Future – Path to Very High Energies: Hadron/*e*+*e*-/Muon Colliders

Vladimir SHILTSEV (Fermilab)

CERN Council Open Symposium on the Update of European Strategy for Particle Physics

13-16 May 2019 - Granada, Spain

Accelerator Science and Technology :
major advances since the 2013 European Strategy

- Impressive technology progress (see Akira's talk) :
  - 11 T Nb_3Sn magnets for HL-LHC
  - 17 GeV of SRF European X-FEL and N_2 doping for Q_0 >10^{10}
- Expanded frontiers of beams :
  - Absolute* luminosity record 2.1e34 at the LHC (* repeat KEK-B '2009)
  - Record 760 kW *p*+ beam power on neutrino target at Fermilab
  - Super-KEKB built and being commissioned
- Beam physics breakthroughs :
  - Ionization cooling of muons demonstration MICE at RAL
  - *e*-lens compensation of *pp* head-on beam-beam effects in RHIC
  - Record beam-beam parameter 0.25 in VEPP2000 *e+e-* "round beams"
  - Bunched beam electron cooling in RHIC
  - Plasma acceleration records 2/4/9 GeV in AWAKE/BELLA/FACET
  - 40 nm beam focus attained at the ATF2 (ILC facility)

…from where we are now

I WILL ATTEMPT TO OVERVIEW

1. Higgs factory implementation options: accelerator physics and technology challenges, readiness, cost and power

2. Path towards the highest energies: how to achieve the ultimate energy and performance, R&D required

3. Promises, challenges and expectations of new acceleration techniques

Higgs Factories

- e+e- linear
  - –*ILC* Input #77
  - –*CLIC* Input #146
- e+e- circular
  - –*FCC-ee* Input #132
  - –*CepC* Input #51
- *μ+μ-* circular
  - –*μ-HF* Input #120

Requirement: high luminosity *O*(10^{34}) at the Higgs energy scale

Usually, compared to the LHC – which is, as a machine **:**

- 27 km long
- SC magnets (8T)
- 150 MW power total
- ~ 10 years to build
- Cost "1 LHC Unit" *

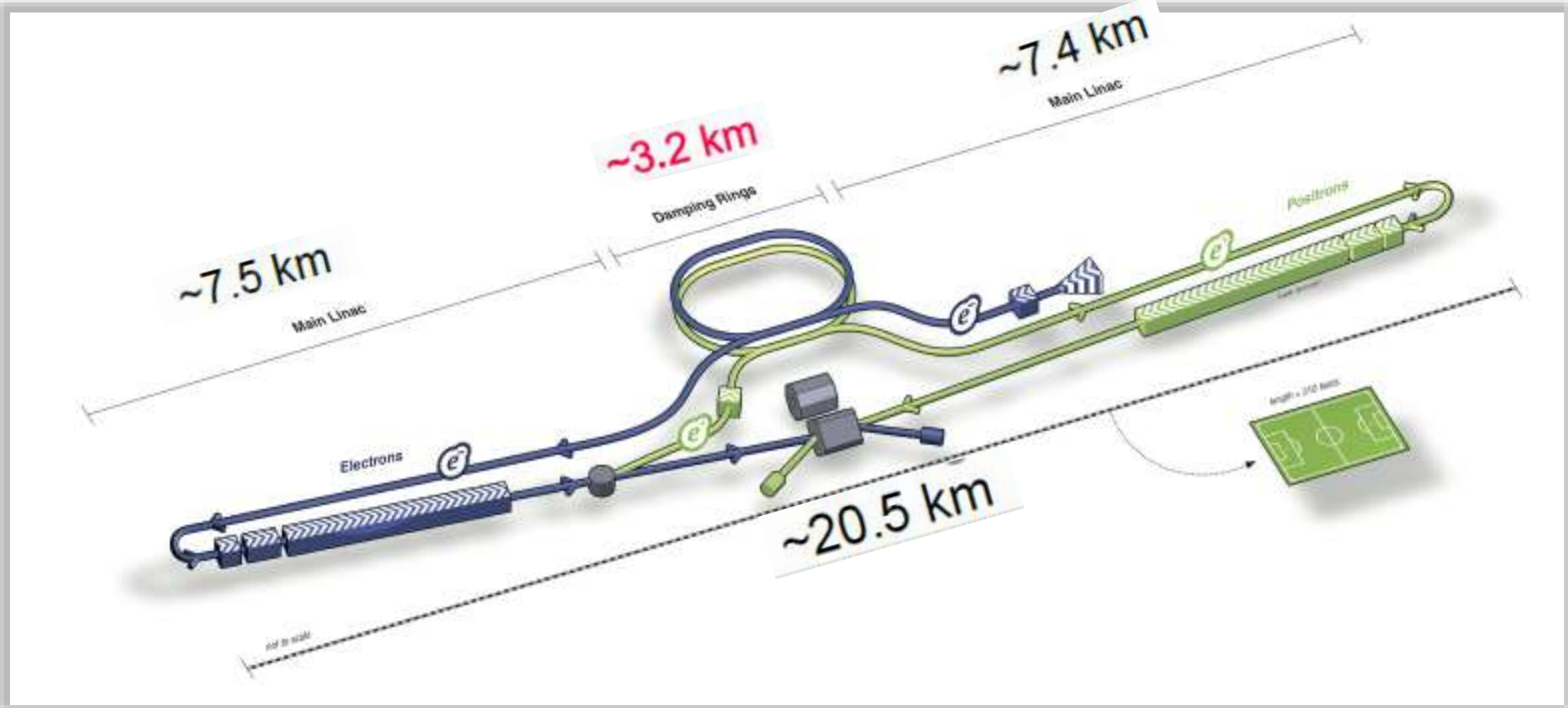
** as a project, i.e. w/o existing tunnel and injectors*

International Linear Collider

Input #66 Input #77

arXiv:1306.6328

TDR



Key facts:

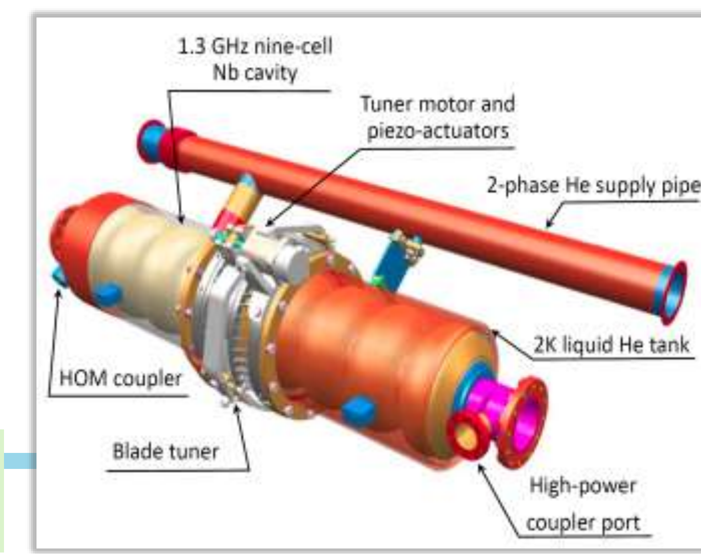
20 km, including 5 km of Final Focus

SRF 1.3 GHz, 31.5 MV/m, 2 K

130 MW site power @ 250 GeV c.m.e.

Cost estimate 700 B JPY*

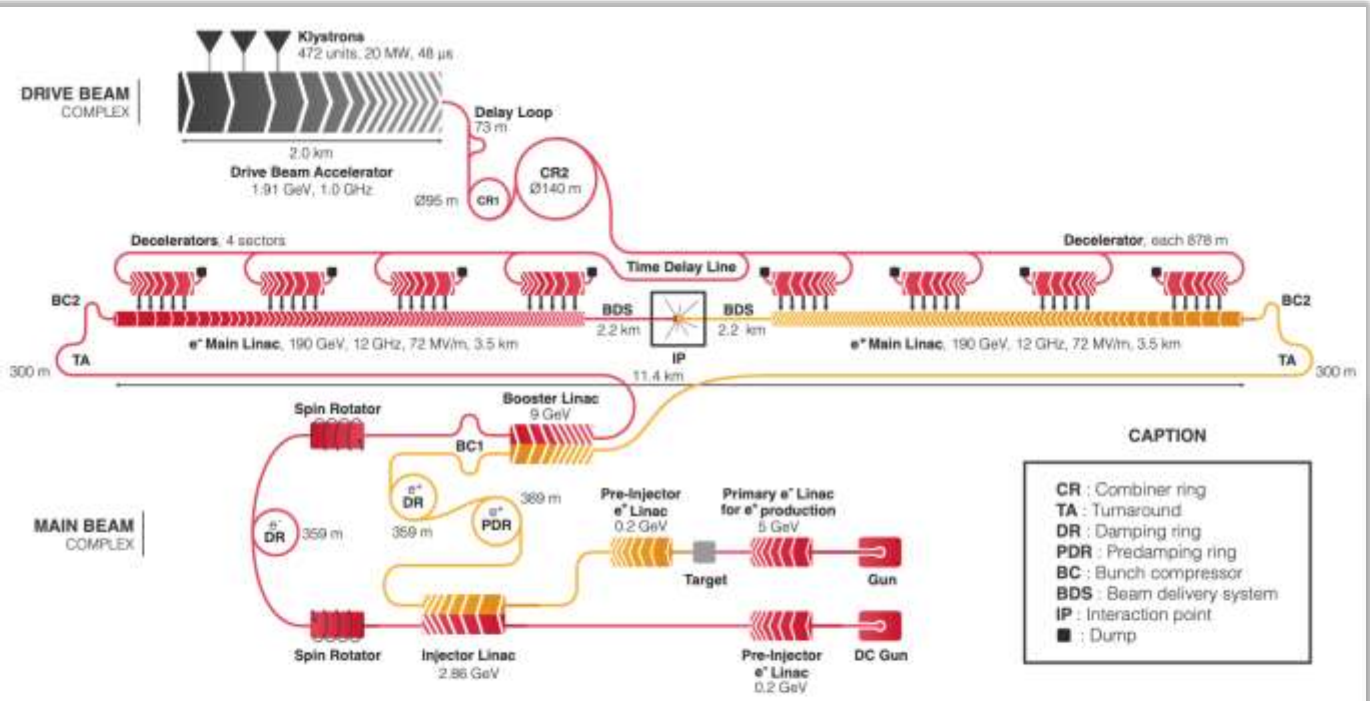
** ± 25% err, includes labor cost*

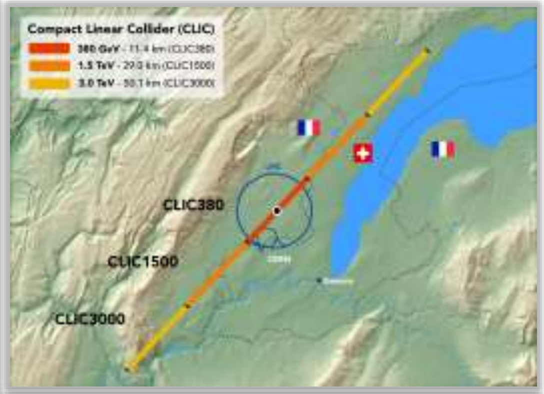


Compact LInear Collider

Input #146

arXiv:1209.2543 CDR





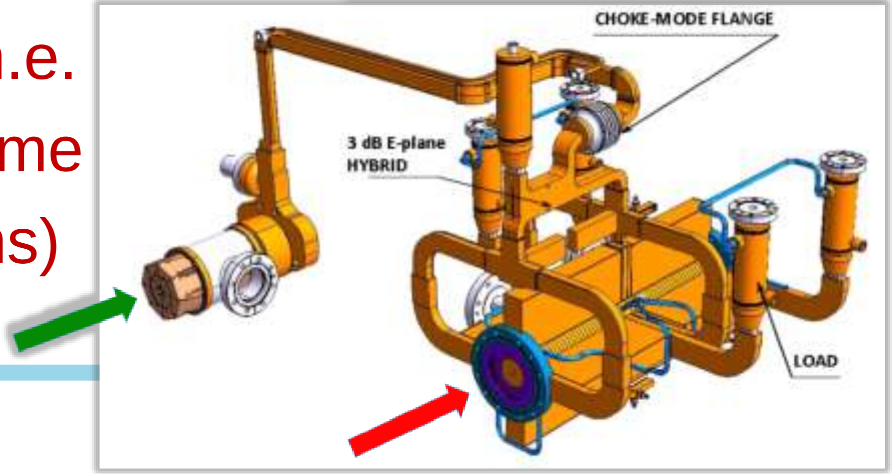
Key facts:

11 km main linac @ 380 GeV c.m.e.

NC RF 72 MV/m, two-beam scheme

168 MW site power (~9MW beams)

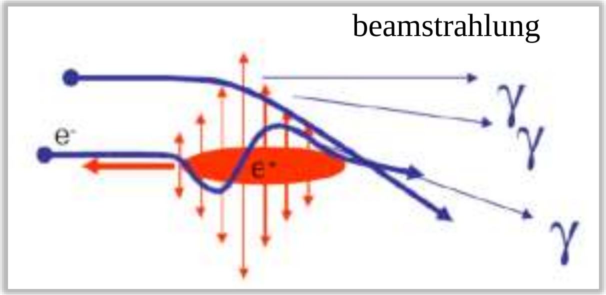
Cost est. 5.9 BCHF ± 25%



Challenges of Linear Colliders Higgs Factories

$$\mathcal{L} \propto H_D \frac{N}{\sigma_x} N n_b f_r \frac{1}{\sigma_y} \quad \sim 10^{34}$$

Luminosity Spectrum (Physics)



- $\delta E/E$ ~1.5% in ILC
- Grows with E: 40% of CLIC lumi 1% off $\sqrt{s}$

Beam Current (RF power limited, beam stability)

- Challenging *e+* production (two schemes)
- CLIC high-current drive beam bunched at 12 GHz (klystrons + 1.4 BCHF)

Beam Quality (Many systems)

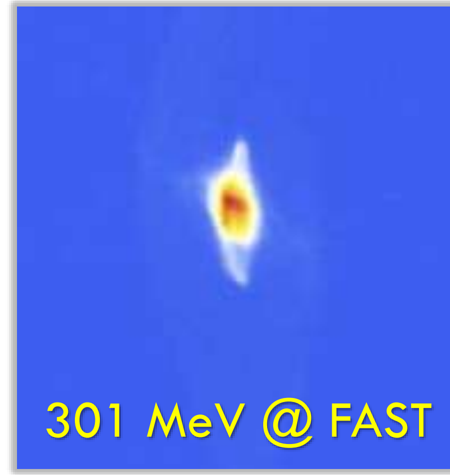
- Record small DR emittances
- 0.1 μm BPMs
- IP beam sizes

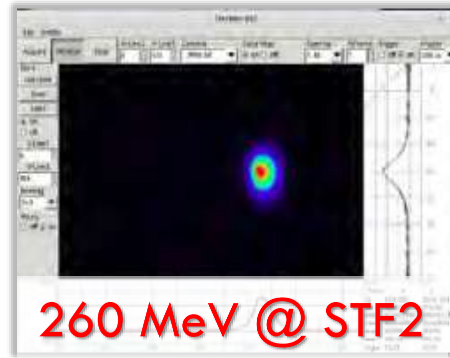
ILC 8nm/500nm

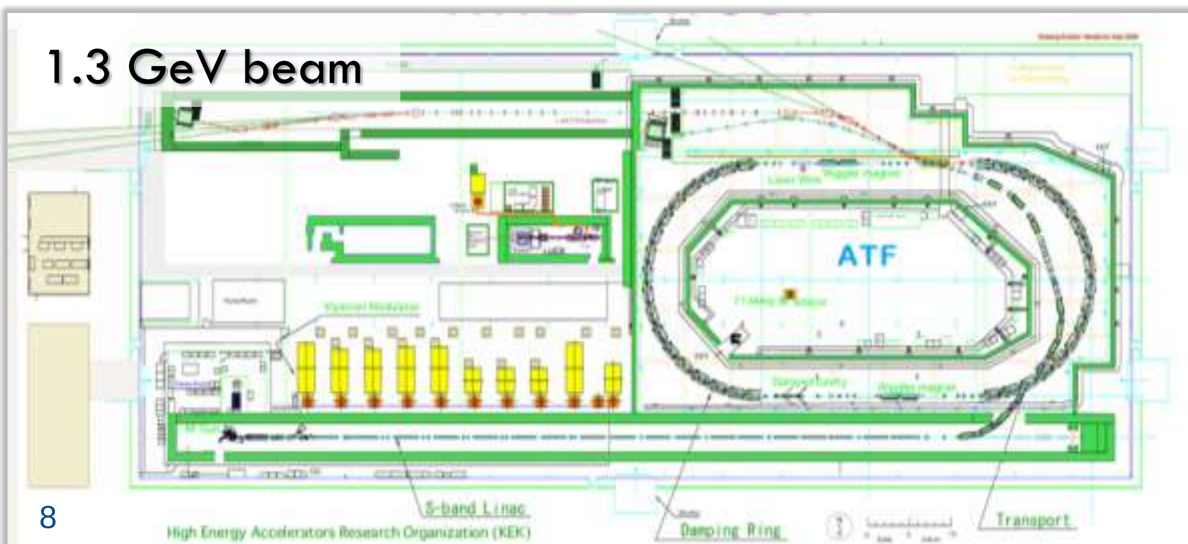
CLIC 3nm/150nm

Recent progress: Linear Colliders

- Accelerating gradients demonstrated with beams:
  - ILC 31.5 MeV/m – FNAL'17, KEK'19
  - CLIC ~100 MeV/m – CLEX@CERN
- Beam focusing
  - 40 nm V beam size ATF2@KEK'16







