Center for Frontiers in Nuclear Science

Workshop

Using Muon Beams from Backscattered Photons on Targets for Various Studies

Organizers:

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Utility of Muons

Charged Lepton Flavor Violation

Muon physics and PSI muon beam lines & future developments

A. Papa, 2020 **Workshop: Physics Opportunities with the Gamma Factory**

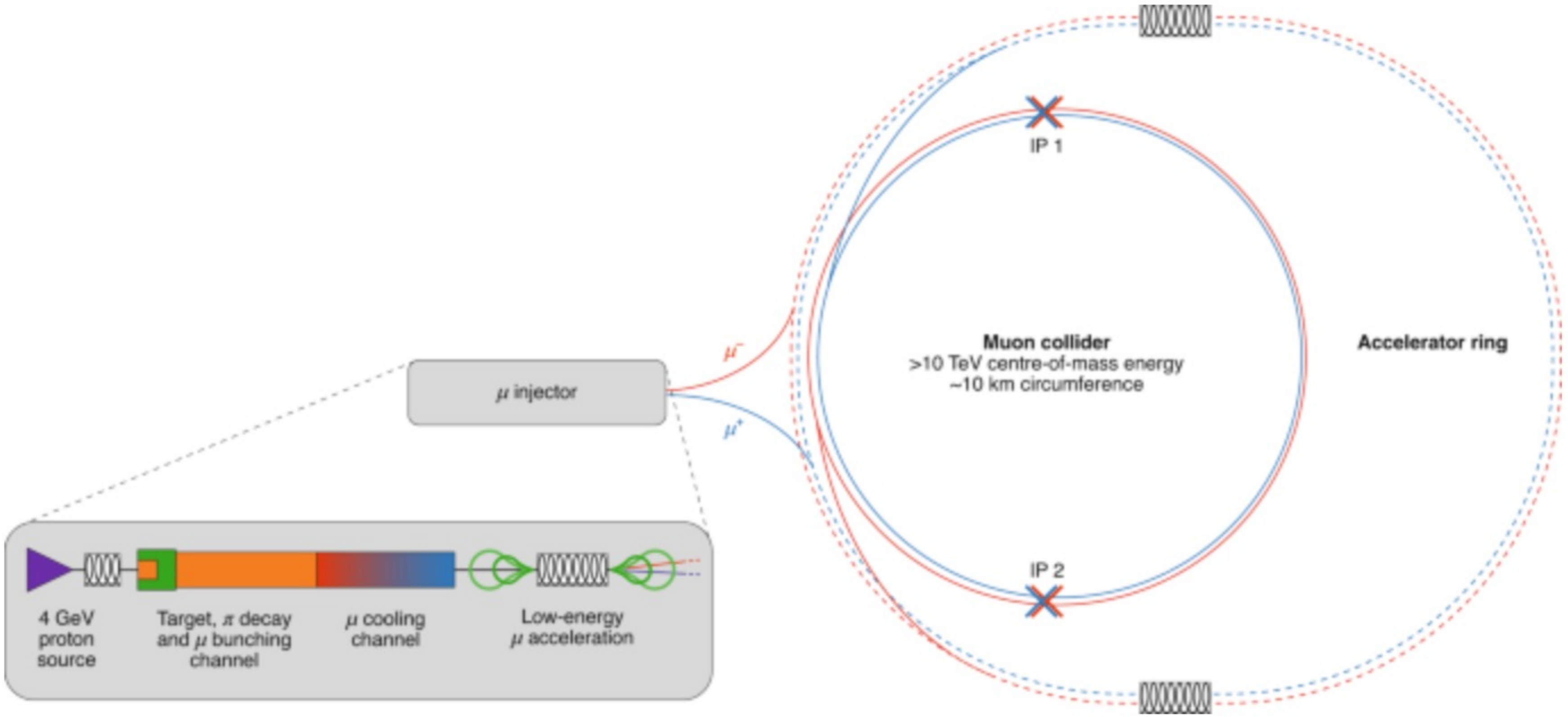
https://indico.mitp.uni-mainz.de/event/214/

	Current upper limit	Future sensitivity
$\mu \to e\gamma$	4.2×10^{-13}	$\sim 4 \times 10^{-14}$
$\mu \to eee$	1.0×10^{-12}	$\sim 1.0 \times 10^{-16}$
$\mu N \to eN'$	7.0×10^{-13}	few $\times 10^{-17}$

