Upgrades to the LHC

Six Lessons to consider

HL-LHC: Luminosity Upgrade

LHeC: ep for the LHC

FCC: A Vision of the 100 TeV

Max Klein
University of Liverpool
ATLAS, H1, LHeC,FCC,ECFA

PIZZA Speech to Liverpool Students March 21st , 2017

LHC: 1984-2050
U = 27 km
10k magnets
10k monitors
.5 GJ stored E
Pileup to 300
150 tons of He
2 GPDs …

1. The increase of energy and luminosity often led to discoveries

Substructure discovered at Stanford

Hofstatter et al: 1957: ep →ep E_e=200 MeV beam: proton finite radius of 1fm

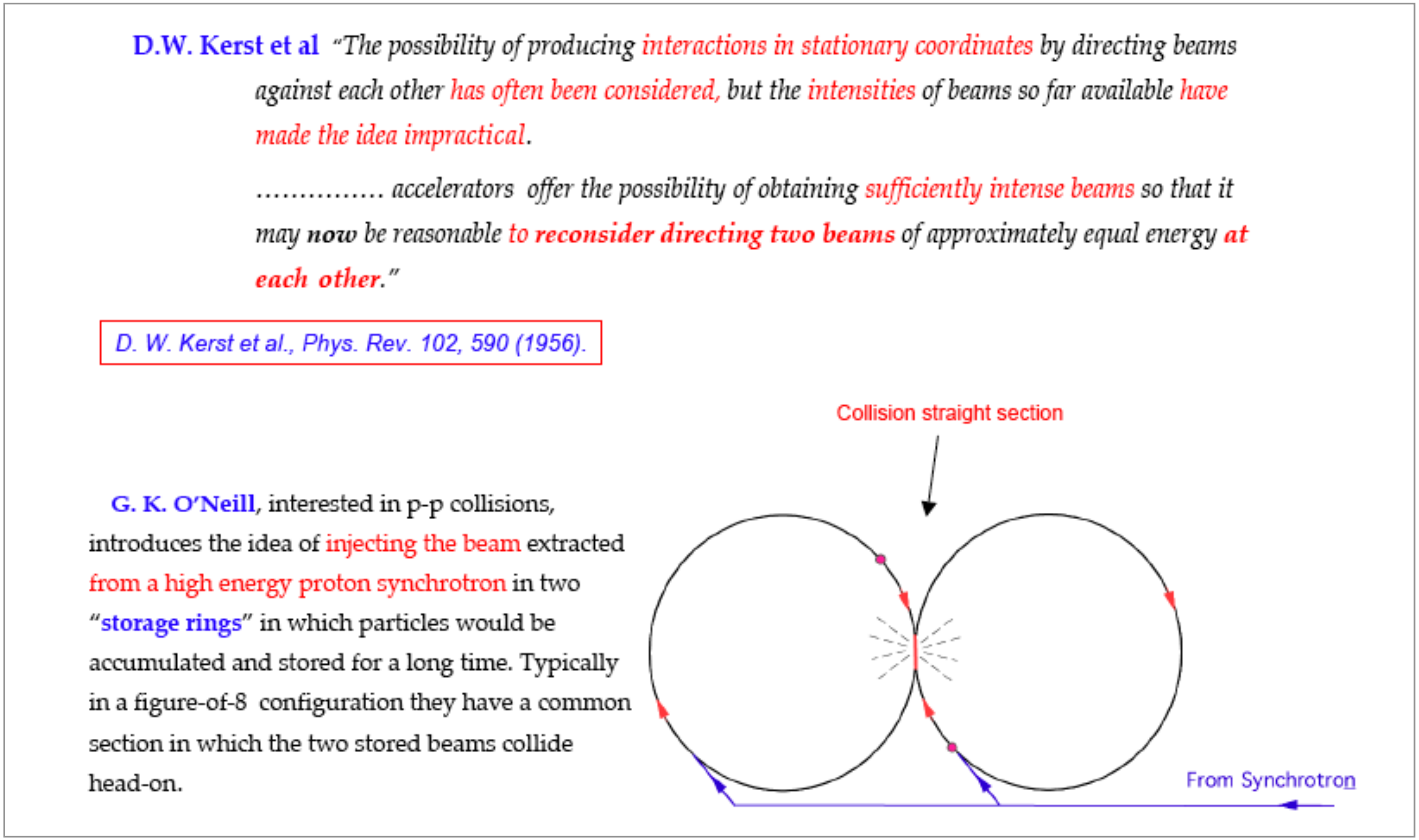
Taylor et al: 1968: ep → eX E_e=1-20 GeV beam (2 mile linac): partons at 0.1fm

W,Z Bosons discovered at CERN

ISR in 1970,
SPS in 1974 Ep=450 GeV (fixed target lh, hh experiments, injector for LHC)
transformed to SppS Collider $L=10^{30-31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ by van der Meer + Rubbia
UA1, UA2: first full acceptance pp detectors to catch W → lnu and MET

Partons came unexpected - despite the Quark Model
W,Z were predicted in $SU_L(2)xU(1)$ electroweak theory

2. Storage rings to conquer high energies



D.W. Kerst et al *"The possibility of producing interactions in stationary coordinates by directing beams against each other has often been considered, but the intensities of beams so far available have made the idea impractical.*

*…………… accelerators offer the possibility of obtaining sufficiently intense beams so that it may **now** be reasonable **to reconsider directing two beams** of approximately equal energy **at each other.**"*

D. W. Kerst et al., Phys. Rev. 102, 590 (1956).

G. K. O'Neill, interested in p-p collisions, introduces the idea of injecting the beam extracted from a high energy proton synchrotron in two "**storage rings**" in which particles would be accumulated and stored for a long time. Typically in a figure-of-8 configuration they have a common section in which the two stored beams collide head-on.

Tazzari, Cern Acc School 2006

fixed target accelerator: $s=2ME$, collider: $s=4E^2$: gain: $2E/M$

First e^+e^- storage ring ADA at Frascati: Bruno Touschek et al.

3. Colliders need time and a community

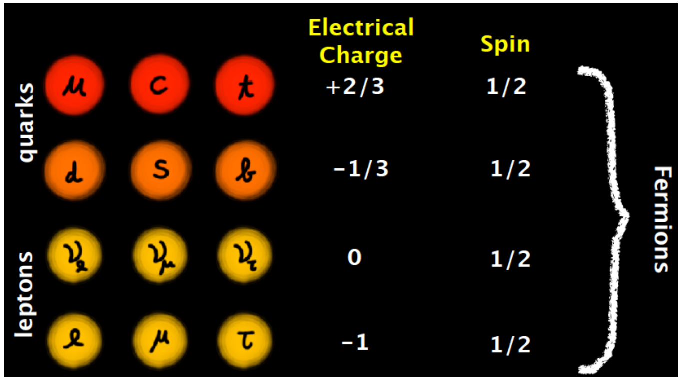
LHC tunnel 2002

10 years from here to the discovery of the Higgs boson …
First large workshop on LHC: Lausanne 1984: LEP first, then LHC, with ep
Letter of Intent of ATLAS is now 25 years old. 10k physicists and engineers are on LHC

4. Decades of establishing the SM are successfully ending

1948 Quantum Electrodynamics QED (Feynman, Schwinger, Tomonaga)

1972 “A Model of Leptons”: S. Weinberg (and independently A. Salam)
$SU_L(2)$ x $U(1)$ - t’Hooft
mixing of neutral gauge fields to obtain photon and Z, angle Θ_W
1973 $SU_c(3)$ Gell Mann et al. QCD - colour + asymptotic freedom



1974 J/Ψ = cc: restored l-q symmetry
4 leptons and 4 quarks

1977 CP violation in 6 quark theory
predict bottom and top
bottom discovered
gauge bosons: photon, Z, W±, and 8 gluons (coloured)

1978 polarised ep→eX :the electron is a r.h. singlet (discovery through precision)
1979 ee → qqg: gluons found in 3-jet events and running of α_s established
1982 W and Z
1995 Top
2012 Higgs

5. Big Questions

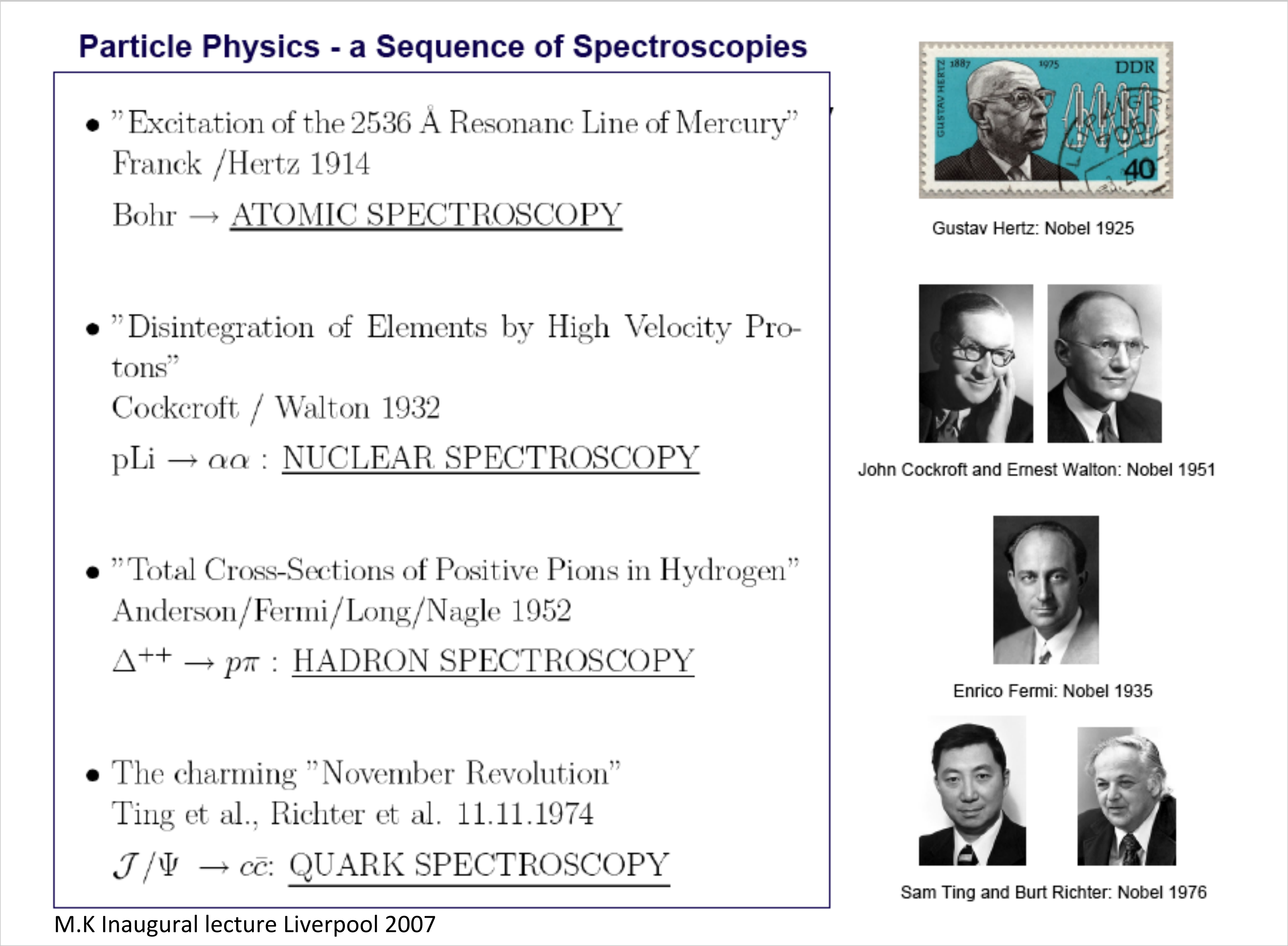
- Do we have too many particles? 12 leptons, 36 quarks, 12 mediators, 1 Higgs = 61
- Is there a further layer of structure (preons?)
- How can we unify the 3 + 1 interactions (SU(5) failed in 1980 but established neutrino physics)
- Why are leptons and quarks different?
- Can one restore the boson-fermion symmetry (SUSY since 1972)
- Why do we have 3 families?
- Neutrino puzzles: Majorana, sterile neutrinos – Oscillations (98), Pontecorvo (57)
- Is the proton stable?
- …
- And: what is “behind” dark matter.. ? Not sure that is a particle physics question?

