e/mu-LHC proposal: initial discussion

11 November 2025, @CERN

μLHC Physics Potential

Ali Can Canbay
Ankara University

Lepton-Hadron Colliders

Limitations of the Standard Model

- The Standard Model (SM) is remarkably successful but incomplete.
- The Higgs mechanism accounts for only about 2% of the visible mass in the universe. The remaining ~98% arises from quark–gluon interactions described by QCD. Yet, key QCD phenomena such as confinement and hadronization remain experimentally unverified.
- The behavior of partons in the small-x and high-Q^2 regimes is still poorly constrained and model dependent.

The Role of Lepton–Hadron Colliders

- **Hadron colliders**: provide extreme energy but suffer from high event complexity and multi-parton backgrounds.
- **Lepton colliders**: have well-defined initial states and low backgrounds, but probe only electroweak interactions.
- **Lepton–hadron colliders** combine both strengths:
  - A lepton beam provides a clean probe: pointlike, structureless, and precisely known kinematics.
  - A hadron target grants direct access to quark and gluon dynamics within nucleons.
  - They enable precision QCD studies: parton distribution functions, gluon saturation, and the running of $\alpha_s(Q^2)$.

Muon-Proton Collider

- **Muon beam advantages:**
  - 200× heavier than the electron → synchrotron radiation negligible, enabling TeV-scale collisions.
  - Beamstrahlung effects are reduced, maintaining narrow energy spread.
- **Proton beam role:**
  - Provides direct access to non-perturbative QCD and small-x gluon structure.

*It unites the **high center-of-mass energy** characteristic of hadron colliders with the **clean experimental environment and measurement precision** of lepton colliders.*

- **Physics potential:**
  - Uniquely suited to explore confinement, hadronization, and parton saturation.
  - Precision Higgs boson phsyics via W/Z fusion at multi-TeV scales.
  - Exceptional reach for Beyond Standard Model (BSM) searches:
    - Resonant production of leptoquarks, excited muons, and color-octet muons (μ_8) possible only in μp interactions.

In-Depth Exploration of QCD and Precision Measurements of the SM

The primary scientific focus of a multi-TeV μp collider would be to advance our understanding of Quantum Chromodynamics (QCD) in regimes that remain beyond the reach of current experiments. Operating at extremely small Bjorken$-x$ values and high Q^2, such a facility would enable the study of high-density gluon matter and the possible onset of parton saturation, which is a fundamental prediction of QCD that has not yet been experimentally verified. The μLHC would therefore open a new window into the non-linear dynamics of strong interactions. It would allow precise investigations of **proton structure, gluon evolution, and hadronic final states in kinematic regions** that have never been explored before.

Beyond its core QCD program, the μLHC would also provide valuable opportunities for **precision tests of the Standard Model**. Although *it is not a dedicated Higgs factory*, the collider's high energy and clean μp collision environment would still make it possible to perform complementary Higgs studies. These studies would include measurements of production cross sections, couplings, and rare decay channels. Such measurements could reveal subtle deviations from the predictions of the Standard Model and help constrain or discover potential new physics effects.

In this way, the μLHC would simultaneously extend our knowledge of QCD by probing the strong force in the high-density and high-energy regime. At the same time, it would enhance the precision frontier through detailed investigations of electroweak processes and Higgs-sector observables. Together, these studies would provide an essential foundation for a deeper and more unified understanding of the Standard Model and its possible extensions.

Small x-Bjorken

Collider	$\sqrt{s}$ [TeV]	$x - Bjorken$	Q^2 [GeV^2]
HERA	$\mathbf{0.319}$	$\mathbf{1.0 \times 10^{-4}}$	$\mathbf{10}$
EIC	0.145	4.8×10^{-4}	2.1
LHeC (ERL 20)	0.748	1.8×10^{-5}	56
LHeC (ERL 50)	$\mathbf{1.18}$	$\mathbf{7.2 \times 10^{-6}}$	$\mathbf{140}$
μLHC	5.3	3.6×10^{-7}	2800

To understand the fundamental dynamics of QCD, particularly the high-density gluon regimes, it is crucial to explore the small x-Bjorken ($< 10^{-4}$) and high-Q^2 ($> 10\ GeV^2$) kinematic region.

- **Small x-Bjorken** corresponds to the region of high parton densities, where gluon saturation effects become significant.
- **Large Q^2** ensures that the interaction remains within the perturbative QCD regime, where theoretical calculations are reliable.

For lepton–hadron colliders, the relation between x-Bjorken and Q^2 is given by $Q^2 = 4x_B E_\mu E_p$.

