Muon cooling for a Higgs Factory at CERN ?

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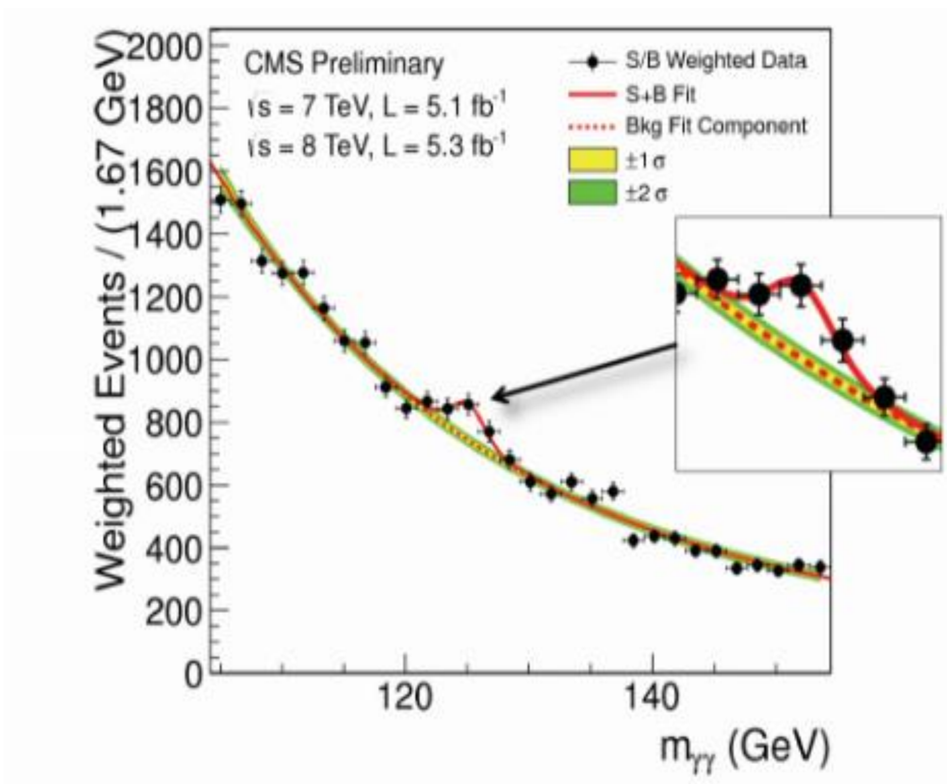
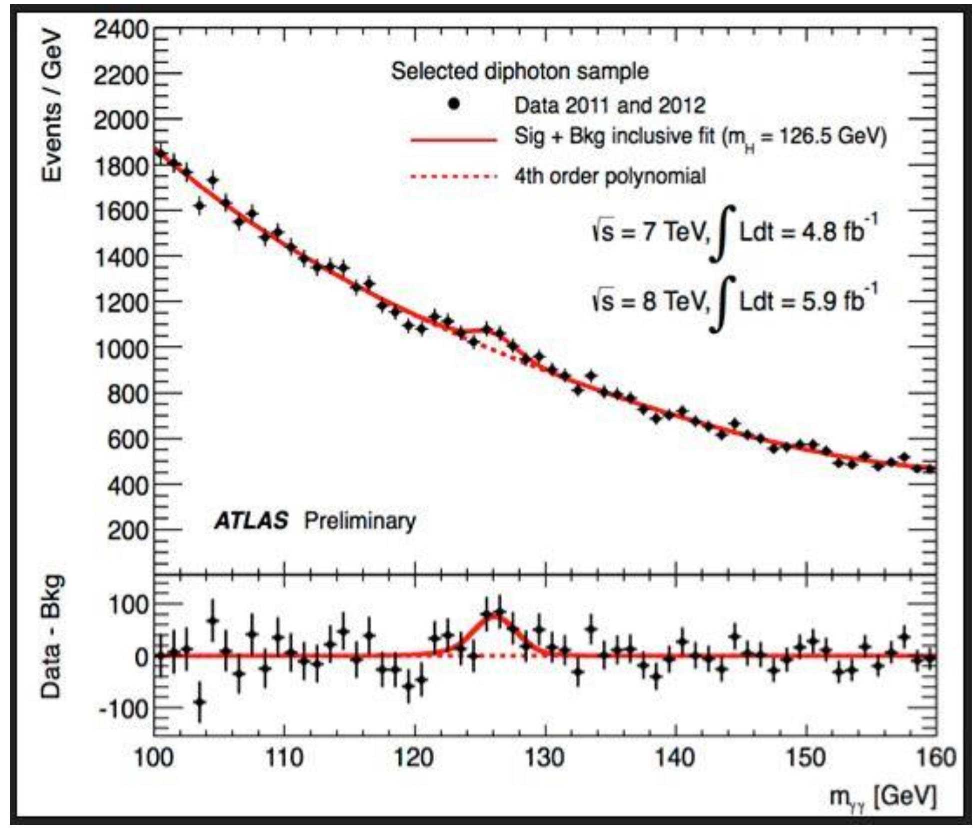
The LHC observation of the Higgs at 125 GeV

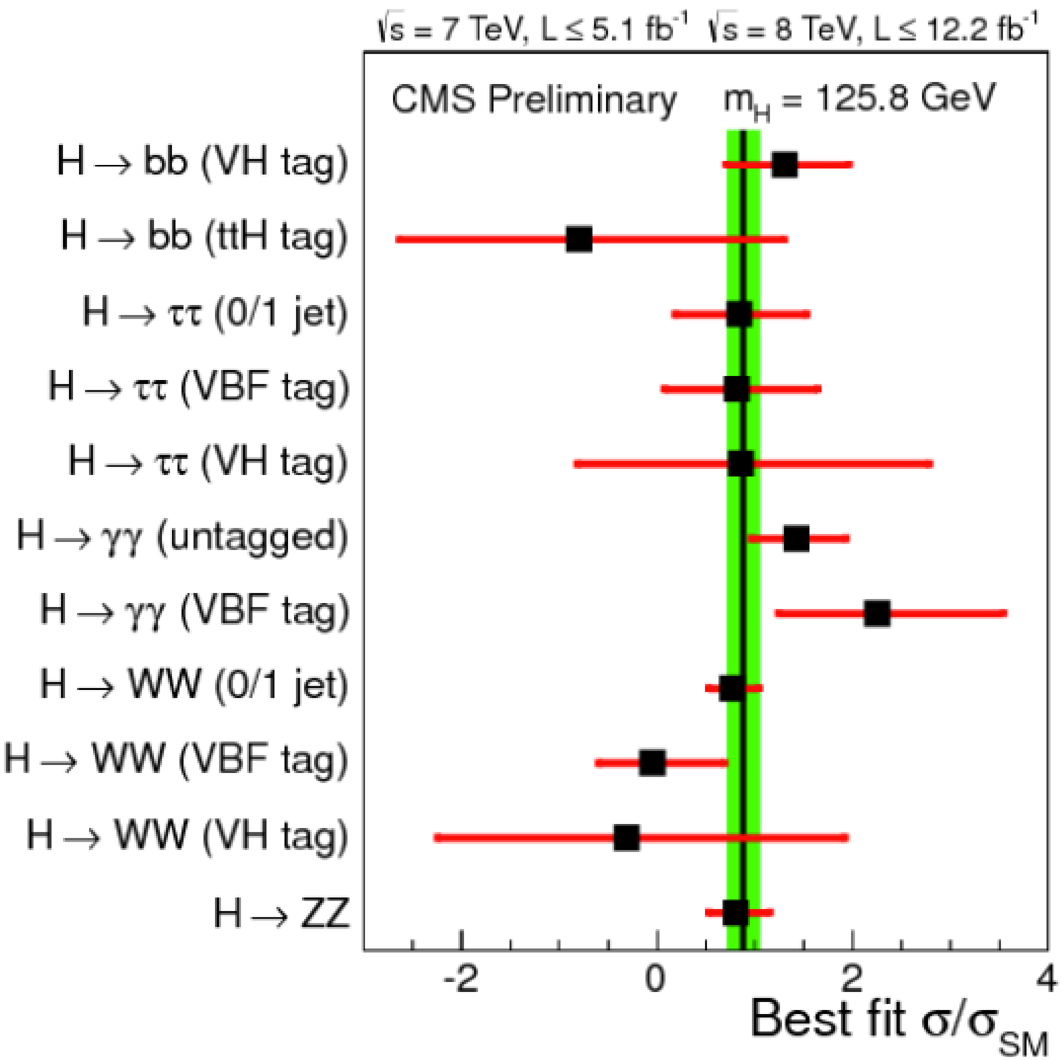
- CMS and Atlas have observed a narrow line of high significance at about 125 GeV mass. compatible with the Standard Model Higgs boson.
  - ATLAS: $m_H = 125.5 \pm 0.2$ (stat) $\pm$ 0.6 (sys) GeV
  - CMS: $m_H = 125.8 \pm 0.4$ (stat) $\pm$ 0.4 (sys) GeV
- Their data are consistent with fermionic and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

