PROCEEDINGS OF SCIENCE

# Muon cooling: a Higgs Factory at CERN ?

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# Muon cooling:
# a Higgs Factory at CERN ?

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## The LHC observation of the Higgs at 125 GeV

- CMS and Atlas have observed a narrow line of high significance at about 125 GeV mass. compatible with the Standard Model Higgs boson.
  - ATLAS: $m_H$ = 125.5 ± 0.2 (stat) ± 0.6 (sys) GeV
  - CMS: $m_H$ = 125.8 ± 0.4 (stat) ± 0.4 (sys) GeV
- Their data are consistent with fermionic and bosonic coupling expected from a SM Higgs particle.
- Searches have been performed in several decay modes, however in the presence of very substantial backgrounds.
- Experimental energy resolutions have been so far much wider of any conceivable intrinsic Higgs width.
- Results of both experiments also exclude other SM Higgs bosons up to approximately 600 GeV.

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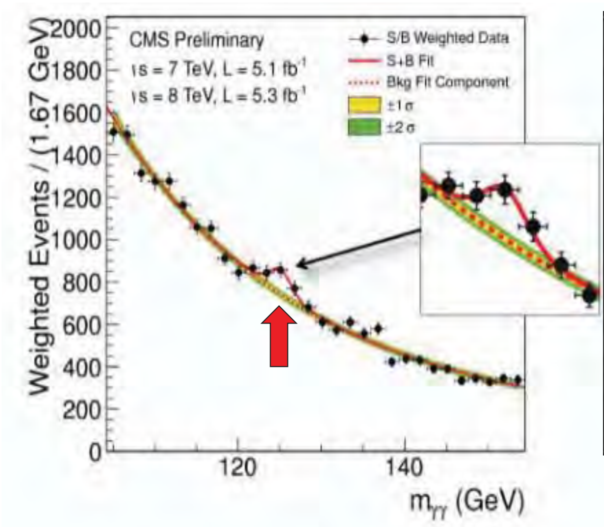
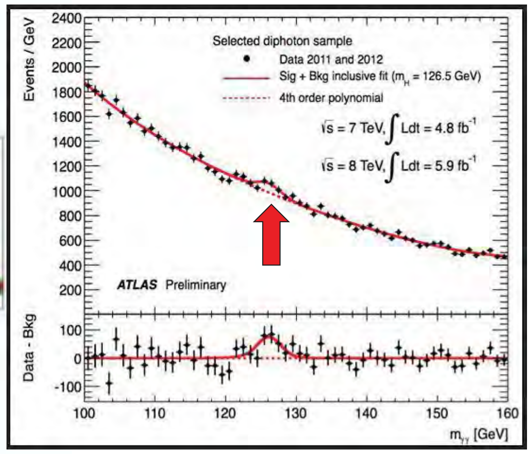
## The discovery

*Signal and background in the H -> 2 γ channel*

**CMS** **ATLAS**

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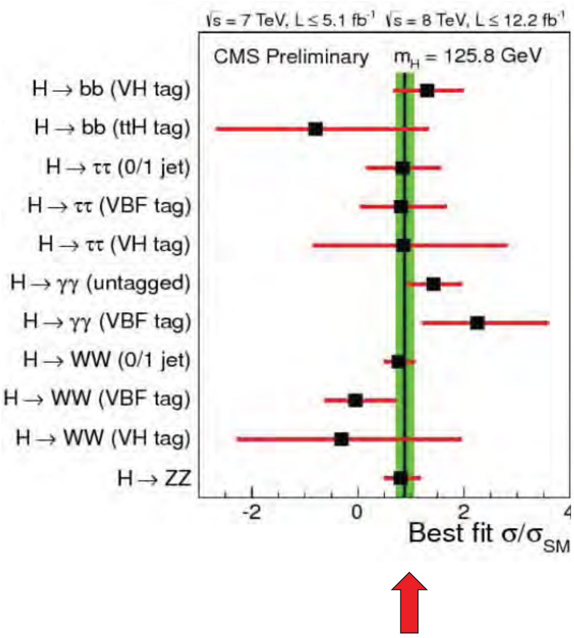
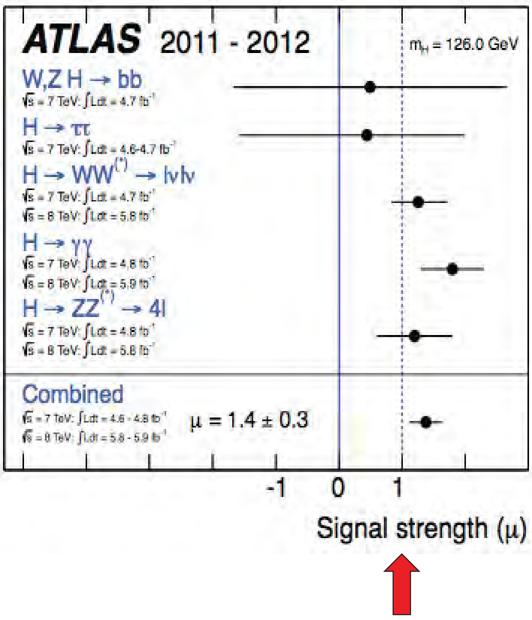
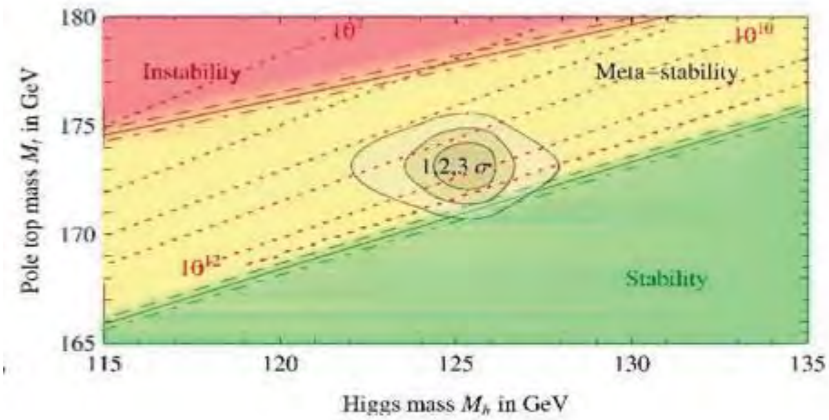
## Present results



## Present situation

- For these values, the electroweak vacuum is claimed metastable, but with a lifetime longer than the age of the Universe.
- The Standard Model can be valid without new physics all the way up to the Planck scale. *Thus, there may be only one standard model (SM) Higgs and no need for the "no fail theorem".*

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

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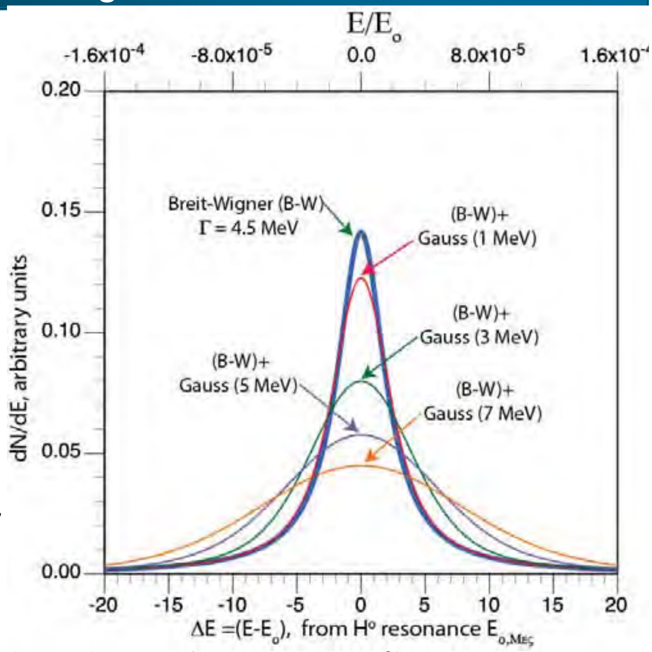
## The Higgs width according to the Standard Model

- Like in the case of the Zo, the determination of the $H_o$ width will be crucial in the determination of the nature of the particle and the underlying theory
- Cross section is shown here, convoluted with a Gaussian beam distribution.
- Signal is not affected only if the rms beam energy width is ≲ a few MeV.




*4.5 MeV wdth:A very demanding resolution R ≈ 0.003% is required*

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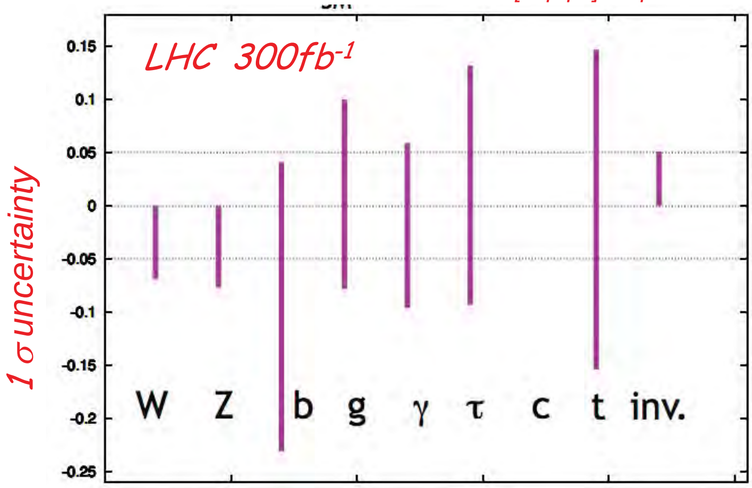
## Ultimate dominance due to systematic effects

- The estimates reflect 1 LHC detector accumulating 300 fb−1 of data, dominated at this level by systematic errors of the ATLAS and CMS collaborations and their best understanding.
- ATLAS and CMS have estimated errors also for 3000 fb−1 from the High-L LHC.
- However such estimates can hardly be a straightforward extrapolation of the current performances.

