Future searches of the Higgs scalar sector.

Carlo Rubbia

INFN and Gran Sasso Science Institute, L'Aquila, Italy

CERN, European Organization for Nuclear Research, Geneva, CH

From the W and Z to the Higgs sector

- The experimental determinations of the Higgs sector will — no doubt — extend the previously well-known observations of the Zo and the W's, where the initial search and discovery with the P-Pbar hadron collider had been followed by the systematic studies with leptons at LEP.
- Additional determinations are needed beyond the LHC in order to place more precisely also this new scalar Ho particle.
- Like in the Zo case, projects should be investigated with leptons rather than hadrons.
- The presently described muon cooling will have greater potentials for distinguishing between a standard Standard Model (SM) and any other collider's alternative.
- In analogy with the Zo at LEP, the single H^o production in the s-state offers conditions of unique cleanliness .

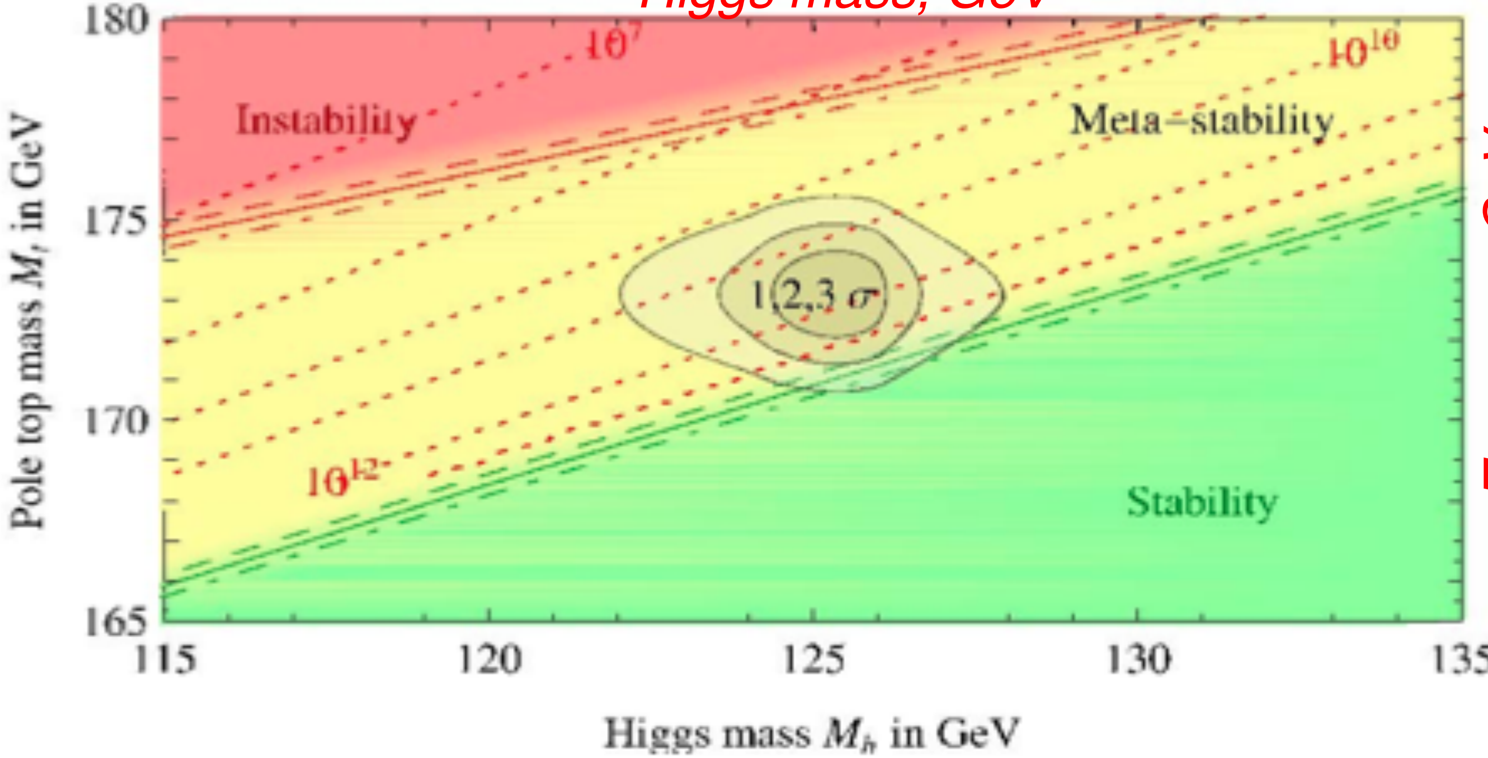
From hadrons to leptons

- The discovery at CERN of the Higgs particle (Ho) at the LHC and of the associated detectors has required a construction time of a quarter of century and investment of ≈ 10 billion Euro.
- A even larger e+e- Collider in a new site is a likely next option, but with a very long timescale and and even greater cost. *Short term approval and construction are rather unlikely.*
- In contrast with the Zo and W's, the *Ho is a scalar (spin = 0) particle,* characterized by a much stronger coupling when initiated from muons rather than from electrons.
- 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 the much smaller dimensions and cost: it *may fit within an already existing site*
- Hwever it demands a substantial R&D in order to produce adequate compression in 6D phase space of the muon beams.

Present expectations

- At the observed Higgs value, the electro-weak vacuum is metastable with a lifetime longer than the age of the Universe.

Higgs mass, GeV



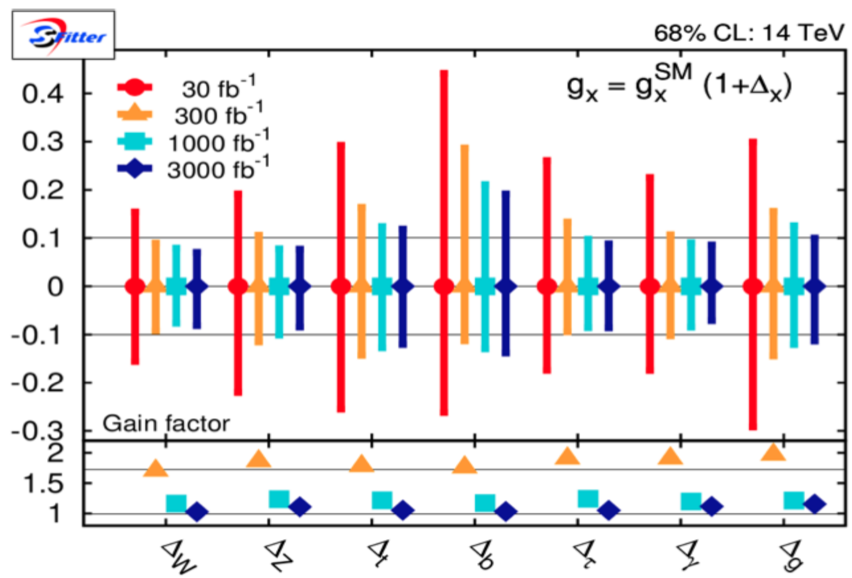
Top mass, GeV

- The SM may then be valid without new physics up to the Planck scale. *Thus, there may be only one Higgs and no need for the "no fail theorem" and no necessity of SUSY at LHC energies.*

arXiv:1310.0763v3 [hep-ph] 30 Dec 2013

Expectations and limits of the LHC

- The HL-LHC luminosity upgrade has been recently approved.
- ATLAS and CMS detectors will be upgraded to handle an instantaneous luminosity of about 5×10^{34} cm^{-2} s^{-1} for operation at $\sqrt{s}$ = 14 TeV at the visible cross section σ_{vis} = 85 mb.
- The proton energy stored in the HL-LHC beams will be about 1000 MJ. Targets for the HL-LHC are of 250 fb^{--1}/year and an integrated luminosity of 3000 fb−1 may be achieved by 2037, *the presently planned termination of the HL-LHC data taking.*
- The HL-LHC may be however capable to perform Higgs related measurements only with persisting uncertainties. For 3000 fb^{-1} estimates are expected to improve only by a factor less than a factor 2.



The need of a better precision

- What precision is needed in order to search for possible additional deviations from the SM, even under the assumption that there is no other additional "Higgs" state at the LHC ?
- Predicted ultimate LHC accuracies for "exotic" alternatives

R.S. Gupta et al.	ΔhVV	$\Delta h\bar{t}t$	Δhbb
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	10%[a],
LHC 14 TeV, 3 ab^{-1}	8%	10%	15%

← *Ultimate at LHC*
1 ab= 10^{-42} cm^2

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

SUSY tan(β)>5

$$\frac{g_{hff}}{g_{h_{SM}ff}} \quad \frac{g_{hVV}}{g_{h_{SM}VV}} \quad \simeq \quad 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

Composite Higgs

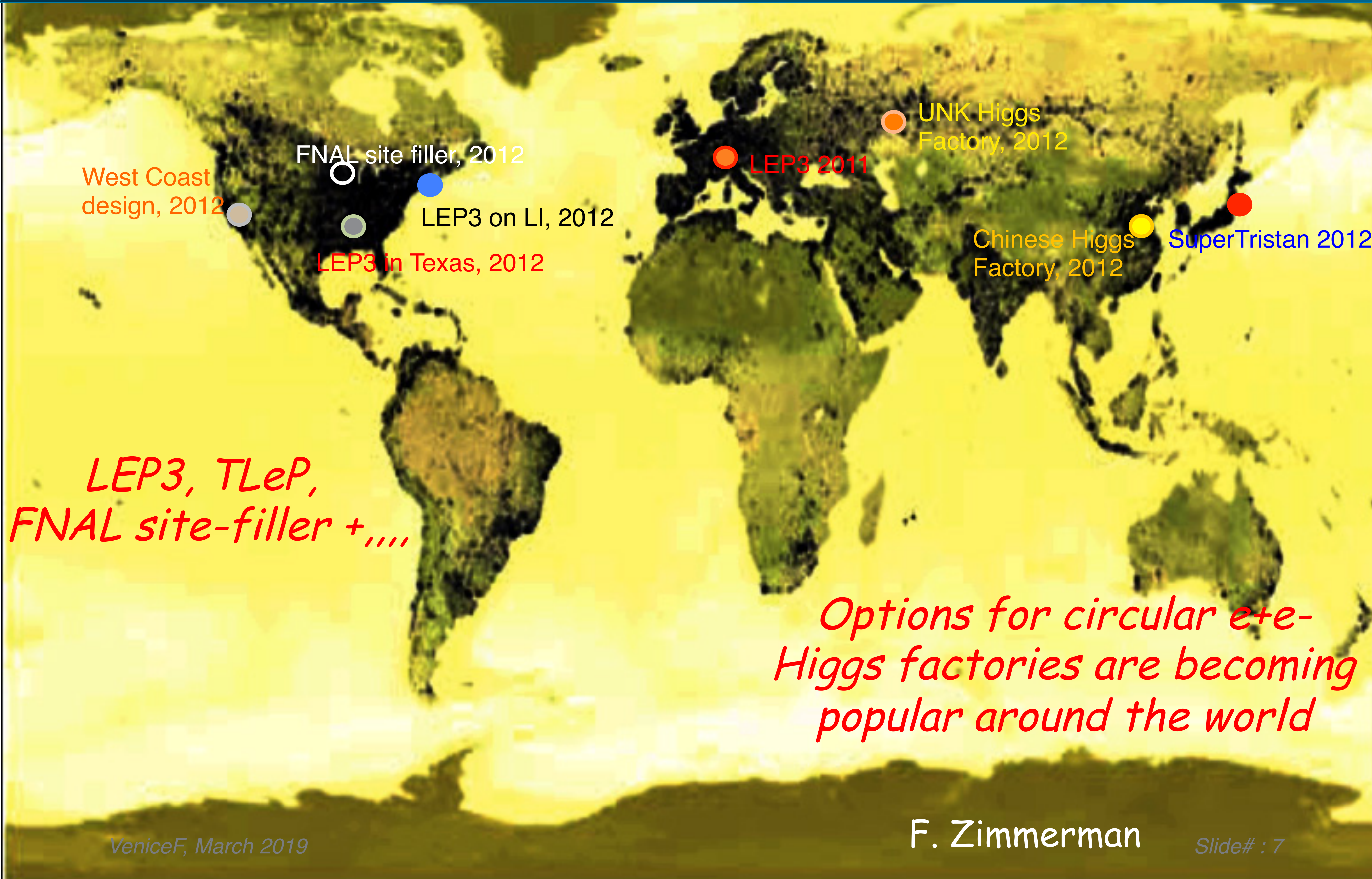
$$\frac{g_{hgg}}{g_{h_{SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \qquad \frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$$

