Accelerator Options for Very High Energy

Frank Zimmermann, CERN

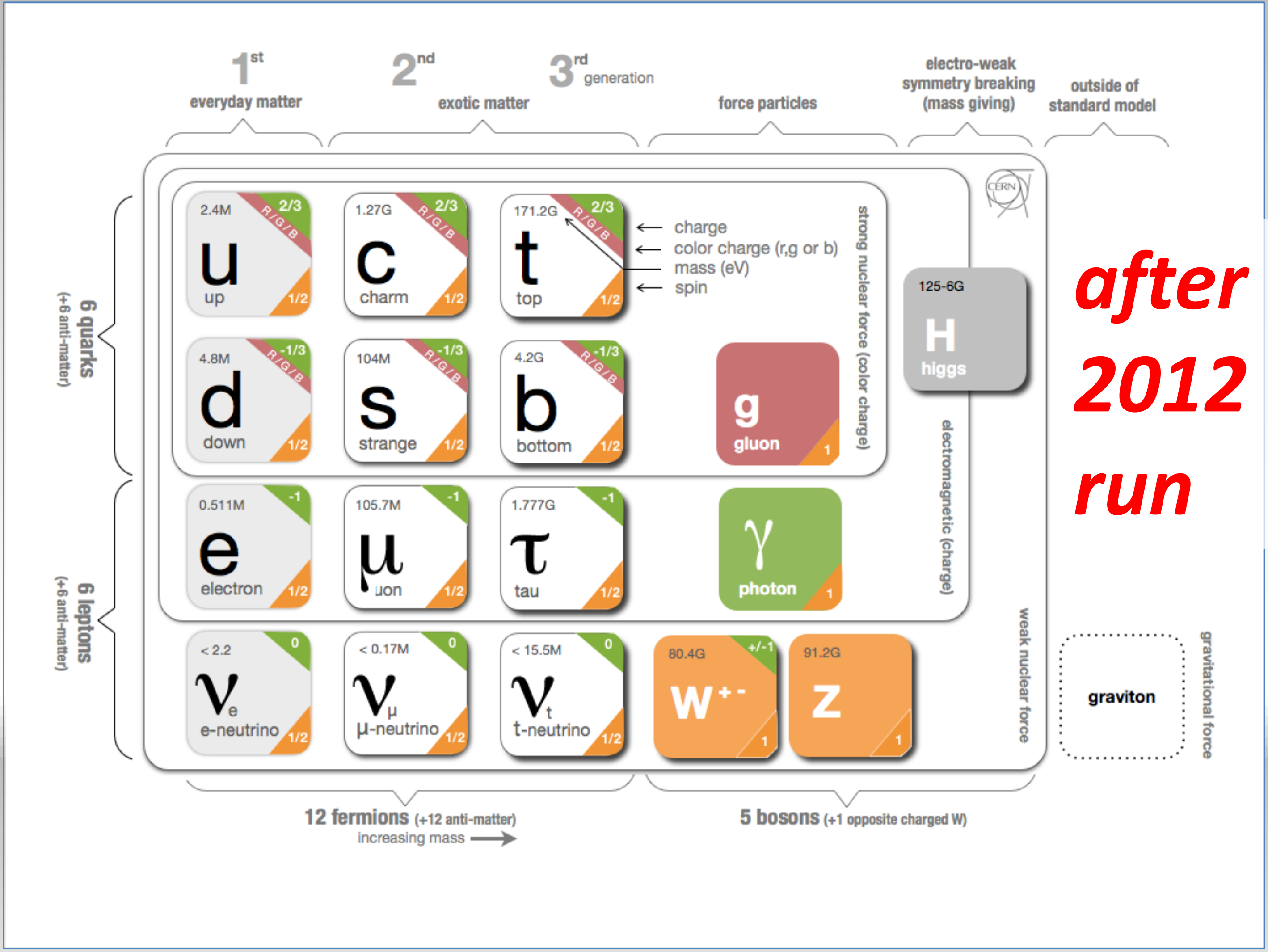
S'Cool, 4 August 2017

Photo: Denver Energy Exploratorium

outline

- hadron colliders
- lepton-hadron colliders
- photon colliders
- lepton colliders
- ultimate limits
- Higgs factories & strategy for future projects

The Standard Model of Particle Physics

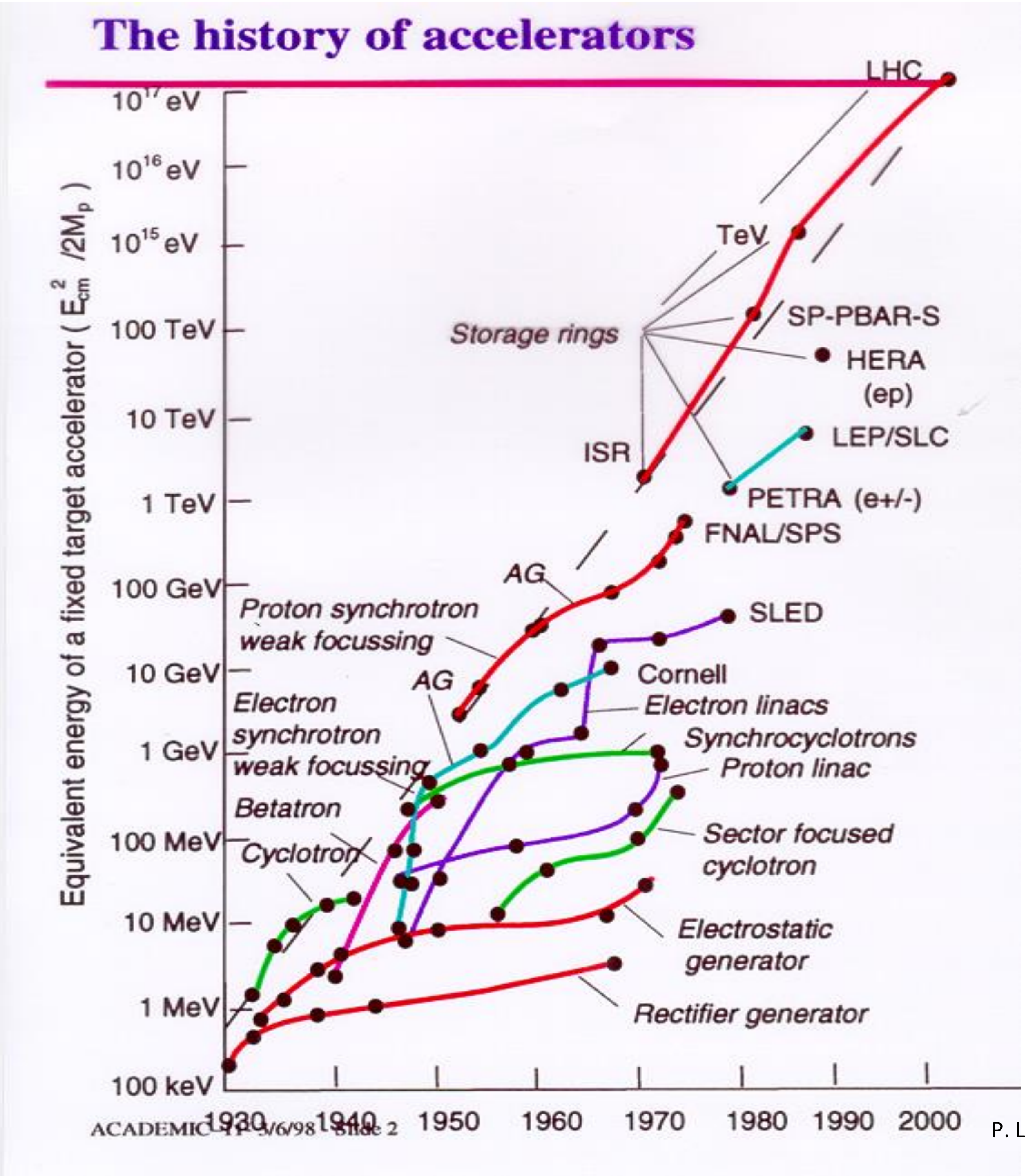


after 2012 LHC run

the most important tool in this story was the particle accelerator!

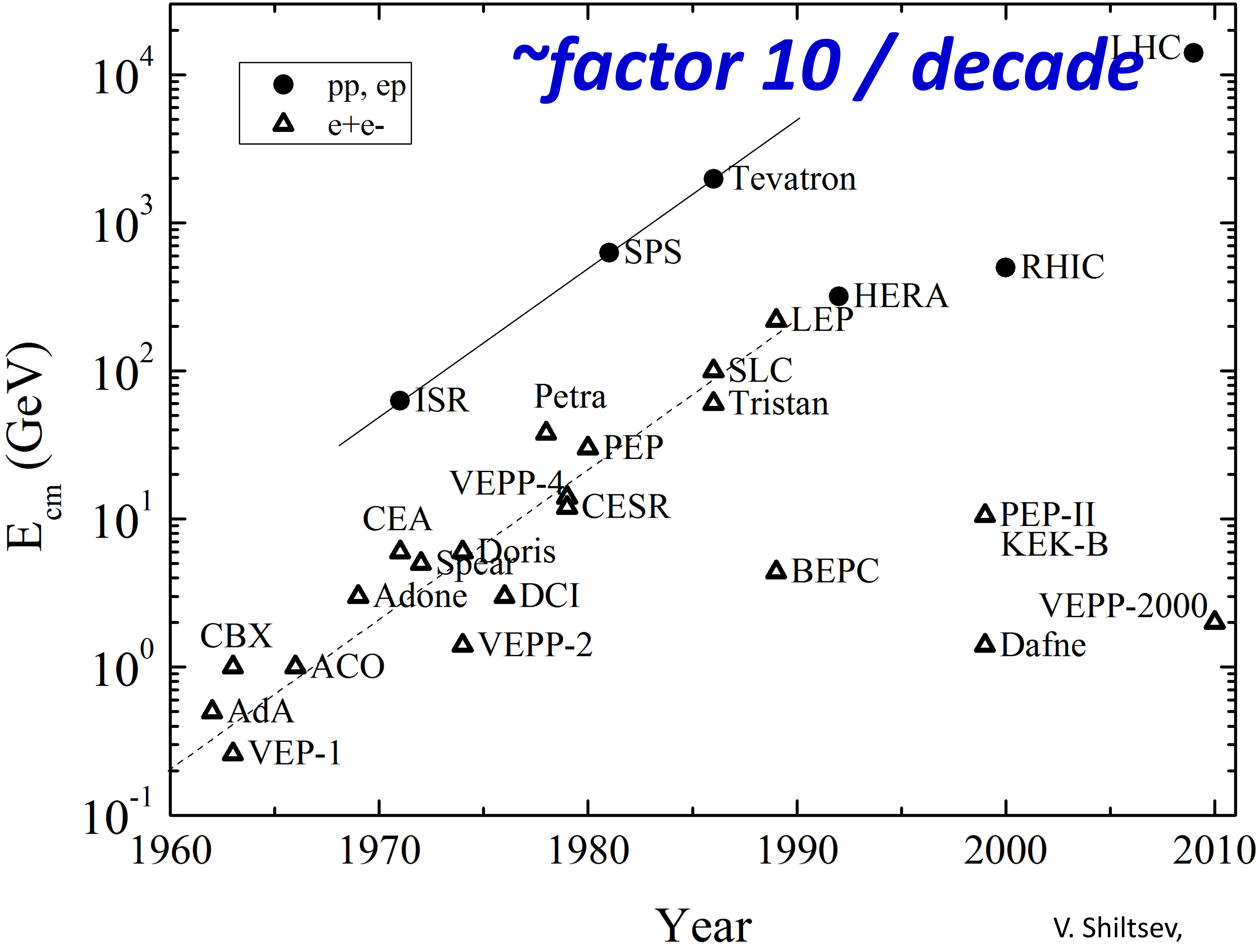
repeated jumps from saturating to emerging technologies

