Colliders Beyond the EIC: a Muon-Ion Collider

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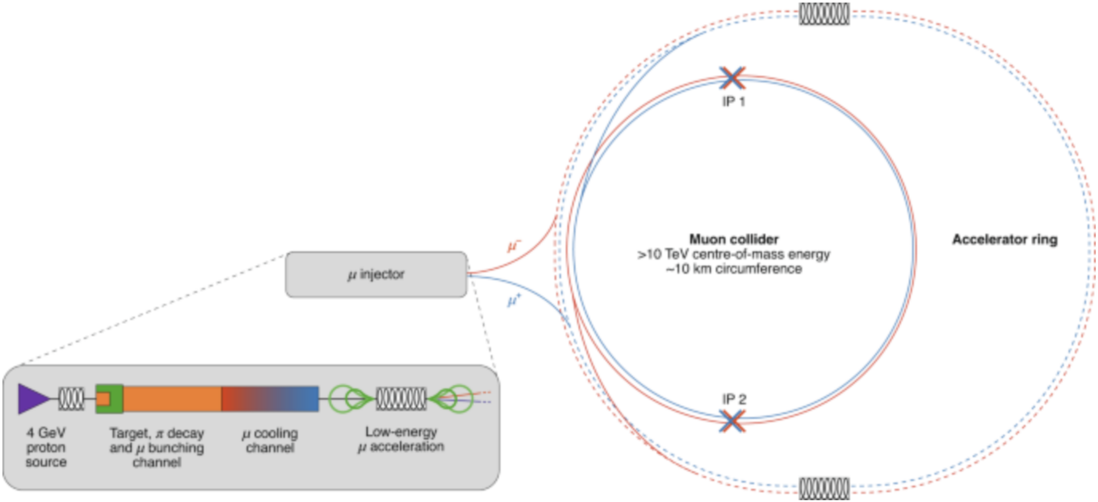
It is reasonable to assume that the EIC physics program will run for about 15 years starting 2035, and possibly extended by another ~5-10 years with detector upgrades.

So we are now in year 2050-2055.

You have 25-30 years to prepare for what comes next! Perfect timing….

Slide from A. Deshpande, https://indico.bnl.gov/event/17909/contributions/73698/attachments/46883/79463/EIC-at-MuIC%20WS%20CFNS.pdf

A Future Muon Collider

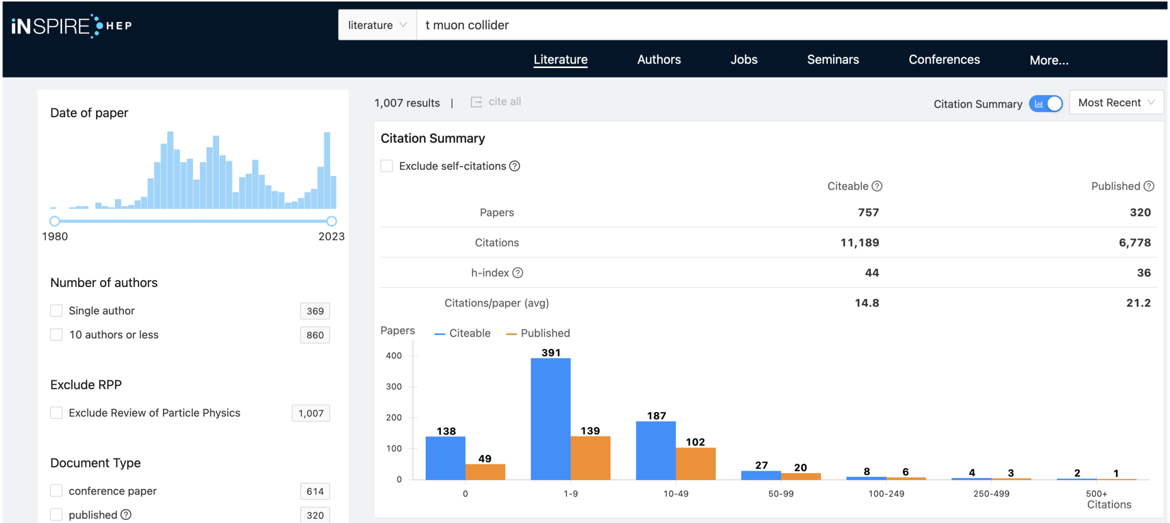


https://muoncollider.web.cern.ch/node/25

A Future Muon Collider

- A future muon collider has strong interest in the community
- Wide physics reach at $\sqrt{s} = 10$ TeV and beyond
- Several papers submitted as part of SNOWMASS process
- Significant R&D work necessary to prove feasibility
- MICE project at Rutherford lab demonstrated 6D cooling
- There is a rich physics program possible along the way to realizing a muon collider!