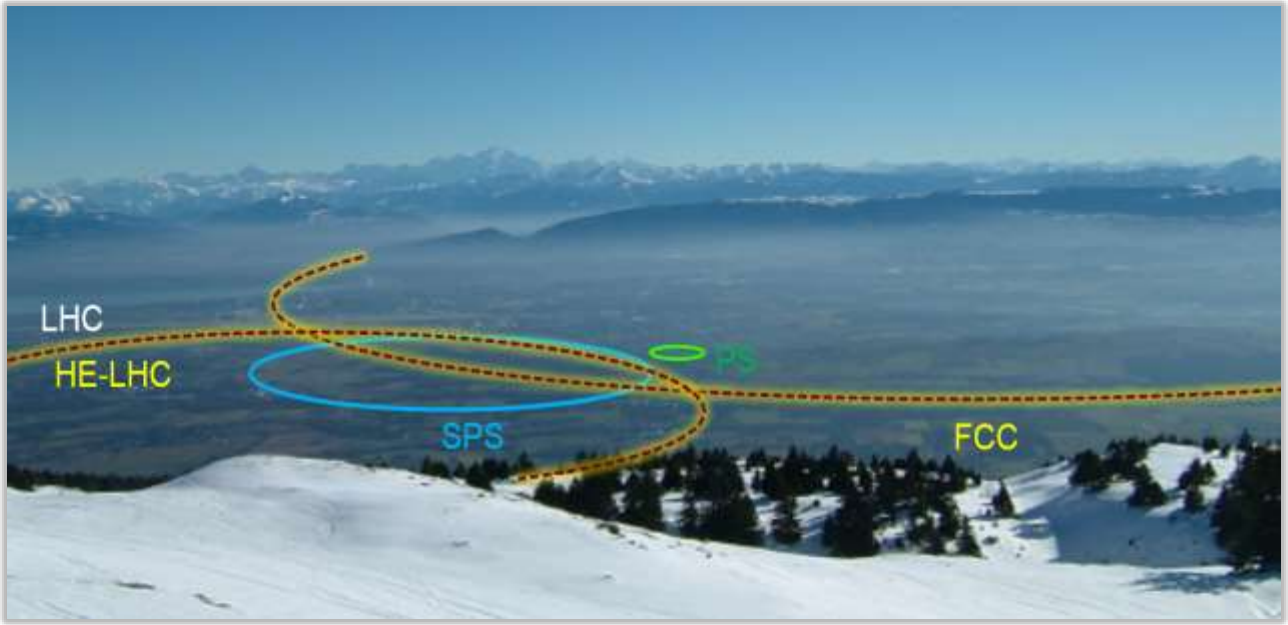
Linear Colliders *e+e-* Higgs Factories

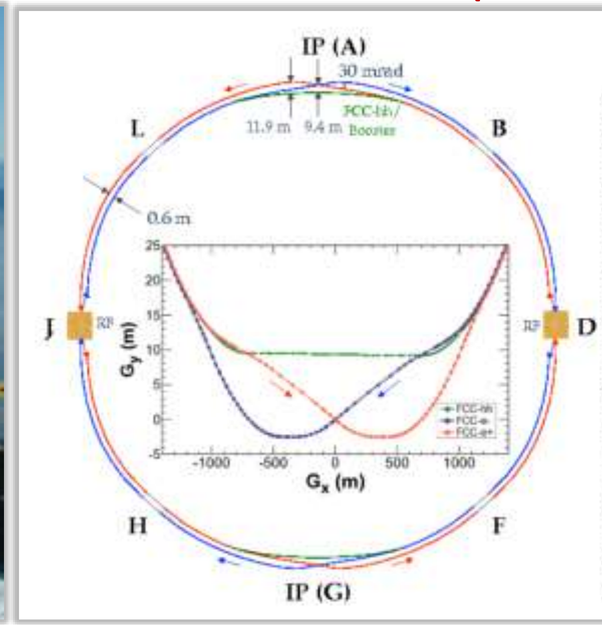
- *Advantages:*
  - Based on mature technology (Normal Conducting RF, SRF)
  - Mature designs: ILC TDR, CLIC CDR and test facilities
  - Polarization (ILC: 80%-30% ; CLIC 80% - 0%)
  - Expandable to higher energies (ILC to 0.5 and 1 TeV, CLIC to 3 TeV)
  - Well-organized international collaboration (LCC) → "we're ready"
  - Wall plug power ~130-170 MW (i.e. <= LHC)
- *Pay attention to:*
  - Cost more than LHC ~(1-1.5) LHC
  - LC luminosity < ring (e.g., FCC-ee), upgrades at the cost:
    - e.g. factor of 4 for ILC: *x2* $N_{bunches}$ and *5 Hz → 10 Hz*
  - Limited LC experience (SLC), two-beam scheme (CLIC) is novel, klystron option as backup
  - Wall plug power may grow >LHC for *lumi* / E upgrades

Circular e+e- Higgs Factories

Input #132

FCC-ee CDR (2018)





Key facts:

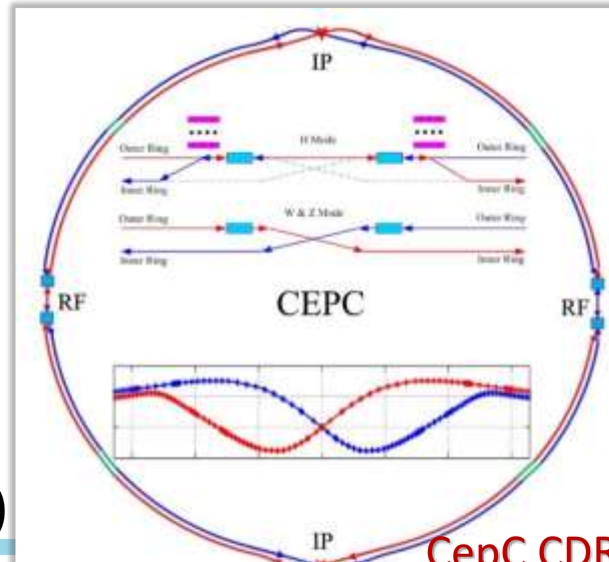
100 km tunnel, three rings (*e-*, *e+*, booster)

SRF power to beams 100 MW (60 MW in CepC)

Total site power <300MW (tbd)

Cost est. *FCCee* 10.5 BCHF (+1.1BCHF for tt)

("< 6BCHF" cited in the *CepC CDR*)



CepC CDR

Input #51 arXiv:1809.00285

Challenges of e+e- Ring HF's

- Power limited regime. Synchrotron radiation power from both beams limited to 100 MW (*P/η*=total cite power) → current *I* is set by power

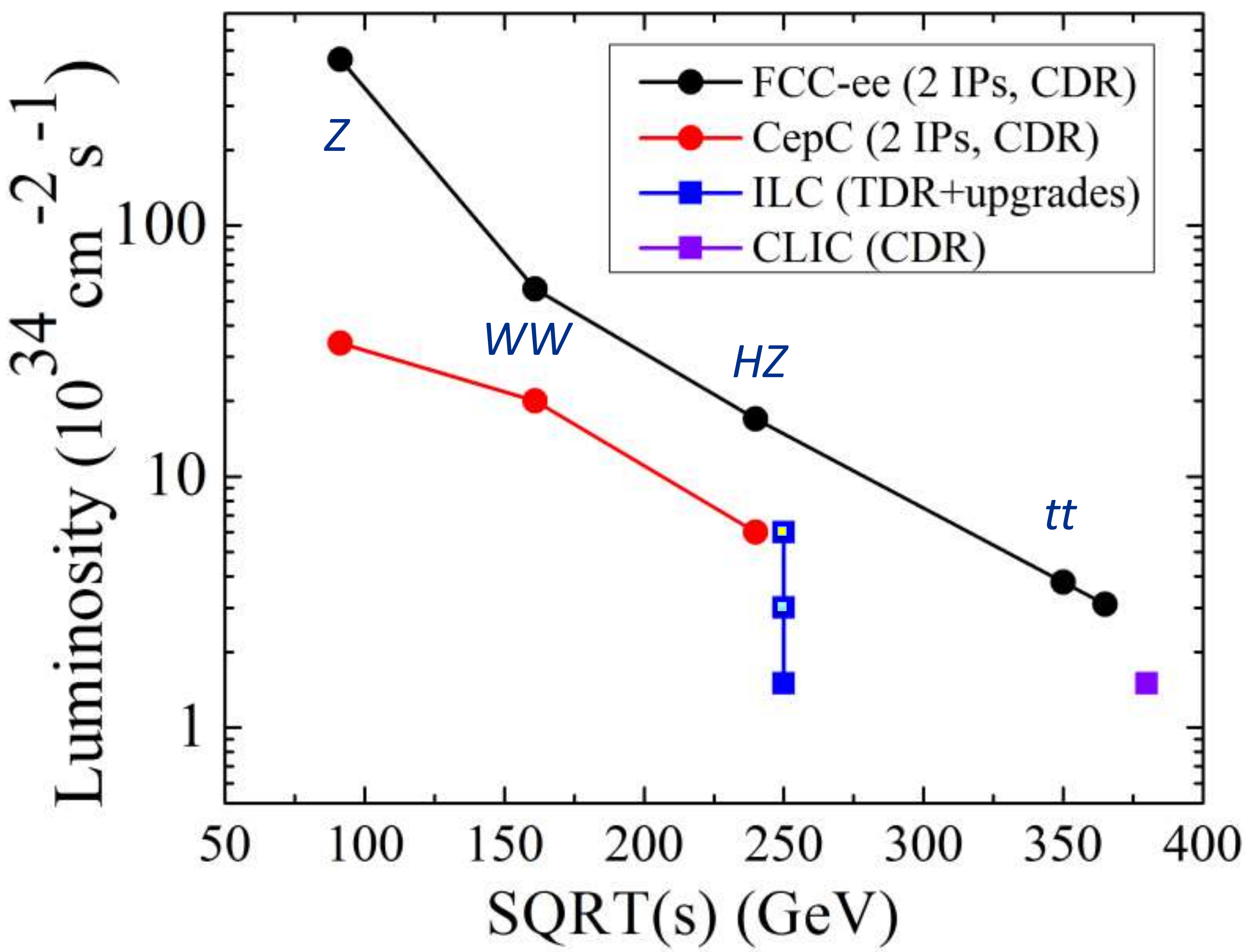
$$I = \frac{e\rho}{2C_\gamma E^4} P_T,$$