Top partners

- Sensitivity to "TeV" new physics for "5 sigma" discoveries may need 1 per-cent to sub 1-per-cent σ accuracies on rates.

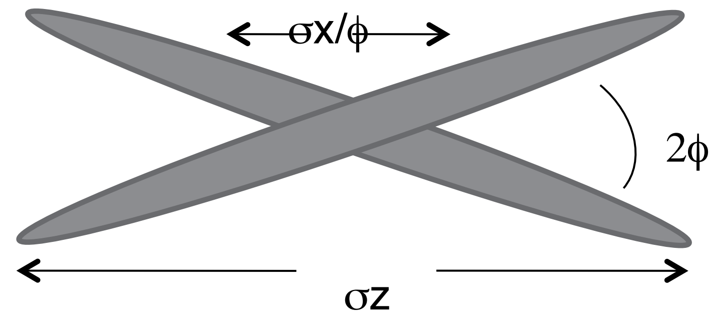
arXiv:1206.3560v3 [hep-ph] 27 Sep 2012

New huge $e^+ e^-$ rings proposals, several times the LHC.



Requirements for the Higgs with a e^+e^- collider

- The luminosity is pushed to the beam-strahlung limit.
- Collisions are at an angle, but with fewer bunches than for a B-Factory: a nano-beam scheme

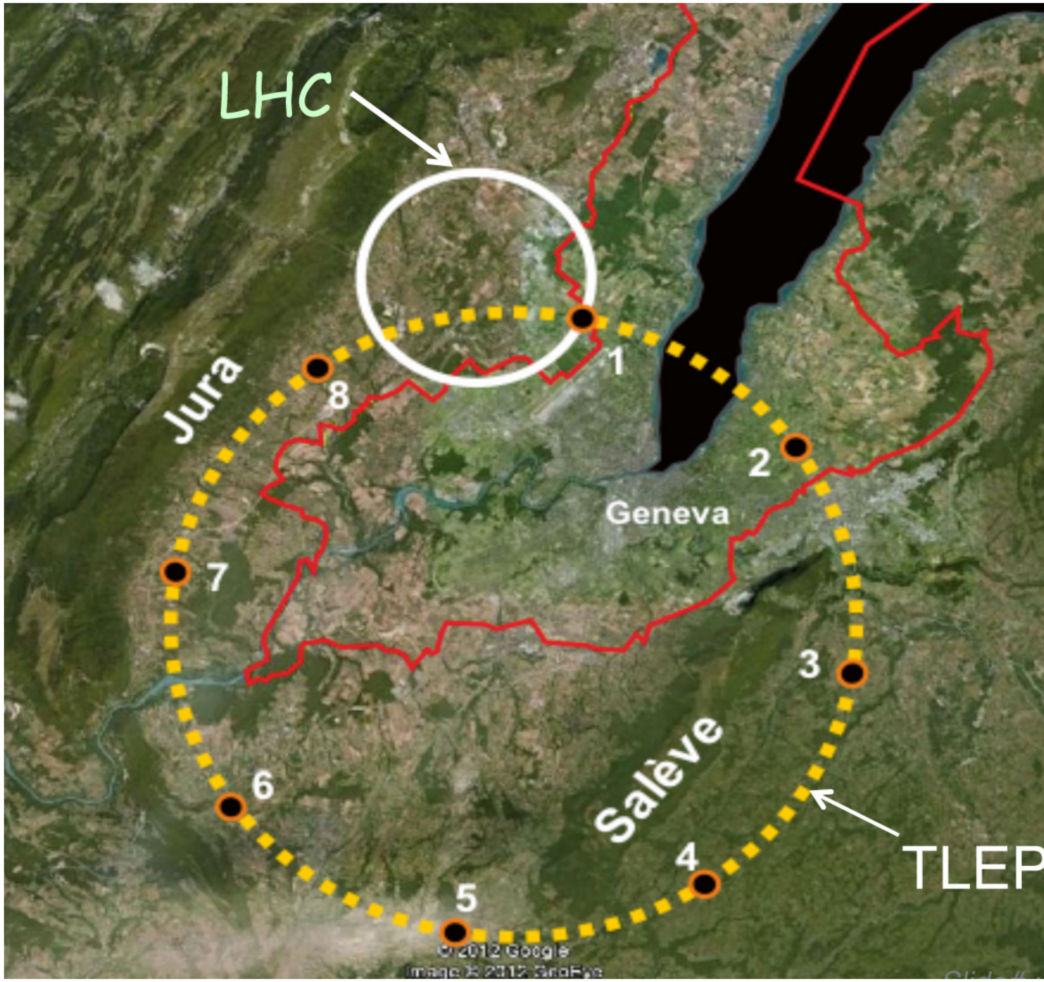


- Luminosity (several x 10^{34} cm^{-2} s^{-1}), costs and power consumption (≈100 MW) are comparable to those of a linear collider ILC.
- In order to reach luminosity (factor ≈ 500 x LEP2) and power consumptions (factor 5 x LEP2) the main cures are
  - Huge ring (100 km for T-LEP)
  - Extremely small vertical emittance, with a beam crossing size the order of 0.01 μ (it has been 3 μ for LEP2)
- *The performance is at the border of feasibility (E_{cm}≈ 250 GeV).*
- *However the H_o width of ≈4.5 MeV cannot be directly observed*

8

Conventional e+e- Ring or Linear Collider ?

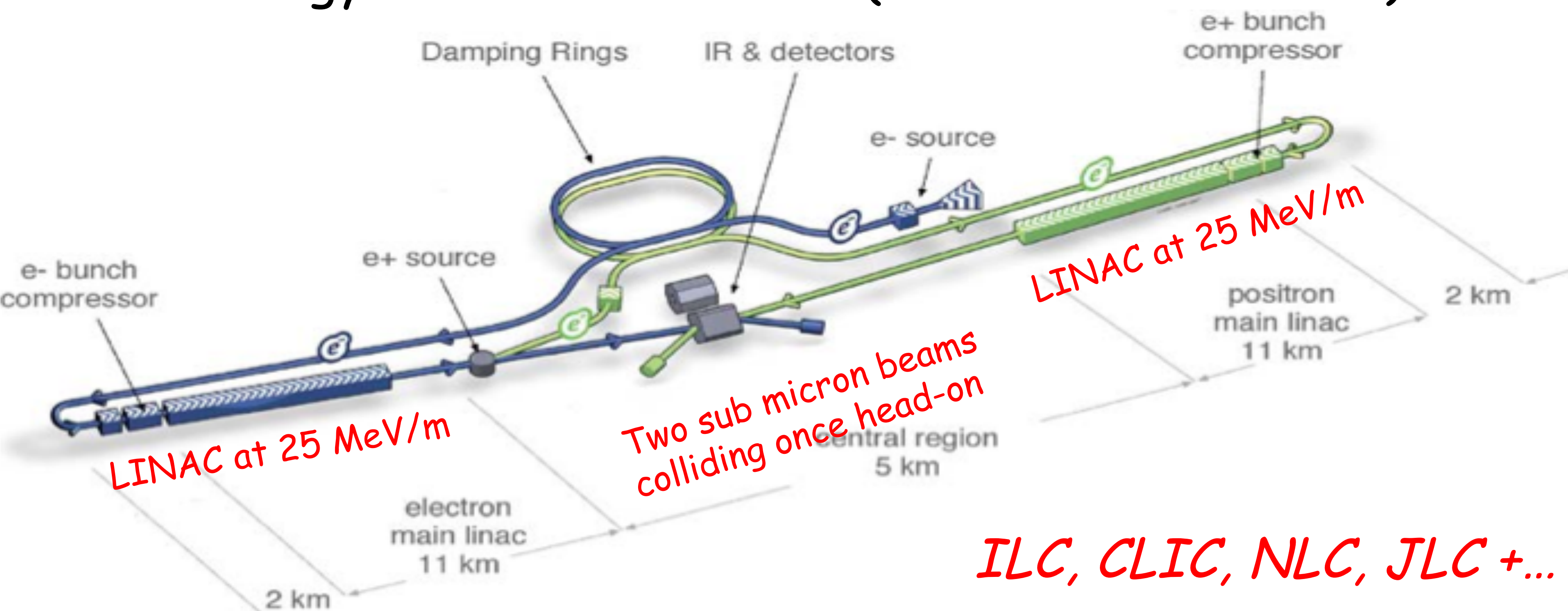
- Several e+e- projects have been described in huge new tunnels. Either (a) a relatively conventional *Collider Ring* and (b) a *Linear Collider (ILC)* are possible.
- As (a) we quote the FCC-ee from CERN of 100 km (3.7 x LEP), in the Geneva area.
- The study comprises a 90-400 GeV e+e- machine (FCC-ee) and a 100 TeV p-p collider (FCC-hh) with also heavy ions and of e-p
- Alternative (b) of a Linear Collider (ILC) is a major new technology, Two bunches of 5 nm (0.005 μm!), each with 2x 10^{10} particles are colliding 14'000 times per second.



ILC, CLIC, NLC, JLC +….

The Linear Collider option

- The International Linear Collider (ILC) is a high-luminosity linear electron-positron collider based on 1.3 GHz superconducting radio-frequency (SCRF) accelerating technology.
- Its energy √s is 200–500 GeV (extendable to 1 TeV).



