Physics Potential of a TeV-Scale Muon-Ion Collider

Darin Acosta, A. Amarilla, E. Barberis, P. Boyella, N. Hurley, W. Li, O. Miguel Colin, M. Munyi, Y. Wang, D. Wood and X. Zuo

RICE

Outline

- Future Collider Context
- MuIC Concept
- DIS potential
- QCD and EWK Couplings
- SM and BSM particle production
- Interesting experimental challenges at a MuIC
- Synergies

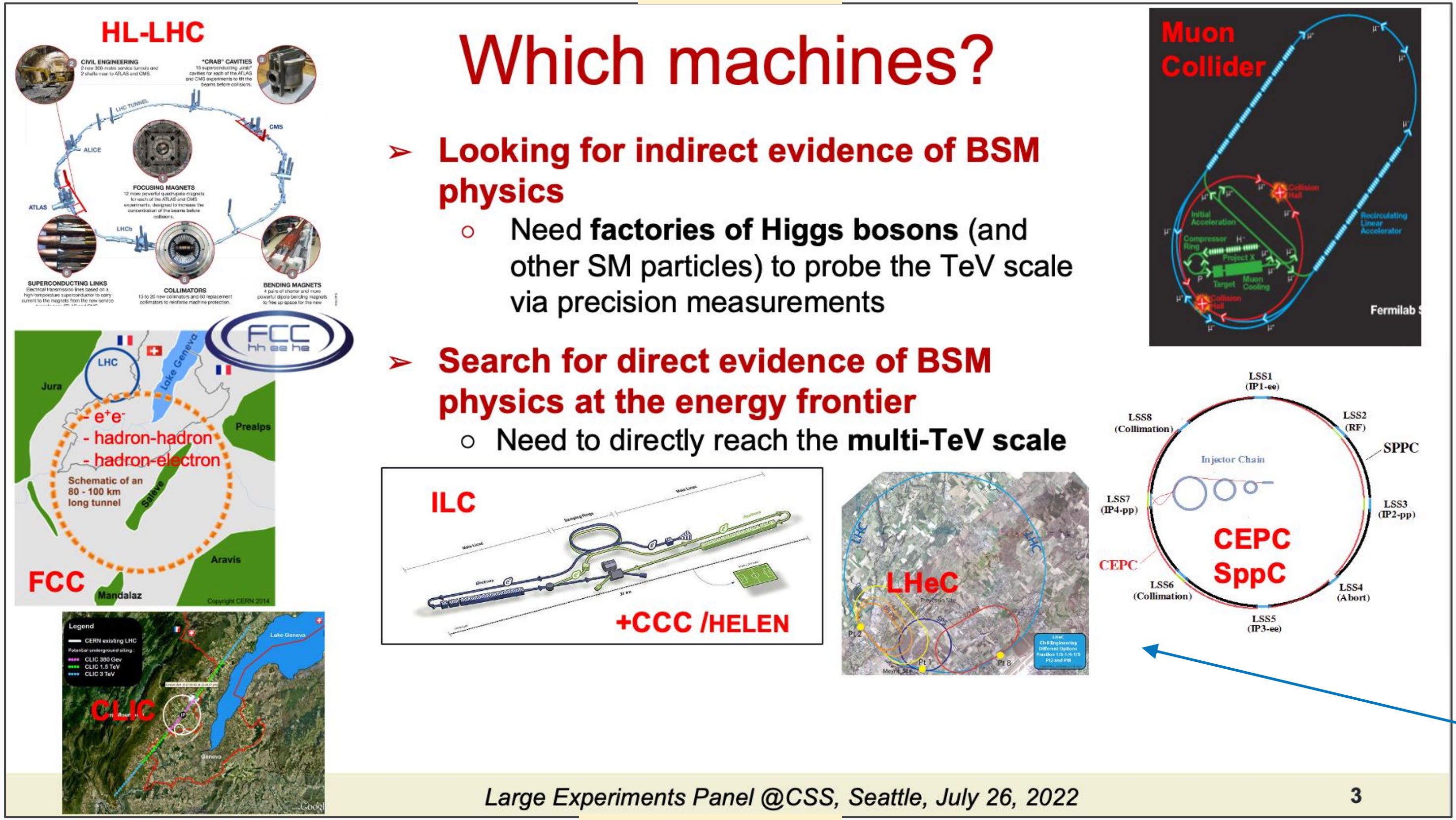
Focus of this talk is on the application of such a facility, not the feasibility or details of a muon accelerator and collider design (but the community is optimistic!)

Moreover, the MuIC concept is in its infancy, with a correspondingly small yet growing community (mostly students)

What Comes Next for an Energy Frontier Collider?

M.Narain, Snowmass:

Go high?



Get creative?

Go big?

DIS?

Go precise?

What Comes Next for an Energy Frontier Collider?

M.Narain, Snowmass:

Large Projects

Project	Construction Start date (yr)	Construction End date (yr)	Construction Cost B$
Higgs Factories			
CepC	2026	2035	12-18
CCC (higgs Fac)	2030	2040	7-12
ILC (higgs Fac)	2028	2038	7-12
CLIC	2041	2048	7-12
FCC-ee	2033	2048	12-18
Multi-TeV Colliders			
Muon Collider (3 TeV)	2038	2045	7-12
Muon Collider (10 TeV)	2042	2052	12-18
SppC	2043	2055	30-80
HE CCC	2055	2065	12-18
HE CLIC (3 TeV)	2062	2068	18-30
FCC-hh	2063	2074	30-50

An off-shore Higgs factory is Recomm. 2c of the 2023 HEPAP P5 committee report

Cost estimates from the ITF report by AF. Please refer to the document for explanations now they were estimated and associated caveats

Link to the report on AF wiki

US R&D toward a 10 TeV pCM collider is Recomm. 6 of the 2023 HEPAP P5 committee report

July 26, 2022

Motivation for Muon Accelerators

- From the HEPAP P5 Committee 2023 report:

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.

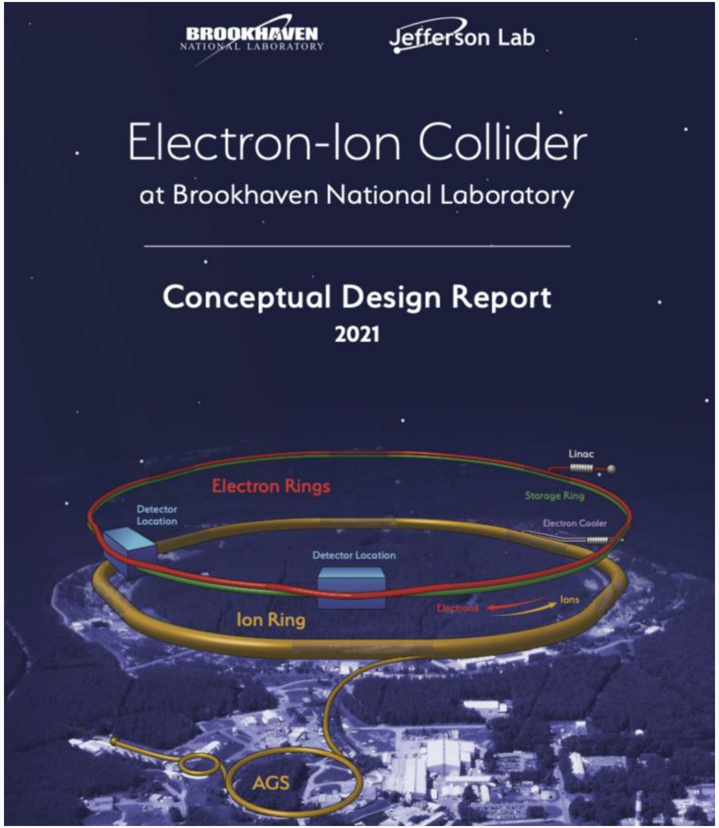
…

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.**

39

Perhaps a MuIC could be a first science demonstrator

New Collider Coming: The Electron-Ion Collider (EIC) at BNL



International facility already CD1 approved by the U.S. DOE Nuclear Physics program.

- Culmination of a 2 decade process
- Science to begin in the 2030s

EIC Conceptual Design Report recently released.
Initial detector design (ECCE) also selected.

Salient points:

- Electron beam energy up to 18 GeV
- Hadron beam energy up to 275 GeV
- $\sqrt{s}$ = 20 -- 140 GeV
- Luminosity 10^{33} -- 10^{34} Hz/cm^2
- Polarized electron, proton and ion beams (any species)

But what if we changed leptons? 🤔

A lot of interest in $\mu^+\mu^-$ colliders

Physics goals:

- ep and eN deep inelastic scattering
- Nucleon spin structure
- Gluon saturation scale (Q_S)

Muon-Ion Collider Concept and Motivation

- The concept of a muon-proton collider has been discussed in the literature since ~25 years ago

- Our recent focused proposal offers an upgrade successor to the EIC
  - **E_{lep} → 100X higher, √s → 10X higher**

- Leverage the Energy Frontier community interest for a muon collider and its associated technology, and apply toward a (first?) science demonstrator: **a muon-hadron collider**
  - Planning should start now, given a ~2 decade path to project approval…

- Basis of proposal for a MuIC at BNL:
  Acosta and Li, NIM A1027 (2022)

- MuIC science case further explored in Snowmass contribution:
  Acosta et al., 2023 JINST 18 P09025

  + some further works in progress by students

A Muon-Ion Collider – Who Ordered That?

Probe a **new energy scale** and nucleon momentum fraction in Deep Inelastic Scattering using a relatively compact machine (add new PDF data!)

- $\sqrt{s} \sim 1$ TeV
- Q^2 up to 10^6 GeV^2
- x as low as 10^{-6}

} **Well beyond the EIC**

i.e. extension of the EIC program and equivalent to the LHeC program, but with a muon accelerator

Provides a science case for a TeV muon storage ring demonstrator toward a multi-TeV μ+μ- collider:

- Precision PDFs in new regimes (incl. spin at BNL)
- QCD, including at extreme parton density
- Precision EWK and QCD measurements
- Higgs and other SM particle production
- BSM / LFUV sensitivity with an initial muon

} Luminosity depending

Facilitate the **collaboration of the nuclear and particle physics communities** around an innovative and forward-looking machine

Broad science program helps share costs, and re-use helps economize

Re-use existing facilities (e.g. Upgrade the EIC at BNL, or FNAL? or CERN?)

First MuIC Workshop, Rice U, December 2023

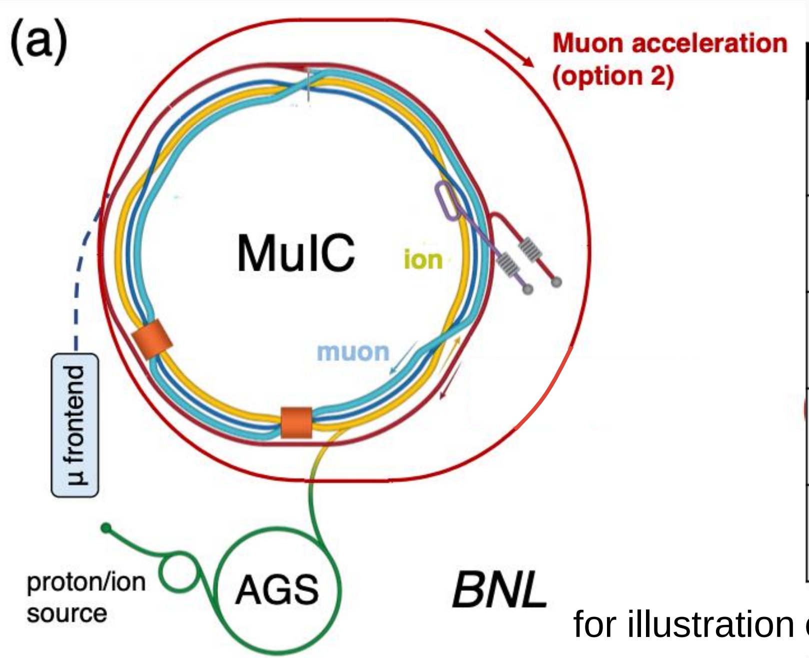
- Dedicated workshop held last December
- https://muic2023.rice.edu/

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) Au	0.9 (0.57)

$\sqrt{s}$ = 1 TeV !

7-8X increase over EIC energy

A Muon-Ion Collider at BNL – Parameters

Acosta et al., JINST 18, P09025 (2023)

Taken from MuC parameters and hadron ring

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

← √s

← Luminosity likely overestimated 10−100X (needs dedicated optimization)

← Beam energies

Staging options reduce number of acceleration stages required for muon beam

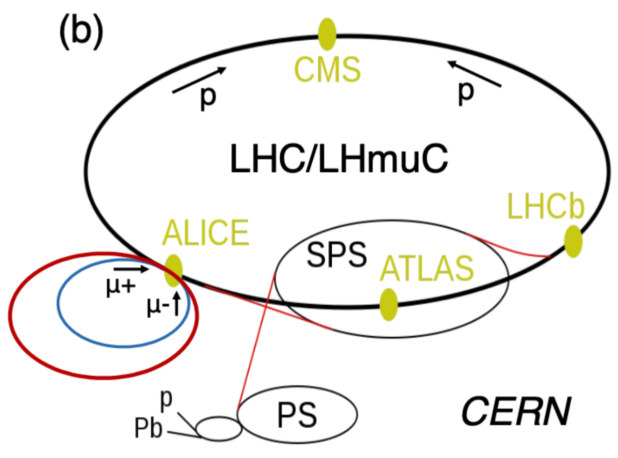
→ Symmetric 1 TeV collider?

