Further developments of the Higgs scalar sector.

Carlo Rubbia

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

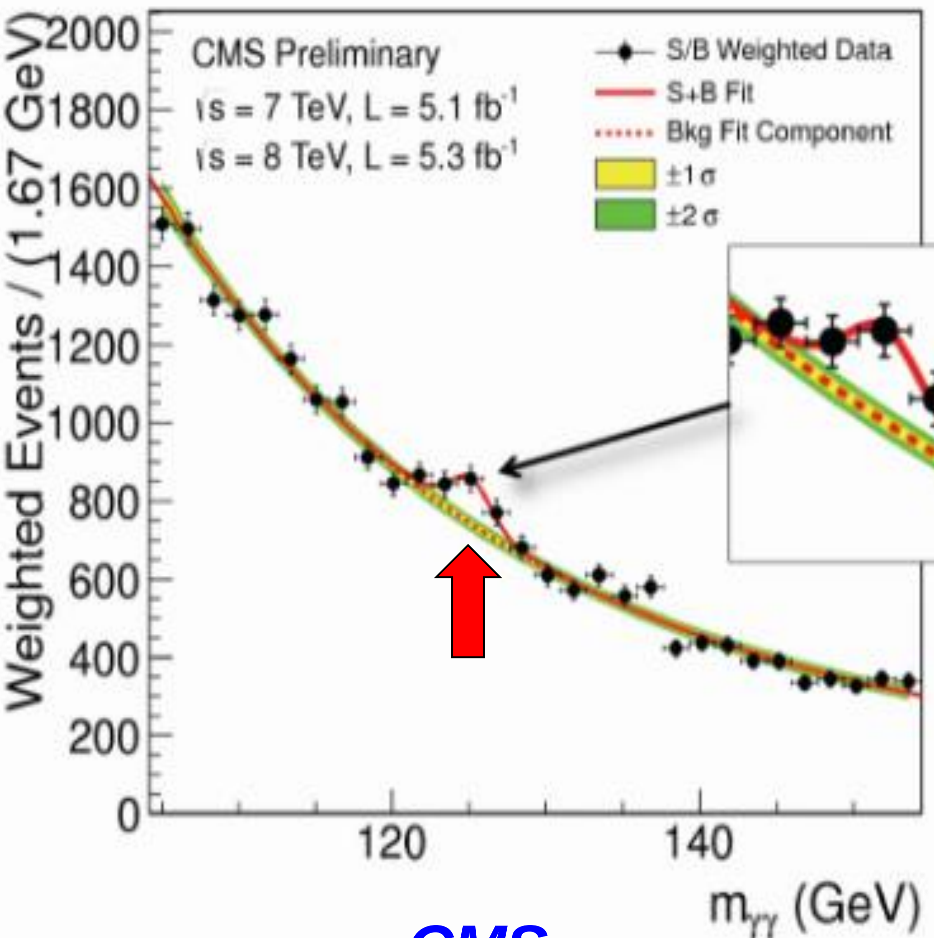
CERN, European Organization for Nuclear Research, Geneva, CH

Life long Member of the Senate of the Italian Republic

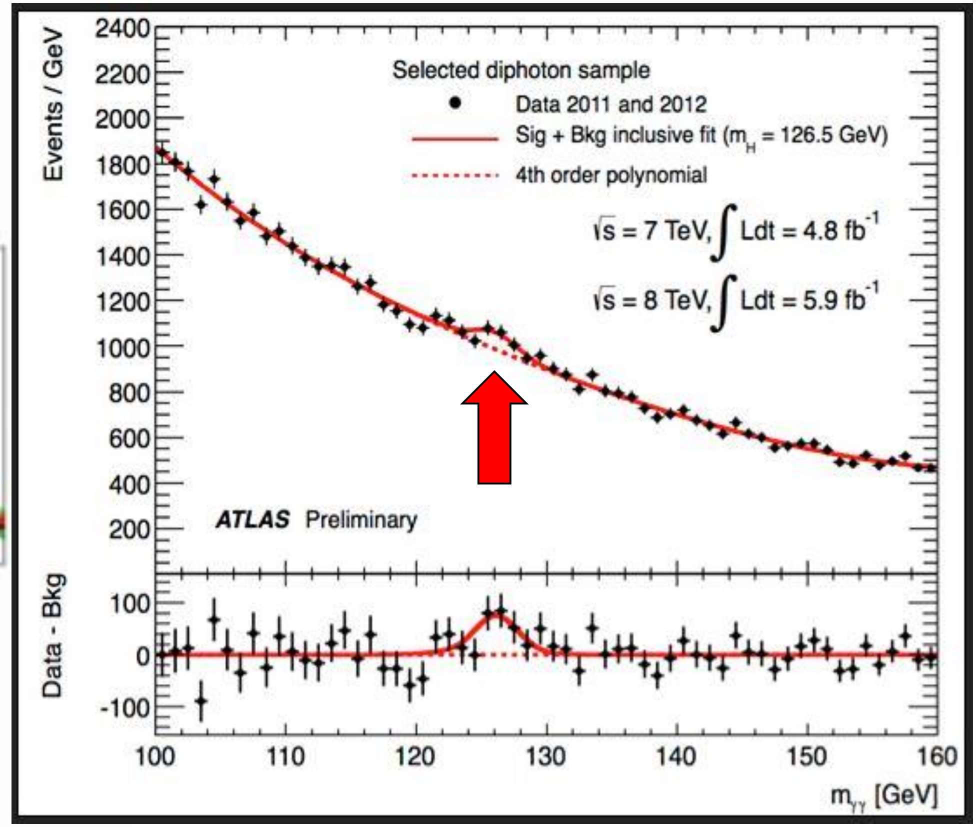
An European collider strategy

- CMS and Atlas have observed at the CERN LHC collider a narrow line of high significance at about 125 GeV mass, compatible with the Higgs boson of the Standard Model .
  - ATLAS: m_H = 125.5 ± 0.2 (stat) ± 0.6 (sys) GeV
  - CMS: m_H = 125.8 ± 0.4 (stat) ± 0.4 (sys) GeV
- At the LHC, Higgs is produced only once every 10^9 collisions. In these two discovery experiments several channels were actually recorded roughly every 10^{12} collisions.
- Searches have been performed in the presence of very substantial backgrounds. Additional uncertainties come from proton structure functions, unknown higher-order perturbative QCD corrections and from non perturbative QCD effects.
- For the future 300 fb^{-1} the typical accuracy has been generally estimated for the various decay modes in about 10% – 15% at the single standard deviation level, depending on the scenario.
- At least 5 standard deviations are needed for confirmations.

- The Higgs discovery at CERN and the typical signals for the 2 γ channel. Observe the huge amplitudes of the background



CMS



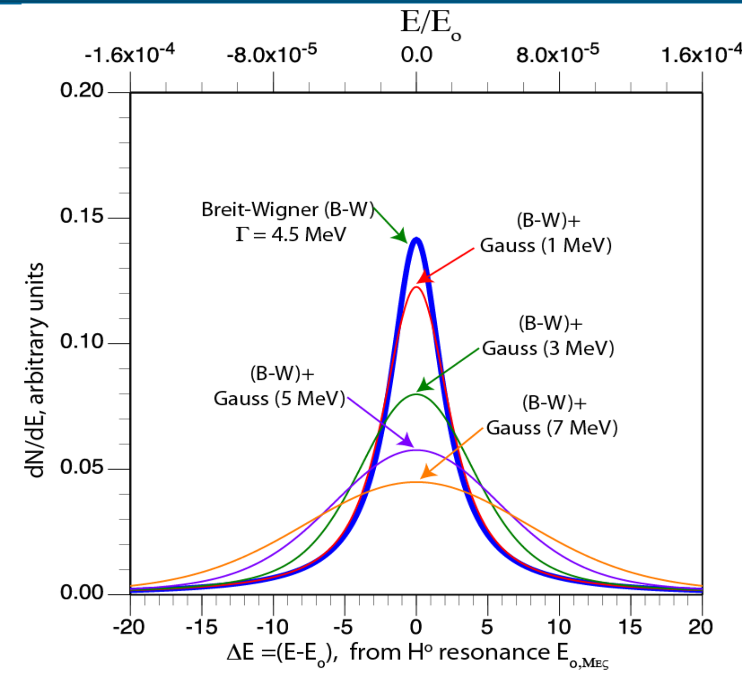
ATLAS

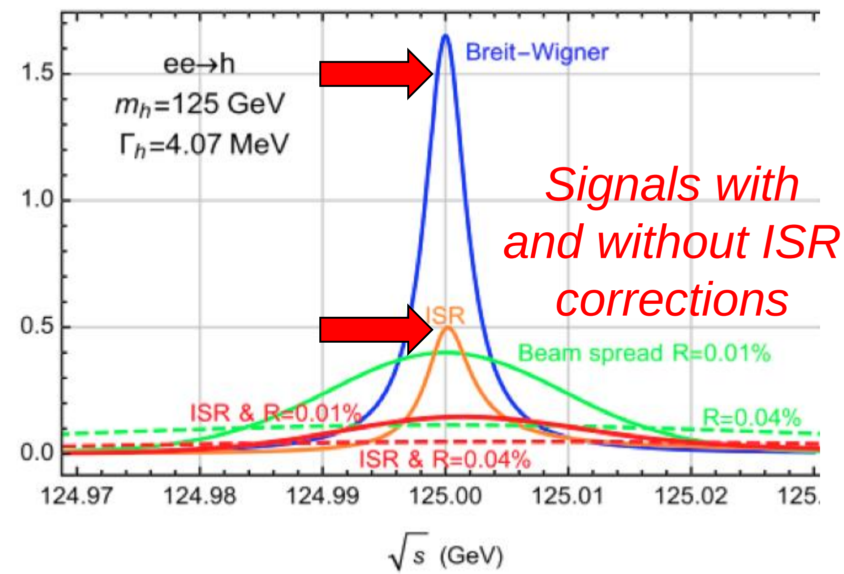
The HL-LHC luminosity upgrade

- During the *next twenty years (!)*, the HL-LHC plans are to further pursue both (1) the hadronic production of the Higgs related sector and (2) the search of the possible existence of additional SUSY particles with 250 fb^{-1}/year and >3000 fb^{-1} by 2035, the ufficial date of LHC termination
- ATLAS and CMS will be upgraded to handle an average number of ≈ 140 pile-up events at each bunch crossing, corresponding to a line density of 1.3 events per mm and an instantaneous luminosity L of about $5 \times 10^{34}\ cm^{-2}s^{-1}$. An even higher L may be expected. The proton energy stored in the HL-LHC will be about 1000 MJ.
- HL-LHC may be already an early "Higgs factory", but only with persisting large uncertainties because of backgrounds.

Properties of the Higgs

- Following the 2012 CERN discovery, a next goal will be to measure with higher precision all the important parameters of *the H_o new scalar*, such as the width and their common and rare branching fractions.
- According to the SM model, the H_o width is however only $\Gamma \approx 4.16$ MeV at a kinetic energy of E = 125.5 GeV, namely $R = \Gamma/E = 3.2 \times 10^{-5}$.
- Radiative corrections (Greco, Han, Liu) are remarkably large.
- A complete fading away of the H_o resonance may occur already for $R \geq 4.0 \times 10^{-4}$, a resolution $\Delta E \approx 50$ MeV.