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




Unambiguous discoveries require 5 σ

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## 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. | $\Delta hVV$ | $\Delta h\bar{t}t$ | $\Delta hbb$ |
|---|---|---|---|
| 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

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

Composite Higgs

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

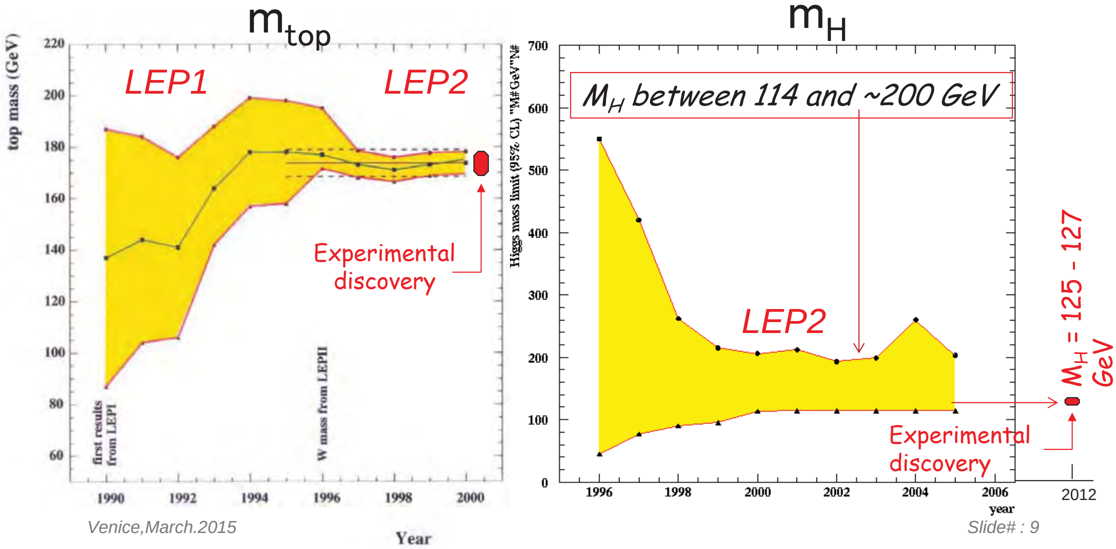
Top partners

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

Venice,March.2015 arXiv:1206.3560v3 [hep-ph] 27 Sep 2012 Slide# : 8

## Predictive power of theory: the case of LEP

- After the p-pbar discovery of the Z°, its detailed studies at LEP in very clean conditions have been an essential second phase. Higher order corrections have anticipated the masses of both the top quark and of the Higgs scalar.

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## Studying the Higgs beyond LHC

- The scalar sector is definitely one of the keys to the future understanding of elementary particle physics.
- *A similar second phase may be also necessary for the $H_o$* and the presence of structure beyond the SM may manifest itself as tiny corrections in the observation of large number of events/year in very clean experimental conditions.
- Two future alternatives are hereby compared:

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

  - A $e^+e^-$ collider at L > $10^{34}$ and a *$Z+H_o$ signal* of ≈ *200 fb.* The circumference of a new, LEP-like ring is of about ≈ 80 km or of a Linear Collider of 31 km.
  - A $\mu^+\mu^-$ collider at L > $10^{32}$ and a *$H_o$ signal in the s-state* of ≈ *20'000 fb*. The collider radius is much smaller, only ≈ 50 m, but the novel "muon cooling" facility is required.

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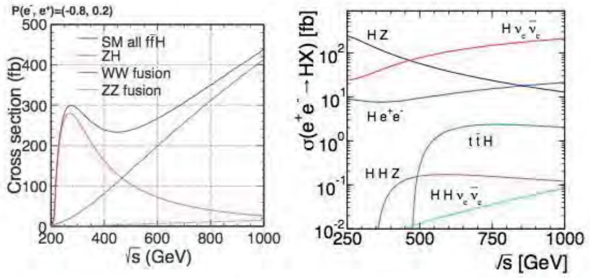
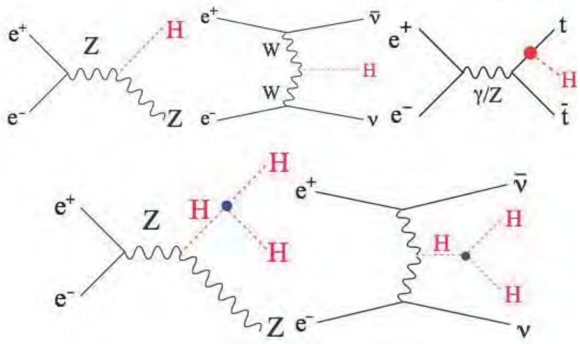
## Production cross sections at the e+ e- collider

- The production cross sections of the Higgs boson with the mass of 125 GeV for e+-e- as a function of the energy √s.
- The cross sections of the production processes as a function of the √s collision 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

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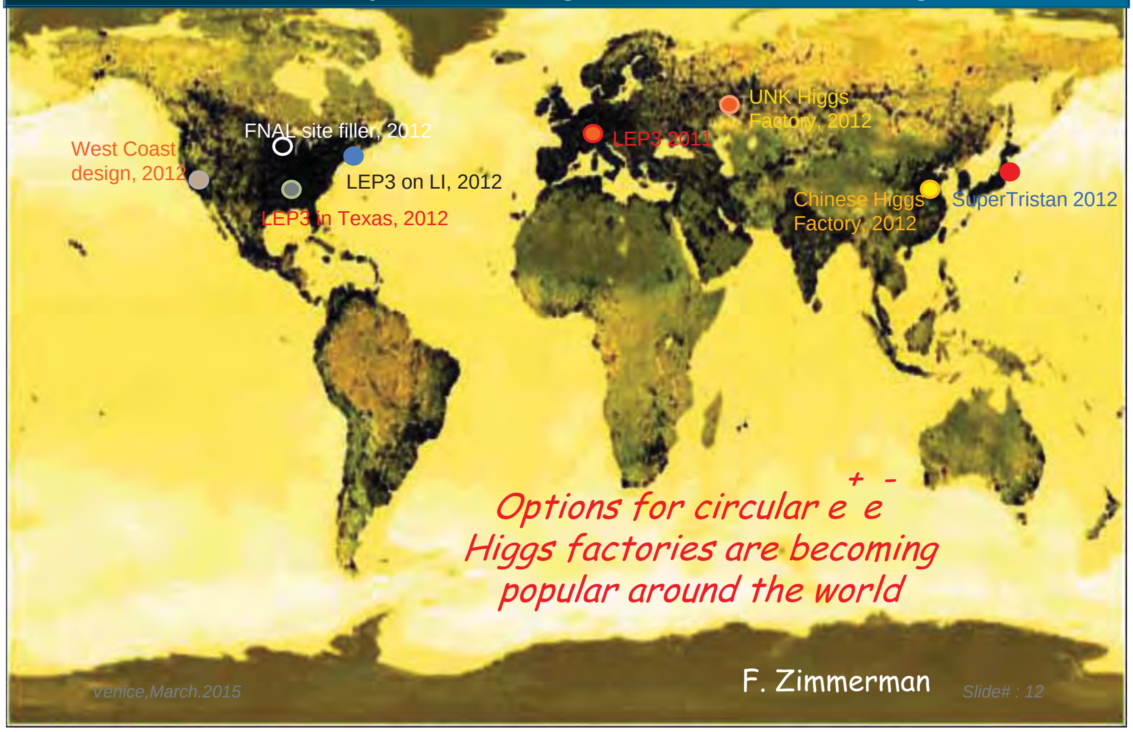
## The first option: a huge e+ e- LEP like ring.