A Muon-Ion Collider at CERN, “LHmuC”

Parameter	LHmuC	
$\sqrt{s_{\mu p}}$ (TeV)	6.5	
$L_{\mu p}$ (10^{33}cm^{-2}s^{-1})	2.8	
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

← Likely unrealistic

- Variation of the LHeC with a TeV muon beam replacing the 50 GeV electron beam
- Could accommodate a μp collider option if an initial 1.5+1.5 TeV $\mu^+\mu^-$ collider is sited at CERN (Intl. Muon Coll. Collab. design)

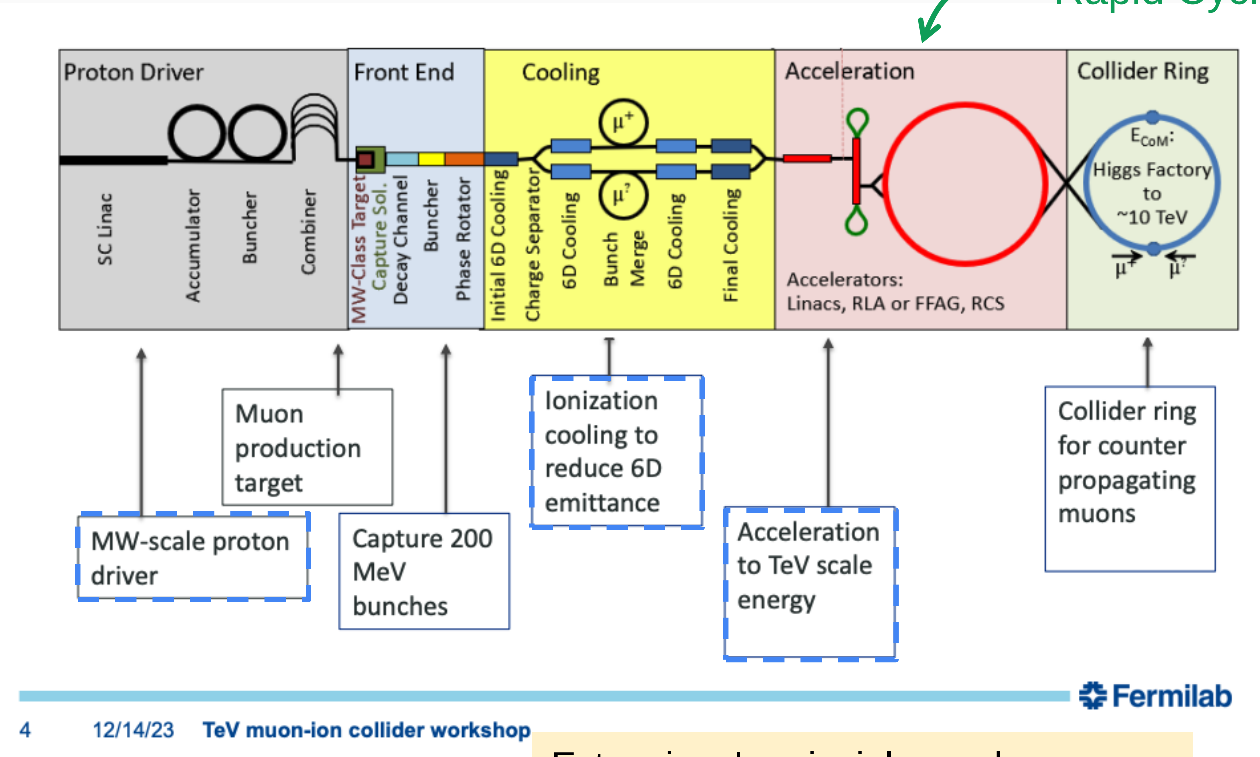


- Equivalent √s would actually exceed that of a 3 TeV $\mu^+\mu^-$ collider

A Muon Acceleration & Collider Complex

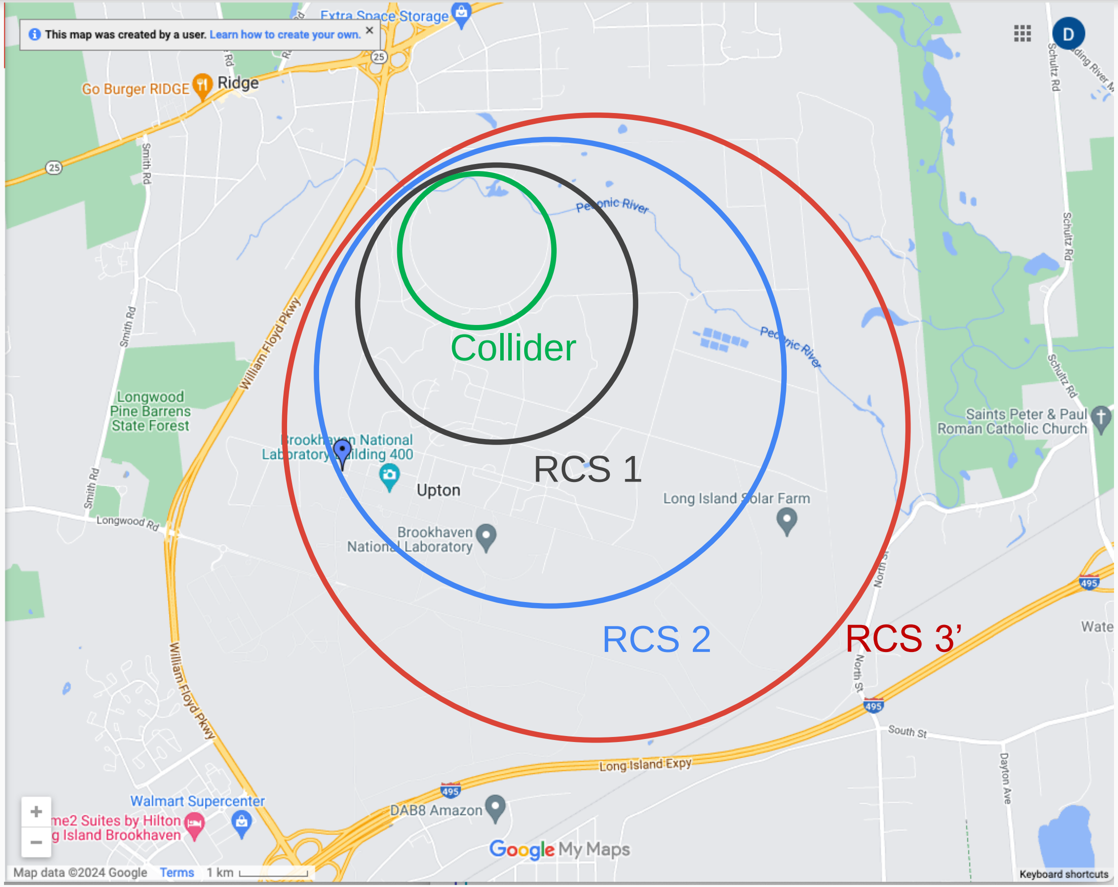
- From Diktys Stratakis, link

Recirculating Linacs,
Rapid Cycling Synchrotrons
(or FFAGs)



Extensive. In principle no show stoppers but requires R&D and $

A BNL Site Filler – Max Size of Accelerating Rings



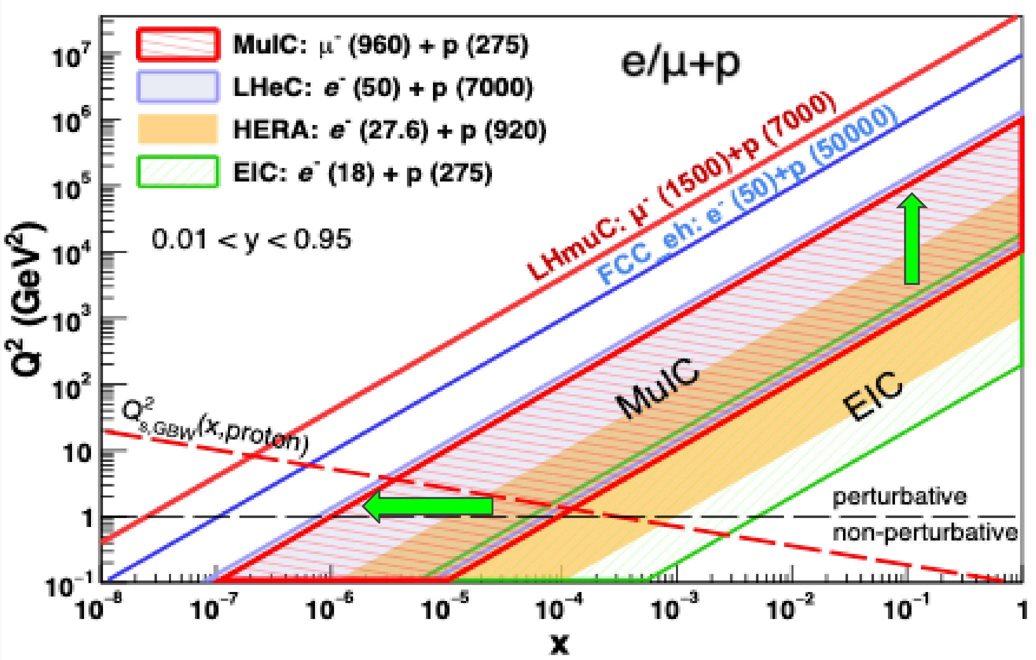
- Maximum accelerator size on BNL site:
  - D ≈ 4.45 km
  - Circumference: 14 km
- Following FNAL MuC plans, RCS 1 achieves √s = 0.7 TeV and RCS 2 √s > 1 TeV
  - Can fit RCS 2 at 10.5 km
- In principle could fit up to a RCS 3’ to go to E_{μ} ~3 TeV

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

Physics Opportunities

DIS Reach in x and Q^2 for ℓp Collisions

- MuIC 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
- 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



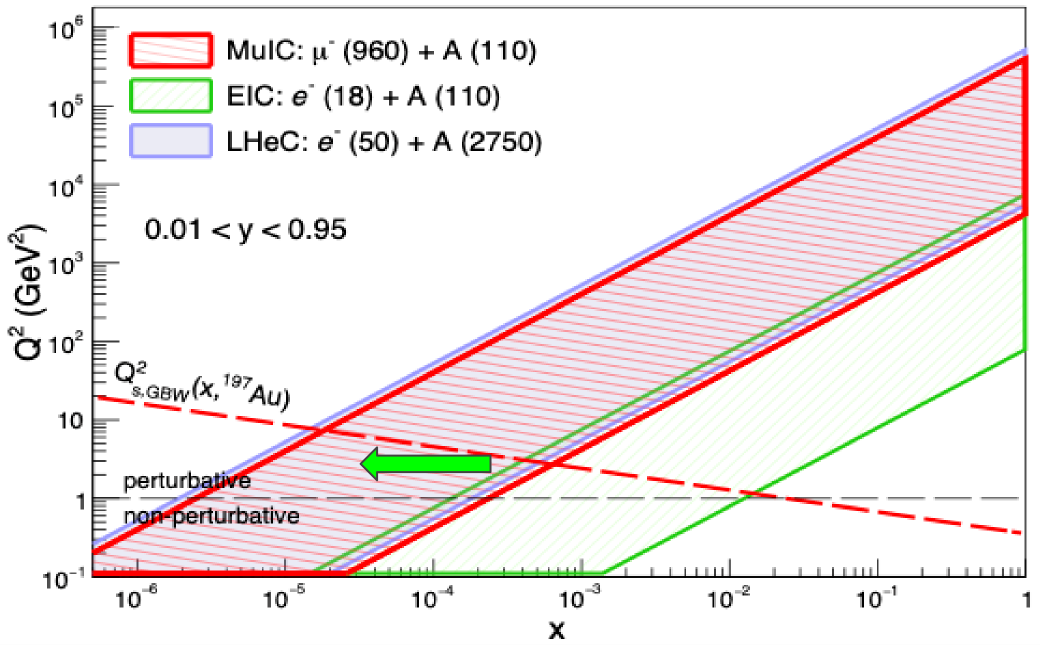
[1] LHeC: 2021 J. Phys. G: Nucl. Part. Phys. 48 110501

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

DIS Reach in x and Q^2 for ℓA Collisions

- Can explore well the predicted region of gluon saturation regime in ions at low x in the GBW model [2]

- A MuIC at BNL also can scan a wide range of ion species, and with beam polarization

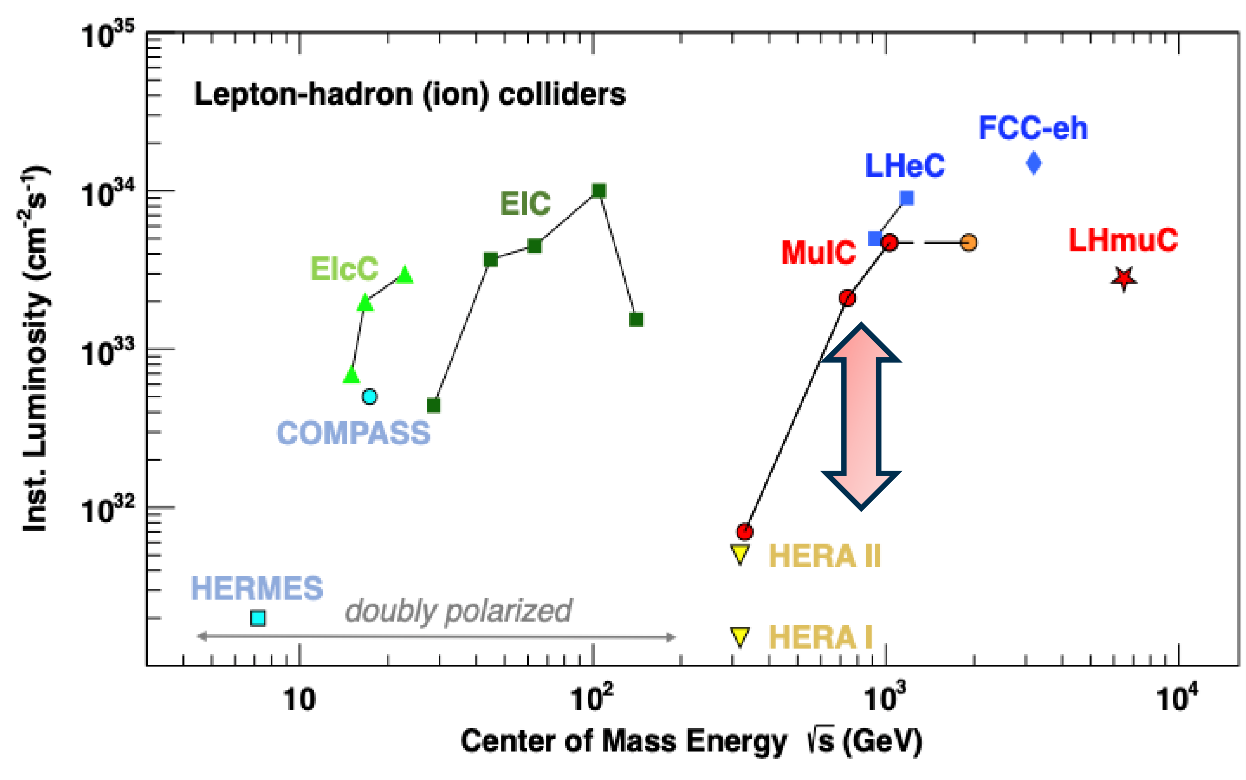


Saturation scale:

$$Q_s^2(A) = A^{1/3} Q_s^2(p)$$

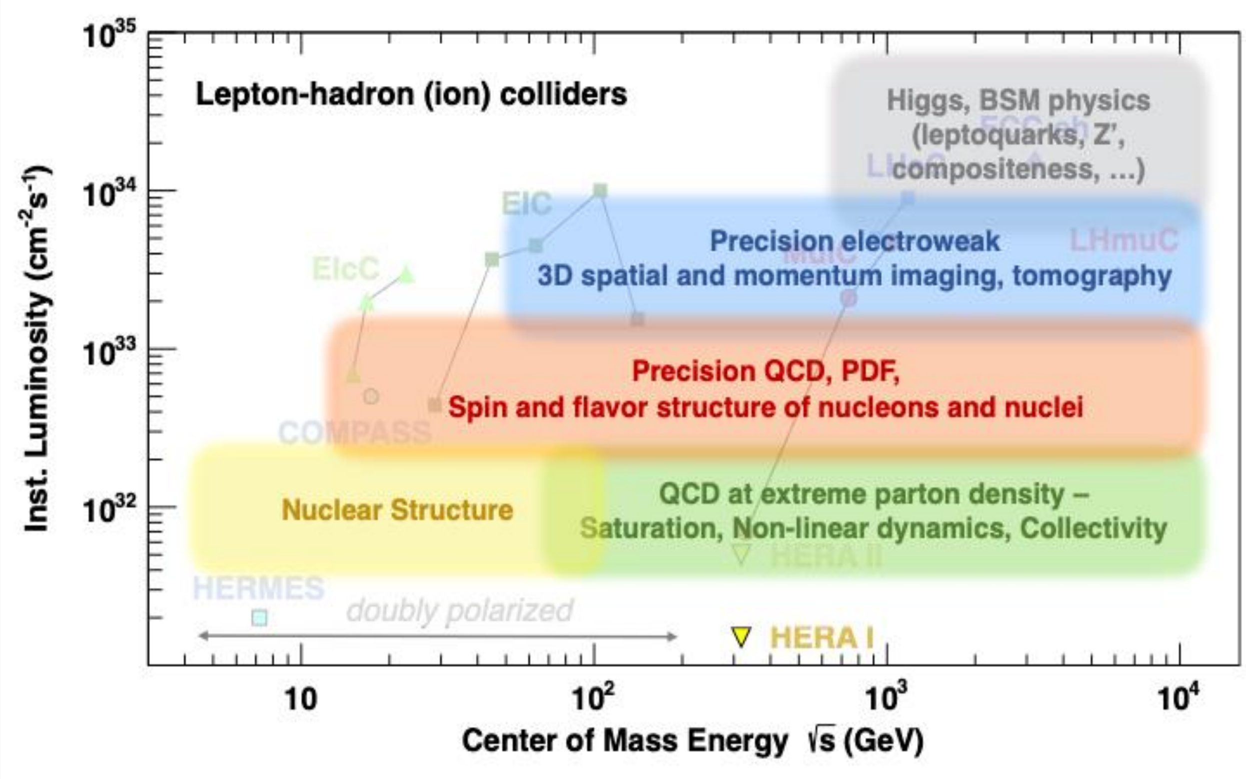
[2] GBW model: Phys. Rev. D 59, 014017 (1998)