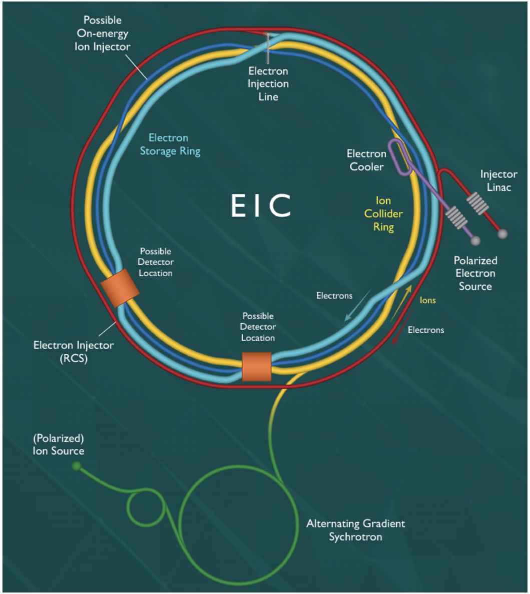
A Long Time Coming



Technical Challenges

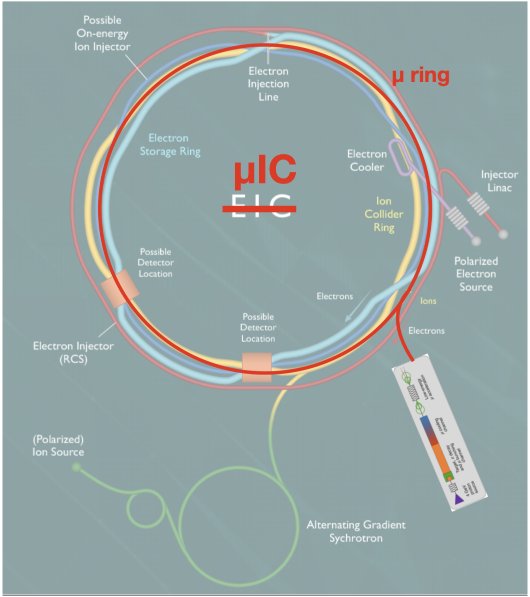
- Requires 40 T solenoids
- RF cavities operating in high gradient field
- Ramp rate of $\sim$T/ms
- Neutrinos pose radiation hazard
- Silicon tracker with 5μm resolution handling 1000 hits/cm^2/bunch

The EIC



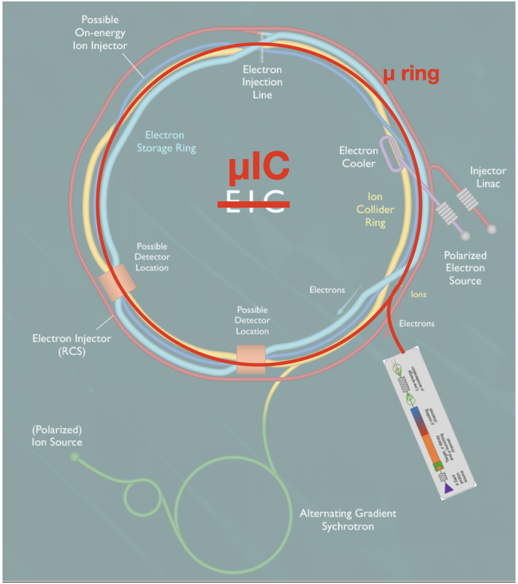
https://www.bnl.gov/eic/machine.php

A μIC!