## Super Tristan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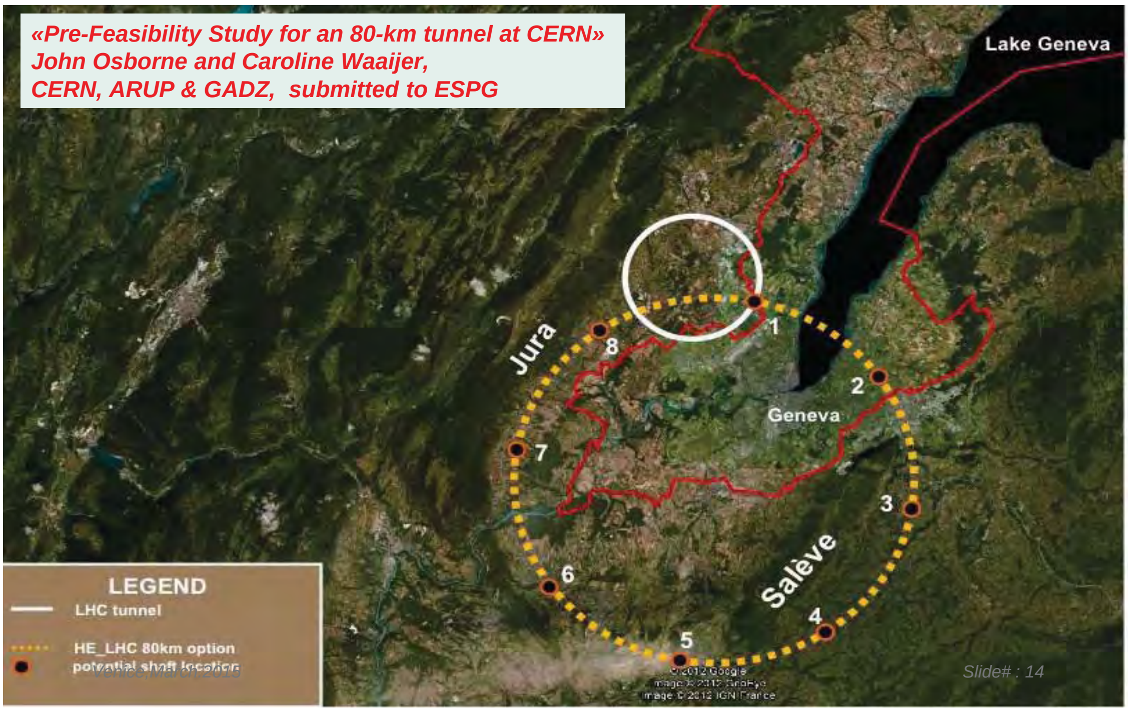
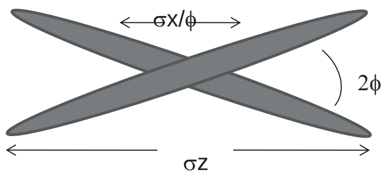
## TLEP tunnel in the Geneva area



## 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 15
  - Huge ring (80 km for SuperTristan or 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*

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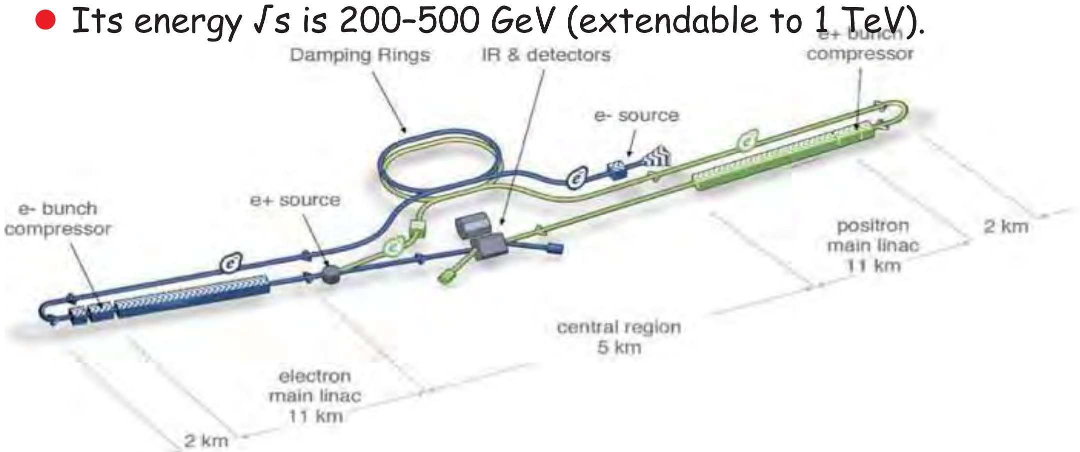
## The ILC option

- 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).




*The total footprint is ~31 km.. To upgrade the machine to Ecms = 1 TeV, the linacs and the beam transport lines would be extended by another ~ 11 km each.*

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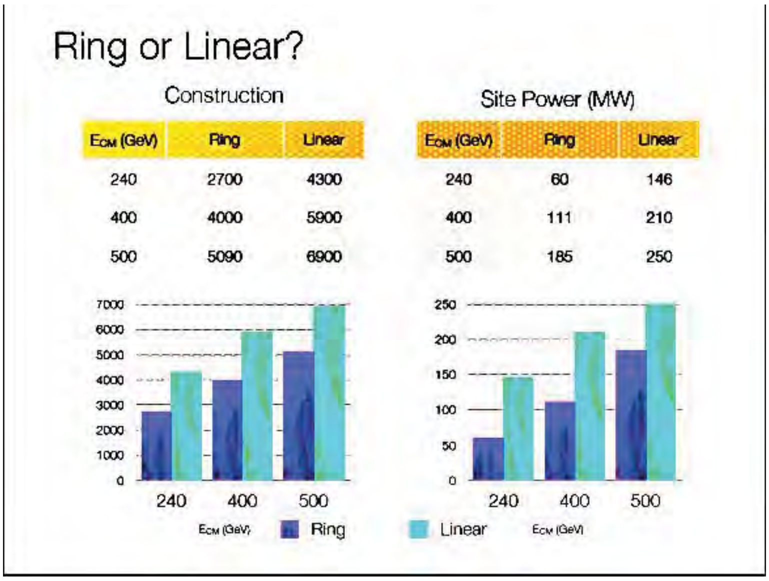
## Super-Tristan vs ILC




| ECM (GeV) | Ring | Linear |
|---|---|---|
| 240 | 2700 | 4300 |
| 400 | 4000 | 5900 |
| 500 | 5090 | 6900 |

| ECM (GeV) | Ring | Linear |
|---|---|---|
| 240 | 60 | 146 |
| 400 | 111 | 210 |
| 500 | 185 | 250 |

Linear collider and circular ring have comparable costs and power consumptions
The more conservative ring alternative is preferred.



## Comparing LHC and e+-e- colliders

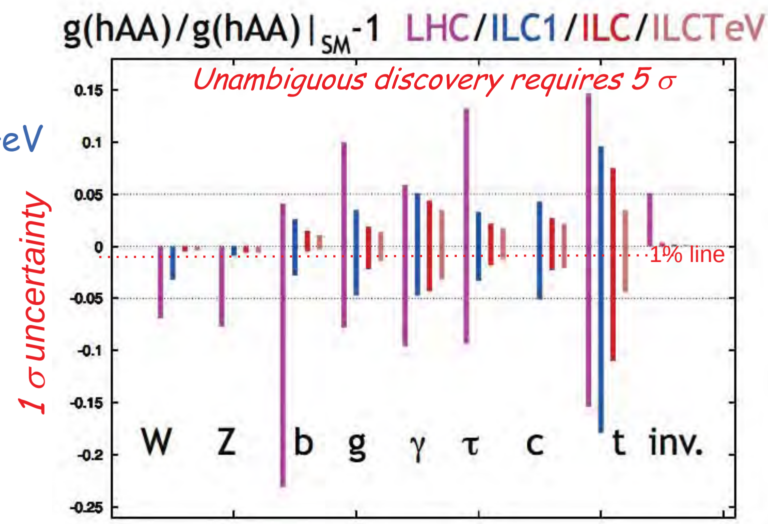
- Compared with th LHC, in order to be fully effective, the energy of an ILC should be increased progressively from 250 GeV till 1 TeV, with correspondingly longer structures and higher powers.

LHC 300 fb-1

Ring or ILC1 250 GeV
250 fb-1

ILC 500 GeV
500 fb-1

ILC TeV 1.0 TeV
1000 fb-1






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

## The second option: a $\mu^+\mu^-$ collider ?

- The direct H° cross section is greatly enhanced in a $\mu^+\mu^-$ collider when compared to an $e^+e^-$ collider, since the s-channel coupling to a scalar is proportional to the lepton mass.
- Like in the well known case of the $Z^0$ production, the H° scalar production in the s-state offers conditions of unique cleanliness .
- An unique feature of such process — if of an appropriate luminosity — is that its actual mass, its very narrow width and most decay channels may be directly measured with accuracy.
- Therefore the properties of the Higgs boson can be detailed over a larger fraction of model parameter space than at any other proposed accelerator method.
- A particularly important conclusion is that it will have greater potentials for distinguishing between a standard SM and the SM-like $H_o$ of SUSY or of other than any other collider.