storage rings have been the frontrunner technology for the last ~50 years



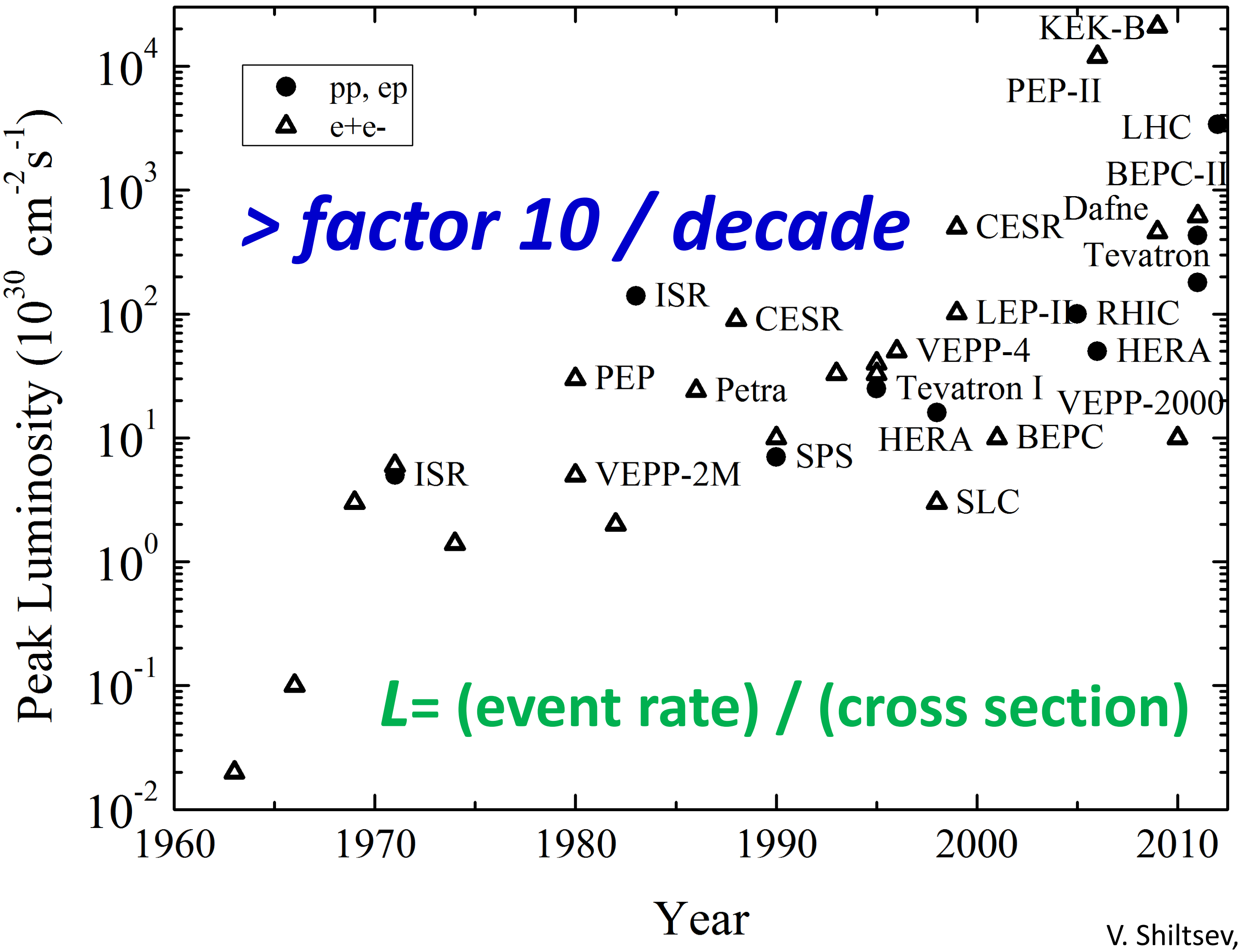
P. Lebrun

particle-collider energies since 1960



V. Shiltsev,
Physics Uspekhi 55 (2012) 965

peak luminosities of particle colliders



> *factor 10 / decade*

***L*= (event rate) / (cross section)**

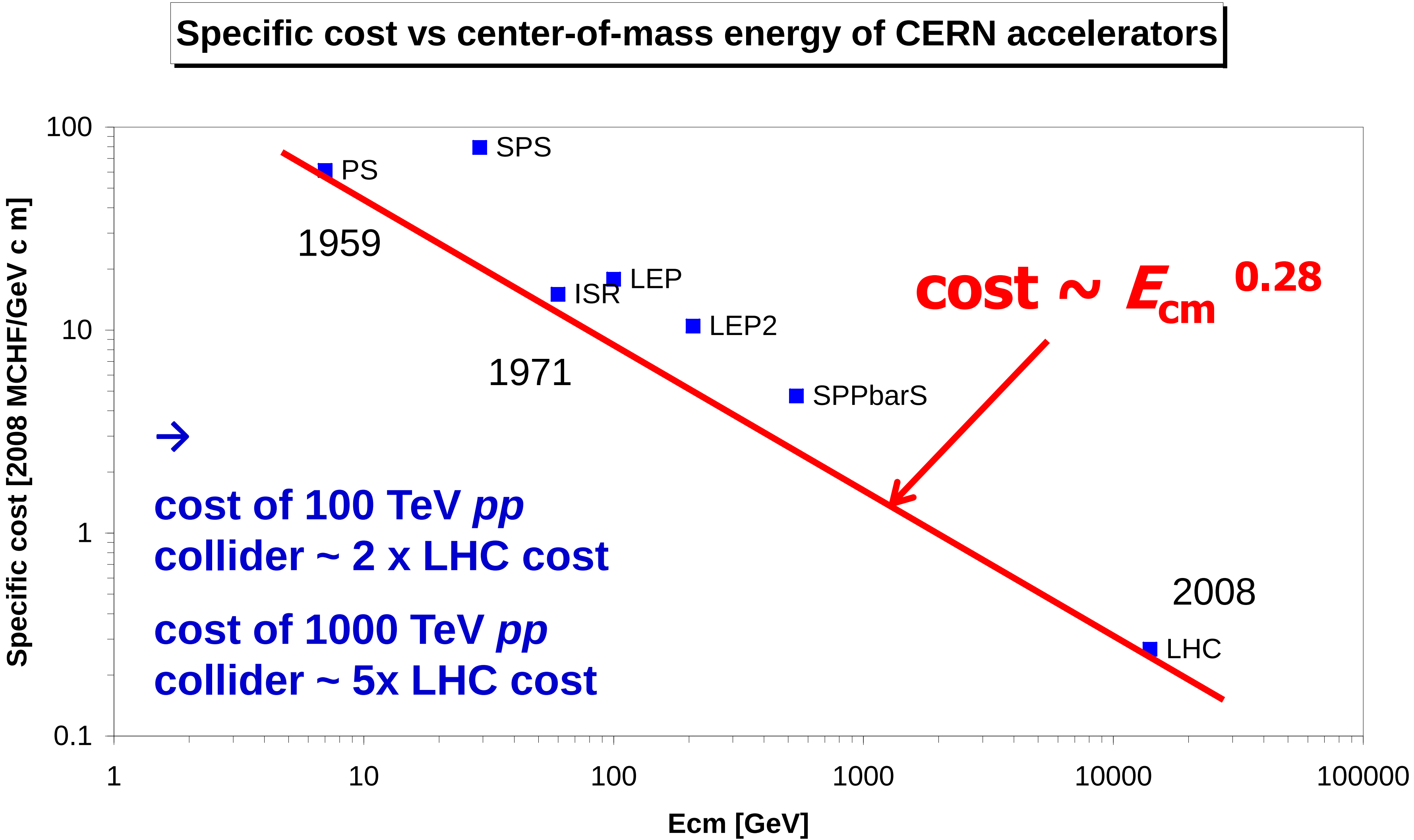
V. Shiltsev,
Physics Uspekhi 55 (2012) 965

1^{st} cyclotron, ~1930
E.O. Lawrence
11-cm diameter
1.1 MeV protons

Large Hadron
Collider (LHC), 2008,
9-km diameter
7 TeV protons

after ~80 years
~10^7 x more energy
~10^5 x larger

remarkable advance in accelerator cost/energy thanks to new technologies



Specific cost vs center-of-mass energy of CERN accelerators

$\text{cost} \sim E_{cm}^{\ 0.28}$

→

cost of 100 TeV *pp* collider ~ 2 x LHC cost

cost of 1000 TeV *pp* collider ~ 5x LHC cost

P. Lebrun, RFTech 2013

hadron colliders

"discovery machines" (hadrons: composite particles)

✓ *W* and *Z* bosons, top quark, Higgs boson

next: supersymmetry, dark matter, extra dimensions, dark energy,…?

maximum energy

$$E_{max} \approx e\,c\,B\,\rho$$

bending radius

LHC: $\rho \approx 3$ km

magnetic field

LHC: superconduncting magnets (*Nb-Ti*) with $B \approx 8.33$ T

higher-energy hadron colliders

- **stronger magnetic fields:**

  Nb-Ti (~8 T) → *Nb_3Sn* (~15 T) → *HTS* (~20 T)

  factor 2.5 in beam energy (“HE-LHC”)

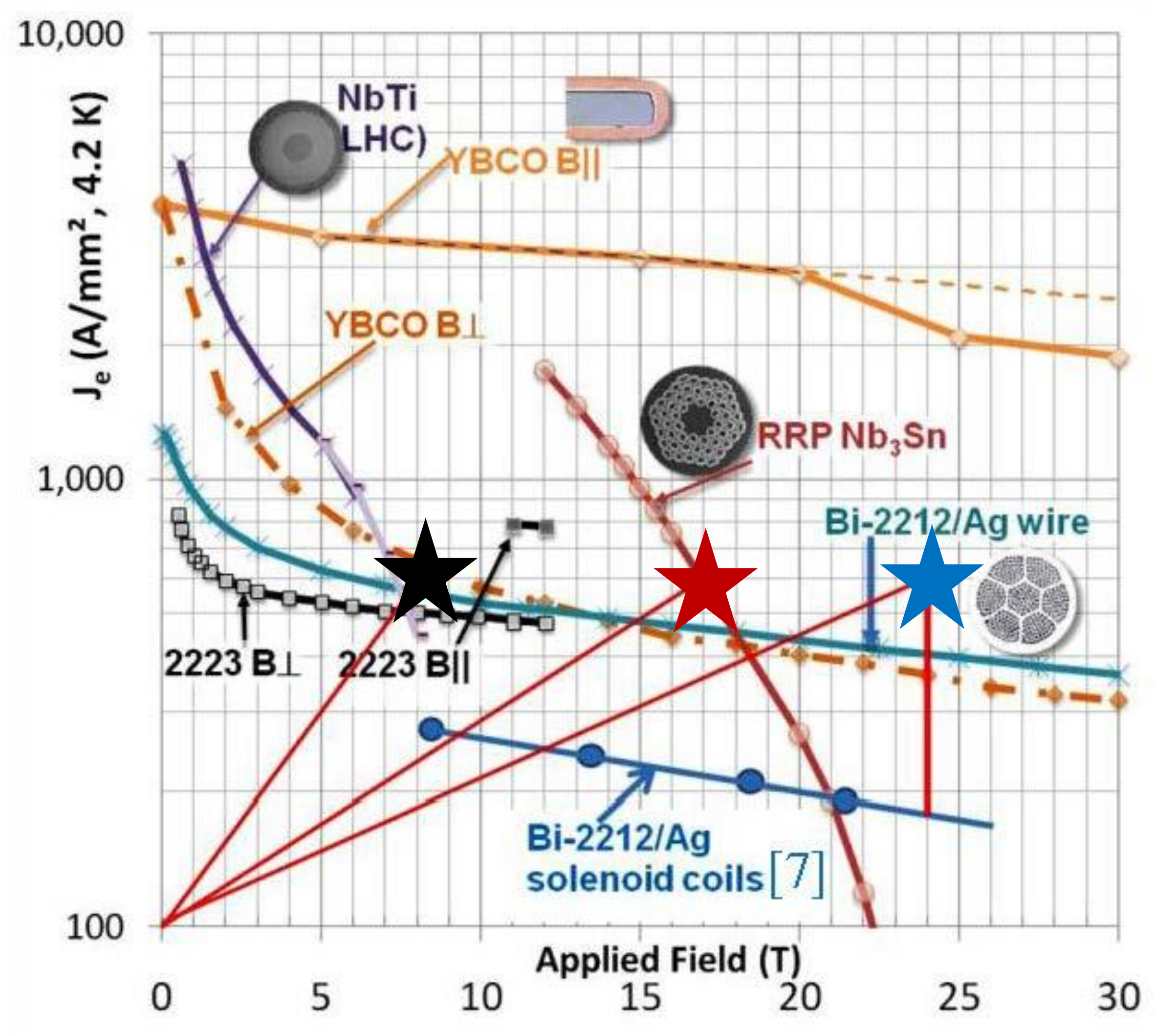
- **larger circumference:**

  27 km (LHC) → 100 km (“FCC-hh”?)

