A complete demonstrator for a muon cooled collider ring

Carlo Rubbia

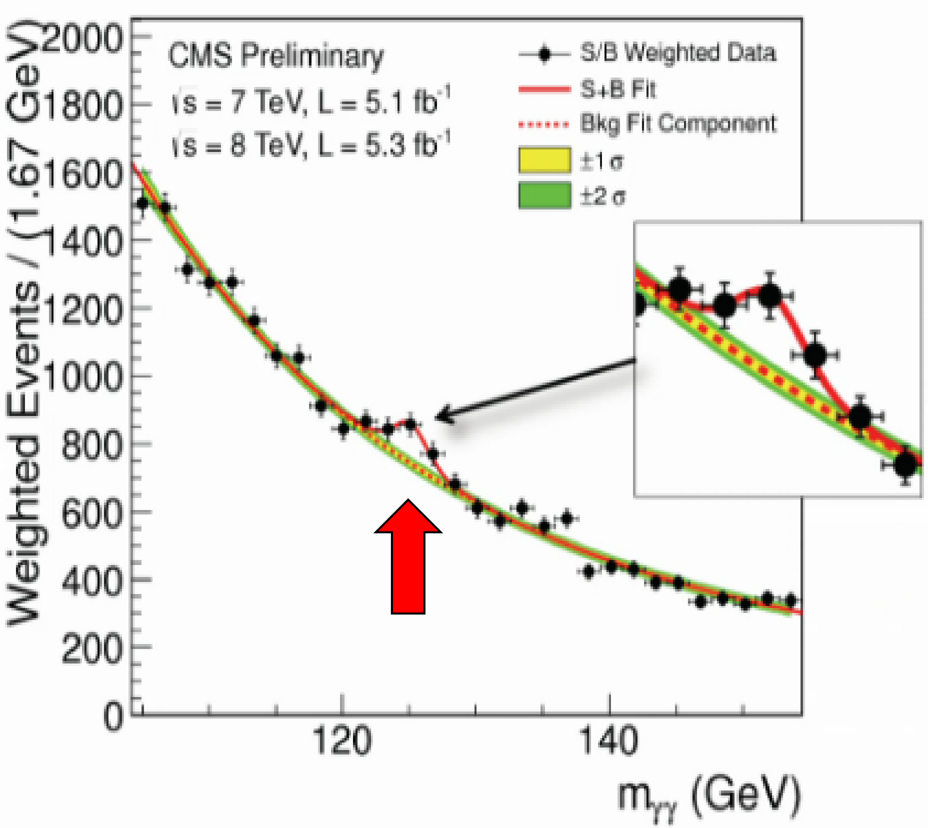
INFN and

Gran Sasso Science Institute, L'Aquila, Italy

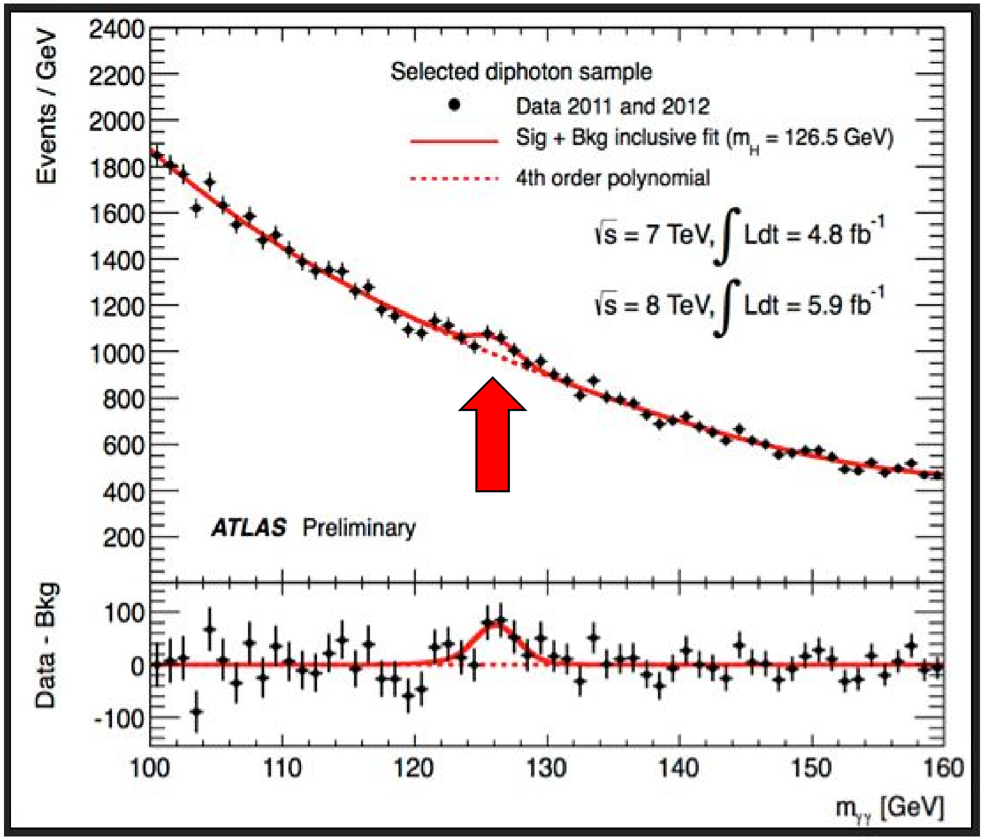
The discovery of the Higgs particle

Signal and background in the H -> 2 γ channel

CMS



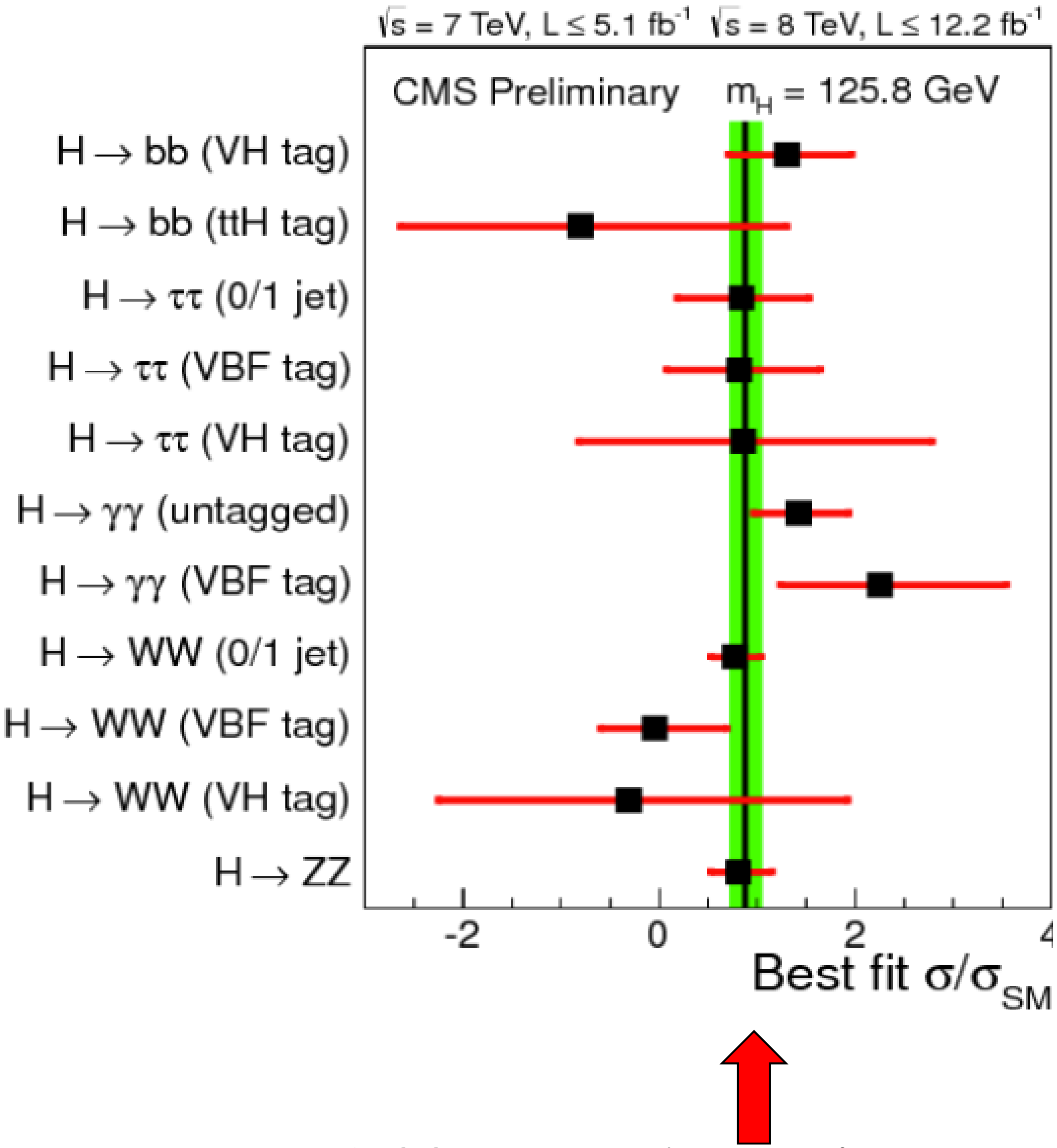
ATLAS

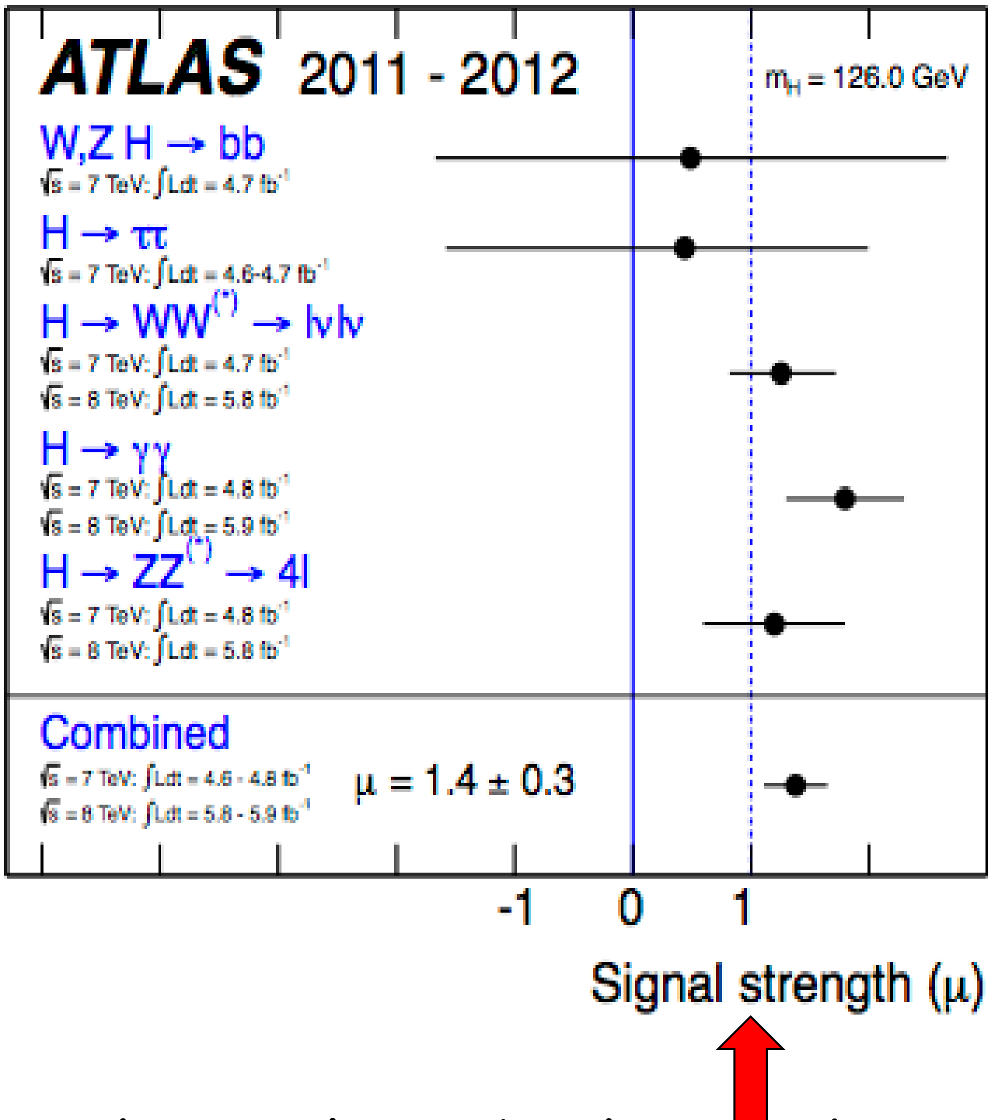


The observation of the Higgs at 125 GeV

- CMS and Atlas have observed a narrow line of high significance at about 125 GeV mass, compatible with the Standard Model Higgs boson.
  - ATLAS: $m_H = 125.5 \pm 0.2$ (stat) ± 0.6 (sys) GeV
  - CMS: $m_H = 125.8 \pm 0.4$ (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.

Present results

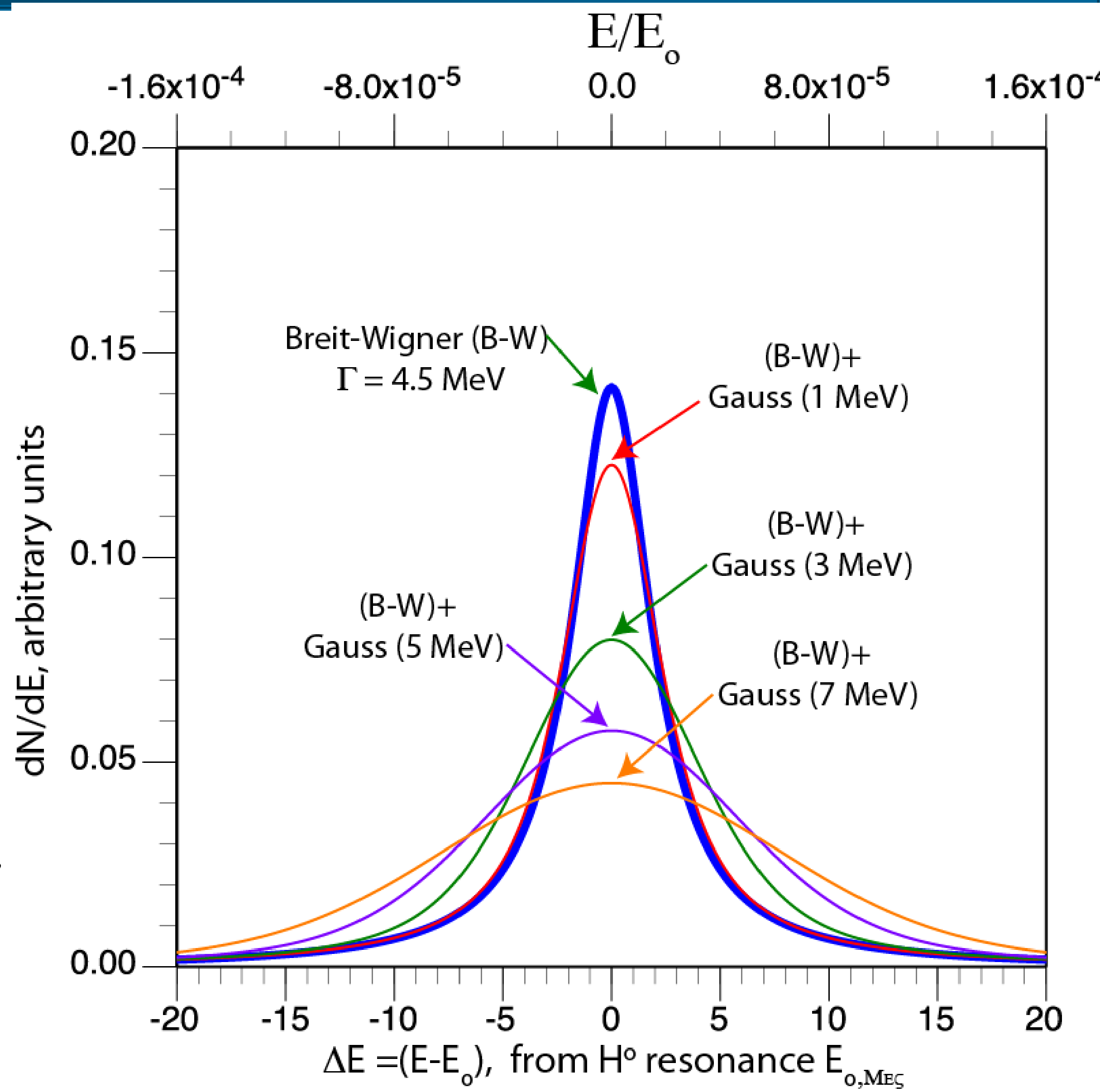




Many different channels but all with very large backgrounds

The Higgs width according to the Standard Model

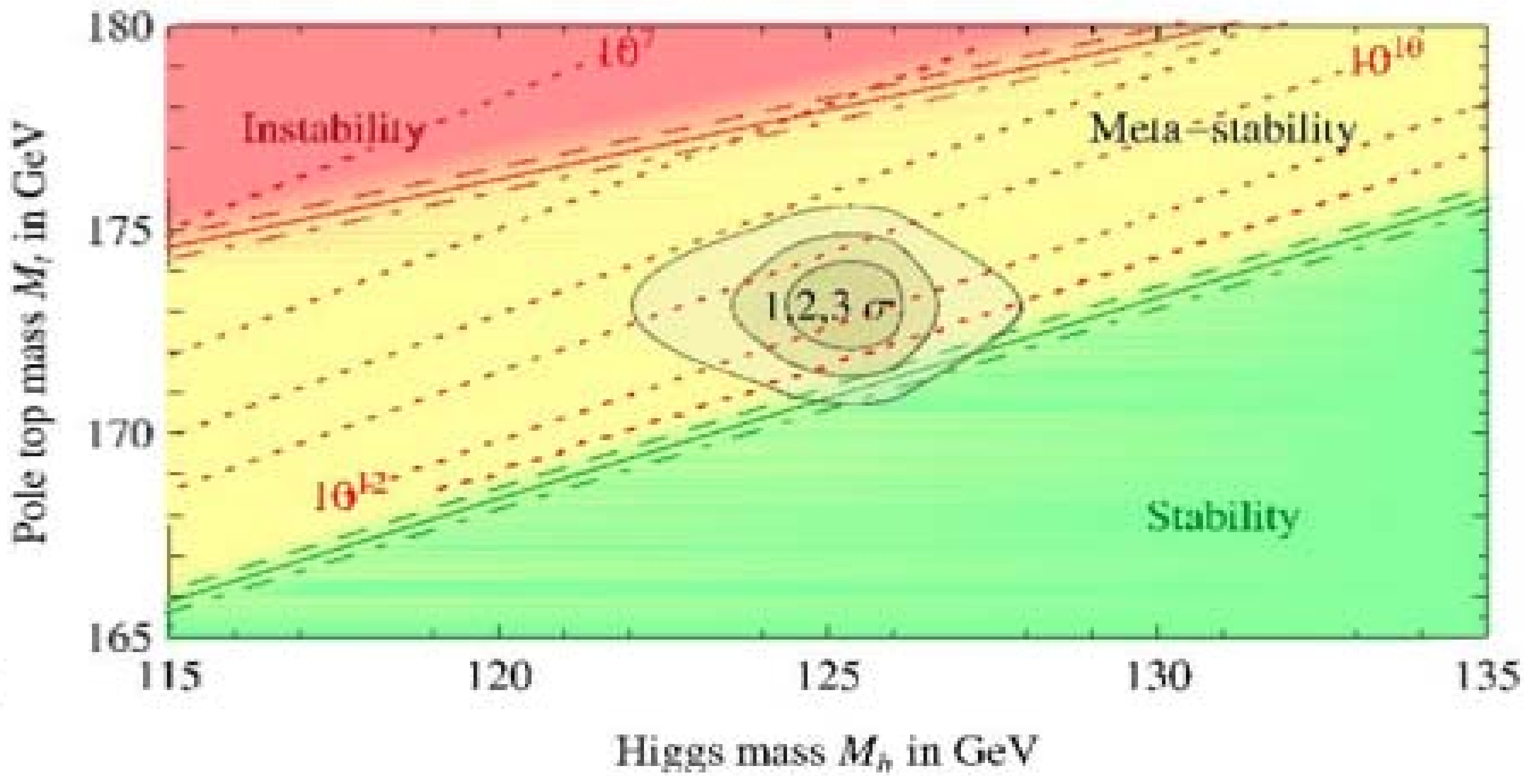
- Like in the case of the Z^0, the determination of the H^0 width will be crucial in the determination of the nature of the particle and the underlying theory
- Cross section is shown here, convoluted with a Gaussian beam distribution.
- Signal is not affected only if the rms beam energy width is ≤ a few MeV.



