Verso un Muon Collider

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Fisica delle Particelle, verso la nuova Strategia Europea

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Outline

- Why a Muon Collider?
- MAP studies
- LEMMA studies
- Backgrounds
- Other ideas?
- Conclusions

Bibliography

- ARIES Muon Collider Workshop, Padova (Italy), July 20 18
  https://indico.cern.ch/event/719240/
- MAP: dedicated JINST volume on "*Muon Accelerators for Particle Physics*"
  http://iopscience.iop.org/journal/1748-0221/page/extraproc46
- LEMMA:
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  - M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, "*Novel proposal for a low emittance muon beam using positron beam on target,*" NIM in Physics Research A, vol. 807, pp. 101-107, 2016
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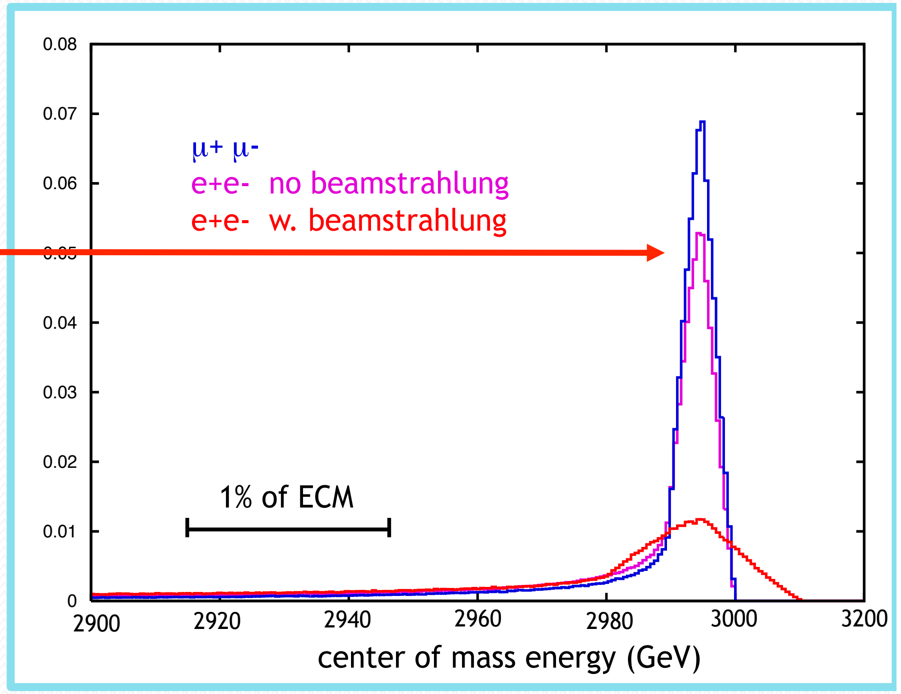
$\mu^+\mu^-$ Colliders vs e^+e^- Colliders

- Muon lifetime is 2.2 μs lifetime at rest
  → fast acceleration after production
- Synchrotron Radiation → Energy loss per turn negligible
- Effect of ISR and beamsstrahlung negligible



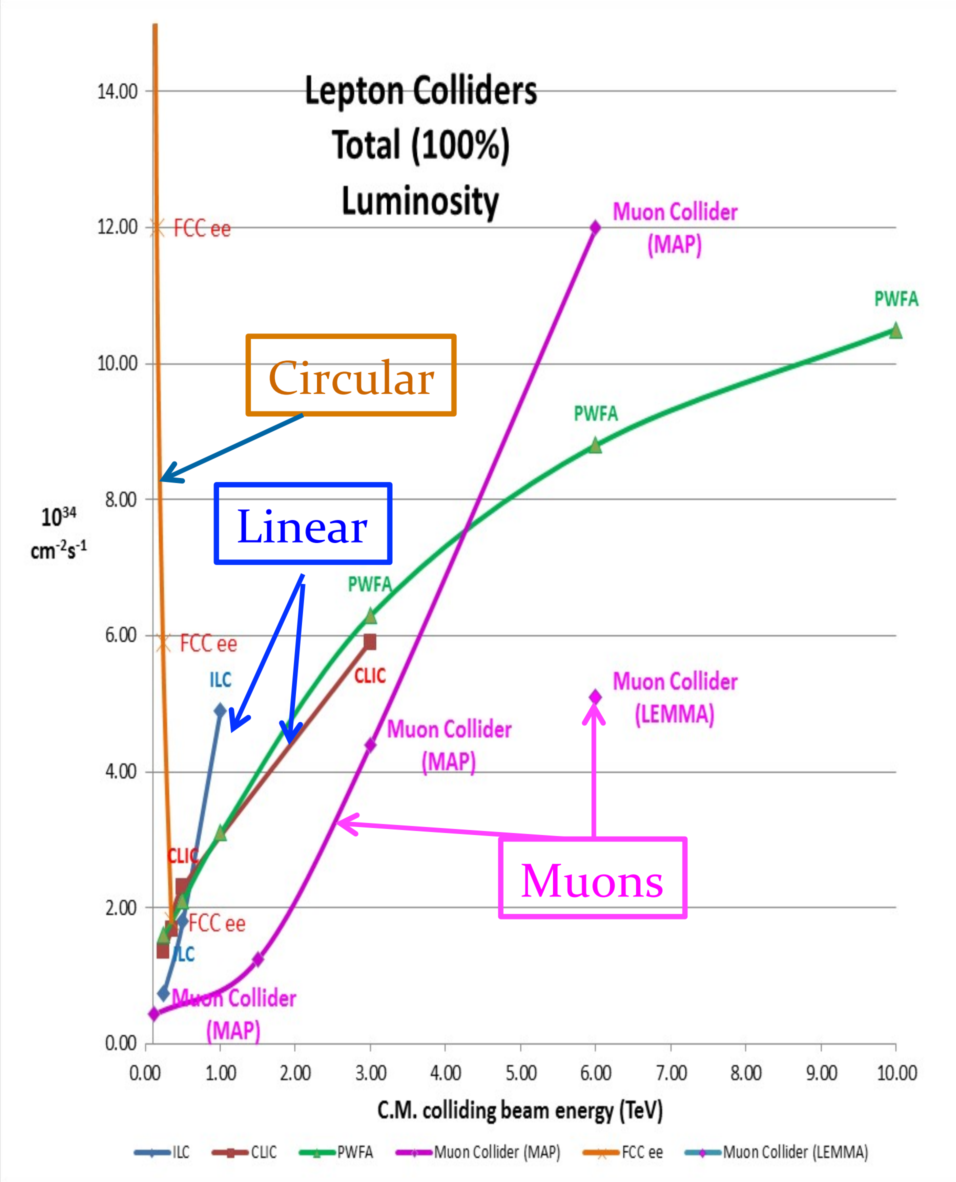
- Muon beams enable colliding beams with very small energy spread → important for Higgs production @125 GeV
- A MC can probe the Higgs resonance directly
  - luminosity required is not so large
- Cross section for *$\mu^+\mu^-$ ◊ Higgs* scales as m^2 of the colliding particles:

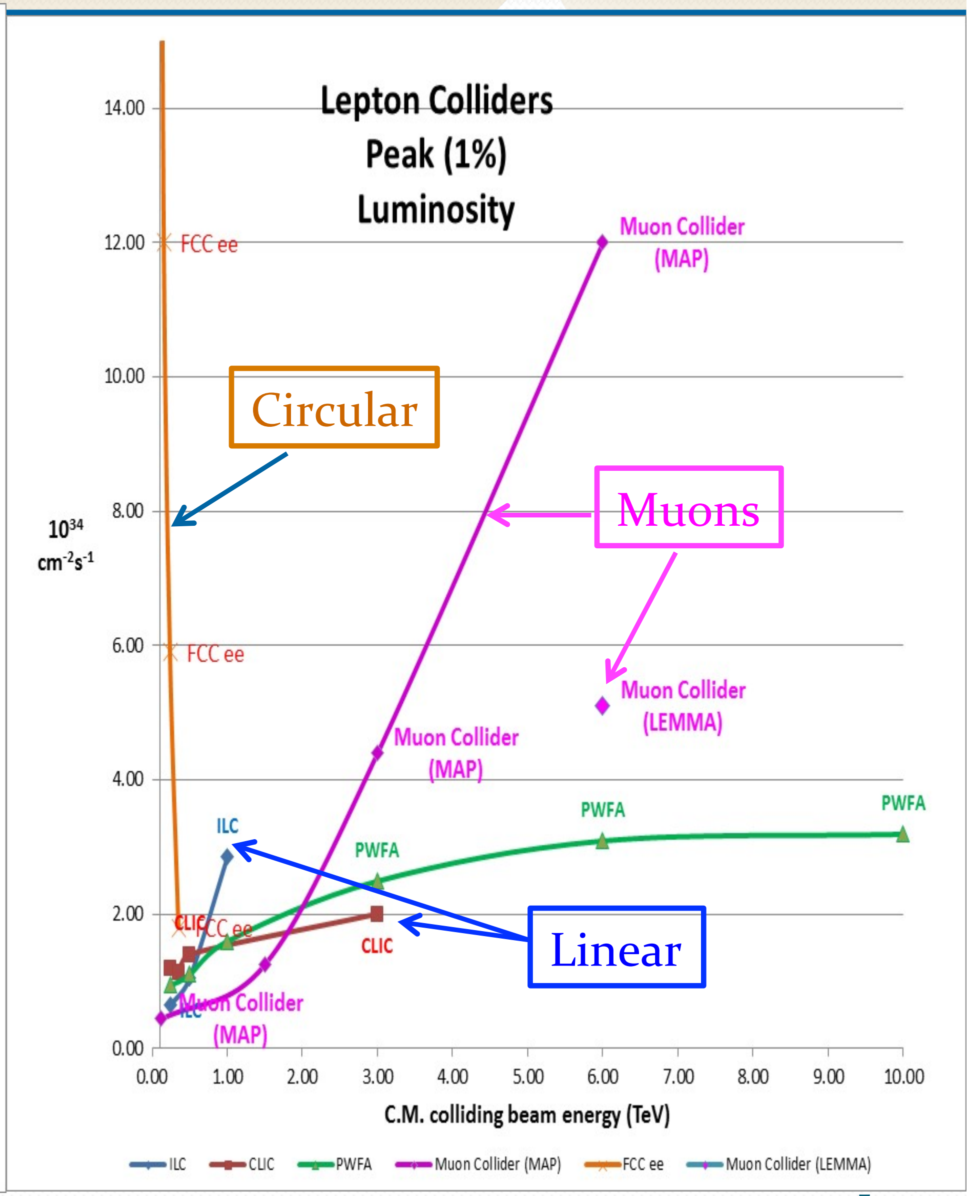
$$\sigma\left(\mu^+\mu^- \to H\right) = \left(\frac{m_\mu}{m_e}\right)^2 \times \sigma\left(e^+e^- \to H\right) = \left(\frac{105.7\,MeV}{0.511\,MeV}\right)^2 \times \sigma\left(e^+e^- \to H\right)$$

$$\sigma\left(\mu^+\mu^- \to H\right) = 4.28 \times 10^4 \sigma\left(e^+e^- \to H\right)$$

