Motivations of a Muon Collider for the Higgs sector

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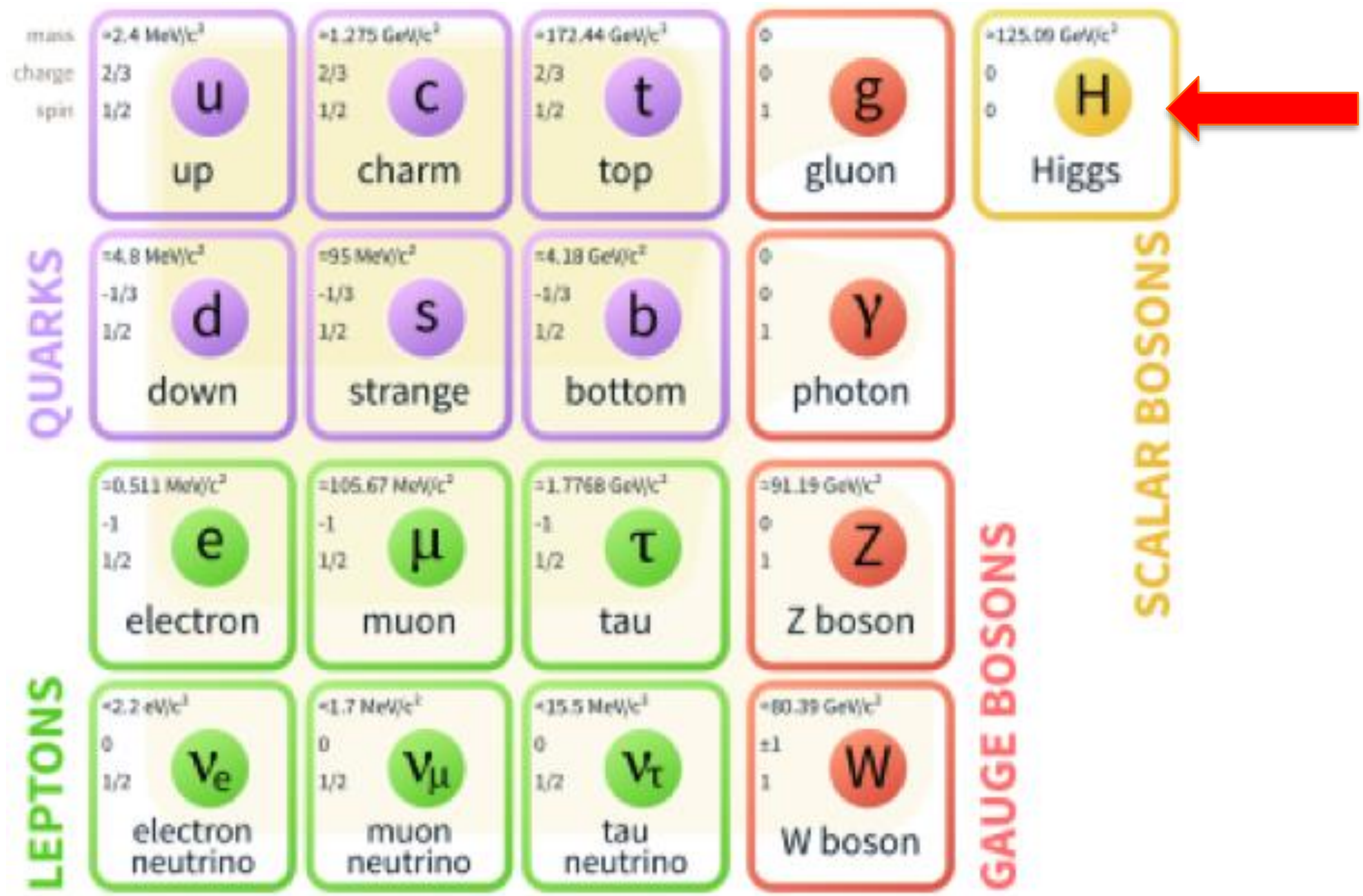
Premise

- The *Standard Model* of particle physics is a monumental description of three of the four fundamental forces in the Universe (electromagnetic, weak, and strong interactions), as well as the classification of all known elementary particles.



The Higgs sector

- The LHC is an essential future program for Higgs physics . See for instance CERN-LPCC-2018-04 : *Higgs Physics at the HL-LHC and HE-LHC. (fentobarn = 10^{-39}, attobarn = 10^{-42}cm^2)*
- The integrated luminosity for the HL-LHC is 3000 fb^{-1} = 3 ab^{-1} at 14 TeV. A subsequent HE-LHC higher energy program may follow with a dataset assumed to be 15 ab^{-1} at 27 TeV.
- However, "*per se*", in spite of its huge progress, HL-LHC, even if followed by HE-LHC, requires also other further extensions.
- While the Zo and W's that are vectors, the Higgs is a *scalar (spin = 0)* for instance characterized by a much stronger coupling when initiated from muons rather than from electrons.
- The Higgs sector (Ho) — no doubt — should follow the previously well-known observations of the Zo and the W's, where the initial search and discovery with the P-Pbar collider had been followed by the systematic lepton studies with LEP.

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 typical 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, $3\,\text{ab}^{-1}$	8%	10%	15%

← Ultimate st.dev. at LHC

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

SUSY tan(β)>5

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

Composite Higgs

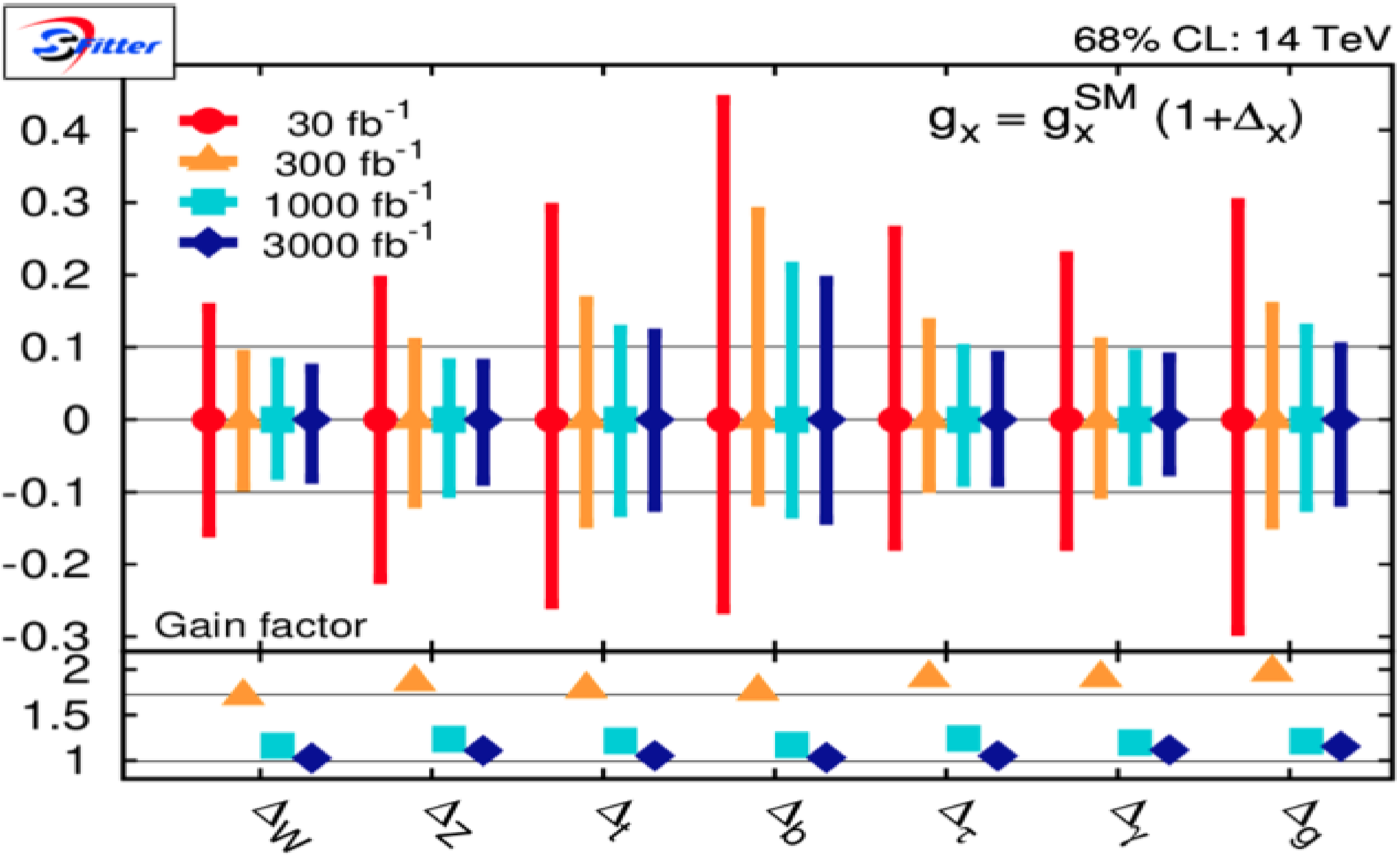
$$\frac{g_{hgg}}{g_{h_{\rm SM}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2, \qquad \frac{g_{h\gamma\gamma}}{g_{h_{\rm SM}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \text{TeV}}{m_T}\right)^2$$