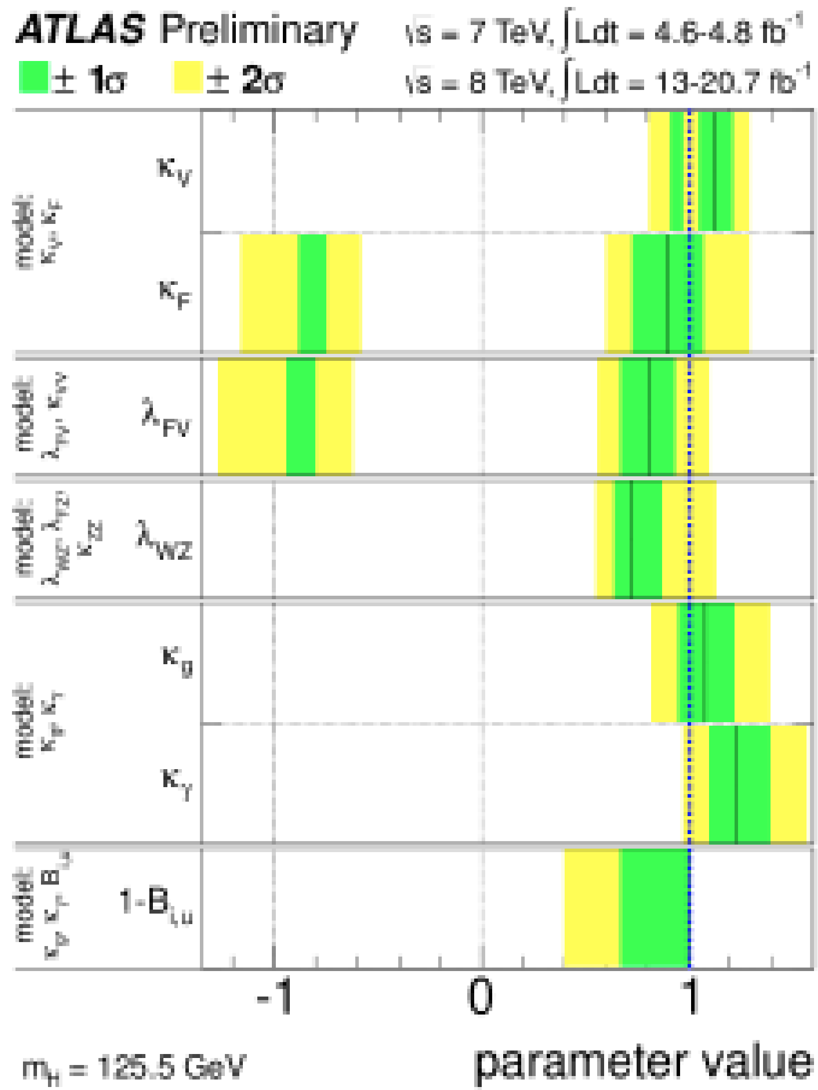
The early dscovery story





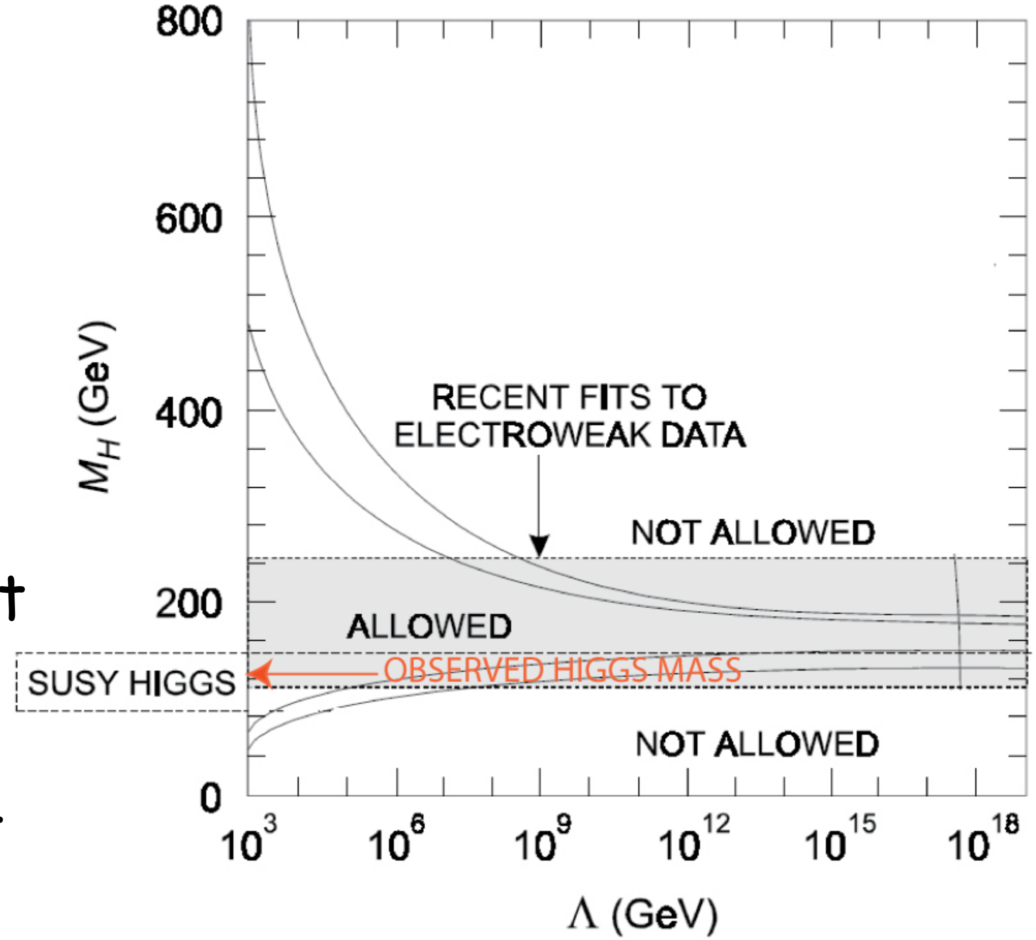
Experimental results





The myth of symmetry breaking at TeV scale

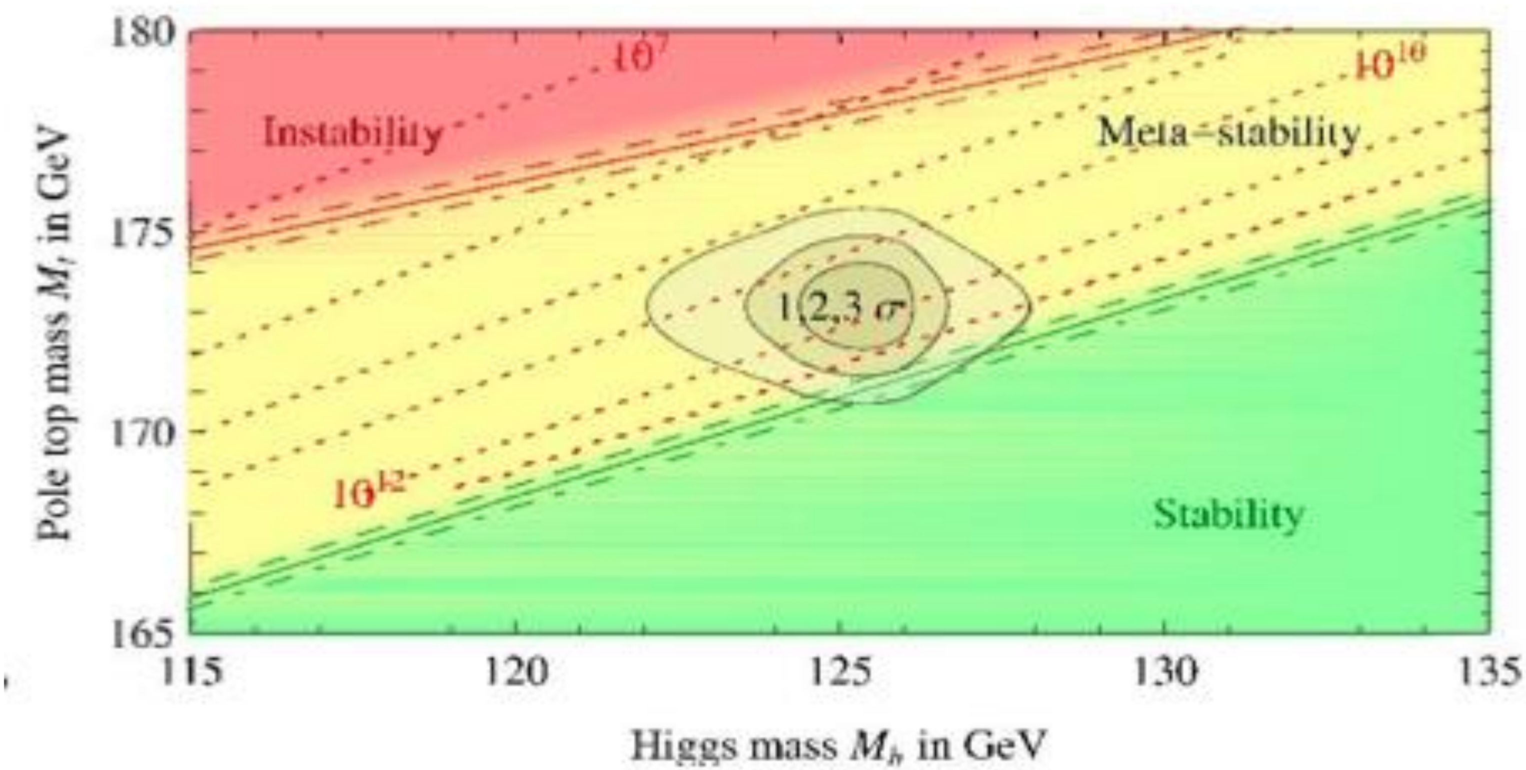
- It had been widely argued by many very influential theorists that "new physics" must also necessarily appear at the TeV scale, one of the the main reasons for arguing for the *necessity of a nearby SUSY*.
- This was based on the argument that the otherwise divergent self-interaction of the Higgs sector does require a cutoff at the TeV scale.



- However, this does not hold for the recently observed Higgs mass of 126 GeV, since stability conditions may allow without novelties a legitimate cutoff even up to the Planck Mass

Present situation

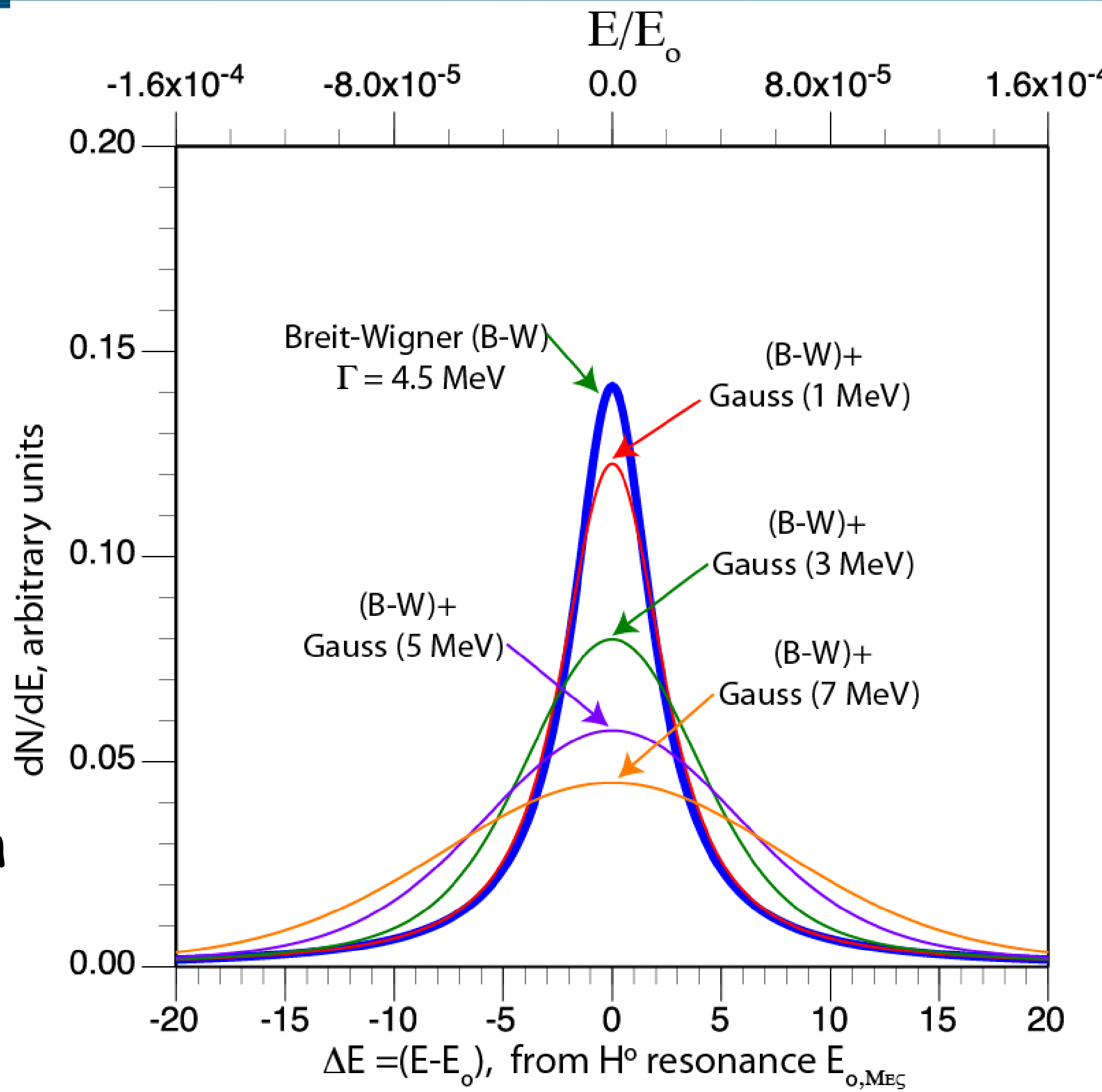
- For these values, the electroweak vacuum is claimed metastable, but with a lifetime longer than the age of the Universe.
- The Standard Model can be valid without new physics all the way up to the Planck scale. *Thus, there may be only one standard model (SM) Higgs and no need for the "no fail theorem".*



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

The Higgs width and the Standard Model

- In particular, 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: the SM prediction is only ≈4 MeV, a formidable task!
- 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.



A very demanding resolution R ≈ 0.003% is required

The future of LHC/Higgs

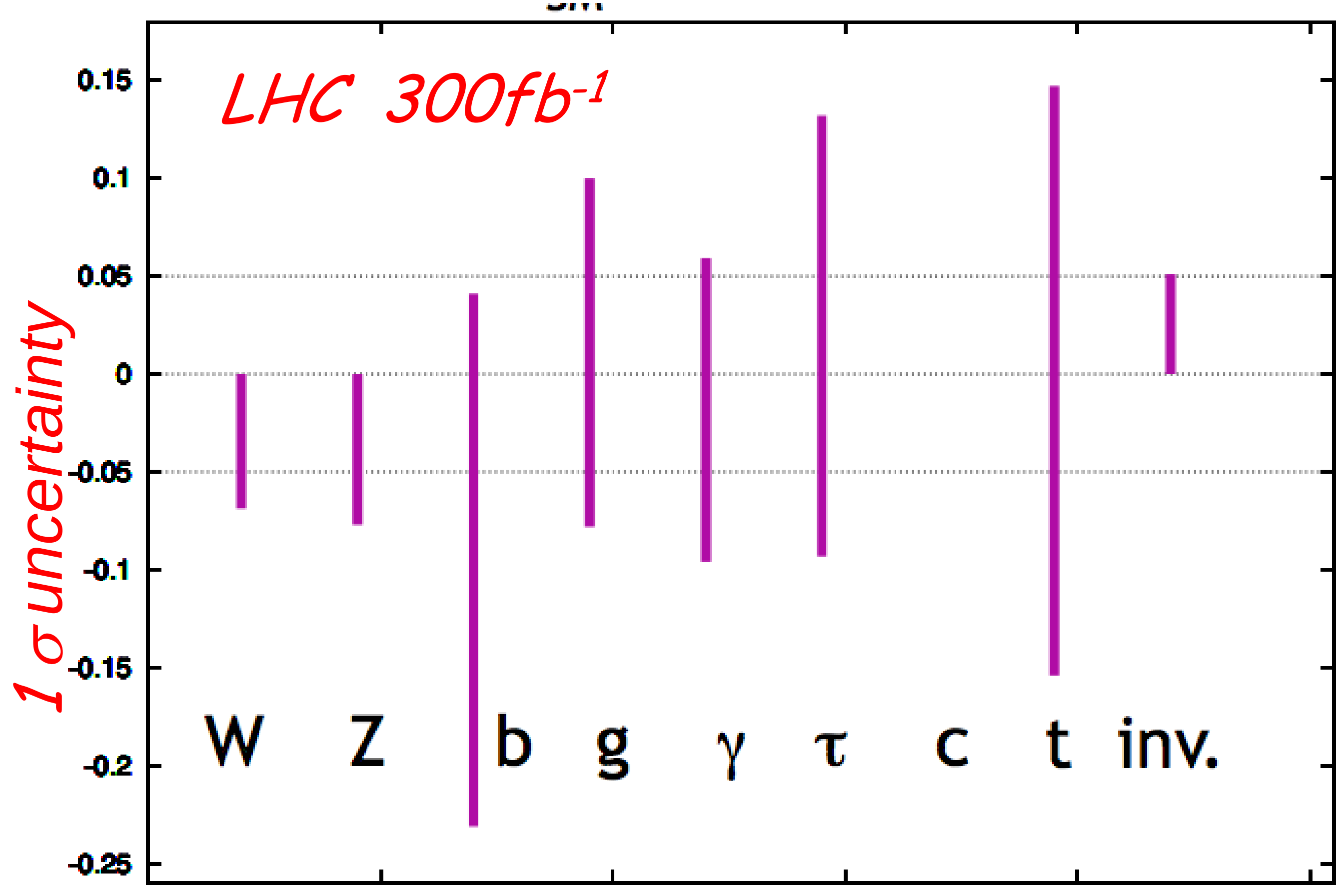
- During the next twenty years (!) CERN plans to pursue the hadronic production of the Higgs related sector and of the possible existence of SUSY. The existence of additional Higgs particles is assumed as unlikely within the LHC energy range.
- Therefore studies will concentrate on the properties of the already discovered mass. The High Luminosity-LHC will already be a sort of "Higgs factory", able to perform relatively accurate (typically $\pm$ 10%) measurements.
- There are plenty of opportunities to check the couplings since a 125 GeV SM Higgs boson has several substantive branching fractions : **B (bb)** 60%, **B (WW)** 20%, **B (gg)** 9%, **B** ($\tau\tau$) 6%, **B (ZZ)** 3%, **B (cc)** 3%, etc.
- **B ($\gamma\gamma$)** with 0.2% is also substantive due to the high mass resolution and relatively low background.

The future of the LHC

- 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.

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

- 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.



Unambiguous discovery requires 5 σ

The need of a better precision

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

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

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

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

SUSY tan(β)>5

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

Composite Higgs

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

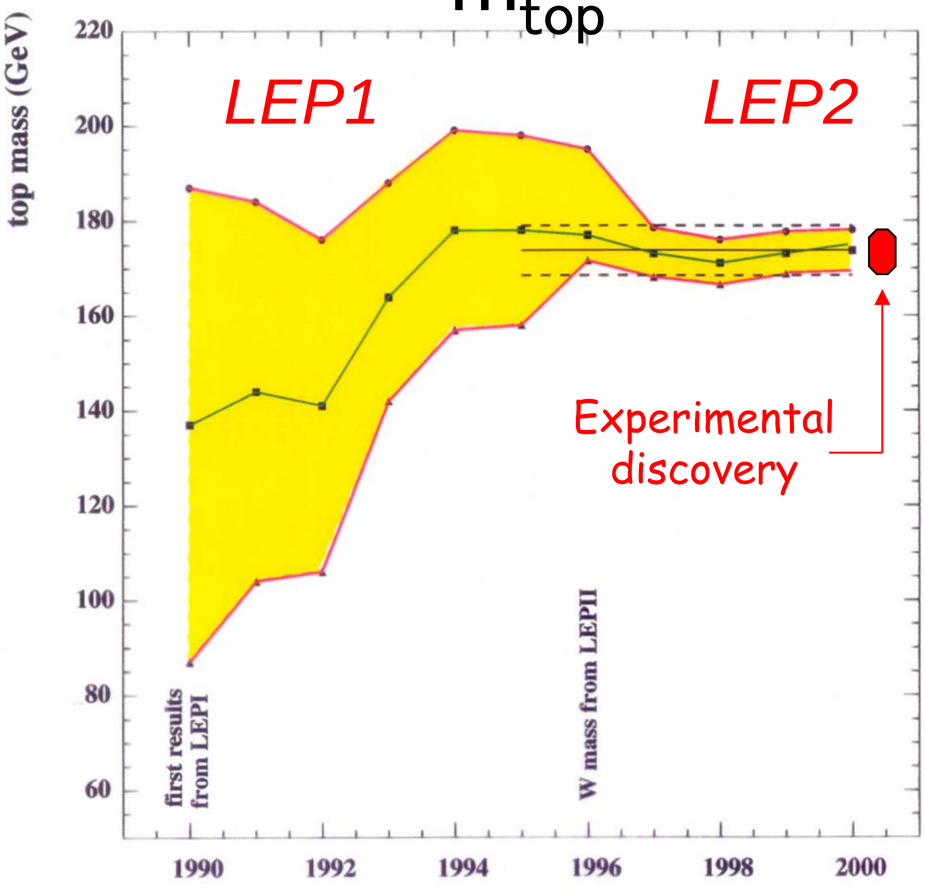
Top partners

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

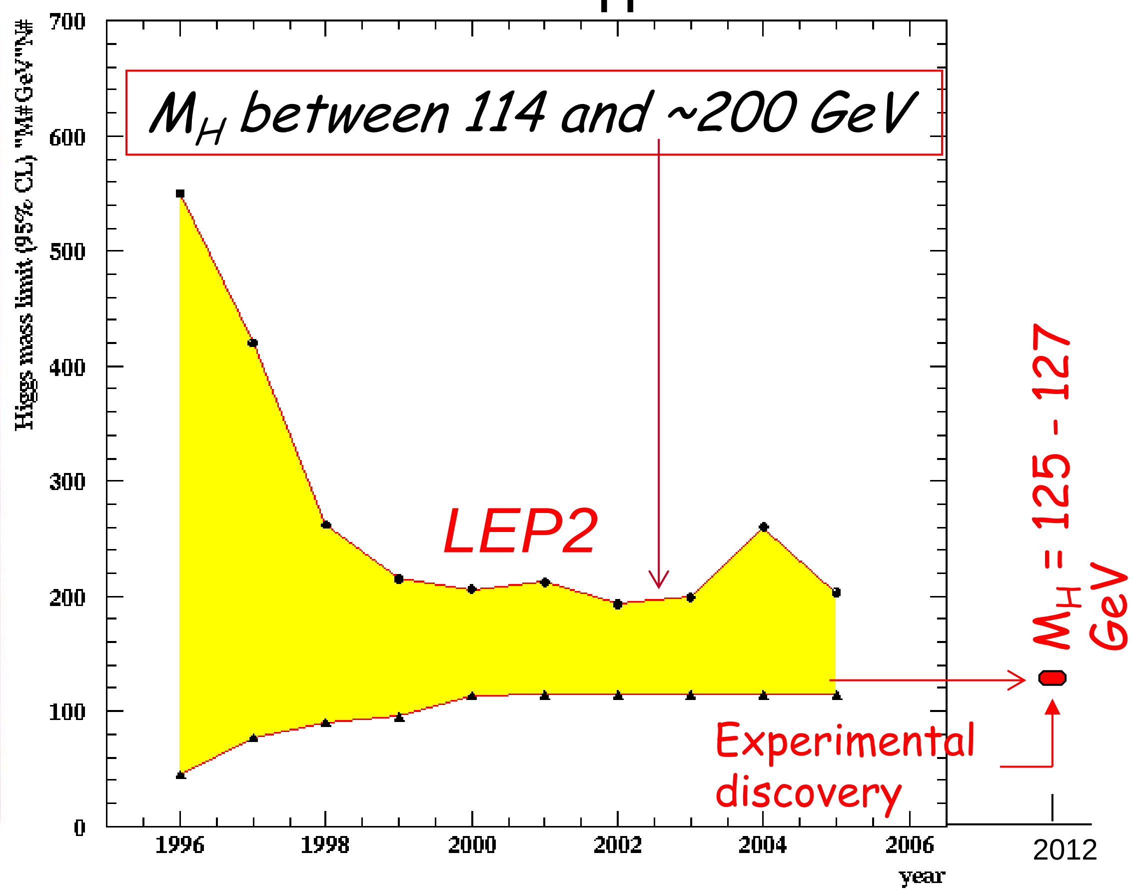
arXiv:1206.3560v3 [hep-ph] 27 Sep 2012

Predictive power of theory: The previous Z case

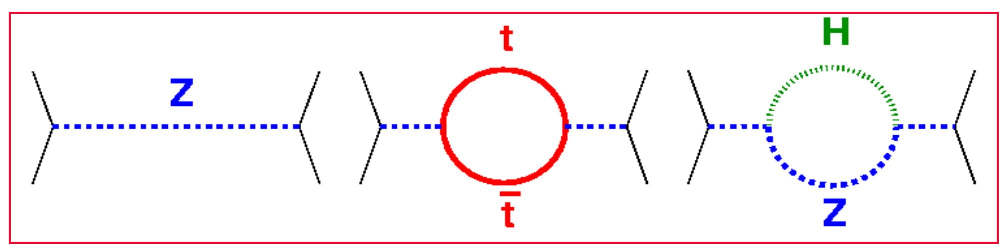
m_{top}



m_H



- Higher order, renormalizable experimental corrections are used to predict existence beyond data (virtual graphs).



