



U.S. DEPARTMENT OF
ENERGY

Office of
Science

Will There Be Energy Frontier Colliders After the LHC?

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Will There Be Energy Frontier Colliders After LHC?

*"Any headline that ends in a question mark
can be answered by the word **NO.**"*



WIKIPEDIA
The Free Encyclopedia

Betteridge's law of headlines

Ian Betteridge, a British technology journalist

Hinchliffe's rule

particle physicist Ian Hinchliffe

Davis' law

(who's Davis ?)

(Yes or No) = (Physics × Feasibility)

- **PHYSICS** case of post-LHC high energy physics machine depends on the LHC discoveries:
 - it might call for a collider (if signals are clear)
 - otherwise, search for signs of new physics in the neutrino/rare decays (*Intensity Frontier*) or astrophysics
- **FEASIBILITY** of an accelerator is actually complex:
 - Feasibility of **ENERGY**
 - Is it possible to reach the E of interest / what's needed ?
 - Feasibility of **PERFORMANCE**
 - Will we get enough physics out there / luminosity ?
 - Feasibility of **COST**
 - Is it affordable to build and operate ?
- **What can we learn/take from the past/present?**

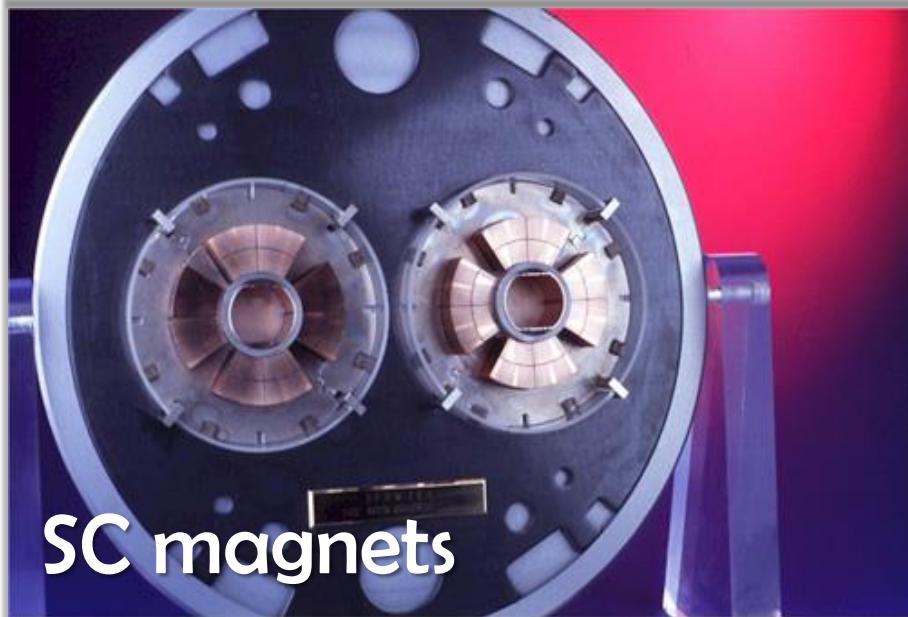
Four “Feasible” Technologies



Normal Conducting Magnets



Normal Conducting RF



SC magnets



SC RF

Analysis:

2014 JINST 9 T07002

17 “Data Points” - Costs of Big Accelerators:

- Actually built:
 - RHIC, MI, SNS, LHC
- Under construction:
 - XFEL, FAIR, ESS
- Not built but costed:
 - SSC, VLHC, NLC
 - ILC, TESLA, CLIC, Project-X, Beta-Beam, SPL, v-Factory

Wide range :

- 4 orders in Energy, >1 order in Power, >2 orders in Length
- Almost 2 orders in cost
 - (normalized to US TPC)

	Cost (B\$) Year	Energy (TeV)	Accelerator technology	Comments	Length (km)	Site power (MW)	TPC range (Y14 B\$)
SSC	11.8 B\$ (1993)	40	SC Mag	Estimates changed many times [6–8]	87	~ 100	19–25
FNAL MI	260M\$ (1994)	0.12	NC Mag	“old rules”, no OH, existing injector [9]	3.3	~ 20	0.4–0.54
RHIC	660M\$ (1999)	0.5	SC Mag	Tunnel, some infrastructure, injector re-used [10]	3.8	~ 40	0.8–1.2
TESLA	3.14 B€ (2000)	0.5	SC RF	“European accounting” [11]	39	~ 130	11–14
VLHC-I	4.1 B\$ (2001)	40	SC Mag	“European accounting”, existing injector [12]	233	~ 60	10–18
NLC	~ 7.5 B\$ (2001)	1	NC RF	~ 6 B\$ for 0.5 TeV collider, [13]	30	250	9–15
SNS	1.4 B\$ (2006)	0.001	SC RF	[14]	0.4	20	1.6–1.7
LHC	6.5 BCHF (2009)	14	SC Mag	collider only — existing injector, tunnel & infrstr., no OH, R&D [15]	27	~ 40	7–11
CLIC	7.4–8.3B CHF(2012)	0.5	NC RF	“European accounting” [16]	18	250	12–18
Project X	1.5 B\$ (2009)	0.008	SC RF	[17]	0.4	37	1.2–1.8
XFEL	1.2 B€ (2012)	0.014	SC RF	in 2005 prices, “European accounting” [18]	3.4	~ 10	2.9–4.0
NuFactory	4.7–6.5 B€ (2012)	0.012	NC RF	Mixed accounting, w. contingency [19]	6	~ 90	7–11
Beta-Beam	1.4–2.3 B€ (2012)	0.1	SC RF	Mixed accounting, w. contingency [19]	9.5	~ 30	3.7–5.4
SPL	1.2–1.6 B€ (2012)	0.005	SC RF	Mixed accounting, w. contingency [19]	0.6	~ 70	2.6–4.6
FAIR	1.2 B€ (2012)	0.003–0.08	SC Mag	“European accounting” [20], 6 rings, existing injector	~ 3	~ 30	1.8–3.0
ILC	7.8 B\$ (2013)	0.5	SC RF	“European accounting” [21]	34	230	13–19
ESS	1.84 B€ (2013)	0.0025	SC RF	“European accounting” [22, 23]	0.4	37	2.5–3.8

! WARNING!