DIS Evolution – Past and Proposed Machines

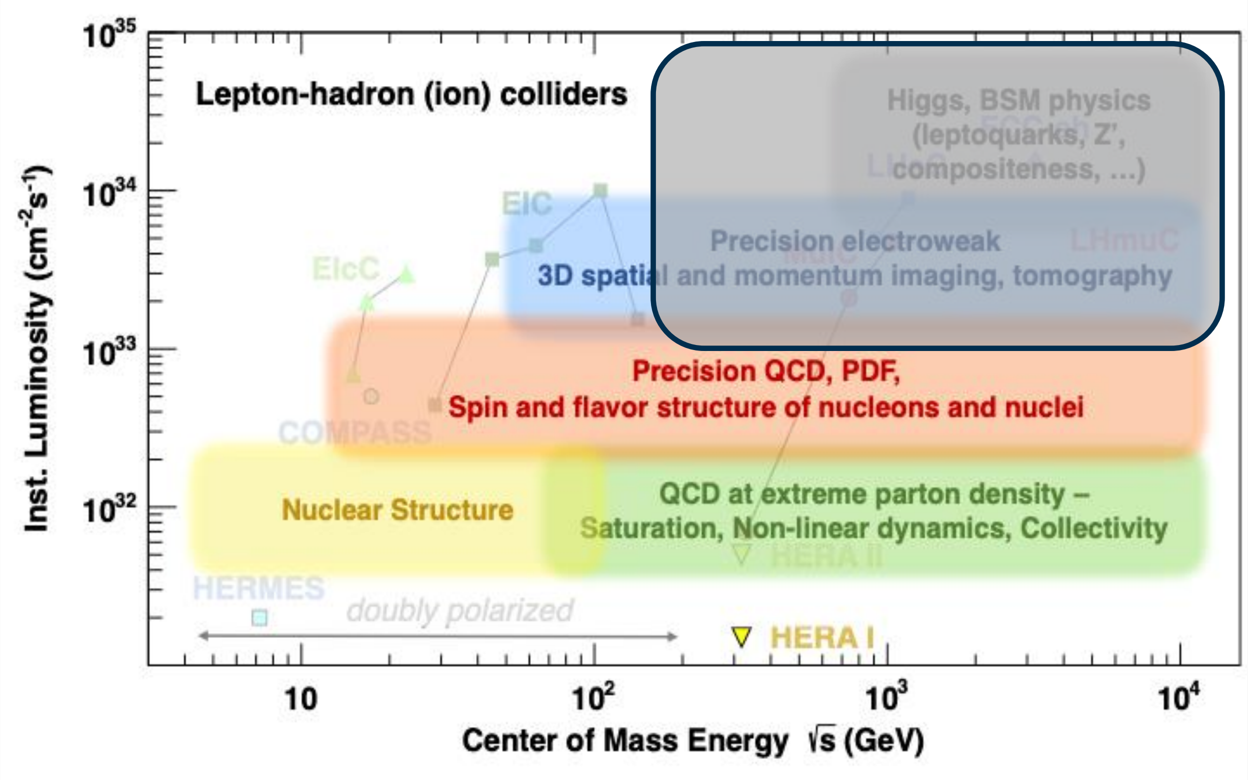


From Rice workshop discussion, beam-beam effects limit luminosity

DIS Evolution and Physics Landscape

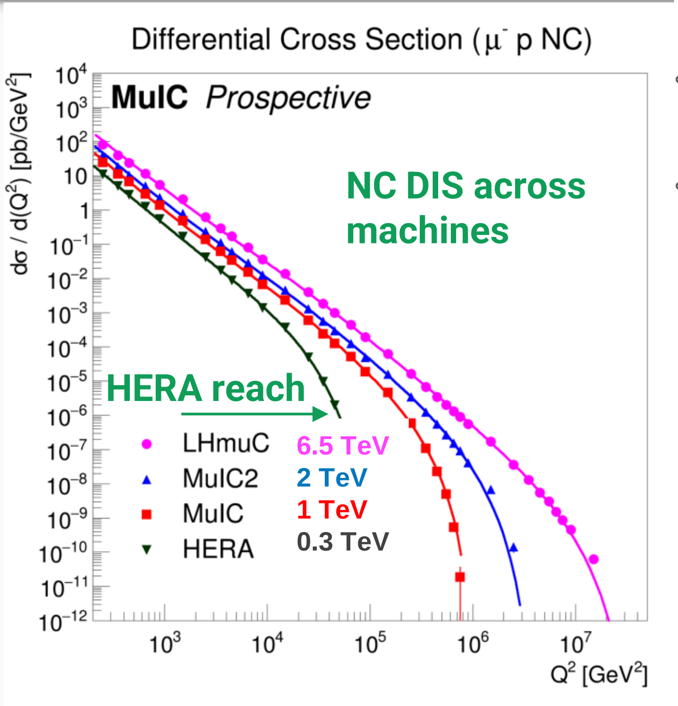


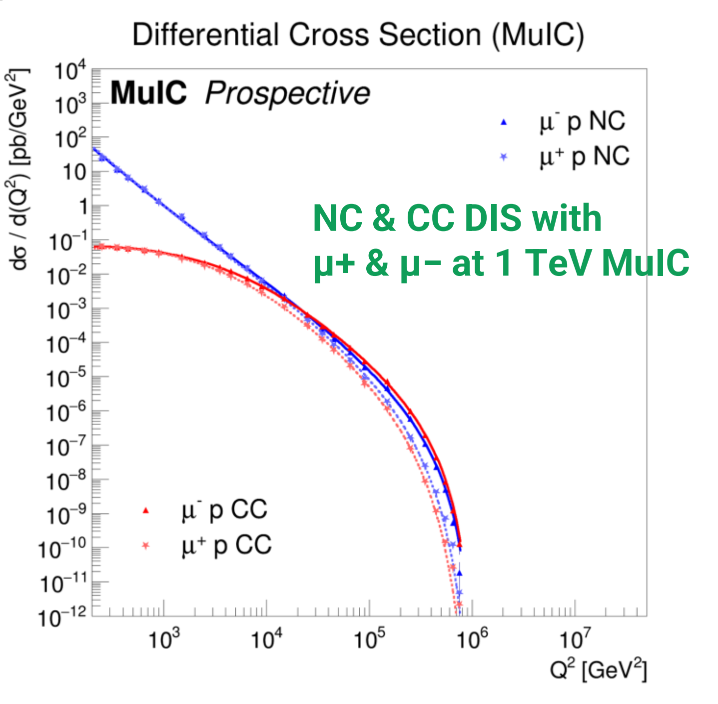
DIS Evolution and Physics Landscape



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

DIS Differential Cross Sections in Q^2 for Different Machines



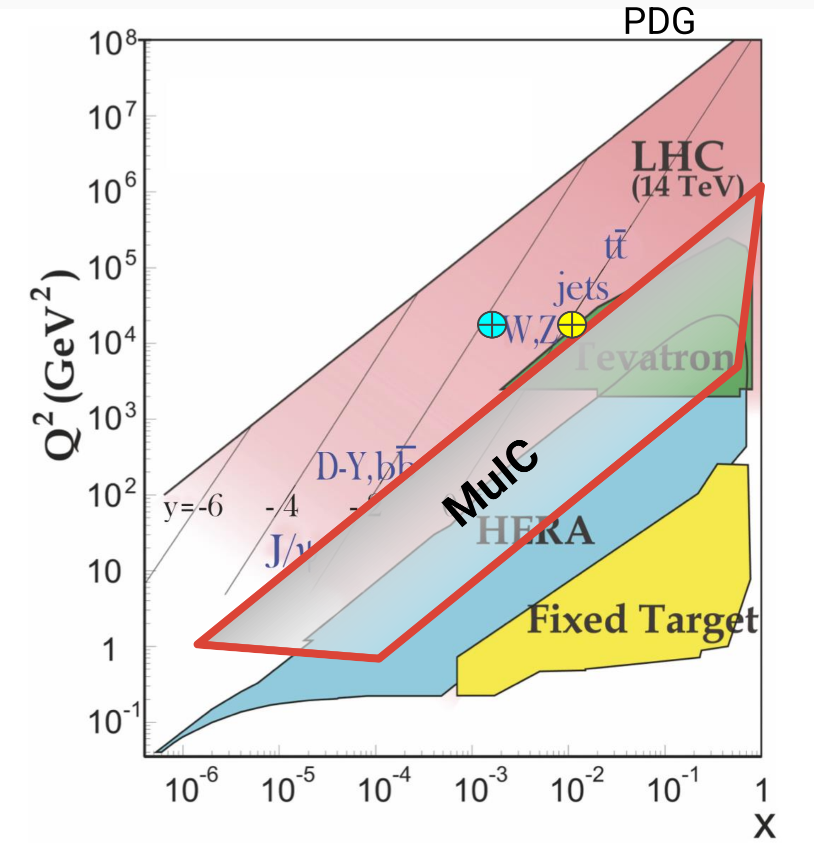


Computed with Pythia8 and NNPDF2.3 PDF set, $0.1 < y < 0.9$

- MuIC can probe well beyond HERA and the electroweak scale
- Highest Q^2 reach will require the largest luminosity (10^{33}–10^{34} Hz/cm^2)
    - But, measurements at lower Q^2 and x can benefit from luminosity orders of magnitude smaller: ~HERA luminosity for the electroweak scale.

PDFs and QCD –
The “Bread and Butter” of DIS experiments

Complementarity to (and input for) Hadron Colliders



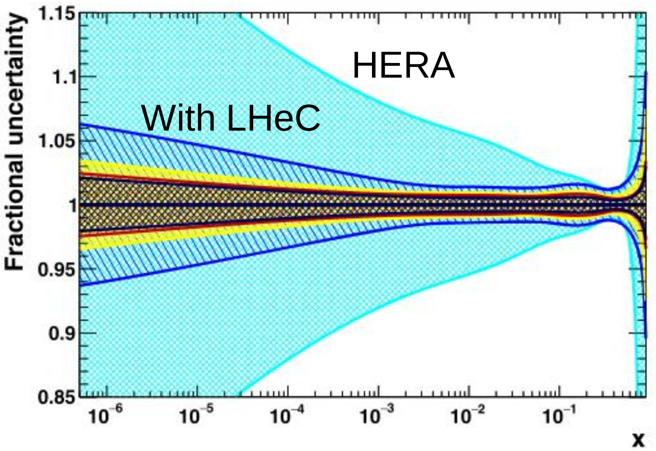
- DIS PDF measurements with an electroweak probe can more cleanly decouple QCD and quark flavor over hadron collider measurements

- The MuIC (or LHeC) can probe the parton densities directly at, or near, the scale for Higgs production at the (HL)LHC, and for a future 100 TeV FCChh
  - PDF uncertainties are generally a limiting factor for calculation precision
  - Reducing uncertainties on pp cross sections to ~1% is critical for Higgs coupling tests

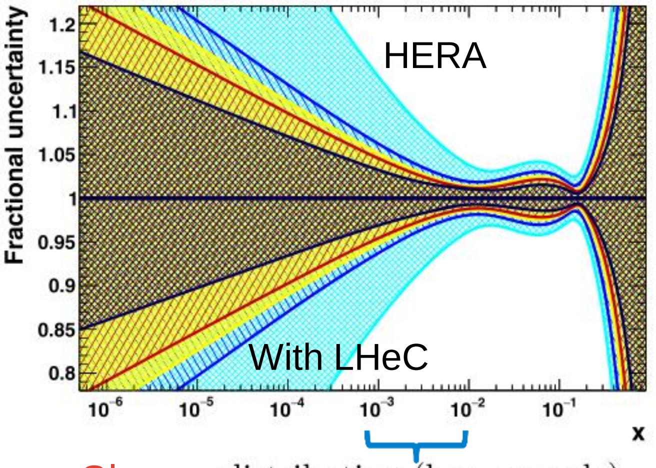
- Useful (necessary?!) input for a future FCChh program
  - As HERA was for the LHC program

Potential Expected PDF Uncertainties

- From LHeC CDR:
  - [2021 J. Phys. G: Nucl. Part. Phys. 48 110501]
  - $Q^2 = 1.9$ GeV^2
  - L = 5, 50, 1000 fb^{-1}
- Greatly improves precision at mid- to low-x

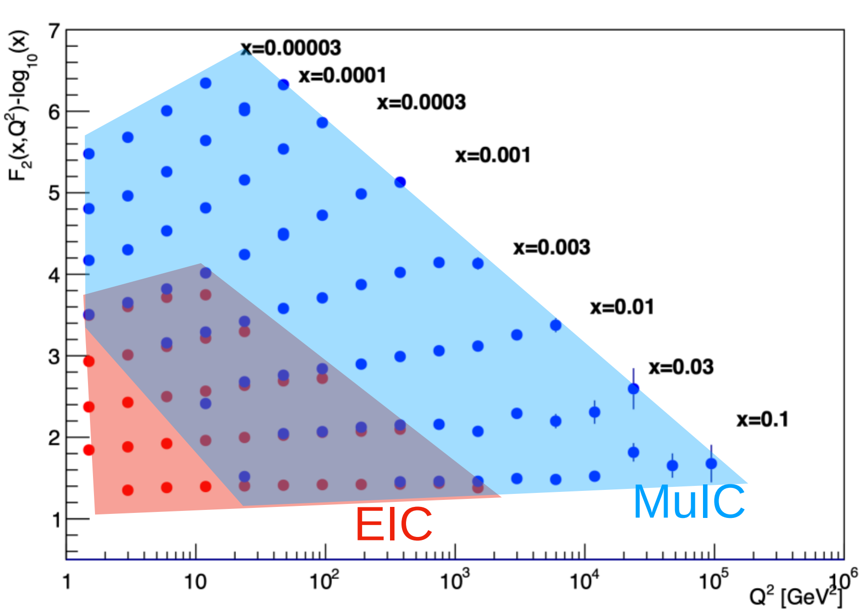


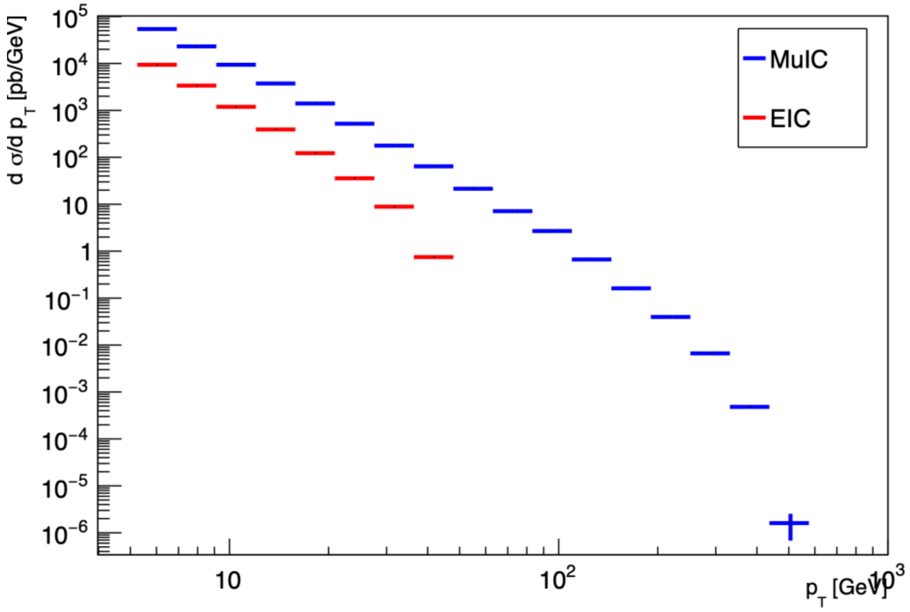
Sea quark distribution ($\log_{10} x$ scale).



