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****."*

Betteridge's law of headlines

Ian Betteridge, a British technology journalist

Hinchliffe's rule

particle physicist Ian Hinchliffe

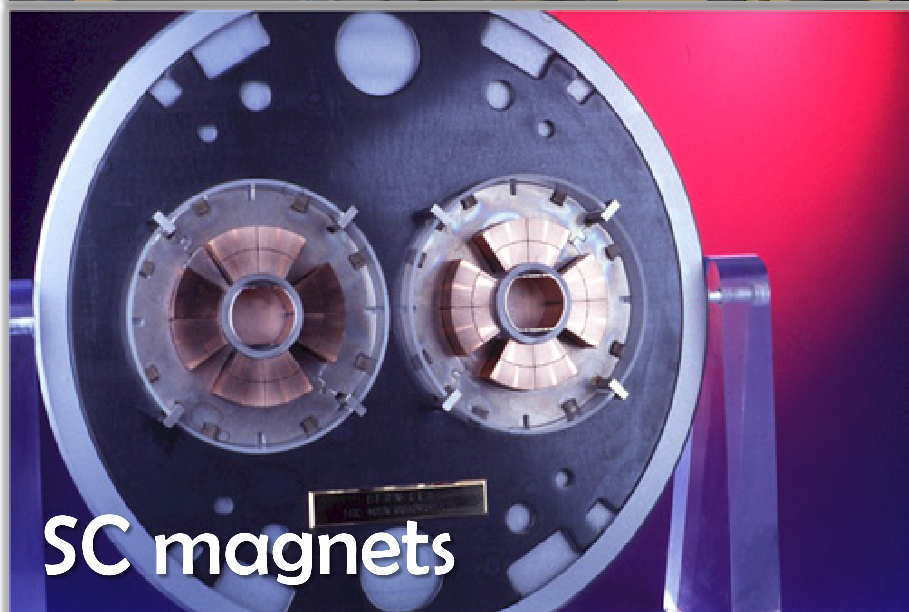
Davis' law

(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



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… in addition to “traditional” technologies of tunneling, electric power and site infrastructures, etc …

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, ν-Factory

Wide range :

- 4 orders in *E*nergy, >1 order in *P*ower, >2 orders in *L*ength
- 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-.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

V.Shiltsev, A phenomenological cost model for high energy particle accelerators

! WARNING !

αβγ - Cost Estimate Model:

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

a) **±33% estimate, for a "green field" accelerators**

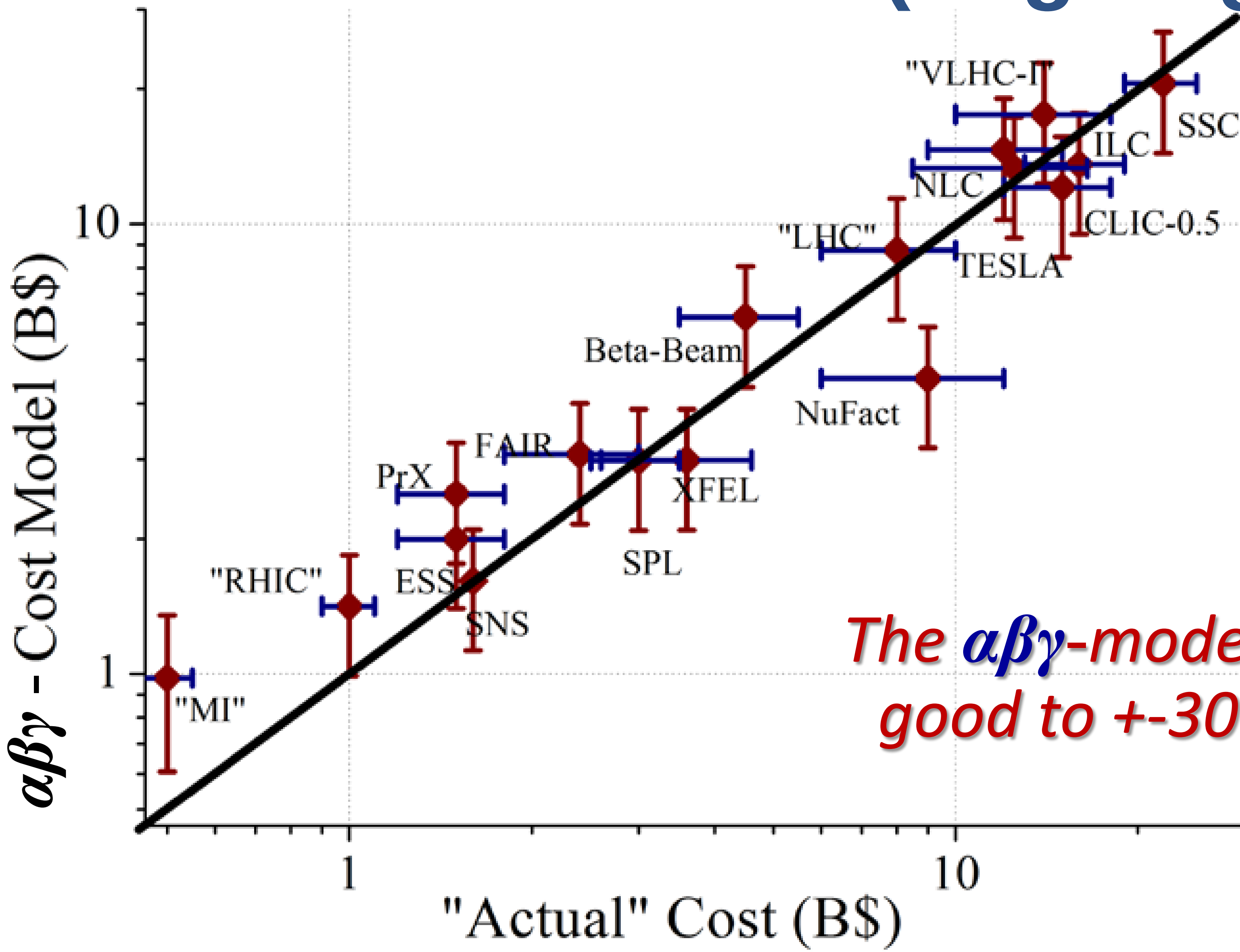
b) **"US-Accounting" = TPC !** (~ 2 × *European Accounting*)

c) **Coefficients** (units: 10 km for *L*, 1 TeV for *E*, 100 MW for *P*)

- **$\alpha \approx$ 2B$/sqrt(*L*/10 km)**
- **$\beta \approx$ 10B$/sqrt(*E*/TeV)** for SC/NC RF
- **$\beta \approx$ 2B$ /sqrt(*E*/TeV)** for SC magnets
- **$\beta \approx$ 1B$ /sqrt(*E*/TeV)** for NC magnets
- **$\gamma \approx$ 2B$/sqrt(*P*/100 MW)**

USE AT YOUR OWN RISK!

