



Accelerators for HEP: Challenges and R&D

Vladimir SHILTSEV (Fermilab)

ICHEP'2020

3 August 2020 - Prague (virtual)

Accelerator R&D

is needed to address feasibility of

ENERGY

0.25 to 100 TeV

14 TeV

COST

B\$, BCHF, BRMB

5 BCHF *

Performance

ab⁻¹, PoTs, P, time to
install, comms'n, ops.

3 ab⁻¹

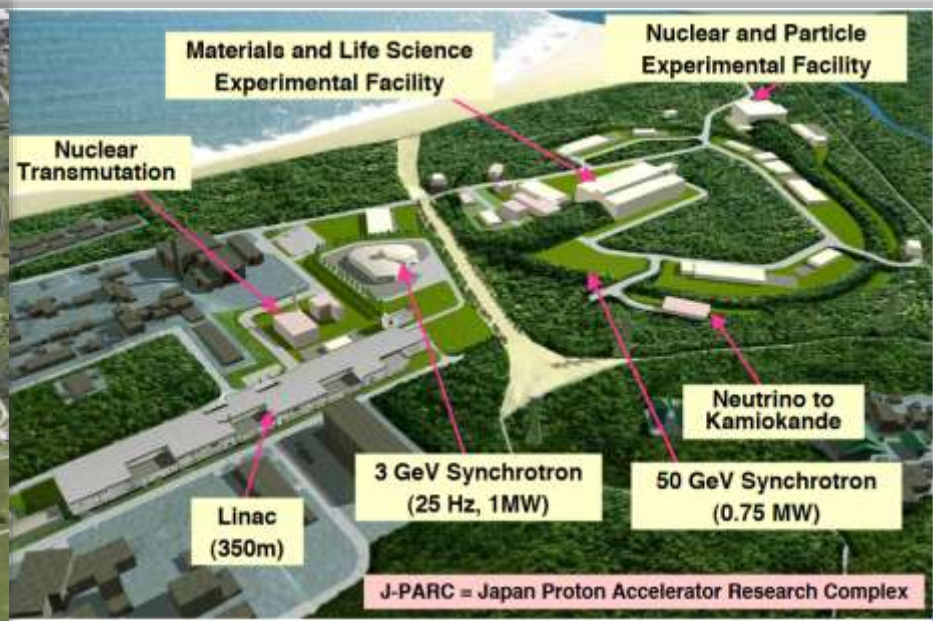
POWER

TWh / year

~1 TWh



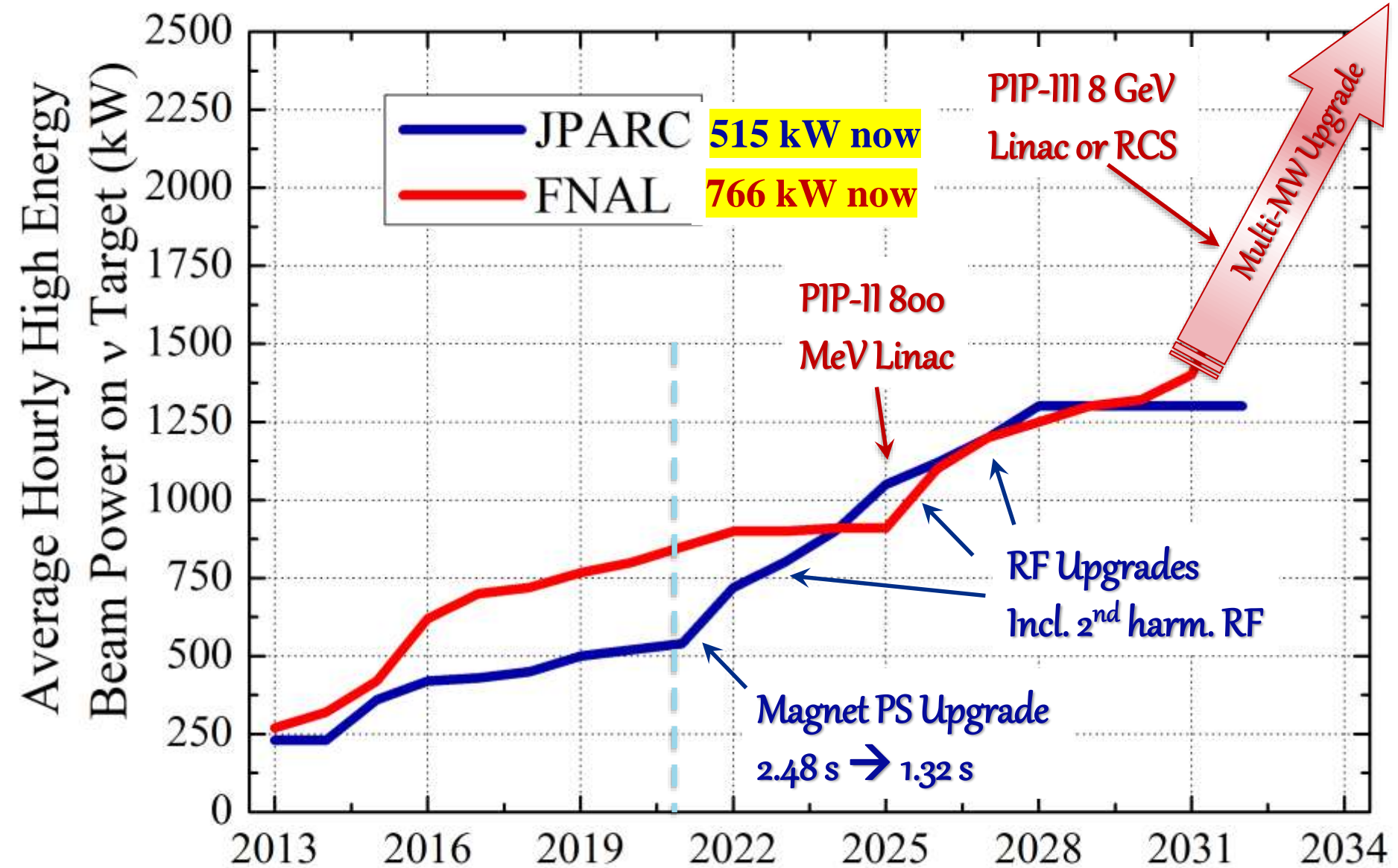
Leading Accelerator Facilities for Neutrino Physics Research



