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

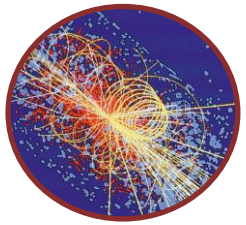
Sokratis Trifinopoulos

Empowering the New Vision in High Energy Physics

Aspen, 03/04/2025

Fans of Muons beyond HEP?

A multi-billion dollar Muon program requires a stable US government with **(partially)** steady HEP Budget



Outline

I. Muon Collider

II. MuSIC

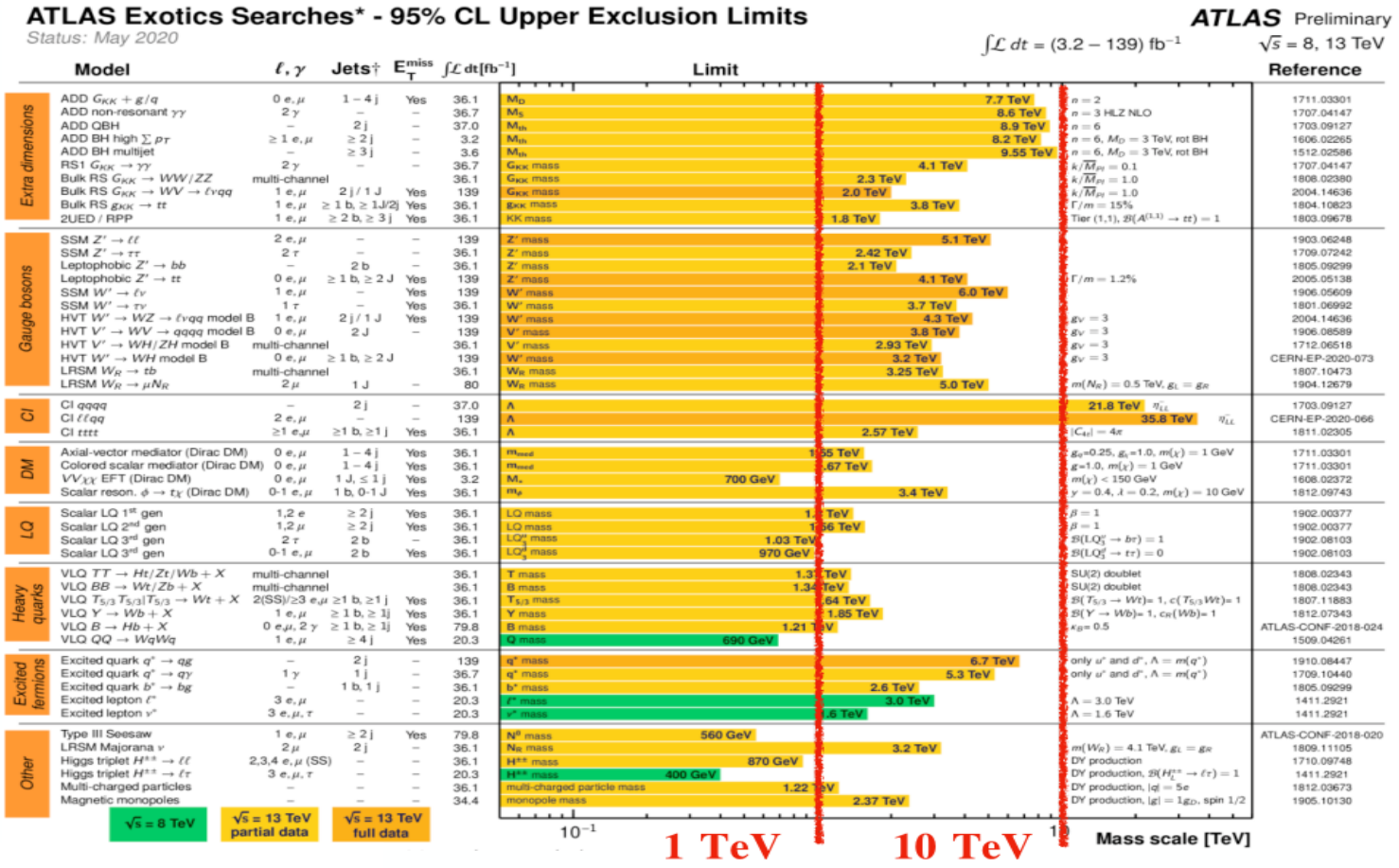
III. BSM at MuSIC

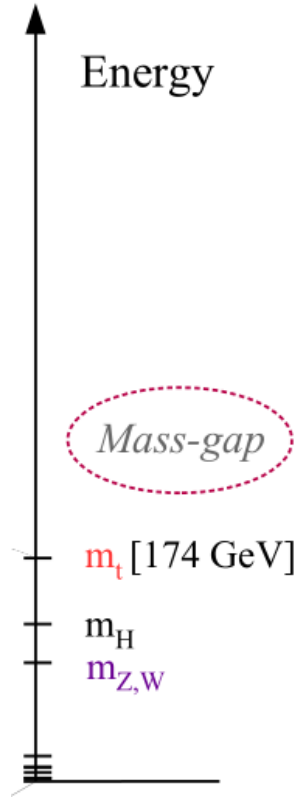
LHC: the past and the future

- 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

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

Still no direct evidence for New Physics!





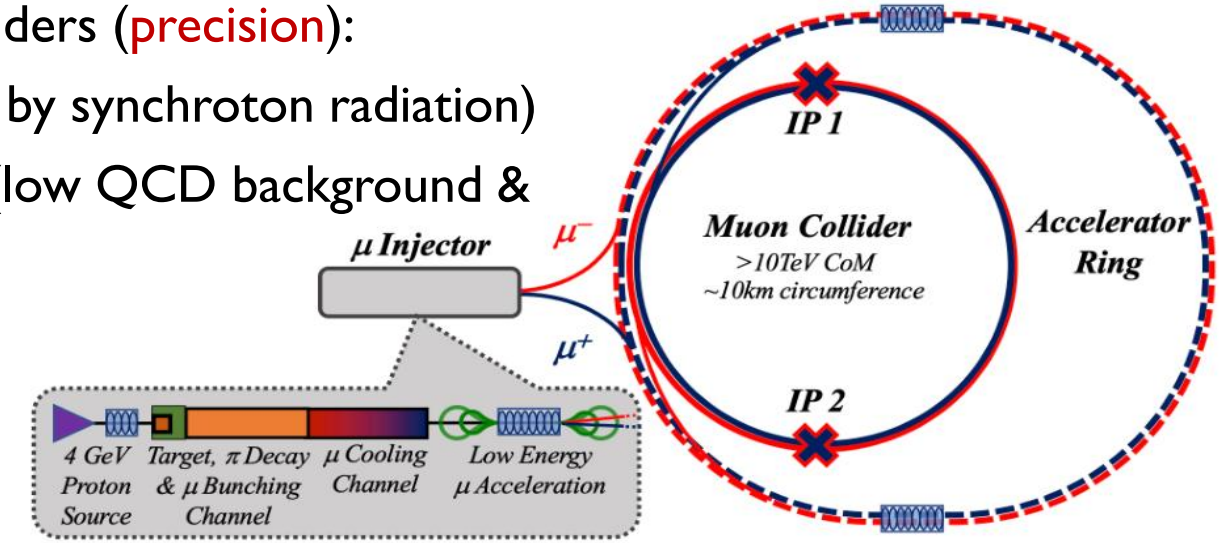
The Flight Towards High Energies

Multi-TeV Muon Collider

see Tao's talk

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

Exploring the Quantum Universe

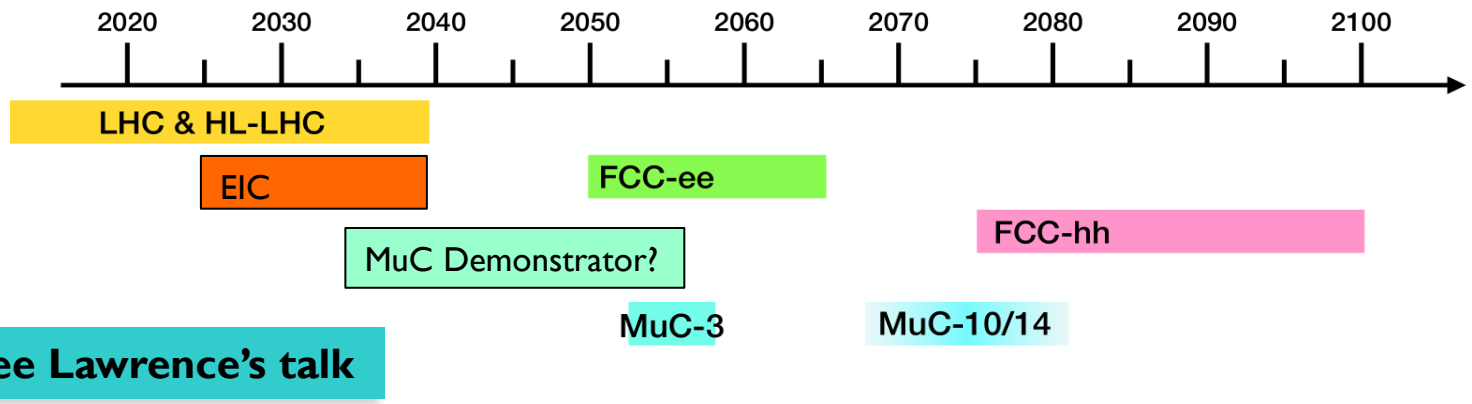
2.3 The Path to a 10 TeV pCM

[P5 Report]

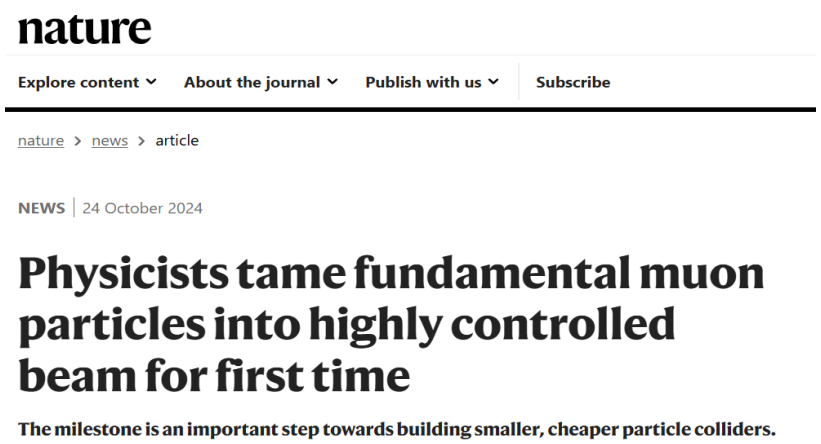
...

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



see Lawrence's talk



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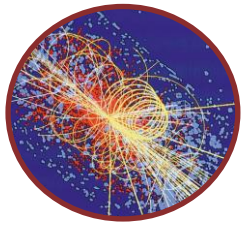
NEWS | 24 October 2024

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



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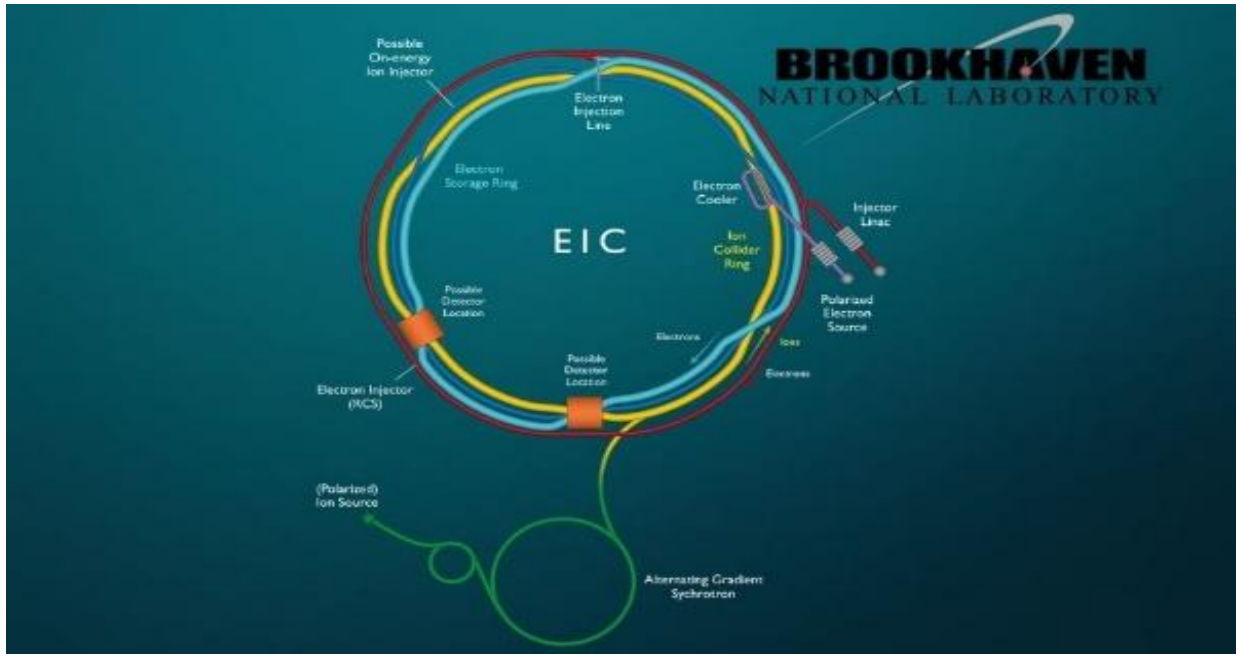
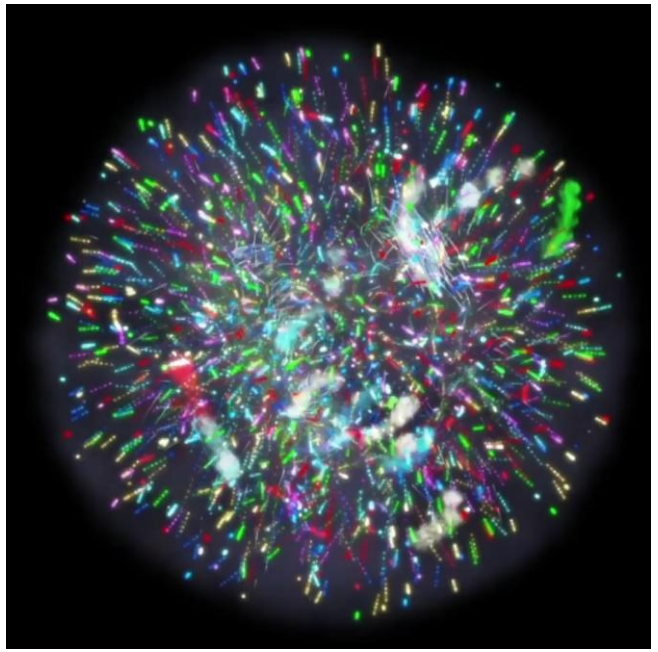
Electron-Ion Collider (EIC)





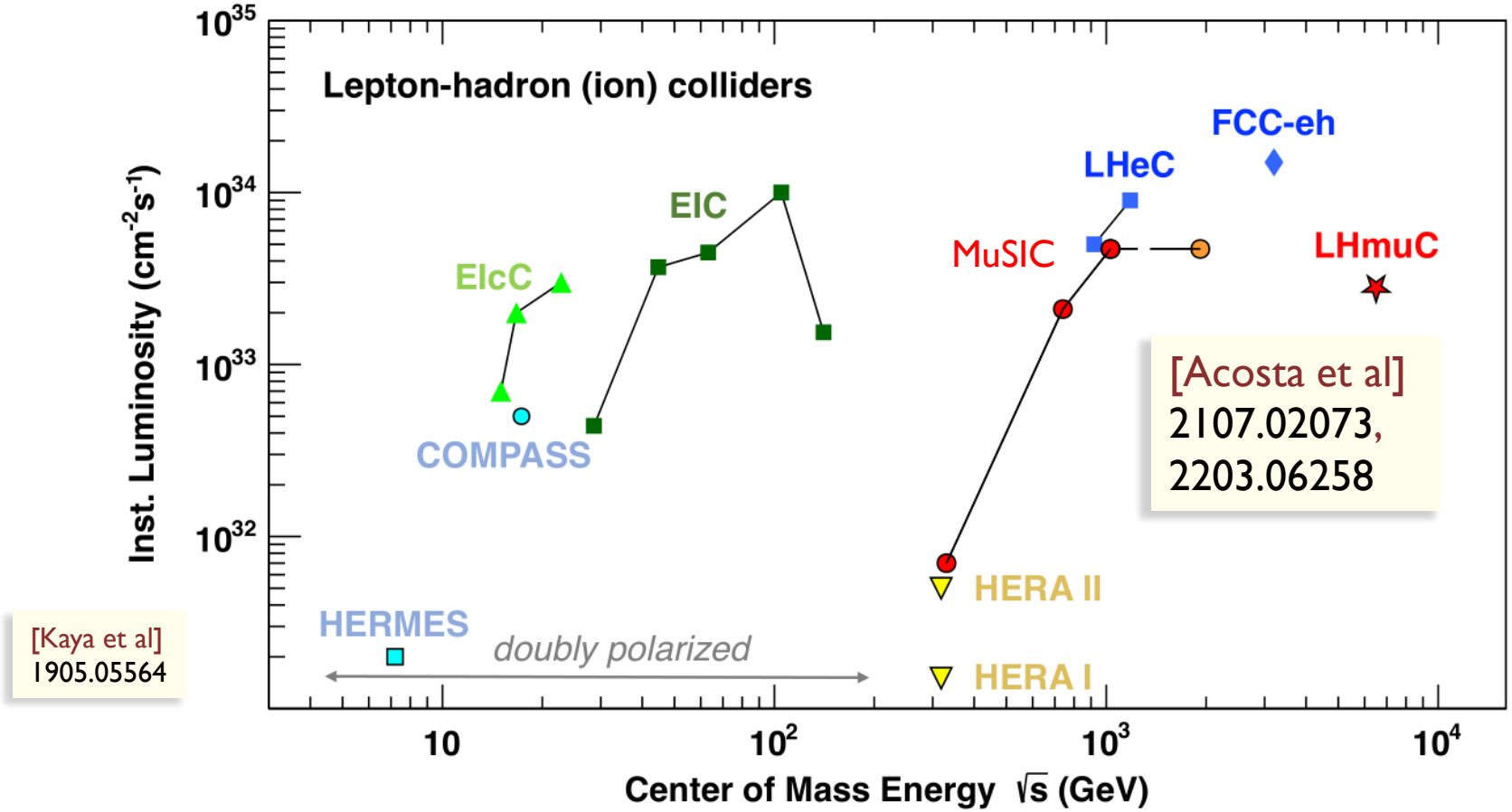
MIT/Jefferson Lab/Sputnik Animation

- Scientific purpose: study the properties of nuclear matter, e.g.3D structure of protons and nuclei, origin of nucleon mass and spin, search for the CGC, nuclear PDFs etc.
- But, also a rich **BSM program**, see:

[Balkin et al] 2310.08827 [Liu,Yan] 2112.02477 [Davoudiasl, Marcarelli, Neil] 2112.04513, 2307.00102, 2402.17821 [Cirigliano et al] 2102.06176 [Gonderinger, Ramsey-Musolf] 1006.5063 [Zhang et al] 2207.10261 [Battel et al] 2210.09287

The next generation lepton-ion colliders

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



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 ≈ 50% $\sqrt{s}$ MuC
- There could be a staged development:

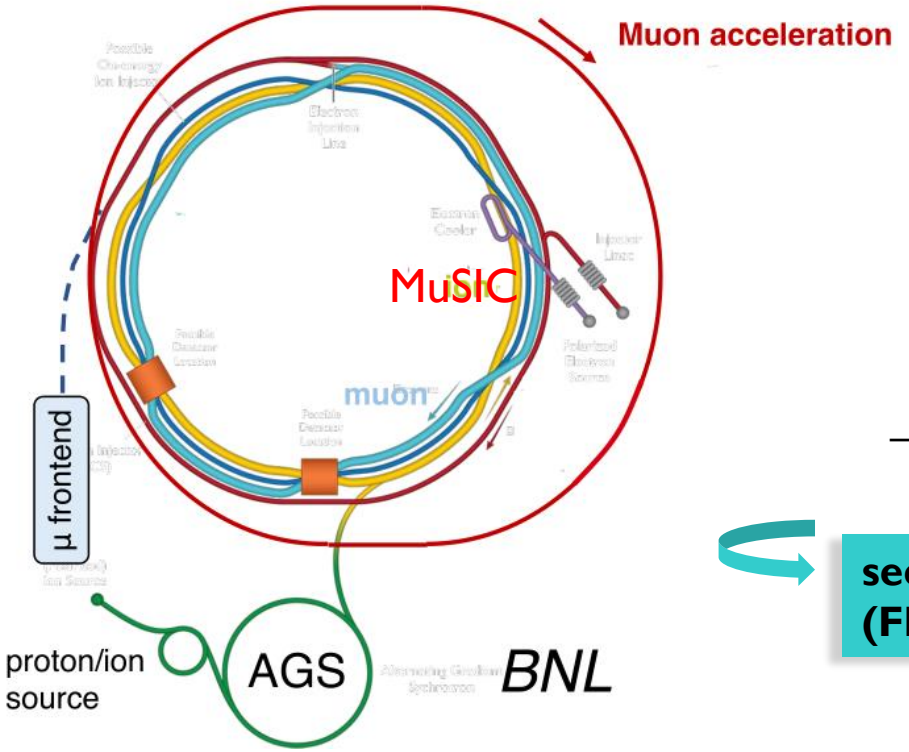
E_p (TeV)	0.275			0.96
E_μ (TeV)	0.1	0.5	0.96	0.96
$\sqrt{s_{\mu p}}$ (TeV)	0.33	0.74	1.0	1.92
L_{int} ($\times 10^{33}$ cm^{-2}s^{-1})	0.07	2.1	4.7	4.7

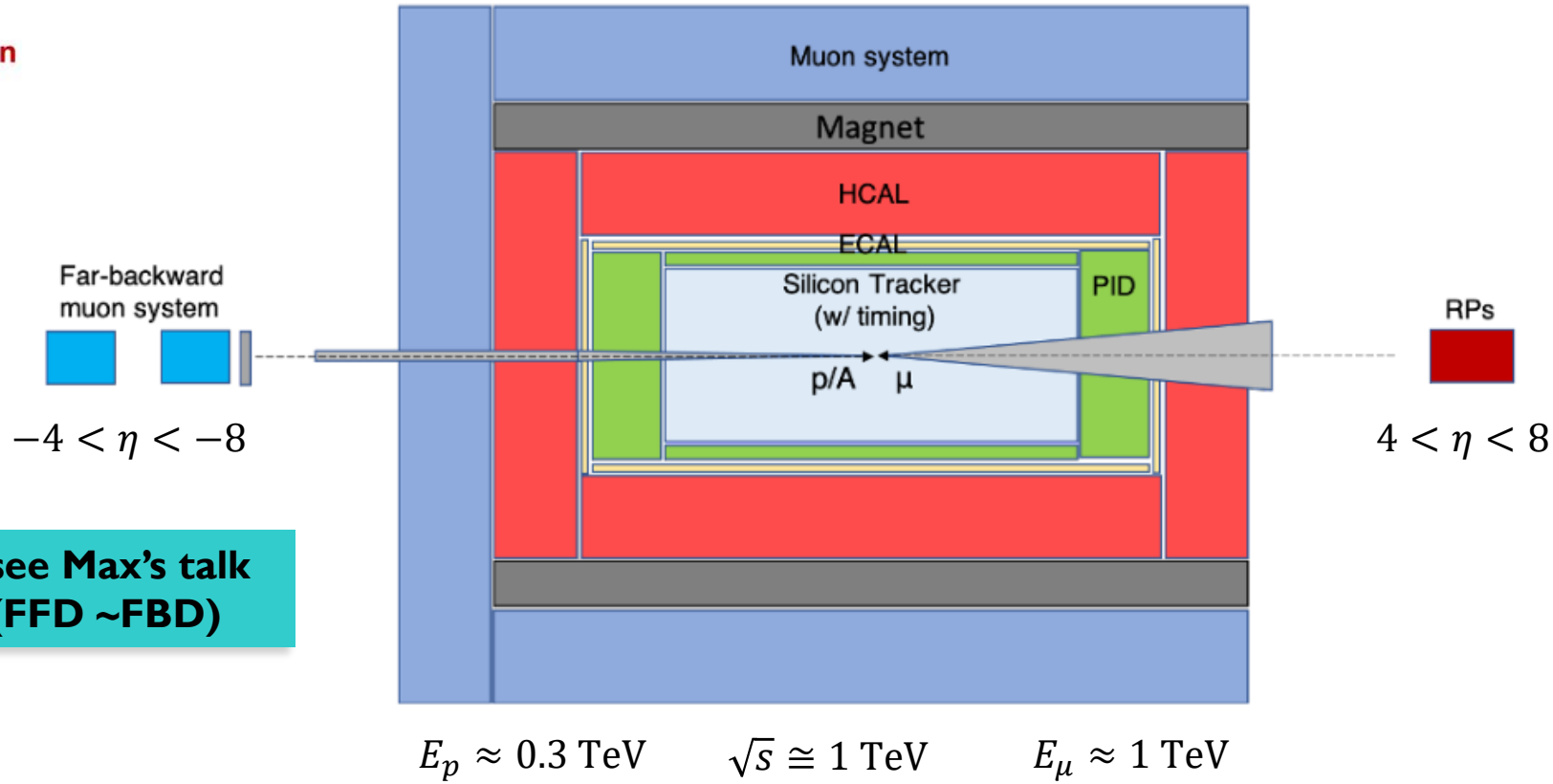
our benchmark

MUSIC copyrights: Settled out of court!
https://indico.cern.ch › detector_10tev_imcc_II

Detector Design Considerations

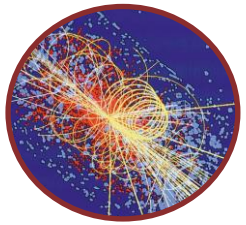
[Acosta et al] 2203.06258]





see Max's talk (FFD ~FBD)

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



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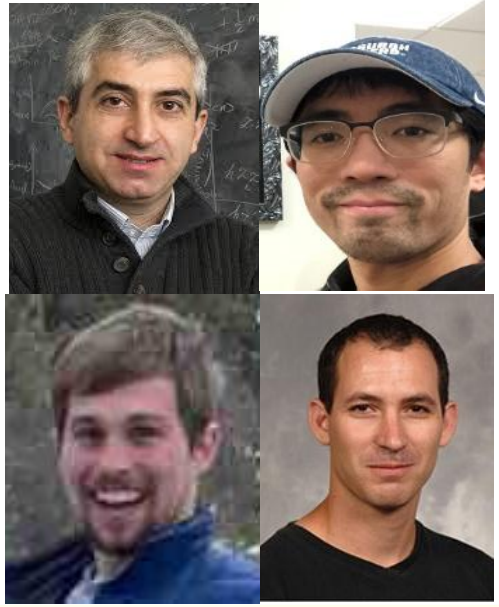


Davoudiasl, Liu, Marcarelli, Soreq, Trifinopoulos] 2412.13289

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.

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

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

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

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

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

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

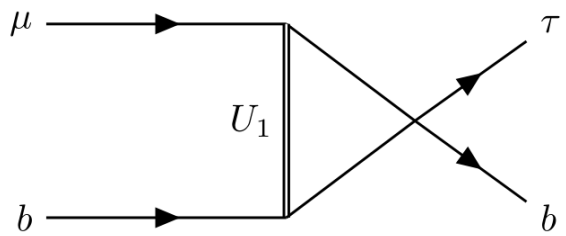
[Agrawal, Howe] 1710.04213 [Fitzpatrick et al] 2306.03128 [Takahashi, Yin] 2105.10493

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

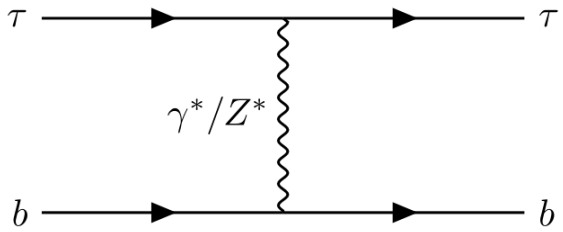
$$\mathcal{L}_{\text{dipole}}^{(5)} \supset \frac{1}{2} \mu_\nu \bar{\nu} F_{\mu\nu} \sigma^{\mu\nu} N \,, \qquad (\mu_\nu \sim v_{\text{EW}}/\Lambda^2)$$

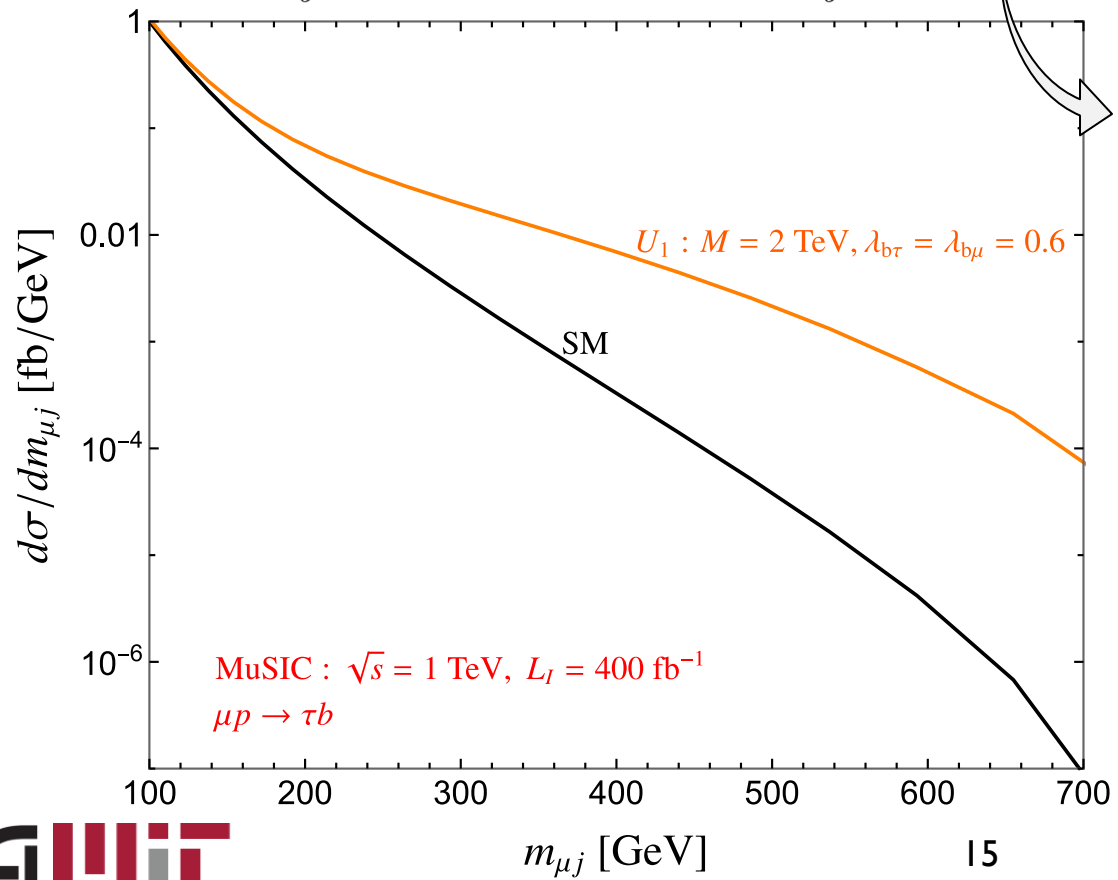
LFV leptoquark interactions: prompt search

Signal:



Background:



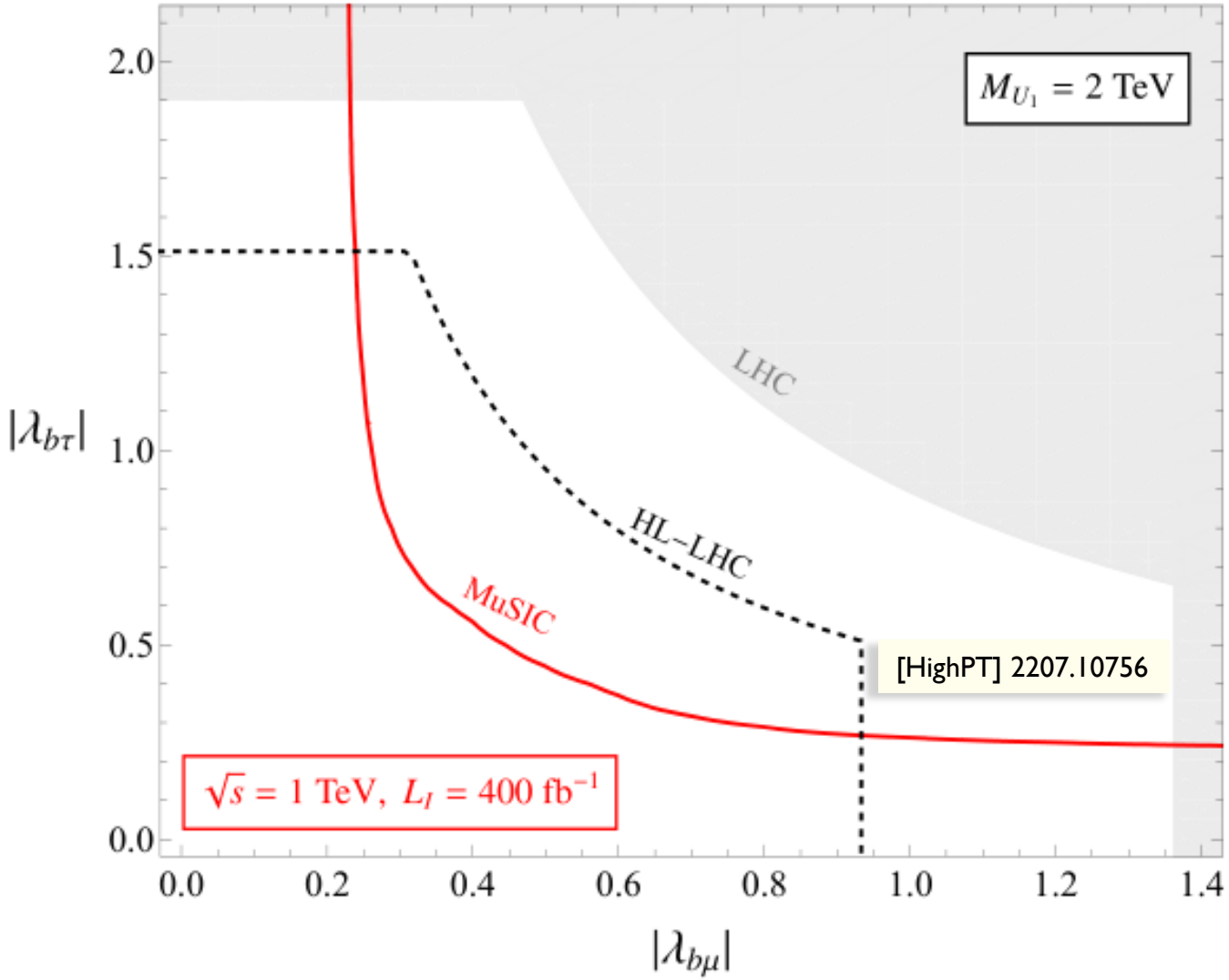


τ content of the muon beam → LePDF

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

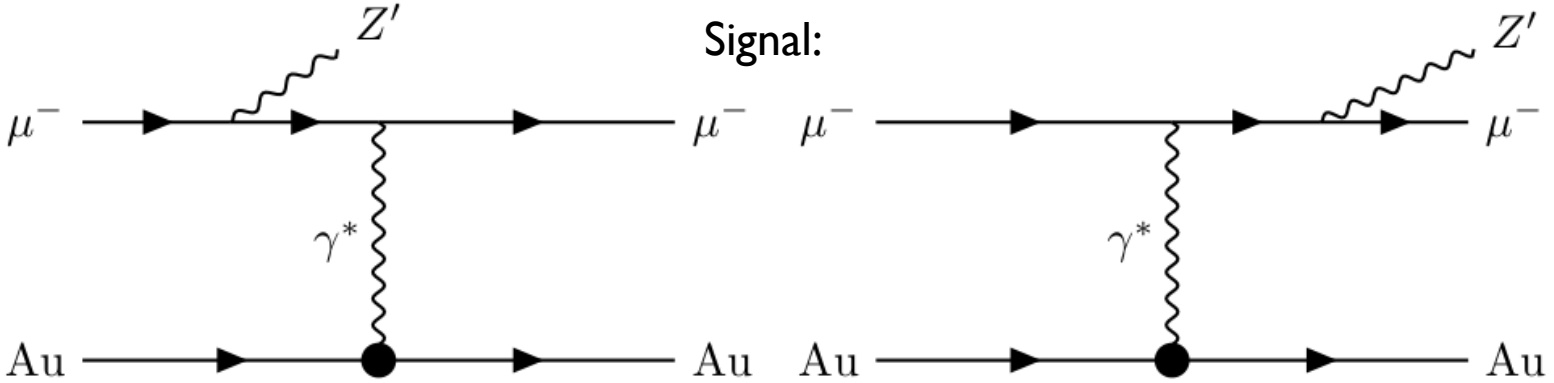
- We convolute the PDFs with the differential cross sections and integrate within the central detector rapidity coverage $|\eta| < 3.5$.
- **Acceptance efficiencies**: *b*-tagging 80% , τ-hadronic decays 75% [ATLAS] 2108.07665, 2305.15962

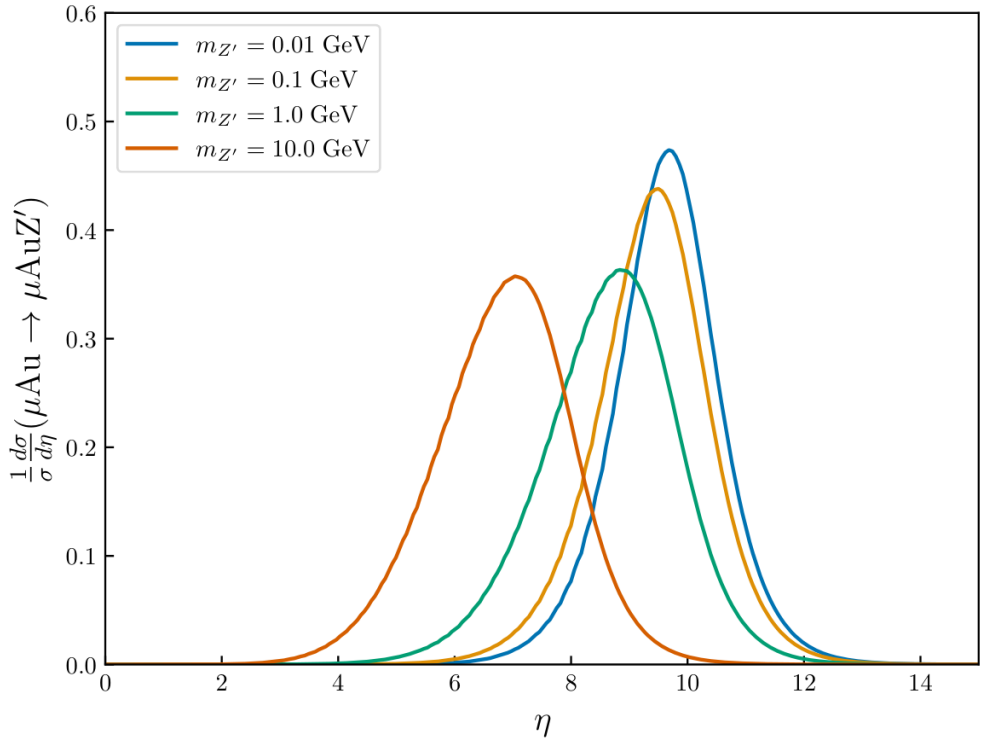
LFV leptoquark reach: MuSIC vs HL-LHC



Z' vector boson: displaced vertices

Signal:





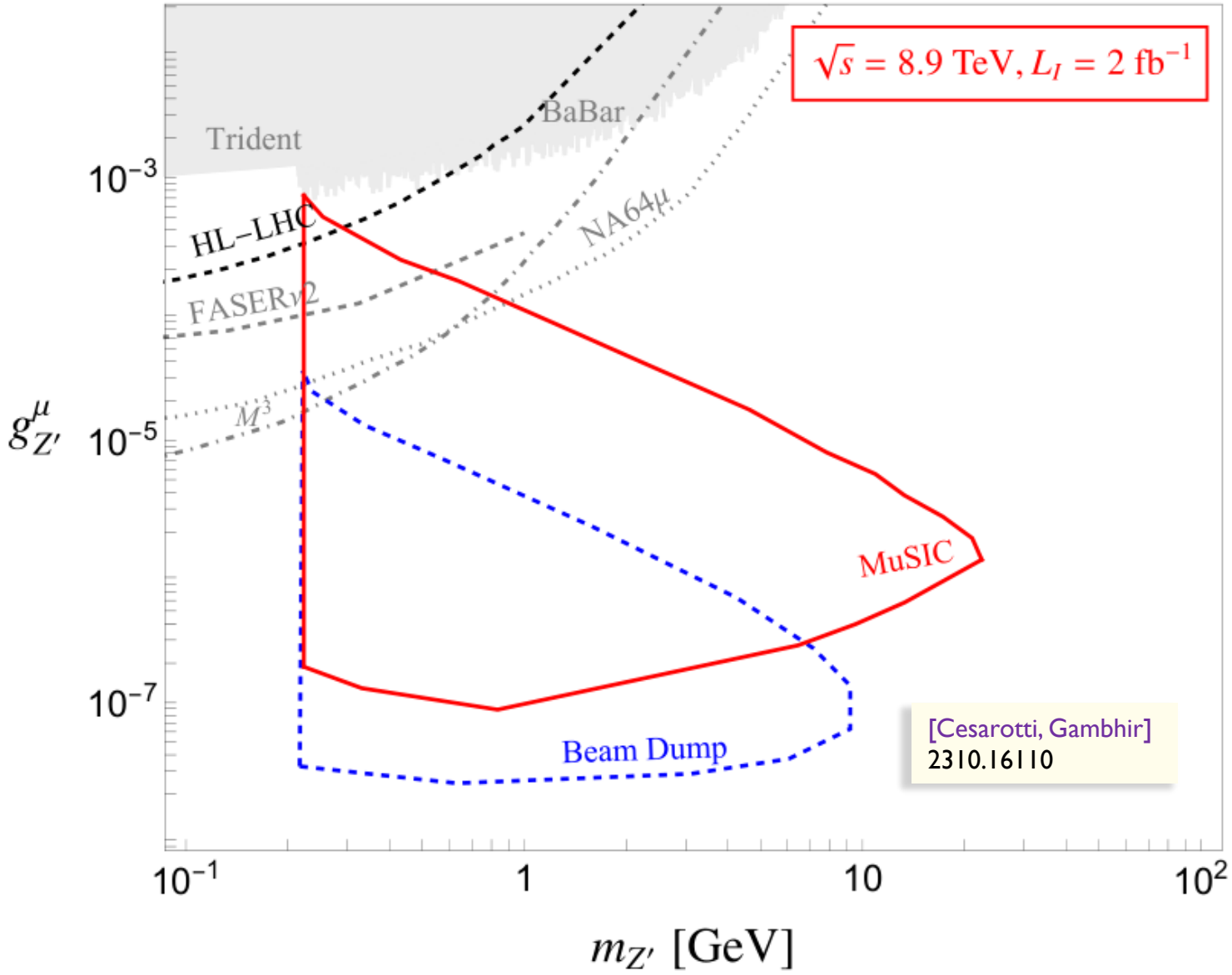
- The cross-section in coherent scattering is Z^2-enhanced.
- The large ion-frame muon energy of $O(100\,\mathrm{TeV})$ leads to highly-boosted Z' in the far-backward direction.
- After traveling some distance ℓ it decays to di-muons with probability:

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

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

- To find the expected number of events, we integrate $P(\ell)$ from $\ell_{\min} = 1\mathrm{mm}$ (veto prompt backgrounds) to $\ell_{\max} = 30\mathrm{m}$ (far-backward muon spectrometer).

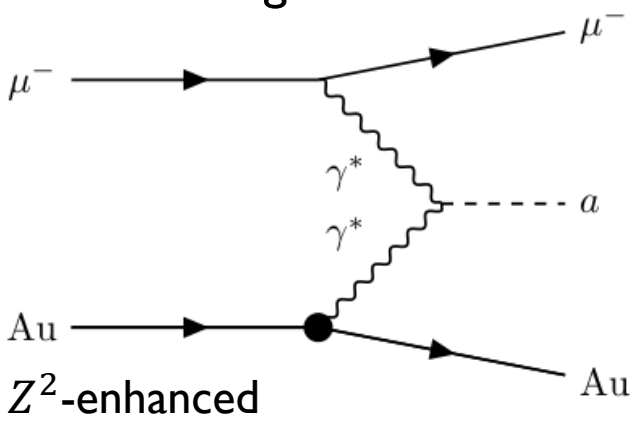
Z' vector boson: MuSIC vs Muon Beam Dumps



[Cesarotti, Gambhir]
2310.16110

Axion-like particles: prompt & displaced

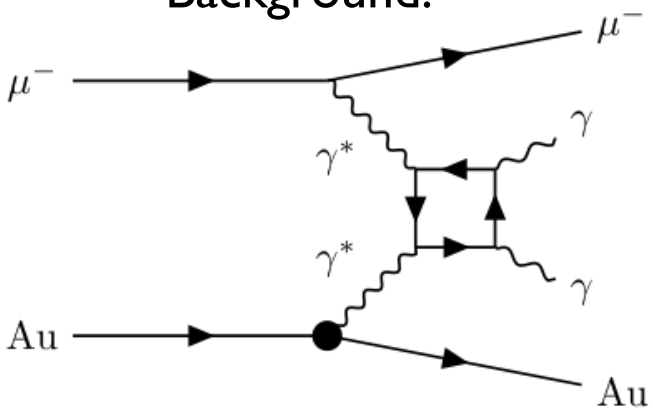
Signal:



Z^2-enhanced coherent scattering

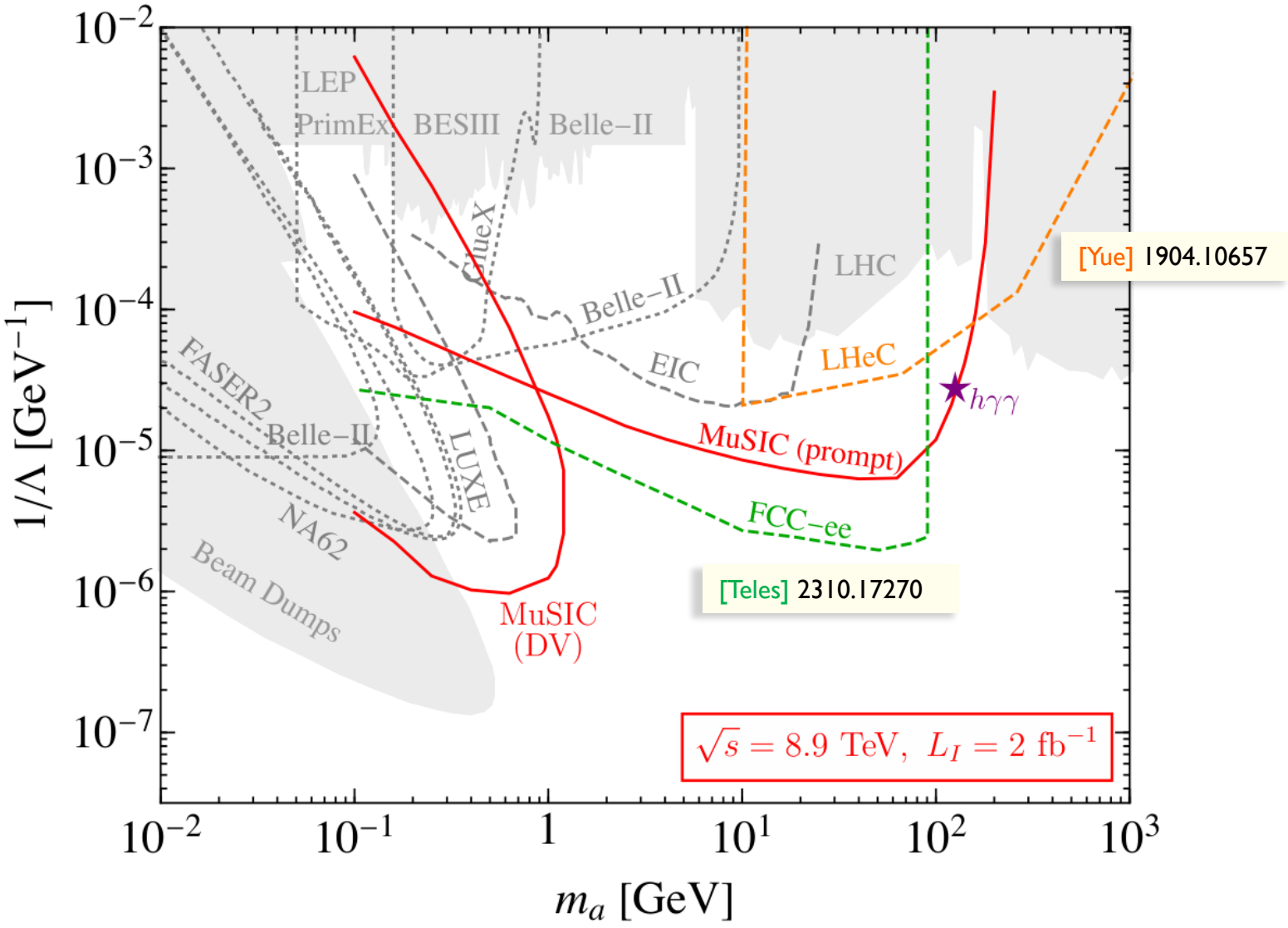
[Balkin, Hen, Liu, Ma, Soreq Williams] 2310.08827
[Balkin, Liu,, Soreq, Ta'el, **Trifinopoulos**] 2310.08827

Background:



- The signal is clean: 2γ + recoil μ^- + intact Au.
- **Prompt**: We perform a resonance search in the invariant mass of two photons.
- **Displaced**: Still occurring within the central region ($10\text{cm} < \ell < 1\text{m}$).
- Unique opportunity to probe also Higgs coherent production via: $\mathcal{L}_h^{\text{int}} = -\frac{h}{4\Lambda_{h\gamma\gamma}} F^{\mu\nu} F_{\mu\nu}$

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

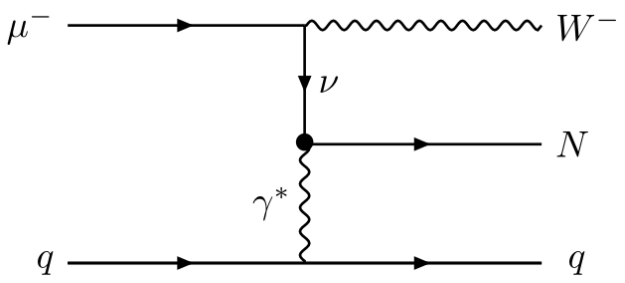


[Yue] 1904.10657

[Teles] 2310.17270

ν_μ magnetic moments: prompt search

Signal:



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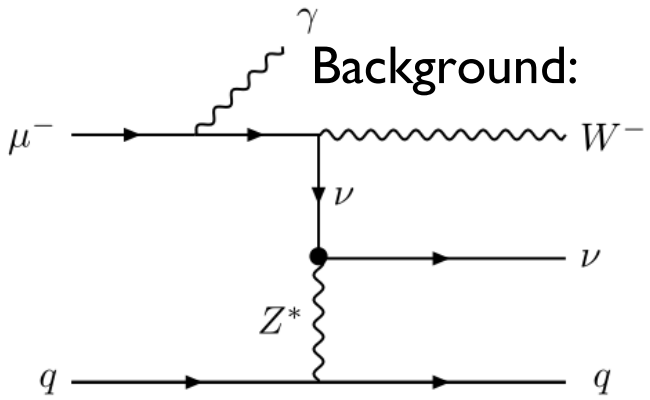
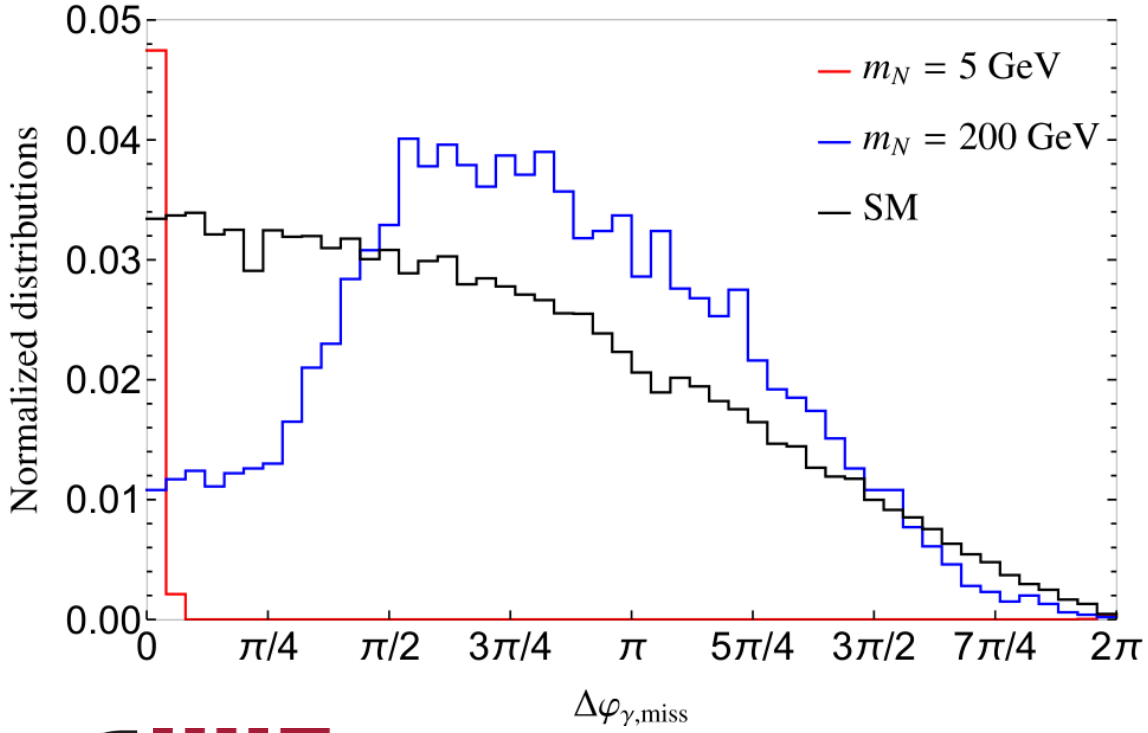
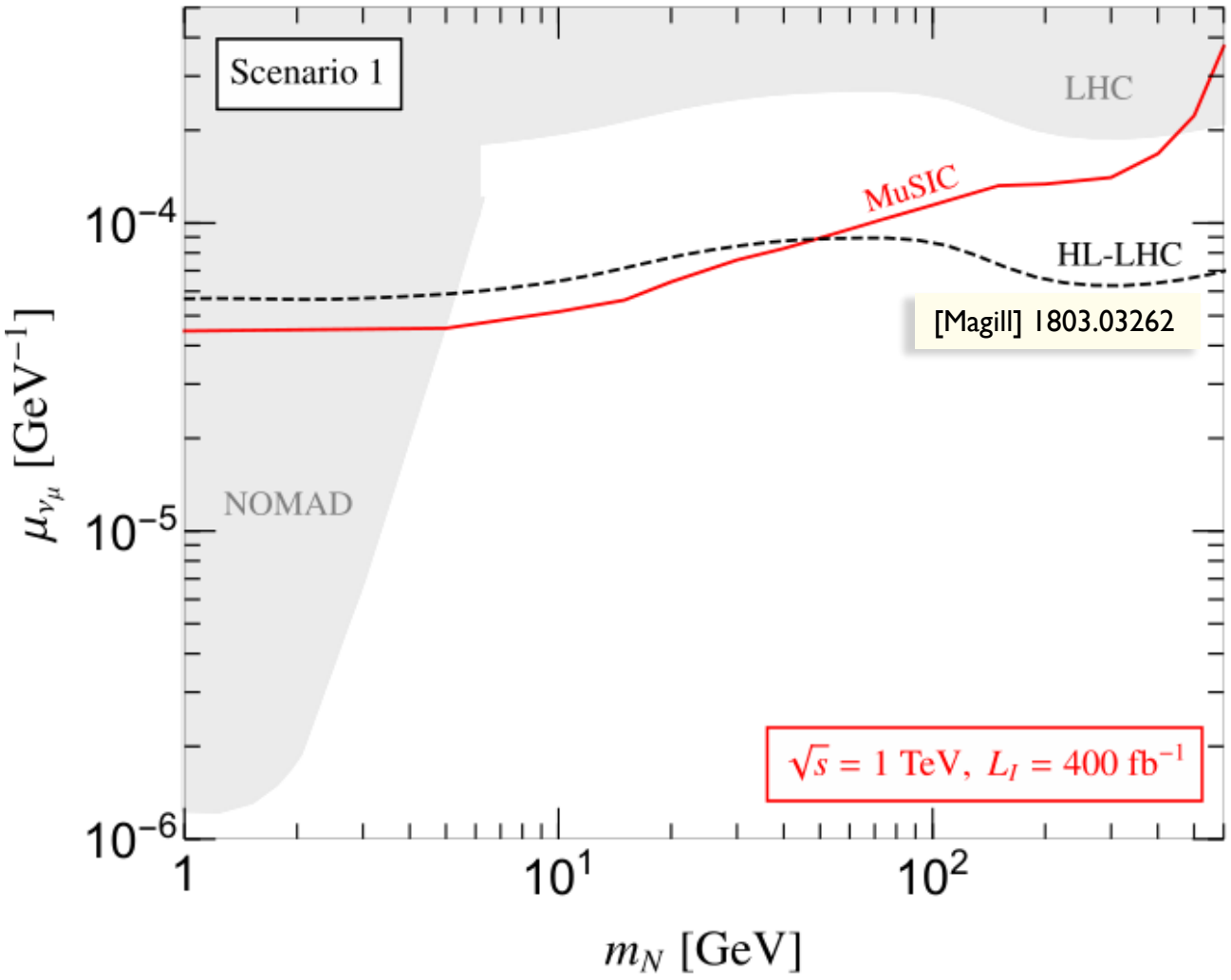




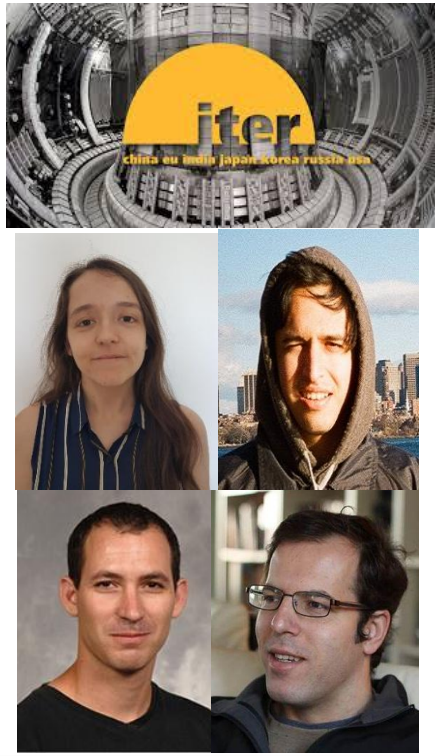
- The HSN is produced via *up-scattering* of SM neutrinos via the dipole operator.
- The HSN subsequently decays to **neutrino+photon**. The missing energy is either collimated or back-to-back with the photon.
- We veto additional neutrinos to suppress the $\nu + \gamma + 3j$ background.

Heavy Sterile Neutrinos: MuSIC vs HL-LHC

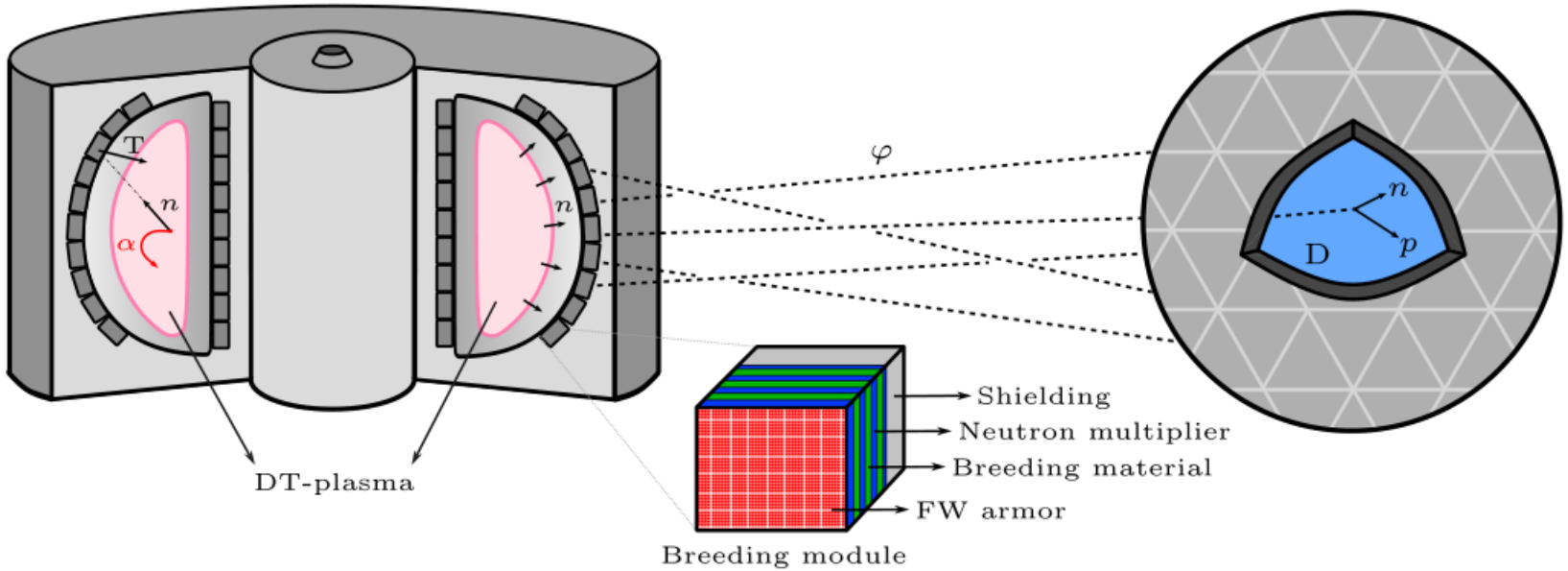


NP Searches beyond Colliders

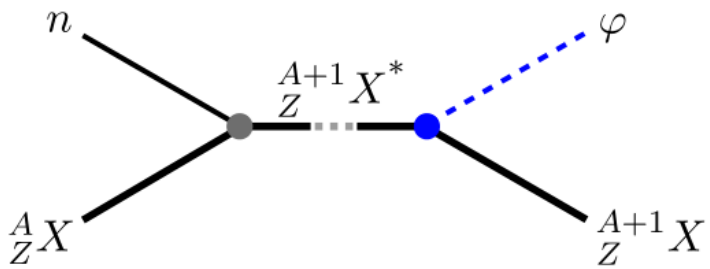
- We can use **Nuclear Fusion** (e.g. ITER) facilities to explore motivated light NP scenaria!



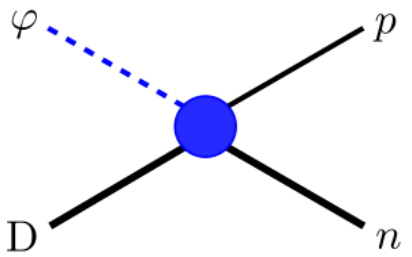
[Baruch, Fitzpatrick, Menzo, Soreq, **Trifinopoulos**, Zupan] 2502.12314



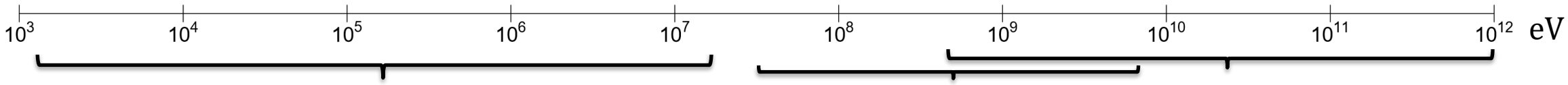
Production

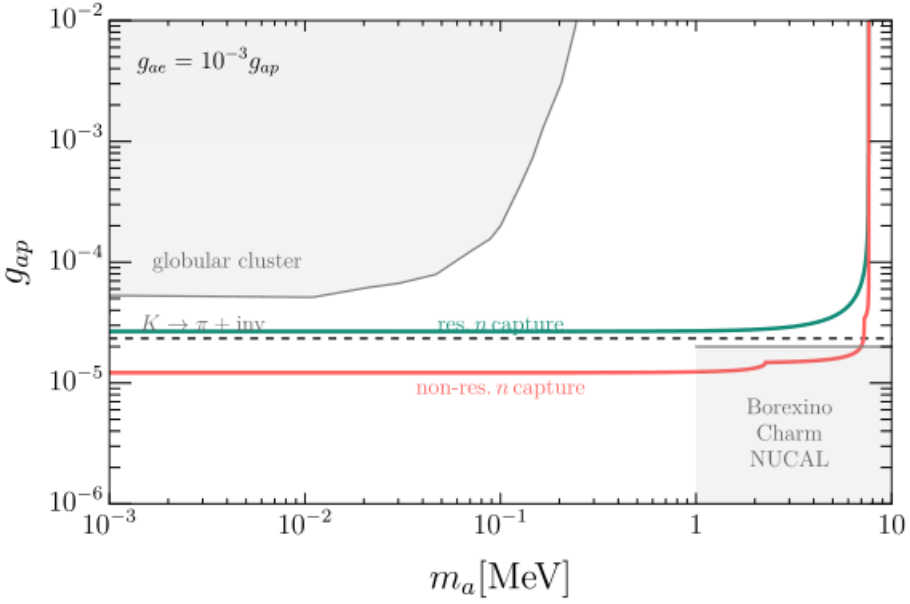


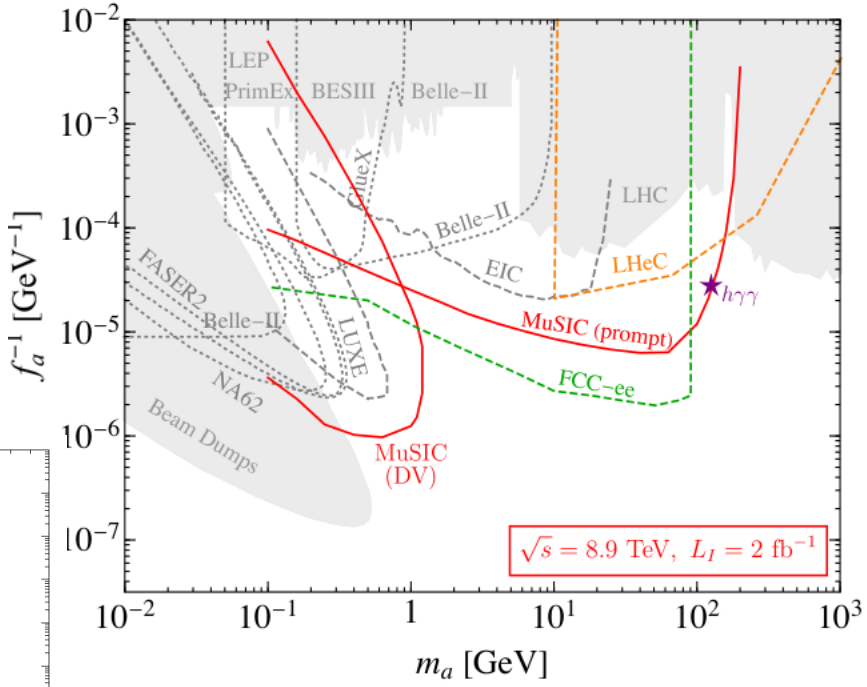
Detection

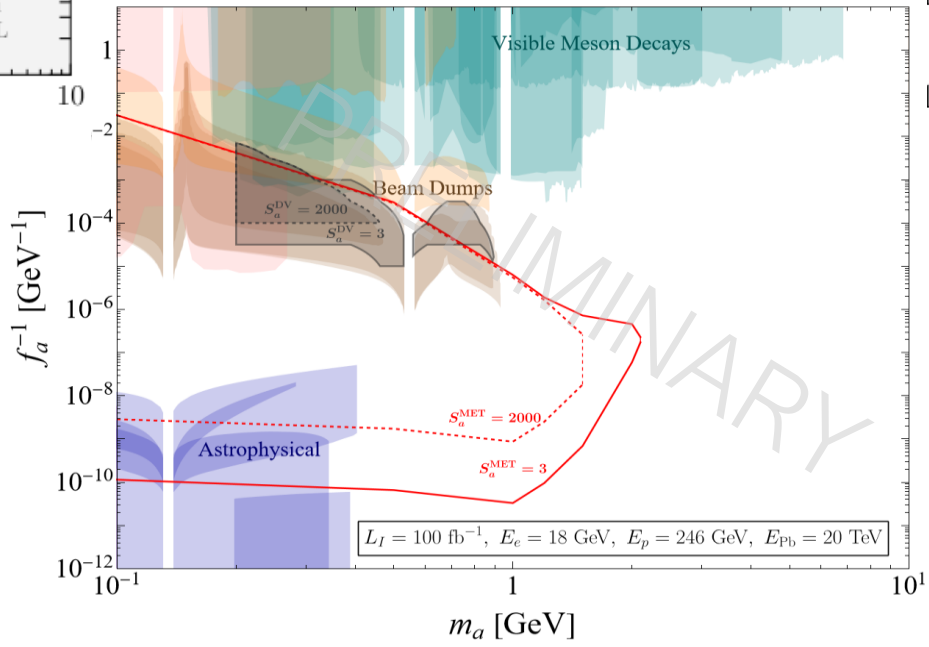


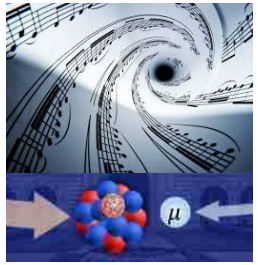
Hunting axion-like particles (ALPs) across all scales