ILC, CLIC, NLC, JLC +...

The total footprint for 500 GeV is ~31 km. To upgrade the machine to Ecms = 1 TeV, the linacs and the beam transport lines would be extended by another ~ 22 km up to 53 km

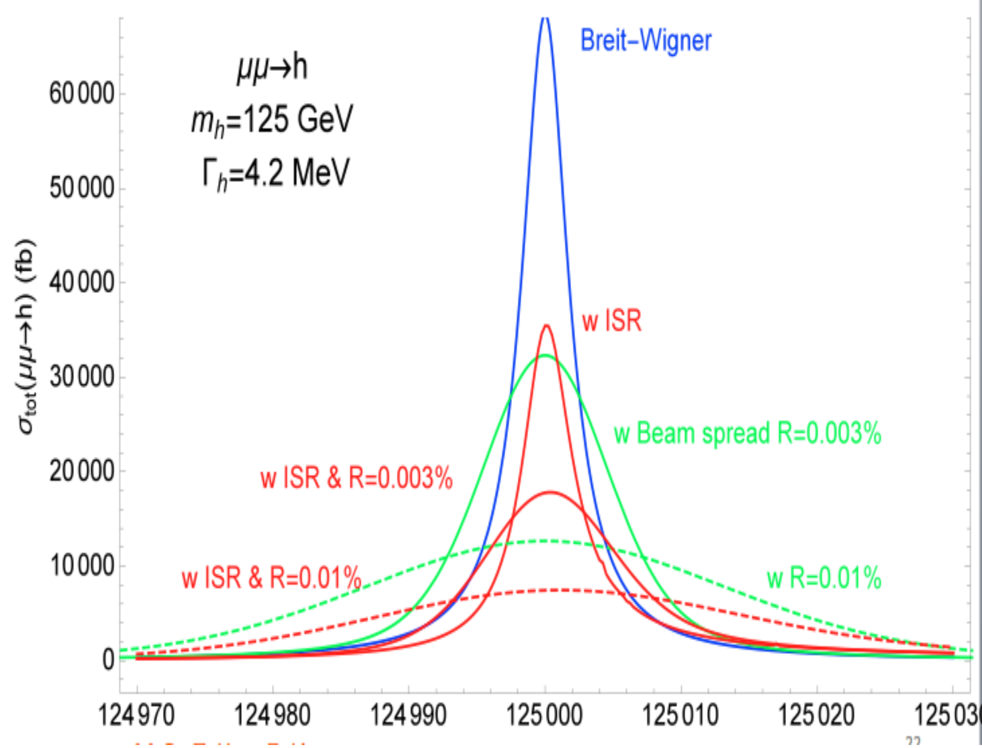
The muon collider is the optimal alternative

- *A $\mu+ \mu-$ collider is highly preferable* because of the much smaller dimensions and cost: it *may fit within an already existing site,* but it demands a substantial R&D in order to produce the adequate compression in 6D phase space for the muon beams.
- 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 $\sqrt{s}$ ≈ 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 x 10^{12}ppp can likely be produced by a high pulsing rate of a few GeV protons at ≈ 5 MWatt.

Comparing $\mu+\mu-$ 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 $\mu+\mu-$ cross sections are 71 pb for resonance profile alone and of 10 pb and 22 pb with both BES and ISR and energy resolutions R = 0.01 % and R = 0.003 %.
- The e+e- cross sections are 0.15 fb for both the BES and ISR effects and R = 0.01 %.
- *In these conditions (R = 0.01 %) the $\mu+\mu-$ rate is ≈ 104 times the e+e− rate.*

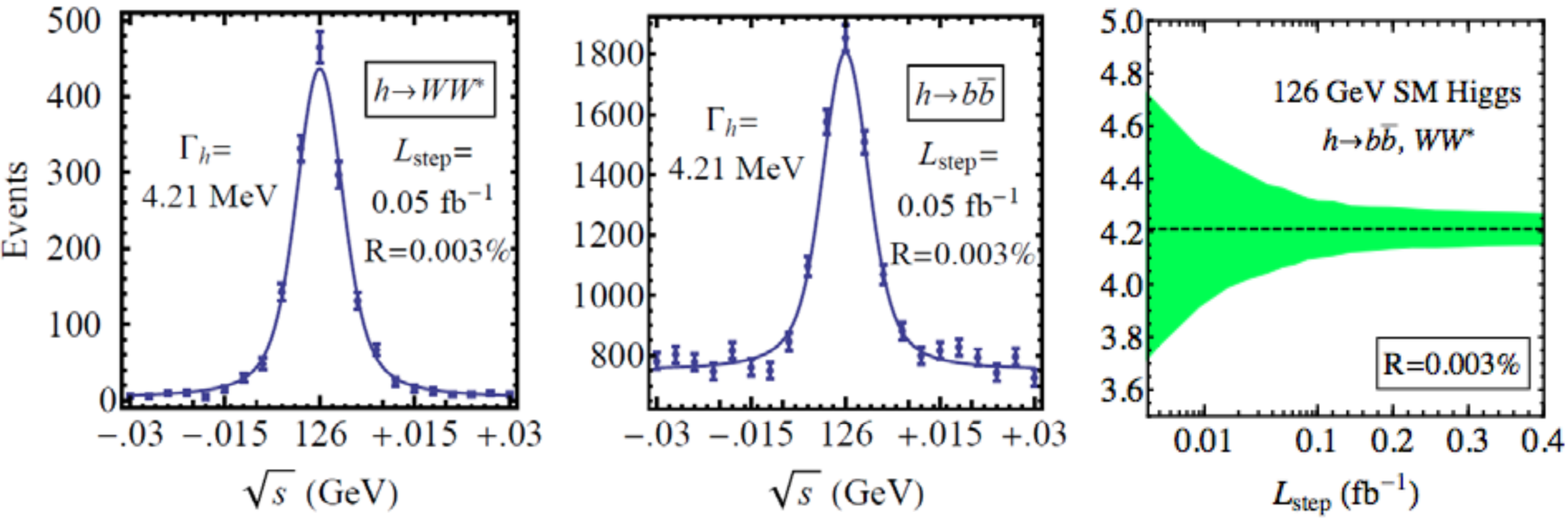
1 femtobarn (fb) $=10^{-39}$ cm^2



125.5 GeV : the Higgs muon resonance

- Signal and background for H → bb, WW* and energy resolution R = 0.003%. folded with a Gaussian energy spread Δ = 3.75 MeV and 0.05 fb^{-1}/step and with detection efficiencies included.
- Effective pb at the √s resonance for two resolutions R and with the SM branching fractions = H → bb 56% and WW*= 23%

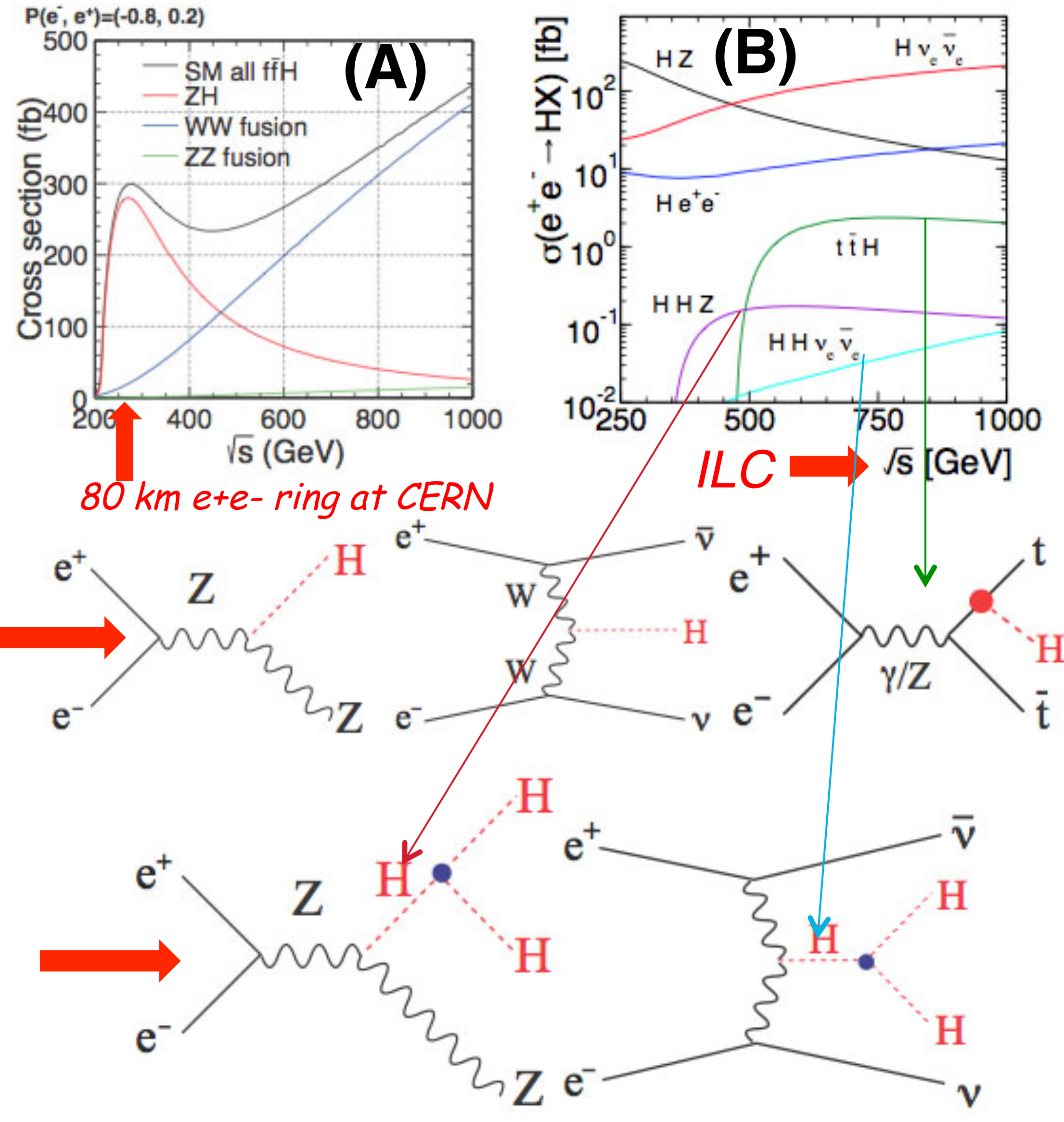
R (%)	$\mu^+\mu^- \to h$ σ_{eff} (pb)	$h \to b\bar{b}$		$h \to WW^*$	
		σ_{Sig}	σ_{Bkg}	σ_{Sig}	σ_{Bkg}
0.01	16	7.6	15	3.7	0.051
0.003	38	18		5.5	



arXiv:1210.7803 [hep-ph].