Fermilab Proton Complex: ID #913
120 GeV
0.75MW
+ 8 GeV experiments

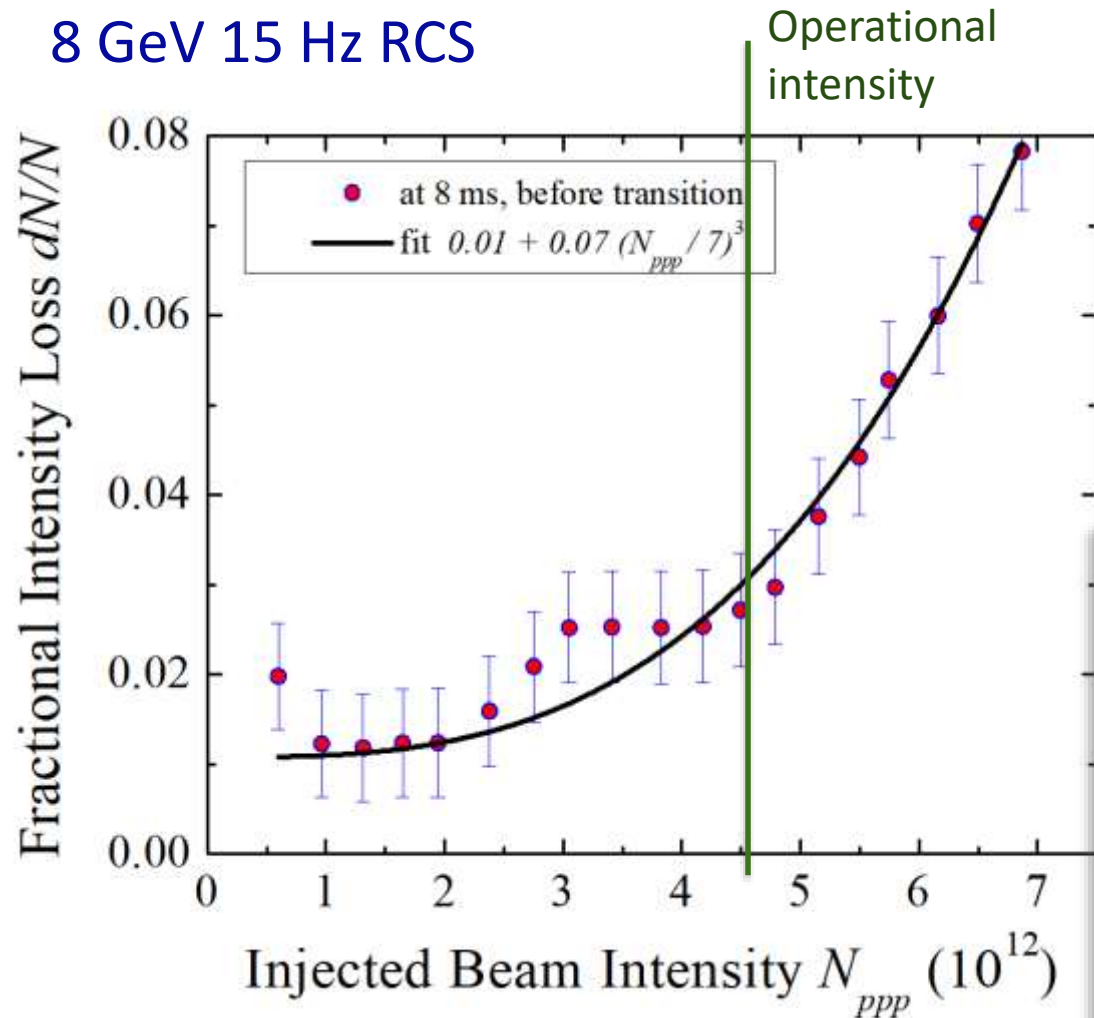
J-PARC Proton Complex: ID #775
30 GeV
0.5MW
+ 3 GeV experiments

Fermilab and J-PARC Power Upgrades



Two Key Challenges: #1 - lower beam losses while increasing intensity

Fermilab Booster
8 GeV 15 Hz RCS



Avg power loss limit $W=1\text{W/m}$:
 $\Delta N/N_{max} < W / (N \gamma)$
(need to decrease with N)

But space-charge effects
 $dN/N \sim [N_{max} / (\epsilon \times \beta \gamma^2)]^3$
(quickly increase with N)

Several approaches:

Larger magnets

Faster acceleration (linacs)

Non-linear Integrable Optics
Space-Charge Compensation
by electron lenses

Integrable Optics Test Accelerator (FNAL)



Challenge #2: Targets, Horns, Beam Windows

- Existing ν targets and horns are good to ~ 0.8 MW, MW and multi-MW targets are under development
 - Issues depend on pulse structure and include radiation damage and thermal shock -waves
 - R&D program to study material properties, new forms (foams, fibers, etc), new target designs (rotating, etc)



NuMI 750 kW horn



Proposed Facilities for Neutrino Research

Protvino-to-ORKA:

70 GeV, 90 (450) kW

$L=2590\text{km}$, $E_\nu \sim 5\text{ GeV}$



ENUBET at CERN-SPS:

400 GeV, 510 kW

$L=40\text{m}$, $E_\nu \sim 0.5\text{-}3.5\text{ GeV}$



ESS Neutrino Superbeams:

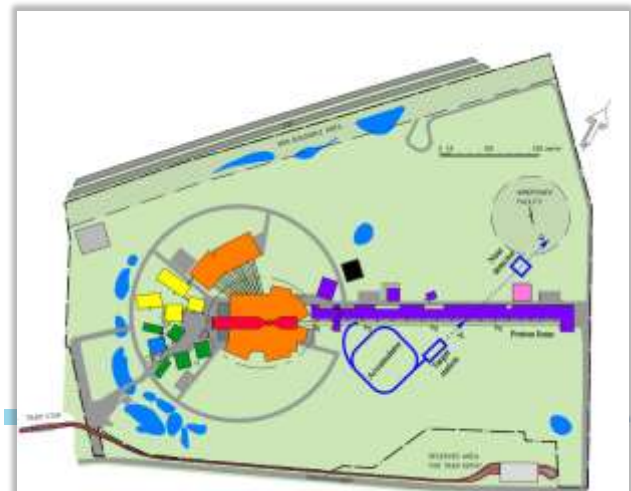
2 GeV, 5 MW

$L=540\text{km}$, $E_\nu \sim 0.3\text{ GeV}$

Challenges:

SC in the accumulator ring

5 MW neutrino target (not spallation)



ν STORM

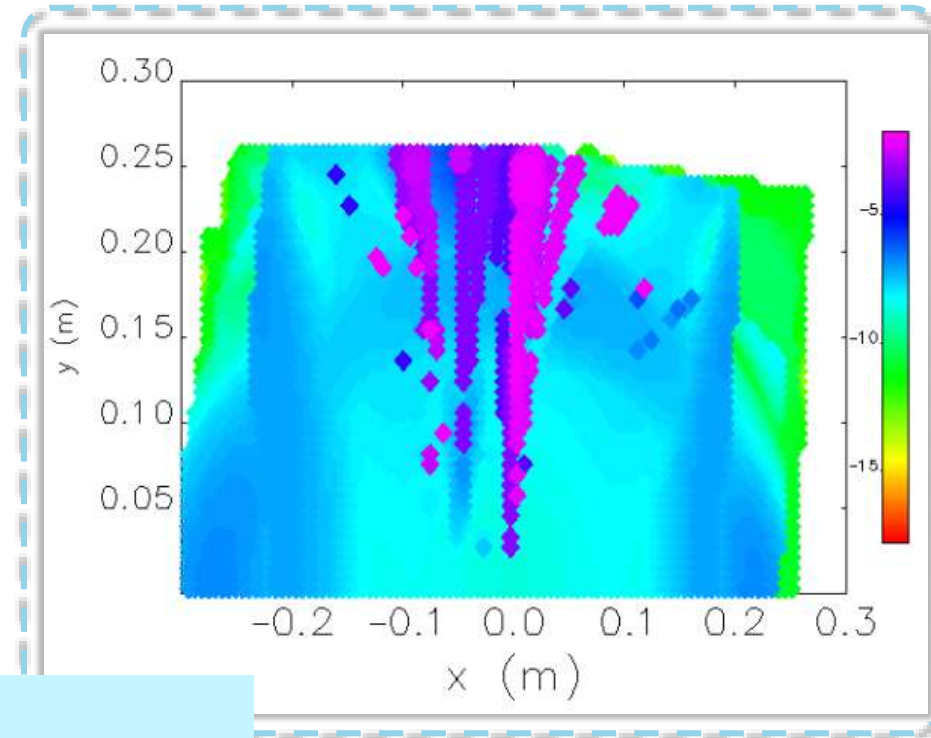
SPS at CERN :

$E=100$ GeV $P_{\text{beam}}=156$ kW

4×10^{13} $p+$ per pulse

$T_{\text{cycle}}=3.6$ s, 2×10 μ s (fast extr.)