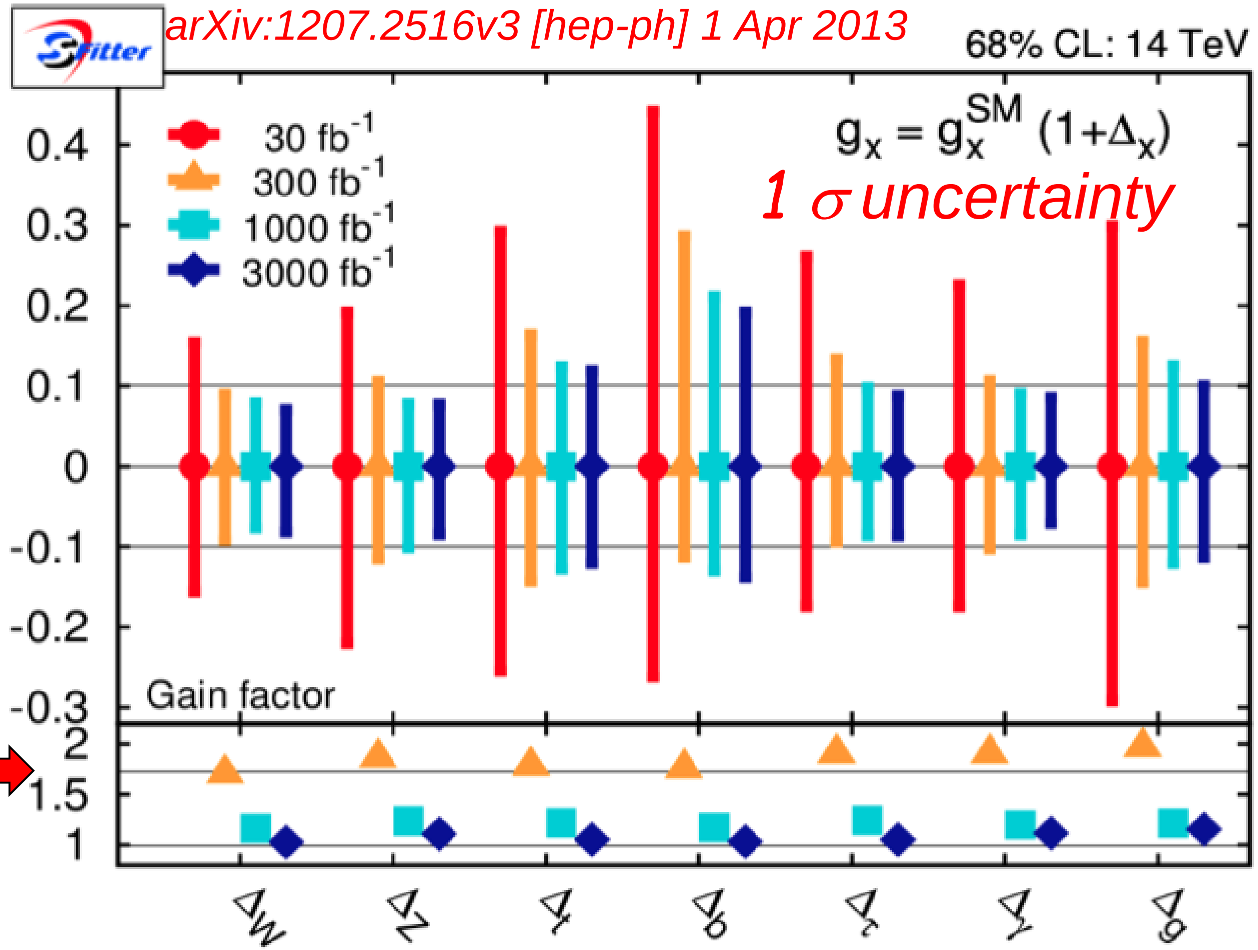
Properties of the Higgs (cont.)

- The Higgs particle, ***being a scalar,*** is characterized by a much stronger direct coupling to muons when compared to electrons.
- H^o has several substantive decay branching fractions : (bb), 60%; (WW), 20%; (gg), 9%; (ττ), 6%; (ZZ), 3%; (cc), 3%. The process (γγ) with 0.2% is also substantive due to its high mass resolution and relatively low background.
- These future experimental determinations are the analogue of the well known previous studies on *the Z^o and the W's,* where the initial search and discovery with the p-pbar collider had been followed by the systematic studies of Z^o with leptons at LEP.
- However the narrow width of the H^o, has to be compared for instance with the much larger Z^o width of 2.5 GeV.

Ultimate LHC uncertainties are due to systematic effects

- Higgs estimates for the LHC detectors with growing amounts of data have been foreseen by ATLAS and CMS collaborations at their best today's understanding.
- ATLAS and CMS have estimated signals from the High-L LHC up to 3000 fb–1.
- Note that the progress is very slow and that less than a factor < 2 in precision is expected from a factor 100 in data.

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



Unambiguous discoveries require 5 σ

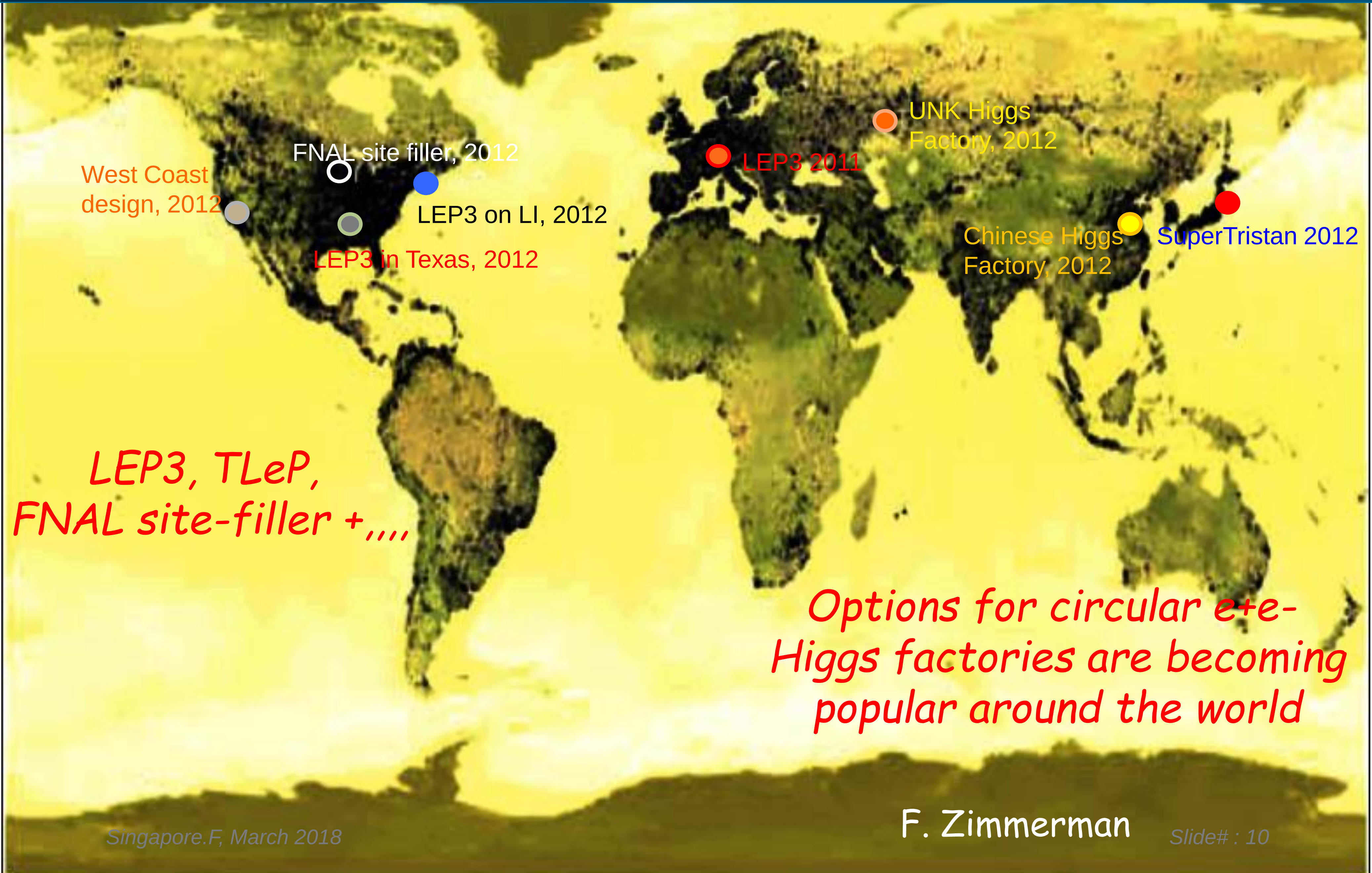
Future alternatives with the LHC tunnel ?

- The *Higher Energy e+e- collider and √s ≈ 240 GeV* ***(LEP3)*** may be constructed in the already existing LHC tunnel.
- A high efficiency of operation would require two rings in the 27 km tunnel: (1) a low emittance e+e- storage ring collider and (2) a separate accelerator injecting periodically electrons and positrons into the storage ring to top up the beams.
- The *Higher-Energy LHC* ***(HE-LHC)*** may collide two proton beams of 16.5-TeV energy, circulating in the LHC tunnel, and new dipoles of about 20-T in a same bending-magnets configuration,
- The centre of mass energy (33 TeV) becomes comparable to the 40 TeV of the cancelled SSC in the US.
- Higher energies may be profitable mainly for SUSY searches.
- However for instance for the detection of H^0 the *background remains too large*.

