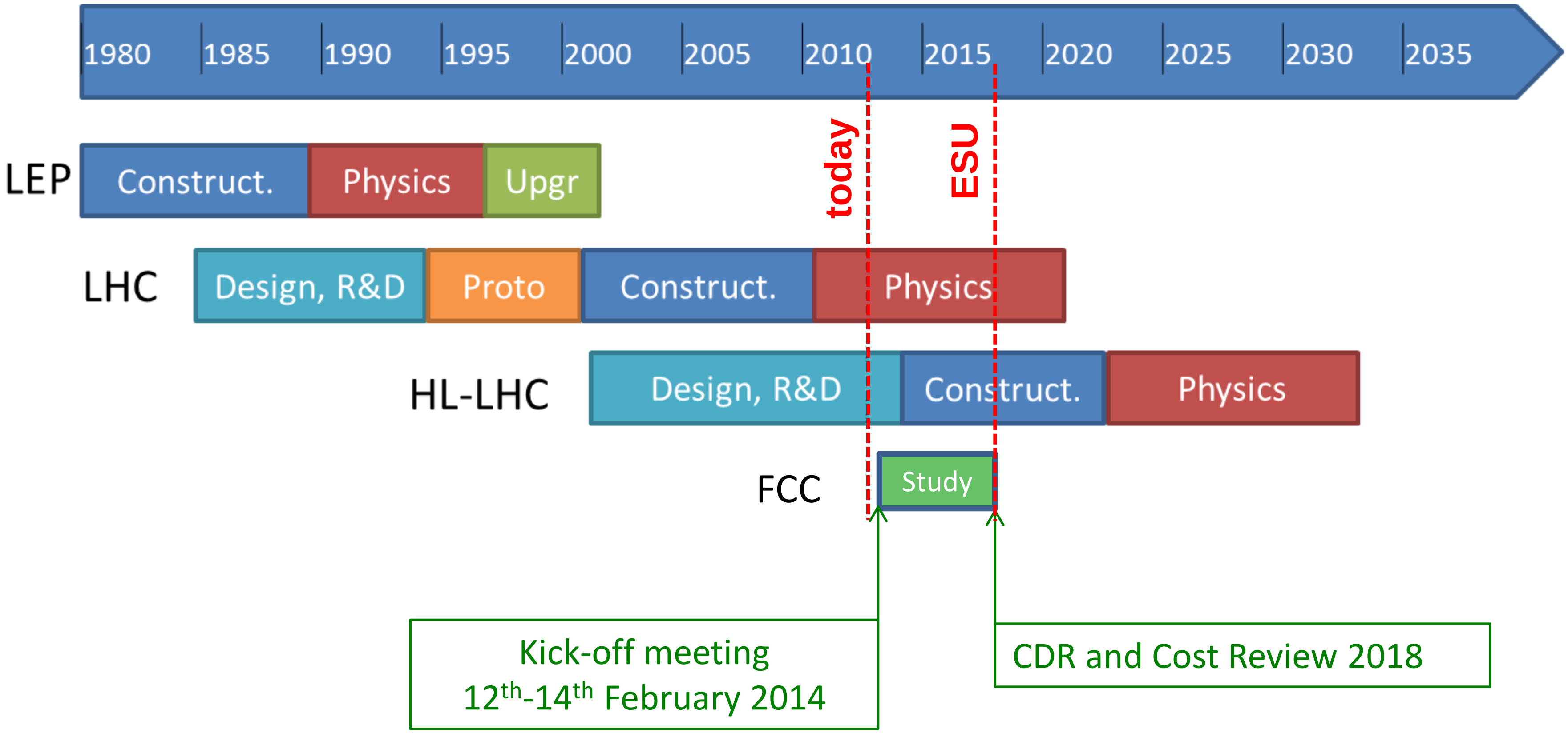
http://indico.cern.ch/e/fcc-kickoff
http://cern.ch/fcc

The Future Circular Colliders (FCC) design study at CERN

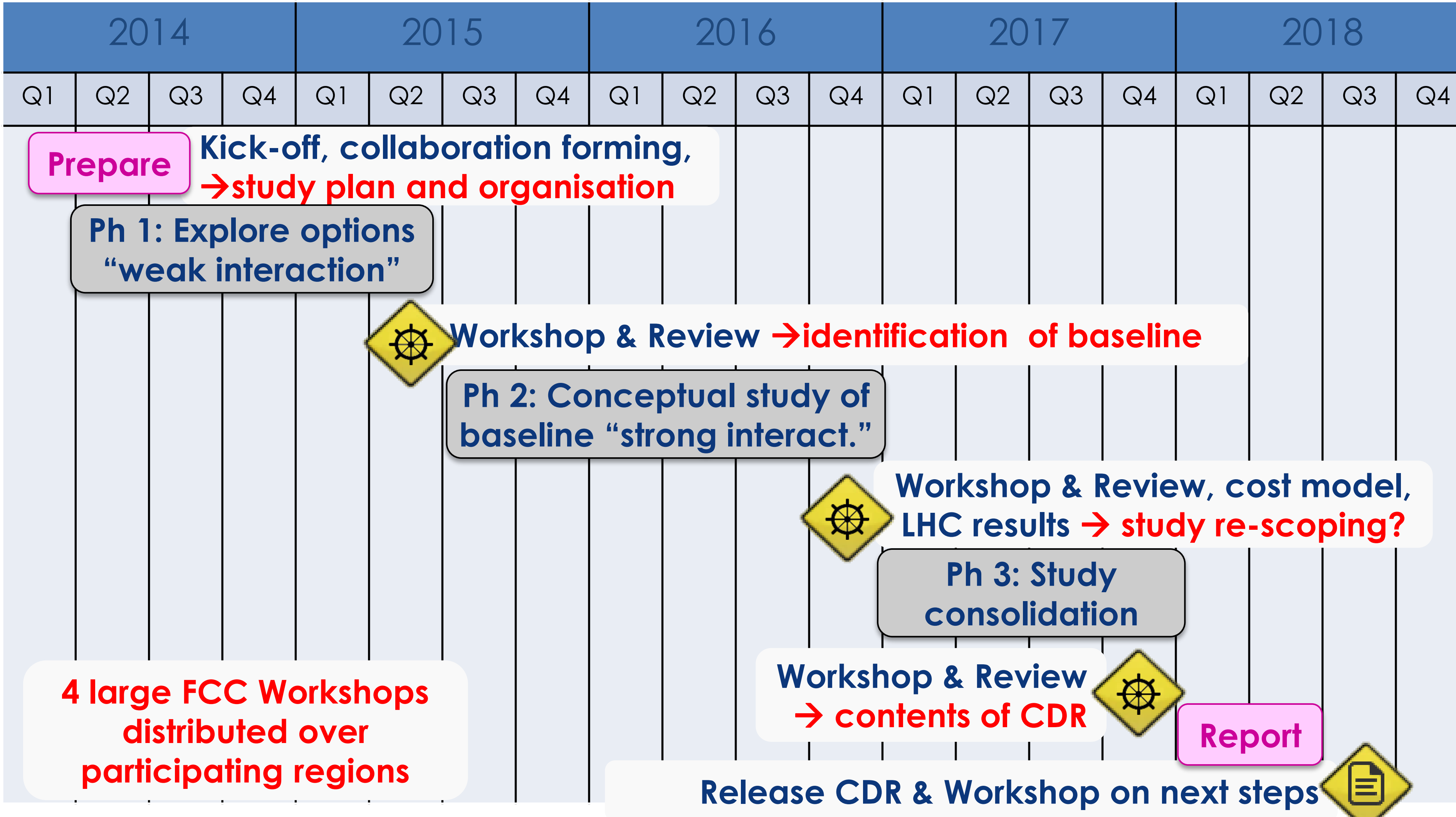
Aiming for CDR and Cost Review for the next ESU (2018)

