Akademia Górniczo-Hutnicza
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Perspectives for HET physics studies at a muon-hadron collider at CERN

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(on behalf of HELP4CERN Study Group)

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Outline

1. LHμC@CERN: physics motivation and benchmarks
2. HET overview: Higgs, electroweak and top
3. Precision Higgs physics at LHμC
4. High-energy $\gamma\gamma$ physics at LHμC
5. Top physics at LHμC
6. Beyond SM and long-term outlook

Why a muon-hadron collider for HET physics?

- A muon-hadron collider combines the clean lepton-hadron initial state of DIS with a multi-TeV centre-of-mass energy, opening a new regime for Higgs, electroweak, top, and BSM studies.
- Relative to an electron-proton collider, replacing the electron beam by a muon beam strongly relaxes the synchrotron-radiation limitation, allowing significantly higher beam energies and hence much larger hard-scattering rates, and pushes the centre-of-mass energy deep into the multi-TeV regime.
- Relative to proton-proton collisions, the μp environment remains experimentally cleaner, with smaller QCD backgrounds for many precision and BSM channels.

Three complementary physics paths at LHμC

LHμC combines three powerful and complementary directions: a strong QCD programme, high-precision Higgs/top/electroweak measurements, and a powerful probe of physics beyond the Standard Model.

Benchmark working points used in this talk

- The present talk focuses on the physics case of the LHμC, using the current working benchmarks:
- The first option: $E_\mu = 500$ GeV, $E_p = 7$ TeV, $\sqrt{s} \simeq 3.7$ TeV, with a $\mathcal{L}_{\rm int} = 250$ fb^{-1}.
- The nominal baseline: $E_\mu = 1$ TeV, $E_p = 7$ TeV, $\sqrt{s} \simeq 5.3$ TeV, with a $\mathcal{L}_{\rm int} = 1000$ fb^{-1}.
- The second option: $E_\mu = 2$ TeV, $E_p = 7$ TeV, $\sqrt{s} \simeq 7.5$ TeV, with a $\mathcal{L}_{\rm int} = 1000$ fb^{-1}.

LHμC physics message

These working points are sufficient to demonstrate the main message of LHμC: already at the 500 GeV, LHμC enters the multi-TeV regime and becomes highly competitive for Higgs, top, electroweak, $\gamma\gamma$, and representative BSM studies.

From HELP4CERN White Paper (in preparation)

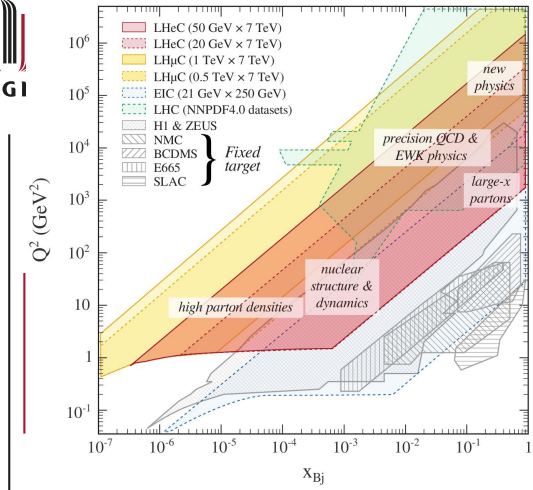
Benchmarks

Machine	**Benchmark**
LHeC	$E_e = 20$, 50 GeV
LHμC (option 1)	$E_\mu = 500$ GeV
LHμC (baseline)	$E_\mu = 1000$ GeV
LHμC (option 2)	$E_\mu = 2000$ GeV
Configuration	**Value**
$\sqrt{s}_{\mu p}$ (option 1)	$\simeq 3.7$ TeV
$\sqrt{s}_{\mu p}$ (baseline)	$\simeq 5.3$ TeV
$\sqrt{s}_{\mu p}$ (option 2)	$\simeq 7.5$ TeV
$\mathcal{L}_{\rm int}$ (option 1)	250 fb^{-1}
$\mathcal{L}_{\rm int}$ (baseline)	1000 fb^{-1}
$\mathcal{L}_{\rm int}$ (option 2)	1000 fb^{-1}

HEl-p4CERN

See talk by Krzysztof Piotrzkowski

Kinematic reach and QCD physics landscape



Available (x, Q^2) plane for the proposed LHμC, compared with fixed-target, collider, and EIC kinematic coverage.