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

Stability of the Higgs sector

- 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".*

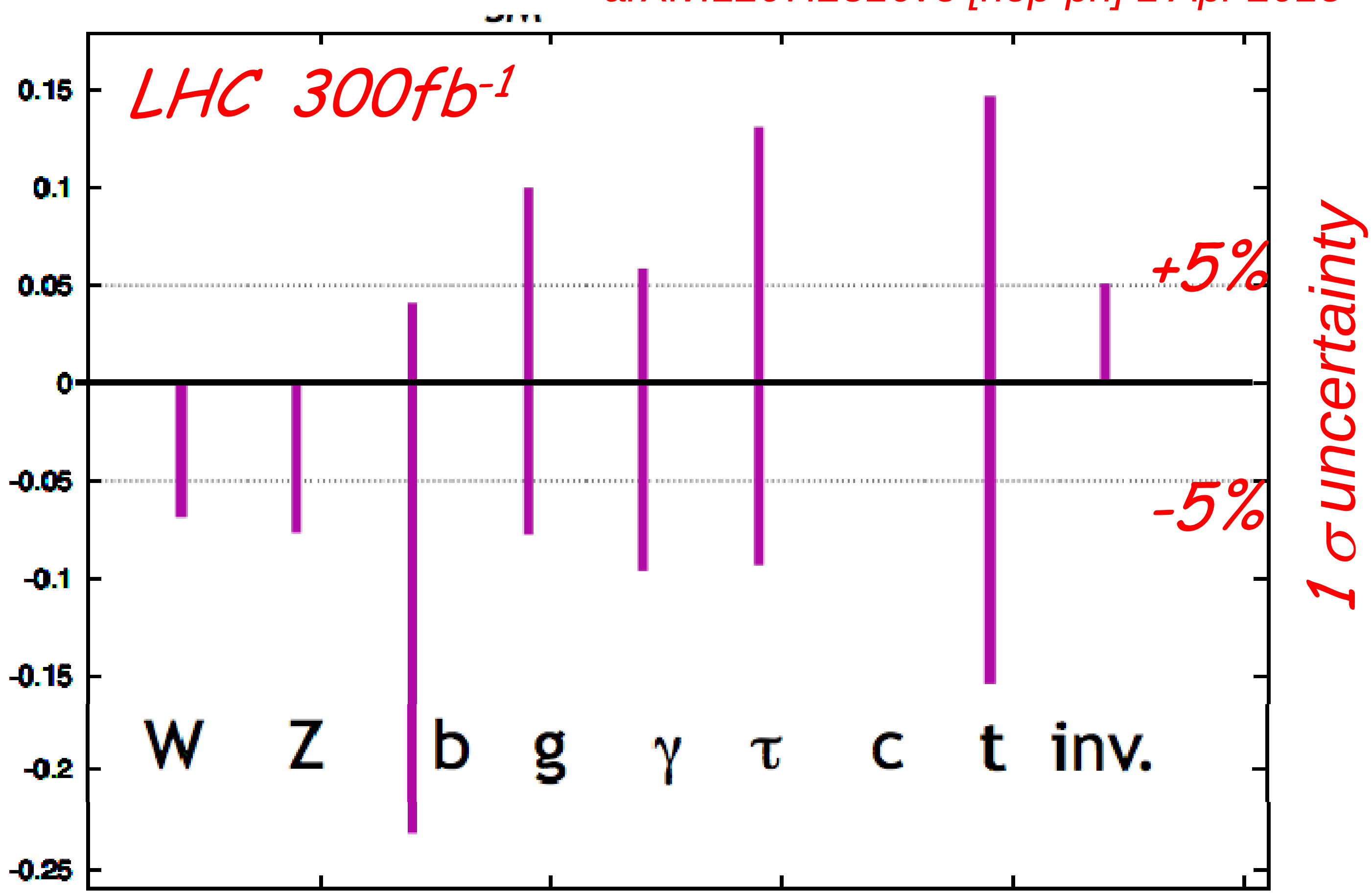


arXiv:1310.0763v3 [hep-ph] 30 Dec 2013

Ultimate LHC uncertainties are 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

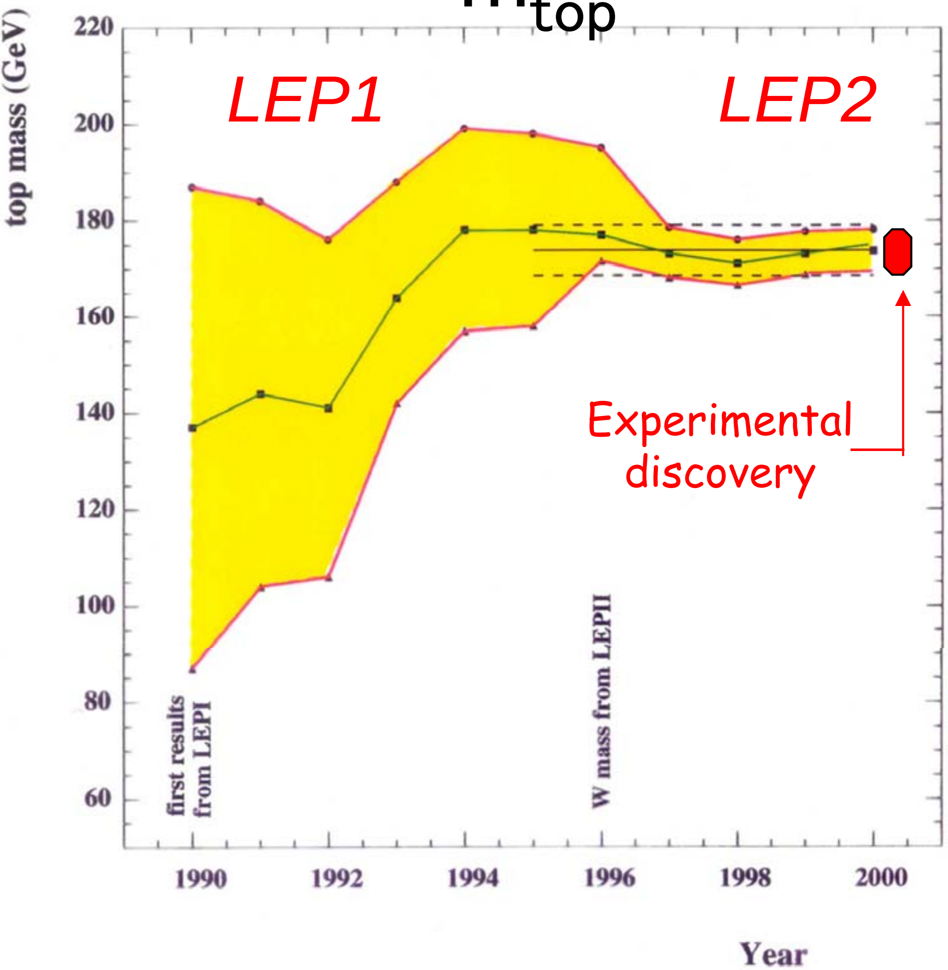


Unambiguous discoveries require 5 σ

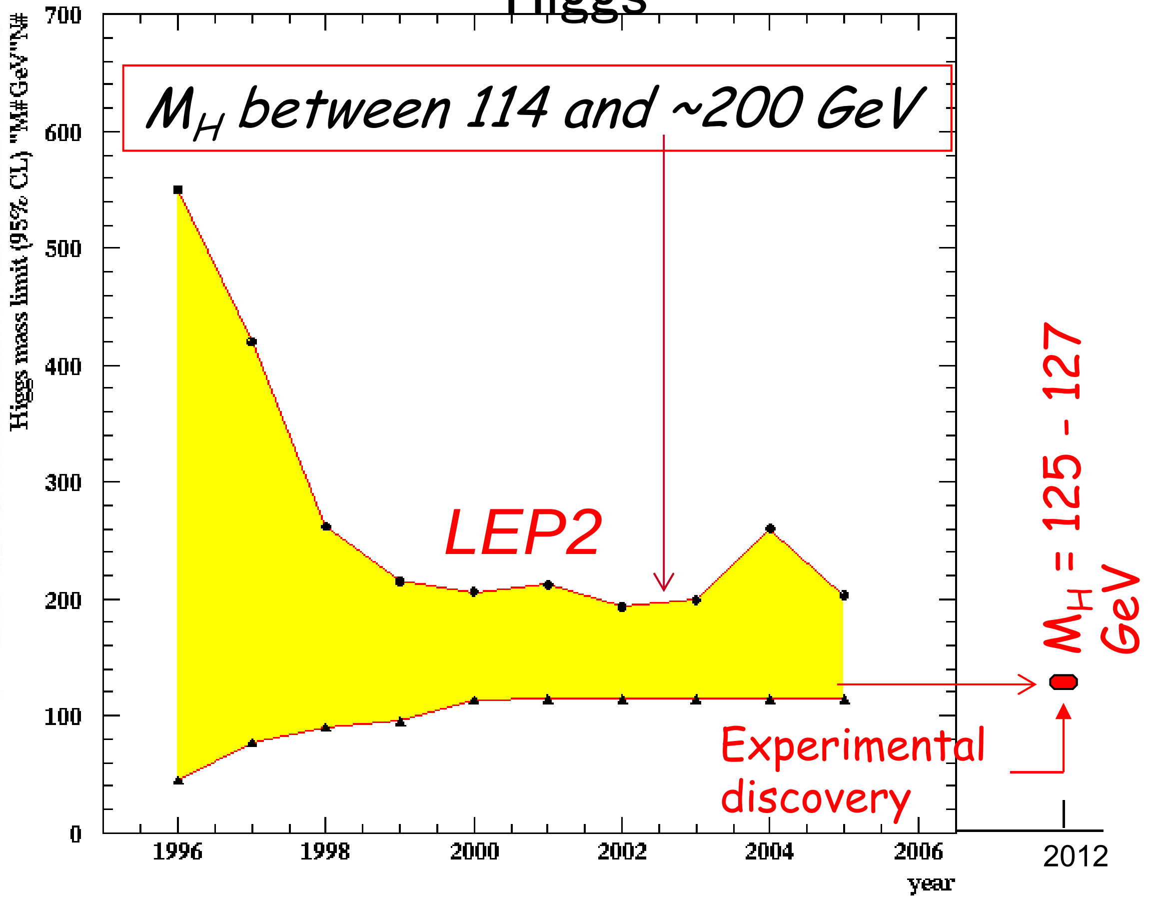
Predictive power of higher diagrams: the case of LEP

- After the p-pbar discovery of the Z^0, 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.

m_{top}

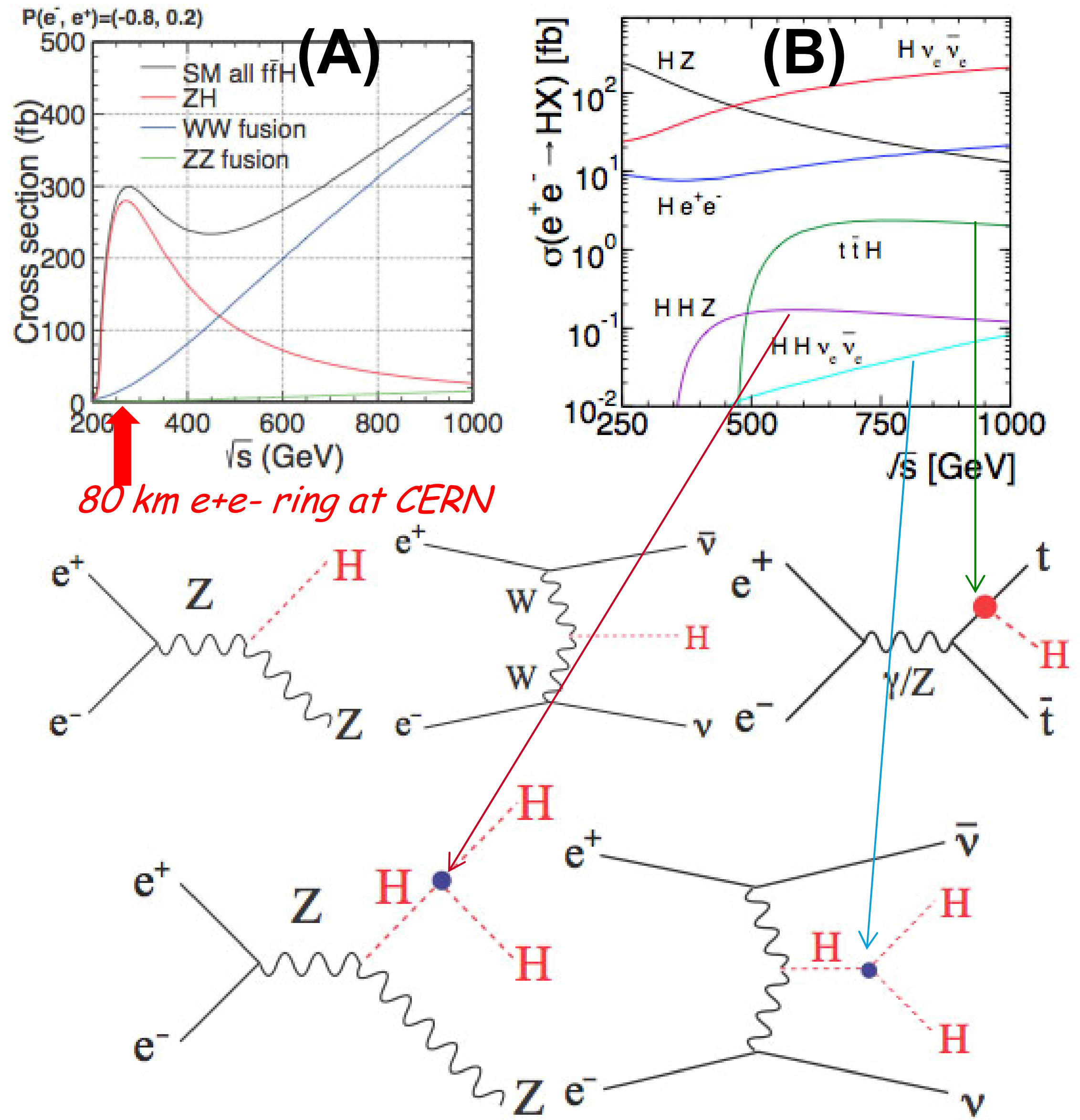


m_{Higgs}



Higgs related higher order electroweak processes

- Production cross sections of the Higgs boson with the mass of 125 GeV for e^+e^- as a function of the energy $\sqrt{s}$ **(A)**
- The cross sections of the production $e^+e^- \rightarrow HX$ as a function of the $\sqrt{s}$ energy **(B)**
- 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



In order to study comprehensively all these processes energies of 0.6-1 TeV are needed

Potential deviations from Standard Model

- 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, $3\,\mathrm{ab}^{-1}$	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

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

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

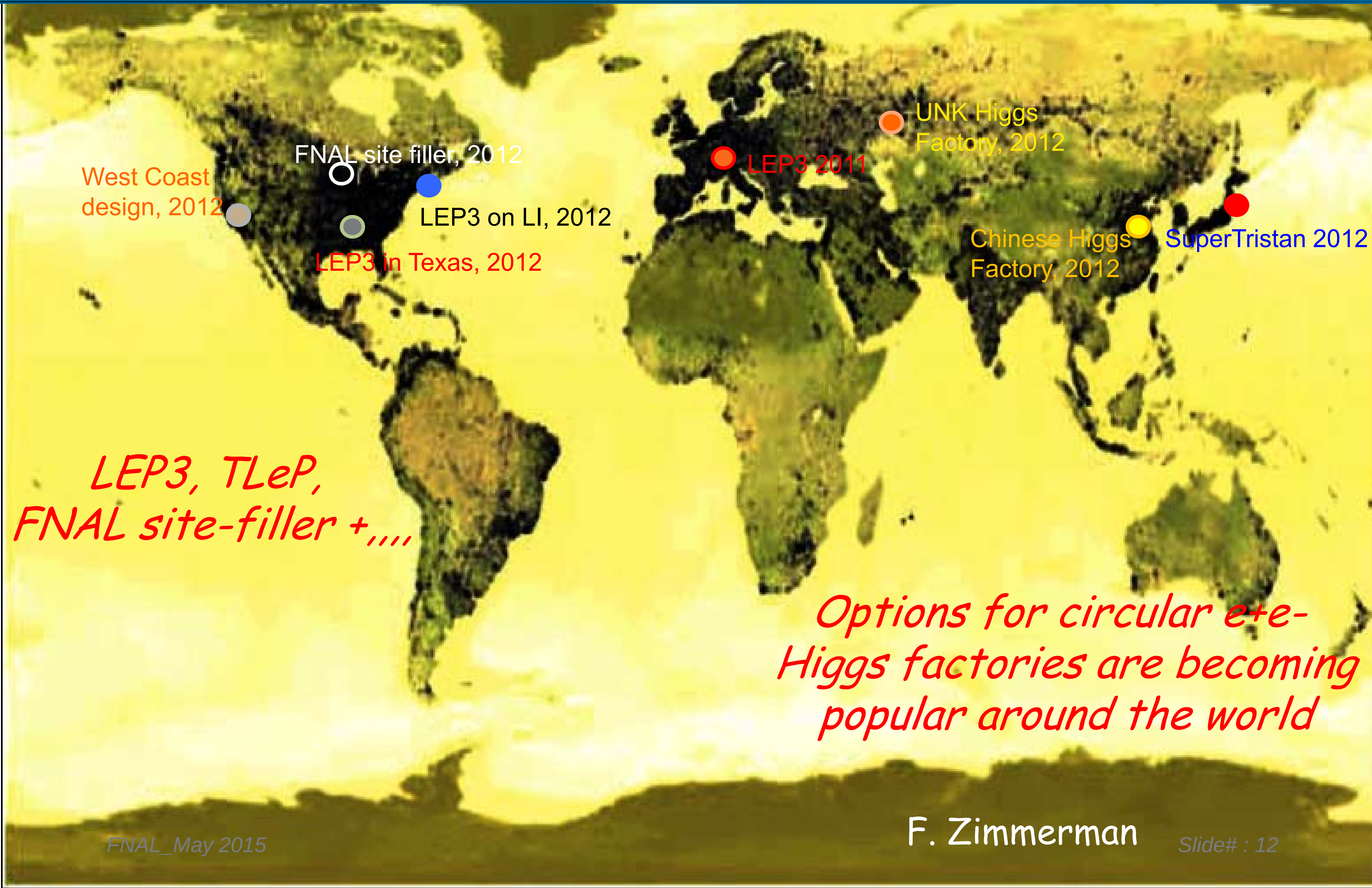
Studying the Higgs signal beyond LHC

- The scalar sector is definitely one of the keys to the future understanding of elementary particle physics.
- *Like in the case of W and Z, with LEP after the pbar-p a similar second phase may be also necessary for the H^0*
- 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 *$Z + H^0$ signal* of *≈ 200 fb.* The circumference of a new, LEP-like ring is of about ≈ 80 km or the length of a Linear Collider is ≈31 km.
  - A $\mu^+\mu^-$ collider at L > 10^{32} and a *H^0 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.
- However a comprehnsive Higgs study requires √s energies of ≈ 1 TeV, only possible with a linear e^+e collider or a $\mu^+\mu^-$ ring.