New: We lost the SM guidance

Reminds on Kelvin, Planck ~1900

Note: 500 ATLAS papers

6. No new spectroscopy appeared – neither 1992 (LEP) nor 2012 (LHC), No SUSY, neither at 100 GeV nor at 1000 GeV → a major surprise



Particle Physics - a Sequence of Spectroscopies

- "Excitation of the 2536 Å Resonanc Line of Mercury"
  Franck /Hertz 1914
  Bohr → ATOMIC SPECTROSCOPY
- "Disintegration of Elements by High Velocity Protons"
  Cockcroft / Walton 1932
  $\mathrm{pLi} \to \alpha\alpha$: NUCLEAR SPECTROSCOPY
- "Total Cross-Sections of Positive Pions in Hydrogen"
  Anderson/Fermi/Long/Nagle 1952
  $\Delta^{++} \to p\pi$: HADRON SPECTROSCOPY
- The charming "November Revolution"
  Ting et al., Richter et al. 11.11.1974
  $\mathcal{J}/\Psi \to c\bar{c}$: QUARK SPECTROSCOPY

Gustav Hertz: Nobel 1925

John Cockroft and Ernest Walton: Nobel 1951

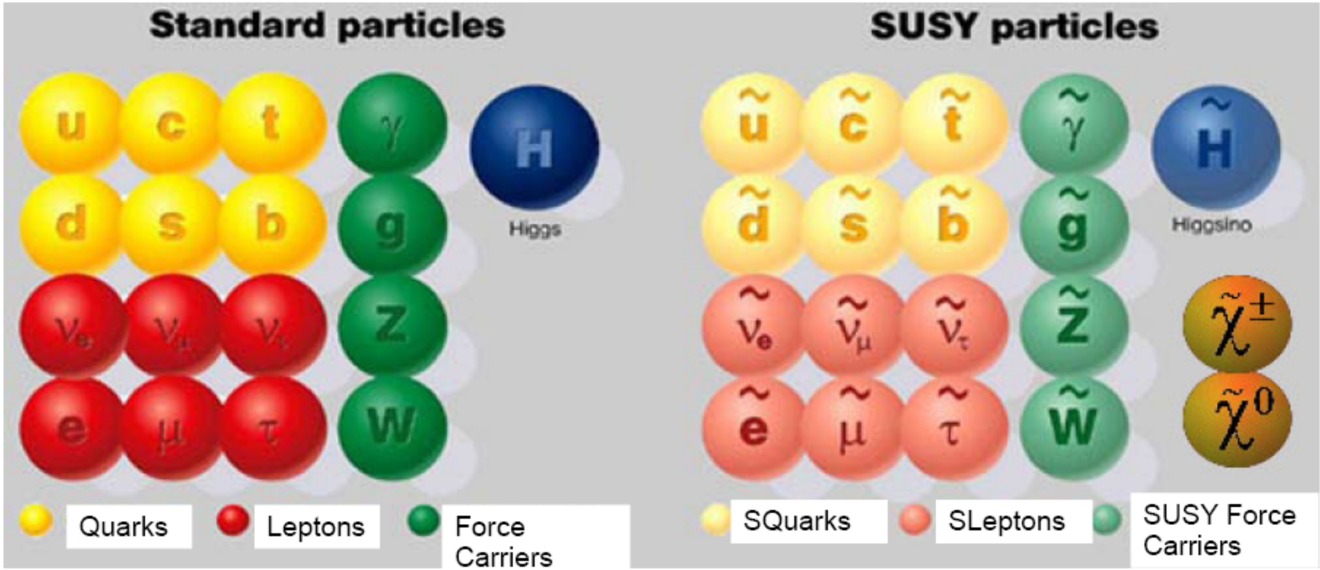
Enrico Fermi: Nobel 1935

Sam Ting and Burt Richter: Nobel 1976

M.K Inaugural lecture Liverpool 2007

A supersymmetric picture of the elementary particle world

J=1/2 J=1 J=0 J=0 J=1/2 J=1/2

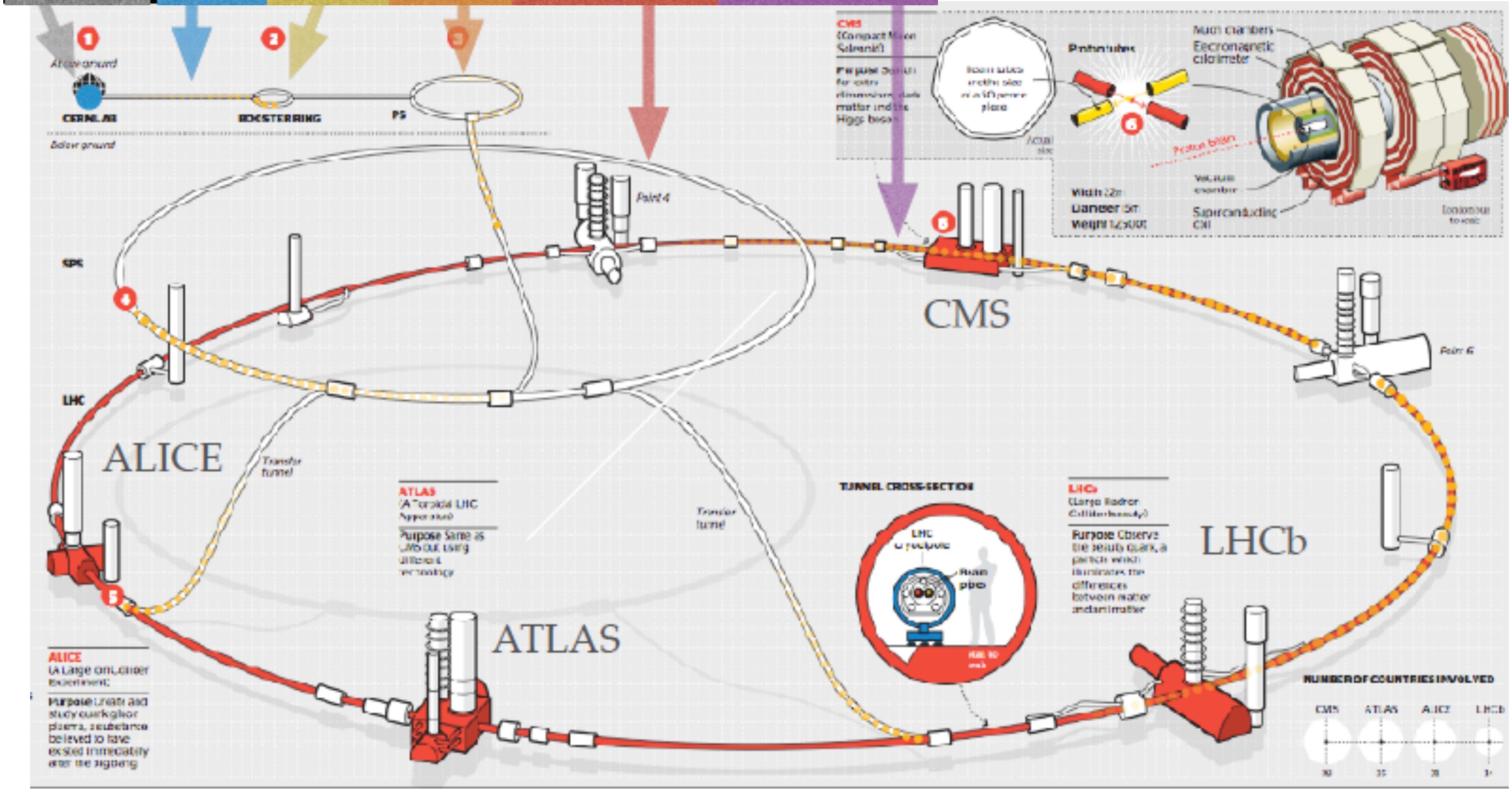


New interactions: e.g. gluino →anti-quark+squark→quark+photino, or W→selectron+sneutrino, or stop → top and lightest susy particle (LSP) etc.

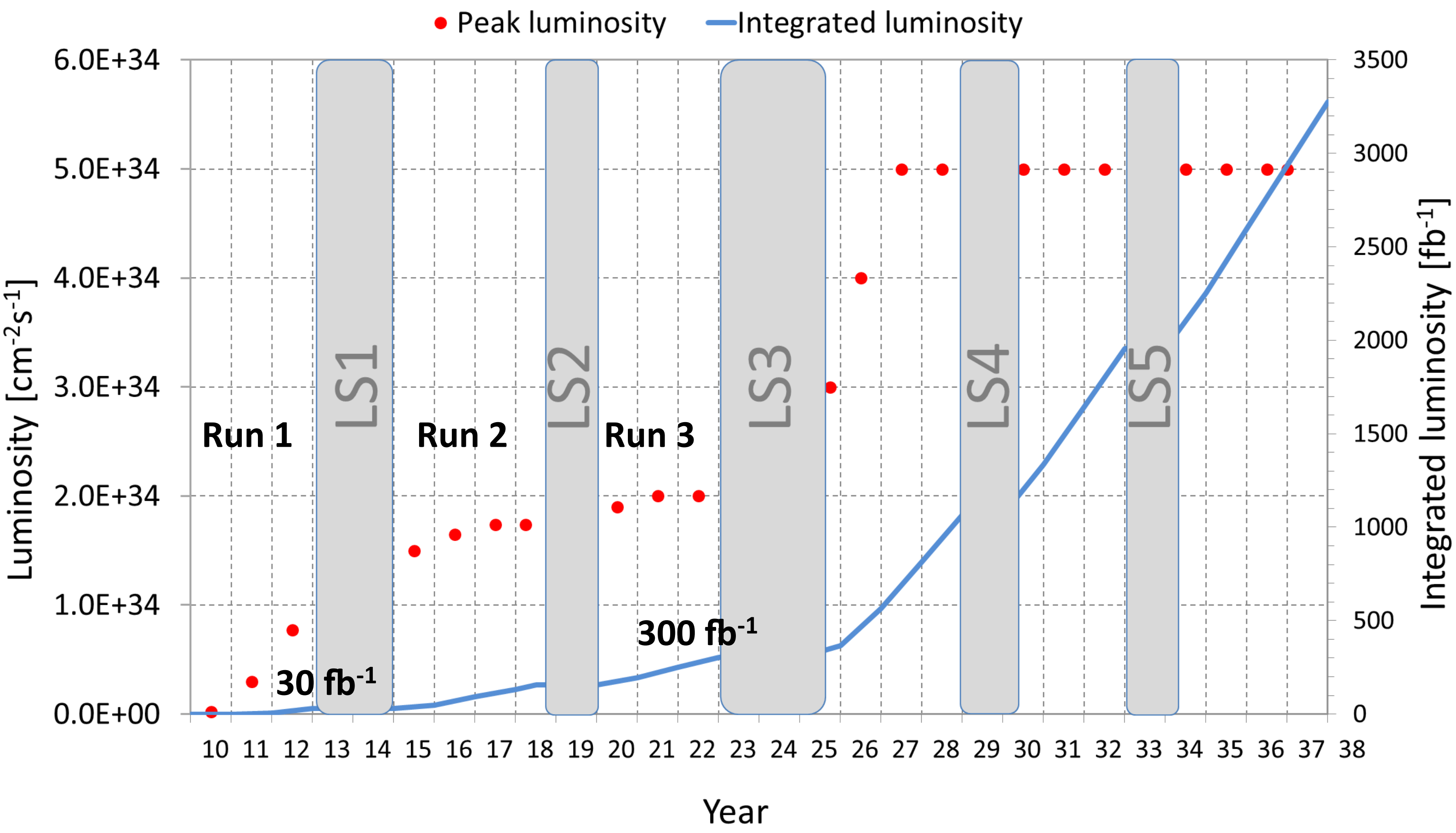
SuperGravity (SUGRA): Goldstino → Gravitino (J=3/2) partner of the Graviton (J=2)
[Gravitino mass plays role of η in SU(2)xU(1) – superHiggs mechanism]

The Large Hadron Collider

hydrogen bottle	LINAC	Booster	PS	SPS	LHC
	0.31c	0.916c	0.9993c	0.999998c	0.999999991c
	50 MeV	1.4 GeV	25 GeV	450 GeV	7 TeV