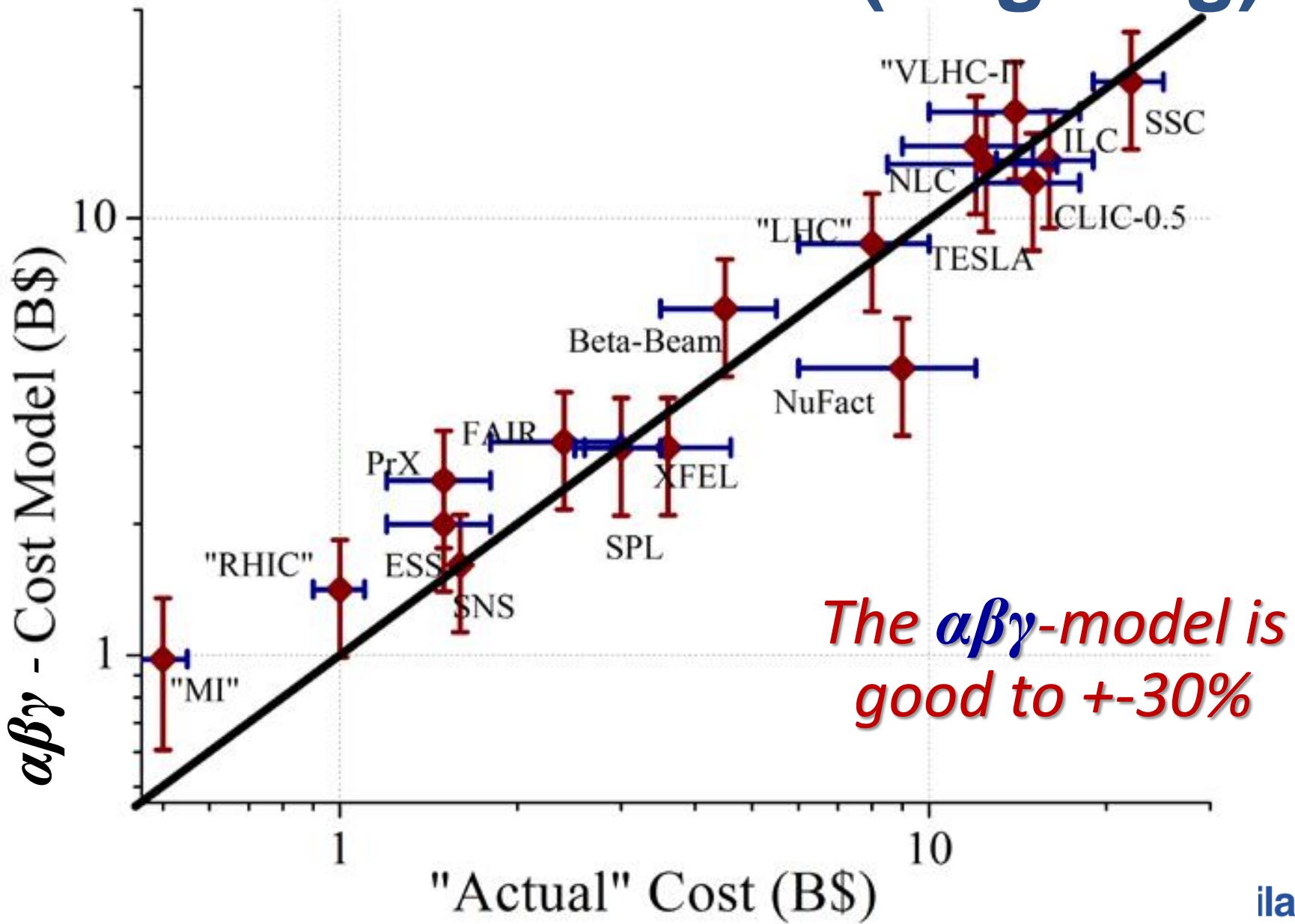
$\alpha\beta\gamma$ - Cost Estimate Model:

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

- a) $\pm 33\%$ estimate, for a “green field” accelerators
- b) “US-Accounting” = TPC ! ($\sim 2 \times$ European Accounting)
- c) Coefficients (units: 10 km for L , 1 TeV for E , 100 MW for P)
 - $\alpha \approx 2 \text{B\$}/\text{sqrt}(L/10 \text{ km})$
 - $\beta \approx 10 \text{B\$}/\text{sqrt}(E/\text{TeV})$ for SC/NC RF
 - $\beta \approx 2 \text{B\$}/\text{sqrt}(E/\text{TeV})$ for SC magnets
 - $\beta \approx 1 \text{B\$}/\text{sqrt}(E/\text{TeV})$ for NC magnets
 - $\gamma \approx 2 \text{B\$}/\text{sqrt}(P/100 \text{ MW})$

USE AT YOUR OWN RISK!

Total Cost vs Model (Log-Log)



Illustrations

Comment:

Sqrt-functions are quite accurate over wide range because such dependence well approximates the “*initial cost*” – effect :

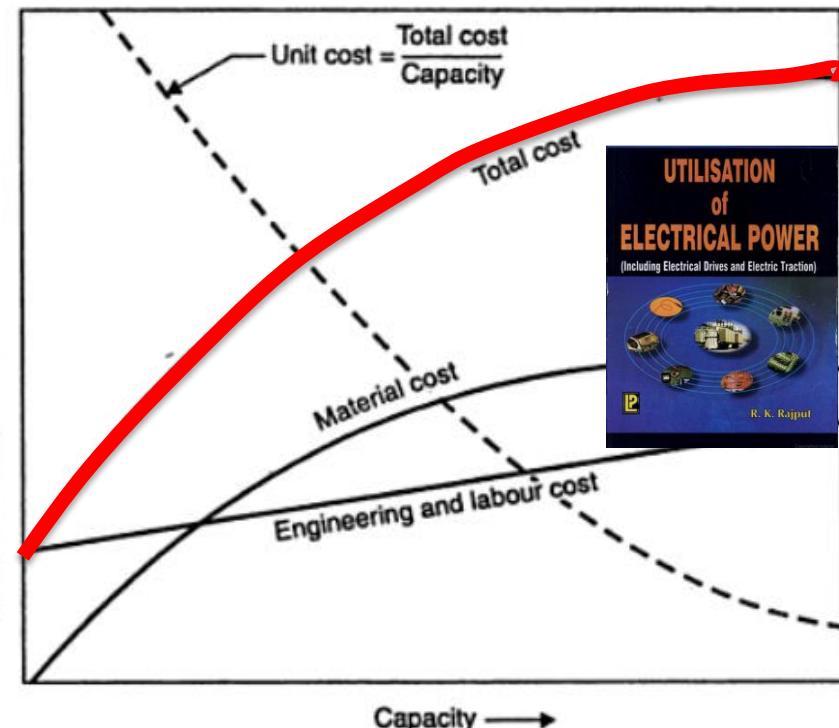
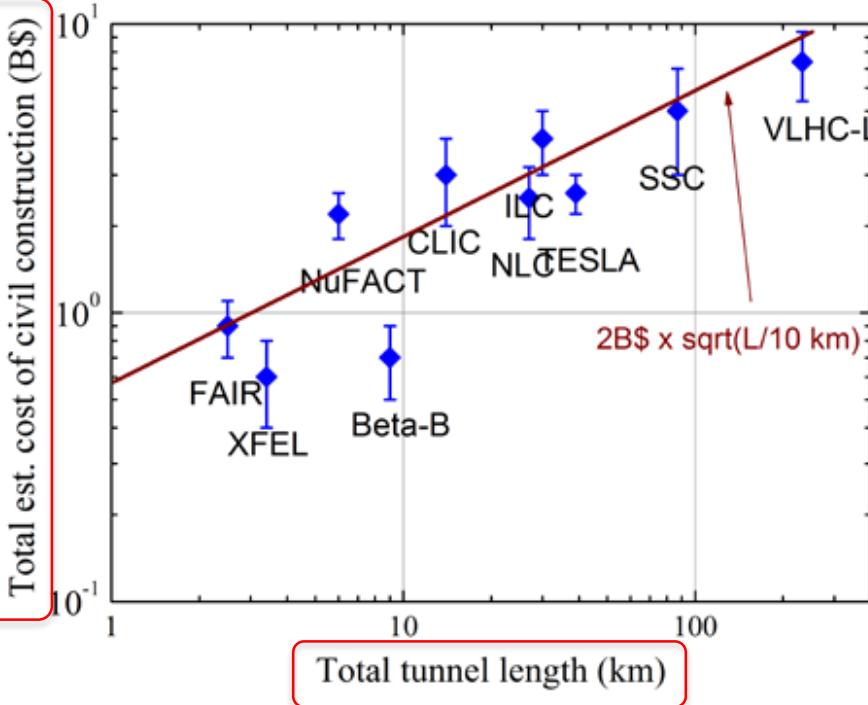
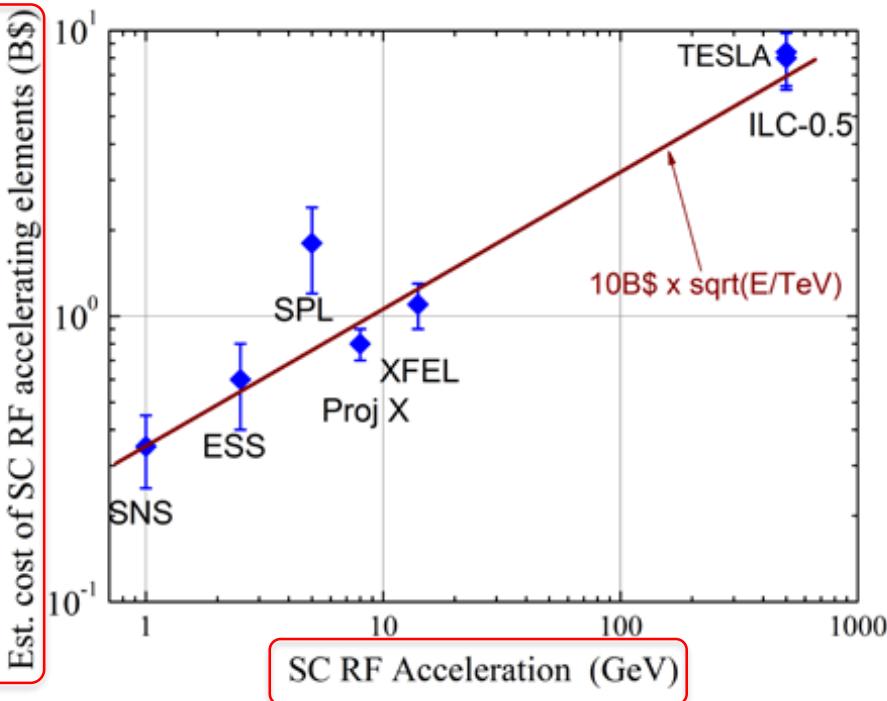


