Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Future Colliders:

ELC-Anzatz

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Physics Limits of Ultimate Beams - III

January 22, 2021 – Snowmass’21 AF1

Content:

- **Part I**
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  - **Ultimate colliders: *ELC-Ansatz*, *Units***
  - **Ultimate colliders: *Limits of E***
  - **Ultimate colliders: *Limits of L***
  - **Ultimate colliders: *Limits of C***
  - **Other considerations: *T***
- **Part II**
  - **Circular *pp* / *ee* / $\mu\mu$**
  - **Linear and Plasma *ee* / $\gamma\gamma$ / $\mu\mu$**
  - **Exotic (crystal) $\mu\mu$ / $\mu\mu$**
- **Conclusions / Q&A / Discussion**

In search of uniform approach to discuss far future/ultimate machines

- **BASED ON EXISTING TECHNOLOGIES**
  - **Circular ee**
  - **Linear *ee*/$\gamma\gamma$**
  - **Circular *pp***
  - **Circular $\mu\mu$**
- **BASED ON EMERGING TECHNOLOGIES**
  - **ERL *ee*/$\gamma\gamma$**
  - **Plasma *ee*/$\gamma\gamma$**
  - **Linear $\mu\mu$ / Plasma $\mu\mu$**
- **EXOTIC SCHEMES**
  - **Crystal linear $\mu\mu/\tau\tau$**
  - **Crystal linear $\tau\tau$**
  - **Crystal circular *pp***

"ELC – Ansatz"

- We will evaluate possible (ultimate) future colliders on base of
  - Feasibility of ***E***nergy
  - Feasibility of ***L***uminosity
  - Feasibility of ***C***ost
- For each machine type / technology we will start with what is the state-of-the-art now and attempt to make *"1-2-several"* orders of magnitude steps in *Energy*
  - see how if affects *Luminosity*
  - see how it affects *Cost*
- Leave it to others to judge where the lower limit on ***L*** and upper limit pn ***C*** are… other limits may appear

“ELC – Ansatz” : Choice of Units

- Units of Energy will be ***TeV***
  - *most often cme = 2 x E_beam, sometimes - per beam*
- Units of Luminosity will be ***ab^{-1}/yr***
  - *e.g.,1e35 over 1e7 sec/yr… HL-LHC will have 0.3 ab^{-1}/yr*
  - *factor of ~2 uncertainty in peak lumi / machine availability*
- Units of power(total facility) will be ***TWh/yr***
  - *Eg CERN/LHC ~200MW and 1.1-1.3 TWh/yr*
- Units of Cost will be ***LHCU***
  - *cost of the LHC construction, approx. 10B$ - see below*
  - *for other machines the cost will be estimated using αβγ model with uncertainty O(2) - see below*
  - *the αβγ model needs to be extended for novel approaches*

Limits on *Energy* (1)

- Linear vs Circular
  - *Circular does not make sense beyond these energies*

$$\Delta U_{SR} = \frac{90\,\mathrm{keV} \cdot E_e^4(\mathrm{GeV})}{R[\mathrm{m}]}$$

$$\Delta U_{SR} < E_e$$

$$E_e < 500\,\mathrm{GeV} \cdot \left(\frac{R}{10\,\mathrm{km}}\right)^{1/3}$$

for muons: $\times \left(\frac{m_\mu}{m_e}\right)^{4/3}$

$$E_\mu < 600\,\mathrm{TeV} \cdot \left(\frac{R}{10\,\mathrm{km}}\right)^{1/3}$$

for protons: $\times \left(\frac{m_p}{m_e}\right)^{4/3}$

$$E_p < 10\,\mathrm{PeV} \cdot \left(\frac{R}{10\,\mathrm{km}}\right)^{1/3}$$

Limits on *Energy* (2)

- Particles don't survive acceleration
  - *Unstable particles*
  - *Lossy transport from cell to cell (loss in plasma material, c-t-c efficiency)*

$$dN/dt = -N/\gamma\tau_0$$

$$\frac{N}{N_0} \approx \left(\frac{m_\mu c^2}{E}\right)^\kappa, \quad \kappa = (m_\mu c/\tau_0 G)$$

Physics – Uspekhi **55** (10)

for muons $G \gg 3\ \mathrm{MeV\ m^{-1}}$

for τ-leptons $G \gg 0.3\ \mathrm{TeV\ m^{-1}}$

$$\left(1 - \frac{\Delta N}{N}\right)^M \lesssim 1$$

$$M = \frac{E}{\Delta E_{cell}} = \frac{5\,\mathrm{TeV}}{5\,\mathrm{GeV}} = 10^3$$

$$M \cdot \frac{\Delta N}{N} \lesssim 1 \Rightarrow \frac{\Delta N}{N} < 10^{-3}$$

Limits on *Energy* (3)

- Corollary limits
  - *Space/area available*
  - *Power available*
  - *Money available*

For example:

Circumference 100 km , $B<16$ T , ***E*** **$<$50 TeV**

Circumference 40,000 km, $B=1$ T, ***E*** **$<$1.3 PeV**

Length 50 km , $G<0.1$ GV/m, ***E*** **$<$5 TeV**

Length 10 km, $G<1$ TV/m, ***E*** **$<$10 PeV**

Limits on *Luminosity* (1)

- General Equation

$$\mathcal{L} = f_0 \cdot n_b \cdot \frac{N_p^2}{4\pi\sigma_{IP}^2}$$

  - *rewrite with norm.emm.*

$$\mathcal{L} \sim f_0 \cdot n_b \cdot \gamma \cdot \frac{N_p^2}{4\pi\varepsilon_n\beta^*}$$

  - *HEP demand*

$$\mathcal{L} \sim s \sim E^2$$

  - *limits, eg, beam power*

$$P = f_0 \cdot n_b \cdot N_p \cdot \gamma \cdot mc^2$$

$$\mathcal{L} \sim \frac{P^2}{f_0 n_b \gamma \cdot 4\pi\varepsilon\beta \cdot m^2c^4} \Rightarrow \mathcal{L} \sim \frac{P^2}{E}$$

Limits on *Luminosity* (2)

- Another example

σ_{IP} is limited (e.g. 1Å)

$$\mathcal{L} \sim \frac{p^2}{f_0 n_b E^2 \cdot 4\pi\sigma_{IP}^2}$$

  - *beam-beam limit*

$$\xi = \frac{r_p N_p}{4\pi\varepsilon_n}$$

  - *space-charge limit*

$$\Delta Q_{sc} = \frac{r_p N_p}{4\pi\varepsilon_n \beta\gamma^2}$$

  - *beam loading*

$$V_L \sim N_p \cdot \text{impedance}$$

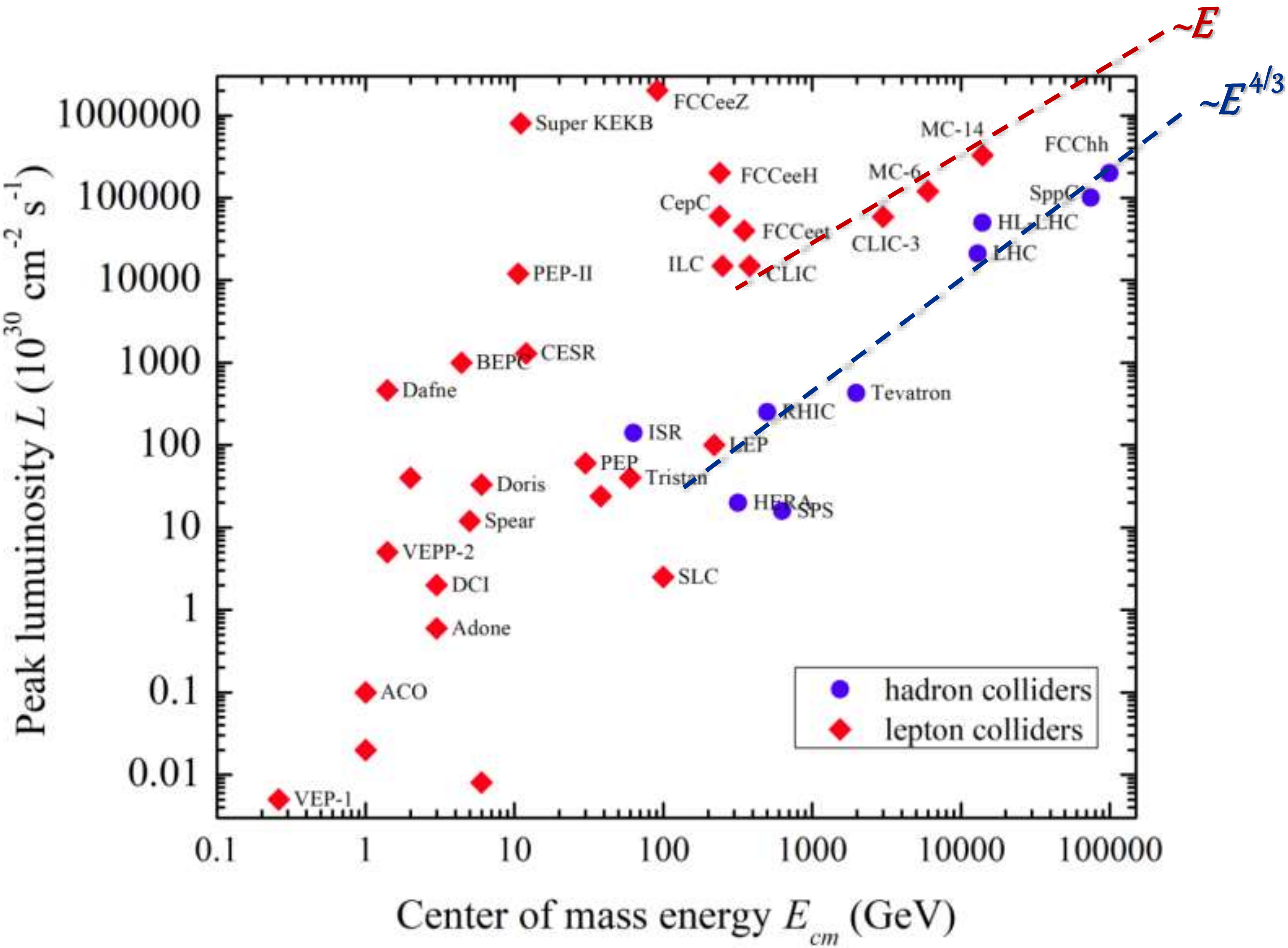
  - *event pile-up*

$$PU \sim \frac{\mathcal{L}}{f_0 n_b} \sigma_{inel}$$

Limits on *Luminosity* (3)

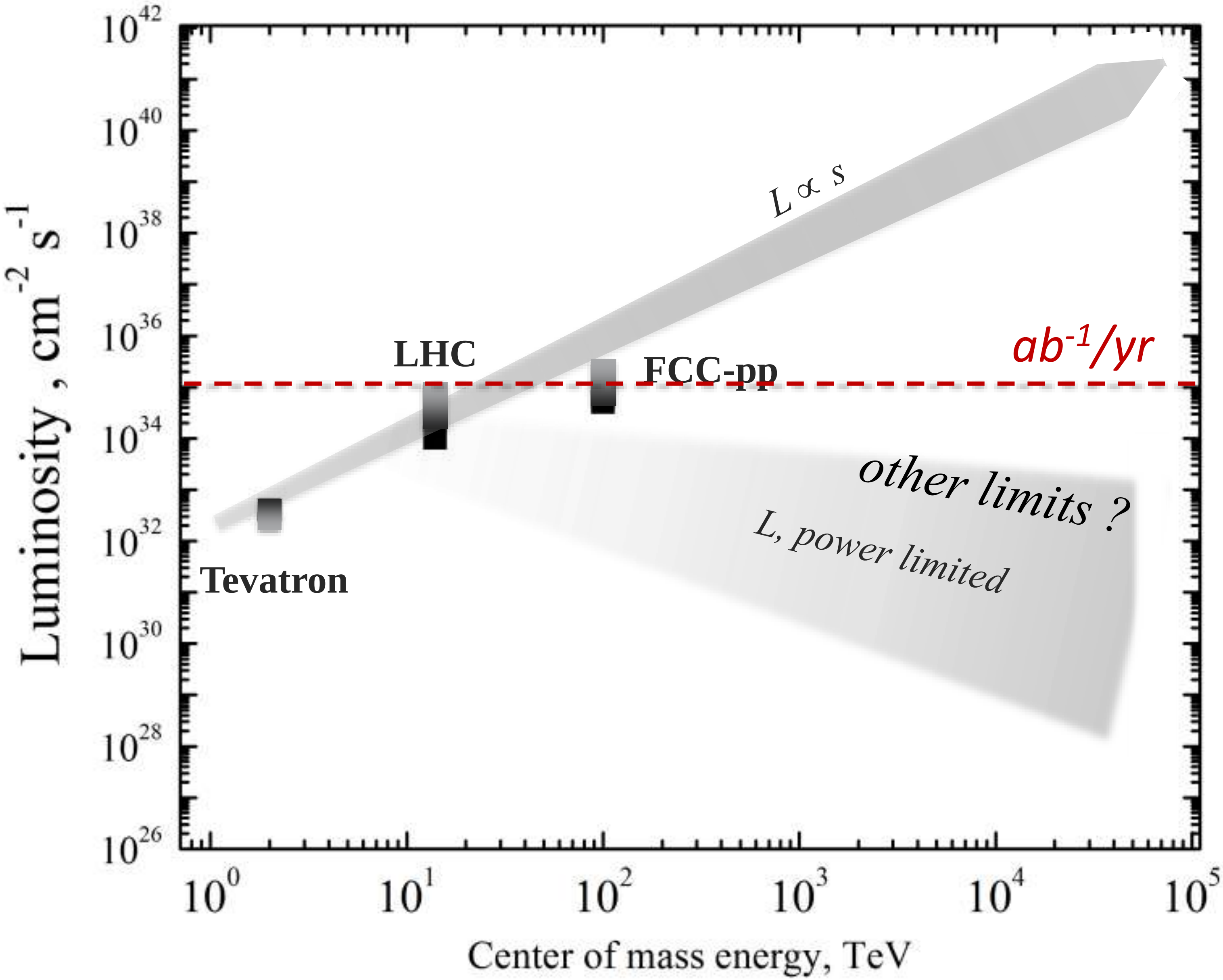
- *particle production* $\frac{dN}{dt}(\mu, e^+)$
- *beamstrahlung* $\delta_E \sim \frac{\gamma^2 N_p}{\sigma_z \sigma_x^2}$
- *synchrotron radiation* $P_{SR} \sim \frac{\gamma^4}{R}$
- *SR/meter* $\sim \frac{\gamma^4}{R^2}$
- *IR rad damage* $\sim PU \cdot E \cdot f_0 \cdot n_b$
- *ν-radiation dose* $D \sim \frac{\dot{N}_p \gamma^3}{R^*}$
- *instabilities* TMCI, RW, e-cloud $N \sim \frac{E}{Z_\perp}$
- *jitter/emittance growth* $\sim \gamma$

All Colliders: Past, Existing, under Discussion



On base of *Shiltsev&Zimmermann, Rev.Mod.Phys.* (2021)

