Towards Muon Collider:

Physics, Technology & Prospects

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Physics Motivation · Detailed Physics · Technology · Projects · Outlook

83 sources (#1–#83) — full bibliography in Backup B30–B31

I. IMCC/MuCol reviews 6	II. Physics overviews 4	III. Higgs 14	IV. BSM searches 10
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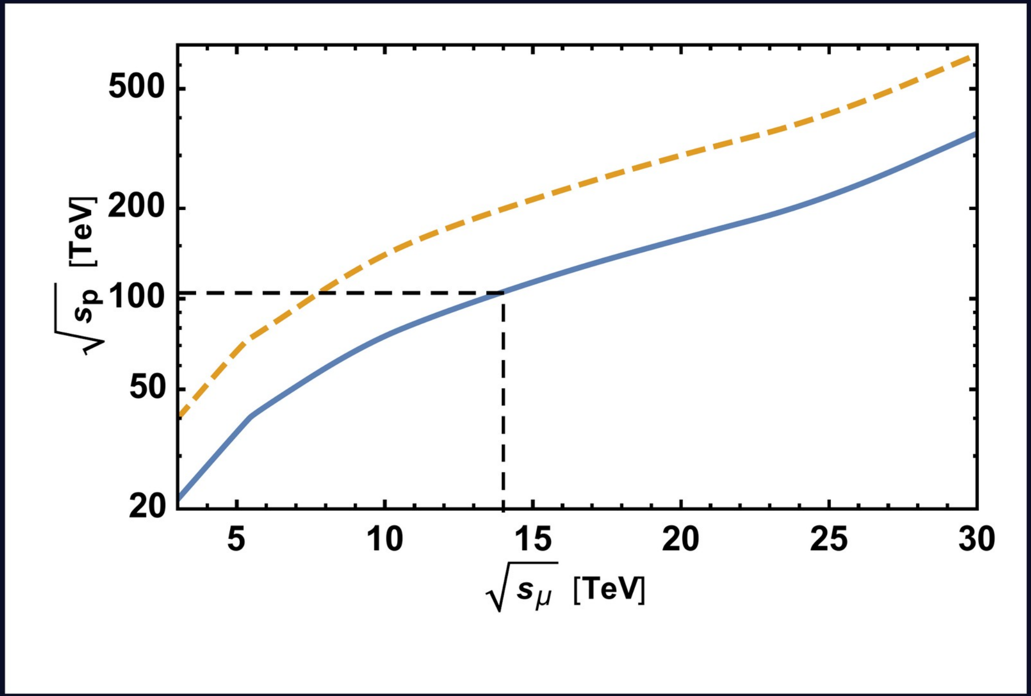
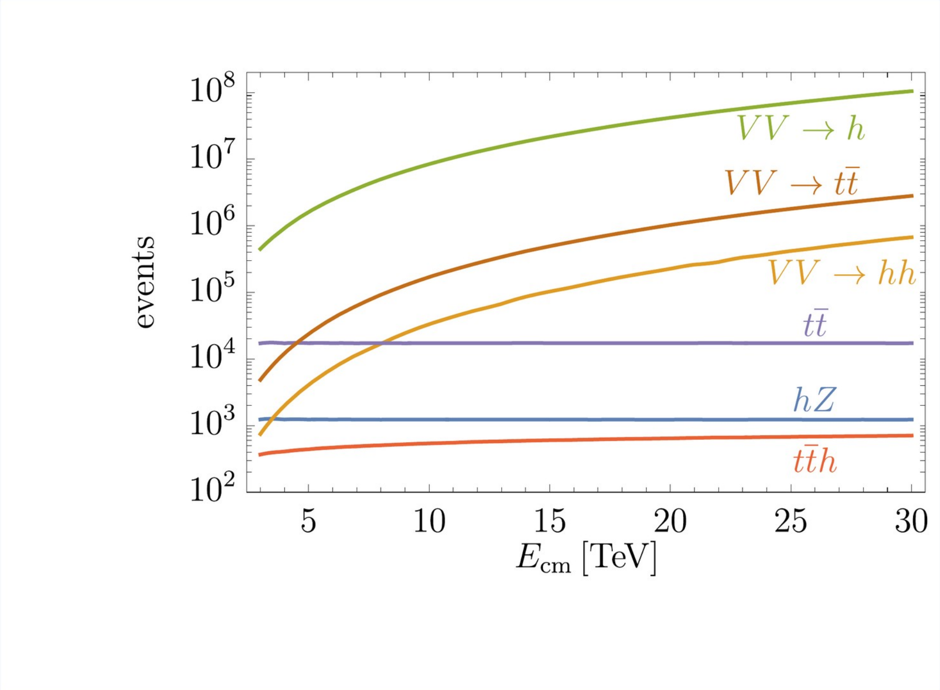
Journals: *EPJ C, JHEP, PRD, Nature.*
Strategy reports: *ESPPU 2020 Update (CERN-ESU-015-2020); ESPPU Accelerator R&D Roadmap 2022 (arXiv:2201.07895); Snowmass 2021 Energy Frontier (arXiv:2211.11084) & Accelerator Frontier Reports; P5 Report 2023 «Exploring the Quantum Universe» (DOE/NSF); NASEM 2025 «Elementary Particle Physics: the Higgs and Beyond»; Update to US National Input to ESPPU 2026 (arXiv:2602.15295).*
Collaboration reports: *IMCC «Towards a muon collider» (EPJ C 2023); IMCC Interim Report (CERN Yellow 2024); IMCC overview 2025; MuCol Consolidated Parameters 2025; US Muon Collider Community White Paper for ESPPU 2025; Snowmass 2022 community summaries.*

Why a Muon Collider? Energy-Precision Frontier in One Machine



√s_p vs √s_μ partonic reach (arXiv:1901.06150, Fig.1 left)



SM event yields vs variable E_cm with L ∝ E_cm² (arXiv:2303.08533, Fig.5 right)

A 14 TeV $\mu^+\mu^-$ collider matches the partonic reach of a ~100 TeV pp machine.

Equivalence (arXiv:1901.06150, Fig.1 dashed line): equal pair-production cross-section for purely electroweak heavy particles with mass ≈ √s_μ / 2 — within a clean lepton environment.

Compact & power-efficient

- 11.4 km ring at 10 TeV → 14 km at 14 TeV
- Site power 230 MW (10T) → 300 MW (14T)
- FCC-hh comparison: 100 km / 550 MW
- Best MW/TeV among multi-TeV proposals

Clean & precise

- Full √s in elementary hard process
- No QCD background, no PDF uncertainty
- Sub-% Higgs couplings; λ_3 to 3.7%; λ_4 unique

Energy-frontier reach

- Direct BSM ~5 TeV (10T) / ~7 TeV (14T)
- Complete WIMP DM coverage
- Higgsino @ 3T · Wino @ 10T · 5-plet @ 14T

Left plot (partonic reach) — arXiv:1901.06150 (Delahaye et al., Input to ESPPU 2019, Fig.1 left); right plot (event yields) — arXiv:2303.08533 (Accettura et al., IMCC 2023, Fig.5 right); energy / luminosity numbers — arXiv:2510.27437 (MuCol MS7 2025); BSM mass reach — arXiv:2103.14043 (Snowmass), arXiv:2504.21417 (IMCC 2025).

Physics Capabilities Across All Future Colliders

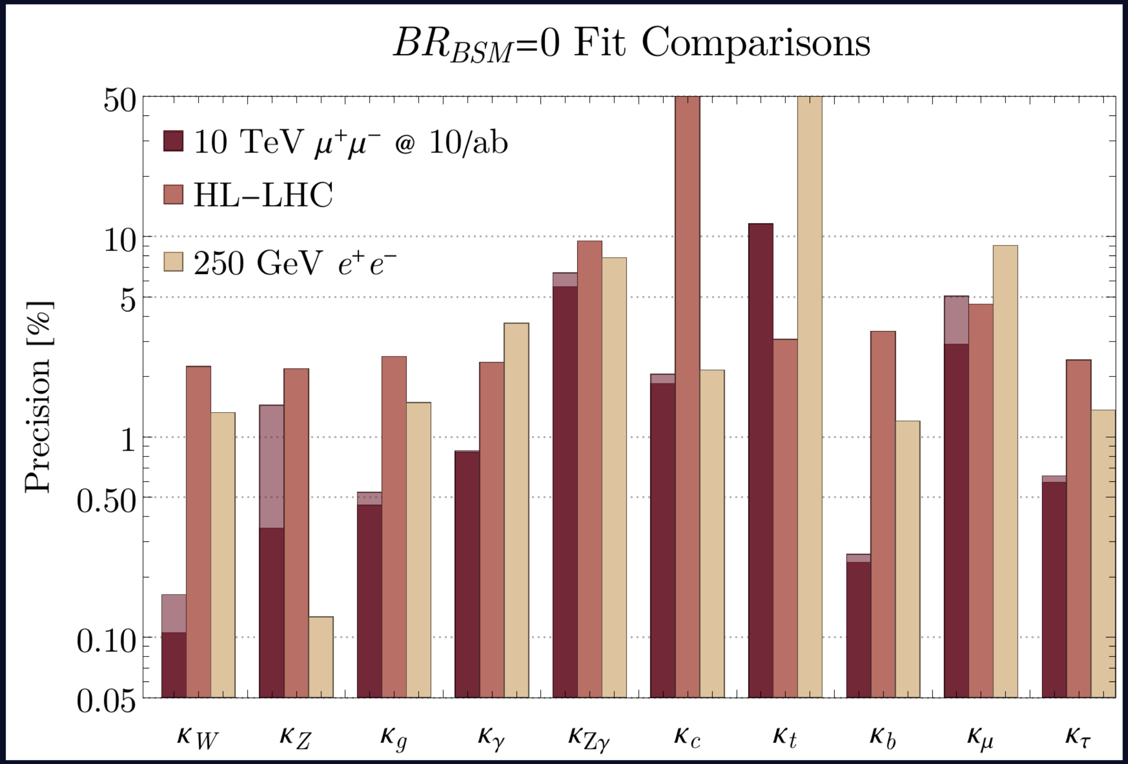
Capability	HL-LHC	FCC-ee	ILC-500	CLIC-3T	μC-3T	μC-10T	μC-14T
Higgs couplings (best κ)	2-4%	0.2-1%	0.5-2%	0.5-2%	0.5-1%	0.1%	<0.1%
λ_3 trilinear	~50%	—	—	10-20%	~10%	3.7%	2.5%
λ_4 quartic	—	—	—	—	—	sensitivity	**measurable**
Γ_H total width	indirect	~1.3%	~2%	~3%	~2%	0.75%	0.5%
Direct BSM reach	~3 TeV	0.2 TeV	0.25 TeV	1.5 TeV	1.5 TeV	~5 TeV	~7 TeV
WIMP DM coverage	partial	light	light	partial	Higgsino	+Wino	+5-plet
m_{top} precision	~300 MeV	~20 MeV	~50 MeV	~50 MeV	~50 MeV	~20 MeV	~20 MeV
y_t Yukawa	~10%	~3%	~3%	—	~2%	~1%	~0.5%
Quantum entanglement (Bell, c_{MB}^2)	—	—	—	—	low signif.	~2σ	**5σ**
EW precision: $\sin^2\theta_W$	—	0.01%	0.05%	—	—	0.005%	0.003%
Ring circumference [km]	27	91	31	50	4.5	11.4	14
Site power [MW]	150	280	300	580	200	230	300
Peak luminosity [10^{34} cm^{-2}s^{-1}]	5	230	1.4	6	1.8	18	30

Best MW per *equivalent-TeV* among multi-TeV proposals:
μC-10T = 23 MW/TeV; FCC-hh ≈ 55 MW per equivalent-TeV (550 MW / ~10 TeV partonic, equivalence per 1901.06150 Fig.1).

λ_4 quartic coupling is unique to μC-14T:
no other proposed machine can measure it (HHH only at μC).

Higgs κ/λ_3 — arXiv:2308.02633, 2203.07256; BSM/WIMP — arXiv:2103.14043, 2504.21417; top — arXiv:2503.11518; sin²ϑ_W — arXiv:2505.00152; Bell — arXiv:2408.05429, 2504.09832; ring/power/L — arXiv:2510.27437 (MuCol MS7 2025), FCC CDR.

Higgs Coupling Precision — κ-Framework Across Stages



Higgs κ comparison μC vs FCC-ee vs HL-LHC vs ILC — arXiv:2308.02633

κ	HL-LHC	FCC-ee	μC-3T	μC-10T	μC-14T
κ_W	1.5%	0.4%	0.5%	0.1%	<0.1%
κ_Z	1.3%	0.2%	0.6%	0.1%	<0.1%
κ_b	3.0%	0.6%	0.7%	0.2%	0.15%
κ_t	3.6%	—	2%	1%	0.5%
κ_τ	1.7%	0.5%	1%	0.4%	0.3%
κ_μ	4%	4%	5%	1%	<1%
κ_γ	1.6%	1%	1.5%	0.4%	0.3%

Why κ-framework? Modification of SM Higgs coupling: $g_{SM} \rightarrow \kappa \cdot g_{SM}$. Effective Lagrangian probe of any deviation from SM.

Why μC dominates: high-energy VBF (10/14 TeV) × 10 ab^{-1} × clean lepton environment × **forward μ tagging |η|<6** breaks κ–Γ_H degeneracy (without it κ_Z **precision ×10 worse)**

Methodology caveat: EW PDF / EVA breaks down at m(tt̄)>7 TeV — NLO EW + QED resummation needed for per-mille precision [arXiv:2506.10733]
All μC values: 10 ab^{-1} at the indicated √s. Refs: 2308.02633 (Forslund-Meade); 2203.07261 (de Blas); 2401.08756 + 2411.00096 (forward μ).

Global κ-fit @10 TeV / 10 ab^{-1} with |η_μ|<6 *(MuC alone, arXiv:2401.08756 Table V):* κ_W ~ 0.5%, κ_Z ~ 0.4%, κ_g ~ 0.7%, κ_γ ~ 1%; **BR(H → invisible) < 4.6×10^{-4} @ 95% CL** *(δres=1%, arXiv:2411.00096 Eq.12)*

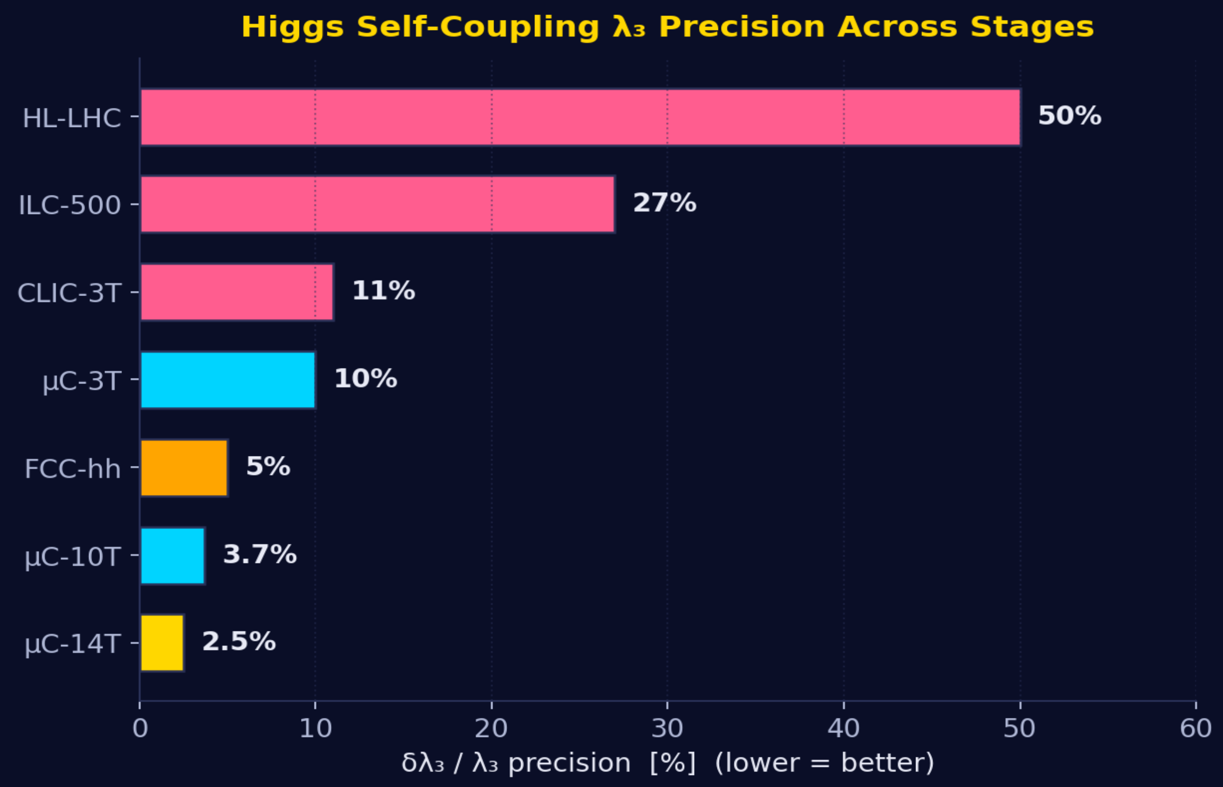
κ plot & table values — arXiv:2308.02633 (Forslund & Meade 2023), arXiv:2203.07261 (de Blas et al.); forward μ |η|<6 fit & κ values — arXiv:2401.08756 (Li, Liu, Lyu 2024, Table V); BR(H → invisible) < 4.6×10^{-4} @ δres=1% — arXiv:2411.00096 (Ruhdorfer-Salvioni-Wulzer 2024, Eq.12); s-channel Higgs-factory baseline — arXiv:2104.05770; NLO EW caveat — arXiv:2506.10733 (Frixione et al. 2025).

Higgs Self-Coupling λ_3 — Probing the EW Potential at μC

Why λ_3 matters: the Higgs self-coupling sets the shape of the EW potential V(H). Direct test of EW phase transition, baryogenesis, vacuum stability.
All numbers below: at $\mu^+\mu^-$ collider, indicated √s, with quoted L_{int}. Measurement channels: $b\bar{b}\gamma\gamma$, $b\bar{b}\tau\tau$, $b\bar{b}b\bar{b}$.

- **Process: $\mu^+\mu^- \to \bar{\nu}\nu$ HH** (via 2× W-fusion → HH)
- **σ(VBF→HH) by stage:**
  1 fb @ 3 TeV (1 ab^{-1})
  8 fb @ 10 TeV (10 ab^{-1})
  15 fb @ 14 TeV (20 ab^{-1})
- **$\delta\lambda_3/\lambda_3$ precision:**
  10% @ 3 TeV
  3.7% @ 10 TeV
  2.5% @ 14 TeV
- **World-leading comparison:**
  HL-LHC ~50%, FCC-ee inaccessible, FCC-hh ~5%
- **EW phase-transition implications:**
  λ_3 deviation > 10% from SM ↔ first-order EWPT ↔ baryogenesis viable

Looking beyond the baseline stages
- **Han et al. 2020 (arXiv:2008.12204)**: $\delta\lambda_3/\lambda_3 \approx 2.0\%$ projected at 30 TeV / 100 ab^{-1}
- **EWPT criterion:** $\delta\lambda_3 \gtrsim$ 10–60% required for strongly-first-order transition — **full μC range probes this decisively.**
- *ILC inaccessible (no HH), FCC-ee inaccessible — μC is the only machine that maps the entire EW-potential shape.*



$\delta\lambda_3/\lambda_3$ vs collider — synthesised from arXiv:2203.07261, 2308.02633

σ(VBF→HH) cross-sections & $\delta\lambda_3/\lambda_3$ per stage — arXiv:2203.07261 (Buttazzo et al.), arXiv:2308.02633 (Forslund & Meade); HL-LHC / FCC-hh comparison — arXiv:2103.14043 (Snowmass 2021); 30 TeV extrapolation (2.0%) — arXiv:2008.12204 (Han et al. 2020).

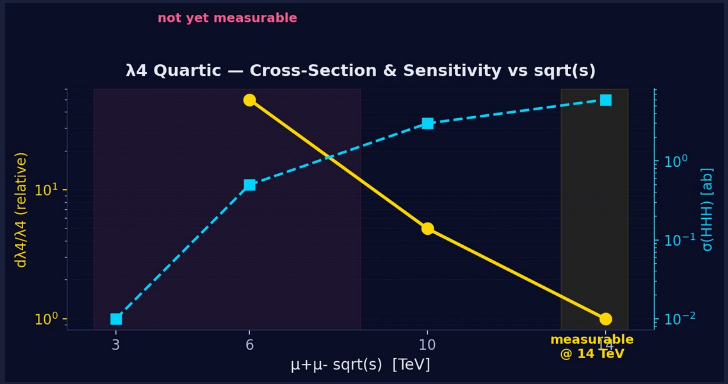
λ_4 Quartic & Γ_H — Unique to the Muon Collider

λ_4 — Higgs Quartic Coupling

- Process: μμ → ν̄ν HHH (VBF)
- **σ(HHH ν̄ν): 4.18 ab @ 10 TeV** / 18.5 ab @ 30 TeV
  → 84 events @ 10 TeV (20 ab^{-1}); 1851 events @ 30 TeV (100 ab^{-1})

- **λ_4 extraction = exceptional privilege of μC**
- Sensitivity ~O(1) @ 10 TeV; $\delta\lambda_4/\lambda_4 < 50\%$ @ 30 TeV

- **Probes V(H) to fourth order**
- Direct implications for EW phase transition
- Constrains models of EW baryogenesis



Refs: arXiv:2003.13628 (Chiesa-Maltoni), 2103.14043 Sec.4, 2308.02633

Γ_H — Higgs Total Width

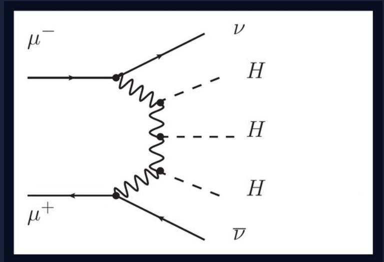
- Currently extracted indirectly at LHC
- **μC: direct width via forward μ tagging |η|<6**
  [arXiv:2401.08756 — Li, Liu, Lyu (UMN, 2024)]

- Method breaks coupling-width degeneracy
  σ(μμ → μμH) ≈ σ_VBF / κ_Z^2

- **Γ_H precision:**
  2.0% @ 3 TeV
  0.75% @ 10 TeV
  0.50% @ 14 TeV

- Channel: ZZ-fusion + forward μ detection
- Detector requirement: tagger |η|<6

$\mu^+\mu^- \to \nu\bar{\nu}$ HHH (VBF) — representative diagram, arXiv:2003.13628 fig.1 top-left



Bottom line: The muon collider is the **only proposed machine** that can measure λ_4 and extract Γ_H directly — both unique to μC.

