Physics Potential, Accelerator Options, and Experimental Challenges of a TeV-Scale Muon-Ion Collider

D. Acosta, W. Li – Rice University

Outline

- MuIC Concept Overview
- Accelerator complex design considerations
- Luminosity considerations
- Revisiting the scientific potential
- Measurement of scattered muons
- Machine-Learning reconstruction method
- Summary

Recent Additional Motivation for Muon Accelerators

- From the HEPAP P5 Committee report released December 2023:

Exploring the Quantum Universe

2.3 The Path to a 10 TeV pCM

Realization of a future collider will require resources at a global scale and will be built through a world-wide collaborative effort where decisions will be taken collectively from the outset by the partners. This differs from current and past international projects in particle physics, where individual laboratories started projects that were later joined by other laboratories. The proposed program aligns with **the long-term ambition of hosting a major international collider facility in the US, leading the global effort** to understand the fundamental nature of the universe.

…

In particular, a muon collider presents an attractive option both for technological innovation and for bringing energy frontier colliders back to the US. The footprint of **a 10 TeV pCM muon collider is almost exactly the size of the Fermilab campus**. A muon collider would rely on a powerful multi-megawatt proton driver delivering very intense and short beam pulses to a target, resulting in the production of pions, which in turn decay into muons. This cloud of muons needs to be captured and cooled before the bulk of the muons have decayed. Once cooled into a beam, fast acceleration is required to further suppress decay losses.

…

Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, each producing world-class science while performing critical R&D towards a muon collider. At the end of the path is an unparalleled global facility on US soil. **This is our Muon Shot.**

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Perhaps a MuIC could be a first science demonstrator

Recent MuIC Workshop @ Rice, December 2023

- https://muic2023.rice.edu/

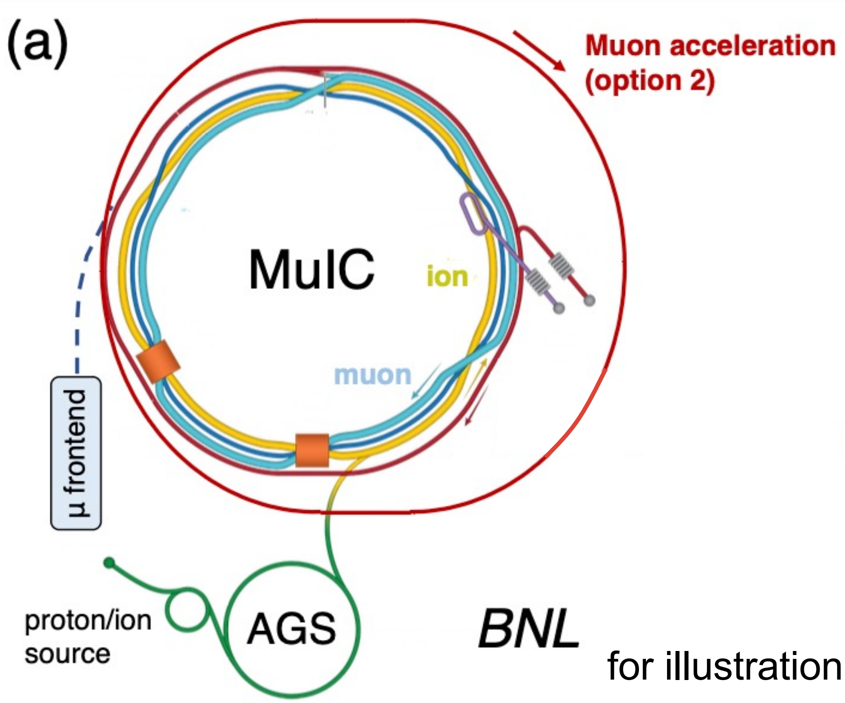
- Today's talk is mostly a synthesis of some of the things discussed at this workshop for MuIC planning, plus some works in progress

Concept Review: A Muon-Ion Collider at BNL

Acosta and Li, NIM A 1027 (2022) 166334

→ **Replace e with μ beam at EIC**

[10 GeV → 1000 GeV]



for illustration only

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

Achievable muon beam energy: **0.3Br**

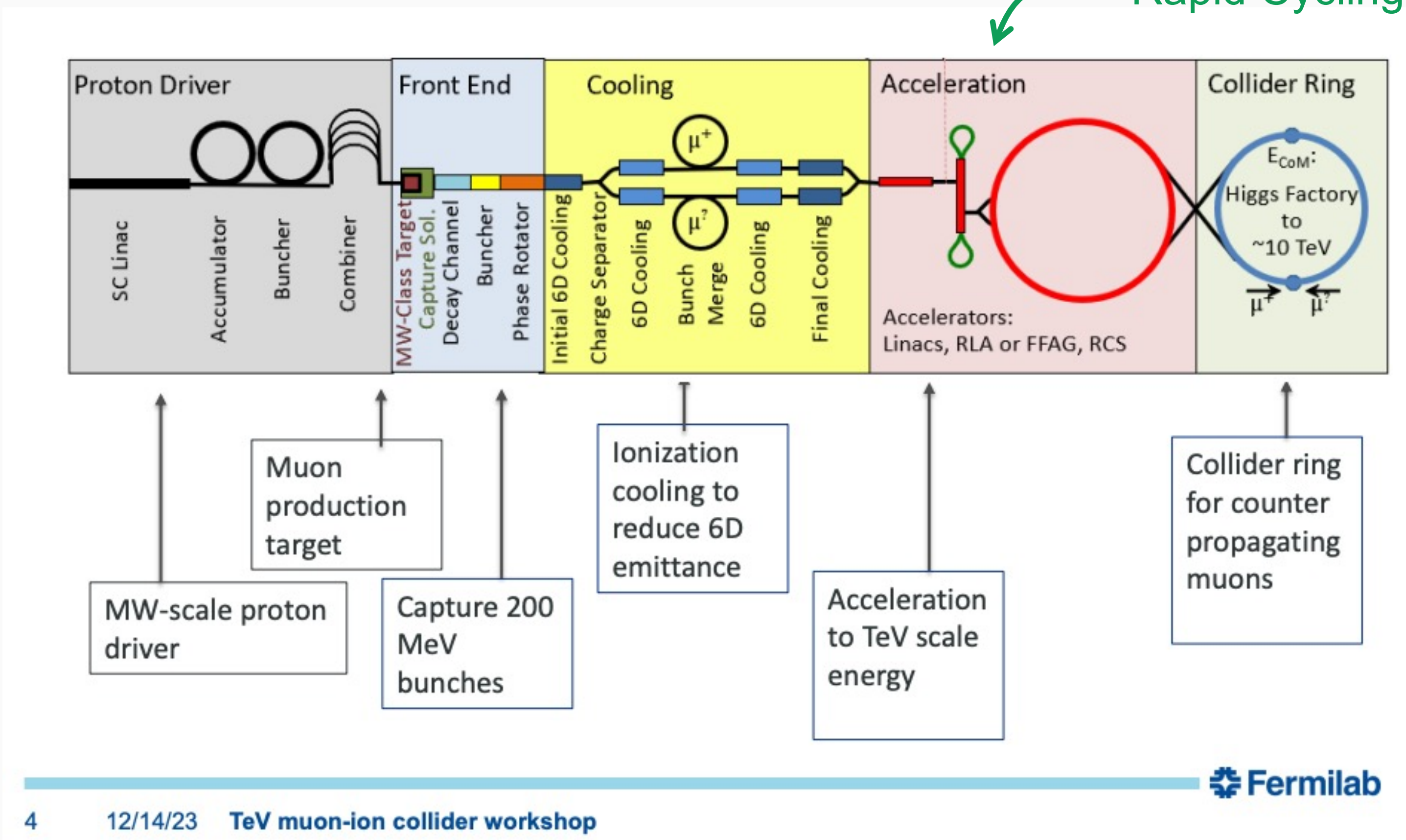
Parameter	1 (aggressive)	2 (realistic)	3 (conservative)
Muon energy (TeV)	1.39	0.96	0.73
Muon bending magnets (T)	16 (FCC)	11 (HL-LHC)	8.4 (LHC)
Muon bending radius (m)		290	
Proton (Au) energy (TeV)		0.275 (0.11/nucleon)	
CoM energy (TeV)	1.24 (0.78)	1.03 (0.65)	0.9 (0.57)

$\boxed{\sqrt{s} = 1 \text{ TeV !}}$ 7-8X increase over EIC energy

A Muon Collider Complex Overview

- From Diktys Stratakis, link

Recirculating Linacs,
Rapid Cycling Synchrotrons



A 10 TeV Muon Collider at Fermilab (Site Filler)

- From Diktys Stratakis → [link]