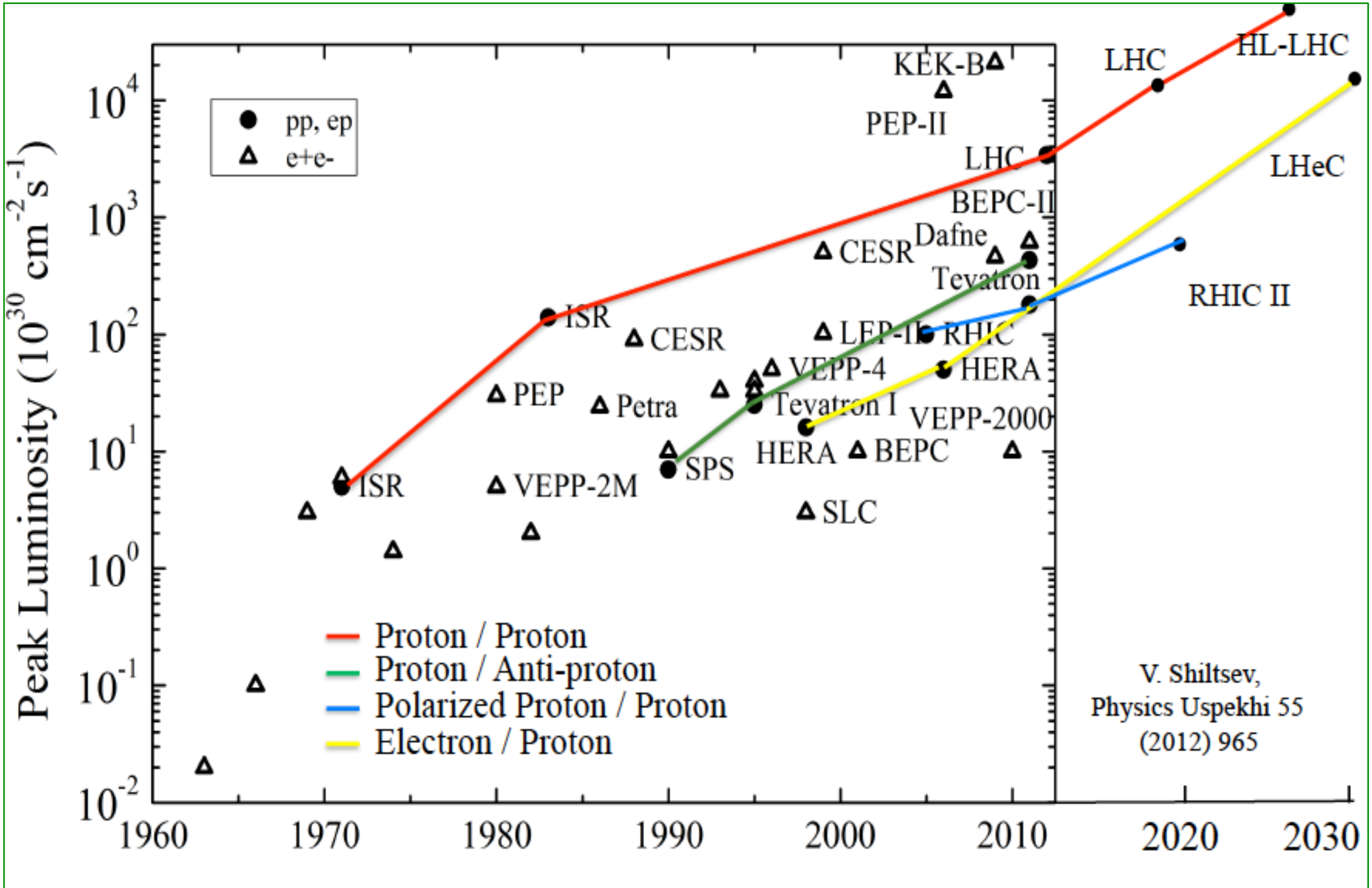


Long Term Planning of the LHC Operation



F. Bordry at the FCC Workshop at Washington DC **March 2015**

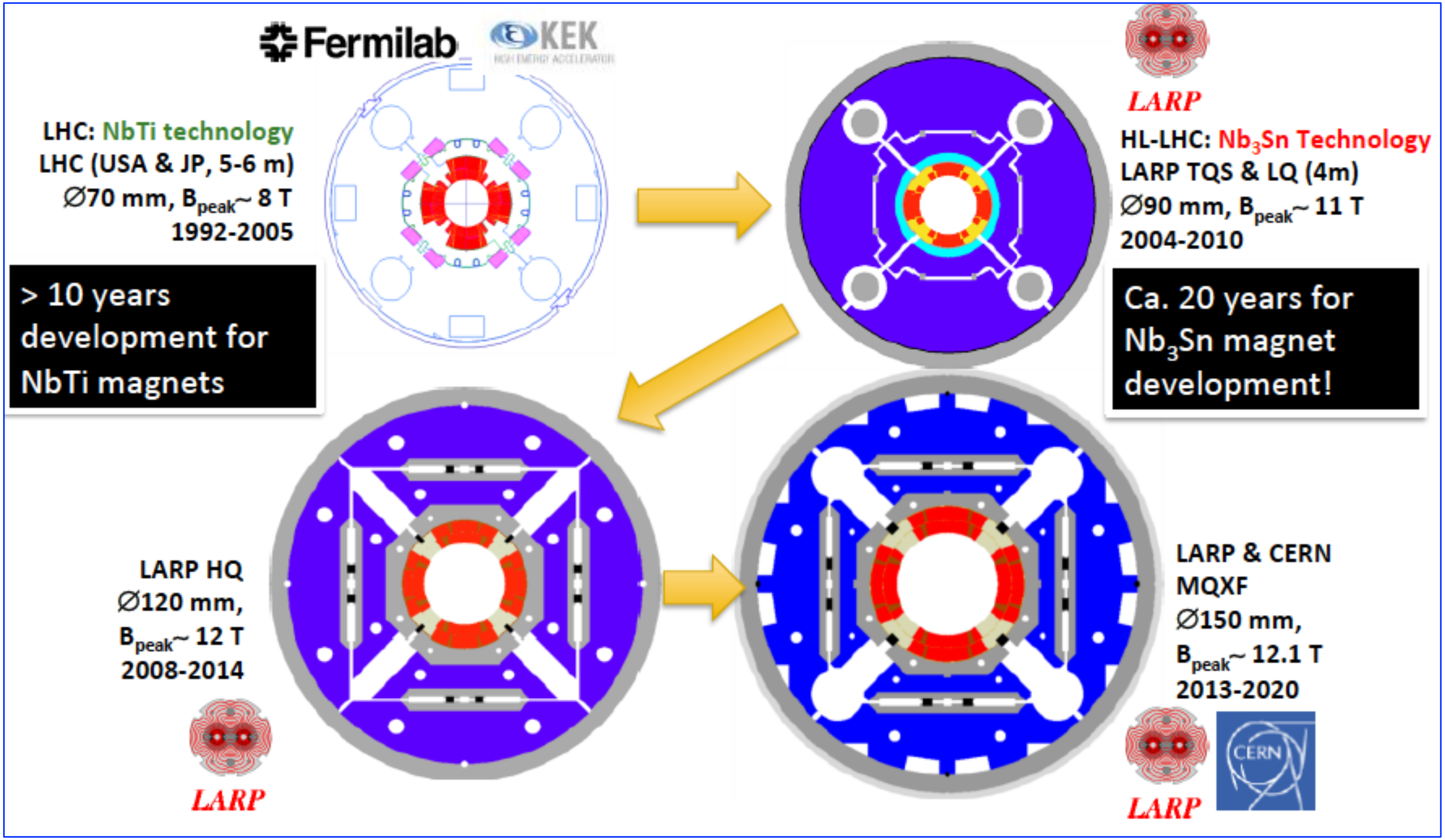
Collider Luminosities vs Year



V. Shiltsev,
Physics Uspekhi 55
(2012) 965

HL LHC – Replacement of Inner Quadrupoles

Inner triplet quadrupoles receive 25MGy of radiation from 300fb^{-1} of pp at the LHC → Larger aperture, larger field to ensure high luminosity performance: 1-2 decades of design



LHC: NbTi technology
LHC (USA & JP, 5-6 m)
Ø70 mm, B_{peak}~ 8 T
1992-2005

> 10 years development for NbTi magnets

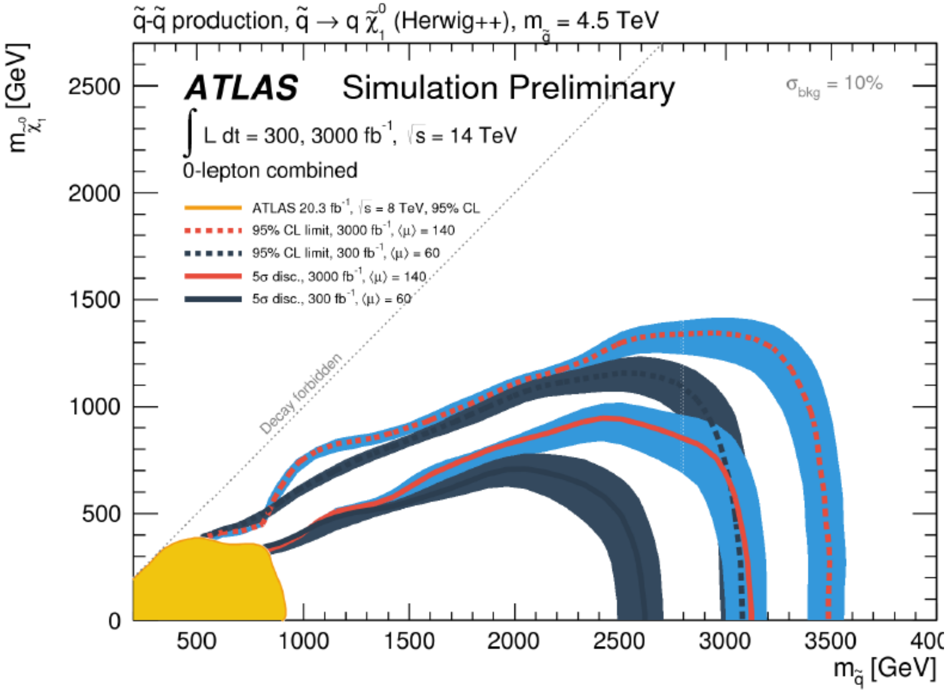
HL-LHC: Nb$_3$Sn Technology
LARP TQS & LQ (4m)
Ø90 mm, B_{peak}~ 11 T
2004-2010

Ca. 20 years for Nb$_3$Sn magnet development!

LARP HQ
Ø120 mm,
B_{peak}~ 12 T
2008-2014

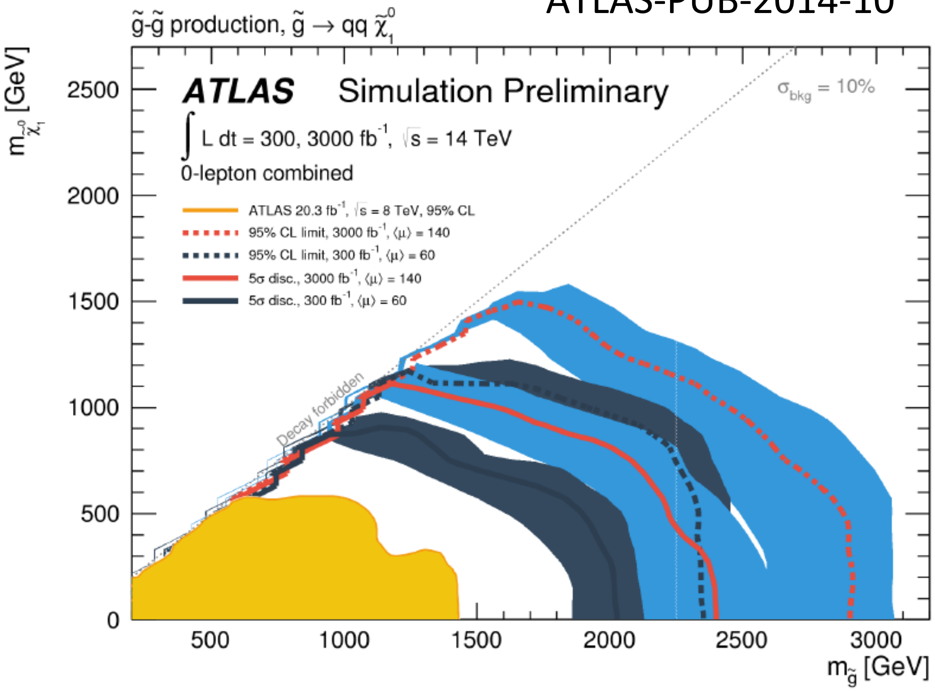
LARP & CERN
MQXF
Ø150 mm,
B_{peak}~ 12.1 T
2013-2020

Luminosity Upgrade – SUSY?



5σ up to ~2.5TeV gluinos

@ HL-LHC



ATLAS-PUB-2014-10

5σ up to ~3TeV squarks

5σ up to ~1.2 TeV stops

5σ up to ~1.3 TeV sbottoms

@ HL-LHC

Replacement of the ATLAS Inner Tracker “ITK”

Biggest part of ATLAS detector upgrade, O(100)MSF, Installation 2024

Coverage up to η=4.0

Pixel system

- 5 layer barrel
- 68 ring end-cap

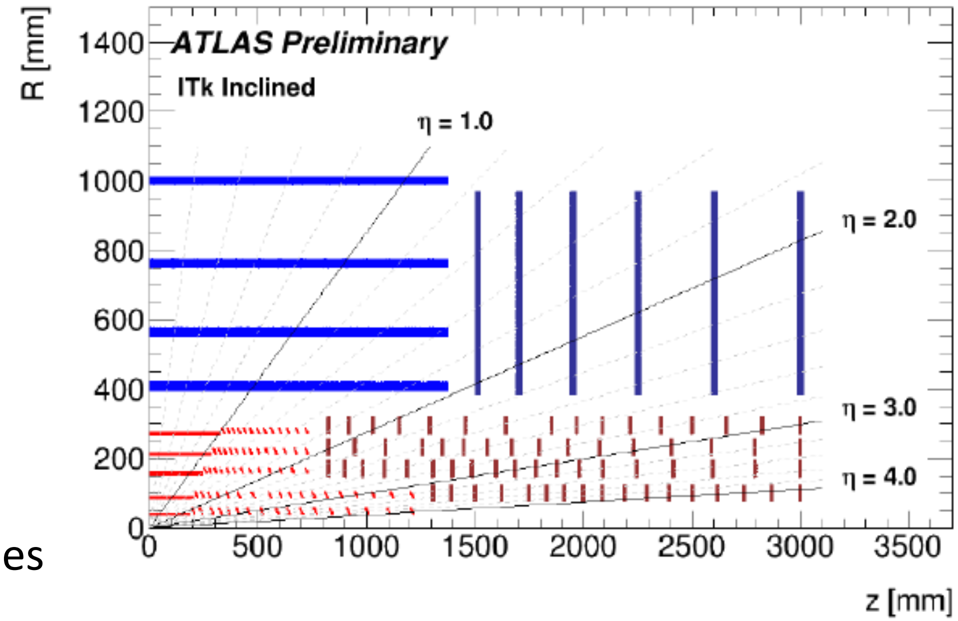
Strip system

- 4 layer barrel
- 6 disk end-cap

UK deliverables:

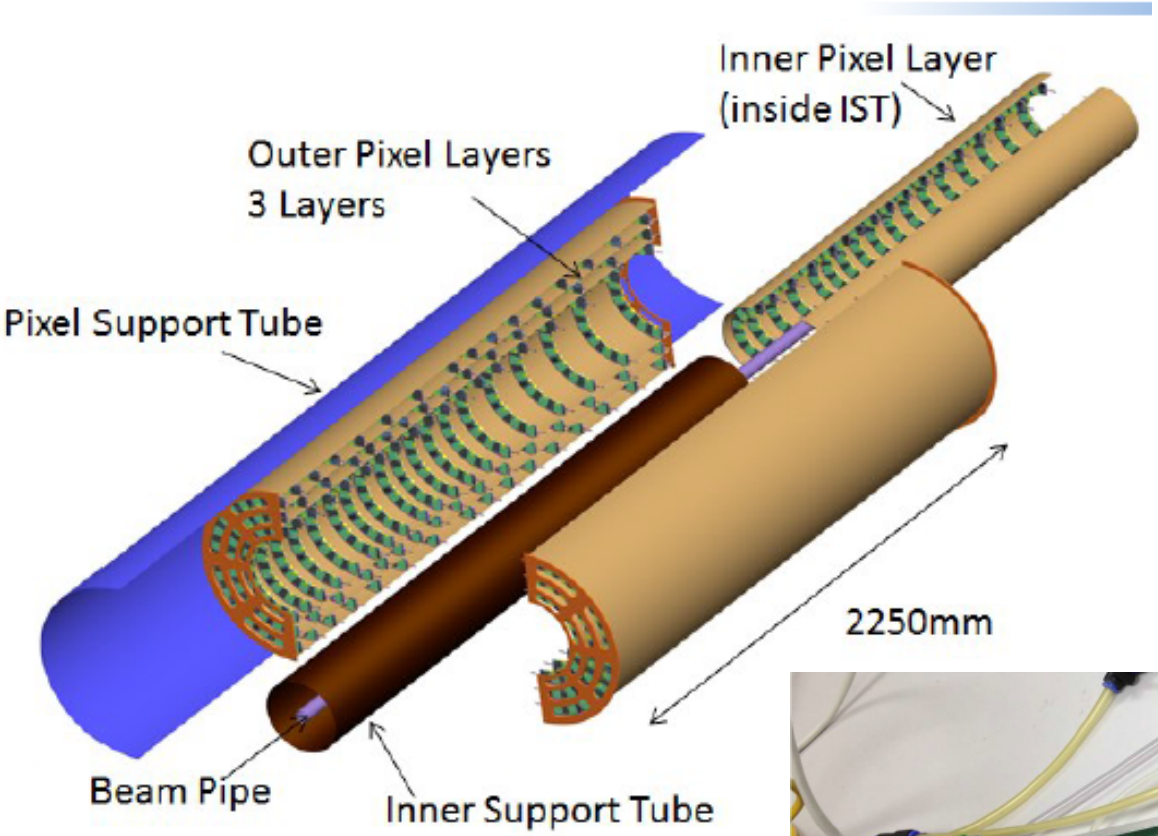
- Pixel endcap 2412 modules
- ½ strip barrel

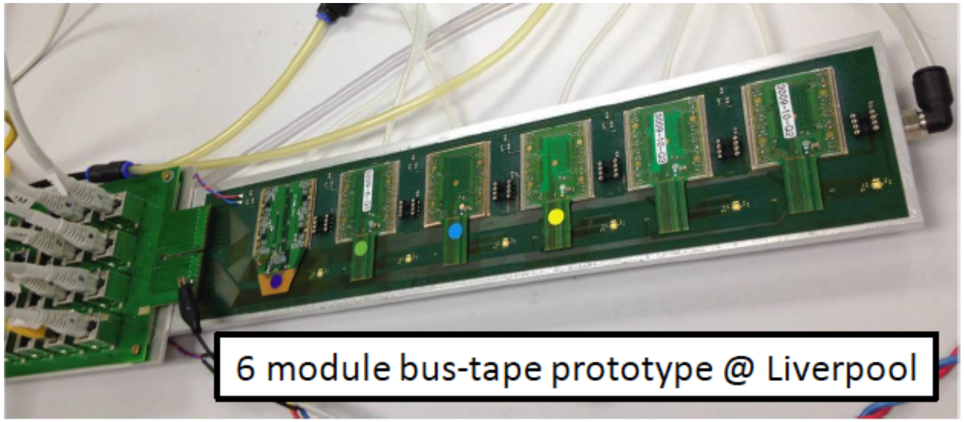
NB. exact layout still under discussion – see Helen’s slides



Major Role: Assembly of the pixel endcap at Liverpool, ground floor

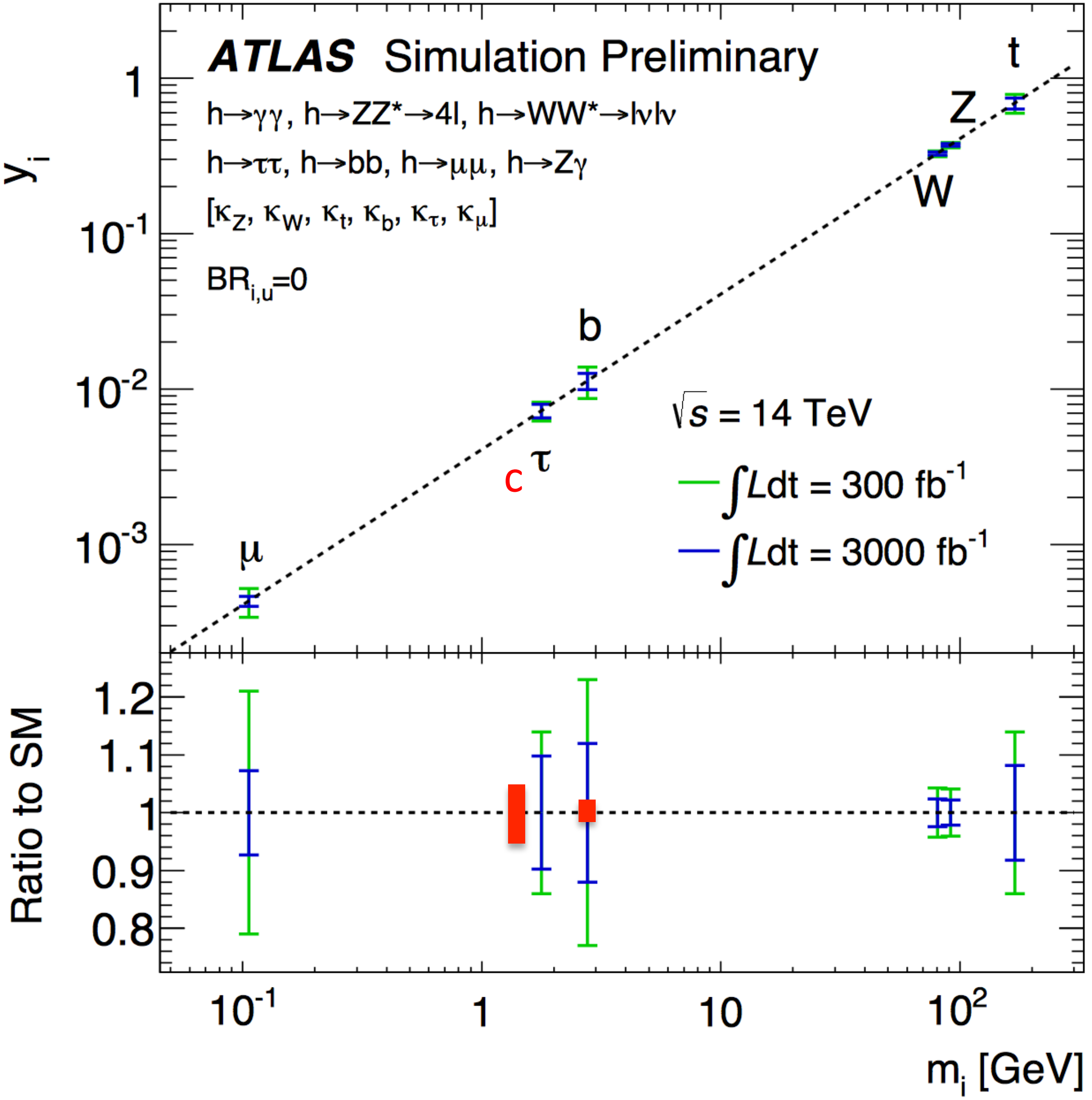
Preparations for ITK at Liverpool




6 module bus-tape prototype @ Liverpool

Mechanics
Electronics
Si Detectors
R+D, DAQ, Software…

Luminosity Upgrade - Higgs



LHeC, $1ab^{-1}$

Work in progress

Br: b 59% c 3%

May transform LHC into high Precision Higgs facility

ATL-PHYS-PUB-2014-016

Location and E-Cost Scaling for e ERL

U(LHeC)=1/3U(LHC), 60 GeV -→ 1/5(LHC) 51 GeV at much reduced cost. SPS: 1/4(LHC)

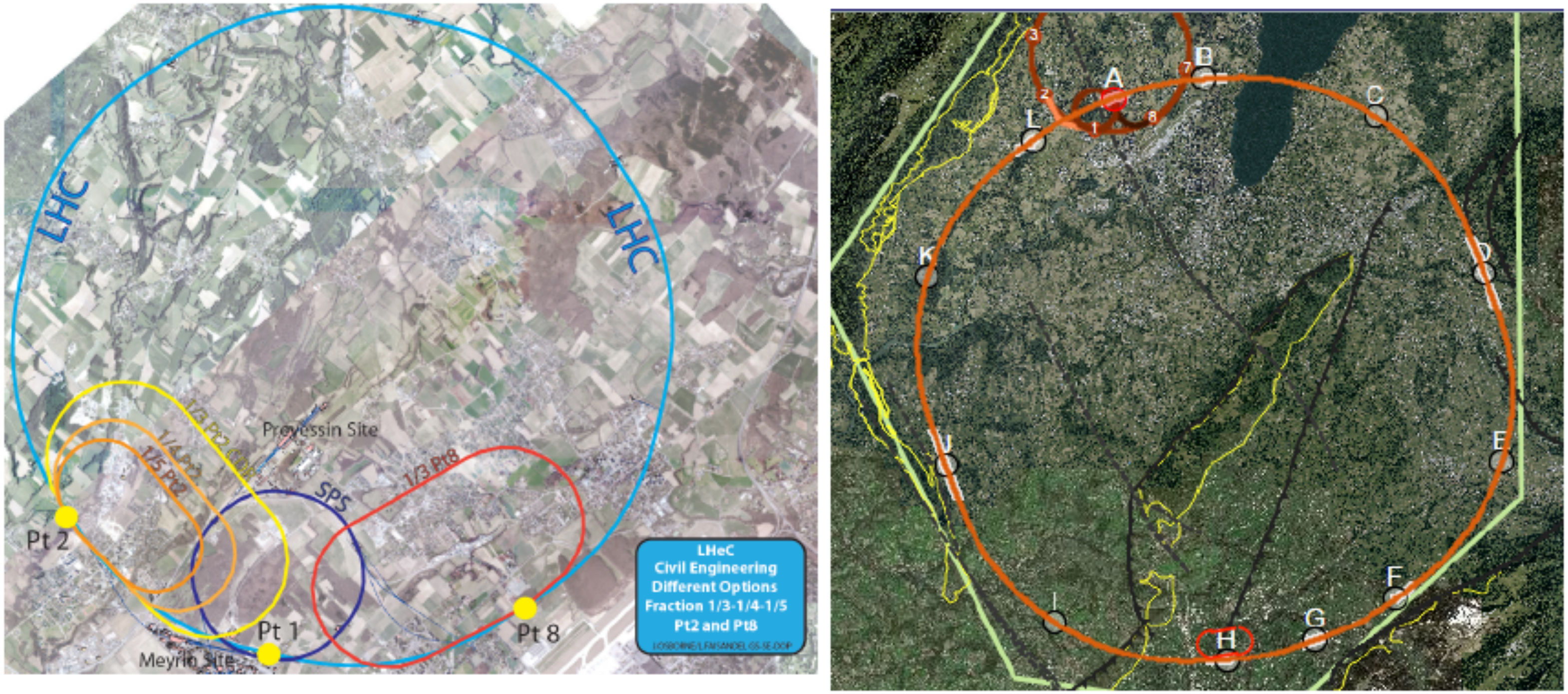


Figure 3: Possible locations of the ERL racetrack electron accelerator for the LHeC (left) and the FCC-he (right). The LHeC is shown to be tangential to Point 2 and Point 8. For Point 2 three sizes are drawn corresponding to a fraction of the LHC circumference of 1/3 (outer, default with $E_e = 60\,\mathrm{GeV}$), 1/4 (the size of the SPS, $E_e = 56\,\mathrm{GeV}$) and 1/5 (most inner track, $E_e = 52\,\mathrm{GeV}$). To the right one sees that the 8.9 km default racetrack configuration appears to be rather small as compared to the 100 km ring of the FCC. Geological considerations suggest a preference for Point H, left from Point G housing one of the large GPDs conceptually while location L may be a possibility too.