Fig. 9.5. Variation of costs of power plant versus its capacity.

Take LHC as an Example:

- **$\alpha\beta\gamma$ – Model:**

- 40 km of tunnels
- 14 TeV c.o.m SC magnets
- ~150 MW of site power

$$2\sqrt{40/10} = 4$$

$$2\sqrt{14} = 7.5$$

$$2\sqrt{150/100} = 2.5$$

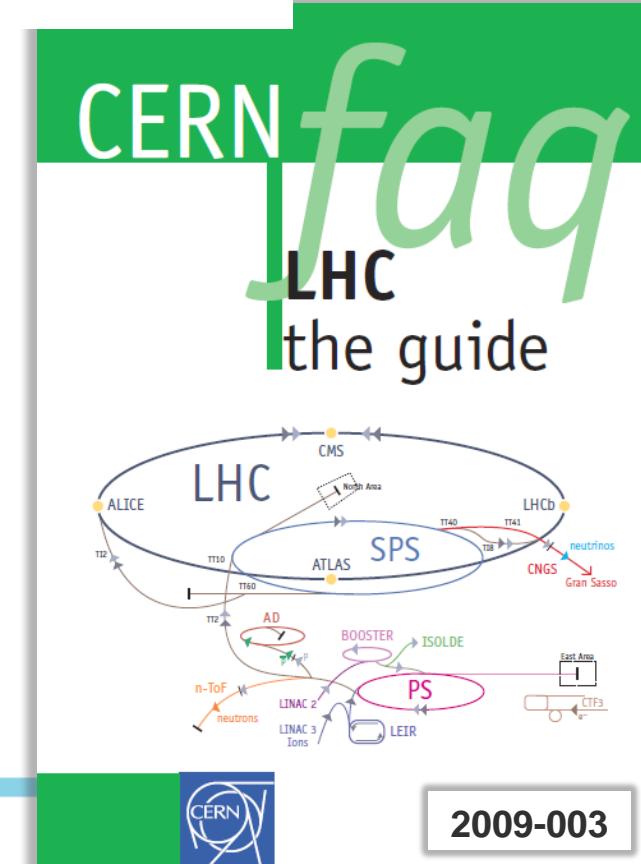
TOTAL PROJECT COST : **14B\$ ± 4.5B\$**

- **CERN LHC Factbook (2009):**

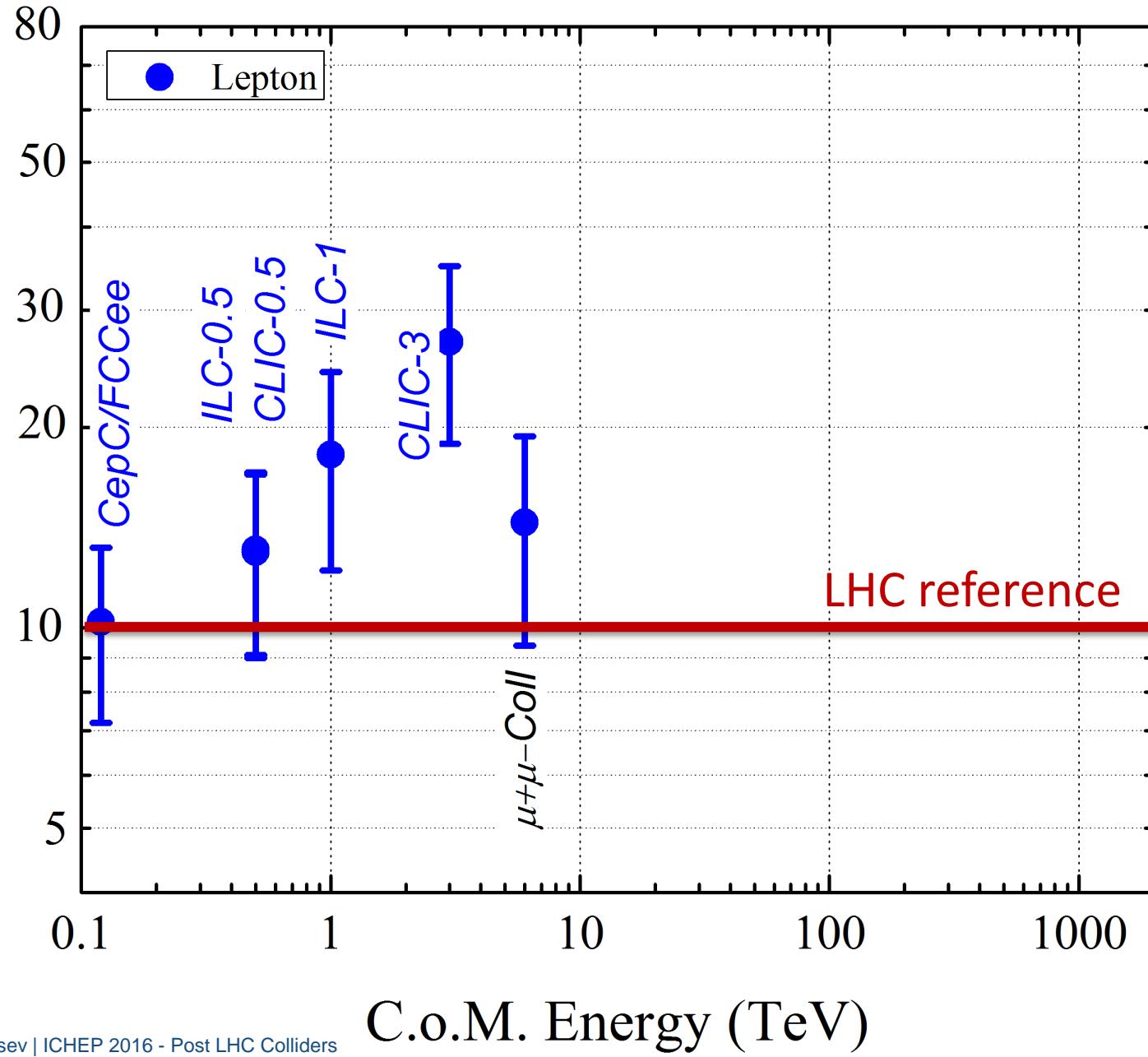
- 6.5 BCHF, incl. **5 BCHF** for accelerator
(European Accounting)
- x 2 to US TPC → **10 BCHF=10B\$**
- Cost of existing injector complex
~30-40% **3-4 B\$**