Possible
On-energy
Ion Injector
Electron
Injection
Line
μ ring
Electron
Storage Ring
μIC
~~EIC~~
Electron
Cooler
Injector
Linac
Ion
Collider
Ring
Possible
Detector
Location
Polarized
Electron
Source
Electrons
Ions
Possible
Detector
Location
Electrons
Electron Injector
(RCS)
(Polarized)
Ion Source
Alternating Gradient
Sychrotron

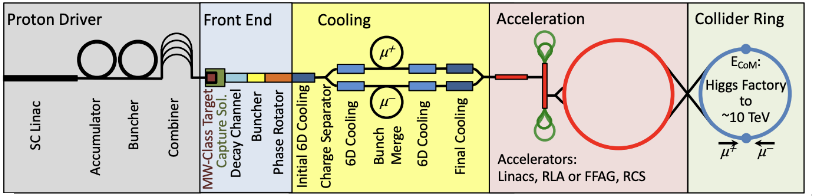
A μIC!



- Build μ frontend as "proof of concept" for $\mu^+\mu^-$ collider
- Reuse EIC Ion beam
- Design to have variable μ energy, 18 GeV - 200 GeV

Muon Generation

- Proton driven scheme
  - Proton on high Z target, produce π's which decay to μ's
  - μ's have wide emittance, need to be cooled
  - Preferentially produce μ^+
  - Selecting polarized μ's reduces luminosity



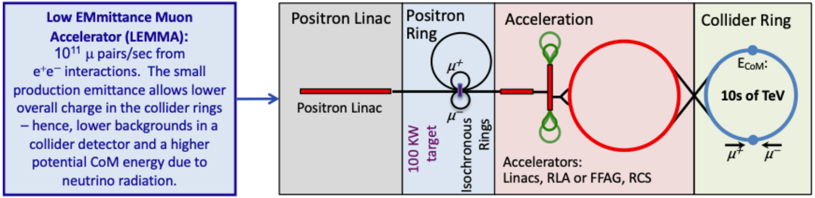
https://muoncollider.web.cern.ch/node/25

Muon Generation - Proton Driven

- Cooling is a non-trivial challenge!
  - From Forum Report arxiv:2209.01318 4 of 5 major challenges in realizing accelerator come from cooling!
    - "operation of RF cavities in high magnetic fields in the front end and cooling channel."
    - "development of a 6D cooling lattice design..."
    - "a direct demonstration and measurement of the ionization-cooling process."
    - "development of very-high-field solenoids to achieve the emittance goals of the Final Cooling system"
  - MICE at Rutherford lab has demonstrate low beam intensity cooling
  - From talk by K. Yonehara here, transmission efficiency through cooling channel is $\approx 20\%$
- It would be great to not need to cool the μ beams!
- However, proton driven scheme has seen the most study and seems to be the most widely accepted method of generating μ

Muon Generation

- e^+e^- annihilation scheme (LEMMA)
  - Muons produced at high energy
  - Low emittance, no cooling needed
  - Requires 45 GeV positron beam on electron target
  - Target heating and luminosity difficulties



https://muoncollider.web.cern.ch/node/25

Muon Generation - LEMMA

- Target heating is a non-trivial challenge
- Cross section $\approx \mu$b compared to $\approx$ mb from proton scheme

Muon current for MAP scheme 10^{13} s^{-1}

LEMMA scheme O(0.7 mJ) positrons lost per produced muon pair

$\Rightarrow$ 100 MW loss yield 1.4 x 10^{11} s^{-1} muons (proton case: 1 x 10^{13} s^{-1})

$\Rightarrow$ Need 70 times denser beam

$\Rightarrow$ Lose 1.4 10^{16} positrons per second

$\Rightarrow$ Pass 1.4 10^{18} positrons through target per second

Assume 3mm thick Be target

$\Rightarrow$ Emittance growth per muon beam passage through target (optimum case)

$\Rightarrow$ Need 100 bunches with 3 x 10^{15} positrons (=22 MJ) to pass through target to obtain required muon beam emittance

$\Rightarrow$ Positron beam energy 2 GJ/burst, 5 burst per second

$\Rightarrow$ Energy deposition in target 60 kJ per pulse (minimum ionisation) 4.5 MK temperature rise per bunch (linear approximation)

$\Rightarrow$ Extremely challenging, not sure even a fluid target can do this

. Schulte Muon Collider, Muon Collider Agora, February 1

Text from talk by D. Schulte at SNOWMASS Agora

Muon Generation - Gamma Factory

- $\mu^+\mu^-$ production from high energy photons (Gamma Factory)
  - Impinge laser pulses on ion beam
  - $N_\gamma \approx 10^{16}$/s backscattered photons at $\approx$ 300 MeV
  - Impinge γ's on stationary target to perform exclusive pion production $\gamma + p \rightarrow \pi^+ + n$ followed by pion decay
  - Cooling not required as π production phase space significantly restricted