- Luminosity determined by bend radius ρ, beam-beam parameter ξ_y, beta function at the IP β_y* and power

$$\mathscr{L}\gamma^3 = \frac{3}{16\pi r_e^2 (m_e c^2)} \left[\rho \frac{\xi_y P_T}{\beta_y^*} H(\beta_y^*, \sigma_z)\right]$$

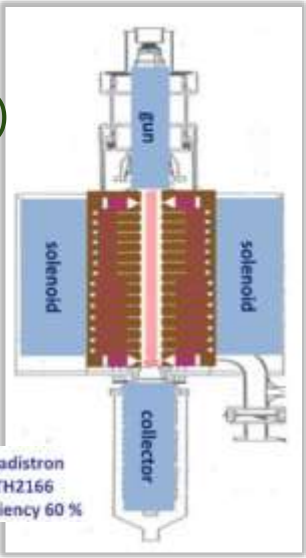
  - ξ_y =0.13 new beam-beam instability; while synchrotron radiation $\Delta E_{turn}/E$ ~ 0.1-5% per turn *Z* to 360 GeV, the beam-strahlung is at IPs only and spreads $\delta E/E$ ~0.1-0.2% , but tails upto 10x that ±2.5% determine 18 min beam lifetime ~18 min → need large acceptance optics β_y* = 0.8-1.6 mm, crab-waist scheme and full energy booster

e+e- Higgs Factories: Circular vs Linear



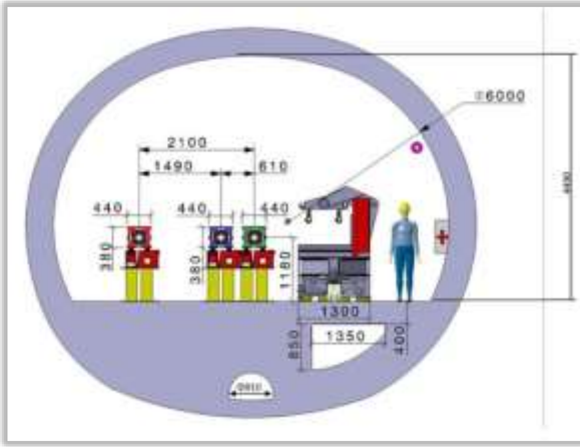
e+e- Ring Higgs Factories

- ***Advantages:***
  - Based on mature technology (SRF) and rich experience → lower risk
  - High(er) luminosity and ratio luminosity/cost; upto 4 IPs, EW factories
  - 100 km tunnel can be reused for a *pp collider* in the future
  - Transverse polarization (τ~ 18 min at *tt*) for ***E*** calibration *O*(100keV)
  - CDRs addressed key design points, mb ready for ca 2039 start
  - Very strong and broad *Global FCC Collaboration*



Strategic R&D ahead :

- High efficient RF sources:
  - Klystron 400/800 MHz η from 65% to >85%
- High efficiency SRF cavities:
  - 10-20 MV/m and high Q_0; Nb-on-Cu, Nb_3Sn
- Crab-waist collision scheme:
  - *Super KEK-B* nanobeams experience will help
- Energy Storage and Release R&D:
  - Magnet energy re-use > 20,000 cycles
- Efficient Use of Excavated Materials:
  - 10 million cu.m. out of 100 km tunnel

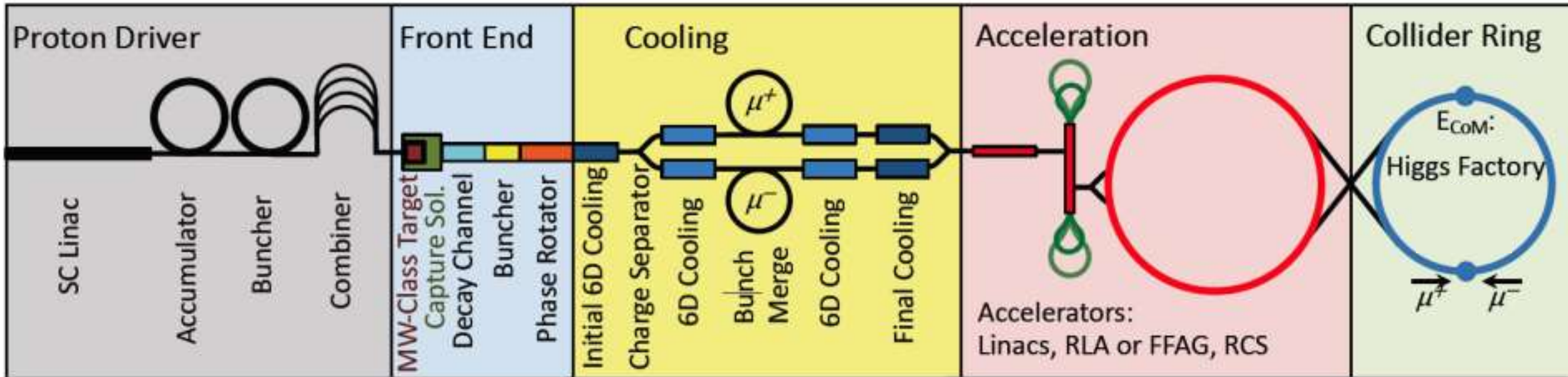


$\mu+\mu-$ Higgs Factory

Input #41 Input #120 Input #141

V. Barger, et al, *Physics Reports* 286, 1-51 (1997)

JINST Special Issue (*MUON*)



Key facts:

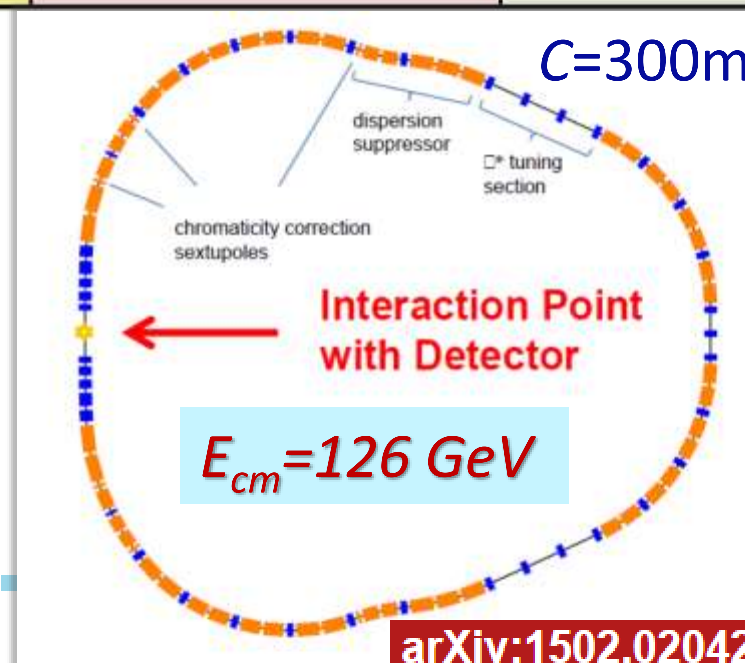
1/100 luminosity requirements (large cross-section in ***s***-channel)

Half the energy 2 x 63 GeV $\mu+\mu- \rightarrow H_0$

Small footprint (<10 km) and low cost

Small(est) energy spread ~3 MeV

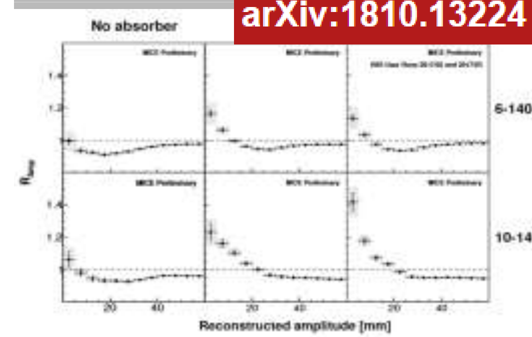
Total site power ~200MW (tbd)

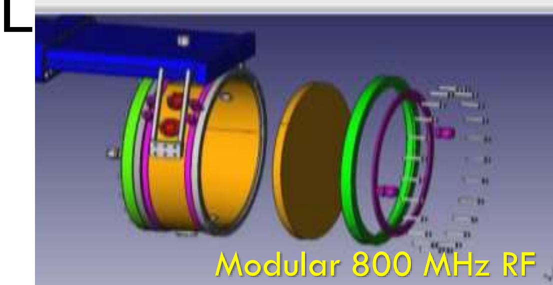


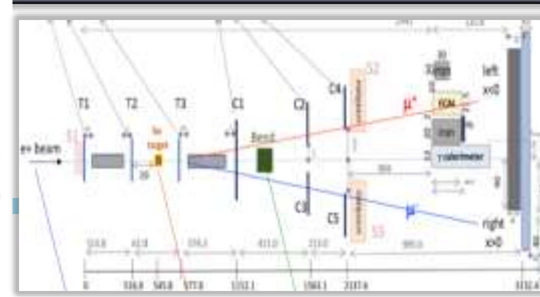
arXiv:1502.02042

Recent progress: *μ+μ- Colliders*

- Ionization cooling of muons:
  - Demonstrated in MICE @ RAL
  - 4D emittance change *O*(10%)
- NC RF 50 MV/m in 3 T field
  - Developed and tested at Fermilab
- Rapid cycling HTS magnets
  - Record 12 T/s – built and tested at FNAL
- First RF acceleration of muons
  - J-PARC MUSE RFQ 90 KeV
- US MAP Collaboration → Int'l
- Low emittance (no cool) concept
  - 45 GeV $e^+ + e^- \rightarrow \mu^+\mu^-$: CERN fixed target