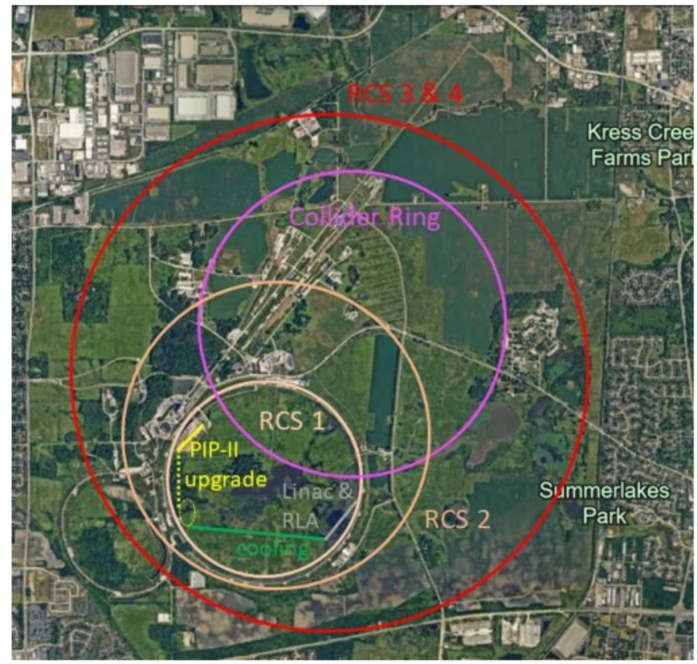
- Linac + RLAs get to 63 –173 GeV
- + RCS 1 gets to 0.45 TeV
- + RCS 2 gets to 1.7 TeV
- + RCS 3 + 4 gets to 5 TeV

Could become MuIC staging options

The accelerating rings are larger than the collider ring because of the need of rapid cycling magnets

Muon Collider at Fermilab

- **10 TeV MuC** concept is in place
- Proton source
  - Post-ACE driver -> Target
- Ionization cooling channel
- Acceleration (4 stages)
  - Linac + RLA → **173 GeV**
  - RCS #1 → **450 GeV (Tevatron size)**
  - RCS #2 → **1.7 TeV (col. ring size)**
  - RCS #3, 4 → **5 TeV (site fillers)**
- Collider ring, 10.5 km long
  - Could be combined with RCS #2



- We like to have a baseline design including a neutrino flux mitigation system

Fermilab

27 12/14/23 **TeV muon-ion collider workshop**

A 10 TeV Muon Collider at Fermilab (Site Filler)

- From Diktys Stratakis → link

- Just Linac + RLAs would allow
  - E_μ = 63 GeV ⇒ MuIC √s = 0.25TeV (<HERA)
  - E_μ = 173 GeV ⇒ MuIC √s = 0.4TeV (>HERA)
    - Extension for FNAL MuC design

- Diameter of RCS 1 is 6.3 km
  - E_μ = 0.45 TeV ⇒ MuIC √s = 0.7TeV (2× HERA)

- Diameter of RCS 2 is 10.5 km
  - E_μ = 1.7 TeV ⇒ MuIC √s > 1TeV (in principle)

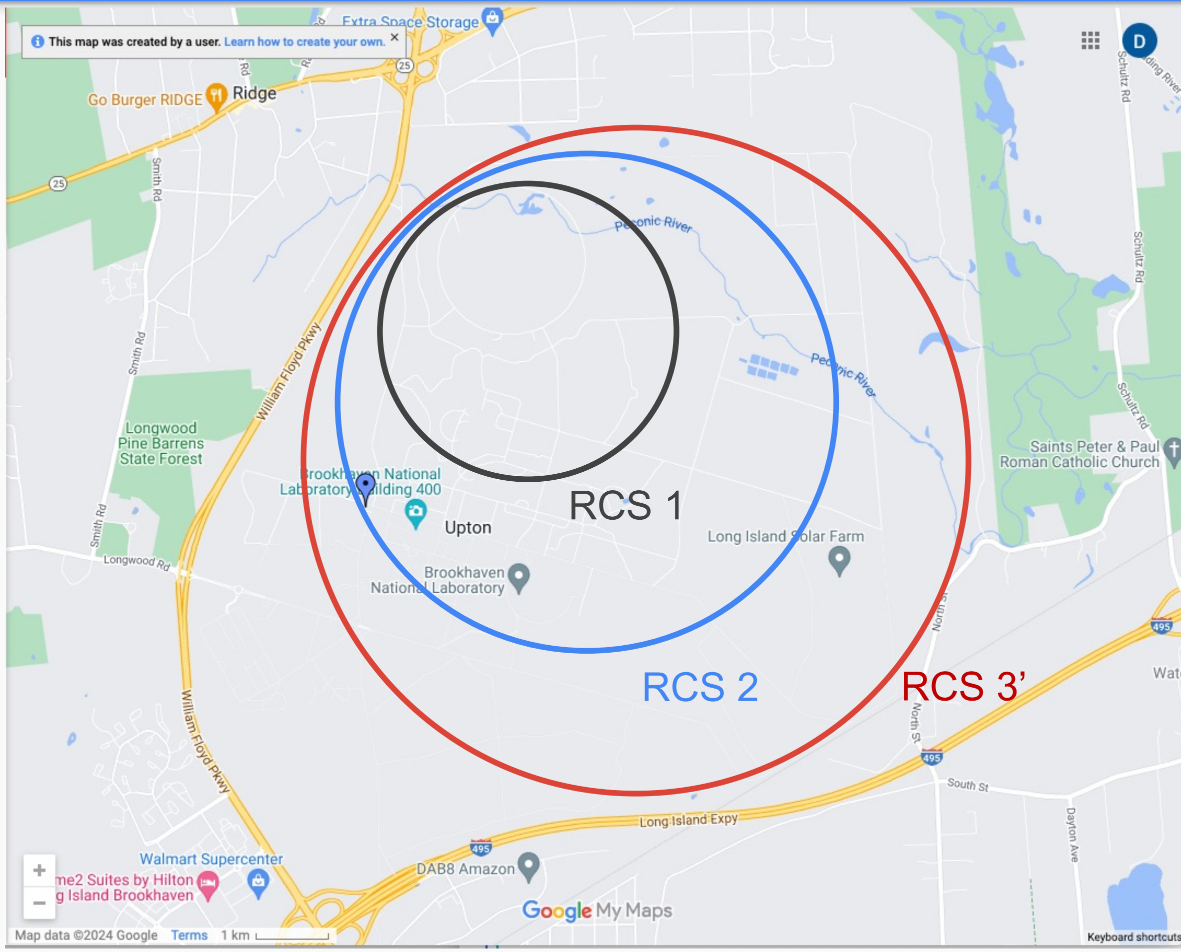
- Do these fit on BNL site?

MuC at Fermilab: Detailed parameters (D. Neuffer)

Parameter	Symbol	Unit	RCSI	RCS2	RCS3	RCS4
Hybrid RCS			No	Yes	Yes	Yes
Repetition rate	f_{ref}	Hz	5	5	5	5
Circumference	C	m	6280	10500	16500	16500
Injection energy	E_{inj}	GeV	173	450	1725	3560
Ejection energy	E_{ej}	GeV	450	1725	3560	5000
Energy ratio	E_{ej}/E_{inj}		2.60	3.83	2.06	1.40
Decay survival rate	N_{ej}/N_{in}		0.85	0.83	0.85	0.89
Acceleration time	T_{acc}	ms	0.97	3.71	8.80	9.90
Revolution period	T_{rev}	μs	21	35	55	55
Number of turns	N_{turn}		46	106	160	180
Required energy gain per tum	ΔE	GeV	6	12	11.5	8.0
Average accel. Gradient	G_{avg}	MV/m	0.96	1.15	0.70	0.48
Bunch population at injection	N_{in}	10^{12}	3.3	2.83	2.35	2.0
Bunch population at ejection	N_{ej}	10^{12}	2.83	2.35	2.0	1.8
Vertical norm. emittance	$\varepsilon_{v,N}$	mm-mrad	25	25	25	25
Horiz. norm. emittance	$\varepsilon_{h,N}$	mm-mrad	25	25	25	25
Long, norm. emittance	$\varepsilon_{z,N}$	eV-s	0.025	0025	0.025	0.025
Total straight length	L_{str}	m	1068	1155	2145	2145
Total NC dipole length	L_{NC}	m	5233	7448	10670	8383
Total SC dipole length	L_{sc}	m		1897	3689	5972
Max. NC dipole field	B_{NC}	T	1.80	1.80	1.80	1.80
Max. SC dipole field	B_{SC}	T		12	15	15
Ramp rate	B'	T/s	1134	970	440	363
Main RF frequency	f_{rf}	MHz	1300	1300	1300	1300
Total RF voltage	V_{rf}	MV	6930	13860	13280	9238