Gluon distribution ($\log_{10} x$ scale).

MuIC Potential for Structure Function & QCD Measurements





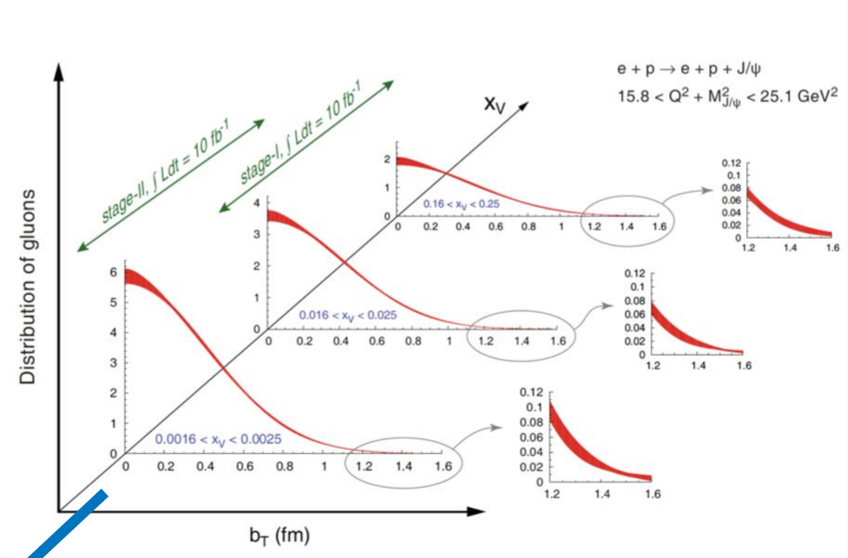
F_2 Structure function projection of EIC vs MuIC

Single jet P_T spectra projection of EIC vs MuIC

Pseudo-data representing one year (at 5×10^{33} Hz/cm^2) of running, ~40 fb^{-1}

Nuclear Structure and Spin at the MuIC

- Transverse Spatial Distributions of Partons
  - Generalized parton distributions (GPDs)



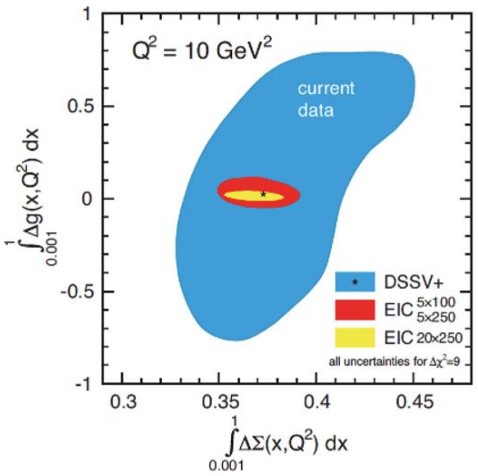
From [EIC Yellow Report]

MuIC can extend EIC measurements to $x \approx 10^{-5}$, and nucleon polarization is possible at BNL

- Spin Structure and the Nucleon Spin Puzzle

"Helicity sum rule"

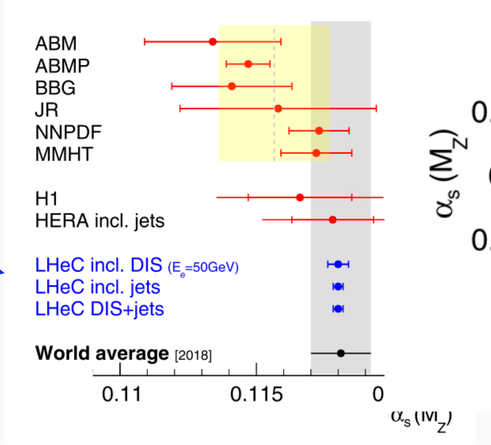
$$\frac{1}{2}\hbar = \underbrace{\frac{1}{2}\Delta\Sigma}_{\text{quark contribution}} + \underbrace{\Delta G}_{\text{gluon contribution}} + \underbrace{\sum_q L_q^z + L_g^z}_{\text{orbital angular momentum}}$$

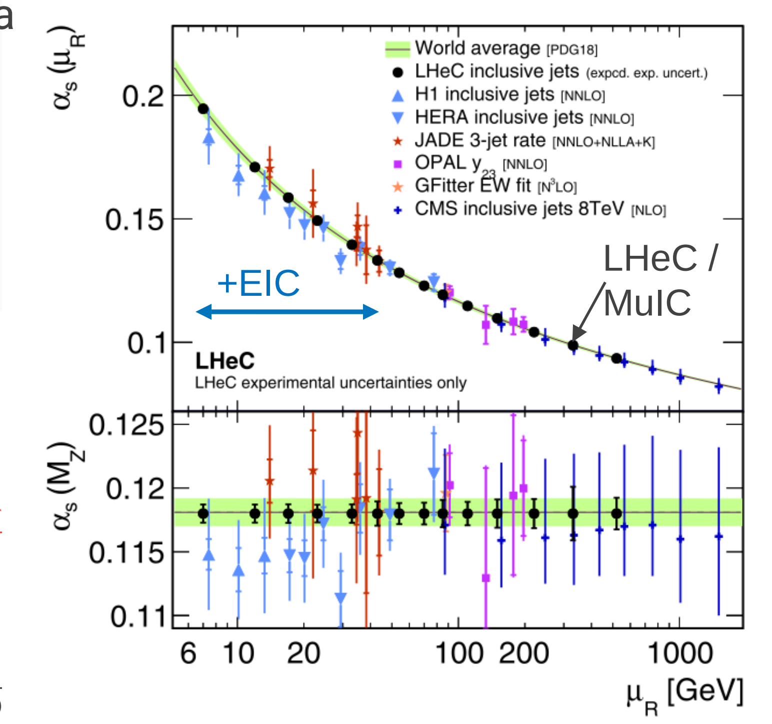


QCD and the Running of α_S

- Measurements can span a broad range to measure $\alpha_S(Q^2)$ in a **single experiment**
  - From DIS inclusive jet cross section measurements, F_L measurements, and from QCD evolution fits to structure function data
  - Removes some inter-experiment systematics

- From the LHeC CDR:
  - Inclusive jets with expected uncertainties for 1 ab^{-1} →
    - (JES uncertainty: 0.5%)
  - Expected α_S (M_Z) uncertainties
    - ±0.00038
    - Even 50 fb^{-1} (~1 year) is competitive

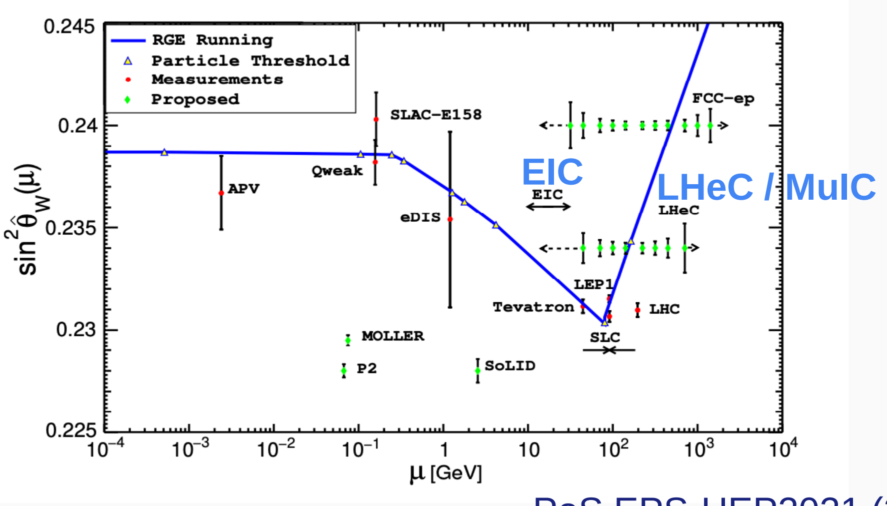


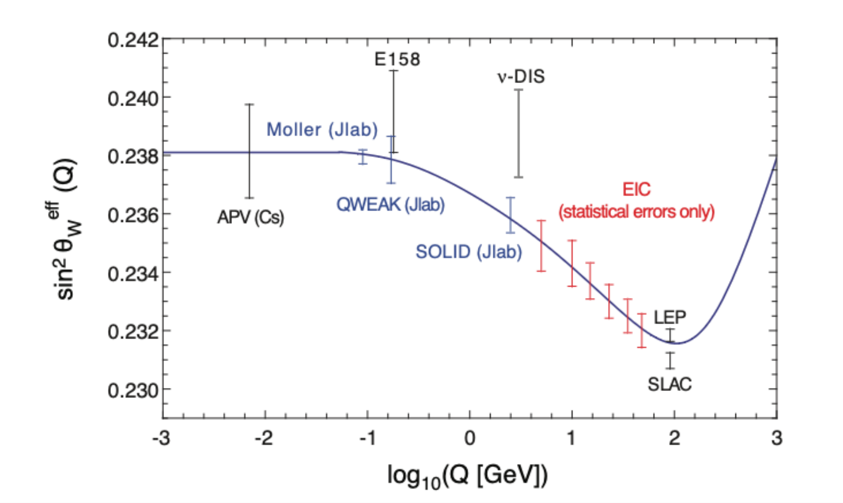


Electroweak

$\sin^2 \theta_W^{eff}$ Measurements

- Probe the effective **weak mixing angle** (and its running) over a wide scale range through combined fits of DIS data with PDFs and couplings
- MuIC would extend the EIC scale coverage, and is equivalent to that of LHeC, whose expected results are shown here
  - **Beam polarization, and ability to change beam from $^1H \rightarrow {}^2H$ at BNL, will further help disentangle couplings from PDFs**





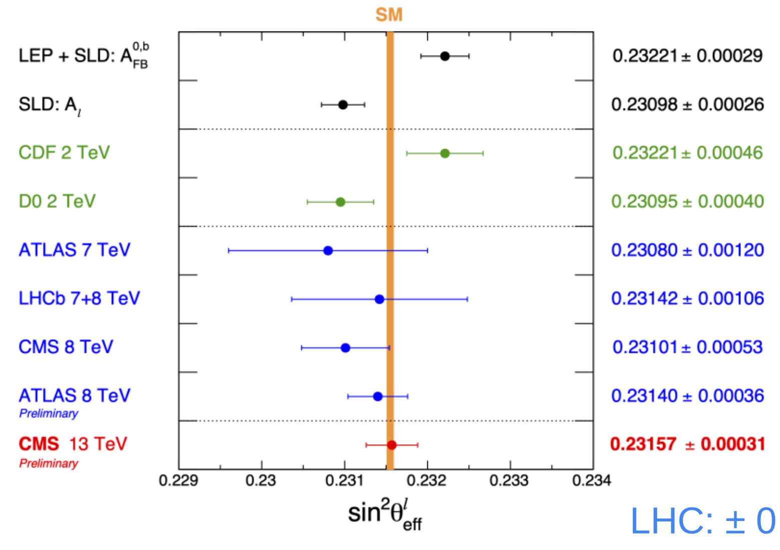
PoS EPS-HEP2021 (2022) 485

EIC arXiv:1212.1701

$Sin^2 \theta_W^{eff}$ Measurements at M_Z

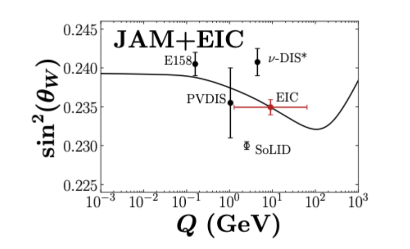
- Drell-Yan angular distribution at LHC

[CMS-PAS-SMP-22-010]



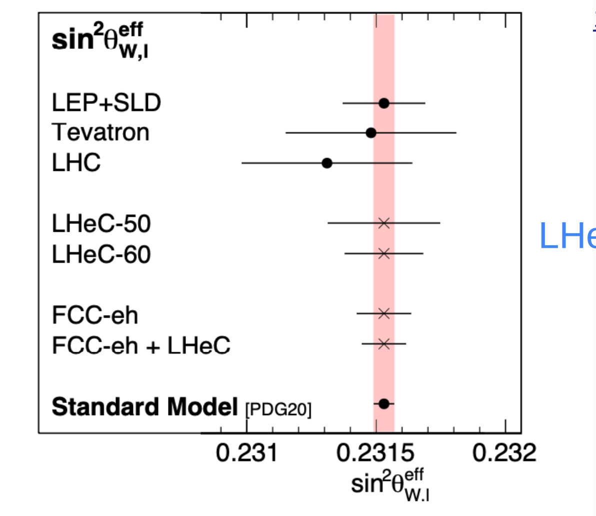
LHC: ± 0.00031

- Future DIS expts.



[PoS EPS-HEP2021 (2022) 485]

[Nucl.Phys.A1026(2022) 122447]



EIC: ±0.0001

LHeC: ± 0.00021

MuIC similar?