Huge mew options of future circular rings

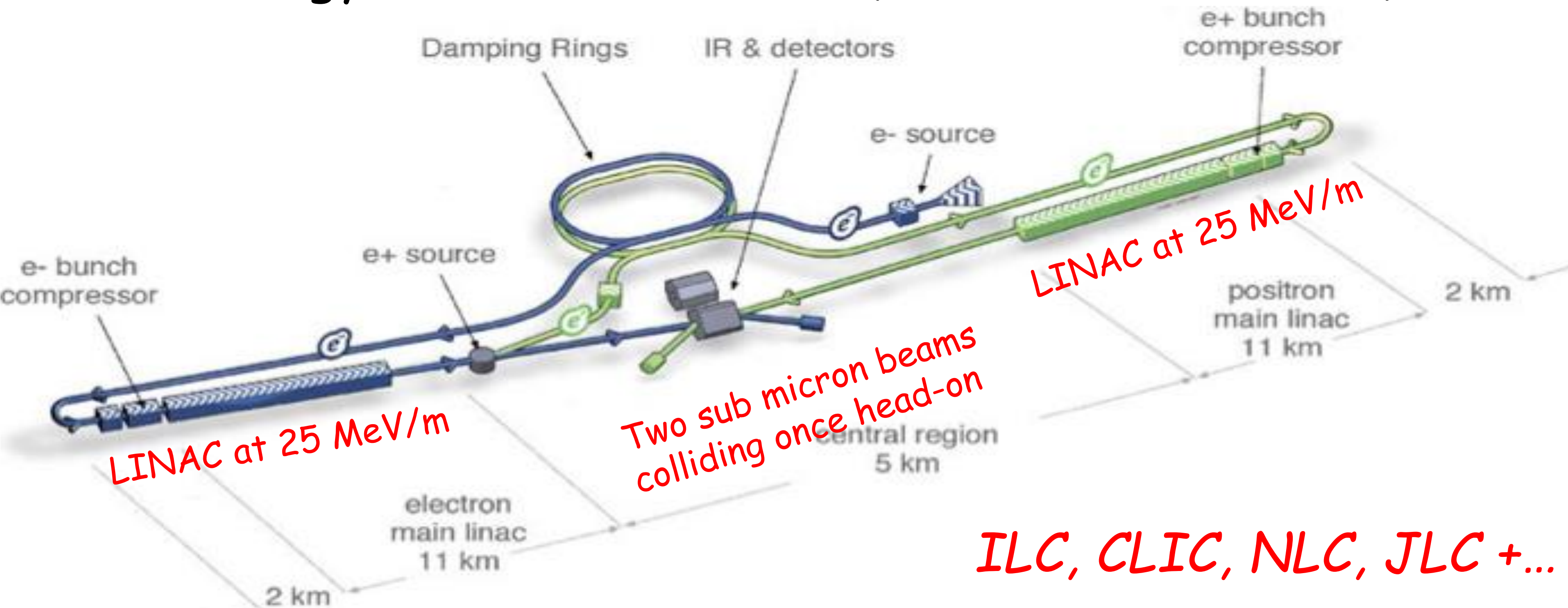
- Two examples of novel e+e Circular Rings are CEPC from China (circumference 54 km, 2x LEP) and FCC-ee from CERN (circumference 100 km, 3.7x LEP), wth an expectation of about 10^6 Higgs in 10 years of operation, essentially from e^+e^- -> H_oZ.
- Such a large luminosity and a synchrotron beam power of the order of 100 MWatt (corresponding to an electricity consumption of 500 MWatt) are realized with a very large number of e+e- bunches (2 x 50 bunches for CEPC) and a very small vertical betatron focal radius of ≈ 1 mm (it was 50 mm for LEP2)..
- Like it has been the case of LEP/LHC, in both instances and especially in China, the e+e- phase is to be followed, by a subsequent phase of pp collisions with SC magnets of very high field (15 -20 Tesla) and approaching the pp limit of 50 to 100 TeV, about 10 x LHC
- Very long range world-wide projects of huge cost and time

Huge $e^+ e^-$ ring proposals, about 4 times the LHC.



The Linear Collider options: ILC, CLIC, NLC, JLC +

- 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 $\sqrt{s}$ 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

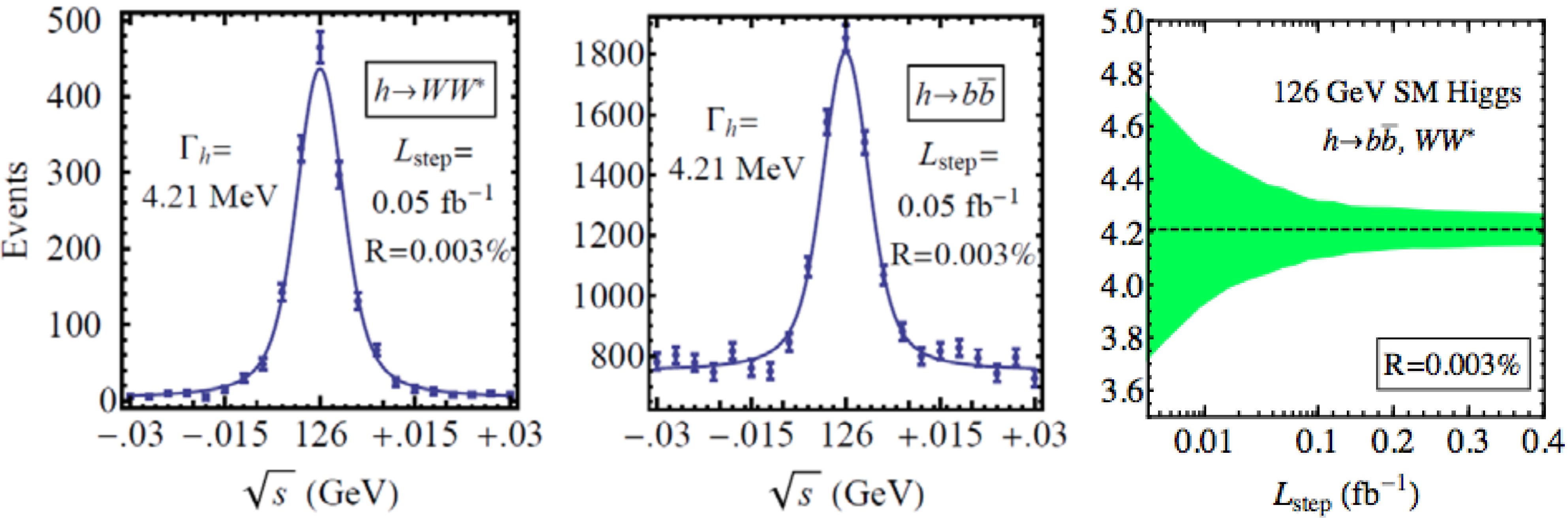
Choosing more realistic facilities

- Colliders of much smaller size, cost and shorter realization time should be investigated. Two main programs are possible:
  - *the s-channel Ho resonance at the 125.5 GeV centre of mass energy* and L ≈ 10^{32}, in order to study the narrow partial Ho decay widths. Being a scalar, Ho may be better produced with *μ+μ−* rather than with e+e-**rings**. It requires phase space compression with a tiny collider ring.of *≈ 50 m radius* (about ½ the CERN PS) but a *resolution ≈ 0.003%*
  - *A higher energy collider, eventually up to 1 TeV* and L ≈ 10^{34} to study the many Higgs processes with leptonic beams. Either e+e- or μ+μ− in the channel *Higgs + X* can be used. Electrons require huge ring dimensions (f.i. FCCee/CEPC/ILC). With stronger bending magnets, μ+μ− may be built also in an existing site. At √s = 1 TeV the *ring radius is ≈ 400 m* (about 4 times the CERN PS) and the *resolution ≈ 0.1 %*

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%

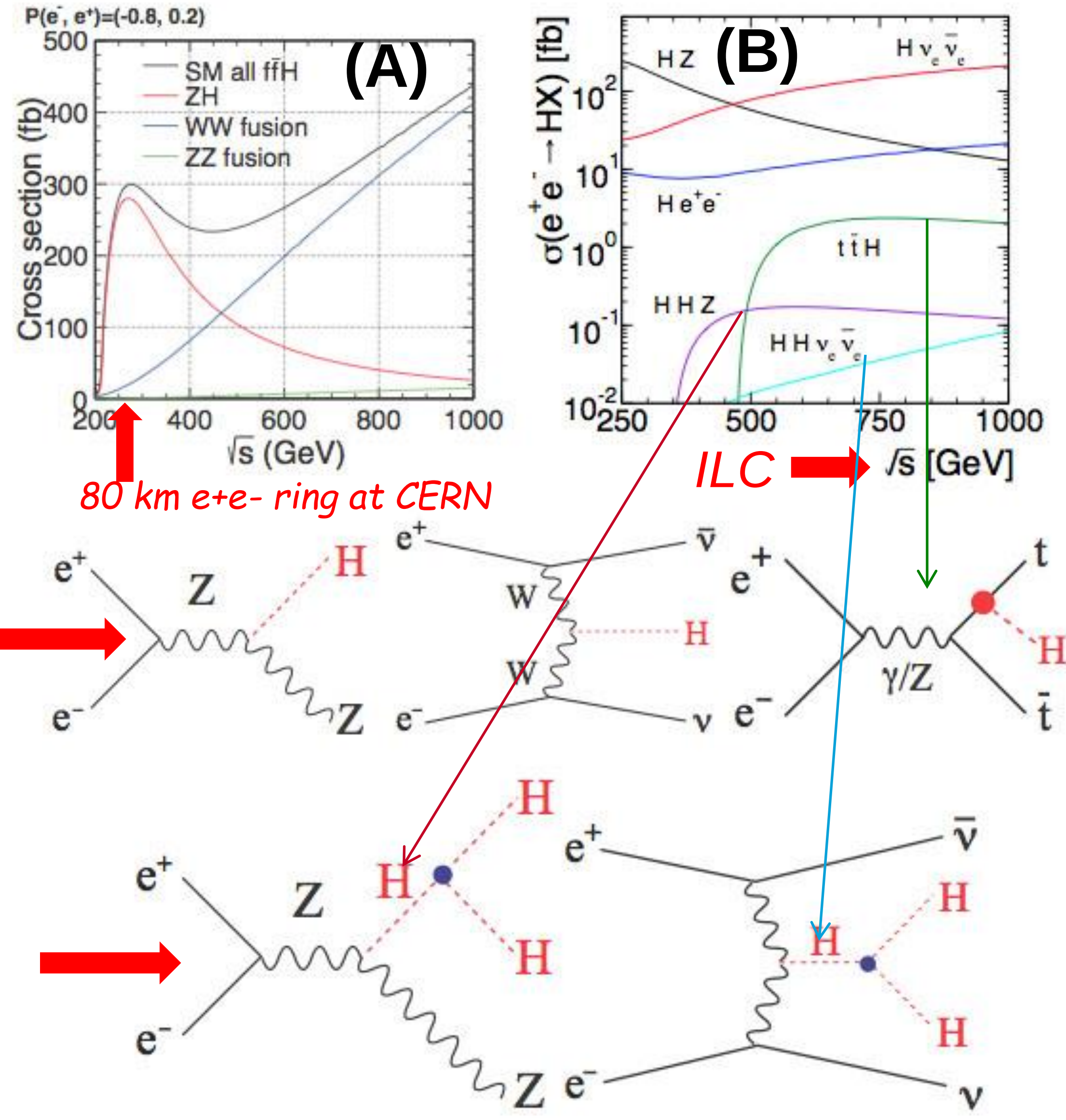
R (%)	$\mu^+\mu^- \to h$ $\sigma_{\rm eff}$ (pb)	$h \to b\bar{b}$ σ_{Sig}	$h \to b\bar{b}$ σ_{Bkg}	$h \to WW^*$ σ_{Sig}	$h \to WW^*$ σ_{Bkg}
0.01	16	7.6	15	3.7	0.051
0.003	38	18		5.5	



arXiv:1210.7803 [hep-ph].