Studies at the Ho peak are not entirely sufficient:

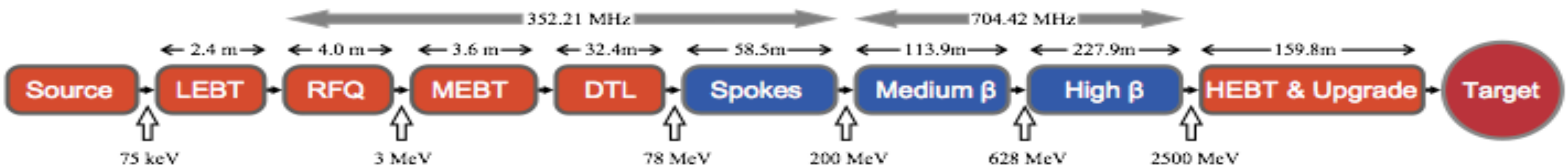
- We need in addition :
- **(A)** Production cross sections of Higgs boson from e+-e-or μ+-μ- as a function of √s
- **(B)** Production cross sections from e+-e-or μ+-μ- -> H + X as a function of the √s energy
  - ➢ The Higgs-strahlung diagram (Left), the W-boson fusion process (Middle) and the top-quark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



Lepton energies up to ≈ 0.5 - 1 TeV are necessary

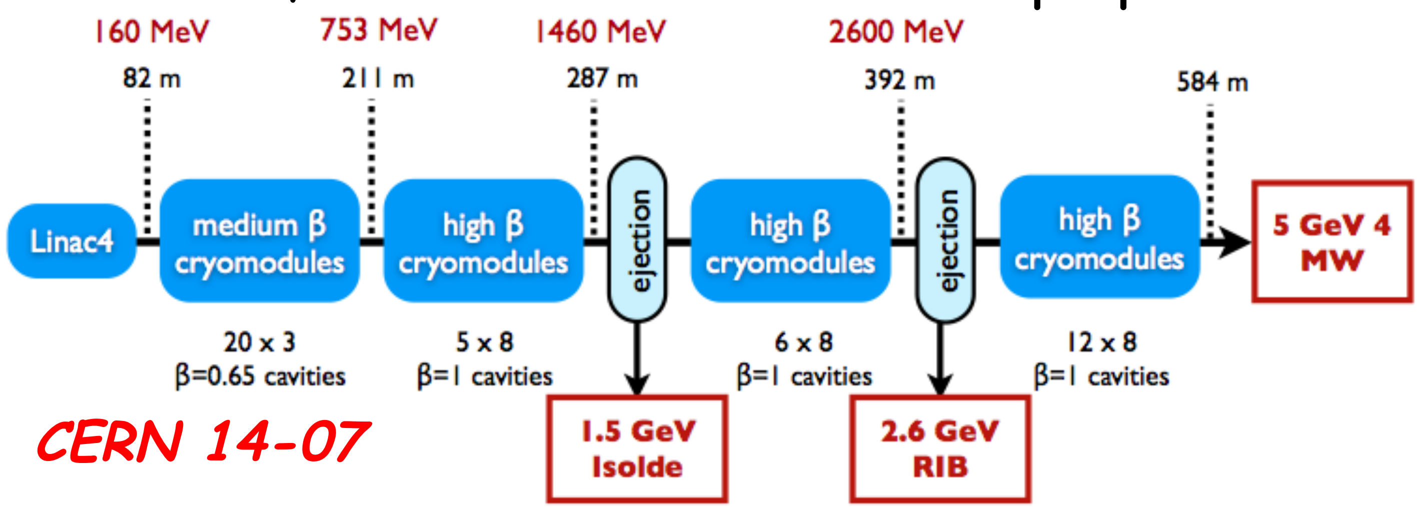
Protons for a muon collider in Europe ?

- The European Spallation Source, now in construction in Lund, with 5 MWatt of protons accelerated to a kinetic energy of 2.0 GeV at 14 Hz and 1.1 x 10^{15} p/p and it may provide adequate intensity and repetition rate for the O(10^{12} μ/pulse) collider program,



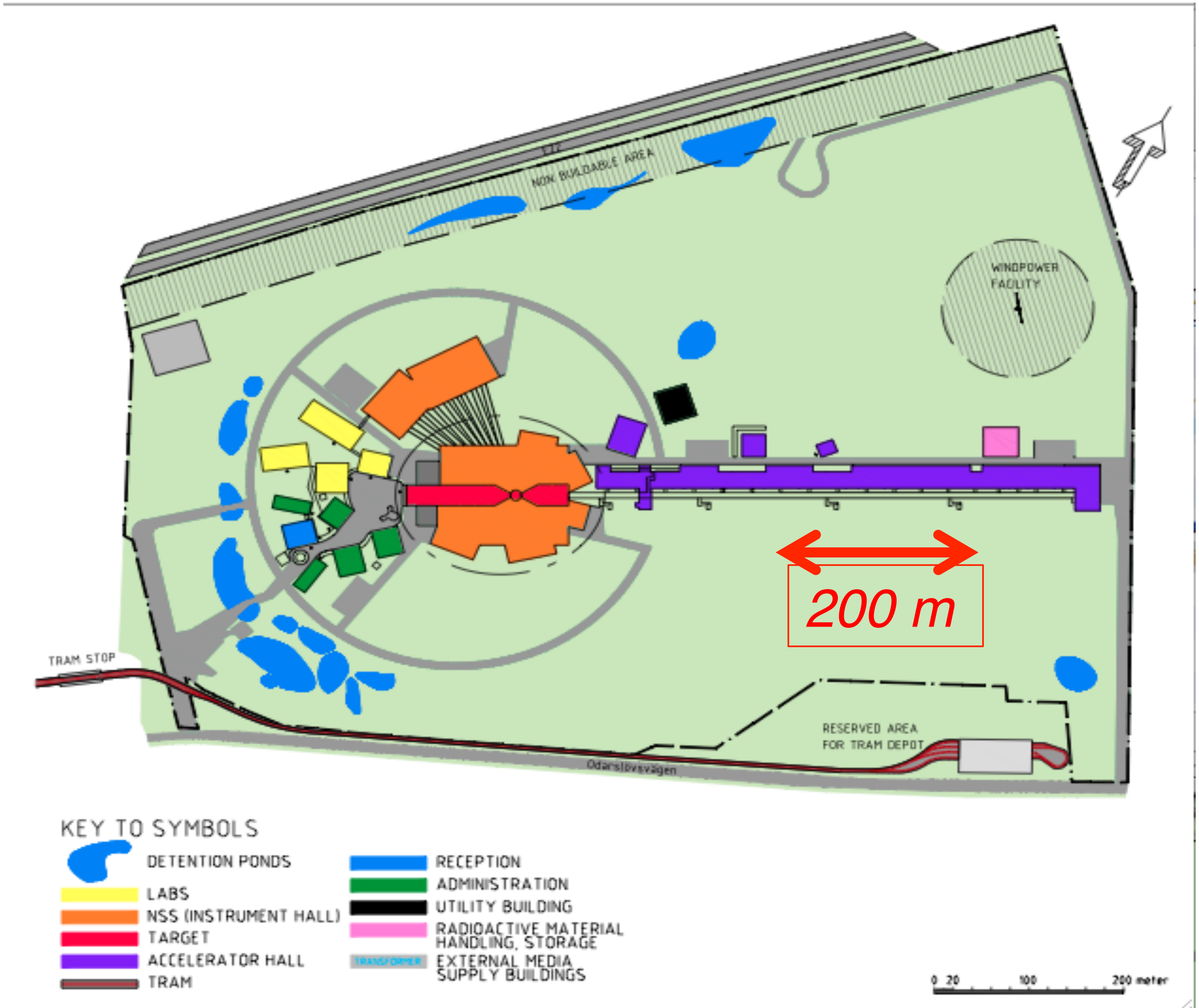
- CERN had considered the HP-HPL, a proton beam of 5 GeV kinetic energy with 50 Hz, 4 MWatt and 1.0 x 10^{14} p/ pulse.

- In 2010 HP-HPL project has been cancelled: *Therefore ESS may remain the main option.*