Higgs Production at the Muon Collider — Stage-by-Stage Yields

All energies refer to √s of $\mu^+\mu^-$ collisions. "—" = channel inaccessible at this stage (kinematically forbidden or sub-dominant).

Process ($\mu^+\mu^- \to$ ...)	125 GeV	3 TeV	10 TeV	14 TeV
σ(VBF → H) [fb]	—	900	3300	4500
σ(VBF → HH) [fb]	—	1	8	15
σ(VBF → HHH) [ab]	—	—	few	few
σ(s-channel μμ→H) [fb]	35 (peak)	—	—	—
σ(Zh) [fb]	—	10	6	4
Total Higgs (typical L_{int})	~50k / 1 fb^{-1}	900k / 1 ab^{-1}	**33M / 10 ab^{-1}**	**90M / 20 ab^{-1}**

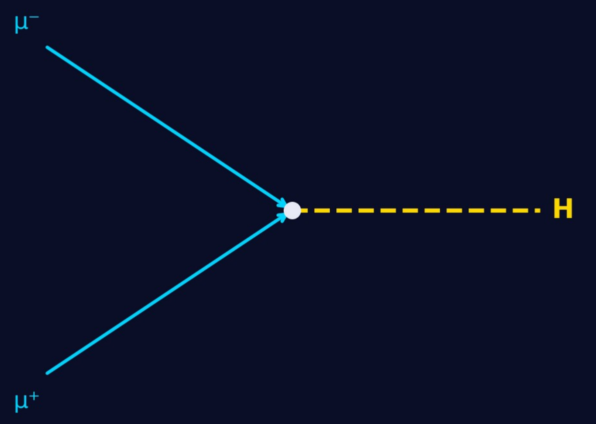
Bottom line: 10 TeV $\mu^+\mu^-$ produces **33M Higgs in 10 ab^{-1}**,
exceeding the FCC-ee Higgs sample (~3M) by 10×
in 1/5th the energy footprint (11.4 km ring vs 91 km).

Full-sim @ 3 TeV (arXiv:2405.19314): $H\to b\bar{b}$ Δσ/σ=0.75%, H→WW* 2.9%, H→γγ 7.6%
@10 TeV ZZ-fusion (arXiv:2401.08756): Δσ/σ=0.75% with |η_μ|<6; *H→ττ 1.3% (arXiv:2601.01674)*
VBF dominant at multi-TeV; s-channel only at √s≈125 GeV; Zh sub-dominant but clean for $H\to b\bar{b}$ tagging

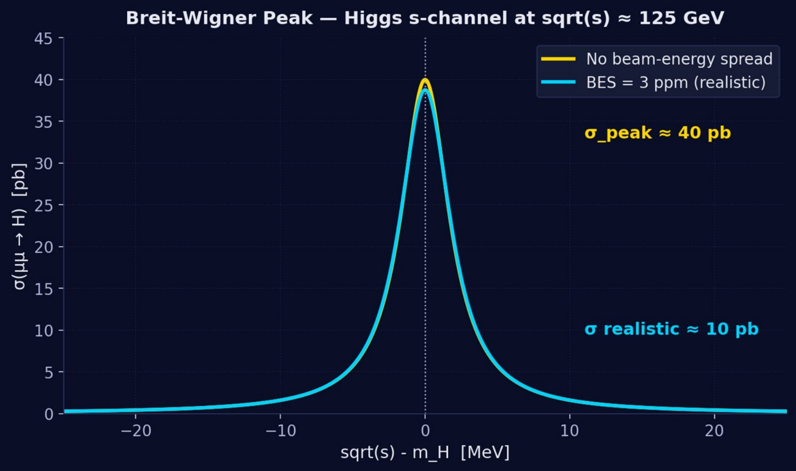
σ(VBF→H/HH/HHH) table values — arXiv:2103.14043 (Snowmass), arXiv:2308.02633 (Forslund & Meade); ZZ-fusion + forward μ Δσ/σ=0.75% — arXiv:2401.08756 (2024); full-sim @ 3 TeV ($H\to b\bar{b}$ 0.75%, H→WW 2.9%, H→γγ 7.6%) — arXiv:2405.19314; H→ττ Δσ/σ=1.3% @10 TeV — arXiv:2601.01674.*

s-channel $\mu^+\mu^- \to H$ — Higgs Factory at $\sqrt{s}$ = 125 GeV

Only the muon collider can directly produce H in the s-channel. *Yukawa enhancement $y_\mu^2 / y_e^2 \approx 4.3 \times 10^4$ vs e^+e^-.*



s-channel $\mu^+\mu^- \to H$ resonance



$\sigma(\mu\mu \to H)$ Breit-Wigner peak at $\sqrt{s}$ = 125 GeV

$$\sigma(\mu^+\mu^- \to H) = (4\pi / m_H^2) \cdot \Gamma(H \to \mu\mu) \cdot \Gamma_H \;/\; [(\sqrt{s} - m_H)^2 + \Gamma_H^2 / 4]$$

$$\to \sigma_{peak}(\sqrt{s}=m_H) = (16\pi / m_H^2) \cdot BR(H \to \mu\mu) \approx 40 \text{ pb (zero BES)}$$

$\to$ ~10 pb realistic with BES R ≈ 0.003% $\to$ ~50 000 H per fb^{-1}

vs e^+e^- Higgs factory ($\sqrt{s}$ = 125 GeV): σ_peak(ee→H) ≈ 0.6 fb → $y_\mu^2 / y_e^2 \approx 4.3\times10^4$ enhancement
Unique to μC: direct Γ_H measurement to O(100 keV) (model-indep.); m_H to 1 ppm via threshold scan; line-shape access.

Why s-channel @ μC

- **$y_\mu^2 \approx 4.3\times10^4 \times y_e^2$**
  enables Higgs as a narrow resonance
- **Direct probe of H–μμ Yukawa**
  inaccessible at e^+e^- machines
- **Direct Γ_H to O(100 keV)**
  model-independent (no SM assumptions)
- **m_H to 1 ppm via line-shape scan**
  full Γ_H / m_H extraction in single facility

Technical requirement

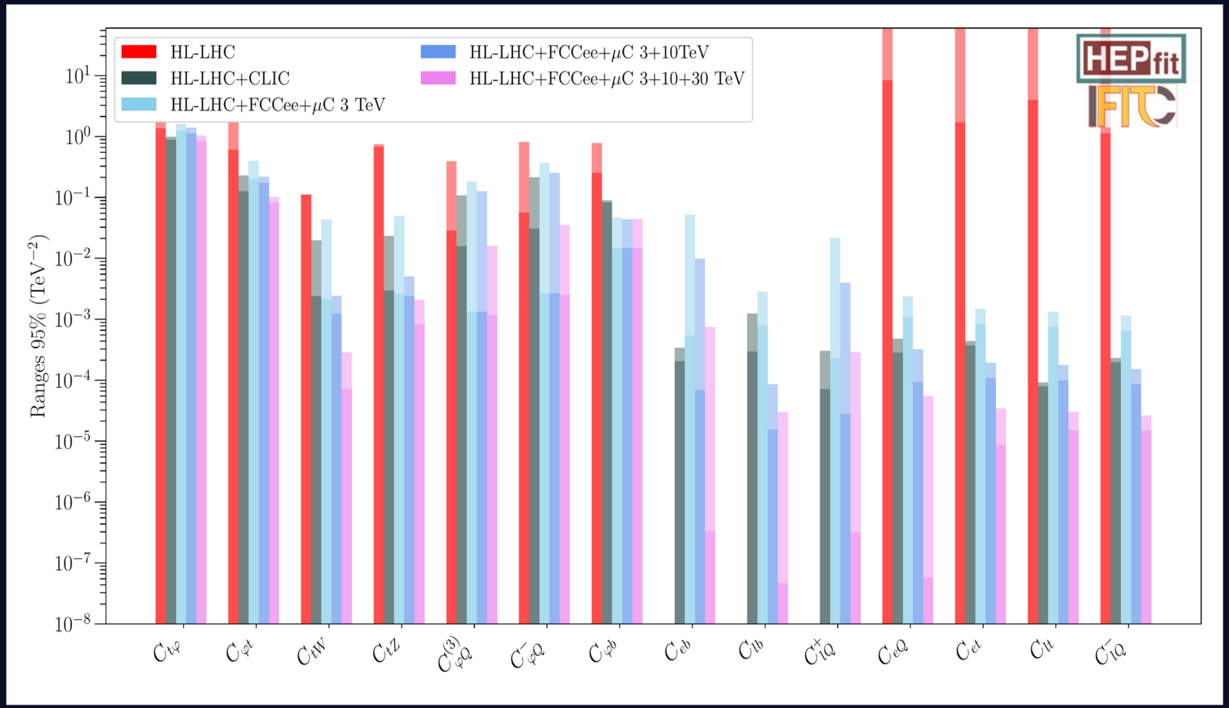
- Beam-energy spread **R = ΔE/E ≈ 0.003%**
  (i.e. ~4 MeV at $\sqrt{s}$=125 GeV)
- Threshold scan over ≈ 4 Γ_H ≈ 16 MeV

Refs: arXiv:2104.05770, 1901.06150, JHEP 08 (2024) 021, 2203.08033

σ_peak≈40 pb, σ_eff with BES 3 ppm — arXiv:2104.05770 (Franceschini & Greco 2021); m_H to 1 ppm via threshold scan — arXiv:1901.06150 (Bartosik et al.); Γ_H model-independent extraction & full scan — arXiv:2203.08033 = JHEP 08 (2024) 021.

Top Quark — Ultimate Precision Across All Observables

Observable	HL-LHC	FCC-ee	ILC-500	μC-3T	μC-10T
m_{top} [MeV]	~300	~20	~50	~50	~20
y_t Yukawa	~10%	~3%	~3%	~2%	**~1%**
Q_t via tt̄γ [%]	~5-10	—	~3	~1.5	**<1**
EW dipole c_{tB} Λ [TeV]	~2.3	—	~5	~8	**13-15**
FCNC Ztc BR	10^{-4}	10^{-5}	10^{-5}	10^{-5}	**10^{-6}**
Composite top Λ	~5 TeV	~10	~10	~20	**>50 TeV**



Top SMEFT operators μC vs CLIC — arXiv:2503.11518

Mega-top factory: O(10^6) tt̄ events @10 TeV / 10 ab^{-1}; **μμ→tt̄h** uniquely available (VBF-dominated above 4-5 TeV; inaccessible at LHC)

Unique SMEFT reach: $\ell^+\ell^-Q\bar{Q}$ four-fermion operators inaccessible at hadron machines; top EW dipole Λ/√|c_{tB}**| ≈ 13-15 TeV** (HL-LHC ≈ 2.3 TeV)

Production modes: s-channel Z*/γ* threshold scan (3T); VBF μμ→ν̄ν tt̄ dominates >6 TeV; tt̄H, tt̄Z @10/14 TeV.

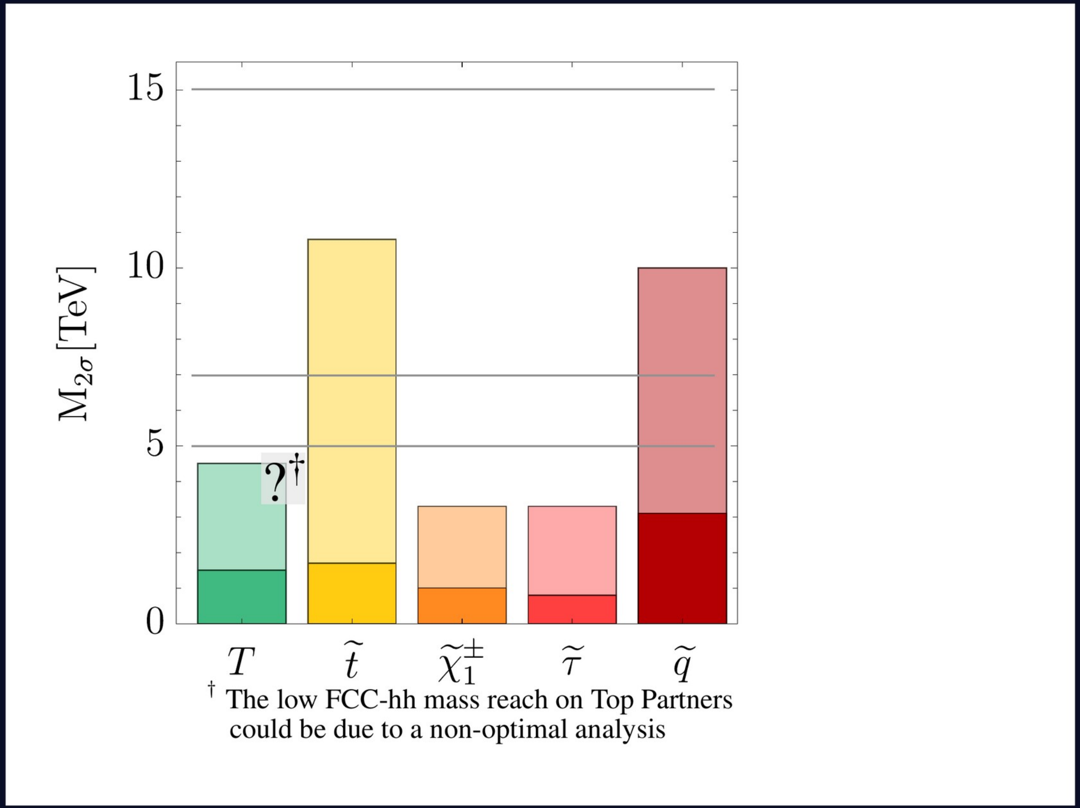
All values: $\mu^+\mu^-$ at indicated √s, 10 ab^{-1}. Refs: arXiv:2410.11015, 2503.11518.

10 TeV μC: leading constraints on all top observables. 14 TeV stage pushes y_t to 0.5%.

comparison table & top EW dipole Λ~13-15 TeV — arXiv:2410.11015 (Han-Liu-Wang 2024); SMEFT figure (right panel, top operators μC vs CLIC) — arXiv:2503.11518 (2025); $\ell^+\ell^-Q\bar{Q}$ four-fermion & EW diboson indirect reach — arXiv:2203.07256.

Direct BSM Mass Reach — Pair-Production at the $\mu^+\mu^-$ Frontier

All energies = √s of $\mu^+\mu^-$ collisions; pair-production kinematic limit $m \lesssim \sqrt{s}/2$. VBF opens single-production above this threshold.



Pair-production 2σ reach across particles — arXiv:2303.08533 Fig. 3

Pair-production rule:

$m \lesssim \sqrt{s} / 2$

μC-3 TeV ($\sqrt{s}$ = 3 TeV, 1 ab^{-1}):
- sleptons, weakly charged ~1.5 TeV
- Higgs compositeness Λ ≈ 20 TeV
- probe natural SUSY (m_χ ≲ 1.5 TeV)

μC-10 TeV (10 ab^{-1}):
- stops, charginos, heavy scalars ~5 TeV
- leptoquarks, vector-like leptons
- 2HDM partners, doubly-charged scalars

μC-14 TeV (20 ab^{-1}):
- extended pair reach ~7 TeV
- 5-plet MDM 10-15 TeV begins
- Z'/W' Drell-Yan resonances

Beyond pair production:
- VBF single-production windows
- Indirect (EFT) probes to O(0.1 PeV)
- Colour-charged via gluon/quark PDF
  (stops, gluinos, coloured LQs) [arXiv:2502.20443]
- Inert Doublet Model (IDM) via VBF @10 TeV
  [arXiv:2411.13729]

Thermal-DM benchmarks: where μC pair-production lands

- Higgsino (Δm≈344 MeV, m_th=1.1 TeV): **μC-3T already covers via soft tracks + DT [arXiv:2405.08858]**
- Wino (Δm=166 MeV, m_th=2.7-2.9 TeV): **μC-10T discovery via disappearing tracks @ r_min=10.2 cm [arXiv:2102.11292]**
- 5-plet MDM (hyper-stable, m_th=10-14 TeV): **μC-14T partial coverage; mono-W/Z/γ EFT to 12-15 TeV [EPJC 83 (2023) 1122]**

→ first machine to cover the full thermal-WIMP catalogue end-to-end.

central figure (pair-production 2σ reach) — arXiv:2303.08533 Fig.3 (Accettura et al., IMCC 2023); mass-reach numbers & BSM catalogue — arXiv:2103.14043 (Snowmass); coloured particles via gluon/quark PDF — arXiv:2502.20443 (Han et al. 2025); Inert Doublet Model via VBF @10 TeV — arXiv:2411.13729.

BSM Spectroscopy at μC — SUSY, Extended Scalars, Heavy Resonances

Reach values shown per √s stage (3 / 10 / 14 TeV of $\mu^+\mu^-$ collisions). VBF + pair production combined; all reach numbers are 2σ unless noted.

SUSY

@ 3 TeV: sleptons up to ~1.5 TeV; light charginos

@ 10 TeV: stops, charginos, neutralinos up to ~5 TeV

@ 14 TeV: extended ~7 TeV; natural SUSY parameter space [Baer 2024]

Methods: pair production + VBF; threshold scans for precision

Searches: long-lived particles (LLPs); coloured states via VBF

Refs: arXiv:2502.20443; arXiv:2103.14043; Baer 2024

Extended Scalars

@ 3 TeV: 2HDM (H,A,H±): $\sigma=10^{-2}$-10^2 fb for m=0.6-1.8 TeV

@ 10 TeV: 2HDM up to ~5 TeV [arXiv:2507.21910 Tab.3]

@ 14 TeV: extended ~7 TeV; doubly-charged $H_5^{\pm\pm}$

Singlet: scalar singlet excluded to ~15 TeV via VBF

Compositeness: Higgs/top compositeness Λ ~20-50 TeV

Refs: arXiv:2507.21910, 2203.07256, 2508.04493

Z' / W' / Heavy res.

@ 3 TeV: Z'/W' up to ~6 TeV via Drell-Yan

@ 10 TeV: Z'/W' up to ~10 TeV; EFT 4-fermion Λ ~100 TeV

@ 14 TeV: Z'/W' up to ~14 TeV; resonance line-shape scans

Channels: DY pair-production + VBF mono-W/Z

HNL: heavy Majorana ν via same-sign leptons

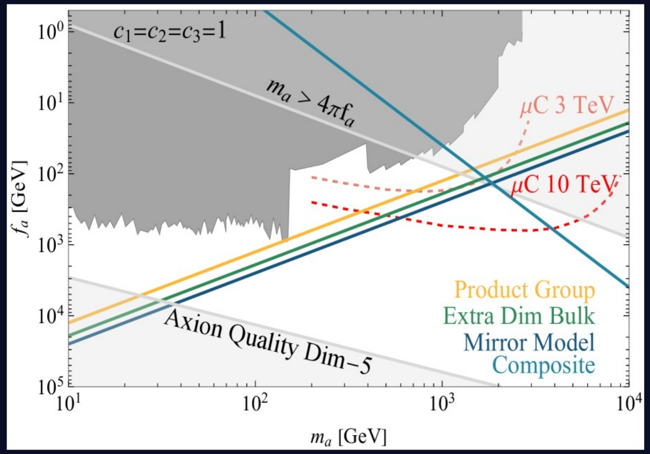
Refs: arXiv:2103.14043 (Snowmass); arXiv:2506.06159 (VBF HNL)

μC explores TeV-scale BSM via multi-channel sensitivity — covers naturalness, composite Higgs, heavy Majorana ν, and the full Z'/W' frontier.

SUSY reach (sleptons/stops/charginos) — arXiv:2502.20443 (Han et al. 2025), arXiv:2103.14043 (Snowmass); Extended Scalars / 2HDM σ & singlet exclusion — arXiv:2507.21910 (Robens-Santos 2025), arXiv:2203.07256; compositeness Λ~20-50 TeV — arXiv:2508.04493; Z'/W' Drell-Yan reach — arXiv:2103.14043 (Snowmass), arXiv:2308.02633 (Forslund-Meade); VBF heavy Majorana ν — arXiv:2506.06159 (Dehghani et al. 2025).

