IDPASC

Otranto School

Joint 9th IDPASC SCHOOL and
XXXI INTERNATIONAL SEMINAR of
NUCLEAR and SUBNUCLEAR PHYSICS
"Francesco Romano"
27 May - 4 June 2019, Otranto (Italy)

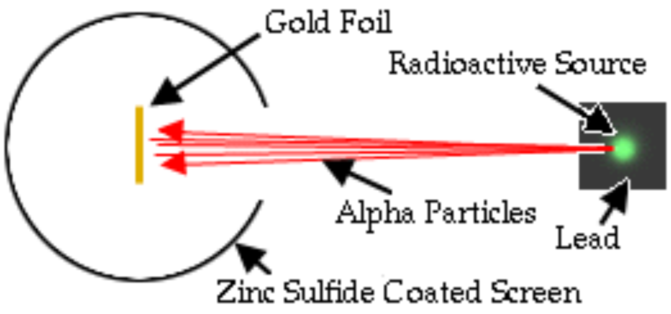
European Strategy Update

Future particle colliders

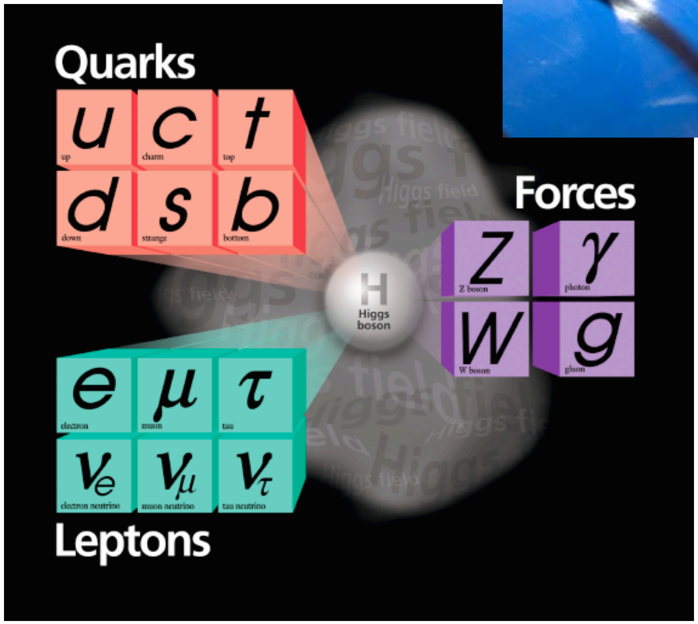
Nadia Pastrone

INFN TORINO

Serra degli Alimini - June 1st, 2019



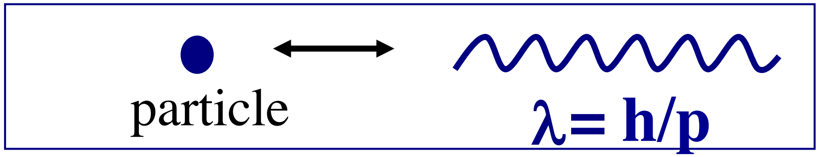
What's Next after LHC?



Whay we can learn impossible to guess....main element surprise....some things look for but see others.....Experiens on pions....sharpening

Enrico Fermi - American Physical Society, NY, **Jan. 29th 1954**
"What can we learn with High Energy Accelerators ? "

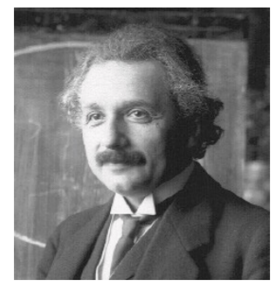
Accelerators: microscopes & telescopes



Louis
de Broglie

- To explore **smaller dimensions:**

$$E = hc/\lambda$$



Albert
Einstein

- To discover **heavier particles:**

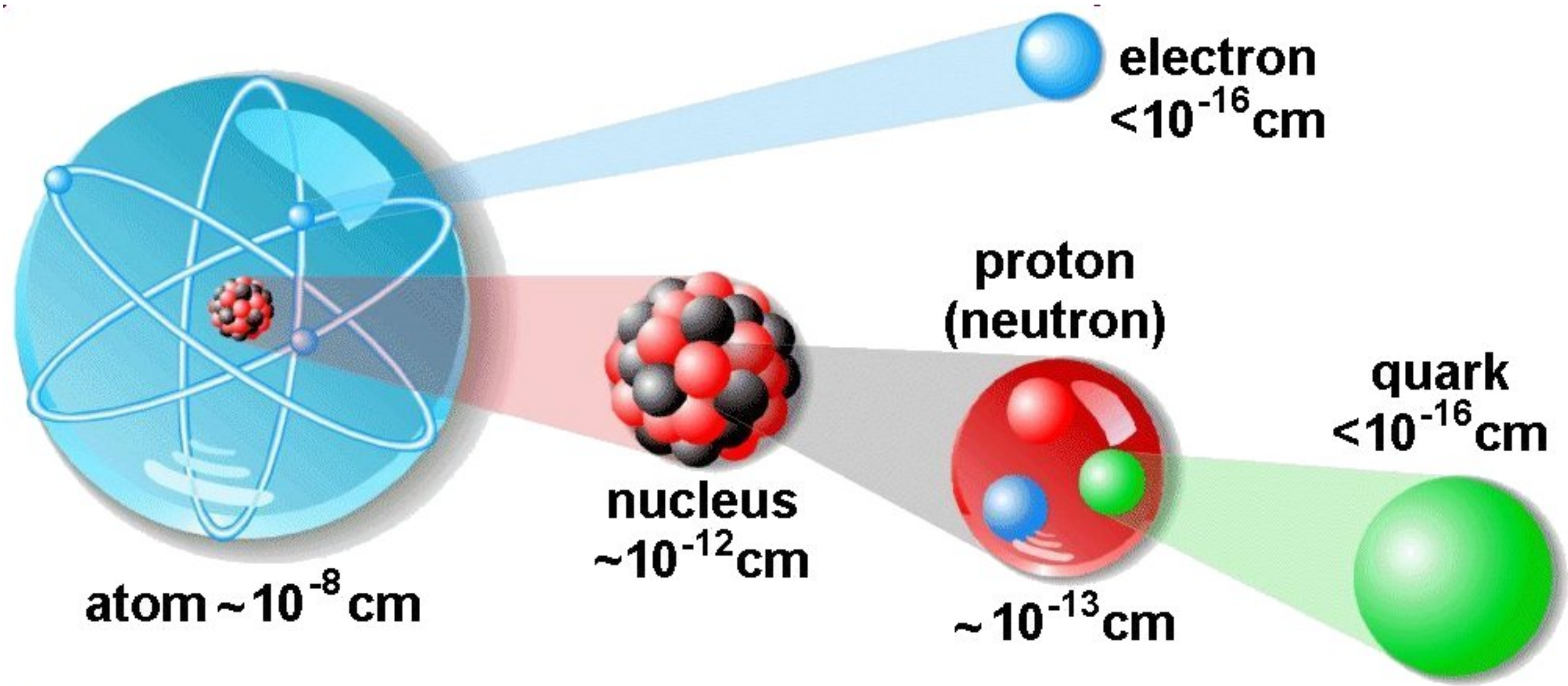
$$E = mc^2$$

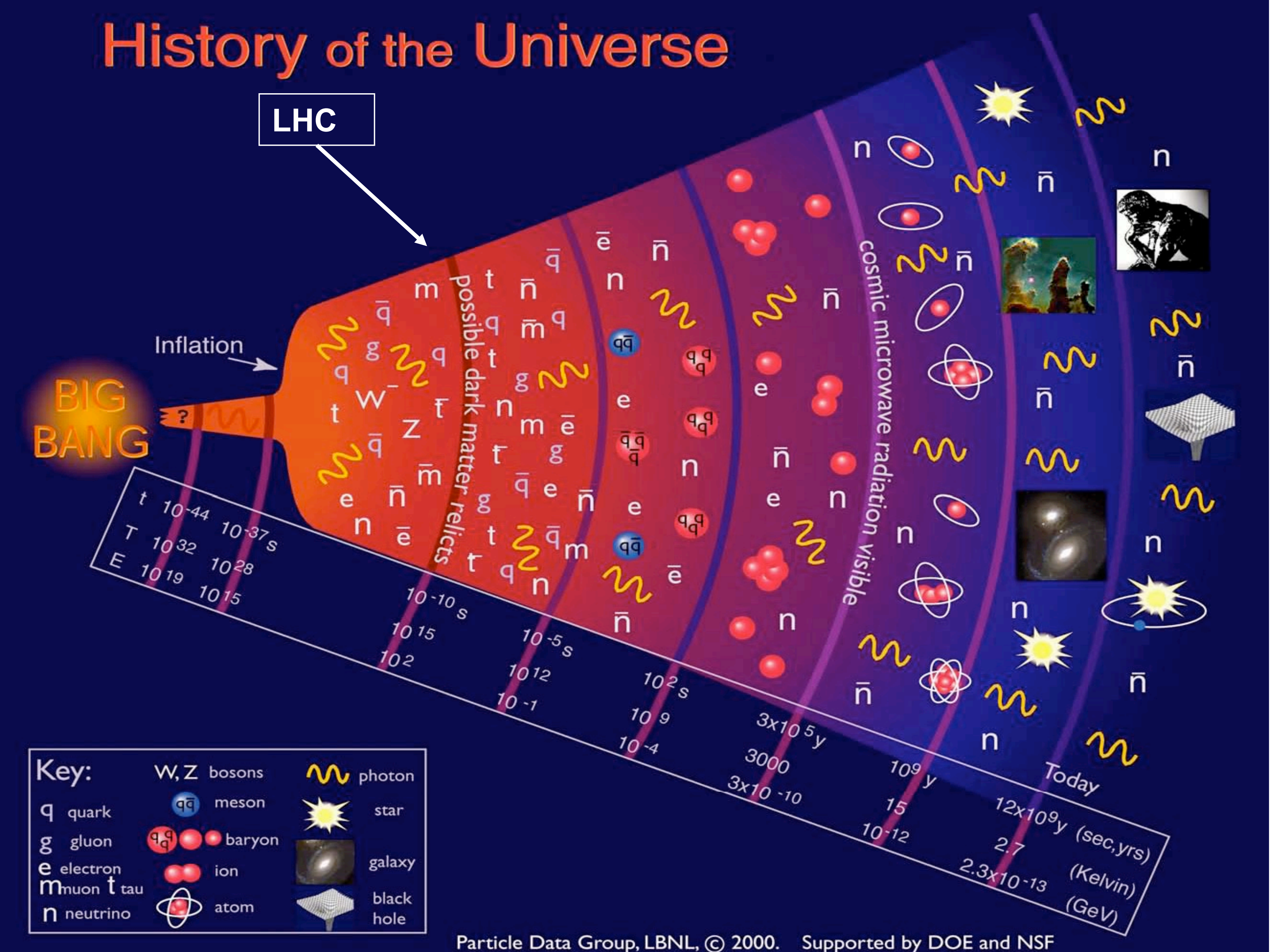
- To reach **higher temperature (early Universe)**

$$E = kT$$

Ludwig
Boltzmann

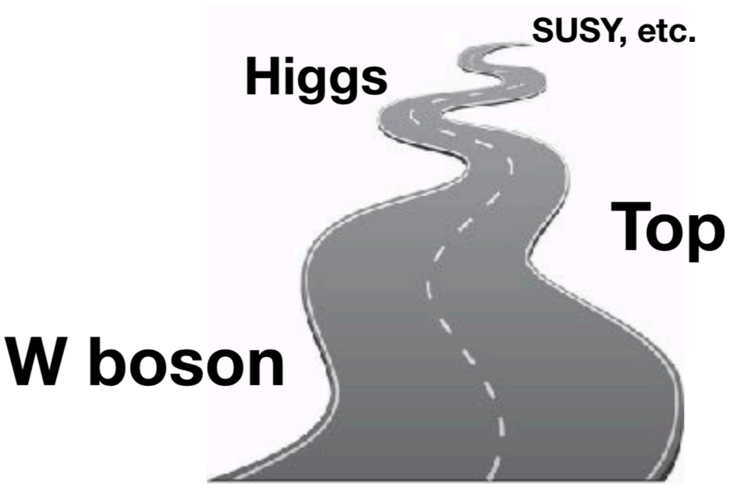
Where are we now?




History of the Universe
LHC
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s 10^-10 s 10^-5 s 10^2 s 3x10^5 y 10^9 y Today 12x10^9 y (sec,yrs)
T 10^32 10^28 10^15 10^12 10^9 3000 15 2.7 (Kelvin)
E 10^19 10^15 10^2 10^-1 10^-4 3x10^-10 10^-12 2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

How do we set a strategy?

HEP before the LHC



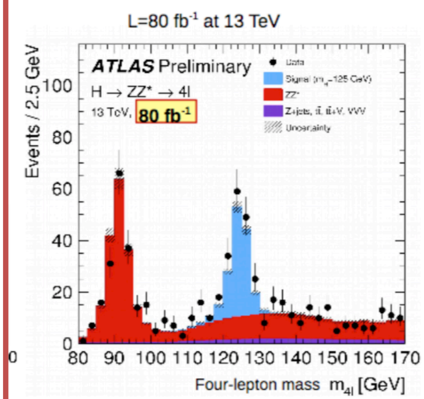
HEP before the F.C.

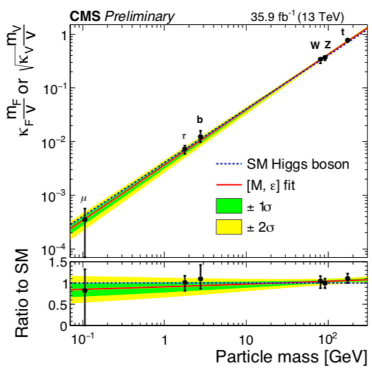
A. Wulzer

Particle physics is not **validation** anymore, rather it is **exploration of unknown territories** *

Physics motivation

The Standard Model under scrutiny: "the" Higgs



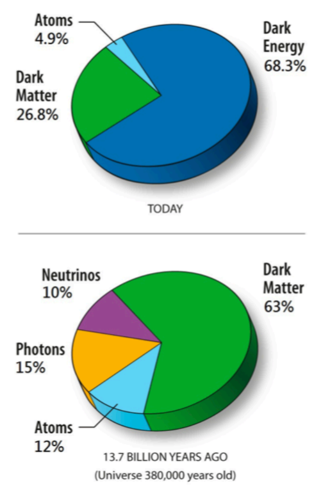


$J^{CP} = 0^+$ $m_{\text{Higgs}} = 125.09(24)\,\text{GeV}$

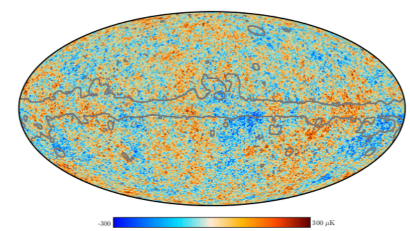
Higgs Factories

Outstanding Questions or Why we need BSM ?

