Novel Proposal of a Low EMittance Muon Accelerator

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Most of the slides from:
M. Boscolo, MAC, LNGS, 10 Oct. 2017

Low EMittance Muon Accelerator team:

INFN institutions involved: LNF, Roma1, Pd, Pi, Ts, Fe

Universities: Sapienza, Padova, Insubria

Contributions from: CERN, ESRF, LAL, SLAC

This new proposal covers different areas of research:
accelerator physics, high energy, theory, engineering material science, …

Many colleagues are interested to collaborate,
informal contacts with international experts has started

We believe in the potential of this idea, but key challenges need to be demonstrated to prove its feasibility.
I will show the work done up to now that may lead to a Conceptual Design Report

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Bertolin Alessandro	5 PD
Checchia Paolo	10 PD
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Collamati Francesco	40 RM1
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Low EMittance Muon Accelerator team

← CSN1 team

Additional national

- M. Ricci **(Uni. Marconi, INFN-LNF)** A. Stella **(LNF),** G. Cavoto **(La Sapienza),** E. Bagli **(INFN-Fe),** M. Prest, M. Soldani, C. Brizzolari **(Uni-Insubria&INFN),** A. Lorenzon, S. Vanini, S. Ventura, D. Dattola**(INFN-Uni. Padova),** A. Wulzer **(Uni. Pd & EPFL)**

Additional international

- P. Raimondi, S. Liuzzo, N. Carmignani **(ESRF)**
- R. Di Nardo, P. Sievers, M. Calviani, S. Gilardoni **(CERN)**
- I. Chaikovska, R. Chehab **(LAL-Orsay)**
- L. Keller, T. Markiewicz **(SLAC)**

ARIES WP6: improving Accelerator PErformance and new Concepts task for muon collider
Task 6.6 Assessment of advanced muon-collider concepts without ionization cooling

outline

1. **Introduction**
2. **Physics Opportunities**
   - Very High Energy
   - Multi-TeV
3. **Low emittance muon beam production concept**
   - Target options
   - Positron Source
   - Multipass scheme
4. **First study of multi-TeV MC parameters**
5. **First design of the e^+ ring**
   - Multiturn simulations
   - First considerations about target thermo-mechanical stresses
   - First considerations on e^+ source
6. **Experimental tests**
   - 45 GeV e^+ beam
   - DAΦNE
7. **Conclusion and Plans**

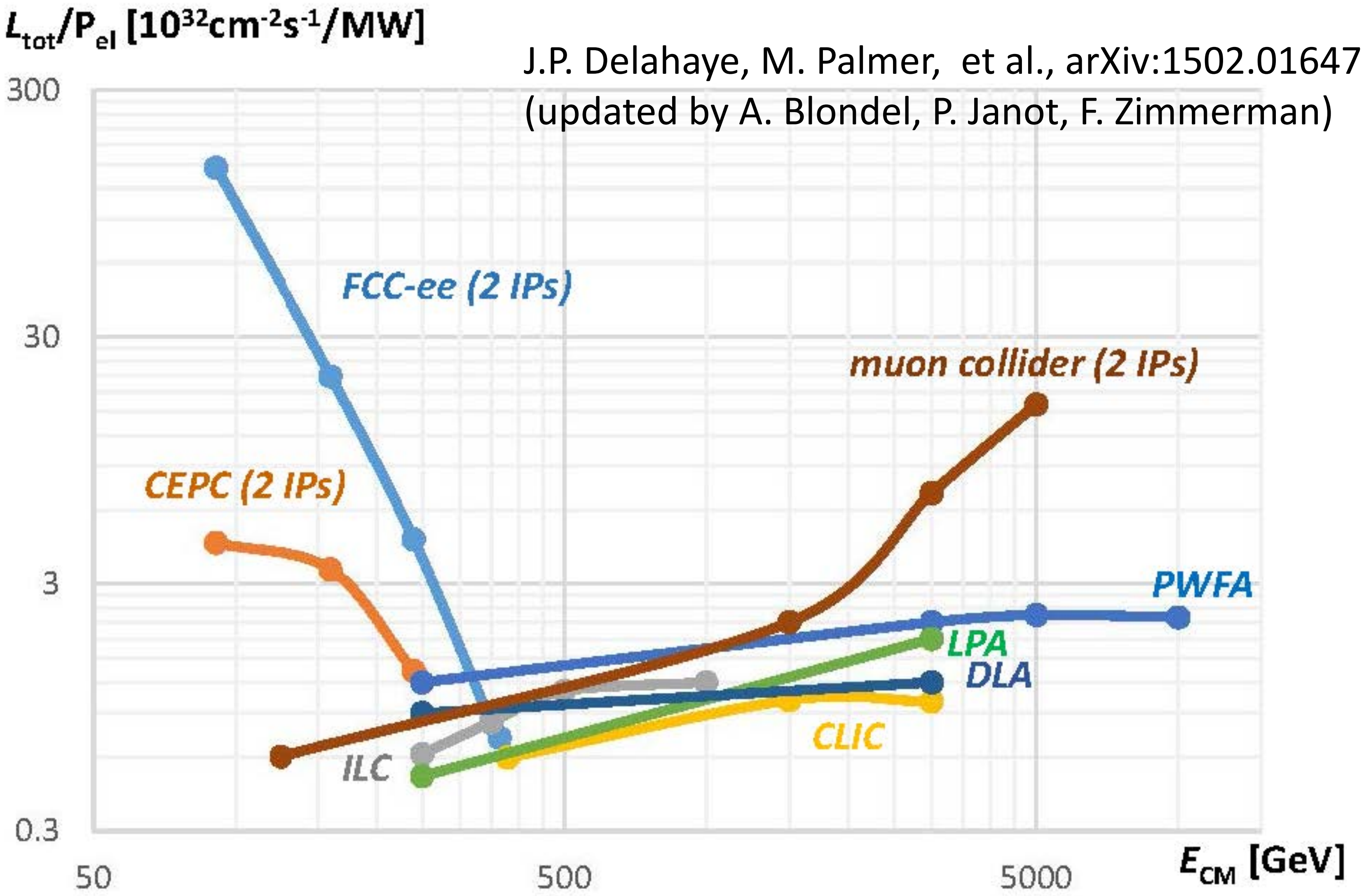
Muon based Colliders

- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of e^+e^- circular colliders)
  - No beamstrahlung (limit of e^+e^- linear colliders)
  - but muon lifetime is 2.2 μs (at rest)
- Best performances in terms of luminosity and power consumption

- Great potentiality if the technology proves its feasibility:
  - cooled muon source
  - fast acceleration
  - μ Collider
  - radiation Safety (muon decay in accelerator and detector)

Muon Colliders potential of extending leptons high energy frontier with high performance

luminosity per wall-plug power vs c.m. energy



The strength of a $\mu-$beam facility lies in its richness:

- Muon rare processes
- Neutrino physics
- Higgs factory
- Multi-TeV frontier

Take 1

Get 4 !

$\mu-$colliders can essentially do the HE program of e^+e^- colliders with added bonus (and some limitations)

Giudice

MultiTeV Lepton Collider Basics

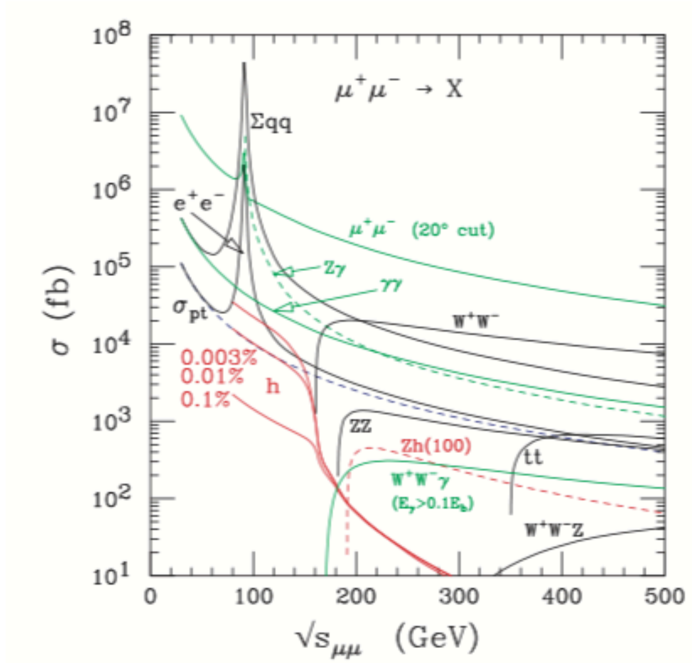
- For √s < 500 GeV
  - SM threshold region: top pairs; W^+W^-; Z^0Z^0; Z^0h; ...
- For √s > 500 GeV
  - For SM pair production (| θ | > 10°)

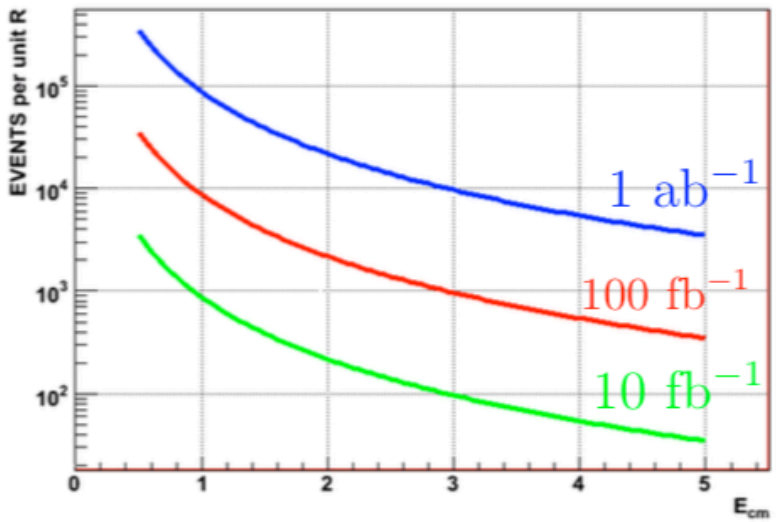
    R = $\sigma / \sigma_{QED}(\mu^+\mu^- \rightarrow e^+e^-)$ ~ flat

$$\sigma_{\rm QED}(\mu^+\mu^- \to e^+e^-) = \frac{4\pi\alpha^2}{3s} = \frac{86.8\ \rm fb}{s({\rm TeV}^2)}$$

  - High luminosity required

Standard Model Cross Sections





$$\sqrt{s} = 3.0\ {\rm TeV} \quad \mathcal{L} = 10^{34}\ {\rm cm^{-2}sec^{-1}}$$
$$\rightarrow 100\ {\rm fb^{-1}year^{-1}}$$

⇒ 965 events/unit of R

Processes with R ≥ 0.1 can be studied

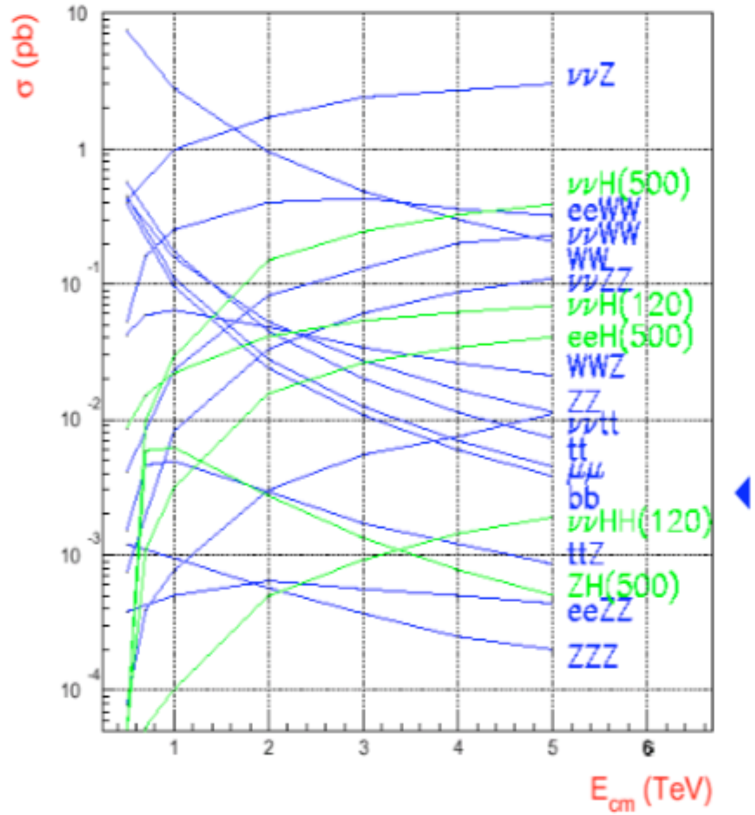
Total - 540 K SM events per year

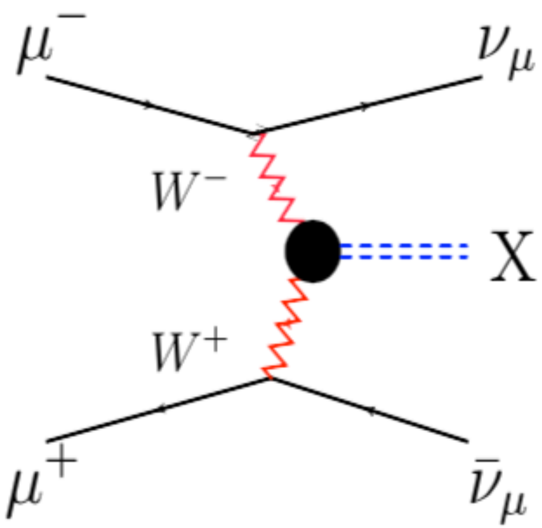
== 10^{36} cm^{-2} s^{-1}@ √s 30 TeV

Vector boson fusion

- For $\sqrt{s}$ > 1 TeV - Fusion Processes
  - Large cross sections
  - Increase with s.
  - Important at multi-Tev energies
  - $M_X^2 < s$
- Backgrounds for SUSY processes
- t-channel processes sensitive to angular cuts

CLIC (or MC e<->μ)





$$\sigma(s) = C \ln(\frac{s}{M_X^2}) + \ldots$$

SM Higgs

(after ~10 years of running)

Error on	μμ resonance	ILC	FCC-ee
m_H (MeV)	0.06	30	8
Γ_H (MeV)	0.17	0.16	0.04
g_{Hbb}	2.3%	1.5%	0.4%
g_{HWW}	2.2%	0.8%	0.2%
$g_{H\tau\tau}$	5%	1.9%	0.5%
$g_{H\gamma\gamma}$	10%	7.8%	1.5%
$g_{H\mu\mu}$	2.1%	20%	6.2%
g_{HZZ}	–	0.6%	0.15%
g_{Hcc}	–	2.7%	0.7%
g_{Hgg}	–	2.3%	0.8%
BR_{invis}	–	<0.5%	<0.1%

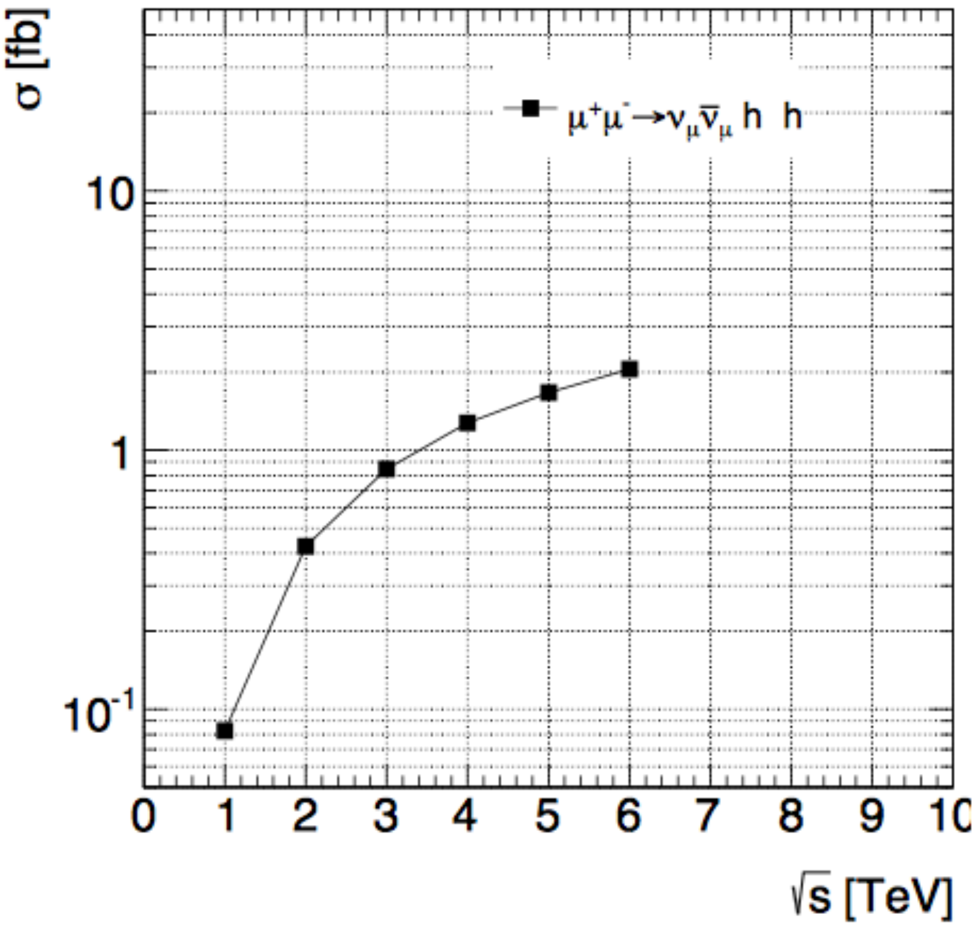
P. Janot

- Resonant Higgs production:
  - Unique measurements of *mh* and *Γh*

  (mh ~ 0.1 MeV, *Γh* ~ 0.2 MeV)

  - Best test of 2nd generation Higgs couplings (h → $\mu^+\mu^-$)
- HZ production:
  - Similar to e^+e^- measurements but lower statistics factor 10 (ILC/CEPC) 100 FCC-ee
- VBF at mutiTeV
  - High xs(O(1Pb)@6TeV) & high lumi better statistics than FCC-ee ?
  - Competitive (probably best) measurement of HH production

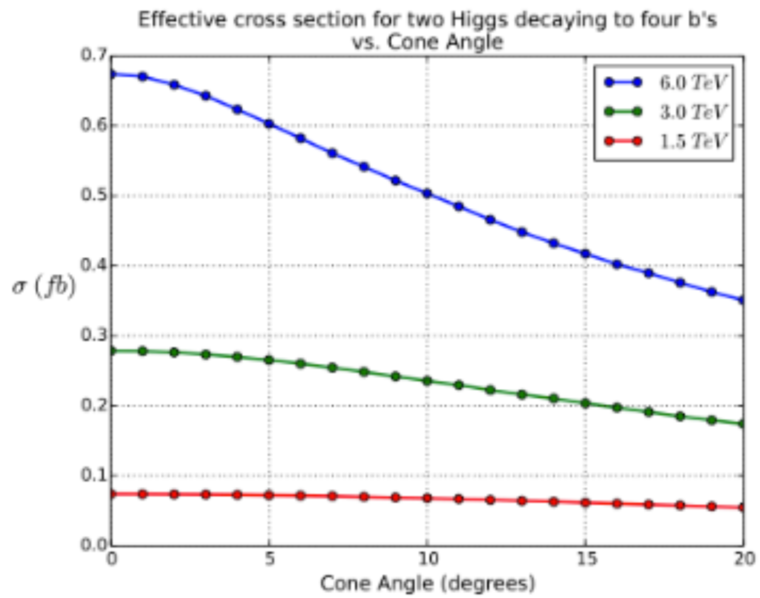
VBF HH production



@sqrt(s) = 3 TeV
μμ->vvHH : 0.9 fb

@sqrt(s) = 6 TeV
μμ->vvHH : 2.1 fb

Machine bkg limitations:
xs with 4b in det. acceptance



Not yet detailed studies

A.Conway, H.Wenzel, R.Lipton and E.Eichten, arXiv:1405.5910

Muon Source

Goals

- **Neutrino Factories**: Rate > 10^{14} μ/sec within the acceptance of a μ ring
- **Muon Collider**: luminosities >10^{34}/cm^{-2}s^{-1} at TeV-scale ($\approx N_\mu^2$ $1/\varepsilon_\mu$)

Options

- Tertiary production through **proton on target:** cooling needed, baseline for Fermilab design study
  production Rate > $10^{13}\mu$/sec $N_\mu = 2\cdot10^{12}$/bunch (5 10^8 μ/sec today @PSI)

- **e^+e^- annihilation**: **positron beam on target**: very low emittance and no cooling needed, baseline for our proposal here
  production Rate $\approx 10^{11}$ μ/sec $N_\mu \approx 6\cdot10^9$/bunch

- **by Gammas** ($\gamma N \to \mu^+\mu^- N$): **GeV-scale Compton γs** not discussed here
  production Rate $\approx 5\cdot10^{10}$ μ/sec $N_\mu \approx 10^6$ (Pulsed Linac)
  production Rate >10^{13} μ/sec $N_\mu \approx$ few$\cdot10^4$ (High Current ERL)
  see also: W. Barletta and A. M. Sessler NIM A 350 (1994) 36-44 ($e^- N \to \mu^+\mu^- e^- N$)

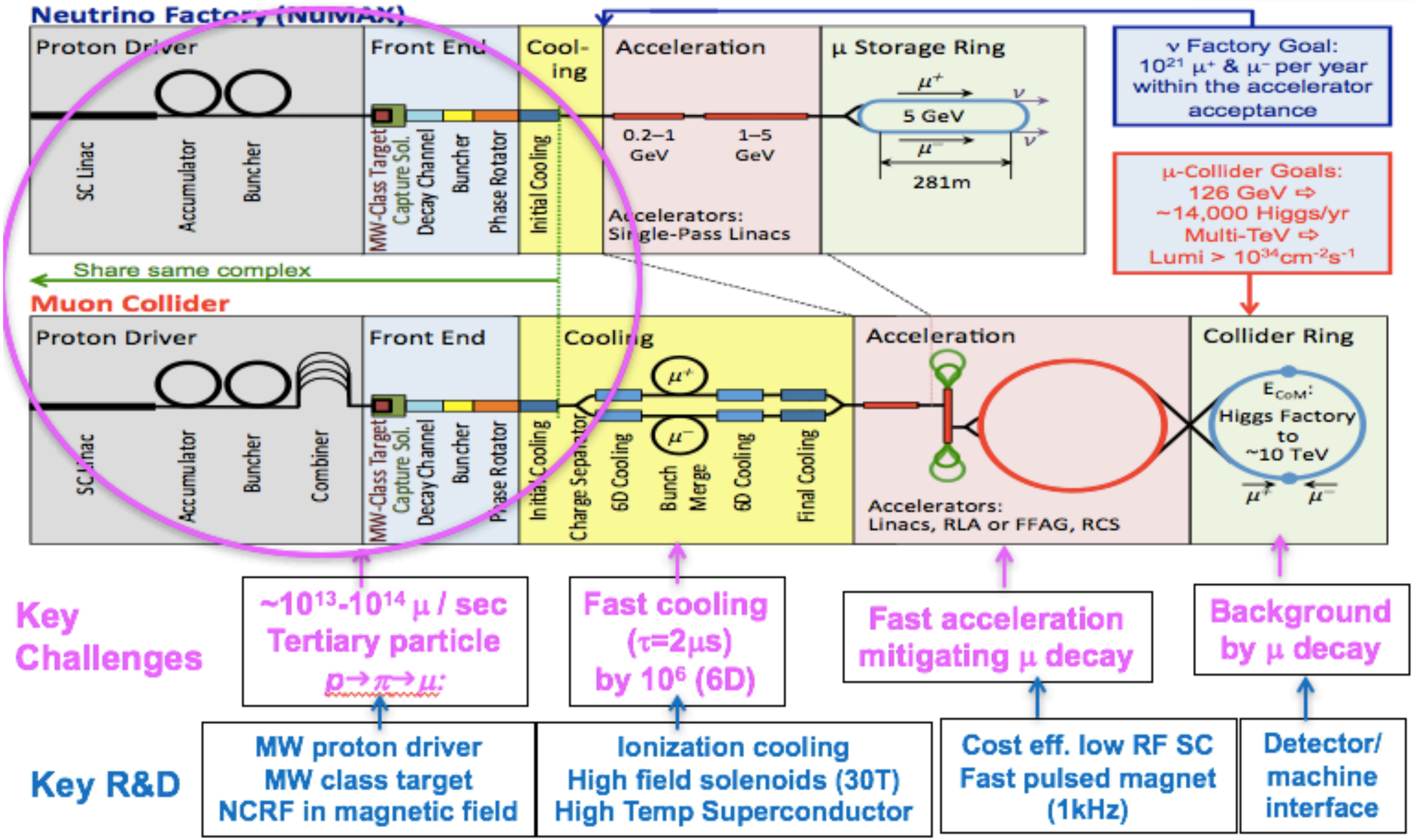
Muon source Comparison

	Physical process	Rate μ/s	normalized emittance e_N [μm-rad]
e+ on target	**e+e-→ μ+μ-**	**0.9×10^{11}**	**0.04**
Protons on target	p N→ πX, kX→ μ X’	10^{13}	25
Compton γ on target	γ N→ μ+μ- N	5×10^{10}	2

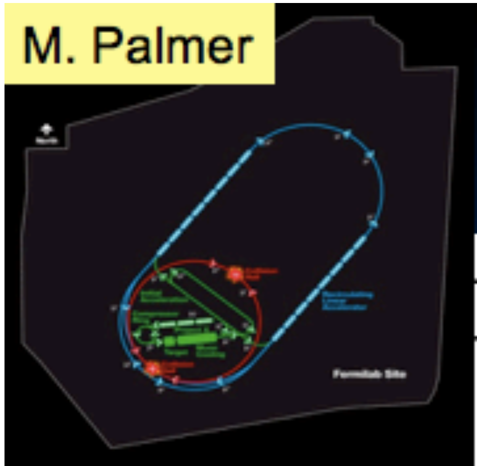
Proton-Based Source

Muon Accelerator Program (MAP) Muon based facilities and synergies

Mark Palmer



M. Palmer



Muon Collider Parameters

Muon Collider Parameters						
		Higgs	**Multi-TeV**			
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*	
CoM Energy	TeV	0.126	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts
⇨ several × 10^{32} [Rubbia proposal: 5×10^{32}]

‘novel’ muon production concept:
e^+ on target

low emittance concept
overcomes cooling

Exploring the potential for a Low Emittance Muon Collider

some <u>References:</u>

- M. Boscolo *et al.*, **"***Studies of a scheme for low emittance muon beam production from positrons on target", ***IPAC17 (2017)**
- M.Antonelli, *"Very Low Emittance Muon Beam using Positron Beam on Target"*, **ICHEP (2016)**
- M.Antonelli *et al.* , *"Very Low Emittance Muon Beam using Positron Beam on Target"*, **IPAC (2016)**
- M. Antonelli, *"Performance estimate of a FCC-ee-based muon collider"*, **FCC-WEEK 2016**
- M. Antonelli, *"Low-emittance muon collider from positrons on target"*, **FCC-WEEK 2016**
- M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, *"Novel proposal for a low emittance muon beam using positron beam on target"*, **NIM A 807 101-107 (2016)**
- P. Raimondi, *"Exploring the potential for a Low Emittance Muon Collider"*, in **Discussion of the scientific potential of muon beams workshop**, CERN, Nov. 18th 2015
- M. Antonelli, **Presentation Snowmass 2013**, Minneapolis (USA) July 2013, [M. Antonelli and P. Raimondi, Snowmass Report (2013) also INFN-13-22/LNF Note

Also investigated by SLAC team:

L. Keller, J. P. Delahaye, T. Markiewicz, U. Wienands:

- *"Luminosity Estimate in a Multi-TeV Muon Collider using $e^+e^- \rightarrow \mu^+\mu^-$ as the Muon Source"*, MAP 2014 Spring workshop, Fermilab (USA) May '14
- Advanced Accelerator Concepts Workshop, San Jose (USA), July '14

Idea for low emittance μ beam

from **proton on target:** p+target$\rightarrow\pi/K \rightarrow \mu$

typically **$P_\mu \approx$ 100 MeV/c** (π, K rest frame)

whatever is the boost P_T will stay in Lab frame →

very high emittance at production point → **cooling needed**!

