Exploring the potential for a

Low Emittance Muon Collider

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Discussion of the scientific potential of muon beams
CERN, November 18th 2015

Outline

- The idea in brief (with processes and scaling law)

- An example: Multi-TeV and Higgs factory collider application

- References:
  - M. Antonelli, M. Boscolo, R. Di Nardo, P. Raimondi, “Novel proposal for a low emittance muon beam using positron beam on target”, NIMA online http://www.sciencedirect.com/science/article/pii/S0168900215013364

  Investigation of this idea by SLAC team:
  - Simulations study by SLAC: L. Keller, J. P. Delehaye, T. Markiewicz, U. Wienands, MAP workshop 2014
  - **Presentation in Snowmass 2013**, Minneapolis (USA) July 2013: [M. Antonelli and P. Raimondi, Snowmass report (2013)] also [LNF-Note]

Idea for low emittance μ beam

Conventional production:

π, K decays from proton on target (p.o.t) have typical Pμ (π, K rest frame)~ 100 MeV/c,

whatever is the boost P_T will stay in Lab frame →
very high emittance at production point → **cooling needed**!

Direct pair production:

Muons produced from $e^+e^- \rightarrow \mu^+\mu^-$ at √s around the $\mu^+\mu^-$ threshold (√s~0.212GeV) in asymmetric collisions (to collect μ^+ and μ^-)

Advantages:

1. low emittance possible: $P\mu$ is tunable with $\sqrt{s}$ in $e^+e^- \rightarrow \mu^+\mu^-$ can be very small close to the $\mu^+\mu^-$ threshold
2. Low background: Lumi 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 gets larger as $\sqrt{s}$ increases use correlation with emission angle (eventually can be reduced with short bunches)

Disadvantages:

- Rate: much smaller cross section wrt protons

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

  i.e. Luminosity= $10^{40}\ cm^{-2}\ s^{-1} \rightarrow \mu$ rates 10^{10} Hz

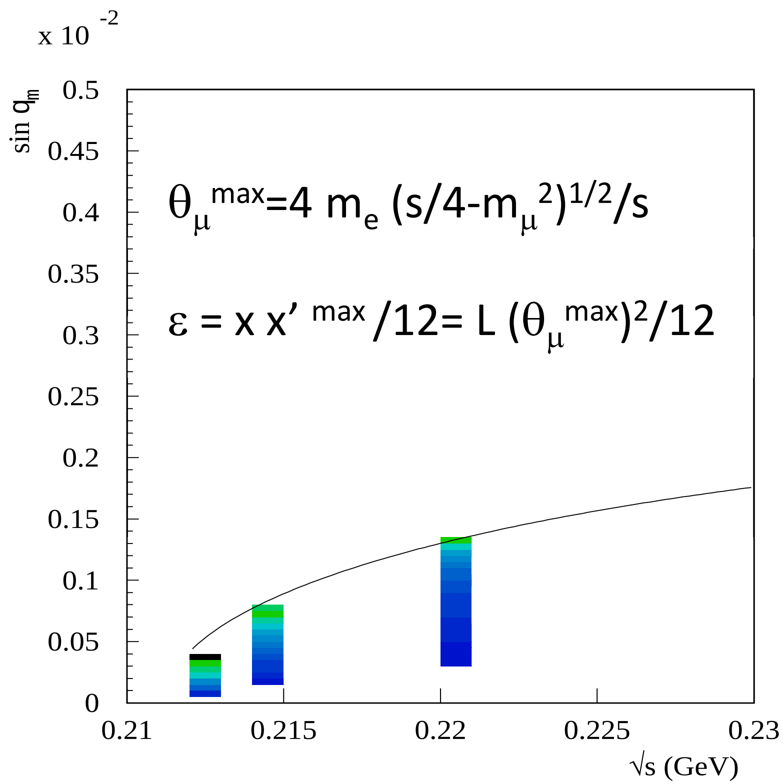
Possible Schemes

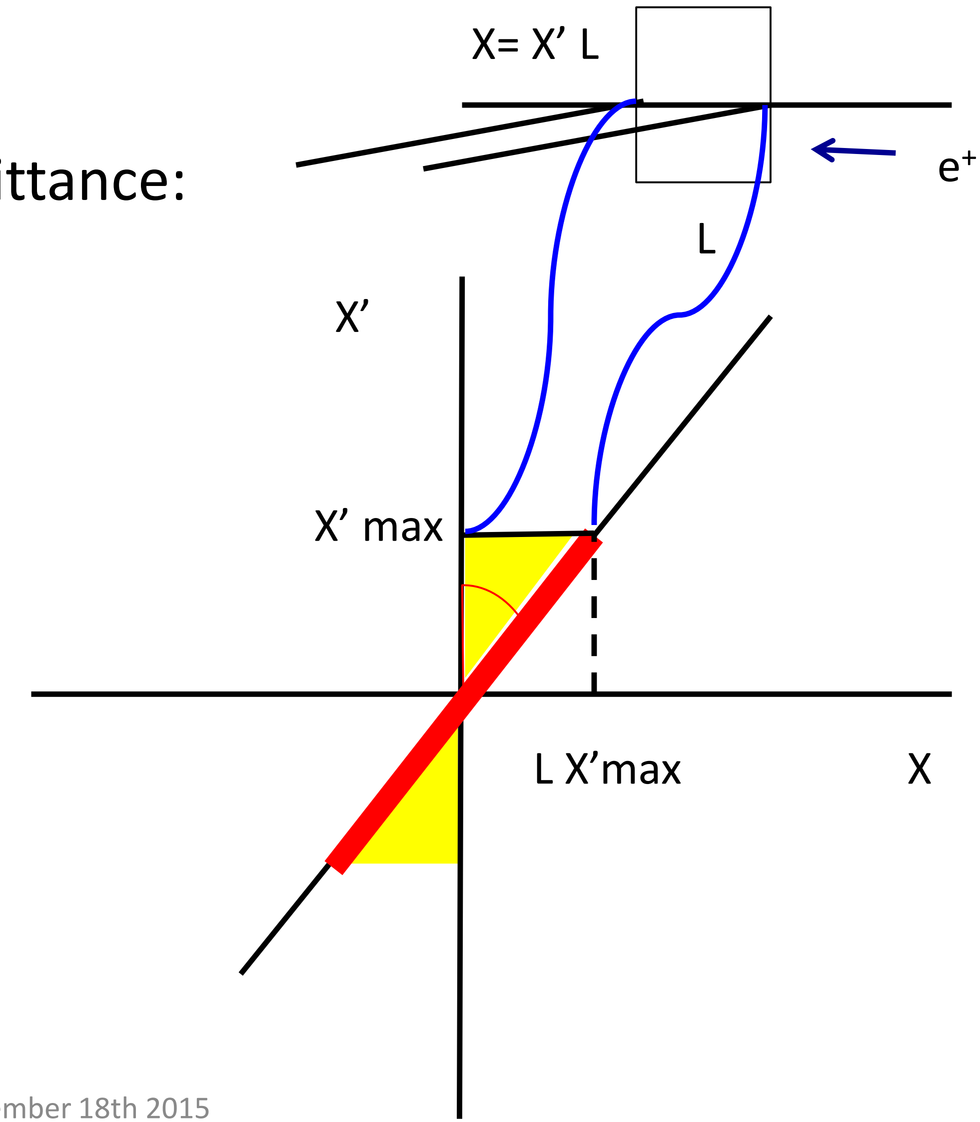
- **Low energy collider with e+/e- beam (e+ in the GeV range):**
  1. Conventional asymmetric collisions (but required luminosity is beyond current knowledge)
  2. Positron beam interacting with continuous beam from electron cooling (too low electron density need 10^{20}electrons/cm^{-3} to obtain an reasonable conversion efficiency to muons)
- **Electrons at rest (seems more feasible):**
  3. e+ on Plasma target
  4. e+ on standard target
  - Need Positrons of ~45 GeV
  - Get γ~200 and laboratory lifetime of about 500 μs