Studying the Higgs beyond LHC ?

- The scalar sector is definitely one of the keys to the future understanding of elementary particle physics.
- After the p-pbar discovery of the Z^o , its detailed studies at LEP and SLAC 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.
- *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.

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

- Two future alternatives are hereby compared:
  - 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 a Linear Collider of 33 km.
  - A $\mu^+\mu^-$ collider at L > 10^{32} and a H_o signal of ≈ 20'000 fb in the s-state. The collider radius is much smaller, only ≈ 50 m, but the novel "muon cooling" facility is necessary.

An adequate e^+e^- collider ?

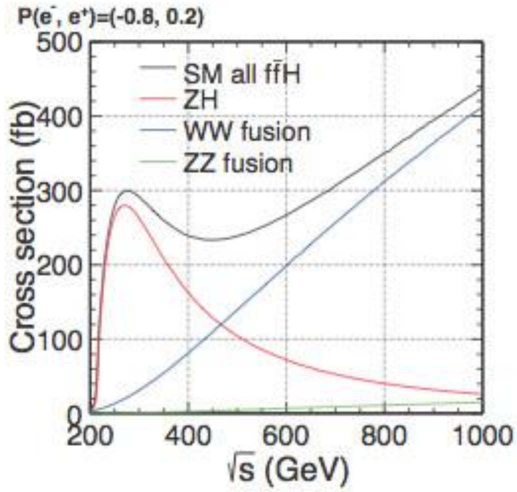
- The LEP2 parameters were $L = 1.25 \times 10^{32}$ $cm^{-2}s^{-1}$, a beam lifetime of 6.0 h, a current of 4 mA and $\beta^* = 1.5, 0.05$ m.
- The extension to the $e^+e^- \to H_0+Z$ requires $E_{cm} \geq 300$ GeV and >500 x its luminosity.
- Some recent possibilities for $E_{cm} > 200$ GeV.

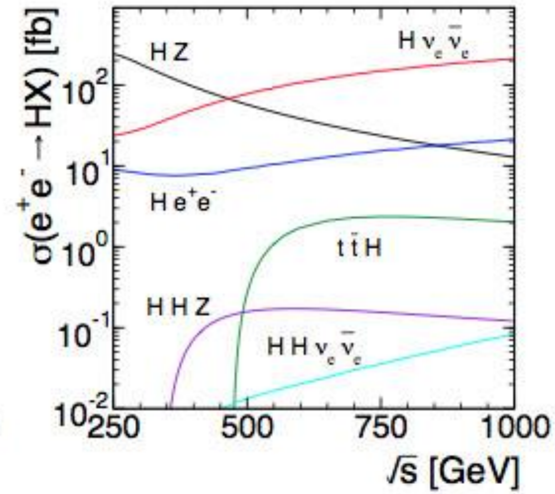
	LEP2	*LEP3*	*SuperTRISTAN*	*VLCC*	*CW250*	*Summers*	
Beam energy	*104.5*	120	200	200	250	120	GeV
Circumference	*26.7*	26.7	60	233	233	13.82	km
Bunch population	*57.5*	133.3	249.2	48.5	48.5	48.5	10^10
betay	*50*	1.2	0.32	10	0.6	0.6	mm
sigy	*3.536*	0.4243	0.0738	0.56	0.0201	0.0244	micron
sigz	*16.1*	3	1.4	6.67	6.67	6.67	mm
half.cross.angle	*0*	0	35	0	17	34	mrad
radiation loss/turn	*3.408*	6.99	18.5	4.42	10.8	9.7	GeV
radiation power (2beams)	*22*	100	74	100.7	100.7	98	MW
Tune shift (y)	*0.065*	0.13	0.155	0.18	0.23	0.2	
Equilibrium energy spread	*0.22*	0.232	0.196	0.096	0.120	0.236	%
Luminosity per IP	***0.0125***	**1.33**	**5.2**	**0.88**	**9.7(4.8)**	**4.4(2.2)**	**10^34**

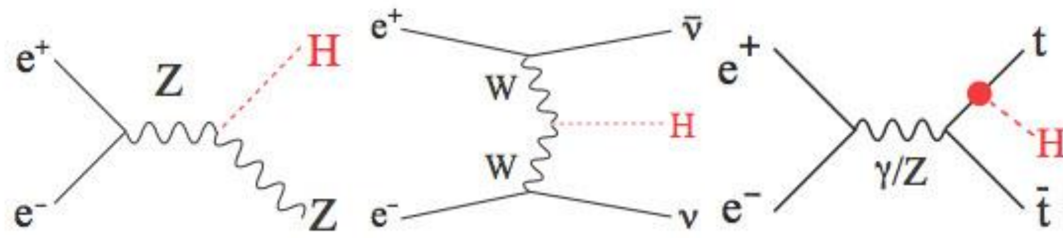
1 fb= 10^{-39} cm^2

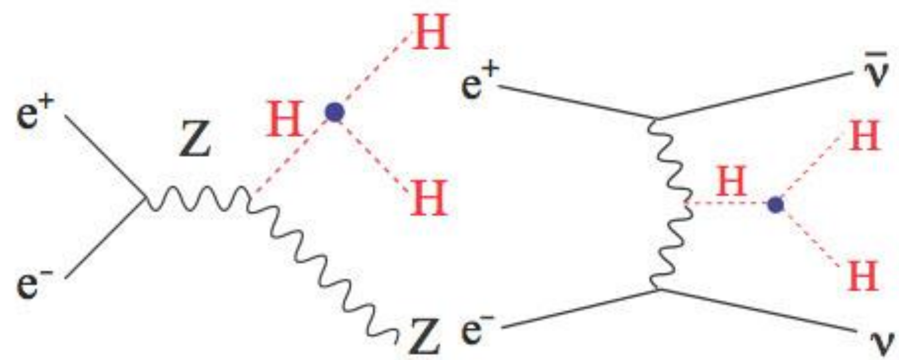
Production cross sections at the e+ e- collider

- 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







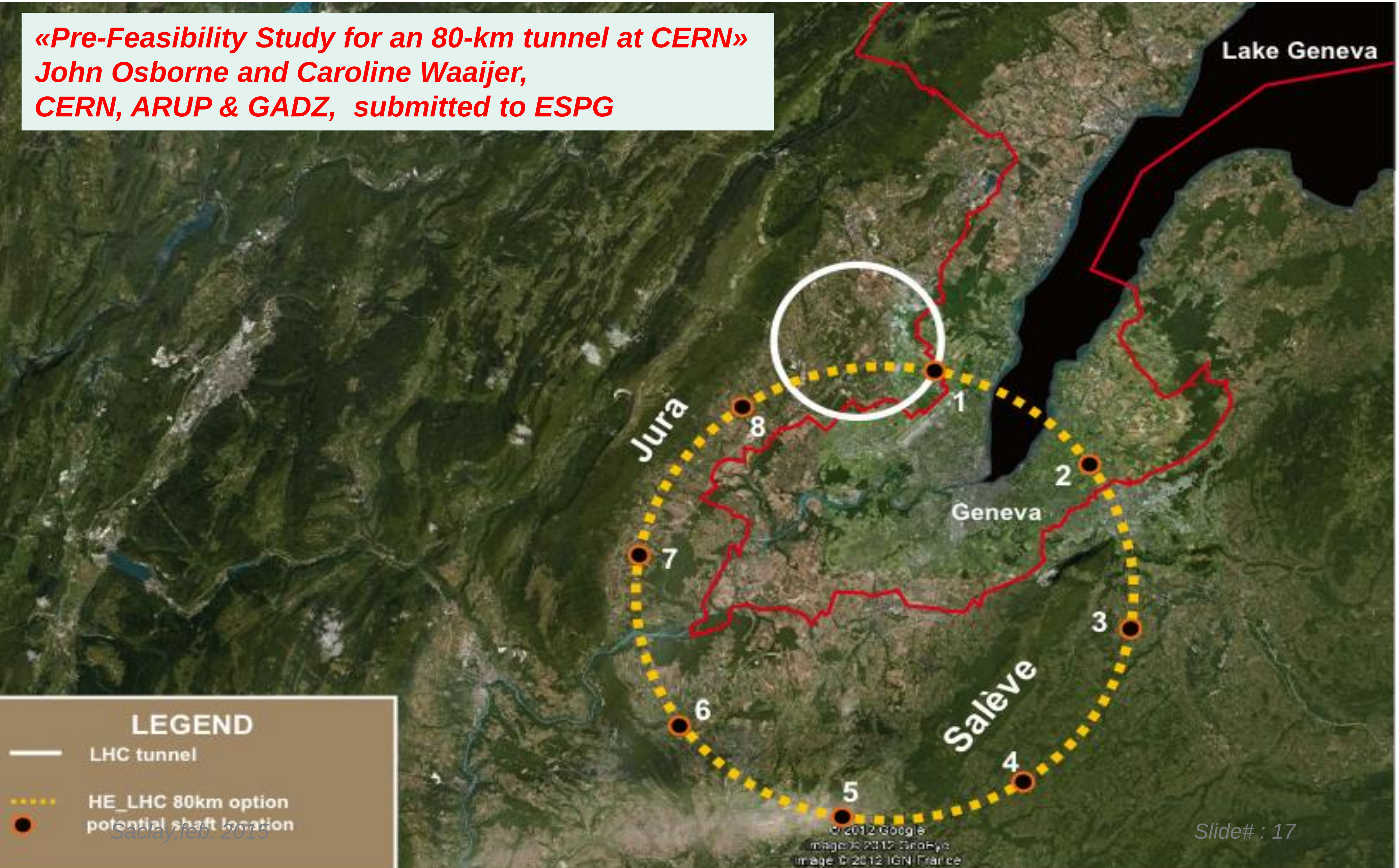


The first option: a huge $e^+ e^-$ LEP like ring.

Super Tristan

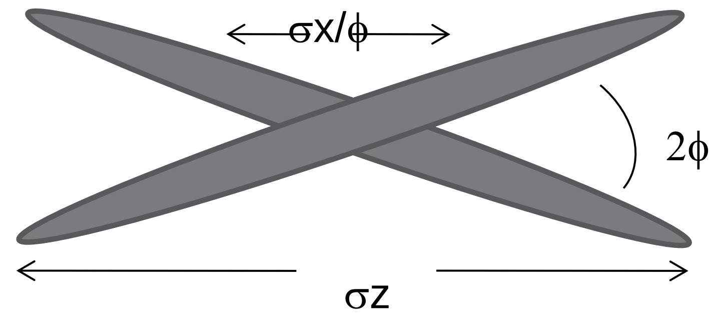
TLEP tunnel in the Geneva area

«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^- collider

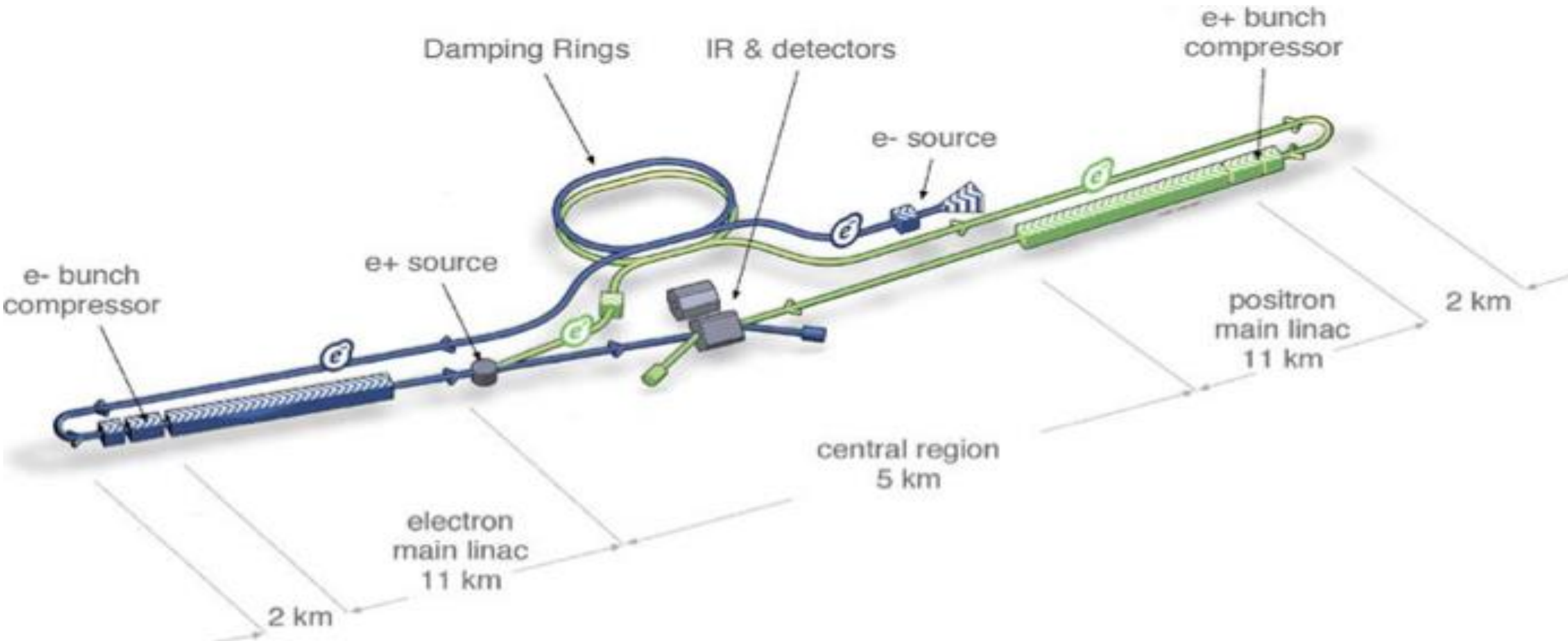
- The luminosity is pushed to the beam-strahlung limit.
- Collisions are at an angle, but with fewer bunches than for a B-Factory: a nano-beam scheme



- 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 ≈ 1000 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).*
- *However the H_o width of ≈4.0 MeV cannot be detected.*

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 $\sqrt{s}$ is 200–500 GeV (extendable to 1 TeV).