from **direct μ pair production**:

Muons produced from $\mathbf{e^+e^-\rightarrow\mu^+\mu^-}$ at $\sqrt{s}$ around the $\mu^+\mu^-$ threshold **($\sqrt{s} \approx$ 0.212GeV)** in asymmetric collisions (to collect μ^+ and μ^-)

NIM A Reviewer: ***"A major advantage of this proposal is the lack of cooling of the muons…. the idea presented in this paper may truly revolutionise the design of muon colliders … "***

Advantages:

1. **Low emittance possible:** θ_μ is tunable with $\sqrt{s}$ in $e^+e^- \rightarrow \mu^+\mu^-$
   θ_μ can be **very small** close to the $\mu^+\mu^-$ threshold
2. **Low background:** Luminosity at low emittance will allow low background and low ν radiation (easier experimental conditions, can go up in energy)
3. **Reduced losses from decay:** muons can be produced with a relatively high boost in asymmetric collisions
4. **Energy spread:** muon energy spread **also small at threshold**, it gets larger as $\sqrt{s}$ increases

Disadvantages:

- Rate: much smaller cross section wrt protons ($\approx$ mb)

  $\sigma(e^+e^-\rightarrow\mu^+\mu^-) \approx 1\ \mu b$ at most

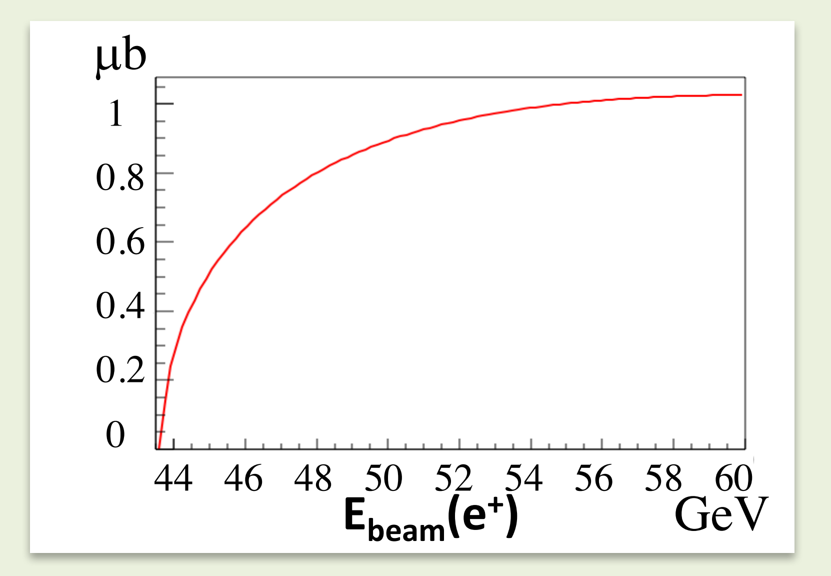
Possible Schemes

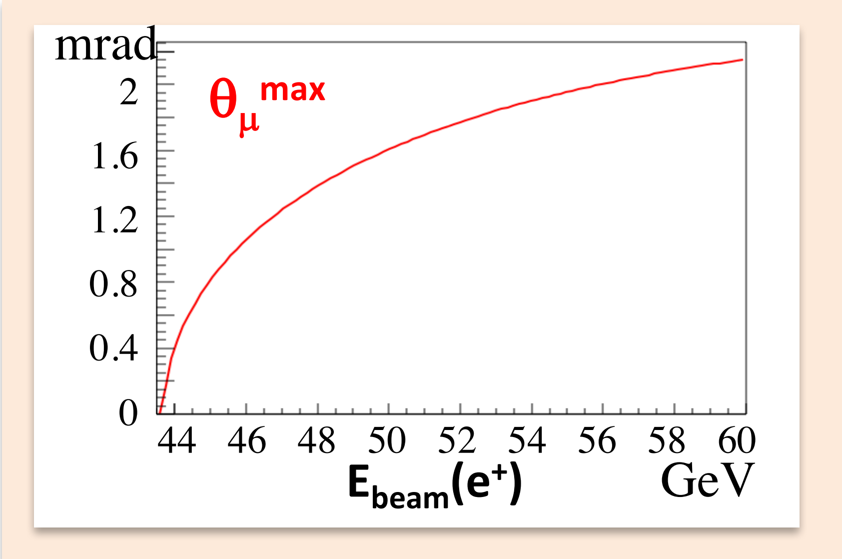
- **Low energy collider with e^+/e^- beam (e$^+$ in the GeV range):**
  1. Conventional asymmetric collisions (but required luminosity $\approx 10^{40}$ is beyond present capability)
  2. Positron beam interacting with continuous beam from electron cooling (too low electron density, 10^{20} electrons/cm^3 needed to obtain a reasonable conversion efficiency to muons)
- **Electrons at rest (seems more feasible):**
  3. e^+ on Plasma target
  4. **e^+ on standard target** (eventually crystals in channeling)
  - **Need Positrons of $\approx$ 45 GeV**
  - $\gamma(\mu)\approx 200$ and μ laboratory lifetime of about 500 μs

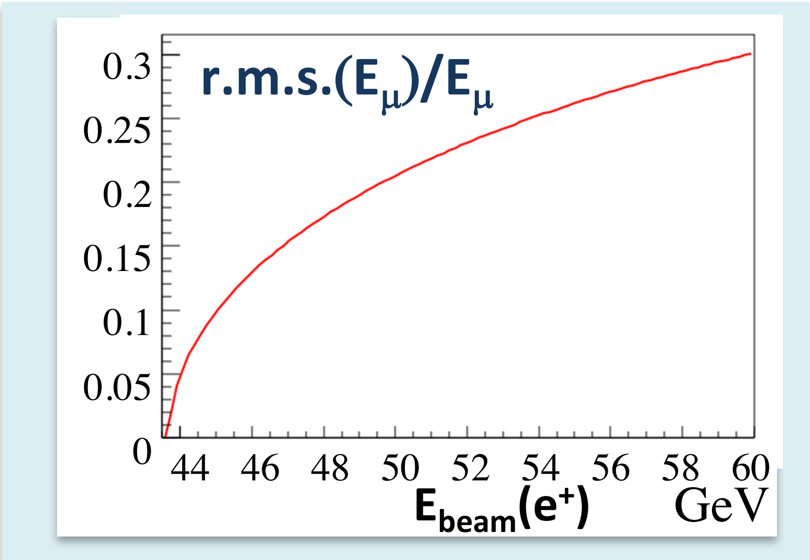
Ideally muons will *copy* the positron beam

Cross-section, muons beam divergence and energy spread as a function of the e+ beam energy

$\sigma(e^+e^- \to \mu^+\mu^-)$



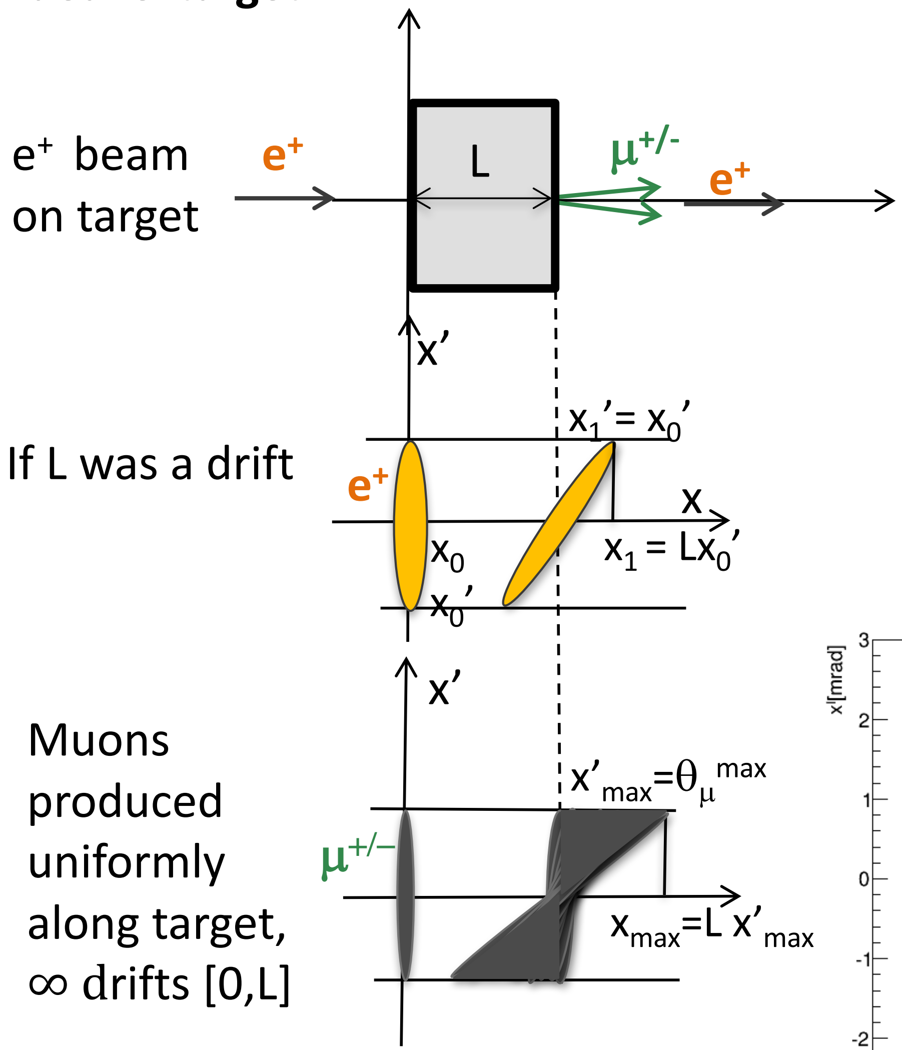


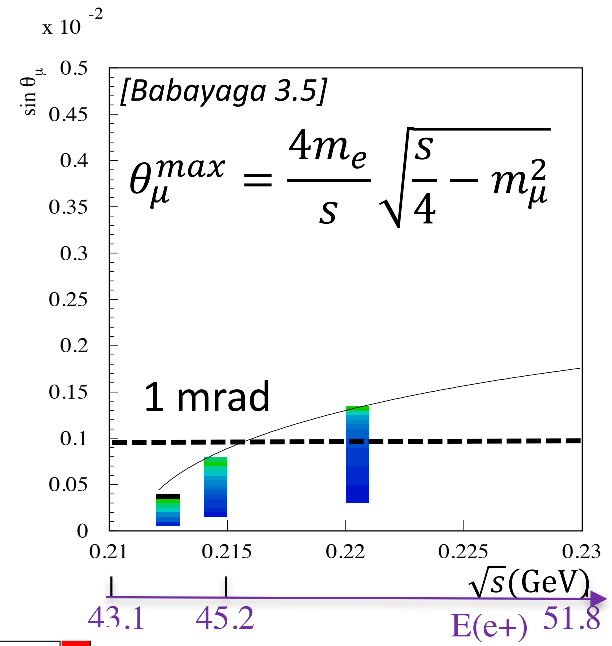


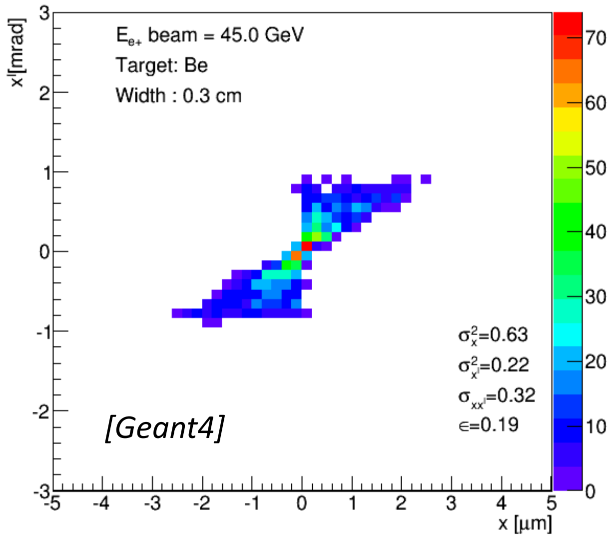
The value of sqrt(s) (*i.e.* $E(e^+)$ for atomic e^- in target) has to maximize the muons production and minimize the beam angular divergence and energy spread

Production contribution to μ beam emittance

ideal e⁻ target







Muon beam at the exit of a 3 mm Be target
ε_μ=0.19 nm
(45 GeV e+ beam)

thin light materials targets have negligible multiple scattering contribution

The emittance contributions due to muon production angle: $\varepsilon_\mu = x\, x'_{max}/12 = L\,(\theta_\mu^{max})^2/12$

→ ε_μ completely determined by L and s -by target thickness and c.o.m. energy

Criteria for target design

Number of $\mu^+\mu^-$ pairs produced per e^+e^- interaction is given by

$$N(\mu^+\mu^-) = \sigma(e^+e \rightarrow \mu^+\mu^-)\ N(e^+)\ \rho(e^-)L$$

$N(e^+)$ number of e^+

$\rho(e^-)$ target electron density

L target length

To maximise $N(\mu^+\mu^-)$:

- **$N(e^+)$** max rate limit set by e^+ source
- **$\rho(e^-)L$** max occurs for L or ρ values giving total e^+ beam loss
  - **e^- dominated target:** radiative Bhabha is the dominant e^+ loss effect, giving a maximal $\mu^+\mu^-$ conversion efficiency $N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e \longrightarrow \mu^+\mu^-)/\sigma_{rb} \approx 10^{-5}$
  - **standard target:** Bremsstrahlung on nuclei and multiple scattering are the dominant effects, Xo and electron density will matter $N(\mu^+\mu^-)/N(e^+) \approx \sigma(e^+e \longrightarrow \mu^+\mu^-)/\sigma_{brem}$

Criteria for target design

Luminosity is proportional to $N_\mu^2 \;\; 1/\varepsilon_\mu$

optimal target: minimizes μ emittance with highest μ rate

- **Heavy materials , thin target**
  - **minimize emittance** (enters linearly) → Copper has about same contributions to emittance from MS and $\mu^+\mu^-$ production
  - high e^+ loss, Bremsstrahlung is dominant, **not optimal μ rate**
- **Very light materials**
  - **maximize conversion efficiency** (enters quad) → H_2
  - even for liquid need O(1m) target, $\varepsilon_\mu \propto L$ → μ **emittance increase**
- **Not too heavy materials (Be, C)**
  - Allow **low emittance with small e^+ loss**

optimal: not too heavy and thin

Criteria for target design

Luminosity is proportional to $N_\mu^2 \; 1/\varepsilon_\mu$

optimal target: minimizes μ emittance with highest μ rate

- **Heavy materials, thin target**
  - to minimize ε_μ : thin target ($\varepsilon_\mu \propto L$) with high density ρ

  Copper: MS and $\mu^+\mu^-$ production give about same contribution to ε_μ

  BUT high e^+ loss (Bremsstrahlung is dominant) so

  $\sigma(e^+\text{loss}) \approx \sigma(\text{Brem+bhabha}) \approx (Z+1)\sigma(\text{Bhabha}) \rightarrow$

  $N(\mu^+\mu^-)/N(e^+) \approx \sigma_\mu/[(Z+1)\sigma(\text{Bhabha})] \approx 10^{-7}$

- **Very light materials, thick target**
  - **maximize $\mu^+\mu^-$ conversion efficiency $\approx 10^{-5}$** (enters quad) → H_2

  Even for liquid targets O(1m) needed → $\varepsilon_\mu \propto L$ increase

- **Not too heavy materials (Be, C)**
  - Allow low ε_μ with small e^+ loss **$N(\mu^+\mu^-)/N(e^+) \approx 10^{-6}$**

not too heavy and thin in combination with stored positron beam to reduce requests on positron source

Application for Multi-TeV Muon Collider as an example

- Use thin target with high efficiency and small e^+ loss
- Positrons in storage ring with high momentum acceptance
- No need of extreme beam energy spread

Preliminary scheme for low emittance μ beam production

Goal:

$@T \approx 10^{11}\ \mu/s$

Efficiency $\approx 10^{-7}$ (with Be 3mm)→

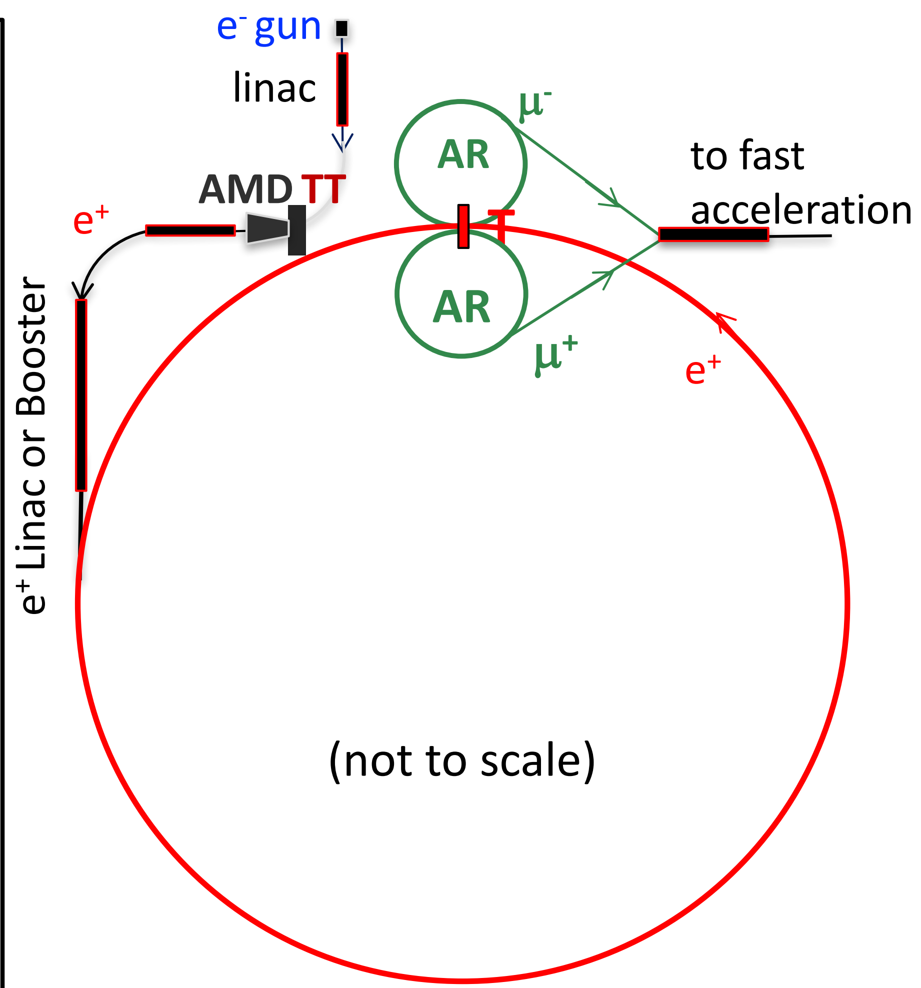
$10^{18}\ e^+/s$ needed @T →

e^+ stored beam with T

need the largest possible lifetime to minimize positron source rate

LHeC like e+ source required rate with lifetime(e+) ≈ 250 turns [i.e. 25% momentum aperture (+/-12%)]

→ $n(\mu)/n(e^+\ \text{source}) \approx 10^{-5}$



Preliminary scheme for low emittance μ beam production

from e^+ SOURCE to RING:

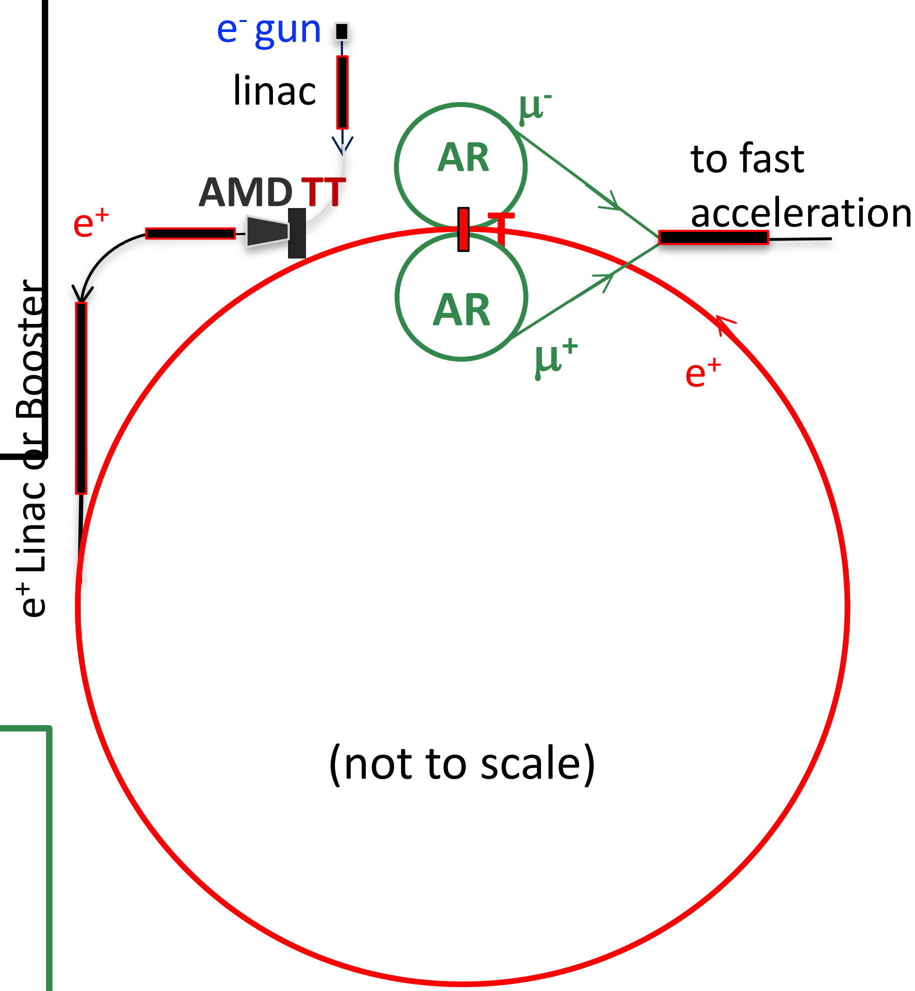
- **e^-** on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.
- Adiabatic Matching Device (**AMD**) for **e^+** collection →
- acceleration (linac / booster) , injection →

e^+ RING:

- **6.3 km 45 GeV** storage ring with target **T** for muon production

from μ^+ μ^- production to collider

- produced by the **e^+** beam on target **T** with **E(μ) ≈ 22 GeV**, $\gamma(\mu) \approx 200 \rightarrow \tau_{lab}(\mu) \approx$ **500μs**
- **AR**: **60 m** isochronous and high mom. acceptance rings will recombine μ bunches for ~ 1 $\tau_\mu^{lab} \approx 2500$ turns
- fast acceleration
- muon collider



Preliminary scheme for low emittance μ beam production

from e^+ SOURCE to RING:

- e^- on conventional Heavy Thick Target (**TT**) for e^+e^- pairs production.
- possibly with γ produced by e^+ stored beam on **T**→
- Adiabatic Matching Device (**AMD**) for e^+ collection →
- acceleration (linac / booster) , injection →

e^+ RING:

- **6.3 km 45 GeV** storage ring with target **T** for muon production

from μ^+ μ^- production to collider

- produced by the e^+ beam on target **T** with **E(μ) ≈ 22 GeV**, $\gamma(\mu) \approx 200 \rightarrow \tau_{lab}(\mu) \approx$ **500μs**
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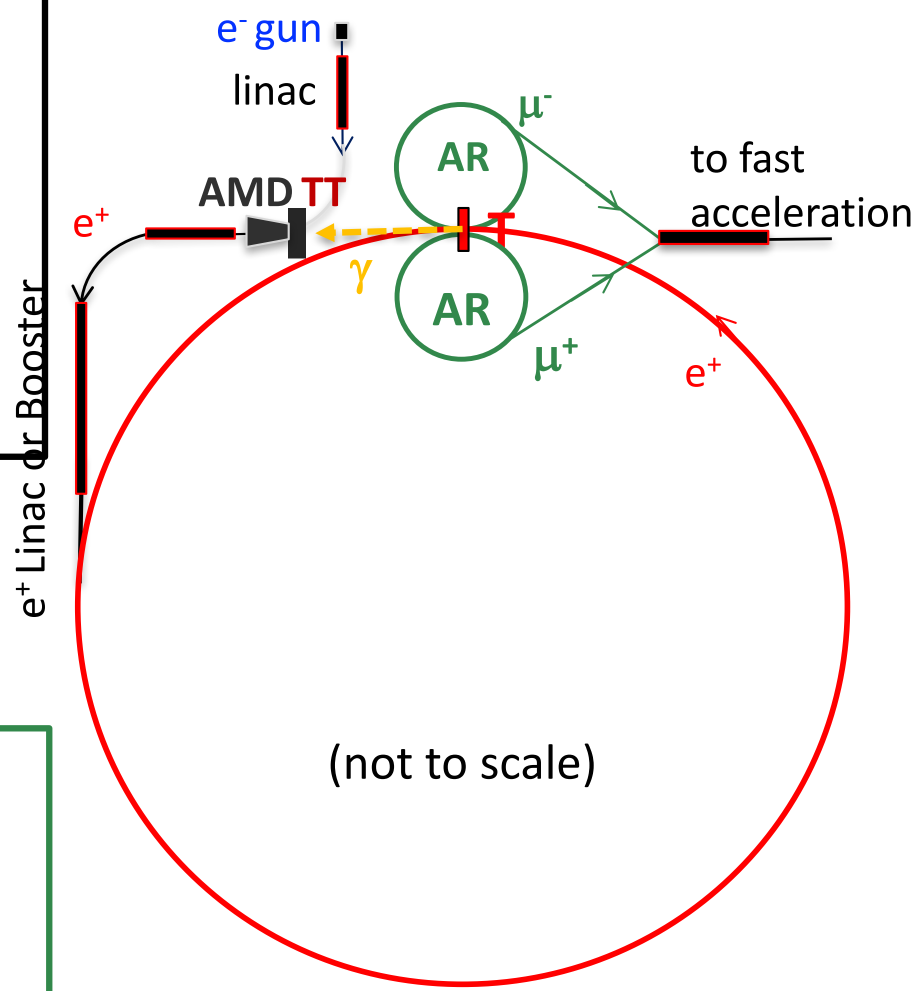
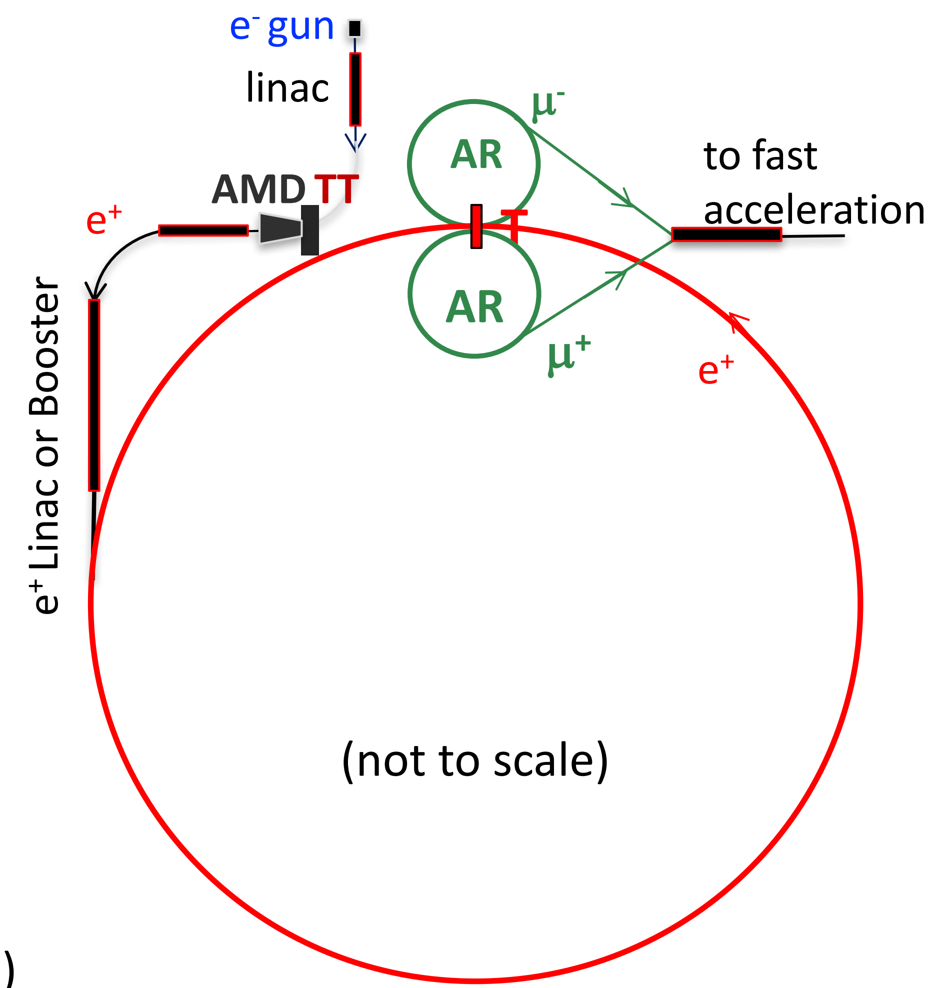


Preliminary scheme for low emittance μ beam production

e+ ring parameter	unit	
Circumference	km	6.3
Energy	GeV	45
bunches	#	100
e^+ bunch spacing = T_{rev} (AR)	ns	200
Beam current	mA	240
$N(e^+)$/bunch	#	$3 \cdot 10^{11}$
U_0	GeV	0.51
SR power	MW	120

(also 28 km foreseen to be studied as an option)



6 TeV μ collider draft Parameters

no lattice yet

$\mu^+\mu^-$ rate = 9 10^{10} Hz

ε_N = 40 nm

[NIM A 807 101-107 (2016)]

if: LHeC like e^+ source
with 25% mom. accept. e^+ ring
and ε dominated by μ production

thanks to very small emittance (and lower beta*) comparable luminosity with lower Nμ/bunch
(→ lower background)

Of course, a design study is needed to have a reliable estimate of performances

Parameter	Units	LEMC-6TeV
LUMINOSITY/IP	cm^{-2} s^{-1}	5.09E+34
Beam Energy	GeV	3000
Hourglass reduction factor		1.000
Muon mass	GeV	0.10566
Lifetime @ prod	sec	2.20E-06
Lifetime	sec	0.06
c*tau @ prod	m	658.00
c*tau	m	1.87E+07
1/tau	Hz	1.60E+01
Circumference	m	6000
Bending Field	T	15
Bending radius	m	667
Magnetic rigidity	T m	10000
Gamma Lorentz factor		28392.96
N turns before decay		3113.76
β_x @ IP	m	0.0002
β_y @ IP	m	0.0002
Beta ratio		1.0
Coupling (full current)	%	100
Normalised Emittance x	m	4.00E-08
Emittance x	m	1.41E-12
Emittance y	m	1.41E-12
Emittance ratio		1.0
Bunch length (zero current)	mm	0.1
Bunch length (full current)	mm	0.1
Beam current	mA	0.048
Revolution frequency	Hz	5.00E+04
Revolution period	s	2.00E-05
Number of bunches	#	1
N. Particle/bunch	#	6.00E+09
Number of IP	#	1.00
σ_x @ IP	micron	1.68E-02
σ_y @ IP	micron	1.68E-02
$\sigma_{x'}$ @ IP	rad	8.39E-05
$\sigma_{y'}$ @ IP	rad	8.39E-05

Radiological hazard due to neutrinos from a muon collider

Colin Johnson, Gigi Rolandi and Marco Silari

TIS-RP/IR/98-34 (1998) (updated by M.A.)

