Novel proposal for a low emittance muon collider

M. Antonelli (LNF)

Outline

- Muons case
- Muon accelerators challenges:
  - **muon production**
    - ✓ **LEMMA**
  - high-gradient acceleration and collider rings
  - Performances
- Conclusions

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

Muon based colliders great potential

As with an e^+e^- collider, a $\mu^+\mu^-$ collider offers a precision probe of fundamental interactions without energy limitations

- **By synchrotron radiation (limit of e^+e^- circular colliders)**
- **By beam-strahlung (limit of e^+e^- linear colliders)**

Muon Collider is the ideal technology to extend lepton high energy frontier in the multi-TeV range with reasonable dimension, cost and power consumption

Muon based Higgs factory takes advantage of a strong coupling to Higgs mechanism by s resonance

IF THE MUON BEAM NOVEL TECHNOLOGY CAN BE DEMONSTRATED TO BE FEASIBLE

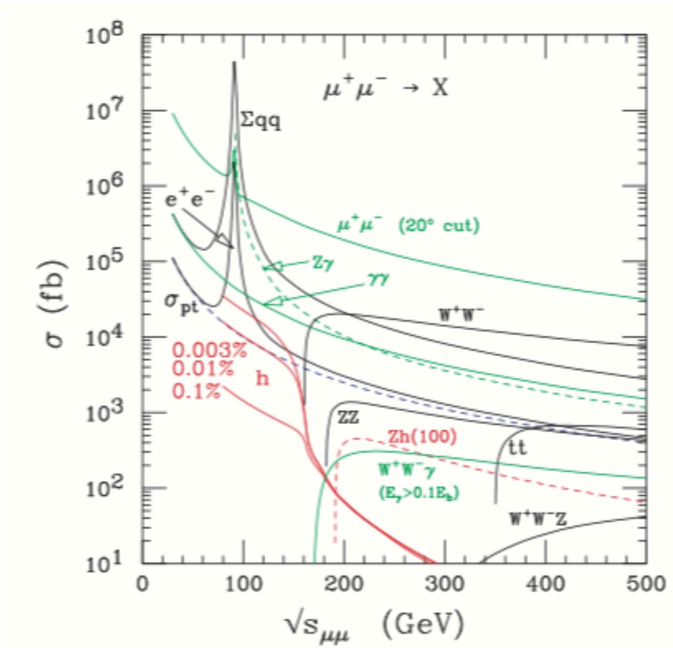
MultiTeV Lepton Collider Basics

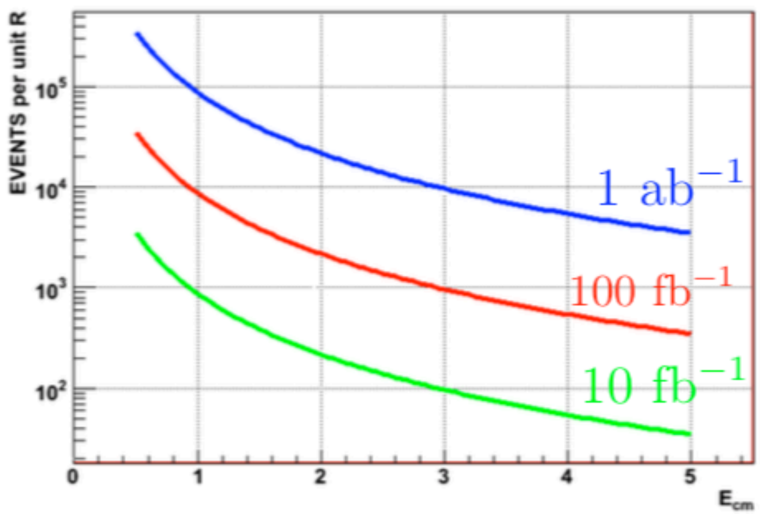
- For $\sqrt{s}$ < 500 GeV
  - SM threshold region: top pairs; W^+W^-; Z^0Z^0; Z^0h; ...
- For $\sqrt{s}$ > 500 GeV
  - For SM pair production (| θ | > 10°)

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

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

Standard Model Cross Sections





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

⇒ 965 events/unit of R

Processes with R ≥ 0.1 can be studied

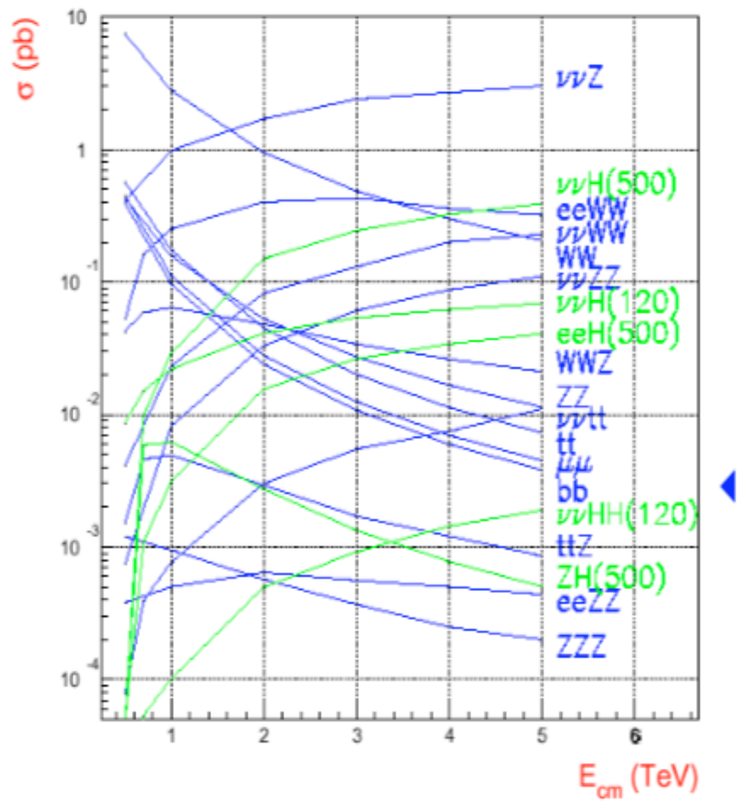
Total - 540 K SM events per year

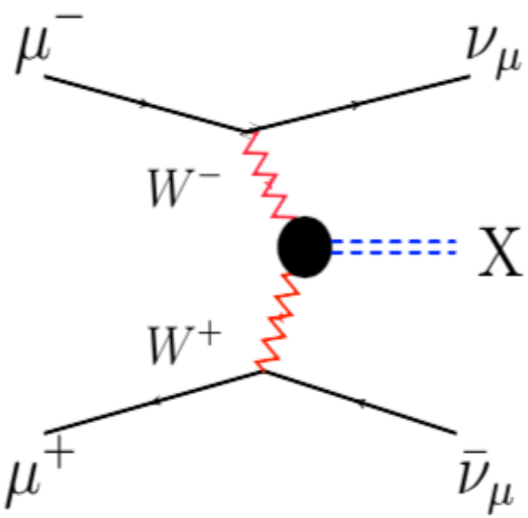
== 10^{36} cm^{-2} s^{-1}@ √s 30 TeV

Vector boson fusion

- For √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)

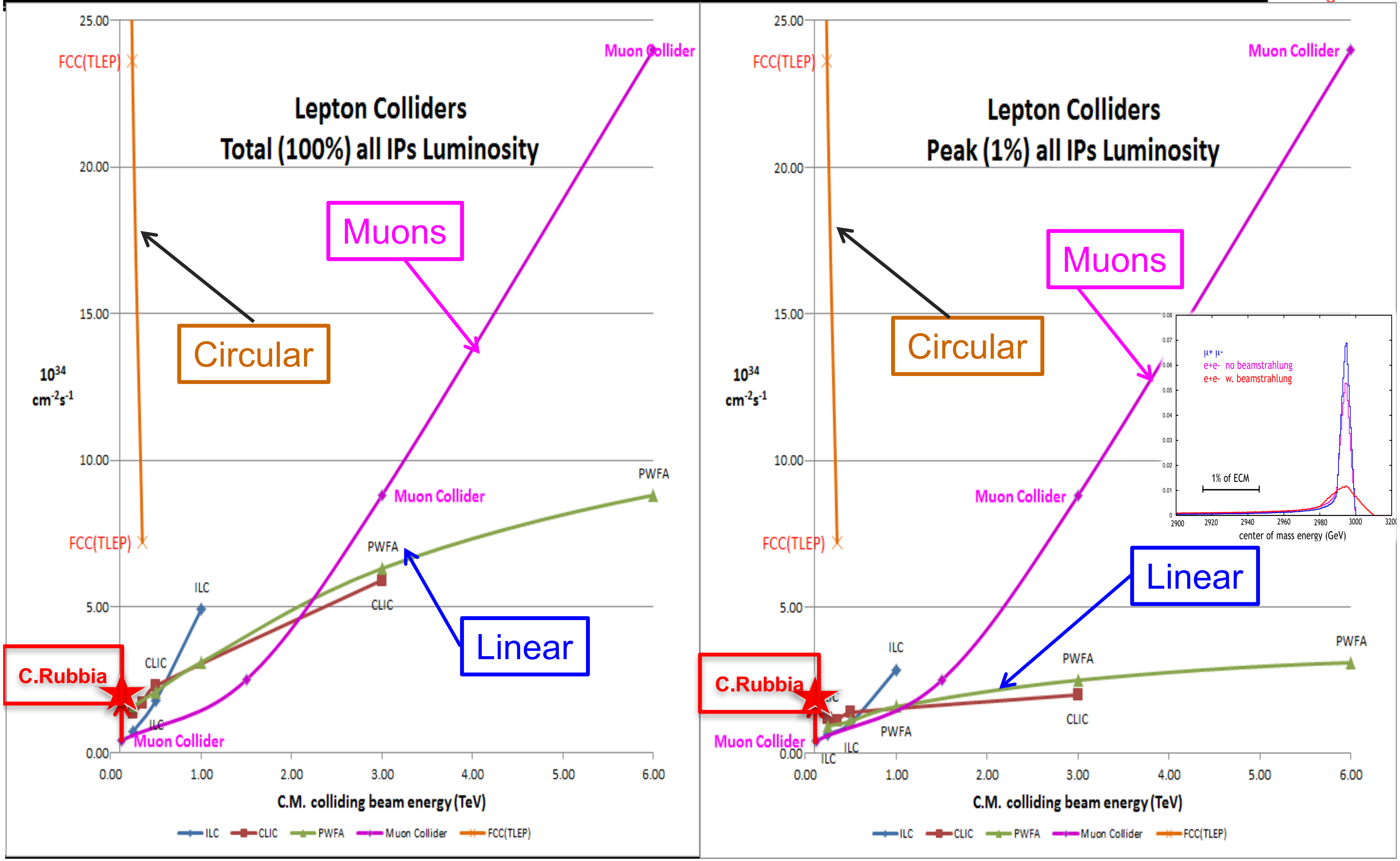
Error on	μμ resonance	ILC	FCC-ee
m_H (MeV)	0.06	30	8
Γ_H (MeV)	0.17	0.16	0.04
g_{Hbb}	2.3%	1.5%	0.4%
g_{HWW}	2.2%	0.8%	0.2%
$g_{H\tau\tau}$	5%	1.9%	0.5%
$g_{H\gamma\gamma}$	10%	7.8%	1.5%
$g_{H\mu\mu}$	2.1%	20%	6.2%
g_{HZZ}	–	0.6%	0.15%
g_{Hcc}	–	2.7%	0.7%
g_{Hgg}	–	2.3%	0.8%
BR_{invis}	–	<0.5%	<0.1%

P. Janot

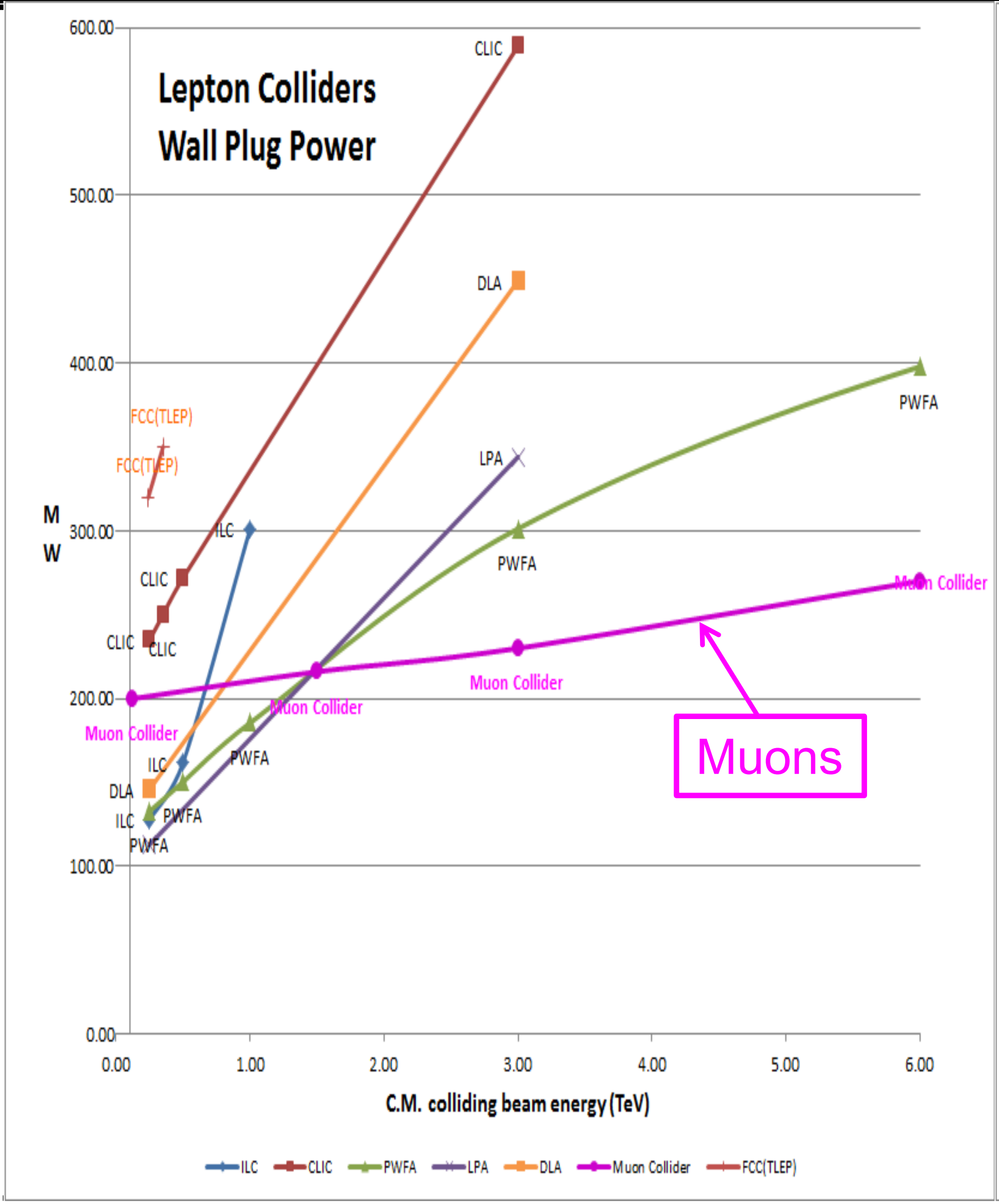
- Resonant Higgs production:
  - Unique measurements of *mh* and *Γh*

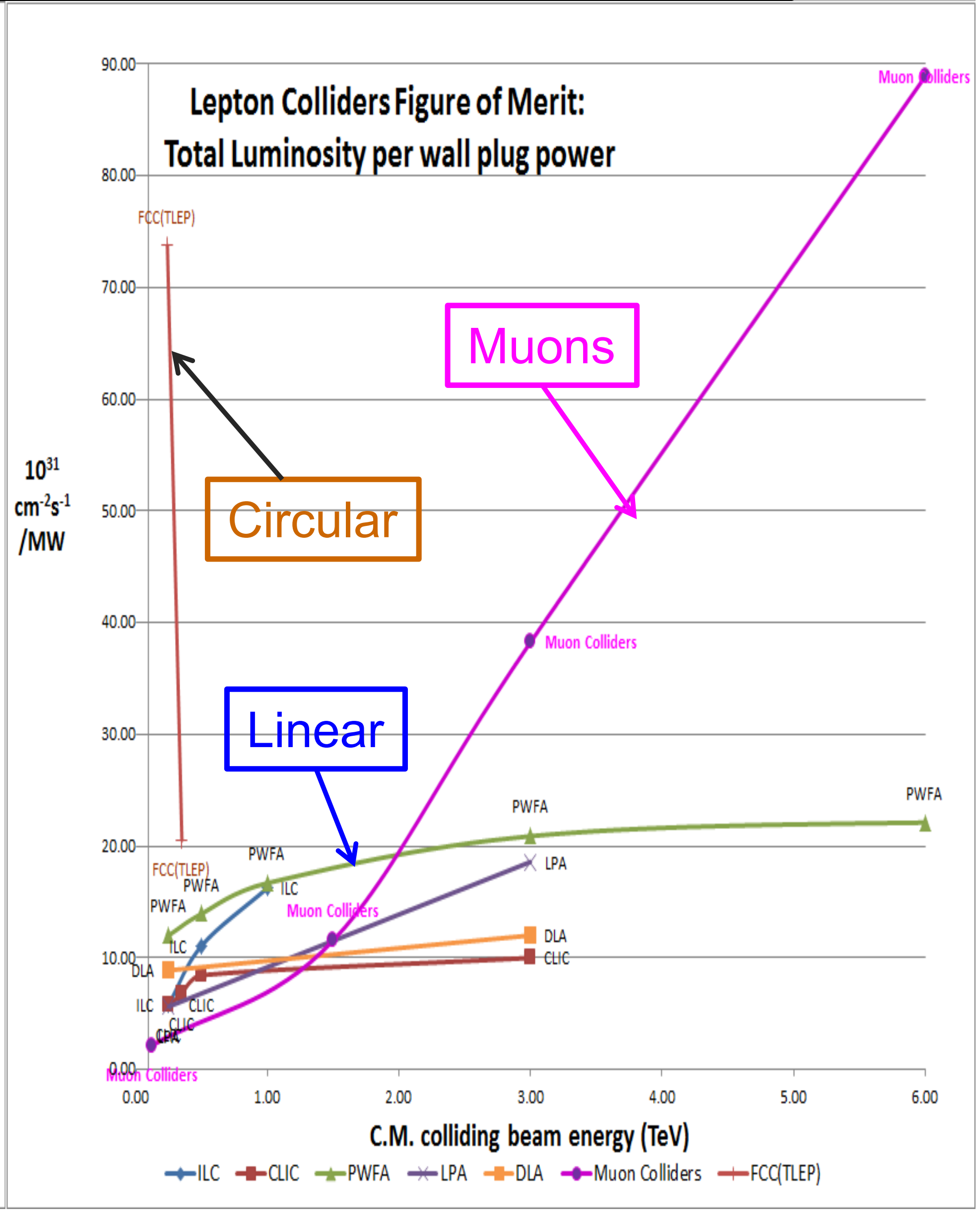
  (mh ~ 0.1 MeV, *Γh* ~ 0.2 MeV)
  - Best test of 2nd generation Higgs couplings (h → *μ+μ−)*
- HZ production:
  - Similar to e^+e^- measurements but lower statistics factor 10 (ILC/CEPC) 100 FCC-ee
- VBF at mutiTeV
  - High xs(O(1Pb)@6TeV) & high lumi better statistics than FCC-ee ?
  - Competitive (probably best) measurement of HH production

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



Muon Colliders extending leptons high energy frontier with potential of considerable power savings





Muon Source

Goals

- **Neutrino Factories**: O(10^{21}) μ/yr within the acceptance of a μ ring
- **Muon Collider**: luminosities >10^{34}/cm^{-2}s^{-1} at TeV-scale ($\sim N_\mu^2 \ 1/\varepsilon_\mu$)

Options

Conventional: Tertiary production through **proton on target** (and then cool), baseline for Fermilab design study

Rate > $10^{13}\mu$/sec $N_\mu = 2\cdot10^{12}$ /bunch

Unconventional:

- **e^+e^- annihilation: positron beam on target** (very low emittance and no cooling needed), baseline for our proposal here
  Rate ~ 10^{11} μ/sec $N_\mu \sim 5\text{x}10^7$ /bunch

- **by Gammas: GeV-scale Compton γs** not discussed here
  Rate ~ $5\cdot10^{10}$ μ/sec $N_\mu \sim 10^6$ (Pulsed Linac) [V. Yakimenko (SLAC)]
  Rate > 10^{13} μ/sec $N_\mu \sim$ few$\cdot10^4$ (High Current ERL)
  see also: W. Barletta and A. M. Sessler NIM A 350 (1994) 36-44

Exploring the potential for a
Low Emittance Muon Collider

References:

- M.Antonelli, *“Very Low Emittance Muon Beam using Positron Beam on Target”*, **ICHEP (2016)**
- M.Antonelli, E.Bagli, M.Biagini, M.Boscolo, G.Cavoto, P.Raimondi and A.Variola, *“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 invetigated 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

Conventional production: from **proton on target**

π, K decays from proton on target have typical **P_μ~ 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**!