Heavy QCD Axions & Lepton-Flavour Violation

Heavy QCD Axions



Combined (m_a, f_a) — arXiv:2509.10605

- Combined (m_a, f_a) sensitivity from 3T+10T
- Mass range: 1 GeV - 10 TeV
- Couplings: $g_{a\gamma}$, g_{aWW}, g_{ahh}
- UV completions overlaid
  (Composite Higgs, mirror models)

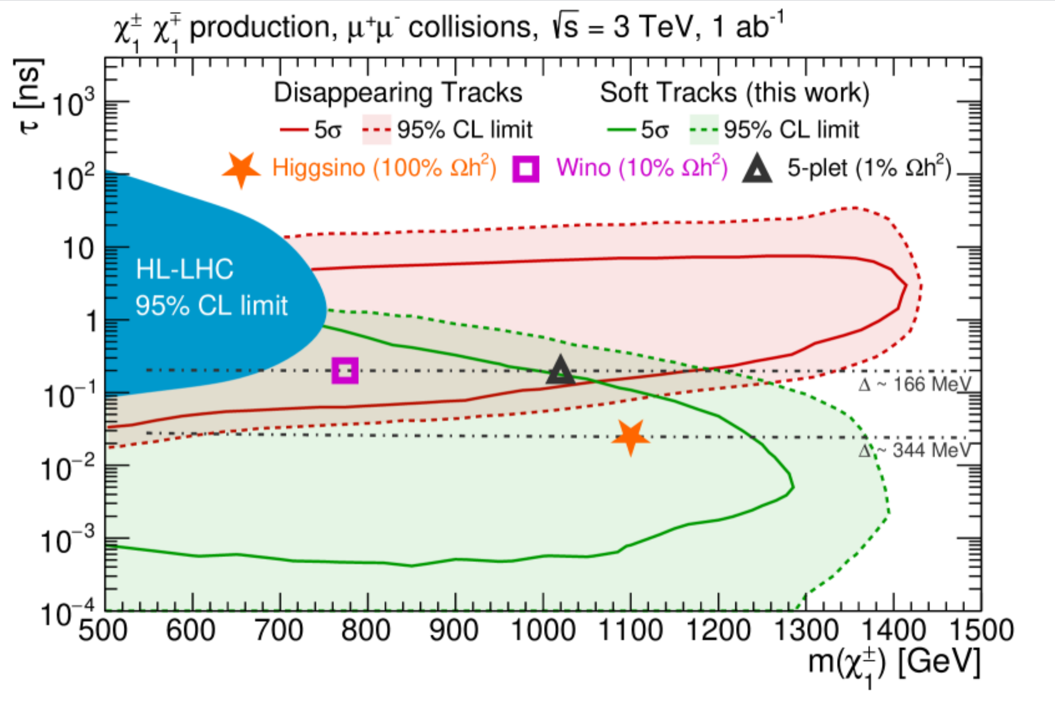
[arXiv:2509.10605]

LFV & Heavy Neutral Leptons

- **SMEFT LFV operators (μ-e, τ-e, τ-μ)**
  [Asadi et al., arXiv:2509.22771]
  Reach in same-sign / opposite-sign leptons
- **HNL via VBF same-sign lepton signal**
  [arXiv:2504.21417, 2506.06159]
  Reach m(HNL) up to ~100 TeV via VBF @ 10 TeV
- **MeV-scale HNL via beam-dump (μ-on-Cu)**
  [JHEP 05 (2024) 283]
- **Gauged $L_\mu - L_\tau$ Z': only μ/τ/ν coupling**
  covers full $(g-2)_\mu$ + B-anomaly region @ $M_{Z'}$ > 100 GeV
  g' ~ 4×10^{-3} @ $M_{Z'}$ = 1 TeV via ISR [arXiv:2101.04956]
- **Per-operator EFT scales Λ ~50-100 TeV**
- **LFV-ALP fixed-target μA→τAa**
  [arXiv:2407.15942]: C_μτ/Λ ~ 1 TeV^{-1} @ 10^{16} MOT (TeV μ-beam on target)

heavy QCD axion (m_a, f_a) sensitivity — arXiv:2509.10605 (2025); SMEFT LFV operators (μ-e, τ-e, τ-μ) — arXiv:2509.22771 (Asadi et al.); HNL via VBF same-sign leptons up to ~100 TeV — arXiv:2504.21417, arXiv:2506.06159; MeV-scale HNL via beam-dump — JHEP 05 (2024) 283; gauged L_μ-L_τ Z' g'~4×10^{-3} @ M_Z'=1 TeV — arXiv:2101.04956.

Complete WIMP Dark-Matter Coverage



Soft-track minimal DM reach — arXiv:2405.08858

Higgsino ($m_{thermal}$ = 1.1 TeV):

accessible already at 3 TeV

via disappearing / soft tracks

[arXiv:2405.08858, Capdevilla et al.]

Wino (m = 2.7 TeV):

accessible at 10 TeV μC via disappearing tracks

[arXiv:2102.11292]

5-plet MDM (10-15 TeV):

begins to be covered at 14 TeV

Indirect EW probes up to O(0.1) PeV

via VBF mono-W/Z/γ [EPJC 83 (2023) 1122]

(g−2)_μ no-lose theorem:

5-step energy ladder guarantees BSM discovery

[arXiv:2101.10334, Capdevilla et al.]

Indirect test μμ→hγ:

$\sigma \propto E^2$, ~63 events @ 30 TeV

no hadronic uncertainty; EDM $d_\mu \lesssim 3\times10^{-22}$ e·cm

[arXiv:2012.02769, 2012.03928]

First machine to cover ALL thermal WIMP scenarios

soft-track MDM reach plot (Higgsino 1.1 TeV @ 3T) — arXiv:2405.08858 (Capdevilla et al. 2024); Wino disappearing tracks @ 10 TeV — arXiv:2102.11292; complete thermal-WIMP coverage / mono-W/Z/γ — EPJC 83 (2023) 1122 (Franceschini et al.), arXiv:2203.07351; (g-2)_μ no-lose theorem — arXiv:2101.10334; indirect μμ→hγ (~63 events @30T) — arXiv:2012.02769, arXiv:2012.03928.

Quantum Information at the Electroweak Scale

- **Two processes complement each other:**
  $\mu^+\mu^- \to H \to ZZ \to 4\ell$ (VBF Higgs decay tomography)
  $\mu^+\mu^- \to ZZ$ (direct) — *non-entangled hypothesis rejected at 2σ*

- **Bell-inequality observable**
  $c_{MB}^2 > 1 \to$ entanglement; $c_{MB}^2 > 2 \to$ Bell violation
  PPT criterion + Negativity N(ρ) metrics

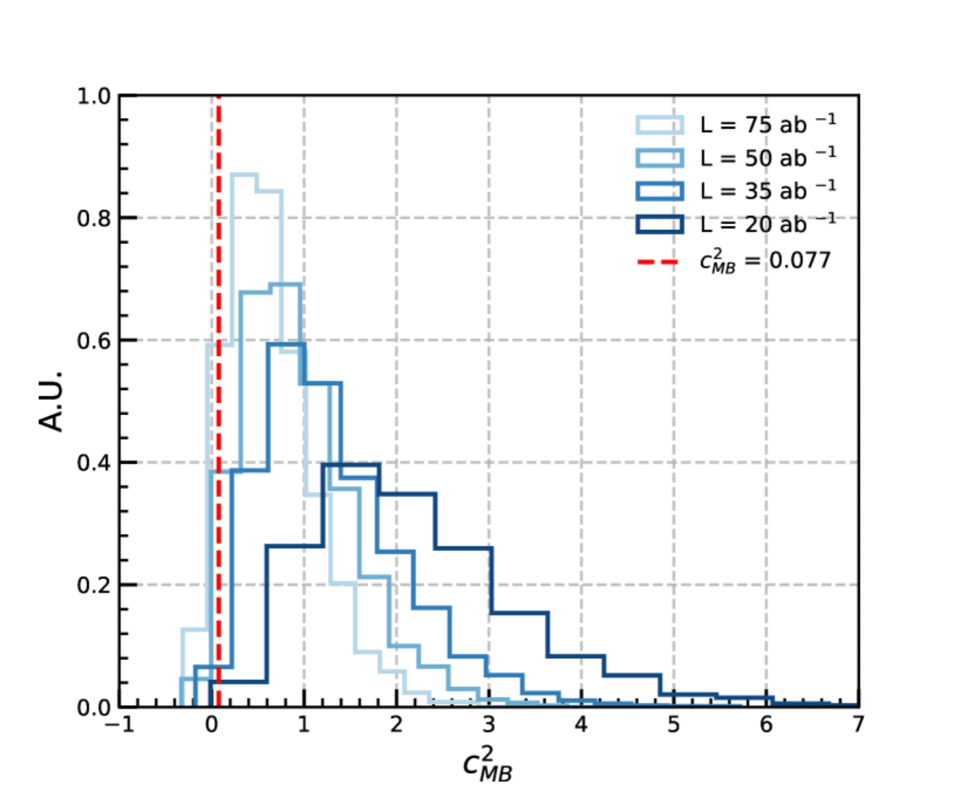
- Direct ZZ (75 ab^{-1} @ 10 TeV): **non-entangled rejected at ~2σ** — *arXiv:2504.09832*
- VBF $H \to ZZ \to 4\ell$ (30 ab^{-1}): **up to 4σ via CGLMP $I_3 \approx 2.5$-2.66** — *arXiv:2408.05429*
- **Three independent metrics confirm entanglement:**
  PPT criterion, Negativity N(ρ), Concurrence C(ρ)

- 5σ requires extended stages or 30 TeV

- **First quantum-information measurements above the electroweak scale**
  (LHC has tested tt̄/ZZ at lower energies only)

- Probes potential decoherence at high energies
- Tests of QM in a new regime

[arXiv:2504.09832, 2408.05429 — direct ZZ analyses]



Bell observable c_MB² — arXiv:2504.09832

direct μμ→ZZ Bell observable c_MB² (non-entangled rejected ≥2σ) — arXiv:2504.09832 (Ding et al. 2025); VBF H→ZZ→4ℓ Bell inequality via CGLMP (up to 4σ @30 ab⁻¹) — arXiv:2408.05429 (Aoude et al. 2024).

Neutrino Programmes from Muon Decays

Collimated ν beam

- μ-decay → 50% ν_μ + 50% $\bar{\nu}_e$
  well-characterised flux + composition
- Forward neutrino detector concept
  located near the storage ring
- **EW precision: $\sin^2\theta_W$ to 0.003% ($\delta \approx 3\times10^{-5}$)**
  via ν-e elastic scattering
  [arXiv:2505.00152]
- Compatible with main collider operation
- **Order-of-magnitude improvement vs NuTeV**
- **Neutrino trident $\mu N \to \mu^+\mu^-\mu N$**
  sensitive to L_μ-L_τ, W self-coupling

ν-portal DM & BSM probes

- **Neutrino-portal DM searches**
  [PRD 111 (2025) 075019]
  ν + DM portal → mono-jet / mono-γ
  improvement of 10× over LHC
- **Beam-dump with accelerated μ**
  muonophilic BSM (HNLs, dark photons, ALPs)
  [JHEP 05 (2024) 283]
- LFV from neutrino oscillations probed in ν beam
- **Beam-dump 0.1-10 GeV ALP / HNL window**
- **μOST fixed-target programme**
  ring-decay muon beam → nucleon structure (TMDs)
  next-generation beyond EIC [arXiv:2506.19301]
- Complementary to FNAL, J-PARC, ESS programmes
- **LFV ALP fixed-target $\mu A \to \tau A a$**
  C_μτ/Λ ~ 1 TeV^{-1} @ 10^{16} MOT [arXiv:2407.15942]
- *μTRISTAN $\mu^+\mu^+$ mode: complementary HNL reach*
  [arXiv:2506.06159]

μC as a ν-physics + BSM-portal facility — beyond the energy frontier

- **EW precision:** $\delta(\sin^2\theta_W) \approx 3\times10^{-5}$ — comparable to LEP+SLD, **10× over NuTeV**
- **BSM portals:** ν-portal DM (10× over LHC), HNL via beam-dump (0.1–10 GeV ALP/HNL window), LFV ALP fixed-target
- **Fixed-target programmes:** μOST nucleon TMDs (next-gen beyond EIC), muonophilic searches — **inaccessible at HL-LHC**
- **Synergy:** *ν beam shares storage-ring infrastructure — added physics value at zero extra cost*

$\sin^2\vartheta$_W to 0.003% ($\delta \approx 3\times10^{-5}$) via ν-e elastic scattering — arXiv:2505.00152; ν-portal DM (ν+DM→mono-jet/γ, 10× over LHC) — PRD 111 (2025) 075019; beam-dump muonophilic BSM (HNL, dark photons, ALPs) — JHEP 05 (2024) 283; μOST fixed-target nucleon TMDs — arXiv:2506.19301 (Klest, PRD 2025); LFV ALP μA→τAa — arXiv:2407.15942.

Technical Challenge #1 — Muon Lifetime → Fast Acceleration Chain

Muons decay in 2.2 μs (rest frame). Must ***produce + cool + accelerate + collide*** *— all before the beam decays.*

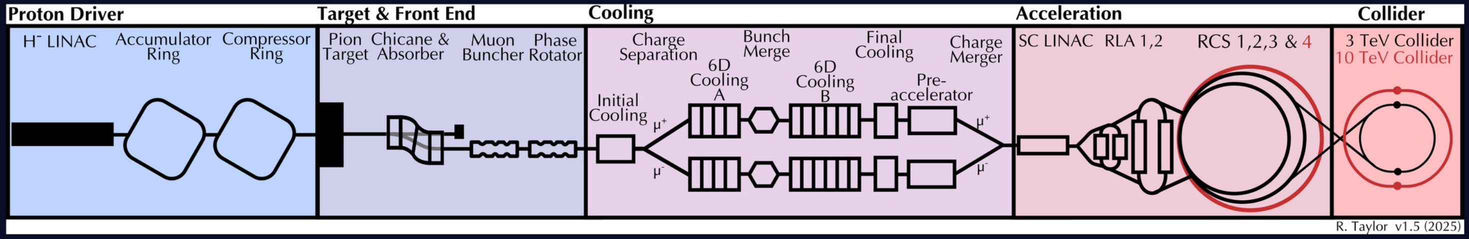
τ_0 = 2.2 μs (at rest)

$\tau_{lab} = \gamma \cdot \tau_0$

At 5 TeV/beam:
$\gamma \approx 4.73\times10^4$
→ τ ≈ 104 ms
→ ~1000 turns / lifetime

Beam energy	γ·τ
1.5 TeV	33 ms
5.0 TeV	104 ms
7.0 TeV	145 ms

MS7 driver: 5 GeV / 2 MW (baseline) · **10 GeV / 4 MW** (option)
Ring 10 TeV: C = 11.4 km, $L = 18\times10^{34}\ cm^{-2}s^{-1}$, wall power ~230 MW (vs ~550 MW FCC-hh)
Strategy: *produce → cool → accelerate fast — <0.5 s, ~5 turns/RCS,* ***>50%***



MuCol accelerator complex (2025) — arXiv:2510.27437

Acceleration chain (MS7 baseline)

- Front end: pre-accelerator + initial cooling (~0.25 GeV)
- 6D ionization cooling: 6 stages, $\varepsilon\perp \div 10^5$; $\varepsilon\| \div 10^2$
- Final cooling: 32 T HTS solenoids → $\varepsilon\perp \approx 25$ μm·rad
- Linac + RLA: 0.25 → 5 GeV → 250 GeV
- **4 RCSs: 250 GeV → 1.5 TeV → 5 TeV (≤5 turns each)**
- **Collider ring: 5 TeV/beam, 11.4 km, B_arc ≈ 14 T**

Total muons: produce → collide in <0.5 s, >50% transmission

Proton driver → Target → Cooling → RCS → Collider Ring

accelerator complex diagram (right image) & MS7 driver / RCS / collider — arXiv:2510.27437 (MuCol MS7 2025); τ_0 / γ·τ formula + beam-energy table — arXiv:2303.08533 (Accettura et al., IMCC EPJC 2023).

Technical Challenge #2 — Ionization Cooling, the Gating Technology

Standard cooling (synchrotron, electron, stochastic) is too slow for muons. ***Ionization cooling*** *reduces emittance in microseconds — but had to be demonstrated.*

$$d\varepsilon_\perp/ds = -\langle dE/ds\rangle \cdot \varepsilon_\perp/(\beta^2 E) + (13.6\ \text{MeV})^2 \cdot \beta_\perp/(2\beta^3 E \cdot m_\mu \cdot X_0)$$

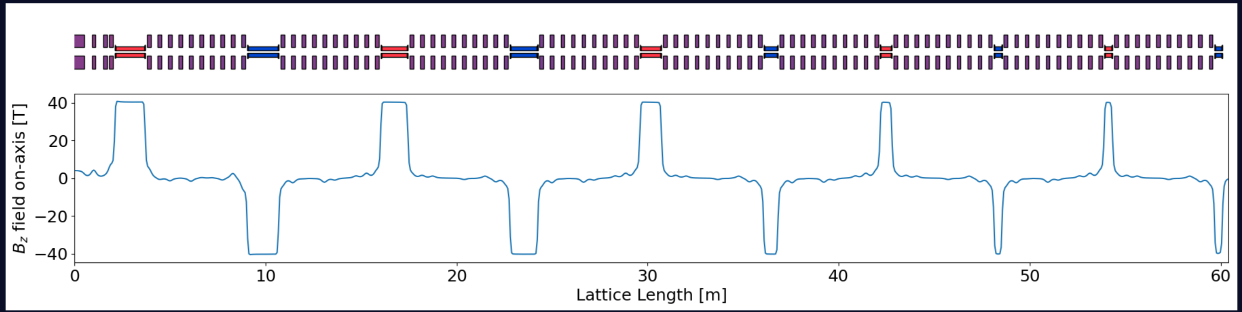
- Energy-loss cooling balanced by multiple-scattering re-heating
- Cooling minimum ε_min at this balance
- Best absorber: liquid H_2 (low Z); LiH practical

- **MICE Nature 578 (2020): first demonstration** — −6% transverse ε for 140 MeV/c μ, LiH/LH_2 in 4 T
- MICE Nature Phys. (2024): detailed transverse-emittance analysis

- **6D demonstrator timeline:**
  site **TT7/CTF3 @ CERN** (preferred) or Fermilab-MTA; CDR ~2030 → build 2032-36 → beam ~2038
  RF: 704 MHz normal-conducting between absorbers; budget ~400 MCHF + 446 FTE-yr

- Full chain: $\varepsilon_\perp$ **reduced by ×10^6** → 25 μm, $\varepsilon_\parallel$ → 0.025 eV·s

Open MS7 challenge: *transmission 2.5×10^{12} achieved vs 3.6×10^{12} target — final-cooling stages still under R&D*



MuCol 6D cooling chain — arXiv:2510.27437

Cooling stage breakdown

- Initial 4D cooling: μ ~200 MeV/c in LH_2/LiH absorbers
- Charge separation + bunch merging (6×→1)
- Rectilinear (Stages A1–A4): ε⊥ ×30 ÷
- Bunch recombination & longitudinal cooling
- Final cooling: 32 T HTS solenoids, low-β focusing

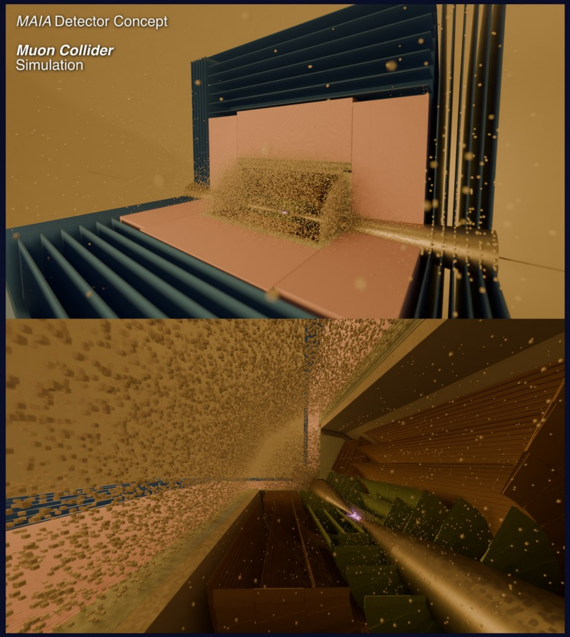
Result: ε⊥ ≈ 25 μm·rad, ε‖ ≈ 25 meV·s
→ luminosity × 10^5 relative to uncooled muons

6D cooling demonstrator (~2038) is the gating element for project approval

dε⊥/ds formula & absorber physics — PDG/Berestetskii (textbook); MICE −6% emittance demonstration — Nature 578 (2020) 53 (MICE Collaboration); MICE 6D transverse emittance — Nature Phys. 20 (2024) 1583; 6D cooling chain layout + demo timeline TT7/CTF3 — arXiv:2510.27437 (MuCol MS7 §14).

Technical Challenge #3 — Beam-Induced Background (BIB)

Source: $\mu \rightarrow e + \nu + \bar{\nu}$ → ~4×10^5 decays per metre of ring → flood of e±, γ, n into detector. Mitigation: shielding + timing + granularity.



MAIA detector with BIB shower — arXiv:2502.00181

Mitigation pyramid

1. Shielding — Tungsten + borated-poly nozzles
angular cut |cosθ| < 0.99 (~10° dead zone)

2. Timing — sub-ns hit time-of-arrival
20-50 ps resolution → reject delayed BIB

3. Granularity — 5 µm pixels, fast electronics
tracker occupancy ~10 GHz/cm²

4. BIB-aware algorithms — pattern recognition
rejecting fake clusters in tracking + calorimetry

Two official 10 TeV detector concepts

MAIA (arXiv:2502.00181, Jan 2025) — 5 T solenoid, **30 ps** VXD timing, Si-W ECAL
MUSIC (arXiv:2511.23273, Nov 2025) — 5 T solenoid, **30-60 ps** tracker, BIB-aware calo

→ Reconstruction efficiency >95% under realistic BIB *(BIB ~600 000 hits/event vs ~250 signal at 1.5 TeV)*

Why BIB is unique to µC

- Muon decay produces real, energetic e±
- Geant4 + FLUKA: showers of MeV-GeV particles
- Up to 10^5 hits/event without mitigation
- Cascades in nozzle materials → delayed secondaries
- **@10 TeV — second BIB source:** incoherent e^+e^- pair production

BIB source rates (~4×10^5 decays/m) & shielding strategy — arXiv:2203.06773 (Ally et al., Snowmass 2022); MAIA concept + BIB illustration (left image) — arXiv:2502.00181 (MAIA, Jan 2025); MUSIC concept specs — arXiv:2511.23273 (MUSIC, Nov 2025); incoherent e^+e^- pairs @10 TeV (2nd BIB source) — arXiv:2311.03280 (Annual Review 2024); occupancy numbers — arXiv:2510.27437 Tables 7.3-7.5 (MS7).