CERN 14-07

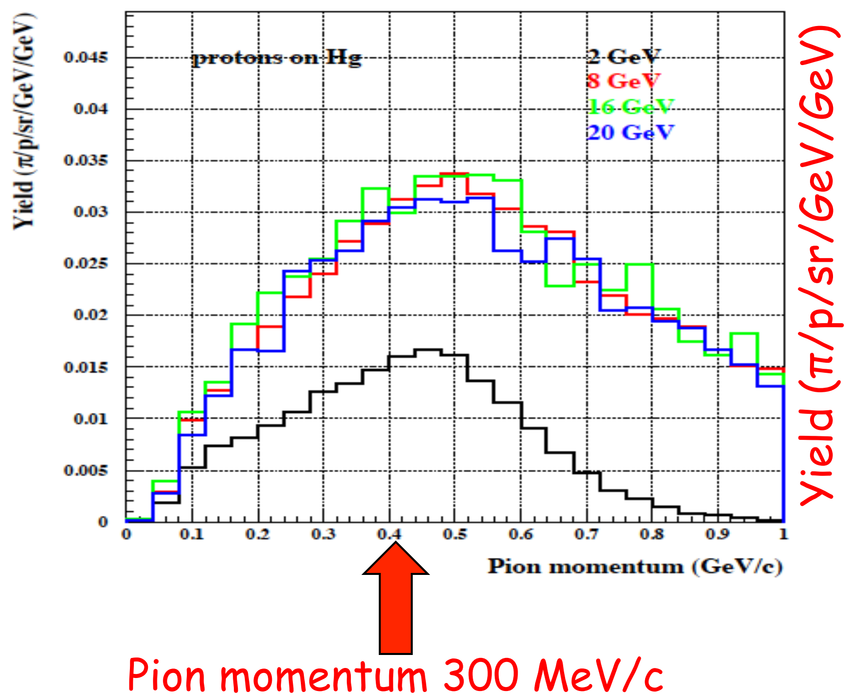
The ESS site



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

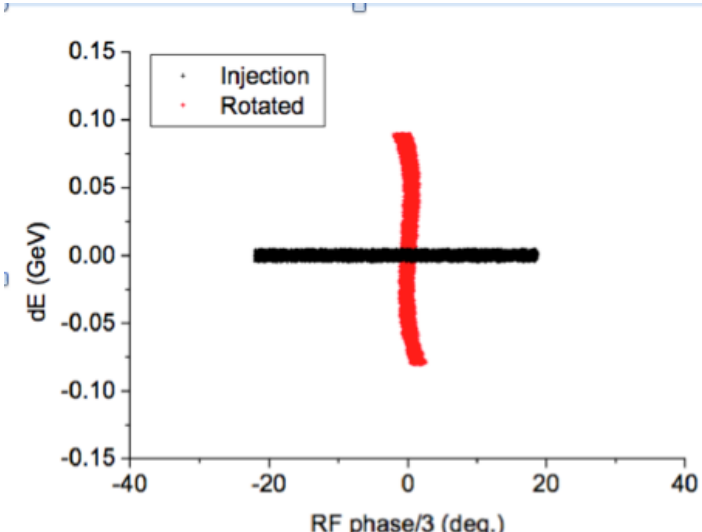
The proton rings

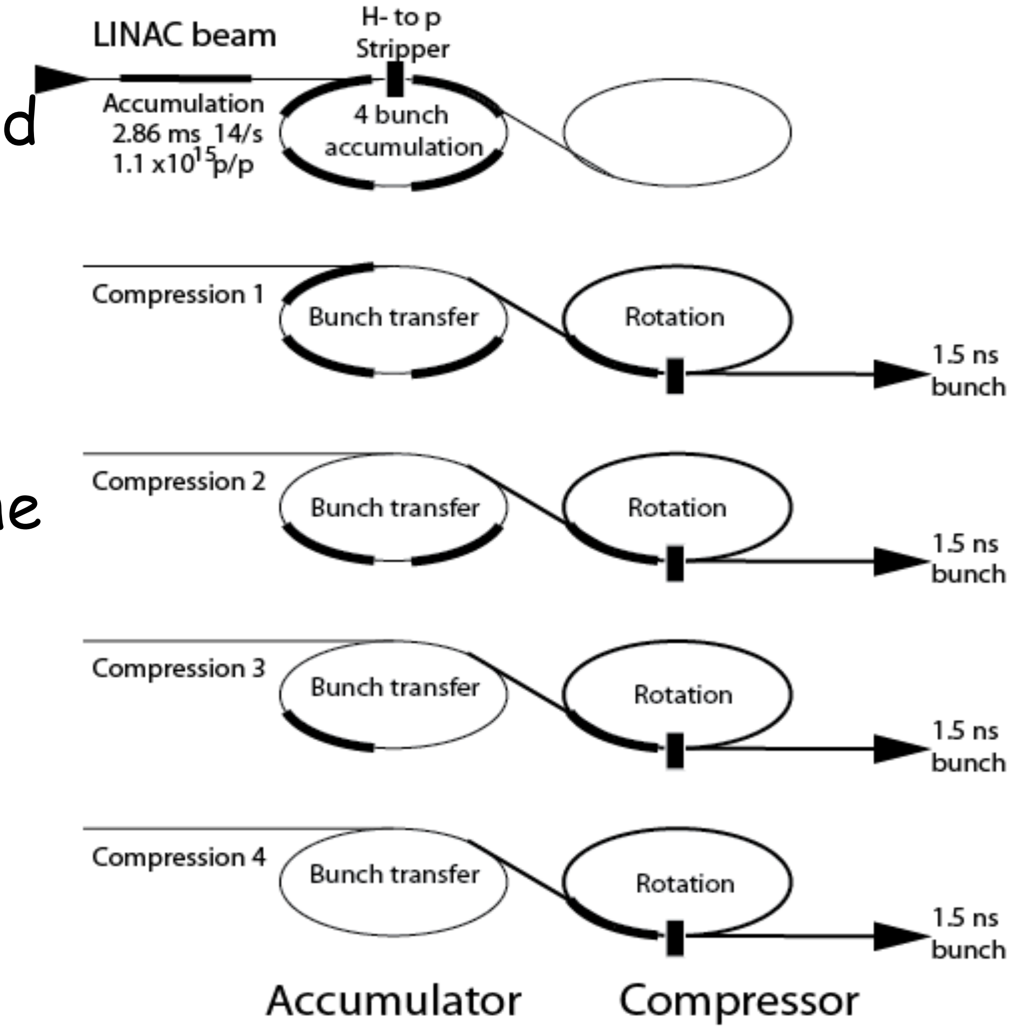
- The rate of the ESS- LINAC may be doubled to 28 Hz.
- Two proton rings of 35 m radius, the *"Accumulator"* collects the LINAC pulse and the *"Compressor"* steers the bunch to 1.5 ns.
- The beam transfer from the LINAC to the Accumulator is performed by a multi-turn injection of negative [p+2e-] ions, 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.



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.

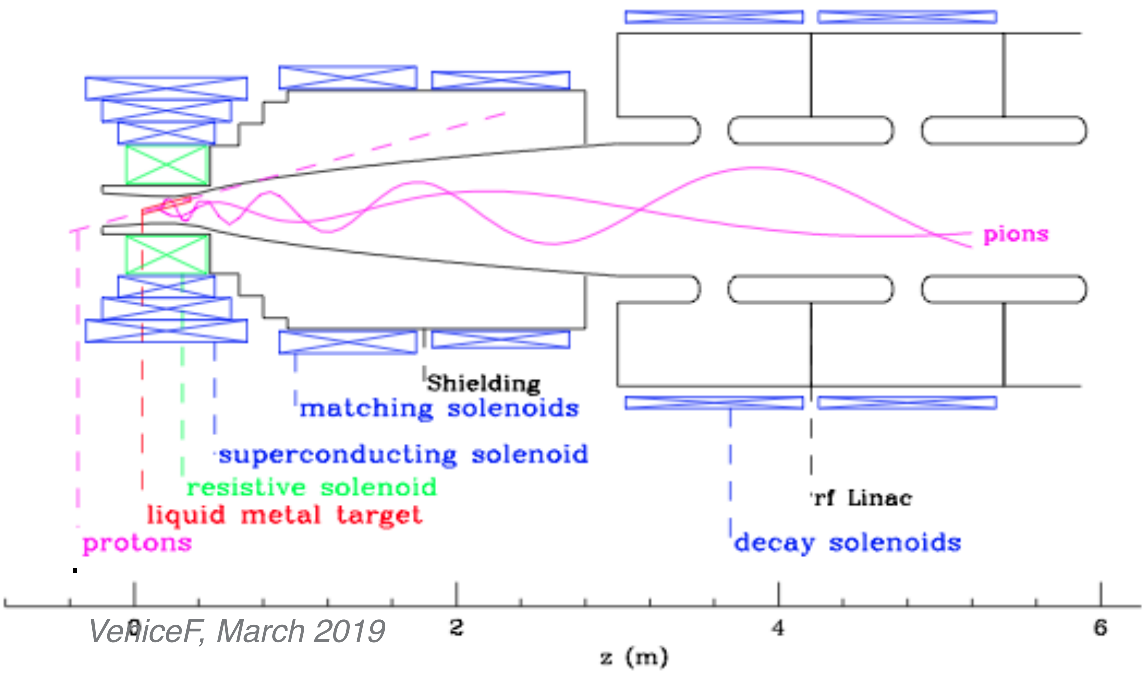




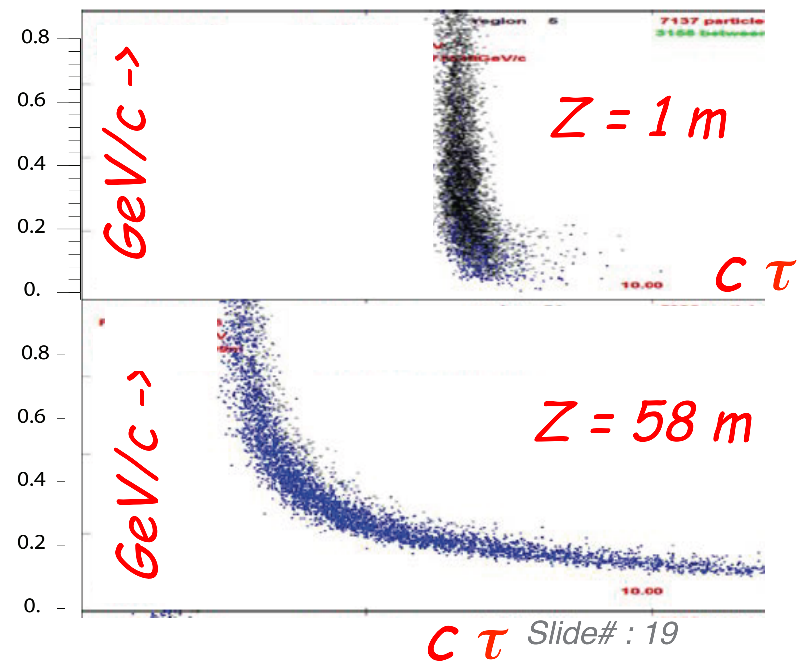
Rings have 35 m radius, wth 4 pulses of 120 ns each separated by 50 ns.

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



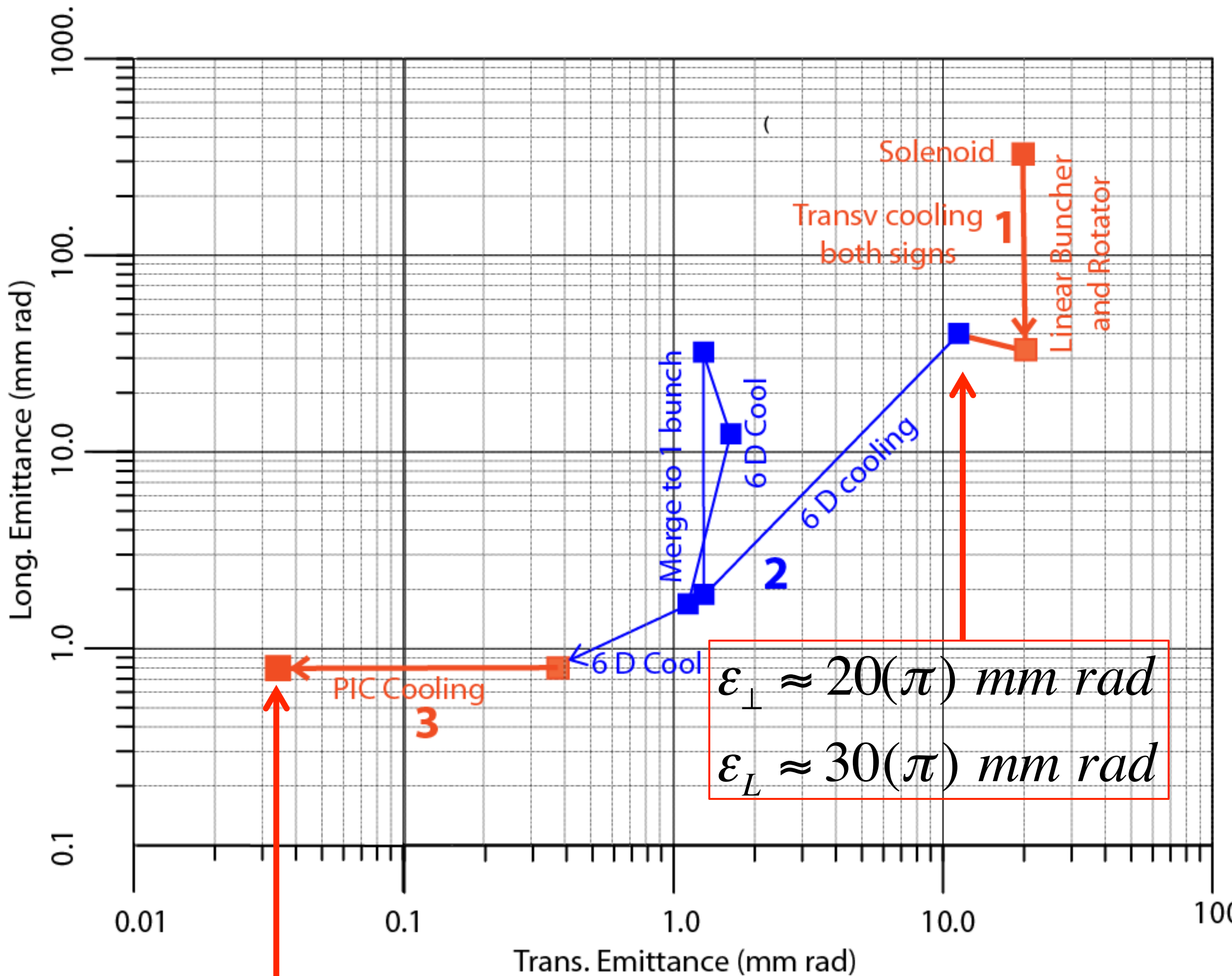
Pions/muons drifting as a function of c τ



