Muon Accelerator Systems at Brookhaven National Laboratory

Ethan Cline

Center for Frontiers in Nuclear Science
Stony Brook University
Stony Brook,NY

Laboratory for Nuclear Science
Massachusetts Institute of Technology
Cambridge, MA

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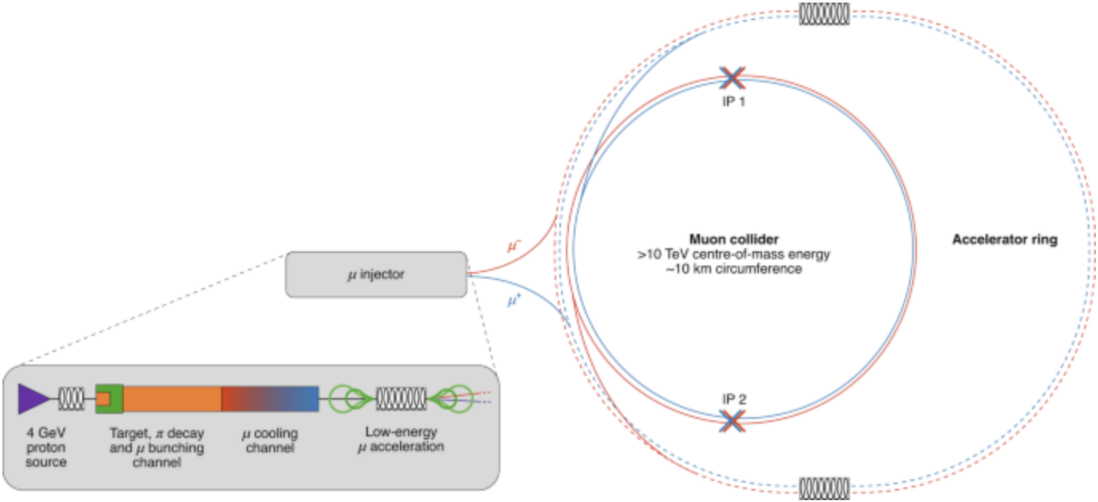
A Future Muon Collider

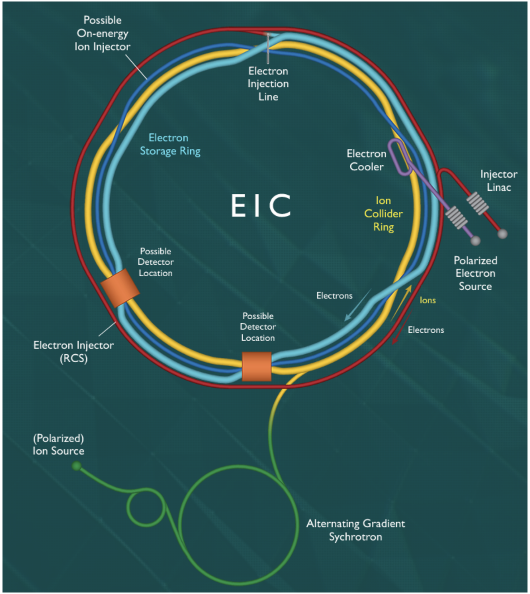


https://muoncollider.web.cern.ch/node/25

A Future Muon Collider

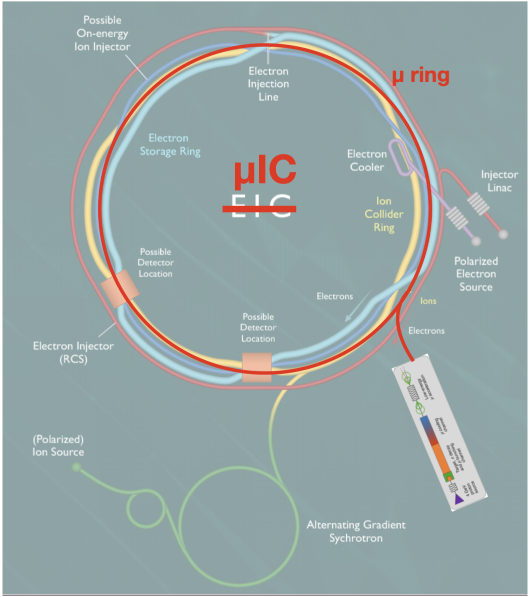
- A future muon collider has strong interest in the community
- Wide physics reach at $\sqrt{s} = 10$ TeV and beyond
- Several papers submitted as part of SNOWMASS process
- Significant R&D work necessary to prove feasibility
- MICE project at Rutherford lab demonstrated 6D cooling (Nature 578, p. 53–59 (2020))
- There is a rich physics program possible along the way to realizing a muon collider!

