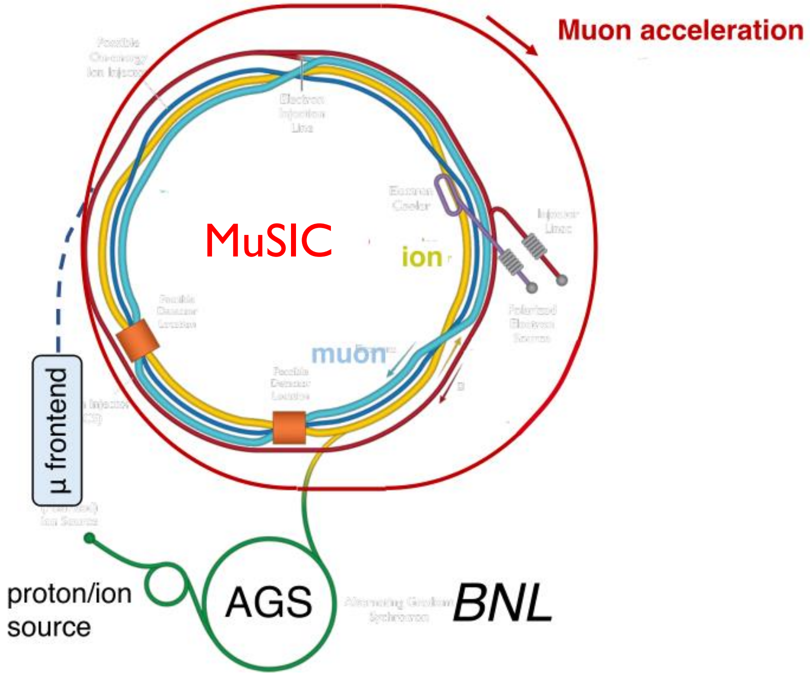
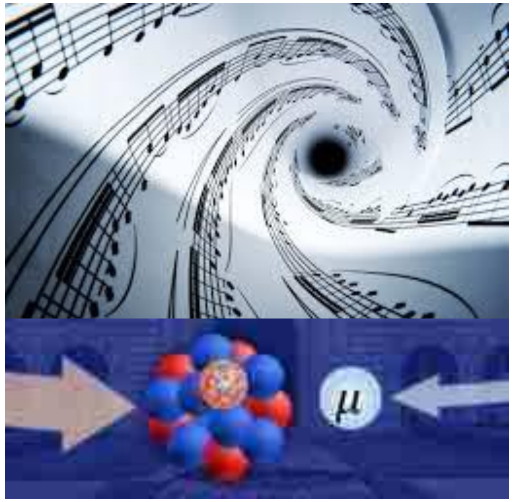
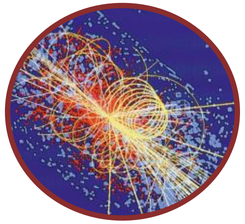




BSM at the Muon Synchrotron Ion Collider: Let the MuSIC play!

Sokratis Trifinopoulos

Uncovering New Laws of Nature at the EIC
Brookhaven National Lab
22/07/2024



Outline

I. Muon Collider

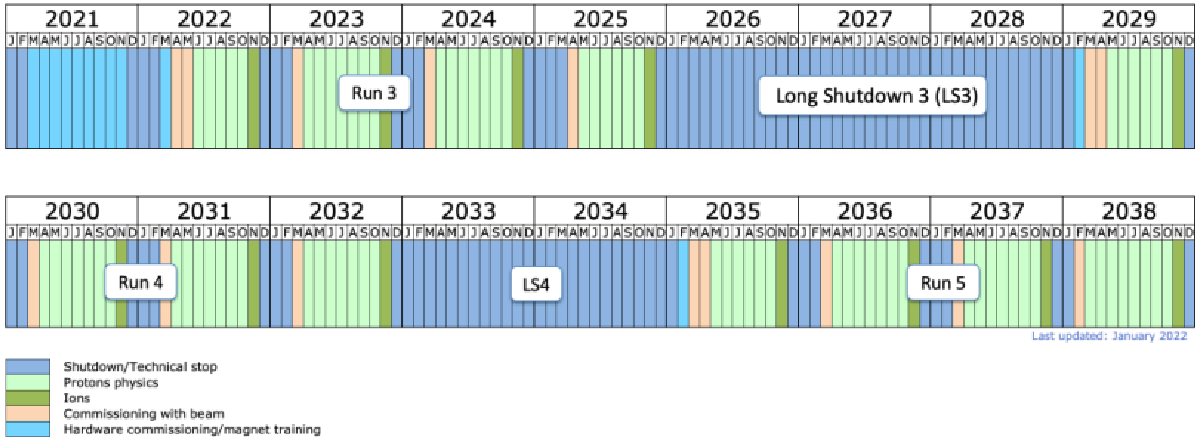
II. MuSIC

III. BSM at MuSIC

LHC: the past and the future

➢ LHC has already provided ground-breaking results:

- ✓ completion of the SM spectrum (**Higgs** boson discovery)
- ✓ exquisite precise measurements of a huge number of other SM processes
- ✓ fundamentally challenged our New Physics expectations at the EW scale

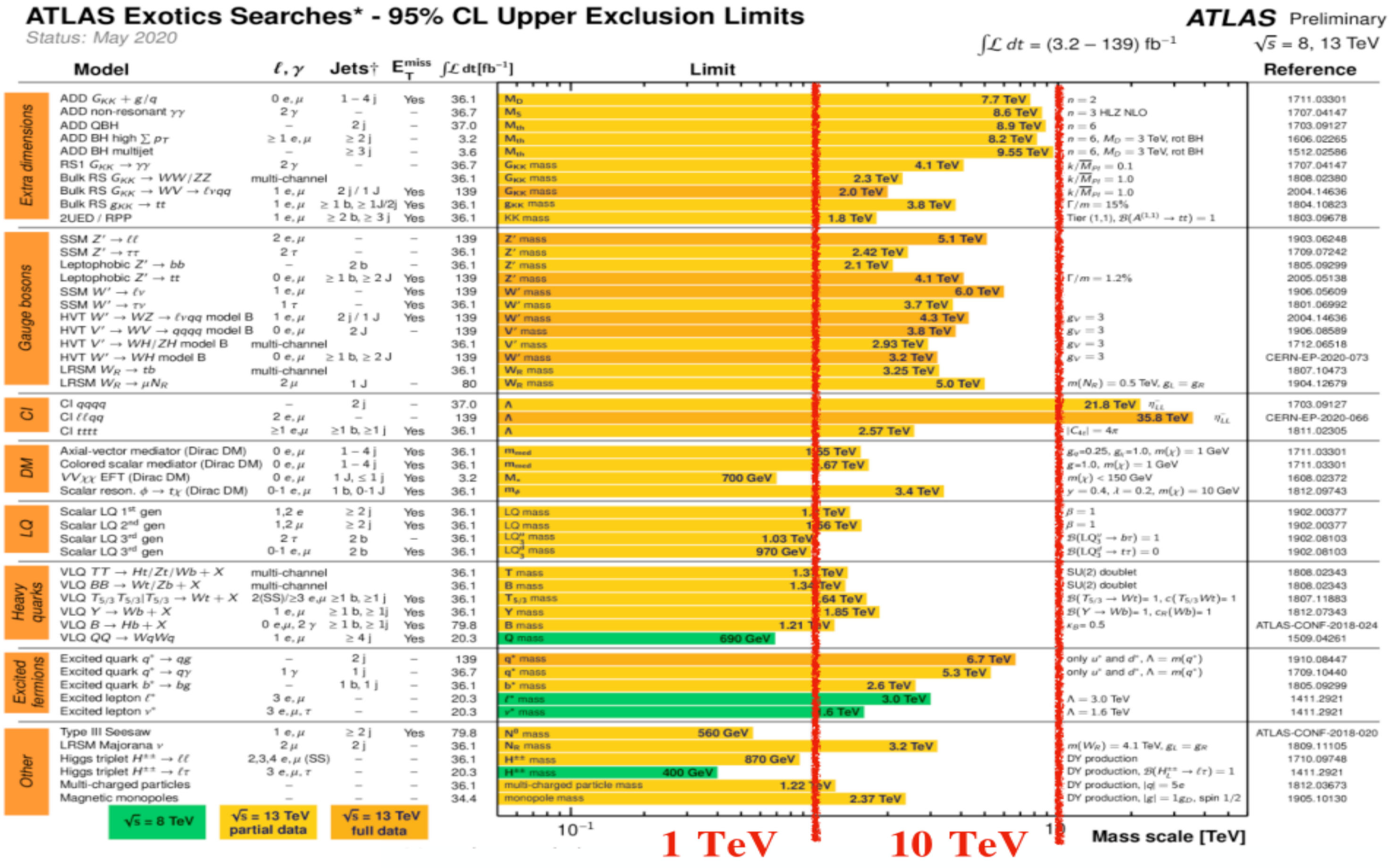


HL-LHC

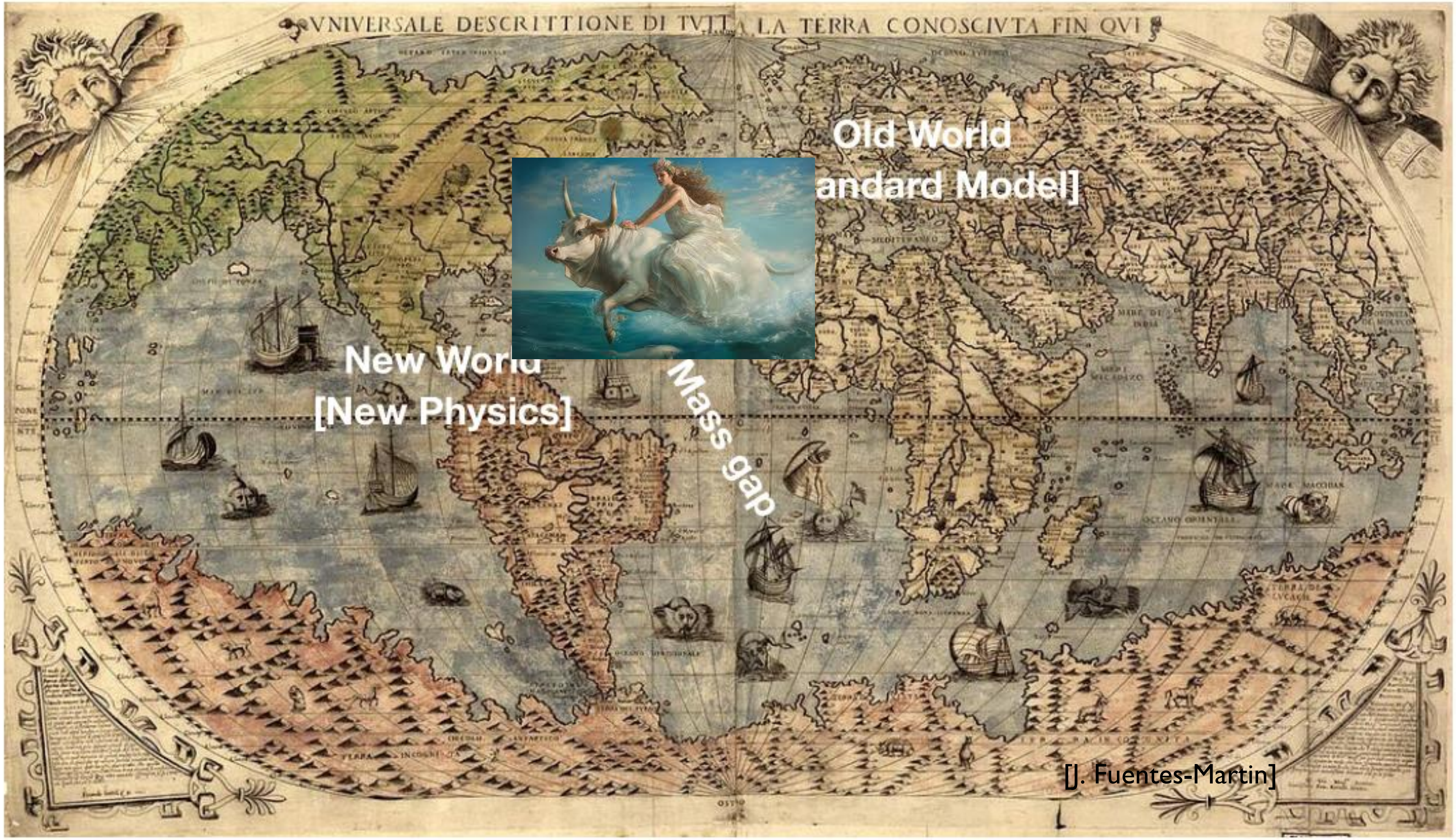
increased Lumi ×10

➢ We are moving towards the HL-phase and there is still lots of data to collect!

Still no direct evidence for New Physics!



The search for Terra Incognita

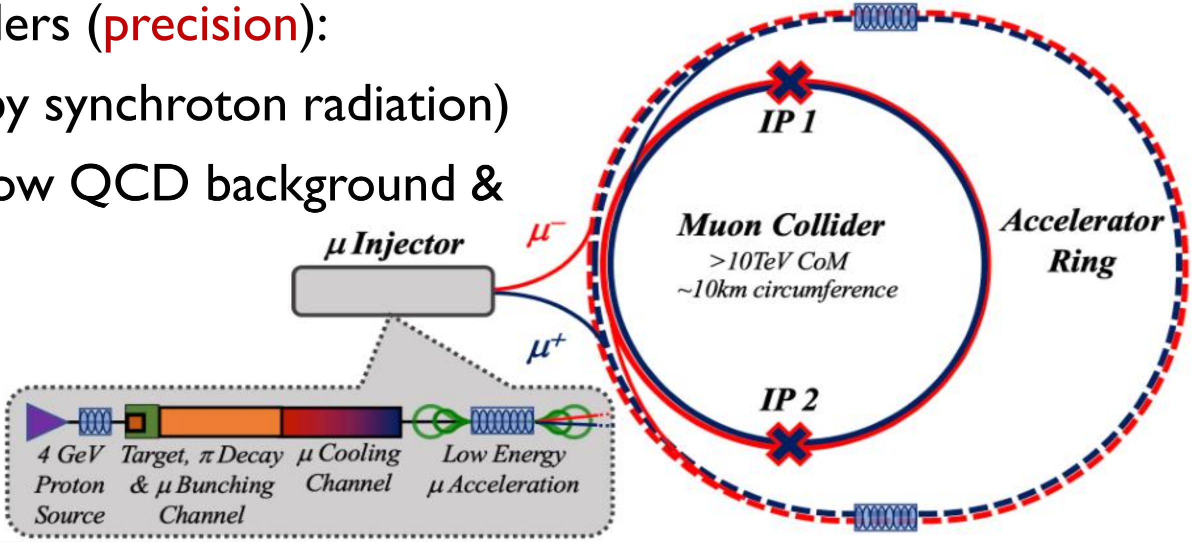


[J. Fuentes-Martin]

Multi-TeV Muon Collider

Muon colliders combine the advantages of both proton-proton (discovery) and electron-positron colliders (precision):

- ✓ high energy reach (not limited by synchroton radiation)
- ✓ high precision measurements (low QCD background & clean initial state)