The muon cooling processes

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

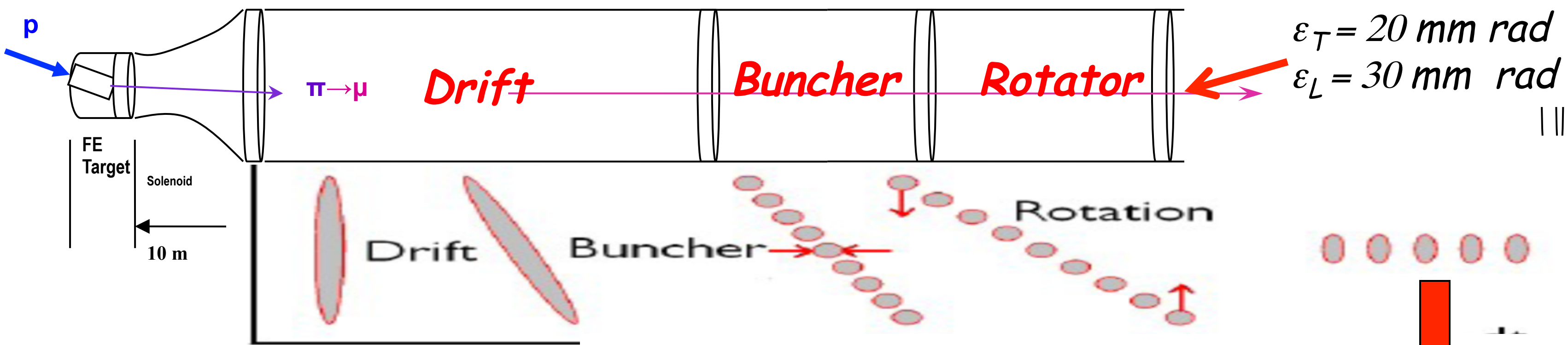
1. Linear transverse cooling of both signs and small Δp increase.
2. Ring cooling in 6D with B brings the μ+ and μ- to a reasonable size Merging and cooling to single bunches
3. Parametric Resonance Cooling (PIC), where the elliptical motion in *x-x'* phase space has become hyperbolic.



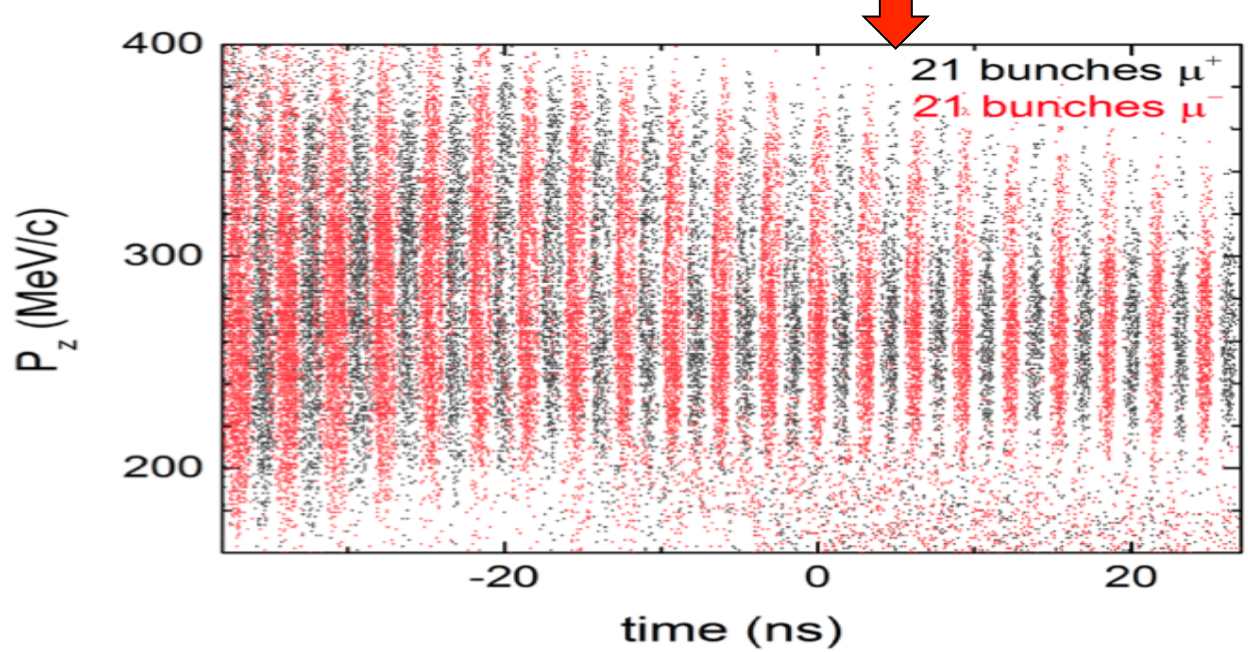
$\varepsilon_\perp = 0.04(\pi)mm\,rad \quad \varepsilon_L = 1.0(\pi)\ mm\ rad$

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 Ionization cooling

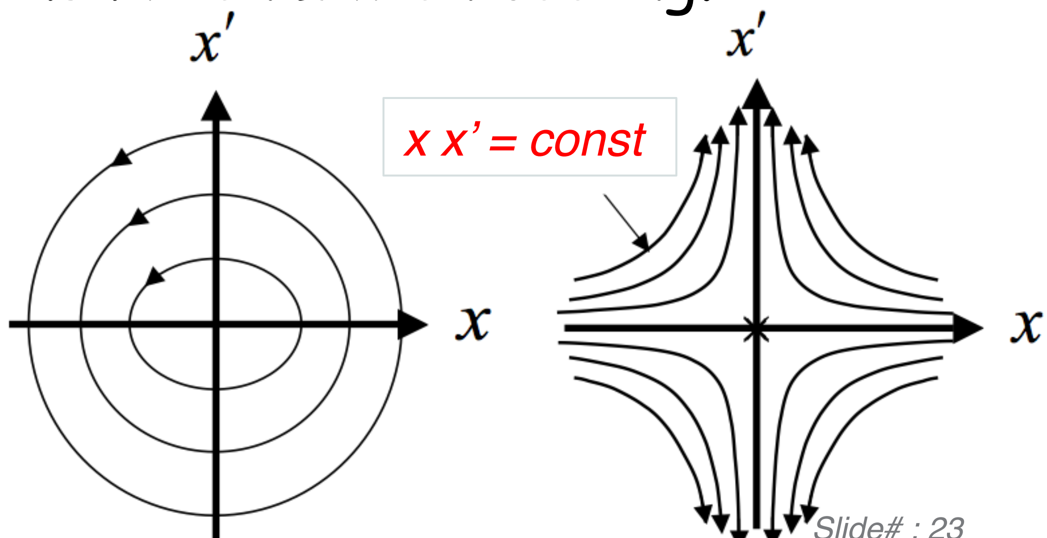
- This method, called "dE/dx cooling" closely resembles to the synchrotron compression of relativistic electrons — with the multiple energy losses in a thin, low Z absorber substituting the synchrotron radiated light.
- The main feature of this method is that it produces an extremely fast cooling, compared to other traditional methods. This is a necessity for the muon case.
- Transverse betatron oscillations are "cooled" by a target "foil" typically a fraction of g/cm^2 thick. An accelerating cavity is continuously replacing the lost momentum.
- Unfortunately for slow muons the specific dE/dx loss is increasing with decreasing momentum. In order to "cool" also longitudinally, chromaticity has to be introduced with a wedge shaped "dE/dx foil", in order to reverse (increase) the ionisation losses for faster particles.

T. Neuffer Particle Accelerators 1983 Vol. 14 pp. 75-90

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.

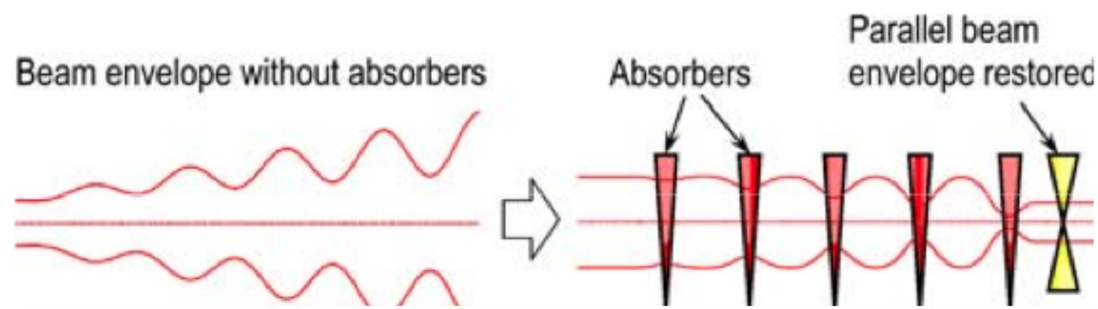
LEFT ordinary oscillations
RIGHT hyperbolic motion induced by perturbations near an (one half integer) resonance of the betatron frequency.