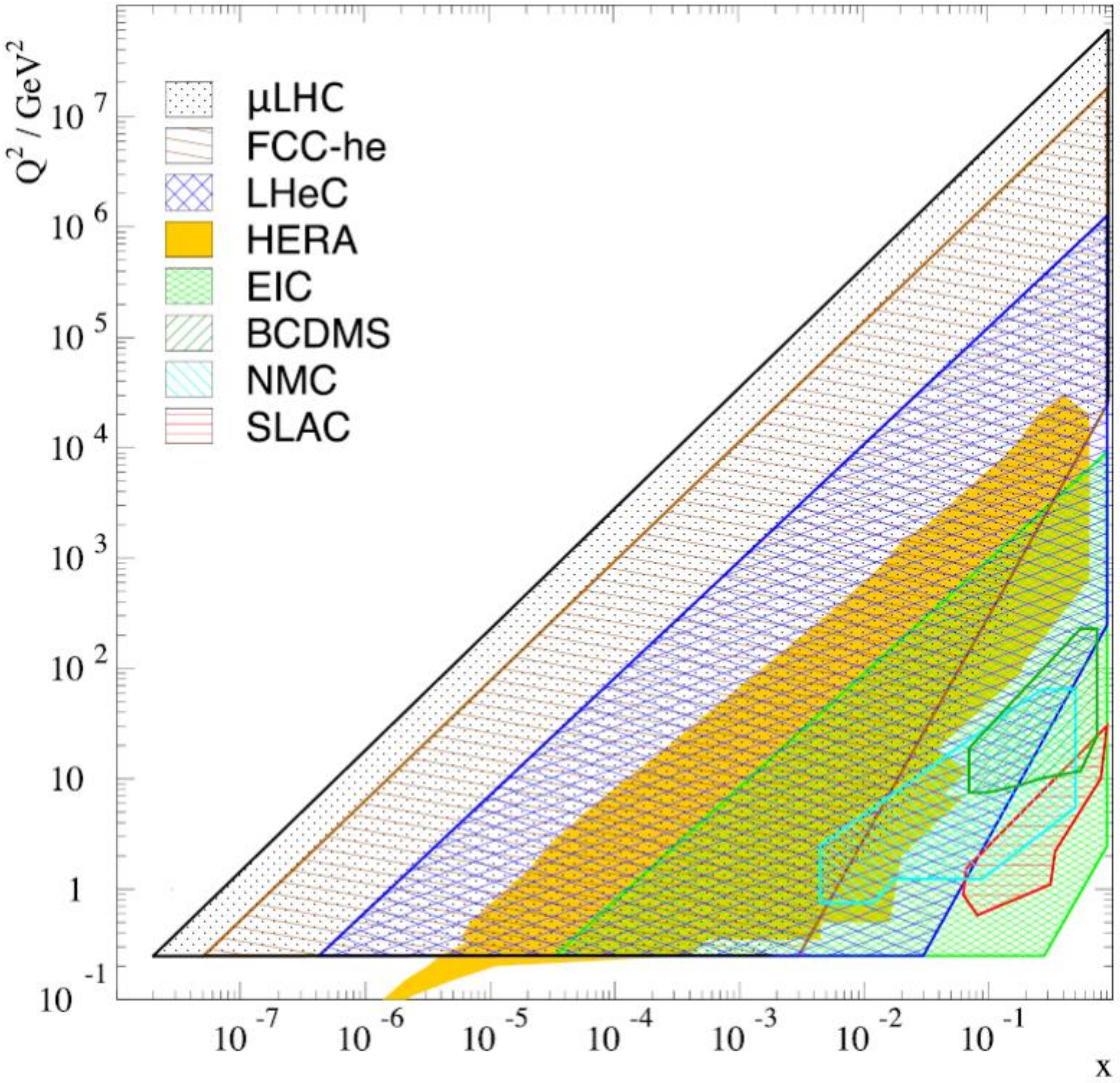
As can be seen from the table, the proposed colliders will allow a much more detailed exploration of the relevant ($x - \mathrm{Q}^2$) region. HERA could only provide limited access to this domain. In contrast, a μLHC would represent a revolutionary step toward probing this region in depth, **offering nearly 16 times higher center-of-mass energy compared to HERA**. It is also provide about **4.5 times higher $\sqrt{s}$ and 20 times higher Q^2 than the LHeC (ERL 50)**.

Small x-Bjorken

The kinematic reach of the μLHC is significantly broader than that of previous and planned facilities. For instance, at a fixed value of $x = 10^{-4}$, it can reach up to $Q^2 \approx 2800\ GeV^2$, while at low momentum transfers such as $Q^2 = 10\ GeV^2$, it can probe record small x-Bjorken values of $x \approx 3.6 \times 10^{-7}$. In comparison, the LHeC under the same conditions reaches only $Q^2 \approx 140\ GeV^2$ and $x \approx 7.2 \times 10^{-6}$.

It extends beyond the LHeC by over an order of magnitude, surpassing even the projected capabilities of the FCC-he.