The EIC

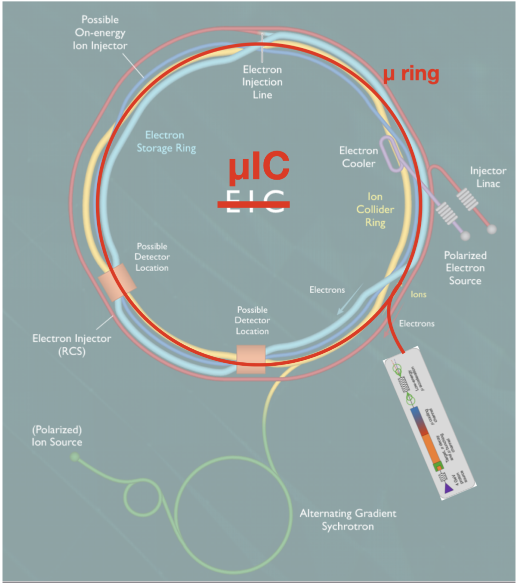


https://www.bnl.gov/eic/machine.php

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)
Low-energy
μ acceleration
μ cooling
channel
Target, π decay
and μ bunching
channel
4 GeV
proton
source
(Polarized)
Ion Source
Alternating Gradient
Sychrotron

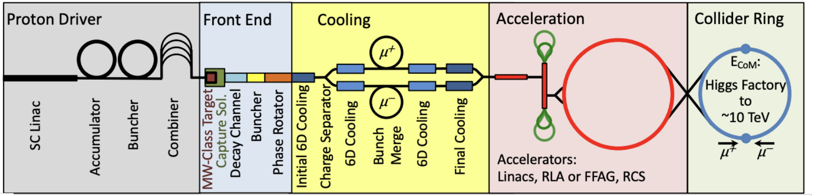
A μIC!



- 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

- Proton driven scheme - reference design for μC
  - 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



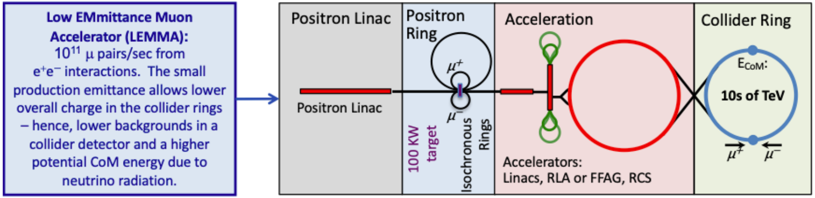
https://muoncollider.web.cern.ch/node/25

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

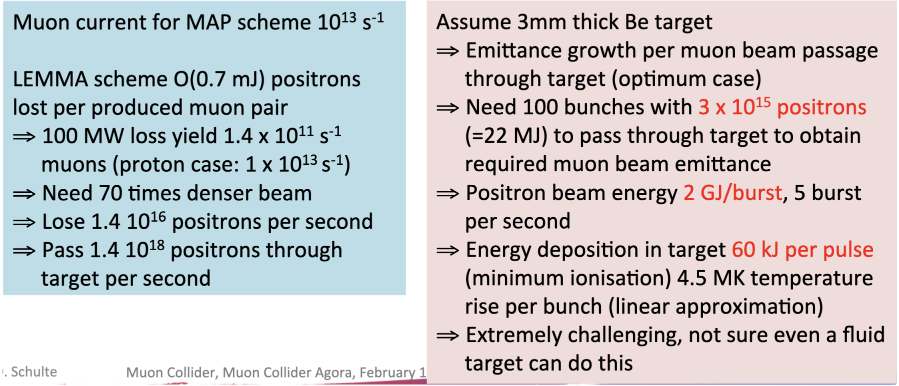


Low EMmittance Muon Accelerator (LEMMA):
10^{11} μ pairs/sec from e^+e^- interactions. The small production emittance allows lower overall charge in the collider rings – hence, lower backgrounds in a collider detector and a higher potential CoM energy due to neutrino radiation.

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

- $\mu^+\mu^-$ production from high energy photons (Gamma Factory)
  - Impinge laser pulses on ion beam
  - $N_\gamma \approx 10^{16}$/s backscattered photons at $\approx$ 400 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

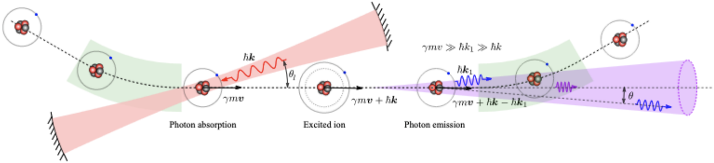


FIG. 20: The Gamma Factory concept: laser photons with the momentum k collide with ultrarelativistic partially stripped ions (with the relativistic Lorentz factor γ_L, mass m, velocity $v = \beta c$, where c is the velocity of light) circulating in a storage ring; resonantly scattered photons with the 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