- Potentially comparable (or better) sensitivity than past measurements

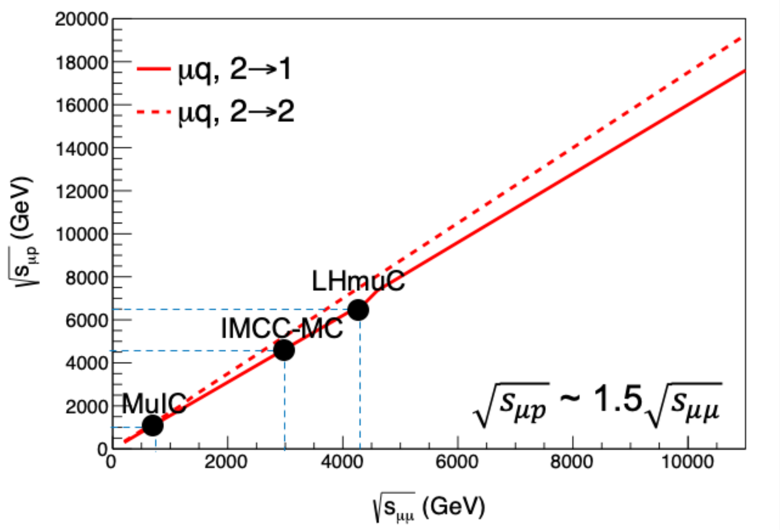
SM and BSM Particle Production and Measurement

Equivalent Reach for Particle Production, μp vs. $\mu^+\mu^-$

- Equivalent parton luminosity of a μp collider for 2→1 and 2→2 processes compared to a μ+μ− collider →

- We find that **a $\mu^+\mu^-$ collider is equivalent to a μp collider of 50% higher √s**, in terms of its discovery potential
  - So with 50% higher √s you can probe much of the same particle physics

- In terms of Higgs boson production, for example, **both are vector boson colliders** since VBF is the dominant cross section

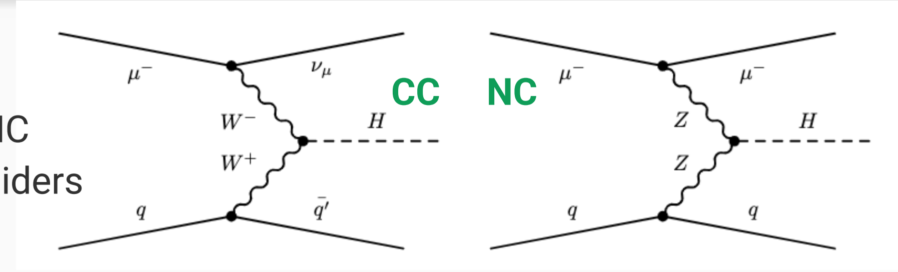


A 1.5x7 TeV LHmuC has √s = 6.5 TeV
- Equivalent to ~4.3 TeV μ+μ−
- In turn equivalent to ~30 TeV pp

Higgs Physics with MuIC

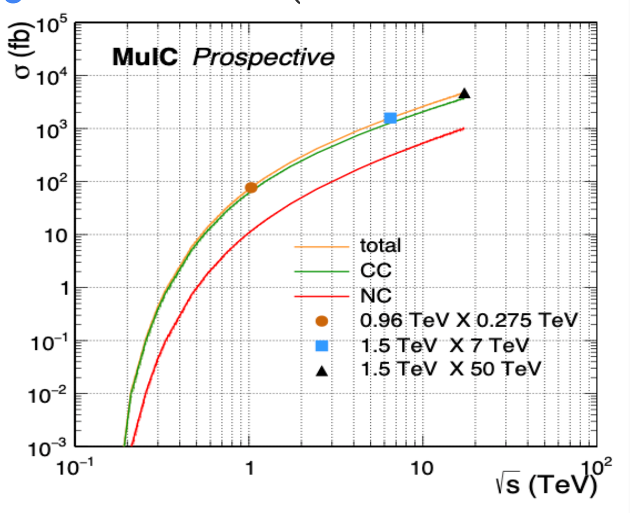
[JINST 18 P09025 (2023)](#)

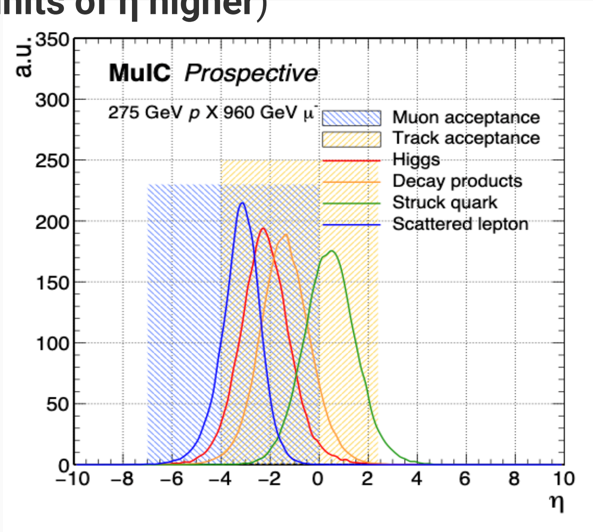
- Vector Boson Fusion mode
  - **σ grows with √s**, with CC exchange larger than NC
  - Cross section comparable to LHeC and $\mu^+\mu^-$ colliders
  - Polarization can increase cross section



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

Computed with MadGraph

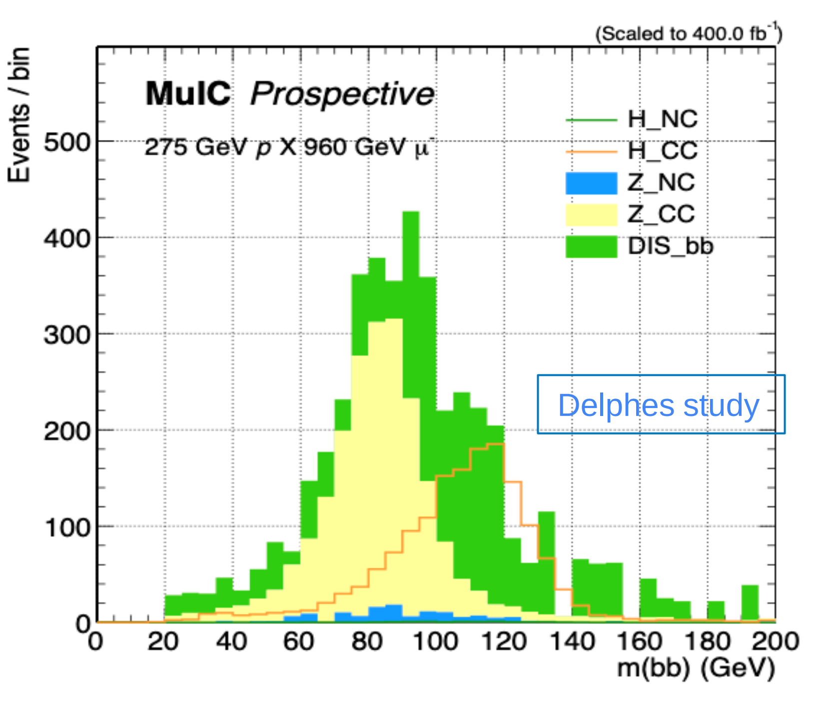




Higgs →bb with MuIC

JINST 18 P09025 (2023)

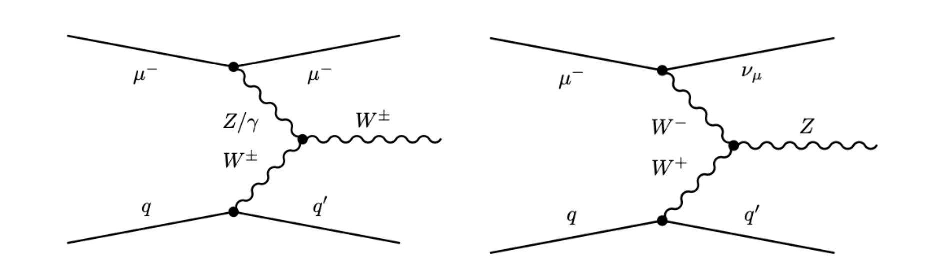
- A pseudo-analysis for H→bb
  - Requirements that enhance CC VBF process over NC DIS bb background:
    - 3 jets in final state (2 b-tagged)
    - muon veto, MET
    - Higgs p_T
  - S/B ~ 1 for H→bb
  - **Expect ~900 selected H→bb in 400 fb^{-1}** (10 years*) **@ 1TeV MuIC**
    - Increases by factor 10 at LHmuC



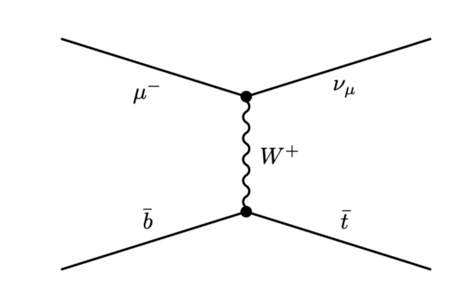
* at L=5x10^{33} Hz/cm^2

Other SM Particle Measurements

- Vector boson production, e.g.
  - Sensitive to **triple gauge couplings**
  - σ(W) = 19 pb for 1 TeV MuIC
    - 2.1×10^4 leptonic W → lν decays into each lepton flavor for 10 fb^{-1}



- Single top production
  - **Direct measurement of $|V_{tb}|$**
  - σ(t) = 1.0 pb for 1 TeV MuIC



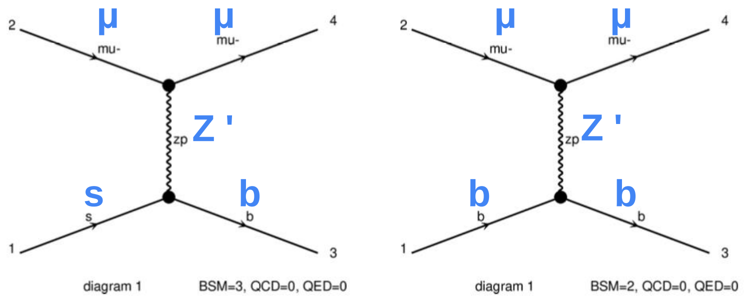
Potential for precision coupling measurements (and maybe mass measurements) with larger σ at higher √s and higher luminosity)

Probing Models Relevant to LFU Violations

- e.g. Consider Z' models and couplings discussed in M.Abdullah et al., Phys. Rev. D 97, 075035 , that couple via O9 operator mostly to 2nd generation leptons (μ) and 2nd and 3rd generation quarks (s, b) to explain anomalies in B meson decays.
  - $$\mathcal{L} \supset Z'^{\mu}\Big[g_\mu \bar{\mu}\gamma^\mu \mu + g_\mu \bar{\nu}_\mu \gamma^\mu P_L \nu_\mu + g_b \sum_{q=t,b} \bar{q}\,\gamma^\mu P_L q + (g_b \delta_{bs} \bar{s}\gamma^\mu P_L b + \text{h.c.})\Big] \quad (6)$$
  - g_μ and g_s are flavor conserving couplings
  - δ_{bs} parameterizes non-flavor conserving couplings
  - $$g_b \delta_{bs} g_\mu (100\ \text{GeV}/m_{Z'})^2 \simeq 1.3 \times 10^{-5} \quad (5)$$

    to fit lepton flavor universality violations

Which admittedly are diminished with latest LHCb measurement that is compatible with the SM

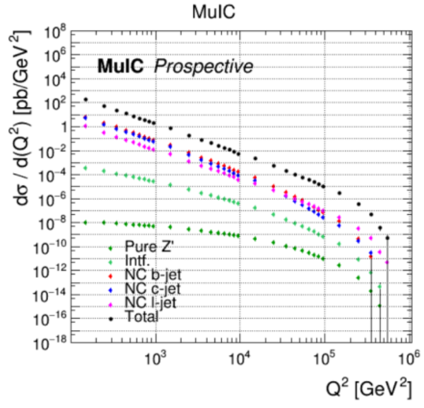


(a) $s\ \mu- \rightarrow b\ \mu-$ (b) $b\ \mu- \rightarrow b\ \mu-$

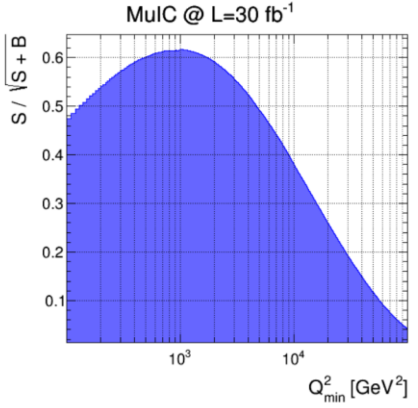
- Consider interference with NC DIS
  - so flavor conserving coupling dominates

Probing Models Relevant to LFU Violations

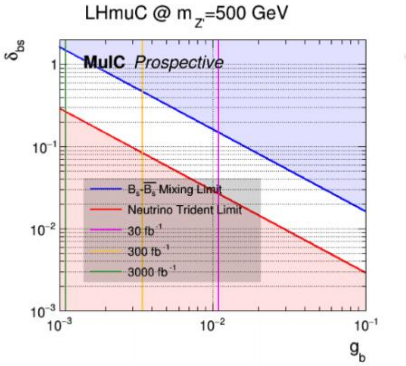
- Perform pseudo-analysis using a cut-and-count approach on the reconstructed Q^2 from the muon, optimized for sensitivity
- Apply b-tagging and mis-tagging efficiencies to final state jet
  - b, c, light: 70%, 10%, 1%
- Derive expected limits
- Conclusion: generally need LHmuC (120 fb^{-1}) to be competitive with HL-LHC (3000 fb^{-1}) for this model