QCD program at LHμC

- The multi-TeV μp configuration extends the DIS kinematic coverage well beyond HERA and significantly beyond the LHeC.
- The same machine that reaches extreme x and Q^2 also strengthens the QCD programme through improved access to proton PDFs, and precise determinations of α_s.
- This motivates the broader CERN bridge-project narrative: LHμC strengthens both the QCD frontier and the HET/BSM programme.

See talk by Piotr Kotko

Representative HET benchmark cross sections

What does this table show?

LHμC as a genuine HET factory: Higgs production is large enough to support precision Higgs physics, including benchmark coupling studies & the top sector benefits the most, enabling both precision top measurements and sensitivity to rare top processes, & even the 500 GeV option opens a qualitatively new regime for electroweak, EFT, and BSM physics.

From HELP4CERN White Paper (in preparation)

Benchmark inclusive cross sections

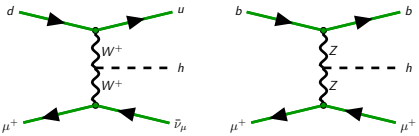
Process	20 GeV LHeC	50 GeV LHeC	500 GeV LHμC	1 TeV LHμC
$\sigma(\ell p \to \nu_\ell H + \text{jet} + X)$ [fb]	52	164	438	731
$\sigma(\ell p \to \ell H + \text{jet} + X)$ [fb]	5.6	19	135	221
$\sigma(\ell p \to \ell\, t\bar{t} + X)$ [pb]	0.0015	0.0323	1.03	2.23
$\sigma(\ell p \to \nu_\ell t + X)$ [pb]	0.55	2.89	21.26	36.77

Key comparisons

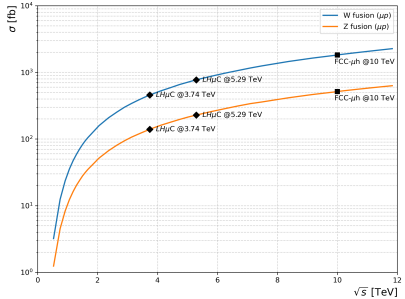
Relative to the 50 GeV LHeC benchmark, the nominal 1 TeV LHμC baseline enhances the benchmark inclusive rates by approximately: $\sim$ 4.5 for charged-current Higgs production, $\sim$ 12 for neutral-current Higgs production, $\sim$ 13 for single-top production, and $\sim$ 69 for $t\bar{t}$ production.

Higgs production at LHμC: channels, rates, and statistics

- Higgs production is dominated by CC VBF, with a subleading but still sizeable NC contribution.
- Using the current benchmarks:
  - 500 GeV LHμC: $\sigma_{\rm CC} \simeq 438$ fb, $\sigma_{\rm NC} \simeq 135$ fb,
  - 1 TeV LHμC: $\sigma_{\rm CC} \simeq 731$ fb, $\sigma_{\rm NC} \simeq 221$ fb.
- For the benchmark integrated luminosities, these correspond to roughly:
  - 1.10×10^5 CC Higgs and 3.38×10^4 NC Higgs events at 500 GeV,
  - 7.31×10^5 CC Higgs and 2.21×10^5 NC Higgs events at 1 TeV.
- This already motivates precision Higgs-coupling studies beyond a mere rescaling of LHeC expectations.



CC: $\mu^+ p \to \bar{\nu}_\mu\, j\, h$ NC: $\mu^+ p \to \mu^+\, j\, h$



Higgs boson production cross sections at LHμC for the CC (W-fusion) and subleading NC (Z-fusion) contributions.

