The ESS Linac to create a Muon Collider

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Premise

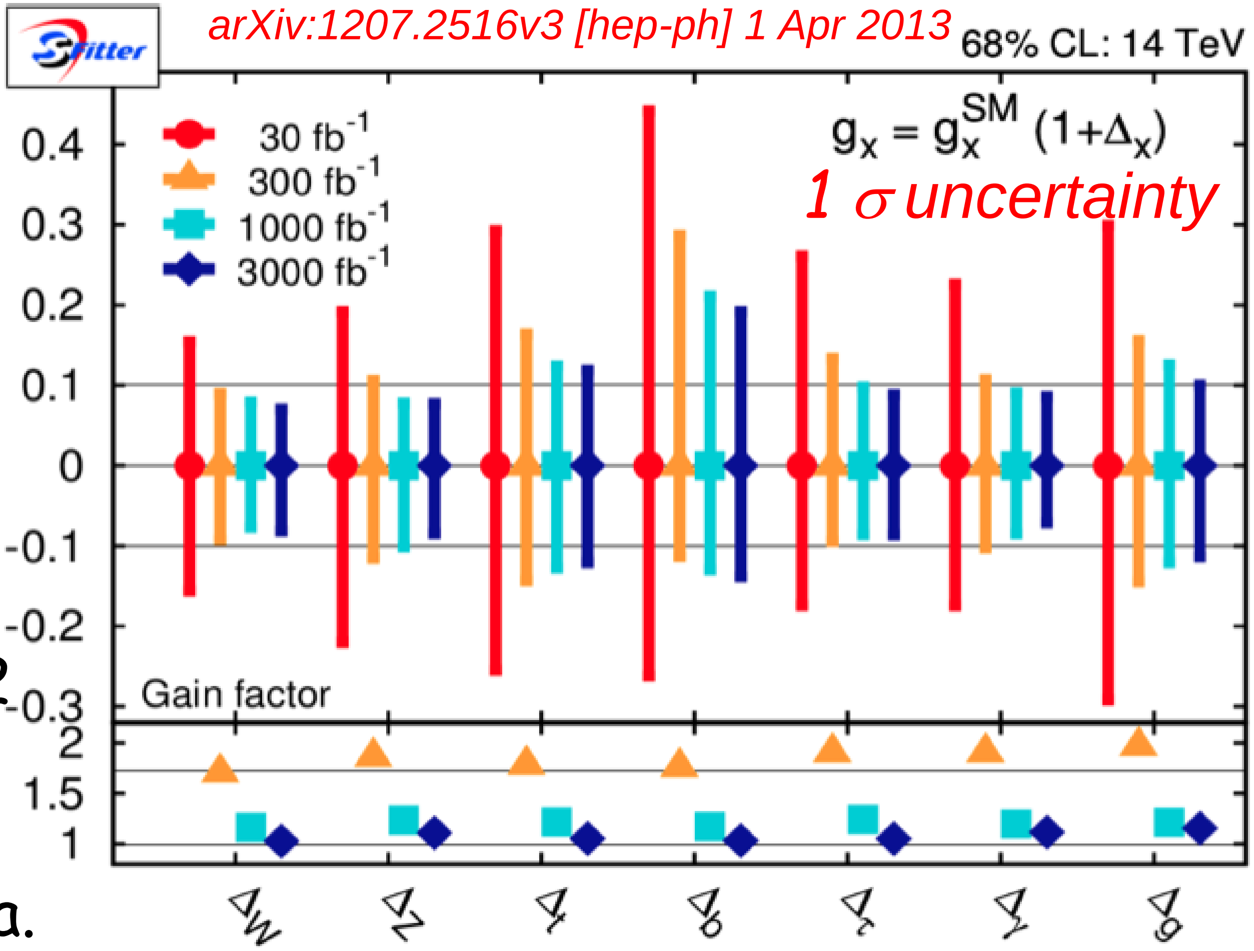
- The experimental discovery of the Higgs particle has required with LHC and the associated detectors a construction time of $\frac{1}{4}$ of a century and an investment of ≈ 10 billion $.
- The liability of hadrons is that they are complex objects with correspondingly complicated interactions that limit their usefulness as probes of short distance structure, both in fixed target and colliding beam experiments.
- A new, huge e+e- collider, for instance in China or at CERN, is a likely novel option, but with very long timescale and huge costs. *Short term approval and construction are rather unlikely.*
- In this paper we suggest that muon beams may be used instead as primary probes, since they combine a "point-like" electron-like nature with a large mass sufficiently immune to radiation.
- The large phase space area of a muon beam can be adequately compressed using "ionization" cooling for instance at the ESS.

A new scalar particle

- The LHC will continue as a future program for Higgs studies. See for instance CERN-LPCC-2018-04 : *Higgs Physics at the HL-LHC and HE-LHC. (fentobarn = 10^{-39}, attobarn = 10^{-42} cm^2)*
- The integrated luminosity for the HL-LHC will be 3000 fb^{-1} = 3 ab^{-1} at 14 TeV. A subsequent higher energy program HE-LHC may follow with a dataset assumed to be 15 ab^{-1} at 27 TeV.
- However, in spite of its huge progress, HL-LHC — even followed by HE-LHC requires also further extensions with lepton beams.
- The Higgs sector (Ho) — no doubt — should follow the well-known previous observations of the Zo and the W's, where the initial search and discovery with the P-Pbar collider has been followed by the systematic lepton studies with LEP.
- The Zo and W's are vectors, while the Higgs is a *scalar* (spin = 0) characterized by a much stronger coupling when initiated from muons rather than from electrons colliders.

Ultimate LHC uncertainties are due to systematic effects

- Higgs estimates reflect the LHC detectors accumulating 300 fb–1 of data, dominated at this level by systematic errors of the ATLAS and CMS collaborations at the best understanding.
- ATLAS and CMS have estimated signals also for 3000 fb–1 from the High-L LHC.
- Note that the progress is very slow and that about a factor < 2 in precision is expected from a factor 100 in data.



arXiv:1207.2516v3 [hep-ph] 1 Apr 2013

1 σ uncertainty

Unambiguous discoveries require 5 σ

Future, large lepton colliders for the Higgs sector

- The Higgs sector requires *another step after the LHC*.
- *LEP3*, a new circular e+e− Higgs factory has been proposed for the LHC tunnel. It would have the advantage of reusing existing infrastructure and experiments, with vastly increased luminosities at the Z, WW and of about L = 10^{34} at the Higgs.
  - However LEP3 has also (i) the impossibility of a precise energy calibration at the WW threshold; (ii) the inability to measure the top-quark properties; and (iii) the lack of a wider perspective for subsequent energy-frontier explorations
- *New e^+e^- colliders* at L > 10^{34}, of huge size, like for instance
  - a ≈ 100 km ring 4x the LHC *(FCC-ee. CEPC)*, but limited to $\sqrt{s} < 250$ GeV, thus missing many Higgs-strahlung and Higgs-Higgs boson diagrams;
  - a Linear Collider (CLIC), eventually to $\sqrt{s} \approx$ 2TeV and ≈ 50 km. This is a major new technology which needs to be developed.
- A *muon collider* is the preferable alternative of much lower cost

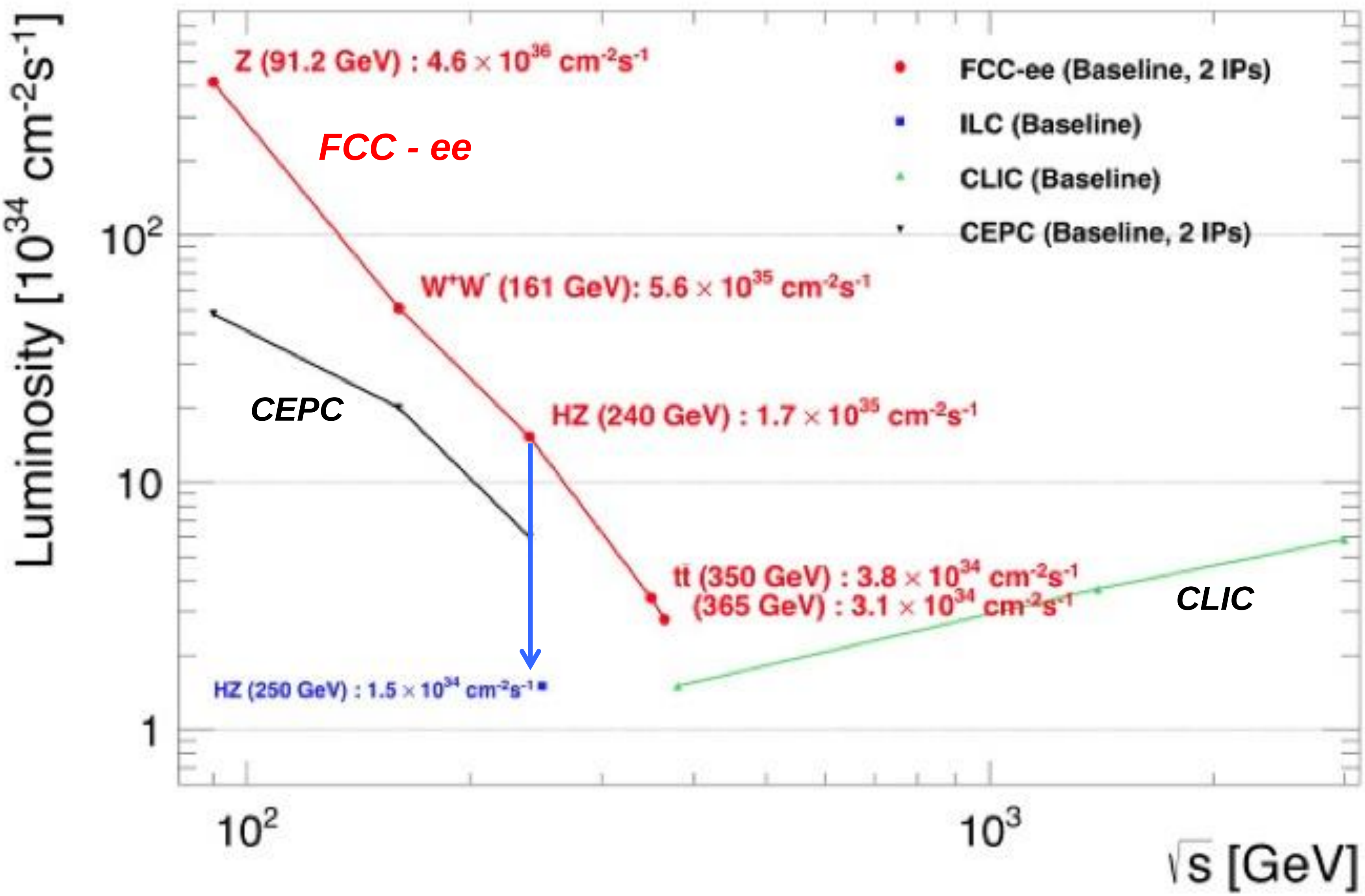
LEP3 vs LEP2

- LEP3 in the LHC tunnel offers e+e- collisions at 240 GeV at 100x the LEP2 luminosity. The beam power is limited to 50 MW/beam by a RF voltage of 9.0 GV/turn. The rms. β_y at collision point is reduced from 5 cm to 1 mm and beam lifetime from 6 h to 12 m.

	LEP2	**LEP3**	**Ratio LEP3/LEP2**
E_b beam energy	104.5 GeV	120 GeV	1.15
beam current	4 mA (4 bunches)	7.2 mA (3 bunches)	1.80
total # e-/beam	2.3e12	4.0e12	1.74
SR power/beam	11 MW	50 MW	4.55
energy loss per turn	3.408 GeV	6.99 GeV	2.05
total RF voltage	3641 MV	9000 MV	2.47
beam-beam tune shift (/IP)	0.025, 0.065	0.126, 0.130	5.04, 2.00
average acc. field	7.5 MV/m	18 MV/m	2.40
effective RF length	485 m	505 m	1.04
RF frequency	352 MHz	1300 MHz	3.69
$b_{x,}$* rms	1.5 m	0.15 m,	0.10
b_y* rms	5 cm	1 mm	1/50
IP beam size x,y	270, 3.5 micron	55, 0.4 micron	0.20 , 0.11
rms bunch length	1.61 cm	0.30 cm	0.19
peak luminosity/IP	1.25×10^{32} cm-2s-1	1.33×10^{34} cm-2s-1	106.4
number of IPs	4	2	2/4
beam lifetime	6.0 hours	12 minutes	1/30