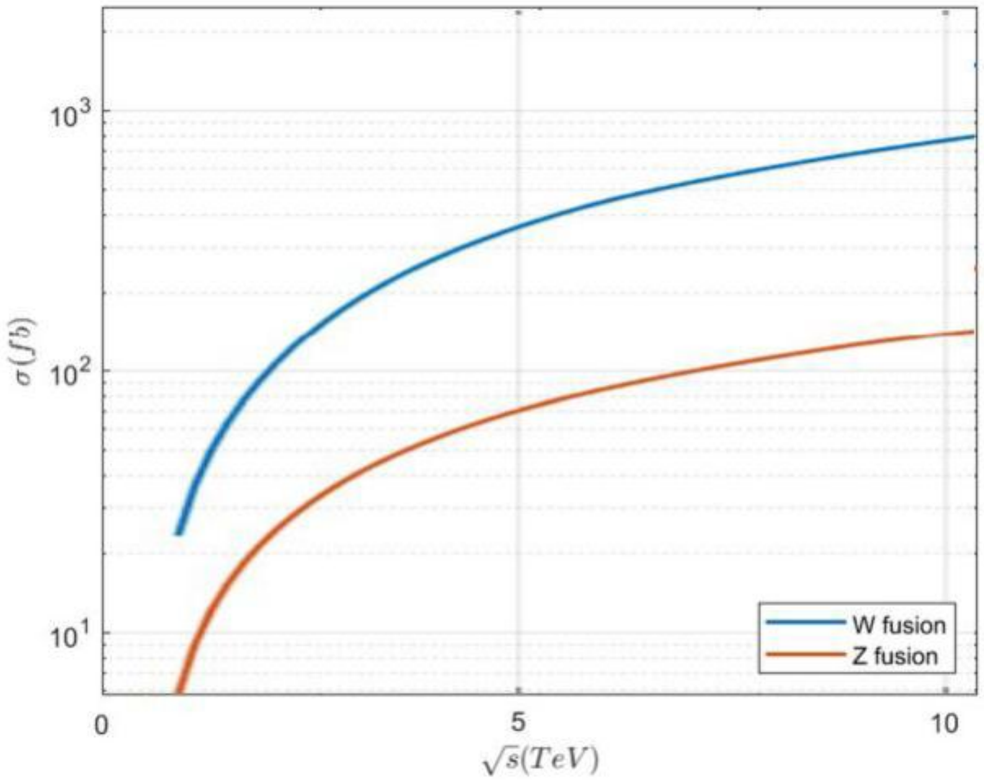
It is therefore evident that the μLHC extends the kinematic plane both toward higher Q^2 and deeper into the small-x region. This expanded coverage is essential not only for testing the fundamental principles of QCD but also for precisely determining parton distribution functions (PDFs), which are vital for analyses at future hadron colliders such as the FCC-hh and SppC. Such a precise test of the Standard Model also provides a solid foundation for searches for new physics.



Higgs production

Cross-sections for Higgs boson production in $\mu^+ p$ collisions via W and Z fusion processes are presented in Figure. The μLHC demonstrates a significantly higher Higgs boson production rate via W and Z fusion in $\mu^+ p$ collisions compared to the LHeC.

In a μp collider, Higgs boson production predominantly occurs through the Vector Boson Fusion (VBF) mechanism. In particular, the W boson fusion process ($\mu^+ \, p \to \, j \, \bar{\nu}_\mu \, h$) exhibits a significantly large cross section due to the high center-of-mass energy. This creates an ideal environment for studying the Higgs boson with high statistical precision.



Higgs production

(Cheung, 2021)

Collider	$\sqrt{s}\ [TeV]$	$L_{int}[fb^{-1}]$	$N_{W fussion}$	$N_{Z fussion}$
LHeC (ERL 20)	0.748	60	1260	200
LHeC (ERL 50)	1.18	14	1020	200
μLHC	5.29	40	15400	3000
μLHC (ERL based)	5.29	17	6500	1300

Collider	**g_{hbb} Coupling Precision (%)**
HL-LHC (CMS Projection)	~4%
LHeC (ERL 50 GeV)	0.97%
μLHC	0.69%

$$\frac{\Delta g_{hbb}}{g_{hbb}} = \frac{1}{2}\sqrt{\left(\frac{\Delta\sigma}{\sigma}\right)^2 + \left(\frac{\Delta\left(\frac{g_{hWW}^2}{\Gamma_h}\right)}{\frac{g_{hWW}^2}{\Gamma_h}}\right)^2}$$

Compared to the LHeC, the μLHC provides more than an order of magnitude increase in the annual Higgs production rate. More importantly, the projected 0.69% precision on the g_{hbb} coupling represents a remarkable improvement over the 4% projection of the HL-LHC. This level of precision would significantly enhance the μLHC's capability to detect potential deviations from the Standard Model in the Higgs sector.

BSM

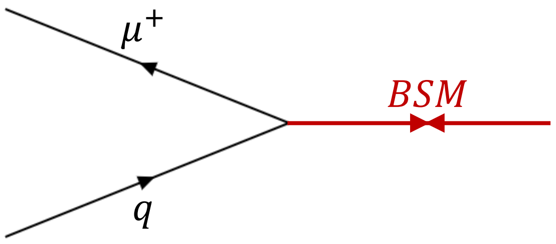
Although no direct discovery of new physics has yet been made at the LHC, several experimental and theoretical discrepancies continue to suggest the existence of phenomena beyond the Standard Model (BSM). Among the most notable of these is the muon’s anomalous magnetic moment (g−2), which exhibits a long-standing tension between experimental results and Standard Model predictions. This discrepancy may point to new particles or interactions that **couple preferentially to second-generation leptons**. In addition, anomalies observed in heavy hadron decays, such as deviations in flavor-changing neutral current processes and potential lepton flavor universality violations, provide further evidence that new dynamics might be at play in the flavor sector.

A multi-TeV μp collider would provide a uniquely powerful platform to investigate these BSM effects with exceptional precision. The combination of high center-of-mass energy, clean experimental conditions, and the distinctive properties of the muon beam would make it possible to directly probe new particles or interactions that could explain these anomalies. Such a collider could explore new gauge bosons, leptoquarks, Squarks or other states that couple simultaneously to quarks and muons, thereby testing many of the theoretical models proposed to account for the current experimental tensions.

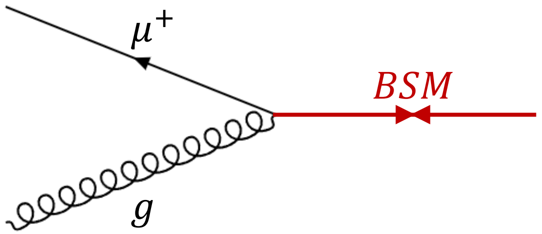
Moreover, **the μLHC’s ability to reach highest energy scale among lepton-hadron colliders that could be built in the 2030s**, would enable indirect sensitivity to heavy BSM states through precision measurements of cross sections, angular distributions, and rare processes. These measurements could reveal small but significant deviations from Standard Model predictions, offering complementary insights to those obtained from direct searches at hadron colliders.