Precision Higgs case study: $h \to b\bar{b}$ and coupling prospects

- A concrete benchmark study already exists for the CC VBF channel $p\mu^+ \to j\,\bar{\nu}_\mu\,h;\ h \to b\bar{b}$.
- Analysis chain used in this study:
  - MG5_aMC@NLO + Pythia6 + FastJet + Delphes,
  - LHeC-like asymmetric detector setup and 75% b-tagging efficiency,
  - selection with exactly two b-jets and

$$|m_{bb} - m_h| < 25\ \mathrm{GeV}.$$

- The statistical uncertainty estimated as $\frac{\Delta\sigma}{\sigma} = \frac{\sqrt{N_s+N_b}}{N_s}$,
- This gives a benchmark on the measurable rate which can be translated into a sensitivity on g_{hbb}:

$$\sigma(p\mu^+ \to j\,\bar{\nu}_\mu\,b\bar{b}) \ \propto\ \frac{g^2_{hWW}\,g^2_{hbb}}{\Gamma_h}\,.$$

	LHμC-500	LHμC-1000
σ_{sig} [pb]	0.24	0.39
$\sigma_{\mathrm{bgd\text{-}Z}}$ [pb]	0.30	0.50
$\sigma_{\mathrm{bgd\text{-}mj}}$ [pb]	357.9	563.8
$\Delta\sigma/\sigma$	1.19%	0.69%
$\Delta g_{hbb}/g_{hbb}$	0.77%	0.60%

Benchmark CC $h \to b\bar{b}$ sensitivities. The coupling reach is obtained from the rate measurement after propagating the external uncertainty on g^2_{hWW}/Γ_h.

Key finding

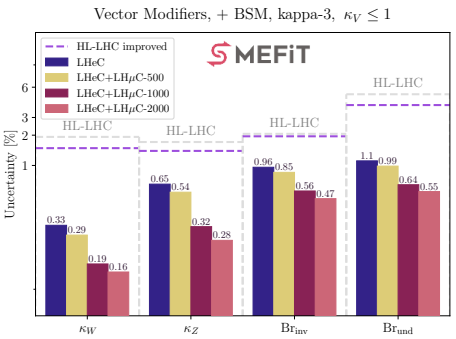
The current LHμC benchmark study already reaches sub-percent sensitivity to g_{hbb} in the CC Higgs channel, improving on the LHeC expectation of about 0.97% [M. Tanaka, DIS2017] and substantially exceeding the HL-LHC expectation of about 4% [1902.00134 [hep-ph]].

Broader Higgs-coupling reach: a global-fit picture

- Beyond the dedicated $h \to b\bar{b}$ benchmark, we also examined a Higgs coupling fit in the kappa-3 framework [JHEP 01 (2020) 139].
- These results are obtained in a first exploratory study:
  - the same systematic factors as in the underlying LHeC-based setup,
  - the statistical error is rescaled using the benchmark LHμC cross sections,
  - and the fit results shown here were obtained with the SMEFiT framework [2604.16596].
- The strongest visible improvement is in the vector sector:

$$\delta\kappa_W \simeq 0.29\% \ (\mathrm{LH}\mu\mathrm{C\text{-}0.5TeV}),\ 0.19\% \ (\mathrm{LH}\mu\mathrm{C\text{-}1TeV}).$$

- The clearest message of the current exploratory fit is the strong projected improvement in the vector sector, especially for κ_W and κ_Z, at the higher-energy LHμC stages.

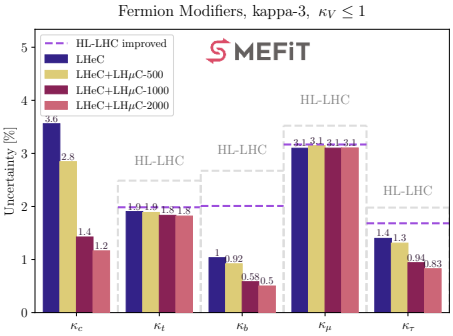


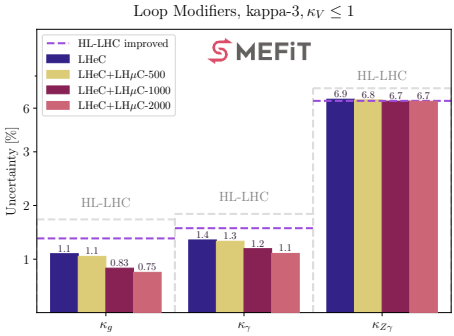
Exploratory vector-modifier result in the kappa-3 framework. The panel compares HL-LHC-based benchmarks with LHeC and with LHeC+LHμC stages.