Fermilab

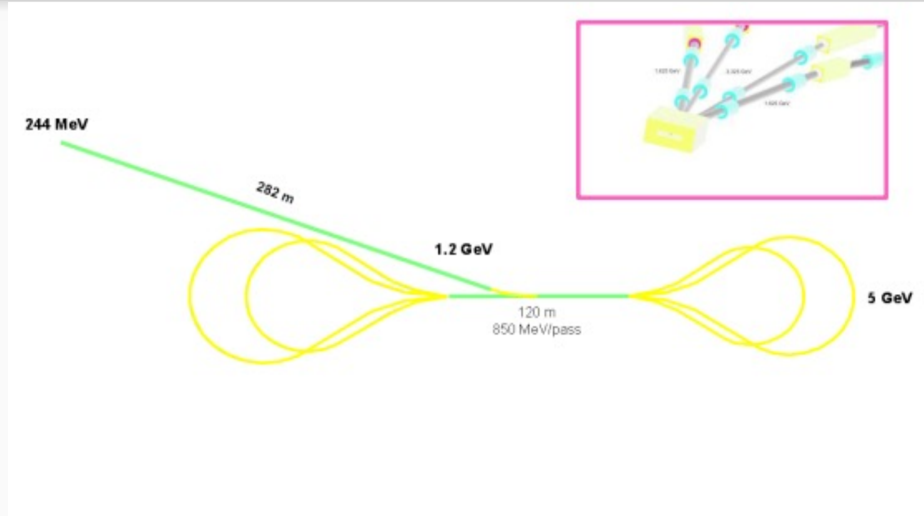
BNL Site Filler – Max Size of Accelerating Rings



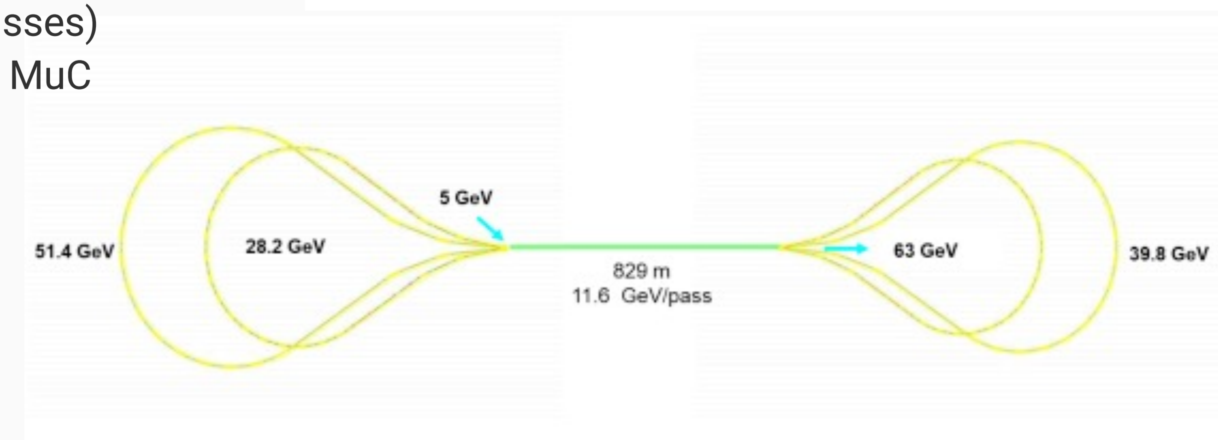
- Maximum accelerator size on BNL site:
  - D ≈ 4.45 km
  - Circumference: 14 km
- Can fit RCS 2 at 10.5 km
- In principle could fit up to a slightly reduced RCS 3’ to go to E_μ ~3 TeV
- RCS 1 achieves √s = 0.7 TeV and RCS 2 √s >1 TeV
- RLAs size are comp. to RCS 1

Recirculating Linear Accelerators

- Linac + RLA 1
  - 0.25 → 1.2 GeV
  - 1.2 → 5 GeV (5 passes)



- RLA 2
  - 5 GeV → 63 GeV (4.5 passes)
  - Up to 173 GeV for FNAL MuC



MuIC Configurations, BNL

Parameter	BNL options → MuIC			
$\sqrt{s_{\mu p}}$ (TeV)	0.33	0.74	1.0	→ **2.0**
~~$L_{\mu p}$ (10^{33}cm^{-2}s^{-1})~~	~~0.07~~	~~2.1~~	~~4.7~~	
Int. Lumi. (fb^{-1}) per 10 yrs	6	178	400	
	Muon			Proton
Beam energy (TeV)	0.1	0.5	0.96	0.275 → **1.0**
N_b (10^{11})	40	20	20	3
f^{μ}_{rep} (Hz)	15	15	15	
Cycles per μ bunch, N^{μ}_{cycle}	1134	1719	3300	
$\varepsilon^{*}_{x,y}$ (μm)	200	25	25	0.3
$\beta^{*}_{x,y}$ @IP (cm)	1.7	1	0.75	5
Trans. beam size, $\sigma_{x,y}$ (μm)	48	7.6	4.7	7.1

Staging: RLAs + RCS1 + RCS2

Muon Collider parameters + BNL/EIC and LHC proton beam parameters

Acosta et al., JINST 18, P09025 (2023)
Taken from MuC parameters and hadron ring

← √s

Lumi unrealistic (see later)

← Beam energies

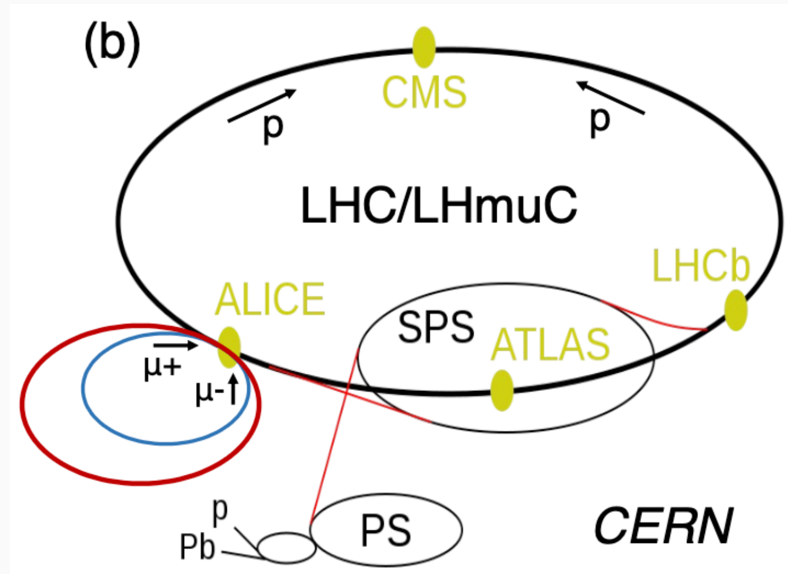
Staging options reduce number of acceleration stages required for muon beam

Symmetric 1 TeV collider.

A CERN "LHmuC" Option

Parameter	LHmuC	
$\sqrt{s_{\mu p}}$ (TeV)	$\boxed{6.5}$	
$L_{\mu p}$ (10^{33}cm^{-2}s^{-1})	~~2.8~~ unrealistic	
Int. Lumi. (fb^{-1}) per 10 yrs	237	
	Muon	Proton
Beam energy (TeV)	1.5	7
N_b (10^{11})	20	2.2
f^{μ}_{rep} (Hz)	12	
Cycles per μ bunch, N^{μ}_{cycle}	3300	
$\varepsilon^*_{x,y}$ (μm)	25	2.5
$\beta^*_{x,y}$ @IP (cm)	0.5	15
Trans. beam size, $\sigma_{x,y}$ (μm)	3	7.1

- Accommodate also a μp collider option if an initial 1.5+1.5 TeV $\mu^+\mu^-$ collider is sited at CERN



- Equivalent √s would actually exceed that of a 3 TeV $\mu^+\mu^-$ collider

Comments on Luminosity

- Ketenoglu et al. (Mod. Phys. Lett. A 37 (2022) 2230013) discuss that previously listed MuIC beam-beam tune-shifts are too high, and obtain lower values by lowering N_μ by factor 100 to get: $L \approx 10^{31} - 10^{32}$ Hz/cm^2

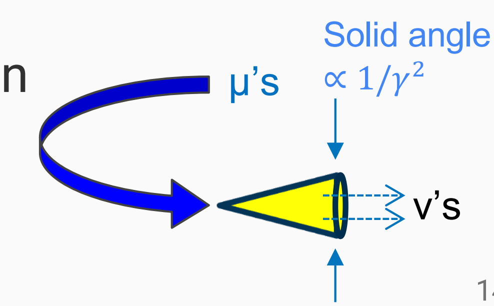
- Christoph Montag at the MuIC workshop made similar remarks in his talk
  - Space charge effects, intrabeam scattering (down factor 240)
  - Beam-beam effects (reduce by factor 100, but could increase μ bunches by 100)
  - Hadron beam emittance growth from muon replacement
  - Suggests increasing beam emittances, lowering muon bunch charge by factor 7, and using 1200 proton bunches (colliding with one at a time)
  - Luminosity reduced by factor 100 : $L \approx 5 \times 10^{31}$ Hz/cm^2
  - Larger beam sizes will lead to challenges for IR design and reduced detector acceptance
  - But effects improve at higher beam energy
  - Colliding with multiple proton bunches at a time also could increase luminosity ($\approx 10^{32}$)

- On the plus side:
  - Increasing emittance may relax cooling requirements
  - Lowering N_μ decreases neutrino radiation background vs. MuC

Neutrino Radiation Background

- Collimated beams of neutrinos from muon decays exist along beam line
- For neutrinos near surface, those that interact just before exiting ground can pose a long-term radiation dose for stationary objects
- Long straight sections further intensify this radiation
- The radiation grows with E, and the collimation effect as E^2
  - Hence studies to place ring deep underground for wider spread of radiation at surface
- For a 1 TeV MuIC with a single muon beam compared to a 10 TeV muon collider, the overall radiation hazard is reduced by a factor:
  - 2 (one beam) × 10^3 (energy dependence) × 10-100 (bunch charge reduction) ≈ **10^5**

- Radiation hazard is much less of a concern in comparison
- But is it negligible?