Blondel, Zimmermann . arXiv:1112.2518v1

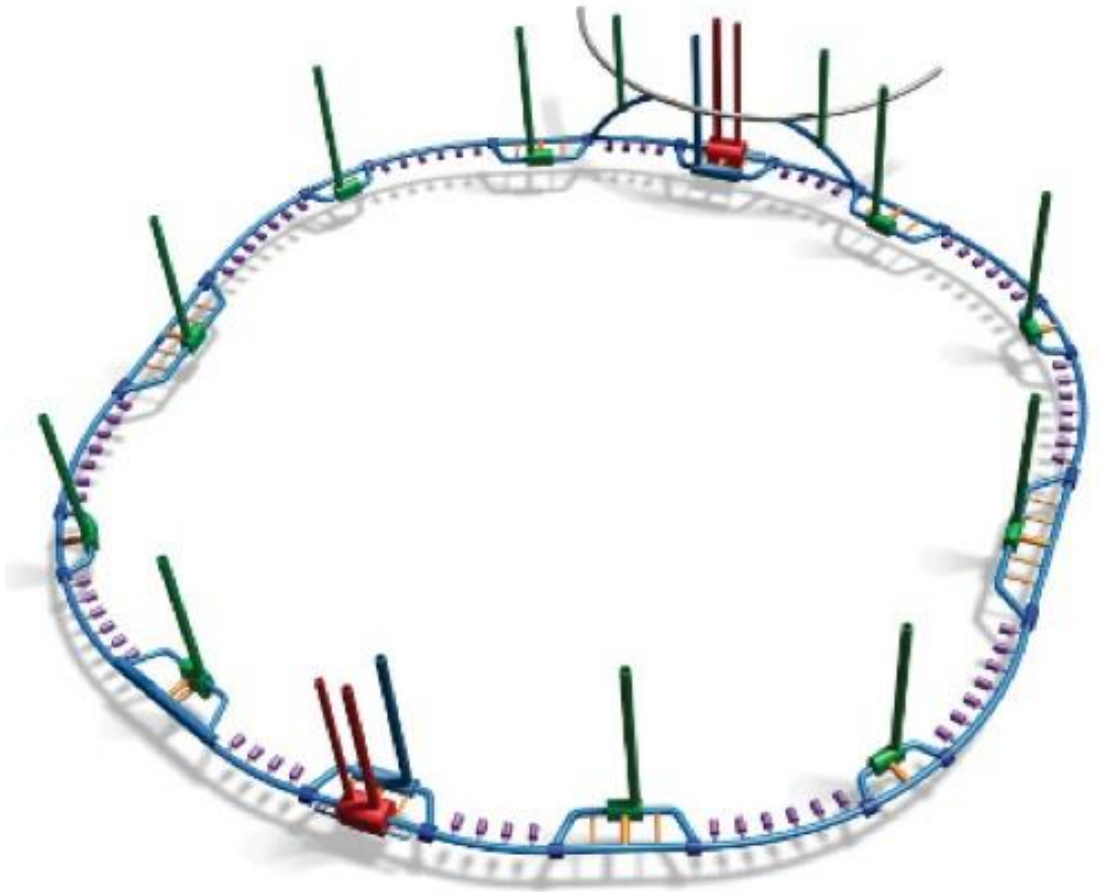
Very large future e+e- colliders

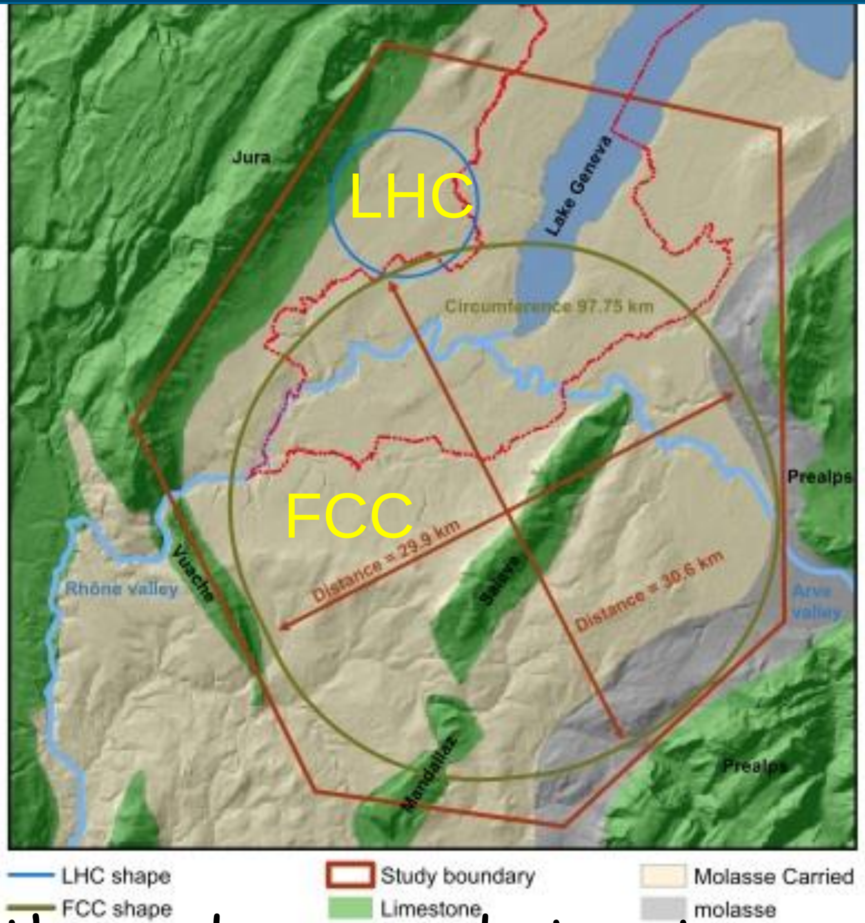


FCC future projects at CERN (today's prices)

- FCC-ee, the future e+e−Circular Collider in a new ~100 km tunnel at CERN can study the entire electroweak (EW) sector (Z and W bosons, Higgs boson, top quark) with √s from 88 to 365 GeV.
- The total capital construction *without experiments* amounts to 10'500 MCHF (Z, W and Higgs) + 1'100 MCHF for the t-tbar working point (total 11'600 MCHF). Civil engineering is 5'400 MCHF (51%), technical infrastructure are 2'000 MCHF (19%) and the accelerator construction is 3'100 MCHF (30%).
- FCC-hh as a single pp project amounts to 24'000 MCHF. Collider investments amount to 13'600 MCHF (57%) of which the 4700 Nb3Sn 16T dipoles are 9'400 MCHF (39%); civil engineering 6'000 MCHF (25%). The the technical infrastructures is 4'400 MCHF (18 %). If after FC-ee, the subsequent cost is 17 000 MCHF.
- After termination of HL-LHC (circa 2034) the programs FCC-ee followed by FCC-hh require, without detectors, an investment of 28'600 MCHF for 70 years, i.e. until the end of the 21st century.

FCC civil engeneering

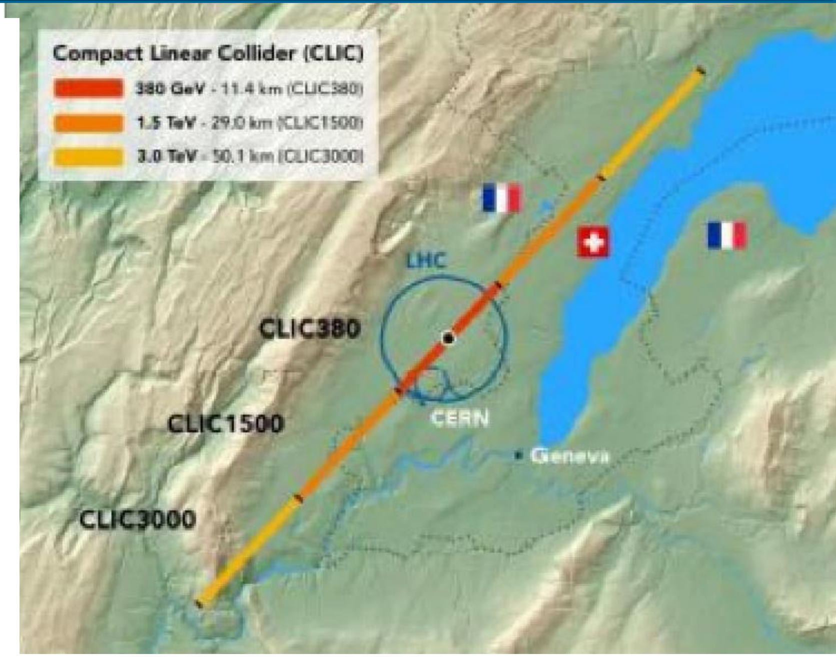


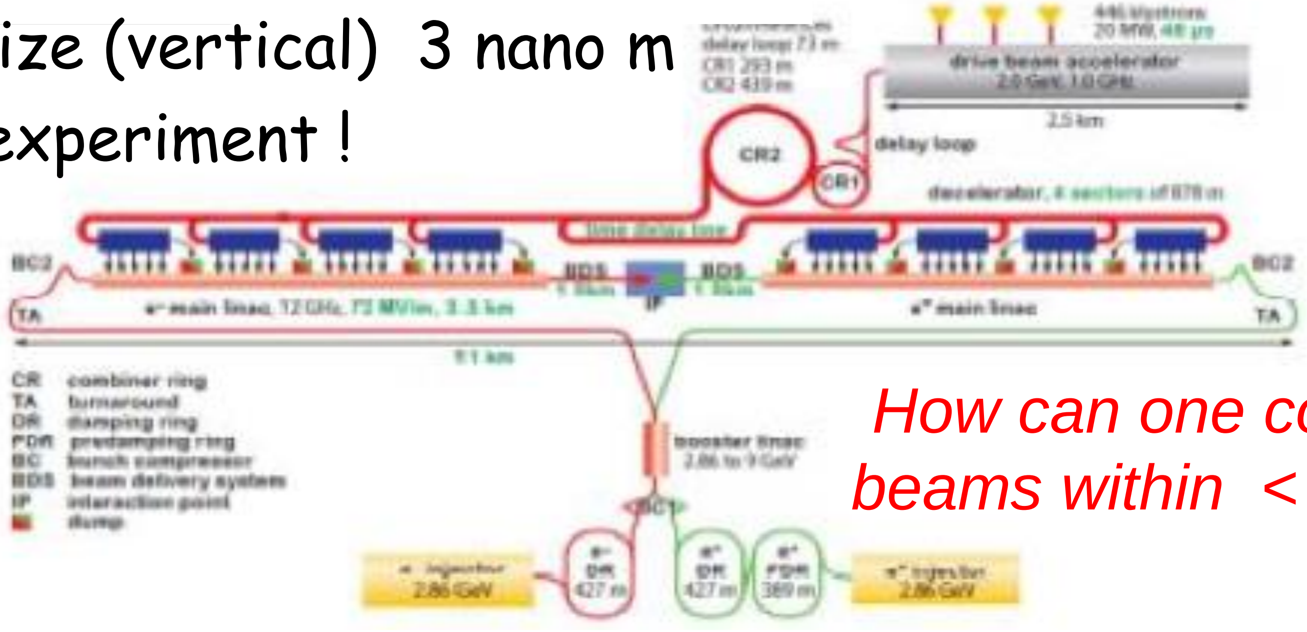


- Left: 3D, not-to-scale schematic of the underground structures.
- Right: boundary (red polygon), LHC (blue) and FCC tunnel (brown)
- Approximately 8 km of bypass tunnels, 18 shafts, 14 large caverns and 12 new surface sites are also planned.

CLIC

- Initial energy 2E = 380 GeV
- Cost ≈ 6700 MSF
- 2020 Decision
- 2020-2025 Preparation phase
- 2025 Construction starts
- 2035 first beams
- 2.2×10^{12} e+e- at 50 hz and $L = 10^{34}$
- IP beam size (vertical) 3 nano m
- Only one experiment !



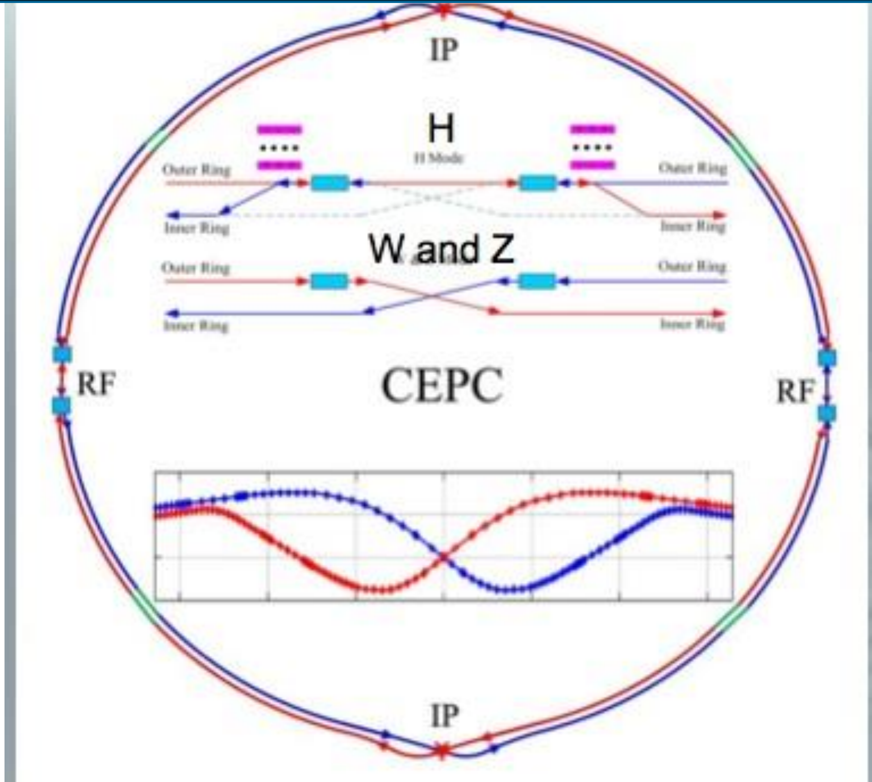


How can one collide two beams within < 0.003 μ ?

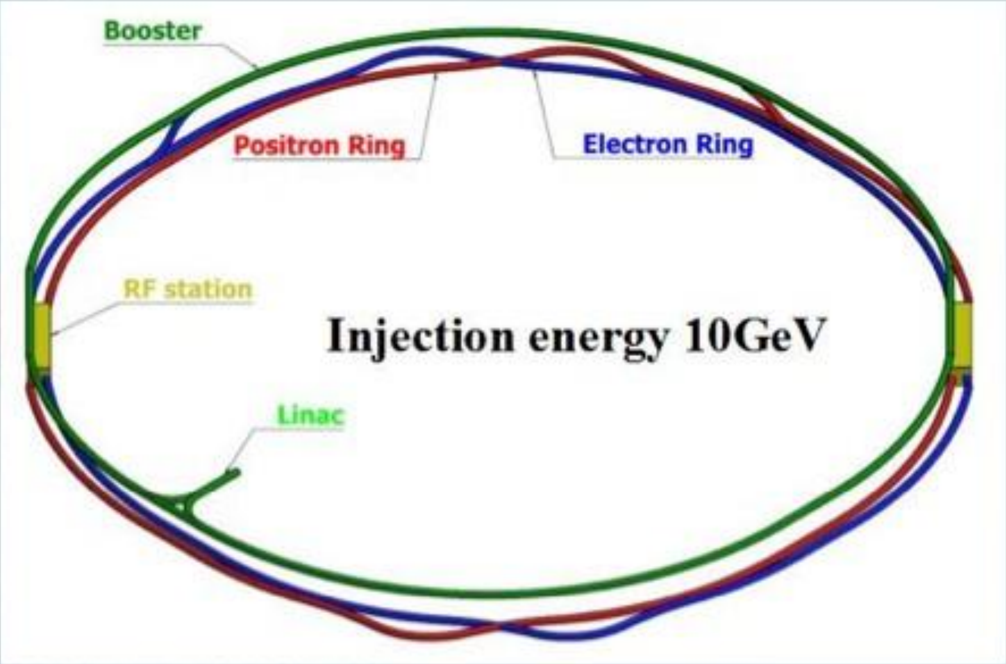
CEPS and SPPC progams in China

- Chinese scientists propose CEPC, the 240 GeV Circular Electron Positron Collider — a e +e– collider located in a 100 -km deep underground tunnel and two large detectors for Higgs studies.
- The accelerator complex consists of a 10 GeV LINAC, damping ring (DR), the Booster, the Collider and several transport lines.
- Like the FCC at CERN, CEPC is producing more than one million Higgs particles. Operation at 91 GeV and at 160 GeV will produce one trillion Z and about 15 million. W + W – pairs
- The Conceptual Design Report (CDR) has been completed in 2018. The on going Technical Design Report (TDR) will be completed by 2022. Construction may start in 2022 and completed by 2030.
- *Experiments can begin as early as 2030* and continue for about 10 years until 2040. The tunnel also hosts a Super Proton Proton Collider (SPPC) where high field SC magnets in excess of 70 TeVwill be installed after 2040