From HELP4CERN White Paper (in preparation)

Higgs&BSM@LHeC: Néstor Armesto

Broader Higgs-coupling reach: fermion and loop sectors





- Fermion sector: the LHμC can substantially improve the precision on selected fermion couplings, especially κ_b, κ_c, and κ_τ. Already at the 1 TeV stage, the combined LHeC+LHμC fit becomes clearly stronger than the HL-LHC benchmark for κ_b and κ_c.
- Loop sector: loop-induced modifiers are not the primary strength of a VBF-driven Higgs programme. Nevertheless, the 1 TeV and 2 TeV stages make κ_g competitive with, and eventually better than, the HL-LHC benchmark.

Electroweak programme and EFT opportunities

EW precision reach at LHμC

- Beyond Higgs rates, LHμC offers a broader electroweak programme based on high-Q^2 DIS, vector-boson fusion, and photon-induced reactions.
- The larger kinematic span relative to the LHeC is expected to strengthen sensitivity to key electroweak observables, in particular m_W and $\sin^2\theta_W$, while also extending the SMEFT lever arm.
- Overall, LHμC is expected to extend the precision electroweak reach beyond that projected for the LHeC. HET@LHeC: Paul Newman

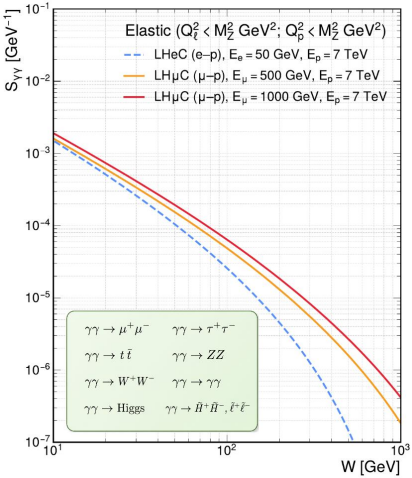
Highlighted EW / EFT opportunities

- High-scale measurements of the weak mixing angle and its running,
- Precision light-quark weak neutral-current couplings via γZ interference and Z exchange,
- Improved sensitivity to m_W in a clean DIS environment,
- Electroweak/top measurements linked to the Wtb vertex and direct sensitivity to V_{ts},
- SMEFT directions complementary to those probed at pp and e^+e^- machines,
- Photon-induced EFT sensitivity in $\gamma\gamma \to W^+W^-$, ZZ, and heavy final states.

High-energy $\gamma\gamma$ physics is a natural part of the LHμC programme

Interesting HET directions

- LHμC naturally operates as *a high-energy $\gamma\gamma$ collider*.
- In the nominal 5.3 TeV baseline, the effective $\gamma\gamma$ centre-of-mass energy extends into the multi-TeV regime, opening a broad programme of clean exclusive measurements.
  - anomalous τ moments,
  - $\gamma\gamma \to W^+W^-$ and anomalous quartic gauge couplings (aQGC),
  - loop-induced $\gamma\gamma \to ZZ$,
  - exclusive $t\bar{t}$ production,
  - light-by-light scattering (LbL)
  - BSM charged-particle pair production.