Sokratis Trifinopoulos

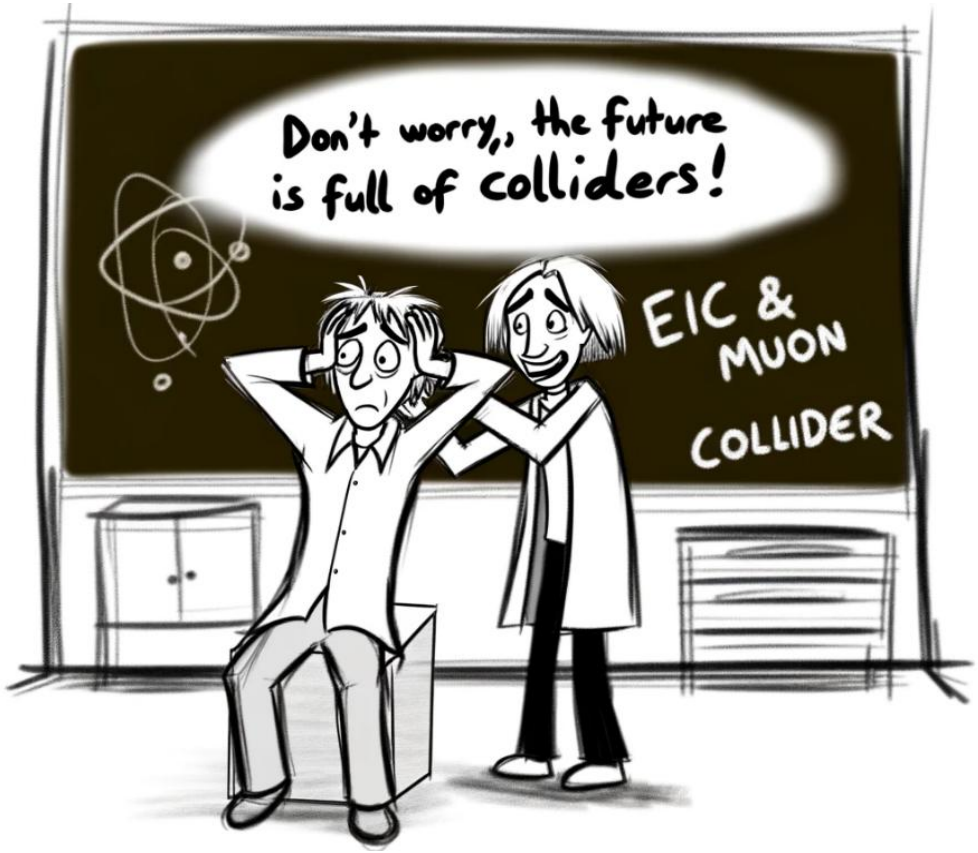
Conclusions

- **MuSIC** offers many synergies with MuC R&D, and between nuclear and particle physics programs, if the two communities 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)	Other Experiments	Features (MuSIC)
LFV U_1 leptoquarks	prompt	HL-LHC	valence lepton
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 an *overture* to further dedicated studies and eventually a white paper for MuSIC in the near future.

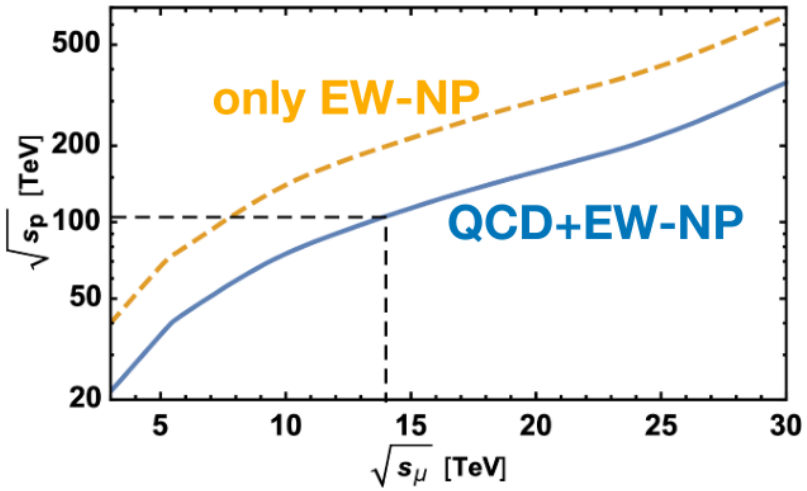
Thank you!

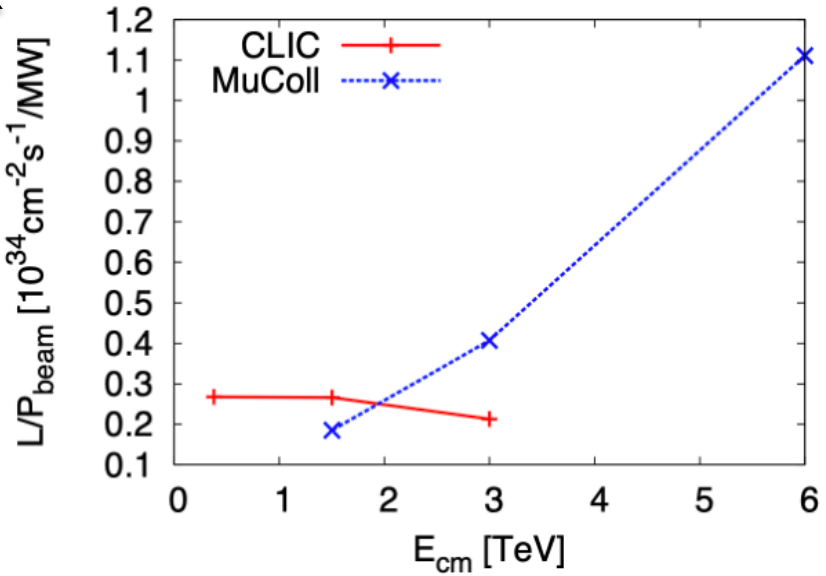

Don't worry,, the future is full of colliders!
EIC & MUON COLLIDER

Why Muon Colliders?

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

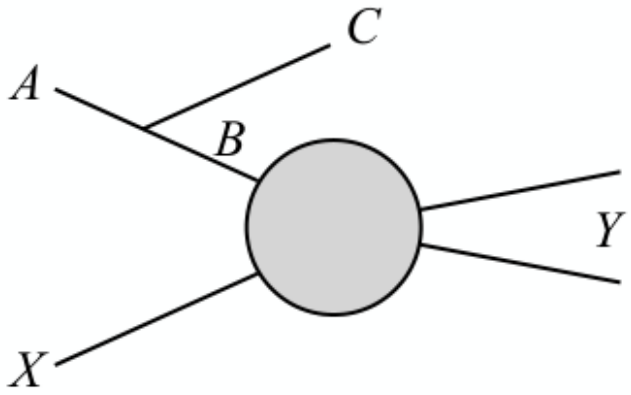
- ✓ high energy reach (not limited by synchroton radiation)
- ✓ high precision measurements (low QCD background & clean initial state)
- ✓ luminosity / beam power increases with energy.
- ✓ all beam energy available in $\mu^+\mu^-$ collisions.





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!

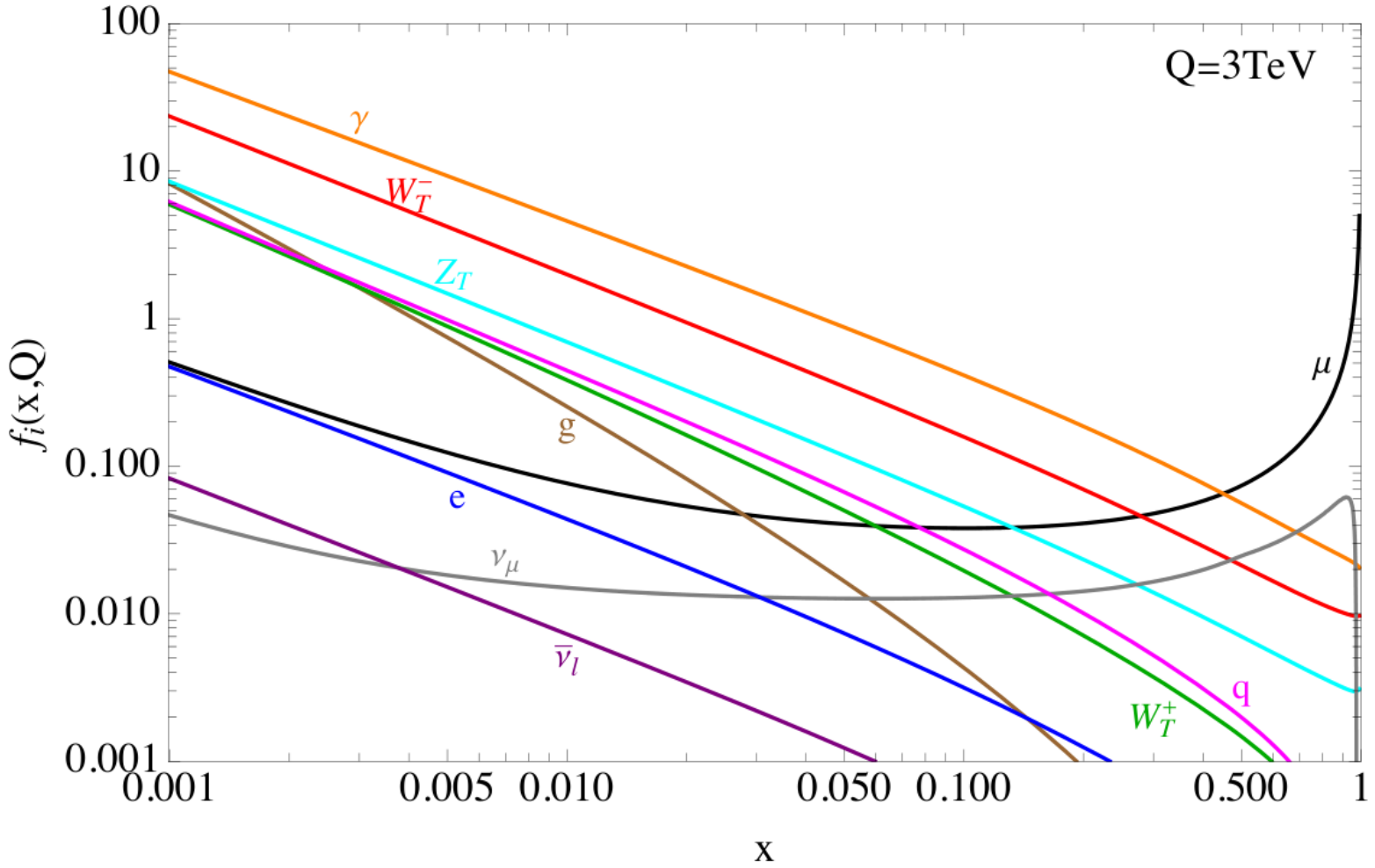


$$\sigma(\mu + X \to \mathrm{Y}) = \sum_B \int_0^1 dx\, f_B(x)\sigma_x(B + X \to \mathrm{Y})$$

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)!!

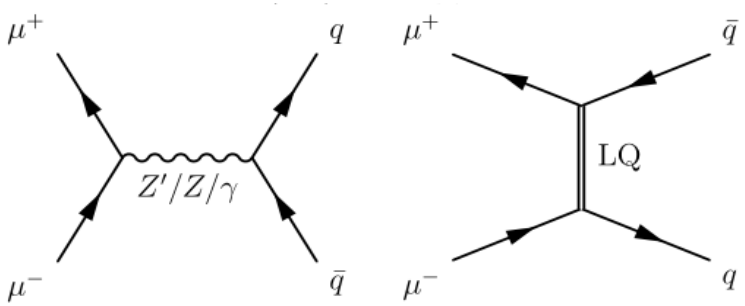
PDFs above the EW scale



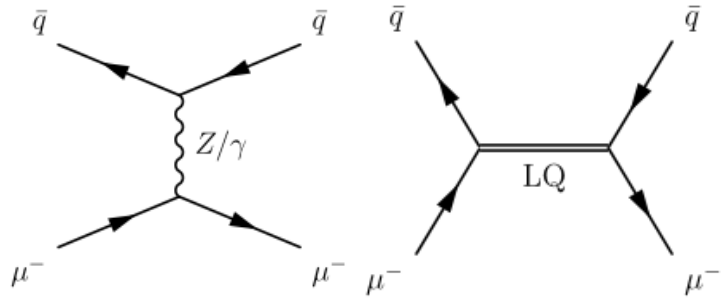
[Garosi, Marzocca, **Trifinopoulos**] 2303.16964, github.com/strifinopoulos/LePDF

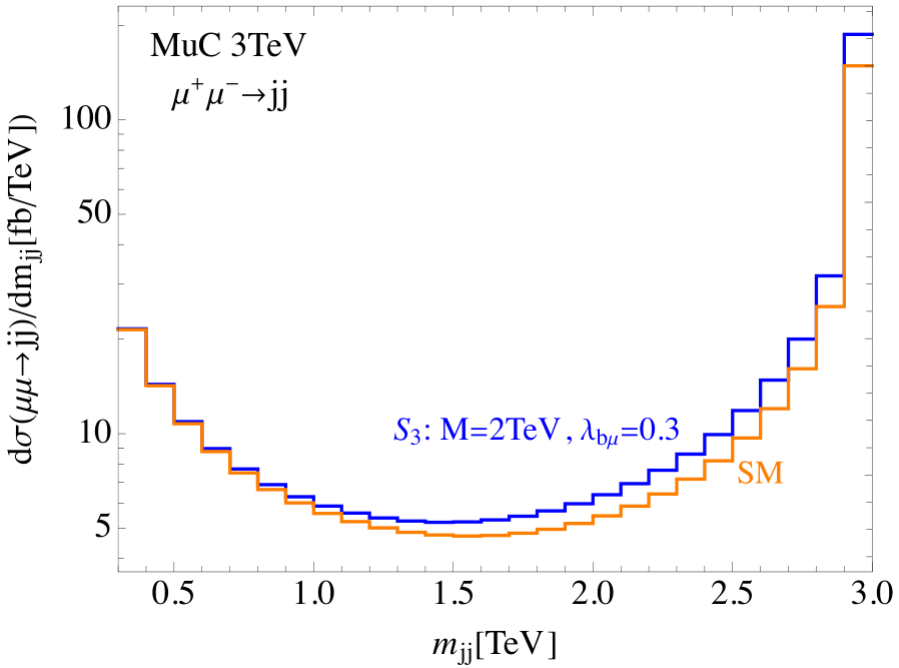
(LHAPDF-format)