A Future Muon-Ion Collider at Brookhaven National Laboratory

E. Cline, '21 Snowmass

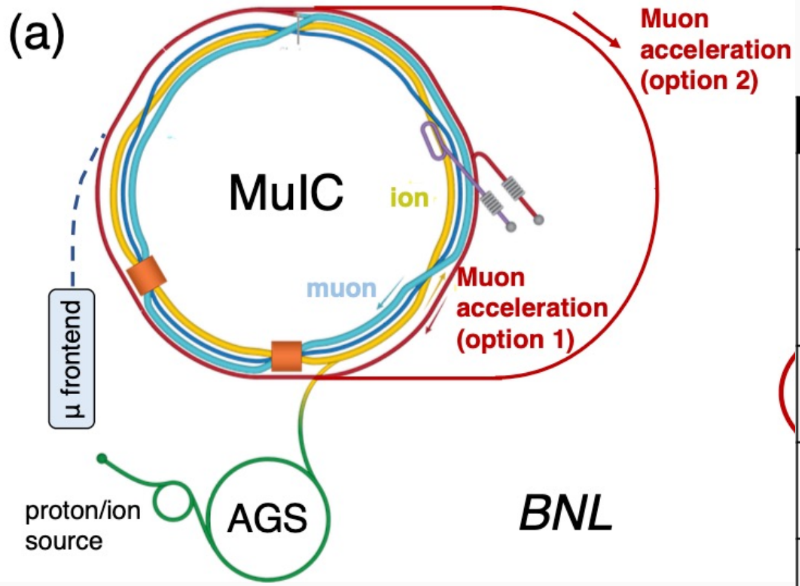
https://indico.cern.ch/event/1072533/contributions/4779239/attachments/2436049/4172090/mup.pdf



Physics Potential of a TeV Muon-Ion Collider
D. Acosta *et al.*, Snowmass '21

https://indico.cern.ch/event/1072533/contributions/4779228/attachments/2435658/4171607/DIS-MuIC-Acosta2.pdf

→ Replace e by μ beam at EIC



Bending radius of RHIC tunnel: **r = 290m**

Achievable muon beam energy: **0.3Br**

Parameter	1 (aggressive)	2 (realistic)	3 (conservative)
Muon energy (TeV)	1.39	0.96	0.73
Muon bending magnets (T)	16 (FCC)	11 (HL-LHC)	8.4 (LHC)
Muon bending radius (m)		290	
Proton (Au) energy (TeV)		0.275 (0.11/nucleon)	
CoM energy (TeV)	1.24 (0.78)	1.03 (0.65)	0.9 (0.57)

$\sqrt{s}$ = 1 TeV !

7-8X increase over EIC energy

See also talk by Ethan Cline in this session

Gamma Factory Low Emittance Muon Source
(Muons from Backscattered Photons on Target)
A. Apyan, , *2020* Workshop: Physics Opportunities with the Gamma Factory
https://indico.mitp.uni-mainz.de/event/214/

Potential advantages of the Gamma Factory photon-beam-driven muon sources

- *Replacing the high-power proton Linac beam by the **LHC-driven GF photon-beam** may turn out to be an exciting, cost-optimising option for the future **muon collider**.*
- ***Producing** and **handling** of **> 1 MW photon beams** may turn out be **easier** than > 1 MW proton beams (less power deposited in the target).*
- ***GF** source could produce **low-emittance muon beams** for which the **muon-cooling** phase may be **avoided.***
- *The almost exact **symmetry** of the π^+ / π^- and μ^+ / μ^- is **assured** (contrary to the proton driven sources).*
- *The above two merits may **facilitate** the design of the **muon collider**.*

EIC Electron Beam Parameters (from EIC Design Study)

Parameter	hadron	electron
Center-of-mass energy [GeV]	104.9	
Energy [GeV]	275	10
Number of bunches	1160	
Particles per bunch [10^{10}]	6.9	17.2
Beam current [A]	1.0	2.5
Horizontal emittance [nm]	9.6	20.0
Vertical emittance [nm]	1.5	1.2
Horizontal β-function at IP β_x^* [cm]	90	43
Vertical β-function at IP β_y^* [cm]	4.0	5.0
Horizontal/Vertical fractional betatron tunes	0.305/0.31	0.08/0.06
Horizontal divergence at IP $\sigma_{x'}^*$ [mrad]	0.103	0.215
Vertical divergence at IP $\sigma_{y'}^*$ [mrad]	0.195	0.156
Horizontal beam-beam parameter ξ_x	0.014	0.073
Vertical beam-beam parameter ξ_y	0.007	0.1
IBS growth time longitudinal/horizontal [hr]	3.4/2.0	-
Synchrotron radiation power [MW]	-	9.0
Bunch length [cm]	6	2
Hourglass and crab reduction factor [16]	0.86	
Luminosity [10^{34} cm^{-2} sec^{-1}]	1.0	

Calculation of Rate of Photon Production

When $\omega_1 << E_e$, as in our case, we have the approximation

$$\omega_2 \approx \frac{4\gamma^2\omega_1}{1 + 4\gamma^2 \dfrac{\omega_1}{E_e}}.$$

Unpolarized Total Cross Section

Following Landau, Lifshitz, Berestetskii and Pitaevskii [5], we set

$$x_1 = 2\gamma \frac{\omega_1}{E_0}(1 - \beta \cos\phi_1).$$

The total unpolarized Compton cross section σ_C^{unp} is then

$$\sigma_C^{unp} = 2\pi r_0^2 \frac{1}{x_1}[(1 - \frac{4}{x_1} - \frac{8}{x_1^2})\ln(1 + x_1) + \frac{1}{2} + \frac{8}{x_1} - \frac{1}{2(1 + x_1)^2}],$$

where $r_0 = 2.81794 \times 10^{-15}$ m is the classical electron radius.