- **80-100 km tunnel infrastructure in Geneva area**
- **design driven by pp-collider requirements with possibility of e+-e- and p-e**
- **CERN-hosted study performed in international collaboration**

FCC study period in the context of LHC



FCC global design study – detailed time line



→ **presently discussions with potential partners (MoUs)**

→ **first international collaboration board meeting at CERN on 9 & 10 September 2014**

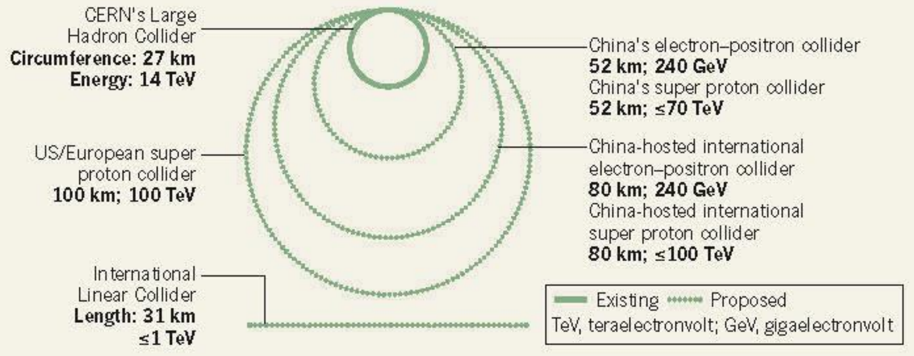
M. Benedikt

CepC/SppC project – latest news in *Nature*

394 | NATURE | VOL 511 | 24 JULY 2014

COLLISION COURSE

Particle physicists around the world are designing colliders that are much larger in size than the Large Hadron Collider at CERN, Europe's particle-physics laboratory.



PARTICLE PHYSICS

China plans super collider

Proposals for two accelerators could see country become collider capital of the world.

BY ELIZABETH GIBNEY

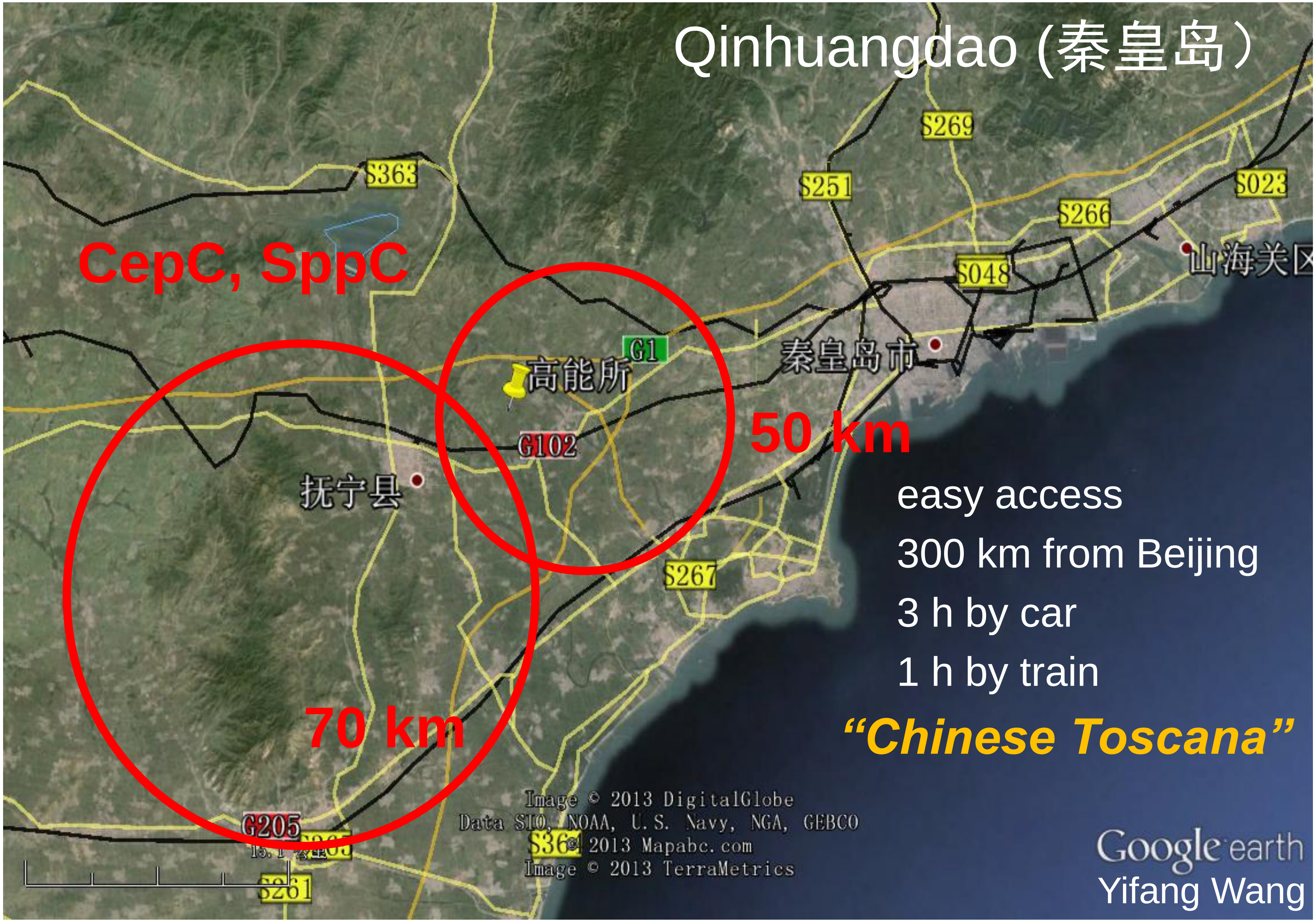
For decades, Europe and the United States have led the way when it comes to high-energy particle colliders. But a proposal by China that is quietly gathering momentum has raised the possibility that the country could soon position itself at the forefront of particle physics.

Scientists at the Institute of High Energy Physics (IHEP) in Beijing, working with international collaborators, are planning to build a 'Higgs factory' by 2028 — a 52-kilometre underground ring that would smash together electrons and positrons. Collisions of these fundamental particles would allow the Higgs China hopes that it would also be a stepping stone to a next-generation collider — a super proton–proton collider — in the same tunnel.

European and US teams have both shown interest in building their own super collider (see *Nature* **503**, 177; 2013), but the huge amount of research needed before such a machine could be built means that the earliest date either can aim for is 2035. China would like to build its electron–positron collider in the meantime, unaided by international funding if needs be, and follow it up as fast as technologically possible with the super proton collider. Because only one super collider is likely to be built, China's momentum puts it firmly in the driving seat.

Electron–positron colliders and hadron colliders such as the LHC complement each other. Hadron colliders are sledgehammers, smashing together protons (a kind of hadron that comprises three fundamental particles called quarks) at high energies to see what emerges. Lower-energy electron–positron machines produce cleaner collisions that are easier to analyse, because they are already smashing together fundamental particles. By examining in detail the interactions of the Higgs boson with other particles, the proposed Chinese collider should, for example, be able to detect whether the Higgs is a simple particle or something more exotic. This would help physicists to work out whether the particle fits with

CepC/SppC study (CAS-IHEP), CepC CDR end of 2014, e^+e^- collisions ~2028; *pp* collisions ~2042



COLLISION COURSE or COLLABOARTION?