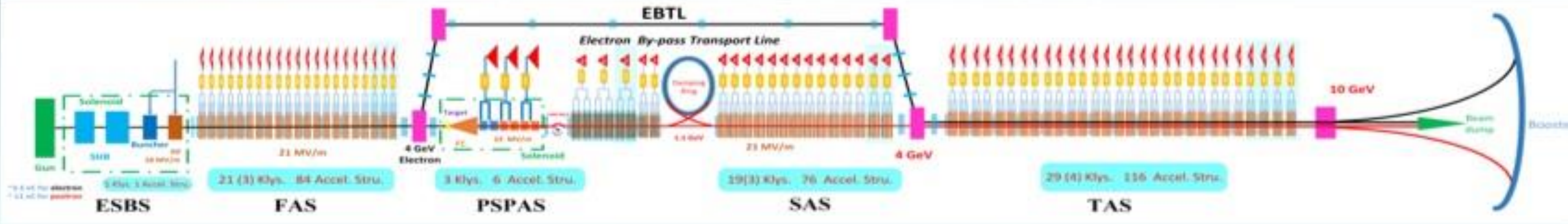
CEPC layout



CEPC collider ring (100km)



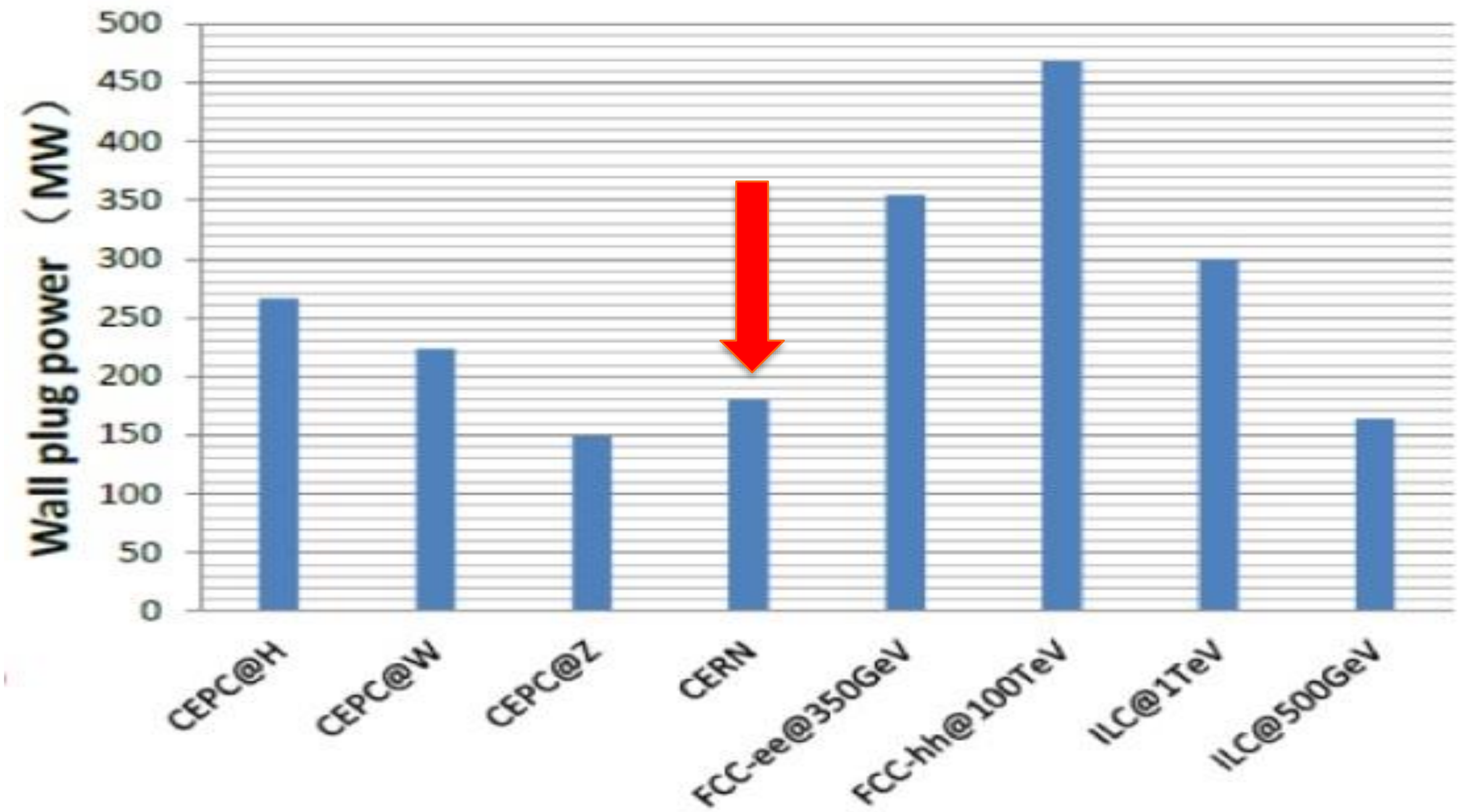
CEPC booster ring (100km)



CEPC Linac injector (1.2km, 10GeV)

Wall powers (MWatt)

- CERN has a typical yearly consumption of about 1.2 Twatt-hours, one third of the consumption of the Canton of Geneva (5 x 10^5 p)
- LHC consumes roughly half of CERN's electricity. A large proportion keeps the superconducting magnets at -271° C



CEPC FCC CLIC

A muon collider as an optimal alternative

- Muons combine a "point-like" electron-like nature with a larger mass immune to radiation.
- ***A $\mu+\mu-$ collider*** is therefore highly preferable because of its small dimension which permit the utilization of an existing site.
- However it demands a substantial R&D in order to produce adequate compression in 6D phase space of the muon beams.
- Muons are unstable particles, decaying into electrons and neutrinos. These backgrounds must be hampered.
- To this effect an additional experimental program based on a small Cooling Ring should be initiated.
- The whole muon collider program could be concluded with a reasonable extension of the ESS, well before the end of the HL-LHC or the CEPC programs

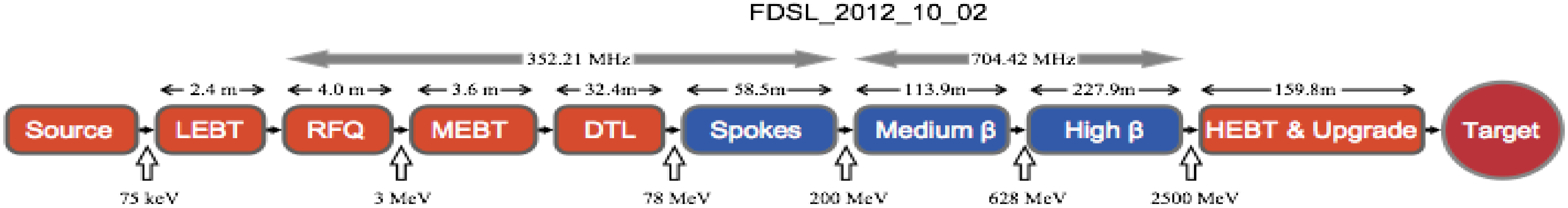
Liouvillian and not liouvillian forces

- Already in the fifties at MURA it was realised that some beam phase-space compression may often be necessary going from the source to the collision point.
- The Liouville theorem states that whenever there is a Hamiltonian (i.e. the force is derivable from a potential) the six dimensional phase space of the beam (q_i, are positions and p_i conjugate momenta) are preserved, namely, $dV/dt = 0$, since the rate of change of volume has to be equal to the volume integral of its divergence.
- This is a very powerful constrain since both magnetic and electric fields in accelerators (conservative forces) are generally all derivable from a Hamiltonian.
- In order to introduce some compression in the beam during acceleration we must provide for a dissipative non-Liouvillian drag force working against the particle speed *and not derivable from a Hamiltonian.*

Muon cooling

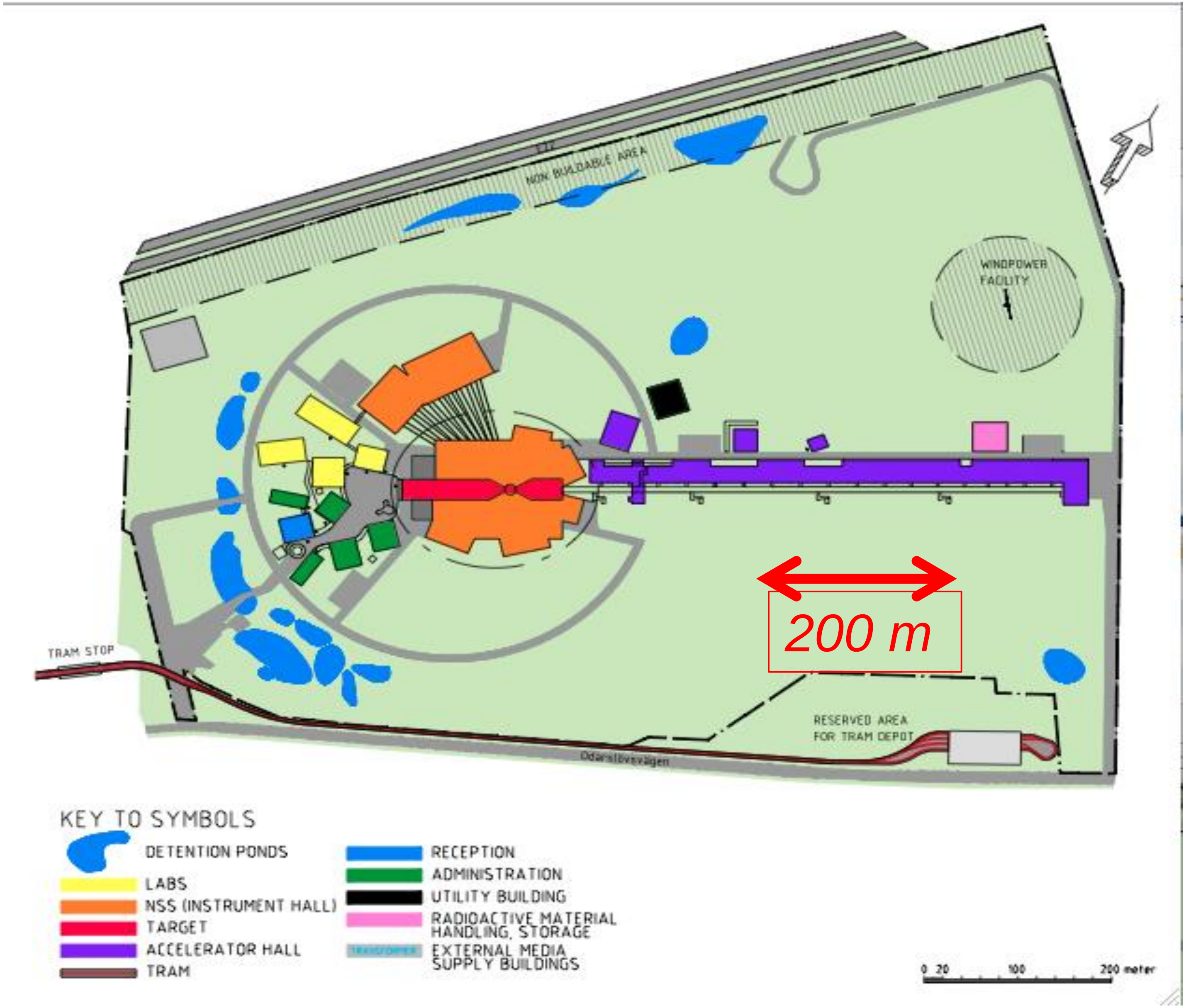
- "Ionization Cooling" was first proposed by Budker and by Skrinsky in the 60's and early 70's. However, there was little substance until Skrinsky and Parkhomchuk developed the idea.
- The initial ideas in the US were presumably due around 1980 to Cline and Neuffer. A Snowmass feasibility study has been organized in 1996 and a US collaboration with DOE organization and funding has been formed in 1997.
- As discussed already in 1994 for instance by Barletta and Sessler, muons may be produced by the two classes of processes:
  - *(A) production from protons, subsequently decaying into muons*
  - *(B) $\mu+\mu-$ pairs from electro-production*.
- During the following two decades Neuffer, Palmer, Cline and many others have greatly expanded ionization cooling of process (A).
- These have been very important developments, but only very few verifying experimental tests have been performed.

The ESS: the muon collider for Europe ?



- The European Spallation Source, now in construction in Lund, with 5 MWatt of protons accelerated to a kinetic energy of 2 GeV at 14 Hz and 1.1 x 10^{15} p/p can be extended to provide intensity and repetition rate for the presently discussed collider program,
- Several other accelerator programs at higher energies for μ+μ- factories have been described in the US (both BNL and FNAL) and elsewhere, all requiring substantial intensity improvements.
- Amongst the many LHC upgrade programs which have been discussed, CERN had also considered the HP-HPL, a H- beam at 5 GeV kinetic energy with 50 Hz, 4 MWatt and 1.0 x 10^{14} p/ pulse.
- However in 2010 CERN has decided on different alternatives and HP-HPL project has been cancelled. ESS remains the main option.

The ESS site


NON BUILDABLE AREA
WINDPOWER FACILITY
TRAM STOP
200 m
RESERVED AREA FOR TRAM DEPOT
Odarslövsvägen
KEY TO SYMBOLS
DETENTION PONDS
LABS
NSS (INSTRUMENT HALL)
TARGET
ACCELERATOR HALL
TRAM
RECEPTION
ADMINISTRATION
UTILITY BUILDING
RADIOACTIVE MATERIAL HANDLING, STORAGE
EXTERNAL MEDIA SUPPLY BUILDINGS
0 20 100 200 meter

Present and future options of the ESS

- ESS will accelerate 2.86 ms long and 62.5 mA proton pulses at 14 Hz and 2 GVolt kinetic energy (p = 2.784 GeV/c, β_p = 0.9476, γ_p = 3.131) with 1.1 x 10^{15} p/pulse and 5.0 Mwatt as a facility for spallation neutron production. First neutrons foreseen soon.
- The duty cycle of the accelerator complex is 4%. Additional space (≈ 160 m) may permit to bring the energy up to 3.5 GeV.
- Major new developments are possible by further additions of the already approved intense source of spallation neutrons.
- As future options,the LINAC repetition could be doubled from 14 Hz to 28 Hz with additional 5 MWatt to new facilities, bringing the duty cycle of the LINAC from 4% to 8%..
- In order to compress with an accumulator ring to short pulses, a multi-turn LINAC injection with negative H- is performed with thin absorbing foils or of an appropriate LASER beam.
- Because of large power, both methods require conclusive proof.

