

MuSIC for New Physics

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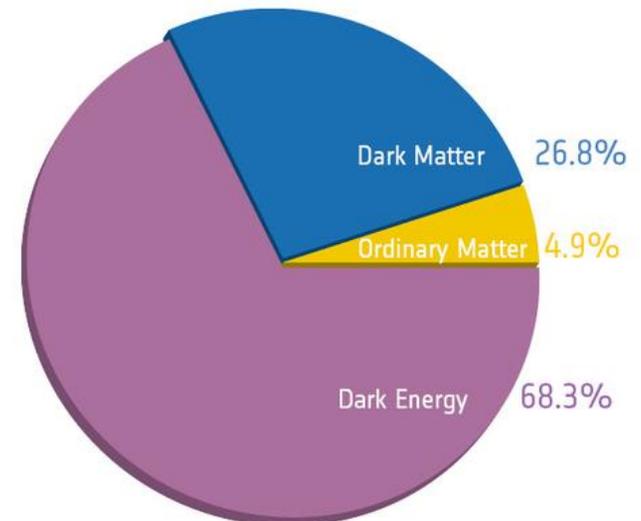
2nd Hokkaido Workshop on Particle Physics at Crossroads
Hokkaido University, Sapporo, Japan, March 3-6, 2026

The Case for New Physics

- Despite great success of SM+GR, new physics is needed
- There is strong experimental evidence for this inference:
 - ★ **Neutrino flavor oscillations** $\rightarrow m_\nu \neq 0$
 - Adding right-handed neutrinos (over a broad range of masses) can explain this
 - ★ **Cosmology**
 - What is holding galaxies together? (dark matter; may have its own sector)
 - What is accelerating cosmic expansion? (dark energy; may be vacuum energy)
 - What caused ordinary matter asymmetry? (requires more CPV)

95% of the Universe is unknown to us!

Planck



There are also theoretical hints:

- Why is gravity so weak?

- Hierarchy between Planck scale and Higgs mass parameter: $\frac{M_H^2}{M_{\text{Pl}}^2} \sim 10^{-34}$
- Why is M_H^2 stable against quantum corrections $\sim \mathcal{O}(M_{\text{Pl}}^2)$?

- Why is CP violation so suppressed in strong interactions?

- Neutron electric dipole moment $\lesssim 10^{-26}$ e.cm; could have been $\mathcal{O}(10^{10})$ times larger

- Why ... ?

Where should we look?

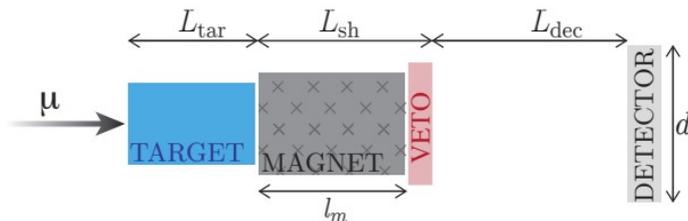
- The preceding questions may point to new *sectors*
- Some may be at high scales ($\gtrsim 1$ TeV), others at low masses ($\lesssim 100$ GeV)
 - $\frac{M_H^2}{M_{\text{Pl}}^2}$ hierarchy generally calls for heavy physics
 - Dark matter, m_ν : wide range of possible scales
- Currently, we do not have strong hints for a new scale
- A broad approach seems reasonable
- Reaching beyond the TeV scale: new colliders
 - Direct access (e.g. physics of Higgs potential):
 - Likely requires ~ 10 TeV parton center of momentum (pCM)
 - A muon collider (MuC) with $\sqrt{s} \sim 10$ TeV can provide the reach
 - A circular hadron collider at $\sqrt{s} \sim 100$ TeV can also access that scale

Towards 10 TeV pCM

From 2023 P5 report: “...we recommend targeted collider R&D to establish the feasibility of a 10 TeV pCM muon collider.”

- A TeV-scale μ -beam can be a milestone along the way to a $\sqrt{s} = 3$ TeV MuC
- One could envision different facilities to leverage such a beam for BSM searches
 - TeV scale μ -beams on target
 - Beam-dump:

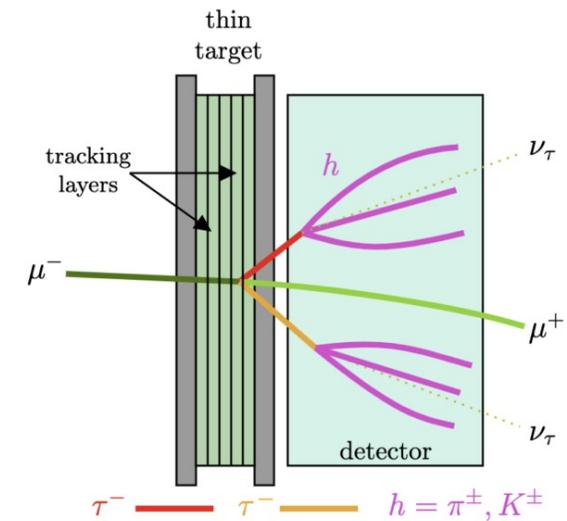
Cesarotti, Homiller, Mishra, Reece, 2202.12302; Cesarotti, Gambhir, 2310.16110



From: 2202.12302

- A thin active target:

Batell, HD, Marcarelli, Neil, Trojanowski, 2407.15942



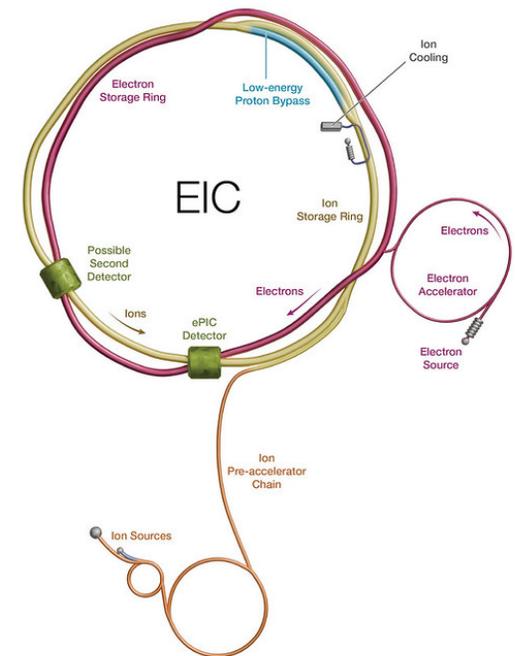
From: 2407.15942

- A muon-ion collider (this talk)
 - Successor to the **Electron Ion Collider (EIC)**

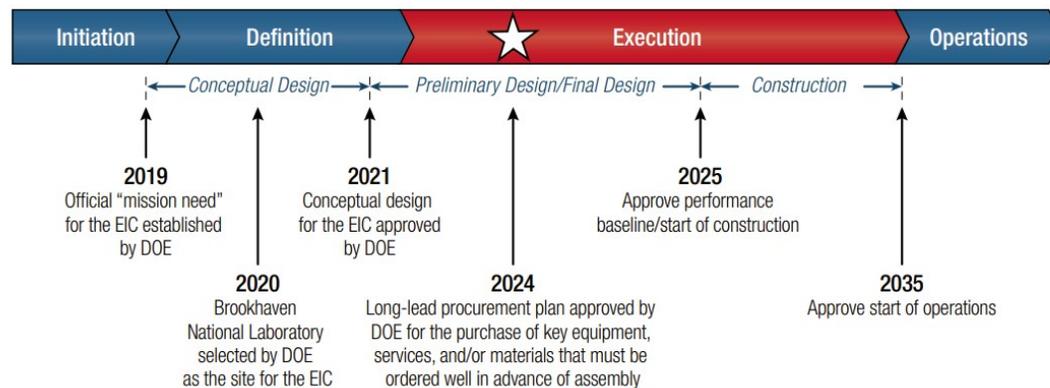
The Electron Ion Collider

2103.05419, EIC Yellow Report

- The only collider to be built (at BNL) in the coming decade
- New frontier in studying hadronic systems: spin composition of nucleons,....
- Large \sqrt{s} , luminosity
 - Up to $E_e = 18$ GeV (design), 110 GeV per nucleon (e -Au)
 - Fixed target equivalent of ~ 4 TeV e -beam
 - $\sim 100 \text{ fb}^{-1}$ per nucleon possible
- Polarization: $\sim 70\%$ for e and p beams
- Large nuclei (high Z): e.g. gold, lead



EIC project timeline



Beyond EIC

- One can consider what could come after the EIC (~ 10 years of running)
- Replacing the e -beam with a TeV scale μ -beam

Early ideas: Ginzburg, 1998; Sultansoy, 1999

More recent work on muon-ion collider (MuIC at BNL): Acosta, Li, 2021; Acosta *et al.*, 2022

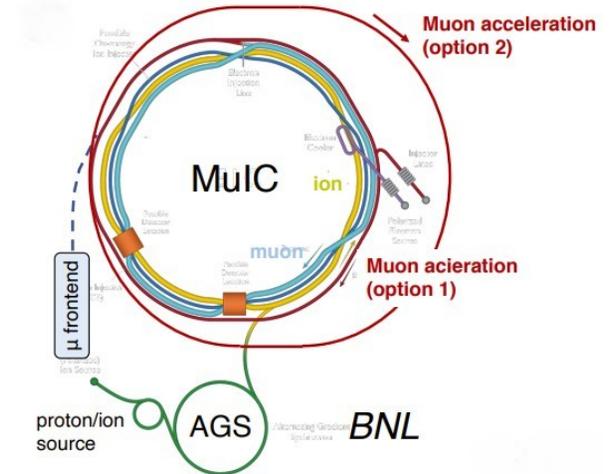
- Supports R&D for the MuC, but also affords new possibilities

- Deeper reach to study hadronic properties:

nucleon spin puzzle, gluon saturation,...

- SM processes, including Higgs production

- Searches for new phenomena (focus of this talk)



From Acosta, Li, 2107.02073

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

QCD/Nuclei

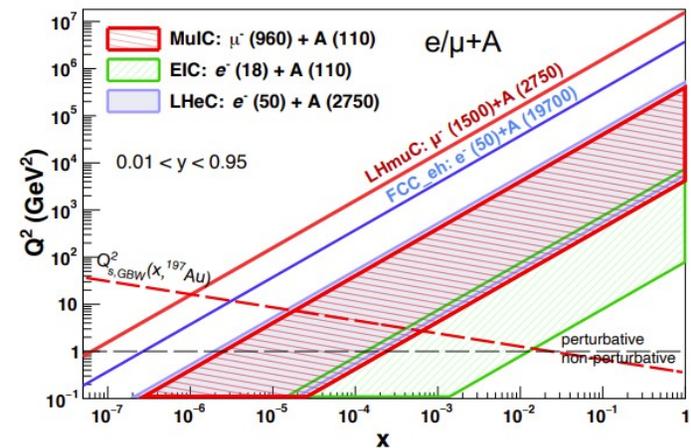
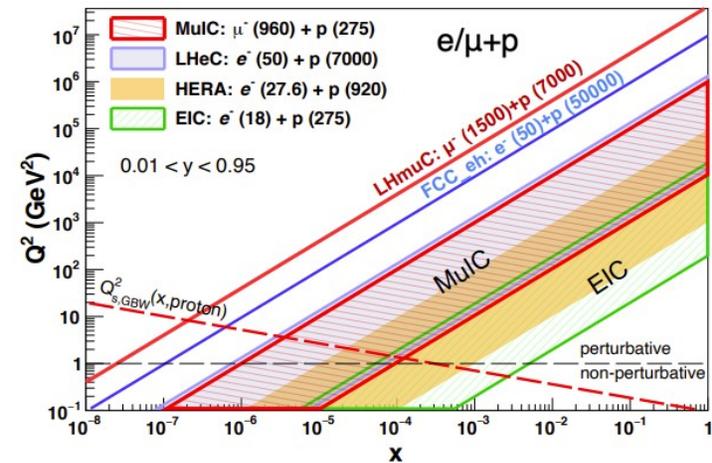
- Example: Gluon Saturation
- Gluon density: steep rise towards small x
- Extreme densities: gluon splitting and fusion equilibrate
- At scale Q_s gluon density saturates