Operating and planned Colliders around the world :

- **HL-LHC: CERN's High-Luminosity LHC: 27 km, 14 TeV;**
- **FCC: European (+US?) super proton collider 100 km, 100 TeV; (*Nature 503, 177; 2013*);**
- **FCC: electron-positron collider 100 km, 400-500 GeV on the way;**
- **China's electron–positron collider 52 km, 240 GeV ;**
- **China's super proton collider 52 km, 70 TeV;**
- **Existing Proposed China-hosted international circular electron–positron collider 80 km, 240 - 400 GeV ;**
- **China-hosted international super proton collider 80 km; 100 TeV.**

Machine parameters of the 100-km FCC hadron collider (value for 83-km FCC in brackets).

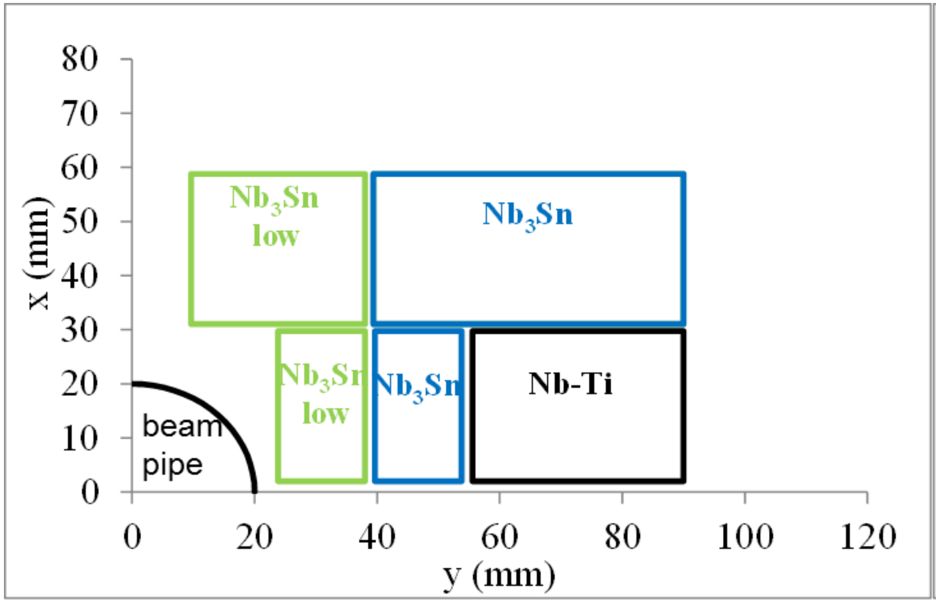
Parameter	LHC	FCC-hadron collider
c.m. Energy [TeV]	14	100
Circumference [km]	26.7	100 (83)
Dipole field [T]	8.33	16 (20)
Number of straight sections	8	12
Sector length [km]	3.3	8.3 (6.9)
Arc length [km]	2.8	7 (5.5)
Number of IPs	4	2 + 2
Peak luminosity [1034 cm-2s-1]	1	5
Beam current [A]	0.584	0.5
RMS bunch length [cm]	7.55	8 (7.55)
Stored beam energy [GJ]	0.392	8.4 (7.0)
SR power per ring [MW]	0.0036	2.4 (2.9)
Arc SR heat load [W/m/aperture]	0.17	28.4 (44.3)
Dipole coil aperture [mm]	56	40
Beam aperture [mm]	~40	26

CRITICAL R&D for 100 TeV pp Collider

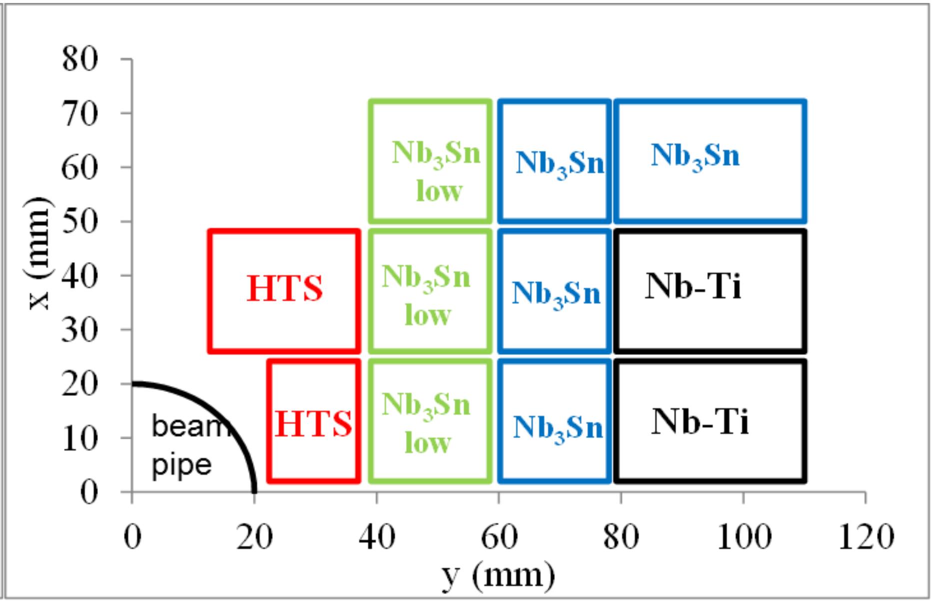
- High-field 16T – 20T superconducting magnets;
- Advanced Cryogenic Engineering in high Synchrotron radiation heat-load environment;
- Long-term stability and integrity of proton beam in vacuum chamber;
- Vacuum integrity of primary beam chamber ;
- Design of beam chamber with RF screens to reduce electromagnetic impedance posed on the path of the beam;
- pp Interaction Region optics with low beta* at 100 TeV ;
- Synchrotron radiation, IR debris and Luminosity control.

cost-optimized high-field dipole magnets

15-16 T: *Nb-Ti & Nb_3Sn*



20 T: *Nb-Ti & Nb_3Sn & HTS*



only a quarter is shown

"hybrid magnets"

example block-coil layout

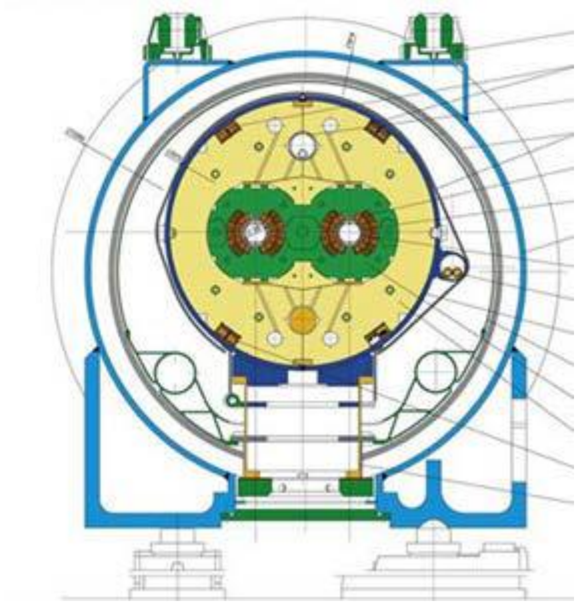
L. Rossi, E. Todesco, P. McIntyre

Physics Procedia (2014): **25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014 :**

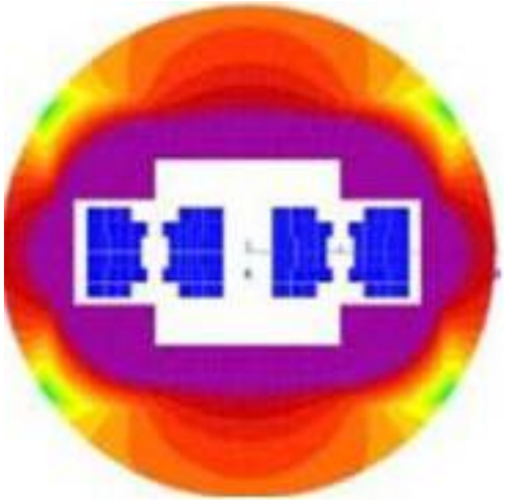
"Beyond the Large Hadron Collider: a first look at cryogenics for CERN future circular colliders",