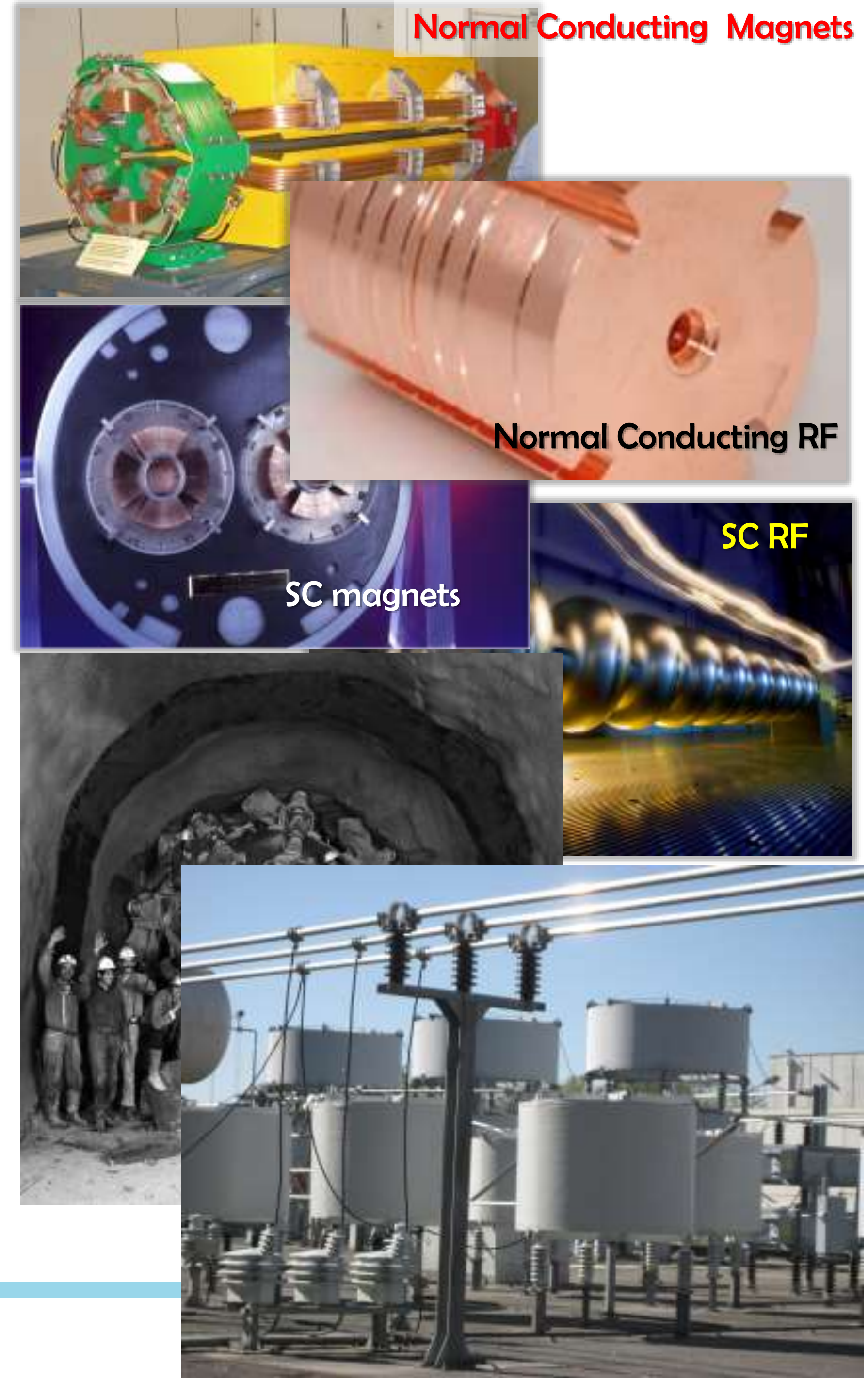
Paradigm Shift looming for > 0.1-1 PeV…



… to be discussed below…

Limits on *Cost* (1)

- Cost is set by technology
  - *Accelerator technology*
  - *Civil construction technology*
  - *Power production, delivery and distribution technology*



2014 Cost 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 !

The ***αβγ*** cost model:

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

a) **Is for a "green field" facility !**

b) **US-Accounting !**

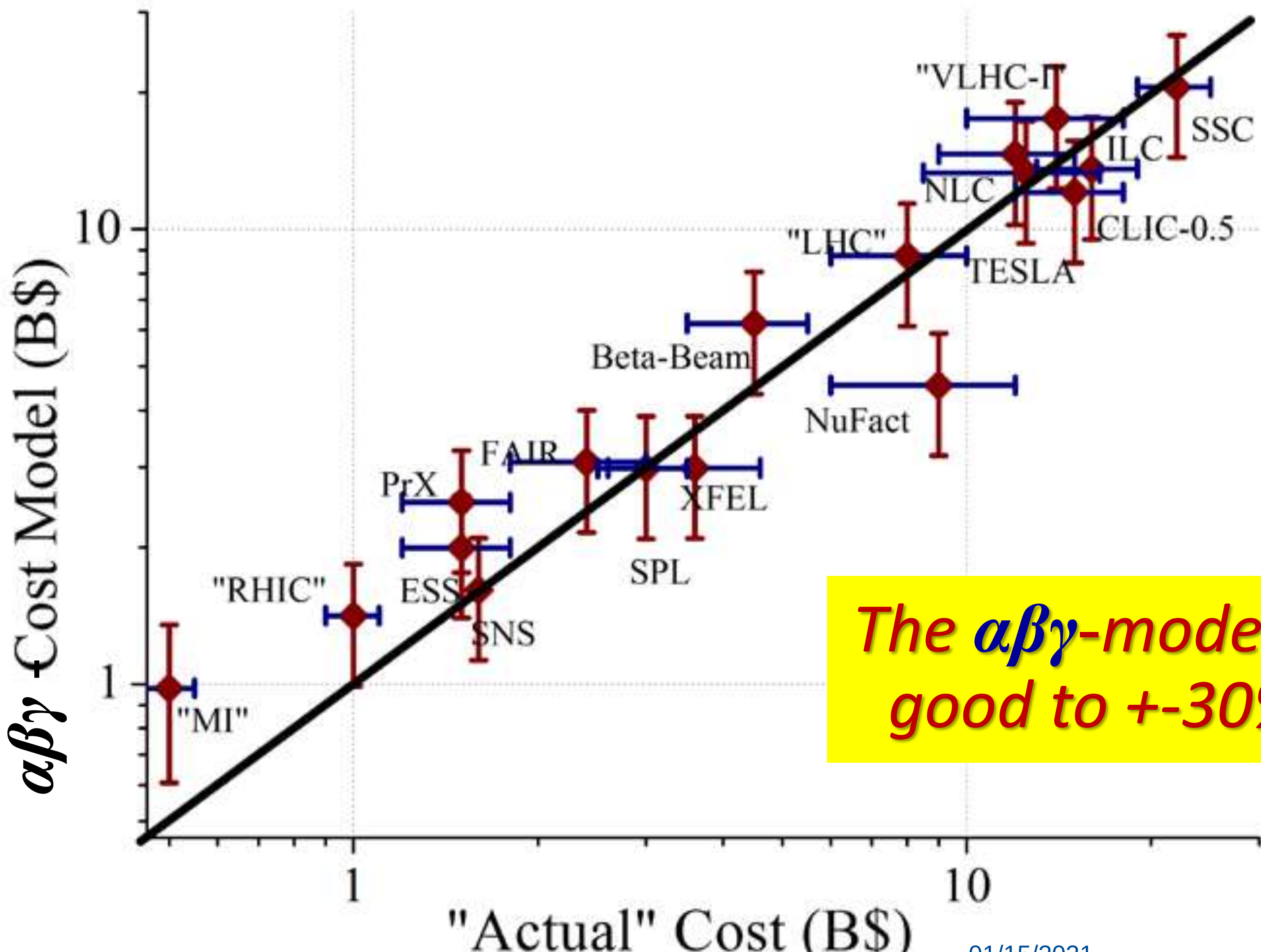
c) **There is hidden correlation btw *E* and technology progress**

d) **Pay attention to units**(10 km for *L*, 1 TeV for *E*, 100 MW for *P*)

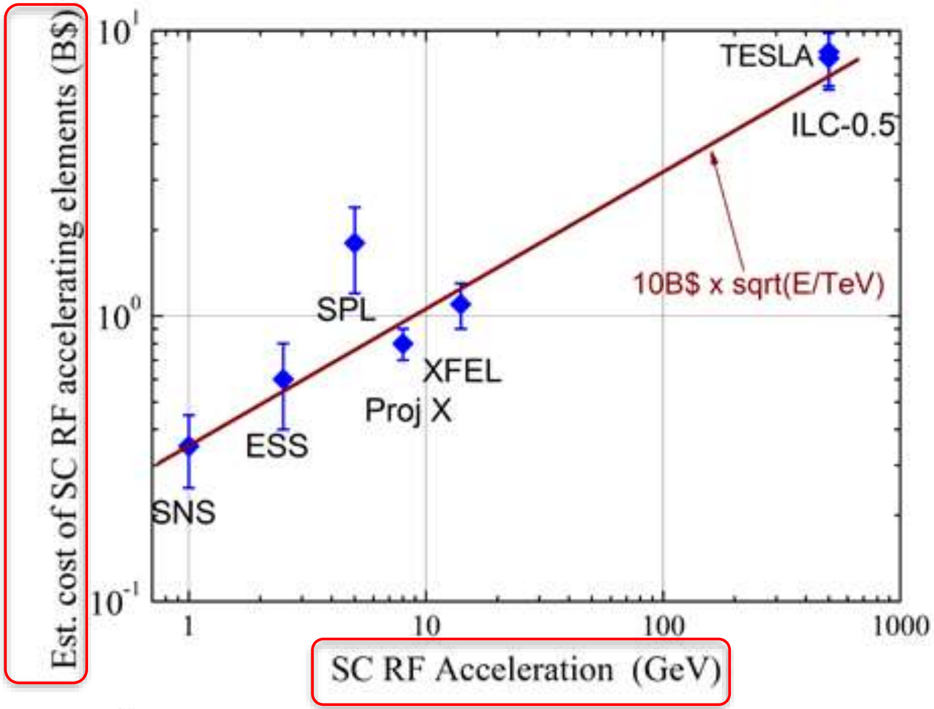
- ***α*≈ 2B$/sqrt(L/10 km)**
- ***β*≈ 10B$/sqrt(E/TeV)** for SC/NC RF
- ***β*≈ 2B$ /sqrt(E/TeV)** for SC magnets
- ***β*≈ 1B$ /sqrt(E/TeV)** for NC magnets
- ***γ*≈ 2B$/sqrt(P/100 MW)**

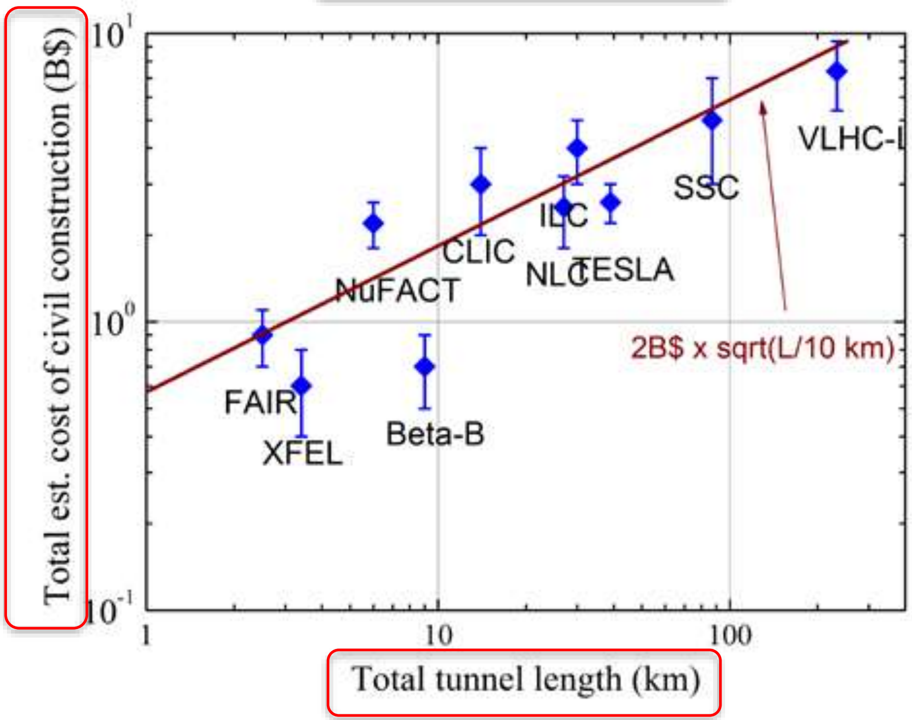
USE AT YOUR OWN RISK!

Total Cost vs *αβγ-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*** :

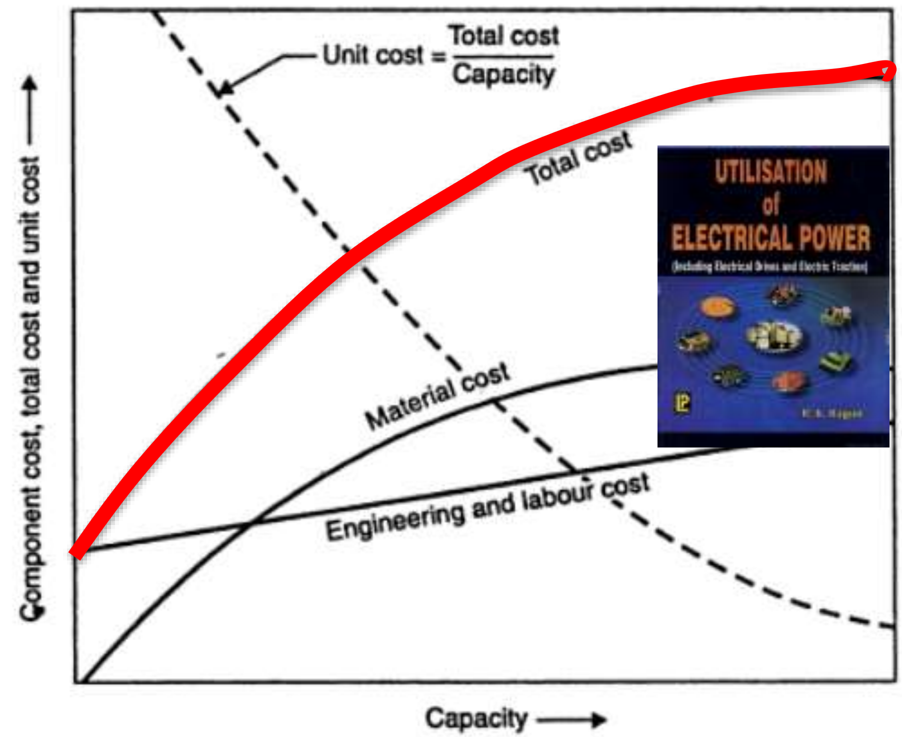


Fig. 9.5. Variation of costs of power plant *versus* its capacity.