BSM

Resonant Productions:



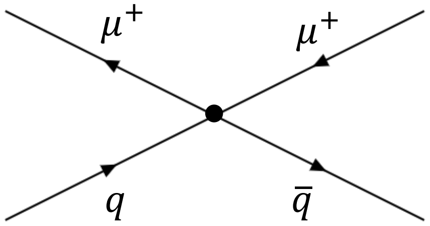
Process	Resonance Type	Signature	Example Models
$\mu + q \to LQ \to \mu + q$	Leptoquark	s-channel peak	Pati–Salam, GUT
$\mu + q \to \tilde{q}$	squark (RPV SUSY)	LQ-like resonance	R-parity violation



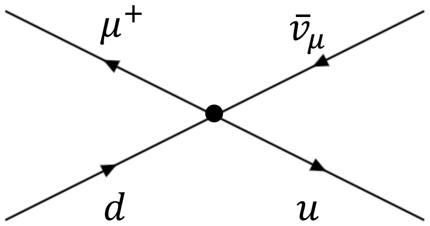
Process	Resonance Type	Signature	Example Models
$\mu + g \to LG \to \mu + g$	Leptogluon	μ + gluon resonance	LG models, Pati–Salam

Contact Interactions:

$$m_{med}^2 \gg t \quad \Rightarrow \quad \frac{1}{t - m_{med}^2} \approx -\frac{1}{m_{med}^2}$$



$$\mathcal{L} \propto \frac{g_{contact}^2}{2\Lambda^2}(\bar{\mu}\Gamma\mu)(\bar{q}\Gamma q)$$



$$\mathcal{L} \propto \frac{g_{contact}^2}{2\Lambda^2}(\bar{\nu}_\mu\Gamma\mu)(\bar{u}\Gamma d)$$

Search for Color-Octet Muons at μLHC

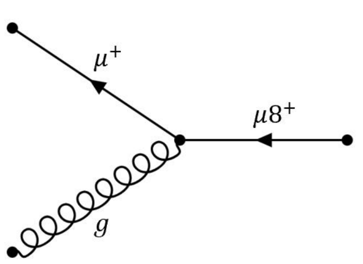
In some composite models, each Standard Model lepton has a strongly interacting color-octet partner called a *leptogluon*. The color-octet muon (μ_8) carries a QCD color charge while sharing the same electromagnetic and weak quantum numbers as the SM muon. This unique hybrid nature makes μ_8 an excellent probe for exploring the composite structure of leptons, with its interactions described by a Lagrangian involving leptons and gluons.

$$\mathcal{L} = \frac{1}{2\Lambda}\{\bar{l}_8^{\alpha} g_s G^{\alpha}_{\mu\nu}\sigma^{\mu\nu}(\eta_L l_L + \eta_R l_R) + h.c.\}$$

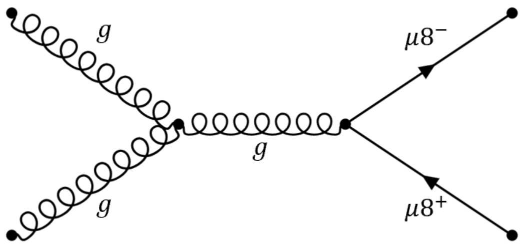
Model repository: github.com/acanbay/Leptogluon_2ndgen_UFO

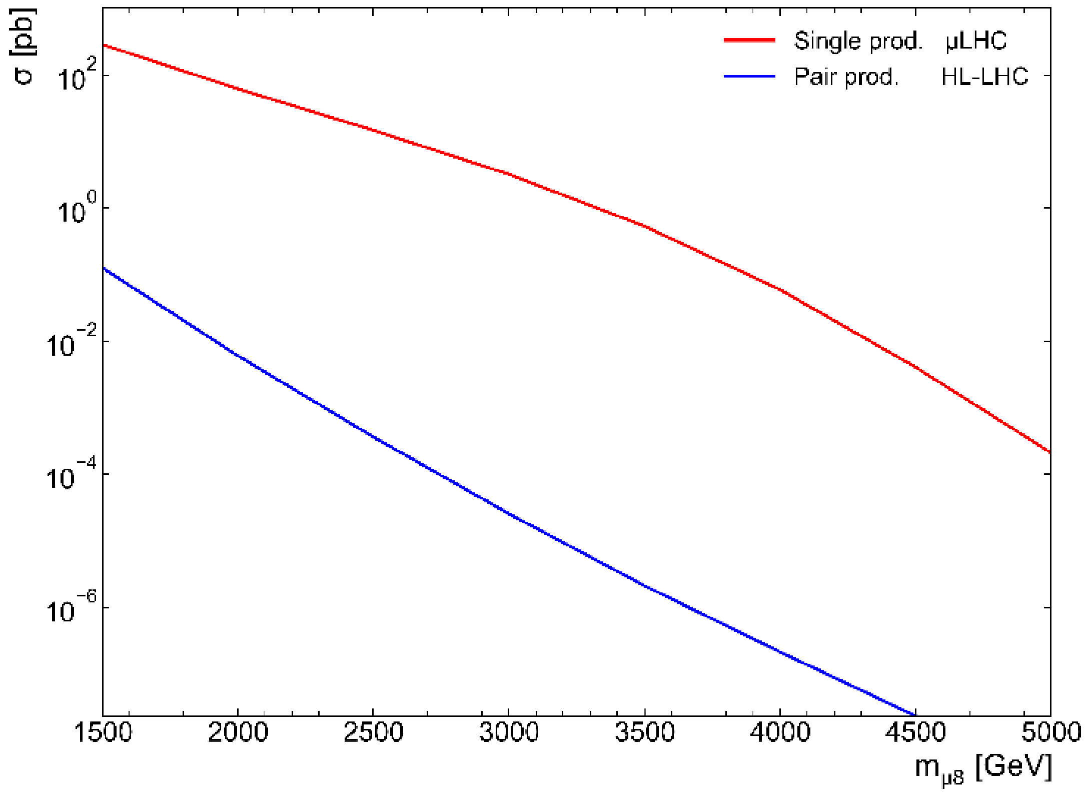
At proton colliders like the LHC and FCC, color-octet muons are mainly produced in pairs. In contrast, at μp colliders, the direct interaction between the incoming muon and a gluon inside the proton enables resonant production via the process $\mu^+ g \to \mu 8^+$.