Total Cost **vs** ***Model*** **(Log-Log)**

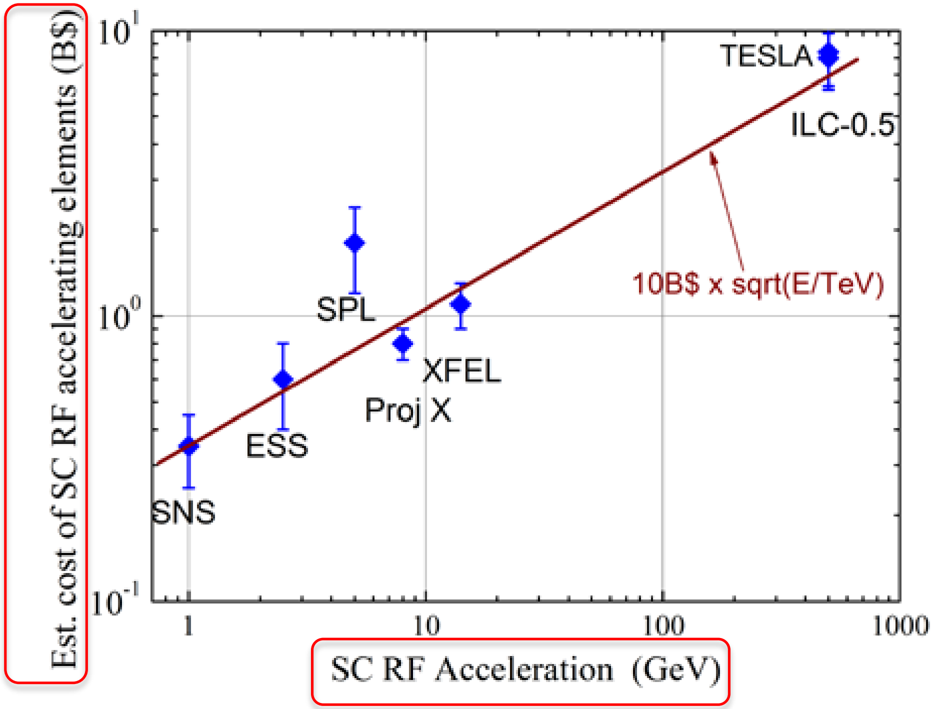


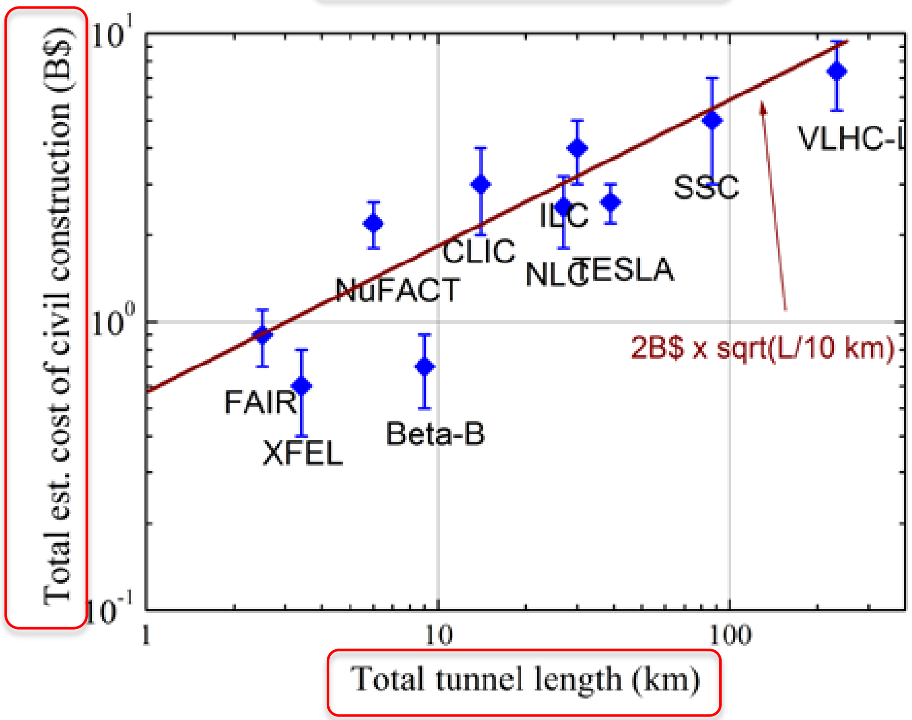
*The **αβγ**-model is good to +-30%*

Illustrations

Comment:

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





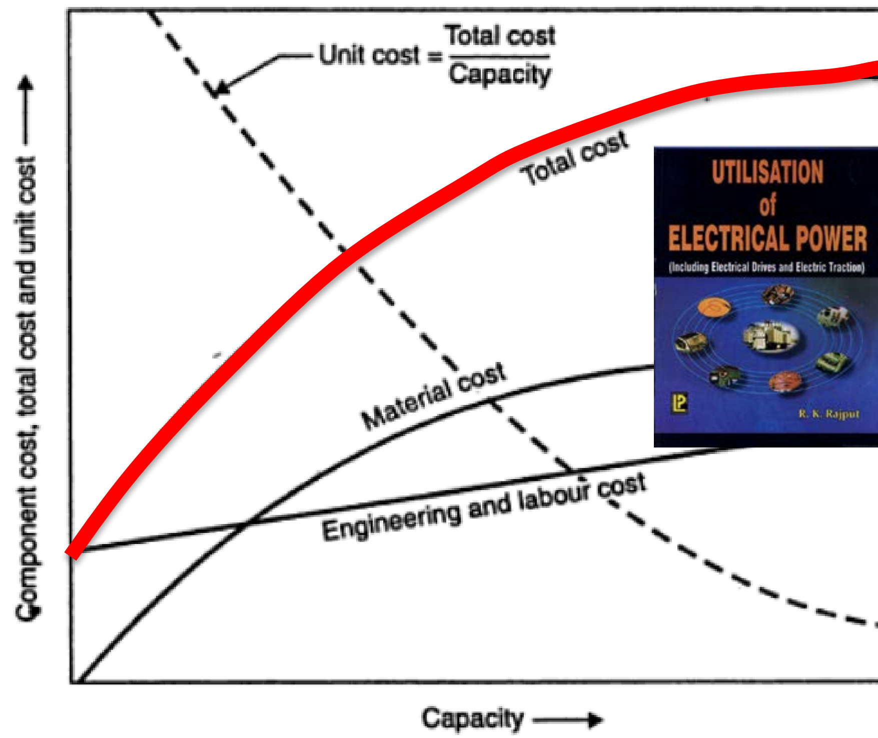


Fig. 9.5. Variation of costs of power plant *versus* its capacity.