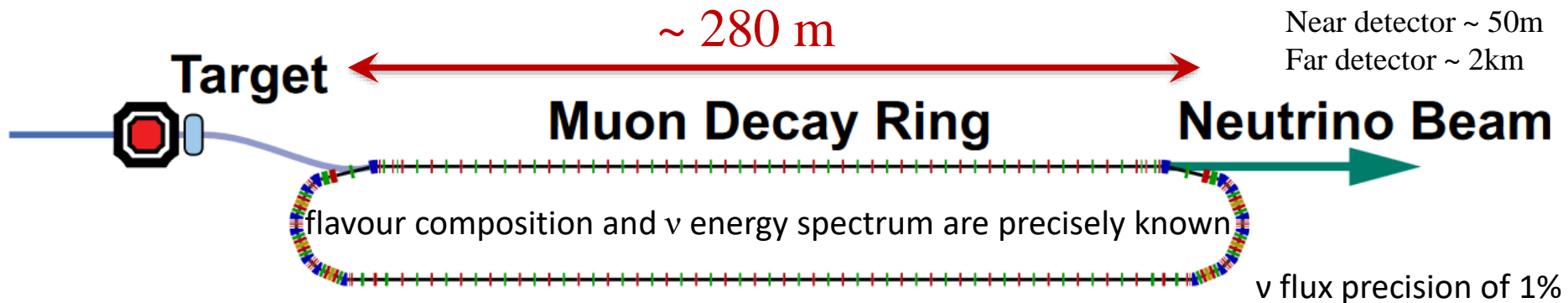
$\mu\pm$ beams 1 GeV/c - 6 GeV/c
momentum spread of 16%



Challenges:

- 300 μ rad emittance \rightarrow 0.5 dia magnets;
- survival $\sim 60\%$ after 100 turns for $\delta P/P \sim 10\%$

Synergy w. ν -Factory



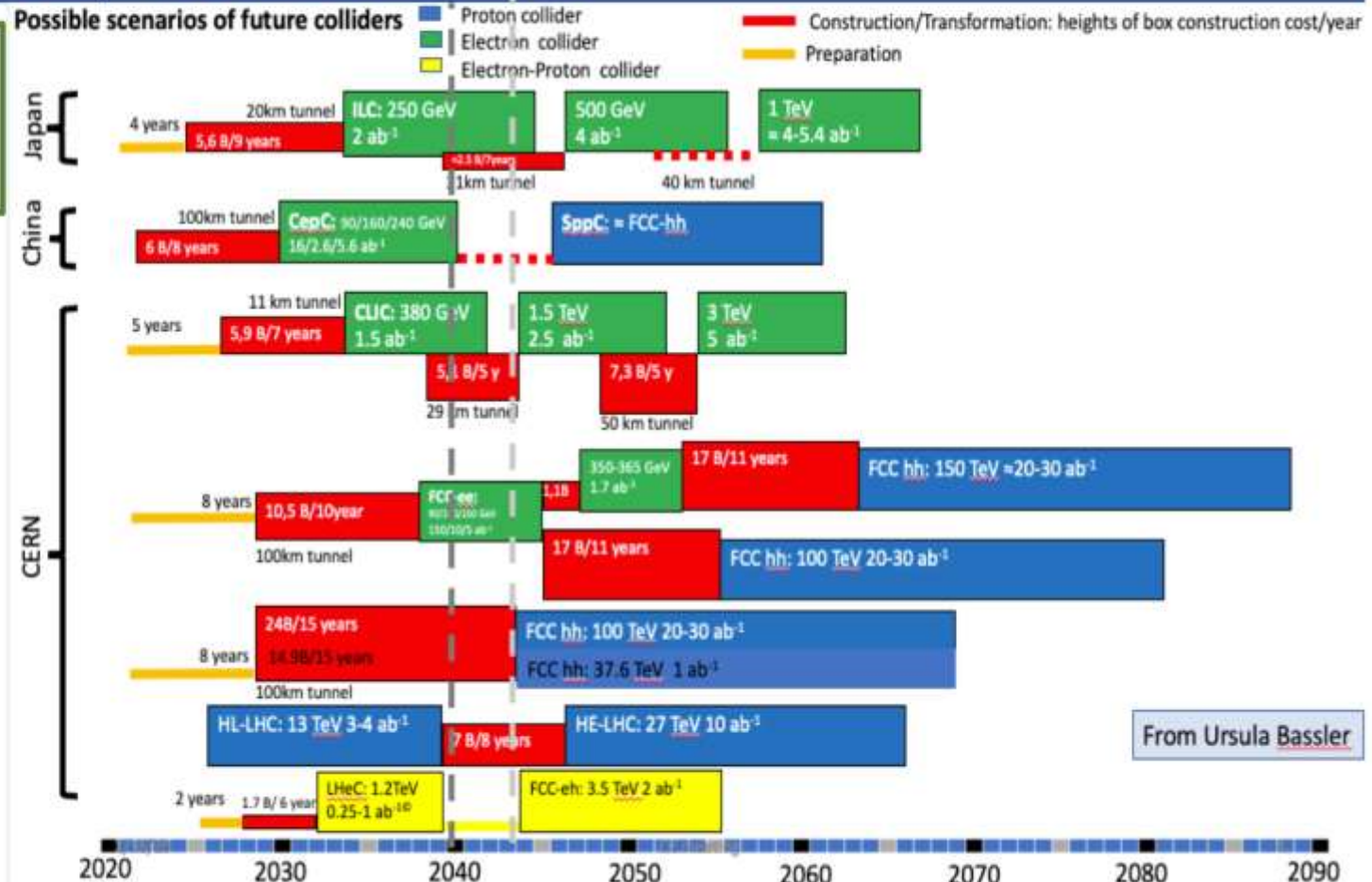
Colliders: (Too) Many on the Table



2020 Strategy Update

3. High-priority future initiatives

Map of possible future facilities submitted as input to the Strategy Update



Colliders: 16 Options at Snowmass'21

Day 1: <https://indico.fnal.gov/event/43871/>

Day 2: <https://indico.fnal.gov/event/43872/>

Machine parameters,
technical maturity &
timeframe

Joint AF-EF Meetings June 24 & July 1, 2020

9:00 AM → 9:10 AM **Introduction: goals, format, etc**

9:10 AM → 9:25 AM **FCCee**
Speaker: Katsunobu Oide (KEK)

9:25 AM → 9:40 AM **CepC**
Speaker: Yu Chenghui

9:40 AM → 9:55 AM **ILC**
Speaker: Shinichiro MICHIZONO (KEK)

9:55 AM → 10:10 AM **CLIC**
Speaker: Steinar Stapnes (FNAL)

10:10 AM → 10:25 AM **EIC**
Speaker: Christoph Montag (BNL)

10:25 AM → 10:40 AM **LHeC**
Speaker: Oliver Bruning (CERN)

10:40 AM → 10:55 AM **HE-LHC**
Speaker: Frank Zimmermann (CERN)

10:55 AM → 11:10 AM **SppC**
Speaker: Jinyu Tang (Institute of High Energy Physics)

11:10 AM → 11:25 AM **FCChh**
Speaker: Michael Benedikt

9:00 AM → 9:10 AM **Introduction: goals, format, etc**

9:10 AM → 9:30 AM **Cold NC-Linear Collider**
Speaker: Emilio Nanni (SLAC National Accelerator Laboratory)

9:30 AM → 9:50 AM **ERL based FCCee**
Speaker: Thomas Roser (BNL)

9:50 AM → 10:10 AM **Gamma-Gamma Higgs factories**
Speaker: Frank Zimmermann (CERN)

10:10 AM → 10:30 AM **Plasma-Laser WFA 1 TeV +**
Speaker: Carl Schroeder (Lawrence Berkeley National Laboratory)

10:30 AM → 10:50 AM **Plasma-Beam WFA 1 TeV +**
Speaker: Spencer Gessner

10:50 AM → 11:10 AM **Structure-beam WFA 1 TeV +**
Speaker: John Power (Argonne National Lab)