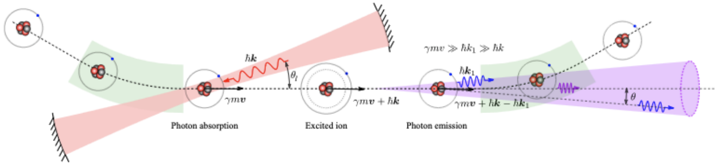
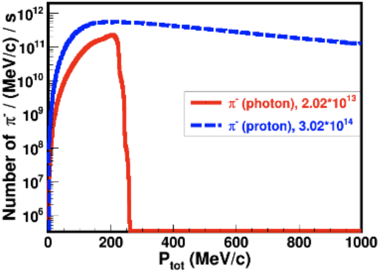
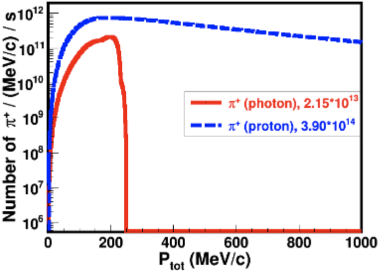


FIG. 20: The Gamma Factory concept: laser photons with the momentum k collide with ultrarelativistic partially stripped ions (with the relativistic Lorentz factor γ_L, mass m, velocity $v = \beta c$, where c is the velocity of light) circulating in a storage ring; resonantly scattered photons with the momentum $k_1 \gg k$ are emitted in a narrow cone with an opening angle $\theta \approx 1/\gamma_L$ in the direction of motion of the ion beam.

Gamma Factory - A. Apyan, M. Krasny, W. Płaczek, https://arxiv.org/pdf/2212.06311.pdf



(a)



(b)

Figure from https://arxiv.org/pdf/2212.06311.pdf

- Comparing pion momentum between proton driven and Gamma Factory appraoches
- GF clearly has more compressed phase space
- Proton driven creates more pions in the long tail

Muon Generation - BACKGAMMON

- $\mu^+\mu^-$ production from high energy photons (BACKGAMMON)
  - Impinge laser pulses on 20 GeV electron beam - Compton scattering
  - $N_\gamma \approx 10^{13}$/s backscattered photons at $\approx$ 5 GeV
  - Impinge γ's on stationary target to pair-produce $\mu^+\mu^-$ at high energy without need for cooling,
  - Can create longitudinally polarized μ's with circularly polarized photons
  - **Could use future EIC electron beam!**

E (GeV)	10	20	30
ω_2 (GeV)	1.54	5.33	10.59
σ_C (10^{-25} cm^2)	5.48	4.74	4.25
$\mathcal{L}$ (10^{38} cm^{-2}-s$^-1$)	1.04	1.04	1.04
R (10^{13} s^{-1})	5.72	4.95	4.43

Backscattered photon energy, total Compton cross section, luminosity and production rate of backscattered photons as function of incident electron energy. Numbers from S. Mtingwa.

BACKGAMMON - S. Mtingwa and M. Strikman, Phys. Rev. Lett. 64, 1522 (1990)