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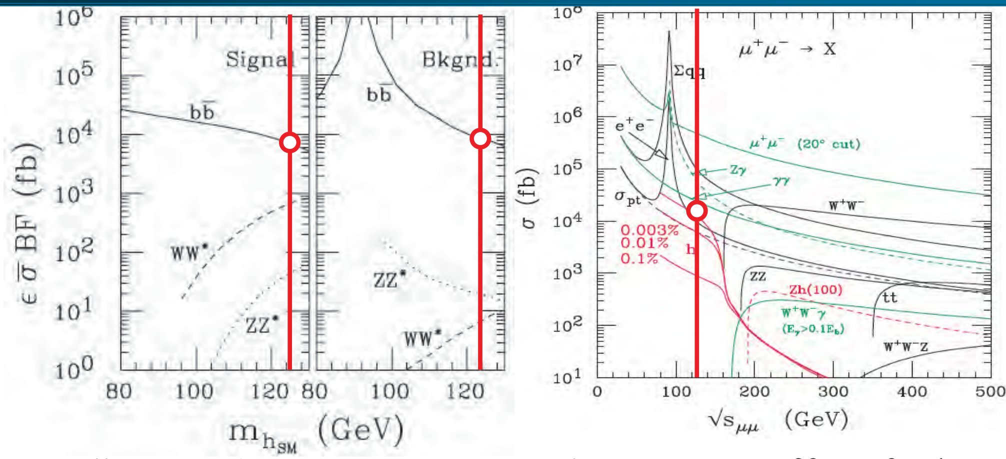
## A muon collider after the discovery of the Higgs




- A $\mu^\pm$ collider with adequate muon cooling and L > $10^{32}$ cm$^{-2}$ s$^{-1}$ .
- Decay electron backgrounds are important: : 2 x $10^{12}$ $\mu^\pm$ decays produce 6.5 x $10^6$ collimated $e^\pm$ decays/meter with $E_{ave} \approx$ 20 GeV.
- The very narrow resonant signal (4.12 MeV ,$\Gamma/M_H$ =3.6 x $10^{-5}$ for the SM) will dominate over most non resonant backgrounds.

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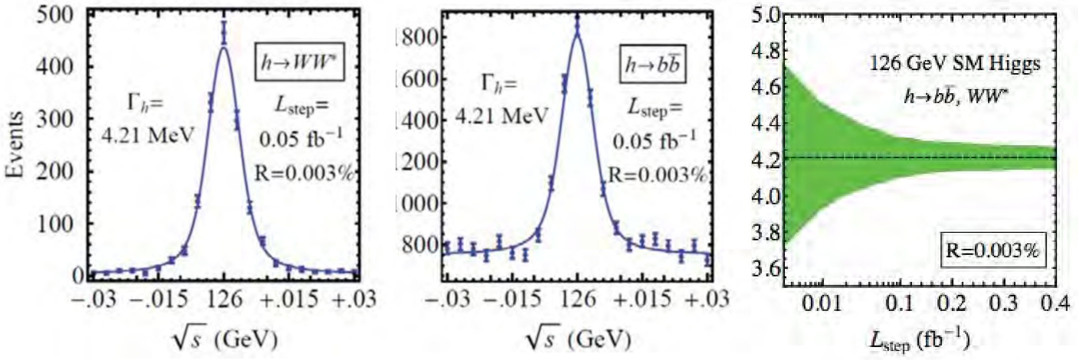
## Leading Higgs processes

- Signal and background for H → bb, WW∗ at a 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%

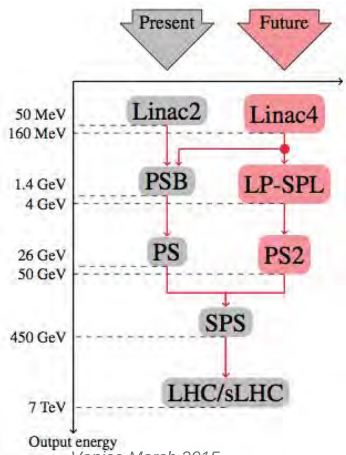
| R (%) | $\mu^+\mu^- \to h$ | $h \to b\bar{b}$ | | $h \to WW^*$ | |
|---|---|---|---|---|---|
| | $\sigma_{\rm eff}$ (pb) | $\sigma_{Sig}$ | $\sigma_{Bkg}$ | $\sigma_{Sig}$ | $\sigma_{Bkg}$ |
| 0.01 | 16 | 7.6 | 15 | 3.7 | 0.051 |
| 0.003 | 38 | 18 | | 5.5 | |

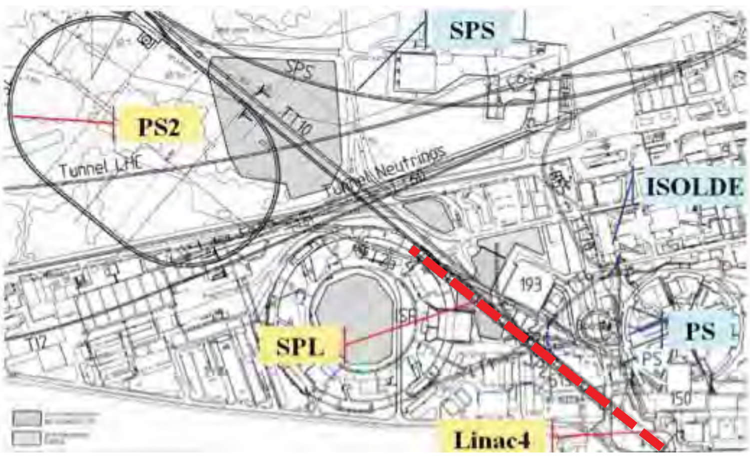



Venice,March.2015 arXiv:1210.7803 [hep-ph]. Slide# : 21

## Future accelerators programs at CERN

- A new LHC injector complex to increase the collider luminosity 10x with the High Luminosity LHC (HL-LHC)).
- Two accelerators (the LP-SPL and a new 50 GeV synchrotron, PS2) would replace the three existing ones (Linac2, the PSB, and the PS), with the injection of the SPS at 50 GeV,

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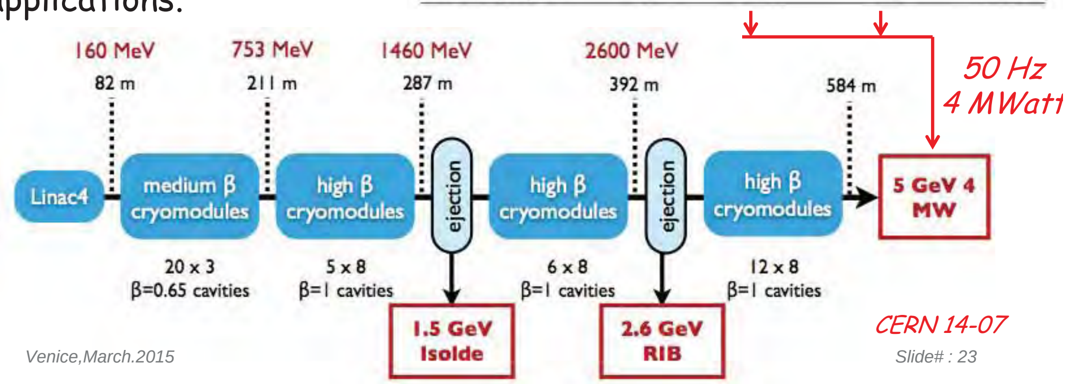
## CERN-SPL parameters

- Layout of superconducting SPL with intermediate extractions.
- SPL design is very flexible and it can be adapted to the needs of many high-power proton beam applications.

| Parameter | Units | HP-SPL Low-current | HP-SPL High-current | LP-SPL |
|---|---|---|---|---|
| Energy | GeV | 5 | 5 | 4 |
| Beam power | MW | 4 | 4 | 0.144 |
| Repetition rate | Hz | 50 | 50 | 2 |
| Average pulse current | mA | 20 | 40 | 20 |
| Peak pulse current | mA | 32 | 64 | 32 |
| Source current | mA | 40 | 80 | 40 |
| Chopping ratio | % | 62 | 62 | 62 |
| Beam pulse length | ms | 0.8 | 0.4 | 0.9 |
| Protons per pulse | $10^{14}$ | 1.0 | 1.0 | 1.13 |

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## A muon based Higgs factory at CERN

- A muon cooled Higgs factory can be easily housed within CERN
- The new 5 GeV Linac will provide at 50 c/s a multi MWatt $H^-$ beam with enough pions/muons to supply the muon factory.
- The basic additional accelerator structure will be the following:
  - Two additional small storage rings with R ≈ 50 m will strip $H^-$ to a tight p bunch and compress the LP-SPL beam to a few ns.
  - Muons of both signs are focused in a axially symmetric B = 20 T field, reducing progressively pt with a horn and B = 2 T
  - A buncher and a rotator compresses muons to ≈ 250 MeV/c
  - Muon Cooling in 3D compresses emittances by a factor $10^6$.
  - Bunches of about $2x10^{12}$ $\mu\pm$ are accelerated to 62.5 GeV
  - Muons are colliding in a SC storage ring of R ≈ 60 m (about one half of the CERN-PS ,1/100 of LHC) where about $10^4$ Higgs events/y are recorded for each of the experiments.