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$**

- **ITF T.Roser talk @ PLUB-II (USD 2021):**
  - existing injector complex **4.6 B$**
  - new accelerator systems **4.06 B$**
  - new infrastructure and civil **2.75 B$**
  - explicit labor **~1.4 B$**

Total: **12.8B$**

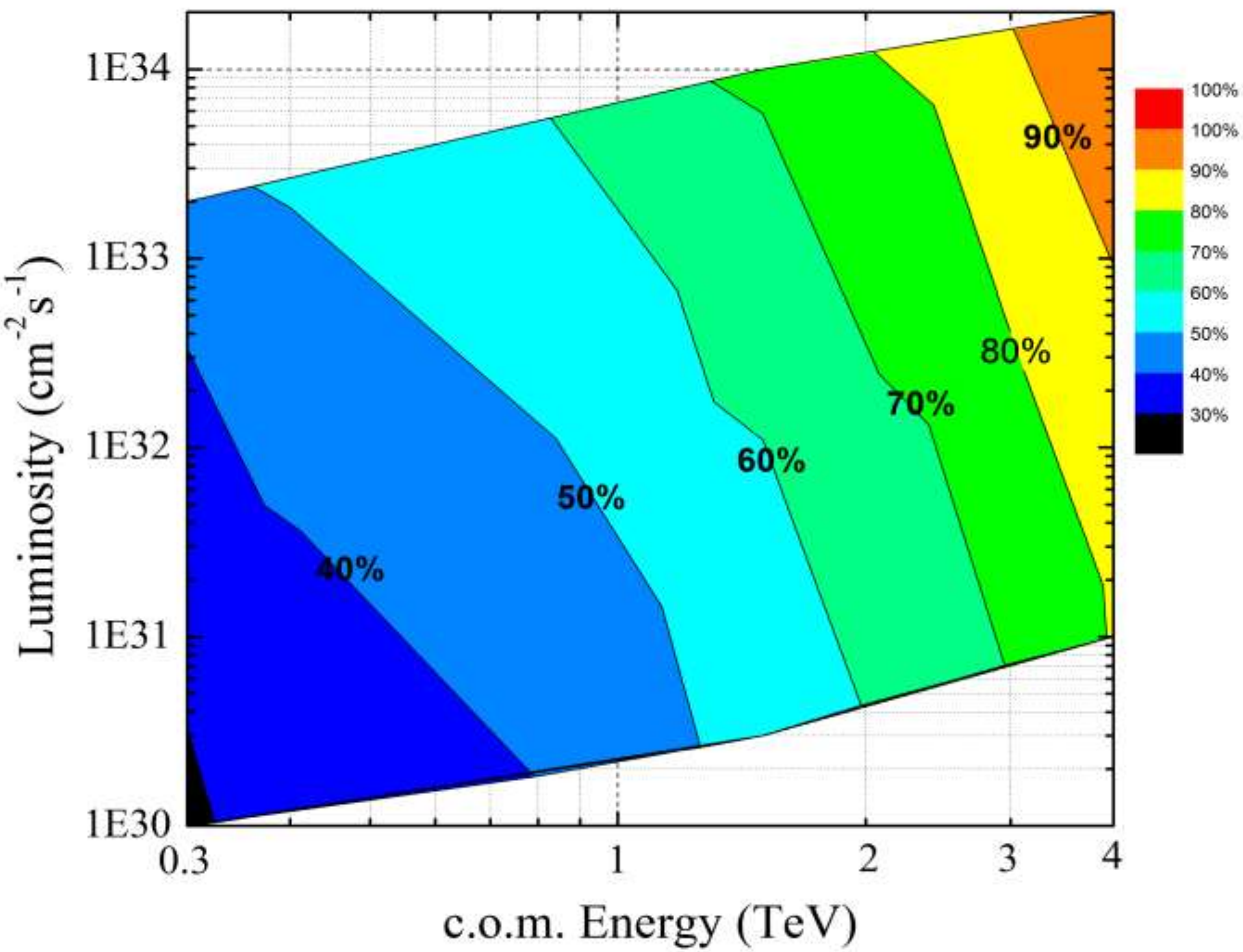
“αβγ – Model” : Caveats

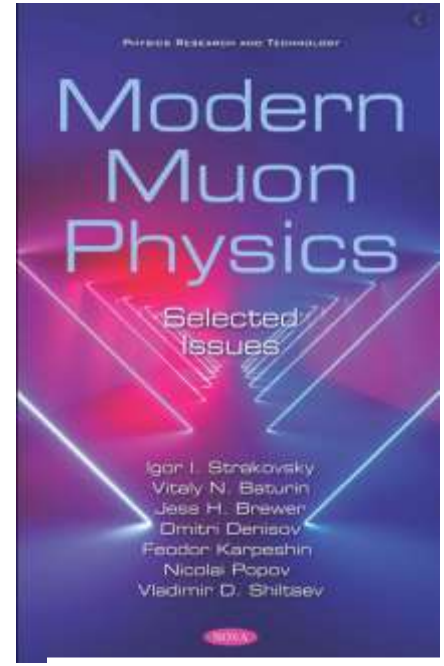
- (once again) note three warning signs:
  - *“…+- 30% …green field… US accounting…“*
  - *rounded powers and coefficients, e.g.,* $\sqrt{x} \approx x^{0.4 \ldots 0.6}$
- Analysis was done in 2013:
  - *inflation 7yrs x 3% = 21%*
  - *many more projects have been costed since then, others updated*
- “*Not-yet-built*” machine costs estim’d by proponents
- “*One person study*” – limited research on the subject
- That’s why:
  - **a) ITF work is very important**
  - **b) I’ll use LHCU for rough estimates/analysis here**

"αβγ – *Model*" : Notes

- Costs of future technologies are not well known:
  - plasma, lasers, crystals, "magic cheap" magnets, tunnels, HTS, etc
- Costs of civil construction and power systems are driven by larger economy (not by us)… "stable"
- Having injector (~1/3 of cost) → factor of 2 in energy reach
- Follows from the model:
  - *C*ost is weak function of luminosity (see next slide)
    - Also, LHC 10B$, HL-LHC 1B$ with x5 increase in luminosity
    - It's OK to start high *E*, low *L*…CESR, Tevatron increased *L* >100x, LHC >10x
  - *C*ost is moderate function of length/circumference
  - *C*ost is strong function of *E*nergy and technology
- Of course, the model does not tell us "what's affordable"
  - but at least allows approximately sort proposals in categories
    - E.g., "Less than LHCU", "1-2 LHCU", "More than 3 LHCU", etc

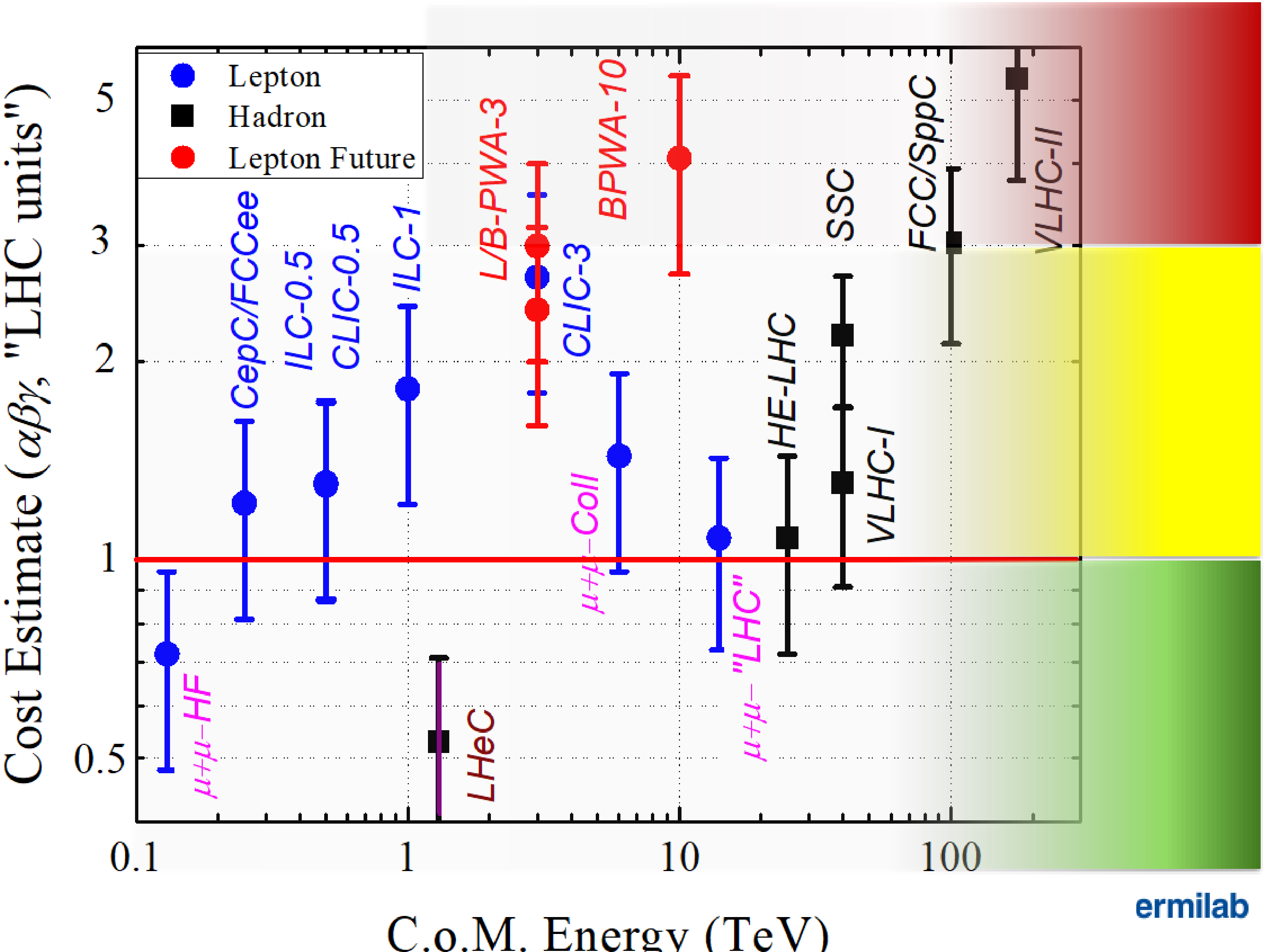
Example: Muon Colliders cost(color) vs *E* vs *Lumi*





Modern Muon Physics: Selected Issues, I.Strakovsky, et al (Nova, 2020)

Some projects discussed @ *EPPSU'19* and *Snowmass'21*



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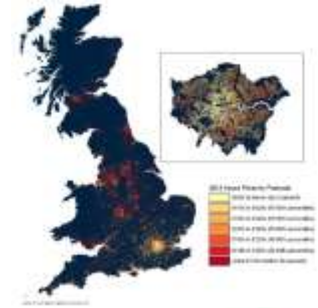
Colliders: Probability to Be Built



~1/ Cost^2 (is it true?)

1/(1 x LHC)^2 = 100%

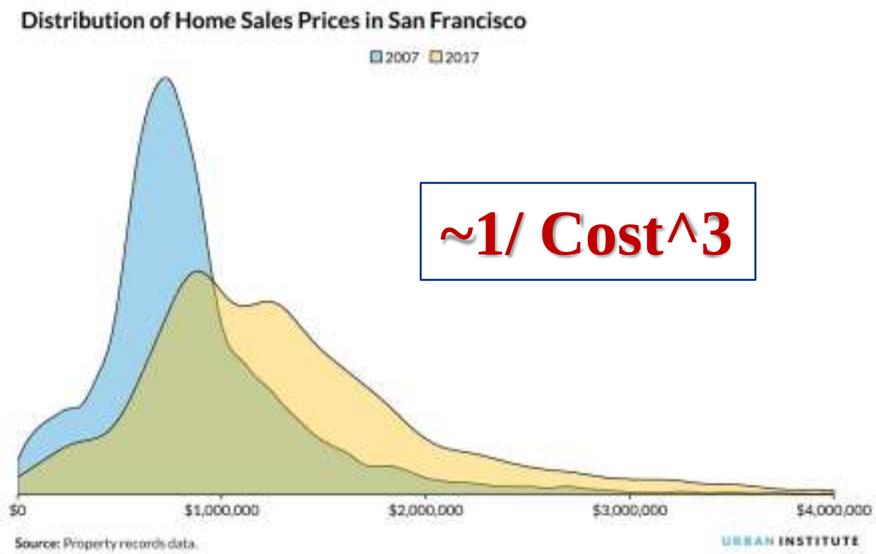
1/(2 x LHC)^2 = 25%

1/(3 x LHC)^2 = 10%

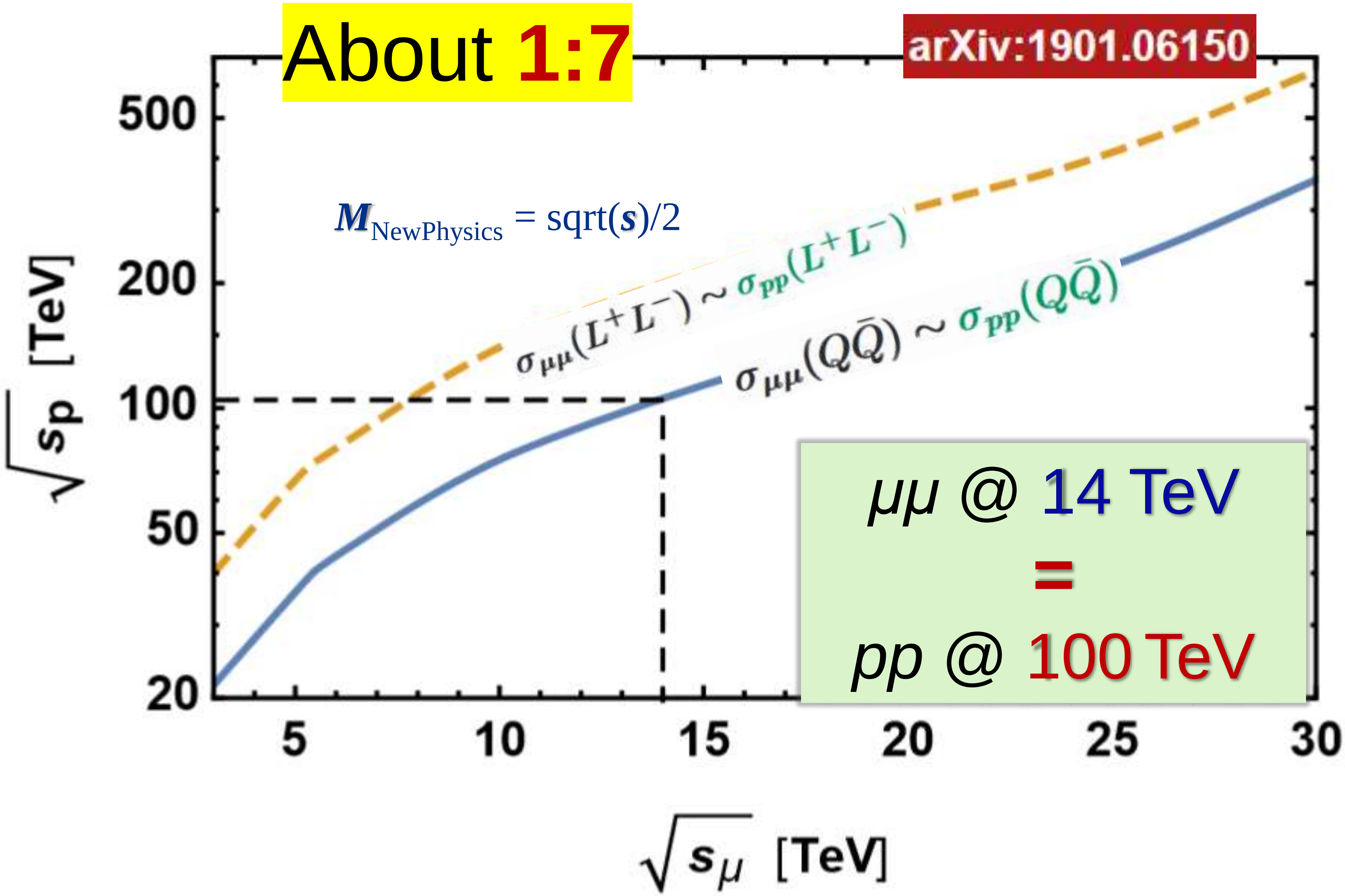
…Tao HAN : *calibration is function of community size, budget and time*