Future Energy Frontier Colliders

- All proposals are focused on :
  - *(Affordable) Cost and (High) Luminosity*
- Usually :
  - *Scale of civil construction grows with Energy*
  - *Cost of accelerator components grows with Energy*
  - *Requirement site power grows with Energy*
- So, the total cost grows with ENERGY
  - Thankfully, not linearly , more like $cost \sim \beta E^{\kappa}$, $\kappa \approx$ ½…2/3
    - *Take ILC as an example: 0.25 → 0.5 → 1 TeV* **0.69 : 1 : 1.67**
  - Still, huge challenge for energies ***E*** some x10 of LHC
  - Choice of technology (β) and *prior investments* are critical

Fermilab

let's consider
Limits of Linear *e+e-* Colliders

- Both ILC and CLIC offer staged approach to ultimate E

- The limits are set by:

  Cost

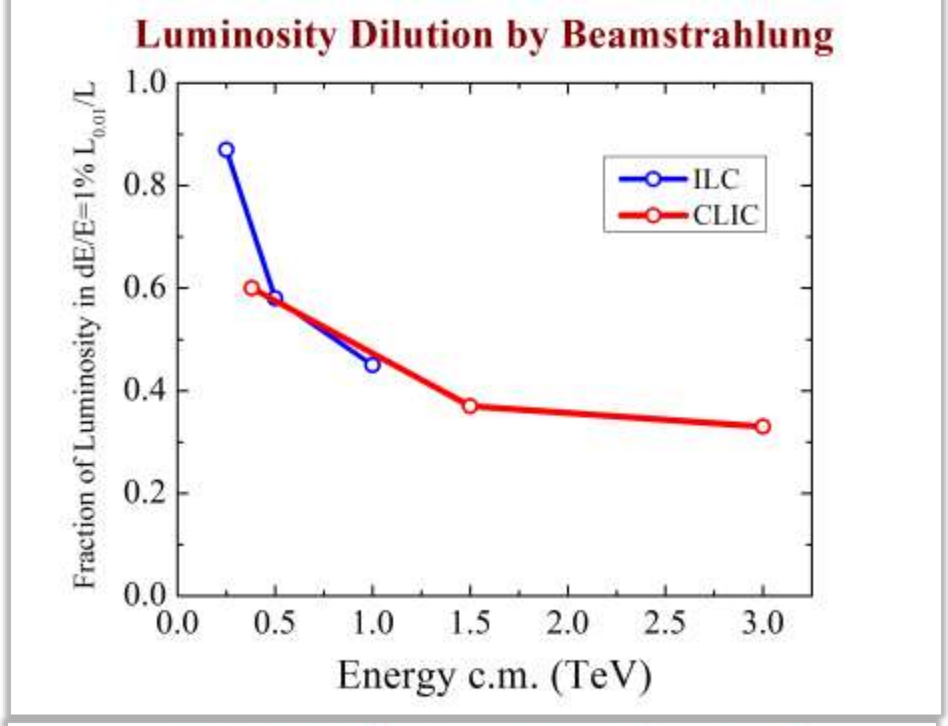
  Electric power required

  Total length

  (complication of) Beamstrahlung

ILC TDR 1 TeV 17 B$ ±25%

CLIC CDR 3 TeV 18.3BCHF ±25%

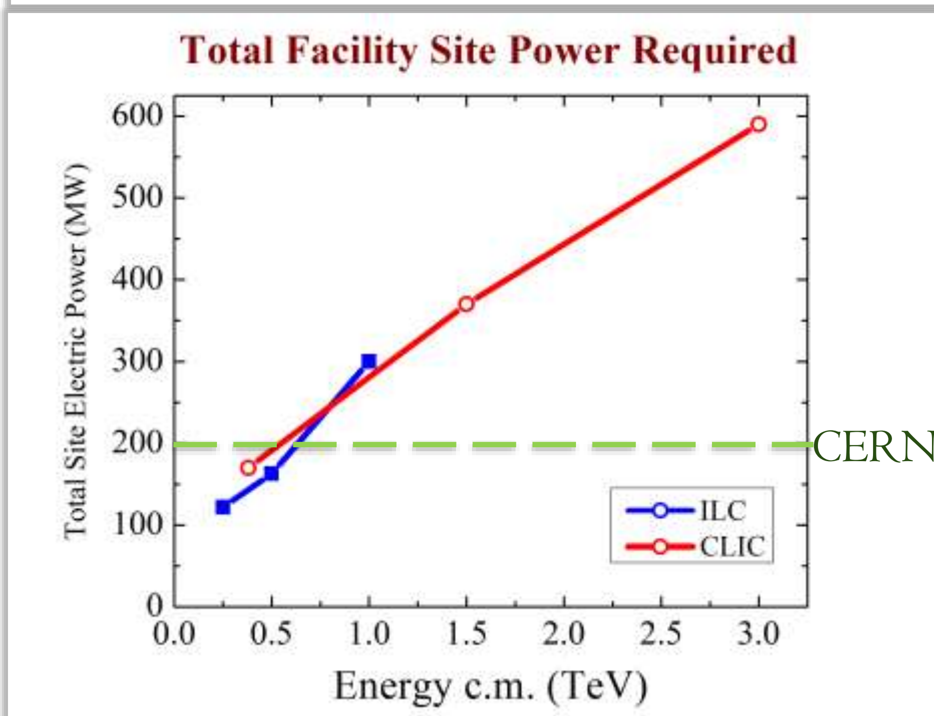


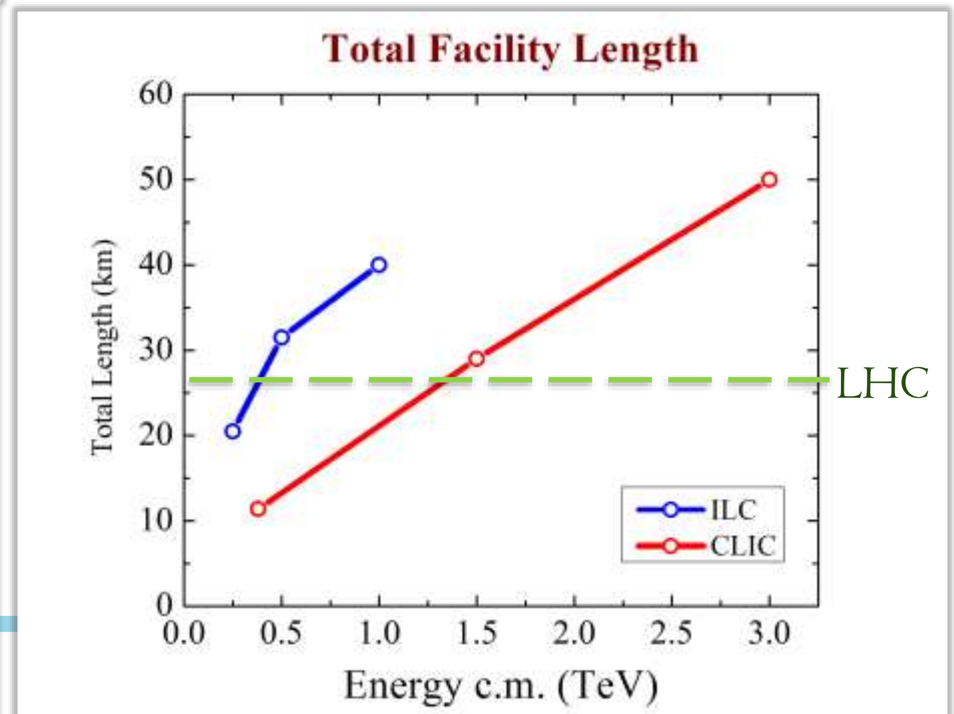
Beamstrahlung rms energy spread :

$$\delta_{BS} \propto \left(\frac{E_{cm}}{\sigma_z}\right)\frac{N^2}{\sigma_x^2}$$