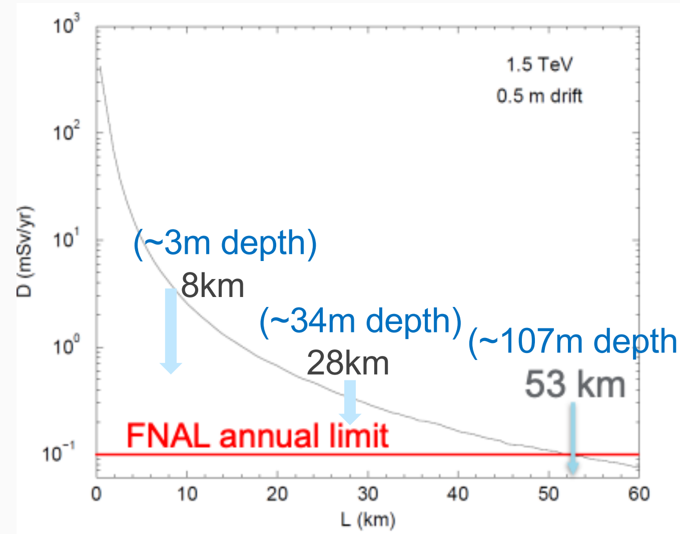
Neutrino Radiation Background

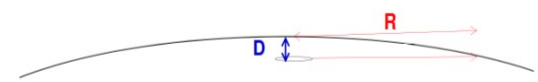
N.Mohkov, Snowmass MC Workshop 2022

- Dose vs distance traveled in soil for 1.5 TeV MC to meet 0.1 mSv/yr from just 0.5m straight section →
- MuIC at BNL might need ~50m straight section at IR? (100X longer!)
- Bunch intensity reduction for MuIC: 10 – 100X
- Energy reduction factor for 1 TeV: $(1.5)^3$ = 3.4X
- ⇒ Still need significant depth: ~34 m

√s = 0.74 TeV

- Lower beam energy to ~0.5 TeV (0.5^3 → 10X)
  - ⇒ Depth ~3m (i.e. near surface)
- Or lower beam energy to 0.7 TeV (0.7^3 → 3X), and reduce straight sections to < 15 m (3.3X) [10X overall]





$R = \sqrt{2R_{earth}D}$

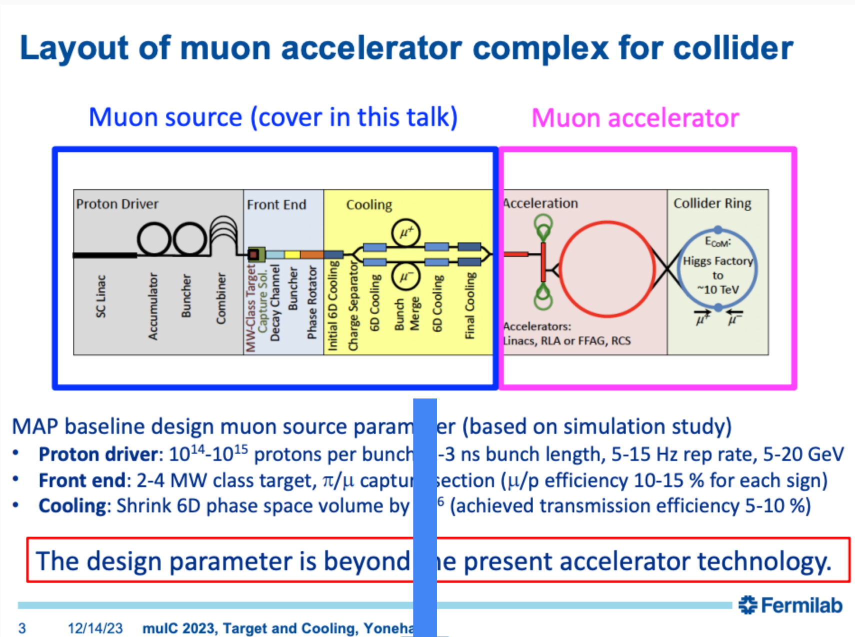
	$\sqrt{s}$ (TeV)	0.5	1	2	3	4
	$N \times 10^{21}$	0.2	0.2	1.2	1.2	1.2
1 mSv	R (km)	0.4	1.1	6.5	12	18
	D (m)	≤1	≤1	3.3	11	25
0.1 mSv	R (km)	1.2	3.2	21	37	57
	D (m)	≤1	≤1	34	107	254

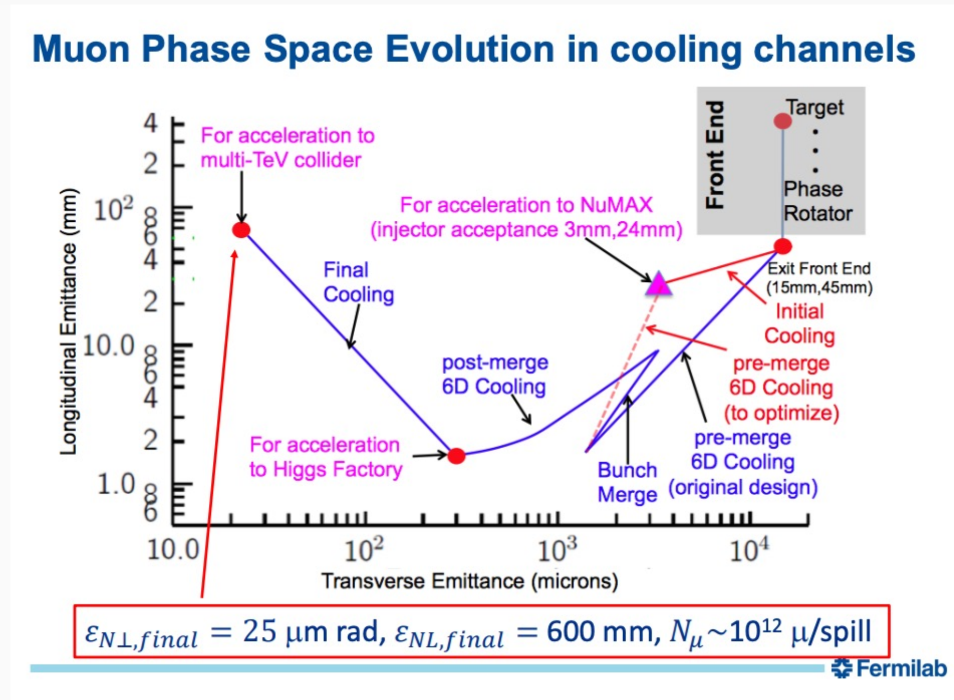
Flip side of neutrino background

- Turning the radiation argument around, can a highly collimated neutrino beam be useful for a high-energy neutrino DIS experiment?
    - Perhaps with more data than collected in the past, if not in energy, for a fixed target experiment?