→ **A factor of 40000**

Lepton Colliders Luminosity

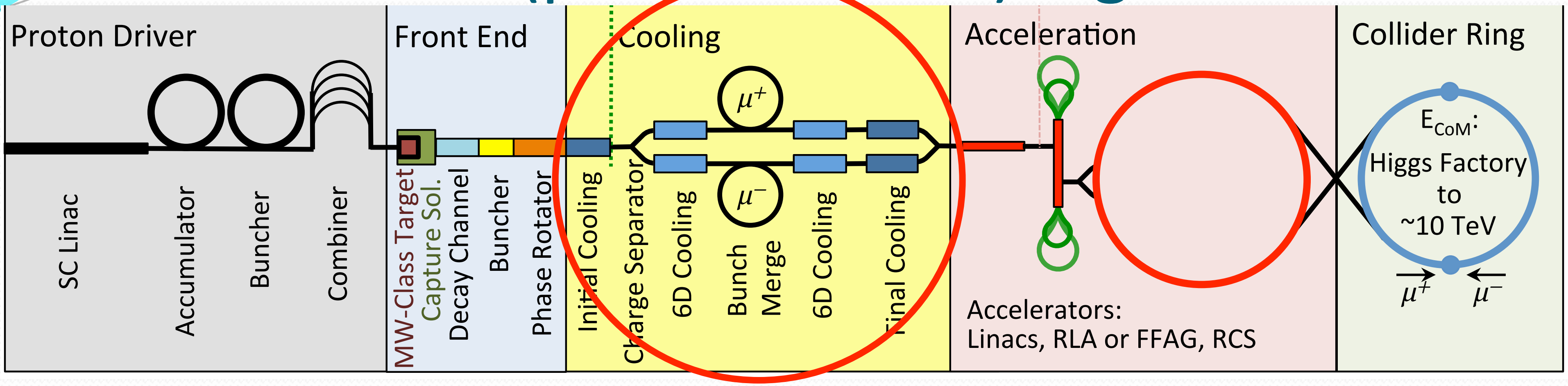




MAP studies

- Idea of MC first introduced in the early 1980's
- Further developed by of world-wide collaborations culminating in 2011 with the US Muon Accelerator Program (MAP) to develop the concepts and address the feasibility of novel technologies required for MC and Neutrino Factories based on **proton driver source**
- Most μ facility designs are based on μ production as tertiary particles by decay of **π** created with an intense, typically several MW, proton beam interacting a heavy material target
- In order to achieve high luminosity in the collider, the resulting μ beam, produced with low energy and hence a limited lifetime, with very large transverse and longitudinal emittances, has to be cooled by approximately five orders of magnitude in the 6D phase space
- Then it has to be accelerated rapidly to mitigate μ decays

Muon Collider (proton source) ingredients



Proton driver: producing high-power multi-GeV bunched H-beam. For a conversion efficiency of about 0.013 μ per proton*GeV, a **proton** beam in the 1-4 MW power range at an energy of 6.75 GeV provides the number of μ required

Buncher: **Accumulator** (forms intense and short (~2 ns) proton bunches) + **Compressor** (rotates bunches 90° in longitudinal phase space) Lines depending on **p** E

π prod. target: must stand **p** high power. Immersed in high solenoidal field to capture and guide π into the decay channel

Front-end: decay channel with solenoidal field and RF cavity, captures μ in a bunch train, time dependent acceleration (different E)

Initial cooling channel: ionization cooling to reduce 6D phase space by a factor of 50, so the muon beam is inside first acceleration stage acceptance

Other ionization cooling stages: to allow for MC high luminosity beam parameters

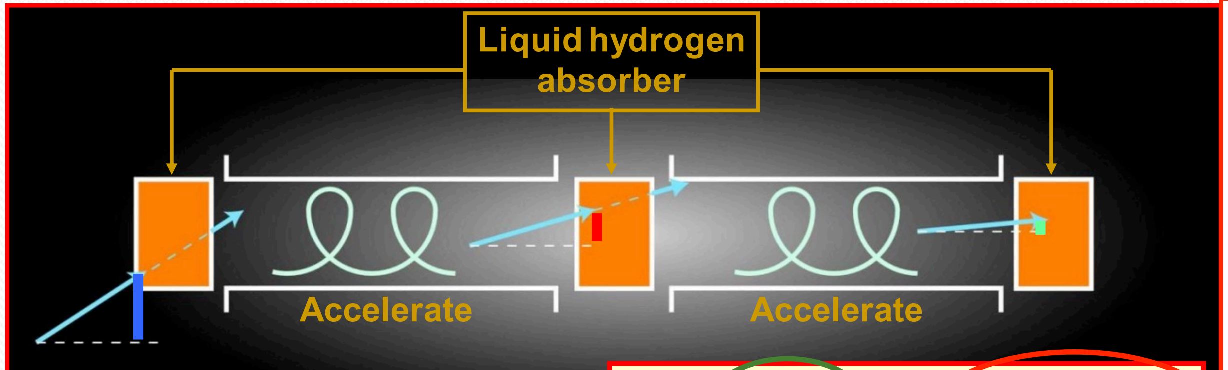
Fast muons acceleration stages, for example Recirculating Linear Accelerator (RLA), Fixed Field Alternate Gradient (FFAG), or Rapid Cycling Synchrotron (RCS)

Muon Collider Rings, 0.25 to 10 TeV c.o.m.

Principle of ionization cooling

- Unique challenge of cooling is muon short lifetime
  - Cooling must take place more quickly than any of the cooling methods presently in use → energy loss in absorbers with RF cavities to replace ΔE, all immersed in high solenoidal field (>30T !!) to focus the beam
  - Net effect: transverse cooling, reduction in p_t at constant p_l

32T SC/34 mm bore with YBCO ceramic by NationalMagLab, Florida Univ.



Emittance change per unit length

$$\frac{d\varepsilon_n}{dX} = \frac{-\varepsilon_n}{\beta^2 E}\left\langle \frac{dE}{dX} \right\rangle + \frac{\beta_t (0.014\ \mathrm{GeV})^2}{2\beta^3 E m_\mu X_0}$$

	Z	FoM	Rel. 4D cooling
H	1	252.6	1.000
He	2	182.9	0.524
Li	3	130.8	0.268
C	6	76.0	0.091
Al	13	38.8	0.024

- Competition between:
  - dE/dx [cooling]
  - Multiple Coulomb Scattering [heating]
- Optimum:
  - Low Z, large X_0
  - Tight focus (β_t)

FoM=(dE/dx X↓0

Proof of principle: Muon Ionization Cooling Experiment (MICE, UK)

MAP Conclusions

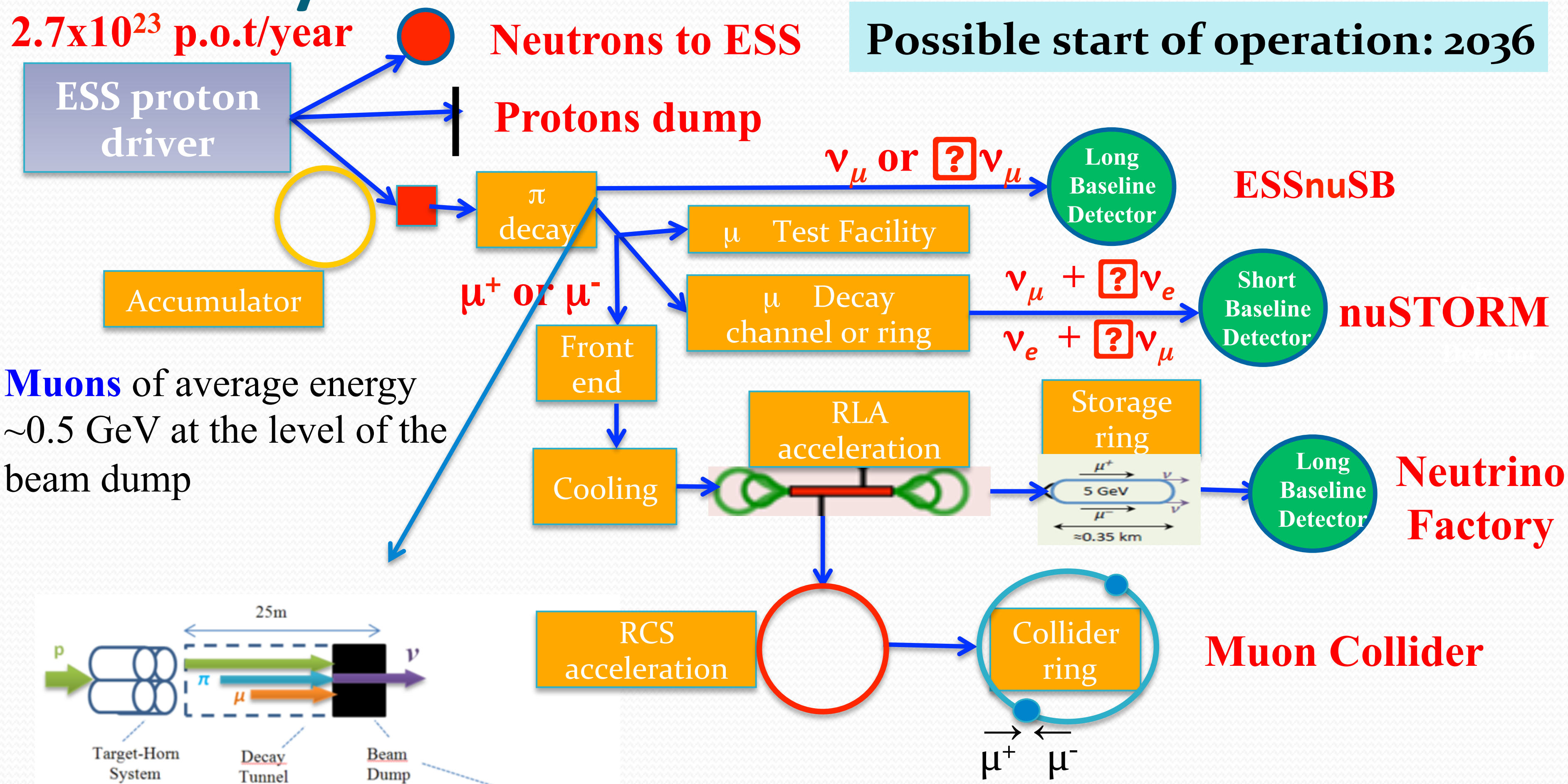
- Multi-TeV MC a potentially only cost-effective route to lepton collider capabilities with $E_{CM} > 5$ TeV
- Capability strongly overlaps with next generation neutrino source options, i.e., neutrino factory
- Key technical hurdles have been addressed:
  - High power target demo (MERIT)
  - Realizable cooling channel designs with acceptable performance
  - Breakthroughs in cooling channel technology
  - Significant progress in collider & detector design concepts

Muon collider capabilities offer unique potential for the future of high energy physics research

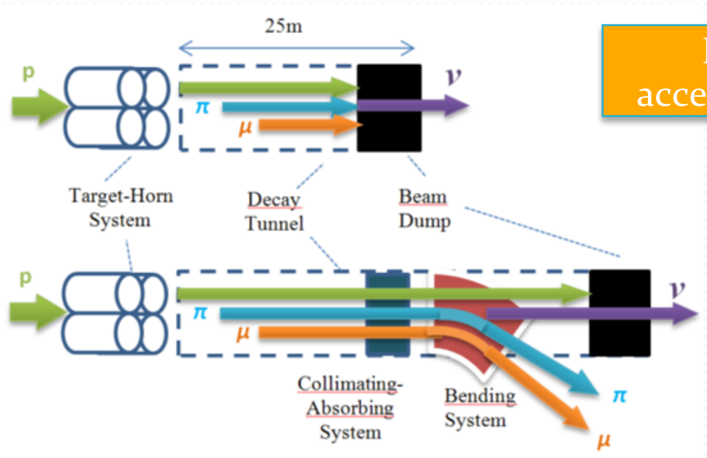
M. Palmer, Padova WS

ESS neutrino and muon facility

Possible start of operation: 2036



Muons of average energy ~0.5 GeV at the level of the beam dump



ESSνSB Design Study, "*Discovery and measurement of leptonic CP violation using an intensive neutrino Super Beam generated with the exceptionally powerful ESS linear accelerator*", approved by EU Dec. 2017, http://essnusb.eu/site/

ESSμSB, ESS

Aims at direct Higgs physics

- *ESSμSB project* is based on the production, accumulation and cooling for a future facility *of intense muon beams* to study the Higgs related scalar sector
- Ingredients easily fit within the existing ESS site:
  - Proton accumulator and compressor rings with a radius of 35 m
  - a **p-π−μ** linear decay channel of about 100 m length converting **μ** to 220 MeV/c;
  - 2 $\mu^{\pm}$ ionization–cooling rings (accumulator, compressor), with ≈ 6 m radius, compressing to two narrow bunches in case followed by PIC cooling rings (giving x10 additional cooling, to be demonstrated);
  - fast recirculating LINAC acceleration system of about few hundreds meter to accelerate μ to the required collision energy
  - $L \approx 10^{32}\ cm^{-2}\ s^{-1}$ $\mu^{+}-\mu^{-}$ collider ring at the Higgs

C. Rubbia, Padova WS

Proton sources summary

- MAP has stopped studies after ~10 years due to cut of US funding
- A complete demonstration of ionization cooling would require a further 30-50 M$ fund → could be part of EU strategy?
- PIC cooling with a small ring (Rubbia's proposal) is an alternative cooling scheme suitable for direct Higgs physics due to its cool beam and high resolution → to be demonstrated → could be part of EU strategy?