Long dashed lines: Q_s as a function of x

y is inelasticity

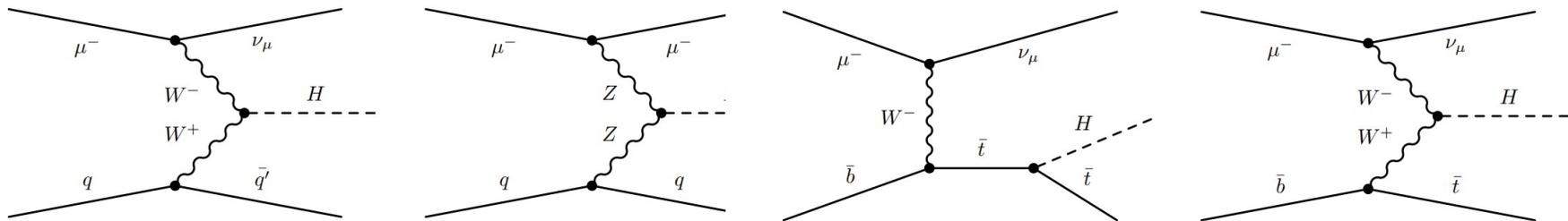
- MuIC: well into saturation regime for protons

From Acosta *et al.*, 2203.06258



SM Processes

- Example: Higgs production From Acosta et al., 2203.06258



	P = -40%	P = -20%	P = -10%	P = 0 %	P = 10%	P = 20%	P = 40%	P = 100%
σ_{CC}	91.1	78.2	71.7	65.1	58.8	52.1	39.0	0
σ_{NC}	12.6	12.1	11.9	11.6	11.4	11.1	10.5	8.9
σ_{tH}	0.0224	0.0187	0.0174	0.0158	0.0139	0.0128	0.0096	0
total	103.7	90.3	83.6	76.7	70.2	63.2	49.5	8.9

Muon beam: 960 GeV

Proton beam: 275 GeV

$\mu^- p$ scattering

	P = 40%	P = 20%	P = 10%	P = 0 %	P = -10%	P = -20%	P = -40%	P = -100%
σ_{CC}	45.0	38.2	35.6	32.1	28.9	25.6	19.2	0
σ_{NC}	12.4	12.0	11.7	11.6	11.3	11.0	10.6	9.1
σ_{tH}	0.0220	0.0190	0.0173	0.0157	0.0142	0.0127	0.0093	0
total	57.4	50.2	47.3	43.7	40.2	36.6	29.8	9.1

$\mu^+ p$ scattering

- Relatively clean environment compared to hadron colliders
 - However, beam-induced backgrounds need to be examined
- tH production: significant destructive interference

New Physics

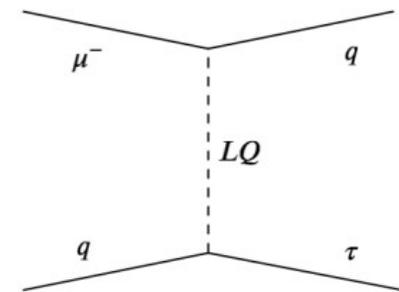
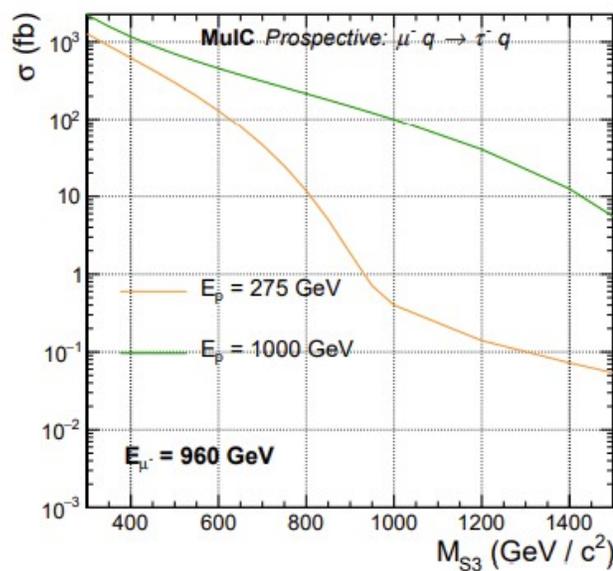
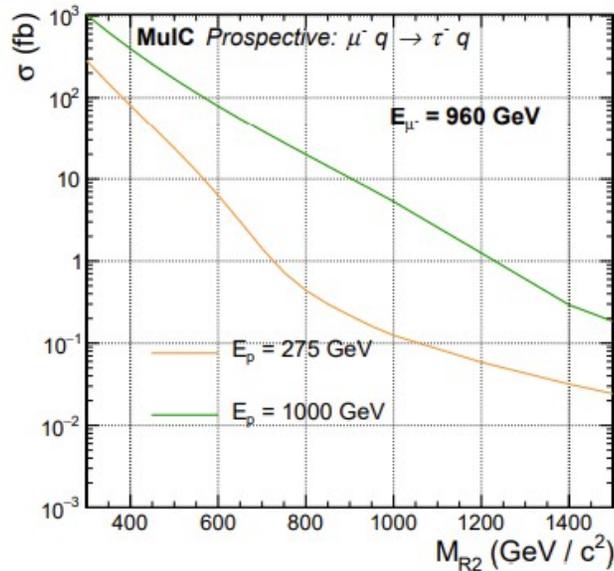
Examples:

- Lepton Flavor Violating (LFV) *scalar leptoquarks*

From Acosta *et al.*, 2203.06258

$$R_2 \sim (3, 2, 7/6)$$

$$S_3 \sim (\bar{3}, 3, 1/3)$$



- Potential test of massive graviton theories

Hatta, 2311.14470

- For $m_{\text{grav}} \gg 100 \text{ MeV}$, effective Planck mass in the TeV regime
- Possibility to measure “gravitational form factors” directly

Muon Synchrotron Ion Collider (MuSIC)*

HD, Liu, Marcarelli, Soreq, Trifinopoulos, 2412.13289

- We will adopt a 1 TeV μ beam
- Proton beam energy: 275 GeV $\Rightarrow \sqrt{s} = 1$ TeV
- Ion beam energy: 100 GeV/nucleon
- Integrated luminosity: $L_I = 400/A$ fb⁻¹
- A is the atomic number of the ion ($A = 1$ for protons)
- We consider a μ^- beam, but μ^+ would also work
 - A μ^+ beam could take advantage of new cooling techniques [Aritome et al., 2410.11367](#)
 - The μ^+ beam has also been utilized in new collider concepts (μ TRISTAN)

[Hamada, Kitano, Matsudo, Takaura, Yoshida, 2022](#)

- New physics discussion is basically the same for μ^\pm
 - We will examine a few simple models

.....

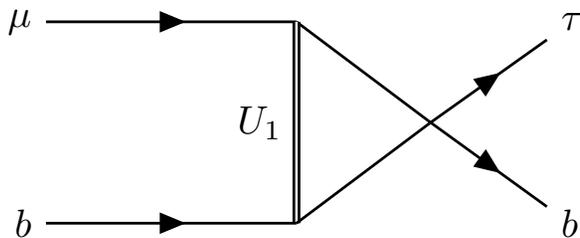
* Same concept as MuIC, but specific parameters and suggested new acronym

LFV Leptoquarks

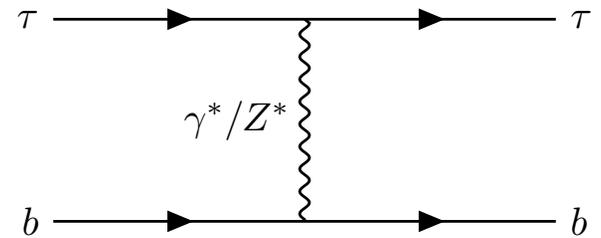
- Assume a *vector leptoquark* $U_1^\mu \sim (\mathbf{3}, \mathbf{1}, 2/3)$, of mass M_{U_1}
- Consider μ - τ LFV process: $q\mu \rightarrow q\tau$
- U_1 main couplings: Q_{3L} and $L_{2,3L}$ (quark and lepton doublets, respectively)

$$\mathcal{L}_{U_1}^{\text{int}} = \lambda_{b\mu} U_1^\alpha (V_{ib} \bar{u}_L^i \gamma_\alpha \nu_\mu + \bar{b}_L \gamma_\alpha \mu_L) + \lambda_{b\tau} U_1^\alpha (V_{ib} \bar{u}_L^i \gamma_\alpha \nu_\tau + \bar{b}_L \gamma_\alpha \tau_L) + \text{h.c.},$$

- V : CKM matrix; U_1 width: $\Gamma_{U_1} = \frac{|\lambda_{b\mu}|^2 + |\lambda_{b\tau}|^2}{12\pi} M_{U_1}$



(signal)



(background)

- b quark: MMHT2015qed PDF [Harland-Lang, Martin, Nathvani, Thorne, 2019](#)
- Lepton PDFs: LePDF [Garosi, Marzocca, Trifinopoulos, 2023](#)

- Event selection and efficiency:

- $|\eta| \lesssim 4$ (based on EIC)