Muon Cooling

- From Katsuya Yonehara, [link]





- Ionization cooling + acceleration
- RF cavities
- High field solenoids (10's of T)

Key design parameter in ionization cooling

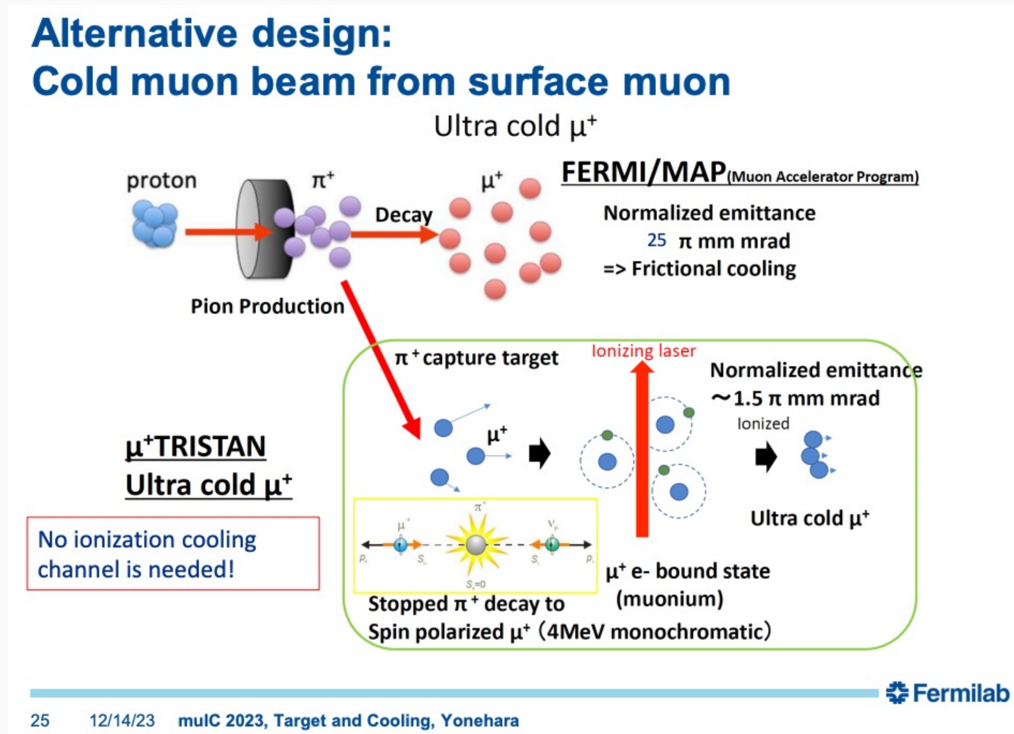
Heated by multiple sc

- **Low Z ionization absorber:** Longer radiation length is better for cooling
- **RF cavity as energy loss compensation:** Higher gradient is better for cooling
- **Magnet to make low beta function at absorber:** Stronger field is better for cooling

Interesting Alternative Cooling Idea for μ+ Only

- From Katsuya Yonehara, [link]

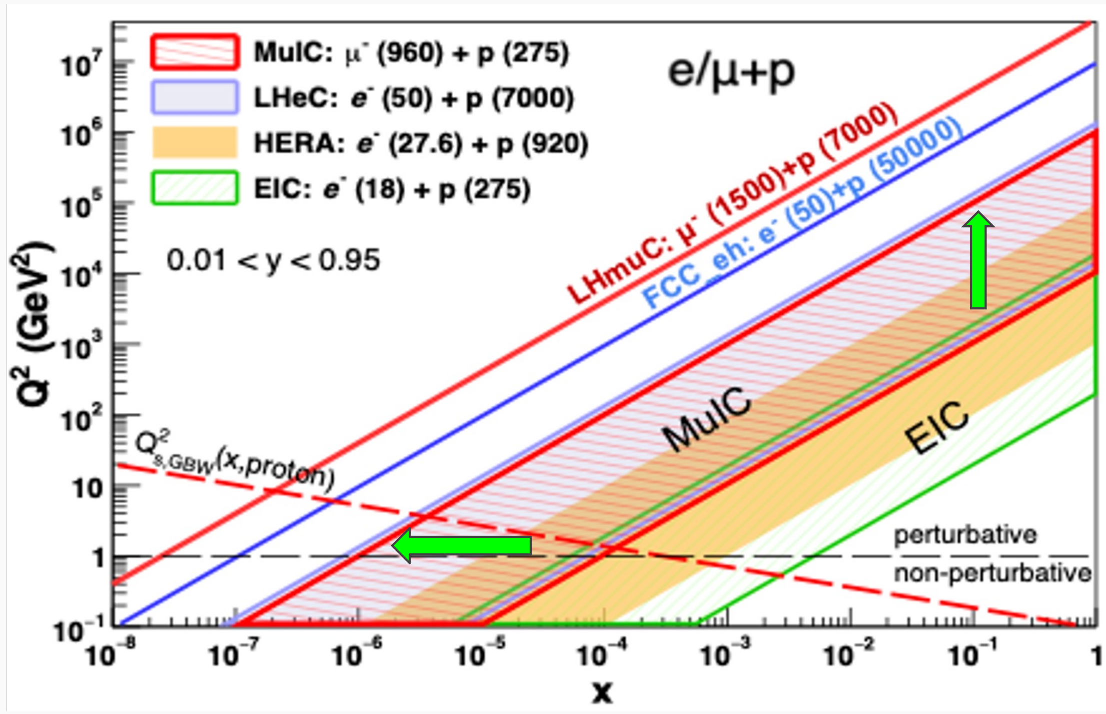
- Capture μ+ with electrons in aerogel (so ultracold), ionize with laser
- No ionization cooling needed!
- Under study at KEK J-PARC for g – 2 experiment
  - P.Bakule et al., arXiv:1306.3810
  - J.Beare et al, arXiv:2006.01947
- Could create 2×10^{10} μ+
  - 100X less than initial Acosta/Wei numbers, but in direction of lowering neutrino bkg
- Could also achieve up to 50% polarization!
- Very small emittance, 1.5μm



Revisiting Physics Opportunities

DIS Reach in x and Q^2 for ℓp Collisions

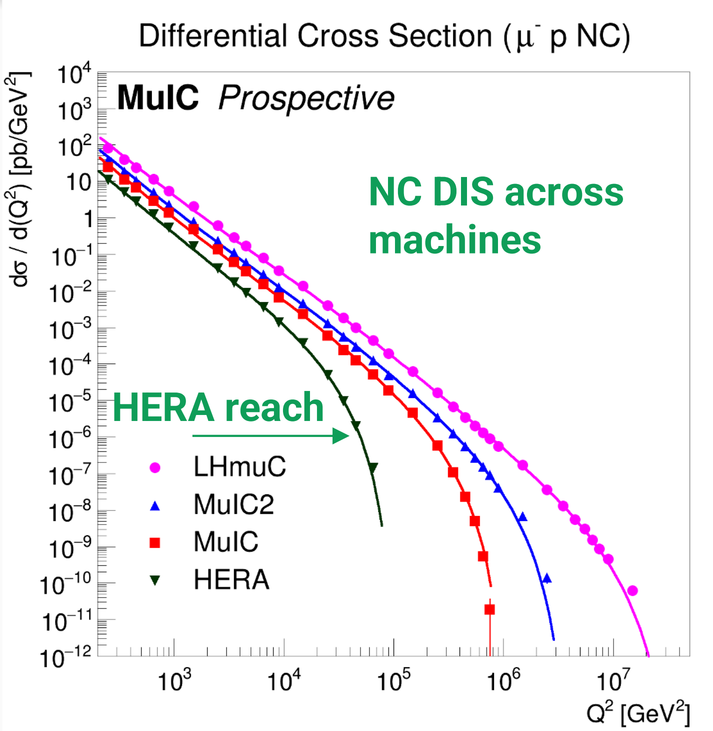
- DIS Expands DIS reach at high Q^2 and low x by 1–3 orders of magnitude beyond HERA and the EIC
- Coverage of MuIC at BNL is nearly identical with that of the proposed Large Hadron electron Collider [1] (LHeC) at CERN with 50 GeV e⁻ beam (with complementary kinematics)
- Potential to see gluon saturation [2] in the proton
- Coverage of a mu-LHC collider at CERN (LHmuC) would significantly exceed even that of the FCC-eh option of a 50 TeV proton beam with 50 GeV e⁻ beam

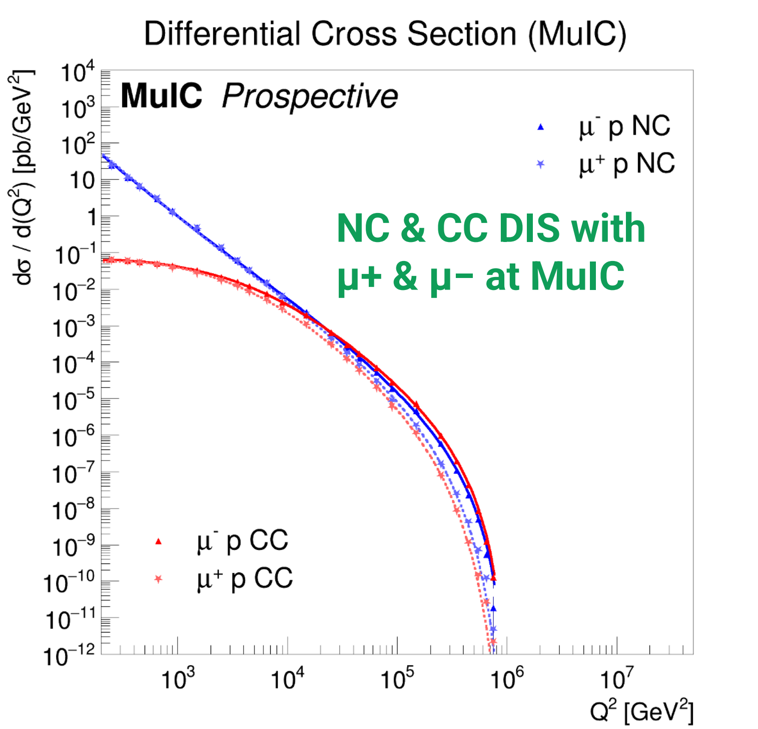


[1] LHeC: 2021 J. Phys. G: Nucl. Part. Phys. 48 110501

[2] GBW model: Phys. Rev. D 59, 014017 (1998)

