FERMILAB-SLIDES-20-080-AD-APC

Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Accelerators for HEP: Challenges and R&D

Vladimir SHILTSEV (Fermilab)

ICHEP'2020

3 August 2020 - Prague (virtual)

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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.

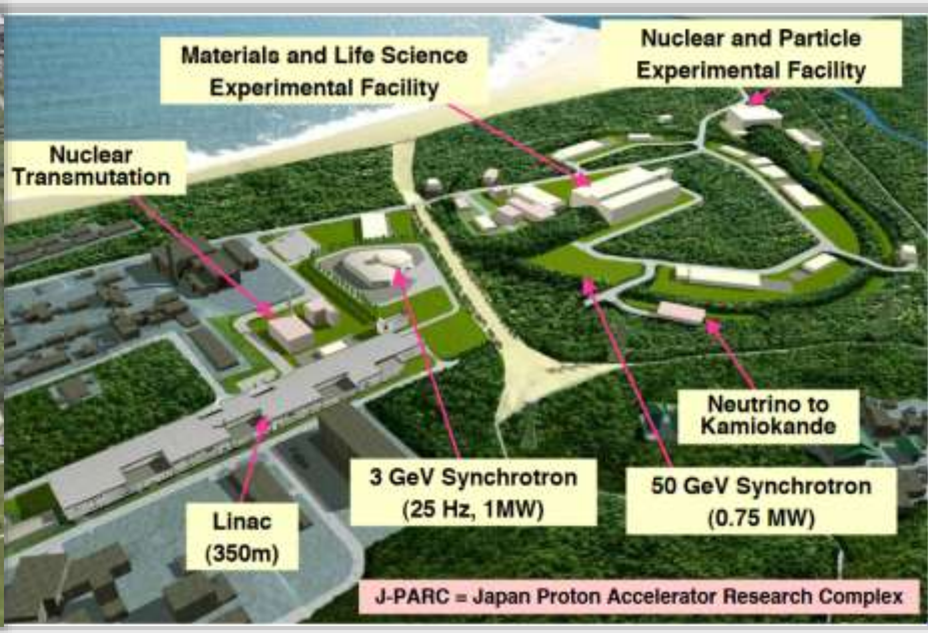
3 ab-1

POWER

TWh / year

~1 TWh

Leading Accelerator Facilities for Neutrino Physics Research



Fermilab Proton Complex: ID #913

120 GeV

0.75MW

+ 8 GeV experiments

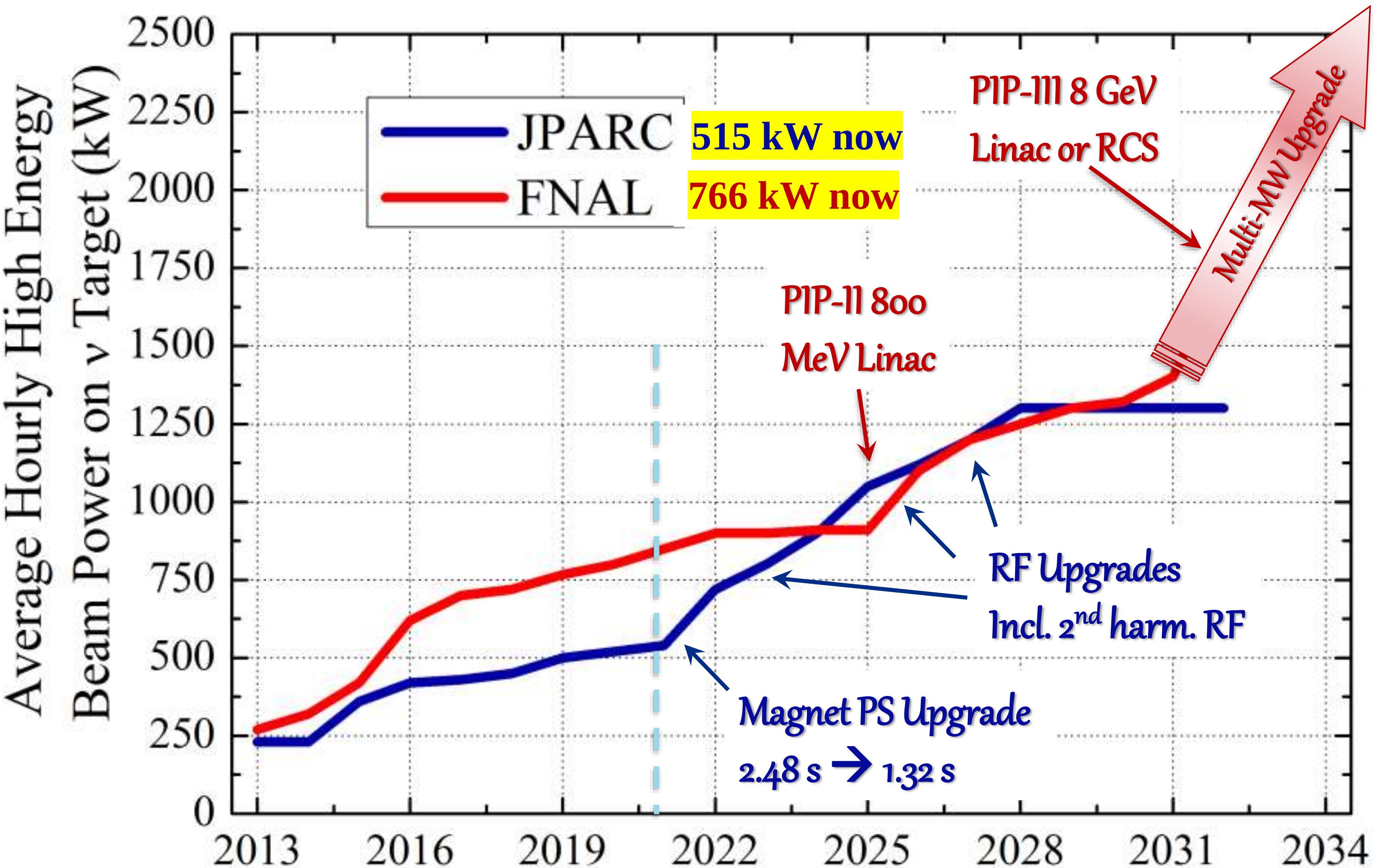
J-PARC Proton Complex: ID #775

30 GeV

0.5MW

+ 3 GeV experiments

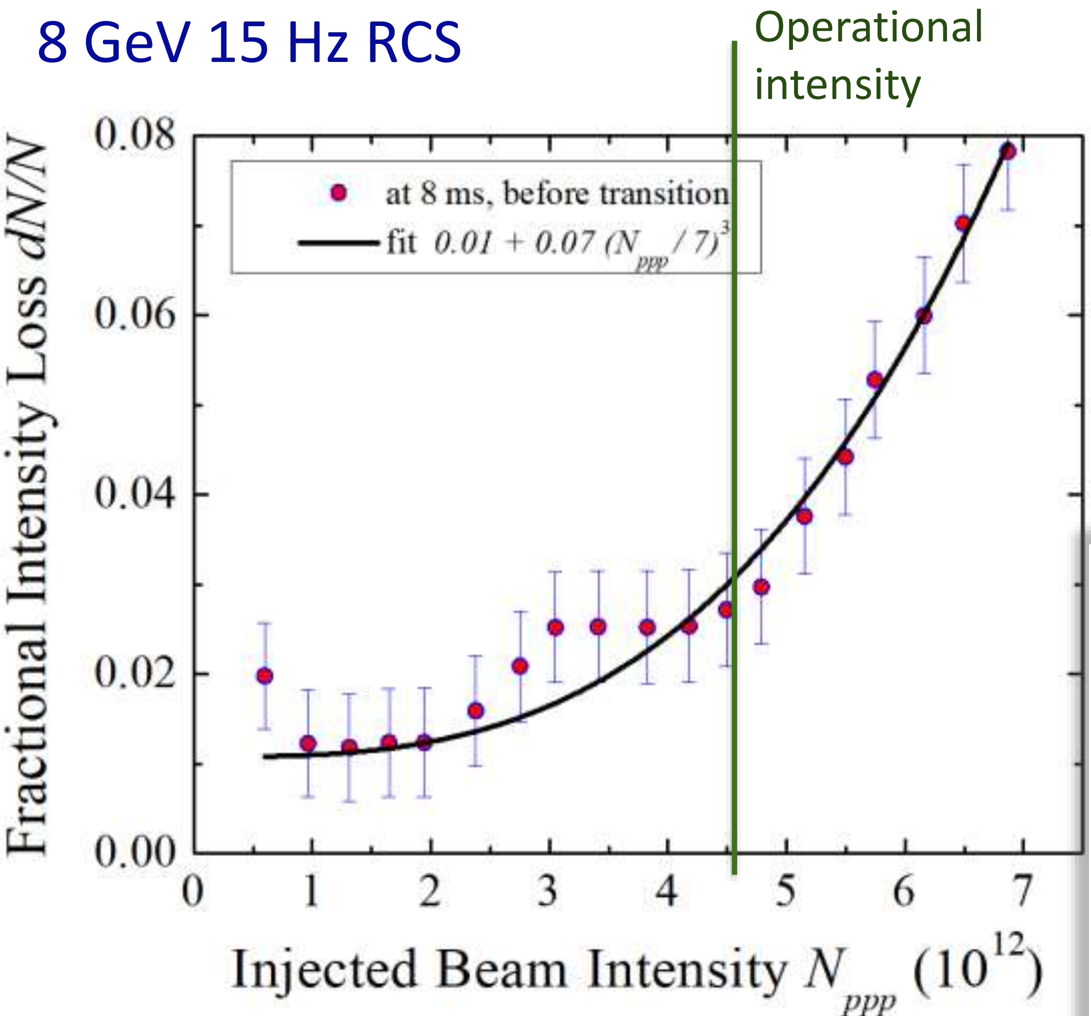
Fermilab and J-PARC Power Upgrades



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

Fermilab Booster

8 GeV 15 Hz RCS



Avg power loss limit W=1W/m:

$\Delta N/N_{max} < W/(N\,\gamma)$

(need to decrease with N)

But **space-charge effects**

$dN/N \sim [\, N_{max}/(\varepsilon \times \beta\gamma^2)\,]^3$

(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)

RaDIATE Collaboration
Radiation Damage In Accelerator Target Environments

Proposed Facilities for Neutrino Research

Protvino-to-ORKA:

70 GeV, 90 (450) kW

L=2590km, E_ν ~5 GeV

ENUBET at CERN-SPS:

400 GeV, 510 kW

L=40m, E_ν ~0.5-3.5 GeV

ESS Neutrino Superbeams:

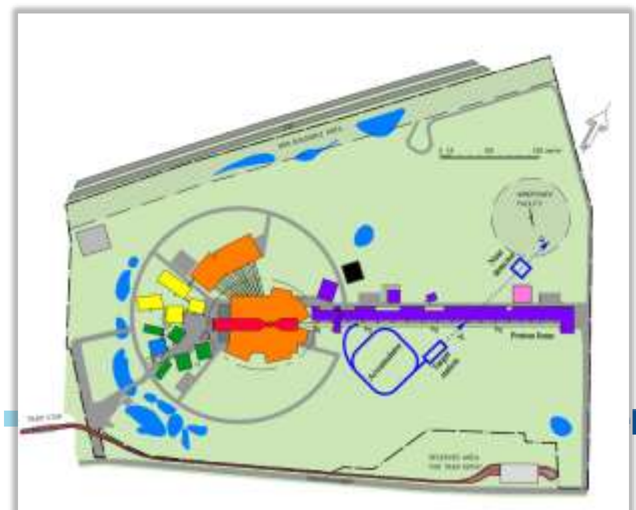
2 GeV, 5 MW

L=540km, E_ν ~0.3 GeV

Challenges:

SC in the accumulator ring

5 MW neutrino target (not spallation)



νSTORM

2017 *JINST* **12** P07018 2017 *JINST* **12** P07020

SPS at CERN :

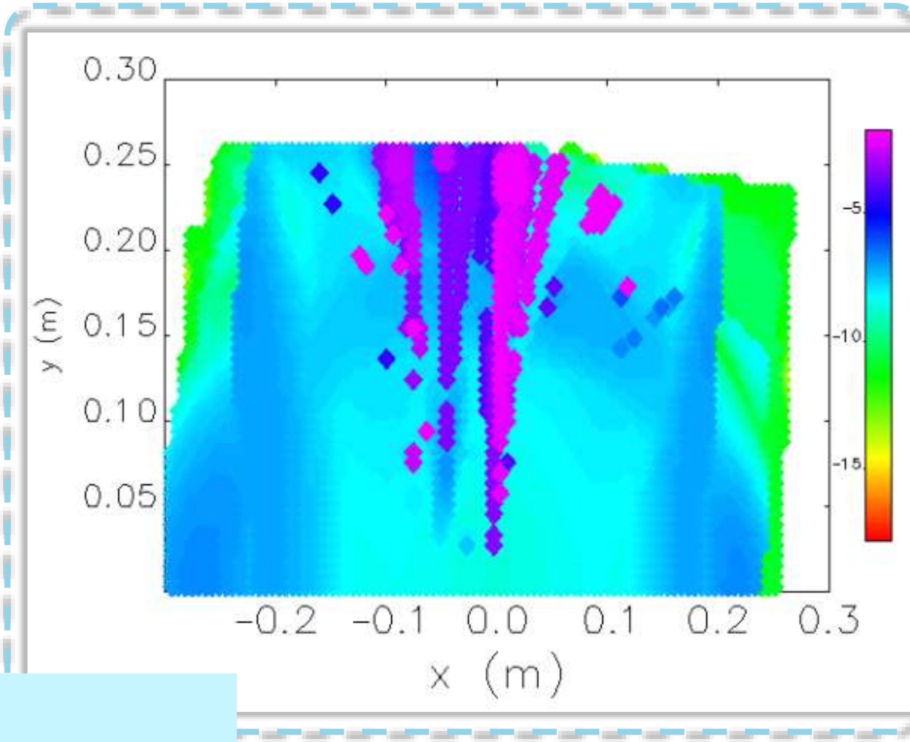
E=100 GeV *P*_beam =**156kW**

4 10^{13} *p*+ per pulse

T_{cycle}=3.6 s, 2 x 10 μs (fast extr.)