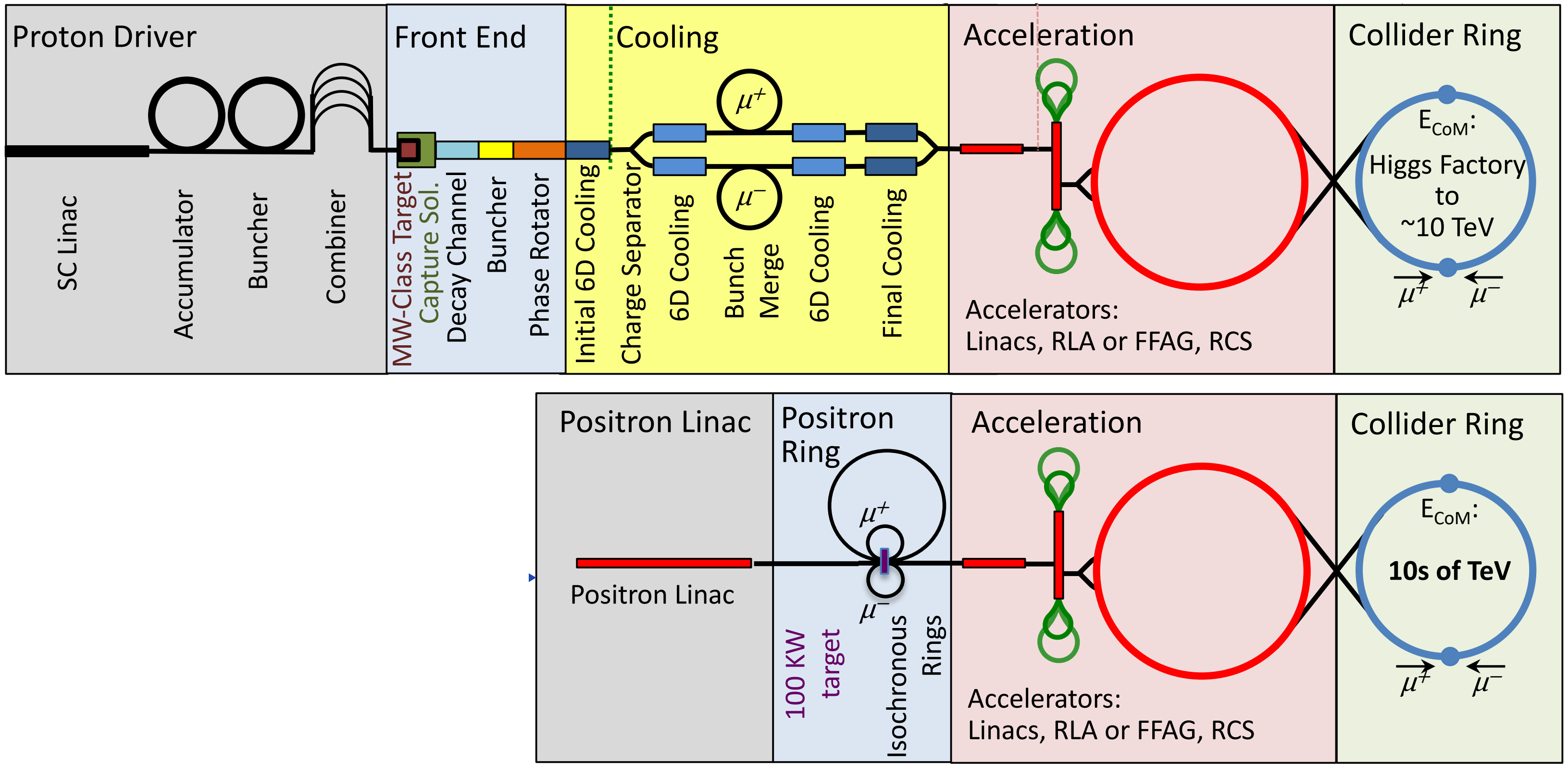
LEMMA studies

- Alternative concept (*idea from P. Raimondi & M. Antonelli first presented at Snowmass 2013*) developed at LNF in the past 2-3 years by a very small group
- At present collaboration includes LNF, Roma1, TO, PoliTO, PD, TS, FE, LAL/Orsay, ESRF → expanding!
- $\mu^{\pm}$ produced by e^+ beam interacting with e^- in a target → μ beam has small emittance and long laboratory lifetime due to the boost of the μ in the laboratory frame
- Most important properties of μ produced by e^+ on target:
  - low and tunable μ momentum in the center of mass frame
  - large boost of γ~200
- Advantages: final state μ highly collimated and with small emittance → cooling not required

LEMMA studies

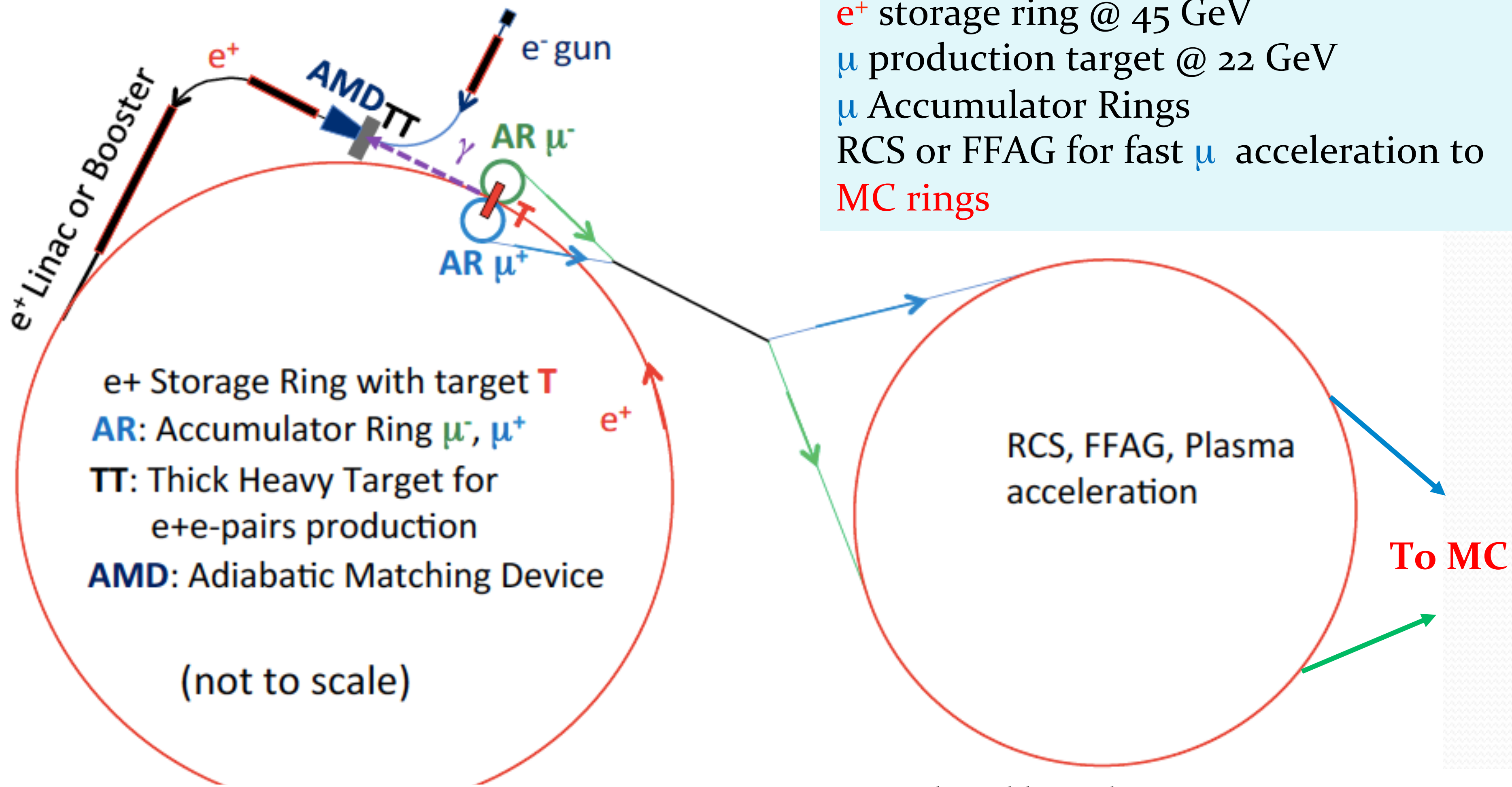
- μ produced with average energy of 22 GeV corresponding to average laboratory lifetime of ~500 μs, which also eases the acceleration scheme
- Possibility of obtaining high luminosity with relatively small μ fluxes thus reducing background rates and activation problems due to high energy μ decays
- While this scheme is appealing for E > TeV collisions, its energy spread is not suitable for a Higgs Factory

LEMMA vs Proton Driver



LEMMA ingredients

- e^+ high intensity source
- e^+ acceleration to 45 GeV
- e^+ storage ring @ 45 GeV
- μ production target @ 22 GeV
- μ Accumulator Rings
- RCS or FFAG for fast μ acceleration to MC rings



Goal: ≈ 10^{11} μ/s produced at target

with target efficiency ≈ 10^{-7} (Be, 3mm)

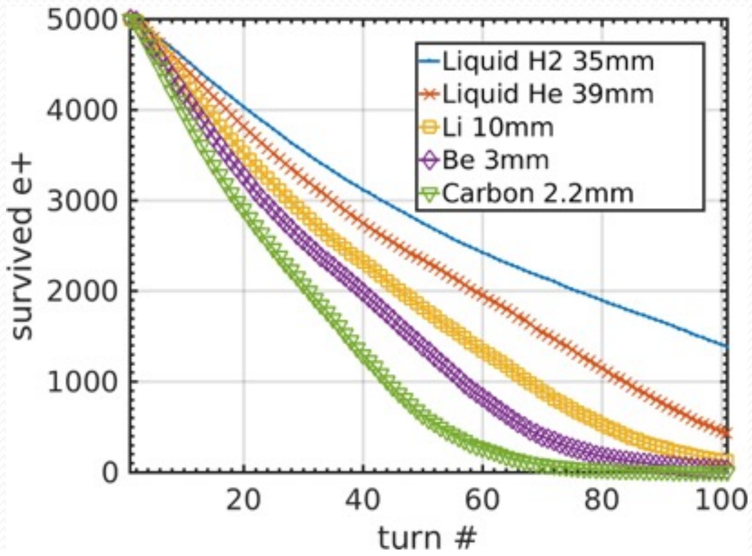
Request: 10^{18} e^+/s needed at target →
45 GeV e^+ storage ring with target insertion

- μ^+/μ^- produced by **e^+** beam on target **T** @ ~ **22 GeV** → $\tau_{lab}(\mu) \approx$ **500μs** ($\gamma(\mu) \approx 200$)
- Accumulator Rings (**AR**) isochronous with high momentum acceptance, recombine μ bunches for ~ 1 $\tau_\mu^{lab} \approx 2500$ turns

e^+ (ring + target) studies

- 45 GeV, 6.3 Km e^+ ring, low emittance, ±6% momentum acceptance
- Multi-turn 6D tracking of **e^+ colliding on an internal target** carried out including Multiple Coulomb Scattering, bremsstrahlung and damping
- Tracking performed for different target materials and thickness
- e^+ lifetime determined by bremsstrahlung and ring momentum acceptance, depending on target material and thickness. MCS dominates horizontal emittance, bremsstrahlung dominates longitudinal emittance

Number of survivor e^+ *vs* number of turns for different target materials. Target thickness chosen for constant muon yield



e^+ ring lattice design

- Needs a very large momentum acceptance, small emittance and long lifetime
- Two designs: 6.3 and 26.7 Km, with same Hybrid Multi Bend Achromat cell, derived from ESRF Upgrade
- 27 km lattice gives potentially equivalent μ beams to the 6.3 km one
- ~430 bunches can be stored with the same e^+ current and same bunch distance
- **Synchrotron radiation losses much more sustainable in longer ring**
- Emittance is reduced by a factor of ~10
- Same energy acceptance (~ ±6 σ_E)

e^+ 45 GeV	Units	e+ ring parameters	
C	Km	6.3	27
N cells	#	32	**64**
n_e (bunches)	#	100	428
n_μ (bunches)	#	1	1
ε_x	nm	6	0.7
Current	A	0.24	0.24
$C_{m,acc}$	m	63	63
Turns for accumulation	#	25	6
N_{e+} / n_e	e+11	3	3
N_μ / n_μ	e+7	4.5*	4.5*
U_0	GeV	0.51	0.12
Synch. power	MW	122	29