Main Leptonic Higgs reactions to about 1 TeV

- **(A)** Production cross sections of Higgs boson from e+-e-or μ+-μ- as a function of the energy √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 ≈ 1 TeV are necessary

Liouvillian and not liouvillian forces

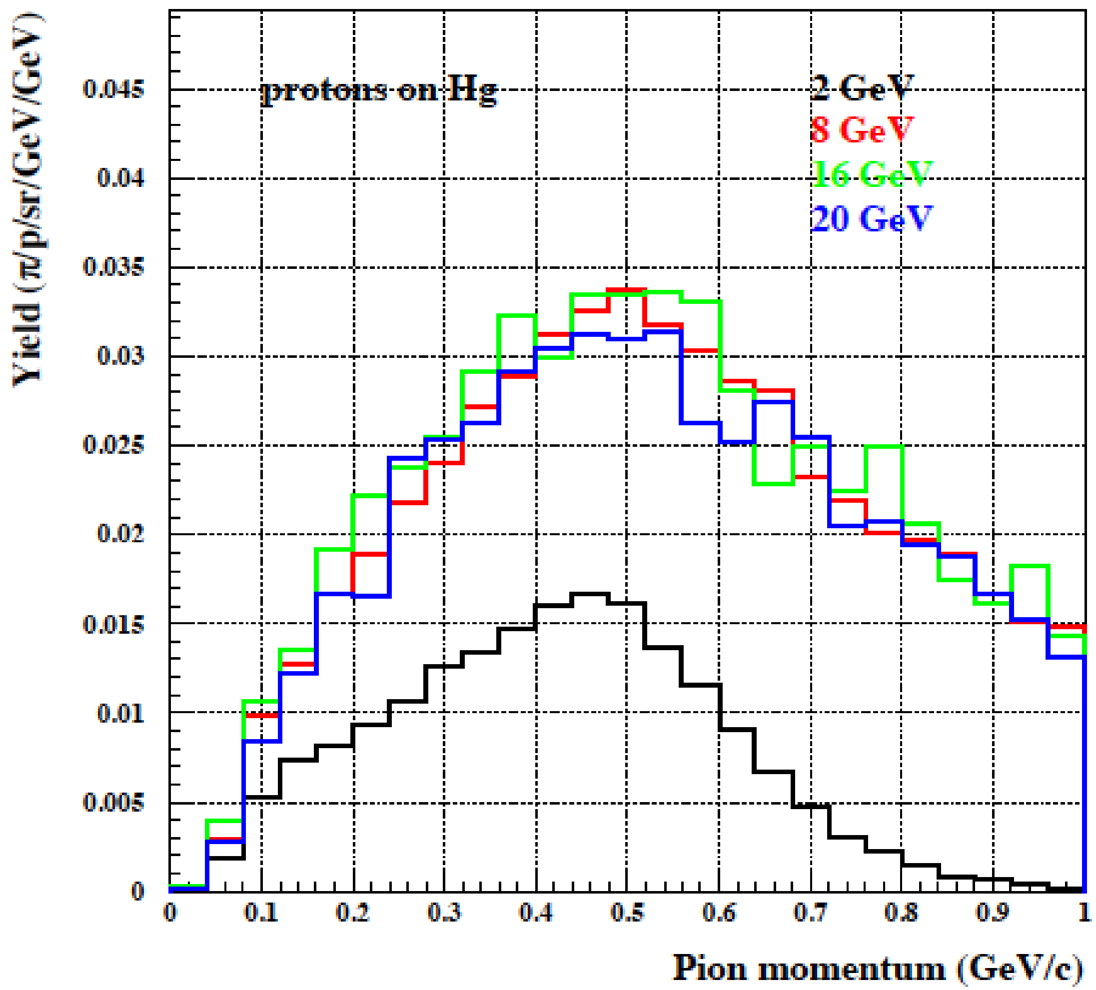
- Already at MURA in the fifties it was realised that some beam phase-space compression may often be necessary going from the source to the collision point.
- The Liouville theorem states that whenever there is a Hamiltonian (i.e. the force is derivable from a potential) the six dimensional phase space 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) μ+μ- 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.

Process (A): choosing the proton energy

- The "proton power" (the number of incoming protons inversely proportional to their energy) is almost independent of proton energy between 8 and 20 GeV and a factor two lower for 2 GeV .
- Therefore the intensity of the secondary pion beams are all primarily dependent on the proton power rather than on their proton energy.



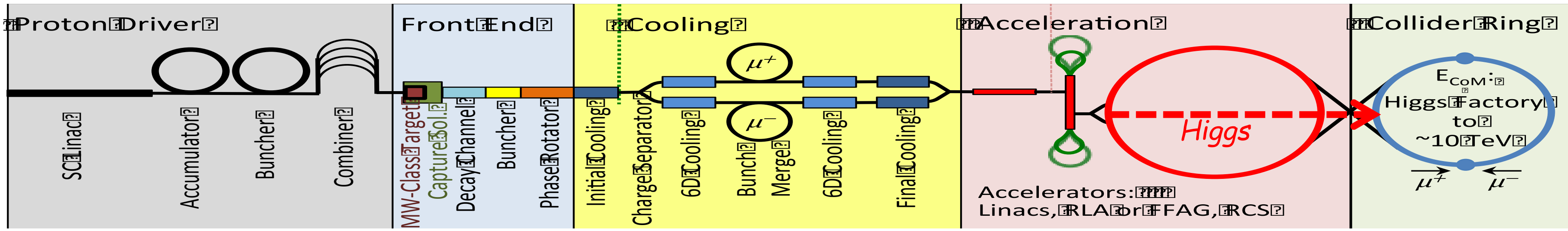
Process (B)

- The claimed advantage of process (B) from a high energy (45 GeV) accelerator is that $\mu^+\mu^-$ pairs near the production threshold are concentrated in a small bunch before acceleration
- But achieved luminosity (B) had been considered at that time as vastly insufficient for any practical realization. Later studies on the process (B) have confirmed such a conclusion
- A more recent study (LEMMA,2013) of process (B) is presently being carried out at the LNF with a positron beam on electrons just above the $\mu^+\mu^-$ production threshold.
- We anticipate the original papers of Antonelli et al., (arXiv:1509. 04454v1) of 2015 and of Boscolo et al, IPAC 2017 of the realization of (1) a 6 TeV ring from a dedicated 45 GeV, 6 km and 3 x 10^{13} e+ ring on 3 mm Be target and L ≈4×10^{34} $cm^{-2}s^{-1}$ and (2) a collider at the H mass (125 GeV) providing a total rate of 6 x 10^{15} Hz of e+ at 43.8 GeV and a claimed muon energy spread of *0.04%*
- These results are described later by the relevant authors

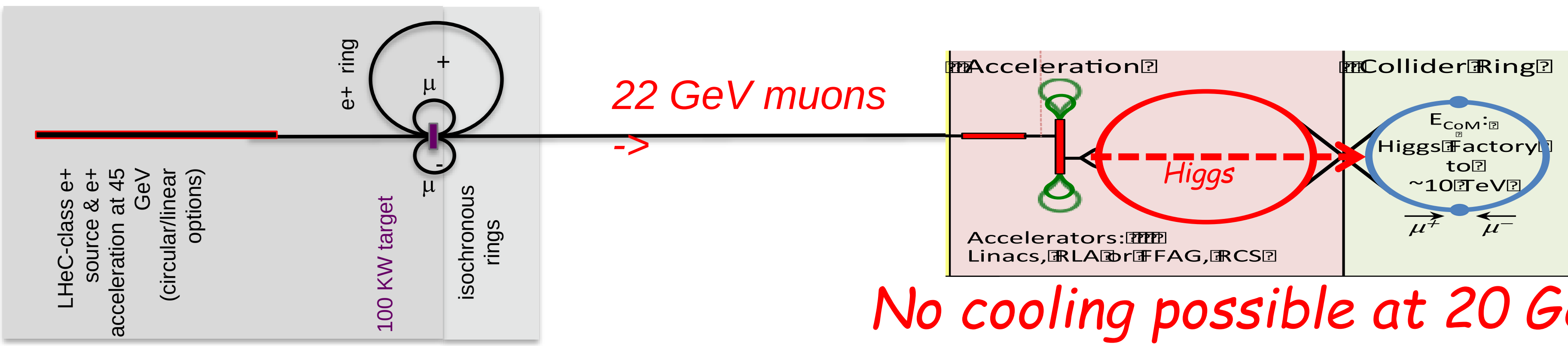
Comparing (A) with (B)

6D cooling at 220 MeV/c

(A)



(B)



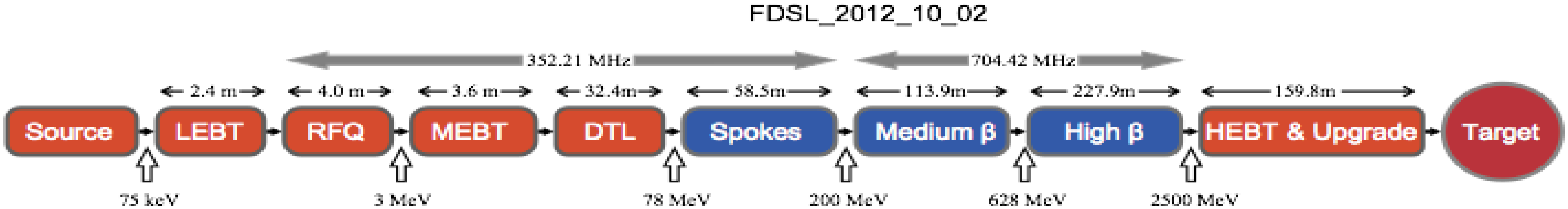
No cooling possible at 20 GeV!

From Boscolo et al

	Physical process	Rate muos/s	Norm.rate [μ mrad]
e+ on target	e+e- -> μ+μ-	0.9×10^{11}	0.04
Protons on target	pN -> μ + X	10^{13}	25

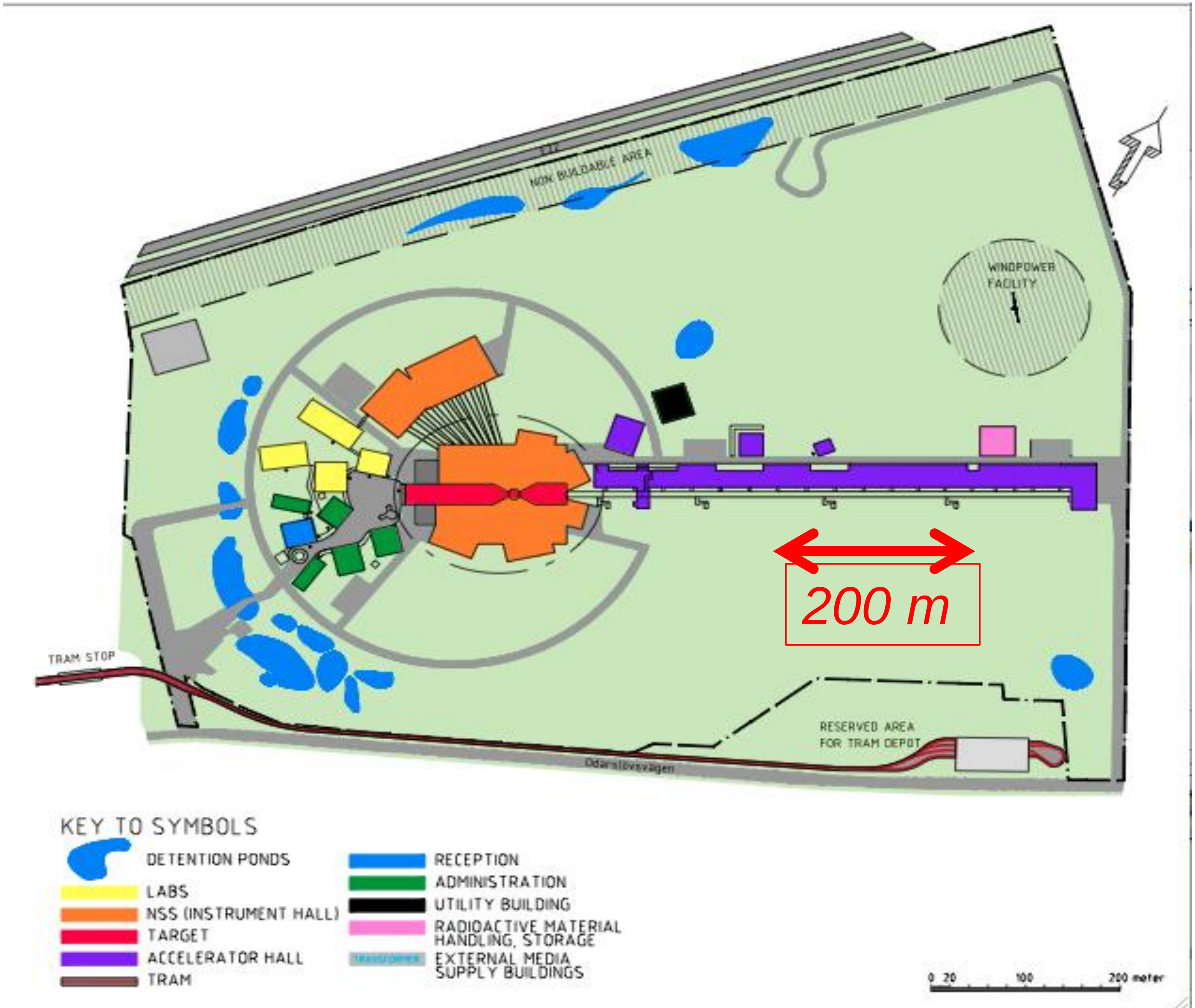
- Higgs at 125 GeV requires a remarkable energy resolution of R = 0.003% in order to ensure a visible signal.