Hardware Demonstrators — Magnets · Target · Cooling Demo

Distributed R&D: HTS magnets — Fermilab & CERN & NHMFL; Target — CERN & BNL/MERIT; Cooling demo — CERN/Fermilab (site TBD)

HTS Magnets — 3 classes

Where: Fermilab, CERN, NHMFL FL, BNL/LBNL

Capture solenoid: 20 T @ 20 K REBCO, 1 m bore

Collider dipoles: 14 T HTS arc — MS7 baseline

Cooling solenoids: 30-40+ T REBCO (final stage R&D)

RCS ramp: ~300 T/s normal-conducting + HTS arcs

Records: 14.1 T HTS @FNAL 2024; 32 T NHMFL 2022; 45.5 T 2019

Budget: 82.5 M CHF + 414 FTE-yr (IMCC 10-yr plan)

Refs: arXiv:2510.27437, 2503.21185

Target Station

Where: CERN (design); BNL/MERIT legacy

Proton driver: 5 GeV/5 MW (10 MW option) — MS7

Baseline: Graphite + 20 T capture solenoid

Alternatives: liquid Hg, Ga, fluidised W

Demonstrated: MERIT 2007 — Hg-jet proof-of-concept

Optimisation: FLUKA geometry [arXiv:2602.16672]

Challenge: radiation tolerance, He-cooled shielding

Refs: arXiv:2510.27437; arXiv:2602.16672

Cooling Demonstrator

Where: CERN North Area or Fermilab MTA

Goal: multi-cell 6D ionization cooling

Components: 21 RF cells × LiH absorbers + solenoids

Schedule: CDR ~2030 → construction 2032-36 → beam 2038

Budget: ~400 M CHF

Heritage: MICE 2008-18 + Nature 578 (2020) demo

Why gating: no demo = no project approval

Refs: Nature 578 (2020); arXiv:2510.27437

Three distributed programmes — HTS, target, cooling demo — converge to support the IMCC technical schedule

HTS magnet specs (REBCO records, 82.5 MCHF / 414 FTE-yr) — arXiv:2503.21185 (IMCC Magnet WG 2025), arXiv:2510.27437 (MS7); target FLUKA geometry (graphite + Ga/W alternatives) — arXiv:2602.16672 (Al-Harthy 2026); cooling-demo heritage — Nature 578 (2020) (MICE), MERIT 2007 (BNL/CERN Hg-jet); RCS / overall schedule — arXiv:2510.27437.

Existing Projects & R&D Programmes — Who is Building Toward a μC?

Four flagship efforts spanning Europe, USA, and historic UK work — coordinated under IMCC.

IMCC — International (CERN)

Founded: 2020, post European Strategy 2020
Scope: 10 TeV μC design — accelerator, detectors, physics
People: >450 researchers, 61+ institutes, 18 countries
Key output: Towards a Muon Collider, EPJC 83 (2023) 864
Next milestone: Evaluation Report Q1 2026 (input to ESG)
Web: muoncollider.web.cern.ch

MuCol — EU Horizon Europe

Period: Mar 2023 – Feb 2027 (€2.195 M EU funding)
Partners: 32 institutes, 10 EU countries; CERN-coordinated
Workpackages: WP1 physics · WP2 design · WP3 magnets · WP4 cooling
Deliverables: 7 milestone reports, regular ESG updates
Latest output: arXiv:2510.27437 — Consolidated Parameters (Oct 2025)
Status: On schedule; demo CDR planning underway

USMCC — United States (formed Feb 2026)

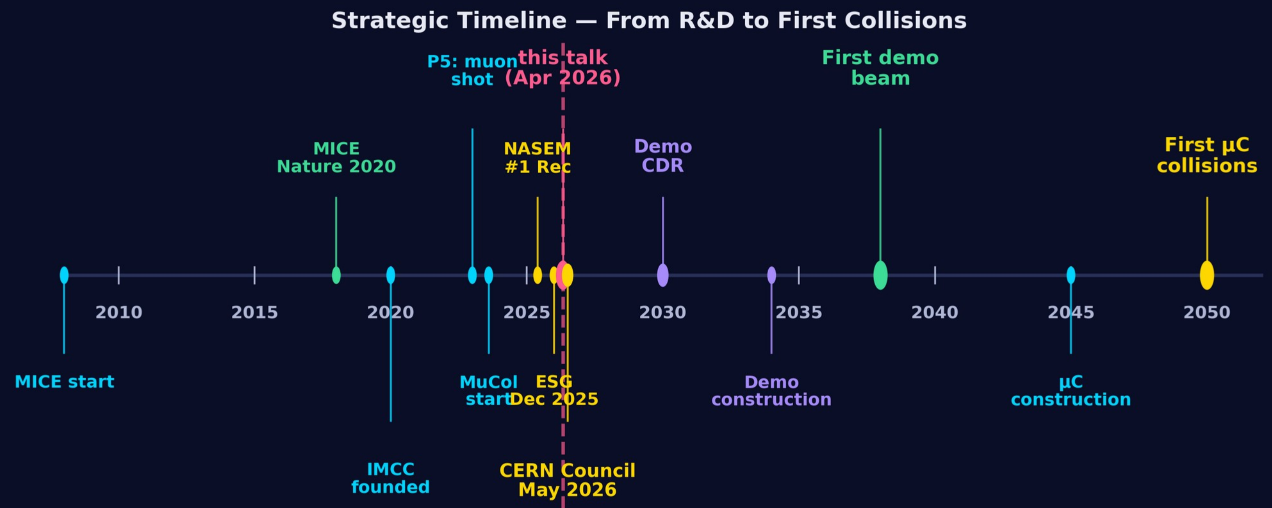
Lead labs: Fermilab + ANL + BNL + universities
P5 (2023): muon-shot priority in HEP strategy
NASEM (Jun 2025): #1 recommendation to DOE — "US should build a μC"
White Paper: arXiv:2503.23695 (326 authors)
US Input ESPPU 2026: arXiv:2602.15295 — 50%/50% US-EU aspiration
Site option: Fermilab Main Injector / MTA candidate

MICE — RAL (completed 2018)

Period: 2008-2018 at Rutherford Appleton Lab, UK
Goal: demonstrate ionization cooling of muons
Key result: Nature 578 (2020) — first cooling demo, −6% transverse ε (140 MeV/c μ)
Follow-up: Nature Phys. (2024) — detailed transverse emittance
Materials: LiH and liquid H_2 absorbers, RF cells, solenoids
Legacy: Proof-of-principle for the full 6D μC cooling chain

IMCC card (>450 researchers, 61 institutes) — arXiv:2303.08533 (EPJC 2023), arXiv:2407.12450 (IMCC Interim 2024); MuCol card (MS7 deliverables) — arXiv:2510.27437; USMCC card (formed Feb 2026, 326 authors) — arXiv:2503.23695 (USMCC WP), arXiv:2602.15295 (US ESPPU input); MICE card — Nature 578 (2020) + Nature Phys. 20 (2024) 1583.

Strategic Landscape — Europe + USA + Roadmap



Europe — ESPPU & ESG

- **ESPPU 2020:** "bright muon beams" R&D endorsed (first European strategy mention)
- **ESG Dec 2025:** µC R&D "supported at appropriate level"; demo funding under negotiation
- **Next:** CERN Council May 2026 → final mandate
- **FCC-ee:** next CERN flagship; µC = longer-term high-energy frontier

USA — P5 2023 & NASEM 2025

- **P5 2023 Rec 4:** "realistic path to a 10 TeV pCM muon collider" — "Our Muon Shot"
- **NASEM 2025 Rec 1:** "host the world's highest-energy collider around the middle of the century"
- **USMCC WP (arXiv:2503.23695):** mid-2040s construction start, ~2050 first collisions
- **Host:** Fermilab candidate site; 326 authors on White Paper

Two independent strategic processes converge on the same technology:

- **CERN Council Budapest May 2026** → final ESG mandate expected; **USMCC formed Feb 2026** → 50 % US / 50 % IMCC aspirational R&D split

Europe card — ESPPU 2020 "bright muon beams"; ESG Dec 2025 (R&D for muon collider supported); USA card — P5 2023 Rec 4 "realistic path to 10 TeV pCM"; NASEM 2025 Rec 1 "host world's highest-energy collider mid-century"; timeline / USMCC formation — arXiv:2503.23695 (USMCC WP, 326 authors), arXiv:2602.15295 (US ESPPU input, Nov 2025).

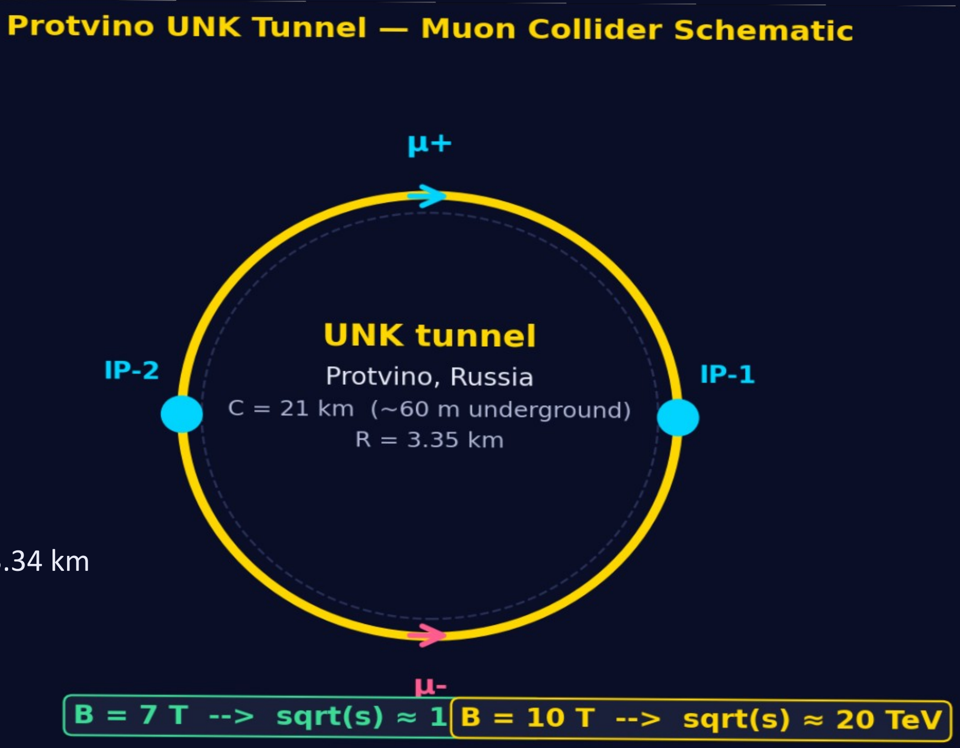
★ Protvino Tunnel Option (Russia, IHEP) — 21 km / 14–20 TeV

Existing infrastructure
- UNK tunnel at IHEP Protvino
- 21 km circumference, ~60 m underground
- Tunnel ~70% complete by 1991; excavation halted (never operational)
- **Tunnel + cooling water + electrical already in place**

Russian community heritage
- μC concept: Budker & Skrinsky (BINP, 1960-70s)
- Ionization cooling: Skrinsky & Parkhomchuk (BINP, 1981)
  — *foundational technique for entire programme*

Proposal & status
- ~15 TeV μC stage in existing 21 km ring
- HTS dipoles, B ≈ 7-10 T
- Russian physics community option
- *Detailed design study to be developed*

Fermilab alternative
- *~10 TeV pCM μC fits on Fermilab site (USMCC 2503.23695)*
- *Best power-per-luminosity efficiency*



Energy & footprint
- Ring rule B·R = p / 0.3 [GeV/c, m, T]; R = 21/(2π) ≈ 3.34 km
- **B = 7 T → √s ≈ 14 TeV (Nb₃Sn-class today)**
- **B = 7.5 T → √s ≈ 15 TeV (HTS-ready, design target)**
- **B = 10 T → √s ≈ 20 TeV (future HTS upgrade)**
- Pulsed power not required (DC operation in collider ring)

Physics output (applicable 14 TeV programme)
- Higgs: $\kappa_{W,Z}$ < 0.1%; λ_3 to 2.5%; **λ_4 measurable**
- Direct BSM: ~7 TeV pair-production reach
- **Complete WIMP DM (incl. 5-plet 10-15 TeV)**
- Top: y_t to 0.5%; Quantum-Bell 5σ achievable

Applicable 14 TeV references:
arXiv:2504.21417, 2103.14043, 2308.02633, 2503.11518

left panel infrastructure — UNK tunnel IHEP Protvino (21 km, ~70% complete by 1991); Russian heritage — Budker & Skrinsky μC concept (BINP, 1960s); Skrinsky & Parkhomchuk ionization cooling (BINP 1981); physics numbers (~15 TeV @ B≈7 T) — arXiv:2504.21417 (IMCC 2025), arXiv:2103.14043 (Snowmass), arXiv:2308.02633 (Forslund & Meade); Fermilab alternative — arXiv:2503.23695 (USMCC WP).

Beyond the Collider — Muon-Beam Programmes (Dual-Use Spectrum)

Six application domains for intense, directed μ-beams that share R&D base with a future muon collider.

μ-Catalyzed Fusion (μCF)

- μ^- replaces e^- → dtμ molecule (~500× smaller)
- d+t → ^{4}He+n + 17.6 MeV; ≈ 100-200 fusions / μ^-
- α-sticking ω ≈ 1% — break-even limiting factor
- Beam-driven; intrinsically safe (off ↔ stop)

Dzhelepov+ Nuovo Cim. 33 (1964) 40; Wu+ PRC 109 (2024) 054625

Muography (Muon Tomography)

- Cosmic μ ⟨E⟩ ≈ 4 GeV, 1 $cm^{-2}\cdot min^{-1}$ baseline
- Penetrates 100+ m of dense rock or metal
- Beams: tunable E & direction → precision NDT
- Pyramids · volcanoes · Fukushima · spent-fuel

Nature 552 (2017) 386; Saracino PoS-Muon4Future2023

Isotopic μ^- Analysis

- μ^- → K-shell mesoatom → muonic X-rays / γ
- X-ray energy ∝ Z; γ split by isotope (e.g. Pb)
- Depth-selective from μ^- stopping range
- Non-invasive — replaces destructive mass spec

Ninomiya+ JRNC 320 (2019) 471; Kubo+ NIM-A 920

Muonium Chemistry / μSR

- μ^+e^- ≈ light H isotope ($m \approx m_p/9$), τ ≈ 2.2 μs
- Probes H-isotope effects & radical chemistry
- μSR: μ^+ as local B-field / spin-dynamics probe
- Magnetism, SC, batteries, soft matter, cultural

Blundell+ Nat. Rev. Methods Primers 1 (2021) 89

Neutrino-Factory Beams

- $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$ — well-defined flavour mix
- Narrow ν cone θ ≈ 1/γ (lab frame); modulatable
- Precision oscillation, νCKM, BSM ν physics
- nuSTORM @ CERN: ν-flux known to ≲ 1 %

nuSTORM arXiv:2505.06137; IMCC arXiv:2407.12450

Muon Lithography

- $\lambda_{dB}(\mu) < \lambda_{dB}(e)$ at equal E ($m_\mu/m_e \approx 207$)
- → sub-nm patterning potential
- Deep penetration → 3-D buried micro-structures
- Long-term R&D direction beyond EUV / e-beam

Conceptual — no dedicated facility yet

μCF card — Dzhelepov-Yermolov-Filchenkov+ JINR Dubna ЛЯП, Nuovo Cim. 33 (1964) 40 (foundational); УФН 160 (1990) 3 (review); Wu+ PRC 109 (2024) 054625; Muography — Nature 552 (2017) 386 (Khufu); MURAVES arXiv:2311.13663; Isotopic analysis — JRNC 320 (2019) 471; μSR — Nat. Rev. Methods Primers 1 (2021) 89; Neutrino factory — arXiv:2505.06137 (nuSTORM), arXiv:2407.12450 (IMCC 2024)

Focus: μ-Catalyzed Fusion · Muography · Isotopic Analysis

Two domains where Russian heritage meets industrial-scale demand — synergetic with a μC front-end.

μ-Catalyzed Fusion (μCF)

Mesoatomic catalysis: μ^- acts as a heavy electron, shrinking molecular size ~500× → tunnel fusion at low T.

Energy-release channels:

$d + t \rightarrow {}^4He + n$ + **17.6 MeV**

$d + d \rightarrow {}^3He + n$ + **3.3 MeV**

$d + d \rightarrow t + p$ + **4.0 MeV**

$p + d \rightarrow {}^3He + \gamma$ + **5.5 MeV**

Mechanism

- μ^- binds in the d-t pair → **dtμ molecule with internuclear distance ≈ $a_0/207$**
- Coulomb barrier crossed by tunneling at **room-temperature kinetic energies**
- μ^- released ~99% of the time → ≈ 150 fusions per muon (α-sticking is limiting loss)

Possible industrial applications

- **Beam-driven oil-shale / deep-rock activation** — μ-beam alternative to hydraulic fracturing
  — μ energy → controllable depth; add D_2O if D-content low; *inherently switchable*
- **Nuclear breeding** — tritium production, isotope generation
- **Intrinsic safety**: chain extinguishes when μ-beam is off — **no runaway**

Dubna heritage (1964-74): *Dzhelepov, **Yermolov**, Filchenkov+ — Nuovo Cim. 33 (1964) 40;*
*Budyashov-**Yermolov**+ p-p-μ in H_2 (1968); Bystritskii-Dzhelepov-**Yermolov**+ JETP 39 (1974) 19*
Reviews: *УФН 160 (1990) 3 (Gerstein-Petrov-Ponomarev); Karnakov СОЖ;* ***Modern:*** *PRC 109 (2024) 054625, arXiv:2511.20951*

Muography — Imaging Dense Objects

Long-range μ tomography by absorption / scattering; mature with cosmic μ, transformative with beams.

- **Cosmic-μ baseline:** ⟨E⟩ ≈ 4 GeV, flux ≈ 1 $\mu \cdot cm^{-2} \cdot min^{-1}$
  — Khufu void (ScanPyramids, Nature 552, 2017); volcano monitoring (Vesuvius, Sakurajima)
  — Fukushima reactor-core imaging (Los Alamos / KEK)
- **Beam-driven muography:** tunable E (depth) and direction → sharper resolution
- Apps: geological prospecting, civil-engineering NDT, nuclear safeguards, archaeology

Refs: *Khufu void — Nature 552 (2017) 386 [arXiv:1711.01576]; Khufu corridor — Nat. Commun. 14 (2023) 1144;*
Sakurajima Sci. Rep. 8 (2018) 3207; MURAVES (Vesuvius) arXiv:2311.13663; Saracino — PoS Muon4Future2023 027

Isotopic μ^- Analysis (collective excitations)

Negative muons capture into the K-shell of the nucleus → mesoatom → collective nuclear excitation.

- **μ^- wavefunction overlaps the nucleus** (Bohr radius ≈ $a_0/207$)
- **Sharp γ-ray and neutron emission lines** = unique isotopic fingerprint
- **Discovery of resonant μ^- absorption** by atomic nuclei — НИИЯФ МГУ + ОИЯИ (ЛЯП)
- Non-invasive isotope assay — no mass spectrometry / sample destruction required
- *Natural partner to muography: same μ-beam line, different energy regime*

Refs: *Ninomiya+ — J. Radioanal. Nucl. Chem. 320 (2019) 471 (Pb isotopes via μ-X-rays);*
Kubo+ — non-destructive elemental analysis with μ^-; Discovery — НИИЯФ МГУ + ОИЯИ ЛЯП

μC front-end (target, capture, cooling, transport) = enabling platform for civilian μ-programmes

μCF panel — Dzhelepov, Yermolov, Filchenkov+ JINR Dubna ЛЯП 1964-74: Nuovo Cim. 33 (1964) 40; JETP 39 (1974) 19; review УФН 160 (1990) 3; modern — Wu+ PRC 109 (2024) 054625; arXiv:2511.20951; Muography panel — Nature 552 (2017) 386 (Khufu); Nat. Commun. 14 (2023) 1144; MURAVES arXiv:2311.13663; Isotopic analysis — JRNC 320 (2019) 471.

Conclusions

Energy reach	14 TeV $\mu^+\mu^-$ matches the partonic reach of a 100 TeV pp machine (IMCC EPJC 2023, Fig. 2) in a clean lepton-collider environment — full $\sqrt{s}$ in the hard process, no PDFs, no pile-up
Higgs	Sub-% κ ($\kappa_{W,Z}$ = 0.1% @ 10T); λ_3 = 3.7%; Γ_H = 0.75%; **λ_4 quartic & H→ττ 1.3% unique to μC** **10 TeV μC self-sufficient** for Higgs programme — no separate factory needed [arXiv:2308.02633, 2401.08756, 2601.01674]
Top	y_t to 1% (10T) / 0.5% (14T); m_{top} = 20 MeV; ultimate EW dipoles FCNC Ztc BR < 10^{-6}; composite-top scale Λ > 50 TeV [arXiv:2503.11518]
BSM	Direct pair-production reach: **5 TeV (10T) / 7 TeV (14T)**; charginos, stops, sleptons, heavy scalars VBF single-production windows; indirect probes ~O(0.1) PeV [arXiv:2303.08533]
Dark Matter	Complete thermal WIMP coverage: **Higgsino @ 3 TeV, Wino @ 10 TeV, 5-plet MDM @ 14 TeV** Soft-track + disappearing-track methods [arXiv:2405.08858]; EPJC 83 (2023) 1122
Beyond	Quantum entanglement & Bell tests in $\mu^+\mu^-$ → ZZ [arXiv:2504.09832] Neutrino programme: $\Delta\sin^2\theta_W / \sin^2\theta_W$ < 0.03%; ν-portal DM; LFV operators in SMEFT
Technology	Compact ~11 km (10T) / 14 km (14T) ring; best **MW/TeV** of any future collider 6D ionization-cooling demonstrator (~2038) — **gating element**; HTS magnets (14.1 T demoed at Fermilab)
Russian option	Protvino UNK tunnel (21 km, IHEP) — **15-20 TeV μC stage possible**; design study to be developed
Decisions	NASEM Jun 2025 ✓ → ESG Dec 2025 ✓ → **CERN Council May 2026** → demo CDR 2030 → demo 2038 → **first collisions ~2050**

The muon collider is the unique answer to both the energy AND precision frontiers.