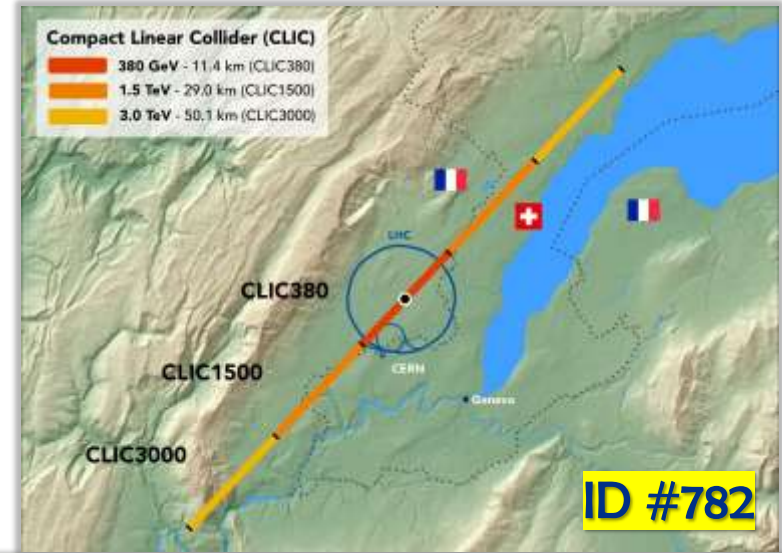
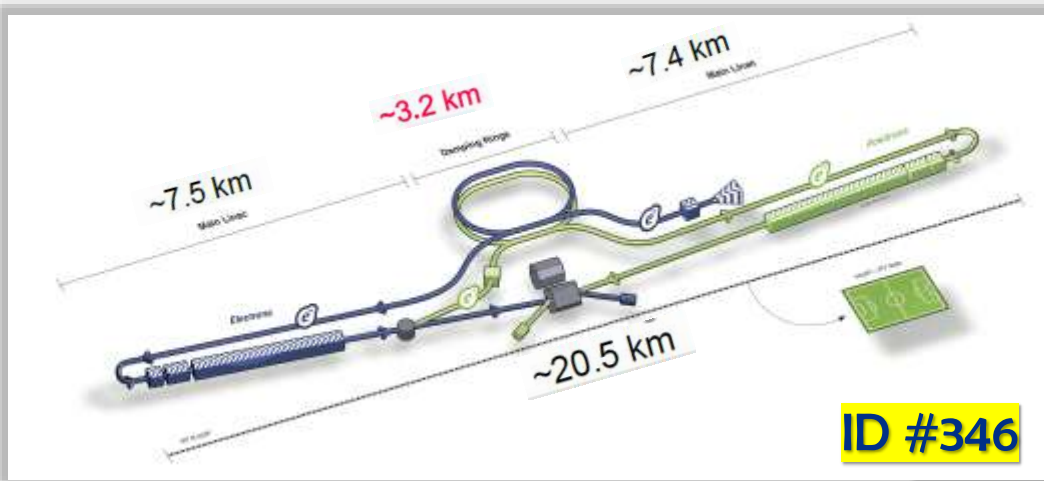
11:10 AM → 11:30 AM **Muon Colliders: Higgs Factory and 3-14 TeV**
Speaker: Daniel Schulte (CERN)

11:30 AM → 12:10 PM **Discussion/ Q&A**

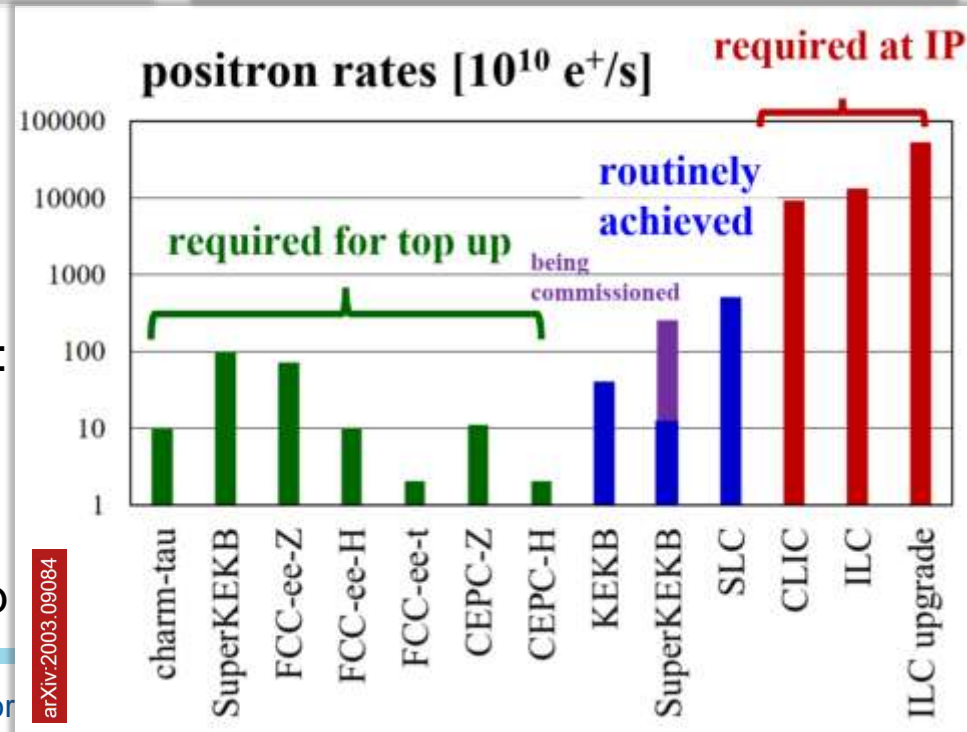
SnowMass2021

Linear Colliders - Higgs Factories: "Ready"

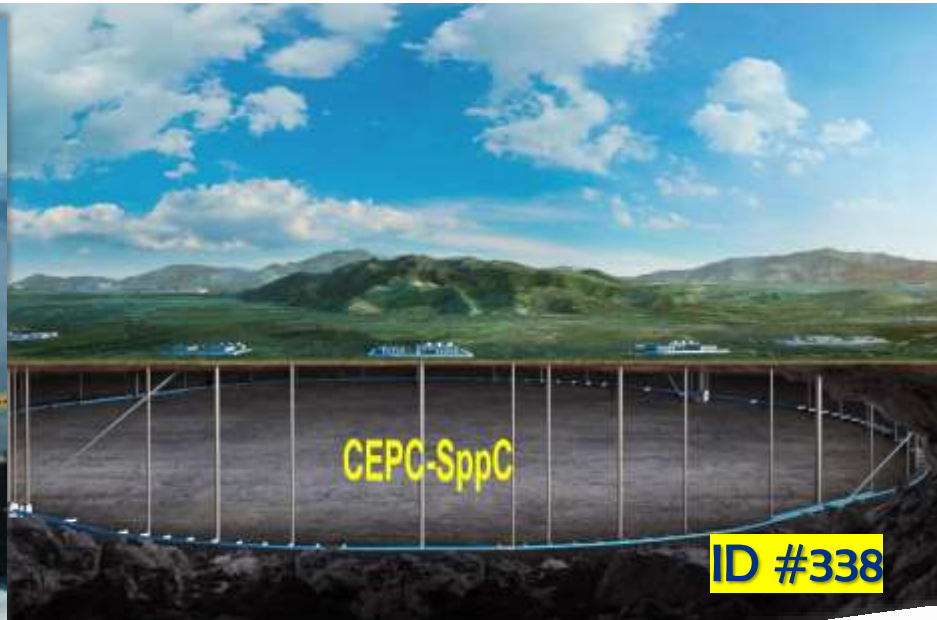
International Linear Collider



- Major R&D completed
- Concerns:
 - Positron production (>20x SLC) →
 - Luminosity and commissioning time:
 - Ground motion, focusing, etc
 - CLIC two-beam scheme is novel
 - Option with klystrons as backup



Circular e+e- Higgs Factories: R&D needed



- 100% feasible... matter of cost, time and desired performance/TWh

- **Challenges:**

- Cost reduction
 - SRF, magnets, tunnel
- Energy efficiency (now $P \sim 300\text{MW}$)
- R&D collaborations (*FCC@CERN*)
 - CepC TDR by 2023