…Mike KORATZINOS : *lower cost?*

→ *1/(1+Cost^2)…*

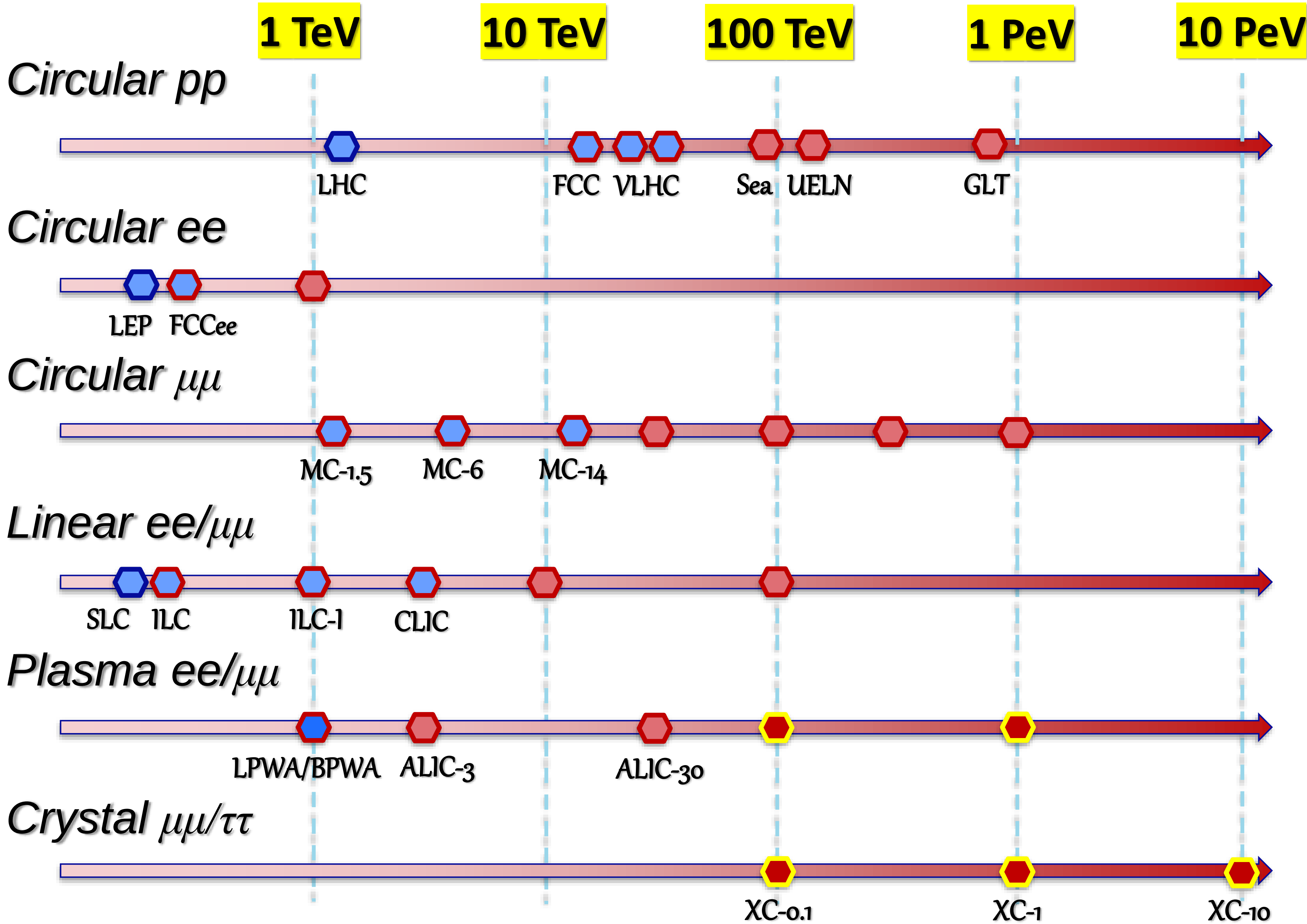


Energy Ranges and Reference Points : *leptons* vs *hadrons*

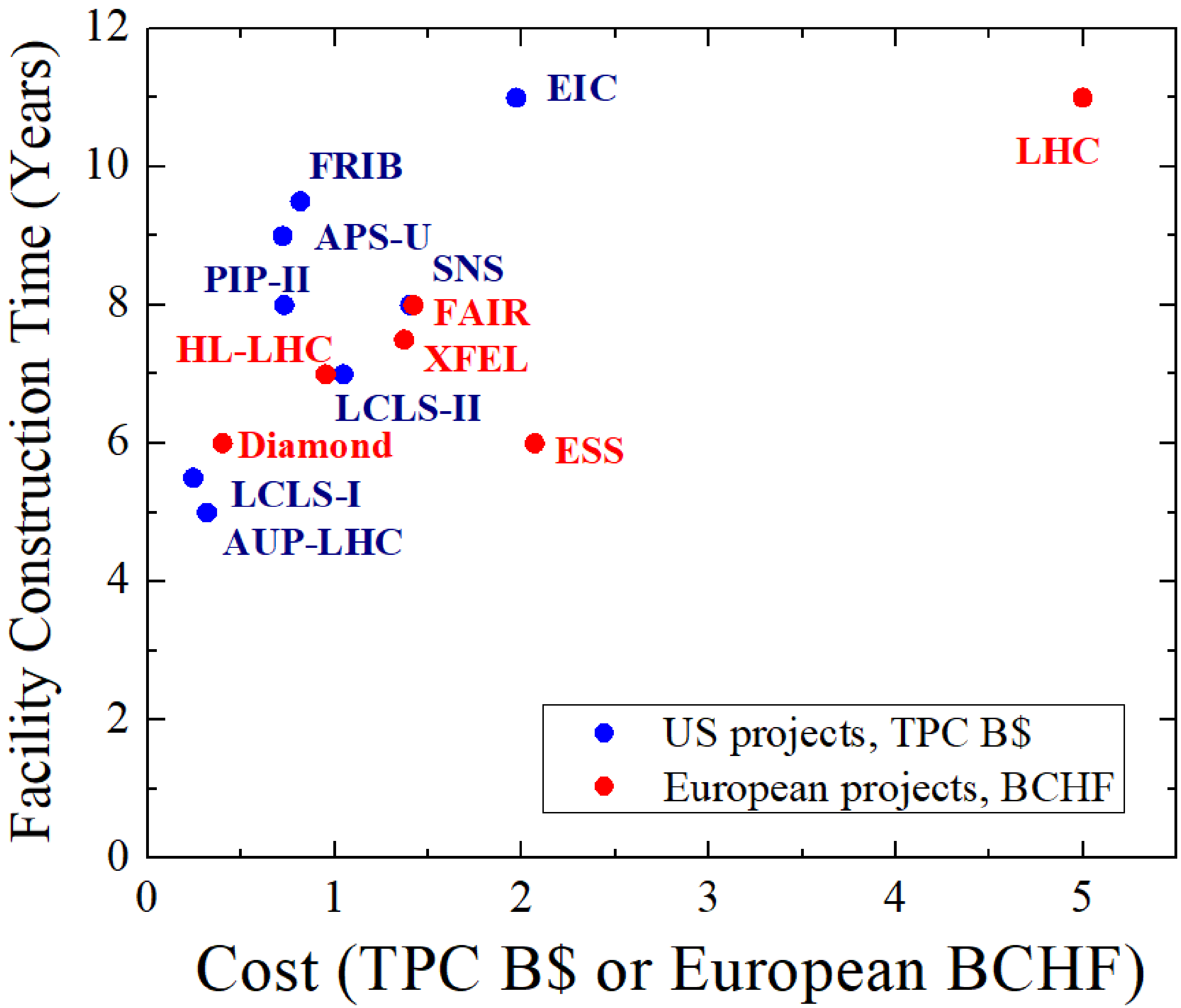


Equivalent reach in *pp* after rescaling for *pdf*'s

Reference Points and (Far) Future



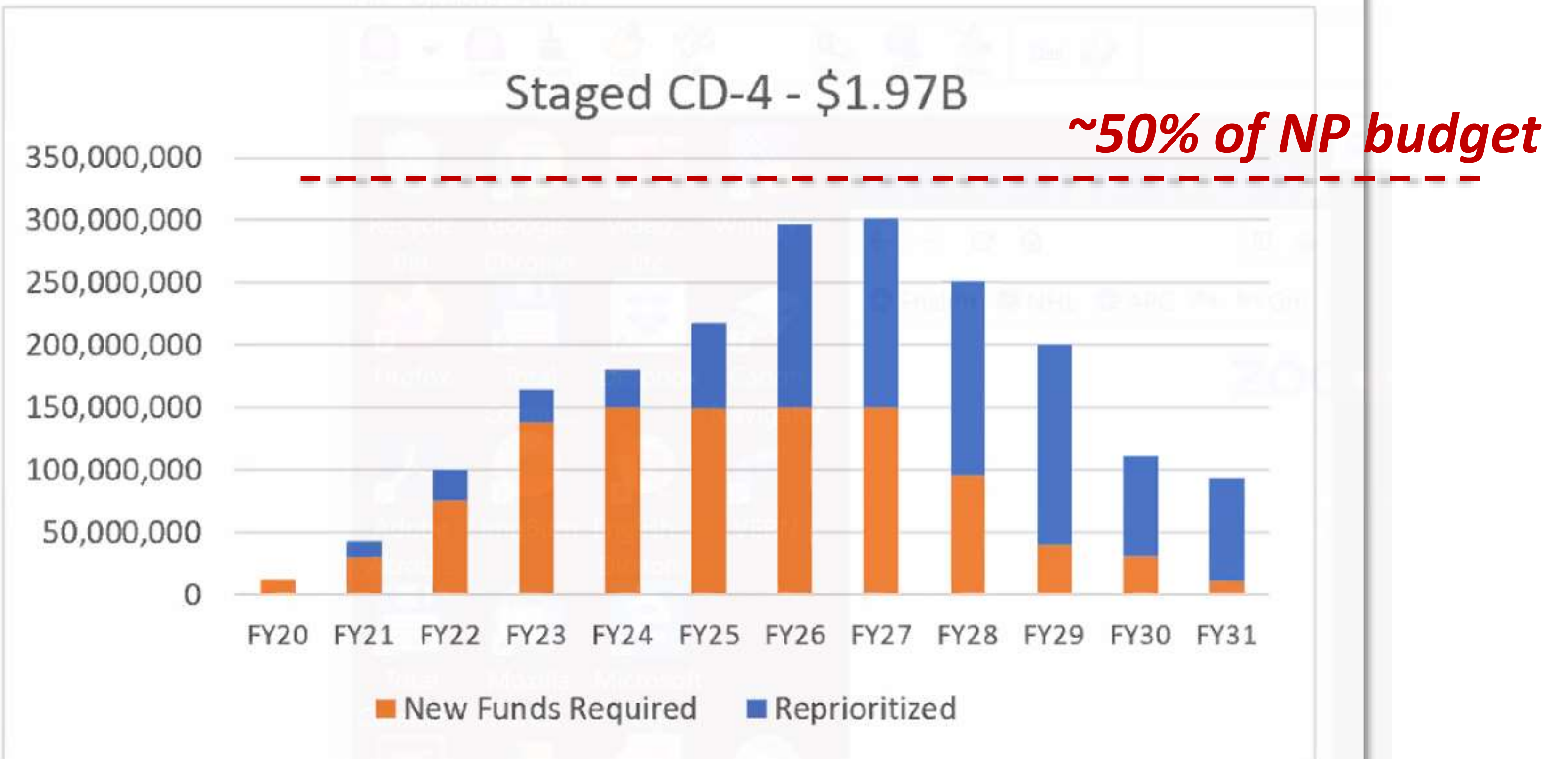
Construction Time… ~SQRT(*Cost*)?



Peak spending rate depends on $$/yr limit and on # of available experts …currently, btw 0.2 to 0.5 B$/yr (total World's HEP ~4B$)

The latest: *EIC at BNL*

Reference Funding Profile



- Reprioritized and New Funding
- FY2021 Budget of $30M supports schedule for CD-1
- Funding Profile Set prior to CD-2
- $100M Investment by New York State for Conventional Construction

"Social Cost" and Social Limits

- There is probably a limit on cost of ultimate accelerators
  - *how much society (national, regional, global) wants/can afford spending on HEP…slowly varies in time (grows?)*
  - *current estimate for global big collider ~* **2-3 LHCU ?**
- Since recently – awareness of the "carbon footprint"/"ecology" limit for large facilities
  - *current estimate for global big collider ~* **1(2) TWH/yr ?**
  - *disturbed environment (land use, radiation, pollutants, etc)*
- Scarcity of materials
  - *Helium, Nb, W, etc* **?**

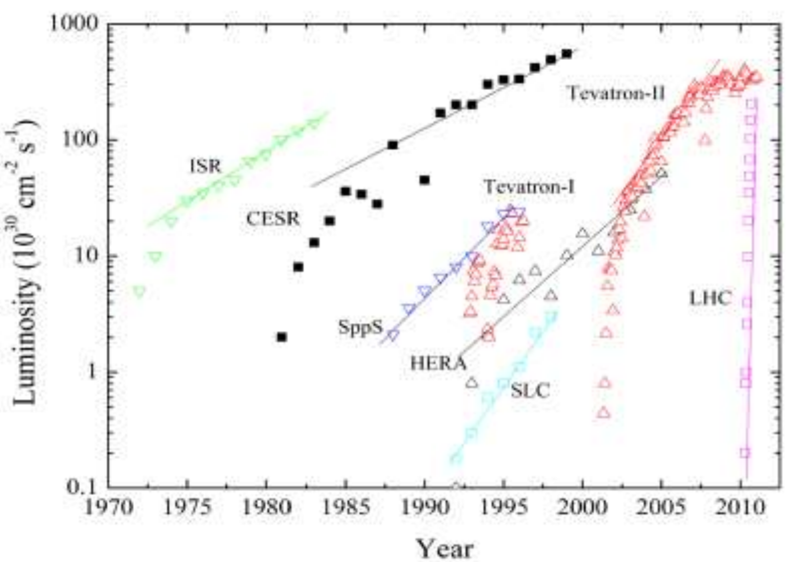
Commissioning Time : *T ~ Complexity*

CPT-theorem – V.Shiltsev *Mod. Phys. Lett. A*, vol. 26, No. 11 (2011) pp. 761-772

The evolution of the performance of continuously improving facilities where every next step brings *x-fold* improvement on top of previous improvement can be further simplified in an approximate formulas:

$$C \cdot P = T \,, \tag{3}$$

where the factor $P = \ln(\text{luminosity})$ is the "*performance*" gain over time interval T, and C is a machine-dependent coefficient equal to average time needed to increase the performance (in the case of colliders — luminosity) by $e = 2.71\ldots$ times, or boost the "performance" P by 1 unit. Both, T and C have the dimension of time,