Top partners

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

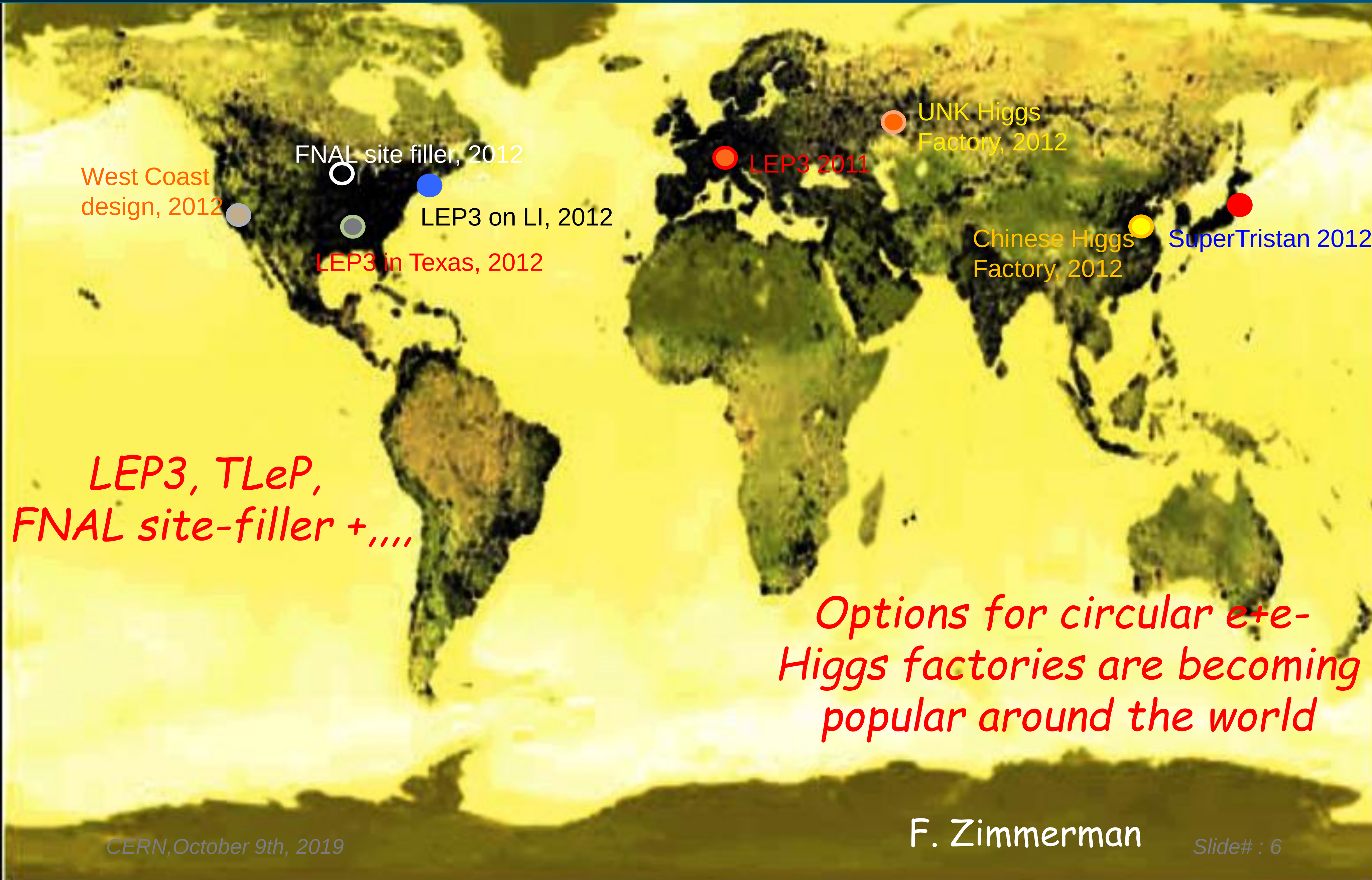
arXiv:1206.3560v3 [hep-ph] 27 Sep 2012

Expected LHC gain factors as a function of the rate



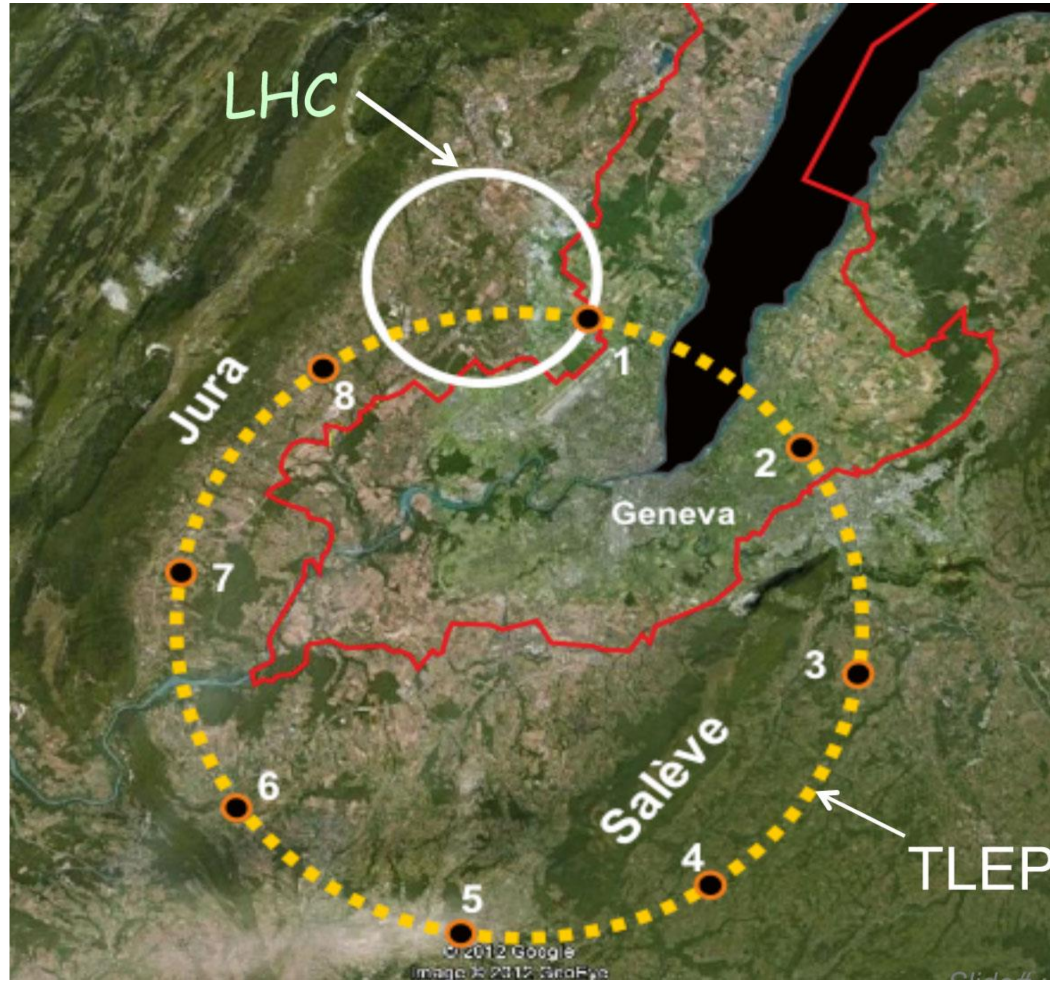
For 3000 fb^{-1}, LHC estimates are expected to improve only by a factor less than a factor 2.

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



Conventional e+e- Ring or Linear Collider ?

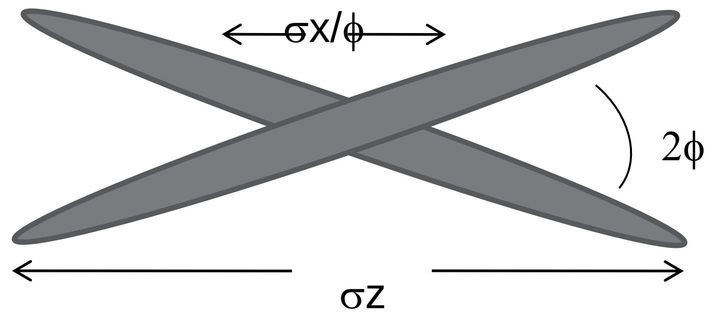
- Several e+e- projects have been described in huge new tunnels. Either (a) a relatively conventional *Collider Ring* and (b) a *Linear Collider (ILC)* are possible.
- As (a) we quote the FCC-ee from CERN of 100 km (3.7 x LEP), in the Geneva area.
- The study comprises a 90-400 GeV e+e- machine (FCC-ee)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



ILC, CLIC, NLC, JLC +….

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 such luminosity (factor ≈ 500 x LEP2) and power consumptions (factor 5 x LEP2) the main cures are
  - Huge ring (100 km for T-LEP)
  - Extremely small vertical emittance, with a beam crossing size the order of 0.01 μ (it has been 3 μ for LEP2)
- *The performance is at the border of feasibility (E_{cm}≈ 250 GeV).*
- *However the H_o width of ≈4.5 MeV cannot be directly observed*