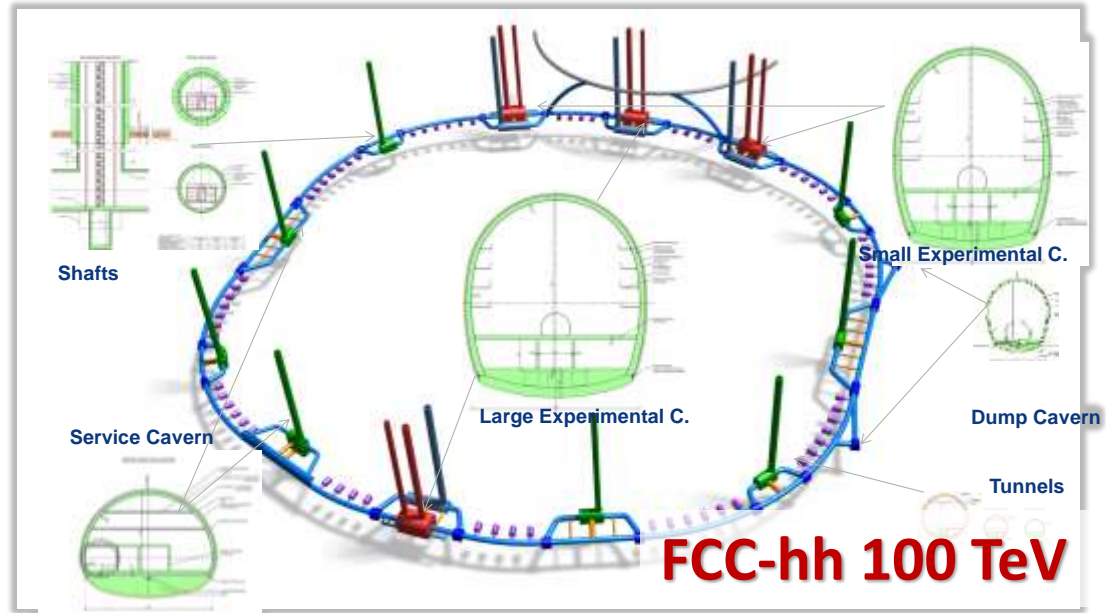
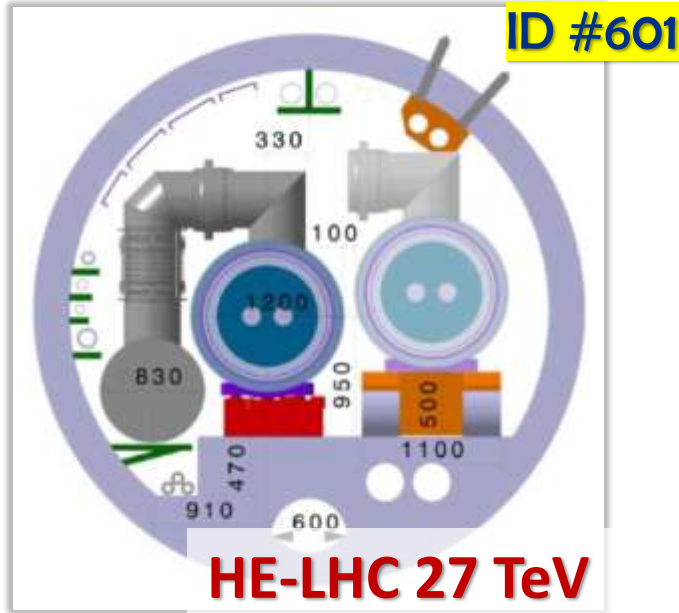
CEPC Accelerator R&D Priority

- 1) CEPC 650MHz 800kW high efficiency klystron (80%) (No commercial products)
- 2) High precision booster dipole magnet (critical for booster operation)
- 3) CEPC 650MHz SC accelerator system, including SC cavities and cryomules
- 4) Collider dual aperture dipole magnets and dual aperture quadrupoles

ID #615, J.Gao et al

Circular pp Colliders

HE-LHC CDR (2018) FCC-hh CDR (2018)



Key facts:

HE-LHC / FCC-hh / SppC**

Long tunnels

– 27 / 100 / 100 km

SC magnets

– 16 / 16 / 12 T

High Lumi / pileup

$O(10^{35})$ / $O(500)$

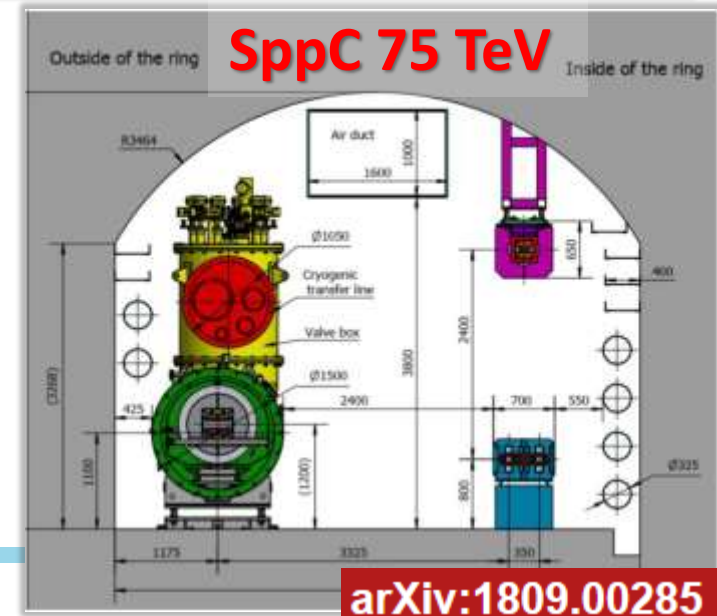
Site power (MW)

– 200 / 500? / ?

Cost (BCHF)

– 7.2 / 17.1 / ?

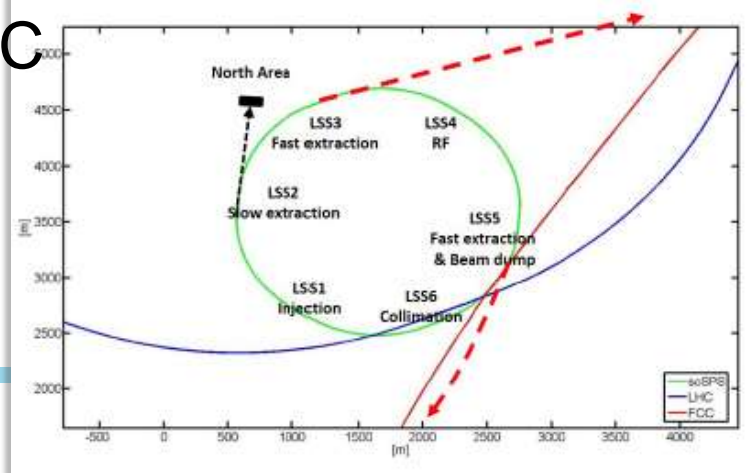
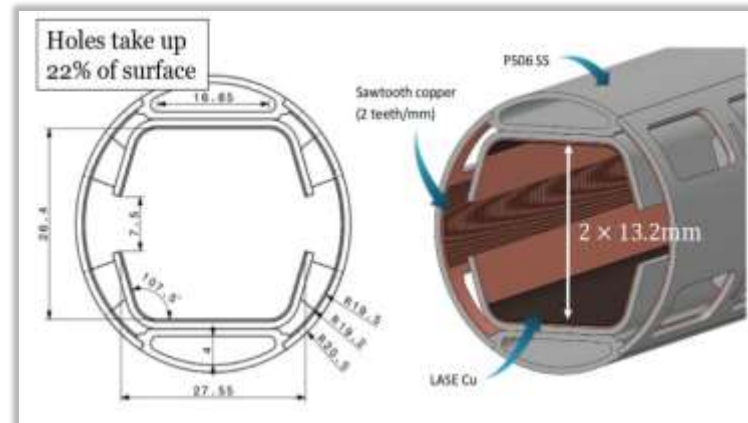
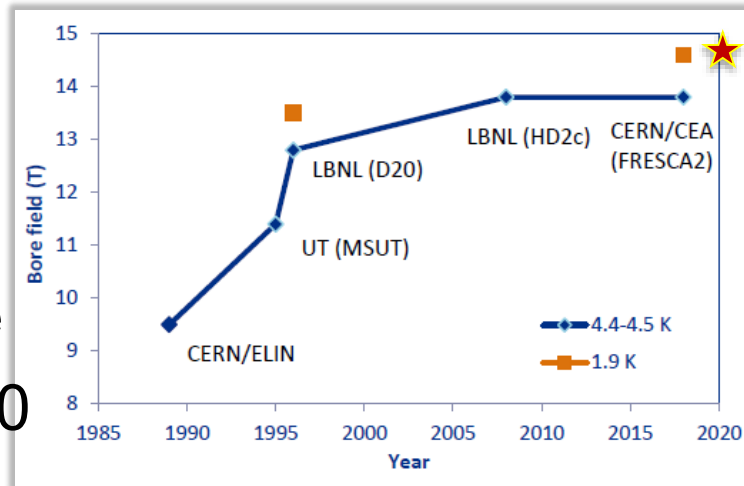
** follow up after e+e- Higgs factories*



arXiv:1809.00285

Strategic R&D Ahead :