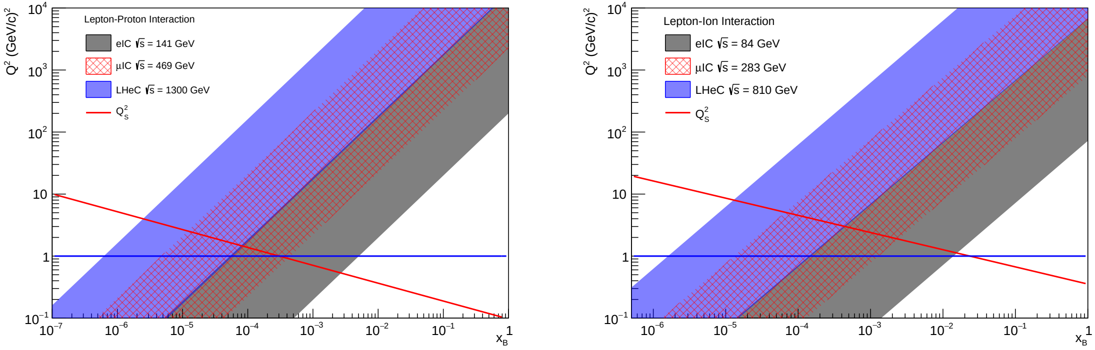
Muon Generation - BACKGAMMON

- Similar low cross section dilemma as LEMMA, production cross section $\approx 5 - 6\ \mu$b
- My hope is that this could be run parasitically to ePIC production running
  - Where could such a setup be situated?
  - If we envision this as a test/R&D facility, how many μ could be produced parasitically before it impacts ePIC running? (ask accelerator folks)

Muon Generation - the EIC

What could be built at the EIC?

- Proton-driven scheme/LEMMA would require significant construction - difficult with ePIC running
- BACKGAMMON could be implemented with minimal interference and collaboration with other groups likely
- Combining some ideas, could we implement an LHC-style Gamma Factory at the EIC? μ from γ backscattered off EIC ions?
  - EIC beam energies lower than LHC, but higher intensities
  - Could 400 MeV γs be produced?
- Alternatively, a BACKGAMMON-Factory? Backscatter γs off e-beam for exclusive π production on nuclear target?
  - Back-of-the-laptop calculation indicates if we want 300 MeV photons, we can use the BACKGAMMON method to get $\approx 6.5 \times 10^{13}$ γ/s
  - Is this small enough energy from e-beam that it could run parasitically to EIC?



Left: Kinematic Reach of μIC for μp collisions. Right: Kinematic Reach of μIC for μAu collisions.

LHeC: https://arxiv.org/pdf/2007.14491.pdf
EIC: https://arxiv.org/pdf/2103.05419.pdf

Muon Decay

- μ lifetime is 2.2×10^{-6} s
- At a beam energy of 18 GeV, this is extended to 3.6×10^{-4}s
- 33 laps around the RHIC ring in 1 lifetime (370 laps at 200 GeV beam)
  - Point in favor for a separate ring?
- Luminosity and storage are a problem
- Electrons from decay go almost in beam direction, are uniformly distributed, have unknown energy, and scatter with beam hadrons
  - Vertical chicane helps here, but detailed study needed for these kinematics

Luminosity in Proton Driven Scheme

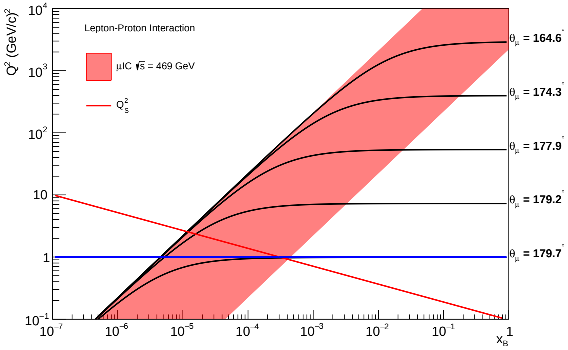
$$\mathcal{L}_{\mu p} = \frac{N^{\mu} N^{p} \min[f_c^{\mu}, f_c^{p}]}{4\pi \max[\sigma_x^{\mu}, \sigma_x^{p}] \max[\sigma_y^{\mu}, \sigma_y^{p}]} H_{hg} \tag{1}$$

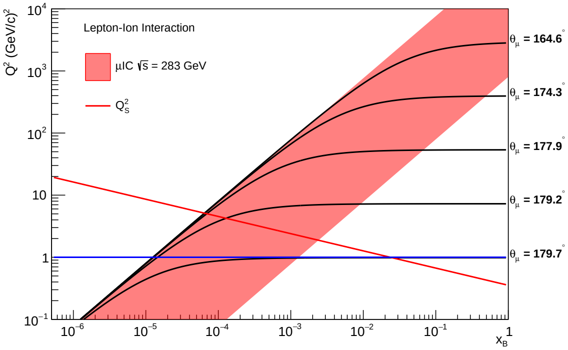
$$\sigma_{x,y} = \sqrt{\beta * \varepsilon / \gamma} \tag{2}$$

$$f_c^{\mu} = N_{\mathrm{laps} * f_{\mathrm{rep}}} \tag{3}$$

	proton driven muon production	proton
E (GeV)	200	275
$N^{\mu,p}$ (10^{11})	30	3
γ	2000	275
ε (μm)	140 (25)	0.2
β (cm)	1.3 (1)	5
$\sigma_{x,y}$ (μm)	30 (10)	6
Number of laps	680	∞
f_c^{μ} (s^{-1})	10,350	N/A
$\mathcal{L}_{\mu p}$ ($cm^{-2}s^{-1}$)	8×10^{31} (5×10^{32})	