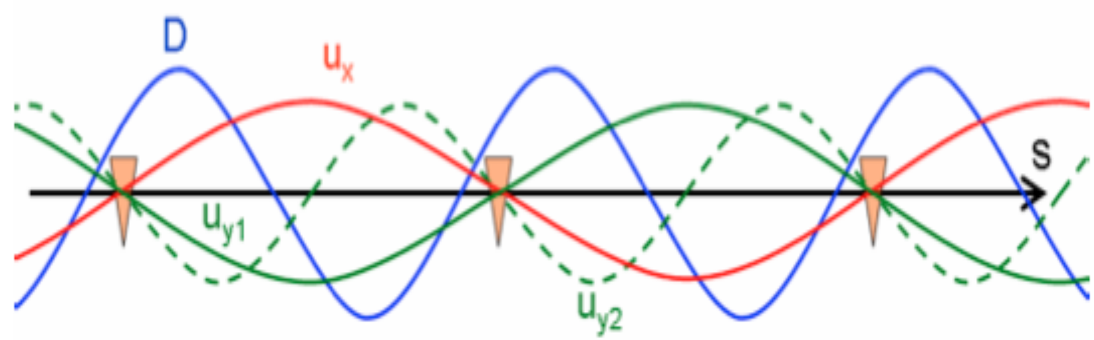


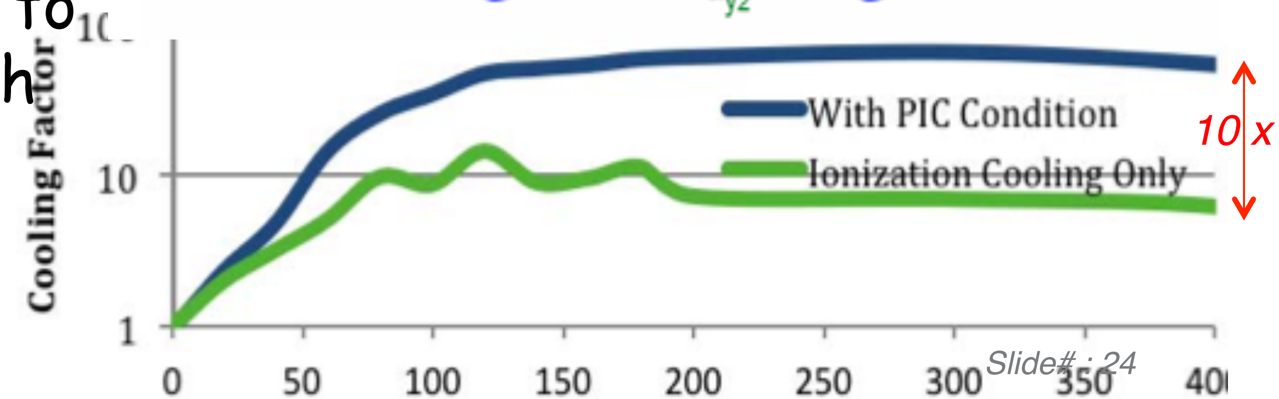
V. S. Morozov et al, AIP 1507, 843 (2012);

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*





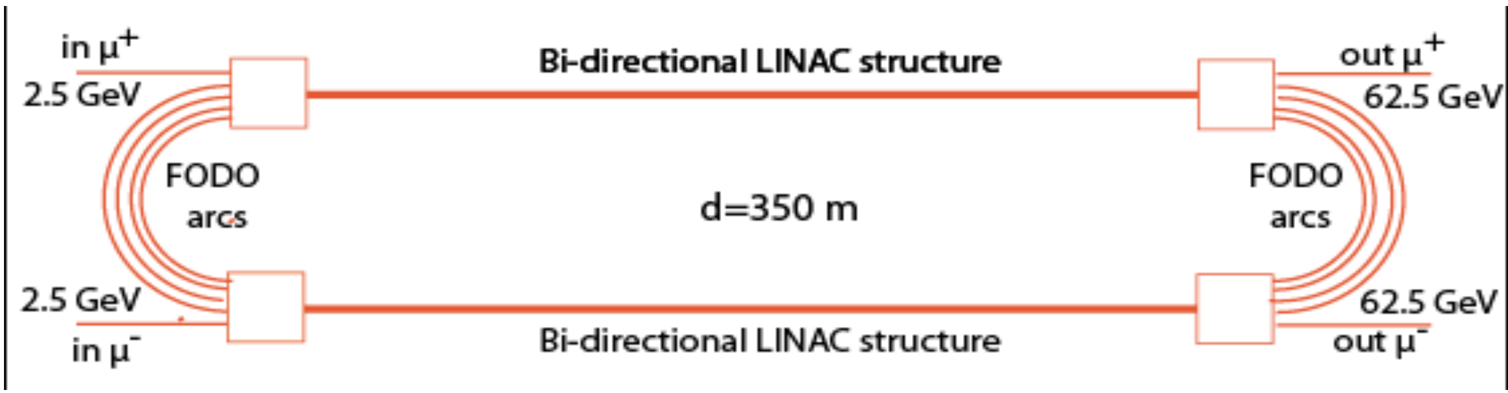


Comments on the cooling process

- 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,
- PIC may expect up to one order of magnitude transverse emittance decrement.

Bunch acceleration to 62.5 GeV

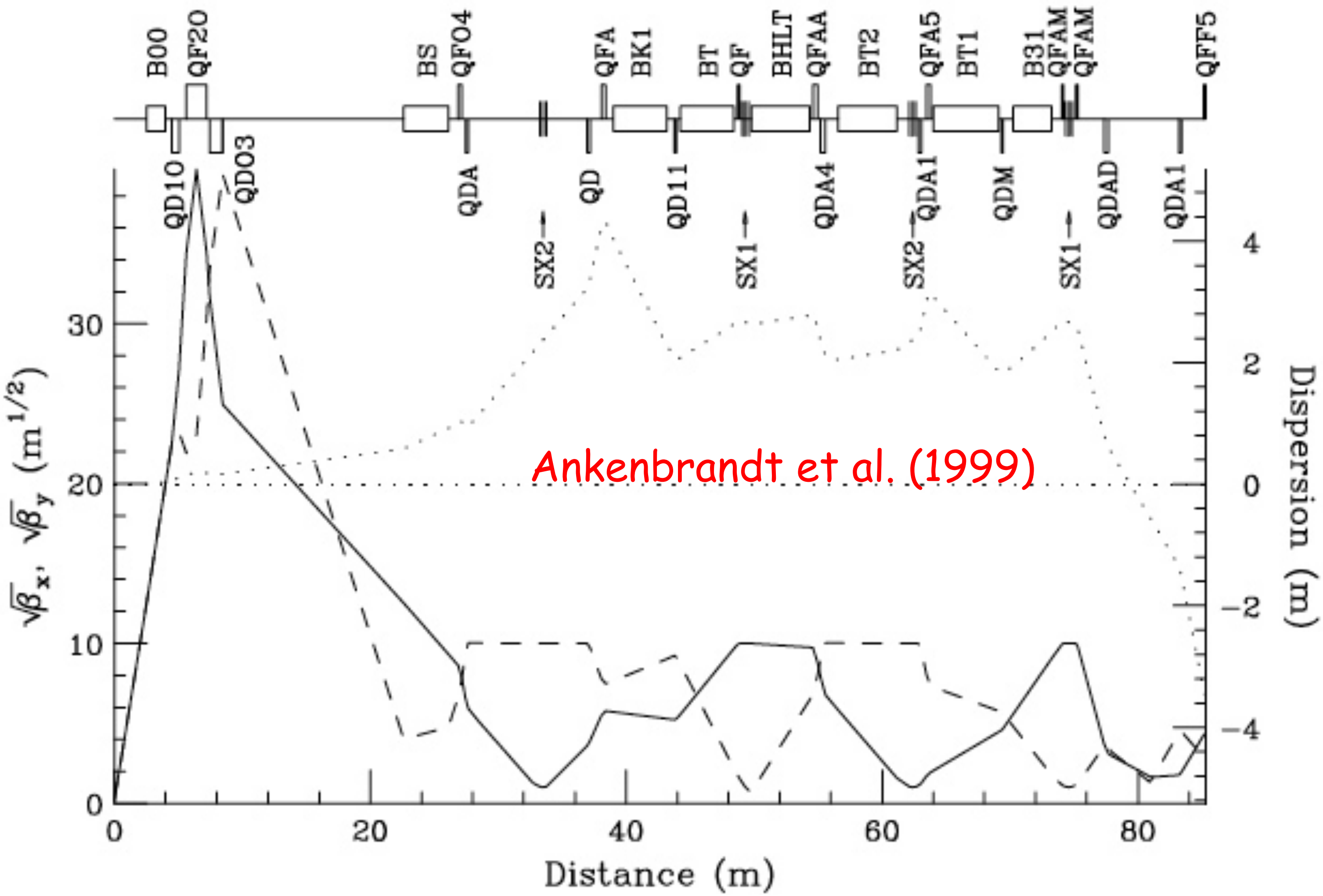
- Next, in order to realize a Higgs Factory at the known energy of 126 GeV, an acceleration system is progressively rising the energy of captured muons to $m_{Ho}/2$
- Adiabatic longitudinal Liouvillian acceleration to p_f= 62.5 GeV/c.
- Both μ+ and μ- are accelerated sequentially in the same LINAC with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



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.



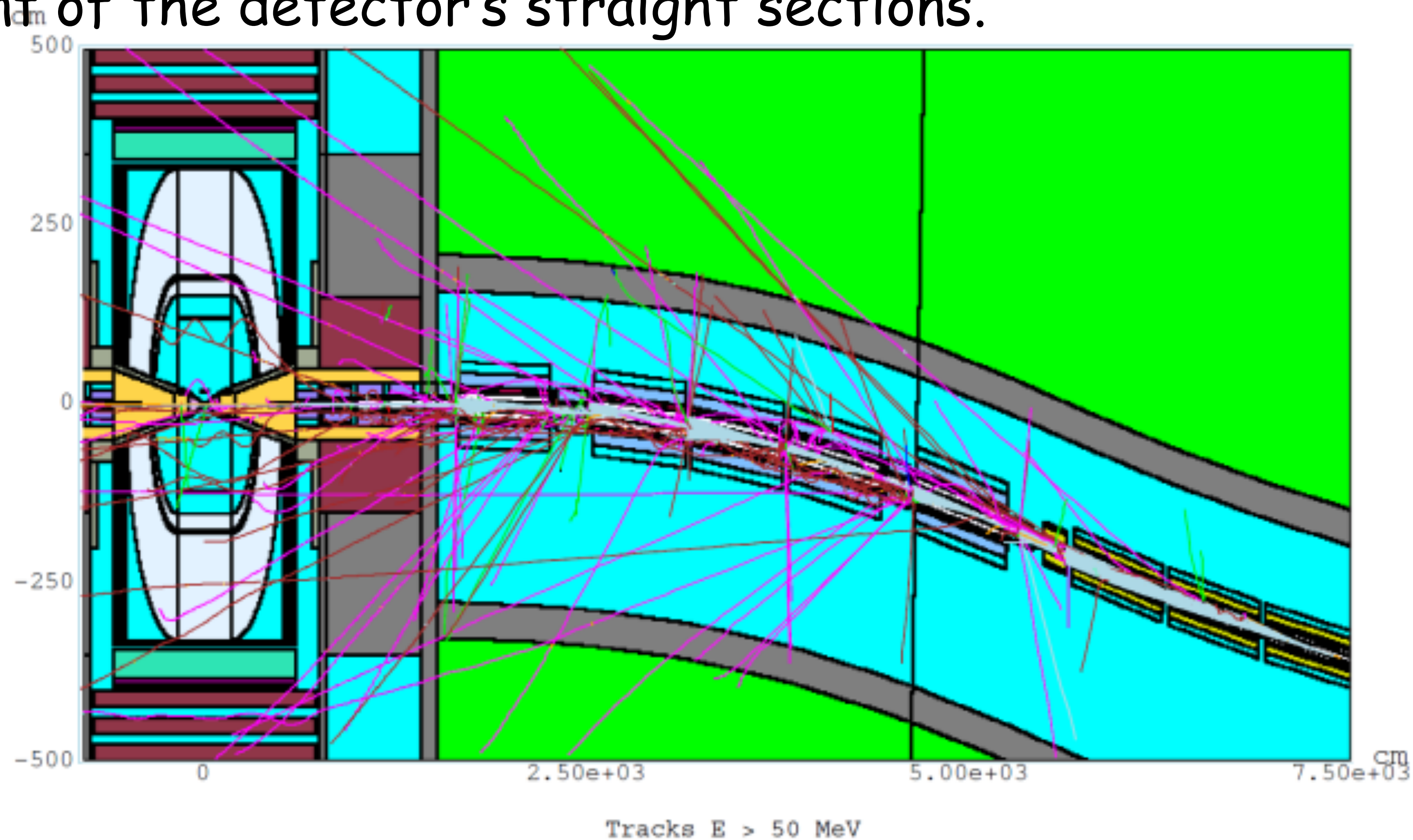
Eatimated performance for the Hº-factory at the ESS