DIS Differential Cross Sections in Q^2





Computed with Pythia8 and NNPDF2.3 PDF set, $0.1 < y < 0.9$

- However, a MuIC luminosity of $\sim 5\times10^{31}$ is at the level of the previous HERA program, as well as Tevatron Run 1, leading to $O(1)$ fb^{-1} in 10 years
- But MuIC can still probe Q^2 well beyond HERA and the electroweak scale, as well as low x
- The luminosity would be less than that projected for the LHeC, however

MuIC Potential Physics Program

- As a DIS collider with $\sqrt{s} \approx 1$ TeV, the potential physics program at a MuIC is an extension of the EIC physics program to higher energies and is quite similar to that of the proposed LHeC:
  - Nucleon structure (PDFs)
  - Nuclear physics
  - QCD
  - Electroweak physics
  - Higgs physics
  - Top quark physics
  - BSM searches

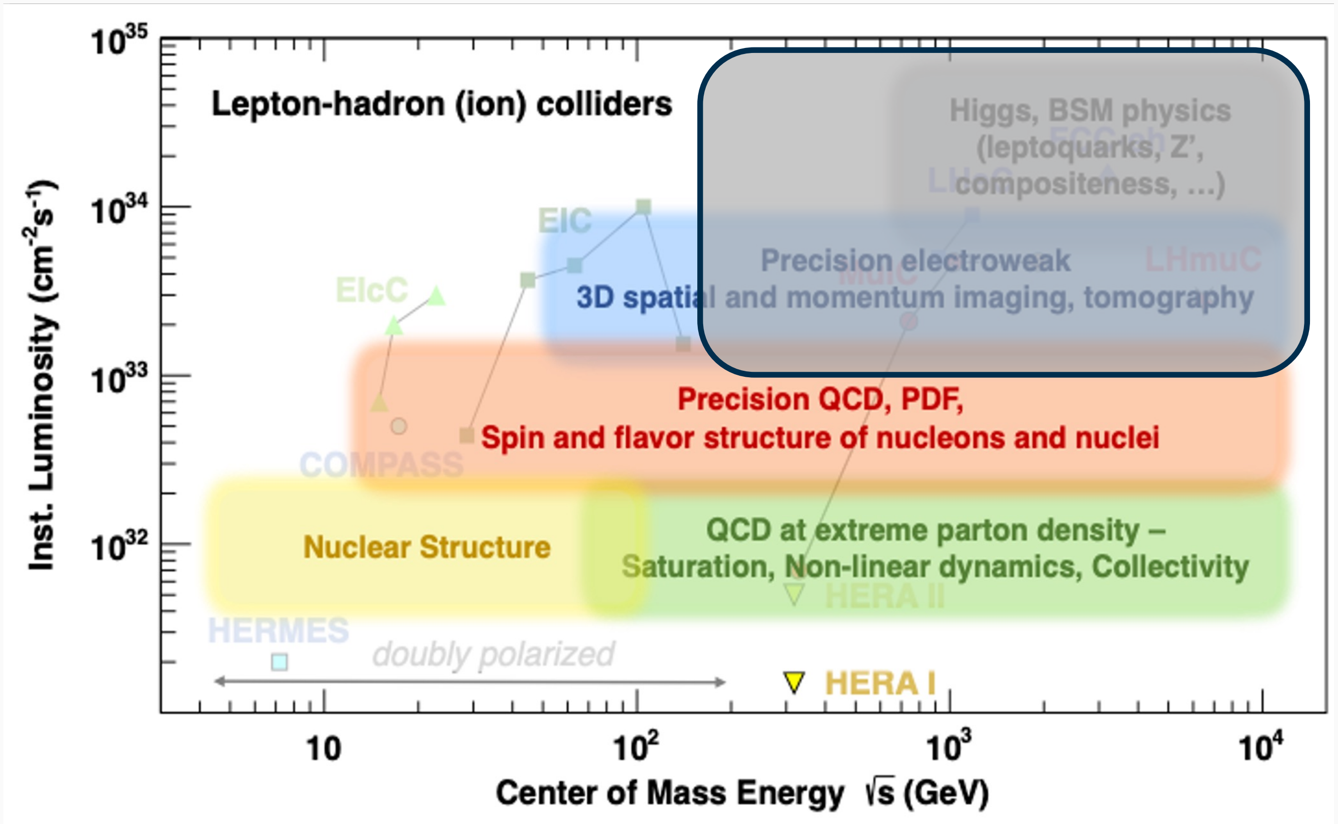
  But this is luminosity driven

- But with some distinctions:
  - Polarization of both beams possible at BNL
    - Spin structure functions in new regimes
  - Different lepton flavor probe
    - Potential new sensitivity to lepton flavor universality violations
  - Significant experimental background conditions

For the EIC physics case, see:
"Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all", A. Accardi et al., Eur. Phys. J. A 52 (2016) 268

For the LHeC physics case, see:
"The Large Hadron–Electron Collider at the HL- LHC", P Agostini et al, 2021 J. Phys. G: Nucl. Part. Phys. 48 110501

DIS Evolution and Physics Landscape

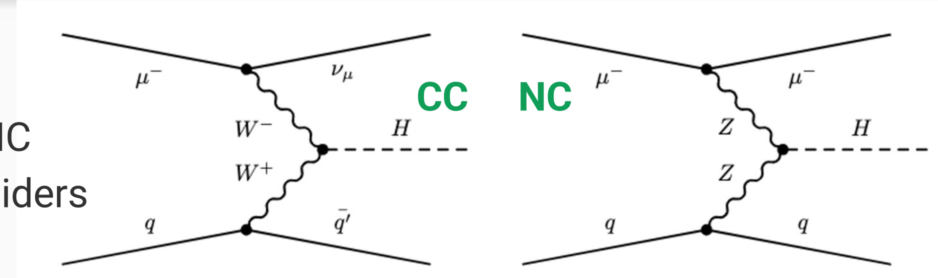


Precision electroweak, Higgs, and BSM physics would be compromised if luminosity limited to $<10^{32}$

Higgs Physics with MuIC

JINST 18 P09025 (2023)

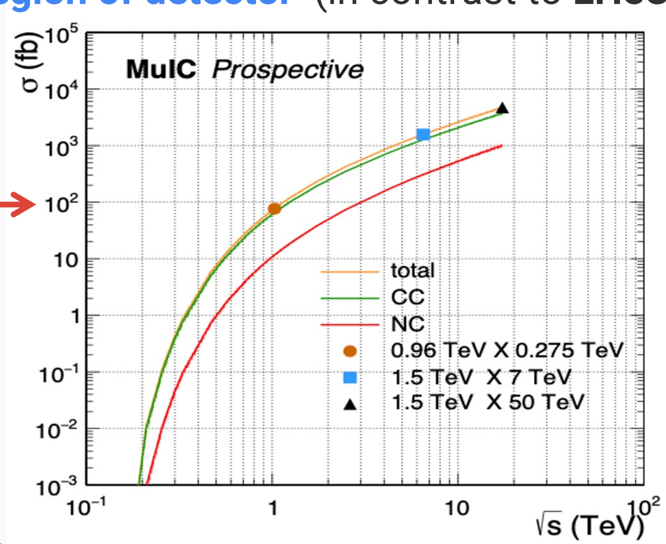
- Vector Boson Fusion mode
  - **σ grows with √s**, with CC exchange larger than NC
  - Cross section comparable to LHeC and $\mu^+\mu^-$ colliders
  - Polarization can increase cross section