μ± beams 1 GeV/c - 6 GeV/c

momentum spread of 16%

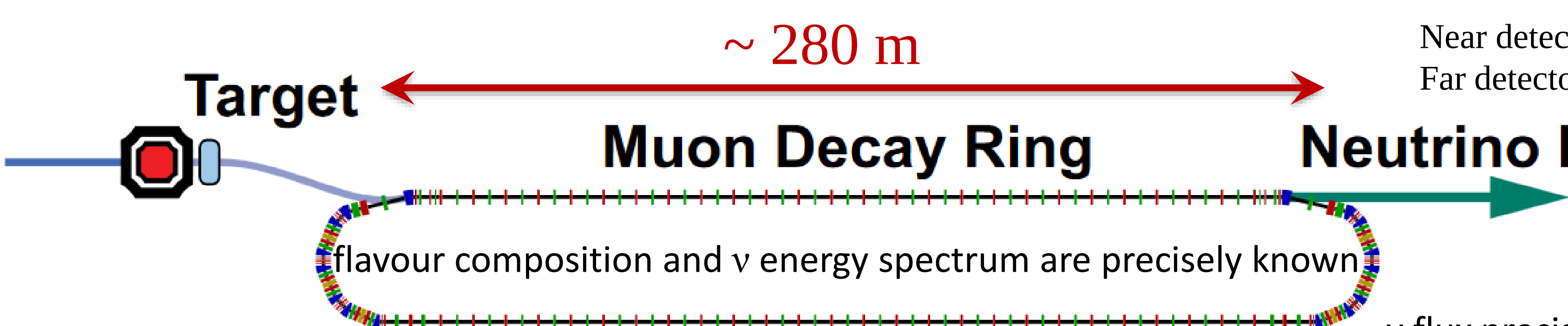


Challenges:

a) 300 μmrad emittance → 0.5 dia magnets;

b) survival ~60% after 100 turns for $\delta P/P$ ~10%

Syngergy w. ν -Factory

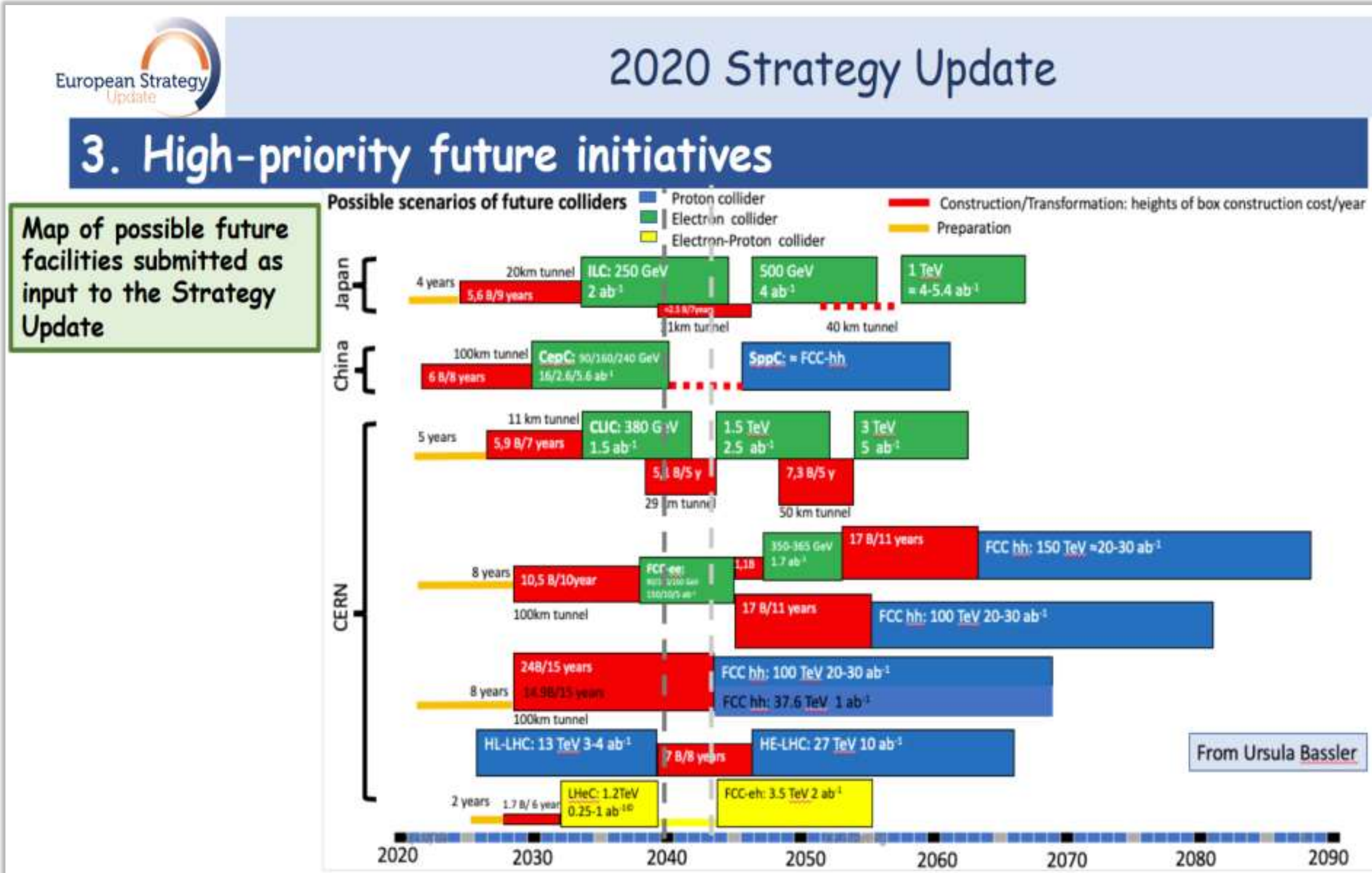


Near detector ~ 50m

Far detector ~ 2km

ν flux precision of 1%

Colliders: (Too) Many on the Table



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

Day 1

- **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: Jingyu Tang (Institute of High Energy Physics
- **11:10 AM** → 11:25 AM **FCChh**
  Speaker: Michael Benedikt

