



Realization, Timeline, Challenges and Ultimate Limits of Future Colliders

Vladimir Shiltsev (Fermilab)

eeFACT'22 – 65th ICFA BD Workshop (INFN Frascati, Sep 12-15, 2022)

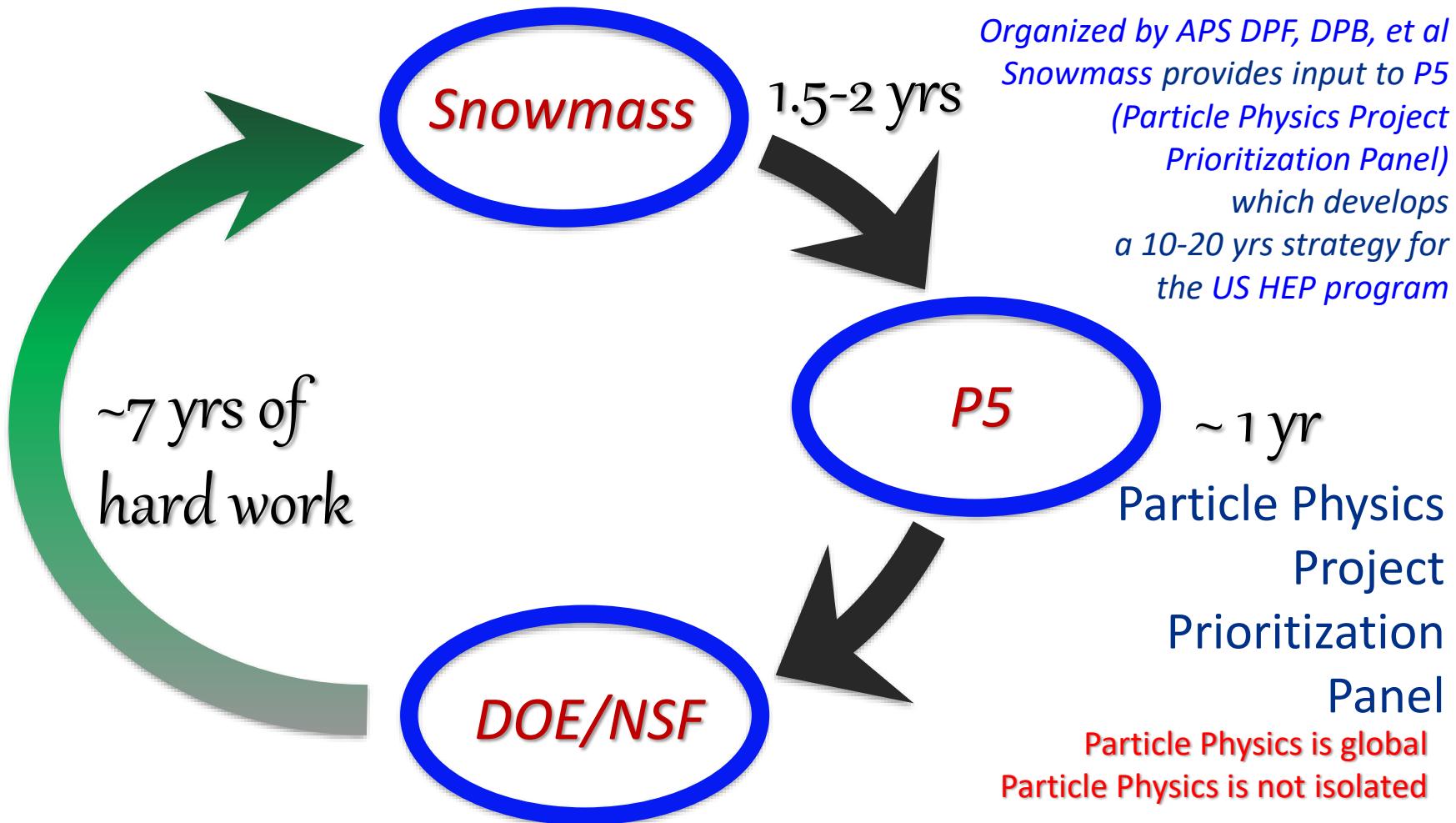
12 September 2022

Content (Plan)

- I. Snowmass'21 Accel. Frontier (4 slides)
- II. Implementation Task Force (7 slides)
- III. On Limits of Colliders (17 slides)

Snowmass'21 Discussions (incl. colliders)

“Snowmass is a particle physics community study”



<https://www.snowmass21.org/>

Snowmass'21 Accelerator Frontier Conveners



Steve Gourlay (LBNL)



Tor Raubenheimer (SLAC)



Vladimir Shiltsev (FNAL)

Topical Group		Topical Group co-Conveners			
AF01	Beam Phys & Accel. Education	Z. Huang (Stanford)	M. Bai (SLAC)	S. Lund (MSU)	
AF02	Accelerators for Neutrinos	J. Galambos (ORNL)	B. Zwaska (FNAL)	G. Arduini (CERN)	
AF03	Accelerators for EW/Higgs	F. Zimmermann (CERN)	Q. Qin (ESRF)	G.Hoffstaetter (Cornell) A.Faus-Golfe (IN2P3)	
AF04	Multi-TeV Colliders	M. Palmer (BNL)	A. Valishev (FNAL)	N. Pastrone (INFN)	J.Tang (IHEP)
AF05	Accelerators for PBC and Rare Processes	E. Prebys (UC Davis)	M. Lamont (CERN)	Richard Milner (MIT)	
AF06	Advanced Accelerator Concepts	C. Geddes (LBNL)	M. Hogan (SLAC)	P. Musumeci (UCLA)	R. Assmann (DESY)
AF07	Accelerator Technology R&D				
	Sub-Group RF	E. Nanni (LBNL)	H.Weise (DESY)	S. Belomestnykh (FNAL)	
	Sub-Group Magnets	G. Sabbi (LBNL)	S. Zlobin (FNAL)	S. Izquierdo Bermudez (CERN)	
	Sub-Group Targets/Sources	C. Barbier (ORNL)	Y. Sun (ANL)	Frederique Pellemeoine (FNAL)	

AF Report: Exec. Summary

“Intro”:

- Since last P5, this Snowmass’21 process

“Future Facilities”:

- **TBD by P5** – accelerator/people need to be part of P5; ITF analysis can greatly help
- **Multi-MW FNAL complex upgrade** will be priority for NF in 2030 (AF ready)
- Many opportunities for Rare Processes (AF ready), incl. **PAR and utilize what we have**
- Several Higgs/EW factories are feasible: **FCCee, C3 and HELEN** to be explored
- O(10 TeV/parton) needed for >2040’s, **muon colliders** to be explored/ pre-CDR by 2030
- Need an **Integrated Future Colliders R&D program** in OHEP to provide design reports by next Snowmass/P5’2030 and engage internationally (FCC, ILC, IMCC)

Accelerator Frontier

S. Gourlay, T. Ranftschneider, V. Shiltsev

G. Arribi, R. Asmussen, C. Barber, M. Bai, S. Belostotsky, S. Berndsen, P. Blot, A. Fouz-Gobbi, J. Galapago, C. Geddes, G. Holzstaetter, M. Hogan, Z. Huang, M. Latent, D. Li, S. Lord, R. Miller, P. Moenneri, E. Nanni, M. Palmer, N. Parsons, F. Pellegrini, E. Petyt, Q. Qin, J. Pover, T. Rose, G. Salhi, D. Shatakin, V.-E. Sun, J. Tang, A. Volinber, B. Wense, F. Zanevsky, A.V. Zlobin, H. Zwicky

For over half a century, high-energy accelerators have been a major enabling technology for particle and nuclear physics research as well as sources of X-rays for photon science research in material science, chemistry and biology. Particle accelerators for energy and intensity frontier research in high energy physics (HEP) continuously drive the accelerator community to invent ways to increase the energy and improve the performance of accelerators, reduce their cost, and make them more power efficient. Despite these past efforts, the increasing size, cost and timescale required for modern and future accelerator-based HEP projects arguably distinguish them as the most challenging scientific research endeavors. In the meantime, the international accelerator community has demonstrated imagination and creativity in developing a plethora of future accelerator ideas and proposals.

Major developments since the last Snowmass/HEPAP P5 strategic planning exercise in 2013-2014 include start of the PIP-II proton factory construction for the LHC/FD neutrino program in the US; emergence of the FCCee/CEPC project for Higgs/EW physics research at CERN and in China, respectively; a significant reduction of activity related to linear collider projects (ILC in Japan and CLIC at CERN); and presumably, the end of the Muon Accelerator Program in the US and creation of the International Muon Collider Collaboration (IMCC) in Europe. The last decade saw several notable planning efforts, including the US DOE GARD Roadmap; Strategic Plan for Particle Physics and the Accelerator R&D Roadmap; EnPRAXIA, etc.

In addition, since the last Snowmass meeting that took place in 2013 was shortly after the confirmation of the Higgs, the goals for the Energy Frontier have changed as result of the LHC’s measurements. While a Higgs/EW factory at 250 to 300 GeV is still the highest priority for the next large accelerator project, the motivation for a TeV or low TeV $\nu \bar{\nu}$ collider has diminished. Instead, the community is focused on a 30+ TeV (parton-to-parton) discovery collider that would follow the Higgs/EW factory. This is an important change that will refine some of the accelerator R&D programs.

The technical maturity of proposed facilities ranges from sketch-ready to those that are still largely unexplored. Over 100 contributed papers have been submitted to the Accelerator Frontier of the US particle-physics-themed community planning exercise, Snowmass’2021. These papers cover a broad spectrum of topics: beam physics and acceleration technologies, accelerators for neutrinos, colliders for Electroweak/Higgs studies and multi-TeV energies, accelerators for *Physics Beyond Standard Models* and rare processes, advanced accelerator concepts, and accelerator technology for Radio Frequency cavities (RF), magnets, targets, and sources.