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)

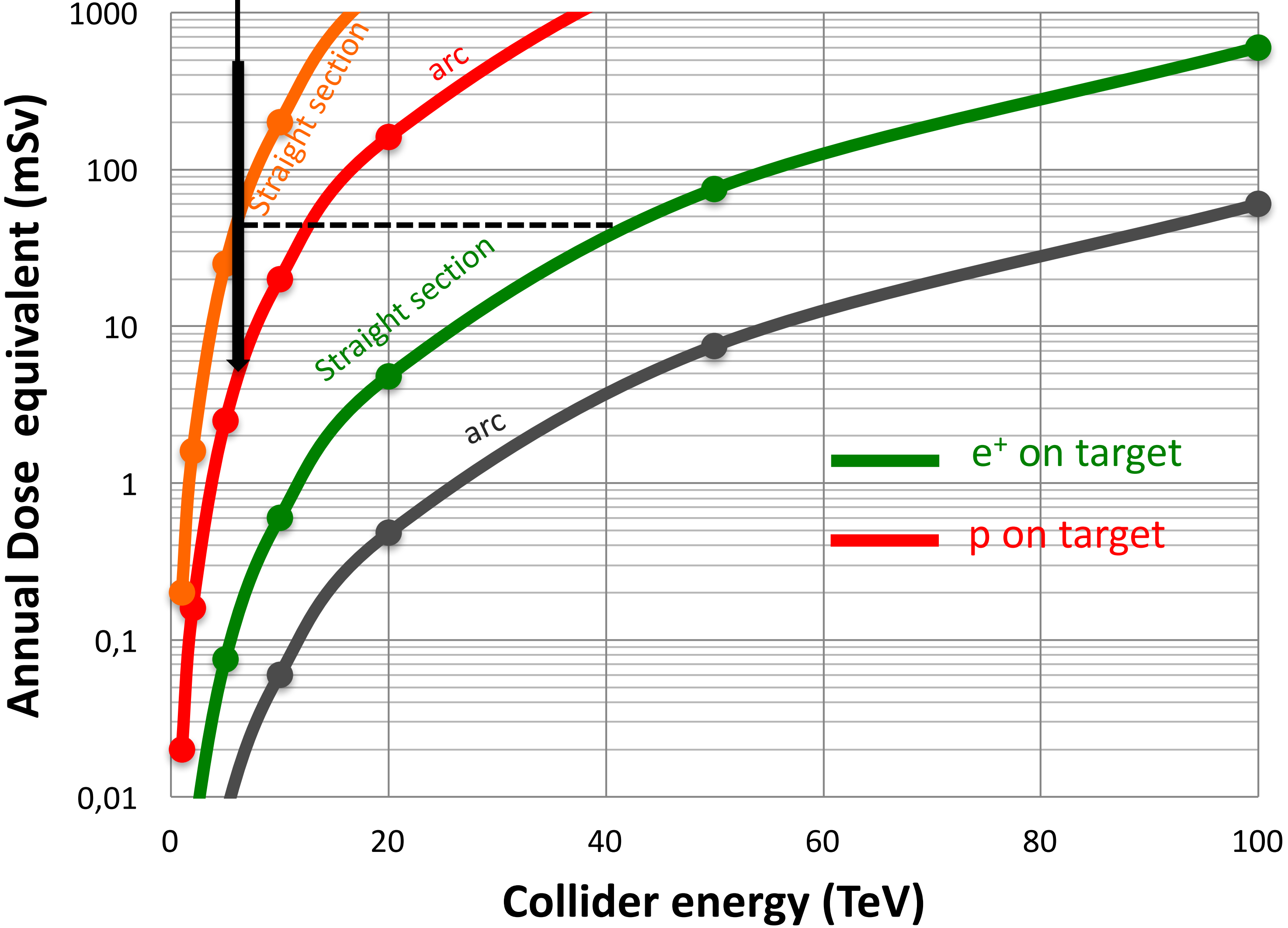
muon rate:

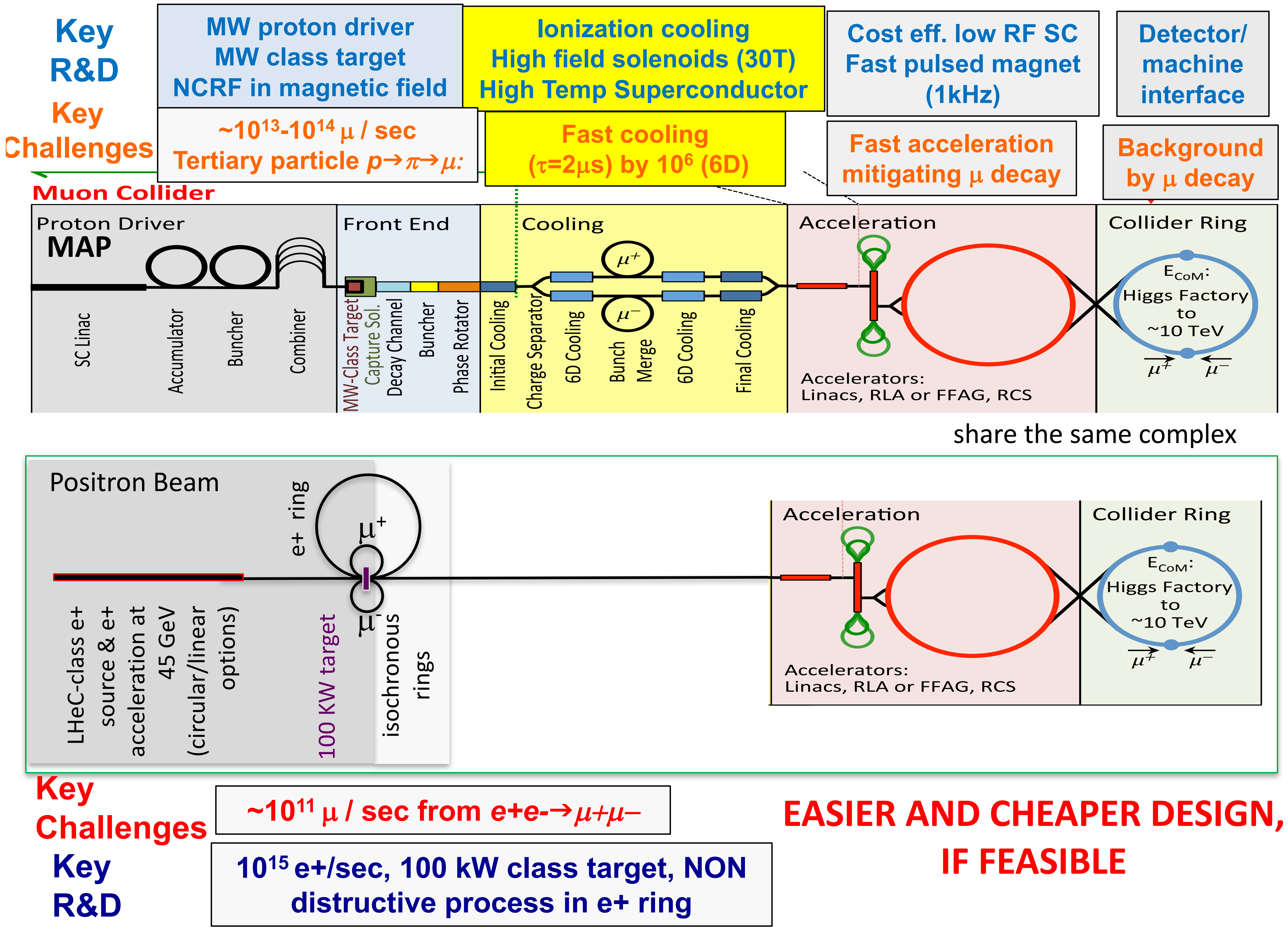
p on target option
3×10^{13} μ/s

e^+ on target option
9×10^{10} μ/s

neutrino dose equivalent/fluence

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

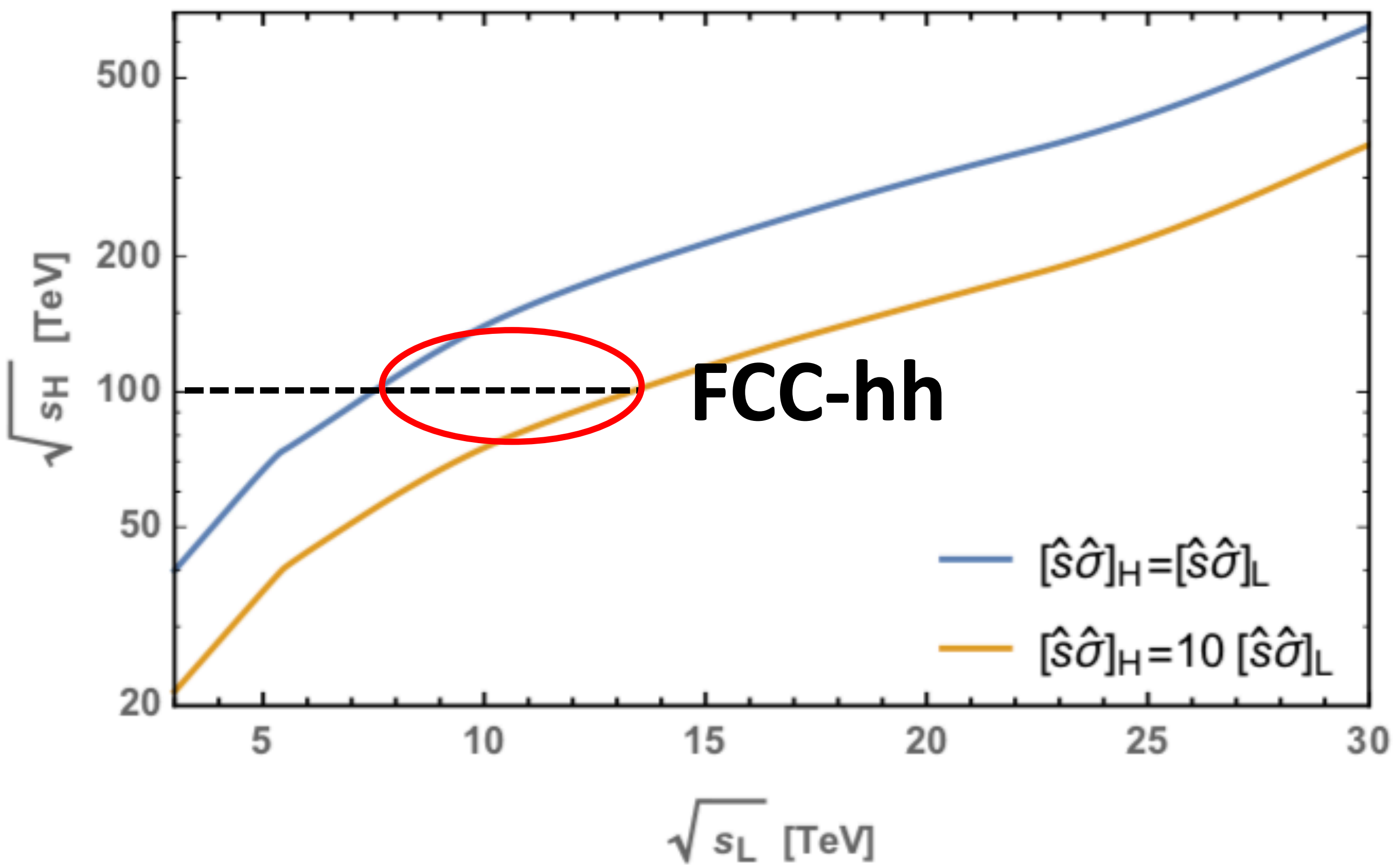



Key R&D
MW proton driver
MW class target
NCRF in magnetic field
Ionization cooling
High field solenoids (30T)
High Temp Superconductor
Cost eff. low RF SC
Fast pulsed magnet
(1kHz)
Detector/ machine interface
Key Challenges
~10^13-10^14 μ / sec
Tertiary particle p→π→μ:
Fast cooling
(τ=2μs) by 10^6 (6D)
Fast acceleration
mitigating μ decay
Background
by μ decay
Muon Collider
Proton Driver
MAP
SC Linac
Accumulator
Buncher
Combiner
Front End
MW-Class Target
Capture Sol.
Decay Channel
Buncher
Phase Rotator
Cooling
Initial Cooling
Charge Separator
6D Cooling
μ+
μ−
Bunch Merge
6D Cooling
Final Cooling
Acceleration
Accelerators:
Linacs, RLA or FFAG, RCS
Collider Ring
E_CoM:
Higgs Factory
to
~10 TeV
μ+
μ−
share the same complex
Positron Beam
LHeC-class e+ source & e+ acceleration at 45 GeV (circular/linear options)
e+ ring
μ+
μ-
100 KW target
isochronous rings
Acceleration
Accelerators:
Linacs, RLA or FFAG, RCS
Collider Ring
E_CoM:
Higgs Factory
to
~10 TeV
μ+
μ−
Key Challenges
~10^11 μ / sec from e+e-→μ+μ−
Key R&D
10^15 e+/sec, 100 kW class target, NON distructive process in e+ ring
EASIER AND CHEAPER DESIGN,
IF FEASIBLE

Muon Colliders potential (hh vs μμ)

A wulzer

hh

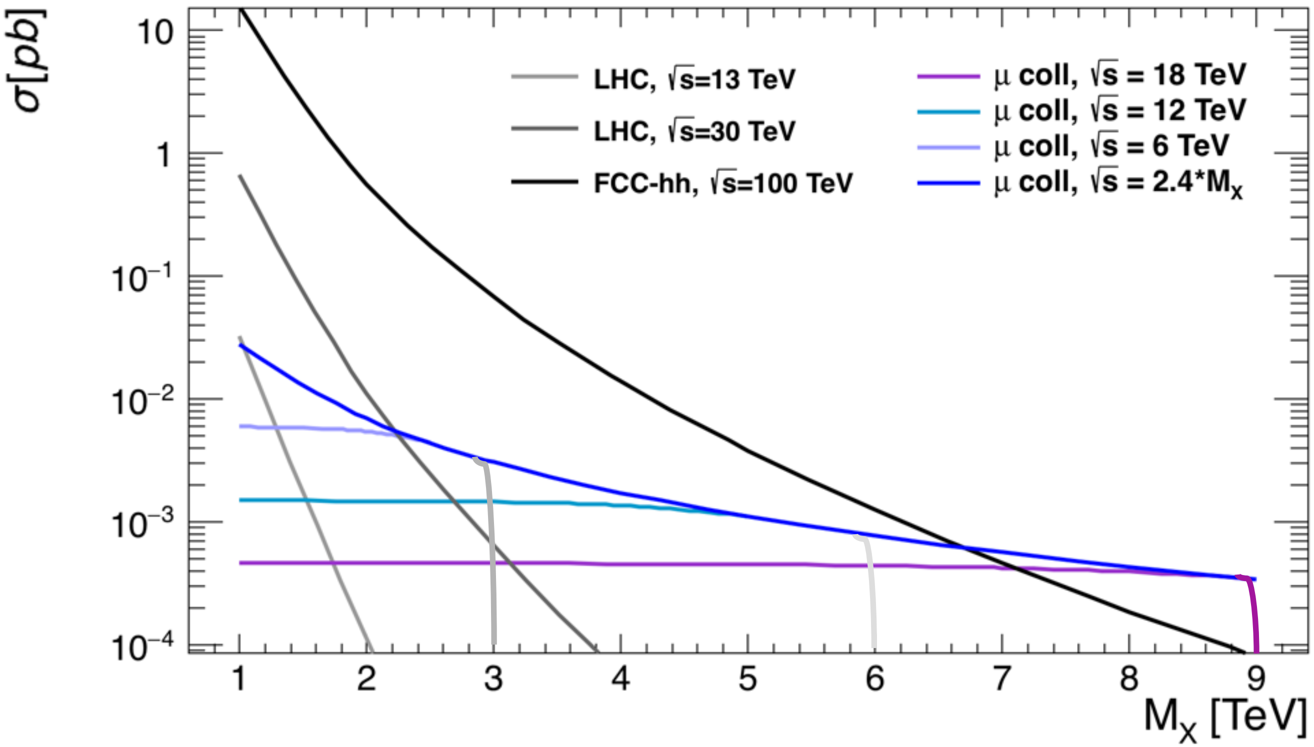


μμ

Not appropriate for squark gluino searches at hh

Muon collider reach: an example

- Study the same benchmark used for White Paper:
  - New heavy particles, both colored and EW charged (~vector like quarks)➔ xsec can be predicted
  - FCC reach stops at M_X = 7 TeV
- Hadron machine pays the price of the exponentially falling PDF ➔ multi-TeV muon machine can be competitive!



[Wulzer]

CMC

CERN Muon Collider

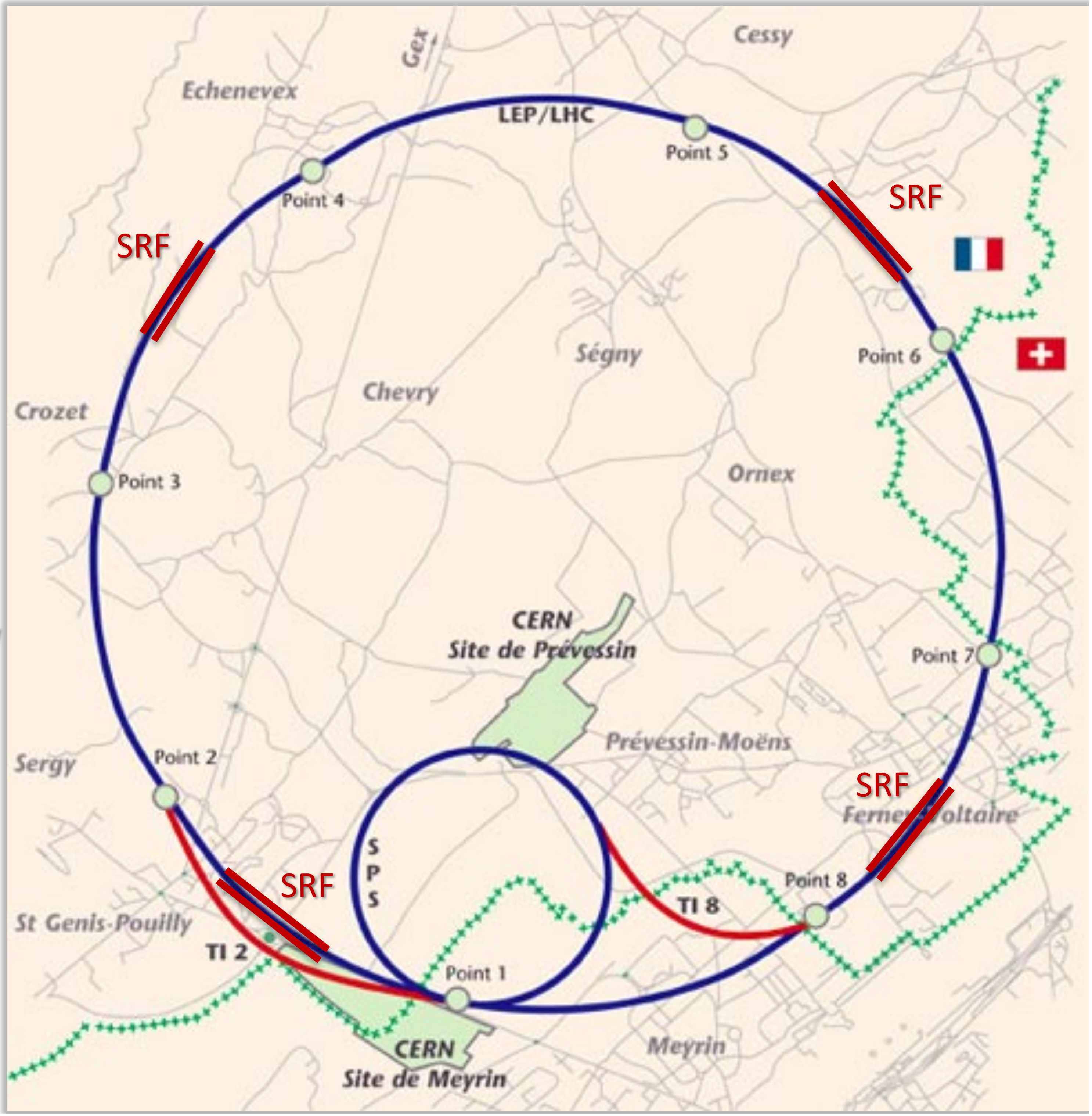
14 TeV cme

LHC tunnel
SPS tunnel and
mb PS

~7GeV SRF

Cost ~LHC

V. Shiltzev Fermilab

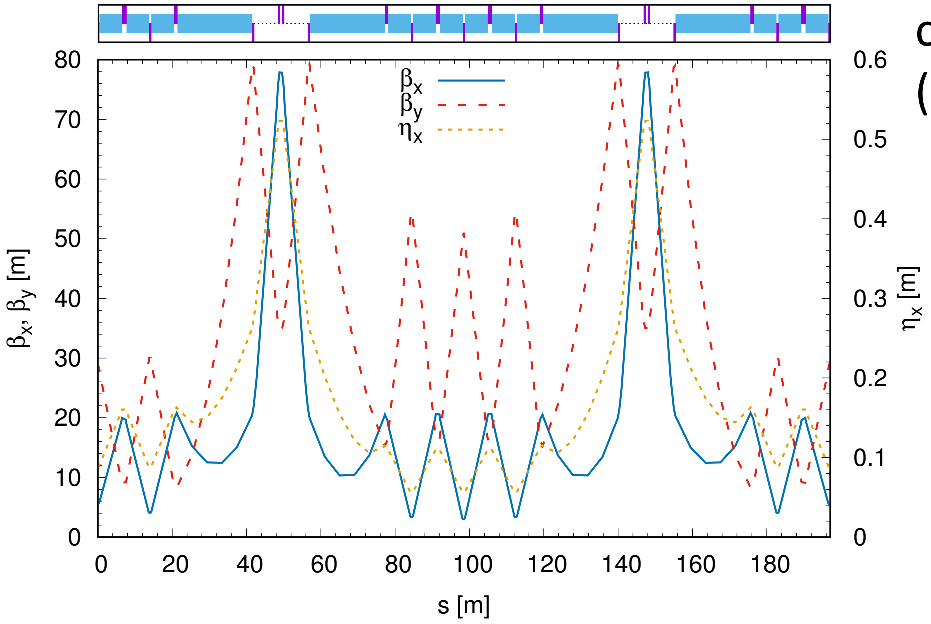


Key topics for this scheme

- **Low emittance and high momentum acceptance 45 GeV e^+ ring**
- **O(100 kW) class target in the e^+ ring for μ^+ μ^- production**
- **High rate positron source**
- **High momentum acceptance muon accumulator rings**

Low emittance 45 GeV positron ring

cell

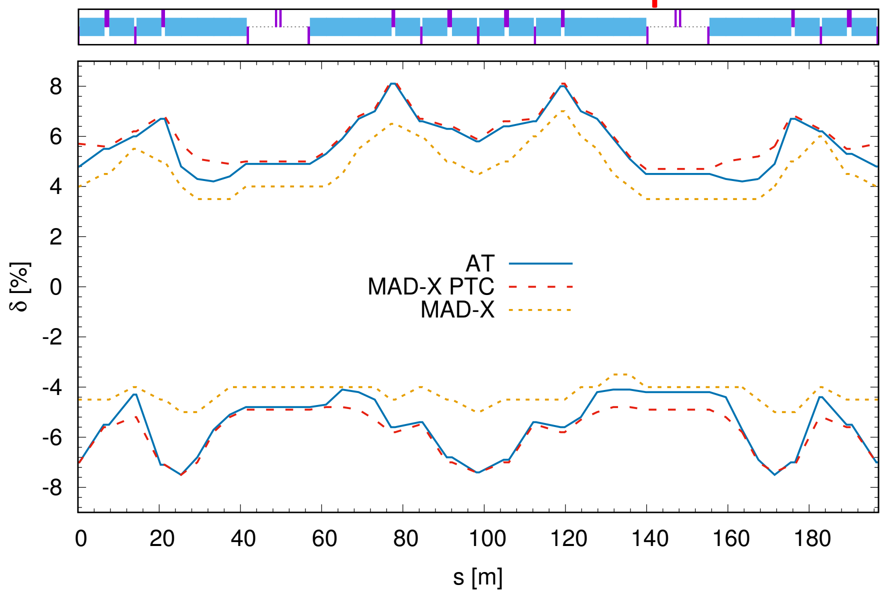


circumference 6.3 km: 197 m x 32 cells
(no injection section yet)

Table e+ ring parameters

Parameter	Units	
Energy	GeV	45
Circumference	m	6300
Coupling(full current)	%	1
Emittance x	m	5.73×10^{-9}
Emittance y	m	5.73×10^{-11}
Bunch length	mm	3
Beam current	mA	240
RF frequency	MHz	500
RF voltage	GV	1.15
Harmonic number	#	10508
Number of bunches	#	100
N. particles/bunch	#	3.15×10^{11}
Synchrotron tune		0.068
Transverse damping time	turns	175
Longitudinal damping time	turns	87.5
Energy loss/turn	GeV	0.511
Momentum compaction		1.1×10^{-4}
RF acceptance	%	± 7.2
Energy spread	dE/E	1×10^{-3}
SR power	MW	120

momentum acceptance



Physical aperture=5 cm constant

no errors

Good agreement between MADX PTC / Accelerator Toolbox,
both used for particle tracking in our studies