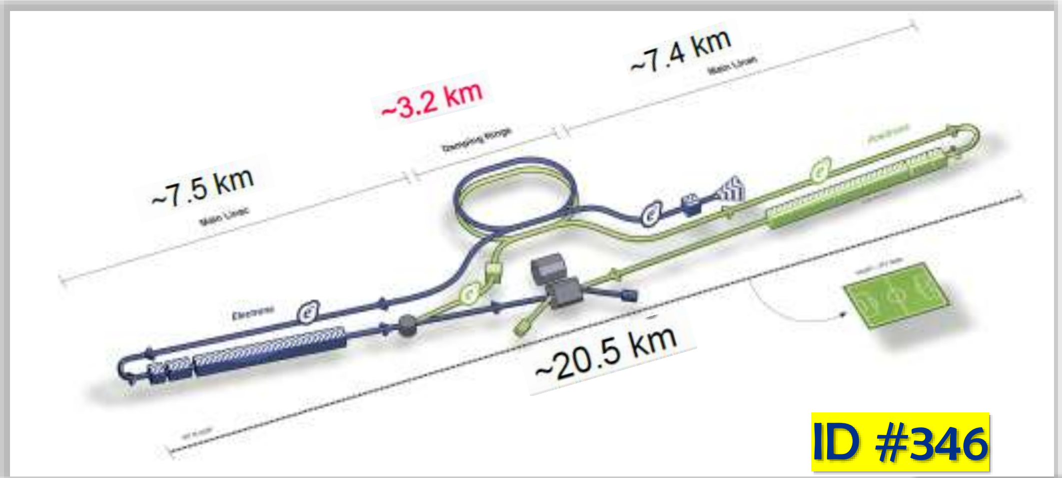
Day 2

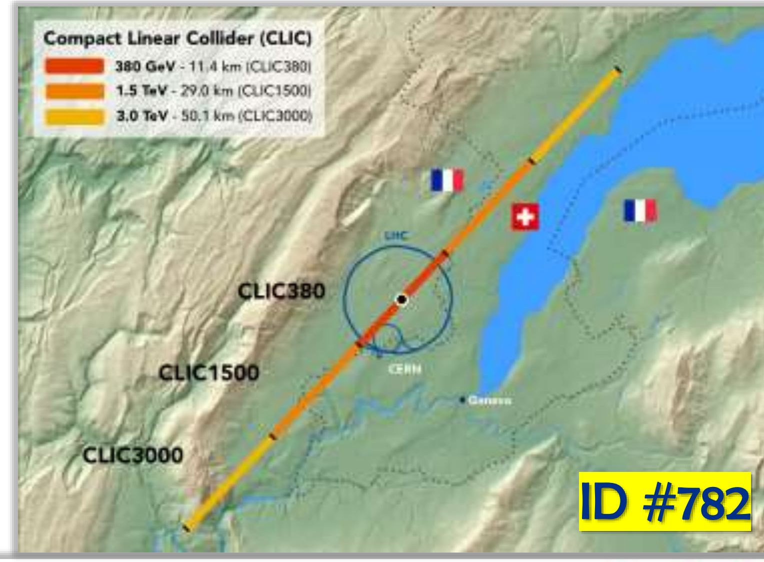
- **9:00 AM** → 9:10 AM **Introduction: gioals, format, etc**
- **9:10 AM** → 9:30 AM **Cold NC-Linear Collider**
  Speaker: Emilio Nanni (SLAC National Accelerator Laboratory)
- **9:30 AM** → 9:50 AM **ERL based FCCee**
  Speaker: Thomas Roser (BNL)
- **9:50 AM** → 10:10 AM **Gamma-Gamma Higgs factories**
  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 Coliders: Higgs Factory and 3-14 TeV**
  Speaker: Daniel Schulte (CERN)
- **11:30 AM** → 12:10 PM **Discussion/ Q&A**

SnowMass2021

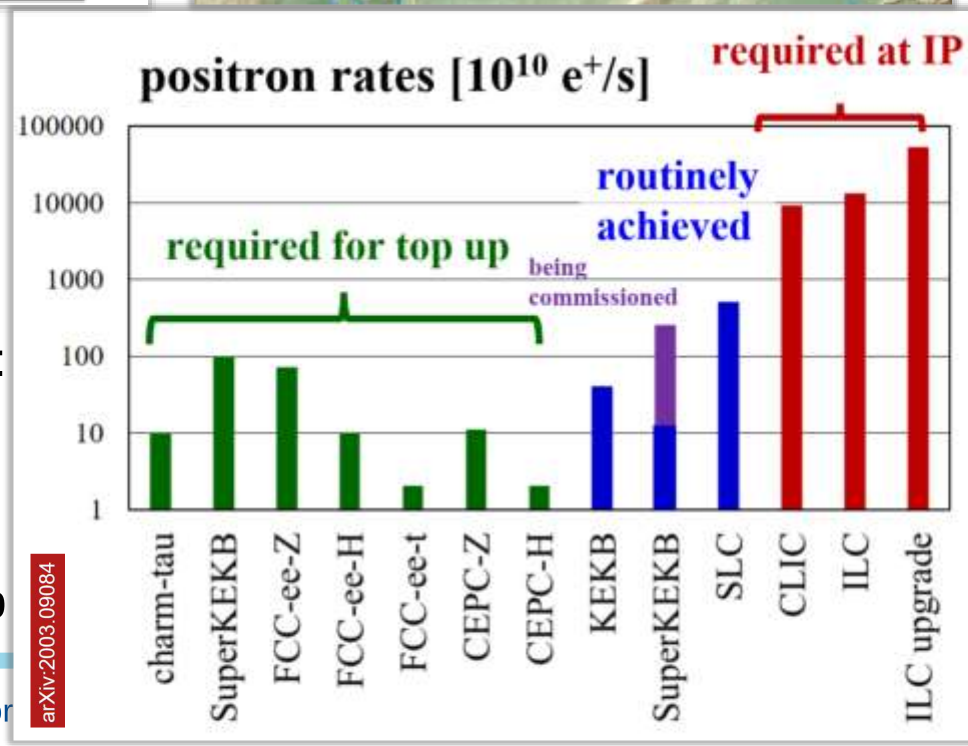
Linear Colliders - Higgs Factories: "Ready"

International Linear Collider

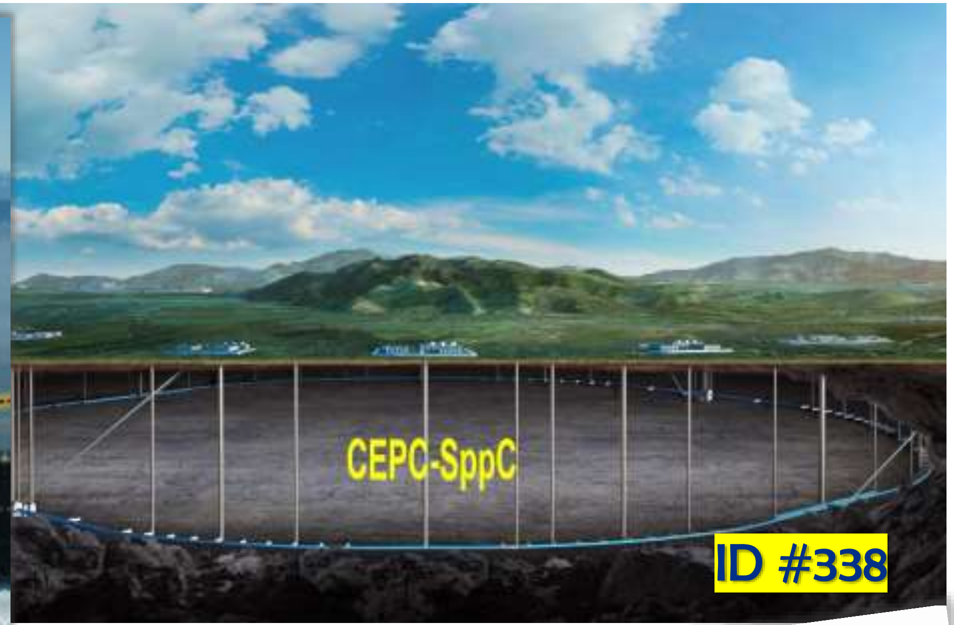




- *Major R&D completed*
- *Concerns:*
  - ➢ Positron production (>20x SLC) →
  - ➢ Luminosity and commissioning time:
    - ➢ Ground motion, focusing, etc
  - ➢ CLIC two-beam scheme is novel
    - ➢ Option with klystrons as backup