Future facility: The accelerator community in the US and globally has a broad array of accelerator technologies and expertise that will be needed to design and construct any of the near-term HEP accelerator projects. P5 will need to prioritize what option(s) should be developed. Planning of accelerator development and research should be aligned with the strategic planning for particle physics and should be part of the P5 prioritization process. Accelerator experts can contribute to the US and international projects under consideration by providing top-level metrics for expected cost-scales and technology/timeline evolution, following the ITF findings.

Among possible actively discussed future facility options are:

- A multi-MW beam power upgrade of the Fermilab neutrino accelerator complex that seems to be the highest priority for the neutrino program in the 2030s; corresponding accelerator technology and beam physics studies are needed to identify the most cost- and power-efficient solutions that could be timely implemented leading to breakthrough results of the DUNE neutrino program;
- Several beam facilities for axion and Dark Matter (DM) searches are shown to have great potential for construction in the 2030s in terms of scientific output, cost and timeline, including PAIR (a 1 GeV, 100 kW PIP-II Accelerator Ring); in general, we should efficiently utilize existing and upcoming facilities to explore dedicated or parallel opportunities for rare process measurements - examples are the SLAC SRF electron linear, MWs of proton beam power potentially available after construction of the PIP-II R&D linear, spires of the future multi-MW FNAL complex upgrade, and at CERN, a Forward Physics Facility at the LHC, etc.;
- In the area of future colliders – several approaches are identified as both promising and potentially feasible, and call for further exploration and support: in the Higgs/EW sector – there is growing support for the FCCee at CERN and proposals of somewhat more advanced linear colliders in the US or elsewhere, such as C³ and HELEN;
- At the energy frontier, the discovery machines such as O(10 TeV c.m.s.) muon colliders have rapidly gained significant momentum. To be in a position for making decisions on collider projects viable for construction in the 2040s and beyond at the time of the next Snowmass/P5, these concepts could be explored technically and demonstrated in pre-CDR level reports by the end of the decade.

The U.S. HEP accelerator R&D portfolio presently contains no collider-specific items. This creates a gap in our knowledge-base and accelerator/technology capabilities. It also limits our national aspiration for a leadership role in particle physics in that the US cannot lead or even contribute to proposals for accelerator-based HEP facilities. To address the gap, the community has proposed that the U.S. establish a national integrated R&D program on future colliders in the DOE Office of High Energy Physics (OHEP) to carry-out technology R&D and accelerator design for future collider concepts. This program would aim to enable synergistic engagement in projects proposed abroad (e.g. FCC, ILC, IMCC). It would support the development of design reports on collider options by the time of the next Snowmass and P5 (2029-2030), particularly for options that can feasibly be hosted in the US, and to create R&D plans for the decade past 2030. Without such a program there may be few accelerator-based proposals for a future P5 to evaluate.

Accelerator R&D: Next Decade

Multi-MW targets:

- 2.4 MW for PIP-III

- 4-8 MW for muon collide

Accelerator & Beam Physics

- High intensity/brightness beams acceleration and control
- High performance computer modeling and AI/ML approaches
- Design integration and optimization, incl energy efficiency

Magnets for colliders and RCSs:

- 16T dipoles
- 40T solenoids
- 1000 T/s fast cycling ones
...coordinated with US MDP

SC/NC RF:

Wakefields:

- collider quality beams
- efficient drivers and staging
- close coordination with Int'l (Euro Roadmap, EUPRAXIA,...)

- 70-120 MV/m C³
- 70 MV/m TW SRF
- new materials, high Q₀
- efficient RF sources



Part II

Collider Implementation Task Force (*Snowmass'21 Accelerator Frontier*)



Implementation Task Force

<https://arxiv.org/abs/2208.06030>

- The Accelerator Frontier **Implementation Task Force (ITF)** is charged with developing metrics and processes to facilitate a comparison between collider projects:
 - Higgs/EW factories (focus of slides below)
 - Lepton colliders with 3 TeV cme
 - Lepton and hh colliders 10+ TeV cme
 - FNAL site-filters and eh colliders
- ITF addressed (four subgroups):
 - Physics reach (impact), beam parameters
 - Size, complexity, power, environment
 - Technical risk, readiness, and R&D required
 - Cost and schedule



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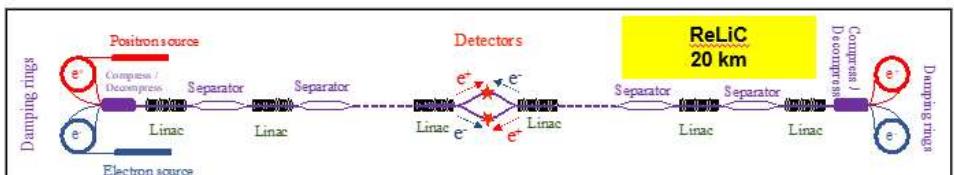
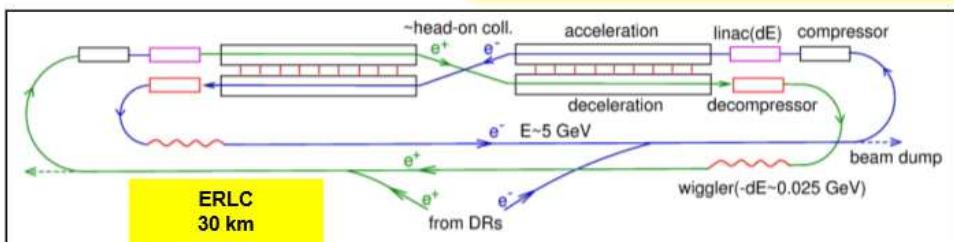
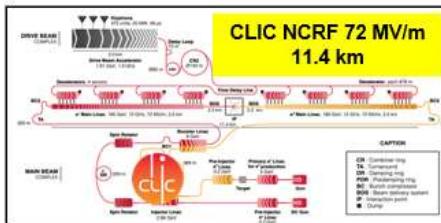
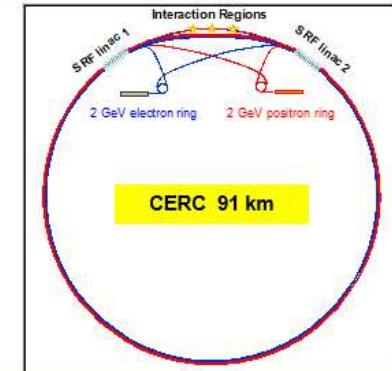
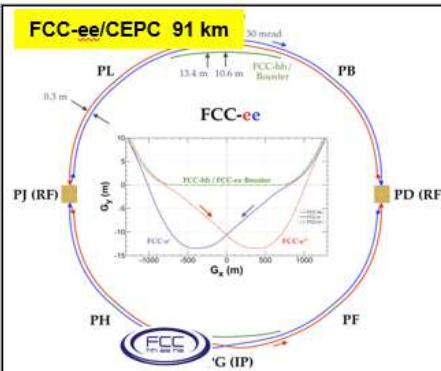
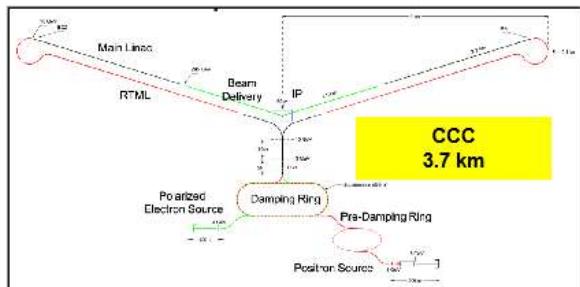
Spencer Gessner
(SLAC)

⁸Below I mostly follow T.Roser presentation in Seattle

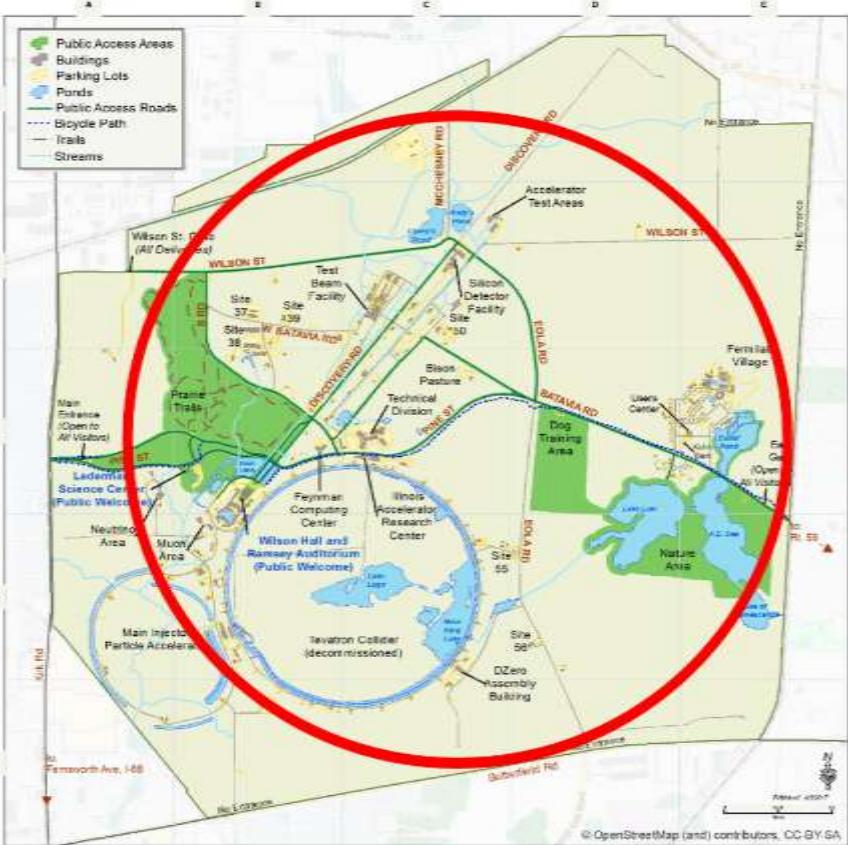
Proposals – Higgs/EW Physics

Higgs factory concepts (10)

