HL-LHC based μh Colliders: synergy with one-pass ERL stage of LHeC

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Member of Plenary ECFA (Jan 2018 – Jul 2020)

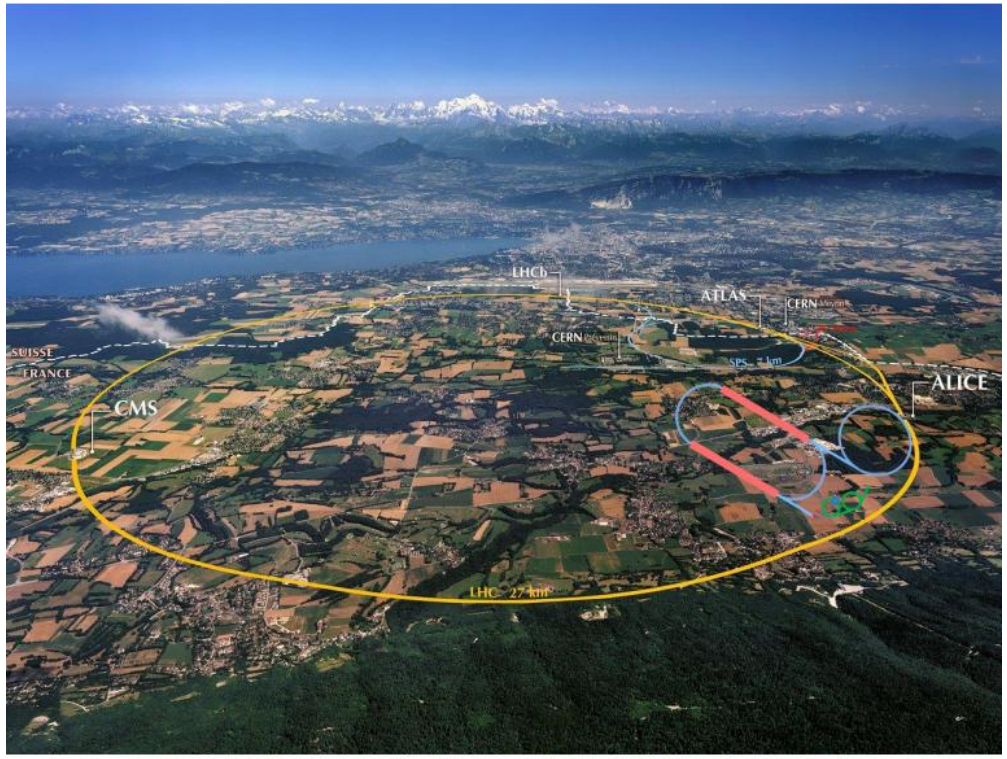

Figure 4. Bird's-eye view of the μLHC inspired from μTRISTAN.

e-Print: 2506.15445 [physics.acc-ph]

1. Why the energy frontier lepton-hadron colliders are the must

2. μLHC: two options
2.1. MC based
2.2. μ^+ ring based

3. μ^+LHC: two options
3.1. μTRISTAN based
3.2. One-pass ERL based

4. Synergy with LHeC: possible challenges

A1. AloHEP software (Burak DAGLI)
A2. μ^+ beam formation (Dilara AKTÜRK)

1.Why the energy frontier lepton-hadron colliders are the must

Lepton-hadron collisions have played an exceptional role in the study of the internal structure of matter: **proton form factors** were first observed in electron scattering experiments, **quarks** were first observed at SLAC deep inelastic electron scattering experiments, **EMC effect** was observed at CERN in deep inelastic muon scattering experiments and so on. **HERA**, the first and still unique electron–proton collider, further explored structure of protons, extended kinematical region by orders, shed light on QCD basics and provided parton distribution functions (PDFs) for adequate interpretation of Tevatron and LHC data.

On the other hand, while the **electro-weak part** of the Standard Model (SM) was **completed with the discovery of Higgs boson**, there are still **large gaps in the QCD part** of the SM: the **confinement** hypothesis has not been proven from the QCD basics, **hadronization** and **nuclearization** phenomena have not been clearly understood.

It should be emphasized that Higgs mechanism is responsible for less than 2% of the mass of visible Universe, while remaining is coming from strong interactions.

Unfortunately, the region of sufficiently **small x-Bjorken ($< 10^{-4}$) at high Q^2 (> 10 GeV^2)**, which is **very important for understanding QCD basics**, **was not covered by HERA.** The centre-of-mass energy of **EIC** is several times **lower than that of HERA.**

To investigate this region, TeV scale lepton–hadron colliders are required. ERL-50 based **LHeC** will give opportunity to **touch this region**.

On the other hand, ***μh* colliders may provide much higher center-of-mass energies. Therefore, clarify QCD basics!**

In addition, **powerful tool for investigating muon related BSM physics.**

lp Colliders Possible to be Built in the 2030s

Collider	$\sqrt{s}\ [TeV]$	$L[cm^{-2}s^{-1}]$	$L_{int}[fb^{-1}]$
HERA	0.319	7.5×10^{31}	0.8 (total)
EIC	0.105	1.0×10^{34}	100/year
LHeC (ERL 20)	0.748	6.0×10^{33}	60/year
LHeC (ERL 50)	1.18	1.4×10^{33}	14/year
μLHC	5.29	4.0×10^{33}	40/year
μLHC (ERL based)	5.29	1.7×10^{33}	17/year

Very important note: lepton-hadron colliders are mainly QCD Explorers, not Higgs factories.

QCD (not H) Explorers

Higgs mechanism is responsible for ≈ 1% of mass of visible universe:

$m_u \approx 2.2$ MeV, $m_d \approx 4.7$ MeV, $m_e \approx 0.511$ MeV, $m_p \approx 938$ MeV, $m_\alpha \approx 3727$ MeV

(visible Universe: 74% H, 24% He)

QCD is responsible for remaining 99% !!!

Luminosity vs energy in lepton-hadron collisions:

- **Higgs physics requires highest lumi,**
- **QCD basics requires highest energy.**

ERL50+LHC with $L = 10^{34}$ cm^{-2} s^{-1} requires **too much wall plug power**, while even this luminosity (if achived) may not be sufficient for precision Higgs boson physics.

Let's leave the Higgs boson to the lepton and hadron colliders !

Clarifying of QCD basics (including confinement hypothesis) may lead to exceptional results (including cosmology, astrophysics and technology) !!!

Muon-proton colliders were proposed three decades ago as an alternative to linac-ring type ep colliders.

Fermi National Accelerator Laboratory

FERMILAB-Conf-97/114

An Asymmetric Muon-Proton Collider: Luminosity Consideration

V.D. Shiltsev

Presented at the *Particle Accelerator Conference PAC 97*,
Vancouver, Canada, May 12-16, 1997

Abstract

An asymmetric muon-proton collider is proposed as an instrument for possible quark structure search. Energy of proton beam is supposed to be some 5-6 times of muon energy. Estimated luminosity of the collider with two rings – the Tevatron accelerator and μ-ring – is found to be of the order of $10^{33}\ s^{-1}cm^{-2}$.

Table 2: Quark-Lepton Collider Projects

Project	Q	p_l	p_q	$L, 10^{31}$
TESLA+HERA-p	350	250	140	~1.0
LEP+LHC	700	90	1300	1–10
μ–ring+Tevatron	350	200	160	10–100

Table 1: Two Options of $\mu - p$ Collider

Parameter	I	II
Muon Energy, E_μ, GeV	200	200
Proton Energy, E_p, GeV	1000	1000
μ Intensity, N_μ/bunch	$2 \cdot 10^{12}$	$5 \cdot 10^{11}$
μ Emittance, $\epsilon_{n\,\mu}$, $10^{-6}\ m$	50	200
Storage turns, n_s	~2000	~2000
μ Pulse rate, f_L	30	10
N bunches (p, μ), M	2	2
Beta at IP β^*_μ, cm	7.5	7.5
β^*_p, cm	15	15
Waist size σ_{IP}, μm	~40	~90
p Emittance ϵ_{np}, 10^{-6} m	12.5	50
p Intensity, N_p/bunch	$1.25 \cdot 10^{12}$	$5 \cdot 10^{12}$
Beam-beam shift ξ_p	0.02	0.0005
ξ_μ	0.026	0.026
Luminosity L, $s^{-1}cm^{-2}$	$1.3 \cdot 10^{33}$	$1.1 \cdot 10^{32}$

Tr. J. of Physics
22 (1998) , 607 – 610.

International Workshop on Linac-Ring
Type ep and γp Colliders

Physics at future ep, γp (linac–ring) and μp colliders

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Abstract

The physical problems for the enumerated colliders are discussed. It is taken into account that all these machines can work only after corresponding parental colliders.

μp collider

It was noted recently that in the frame on the $\mu^+\mu^-$ project one can develop with relatively small additional efforts μp collider with $\sqrt{s} = 4$ TeV and[2] $calL \approx 3 \cdot 10^{35}$ $cm^{-2}s^{-1}$. It will be really new machine with high potential supplemented strongly to that of other colliders of next generation.