Take LHC as an Example:

- ***αβγ* – Model:**
  - 40 km of tunnels
  - 14 TeV c.o.m SC magnets
  - ~150 MW of site power

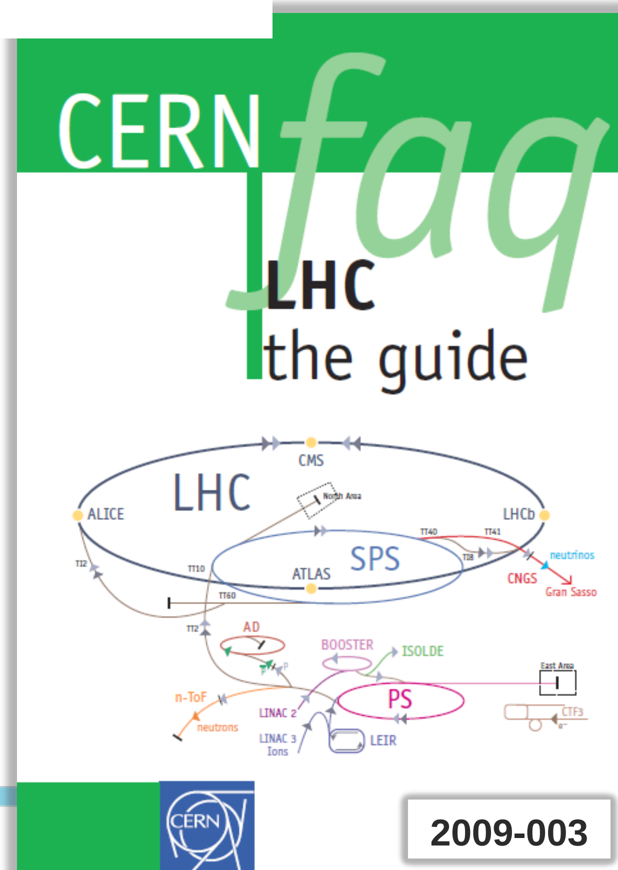
$$2\sqrt{40/10} = 4$$
$$2\sqrt{14} = 7.5$$
$$2\sqrt{150/100} = 2.5$$