Name	CM energy range
FCC-ee	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
CEPC	e+e-, $\sqrt{s} = 0.09 - 0.37$ TeV
ILC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CLIC (Higgs factory)	e+e-, $\sqrt{s} = 0.09 - 1$ TeV
CCC (Cool Copper Collider)	e+e-, $\sqrt{s} = 0.25 - 0.55$ TeV
CERC (Circular ERL collider)	e+e-, $\sqrt{s} = 0.09 - 0.60$ TeV
ReLiC (Recycling Linear Collider)	e+e-, $\sqrt{s} = 0.25 - 1$ TeV
ERLC (ERL Linear Collider)	e+e-, $\sqrt{s} = 0.25 - 0.50$ TeV
XCC (FEL-based $\gamma\gamma$ collider)	ee ($\gamma\gamma$), $\sqrt{s} = 0.125 - 0.14$ TeV
MC (Higgs factory)	$\mu^+\mu^-, \sqrt{s} = 0.13$ TeV



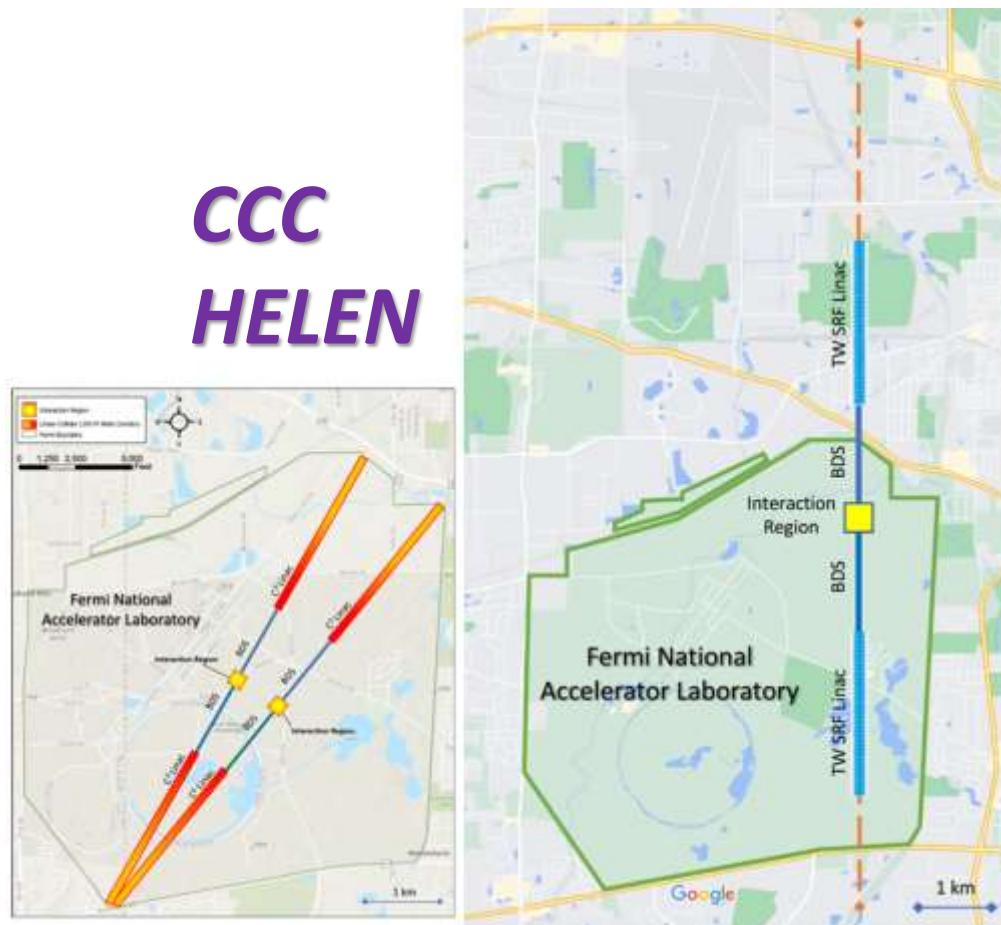
250 GeV cme Fermilab Site-Fillers



ccc
HELEN



16-km collider e^+e^- ring
<https://arxiv.org/abs/2203.08088>



cool- or SC-RF e^+e^- linear colliders
7-km for 250 GeV, 12-km 0.5+ TeV
<https://arxiv.org/abs/2203.08211>
<https://arxiv.org/abs/2110.15800>



Higgs factory summary table

- Main parameters of the submitted Higgs factory proposals.
- The cost range is for the single listed energy.
- The superscripts next to the name of the proposal in the first column indicate:
 - (1) Facility is optimized for 2 IPs. Total peak luminosity for multiple IPs is given in parenthesis;
 - (2) Energy calibration possible to 100 keV accuracy for MZ and 300 keV for MW ;
 - (3) Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes

Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B\$]	Est. operating electric power [MW]
FCC-ee ^{1,2}	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC ^{1,2}	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC ³ - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC ³ - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC ³ (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150
CERC ³ (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC ^{1,3} (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC ³ (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	250
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	90
Muon Collider Higgs Factory ³	0.13	0.01	>10	19-24	4-7	200

Fermilab site-filters

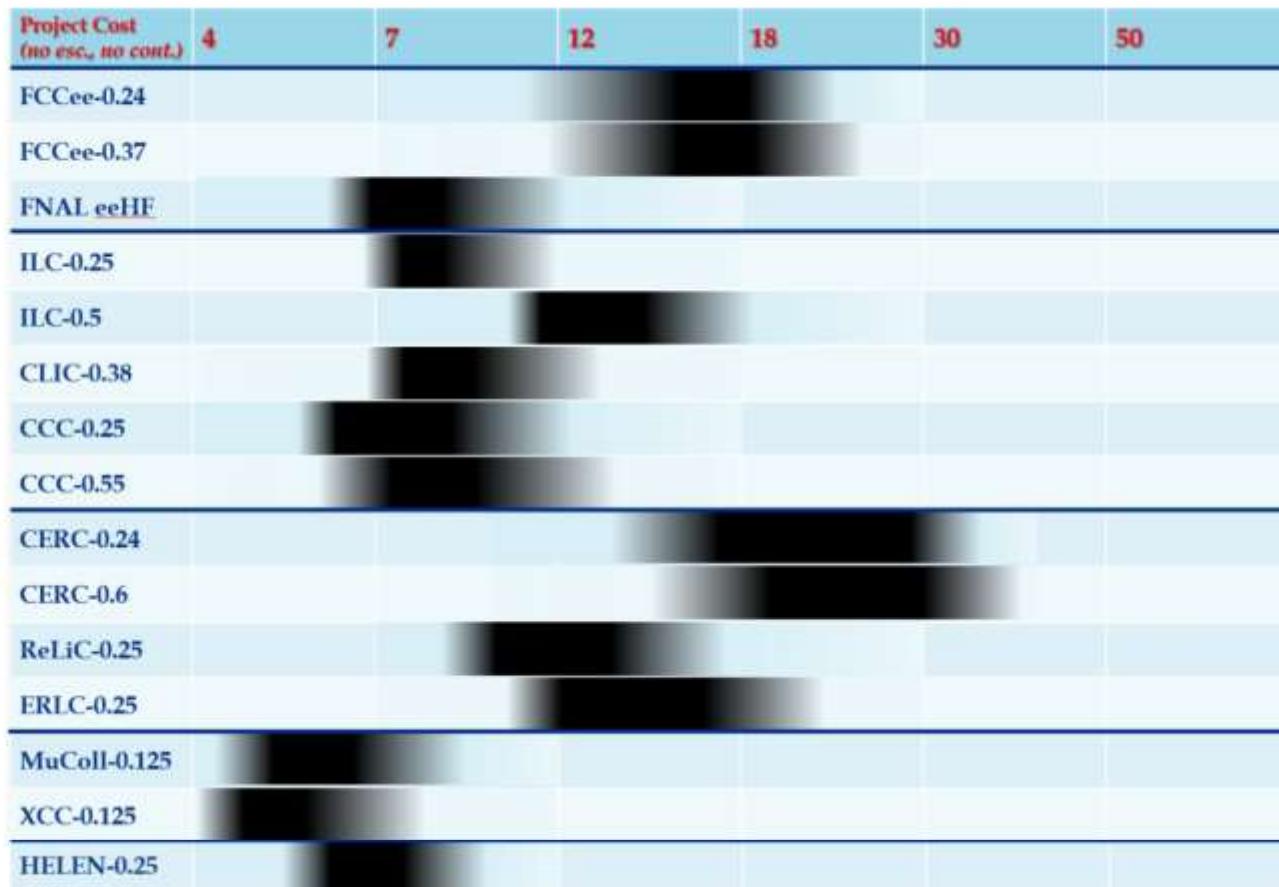


Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B\$]	Est. operating electric power [MW]
High Energy LeptoN (HELEN) e^+e^- colider	0.25 (0.09-1)	1.4	5-10	13-18	7-12	~110
e^+e^- Circular Higgs Factory at FNAL	0.24 (0.09-0.24)	1.2	3-5	13-18	7-12	~200