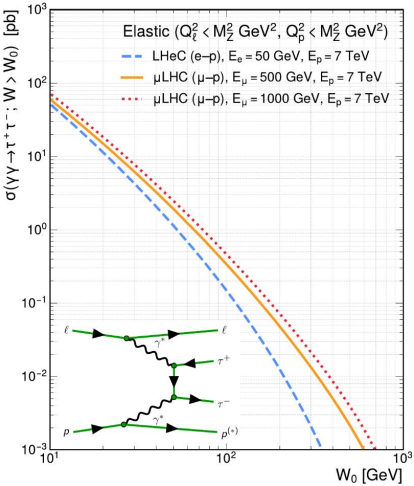


Elastic photon-photon luminosity spectrum $S_{\gamma\gamma}$ as a function of the $\gamma\gamma$ invariant mass W, comparing the LHeC and LHμC benchmark configurations.

Benchmark $\gamma\gamma$ channel: $\tau^+\tau^-$ and anomalous τ moments

LHμC $\tau^+\tau^-$ physics message

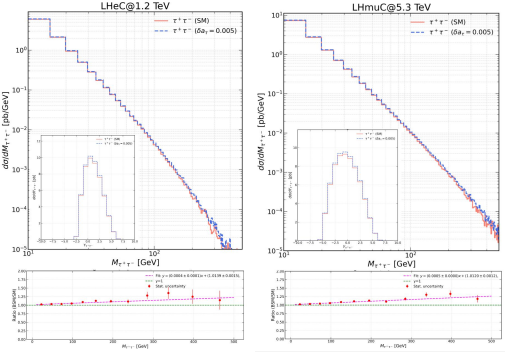
- The elastic $\gamma\gamma \to \tau^+\tau^-$ rate at LHμC for $W_0 = 10$ GeV is already very large, with $\sigma_{\rm el} \simeq 58.5$ pb at 3.7 TeV, and about 70.3 pb at the nominal 5.3 TeV baseline.
- This provides a high-statistics probe of the $\gamma\tau\tau$ vertex and anomalous magnetic (a_τ) and electric (d_τ) dipole moments.
- Anomalous contributions harden the high-$M_{\tau\tau}$ tail, making the invariant-mass spectrum the key discriminating observable.
- This is one of the cleanest examples of how LHμC combines high energy with a low-background exclusive topology.



Elastic $\gamma\gamma \to \tau^+\tau^-$ cross section above the threshold W_0, comparing the LHeC and LHμC benchmark configurations.

Current limits and high-$M_{\tau\tau}$ sensitivity to δa_τ

- For the benchmark deformation $\delta a_\tau = 0.005$, the deviation from the SM remains small at low $M_{\tau\tau}$, but grows in the high-$M_{\tau\tau}$ tail; this is the main source of sensitivity.
- Compared with the LHeC benchmark, the nominal LHμC setup probes a harder kinematic regime and retains better statistical reach in the tail, giving stronger sensitivity leverage on anomalous τ dipole couplings.
- These distributions therefore indicate good expected sensitivity at LHμC, but a quantitative projected limit still requires a dedicated detector-level statistical analysis.



Tail-driven sensitivity

The sensitivity to anomalous τ dipole couplings is tail-driven. Relative to the LHeC benchmark, LHμC combines a larger event sample with a stronger high-$M_{\tau\tau}$ lever arm, making it a promising benchmark for a_τ and d_τ studies.

Current LHC limits on a_τ

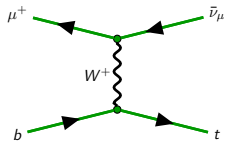
CMS exclusive pp photon-induced $\tau^+\tau^-$ production gives $a_\tau \in [-0.0022, 0.0041]$ [2406.03975 [hep-ex]], while the ATLAS high-mass $\tau^+\tau^-$ analysis gives $a_\tau \in [-0.0024, 0.0047]$ (95% CL) [2503.19836 [hep-ex]].