Data we definitely cannot explain! matter-antimatter asymmetry,
dark matter
dark energy
inflation



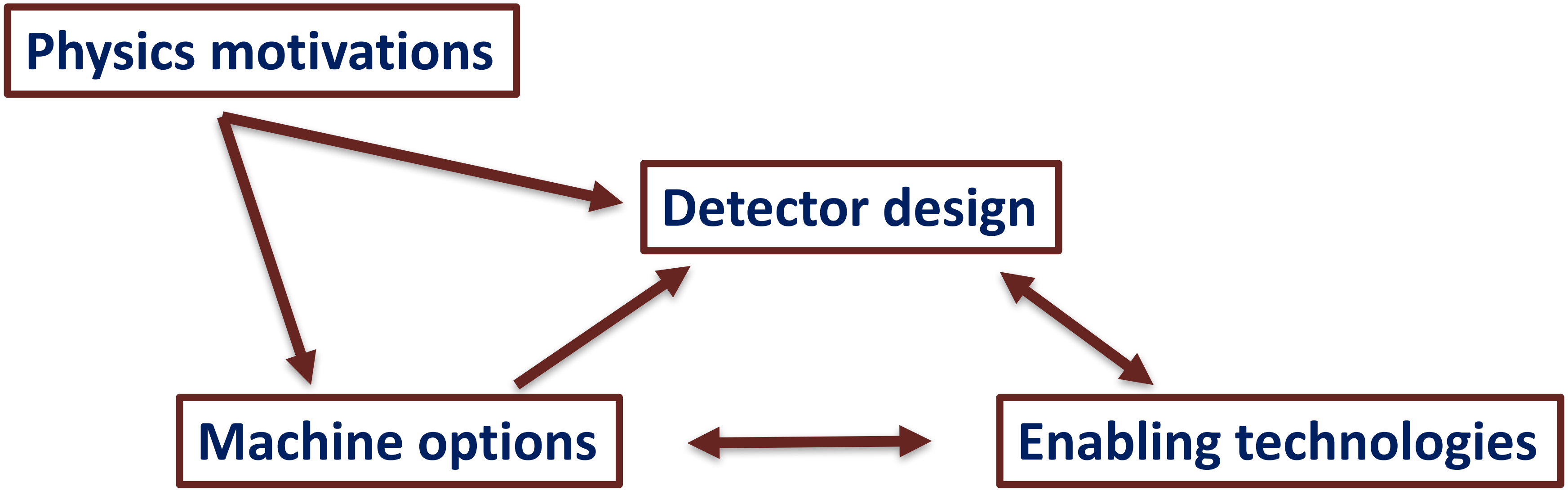
SM + gravity ≠ cosmos



Can we understand this with BSM particle physics ?

Discovery machines

What's Next after LHC?



See also lectures by Albert De Roeck and Michelangelo Mangano

Which particles?

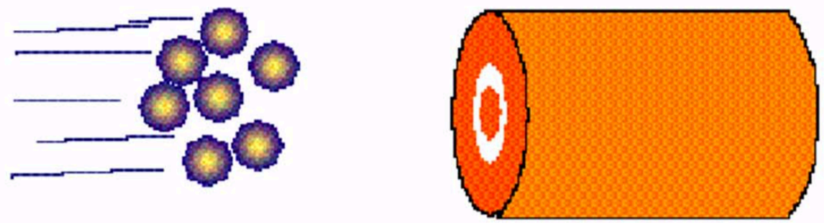
- **leptons** ➔ fundamental particles
- **hadrons** ➔ made by quarks (fundamental particles)
  - stable (electrons, protons)
  - unstable (muons) ➔ decay in the machine and/or in the detector

Machine options: collision mode

W = Energy available in center-of-mass for making new particles

For fixed target :

$$E_{c.m} \cong \sqrt{2 m_T E_B}$$



... and we rapidly run out of money trying to gain a factor 10 in c.m. energy

But a storage ring , colliding two beams, gives:

$$E_{c.m.} \cong 2\ E_B$$

Problem: Smaller probability that accelerated particles collide .... "Luminosity" of a collider

$$L = N_1 N_2 \frac{1}{A} \frac{\beta c}{2\pi R} \approx 10^{29} \ldots 10^{34}\, cm^{-2} s^{-1}$$

Machine design

- A particle Accelerator is a machine designed to transfer energy to a charged particle beam. In most cases the particle beam extracts energy from an electromagnetic field that is stored or traveling in low losses structures, called cavities. Obviously beam has to live in vacuum.

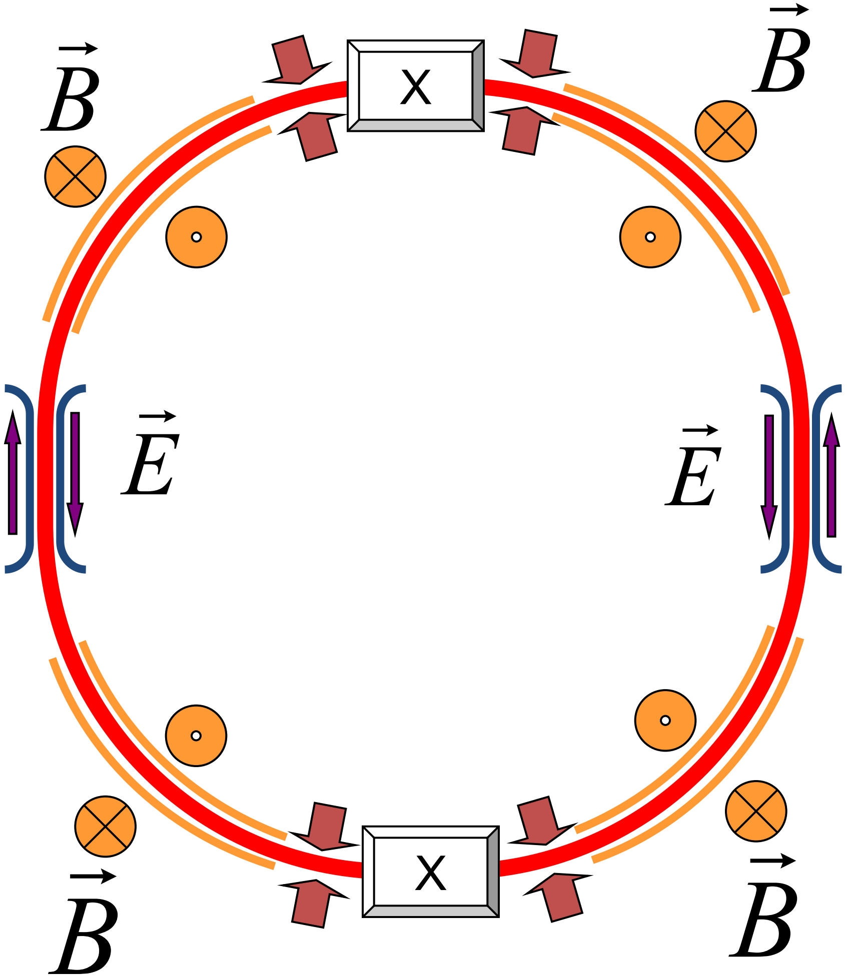
$$\Delta E = q\,V$$

- Particles are taking energy from the electric field, $\boldsymbol{E}$, and are guided by the magnetic field, $\boldsymbol{B}$, according to the Lorentz equation:

$$\boldsymbol{F}_{em} = q\,(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

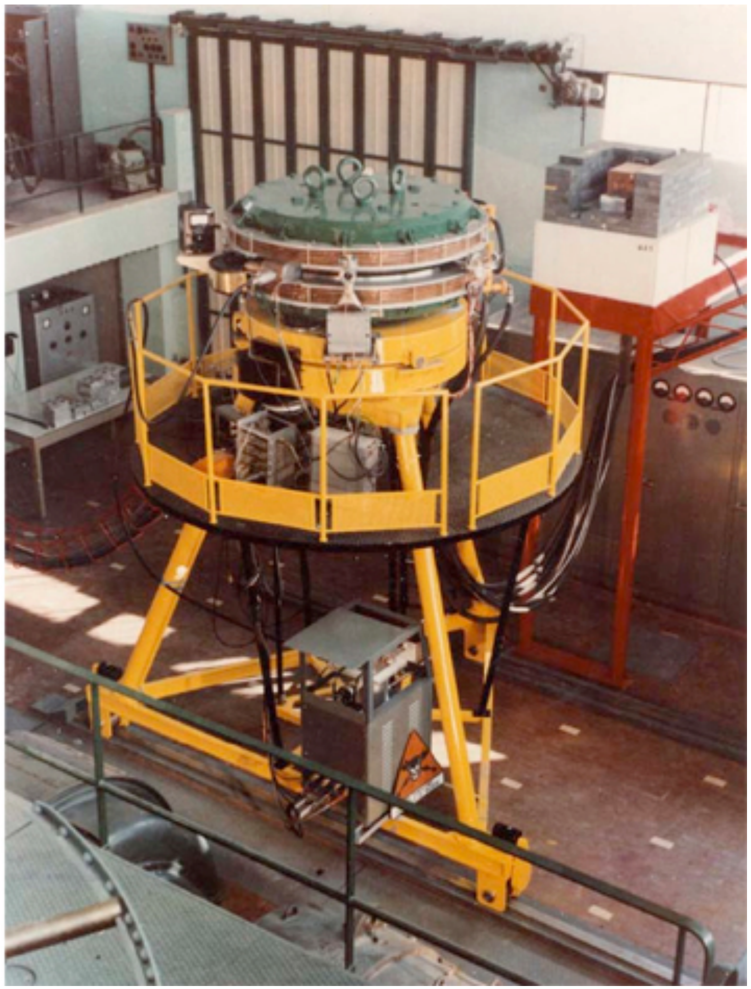
- The charged accelerated particles can be:
  - **electrons** (& positrons)
  - **protons** (& antiprotons)
  - **ions**
- An intense primary beam can be used to produce a secondary beam that could not be accelerated: photons, neutrons, neutrinos, etc.

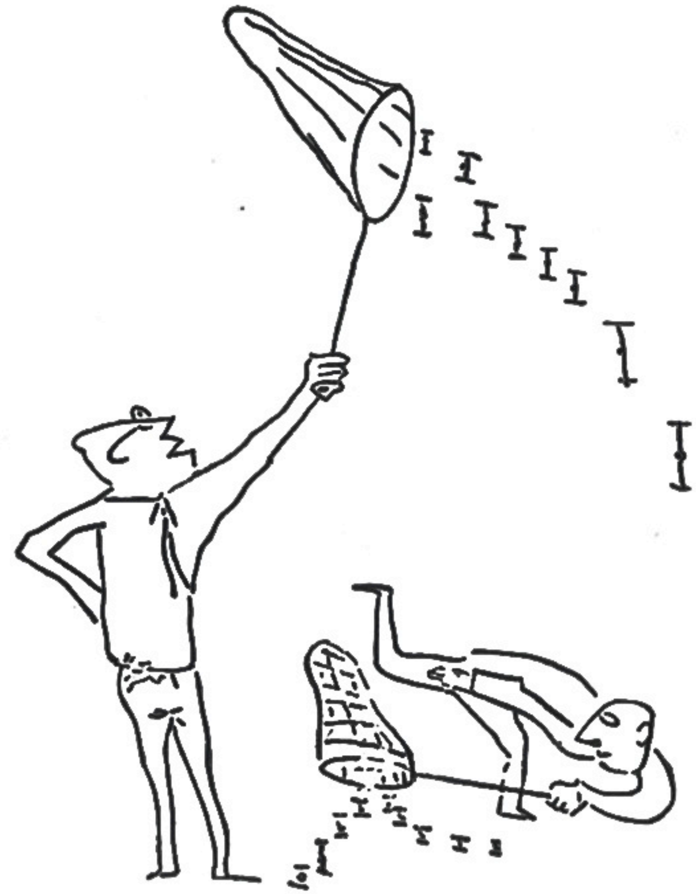
Circular collider scheme



First e^+e^- collider @ INFN-Frascati

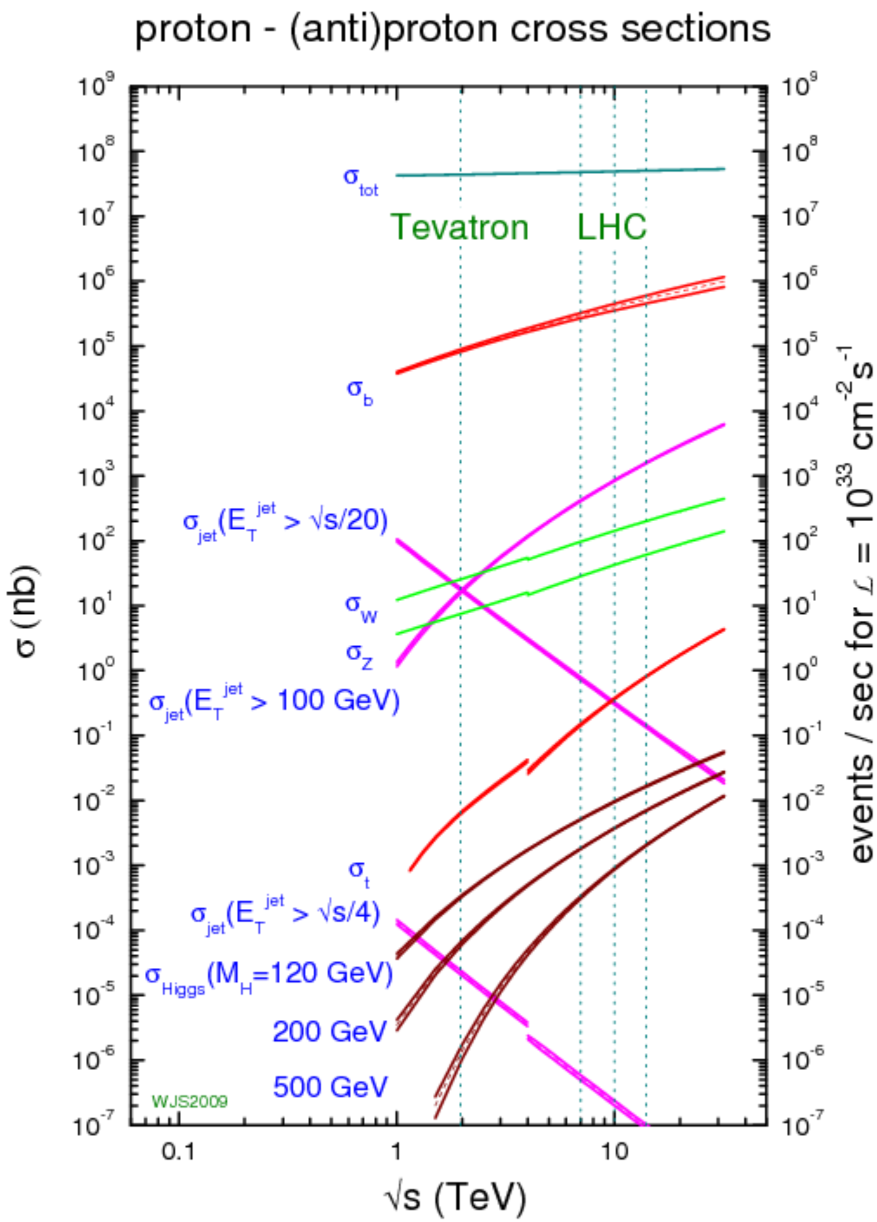
AdA - Anello di Accumulazione (1960)