Philippe Lebrun*, Laurent Tavian, CERN

LHC



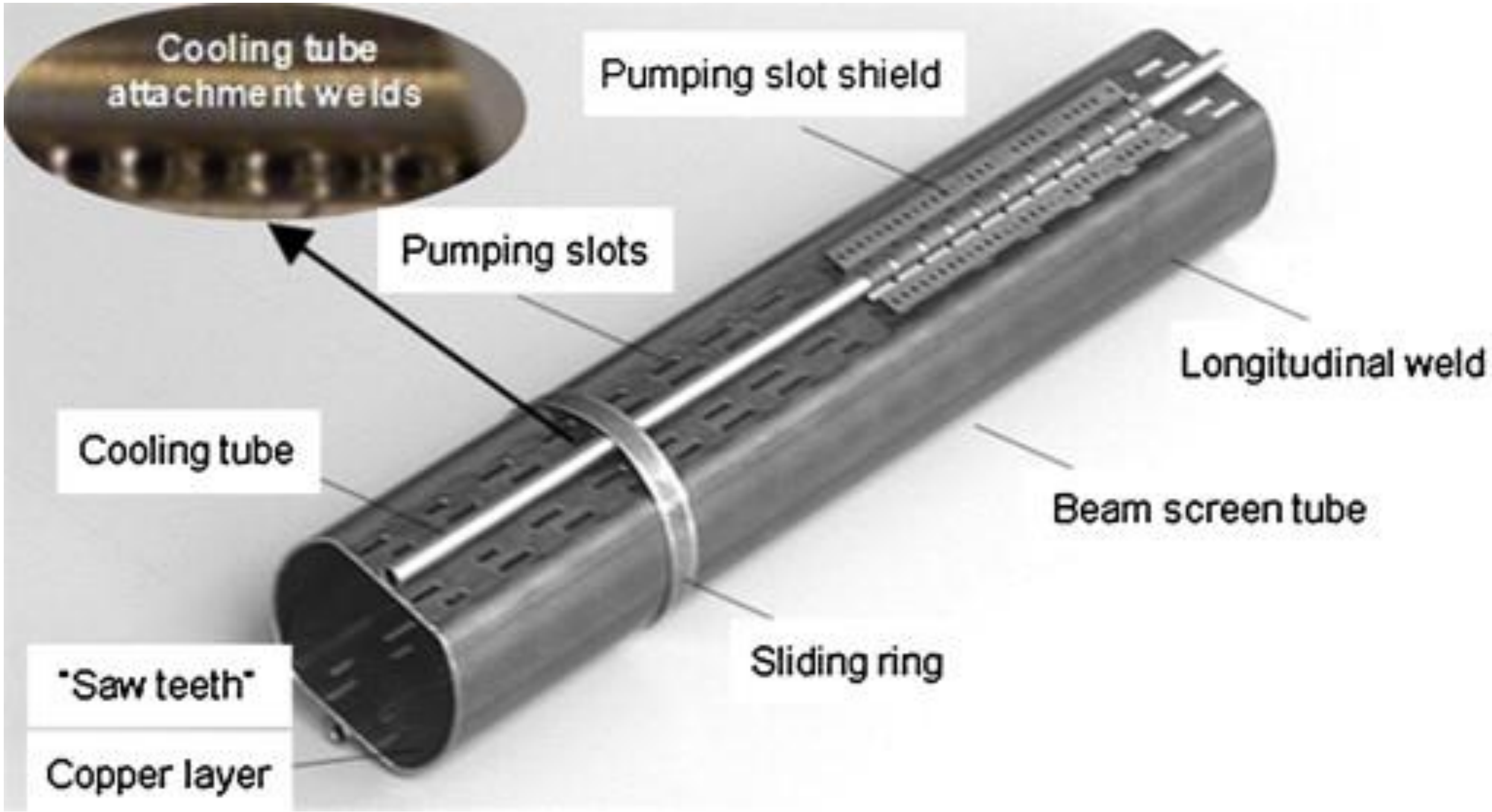
FCC



0.57m 0.78m

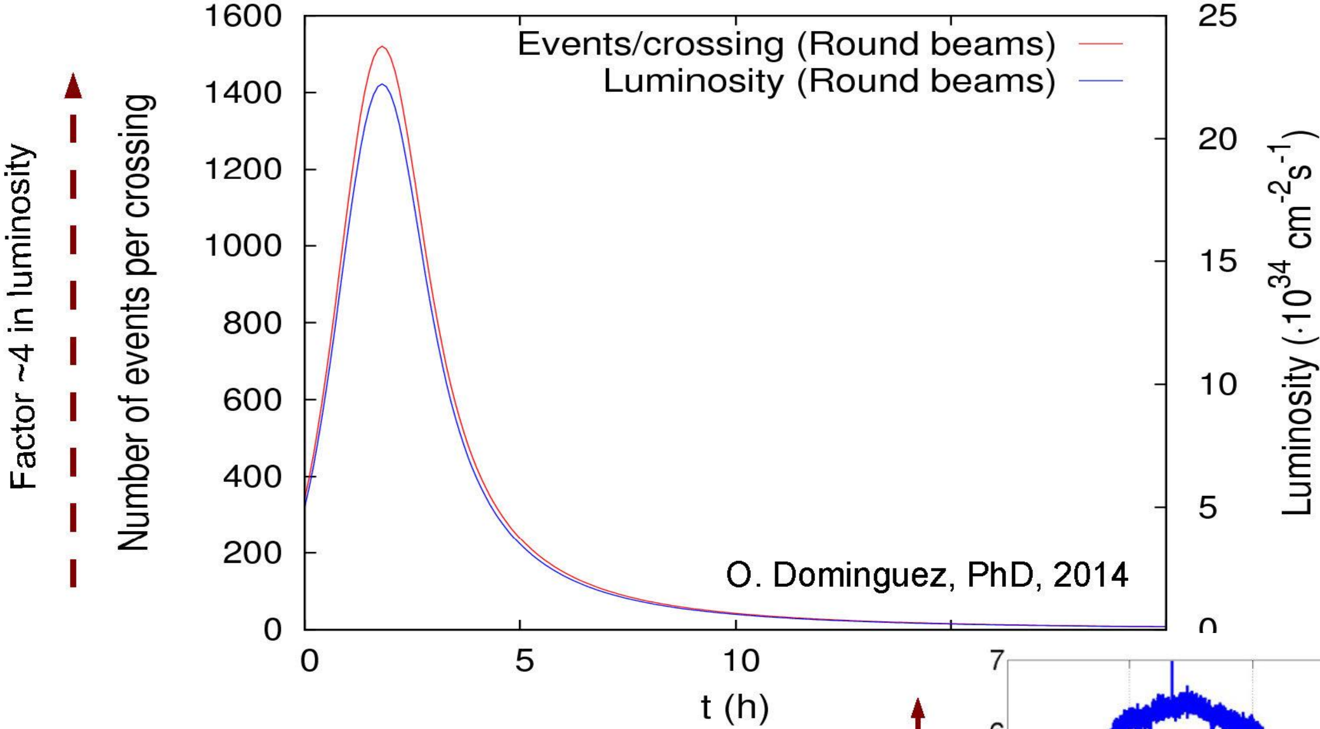
~0.8 m~1.1 m~1.2 m

Vacuum beam pipe for SR and Instability Control



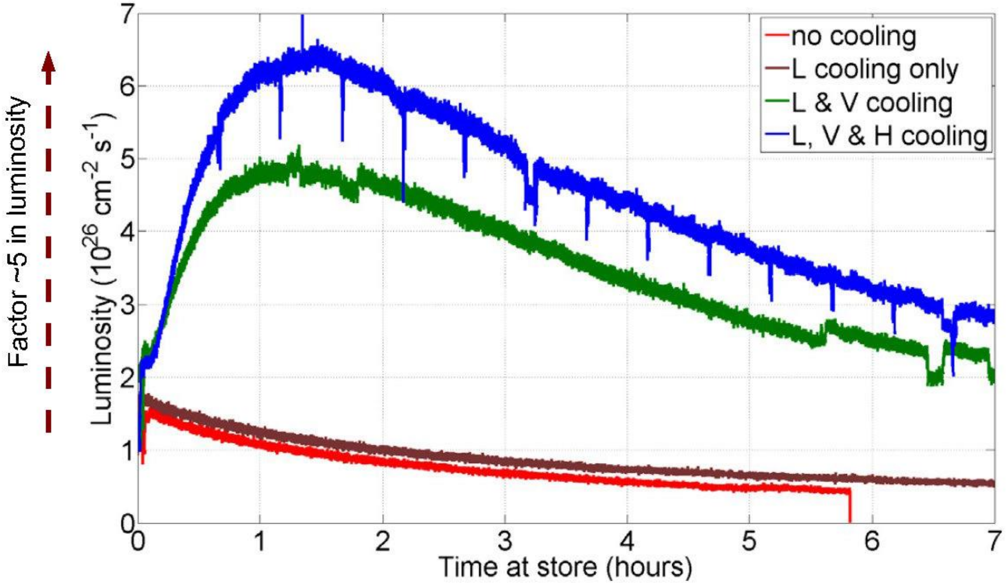
LHC-type beam pipe?

luminosity evolution with syn. rad. damping