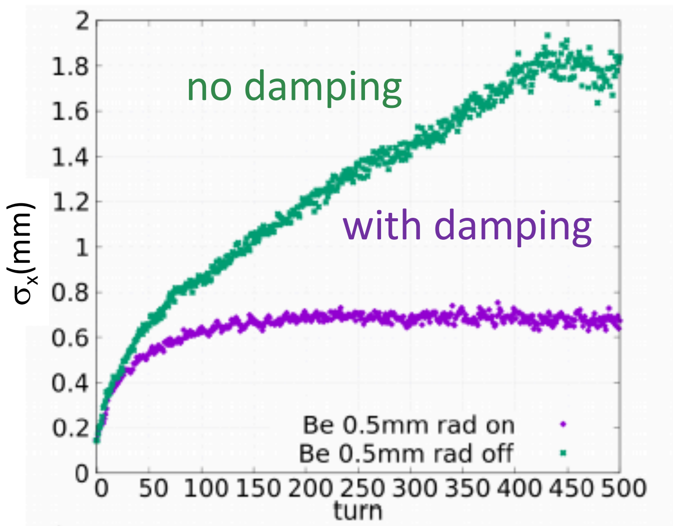
Multi-turn simulations

1. Initial 6D distribution from the equilibrium emittances
2. 6D e^+ distribution tracking up to the target (AT and MAD-X PTC)
3. tracking through the target (with Geant4beamline and FLUKA and GEANT4)
4. back to tracking code

At each pass through the muon target the e+ beam

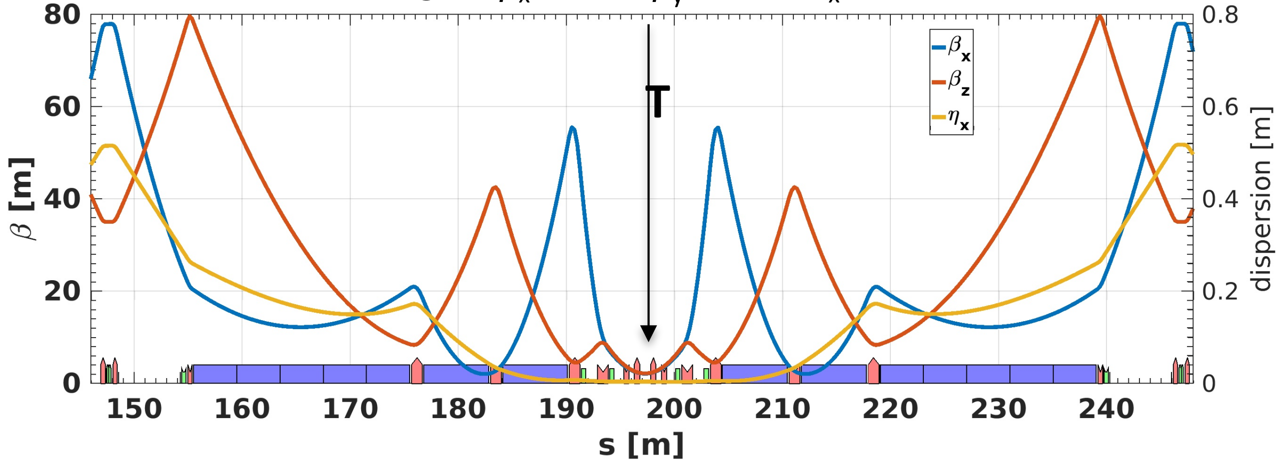
- gets an angular kick due to the **multiple Coulomb scattering**, so at each pass changes e^+ beam divergence and size, resulting in an emittance increase.
- undergoes **bremsstrahlung energy loss**: to minimize the beam degradation due to this effect, D_x=0 at target

- in addition there is natural radiation **damping** **(**it prevents an indefinite beam growth)



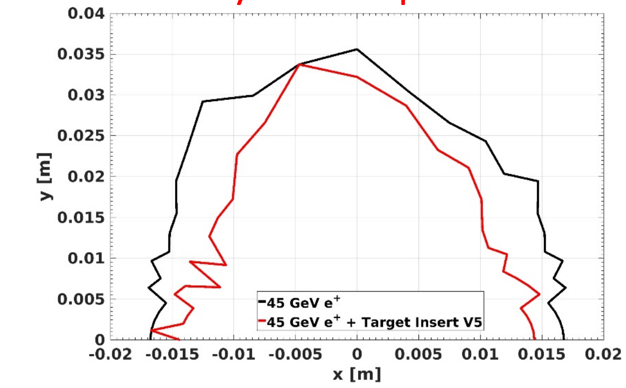
Preliminary low-β IR for muon target insertion

@target: β_x=1.6m; β_y=1.7m; D_x=5.4mm

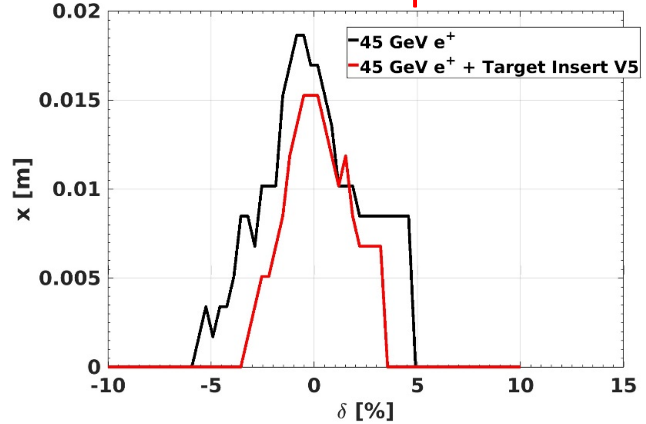


- **@target location:**
  - **$D_x \approx 0$**
  - **low-β**
- Further optimizations are underway:
  - match the transverse minimum beam size with constraints of target thermo-mechanical stress
  - match with other contributions to muon emittance (production, accumulation)
  - dynamic and momentum aperture can be optimized

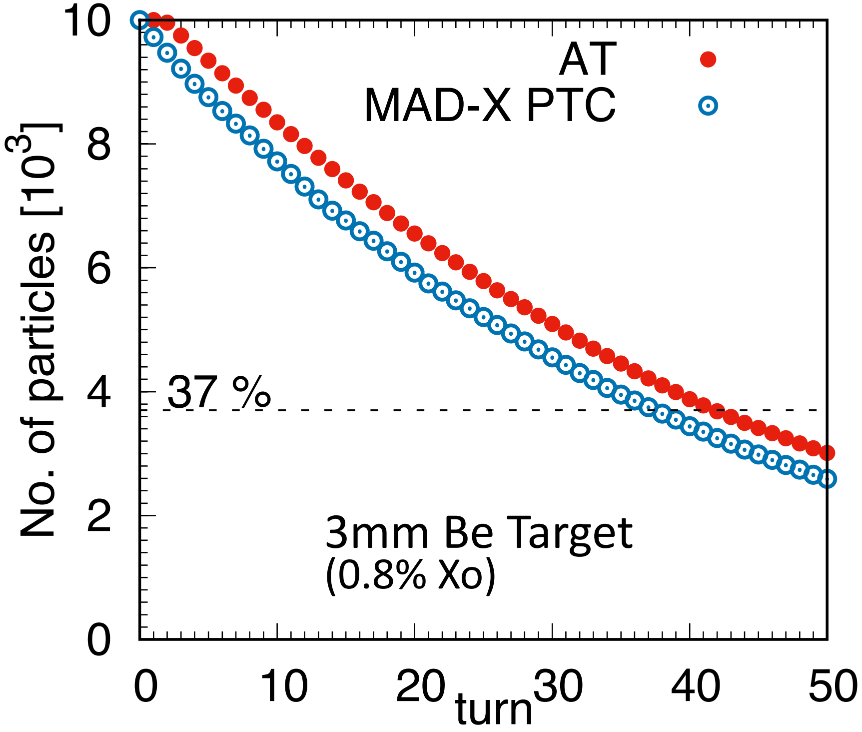
Dynamic Aperture

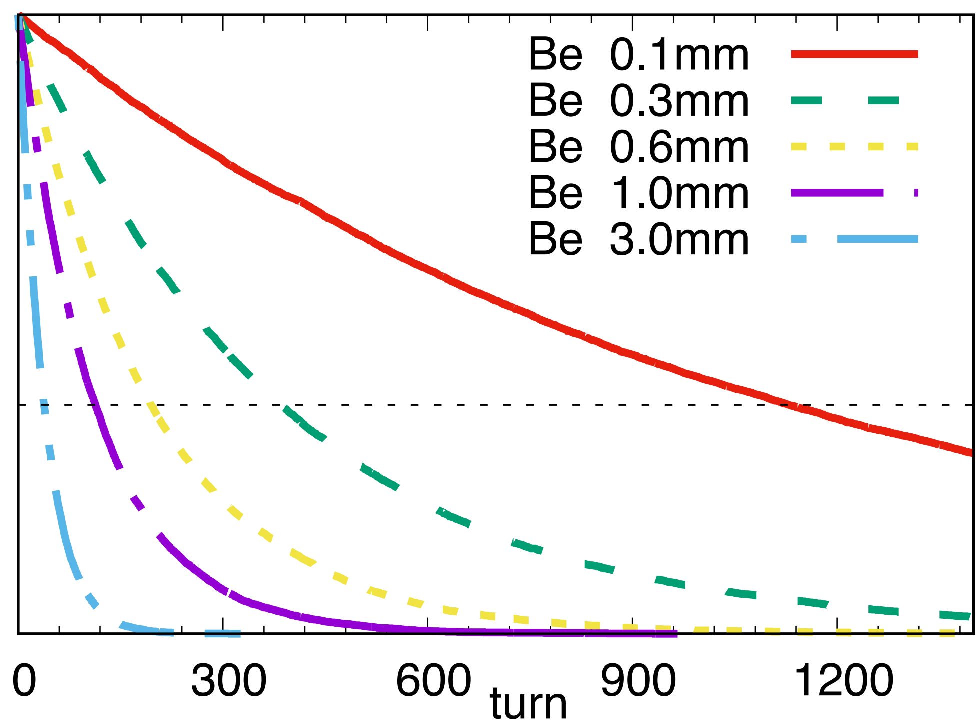


Momentum Aperture



e+ lifetime with Be target





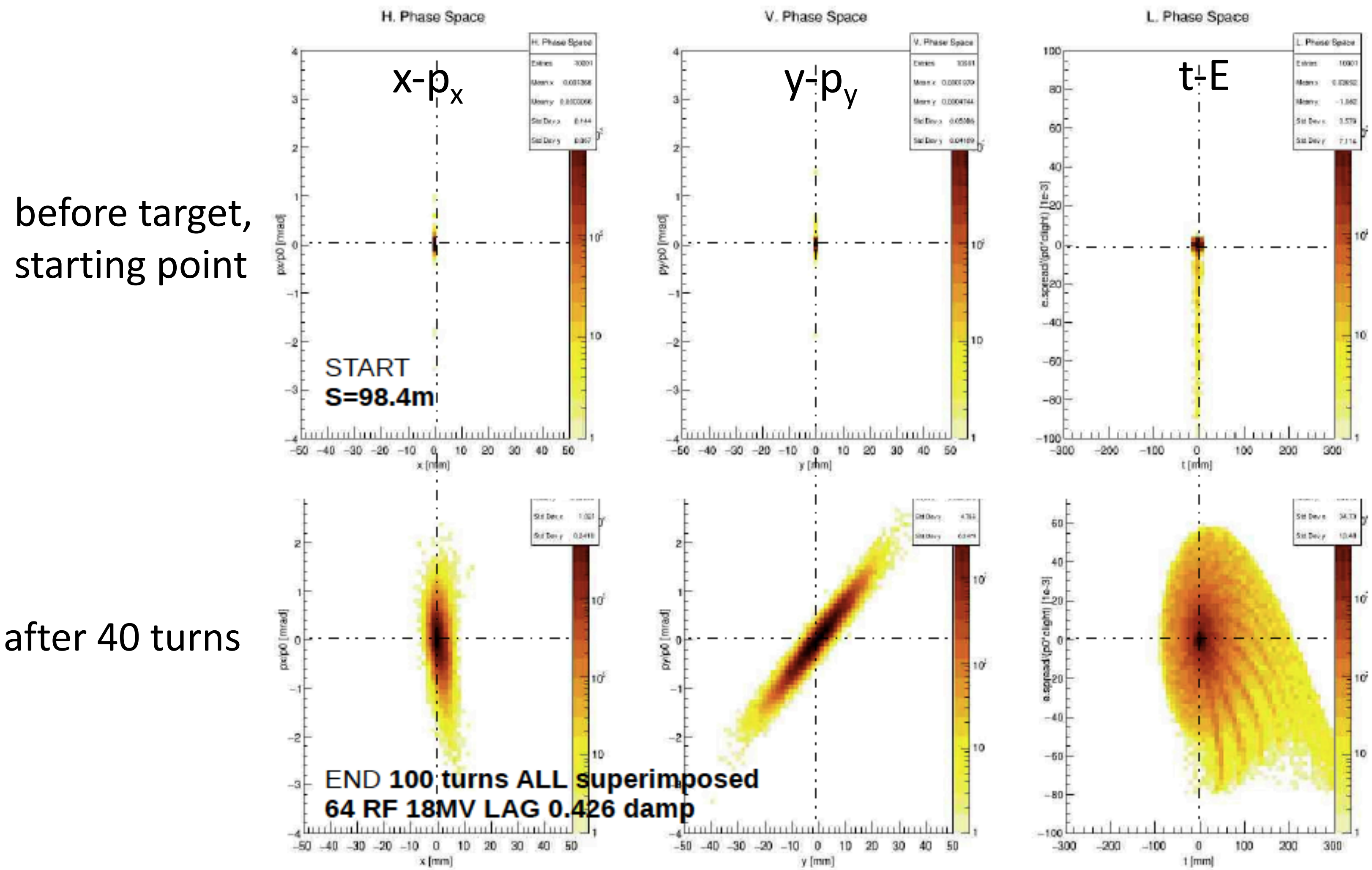
determined by **bremsstrahlung and momentum acceptance**

Lifetime with ~ 40 turns

Lifetime ∝ 1/thickness as expected

2-3% e+ losses happen in the first turn

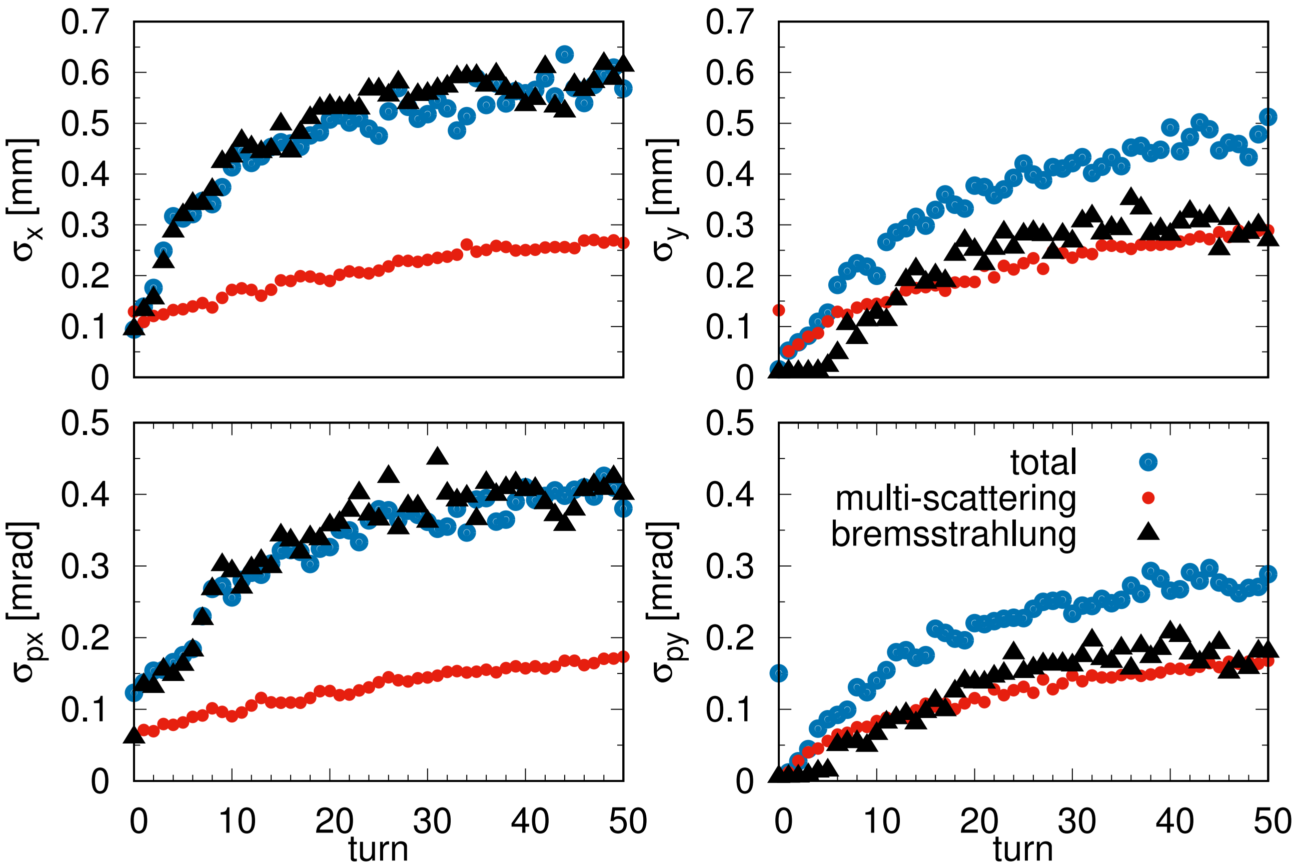
e+ ring with target: beam evolution in the 6D phase space



MAD-X PTC & GEANT4 6-D tracking simulation of
e+ beam with 3 mm Be target along the ring (not at IR center in this example)

Evolution of e+ beam size and divergence

3mm Be Target (0.8% Xo) at center of IR



bremsstrahlung and multiple scattering artificially separated by considering alternatively effects in longitudinal (dominated by **bremsstrahlung**) and transverse (dominated by **multiple scattering**) phase space due to target; in **blue** the combination of both effects (realistic target)

Some bremsstrahlung contribution due to residual dispersion at target

multiple scattering contribution in line with expectation: $\sigma_{MS} = \frac{1}{2}\sqrt{n}\,\sigma'_{MS}\,\beta$

one pass contribution due to the target: $\sigma'_{MS} = 25\ \mu\text{rad}$

n number of turns

Control of emittance growth

Emittance growth controlled with proper lattice parameters

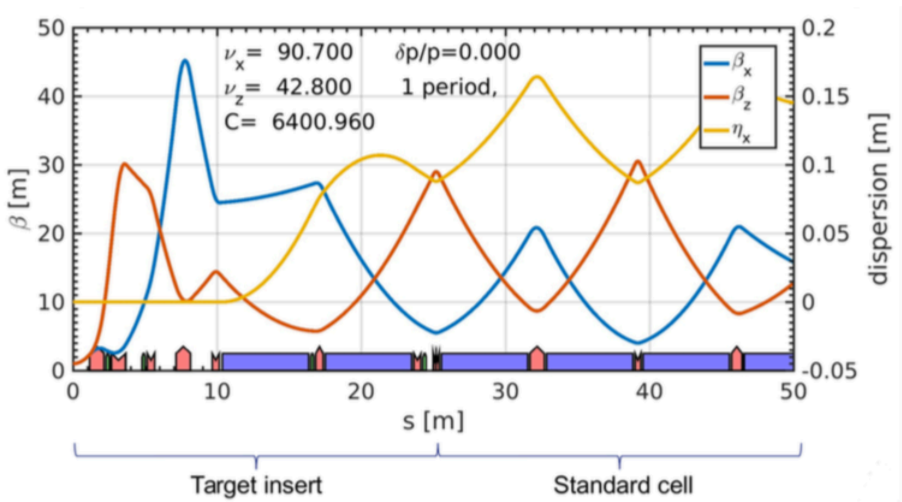
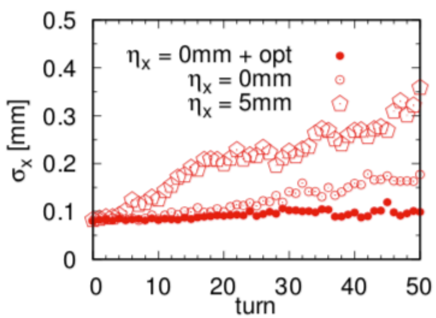
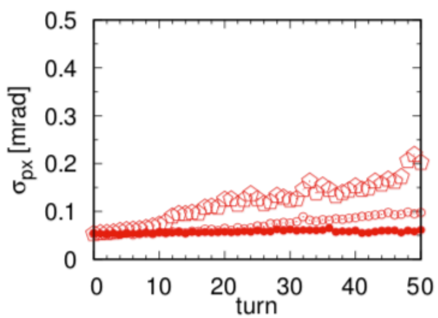
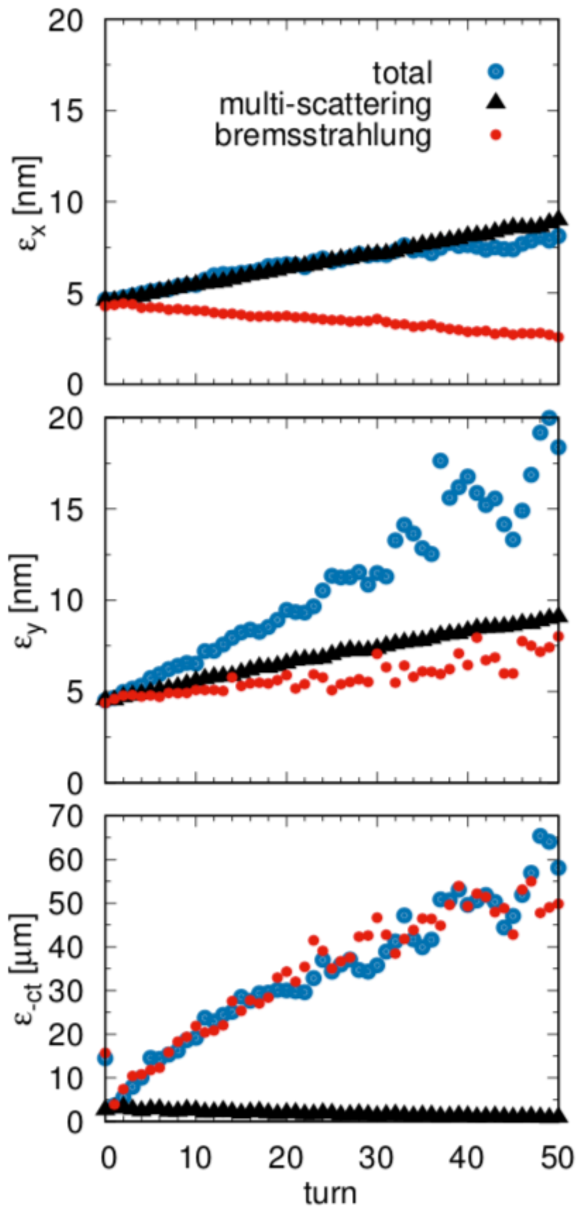


FIG. 9. Target insertion region and 25 m of the cell.

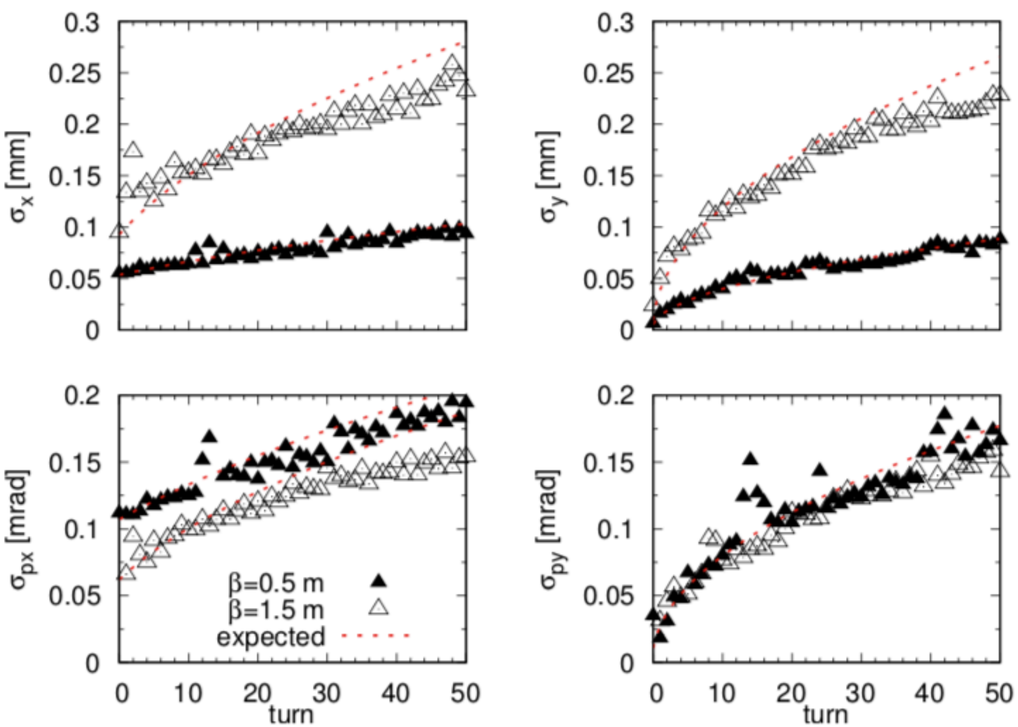






Control of emittance growth

Emittance growth controlled with proper lattice parameters



multiple scattering contribution in line with expectation:
one pass contribution due to the target: $\sigma'_{\mathrm{MS}} = 25\ \mu\mathrm{rad}$

$$\sigma_{\mathrm{MS}} = \frac{1}{2}\sqrt{n}\,\sigma'_{\mathrm{MS}}\,\beta$$

n number of turns

Muon emittance

$$\varepsilon(\mu) = \varepsilon(e^+) \oplus \varepsilon(MS) \oplus \varepsilon(rad) \oplus \varepsilon(prod) \oplus \varepsilon(AR)$$

$\varepsilon(e^+)$ = e^+ emittance
$\varepsilon(MS)$ = multiple scattering contribution
$\varepsilon(rad)$ = energy loss (brem.) contribution
$\varepsilon(prod)$ = muon production contribution
$\varepsilon(AR)$ = accumulator ring contribution

would like all contributions of same size

knobs:

- β_x β_y @target & target material
- β_x β_y D_x @target & target material
- $E(e^+)$ & target thickness
- AR optics & target

with constraints from target survival

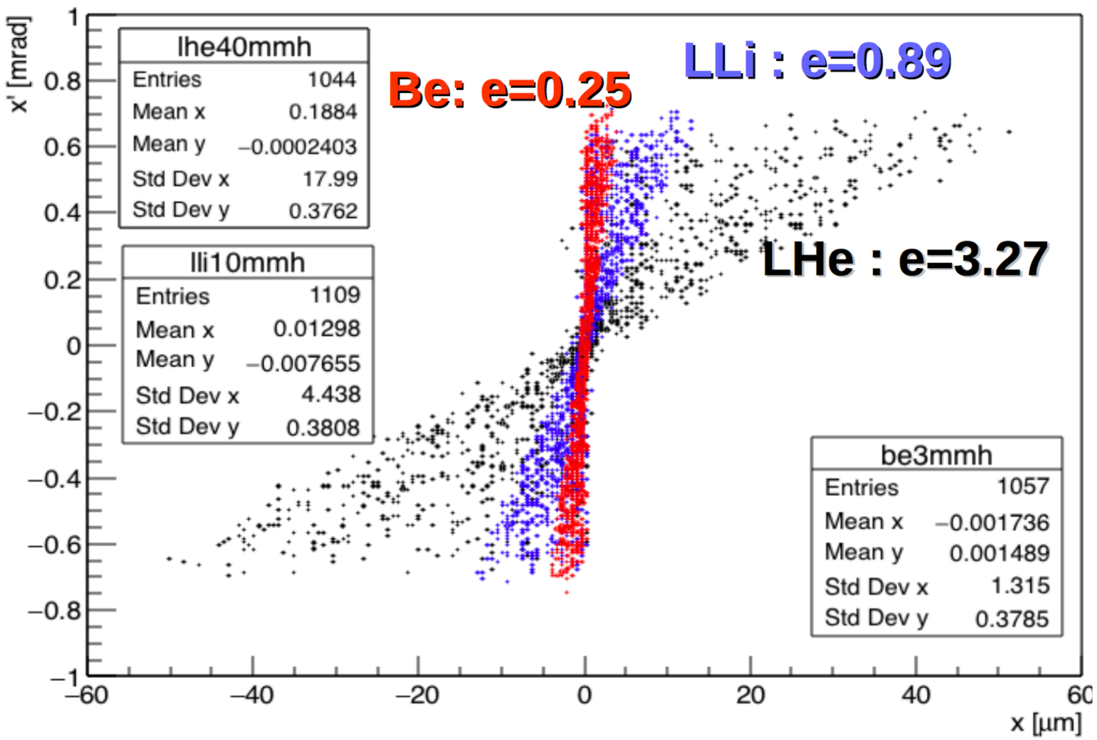
now: $\varepsilon(\mu)$ dominated by $\varepsilon(MS) \oplus \varepsilon(rad)$ -> lower β-functions at target with beam spot at the limit of the target survival