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*~300MW)
  - 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)

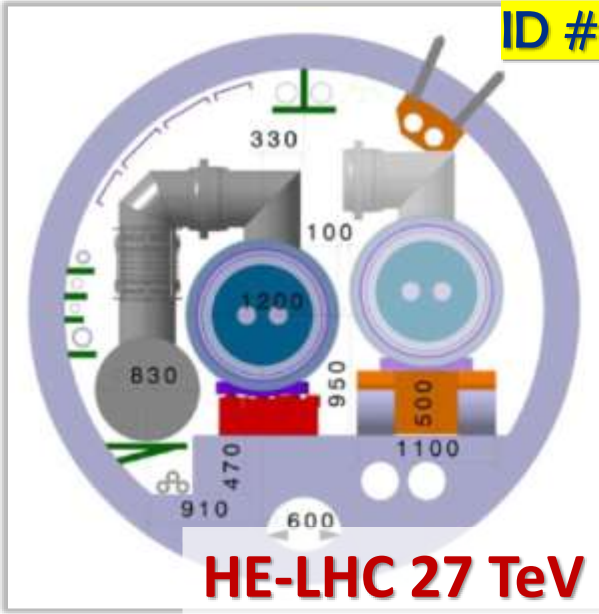
3) CEPC 650MHz SC accelerator system, including SC cavitie and cryomules

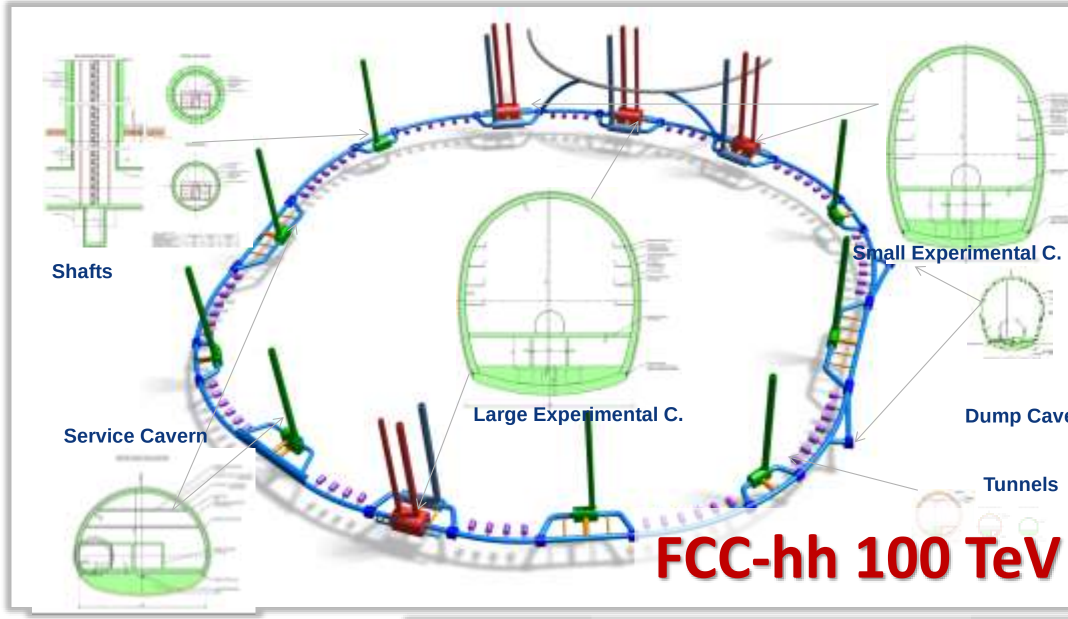
4) Collider dual aperture dipole magnets and dual apertur qudrupoles

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

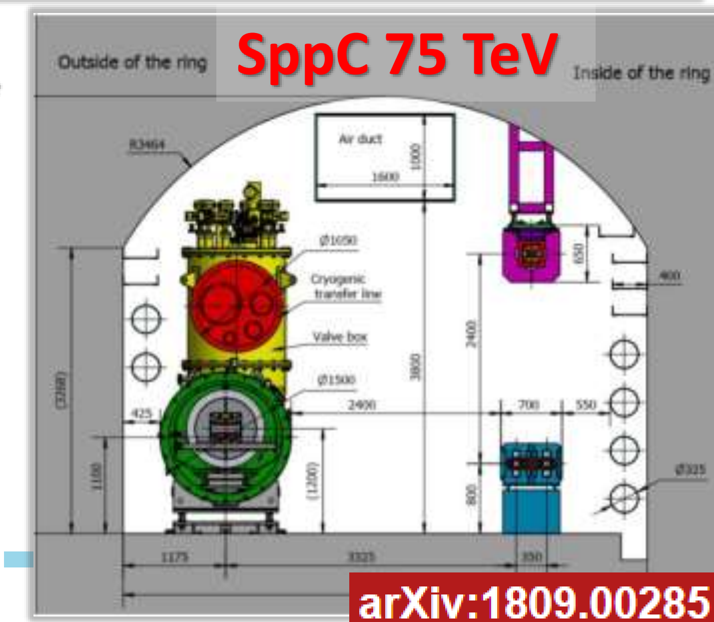
SC magnets – 16 / 16 / 12 T

High Lumi / pileup *O*(10^{35}) / *O*(500)

Site power (MW) – 200 / 500? / ?

Cost (BCHF) – 7.2 / 17.1 / ?

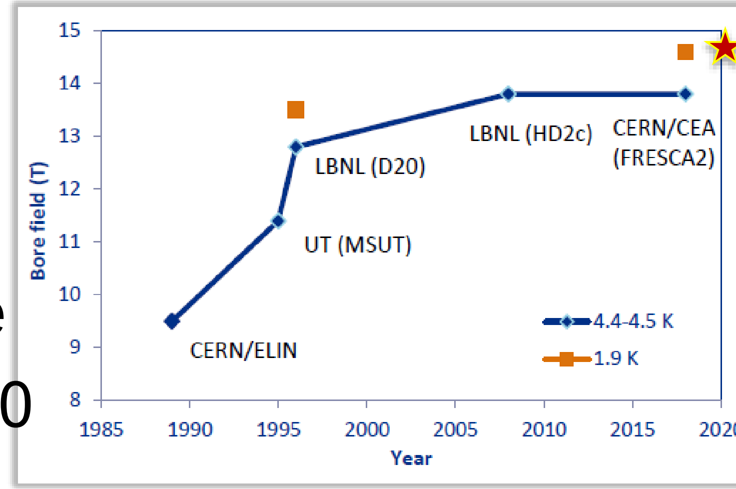
** follow up after e+e- Higgs factories*