Luminosity of μp collisions

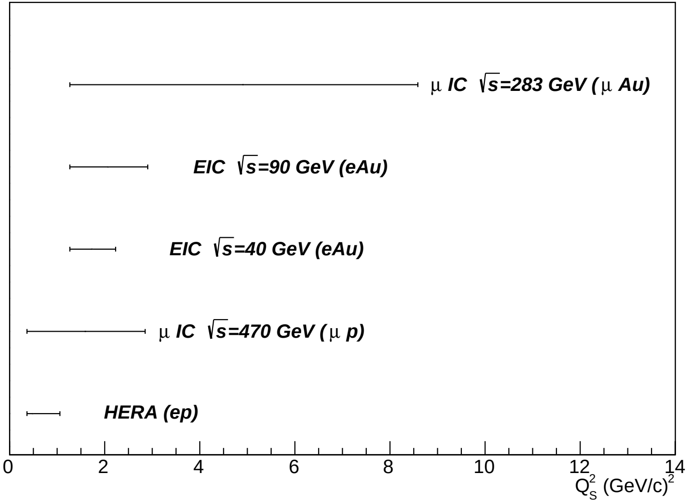




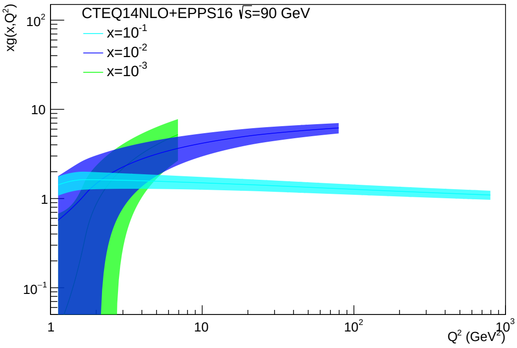
Left: Lines of constant θ at the μIC for μp collisions. Right: Lines of constant θ at the μIC for μAu collisions.

Saturation Scale

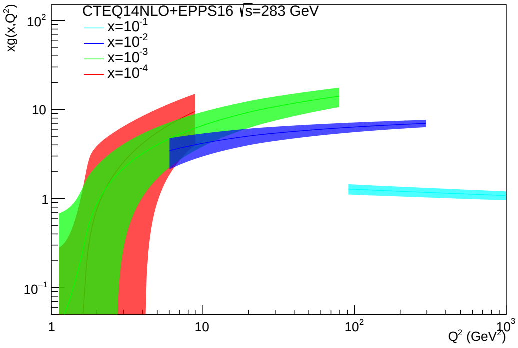
$x \leq 0.01$



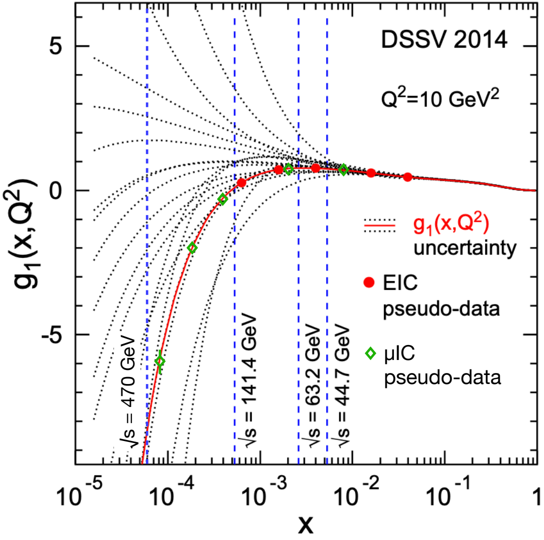
Saturation scale in the GBW model



EIC coverage for xg



μIC coverage for xg



- Extraction of g1 from DSSV collaboration
- EIC pseudo-data 10 fb^{-1} sampled luminosity, μIC pseudo-data from 0.9 fb^{-1}
- Figure reproduced from: https://arxiv.org/abs/1708.01527