Direct μ 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^-)

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:** $P\mu$ is tunable with √s in $e^+e^- \rightarrow \mu^+\mu^-$ $P\mu$ 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 √s increases, one can use correlation with emission angle (eventually it can be reduced with short bunches)

Disadvantages:

- Rate: much smaller cross section wrt protons

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

i.e. Luminosity(e+e-)= 10^{40} cm^{-2} s^{-1} → gives μ rates 10^{10} Hz

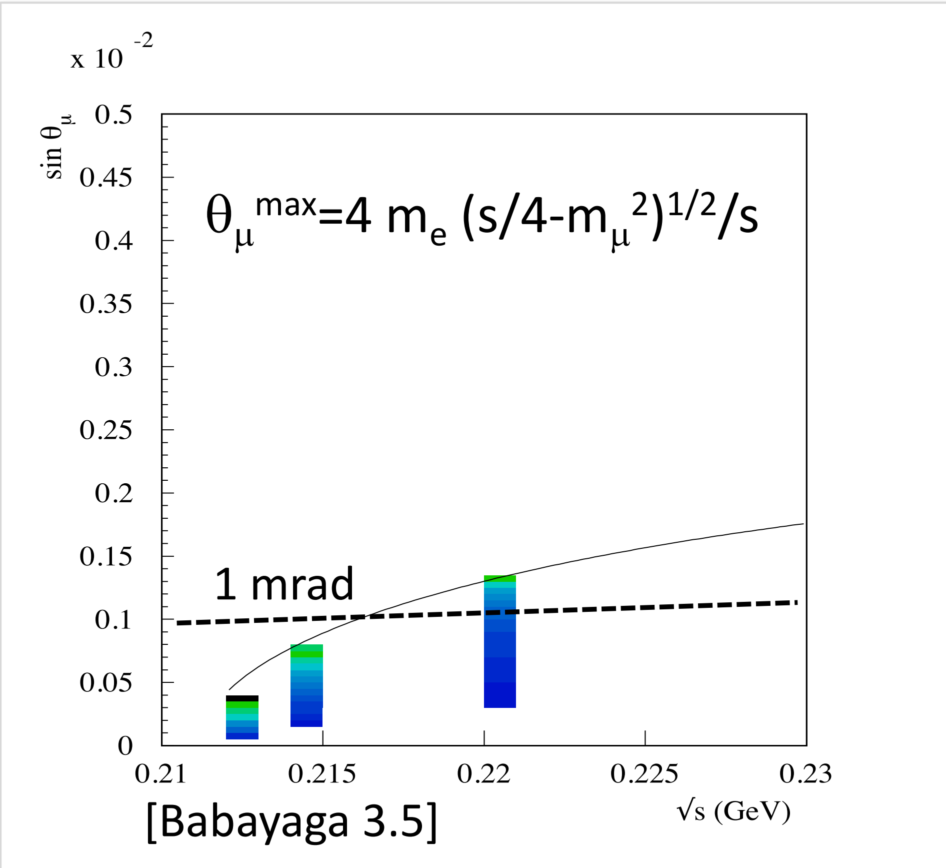
Possible Schemes

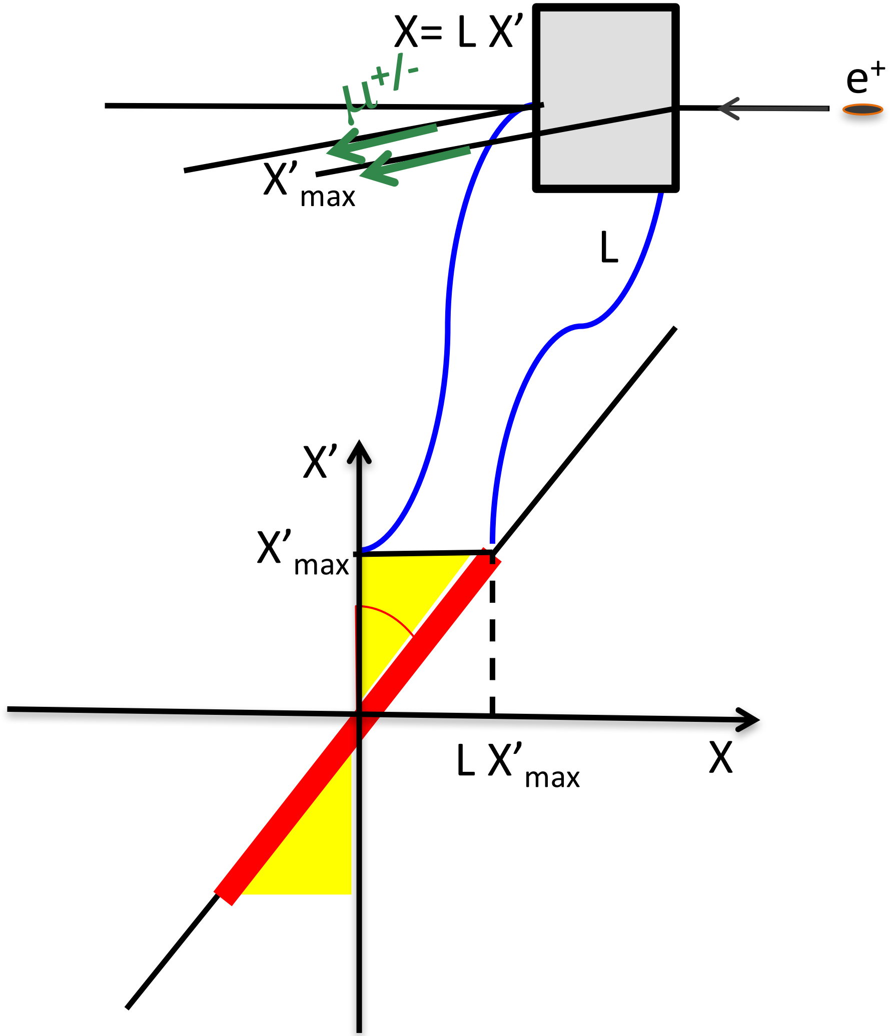
- **Low energy collider with e+/e- beam (e+ in the GeV range):**
  1. Conventional asymmetric collisions (but required luminosity is beyond current knowledge)
  2. Positron beam interacting with continuous beam from electron cooling (too low electron density, 10^{20} electrons/cm^{-3} needed to obtain an 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 ~45 GeV
  - $\gamma(\mu)$~200 and μ laboratory lifetime of about 500 μs

Ideally muons will *copy* the positron beam

Muons angle contribution to μ beam emittance

The target thickness and c.o.m. energy completely determine the emittance contributions due to muon production angle





$$\varepsilon_\mu = x\, x'_{max}/12 = L\,(\theta_\mu^{max})^2/12$$

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)
    $(\rho^- L)_{max} = 1/\sigma(\text{radiative bhabha}) \approx 10^{25}\ \text{cm}^{-2}$
    (beam lifetime determined by radiative 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 focusing effects) ➔ increase ρ^-
  - Conventional target $(\rho^- L)_{max}$ depends on material (see next slides)

Criteria for target design

Bremsstrahlung 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) → Copper has about same contributions to emittance from MS and $\mu^+\mu^-$ production
  - high e^+ loss (Bremsstrahlung 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

optimal: not too heavy and thin

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^+ impinging beam

- Emittance at E_μ = 22 GeV:

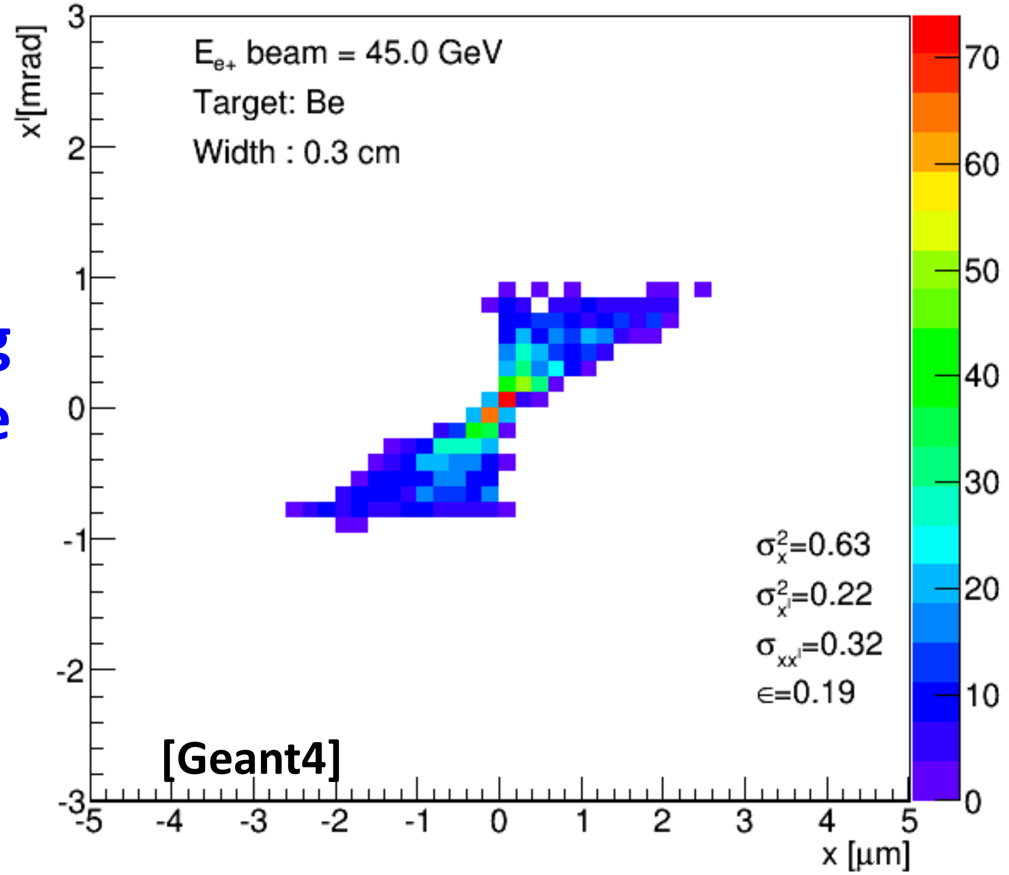
  $\varepsilon_x = 0.19 \cdot 10^{-9}$ m-rad

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)

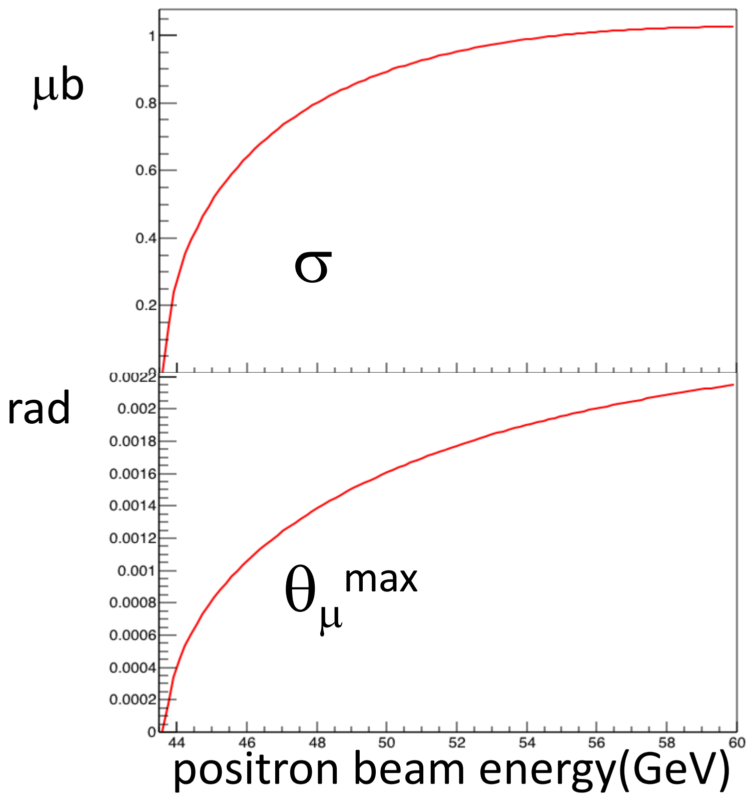
- Conversion efficiency: 10^{-7}
- Muons beam energy spread: 9%

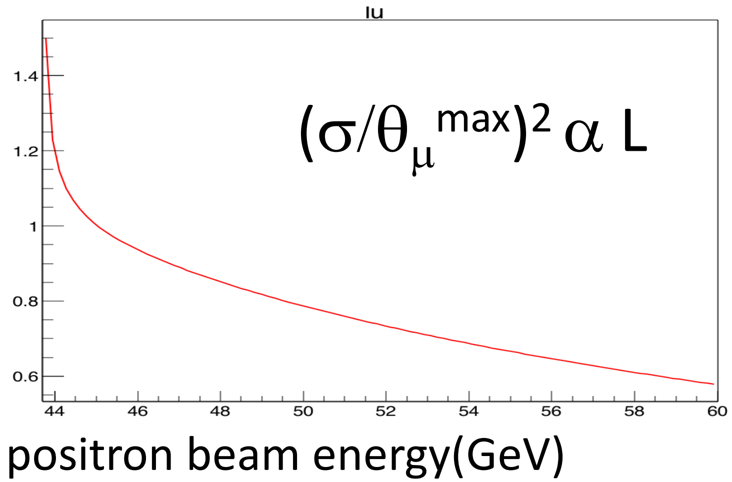
Muons at the target exit surface



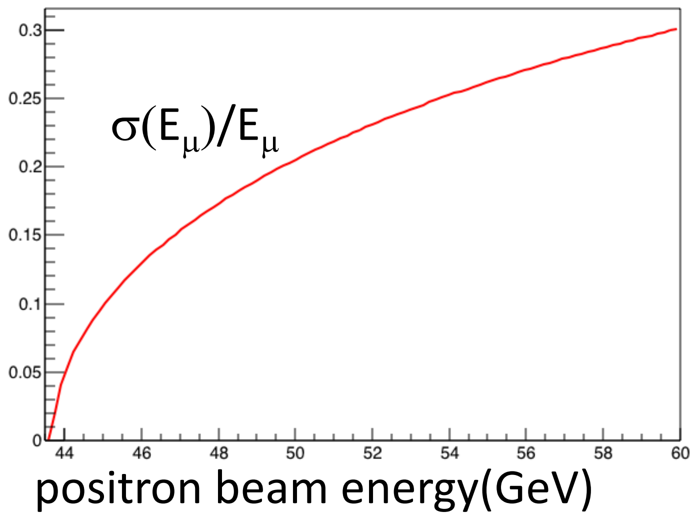
Luminosity vs e$^+$ beam energy

Is there an optimal value for the positron beam energy?





Valid for θ_μ^{max} dominated emittance



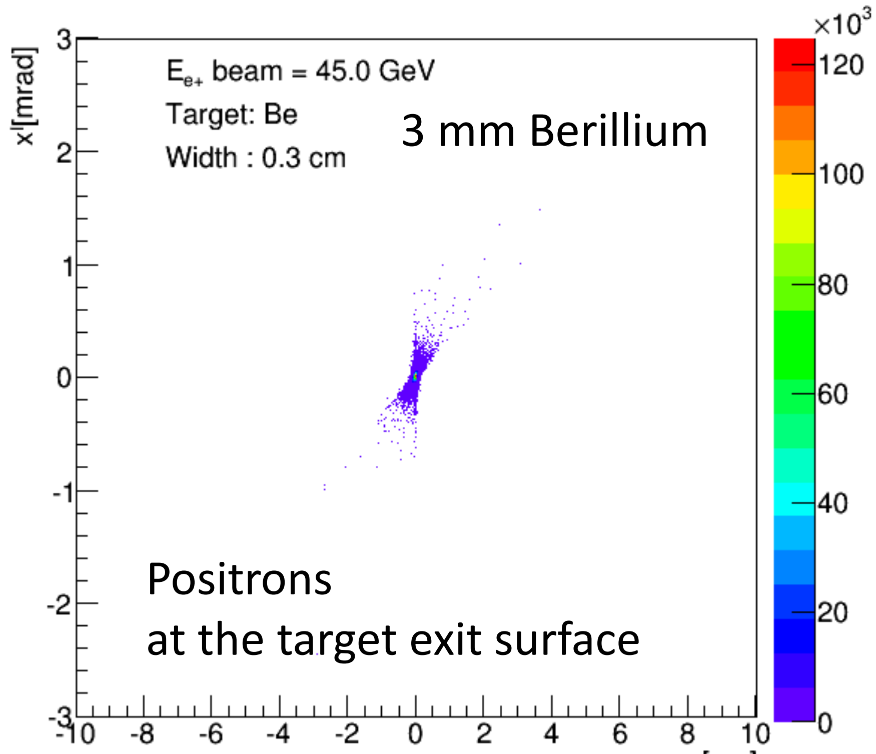
M. Antonelli

Positrons Storage Ring Requirements

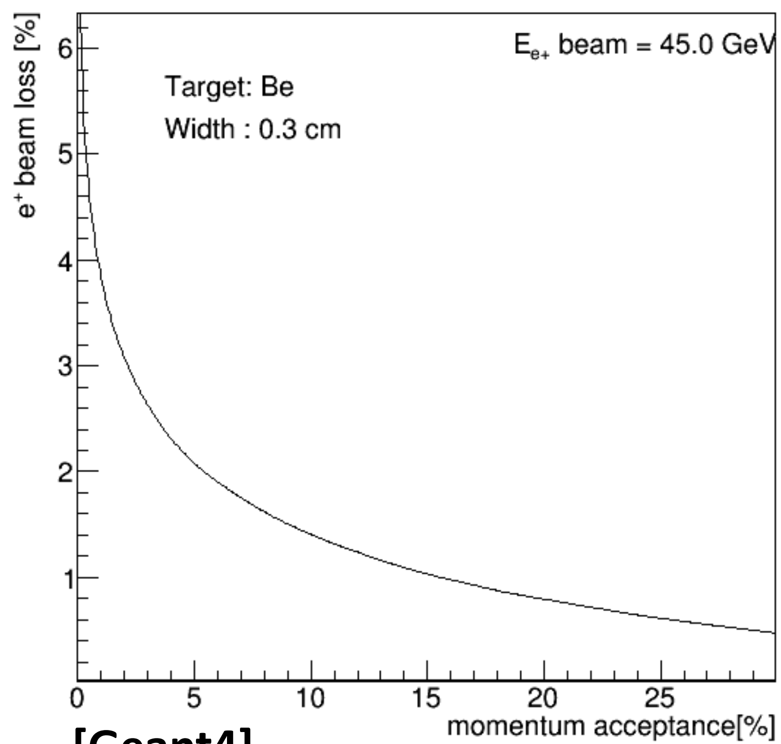
- Transverse phase space almost not affected by target
- Most of positrons experience a small energy deviation:

  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



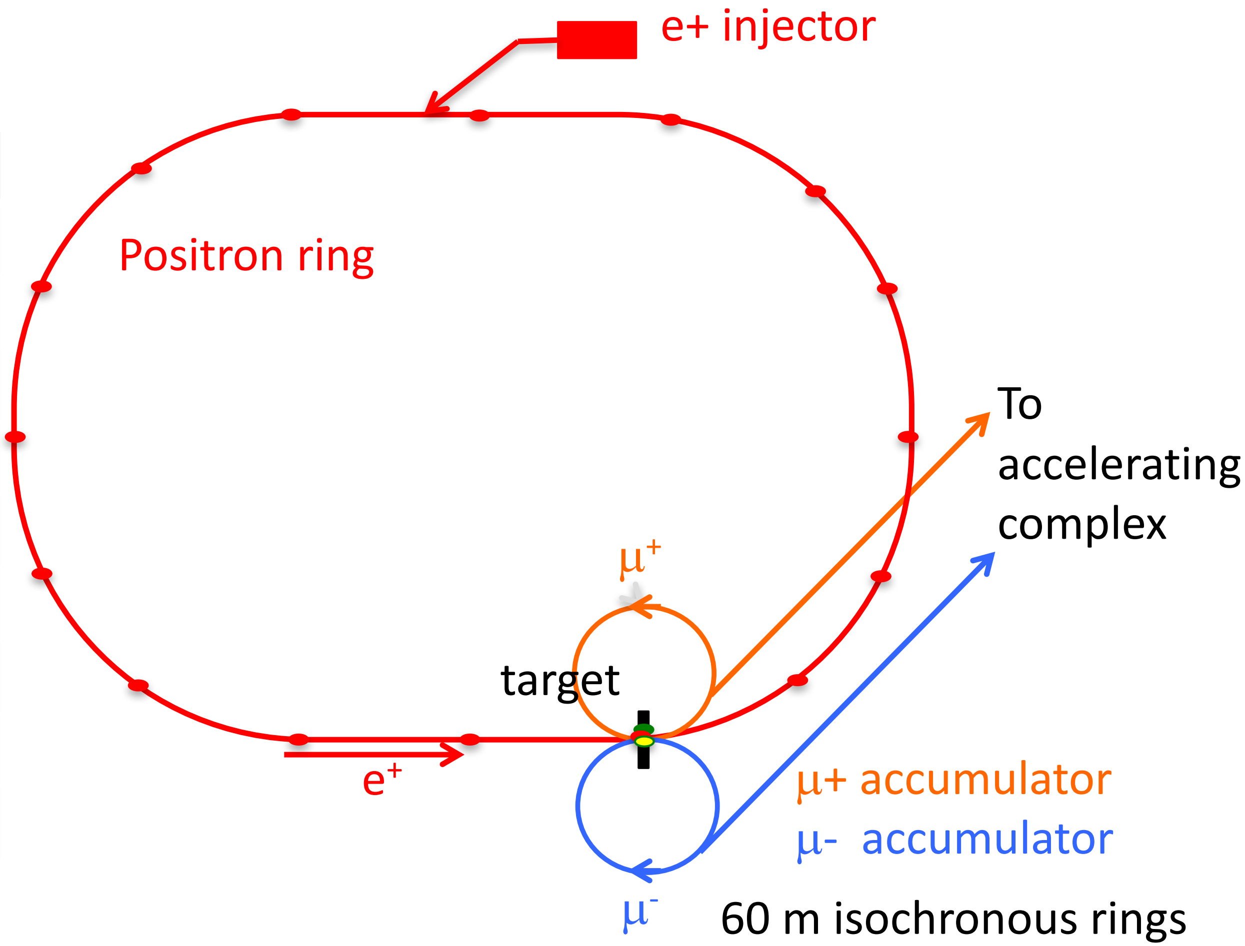
[Geant4]



[Geant4]

Schematic Layout for muon source from e+

Circumference	6 km
ρ	0.6 km
number e+ bunches	100
e+ bunch spacing	200 ns
Beam current	240 mA
e+ Particles/bunch	$3 \cdot 10^{11}$
Rate e+ on target	$1.5 \cdot 10^{18}$ e^+/s
U_0	0.58 GeV
P_{tot}	139 MW
B	0.245 T



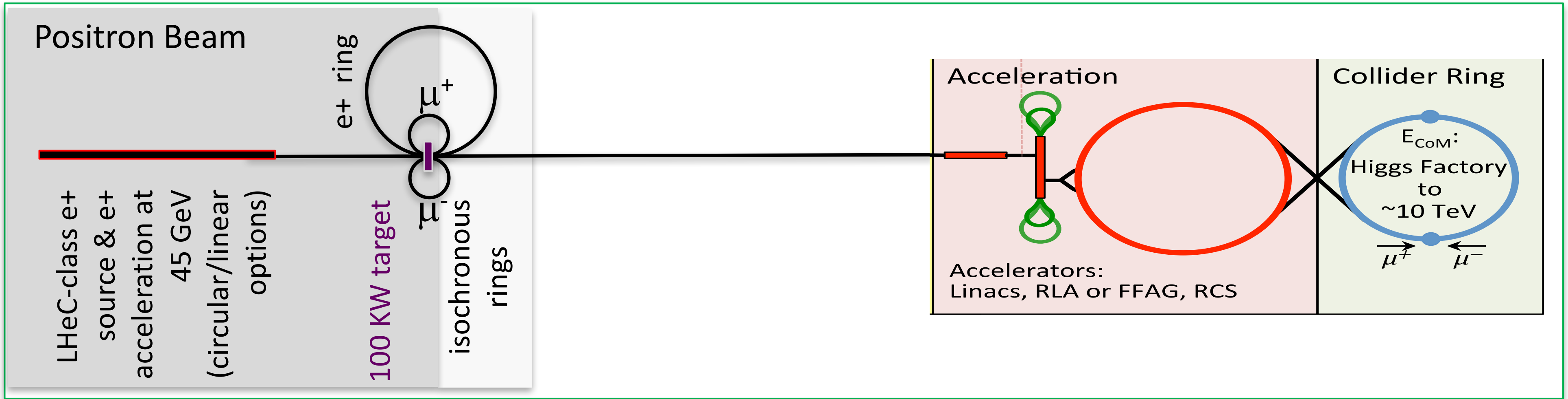
60 m isochronous rings recombine bunches for ~ 1 τ_μ^{lab} ~2500 turns

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

Key point:

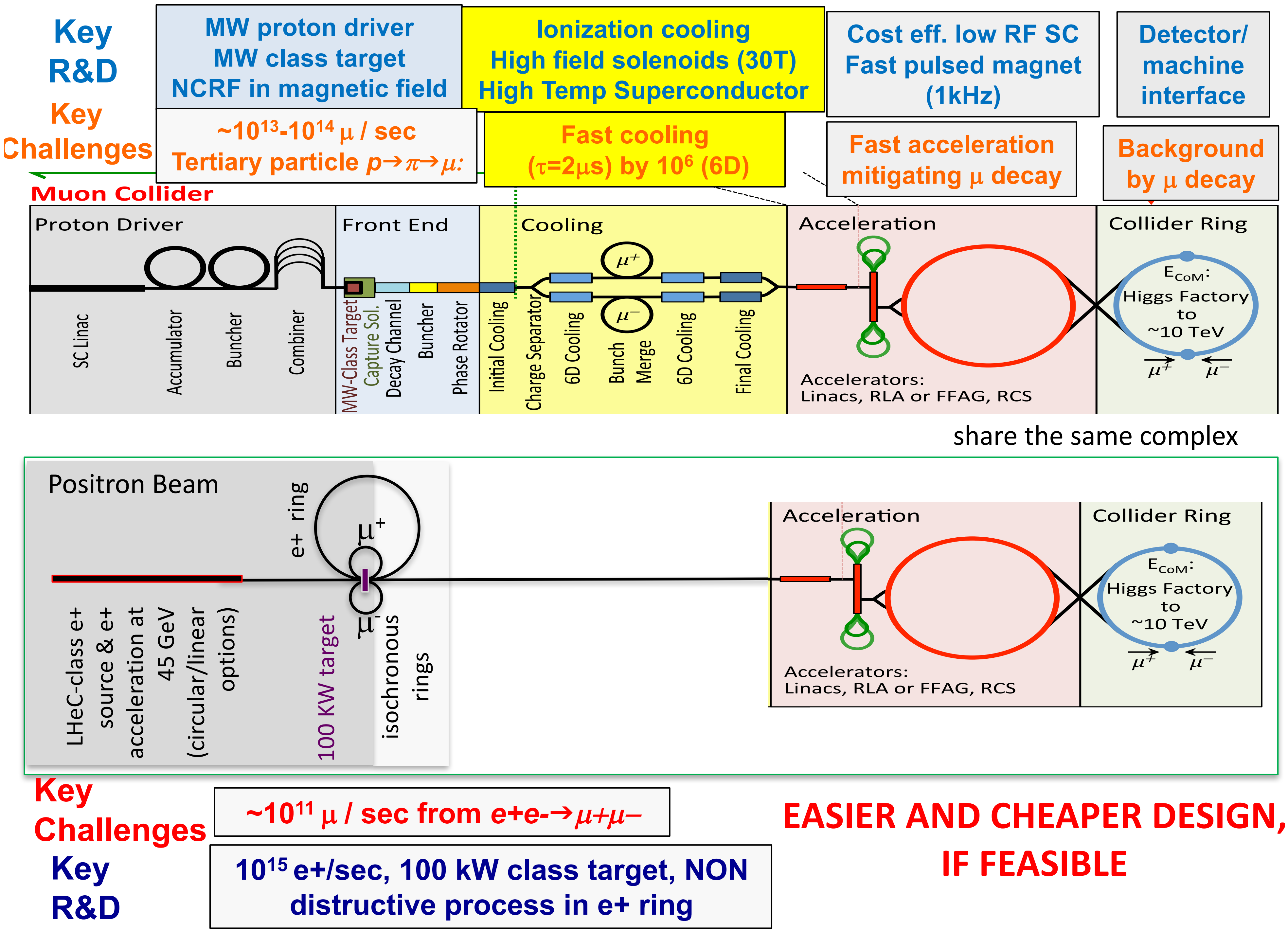
Positron source requirements strictly related to the e^+ ring momentum acceptance

Muon Collider:
Schematic Layout for positron based muon source



Key Challenges — ~10^{11} μ / sec from $e^+e^- \rightarrow \mu^+\mu^-$

Key R&D — 10^{15} e+/sec, 100 kW class target, NON distructive process in e+ ring


Key R&D
Key Challenges
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
~10^{13}-10^{14} μ / sec
Tertiary particle $p \to \pi \to \mu$:
Fast cooling
(τ=2μs) by 10^6 (6D)
Fast acceleration mitigating μ decay
Background by μ decay
Muon Collider
Proton Driver
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
e+ ring
μ+
μ-
LHeC-class e+ source & e+ acceleration at 45 GeV (circular/linear options)
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 $e^+e^- \to \mu^+\mu^-$
Key R&D
10^{15} e+/sec, 100 kW class target, NON distructive process in e+ ring
EASIER AND CHEAPER DESIGN, IF FEASIBLE

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.

Low EMittance Muon Accelerator Draft Parameters

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

Of course, a design study is needed to validate this table

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

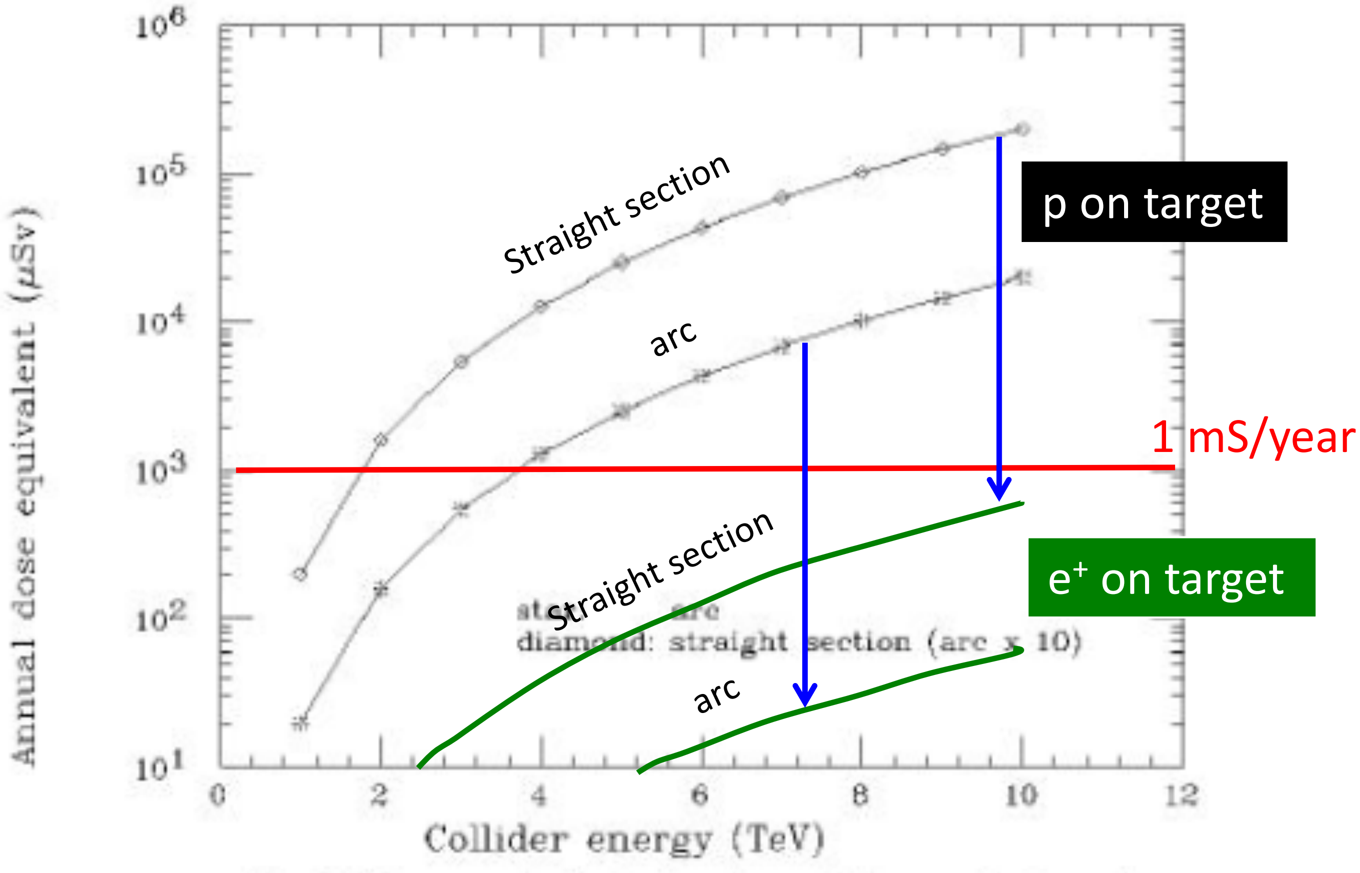


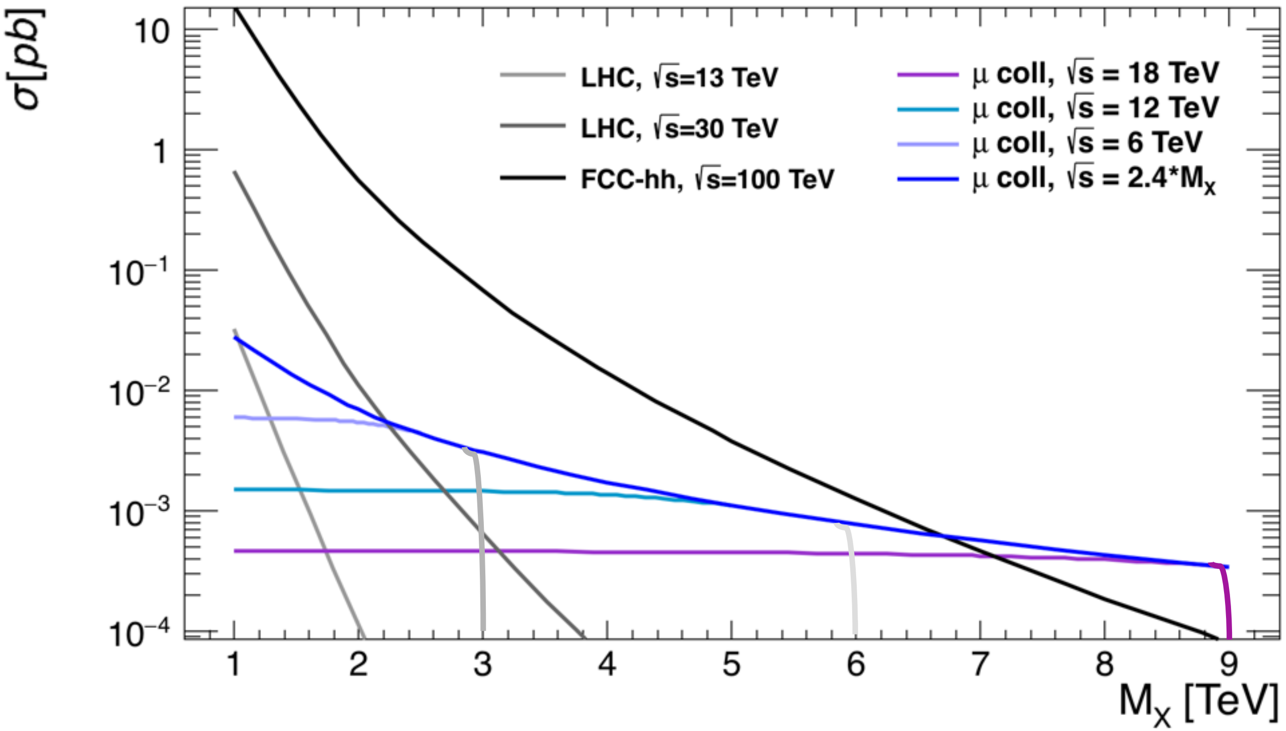
Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

muon rate: p on target option 3 10^{13} μ/s

e^+ on target option 9 10^{10} μ/s

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]

Key Feasibility Issues

Positron Source

Muon Target

Positron Ring

HIGH rate

Non destructive

Mom. acceptance

Targets survival

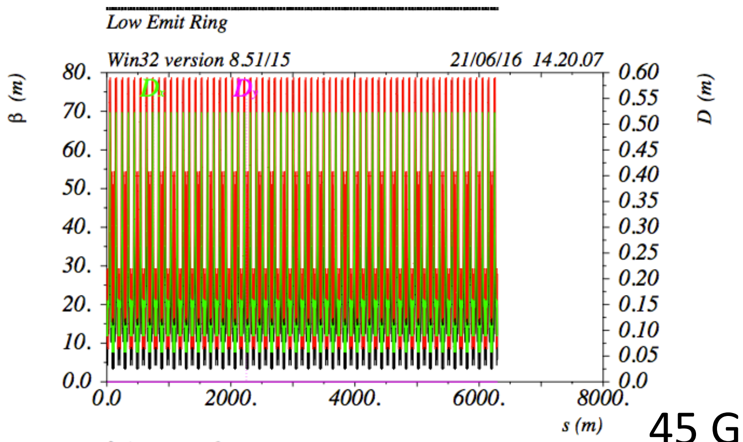
NEED
deep investigation
(design study)