Baseline of ep at (HL+HE)-LHC and FCC-eh

.. a 3 turn, two fold, high current, 802 MHz energy recovery linac

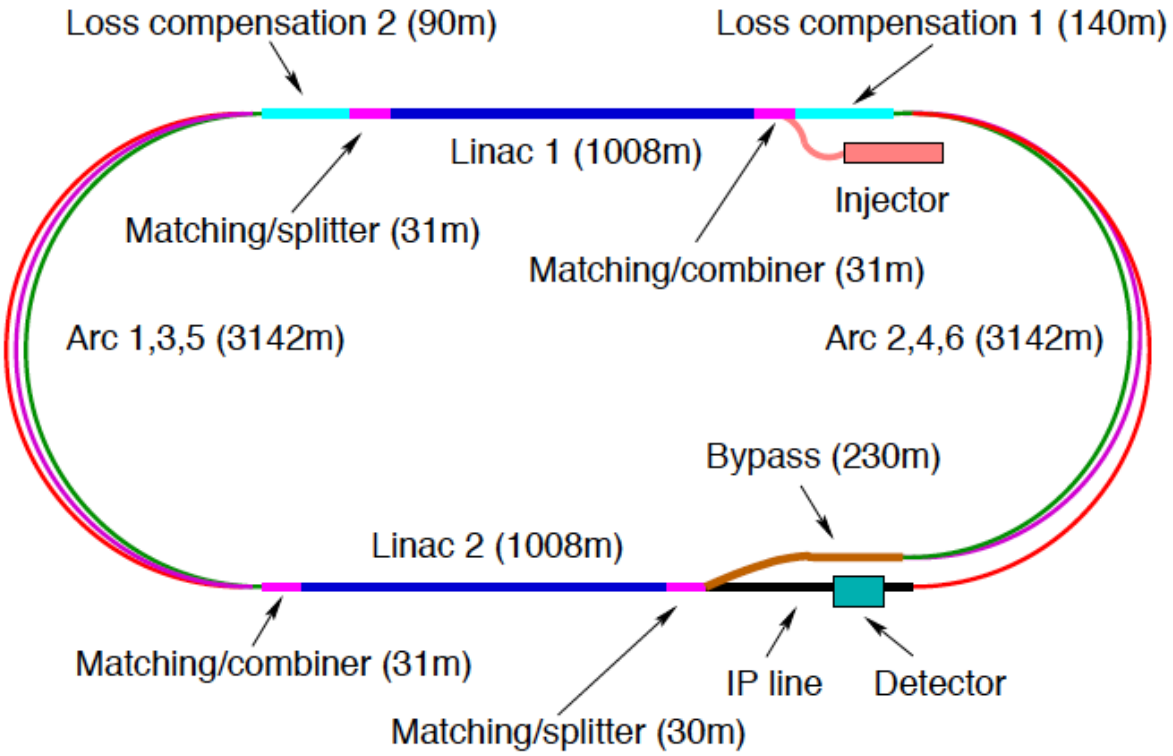
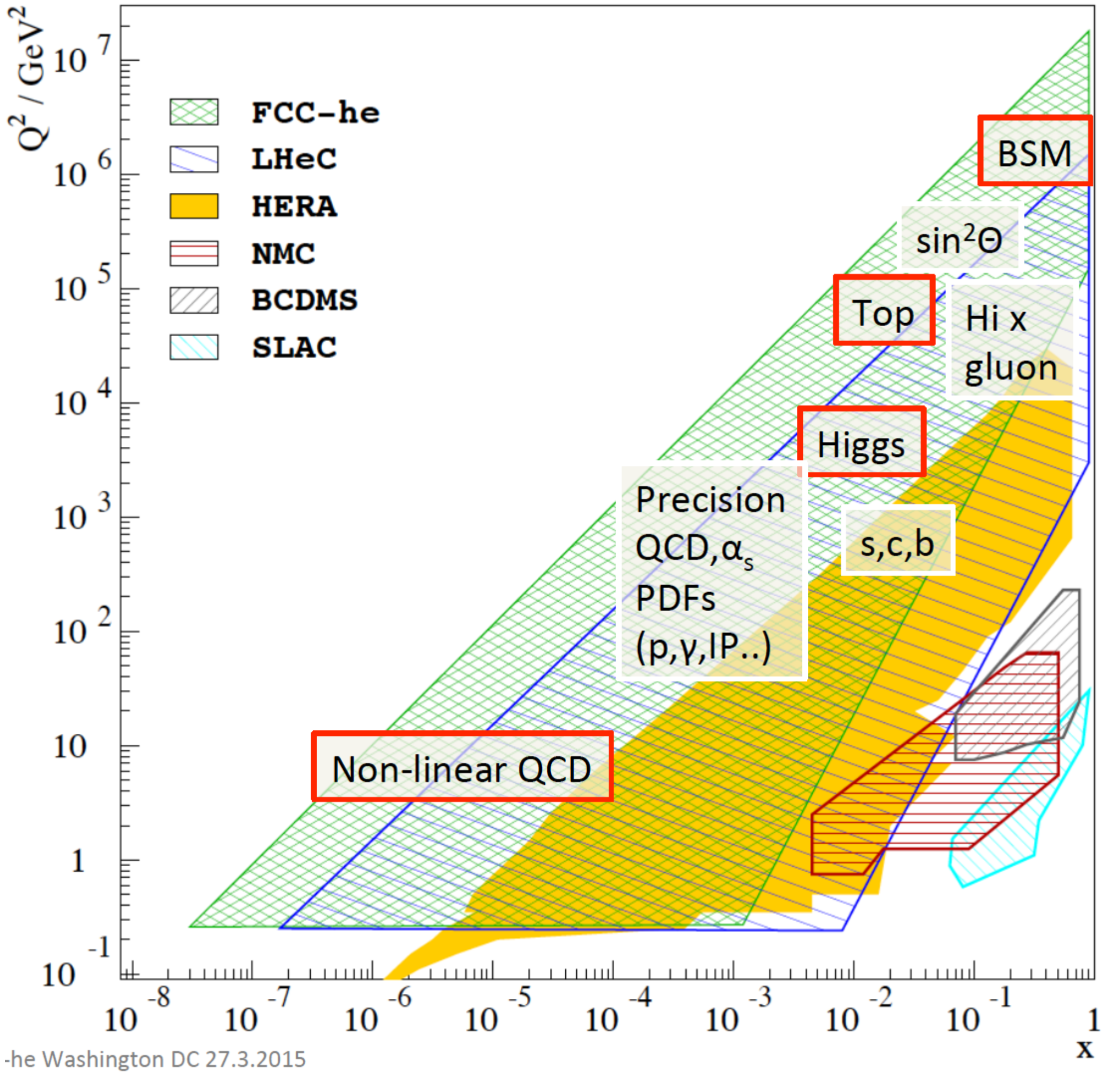


Figure 2: Schematic view of the default LHeC configuration. Each linac accelerates the beam to 10 GeV, which leads to a 60 GeV electron energy at the interaction point after three passes through the opposite lying linac structures made of 60 cavity-cryo modules each. The arc radius is about 1 km and the circumference chosen to be 1/3 of that of the LHC. The beam is decelerated for recovering the beam power after having passed the IP.

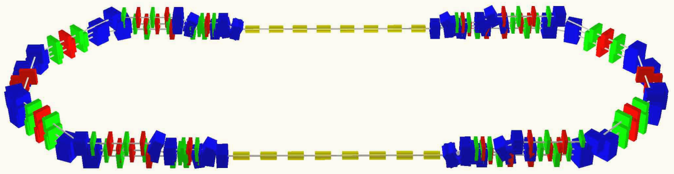
LHC Electron Beam Upgrade



Luminosity of order 10^{34}cm^{-2} s^{-1}
in concurrent ep-pp operation

LHeC

- -Finest microscope of the world
- -The next machine which sees H
- -Transforms LHC in precision lab.
- -PDFs gain O(.5)TeV search range
- -Revolution of nuclear structure



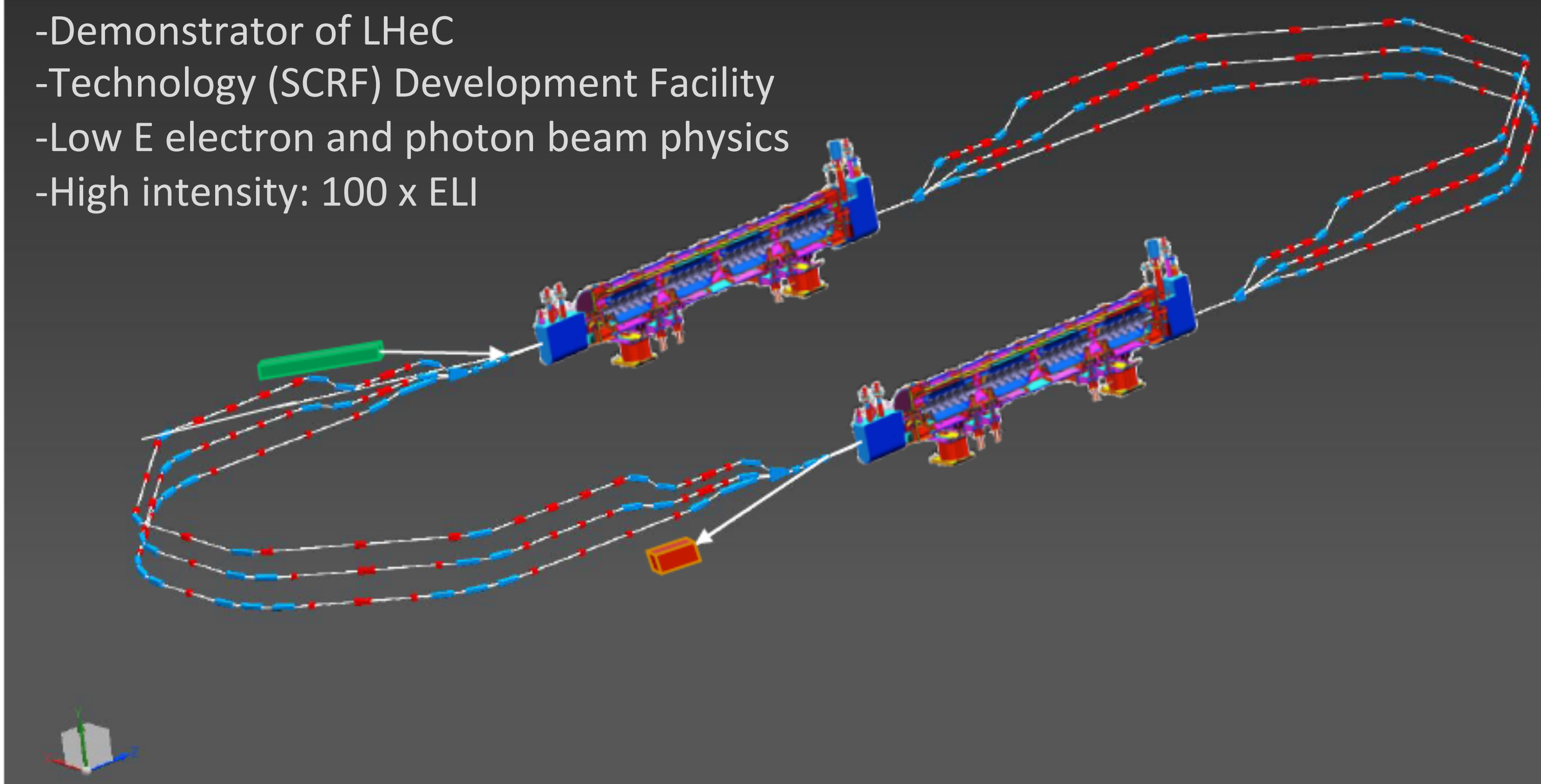
ERL Facility:
Two LINACS 150 MeV, 3 passes
with energy recovery → 900MeV

Design Concept 2015
AsTEC, BINP, CERN, Jlab +
scRF, ERL, Physics, Tests

Powerful ERL for Experiments (ep.γp): PERLE at Orsay

PERLE at Orsay: New Collaboration: BINP, CERN, Daresbury/Liverpool, Jlab, Orsay +

CDR publication imminent.
3 turns, 2 Linacs, 15mA, 802 MHz ERL facility
-Demonstrator of LHeC
-Technology (SCRF) Development Facility
-Low E electron and photon beam physics
-High intensity: 100 x ELI