Ideally muons will *copy* the positron beam

Processes at √s ~ 0.212 GeV e^+ on target

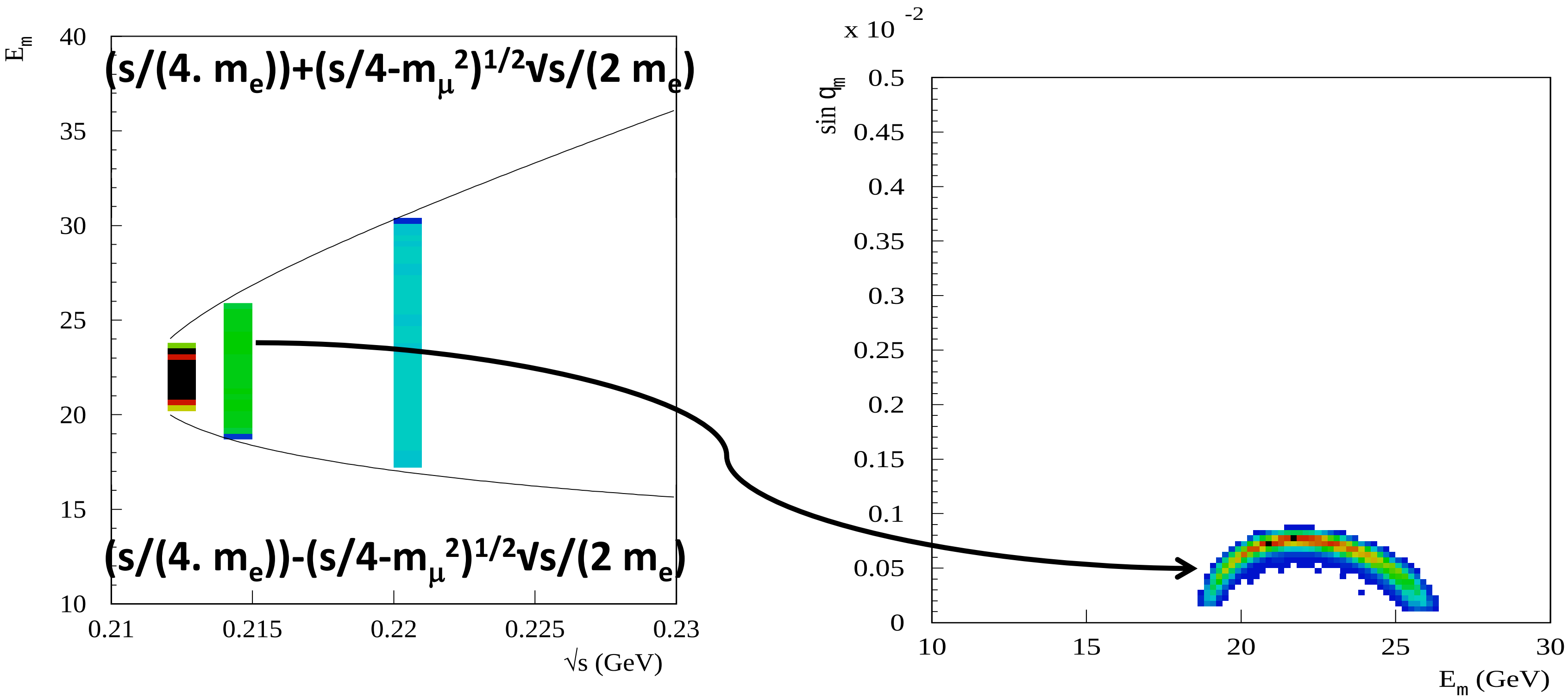
Muons angle contribution to emittance:





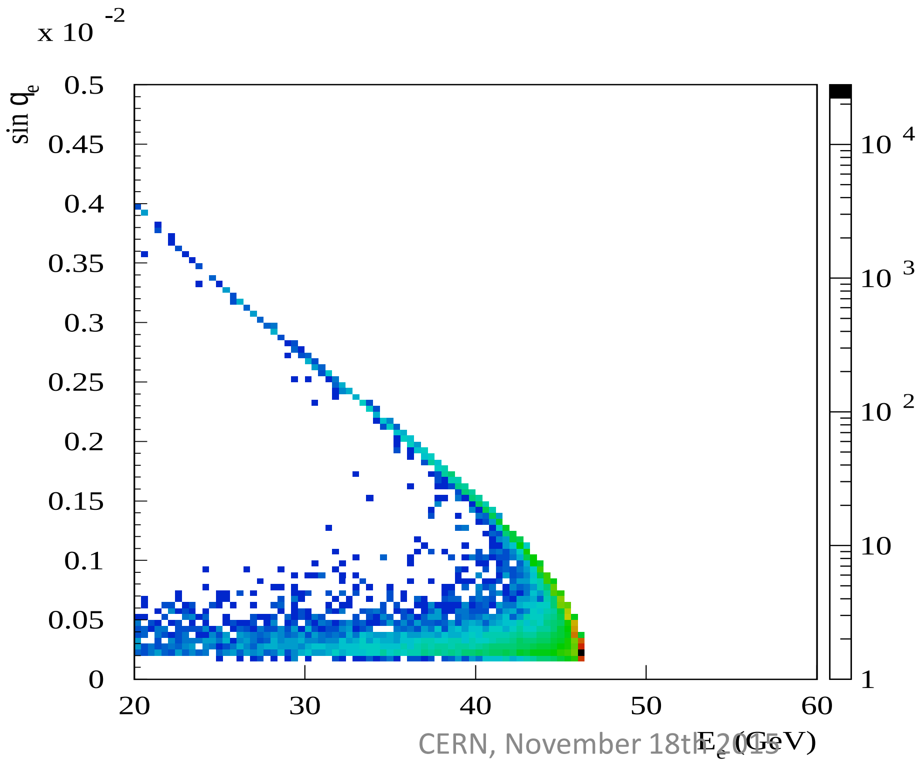
Processes at √s ~ 0.212 GeV e^+ on target