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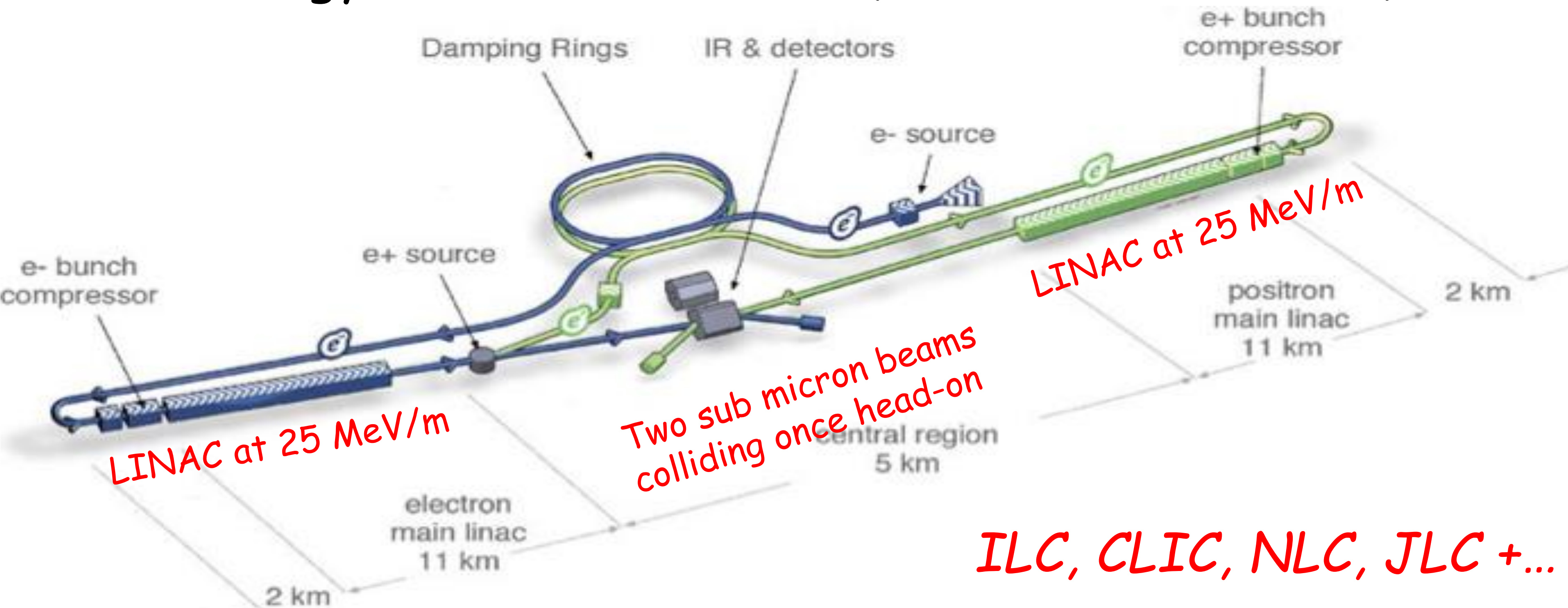
The Linear Collider option

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



ILC, CLIC, NLC, JLC +...

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

A muon collider as an optimal alternative

- Muons combine a "point-like" electron-like nature with a larger mass immune to radiation.
- ***A $\mu+\mu-$ collider*** is therefore highly preferable because of its small dimension which permits the utilization of an existing site.
- However it demands a substantial R&D in order to produce adequate compression in 6D phase space of the muon beams.
- To this effect an **additional experimental program based on a small Cooling Ring should be initiated.**

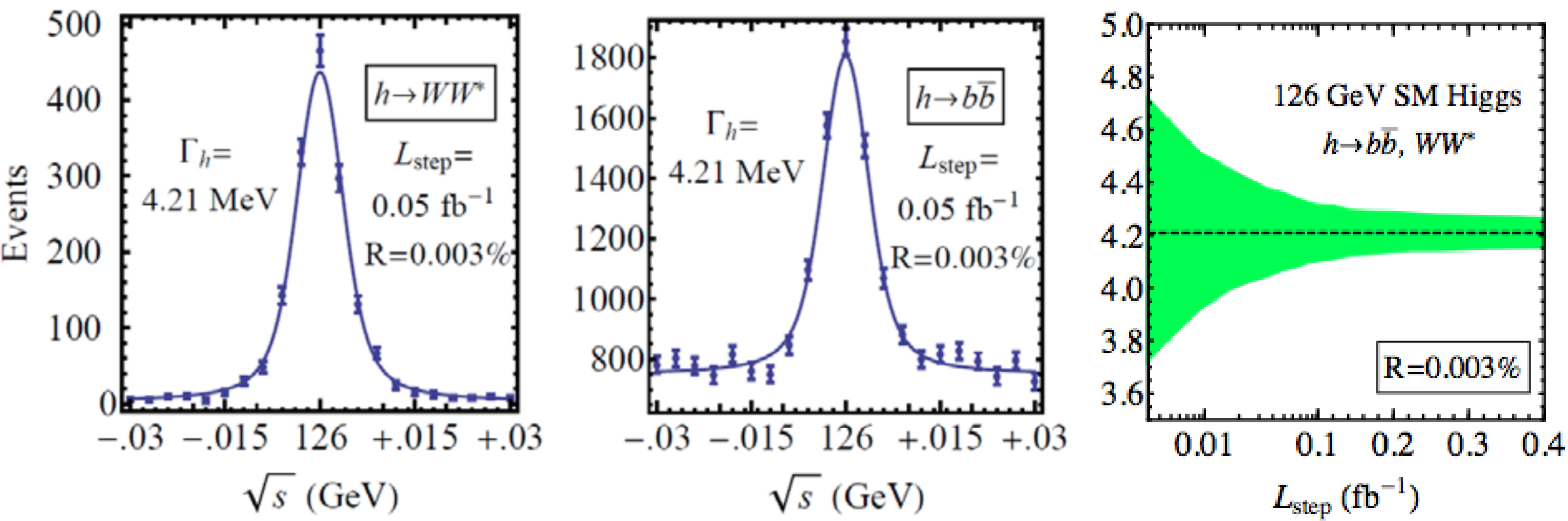
Two main future alternatives for the Higgs physics

- Two adequate alternatives of a $\mu+\mu-$ collider will be discussed:
  - the s-channel resonance at the Ho mass, to study with ≈ 40'000 fb and L > 10^{32} all decay modes with small backgrounds;
  - A higher energy collider, eventually up to √s ≈ 0.5-1 TeV and L > 10^{34} to study all other Higgs processes of the scalar sector.
- The colliding beams ring can easily fit within existing locations:
  - For √s = 126 GeV the ring *radius is ≈ 50 m* (about 1/2 of the CERN PS or 1/100 of LHC) but with the *resolution ≈ 0.003%*
  - For √s = 0.5 TeV the corresponding ring *radius is ≈ 200 m* (about twice the CERN PS) and the *resolution ≈ 0.1 %*
- Two $\mu+\mu-$ bunches of 2 x 10^{12}ppp can likely be produced by a high pulsing rate of a few GeV protons at ≈ 5 MWatt.

√s = 125.5 GeV : the Higgs muon resonance

- Signals and backgrounds for H → WW∗, and bb with energy resolution R = 0.003%. 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	

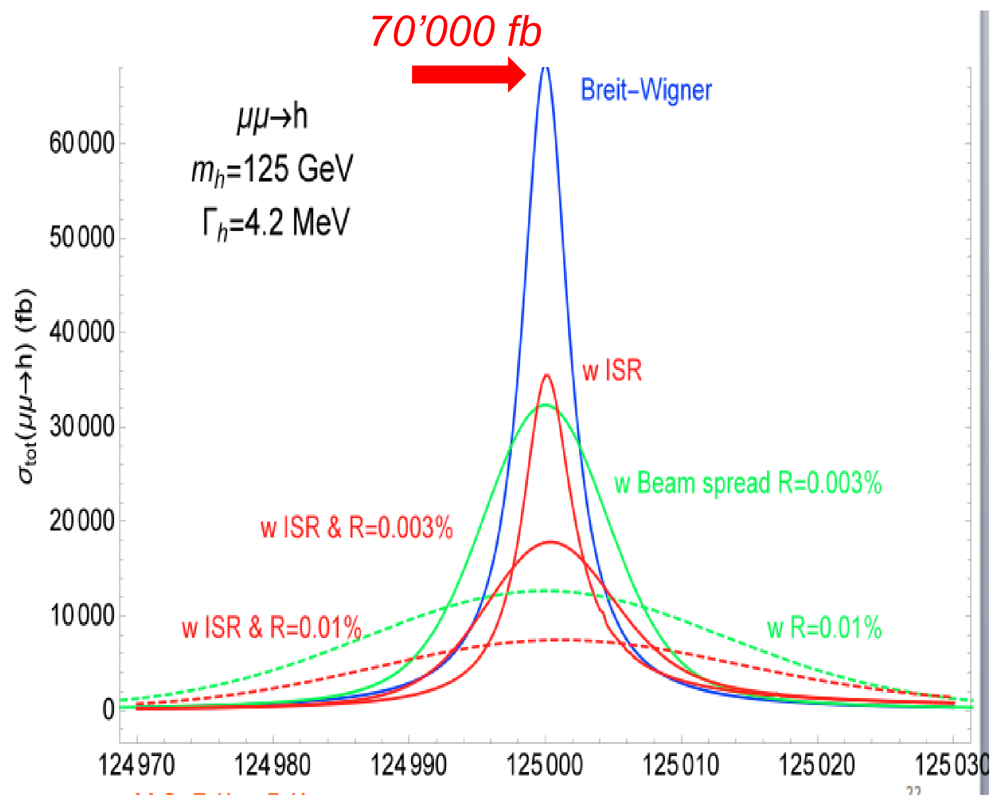


arXiv:1210.7803 [hep-ph].