Super-Tristan vs ILC

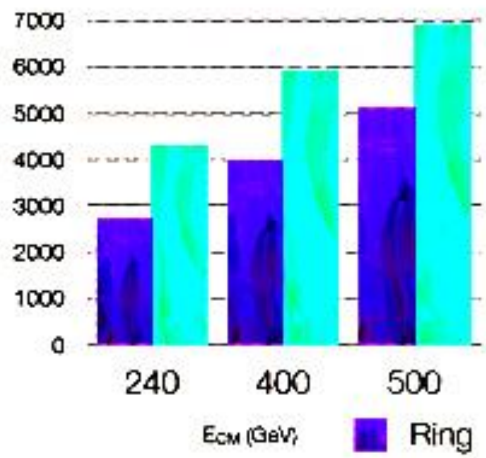
Ring or Linear?

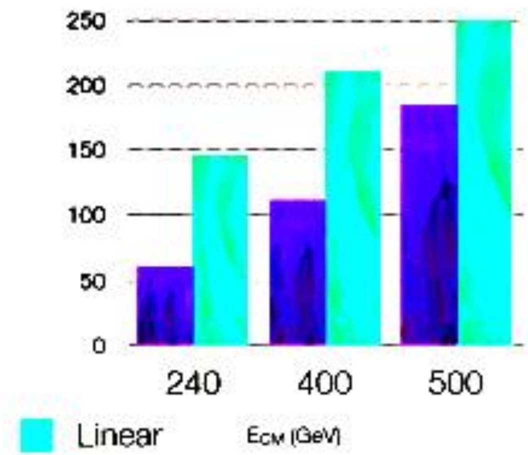
Construction

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.

Comparing LHC and e+-e- colliders

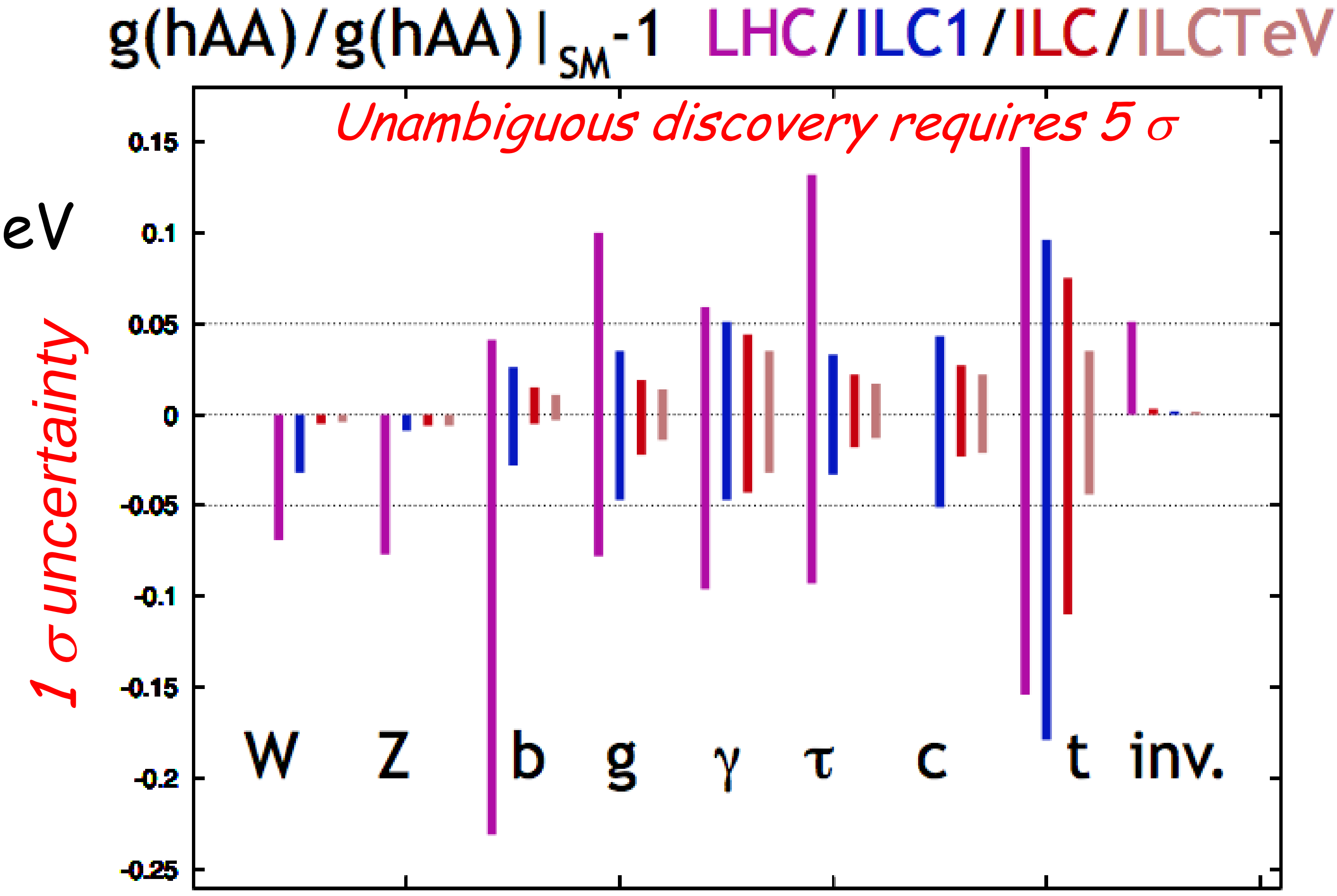
- Any deviations from Standard Model behaviour, if they exist, are likely to be small. Precision measurements of scalar state will be critical for establishing and testing the theory.

LHC 300 fb-1

Ring or ILC1 250 GeV
250 fb-1

ILC 500 GeV
500 fb-1

ILCTeV 1.0 TeV
1000 fb-1

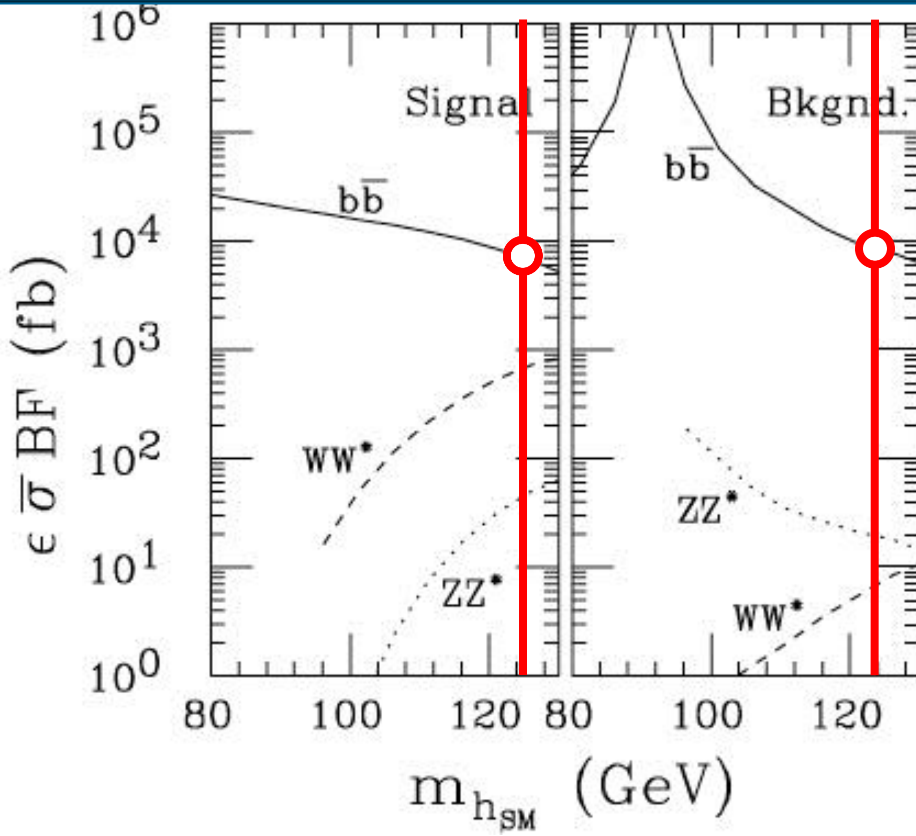


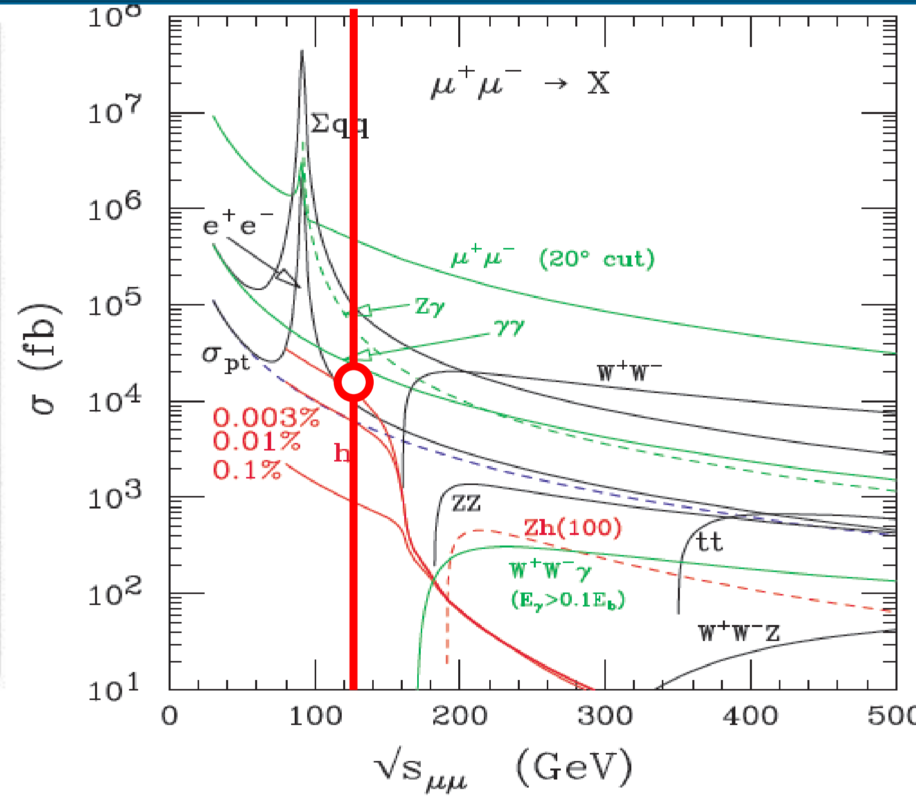
arXiv:1207.2516v3 [hep-ph] 1 Apr 2013

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

- The direct H^o 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^o 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.

A muon collider after the discovery of the Higgs

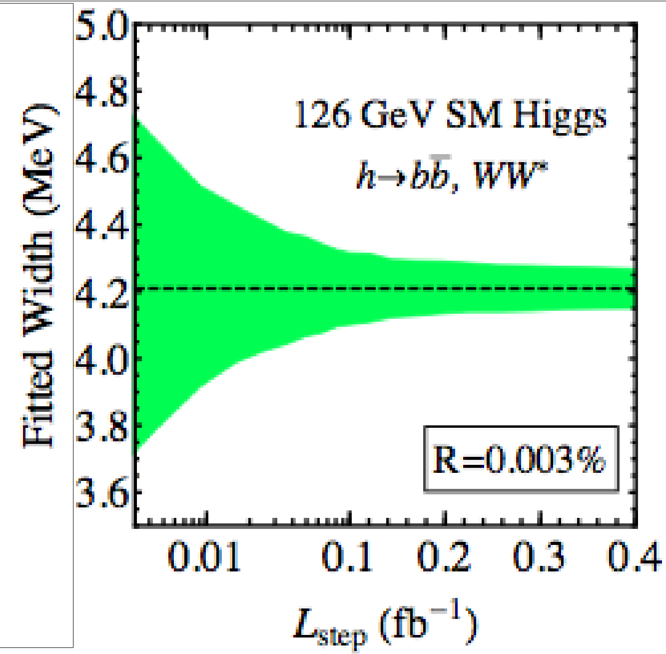




- A $\mu^{\pm}$ collider with adequate muon cooling and L > 10^{32} cm^{-2} s^{-1} .
- Decay electron backgrounds are important: : 2 x 10^{12} $\mu^{\pm}$ decays produce 6.5 x 10^{6} collimated $e^{\pm}$ decays/meter with E_{ave}≈ 20 GeV.
- The very narrow resonant signal (4.12 MeV ,Γ/M_H =3.6 x 10^{-5}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

Leading Higgs processes

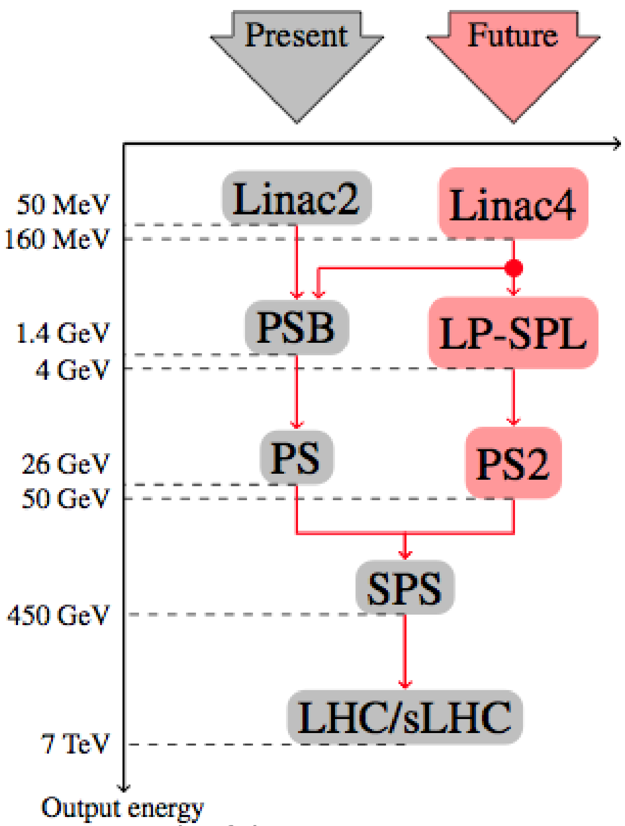
- Signal and background for H → bb, WW* at a energy resolution R = 0.003%. folded with a Gaussian energy spread Δ = 3.75 MeV and 0.05 fb^{-1}/step and with detection efficiencies included.
- Effective pb at the √s resonance for two resolutions R and with the SM branching fractions = H → bb 56% and WW*=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

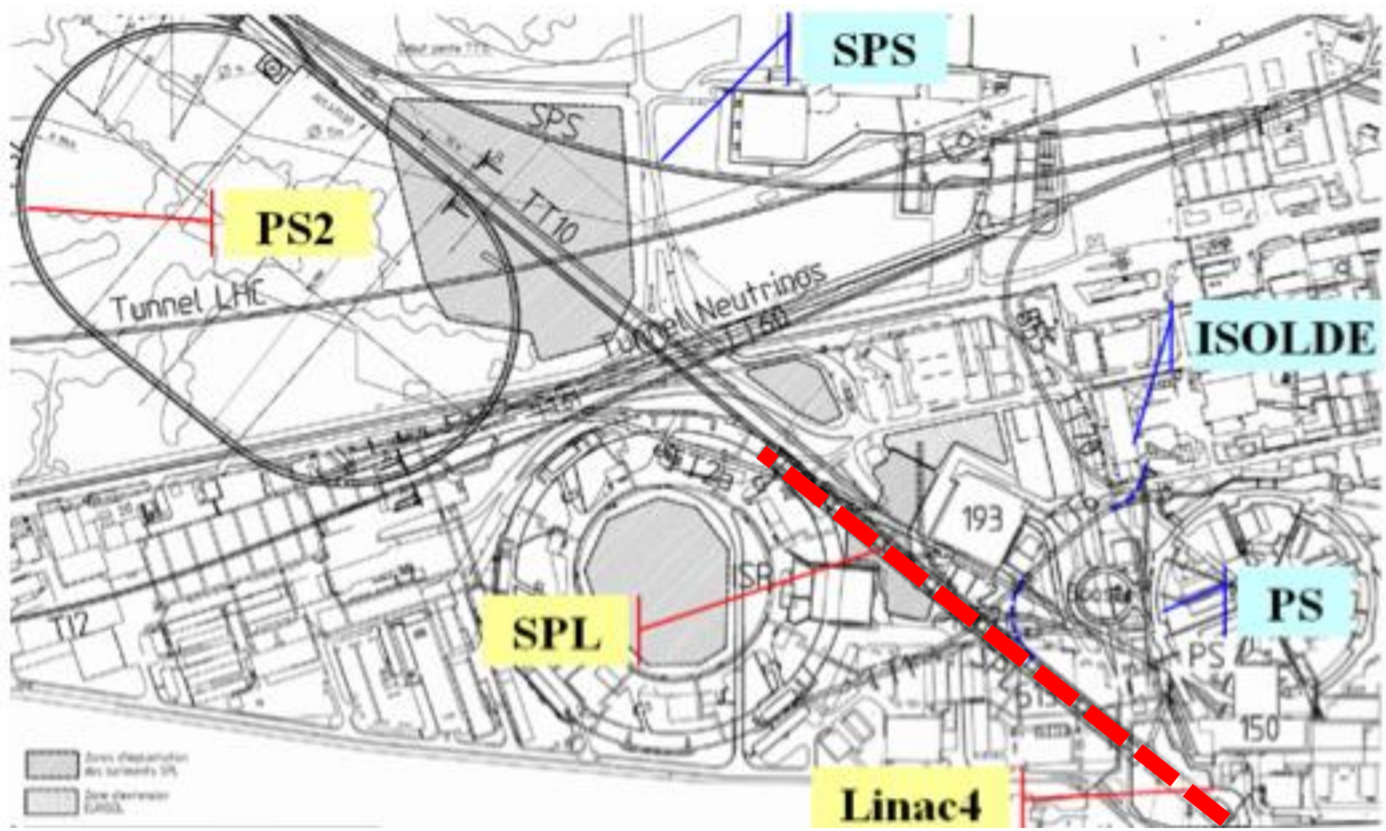


arXiv:1210.7803 [hep-ph].