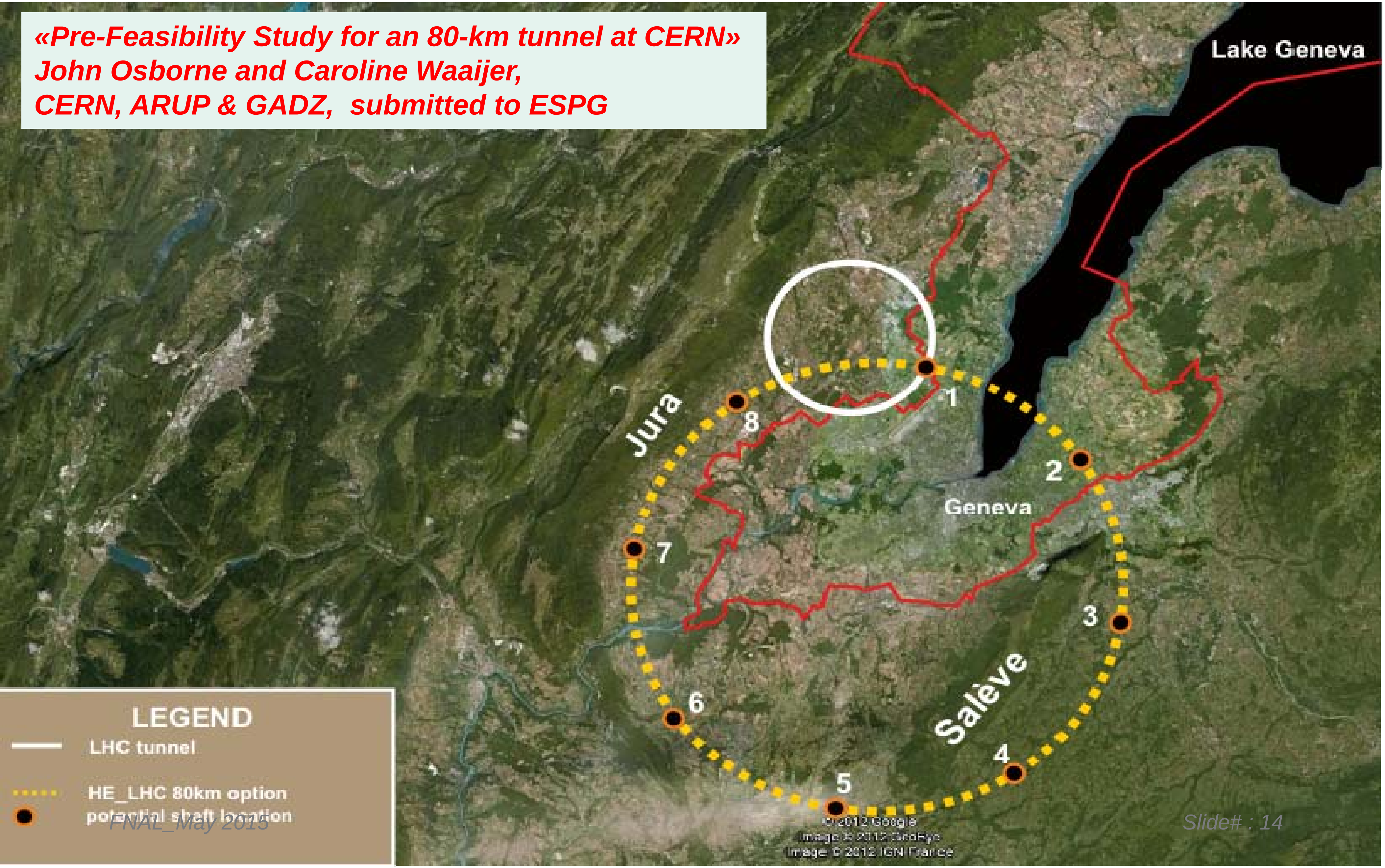
The first option: a huge $e^+ e^-$ LEP like ring.



Super Tristan

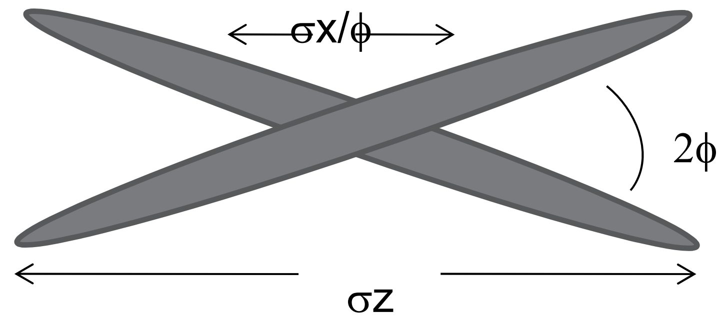
TLEP tunnel in the Geneva area

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG



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

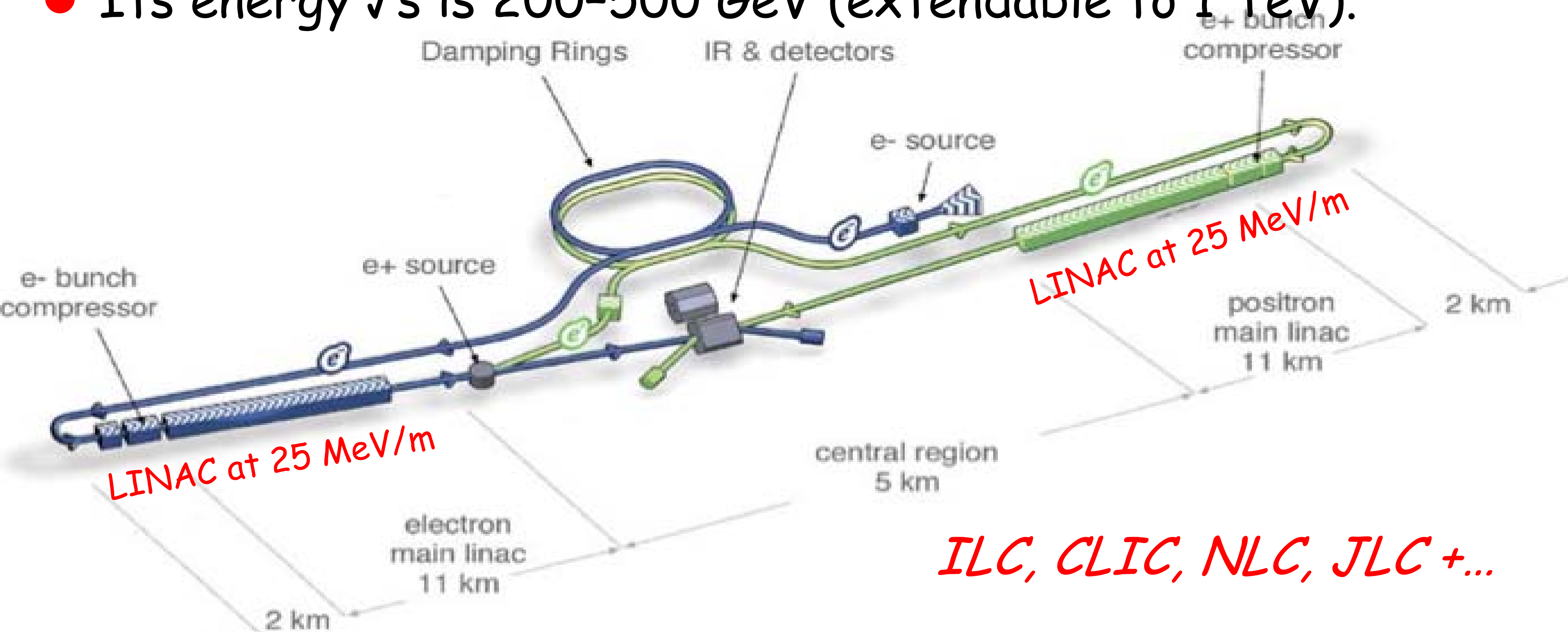
- The luminosity is pushed to the beam-strahlung limit.
- Collisions are at an angle, but with fewer bunches than for a B-Factory: a nano-beam scheme



- 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 (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).*
- *The Higgs width, H-strahlung and double Higgs diagrams cannot be studied by any acceptable e^+e^- ring collider.*

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).



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.

A comprehnsive Higgs study requires √s ≈ 1 TeV,

Super-Tristan vs ILC

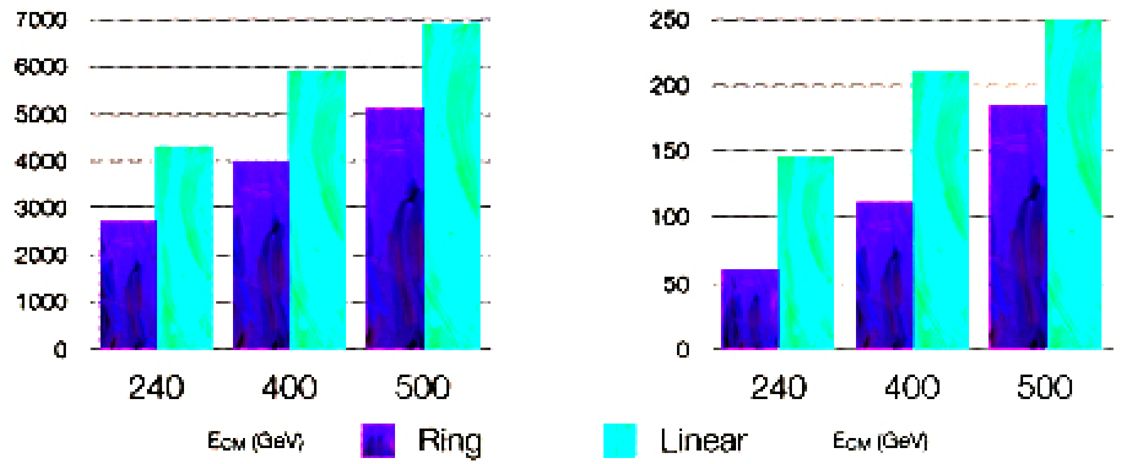
Ring or Linear?

Construction

E_{CM} (GeV)	Ring	Linear
240	2700	4300
400	4000	5900
500	5090	6900

Site Power (MW)

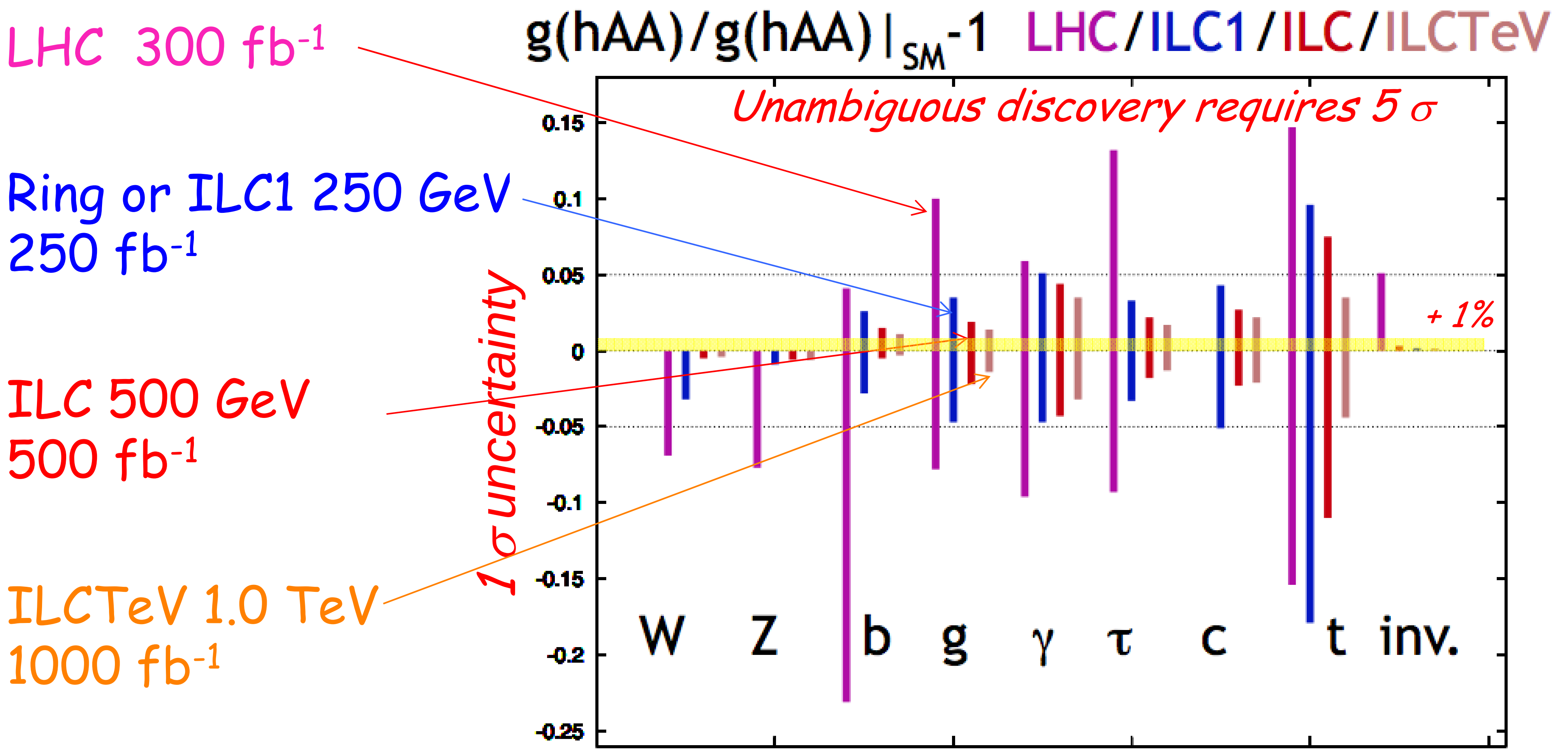
E_{CM} (GeV)	Ring	Linear
240	60	146
400	111	210
500	185	250



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

Predictions for the Higgs at 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 to ≈ 1 TeV, with correspondingly longer structures and higher powers.



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

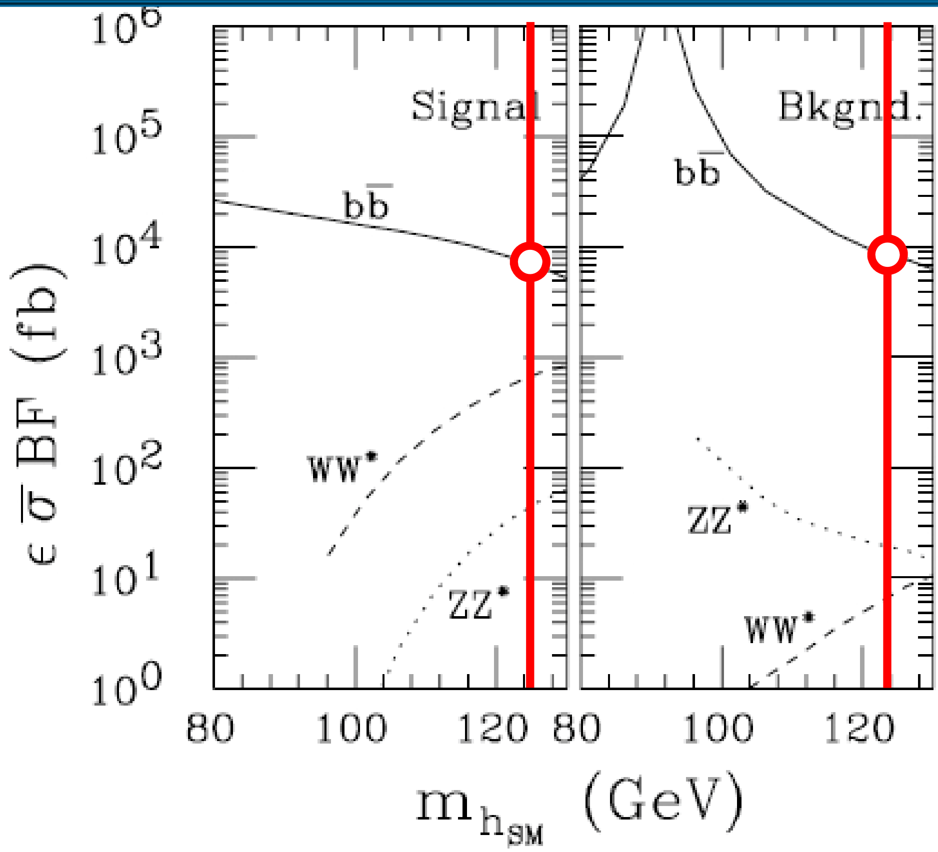
Two Higgs related μ+μ- collider alternatives