Comparing μ+μ- and e+e- at the Ho resonance peak

- The narrow Ho width may be quantified convoluting the Breit-Wigner resonance with a gaussian Beam Energy Spread (BES) and the Initial State Radiation (ISR) QED effects.
- The *μ+μ- cross sections* are 71 pb for resonance profile alone and of 10 pb and 22 pb with both BES and ISR and energy resolutions R = 0.01 % and R = 0.003 %. picobarn = 10^{-36} cm^2)
- The *e+e- cross sections* are 0.15 fb for both the BES and ISR effects and R = 0.01 %.
- *In these conditions (R = 0.01 %) the μ+μ- rate is ≈ 10'000 times the e+e- rate.*

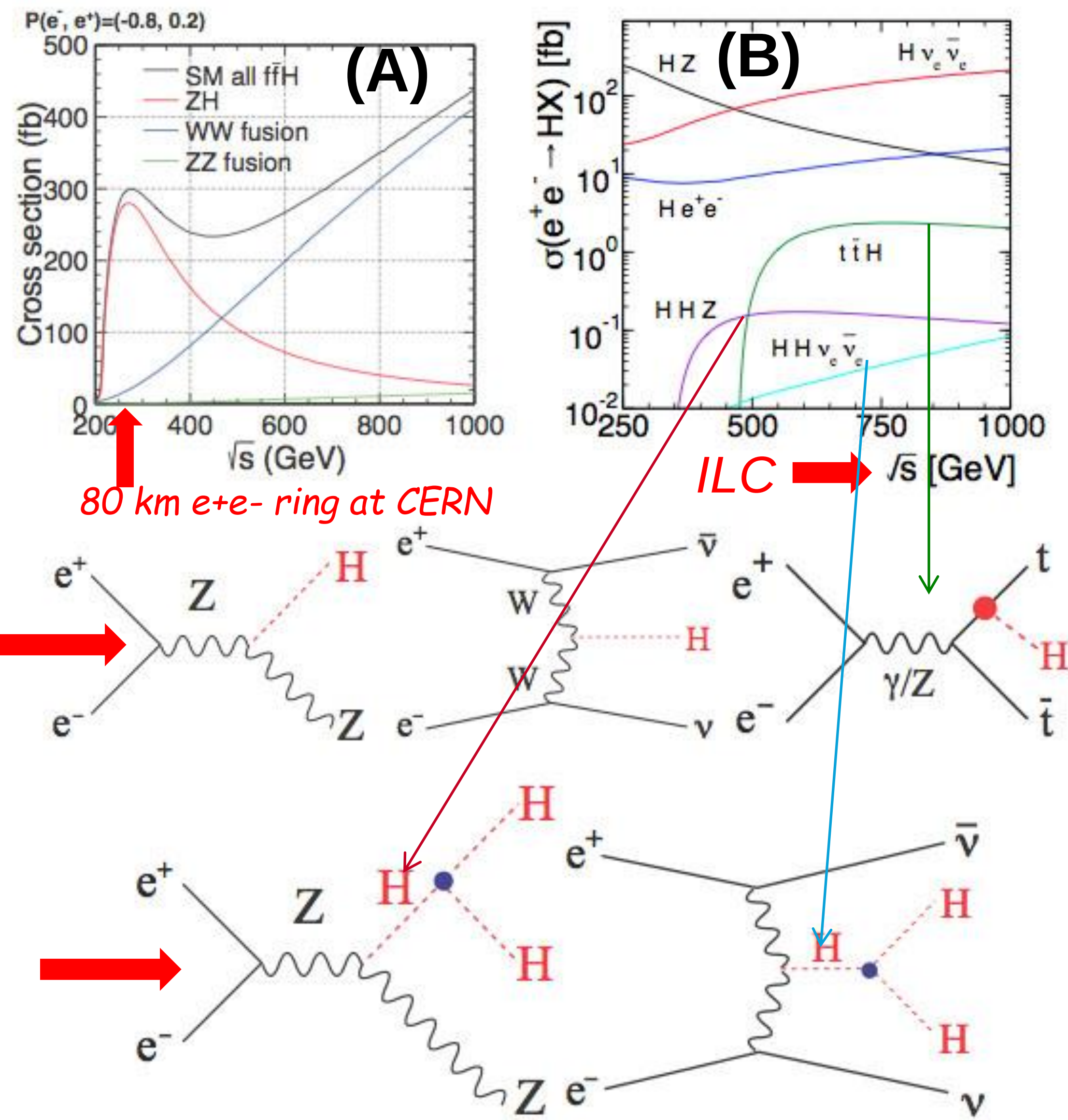
1 femtobarn (fb) = 10^{-39} cm^2



Huge BES an ISR correctins

Studies at the Ho peak are not entirely sufficient:

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



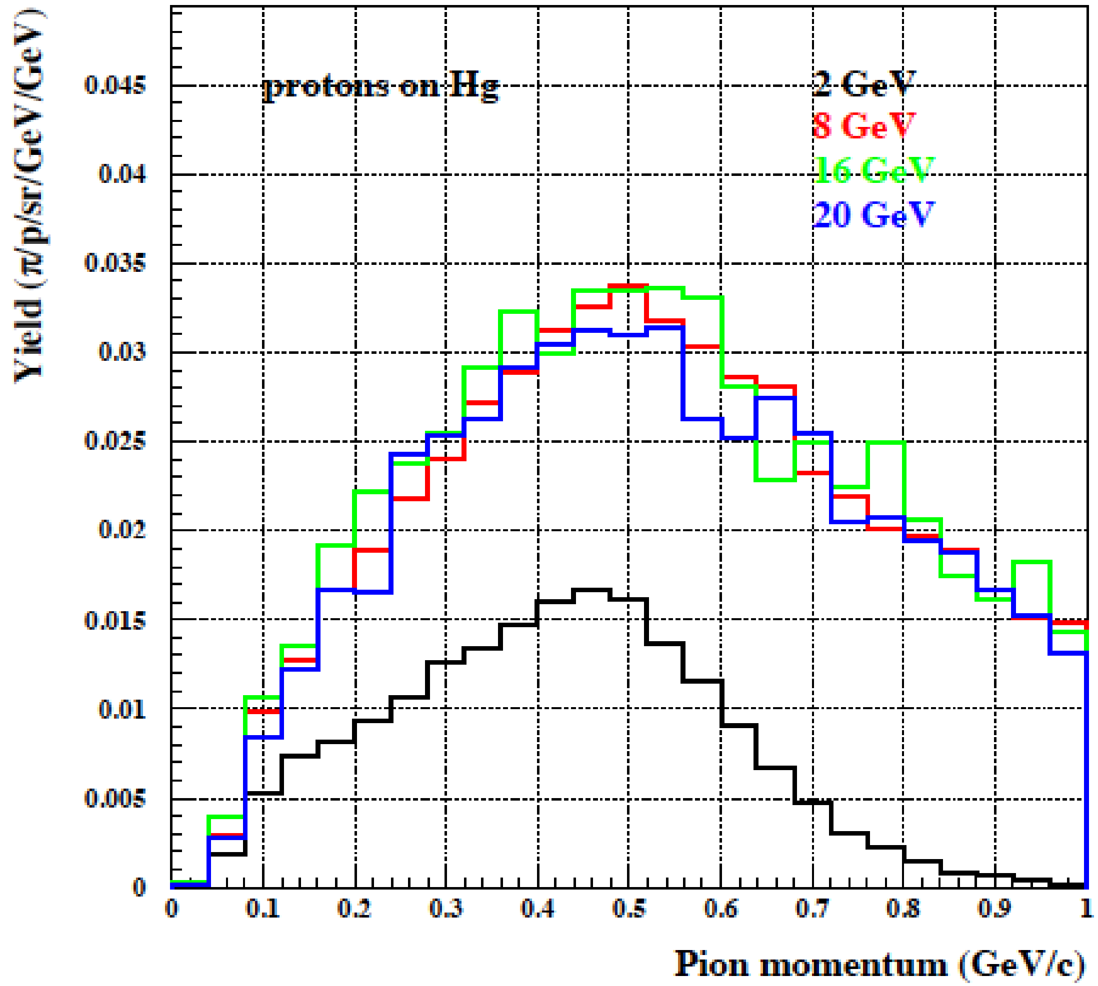
Lepton energies up to ≈ 0.5 - 1 TeV are necessary

Muon cooling

- "Ionization Cooling" was first proposed by Budker and by Skrinsky in the 60's and early 70's. However, there was little substance until Skrinsky and Parkhomchuk developed the idea.
- The initial ideas in the US were presumably due around 1980 to Cline and Neuffer. A Snowmass feasibility study was organized in 1996 and a US collaboration with DOE organization and funding was formed in 1997.
- As discussed already in 1994, for instance by Barletta and Sessler, muons may be produced by the two classes of processes:
  - *(A) production from protons, subsequently decaying into muons*
  - *(B) μ+μ- pairs from electro-production*.
- During the following two decades Neuffer, Palmer, Cline and many others have greatly expanded ionization cooling of process (A).
- These have been very important developments, but only very few verifying experimental tests have been performed.