TPC : ~13-14B\$

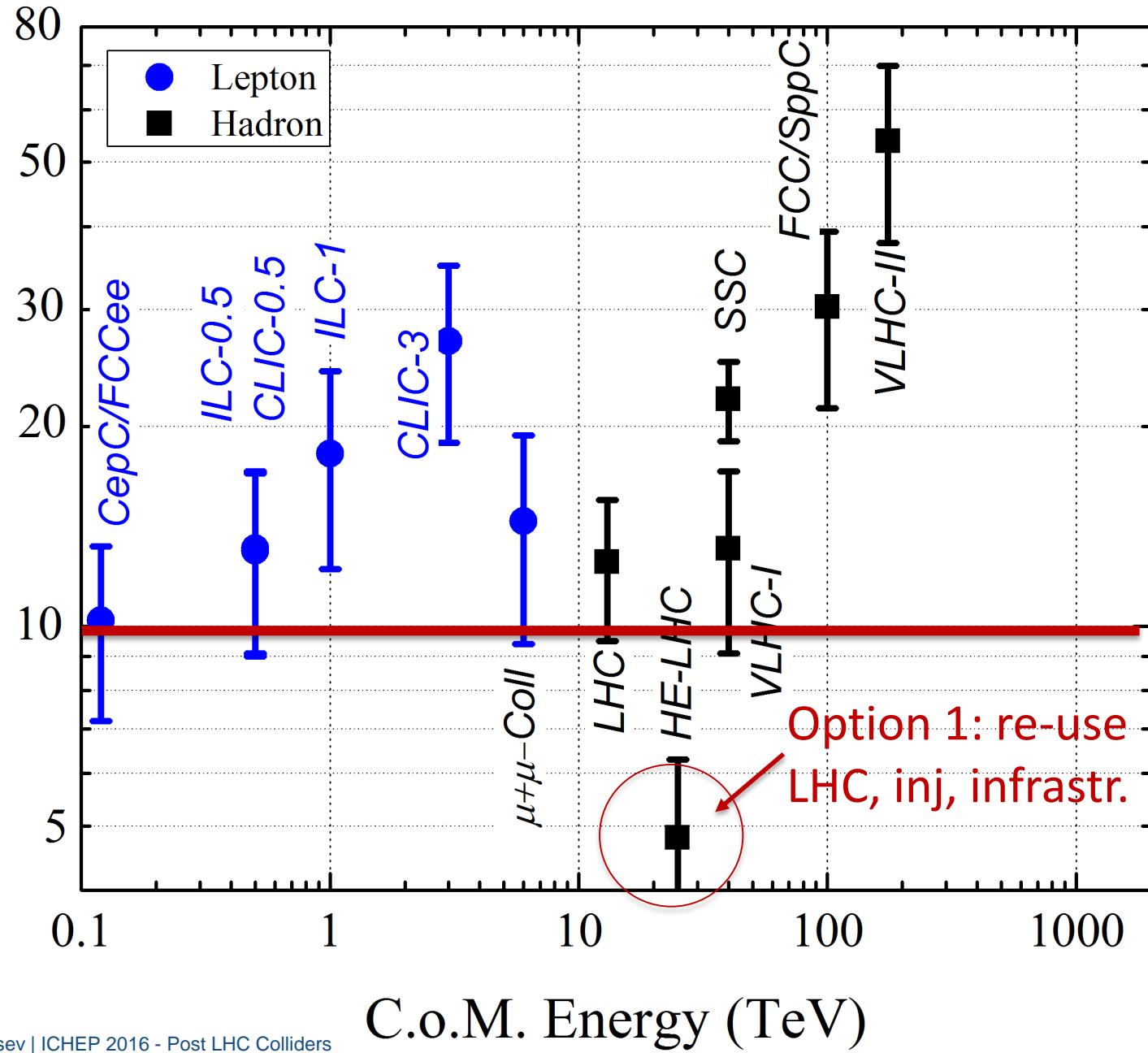
(of which CERN paid 10 over ~8 yrs)



Cost Estimate (2016 B\$ TPC)