Cost Estimates for Higgs Factories

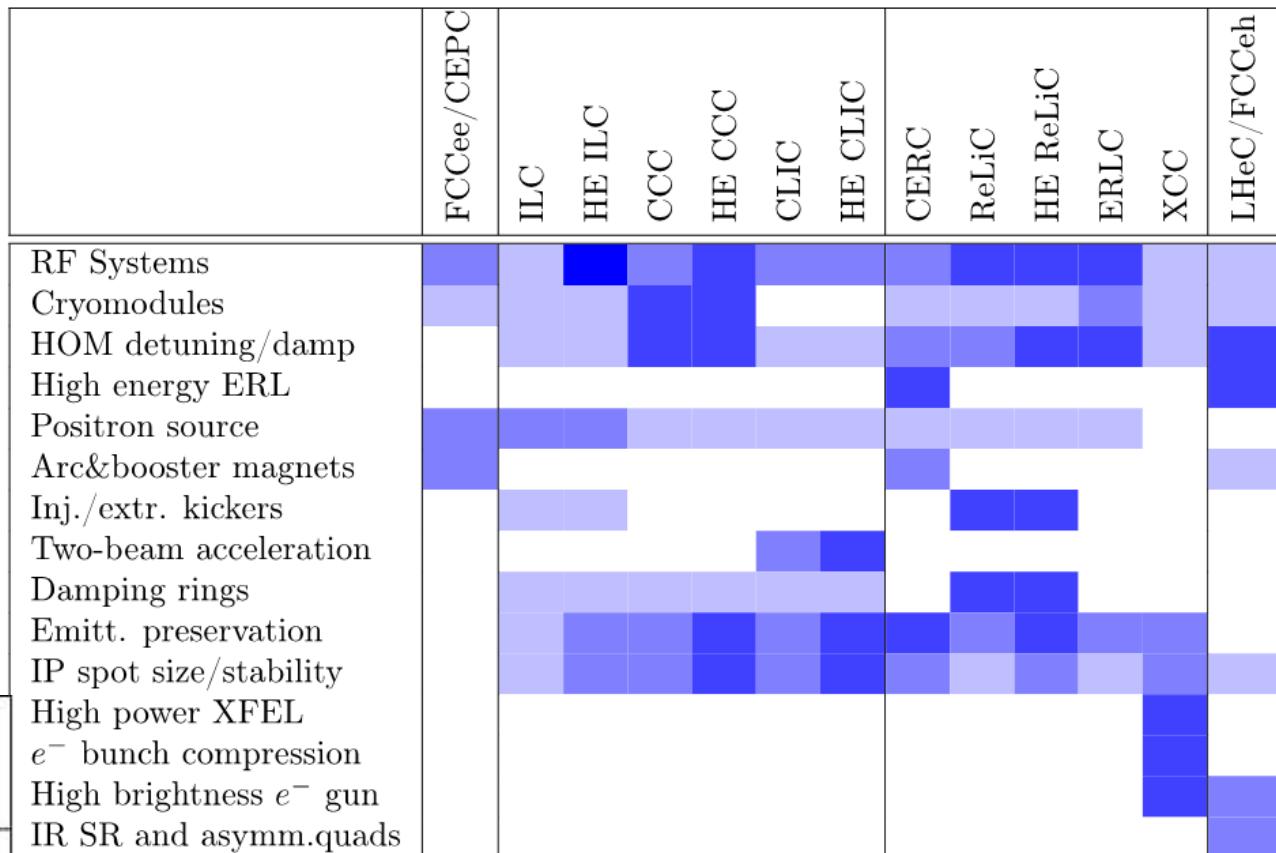
- The ITF cost model for the EW/Higgs factory proposals.
- Horizontal scale is approximately logarithmic for the project total cost in 2021 B\$ without contingency and escalation.
- Black horizontal bars with smeared ends indicate the cost estimate range for each machine.



ITF Report – T.Roser, et al, [arXiv:2208.06030](https://arxiv.org/abs/2208.06030)

ITF Technical Risk Registry

- Technical risk registry of accelerator components and systems for future e^+e^- and ep colliders: lighter colors indicate progressively higher TRLs (less risk), white is for either not significant or not applicable.



ITF Table 14: "Design Status": I - TDR complete, II - CDR complete, III - substantial documentation; IV - limited documentation and parameter table; V - parameter table. Overall risk tier category ranging from Tier 1 (lower overall technical risk) to Tier 4 (multiple technologies that require further R&D).



Luminosity per Power

Circular ee

ERL based ee

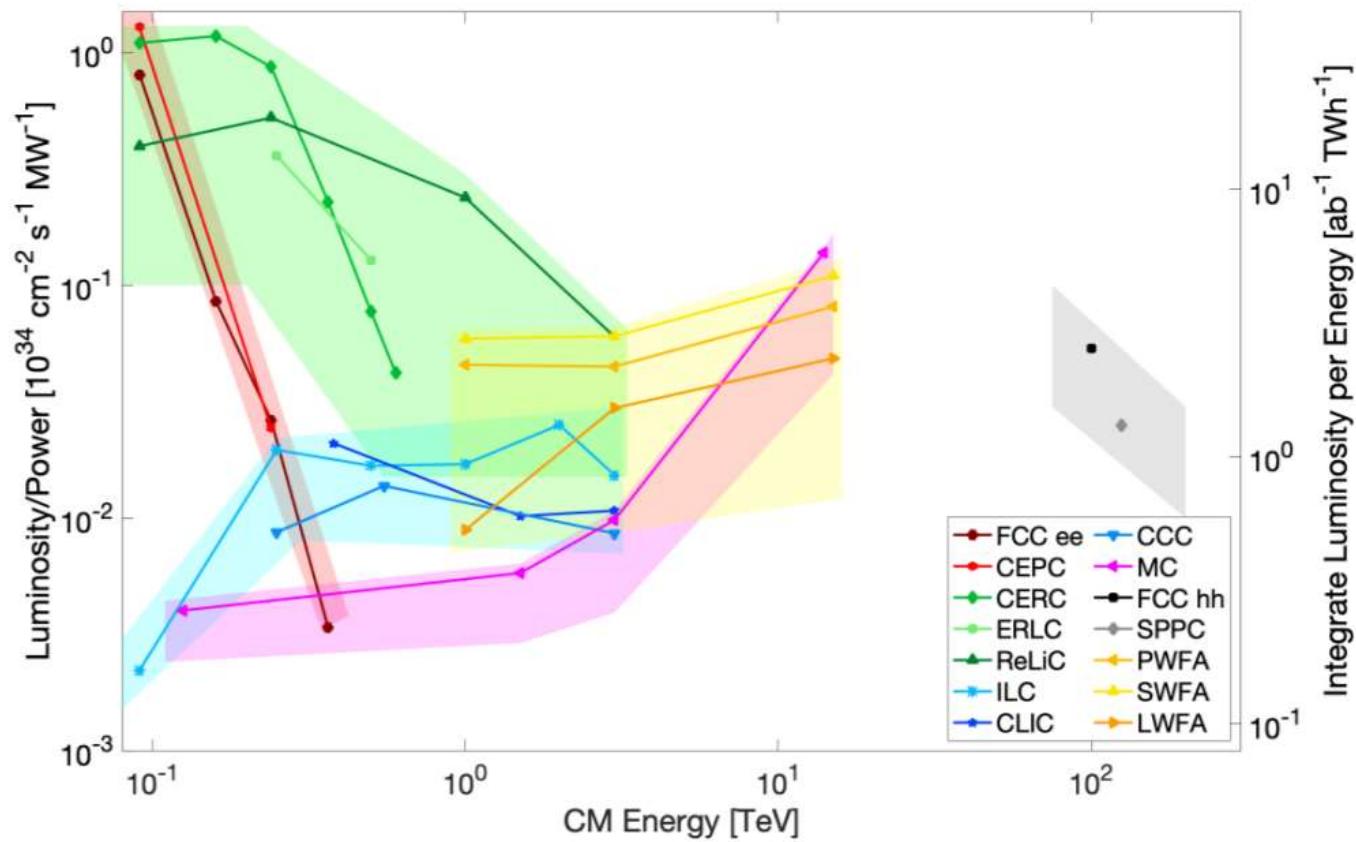
Linear ee

Muon coll

Wakefield

Hadron pp

- Figure-of-merit Peak Luminosity (per IP) per Input Power and Integrated Luminosity per TWh.
- Integrated luminosity assumes 10^7 seconds per year.
- The luminosity is per IP.
- Data points are provided to the ITF by proponents of the respective machines.
- The bands around the data points reflect approximate power consumption uncertainty for the different collider concepts.



Once again: luminosity and power consumption values have not been reviewed by ITF - we used proponents' numbers.

Part III

Limits of Colliders

(as discussed at the *Snowmass'21 Accelerator Frontier Topical Group 1 Workshop “Physics Limits of Ultimate Beams”*, Jan. 2022;

mostly following

V.Shiltsev, Proc. IPAC'21, WEPAB017)

How ultimate colliders might look like?