$\gamma\gamma$@UPC@ATLAS: Lydia Beresford

Top physics at LHμC: production mechanisms

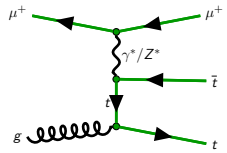
- The top sector provides one of the clearest HET benchmarks for LHμC, since both single-top and $t\bar{t}$ production become statistically powerful channels at the nominal baseline.
- Single-top production is dominated by charged-current DIS, with representative subprocess $\mu^+ b \to \bar{\nu}_\mu\, t$, mediated by t-channel W^+ exchange in the 5-flavor scheme.
- Top-pair production is dominated by neutral-current lepton–gluon scattering, with representative process $\mu^+ g \to \mu^+ t\bar{t}$, driven mainly by $\gamma^* g \to t\bar{t}$, while $Z^* g \to t\bar{t}$ is subleading.
- The top advantage is not only a formal cross-section enhancement: it is also supported by favourable acceptance, making the programme experimentally promising after realistic selections.

LO CC single-top production



CC DIS with t-channel W^+ exchange (5F scheme) with inclusive rates: $\sigma = 21.26$ pb, and 36.77 pb.

LO NC top-pair production



Dominant hard subprocess: $\gamma^* g \to t\bar{t}$; $Z^* g \to t\bar{t}$ is subleading with inclusive rates: $\sigma = 1.03$ pb, and 2.23 pb.

Why LHμC is also a distinctive BSM machine

- $\mu^+ p$ collisions provide a distinctive BSM environment: a point-like muon beam scatters from quarks and gluons at multi-TeV centre-of-mass energy.
- The key advantage is channel-specific: μq and μg initial states can directly probe new particles coupled to second-generation leptons,

$$\mu q \to X, \qquad \mu g \to X.$$

- This enables resonant single production of states that may be harder to isolate through pair production or inclusive searches at hadron colliders.
- The LHμC is naturally powerful for BSM scenarios tied to second-generation leptons.
- Representative examples include:
  - R-parity-violating squark searches,
  - color-octet muons (leptogluons),
  - excited leptons,
  - contact interactions,
  - and other muon-coupled new-physics scenarios.

RPV squarks at LHμC: resonant μq production

- R-parity-violating SUSY allows lepton-quark-squark couplings. The relevant superpotential terms are

$$W_{\text{RPV}} = \epsilon_i L_i \cdot H_u + \frac{1}{2}\lambda_{ijk} L_i \cdot L_j \bar{E}_k + \lambda'_{ijk} L_i \cdot Q_j \bar{D}_k + \frac{1}{2}\lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k$$

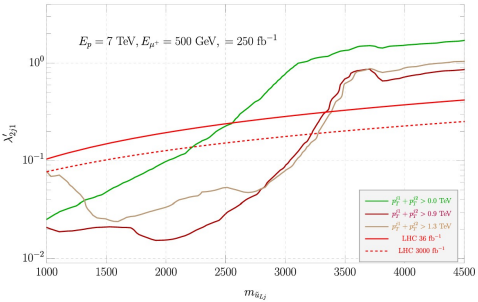
- The LHμC benchmark focuses on the LQD-type term

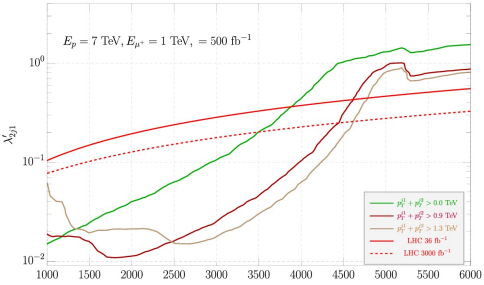
$$W_{\text{RPV}} \supset \lambda'_{ijk} L_i Q_j \bar{D}_k,$$

where $i = 2$ selects the muon generation.

- The neutral-current benchmark is $p\mu^+ \to d\,\mu^+$, mediated by a resonant squark in the μq channel.
- The signal is selected with one reconstructed muon and at least one jet; high jet-p_T-sum thresholds suppress the DIS-like SM background.
- In favourable neutral-current channels, $\lambda'_{2j1} \sim$ 0.01-0.02 can be tested for $m_{\tilde{q}} \sim$ 1-3 TeV.

[Phys. Rev. D 103 (2021) 116009.]