Process (A): choosing the proton energy

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



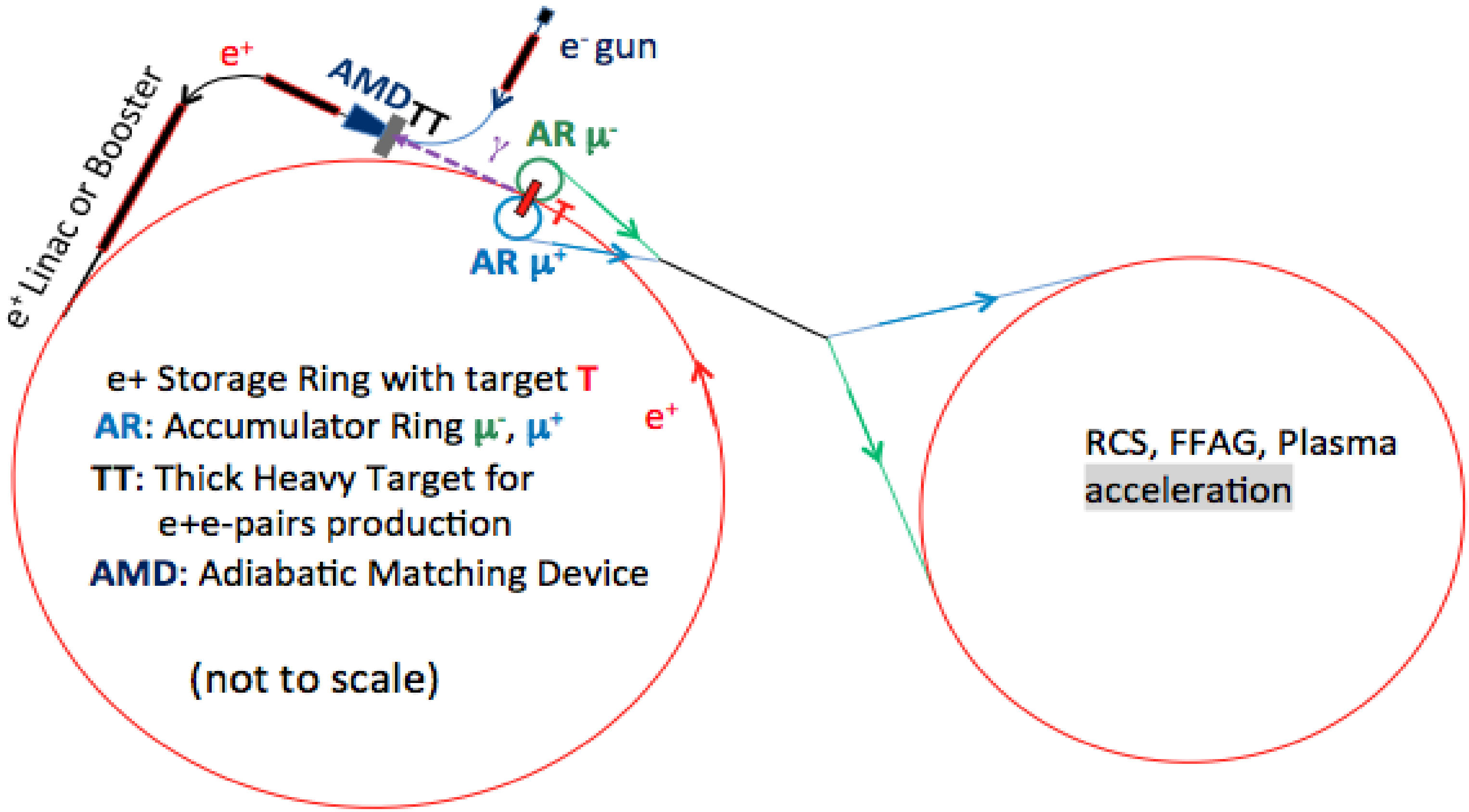
P. Sala: prediction

Process (B)

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

The LEMMA project

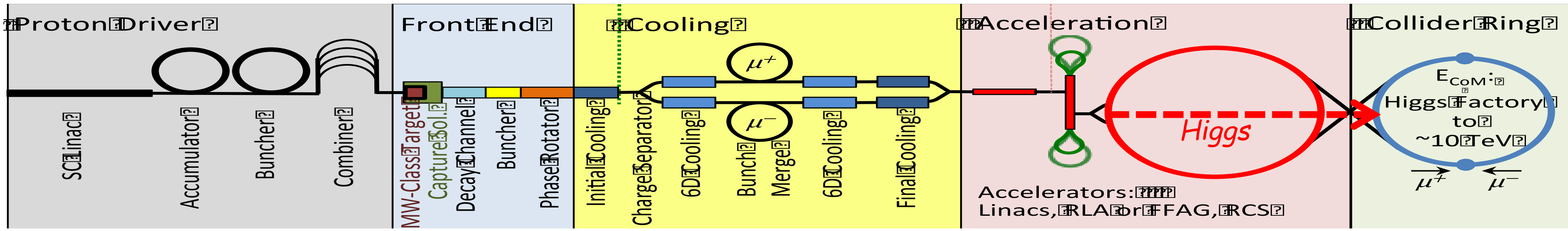
- Low EMittance Muon Accelerator (LEMMA) is based on muon pair production by a positron beam impinging on electrons at rest in a target, constrained into a very small longitudinal and transverse phase space regions.



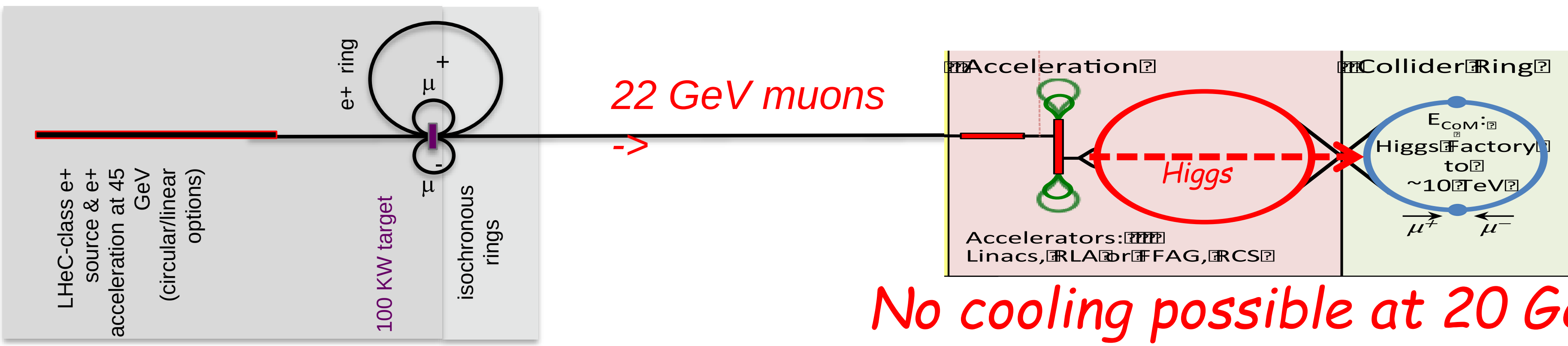
Comparing (A) with (B)

6D cooling at 220 MeV/c

(A)



(B)



No cooling possible at 20 GeV!

From Boscolo et al

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

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

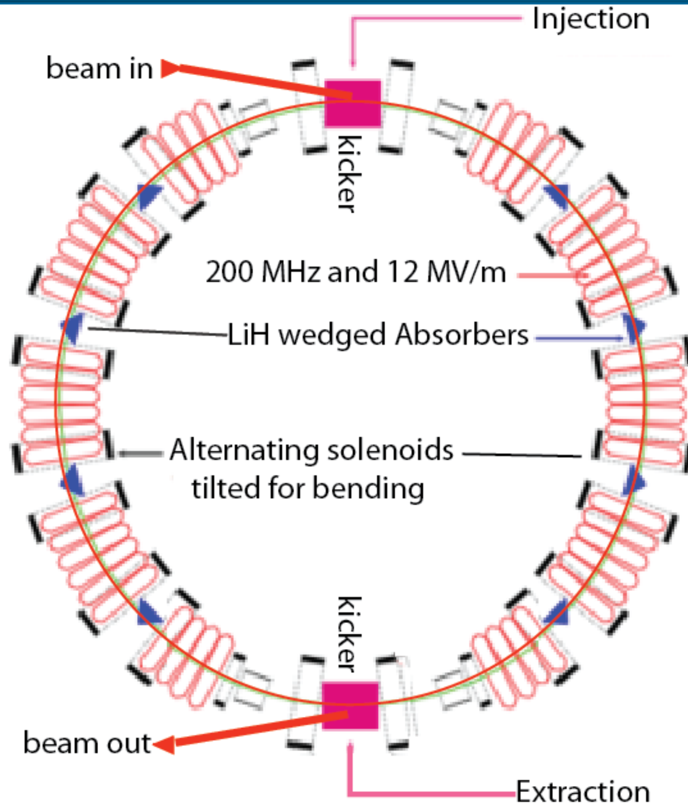
The realization of the Initial Cooling Experiment

- Physics requirements and the studies already undertaken with muon cooling suggest that a next step, prior to, but adequate for a specific physics program *could be the practical realization of an appropriate cooling ring demonstrator.*
- Indicatively this corresponds to the realization of an unconventional *tiny ring of 20 to 40 meters circumference* in order to achieve the theoretically expected longitudinal and transverse emittances of asymptotically cooled muons.
- The injection of muons from pion decays could be coming from some existing accelerator at a reasonable intensity.
- The goal is to prove experimentally the full 3D cooling.
- The other facilities, namely (1) the pion/muon production, (2) the final, high intensity cooling system (3) the subsequent muon acceleration and (4) the accumulation in a storage ring could be constructed later and only after the success of the initial cooling experiment has been confirmed at a lower cost.

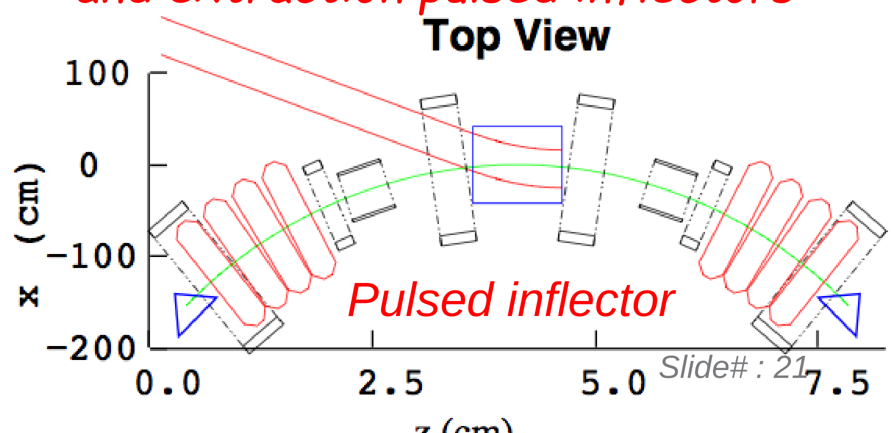
The RFOFO Ionization Cooling

- The design is based on solenoids tilted in order to ensure also bending. The LiH absorbers are wedge shaped to ensure longitudinal cooling.