(a) $m_{Z'} = 500$ GeV

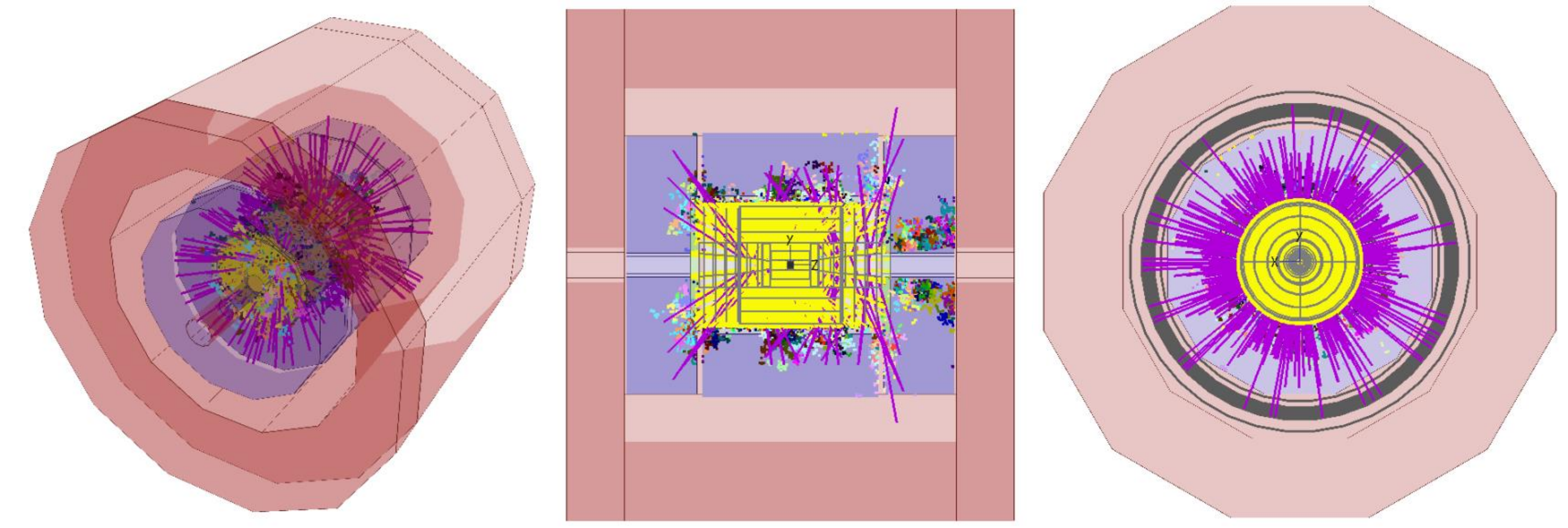


(b) $m_{Z'} = 500$ GeV



(a) LHmuC

Detector Considerations & Challenges

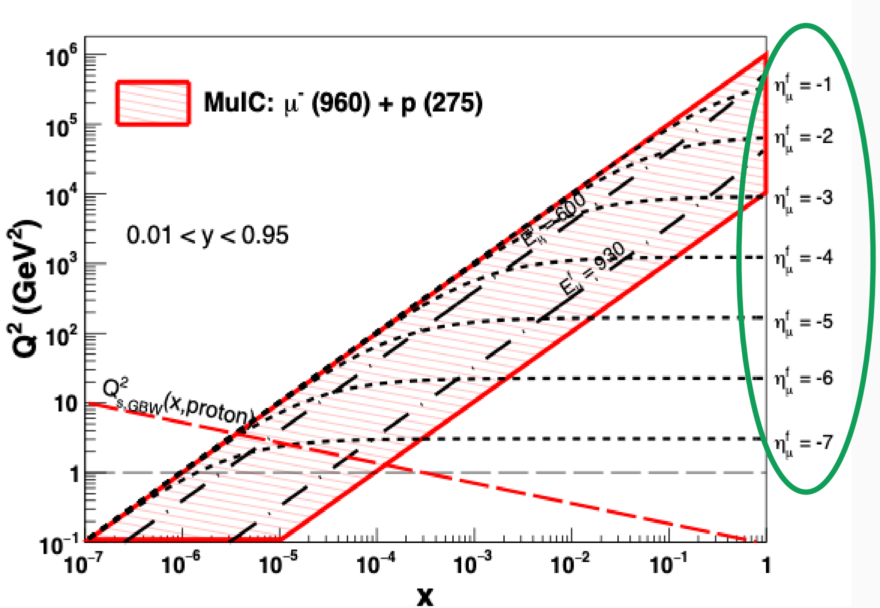


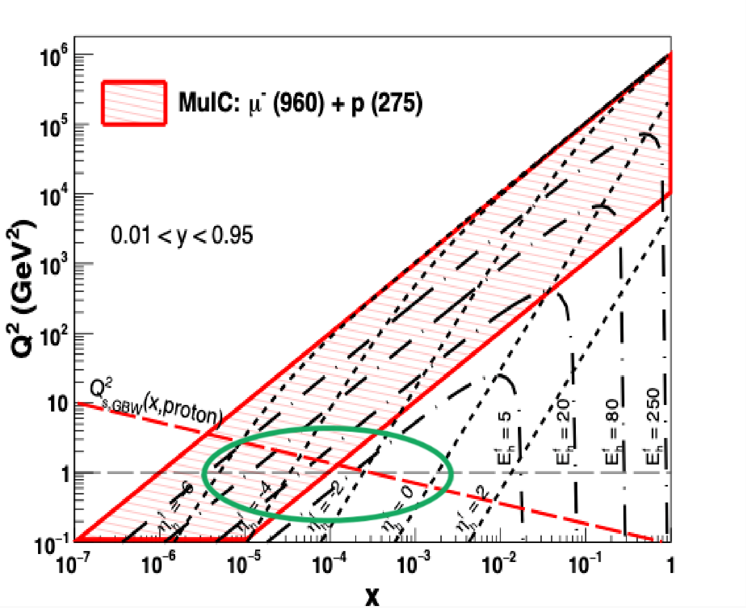
Simulation with beam induced backgrounds (BIB)

MuIC Kinematics (E,η in Q^2 - x plane)

- Scattered muon

Scattered jet





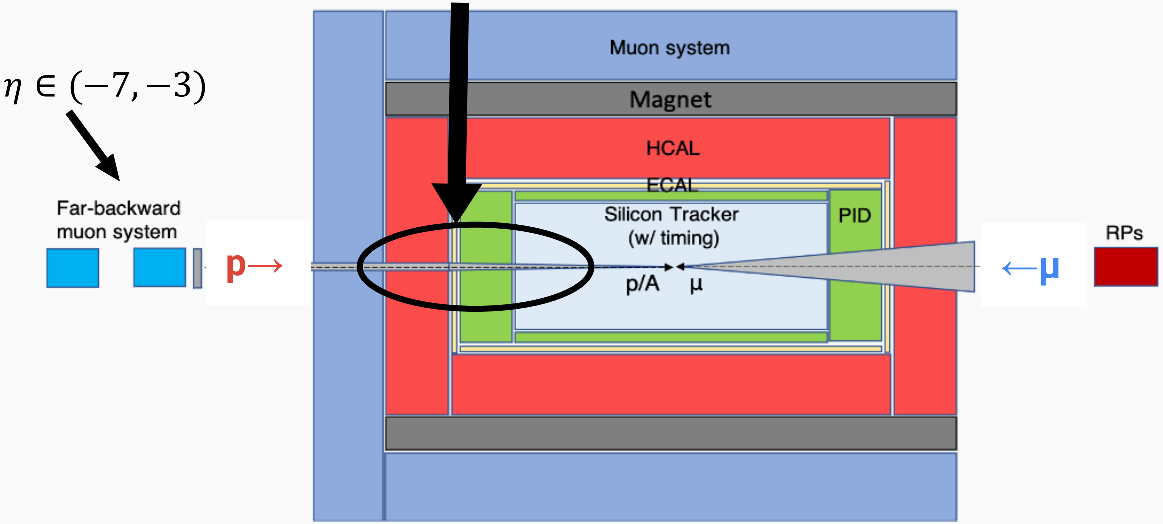
- Backward tagging of muons to η= −7 (2 mrad!)

Hadronic system −5 < η < 2.4

Quite different from EIC and LHeC kinematics

Detector Considerations and Challenges

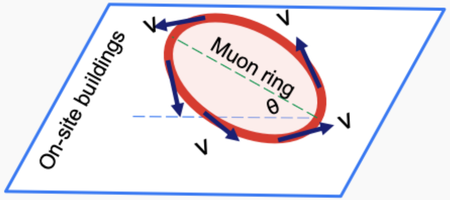
- Starting point: **Modified $\mu^+\mu^-$ conceptual detector design**
- Hadron PID over a wide phase space, with good timing measurements to reduce BIB
- Measurement of scattered muons at high η (far-backward) up to TeV scale
  - Useful also for an experiment at a $\mu^+\mu^-$ collider to tag/veto NC VBF processes (see backup), and perhaps measure luminosity from Bhabha scattering
- For MuIC ideally remove one shielding nozzle, **keep only on incoming muon side**



	Main requirements
Muons	**-7<η<0, σ(p)/p < 5%**
Tracking	−5<η<2.4
PID (π/k/p)	**-4<η<2.4, p<100 GeV**
Calorimetry (jets, photons)	-5<η<2.4

Beam Induced Background, and Neutrino Radiation

- Muon colliders entail a significant beam induced background from μ decays and subsequent interactions with materials
  - Experiment requires shielding, high granularity, and excellent time resolution
  - **But this challenge has much in common with hadron collider experiments with high pileup**
- The abundant neutrinos pose a radiation risk from the highly collimated beam just before it exits the ground, particularly from any long straight sections
  - Dose depends inversely on the square of the opening angle (~1/γ) and on the energy: **~ E^3**
  - Thus the radiation at 1 TeV is only 1% of that at 5 TeV, for example
  - **At low luminosity and energy, collider may be perfectly fine on the surface**
- Otherwise situate deep underground, or on a "remote island"
  - With a small tilt, BNL might be considered such an island! ☺



Tilt the disk plane at a small angle to direct straight sectors toward land/sea and sky?

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?

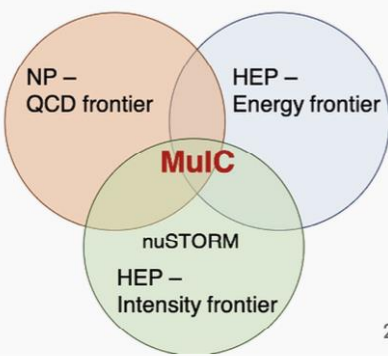
Other Experimental Concerns: Luminosity Measurement

- 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?

MuIC Synergies

- Siting a muon collider at a facility with a high energy hadron ring opens up a very interesting additional, complementary science program
  - Would be an exciting upgrade to the EIC
  - But siting at FNAL or CERN is also very interesting and synergistic
- Re-use of some existing hadron accelerator infrastructure may help allay some cost
  - And can still benefit from a lower initial muon beam energy if collided with TeV scale hadron beam
- A MuIC provides a science case for an initial muon collider demonstrator
  - Luminosity demands for proton/nuclear structure measurements at extreme parton density (low x) are much less stringent than the ultimate needs for Higgs studies, etc.
- Similar detector needs to future $\mu^+\mu^-$ and FCC-hh experiments
  - Good timing for background mitigation, high eta muon spectrometer(s)
- A MuIC would address particle physics, nuclear physics, and intensity frontier interests
  - Two communities to join in detector development and construction
  - Joint funding from particle and nuclear physics programs? (as for the LHC program)



Summary and Conclusions

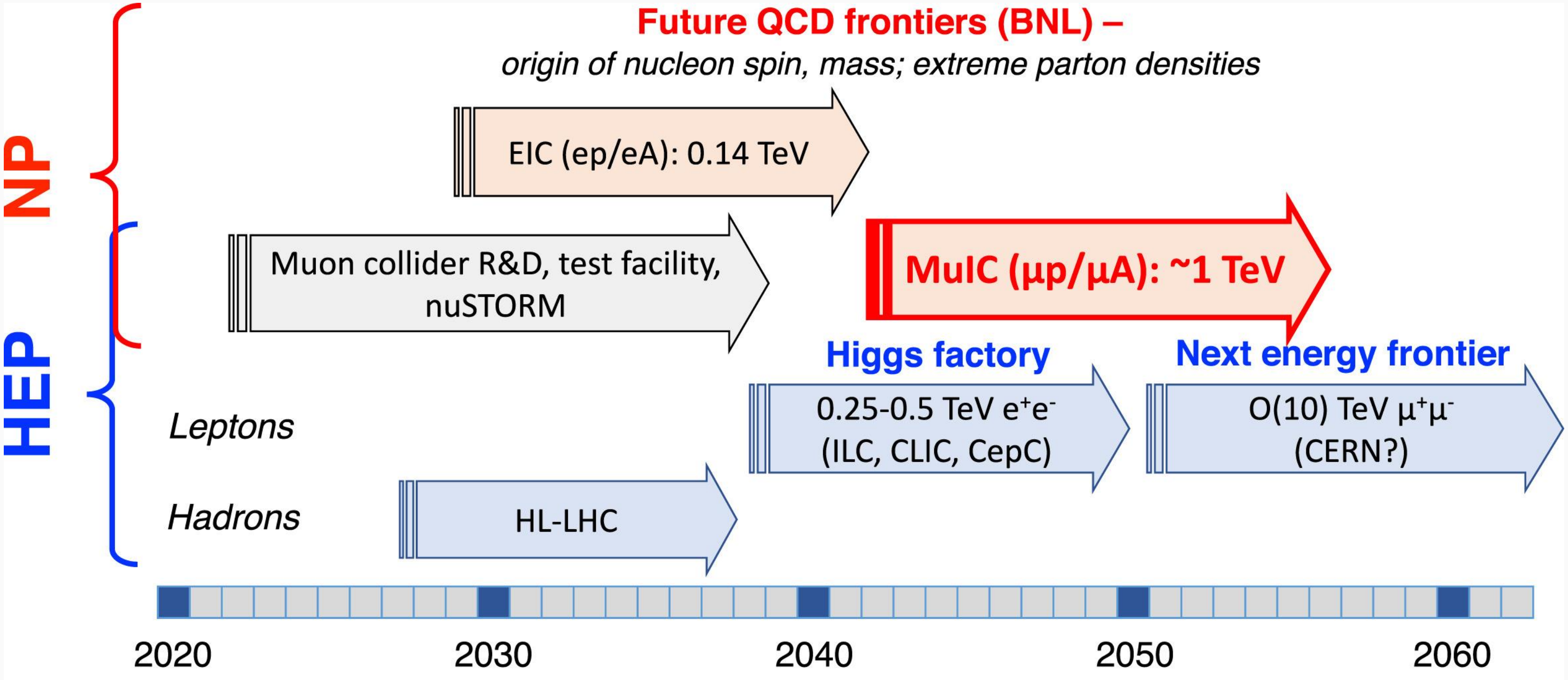
- Collisions of a TeV-scale muon beam with a high-energy proton/ion beam provides a novel way to explore a new regime in DIS at high Q^2 and at low x
  - Options include BNL ($\sqrt{s}$ = 1-2 TeV) as an EIC upgrade, CERN/LHC ($\sqrt{s}$ = 6.5 TeV), or at FNAL depending on how the US muon program develops!
- Luminosity could be a challenge, and needs dedicated accelerator study
  - However, there is much to study at much lower luminosity
- Science includes PDFs (μp and μN) and QCD in novel regimes, but also electroweak and BSM with sufficient luminosity
  - Improved PDFs are also necessary input to future (and current!) hadron colliders
- Time may be running out (or long…) for an LHeC collider at HL-LHC, or an FCC-eh collider, to similarly reach the TeV scale in DIS
  - Time to explore other options !
- Many synergies with muon collider development, and between nuclear, particle, and intensity frontier physics programs
- What interesting physics opportunities do you see?
- Join us at https://mailman.rice.edu/mailman/listinfo/muic

Acknowledgements

- This work is in part supported by the Department of Energy, United States grant numbers DE-SC0010103, DE-SC0023351 (D.A.), DE-SC0005131 (W.L.)