"Catching data"
drawing by Bruno Touschek,
probably 1974

Production cross sections

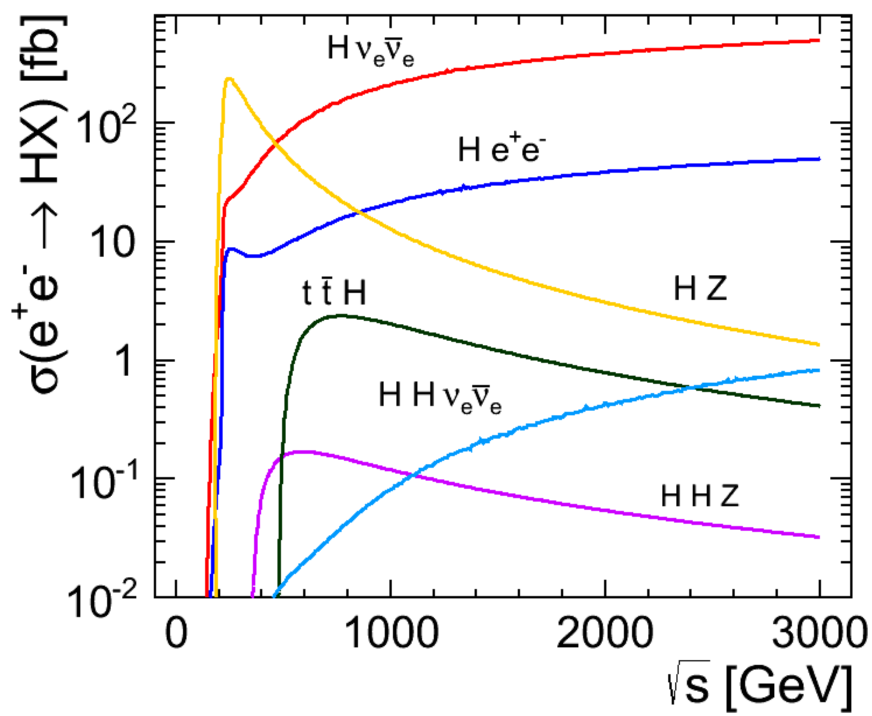


HIGH LUMINOSITY is strongly REQUIRED

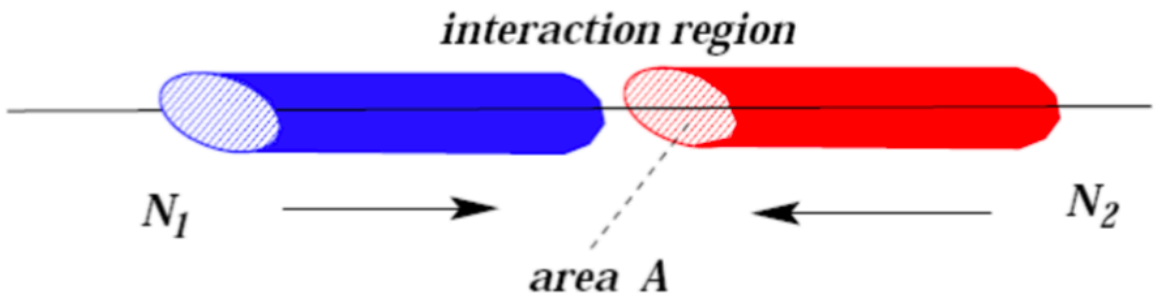
EVENT RATE (Hz) = $\mathcal{L}$ x σ

Luminosity [$cm^{-2}\ s^{-1}$]

Cross section [cm^2]



Machine parameter: luminosity



Increased bunch intensities

$$\mathcal{L} = \frac{N_1 N_2 f_{\text{rev}} k_B}{4\pi\beta^* \epsilon_{xy}} F$$

Beam area

Reduced β* (given by magnetic focussing)

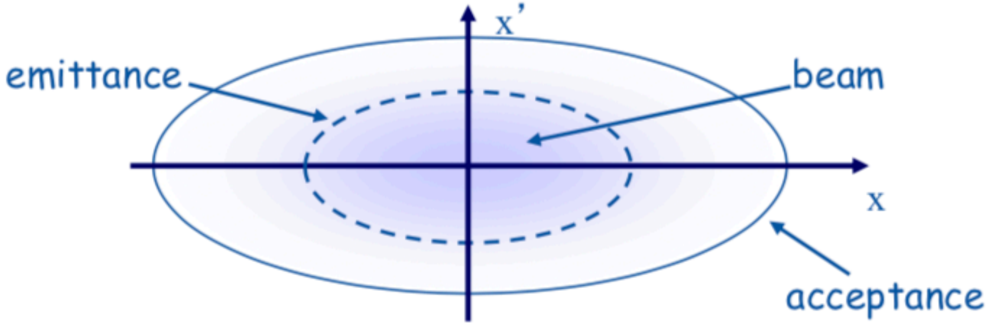
Reduced emittance

Decreased crossing angle => larger F (geometric reduction factor)

$$\frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_x}\frac{\phi}{2}\right)^2}}$$

Beam parameter: transverse emittance

- To be rigorous we should define the emittance slightly differently.
- Observe all the particles at a single position on one turn and measure both their position and angle.
- This will give a large number of points in our phase space plot, each point representing a particle with its co-ordinates x, x'.



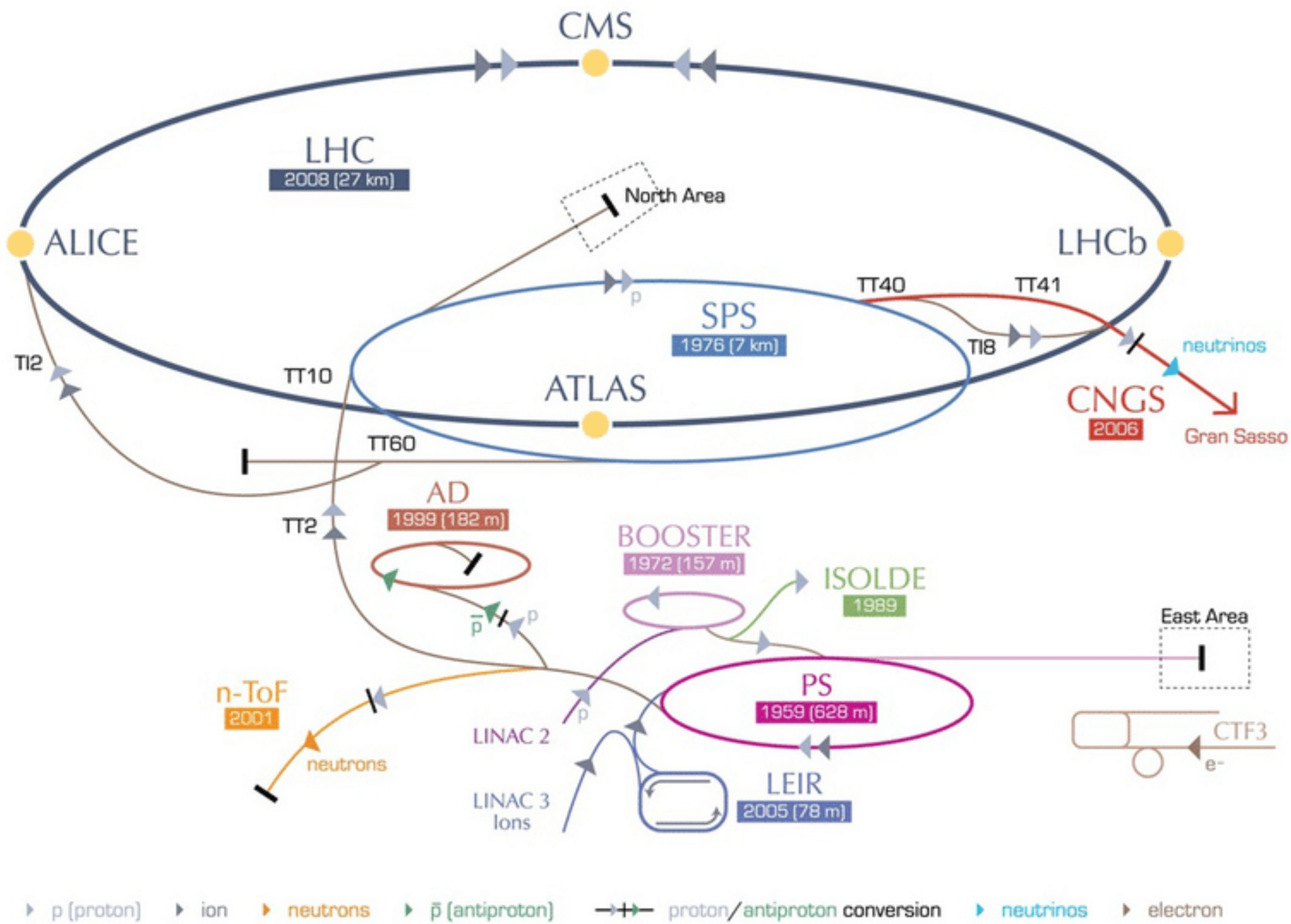
Symbol: ε

Expressed in 1σ, 2σ,..

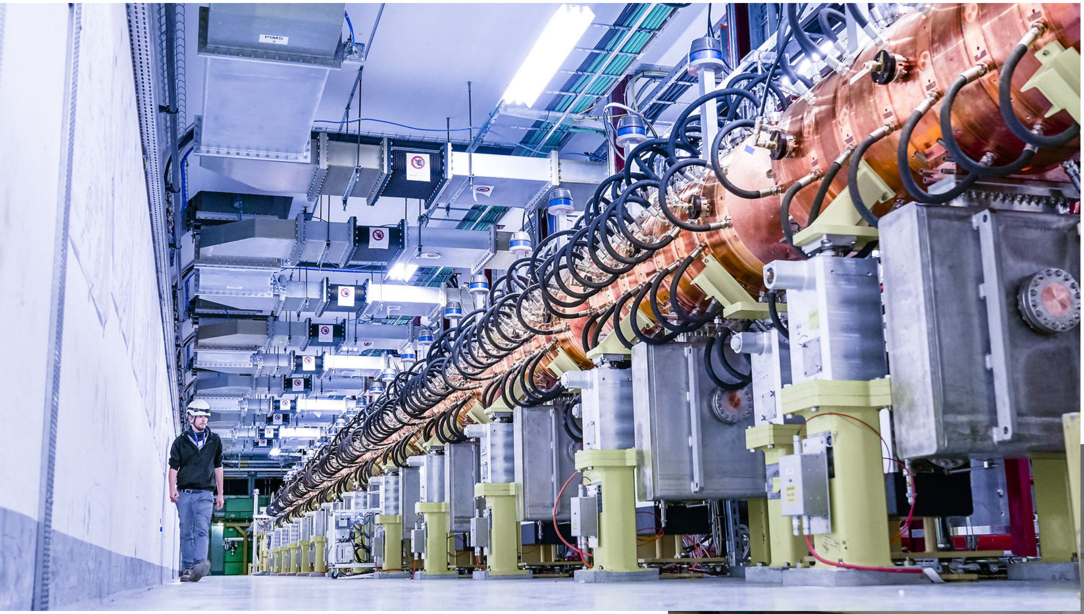
Units: mm mrad

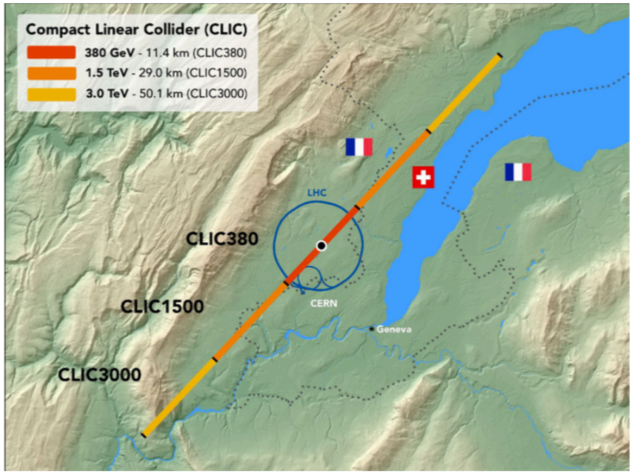
- The **emittance** is the **area** of the ellipse, which contains all, or a defined percentage, of the particles.
- The **acceptance** is the maximum **area** of the ellipse, which the emittance can attain without losing particles

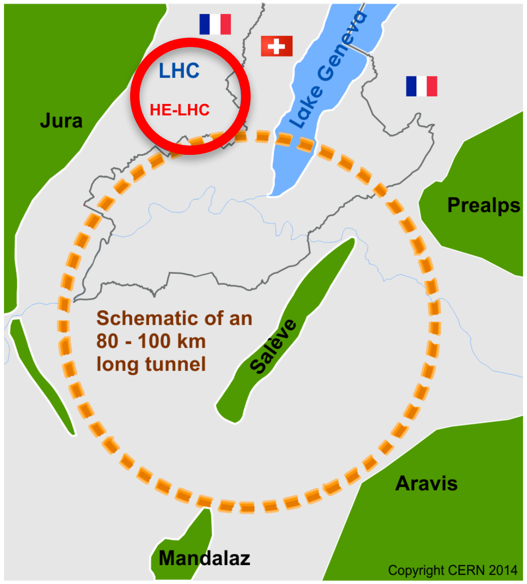
Accelerator complex @ CERN

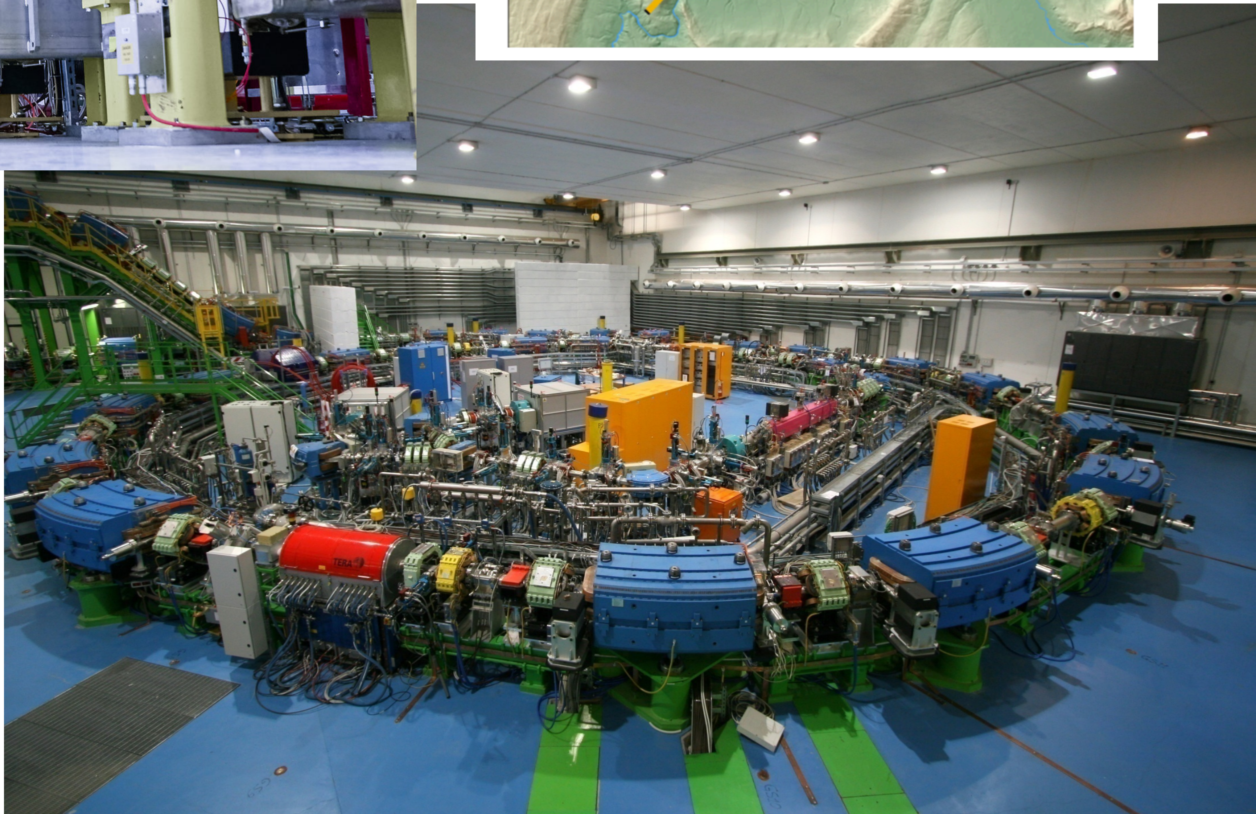


Collider: linear or circular?