[Snomass reports] 2203.08033, 2203.07224, 2203.07256, 2203.07261

[White paper] 2303.08533

[P5 Report]

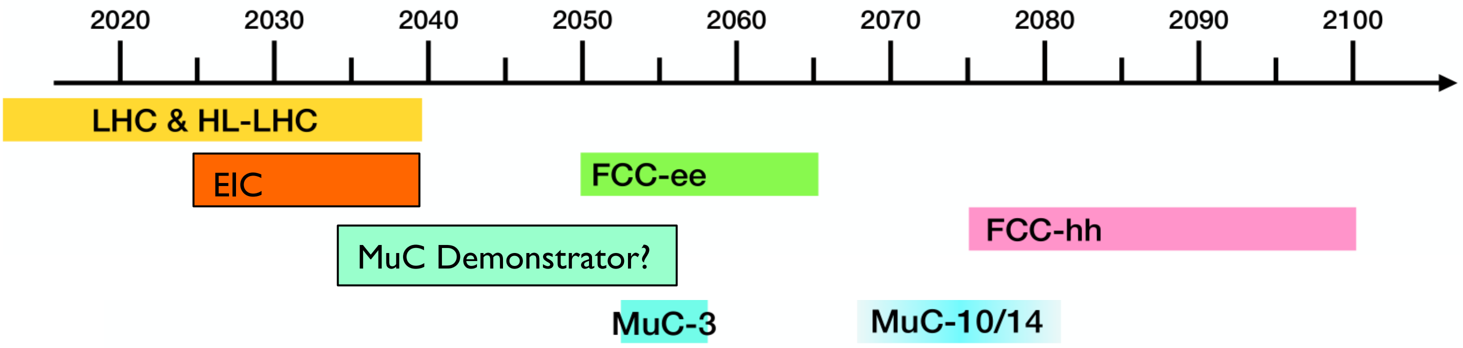
Exploring the Quantum Universe

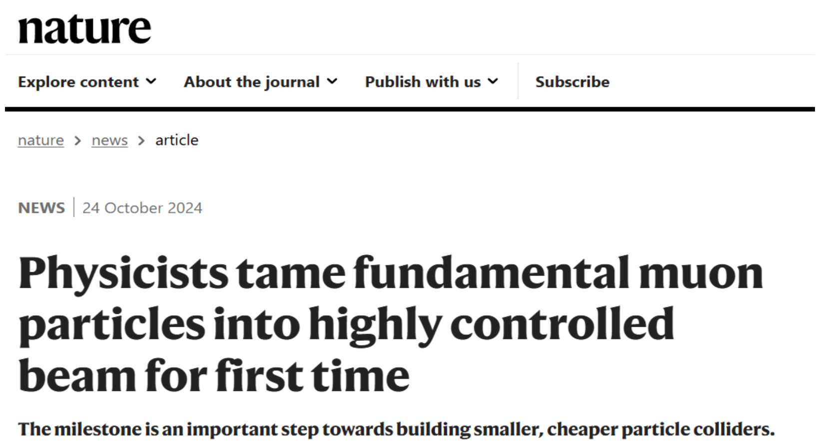
2.3 The Path to a 10 TeV pCM

...

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.**

Timelines

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nature > news > article

NEWS | 24 October 2024

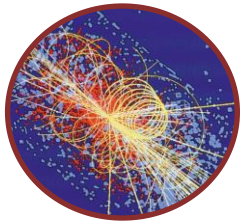
Physicists tame fundamental muon particles into highly controlled beam for first time

The milestone is an important step towards building smaller, cheaper particle colliders.

MuC R&D: Lots of progress on all fronts, **no show-stoppers** so far

[Aritome et al] 2410.11367

Sokratis Trifinopoulos



Outline

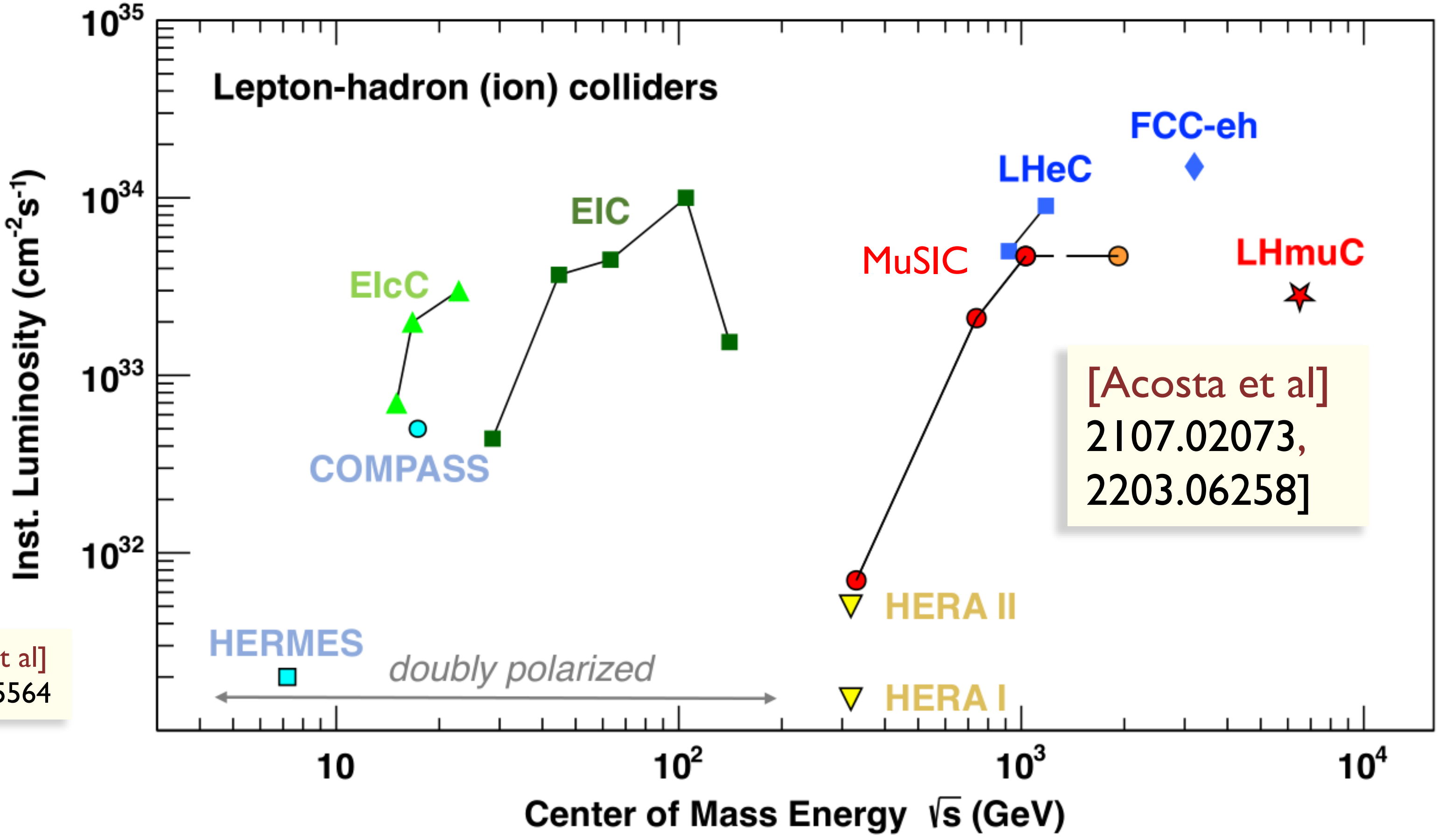
I. Muon Collider

II. MuSIC

III. BSM at MuSIC

The next generation lepton-ion colliders

- The EIC is a **very powerful machine**. But, what comes next?



[Acosta et al] 2107.02073, 2203.06258]

[Kaya et al] 1905.05564

Why should we play this MuSIC?

- By utilizing the existing infrastructure at BNL , MuSIC could directly succeed the EIC after its mission is completed (~2040) and reach a center-of-mass energy $\sqrt{s} = 1\,\mathrm{TeV}$.

Re-use of existing infrastructure allays some cost!

[Acosta et al] 2107.02073, 2203.06258

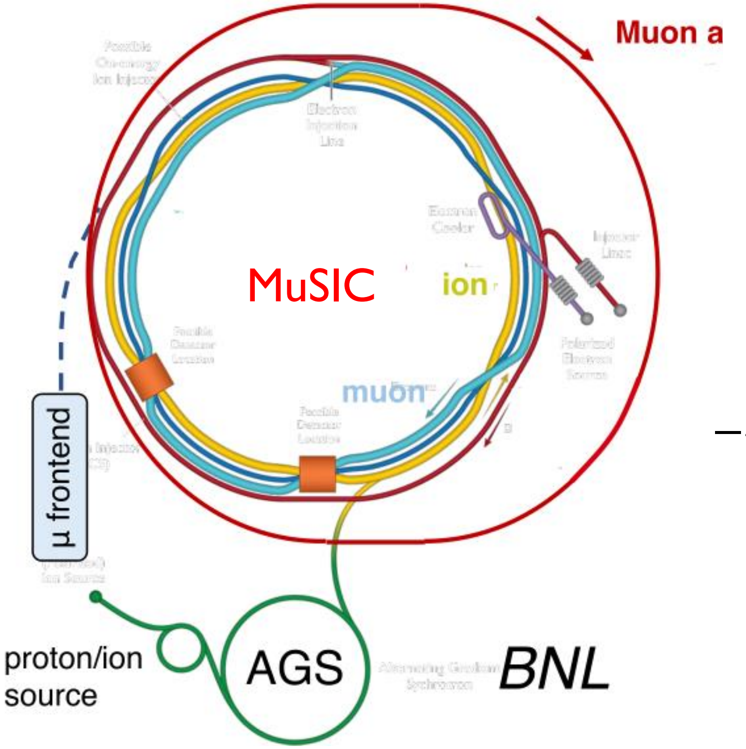
- **Dual appeal (and funding?)**: MuSIC establishes a new QCD frontier (nuclear physics), while also facilitating the development of a high-energy muon storage ring (particle physics).
- Discovery potential: $\sqrt{s}$ MuSIC $\approx$ 50% $\sqrt{s}$ MuC
- There could be a staged development:

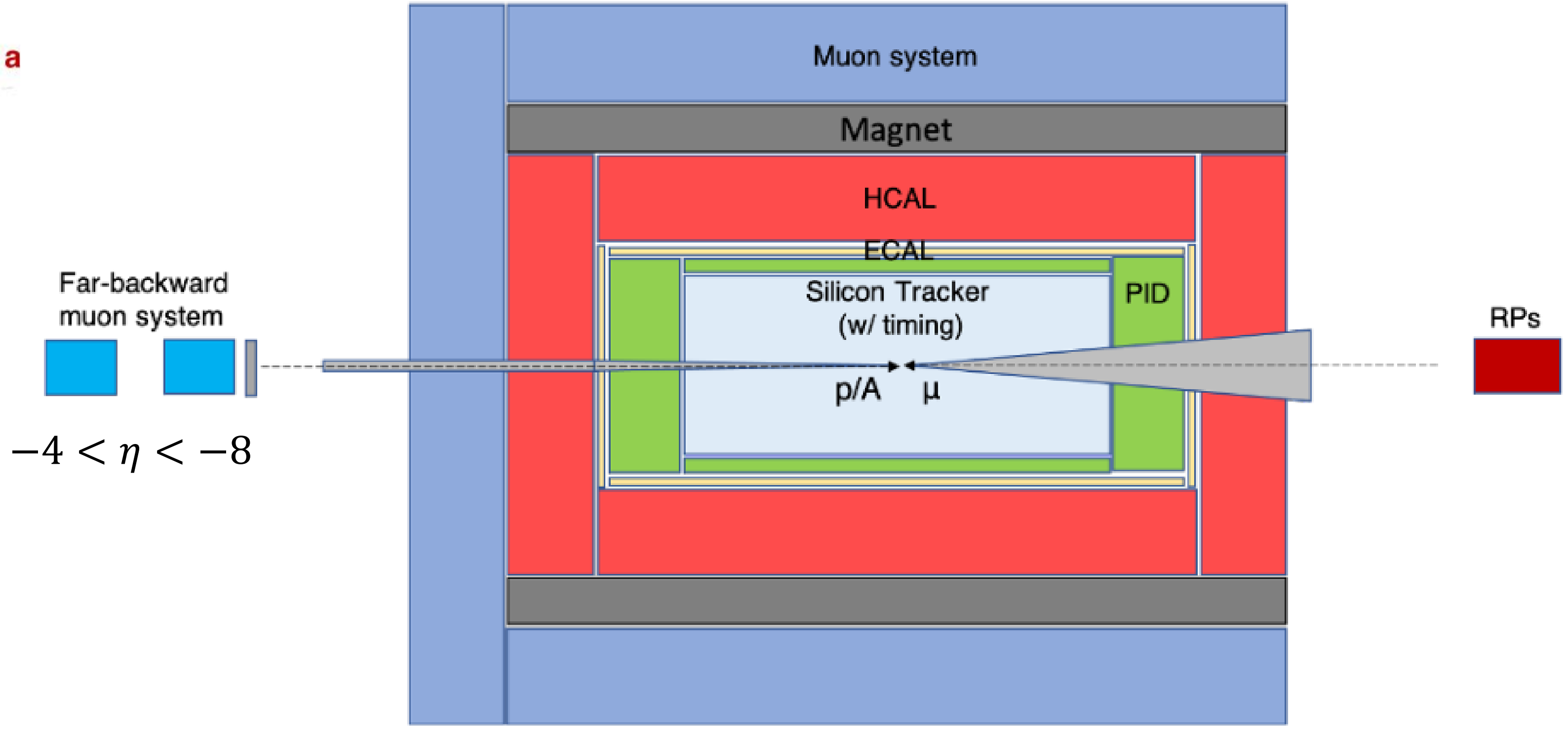
E_p (TeV)	0.275			0.96
E_μ (TeV)	0.1	0.5	0.96	0.96
$\sqrt{s_{\mu p}}$ (TeV)	0.33	0.74	1.0	1.92
L_{int} ($\times 10^{33}$ cm^{-2}s^{-1})	0.07	2.1	4.7	4.7

our benchmark

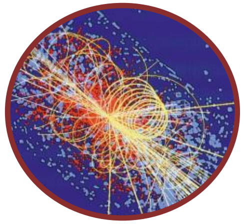
Detector Design Considerations

[Acosta et al] 2203.06258]





$E_p \approx 0.3$ TeV $\sqrt{s} \cong 1$ TeV $E_\mu \approx 1$ TeV

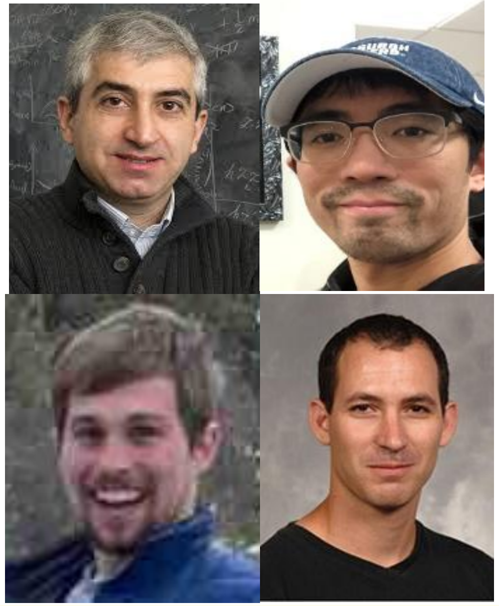


Outline

I. Muon Collider

II. MuSIC

III. BSM at MuSIC



Davoudiasl, Liu, Marcarelli, Soreq, Trifinopoulos] 24XX.XXXXX

BSM Models

We consider four *simplified* BSM models. See also: [Cheung, Wang] 2101.10476 [Hatta] 2311.14470

1. **Leptoquark $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$**: Enables study of $\mu - \tau$ lepton-flavor violation (LFV) at tree-level. U_1 is additionally motivated by B-anomalies and as portal to dark matter.