Backup

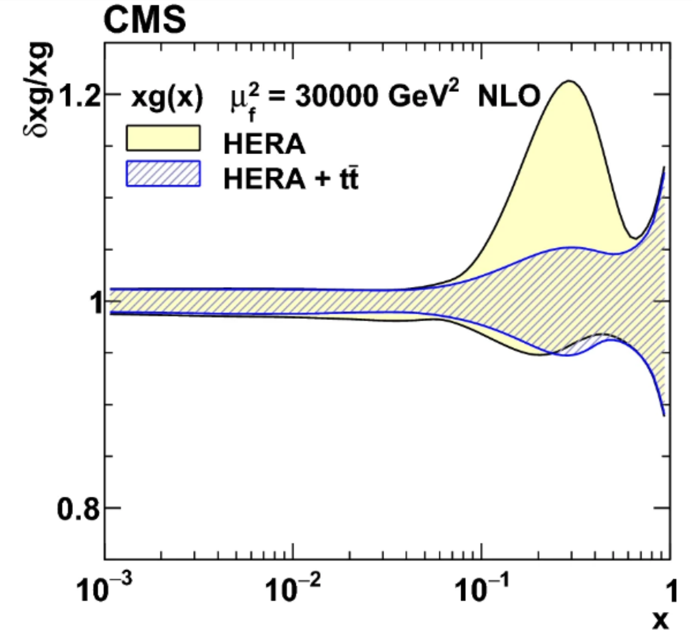
Possible Timeline



A possible roadmap to future muon colliders in NP and HEP

Hadron Collider PDF Fits Require DIS Data

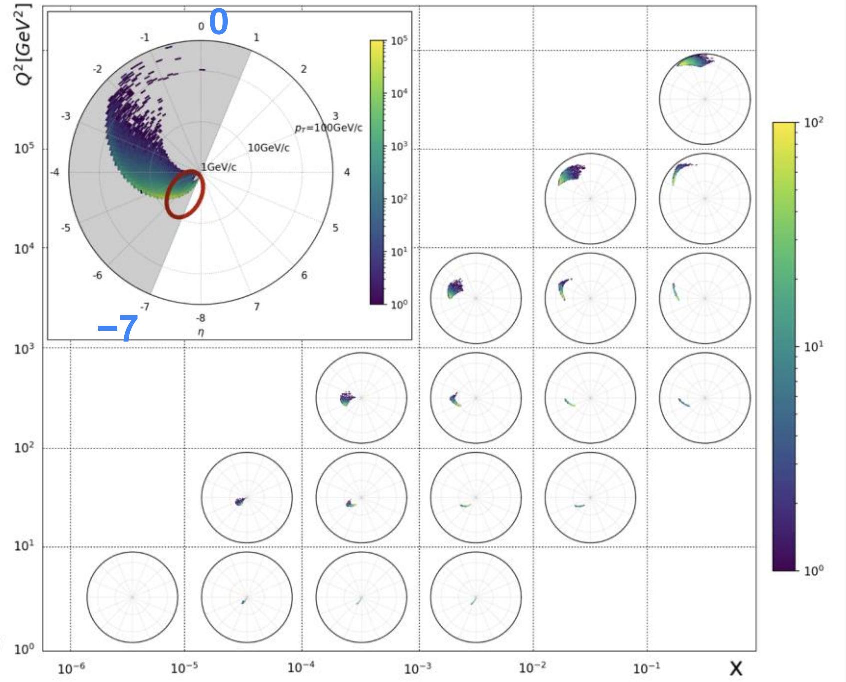
- While LHC data are used to extract parton densities from jet, Drell-Yan, W, and top production cross section measurements,
- DIS measurements are needed as input to constrain LHC PDF fits
  - e.g. extracting the gluon density from tt triple differential cross section data →
- DIS data also reduce PDF uncertainties for hadron collider process calculations



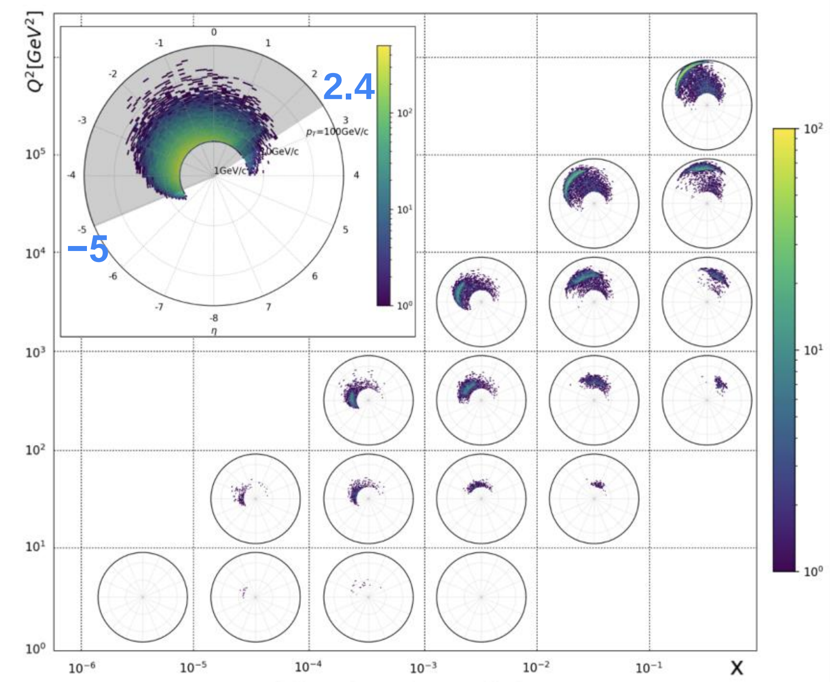
CMS, Eur. Phys. J. C 80 (2020) 658

Kinematics

- Scattered muon (far backward→ central with Q^2)   Scattered jet (More central)



Distribution of Scattering Muon



Distribution of Jets

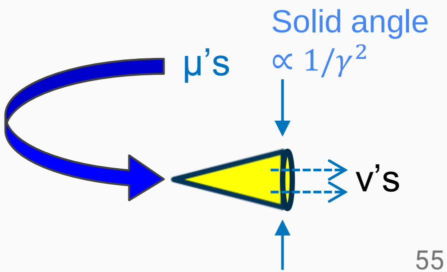
- Backward tagging of muons to η= −7   Hadronic system −5 < η < 2.4

Quite different from EIC kinematics

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) × 5^3 (energy dependence) × 10-100 (bunch charge reduction) ≈ **2.5×10^4**

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



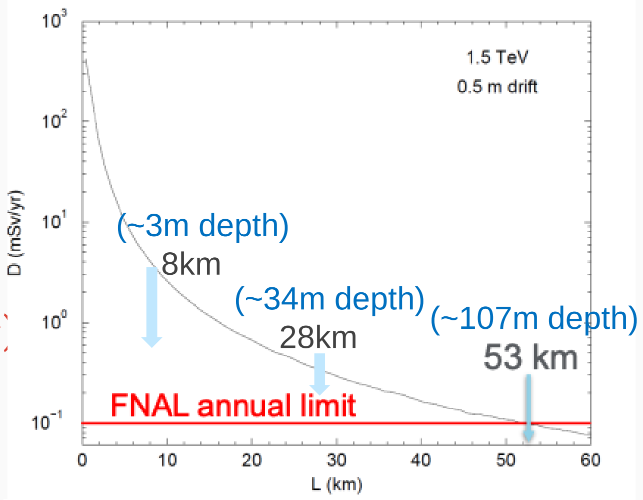
Neutrino Radiation Background

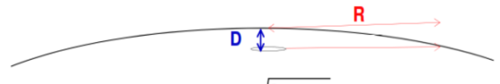
N.Mohkov, Snowmass MC Workshop 2022

- 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 (cancels↑)
- 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

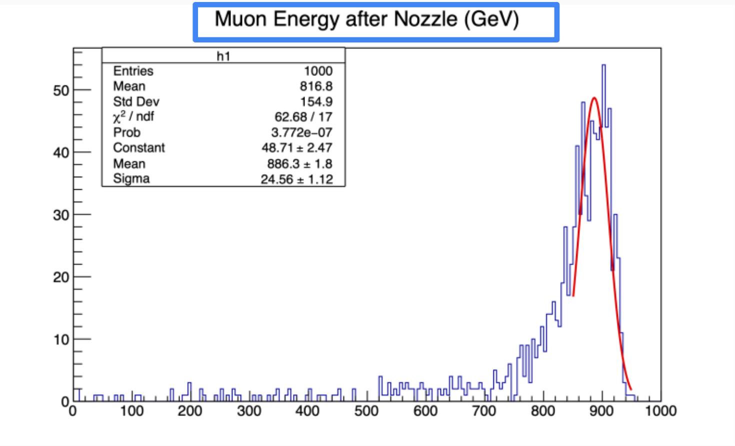
- Turning the radiation argument around, can a highly collimated neutrino beam be useful for a high-energy neutrino DIS experiment?
  - Perhaps with more data than collected in the past, if not in energy, for fixed target?

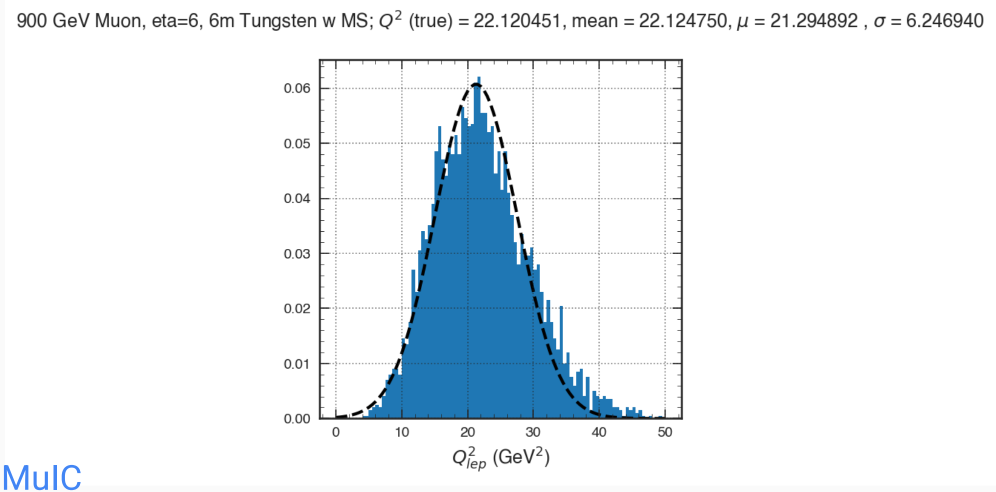
- Also makes for a "neutrino-hadron collider" in principle, but with very much lower luminosity
  - Blow-up of transverse beam size area in 50m section (~10^6 X)
  - Rate of muon decays (~1000X less *ν* per muon for 1000 turns per μ lifetime)
  - Fraction of decays in straight section (~100X less for 50m/4000m)
  - ⇒ Luminosity ~11 orders of magnitude smaller: L ~ 10^{20} (?)
  - Also how to disentangle from muon-hadron DIS?

Example of Shielding 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



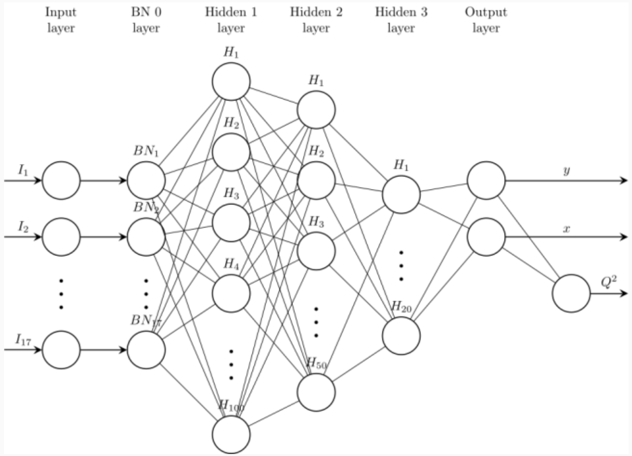


- This affects measurements:
  - e.g. 30% smearing for $Q^2 = 20$ GeV^2 → from reconstructed muon quantities
  - So ideally we would like not to have the shielding cone in the backward direction for MuIC

Machine Learning Methods to Reconstruct DIS Variables

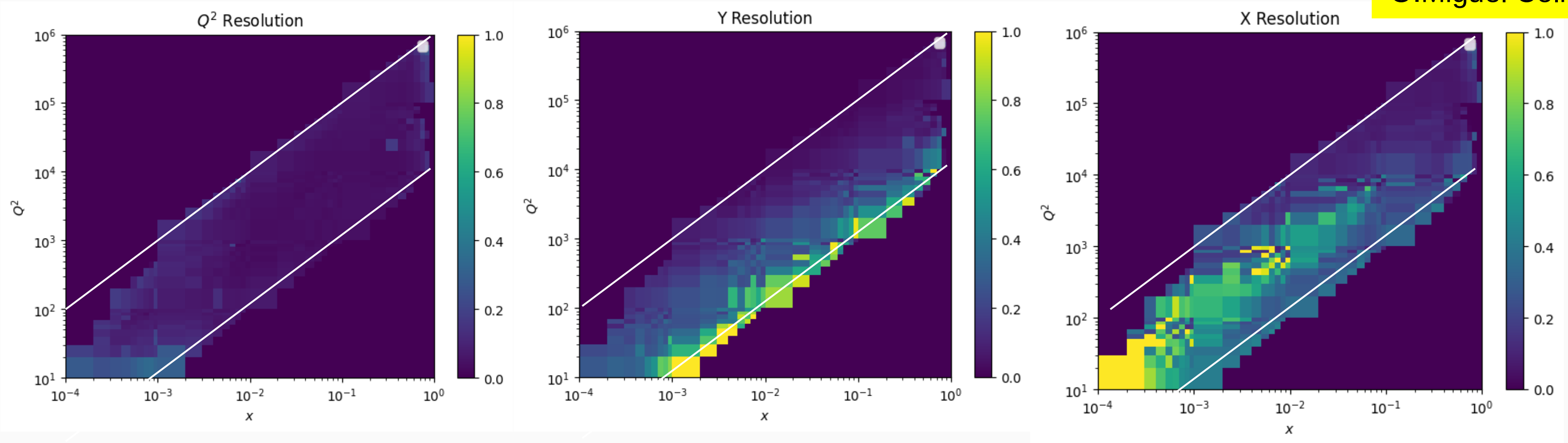
Work in progress:
O.Miguel Colin, A.Amarilla

- 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

DIS Resolution Studies

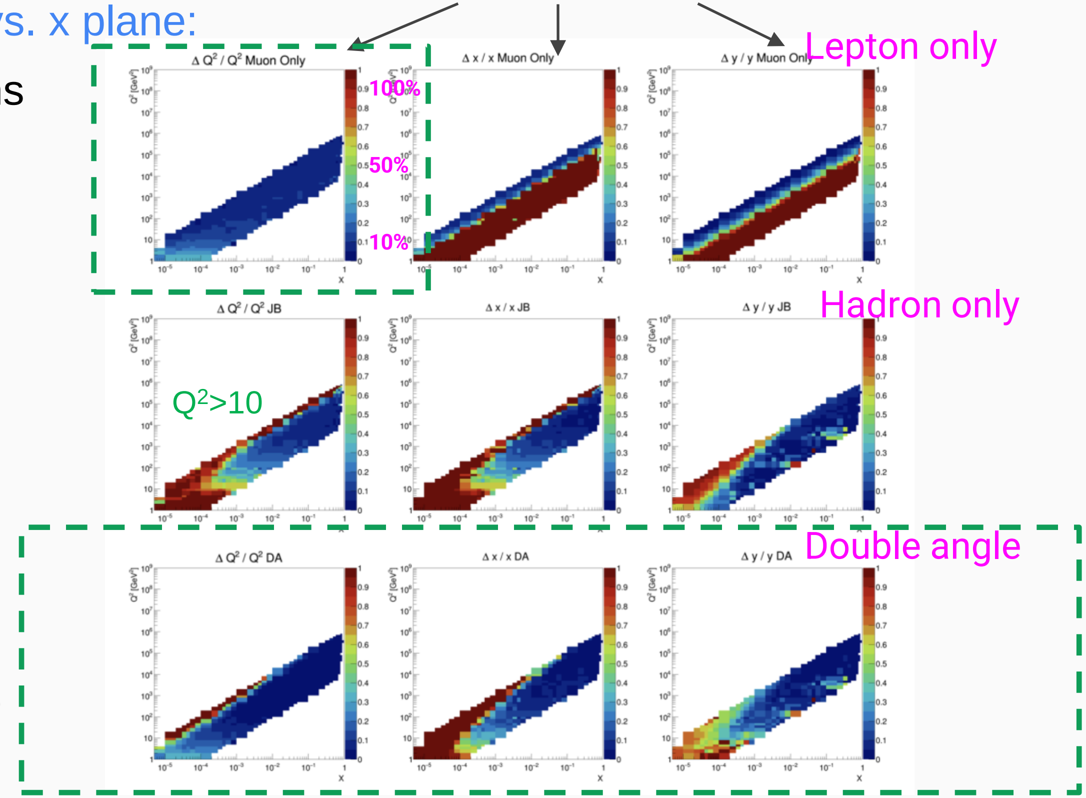
Simple assumptions of detector resolutions to smear particles from PYTHIA 8