Muon Generation

- $\mu^+\mu^-$ 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

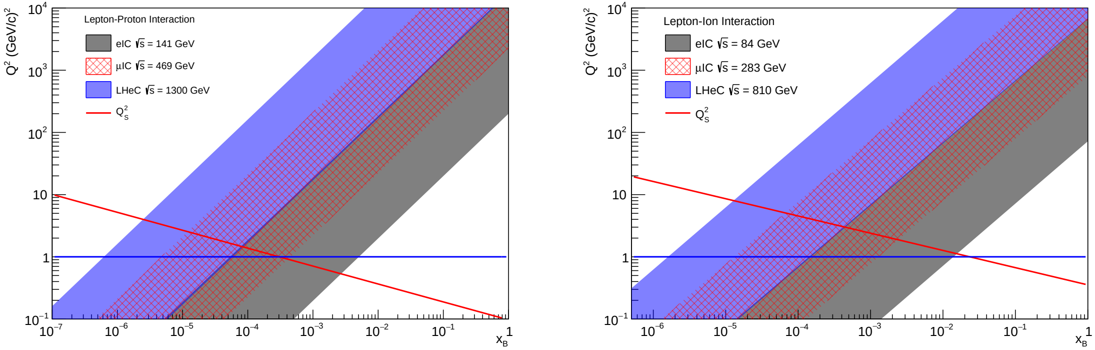
- Similar low cross section dilemma as LEMMA, production cross section $\approx 5 - 6\ \mu$b
- My hope is that this could be run parasitically to ePIC production running
  - Where could such a setup be situated?
  - If we envision this as a test/R&D facility, how many μ could be produced parasitically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

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? Haven't had a chance to do any math
- 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 400 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?

Physics Reach



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

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

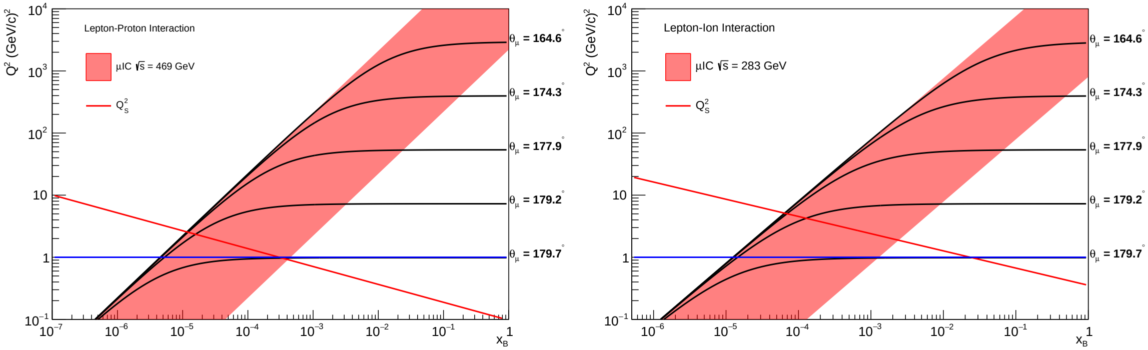
$$\sigma_{x,y} = \sqrt{\beta * \varepsilon / \gamma} \tag{2}$$

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

	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

Scattered Muon Reach



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

Summary

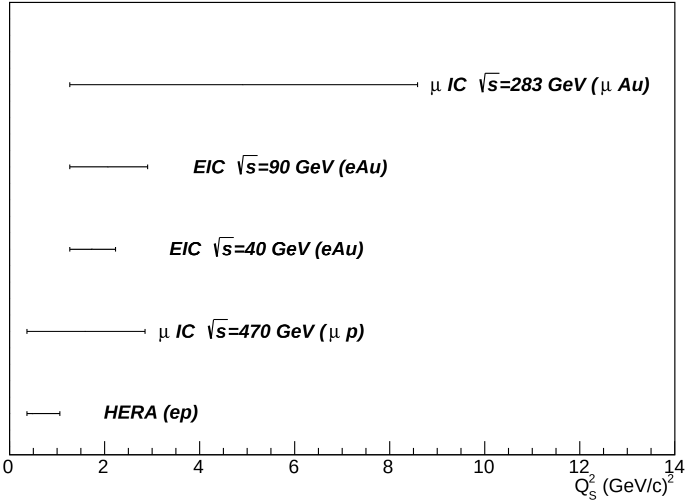
- Muon collider collaborations have clearly demonstrated need for future collider
- R&D on a high-energy, high-intensity source of muons is desirable
- EIC design underway via CD process
- Possible synergy between nuclear and particle physics community at the site of the future EIC
- Rich physics program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

Thank you!