- 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.
- A peak collider luminosity of 4 x 10^{32} cm^{-2} s^{-1} is achieved *with PIC cooling*
- 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 detector.
- An arrangement with at least two detector positions is raccomended.

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	4.24×10^{31}	cm^{-2} s^{-1}
Luminosity + PIC (10 x)	4.2×10^{32}	cm^{-2} s^{-1}
Higgs cross section	3.0×10^{-35}	cm^2
Higgs @10^7 s/y, no PIC	1.2×10^4	ev/y
Higgs @10^7 s/y + PIC	**1.2×10^5**	**ev/y**
Higgs -> γγ, 10^7 s/y + PIC	≈ 2400	ev/y
Tune shift with PIC	0.086	

Muon related backgrounds

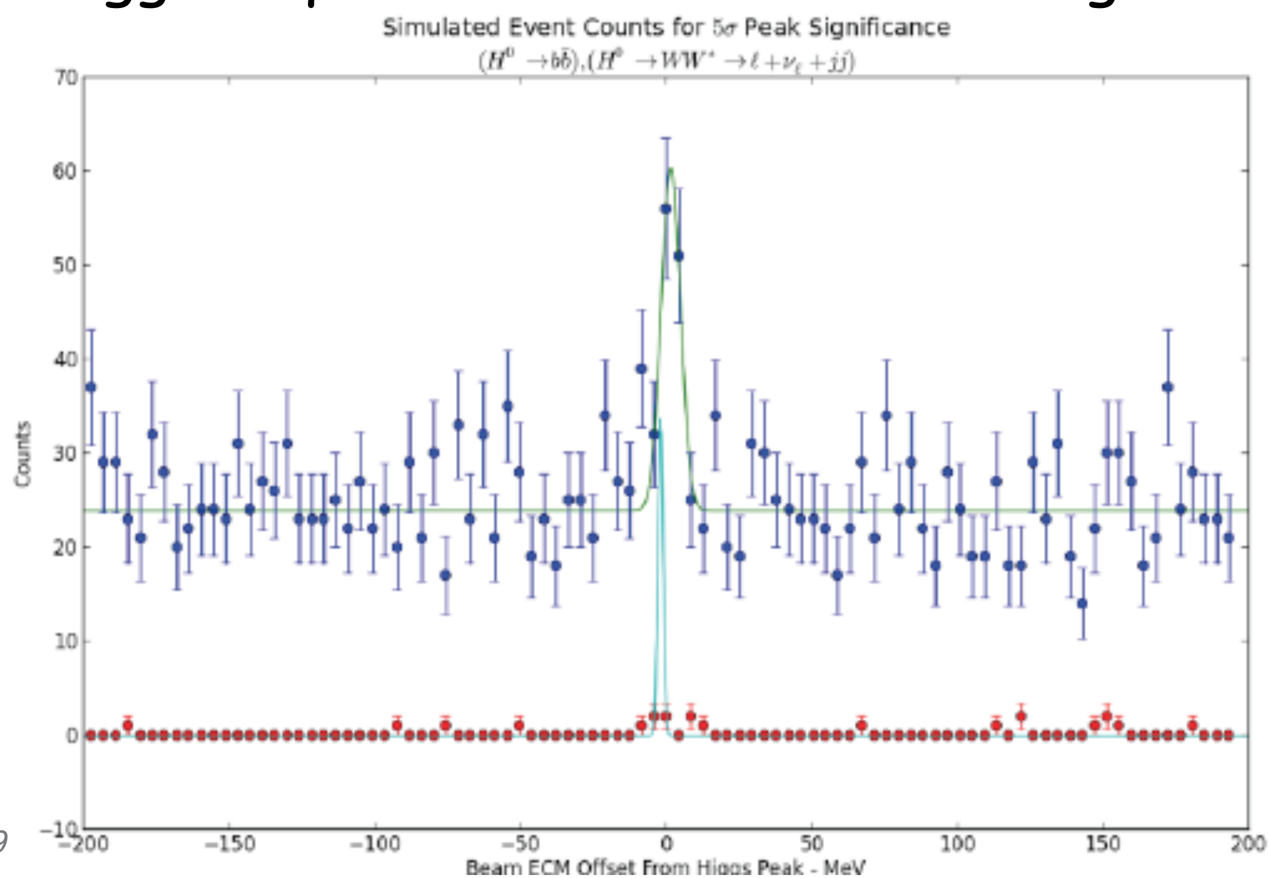
- A major problem is caused by muon decays, namely electrons from μ decay inside the detector with ≈ $2x10^3$ e/meter/ns, however collimated within an average angle of 10^{-3} rad.
- A superb collimation is required with the help of absorbers in front of the detector's straight sections.



Drozhdin, Mokhov et al.

Finding the exact location of the Higgs

- Presently the Higgs mass is known to some 600 MeV. It will be known to ≈ 100 MeV from the LHC with 300 fb-1 . But at a muon collider we need to find M_H to ~4 MeV and then select the resonance location.
- Finding the Higgs requires a few months running at 1.7 x 10^{31} luminosity.



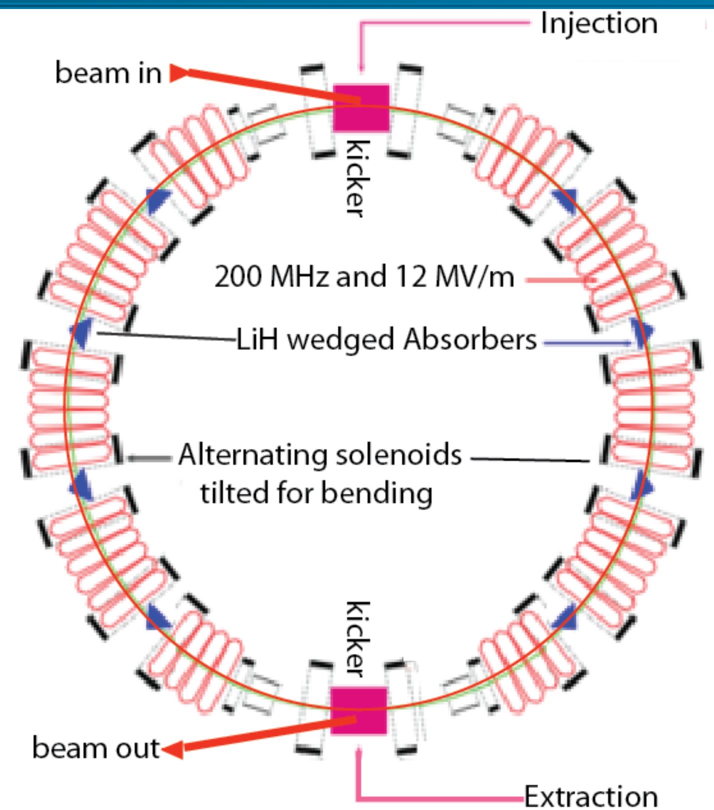
the Initial Cooling Experiment

- 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 some existing accelerator at a reasonable intensity.
- 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 low cost.

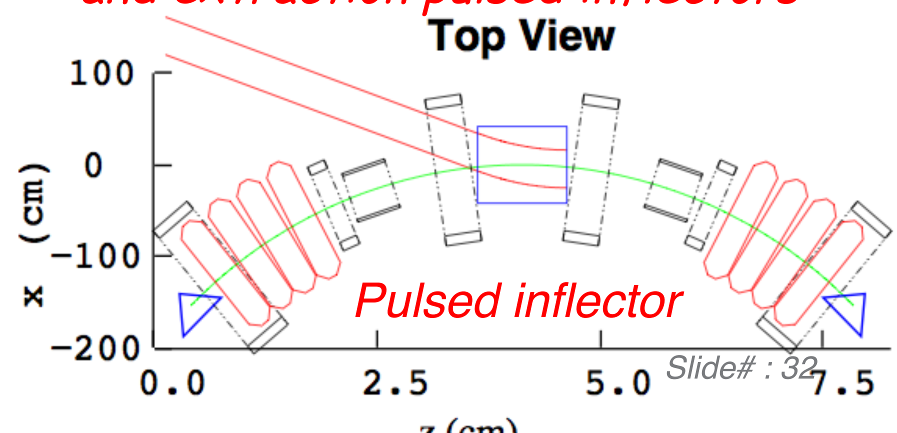
The RFOFO Ionization Cooling

- 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*



Summary of the ESSμSB ring configurations

- All the described rings dimensions may easily fit within the existing ESS site or eventually located at CERN.
  - A proton accumulator and compressor rings with a radius of 35 m. subdivided from 14 to 42 bunch/s;
  - A $\pi - \mu$ linear decay channel of about 100 m length converting muons to 220 MeV/c;
  - a pair of robust μ^+ and μ^+ ionization-cooling rings each with ≈ 6 m radius, compressing to two narrow bunches eventually followed by PIC cooling rings;
  - a fast re-circulating LINAC acceleration system of about few hundred m to bring muons to both required collision energies;
  - a collider ring at 7 Tesla and ≈ 50 m radius for option (1) and ≈ 200 m for option (2) with two two narrow bunches and two interaction points where detectors are located with ≈ 2x 10^{12} muons of each sign.

Thank you !

"I'm starting to get concerned about global warming."