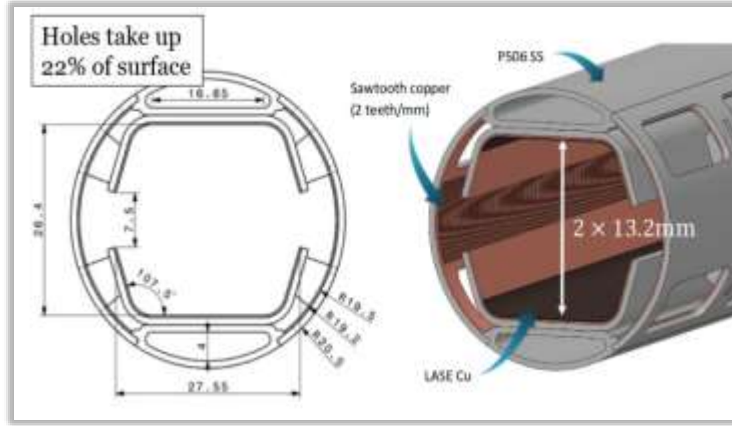


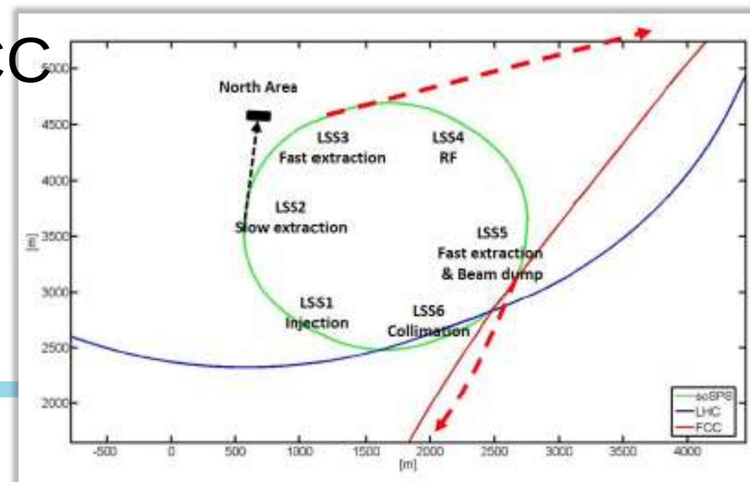
Strategic R&D Ahead :