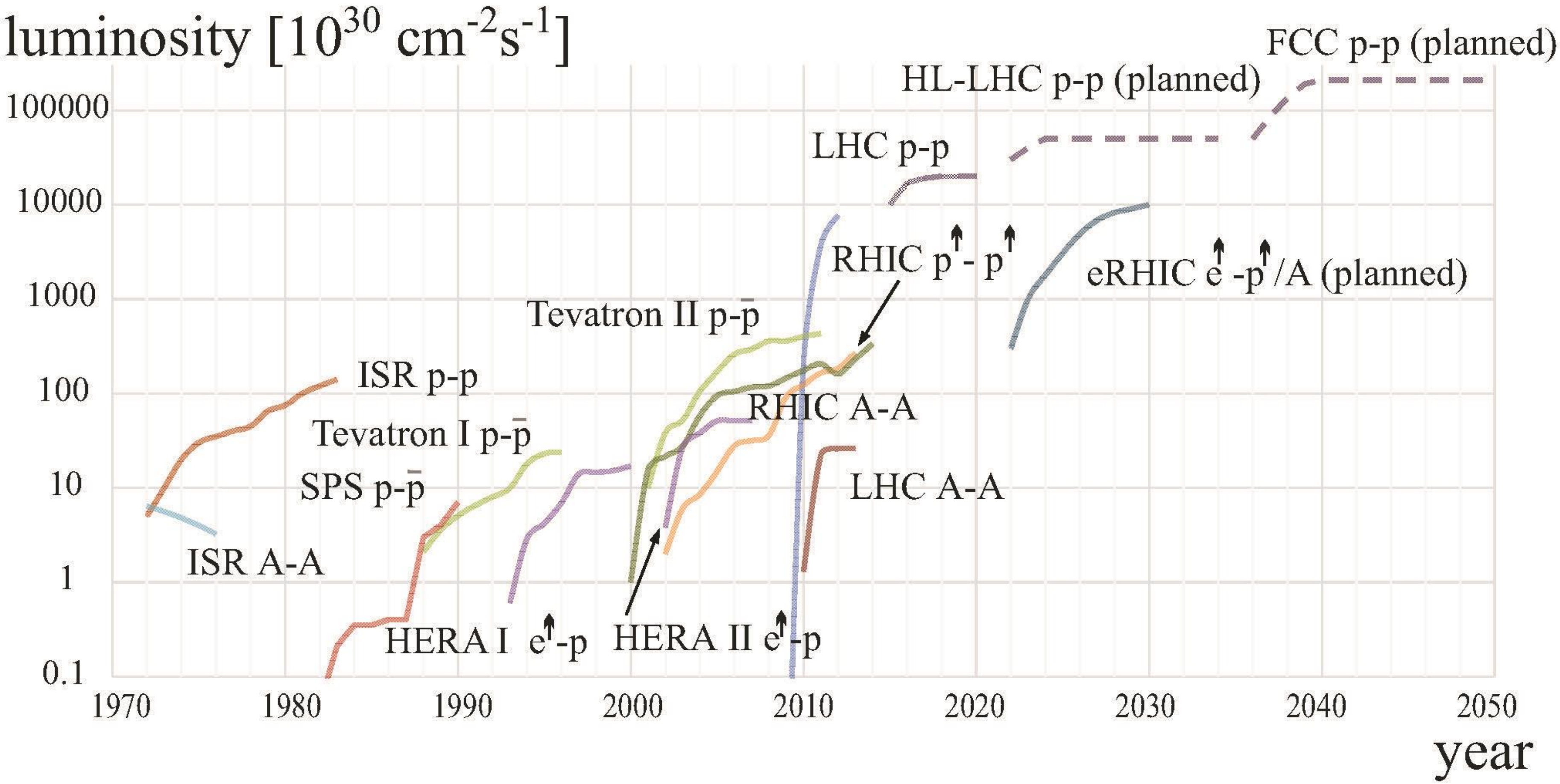
emittance control by noise excitation!?

M. Blaskiewicz et al.



R. Tomas

hadron-collider peak luminosity vs. year



Courtesy W. Fischer

LHC run 1 (2012-13) accumulated more integrated luminosity than all previous hadron colliders together!

A 100 TeV pp Collider will not be cheap!!!