→ Luminosity :

$$L \propto P_{beam}\sqrt{\frac{\delta}{\gamma\varepsilon_y}}H_D$$

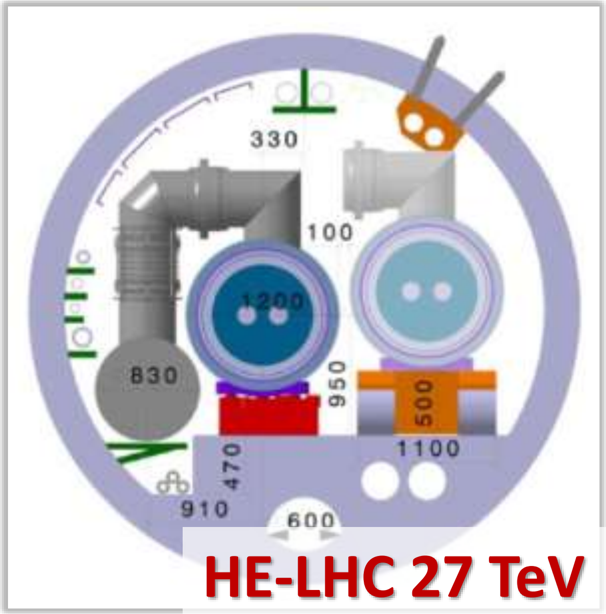


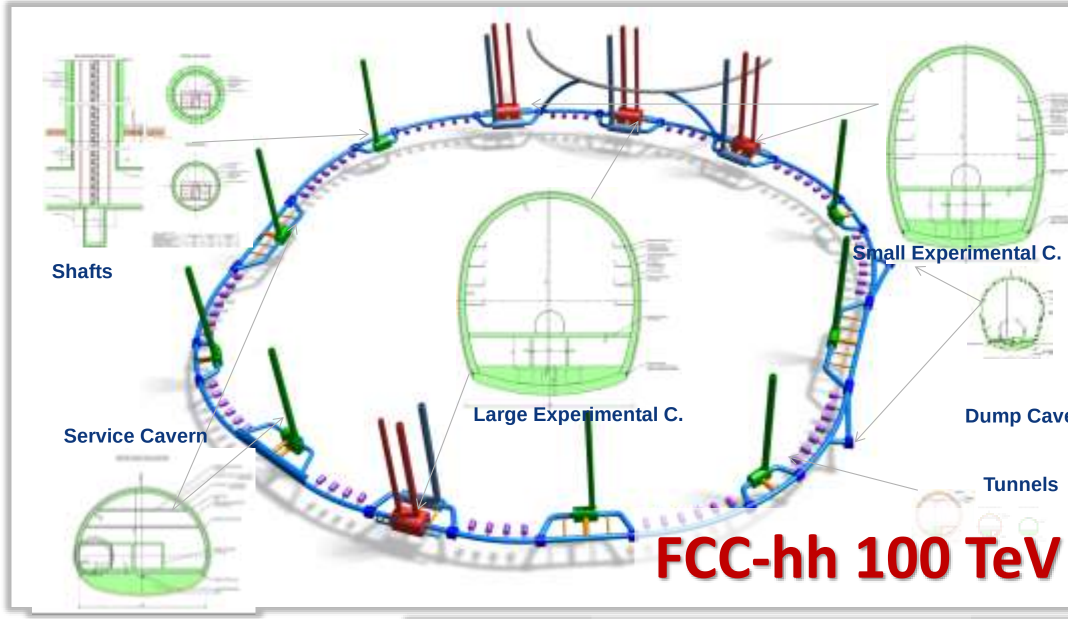


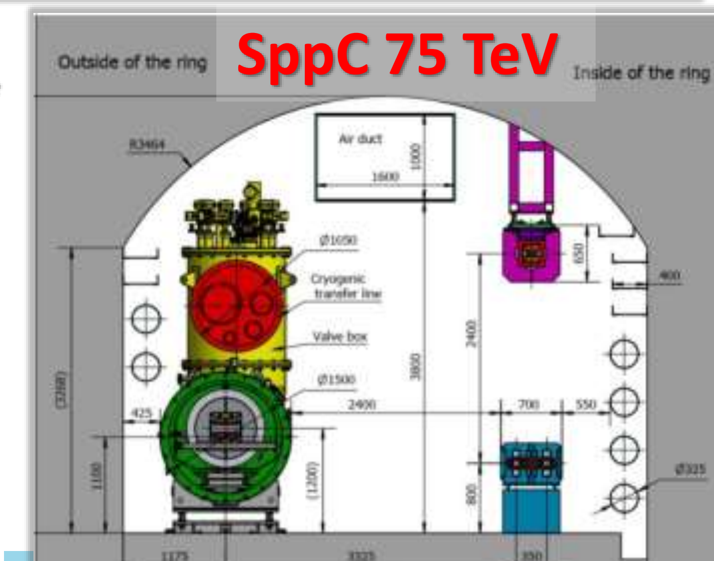
Circular *pp* Colliders

Input #133 Input #136

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







Input #51 arXiv:1809.00285

Key facts: *HE-LHC / FCC-hh* / SppC**

Large tunnel – 27 / 100 / 100 km

SC magnets – 16 / 16 / 12 T

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

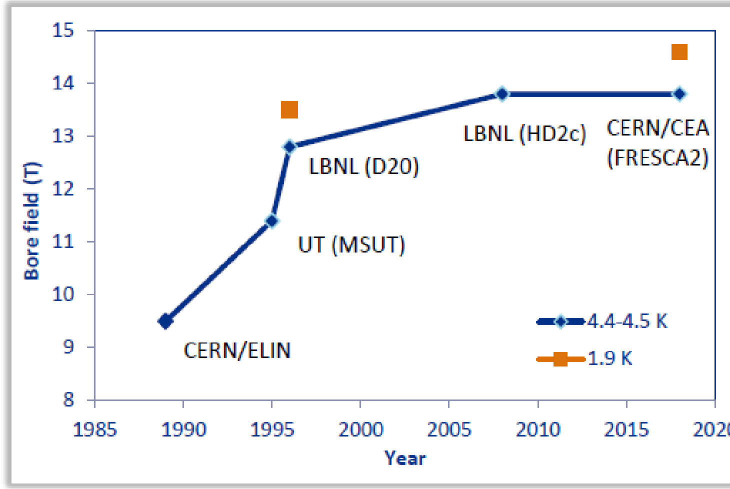
Site power (MW) – 200 / 500? / ?

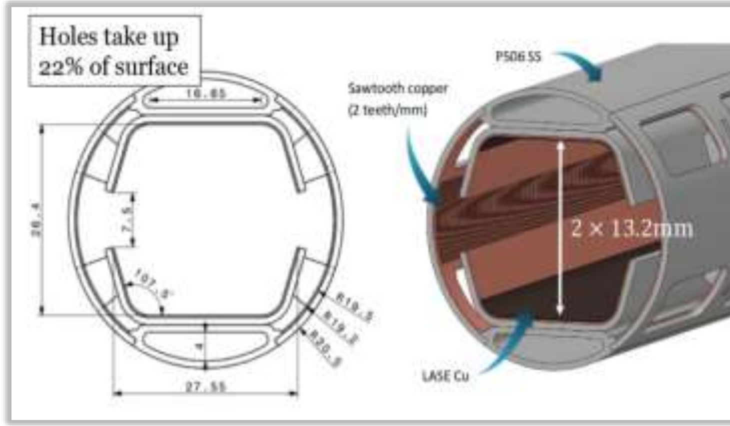
Cost (BCHF) – 7.2 / 17.1 / ?

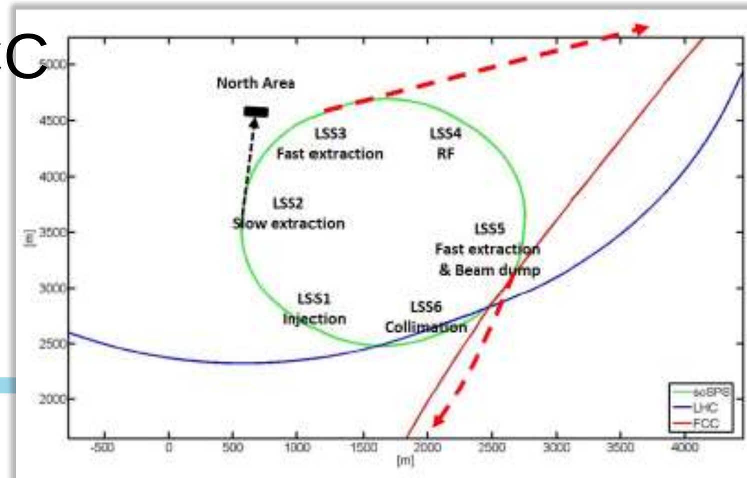
** follow up after e+e- Higgs factories*

Strategic R&D Ahead :

- High field dipoles:
  - Nb3Sn 16 T / iron-based 12 T, wire
  - (see also Akira's talk)
- 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

Unique opportunities :

- *ion-ion* collisions **Input #056**
- *ep/ei* collisions **Input #159**
  - *~60 GeV e- Energy Recovery Linac*