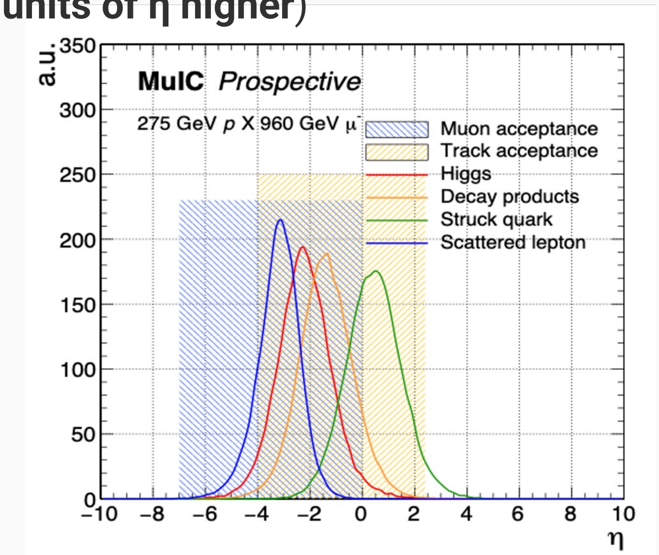


- Acceptance
  - All final state objects, other than the muon, are in **central region of detector** (in contrast to **LHeC: +3 units of η higher**)

But VBF Higgs xsec is < 100 fb at MuIC

Computed with MadGraph

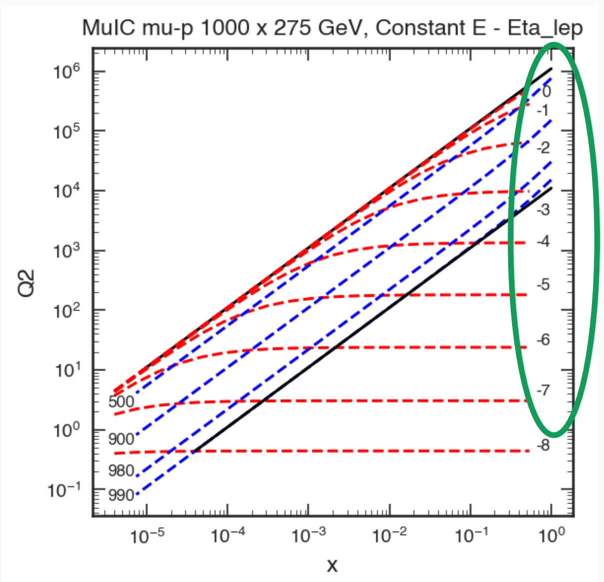




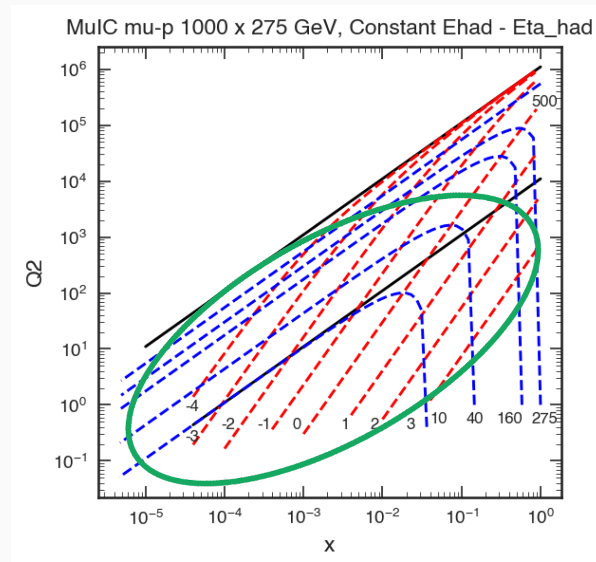
Detector Considerations and Challenges

MuIC Kinematics (E,η in Q^2-x plane)

- Scattered muon



Scattered jet



- Backward tagging of muons to η= −7

Hadronic system −5 < η < 2.4

Quite different from EIC kinematics

A Far Backward Muon Spectrometer Design Study

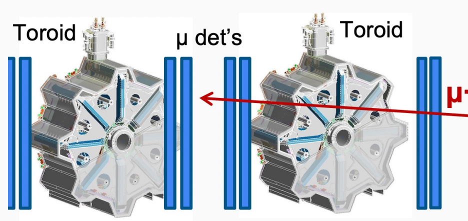
Work in progress: DA, O.Miguel Colin, M.Munyi

- To begin to address some of the feasibility questions for a MuIC experiment, we initiated a GEANT-4 study of a muon spectrometer
  - Studied TeV muon scattering and energy loss in the tungsten shielding cone (covers |η|> 3)
    - In case we cannot entirely remove it, or want to apply the design also for a Muon Coll. experiment to tag NC VBF processes (see next slide)
- Exploring using an (ATLAS) toroidal magnet design for bending as a strawman design
  - Will study the necessary detector resolution for precision momentum measurements

ATLAS-PHOTO-2022-007-6

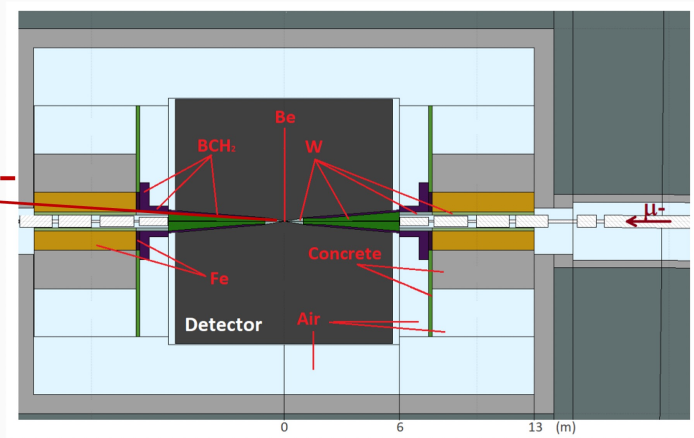
Layout adapted from Collamati et al. on $\mu^+\mu^-$ collider: arXiv:2105.09116

ATLAS Endcap Toroids



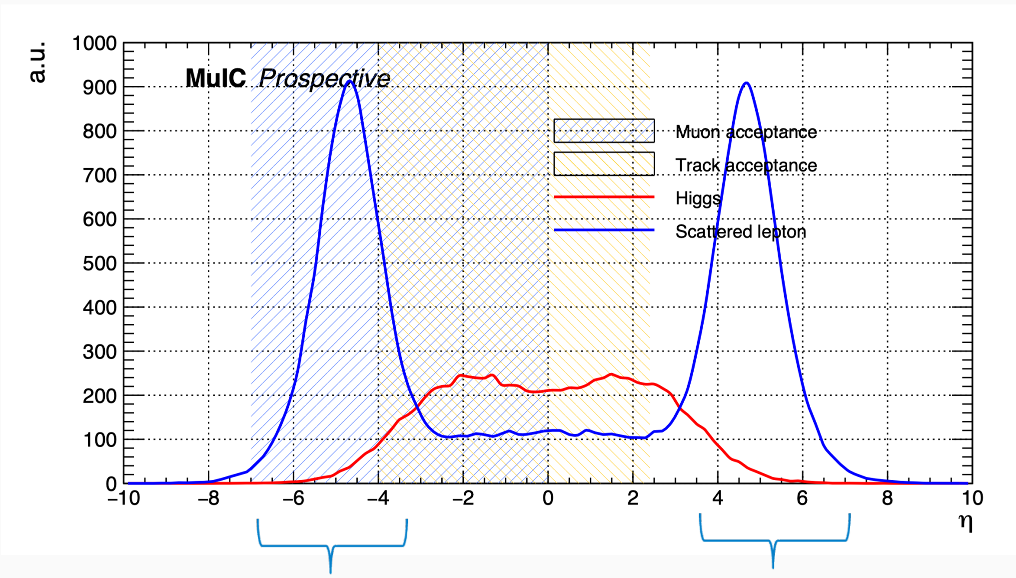
Option 1:
Z = 300 m $-6.35 < \eta < -4.75$
Z = 60 m $-4.75 < \eta < -3.15$

Distance not to scale



VBF Higgs Production for a 10 TeV $\mu^+\mu^-$ Collider

- Pseudorapidity distribution for scattered lepton in VBF Higgs production
- 5 x 5 TeV