Circumference	33	m
Total number of cells	12	
Cells with rf cavities	10	
Maximum axial field	2.77	Tesla
Coil tilt angle (degree)	3	degr
Average vertical field (T)	0.125	Tesla
Average momentum	220	MeV/c
Minimum transverse beta function	38	cm
Maximum dispersion function	8	cm
Wedge opening angle	100	degr
Wedge thickness on-axis	28	cm
Cavities rf frequency)	201.25	Mhz
Peak rf gradient	12	MV/m
Cavities rf phase from crossing	25	degr

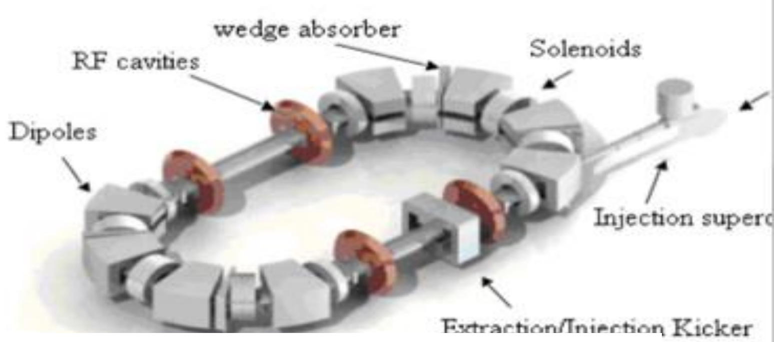


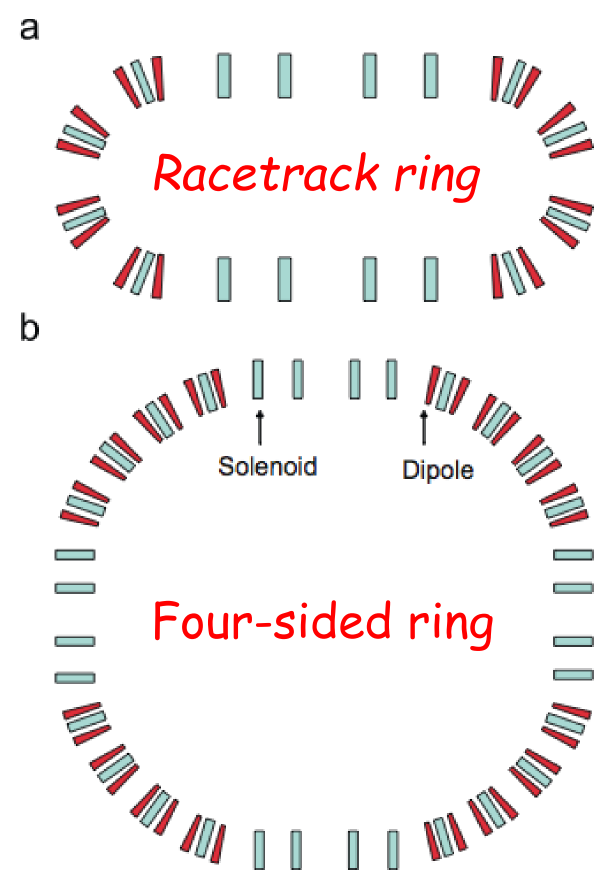
Two separate, 180 apart injection and extraction pulsed inflectors*



A solenoid-dipole ring cooler for a muon collider

- Another exemplificative cooling 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.





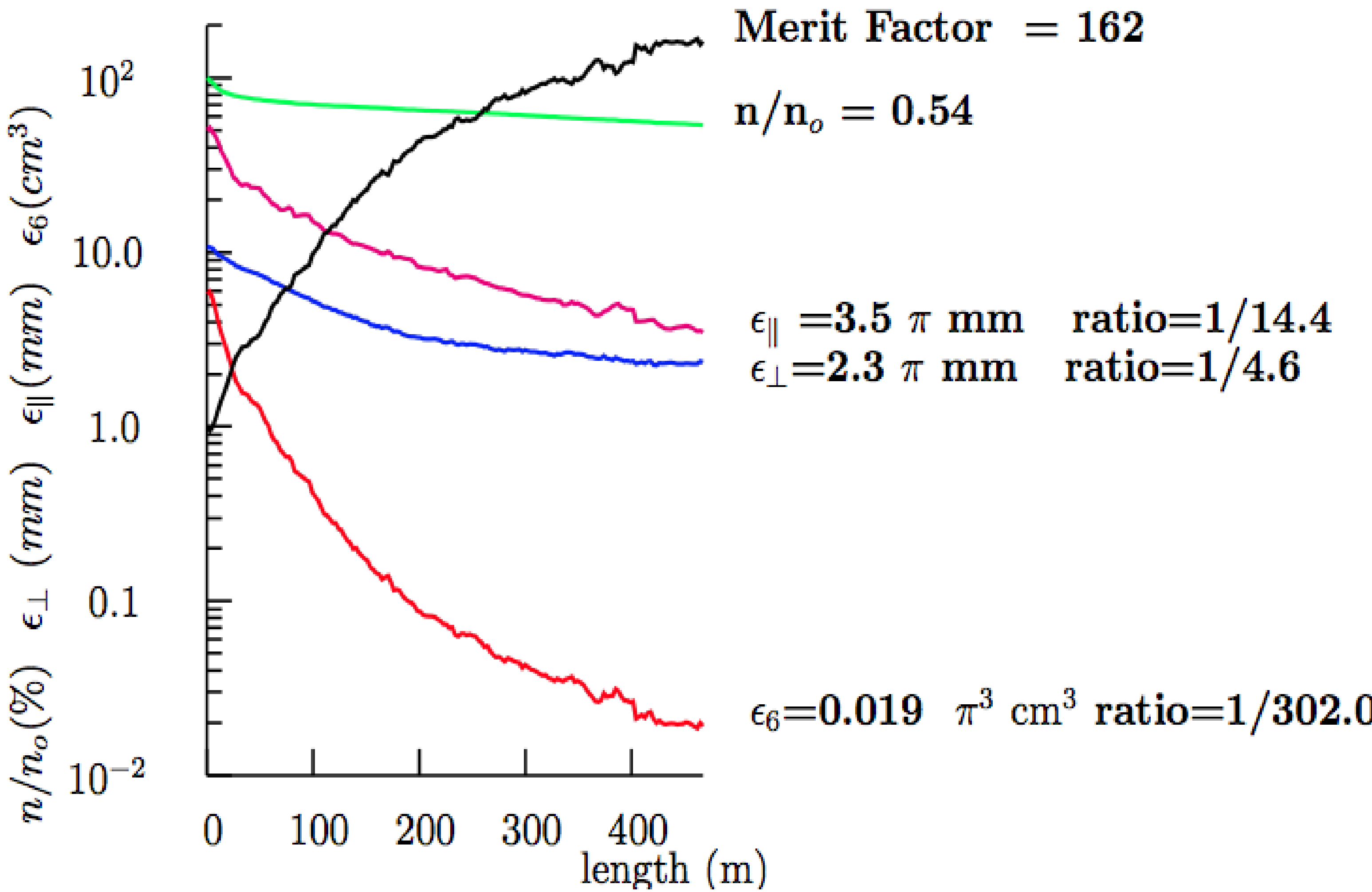
Parameters of the four-sided and achromatic ring cooler.

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

Properties of a "RFOFO" Cooling Ring

- The muon emittances of the RFOFO ring after the first linear rotation may be $e_{V,H}$ = 20 (π) mm rad and e_L = 30 (π) mm rad with a r.m.s. energy spread is about 10 %.
- After cooling, the ultimate normalized hydrogen driven equilibrium emittances at 250 MeV/c are expected to be $e_{V,H}$ = 0.4 (π) mm rad and e_L = 1.0 (π) mm rad.
- This corresponds to the huge 6D compression factor of 50 x 50 x 30 = 75'000, i.e. a Merit Factor M = *(Initial 6D)/(final 6D) x transmission* of the order of 15'000 = 75'000/5 with a total number of muons due to decay losses of a factor 5.
- In an estimated *"RFOFO" Cooling Ring*, a merit factor of 162 had been observed after 16 turns of the ring.
- Doubling the number of turns of the RFOFO cooling ring will ensure the required compression to attain the required equilibrium of emittances after the first linear rotation .

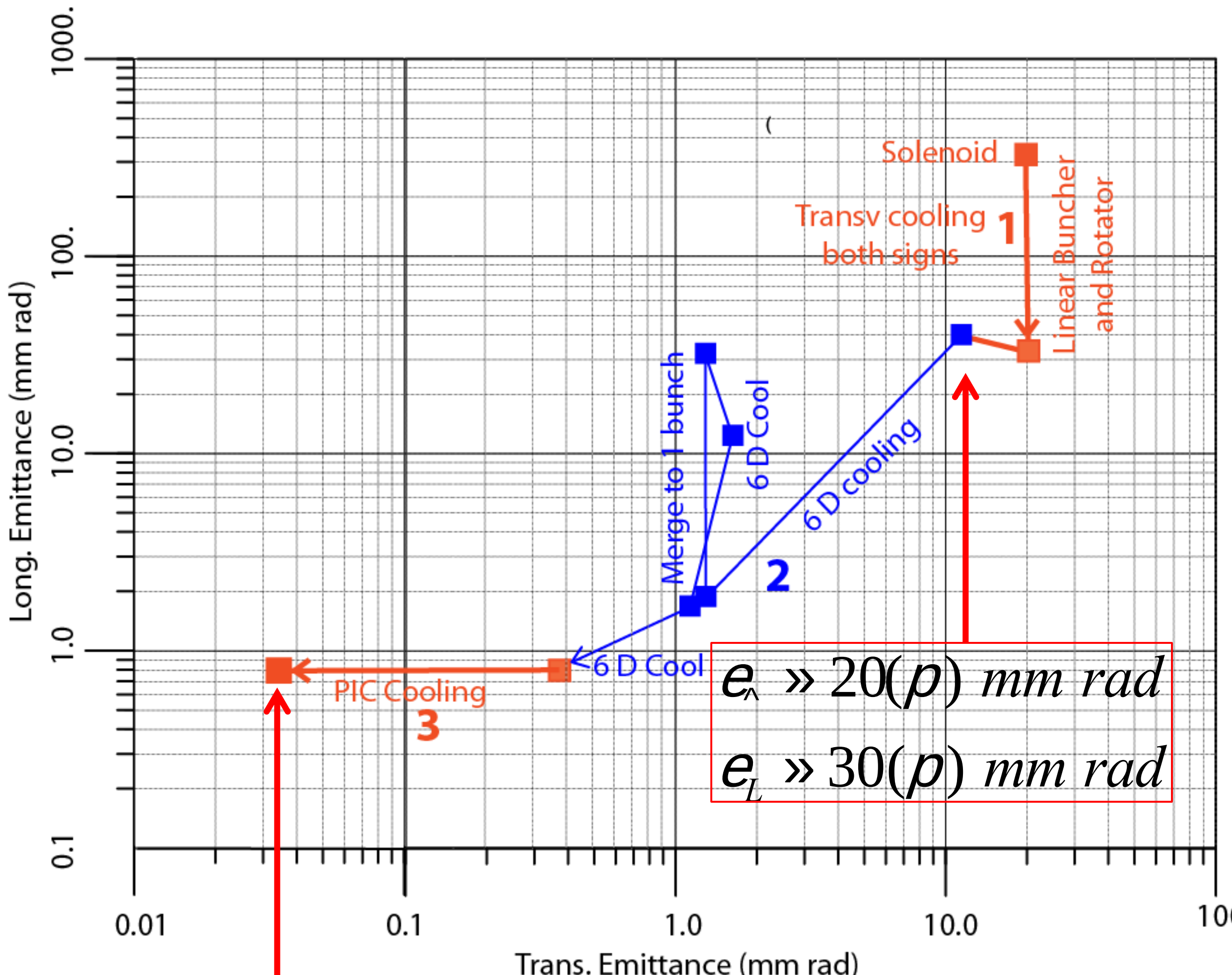
- Predicted merit factor of a *"RFOFO" Cooling Ring* after 16 turns and a muon survival of 54% (Palmer et al.)