μLHC: $\mu^+ g \to \mu 8^+$



HL-LHC: $p\,p \to \mu 8^+ \mu 8^-$

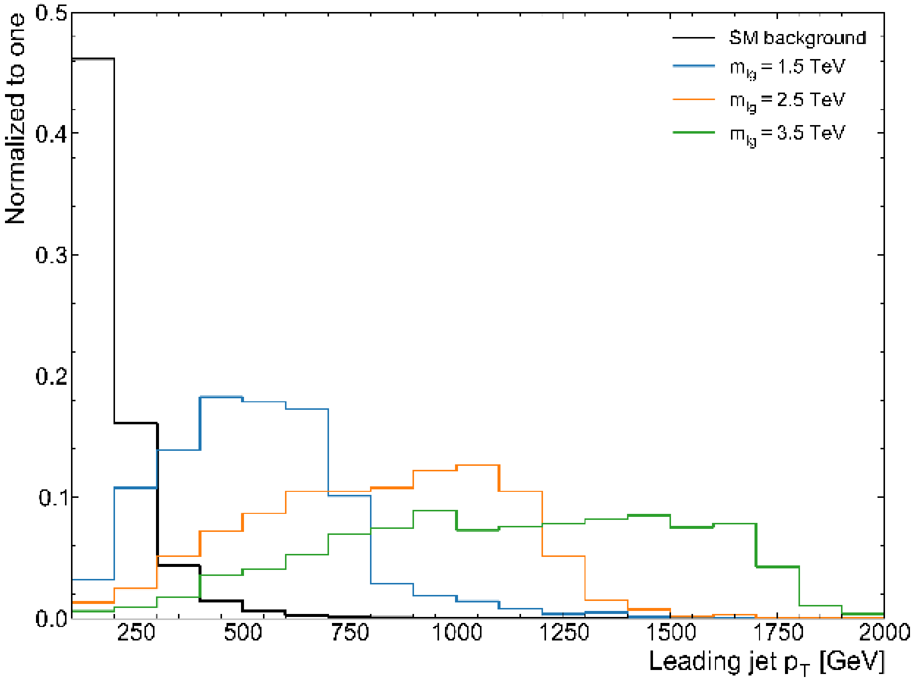


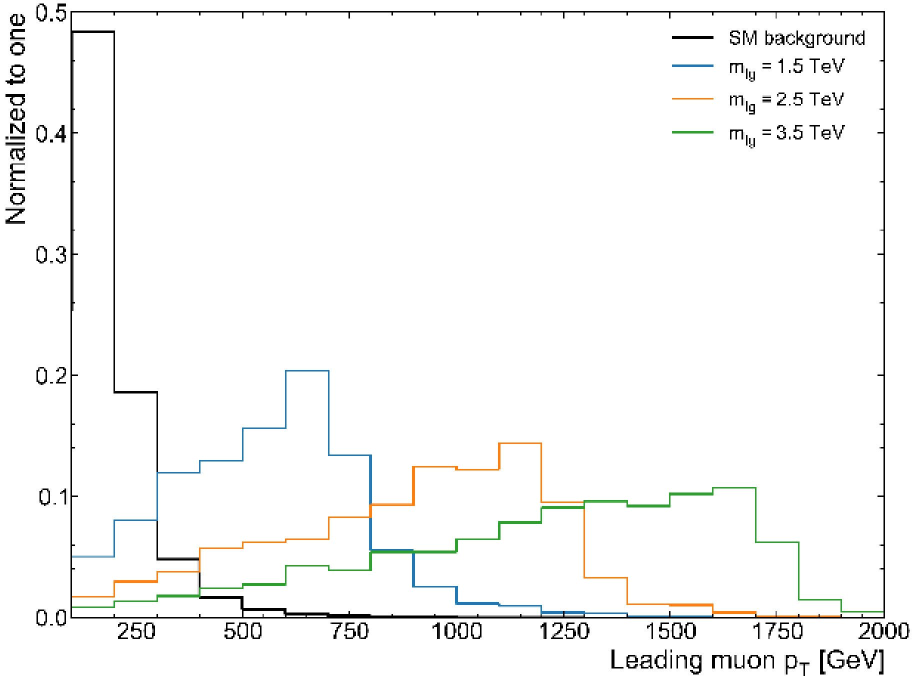


Search for Color-Octet Muons at μLHC

Event generation for the μLHC was performed using **MadGraph5** [Alwall 2011] with the **Color-Octet Muon UFO Model** [Canbay 2025] implemented in **FeynRules** [Alloul 2014], setting the compositeness scale to $\Lambda = m_{\mu 8}$, beam energies to $E_\mu = 1\,TeV$ and $E_p = 7\,TeV$. The generated parton-level events were subsequently processed with **Pythia8** [Sjöstrand 2008] for parton showering and hadronization