- $e^+e^- \to \mu^+\mu^-$ muons energy spread:



Processes at $\sqrt{s} \sim 0.212$ GeV e^+ on target

- $e^+e^- \rightarrow e^+ e^- (\gamma\text{'s})$ is the dominant process
- babayaga for "large" angles and Bbrems for collinear (dominant $\sigma \sim 150$ mb)



Criteria for target design:

- **Number of $\mu^+\mu^-$ pairs produced per interaction:**

$$n(\mu^+\mu^-) = n^+ \rho^- L\, \sigma(\mu^+\mu^-)$$

n^+ = number of e^+

ρ^- = target electron density

L = target length

- **ρ^- L costraints**
  - Ideal target (e^- dominated)
    $(\rho^- L)_{max} = 1/\sigma(\text{rad. bhabha}) \approx 10^{25}\ \text{cm}^{-2}$
    (beam lifetime determined by rad bhabha)
  - With $(\rho^- L)_{max}$ one has a maximal $\mu^+\mu^-$ production efficiency ~10^{-5}
  - Muon beam emittance increases with L (in absence of intrinsic focussing effects) ➔ increase ρ^-
  - Conventional target $(\rho^- L)_{max}$ depends on material (see next slides)

Conventional target option

- Brems on nuclei and multiple scattering (MS) are the dominant effects in real life… Xo and electron density will matter
- Heavy materials
  - minimize emittance (enters linearly) ➔ Cu has ~ same contributions to emittance from MS and $\mu^+\mu^-$ production
  - high e^+ loss (brems is dominant)
- Very light materials
  - maximize production efficiency(enters quad) ➔ H_2
  - even for liquid need O(1m) target ➔ emittance increase
- Not too heavy materials(Be, C)
  - Allow low emittance with small e^+ loss

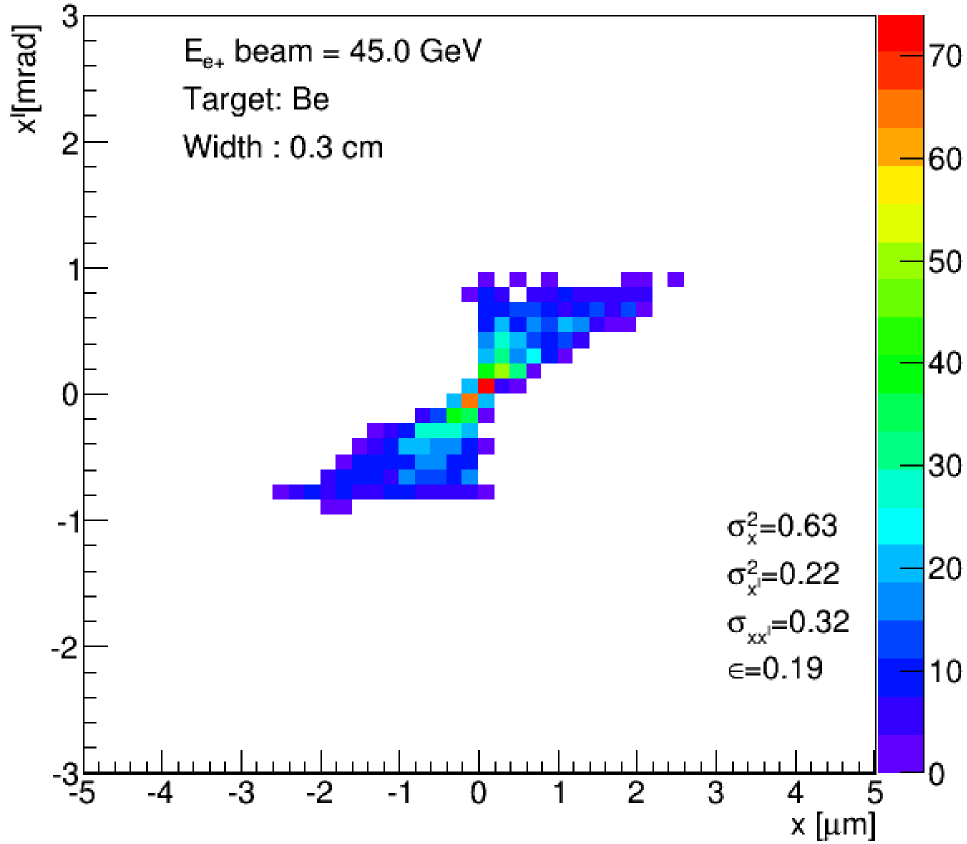
Application for Multi-TeV muon Collider as an example