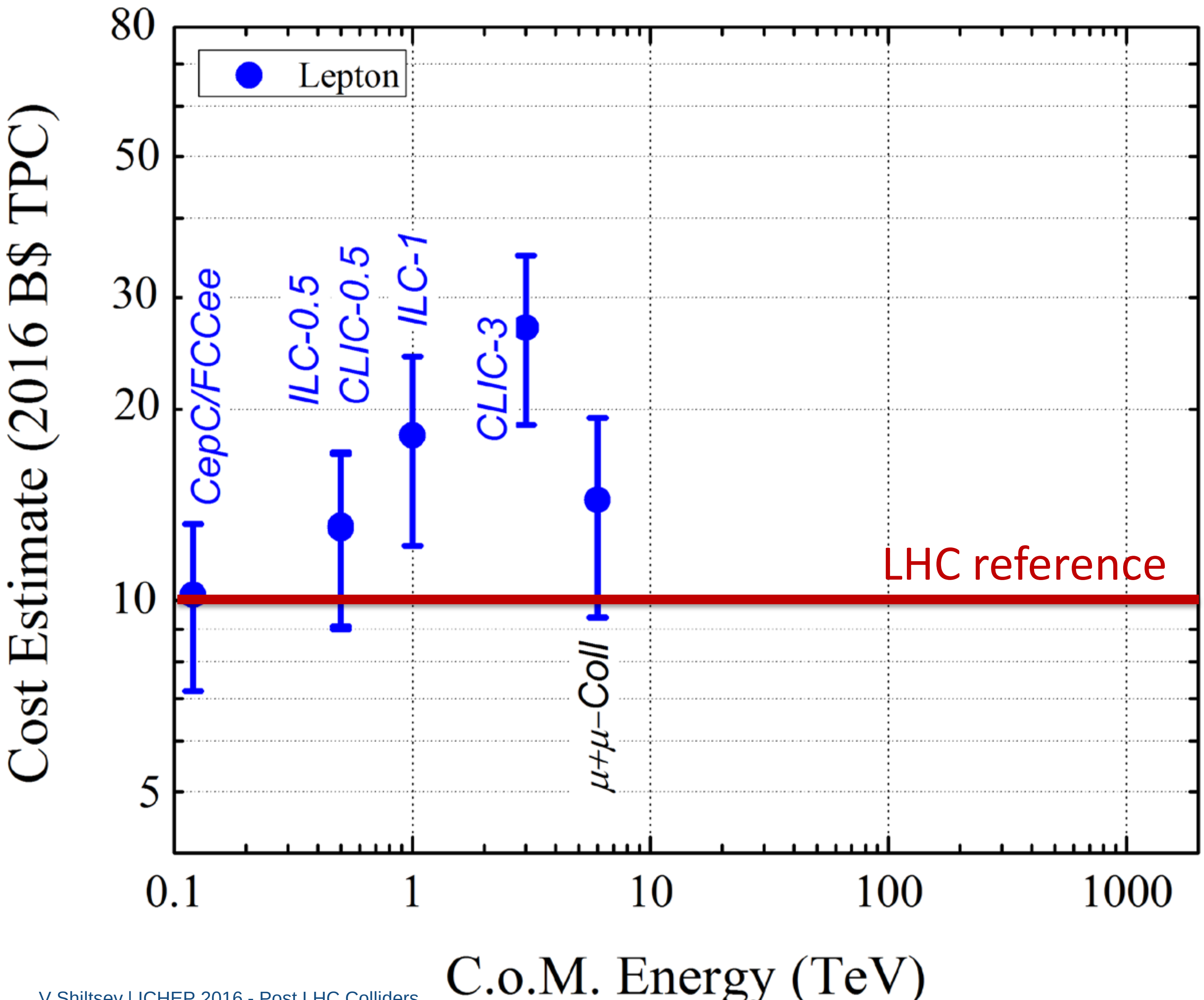
TOTAL PROJECT COST : **14B$ ± 4.5B$**

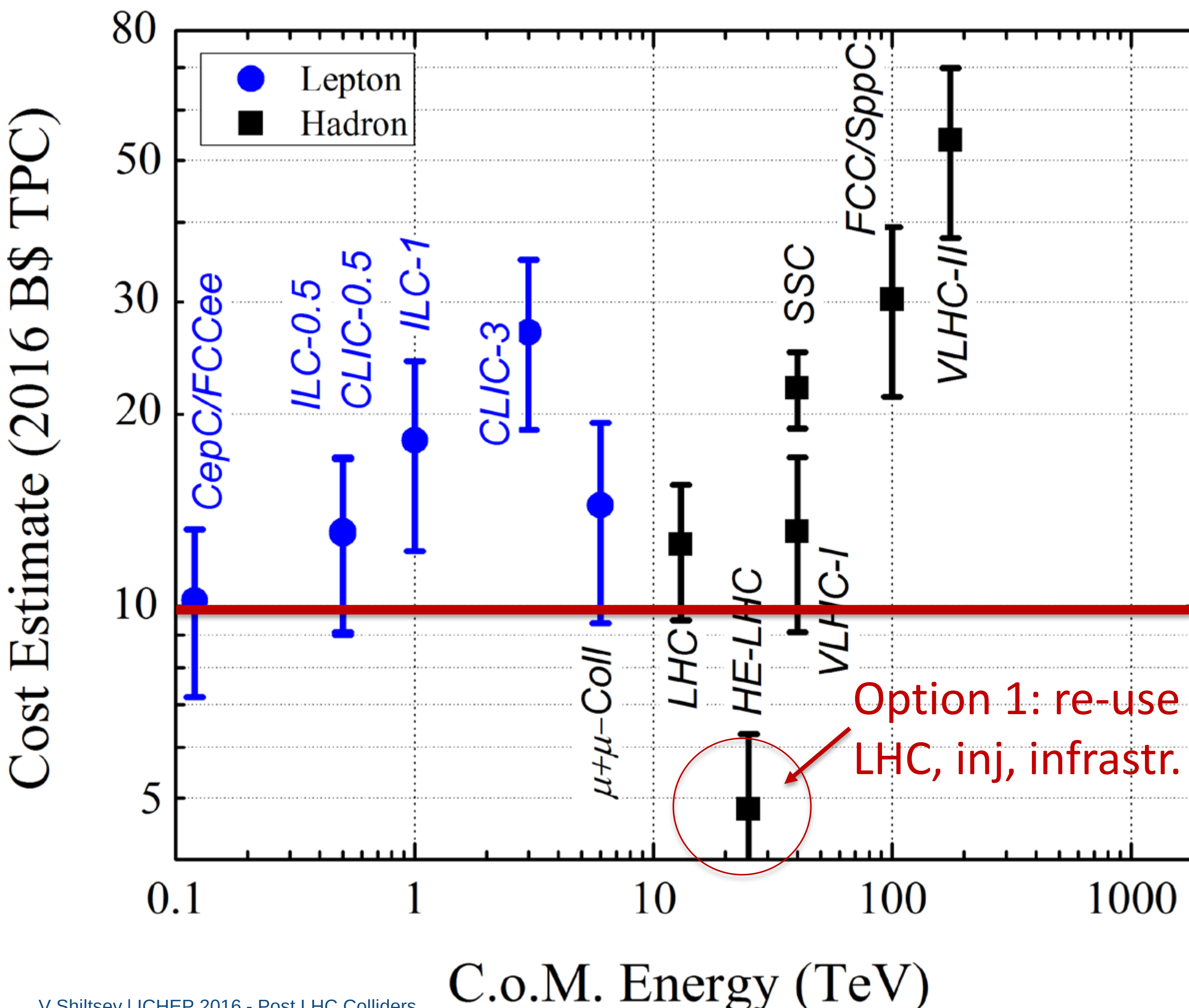
- **CERN LHC Factbook (2009):**
  - 6.5 BCHF, incl. **5 BCHF** for accelerator (European Accounting)
  - x 2 to US TPC → **10 BCHF=10B$**
  - Cost of existing injector complex ~30-40% **3-4 B$**

TPC : ~**13-14B$**

(of which CERN paid 10 over ~8 yrs)