- 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

All that might take 12-18 years







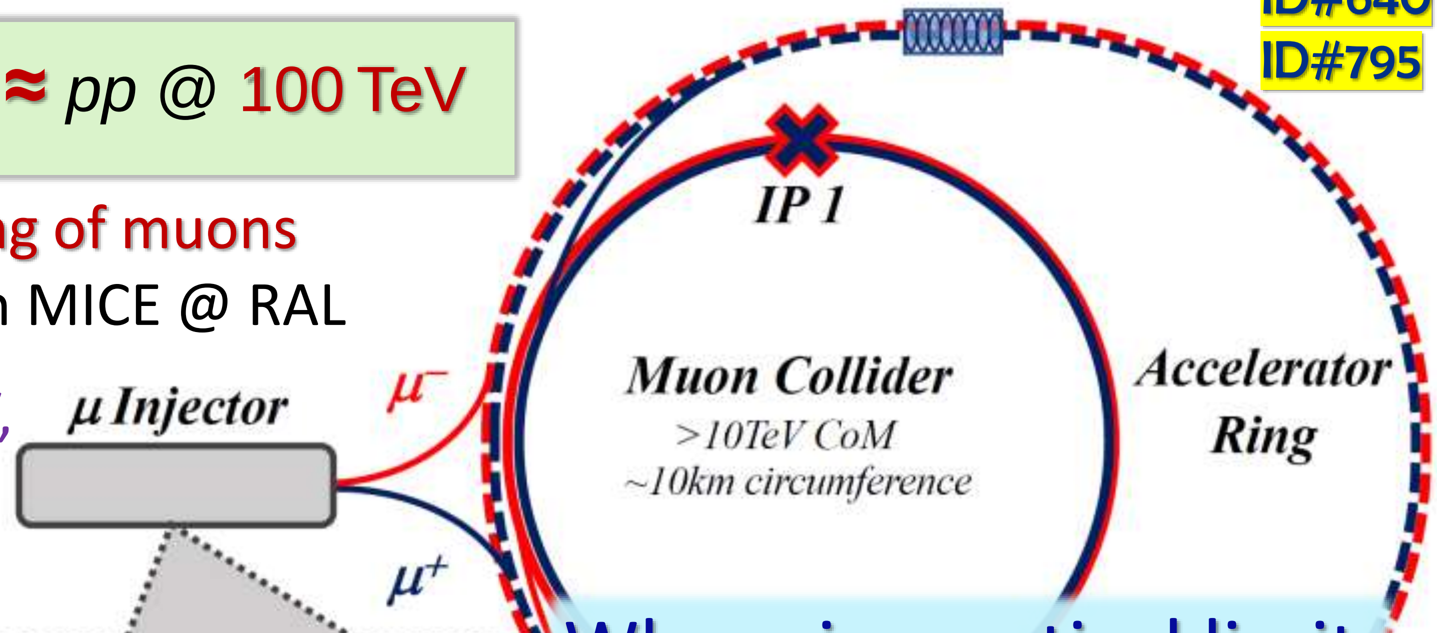
3-14 TeV Muon Colliders: Active R&D

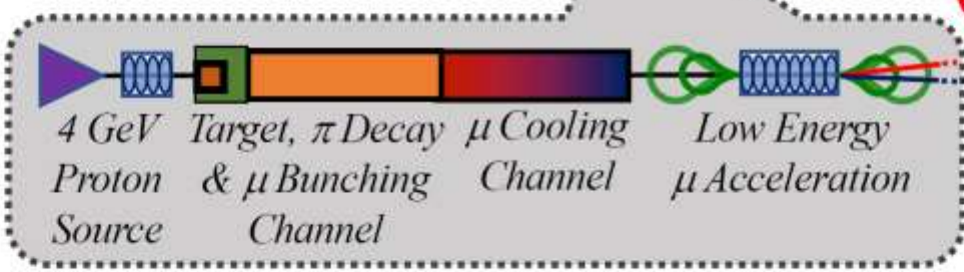
ID #53
ID#640
ID#795

μμ @ 14 TeV **≈** *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

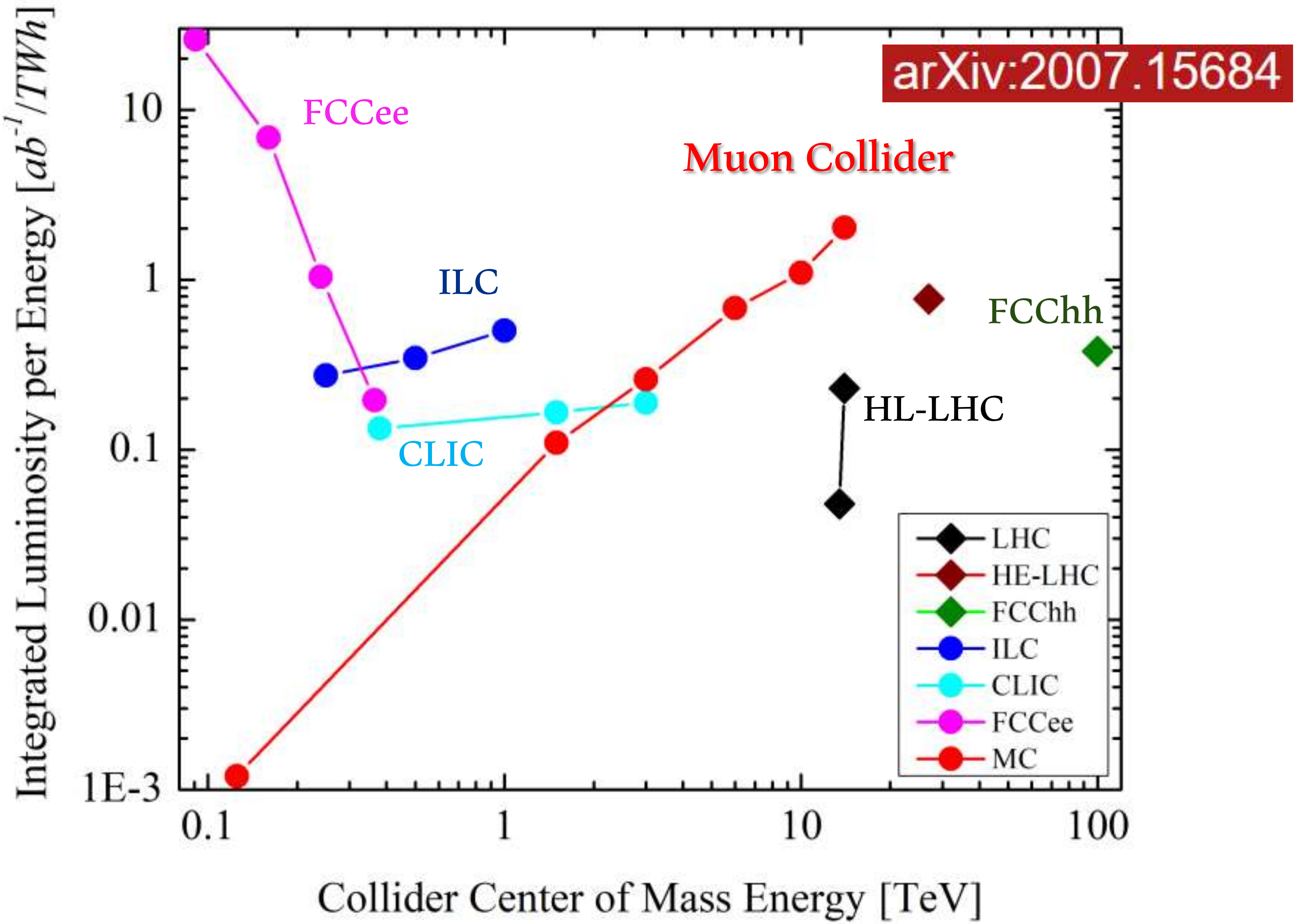
R&D required on: *μ production and cooling, fast acceleration (magnets, RF), MDI, large aperture 12 T magnets, ν-radiation*

Int'l MC-Collaboration – contact D.Schulte(CERN) :

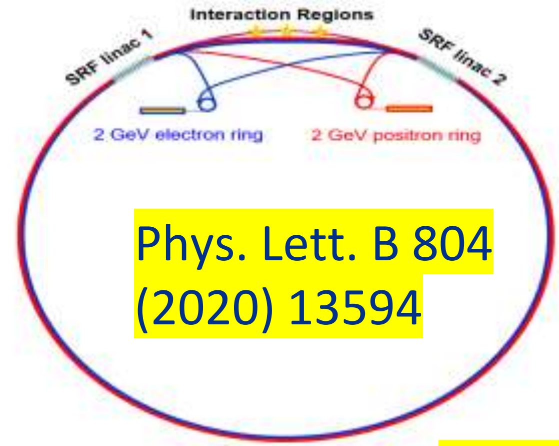
CDR in 4 yrs, test facility 6 yrs + 4 more years for TDR

K.Long, et. al, arXiv:2007.15684

Energy Efficiency of Future Colliders



New (Realistic) Ideas



Phys. Lett. B 804 (2020) 13594

Energy Recovery Linac (ERL) FCCee:

240 GeV, 100 km, 3-10x less RF power /ab^{-1}

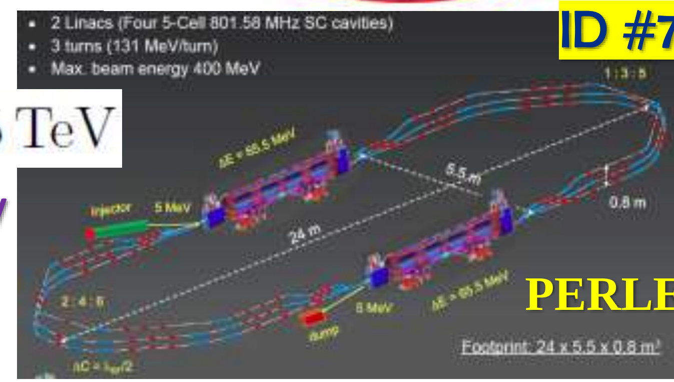
Challenges: emittances, beam-beam, 60 GeV SRF

ERL-based LHeC (or FCCeh):

60 GeV SRF, 6-9 km $\sqrt{s} = 1.3\,\mathrm{TeV}$ $\sqrt{s} = 3.5\,\mathrm{TeV}$

O(1ab^{-1}), 1.6 BCHF R&D: ERL PERLE@Orsay

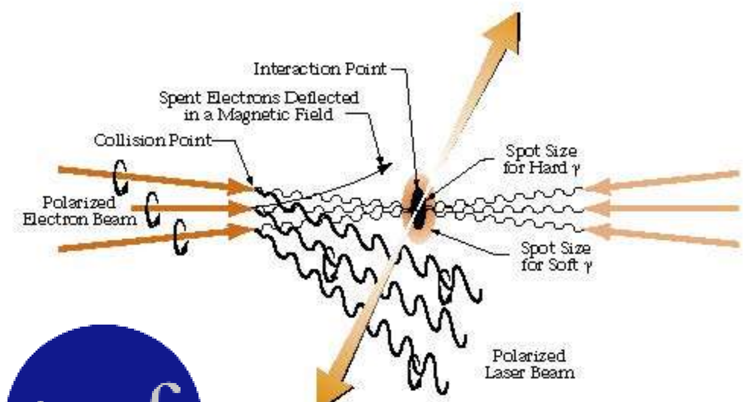
ID #729



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*

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

ID #1001 ID #105 ID #1037

Proof-of-principle over past 2 decades:

Three ways to excite plasma (drivers)

laser *dE* ~ 4.3 GeV (10^{18} cm^{-3} 9cm)