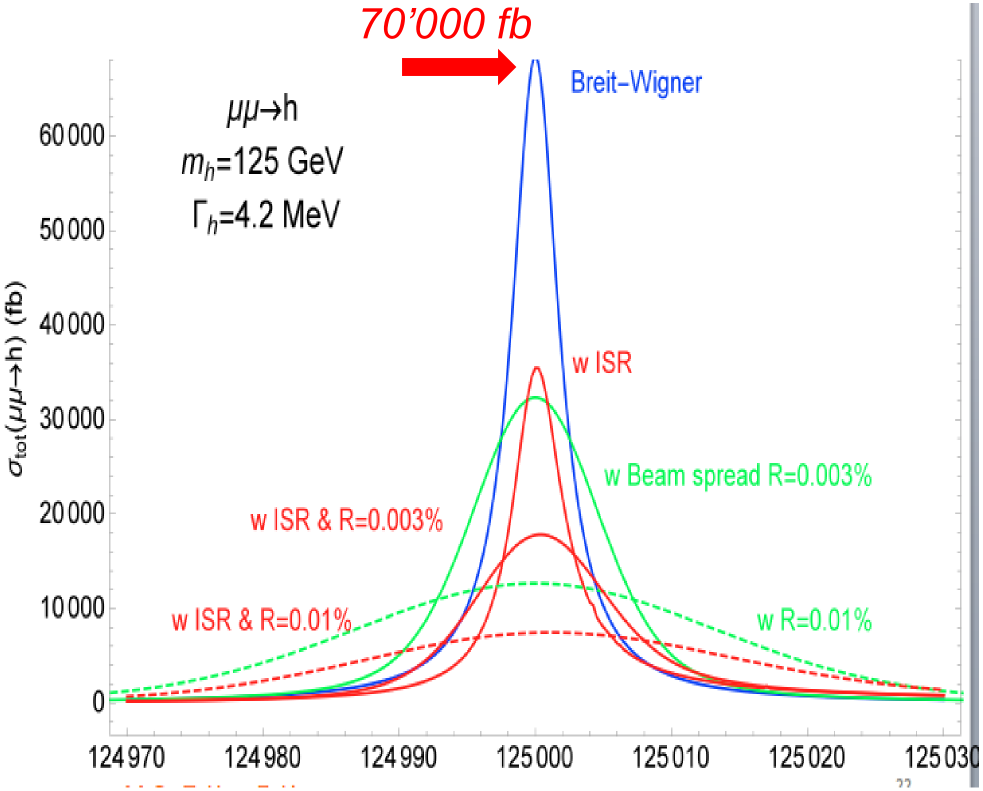
Two μ+ μ– future alternatives for the Higgs physics

- Two adequate alternatives of a $\mu+\,\mu-$ collider will be discussed:
  - the s-channel resonance at the Ho mass, to study with ≈ 40'000 fb and $L > 10^{32}$ all decay modes with small backgrounds;
  - A higher energy collider, eventually up to $\sqrt{s} \approx 0.5$-1 TeV and $L > 10^{34}$ to study all other Higgs processes of the scalar sector.
- The colliding beams ring can easily fit within existing locations:
  - For $\sqrt{s} = 126$ GeV the ring *radius is ≈ 50 m* (about 1/2 of the CERN PS or 1/100 of LHC) but with the *resolution ≈ 0.003%*
  - For $\sqrt{s} = 0.5$ TeV the corresponding ring *radius is ≈ 200 m* (about twice the CERN PS) and the *resolution ≈ 0.1 %*
- Two $\mu+\,\mu-$ bunches of 2×10^{12}ppp can likely be produced by a high pulsing rate of a few GeV protons at ≈ 5 MWatt (ESS).

Comparing μ+μ- and e+e- at the Ho resonance peak

- The narrow Ho width may be quantified convoluting the Breit-Wigner resonance with a gaussian Beam Energy Spread (BES) and the Initial State Radiation (ISR) QED effects.
- The *μ+μ- cross sections* are 71 pb for resonance profile alone and of 10 pb and 22 pb with both BES and ISR and energy resolution R = 0.01 % and R = 0.003 %. (1 pb = 10^{-36} cm^2)
- The e+e- cross sections are 0.15 fb for both the BES and ISR effects and R = 0.01 %.
- *In these conditions, the μ+μ- is ≈ 100'000 times the e+e- cross section.*

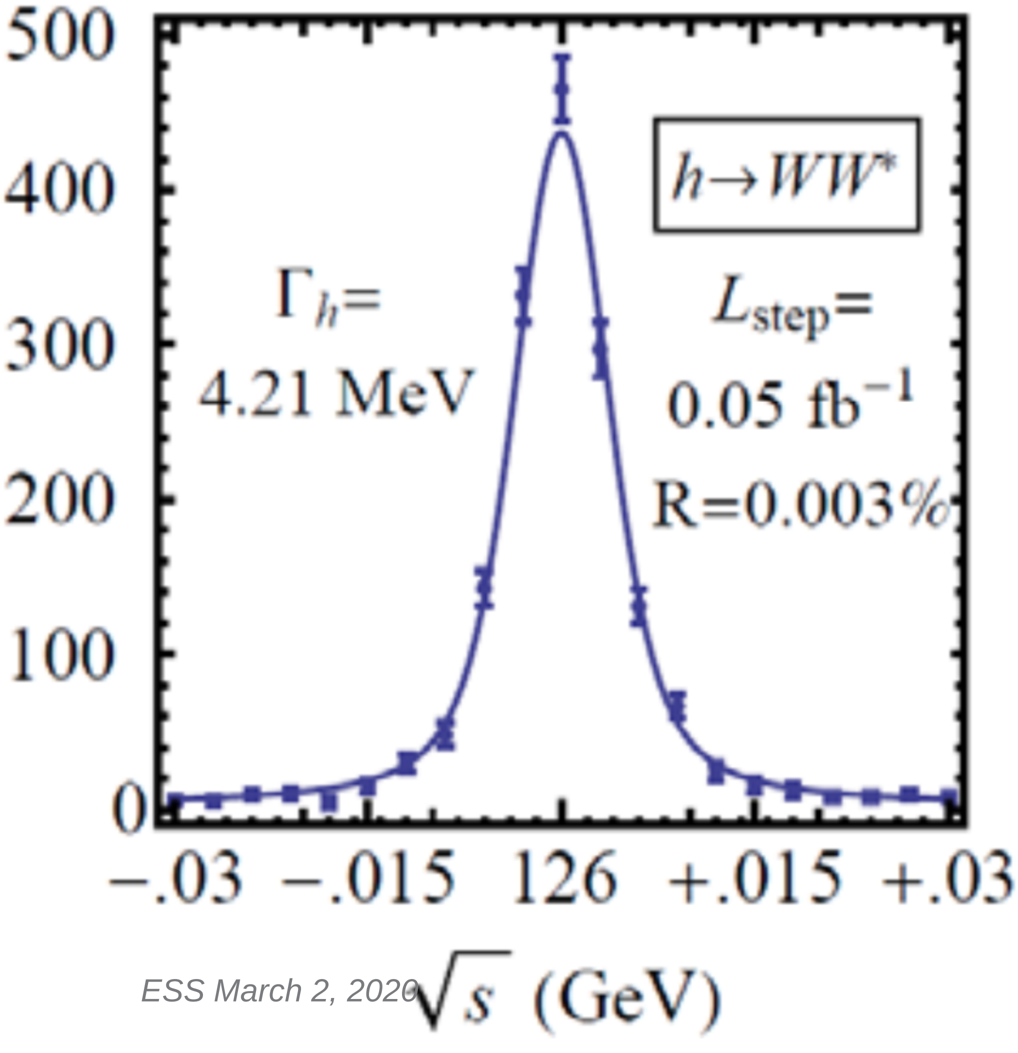
1 femtobarn (fb) = 10^{-39} cm^2

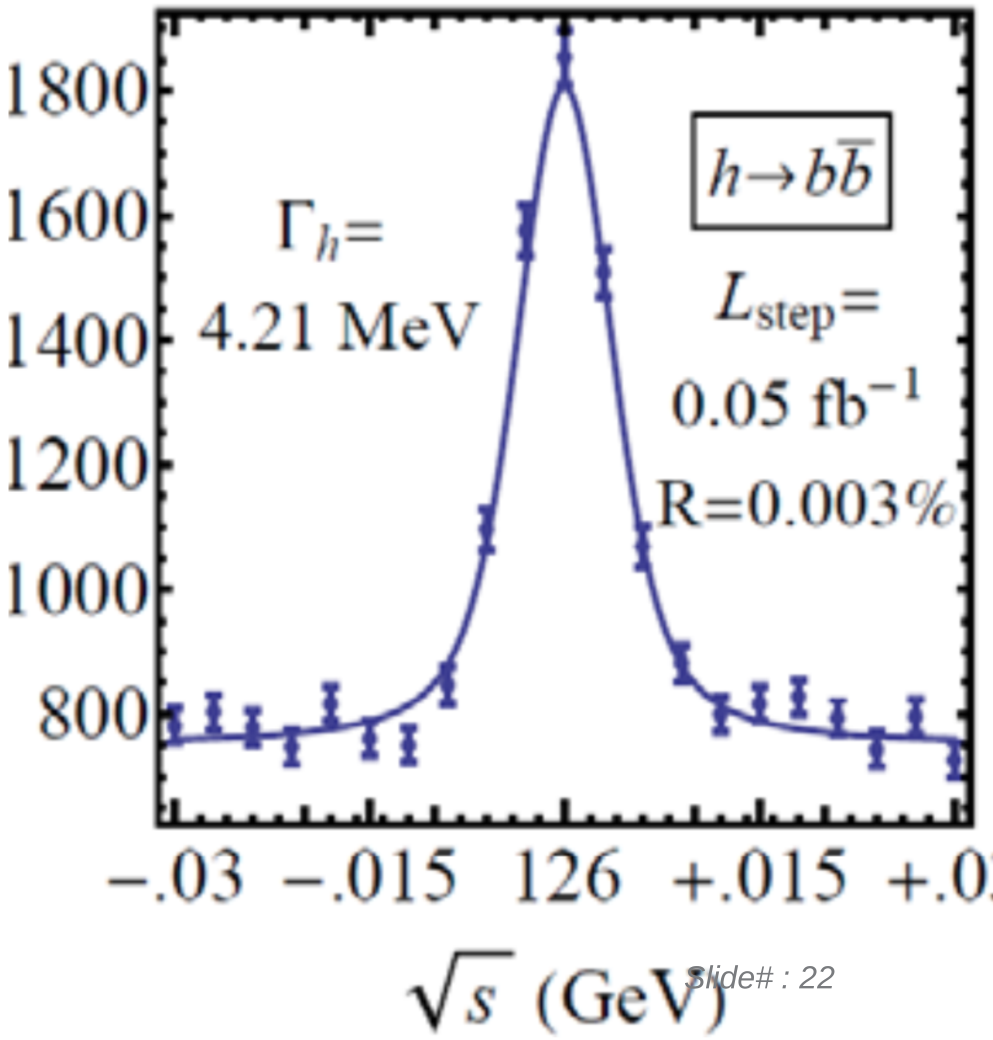


Huge BES an ISR correctins

√s = 125.5 GeV : the Higgs muon resonance

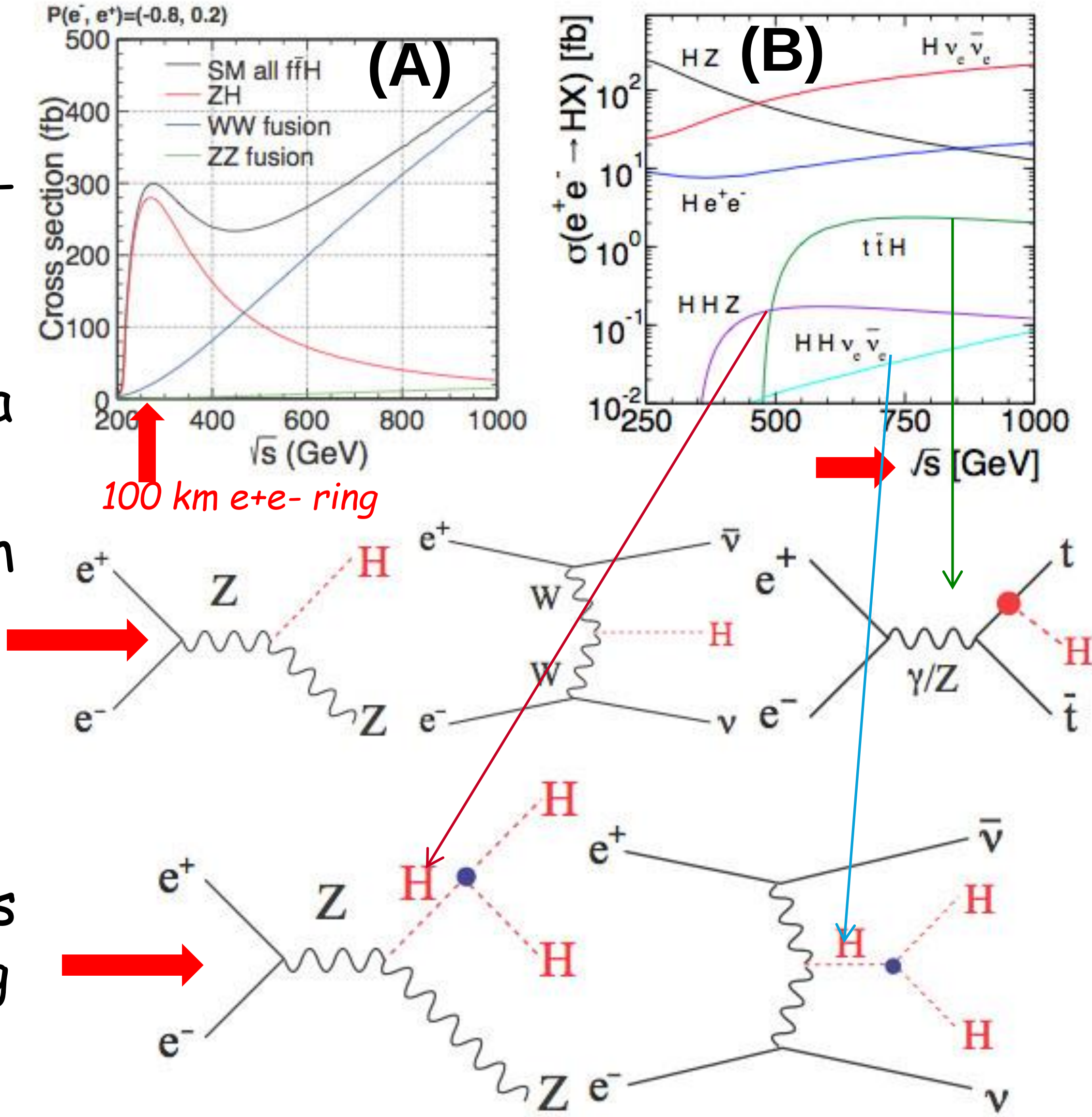
- Signals and backgrounds for H → WW∗, and bb with energy resolution R = 0.003%. with a Gaussian energy spread Δ = 3.75 MeV and 0.05 fb^{-1}/step and with detection efficiencies included.