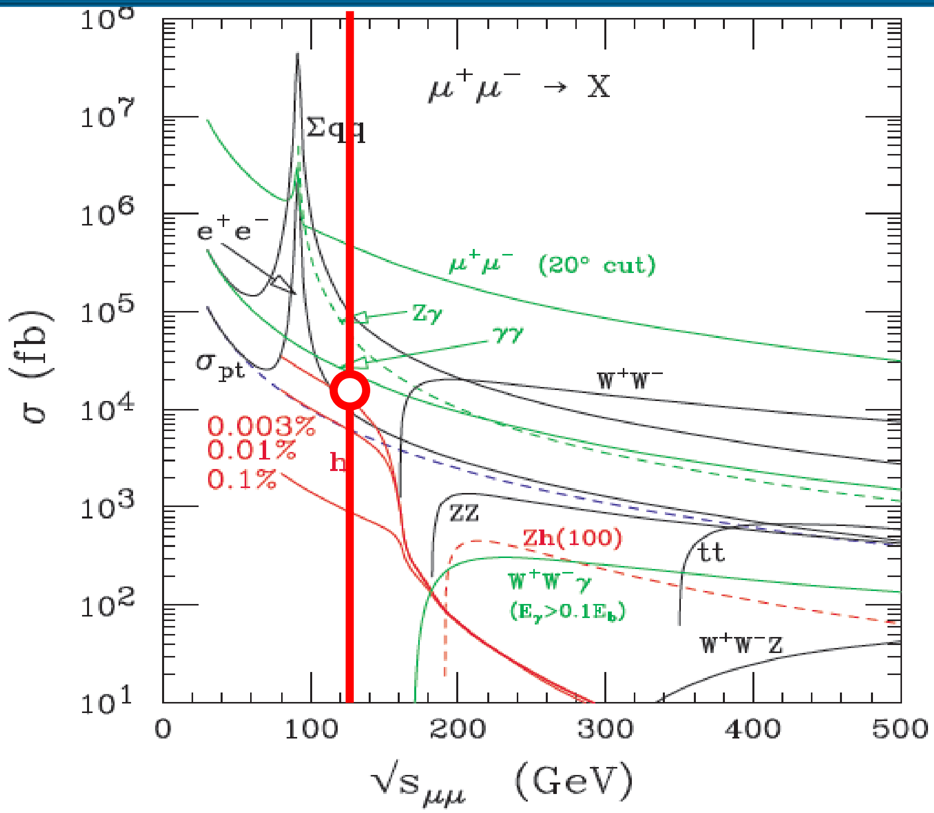
- Replacing electron with cooled muons may offer two main and independent programmes:
  - A Higgs factory ring in the the s-channel resonance at $\sqrt{s}$ = 126 GeV in which its very narrow width and most decay channels may be accurately measured
  - A higher energy collider ring eventually up to the TeV and of luminosity comparable to one of a e^+e^- linear collider
- These rings can easily fit within the CERN site.
  - For $\sqrt{s}$ = 126 GeV the ring radius is ≈ 50 m (about 1/2 of the CERN PS or BNL AGS) and *resolution ≈ 0.003%*
  - For $\sqrt{s}$ = 1 TeV the corresponding ring radius is ≈ 400 m (less than ½ of the CERN SPS) and *resolution ≈ 0.1 %*
- Both alternatives must cool and accelerate to the required $\sqrt{s}$ about 2 x 10^{12} muons with 5 MWatt, 10/50 s^{-1} protons at ≥ 5 GeV.
- But the need of a LINAC to accelerate both μ^+ and μ^- up to 62.5 and 500 GeV respectively in order to fit within the CERN site needs a packed recirculating structure which must be studied.

1.-The direct s-channel Higgs production in a $\mu^+\mu^-$ collider

- The direct H^0 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^0 scalar production in the s-state offers conditions of unique cleanliness .
- A 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^0 of SUSY or of other than any other collider.

A muon collider in order to determine the Higgs channels



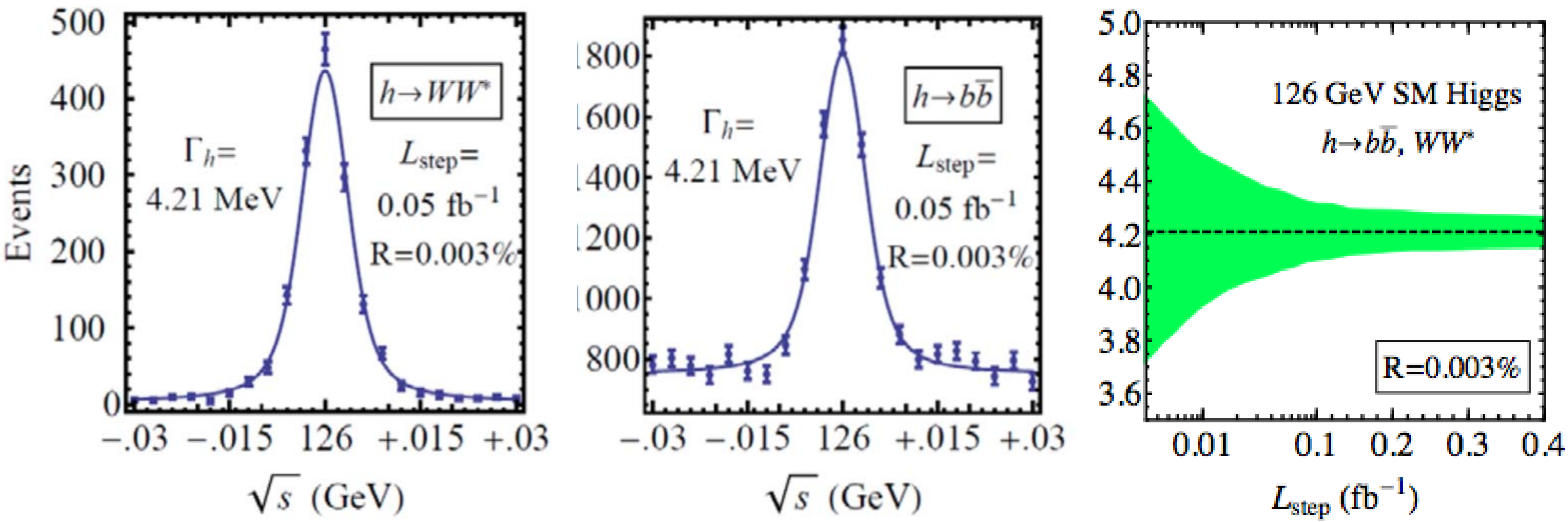


- A $\mu^\pm$ collider with adequate muon cooling and L > 10^{32} cm^{-2} s^{-1} .
- Decay electron backgrounds are important: : 2 x 10^{12} $\mu^\pm$ decays produce 6.5 x 10^6 collimated $e^\pm$ decays/meter with E_{ave}≈ 20 GeV.
- The very narrow resonant signal (4.12 MeV ,Γ/M_H =3.6 x 10^{-5} for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

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)	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].

2.-Muon cooling at TeV energies

- Over the past decade, there has been significant progress in developing the concepts and technologies needed to produce, capture, cool and accelerate **O(10^{21})** muons per year.
- Extensive studies have been performed during the late nineties in the US in EU and elsewhere and widely discussed inseveral international workshops and by the MICE collaboration.
- Conclusions were that acceleration of cooled muon rings at TeV energies was a perfect alternative to the ILC program.
- The recent discoveries of the Higgs particle at 125 GeV and the observation of the sin(θ_{13}) neutrino oscillation mechanism have strongly revived also the interest for these studies.
- In addition to the Higgs developments, a neutrino factory (NF), where high-energy muons decay to produce an intense beam of neutrinos and antineutrinos is considered as a very interesting alternative which has been widely analized and shown feasible.

Baseline US parameters for a high energy muon cooling

- Two circular colliders with energies of 3 TeV and 400 GeV have been considered in the US. with a respective circumference of 6 km (SPS like) and 1 Km (ISR like).
- Both arrangements could easily fit within the present CERN site
- But a powerful LINAC is needed in order to accelerate both $\mu^{\pm}$ up to 1.5 TeV.

COM energy (TeV)	3	0.4
p energy (GeV)	16	16
p's/bunch	2.5×10^{13}	2.5×10^{13}
Bunches/fill	4	4
Rep. rate (Hz)	15	15
p power (MW)	4	4
μ/bunch	2×10^{12}	2×10^{12}
μ power (MW)	28	4
Wall power (MW)	204	120
Collider circum. (m)	6000	1000
Ave bending field (T)	5.2	4.7
rms $\Delta p/p$ (%)	0.16	0.14
6D $\epsilon_{6,N}$ $(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}
rms ϵ_n (π mm mrad)	50	50
β^* (cm)	0.3	2.6
σ_z (cm)	0.3	2.6
σ_r spot (μm)	3.2	26
σ_θ IP (mrad)	1.1	1.0
Tune shift	0.044	0.044
n_{turns} (effective)	785	700
Luminosity ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	7×10^{34}	10^{33}
Higgs/yr		$\approx 10^4$

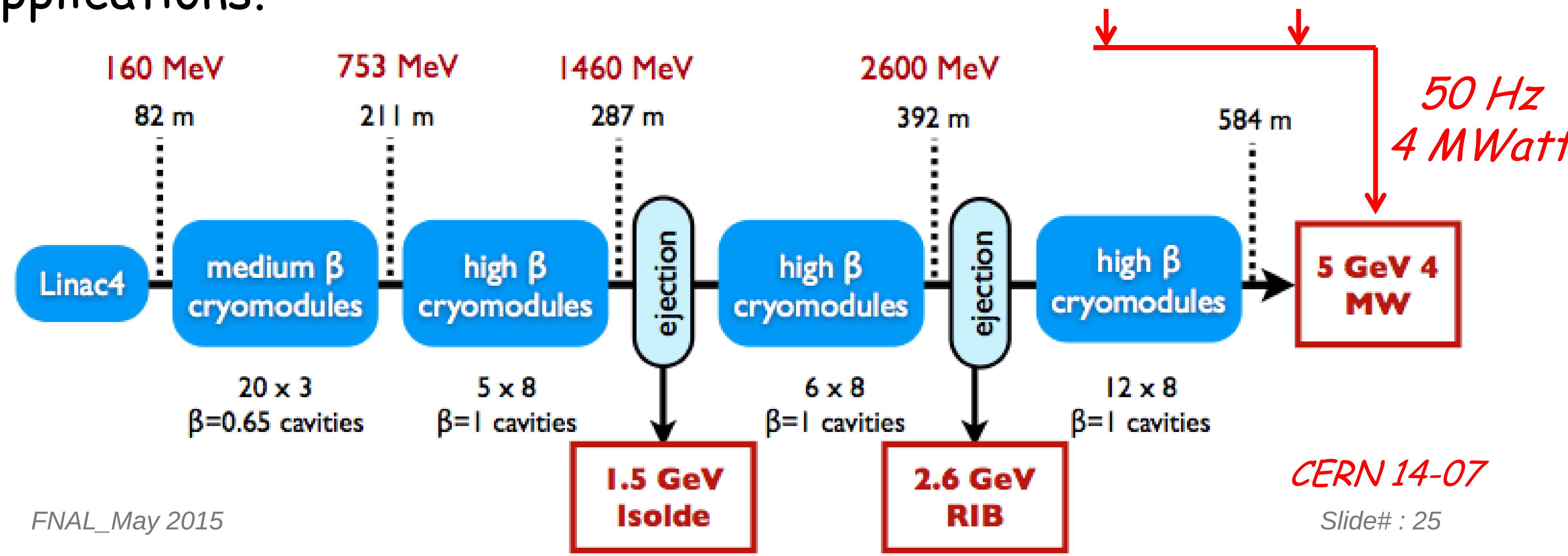
$L = 7 \times 10^{34}$

C. Ankenbrandt et al., Physical Review STAB 2, 081001 (1999),
M. Alsharo'a et al., Physical Review STAB 6, 081001 (2003).

Protons for a muon based Higgs factory at CERN

- 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		LP-SPL
		Low-current	High-current	
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



CERN 14-07

A tentative proposal for a Higgs factory at CERN

- The 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 p_t 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 1-2 x 10^{12} $\mu^{\pm}$ are accelerated to 62.5 GeV with an unconventional, bi-directional recirculating LINAC ≈200 m long.
- Muons are colliding in a SC storage ring of R ≈ 60 m (about one half of the CERN-PS , 1/100 of LHC) where > 10^4 Higgs events/y are recorded for each of the experiments.

The site layout

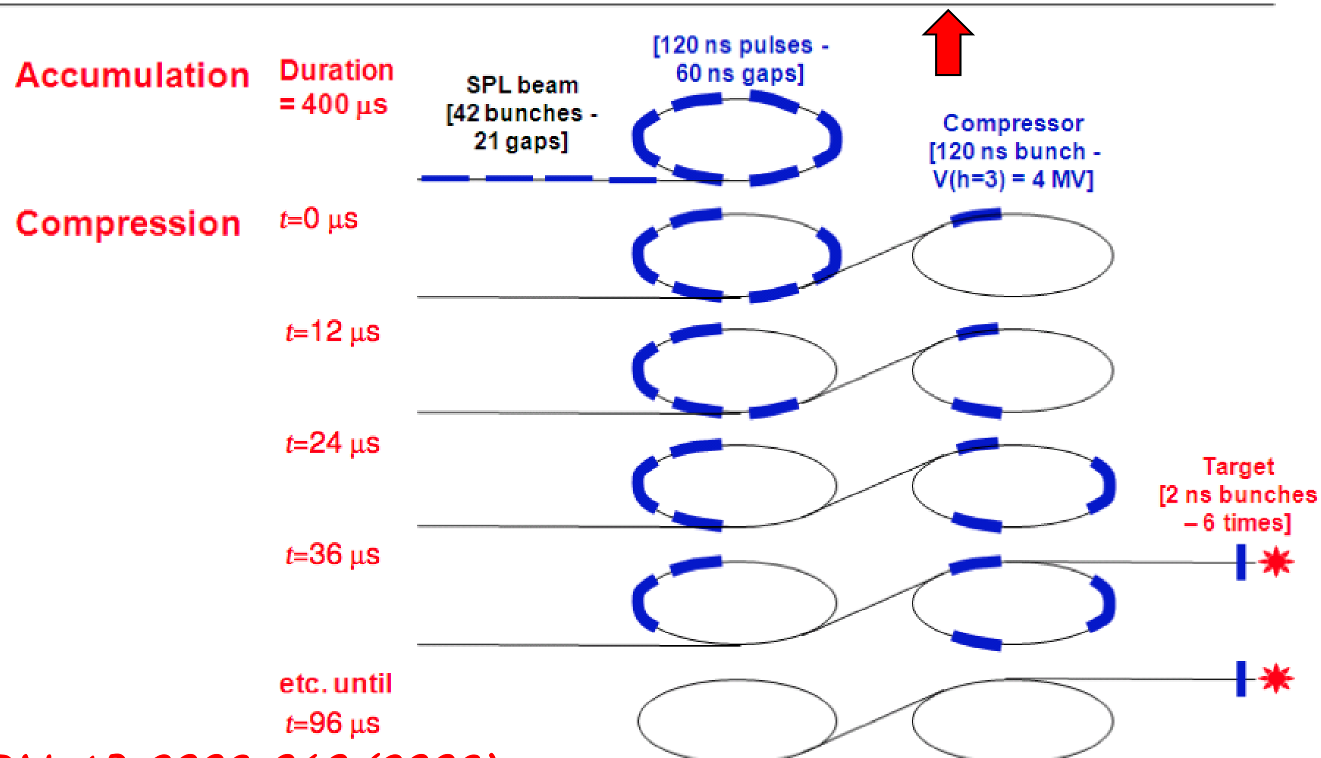
ITEM	length (m)
PS4 LINAC, 160 MeV(*)	*82*
SPL LINAC, 5.0 GeV(*)	*500*
Accumulator & Compressor	r = 50 m
Target and Horn, 20 Tesla	6
Drift, Buncher & Rotator	116
Linear muon cooler (MICE)	80
Two (+ and-) 6D cooling rings	r = 6 m
PIC resonance cooling rings	r = 4 m
Acceleration to 62.5 GeV	380
Collider ring	r = 60 m

(*) The PS4 and the SPL LINACS are part of the planned LHC programme. (r is the radius of the circular rings)

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

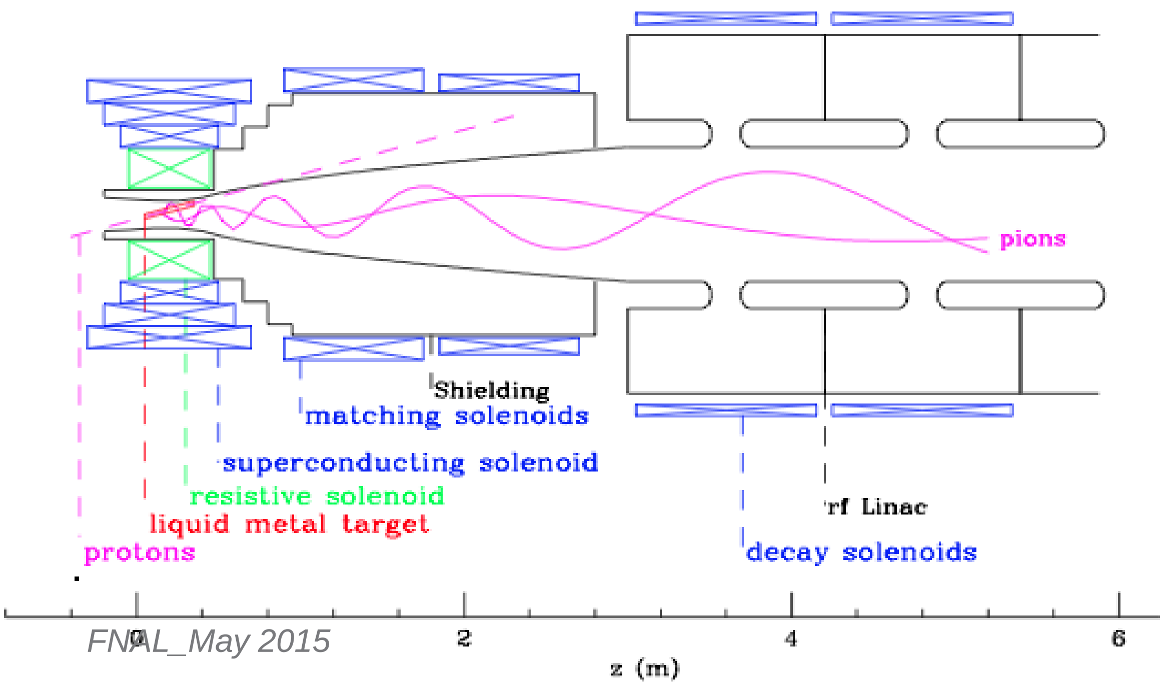


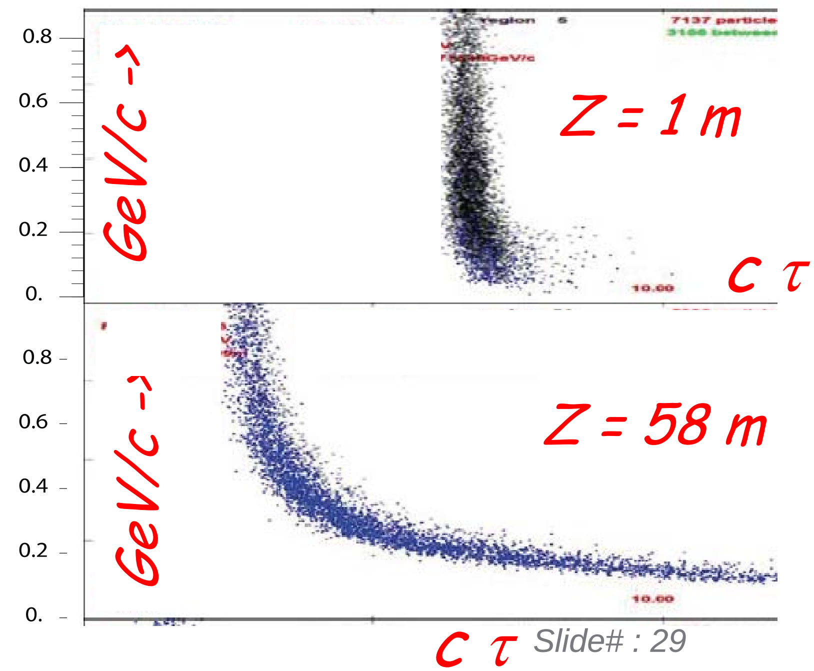
CERN-AB-2008-060 (2008)