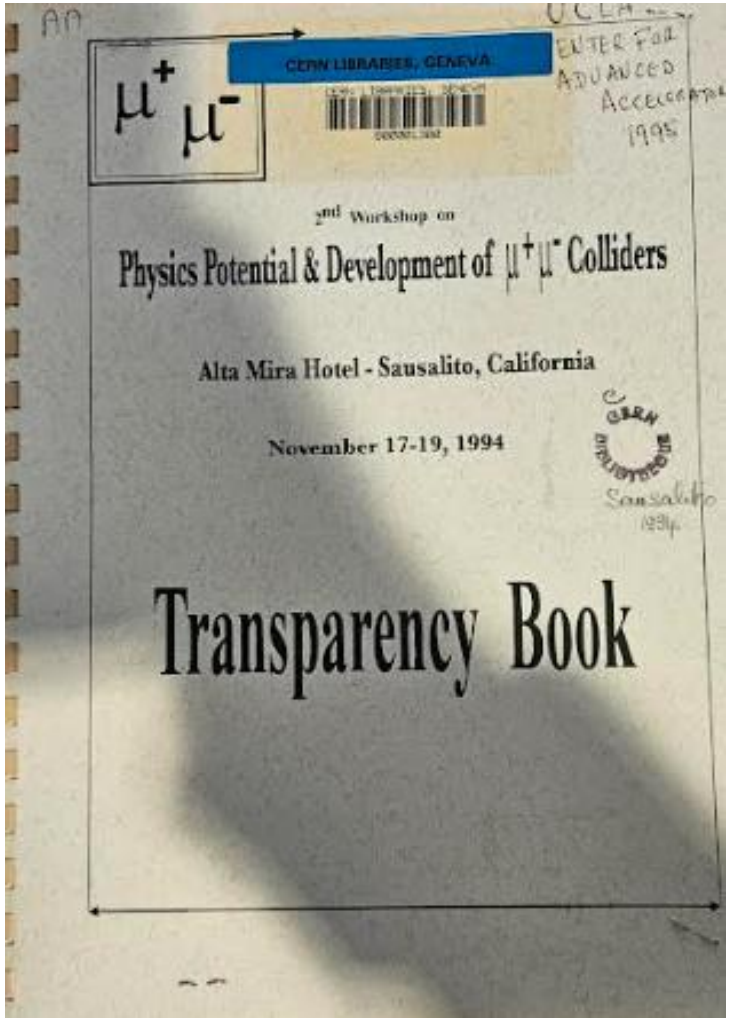
Luminosity is overestimeted by more than two orders !

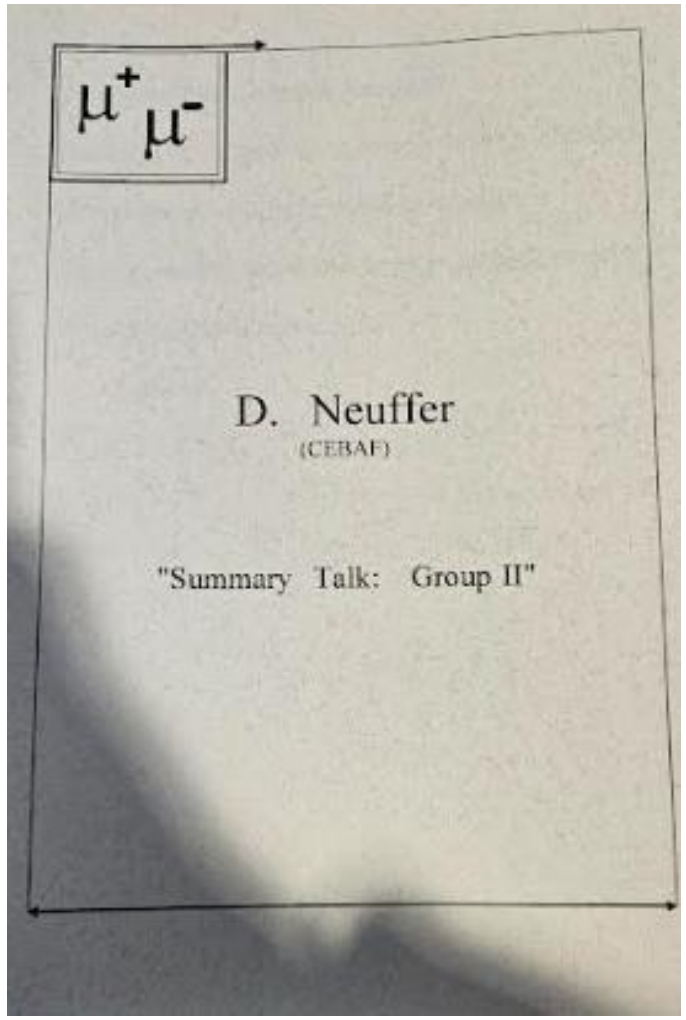
For the history and current status of the MC and HC based muon-hadron colliders, see reviews:

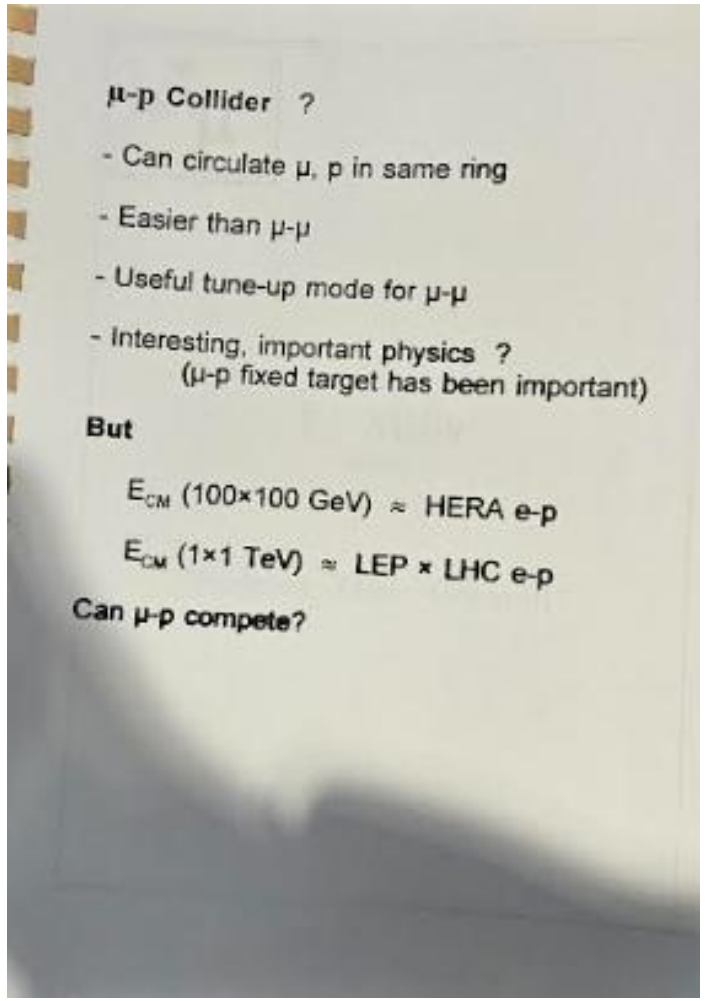
S. Sultansoy, The post-HERA era: brief review of future lepton-hadron and photon-hadron colliders, DESY Preprint DESY-99-159 (1999); arXiv:hep-ph/9911417

B. Ketenoglu, B. Dagli, A. Ozturk, and S. Sultansoy, Review of muon-proton and muon-nucleus collider proposals, Mod Phys Lett A 37, (2023).
DOI: 10.1142/S0217732322300130

Muon-proton colliders were first mentioned in 1994







2025

? → !!!

No

Essentially Easier

Yes

YES !!!

μLHC

E_{CM} (1×7 TeV)

>> LEP × LHC e-p

Obviously yes !!!

2. µLHC: two options
2.1. MC based
2.2. μ^+ beam based

Luminocity calculations: AloHEP (for details see Appendix 1)

1 TeV μ^+ beam (for details see Appendix 2)

2.1. MC and HL-LHC based μp colliders

A LETTERS JOURNAL EXPLORING THE FRONTIERS OF PHYSICS

Luminosity and physics considerations on HL-LHC–and HE-LHC–based μp colliders

Umit Kaya[1], Bora Ketenoglu[2], Saleh Sultansoy[3] and Frank Zimmermann[4]

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Citation Umit Kaya *et al* 2022 *EPL* **138** 24002

DOI 10.1209/0295-5075/ac4f98

Abstract

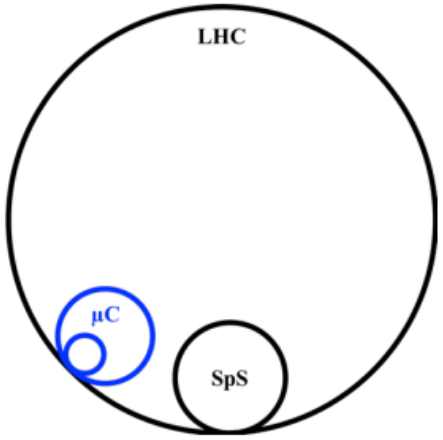
Construction of the future muon collider tangential to the Large Hadron Collider will give opportunity to realize μp collisions at multi-TeV center-of-mass energies. Using the nominal parameters of high-luminosity and high-energy upgrades of the LHC, as well as the design parameters of muon colliders, it is shown that $L_{\mu p}$ of the order of 10^{33} cm^{-2}s^{-1} is achievable for different options with $\sqrt{s_{\mu p}}$ from 4.58 TeV to 12.7 TeV. Certainly, the proposed μp colliders have a huge potential for clarifying QCD basics and searches for new physics.

Table 4. Center of mass energies and luminosities of HL-LHC based μp colliders

E_μ, TeV	√s, TeV	L (nominal), 10^{33} cm^{-2}s^{-1}	L (upgraded), 10^{33} cm^{-2}s^{-1}
0.75	4.58	0.95	1.4
1.5	6.48	0.84	2.1
3	9.16	0.57	1.5

Table 7. Achievable x Björken values at the LHC based μp colliders.

√s, TeV	Q^2= 1 GeV^2	Q^2= 25 GeV^2
4.58	4.8×10^{-8}	1.2×10^{-6}
~ 6.4	2.5×10^{-8}	6.1×10^{-7}
~ 9	1.3×10^{-8}	3.1×10^{-7}
12.7	6.2×10^{-9}	1.6×10^{-7}



But muon cooling problem !!!