- **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

ITF's Look Beyond Higgs Factories

	CME (TeV)	Lumi per IP (10 ³⁴)	Years, pre- project R&D	Years to 1 st Physics	Cost Range (2021 B\$)	Electric Power (MW)
FCCee-0.24	0.24	8.5	0-2	13-18	12-18	280
ILC-0.25	0.25	2.7	0-2	<12	7-12	140
CLIC-0.38	0.38	2.3	0-2	13-18	7-12	110
HELEN-0.25	0.25	1.4	5-10	13-18	7-12	110
CCC-0.25	0.25	1.3	3-5	13-18	7-12	150
CERC(ERL)	0.24	78	5-10	19-24	12-30	90
CLIC-3	3	5.9	3-5	19-24	18-30	~550
ILC-3	3	6.1	5-10	19-24	18-30	~400
MC-3	3	2.3	>10	19-24	7-12	~230
MC-10-IMCC	10-14	20	>10	>25	12-18	O(300)
FCChh-100	100	30	>10	>25	30-50	~560
Collider-in-Sea	500	50	>10 ¹⁷	>25	>80	»1000

Factors and Limits

- Main factors to consider feasibility of future colliders used to be
 - Feasibility of **Energy**
 - Feasibility of **Luminosity**
 - Feasibility of **Cost**
- The *European Strategy* (2019) and *Snowmass'21* discussions revealed additional limits:
 - **Time** to construct and commission
 - **Societal limits**: # of experts, size of facility, radiation, etc
 - **Environmental impacts**: power consumption, carbon footprints, scarcity of resources (*He*, *Nb*, *W*, etc), excavated materials, etc

Here we will only briefly touch some important points

Limits on Energy

- Synchrotron radiation defines linear vs circular if $U_{SR} < E$

$$U_{SR} = C_\gamma \frac{E^4}{\rho} = 88.46 \frac{r_0}{r_e} \left(\frac{m_e}{m_0} \right)^3 \frac{E^4 [GeV]}{\rho [m]}$$

- for e-/e+: $E_{cm} \leq 500 \text{ GeV} \left(\frac{\rho}{10 \text{ km}} \right)^{\frac{1}{3}}$
- for muons: $E_{cm} \leq 600 \text{ TeV} \left(\frac{\rho}{10 \text{ km}} \right)^{\frac{1}{3}}$
- for protons: $E_{cm} \leq 10 \text{ PeV} \left(\frac{\rho}{10 \text{ km}} \right)^{\frac{1}{3}}$

- Production and survival: unstable particles such as muons

$$\frac{dN}{dt} = -\frac{N}{\gamma \tau_0}; \quad \gamma = \gamma_i + Z \frac{dy}{dz}$$

where τ_0 is the lifetime, $\tau_0 \sim 2.2 \mu\text{s}$ for muons...
requires fast acceleration

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

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

- Staging efficiency (losses) per stage for M stages $\geq \eta = 1 - 1/M$

- Technology within limited space /area:

Circumference 100 km, $B < 16 \text{ T}$, $E < 50 \text{ TeV}$

Circumference 40,000 km, $B = 1 \text{ T}$, $E < 1.3 \text{ PeV}$

Length 50 km, $G < 0.1 \text{ GV/m}$, $E < 5 \text{ TeV}$

Length 10 km, $G < 1 \text{ TV/m}$, $E < 10 \text{ PeV}$

• Fermilab

Limits on Luminosity (some)

- General Equation

- sheer beam power*

$$L = f_0 n_b N^2 / 4\pi \sigma^2$$

$$P_b = f_0 n_b N \gamma m c^2$$

$$L = P_b^2 / (4\pi \gamma n_b \epsilon \beta^* m^2 c^4) \propto P_b^2 / E$$

- e/p SR rad. power*

$$L \propto (\xi / \beta^*) (P_{SR} / 2\pi R) (R^2 / \gamma^3))$$

- $\mu \rightarrow \nu$ radiation dose*

$$D \propto (dN/dt) E^3 / \Phi$$

flux dilution factor

$$L \propto B \frac{D\Phi}{E^2} \frac{N}{4\pi \epsilon_n \beta^*}$$

- LC power, BS, jitter*

$$L \propto (P/E) (N_\gamma / \sigma_y)$$



$\alpha\beta\gamma$ vs ITF 30-parameter cost model

Higher energy → usually bigger size, more power and higher costs:

- Where is the societal limit on the cost of colliders?
- Cost ranges estimates – detailed vs parametric models



The $\alpha\beta\gamma$ cost model (2014):

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

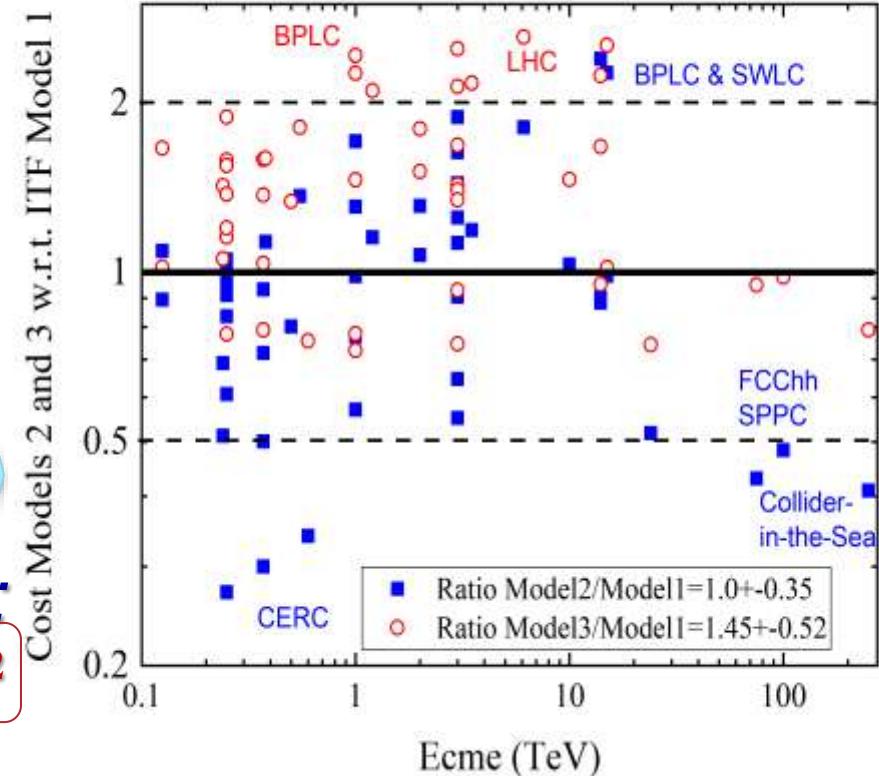
$\alpha \approx 2 \text{B\$}/\sqrt{L/10 \text{ km}}$ for tunnel/civil

$\beta \approx 10 \text{B\$}/\sqrt{E/\text{TeV}}$ for SC/NC RF

$\beta \approx 2 \text{B\$}/\sqrt{E/\text{TeV}}$ for SC magnets

$\beta \approx 1 \text{B\$}/\sqrt{E/\text{TeV}}$ for NC magnets

$\gamma \approx 2 \text{B\$}/\sqrt{P/100 \text{ MW}}$ for site power



ITF Report - Figure 7: Ratio of the estimates of the three-parameters $\alpha\beta\gamma$ Model (#2) and Model 3 to the 30-parameter cost Model 1 for future collider projects vs E_{cm} .

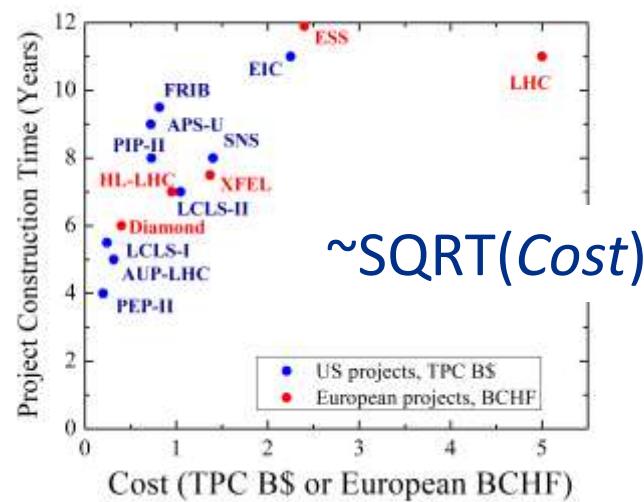
Accelerators Timeline $X+Y+Z \leq ?$

Bigger size and cost → longer:

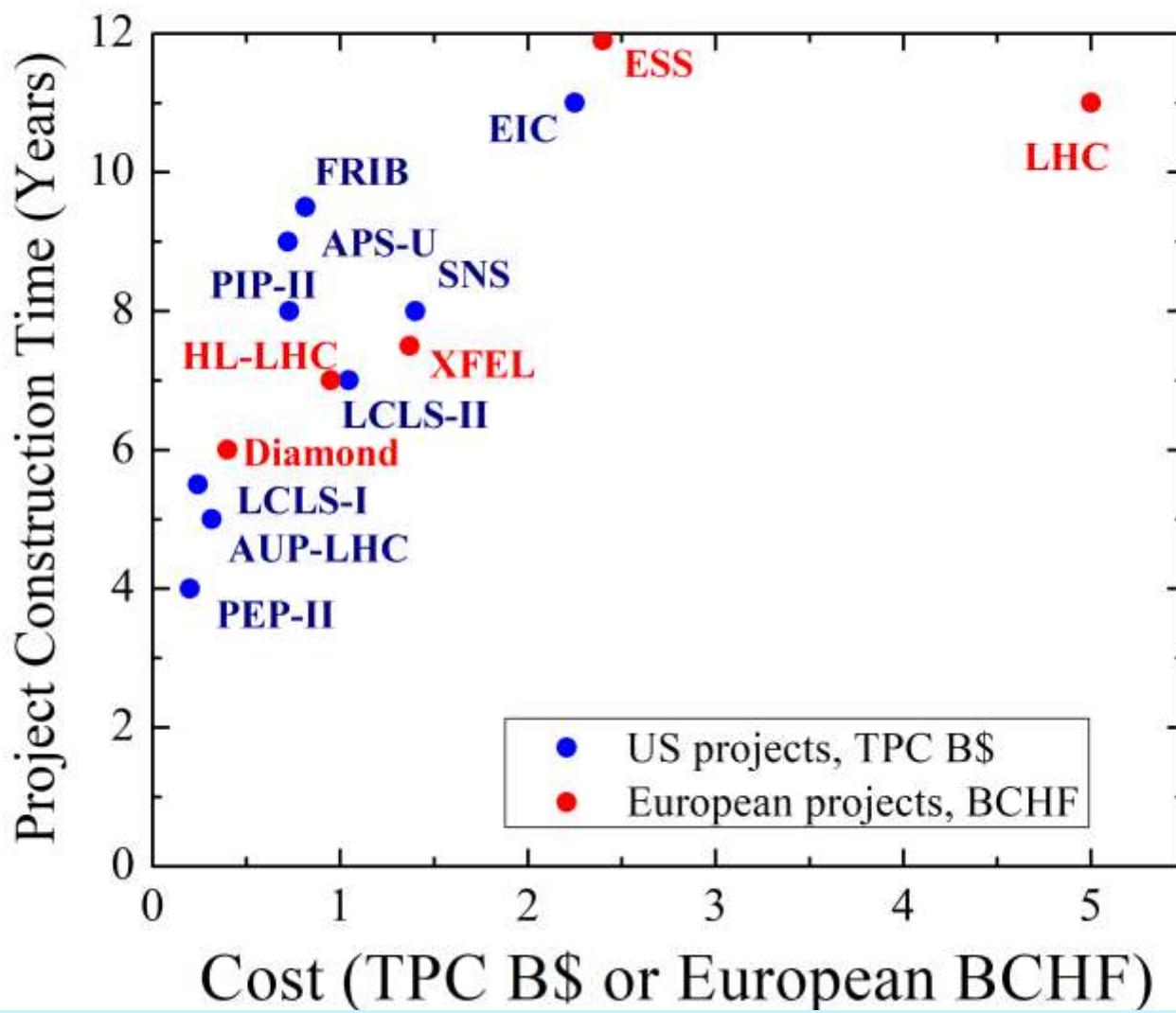
- Pre-project R&D X years
 - Depends on novelty
- Construction project Y years
 - Annual peak <0.5B\$/year ?
 - “Oide law”: *need ~1 expert to spend (intelligently) 1 M\$/year*
 - NB: <4500 experts worldwide
- Commissioning Z years
 - Depends on complexity
 - Past large colliders:
 - 5 yrs** +4 (SLC, DAFNE, BEPCII)
 - 3 (PEP-II, Tevatron-I, LEP-II)