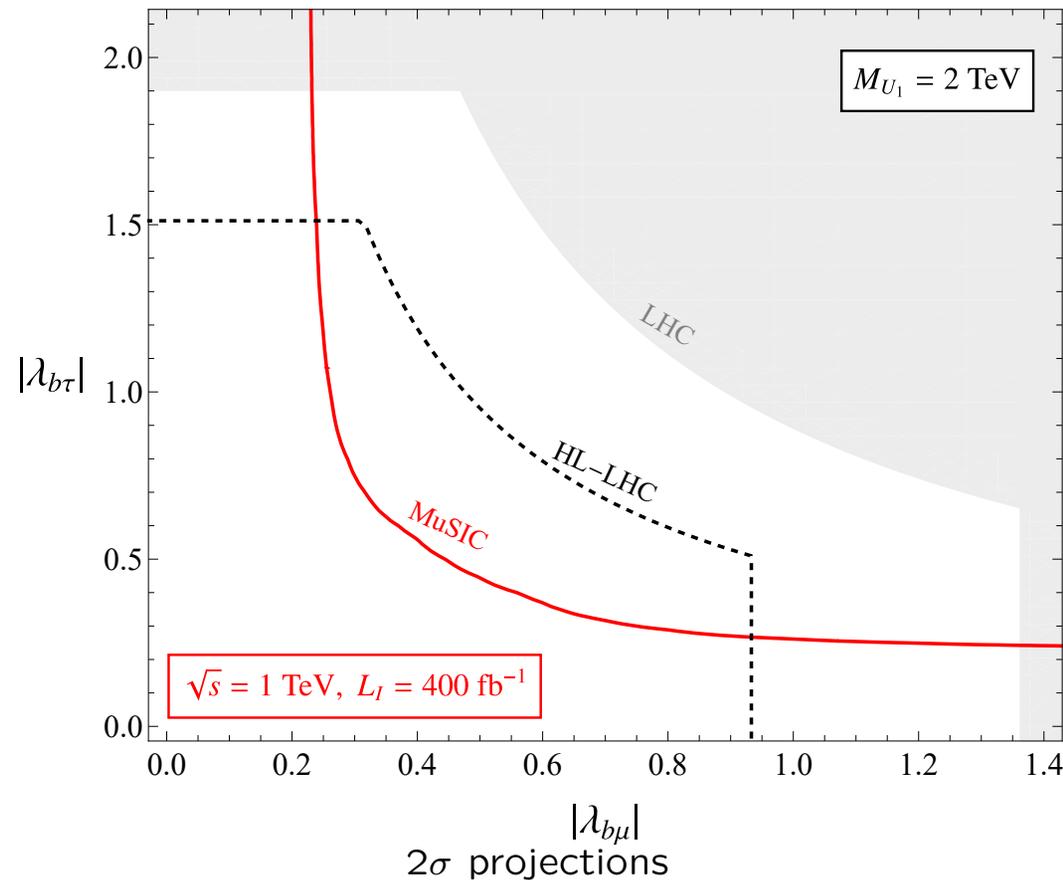
- Hadronic calorimeter resolution: $\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E[\text{GeV}]}} \oplus 10\%$

- b -tagging: 80% ; τ hadronic decays: 75%

[acceptance efficiencies from ATLAS leptoquark searches (2108.07665, 2305.15962)]

- LHC limits: HighPT Allwicher, Faroughy, Jaffredo, Sumensari, Wilsch, 2022

- μ beam: some polarization, can probe chiral structure of couplings



Axion-like Particles (ALPs)



Krzysztof Golik, Wikipedia

- Can arise in a variety of models
- Pseudo-scalars from global symmetry breaking
 - Massless in the limit of good global symmetry
 - QCD pions: spontaneously broken approximate chiral symmetry
 - Can be naturally light states
- We will take an effective field theory (EFT) approach, cutoff scale Λ
- Focus mainly on photon coupling (For an EIC study, see Balkin *et al.*, 2310.08827)

$$\mathcal{L}_a^{\text{int}} = -\frac{a}{4\Lambda} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$F_{\mu\nu}$: photon field strength tensor; $\tilde{F}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}$

- ALP width: $\Gamma_{a\rightarrow\gamma\gamma} = \frac{m_a^3}{64\pi\Lambda^2}$

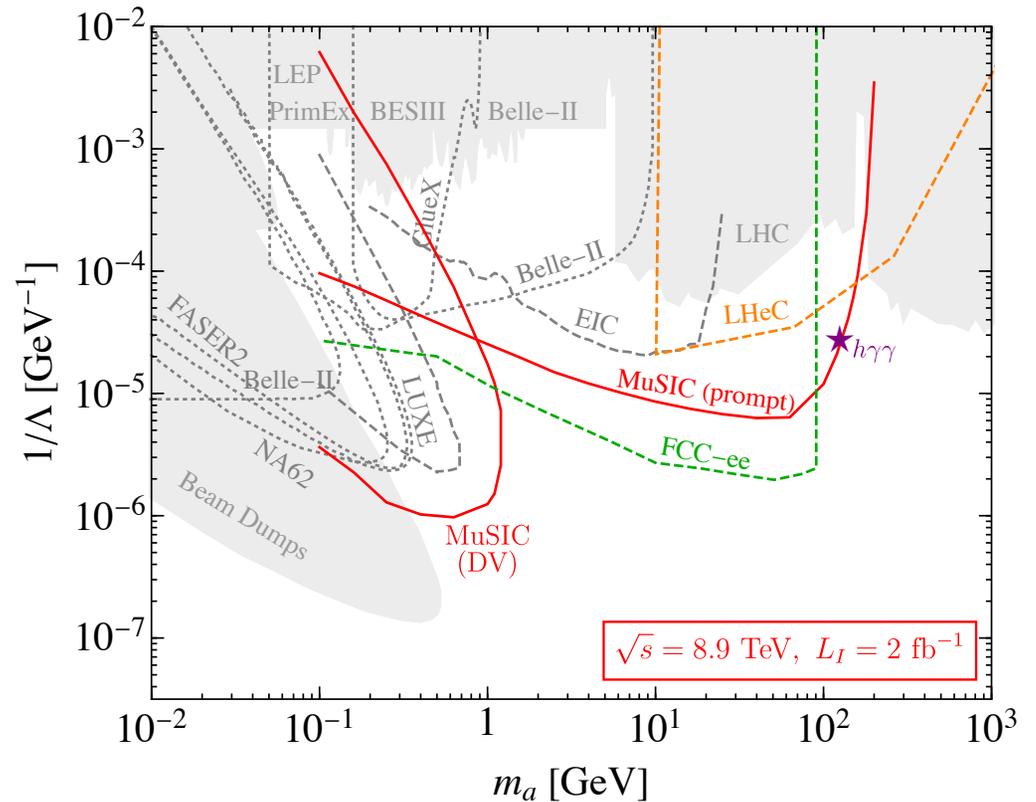
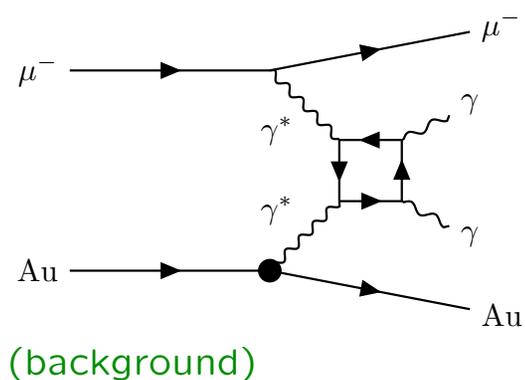
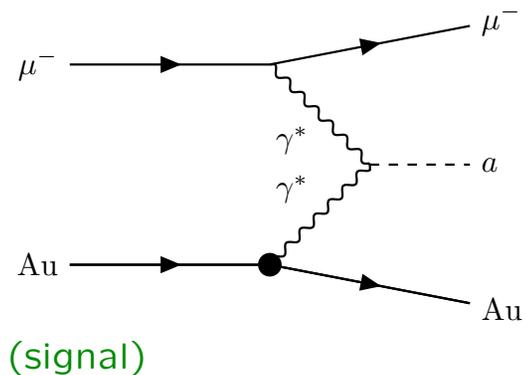
MuSIC for ALPs