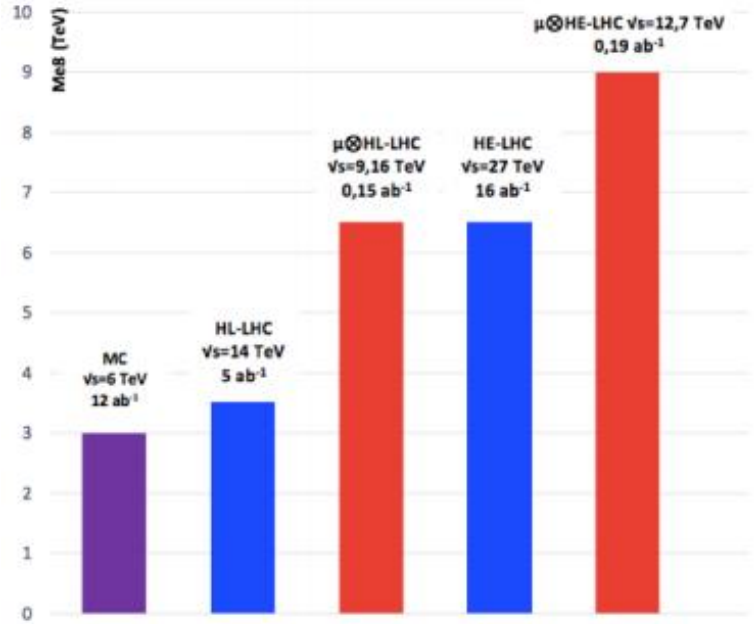


Figure 2. Discovery Limits for Color Octet Muon at the MC with √s=6 TeV, HL-LHC, HE-LHC and corresponding μp Colliders

2.2. μ^+ beam based

μLHC: Antimuon Ring and HL-LHC based μ^+p Collider

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[*]*Corresponding Author:* ssultansoy@etu.edu.tr

Abstract

Conceptual design and performance evaluation of HL-LHC based antimuon-proton collider (μLHC) are presented. Leveraging the μTRISTAN concept based on established J-PARC ultra-cold μ^+ beam technology, μLHC will give the opportunity to achieve a 5.3 TeV center-of-mass energy, significantly surpassing EIC and LHeC. Two booster ring options for μ^+ acceleration, namely, a μTRISTAN-based and a repurposed LHeC ERL-based systems, are explored. Achievable luminosities are predicted to exceed 10^{33} cm^{-2}s^{-1}. The μLHC offers substantially wider kinematic plane coverage, particularly in small-x and high-Q^2 regions, significantly contributing to QCD basics and Higgs boson properties. Its unique potential for BSM physics extends to muon-related phenomena like excited muons, color-octet muons, leptoquarks, and contact interactions. A possible detector concept is also outlined. Given the maturity of ultra-cold μ^+ beam technology, μLHC is highly feasible for earlier realization than the muon collider, positioning it as a critical tool for the future of high energy physics.

Keywords: lepton-hadron collider, μLHC, luminosity, QCD, BSM physics

e-Print: 2506.15445 [physics.acc-ph]

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Leveraging the μTRISTAN concept **based on established J-PARC ultra-cold μ^+ beam technology**, μLHC will give the opportunity to achieve a **5.3 TeV center-of-mass energy**, significantly surpassing EIC and LHeC.

Two booster ring options for μ^+ acceleration, namely, a **μTRISTAN-based** and a **repurposed LHeC ERL-based** systems, are explored.

Achievable **luminosities** are predicted to **exceed 10^{33} cm^{-2}s^{-1}.**

The μLHC offers substantially wider kinematic plane coverage, particularly in **small-x and high-Q^2** regions, significantly contributing to **QCD basics and Higgs boson properties**.

Its **unique potential for BSM physics** extends to muon-related phenomena like excited muons, color-octet muons, leptoquarks, and contact interactions.

A possible detector concept is also outlined.

Given the maturity of ultracold μ^+ beam technology, **μLHC is highly feasible for earlier realization than the muon collider**, positioning it as a critical tool for the future of high energy physics.

3. μ^+LHC: two options

3.1. μTRISTAN based

3.2. One-pass ERL based

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Figure 4. Bird's-eye view of the μLHC inspired from μTRISTAN.

LHeC's ERL-based boosting ring (Frank's proposal)

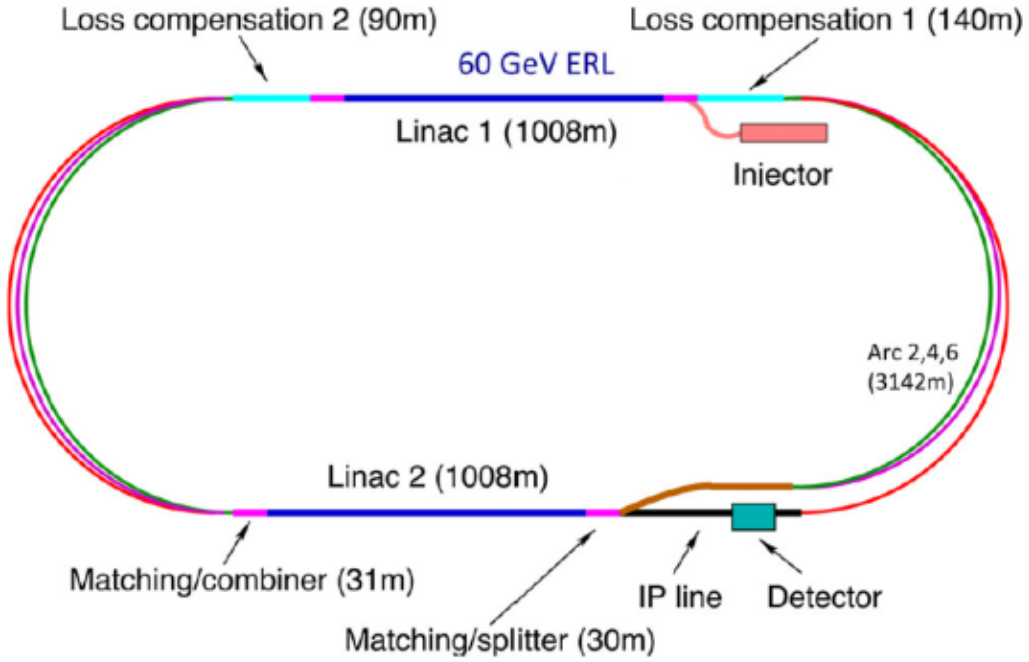


Figure 5. Schematic view of the three-turn LHeC configuration at 60 GeV final energy scale with two oppositely positioned electron linacs and three arcs housed in the same tunnel.

As seen in Figure 1 and Figure 5, ERL tunnel to be built for LHeC has similar structure of the booster ring of the μTRISTAN project, which plans to accelerate anti-muons up to 1 TeV energies.

While both facilities share a similar "race-track" shape, a key distinction lies in the LHeC incorporating two parallel linacs, each approximately 1 km in length instead of 3 km.

Therefore, the LHeC's ERL tunnel can be repurposed as a muon booster ring for an ERL-based μLHC. A schematic view of this proposal is given in Figure 6.

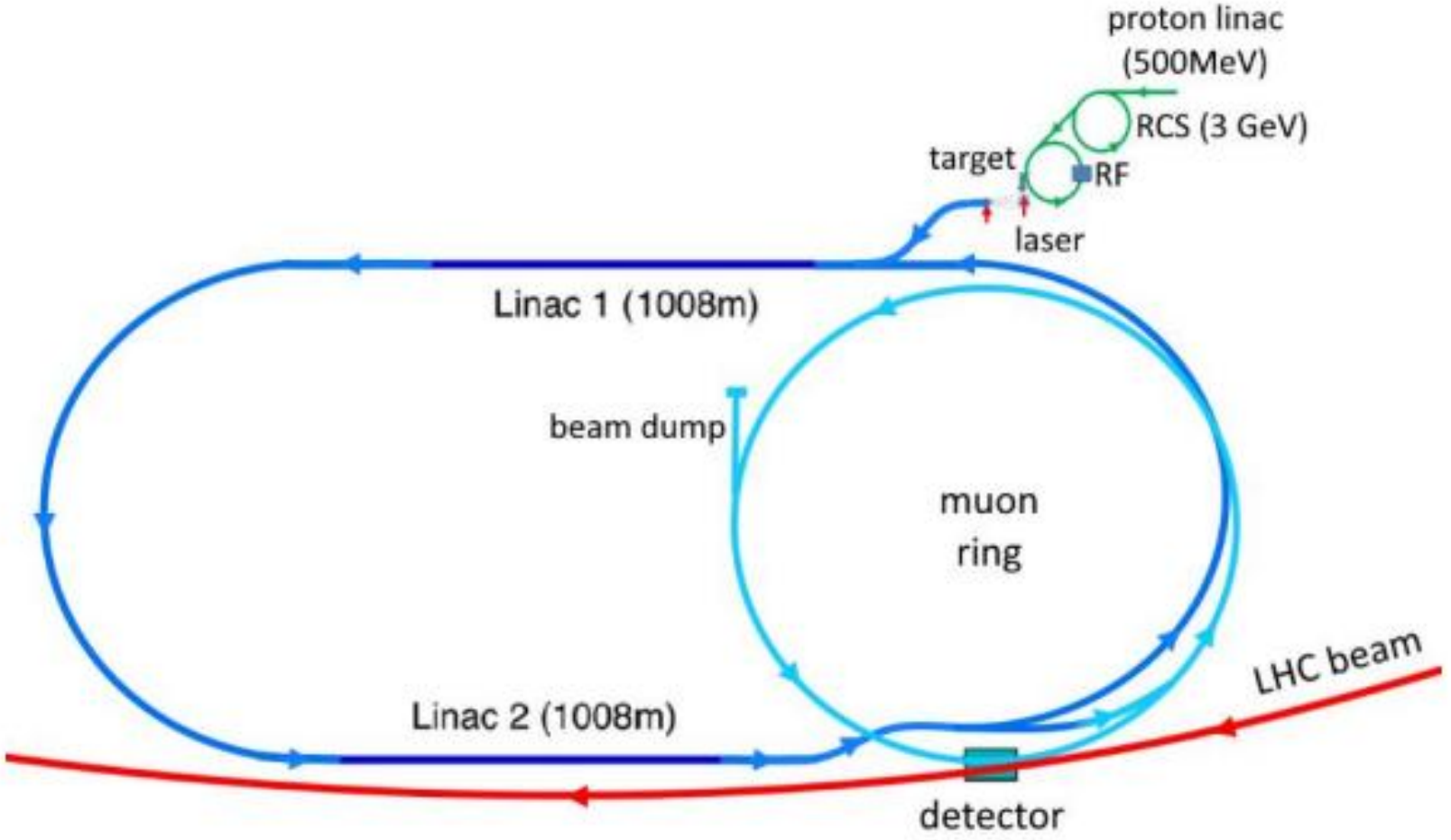


Figure 6. Schematic view of the μLHC, showing a booster ring and main ring compactly integrated within the ERL tunnel, in a manner similar to that proposed for μTRISTAN.