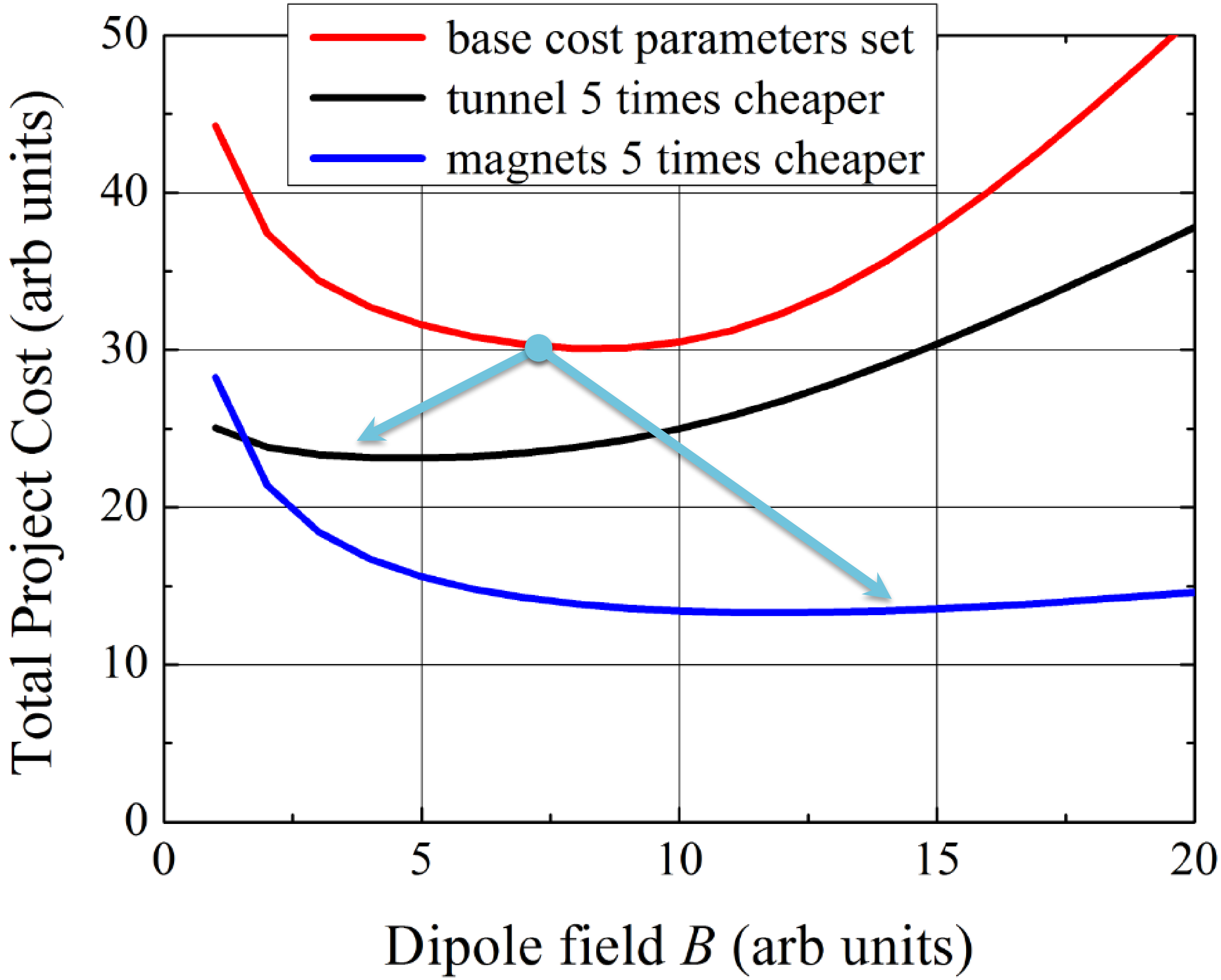



Lepton
Cost Estimate (2016 B$ TPC)
80
50
30
20
10
5
0.1
1
10
100
1000
C.o.M. Energy (TeV)
CepC/FCCee
ILC-0.5
CLIC-0.5
ILC-1
CLIC-3
μ+μ−Coll
LHC reference


Lepton
Hadron
Cost Estimate (2016 B$ TPC)
C.o.M. Energy (TeV)
80
50
30
20
10
5
0.1
1
10
100
1000
CepC/FCCee
ILC-0.5
CLIC-0.5
ILC-1
CLIC-3
μ+μ–Coll
LHC
HE-LHC
SSC
VLHC-I
FCC/SppC
VLHC-II
Option 1: re-use
LHC, inj, infrastr.

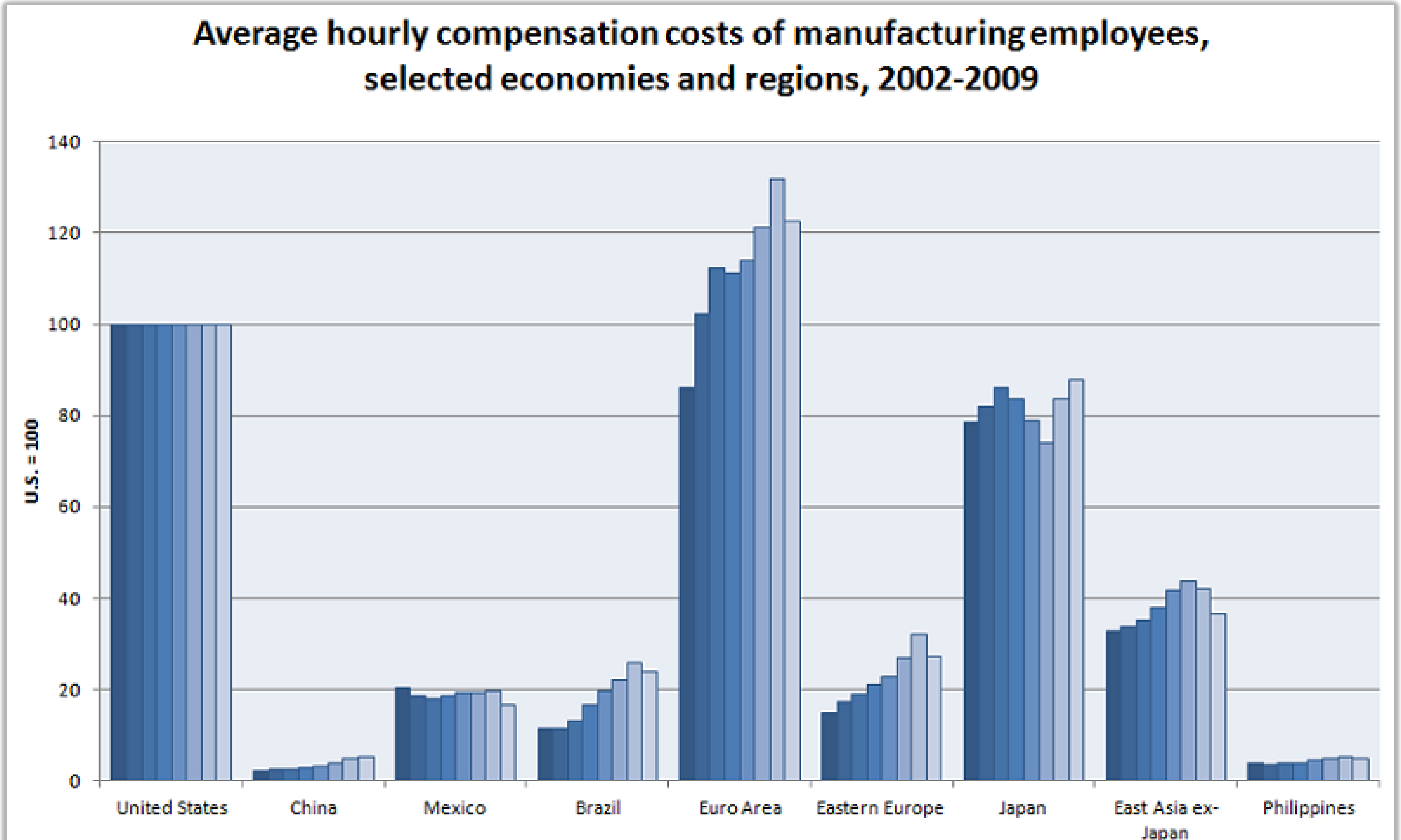
Option 2 : Develop Technology to Lower Cost

100 TeV *pp* : Qualitative Cost Dependencies



* for illustration purposes only

Option 3: *"Move to China !"*



Note: For a description of the economic groups, see the technical notes at www.bls.gov/ilc/ichcctn.pdf, Table 2.
Source: U.S. Bureau of Labor Statistics, International Labor Comparisons.