- μ Acceleration
- Collider Ring
- Collider MDI
- Collider Detector

(mostly) independent on muon source
Benefit from MAP studies

LEMMA at the staring line

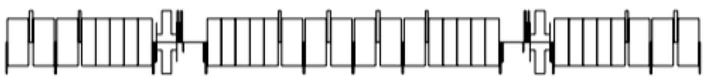
First Optics for e^+ ring

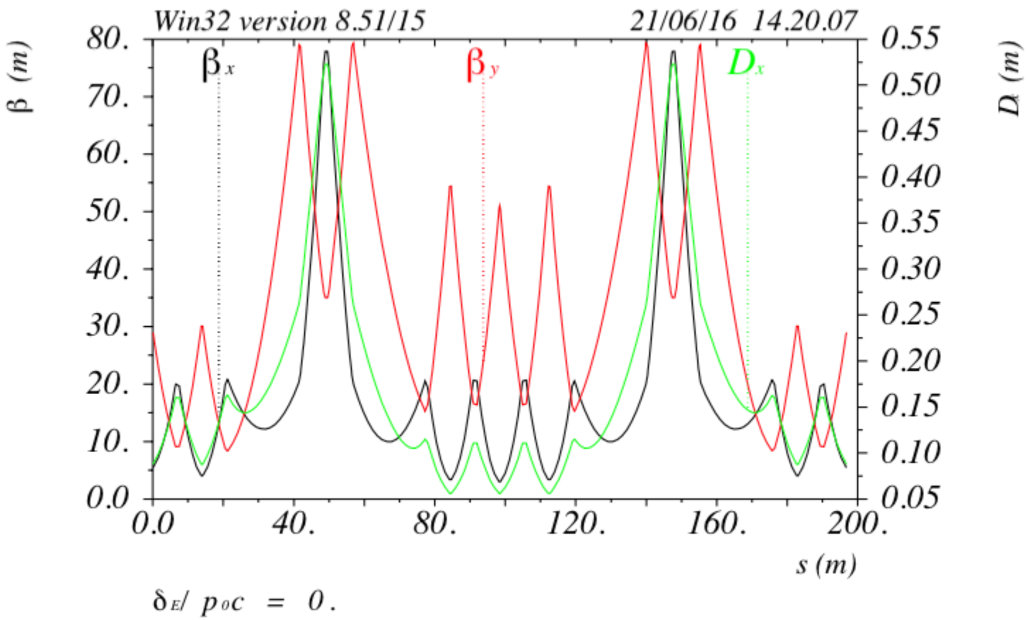


45 GeV

6.3 km

32 cells of 197m

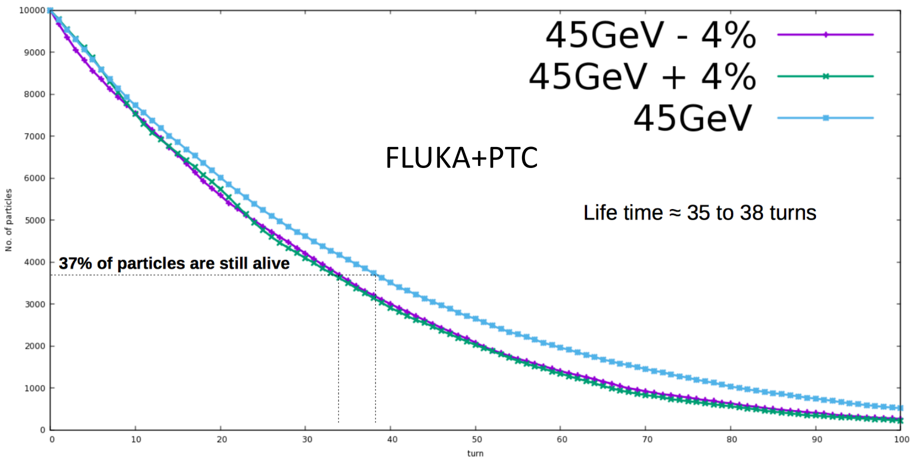




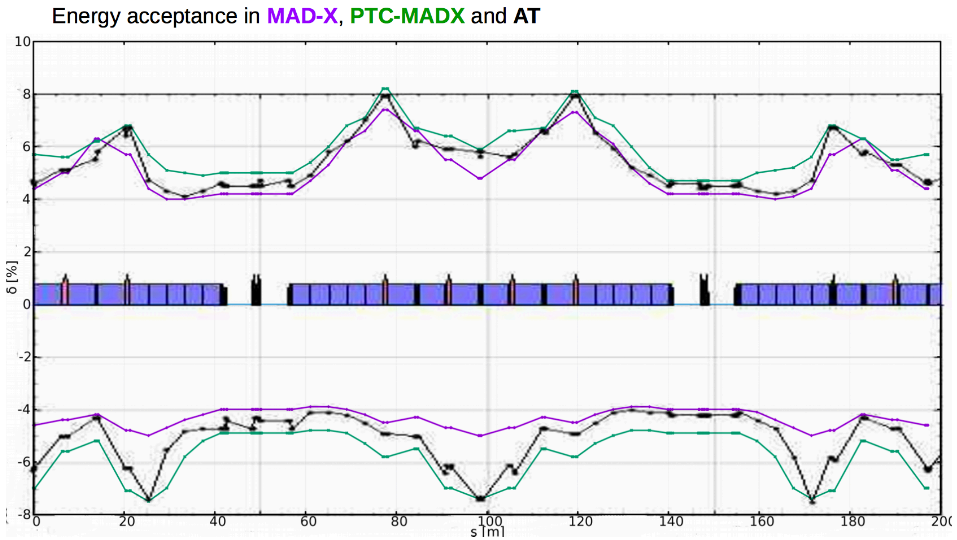
		pos_Ring
Parameter	Units	e+
Energy	GeV	45
Circumference	m	6300
Bending radius	m	709.6
Magnetic rigidity	T m	150
Lorentz factor		88062.62
Coupling (full current)	%	1
Emittance x (from model)	m	5.73E-09
Emittance y	m	5.73E-11
Bunch length (zero current)	mm	3.6
Beam current	mA	240
RF frequency	Hz	5.00E+08
RF voltage	GV	0.768
Revolution frequency	Hz	4.76E+04
Harmonic number	#	10508
Revolution period	s	2.10E-05
Number of bunches	#	100
N. Particle/bunch	#	3.15E+11
Syncronous phase	#	0.73
Syncrotron frequency	Hz	2415.31
Synchrotron tune	#	5.08E-02
synchrotron period	turns	19.70
Overvoltage		1.50
Transverse damping time	turns	175.00
Transverse damping time	s	0.0037
Longitudinal damping time	turns	87.50
Longitudinal damping time	s	1.84E-03
Energy Loss/turn	GeV	0.511
Momentum compaction		1.21E-04
B field	T	0.211
Rf energy acceptance	%	3.98
Energy spread (SR)	dE/E	1.00E-03
SR power loss	GW	0.12
SR power/Circumference	kW/m	19.48

First multi turn simulations (still very preliminary)

Use different methods: AT/PTC/MADX (optics)+ GEANT/FLUKA (target)



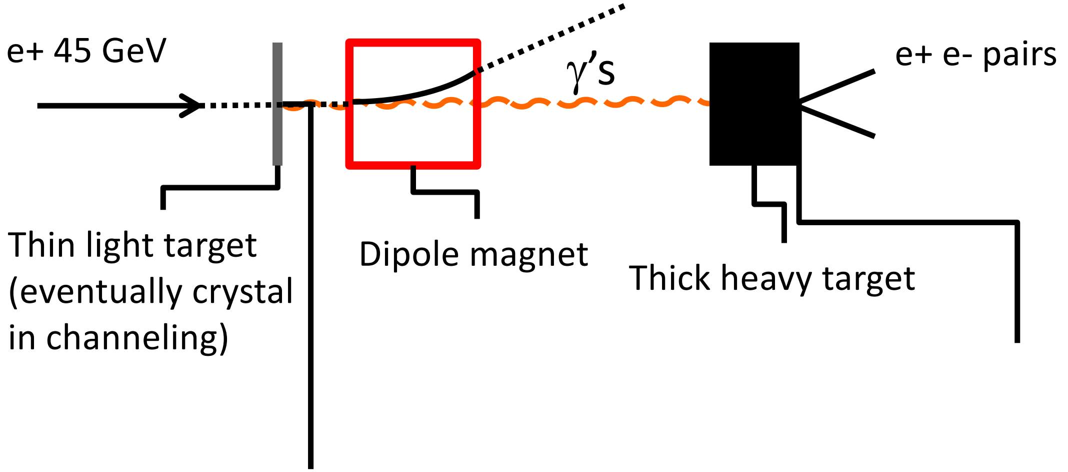
Results from other combinations within 10%



- Dedicated “interaction” region under study to decrease losses and beam size increase
- Emittance contribution from various sources have to be matched
- Optimize momentum aperture
- Design muon accumulator rings

Embedded positron source?

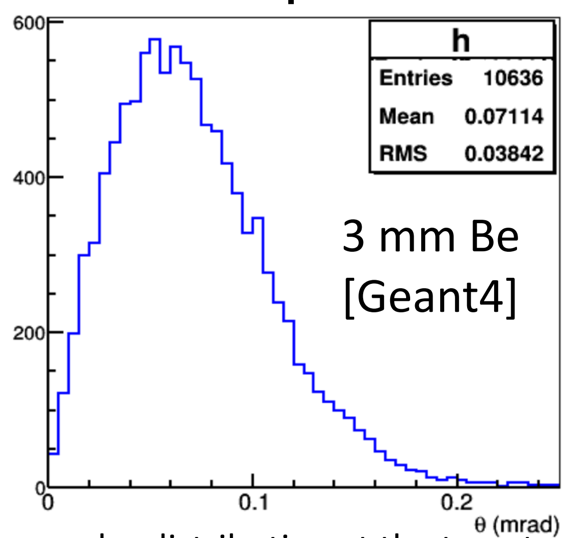
Positron source extending the target complex?
Possibility to use the γ's from the μ production target to produce e+



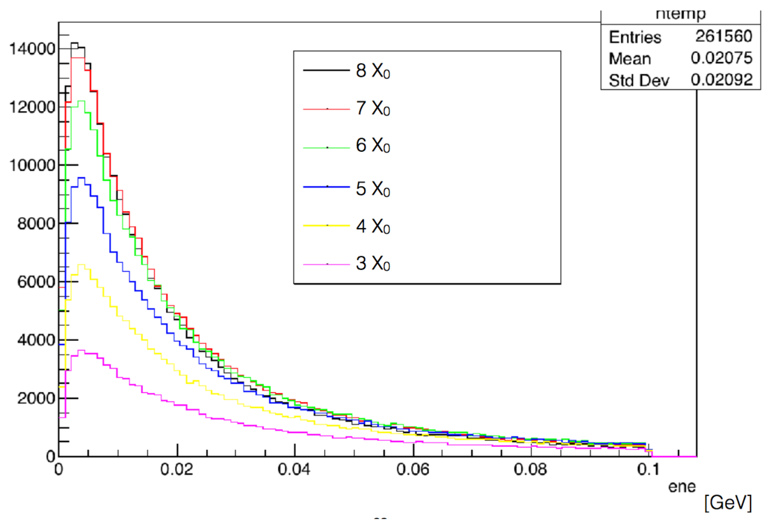
Positron collection
based on Adiabatic Matching Device
under study

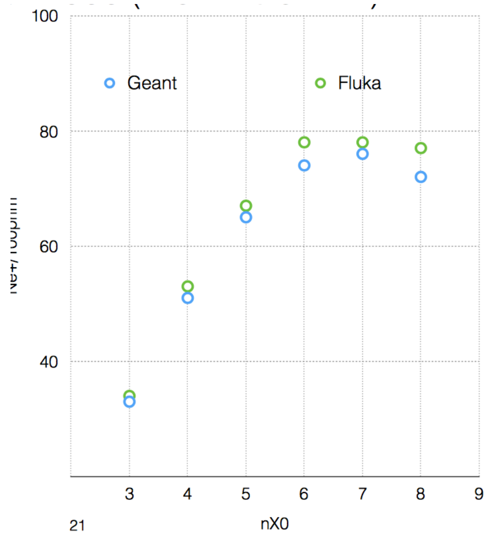
Proposed for example for CLIC

Produce a fraction of e+
of the incoming positron beam



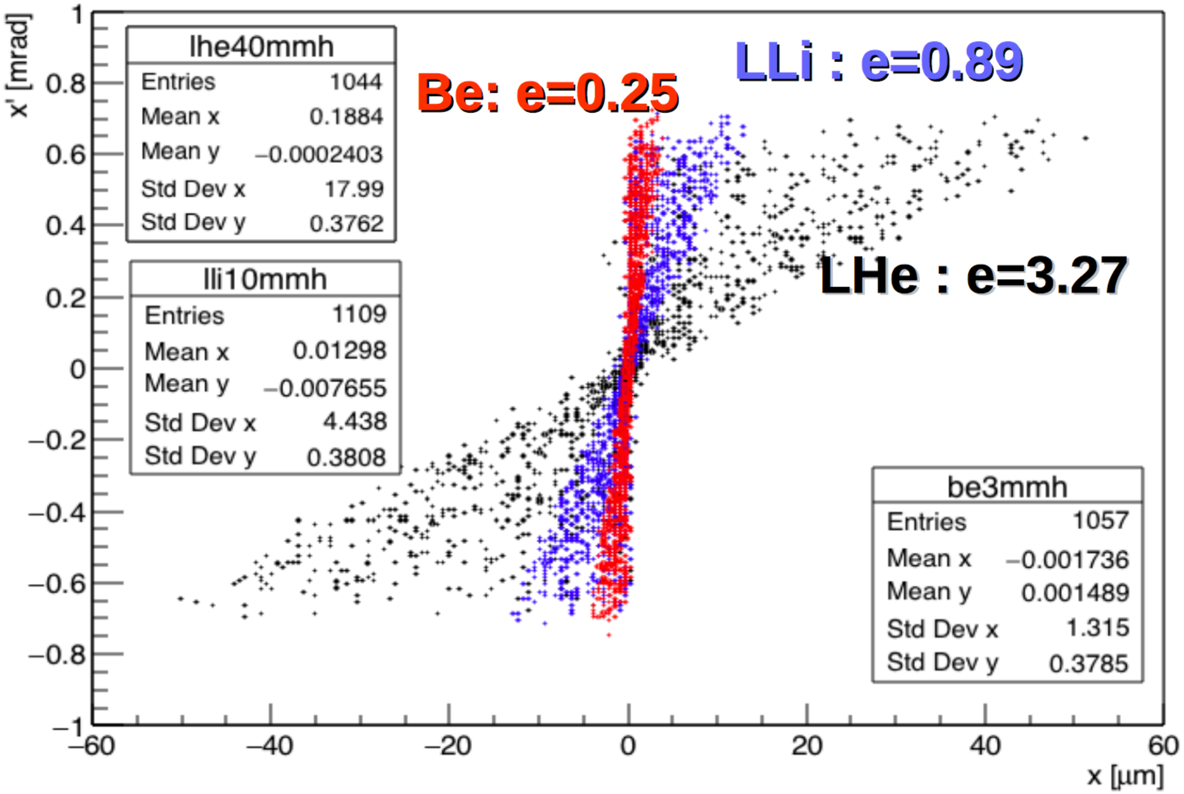
γ's angular distribution at the target exit



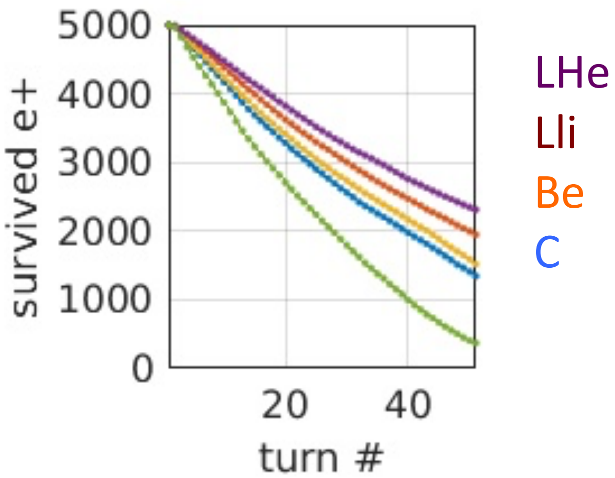


Going to lighter targets for μ production

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



LLi might be a good option



Proposed/tested for targets for n production

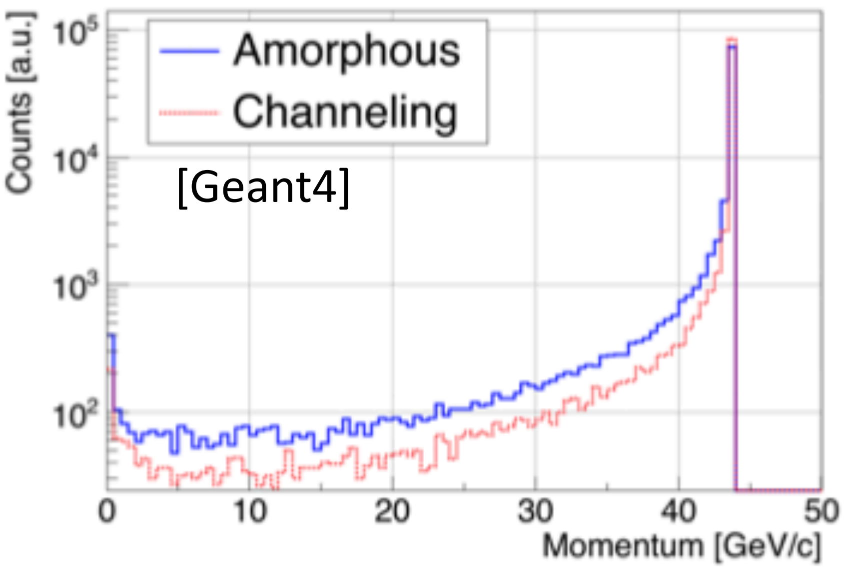
High Boiling point 1615 K
Mass evaporation?
Safety?

Crystals as a target ?