- **High field dipoles:**
 - Nb₃Sn 16 T / iron-based 12 T, wire
 - 14.5 T achieved at FNAL in June'20
- **Intercept of synchr radiation :**
 - 5 MW FCC-hh / 1 MW CepC
- **Collimation :**
 - x7 LHC circulating beam power
- **Optimal injector:**
 - 1.3TeV scSPS, 3.3 TeV in LHC/FCC
- **Overall machine design :**
 - IRs, pileup, vacuum, etc
 - Power and cost reduction



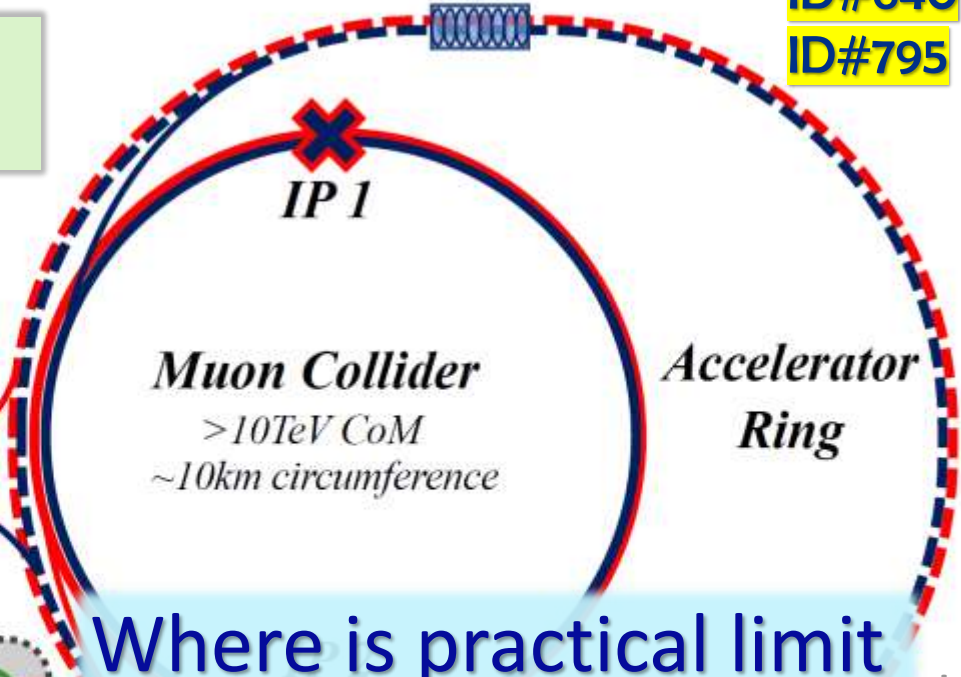
3-14 TeV Muon Colliders: Active R&D

ID #53
ID#640
ID#795

$\mu\mu$ @ 14 TeV \approx pp @ 100 TeV

Ionization cooling of muons demonstrated in MICE @ RAL

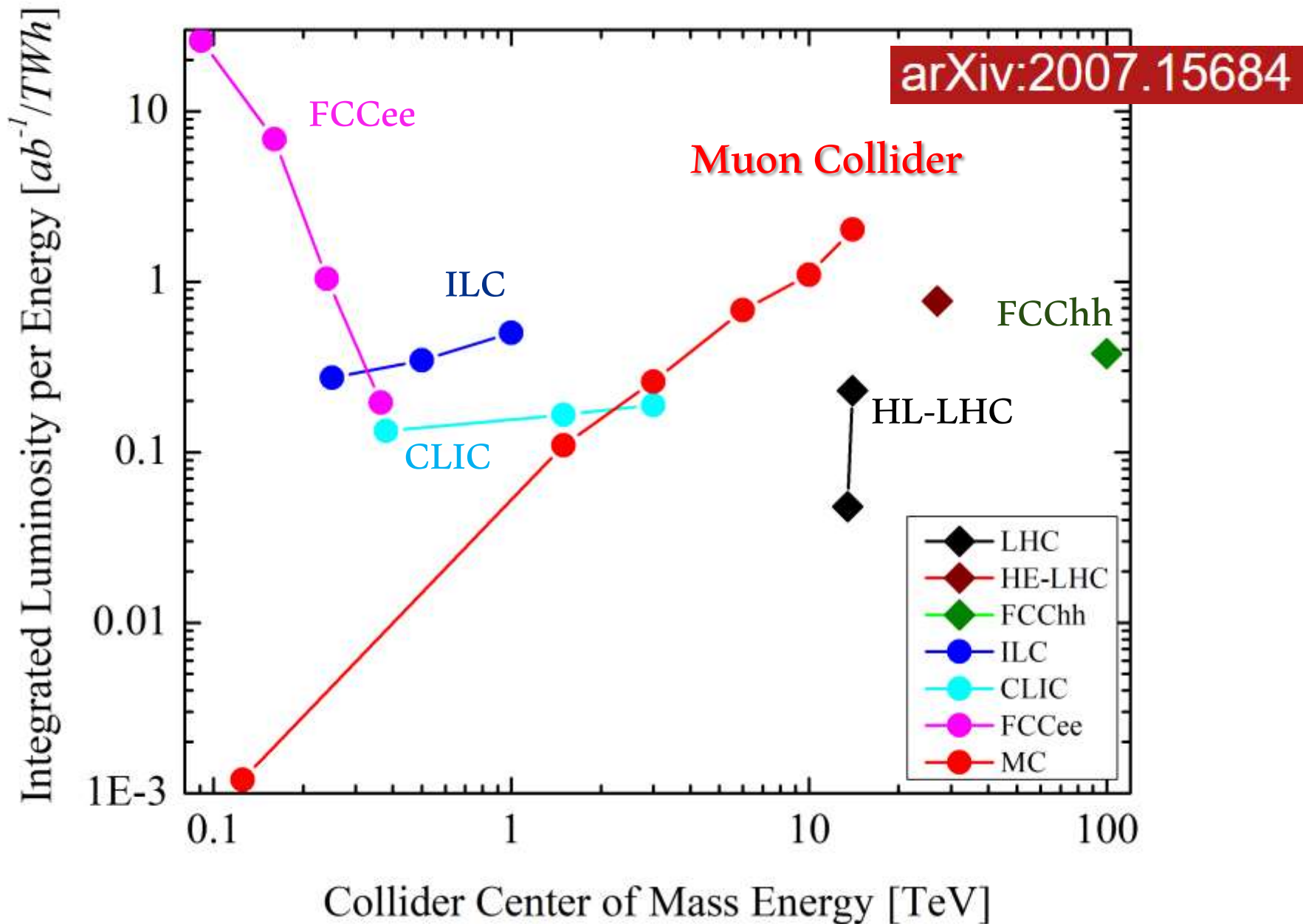
ZDRs for 1.5 TeV, 3 TeV, 6 TeV and 14 TeV



Where is practical limit of the Muon Colliders?
14...30...100 TeV?

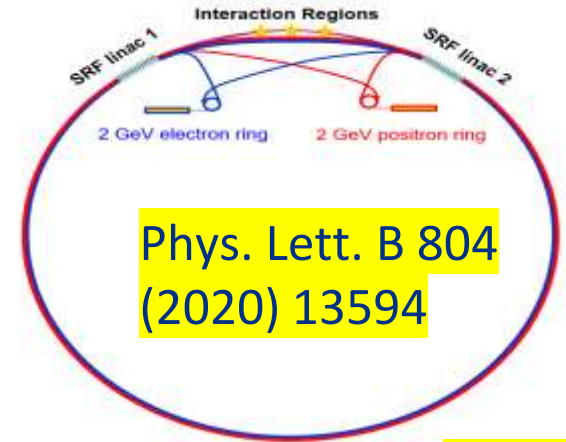
MC is generally within reach of modern accelerator technologies
R&D required on: μ production and cooling, fast acceleration (magnets, RF), MDI, large aperture 12 T magnets, ν -radiation
Int'l MC-Collaboration – contact D.Schulte(CERN) :
CDR in 4 yrs, test facility 6 yrs + 4 more years for TDR