  another factor 3 in beam energy

Combined (“FCC-hh”): an order of magnitude in energy! - 100 TeV *pp* collisions

pushing SC magnet technology



Nb-Ti **~8 T (LHC, 2005)**

→

Nb_3Sn **~15-17 T (HL-LHC, 2025; FCC-hh,~ 2040)**

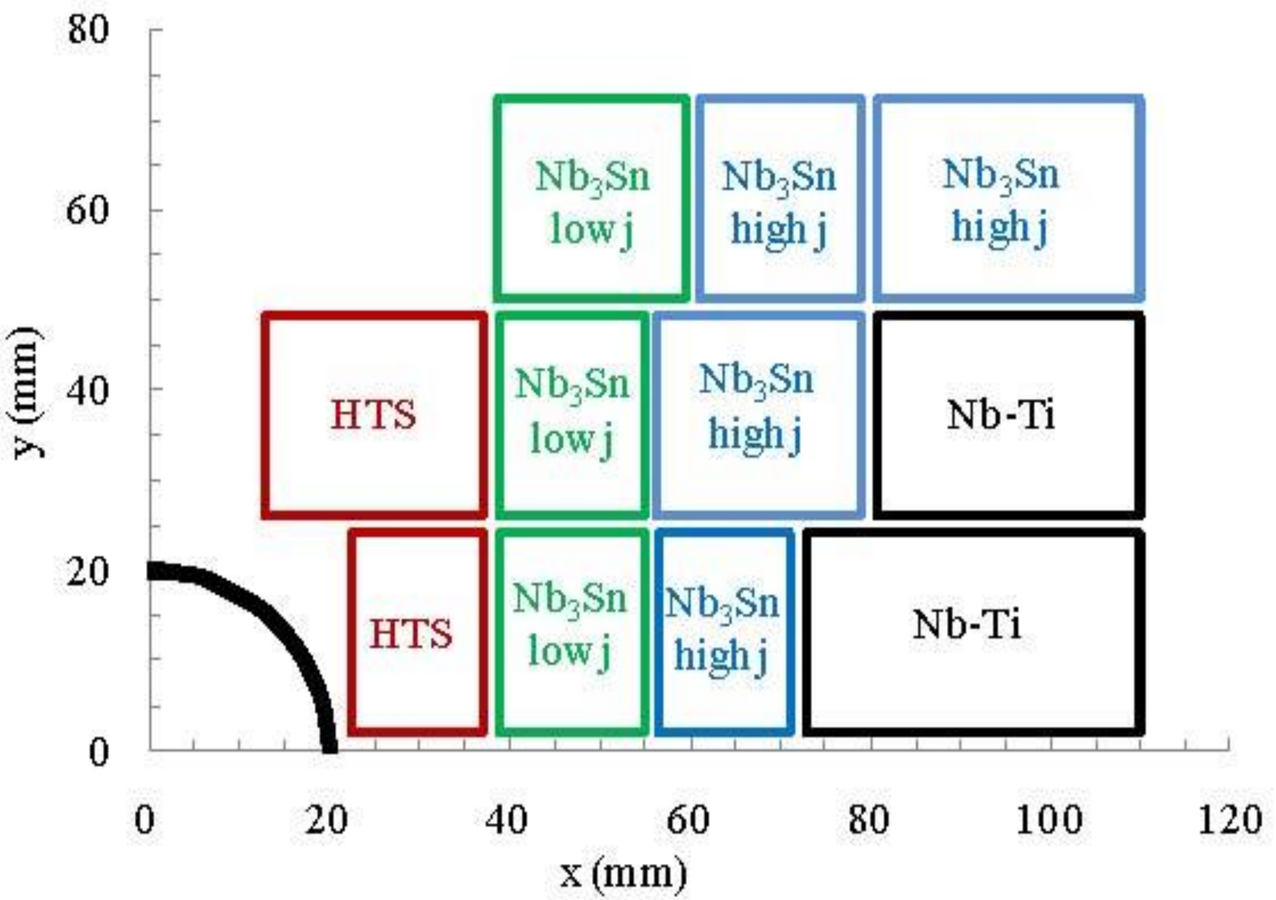
→

HTS **~12-24 T?**

Bi-2212: only round-wire superconductor at fields > 18 T

P. McIntyre et al, Proc. EuCARD-AccNet workshop HE-LHC10, Malta, Oct. 2010, Yellow Report CERN-2011-003
P. Lee, Compilation of current j_e data, http://www.magnet.fsu.edu/magnettechnology/research/asc/plots.html

20-T hybrid magnet



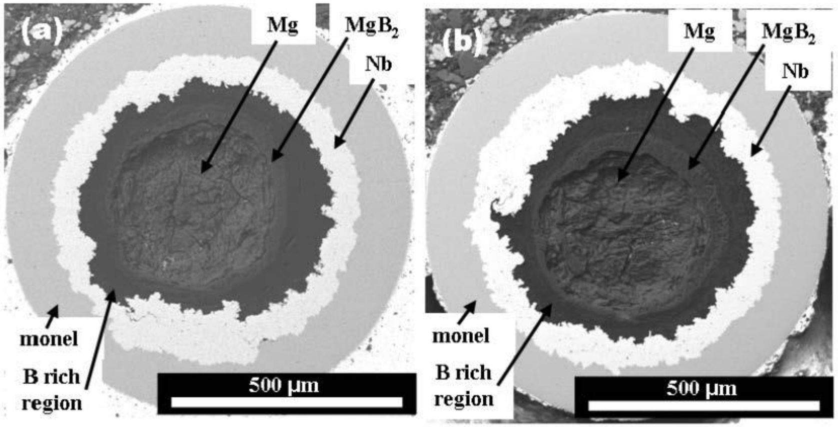
E. Todesco,
L. Rossi,
P. McIntyre

Block layout of *Nb-Ti* & *Nb$_3$Sn* & *HTS* (*Bi*-2212) 20-T dipole-magnet coil. Only one quarter of one aperture is shown.

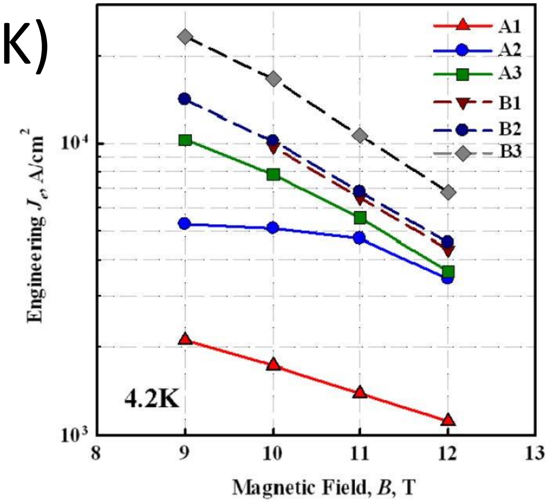
A lot of stored energy in both magnets and beams!

novel superconductor options

***MgB_2* discovered 2001**, conventional SC (T_c=39 K)

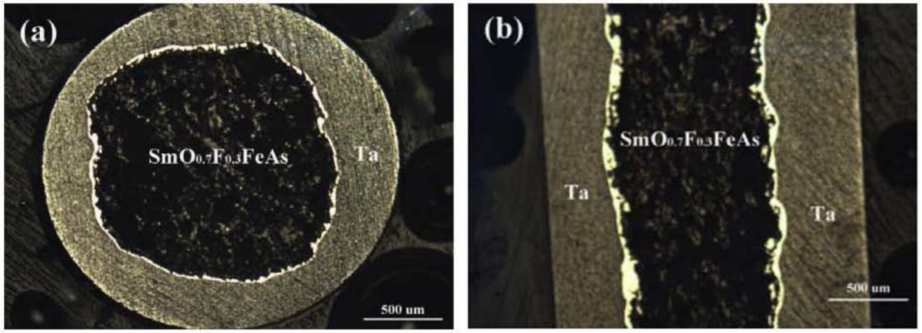


Back scattered SEM images *Mg*B_2 wires [G.Z. Li et al, Supercond. Sci. Technol. 25 (2012) 115023]

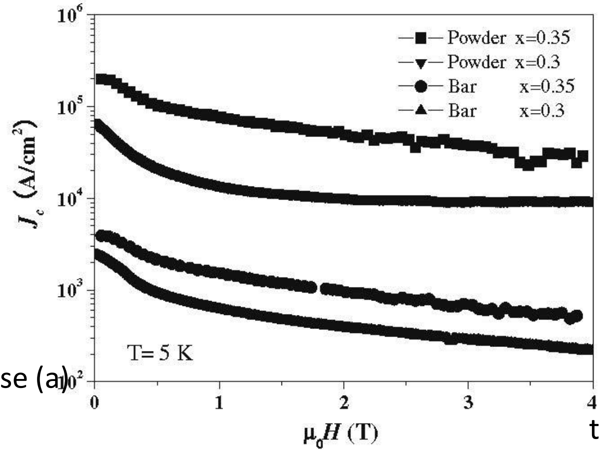


Engineering J_e versus B curves of *MgB_2* wires at 4.2 K.

iron-based SC, discovered 2006, new type of SC with high T_c



Photograph of the SmFeAsO1xFx wires. SEM images for a typical transverse (a) and a longitudinal (b) cross-section of the wire after heat treatment

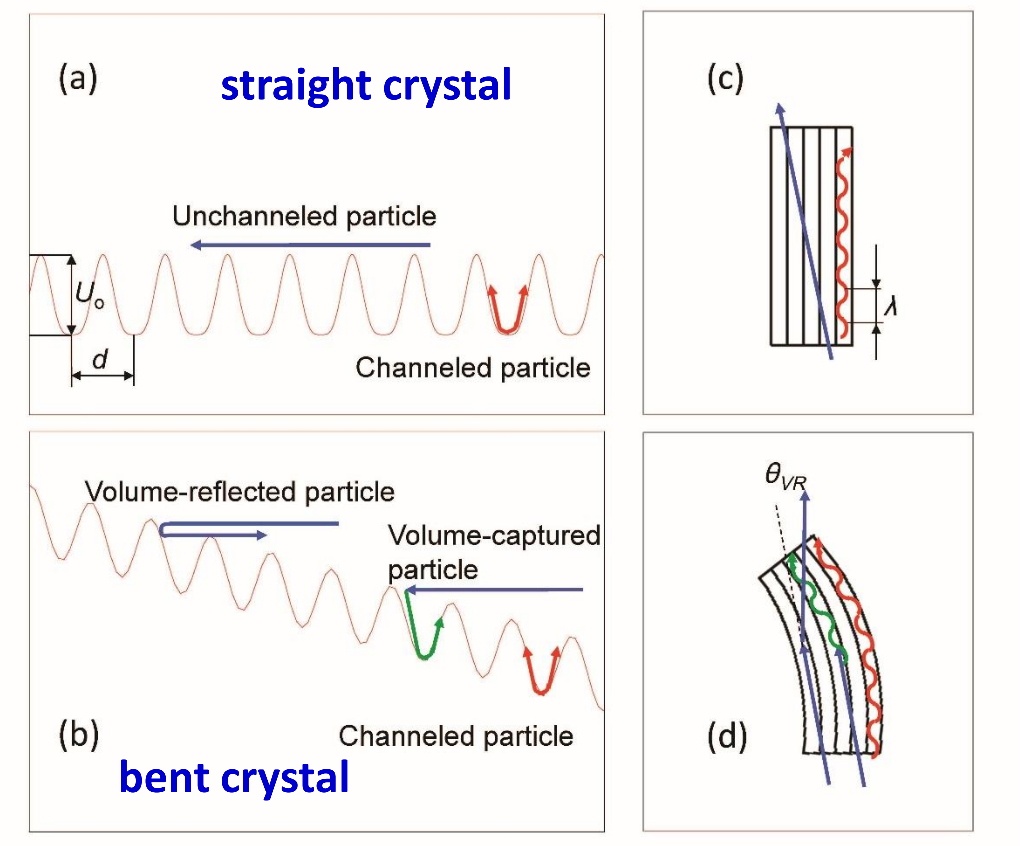


Magnetic field dependence of J_c at 5 K for the bar and powder of SmFeAsO1xFx wires [Z. Gao, et al, Supercond. Sci. Technol. 21 (2008) 112001]

thanks to E. Alp

→ magnets with higher fields or lower cost !

world’s strongest “magnets” – *crystals!*



W. Scandale, MPL A (2012)

crystal focusing strength

ϕ~20-60 eV/Å^2

B_{max}≈2000 T !