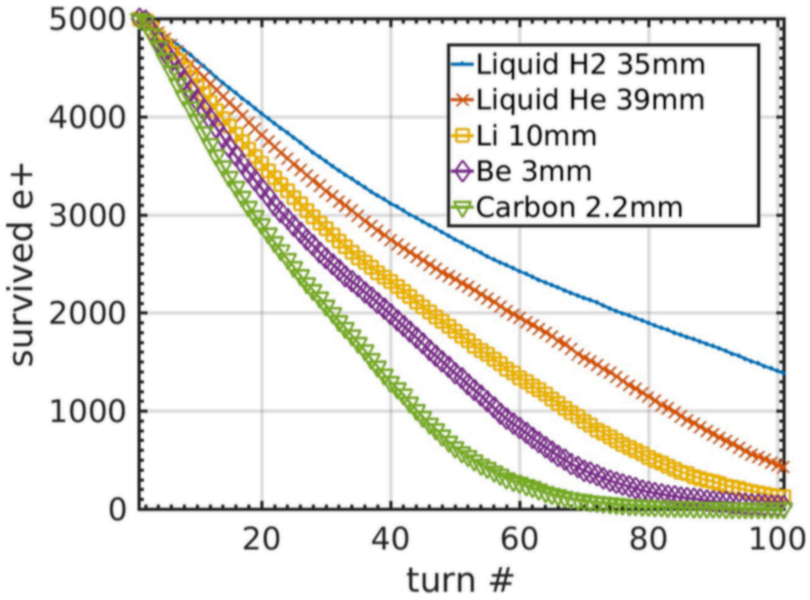
also test different material

- crystals in channeling better: $\varepsilon(MS)$, $\varepsilon(rad)$, $\varepsilon(prod)$ (also gain in lifetime)
- light liquid jet target better: $\varepsilon(MS)$, $\varepsilon(rad)$
  also gain in lifetime & target power removal

Going to lighter targets for μ production

Be Beryllium
LLi Liquid Lithium, might be a good option (Proposed/tested for targets for n production)
LHe Liquid Helium





e = muon emittance at production [10^{-9}m-rad]

$E(e^+)$=45 GeV

Look to light liquid targets to reduce problems of thermo-mechanical stresses

Target: thermo-mechanical stresses considerations

Beam size as small as possible (matching various emittance contribution), but

- constraints for power removal (200 kW) and temperature rise
- to contrast the temperature rise

  move target (for free with liquid jet) and

  e^+ beam bump every 1 bunch muon accumulation

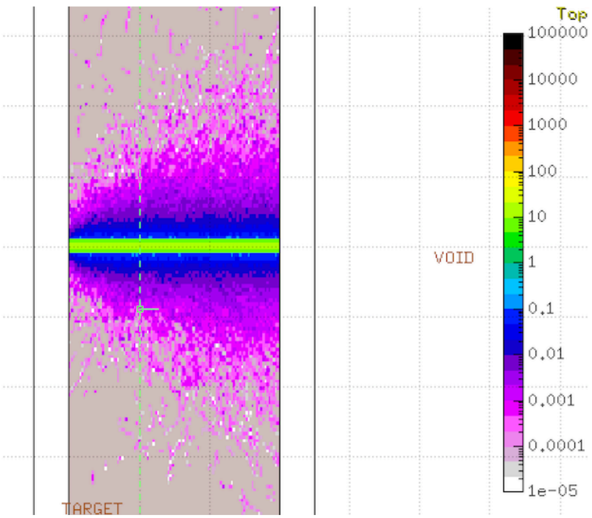
- **Solid target**: simpler and better wrt temperature rise
  - Be, C

  Be target: @HIRadMat safe operation with extracted beam from SPS, beam size 300 μm, $N=1.7\times10^{11}$ p/bunch, up to 288 bunches in one shot [Kavin Ammigan 6th High Power Targetry Workshop]
- **Liquid** target: better wrt power removal
  - Li, difficult to handle lighter materials, like H, He
    - LLi jets examples from neutron production, Tokamak divertor

(200 kW beam power removal seems feasible) , minimum beam size to be understood

Conventional options for μ target

- Aim at bunch (3×10^{11} e^+) transverse size on the 10 μm scale: rescaled from test at HiRadMat (5×10^{13}p on 100μm) with **Be-based** targets and **C-based** (HL-LHC) [F. Maciariello *et al.*, IPAC2016]
- No bunch pileup ⟶ Fast rotating wheel (20000 rpm)
- Power removal by radiation cooling (see for instance PSI muon beam upgrade project HiMB) [A. Knecht, NuFact17]]
- Need detailed simulation of thermo-mechanical stresses dynamics
  - Start using FLUKA + Ansys Autodyn (collaboration with CERN EN-STI)

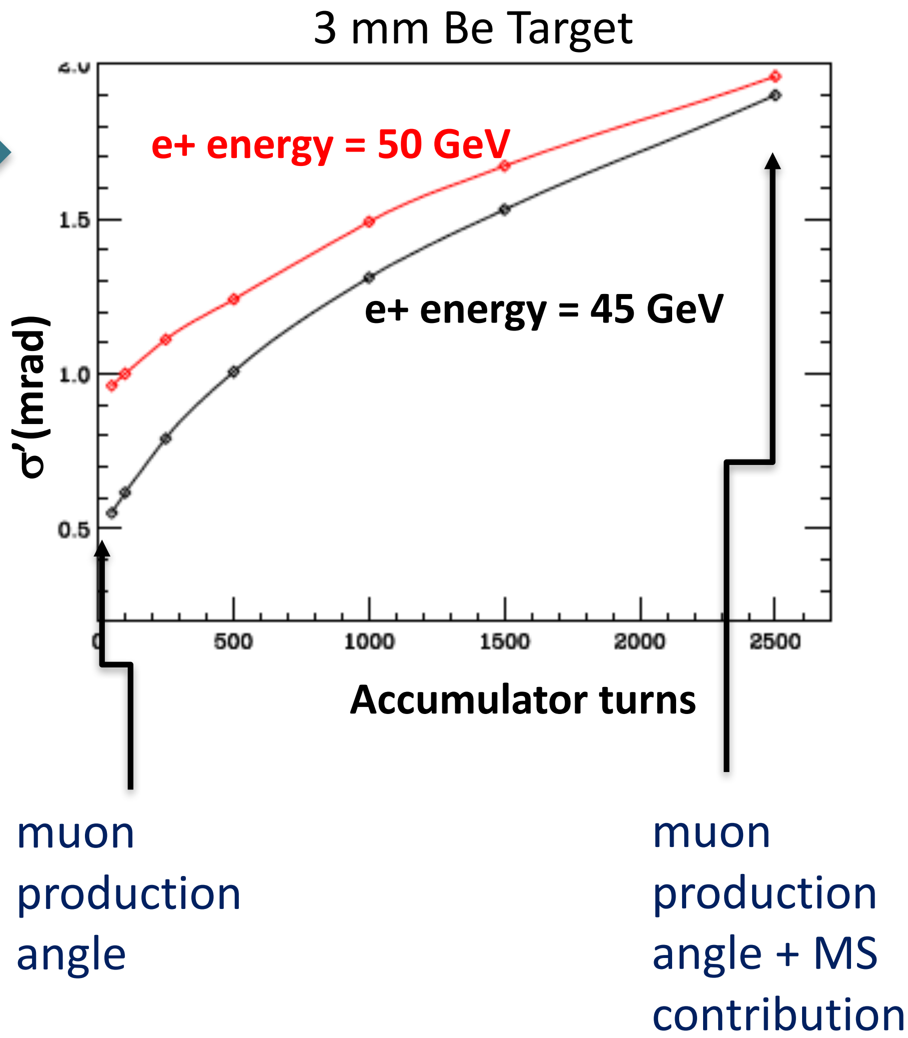


- Experimental tests:
  - **FACET-II** available from 2019
    10^{11} e-/bunch, 10 μm spot size, 100 Hz
  - **DAFNE** available from 2020, see later

μ Accumulator Rings considerations

isochronous optics with high momentum acceptance ($\delta \gtrsim 10\%$)
optics to be designed

Multiple Scattering effect using one-turn matrix



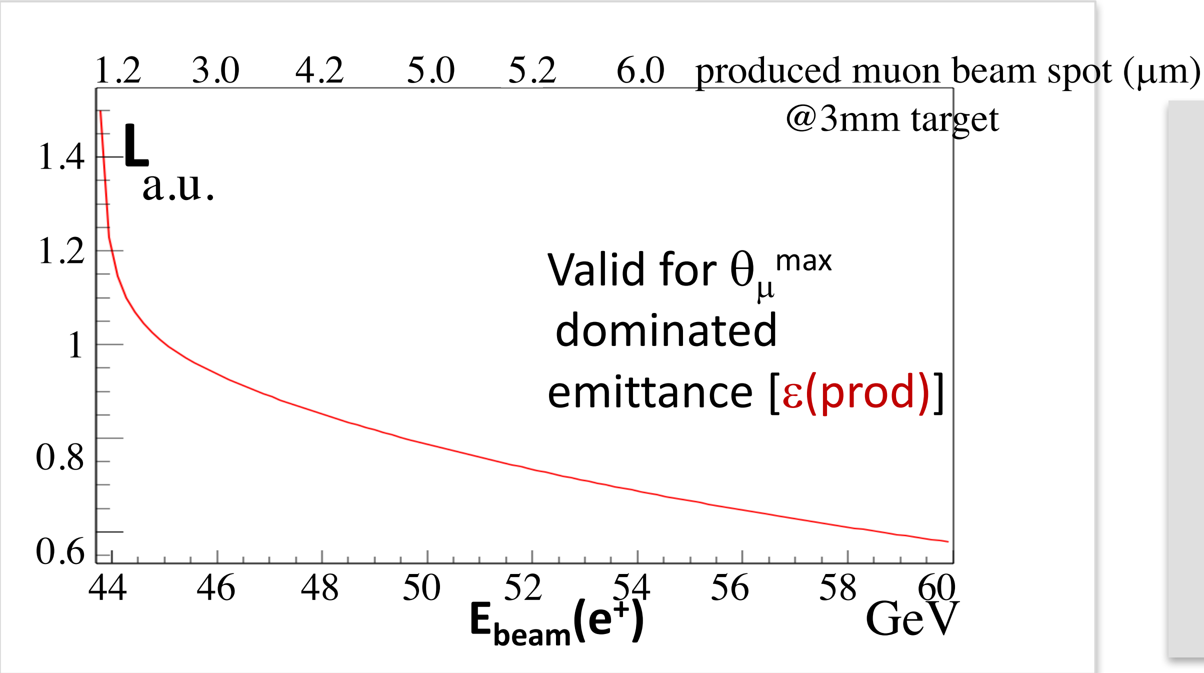
beam divergence:
a factor 3-2 increase at 45-50 GeV w.r.t. muon production angle contribution
beam size:
depends on optics need low-β to suppress size increase

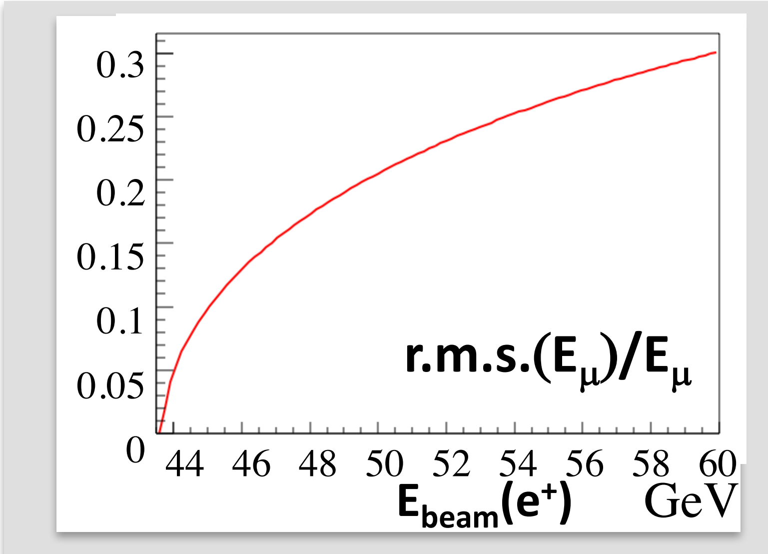
this contribution can be strongly reduced with crystals in channeling

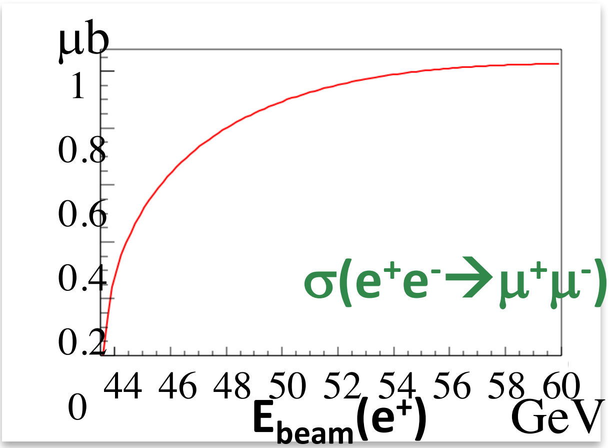
better performances at 50 GeV provided >15% momentum acceptance

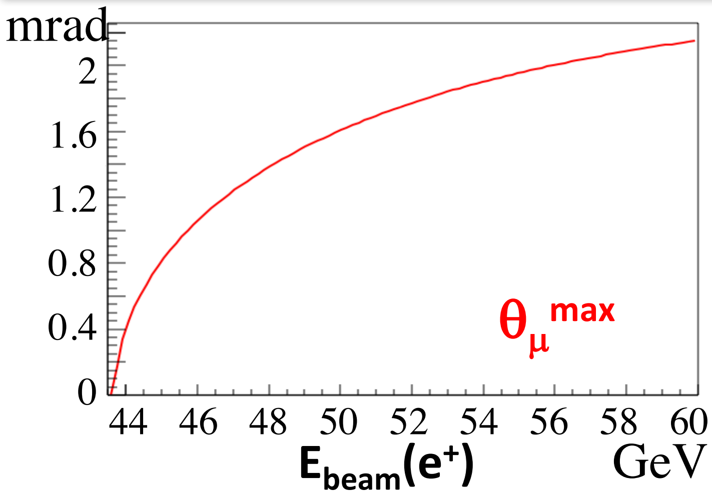
Luminosity of $\mu^+\mu^-$ Collider vs e^+ beam energy

Optimal working point for $\varepsilon(e^+) \cong \varepsilon(MS) \cong \varepsilon(rad) \cong \varepsilon(prod) \cong \varepsilon(AR)$
and sustainable beam spot on target
$\varepsilon(prod)$ and μ intensity $\propto$ positron beam energy:









Positron sources: studies on the market

- Summary of e^+ sources projects (all very aggressive):

In [F. Zimmermann, et al., '**POSITRON OPTIONS FOR THE LINAC-RING LHEC'**, WEPPR076 Proceedings of IPAC2012, New Orleans, Louisiana, USA]

	SLC	CLIC	ILC	LHeC pulsed	LHeC ERL
E [GeV]	1.19	2.86	4	140	60
$\gamma\epsilon_x$ [μm]	30	0.66	10	100	50
$\gamma\epsilon_y$ [μm]	2	0.02	0.04	100	50
$e^+[10^{14}\mathrm{s}^{-1}]$	0.06	1.1	3.9	18	440

➢ This is a key issue to be studied

Example of Positron Source for CLIC

[L.Rinolfi *et al.* NIM B **309** (2013)50-55]

The target represented on the figure is a conventional one.

It would be also possible to have an *hybrid positron source* using a crystal providing channeling radiation and an amorphous converter for photon conversion into e+e- pairs

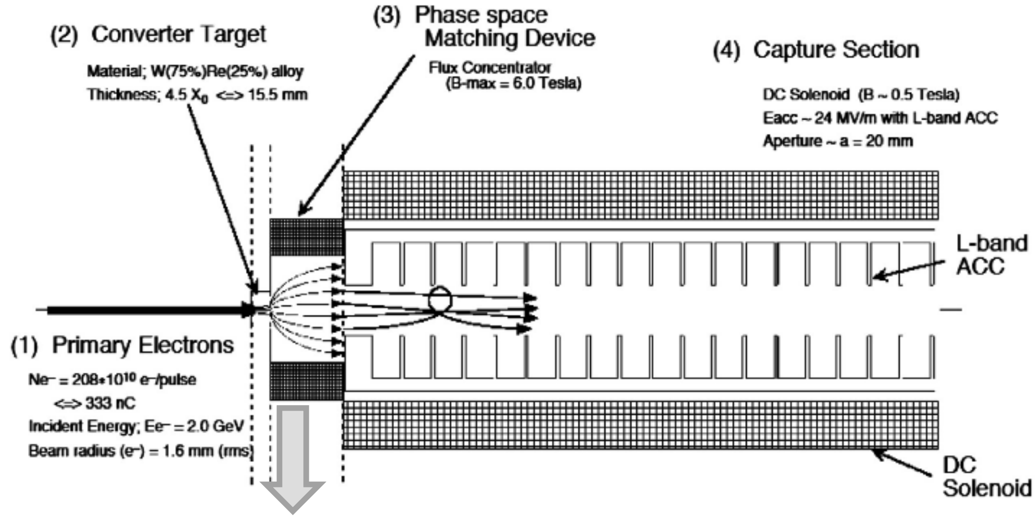
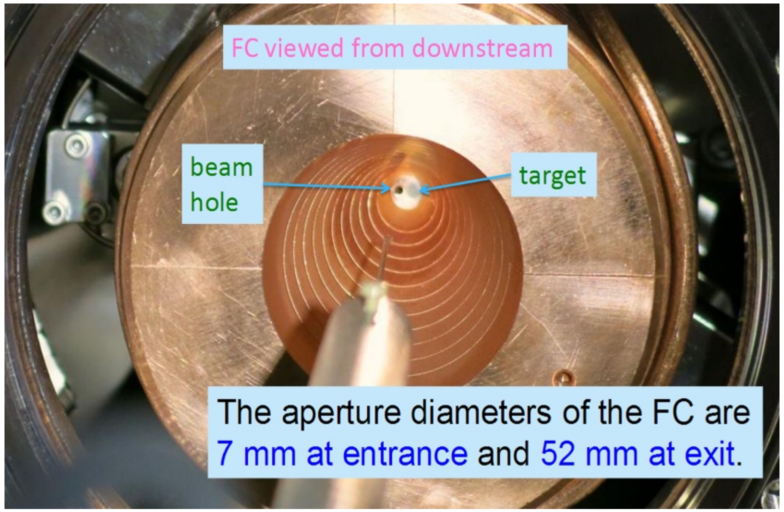


Fig. 2. Layout of the CLIC e+ source with a single target.

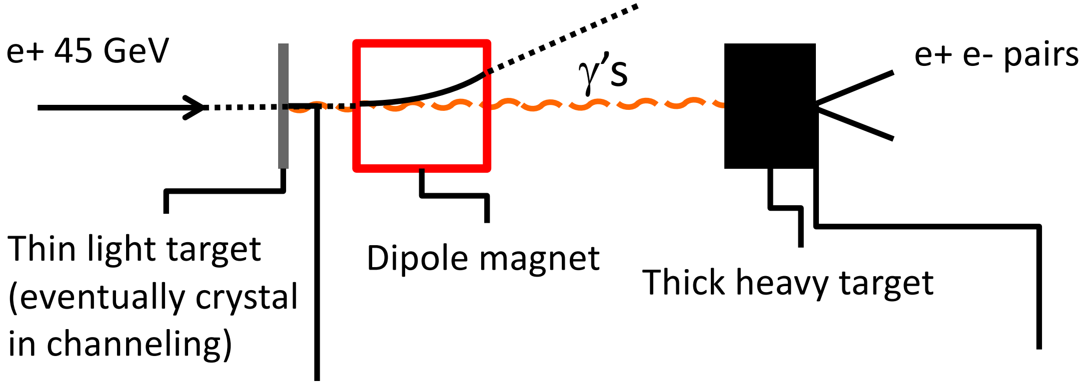


Flux concentrated used for the Adiabatic Matching Device
(from T.Kamitani, LCWS-2014,Belgrade)

Embedded positron source?

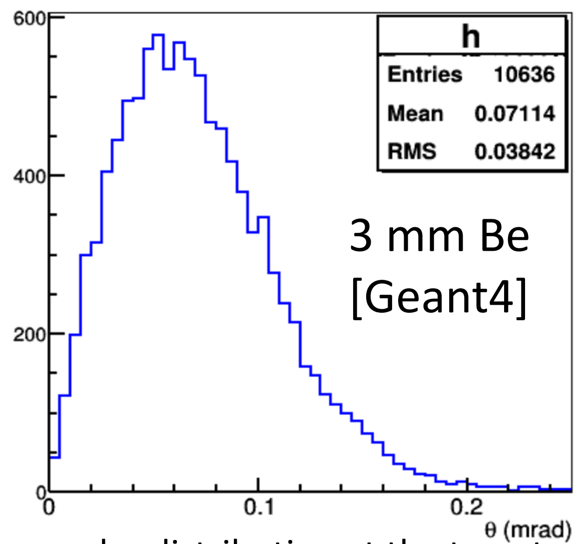
Positron source extending the target complex?
Possibility to use the γ's from the μ production target to produce e+

Focusing based on AMD under study promising preliminary results on collection efficiency

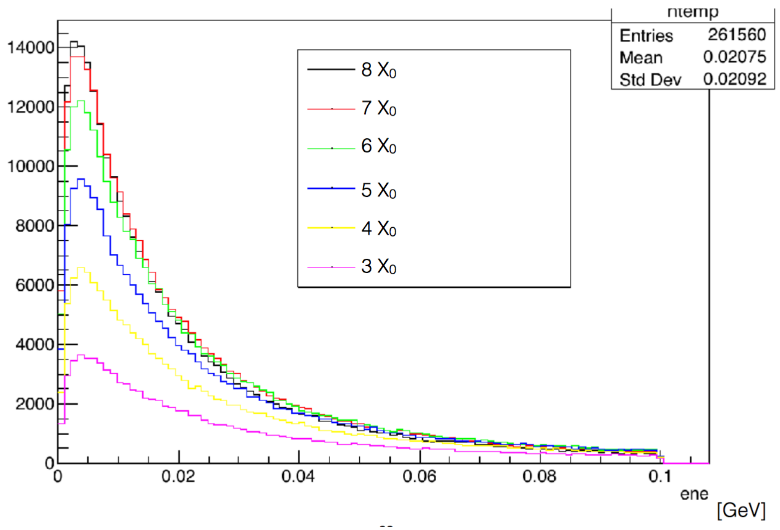


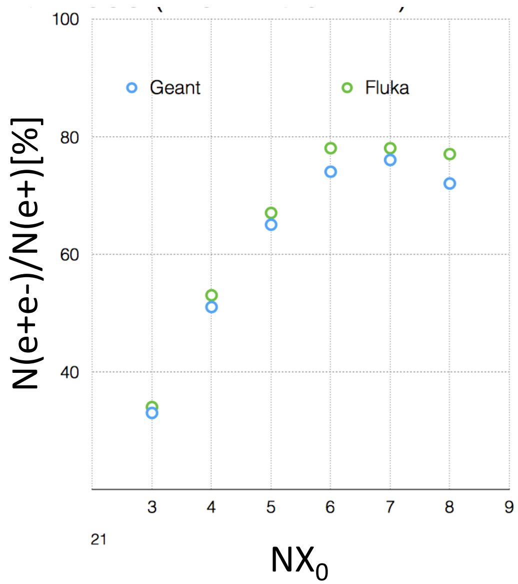
Produce a fraction of e+
of the incoming positron beam

high rate energy γ thanks to very thin target and cw structure of the stored beam



γ's angular distribution at the target exit





FOCUSING SYSTEMS FOR POSITRON BEAMS

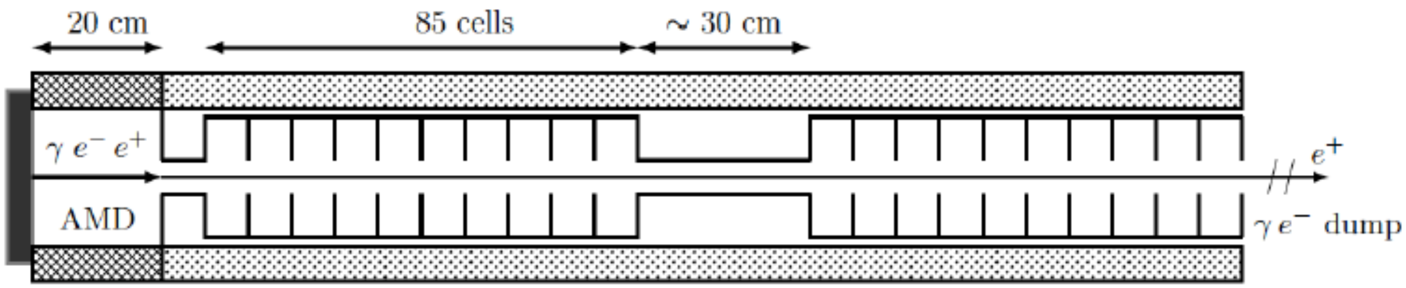
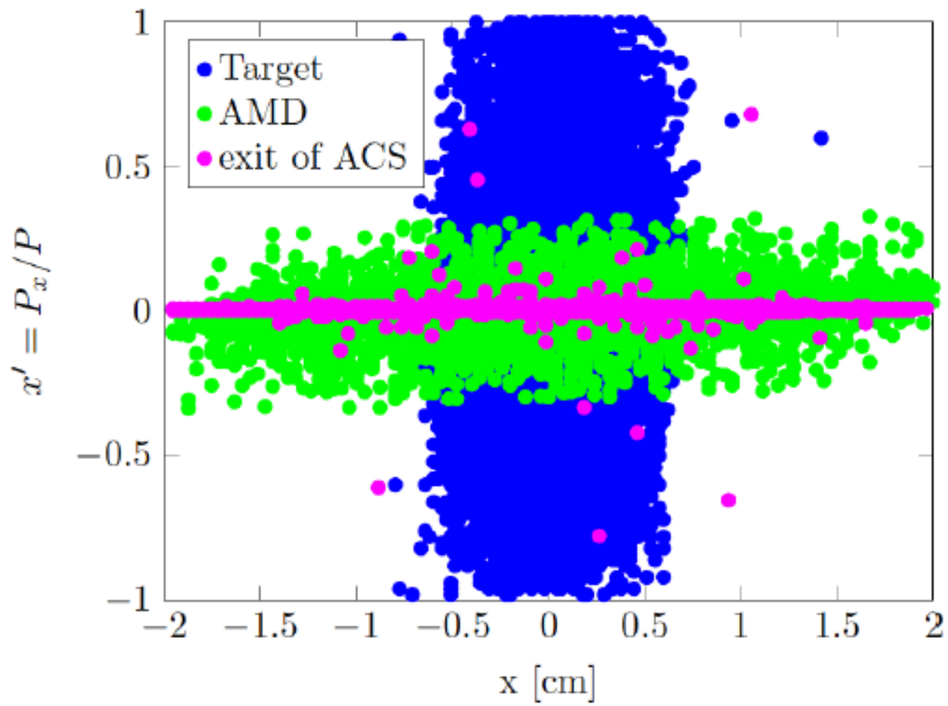


Figure 4.7: A fundamental scheme of the positron capture and primary acel-erattion - A capture section based on the AMD followed by a pre-injector linac is used to capture and accelerate the positron beam up to the ~200 MeV.