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 2.0 GeV at 14 Hz and 1.1 x 10^{15} p/p it can provide the adequate intensity and repetition rate for the presently discussed collider program,
- Several other accelerator programs at higher energies for $\mu+\mu-$ 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
RESERVED AREA FOR TRAM DEPOT
Odarslövsvägen
200 m
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

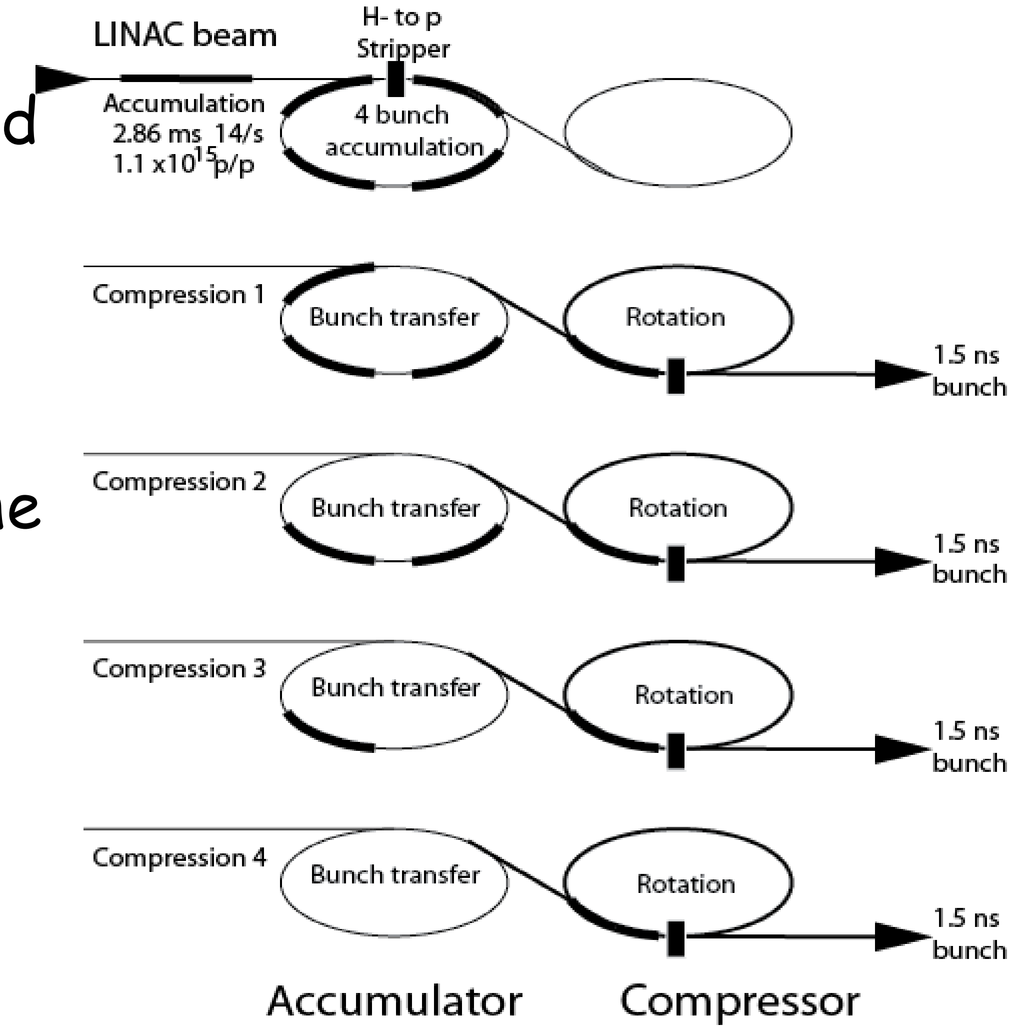
- ESS will accelerate 2.86 ms long and 62.5 mA proton pulses at 14 Hz and 2 GVolt kinetic energy (p = 2.784 GeV/c, β_p = 0.9476, γ_p = 3.131) with 1.1 x 10^{15} p/pulse and 5.0 Mwatt as a facility for spallation neutron production. First neutrons foreseen by 2019.
- The duty cycle of the accelerator 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 ESS approved intense source of spallation neutrons.
- As future option, 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.

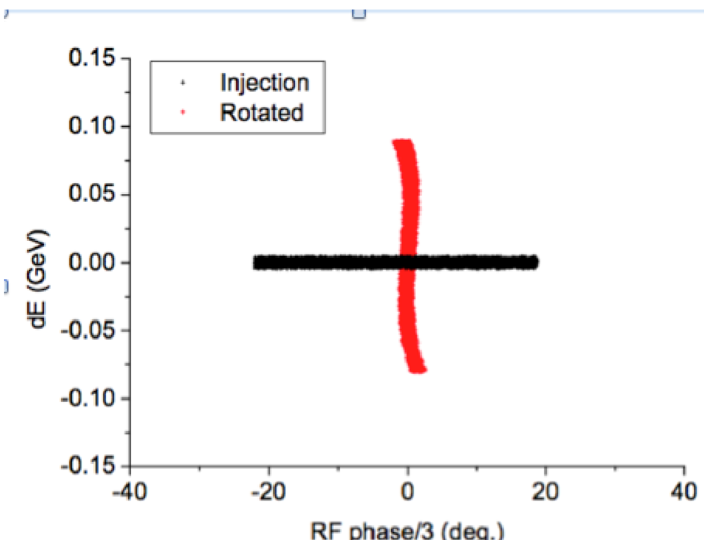
Intense muon beams for Higgs studies

- 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.

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.



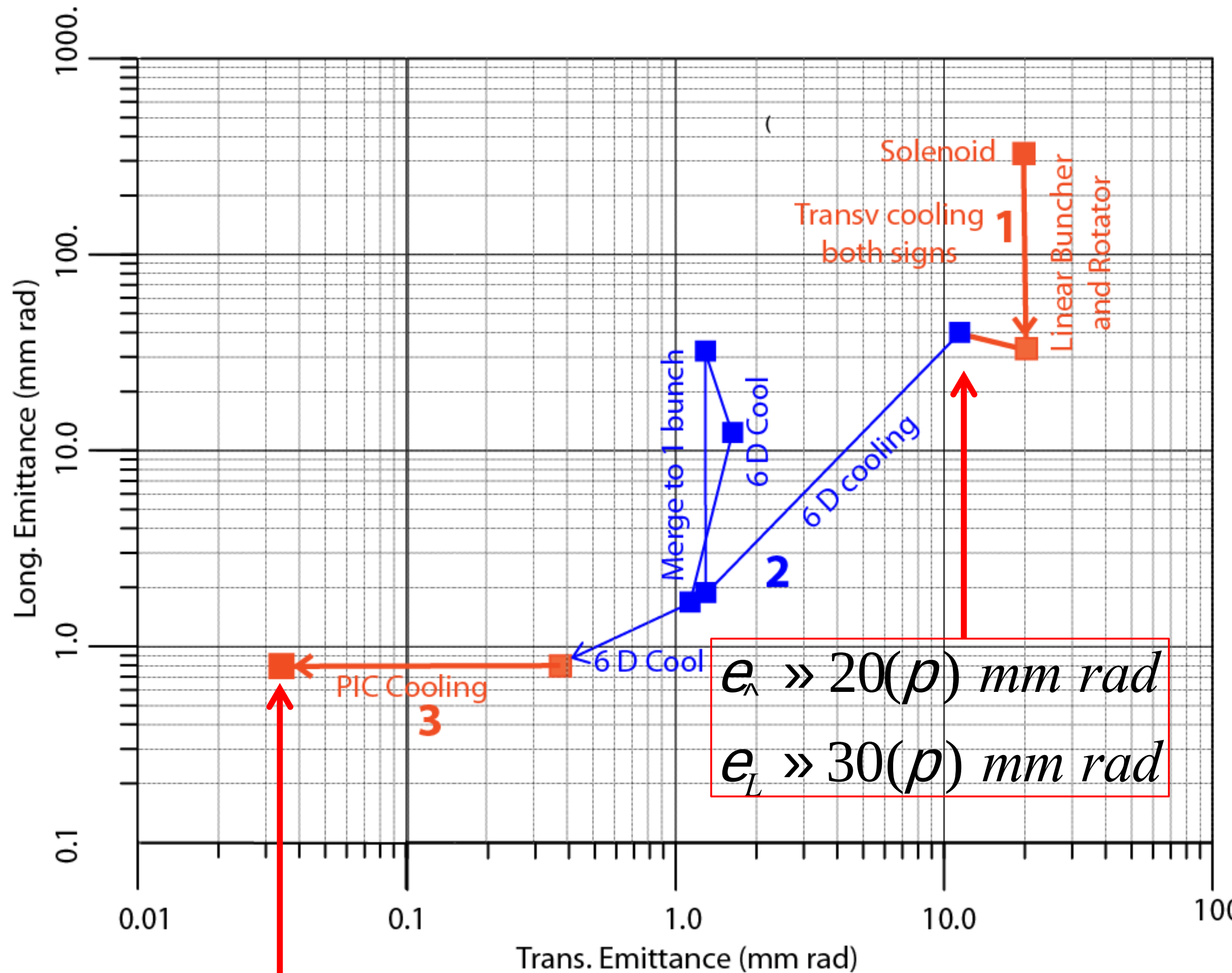


Rings have 35 m radius, wth 4 pulses of 120 ns each separated by 50 ns.