Katsunobu Oide - KEK



Construction Time... ~ $\text{SQRT}(\text{Cost})$?



ITF Report - Figure 11: Construction time for recent large accelerator projects in the US and Europe.

- 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\$)

Circular e+e- Colliders

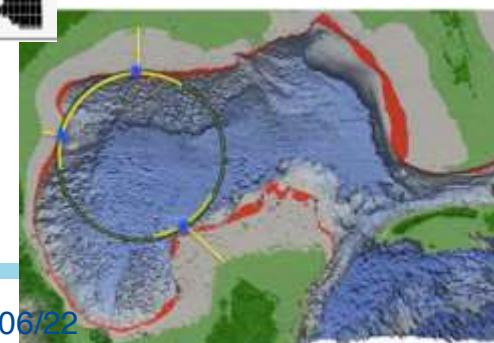
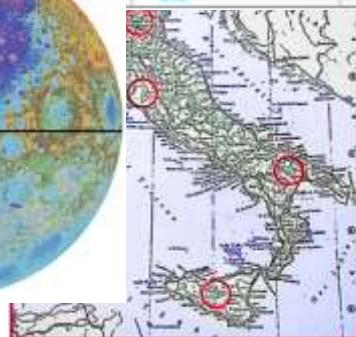
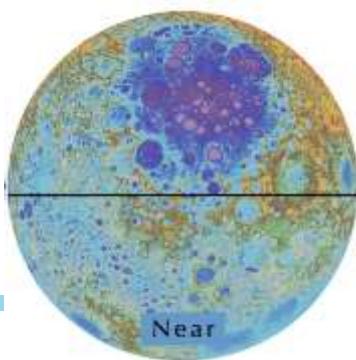
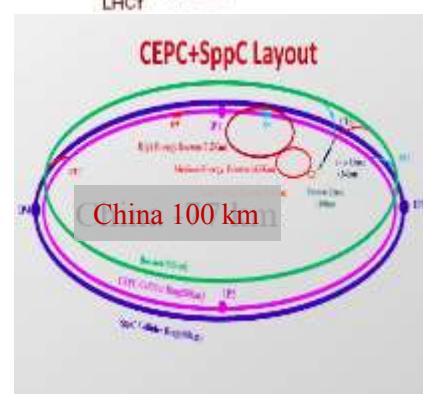
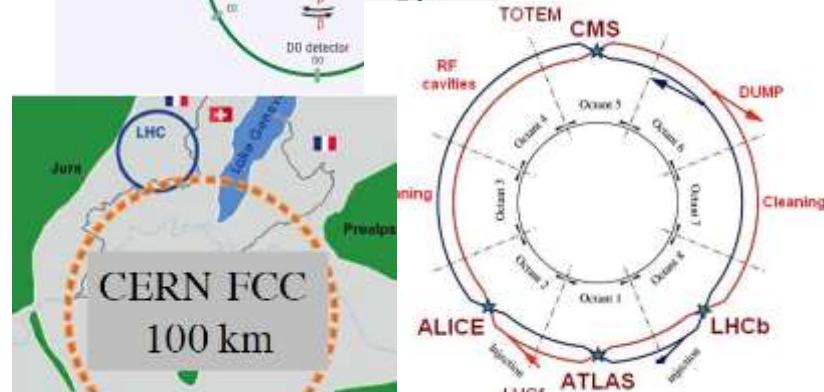
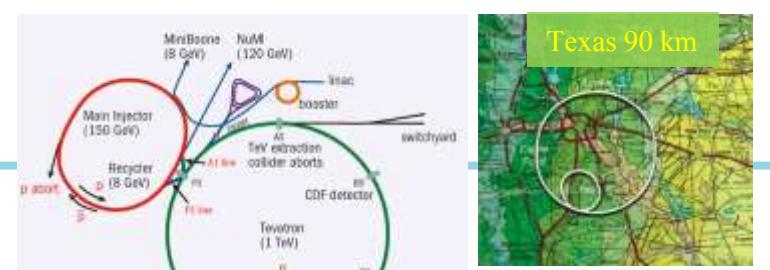
- Let's skip them... dead end... SR power