- Consider the process $\mu \text{Au} \rightarrow \mu \text{Au} a$
 - 100% γ efficiency assumed for $E_\gamma > 1.0 \text{ GeV}$ and $|\eta_\gamma| < 4.0$
 - Displaced γ vertex resolution: 10 cm; detector length: 1 m
- Higgs coherent production via: $\mathcal{L}_h^{\text{int}} = -\frac{h}{4\Lambda_{h\gamma\gamma}} F^{\mu\nu} F_{\mu\nu}$

$$\Lambda_{h\gamma\gamma} = \pi v_{\text{EW}} / (2\alpha I) ; v_{\text{EW}} \approx 246 \text{ GeV} ; I \simeq -1.46$$



Cristo Vlahos; Wikipedia



2 σ projections

Heavy Sterile Neutrinos

- Consider a dim-5 operator, magnetic transition moment

$$\mathcal{L}_{\text{dipole}}^{(5)} \supset \frac{1}{2} \mu_\nu \bar{\nu} F_{\mu\nu} \sigma^{\mu\nu} N$$

ν : active neutrino ; N : heavy sterile neutrino; μ_ν : strength of transition (1/mass)

- The gauge invariant EFT interactions, below cutoff $\Lambda \gtrsim \text{TeV}$

$$\mathcal{L}_{\text{dipole}}^{(6)} \supset \frac{c_B}{\Lambda^2} g' B_{\mu\nu} \bar{L}^\alpha \tilde{H} \sigma^{\mu\nu} N + \frac{c_W}{\Lambda^2} g W_{\mu\nu}^a \bar{L}^\alpha \sigma^a \tilde{H} \sigma^{\mu\nu} N$$

$B_{\mu\nu}$ and $W_{\mu\nu}^a$: hypercharge and SU(2) field strength tensors ; H : Higgs doublet

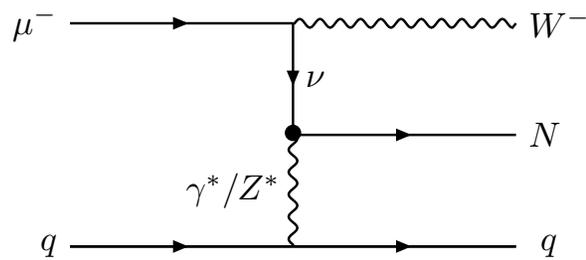
- After EWSB: $\mathcal{L}_{\text{dipole}} \supset \frac{1}{2} \mu_\nu \bar{\nu} F_{\mu\nu} \sigma^{\mu\nu} N + d_Z \bar{\nu} Z_{\mu\nu} \sigma^{\mu\nu} N + d_W \bar{\ell} W_{\mu\nu}^- \sigma^{\mu\nu} N$

with

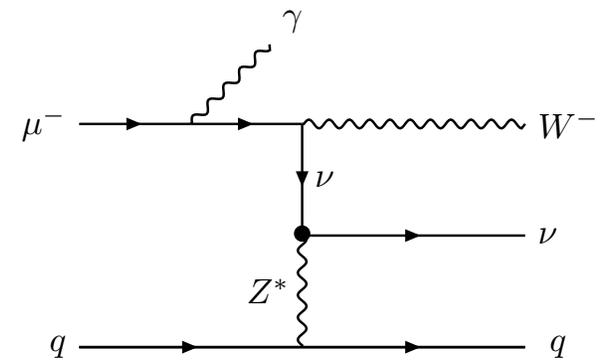
$$\begin{aligned} \mu_\nu &= \frac{\sqrt{2} v e}{\Lambda^2} (c_B + c_W) \\ d_Z &= \frac{v e}{\sqrt{2} \Lambda^2} (c_B \tan \theta_W - c_W \cot \theta_W) \\ d_W &= \frac{v e}{\Lambda^2} \frac{c_W}{\sin \theta_W} \end{aligned} \tag{1}$$

- We will consider two cases:

1. only $\mu_\nu \neq 0$ (partial result)
2. $c_W = 0$ and $d_Z = \frac{1}{2} \mu_\nu \tan \theta_W = \frac{v e}{\sqrt{2} \Lambda^2} c_B \tan \theta_W$.