A. Get the energy ("one particle"): C~O(1) yr – for known technologies, longer for new, ~# of elements
B. Get the (ultimate) luminosity: depends on luminosity risk – eg for P=4.5 (risk ~100 in L) and C~2 → T can be as long as T=4.5x2=9 yrs

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  - Other considerations: *T*
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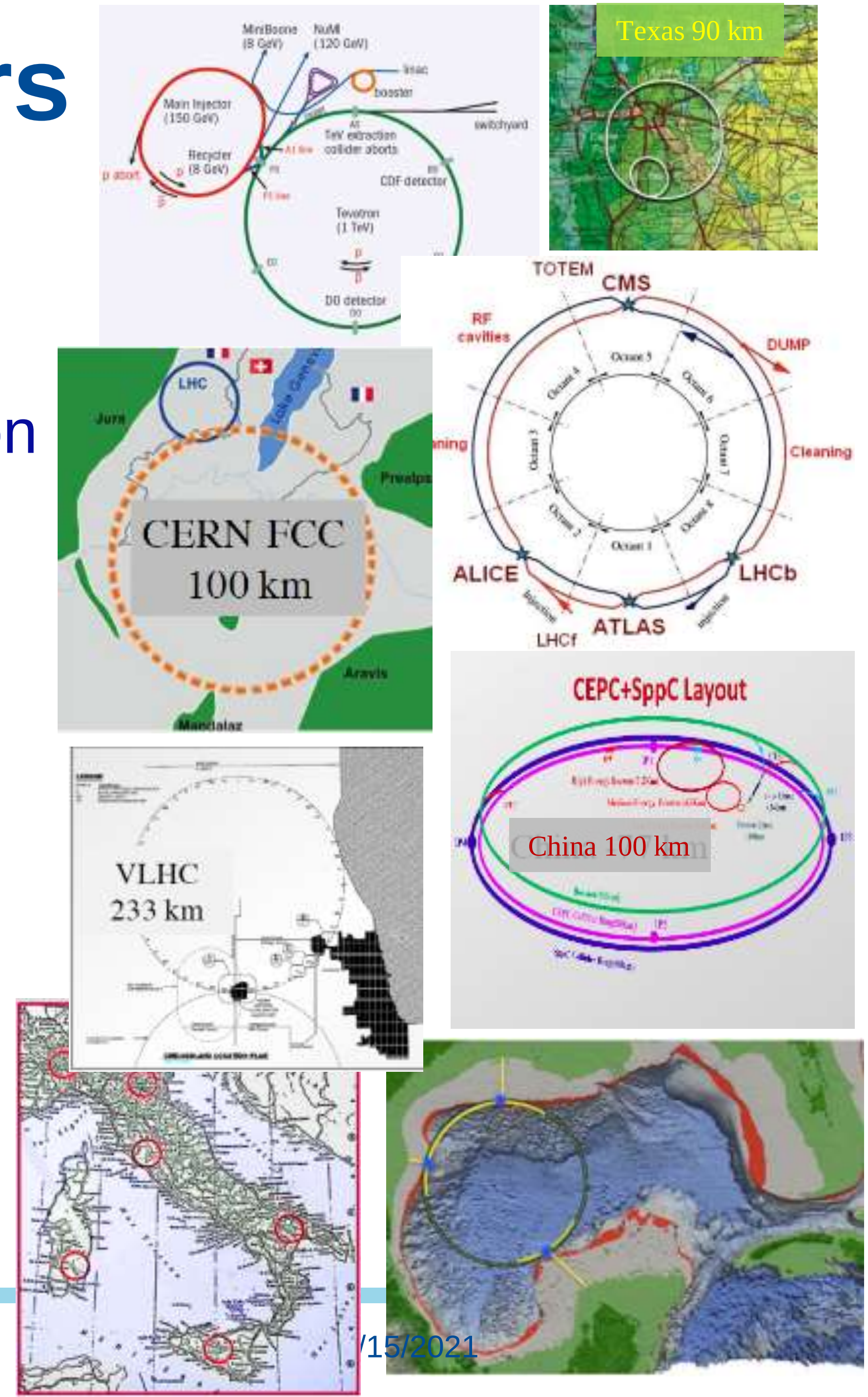
- **Conclusions / Q&A / Discussion**

Circular *pp* Colliders

- Can use Tevatron and LHC as reference pointw
- Parameter sets exist for SCC, FCC-hh, SppC, VLHC, Eloisatron
- Major advantages:
  - known technology and physics
  - good power efficiency ab^{-1}/TWh
- Major limitations:
  - Size (magnetic field *B*)
  - Power
  - Beam-beam, burn-off, instabilities
  - Synchrotron radiation
  - Cost



pp Luminosity

$$\mathcal{L} \sim f_0 \gamma n_b \frac{N_0^2}{4\pi \varepsilon_n \beta^*}$$

- Beam-beam limit #1

$$\xi = \frac{n_b N}{4\pi \varepsilon_n}$$

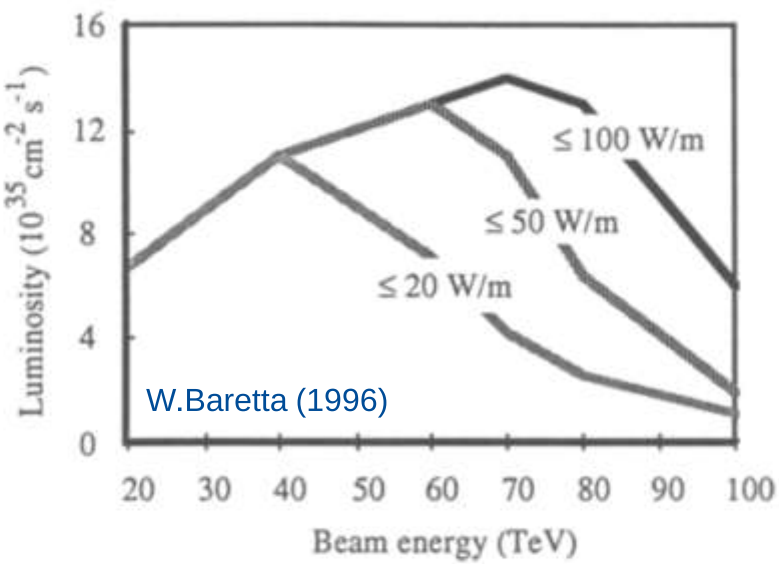
$$\mathcal{L} \sim \xi \cdot \frac{f_0 \gamma n_b N_0}{\beta^*}$$

- Synchrotron radiation :
  - Total power
  - or SR/meter

$$P_{SR} \simeq n_b N_0 \frac{\gamma^4}{R} \cdot f_0$$

$$\mathcal{L} \sim \frac{\xi}{\beta^*} \cdot \frac{P_{SR} \cdot R}{\gamma^3} \sim \frac{\xi}{\beta^*} P_{SR} \frac{1}{B\gamma^2}$$

$$\mathcal{L} \sim \frac{\xi}{\beta^*} \left(\frac{P_{SR}}{2\pi R}\right) \cdot \frac{R^2}{\gamma^3} \sim \frac{\xi (P_{SR}/m)}{\beta^* \cdot \gamma B^2}$$



Other limits

- Pile up
- IR radiation damage
- Resistive wall instability
- TMCI
- e-cloud
- Turn around time vs *L*uminosity evolution

$$PU = \mathcal{L} \cdot \sigma_{in}$$

$$\mathcal{L} = f_0 n_b \frac{PU}{\sigma_{in}} \sim \frac{PU}{\tau_{BB} \cdot \log E}$$

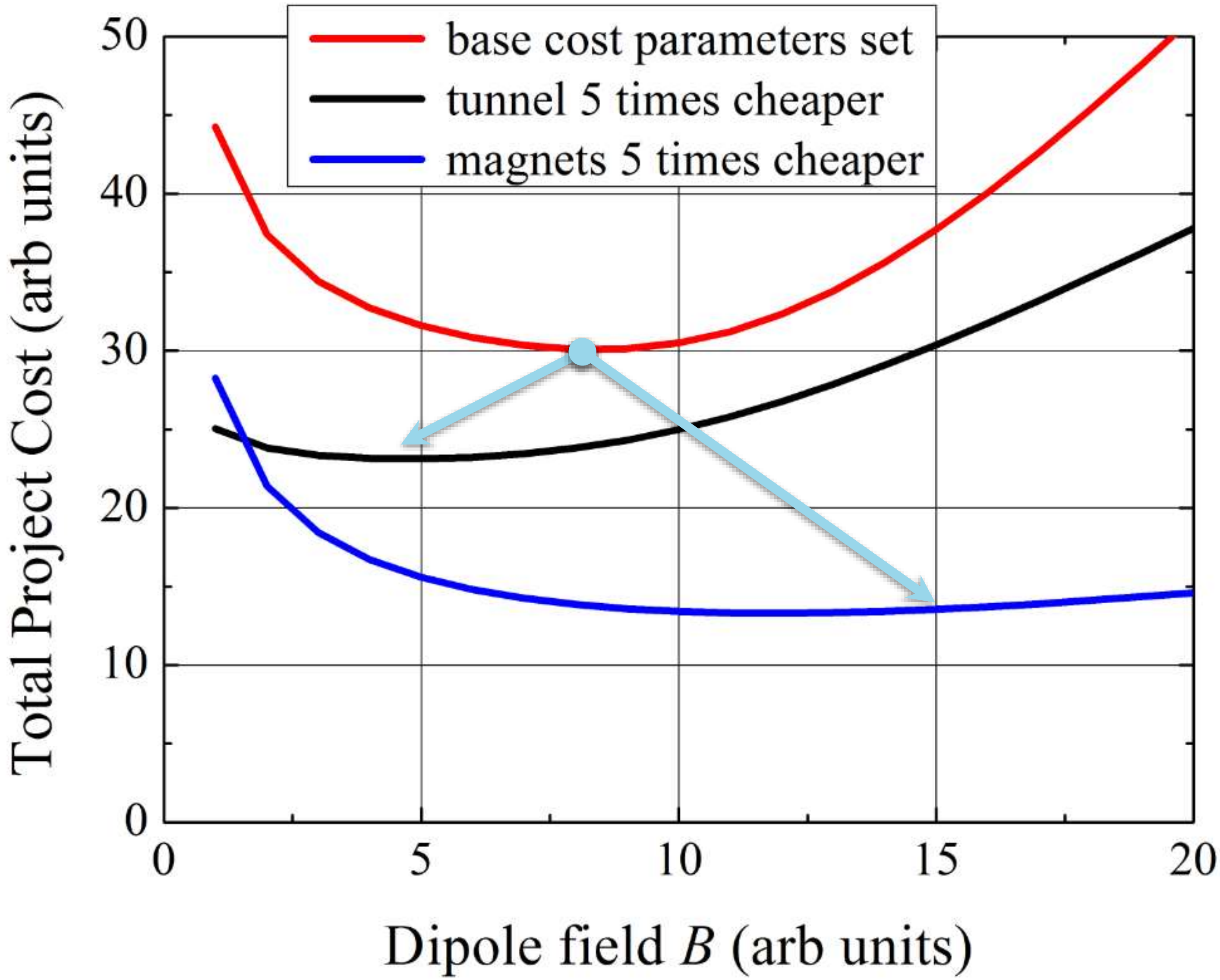
$$Rad = \mathcal{L} \cdot E$$

$$\rightarrow \quad \mathcal{L} \sim \frac{Rad}{E}$$

$$N_{\mathrm{RW}} \equiv \tau_{\mathrm{RW}} f_0 = \frac{\sqrt{2\pi (E_{\mathrm{p}}/e) a^3}}{I_{\mathrm{B}} Z_0 \langle \beta \rangle} \sqrt{\frac{(1 - \Delta \nu)\sigma_{\mathrm{W}}}{c R^3}}.$$

$$N_{\mathrm{thr}} = 1.24 \times 10^{10} \times \sqrt{\frac{\sigma_{\mathrm{s}}}{0.1\ \mathrm{m}} \frac{E}{3\mathrm{TeV}} \frac{\nu_{\mathrm{s}}}{0.005}} \times \left(\frac{a}{0.9\ \mathrm{cm}}\right)^3 \frac{520\ \mathrm{km}}{C} \times \frac{250\ \mathrm{m}}{\langle \beta \rangle}$$

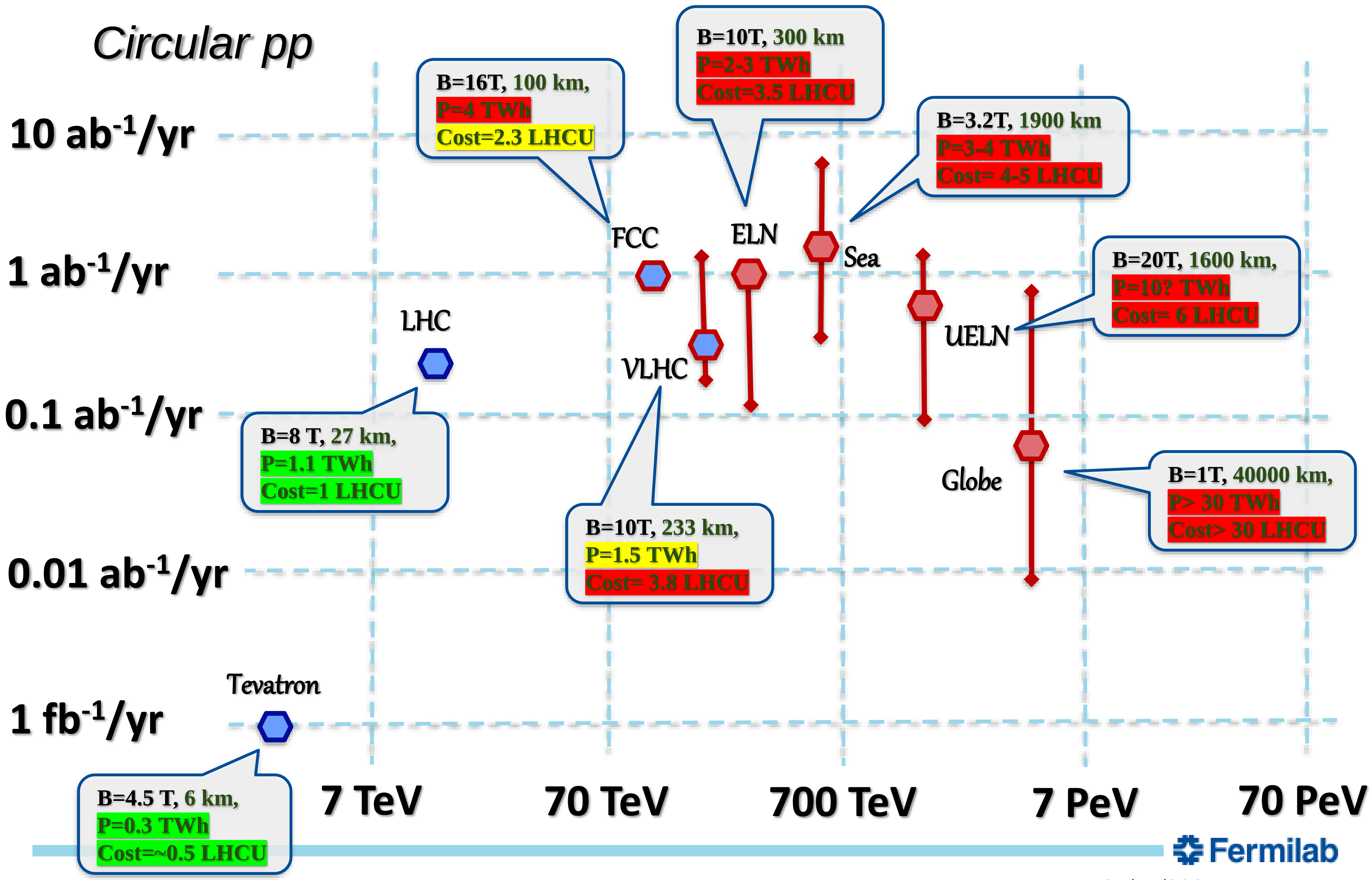
Qualitative Cost Dependencies - 100 TeV *pp*