SSRF
China

- 432 m
- 3.5 GeV
- 1.2B RMB

2007

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

Account infl'n, convert to USD and scale to sqrt(1 km):

350 M$*** ***772 M$ ***1040 M$*** ***1024 M$***

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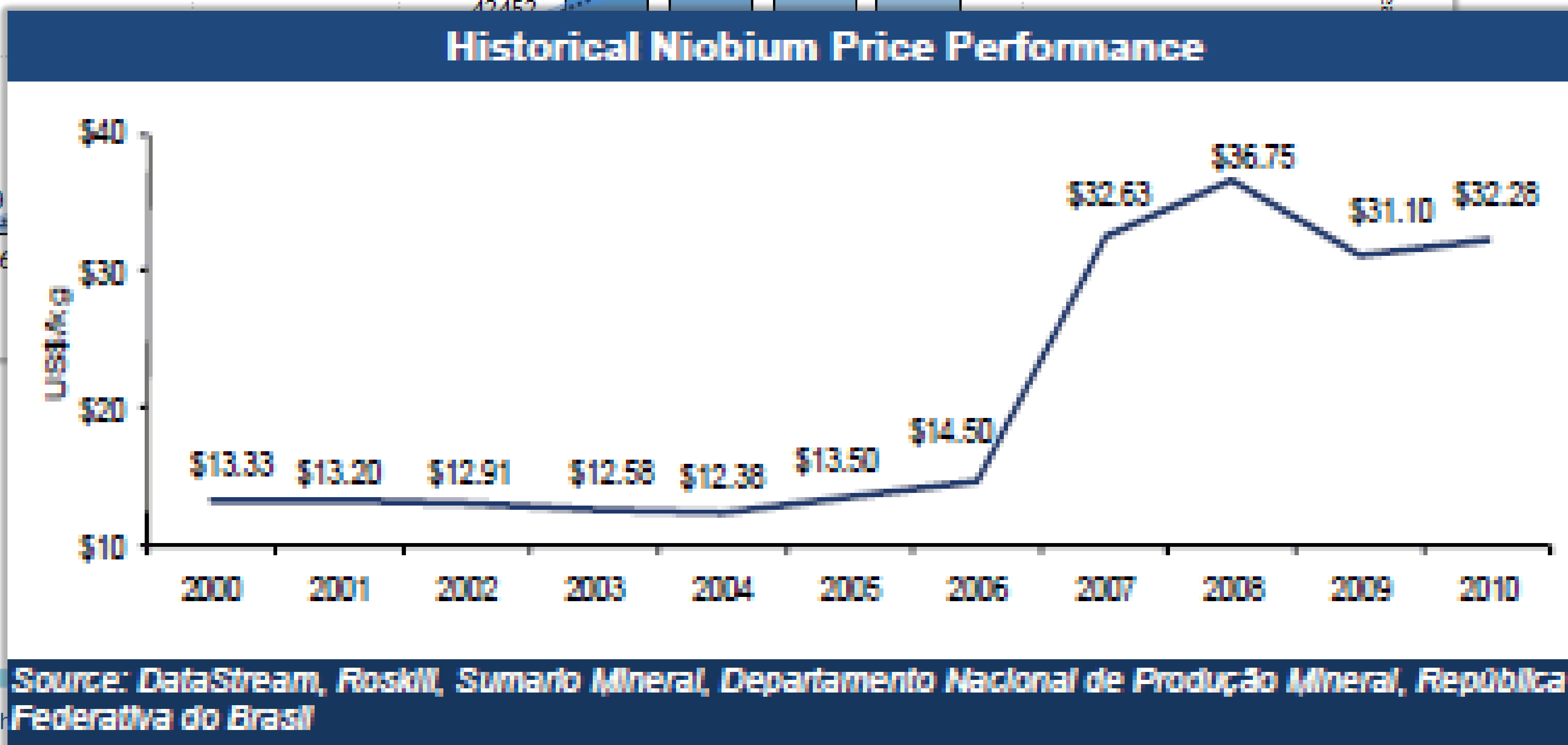
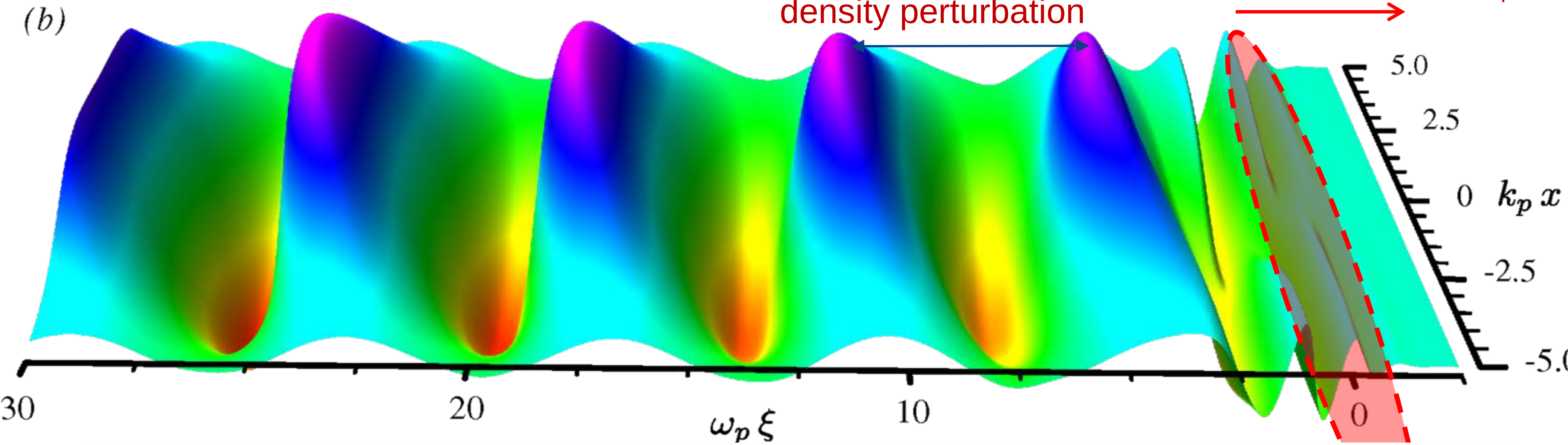
“Move to China !” - Caveats



Option 4: New Technology- Plasma

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



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

Option A:

Short intense e-/e+/p bunch

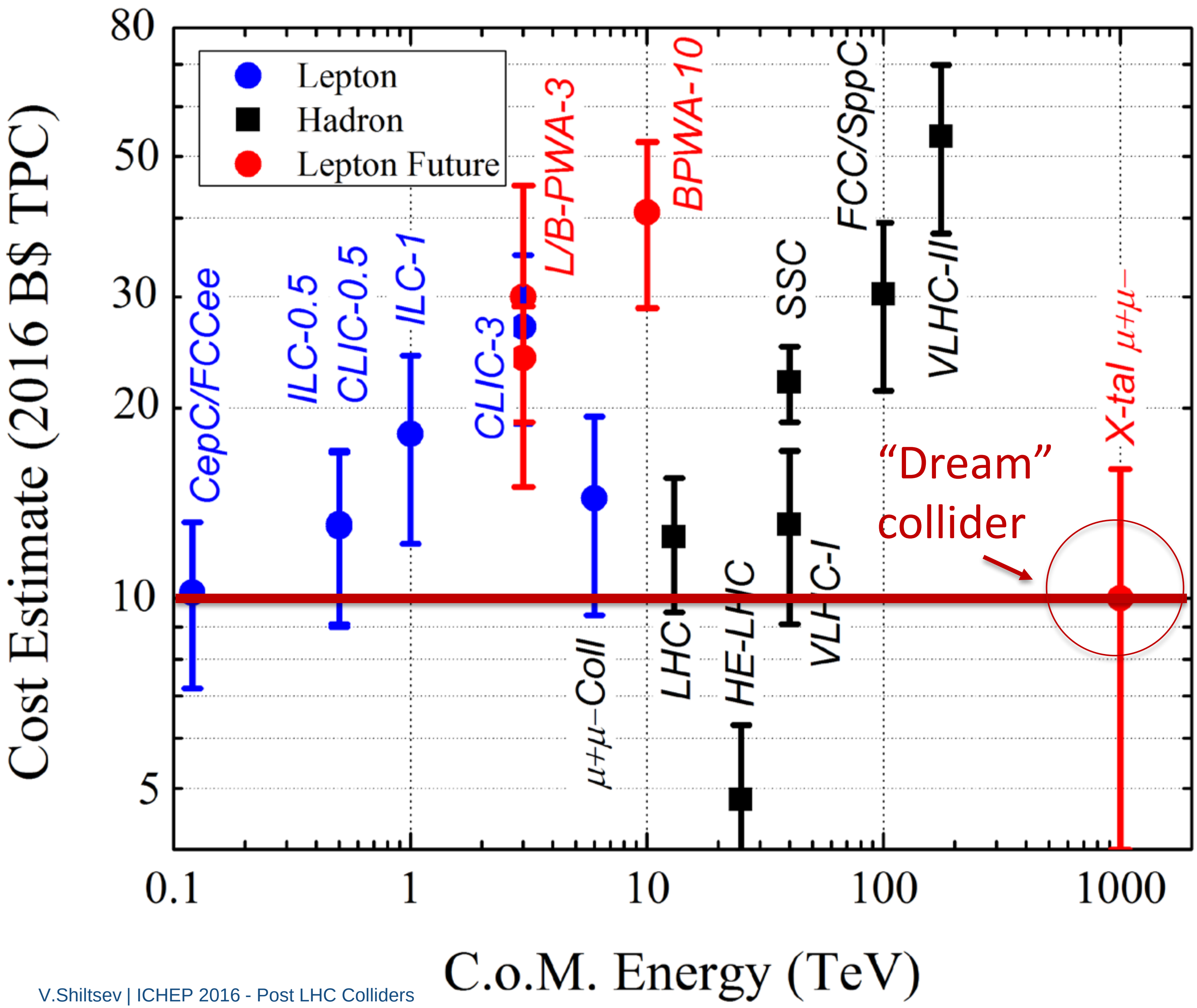
Few 10^{16}cm^{-3}, **6 GV/m** over 0.3m

Option B:

Short intense laser pulse

~10^{18}cm^{-3}, **50 GV/m** over 0.1m

First looks into "Plasma-Collider": **staging kills ! <*E*>~2 GV/m,ε**


Lepton
Hadron
Lepton Future
CepC/FCCee
ILC-0.5
CLIC-0.5
ILC-1
CLIC-3
L/B-PWA-3
BPWA-10
μ+μ−Coll
LHC
HE-LHC
SSC
VLHC-I
FCC/SppC
VLHC-II
X-tal μ+μ−
"Dream" collider
Cost Estimate (2016 B$ TPC)
C.o.M. Energy (TeV)
80
50
30
20
10
5
0.1
1
10
100
1000

“Dream” Collider: Choices

- Far Future “Energy Frontier” assumes
  - 300-1000 TeV (*20-100 × LHC*)
  - “decent luminosity” (TBD)
- Surely we know:

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**

circular collider

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

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

linear collider

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

"Phase-Space" is Further Limited

- "Cost Feasibility": for 20-100 × LHC
  - < 10 B$
  - < 10 km
  - < 10 MW (beam power, ~100MW total)

→**New technology should provide >30 GeV/m @ total component cost <1M$/m (~NC magnets now)**