What's next	CERN Council **Budapest May 2026** → ESG mandate · **demo CDR ~2030** · ionization-cooling demo ~2038 · **first $\mu^+\mu^-$ collisions ~2050**

https://www-hep.sinp.msu.ru/~dudko/muon - more details

Key numbers — arXiv:2510.27437 (MuCol MS7 2025), arXiv:2504.21417 (IMCC 2025), arXiv:2308.02633 (Snowmass Higgs Forum); strategy — P5 2023 Rec 4, NASEM 2025 Rec 1, ESG Dec 2025, arXiv:2503.23695 (USMCC WP); DM — arXiv:2405.08858 (Capdevilla et al.); quantum — arXiv:2504.09832 (Aoude et al.).

Back-UP

Additional Material — Detailed Physics, Technology, Refs

36 backup slides · arXiv references inline

[B1] — Accelerator chain — MuCol MS7 (Oct 2025) parameter table

Stage	Key parameter	Value (MS7, 10 TeV baseline)
Proton driver	Energy / Power	5 GeV linac+RCS / 5 MW (10 MW option)
Target + capture	Solenoid	20 T HTS, 1 m bore (graphite/Hg)
6D cooling	Stages	5 stages, ε reduction ~10^6
Final cooling	$\varepsilon_\perp$ / $\varepsilon_\parallel$	25 µm / 0.025 eV·s
Bunch	N_μ per bunch / f_{rep}	1.8×10^{12} µ / 5 Hz
RLA + RCS	Acceleration	Re-circulating linac → 4-stage RCS, 5 TeV/beam
Collider ring	Circumference / B_arc	**11.4 km / 14 T HTS dipoles** *(was 10 km / 16 T in MS5)*
IP optics	β^* / σ_z	1.5 mm / 1.5 mm
Luminosity (10 TeV)	L	**1.8×10^{35} cm^{-2}s^{-1}** *(MS5 design: 2×10^{35})*
Site power	Total	230 MW (10 TeV) / 300 MW (14 TeV)

Open challenge: transmission gap — achieved 2.5×10^{12} µ/bunch vs target 3.6×10^{12}. Main R&D priority for next 5 years (MS7 Sec. 7).

Wall-power efficiency in context

- µC-10T: **230 MW / 10 TeV = 23 MW/TeV** vs FCC-hh: ~550 MW / 100 TeV pp ≈ 55 MW/TeV (pCM equivalent ~10 TeV) [arXiv:2007.15684]

→ *µC = best MW/TeV of any proposed multi-TeV machine.*

parameter table & MS7 baseline — arXiv:2510.27437 (MuCol MS7 Oct 2025, Tables III-V); MS5→MS7 evolution (C 10→11.4 km, B_arc 16→14 T, L 20→18×10^{34}) — arXiv:2411.02966 (MuCol MS5, Nov 2024).

[B2] — Proton driver: 5 GeV linac + RCS, staging, pion yields (MS7)

Driver concept (MS7, arXiv:2510.27437)

- 5 GeV proton linac + RCS (Rapid-Cycling Synchrotron)
- Bunch length ~2 ns, intensity 5×10^{13} p/cycle
- Repetition rate 5 Hz (baseline) / up to 15 Hz
- 32 RF stations in first RCS; TESLA 1.3 GHz cavities
- FLUKA target simulation [arXiv:2602.16672]

Staging plan

- Stage 1 (10 TeV): 5 MW driver baseline (ramp from 2 MW)
- **Stage 2 (14 TeV option): 10 MW driver (ramp from 4 MW)**
- Synergy: Fermilab PIP-II → DUNE → μC driver

Pion production yields

- Yield $Y(\pi^+ + \pi^-)$ / proton ≈ 0.6 (graphite)
- Capture efficiency in 20 T solenoid ≈ 50%
- Net μ yield ≈ 0.15 μ / proton at production
- Muons per bunch at collider: N_μ **= 1.8×10^{12} (MS7 target, transmission 2.5×10^{12} → 3.6×10^{12})**

6D ionization-cooling demonstrator — schedule & deliverables

Year	Milestone	Lead site
2026-30	CDR drafting + prototype cell at TT7/CTF3 testbed	CERN North Area
2030	Conceptual Design Report — go/no-go decision	IMCC + USMCC
2032-36	Demonstrator construction (~21 cells, LiH absorbers)	CERN or Fermilab MTA
~2038	First beam: end-to-end 6D cooling demonstration	TBD
~2045	Collider ring construction begins	CERN or FNAL

driver concept + staging (5 GeV / 2 MW baseline) — arXiv:2510.27437 (MuCol MS7 Sec. 3);   pion yield numbers — arXiv:2303.08533 (Accettura et al. 2023 Sec. 4);   FLUKA target sim — arXiv:2602.16672 (Al-Harthy 2026);   demonstrator TT7/CTF3 — arXiv:2407.12450 (IMCC Interim 2024 §14).

[B3] — Target station: solenoid field, geometry, radiation

Solenoid (FLUKA-optimized, arXiv:2602.16672)

- Peak field: 20 T on axis (HTS REBCO); 5 T downstream
- Bore: 1 m diameter, L=2 m core (FLUKA opt R=0.7 m)
- Adiabatic field taper: 20 T → 1.5 T over 12 m
- Captures $\pi^+ + \pi^-$ in single channel

Target geometry

- Graphite baseline: 30 cm × 1.5 cm radius rod
- Liquid alternative: Hg, Ga jets (MERIT 2007 demo)
- Fluidised W as third option
- Cooling: high-velocity He gas; 14 MW power load

Radiation environment

- Dose at solenoid coils: ~10 MGy/year
- Tungsten + heavy-water shielding
- Neutron flux $<10^{15}$ n/cm^2/year at HTS layer
- FLUKA / Geant4 design optimisation

(FLUKA for pion yields; Geant4 for radiation damage)
[arXiv:2602.16672 — Al-Harthy 2026]

Pion → muon yield chain (FLUKA-validated)

Step	Quantity	Value	Comment
1. p + C → π	$Y(\pi^+ + \pi^-)/p$	≈ 0.6	graphite, 5 GeV p
2. capture	ε_capture	≈ 50 %	20 T solenoid + 12 m taper
3. decay → μ	BR(π → μν)	≈ 100 %	cτ(π) ≈ 7.8 m
Net	Y(μ)/p	≈ 0.15	drives 5 MW driver requirement
Bunch target	N_μ/bunch	1.8×10^{12}	MS7 baseline (10 TeV)

solenoid geometry (FLUKA-opt) — arXiv:2602.16672 (Al-Harthy 2026); target alternatives + capture — arXiv:2510.27437 (MS7 Sec. 4); Hg/Ga jet demo — MERIT experiment (2007, BNL/CERN).

[B4] — 6D ionization cooling — full equations & 5-stage chain

$$\text{Transverse: } d\varepsilon_{\perp}/ds = -\langle dE/ds\rangle \cdot \varepsilon_{\perp}/(\beta^2 E) + (13.6\ \text{MeV})^2 \cdot \beta_{\perp}/(2\beta^3 E \cdot m_{\mu} \cdot X_0)$$

$$\text{Longitudinal: } d\varepsilon_z/ds = -2\cdot(\partial\langle dE/ds\rangle/\partial E)\cdot \varepsilon_z/(\beta^2 E) + \text{diffusion}$$

Stage	ε⊥ in (μm)	ε⊥ out (μm)	ε_z evol	Length / B
1. Initial	17 000	3 000	70 → 50 mm	100 m / 4 T
2. Pre-merge	3 000	500	50 → 30 mm	150 m / 6 T
3. Bunch merge	500	500	30 → 30 mm	30 m
4. 6D cool	500	120	30 → 1.5 mm	300 m / 10 T
5. Final cool	120	25	1.5 → 70 mm	100 m / 40 T

MICE experimental verification (Nature 2020): −6% transverse ε for 140 MeV/c muons; LiH and LH_2 absorbers; 704 MHz RF between absorbers; Be end-walls tested in 3 T field. Nature Phys. (2024) — detailed transverse-emittance analysis.

Open status: 6D cooling never demonstrated end-to-end
- MICE proved single-cell 4D transverse cooling (−6 % ε⊥, Nature 578)
- Multi-cell 6D chain (incl. bunch merge + final cool) still on R&D path
- **Cooling demonstrator (TT7/CTF3 @ CERN) targeted CDR ~2030 → first beam ~2038**
- *Until then, 6D performance is the largest project-approval risk*

cooling equations + 5-stage parameters — arXiv:2303.08533 Sec.5 (IMCC 2023); MS7 updated numbers — arXiv:2510.27437; MICE −6% ε result — Nature 578 (2020) 53; MICE detailed analysis — Nature Phys. 20 (2024) 1583.

[B5] — Final cooling stage — parameters & expected ε_min

Goal
- Bring transverse emittance from 120 µm → 25 µm
- Accept longitudinal emittance growth 1.5 mm → 70 mm

Key design parameters
- Absorber: high-density liquid H_2 slabs
- **Solenoid B ≥ 40 T required (highest in chain — HTS REBCO only)**
- Lattice $\beta_\perp \approx 1$ cm at absorber centre
- Acceleration: ~0.5 GeV/m RF interleaved

Expected output (per beam)
- $\varepsilon_\perp = 25$ µm (×10^3 from initial)
- $\varepsilon_z = 70$ mm
- Particle survival: ~50% in final cooling
- Polarisation preservation under study

Key risk: maintaining $\beta_\perp$ at 1 cm in a 40 T REBCO solenoid

Final-cooling solenoid R&D

Records achieved
- NHMFL REBCO insert (2019): 45.5 T (all-SC hybrid)
- NHMFL standalone HTS (2022): 32 T
- Fermilab HTS dipole (2024): 14.1 T (accelerator-class)

IMCC target & gap
- ≥40 T in 1 m bore for the final-cooling cell
- Requires new HTS winding technology + quench protection
- **$\varepsilon_\perp = 25$ µm cannot be reached below 40 T**

Investment plan
- Magnet programme: 82.5 MCHF + 414 FTE-yr
- 10-year IMCC R&D roadmap (3 magnet classes)

[arXiv:2503.21185, IMCC Magnet WG 2025]

final cooling parameters (≥40 T solenoid, $\beta_\perp$=1 cm) — arXiv:2510.27437 (MS7 Sec. 5);   IMCC interim design basis — arXiv:2407.12450 (Interim Report 2024 Sec. 5.4);   magnet R&D plan & budget — arXiv:2503.21185 (IMCC magnet WG 2025).

[B6] — BIB mitigation — nozzle CAD, timing cuts, occupancy

Nozzle design

- Tungsten cone, ~10° half-angle, length ~6 m
- Borated polyethylene jacket (neutron absorber)
- Coverage: $|\cos\theta| < 0.99$ dead zone (forward)

Timing cuts

- ToF window: 20-50 ps after t_0
- Drift-time correction track-by-track
- Rejects prompt (e±, γ) + delayed (n) BIB

Occupancy by subdetector

- Vertex pixel: 10 GHz/cm² → 10 occupied / 5-µm pixel
- Tracker (Si): 1 GHz/cm²
- ECAL: 100 MHz/cm²
- HCAL: 10 MHz/cm²

BIB particle spectra (MARS15, 2203.07964)

- ⟨p_γ⟩ = 6.4 MeV; ⟨p_n⟩ = 477 MeV; ⟨p_had⟩ = 481 MeV
- **@10 TeV — new BIB source: incoherent e^+e^- pair production** (collimated by 5 T solenoid)

Result after cuts: >95% reconstruction efficiency

[arXiv:2502.00181 — MAIA; arXiv:2511.23273 — MUSIC]

nozzle design + timing cuts + occupancy — arXiv:2203.06773 (Ally et al., Snowmass 2022); BIB spectra ⟨p_γ⟩=6.4 MeV, ⟨p_n⟩=477 MeV (MARS15) — arXiv:2203.07964; incoherent e^+e^- pairs @10 TeV (2nd source) — arXiv:2311.03280 (Annual Review 2024); reco eff >95% — arXiv:2502.00181 (MAIA); MUSIC BIB validation — arXiv:2511.23273.

[B7] — HTS magnet R&D landscape — REBCO, Bi-2212, Nb3Sn

Magnet	Field [T]	Year	Status / use
NHMFL REBCO insert (record)	45.5	2019	Lab demonstrator
NHMFL 32 T all-superconducting	32	2022	User magnet (NMR)
Fermilab HTS dipole	14.1	2024	Accelerator-class
LBNL HD2 (Nb3Sn)	13.8	2008	LHC R&D
IMCC target solenoid (planned)	20	~2032	20 T HTS, 1m bore
IMCC collider arc dipole	14	MS7 baseline	HTS, 11.4 km ring
Final cooling solenoid (R&D)	30-40+	>2035	Hardest target
Bi-2212 cable (LBNL/BNL)	20	2024	Round wire feasibility

Three magnet classes (IMCC 10-year R&D plan, arXiv:2503.21185)

- Collider arc dipoles: 14 T Nb_3Sn (HTS insert)
- 6D cooling solenoids: 30-40+ T REBCO (final stage)
- RCS ramping: ~300 T/s normal-conducting + HTS arcs

Critical-current density

- REBCO: J_e > 1 kA/mm² at 20 T, 4.2 K
- Bi-2212 round wire: J_e ~700 A/mm² at 27 T

Constraints

- Quench protection (no thermal margin at high J_e)
- Hoop stress < 700 MPa
- AC losses in 5 Hz RCS dipoles — active R&D

Budget & resources (IMCC 10-yr plan)

- 82.5 M CHF + 414 FTE-years for magnet R&D
- Joint Fermilab + CERN + NHMFL + LBNL + BNL effort

[B8] — MAIA detector concept — layers, materials, η, BIB rejection

Layer-by-layer design

- Vertex (Si pixel 25×25 µm², 30 ps timing) — r = 3-7 cm
- Inner tracker (Si strip) — r = 10-65 cm
- Solenoid 5 T
- ECAL: Si-W sampling, 22 X_0
- HCAL: Fe + scintillator, 5 λ_I
- Air-core muon spectrometer

Coverage

- |η| < 2.5 main acceptance
- **Forward µ taggers (planned) extend to |η| < 6**

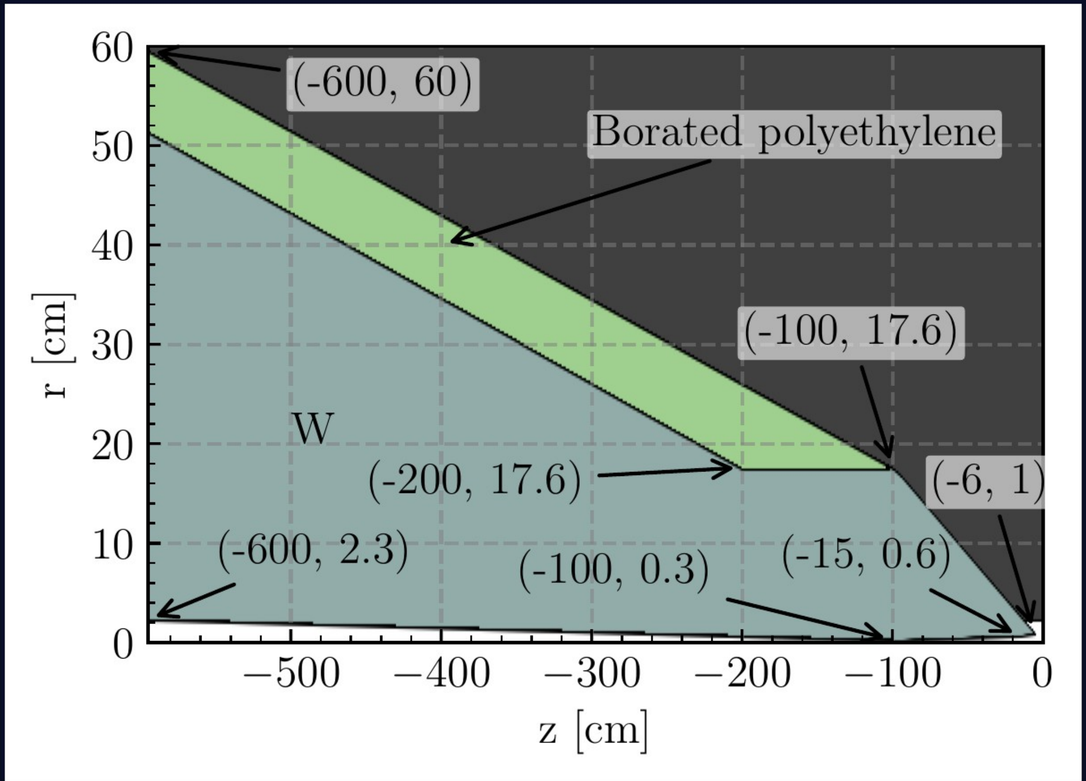
BIB rejection

- Tungsten nozzles (10° opening)
- 30 ps VXD timing → reject delayed BIB
- Time window [−250, +300] ps around bunch crossing
- *BIB scale: ~600 000 hits/event vs ~250 signal (@1.5 TeV)*
- **Reconstruction efficiency >95%**

BIB overlay algorithm with azimuthal randomization

→ community standard; results in MS7 Tables 7.3-7.5

22 authors (Jan 2025) [arXiv:2502.00181]



MAIA cross-section — arXiv:2502.00181

[B9] — MUSIC detector concept — full Geant4 simulation

Concept

- Full Geant4 simulation with detailed material budget
- Central tracking + calo + μ-system
- Focus: e / γ / μ / jet / flavour-ID
- Validated for Higgs@10 TeV
- **$H \to b\bar{b}$ and $HH \to 4b$ reconstructed under BIB**

Subdetectors (detail)

- VXD: 5 barrel layers r=2.9-10.1 cm, 25×25 μm², 30 ps timing
- Inner Tracker: 50×1000 μm macropixels, 60 ps
- 5 T solenoid
- Calo: optimised for BIB-aware reconstruction
- Muon-system: gas-based + Si in barrel

Radiation environment

- ~1 MGy/yr ionizing + ~10^{15} n/cm²/yr at VXD
- IR config EU24 (lattice v0.8) — compatible with MS7

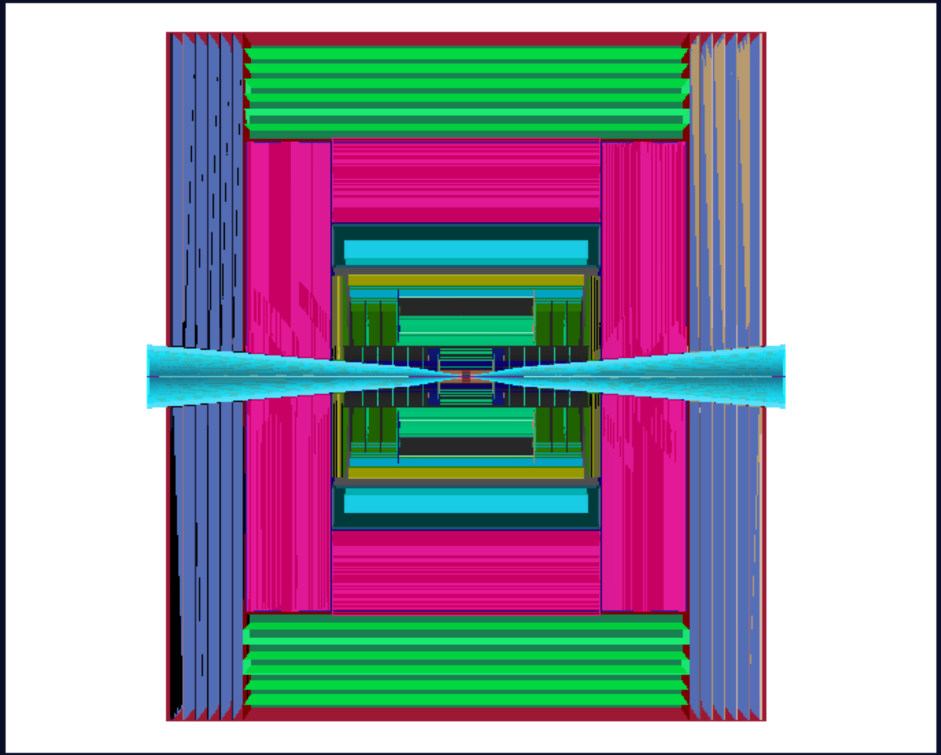
Status

- 64 authors, INFN-led (Nov 2025); complementary to MAIA
- Likely a second μC detector concept

vs MAIA — key distinctions

- Same VXD silicon (25×25 μm², 30 ps); same 5 T solenoid in tracker
- Calo: CLIC-adapted HCAL (vs MAIA Fe-scint); MuC-dedicated ECAL
- 1.8 T reverse field in HCAL (MUSIC only)
- *Two-detector strategy mirrors LHC ATLAS / CMS*

[arXiv:2511.23273]



MUSIC rendering — arXiv:2511.23273

[B10] — κ-framework definitions & global-fit methodology

κ-framework definitions

- κ_i^2 = σ·BR (observed) / σ·BR (SM)
- Couplings vary independently around 1
- Width $\Gamma_H = \Sigma\, \Gamma_i(\kappa_i)$

Global fit methodology

- Joint likelihood over all production × decay channels
- Profile likelihood for individual κ_i
- Includes theory, experimental, BIB systematics

Breaking κ-Γ_H degeneracy

- Flat direction in NWA: simultaneous κ_f, $\kappa_V \times t + \Gamma_H \times t^4$ leaves observables invariant
- Off-shell VV→VV (μμ→4j) breaks degeneracy: κ_W = 3.4%@3T → 0.84%@10T
- Forward μ tagging |η|<6 (inclusive ZZ-fusion): Δσ/σ=0.38%, BR_{inv}**<4.6×10⁻⁴**
- Without it κ_Z **precision ×10 worse [arXiv:2401.08756, 2411.00096]**

Global κ-fit results — μC 10 TeV / 10 ab^{-1} / |η_μ| < 6

Method	Channel	Key observable	Precision
On-shell VBF κ-fit	μμ → νν̄ + H/HH	σ × BR	κ_W ~ 0.2 %, κ_Z ~ 0.4 %
Off-shell VV → VV	μμ → 4 jets	high-m_VV tail	κ_W = 0.84 % @ 10 T
Inclusive ZZ-fusion	tag forward μ (|η| < 6)	Γ_H direct + BR_inv bound	Γ_H = 0.75 %, BR_inv < 4.6×10^{-4}
CP-azimuth in hZZ	forward-μ angular dist.	CP-odd coupling extraction	first sub-% probe

κ-framework & NWA flat direction — arXiv:2308.02633 (Forslund & Meade, JHEP 2023); forward μ degeneracy-breaking (κ_Z, BR_inv) — arXiv:2401.08756 (Li, Liu, Lyu 2024); BR_inv<4.6×10⁻⁴ + κ_Z ×10 effect — arXiv:2411.00096 (Ruhdorfer-Salvioni-Wulzer 2024); NLO EW caveat — arXiv:2506.10733 (Frixione et al. 2025).