Test at DAΦNE

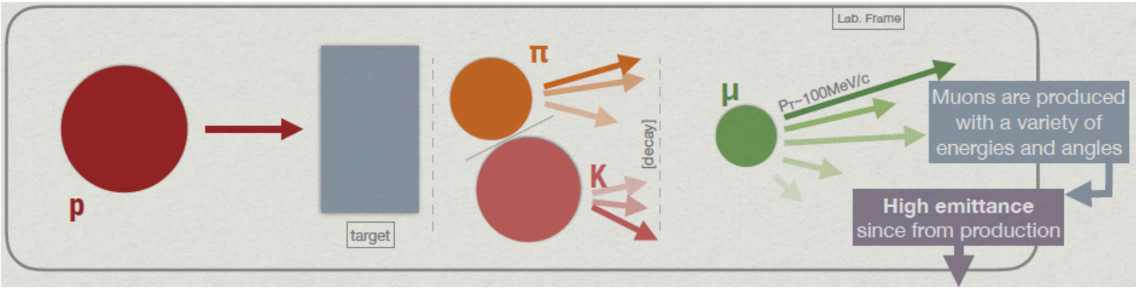
- **Test of the ring-plus-target scheme:**
  - **beam dynamics**
  - **target heat load and thermo-mechanical stress**

GOAL:

- Benchmark simulations with experimental data to validate LEMMA studies.
- Measurements on targets: various materials and thicknesses can be envisaged.
  - ➢ as validation for LEMMA studies
  - ➢ interesting in the test itself

Test at CERN-NA

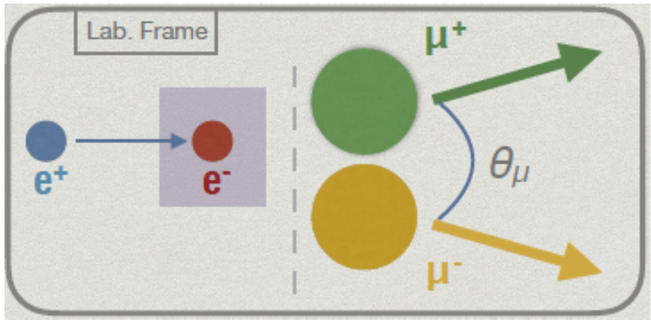
Proton-based production: muons as tertiary particles with tipically $P_T^{\mu} \sim 100$ MeV



COOLING mandatory

Direct production as in LEMMA proposal : $e^+e^- \rightarrow \mu^+\mu^-$ close to production threshold

$E(e^+) \sim 45$ GeV => $E(\mu^+) \sim 22$ GeV, $\gamma(\mu) \sim 200$ => $\tau_{LAB} \sim 500\mu s$

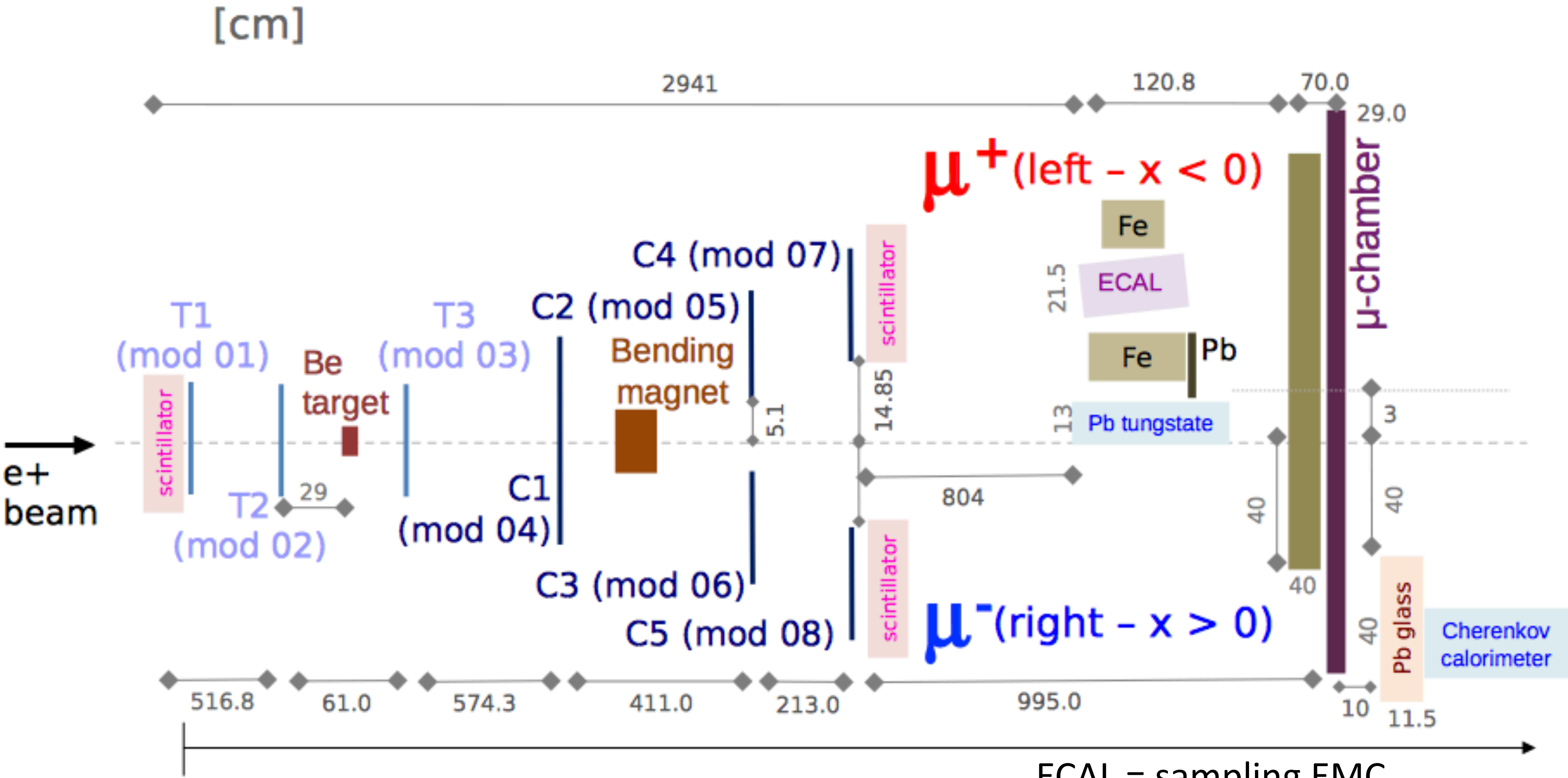


- Very small emittance => **no cooling needed!**
- Low background
- Large boost at production
  - Reduced losses from muon decays
- Much smaller muon production cross section
  - ~1μb for e^+ source *vs* ~1mb for proton source

Several critical aspects must be experimentally verified to validate the approach (*e.g.*):

- optimization of the target features
- degradation of the positron beams (in order to recirculate)
- efficiency of the $\mu+\mu-$ production, and parameters of the produced beams

Experimental set-up



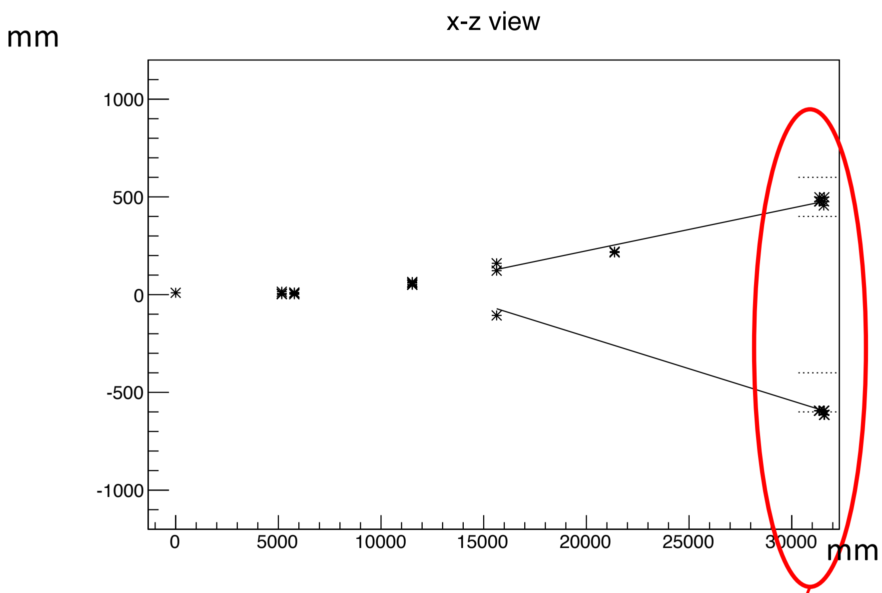
T = Si Telescope
C = Si chambers

ECAL = sampling EMC
Pb tungstanate = CMS like EMC
Pb glass = lead glass EMC

EXPERIMENTAL SETUP

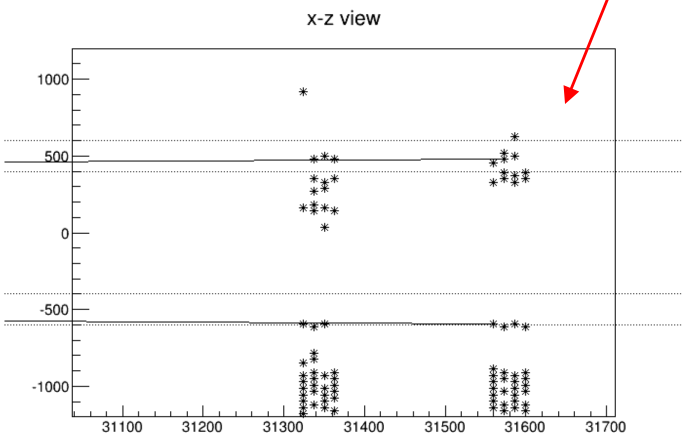
Track reconstruction based on information from silicon detectors and muon chamber

Run 4616 45 GeV positrons



Analysis in progress

Zoom on muon chamber



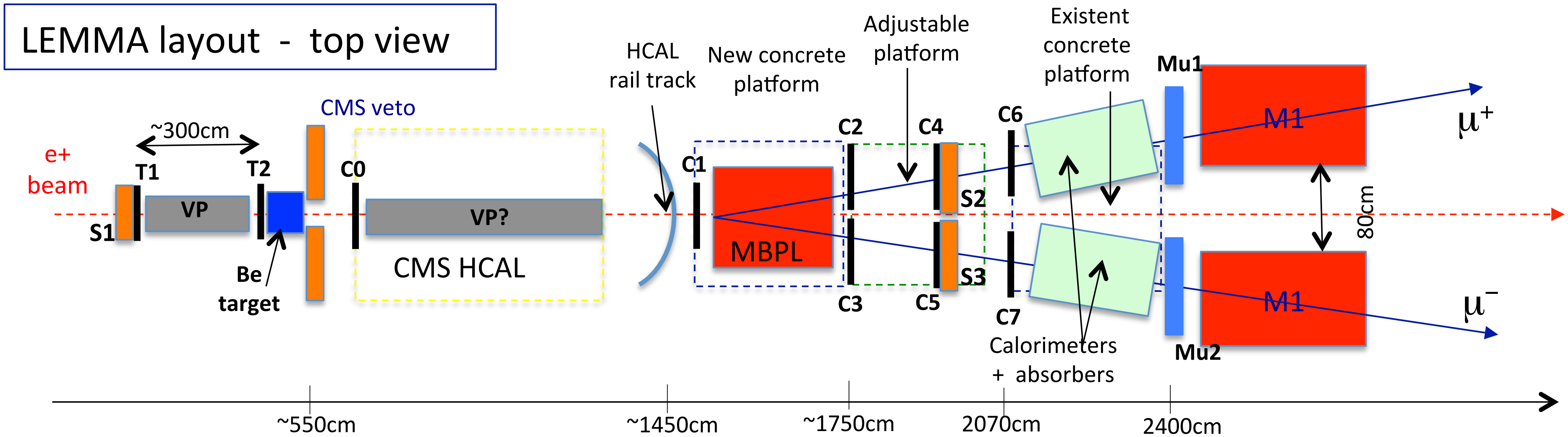
Muon chamber noisy!

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.

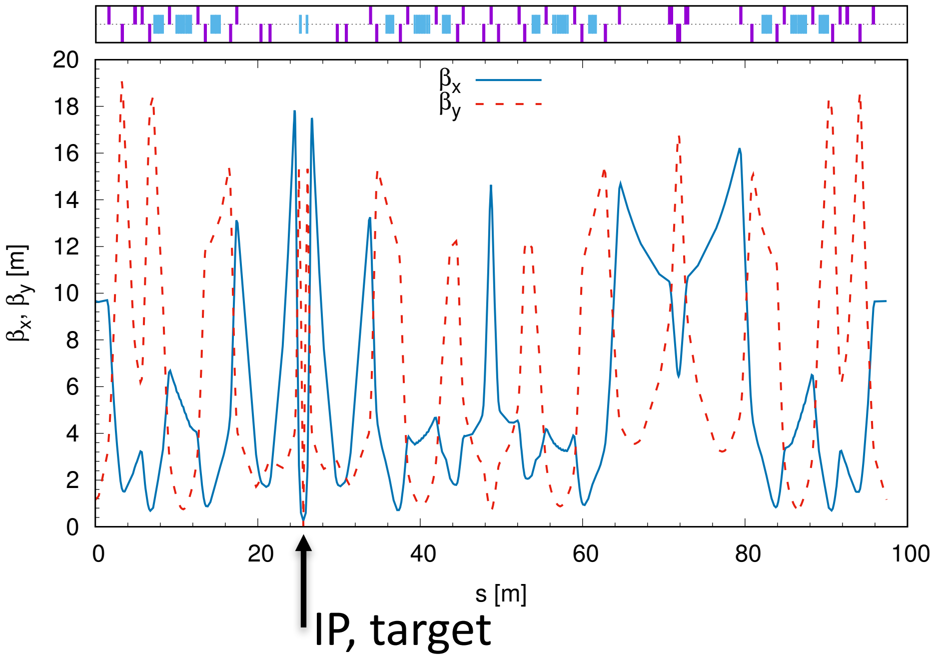
- Experimental setup modified with respect to the 2017 TB, also to account the different experimental hall (H4 -> H2)
  - additional tracking;
  - new calorimeters

LEMMA layout - top view



Test at DAΦNE

- The SIDDHARTA-2 run will end on 2019
- Test proposed after this run
- The target is at the IP:
  - To minimize modifications of the existing configuration
  - low-β and D_x=0 is needed
- First studies with the SIDDHARTA optics and target placed at the IP.
- Possible different locations for the target can be studied



SIDDHARTA 2008 optics

β_x^*=26cm; β_y^*=0.9cm

σ_x^*=0.27mm; σ_y^*=4.4μm

ε_x = 0.28 μm

Goals of the Test at DAΦNE

- Beam dynamics studies of the ring-plus-target scheme:
  - transverse beam size
  - current
  - lifetime

- Measurements on target:
  - temperature (heat load)
  - thermo—mechanical stress

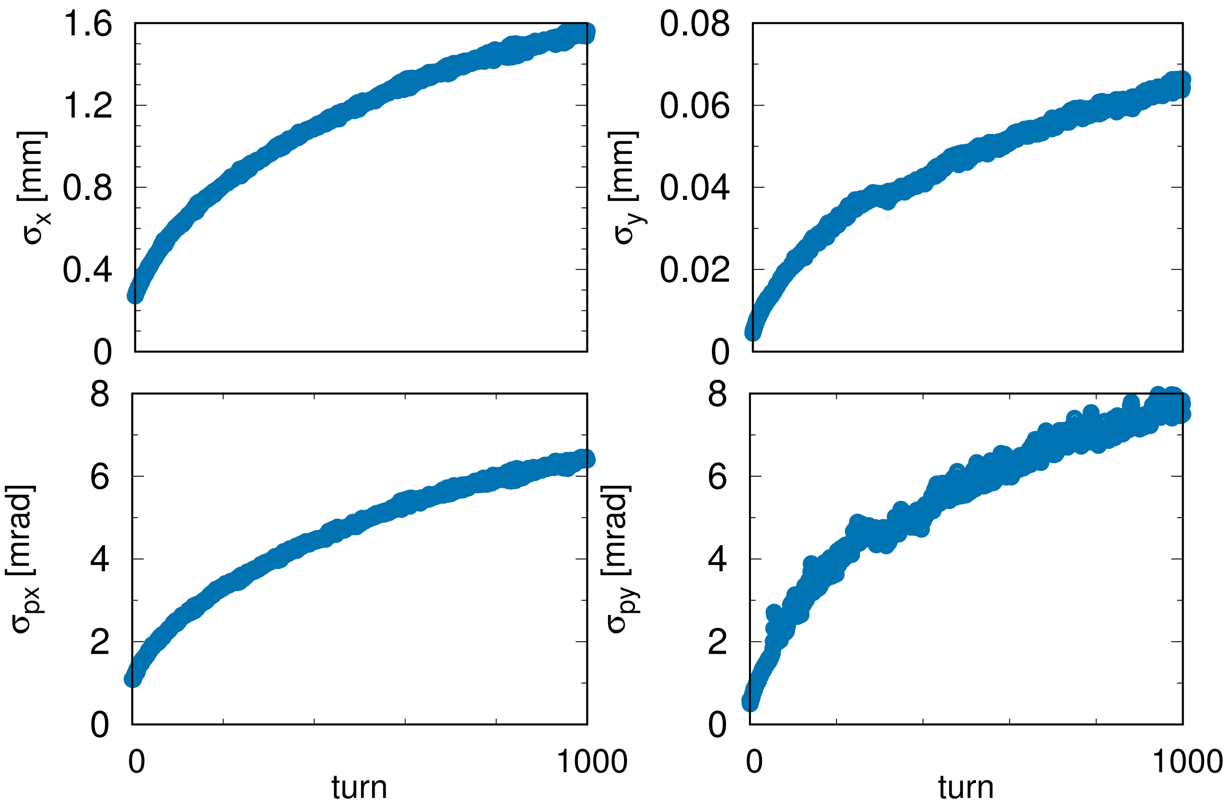
Table 8: DAFNE parameters for the test with thin target at IP.

Parameter	Units	
Energy	GeV	0.51
Circumference	m	97.422
Coupling(full current)	%	1
Emittance x	m	0.28×10^{-6}
Emittance y	m	0.21×10^{-8}
Bunch length	mm	15
Beam current	mA	5
Number of bunches	#	1
RF frequency	MHz	368.366
RF voltage	kV	150
N. particles/bunch	#	1×10^{10}
Horizontal Transverse damping time	ms/turns	42 / 120000
Vertical Transverse damping time	ms/turns	37 / 110000
Longitudinal damping time	ms/turns	17.5 / 57000
Energy loss/turn	keV	9
Momentum compaction		1.9×10^{-2}
RF acceptance	%	$\pm$ 1

Given the limited energy acceptance of the ring (~1%), we plan to insert light targets (Be, C) with thickness in the range 10-100μm.
Crystal targets can be foreseen too, modified G4 tool needed for the simulation

Evolution of e+ beam size and divergence

Beam evolution in the ring with 50μm Be target at IP

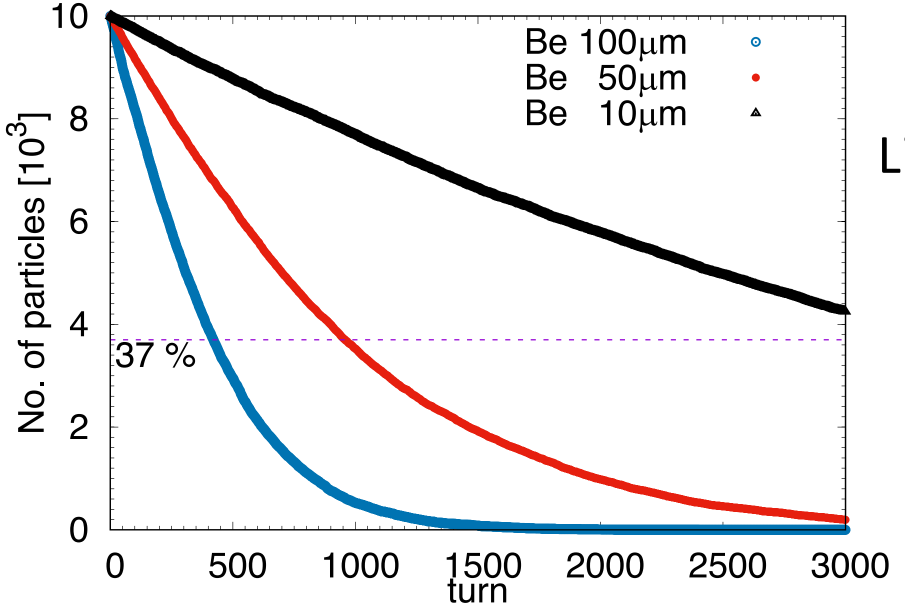


first turn, before target

σ_x^* = 0.27 mm

σ_y^*=4.4μm

e+ lifetime with Be target

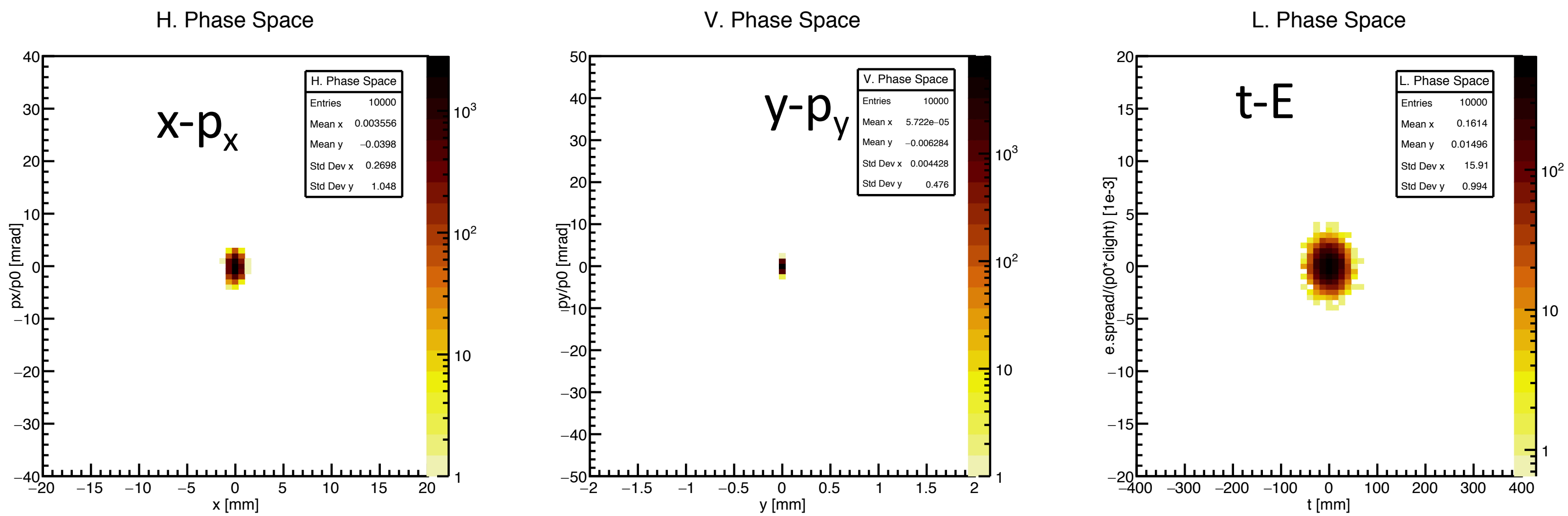


Lifetime with ~ 3500 turns for 10μm Be target
as short as 1.6 ms

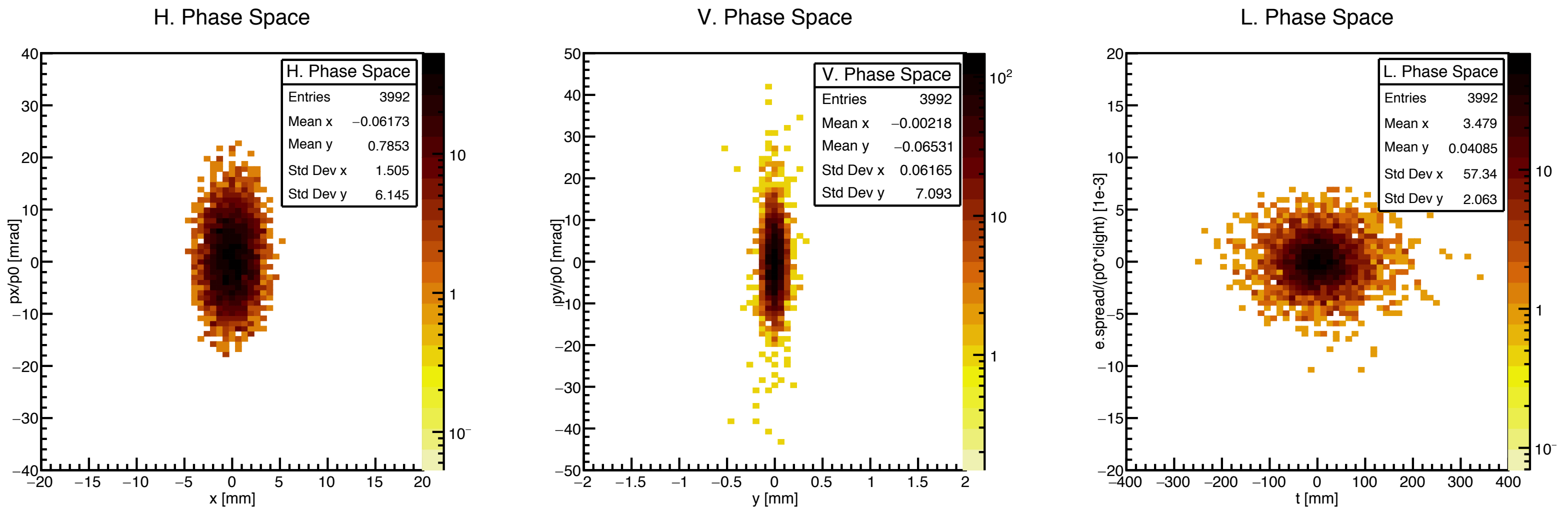
- Beam will not be stored
- Injection in single bunch mode
- turn-by-turn beam size and charge measurement

DAFNE e^+ ring with 50μm Be target: beam evolution in the 6D phase space

before target, starting point

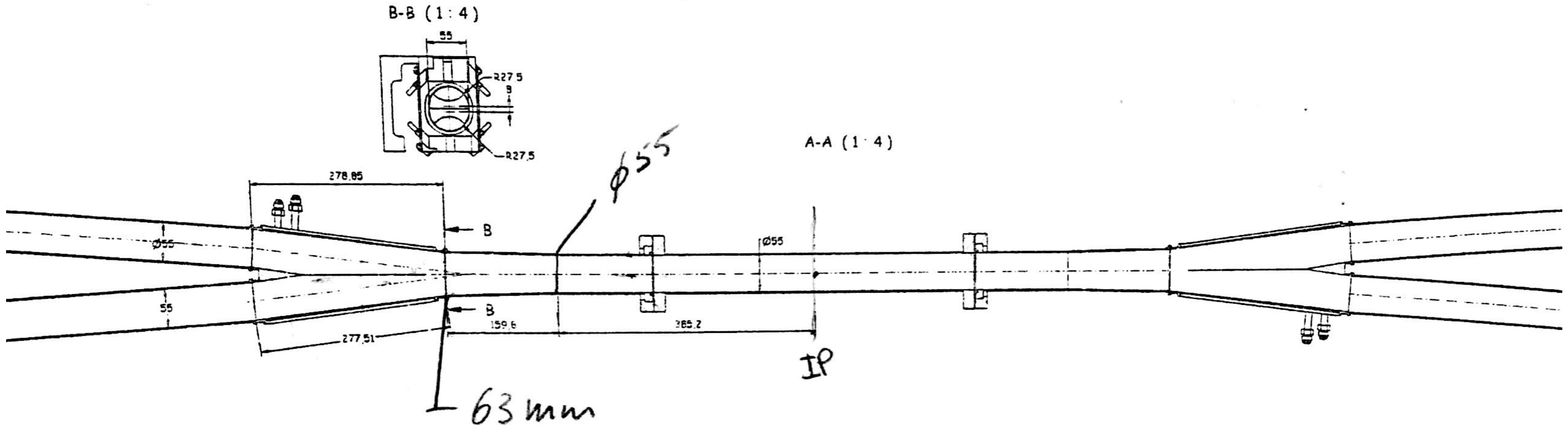


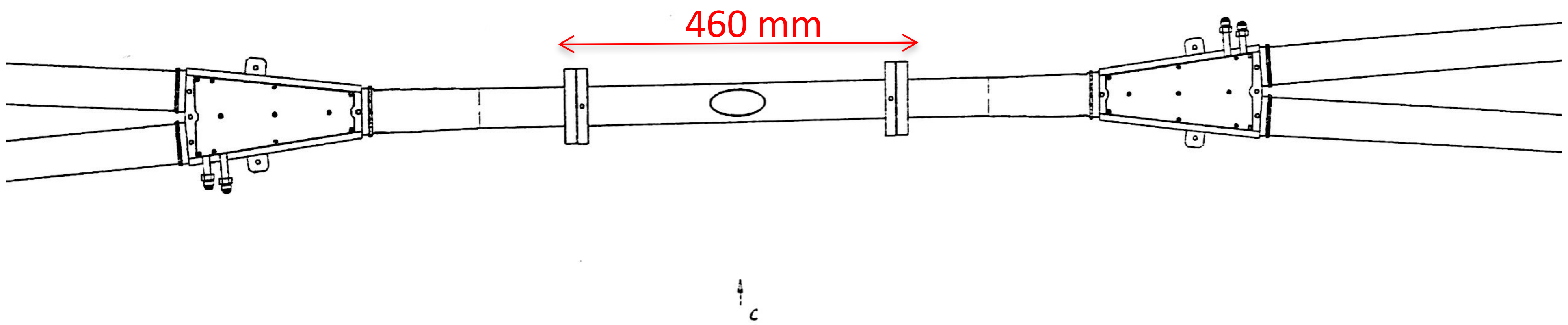
after 900 turns



MAD-X PTC & GEANT4 6-D tracking simulation

SIDDHARTA IR





Diagnostics for the test at DAFNE

beam characterization after interaction with target:

- additional beam diagnostic to be developed:
  - turn by turn charge measurement (lifetime)
    - ✓ existing diagnostic already used for stored current measurement
    - ✓ need software and timing reconfiguration
  - turn by turn beam size
    - ✓ beam imaging with synchrotron radiation
    - ✓ DAFNE CCD gated camera provides gating capabilities required to measure average beam size at each turn.
    - ✓ software modification and dedicated optics installation required.