* for illustration purposes only

Fermilab

pp Colliders: *Lumi* and *Cost* vs *Energy*



"Globaltron" and other ideas

- Cost saving magnets
  - superferric
  - permanent
- Better/cheaper conductors
  - Iron-based SC, graphene?
- Can they give factor of ~5 in $$/(Tm)?
  - (doubts so far)… leave it to AF7

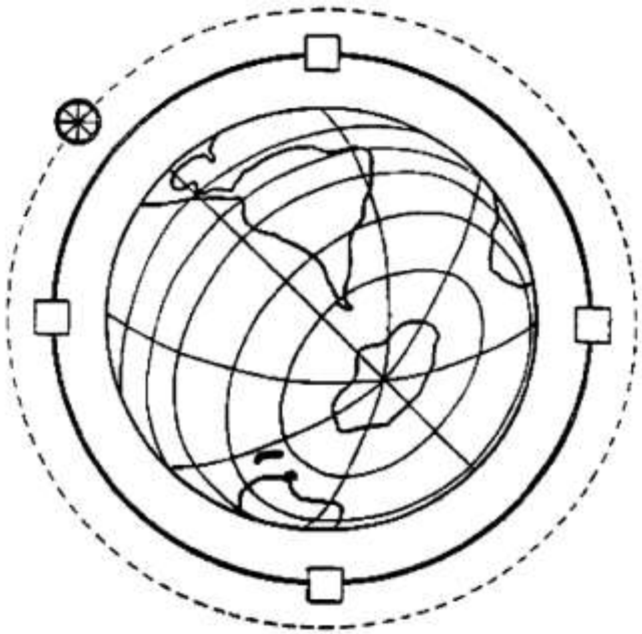
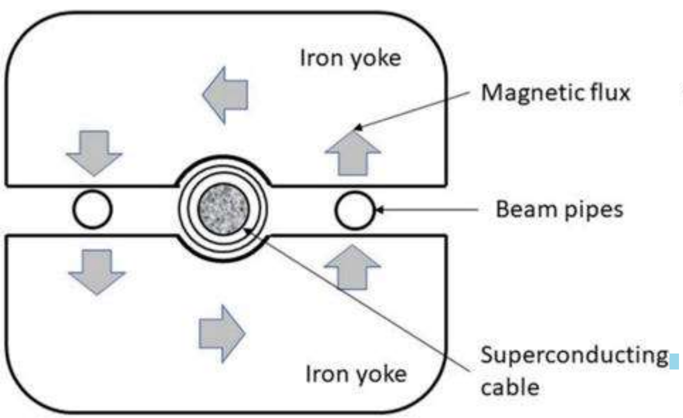
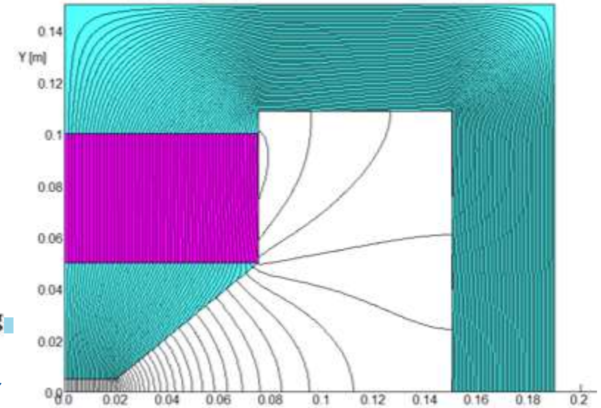


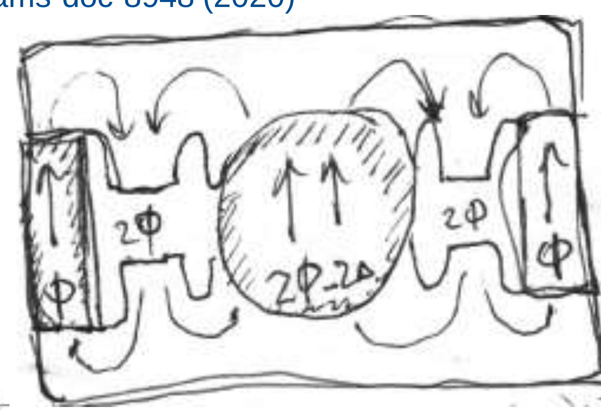
Figure 6. Enrico Fermi's "ultimate accelerator" encircling Earth.

as Enrico Fermi's ultimate accelerator or "globaltron" [46] (see Fig. 6), whose cost would exceed \$20,000B even under a modest estimate of \$0.5B per kilometer of a high-tech accelerator.



V.Kashikhin, FNAL beams-doc-8948 (2020)





Circular *e+e-* Colliders

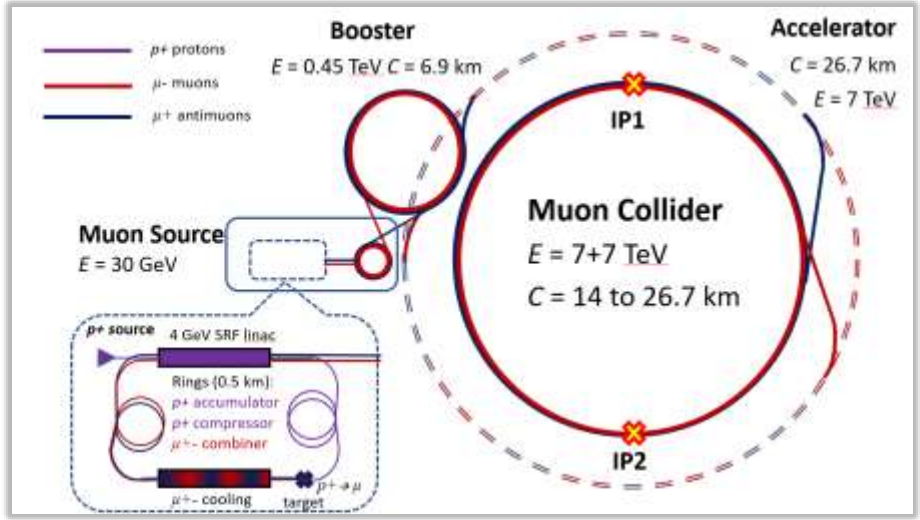
- Let's skip them… dead end… SR power

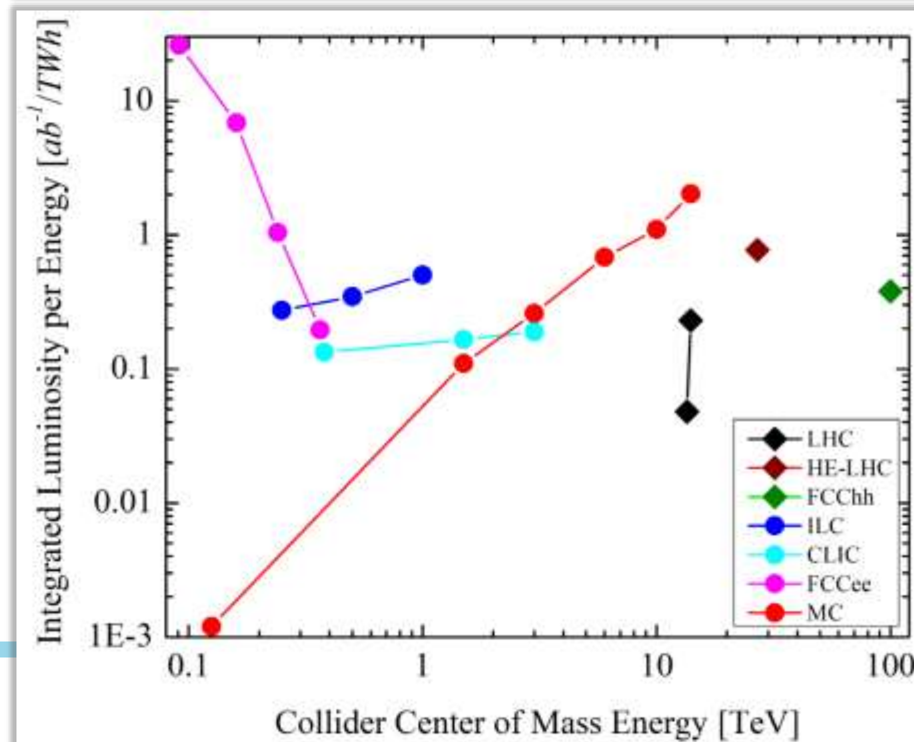
$$L = \frac{3}{16\pi r_e^2 (m_e c^2)} \frac{\xi_y P_T}{\beta_y^*} \rho \gamma^{-3}$$

- E.g. >0.5 TeV ring will be
  - Big (>200-300 km?)
  - Low luminosity O(10 fb-1/yr)
  - A lot of RF → expensive **>1.5-2 LHCU**

Circular Muon Colliders

- Parameter sets exist for 1.5, 3, 6, 10, 14 TeV
- Major advantages:
  - factor of x7 in *E*_reach
  - best power efficiency ab^{-1}/TWh
  - Traditional core technologies
- Major limitations:
  - Muon production
  - Muon cooling
  - Neutrino radiation





NATURE PHYSICS | www.nature.com/naturephysics

arXiv:2007.15684

Muon colliders to expand frontiers of particle physics

Jan 28, 2021

Muon colliders offer enormous potential for the exploration of the particle physics frontier but are challenging to realize. A new international collaboration is forming to make such a muon collider a reality.

K. R. Long, D. Lucchesi, M. A. Palmer, N. Pastrone, D. Schulte and V. Shiltsev

MC Luminosity

- $L \sim B$ field
- Assuming :
  - Enough muons can be produced
  - *L ~ Power x Energy*
  - At some energy, neutrino radiation sets the limit
  - Ultimate lumi depends on suppression factor $\mathbf{\Phi}$

$$\mathcal{L} = f_c \, \gamma \, n_b \cdot \frac{N_0^2}{4\pi \varepsilon \beta^*}$$

$$f_c \sim f_{rep} \cdot 300 \cdot B$$

$$\dot{N} = N_0 \cdot n_b \cdot f_{rep} \sim 2 \cdot 10^9 \cdot 5 \sim 10^{12}/s$$

$$\mathcal{L} \sim B \cdot P \cdot \gamma \cdot \frac{N_0}{\varepsilon}$$

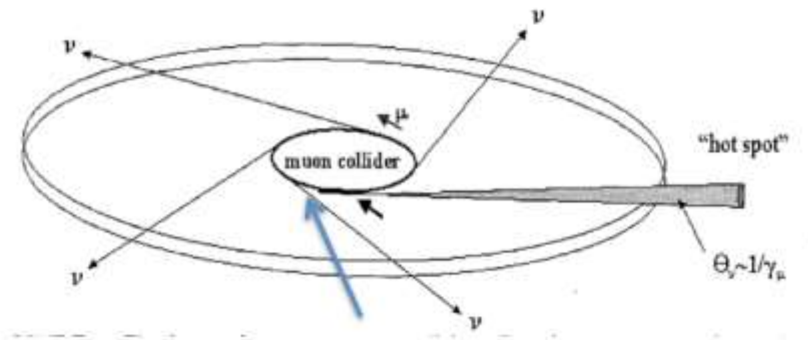
$$D(\text{dose}) \sim f_{rep} \cdot N_0 \cdot n_b \cdot \frac{\gamma^3}{\Phi} \qquad D \sim \frac{P\gamma^2}{\Phi}$$

$$\text{Power} \sim \frac{D\Phi}{\gamma^2} \leq P_0$$

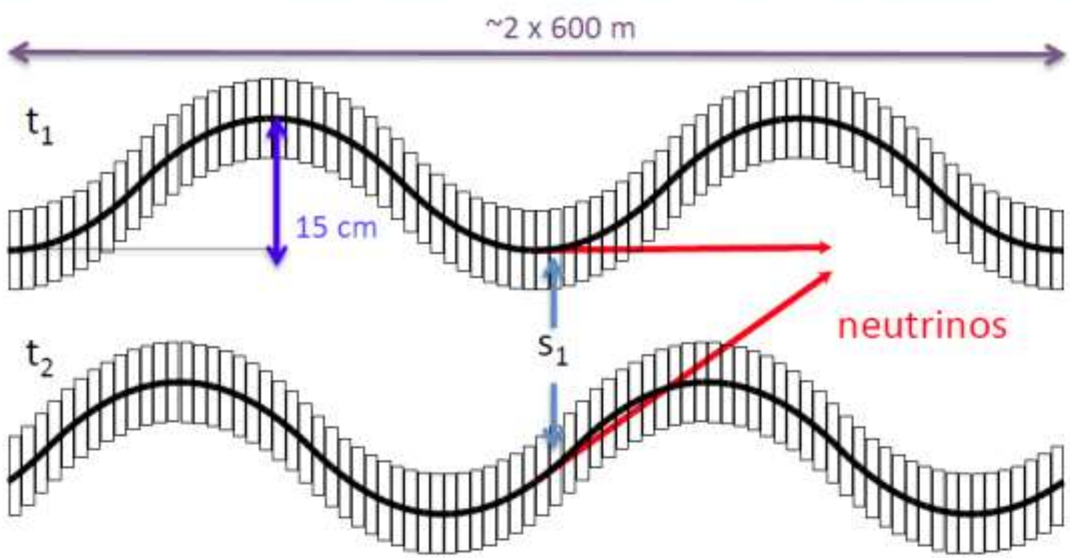
$$\mathcal{L} \sim \frac{B}{f_{rep}} \cdot \frac{(D\Phi)^2}{\varepsilon \gamma^4}$$