   [Bordone et al] 1712.01368, 1805.09328, [Di Luzio et al] 1708.08450, [Greljo et al] 1802.04274, [Baker, Faroughy, **Trifinopoulos**] 2109.08689

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

2. **Muonphilic Z':** Light vector gauge boson below the electroweak scale. [He et al] PhysRevD.43.R22

$$\mathcal{L}_{Z'}^{\rm int} = -g_{Z'}^\mu \bar{\mu} \gamma_\alpha \mu Z'^\alpha$$

3. **Axion-like Particles:** Theoretically-motivated heavier versions of the QCD axion.

   [Agrawal, Howe] 1710.04213 [Fitzpatrick et al] 2306.03128 [Takahashi, Yin] 2105.10493

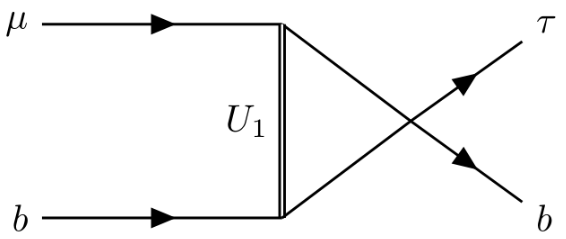
$$\mathcal{L}_a^{\rm int} = -\frac{a}{4\Lambda} F^{\mu\nu} \tilde{F}_{\mu\nu}$$

4. **Heavy Sterile Neutrinos:** Accessed via a effective dipole operator: [Ismail, Jana, Abraham] 2109.05032

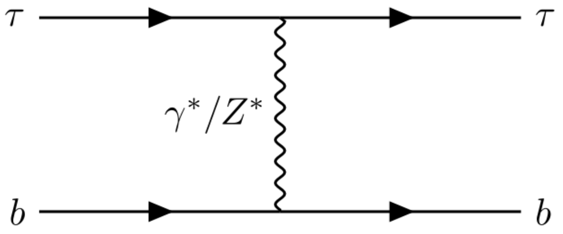
$$\mathcal{L}_{\rm dipole}^{(5)} \supset \frac{1}{2} \mu_\nu \bar{\nu} F_{\mu\nu} \sigma^{\mu\nu} N \,, \qquad (\mu_\nu \sim v_{\rm EW}/\Lambda^2)$$

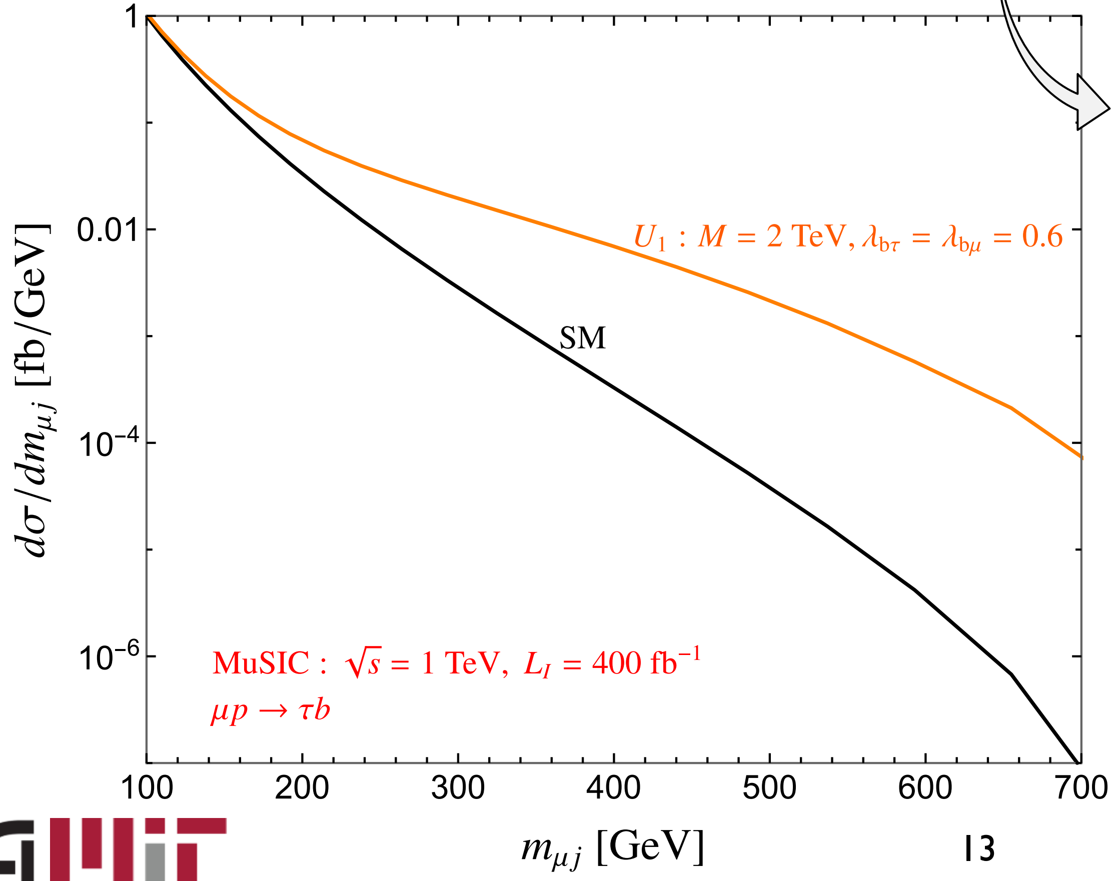
LFV leptoquark interactions: prompt search

Signal:



Background:



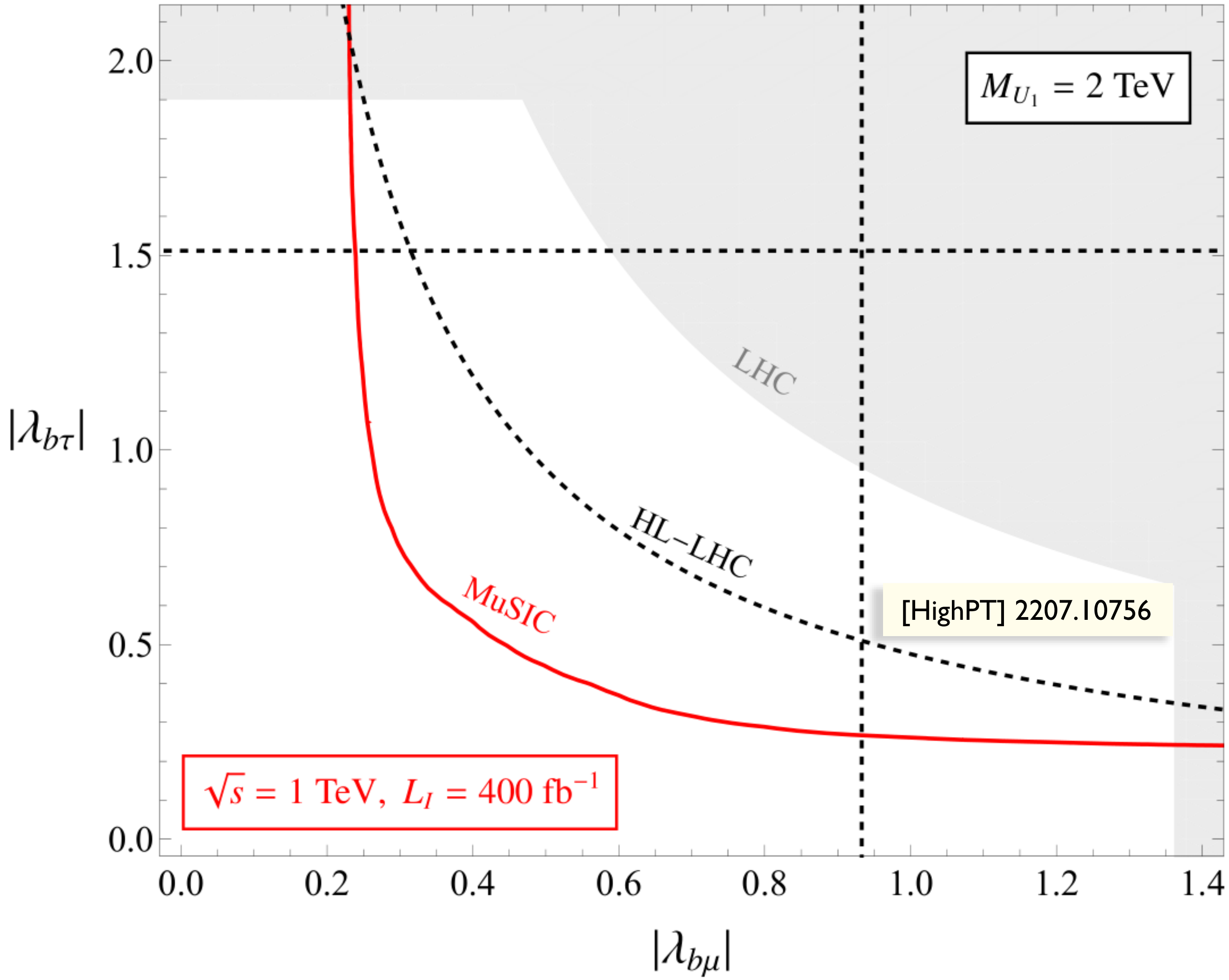


τ content of the muon beam → LePDF

[Han, Ma, Xie] 2007.14300, 2103.09844
[Garosi, Marzocca, **Trifinopoulos**] 2303.16964,
github.com/strifinopoulos/LePDF

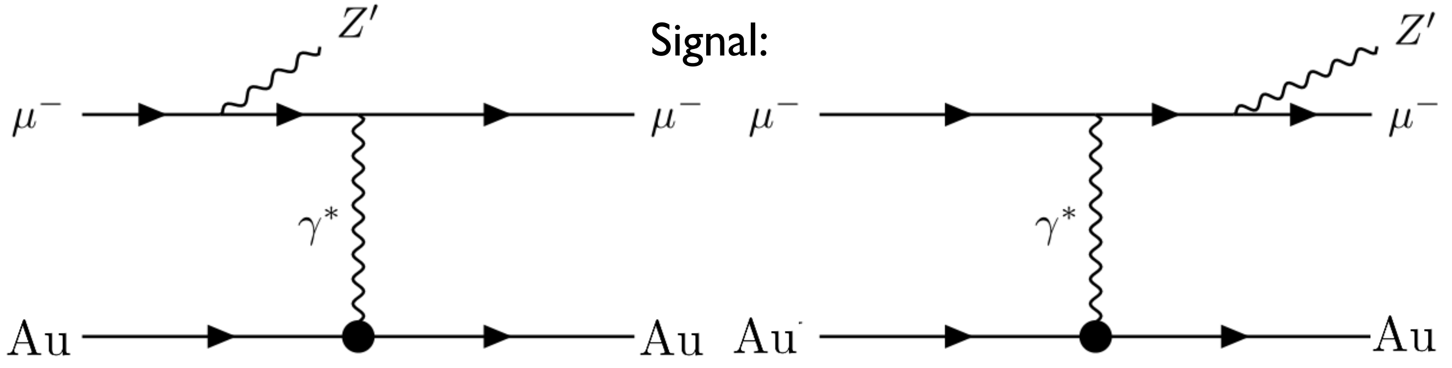
- We convolute the PDFs with the differential cross sections and integrate within the central detector rapidity coverage $|\eta| < 3.5$.
- **Acceptance efficiencies**: *b*-tagging 80% , τ-hadronic decays 75% [ATLAS] 2108.07665, 2305.15962

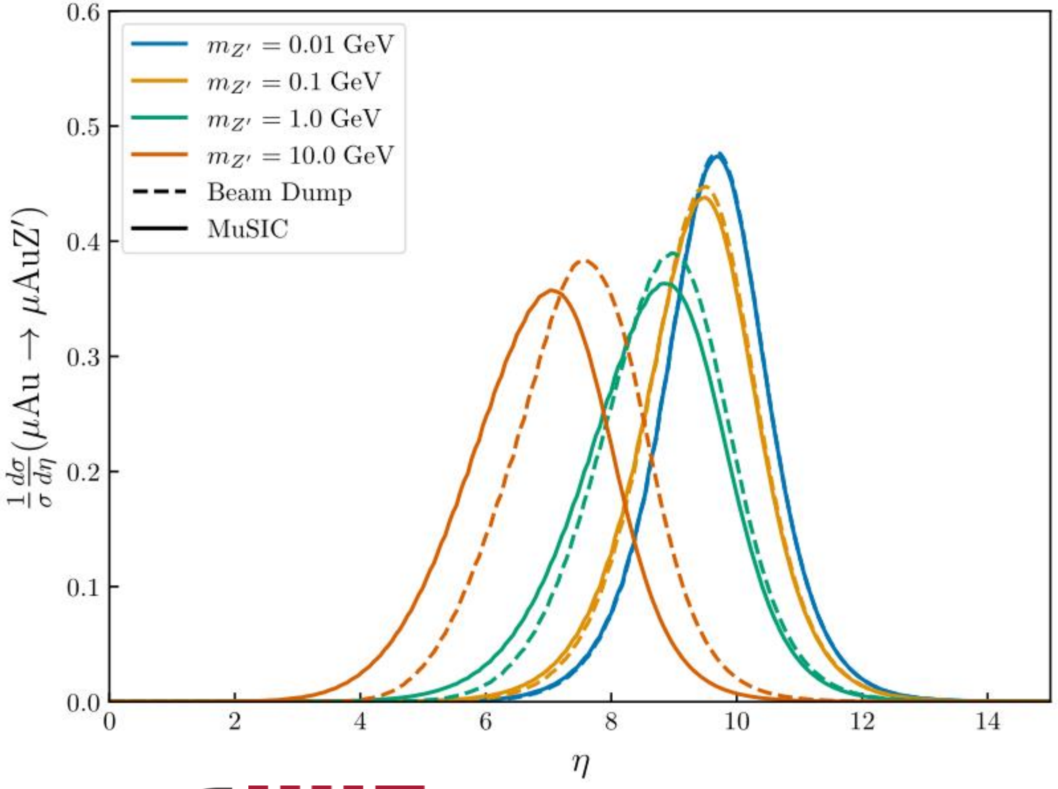
LFV leptoquark reach: MuSIC vs HL-LHC



Z' vector boson: displaced vertices

Signal:





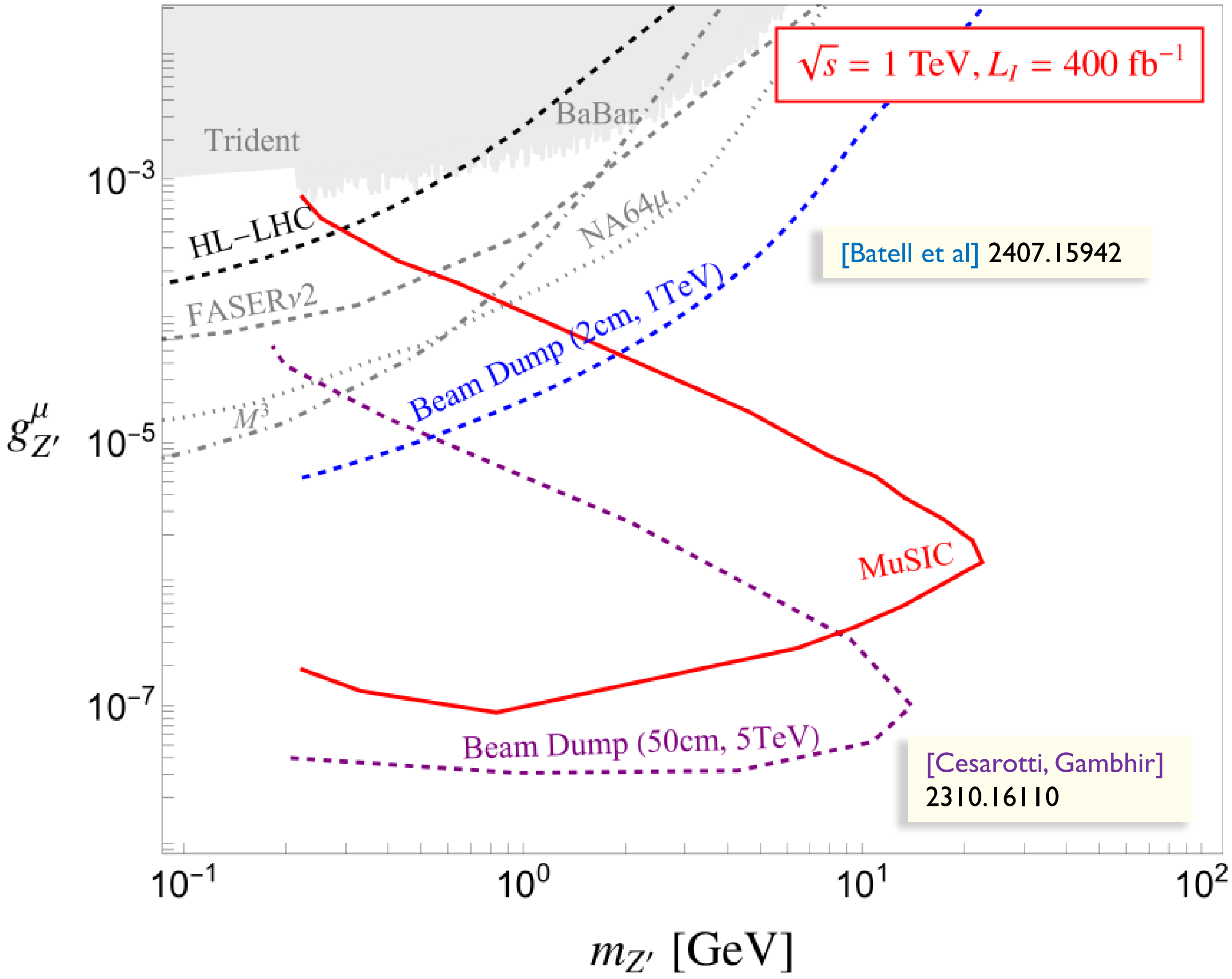
- The cross-section in coherent scattering is Z^2-enhanced.
- The large ion-frame muon energy of $O(100\,\text{TeV})$ leads to highly-boosted Z' in the far-backward direction.
- After traveling some distance ℓ it decays to di-muons with probability:

$$P(\ell) = \frac{e^{-\ell/L_{Z'}}}{L_{Z'}}, \qquad L_{Z'} = \beta\gamma/\Gamma_{Z'}$$

boost factor $=|\vec{p}|/M$

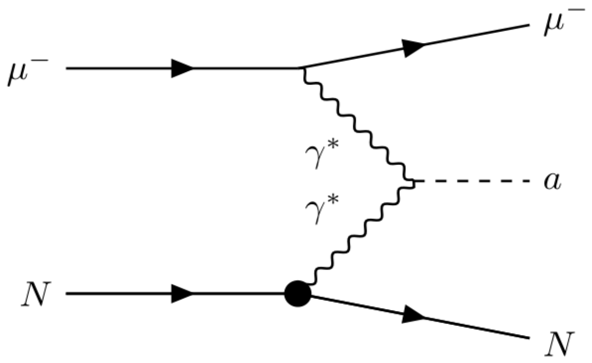
- To find the expected number of events, we integrate $P(\ell)$ from $\ell_{\text{min}} = 1\text{mm}$ (veto prompt backgrounds) to $\ell_{\text{max}} = 30\text{m}$ (distance to the far-backward muon spectrometer) and $d\sigma/d\eta$ within $-4 < \eta < -8$.

Z' vector boson: MuSIC vs Muon Beam Dumps



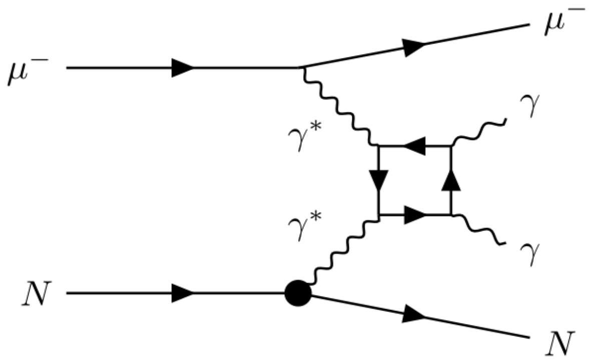
Axion-like particles: MuSIC vs FCC-ee & LHeC

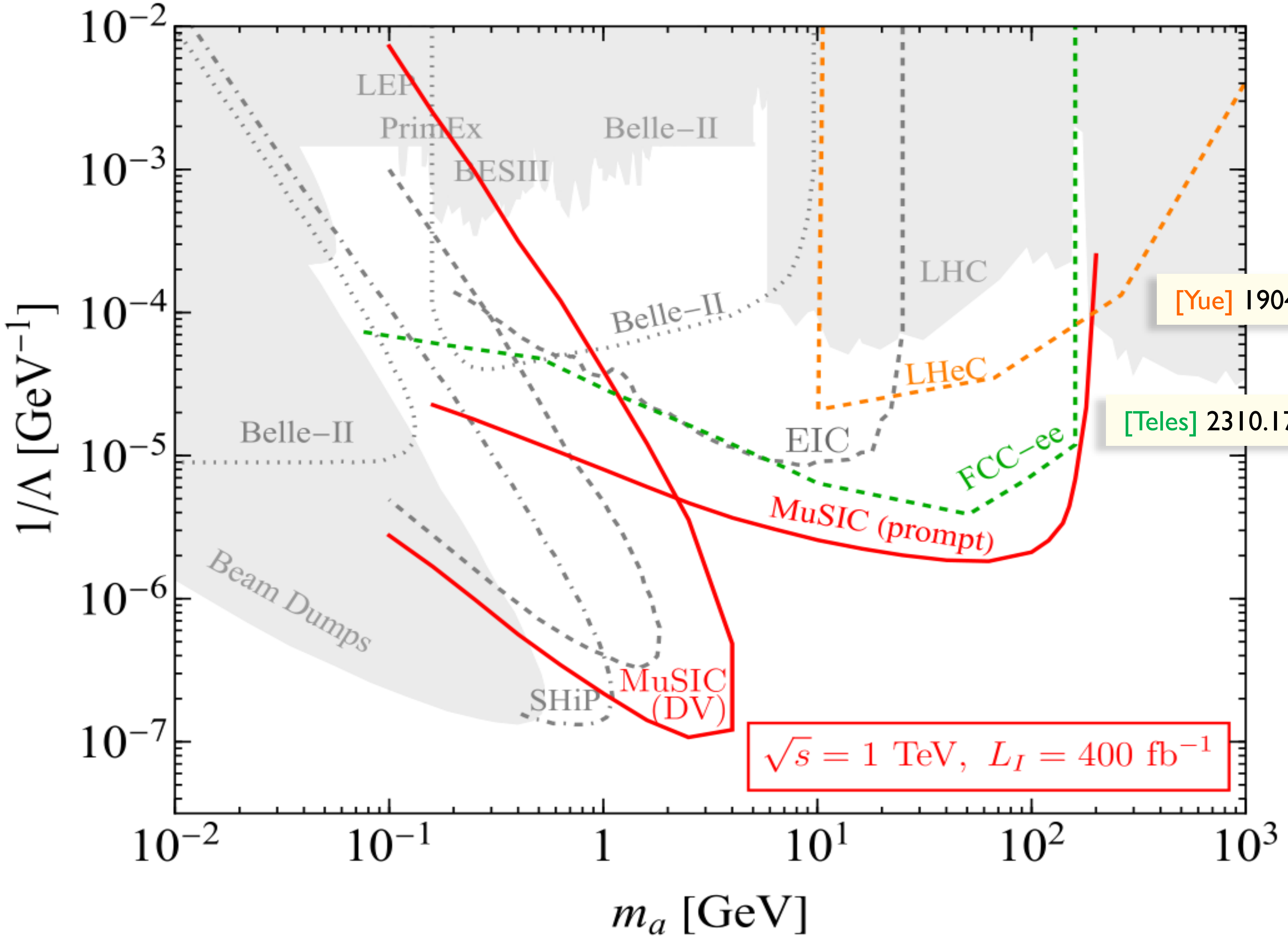
Signal:



see **Hongkai's talk** and [Balkin et al] 2310.08827

Background:



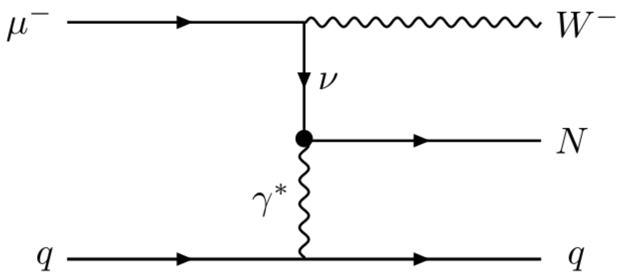


[Yue] 1904.10657

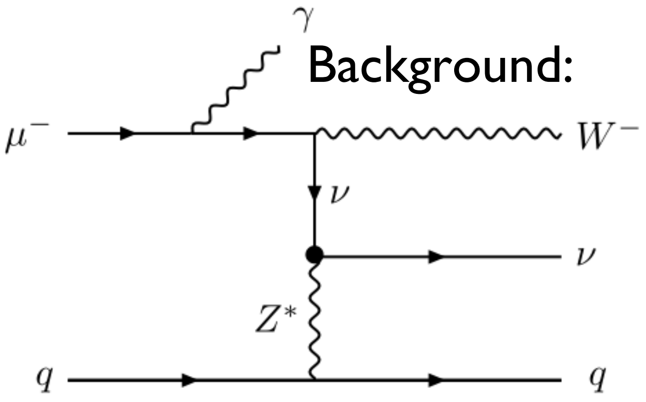
[Teles] 2310.17270

ν_μ magnetic moments: prompt search

Signal:

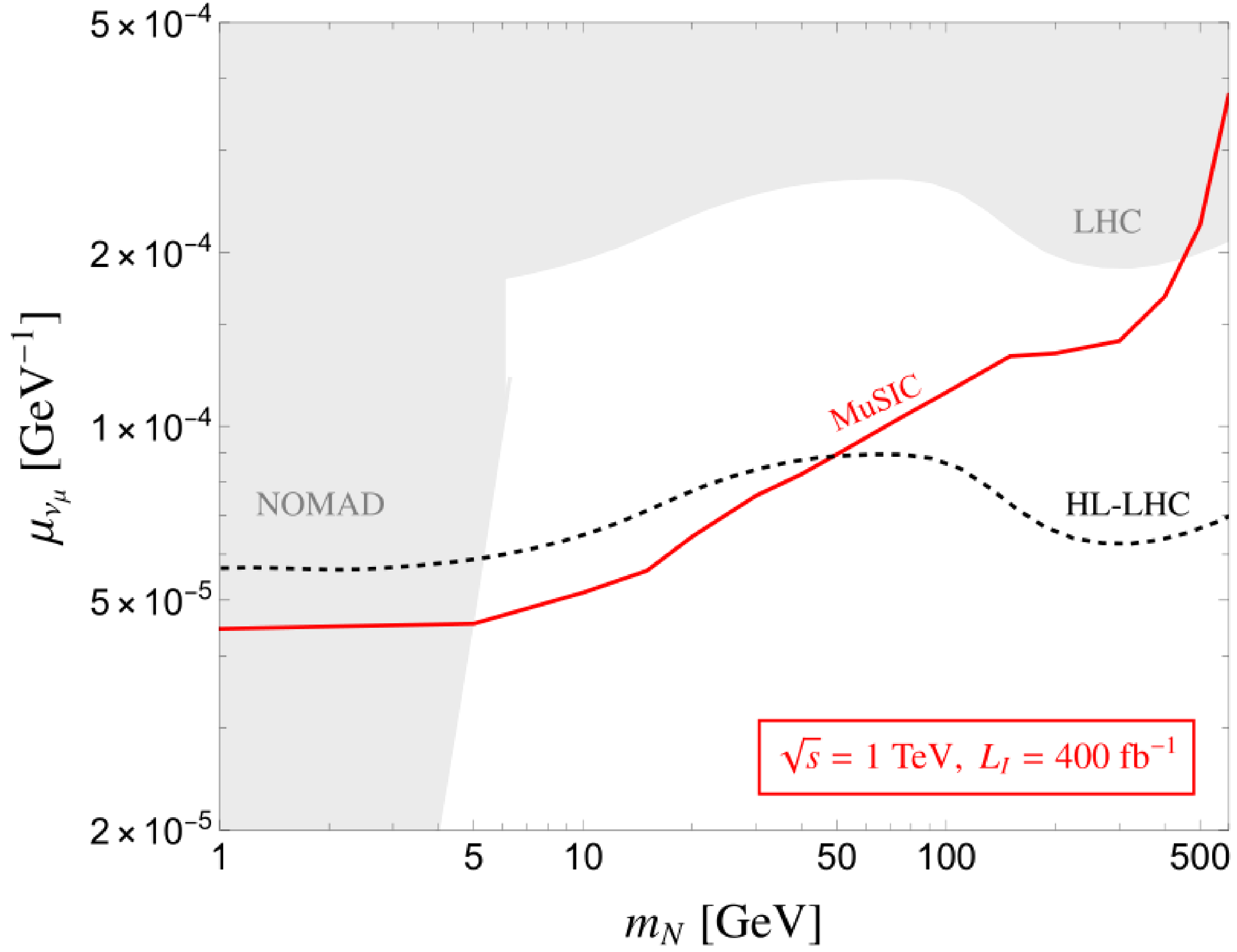


Background:



- The HSN is produced via *up-scattering* of SM neutrinos via the dipole operator.
- The the azimuthal angle between the missing energy and the photon, can either be collimated or separated by π. This characteristic can be very distinct from the SM background.
- We veto additional neutrinos $\Longrightarrow \nu + \gamma + 3j$ final state.