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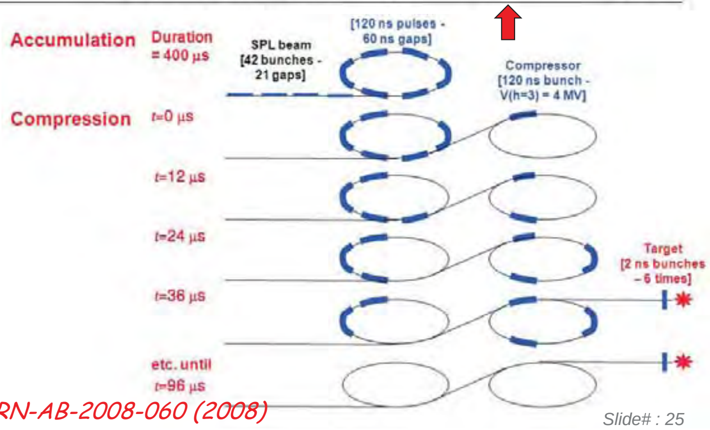
## Two coupled rings to build a tight proton bunch

- A tight p bunch may be realized with a pair of rings with R≈50 m (Accumulator and Compressor).
- The H⁻ beam produced by the SPS LINAC at 5 GeV is stripped to p produce a number of short pulses , condensed into a few, shorter (2ns) bunches
- "A Feasibility study of accumulator and compressor for SPL".

| Ring | Parameter | Units | 6 bunches | 3 bunches |
|---|---|---|---|---|
| Accumulator | Circumference | m | 318.5 | 185.8 |
| | Accumulation turns | | 690 | 1180 |
| | Type of magnets | | NC | SC |
| Compressor | Circumference | m | 314.2 | 200 |
| | Compression turns | | 36 | 86 |
| | RF voltage at $h = 3$ | MV | 4 | 1.7 |
| | Transition gamma | | 2.3 | 2.83 |
| | Type of magnets | | SC | NC |
| | Interval between bunches | μs | 12 | 30 |




CERN-AB-2008-060 (2008)

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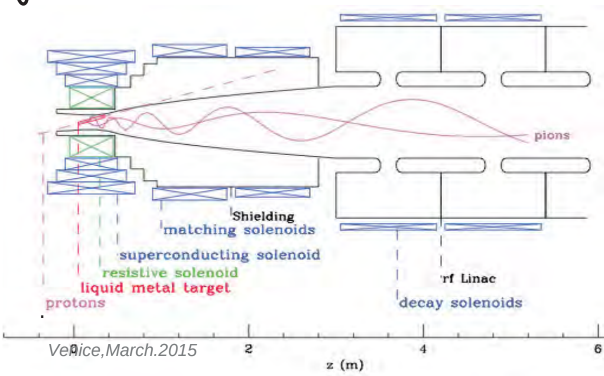
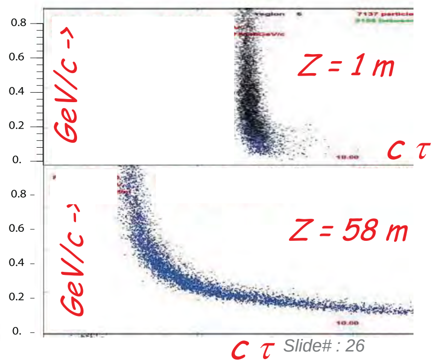
## Target and focussing in a axially symmetric B field

- 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

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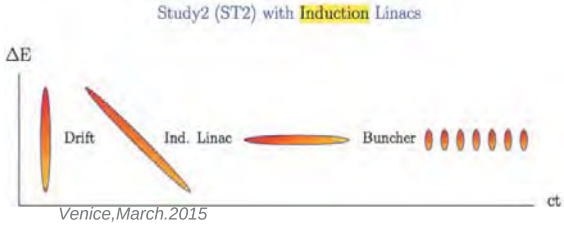
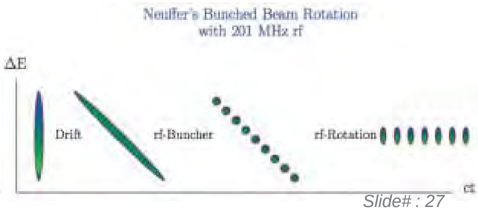
## Beam energy compression

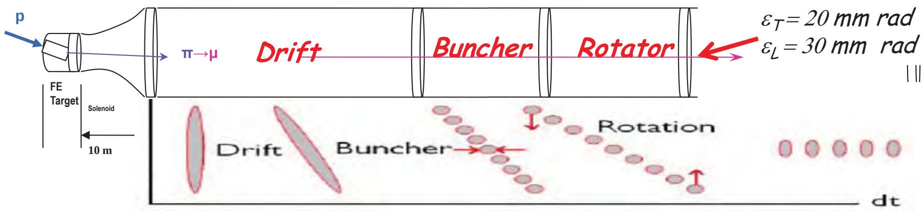
- Initially, there is a small spread in time, but a very large spread in energy. The target is followed by a drift space, where a strong correlation develops between time and energy.
- Two different methods my be used in order to provide nearly non-distorting phase rotation;:
  - 260 m of Induction linacs, see FS2 design report(**BNL**-52623).
  - Neuffer's RF bunched beams with RF rotation (IPAC 2013).
- Induction linacs reduce the r.m.s energy spread to 4.4% and after bunching to a spread to ≈ 8%. In the Neuffer's scheme, the final rms energy spread is 10.5%.



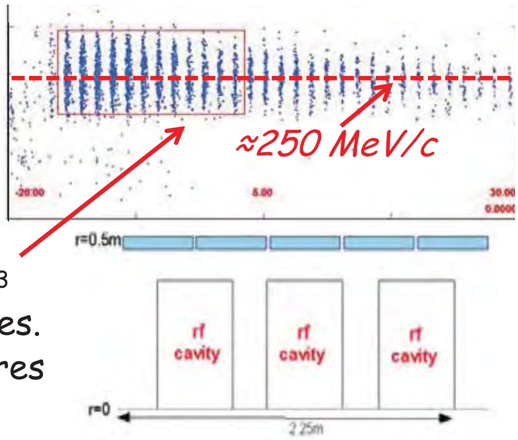



## Buncher and rotator to compress muon beam spectrum




| Front End section | Length m | #rf cavities | Frequencies MHz | # of freq. | RF gradient | RF peak power requirements |
|---|---|---|---|---|---|---|
| Buncher | 33 | 37 | 319.6 to 233.6 | 13 | 4 to 8 MV/m | ~1 to 3.5 MW/freq |
| Rotator | 42 | 56 | 230.2 to 202.3 | 15 | 12.5 MV/m | ~2.5 MW/cavity |

- 4 MW of protons at 5 GeV
- 50 pulses/s and 1.0 x $10^{14}$ ppp
- Muons of both signs are collected
- A very efficient capture : 1.2 x $10^{13}$ muons/pp within the 12 best bunches.
- Train of many muon bunches, requires recombination and signs
- Solenoidal coils at about 2 T



## 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*

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## Muon cooling ring: transverse emittance

- The emittance $\varepsilon_N$ evolves whereby dE/dx losses are balanced by multiple scattering (Neuffer and McDonald):

Cooling / Scattering

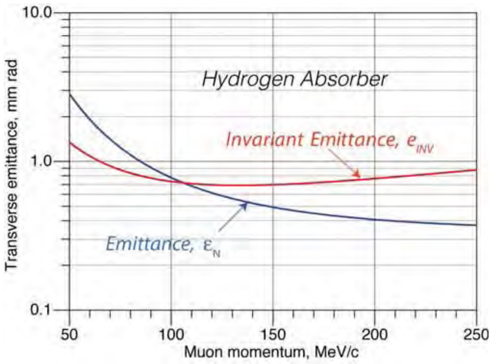
$$\frac{d\varepsilon}{dz} \approx \frac{\varepsilon}{\beta^2 E}\frac{dE}{dz} + \frac{\beta^*(13.6)^2}{2\beta^3 E m_\mu X_o} \rightarrow 0$$

*$\beta^*$ = beta at cross; $m_\mu, \beta_\mu$ = mu values; $X_o$ = Rad. Length; dE/dz = ioniz. Loss*

- The cooling process will continue until an equilibrium transverse emittance has been reached:

$$\varepsilon_N \rightarrow \frac{\beta^*(13.6\ \ MeV/c)^2}{2\beta_\mu m_\mu}\frac{1}{(X_o\, dE/dz)}$$

- The equilibrium emittance $\varepsilon_N$ and its invariant $\varepsilon_N/\beta\gamma$ are shown as a function of the muon momentum.
- For $H_2$ and $\beta^*$= 10 cm, $\varepsilon_N/\beta\gamma \leq 700$ mm mr from 80 to 300 MeV/c




*For a 125 GeV collider and $\beta^*$= 5 cm bunch equil. transverse size is ≈ 240 μ*

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## Muon cooling ring: longitudinal emittance

- *Longitudinal* balance is due to heat producing straggling balancing dE/dx cooling. A dE/dx radial wedge is needed in order to exchange longitudinal and transverse phase-spaces.
- Balancing heating and cooling for a Gaussian distribution limit:

Intrinsic Energy loss — Wedge shaped absorber — Straggling

$$\frac{d(\Delta E)^2}{dz} = -2(\Delta E)^2 \left[ f_A \frac{d}{dE}\left(\frac{dE_o}{ds}\right) + f_A \frac{dE}{ds}\left(\frac{d\delta}{dx}\right)\frac{\eta}{E\delta} \right] + \frac{d(\Delta E)^2_{straggling}}{dz}$$