Summary

- Muon collider collaborations have clearly demonstrated need for future collider
- R&D on a high-energy, high-intensity source of muons is desirable
- EIC design underway via CD process
- Possible synergy between nuclear and particle physics community at the site of the future EIC
- Rich physics program with μIC

CFNS Workshop Last Spring

Using muons from backscattered photons on targets for various studies at the EIC

5 April 2023
Remote
US/Eastern timezone

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- Timetable
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- Registration
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Local Organizer
ethan.cline@stonybrook...

Most proposals involving the use of muon beams utilize protons on targets to produce pions, which then decay into muons for various studies. Such muon beams usually require emittance cooling before they are useful. However, an alternative is to use muon beams produced by backscattered photon beams on suitable targets, thereby obviating the need for muon beam cooling. Preliminary studies indicate that the EIC's electron beam of ~20 GeV yields ~5 x 10^13 photons/sec of energy ~5 GeV. Simulations are currently being performed to understand the kinematics of muons produced from the EIC backscattered photons on various targets.

In this workshop, we will look deeper into muon beams from backscattered photons on various targets and discuss physics implications from their use. This should be an important extension of the EIC.

Starts 5 Apr 2023, 06:00
Ends 5 Apr 2023, 23:00
US/Eastern

Remote
Zoom link TBA

Paul Gueye
Sekazi Mtingwa

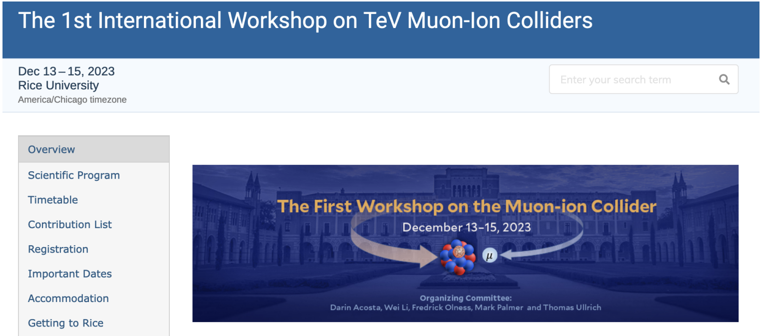
There are no materials yet.

The call for abstracts is open
You can submit an abstract for reviewing.
Submit new abstract

Registration
You are registered for this event.
10
See details

https://indico.bnl.gov/event/17909/

Upcoming Workshops



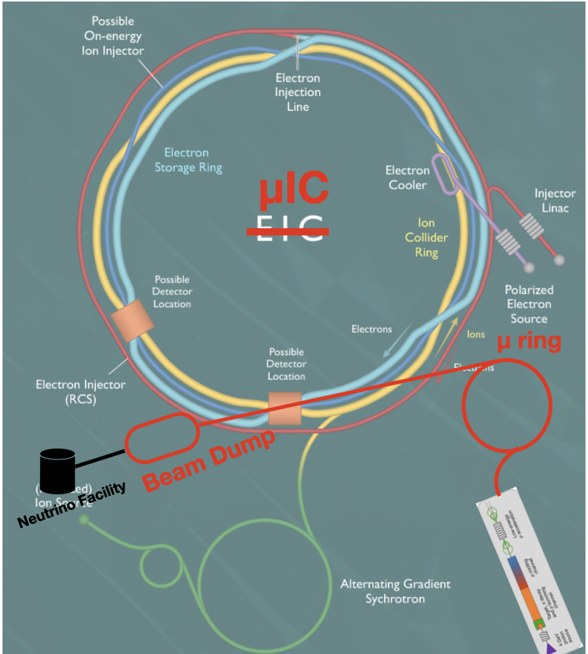
https://indico.cern.ch/event/1276216/overview

Also keep an eye out for a CFNS workshop - March 26, 2024

Thank you!

Any Questions?

A μIC v2!



Possible
On-energy
Ion Injector
Electron
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Linac
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Collider
Ring
Possible
Detector
Location
Polarized
Electron
Source
Electrons
Ions
μ ring
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Beam Dump
Neutrino Facility
Alternating Gradient
Sychrotron