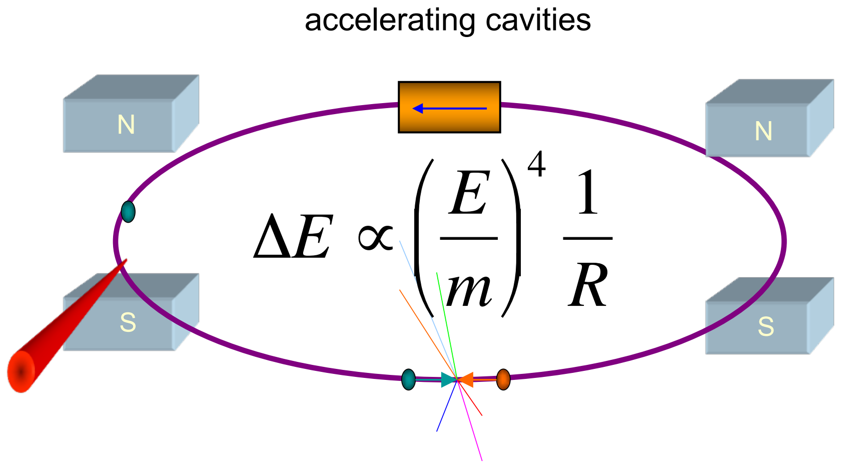






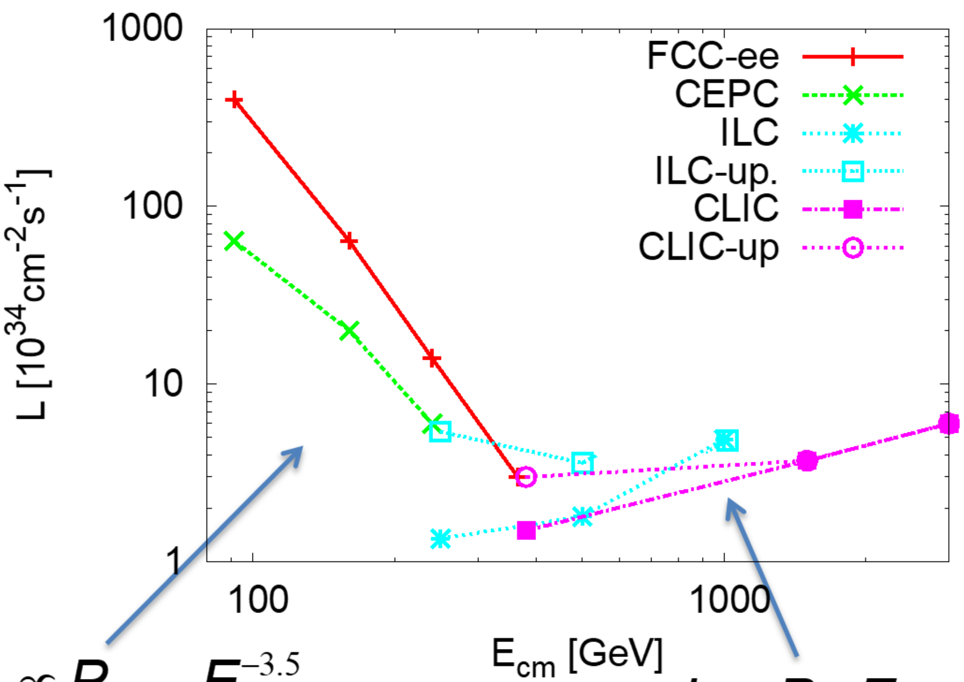
Lepton Colliders at High Energies

Accelerate beam in many turns
Use beam many times
Synchrotron radiation grows rapidly with energy
- At LEP2 lost 2.75GeV/turn for E=105 GeV



$$\Delta E \propto \left(\frac{E}{m}\right)^4 \frac{1}{R}$$

Luminosity per facility

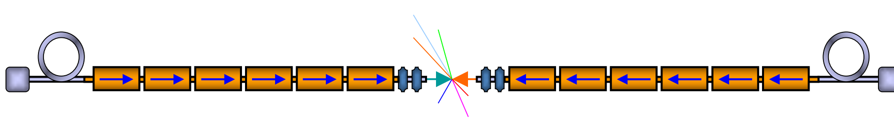


$L \propto P_{synrad} E_{cm}^{-3.5}$

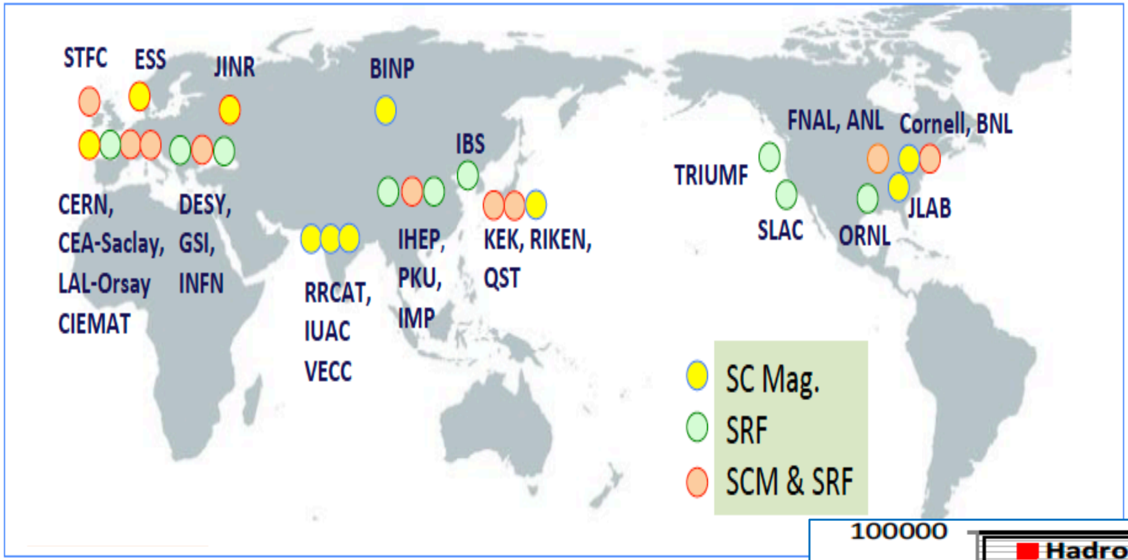
$L \propto P_{RF} E_{cm}$

Use a linac to avoid synchrotron radiation

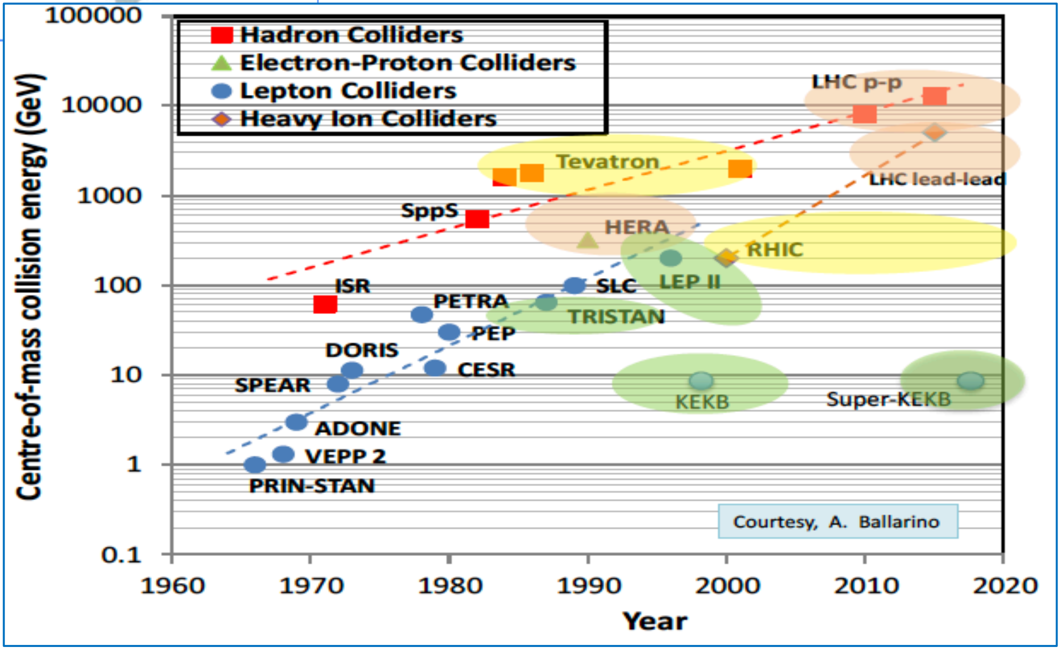
Use muons



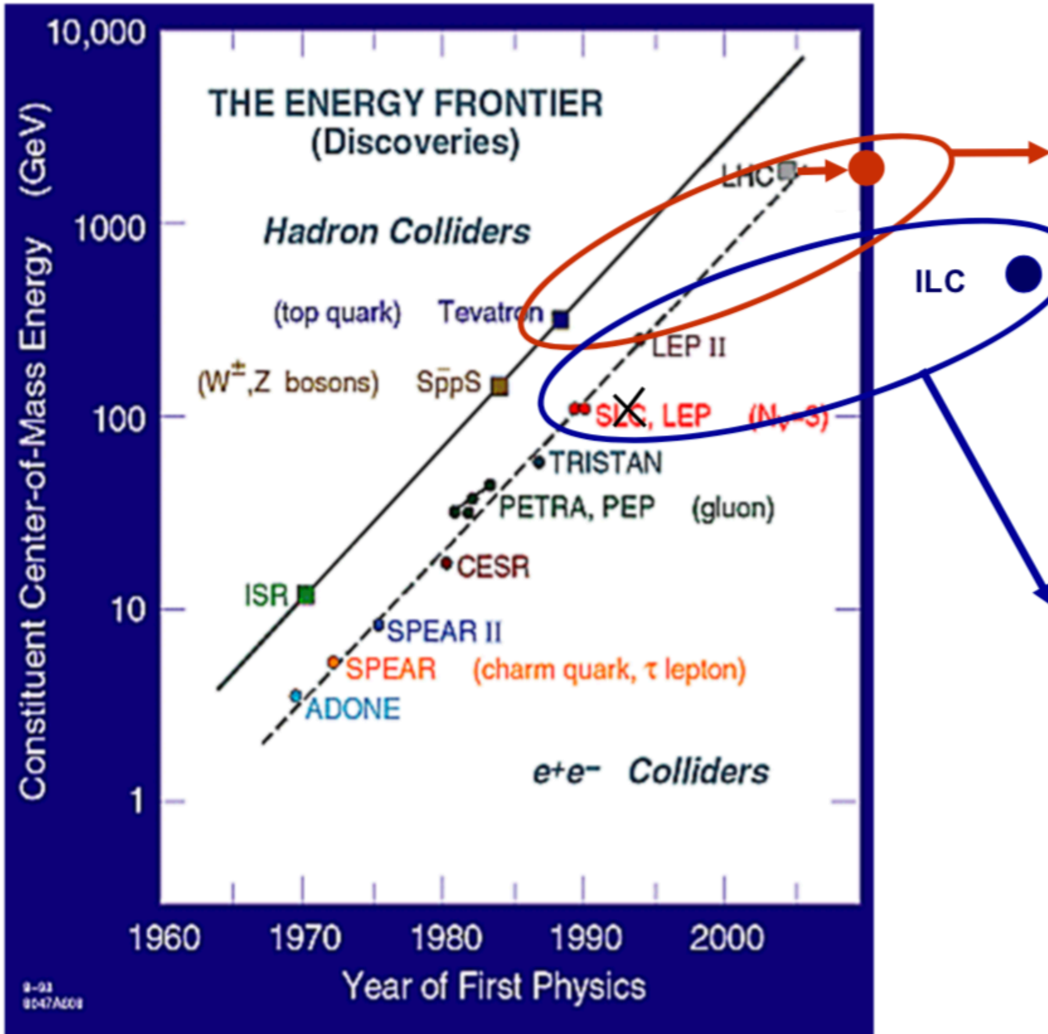
Use of Superconducting technology



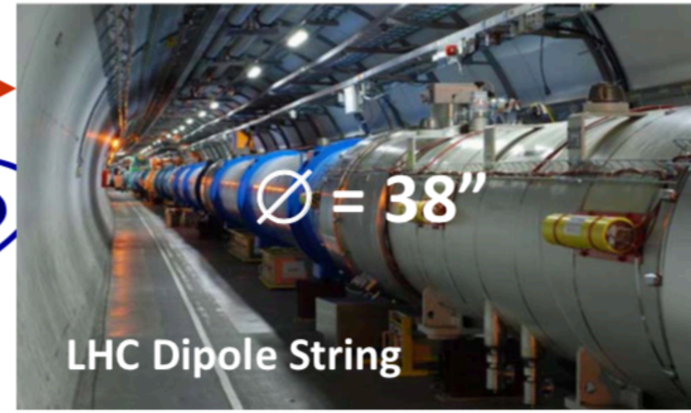
High-energy and High-Intensity frontier accelerators are relying on superconductivity



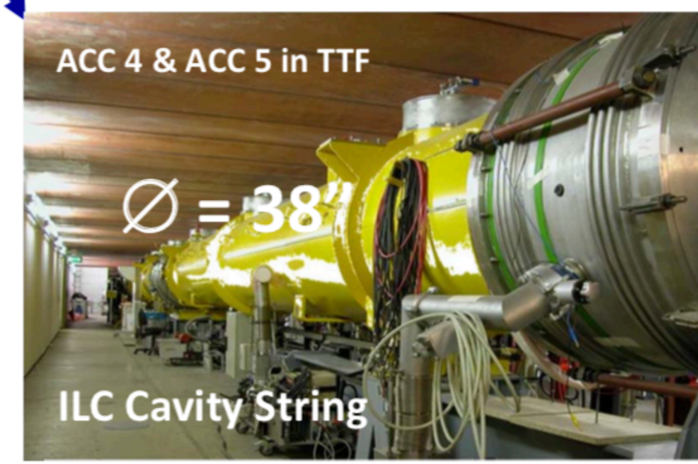
Enabling technology



Superconducting Dipoles



Superconducting RF Cavities



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

V. Shiltsev

- Impressive technology progress:
  - 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

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*
  - *CLIC*
- *e+e-* circular
  - *FCC-ee*
  - *CepC*
- *μ+μ-* circular
  - *μ-HF*