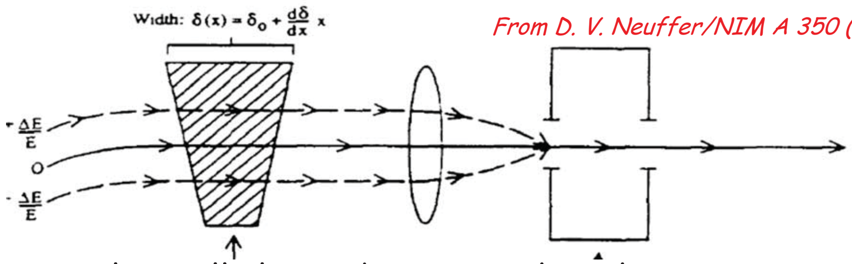
  - $dE/dz$ $f_A\, dE/ds$ where $f_A$ is the fraction of the transport length occupied by the absorber, which has an energy absorption coefficient $dE/ds$
  - η is the chromatic dispersion at the absorber and δ and $d\ /dx$ are the thickness and radial tilt of the absorber
  - the straggling (H2) is given by $\frac{d(\Delta E)^2_{straggling}}{dz} = \frac{\pi (m_e c^2)^2 (\gamma^2+1)}{4\ln(287)\alpha X_o}$



## Longitudinal balance (cont.)

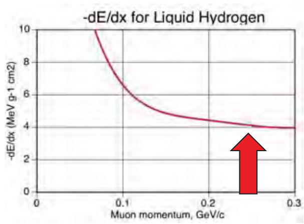
- The thickness of the absorber must vary with the transverse position, producing the appropriate the energy dependence of energy loss, resulting in a decrease of the energy spread

*From D. V. Neuffer/NIM A 350 (1994) 27-35*




- Energy cooling will also reduce somewhat the transverse cooling, according to the Robinson's law on sum of damping decrements.

$$2g_\perp + g_L \cong 2$$

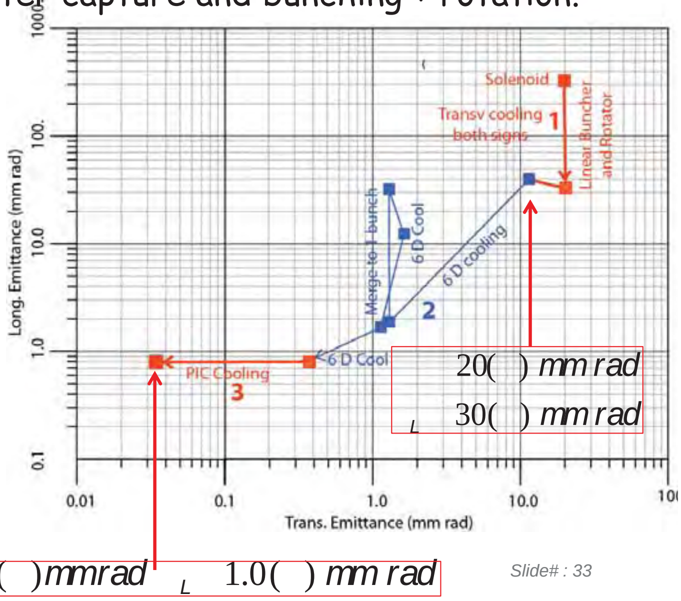



dE/dx loss as a function of the muon momentum for hydrogen (very near to min for 250 MeV/c)

## Describing the full cooling procedure

- Three successive steps are required in order to bring the cooling process at very low energies (initially at ≈250 MeV/c and later at≈ 100 MeV/c), after capture and bunching + rotation.

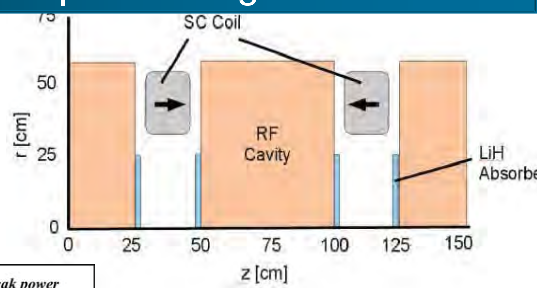
1. Linear transverse cooling of both signs amd small Δp increase.
2. Ring cooling in 6D with B brings the μ+ and μ- to a reasonable size Merging and cooling to single bunches
3. PIC resonance cooling. where the normal elliptical motion in *x*-*x'* phase space has become hyperbolic.





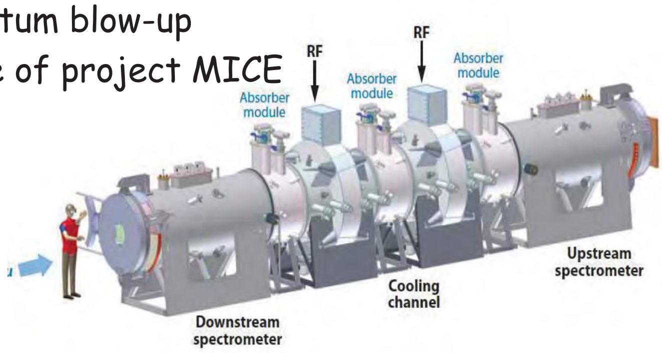

## 1.-Linear transverse pre-cooling

- Muons of both signs are cooled transversally with LiH absorbers and simultaneously accelerated with RF cavities at 200 MHz.
- 2 Tesla solenoidal focussing



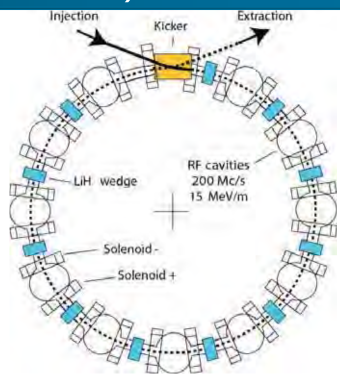

| *Component* | *Length m* | *#rf cavities* | *Frequencies MHz* | *# of freq.* | *RF gradient* | *RF peak power requirements* |
|---|---|---|---|---|---|---|
| Cooler | 75 m | 100 | 201.25 MHz | 1 | 16 MV/m | ~4MW/cavity Total peak 400 MW |

- Slight longitudinal momentum blow-up
- Method similar to the one of project MICE

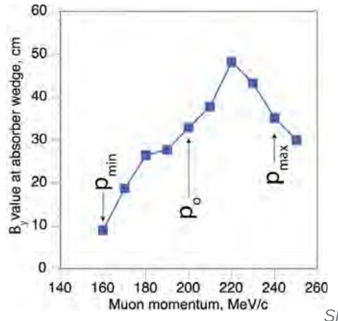


## 2.-The cooling ring (Balbekov, Palmer)

- An idealized muon cooling process has been numerically evaluated in 6D by Balbekov and by Palmer et al. in a small ring and for $p_\mu \approx 200$ MeV.
- In order to increase the incoming muon acceptance, strong focussing is performed with solenoids in alternate directions, rather than with q-poles (RFOFO).




| | | |
|---|---|---|
| Circumference | 33 | m |
| Cells | 12 | |
| Max Bz | 2.7 | T |
| Coil Tilts | 2.6 | deg. |
| Ave Momentum | 220 | MeV/c |
| Min Trans. Beta | 35-40 | cm |
| Dispersion | 8 | |
| Wedge Material | $H_2$ or LiH | |
| Central thickness | 28.6 | cm |
| Wedge angle | 100 | deg |
| RF Cavities/cell | 6 | |
| Frequency | 201.25 | Mhz |
| Gradient | 12 | MV/m |

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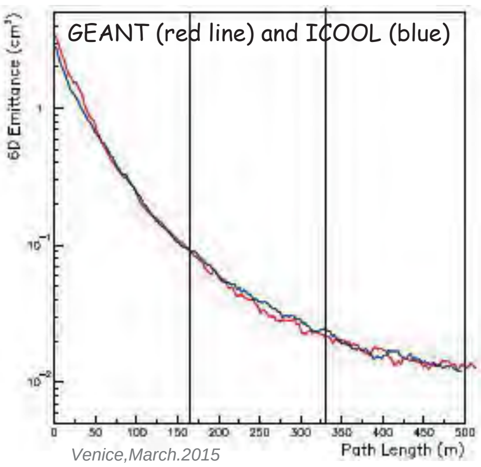
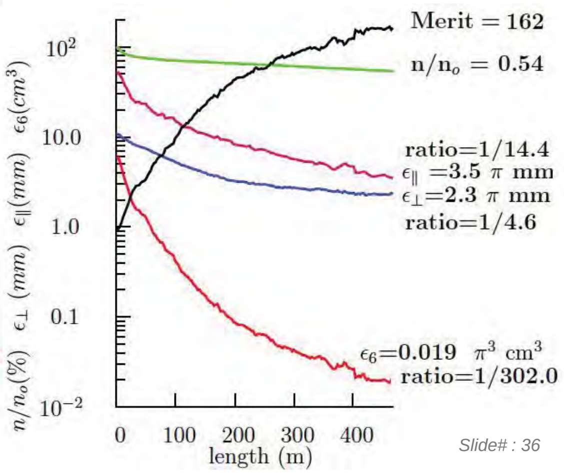
## Performance of Palmer et al. design

- A first estimate of the expected cooling process is given. This is not an engineering design: for instance injection, extraction, etc. have still to be evaluated.
- The so called "merit factor" in the 6D takes into account the fractional loss of muons in the process and due to decays.