Conclusion

- We presented a novel scheme for the production of muons starting from e^+ beam on target
- We discussed the key challenges of this idea:
  - Low emittance and high momentum acceptance 45 GeV e^+ ring
  - O(100 kW) class target in the e^+ ring for $\mu^+ \mu^-$ production
  - High rate positron source
  - High momentum acceptance muon accumulator rings

First design of low emittance e^+ ring with preliminary studies of beam dynamics

Optimization requires other issues to be preliminary addressed:

target material & characteristics
e^+ accelerator complex
muon accumulator rings design
luminosity parameters optimization

Preliminary studies for a low emittance muon source are promising

We will continue to optimize all the parameters, lattices, targets, etc. in order to assess the ultimate performances of a muon collider based on this concept

Back-up

Accelerator design contributors

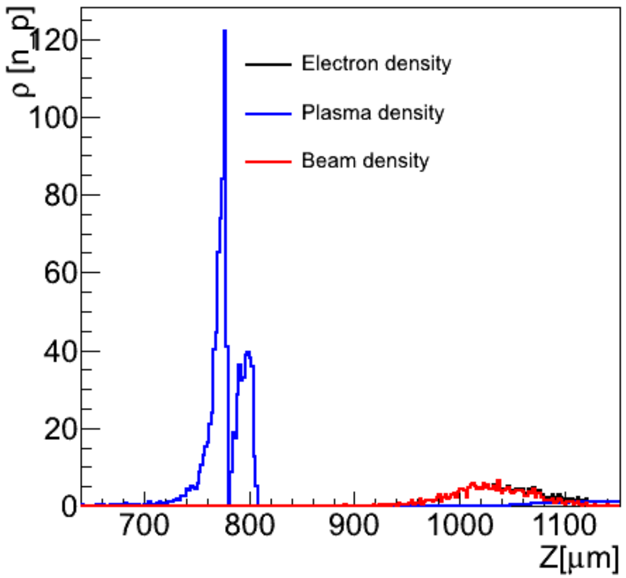
- optics and beam dynamics :
  - M. Antonelli, M. Biagini, O. Blanco, M. Boscolo, F. Collamati, S. Guiducci, L. Keller(SLAC), S. Liuzzo(ESRF), P. Raimondi(ESFR)
- positron source scheme:
  - A. Bacci, I. Chaikovska(LAL), R. Chehab(LAL), F. Collamati
- Test at DAFNE
  - D. Alesini, O. Blanco, M. Boscolo, A. Ghigo, A. Stella
- Temperature measurements of target:
  - R. Li Voti, L. Palumbo (SBAI, Sapienza)
- Target:
  - M. Iafrati, M. Ricci, L. Pellegrino,
  - M. Calviani (CERN), S. Gilardoni (CERN), P. Sievers(CERN)

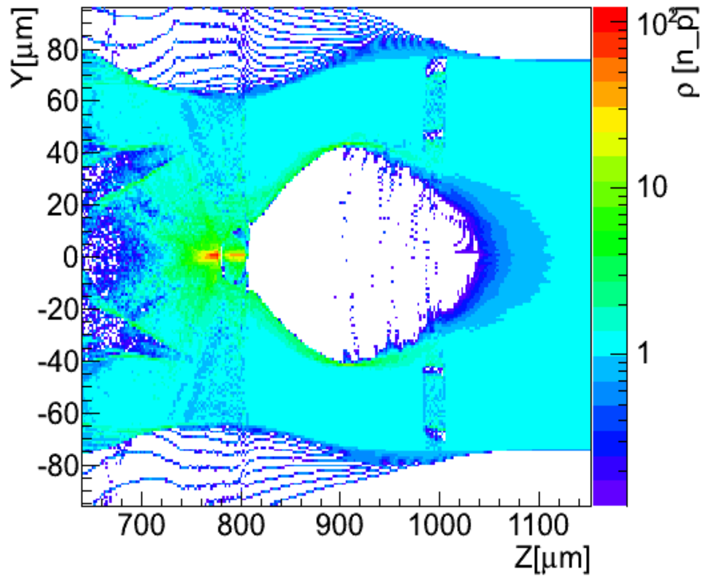
Experimental team

- experiment at H4 CERN
  - M. Antonelli, F. Anulli, A. Bertolin, M. Boscolo, C. Brizzolari, G. Cavoto, F. Collamati, R. Di Nardo, M. Dreucci, F. Gonella, F. Iacoangeli, A. Lorenzon, D. Lucchesi, M. Prest, M. Ricci, R. Rossin, M. Rotondo, L. Sestini, M.Soldani, G. Tonelli, E. Vallazza, S. Vanini, S. Ventura, M. Zanetti

Few statements on the plasma option

- Plasma would be a good approximation of an ideal electron target ++ autofocussing by Pinch effect
- enhanced electron density (up x100) can be obtained at the border of the blow-out region
- Simulations for $n_p=10^{16}$ e-/cm^3 $\Rightarrow$ e- high density region ~ 100 μm (C. Gatti, P. Londrillo)
- high density region ~ $1/\sqrt{n_p}$
- In our case plasma with n_p~10^{20} particles/cm^3 is needed to get useful e- densities in very small region, it doesn't seem viable.



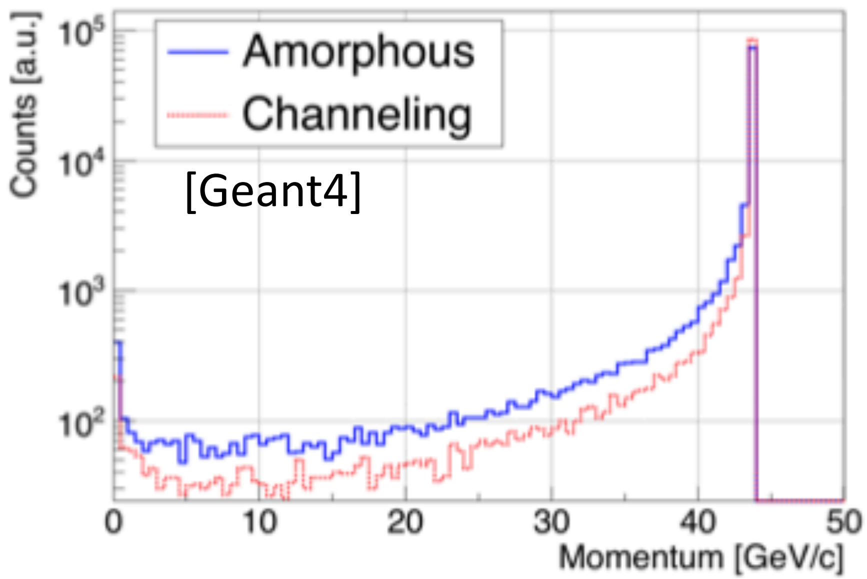


Crystals as a target ?

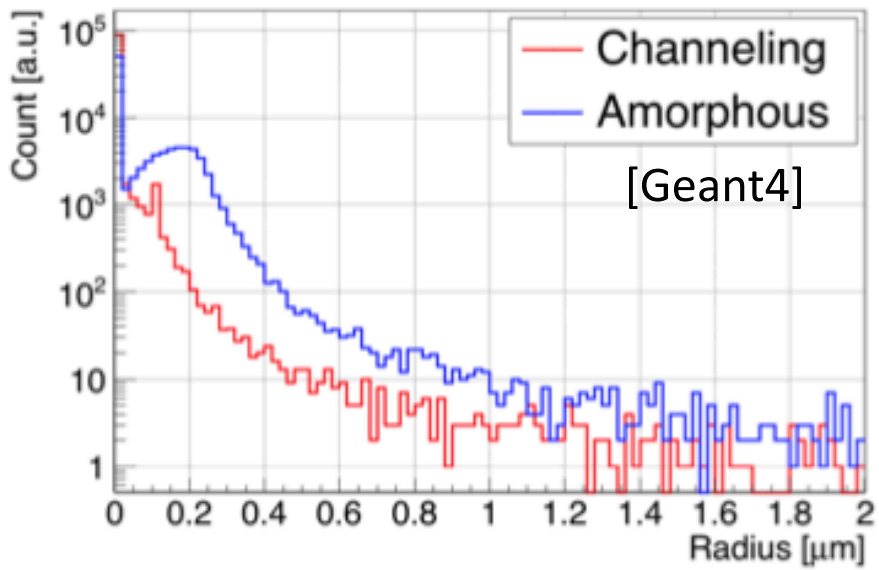
Positrons

43.8 GeV e^+
4.1 mm Si Target
Channeling plane: (110)

Momentum



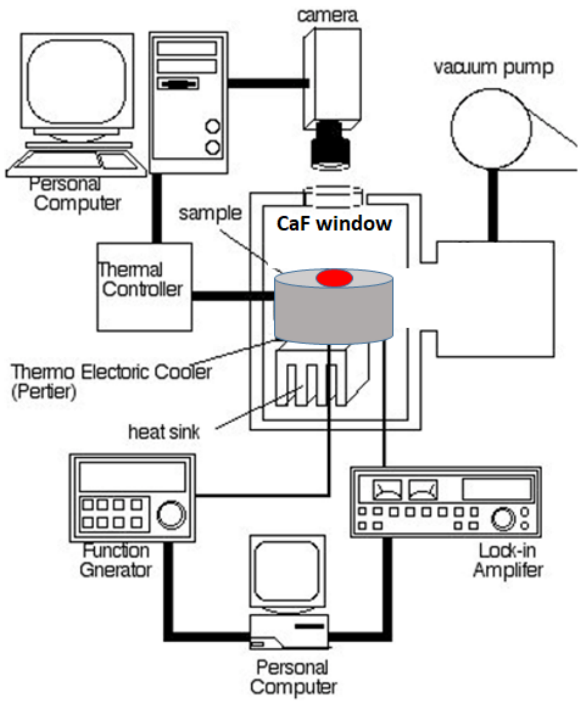
Position



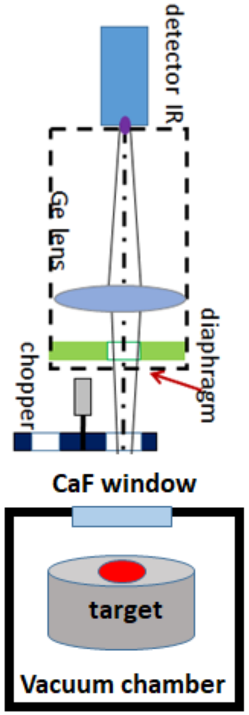
Temperature measurement in situ on the target

passive infrared:

very good spatial resolution 7.5µm~3µm/pixel. The frame rate can vary from 60Hz to 5000Hz



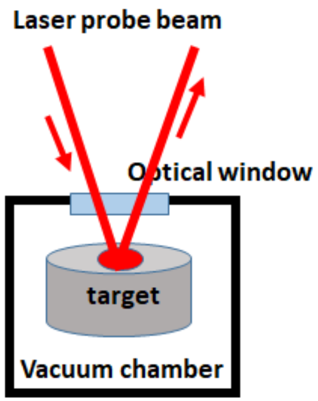
Experimental Setup - IR Emittance

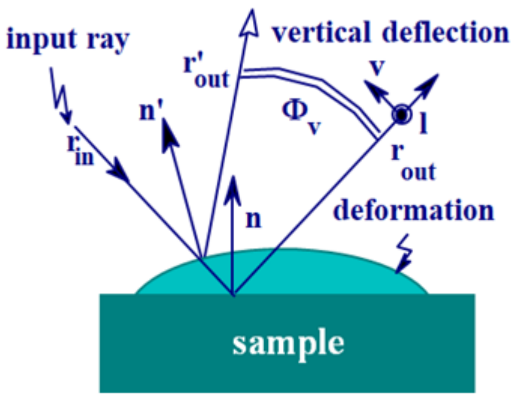


Infrared radiometry:

temperature dynamics in the microsecond range, no spatial resolution

Target deformation measurement





contactless laser technique to measure indirectly the temperature.

This technique is very sensitive and can detect very weak deformation of the order of some picometer corresponding to less than 1°C. After a proper calibration can be used to follow the ultrafast dynamic of the temperature of the target

Possible target: 3 mm Be

45 GeV e^+ impinging beam

- Emittance at E_μ = 22 GeV:

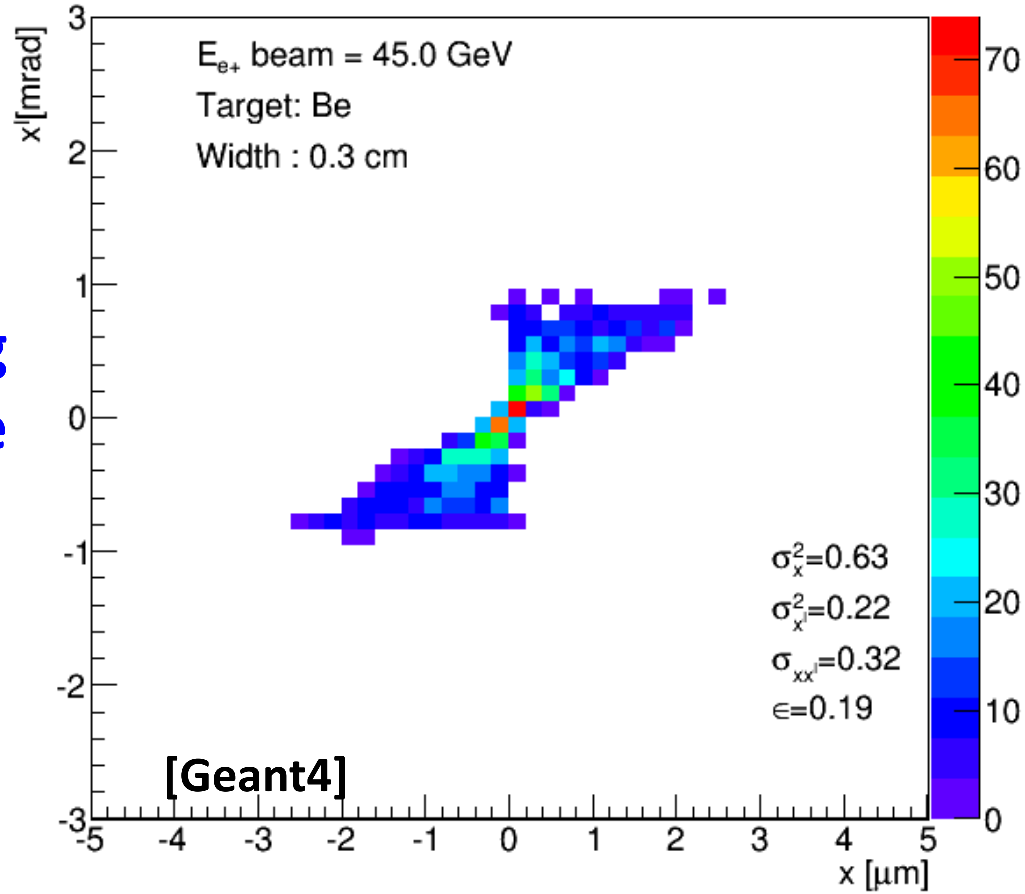
  $\varepsilon_x = 0.19 \cdot 10^{-9}$ m-rad

Multiple Scattering contribution is negligible

-> μ after production is not affected by nuclei in target
-> e+ beam emittance is preserved, not being affected by nuclei in target (see also next slide)

- Conversion efficiency: 10^{-7}
- Muons beam energy spread: 9%

Muons at the target exit surface

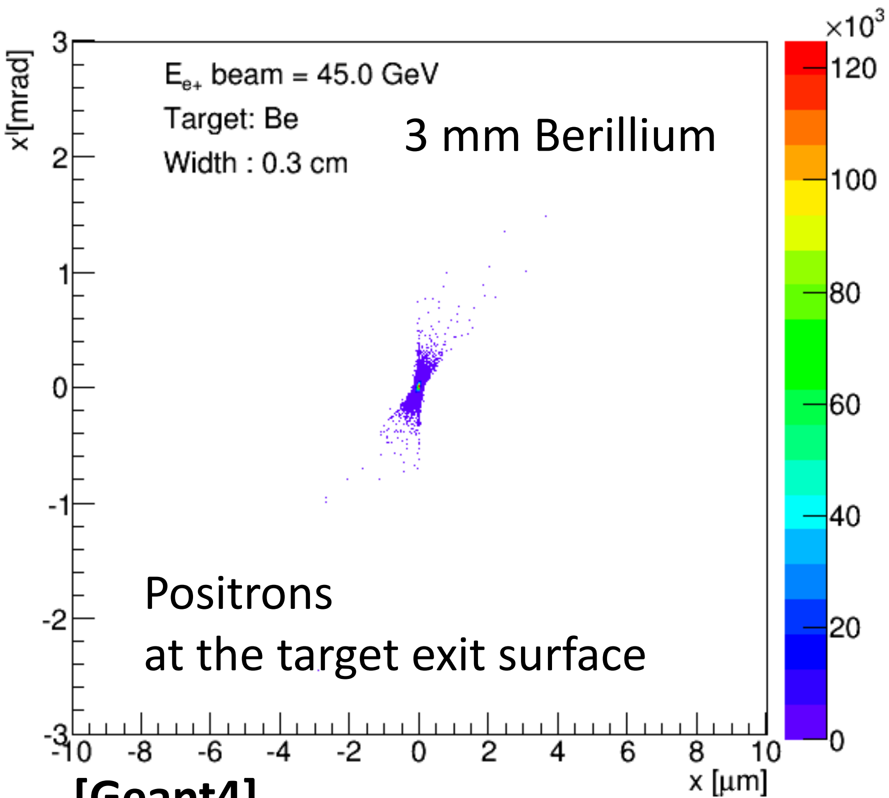


Positrons Storage Ring Requirements

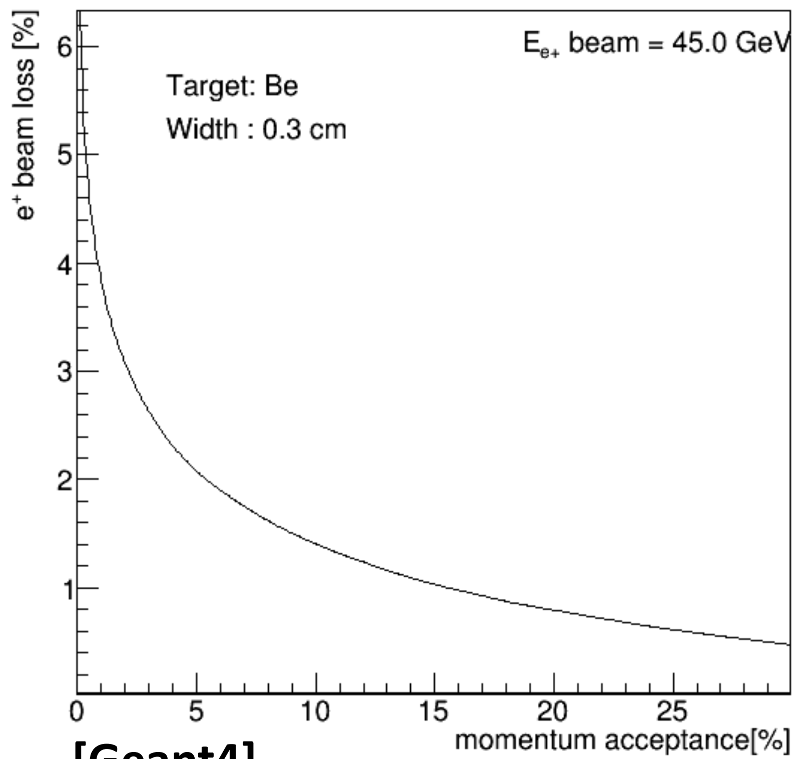
- Transverse phase space almost not affected by target
- Most of positrons experience a small energy deviation:

  A large fraction of e^+ can be stored (depending on the momentum acceptance)

  - 10% momentum acceptance will increase the effective muon conversion efficiency (produced muon pairs/produced positrons) by factor 100



[Geant4]



[Geant4]

Muon beam parameters

Assuming

- a positron ring with a total 25% momentum acceptance (10% easily achieved) and
- ~3 × LHeC positron source rate

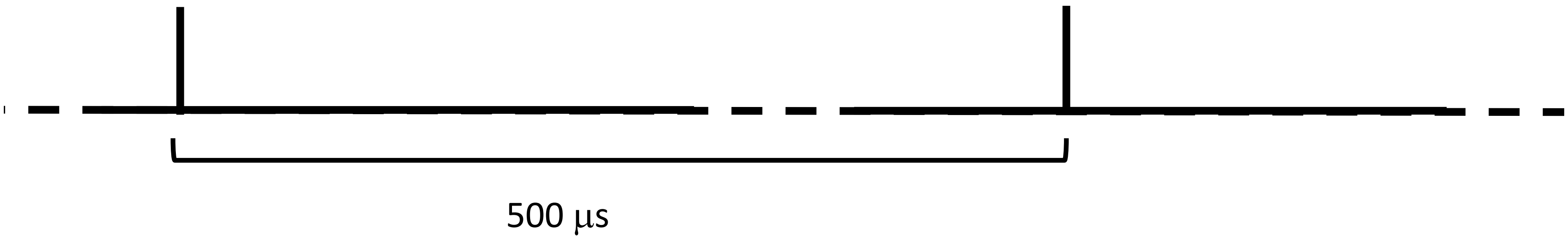
	positron source	proton source
μ rate[Hz]	$9 \cdot 10^{10}$	$2 \cdot 10^{13}$
μ/bunch	$4.5 \cdot 10^{7}$	$2 \cdot 10^{12}$
normalised ϵ [μm-mrad]	40	25000

Very small emittance, **high muon rates** but relatively small bunch population:

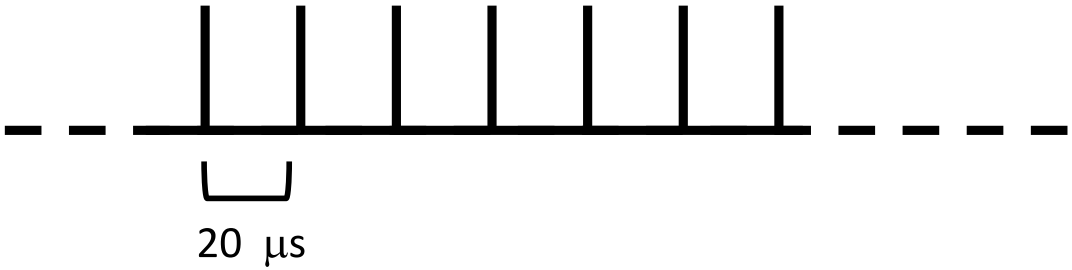
- The actual number of μ/bunch in the muon collider can be larger by a factor ~ τ_{μ}^{lab}(HE)/500 μs (~100 @6 TeV) by topping up.

rebunching at 6 TeV

bunch structure from production



bunch structure at collider

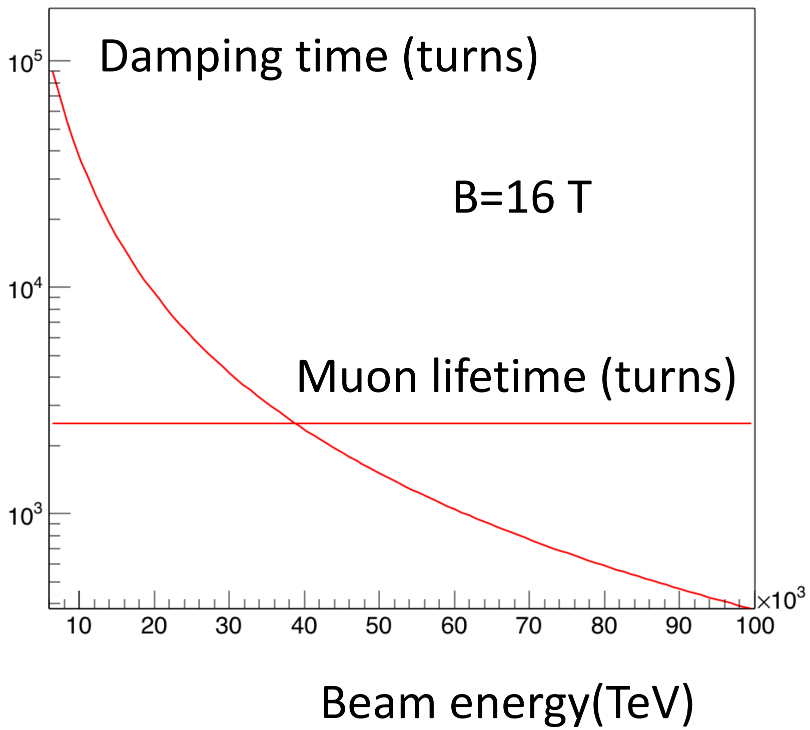


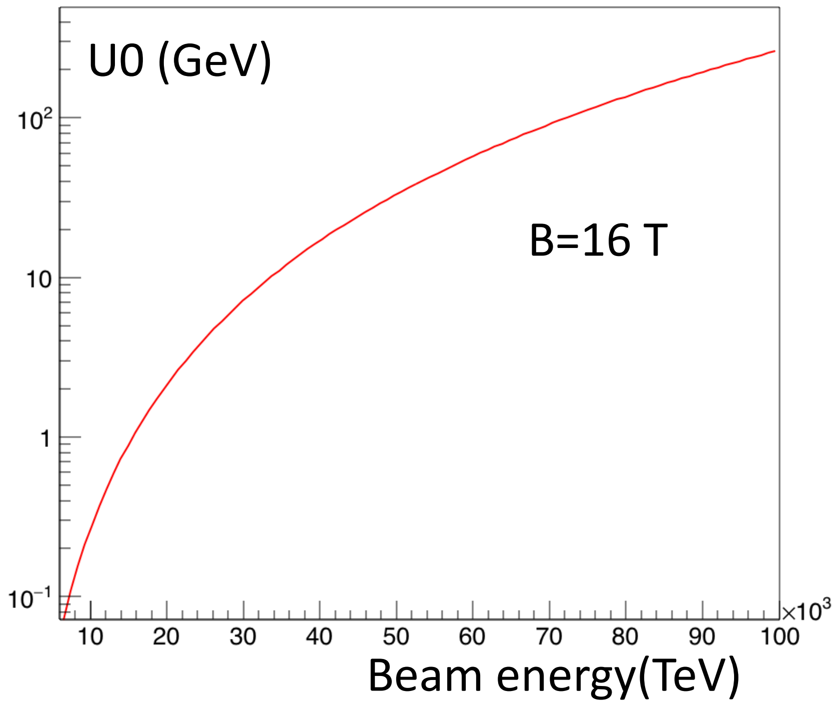
perform continuous injection every 500 μs

rebunch effective for ~ 1 muon lifetime 66 ms (factor 66/0.5)