Key facts: *LHeC / FCC-eh*

6-9 km tunnel

Energy LHeC $\sqrt{s} = 1.3\,\mathrm{TeV}$

FCC-eh $\sqrt{s} = 3.5\,\mathrm{TeV}$

SRF 800 MHz CW

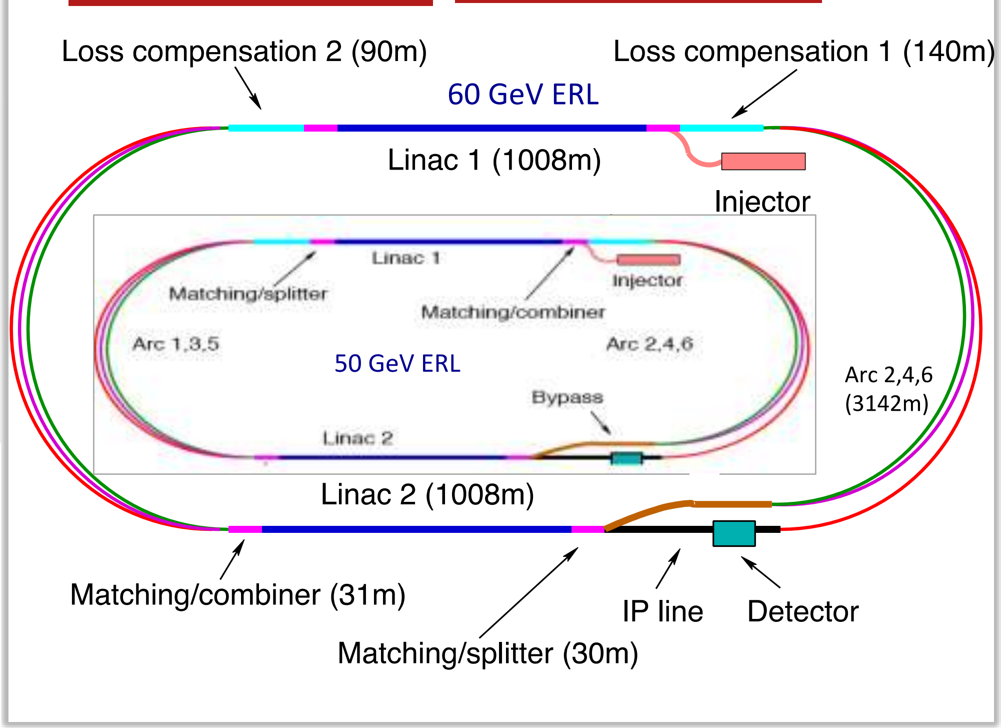
Luminosity $O(10^{34})$

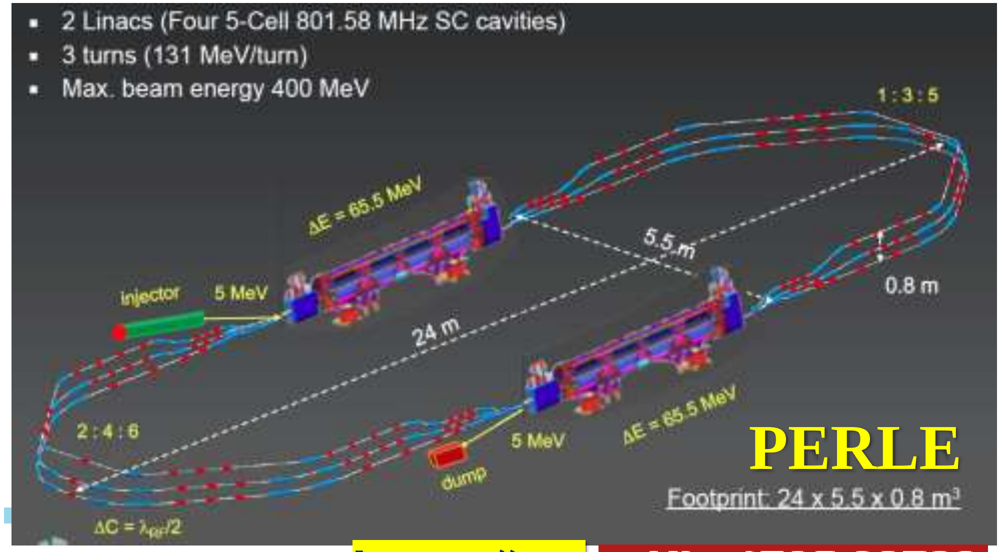
Site power ~100 MW

Cost ~1.3-1.6 BCHF *

Key R&D: PERLE @ Orsay →

arXiv:1810.13022 arXiv:1206.2913 CDR





Input #147 arXiv:1705.08783

High Energy $\mu+\mu-$ Colliders

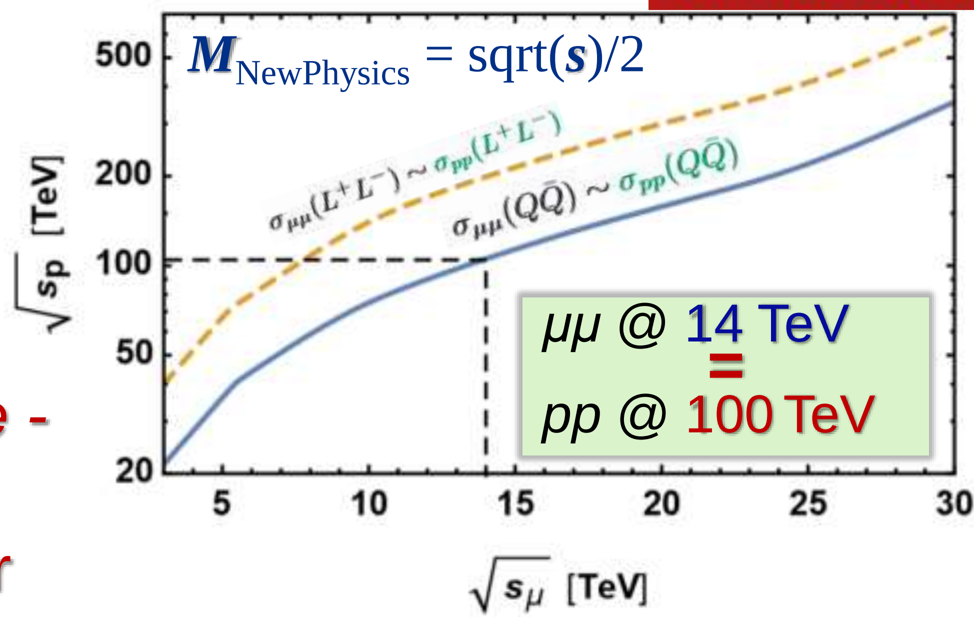
Input #120

JINST Special Issue (*MUON*)

arXiv:1901.06150

Advantages:

- ***μ***'s do not radiate / no beamstrahlung→ acceleration in rings → *low cost & great power efficiency*
- ~ *x7* energy reach vs *pp*



Offer *"moderately conservative - moderately innovative"* path **to cost affordable** energy frontier colliders:

- US MAP feasibility studies were very successful → MCs can be built with present day SC magnets and RF; there is a well-defined path forward
- ZDRs exist for 1.5 TeV, 3 TeV, 6 TeV and 14 TeV * in the LHC tunnel

** more like "strawman" parameter table*

Key to success:

- Test facility to demonstrate performance implications - muon production and 6D cooling, study LEMMA e^+-45 GeV + e^- at rest → μ^+-μ^- , design study of acceleration, detector background and neutrino radiation

Finding *Common Denominators* * – Three Factors

** to be further discussed in the Symposium's accelerator sessions*

- ***F1*** **"Technology Readiness" :**

Green	-	TDR
Yellow	-	CDR
Red	-	R&D

- ***F2*** **"Energy Efficiency"**

Green	:	100-200 MW
Yellow	:	200-400 MW
Red	:	> 400 MW

- ***F3*** **"Cost" :**

Green	:	< LHC
Yellow	:	1-2 x LHC
Red	:	> 2x LHC

Higgs Factories	Readiness	Power-Eff.	Cost
ee Linear *250 GeV*			
ee Rings *240GeV/tt*			
μμ Collider *125 GeV*			*
Highest Energy			
ee Linear *1-3TeV*			
pp Rings *HE-LHC*			
FCC-hh/SppC			
μμ Coll. *3-14 TeV*			*

7-10 YEARS FROM NOW
WITH PROPOSED ACTIONS / R&D DONE / TECHNICALLY LIMITED

- ***ILC:***
  - Some change in cost (~6-10%)
  - All agreements by 2024, then
  - **Construction** (2024-2033)
- ***CLIC:***
  - TDR & preconstr. ~2020-26
  - **Construction** (2026-2032)
  - 2 yrs of commissioning
- ***CepC:***
  - Some change in cost & power
  - TDR and R&D (2018-2022)
  - **Construction** (2022-2030)
- ***FCC-ee:***
  - Some change in cost & power
  - **Preparations** 2020-2029
  - Construction 2029-2039
- ***HE-LHC:***
  - **R&D and prepar'ns** 2020-2035
  - Construction 2036-2042
- ***FCC-hh*** (w/o FCC-ee stage)***:***
  - **16T magnet prototype** 2027
  - Construction 2029-2043
- ***μ^+-μ^- Collider :***
  - **CDR completed** 2027, cost known
  - Test facility constructed 2024-27
  - Tests and TDR 2028-2035

ALTERNATIVE ACCELERATION TECHNIQUES

promise, status and challenges

Plasma Wakefield Accelerators

Input #7 Input #109
Input #58 Input #95

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

Key facts:

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)

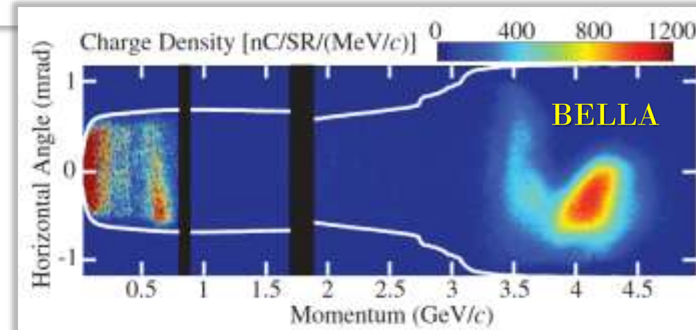
p+ bunch *dE* ~ 2 GeV (~10^{15} cm^{-3} 10m)