* Keep Ne^+ fixed

Synergy with Synchrotron Light Sources

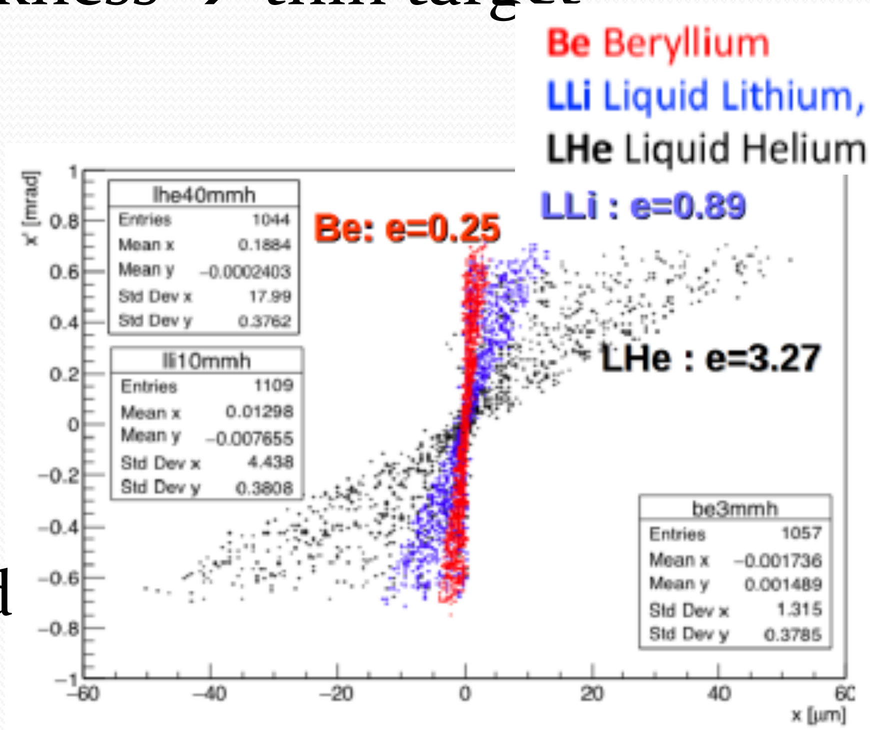
Muon production target studies

- Core topic for LEMMA success
- Thermo-mechanical stress is main issue due to the very high Peak Energy Density Deposition
- Beam size as small as possible (matching various emittance contributions), but…
  - constraints for power removal (200 kW) and T rise
  - to contrast T rise
    - **move target** (for free with liquid jet) and
    - **e^+ beam bump** every 1 bunch muon accumulation

Synergy with CERN studies (HiRadMat, ARIES)

Studies for μ production target

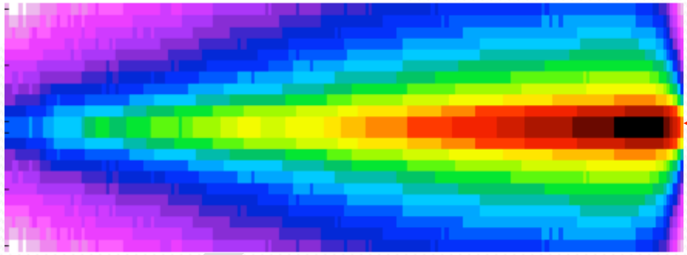
- Dominant process collinear radiative Bhabha scattering
- Max rate target is e^- dominated → high Z
- μ emittance increases with thickness → thin target
- Minimize e^+ losses → low Z
- Not too heavy materials (Li, Be, C)
  - combine low ε_μ and small e^+ loss
  - μ production efficiency ~ 10^{-6}
- Thin light materials targets have small MCS contribution, μ production emittance is dominated by thickness (μ pass 2500 times)



Alternative options like H pellet, crystals or more exotic targets are under consideration

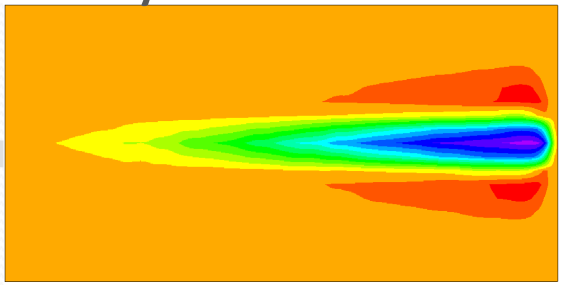
Modeling of thermo-mechanical stresses with Finite Elements analysis (PoliTo)

Energy Deposition



Particle beam

Density

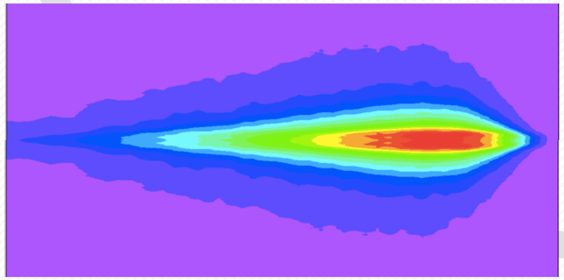


Structural/ Mechanical engineering

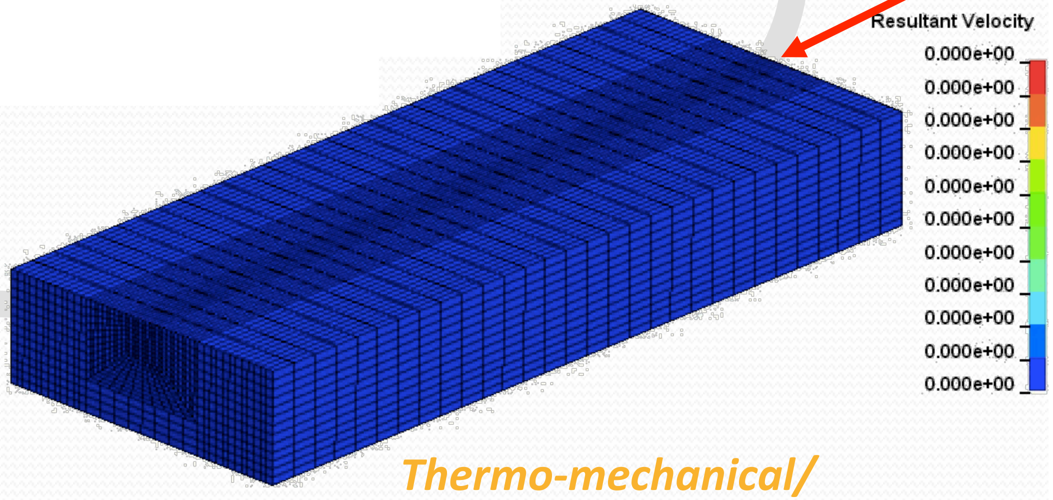
Shockwave travelling induces density variation

$P_{expected} \sim E_{deposited}$

Pressure



Thermodynamics/ hydrodynamics



Thermo-mechanical/ simulation

Material testing @ DYNLab

Pressure gradients produce mechanical response

PoliTO/DYNLab

Positron source requirements

	Be 3mm			LI 10mm			H2 lIquid 35mm		
Ring energy acceptance %	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)	e^+ beam lifetime (turns)	ΔN/sec	P e^+ drive beam (MW)
5	35	2.69E+16	277	45	2.11E+16	217	78	1.21E+16	125
10	47	2.01E+16	207	62	1.53E+16	157	107	8.86E+15	91

- Drive beam power is given by the number of e^+/sec accelerated up to 45 GeV
- Need to increase ring energy acceptance $\Delta p/p$ in order to reduce requirements on e^+ source!
- **Present:** **$\Delta p/p = \pm 6\%$, $\tau = 40$ turns, $e^+/s = 2.4\times10^{16}$, P= 250 MW**
- **Goal:** **$\Delta p/p = \pm 10\%$, $\tau > 100$ turns, $e^+/s < 10^{16}$, P < 100 MW**
- **Ongoing studies on embedded e^+ source from γ coming downstream from target**

e^+ production rates achieved so far (SLC) and needed

	S-KEKB	SLC	CLIC (3 TeV)	ILC (*H*)	FCC-ee (*Z*)	LEMMA
10^{14} e^+ / s	0.025	0.06	1.1	2	0.05	100

State of the art

Synergy with ALL e^+e^- future colliders

LEMMA pros&cons and challenges

- **Pros:**
  - Small emittance muon beam → no cooling needed
  - Lower charge → lower backgrounds in MC
  - Less boundary radiation limitations (neutrinos) from μ decay
  - Possibility of higher c.o.m. energies (>3 TeV)
- **Cons:**
  - Energy spread too large for a Higgs Factory
  - Lower μ production rate
  - High intensity e^+ source

- Development of appropriate accelerator optics for e^+ storage ring
- Choice of the target (one of the crucial aspects for success)
- Development of techniques to achieve and maintain high μ rates
- Several technical challenges to be addressed

LEMMA (ring+target) tests @ DAΦNE

- Unique opportunity of studying a (beam+target) system in a storage ring:
  - Beam dynamics study of the ring+target scheme:
    - transverse beam sizes, current, lifetime
- Measurements on target:
  - temperature (heat load), thermo-mechanical stress

GOAL of the experiment:

- Validation LEMMA studies, benchmarking data/ simulations
- Target tests: various targets (materials and thicknesses)

Ref. M. Boscolo, M. Antonelli, O. Blanco, S. Guiducci, A. Stella, F. Collamati, S. Liuzzo, P. Raimondi, R. Li Voti *"Proposal of an experimental test at DAΦNE for the low emittance muon beam production from positrons on target"*, in publication in **IOP Conf. Series: Journal of Physics: Conf. Series** (IPAC18) also LNF-18/02(IR).

LEMMA summary

R&D profit of synergy/collaboration with worldwide projects

- **Low emittance/large acceptance rings:**
  - 5th generation Synchrotron Light Sources, ESRF/Grenoble
- **Targets:**
  - ARIES EU project, STI group at CERN, e^+ sources studies, PoliTO
- **High intensity e^+ source:**
  - FCCee, CEPC, CLIC, ILC, LAL/Orsay
- μ accumulation, acceleration and collision:
  - worldwide studies (MAP et al)
- **Backgrounds studies:**
  - Helmholtz-Zentrum, Fermilab

Unique opportunity to tests interaction of e^+ beam on target @ DAΦNE

Workshop on 17/12 @ LNF: DAΦNE as Open Accelerator Test Facility in 2020

An international collaboration would boost the project and

Background issues in a MC (in short)

1. **Protection of magnets from μ-decay radiation**
   - electrons from μ-decays deposit power in SC magnets. Mitigations:
     - limit magnet length
     - install tight W masks in interconnect regions and thick W liners inside magnet apertures
2. **Suppression of μ-decay backgrounds in detectors**
   - detector performances depend on the rate of background particles arriving to each subdetector. Mitigations:
     - High-field SC dipoles, interlaced with quadrupoles and W shields in the FF
     - W nozzles with proper angles depending on beam energy very close to the IR
     - Performant detectors exploiting timing gates
3. **Protection of people from off-site neutrino-induced radiation**
   - radiation by DIS in rock where neutrino beam intersects Earth's surface imposes limits on c.o.m. energy and luminosity. Mitigations:
     - avoid as much as possible straight sections
     - introduce a r duce "wobbling"