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

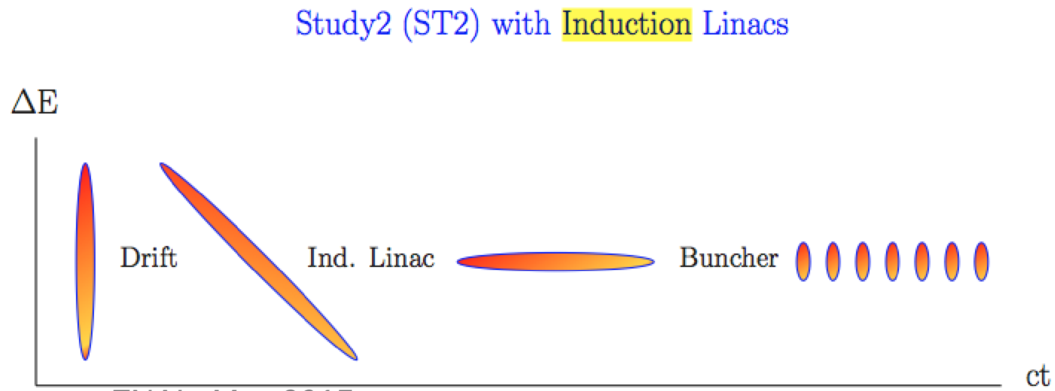
Pions/muons drifting as a function of c τ

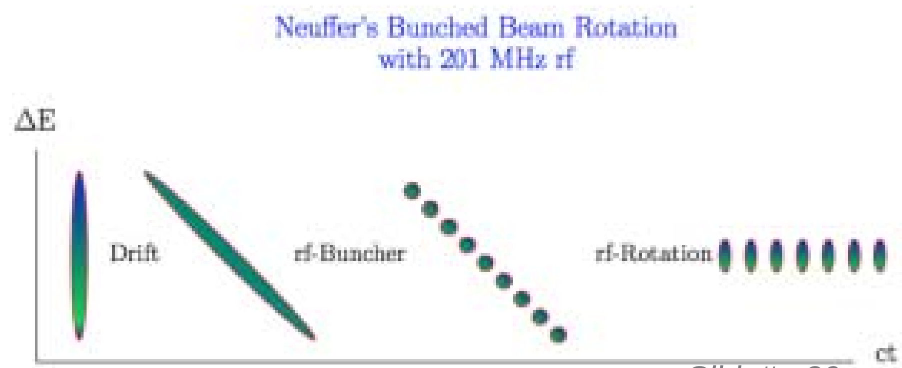




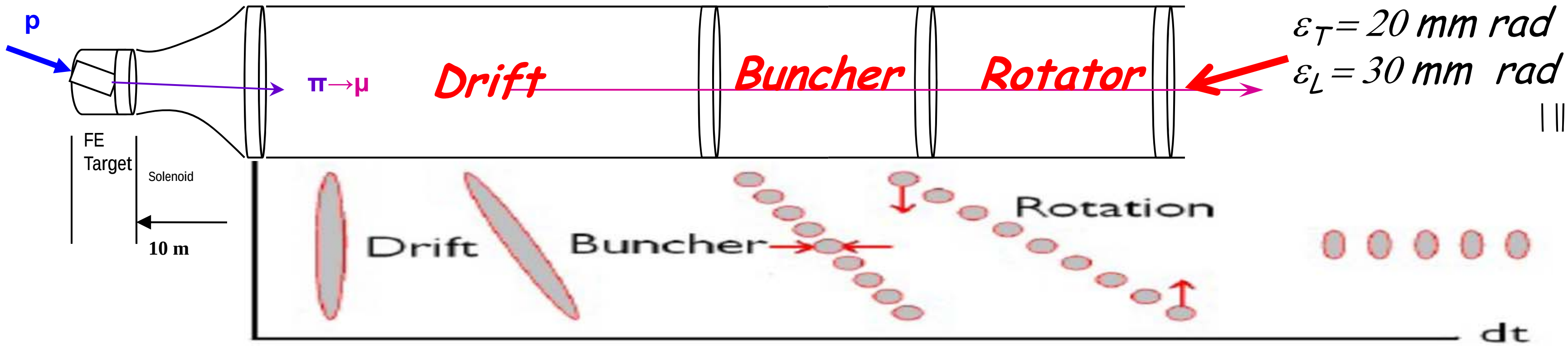
Beam energy compression

- 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%.

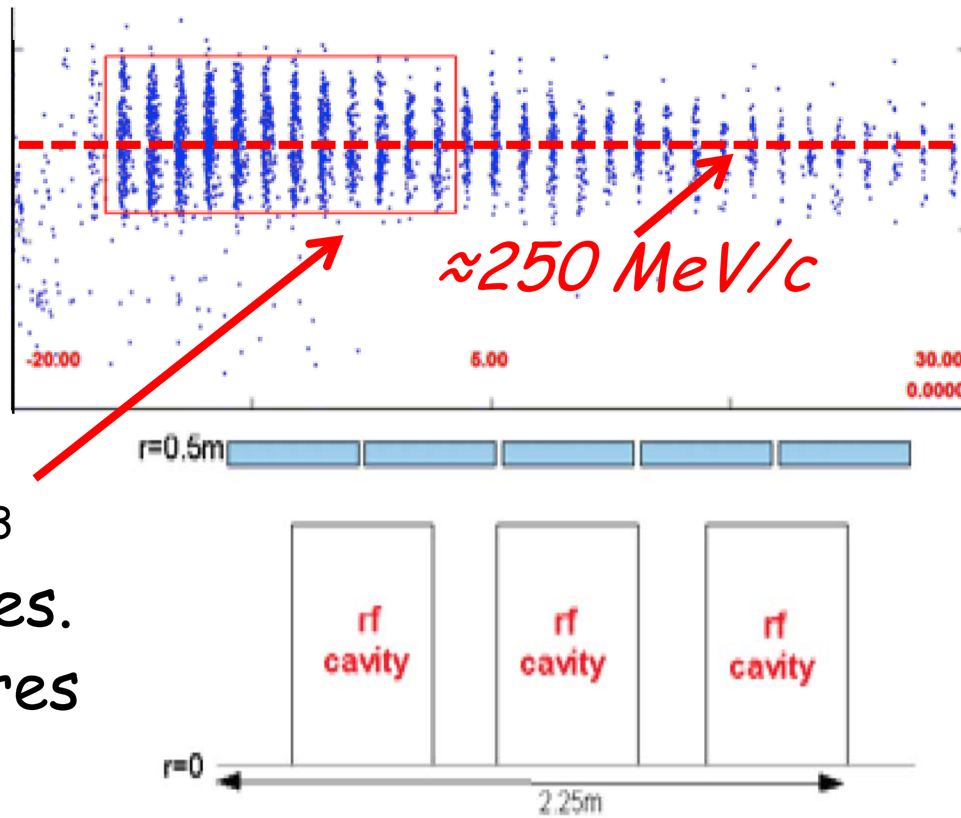




Buncher and rotator to compress muon beam spectrum



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 p pulses/s with 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 later recombination and signs
- Solenoidal coils at about 2 T

Ionization cooling

- This method, called "*dE/dx* cooling" closely resembles 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.

D. Neuffer, Particle Accelerators 1983, Vol. 14, pp. 75-90

Muon cooling ring: transverse emittance

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

Cooling — Scattering

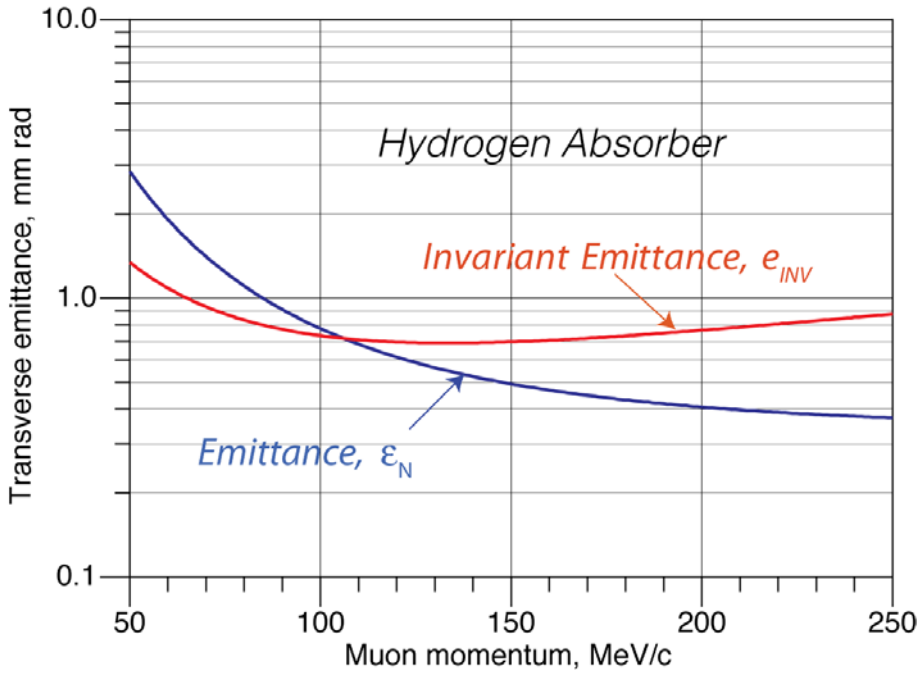
$$\frac{d\varepsilon}{dz} \approx \frac{\varepsilon}{\beta^2 E}\frac{dE}{dz} + \frac{\beta^*(13.6)^2}{2\beta^3 E m_\mu X_o} \rightarrow 0$$

β^* = beta at cross
m_μ,β_μ = 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 ε_N and its invariant $\varepsilon_N/\beta\gamma$ are shown as a function of the muon momentum.
- For H_2 and β^*= 10 cm, $\varepsilon_N/\beta\gamma \lesssim 700$ mm mr from 80 to 300 MeV/c



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

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

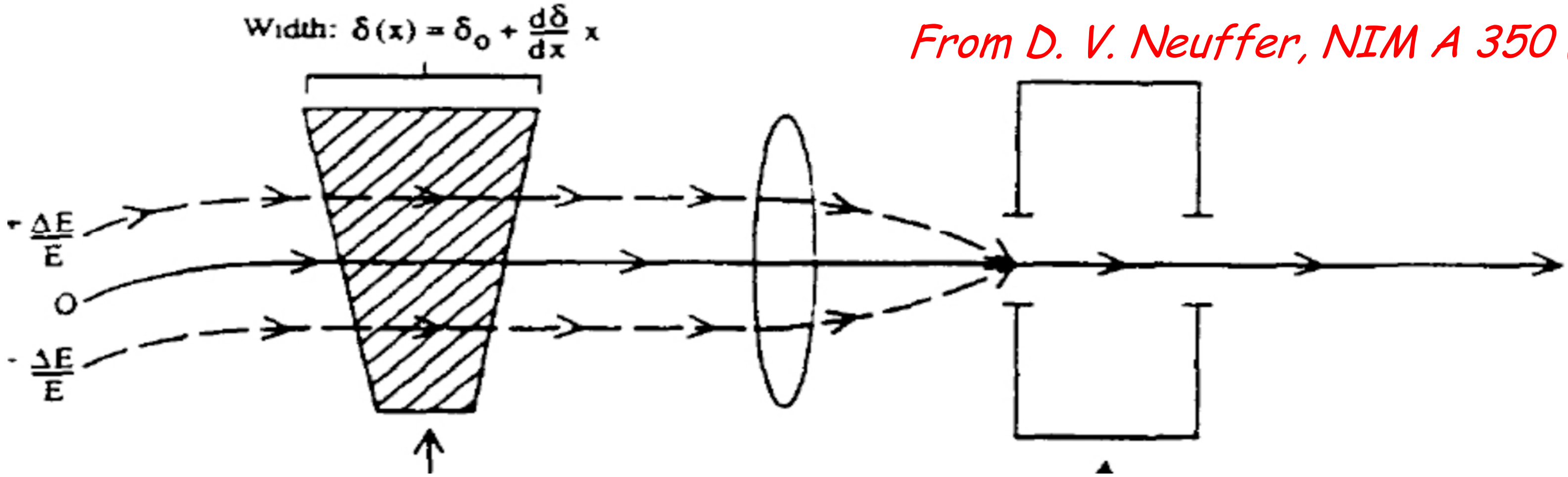
$$\frac{d(\Delta E)^2}{dz} = -2(\Delta E)^2 \left[f_A \frac{d}{dE}\left(\frac{dE_o}{ds}\right) + f_A \frac{dE}{ds}\left(\frac{d\delta}{dx}\right)\frac{\eta}{E\delta} \right] + \frac{d(\Delta E)^2_{straggling}}{dz}$$

  - $dE/dz = f_A \, dE/ds$ 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 $d\delta/dx$ are the thickness and radial tilt of the absorber
  - the straggling (H2) is given by $\dfrac{d(\Delta E)^2_{straggling}}{dz} = \dfrac{\pi (m_e c^2)^2 (\gamma^2 + 1)}{4 \ln(287) \alpha X_o}$

Longitudinal balance (cont.)

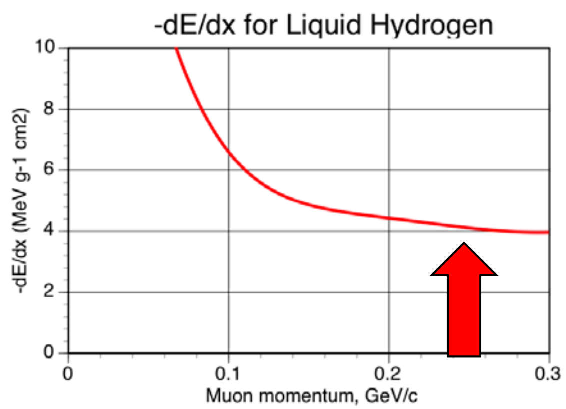
- The thickness of the absorber must vary with the transverse position, producing the appropriate energy dependence of energy loss, resulting in a decrease of the energy spread

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.

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

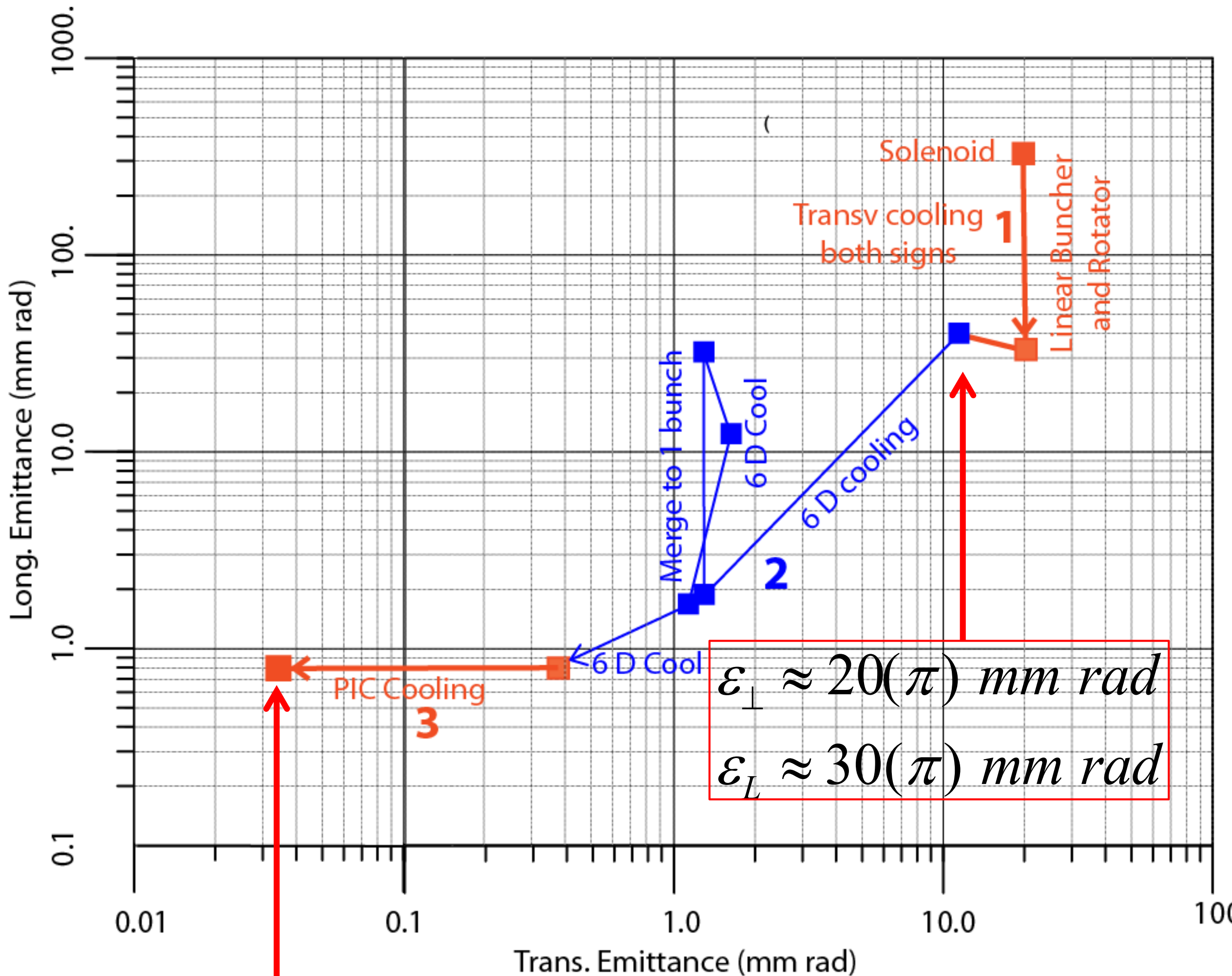


dE/dx loss as a function of the muon momentum for hydrogen (very near to min for 250 MeV/c)