		Process	Model	Nevents
Signal	**:**	$\mu^+ p \rightarrow \mu 8^+,\ \mu 8^+ \rightarrow \mu^+ g$	Color-Octer Muon UFO	100k
Background	**:**	$\mu^+ p \rightarrow \mu^+ j$	sm-full	100k

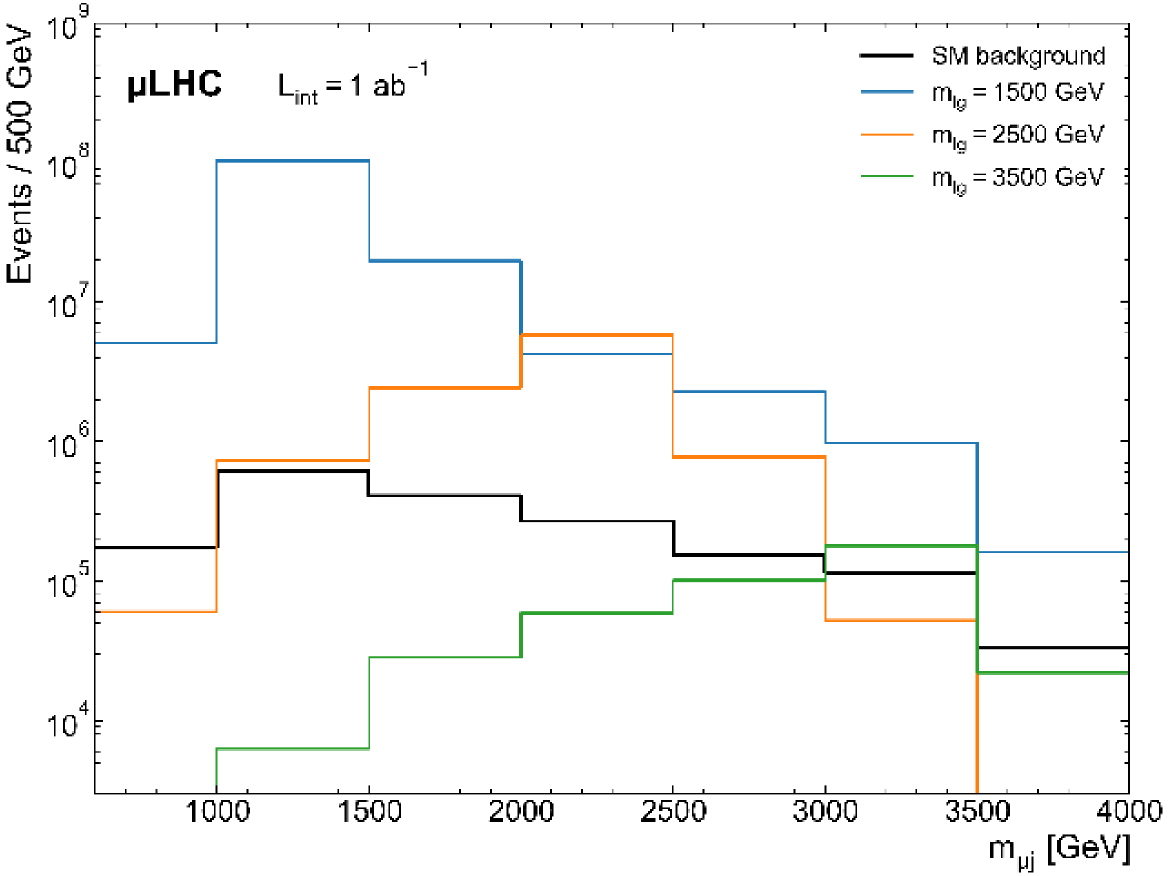




Search for Color-Octet Muons at μLHC

Event reconstruction and analysis were conducted using **MadAnalysis5** [Conte 2013], where suitable selection criteria (cuts) were applied to optimize the signal-to-background discrimination. The applied selection cuts and their sequential effects on the signal and background event numbers are summarized below.