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

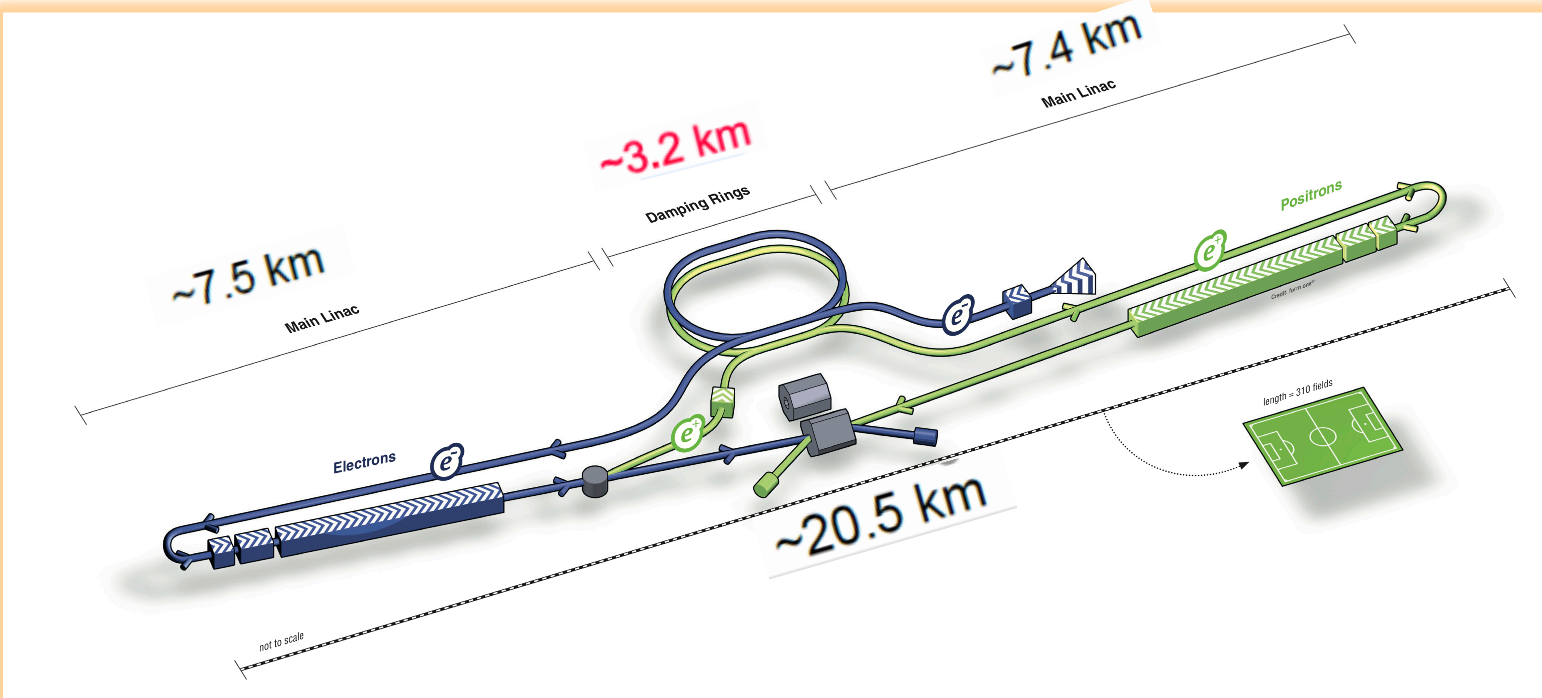
Usually, compared to the LHC – which is, as a machine **:**

- 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

arXiv:1306.6328
TDR



Key facts:

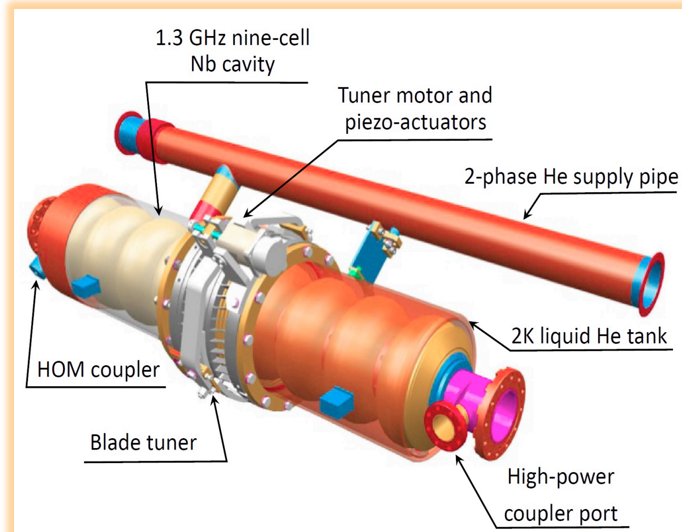
20 km, including 5 km of Final Focus

SRF 1.3 GHz, 31.5 MV/m, 2 K

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

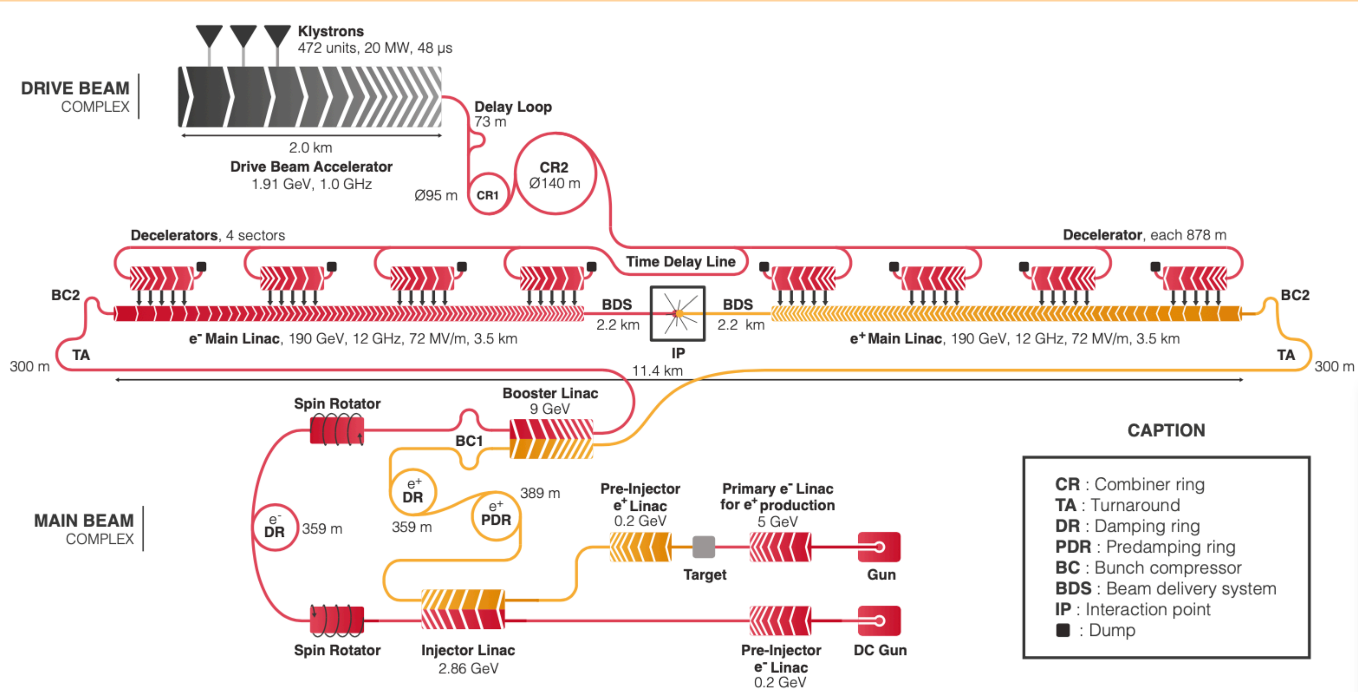
Cost estimate 700 B JPY*

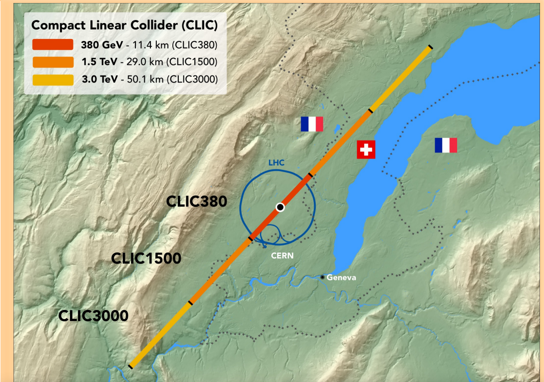
** ± 25% err, includes labor cost*

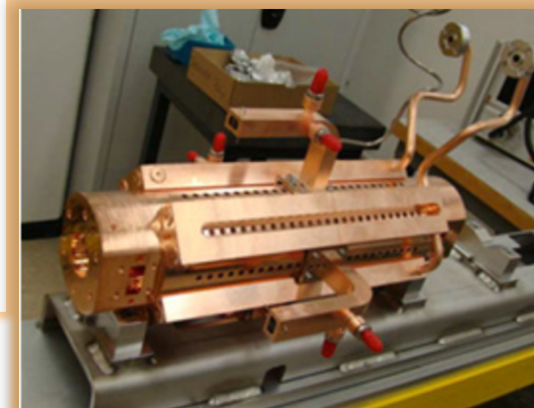


Compact LInear Collider

arXiv:1209.2543 **CDR**







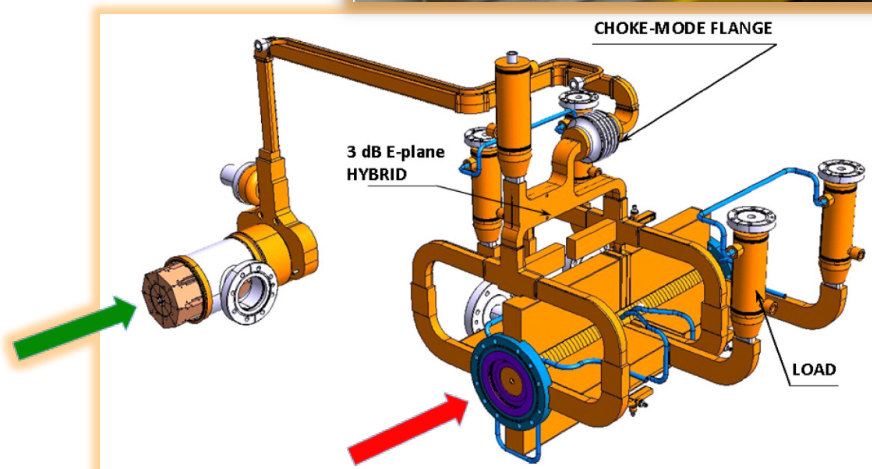
Key facts:

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

NC RF 72 MV/m, two-beam scheme

168 MW site power (~9MW beams)

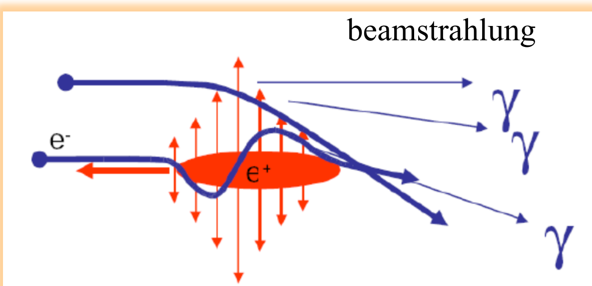
Cost est. 5.9 BCHF ± 25%



Challenges of Linear Colliders Higgs Factories

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

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)

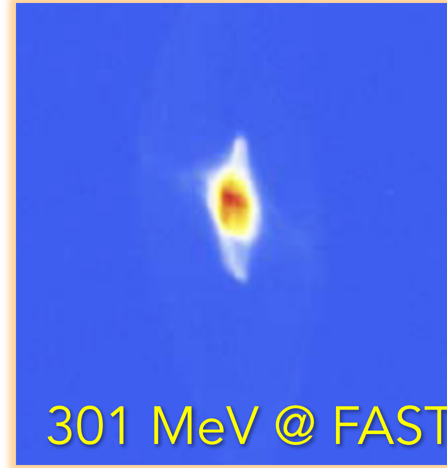
Beam Quality
(Many systems)

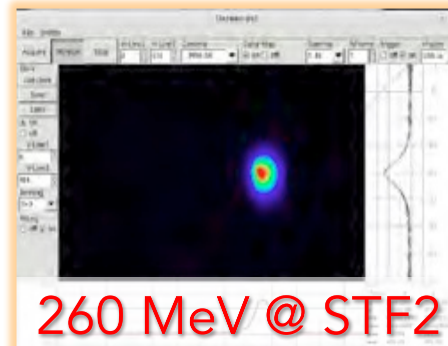
- Record small DR emittances
- 0.1 μm BPMs
- IP beam sizes

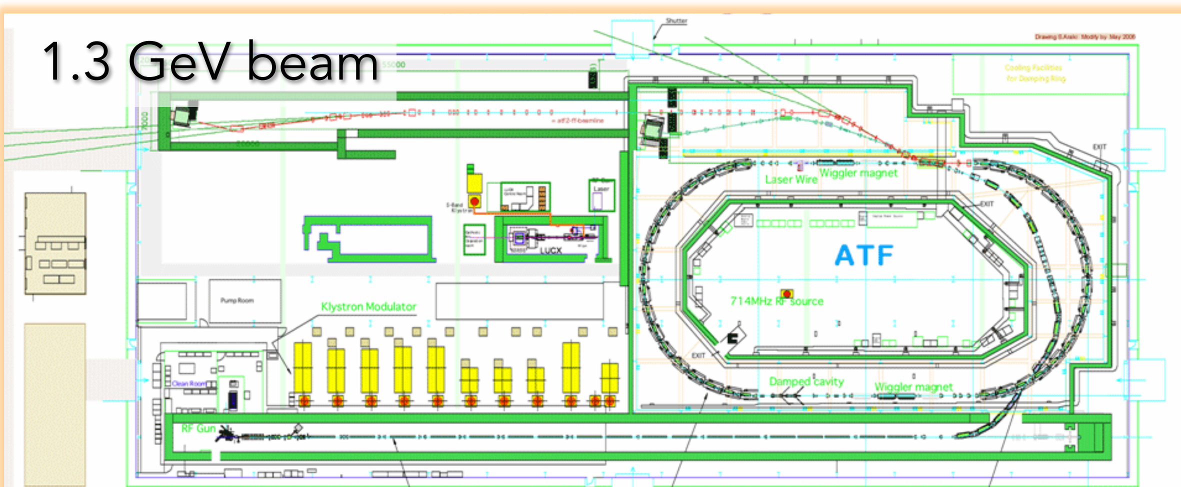
ILC 8nm/500nm
CLIC 3nm/150nm

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



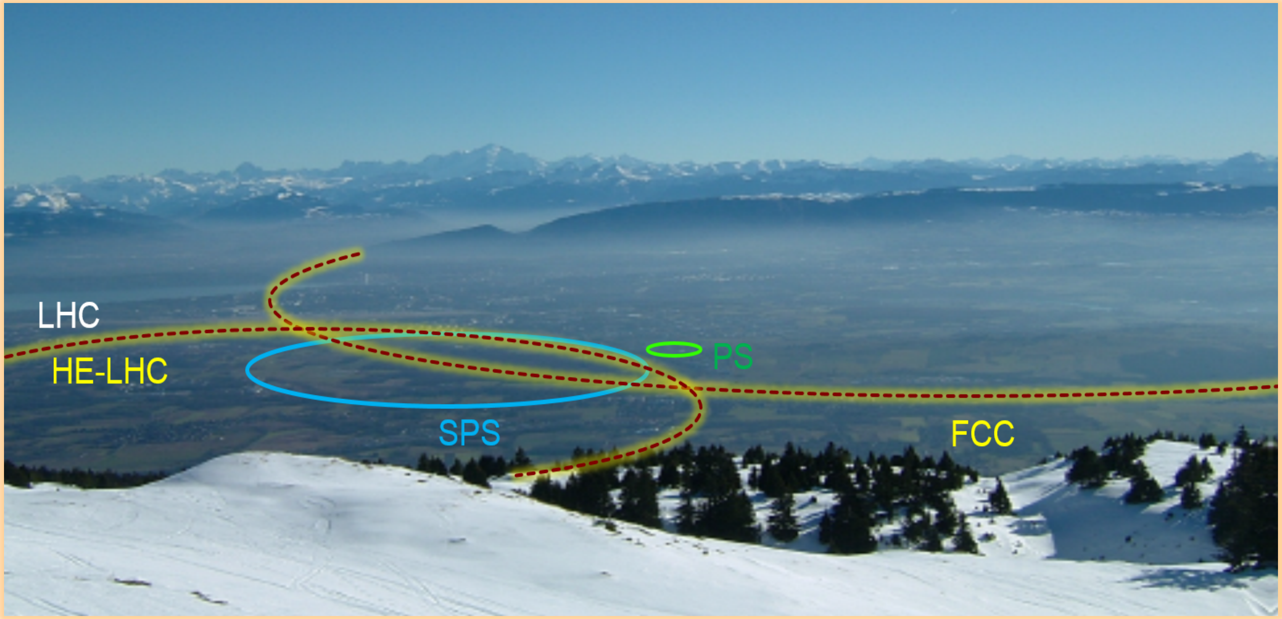




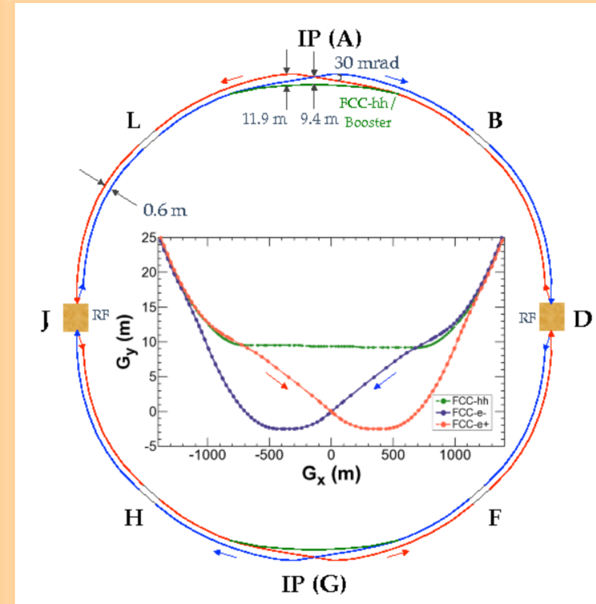
Linear Colliders *e+e-* Higgs Factories

- *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



FCC-ee CDR (2018)