Heavy Sterile Neutrinos: MuSIC vs HL-LHC



[Magill] 1803.03262

Conclusions

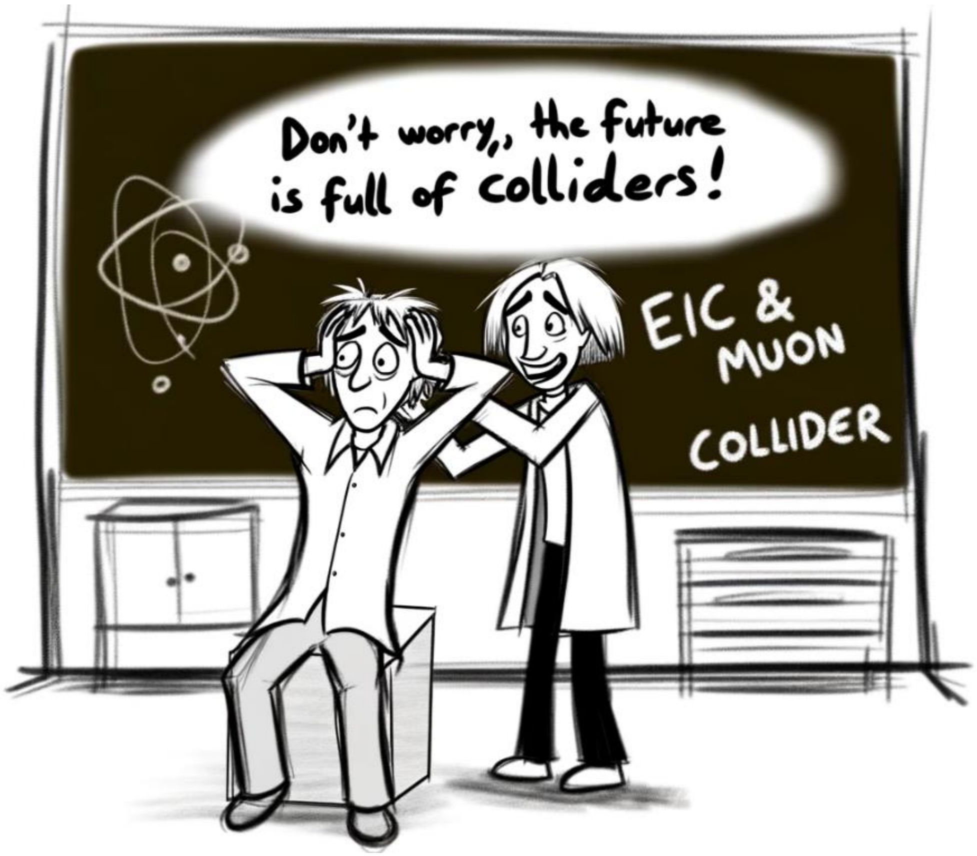
- **MuSIC** offers many synergies with MuC R&D, and between nuclear and particle physics programs, if we all agree to work together!

- We scrutinized four scanaria with explicit BSM mediators both below and above the energy threshold of MuSIC.

BSM candidate	**Search (MuSIC)**	**Competition**	**Features (MuSIC)**
LFV U_1 leptoquarks	prompt	HL-LHC	valence particles
Muonphilic Z'	displaced	Beam Dumps, HL-LHC	far-backward detector, coherent scattering, valence lepton
Axion-like particles	prompt & displaced	FCC-ee, LHeC	coherent scattering
Sterile Neutrinos	prompt	HL-LHC	mono-neutrino

- We hope that our findings will serve as a *overture* to further dedicated studies and eventually a white paper for MuSIC in the near future.

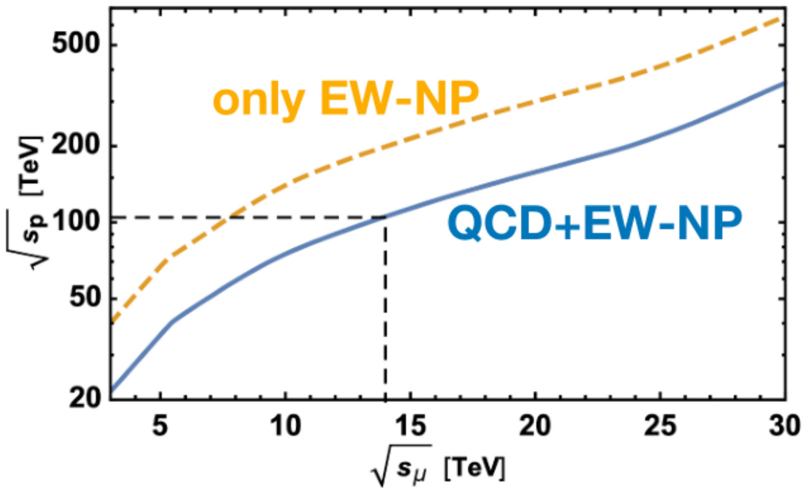
Thank you!

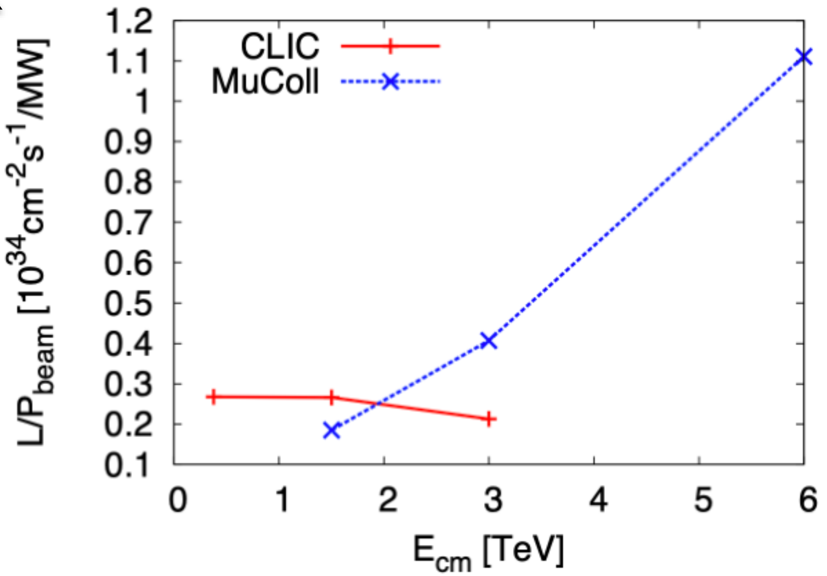

Don't worry, the future is full of colliders!
EIC &
MUON
COLLIDER

Why Muon Colliders?

Muon colliders combine the advantages of both proton-proton (discovery) and electron-positron colliders (precision):

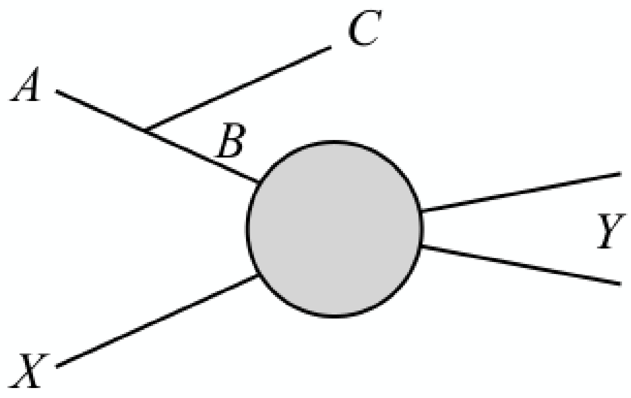
- ✓ high energy reach (not limited by synchroton radiation)
- ✓ high precision measurements (low QCD background & clean initial state)
- ✓ luminosity / beam power increases with energy.
- ✓ all beam energy available in $\mu^+\mu^-$ collisions.





Muon PDFs and DGLAP equations

- At zeroth order in perturbation theory the muon carries all the momentum of the beam.
- At high energies, collinear radiation emitted by splitting of the initial state must be considered. [Han, Ma, Xie] 2007.14300, 2103.09844
- The hard scattering can be factorized and the radiation is resummed by introducing the Parton Distribution Functions (**PDFs**) of a lepton!

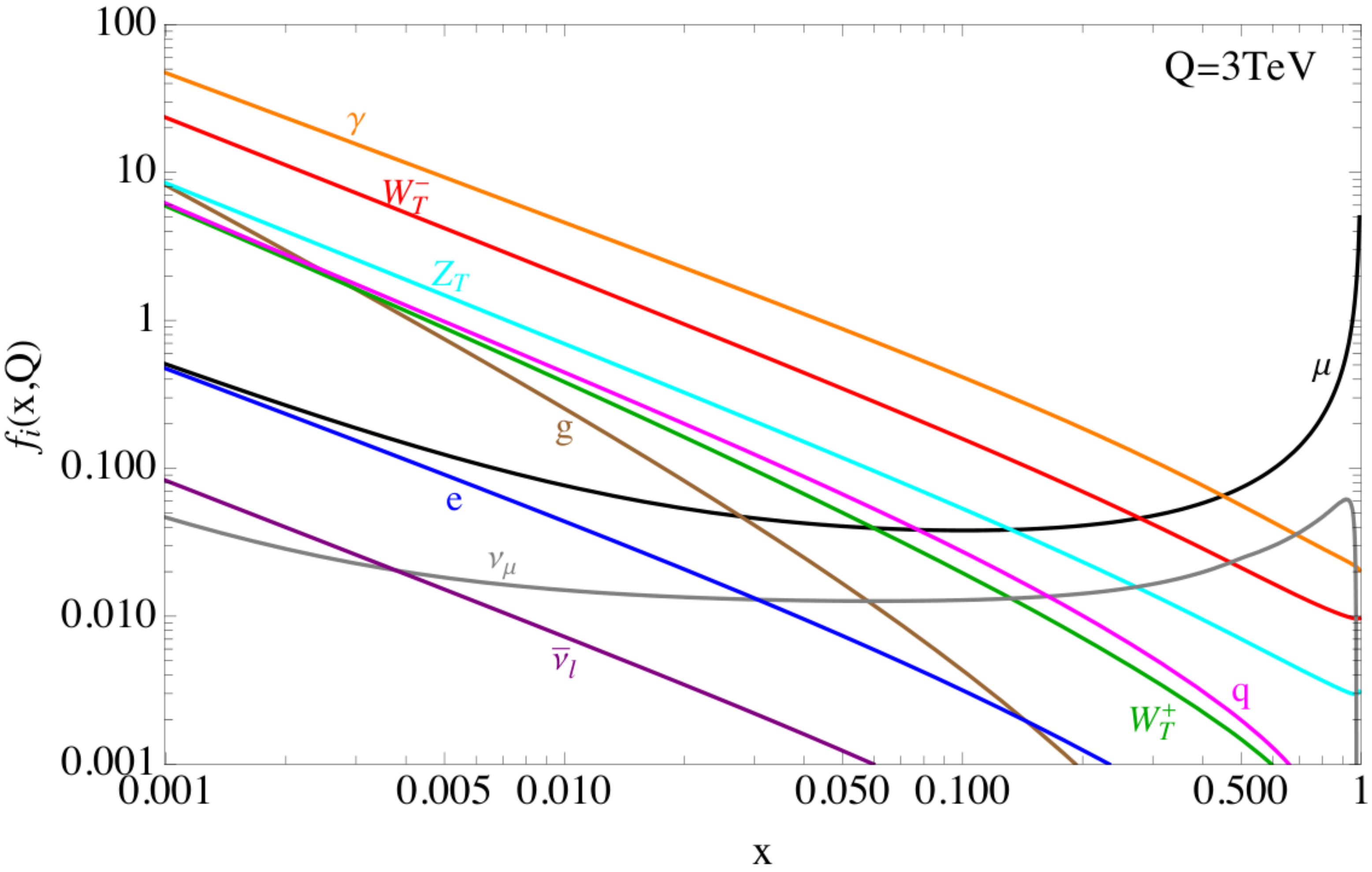


$$\sigma(\mu + X \to Y) = \sum_B \int_0^1 dx\, f_B(x) \sigma_x(B + X \to Y)$$

determined by the perturbative **DGLAP evolution** under the full unbroken SM gauge group

The muon beam includes all other SM particles (including quarks and gluons)!!

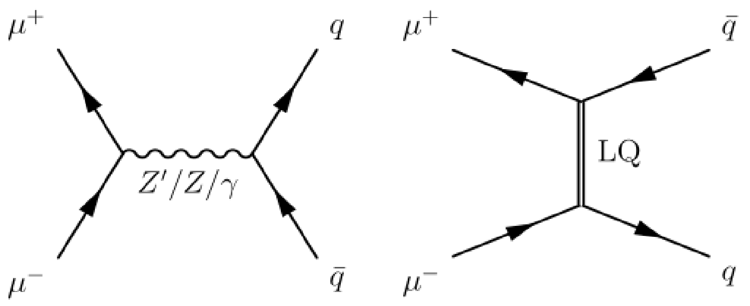
PDFs above the EW scale



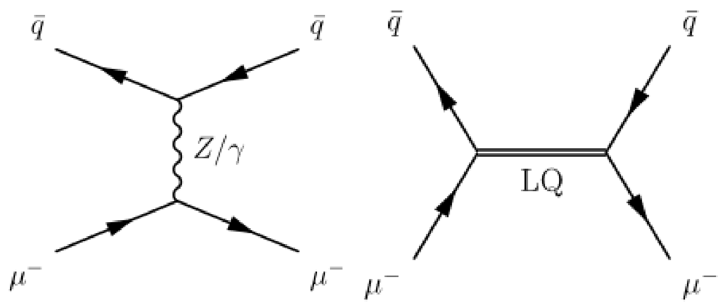
[Garosi, Marzocca, **Trifinopoulos**] 2303.16964, github.com/strifinopoulos/LePDF

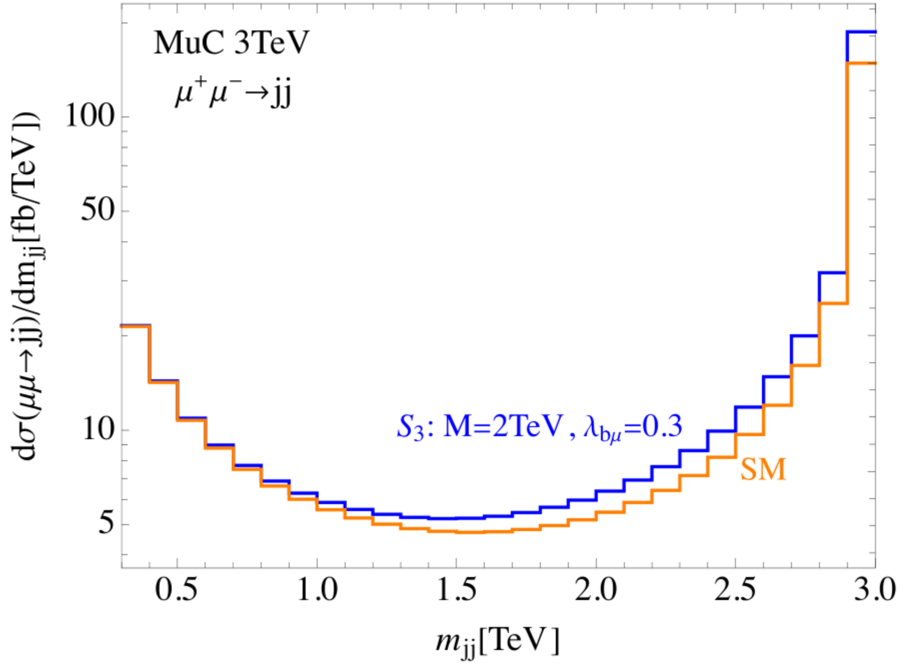
(LHAPDF-format)