Describing the full cooling procedure

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

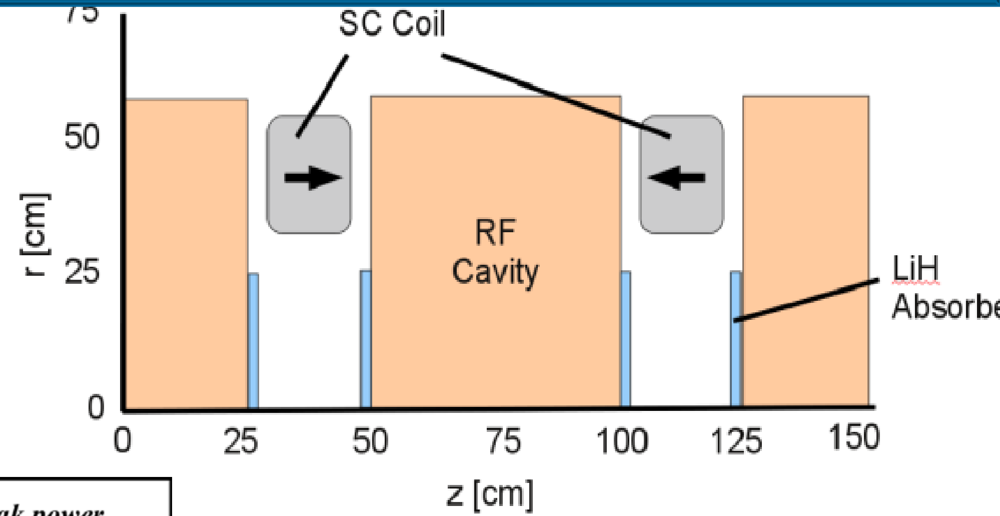
1. Linear transverse cooling of both signs amd small Δp increase.
2. Ring cooling in 6D with B brings the μ^+ and μ^- to a reasonable size Merging and cooling to single bunches
3. PIC resonance cooling. where the normal elliptical motion in x-x' phase space has become hyperbolic.



$$\varepsilon_\perp \approx 20(\pi)\ mm\ rad$$
$$\varepsilon_L \approx 30(\pi)\ mm\ rad$$

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

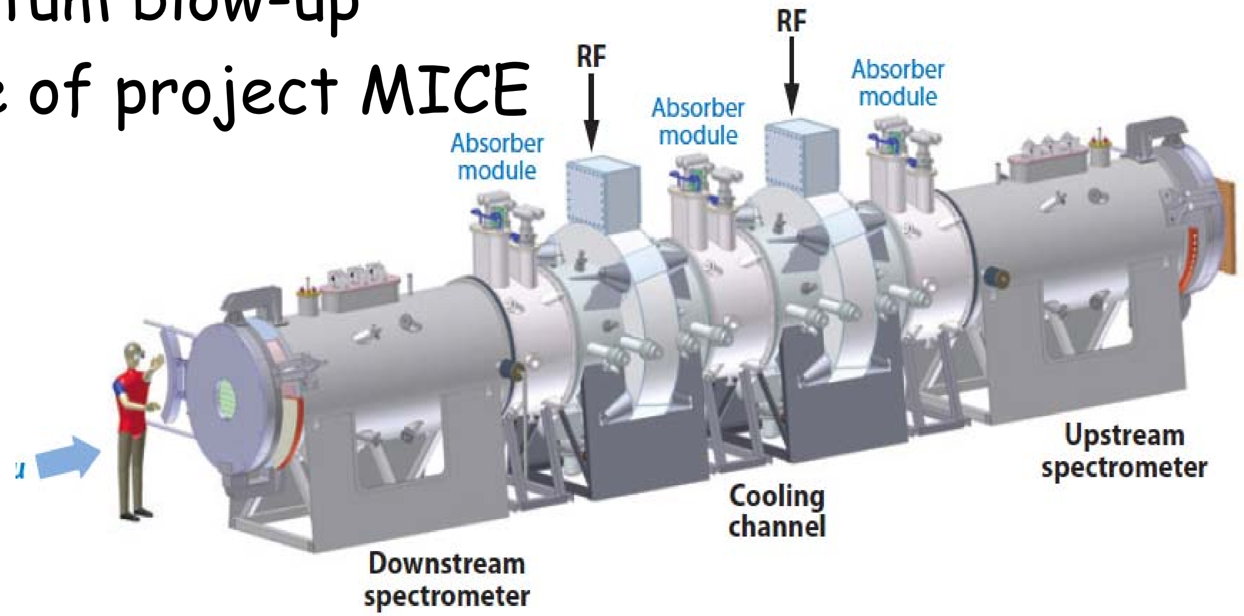
1.-Linear transverse pre-cooling



- 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



Hardware implementations of muon cooling

- A main muon cooling hardware implementation over the last decade has been the MICE experiment.
- So far only Step I has been completed
- Step IV was foreseen in 2016
- Step VI after 2019
- But in Aug 2014 the DOE T and M review board has reassessed the muon accelerator program MICE and its early closure

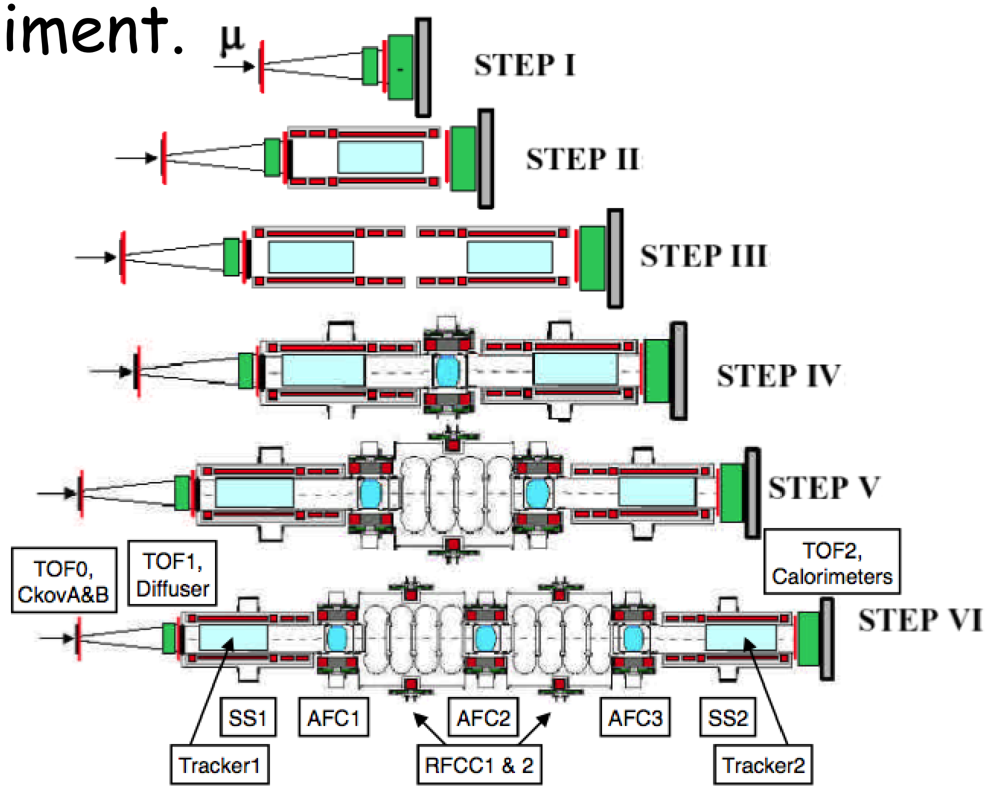


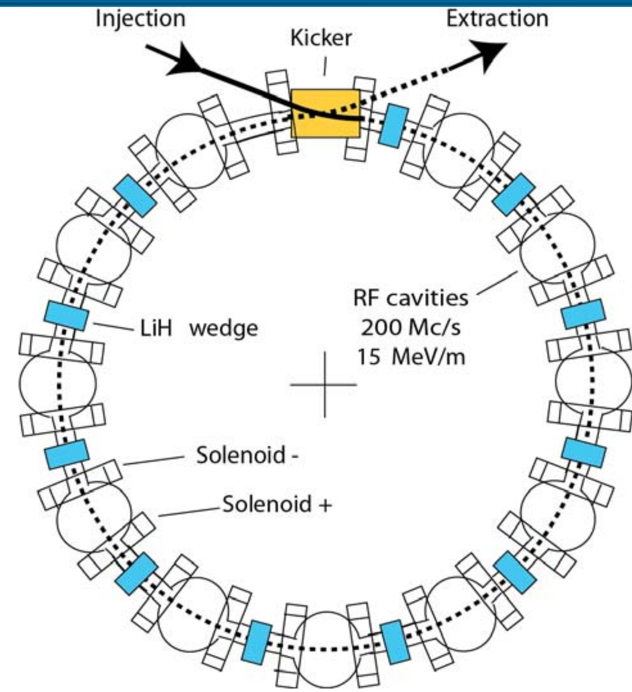
Figure 1: The six experimental steps as envisioned in the MICE proposal. Step I wa

In particular, the panel recommends to "realign activities in accelerator R&D with the P5 strategic plan. Redirect muon collider R&D and consult with international partners on the early termination of the MICE muon cooling R&D facility."

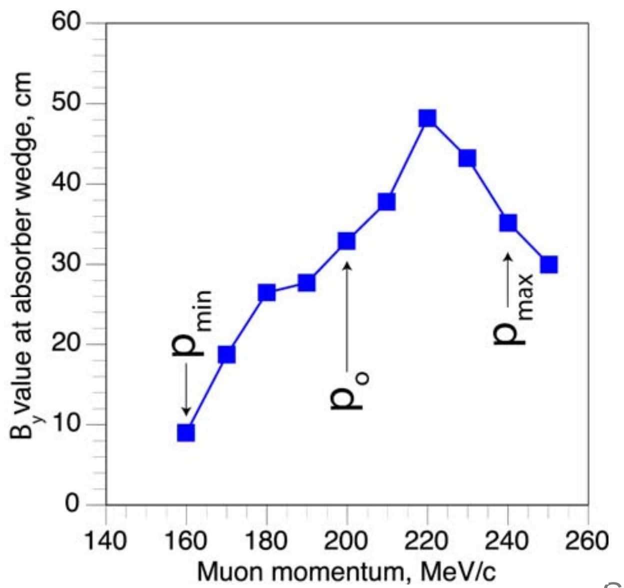
However a MICE like experiment is an essential part of an initial cooling experiment and it should be continued

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).

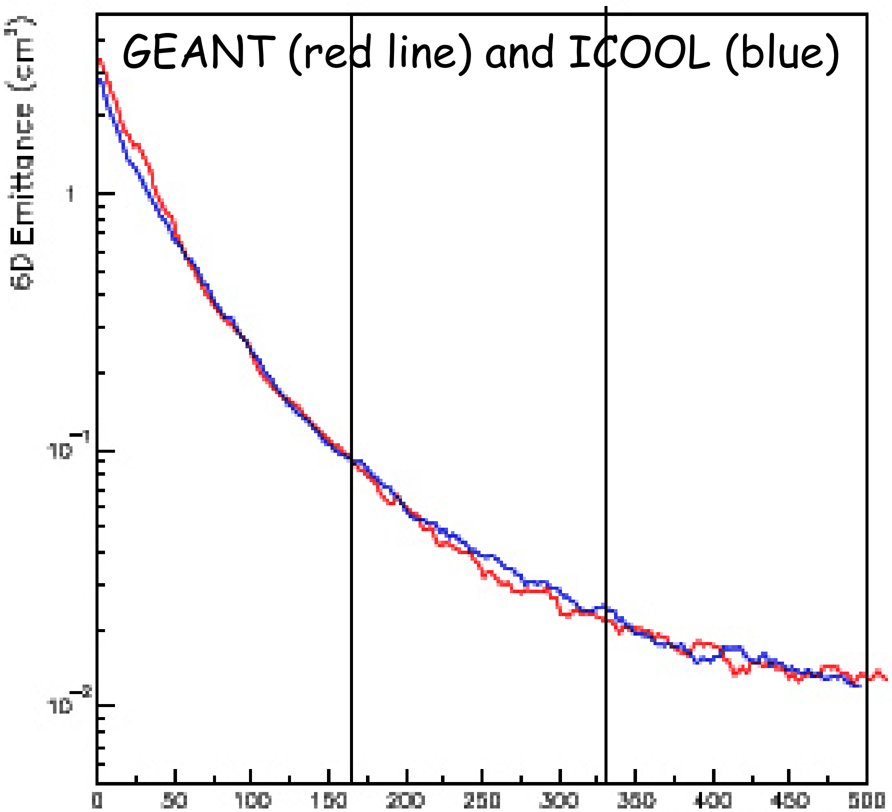


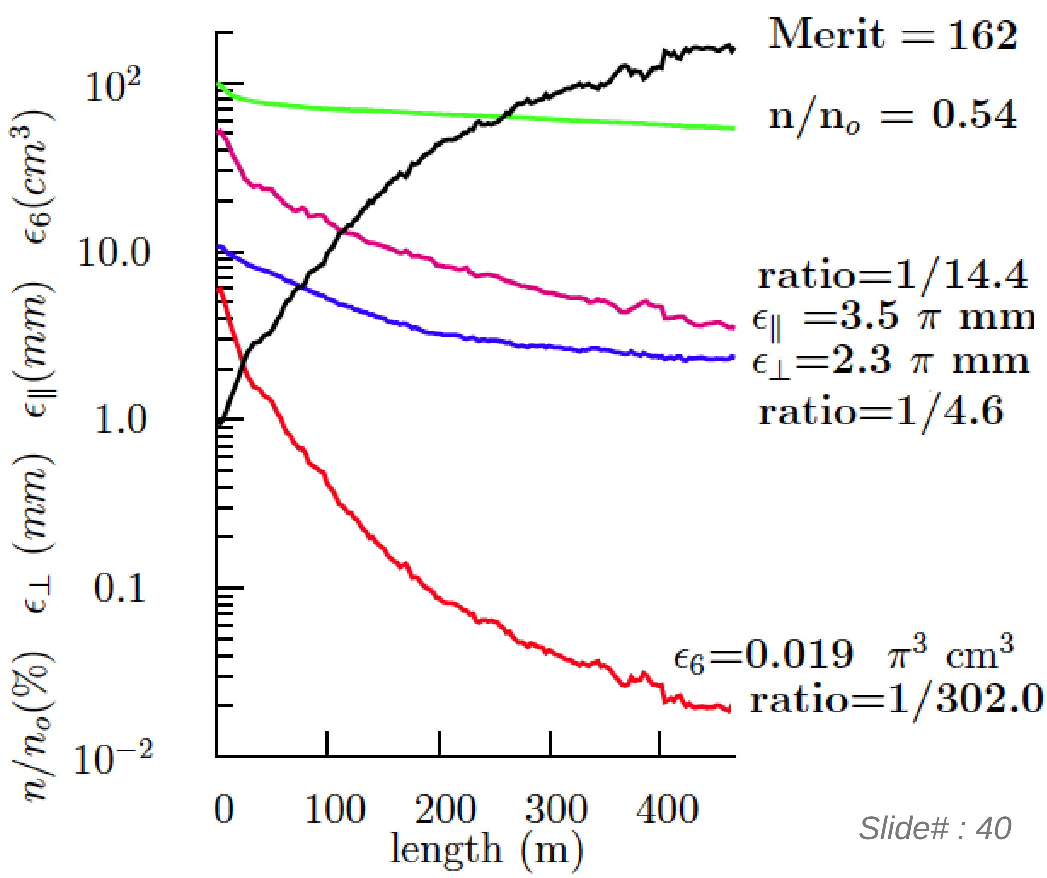
Circumference	33	m
Cells	12	
Max Bz	2.7	T
Coil Tilts	2.6	deg.
Ave Momentum	220	MeV/c
Min Trans. Beta	35-40	cm
Dispersion	8	
Wedge Material	H_2 or LiH	
Central thickness	28.6	cm
Wedge angle	100	deg
RF Cavities/cell	6	
Frequency	201.25	Mhz
Gradient	12	MV/m



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.

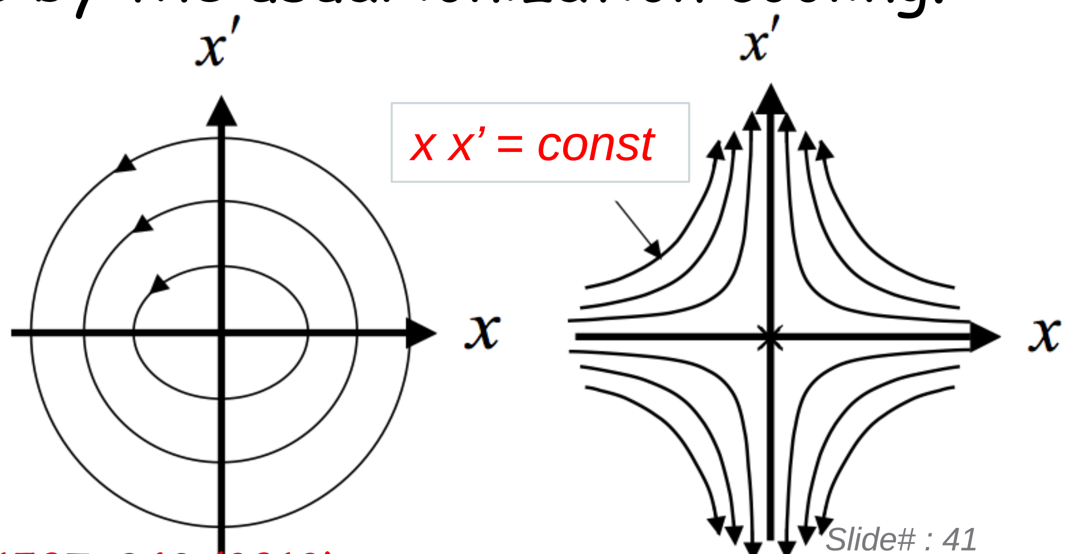




3.-PIC, the Parametric Resonance Cooling of muons

- 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.

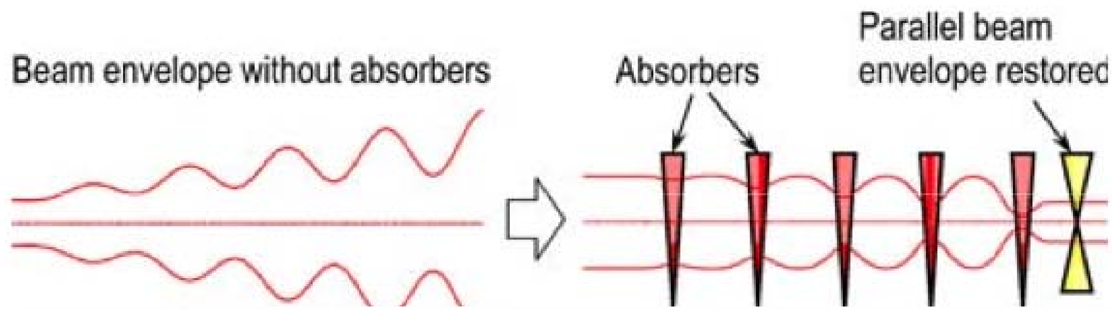
LEFT ordinary oscillations
RIGHT hyperbolic motion
induced by perturbations
near an (one half integer)
resonance of the betatron
frequency.