The complete cooling process

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

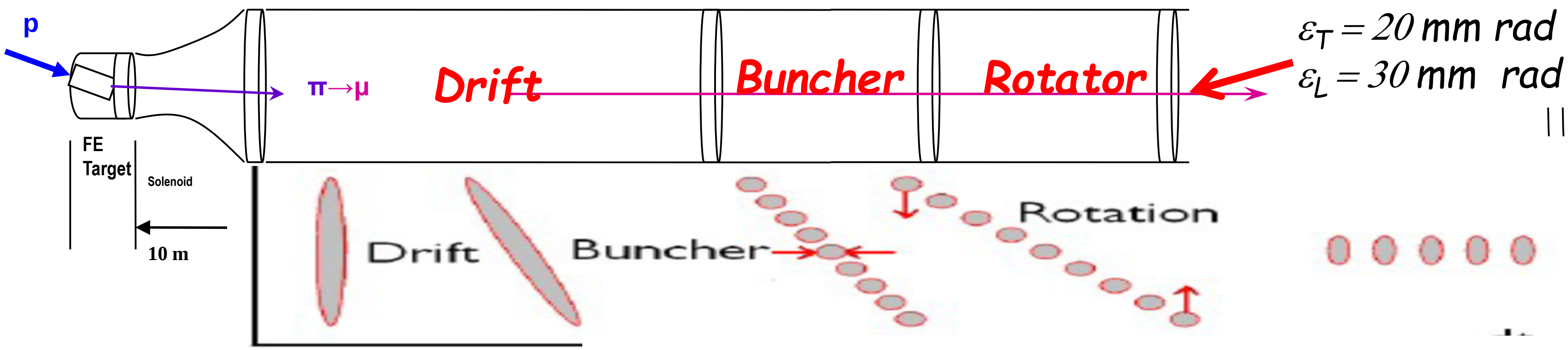
1. Linear transverse cooling of both signs and small Δp increase.
2. Ring cooling in 6D with B brings the μ+ and μ- to a reasonable size Merging and cooling to single bunches
3. Parametric Resonance Cooling (PIC), where the elliptical motion in *x-x'* phase space has become hyperbolic.



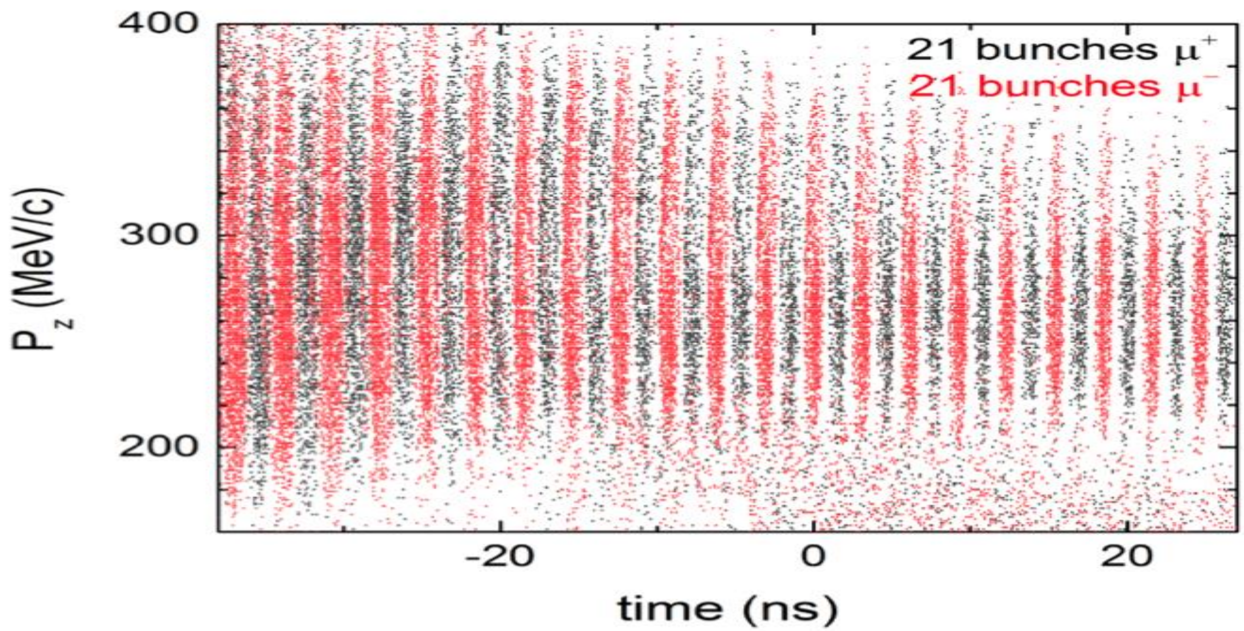
$\epsilon_\perp = 0.04(\pi)\, mm\, rad \quad \epsilon_L = 1.0(\pi)\ mm\ rad$

Step 1.-The initial beam transport

- Initially, there is a small spread in time, but a very large spread in energy. The target is followed by a drift space, where a strong correlation develops between time and energy.

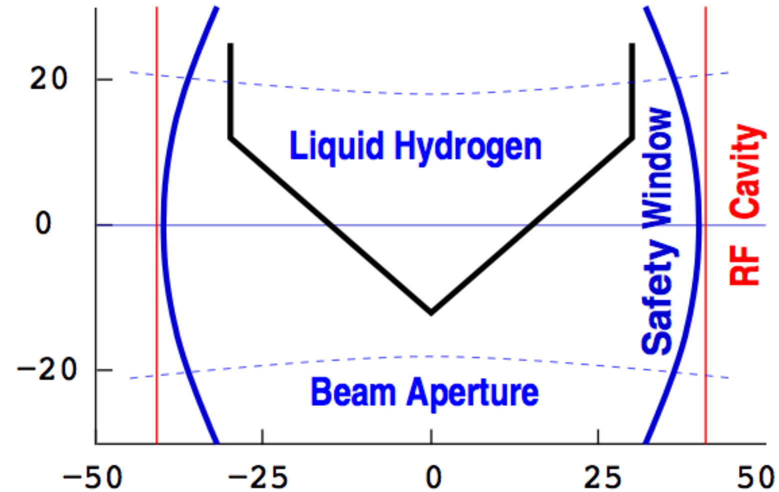


- Strings of both signs are accumulated since half-way between each of the stable RF phase for one sign there is a stable phase for the opposite sign.



Step 2.- The 6-D cooling

- The linear initial muon processing facilitates the further subsequent injection in a cooling ring.
- Secondary protons are removed by an absorber and two cooling rings separate the charges. A wedge absorber is placed such that high momenta pass through more material than low momenta, so that all three dimensions can be cooled.
- The initial several bunches of each sign can be initially cooled and later, at an intermediate stage, bunch rotated and each accumulated in one bunch which is extracted at the end of the cooling process.
- The wedge has a central thickness of 28 cm, a total wedge opening angle of 100º and is rotated 30º from the vertical to match the maximum of the dispersion.

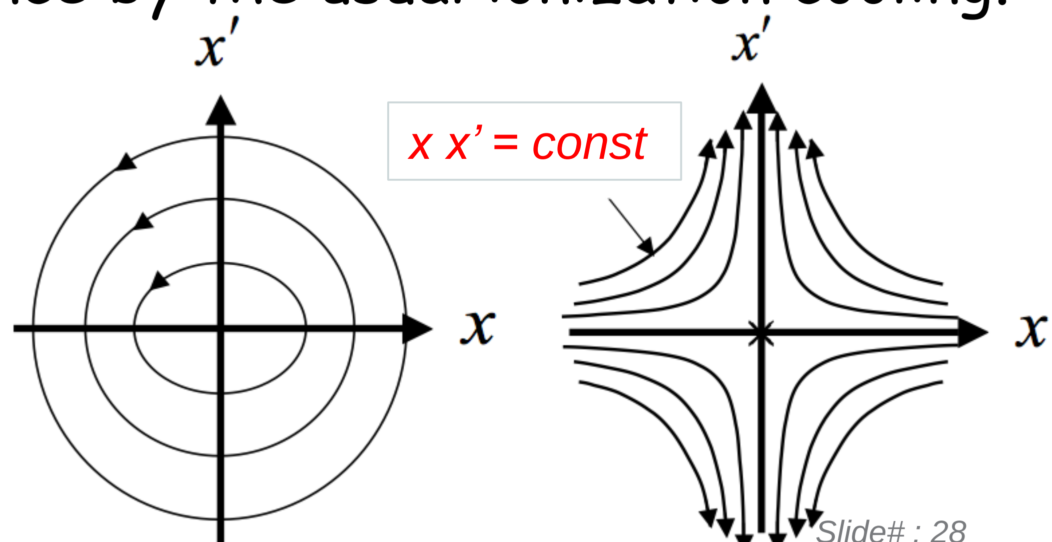


R. Palmer et al. arXiv:physics/0504098 v1, 2005

Step 3.- PIC, the Parametric Resonance Cooling

- Ionization cooling: adding a second parametric resonance ring is expected to lead to a beam with much smaller transverse sizes.
- A linear magnetic transport channel has been designed by Ya.S. Derbenev et al. where a half integer resonance is induced such that the normal elliptical motion of particles in x-x' phase space becomes hyperbolic, with particles moving to smaller x and larger x' at the channel focal points.
- Thin absorbers and RF placed at the focal points of the channel then cool the angular divergence by the usual ionization cooling.