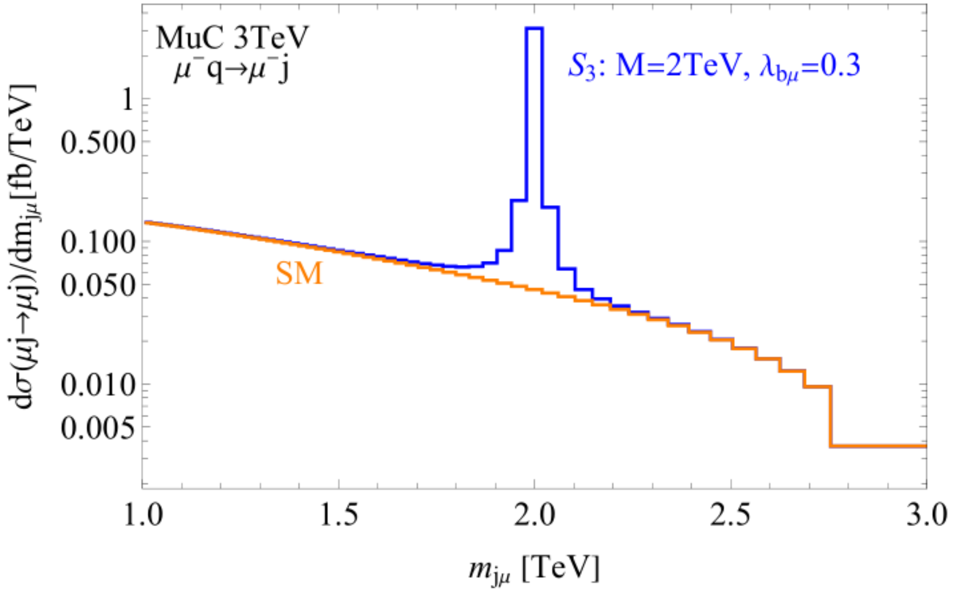
Prompt signatures at a 3 TeV Muon Collider



[Azatov, Garosi, Greljo, Marzocca, Salko, **Trifinopoulos**] 2205.13552



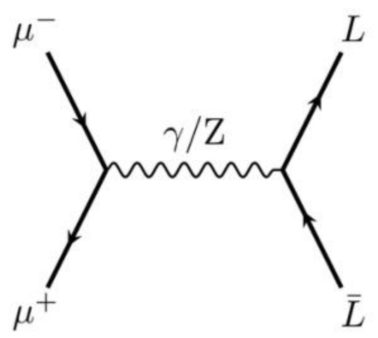




MuC is a Gauge Boson Collider

- At high energies EW Sudakov double logs enhance the gauge boson content and vector-boson fusion becomes dominant!
- PDFs are important! $\mathcal{O}(50\%)$ discrepancies arise from a fixed-order calculation.

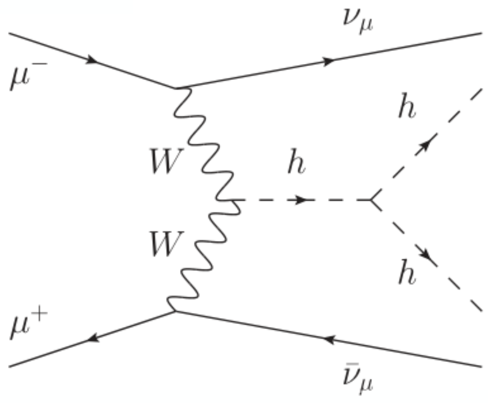
MuC overqualifies as a Higgs factory!

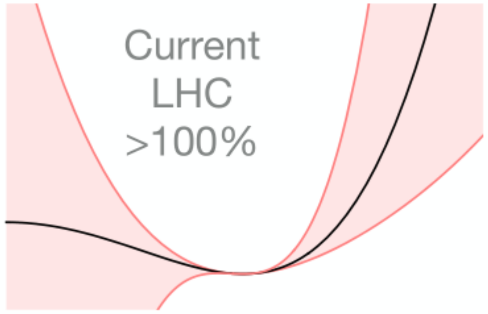


$$\sigma \sim \frac{1}{E^2}$$

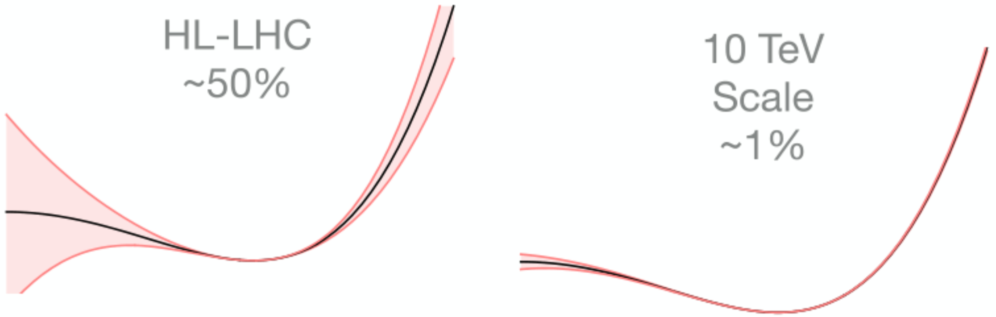
$$\sigma \sim \frac{1}{M^2} \log^2 \frac{E^2}{M}$$

[K, F. DiPetrillo]





We only know there's a minimum

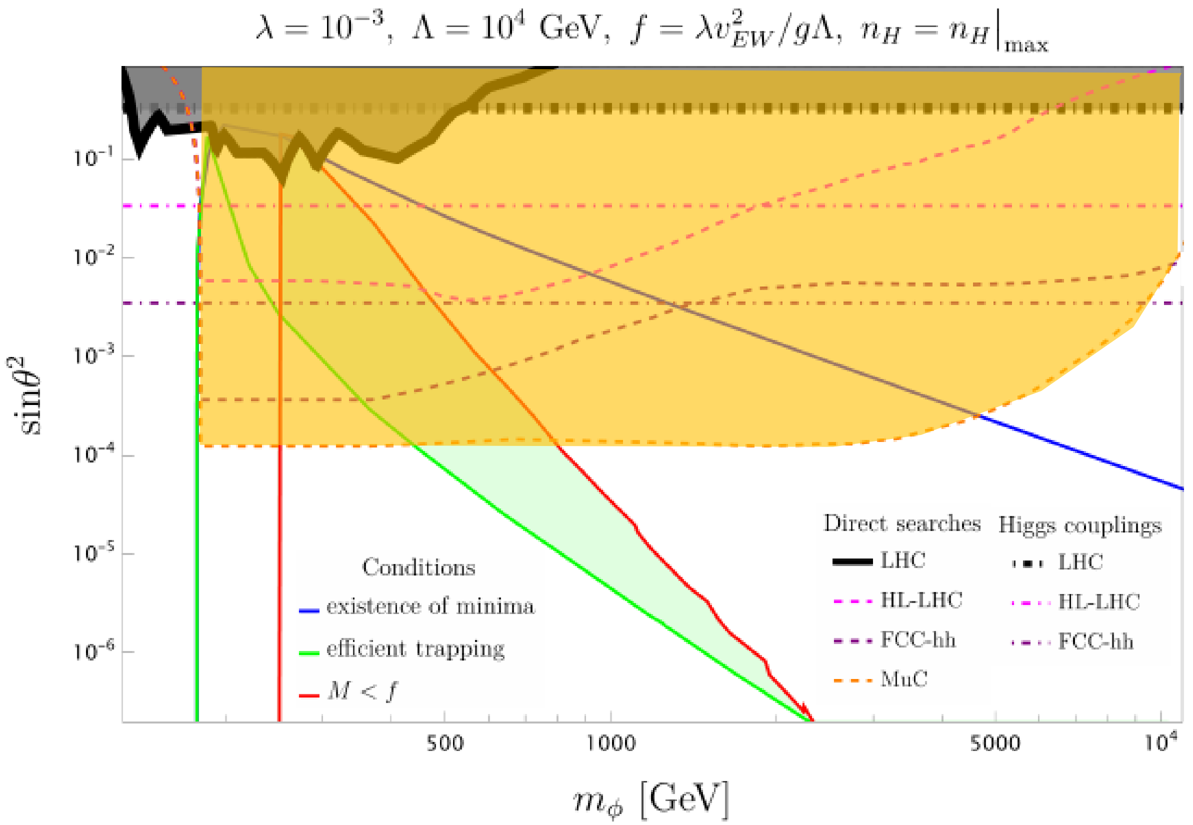


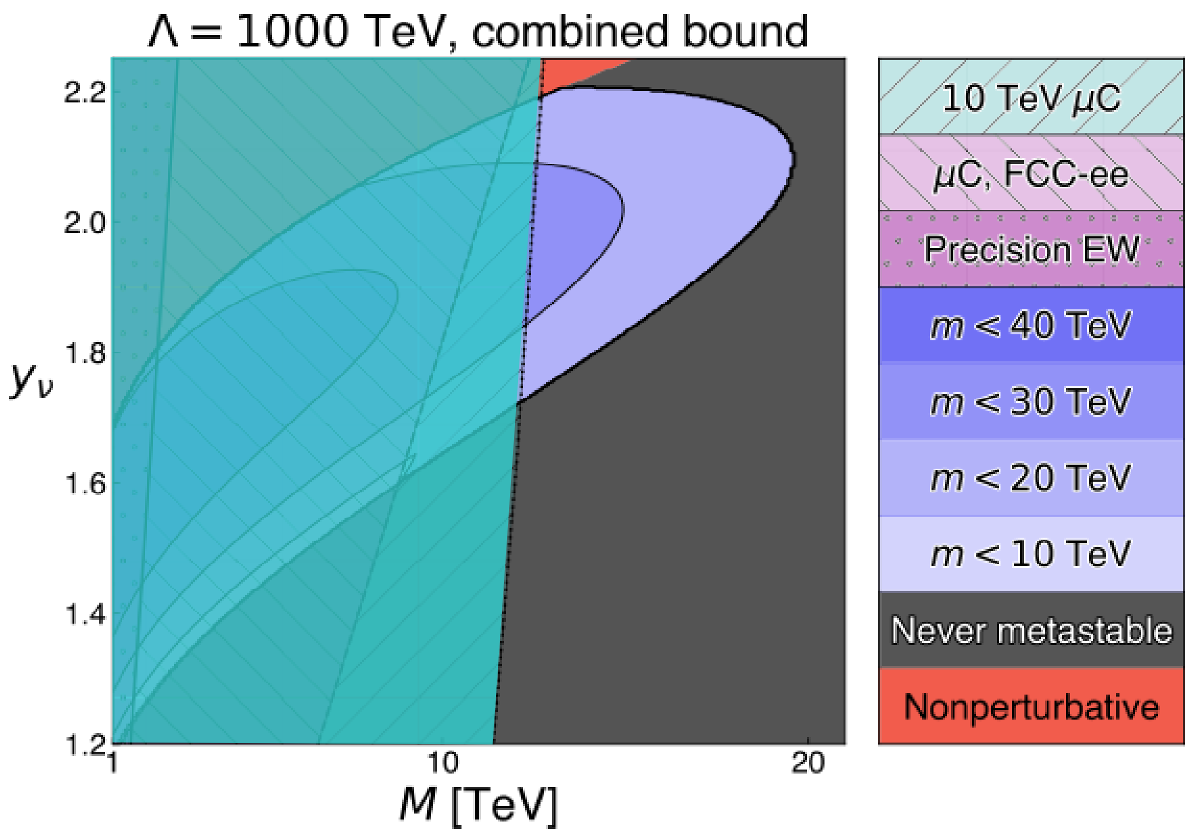
Sokratis Trifinopoulos

The hierarchy problem at the MuC

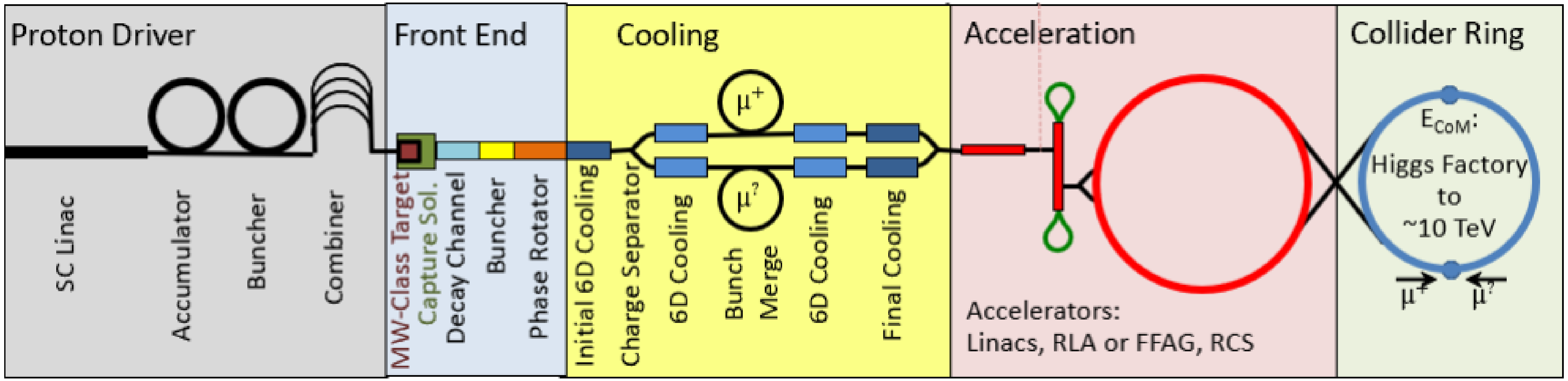
Attracting the Electroweak Scale to a Tachyonic Trap
Trifinopoulos, Vanvlasselaer, 2210.13484

Spontaneous symmetry breaking, gauge hierarchy and electroweak vacuum metastability Benevedes, Steingasser, **Trifinopoulos** 2408.10297





Muon Collider (design)



Produce short, intense proton bunch

Protons in target produce pions which decay into muons muons are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

Collision

Would be easy if the muons did not decay
Lifetime is $\tau = \gamma \times 2.2\ \mu s$