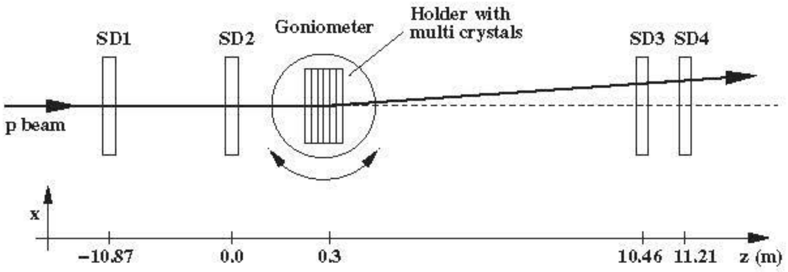
$\lambda=2\pi\beta=2\pi\ (E/\phi)^{1/2}$

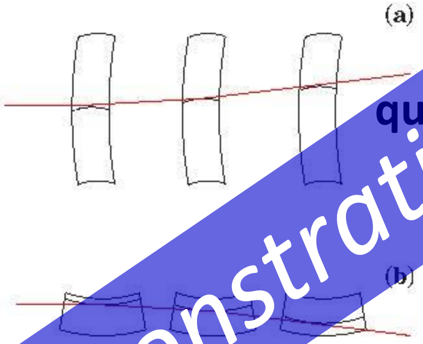
S.A. Bogacz, D. Cline, 1997

since 1978 crystals are used for extracting high-energy protons or ions from storage rings; can they be used for a circular collider?! possible problems: “**dechanneling**” due to interactions w. crystal nuclei & e$^-$; **heating**; **staging** – atomic-scale positioning?; **synchrotron radiation**

staging of crystal deflectors

proof of principle demonstration!

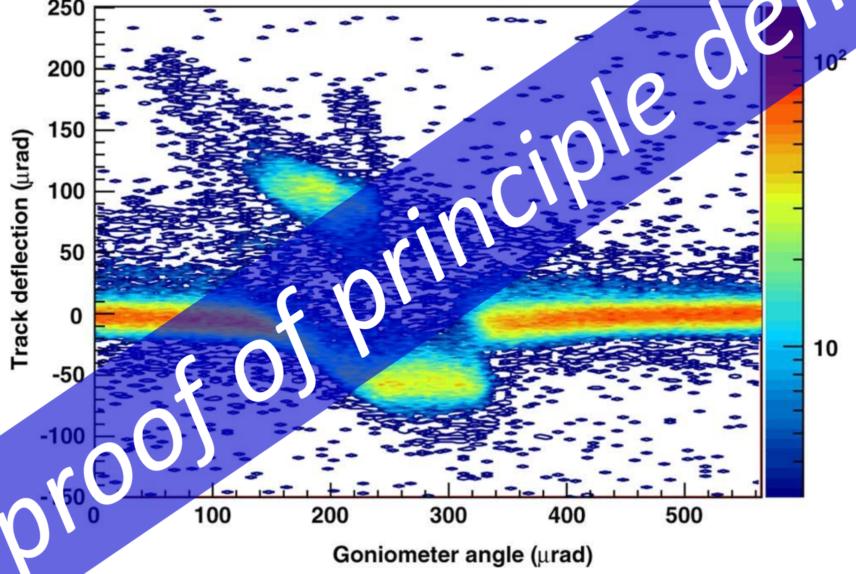




quasimosaic

strip crystals

schematic layout of the experimental setup used to study multiple volume reflection at the H8 beam line of the CERN SPS

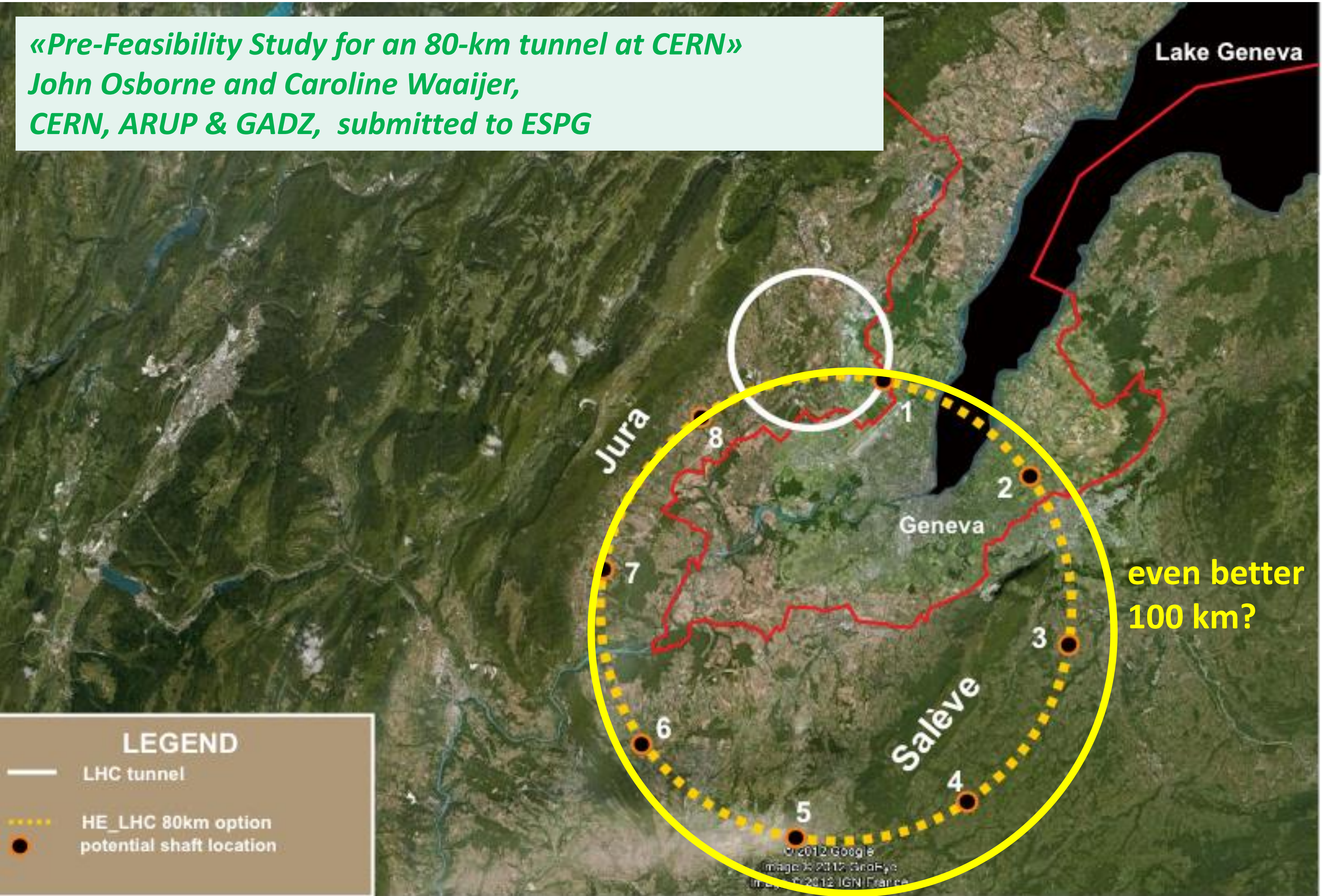


6 strip crystals in series
(each 2 mm long):
400 GeV/c protons
deflected by 40±2 μrad
[effective field 16 T]
with efficiency 0.93±0.04

W. Scandale et al, Observation of Multiple Volume Reflection of Ultrarelativistic Protons by a Sequence of Several Bent Silicon Crystals, Phys.Rev.Lett. 102 (2009) 084801

80/100km tunnel, Geneva area – “best” option

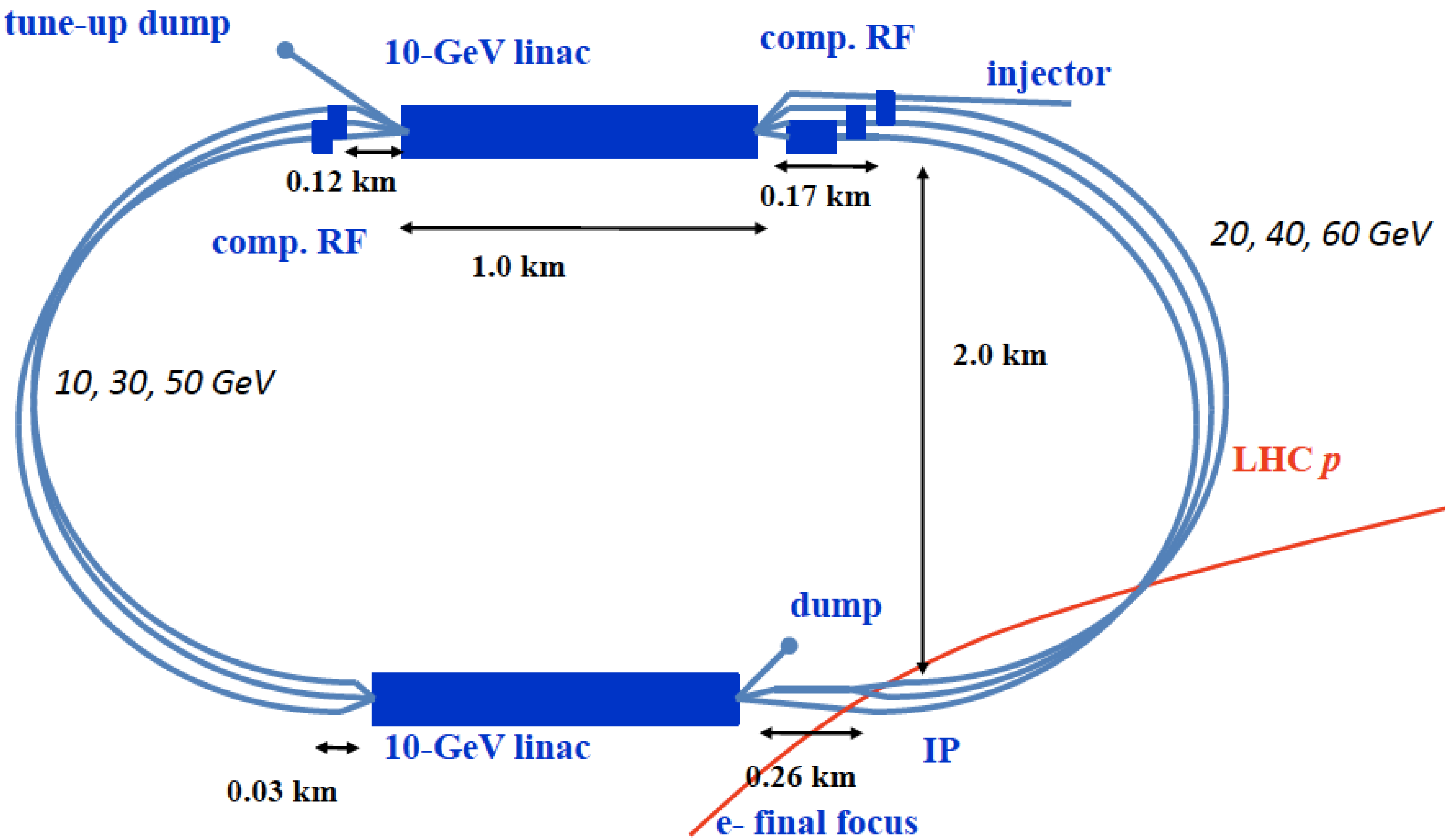
«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG



even better
100 km?