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

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

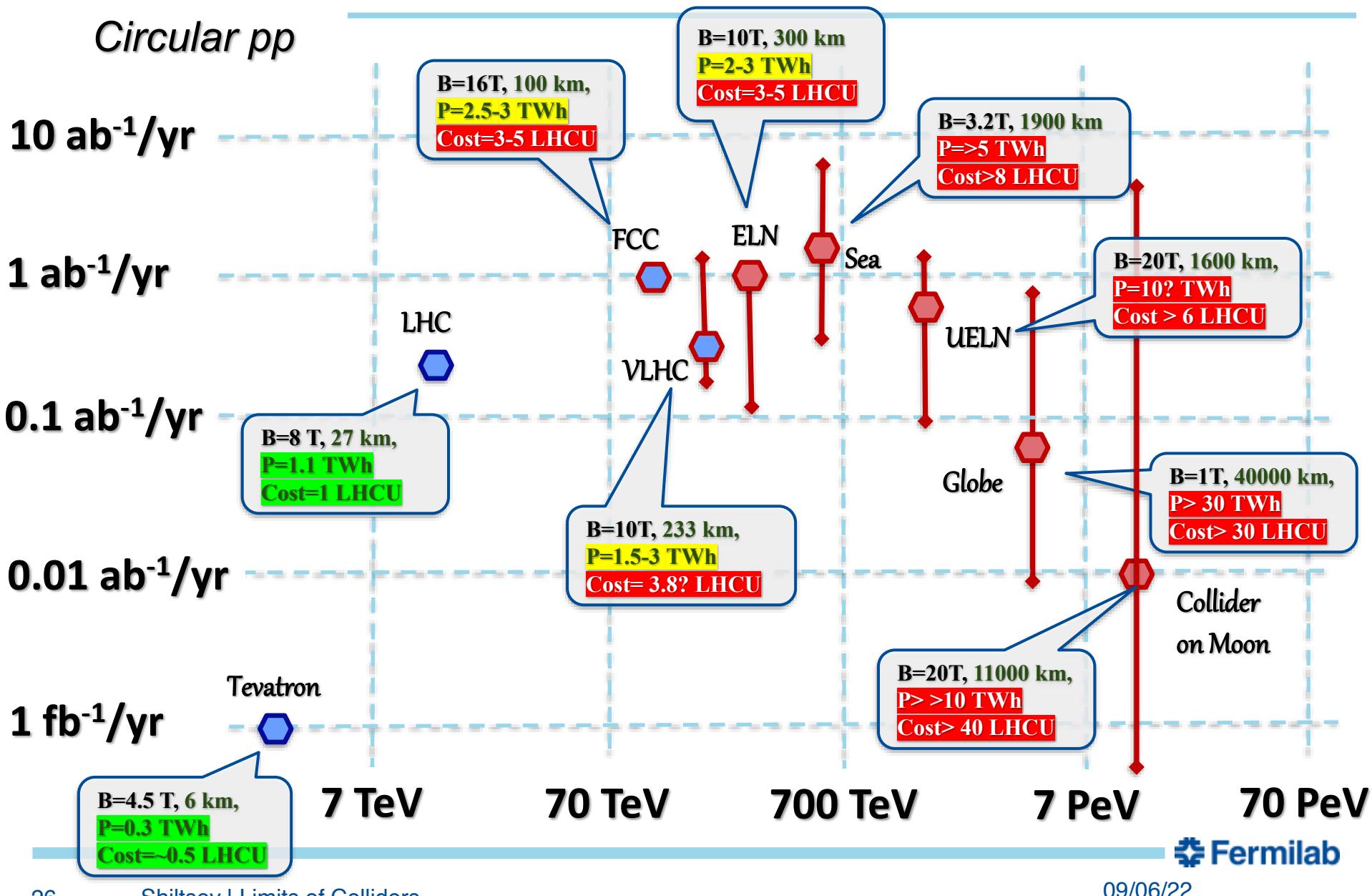
Circular pp Colliders

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



pp Colliders: Lumi and Cost vs Energy

Circular pp



MC: *Lumi and Cost vs Energy*

Circular $\mu\mu$

$10 \text{ ab}^{-1}/\text{yr}$

$1 \text{ ab}^{-1}/\text{yr}$

$0.1 \text{ ab}^{-1}/\text{yr}$

$0.01 \text{ ab}^{-1}/\text{yr}$

$1 \text{ fb}^{-1}/\text{yr}$

1 TeV

10 TeV

100 TeV

1 PeV

10 PeV

B=10 T, 2.5 km, $\Phi=1$
P=1 TWh
Cost=0.5 LHCU

B=10 T
6 km, $\Phi=1$
P=1.3 TWh
Cost=0.7-1 LHCU

B=10 T, $\Phi=1$
27(14) km
P=1.5-2 TWh
Cost=1-2 LHCU

B=10 T, $\Phi=10$
27 km
P=2 TWh
Cost=1.6-2.5 LHCU

B=10 T, $\Phi=100$
100 km
P=3.5 ? TWh
Cost=3-5 LHCU

B=10 T, $\Phi=100$
300 km
P=5 ? TWh
Cost=>5 LHCU

B=10 T, $\Phi=100$
1000 km
P=9 ? TWh
Cost=>8 LHCU

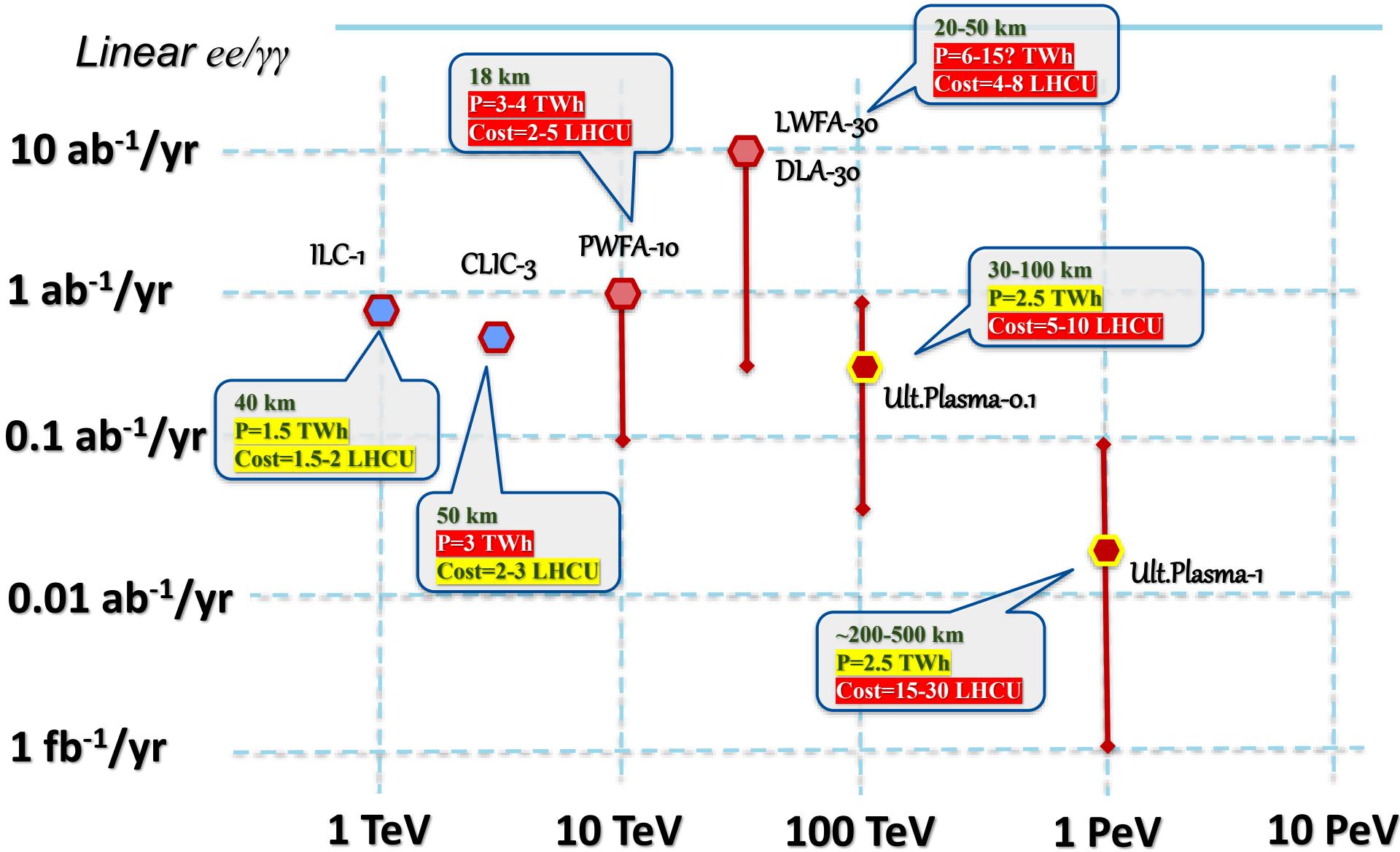
MC-1.5

MC-6

MC-14



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



Exotic Colliders

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

- 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?)

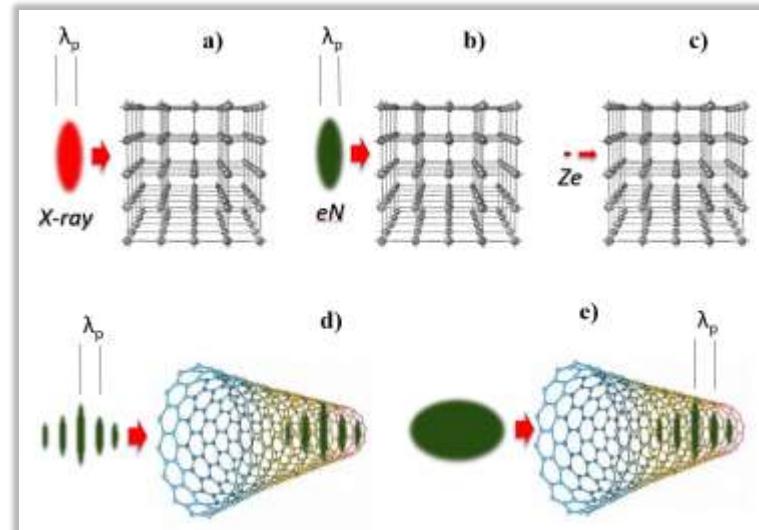
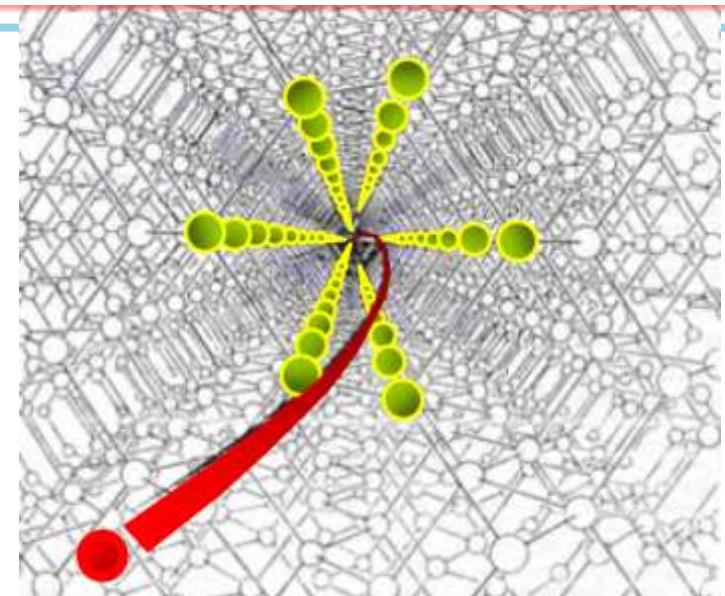
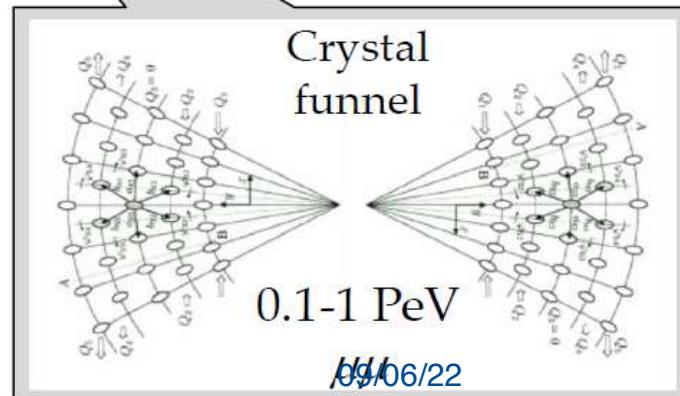
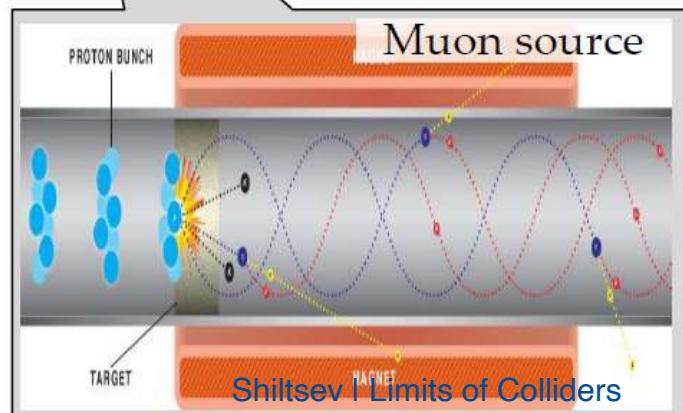
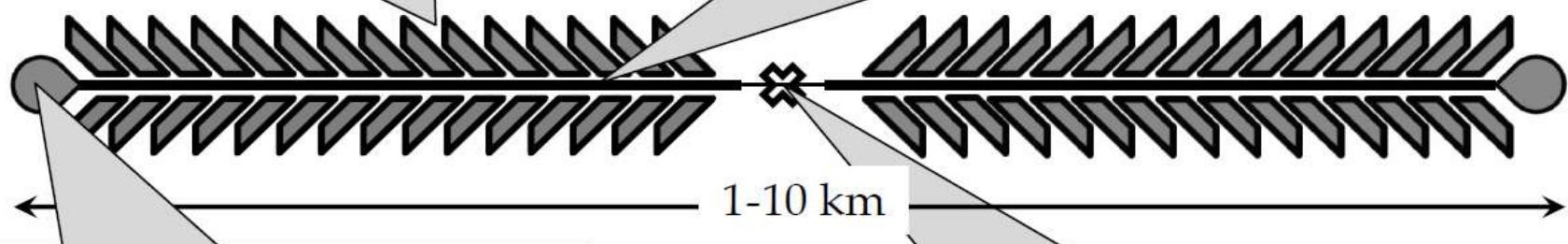
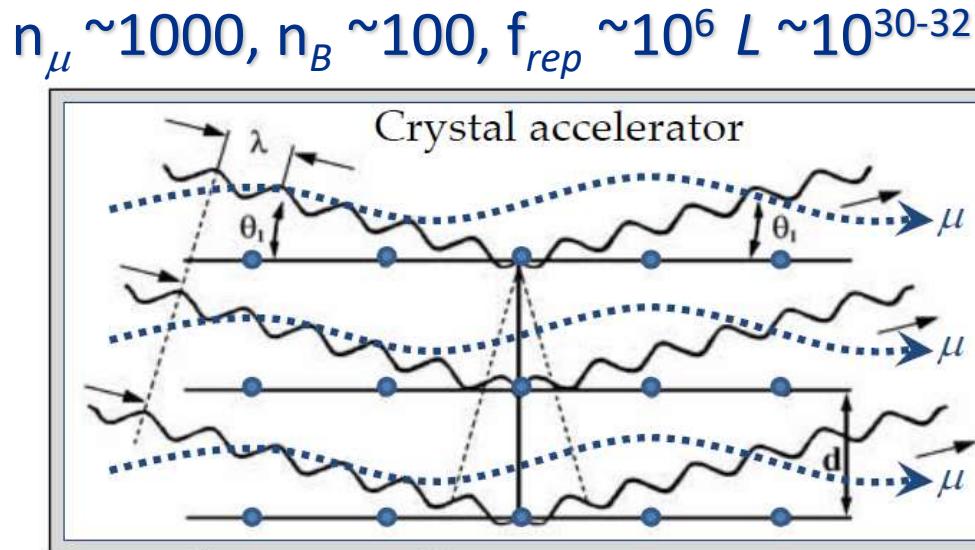
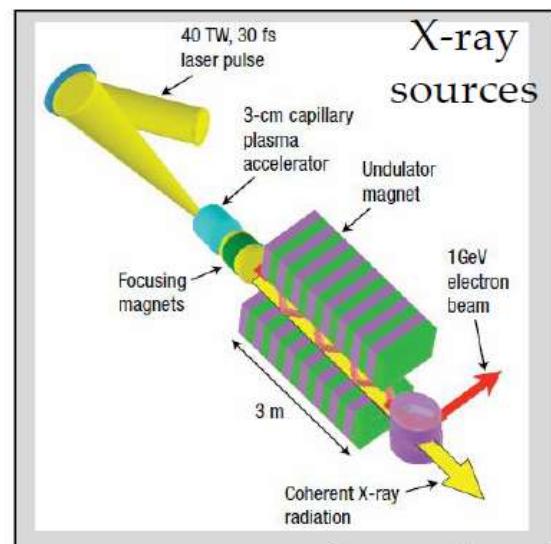