The cooling process

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

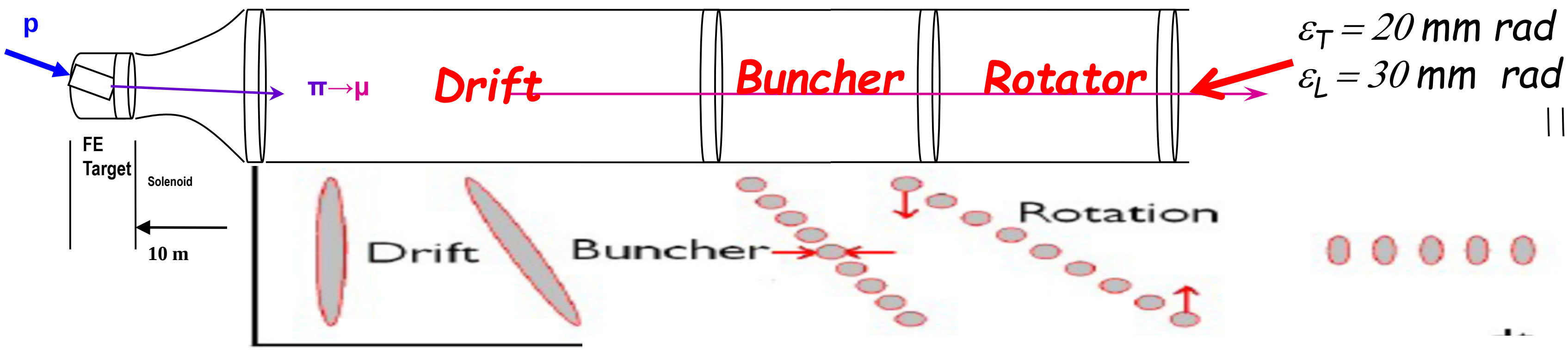
1. Linear transverse cooling of both signs and small Δp increase.
2. Ring cooling in 6D with B brings the μ+ and μ- to a reasonable size Merging and cooling to single bunches
3. Parametric Resonance Cooling (PIC), where the elliptical motion in *x-x'* phase space has become hyperbolic.



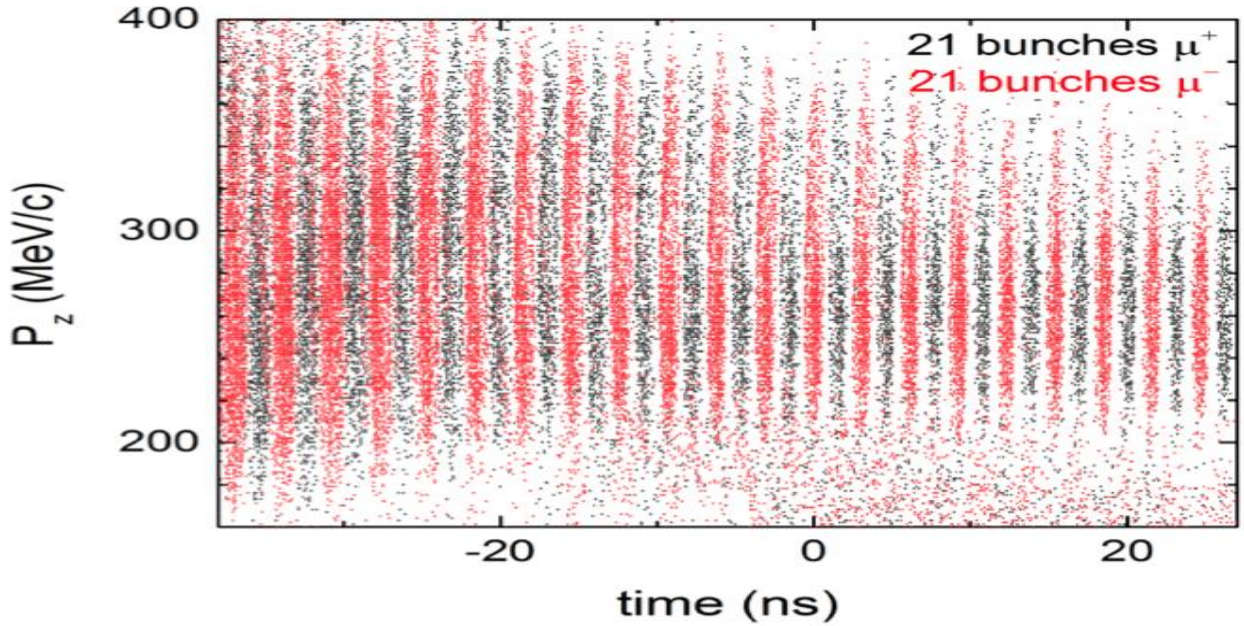
$\varepsilon_\perp = 0.04(\pi)\, mm\, rad \quad \varepsilon_L = 1.0(\pi)\ mm\ rad$

1.-The initial 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.

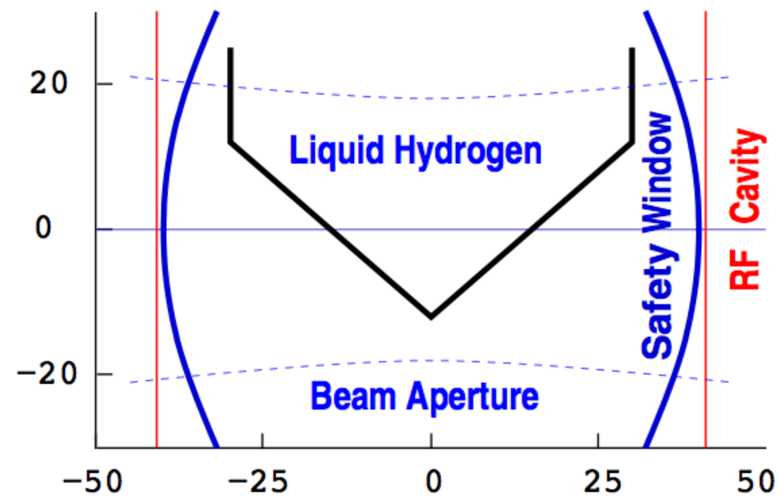


- Strings of both signs are accumulated since half-way between each of the stable RF phase for one sign there is a stable phase for the opposite sign.



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 100º and is rotated 30º from the vertical to match the maximum of the dispersion.

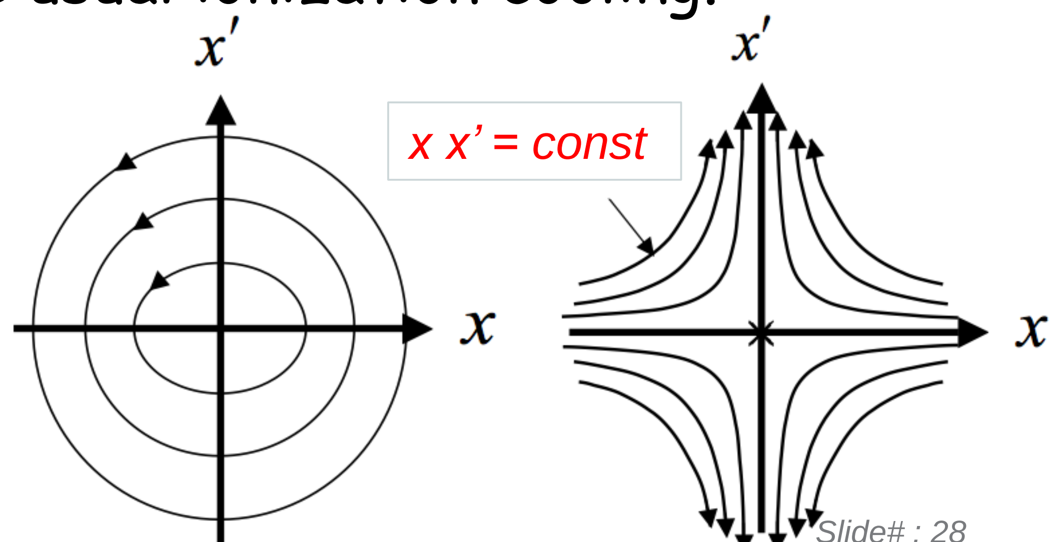


R. Palmer et al. arXiv:physics/0504098 v1, 2005

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.

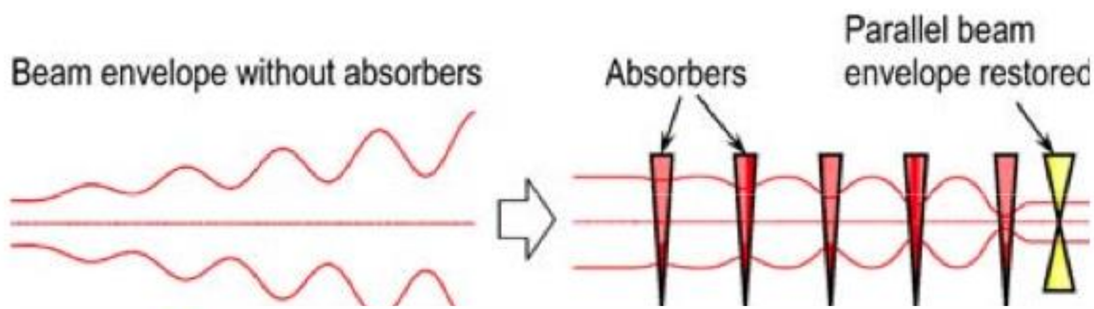
LEFT ordinary oscillations
RIGHT hyperbolic motion induced by perturbations near an (one half integer) resonance of the betatron frequency.

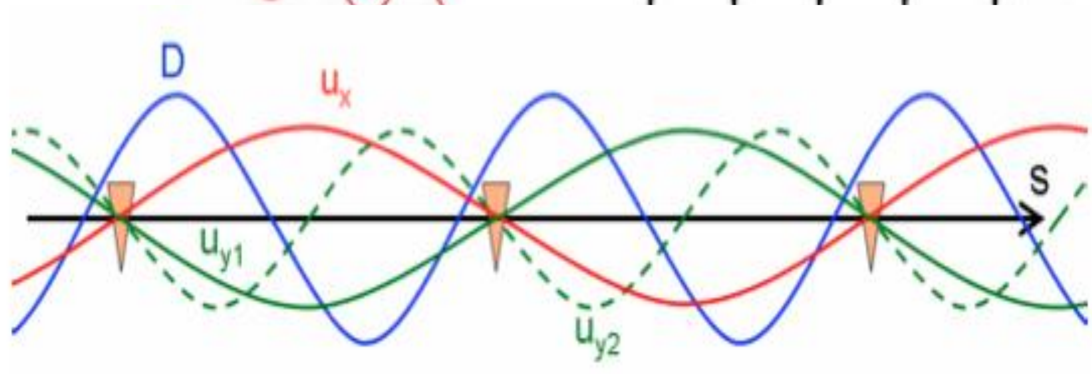


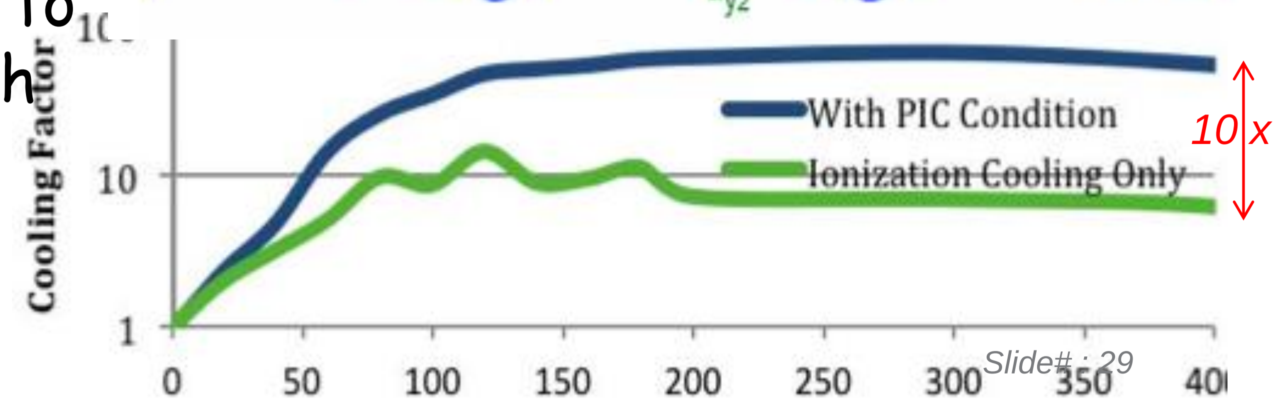
V. S. Morozov et al, AIP 1507, 843 (2012);