Key facts:

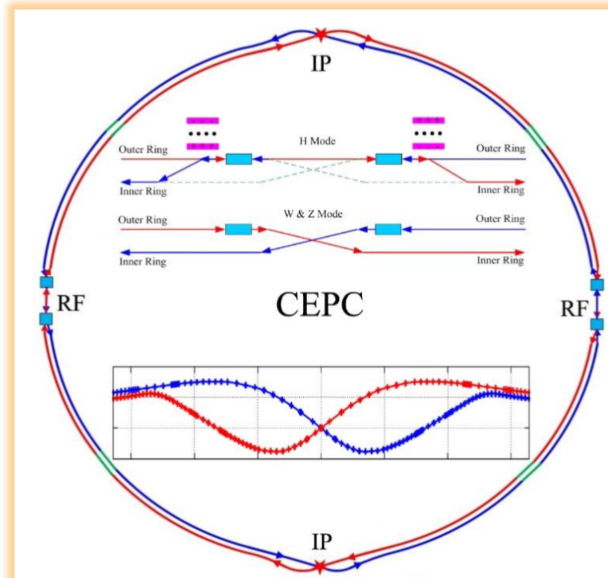
100 km tunnel, three rings (*e-*, *e+*, booster)

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

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

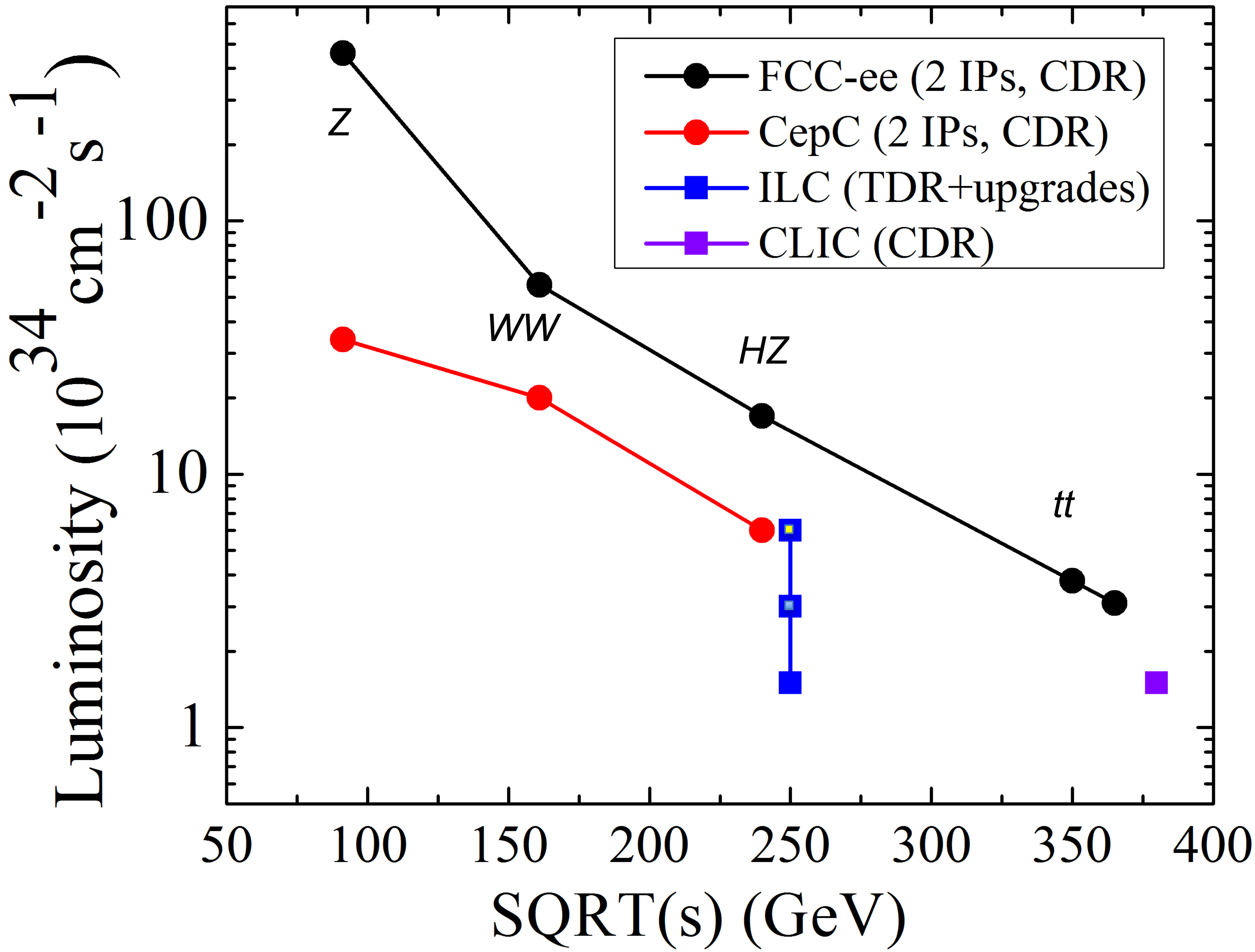
$$I = \frac{e\rho}{2C_\gamma E^4} P_T,$$

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

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

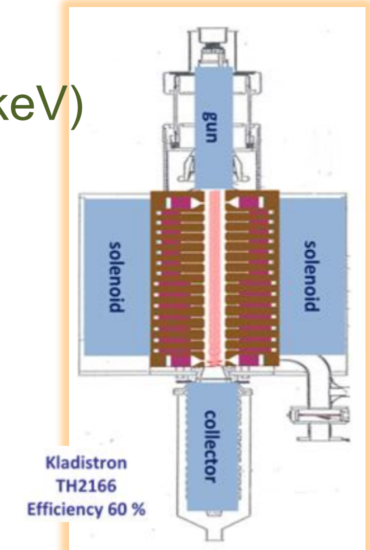
- ξ_y =0.13 new **beam-beam instability**; while synchrotron radiation $\Delta E_{turn}/E \sim$ 0.1-5% per turn *Z* to 360 GeV, the beam-strahlung is at IPs only and spreads $\delta E/E$ ~0.1-0.2% , but tails upto 10x that ±2.5% determine 18 min beam lifetime ~18 min → need large acceptance optics β_y*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

e+e- Higgs Factories: Circular vs Linear



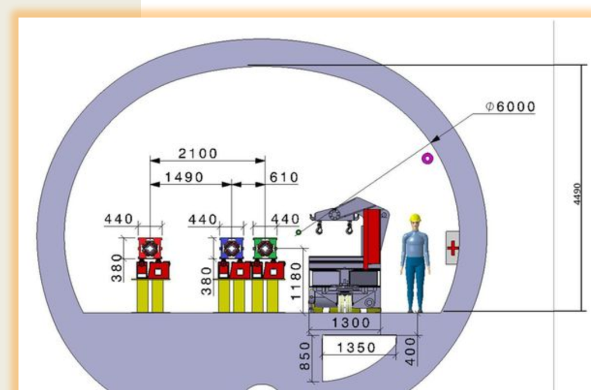
e+e- Ring Higgs Factories

- ***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 ($\tau \sim$ 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 :

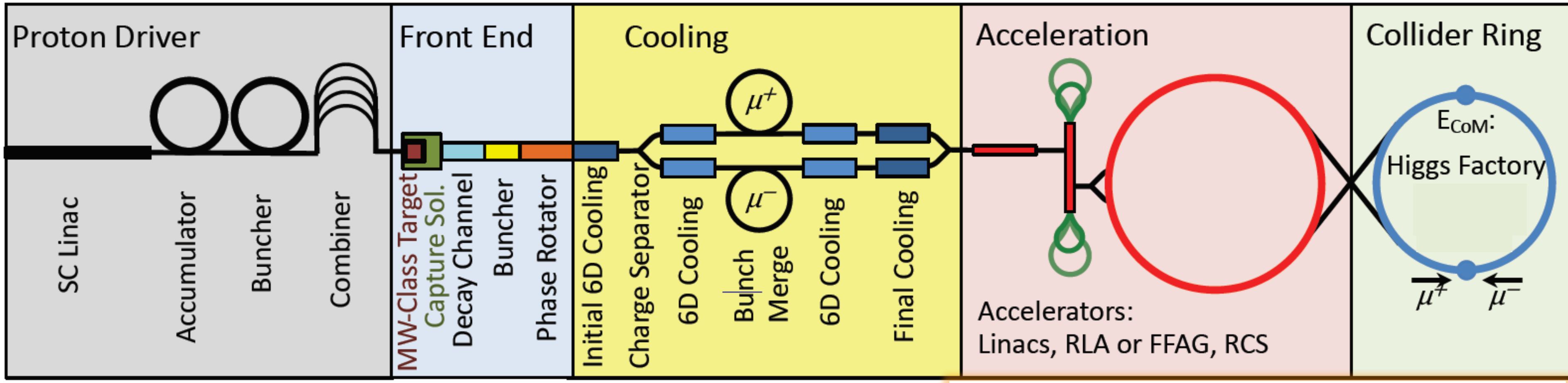
- High efficient RF sources:
  - Klystron 400/800 MHz η from 65% to >85%
- High efficiency SRF cavities:
  - 10-20 MV/m and high Q_0; Nb-on-Cu, Nb_3Sn
- Crab-waist collision scheme:
  - *Super KEK-B* nanobeams experience will help
- Energy Storage and Release R&D:
  - Magnet energy re-use > 20,000 cycles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



$\mu^+\mu^-$ Higgs

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

JINST Special Issue (*MUON*)



Key facts:

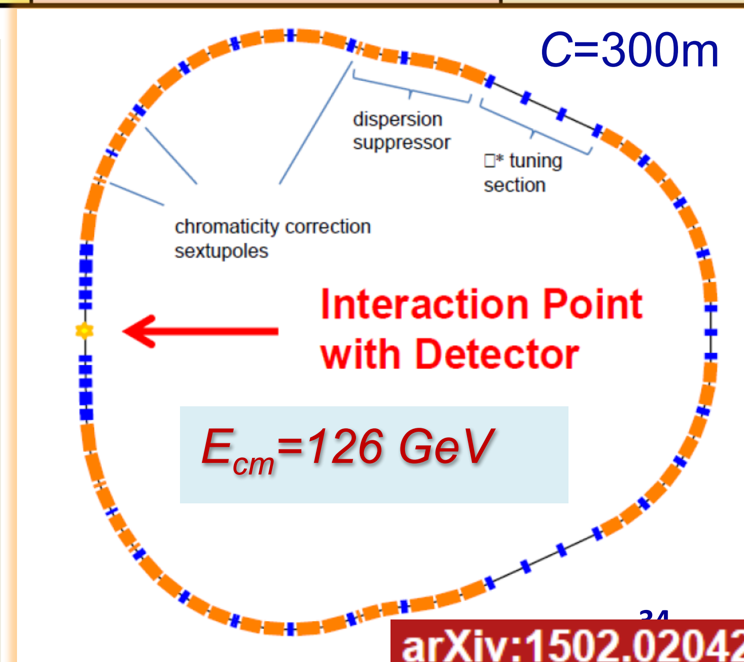
1/100 luminosity requirements (large cross-section in *s*-channel)

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

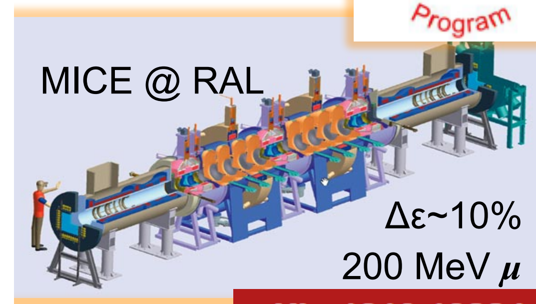
Total site power ~200MW (tbd)



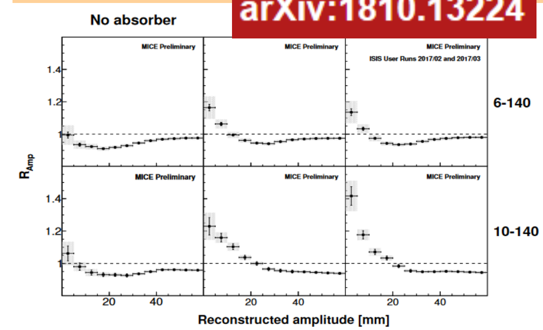
arXiv:1502.02042

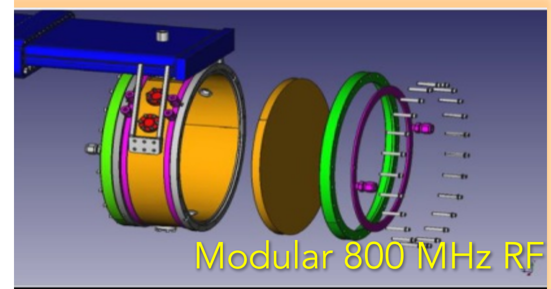
Recent progress: *μ+μ- Colliders*

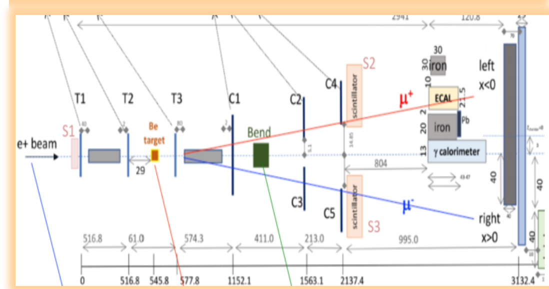
- Ionization cooling of muons:
  - Demonstrated in MICE @ RAL
  - 4D emittance change *O*(10%)
- NC RF 50 MV/m in 3 T field
  - Developed and tested at Fermilab
- Rapid cycling HTS magnets
  - Record 12 T/s – built and tested at FNAL
- First RF acceleration of muons
  - J-PARC MUSE RFQ 90 KeV
- US MAP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



arXiv:1810.13224







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 $cost \sim \beta E^{\kappa}$, $\kappa \approx ½ \ldots 2/3$
    - *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

let's consider

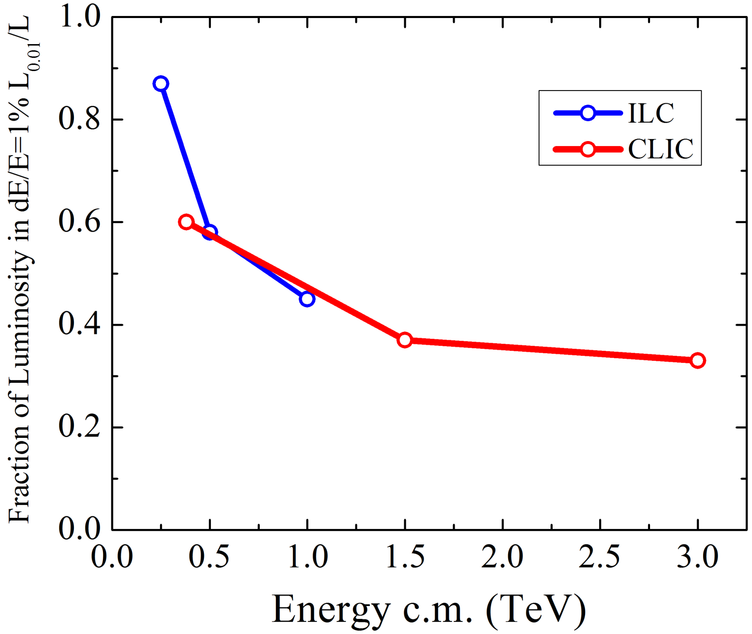
Limits of Linear *e+e-* Colliders

- Both ILC and CLIC offer staged approach to ultimate *E*
- The limits are set by:

ILC TDR 1 TeV 17 B$ ±25%
CLIC CDR 3 TeV 18.3BCHF ±25%

Cost
Electric power required
Total length
(complication of) Beamstrahlung

Luminosity Dilution by Beamstrahlung



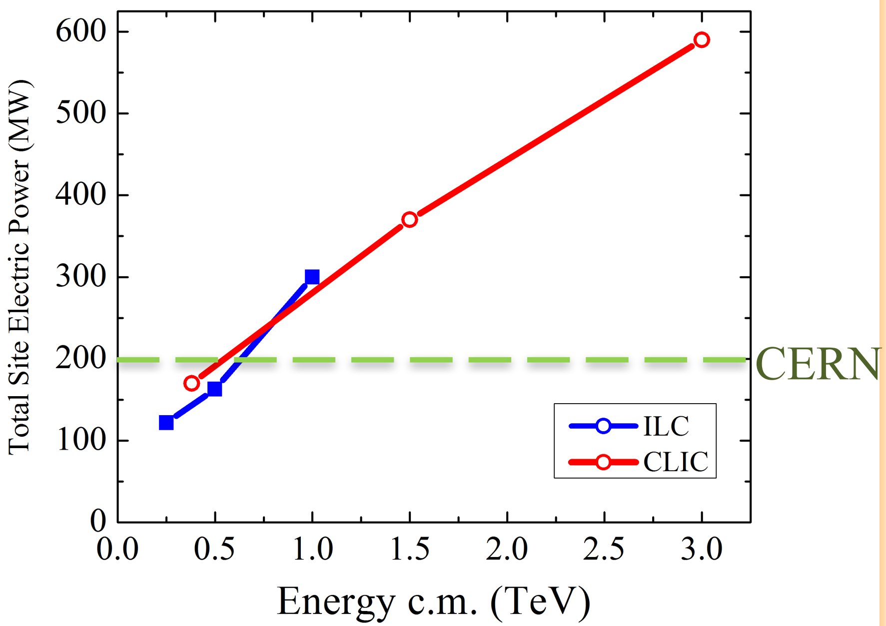
Beamstrahlung rms energy spread :

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

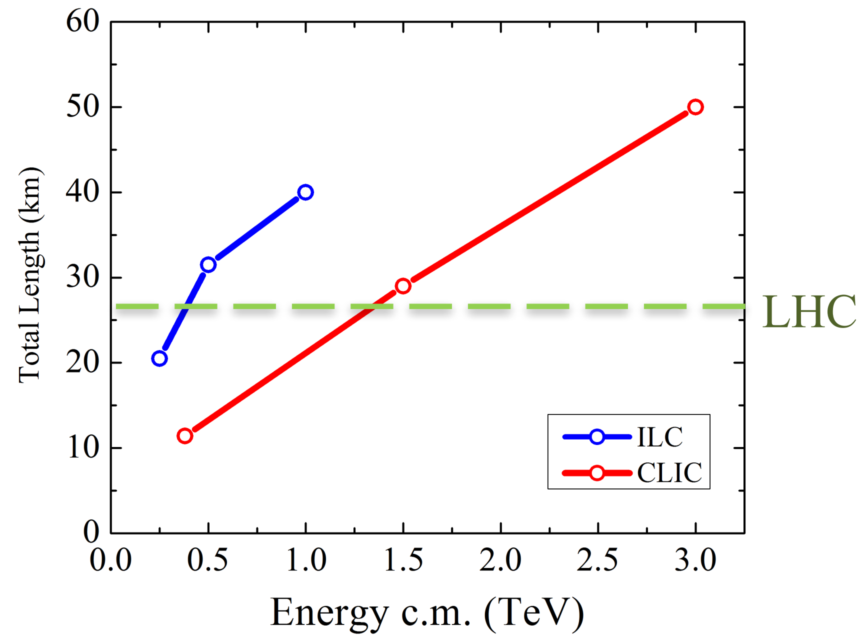
→ Luminosity :

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

Total Facility Site Power Required



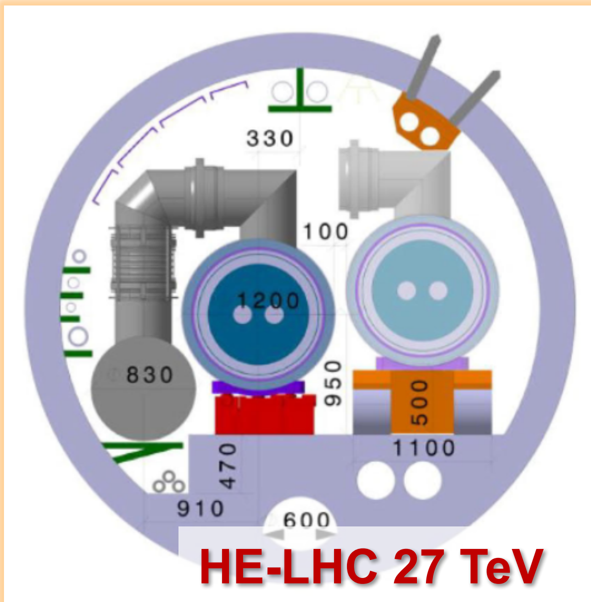
Total Facility Length

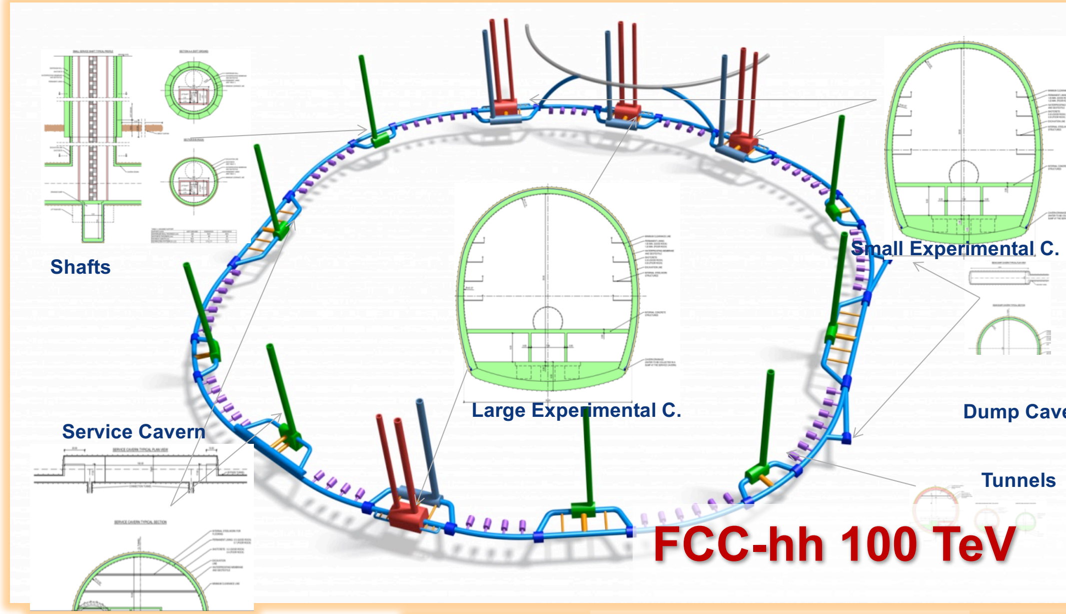


Circular *pp* Colliders

HE-LHC CDR (2018)

FCC-hh CDR (2018)

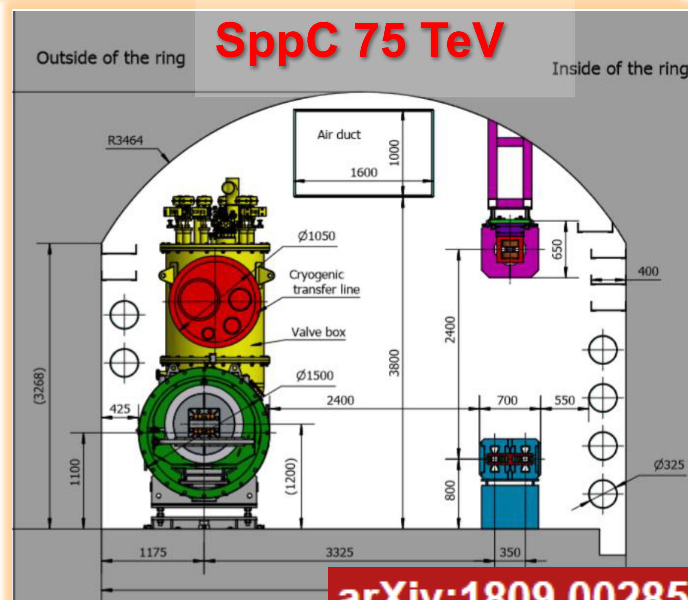




Key facts: *HE-LHC / FCC-hh* / SppC**

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 / ?

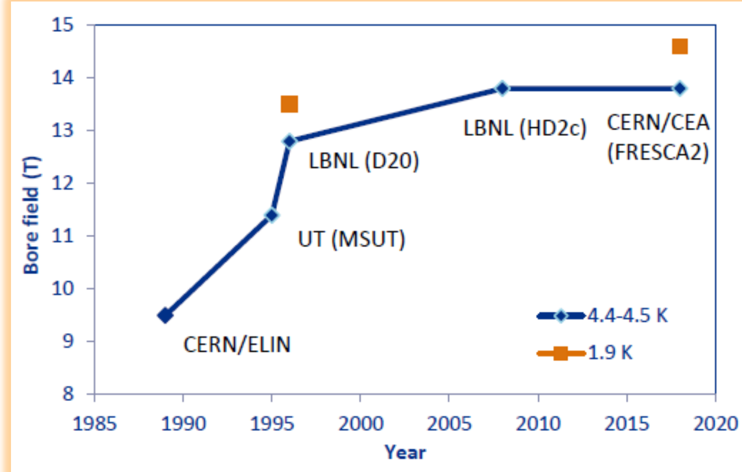
** follow up after e+e- Higgs factories*

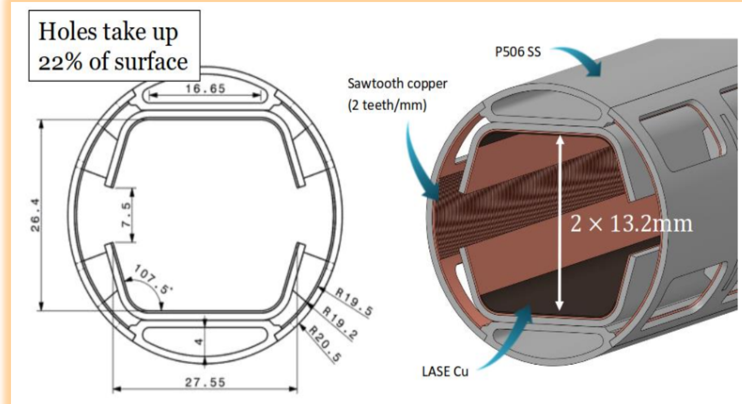


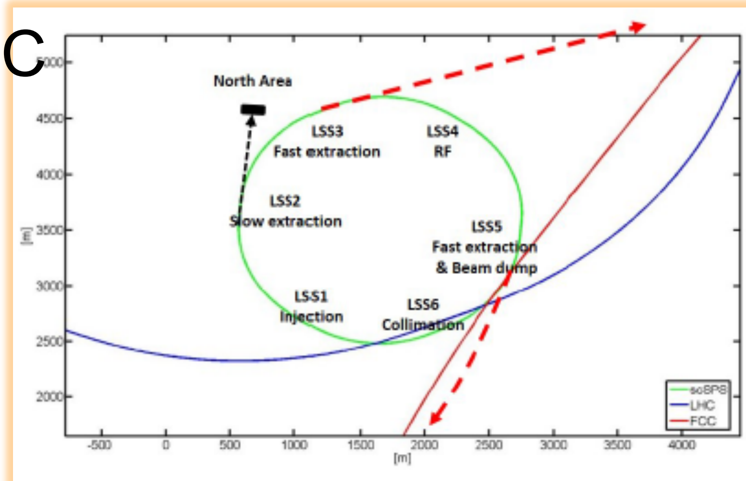
arXiv:1809.00285

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
- *ep/ei* collisions
  - *~60 GeV e- Energy Recovery Linac*