Any Questions?

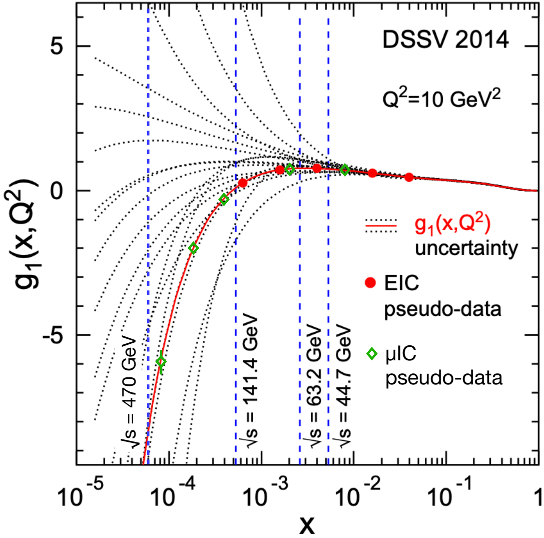
Saturation Scale

$x \leq 0.01$



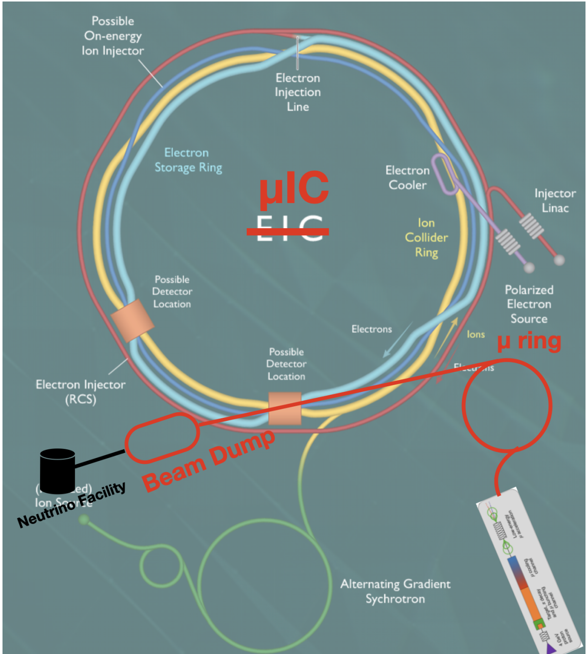
Saturation scale in the GBW model

g1

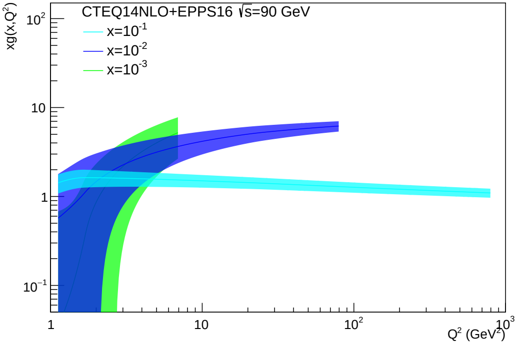


- Extraction of g1 from DSSV collaboration
- EIC pseudo-data 10 fb^{-1} sampled luminosity, μIC pseudo-data from 0.9 fb^{-1}
- Figure reproduced from: https://arxiv.org/abs/1708.01527

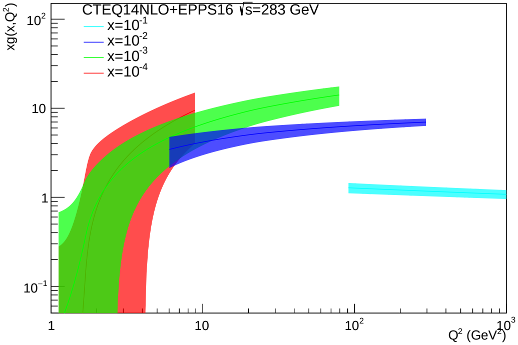
A μIC v2!


Possible On-energy Ion Injector
Electron Injection Line
Electron Storage Ring
μIC
~~EIC~~
Electron Cooler
Injector Linac
Ion Collider Ring
Possible Detector Location
Polarized Electron Source
Electrons
Ions
μ ring
Electrons
Possible Detector Location
Electron Injector (RCS)
Beam Dump
Neutrino Facility
(Polarized) Ion Source
Alternating Gradient Sychrotron
Low-energy μ acceleration
μ cooling channel
Target, π decay and μ bunching channel
4 GeV proton source

Measuring the Gluon PDF in Ions



EIC coverage for xg



μIC coverage for xg