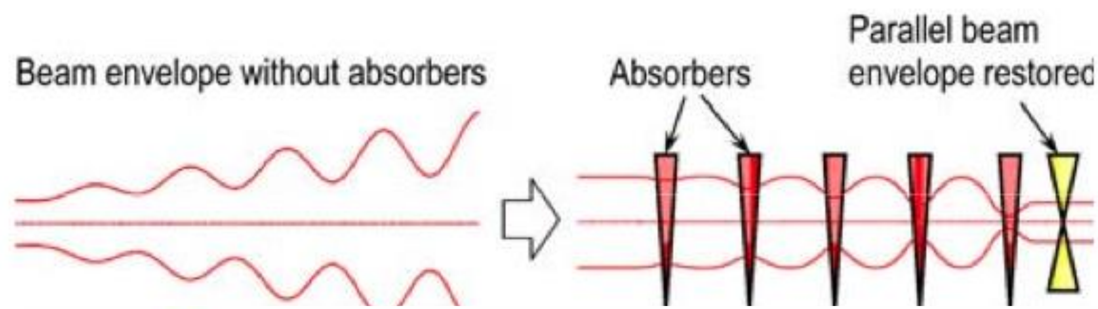
LEFT ordinary oscillations
RIGHT hyperbolic motion induced by perturbations near an (one half integer) resonance of the betatron frequency.

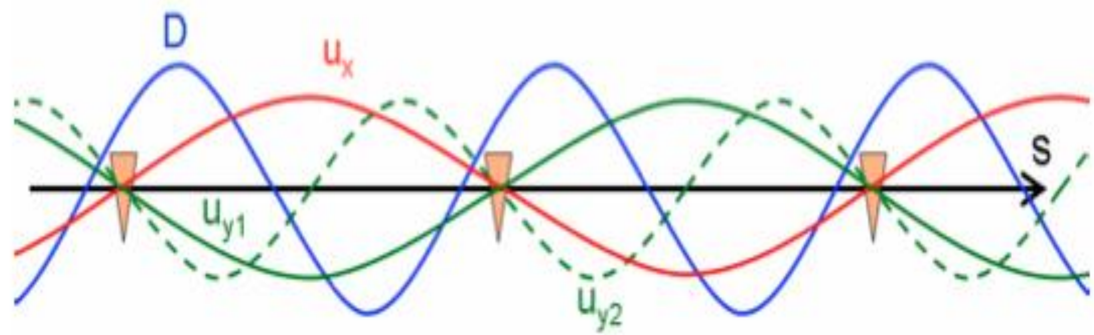


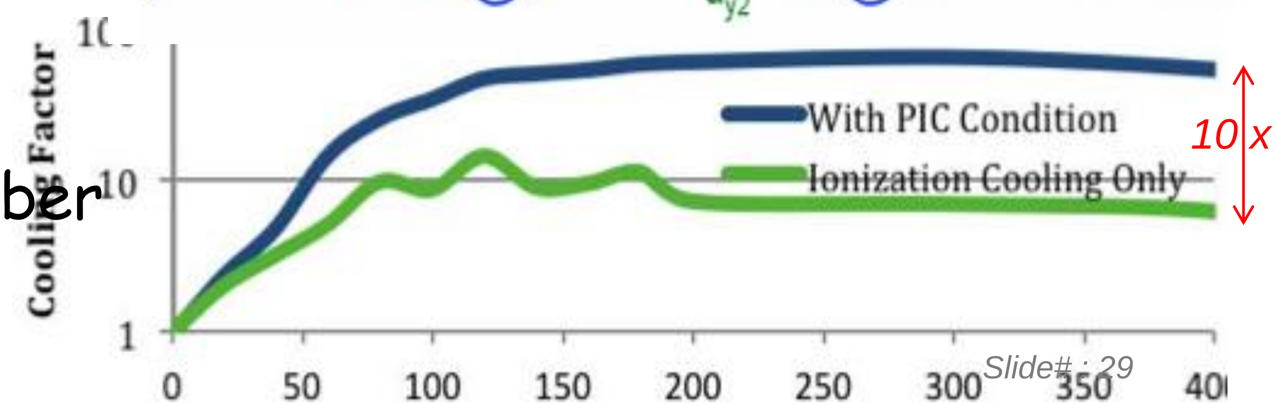
V. S. Morozov et al, AIP 1507, 843 (2012);

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 (with RF) by tapering the absorbers and placing them at points of appropriate dispersion, vertical β and two horizontal β□σ.
- Cooling factors (ratio of initial to final 6D emittance) with and without the PIC vs number of cells: *about 10x gain*







Comments on the cooling process

- A conventional muon cooling ring should present no unexpected behaviour and good agreement between calculations and experiment is expected both transversely and longitudinally
- The novel Parametric Resonance Cooling (PIC) involving instead the balance between a strong resonance growth and ionization cooling may involve significant and unexpected conditions which are hard to predict. Reported predictions are for $\approx 10^{10}$ p/bunch
- Therefore the experimental demonstration of the cooling must be concentrated on such a resonant behaviour
- On the other hand the success of the novel Parametric Resonance Cooling may be a premise for an optimal luminosity, since the expected Higgs rate is proportional to the inverse of the transverse emittance
- PIC may expect up to one order of magnitude transverse emittance decrement

Eatimated performance for the H°-factory at the ESS

- Two asymptotically cooled μ bunches of opposite signs collide in two low-beta interaction points with β*= 5 cm and a free length of about 10 m, where the two detectors are located.
- A peak collider luminosity of 4 x 10^{31} cm^{-2} s^{-1} is achieved *without PIC cooling*
- The bunch transverse rms size is 0.05 mm and the μ–μ tune shift is 0.086.
- The SM Higgs rate is ≈ 1,2 x 10^4 ev/year (10^7 s) in each detector.
- An arrangement with at least two detector positions is reccomended.

Proton kinetic energy	2.0	GeV
Proton power	5.0	MW
Proton event rate	56 =14x4	ev/s
Timing proton collisions	17.86	ms
Protons/collision	2.5×10^{14}	p/coll
Final muon momentum	62.5	GeV/c
Final muon lifetime	1.295	ms
Total μ surv. fraction	0.07	
μ+ at collider ring	2.93×10^{12}	μ/coll
μ- at collider ring	1.89×10^{12}	μ/coll
Inv. transv. emittance, ε_N	0.37	π mm rad
Inv. long. emittance	1.9	π mm rad
Beta at collision $\beta_x = \beta_y$	5.0	cm
Circumf. of collider ring	350	meters
Effective luminosity turns	555	
Effective crossing rate	29’970	sec-1
Luminosity no PIC	4.24×10^{31}	cm^{-2} s^{-1}
Luminosity + PIC (10 x)	4.2×10^{32}	cm^{-2} s^{-1}
Higgs cross section	3.0×10^{-35}	cm^2
Higgs @10^7 s/y, no PIC	**1.2×10^4**	**ev/y**
Higgs @10^7 s/y + PIC	**1.2×10^5**	**ev/y**
Higgs -> γγ, 10^7 s/y + PIC	≈ 2400	ev/y

Conclusions

- All the described activities may fit within the existing ESS site or eventually located at CERN or elsewhere (China).
  - *proton accumulator and compressor rings* with a radius of 35 m, transforming from 14 to 42 bunch/s;
  - A $\pi - \mu$ *linear decay channel* with both muon signs of about 100 m length converting muons to 250 MeV/c and Δp/p at ±10 %;
  - a pair of robust μ^+ and μ^+ *ionization-cooling rings* each with ≈ 6 m radius, compressing to two narrow bunches, eventually followed by two additional PIC cooling rings;
  - a fast *re-circulating LINAC acceleration* system of about few hundred m to bring muons to both required collision energies;
  - a *collider ring at 7 Tesla and* ≈ 50 m radius for √s = 126 GeV (1) and ≈ 200 m for √s = 0.5 TeV (2) with two two narrow muon bunches and two interaction points where detectors are located with ≈ 2x 10^{12} muons/pulse of each sign.

12'000 Higgs/y @10^7 s/y without PIC

Muon related backgrounds

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

Drozhdin, Mokhov et al.

The Higgs production colliders

- **Advantages**
  - Large cross sections σ ($\mu^+\mu^- \to h$) = 41 pb in s-channel resonance and $\mu^+\mu^- \to ZH$ of 0.2 pb at $\sqrt{s}$ = 500 GeV.
  - Small size footprint: it may fit within an existing site
  - No synchrotron radiation and beam strahlung problems
  - Precise measurements of line shape and decay widths
  - Exquisite measurements of all channels and tests of SM.
  - The cost of the facility, provided cooling will be successful, is less than 1/10 of one of the LHC.
- **Challenges.**
  - A low cost demonstration of muon cooling must be done first
  - Muon 2D and 3D cooling needs to be fully 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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Forget About Electrons And Protons; The Unstable Muon Could Be The Future Of Particle Physics

- https://www.forbes.com/sites/startswithabang/2019/08/22/forget-about-electrons-and-protons-the-unstable-muon-could-be-the-future-of-particle-physics/

Thank you !