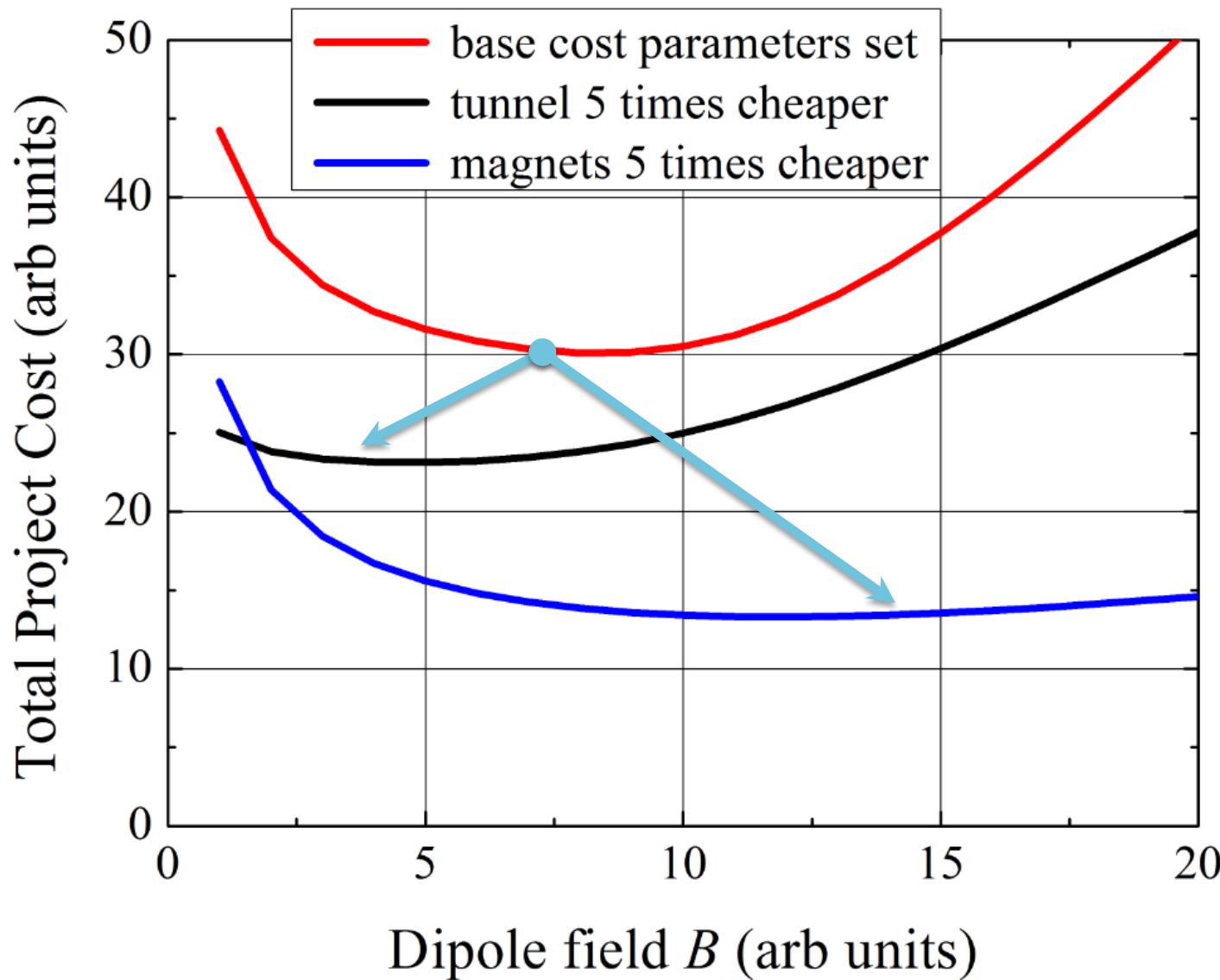


Cost Estimate (2016 B\$ TPC)



Option 2 : Develop Technology to Lower Cost

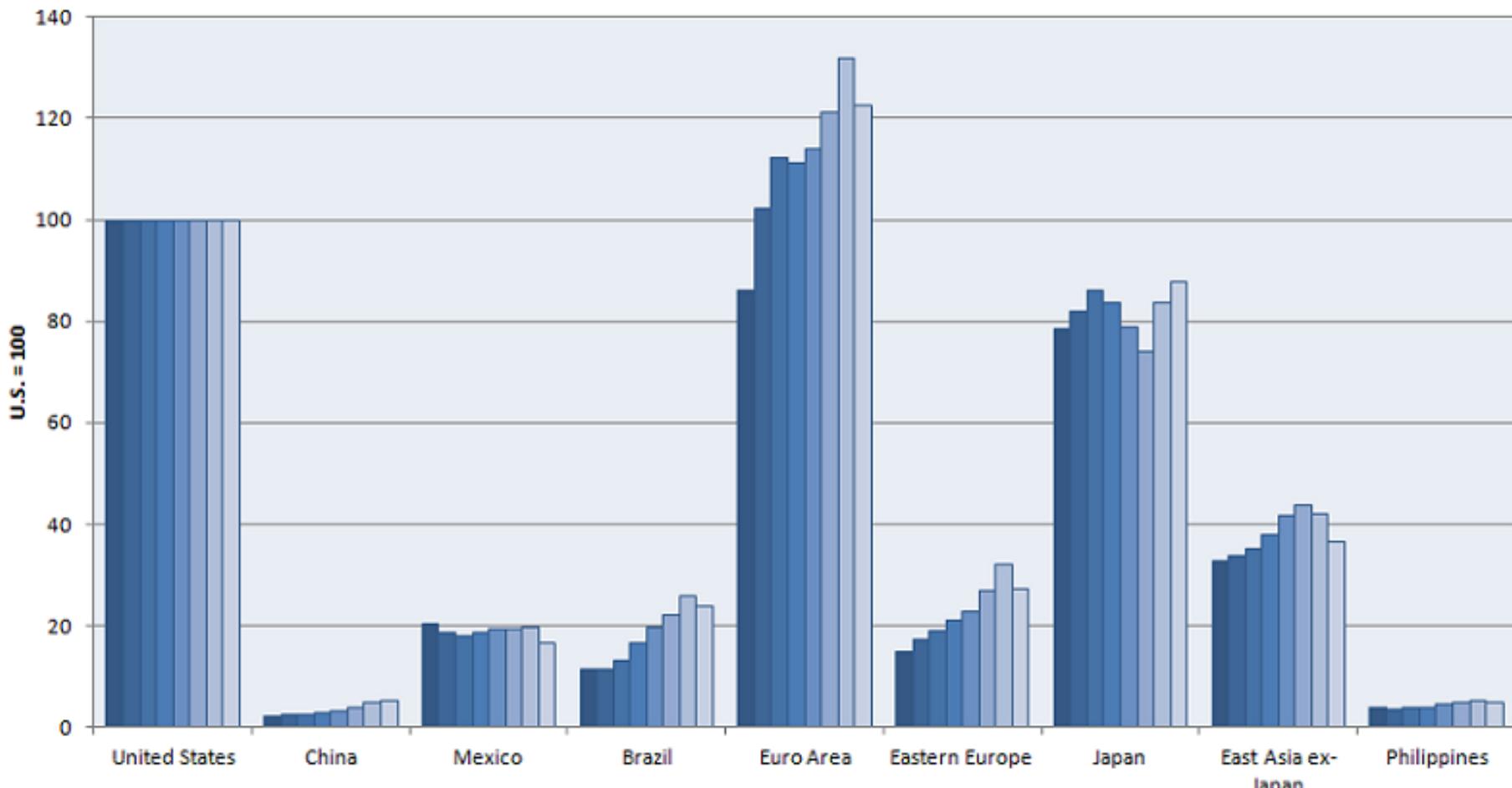
100 TeV pp : Qualitative Cost Dependencies



* for illustration purposes only

Option 3: “Move to China !”

Average hourly compensation costs of manufacturing employees,
selected economies and regions, 2002-2009



Note: For a description of the economic groups, see the technical notes at www.bls.gov/ilc/ichccn.pdf, Table 2.

Source: U.S. Bureau of Labor Statistics, International Labor Comparisons.

SSRF China



- 432 m
 - 3.5 GeV
 - 1.2B RMB
- 2007

Account infl'n, convert to USD and scale to $\sqrt{1 \text{ km}}$:

350 M\$

772 M\$

1040 M\$

1024 M\$

Spring-8 Japan



- 1436 m
 - 8 GeV
 - 11 BY
- 1997

Diamond UK



- 562 m
 - 3 GeV
 - 383 M £
- 2007

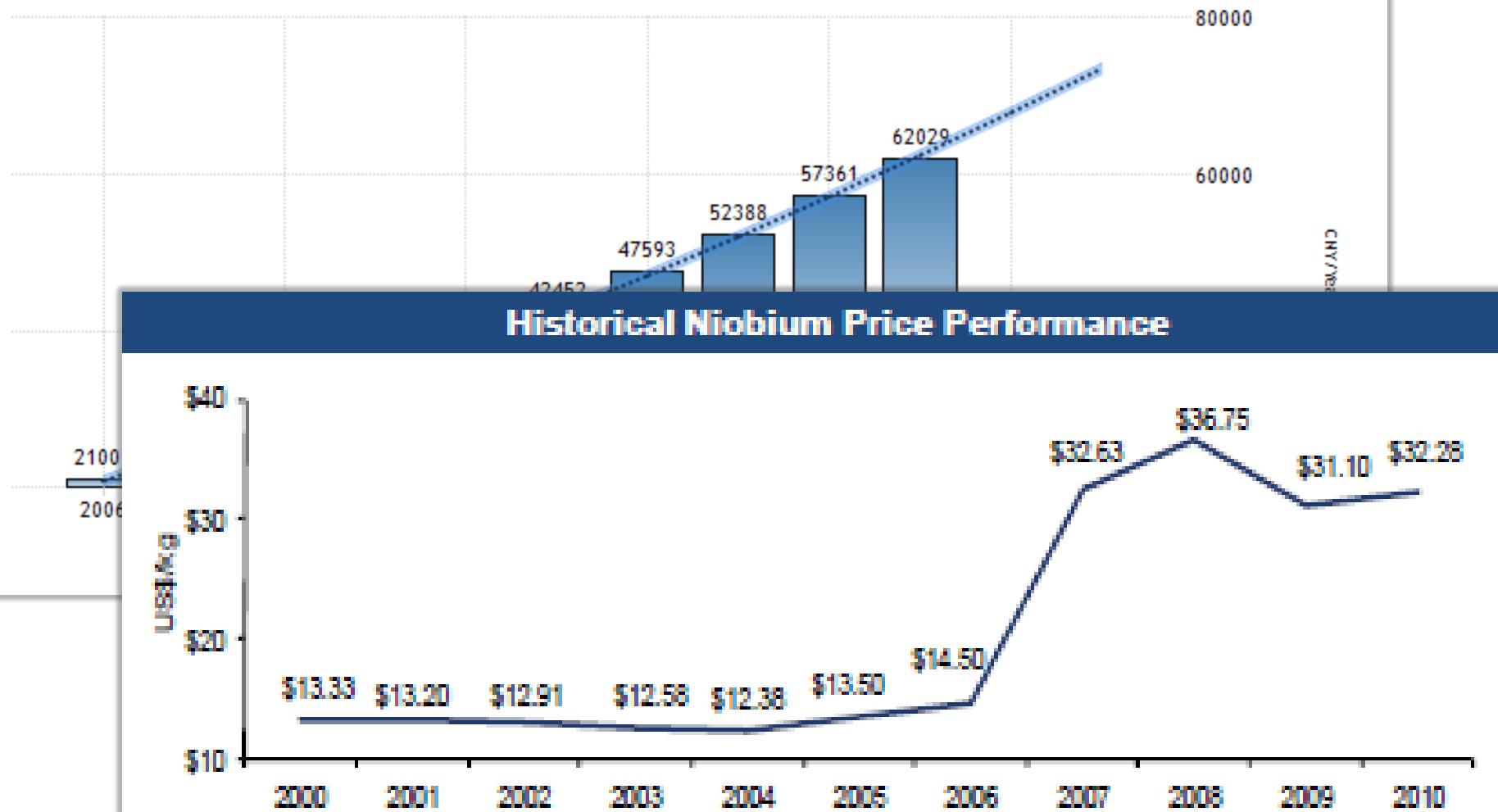
NSLSII USA



- 792 m
 - 3 GeV
 - 912 M\$
- 2015

“Move to China !” - Caveats

CHINA AVERAGE YEARLY WAGES

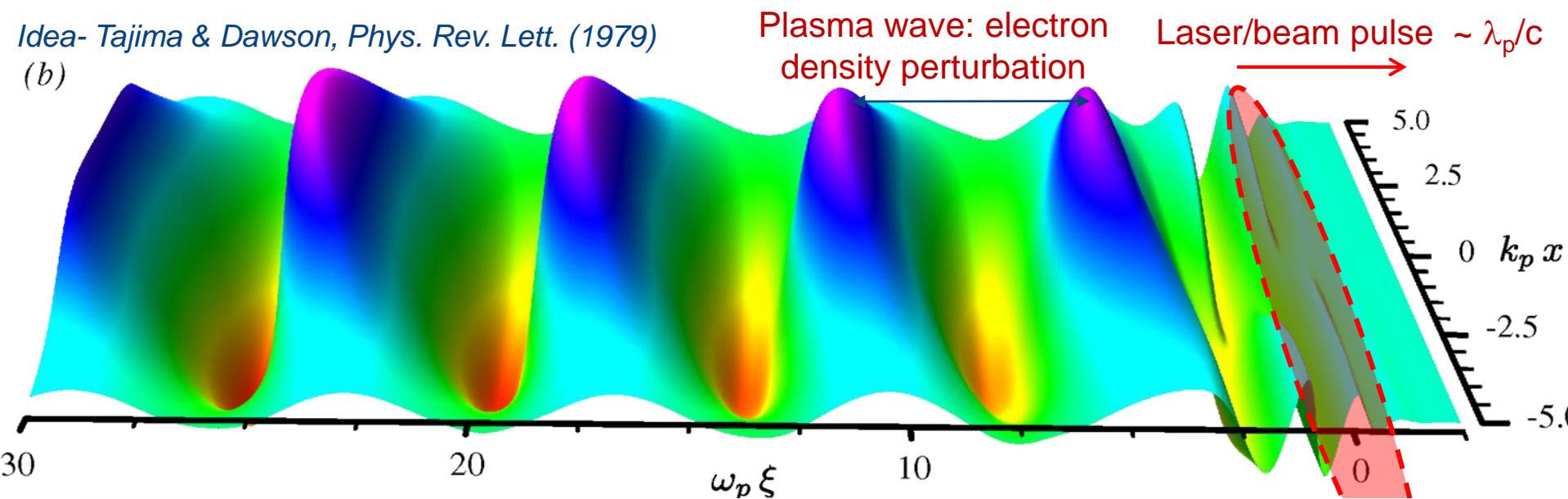


Source: DataStream, Roskill, Sumário Mineral, Departamento Nacional de Produção Mineral, República Federativa do Brasil

Option 4: New Technology- Plasma

Idea- Tajima & Dawson, Phys. Rev. Lett. (1979)

(b)



$$E_0 = \frac{m_e c \omega_p}{e} \approx 100 \left[\frac{\text{GeV}}{m} \right] \cdot \sqrt{n_0 [10^{18} \text{cm}^{-3}]}$$

Option A:

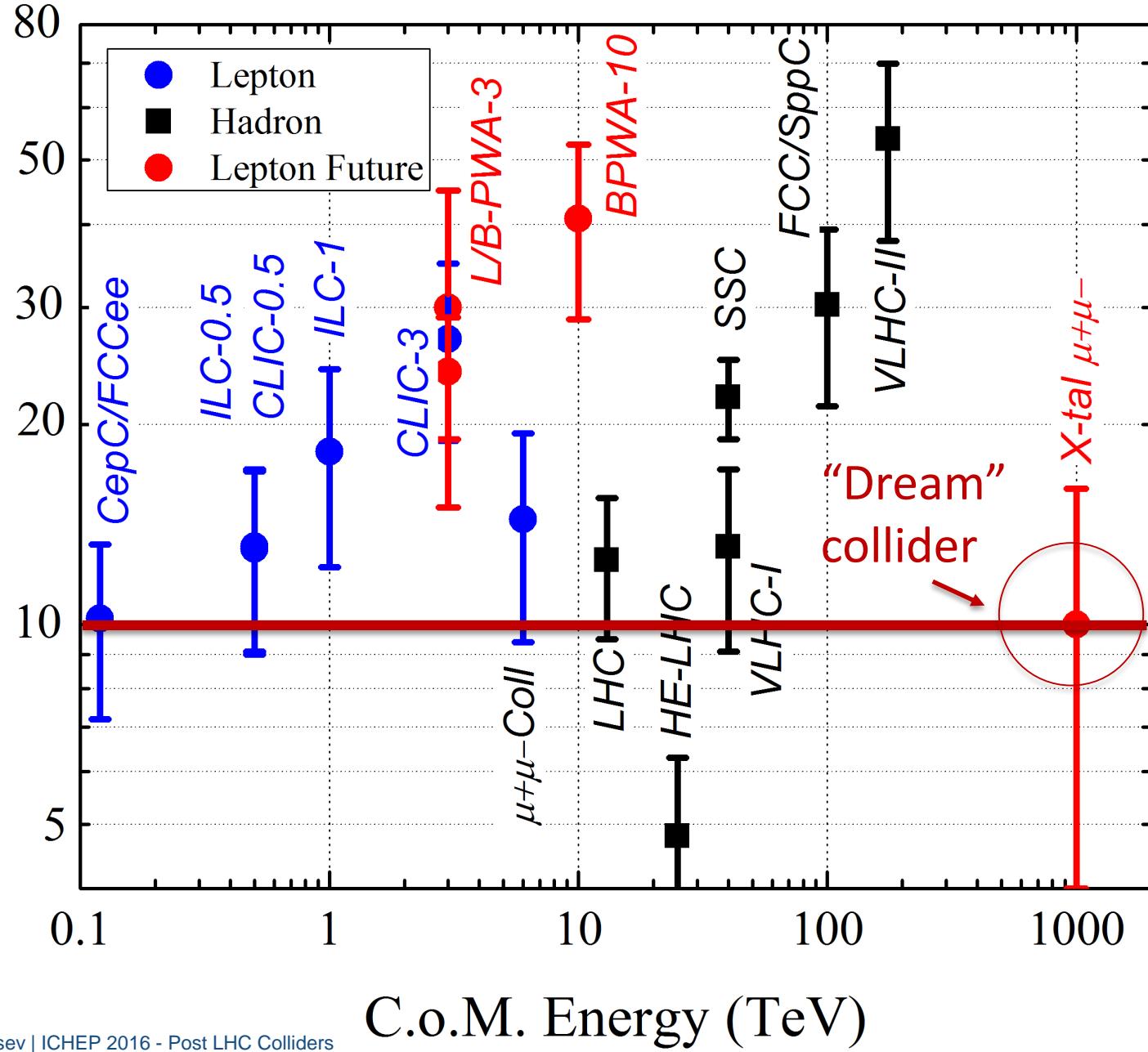
Short intense e-/e+/p bunch
Few 10^{16}cm^{-3} , 6 GV/m over 0.3m

Option B:

Short intense laser pulse
 $\sim 10^{18} \text{cm}^{-3}$, 50 GV/m over 0.1m

First looks into “Plasma-Collider”: **staging kills !** $\langle E \rangle \sim 2 \text{ GV/m}, \varepsilon$

Cost Estimate (2016 B\$ TPC)



“Dream” Collider: Choices

- Far Future “Energy Frontier” assumes
 - ❖ 300-1000 TeV ($20-100 \times LHC$)
 - ❖ “decent luminosity” (TBD)
- Surely we know: **circular collider**

1. For the same reason there is no circular $e+e-$ collider above Higgs-F there will be no circular pp colliders beyond 100 TeV → **LINEAR**

2. Electrons radiate 100% **linear collider**
beam-strahlung (<3 TeV)
and in focusing channel
(<10 TeV) → $\mu+\mu-$ or pp

$$L \propto \frac{\eta P_{\text{wall}}}{E^3} \frac{\xi_y}{\beta_y}$$

$$L \propto \frac{\eta_{\text{linac}} P_{\text{wall}}}{E} \frac{N_\gamma}{\sigma_y}$$

“Phase-Space” is Further Limited

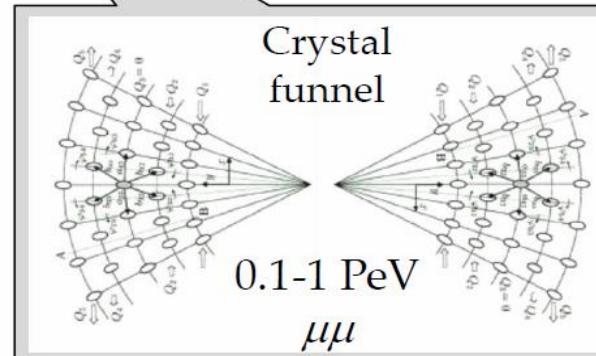
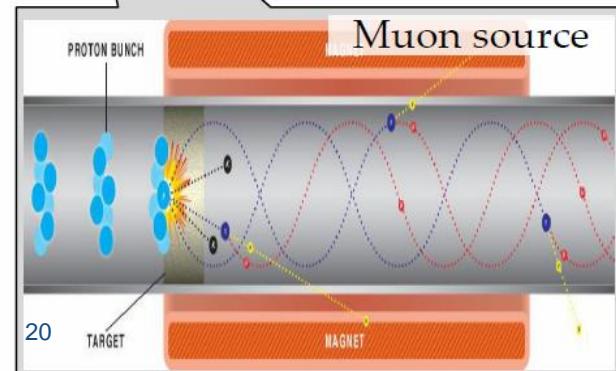
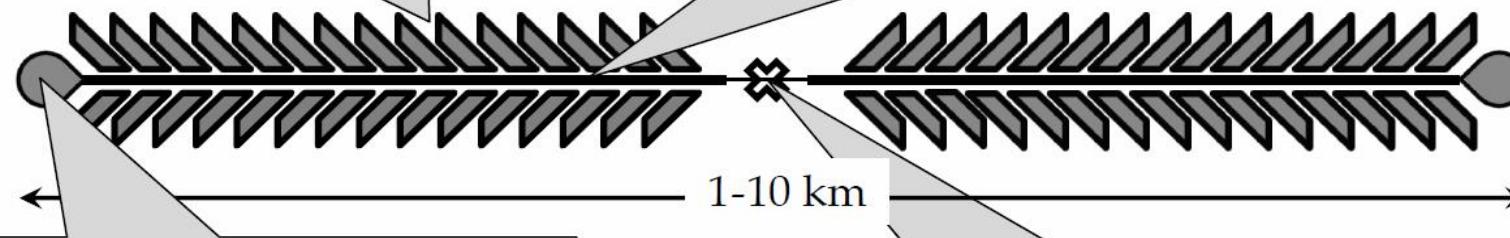
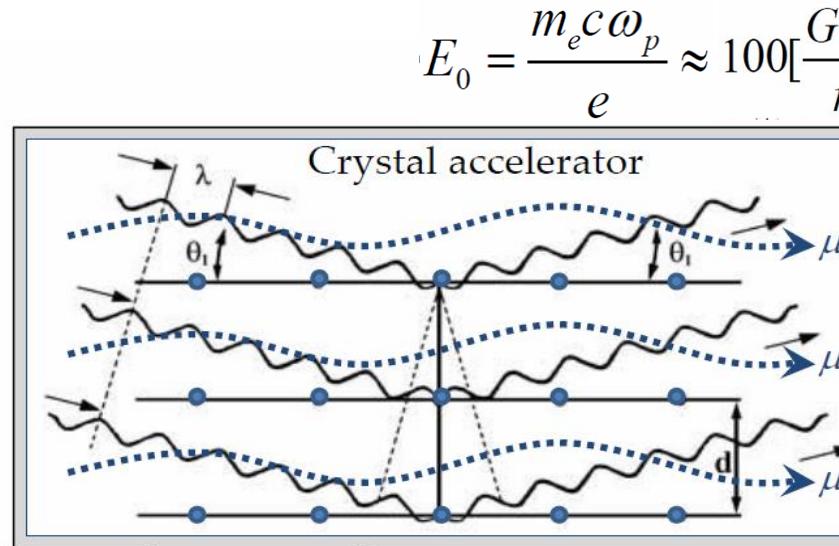
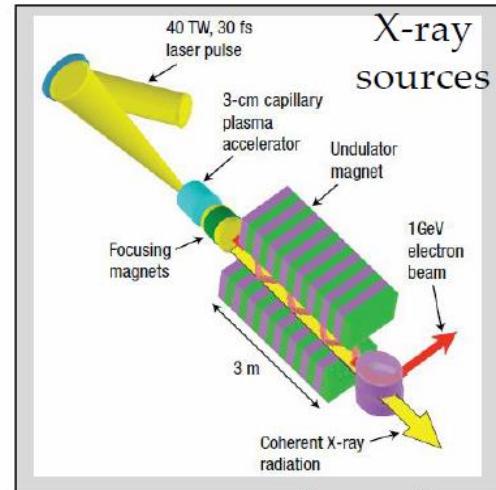
- “Cost Feasibility”: for $20-100 \times \text{LHC}$
 - ❖ $< 10 \text{ B\$}$
 - ❖ $< 10 \text{ km}$
 - ❖ $< 10 \text{ MW}$ (beam power, $\sim 100\text{MW}$ total)
- New technology should provide $>30 \text{ GeV/m}$ @
total component cost $<1\text{M\$/m}$ ($\sim \text{NC}$ magnets now)