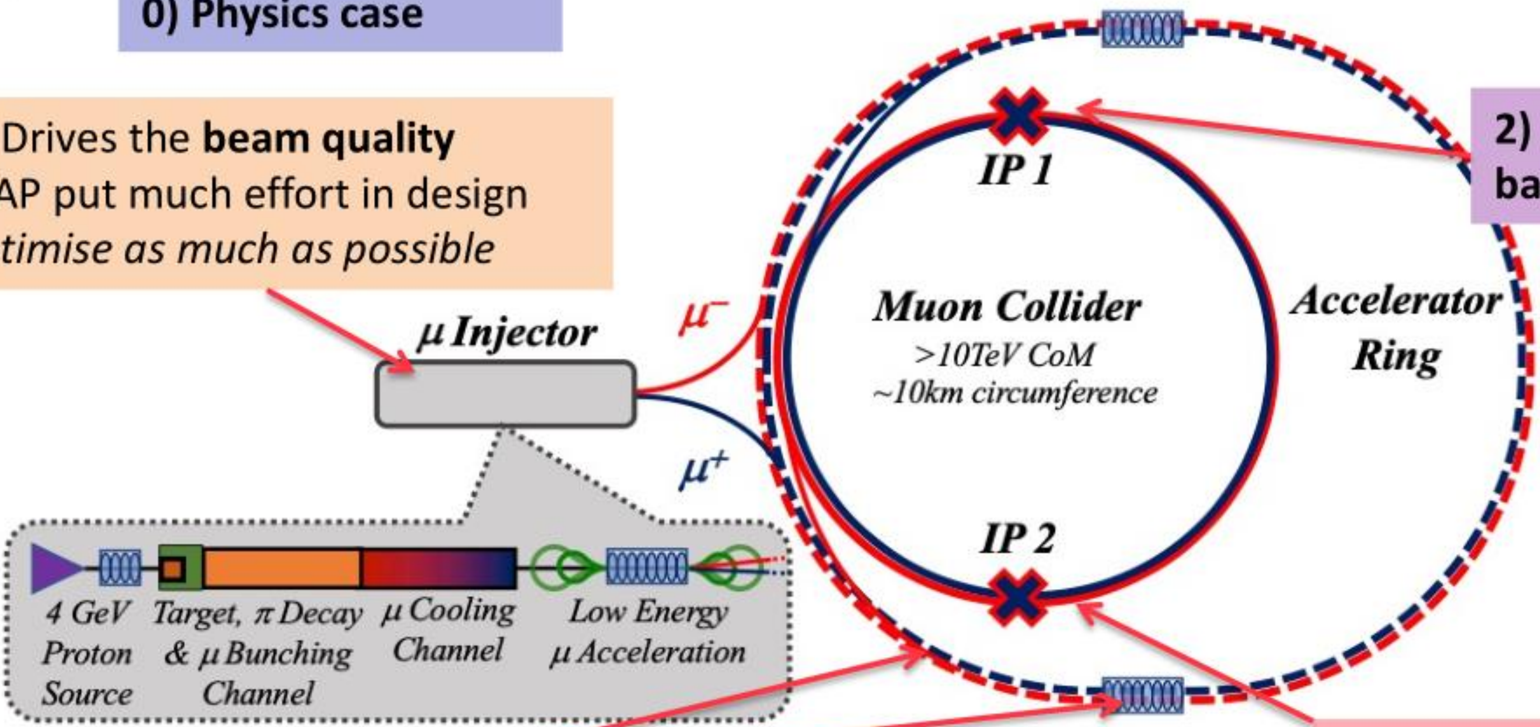
Key Challenges

MuCo

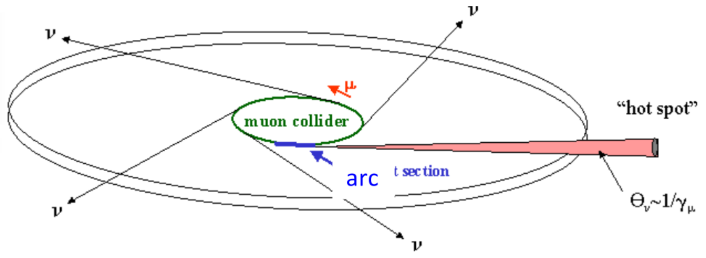
International MUON Collider Collaboration

0) Physics case

4) Drives the **beam quality**
MAP put much effort in design
optimise as much as possible



2) Beam-induced background



3) Cost and **power** consumption limit energy reach
e.g. 35 km accelerator for 10 TeV, 10 km collider ring
Also impacts **beam quality**

1) Dense neutrino flux
mitigated by mover system
and site selection

Luminosity Scaling

- Muon Collider:

$$\mathcal{L} \propto \gamma \langle B \rangle \sigma_\delta \frac{N_0}{\epsilon \epsilon_L} f_r N_0 \gamma$$

High energy

High field in collider ring
= small ring
= many collisions

Large energy acceptance
= short bunch
= small betafunction

Dense beam

High beam power

- MuSIC:

number of particles/beam bunch

bunch frequencies ($f_c^\mu = N_c f_{\text{rep}}$)

$$\mathcal{L}_{\mu p} = \frac{N^\mu N^p}{4\pi \max[\sigma_x^\mu, \sigma_x^p] \max[\sigma_y^\mu, \sigma_y^p]} \min[f_c^\mu, f_c^p]$$

$$\sigma_{x,y}^{\mu,p} = \sqrt{\varepsilon_{x,y}^* \beta_{x,y}^* m^{\mu,p} / E^{\mu,p}}$$

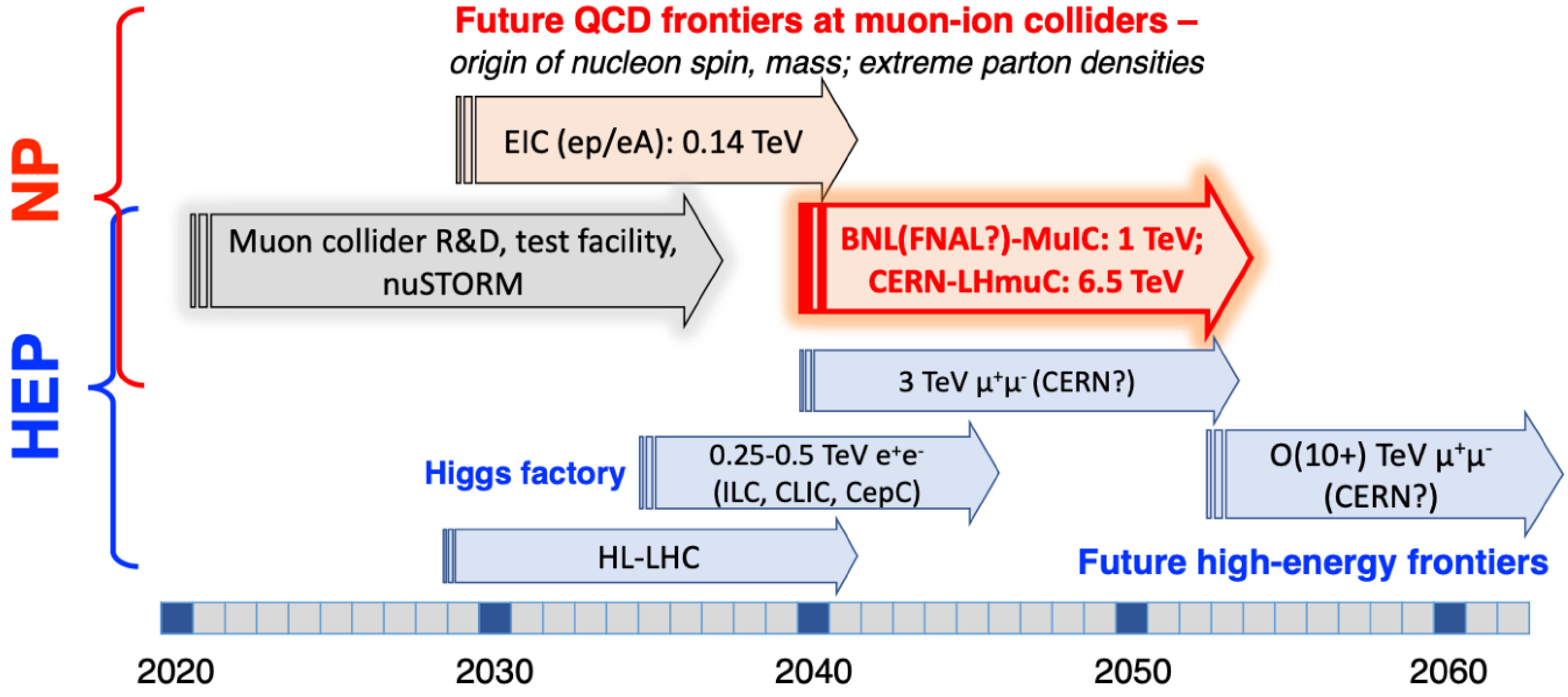
amplitude function

transverse emmitance

[Acosta et al] 2203.06258]
[Kaya et al] 1905.05564

A possible roadmap to future MuC

[Acosta et al] 2203.06258]

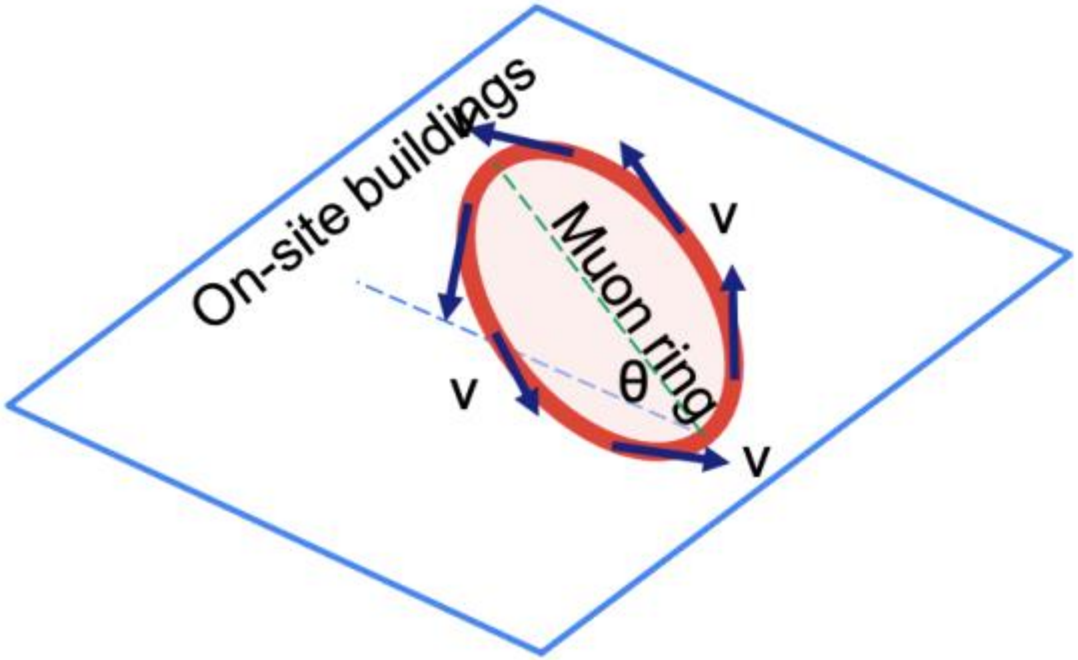


Detector Performance

[Acosta et al] 2203.06258]

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

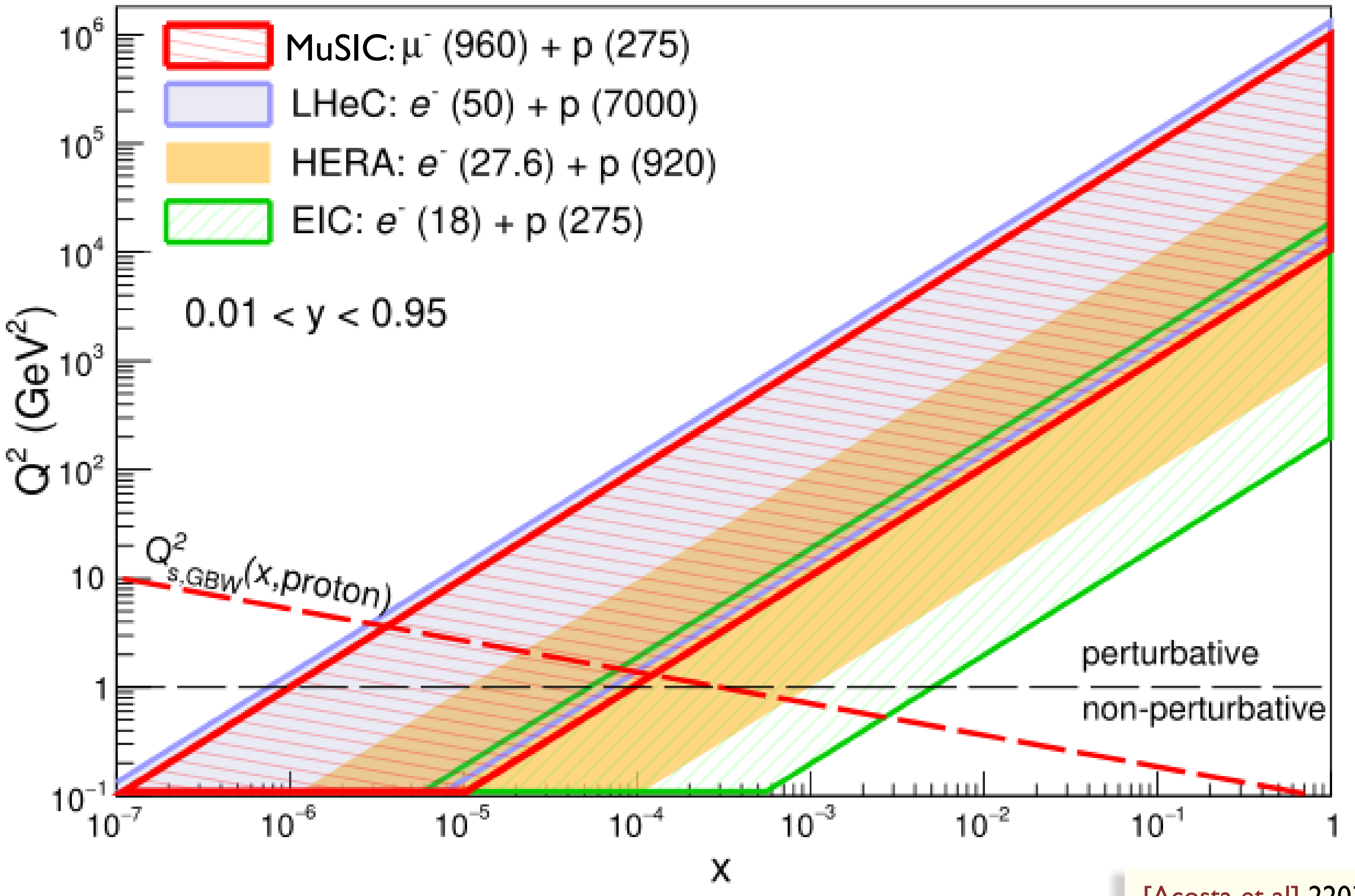
Neutrino Radiation



By tilting the muon by a small angle, e.g., $\theta \lesssim 1^\circ$, it would be sufficient to direct most of neutrinos toward the air in one direction and toward the ground and sea in the other direction for a given straight section, with little impact on buildings nearby.