Fig. 2. Possible ways to excite plasma wakefields in crystals or/and nanostructures: (a) by short X-ray laser pulses; (b) by short high density bunches of charged particles; (c) by heavy high-Z ions; (d) by modulated high current beams; (e) by longer bunches experiencing self modulation instability in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

Xtal Collider

$n \sim 10^{22} \text{ cm}^{-3}$, $10 \text{ TeV/m} \rightarrow 1 \text{ PeV} = 1000 \text{ TeV}$



XtalC Luminosity

- Considerations :

- Angstrom size at IP
 - Muons/bunch < Xtal electrons excited
 - Employ many channels
 - Limit beam power O(10MW)
 - Combine *n_channels* to gain L via *crystal funnel* (? Is it possible)

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

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

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

$$N_0 \sim 10^3$$

$$n_{\text{ch}} \sim 100$$

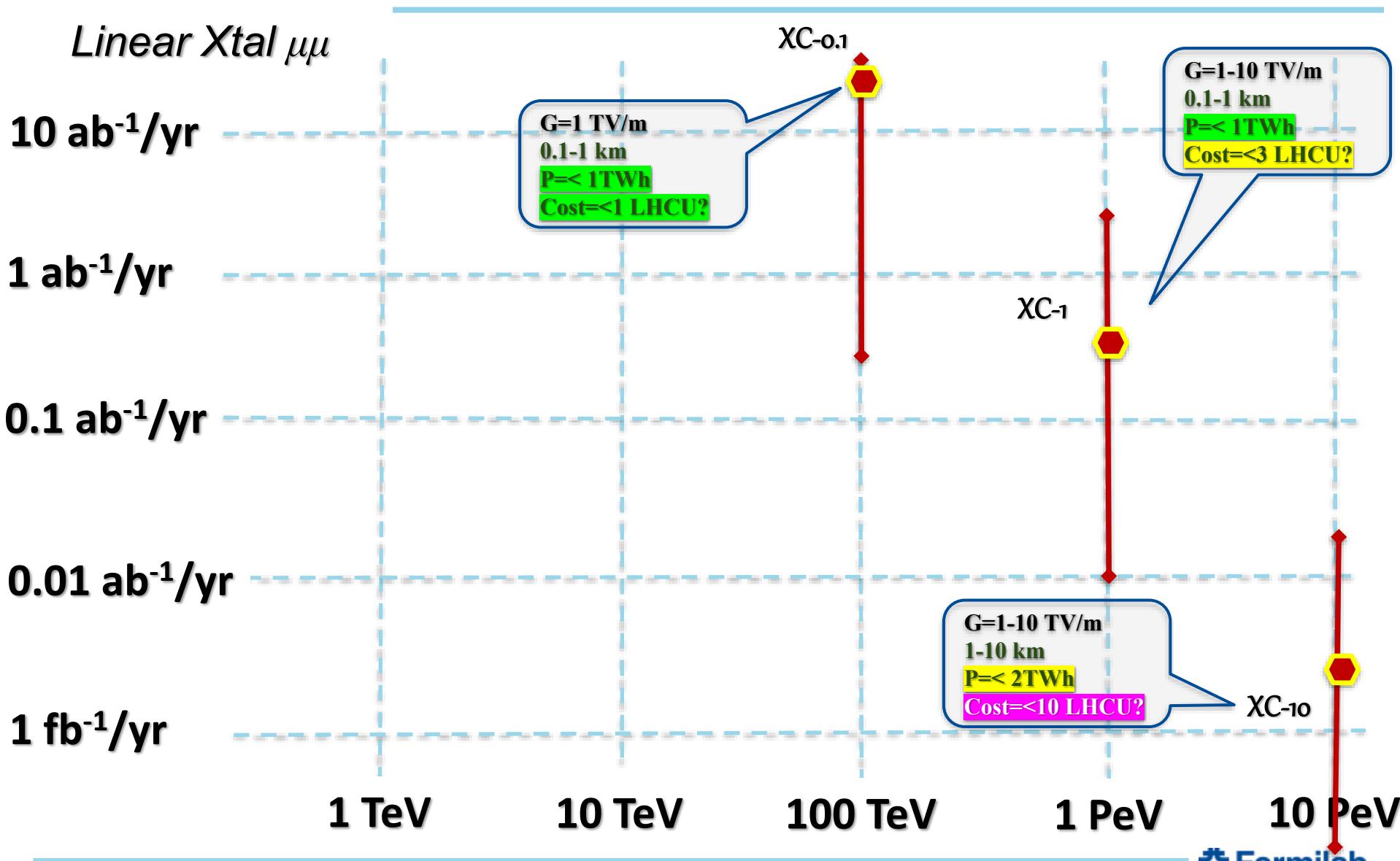
gain a factor of n_{ch}

$$P = f n_{\text{ch}} N E$$
$$f = 10^6 \text{ Hz}$$

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

milab

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*
 - *There are other important factors (CO₂ footprint, etc)*
- **Cost:**
 - Critically dependent on core acceleration technology
 - Existing injectors and infrastructure greatly help
- **High Energy means low Luminosity :**
 - Don't expect more than 0.1-1 ab⁻¹/yr at 30TeV - 1 PeV
 - Assume Power limited to 1-3 TWh/yr (1-3 x LHC)

Main Conclusions (2):

- **For considered collider types:**
 - Circular pp – limit is ~ 100 TeV (14 TeV cme per parton)
 - Circular ee – limit is $\sim 0.4\text{-}0.5$ 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 Luminosity
- **Muons are particles of the future**

Helpful/cited references (next slide)



(Some Useful) References:

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11. 2019 Crystal Workshop - eds. T.Tajima, et al, *Beam Acceleration in Crystals and Nanostructures* (World Scientific, 2020)
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Thanks for your attention!



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 - *Marica and Organizers of the eeFACT'22 Workshop*
- ... as final note, tons of material (all reports, etc) available at:

<https://snowmass21.org/accelerator/start>



Back up slides