Main Parameters of μ^+p Colliders

Table 1. Main parameters of μ^+ beam.

Parameter	μTRISTAN-based	ERL-based
Number of muons per bunch [10^9]	17	7.2
Beam energy [GeV]	1000	
β_x @ IP [cm]	3	
β_y @ IP [cm]	0.7	
Bunch length [mm]	2	
Norm. horizontal emittance [μm]	4	
Norm. vertical emittance [μm]	4	
Number of bunches per ring	40	
Collision frequency [MHz]	4	
Circumference [km]	3	

The proton beam parameters utilized for luminosity calculations in the μLHC collider are adopted from the ERL60-upgraded proton parameters developed for the LHeC and are presented in Table 2 (Table 2.11 in [12]).

Table 2. ERL60-upgraded proton parameters.

Parameter	p
Number of Particle per Bunch [10^{10}]	22
Beam Energy [TeV]	7
β function @ IP [cm]	7
Norm. Emittance [μm]	2
Number of Bunches per Ring	2760
Rev. frequency [Hz]	11245
Circumference [km]	26.7

Table 3. Main parameters of the μTRISTAN- and ERL-based μ^+p collider.

Parameter	μTRISTAN-based		ERL-based	
$\sqrt{s}$ [TeV]	5.29		5.29	
L [10^{33} $cm^{-2}s^{-1}$]	4.1		1.7	
Parameter	μ^+	p	μ^+	p
$\sigma_{x,y}$ [μm]	4.3	4.3	4.3	4.3
$\xi_{x,y}$ [10^{-4}]	600	10	600	4.4

The Detector Concept
(Uludağ University group)

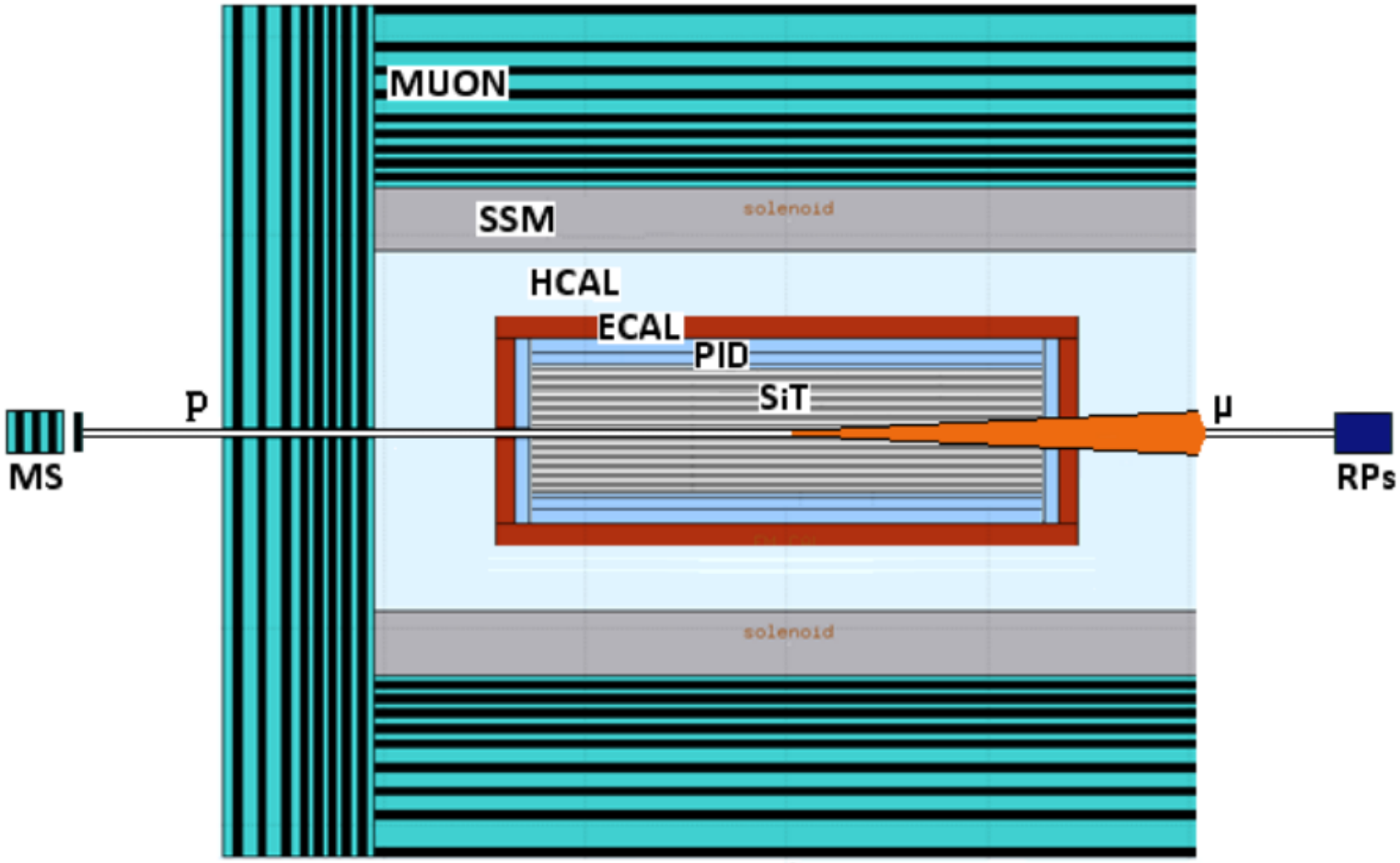


Figure 8. Schematic view of the designed detector at muon-proton colliders.

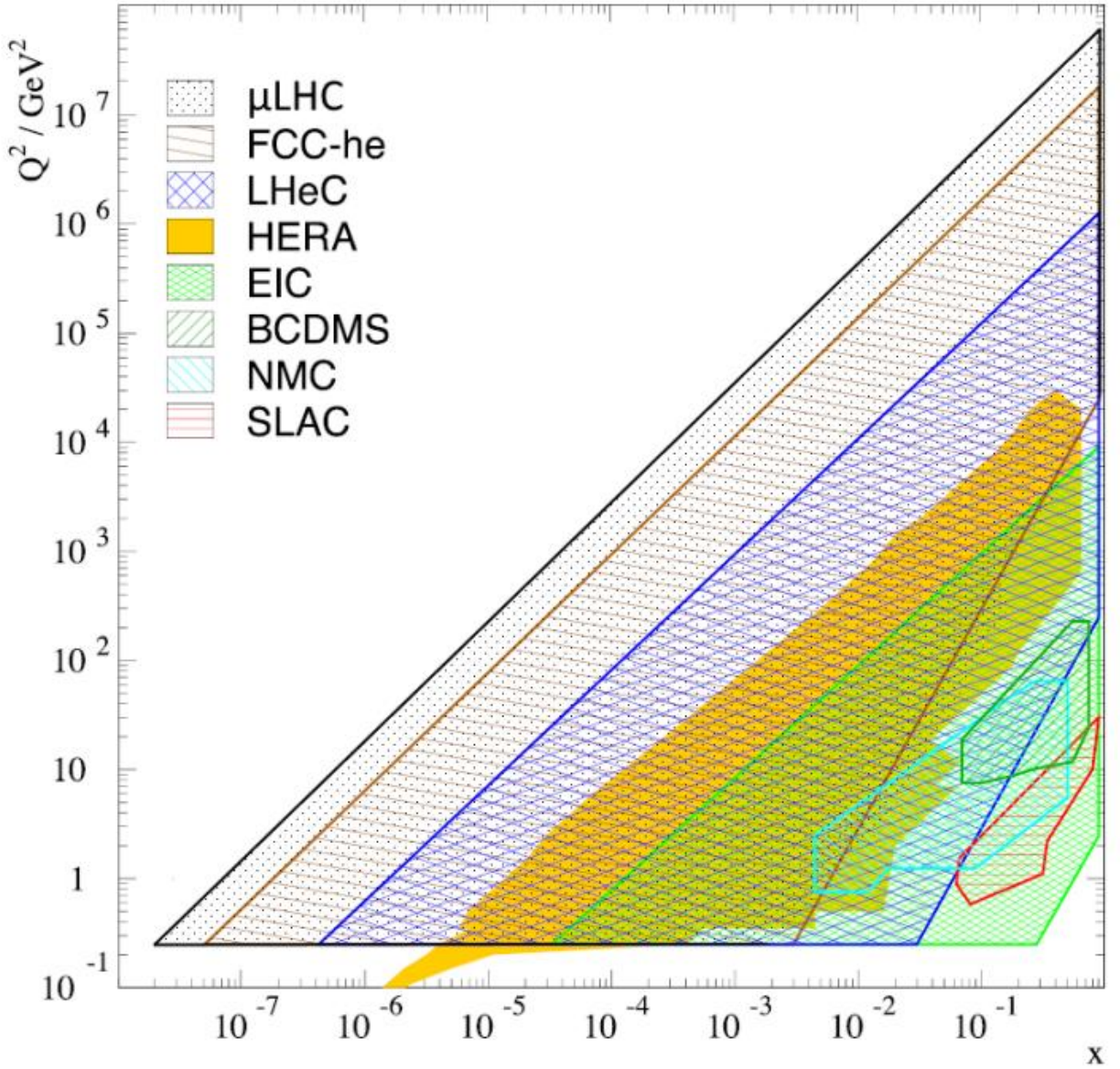


Figure 11. Coverage of the kinematic plane in deep inelastic lepton–proton scattering.