[B11] — λ_3 trilinear analyses — observables & full table

Stage	Channel	σ(HH) [fb]	Events / L_int	$\delta\lambda_3 / \lambda_3$
HL-LHC	gg → HH	30	60-100	~50%
FCC-ee	indirect (loops)	—	—	inaccessible
ILC-500	Zhh, e+e-→ννhh	0.16-0.7	few	27-50%
CLIC-3T	WW-fusion → HH	0.5	few hundred	10-20%
μC-3T	VBF → HH	1	1000 / 1 ab^{-1}	~10%
μC-10T	VBF → HH	8	$8{\times}10^4$ / 10 ab^{-1}	**3.7%**
μC-14T	VBF → HH	15	$3{\times}10^5$ / 20 ab^{-1}	**2.5%**
μC-30T (Han 2020)	VBF → HH (extrap.)	30	$1.5{\times}10^6$ / 100 ab^{-1}	**2.0%**
FCC-hh	gg → HH	150	$1.5{\times}10^6$ / 30 ab^{-1}	~5%

Observables

- m(HH) line-shape near threshold (κ_λ enters via box+triangle interference)
- HH branching ratios (bbγγ, bbττ, 4b)
- Differential angle θ* (Higgs in HH frame)

Key takeaways for the audience

- μC-10T beats HL-LHC by ×13 on $\delta\lambda_3/\lambda_3$ (3.7 % vs ~50 %)
- ×5 better than CLIC-3T at the same energy class; **FCC-ee inaccessible** (no HH channel)
- Han et al. 2020 (arXiv:2008.12204): **ladder 25 % → 5.6 % → 2.0 %** at 3 / 10 / 30 TeV — full energy-frontier coverage of EW potential

HH comparison table rows — arXiv:2203.07261 (de Blas et al. 3 TeV, 2022); μC 3.7%/2.5% sensitivity numbers — arXiv:2308.02633 (Forslund & Meade 2023); HH cross-sections at multi-TeV — arXiv:2103.14043 (Snowmass 2021); 30 TeV extrapolation $\delta\lambda_3$=2.0% — arXiv:2008.12204 (Han et al. 2020).

[B12] — λ_4 quartic measurement plan — 10-30 TeV

Process

- $\mu^+\mu^- \to \bar{\nu}\nu$ HHH (VBF triple Higgs)
- Sensitive to κ_4 in QQQ vertex of V(H)

Yields (arXiv:2003.13628 Chiesa-Maltoni)

- $\sigma(HHH\bar{\nu}\nu)$ = 4.18 ab @ 10 TeV → 84 events @ 20 ab^{-1}
- $\sigma(HHH\bar{\nu}\nu)$ = 18.5 ab @ 30 TeV → **1851 events @ 100 ab^{-1}**
- Acceptance $|y|<6$ essential — b-quarks forward at 30 TeV

Sensitivity

- **Order-1 deviation from SM detectable @ 10 TeV**
- **$\delta\lambda_4/\lambda_4$ < 50% @ 30 TeV**
- First measurement of self-coupling at quartic order
- Probes EW phase transition + dim-8 EFT operators

Why only μC?

- FCC-hh: σ much smaller, BIB intractable
- e^+e^- machines: too low cross-section
- **Only μC offers clean VBF environment + high $\sqrt{s}$**

$\sigma(HHH\bar{\nu}\nu)$ yields & event counts (84/1851) — arXiv:2003.13628 (Chiesa-Maltoni 2020); acceptance $|y|<6$ + HHH systematics — arXiv:2103.14043 (Muon Smasher's Guide 2021); EW phase-transition motivation — arXiv:2308.02633 (Forslund & Meade 2023).

[B13] — Γ_H direct extraction via forward μ tagging |η| < 6

Concept
- Forward μ taggers in nozzle aperture
- Detect outgoing μ from VBF events
- Inclusive $\sigma(\mu\mu \to \mu\mu H)$ measurement

Why critical?
- Breaks $\kappa_Z - \Gamma_H$ degeneracy
- Direct constraint on total Higgs width
- **Without it: Γ_H precision degrades ~5×**

Achievable precision
- 2.0% @ 3 TeV
- **0.75% @ 10 TeV**
- **0.50% @ 14 TeV**

Two complementary methods
- Inclusive ZZ-fusion + forward μ ($\Delta\sigma/\sigma$=0.38% @10 TeV)
- Off-shell VV→VV 4j: κ_W = 3.4%@3T / 0.84%@10T
- **$BR_{inv} < 4.6\times10^{-4}$ @95%CL**
- CP-structure hZZ recovered from forward μ azimuth

Detector R&D challenges
- BIB occupancy in forward region
- Tagger placement inside nozzle materials
- Active R&D — MAIA + MUSIC concepts

[arXiv:2401.08756, 2411.00096, 2308.02633]

inclusive ZZ-fusion 0.38% & BR_inv<4.6×10^{-4} — arXiv:2401.08756 (2024), arXiv:2411.00096 (2024); off-shell VV→VV κ_W=0.84% @10T — arXiv:2308.02633 (Forslund & Meade 2023); MAIA/MUSIC forward μ R&D anchor — arXiv:2407.12450 (IMCC Interim 2024).

[B14] — s-channel μμ → H — beam-energy spread & scan strategy

Cross-section formula

$\sigma(\mu\mu \to H)$ at peak = $(4\pi / m_H^2) \cdot \Gamma(H\to\mu\mu) / \Gamma_H^2$
$\sigma_{peak} \approx 40$ pb (zero spread) ; ~10 pb after BES smear

Beam-energy spread (BES) requirements

- **$\Delta p/p < 3$ ppm needed**
- Achieved in MICE storage rings ~10 ppm
- μC operating point: 1 ppm baseline goal
- Synchrotron radiation damping helps (limited for μ)

Scan strategy

- Step √s in 1-2 MeV increments across resonance
- 10^4 Higgs / point at 1 fb^{-1}
- Direct line-shape → Γ_H **measurement to O(100 keV); m_H to 1 ppm**

Effective cross-section (R=0.003%, BES+ISR)

- $\sigma_{eff}(\mu\mu\to H) \approx 22$ pb; $H\to b\bar{b}$ signal 12 pb, bkg 20 pb
- Inaccessible at e^+e^- machines (Y_e/Y_μ ratio)

Refs: arXiv:2104.05770, 1901.06150, 2203.08033, JHEP 08 (2024) 021

BES scenarios → m_H and Γ_H precision

BES R = Δp/p	σ_eff(μμ→H)	Δm_H precision	Γ_H precision	Status
0 (ideal)	≈ 40 pb	—	—	physics only
10 ppm	≈ 22 pb	≈ 100 keV	≈ 1 MeV	MICE-era achievable
3 ppm	≈ 10 pb	≈ 30 keV	≈ 300 keV	MS7 baseline
1 ppm	≈ 5 pb	≈ 1 ppm = 0.13 MeV	≈ 100 keV	μC target — R&D

Programme requirements

- Total L for full scan: ~5 fb^{-1} over 21 √s points (5 ppm step)
- Run time: ~3-5 years at dedicated 125 GeV stage
- Energy-spread design = **largest open R&D** of the Higgs-factory option

vs e^+e^- Higgs factory @ 240 GeV

- FCC-ee Γ_H from σ(ZH) recoil method: ~2 % (model-dep.)
- μC s-channel: Γ_H direct from peak height — **O(100 keV)**

qualitatively different: line-shape vs counting

σ_peak formula & BES requirement Δp/p<3 ppm — arXiv:2104.05770 (Franceschini & Greco 2021); m_H to 1 ppm scan strategy — arXiv:1901.06150 (Bartosik et al. 2019); σ_eff=22 pb with ISR+BES & full scan analysis — arXiv:2203.08033 = JHEP 08 (2024) 021.

[B15] — Top SMEFT — Wilson-coefficient table (μC vs CLIC vs HL-LHC)

Entries: *95% CL reach on the effective scale* **Λ [TeV]** *(SMEFT operators normalised as $L \supset \Sigma\, C_i \cdot O_i / \Lambda^2$, with $C_i = 1$). "—" inaccessible at this collider; "n/a" not analysed.*

Coeff.	Operator	HL-LHC Λ [TeV]	CLIC-3T Λ [TeV]	μC-10T Λ [TeV]	μC-14T Λ [TeV]
C_{tW}	(t̄·σ·γμν)·t·W_μν	~2.3	~4	~14	~20
C_{tB}	(t̄·σ_μν)·t·B_μν	~2.0	~3.5	~11	~16
C_{tG}	(t̄·σ·G)·t	~4	~3	~10	~14
$C_{t\phi}$	(ϕ†ϕ)·(Q̄·t·ϕ̃)	~1.5	~2	~8	~12
$C_{\phi Q+}$	(ϕ†iD_μϕ)·(Q̄γ^μQ)	~1.5	~2	~7	~10
$C_{\phi Q-}$	(ϕ†iD_μτϕ)·(Q̄γ^μτQ)	~1.5	~2	~7	~10
$C_{\phi t}$	(ϕ†iD_μϕ)·(t̄γ^μt)	~1.3	~1.8	~6	~9
C_{tt}	(t̄γ^μt)·(t̄γ_μt)	n/a	n/a	~5	~7
C_{Qt}	(Q̄γ^μQ)·(t̄γ_μt)	n/a	n/a	~5	~7
$\ell^+\ell^-Q\bar{Q}$	4-fermion (μC-only)	—	—	~100	~100

Unique μC advantage: $\ell^+\ell^-Q\bar{Q}$ four-fermion operators **inaccessible at LHC**; μμ→tt̄h channel uniquely available (VBF dominates >4 TeV) → logarithmic enhancement of dipole operators.

Refs: arXiv:2503.11518 (μC vs CLIC), 2410.11015 (top EW dipoles)

Wilson-coefficient reach table — arXiv:2503.11518 (μC vs CLIC, 2025); EW dipole log-enhancement mechanism (Λ~13-15 TeV vs 2.3 TeV HL-LHC) — arXiv:2410.11015 (Han-Liu-Wang 2024); $\ell^+\ell^-Q\bar{Q}$ four-fermion Λ~100 TeV — arXiv:2203.07256 (Snowmass 2022).

[B16] — Top Yukawa y_t + EW dipoles — analysis details

y_t Yukawa

- Channels: tt̄H, single-top H, tH+jet at 10/14 TeV
- σ(tt̄H) at 10 TeV ≈ 1 fb → 10^4 events / 10 ab^{-1}
- **y_t precision: 1% (10T) → 0.5% (14T)**

EW dipole moments (arXiv:2410.11015 Han-Liu-Wang)

- Chromo-magnetic dipole (gluon coupling)
- Electric / weak dipole moments (γ, Z couplings)
- **$\Lambda/\sqrt{|c_{tB}|}$ ≈ 13-15 TeV @10 TeV** (HL-LHC ≈ 2.3 TeV)
- Reach for c_tG: |c_tG| < 0.001 (10T)
- tt̄h VBF dominates above √s ≈ 4-5 TeV → log enhancement

Q_t electric charge

- Direct measurement via Q^2 spectrum in tt̄γ
- **Improvement over LHC: factor 5-10**

Refs: arXiv:2503.11518, arXiv:2410.11015, arXiv:2203.07256

Top precision benchmarks — HL-LHC vs ILC vs μC

Observable	HL-LHC	ILC-500	FCC-ee	μC-10T	μC-14T
y_t Yukawa precision	~5-10 %	~1 %	~3 %	**1 %**	**0.5 %**
Λ/√|c_tB| EW dipole [TeV]	2.3	—	—	**13-15**	**18-20**
|c_tG| chromo-magnetic	~4 TeV^{-2}	—	—	**0.001**	0.0005
σ(tt̄H) [fb]	—	—	—	~1	~3
$\ell^+\ell^-Q\bar{Q}$ four-fermion Λ [TeV]	—	—	—	**~100**	**~100**

y_t channels (tt̄H, single-top H, tH+jet) — arXiv:2503.11518 (2025); Λ/√|c_tB|~13-15 TeV vs 2.3 TeV HL-LHC & c_tG<0.001 — arXiv:2410.11015 (Han-Liu-Wang 2024); Q_t electric charge factor 5-10 — arXiv:2203.07256 (Snowmass 2022).

[B17] — Direct BSM mass reach — per-particle table

BSM particle	HL-LHC	ILC-500	μC-3T	μC-10T	μC-14T
Chargino $\tilde{\chi}_1^+$	~0.9 TeV	~0.25	1.5	5.0	7.0
Neutralino $\tilde{\chi}_1^0$	~0.5	~0.25	1.5	5.0	7.0
Stop $\tilde{t}_1$ (s-ch)	~1.4	—	1.5	5.0	7.0
Coloured (gluon-fusion)	—	—	—	~5	~7
Slepton $\tilde{e}_{L,R}$	~0.7	~0.25	1.5	5.0	7.0
2HDM H/A (m=0.6-1.8 TeV)	~1.0	—	$\sigma=10^{-2}$-10^{2} fb	~5	~7
Singlet scalar (VBF)	—	—	~10	~15	~20
IDM (VBF DM)	—	—	—	covered	extended
Doubly-charged H	~1.2	—	1.5	5.0	7.0
Z' (sequential)	~6.5	—	~6	~12	~18
W' (right-handed)	~6.0	—	~5	~10	~14
HNL (Majorana) DY	~0.5	0.25	1.5	5.0	7.0
HNL (VBF, t-channel)	—	—	~10	~100	~100+
Heavy axion (m_a)	—	—	~1.0	~3.0	~5.0

Reading notes

- All masses in TeV unless noted; μC entries = 95 % CL pair-production limits at the indicated $\sqrt{s}$ and 10 ab^{-1} (1 ab^{-1} for 3 TeV; 20 ab^{-1} for 14 TeV).
- **Coloured (gluon-fusion)** reach uses stop pair via gg-fusion EWA [arXiv:2502.20443]; **IDM (VBF DM)** rows cite arXiv:2411.13729 — mass span ~1-5 TeV.
- **HNL (VBF, t-channel)** reach 100 TeV assumes $|V_{\mu N}| \gtrsim 10^{-3}$ (arXiv:2506.06159). **Heavy axion** row from arXiv:2509.10605 (m_a window 1 GeV - several TeV).
- Coloured + IDM + axion rows are **μC-unique entries** — HL-LHC and ILC blank by construction (no clean lepton VBF channels at TeV).

EW-charged particle reach (chargino, neutralino, slepton) — arXiv:2303.08533 (IMCC 2023), arXiv:2103.14043 (MSGuide 2021); coloured production (stops, gluinos, LQs via PDF) — arXiv:2502.20443 (Han et al. 2025); extended scalars / IDM / doubly-charged — arXiv:2203.07256, arXiv:2507.21910, arXiv:2411.13729, arXiv:2508.04493; heavy QCD axion — arXiv:2509.10605.

[B18] — 2HDM Type I / II — reach in parameter space

2HDM model basics

- Two Higgs doublets Φ_1, Φ_2 → h, H, A, H^+
- Free parameters: tan β, cos(β−α), m_H/A/H^+
- Type I: only Φ_2 couples to fermions
- Type II: Φ_2 to up-quarks, Φ_1 to down + leptons (MSSM-like)

μC reach (arXiv:2507.21910 Tab. 3)

- @3 TeV: σ(H,A,H±) = 10^{-2}-10^{2} fb for m=0.6-1.8 TeV
- **@10 TeV: pair reach up to 5 TeV per scalar**
- **@14 TeV: up to 7 TeV per scalar**
- VBF single production extends further; s-channel μμ→H,A in narrow tanβ windows

s-channel μμ → A (Type-II 2HDM, narrow tan β window)

- σ(μμ→A) ∝ $\tan^2\beta$ × BR(A→μμ); resonant Breit-Wigner enhancement
- tan β = 30, m_A = 800 GeV → σ_peak ≈ 0.5 fb (zero BES) → **~500 events / 1 fb^{-1}**
- Inaccessible at e^+e^- ($y_\mu^2/y_e^2 \approx 4.3 \times 10^4$ enhancement); requires energy scan

Singlet scalar extension

- $\sin^2\gamma$ (mixing angle) excluded for m_S > 2 TeV via VBF
- **Excludes singlet scalar to ~15 TeV @10 TeV μC**

Coverage in (tan β, m_H) plane

- Closes alignment-limit corners inaccessible at FCC-ee
- Probes both Wrong-Sign Yukawa and CP-odd regions

[arXiv:2507.21910, 2203.07256]

2HDM pair-production reach & cross-sections @3 TeV (Tab. 3) — arXiv:2507.21910 (Robens-Santos 2025); singlet scalar $\sin^2\gamma$ exclusion & alignment-limit coverage — arXiv:2203.07256 (Snowmass 2022).

[B19] — Doubly-charged Higgs & seesaw-II model

Type-II seesaw mechanism

- Triplet Higgs $\Delta = \{\delta^{++}, \delta^{+}, \delta^{0}\}$ couples to LL
- Generates Majorana ν masses via vev v_Δ
- δ^{++} produces same-sign lepton-pair signature

μC reach

- Pair production $\mu^{+}\mu^{-} \to \delta^{++}\,\delta^{--}$ reaches √s/2
- **10 TeV: m(δ^{++}) up to ~5 TeV**
- **14 TeV: up to ~7 TeV**
- VBF single production extends to ~10 TeV
- Georgi-Machacek $H_5^{++}H_5^{--}$: ~4 TeV direct, ~5 TeV w/ VBF

Signatures

- **Spectacular: 4 same-sign leptons (ee, μμ, eμ)**
- Lepton-flavour fractions probe Yukawa coupling y_LL
- Constraint on ν-mass spectrum (normal vs inverted hierarchy)

[arXiv:2508.04493]

Doubly-charged Higgs reach by model — current limits vs μC

Model	Mechanism	LHC Run 2 limit	μC-10T	μC-14T
Type-II seesaw δ^{++}	γγ-fusion pair	≈ 1.2 TeV	**≈ 5 TeV**	**≈ 7 TeV**
Georgi-Machacek H_5^{++}	ZZ-fusion + s-channel	≈ 0.85 TeV	≈ 4 TeV (direct)	≈ 5 TeV (+ VBF)
Left-Right H_3^{++}	DY pair	~1 TeV	≈ 5 TeV	≈ 7 TeV
BIB cleaning	4 same-sign hard ℓ + timing cut	—	ε > 90 %	ε > 90 %

Type-II seesaw δ^{++} pair production (reach 5/7 TeV @ μC-10T/14T) — arXiv:2508.04493 (2025); Georgi-Machacek $H_5^{++}H_5^{--}$ ~4 TeV direct, ~5 TeV + VBF — arXiv:2308.02633 (Forslund & Meade 2023).