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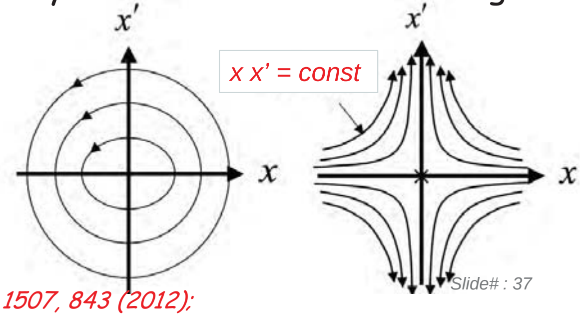
## 3.-PIC, the Parametric Resonance Cooling of muons

- Combining ionization cooling with parametric resonances is expected to lead to muon with much smaller transv. 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.

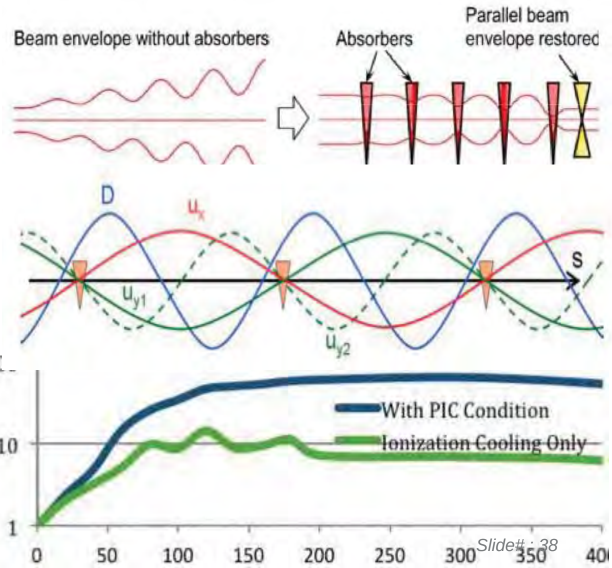
*LEFT ordinary oscillations*
*RIGHT hyperbolic motion induced by perturbations near an (one half integer) resonance of the betatron frequency.*




Venice,March.2015 *V. S. Morozov et al, AIP 1507, 843 (2012);* Slide# : 37

## 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 stabilizes 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.
- Comparison of cooling factors (ratio of initial to final 6D emittance) with and without the PIC condition vs number of cells: more than 10x gain

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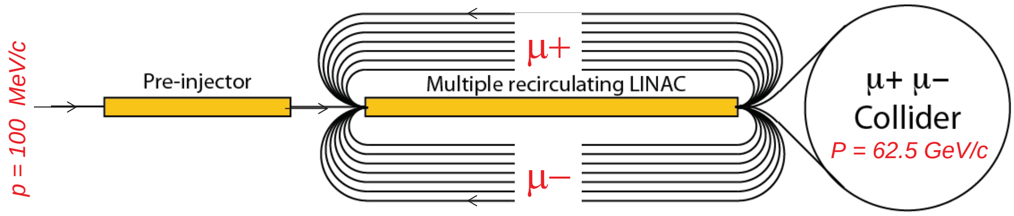
## Bunch acceleration to 62.5 GeV

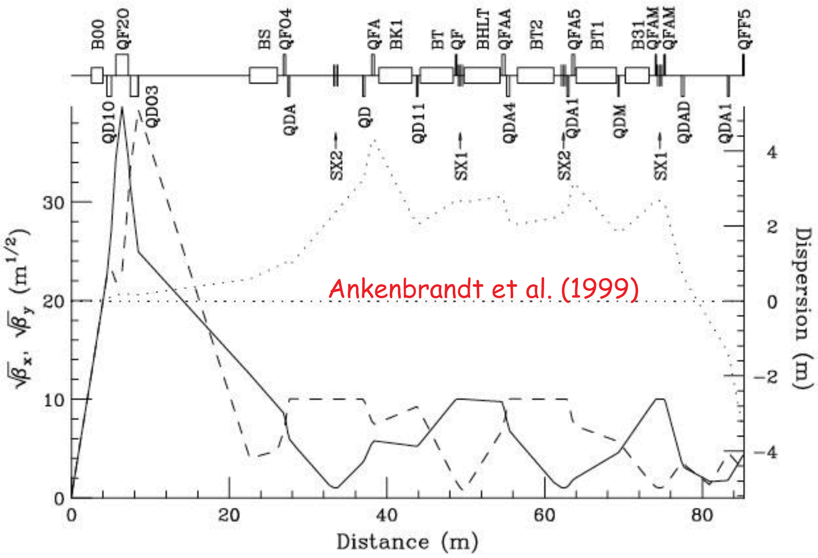
- In order to realize a Higgs Factory at the known energy of 126 GeV, an acceleration system is progressively rising the energy of captured muons to $m_{Ho}/2$, with the help of a series of several re-circulating RLAs.
- Adiabatic longitudinal Liouvillian damping from p ≈ 0.10 GeV/c to $p_f$= 62.5 GeV/c.
- Recirculating energy gain/pass, tentatively = 62.5/8 = 7.75 GeV






## 6.-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 of the H°-factory

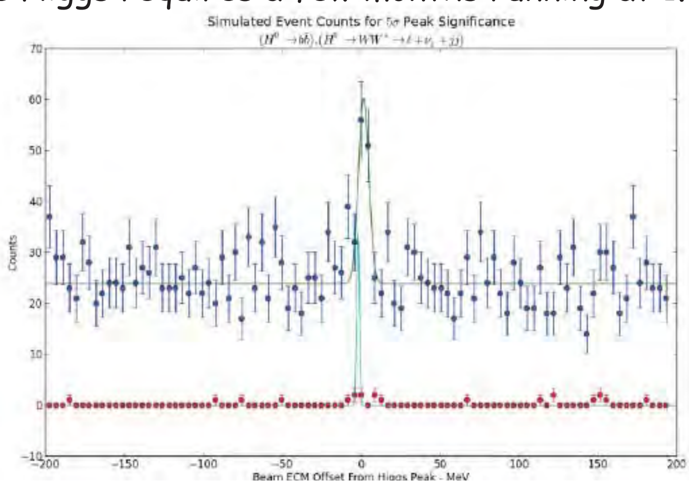
- Two asymptotically cooled μ bunches of opposite signs collide in two low-beta interaction points with β*= 5 cm and a free length of about 10 m, where the two detectors are located.
- The bunch transverse rms size is 0.05 mm and the μ–μ tune shift is 0.086.
- A luminosity of $5 \times 10^{32}$ $cm^{-2}$ $s^{-1}$ is achieved with 1 $\times 10^{12}$ μ/bunch.
- The SM Higgs rate is ≈ 44’000 ev/year in each detector.
- An arrangement with at least two detector positions is reccomanded

| | | |
|---|---|---|
| Proton energy | 5 | GeV |
| **Proton power** | **4** | **MW** |
| Event rate | 50 | c/s |
| Protons/pulse | 10^14 | ppp |
| Muons, each sign | 6 x10^12 | pp |
| Cooled fraction | 0.16 | |
| Final momentum | 62.5 | GeV/c |
| Final gamma | 589.5 | |
| Final muon lifetime | 1.295 | ms |
| **Colliding, each sign** | **1 x 10^12** | **pp** |
| Collider circumf. | 360 | m |
| Transverse emittances | 0.04 | mm rad |
| Bunch transv, rms | 51. | μ |
| Long emittance | 1 | mm rad |
| No of turns | 1110 | |
| No effective turns | 555 | |
| Crossing/sec | 27760 | |
| **Luminosity** | **5 x10^32** | **cm-2 s-1** |
| Cross section | 1.0 x10^-35 | cm2 |
| **Ev/y(10^7 s)** | **44’000** | |



## Finding the 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.



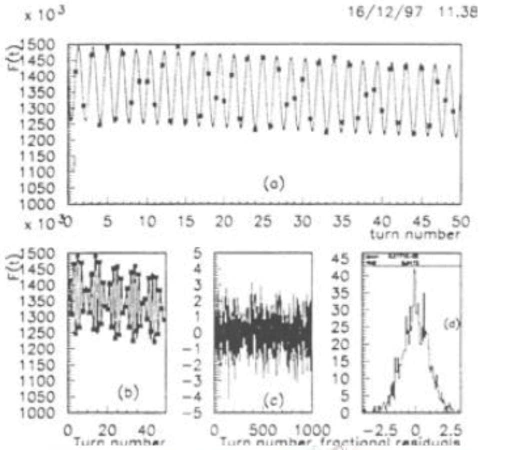
## Polarization & Energy measurement

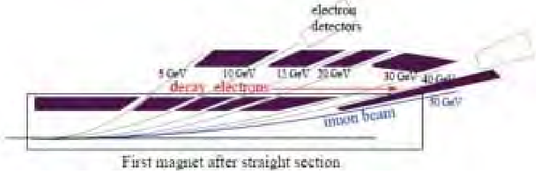
- The effects of polarization are visible in the single electron decay angular distributions.