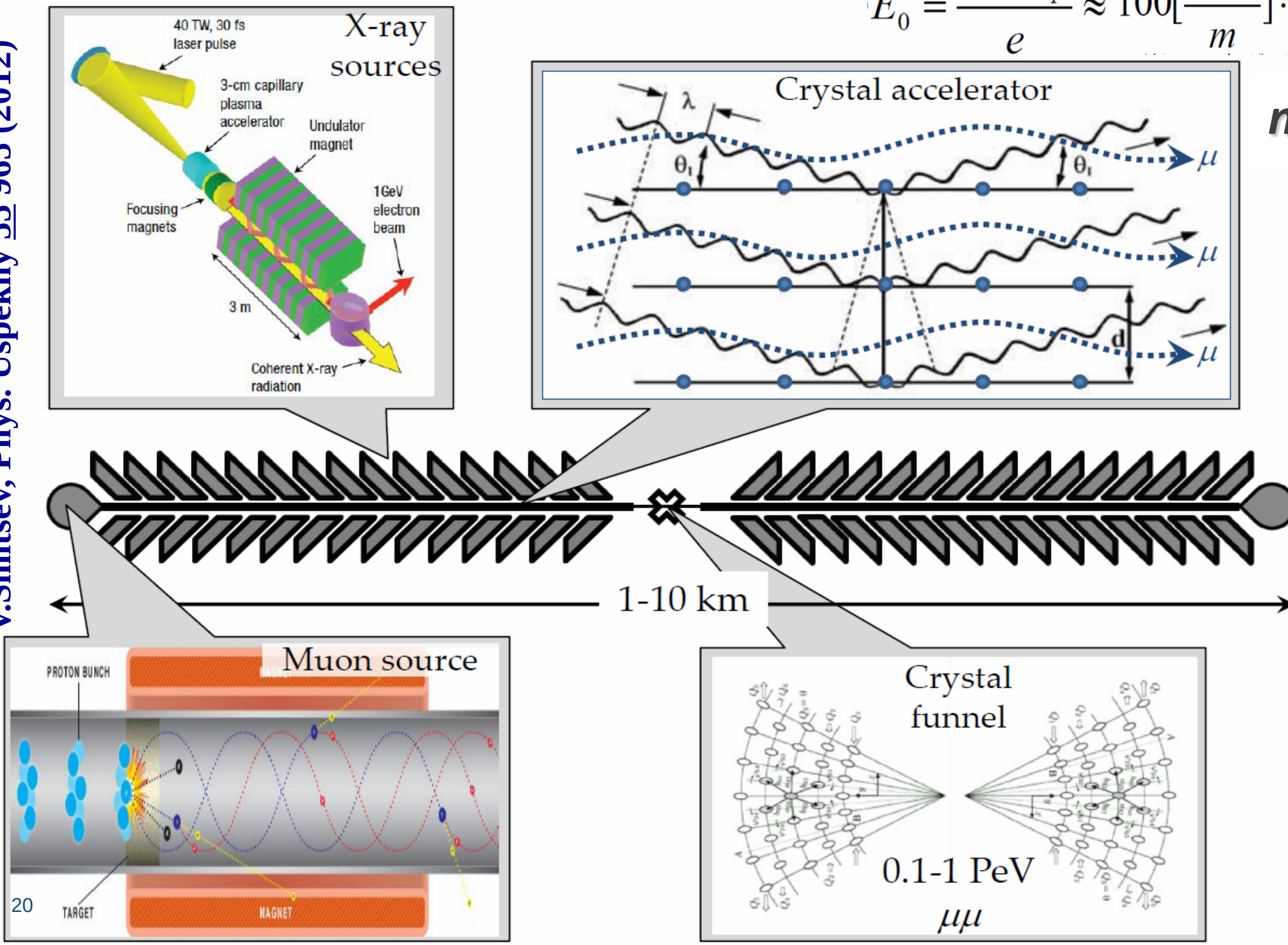
SC magnets equiv. ~ 0.5 GeV per meter (LHC)

3. Only one option for >30 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)

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



***n*~10²² cm⁻³,**

10 TeV/m

→

1 PeV = 1000 TeV

n_μ ~1000

n_B ~100

f_{rep} ~10^6

L ~$10^{30\text{-}32}$

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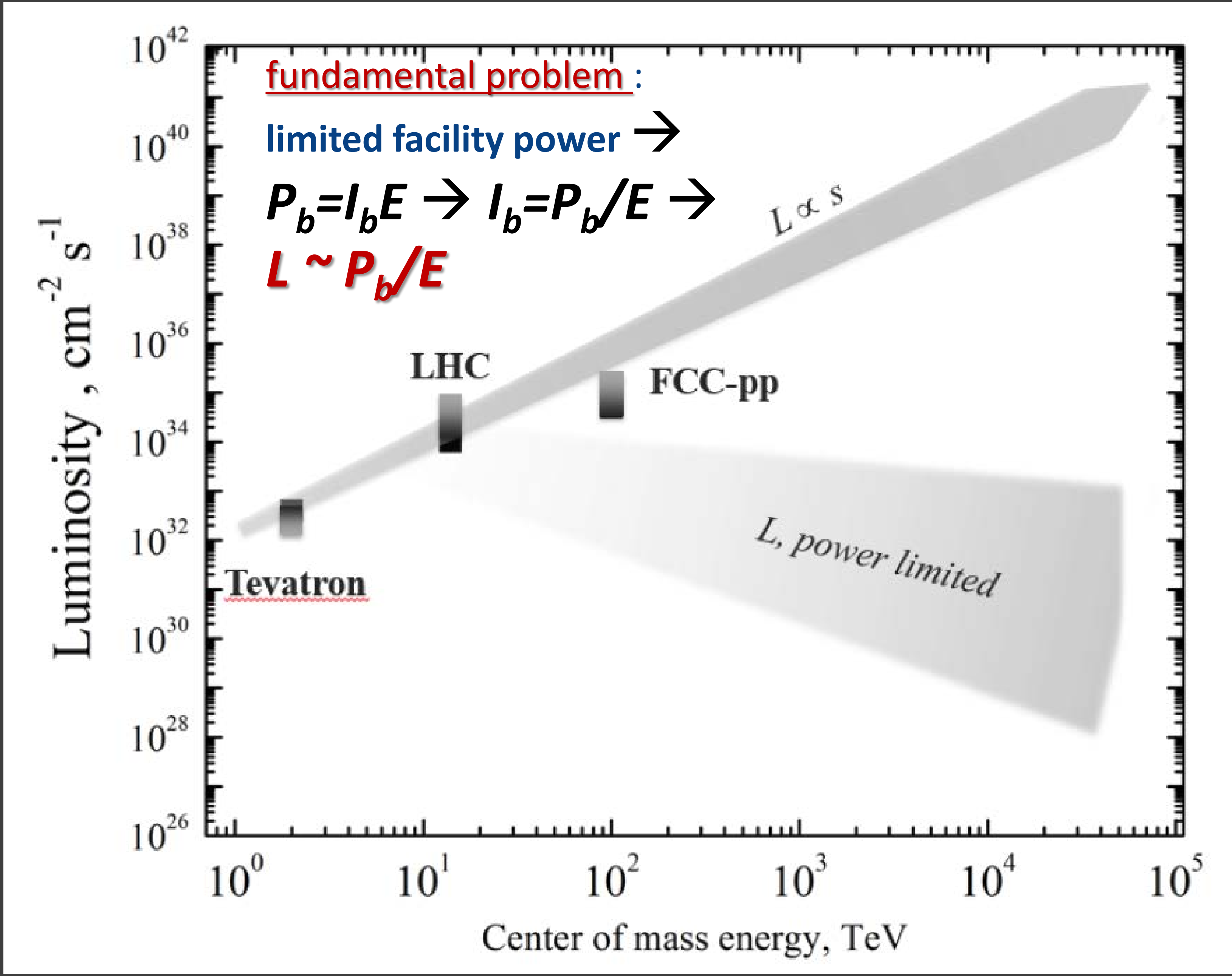
Paradigm Shift : *Energy* vs *Luminosity*



HEP's "Far" Future

- **Good News**
  - options **EXIST**
    - 300-1000 TeV muons in plasma/crystals
- **Bad News**
  - It will be

High

Energy

Low

Luminosity

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 μμ will be a H.E.L.L. collider

Thank You for Your Attention!

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