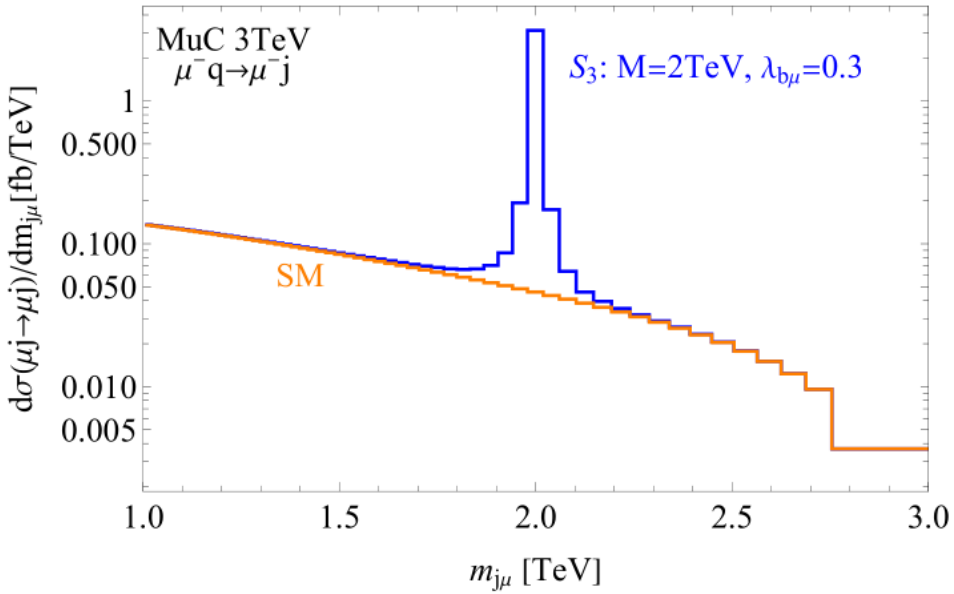
Prompt signatures at a 3 TeV Muon Collider



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



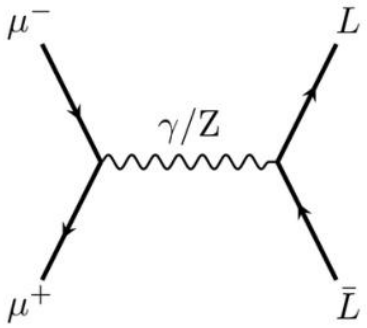




MuC is a Gauge Boson Collider

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

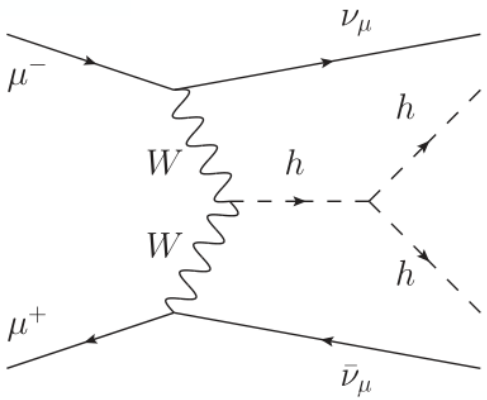
MuC overqualifies as a Higgs factory!

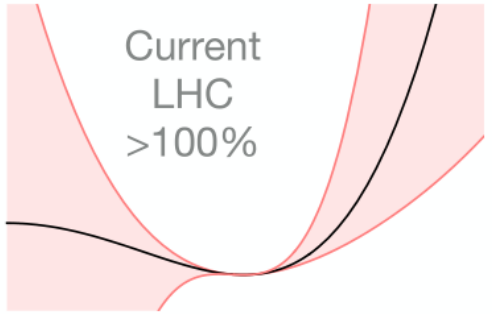


$$\sigma \sim \frac{1}{E^2}$$

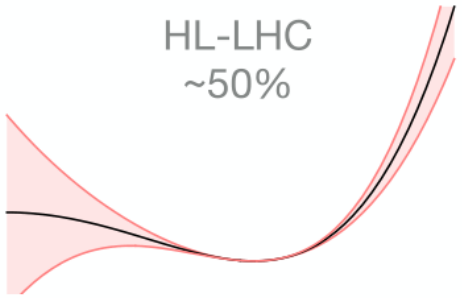
$$\sigma \sim \frac{1}{M^2} \log^2 \frac{E^2}{M}$$

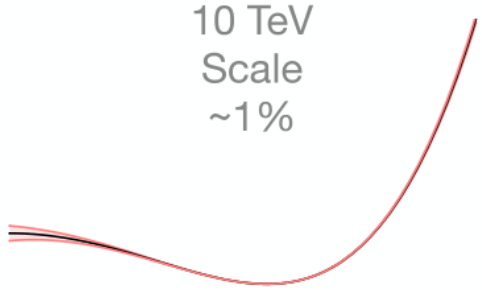
[K, F. DiPetrillo]





We only know there's a minimum

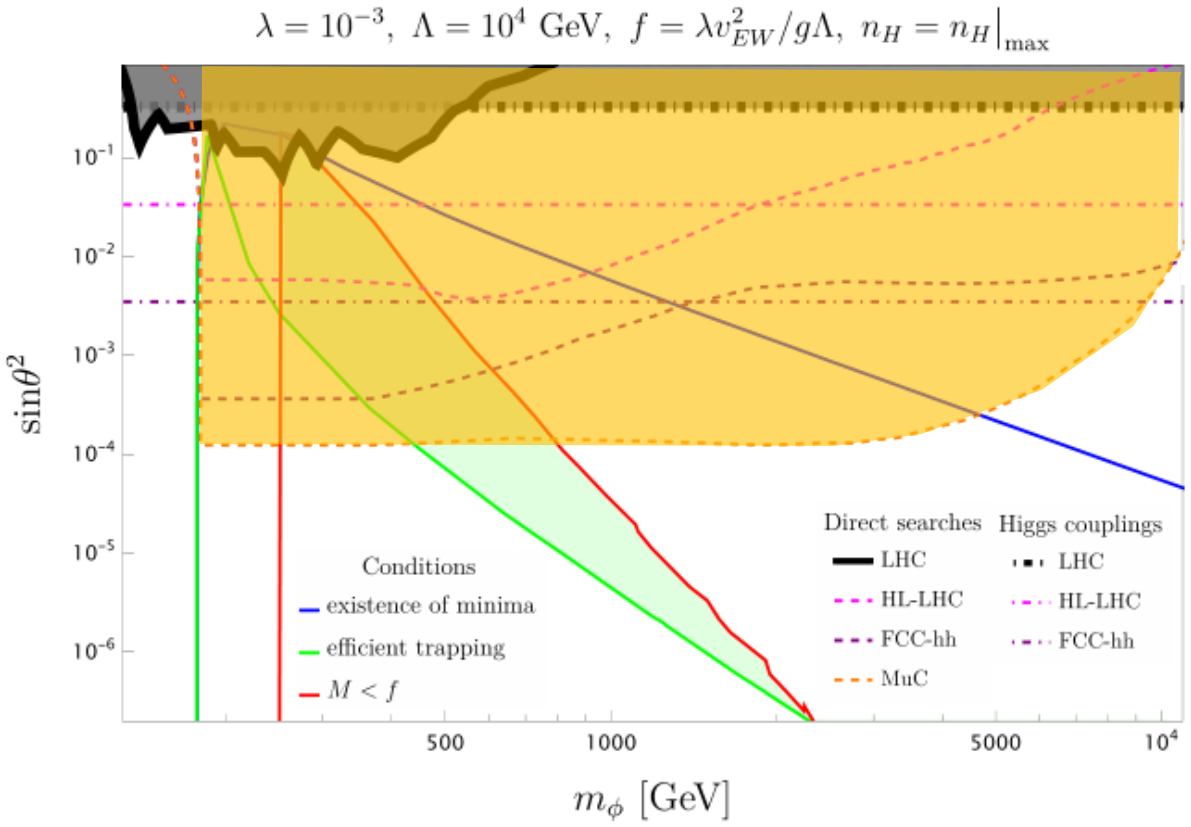


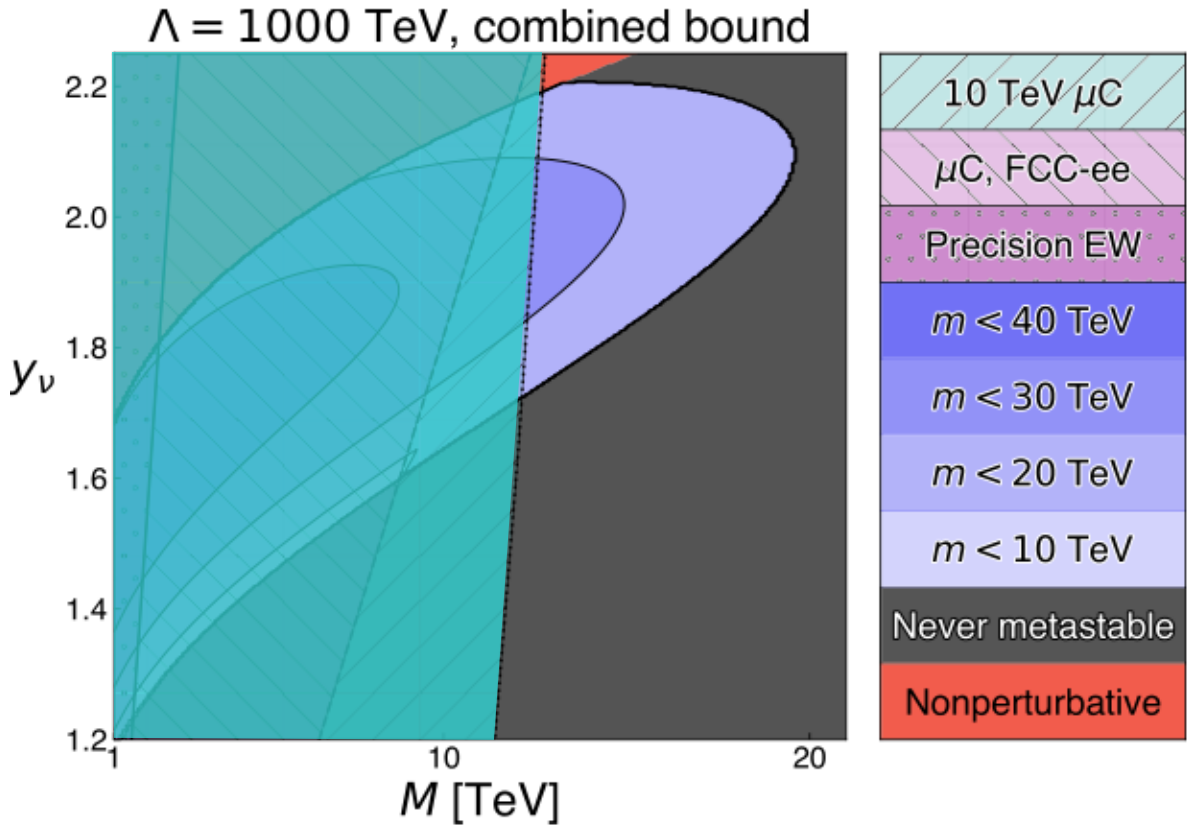


The hierarchy problem at the MuC

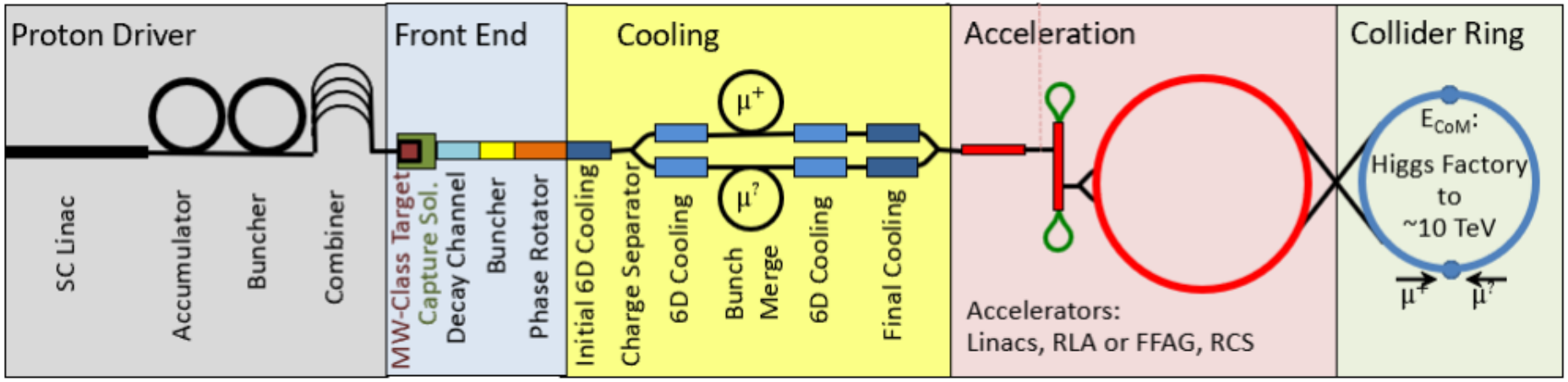
Attracting the Electroweak Scale to a Tachyonic Trap **Trifinopoulos**, Vanvlasselaer, 2210.13484

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

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

Acceleration to collision energy

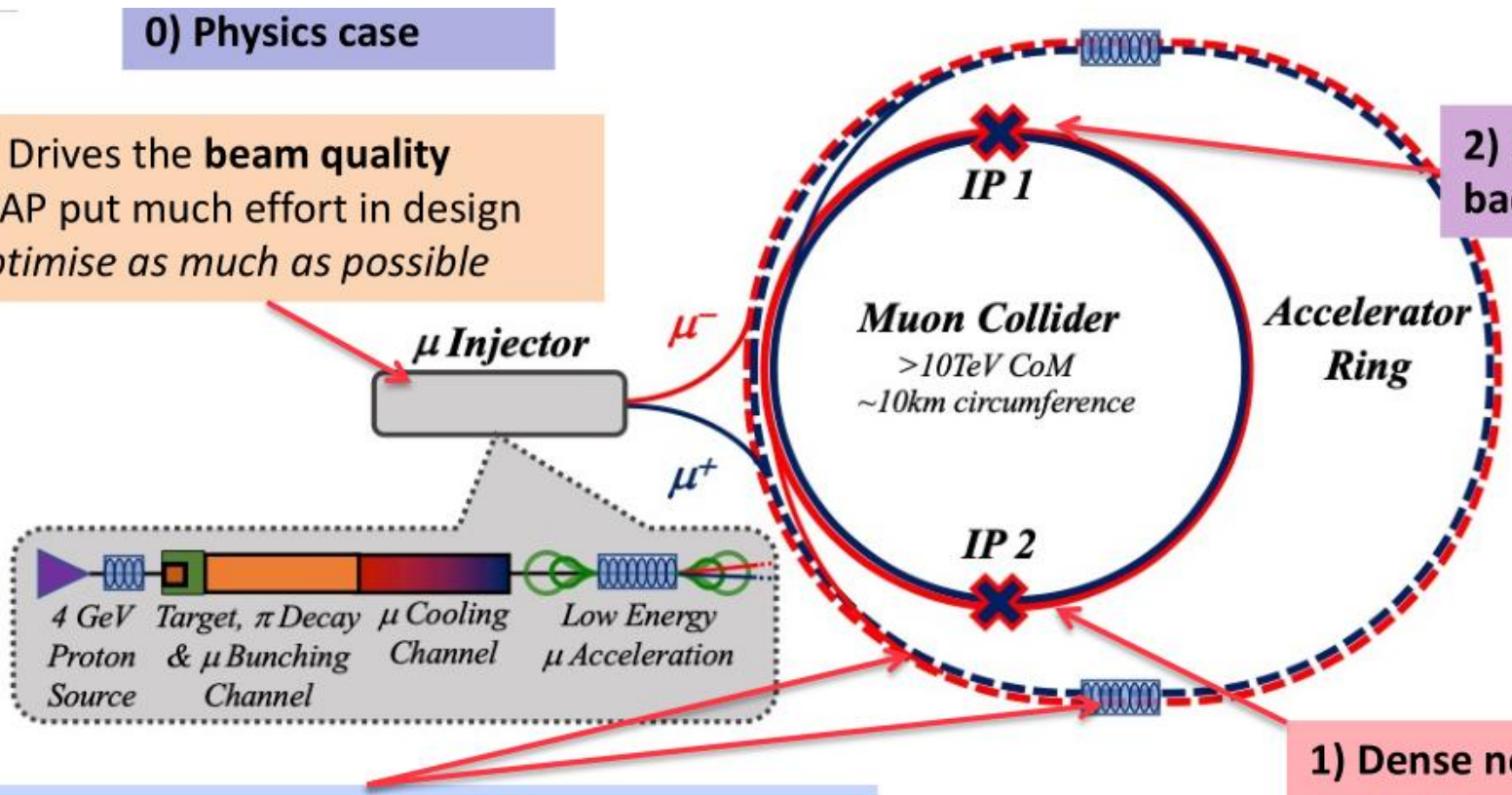
Collision

Key Challenges

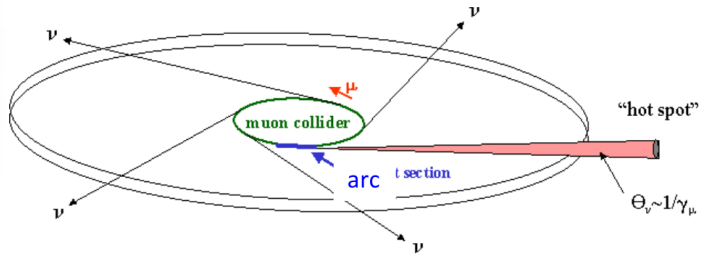
MuCo

0) Physics case

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



2) Beam-induced background



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

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

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:

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

number of particles/beam bunch

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

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

amplitude function

transverse emmitance

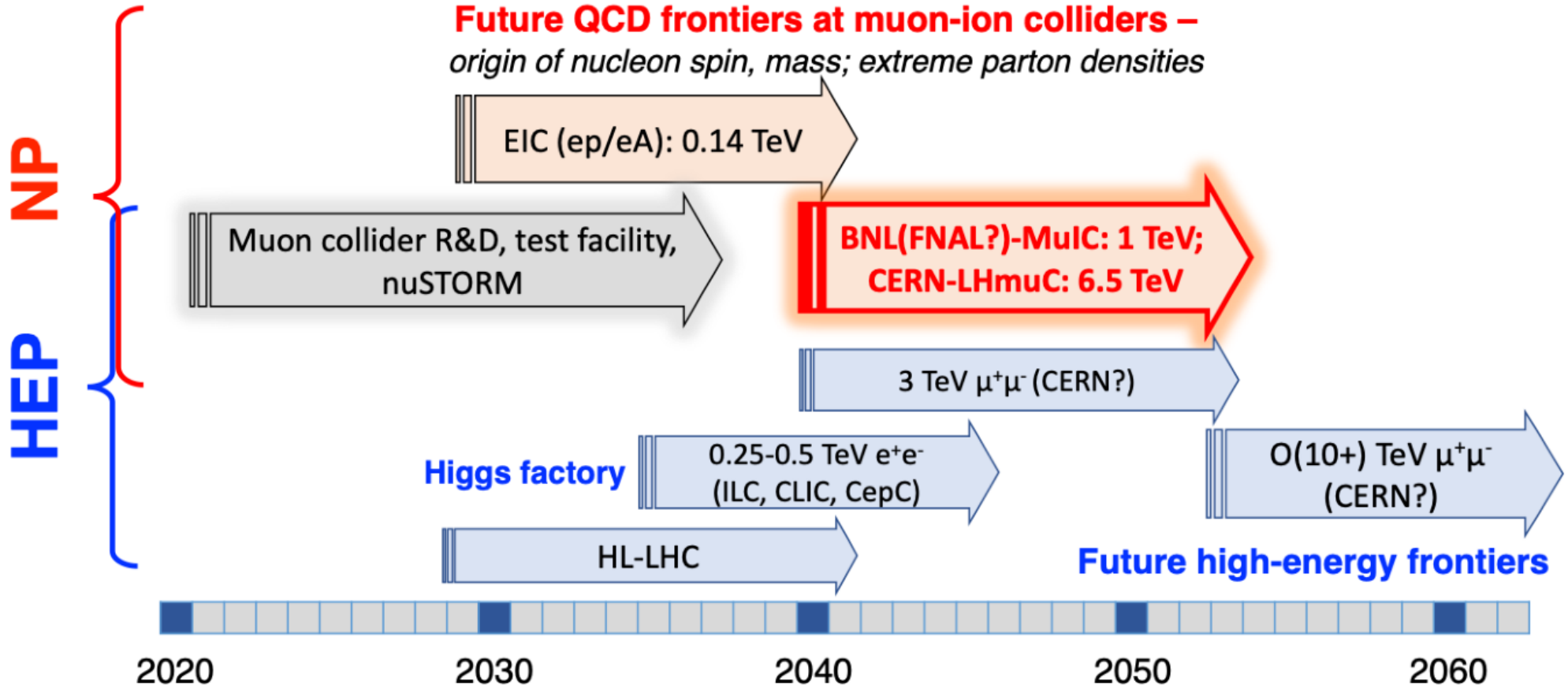
[Acosta et al] 2203.06258]
[Kaya et al] 1905.05564

MuSIC luminosity estimates

Parameter	Muon	Proton
Energy (TeV)	0.96	0.275
CoM energy (TeV)	1.03	
Bunch intensity (10^{11})	20	3
Norm. emittance, $\varepsilon_{x,y}$ (μm)	25	0.2
$\beta^*_{x,y}$ @IP (cm)	1	5
Trans. RMS beam size, $\sigma_{x,y}$ (μm)	5.2	5.8
Muon repetition rate, f_{rep} (Hz)	15	
Cycles/Collilsions per muon bunch, N_c	3279	
$L_{\mu p}$ ($10^{33}cm^{-2}s^{-1}$)	7	

A possible roadmap to future MuC

[Acosta et al] 2203.06258]

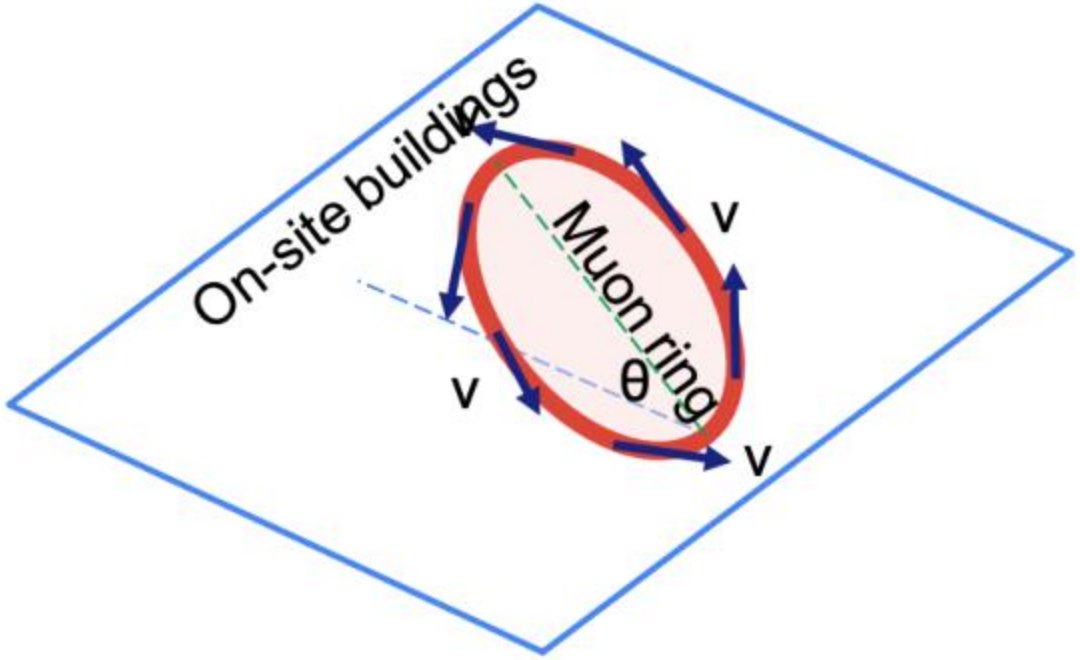


Detector Performance

[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	$\frac{50\%}{\sqrt{E}} \otimes 10\%$	$\frac{0.087}{\sqrt{12}}$

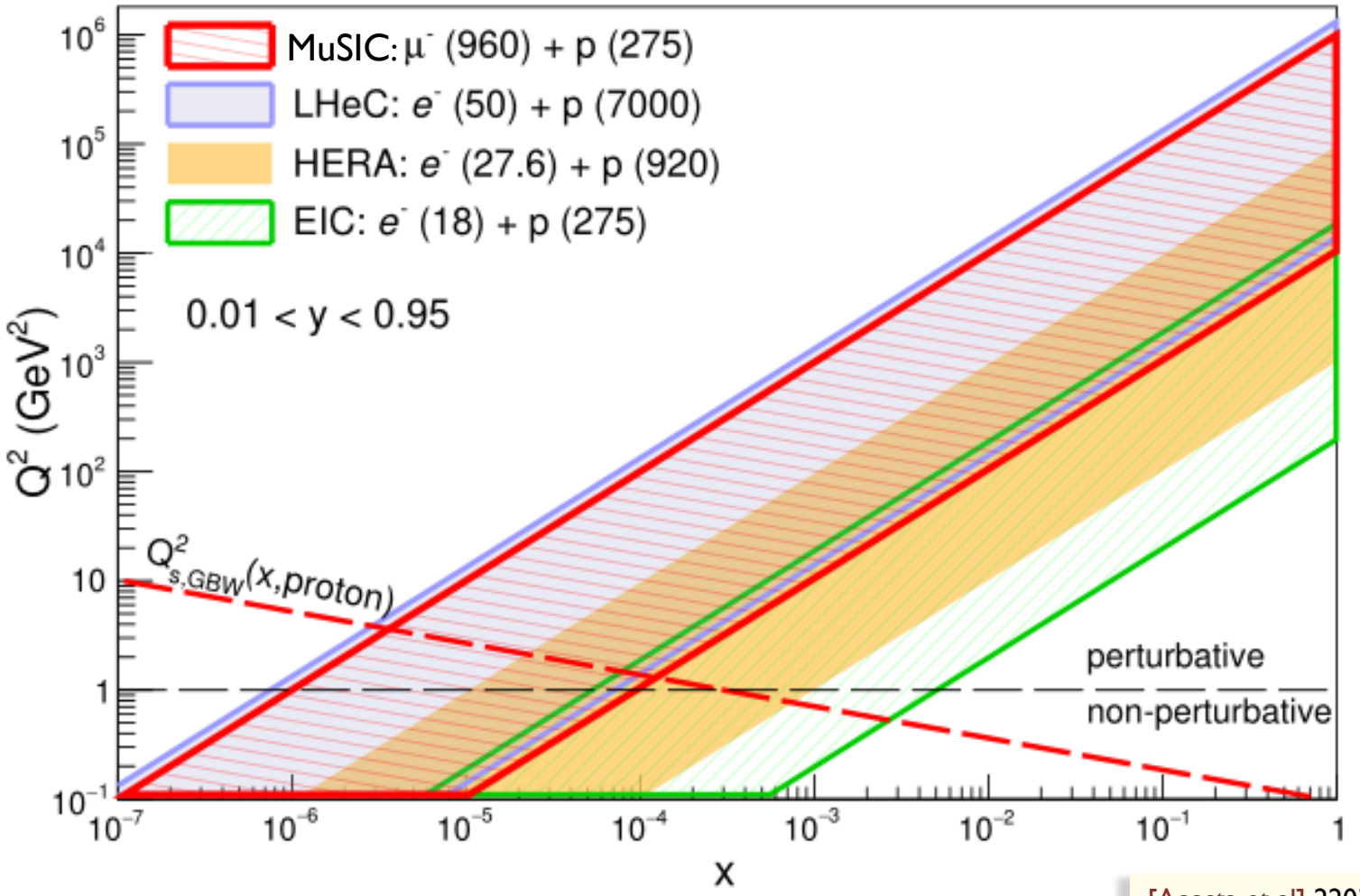
Neutrino Radiation



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.

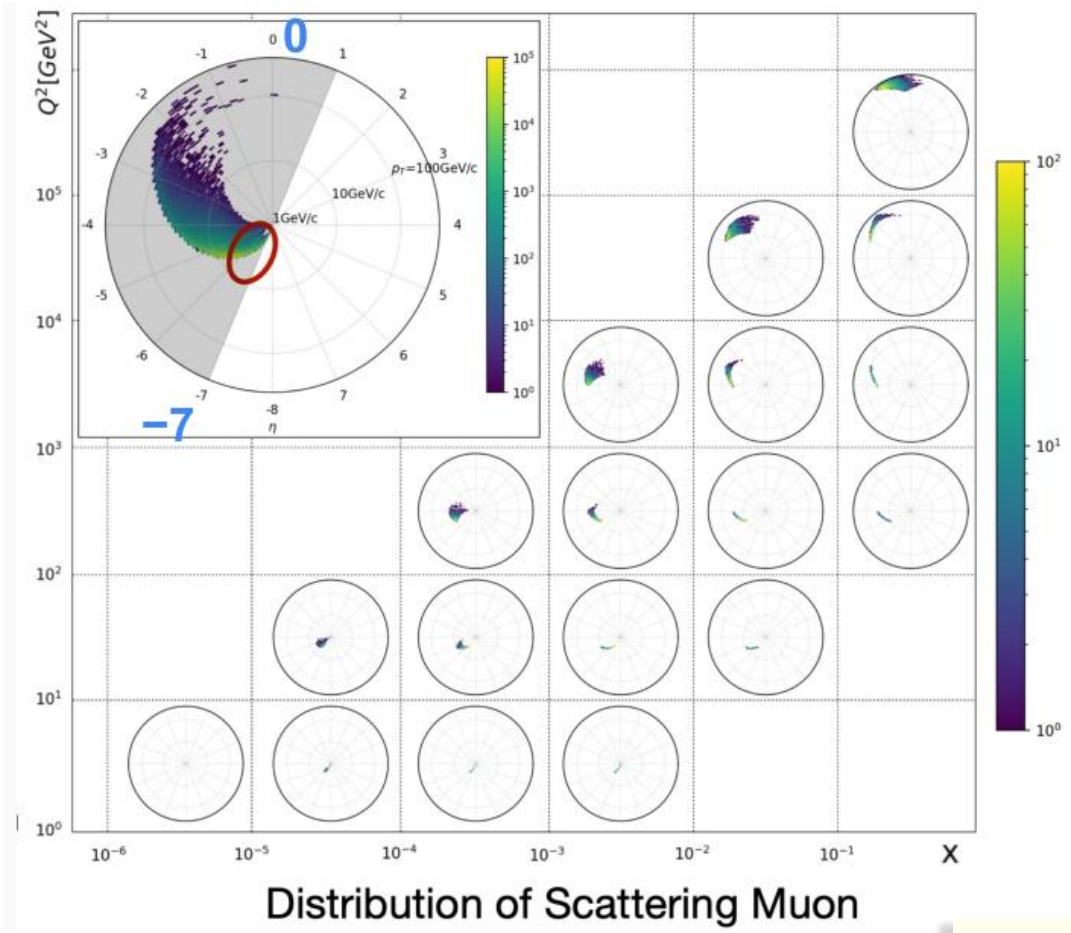
[Acosta et al] 2203.06258]

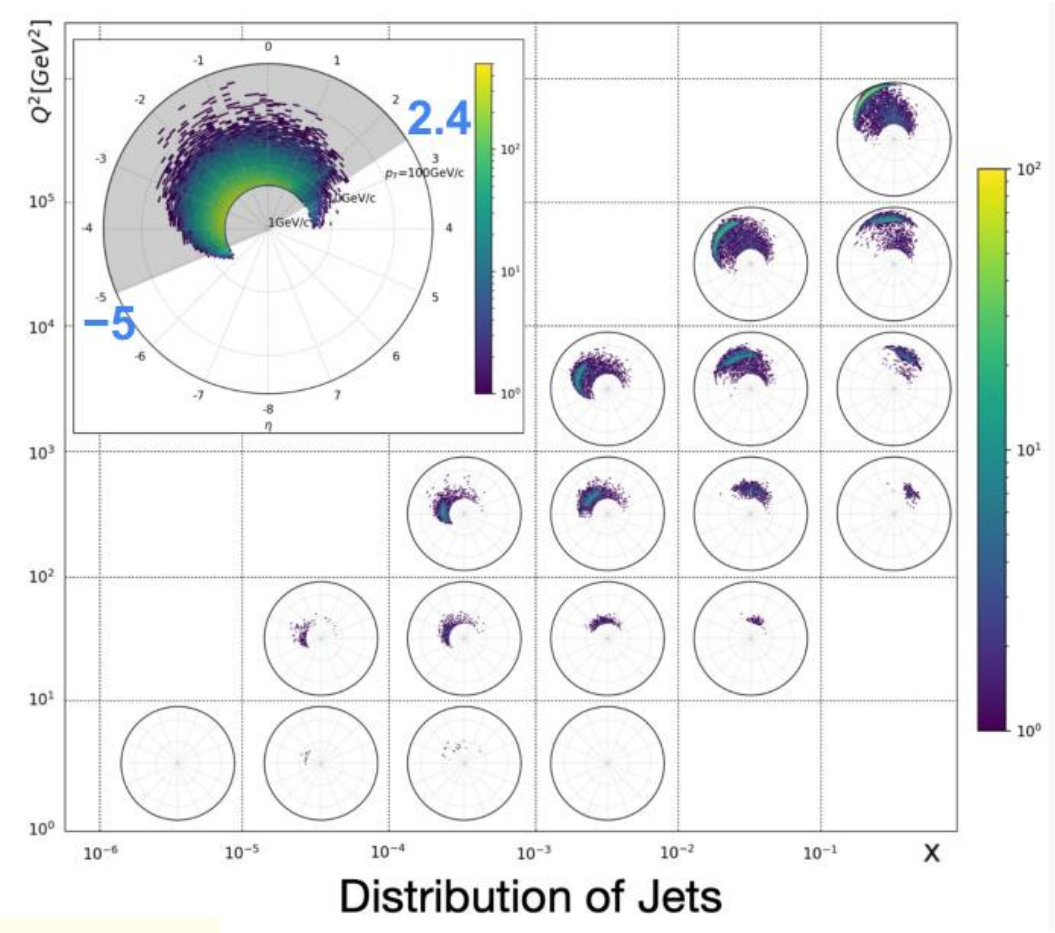
Kinematical coverage in DIS



[Acosta et al] 2203.06258]