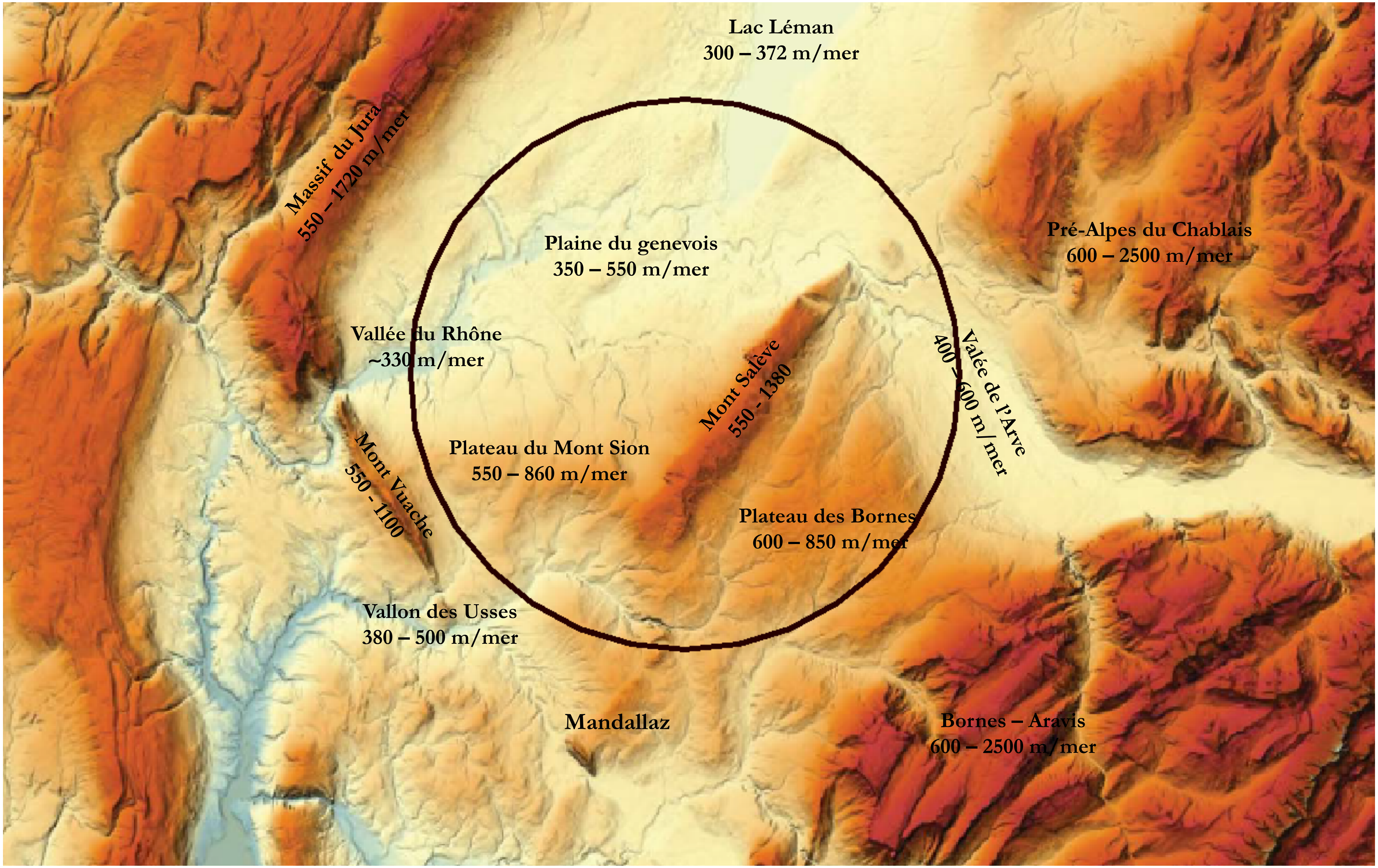
See https://indico.lal.in2p3.fr/event/3428/

Robert Jungk (1966)

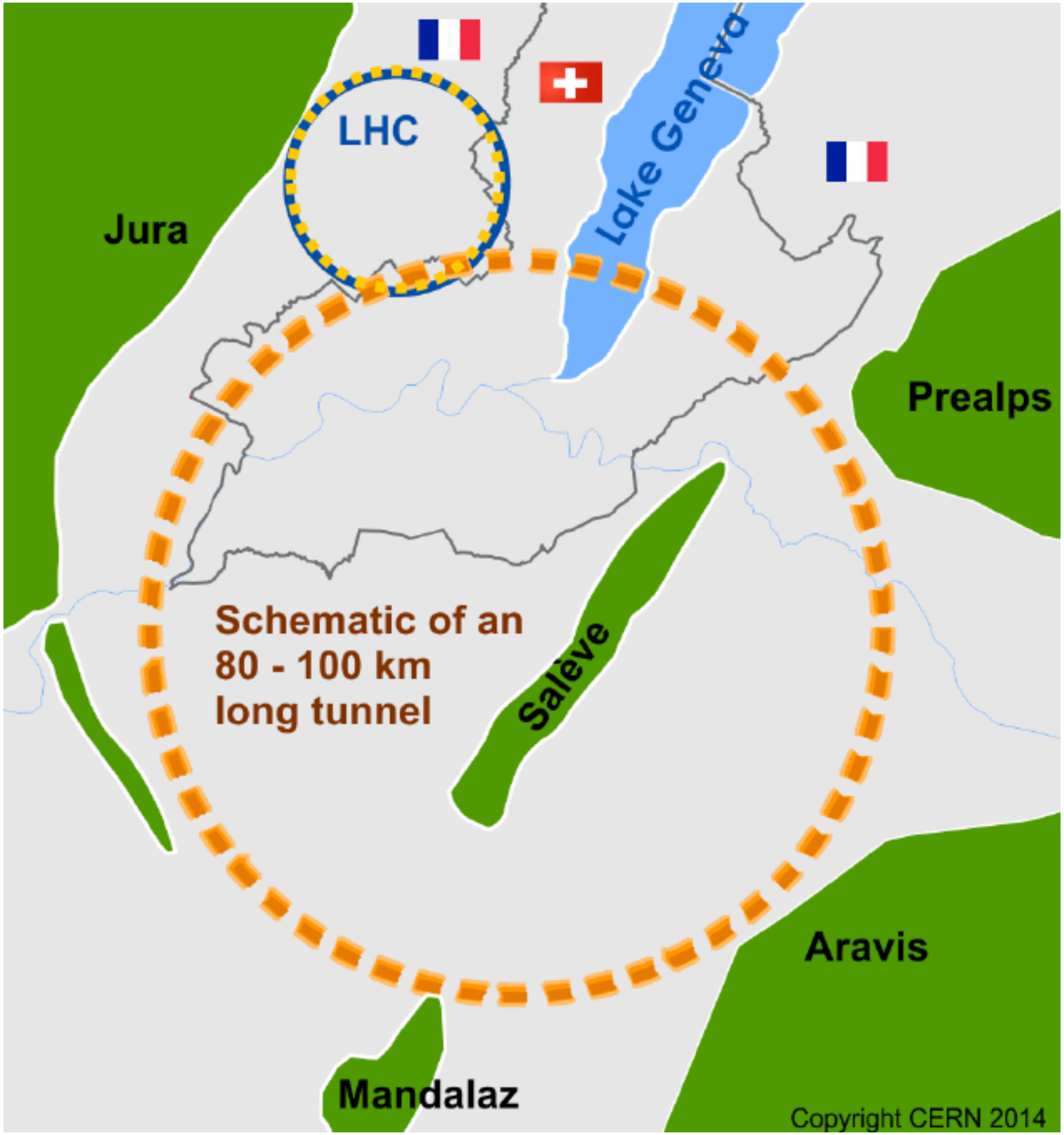
Die grosse Maschine
-auf dem Weg in eine andere Welt

The big machine
-on the road into a new world

FCC

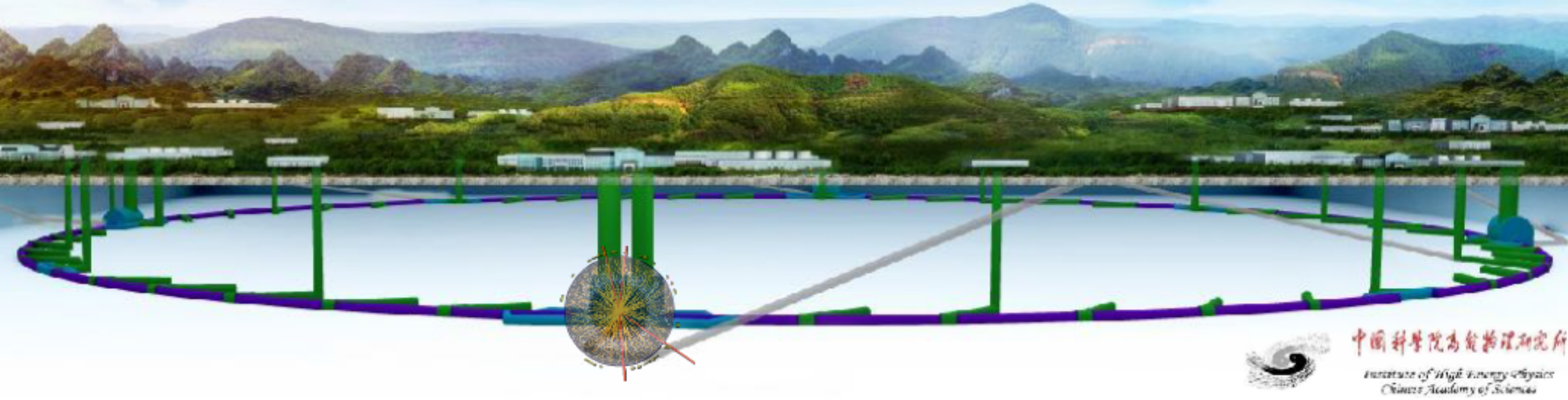


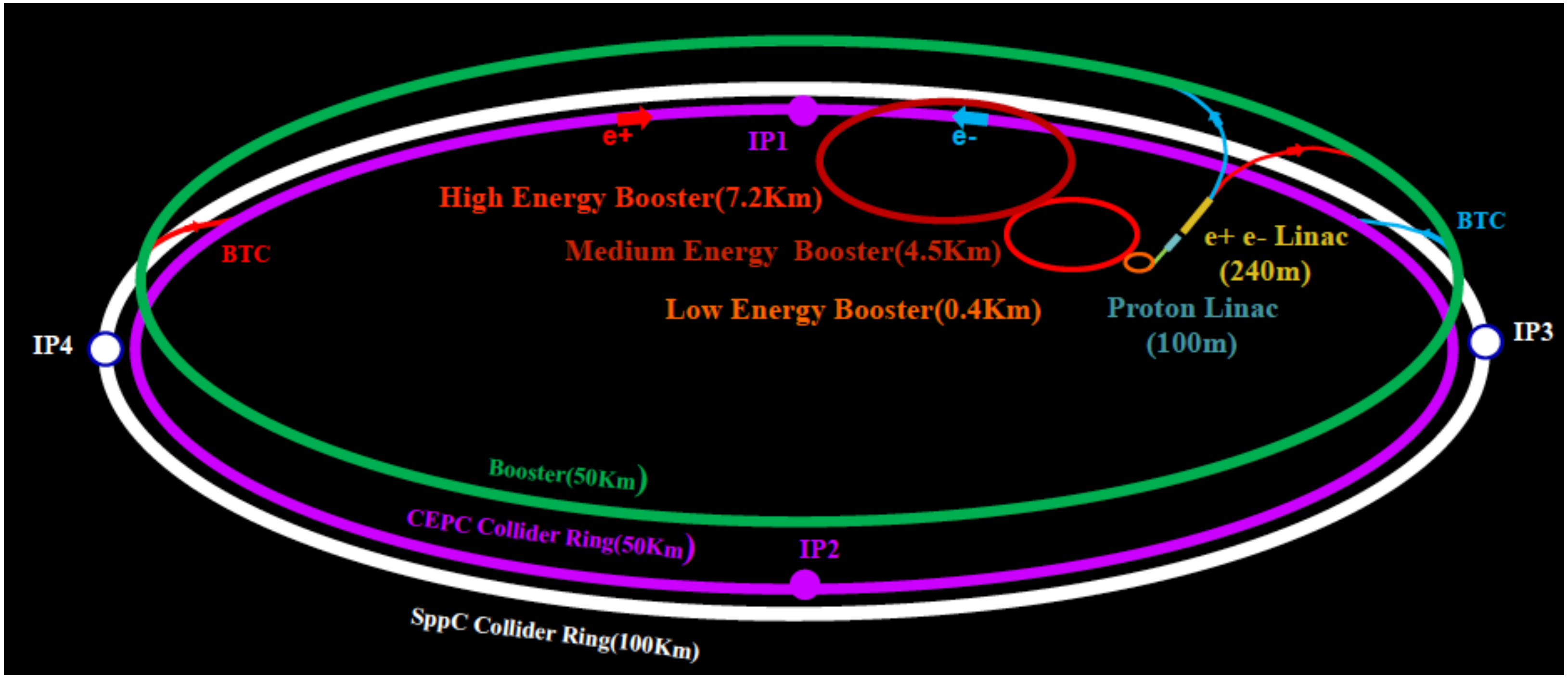
J.Osborne FCC Meeting Washington 3/15



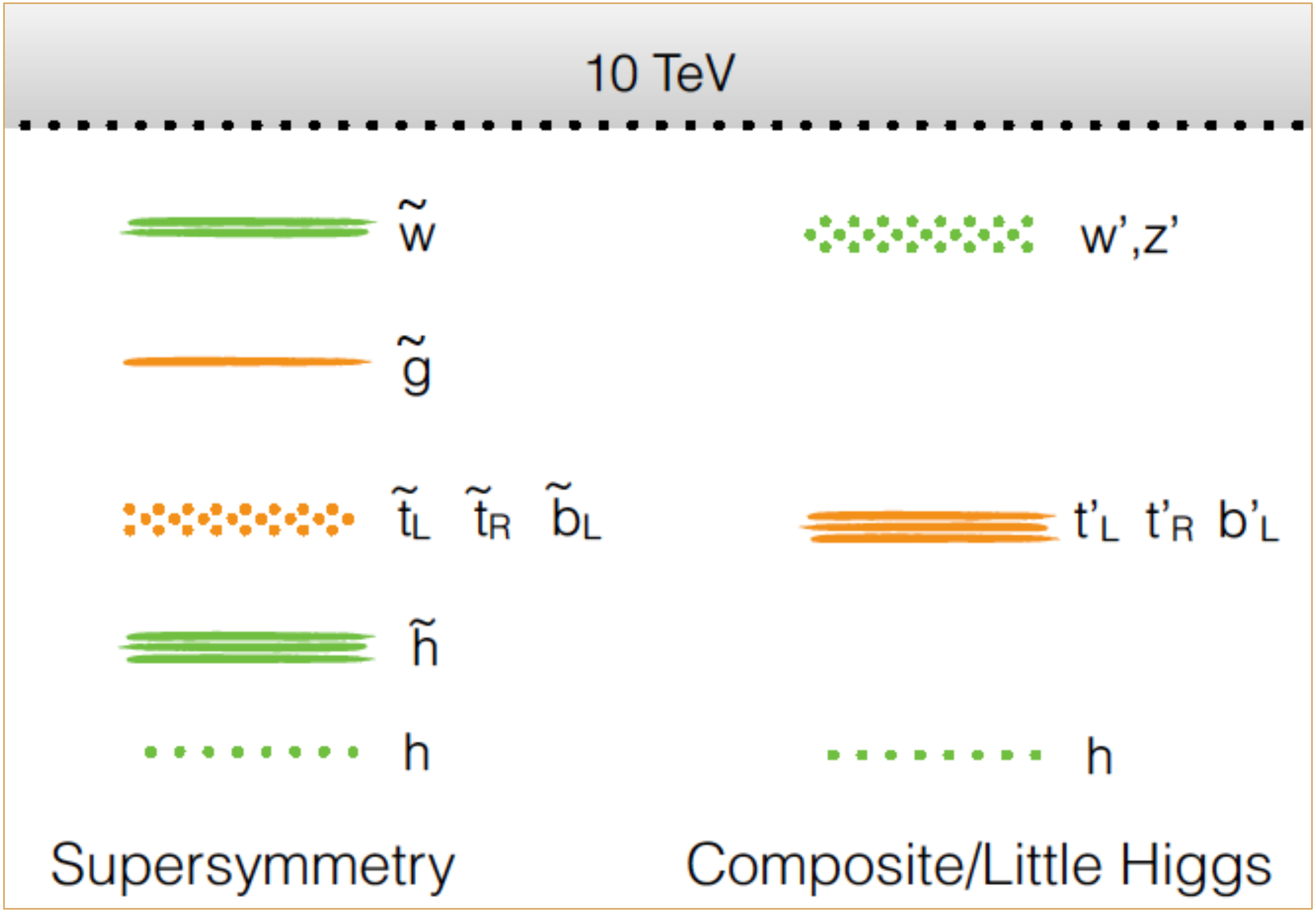
Similar plans in China, cf colloquium last week at Liverpool