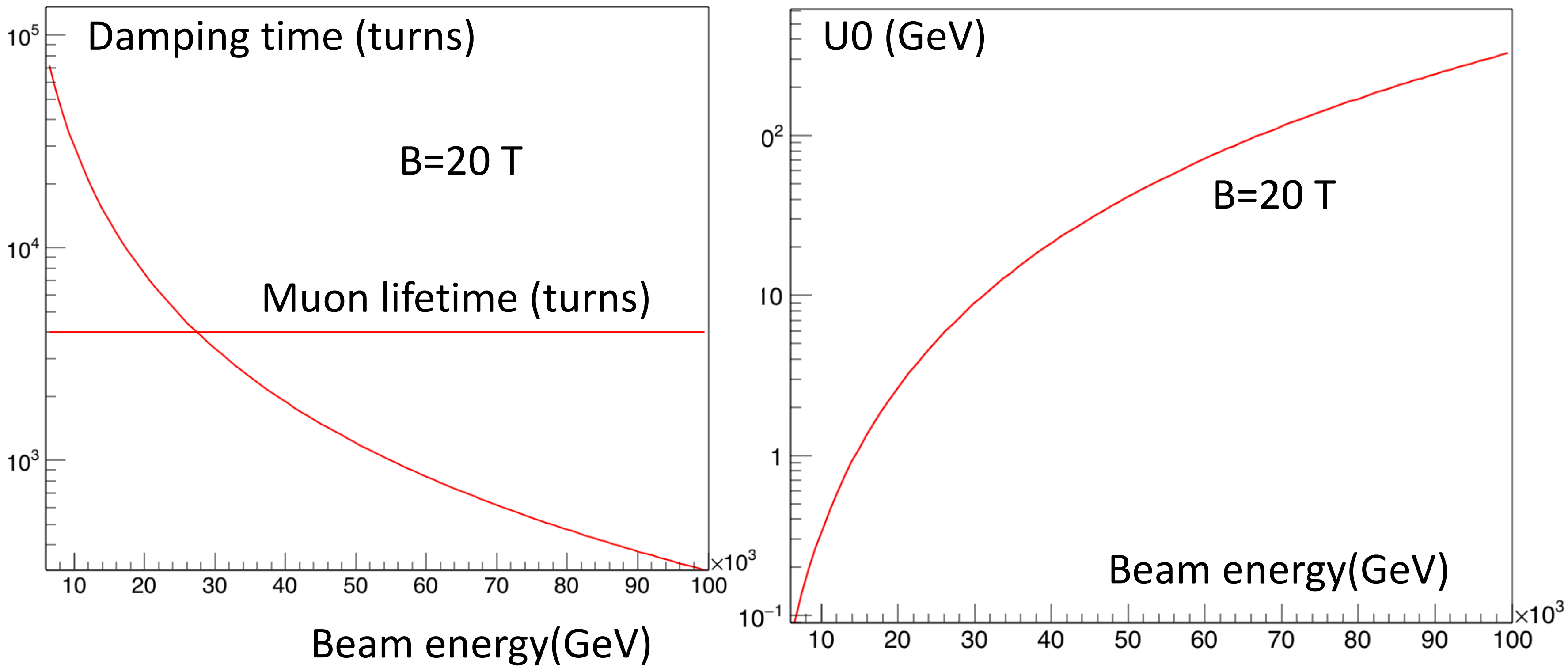
no damping -> fill transverse phase space maintaining lumi increase

SR and damping in μ collider



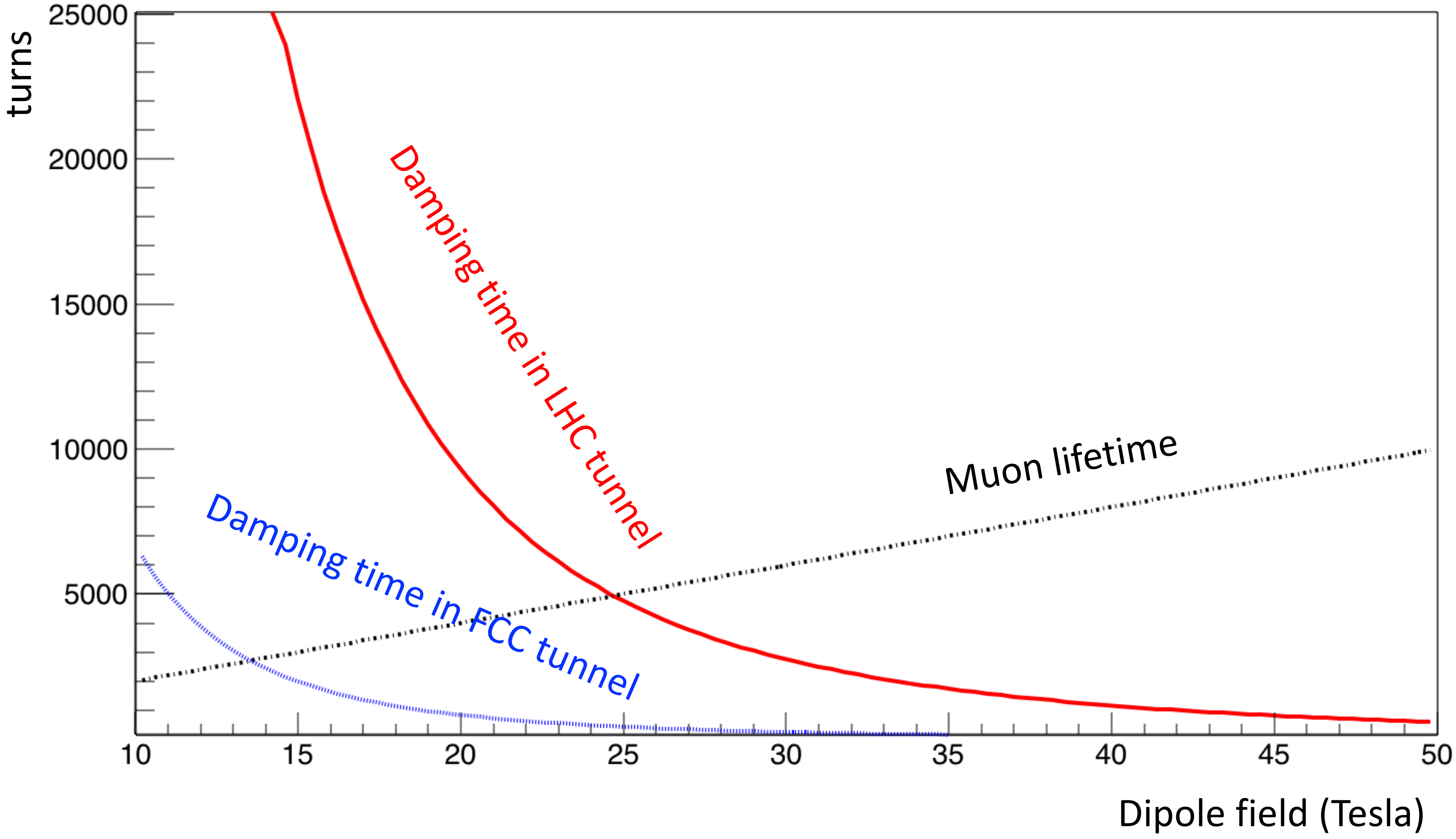


SR and damping in μ collider

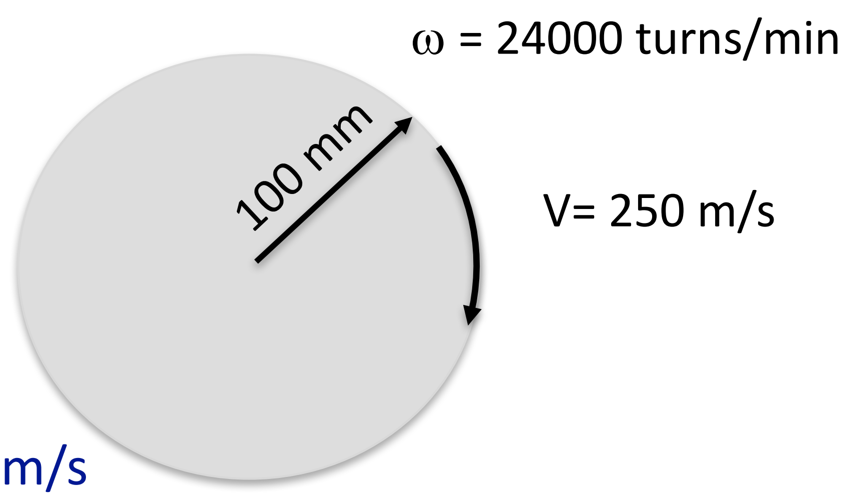


$U_o = 5.5 \times 10^{-18}\ \gamma^4/\rho$

Damping time & muon lifetime



Solid target



- Rotating disc
  - 24000 turns/min
  - Radial velocity V= 2 π ω(in turns) r=250 m/s
- Bunch spacing of ΔT=200ns
  - Bunch separation on target L = V ΔT= 50 μm
  - 12500 bunches in 1 turn

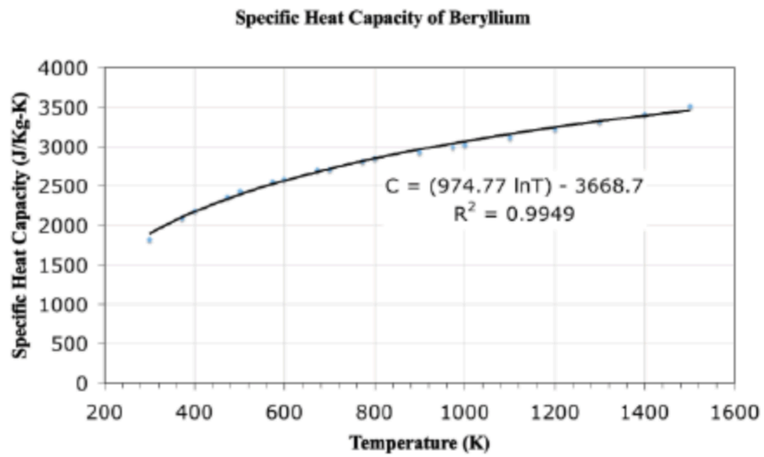
2D axisymmetric model showing effective total strain

4.9 x 10^{13} protons, σ = 0.3 mm, $\Delta T \sim 1025$ °C, 0.25 mm thick window

End of beam pulse

t = 7.2 μs, $T_{max} \sim 1050$ °C, $\varepsilon_{max} \sim 3.6$ %

- Use 300 µm round e+ beam, 0.25 mm Be target, 5 x 10^{13} e+/b
- dE/e+ = (2.0 MeV.cm2/g)(1.85 g/cm3)(0.025 cm) = 0.09 MeV/e+
- dE = 5x 10^{13} 0.09 1.6 1.6 x 10^{-13} j/MeV = 0.74j
- dV = pi (0.025 cm)(0.03 cm)**2 = 7 x 10^{-5} cm3
  m = dV ρ = 0.00013 g
  Cp = spec. heat Be = 1.8 j/g°C @ 373 K ; C = Cp m = 0.00024
- dT =dE/C = 3083 °C
- Cp = spec. heat Be = 2.8 j/g°C @ 1000 K ; C = Cp m = 0.0005
- dT =dE/C = 2000 °C
- x2 wrt LS-DYNA ?



- Scale for n= 3 x 10^{11}
- $(300\mu m)^2/200=(21\mu m)^2$

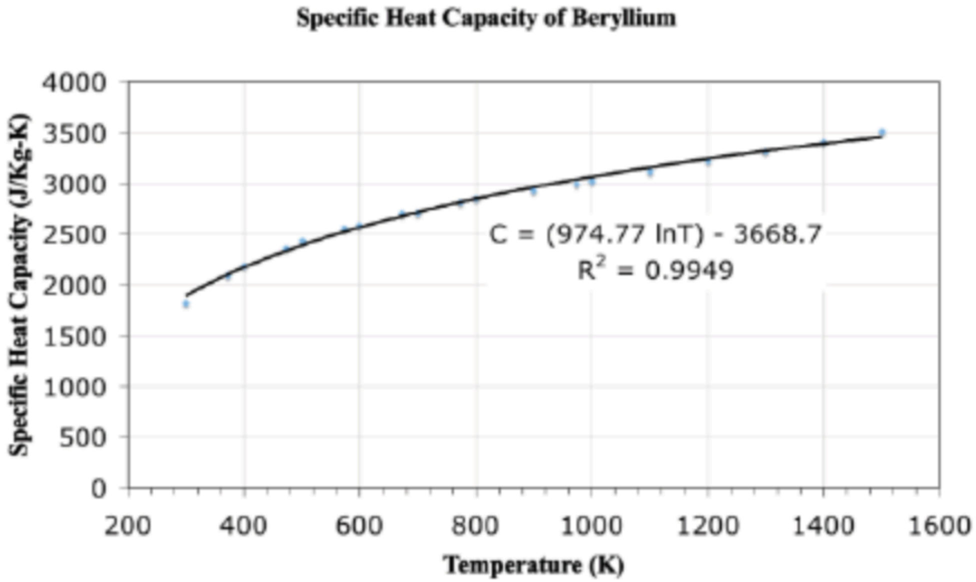
Solid target

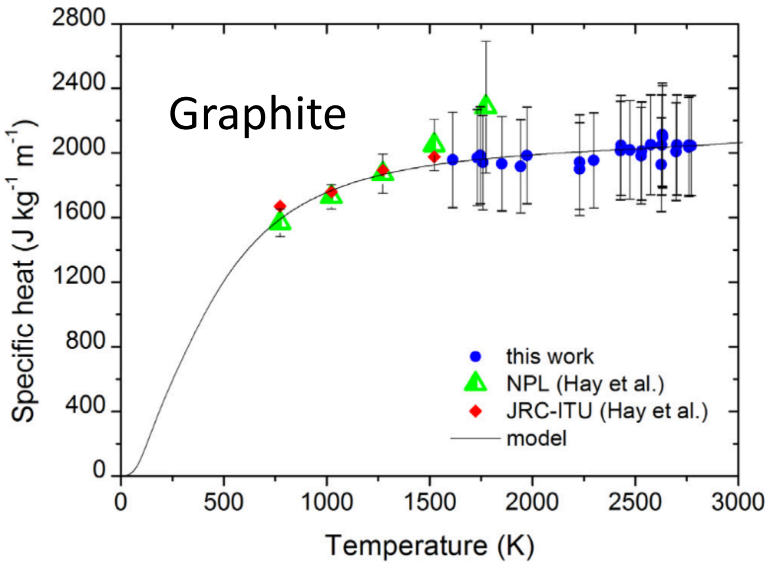
- Use 5 µm round e+ beam, 0.3 cm Be target, 3 x 10^{11} e+/b

$Cp = 0.97477 \ln T - 3.6687$

$Dq = Cp\ DV\ \rho\ dT$

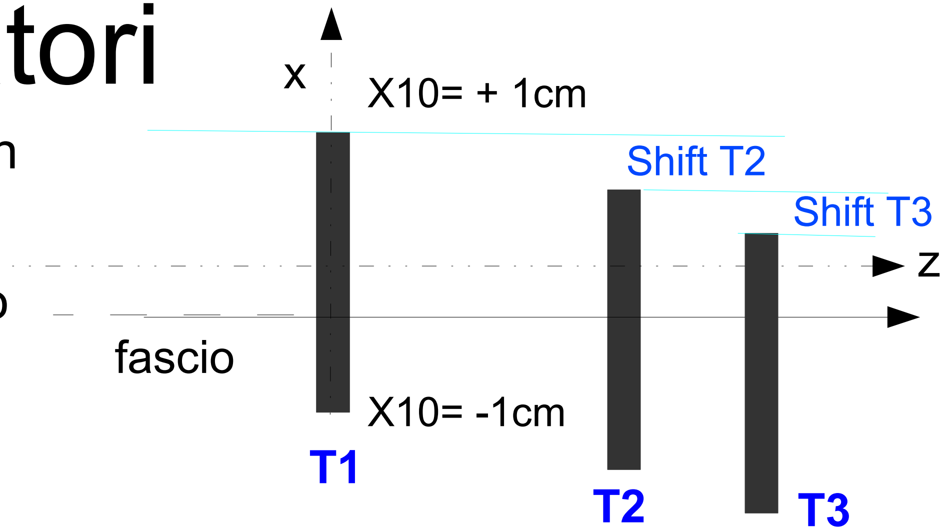
$Q = DV\ \rho\ [(0.97477\ T(\ln T-1) - 3.6687\ T) - 0.97477 \times 373(\ln 373-1) - 3.6687 \times 373)\ ]$

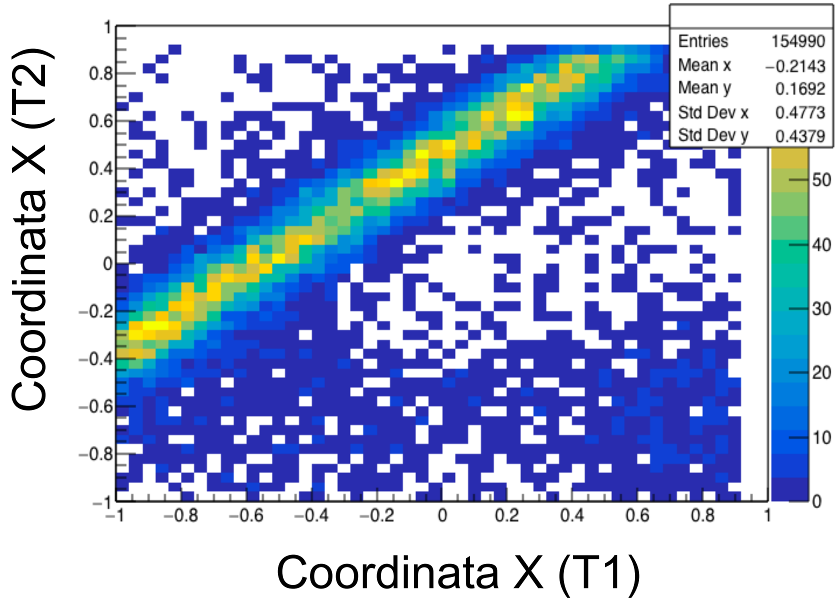


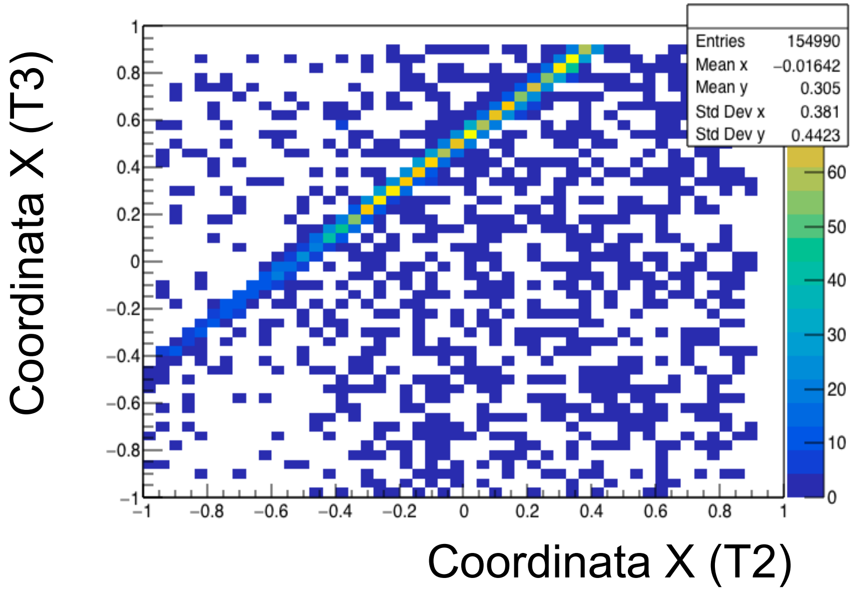


Allinemanto tracciatori

- Allineamento dei tracciatori effettuato con i run di calibrazione senza targhetta:
  - positroni da 22 GeV presi con campo magnetico diretto e invertito
  - Esempi relativi a T2 e T3 (tracciatori prima del dipolo)







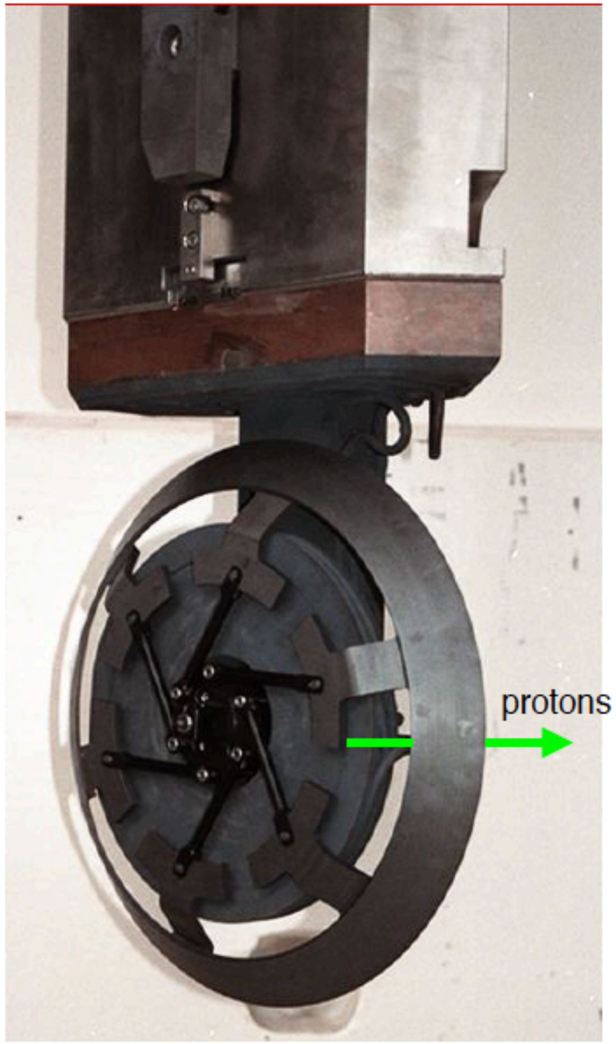
Shift relativo T2 rispetto a T1: 0.5 cm
Spread fascio in X: 0.26 mrad

In corso allineamento dei tracciatori dopo il dipolo:
- 1) misure dei geometri
- 2) confronto tra direzioni predette e posizione misurate nei due bracci dello spettrometro

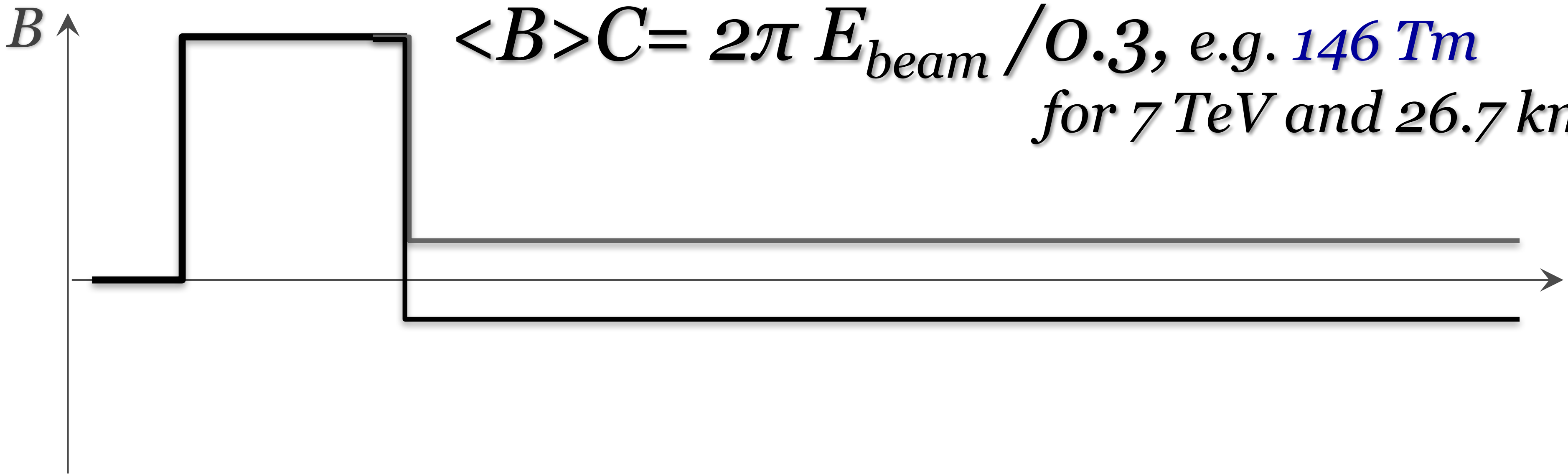
Target wheel of TgE station

PAUL SCHERRER INSTITUT

- 40 mm polycrystalline graphite
- ~40 kW power deposition
- Temperature 1700 K
- Radiation cooled @ 1 turn/s
- Beam loss 12% (+18% from scattering)



Assume RCS Acceleration



$<B>C = 2\pi E_{beam}/0.3$, e.g. 146 Tm

for 7 TeV and 26.7 km

Example: 7 TeV, 26.7 km tunnel, 16T max

$$\frac{2\pi}{0.3} E_{max} = < B > C = B_{max} \Pi C \frac{2R}{R(1+f)+1-f}$$

146 T × km 26.7km 16T 0.85 0.4=1/2.5

then :

$f = \frac{B_{max}}{B_{min}}$	$R = \frac{f-1}{f-4}$	B_{min}	E_{inj}
4.2	16	3.8T	0.45TeV
4.5	7	3.5T	1TeV
5	4	3.2T	4TeV
8	1.75	2.0T	9.1TeV

Example 2: 1 TeV, 6.9km tunnel, 16T max

$$\frac{2\pi}{0.3}E_{max} = \langle B \rangle C = B_{max}\Pi C\frac{2R}{R(1+f)+1-f}$$

20.9 T × km   6.9km   16T   0.9   0.21=1/5

then :

$f = \frac{B_{max}}{B_{min}}$	$R = \frac{f-1}{f-9}$	B_{min}	E_{inj}
10	9	1.6T	110 GeV
9.5	17	1.7T	60 GeV

To sum up: 14 TeV *CMC*

- **One can build a 14 TeV cme *$\mu+\mu-$* collider at CERN if:**
  - Re-use tunnels 26.7km LHC, 6.9km SPS, 0.7km PS
  - 16 T SC magnets (DC), need ~5 km
  - Pulsed ±3.5 T magnets, with ramp ~100ms, need ~20km
  - Pulsed ±2 T magnets, with ramp ~10ms, need ~6km
  - Pulsed ±1 T magnet, with ramp ~1ms, need ~1km
- **The *αβγ*-model predicts TPC ~12B$ ±4**
  - 5B$ SC magnets, 3B$ NC magnets, 2B$ SRF, 2B$ 100MW power infrst.
  - ~ cost of LHC; ~6B$ in European accounting
- **"Free cookie" – if one has 24 T SC magnets**
  - Either 4x luminosity can be achieved with collider in SPC tunnel – that requires 7 km of 24T magnets
  - Or 7 TeV cme in the LHC tunnel with just 3T pulsed magnets