— Heavy QCD axions — combined sensitivity & UV completions

Heavy QCD axion definition

- m_a ≫ m_π (1 GeV - 10 TeV range)
- f_a in 100 GeV - PeV range (heavy KSVZ/DFSZ-like)
- Couplings: g_aγ, g_aWW, g_ahh, g_aff

Combined sensitivity (3T + 10T)

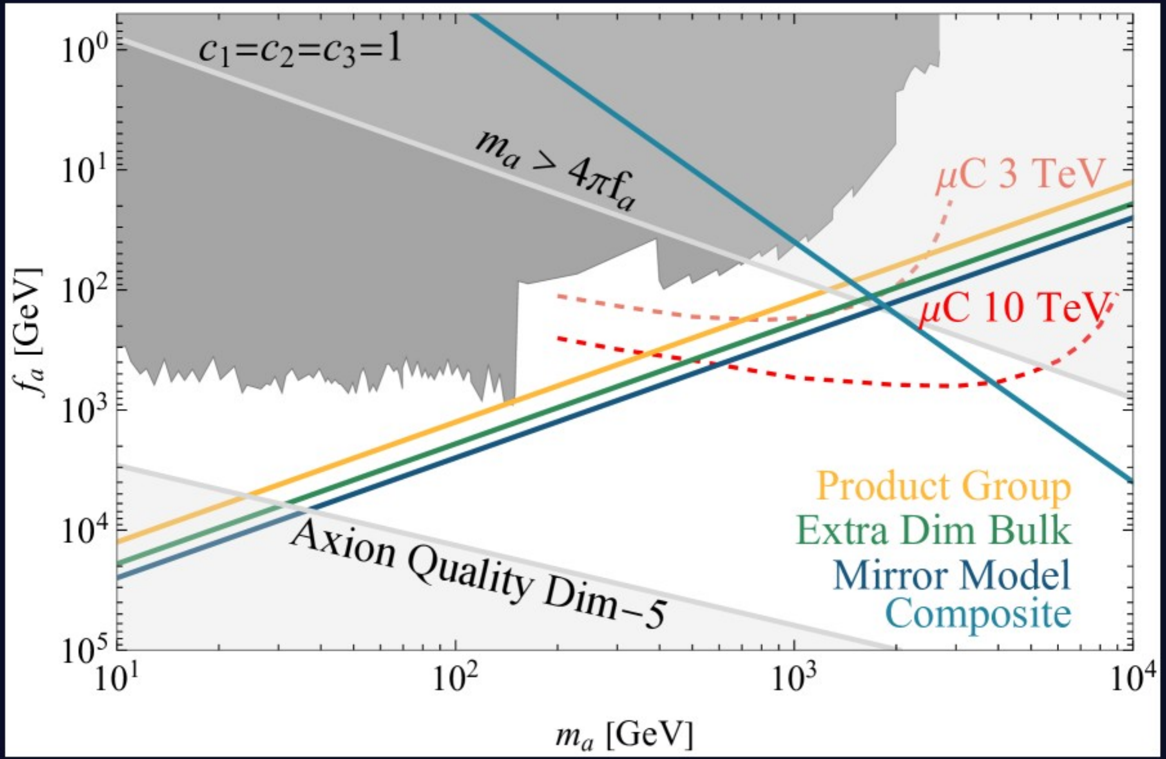
- Dominant: μμ → μμa via γγ/ZZ* VBF (t-channel)
- a → gg (BR > 0.95); dijet 130 < M_jj < 9800 GeV
- Mono-photon, γγ resonance, aZ associated channels
- Reach m_a up to several TeV @ f_a ~ TeV — inaccessible to HL-LHC

UV-completion overlays

- Composite Higgs (PNGB axion)
- Mirror-world axions
- Heavy-fermion KSVZ-type

Reach in (m_a, f_a): exceeds all proposed colliders for m_a > 100 GeV

[arXiv:2509.10605]



Combined (m_a, f_a) — arXiv:2509.10605

[B21] — LFV SMEFT operators table & per-operator reach

Operator	Flavour	Process	μC-10T Λ [TeV]
O_eW	μ-e	$\mu^+\mu^- \to e\gamma$ + jets	~80
O_eB	μ-e	$\mu^+\mu^- \to e\gamma$	~70
O_eϕ	μ-e	$\mu^+\mu^- \to eH$	~50
O_eW	τ-e	$\mu^+\mu^- \to e\tau$ + jets	~60
O_eB	τ-μ	$\mu^+\mu^- \to \mu\tau\gamma$	~55
4-fermion (LLLL)	μ-e	Same-sign ee	~100
4-fermion (LLRR)	τ-μ	Opposite-sign μτ	~85
O_LeQu (V)	τ-μ	$\mu\mu \to \tau\bar{\tau} + b\bar{b}$	~60

- **Same-sign lepton signature: distinctive, low background**
- Heavy Neutral Leptons appear as intermediate t-channel state
- Strongly constrains low-scale seesaw and leptoquark models
- **Per-operator Λ reach often > 100 TeV — better than any other collider**

Lepton-Flavour-Violating ALP (μ→τ)

- $\mu A \to \tau A a$ with pre-collider μ beam (10^{16} MOT)
- Sensitivity $C_{\mu\tau}/\Lambda \sim 1\ \mathrm{TeV}^{-1}$ for $m_a > m_\tau + m_\mu$

[arXiv:2509.22771 (Asadi), 2407.15942 (LFV ALP)]

[B22] — HNL discovery via same-sign leptons + VBF

Heavy Neutral Lepton (HNL) framework

- Right-handed Majorana ν: N_R
- Mixes with active ν via Yukawa: V_lN ≲ 0.001
- Mass scale: GeV - several TeV

VBF single-production signal

- $\mu^+\mu^- \to W^+W^-$ via VBF → 2× N_R
- Each N_R → ℓ^+ jj (or ℓ^- jj) via Majorana mass
- **Same-sign 2-lepton + 4-jet signature**

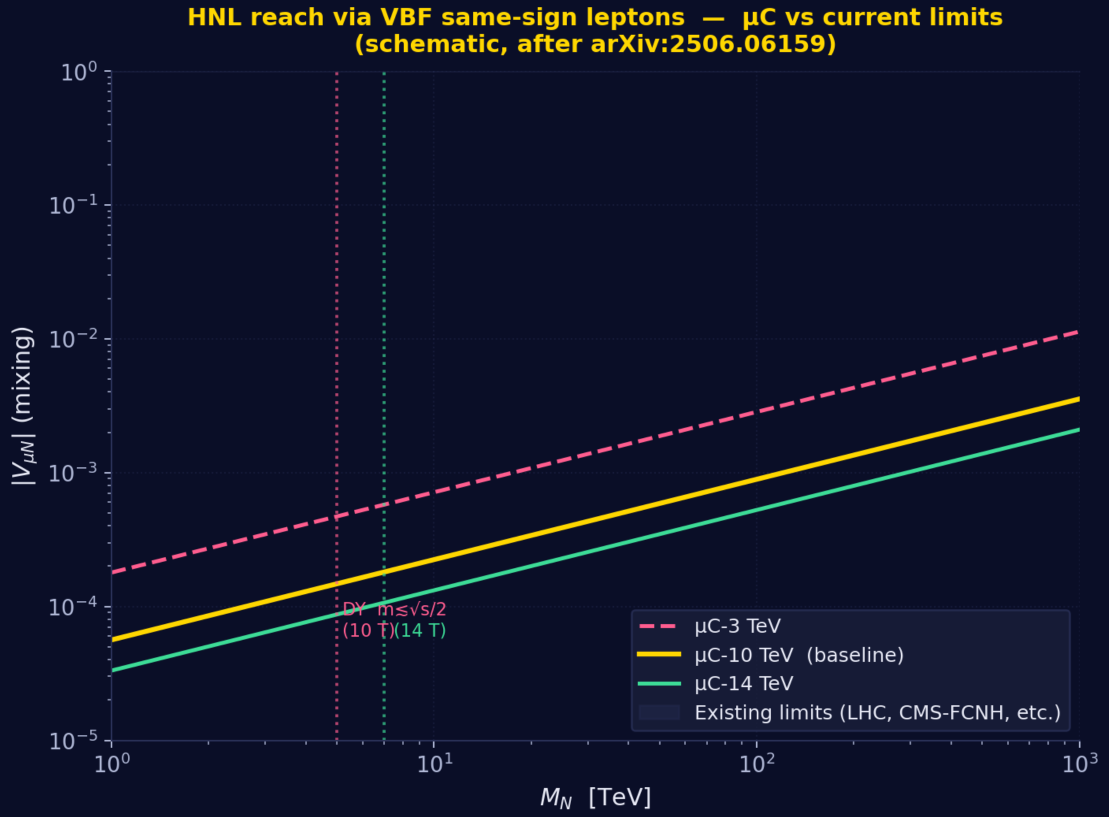
μC reach (10 TeV, arXiv:2506.06159)

- t-channel VBF dominates for M_N ≫ √s
- Sensitivity to **M_N ~ 100 TeV** at |V_μN| ≳ 10^{-3}
- **2-3 orders of magnitude above kinematic threshold**
- $\mu^+\mu^+$ mode (μTRISTAN 2 TeV) complementary
- Per-flavour Majorana phase probed

Implications

- Direct test of low-scale seesaw mechanism
- Possible link to leptogenesis
- Strong complementarity with neutrino-portal DM searches

[arXiv:2506.06159, 2504.21417]



HNL reach |V_μN| vs M_N — μC stages vs current limits (schematic, after arXiv:2506.06159)

μC-10T reaches M_N ~ 100 TeV via VBF t-channel — 2-3 orders of magnitude above kinematic DY threshold (√s/2).

[B23] — Higgsino discovery — soft-track method (Capdevilla 2024)

The challenge

- Higgsino (m_th = 1.1 TeV) nearly degenerate: Δm ≈ 344 MeV (loop-level)
- Lifetime of chargino τ ~ 30 ps → cτ ~ 1 cm
- Soft track + missing energy = signature

The Capdevilla 2024 breakthrough

- Soft-track tagging using p_T ∈ [500 MeV, 1 GeV]
- Drell-Yan μμ pair production σ ≈ 12.53 fb @ 3 TeV
- Soft-track efficiency ~45% with BIB; 0.08 fake tracks/event
- Hit-level timing cuts ±0.5 ns reject BIB
- **Recovers thermal Higgsino discovery already at 3 TeV μC**

Predicted reach

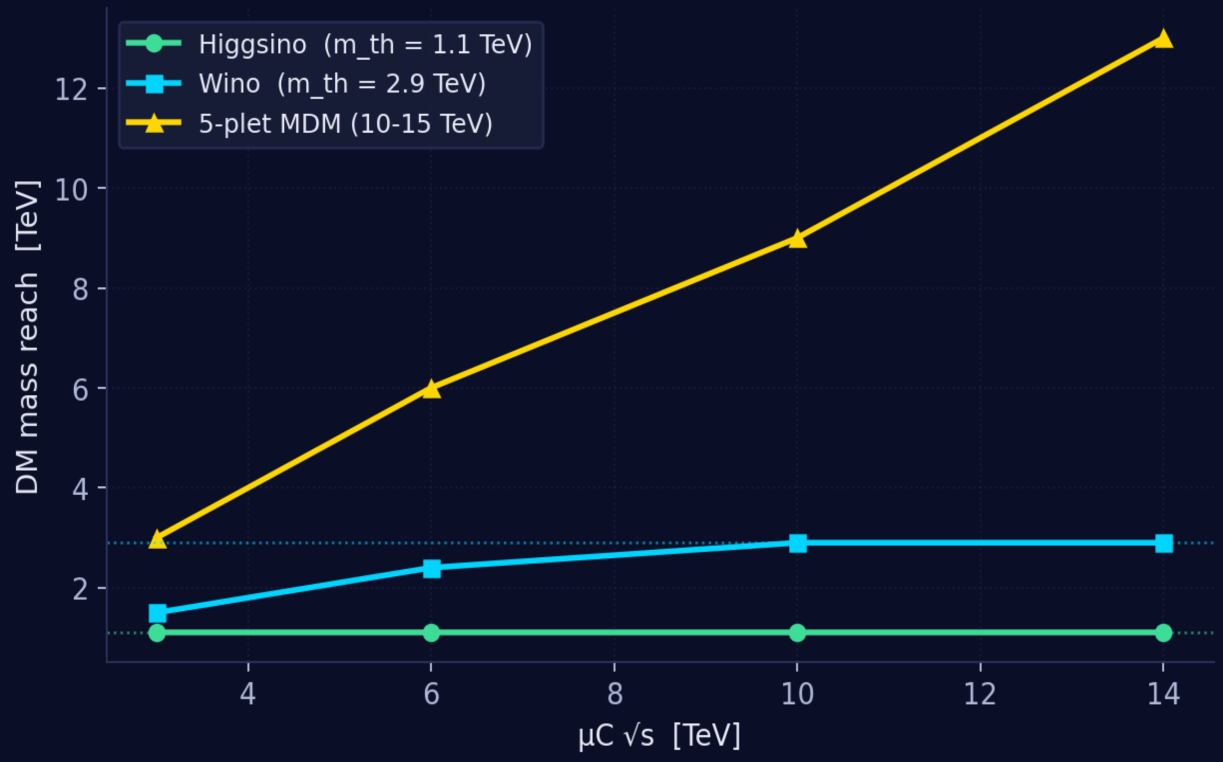
- **μC-3T: $m(\tilde{\chi}_1^+)$ up to ~1.5 TeV → thermal Higgsino covered**
- μC-10T: up to ~5 TeV (well into 2.9 TeV Wino region)
- Combined with disappearing-track searches

Crucial for cosmology

- Thermal Higgsino is the lightest SUSY DM benchmark
- Discovery would establish electroweak DM origin

[arXiv:2405.08858 — Capdevilla et al.]

Thermal-WIMP Coverage at Muon Collider Stages



Thermal-WIMP coverage by stage

[B24] — Wino disappearing tracks at 10 TeV

Wino phenomenology

- SU(2)_L triplet $\tilde{\chi} = (\tilde{\chi}^+, \tilde{\chi}^0, \tilde{\chi}^-)$
- **Thermal mass: $m_\chi \approx$ 2.7-2.9 TeV**
- Chargino: $\Delta m \approx$ 166 MeV, $c\cdot\tau \approx$ 6 cm → disappearing tracks
- cf. Higgsino: $\Delta m \approx$ 344 MeV, $c\cdot\tau \approx$ 6.6 mm (much harder)

Signal characterisation (arXiv:2102.11292 Han-Liu-Wang-Xie)

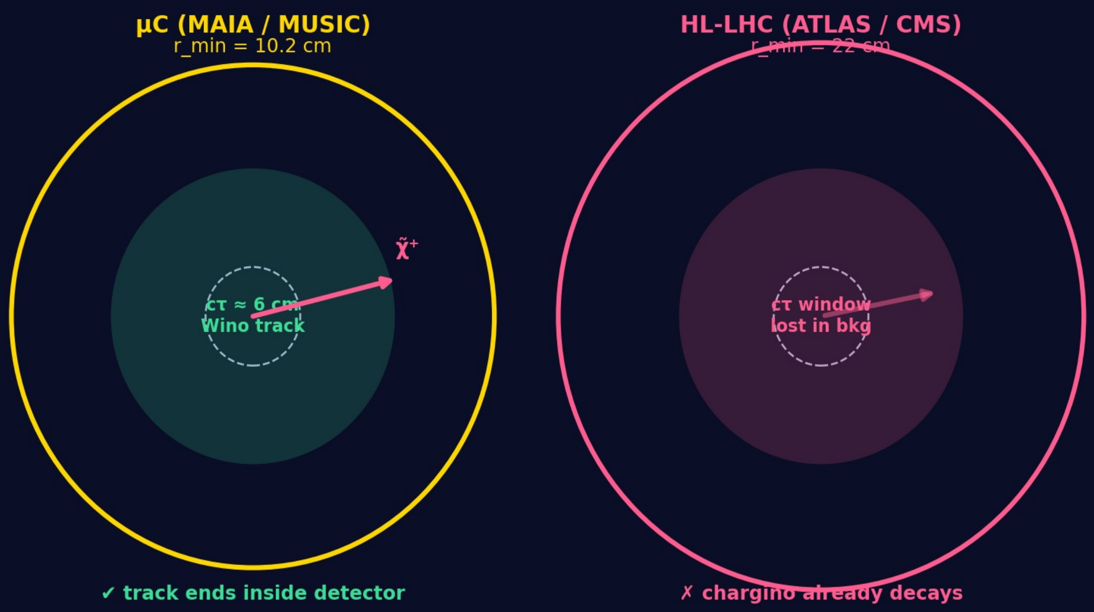
- Detector minimum radius r = 10.2 cm (vs HL-LHC 22 cm)
- Track length: 3-15 cm before decay
- Final soft pion ($\Delta m \approx$ 166 MeV, just above m_π): hard to detect
- ~10000 DY pairs/scenario expected at 10 TeV
- Trigger: high-p_T track without continuation in outer layers
- Backgrounds: secondary interactions, fake tracks (BIB)

μC reach (10 TeV)

- **Pair-production: $m_\chi \lesssim \sqrt{s}/2$ = 5 TeV → covers 2.7 TeV thermal**
- **5σ discovery at 10 ab^{-1}**

[arXiv:2102.11292, 2405.08858; EPJC 83 (2023) 1122]

Disappearing-track geometry — μC has 2× shorter inner radius



Disappearing-track inner-radius geometry — μC vs HL-LHC (schematic)

Key operating numbers @ μC-10T (arXiv:2102.11292)

- ~10 000 DY chargino pairs / 10 ab^{-1} at $\sqrt{s}$ = 10 TeV
- Track length 3-15 cm before disappearance; **$S/\sqrt{B} \gtrsim 5\sigma$ at 10 ab^{-1}**
- Soft-track tagging extends coverage to Higgsino (Δm=344 MeV, $c\tau$=6.6 mm)

Wino disappearing tracks ($c\cdot\tau$~6 cm, r_min=10.2 cm vs HL-LHC 22 cm, ~10000 DY pairs) — arXiv:2102.11292 (Han-Liu-Wang-Xie); soft-track complement — arXiv:2405.08858 (Capdevilla et al. 2024); full MDM coverage — EPJC 83 (2023) 1122 (Franceschini et al.).

[B25] — 5-plet minimal dark matter at 14 TeV

5-plet MDM phenomenology

- $SU(2)_L$ quintuplet (Y=0) — Cirelli, Strumia & co.
- Thermal target: $m_\chi \approx$ 10-15 TeV (cosmologically motivated)
- Hyper-stable: $\Lambda \gtrsim 10^{25}$ GeV for proton decay protection

μC-14T reach

- Pair production reach: $m_\chi \lesssim$ 7 TeV (partial coverage of thermal target)
- Indirect (VBF mono-W/Z) extends to ~12-15 TeV
- **First proposed collider to reach 5-plet thermal mass**

Complete WIMP coverage (Muon Smasher's Guide, arXiv:2103.14043)

Full thermal MDM at E ~ 6-14 TeV depending on multiplet type

Cosmological significance

- Closes the 'minimal DM' classification of Cirelli et al.
- Completes the thermal WIMP coverage program

[arXiv:2103.14043, 2203.07351; EPJC 83 (2023) 1122]

Thermal WIMP coverage by multiplet — μC stage map

Multiplet	Thermal m_th	Signature	μC stage that covers
Higgsino (doublet, Y=½)	1.1 TeV	soft tracks + DT (Δm=344 MeV, cτ=6.6 mm)	**μC-3T (direct)**
Wino (triplet, Y=0)	2.7-2.9 TeV	disappearing tracks (Δm=166 MeV, cτ=6 cm)	**μC-10T (direct)**
5-plet (quintuplet, Y=0)	10-15 TeV	VBF mono-W/Z/γ + indirect EW	**μC-14T partial / 30T full**

complete thermal-WIMP coverage by multiplet — arXiv:2103.14043 (Muon Smasher's Guide); full MDM reach — EPJC 83 (2023) 1122 (Franceschini et al.); MDM classification (original 5-plet stability) — arXiv:2203.07351 (Cirelli & Strumia review).

[B26] — EW precision: $\sin^2\theta\_W$ from ν-e scattering

Measurement method

- ν-e elastic scattering at a forward μ-storage-ring detector
- 50% ν_μ + 50% ν̄_e from μ decays — well-characterised flux
- Recoil electron kinematics directly probes $\sin^2\theta\_W$

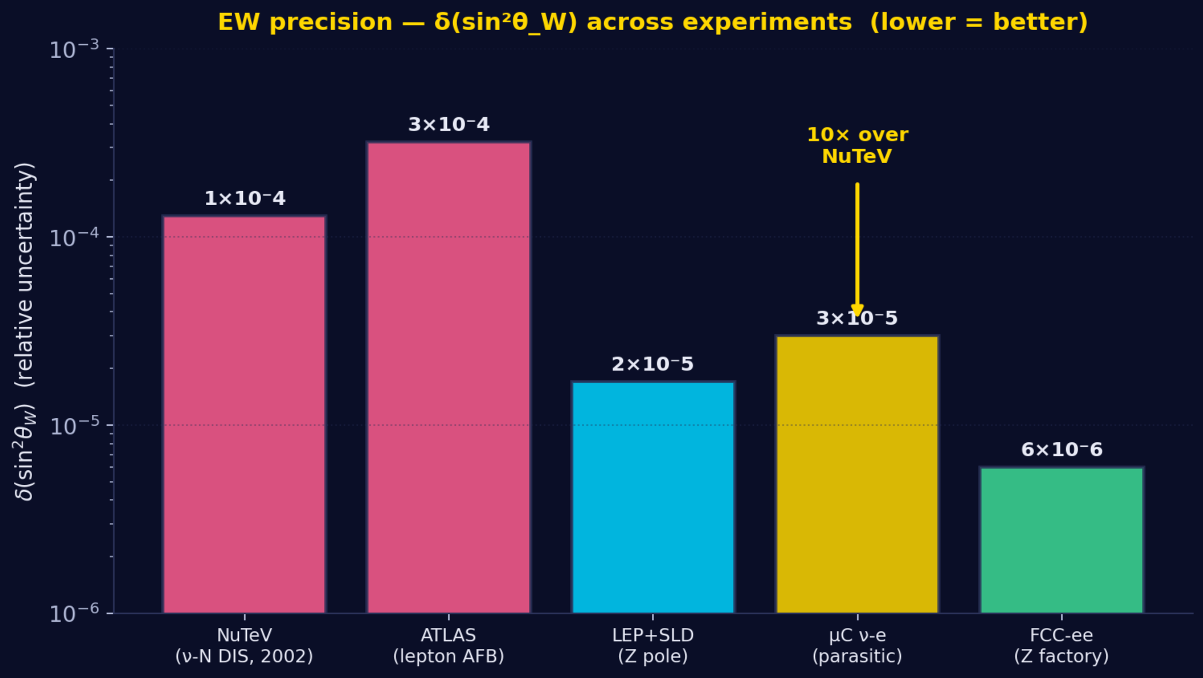
Precision target

- **$\delta(\sin^2\theta\_W) \approx 3\times10^{-5}$ — comparable to LEP+SLD**
- 10× improvement over NuTeV (1.3×10^{-4})
- Run parasitically with main collider operation

Related observables

- Z-pole α_QED running, m_W, m_top via global EW fits
- Unique $\ell^+\ell^-Q\bar{Q}$ dim-6 operators (inaccessible at LHC)
- Λ ~ 100 TeV reach via di-boson EW [2203.07256, 2503.11518]
- Combination with collider Z' resonance scan

[arXiv:2505.00152, 2203.07256, 2503.11518; PRD 111 (2025) 075019]



δ(sin²ϑ_W) precision benchmarks — log scale, lower is better

Setup & broader reach

- Forward parasitic ν-detector on storage-ring straight; runs simultaneously with collider
- 50 % ν_μ + 50 % ν̄_e from μ decays — flux known to ≲ 1 %
- Same dataset → $\ell^+\ell^-Q\bar{Q}$ dim-6 operators (Λ ~ 100 TeV via WW/ZZ EW)
- Plus ν-portal DM mono-jet/γ — 10× over LHC [PRD 111 075019]

$\sin^2\vartheta\_W$ from ν-e elastic ($\delta\approx3\times10^{-5}$, 10× over NuTeV) — arXiv:2505.00152; $\ell^+\ell^-Q\bar{Q}$ dim-6 + diboson EW (Λ~100 TeV) — arXiv:2203.07256 (Snowmass), arXiv:2503.11518 (2025); ν-portal DM context — PRD 111 (2025) 075019.