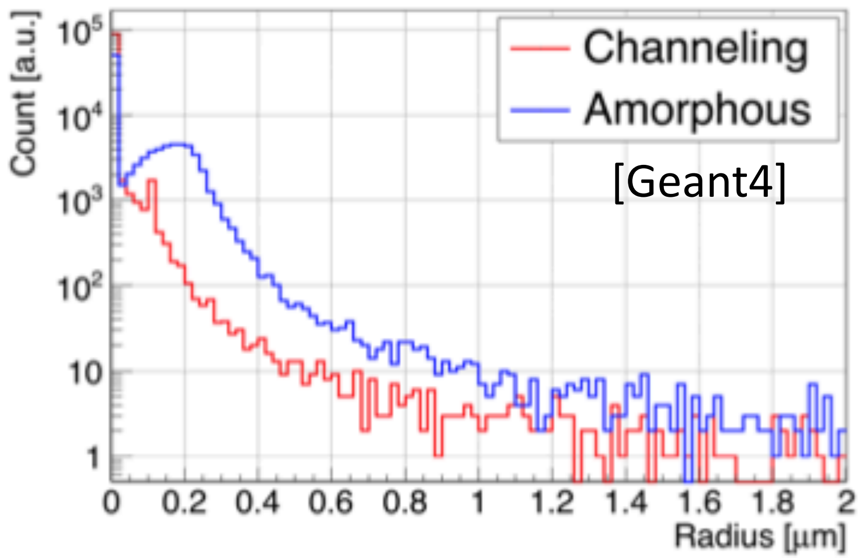
Positrons

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

Momentum



Position



Tests with e^+ beam

Use tertiary 45 GeV e^+ beam in CERN North area (H4)
(ask for 2 weeks of beam time for next year)

- Low intensity (one by one e^+ tracking) with crystals and amorphous targets:

  measure beam degradation (emittance energy spectrum)

  measure produced photons flux and spectrum

- High intensity (up to 5 x 10^6 /spill) with amorphous targets:

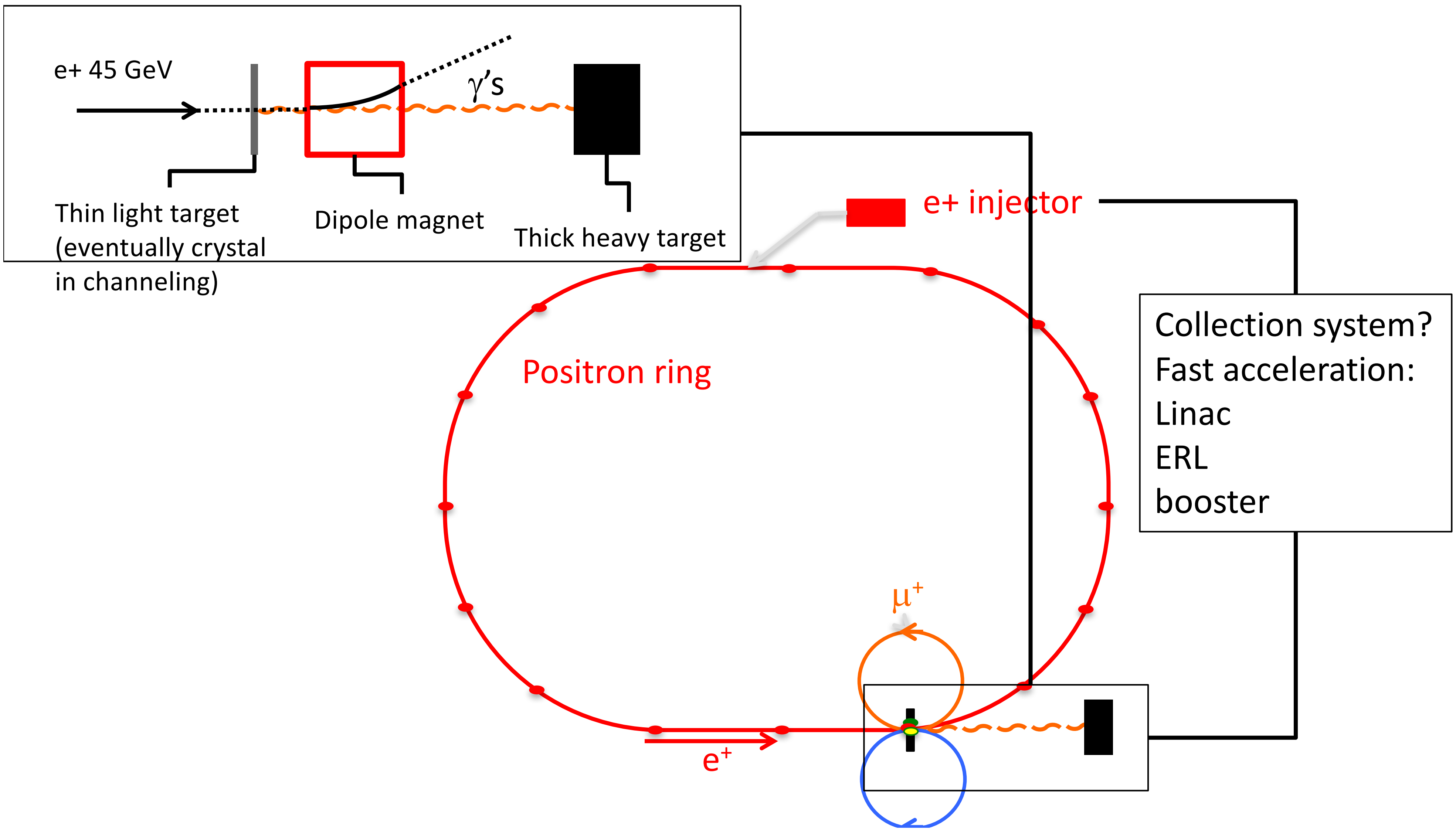
  measure muon production rate and muons kineamatic properties

Conclusion

- Very low emittance muon beams can be obtained by means of positron beam on target
- Low emittance would allow to extend the center of mass energy
- interesting muon rates require:
  - Challenging positron source (synergy with LHeC/FCC-eh, ILC,…)
  - Positron ring with high momentum acceptance (synergy with next generation SL sources and FCC-ee)
  - Thin targets surviving to ~100 KW
- We are working on all these issues
- fast muon acceleration concepts and collider rings design studied by MAP

Backup Slides

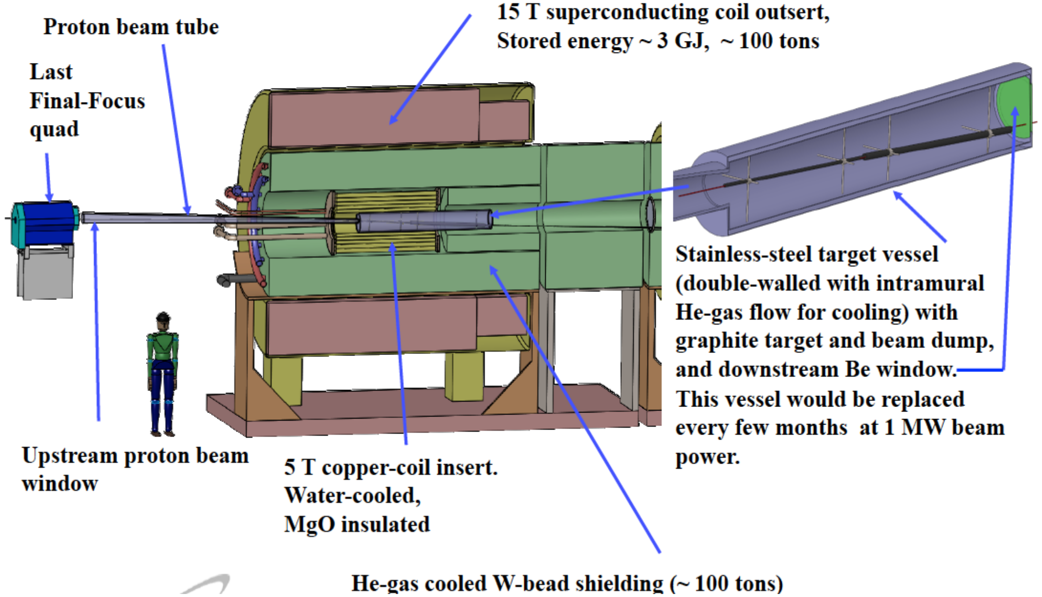
Embedded positron source?



MAP muon generation by Proton driver

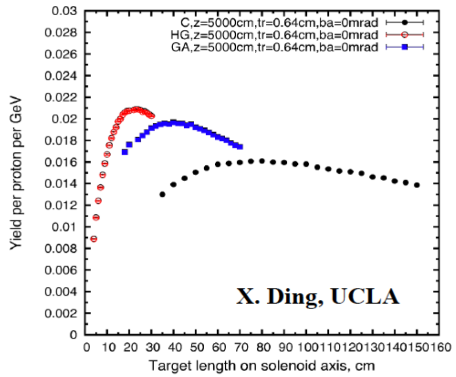
H.Kirk (BNL)

A Graphite Target Core



- MW-Class proton driver at ~5-10 GeV
- Capture solenoid system (μ^+ & μ^-)
  - 15 T outsert, 5 T insert
  - ~3GJ stored energy

Choice of Target Materials II



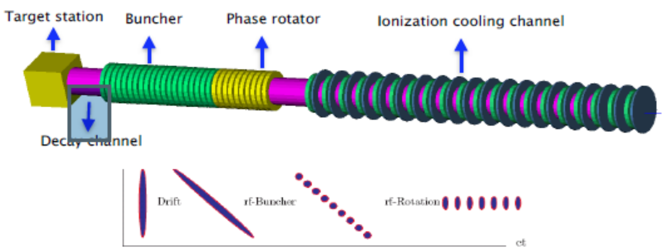
- High Z (e.g. Hg)
- Mid Z (e.g. Ga)
- Low Z (e.g. Carbon)

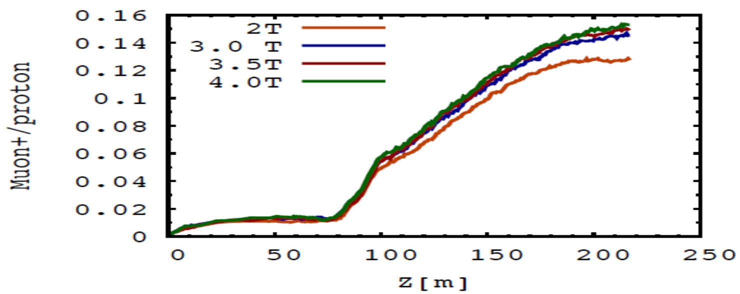
A 25% advantage of using high-Z Hg compared to low-Z Carbon
Low-z Carbon is attractive due to it's simplicity and robustness

Proton Beam: KE = 6.75 GeV
Normalization: For Hg $\Sigma(\mu^+ + \mu^-)$/proton ≈ 1

- Initial operation with 1MW carbon target
- Upgrade to multi-MW with Liquid Metal Jet Technology (demonstrated in MERIT Experim.)

H.K.Sayed (BNL)

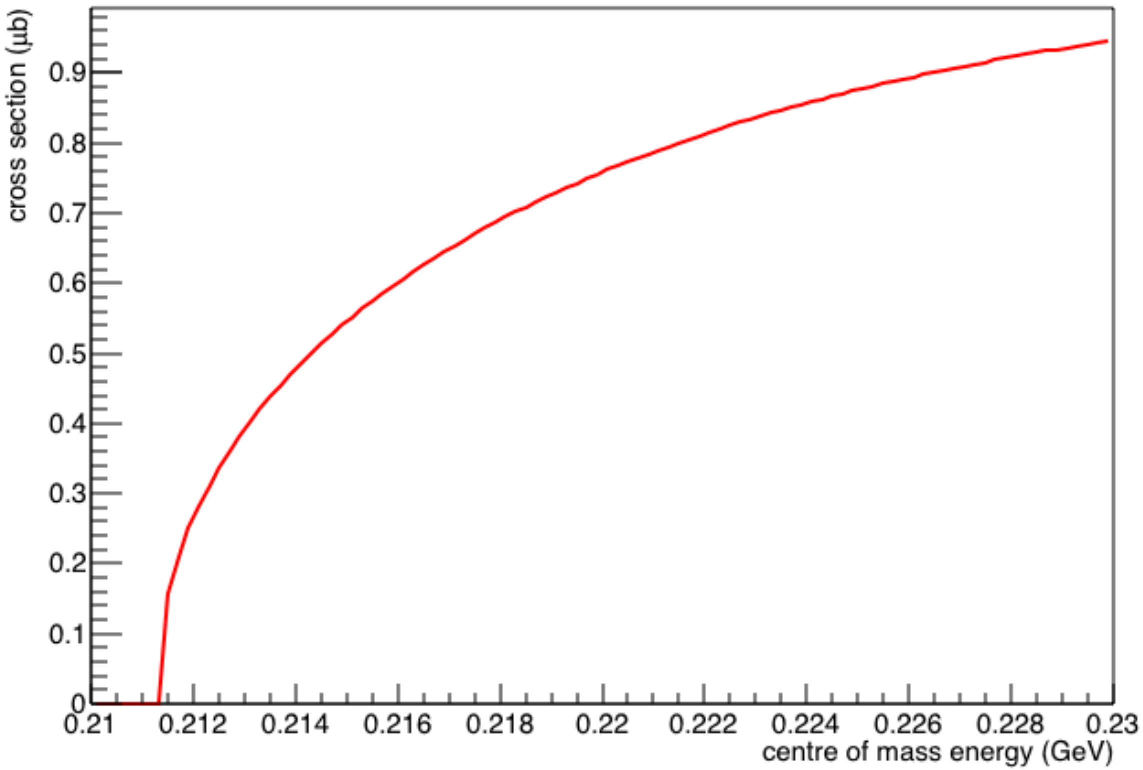




Muon per proton production at Front End exit

Processes at √s around 0.212 GeV

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

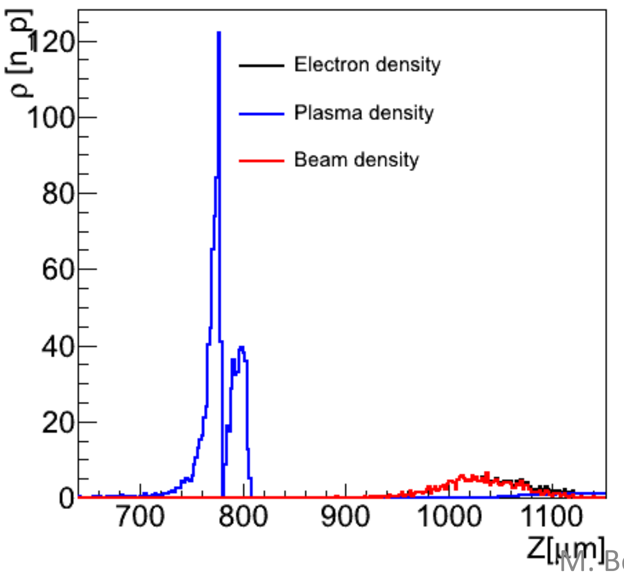


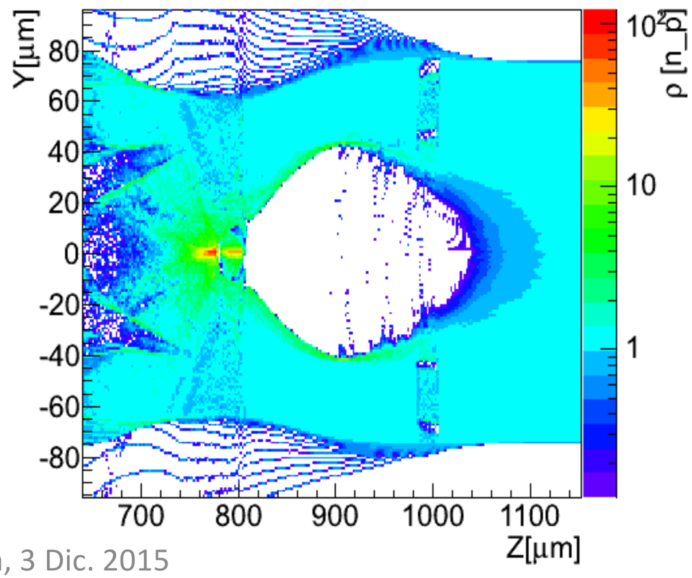
Muonium production also investigated:
  huge cross section (mb range)
  10^{-4} eV width

Not viable…. Deeper studies?

Few statements on the plasma option

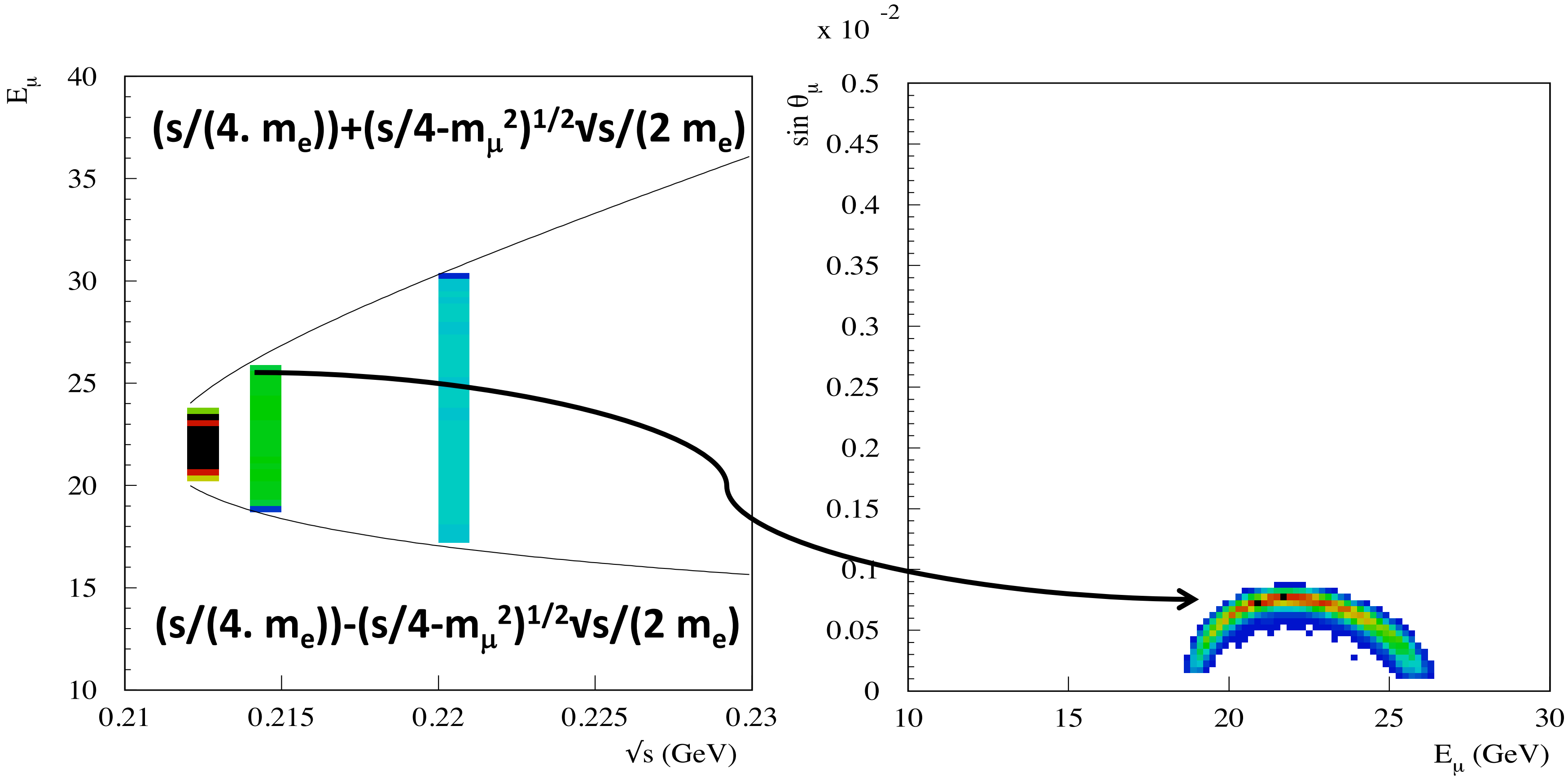
- Plasma would be a good approximation of an ideal electron target ++ autofocussing by Pinch effect
- enhanced electron density can be obtained at the border of the blow-out region (up x100)
- Simulations for $n_p = 10^{16}$ electrons/cm^3 (C. Gatti, P. Londrillo)
- Region size decreases with $1/\sqrt{n_p}$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