Studies at the Ho peak are not entirely sufficient:

- We need in addition :
- **(A)** Production cross sections of WW, ZZ, ZH fusion from e+-e- as a function of √s
- **(B)** Production cross sections from e+-e-or µ+-µ- -> H + X as a function of the √s energy
  - ➢ The Higgs-strahlung diagram (Left), the W-boson fusion process (Middle) and the top-quark association (Right).
  - ➢ Double Higgs boson diagrams via off-shell Higgs-strahlung (Left) and W-boson fusion (Right) processes



100 km e+e- ring

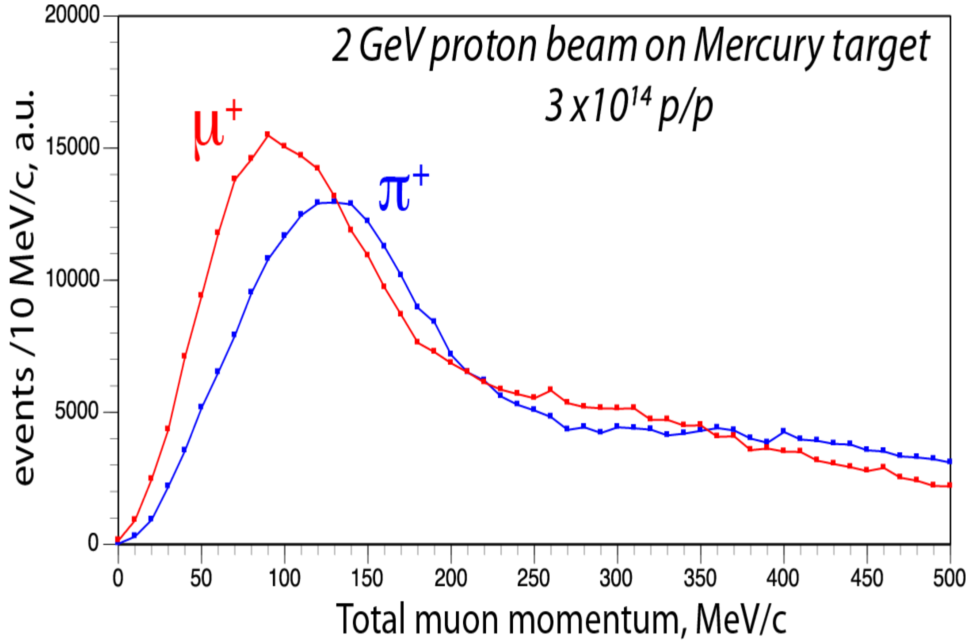
Lepton energies up to ≈ 0.5 - 1 TeV are necessary

Intense muon beams for Higgs studies

- The ***ESSμSB project*** is based on the production, accumulation and cooling for a future facility *of intense muon beams* to study the Higgs related scalar sector.
- A practical $\mu + -\mu -$ Higgs factory as a next facility consists of
  - a high-intensity H^- source feeding p-compressor rings;
  - a p□$\pi - \mu$ decay channel at a optimal muon momentum compression to about 220 MeV/c;
  - a robust $\mu^{\pm}$ ionization-cooling system, compressing the bunches in 6D;
  - a fast recirculating LINAC acceleration system to bring muons to the required energy where collisions are recorded;.
  - a $L \approx 10^{32}$ cm^{-2} s^{-1} $\mu^+ - \mu^-$ collider ring at the Higgs mass and a $L \approx 10^{34}$ cm^{-2} s^{-1} $\mu^+ - \mu^-$ collider in the sub-TeV range.
- The large ESS proton intensity is directly related to the relatively short muon lifetime

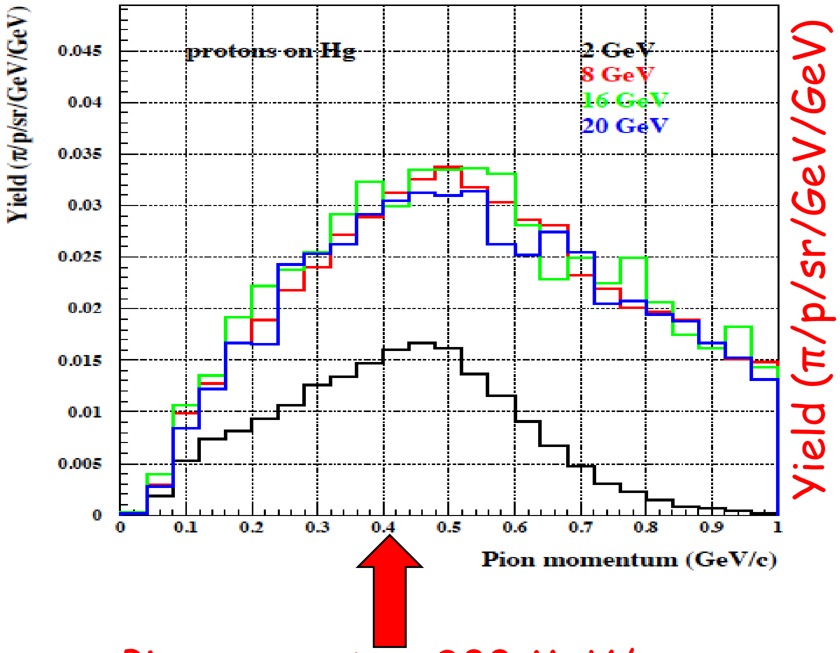
ESS production at 2.0 GeV

- A GEANT4 simulation has been used for charged pion and kaon in a mercury target at the kinetic energy of 2.0 GeV.
- The 3.3×10^{14} p/pulse generate 3.85×10^{13} π+/pulse and 2.64×10^{13} π-/pulse in the forward direction with respect to the beam and a transverse momentum at production < 250 MeV/c. The peak of the momentum distributions is at about 120 MeV/c.
- The π are decaying with a mean lifetime of ct = 7.8 m, corresponding to path of 8.94 m at the most probable momentum of 160 MeV/c
- The μ have ct = 659.1 m, and the longer decay length of 1370 m at 220 MeV/c



The proton rings

- The rate of the ESS- LINAC may be doubled to 28 Hz.
- Two proton rings of 35 m radius, the "*Accumulator*" collects the LINAC pulse and the "*Compressor*" steers the bunch to 1.5 ns.
- The beam transfer from the LINAC to the Accumulator is performed by a multi-turn injection of negative [p+2e-] ions, stripped at the entrance of the Accumulator ring, either with a thin absorbing carbon foil or of an appropriate LASER beam.
- The pion spectrum produced by a given "proton power" (the number of protons inversely proportional to its energy) is nearly independent of proton kinetic energy between 8 and 20 GeV and a only a factor two lower for 2 GeV.



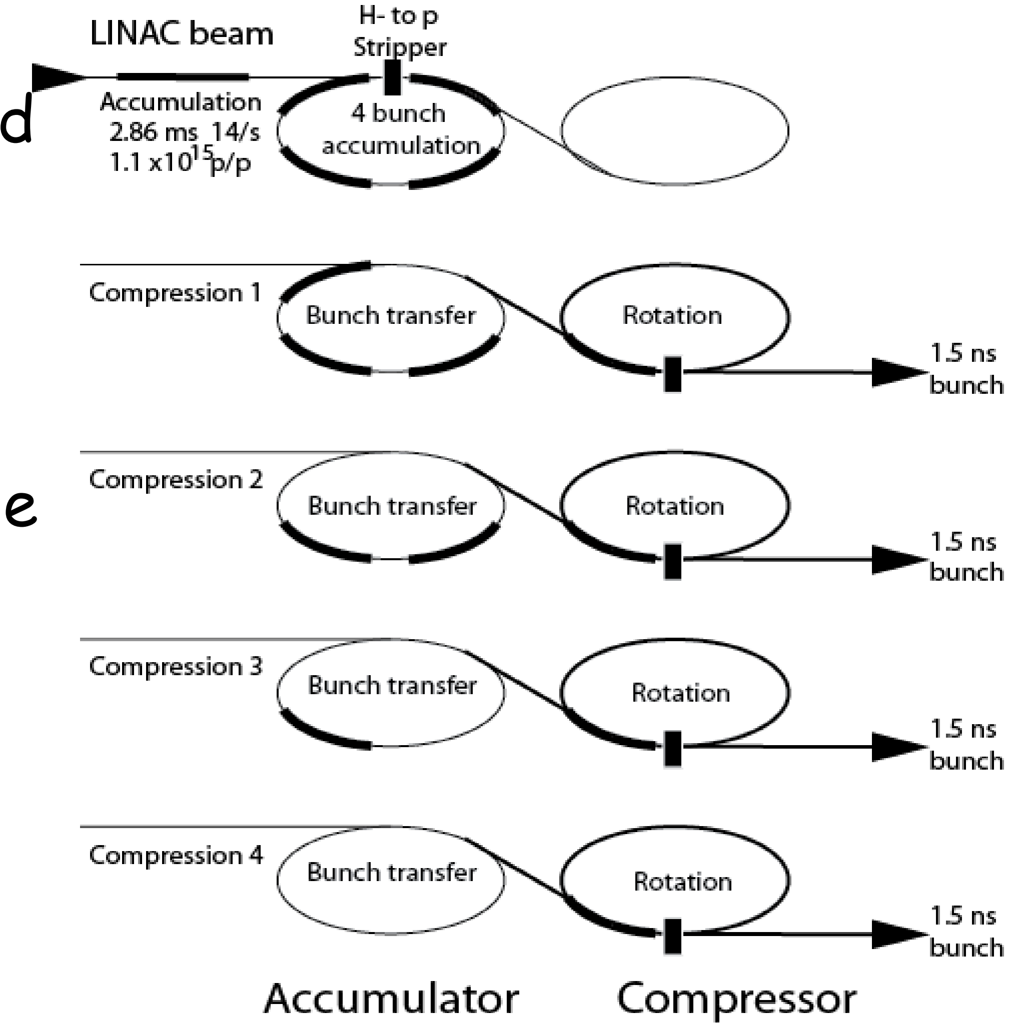
Yield (π/p/sr/GeV/GeV)

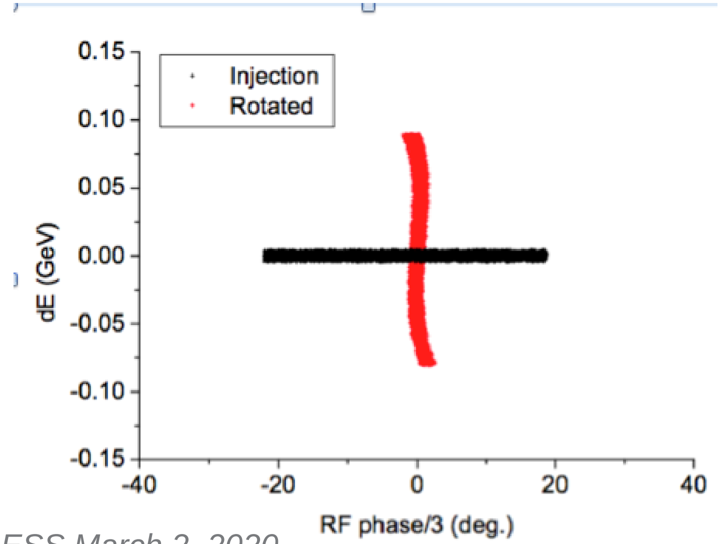
P. Sala: prediction

Pion momentum 300 MeV/c

Accumilator and compressor rings for H-

- In order to make use of a 5 MWatt/pulse from the ESS and the requirement of 1.5 ns long proton pulses, 2 coupled rings (Accumulator and Compressor) may subdivide the beam pulse into four pulses and operate the secondary beam at 4 x 14 = 56 Hz and a 17.8 ms bunch rate.



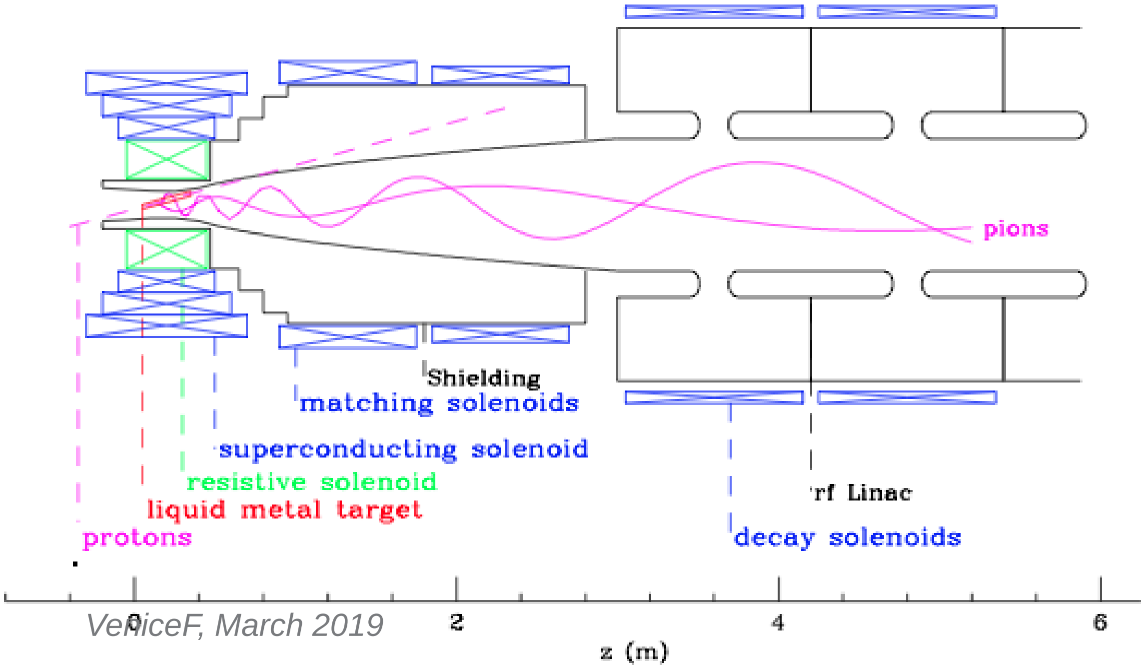


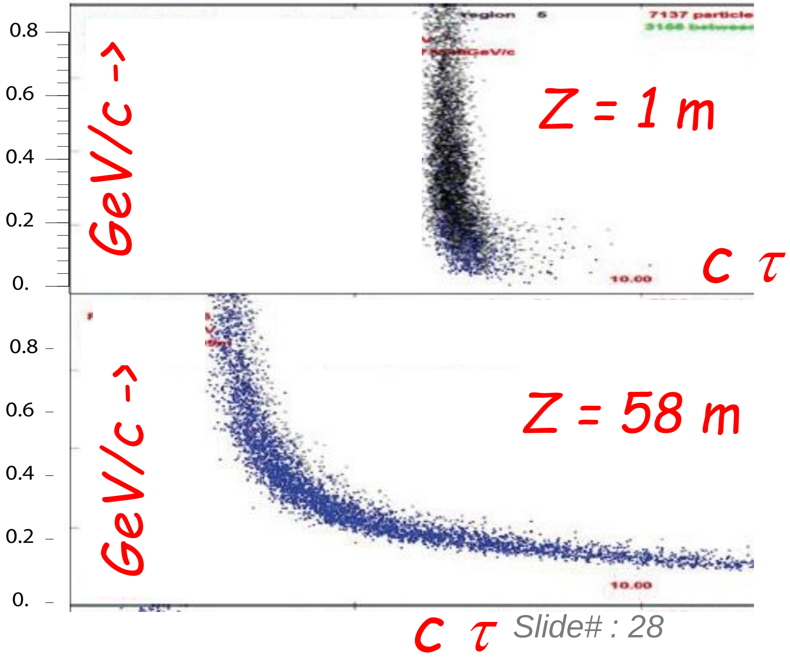
Rings have 35 m radius, wth 4 pulses of 120 ns each separated by 50 ns.