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*





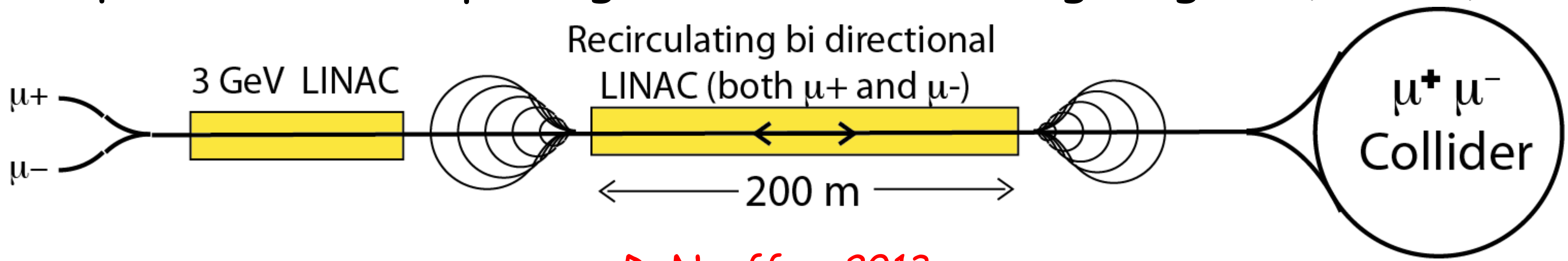


Comments on the cooling process

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

Bunch acceleration to 62.5 GeV

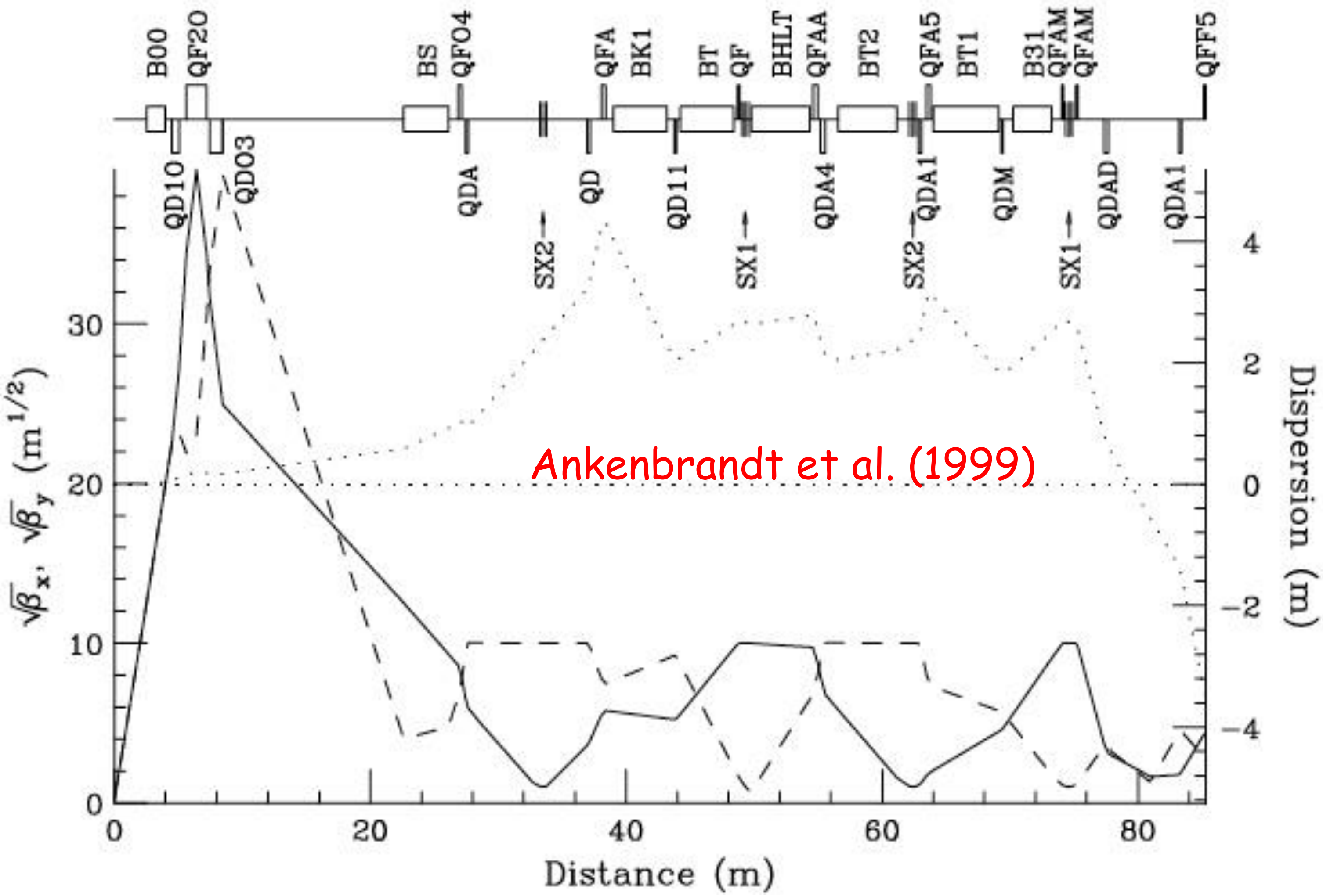
- Next, in order to realize a Higgs Factory at the known energy of 126 GeV, an acceleration system is progressively rising the energy of captured muons to $m_{Ho}/2$
- Adiabatic longitudinal Liouvillian acceleration to p_f= 62.5 GeV/c.
- Both μ+ and μ- are accelerated sequentially in the same LINAC with 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)
- A similar layout for the second phase with √s ≈ 0.5 TeV will require twice the passages and recirculating lengths (400 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.



Summary of the ESSμSB ring configurations

- All the described rings dimensions may easily fit within the existing ESS site
  - 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 recirculating LINAC acceleration system of about few hundred m to bring muons to the required collision energy;
  - 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.

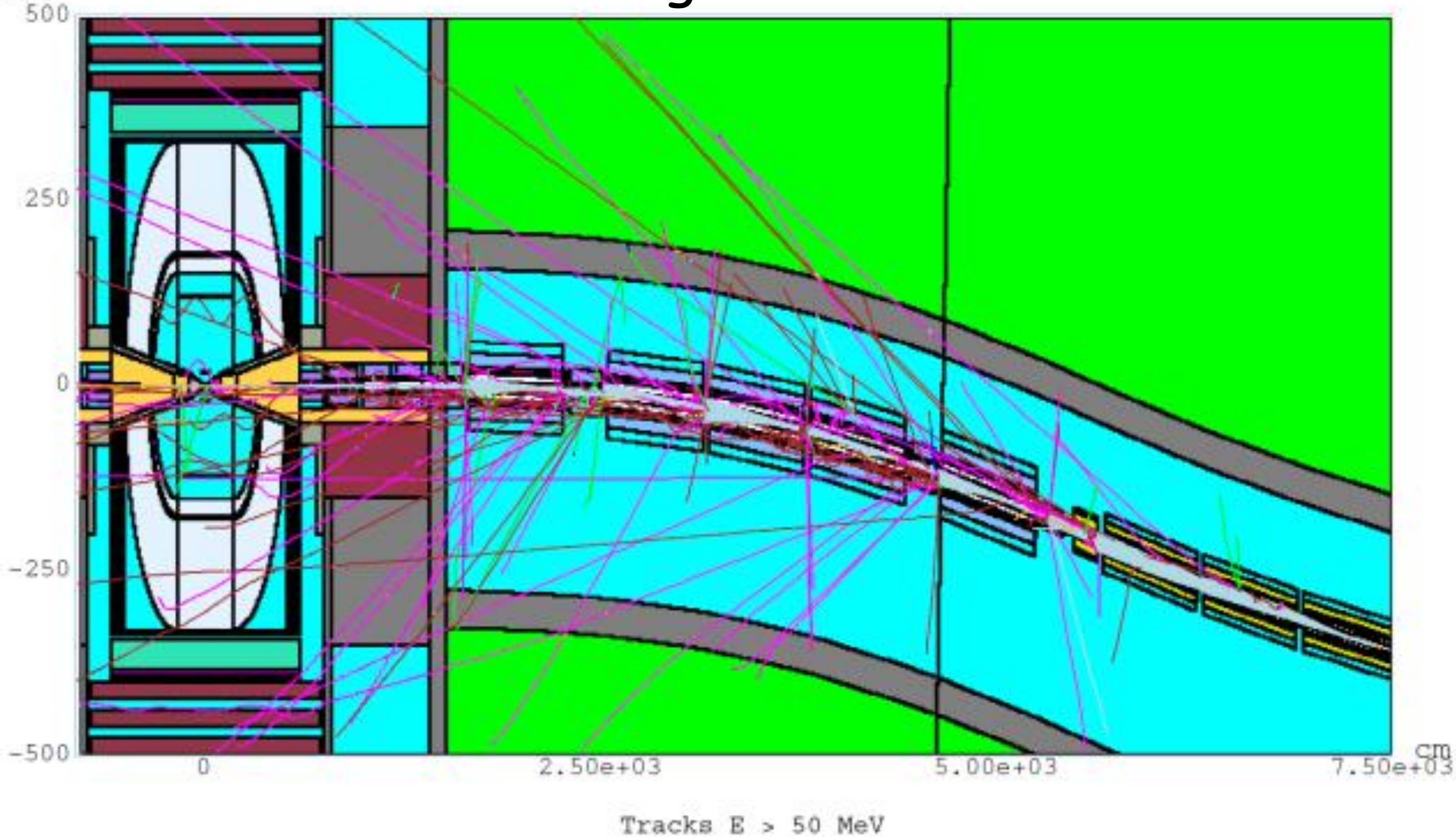
Eatimated performance for the H^o-factory at the ESS

- 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	2.5×10^{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	2.93×10^{12}	μ/coll
μ- at collider ring	1.89×10^{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^{31}	cm^{-2} s^{-1}
Luminosity + PIC (10 x)	4.2 x 10^{32}	cm^{-2} s^{-1}
Higgs cross section	3.0 x 10^{-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 -> $\gamma\gamma$, 10^7 s/y + PIC	≈ 2400	ev/y
Tune shift with PIC	0.086	