- 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

Possible target: 3 mm Be

- 45 GeV e^+ beam
- Emittance at 22 GeV: 0.19 $*10^{-9}$ (MS contr. negligible)
- Conversion efficiency: 10^{-7}
- Beam energy spread: 9%

Muons at the target exit surface

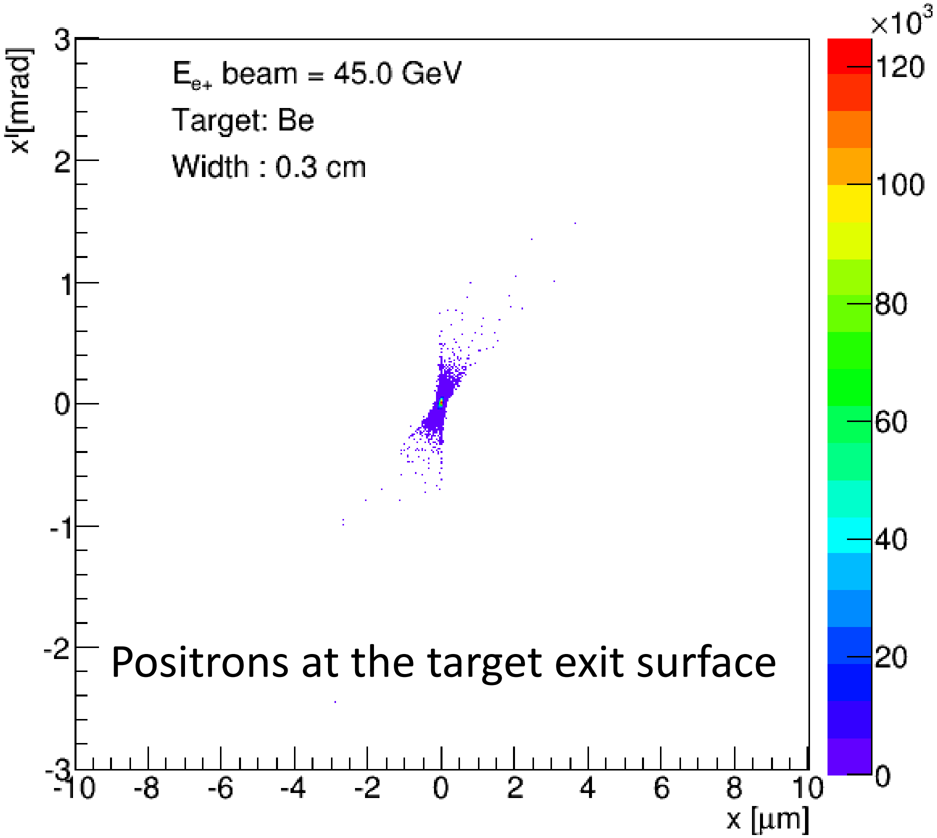


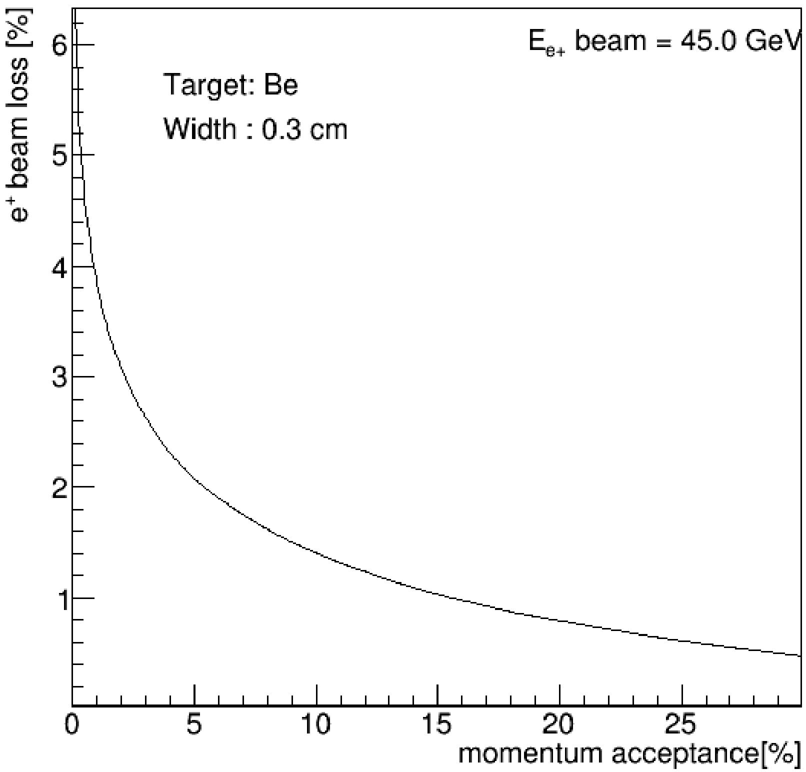
Positrons storage ring requirements