Phenomenological Cost Model: Conventional Technology

$$\text{Cost} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

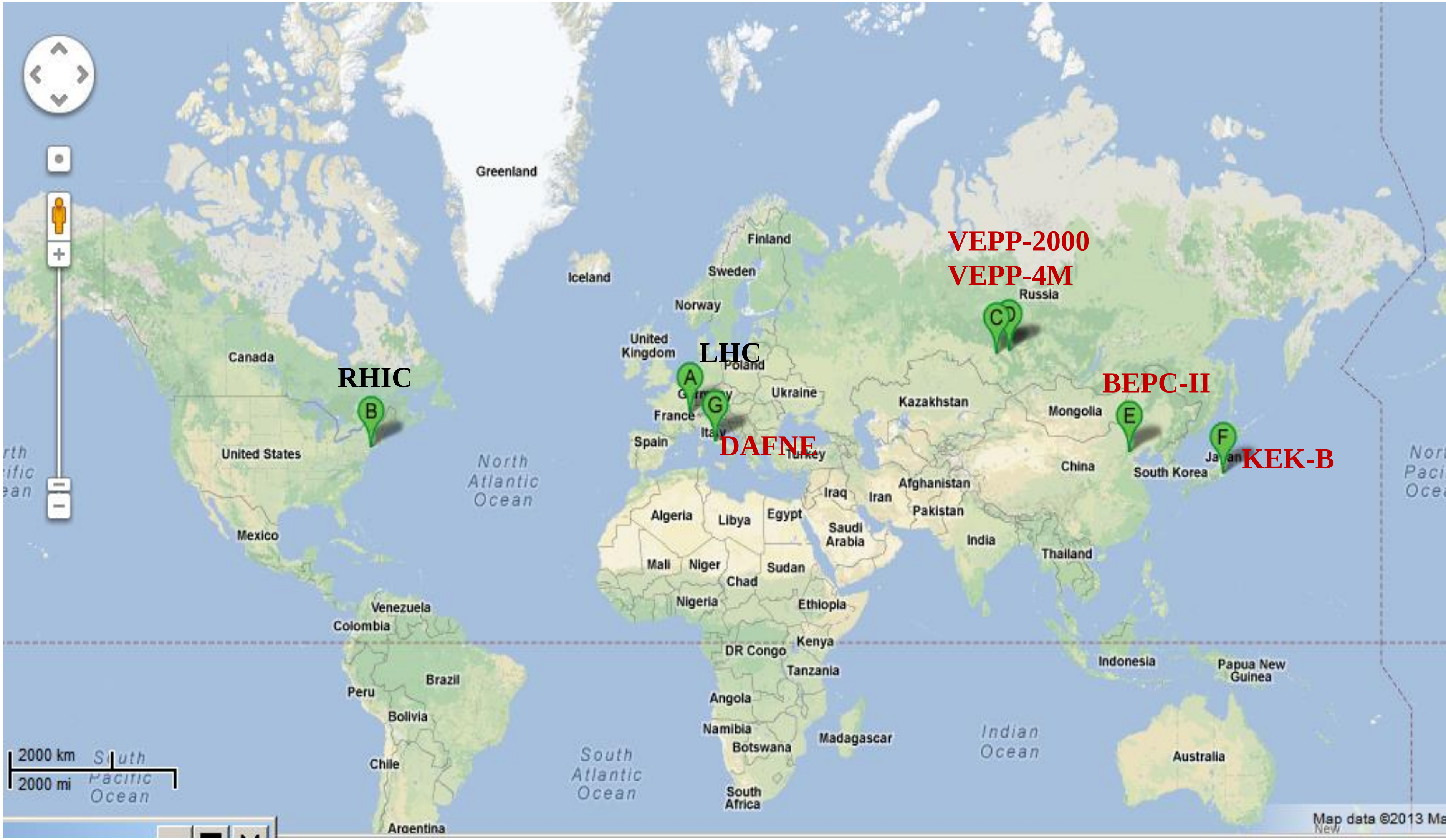
"Total Project Cost " — "Tunnel Length" Civil Construction — "Energy" – Cost of Accelerator Components — "Site Power" Infrastructure

where α,β,γ – technology dependent constants

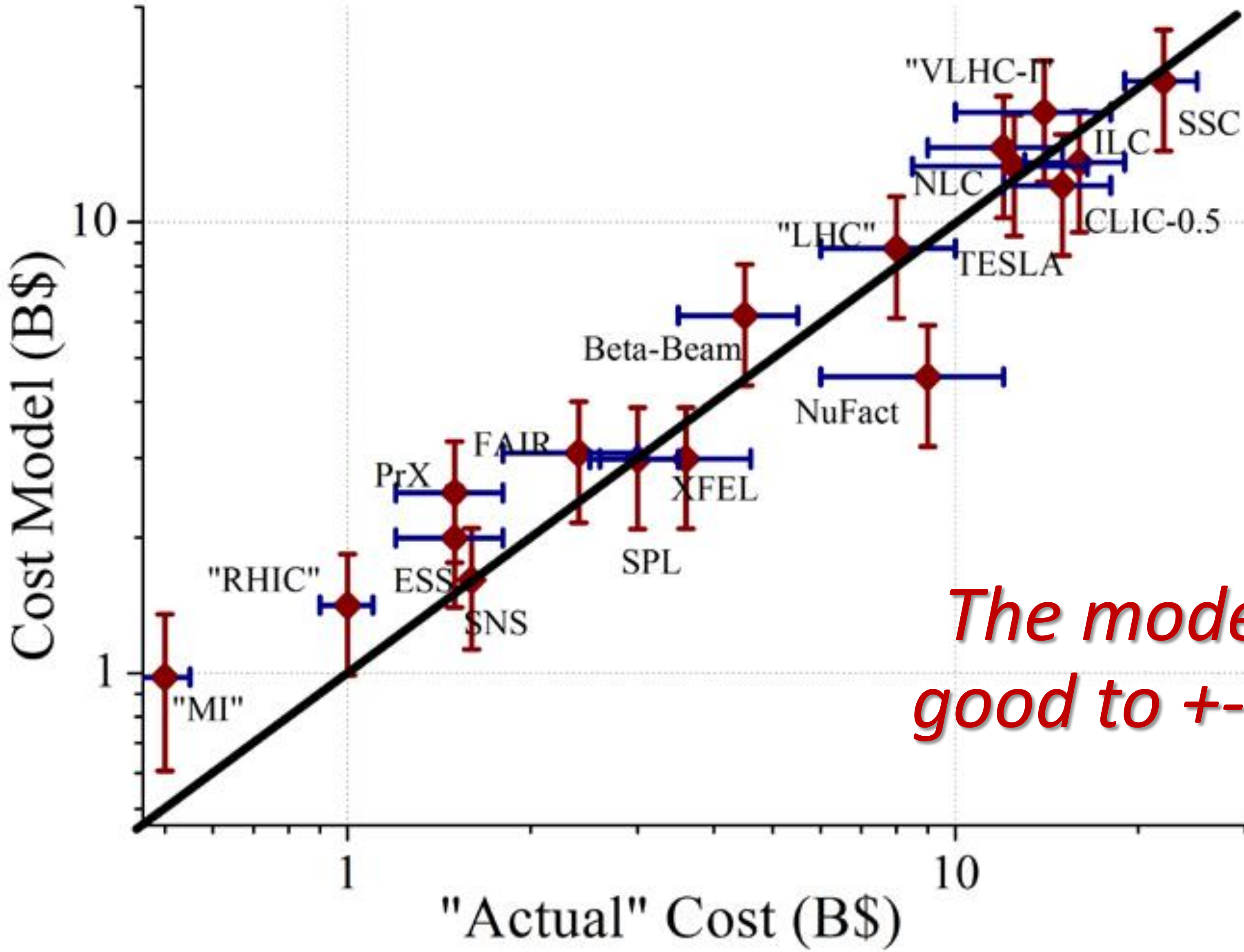
- **α≈ 2B$/sqrt(L/10 km)**
- **β≈ 10B$/sqrt(E/TeV)** for RF
- **β≈ 2B$/sqrt(E/ TeV)** for SC magnets
- **β≈ 1B$ /sqrt(E/TeV)** for NC magnets
- **γ≈ 2B$/sqrt(P/100 MW)**

Courtesy: V. Shiltsev

29 Colliders Built… 7 Work "Now"



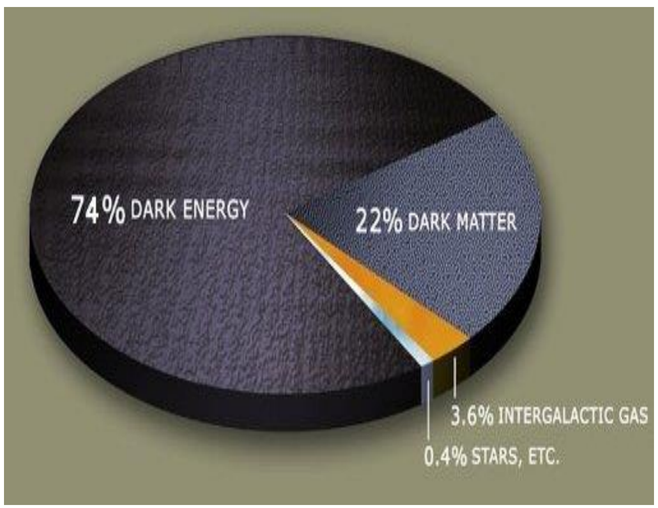
Total Cost vs Model (Log-Log)



The model is good to +-30%

Dark Content of the Vacuum:

"Alternative energy" frontier can be explored in laboratory with relatively small-scale experiments but using collider technologies of ultra-high vacuum, precision radio-frequency cavities, atoms and lasers, etc.