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

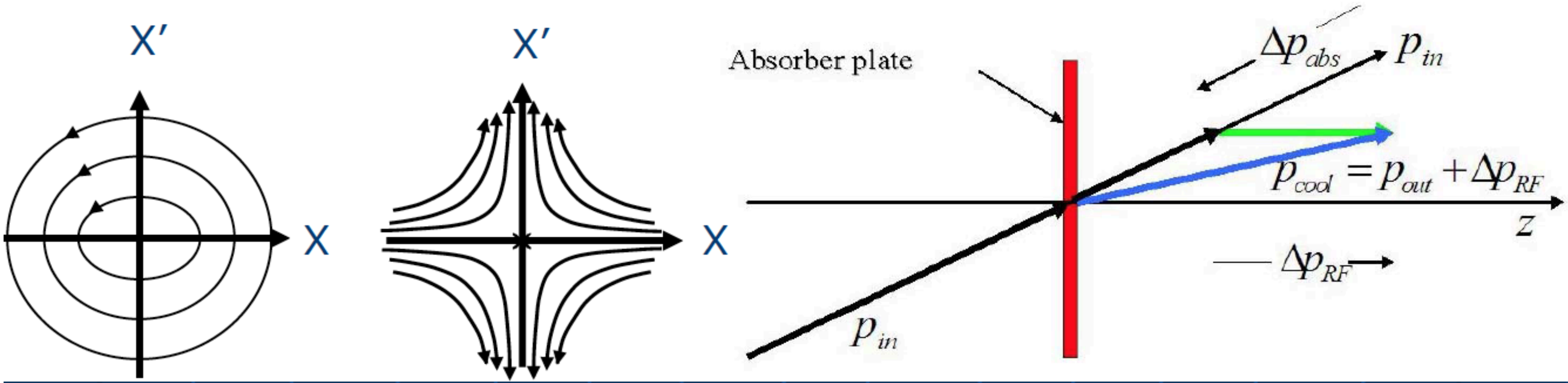
$e^+e^- \rightarrow \mu^+\mu^-$ muons energy spread:



Parametric-resonance Ionization Cooling
see Derbenev, Johnson, Beard

Excite ½ integer parametric resonance (in Linac or ring)
- Like vertical rigid pendulum or ½-integer extraction
- Elliptical phase space motion becomes hyperbolic
- Use xx′=const to reduce x, increase x′
- Use IC to reduce x′

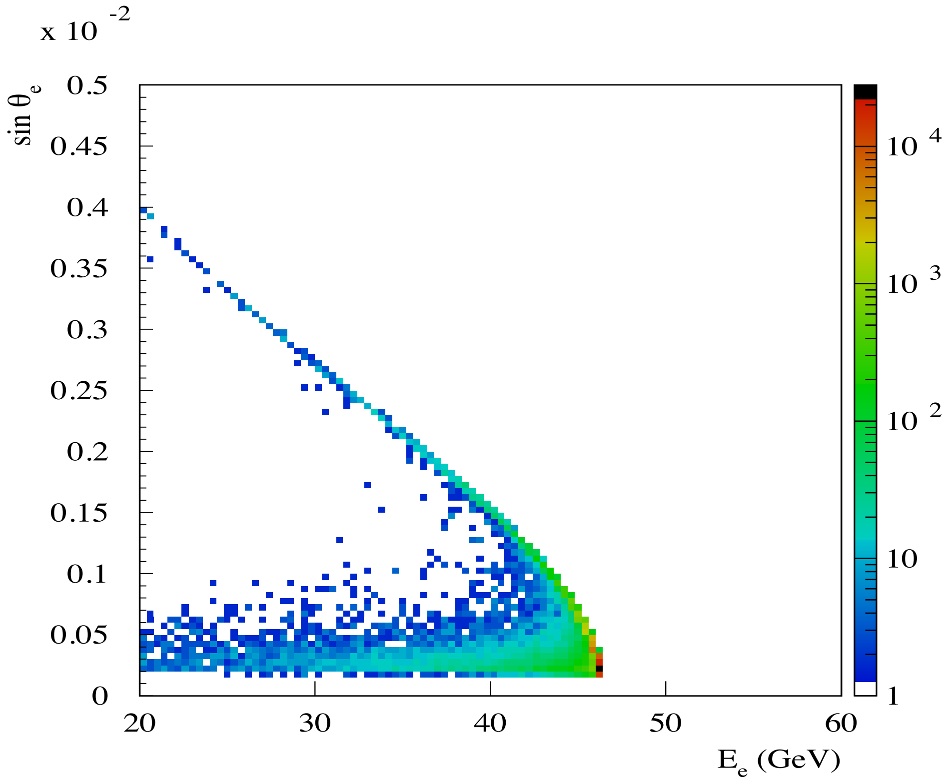
Detuning issues being addressed (chromatic and spherical aberrations, space-charge tune spread). Simulations underway. New progress by Derbenev.



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

$e^+e^- \rightarrow e^+ e^-(\gamma's)$ is the dominant process

- Babayaga for "large" angles and
- BBBrems for collinear (dominant σ ~ 150 mb, $\delta E/E<2\%$)



Positron sources: studies on the market

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

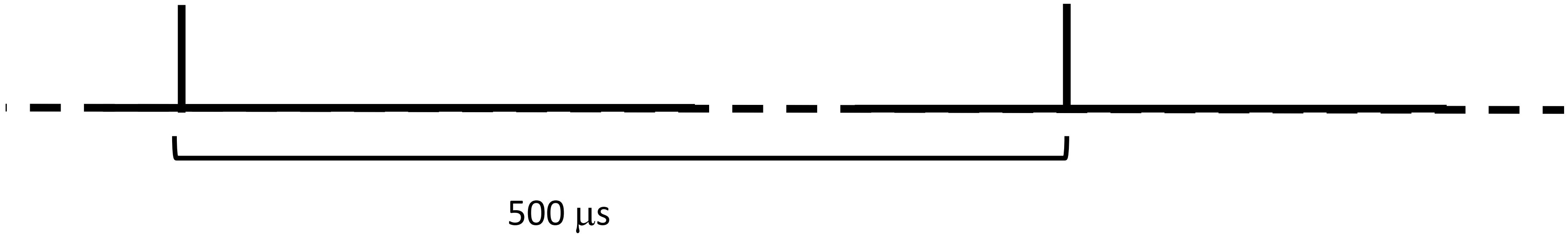
In [F. Zimmermann, et al., '**POSITRON OPTIONS FOR THE LINAC-RING LHEC',** WEPPR076 Proceedings of IPAC2012, New Orleans, Louisiana, USA]

	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

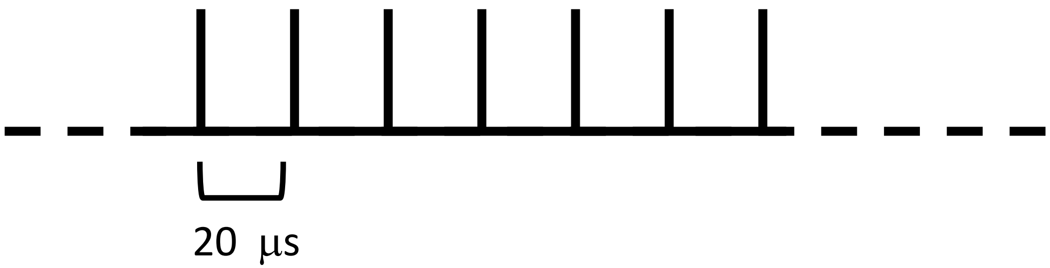
➢ <u>This is the most critical issue</u>

rebunching at 6 TeV

bunch structure from production



bunch structure at collider



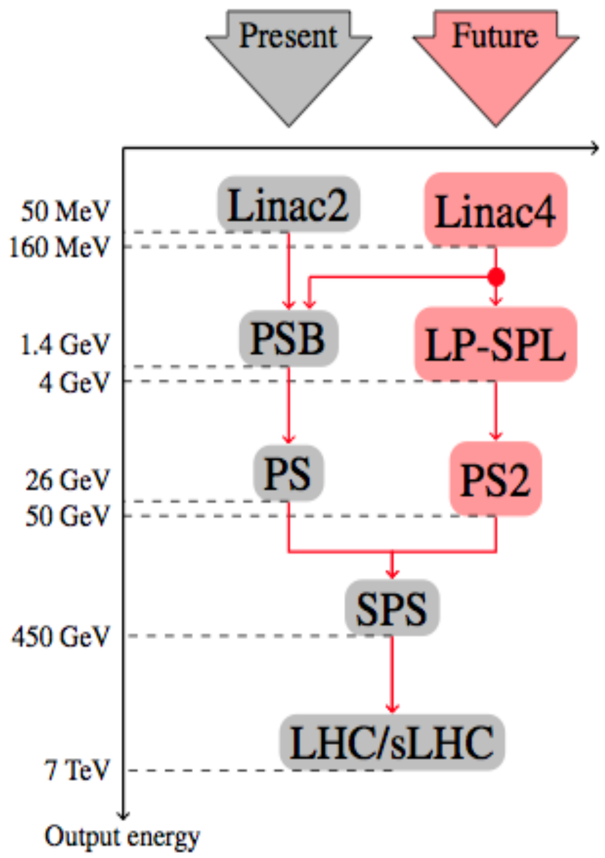
perform continuous injection every 500 μs

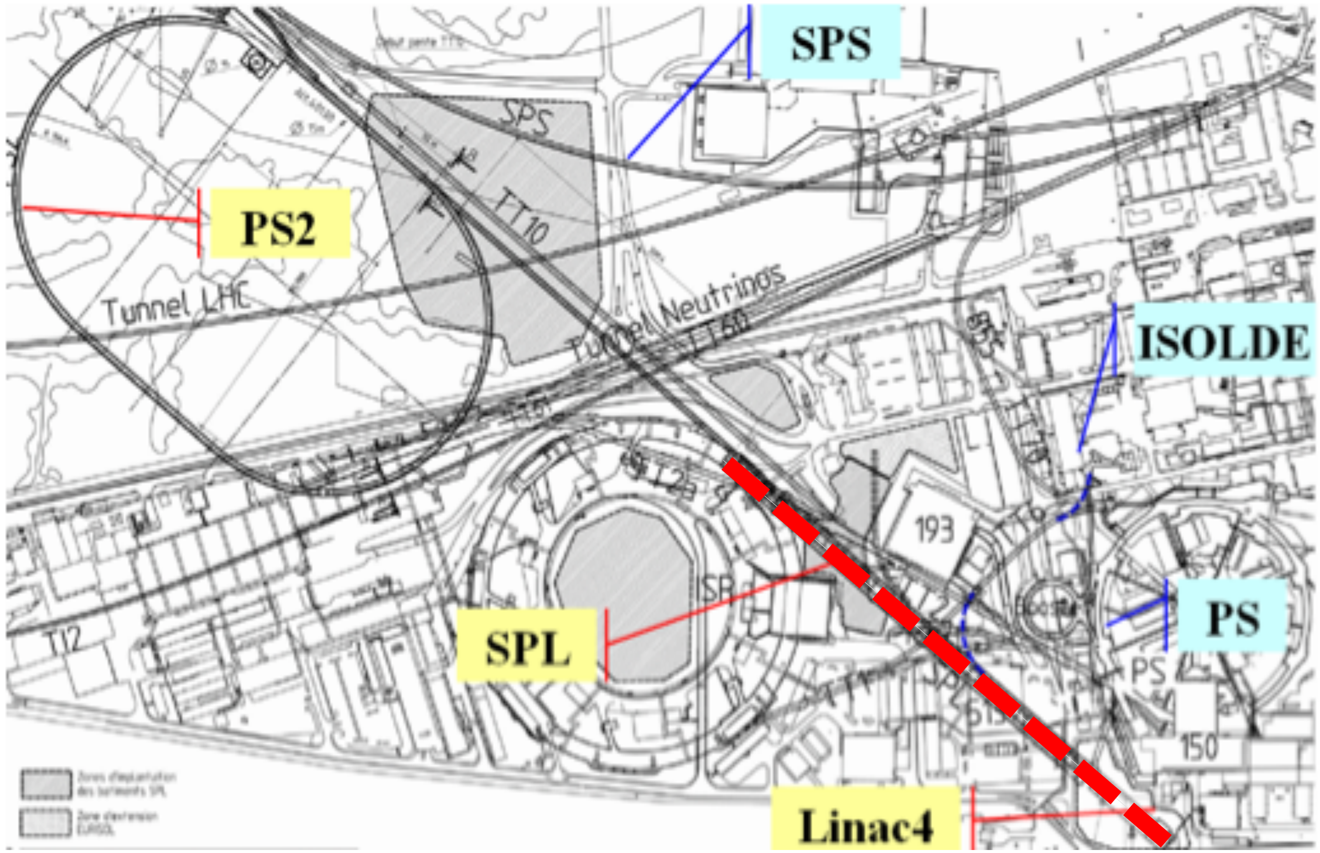
rebunch effective for ~ 1 muon lifetime 66 ms (factor 66/0.5)

no damping -> fill transverse phase space maintaining lumi increase

Future accelerators programs at CERN

- A new LHC injector complex to increase the collider luminosity 10x with the High Luminosity LHC (HL-LHC)).
- Two accelerators (the LP-SPL and a new 50 GeV synchrotron, PS2) would replace the three existing ones (Linac2, the PSB, and the PS), with the injection of the SPS at 50 GeV,

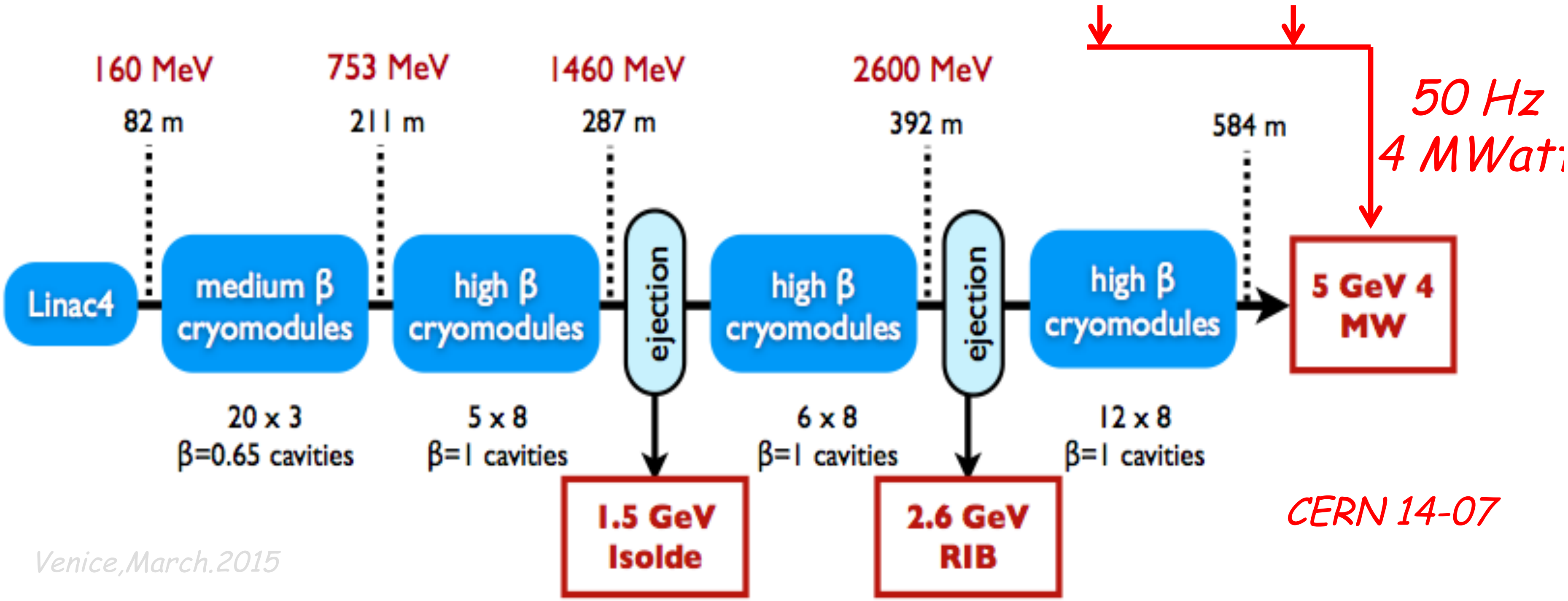




CERN-SPL parameters

- Layout of superconducting SPL with intermediate extractions.
- SPL design is very flexible and it can be adapted to the needs of many high-power proton beam applications.

Parameter	Units	HP-SPL		LP-SPL
		Low-current	High-current	
Energy	GeV	5	5	4
Beam power	MW	4	4	0.144
Repetition rate	Hz	50	50	2
Average pulse current	mA	20	40	20
Peak pulse current	mA	32	64	32
Source current	mA	40	80	40
Chopping ratio	%	62	62	62
Beam pulse length	ms	0.8	0.4	0.9
Protons per pulse	10^{14}	1.0	1.0	1.13



CERN 14-07

A muon based Higgs factory at CERN

- A muon cooled Higgs factory can be easily housed within CERN
- The new 5 GeV Linac will provide at 50 c/s a multi MWatt H- beam with enough pions/muons to supply the muon factory.
- The basic additional accelerator structure will be the following:
  - Two additional small storage rings with R ≈ 50 m will strip H- to a tight p bunch and compress the LP-SPL beam to a few ns.
  - Muons of both signs are focused in a axially symmetric B = 20 T field, reducing progressively pt with a horn and B = 2 T
  - A buncher and a rotator compresses muons to ≈ 250 MeV/c
  - Muon Cooling in 3D compresses emittances by a factor 106.
  - Bunches of about 2x1012 m± are accelerated to 62.5 GeV
  - Muons are colliding in a SC storage ring of R ≈ 60 m (about one half of the CERN-PS ,1/100 of LHC) where about 104 Higgs events/y are recorded for each of the experiments.