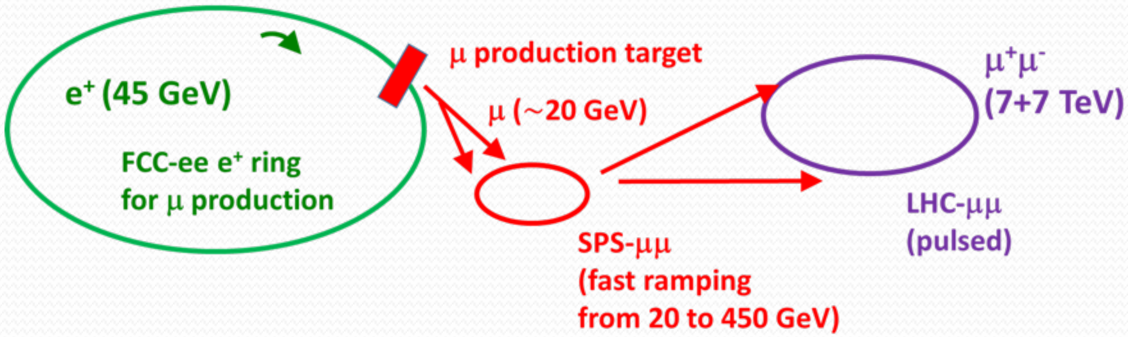
Studies ongoing at INFN-Padova

LEMMA studies have triggered some other (crazy ?) ideas…

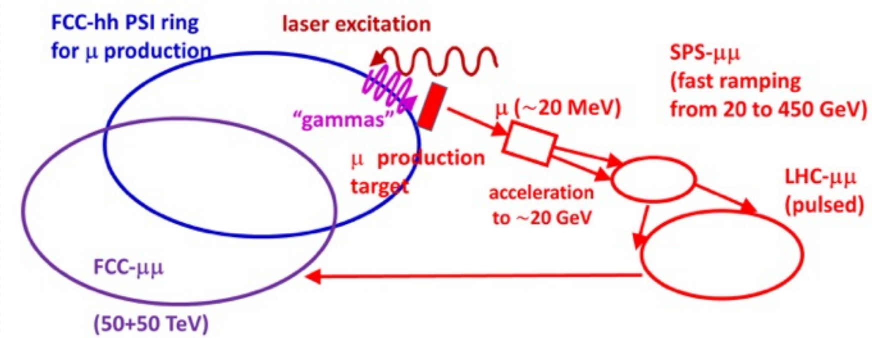
LHC/FCC-based MC

- Different scenarios for muons and e+ source (for LEMMA scheme) using LHC or FCC-hh or FCC-ee

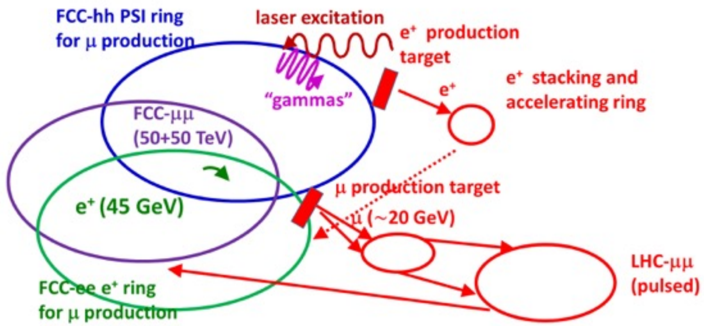
14 TeV μ collider LHC-μμ with FCC-ee μ± production



100 TeV μ collider FCC-μμ with FCC-hh PSI μ± production



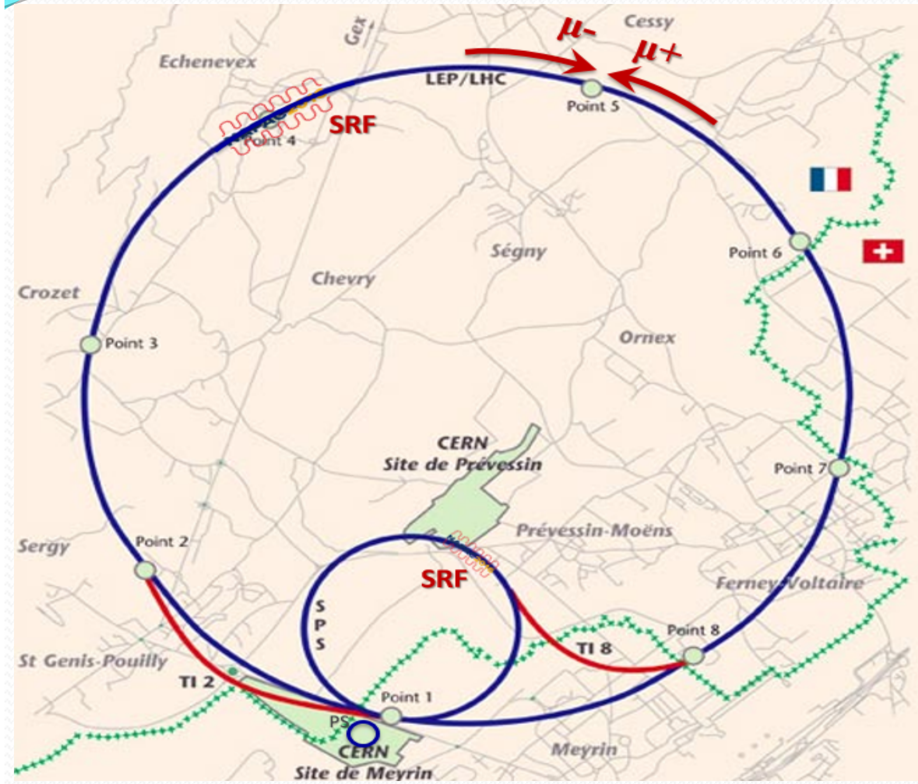
100 TeV μ collider FCC-μμ with FCC-hh PSI e+
& FCC-ee μ± production



F. Zimmerman, Padova WS

14 TeV collider scenarios

D. Neuffer, Padova WS



	1)	2)	3)
Parameter	**PS**	**MAP**	**LEMMA**
Luminosity, $cm^{-2}s^{-1}$	$1.2\cdot10^{33}$	$3.5\cdot10^{35}$	$2.4\cdot10^{32}$
Beam δE/E	0.1%	0.1%	0.2%
Rep rate, Hz	5	5	2200
N_μ/bunch	$1.2\cdot10^{11}$	$2\cdot10^{12}$	4.5×10^{7}
n_b	1	1	1
$\varepsilon_{t,N}$, mm-mrad	25	25	0.04
β^*, mm	1	1	0.2
σ^*(IR), μm	0.6	0.6	0.011
Bunch length, m	0.001	0.001	0.0002
μ production source	24 GeV p	8 GeV p	45 GeV e^+
p or e/pulse	$8\cdot10^{12}$	$2\cdot10^{14}$	$3\cdot10^{13}$
Driver beam power	0.15 MW	1.3 MW	40 MW

- Pulsed 14 TeV MC in the CERN LHC tunnel
- Re-use of existing tunnels and CERN injection complex
- limit μ to ~10^{13}/s
- τ_μ= 0.146 s @ 7TeV (800 turns)

$$L = \frac{f_o n_B n_t N_{\mu^+} N_{\mu^-} \gamma}{4\pi\varepsilon_{t,N}\beta_t^*}$$

SOURCE OPTIONS:

1) PS @ CERN as p source

2) MAP scaled from 6 TeV

3) LEMMA: scaled from 6Km ring

MC Working Group

The Laboratory Directors Group @ CERN formed a Muon Colliders Working Group in charge to prepare the input for discussion towards the 2020 European Particle Physics Strategy Update (EPPSU)

- The goal of the WG is to assess the present status of past studies in the field and to identify, review and recommend further R&D to be compared to the other future accelerator projects for HEP (lepton and hadron colliders):
  - common physics benchmarks as well as a set of machine parameters must be agreed and defined
  - different options must be evaluated to highlight potential and issues.
  - feasibility studies could be proposed to complete the study after 2018 on novel ideas, while issues and resources need to be estimated

Jean Pierre Delahaye, CERN
Marcella Diemoz, INFN. Italy
Ken Long, Imperial College, UK
Bruno Mansoulie, IRFU, France
Nadia Pastrone, INFN, Italy, chair

Daniel Schulte, CERN
Andrea Wulzer, EPFL and CERN
Lenny Rivkin, EPFL and PSI, Switzerland (ex officio)
+++ MAP, LEMMA et al. support/discussions

What’s next?

- Further work is desirable to understand/proof the proposed solutions to technical challenges
  - Muon cooling technology
  - Detector backgrounds from μ decays
  - Low emittance μ from positrons
- EU strategy could support a follow-up of MAP to demonstrate 6D ionization cooling and/or PIC cooling
- EU strategy could support LEMMA R&D with a breakthrough towards new technologies (ex. targets)

It seems absolutely worthwhile to pursue MC studies

BUT

there is need for a clear and strong commitment

Conclusions

- MC is the only cost-effective opportunity for lepton colliders to go to **$E_{cm} > 3$ TeV**
- New impulse given recently from **LEMMA** idea to avoid cooling
- In all present options significant R&D is required towards start-to-end design
- Technological developments can inspire new spin-offs
- Great challenge at international level and fantastic opportunity for young people
- **An international effort will have the strength to find new ideas/solutions, validate the present ones, overcome technological issues**
- It is very important that INFN is involved in these studies:

MC Working Group (chair N. Pastrone) in charge to prepare input for discussion toward EPPSU

Thank you

”Physics is like sex: sure, it may give some practical results, but that’s not why we do it”
R. P. Feynman

Backup slides

Why Muons?

Physics Frontiers

- **Intense and cold muon beams ⇨ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\,MeV/c^2$$
$$\tau_\mu = 2.2\,\mu s$$

Colliders

- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs → $\sim\left(\frac{m_\mu^2}{m_e^2}\right) \cong 4\times 10^4$
  - Reduced synchrotron radiation ⇨ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT* accelerator complex/detector must be able to handle the impacts of μ decay**