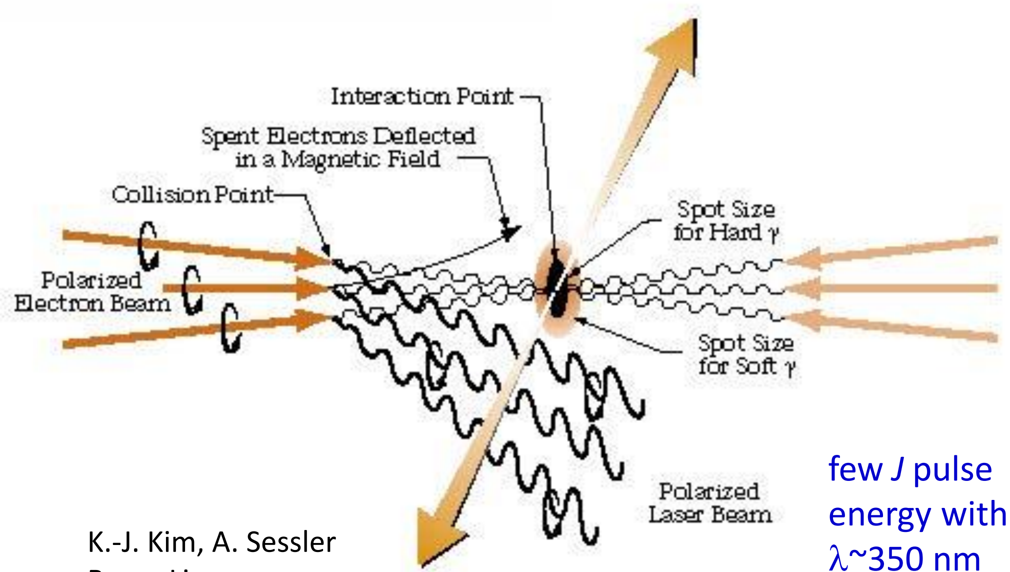
lepton-hadron colliders

MIT-SLAC (1967-73)→ HERA (1990-2007) → **LHeC** (2025-32?)



6-pass 2x10-GeV recirculating linac with energy recovery

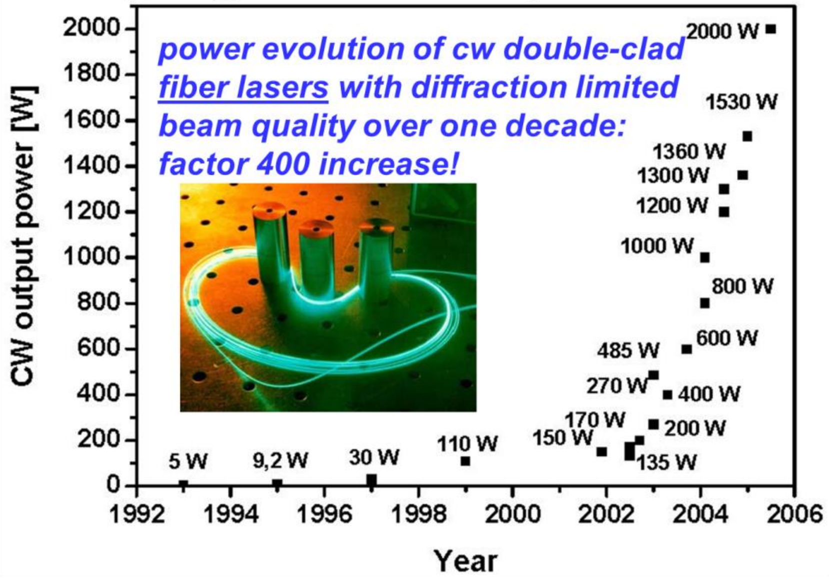
$\gamma\gamma$ colliders e^- & laser or FEL



K.-J. Kim, A. Sessler
Beam Line
Spring/Summer 1996

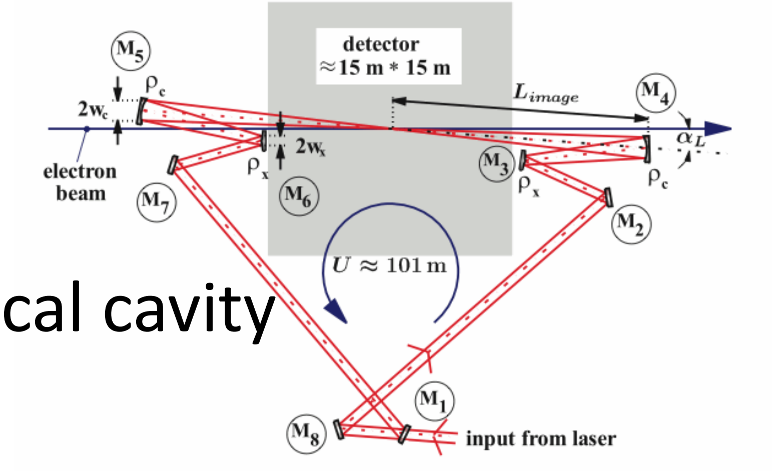
few *J* pulse energy with λ~350 nm

laser progress: example fiber laser



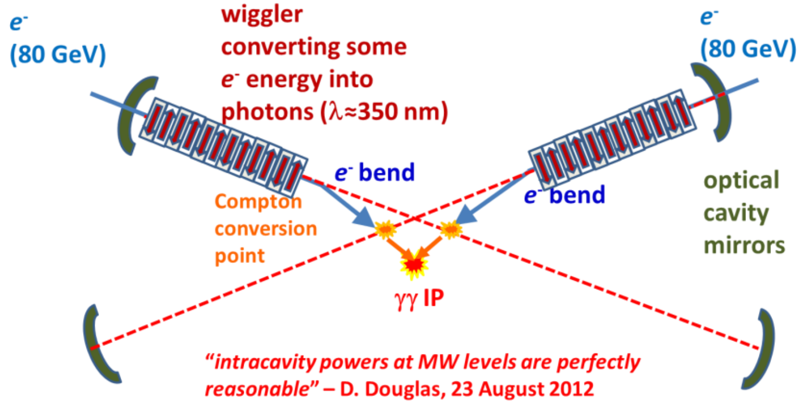
power evolution of cw double-clad fiber lasers with diffraction limited beam quality over one decade: factor 400 increase!

Source: Fiber Based High Power Laser Systems,
Jens Limpert, Thomas Schreiber, and Andreas Tünnermann



optical cavity

FEL option



"intracavity powers at MW levels are perfectly reasonable" – D. Douglas, 23 August 2012

example: λ_u=50 cm, B=5 T, L_u=50 m, 0.1%P_{beam}≈25 kW

combining photon science & particle physics!

lepton colliders

"precision instruments" (fundamental particles)

- circular colliders
  - e^+e^-
  - $\mu^-\mu^+$
- linear e^+e^- colliders
  - normal or superconducting μ-wave linac
  - dielectric or plasma-based linac
  - crystal accelerator

circular e^+e^- colliders

max. beam energy limited by synchr. radiation

$$\boldsymbol{E}_{\mathbf{max}}[100\text{ GeV}]\approx(\boldsymbol{P}_{\mathbf{SR}}[70\text{MW}]\ \rho^{\mathbf{2}}[\text{km}]/\boldsymbol{N}_{\boldsymbol{e}}[10^{12}])^{1/4}$$

SR power
~1/2 **wall plug power**
with 50% RF efficiency

bending radius
LHC: ρ≈3 km

#e±
(for luminosity)

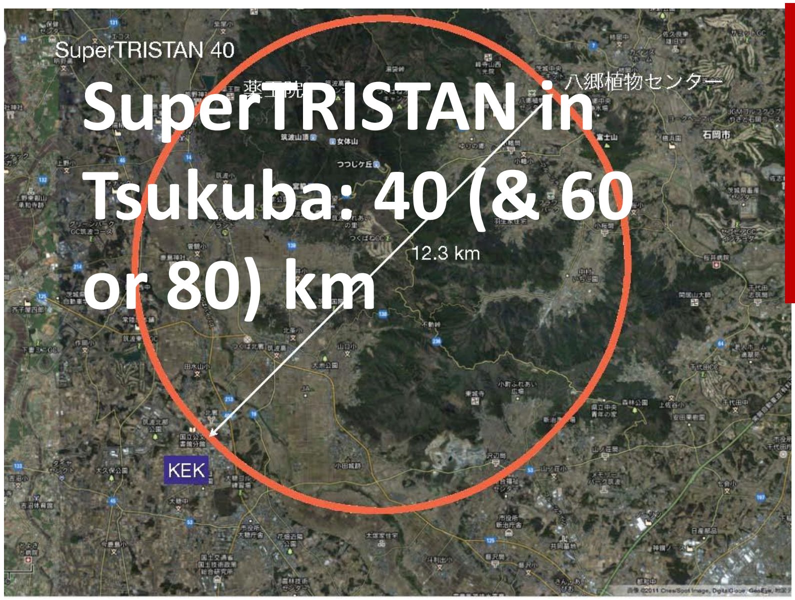
largest circular colliders:

highest energy: LEP (27 km), 104.5 GeV/beam

→ e.g. *C* = 80 or 100 km would give

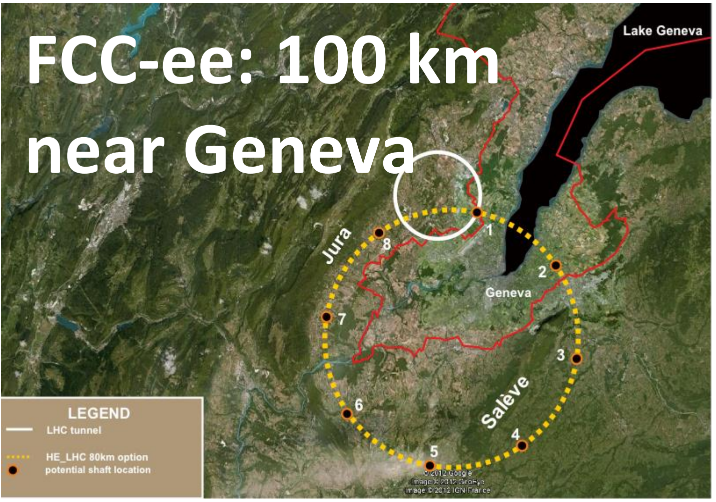
another factor 2 in beam energy, 175-200 GeV

proposed circular e^+e^- colliders



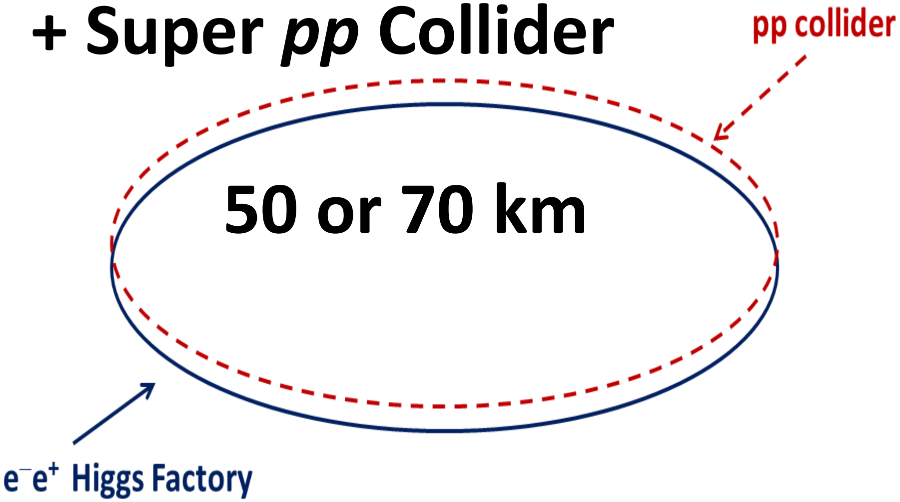
SuperTRISTAN in Tsukuba: 40 (& 60 or 80) km