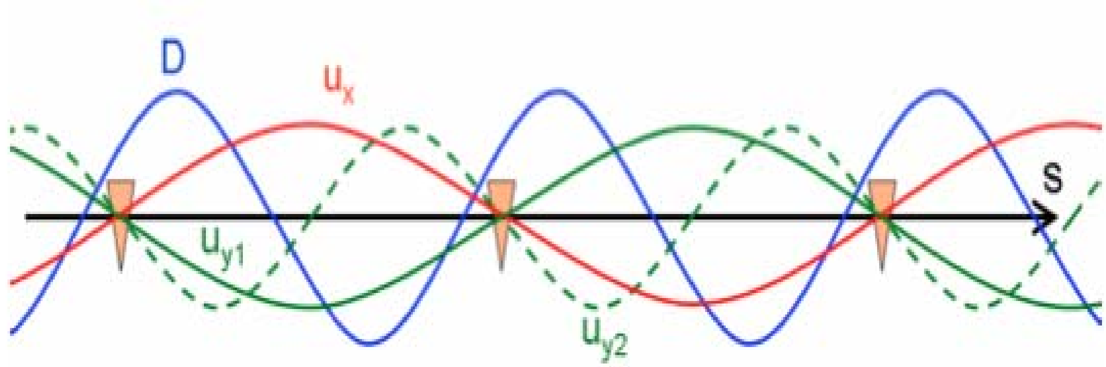


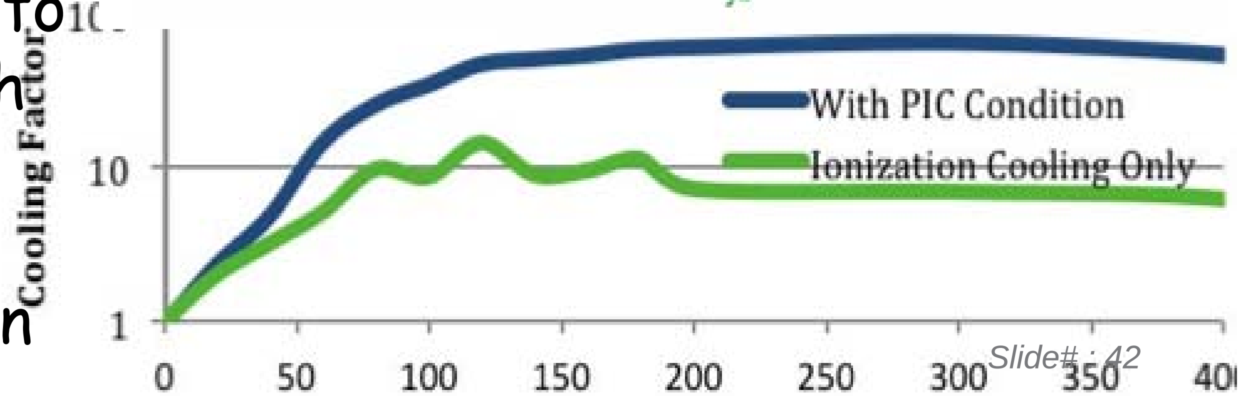
V. S. Morozov et al, AIP 1507, 843 (2012);

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

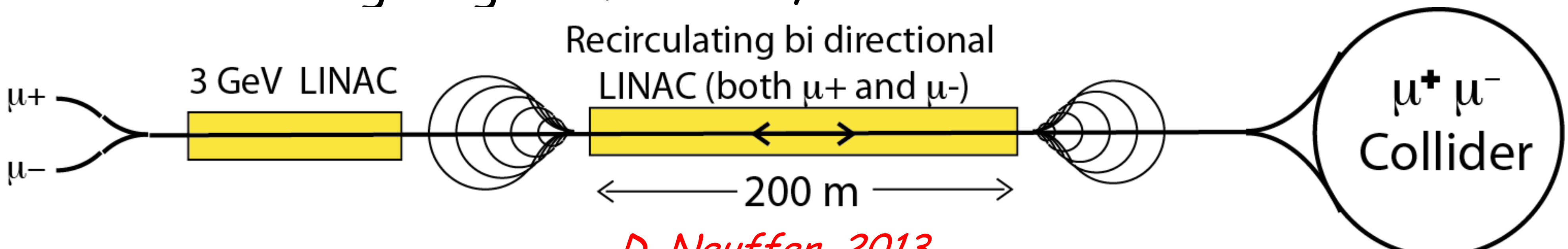






Bunch acceleration to 62.5 GeV

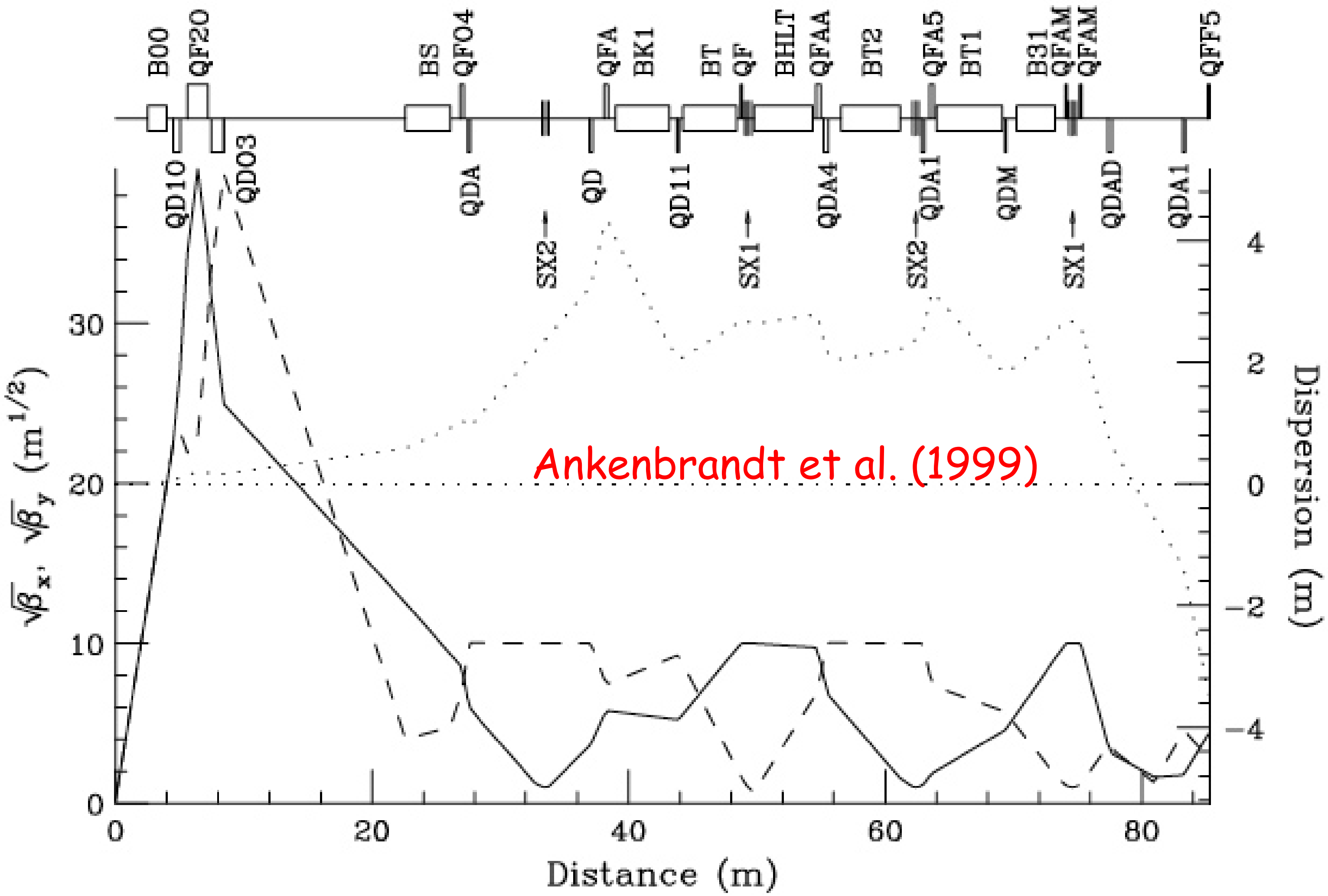
- In order to realize a Higgs Factory at the known energy of 126 GeV, an acceleration system is progressively rising the energy of captured muons to $m_{H^0}/2$
- Adiabatic longitudinal Liouvillian acceleration to p_f= 62.5 GeV/c.
- Both μ^+ and μ^- are accelerated sequentially in the same LINAC with 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 $\sqrt{s}$ ≈ 1 TeV will require a recirculating length of 1.6 km, still well within CERN site.



D. Neuffer, 2013

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 5×10^{32} cm^{-2} s^{-1} is achieved with 1×10^{12} μ/bunch.
- The SM Higgs rate is ≈ 44'000 ev/year in each detector.
- An arrangement with at least two detector positions is reccomended

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**	

Determining the muon energies with extreme precision

- The extremely narrow Higgs width is unprecedented
- At each pulse, the energy of the muons has to be determined with an accuracy of the order of $\sigma_E/E \approx 3 \times 10^{-5}$.
- A method has been described by Raja and Tollestrup in 1998.
  - Electron energy polarized from μ decay; Pe ≈~25% → 10%.
  - Electron energy in the lab given by $< E_{lab} >= \frac{7}{20} E_\mu (1 + \frac{\beta}{7} \hat{P})$
  - Polarization precess each turn is $\omega = \gamma(g-2)/2 \times 2\pi$
  - the total energy E(t) due to the decay electrons observed during turn t in the e.m. calorimeter will have the expression

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

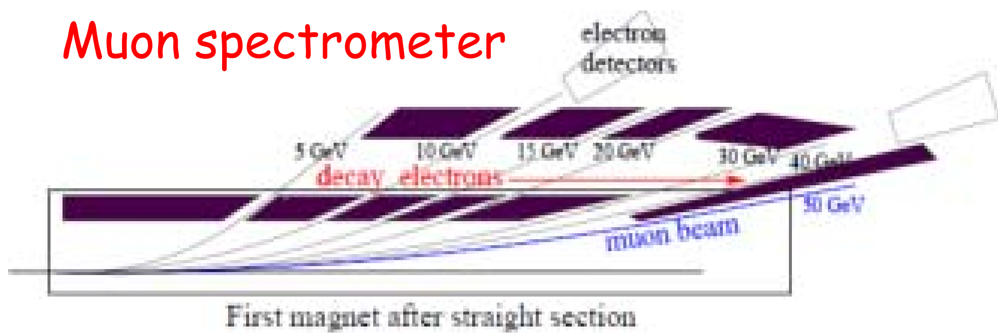
  - The electron-rate is extremely high (≈ 10^5 ev/pulse)
  - Since frequencies can be measured very precisely, E(t) and δE can be measured to a few hundred keV at each pulse

Raja and Tollestrup (1998) Phys. Rev. D 58 013005

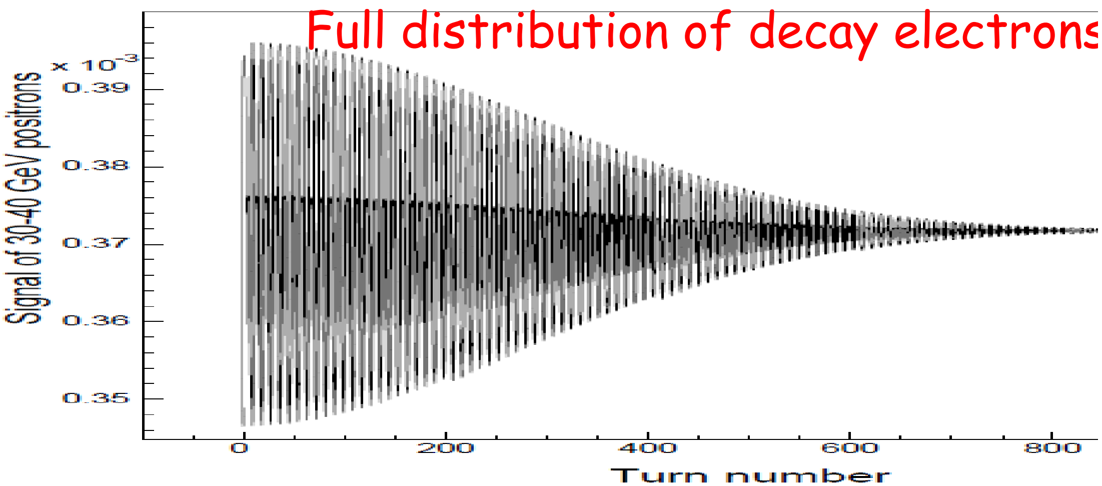
The muon decay spectrometer

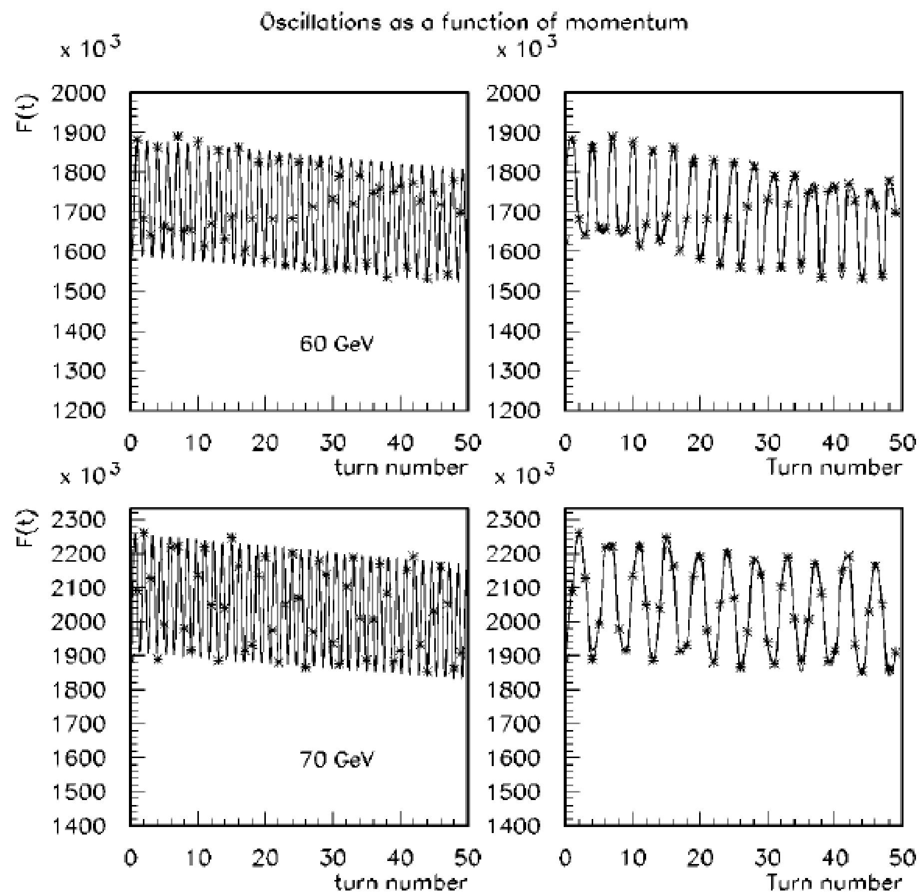
- Electron rate is observed with a transverse B field of 4 T.
- Simulated data and the fitted function at integer values of the turn number for 50 turns for 60 GeV/ c and 70 GeV/c μ's.