Staged Neutrino Factory and Muon Colliders

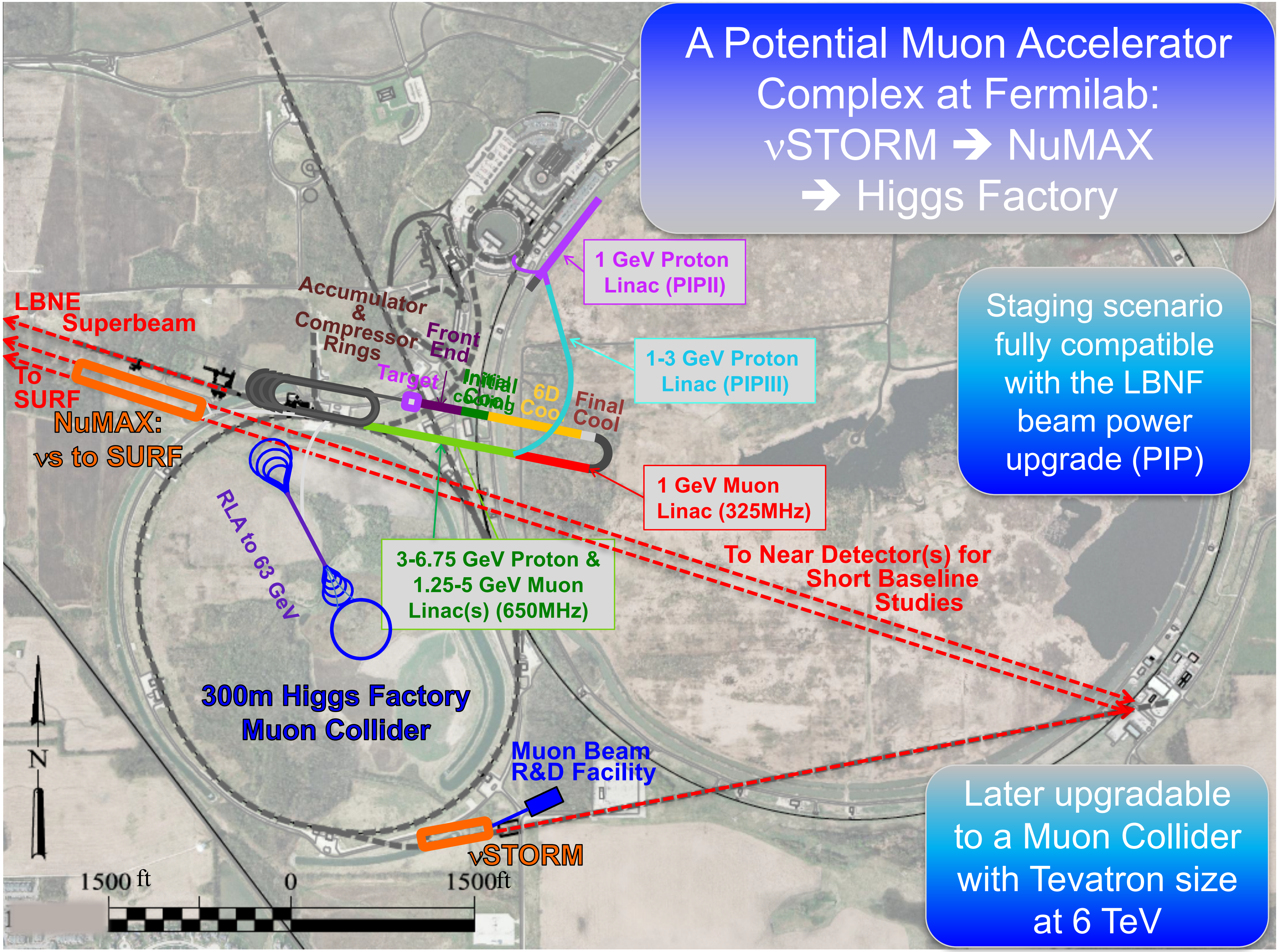
Increasing complexity and challenges / main parameters

Neutrino Factory at intensity frontier

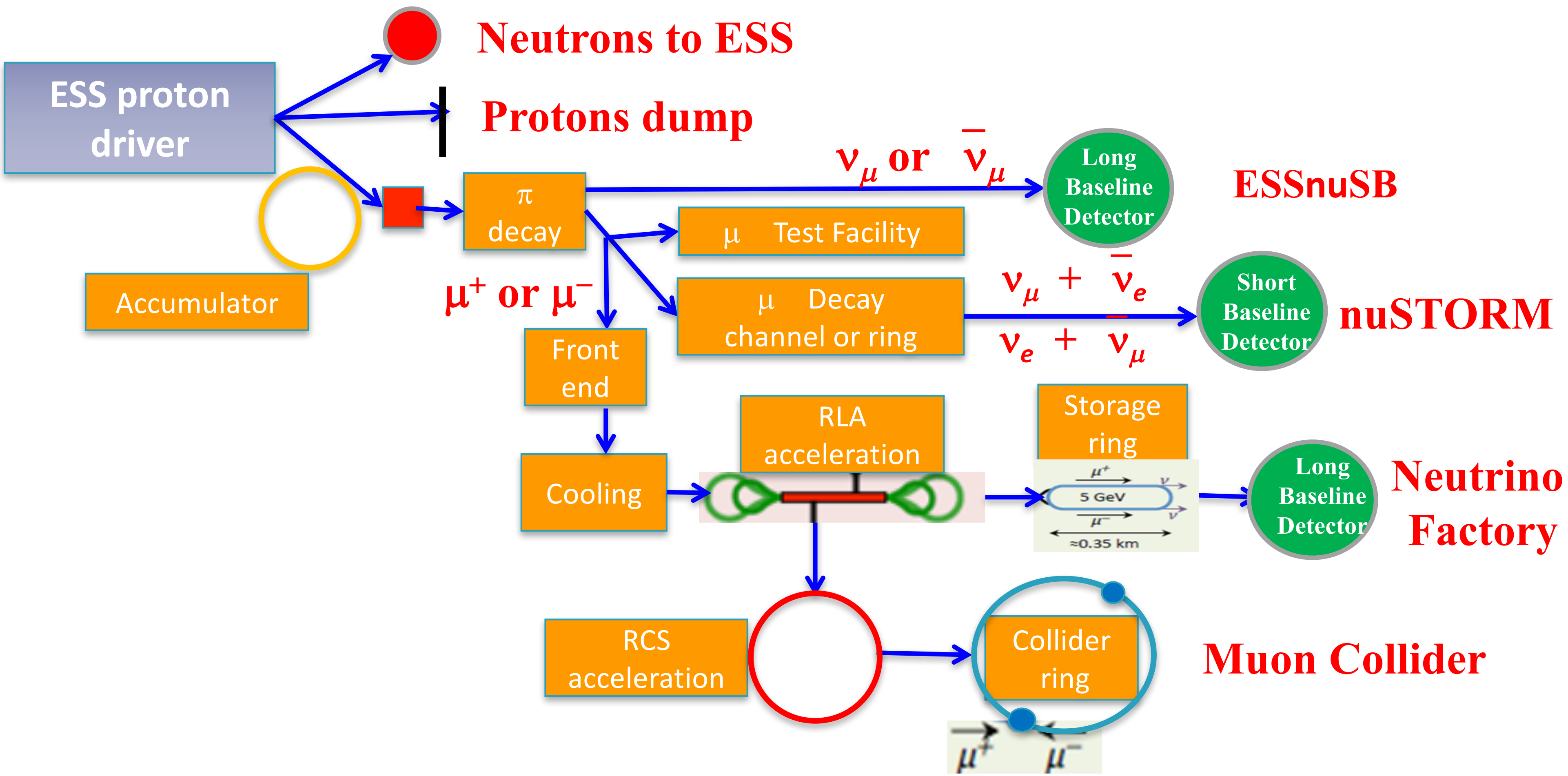
System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Performance	ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
	Stored μ+ or μ-/year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
Detector	*Far Detector:*	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND / Mag LAr
	Distance from Ring	km	1.9	1300	1300	1300
	Mass	kT	1.3	100 / 30	100 / 30	100 / 30
	Magnetic Field	T	2	0.5-2	0.5-2	0.5-2
	Near Detector:	Type	SuperBIND	Suite	Suite	Suite
	Distance from Ring	m	50	100	100	100
	Mass	kT	0.1	1	1	2.7
	Magnetic Field	T	Yes	Yes	Yes	Yes
Neutrino Ring	Ring Momentum	GeV/c	3.8	5	5	5
	Circumference (C)	m	480	737	737	737
	Straight section	m	184	281	281	281
	Number of bunches	-		60	60	60
	Charge per bunch	1×10^{9}		6.9	26	35
Acceleration	Initial Momentum	GeV/c	-	0.25	0.25	0.25
	Single-pass Linacs	GeV/c	-	1.0, 3.75	1.0, 3.75	1.0, 3.75
		MHz	-	325, 650	325, 650	325, 650
	Repetition	Hz	-	30	30	60
Cooling			No	No	Initial	Initial
Proton Driver	Proton Beam Power	MW	0.2	1	1	2.75
	Proton Beam	GeV	120	6.75	6.75	6.75
	Protons/year	1×10^{21}	0.1	9.2	9.2	25.4
	Repetition	Hz	0.75	15	15	15

Muon Collider at the energy frontier

		Higgs Factory		Top Threshold Options		Multi-TeV Baselines		
Parameter	*Units*	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top† Production/10^7sec		3,500*	13,500*	7,000†	60,000†	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	4#	4	4	4	4	4	1.6
Cooling		**6D no final**		**Full 6D**				


A Potential Muon Accelerator Complex at Fermilab:
νSTORM ➔ NuMAX ➔ Higgs Factory
Staging scenario fully compatible with the LBNF beam power upgrade (PIP)
Later upgradable to a Muon Collider with Tevatron size at 6 TeV
LBNE Superbeam
To SURF
NuMAX: νs to SURF
Accumulator & Compressor Rings
Front End
Target
Initial
6D Coo
Final Cool
1 GeV Proton Linac (PIPII)
1-3 GeV Proton Linac (PIPIII)
1 GeV Muon Linac (325MHz)
3-6.75 GeV Proton & 1.25-5 GeV Muon Linac(s) (650MHz)
RLA to 63 GeV
To Near Detector(s) for Short Baseline Studies
300m Higgs Factory Muon Collider
Muon Beam R&D Facility
νSTORM
N
1500 ft
0
1500ft

ESS neutrino and muons facility



J.P.Delahaye ESS_NuSTORM

Beam characteristics

Main ESS facility parameters concerning the proton beam.

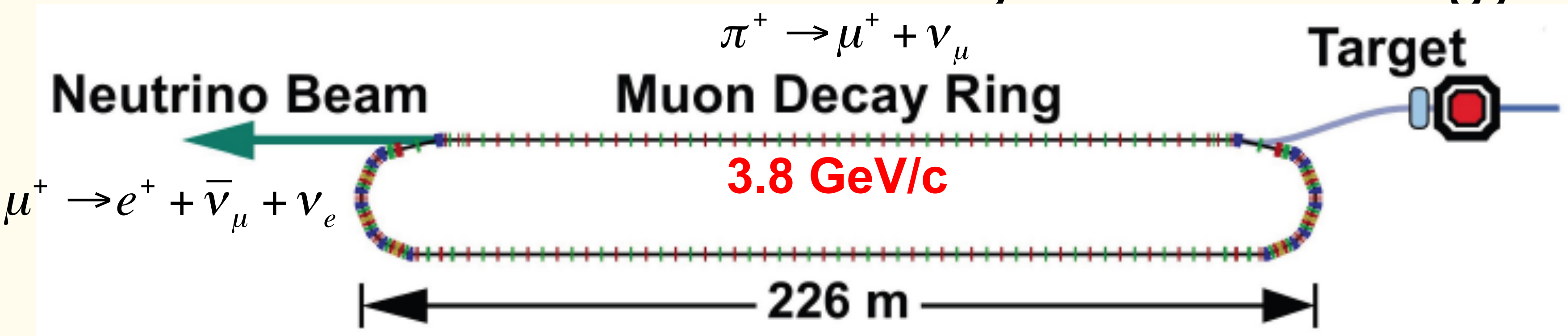
Parameter	Value
Average beam power	5 MW
Proton kinetic energy	2.0 GeV
Average macro-pulse current	62.5 mA
Macro-pulse length	2.86 ms
Pulse repetition rate	14 Hz
Maximum accelerating cavity surface field	45 MV/m
Maximum linac length (excluding contingency and upgrade space)	352.5 m
Annual operating period	5000 h
Reliability	95%

Number of neutrinos per m^2 crossing a surface placed on-axis at a distance of 100 km from the target station during 200 days for 2.0 GeV protons and positive and negative horn current polarities.

	Positive		Negative	
	N_ν $(\times 10^{10})/\mathrm{m}^2$	%	N_ν $(\times 10^{10})/\mathrm{m}^2$	%
ν_μ	396	97.9	11	1.6
$\bar{\nu}_\mu$	6.6	1.6	206	94.5
ν_e	1.9	0.5	0.04	0.01
$\bar{\nu}_e$	0.02	0.005	1.1	0.5

nuSTORM: Neutrinos from STORed Muons

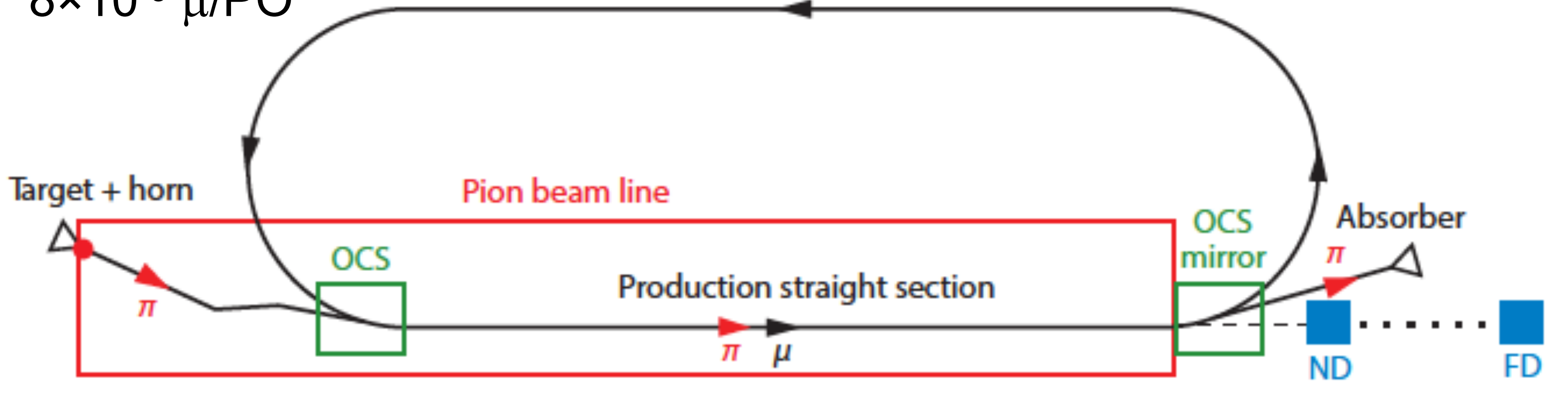
- nuSTORM: storage ring for 3.8 GeV/c muons that can be realised now without any new technology

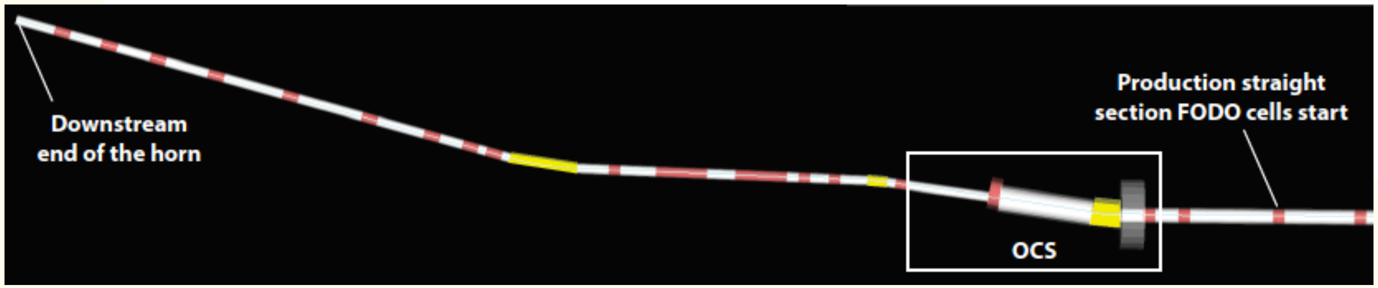


  - Pions of 5 Gev/c captured and injected into ring.
  - 52% of pions decay to muons before first turn: $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - This creates a first flash of neutrinos from pion decays
  - Ring designed to store muons with p = 3.8 GeV $\pm$ 10%
  - Muons decay producing neutrinos: $\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$
  - Creates hybrid beam of neutrinos from pion & muon decay

nuSTORM Facility

- nuSTORM facility:
  - 120 GeV protons on carbon or inconel target (100 kW)
  - NuMI-style horn for pion collection
  - Injection pions (5 GeV/c ± 10%) into storage ring: 0.09 π/POT
  - Storage ring: large aperture FODO lattice (3.8 GeV/c ± 10%) muons: 8×10^{-3} μ/PO



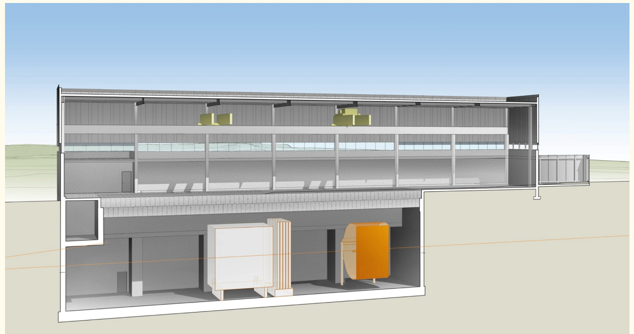


nuSTORM at Fermilab

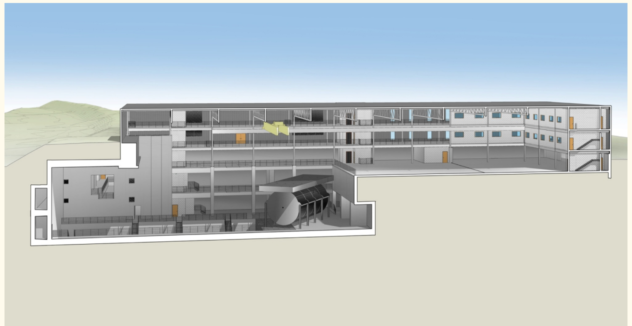
- nuSTORM could be sited at Fermilab

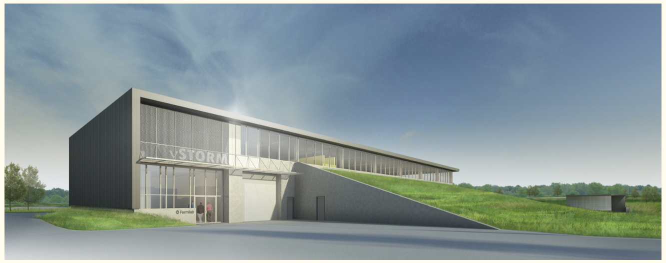
  Proposal to FNAL PAC: arXiv: 1308.6822

Near Detector Hall

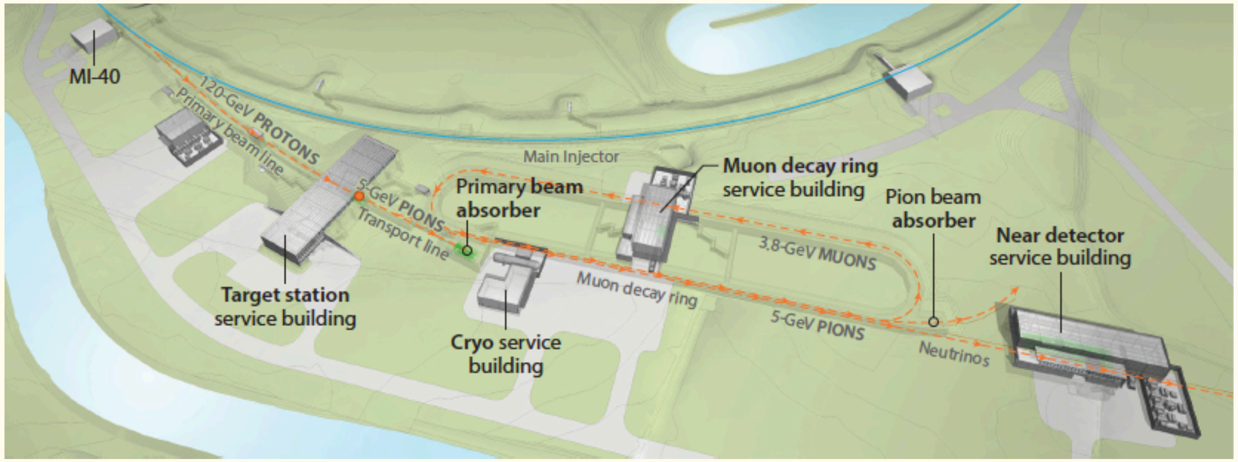


Far Detector Hall (D0)