Future accelerators for CERN-HL-LHC

- 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,

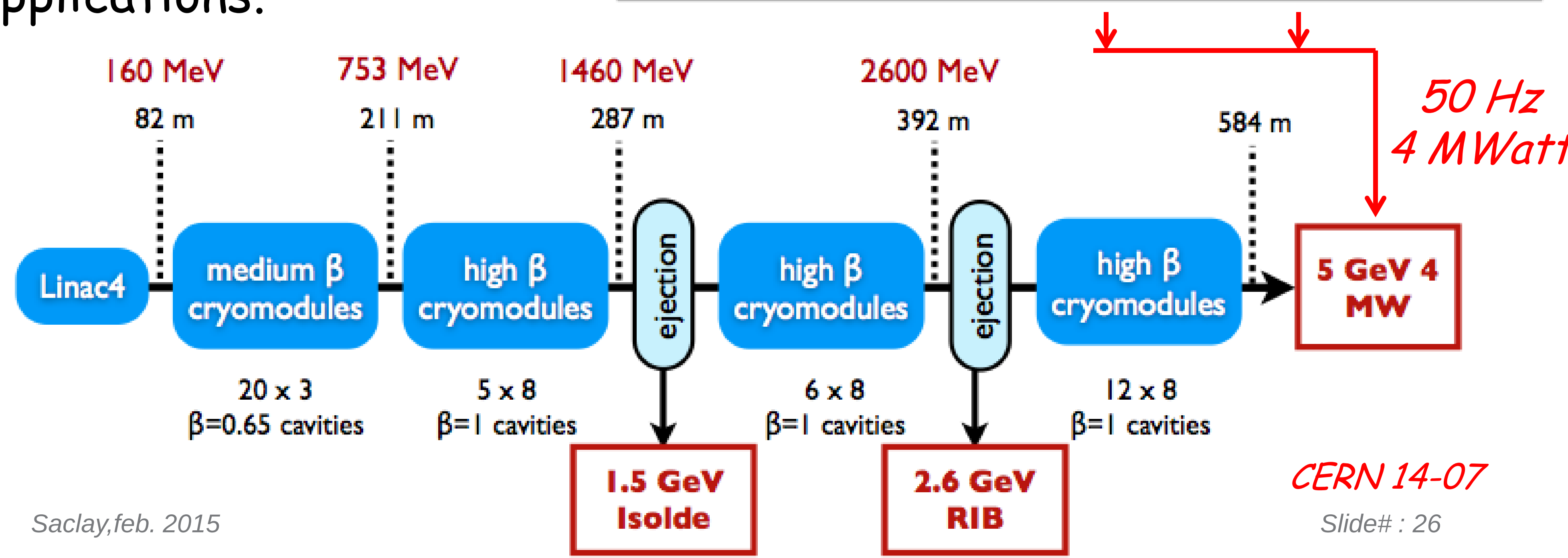




CERN-SPL parameters

- 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



CERN 14-07

A muon based Higgs factory for CERN

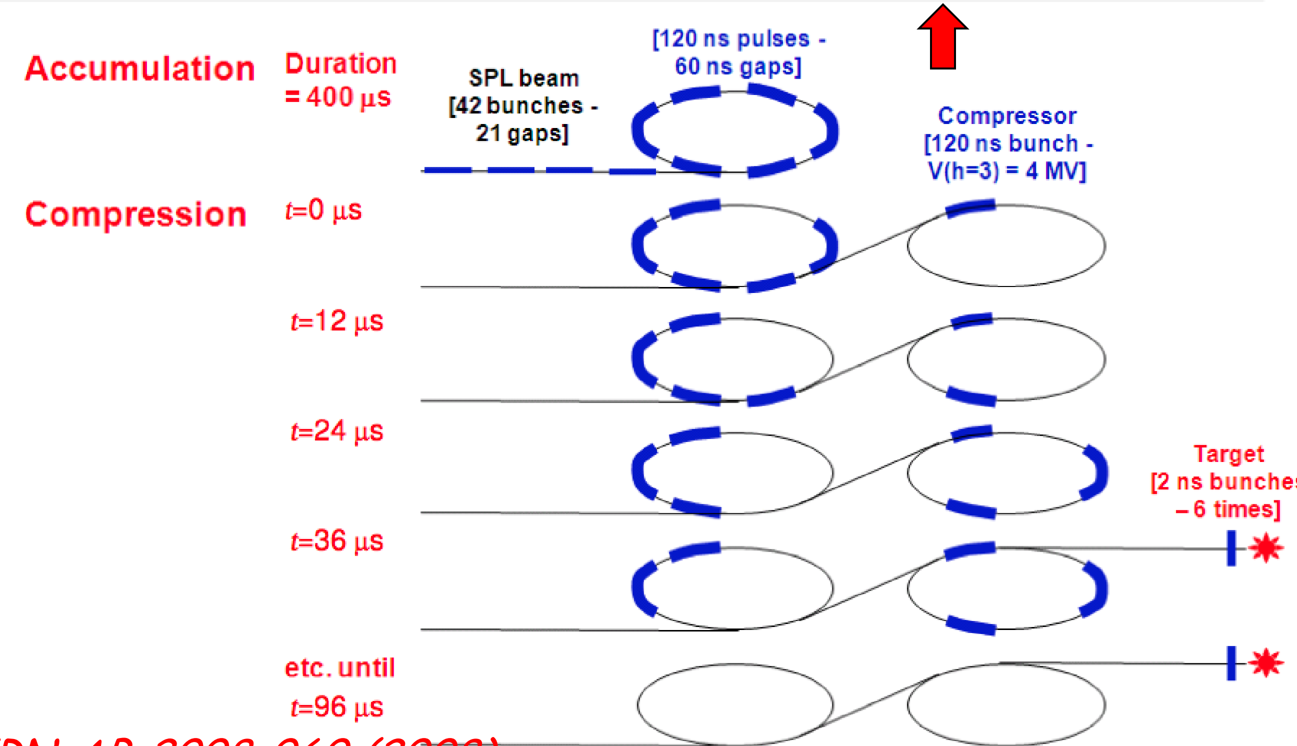
- A muon cooled Higgs factory can be easily housed within the present CERN.
- The new 5 GeV Linac will provide at 50 c/s a multi MWatt H^- beam with enough pions/muons to supply also the factory.
- The basic additional accelerator structure will be the following:

1. 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.
2. Muons of both signs are focused in a axially symmetric B = 20 T field, reducing progressively pt with a horn and B = 2 T
3. A buncher and a rotator compresses muons to ≈ 250 MeV/c
4. Muon Cooling in 3D compresses emittances by a factor 10^6.
5. Bunches of about 10^{12} $\mu^{\pm}$ are accelerated to 62.5 GeV
6. Muons are colliding in a SC storage ring of R ≈ 60 m where about 10^4 Higgs events/y are recorded for each experiment.

1.- CERN accumulator and compressor

- 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

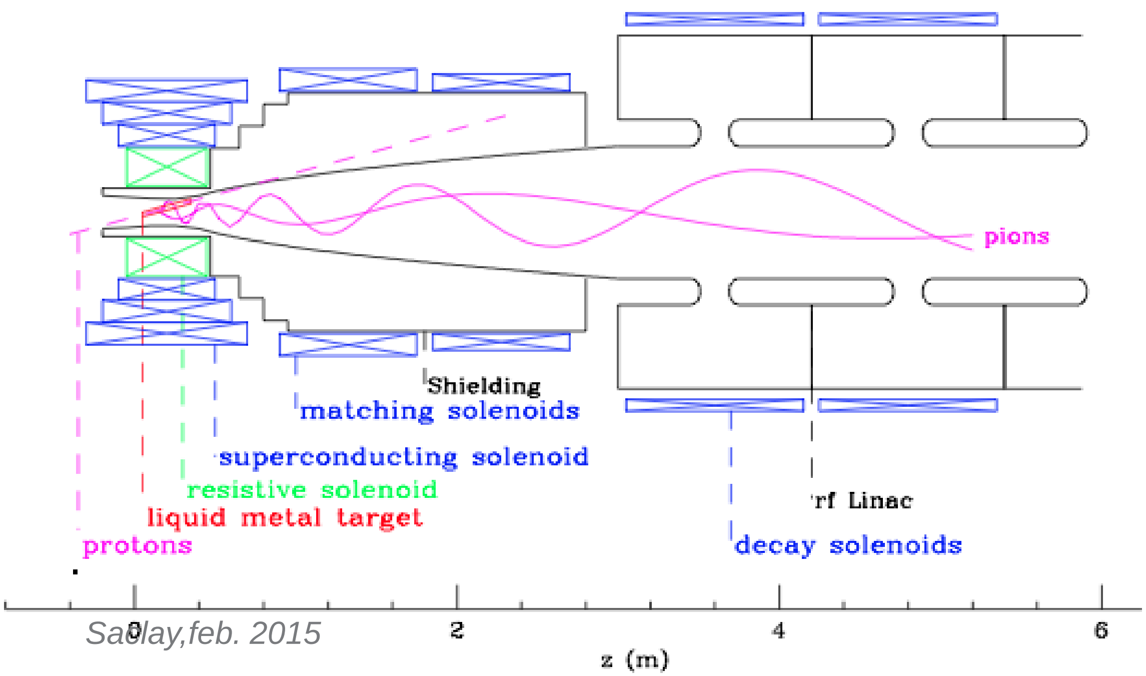


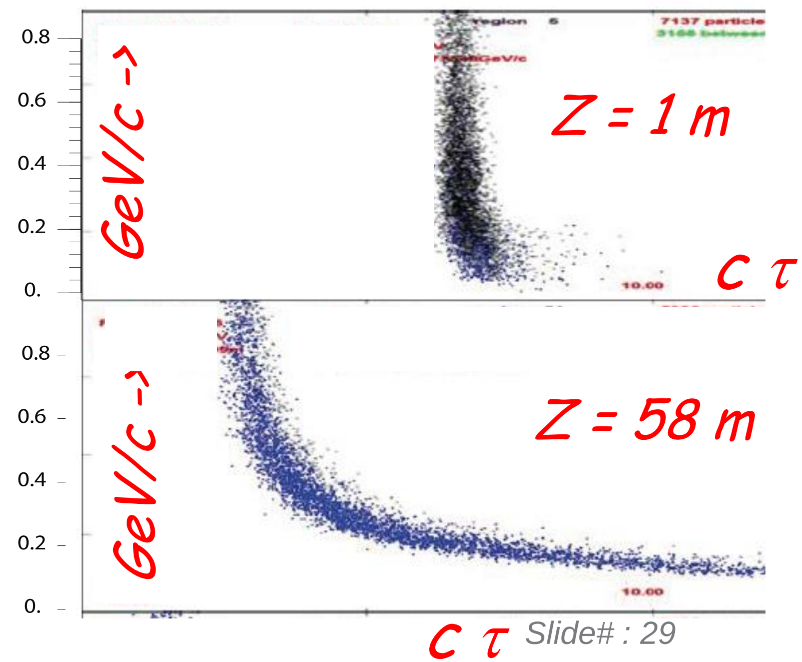
CERN-AB-2008-060 (2008)

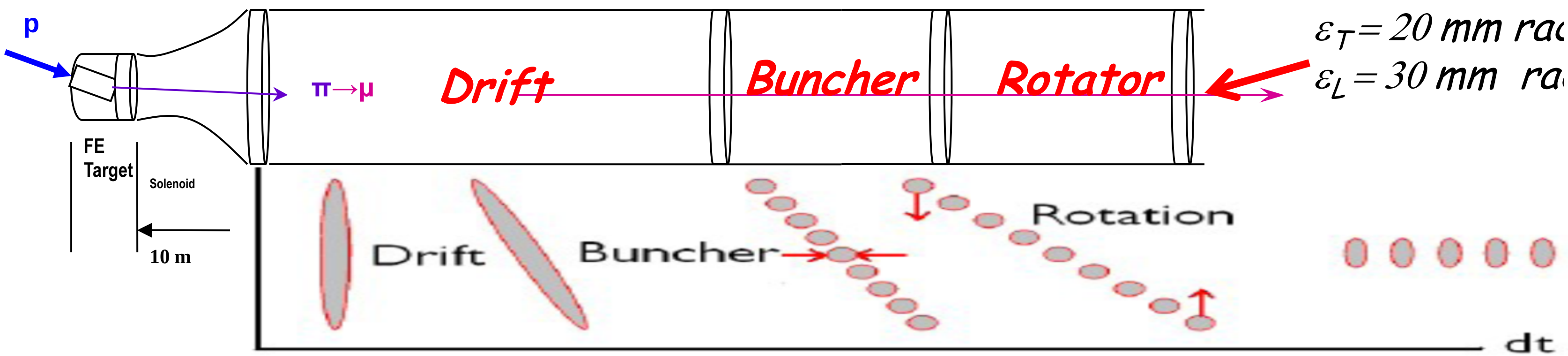
2.-Target and solenoidal capture

- 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

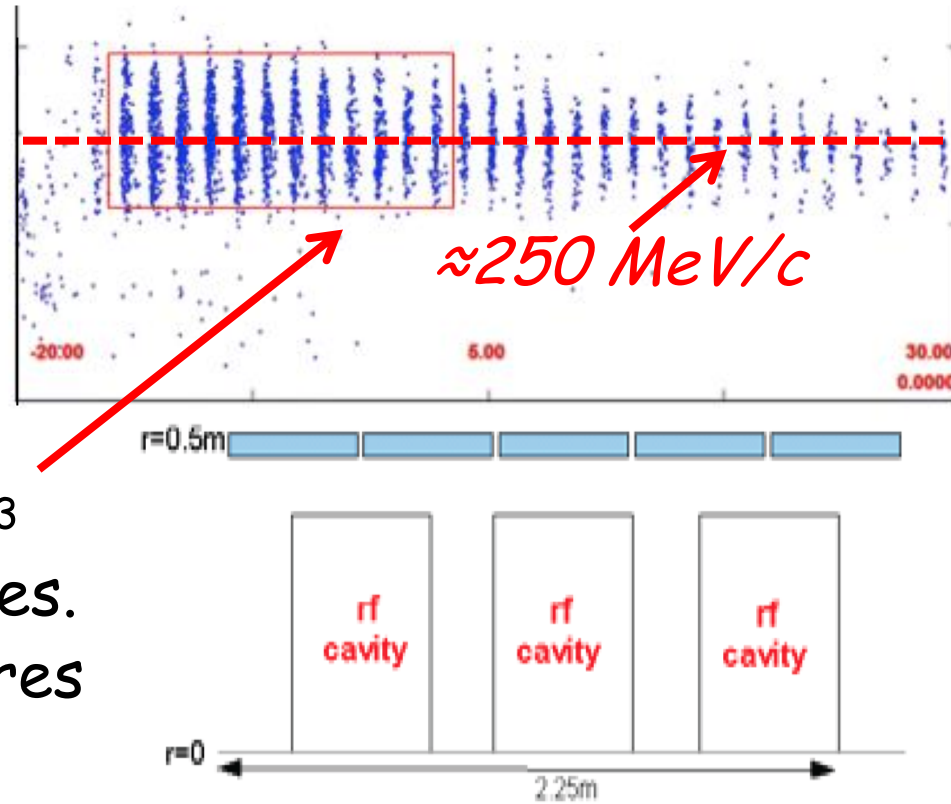






Front End section	*Length m*	*#rf cavities*	*Frequencies MHz*	*# of freq.*	*RF gradient*	*RF peak power requirements*
Buncher	33	37	319.6 to 233.6	13	4 to 8 MV/m	~1 to 3.5 MW/freq
Rotator	42	56	230.2 to 202.3	15	12.5 MV/m	~2.5 MW/cavity