(signal)



(background)

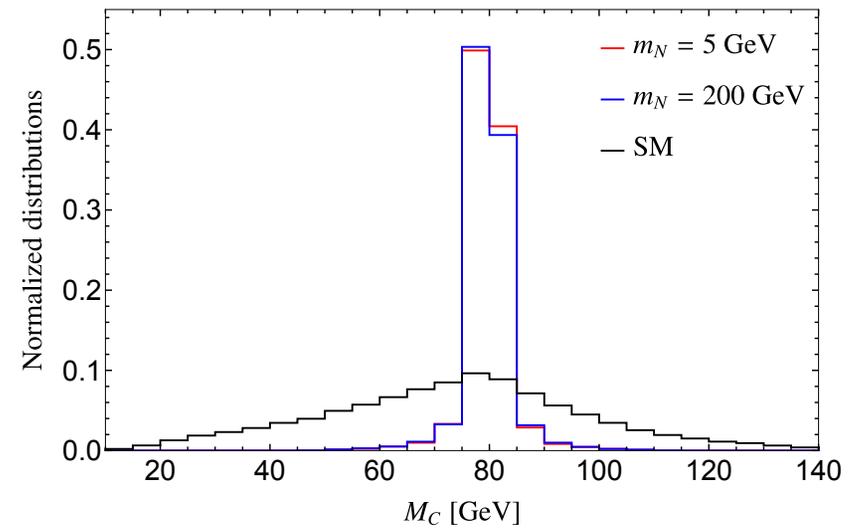
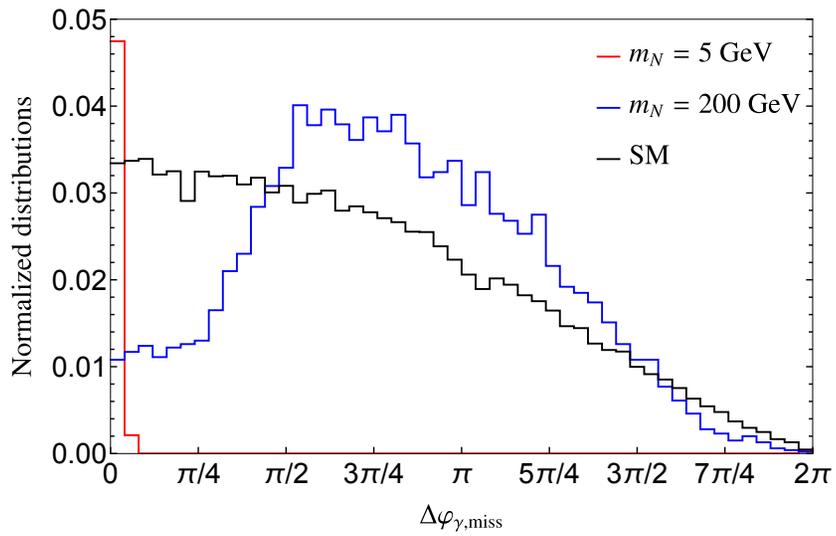
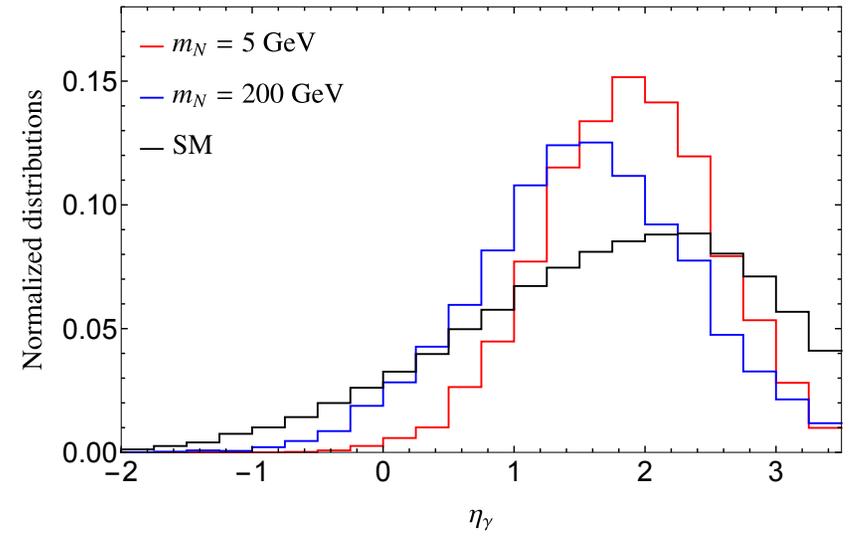
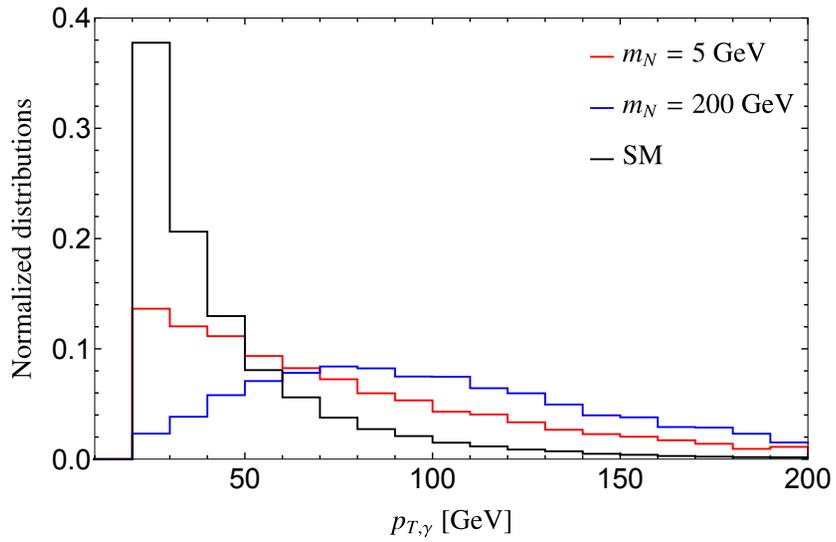
- Up-scattering of ν to $N(\rightarrow \nu_\mu \gamma)$ at MuSIC

For a study at the EIC, see: [Batell, Ghosh, Han, Xie, 2210.09287](#)