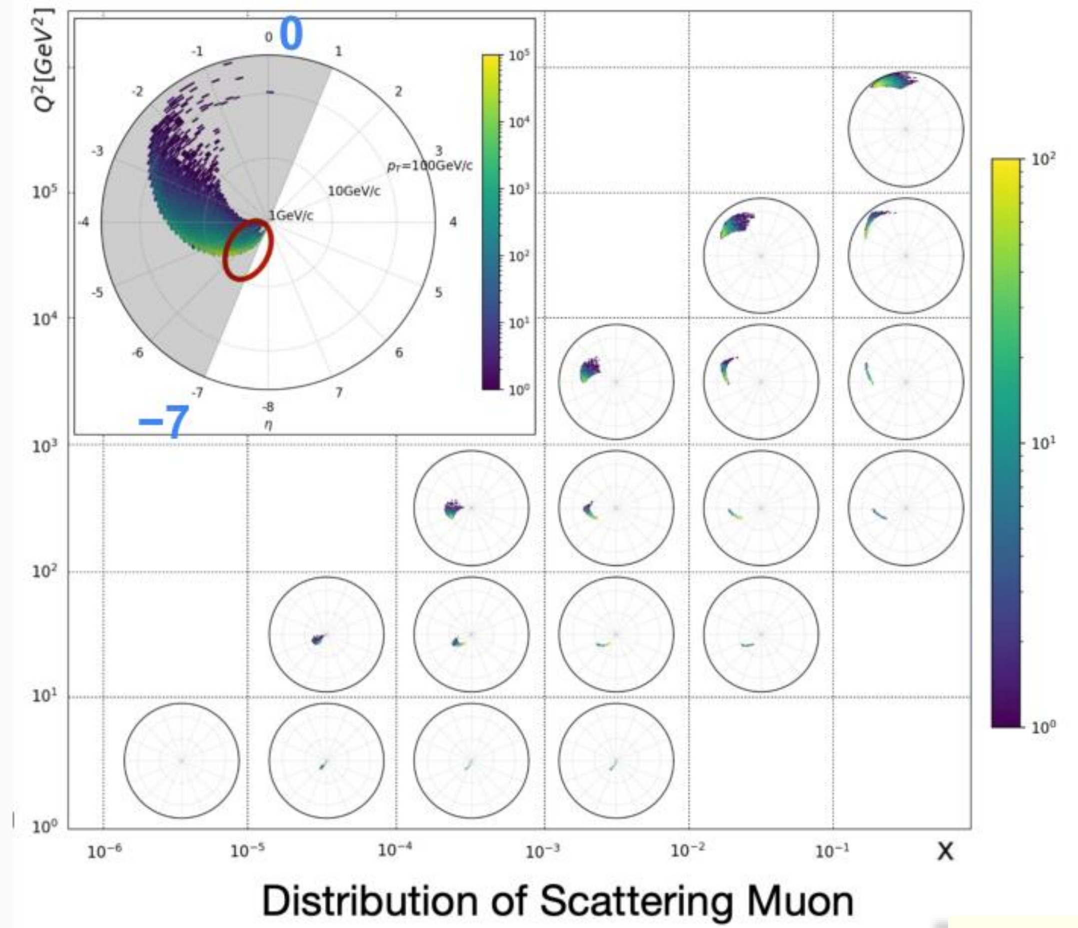
[Acosta et al] 2203.06258]

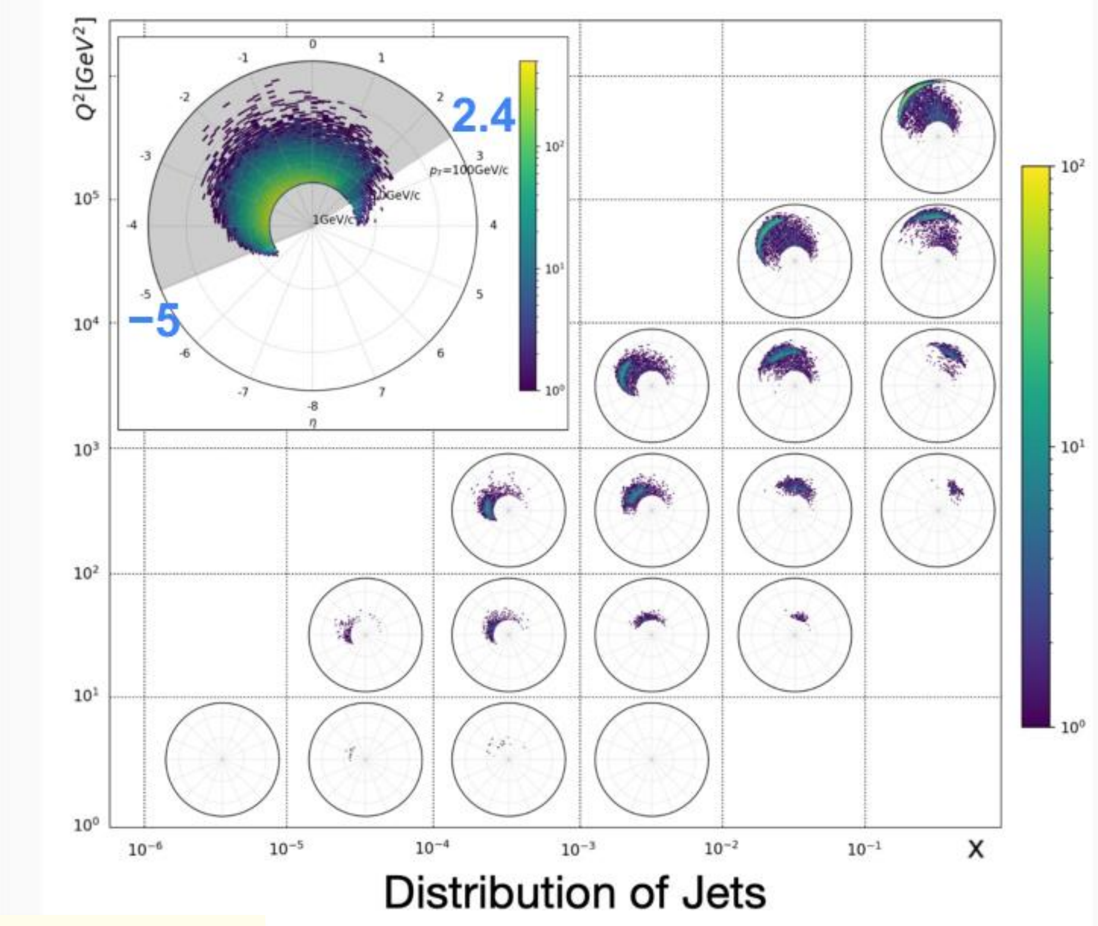
Kinematical coverage in DIS



[Acosta et al] 2203.06258]

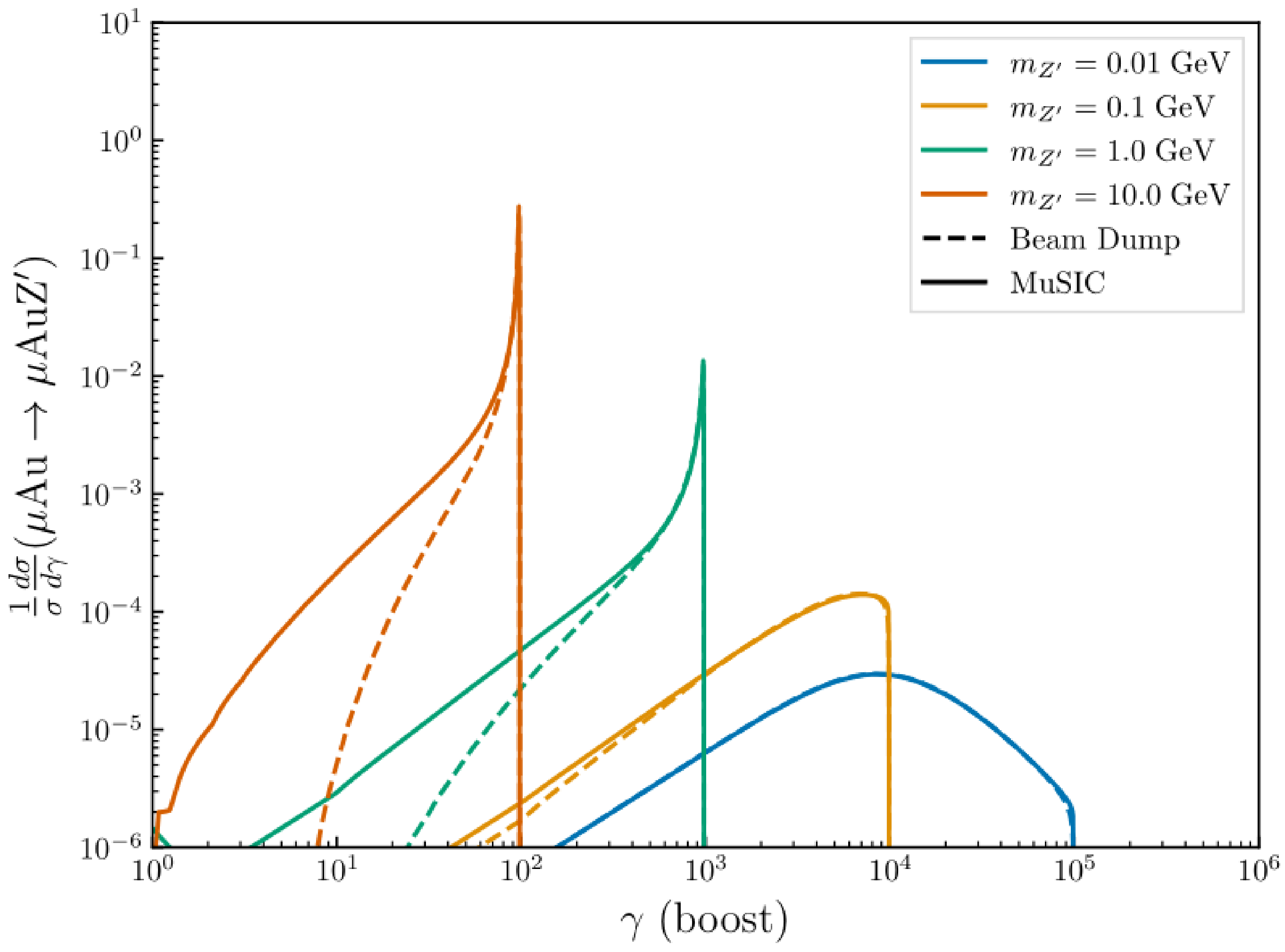
Kinematic distributions in MuSIC





[Acosta et al] 2203.06258]

Z' vector boson boost factors



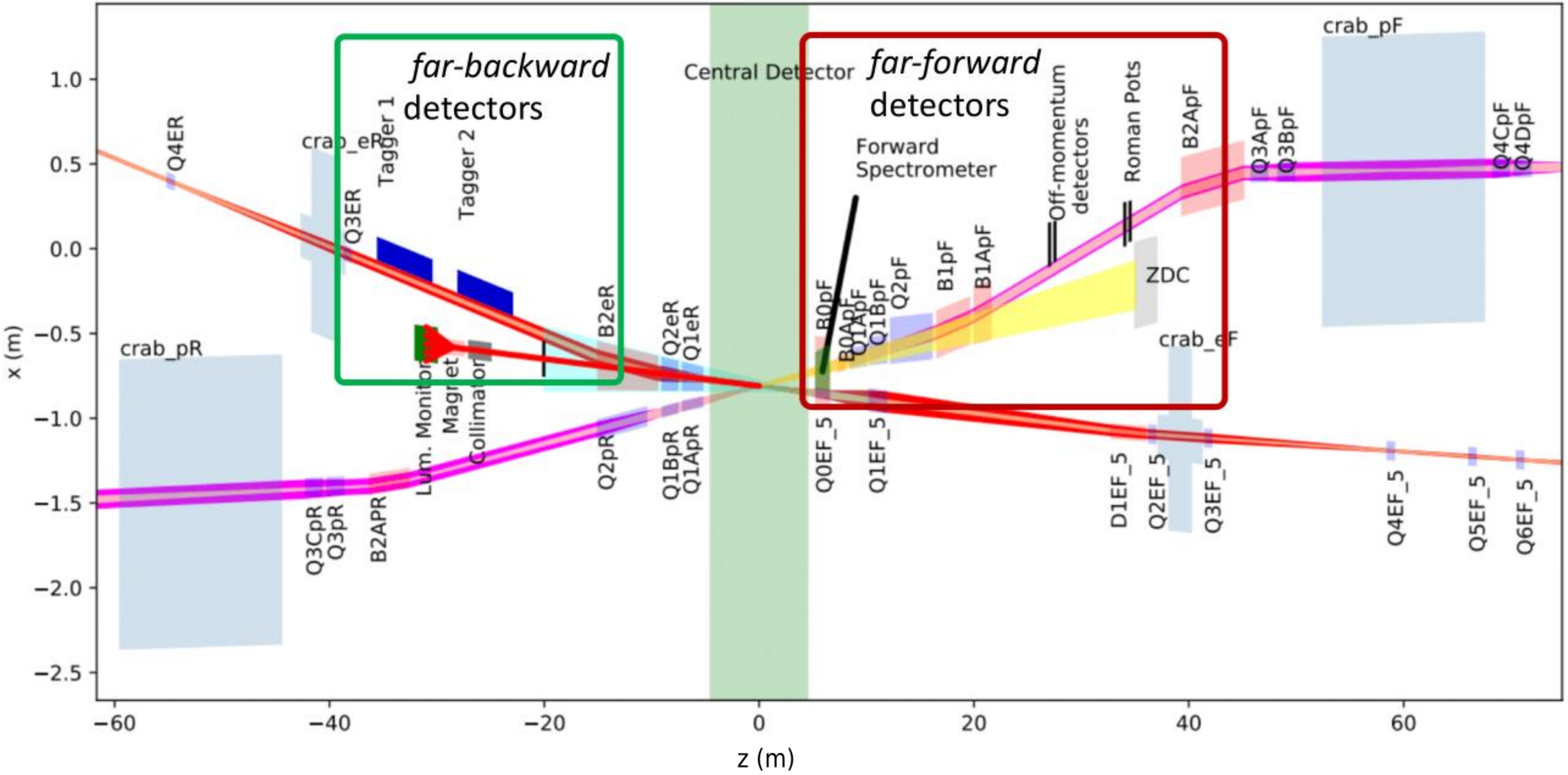
BSM Phenomenology at EIC?

- The EIC is a **very powerful machine**. Can we use it for BSM physics?

1. Axion-like particles (**ALPs**) with couplings to the photons.
   [Balkin et al] 2310.08827 [Liu, Yan] 2112.02477
2. Lepton-Flavour-Violating ALPs
   [Davoudiasl, Marcarelli, Neil] 2112.04513 2402.17821 [Cirigliano et al] 2102.06176
3. Light Leptoquarks
   [Gonderinger, Ramsey-Musolf] 1006.5063 [Zhang et al] 2207.10261
4. Heavy Neutral Leptons
   [Battel, Ghosh, Han, Xie] 2210.09287
5. Light vector bosons with displaced vertices
   [Davoudiasl, Marcarelli, Neil] 2307.00102
6. Heavy Gravitons
   [Hatta] 2311.14470

we: ALPs coupling to gluons!

EIC Interaction Region Layout



Far-forward detector