CepC and SppC in China



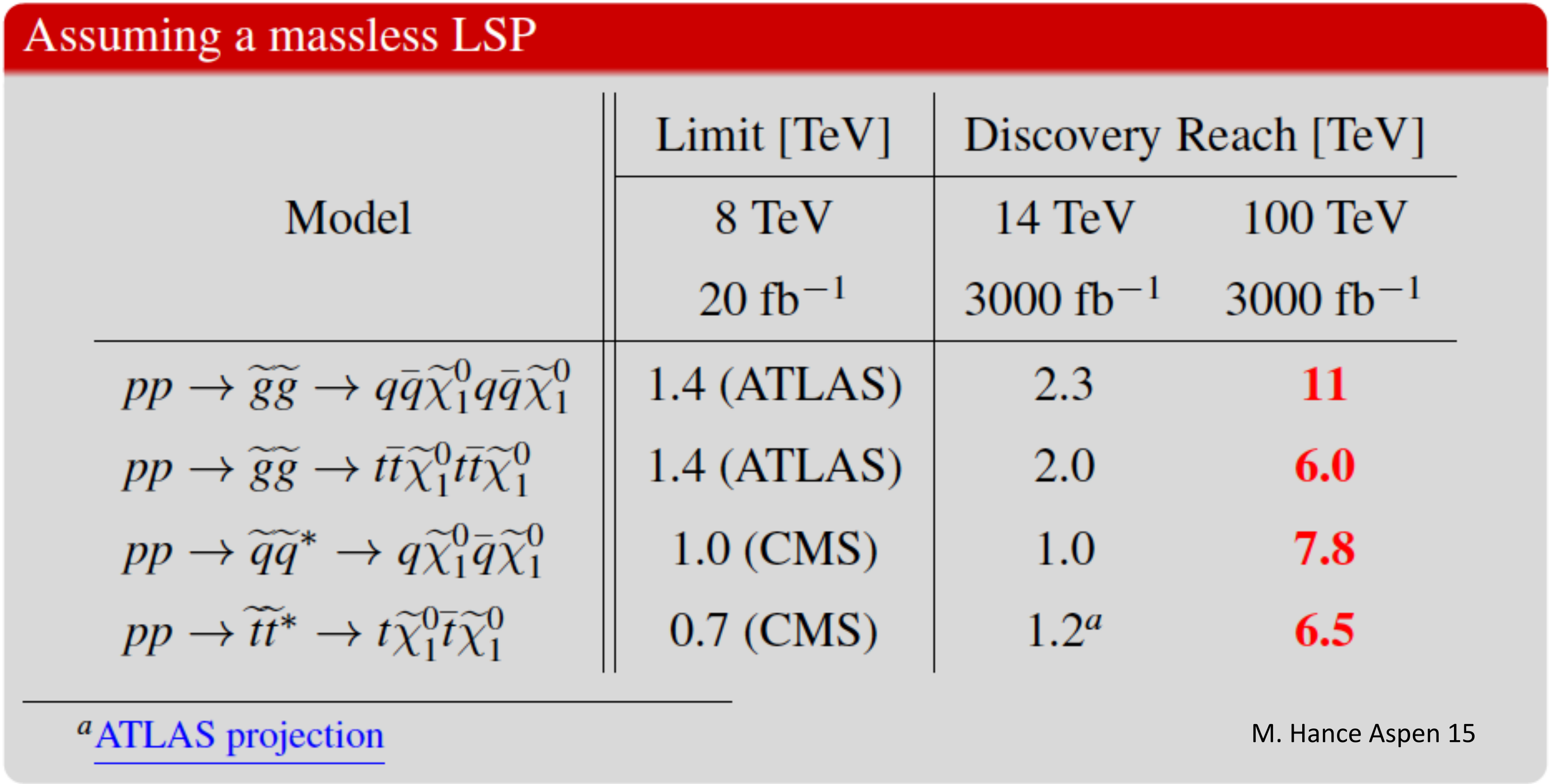


Theory to pave new ways



“Colored” Naturlness N.Craig Aspen 1/15

Future SUSY



Assuming a massless LSP

Model	Limit [TeV]	Discovery Reach [TeV]	
	8 TeV 20 fb^{-1}	14 TeV 3000 fb^{-1}	100 TeV 3000 fb^{-1}
$pp \to \tilde{g}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$	1.4 (ATLAS)	2.3	**11**
$pp \to \tilde{g}\tilde{g} \to t\bar{t}\tilde{\chi}_1^0 t\bar{t}\tilde{\chi}_1^0$	1.4 (ATLAS)	2.0	**6.0**
$pp \to \tilde{q}\tilde{q}^* \to q\tilde{\chi}_1^0 \bar{q}\tilde{\chi}_1^0$	1.0 (CMS)	1.0	**7.8**
$pp \to \tilde{t}\tilde{t}^* \to t\tilde{\chi}_1^0 \bar{t}\tilde{\chi}_1^0$	0.7 (CMS)	1.2[a]	**6.5**

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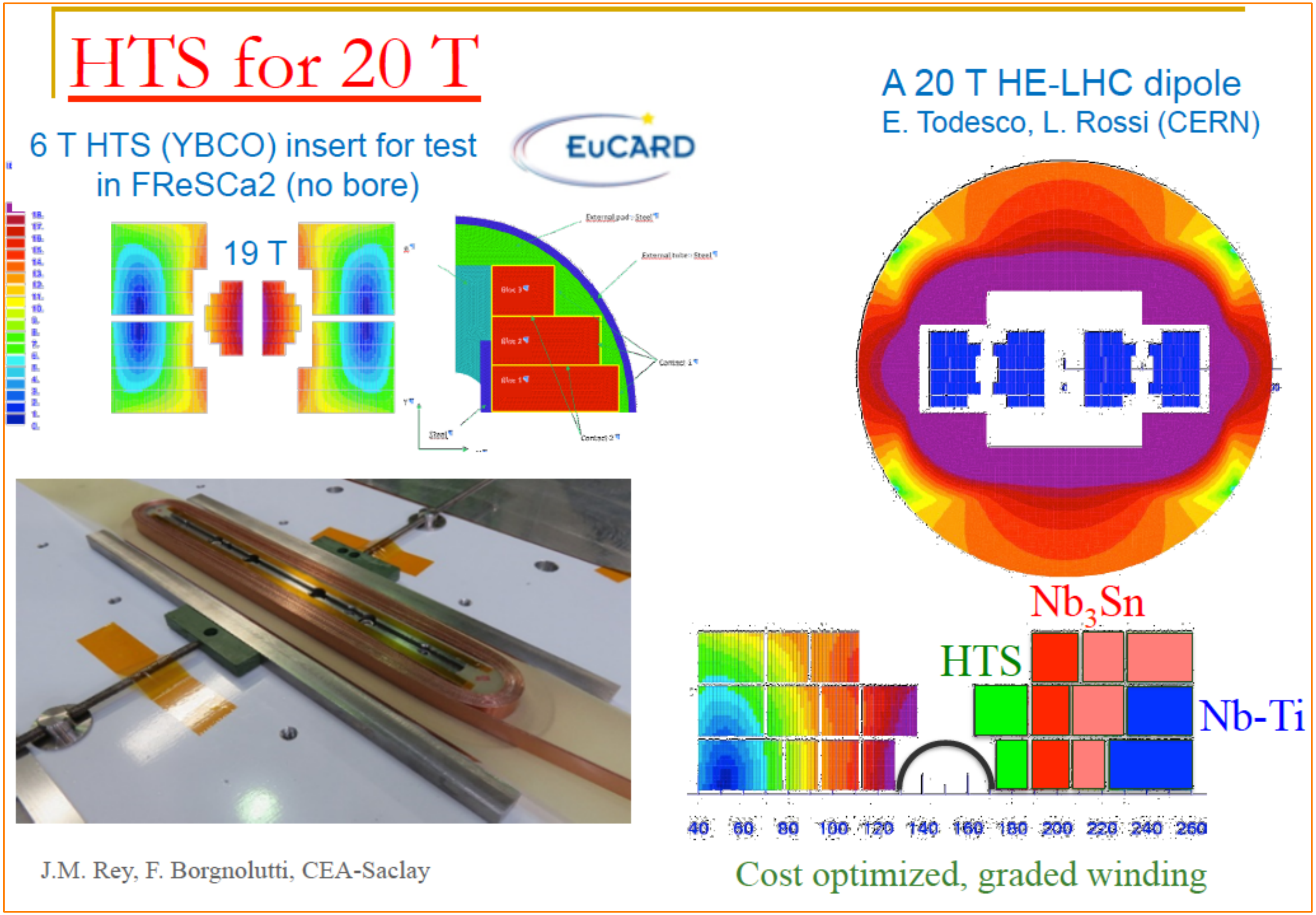
[a] ATLAS projection

M. Hance Aspen 15

SUSY is too beautiful to not exist but it is broken heavier and heavier

For the FCC to be built we need overriding reasons which the society can accept for the project to go ahead. Magnets and theory are the main challenges of the FCC.

Design of High Field Dipoles



HTS for 20 T

6 T HTS (YBCO) insert for test in FReSCa2 (no bore)

EuCARD

A 20 T HE-LHC dipole

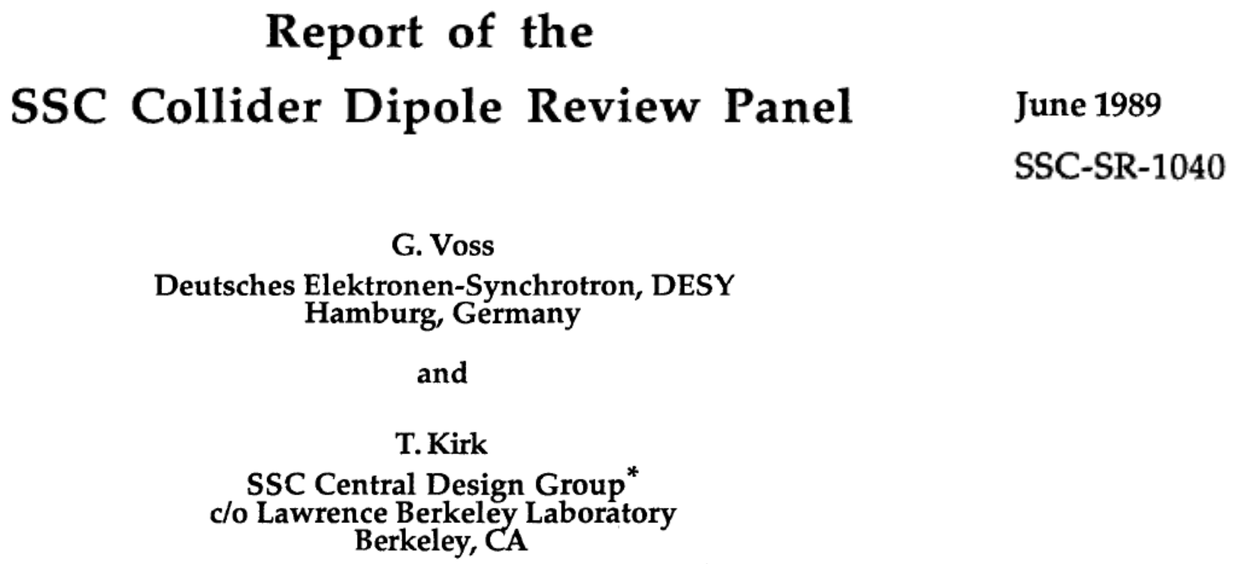
E. Todesco, L. Rossi (CERN)