Neutrino Radiation Mitigation Φ~100 possible

disk width ≅ 4 m at 30 km



Move collider ring components, e.g. vertical bending with 1% of main field



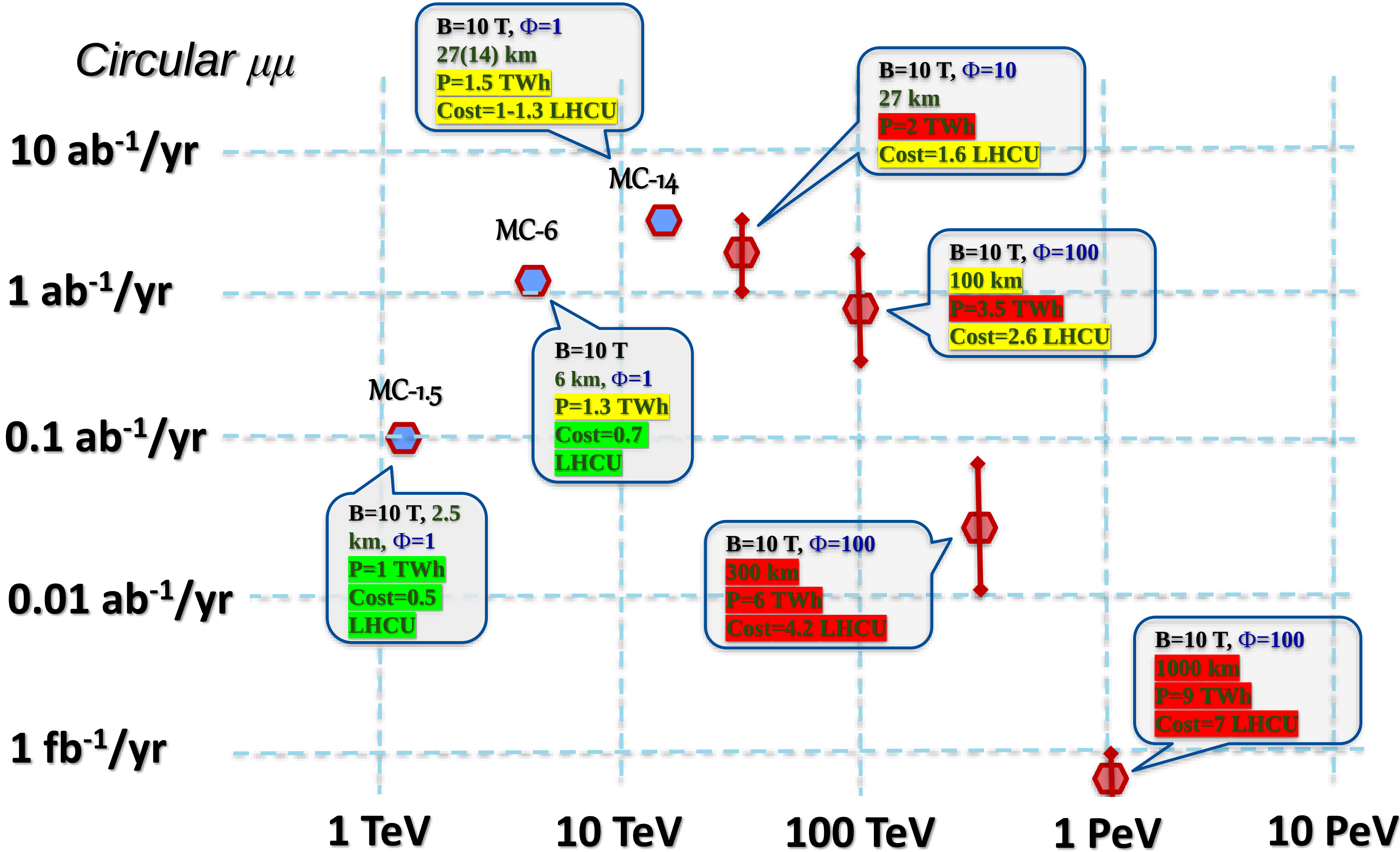
Opening angle ± 1 mradian

O(100) larger than decay cone
⇒ gain O(100) in radiation

In straights, additional improvement in horizontal

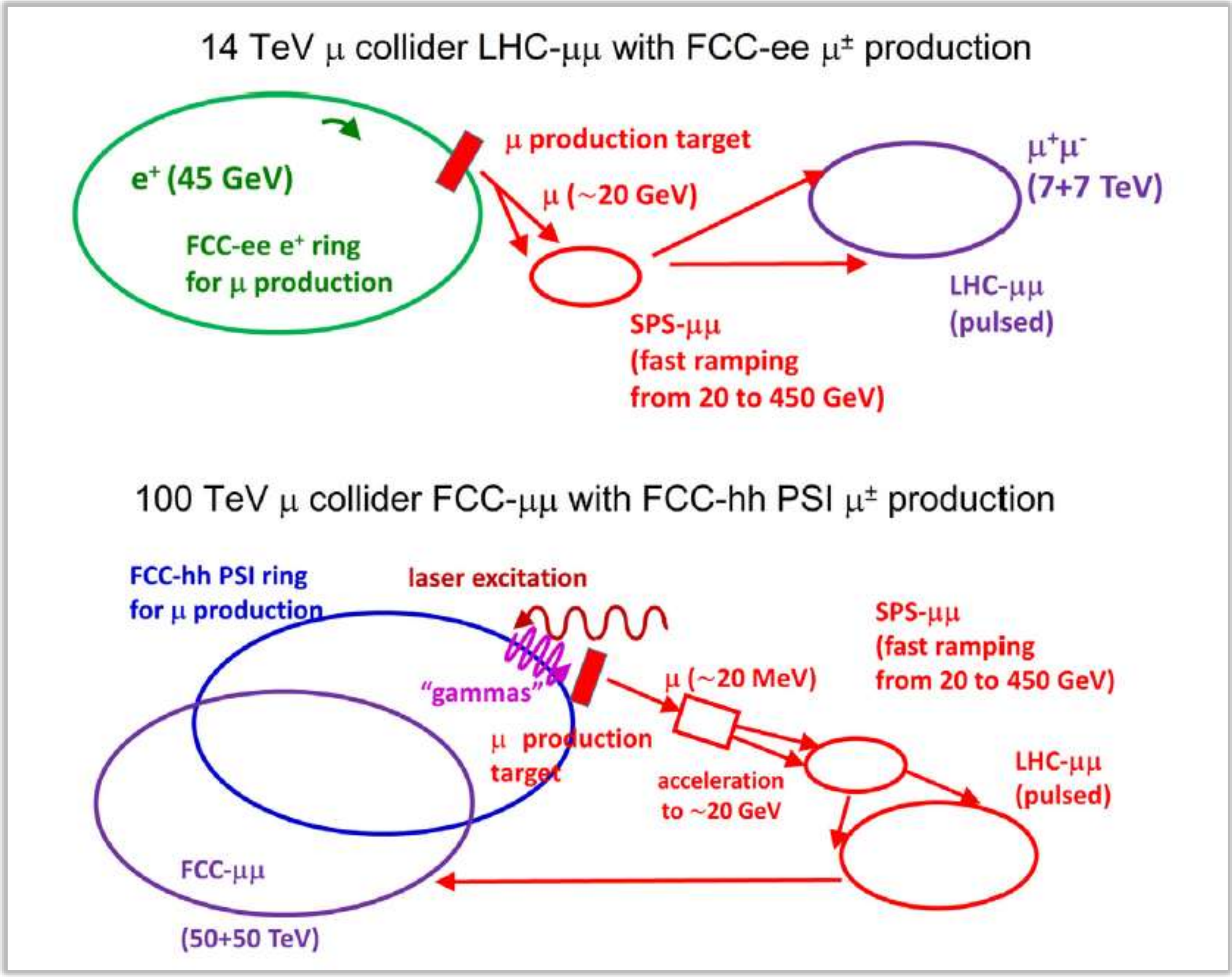
Need to study impact on beam and operation, e.g. dispersion control

MC: *Lumi* and *Cost* vs *Energy*



New muon production schemes

- *LEMMA* and *Gamma-Factory*
  - small emittance
  - Intensity N/emm?
  - beam-beam
- Both require (expensive?) aux. *e*+ or *p*+ machines



F. Zimmermann Nuclear Inst. and Methods in Physics Research, A 909 (2018) 33–37

Linear *lepton* Colliders

- Mostly *e+e-/e-e-/γγ*
  - Muons possible, but μ-sources are expensive (and limited prod'n *dN/dt*)
  - Protons possible, but lose factor of 7 in effective cme energy reach in *hh*
  - *NC RF, SC RF, plasma, wakefields*
- Major advantages:
  - No SR losses
  - RF acceleration well developed
- Major limitations:
  - *L* scales with power, jitter/size and beamstrahlung
  - plasma/wakefield acceleration is not fully matured yet (many unknowns - energy staging, *e+*, power, cost, etc)

$$E_b = eGL$$

$$\mathcal{L} = (N_e n_b f_r)\left(\frac{1}{\sigma_y^*}\right)\left(\frac{N_e}{\sigma_x^*}\right)\frac{H_D}{4\pi}$$

$$\eta \equiv P_b / P_{\rm wall}$$

$$N_e n_b f_r = \eta P_{\rm wall} / eE_{\rm c.m.e.}$$

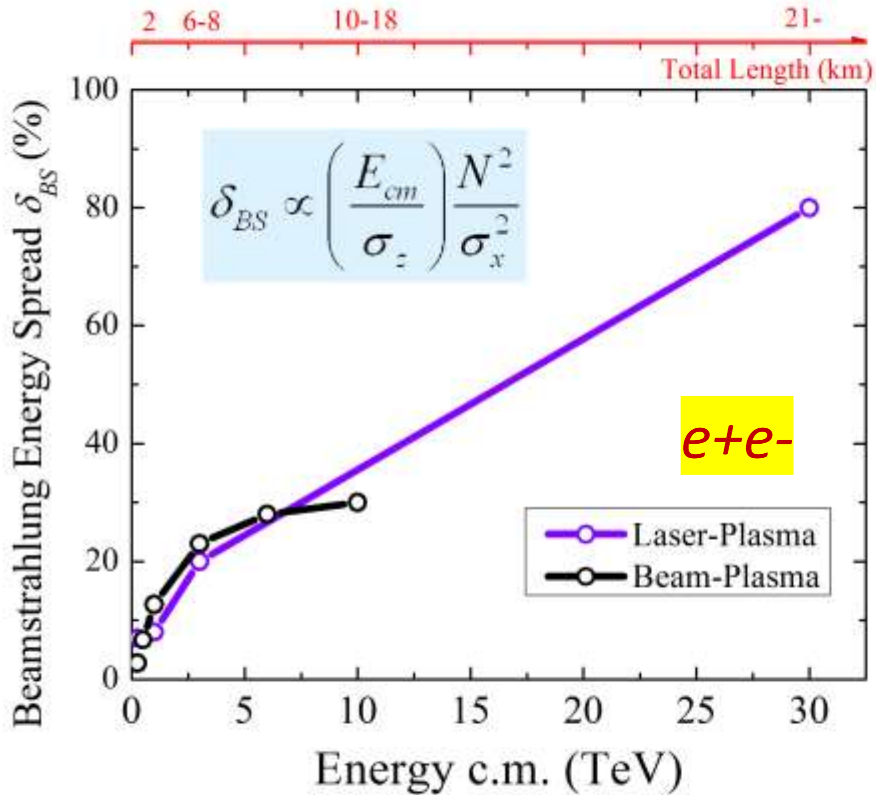
$$L \propto \frac{\eta_{\rm linac} P_{wall}}{E}\frac{N_\gamma}{\sigma_y}$$

(luminosity spectrum) $N_\gamma \simeq \frac{2\alpha r_e N}{\sigma_x}$

ee/γγ or μμ Linear Collider Luminosity

see detail analysis in eg D.Schulte, *Rev.Accel.Sci.Tech.* 9 (2016): 209-233.

- Other considerations :
  - Positron production and acceleration in plasma
    - Can be solved by switching to *ee/γγ*
  - Beamstrahlung
    - Can be solved by ultrashort bunches or switching to *ee/γγ* or μμ
      (see M.Peskin @ PLUB-II and Swapan C. talk today)
  - Instabilities in RF structures or plasma
  - Jitter/emittance control
    - Problems grow with more elements and smaller beams at IP → limit at 1A

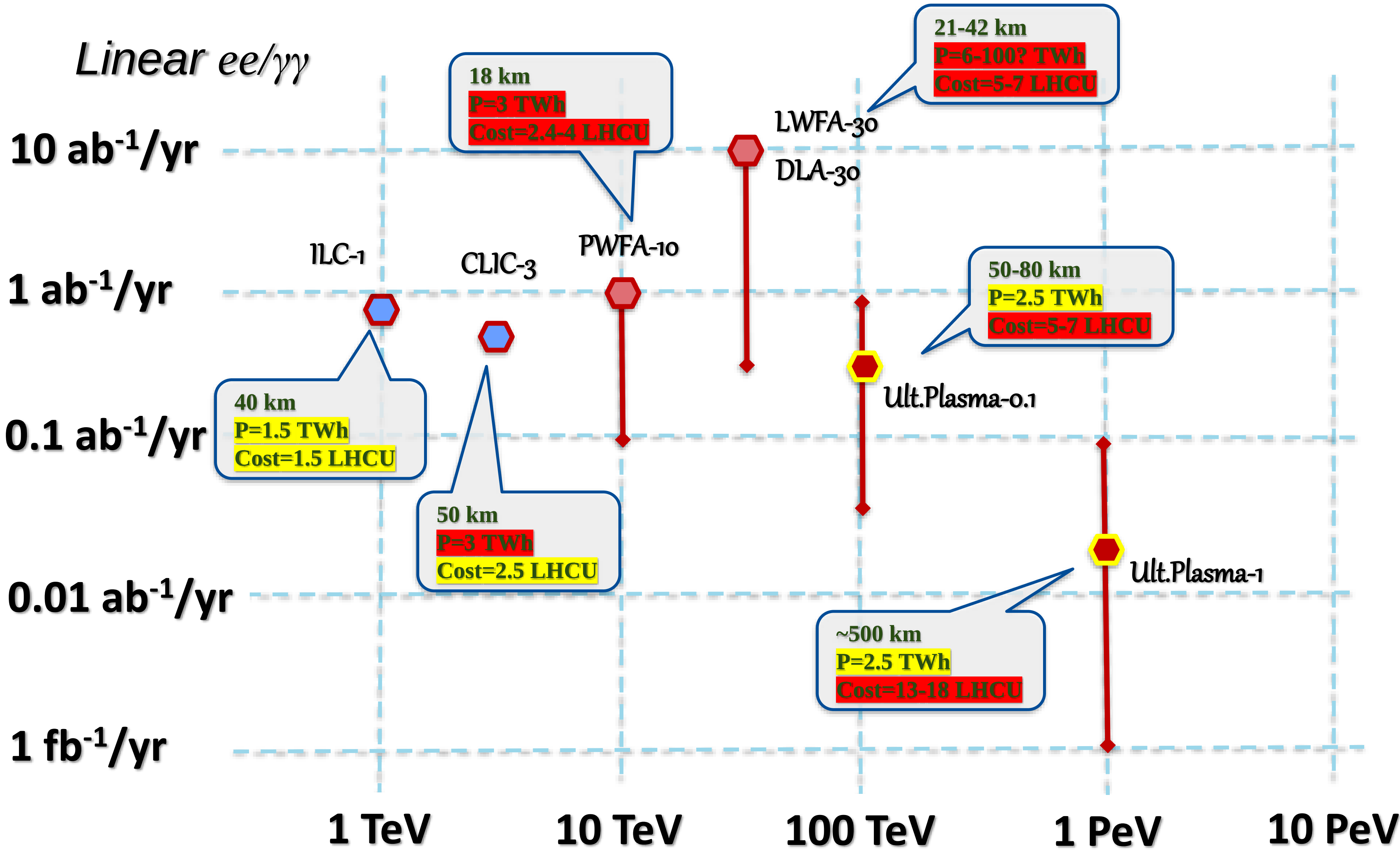


$$\delta_B \approx \frac{24}{3\sqrt{3}\pi^{3/2}} \frac{r_e^3 \gamma N_b^2}{\sigma_z(\sigma_x^* + \sigma_y^*)^2} \approx \frac{24}{3\sqrt{3}\pi^{3/2}} \frac{r_e^3 \gamma N_b^2}{\sigma_z \sigma_x^{*2}}$$

$$\mathcal{L} \propto \frac{n_\gamma^{3/2}}{\sqrt{\sigma_z}} \frac{1}{\sigma_y} N n_b f_r.$$