Pion target and focussing in a axially symmetric B field

- Liquid metal target is immersed in high field solenoid (20 T)
  - Proton beam is oriented with about 20° with respect to axis
  - Particles with $p_t < 0.25$ GeV/c are trapped (about ½ of all)
  - Pions decay into muons
  - Focussing both signs of particles
- The MERIT/CERN experiment has successfully injected a Hg-jet into a 15-T solenoid

Pions/muons drifting as a function of c τ

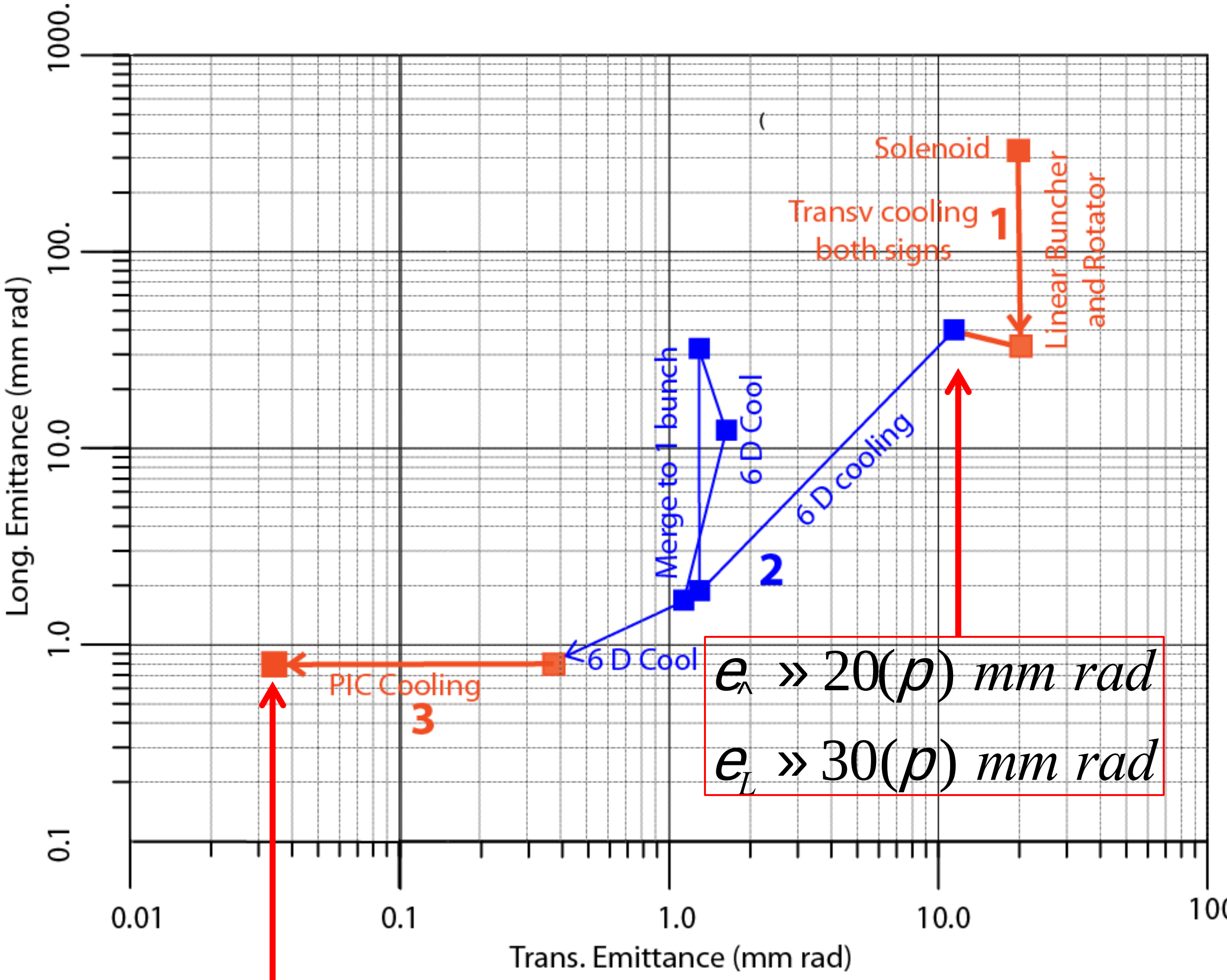




The cooling process

- Three successive steps are required in order to bring the cooling process at very low energies, after capture and bunching + rotation.

1. Linear transverse cooling of both signs and small Δp increase.
2. Ring cooling in 6D with B brings the μ+ and μ- to a reasonable size Merging and cooling to single bunches
3. Parametric Resonance Cooling (PIC), where the elliptical motion in *x-x'* phase space has become hyperbolic.



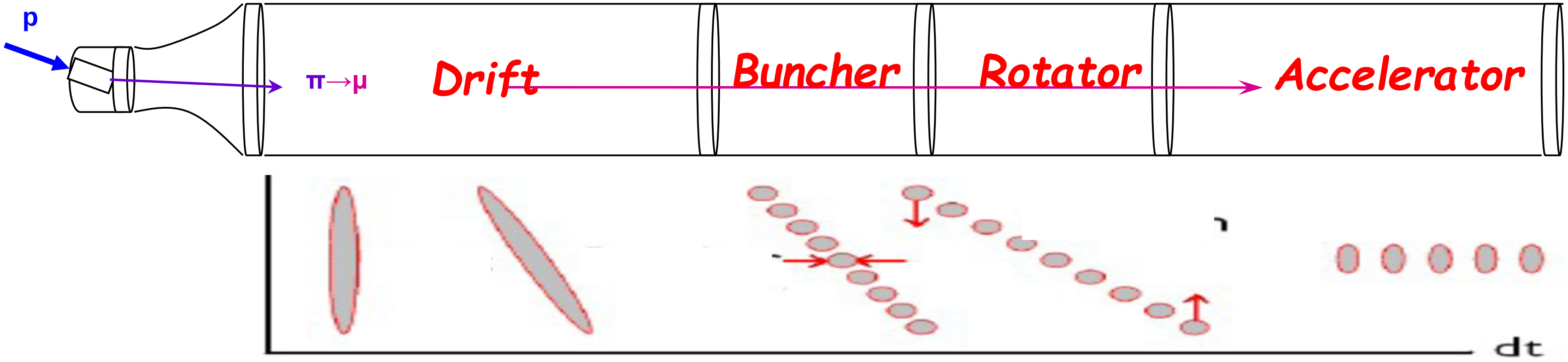
$$e_{\wedge} \text{ » } 20(p)\ mm\ rad$$

$$e_{L} \text{ » } 30(p)\ mm\ rad$$

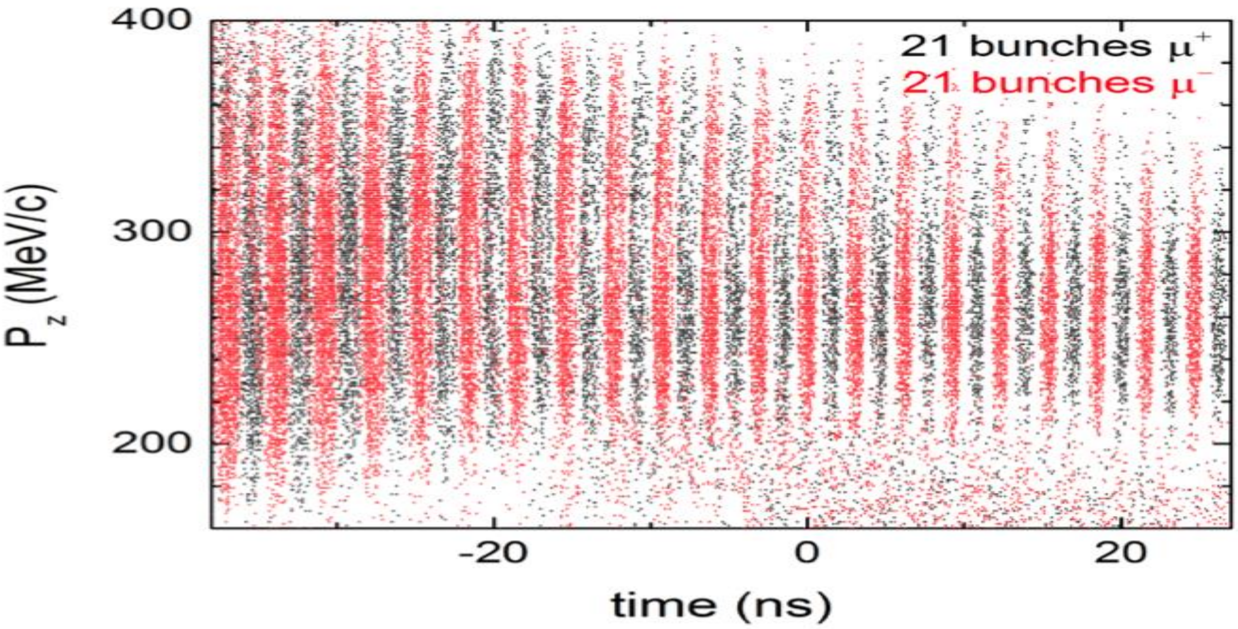
$$e_{\wedge} = 0.04(p)\, mm\, rad \quad e_{L} = 1.0(p)\ mm\ rad$$

1.-The initial linear beam transport

- Initially, there is a small spread in time, but a very large spread in energy. The target is followed by a drift space, where a strong correlation develops between time and energy.

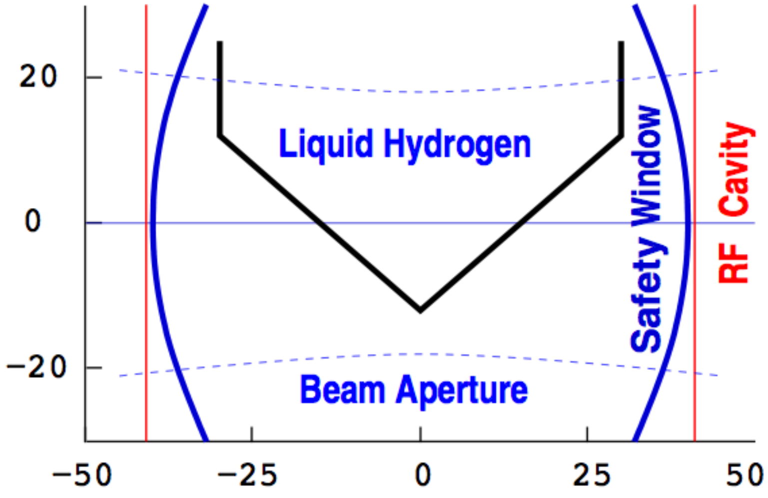


- Strings of both signs are accumulated since half-way between each of the stable RF phase for one sign there is a stable phase for the opposite sign.



2.- The 6-D cooling

- The linear initial muon processing facilitates the further subsequent injection in a cooling ring.
- Protons are removed by an absorber and two cooling rings separate the charges. A wedge absorber is placed such that high momenta pass through more material than low momenta, so that all three dimensions can be cooled.
- The initial several bunches of each sign can be initially cooled and later, at an intermediate stage, bunch rotated and each accumulated in one bunch which is extracted at the end of the cooling process.
- The wedge has a central thickness of 28 cm, a total wedge opening angle of 100° and is rotated 30° from the vertical to match the maximum of the dispersion.

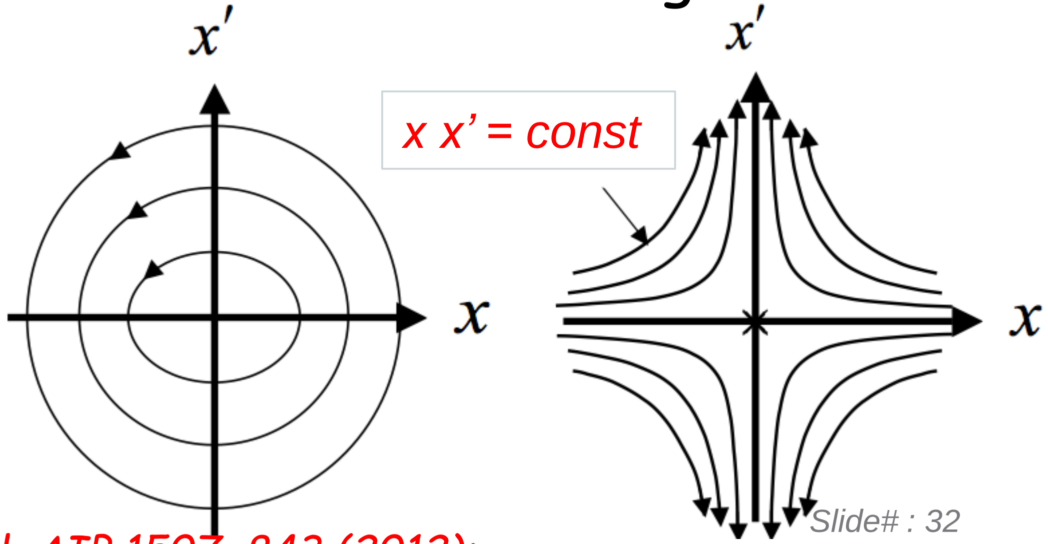


R. Palmer et al. arXiv:physics/0504098 v1, 2005

3.- PIC, the Parametric Resonance Cooling

- Combining ionization cooling with parametric resonances is expected to lead to muon with much smaller transverse sizes.
- A linear magnetic transport channel has been designed by Ya.S. Derbenev et al where a half integer resonance is induced such that the normal elliptical motion of particles in *x*-*x*′ phase space becomes hyperbolic, with particles moving to smaller *x* and larger *x*′ at the channel focal points.
- Thin absorbers placed at the focal points of the channel then cool the angular divergence by the usual ionization cooling.

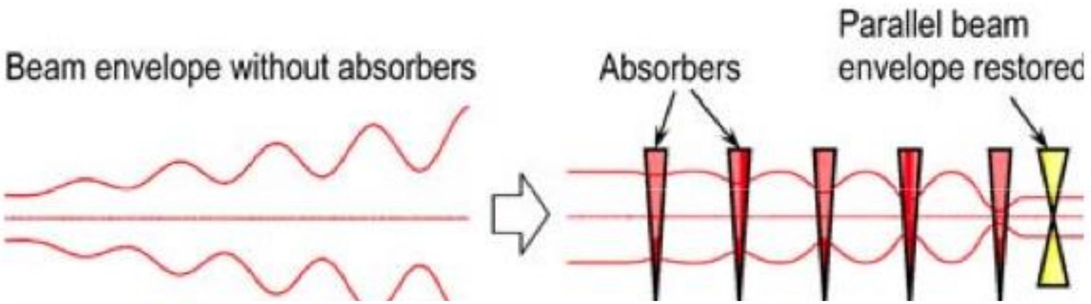
LEFT ordinary oscillations
RIGHT hyperbolic motion induced by perturbations near an (one half integer) resonance of the betatron frequency.