Conclusions

Construction of energy frontier lepton-hadron colliders is the must for two reasons:

- Clarification of strong interactions (including QCD basics), which are responsible for 98% of mass of the visible Universe,
- Providing PDF's for adequate interpretation of the HL-LHC (as well as FCC-hh and SppC) data.

Lepton-hadron colliders based on the FCC and SppC have been dropped from the agenda, as FCC-ee and CEPC have been chosen as the first phases (a mistaken decision, in my opinion). At best, these hadron colliders could be built in the 2050s. **Therefore, lepton-hadron collisions could be achieved in the 2070s.**

Because the LHC has the highest-energy hadron beams, CERN is the most suitable place for building energy frontier lepton-hadron colliders. μLHC is the sole realistic way to multi-TeV center-of-mass energy scale at lepton-hadron interactions in 2030s.

In addition, μLHC will provide a unique opportunity to investigate muon-related BSM physics.

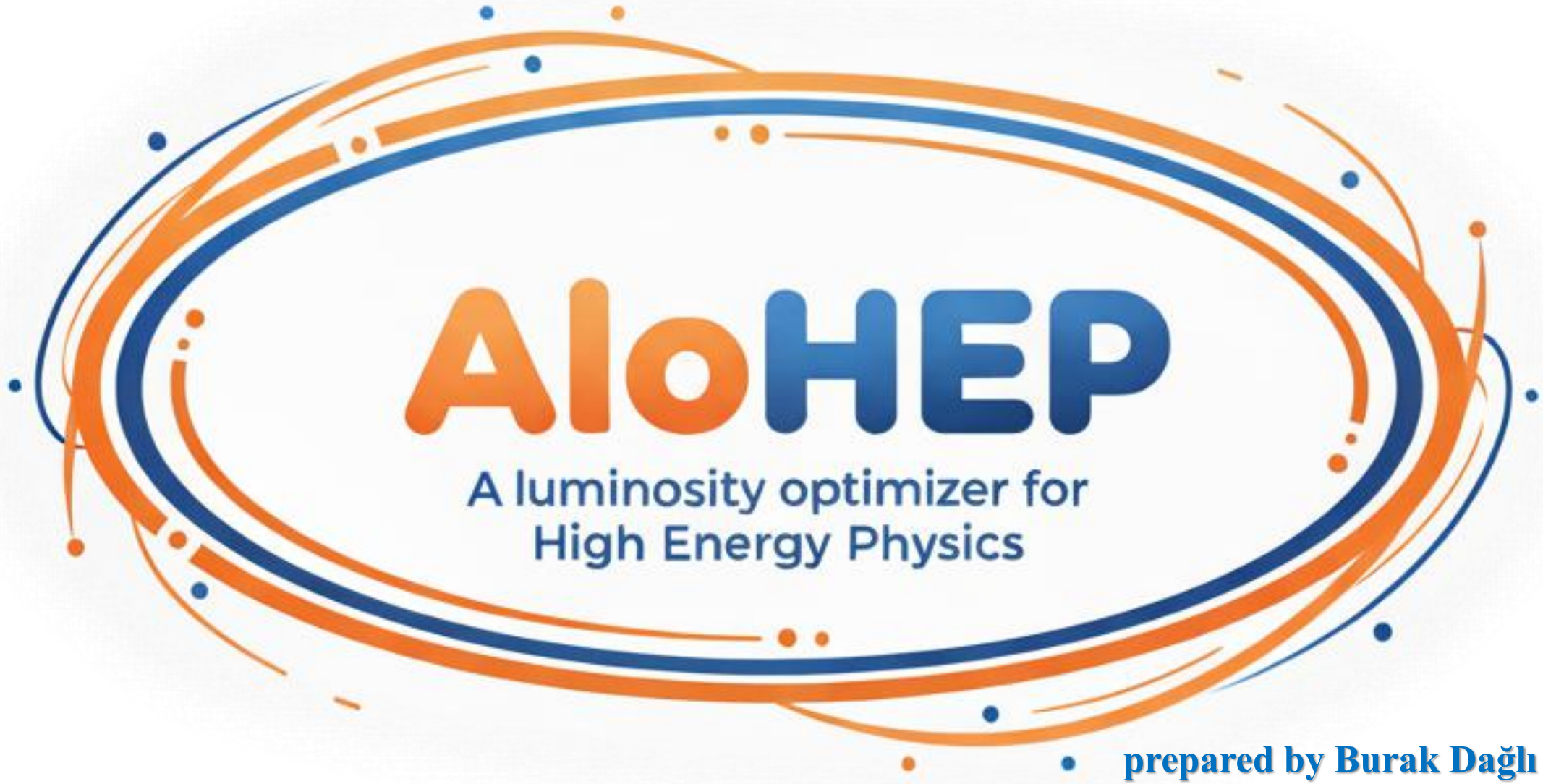
Finally, I recommend including of the μLHC proposal in the ESPP update.

Appendices

A1. AloHEP software (Burak DAGLI)

A2. μ^+ beam formation (Dilara AKTÜRK)

Appendix 1



prepared by Burak Dağlı
(PhD student, TOBB ETU)

AloHEP (A luminosity optimizer for High Energy Physics)

Recent developments in lepton-hadron collisions have increased the need for software capable of modeling and simulating the interaction region of such colliders in detail.

In this context, the prototype of **AloHEP** (*A Luminosity Optimizer for High Energy Physics*) was developed and released in 2017 by the TOBB ETÜ High Energy Physics (YEF) Group for linac-ring type electron-proton colliders (HEPForge, 2025).

The software was subsequently updated in 2022 to include almost all collider types and various colliding beam species (YEF ETU, 2025).

Collider Type	CAIN	GUINA-PIG	AloHEP
ee	X	X	X
μμ			X
pp (AA)			X
μe			X
ep (eA)			X
μp (μA)			X
γγ	X		
γp (γA)			

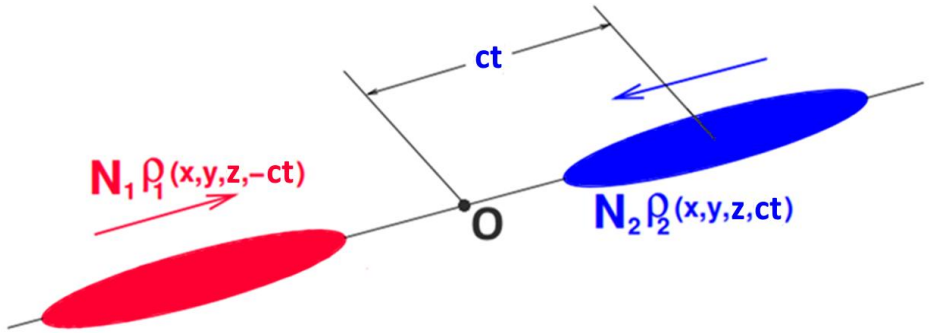
HEPForge, “A Luminosity Optimizer for High Energy Physics”, https://alohep.hepforge.org/, Last access date: 22 October 2025

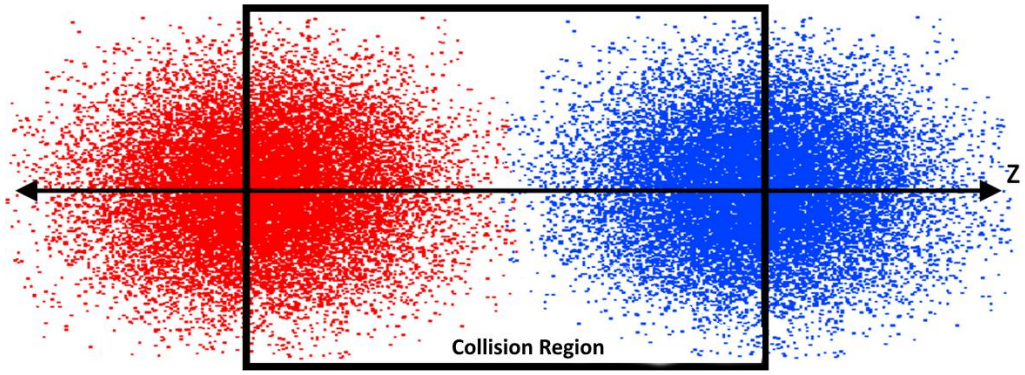
YEF ETU. “AloHEP Software”. https://github.com/yefetu/ALOHEP, Last access date: 22 October 2025

AloHEP (A luminosity optimizer for High Energy Physics)

- AloHEP (A luminosity optimizer for High Energy Physics) is a dedicated software tool for accelerator design, focusing on beam dynamics calculations on interaction region of ll, hh (AA) and also lh colliders.

- It computes crucial parameters like luminosity, tune-shift, and disruption for various collider types (linear, circular, linac-ring) and diverse beams (electrons, positrons, muons, protons, nuclei).