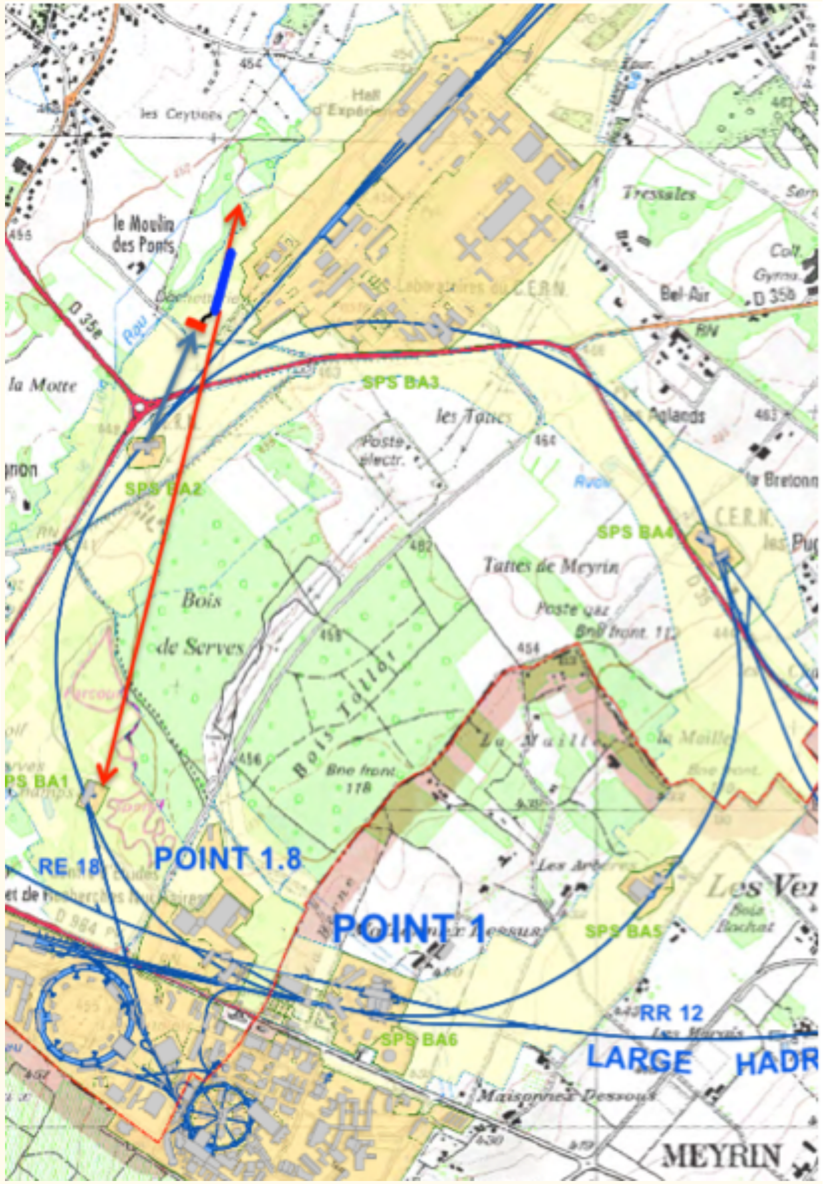
Target building



nuSTORM at CERN

- nuSTORM could be sited at CERN
- Target station in North Area

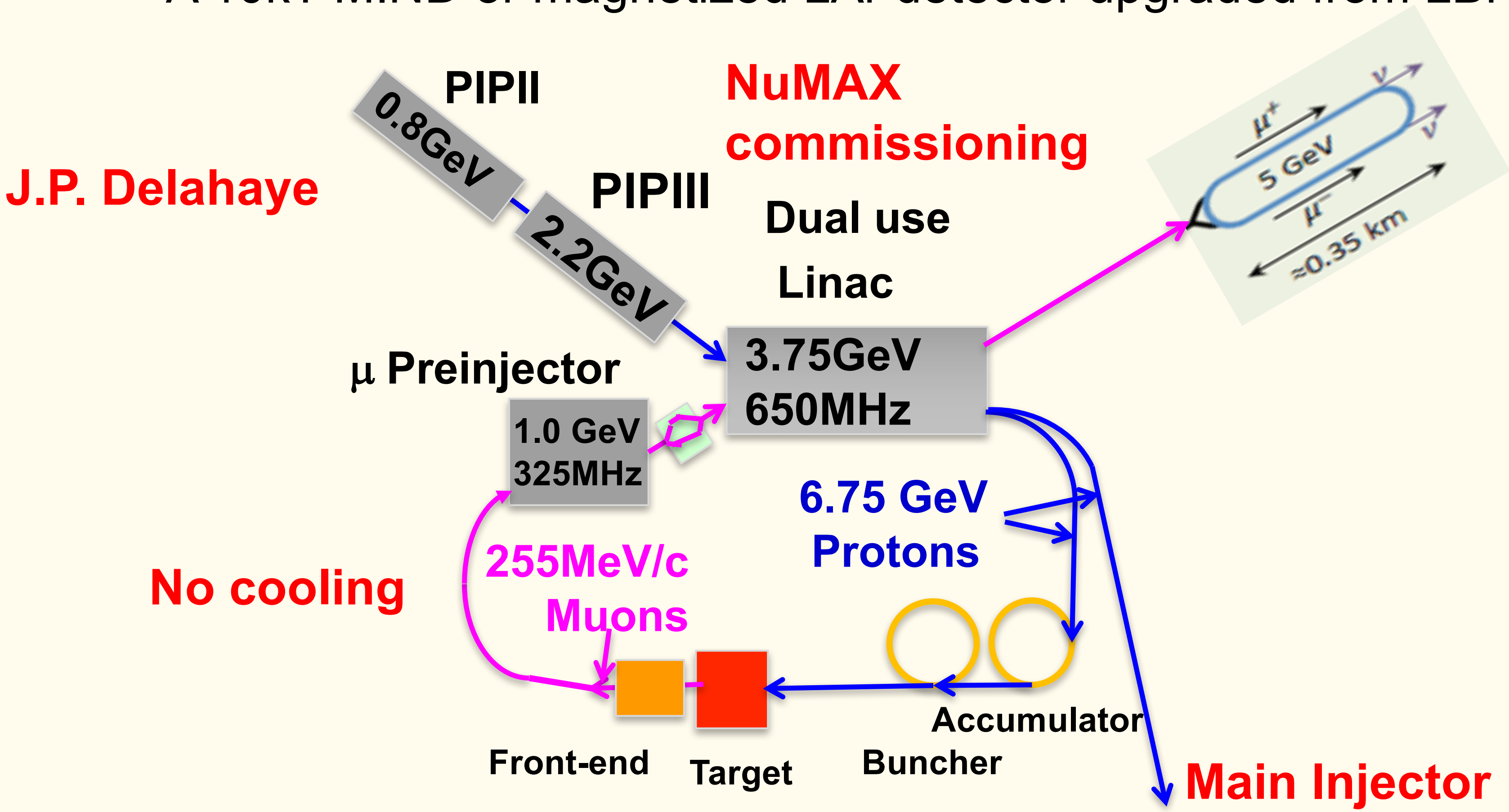
  EoI to CERN: arXiv:1305.1419



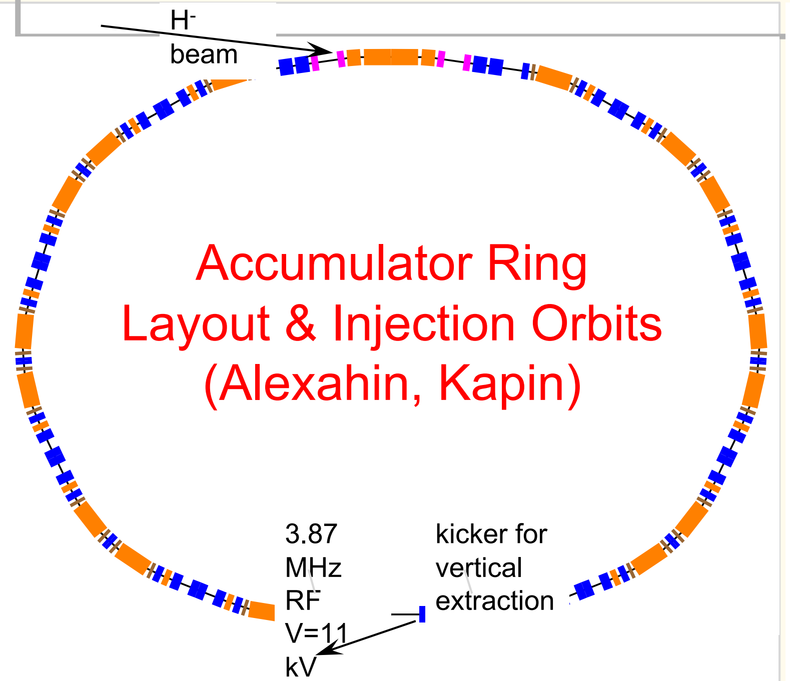
- For two detector oscillation search: near detector in North Area and far detector in Point 1.8

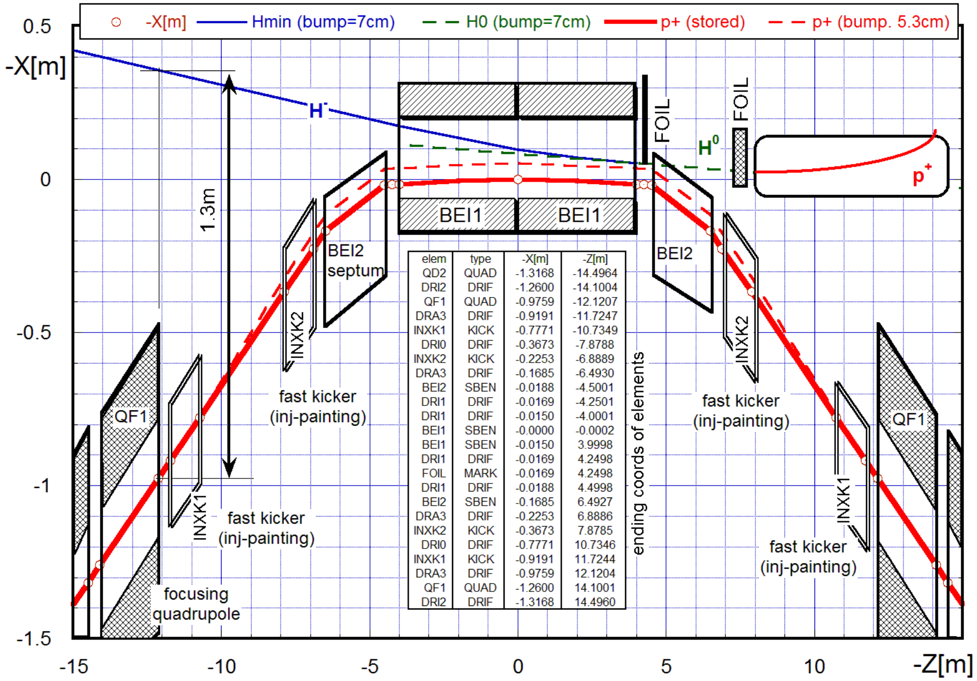
NuMAX: Neutrino Factory FNAL/Sanford

- Neutrinos from a Muon Accelerator CompleX (NuMAX)
  - Neutrino Factory with 10^{20} straight muons decays/year @ 5 GeV
  - Muon ring at 5 GeV pointing neutrino beam towards Sanford
  - A 10kT MIND or magnetized LAr detector upgraded from LBNE

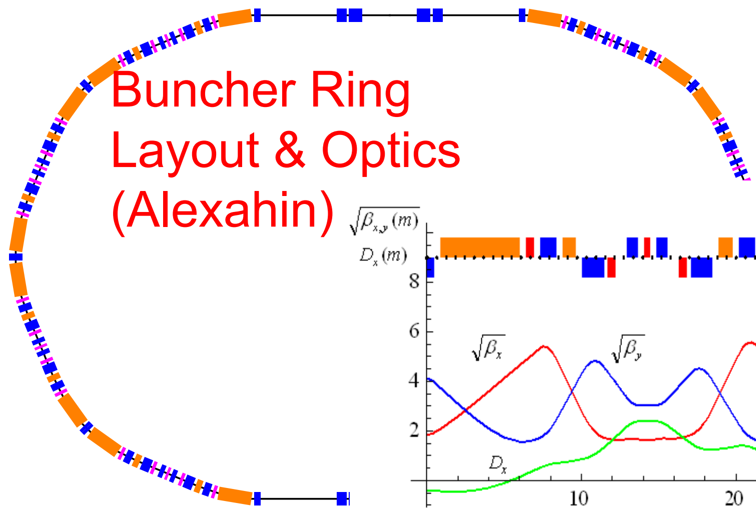


Proton Driver

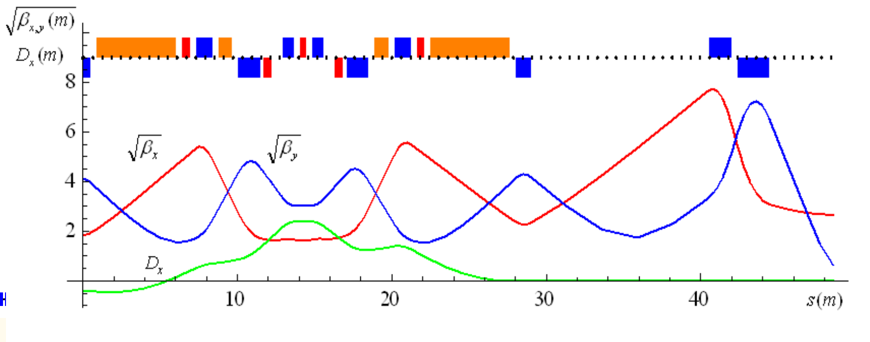




elem	type	-X[m]	-Z[m]
QD2	QUAD	-1.3168	-14.4964
DRI2	DRIF	-1.2600	-14.1004
QF1	QUAD	-0.9759	-12.1207
DRA3	DRIF	-0.9191	-11.7247
INXK1	KICK	-0.7771	-10.7349
DRI0	DRIF	-0.3673	-7.8788
INXK2	KICK	-0.2253	-6.8889
DRA3	DRIF	-0.1685	-6.4930
BEI2	SBEN	-0.0188	-4.5001
DRI1	DRIF	-0.0169	-4.2501
DRI1	DRIF	-0.0150	-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 staight +
1 arc cell

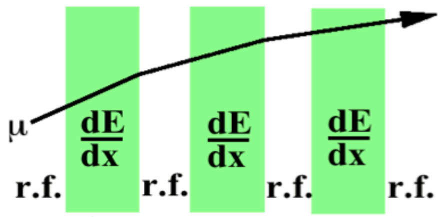


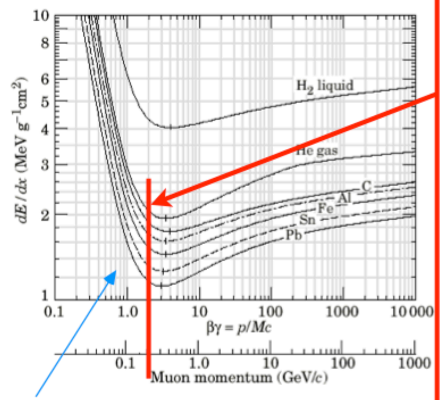
- ✓ Based on 6-8 GeV Linac Source
- ✓ Accumulator & Buncher Ring Designs in hand
- ✓ H- stripping requirements same as those established for Fermilab's Project X

M. Palmer

Muon Ionization Cooling

- Muons cool via dE/dx in low-Z medium





- ionization minimum is ≈ optimal working point:
  - longitudinal +ive feedback at lower p
  - straggling & expense of reacceleration at higher p

– Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

– RF cavities between absorbers replace ΔE

– Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp(0.014\ \text{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

(emittance change per unit length)

- 2 competing effects ⇒ ∃ equilibrium emittance

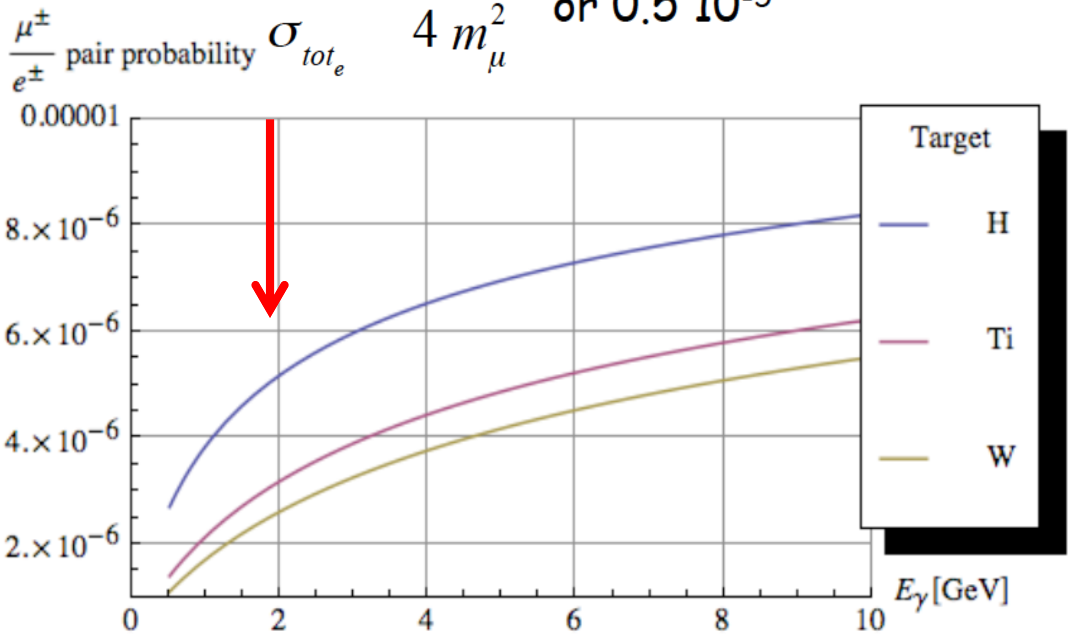
Kaplan

Muon generation by GeV-scale Compton γs

V.Yakimenko (SLAC)

Probability of creating $\mu+\mu-$ pairs as a function of the incident photon energy

$$\frac{\sigma_{tot_\mu}}{\sigma_{tot_e}} \approx \frac{1}{4}\frac{m_e^2}{m_\mu^2}$$ or $0.5\ 10^{-5}$



2GeV γ beam	Pulsed Linac	ERL
e-beam energy [GeV]	36	11
Laser wavelength [μm]	10	1
Bunch charge [nC]	10	1.5
Rep. rate [kHz]	0.2	20 / 200
Bunches per beam	250	
Average current [mA]	2	30 / 300
e-beam power [MW]	18	330 / 3300
e-to-γ convers. efficiency	3	0.33
γ-beam power [MW]	3	20 / 200
Total AC-to-γ efficiency	10%	20% / 75%
Peak $\mu^+\mu^-$ [per bunch]	10^6	$3\ 10^4$
Average $\mu^+\mu^-$ [per second]	$5\ 10^{10}$	$3\ 10^{11}$ / $3\ 10^{12}$

- Brightness 10^3 larger than with proton driver
- 10^3 too low with pulsed linac
- 10^2 flux increase with high current ERL
- Approaching intensities desired for NF (but train structure not favorable for collider luminosity, N^2 issue)