SC magnets equiv. $\sim 0.5 \text{ GeV per meter (LHC)}$

**3. Only one option for $>30 \text{ GeV/m}$ known now:
dense plasma → that excludes *protons* → only muons**

“Dream” Collider = Muons + Acceleration in Crystals + Continuous Focusing (Channeling)

V.Shiltsev, Phys. Uspekhy 55 965 (2012)



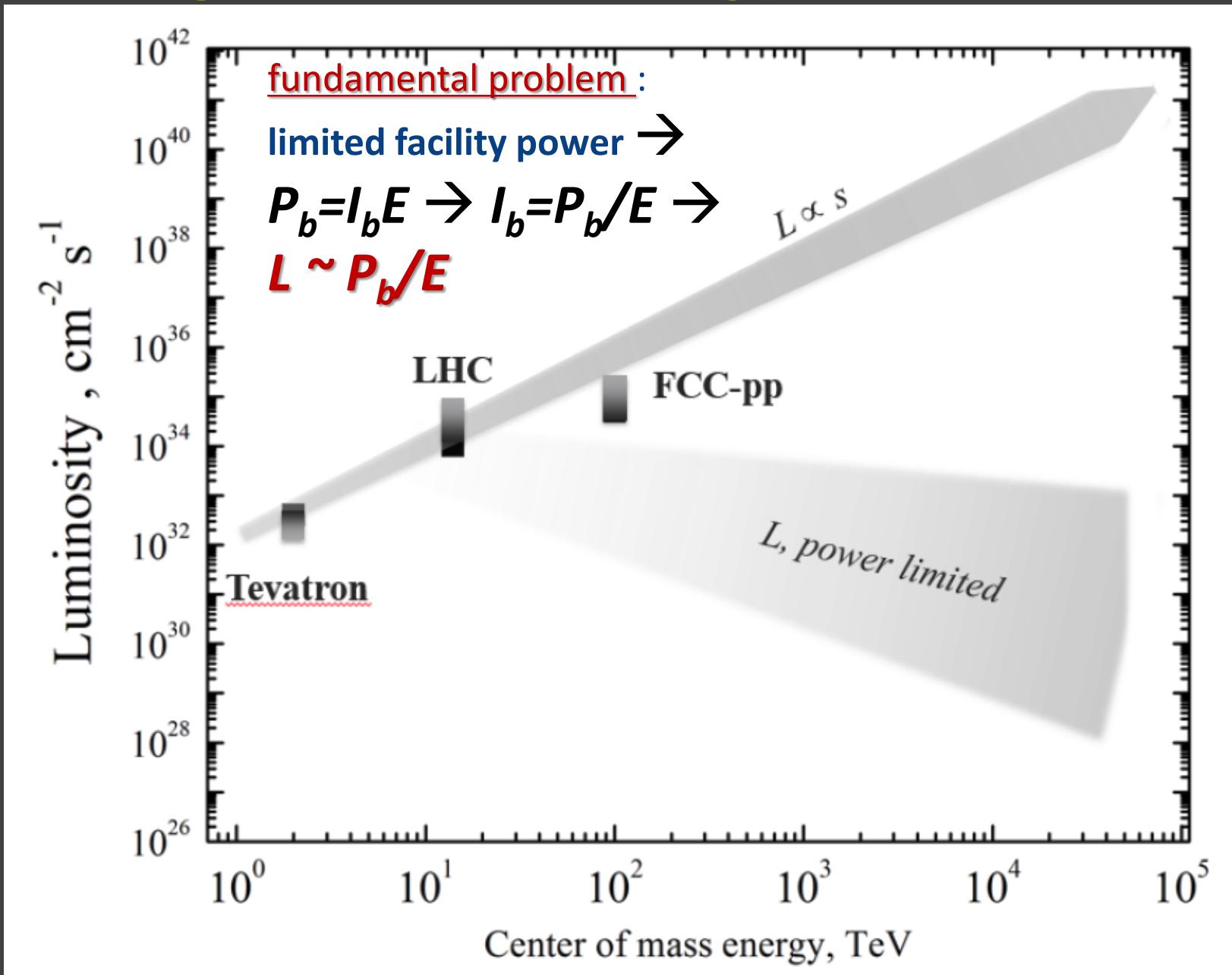
$$E_0 = \frac{m_e c \omega_p}{e} \approx 100 \left[\frac{\text{GeV}}{m} \right] \cdot \sqrt{n_0 [10^{18} \text{cm}^{-3}]} \cdot \sqrt{\epsilon}$$

$n \sim 10^{22} \text{ cm}^{-3}$,
10 TeV/m
→

1 PeV =
1000 TeV

$n_\mu \sim 1000$
 $n_B \sim 100$
 $f_{rep} \sim 10^6$
 $L \sim 10^{30-32}$

Paradigm Shift : Energy vs Luminosity



HEP's “Far” Future

- **Good News**
 - options **EXIST**
 - 300-1000 TeV muons in plasma/crystals
- **Bad News**
 - It will be
 - H**igh
 - E**nergy
 - L**ow
 - L**uminosity

So - Will There Be Energy Frontier Colliders after LHC?

- (My) Short Answer is **May Be**
- Long(er) Answer :
 - *it is LHC results dependent (motivation)*
 - *if based on current technologies (SRF, SCMag, etc)*
only HE-LHC is cost feasible (<LHC), some are close (CepC/FCCee, ILC, Muon Coll, VLHC-I), others need significant R&D (FCC)...or in China (?)
 - *hopeful technology of plasma acceleration*
is very expensive now, need 3 decades of R&D;
“dream” 1PeV Xtal $\mu\mu$ will be a H.E.L.L. collider

*Thank You for Your
Attention!*