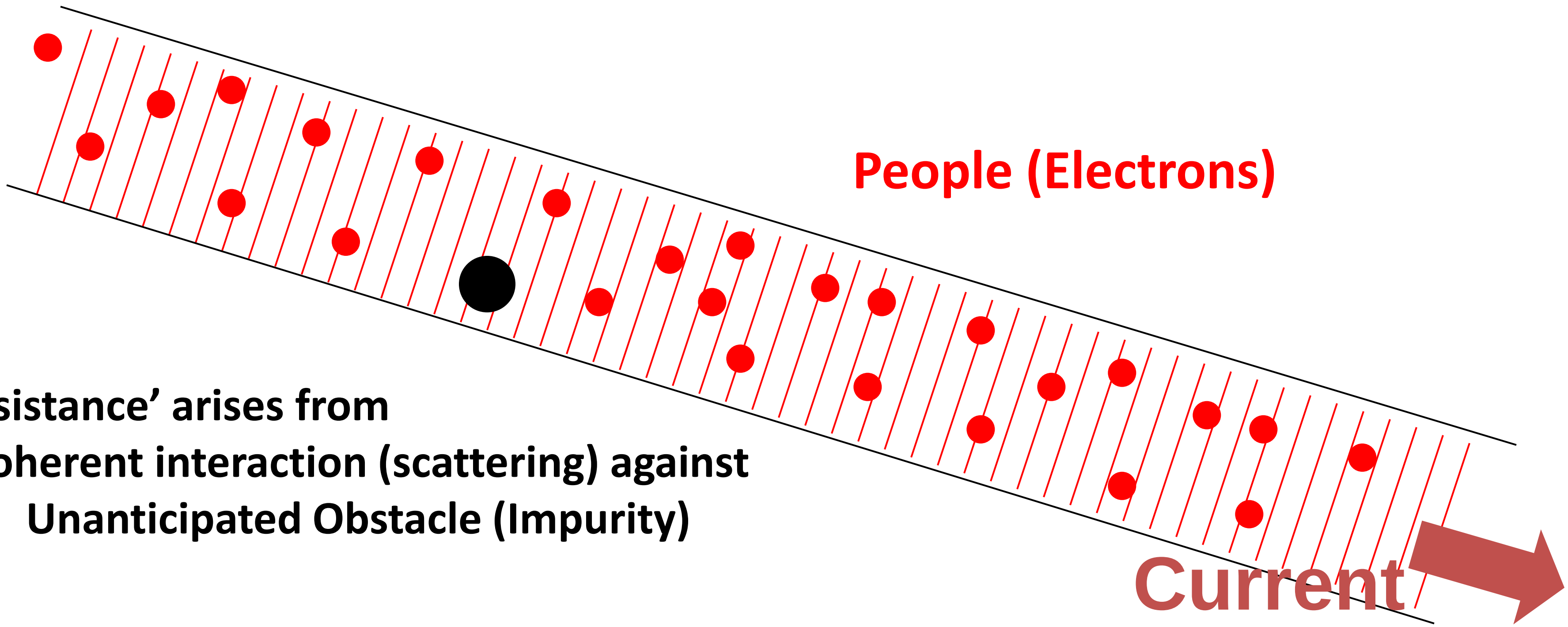


- → ***Cavity electrodynamics of RF cavities coupled via the "dark" sector;***
- → ***"Atom Beam" interferometry of gravitationally falling "ultra-cold" atoms;***
- → ***Muon channeling in crystals;***
- → ***Clever "fixed target" experiments, etc.***

Dark matter-energy density equivalent to an electric field of 12 V/m!

We need a new paradigm of Collaborations analogous to: Superconductivity/Super-fluidity !!

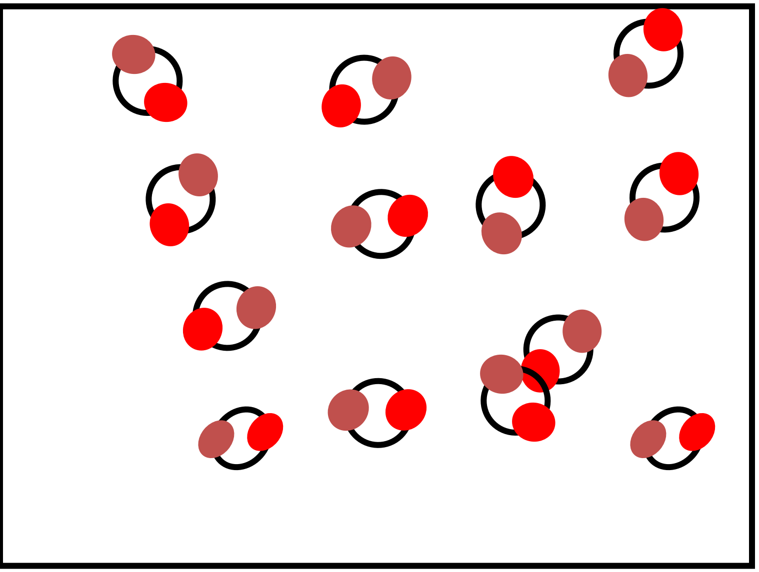
Superconductivity – a quantum effect



'Resistance' arises from
Incoherent interaction (scattering) against
Unanticipated Obstacle (Impurity)

Superconductivity = Super-fluidity of charge
(coherent program) = (smooth collaboration)