- 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



4.-Ionization cooling of muons

- 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

Muon cooling ring: transverse emittance

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

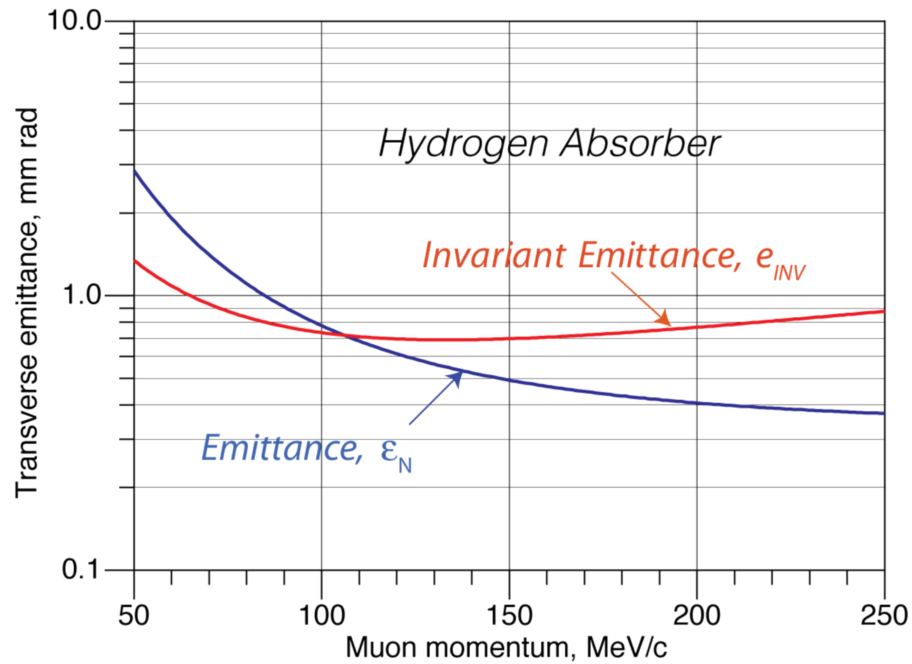
Cooling — Scattering

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

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, $\varepsilon_N/\beta\gamma \leq 700$ 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:

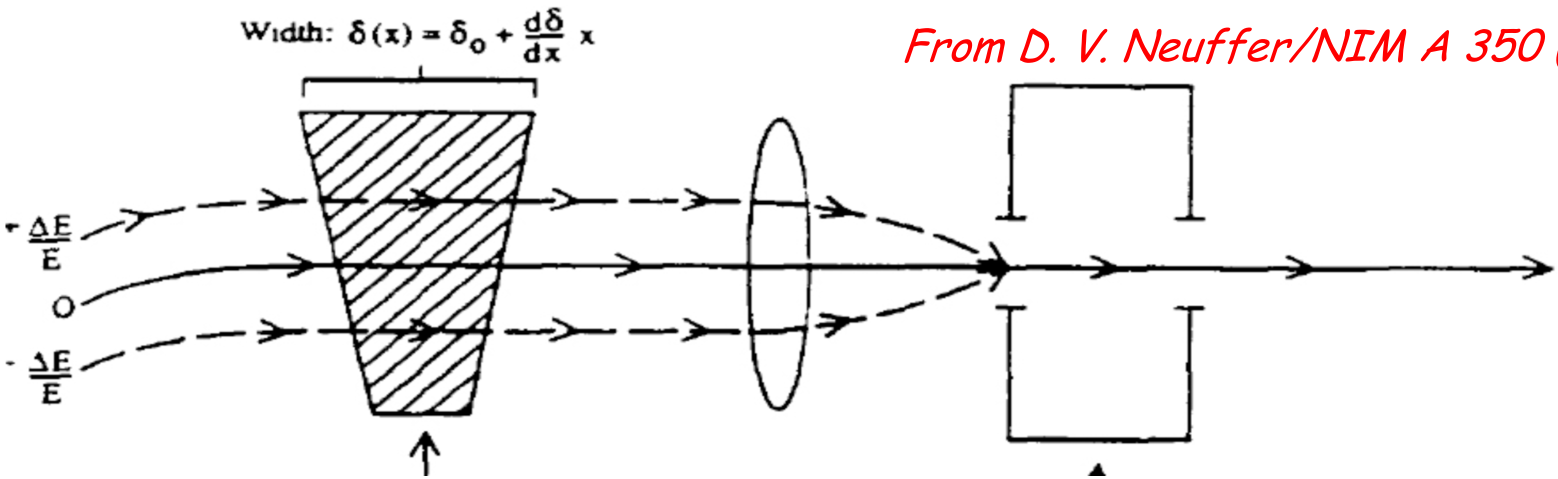
Intrinsic Energy loss — *Wedge shaped absorber* — *Straggling*

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

- $dE/dz = f_A\, dE/ds$ 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 dd/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.

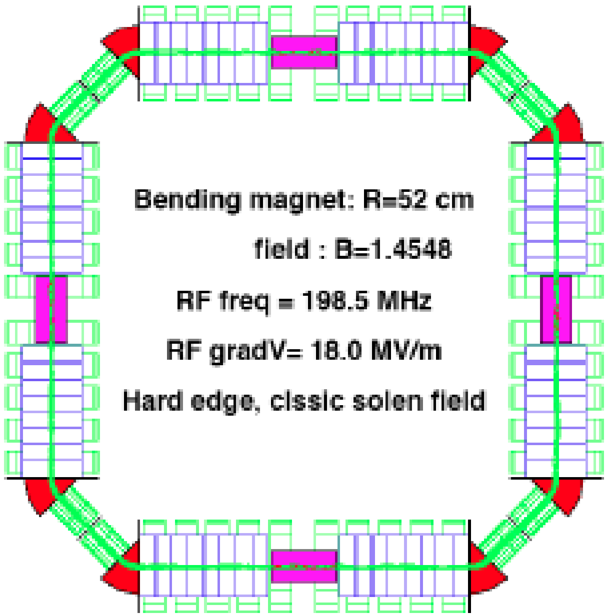
$$2\gamma_\perp + \gamma_L \cong 2$$

- At moderate B, E_{RF}, λ_{RF}, equilibrium 6-D "naïve" cooling is for H_2:

$$\varepsilon_\perp \approx 0.3\times 10^{-3} m \quad \varepsilon_L \approx 1.0\times 10^{-3} m \quad \sigma_E = 3\ MeV \quad \sigma_z = 5\ cm$$

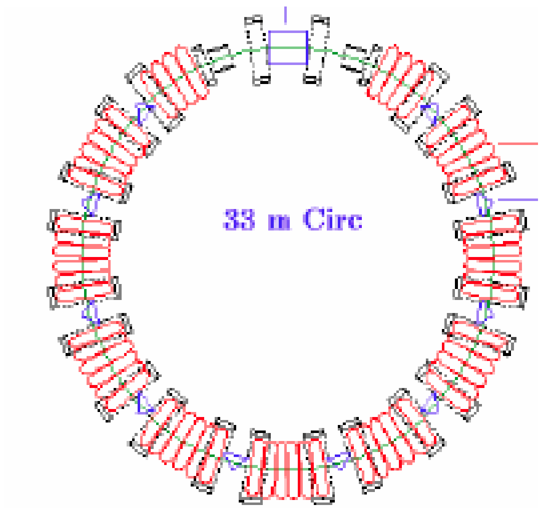
Examples of muon cooling arrangements

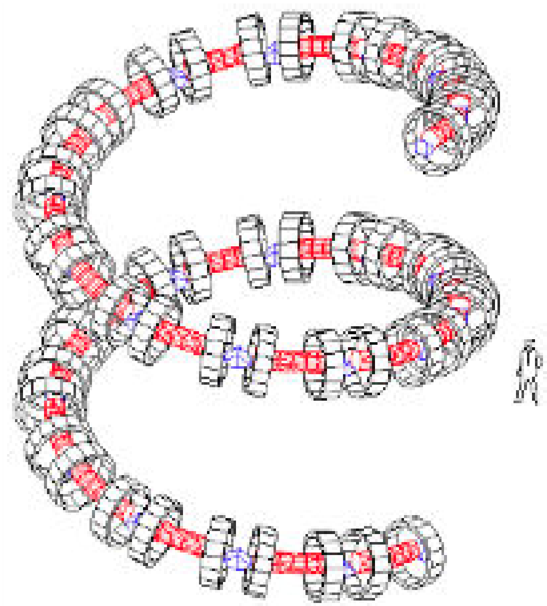
- Some practical but still conceptual descriptions of muon coolers
- The average muon momentum is 220 MeV/c and the approximate diameter ≈ 10 m.
- Acceptance increased to ≈ ± 20 % with solenoids



"Tetra" ring (Balbekov)

RFOFO ring (Palmer)

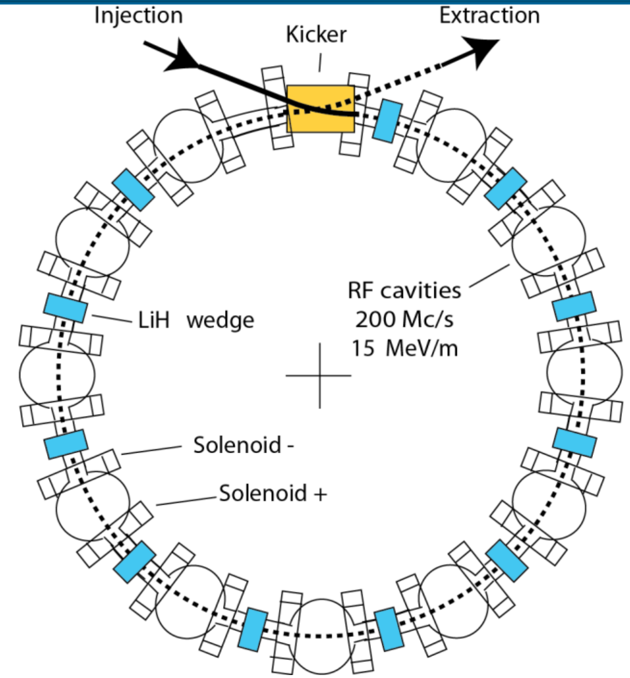




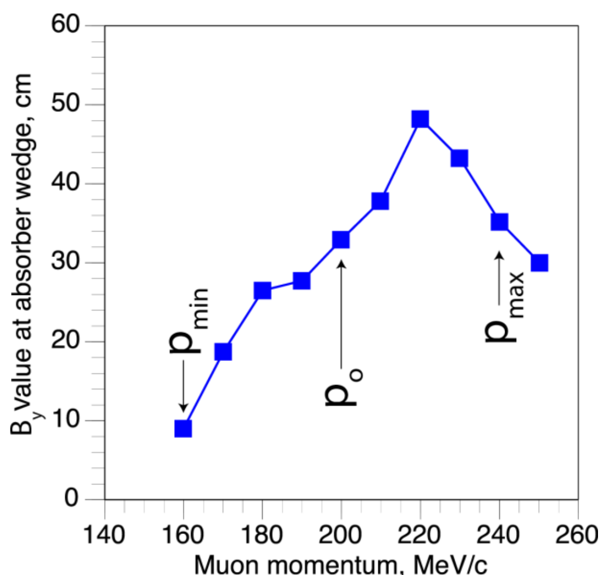
"Guggenheim" version (Klier)

Simulation of 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).

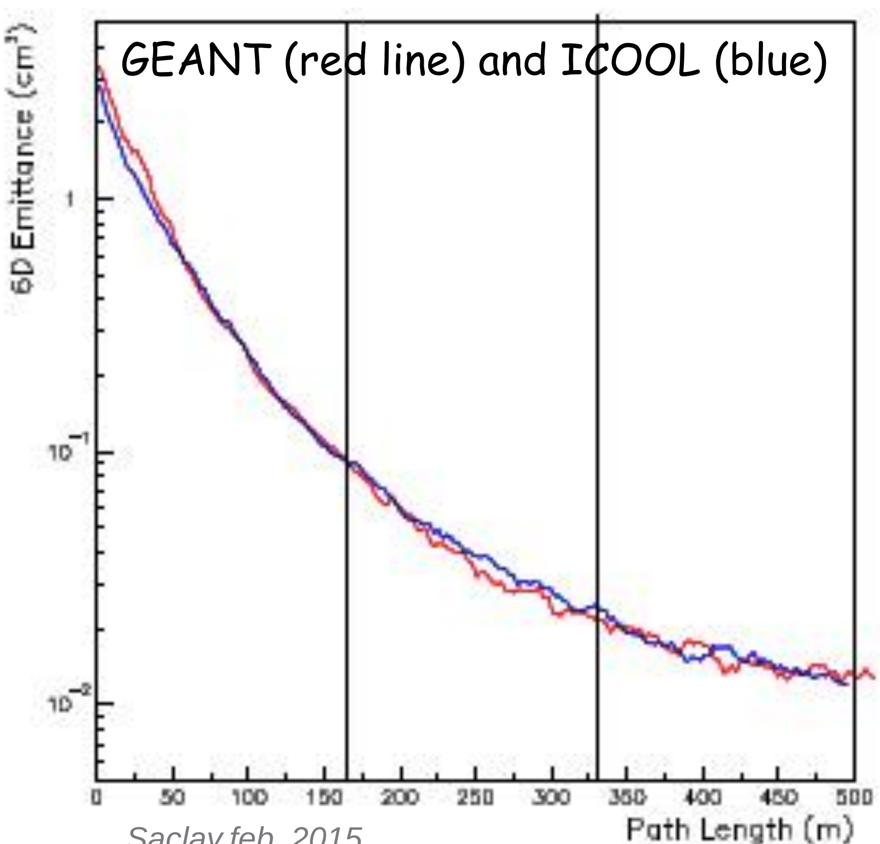


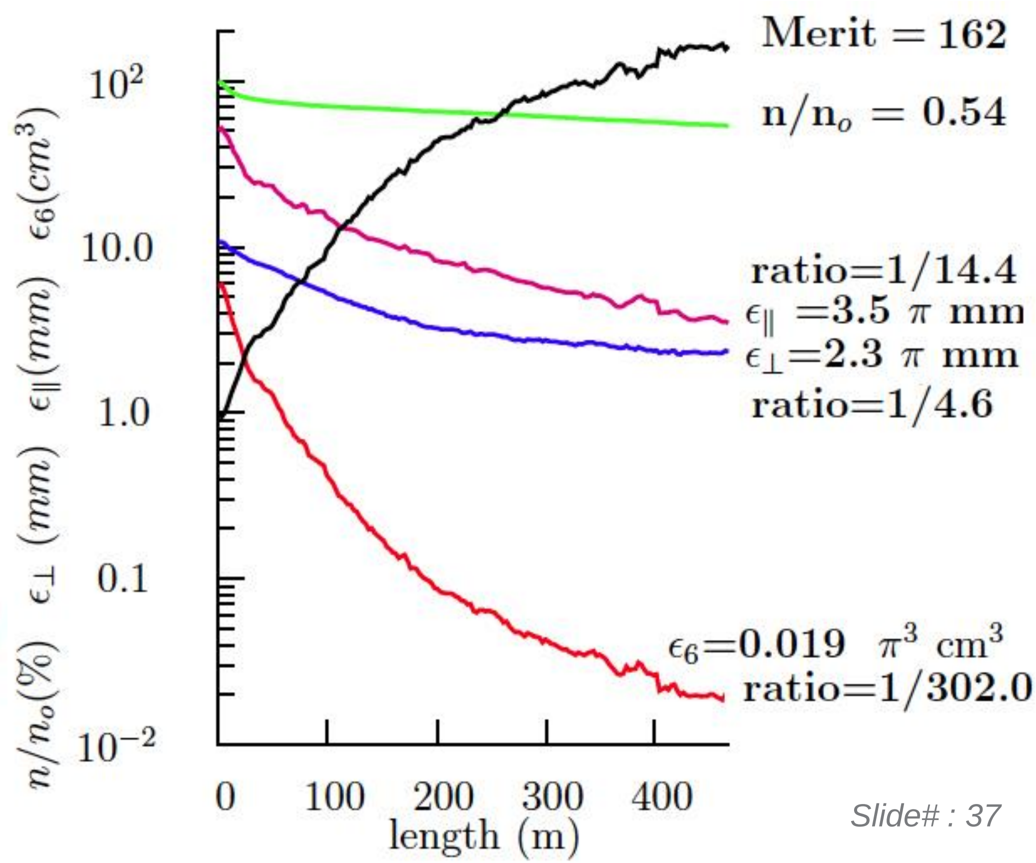
Circumference	33	m
Cells	12	
Max Bz	2.7	T
Coil Tilts	2.6	deg.
Ave Momentum	220	MeV/c
Min Trans. Beta	35-40	cm
Dispersion	8	
Wedge Material	H_2 or LiH	
Central thickness	28.6	cm
Wedge angle	100	deg
RF Cavities/cell	6	
Frequency	201.25	Mhz
Gradient	12	MV/m