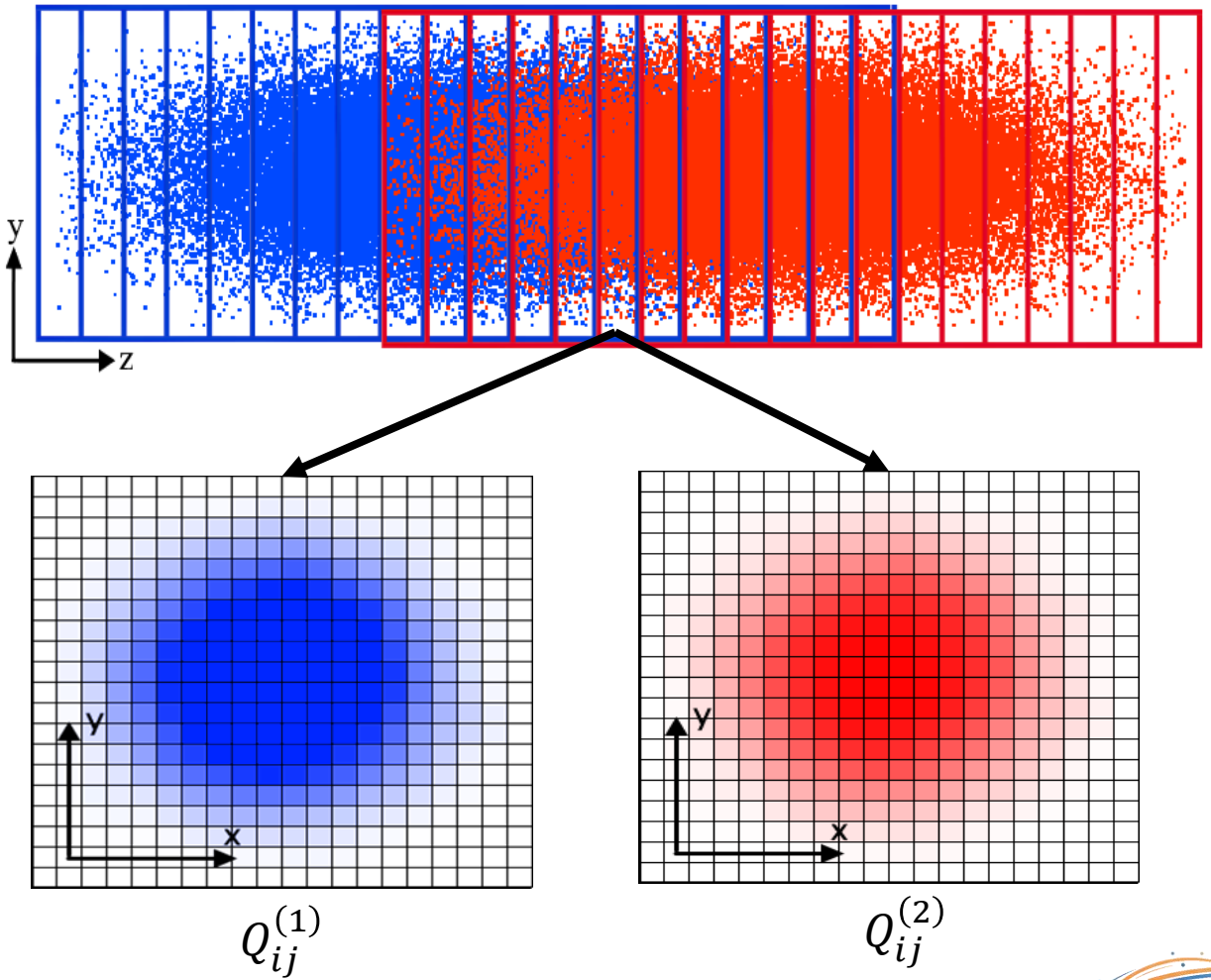




- In the AloHEP software, identical superparticles representing the real particles within the bunch are randomly distributed in three dimensions according to a normal distribution.

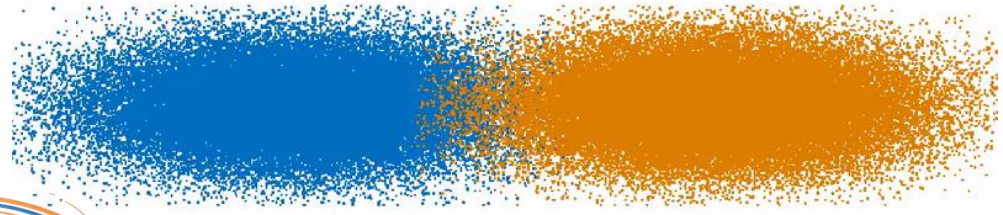
- The collision region is defined as a rectangular prism and adjusted so that its center coincides with the Interaction Point.

Luminosity Calculation in AloHEP



$$\mathcal{L} = 2N_1N_2f_c\frac{c\delta t}{\delta x\delta y\delta z N_{sp}^2}\sum_n\sum_k\sum_{ij}Q_{ij}^{(1)}Q_{ij}^{(2)}$$

Here, N_1 and N_2 correspond to the number of particles contained in the colliding bunches, fc represents the number of bunch collisions per second, and N_{sp} denotes the number of super particles, n represents each time step, k refers to each intersecting slice, and the matrices $Q_{ij}^{(1)}$ and $Q_{ij}^{(2)}$ represent the particle distributions of the intersecting slices.



AloHEP
A luminosity optimizer for High Energy Physics

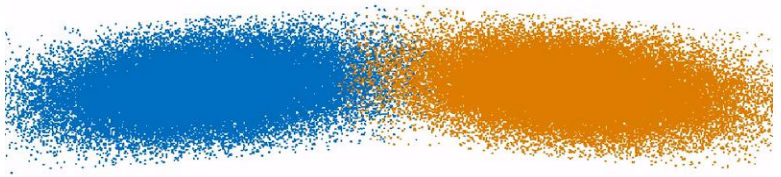
Considered Effects in AloHEP

There are several factors in the collision region that change the direction and shape of the bunch. To obtain more realistic results, these factors must be taken into account. The most important of them are:

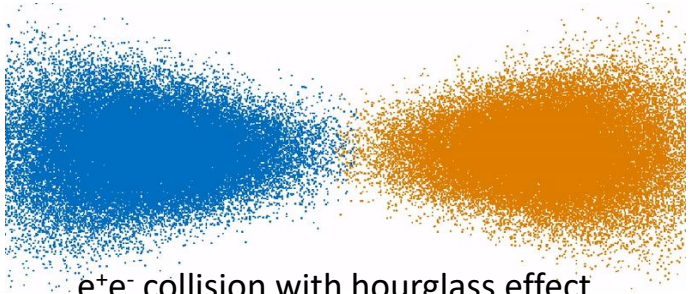
- The crossing angle
- The hourglass effect
- Beam–beam interactions

In symmetric colliders, the effects of the hourglass effect and the crossing angle can be calculated analytically and independently of each other. However, in asymmetric colliders — and when these effects need to be considered together — simulations, i.e., numerical calculations, are required.

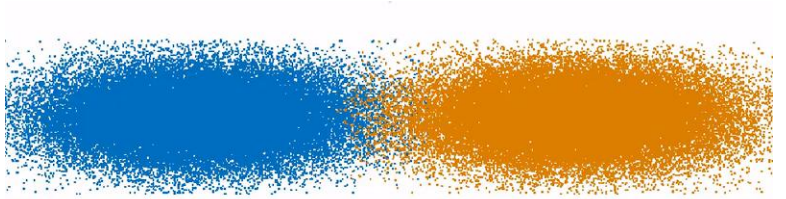
Some example animations of symmetric collisions simulated in the AloHEP



pp collision with a crossing angle



e^+e^- collision with hourglass effect



e^+e^- collision with beam-beam interactions

Comparison of AloHEP with other Simulation Tools

Comparison of collision region simulation tools according to the effects they include in the calculations are given in the table.

AloHEP is planned to include more effects, which will help achieve luminosity values that are closer to realistic conditions.

It will also continue to be developed to improve its accuracy and performance.

Effects	CAIN	GUINEA-PIG	(current) AloHEP	(planned) AloHEP
Pinch effect	X	X	X	X
Beamstrahlung	X	X		X
Pair production	X	X		X
Initial state Radiation		X		X
Hourglass effect			X	X
Beam offset			X	X
Crossing angle			X	X
Crab-crossing				X

AloHEP
A luminosity optimizer for High Energy Physics

Examples of AloHEP Usage: Luminosity of MuIC for BNL

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A muon–ion collider at BNL: The future QCD frontier and path to a new energy frontier of $\mu^+\mu^-$ colliders

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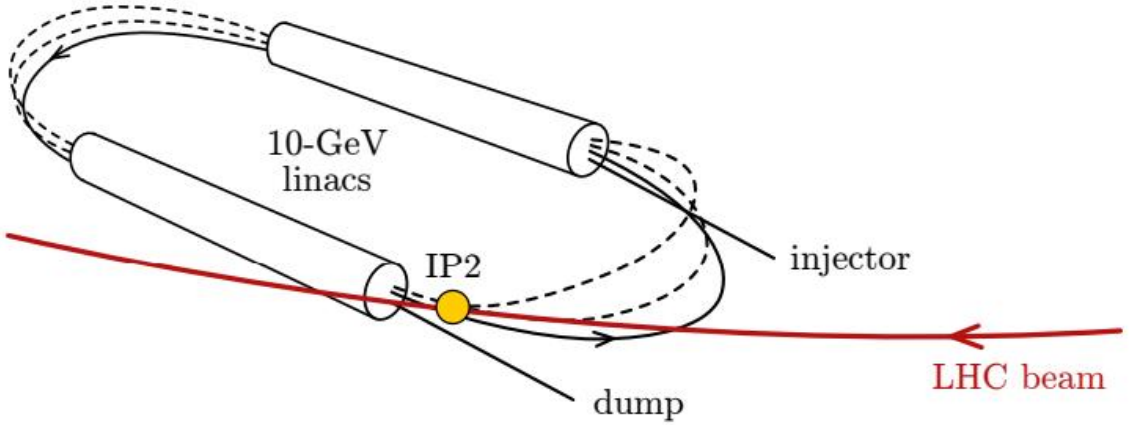
ABSTRACT

We propose the development and construction of a novel muon–ion collider (MuIC) at Brookhaven National Laboratory (BNL) in the USA as an upgrade to succeed the electron–ion collider (EIC) that is scheduled to commence in the early 2030s, by a joint effort of the nuclear and particle physics communities. The BNL facility could accommodate a muon storage beam with an energy up to about 1 TeV with existing magnet technology. When collided with a 275 GeV hadron beam, the MuIC center-of-mass energy of about 1 TeV will extend the kinematic coverage of deep inelastic scattering physics at the EIC (with polarized beams) by more than an order of magnitude in Q^2 and x, opening a new QCD frontier to address many fundamental scientific questions in nuclear and particle physics. This coverage is comparable to that of the proposed Large Hadron–Electron Collider (LHeC) at CERN, but with complementary lepton and hadron kinematics, ion species, and beam polarization. Additionally, the development of a MuIC at BNL will focus the worldwide R&D efforts on muon collider technology and serve as a demonstrator toward a future muon–antimuon collider at $\mathcal{O}(10)$ TeV energy, which is an attractive option to reach the next high energy frontier in particle physics at an affordable cost and a smaller footprint than a future circular hadron collider. We discuss here the possible design parameters of the MuIC, kinematic coverage, science cases, and detector design considerations including resolution estimates on DIS kinematic variables. A possible road map toward the future MuIC and muon–antimuon colliders is also presented.