Key facts: *LHeC / FCC-eh*

6-9 km tunnel

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

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

SRF 800 MHz CW

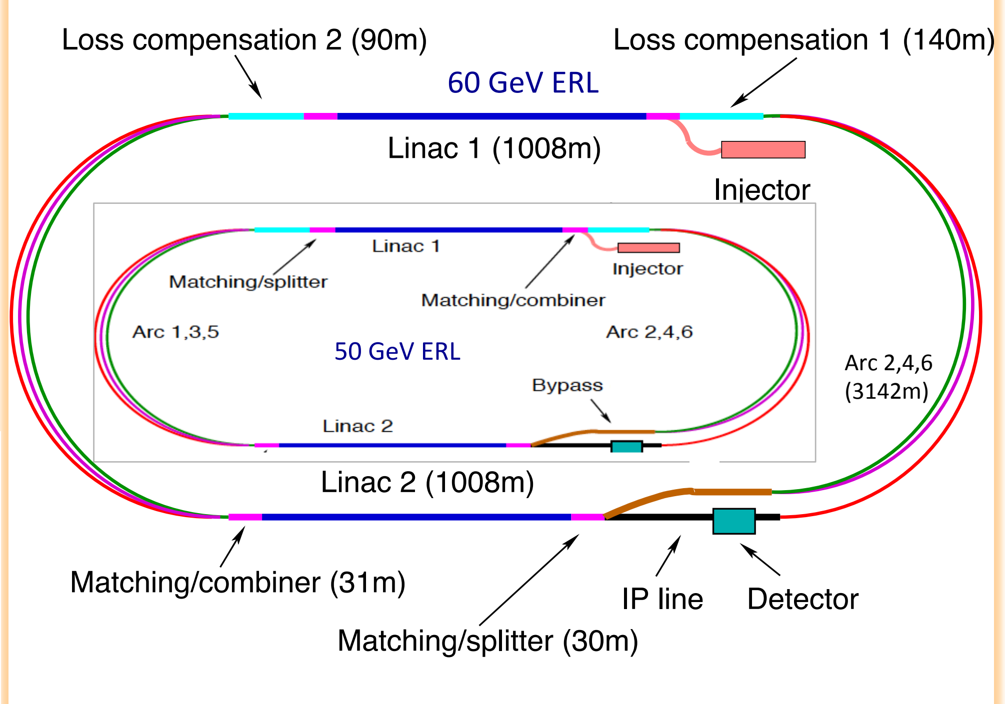
Luminosity $O(10^{34})$

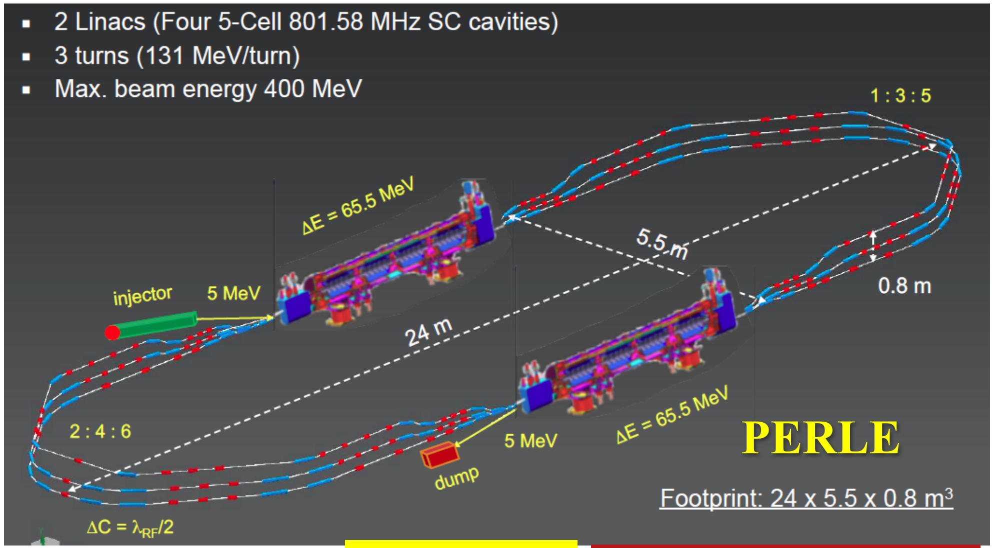
Site power ~100 MW

Cost ~1.3-1.6 BCHF *

Key R&D: PERLE @ Orsay →

arXiv:1810.13022 arXiv:1206.2913 CDR





Input #147 arXiv:1705.08783

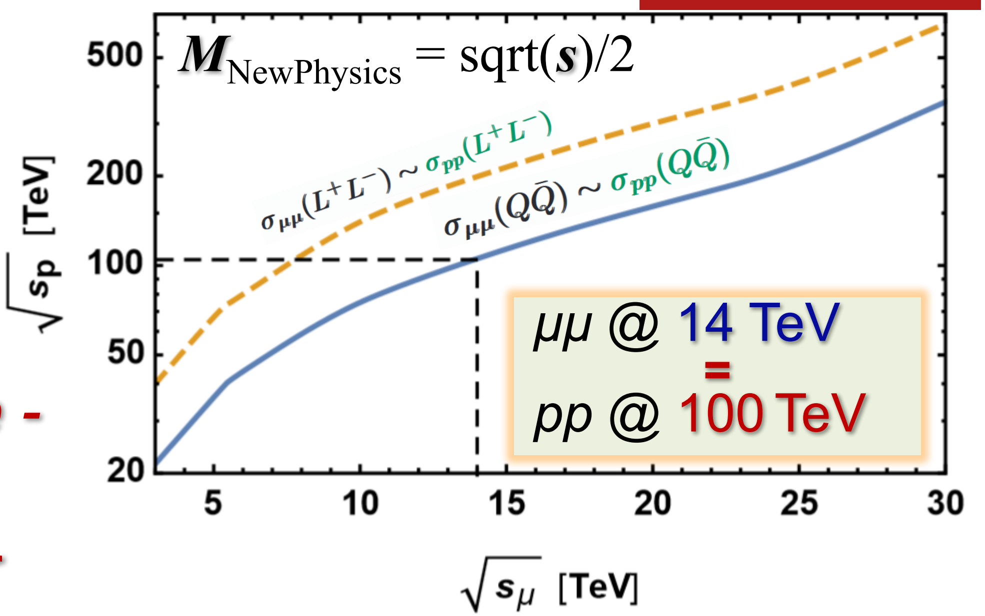
High Energy $\mu+\mu-$ Colliders

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

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

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

Conclusions and outlook

- **Future circular lepton colliders** are **combining concepts and techniques** developed, implemented and **demonstrated by past and present circular colliders**
- **All key technologies and concepts are available** and will profit from design optimization during project preparation and CE construction phases.
  - **Efficient RF power generation and efficient SRF structures**, with benefit for many RF applications
  - **Optimized engineering design** for cost efficient construction, availability, maintainability.
- **Future hadron colliders are based on high-field Nb_3Sn and/or HTS magnets**, whose development represents a challenging **R&D requiring long-term planning and funding**
- **Muon Colliders** require a **strong international effort on R&D** after completing simulation and design studies

Accelerator Technologies advanced in Particle Physics

Type	Acclerator	Op. Years	Beam Energy (TeV)	B [T]	E [MV/m]	Pioneering/Key Technology
CC hh	Tevatron	1983-2011	2 x 0.5	4 T		Superconducting Magnet (SCM)
	HERA	1990 -2007		4.68 T		SCM, e-p Collider,
	RHIC	2000 ~		3.46 T		SCM
	SPS LHC HL-LHC	1981-1991 2008 ~ Under constr.	2 x 0.42 2 x (6.5 >> 7)	(NC mag.) 7.8T -->8.4 11~12		P-bar Stochastic cooling SCM (NbTi) at 1.8 K, SRF SCM (Nb_3Sn), SRF, e-cooling
CC ee	TRISTAN	1986-1995	2 x 0.03		5	SRF (Nb-bulk), SCM-IR-Quad (NbTi)
	LEP	1989-2000	2 x 0.55		5	SRF (Nb-Coating) , SCM-IRQ
	KEKB Super-KEKB	1998~2010 2018 ~	0.002+0.008 0.004+0.007		5 5	Luminosity, SRF Crabbing, SCM-IRQ Luminosity, Nano-beam, SCM-IRQ
LC ee	SLC/PEP-II	1988/98~2009	2 x 0.5			Normal conducting RF
	(Eu-XFEL)	(2018 ~)	(0.0175)		(23.6)	SRF (Nb-bulk)

Technical Challenges in Energy-Frontier Colliders proposed

		Ref.	E (CM) [TeV]	Luminosity [1E34]	AC-Power [MW]	Value [Billion]	B [T]	E: [MV/m] (GHz)	Major Challenges in Technology
CC hh	FCC-hh	CDR	~ 100	< 30	580	24 or +17 (aft. ee) [BCHF]	~ 16		High-field SC magnet (SCM) - Nb3Sn: Jc and Mechanical stress Energy management
	SPPC	(to be filled)	75 – 120	TBD	TBD	TBD	12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
CC ee	FCC-ee	CDR	0.18 - 0.37	460 – 31	260 – 350	10.5 +1.1 [BCHF]		10~20 (0.4 / 0.8)	High-Q SRF cavity at < GHz, Nb Thin-film Coating Synchrotron Radiation constraint Energy efficiency (RF efficiency)
	CEPC	CDR	0.046 - 0.24 (0.37)	32~ 5	150 – 270	5 [B$]		20 (~ 40) (0.65)	High-Q SRF cavity at < GHz, LG Nb-bulk/Thin-film Synchrotron Radiation constraint High-precision Low-field magnet
LC ee	ILC	TDR update	0.25 (-1)	1.35 (– 4.9)	129 (– 300)	< 5.3 > [BILCU]		31.5 – (45) (1.3)	High-G and high-Q SRF cavity at GHz, Nb-bulk Higher-G for future upgrade Nano-beam stability, e+ source, beam dump
	CLIC	CDR	0.38 (- 3)	1.5 (- 6)	160 (- 580)	5.9 [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

Technical Challenges in Energy-Frontier Colliders proposed

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	S[illegible]	(to be filled)			120		12 - 24		High-field SCM - IBS: Jcc and mech. stress Energy management
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	CLIC	CDR	0.38	1.5	160 (- 580)	5.9 [BCHF]		72 – 100 (12)	Large-scale production of Acc. Structure Two-beam acceleration in a prototype scale Precise alignment and stabilization. timing

Major Technical Challenges:

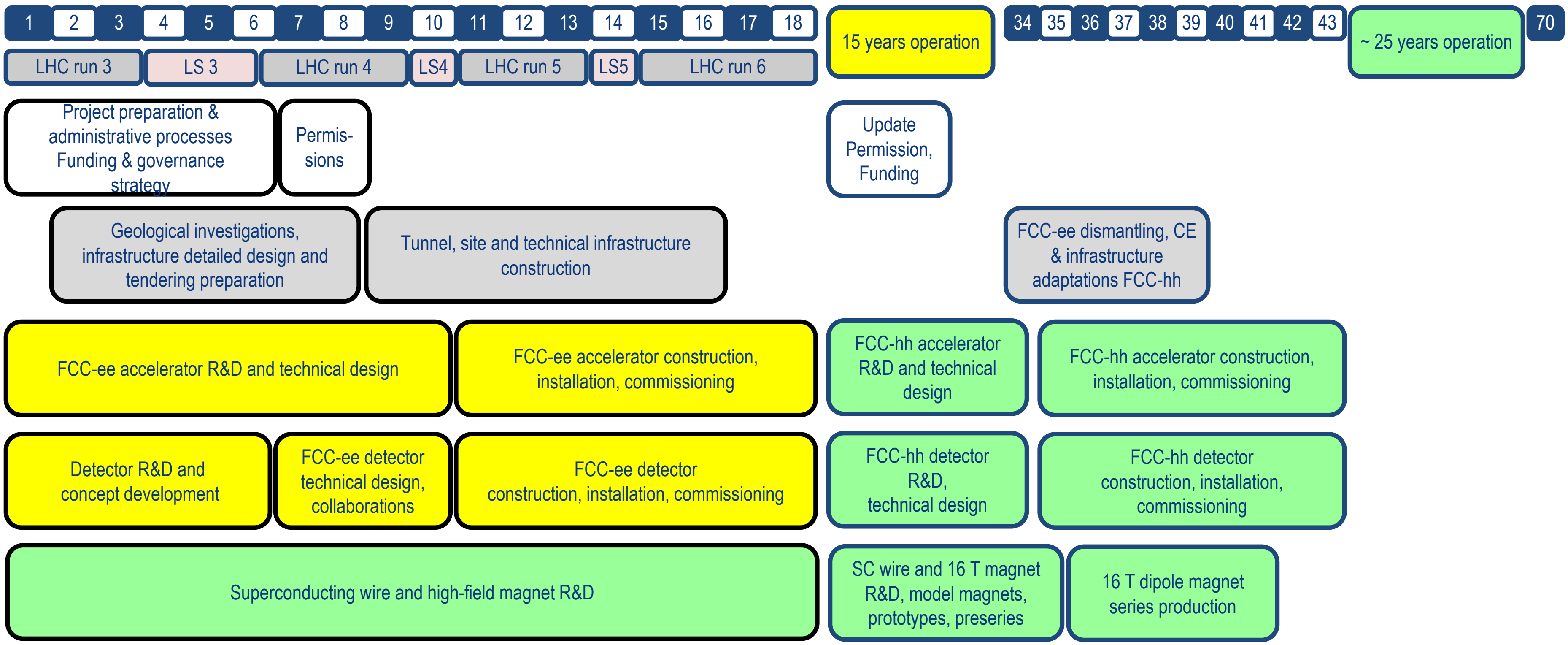
Hadron Colliders:

- High-field magnet
- Energy management

Lepton Colliders:

- SRF cavity: High-Q and -G (to prepare for upgrade)
- NRF acc. Struct.: large scale, alignment, tolerance, timing
- Energy management

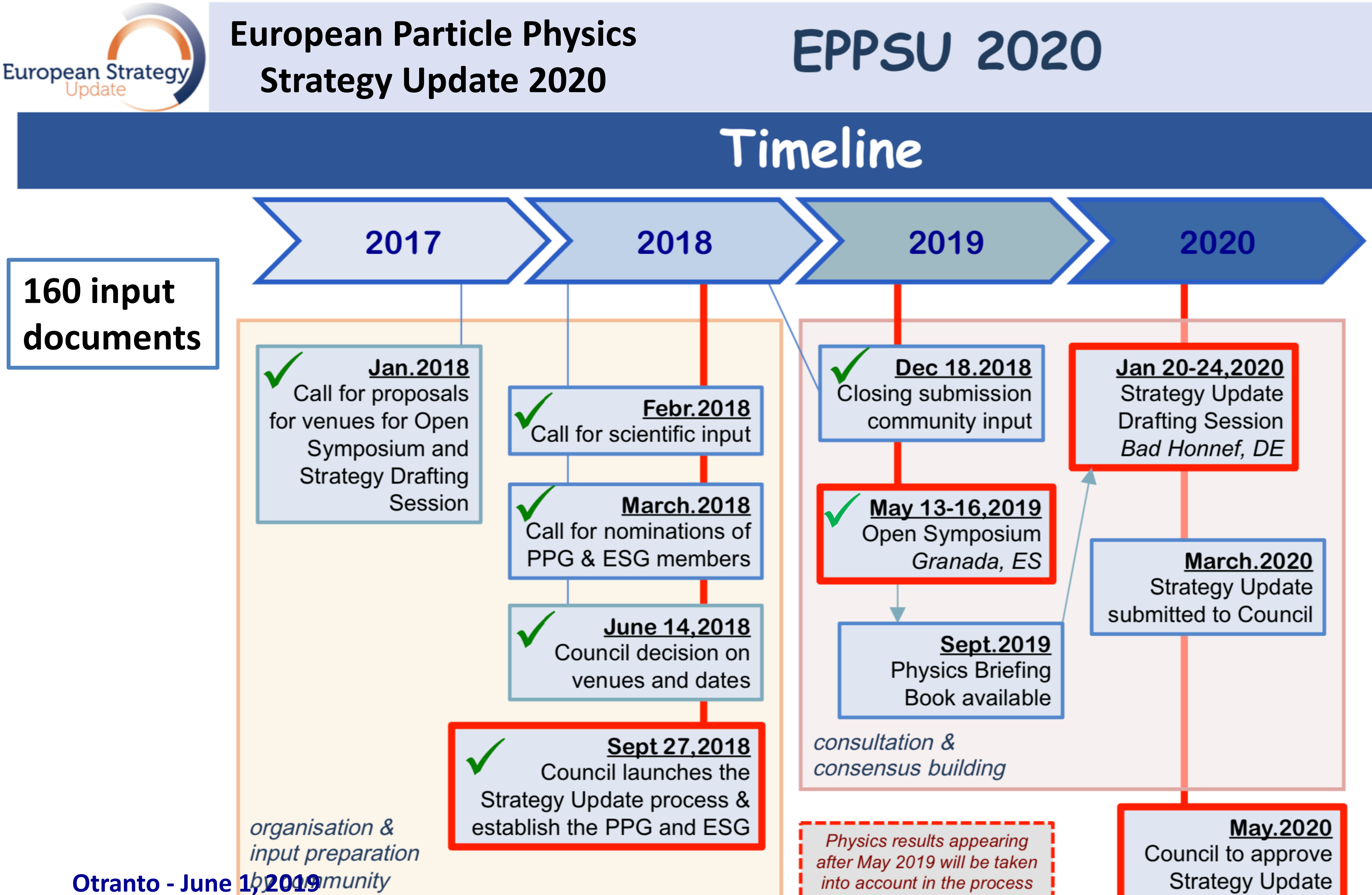
FCC integrated project technical schedule



FCC integrated project plan is fully integrated with HL-LHC exploitation and provides for seamless further continuation of HEP in Europe.

Now drafting the Briefing Book….

160 input documents



Expect Shortage of Expert Accelerator Workforce

- ***"Oide Principle"*** :

  1 Accelerator Expert

  can spend intelligently

  (only) ~1 M$ a year
- \+ it takes significant time to get the team together (XFEL, ESS)
- Scale of the team: 10B$/10 years=1 B$/yr → need 1000 experts ← world's total now ~4500

K.Oide (KEK)