Performance of Palmer et al. design

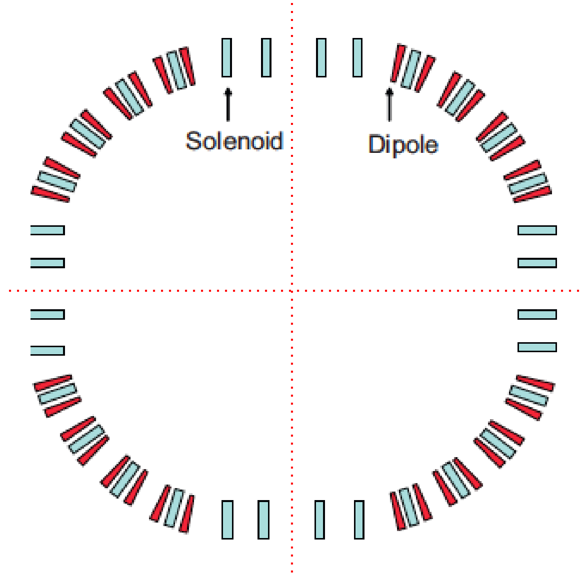
- A first estimate of the expected cooling process is given. This is not an engineering design: for instance injection, extraction, etc. have still to be evaluated.
- The so called "merit factor" in the 6D takes into account the fractional loss of muons in the process and due to decays.

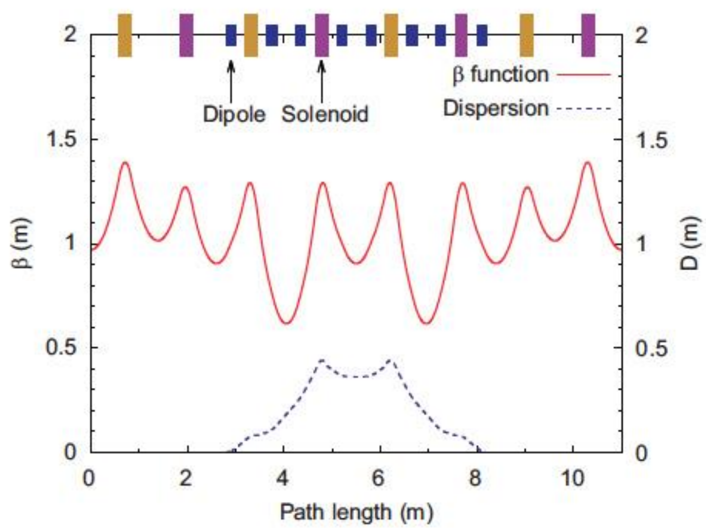


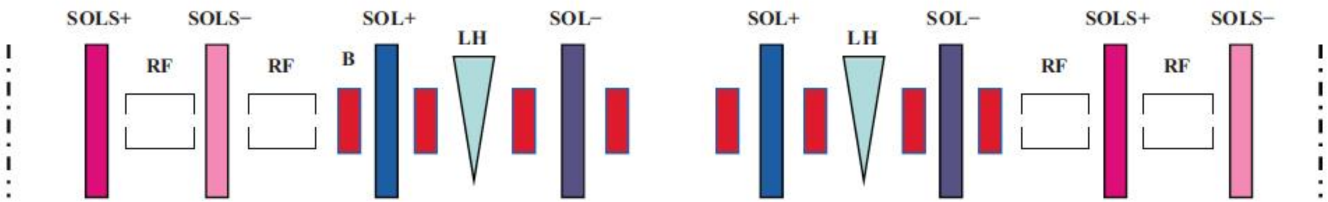


A straightforward design for the achromatic cooling ring

- 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.

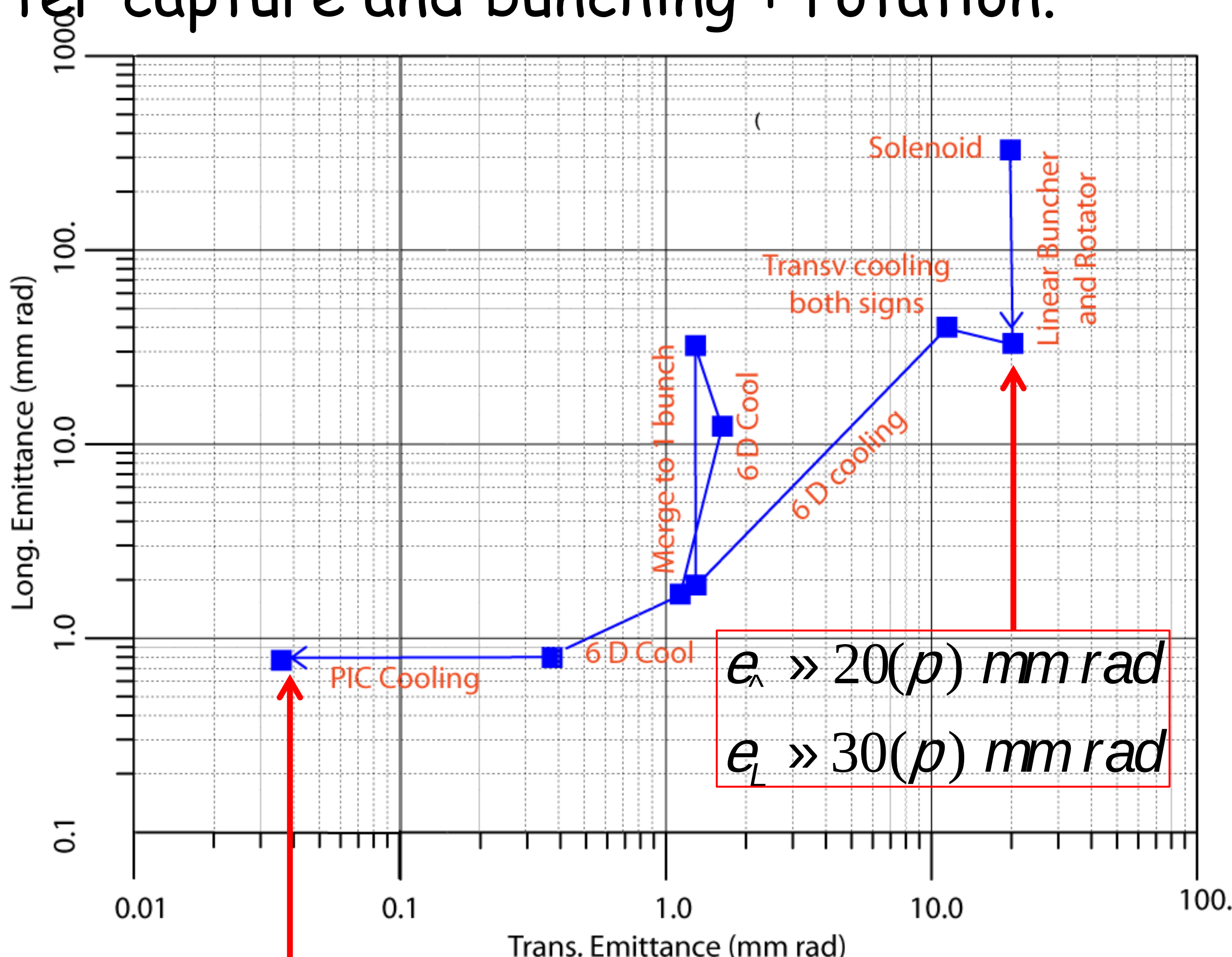






Describing the full cooling procedure

- A number of successive steps is 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.
  - Particle of both signs are transvers. cooled with small Δp increase.
  - Cooling in 6D with a B field brings the μ+ and μ- to a reasonable size
  - Merging and further cooling of 1+1 bunches
  - PIC cooling at ≈100 MeV/c where the normal elliptical motion in *x-x′* phase space has become hyperbolic.



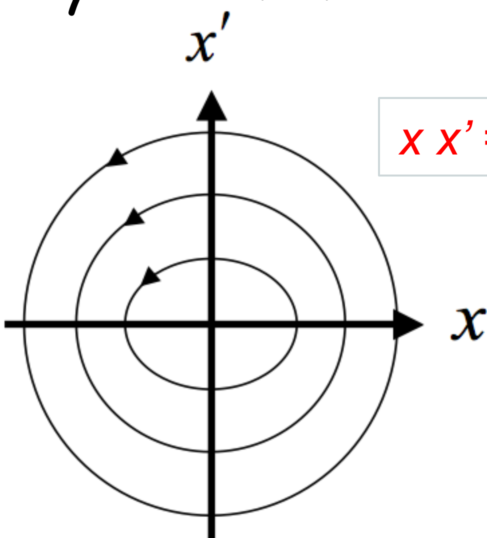
$$\epsilon_\perp \approx 20(\pi)\ mm\ rad$$
$$\epsilon_L \approx 30(\pi)\ mm\ rad$$

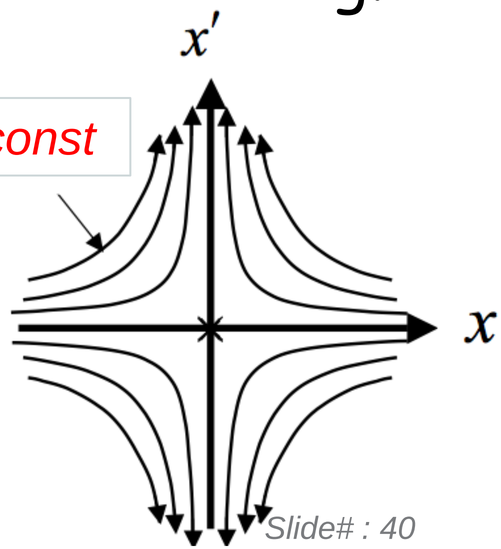
$$\epsilon_\perp = 0.04(\pi) mm rad \quad \epsilon_L = 1.0(\pi)\ mm\ rad$$

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 channel's focal points 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.

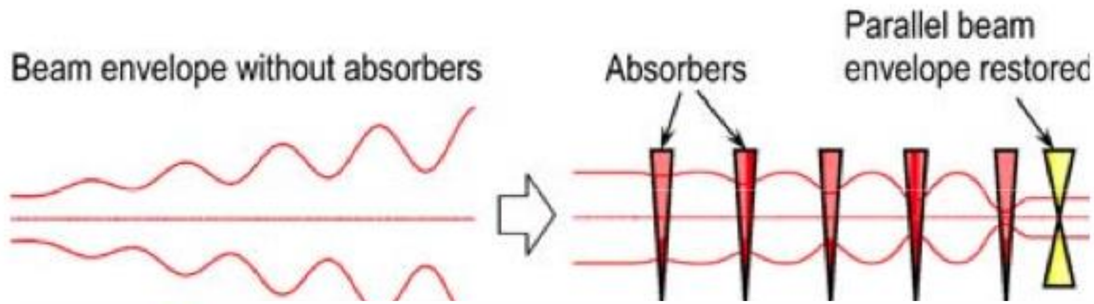


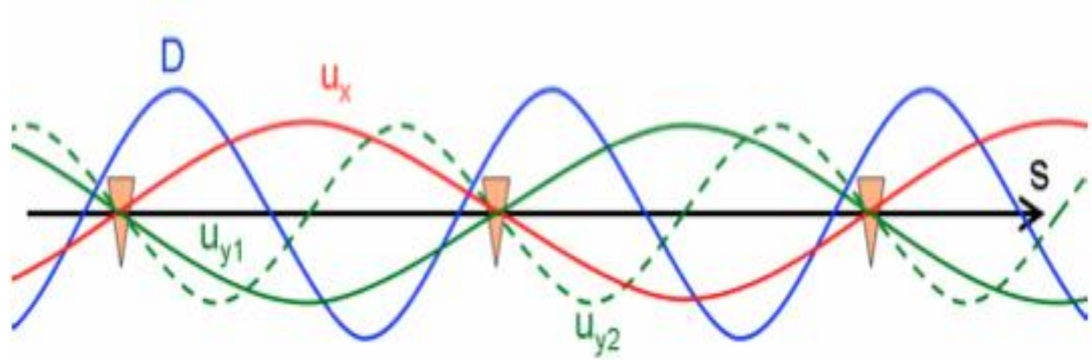


V. S. Morozov et al, AIP 1507, 843 (2012);

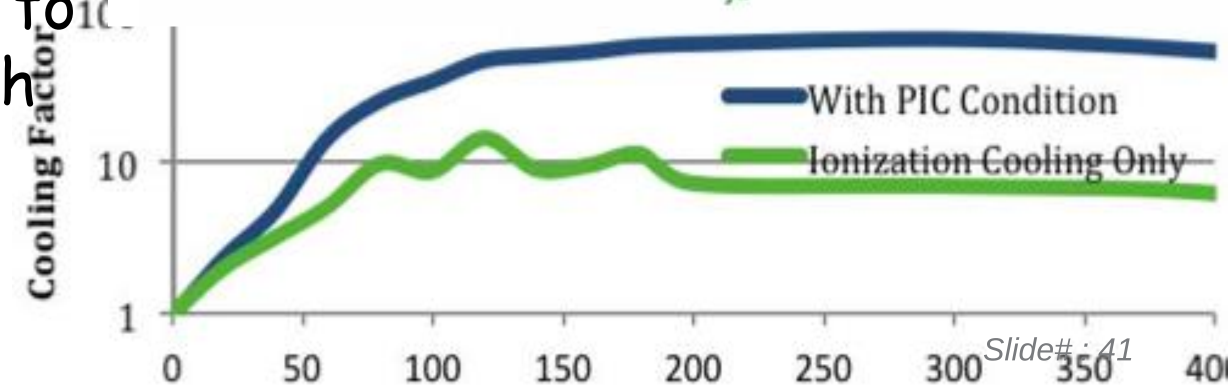
Details of PIC

- Without damping, the beam dynamics is not stable because the beam envelope grows with every period. Energy absorbers at the focal points 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.