Muon spectrometer



Full distribution of decay electrons

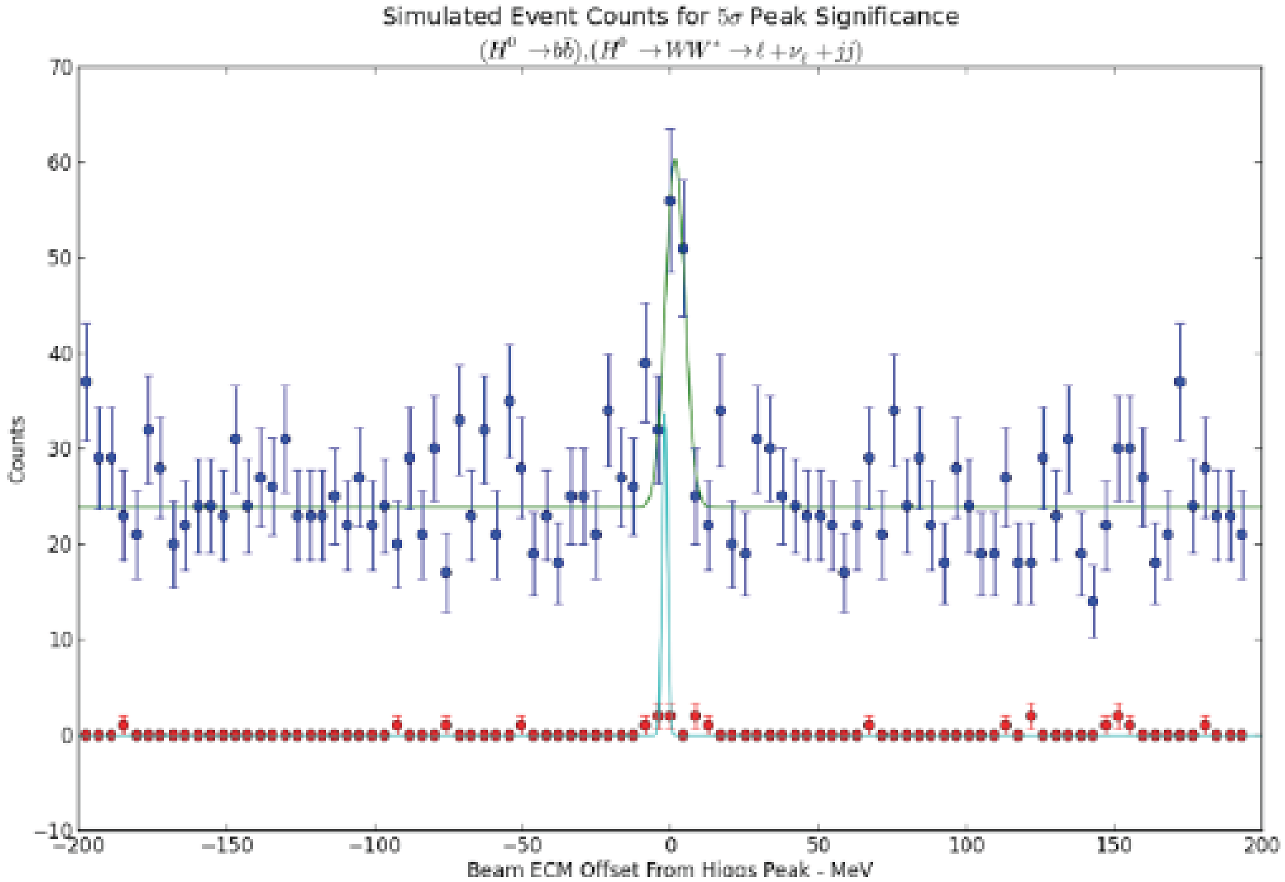




P = 0.26 is assumed with a fractional fluctuation of 0.5 x 10^{-2} per point

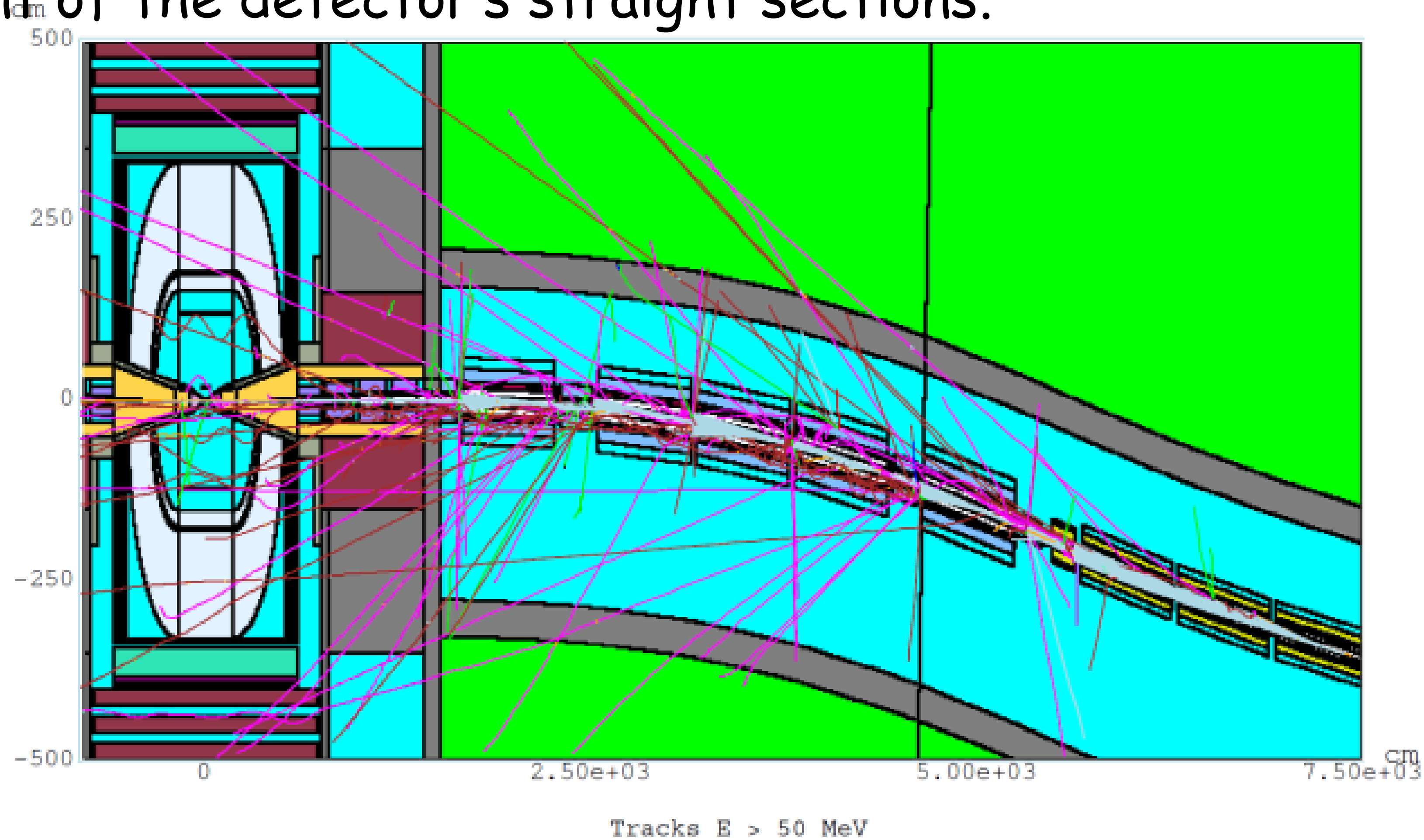
Finding the location of the Higgs

- 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 1.7×10^{31} luminosity.



Muon related backgrounds

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



Drozhdin, Mokhov et al.

The muon Higgs collider:

- **Advantages**
  - Large cross section σ ($\mu^+\mu^- \rightarrow h$) = 41 pb in s-channel resonance, compared to $e^+e^- \rightarrow ZH$ 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

The next step: the realization of the Initial Cooling Experiment

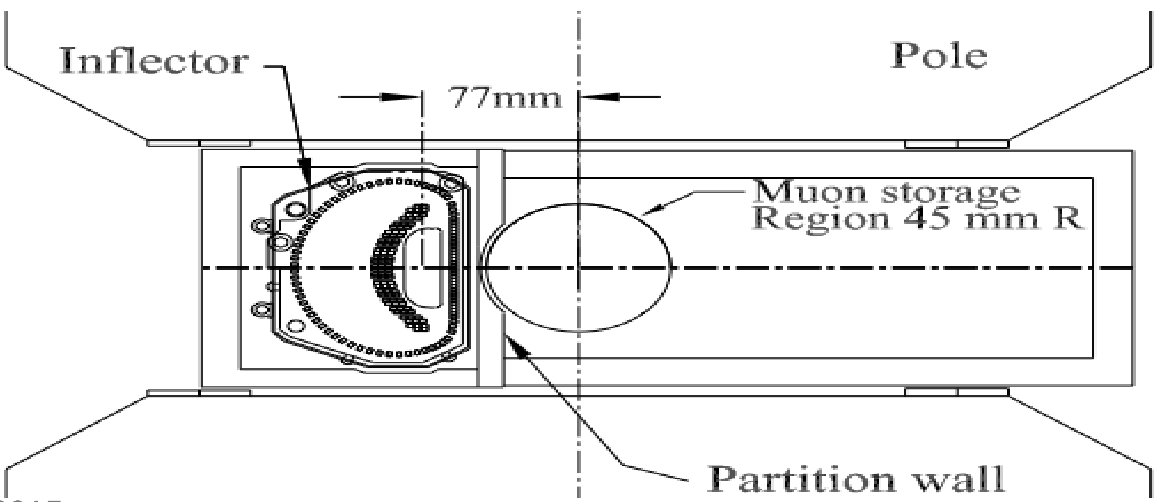
- Physics requirements and the studies already undertaken with muon cooling suggest that a next step, prior to but adequate for a specific physics programme *could be the practical realization of an appropriate cooling ring demonstrator.*
- Indicatively this corresponds to the realization of unconventional *small 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 proof 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.

Early description of the cooling experiment

- A cooling ring is preferable to an open structure
- In order to introduce a first major reduction in the transverse and longitudinal emittances:
  - 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.
  - Wedge shaped absorbers in order to ensure the Robinson's law on sum of damping decrements.
- The initial pion beam is produced by a short (≈1-2 ns) proton bunch. Pions decay into a appropriate muon beam which is injected in the ring. The beam line is used to select the muon beam with an suitable divergence and with adequate dp/p.
- The present description is based on the CERN-PS although another accelerator (FNAL booster, SIN, *etc.*) might be used.

Muon beam injection

- The method of muon injection closely follows the well known g-2 experiments at CERN, BNL and FNAL, although at a much lower muon momentum. An appropriate inflector has been used in order inject the muon beam into the ring.
- The optimally stored momentum selected is ≈ 250 MeV/c and the injected momentum spread may be of order of few % r.m.s.
- Alternatively the spontaneous π/μ backward decays of a pion beam traversing the ring straight section could be used to capture backward decaying muons without the need of a kicker.



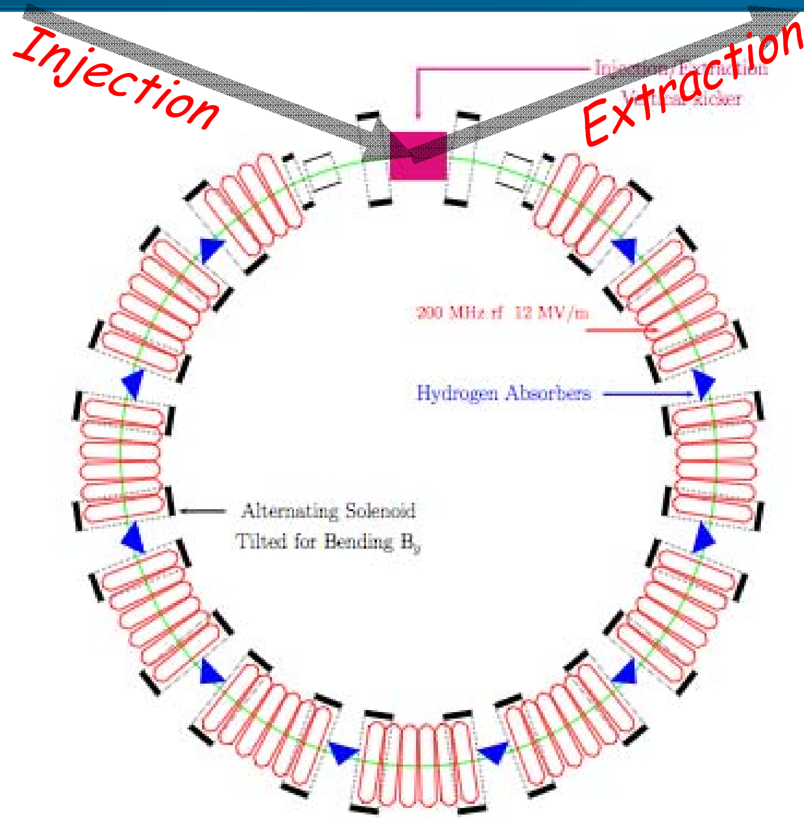
Example of the inflector of the g - 2 experiment

Some examples: The RFOFO Ionization Cooling

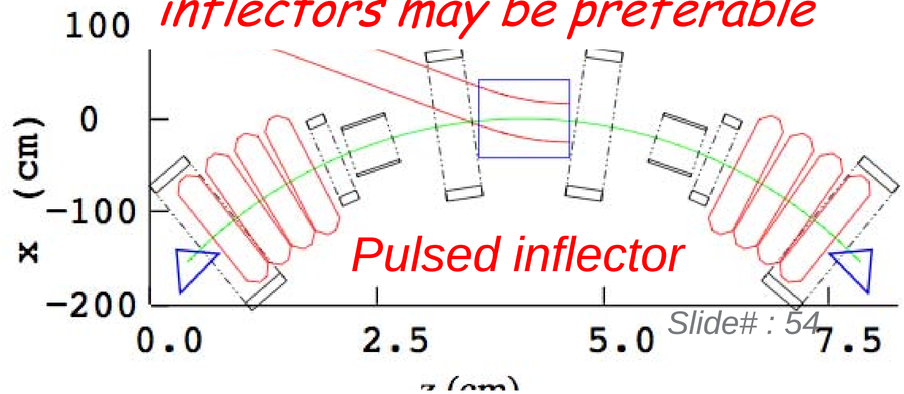
- The design by Palmer *et al.* is based on solenoids tilted in order to ensure also bending. The H absorbers are wedge shaped to ensure longitudinal cooling.

arXiv:physics/0504098 v1 14 Apr 2005

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

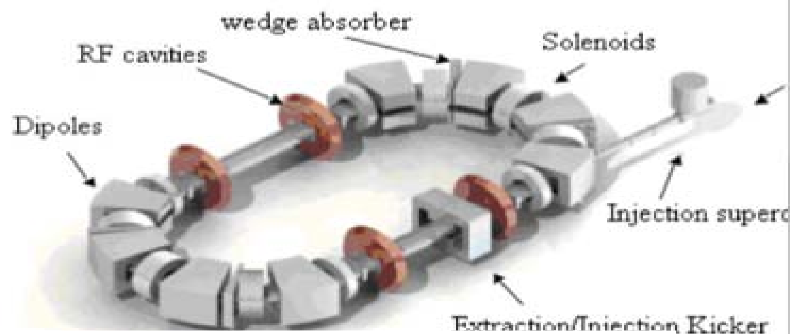


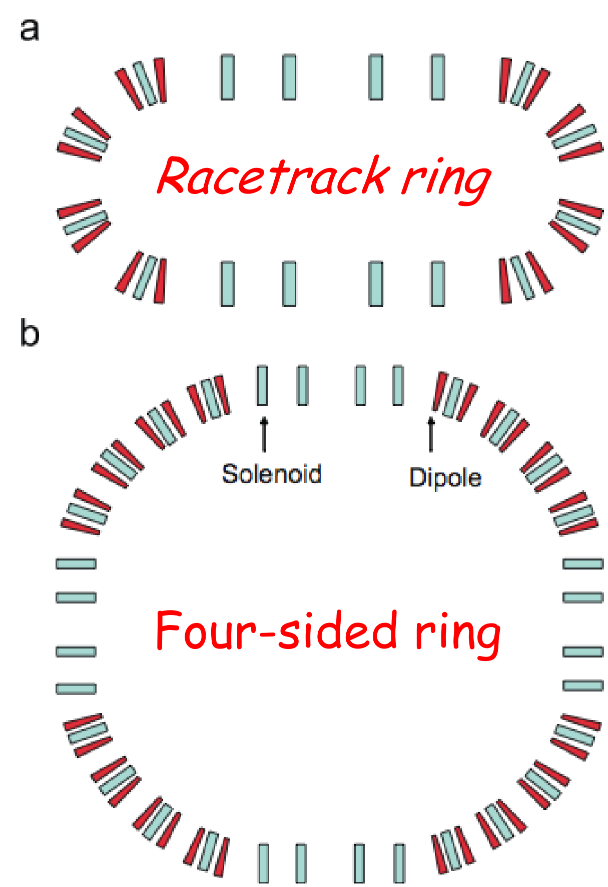
Two separate, 180 apart injection and extraction pulsed inflectors may be preferable*



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.



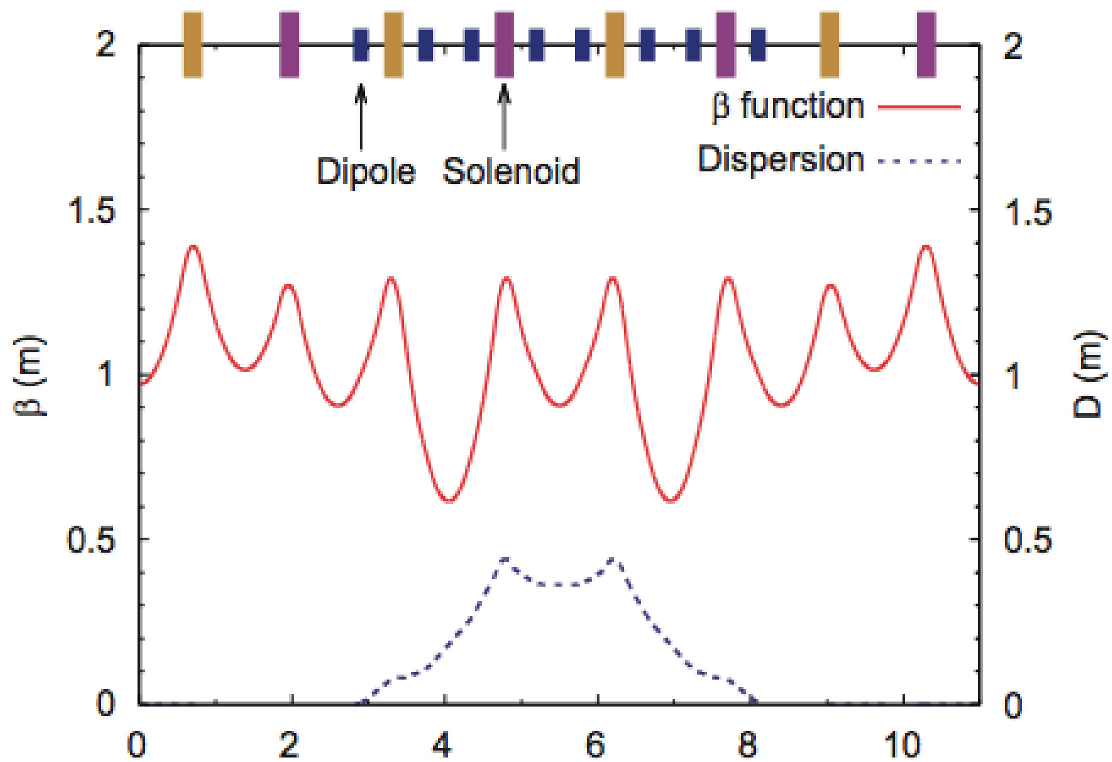


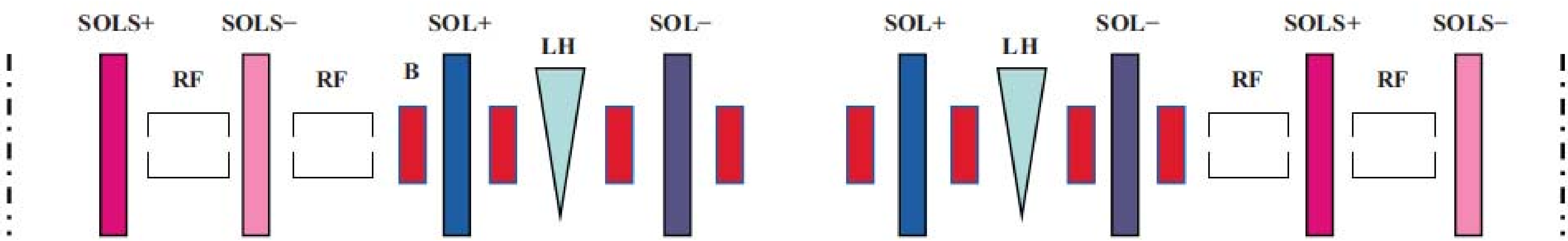
Parameters of the four-sided and achromatic ring cooler.

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

An achromatic cooling ring

- Arcs are achromatic both horizontally and vertically. The dispersion is zero in the straight sections between the arcs.
- The four-sided ring has four 90° arcs with 8 dipoles separated by alternately oriented solenoids (SOL+ and SOL-).





Expected ring performance

- Starting from a typical initial emittance of about 20 (π) mm rad tranversally and longitudinally, the 3D cooled emittance should be demonstrated in agreement with calculations when reaching the equilibrium asymptotic ring situation.
- During the cooling, an appropriate number of standard pickup electrodes should be used in order to observe the beam signals.
- The cooled beam should then be extracted with a second kicker. The transverse emittances and/or the momentum spread are measured by an appropriate beam analysis transport.
- The behavior under PIC cooling conditions may be separately tested in the same ring structure but at a very different tuning point near the semi-integer resonances.
- The injected beam conditions should correspond to the requirements of the PIC conditions, namely a much narrower transverse angular spread and a small momentum spread as expected after the first cooling in the final setup.

- 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 a resonant 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 emittance, hence about one order of magnitude of increment is expected from PIC.

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^0 scalar in the s-state, in analogy with the two steps of the Z with the pbar-p and LEP programmes and where the mass, total and partial widths of the H^0 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 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 ν factory.

A proposal for discussion:

- It is proposed to develop an international team with the aim of designing, financing and constructing the above described cooling muon ring for the Initial Cooling Experiment.
- A campaign of extensive measurements, hopefully confirming the expectations of muon cooling theory could then be performed, starting for instance with a single proton bunch and the CERN-PS accelerator.
- Alternatively, this experiment might be realized either at the Fermilab Booster, at the BNL-AGS or even elsewhere (UK, Switzerland).

Thank you !