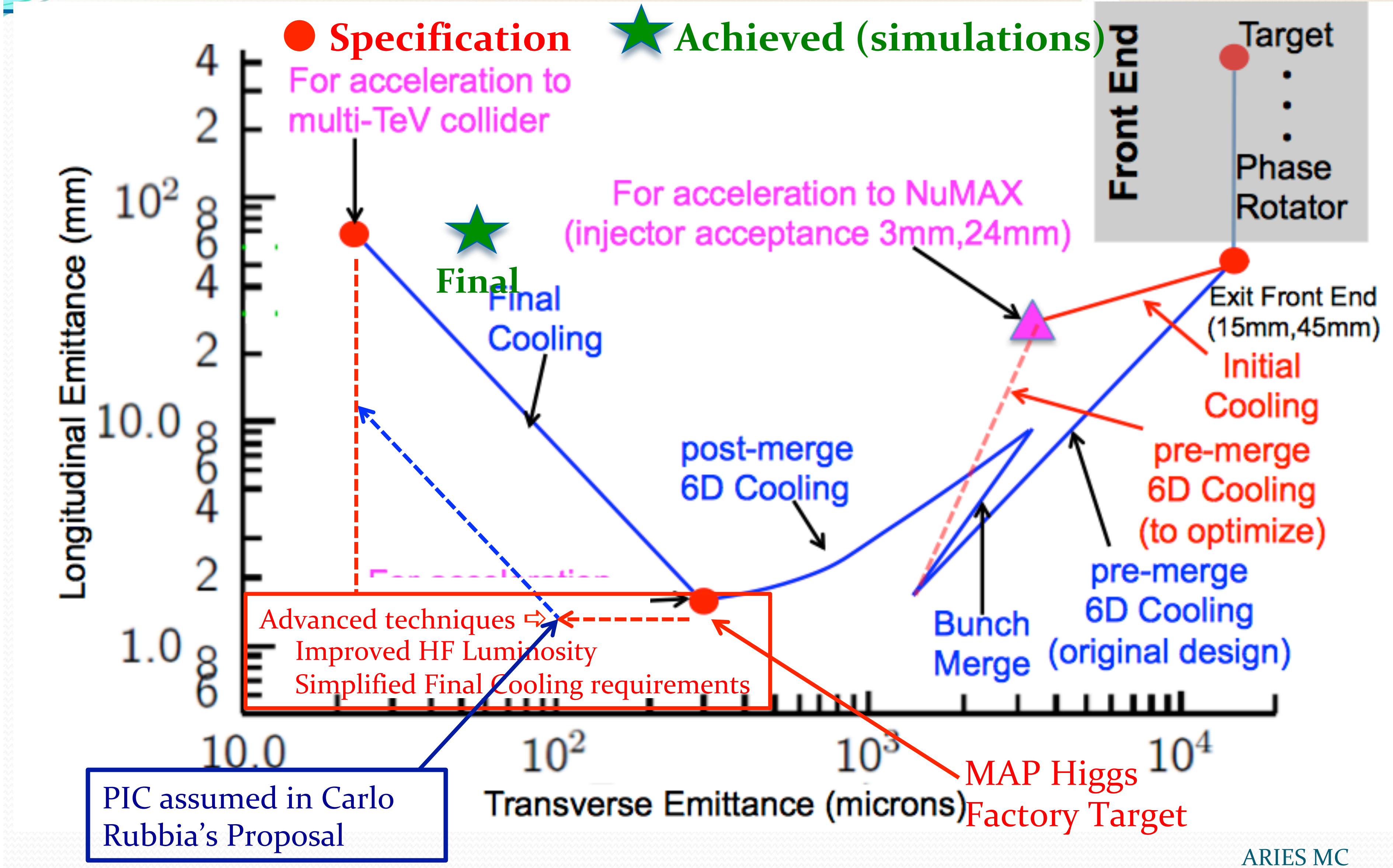
Collider Synergies

- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

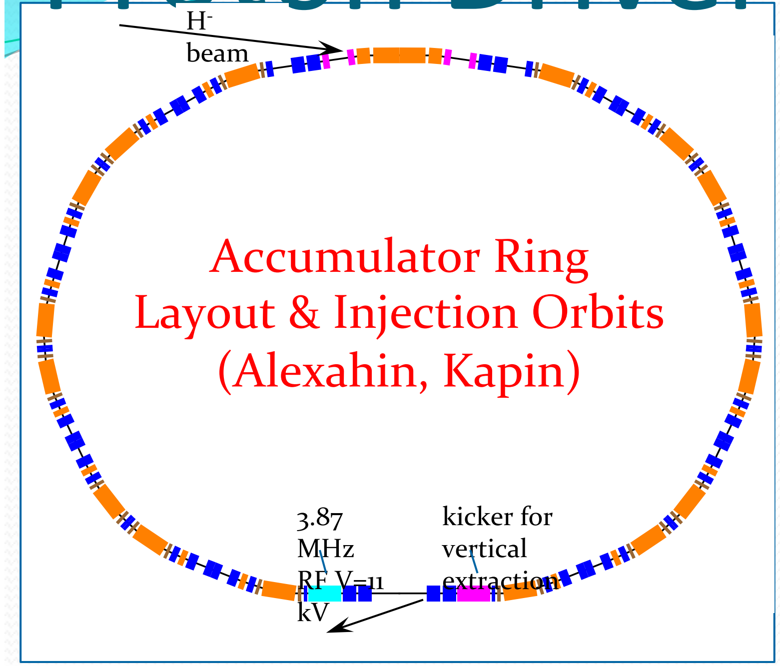
$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$$
$$\mu^- \to e^- \bar{\nu}_e \nu_\mu$$

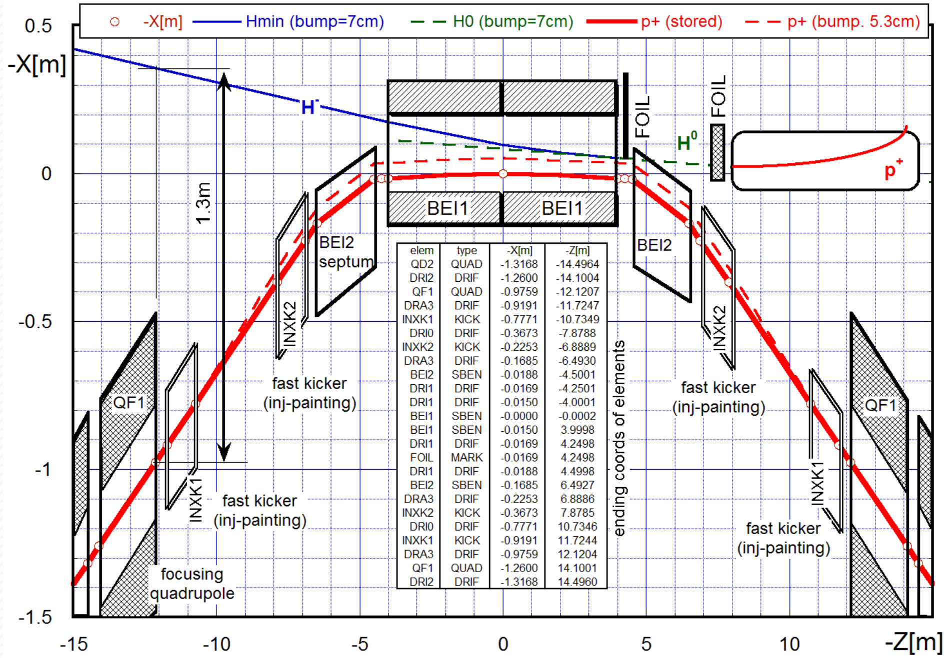
M. Palmer, Padova WS

Ionization Cooling: emittance path

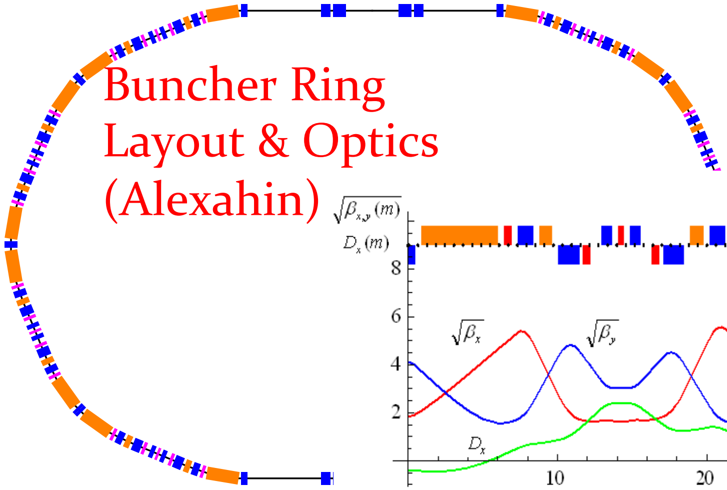


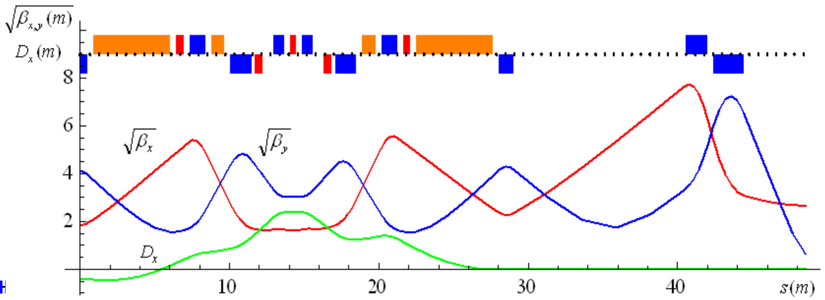
Proton Driver





elem	type	-X[m]	-Z[m]
QD2	QUAD	-1.3168	-14.4964
DRI2	DRIF	-1.2600	-14.1004
QF1	QUAD	-0.9759	-12.1207
DRA3	DRIF	-0.9191	-11.7247
INXK1	KICK	-0.7771	-10.7349
DRI0	DRIF	-0.3673	-7.8788
INXK2	KICK	-0.2253	-6.8889
DRA3	DRIF	-0.1685	-6.4930
BEI2	SBEN	-0.0188	-4.5001
DRI1	DRIF	-0.0169	-4.2501
DRI1	DRIF	-0.0150	-4.0001
BEI1	SBEN	-0.0000	-0.0002
BEI1	SBEN	-0.0150	3.9998
DRI1	DRIF	-0.0169	4.2498
FOIL	MARK	-0.0169	4.2498
DRI1	DRIF	-0.0188	4.4998
BEI2	SBEN	-0.1685	6.4927
DRA3	DRIF	-0.2253	6.8886
INXK2	KICK	-0.3673	7.8785
DRI0	DRIF	-0.7771	10.7346
INXK1	KICK	-0.9191	11.7244
DRA3	DRIF	-0.9759	12.1204
QF1	QUAD	-1.2600	14.1001
DRI2	DRIF	-1.3168	14.4960

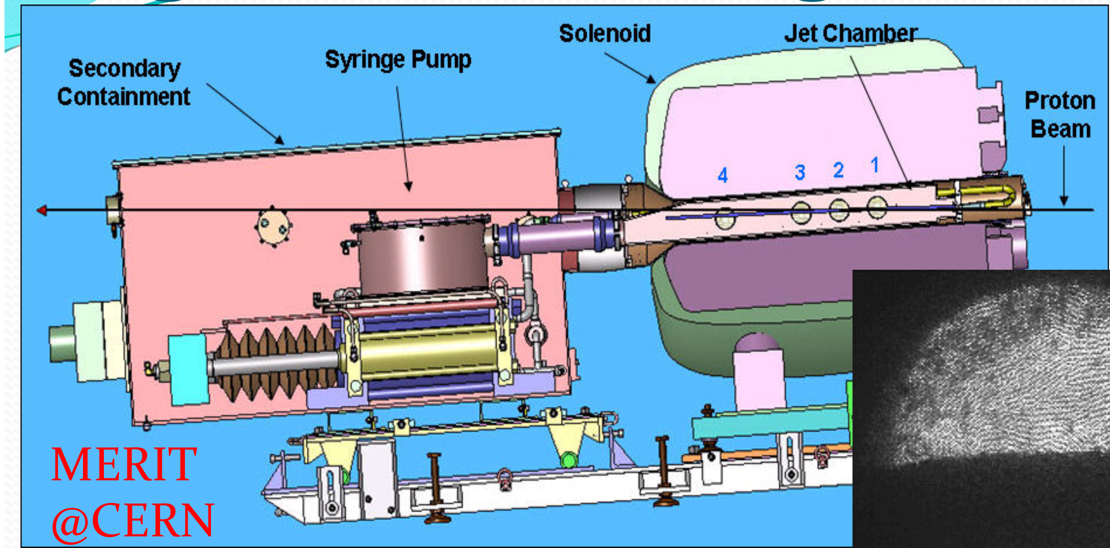


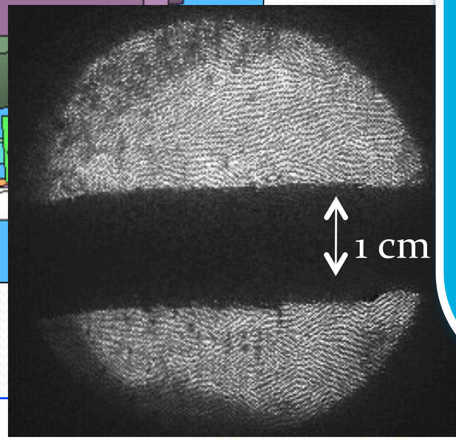


Optics:
½ straight +
1 arc cell

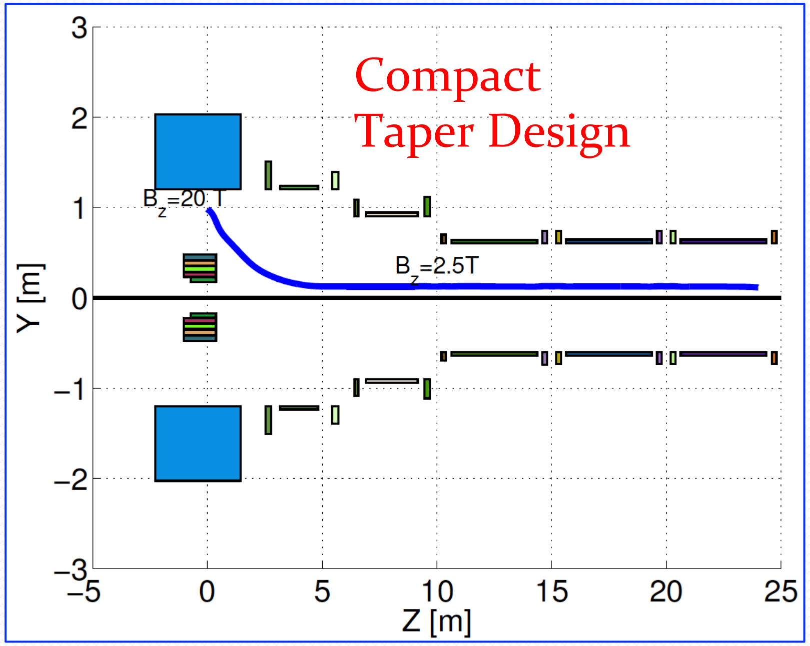
- ✓ Based on 6-8 GeV Linac Source
- ✓ Accumulator & Buncher Ring Designs in hand
- ✓ H- stripping requirements same as those established for Fermilab's Project X