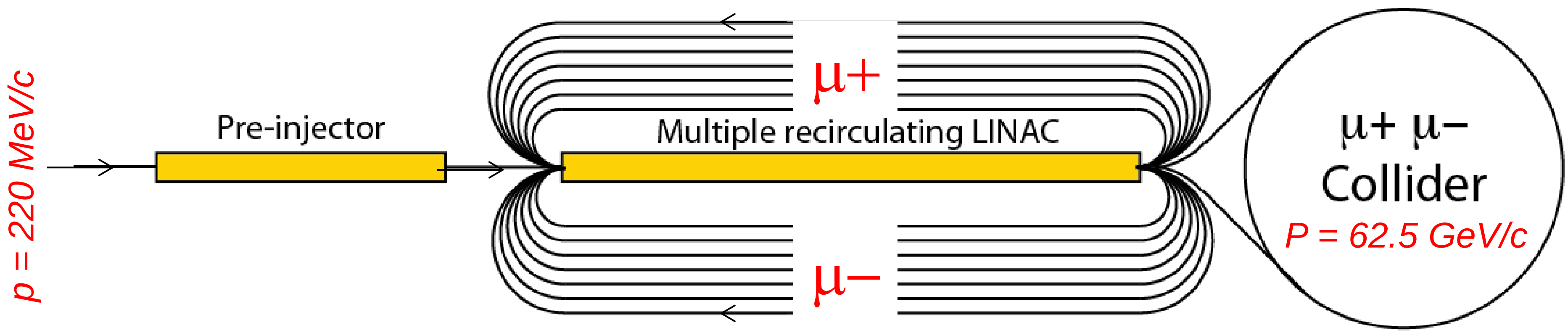


- Comparison of cooling factors (ratio of initial to final 6D emittance) with and without the PIC condition vs number of cells:



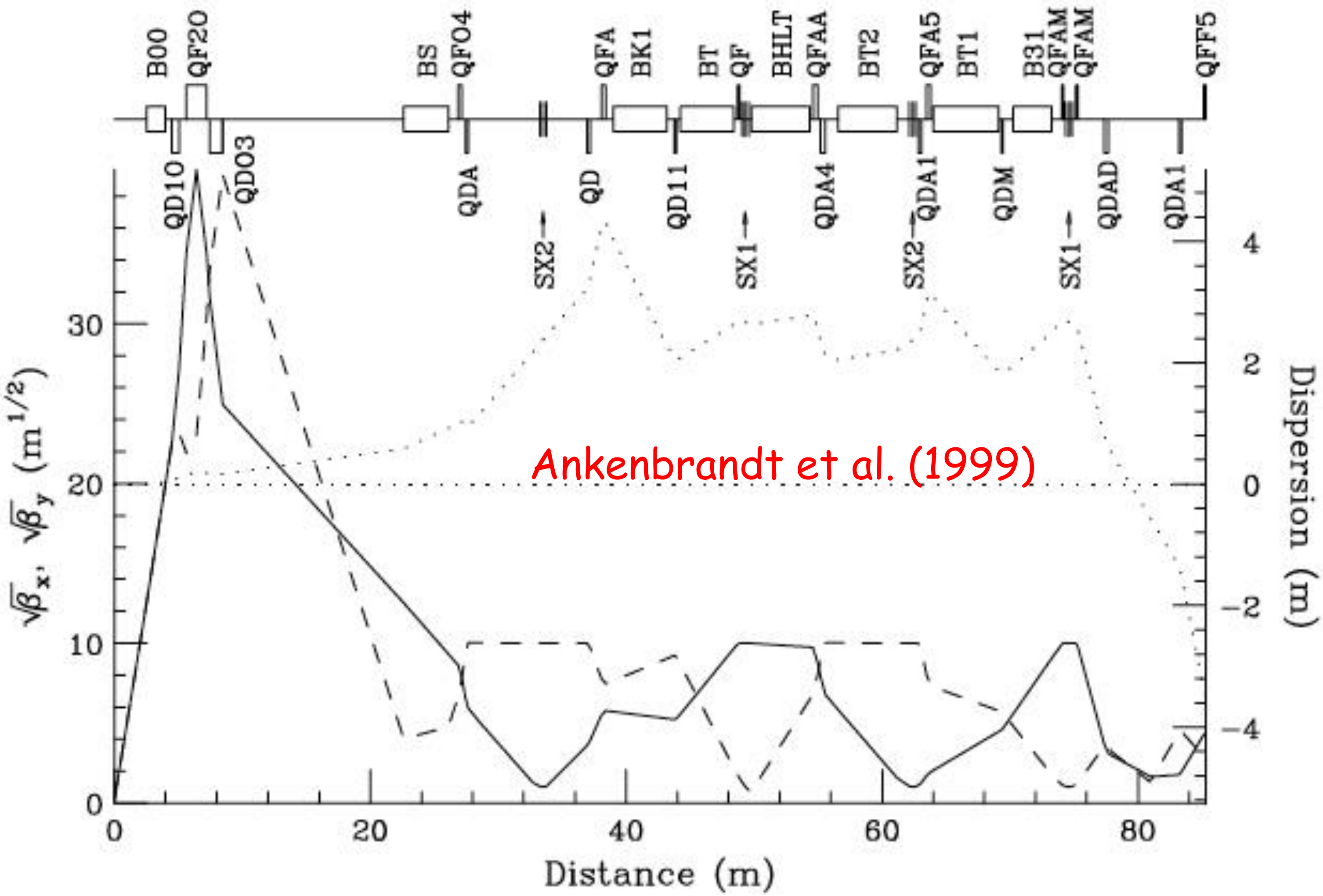
5.- Bunch acceleration to 62.5 GeV

- 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_i = 0.22 GeV/c to p_f= 62.5 GeV/c.
- Recirculating energy gain/pass = 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.



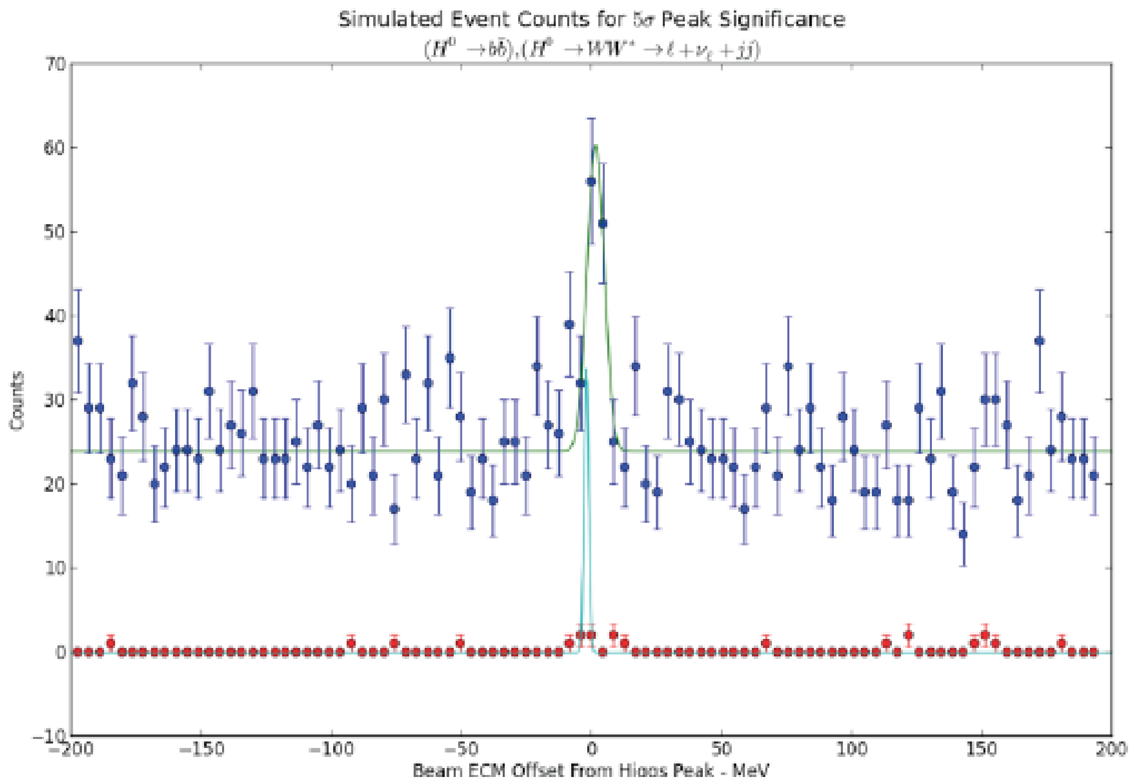
Eatimated performance of the H°-factory

- 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 x 10^{32} cm^{-2} s^{-1} is achieved with 1 x10^{12} μ/bunch.
- The SM Higgs rate is ≈ 44'000 ev/year in each detector.

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.



Preparatory work on the Z^o and search for rare decays

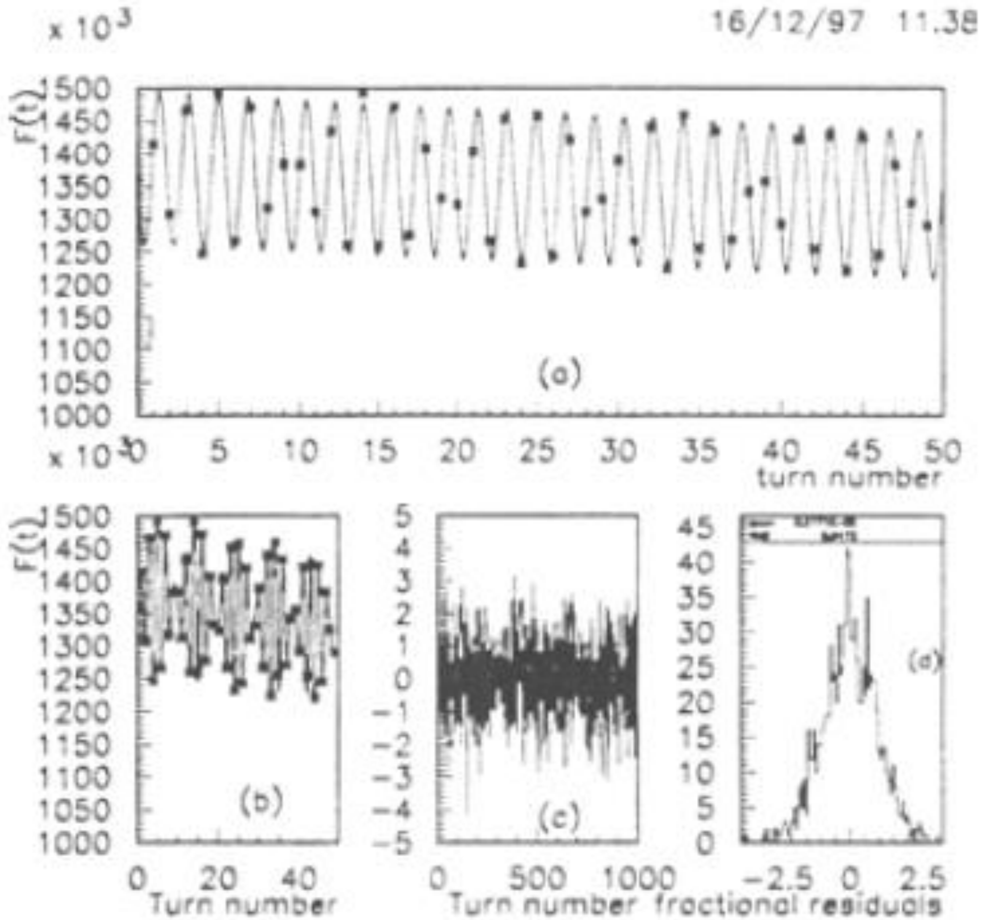
- Running of the Zo peak is an excellent tuning up of the μμ collider.
- Measurements of the luminosity, suppression of backgrounds, spin precession at manageable parameters
- The cross section is very large, σ = ~30000 pb. Therfore one expects 30'000 Z/day with L = 10^{31} cm-2 s-1.
- Useful Physics at Z ?
  - E, ΔE to ~0.1 MeV or less
  - $\mu^+\mu^- \rightarrow Z_0$
- Then move to 126 GeV and study the Higgs

Polarization & Energy measurement

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

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

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



- Measure ω from fluctuations in electron decay energies
- The e-rate is of 10^6 decays/m
- Since frequencies can be very precisely measured, energy E, and δE can be measured to a few hundred keV or even better

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

The muon Higgs collider:

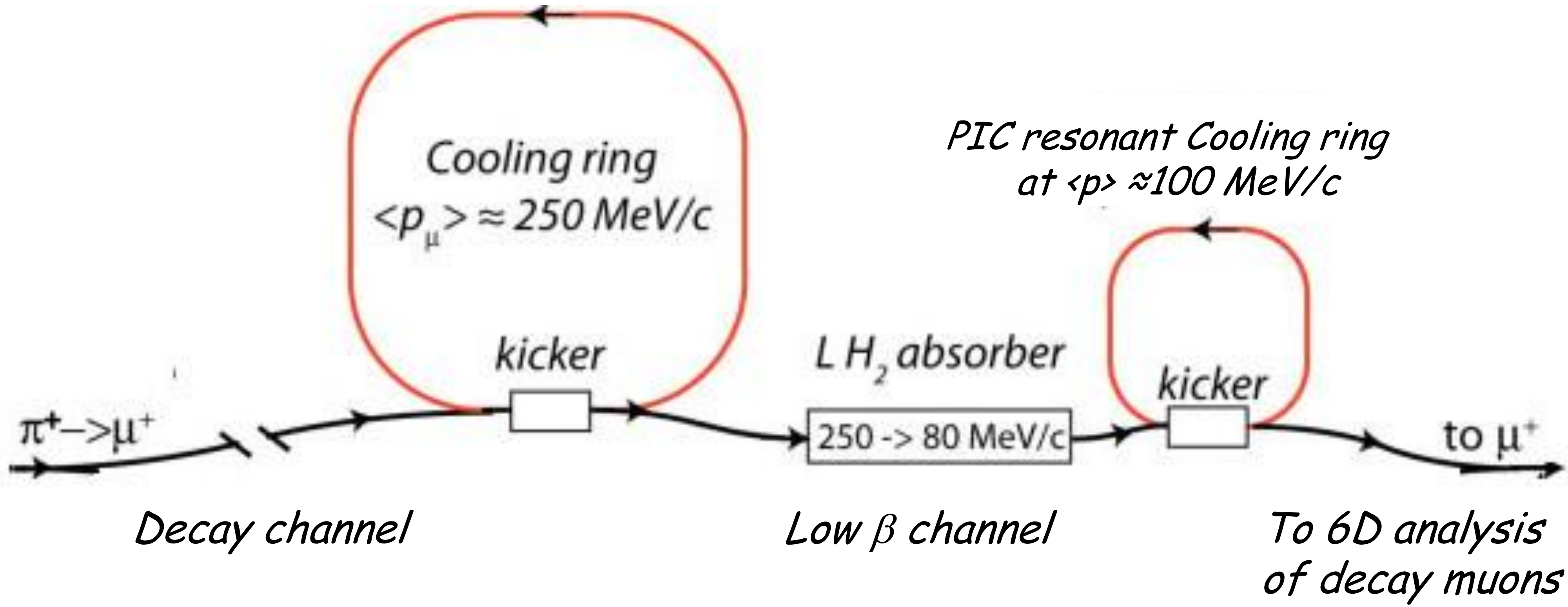
- **Advantages**
  - Large cross section σ ($\mu^+\mu^- \rightarrow h$) = 41 pb in s-channel resonance, compared to $e^+e^- \rightarrow ZH$ and 0.2 pb.
  - Small size footprint: it may fit in the CERN site
  - Cost so far unknown but far smaller than the ILC.
  - No synchrotron radiation and beamstrahlung 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.
- **Challenges**
  - Muon 4D and 6D cooling needs to be demonstrated
  - Need ulimately 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 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.

The initial cooling experiment

- A single sign muon cooling arrangement with two rings , either μ+ or μ- is required and with few particles
- A low intensity pion-> muon beam is produced from an appropriate accelerator in the form of a very short pulse



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

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

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^o 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^o 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 ν factory.

Professional endorsement

New boson sparks call for 'Higgs factory'

Jul 5, 2012 15 comments

Former CERN boss Carlo Rubbia wants a muon collider

CERN's discovery of a new fundamental particle – most likely a Higgs boson – was barely hours old when physicists speaking at this year's Lindau Nobel Laureate Meeting in Germany argued the case for a new facility to measure its properties in detail. Speaking out in favour of a new machine was former CERN boss Carlo Rubbia, who shared the 1984 Nobel Prize for Physics for the discovery of the W and Z bosons. "The technology is there to construct a Higgs factory," he claimed. "You don't need €10bn; it could be done relatively cheaply."

physicsworld.com
BEST SPECIALIST SITE FOR JOURNALISM 2011

"With a Higgs of 125 GeV we need only a modest machine, perhaps not a large linear collider." Rubbia points out that muons colliding at a combined energy of roughly 125 GeV would suffice – just over half the energy of LEP and requiring a machine with a much smaller radius.