[B27] — Quantum entanglement: tomography & Bell observables

Process and observable

- $\mu^+\mu^- \to ZZ$ at $\sqrt{s} \geq 1$ TeV
- Decay channel: 4 charged leptons (e, μ)
- Spin-density matrix ρ extracted from angular distributions

Bell-inequality observable c_MB^2

- $c\_MB^2 = \max\_\{\hat{n}_1,\hat{n}_2\} |C\_ij(\hat{n}_1,\hat{n}_2)|$ (Mermin-Bell-like)
- **$c\_MB^2 > 1$ → quantum entanglement**
- **$c\_MB^2 > 2$ → Bell-inequality violation**

Sensitivity at μC

- 10 TeV / 10 ab^{-1}: 2σ entanglement evidence
- **14 TeV / 20 ab^{-1}: 5σ Bell violation**
- **First quantum-information tests above the EW scale**

Two complementary processes

- Direct annihilation μμ→ZZ: non-entangled hypothesis rejected at 2σ
- VBF H→ZZ: decays of resonant boson
- Metrics: PPT criterion, Negativity N(ρ), C^2_MB (Mermin-Bell)
  [arXiv:2504.09832, 2408.05429 — Aoude, Han, Mårtensson, Ruiz]

c_MB^2 progression with √s — arXiv:2504.09832 Fig. 2

√s [TeV]	L [ab^{-1}]	c_MB^2 (peak)	Significance	Process
3	1	≈ 1.4	marginal entangl.	μμ→ZZ
10	10	≈ 1.7	**2σ entangl.**	μμ→ZZ
10 (VBF)	30	$I_3 \approx 2.66$	**up to 4σ CGLMP**	VBF H→ZZ→4ℓ
14	20	≈ 2.3	**5σ Bell viol.**	μμ→ZZ
30	100	≈ 2.6	decisive Bell	both

Three metrics, three confirmations

- PPT criterion: tests separability of ρ
- Negativity N(ρ): entanglement monotone
- Concurrence C(ρ): mixed-state entanglement

Note: LHC has tested entanglement only in tt̄ and ZZ at lower energies. μC opens the regime above the EW scale.

75 ab^{-1} vs 10 ab^{-1} inconsistency:
2504.09832 quoted 2σ at 75 ab^{-1} for direct μμ→ZZ; 2408.05429 used 30 ab^{-1} per stage for VBF H→ZZ — different processes, not assumptions.

μμ→ZZ Bell violation (5σ @14T/20ab^{-1}; PPT/Negativity) — arXiv:2504.09832 (Aoude et al. 2025); VBF H→ZZ→4ℓ entanglement (CGLMP I_3~2.5-2.66, up to 4σ) — arXiv:2408.05429 (Ruzi et al. 2024).

[B28] — ν-portal DM + beam-dump experiments

ν-portal DM model

- DM couples to SM via mixing with active neutrinos
- Lagrangian: $L \supset g_\chi \bar{\chi} \nu \phi$ + h.c.   (g_χ effective coupling)
- Signatures: mono-jet, mono-γ, missing transverse energy

μC reach

- **m_{DM} from MeV up to ~100 TeV at 14T stage**
- 10× improvement over LHC mono-X searches

[PRD 111 (2025) 075019]

Beam-dump experiments

- μ-on-Cu absorber → muonophilic BSM (HNLs, dark photons, ALPs)
- Reach in coupling g down to $\sim 10^{-6}$ for MeV-GeV BSM particles
- Complementary to FNAL, J-PARC, ESS programmes

[JHEP 05 (2024) 283]

μOST fixed-target programme

- Ring-decay muon beam → nucleon multidimensional structure (TMDs)
- Next-generation fixed-target physics beyond EIC
- *Synergistic use of degrading μ-beam — no extra infrastructure*

[arXiv:2506.19301]

Three synergistic uses of the same μ-beam infrastructure

Programme	Energy scale	Target coupling	Primary observable
ν-portal DM	$m_{DM} \lesssim 100$ TeV	$y_{\chi\nu}$ portal coupling	mono-jet / mono-γ + missing E_T
μ-beam-dump	MeV - GeV BSM	$g \gtrsim 10^{-6}$	HNL / dark photon / ALP decays
μOST fixed-target	$\sqrt{s_{FT}} \approx 137$ GeV	QCD nucleon structure	TMD / GPD spin-momentum maps

ν-portal DM (m_{DM} up to ~100 TeV, 10× over LHC) — PRD 111 (2025) 075019;   μ-beam-dump ($g \sim 10^{-6}$, MeV-GeV BSM) — JHEP 05 (2024) 283;   μOST fixed-target TMD nucleon structure — arXiv:2506.19301 (Klest, PRD 112 L051504 2025).

[B29] — Protvino UNK tunnel — detailed parameters & civil engineering

UNK tunnel facts (IHEP Protvino)

- Tunnel ~70% complete by 1991; excavation halted (never operational)
- Circumference: 21 km → R = 3.34 km
- Depth: ~60 m underground (rock cover)
- Tunnel inner diameter: ~5 m
- Cooling water + electrical infrastructure on-site

Magnet requirements (μC operation)

- Ring rule: B·R = p / 0.3 [GeV/c, m, T]
- **B = 7 T → p_max ≈ 7.5 TeV/c → √s ≈ 15 TeV**
- **B = 10 T → p_max ≈ 10 TeV/c → √s ≈ 20 TeV**
- HTS REBCO dipoles, 1.0 m bore, DC operation in collider ring

Engineering gaps to fill

- Pre-accelerator chain (proton driver + cooling)
- Radiation shielding for ν decay-product flux
- Detector caverns at IPs
- Cryogenic plant for HTS magnets

Cost advantage: existing tunnel saves ~50% of civil construction

Comparison: Fermilab alternative (USMCC WP arXiv:2503.23695)

- *10 TeV pCM fits on Fermilab site (Main Injector tunnel area)*
- *Best power-per-luminosity efficiency among proposals*

Protvino UNK vs Fermilab site option — key parameters

Parameter	Protvino UNK	IMCC baseline	Fermilab option
Circumference	21 km (existing)	11.4 km (new build)	≈ 16 km (Main Injector area)
Depth / cover	~60 m underground (granite, low rad.)	site-dependent	shallow (alluvium)
Status	**~70% built 1991, dormant**	design only	site available
B_arc / √s window	7-10 T HTS → 15-20 TeV	14 T HTS → 10 TeV	14 T HTS → 10 TeV
Civil construction saving	~50 % over greenfield site	—	moderate
Published design	*none — community proposal*	arXiv:2510.27437 (MS7)	arXiv:2503.23695 (USMCC WP)

Protvino UNK tunnel facts (21 km, ~70% complete 1991, IHEP) — see body refs; physics applicability (~15 TeV @ B=7 T) — arXiv:2504.21417 (IMCC 2025), arXiv:2103.14043 (MSGuide); Fermilab alternative — arXiv:2503.23695 (USMCC WP 2025).

[B30] — Complete reference list — Reviews · Higgs · Top · BSM

Reviews & Strategy

- arXiv:2303.08533 — Accettura et al. (IMCC), EPJC 83 (2023) 864
- arXiv:2504.21417 — Aleksahin et al. (IMCC, 2025)
- arXiv:2103.14043 — Al Ali et al., Muon Smasher's Guide
- arXiv:2503.23695 — USMCC White Paper (NASEM 2025)
- arXiv:2510.27437 — MuCol Consolidated Parameters
- arXiv:2407.12450 — IMCC Interim Report (2024)

Higgs precision

- arXiv:2308.02633 — Forslund & Meade, Higgs width
- arXiv:2203.07261 — de Blas et al., 3 TeV physics case
- arXiv:2104.05770 — Franceschini & Greco, Higgs & BSM at μC
- arXiv:2401.08756 — Li et al., forward μ tagging
- arXiv:2411.00096 — Ruhdorfer-Salvioni-Wulzer, BR_inv
- arXiv:2601.01674 — Dewyspelaere et al., H→ττ
- arXiv:2506.10733 — Frixione et al., NLO EW precision

Top quark

- arXiv:2503.11518 — Top operators at future colliders
- arXiv:2410.11015 — Top EW dipole moments
- arXiv:2203.07256 — Snowmass top physics summary

BSM (SUSY, scalars, axions, LFV)

- arXiv:2502.20443 — Han et al., colorful production
- arXiv:2507.21910 — 2HDM at μC
- arXiv:2508.04493 — Doubly-charged Higgs (seesaw-II)
- arXiv:2509.10605 — Heavy QCD axions combined
- arXiv:2509.22771 — Asadi et al., LFV SMEFT
- arXiv:2003.13628 — Chiesa-Maltoni, λ_4 quartic
- arXiv:2101.10334 — Capdevilla, g-2 no-lose
- arXiv:2102.11292 — Han-Liu-Wang, Wino DT
- arXiv:2506.06159 — VBF HNL up to 100 TeV
- arXiv:2101.04956 — Gauged L_μ-L_τ
- arXiv:2411.13729 — Inert Doublet DM

[B31] — Complete reference list — Detector · Tech · Quantum · Neutrino

Detectors & reconstruction
- arXiv:2502.00181 — MAIA detector (Jan 2025)
- arXiv:2511.23273 — MUSIC detector (Nov 2025)
- arXiv:2203.06773 — BIB studies
- arXiv:2203.07964 — Simulated detector performance
- arXiv:2405.19314 — BIB-aware detector sim @ 3 TeV
- arXiv:2601.01674 — $H \to \tau\tau$ reconstruction
- arXiv:2411.00096 — Forward muon detector $|\eta|<6$

Accelerator / cooling / magnets
- arXiv:2407.12450 — IMCC acc. complex review
- arXiv:2510.27437 — MuCol MS7 Consolidated Parameters
- arXiv:2503.21185 — IMCC magnet R&D
- arXiv:2602.16672 — FLUKA target optimisation
- Nature 578 (2020) — MICE ionization-cooling demo
- Nature Phys. (2024) — MICE detailed results
- arXiv:2506.10733 — NLO EW precision phenomenology

Quantum · Neutrino · Fixed-target
- arXiv:2504.09832 — Quantum entanglement in ZZ (direct + VBF)
- arXiv:2408.05429 — Earlier ZZ entanglement analysis
- arXiv:2505.00152 — $\sin^2\theta$_W from ν-e
- PRD 111 (2025) 075019 — ν-portal DM
- JHEP 05 (2024) 283 — beam-dump with muons
- arXiv:2506.19301 — μOST fixed-target (Klest)
- arXiv:2407.15942 — LFV ALP from μ-beam

Strategy documents
- NASEM 2025 — National Academies Report
- ESG Dec 2025 — European Strategy Group
- P5 2023 — US Particle Physics Project Prioritisation
- arXiv:2503.23695 — USMCC White Paper (326 authors)
- arXiv:2602.15295 — US National Input ESPPU 2026

[B32] — Precision Phenomenology — NLO EW Framework

Why this matters at multi-TeV μC

- Sub-% precision (Higgs, top) requires NLO EW + QED resummation
- Standard EWA / EW-PDF used in early μC papers — breaks at high m

Where EWA breaks down (arXiv:2506.10733 Frixione et al.)

- EWA/ME ratio deforms factor 2-6 at $m(t\bar{t}) > 7$ TeV
- Same for $m(WW) > 8$ TeV; Sudakov logs ~$\times 10^{-1}$ in tails
- Power-corrections m_V^2 / Q^2 spoil cross-section predictions

Required framework

- NLO EW matching (one-loop virtual + real EW emission)
- QED ISR resummation (DGLAP-like in α_{em})
- Sudakov resummation in high-energy tails
- Universal: applies to e^+e^- AND $\mu^+\mu^-$

Status

- Implemented in MadGraph5_aMC@NLO (Frixione-Maltoni-Pagani-Zaro)
- EVA approach [arXiv:2111.02442] as cross-check
- **Critical for ESPPU 2026 precision claims**

[arXiv:2506.10733, 2111.02442]

EWA vs NLO EW + QED resummation

EWA (standard)

- Leading-log approximation
- γ, W, Z PDFs in lepton
- Power corrections m_V^2/Q^2 neglected
- **Breaks at m > 7-8 TeV (×2-6 deviation)**
- Tail Sudakov logs not resummed
- *Available since 2010s, used in early μC papers*

NLO EW + QED resummation

- One-loop virtual + real EW emission matched
- QED ISR resummed (DGLAP-like in α_{em})
- Sudakov logs resummed in tails
- Power-corrections retained (mass effects exact)
- **Valid across full phase space**
- *Implemented in MG5_aMC@NLO (2025)*

[B33] — Forward Muon Detector — Design Requirements (|η|<6)

Kinematic motivation

- ZZ-fusion → H: outgoing μ at $\theta \approx 0.02°$ @ 10 TeV
- Requires $|\eta| < 6$ coverage (corresponding to $\theta > 0.27°$)
- **Without forward μ: ZZ-fusion channel inaccessible**

Coverage options & sensitivity

- $|\eta| < 4$: $\Delta\sigma/\sigma \approx 15\%$ (degraded by ×40)
- **$|\eta| < 6$: $\Delta\sigma/\sigma \approx 0.38\%$** ← baseline
- $|\eta| < 8$: marginal further gain
- Energy resolution δ_res = 1% required (10% degrades 3-4×)

Physics benchmarks

- Breaks κ_z-Γ_H degeneracy → 0.75% Γ_H precision @ 10 TeV
- **BR(H→inv) < 4.6×10^{-4} @ 95% CL**
- CP-structure of hZZ recovered from forward μ azimuth

Engineering challenges

- Tagger placement inside nozzle / shielding region
- BIB occupancy in forward (10× higher than central)
- Active R&D in MAIA, MUSIC concepts

[arXiv:2411.00096, 2401.08756]

Forward-μ acceptance: |η| → Δσ/σ (ZZ-fusion)

|η| range	θ_min	Δσ/σ (Γ_H)	Note
$\|\eta\| < 2.44$	$\theta > 5.1°$	—	central tracker only
$\|\eta\| < 4$	$\theta > 2.1°$	≈ 15%	ZZ-fusion degraded ×40
$\|\eta\| < 6$	$\theta > 0.27°$	≈ 0.38%	BASELINE — MS7 + MAIA / MUSIC
$\|\eta\| < 8$	$\theta > 0.04°$	≈ 0.35%	marginal further gain
nozzle	—	—	BIB shielding — no tracking

Why baseline at |η| = 6

- Lifts the κ_Z – Γ_H flat direction in the global Higgs fit
- **BR(H → invisible) probed to 4.6×10^{-4} (CL 95%)**
- CP structure of hZZ recovered from forward-μ azimuth
- *Same forward region houses the second BIB source (incoherent e^+e^-); shielding & tracker R&D coupled*
- *Engineering: detector inside nozzle, 10× central occupancy*

[B34] — Gauged $L_\mu - L_\tau$ — $(g-2)_\mu$ Driver + Generic Dark-Sector Probe at MuC

Model: gauged $L_\mu - L_\tau$ extension of SM

- New U(1)' gauge boson Z' coupling only to μ, τ, ν_μ, ν_τ
- Anomaly-free without extra fermions; minimal flavour structure
- **Primary motivation: $(g-2)_\mu$ anomaly + portal to dark sector**
- *Status note: R_K(*) measurements (LHCb 2022-2024) now SM-consistent — L_μ-L_τ retained here as $(g-2)_\mu$ explanation + benchmark dark-sector probe, not as B-anomaly driver*

Four search channels at μC

- I. $\mu^+\mu^- \to \mu^+\mu^-$ (s-channel Z' resonance)
- **II. $\mu^+\mu^- \to \mu^+\mu^- + \gamma_{ISR}$ (ISR-enhanced)**
- III. $\mu^+\mu^- \to \tau^+\tau^-$ via Z' s-channel
- IV. $\mu^+\mu^- \to \nu\nu$ via Z' s-channel (invisible)

Sensitivity (arXiv:2101.04956)

- Channel II (ISR) most powerful at high $M_{Z'}$
- **$g' \sim 4\times10^{-3}$ reach at $M_{Z'}$ = 1 TeV**
- **Covers full $(g-2)_\mu$ allowed band for $M_{Z'}$ > 100 GeV**
- *Existing limits (LEP, NA64, BaBar, COHERENT) exclude only low-mass region < 10-100 GeV — TeV scale wide open*
- **Unique to μC — invisible to LHC, FCC-ee**

Why this matters beyond $(g-2)_\mu$

- Z' = generic dark-photon-like portal probed cleanly at μC
- If discovered, opens window on dark-sector mediators with muonphilic couplings

[arXiv:2101.04956 — Huang-Queiroz-Rodejohann]

[B35] — Colorful Production at MuC — Stops, Gluinos, LQs via PDF

Non-trivial muon-beam content (arXiv:2502.20443 Han 2025)

- Muon = quasi-free EW state, but partonic content emerges at high E
- PDFs of gauge bosons (γ, W, Z) in μ: well-established (EWA)
- **PDFs of quarks/gluons in μ — new development**
- Origin: γ → qq̄, W → qq', γ → gg (via quark loops)

Production channels

- Single coloured particle: μμ → q* g, gg → t̃t̃*
- Pair production: μμ → gg → t̃t̃*, μμ → qq̄ → LQ LQ̄
- Reach: stops, gluinos, coloured LQs up to ~√s/2

Comparison with pp colliders

- pp: large σ but huge backgrounds, pile-up, jet contamination
- μμ: smaller σ but **clean lepton environment**, no pile-up
- Complementary to HL-LHC for full BSM coverage

Significance

- Extends μC reach beyond pure μμ-annihilation channels
- Critical for SUSY (stops, gluinos) and leptoquark searches

[arXiv:2502.20443 — Han, 2025]

Coloured-particle reach @ μC-10T (arXiv:2502.20443 Tab. I)

State	Channel	LHC Run 2	μC-10T (95 % CL)
Stop t̃t̃*	gg → t̃t̃* via μ-PDF	1.3-1.9 TeV	≈ 5 TeV
Gluino g̃g̃	gg fusion	2.2-2.4 TeV	≈ 4-5 TeV
LQ pair (q q̄)	qq̄ via μ-PDF	~1.7 TeV	≈ 5 TeV
Single LQ	γq → LQ	~1.7 TeV	up to ≈ 8 TeV
Vector-like q	qq̄ pair / γq single	~1.5 TeV	≈ 5-6 TeV

Why this beats HL-LHC

- Clean μμ environment: no pile-up, no jet contamination
- **Single-particle channels (γq) reach ~√s exclusively at μC**
- Coloured reach + EW reach unified in one machine
- *Closes a major BSM gap: 14T stage probes stops to 7 TeV*

[B36] — μOST Fixed-Target + LFV ALP — Synergy with Ring

μOST — Fixed-Target Programme

Concept
- Use ring-decay μ-beam (degrading muons) for fixed-target
- No extra infrastructure — synergy with main collider

Physics target
- Nucleon multidimensional structure (TMDs, GPDs)
- Next-generation programme beyond EIC
- High-energy μ-beam → access to new kinematic regime

Energy reach
- μ-beam from decay sees Lorentz boost $\gamma \approx 5\times10^4$
- Fixed-target $\sqrt{s} \approx$ 100-200 GeV equivalent
- Resolves nucleon structure at 10^{-2}-10^{-3} fm scale

Synergy with Tevatron/EIC heritage
- Builds on COMPASS/SMC fixed-target μ-physics

[arXiv:2506.19301 — Klest 2025]

LFV ALP search (μ→τ)

LFV ALP framework
- Axion-like particle with lepton-flavour violating coupling
- Operator: (1/Λ) · μ̄ γ^μ τ · ∂_μ a
- Motivated by τ-lepton-philic UV completions

Search channel
- μA → τAa using pre-collider μ-beam (10^{16} MOT)
- Final state: τ + missing energy + recoil nucleus
- Background: μ→τ scattering off nuclei (small)

Sensitivity
- **C_μτ / Λ ~ 1 TeV^{-1} for m_a > m_τ + m_μ**
- Better than τ-decay constraints by orders of magnitude
- Probes LFV at high-energy scale not accessible elsewhere

Synergy with main collider
- Same μ-beam infrastructure — no duplicate cost
- Complementary to S12 LFV SMEFT operators search

[arXiv:2407.15942]