Energy Efficiency of Future Colliders

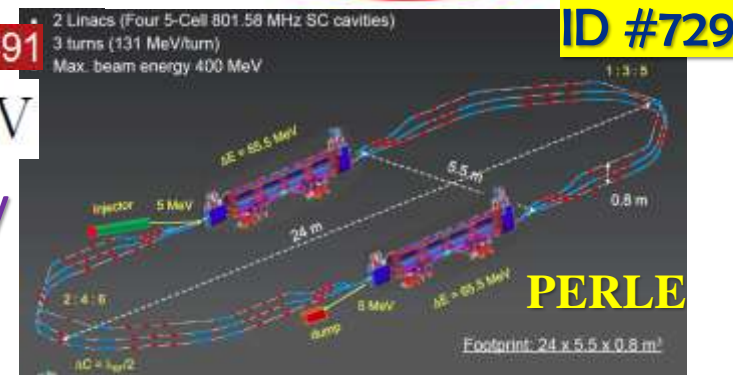


New (Realistic) Ideas

Energy Recovery Linac (ERL) FCCee:
 240 GeV, 100 km, 3-10x less RF power /ab⁻¹
 Challenges: emittances, beam-beam, 60 GeV SRF



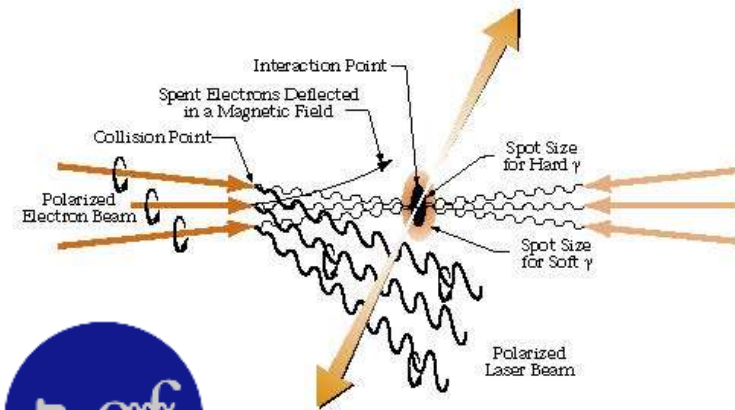
ERL-based LHeC (or FCCeh): arXiv:2007.14491
 50 GeV SRF, 6 km $\sqrt{s} = 1.2$ TeV $\sqrt{s} = 3.2$ TeV
 O(1ab⁻¹), 1.4 BCHF R&D: ERL PERLE@Orsay



Gamma-Gamma Higgs-Factories:
 Need only 80 GeV e⁻ to reach Higgs, RLA
 R&D: design, laser vs FEL, cost, Lumi/TWh

“Gamma-Factory”:

LHC ions + laser → O(GeV) γ's → e⁺, μ's
 proof-of-principle done; R&D: high flux



ID #771



Advanced Accelerator R&D: Plasma Wakes

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

ID #1001 ID #105 ID #1037

Proof-of-principle over past 2 decades:

Three ways to excite plasma (drivers)

laser $dE \sim 4.3 \text{ GeV}$ (10^{18} cm^{-3} 9cm)

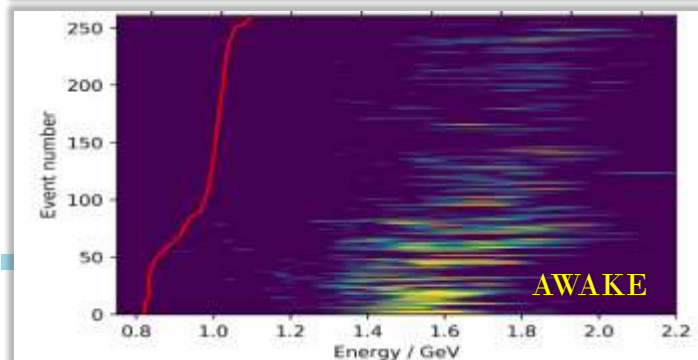
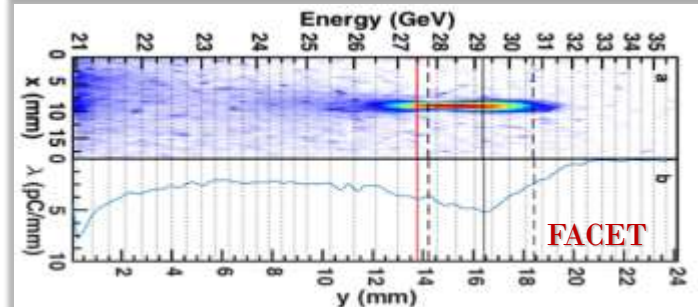
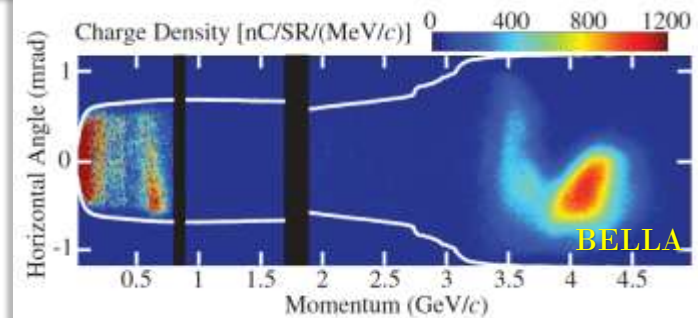
e- bunch $dE \sim 9 \text{ GeV}$ ($\sim 10^{17} \text{ cm}^{-3}$ 1.3m)

p+ bunch $dE \sim 2 \text{ GeV}$ ($\sim 10^{15} \text{ cm}^{-3}$ 10m)

In principle, feasible for e+e- collisions, but too early to count – need more R&D:

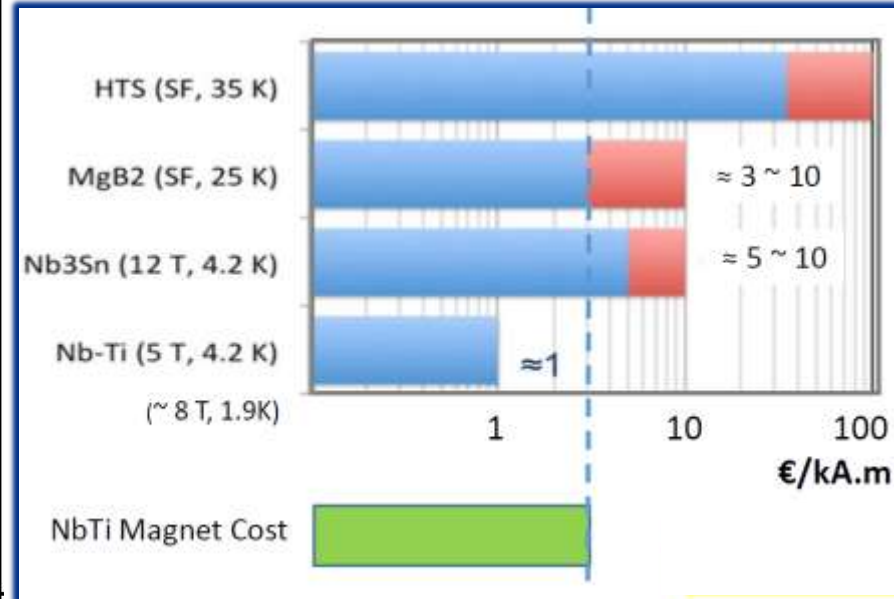
- acceleration of positrons, beamstrahlung
- staging efficiency, E_{max} , power efficiency
- emittance control vs vibrations & scatter

Active collaborations focused on applications: ALEGRO, BELLA, FACET-II, EuPRAXIA,...