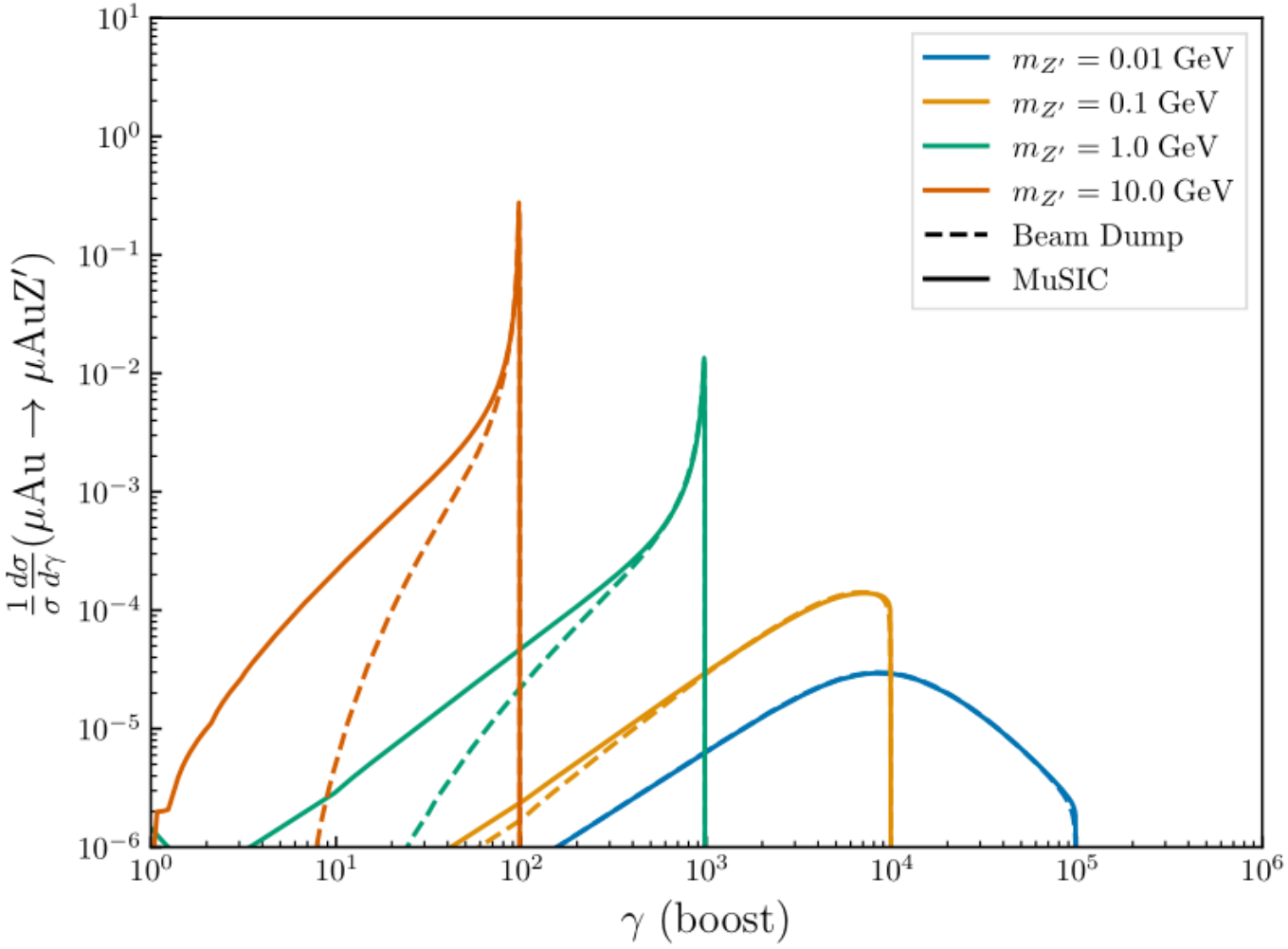
Kinematic distributions in MuSIC



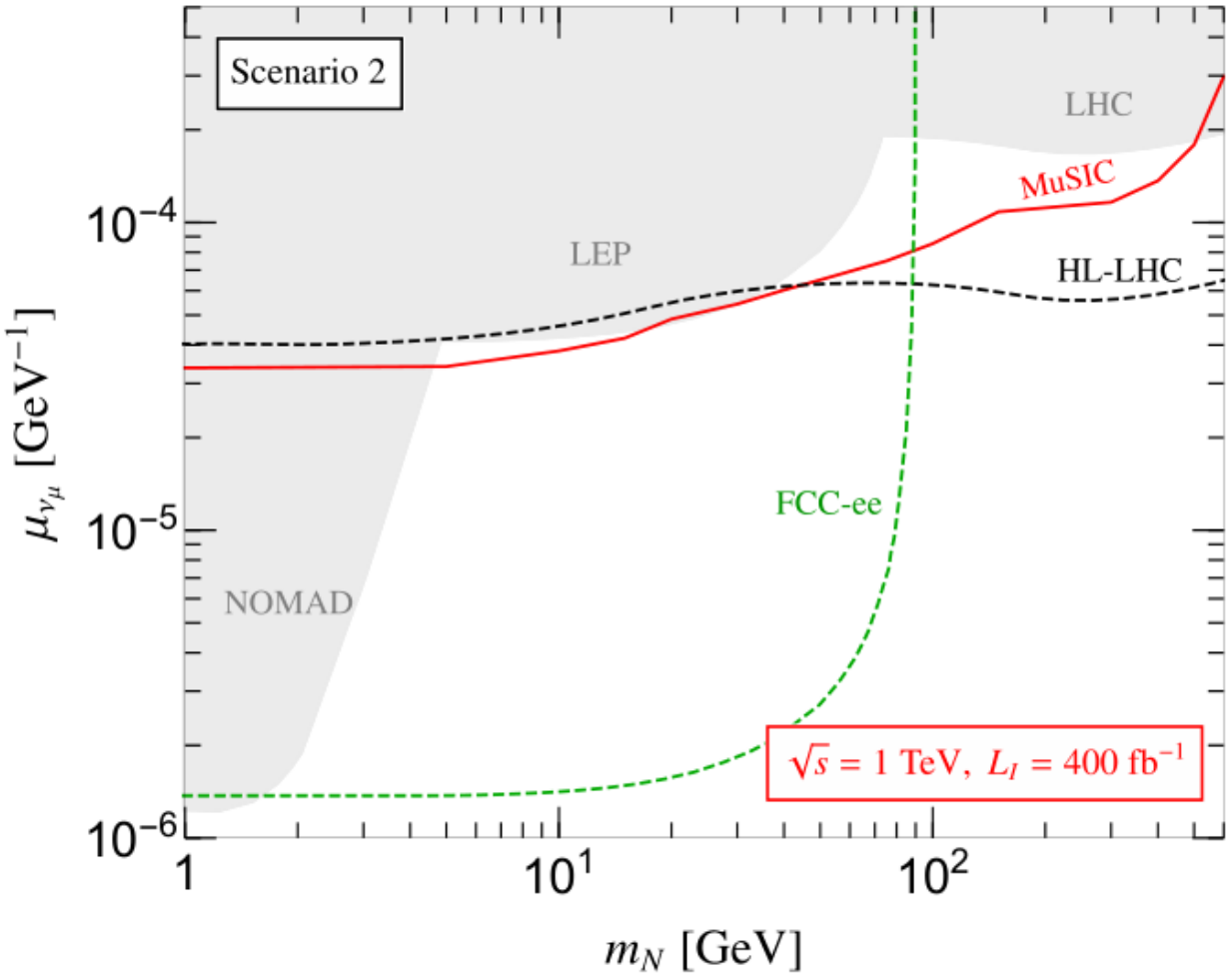


[Acosta et al] 2203.06258]

Z' vector boson boost factors



HSN via dim-6 SU(2) invariant operators



- When the EW symmetry is restored, we should also consider:

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

which induce:

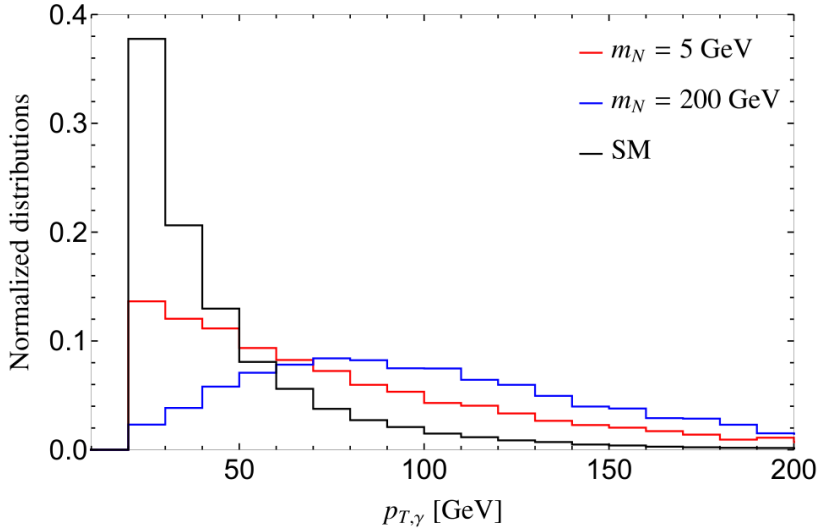
$$\mathcal{L}_{\text{dipole}} \supset \frac{1}{2} \mu_\nu \bar{\nu} F_{\mu\nu} \sigma^{\mu\nu} N + d_Z \bar{\nu} Z_{\mu\nu} \sigma^{\mu\nu} N + d_W \bar{\ell} W^-_{\mu\nu} \sigma^{\mu\nu} N$$

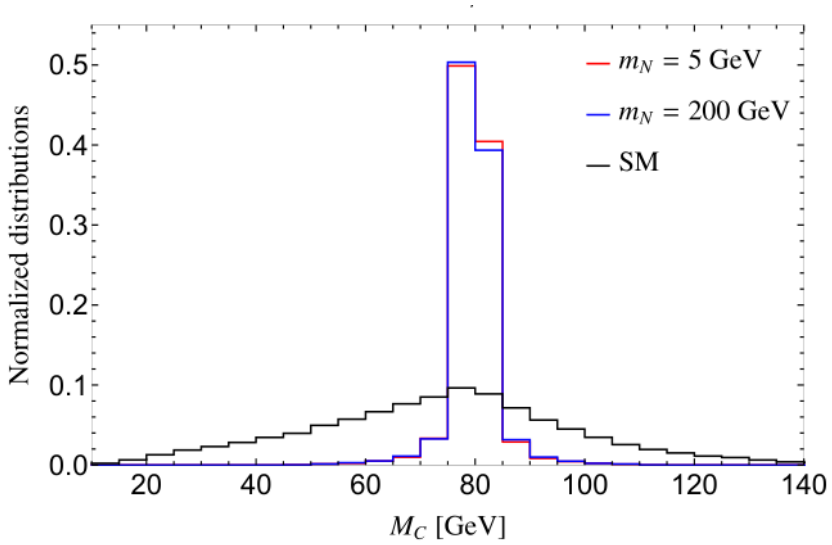
$$\frac{\sqrt{2} ve}{\Lambda^2}(c_B + c_W) \qquad \frac{ve}{\sqrt{2}\Lambda^2}(c_B \tan\theta_W - c_W \cot\theta_W) \qquad \frac{ve}{\Lambda^2} \frac{c_W}{\sin\theta_W}$$

- We focused on the following scenaria:

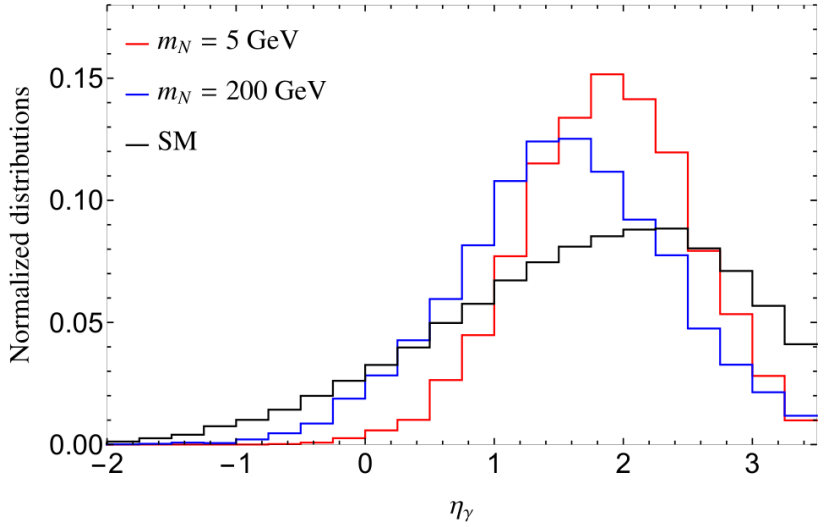
1. only $\mu_\nu \neq 0$,
2. $c_W = 0$ and $d_Z = \frac{1}{2}\mu_\nu \tan\theta_W = \frac{ve}{\sqrt{2}\Lambda^2} c_B \tan\theta_W$.

HSN kinematical distributions





W candidate mass

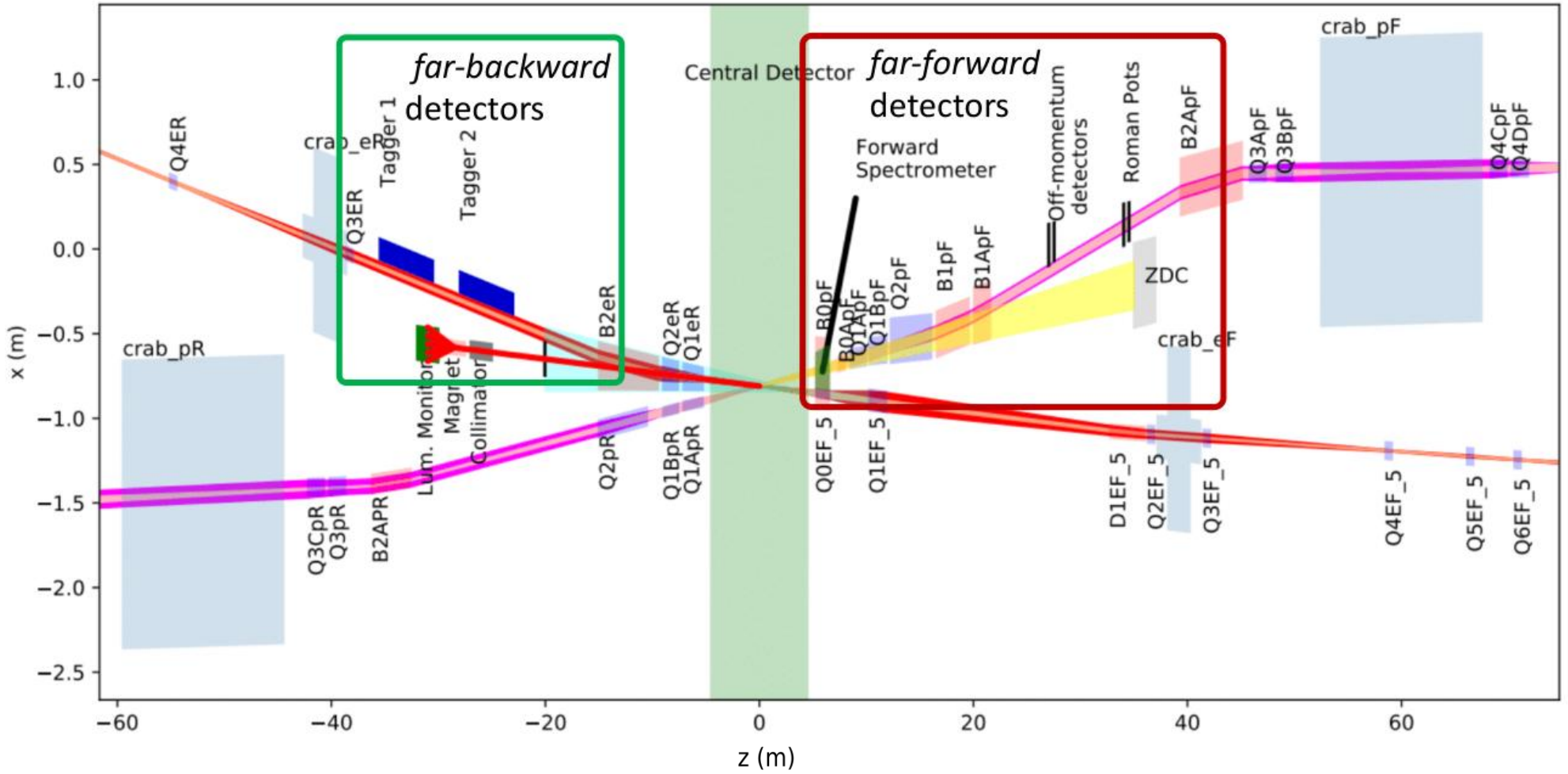


BSM Phenomenology at EIC?

- 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

EIC Interaction Region Layout



Far-forward detector