- The parameters of the muon-ion collider proposed in the paper were entered into AloHEP and it was seen that they calculated the luminosity value in an overly optimistic way.
- While the luminosity value given in the article is $7\times10^{33}cm^{-2}s^{-1}$, the realistic value calculated with **AloHEP** is **$3.6\times10^{31}cm^{-2}s^{-1}$**.
- For details: B. Dagli, B. Ketenoglu and S. Sultansoy, Comment on μp and μA Luminosities of Muon-Ion Collider at BNL, arXiv:2211.07513 [physics.acc-ph], https://arxiv.org/abs/2211.07513

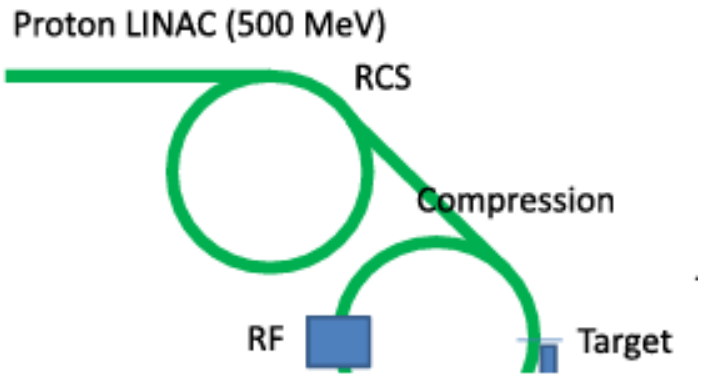
Luminosity Calculation for Single-pass ERL-based LHeC

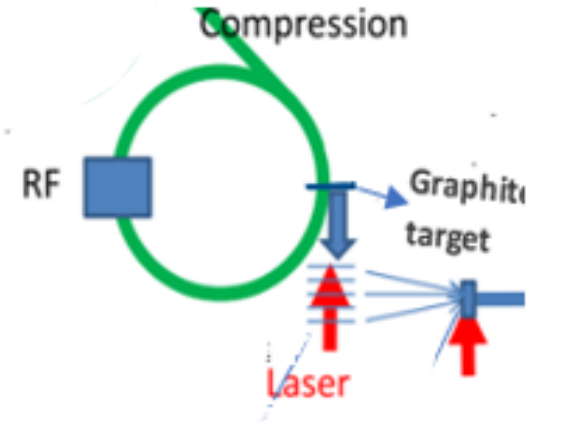
Parameter	Single-pass ERL based LHeC	
$\sqrt{s}$ [GeV]	748	
L [10^{33} $cm^{-2}s^{-1}$] (nominal)	5.68	
L [10^{33} $cm^{-2}s^{-1}$] (effective)	5.99	
Beam type	e^-	p
$\sigma_{x,y}$ [μm]	10.7	10.7
Beam-beam parameters	Disruption ($D_{x,y}$)	BB Tuneshift ($\xi_{x,y}$)
	10.6	4.71×10^{-4}



Appendix 2

μ^+ BEAM FORMATION BASED ON μTRISTAN





“ultra-cold muons”

**The expressions underlined in the slides are taken directly from the article.

prepared by Dilara Aktürk
(MsC student, TOBB ETU)

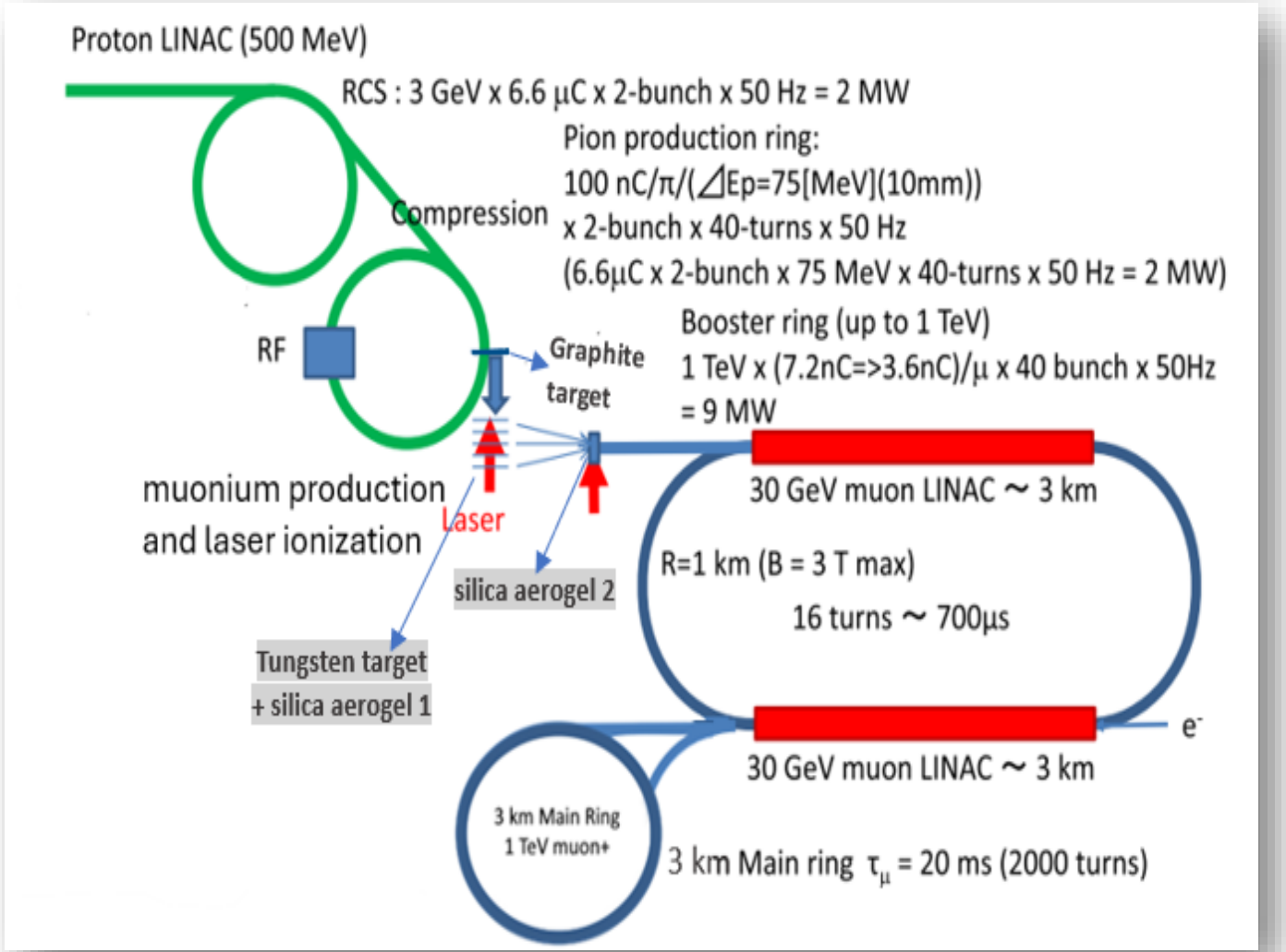
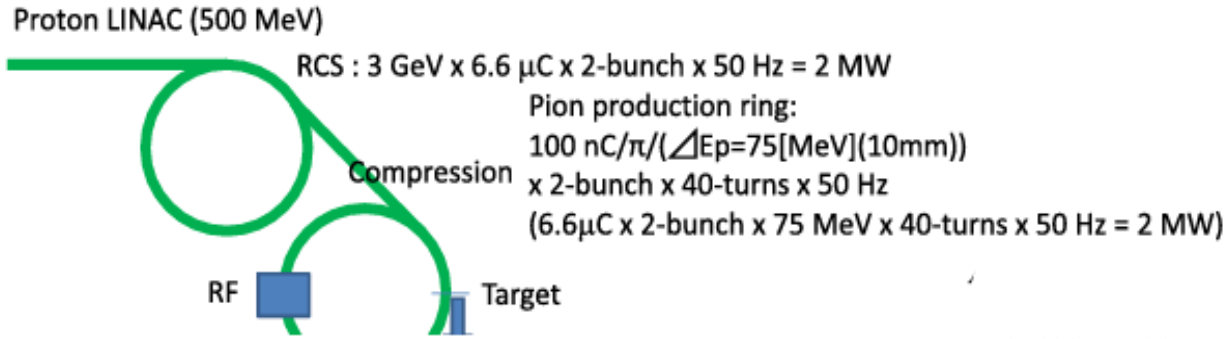


Fig 1. Schematic view of conceptual design **[1]**

Fig 2. Birds'-eye view of the μLHC inspired from μTRISTAN **[2]**

Proton Accelerator and Pion Production Ring:

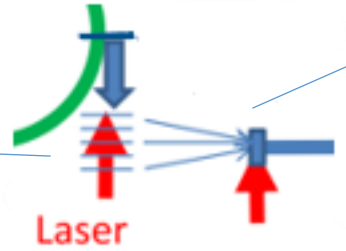


The first stage of μ^+production is to deliver a proton beam to the pion production target. The authors assume the beam parameters of the proton LINAC and RCS (Rapid-Cycling Synchrotron) to be similar to those in J-PARC with a beam power of 2 MW.