Cost – Focused R&D

- Many project cost estimates become available at the EPPSU
- Will continue @ Snowmass'21
- **“Performance-cost”** optimization is critical: e.g. (A.Yamamoto, Granada)



- It takes time to reach the **cost-performance** goals:
Nb₃Sn, 12-14 T : 5-10 yrs short-model R&D
Nb₃Sn, 14-16 T : 10-15 yrs short-model R&D
 following by ~10 yrs for prototype/pre-series
 (A.Yamamoto, EPPSU, Granada 2019)

Project	TeV	Cost
ILC	0.25	4.8-5.3 BILCU
	0.5	8.0 BILCU
	1	+(n/a)
CLIC	0.38	5.9 BCHF
	1.5	+ 5.1 BCHF
	3	+7.3 BCHF
CEPC	0.24	5 B USD
		+(n/a)
FCC-ee	0.24	10.5 BCHF
	0.35	+1.1 BCHF
LHeC	1.3	1.75* BCHF
HE-LHC	27	7.2 BCHF
FCC-hh	100	17(+7) BCHF
FCC-eh	3.5	1.75 BCHF
Muon Coll	14	10.7* BCHF

[arXiv:2003.09084](https://arxiv.org/abs/2003.09084)

Acknowledgements

Input/useful discussions with:

Frank Zimmermann (CERN)

Steve Gourlay (LBNL)

Tor Raubenheimer (SLAC)

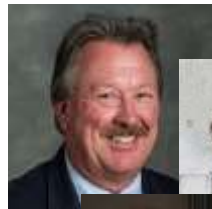
Dmitri Denisov (BNL)

Meenakshi Narain (UB)

Jorgen D'Hondt (ECFA)

arXiv:2003.09084

“Modern and Future Colliders”
(RMP review)



don't miss his plenary talk on Colliders on Wed !

EPPSU-Snowmass'21 input from:

M.Benedikt (CERN), P.Bhat (FNAL), C.Biscari (ALBA), A.Blondel (CERN), J.Brau (UO), O.Bruning(CERN), A.Canepa (FNAL), W.Chou (IHEP, China), J.P.Delahaye (CERN), D.Denisov (BNL), V.Dolgashev (SLAC), E.Gschwendtner (CERN), A.Grasselino (FNAL), M.Klein (CERN), W.Krasny (CNRS), M.Lamont (CERN), W.Leemans (DESY), E.Levichev (BINP), K.Long (ICL), D.Lucchesi (INFN), B.List (DESY), H.Montgomery (JLab), P.Muggli (MPG), D.Neuffer (FNAL), H.Padamsee (Cornell), M.Palmer (BNL), N.Pastrone (INFN), Q.Qin (IHEP), L.Rivkin (EPFL/PSI), A.Romanenko (FNAL), T.Roser (BNL), M.Ross (SLAC), D.Schulte (CERN), A.Seryi (Jlab), T.Sen (FNAL), A.Valishev (FNAL), F.Willeke (BNL), A.Yamamoto (KEK), V.Yakovlev, A.Zlobin (FNAL)



*Thank You for
Your Attention!*

BACK UP SLIDES

Summary:

- Remarkable progress of the projects/proposals/technologies:
 - esp. ILC, CLIC, FCC-*ee*, -*hh*, CepC, μ -Colliders, plasma, ...
 - allow in-depth evaluation of readiness, power and costs
- Higgs Factories Implementation :
 - several feasible options on the table
 - the choice might define high-energy future collider choice
- Highest Energy Future Colliders:
 - demand very high AC power & cost; some options to save
 - each machine has a set of key R&D items for next 7-10 yrs
 - core acceleration technology R&D – SC magnets, SRF and plasma – are of general importance and help all - *pp/ee/ $\mu\mu$*
- We also expect to gain valuable experience from the machines to be built and operated over the next decade
 - (see next slide)

	Country	Facility	Experience
<i>SuperKEKB</i>	Japan	7+4 GeV e^+e^- , 8e35	nano-beams scheme
<i>HL-LHC</i>	CERN	x5 LHC luminosity	Nb ₃ Sn magnets, crab cavities
<i>NICA</i>	Russia	ii/pp 11-27 GeV	electron and stochastic cooling
<i>PIP-II</i>	USA	SRF linac to double # ν 's	CW SRF, >1 MW targetry
<i>ESS</i>	Sweden	5 MW pulsed SRF	SRF, cryo, targetry
<i>LCLS-II-HE</i>	USA	8 GeV CW SRF	efficient SRF, cryo
<i>SuperC-Tau</i>	Russia	2-6 GeV e^+e^-	crab waist scheme
<i>EIC</i>	USA	20-140 GeV ep/ei	polarization, cool'g

EPPSU and Snowmass'21

CERN Council Open Symposium on the Update of

European Strategy for Particle Physics

13-16 May 2019 - Granada, Spain



CERN-ESU-004
30 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Electroweak Physics: Richard Keith Ellis¹, Beate Heinemann^{1,3} (Co-chairs)
Jorge de Blas^{4,5}, Maria Cepedó⁶, Christophe Geisler^{2,3}, Fabio Maltoni^{6,9}, Alejandro Nunez¹⁰,
Elisabeth Petit¹¹, Riccardo Rattazzi¹², Wouter Vankerkele¹³ (Contributors)

Strong Interactions: Jürgen D'Honn¹⁴, Krzysztof Radicki¹⁵ (Co-chairs)
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Nevus Arinovic¹⁸, Daniel Baur¹⁹, David d'Enterria²⁰, Jetyana Galaydskiy²¹, Thomas Gehrmann²²,
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Flavour Physics: Beles Gayle³², Antonio Zoccol³³ (Co-chairs)
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Godvyn Hiller⁴³, Gino Isidori⁴⁴, Yoshihisa Kiyo⁴⁵, Alberto Lattanzi⁴⁶, Yusuf Nir⁴⁷,
Marc-Helene Schune⁴⁸, Marco Senni⁴⁹, Stephan Steinhauser⁵⁰, Carlos Pena⁵¹ (Contributors)

Neutrino Physics & Cosmic Messengers: Stan Bilenca⁵², Marco Zito^{53,54} (Co-chairs)
Albert De Roeck⁵⁵, Thomas Schwetz⁵⁶ (Scientific Secretaries)
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Beyond the Standard Model: Gian F. Giudice⁶⁶, Paul Schyman^{67,68} (Co-chairs)
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Andreas Wulzer^{80,81} (Contributors)

Dark Matter and Dark Sector: Shoji Ando⁸², Marcelo Garcia⁸³ (Co-chairs)
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Konstantinos Petrakis⁸⁹, Christoph Weniger⁹⁰ (Scientific Secretaries/Contributors)

Acceleration Science and Technology: Caterina Innocenti⁹¹, Leonard Roko⁹² (Co-chairs)
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Michael Benedick⁹⁵, Pierluigi Carrone⁹⁶, Eddy Gschwendtner⁹⁷, Erik Jensen⁹⁸, Mike Lamont⁹⁹,
Wim Leeman¹⁰⁰, Lucio Rossi¹⁰¹, Daniel Schulte¹⁰², Mike Seidel¹⁰³, Vladimir Shalunov¹⁰⁴,
Steinar Stapnes¹⁰⁵, Akihiro Yamamoto¹⁰⁶ (Contributors)

Instrumentation and Computing: Xinchou Lou¹⁰⁷, Brigitta Vachon¹⁰⁸ (Co-chairs)
Roger Innes¹⁰⁹, Tereza Luszczak¹¹⁰ (Scientific Secretaries)

2020 UPDATE OF THE EUROPEAN STRATEGY
FOR PARTICLE PHYSICS

by the European Strategy Group



<https://cafpe.ugr.es/epps2019/>

<https://snowmass21.org/>

SnowMass2021

How much does it cost?

The cost for the machine alone is about 4.6 billion CHF (about 3 billion Euro). The total project cost breaks down roughly as follows:

Construction costs (BCHF)	Personnel	Materials	Total
LHC Machine and areas	0.92	3.68	4.60 ^{*)}
CERN share to Detectors	0.78	0.31	1.09
LHC injector upgrade	0.09	0.07	0.16
LHC computing (CERN share)	0.09	0.09	0.18
Total	1.88	4.15	6.03

^{*)} (including 0.43 BCHF of in-kind contributions)

CERN-Brochure-2008-001-Eng



Cost of the LHC

CERN-Brochure-2017-002-Eng

How much does it cost?

The total cost for the LHC, detectors and computing is as follows:

	Material costs (MCHF)
LHC machine and areas ^{*)}	3756
CERN share to detectors and detector areas ^{**)}	493
LHC computing (CERN share)	83
Total	4332

^{*)} This includes: Machine R & D and injectors, tests and pre-operation.

^{**)} Contains infrastructure costs (such as caverns and facilities). The total cost of all LHC detectors is about 1500 MCHF.