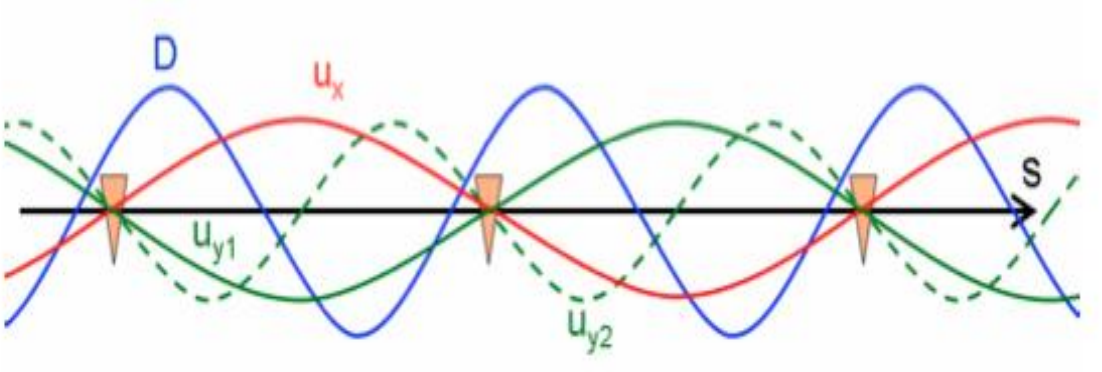


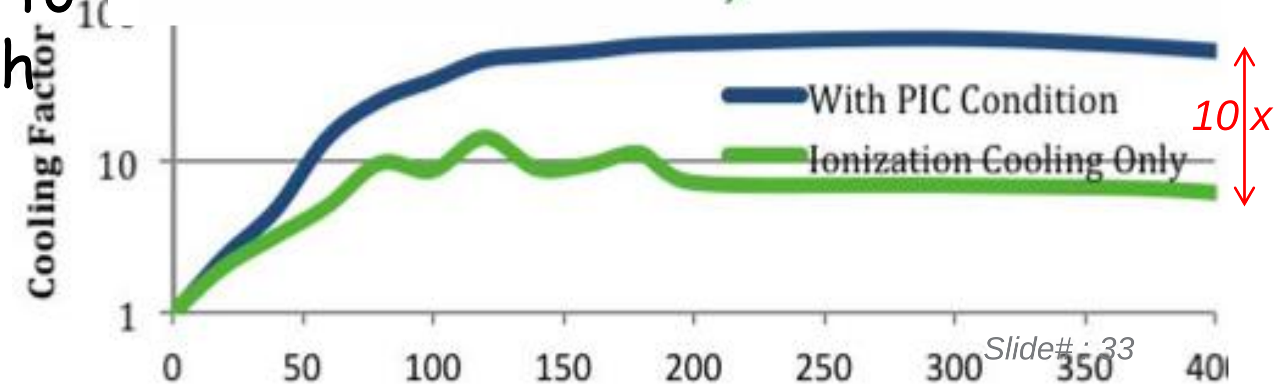
V. S. Morozov et al, AIP 1507, 843 (2012);

Details of PIC

- Without damping, the beam dynamics is not stable because the beam envelope grows with every period. Energy absorbers at the focal points stabilize the beam through the ionization cooling.
- The longitudinal emittance is maintained constant tapering the absorbers and placing them at points of appropriate dispersion, vertical β and two horizontal β□σ.
- Comparison of cooling factors (ratio of initial to final 6D emittance) with and without the PIC condition vs number of cells: *about 10x gain*





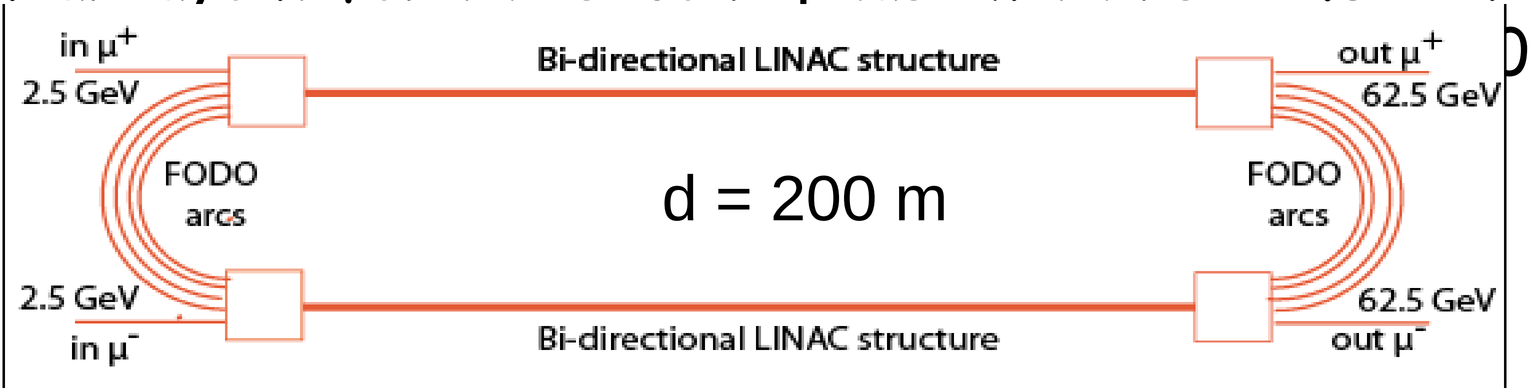


Comments on the cooling process

- A conventional muon cooling ring should present no unexpected behaviour and good agreement between calculations and experiment is expected both transversely and longitudinally
- The novel Parametric Resonance Cooling (PIC) involving instead the balance between a strong resonance growth and ionization cooling may involve significant and unexpected conditions which are hard to predict.
- Therefore the experimental demonstration of the cooling must be concentrated on such a resonant behaviour.
- On the other hand the success of the novel Parametric Resonance Cooling may be a premise for an optimal luminosity, since the expected Higgs rate is proportional to the inverse of the transverse emittance,
- However PIC may expect up to one order of magnitude decrement in the transverse emittance.

Bunch acceleration to 62.5 GeV

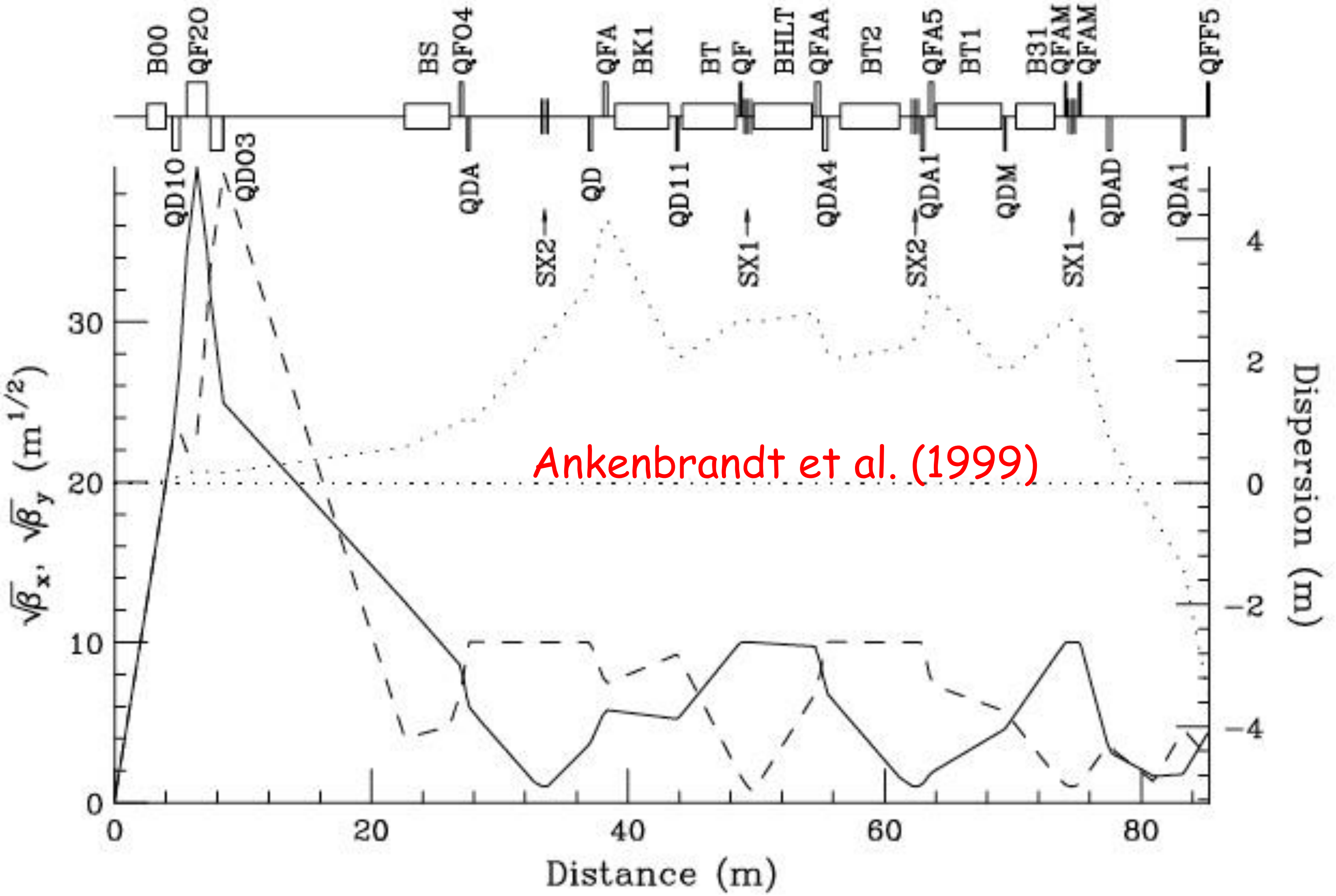
- Next, in order to realize a Higgs Factory at the known energy of 126 GeV, an acceleration system is progressively rising the energy of captured muons to $m_{Ho}/2$
- Adiabatic longitudinal Liouvillian acceleration to p_f= 62.5 GeV/c.
- Both μ+ and μ- are accelerated sequentially in the same LINAC with opposite polarity RF buckets
- Two recirculating LINAC and 25 MeV/m with f.i. 5 GeV energy/step with 4 bi-directional passages to 63 GeV (≈ 200 m long)
- A similar layout for the second phase with √s ≈ 0.5 TeV will requi 00 m)



D. Neuffer, 2013

Muons collide in a storage ring of R ≈ 60 m

- Lattice structure at the crossing point, including local chromaticity corrections with $\beta_x = \beta_y = \beta^* = 5$ cm.



Ankenbrandt et al. (1999)

Higgs luminosity at ESS

- The luminosity is given by a formula where:

$$L = f\frac{N^{+}N^{-}}{4pe_{rms}b}$$

  - $N^+ = N^- = 2.5 \times 10^{12}$ μ/pulse
  - f is the number of effective luminosity crossings: 43 x 555 =23'865/s
  - $\varepsilon_{rms} = \varepsilon_N/589.5 = 0.36 \times 10^{-4}$ rad cm, with H_2
  - $\beta* = 5$ cm is beta at crossing in both dimensions
- Luminosity is $L = 5 \times 10^{31}$ cm^{-2} s^{-1} at each collision crossing
- The cross section at the maximum folded with a $\Delta E = 3.4$ MeV is 1.0×10^{-35} cm^2. Hence the Ho event rate is 1.2×10^4 events for 10^7 s/y . In 10 y and two crossings: 1/4 million Ho events
- If novel Parametric Resonance Cooling (PIC) is successful, ε_{rms} is reduced by a factor 10 and 1.2×10^5 events/year/i.p.

Eatimated performance for the Hº-factory at the ESS

- Two asymptotically cooled μ bunches of opposite signs collide in two low-beta interaction points with β*= 5 cm and a free length of about 10 m, where the two detectors are located.
- *with PIC cooling* a peak collider luminosity of 4 x 10^{32} cm^{-2} s^{-1} is achieved
  - The bunch transverse rms size is 0.05 mm and the μ–μ tune shift is 0.086.
  - The SM Higgs rate is ≈ 10^5 ev/year (10^7 s) in each of the detectors.
  - An arrangement with at least two detector positions is recommended.