J.M. Rey, F. Borgnolutti, CEA-Saclay

Cost optimized, graded winding

Sc wire: higher current, higher field. Reduced losses. NbTi: 15T at 10K, Nb_3Sn: 25Tat4K, HTC inserts YBCO

Cost is a major factor: today: Nb_3N is 5 times the NbTi cost and HTC is 10 times Nb3N (O.Bruening at KET 2/17)



Report of the
SSC Collider Dipole Review Panel

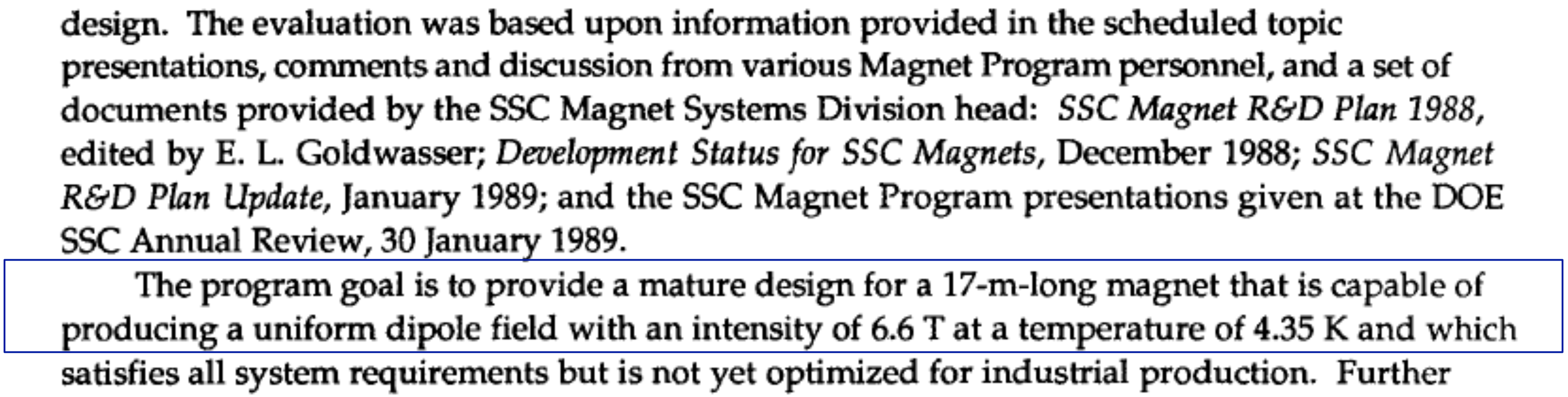
June 1989

SSC-SR-1040

G. Voss
Deutsches Elektronen-Synchrotron, DESY
Hamburg, Germany

and

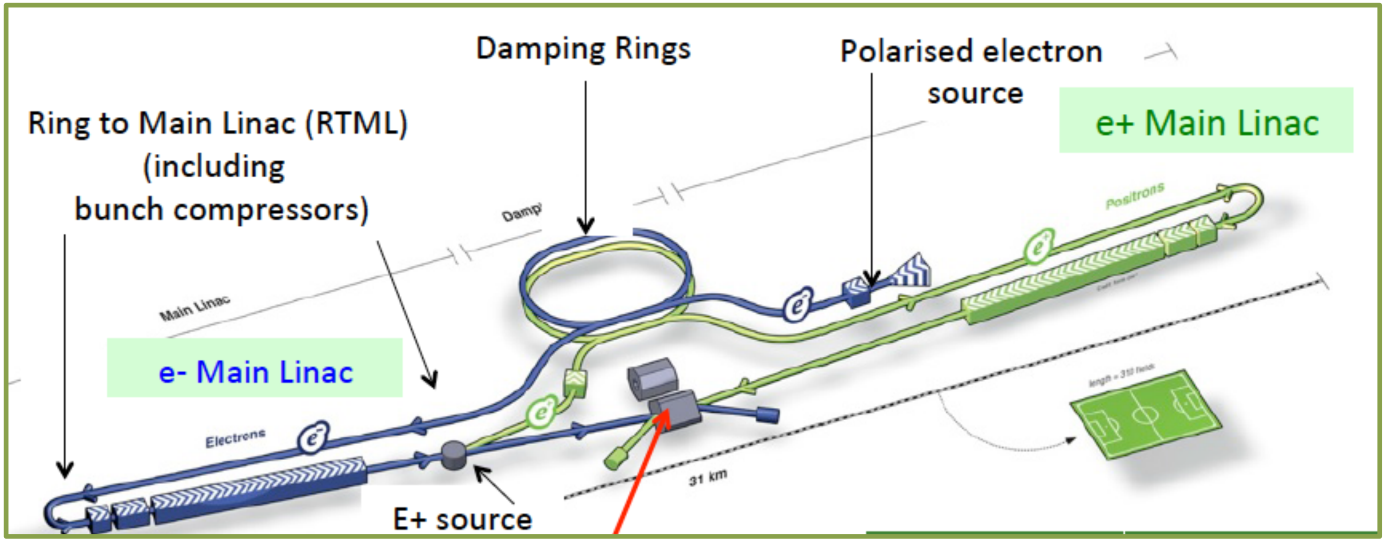
T. Kirk
SSC Central Design Group*
c/o Lawrence Berkeley Laboratory
Berkeley, CA



design. The evaluation was based upon information provided in the scheduled topic presentations, comments and discussion from various Magnet Program personnel, and a set of documents provided by the SSC Magnet Systems Division head: *SSC Magnet R&D Plan 1988*, edited by E. L. Goldwasser; *Development Status for SSC Magnets*, December 1988; *SSC Magnet R&D Plan Update*, January 1989; and the SSC Magnet Program presentations given at the DOE SSC Annual Review, 30 January 1989.

The program goal is to provide a mature design for a 17-m-long magnet that is capable of producing a uniform dipole field with an intensity of 6.6 T at a temperature of 4.35 K and which satisfies all system requirements but is not yet optimized for industrial production. Further

Linear electron-positron colliders



ILC in Japan

ee → ZH:

E_e >120 GeV

ee → tt

E_e > 180 GeV

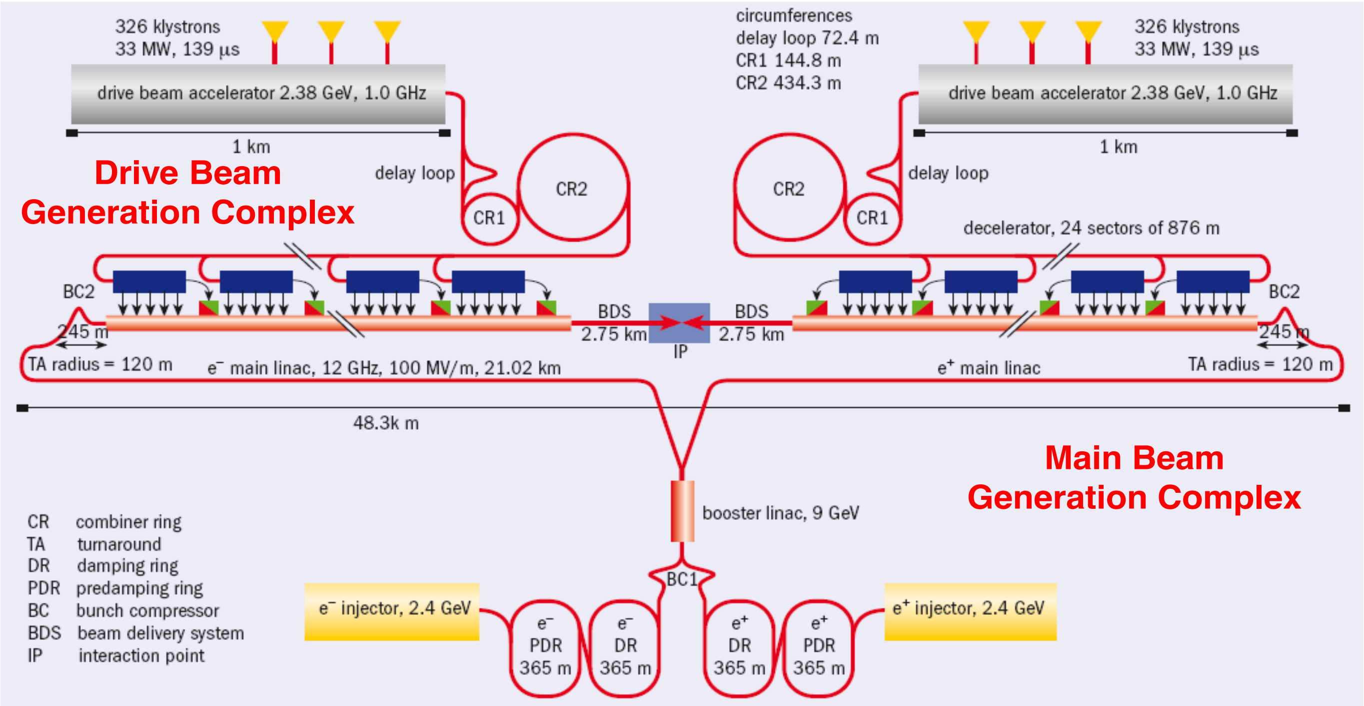
CLIC at CERN

ee → sparticles

E_e as large as ?

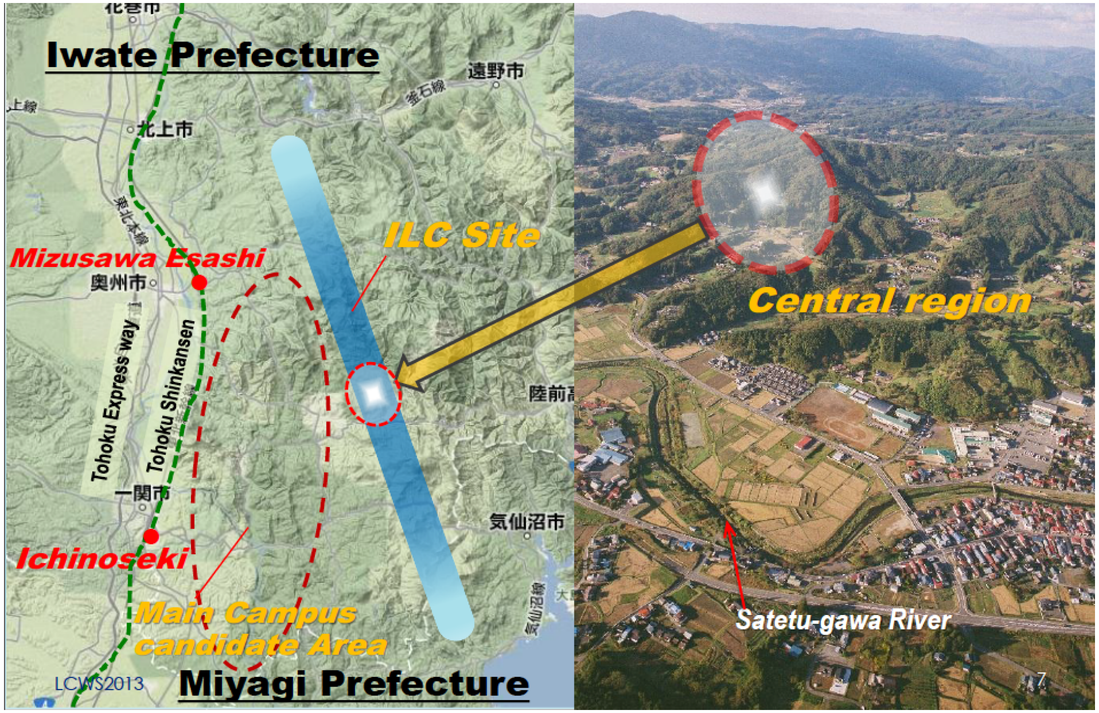
max E_e=1.5 TeV

Low E_e: H+top



Linear electron-positron colliders

ILC



Huge enterprises
[e+, drive beams,
power, CE, length..]

New since 2016:
No BSM in their
energy range
(so far) − uncertain

→ Revival of circular
ee colliders − FCC-ee,
CepC − for Higgs (Z,t)

CLIC

The Upgrades of the LHC will endure for your lifetime as physicists. They will change our understanding of nature, answer some of the “big questions” and pose new ones.

They rely on the development of technology, theory, experimentation and cannot be pursued if the old concepts of walls and nationalism win.

Actually CERN, also Dubna, were built in the early 50ies to overcome the division of the world. That has been the undisputed base for its success and its persistent attraction.

1st session of CERN Council, 15.2.1952 - Niels Bohr watching us..

“The future belongs to those who believe in the beauty of their dreams.”

Anna Eleanor Roosevelt
(1884-1962)

Universal Declaration of Human Rights (1948)

cited by Frank Zimmermann at the FCC Meeting at Washington DC, March 2015

Designing the FCC-hh

- synchrotron radiation power → associated cryogenics power (after various technological improvements and mitigation – higher beam-screen temperature etc.) limits maximum number of protons (e.g. 10^{15}p/beam or beam current of ~0.5 A for 100 km ring at 100 TeV c.m.)
- maximum beam current + "turnaround time" (FCC + inj.) constrain integrated luminosity
- maximum peak pile up ~1000 or ~200 limits peak luminosity at 25 ns and 5 ns bunch spacing, respectively
- maximum acceptable beam-beam tune shift 0.01 or 0.03 + optics (minimum β^* ~0.3-1.1 m) also limits peak luminosity

F.Zimmermann 1/17