Muon related backgrounds

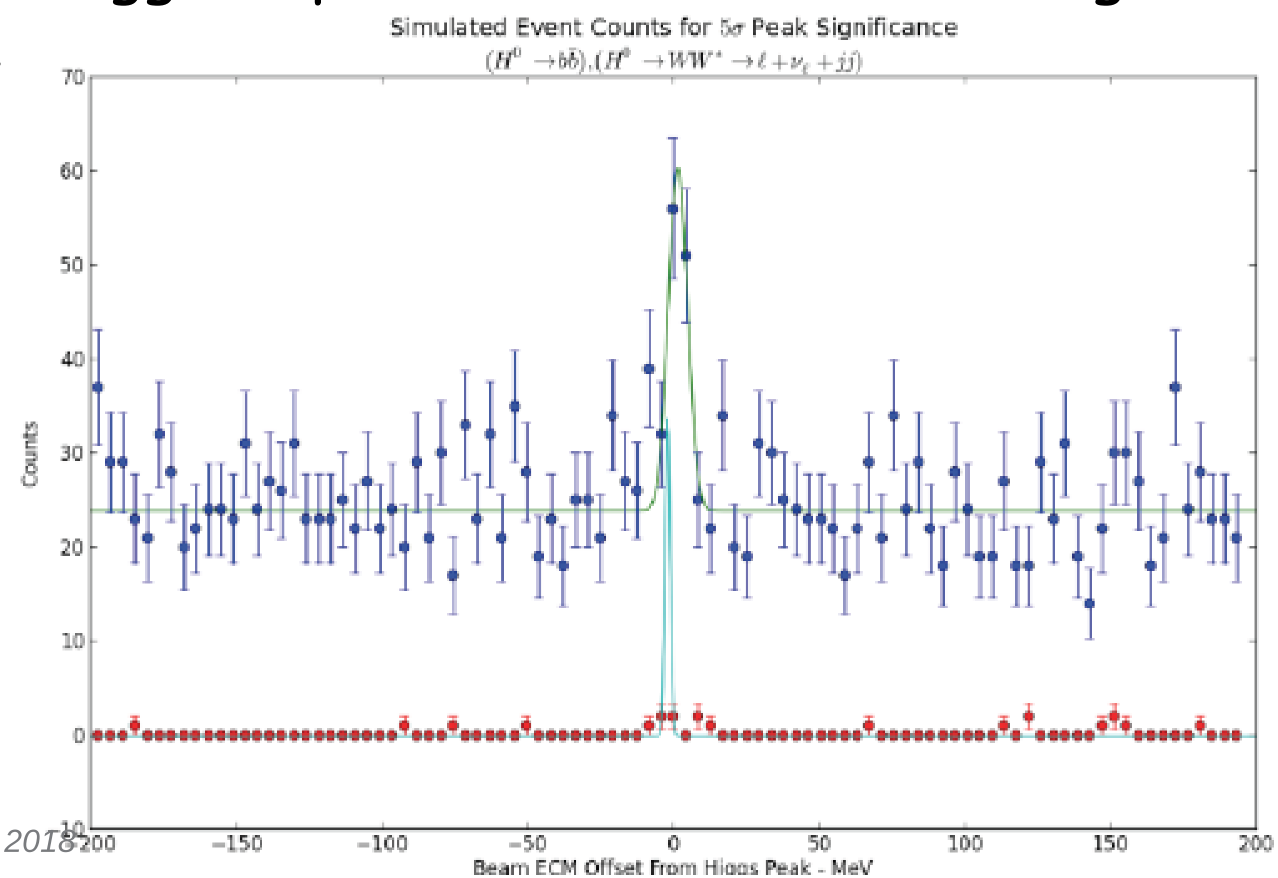
- A major problem is caused by muon decays, namely electrons from μ decay inside the detector with ≈ $2x10^3$ e/meter/ns, however collimated within an average angle of 10^{-3} rad.
- A superb collimation is required with the help of absorbers in front of the detector's straight sections.



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.



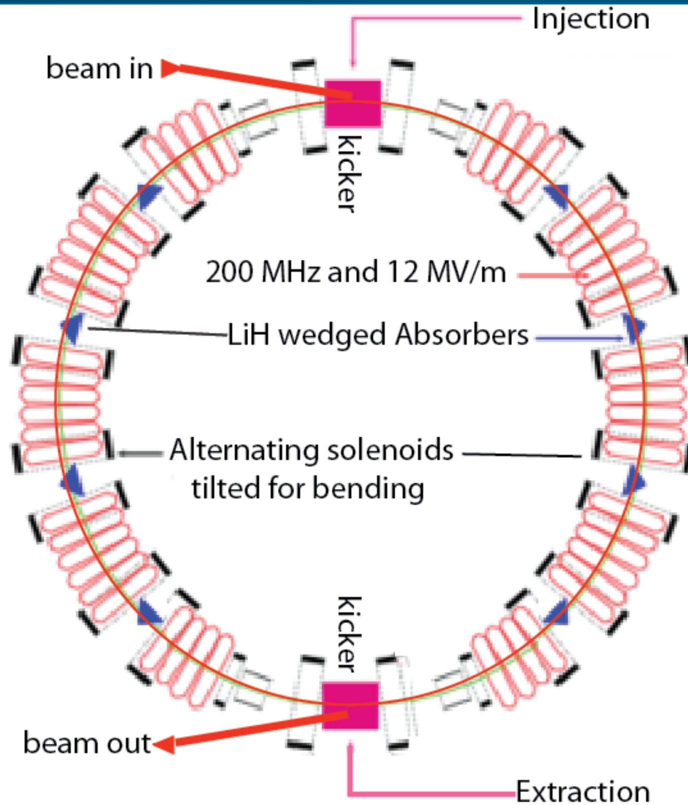
the Initial Cooling Experiment

- 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.

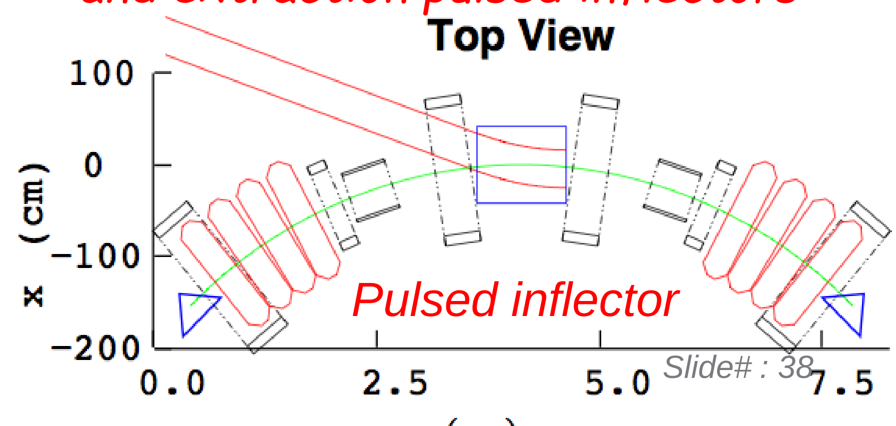
The RFOFO Ionization Cooling

- 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

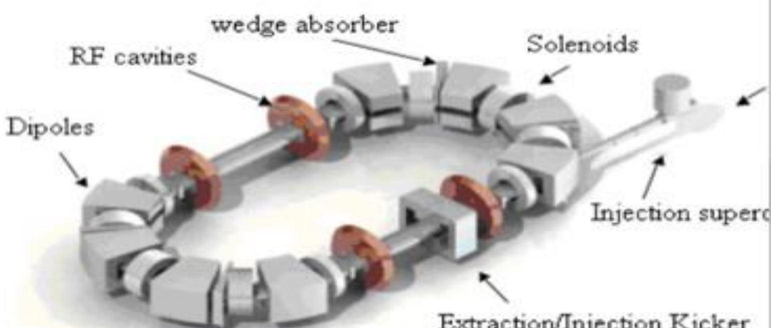


Two separate, 180 apart injection and extraction pulsed inflectors*



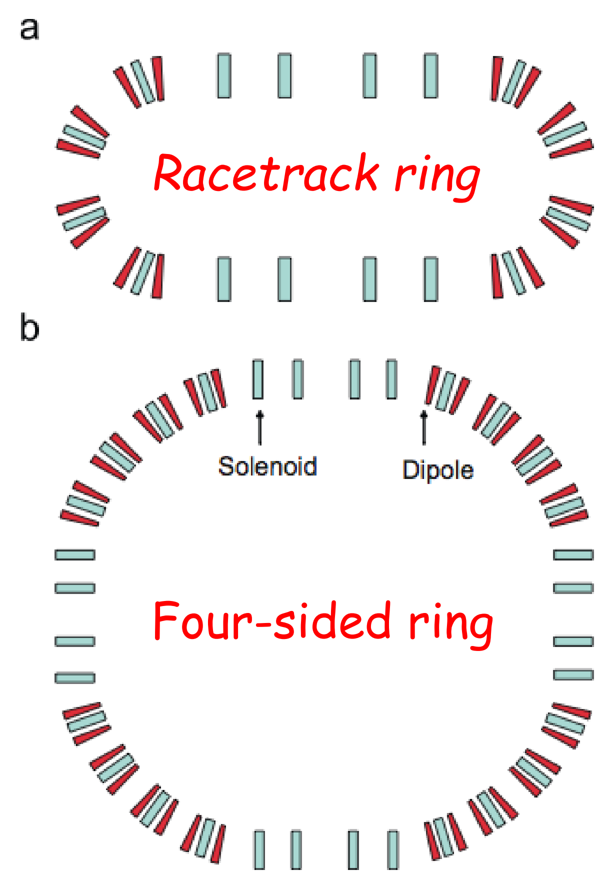
A solenoid-dipole ring cooler for a muon collider

- Another exemplificative cooing ring is the one of Garren et al. (NIM, A 654 (2011) 40–44).
- Injection/extraction kickers are used in a straight section; a superconducting flux pipe is used for the injected beam.



Parameters of the four-sided and achromatic ring cooler.

Momentum (MeV/c)	220
Superperiods	4
Number of dipoles	32
Number of straight solenoids	16
Number of arc solenoids	16
Arc length (m)	6
Straight section length (m)	5
Dipole length and field	0.2 m, 0.72,045 T
Dipole bend and edge angles (deg.)	11.25, 2.8,125
Arc solenoid length and field	0.25 m, 3.38,290 T
Straight section solenoid length and field	0.25 m, 2.91,555 T
Superperiod length and xytunes	11 m, 1.75
Circumference (m)	44



Muon colliders

- **Advantages**
  - Large cross sections σ ($\mu^+\mu^- \rightarrow h$) = 35 pb in s-channel resonance and 0.2 pb for $\mu^+\mu^- \rightarrow ZH$ of at ≈ ½ TeV.
  - Small size footprint: they may fit within the ESS site
  - No synchrotron radiation and beamstrahlung problems
  - Precise measurements of line shape and total decay width Γ
  - Exquisite measurements of all channels and tests of SM.
  - The cost of the facility, provided cooling will be successful, is of the order of a fraction 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 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

Thank you !

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