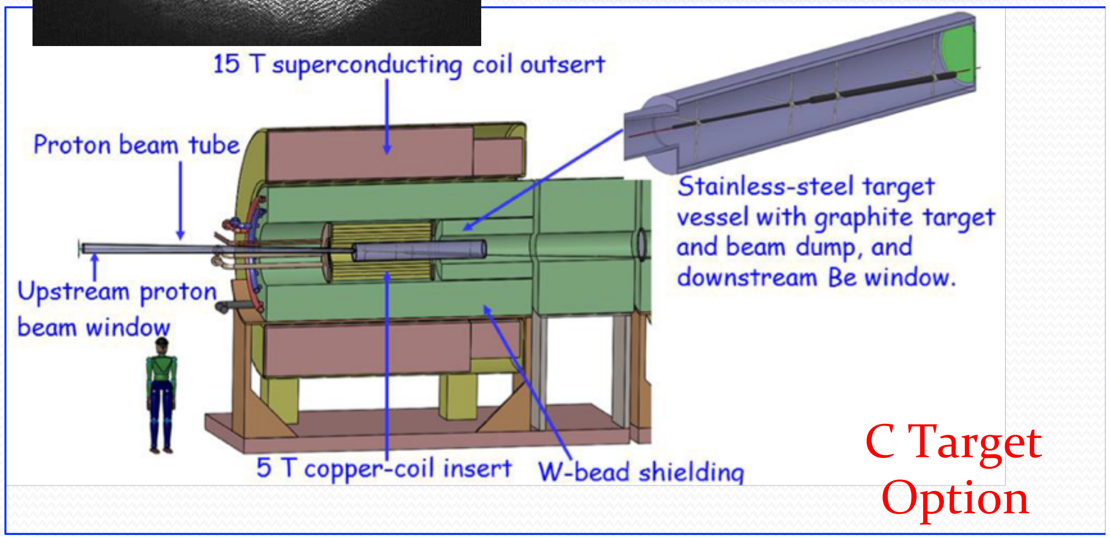
High Power Target





- ✓ MERIT Expt:
  - LHg Jet in 15T
  - Capability: 8MW @70Hz
- ✓ MAP Staging aims at 1-2 MW ⇨ C Target
- ✓ Improved Compact Taper Design
  - Performance & Cost





Muon Ionization Cooling Experiment (MICE, UK)

K. Long, Padova WS

❖ Proof of principle:

❖Design, build commission tight-focusing, high-acceptance solenoid lattice

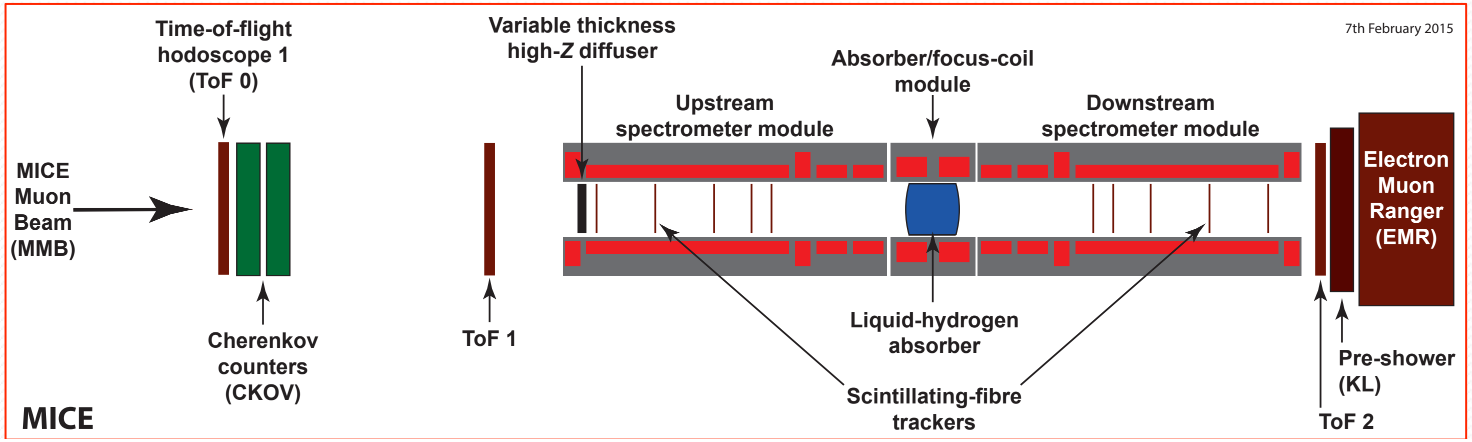
❖Demonstrate integration and operation of liquid-hydrogen absorbers

❖Measure material properties that determine the ionization-cooling effect

❖Demonstrate the principal of ionization-cooling: **study ionization cooling as a function of beam conditions and lattice settings**

- **Ionization cooling observed**
  - Using LiH and LH_2 absorbers → **A major milestone**
- Future: build on successful execution of MICE program to
  - **Design and implement a 6D cooling experiment**
  - Establish a particle-physics program based on high-intensity, high-energy muon beam (nuSTORM)

Note:
- no RF for acceleration
- only normalized emittance measured

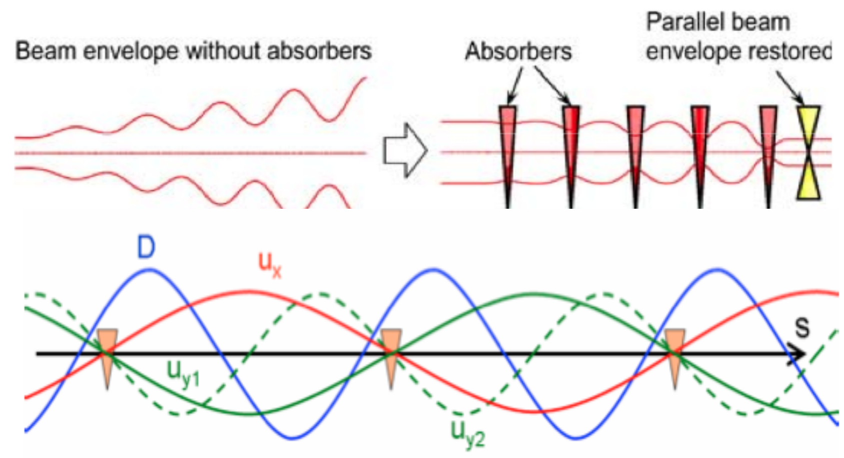


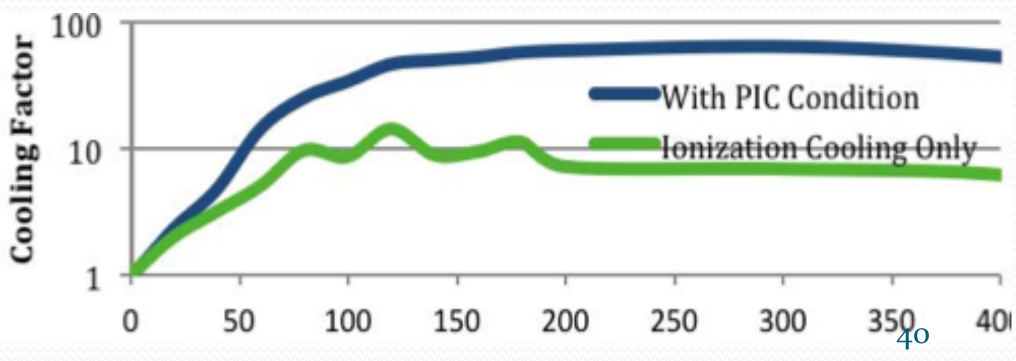
PIC, Parametric Resonance Cooling

C. Rubbia

- 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 by tapering the absorbers and placing them at points of appropriate dispersion, vertical β and two horizontal β' σ
- Comparison of cooling factors (ratio of initial to final 6D emittance) with and without the PIC condition vs number of cells: *about 10 x gain*
- Balance between strong resonance growth and ionization cooling may involve significant and unexpected conditions which are hard to predict

experimental demonstration needed



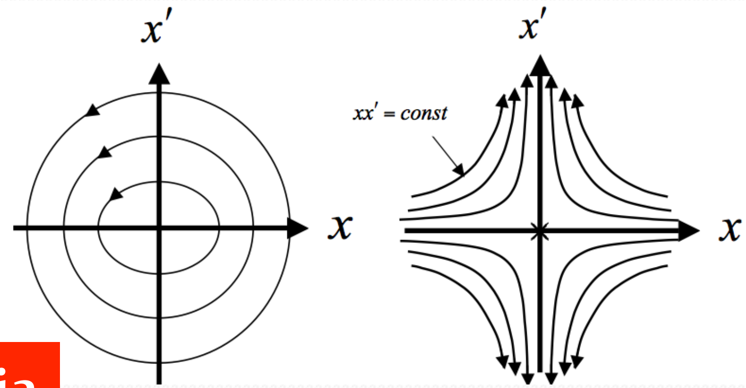


Parametric Resonance Cooling

- Combining ionization cooling with parametric resonances (PIC) is expected to lead to muon with much smaller transverse sizes
- A linear magnetic transport channel 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
- Proof of principle needed

LEFT ordinary oscillations
RIGHT hyperbolic motion
induced by perturbations near a (one half integer) betatron resonance

C. Rubbia



SLEM: Source of Low Emittance Muons

- Proposed R&D to produce low emittance muon beams for a future MC
- Based on **LEMMA** scheme
- **SLEM** would focus on key challenges that need to be demonstrated to prove LEMMA feasibility:
  - positron ring and muon Accumulator Rings studies
  - positrons and muons production target studies
  - tests of targets at DAΦNE
  - MC decay-induced background studies
- INFN shown interest: **LNF, RM1, PD, TO, FE, MI + PoliTO**
- International laboratories interested (**LAL, SLAC, CERN ?**)

DAΦNE Layout for the LEMMA Test

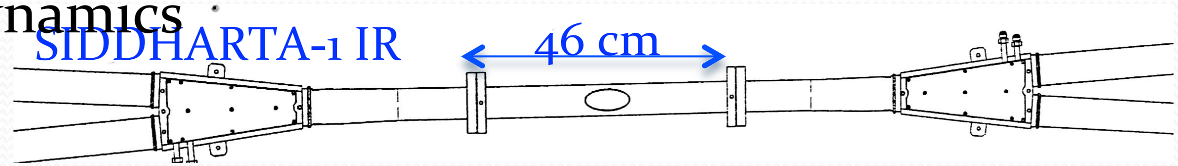
The target will be placed at the SIDDHARTA IP because:

- low-β and D_x=0 is needed (similarly to IP requirements)
- to minimize modifications of the existing configuration

Possible different locations for the target can be studied

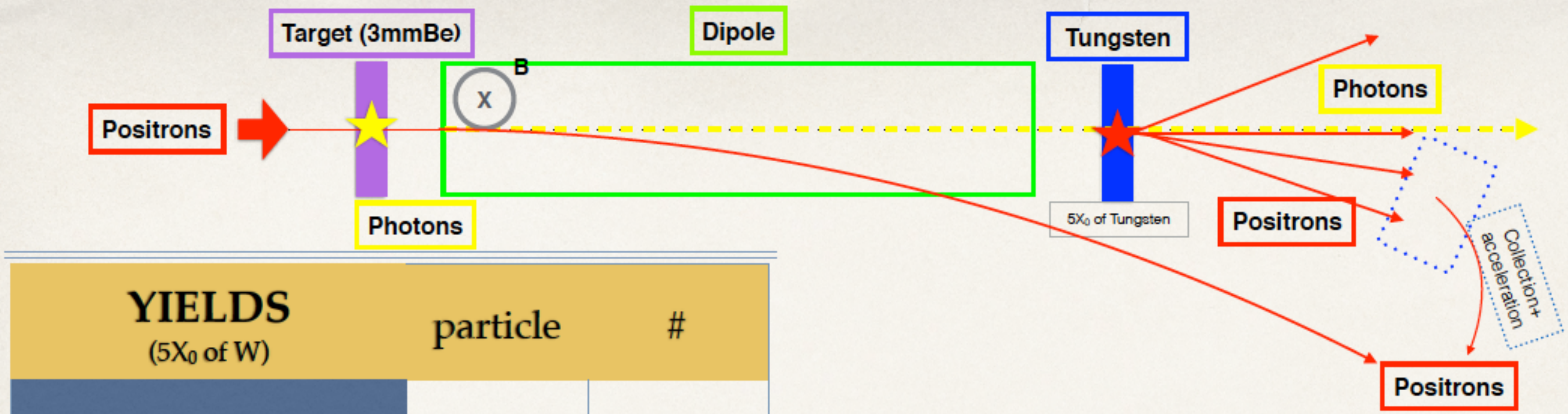
For the preparation of this experiment we need:

1. Full design of vacuum chamber IR and target insertion system
2. Target design
3. Diagnostics for target thermo-mechanical stress measurements
4. Beam diagnostics
5. Injection scheme (on axis)
6. Optics and beam dynamics



Given the limited energy acceptance of the ring we plan to insert **light targets (Be, C)** with thickness in the range ≈ **100 μm**. Crystal targets can be foreseen too.