SLAC/LBNL design: 27 km



FCC-ee: 100 km near Geneva

IHEP/Beijing CHF
+ Super *pp* Collider



FNAL site filler, 16 km

& FNAL VLLC 233 km ring

circular $\mu^+\mu^-$ colliders

synchrotron radiation smaller than for $e^\pm$ by factor $(m_e/m_\mu)^4 \approx 6 \times 10^{-10}$

maximum beam energy limited by ν radiation

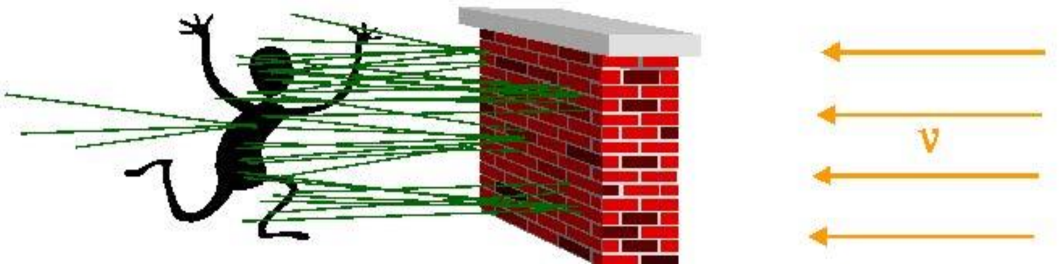
$$\boldsymbol{E}_{\mathbf{max}}[\mathrm{TeV}] \approx (\boldsymbol{D}[\mathrm{mSv/y}]\boldsymbol{L}^2[\mathrm{km}]/(\mathbf{d}\boldsymbol{N}_\mu\mathbf{/d}\boldsymbol{t}[10^{13}/\mathrm{s}]))^{1/3}$$

B. King, 1999

radiation dose / year at distance *L*

distance

#μ into collider / s



other issues:
μ production, μ cooling,
μ acceleration, …

energy limited to a few TeV

linear e^+e^- colliders

max. beam energy limited by accel. gradient

$E_{max} \approx 1/3\ G\ L$

accelerating gradient

total length

other issues:
luminosity, power, e^+ production, spot sizes, beamstrahlung (synchrotron radiation in collision),…

for example: L=30 km ; max G from surface breakdown

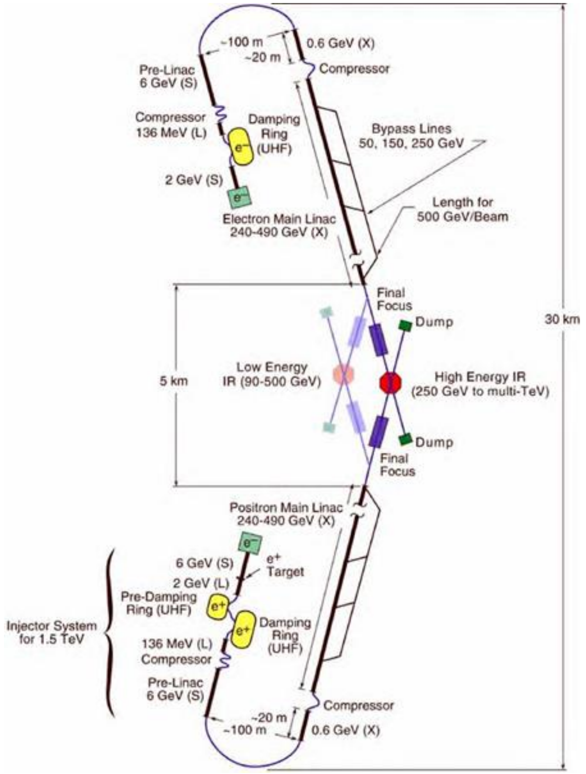
G=30 MV/m → $E_{max} \approx$ 300 GeV (SC RF)

G=100 MV/m → $E_{max} \approx$ 1 TeV (NC RF)

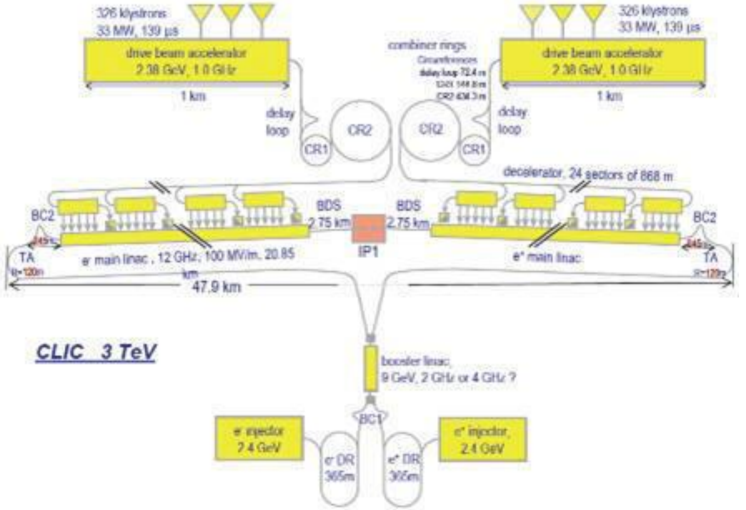
higher linear-collider energy needs higher gradients!
(dielectric, plasma, crystals … see later)

proposed linear e^+e^- or $\gamma\gamma$ colliders

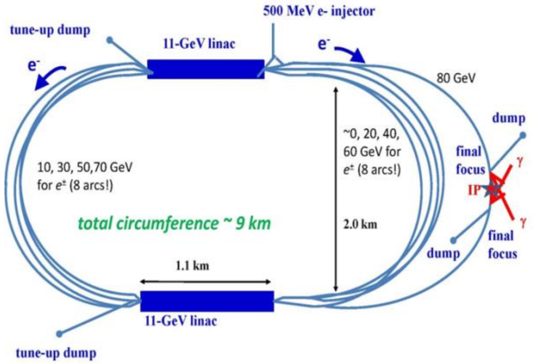
ILC (SC)
31 km
500 GeV
c.m.



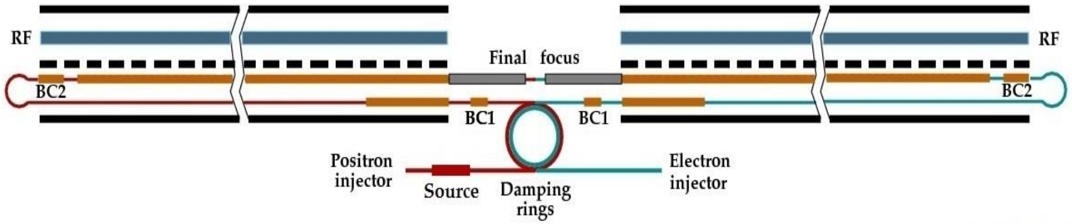
CLIC
(NC),
48 km
3 TeV
c.m.



SAPPHiRE (800-MHz SC, ERL)
2 km linac, 9 km circumference,
160 GeV c.m.:



X-band (NC), 3.6 km, 170 GeV c.m.:



dielectric & plasma accelerators

dielectric materials (quartz, diamond, garnets,….)

higher breakdown limits than metals;
dielectric structures driven in THz,
optical or near-IR regime

G=1-3 GV/m

driven by e^- beam or by laser (external fiber laser or integrated semiconductor laser)

plasma acceleration

$G \approx 100$ GV/m $(n_0\ [10^{18}\ \mathrm{cm}^{-3}])^{1/2}$; $n_0 \approx 10^{17}$-10^{18} cm^{-3}

driven by laser, e^- beam, or p beam

unlimited acceleration is predicted to be possible ?!

Kostyukov, Nerush, Litvak, 2012

crystal accelerators

acceleration in crystal channels

G≈ 10 TV/m (n_0 [10^{22} cm^{-3}])$^{1/2}$; n_0 ≈10^{22}-10^{23} cm^{-3}

driven by x-ray laser

now/soon available!

LCLS, Spring-8, XFEL, SwissFEL …

<u>max. energy</u> set by radiation emission due to betatron oscillations between crystal planes

E_{max} ≈300 GeV for e^+, 10^4 TeV μ, 10^6 TeV for p ?!

Chen & Noble 1997; Dodin & Fisch 2008; Shiltsev '12

[*is there no equivalent limit for lower-density plasmas?*]

10 TV/m – disposable crystal accelerator

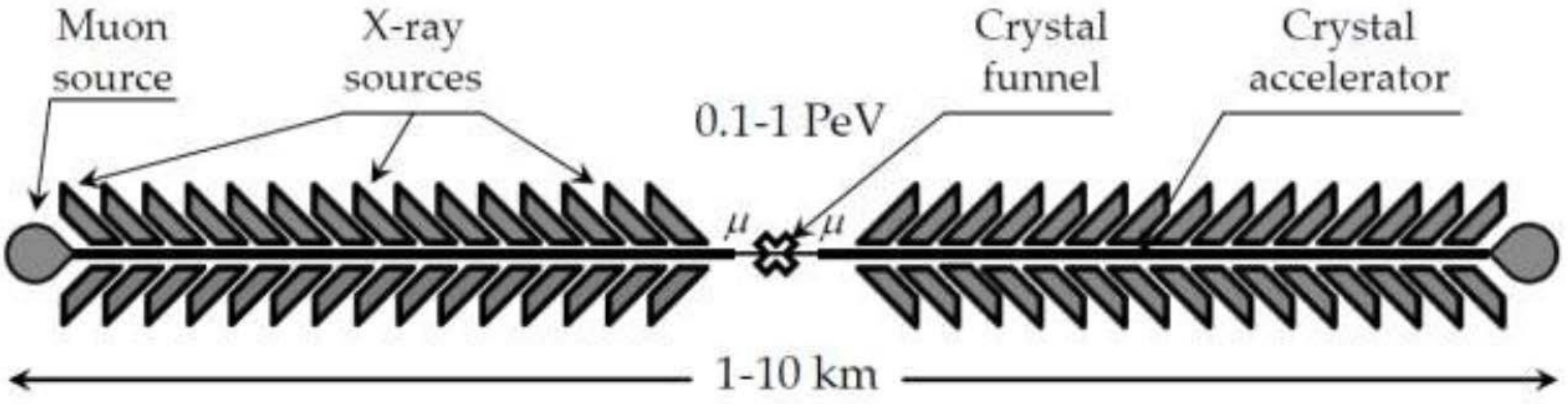
or 0.1 TV/m – reusable crystal accelerator

side injection of x-ray pulses using long fibers

$e^\pm$ may soon run out of steam in the high-gradient world!