To include polarization effects, one write can write [6]

$$\sigma_C = \sigma_C^{unp} + 2\lambda_e P_c \sigma_1, \tag{5}$$

where λ_e is the mean electron helicity ($|\lambda_e|^2 \leq \frac{1}{2}$), P_c is the Stokes parameter that gives the degree of photon circular polarization given by

$$P_c = \frac{(I_L - I_R)}{I_0}, \tag{6}$$

with I_L, I_R and I_0 being the left circularly polarized, right circularly polarized and total photon intensities. Finally,

$$\sigma_1 = \frac{2\sigma_0}{x_1}[(1 + \frac{2}{x_1})\ln(1 + x_1) - \frac{5}{2} + \frac{1}{1 + x_1} - \frac{1}{2(1 + x_1)^2}], \tag{7}$$

with $\sigma_0 = \pi(\frac{e^2}{m_e c^2}) = 2.5 \times 10^{-29}$ m^2.

Rate of Backscattered Photons

From the luminosity L, the rate of backscattered photons R is simply

$$\frac{dN}{dt} = \sigma_C L. \tag{9}$$

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We use the Suzuki formula [8], where

$$L = N_e N_{ph} f \frac{\cos(\frac{\phi}{2})}{2\pi} \frac{1}{\sqrt{\sigma_{ye}^2 + \sigma_{yph}^2}\sqrt{(\sigma_{xe}^2 + \sigma_{xph}^2)\cos^2(\frac{\phi}{2}) + (\sigma_{ze}^2 + \sigma_{zph}^2)\sin^2(\frac{\phi}{2})}}, \tag{8}$$

where N_e is the number of electrons in a bunch, N_{ph} is the numbers of photons in a laser pulse, f is the electron-photon bunch collision frequency, ϕ is two times the crossing angle of the lines defined by the incident electron and photon momenta, and the σ's define the rms sizes of electron and photon beam dimensions at the interaction point, with z being the longitudinal direction according to Suzuki's notation. The electron rms beam sizes

Laser Parameters

The frequency f at which electron bunches come into the interaction point with the laser pulses is equal to the number of electron bunches in the storage ring (1,160) times the revolution frequency of the electrons around the circumference (3,833.94 meters), or

$$f = \beta c \frac{1160}{3833.94} = 90.7\,\text{MHz}. \tag{10}$$

Müller *et al.* have reported developing a laser system centered at 1046 nm wavelength λ, 254 fs pulse duration, 80 MHz pulse repetition rate, and 10.4 kW average output power P [7]. We note that this is not quite at the 90.7 MHz rep rate for our application; however, that gap should be closed in the near future. Thus, we will assume a laser pulse rep rate of 90.7 MHz.

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Optics Letters

10.4 kW coherently combined ultrafast fiber laser

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An ultrafast laser delivering 10.4 kW average output power based on a coherent combination of 12 step-index fiber amplifiers is presented. The system emits close-to-transform-limited 254 fs pulses at an 80 MHz repetition rate, and has a high beam quality ($M^2 \leq 1.2$) and a low relative intensity noise of 0.56% in the frequency range of 1 Hz to 1 MHz. Automated spatiotemporal alignment allows for hands-off operation.

https://doi.org/10.1364/OL.392843

and intensity beam splitters [11]. For Gaussian beams, filled-aperture combining is more efficient and hence preferred over tiled-aperture combining at theoretical maximum efficiencies of 100% and 68% [12]. In the filled-aperture schemes, intensity beam splitters offer some practical advantages, such as lower coating absorption compared to polarization beam splitters, lower cost than diffractive optical elements, and easy replacement in the case of damage, leading to the demonstration of a 3.5 kW average-power ultrafast laser [11].

In this contribution, the successor of the system described in Ref. [11] is presented, demonstrating improvement in all

TABLE II. Output Parameter Values vs. E_e

E_e (GeV)	10	20	30	40	50
ω_2 (GeV)	1.54	5.33	10.59	16.84	23.81
σ_C ($\times 10^{-25}$ cm^2)	5.48	4.74	4.25	3.89	3.63
L ($\times 10^{38}$ cm^{-2}-sec^{-1})	1.04	1.04	1.04	1.04	1.04
R ($\times 10^{13}$ sec^{-1})	5.72	4.95	4.43	4.06	3.78

Future Possibilities

- Parasitic studies of muon production from backscattered photons at the EIC, similar to GF studies at CERN
- Ascertain the degree of muon beam cooling needed from backscattered photons on targets
- Parasitic mu to e studies of CLFV at the EIC
- Possibility of CERN GF/EIC partnership for photon beam studies
- Studies of plasma wakefield acceleration of muon beams as a step towards a mu+/mu- collider