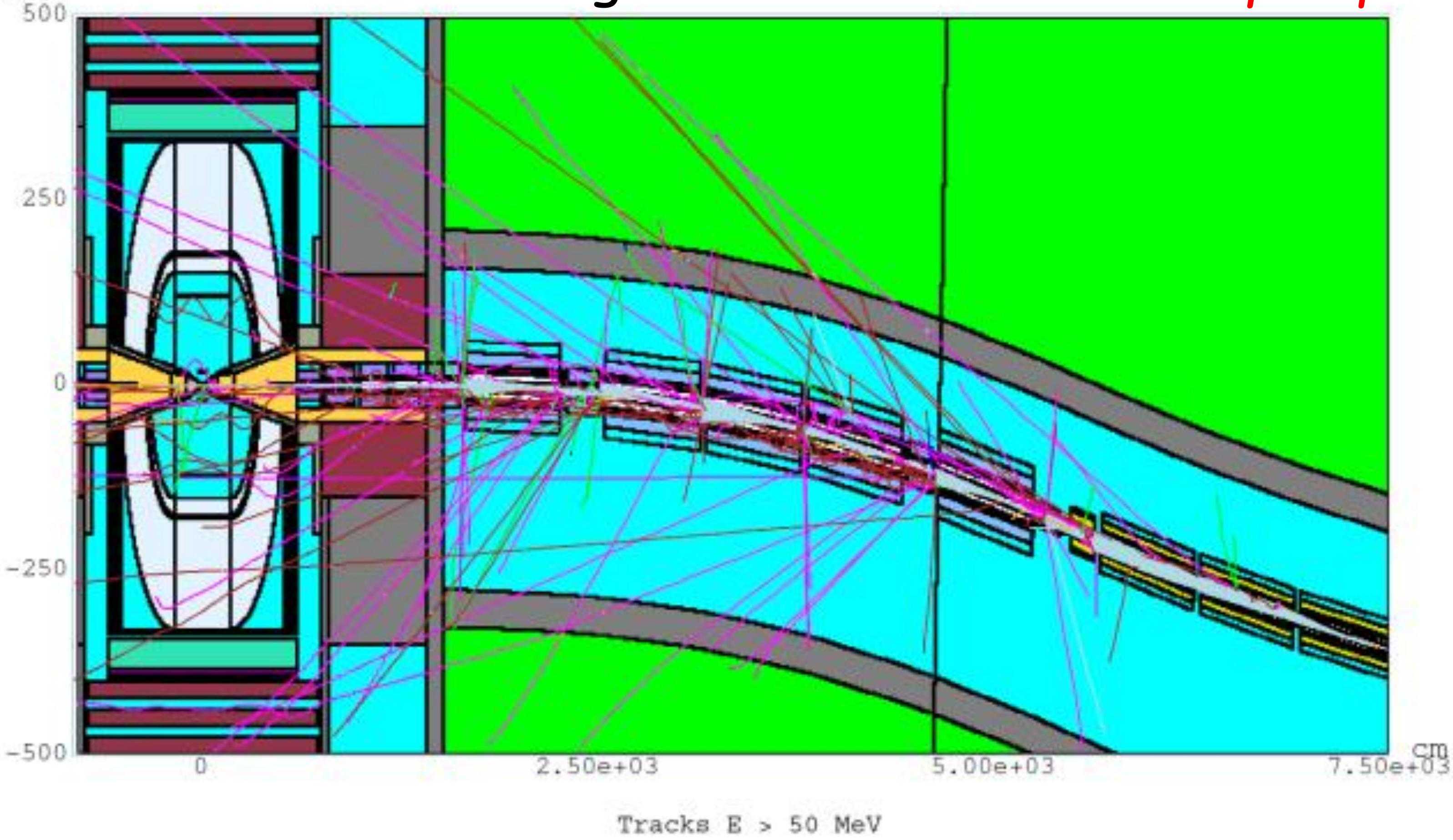
Proton kinetic energy	2.0	GeV
Proton power	5.0	MW
Proton collisions	56 =14x4	ev/s
Timing proton collisions	17.86	ms
Protons/collision	2.5x10^{14}	p/coll
Final muon momentum	62.5	GeV/c
Final muon lifetime	1.295	Ms
Total μ surv. fraction	0.07	
μ+ at collider ring	2.93x10^{12}	μ/coll
μ- at collider ring	1.89x10^{12}	μ/coll
Inv. transv. emittance, ε_N	0.37	π mm rad
Inv. long. emittance	1.9	π mm rad
Beta at collision $\beta_x = \beta_y$	5.0	cm
Circumf. of collider ring	350	m
Effective luminosity turns	555	
Effective crossing rate	29’970	sec-1
Luminosity no PIC	4.24 x $10^{\cancel{31}}$	cm^{-2} s^{-1}
Luminosity + PIC (10 x)	4.2 x $10^{\cancel{32}}$	cm^{-2} s^{-1}
Higgs cross section	3.0 x $10^{-\cancel{35}}$	cm^2
Higgs @10^7 s/y, no PIC	1.2 x 10^4	ev/y
Higgs @10^7 s/y + PIC	**1.2 x 10^5**	**ev/y**
Higgs -> γγ, 10^7 s/y + PIC	≈ 2400	ev/y
Tune shift with PIC	0.086	

Without PIC

1.2 x 10^4 ev/year

Muon related backgrounds

- A major problem is caused by muon decays, namely electrons from μ decay inside the detector with ≈ 2×10^{3} e/meter/ns, however collimated within an average angle of 10^{-3} rad.
- A superb collimation is required with the help of absorbers in front of the detector's straight sections. *This is an open problem*



Drozhdin, Mokhov et al.

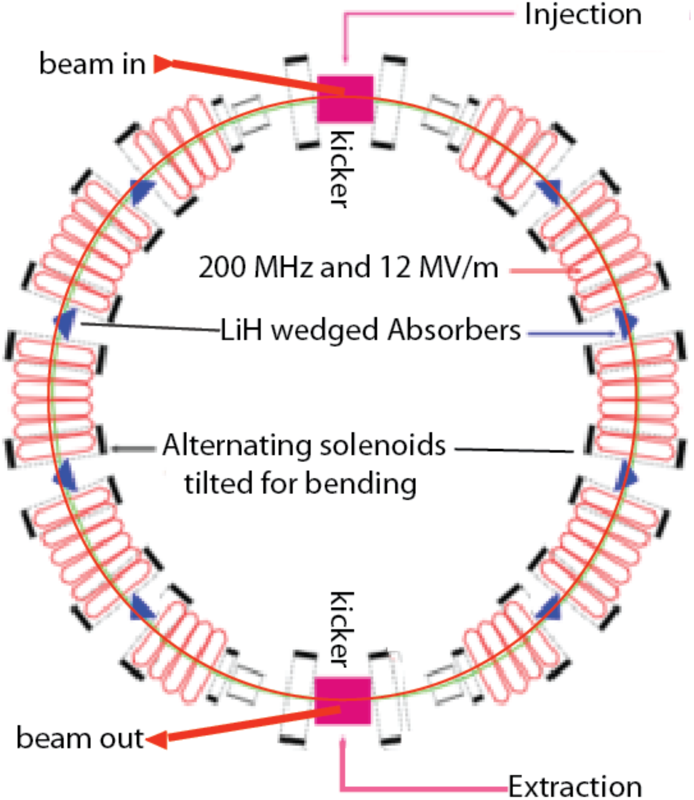
The realization of the Initial Cooling Experiment

- Physics requirements and the studies already undertaken with muon cooling suggest that a next step, prior to but adequate for a specific physics programme *could be the practical realization of an appropriate cooling ring demonstrator.*
- Indicatively this corresponds to the realization of an unconventional *tiny ring of 20 to 40 meters circumference* in order to achieve the theoretically expected longitudinal and transverse emittances of asymptotically cooled muons.
- The injection of muons from pion decays could be coming from an existing proton accelerator of modest intensity ($\leq 10^{11}$ ppp) .
- The goal is to prove experimentally the full 3D cooling.
- The other facilities, namely (1) the pion/muon production, (2) the final, high intensity cooling system (3) the subsequent muon acceleration and (4) the accumulation in a storage ring could be constructed later and only after the success of the initial cooling experiment has been confirmed at a lower cost.

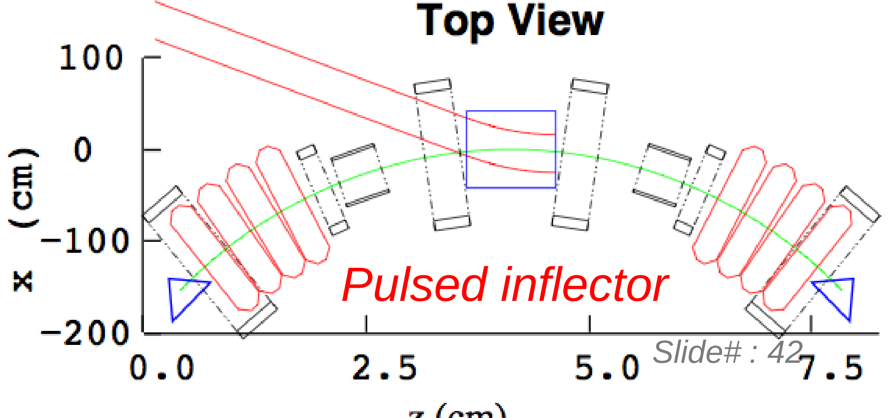
The RFOFO Ionization Cooling

- The design is based on solenoids tilted in order to ensure also bending. The LiH absorbers are wedge shaped to ensure longitudinal cooling.

Circumference	33	m
Total number of cells	12	
Cells with rf cavities	10	
Maximum axial field	2.77	Tesla
Coil tilt angle (degree)	3	degr
Average vertical field (T)	0.125	Tesla
Average momentum	220	MeV/c
Minimum transverse beta function	38	cm
Maximum dispersion function	8	cm
Wedge opening angle	100	degr
Wedge thickness on-axis	28	cm
Cavities rf frequency)	201.25	Mhz
Peak rf gradient	12	MV/m
Cavities rf phase from crossing	25	degr



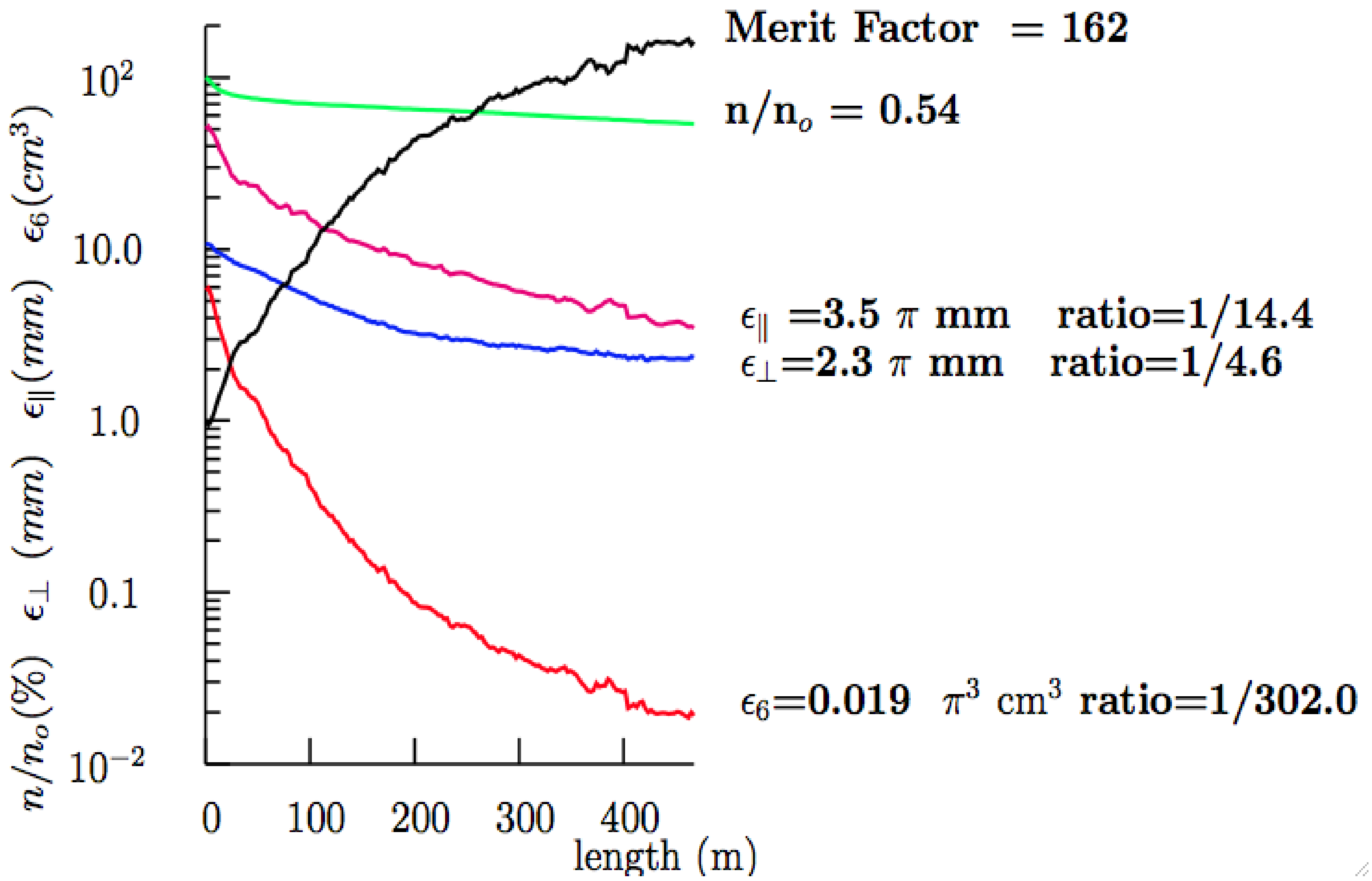
Two separate, 180 apart injection and extraction pulsed inflectors*



Properties of a “RFOFO” Cooling Ring

- The muon emittances of the RFOFO ring after the first linear rotation may be $e_{V,H}$ = 20 (π) mm rad and e_L = 30 (π) mm rad with a r.m.s. energy spread is about 10 %.
- After cooling, the ultimate normalized hydrogen driven equilibrium emittances at 250 MeV/c are expected to be $e_{V,H}$ = 0.4 (π) mm rad and e_L = 1.0 (π) mm rad.
- This corresponds to the huge 6D compression factor of 50 x 50 x 30 = 75'000, i.e. a Merit Factor M = *(Initial 6D)/(final 6D) x transmission* of the order of 15'000 = 75'000/5 with a total number of muons due to decay losses of a factor 5.
- In an estimated *“RFOFO” Cooling Ring*, a merit factor of 162 had been observed after 16 turns of the ring.
- Doubling the number of turns of the RFOFO cooling ring will ensure the required compression to attain the required equilibrium of emittances after the first linear rotation .

- „Predicted merit factor of a “*RFOFO*” *Cooling Ring* after 16 turns and a muon survival of 54% (Palmer et al.)



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- On the other hand the success of the novel Parametric Resonance Cooling may be a premise for an optimal luminosity, since the expected Higgs rate is proportional to the inverse of the transverse emittance,
- PIC may expect up to one order of magnitude transverse emittance decrement.

Conclusions

- After the Initial Cooling Experiment has been fylly demonstrated, the final activities may consist of
  - *proton accumulator and compressor rings* with a radius of 35 m, transforming from 14 to 42 bunch/s;
  - A $\pi - \mu$ *linear decay channel* with both muon signs of about 100 m length converting muons to 250 MeV/c and Δp/p at ±10 %;
  - a pair of robust μ^+ and μ^+ *ionization-cooling rings* each with ≈ 6 m radius, compressing to two narrow bunches, eventually followed by two additional PIC cooling rings;
  - a fast *re-circulating LINAC acceleration* system of about few hundred m to bring muons to required collision energies i.e.
  - a *collider ring at 7 Tesla and (1)* ≈ 50 m radius for $\sqrt{s} = 126$ GeV and (2) ≈ 200 m for $\sqrt{s} = 0.5$ TeV (2):
  - two two narrow μ bunches and two interaction points where detectors are located with ≈ 2x 10^{12} μ /pulse of each sign.

12'000 Higgs/y @10^7 s/y without PIC

The Higgs production colliders

- **Advantages**
  - Large cross sections σ ($\mu^+\mu^- \rightarrow h$) = 41 pb in s-channel resonance and $\mu^+\mu^- \rightarrow$ ZH of 0.2 pb at $\sqrt{s}$ = 500 GeV.
  - Small size footprint: it may fit within an existing site
  - No synchrotron radiation and beamstrahlung problems
  - Precise measurements of line shape and decay widths
  - Exquisite measurements of all channels and tests of SM.
  - The cost of the facility, provided cooling will be successful, is less than 1/10 of one of the LHC.
- **Challenges**.
  - A low cost demonstration of muon cooling must be done first.
  - Muon 2D and 3D cooling needs to be fully demonstrated
  - Need ultimately very small c.o.m energy spread (0.003%)
  - Backgrounds from constant muon decay
  - Significant R&D required towards end-to-end design

Article from FORBES

<u>Ethan Siegel,</u> FORBES Senior Contributor

Aug 22, 2019

Forget About Electrons And Protons; The Unstable Muon Could Be The Future Of Particle Physics

- https://www.forbes.com/sites/startswithabang/2019/08/22/forget-about-electrons-and-protons-the-unstable-muon-could-be-the-future-of-particle-physics/

Thank you !