→ need to change particle type

linear X-ray crystal μ collider

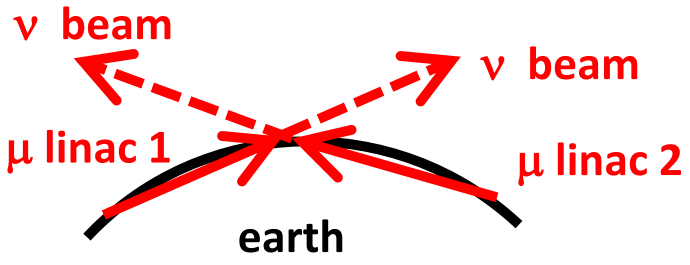


Vladimir Shiltsev, 2012

issues:

μ production rate

neutrino radiation



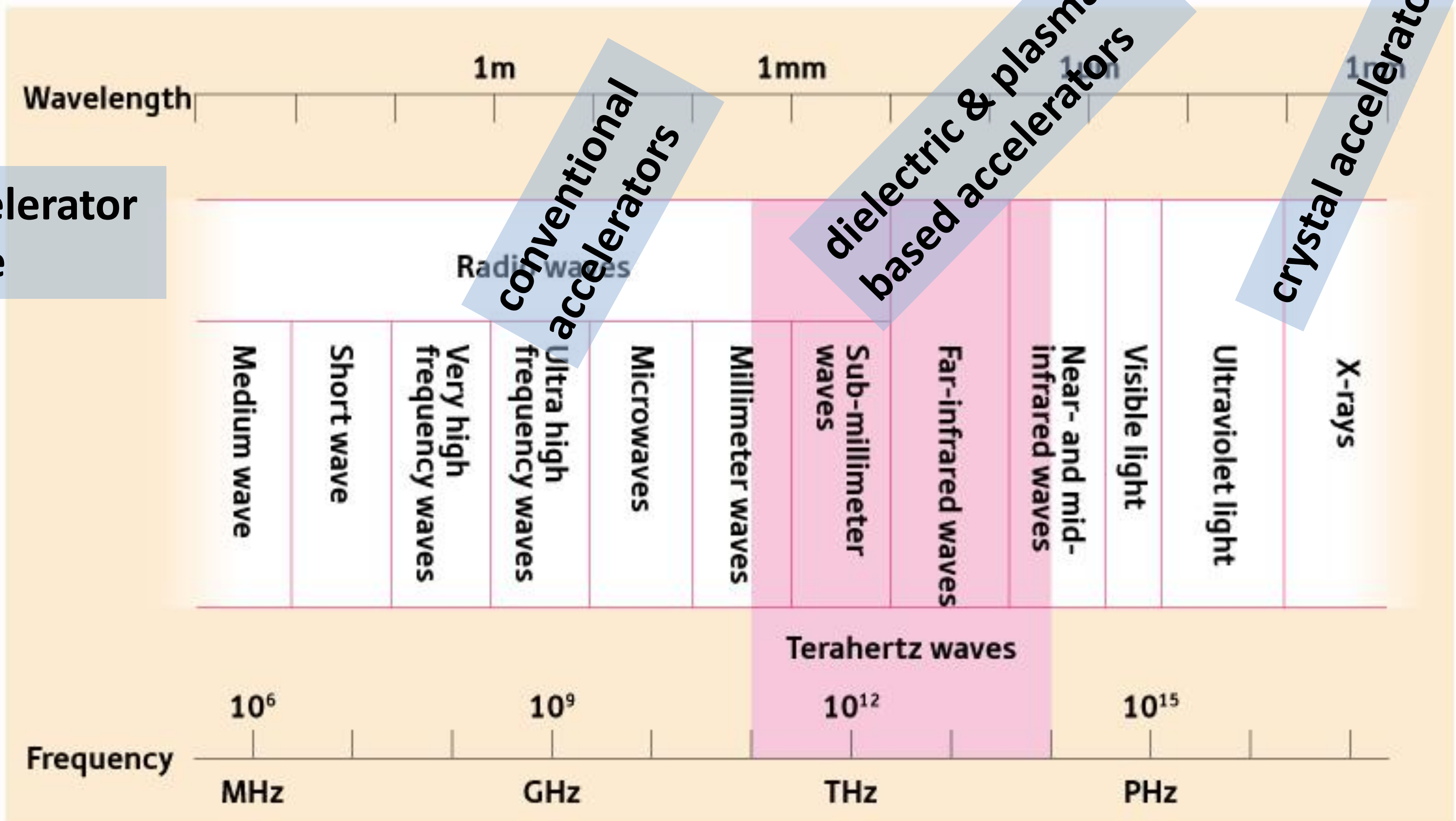
far-reach future colliders

inspired by
V. Shiltsev, 2012,
Physics-Uspekhi

	dielectric	**plasma**	**crystal**
accelerating media	micro-structures	ionized plasma	solid crystals
energy source option 1	opt. laser	*e*- bunch	x-ray laser
option 2	e^- bunch	*p* bunch	
option 3	*p* bunch	opt. laser	
preferred particles	any stable	e^-, μ-	p^+, μ^+
max. accel. gradient	1-3 GV/m	30-100 GV/m	0.1-10 TV/m
c.m. energy in 10 km	3-10 TeV	3-50 TeV	10^3-10^5 TeV
#stages/10 km option 1	10^5-10^6	~100	
option 2	10^4-10^5	10^3-10^4	~2
option 3	2-10	2-10^2	

towards shorter wavelengths

accelerator type



conventional accelerators

dielectric & plasma based accelerators

crystal accelerators

accelerator power source

tetrodes, IOTs, klystrons, solid-state amplifiers,…

e- (*p*) beam or laser

intense X-ray laser

highest-energy particles

4 July 2012 CERN, Geneva, Switzerland

Higgs boson – “God particle”? – mass 1.25×10^{11} eV, neither matter nor force!

15 October 1991 Dugway Proving Ground, Utah, U.S.A.

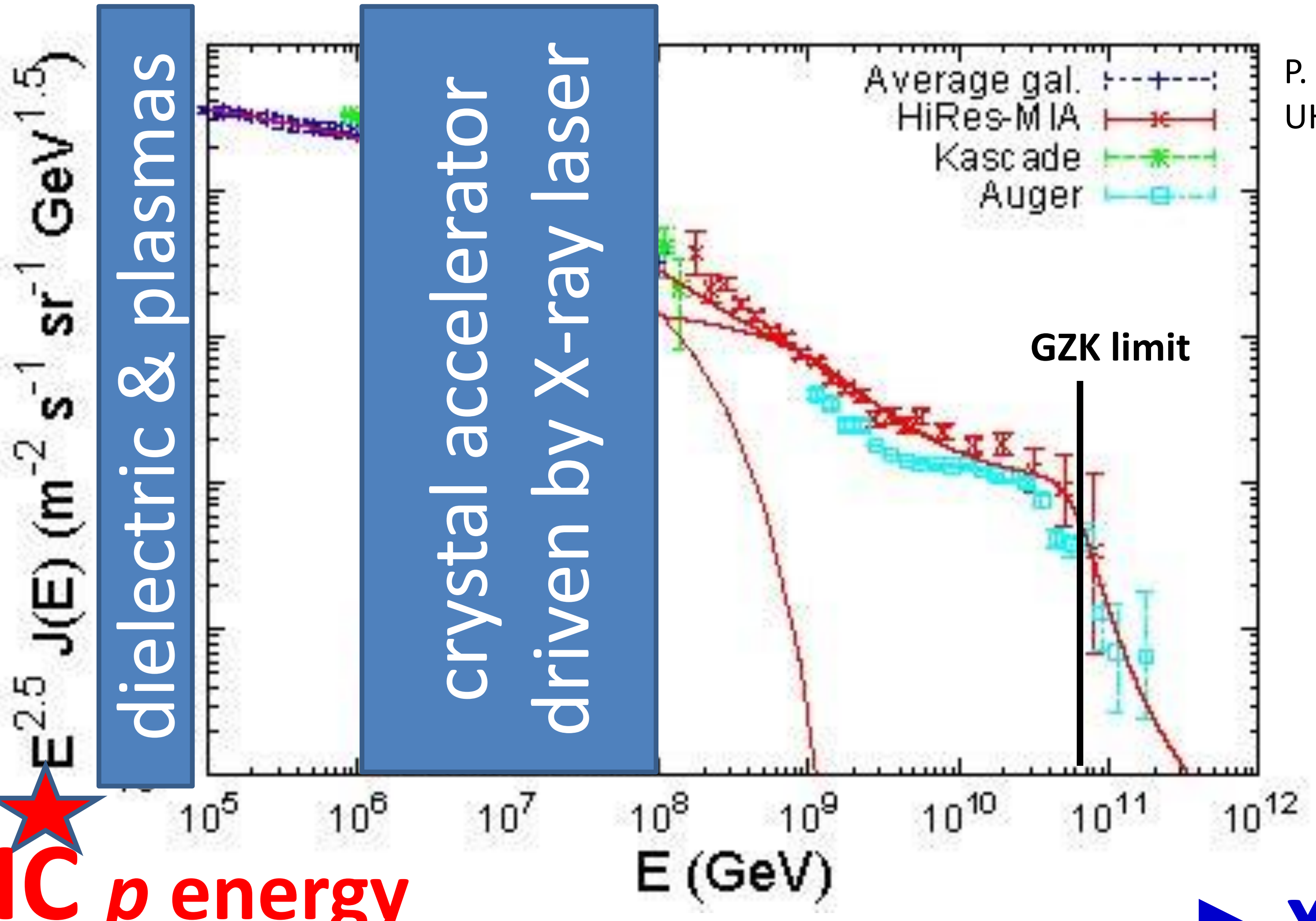
“Oh-my-God-particle”!

(kinetic) energy 3×10^{20} eV

(=3×10^{11} GeV = 300 EeV)!

10^{45} $m^{-2}s^{-1}sr^{-1}GeV^{1.5}$!

cosmic-ray energy spectrum



dielectric & plasmas

crystal accelerator driven by X-ray laser

P. Blasi,
UHECR2012

LHC *p* energy

x10^8

ultimate limit of electromagnetic acceleration

$E_{cr} \approx 10^{18}$ V/m critical field for e^+e^- pair creation - $\hbar/(m_e c)\ e\ E_{cr} \sim m_e c^2$

reaching Planck scale of 10^{28} eV would need 10^{10} m long accelerator [10^{10} m= 1/10th of distance earth-sun]

“not an inconceivable task for an advanced technological society”

P. Chen, R, Noble, SLAC-PUB-7402, April 1998

step back to 2013-2030

quo vadis, HEP?

- **LHC results**
  - 2012 discovery of Higgs boson
  - so far no indication of any new physics up to 100s of GeV
  - perhaps higher-energy run in 2015-17 will uncover new physics at 1-2 TeV
- **Higgs factory could (should?) be 1st stage of next machine**
- **different upgrade paths & strategies**

pp Higgs factories

LHC is the 1st Higgs factory!

E_{CM}=8-14 TeV, $\widehat{L} \sim 10^{34}$cm^{-2}s^{-1}

1 M Higgs produced so far – more to come!

15 H bosons / min – and more to come

HL-LHC (~2022-2030):

E_{CM}=14 TeV, $L \sim 5$x10^{34}cm^{-2}s^{-1} (leveled)

10x more Higgs

HE-LHC: in LHC tunnel (2040-?)

E_{CM}=33 TeV, $L = 5$x10^{34}cm^{-2}s^{-1}

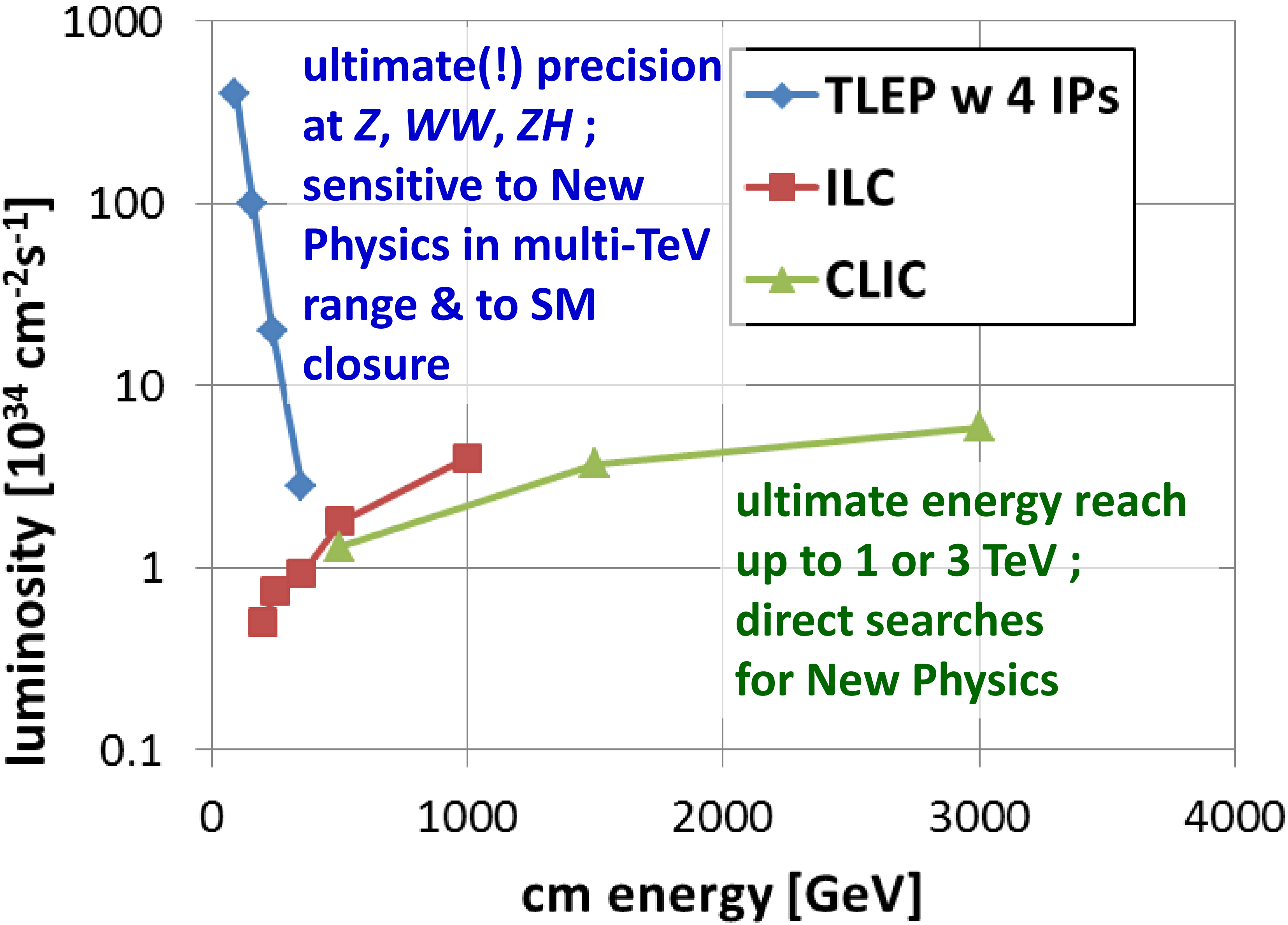
6x higher cross section for *H* self coupling