Variable	**Value**
Number of jets	≥ 1
Number of leptons	$= 1$
Leading jet p_T	$> 400\ GeV$
Leading muon p_T	$> 400\ GeV$
Leading jet $\lvert\eta\rvert$	< 3.5
Leading muon $\lvert\eta\rvert$	< 3



Search for Color-Octet Muons at μLHC

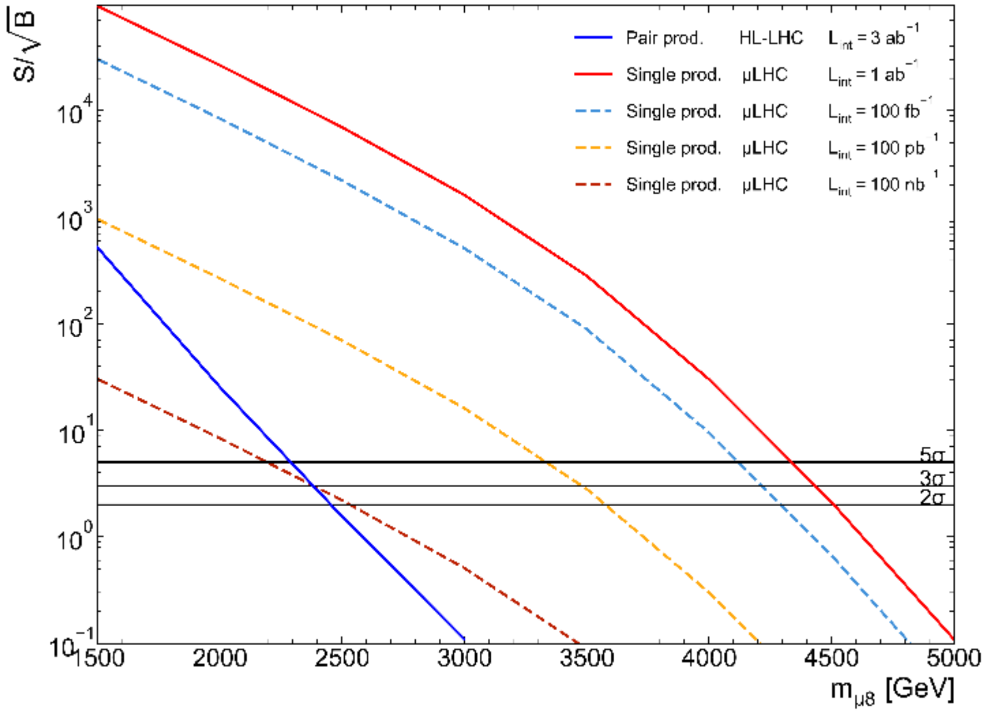
A parallel analysis for pair production at the HL-LHC was performed, where preselection cuts were applied to obtain a final state with two muons and two jets

Signal : $p\,p \rightarrow \mu8^{+}\,\mu8^{-},\ \mu8^{\pm} \rightarrow \mu^{\pm}\ g$

Background : $p\,p \rightarrow \mu^{+}\,\mu^{-}\,j\,j$

Variable	**Value**
Number of jets	≥ 2
Number of leptons	$= 2$
Leading jet/muon p_T	$> 300\ GeV$
Second leading jet/muon p_T	$> 250\ GeV$
Leading and second leading jet $\lvert\eta\rvert$	< 3.5
Leading and second leading muon $\lvert\eta\rvert$	< 3

The statistical significance $(S/\sqrt{B})$ values for the μ8 analyses at μLHC and HL-LHC, calculated for various integrated luminosities, are given in the graph.



The **μLHC** can probe higher μ_8 masses than the **HL-LHC**, with estimated 5σ discovery limits of about **4300 GeV** and **2300 GeV**, respectively.

Even with an integrated luminosity of only 100 nb^{-1}, the μLHC surpasses the HL-LHC in discovery reach, demonstrating its remarkable potential for exploring new physics at the energy frontier. **A similar situation is expected for leptoquarks and squarks as well.**

Key Physics Questions and the Role of the µLHC

In ***"Perspectives and Questions: Toward an Expansive Agenda for Particle Physics"*** (Chris Quigg, FERMILAB-CONF-22-526-T), key scientific questions were outlined to guide the long-term direction of particle physics. The study aims to identify the most fundamental challenges of the field and to connect theoretical developments with future experimental opportunities. The questions cover a wide range of topics, including the structure of QCD, the mechanism of confinement, the origin of flavor, and the possible existence of new particles and interactions.

A lot of these open questions can be explored with a future multi-TeV µp collider (µLHC). **The next slide lists the issues where muLHC will make an exceptional contribution.**

Perspectives and Questions:
Toward an Expansive Agenda for Particle Physics

Chris Quigg*

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia Illinois 60510 USA

(Dated: October 9, 2025)

Global celebration greeted the 2012 discovery at CERN's Large Hadron Collider of a particle that matches the textbook description of the Higgs boson. That achievement validated a remarkable chain of theoretical reasoning that combined the prescriptive notion of electroweak gauge symmetry with a simple, but *ad hoc*, embodiment of spontaneous symmetry breaking. It was made possible by generational triumphs of accelerator art and experimental technique, and by human resourcefulness and collaboration on a global scale, all sustained by the enlightened support of many governments and institutions.

Some imagine that, once the keystone of the standard model of particle physics has been set, our subject is over. Others worry that we may be at an impasse because no comparable wonders have appeared, leaving us without well-defined clues to a more complete paradigm. I am neither so readily satisfied nor so easily discouraged: we have so much more to learn! This essay surveys many questions that, taken together, constitute an inspiring array of opportunities to enhance our understanding of the physical world.

Key Physics Questions and the Role of the µLHC

Direct reach:

The µLHC could directly explore new forms of matter and strong interaction dynamics.

- **(50)** Search for new species of quarks and leptons with exotic color or charge signatures through µ–p interactions.
- **(85–87)** Provide precision measurements of **Generalized Parton Distributions (GPDs)** and **Transverse Momentum Distributions (TMDs)**, enabling insight into 3D nucleon structure, parton correlations, and non-perturbative QCD phenomena.
- **(106)** Probe color confinement and search for possible free colored states in the highest-energy µp collisions.