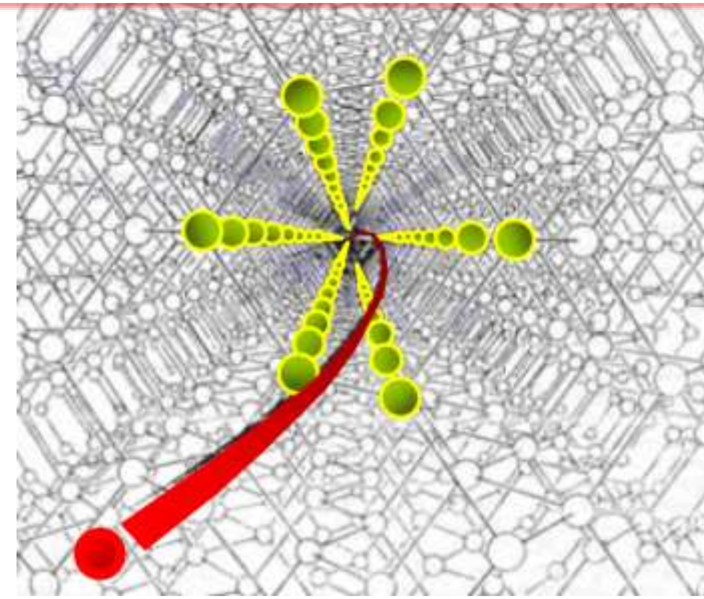
(T.Raubenheimer, PRSTAB 2000)

Linear RF and Plasma: *Lumi* and *Cost* vs *Energy*



Exotic Colliders

$$E\,[\mathrm{GV/m}] \approx 100\sqrt{n_0\,[10^{18}\,\mathrm{cm}^{-3}]}$$



- Acceleration in structured media, eg CNTs or crystals (***only muons!!!***)
- Major advantages:
  - solid density → 1-10 TV/m gradients
  - continuous focusing and acceleration (no cells, one long channel, particles get strongly cooled *betatron radiation*)
  - small size promises low cost
- Major limitations:
  - "blue sky", *O*(10) papers, plans for proof-of-principle experiment *E336* @FACET-II (S.Corde, T.Tajima, et al)
  - how to drive Xtals? lasers, beams?
  - Cost is unknown, power is unknown, luminosity - (how low?)

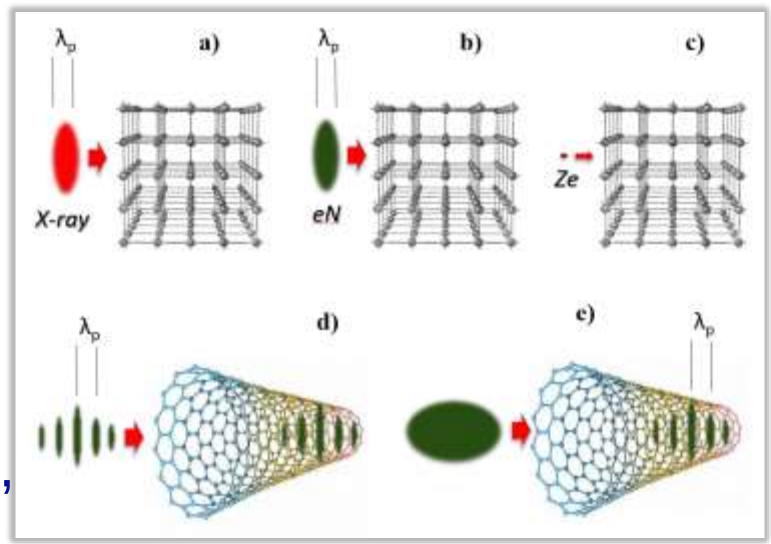


Fig. 2. Possible ways to excite plasma wakefields in crystals or/and nanostructures: (a) by short X-ray laser pulses; (b) by short high density bunches of charged particles; (c) by heavy high-Z ions; (d) by modulated high current beams; (d) by longer bunches experiencing self modulation instability in the media.

Acceleration in Xtals book (T.Tajima, et al 2020)

Exotic Coliders: Line of Thinking

$$E_{cm}$$

Size is limited <10 km → calls for the highest gradients → crystals → muons

$$L = f\frac{N_1 N_2}{A}$$

Luminosity calls for more particles in the smallest beam size

$$A \sim 1\ \text{Å}^2 = 10^{-16}\text{cm}^{-2}$$

This is the smallest beam size at IP

$$P = f n_{ch} \cdot NE$$

The power is limited <10MW → ***N*** is small at high ***E*** → *low* ***L***

XC Luminosity

$$L = f N^2 / A$$

- Considerations :
  - Muons/bunch < Xtal electrons excited

$$100\lambda_p \times \lambda_p^2$$

$$N_0 \sim 10^3$$

  - Employ many channels

$$n_{ch} \sim 100$$

gain a factor of n_{ch}

  - Limit beam power O(10MW)

$$P = f n_{ch} N E$$

  - Combine *n_channels* to gain ***L*** via ***crystal funnel*** (? Is it possible)

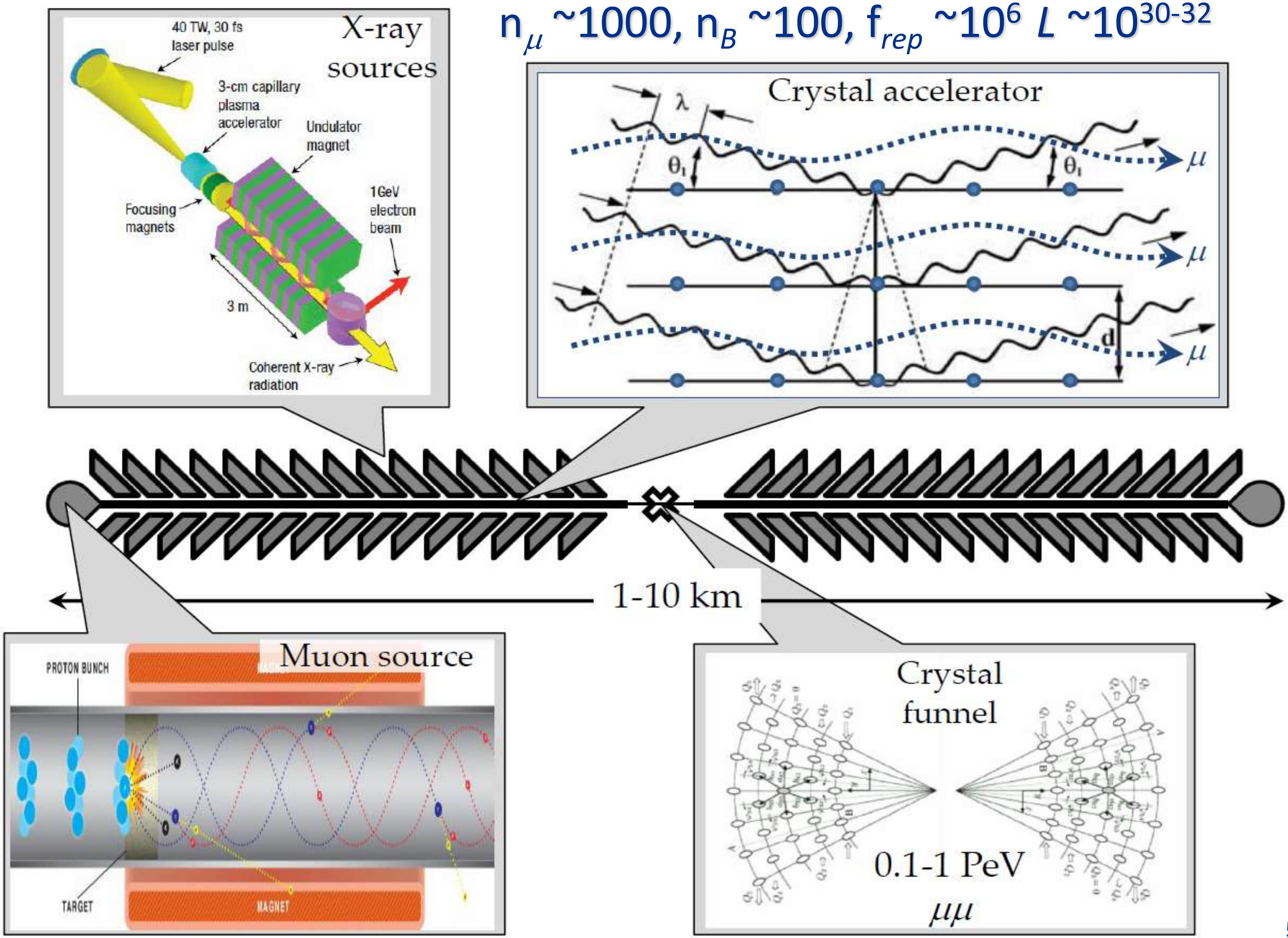
$$f = 10^6 \text{ Hz}$$

$$L\,[\text{sm}^{-2}\,\text{s}^{-1}] \approx 4 \times 10^{33\text{–}35}\ \frac{P^2\,[\text{MW}]}{E^2\,[\text{TeV}]\, f n_{ch} [10^8\ \text{Hz}]}$$

Xtal Collider

n~10^{22} cm^{-3}, **10 TeV/m** → 1 PeV = 1000 TeV

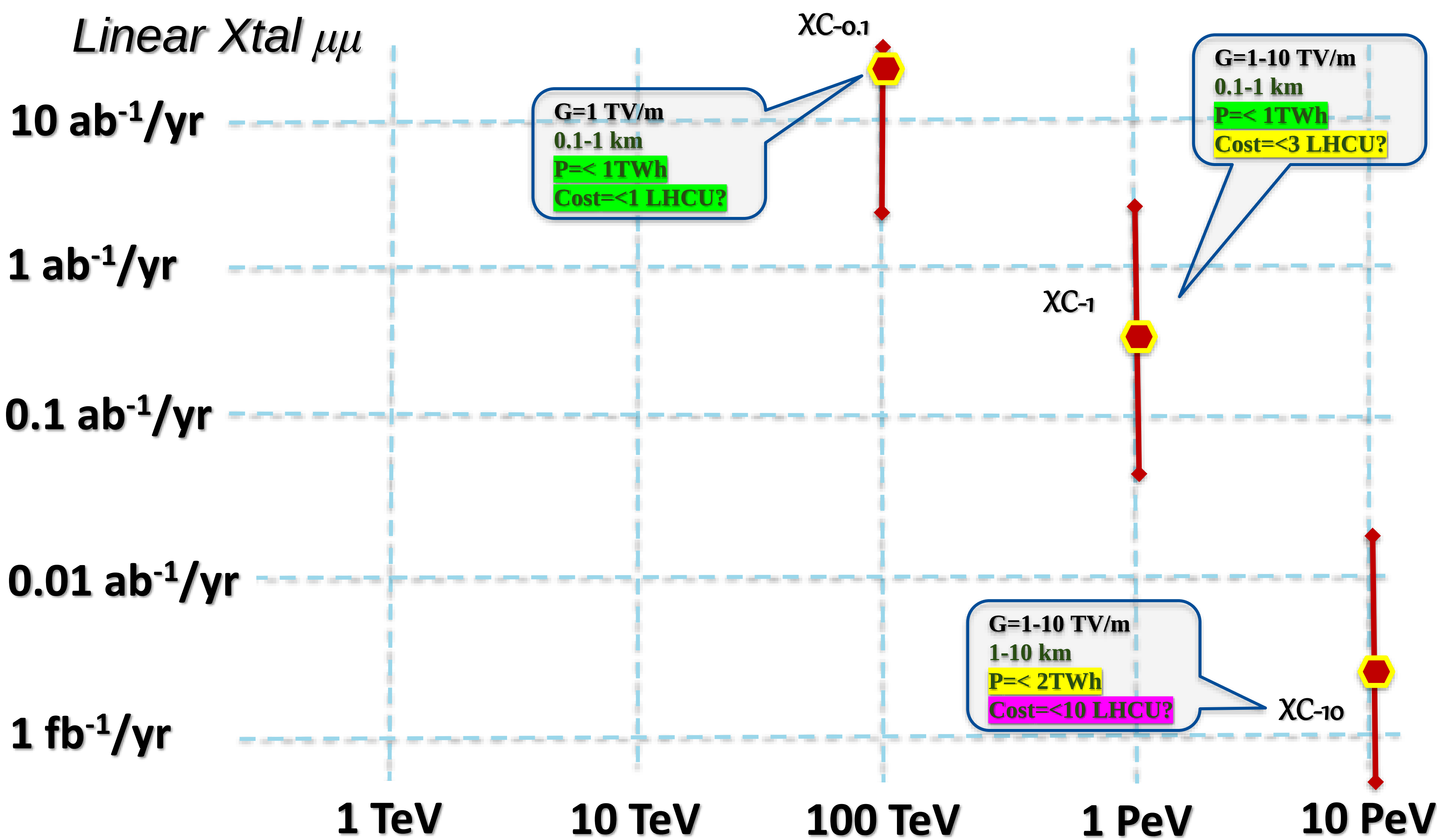
n_μ ~1000, n_B ~100, f_{rep} ~10^6 L ~$10^{30\text{-}32}$



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

b

Xtal Colliders: *Lumi* and *Cost* vs *Energy*



Main Conclusions:

- **For ultimate high energy colliders:**
  - **Major thrust is *Energy***
  - **Major concern/limit *is Cost***
  - **Main focus is *Luminosity* and *Power***
- **Cost:**
  - **Critically dependent on core acceleration technology**
  - **Existing injectors and infrastructure greatly help**
- **High *E*nergy means low *L*uminosity :**
  - **Don't expect more than 0.1-1 ab^{-1}/yr at 30TeV-1 PeV**
  - **Assume *P*ower limited to 1-3 TWh/yr**

Main Conclusions (2):

- **For considered collider types:**
  - **Circular *pp* – limit is close or below 100 TeV (14 TeV cm)**
  - **Circular *ee* – limit is ~0.4-0.5 TeV**
  - **Circular $\mu\mu$ – limit is between 30 and 100 TeV**
  - **Linear RF *ee*/$\gamma\gamma$ } – limit is between 3 and 10 TeV**

    Plasma *ee*/$\gamma\gamma$
  - **Exotic crystal $\mu\mu$ – promise of 0.1-1 PeV, low *L*uminosity**
- **Muons are particles of the future**

Helpful/cited references (next slide)

(Some) References:

1. *αβγ* model – V.Shiltsev, *JINST* 9 T07002 (2014).
2. RMP Colliders – V.Shiltsev, F.Zimmermann, *Rev.Mod.Phys.* (2021); see also arxiv
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12. *CPT*-theorem – V.Shiltsev *Mod. Phys. Lett. A*, vol. 26, No. 11 (2011) pp. 761-772
13. Cheap magnets – V.Kashikhin, Fermilab beams-doc-8948 (2021)

Thank You for Your Attention!