- 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)

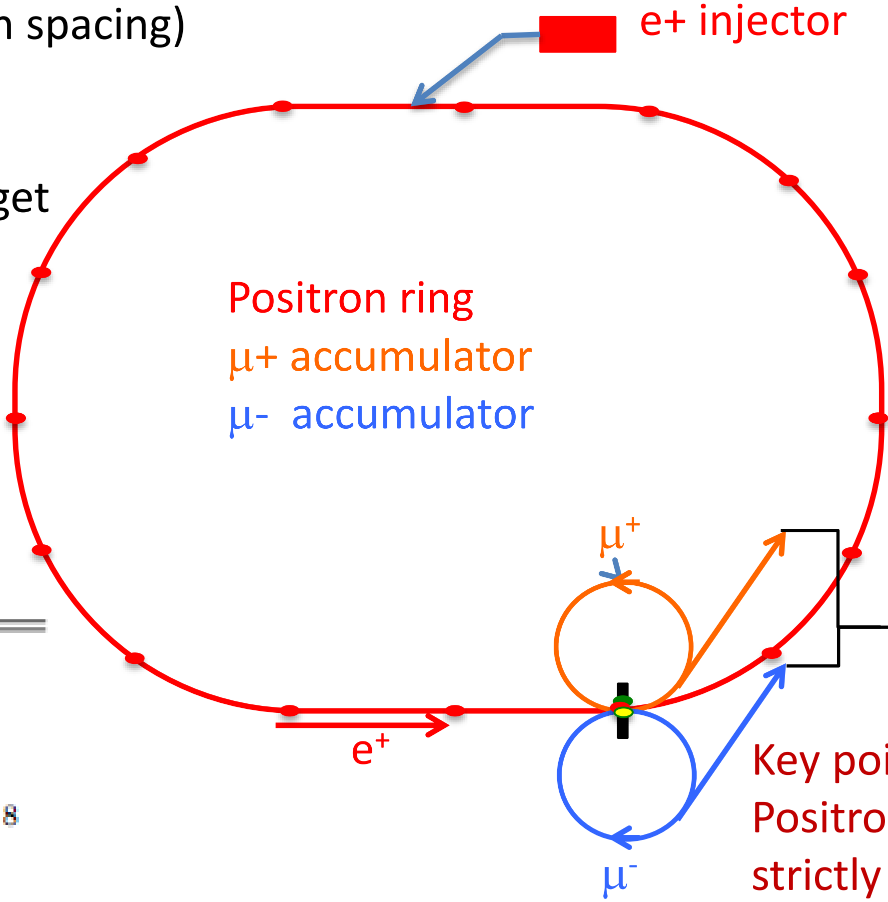
  – 10% momentum acceptance will increase the effective muon conversion efficiency (produced muon pairs/produced positrons) by factor 100





Schematic Layout

- 6 km positron ring (ρ = 0.6 km)
- Nb=100 (200ns bunch spacing)
- $I_{tot}(e+)$ = 240 mA
- $3 \cdot 10^{11}$ e^+ per bunch
- $1.5 \cdot 10^{18}$ e^+/s on target