Macroscopic collective (quantum) phenomena



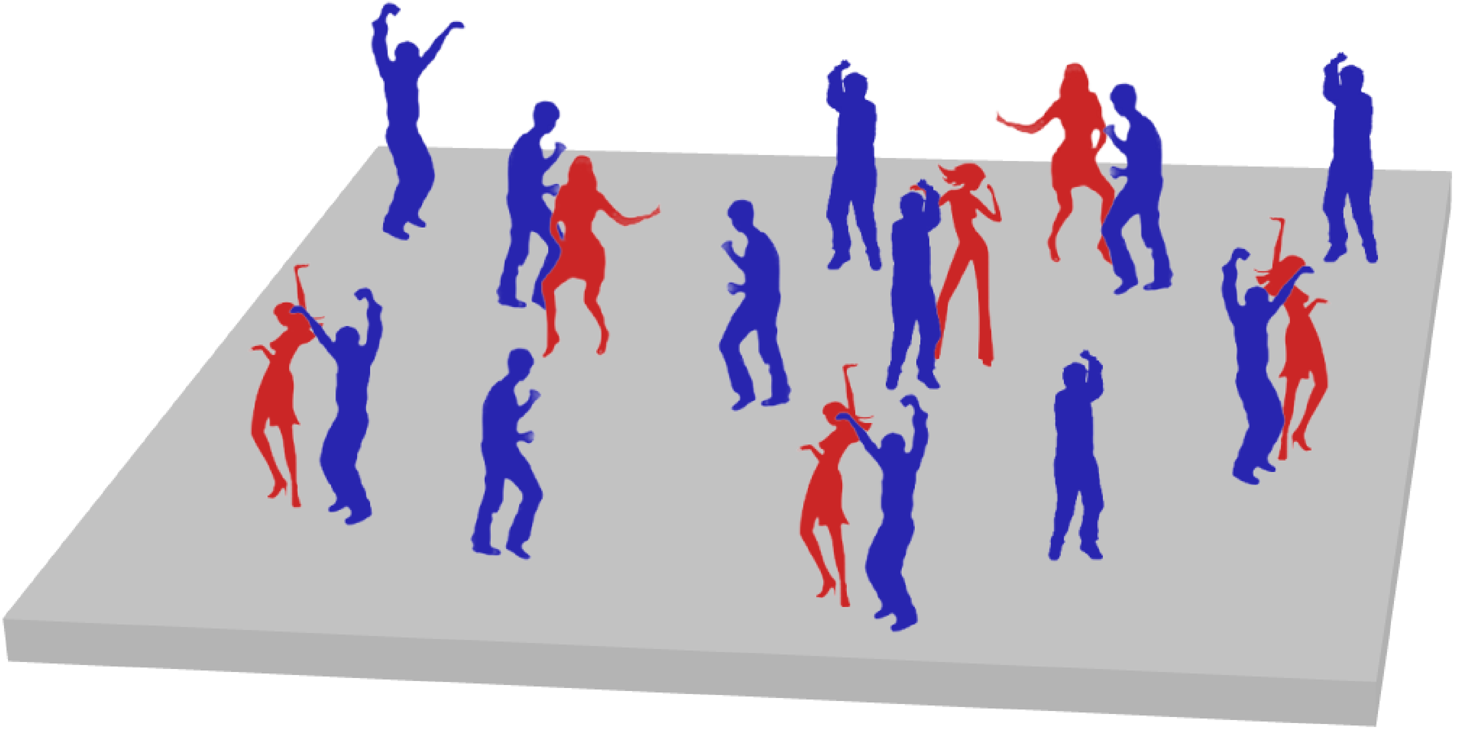
TRADITIONAL CLOSE DANCE

“Atom Pairs” for Superfluidity

“Cooper pairs” for Superconductivity

“Matched Collaborators” in Science

What if more men are on the dance floor ……?



Superfluid and superconducting dance with unequal populations

Does an excess population of men stop the dance?

(quenching of superfluidity or superconductivity)

→ no collaborative research

Do the excess men stay off the dance flooor?

(phase separation below the 'lambda point': 1.9 degree vs. 4 degree K liquid He)

→ Exclusion from Collaboration

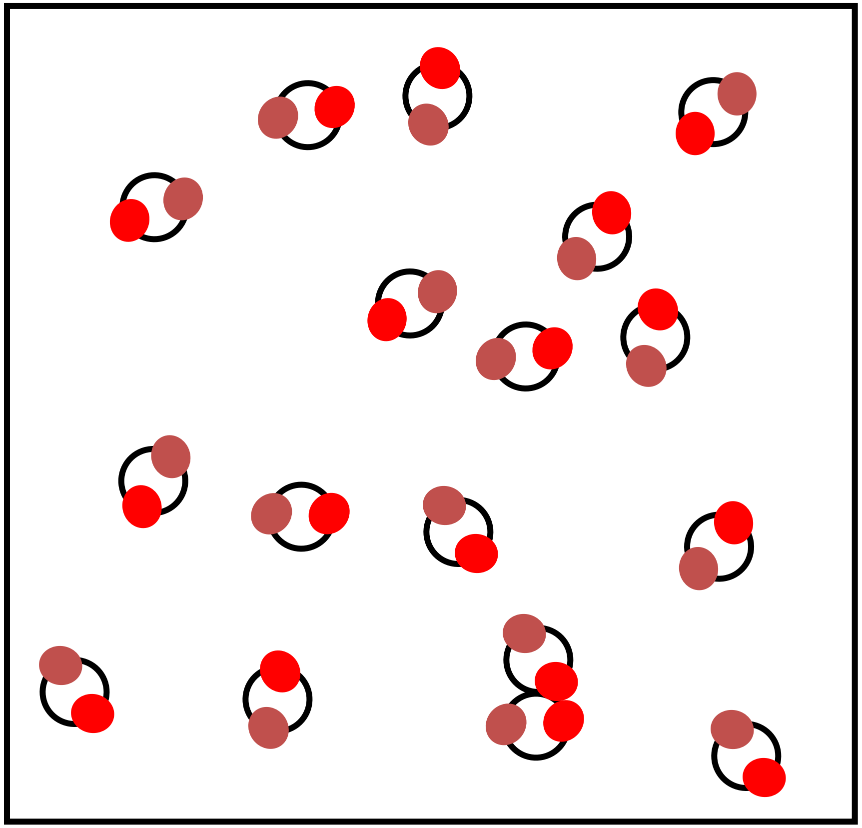
Do the excess men lead to a new dance where the partners are no longer matched but higher order coherence?

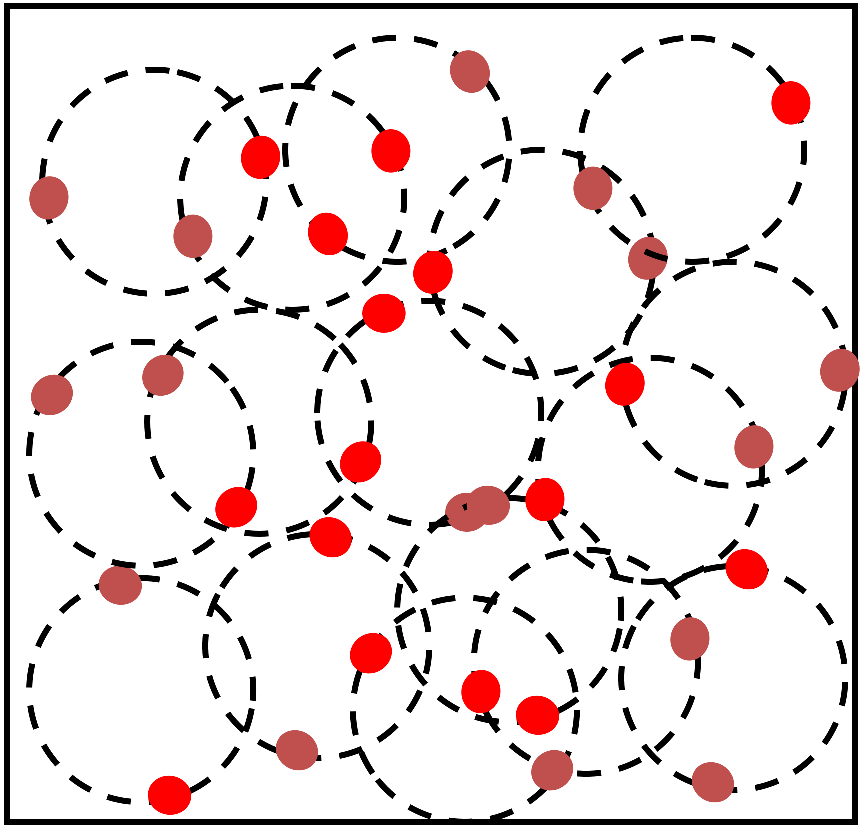
(quark superfluidity or superconductivity, new types of superconductors, FFLO)

→ Higher Order GLOBAL Collaborations of Today

TRADITIONAL CLOSE DANCE
Atom Pairs

MODERN DANCE
Electron pairs





Bose Einstein condensate of molecules

Collaboration within one institution
Or
Similar institutions

BCS Superconductor

Today's GLOBAL COLLABORATION
Diverse Stakeholders

Thank you !!!

US strategy (P5 report)

Particle Physics Projects Prioritisation Panel (P5) ; report released in May 2014; based on the input from particle physics community; covering 10-year roadmap (not directly including FCC); **important message: particle physics is a global effort**, **more than 40 (unranked) recommendations**, e.g.

- total budget increase by 20%-25%
- **continue contribution to LHC and HL-LHC and all activities in LHC experiments**
- **modest and appropriate engagement in ILC accelerator** and detector design, limited to those domains where US expertise exists.
- wish to **host a new world class facility for neutrino physics with the help of the international community**
- **support for accelerator R&D** to strengthen partnerships between facilities, research institutes, universities and industry.
- **participation in global conceptual design studies**
- playing a **leadership role in SC high-field magnet technology**
- Muon Accelerator Program (MAP) should be pursued as integrated part of the GARD program, with **early termination of MICE**
- **recommendations will be taken up by sub-panels** that will relate to the allocation of budgets