FCC-hh in new100 km tunnel (2040?)

E_{CM}=84-104 TeV, $L = 5$x10^{34}cm^{-2}s^{-1}

42x higher cross section for *H* self coupling

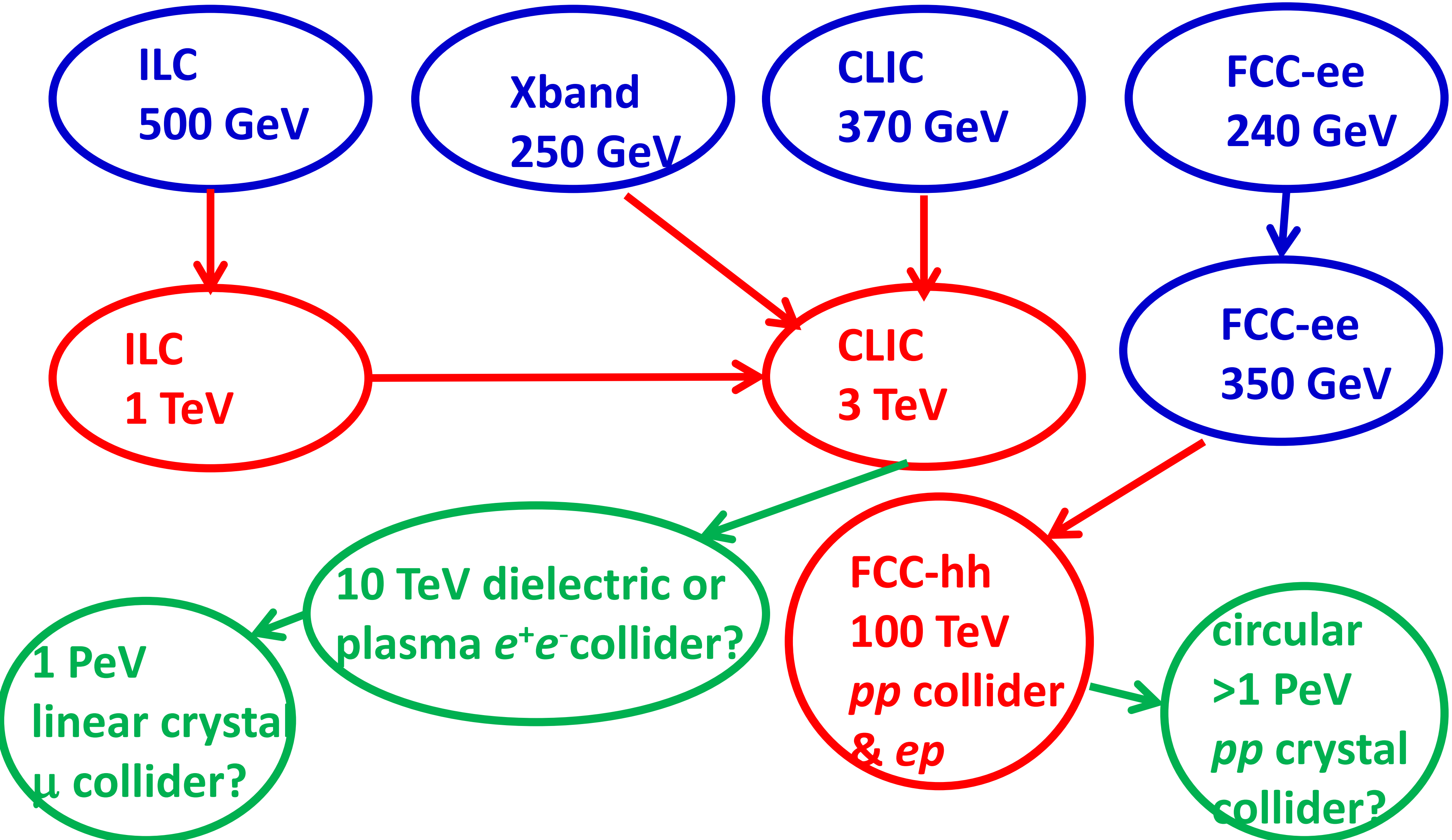
e^+e^- Higgs factories: luminosity



ultimate(!) precision at *Z*, *WW*, *ZH* ; sensitive to New Physics in multi-TeV range & to SM closure

ultimate energy reach up to 1 or 3 TeV ; direct searches for New Physics

proposed e^+e^- Higgs factories & possible 1st & 2nd upgrades



ILC
500 GeV

Xband
250 GeV

CLIC
370 GeV

FCC-ee
240 GeV

ILC
1 TeV

CLIC
3 TeV

FCC-ee
350 GeV

10 TeV dielectric or plasma e^+e^- collider?

FCC-hh
100 TeV
pp collider
& *ep*

1 PeV
linear crystal
μ collider?

circular
>1 PeV
pp crystal
collider?

possible long-term strategy - 1

ILC
500 GeV
SC 1.3 GHz
klystrons
31.5 MV/m
31 km

ILC
1 TeV
SC 1.3 GHz
klystrons
45 MV/m?
41 km

CLIC
3 TeV
drive beam
NC 12 GHz
100 MV/m
48 km

DWAC
10 TeV
drive beam
D 26 GHz
270 MV/m
48 km

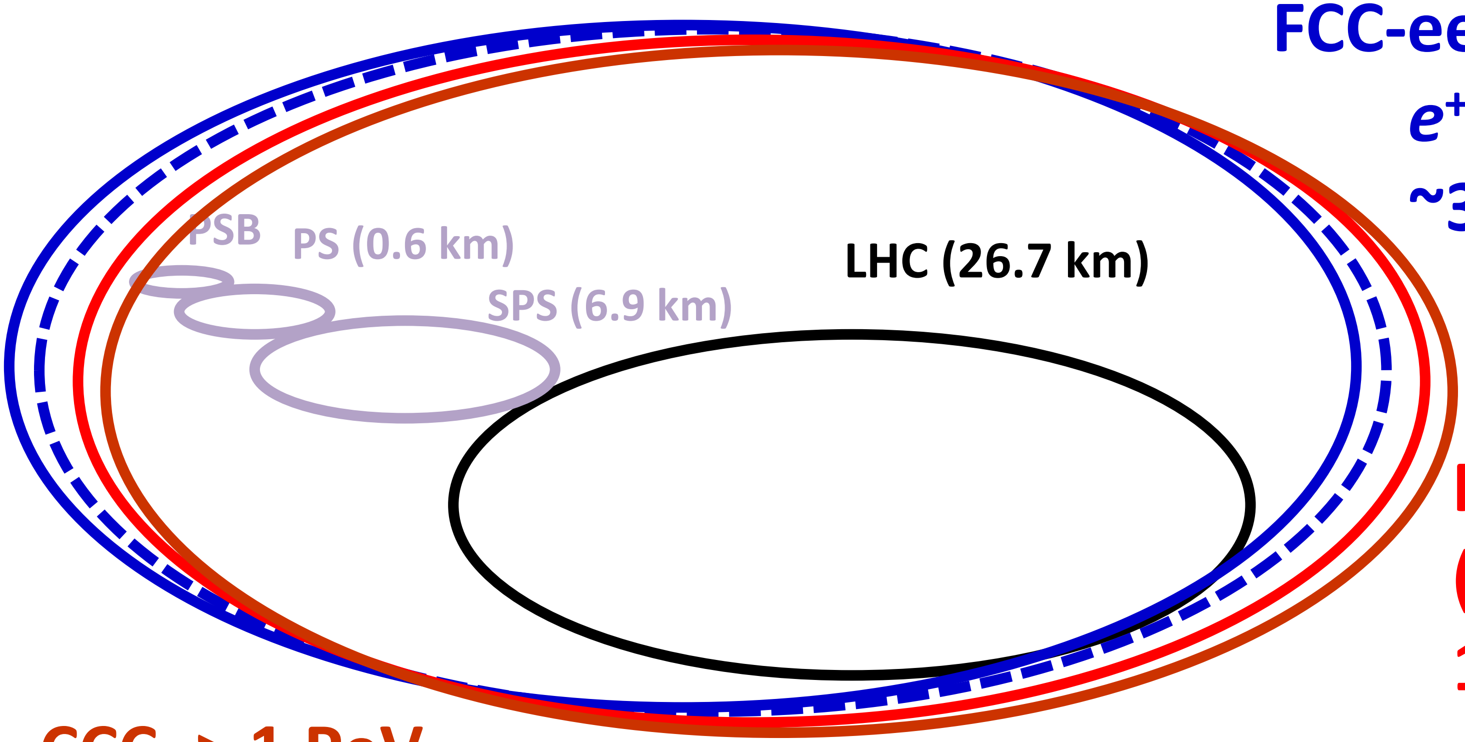
XRCMC
1000 TeV,
drive
beam for
X-ray
lasers,
crystal
27 GV/m
48 km

e^+e^- collisions up 10 TeV c.m.

1 PeV $\mu^+\mu^-$
collisions

possible long-term strategy - 2

(CERN implementation)



**FCC-ee (100 km,
e^+e^-, up to
~350 GeV c.m.)**

**FCC-hh
(*pp*, up to
100 TeV c.m.)**

“same” detectors!

CCC, > 1 PeV

& $e^{\pm}$ **(120 GeV) –** p **(7, 16 & 50 TeV)** collisions (**[(V)HE-]TLHeC)**

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

followed by >1 PeV circular crystal collider (CCC)?!

conclusions

bright future for accelerator-based HEP!

- accelerators getting cheaper
- new technologies emerging

several different routes to 10-TeV/100-TeV & 1 PeV collisions

e.g. linear path: ILC→CLIC →DWAC→ XRCMC

circular path:TLEP→VHE-LHC→CCC

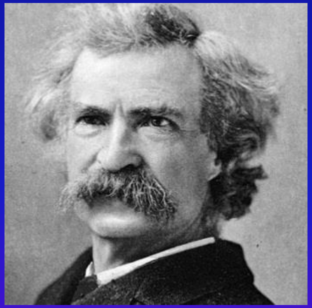
crystals may be key for both

bending and/or acceleration

eventually outer-space solar-system accelerator needed to reach Planck mass

is future circular or linear or both?

“A circle is a round straight line with a hole in the middle.”



Mark Twain,
in "English as She Is Taught",
Century Magazine, May 1887