Indirect sensitivity:

Through precision measurements, µLHC can constrain SM parameters and test fundamental symmetries.

- **(43–46)** Tests of electroweak universality and possible lepton-flavor-violating interactions.
- **(59, 63)** Precision studies of top-quark couplings and rare flavor-changing processes.
- **(83, 84, 90)** Examination of factorization limits, parton correlations, and spatial configurations within the proton at small x and high Q^2.

Potential direction:

- **(40)** A µp collider may also contribute to refining our understanding of the "periodic table" of elementary particles by uncovering possible substructure or new families beyond the known generations.

You can see the content for each question on the backup slide.

Conclusion

μLHC has the potential to make major contributions to both of the central frontiers in modern high-energy physics, which are the precision frontier and the energy frontier.

- From the precision perspective, **μLHC** would enable extremely accurate measurements within the Standard Model framework. It would allow the determination of Higgs boson couplings with an accuracy that surpasses the expected performance of the HL-LHC. In addition, it would make it possible to explore the small$-x$ region of QCD, where the behavior of gluons becomes highly nonlinear and parton saturation effects are expected to occur. These studies would significantly deepen our understanding of the strong interaction and the structure of the proton.
- From the energy perspective, **μLHC** would provide access to BSM physics phenomena. Through distinctive processes, including resonant and contact interactions, the collider could reach energy scales that are far beyond those accessible at existing or planned facilities.

The ability to achieve **both high precision and high energy in a single experimental environment** makes the μLHC a facility that complements current collider programs while also offering capabilities that exceed them in several key areas.

In conclusion, **μLHC** represents a crucial step forward for the future of particle physics. It provides the means to explore uncharted kinematic regions, to test the limits of QCD, and to search for entirely new forms of matter and interaction. **For these reasons, a systematic investigation of this concept, including its accelerator design, detector technologies, and full physics potential, is essential for defining the long-term global strategy of high-energy physics.**

References

- Acosta, D., Barberis, E., Hurley, N., Li, W., Miguel Colin, O., Wang, Y., Wood, D., and Zuo, X. (2023). The potential of a TeV-scale muon–ion collider. Journal of Instrumentation, 18(09), P09025.
- Akturk, D., Canbay, A. C., Dagistanli, H., Dagli, B., Kaya, U., Ketenoglu, B., Kilic, A., Kocak, F., Ozturk, A., Sultansoy, S., Tapan, I., Zimmermann, F. (2025). μLHC: Antimuon Ring and HL-LHC based μ+p Collider, https://doi.org/10.48550/arXiv.2506.15445.
- Alloul, A., Christensen, N. D., Degrande, C., Duhr, C., & Fuks, B. (2014). FeynRules 2.0—A complete toolbox for tree-level phenomenology. *Computer Physics Communications*, *185*(8), 2250-2300.
- Alwall, J., Herquet, M., Maltoni, F., Mattelaer, O., & Stelzer, T. (2011). MadGraph 5: going beyond. *Journal of High Energy Physics*, *2011*(6), 1-40.
- Canbay, A. C., & Kaya, U. (2025). Leptogluon_2ndgen_UFO: A UFO Model for the Color-Octet Muon [Computer software]. https://doi.org/10.5281/zenodo.15676777.
- Cheung, K., & Wang, Z. S. (2021). Physics potential of a muon-proton collider. *Physical Review D*, *103*(11), 116009.
- Conte, E., Fuks, B., & Serret, G. (2013). MadAnalysis 5, a user-friendly framework for collider phenomenology. *Computer Physics Communications*, *184*(1), 222-256.
- Quigg, C. (2025). Perspectives and Questions: Toward an Expansive Agenda for Particle Physics. *arXiv preprint arXiv:2510.06348*.
- Sjöstrand, T., Mrenna, S., ve Skands, P. 2008. A brief introduction to PYTHIA 8.1. Computer Physics Communications, 178(11), 852-867.

Backup Slide: Key Physics Questions

[Quigg 2025]

40. Have we found the "periodic table" of elementary particles? Is the cartoon in Figure 1 complete12?

43. Are there additional electroweak gauge bosons, beyond $W^{\pm}$ and Z?

44. Is charged-current universality exact? What about charged-lepton flavor universality?

46. Can we find evidence for charged-lepton flavor violation?

50. Are there new species of quarks and leptons, perhaps bearing exotic electric or color charges?

59. How well can we constrain the quark-mixing matrix element Vtb in single-top production, or in other observables?

63. Can we find evidence of flavor-changing top decays $t \to (Z, \gamma)(c, u)$?

83. To what degree might we derive the parton model from first-principles quantum chromodynamics for lepton–hadron and hadron–hadron collisions? In what circumstances does factorization hold?

84. What are the limitations of the one-dimensional ∞-momentum-frame parton model?

85. What can generalized parton distributions (GPDs) and Transverse Momentum Distributions (TMDs) teach us about the static properties and interactions of nucleons and other hadrons?

86. Will high-energy collisions reveal new phenomena within QCD? Can we use machine learning to characterize untriggered or pile-up events beyond the traditional classes of diffraction and short-range or-der18?

87. How will correlations among partons in a proton manifest themselves?

90. Might event structures distinguish spatial configu-rations of partons within protons, such as three separated quarks, quark–diquark, compact triquark, or flux tube? Are there any useful analogies to nucleus–nucleus collisions?

106. Can we prove that quantum chromodynamics confines color19? Will free quarks (or other colored objects) be observed?