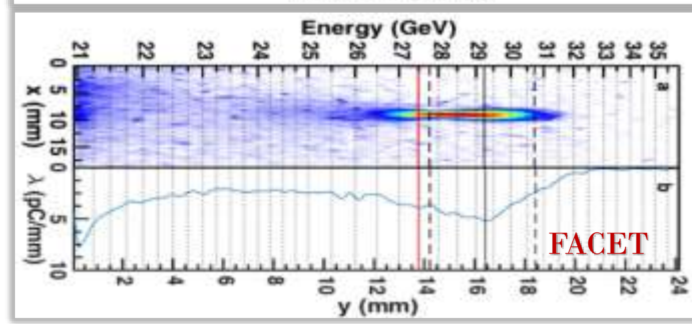
Impressive proof-of-principle demos

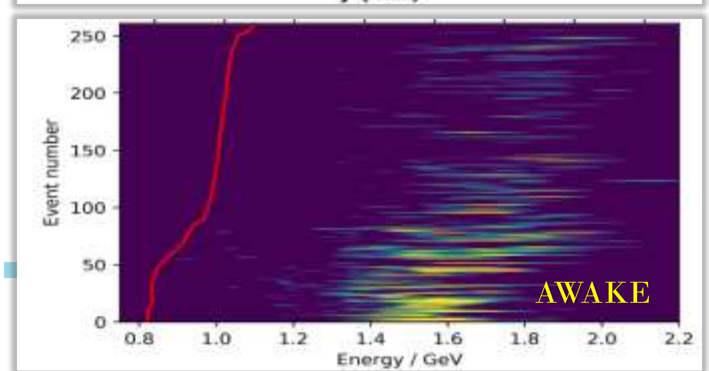
In principle, feasible for *e+e-* collisions

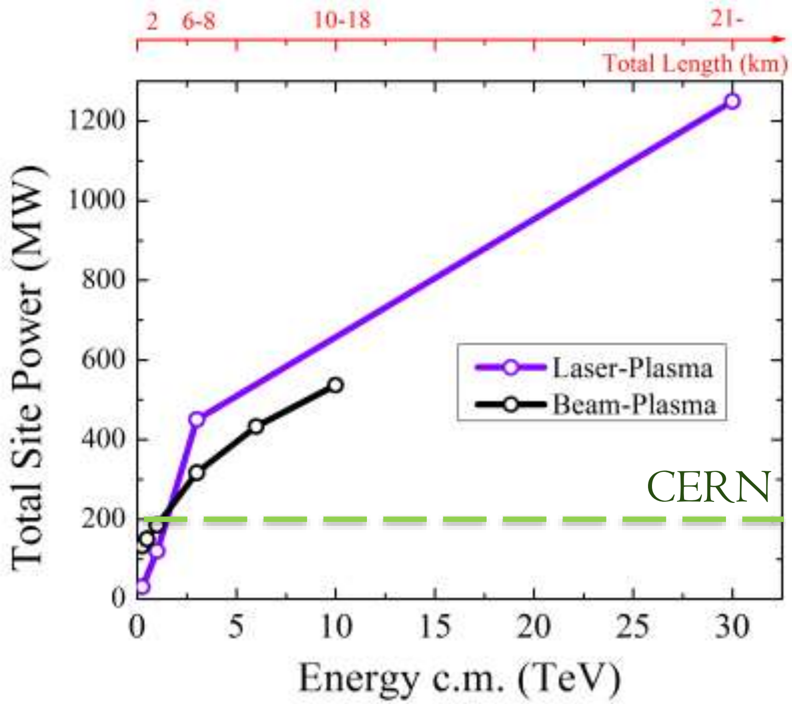
Collider cost and power will greatly depend on the driver technology:

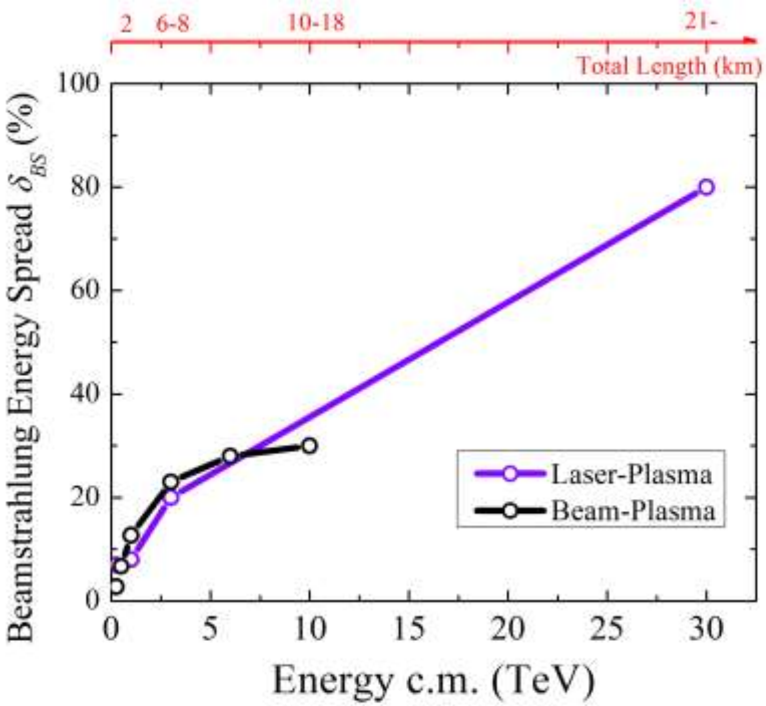
- lasers, super-beams of electrons or protons











Input #7

arXiv:1308.1145

Plasma Colliders :

- Key Issues to Study:
  - acceleration of positrons
  - Staging efficiency
  - emittance control vs scatter
  - beamstrahlung
  - HP lasers / HP operation
  - power efficiency

  * the first four can be addressed by using μ's in 10^{22} cm^{-3} crystals – up to 1 PeV

- Plenty of interest and opportunities:
  - **Collaborations:** *EuPRAXIA, ALEGRO study, ATHENA*
  - **Facilities:** *PWASC, ELBE/HZDR, AWAKE, CILEX, CLARA and SCAPA, EuPRAXIA @ SPARC_LAB at INFN-LNF, Lund, JuSPARC at FZJ and FLASHFor-ward and SINBAD at DESY; also in Japan (ImPACT), China (SECUF) and in the US (FACET-II BELLA)*
  - Advanced Acceleration Concepts **US roadmap** : **CDR by 2035**
  - Proposals of plasma *e*- injectors:
    - 100 MeV to IOTA (FNAL)
    - 700 MeV to PETRA-IV booster (DESY)

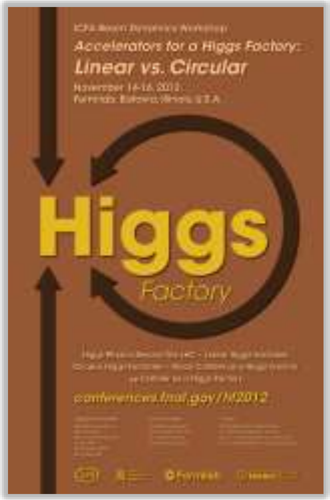
Summary:

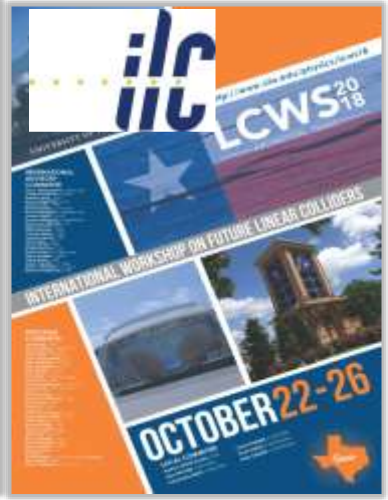
- Remarkable progress of the projects/proposals/technologies:
  - esp. ILC, CLIC, FCC-*ee*, -*hh*, CepC, *μ*-Colliders, plasma, …
  - allow in-depth evaluation of readiness, power and costs
- Higgs Factories Implementation :
  - several feasible options on the table
  - the choice might define high-energy 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)

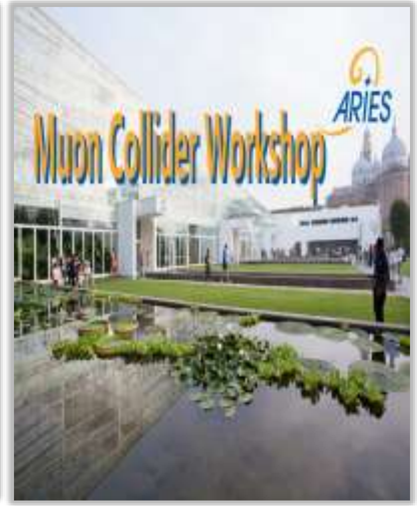
	Country	Facility	Experience
SuperKEKB	Japan	7+4 Gev *e+e-*, 8e35	nano-beams scheme
HL-LHC	CERN	x5 LHC luminosity	Nb_3Sn magnets, crab cavities
NICA	Russia	*ii/pp* 11-27 GeV	electron and stochastic cooling
PIP-II	USA	SRF linac to double # ν's	CW SRF, >1 MW targetry
ESS	Sweden	5 MW pulsed SRF	SRF, cryo, 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

Acknowledgements

greatly appreciate input from:







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

Thank You for Your Attention!

* In depth discussions in the parallel sessions:

- – LHC HL HE
- – FCC
- – Linear Colliders
- – Higgs Factories
- – Muon Colliders
- – Present plasma
- – Future plasma
- – Neutrino beams
- – Beyond colliders
- – Energy efficiency

BACK UP SLIDES

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.*