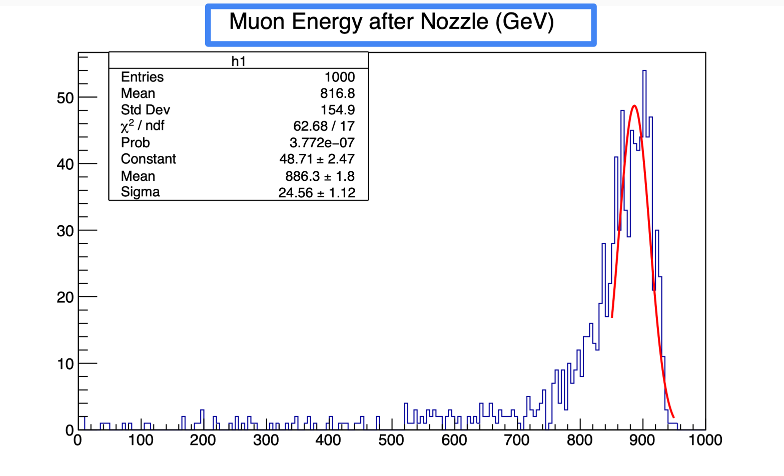


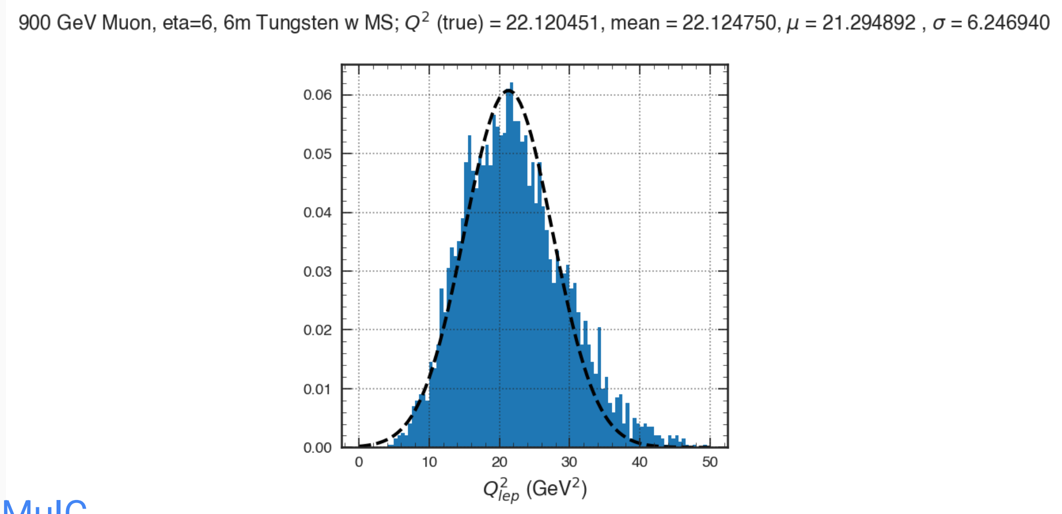
- Scattered muons in far backward and forward regions similar to MuIC

Example of Impact on Muon Measurements

Work in progress: DA, O.Miguel Colin, M.Munyi

- A 1 TeV muon loses ~20% of its energy going through a 6m tungsten cone, with a long tail
- Also, multiple scattering smears the outgoing angle



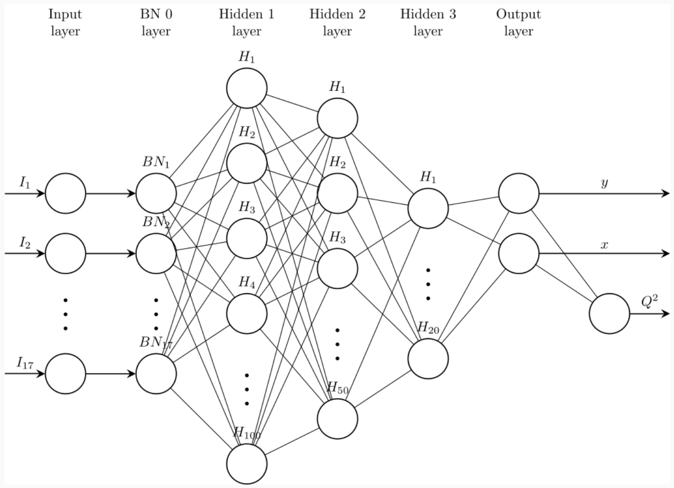


- This affects measurements:
  - e.g. 30% smearing for Q^2 = 20 GeV^2 → from reconstructed muon quantities
  - So ideally we would like not to have the shielding cone in the backward direction for MuIC

Machine Learning Methods to Reconstruct DIS Variables

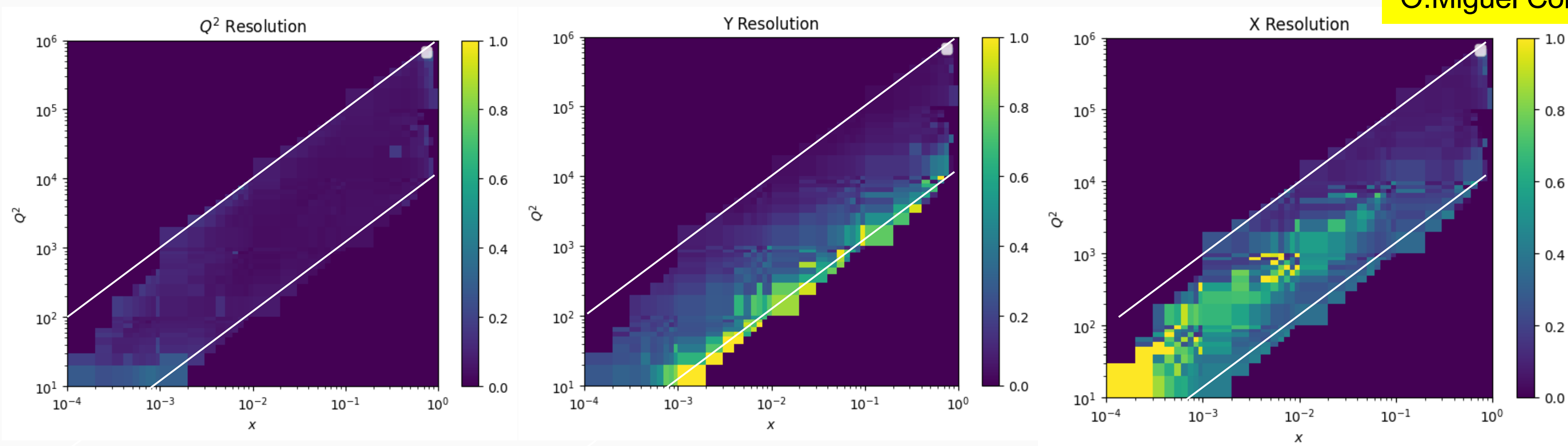
Work in progress:
O.Miguel Colin, A.Amarilla

- The lepton method, or any of the other well-known DIS approaches (DA, JB) do not use all of the available scattering information, and have (different) regions of good and poor resolution
- We started using a machine-learning approach to reconstruct Q^2, x, and y as a proxy for the best method we can use
- Applying this to gen level final state particles, smeared by detector resolutions
- Input variables:
  - muon energy (outgoing)
  - muon eta (outgoing)
  - Shower - Sum of energy deposited in calorimeter
  - Shower - Sum of momentum in x direction
  - Shower - Sum of momentum in y direction
  - Shower - Sum of momentum in z direction
  - Shower - Sum of (energy - momentum in z direction)
  - Reconstructed Jaquet-Blondel Angle (Direction of shower)
  - Reconstructed Lepton Method: Q^2, x, y
  - Reconstructed Jaquet-Blondel Method: Q^2, x, y
  - Reconstructed Double Angle Method: Q^2, x, y



Machine Learning Methods to Reconstruct DIS Variables

Work in progress:
O.Miguel Colin, A.Amarilla



- Uses detector variable smearing as in [Acosta and Li, NIM A 1027 (2022) 166334](), but not yet any smearing from a shielding cone
- Aiming to get better resolution than any single standard approach
- Still a work in progress (e.g. need to improve x resolution)
- Can be used to optimize necessary detector resolutions and coverage

Other Experimental Concerns: Luminosity Measurement

- Luminosity measurement via the $\mu p \rightarrow \mu p \gamma$ process (analog to HERA and EIC measurement) would be challenging at a MuIC with the large BIB
  - **May already have a large γ flux even if all other charged particles are swept away**
  - **This also may plague roman pot measurements for scattered protons (?)**
- Find another normalization process?

Summary and Conclusions

- Taking beam effects into account, reducing the muon charge by a factor 100 from Acosta/Wei initial numbers, the MuIC luminosity is more realistically in the range $L = 10^{31} - 10^{32}$ Hz/cm^2 [leading to O(1 fb^{-1}) in 10 year program]
  - But we should explore all possibilities to achieve higher luminosity!
- A 1 TeV MuIC has much less neutrino radiation by factor ~10^5 compared to a 10 TeV collider, but it is not negligible
  - Placing a MuIC near ground level is consistent with reducing the muon charge 100X, with a beam energy up to ~0.5 TeV, and/or limiting straight sections to < 50 m [Or more creative solutions as for the 10 TeV MC]
- A 0.7 TeV MuIC would require just one Rapid Cycling Synchrotron ring, while 1.0 TeV likely two accelerating rings.
  - These would fit on the BNL site along with RLAs (as with FNAL)
- The accelerators could equally well accelerate protons for a more symmetric machine (at the expense of a new hadron storage ring)
- For μ+ only, which is okay for DIS, an alternative (and simpler? cheaper?) way using laser ablation is in development to cool muons to get low emittance, and high polarization
- Physics program would be predominantly DIS studies, unless we can increase the luminosity
  - Higgs physics requires more luminosity
  - But PDFs measurements are an important ingredient for a future FCChh program (just as HERA was for LHC)

Backup