Particle	Detector	Resolution	
		$\frac{\sigma(p)}{p}$ or $\frac{\sigma(E)}{E}$	$\sigma(\eta,\varphi)$
(Forward) Muons	e.g., MPGD	$0.01\%\, p \oplus 1\%$	0.2×10^{-3}
Charged particles ($\pi^\pm, K^\pm, p/\bar{p}, e^\pm$)	Tracker + PID	$0.1\%\, p \oplus 1\%$	$\left(\frac{2}{p} \oplus 0.2\right)\times10^{-3}$
Photons	EM Calorimeter	$\frac{10\%}{\sqrt{E}} \oplus 2\%$	$\frac{0.087}{\sqrt{12}}$
Neutral hadrons (n, K_L^0)	Hadronic Calorimeter	$\frac{50\%}{\sqrt{E}} \oplus 10\%$	$\frac{0.087}{\sqrt{12}}$

- Muons: 10% at 1 TeV, $\eta > -7$
- Hadrons: $-4 < \eta < 2.4$ (shielding)

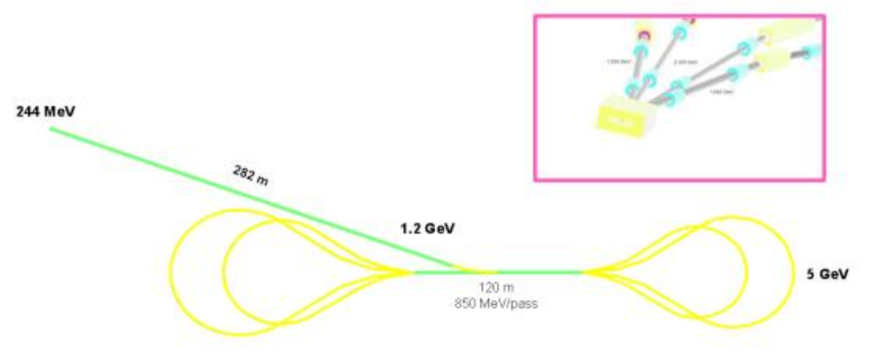
Resolutions of reconstructed Q^2, x and y with 3 methods

Q^2 vs. x plane:



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

A 10 TeV Muon-Muon Collider at Fermilab (Site Filler)

- From Diktys Stratakis → [link]

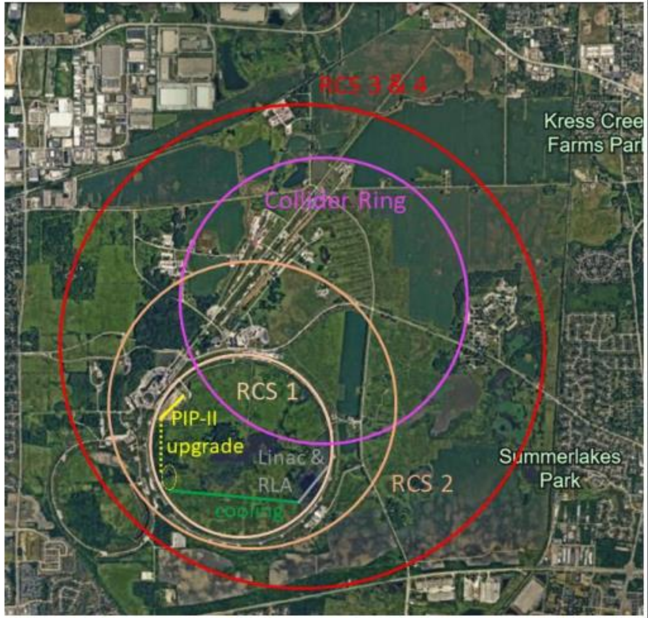
- Linac + RLAs get to 63 –173 GeV
- + RCS 1 gets to 0.45 TeV
- + RCS 2 gets to 1.7 TeV
- + RCS 3 + 4 gets to 5 TeV

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)

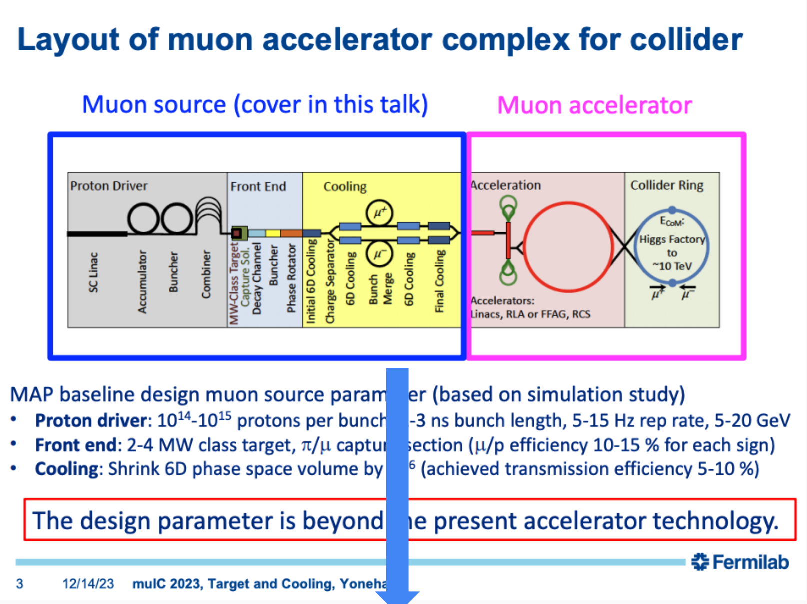
- From Diktys Stratakis → [link]
- Just Linac + RLAs would allow
  - E_μ = 63 GeV ⇒ MuIC √s = 0.25TeV (<HERA)
  - E_μ = 173 GeV ⇒ MuIC √s = 0.4TeV (>HERA)
    - Extension for FNAL MuC design
- Diameter of RCS 1 is 6.3 km
  - E_μ = 0.45 TeV ⇒ MuIC √s = 0.7TeV (2× HERA)
- Diameter of RCS 2 is 10.5 km
  - E_μ = 1.7 TeV ⇒ MuIC √s > 1TeV (in principle)
- Do these fit on BNL site?

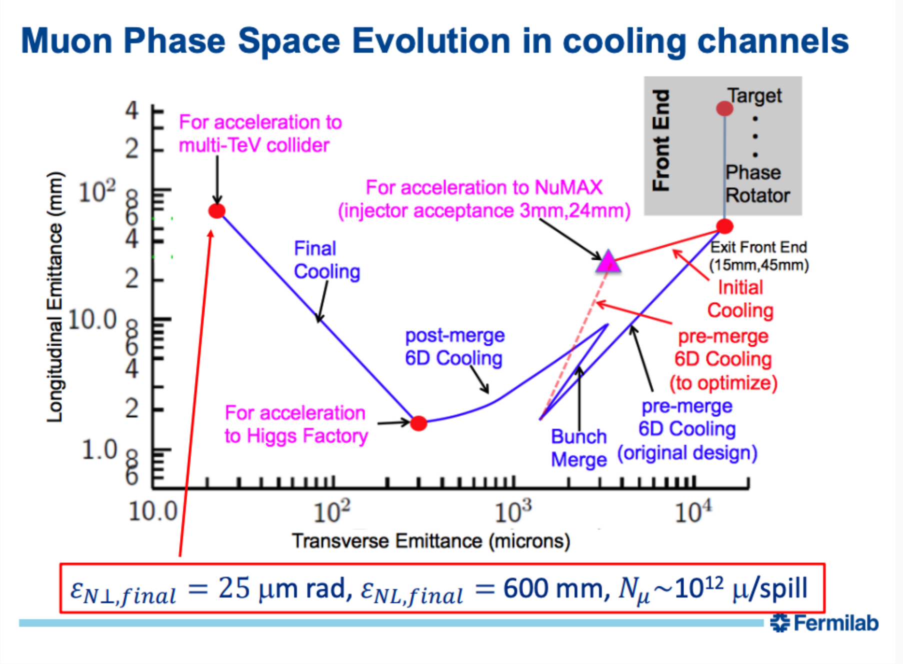
MuC at Fermilab: Detailed parameters (D. Neuffer)

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

Muon Cooling

- From Katsuya Yonehara, link





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

Key design parameter in ionization cooling

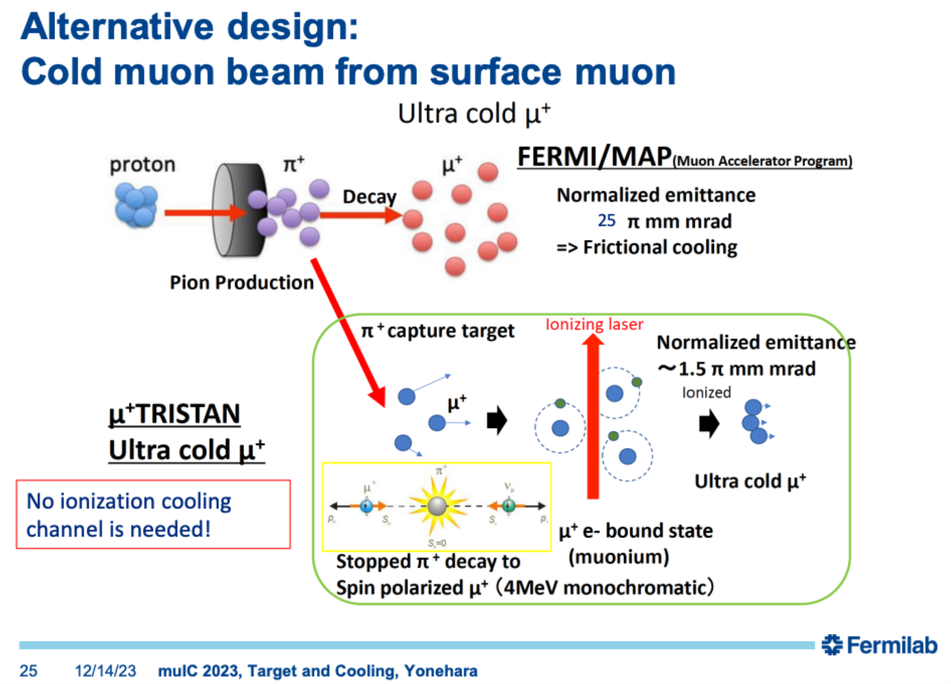
- **Low Z ionization absorber:** Longer radiation length is better for cooling
- **RF cavity as energy loss compensation:** Higher gradient is better for cooling
- **Magnet to make low beta function at absorber:** Stronger field is better for cooling

Heated by multiple sc[…]

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



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

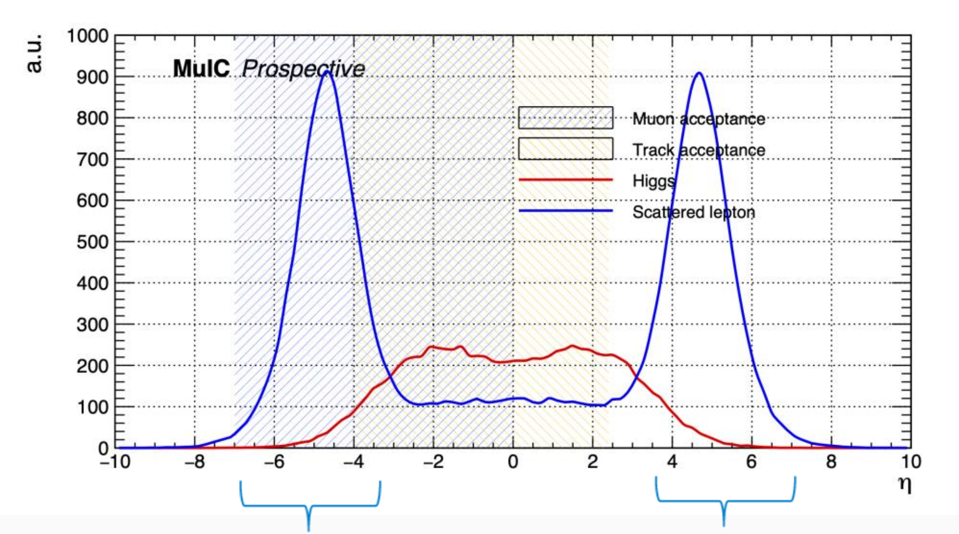
- Christoph Montag at the MuIC workshop made similar remarks in his talk
  - Space charge effects, intrabeam scattering (down factor 240)
  - Beam-beam effects (reduce by factor 100, but could increase μ bunches by 100)
  - Hadron beam emittance growth from muon replacement
  - Suggests increasing beam 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

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

- Pseudorapidity distribution for scattered lepton in VBF Higgs production

- 5 x 5 TeV

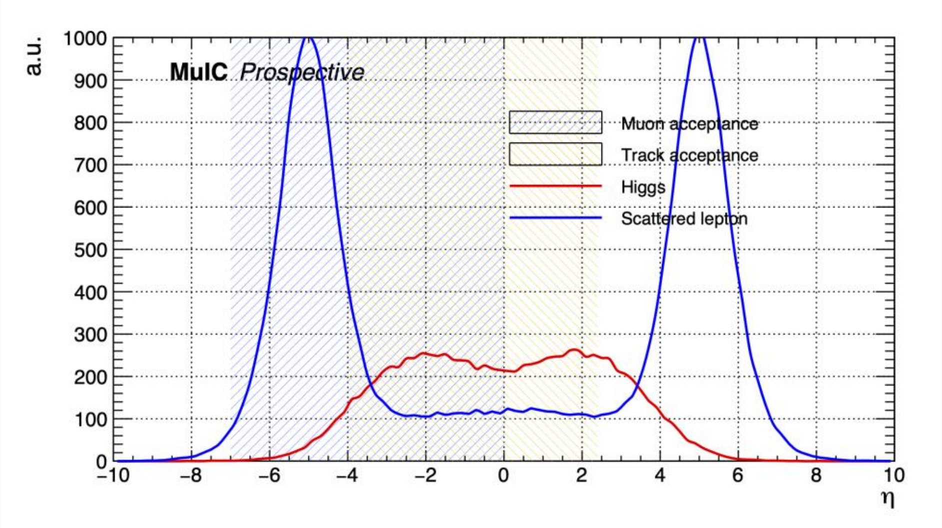


- Scattered muons in far backward and forward regions similar to MuIC

VBF Higgs Production for $\mu^+\mu^-$ Collider

- Pseudorapidity distribution for scattered lepton in VBF Higgs production

- 7 x 7 TeV



- Scattered muons in far backward and forward regions