Muons accumulators:
60 m isochronous rings
recombine bunches

$$n_b = \sum_{i=1}^{N_T} e^{-\Delta t(N_T - i)/\tau_\mu^{lab}}$$

for ~ 1 τ_μ^{lab} ~2500 turns

To accelerating complex

B [T]	0.245
$E_{critical}$ [keV]	315
e^+ rate [Hz]	$1.5 \cdot 10^{18}$
$< N_\gamma >$	5763
U_0 [GeV]	0.578
P_{tot} [MW]	139

Key point:
Positron source requirements strictly related to the momentum acceptance

Muon beam parameters

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

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

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

- In the muon collider, particles per bunch can be increased by a factor ~ τ_{μ}^{lab}(HE)/500μs

(~100 for 6 TeV muon collider)

possible thanks to low emittance and divergence values

LEMC Draft Parameters

Parameter	Units	LEMC-6TeV	LEMC-H
LUMINOSITY/IP	$cm^{-2} s^{-1}$	5.09E+34	1.69E+31
Beam Energy	GeV	3000	62.5
Hourglass reduction factor		1.000	1.000
Muon mass	GeV	0.10566	0.10566
Lifetime @ prod	sec	2.20E-06	2.20E-06
Lifetime	sec	0.06	0.00
c*tau @ prod	m	658.00	658.00
c*tau	m	1.87E+07	3.89E+05
1/tau	Hz	1.60E+01	7.68E+02
Circumference	m	6000	150
Bending Field	T	15	15
Bending radius	m	667	14
Magnetic rigidity	T m	10000	208
Gamma Lorentz factor		28392.96	591.52
N turns before decay		3113.76	2594.80
β_x @ IP	m	0.0002	0.0002
β_y @ IP	m	0.0002	0.0002
Beta ratio		1.0	1.0
Coupling (full current)	%	100	100
Normalised Emittance x	m	4.00E-08	4.00E-08
Emittance x	m	1.41E-12	6.76E-11
Emittance y	m	1.41E-12	6.76E-11
Emittance ratio		1.0	1.0
Bunch length (zero current)	mm	0.1	0.1
Bunch length (full current)	mm	0.1	0.1
Beam current	mA	0.048	0.1
Revolution frequency	Hz	5.00E+04	2.00E+06
Revolution period	s	2.00E-05	5.00E-07
Number of bunches	#	1	1
N. Particle/bunch	#	6.00E+09	1.20E+08
Number of IP	#	1.00	1.00
σ_x @ IP	micron	1.68E-02	1.16E-01
σ_y @ IP	micron	1.68E-02	1.16E-01
$\sigma_{x'}$ @ IP	rad	8.39E-05	5.81E-04
$\sigma_{y'}$ @ IP	rad	8.39E-05	5.81E-04