The two-bunch proton beam with bunch charge 6.6 μC (= 4.1×10^{13} protons) is accelerated to 3 GeV, with a repetition rate of 50 Hz.

The operation at 50 Hz is set by the lifetime of the muon at an energy of 1 TeV, $\gamma\tau_\mu$ = 20 ms, so that a new beam is injected after the muons have spent their lifetime in the storage ring.

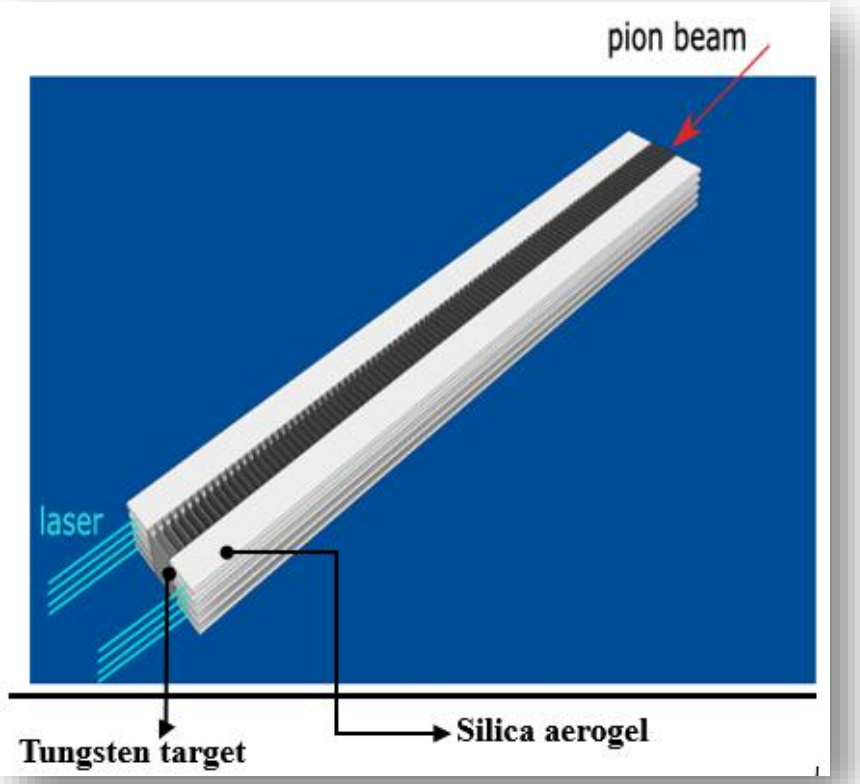
The 3 GeV proton beam is transported to the pion production ring, where the graphite target with a thickness of 10 mm is placed. The proton beam is recirculated to repeatedly hit (40 times for each bunch) the target. The energy loss of each proton in the collision is estimated to be 75 MeV (2.5% energy loss), which amounts to 2 MW power consumption used for the recovery of the beam energy. The cross-section of the pion production process, $p + \mathrm{C} \rightarrow \pi + X$, is 150 mb at a proton energy of 3 GeV.



Tungsten target + silica aerogel 1

Silica aerogel 2

#1



A 10-meter-long structure consisting of 1000 layers of 1-mm thick tungsten foils (dark regions), each separated by a 1-cm gap & a 10-meter-long layered silica-aerogel (placed just next to the tungsten foils) (white regions).

#2

A very thin ("size of a few centimeters"), layered silica-aerogel; without any tungsten target.

- Ultra-cold μ^+ that produced in the first target are transported into the thin aerogel, where they re-form muonium atoms.
- The μ^+ micro-bunches generated by the two proton bunches reach the second aerogel sequentially and by applying an appropriate delay to the *Lyman-α* laser pulse, the two micro-bunches are temporally overlapped, as stated in the paper: "The two bunches of muons … are combined at the second muon target by tuning the timing of the laser irradiation."

Because the target is extremely thin (thicker material would increase the energy spread and reduce the ionization probability), an overall efficiency of ~ 50% is assumed for this stage.

→ "Such high efficiency should be possible since a very thin target is used for the uniform muon energy."

- In the first aerogel, the 60% vacuum yield refers to the fraction of muonium atoms that successfully escape through the aerogel pores into the vacuum region. The silica aerogel is arranged vertically in layers along a length of 10 meters ("The aerogel target needs to have a length of 10m with a layer structure in the vertical direction so that one can shoot lasers in the gaps."). Here, the free muonium atoms (still within the aerogel structure but already in the vacuum regions between the layers) are ionized using a *Lyman-α* laser.

- In the paper, the process of focusing and transporting ultra-cold muons produced at the first target toward the second aerogel target is mentioned with only the sentence provided: "The ultra-cold muons spread over 10 m are in turn collected and transported to the second aerogel target with a size of a few centimeters.", without any technical details given. However, since the paper refers to the J-PARC *g-2* beamline, it can be assumed that similar focusing and transport systems are used here as well.

Total Production Rate:

"By taking into account 40 turns of the p beam… we have 9.0×10^{13} μ/s." → This represents the total number of μ^+ that can be produced per second by the designed system: "muon yield"

Yield per Proton:

"… with our design, 5.5×10^{-4} μ/p…" → This indicates that, after the entire cooling - collection chain, each proton hitting the target produces approximately 5.5×10^{-4} usable surface muons, on average (the average number of usable μ^+ obtained per proton hitting the target).

	Efficiency:
1) π Production: p + C → π + X (3 GeV p, 10 mm graphite target)	0.016 π/p
2) Pion transportation → stopping target: Transportation to the layered W foil within 40 turns + complete stopping	0.50
3) Surface μ^+ → muonium → ultra-cold μ^+ (first aerogel): $0.52 \times 0.60 \times 0.60 \times 0.73 = 0.14$	
Muonium production =	0.52
Vacuum yield =	0.60
After the loss of muoniums due to decay =	0.60
Lazer ionization =	0.73
4) Ultra-cold muons at the second muon target:	0.50

$$= 0.016 \times 0.50 \times 0.14 \times 0.50 = 5.5 \times 10^{-4}\, \mu^+/\mathrm{p}$$

1) The interaction of 3 GeV protons with the graphite target results in μ^+ production at a rate of ~ 1.6%.

2) Half of the produced μ^+ are transported to the 10-meter-long multilayer W foil structure and are fully slowed down.

3) μ^+ → surface μ^+ → Muonium (μ^+e^-) is formed within the aerogel (52%).

60% of the muonium atoms escape into vacuum; 60% are ionized by a *Lyman-α* laser before decaying; 73% of the ionized μ^+ are transformed into ultra-cold muons.

4) Second Target: The ultra-cold muons produced in the first stage are collected over a 10 meter range and the same process is repeated in the second aerogel target. The two muon bunches are combined by tuning the laser timing → An overall efficiency of 50% is assumed for this stage.

- Two proton bunches are injected into each cycle.
- Each bunch hits the graphite target over 40 turns and produces its own π/μ bunch.

  The ultra-cold muons formed in the first aerogel are transported over a 10 meter beamline and reach the second aerogel target.
- The muonium atoms are ionized by the *Lyman-α* laser in the second target, the ionized μ^+ has a very small momentum spread.
- The authors state that the two bunches of muons from the pion production ring are combined at the second muon target by tuning the timing of the laser irradiation.

  → This approach effectively combines the two into a single bunch, allowing twice the charge to be injected into the final acceleration stage. Since only one bunch synchronization per line is required, RF phase control is simplified (The term "combined" in this sentence refers to the timing-based synchronization of the two muon bunches.).

"…An overall efficiency of 50% is assumed.": "The production efficiency … 50%."

→ 50% : This value refers only to the efficiency of the second aerogel.

1) All ultra-cold muons generated in the first aerogel are transferred to the second target (with a transport efficiency ~ 100%.)

2) Re-formation of muonium in the second target → vacuum escape → A hypothetical efficiency factor is used by assuming that half of the laser ionization processes are successful.

→ According to the thin target and uniform energy distribution, it is suggested that the efficiency in this stage could be significantly higher than the previous 14% chain. A forward-looking / hypothetical efficiency factor of 0.5 (50%) is assumed. This factor is then multiplied by the 14% production efficiency achieved in the first aerogel: $0.14 \times 0.5 = 0.068 = 6.8\%$

For a similar beamline at J-PARC, a muon yield of 1×10^{-7} μ^+/p has been stated, indicating that the new design achieves an improvement by a factor of ~ 10^5 (O(10^5)). → "Enhancement factor" → This result indicates an increase in the yield.

With the same 3 GeV, 2 MW proton source, the μTRISTAN design generates ~ 9×10^{13} ultra-cold muons per second, while the J-PARC MLF provides ~ 10^9 μ^+/s. → **O(10^5)**

References:

[1] Hamada, Y., Kitano, R., Matsudo, R., Takaura, H., & Yoshida, M. (2022).

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https://doi.org/10.1093/ptep/ptac059

[2] Akturk, D., Canbay, A. C., Dagistanli, H., Dagli, B., Kaya, U., Ketenoglu, B., ... & Zimmermann, F. (2025).

μLHC: Antimuon Ring and HL-LHC based $\mu^{+}p$ Collider.

e-Print: 2506.15445 [physics.acc-ph]