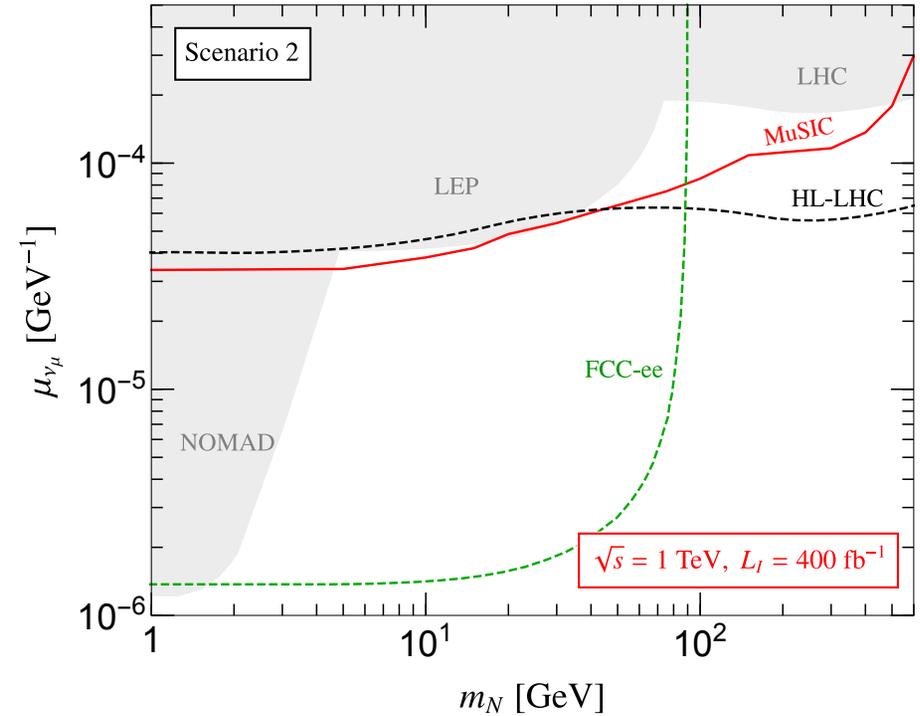
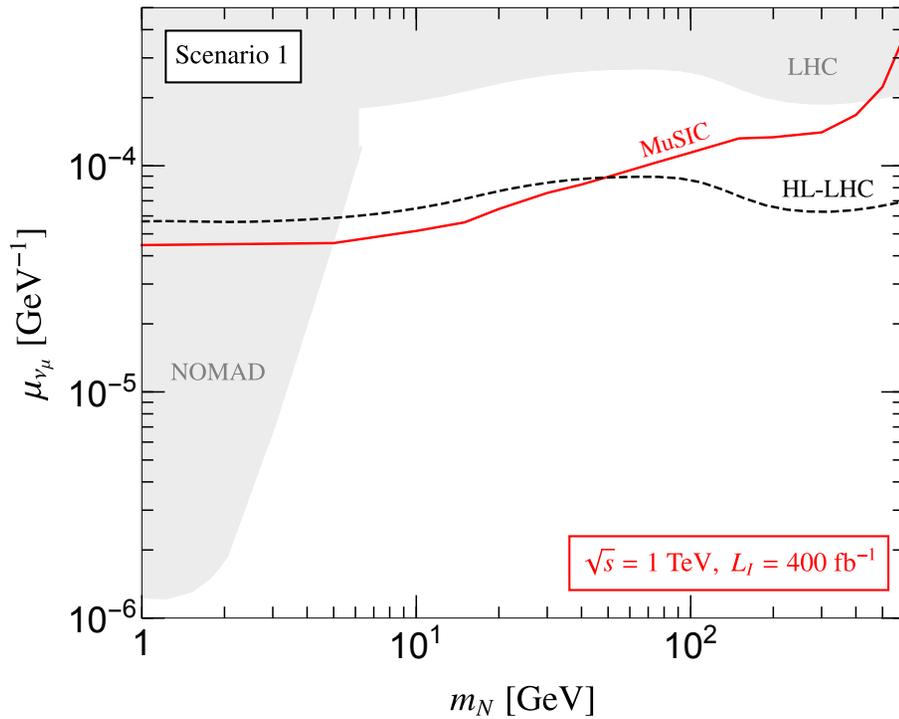
- We require $W \rightarrow jj$ to avoid additional neutrinos
- Azimuthal angle between E_{miss} and γ : $\Delta\varphi_{\gamma, \text{miss}}$ a handle
- Background: $\nu + \gamma + 3$ jets
- Signal and background generated using MadGraph5_aMC@NLO
- Three di-jet pairs: choose M_c closest to M_W and require $|M_c - M_W| < 5$ GeV
- The LHC bound: rescaling limit based on 36.1 fb^{-1}

[Magill, Plestid, Pospelov, Tsai, 2018](#)

Kinematic Handles



Projections



- HL-LHC: 3 ab^{-1} ; FCC-ee (Z -pole): 204 ab^{-1}
- HL-LHC, FCC-ee projections: rescaling LHC (36.1 fb^{-1}), LEP1 (200 pb^{-1}) limits

Magill, Plestid, Pospelov, Tsai, 2018

Concluding Remarks

- A Muon collider can provide a path to probing the ~ 10 TeV scale
 - *E.g.*, possible new physics underlying the Higgs potential
- A ~ 1 TeV beam can be a milestone towards this goal
- We highlighted the potential of a muon-ion collider in a few directions
 - Advances in nuclear physics
 - Study of high energy SM processes
 - Search for new phenomena (BSM)
- We focused on the last thrust and showed that a 1 TeV muon beam colliding with protons and heavy ions (MuSIC) can reach into new and interesting parameter space, for a few sample BSM scenarios
- The timeline for such a facility can match the muon beam R&D efforts and the maturation of the envisioned EIC program at BNL