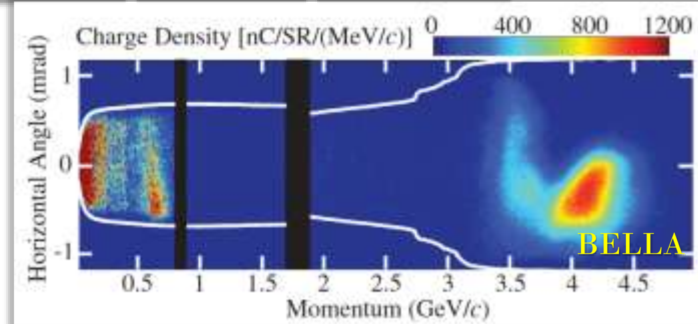
e- bunch *dE* ~ 9 GeV (~10^{17} cm^{-3} 1.3m)

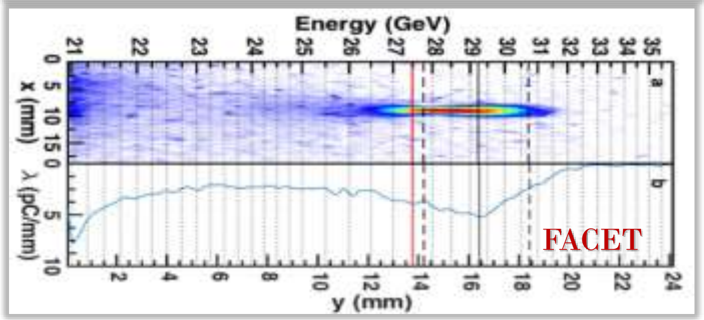
p+ bunch *dE* ~ 2 GeV (~10^{15} cm^{-3} 10m)

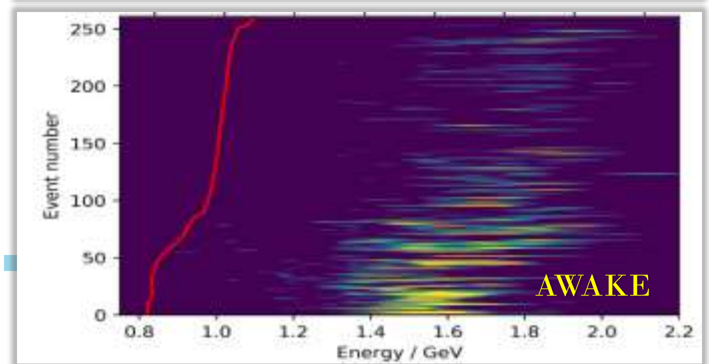
In principle, feasible for *e+e-* collisions, but too early to count – need more R&D:

- 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,…





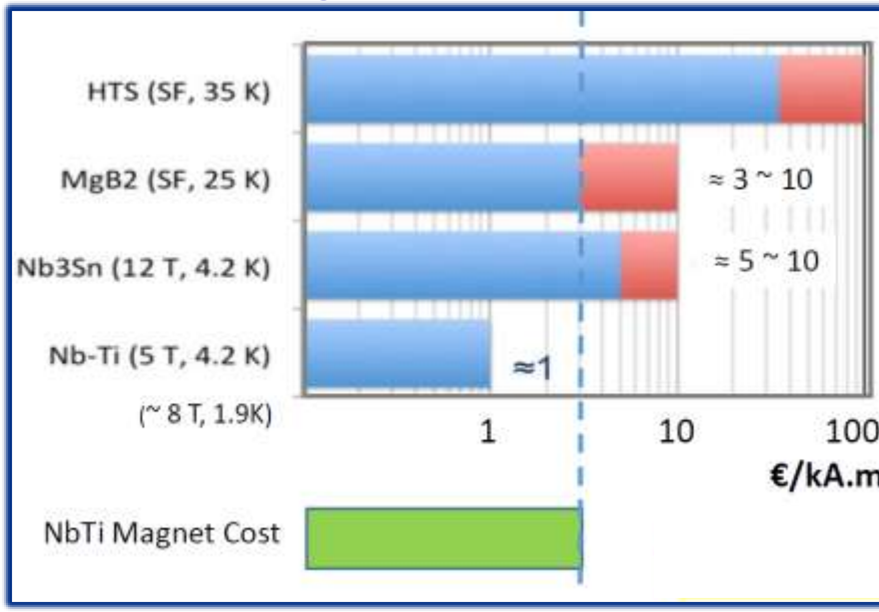


Project	TeV	Cost
ILC	0.25	4.8-5.3BILCU
	0.5	8.0 BILCU
	1	+(n/a)
CLIC	0.38	5.9 BCHF
	1.5	+ 5.1 BCHF
	3	+7.3 BCHF
CEPC	0.24	5 B USD
		+(n/a)
FCC-ee	0.24	10.5 BCHF
	0.35	+1.1 BCHF
LHeC	1.3	1.75* BCHF
HE-LHC	27	7.2 BCHF
FCC-hh	100	17(+7) BCHF
FCC-eh	3.5	1.75 BCHF
Muon Coll	14	10.7* BCHF

arXiv:2003.09084

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.Yamomoto, Granada)



- It takes time to reach the cost-performance goals:

Nb_3Sn, 12-14 T : 5-10 yrs short-model R&D

Nb_3Sn, 14-16 T : 10-15 yrs short-model R&D

following by ~10 yrs for prototype/pre-series

(A.Yamomoto, EPPSU, Granada 2019)

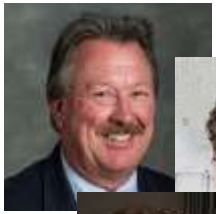
Acknowledgements

Input/useful discussions with:

Frank Zimmermann (CERN)

arXiv:2003.09084

"Modern and Future Colliders" (*RMP* review)




Steve Gourlay(LBNL)
Tor Raubenheimer (SLAC)
Dmitri Denisov (BNL)
Meenakshi Narain (UB)

SnowMass2021

Jorgen D'Hondt (ECFA)

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.Luccessi (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.Yamomoto (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/μμ*
- 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
SuperKEKB	Japan	7+4 Gev *e+e-*, 8e35	nano-beams scheme
HL-LHC	CERN	x5 LHC luminosity	Nb_3Sn magnets, crab cavities
NICA	Russia	*ii/pp* 11-27 GeV	electron and stochastic cooling
PIP-II	USA	SRF linac to double # ν's	CW SRF, >1 MW targetry
ESS	Sweden	5 MW pulsed SRF	SRF, cryo, targetry
LCLS-II-HE	USA	8 GeV CW SRF	efficient SRF, cryo
SuperC-Tau	Russia	2-6 GeV *e+e-*	crab waist scheme
EIC	USA	20-140 GeV *ep/ei*	polarization, cool'g

EPPSU and *Snowmass'21*


CERN-ESU-004
30 September 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

Electroweak Physics:

Strong Interactions:

Flavour Physics:

Neutrino Physics & Cosmic Messengers:

Beyond the Standard Model:

Dark Matter and Dark Sector:

Accelerator Science and Technology:

Instrumentation and Computing:

https://snowmass21.org/

SnowMass2021

Cost of the LHC

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

CERN-Brochure-2017-002-Eng

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.*