$$< E_{lab} >= \frac{7}{20} E_\mu (1 + \frac{\beta}{7} \hat{P})$$

$$E(t) = Ne^{(-\alpha t)}(\frac{7}{20} E_\mu (1 + \frac{\beta}{7}(\hat{P} cos\omega t + \phi)))$$

- Measure ⌉ from fluctuations in electron decay energies
- The e-rate is extremely high
- Since frequencies can be very precisely measured, energy E, and δE can be measured to a few hundred keV or even better



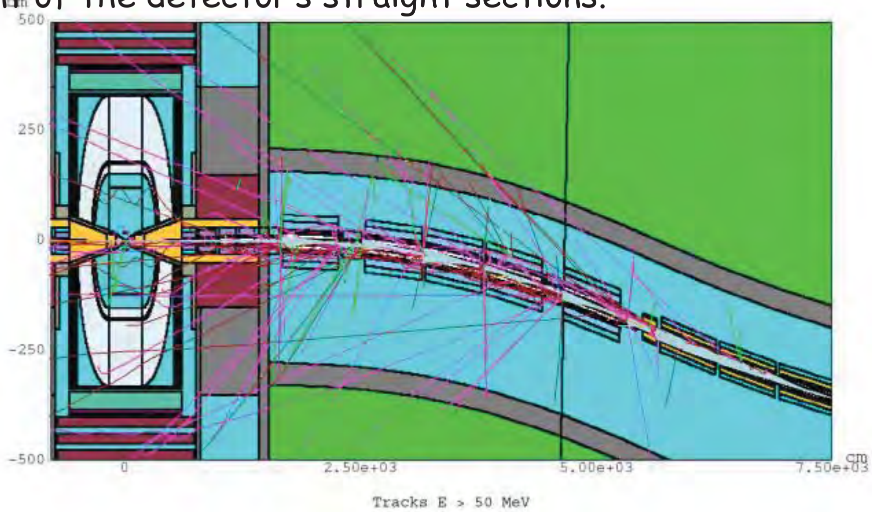




*Muon spectrometer*

Venice,March.2015 Raja and Tollestrup (1998) Phys. Rev. D 58 013005 Slide# : 43

## Muon related backgrounds:an open problem

- A major problem is caused by muon decays, namely electrons from $\mu$ decay inside the detector with ≈ 2x10³ 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.




Venice, '4

## The muon Higgs collider:

- **Advantages**
  - Large cross section σ ($\mu^+\mu^- \to h$) = 41 pb in s-channel resonance, compared to $e^+e^- \to ZH$ with 0.2 pb at 250 GeV.
  - Small size footprint: it may fit in the CERN site
  - Cost so far unknown but far smaller than the ILC.
  - 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.
  - A low cost demonstration of muon cooling can be done first.
- **Challanges**
  - 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

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## The next step: the realization of the Initial Cooling Experiment

- Physics requirements and the studies already undertaken with muon cooling suggest that the next step, prior to but adequate for a specific physics programme *could be the practical realization of a full scale cooling demonstrator.*
- Indicatively this corresponds to the realization of a cascade of unconventional but *very small rings of few meters radius*, in order to achieve the theoretically expected longitudinal and transverse emittances of asymptotically cooled muons.
- The injection of muons from pion decays could be extracted from some existing accelerator at low intensity.
- The goal is of experimentally demonstrate the full 6D 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.

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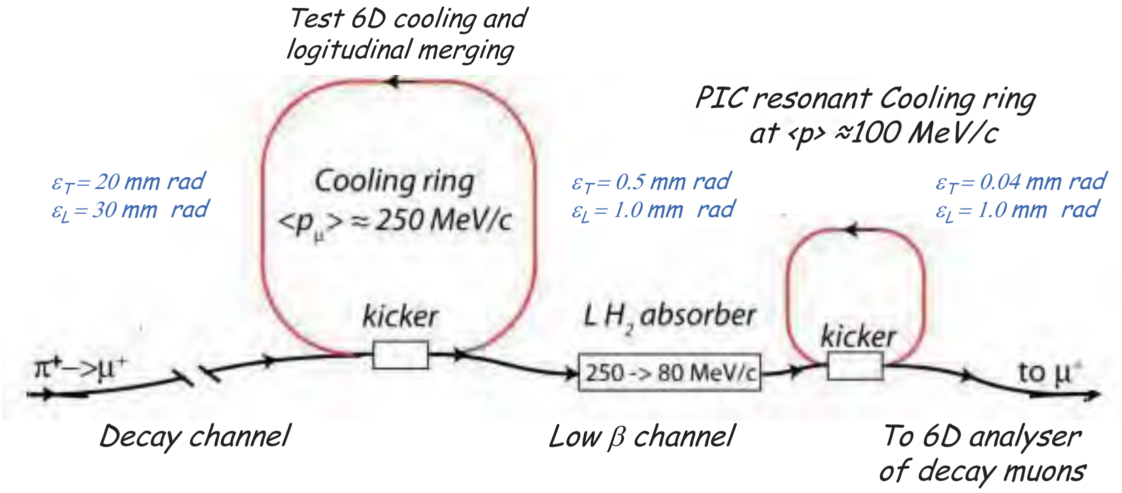
## Exemplificative initial cooling experiment

- A given sign muon cooling arrangement (μ+ or μ-) is required and with few particles in a very short pulse and two rings.

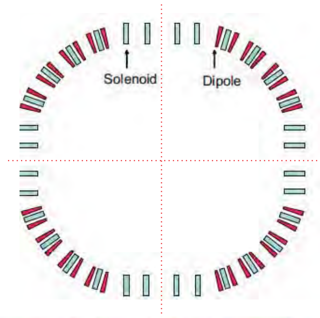


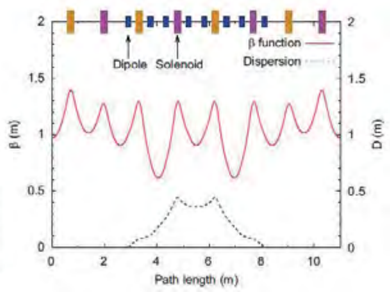

0.04( )mmrad $_L$ 1.0( ) mm rad

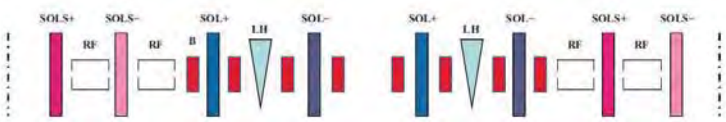


## A straightforward design for the achromatic cooling ring

- A realistic study is the one of Garren et al. (NIM, 2011).
- The four-sided ring has four 90° arcs with 8 dipoles separated by solenoids.
- Arcs are achromatic both horizontally and vertically. The dispersion is zero in the straight sections between the arcs.
- Injection/extraction kickers are used in a straight section; a superconducting flux pipe is used for the injected beam.



## The proposed initial cooling experiment

- A first "wide band" cooling ring must collect the widest muon spectrum peaked around 250 MeV/c and to introduce a first major reduction in the transverse and longitudinal emittances, namely:
  - solenoids instead of quadrupoles have a wider acceptance
  - with a few turns, only integer resonances are harmful
  - As a first cooler, the ionization absorber does not have to be made with $LH_2$: other solid materials (LiH) may be used.
- An intermediate $LH_2$ absorber ≈3 m long inside a low $\beta*$ channel reduces the vector muon momenta by range.
- The resulting beam must then be extracted and its momentum substantially reduced to about 100 MeV/c.
- A second "deep freezer" cooling PIC ring must ensure an required asymptotic beam emittances

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- The first 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) involves instead the balance between a strong resonance growth and ionization cooling and it may involve significant and unexpected conditions which are hard to predict.
- Therefore the experimental demonstration of the cooling must be concentrated on such behaviour.
- On the other hand the success of the novel Parametric Resonance Cooling is a necessary premise for a viable luminosity of the initial proton parameters of the future CERN accelerators since the expected Higgs luminosity is proportional to the inverse of the transverse emittances, hence with about one order of magnitude of increment expected from PIC.

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## Conclusions

- The recent discovery of the Higgs particle of 125 GeV at CERN has highlighted the unique features of the direct production of a H° scalar in the s-state, in analogy with the two steps of the Z with the PbarP and LEP programmes and where the mass, total and partial widths of the H° can be directly measured with a remarkable accuracy and a very large number of events.
- *A high energy $\mu^+\mu^-$-collider is the only possible circular high energy lepton Higgs collider that can be easily situated within the existing CERN (or FNAL) sites.*
- A first step to could be the practical and experimental realization of a *full scale cooling demonstrator*, a relatively modest and low cost system but capable to conclusively demonstrate "ionization cooling" at the level required for a Higgs factory and eventually as premise for a subsequent multi-TeV collider and/or a long distance $\nu$ factory.

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# Thank you !

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