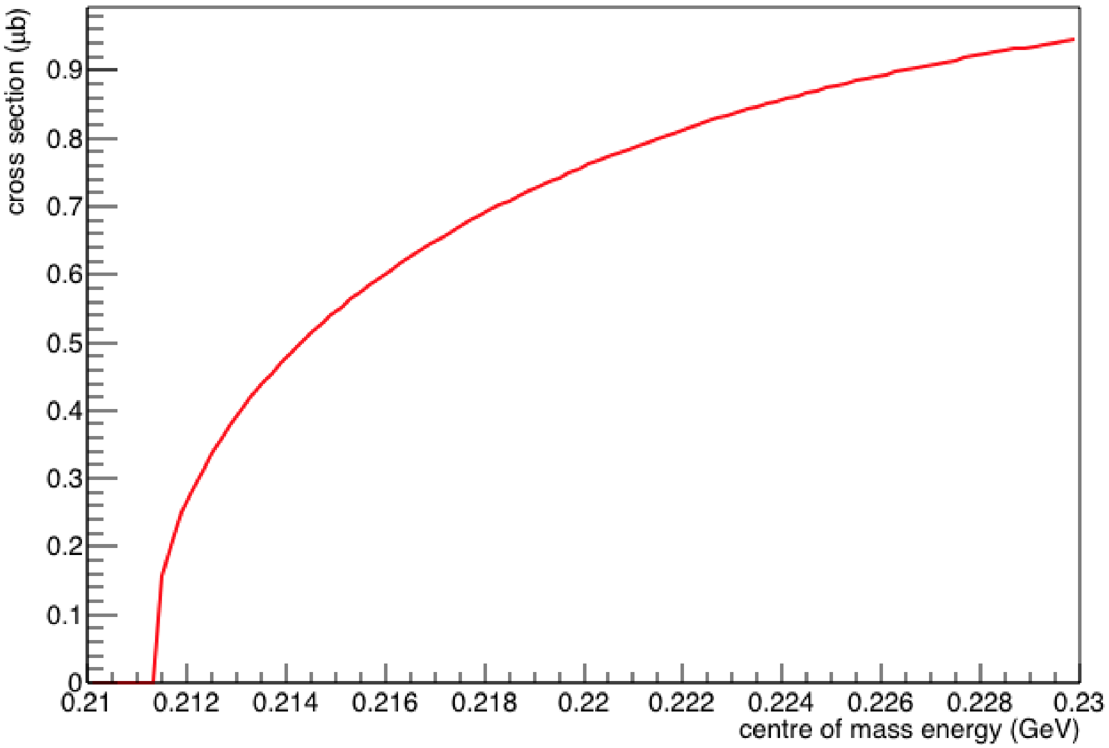
Conclusions

- Very low emittance muon beams can be obtained by means of positron beam on target
- interesting muon rates require:
  - Challenging positron source (synergy with LHeC, ILC, FCC-ee…)
  - Positron ring with high momentum acceptance (synergy with next generation SL sources)
- fast muon acceleration concepts deeply studied by MAP
- Final focus design can profit of studies on ….

Backup Slides

Processes at √s around 0.212 GeV

- Bhabha scattering, $\mu^+\mu^-$ production $\gamma\gamma$ (not relevant)
- $e^+e^-\rightarrow\mu^+\mu^-$ cross section:

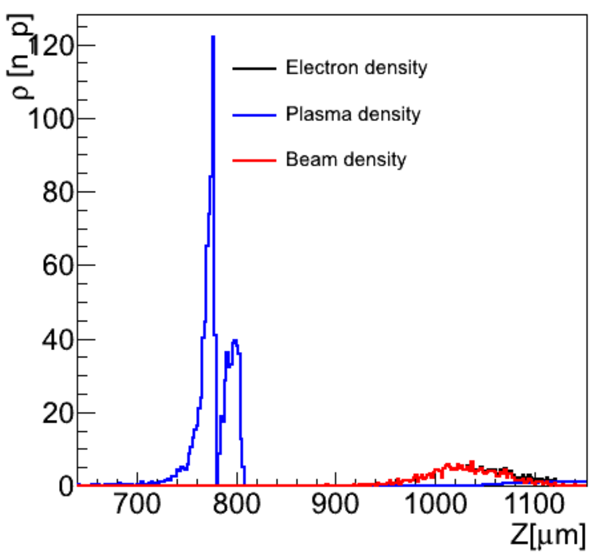


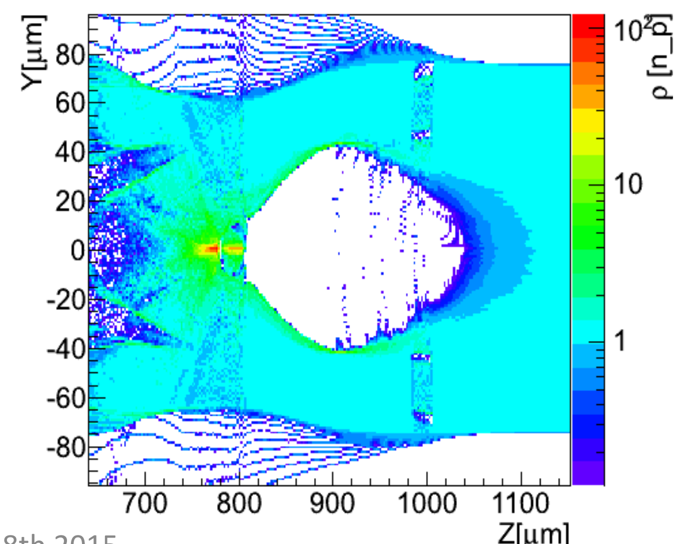
Muonium production also investigated:
huge cross section (mb range)
10^{-4} eV width

Not viable…. Deeper studies?

Few statements on the plasma option

- Plasma would be a good approximation of an ideal electron target ++ autofocussing by Pinch effect
- enhanced electron density can be obtained at the border of the blow-out region (up x100)
- Simulations for $n_p=10^{16}$ electrons/cm^3 (C. Gatti, P. Londrillo)
- Region size decreases with $1/\sqrt{n_p}$ even don't know if blowout occurs at $n_p\sim10^{20}$electrons/cm^3





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
$e^+[10^{14}\text{s}^{-1}]$	0.06	1.1	3.9	18	440

➢ This is the most critical issue