Embedded e+ source to relax e+ source requirements



YIELDS (5X_0 of W)	particle	#
Primary Particles	e^+	100
Primary Particles lost due to target (DE 4%)	e^+	**3**
Exiting Beryllium	γ	10.8
Entering Tungsten	γ	10.6
Exiting Tungsten	e^+	**65**

It would be sufficient to be able to collect **5%** (3/65) of these e^+ to compensate the loss of primary positrons in the target

Collection Efficiency?

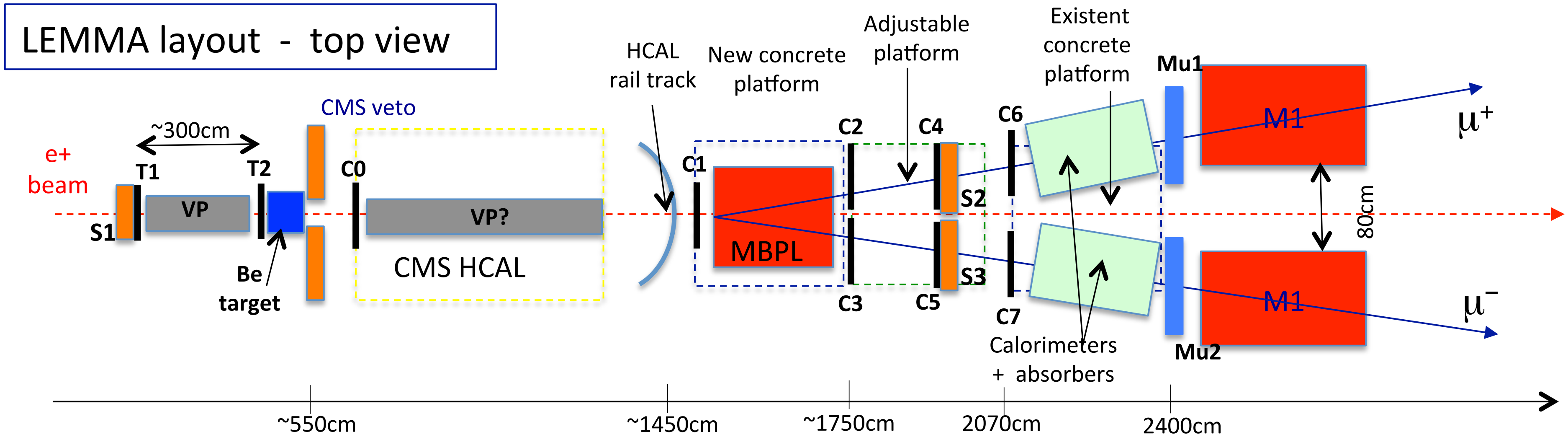
No studies performed yet on how to collect, accelerate and re-inject this positrons

Experimental Test @CERN-North Area 2018 experimental layout

- Study of kinematic properties of the produced muons
  - Measure the $\mu^+\mu^-$ production rate for the provided positron beam features (momentum and energy spread)
    - Use Bhabha events for normalization
  - Measure muons momentum and emittance
- Trigger for Signal and Normalization events provided by the coincidence of the 3 scintillator S1 (intercept the incoming beam) and S2 and S3 intercepting the outcoming muons.

- Experimental setup modified with respect to the 2017 TB, also to account the different experimental hall (H4 -> H2)
  - additional tracking;
  - new calorimeters

LEMMA layout - top view



Radiological hazard due to neutrino from a MC

- Studies by:
  - B.J.King, Proc. EPAC98 and PAC99
  - C. Johnson, G. Rolandi, M. Silari, TIS-RP/IR/98-34 (1998)
  - J.D. Cossairt, N.L. Grossman, E.T. Marshall, Health Phys. 73 (1997)

Muon rate:

p on target option

3×10^{13} μ/s

e^+ on target option

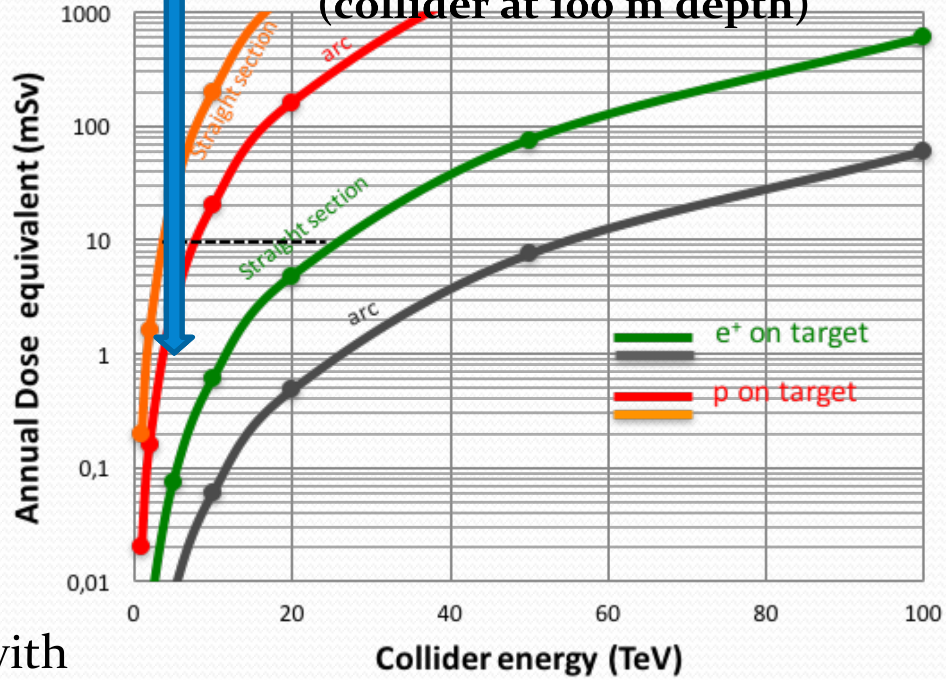
9×10^{10} μ/sx

Neutrino dose equivalent/ fluence

[J.D. Cossairt, N.L. Grossman and E.T . Marshall, Health Phys. 73 (1997), 894-898]

MAP design for a 6 TeV MC (500 m depth)

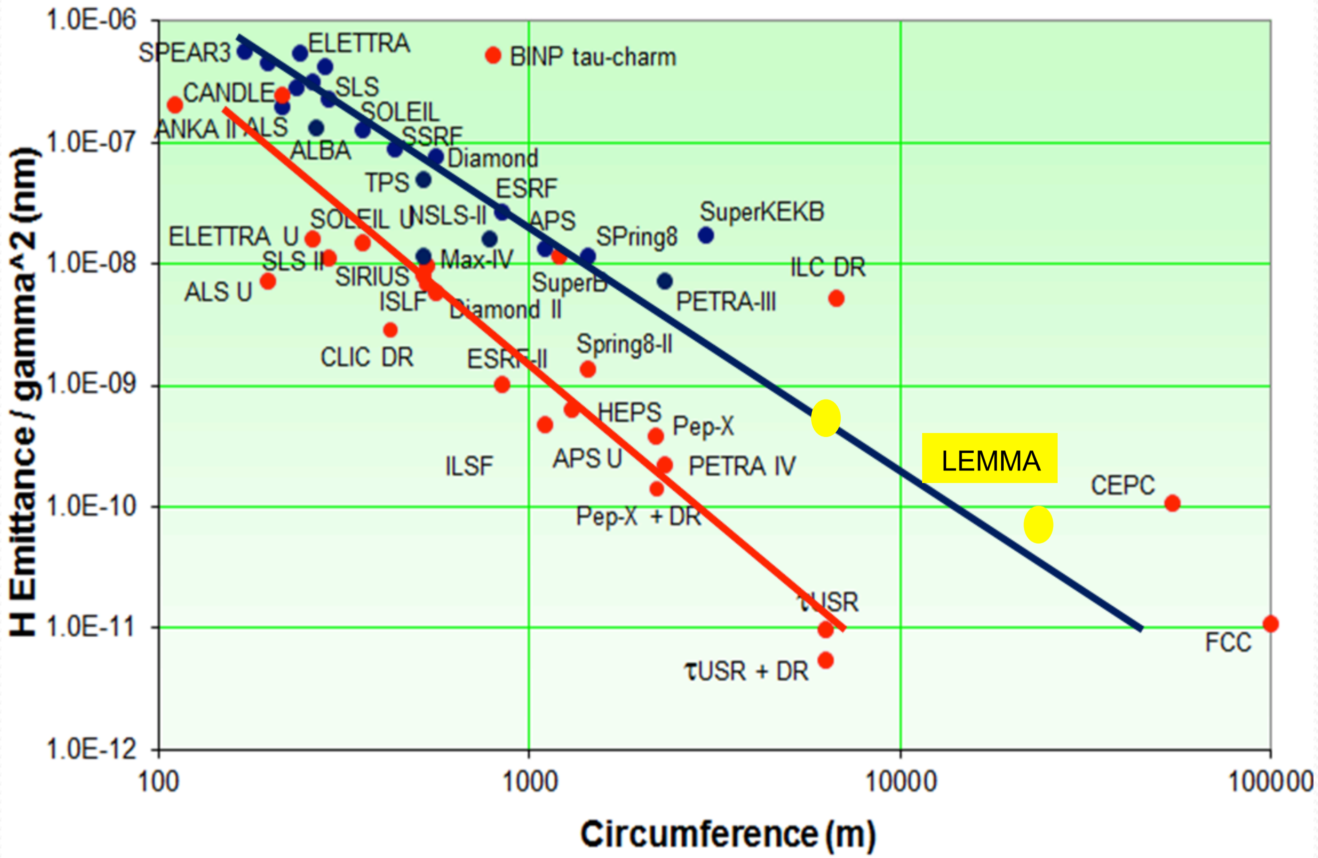
Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)



(μ-beam energy)

Plot based on C. Jonhson et al, updated with LEMMA by M. Antonelli

Emittance trend in storage rings



Emittance normalized to beam energy vs. circumference for storage rings in operation (blue dots) and under construction or being planned (red dots). Ongoing generational change indicated by the transition from the blue line to the red line. (R. Bartolini, LER-2014, updated 2016). LEMMA 6 km and 27 km shown in yellow

TIARA Accelerator R&D input for ES

- In 2013 TIARA (Test Infrastructure and Accelerator Research Area) issued a document for EU Strategy recommendations, identifying Key Accelerators Research Areas (KARA) and Key Technical R&D Issues (KIT) in 3 domains: Components, Technologies, Concepts
- A new document will be issued in 2019 for next ES
- R&D needed for MC is contained in KARA/KIT lists (extract below)

Accelerator Design	Design for reliability and availability
	Beam Losses and Machine protection at High Beam Power
Beam Dynamics	Enhanced Beam Modeling Tools and Experimental Validation Tools
	High Luminosity and High Energy Hadron and Lepton Colliders
	Beam Stability and Lifetimes in Circular Accelerators
	Small Emittance Beam Generation and Transport
	Fast Acceleration for Unstable Particles
Beam cooling	Ionization cooling

Relevant to MC

Deliverable for WP4, Joint R&D Programming, available at https://cds.cern.ch/record/1648431