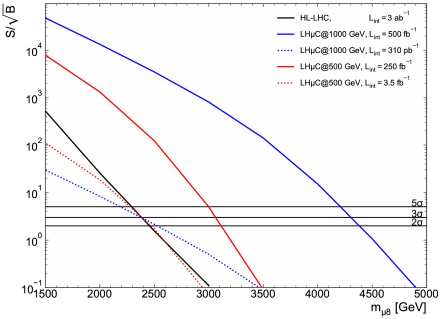
Color-octet muons at LHμC: resonant μg production

- In composite-lepton scenarios, the SM muon can have a color-octet partner μ_8, also called a leptogluon. The effective interaction is [2506.15445 [physics.acc-ph]]

$$\mathcal{L} = \frac{1}{2\Lambda}\left\{\bar{\ell}_8^{\alpha}\, g_s G_{\mu\nu}^{\alpha}\, \sigma^{\mu\nu}\left(\eta_L \ell_L + \eta_R \ell_R\right) + \text{h.c.}\right\}.$$

Here ℓ_8^{α} is the color-octet lepton, $G_{\mu\nu}^{\alpha}$ is the gluon field strength, Λ is the compositeness scale, and $\eta_{L,R}$ are chiral factors.

- The benchmark assumes $\Lambda = m_{\mu_8}$ and targets the resonant single-production channel $\mu g \to \mu_8 \to \mu g$.
- Signal topology: $\mu p \to \mu_8 X \to \mu j X$, with one high-$p_T$ muon and one high-p_T jet.
- Dominant background: $\mu p \to \mu j X$, from SM neutral-current DIS-like scattering.
- The key advantage is the direct μg initial state; pp searches mainly rely on QCD pair production.



Representative 5σ reach

Setup	m_{μ_8} reach
HL-LHC, 1 ab^{-1}	~ 2.3 TeV
LHμC, $E_\mu = 500$ GeV, 250 fb^{-1}	~ 3.0 TeV
LHμC, $E_\mu = 1$ TeV, 500 fb^{-1}	~ 4.2 TeV

Toward FCC-μh: final outlook and take-home points

- The long-term perspective goes well beyond the 5.3 TeV baseline.
- The FCC-hh era is explicitly connected to a future high-energy μp option, turning the current LHμC concept into a stepping stone toward even more powerful HET and BSM programmes.
- In particular, a future FCC-μh machine, with representative $\sqrt{s_{\mu p}} \sim 15$ and 30 TeV configurations would extend:
  - Higgs statistics and coupling reach,
  - top and rare-top production,
  - high-mass electroweak and $\gamma\gamma$ studies,
  - and resonant BSM sensitivity.

HET@LHμC

(1) LHμC is a serious HET factory;
(2) the top sector is one of its clearest near-term strengths;
(3) Higgs, EW, EFT, and $\gamma\gamma$ studies are all strongly motivated;
(4) the concept also provides a natural bridge toward FCC-era μp physics.

Summary and Conclusions

QCD & DIS frontier

Multi-TeV μp scattering extends the accessible (x, Q^2) plane well beyond HERA and the EIC/LHeC, strengthening the PDF, small-x, and α_s programme.

Top and rare-top physics

The top sector gives the clearest rate gain: already the 500 GeV LHμC benchmark enhances $t\bar{t}$ production by ~ 32 relative to the 50 GeV LHeC case, motivating precision top and FCNC studies.

Higgs–EW precision

Large CC/NC Higgs samples enable concrete coupling studies; the $h \to b\bar{b}$ benchmark reaches sub-percent sensitivity to g_{hbb}, while EW/SMEFT observables gain a larger high-Q^2 lever arm.

$\gamma\gamma$ and BSM portals

Photon-induced channels provide high-statistics $\tau^+\tau^-$ samples and high-mass $WW, ZZ, t\bar{t}$ probes, while direct μq and μg portals target RPV squarks, color-octet muons, and other muon-coupled BSM states.

Looking ahead: LHμC is not simply an energy upgrade of the LHeC; it opens a multi-TeV lepton-hadron regime where QCD, Higgs, electroweak, top, photon-induced, and several BSM studies become quantitatively competitive.

THANK
YOU!

The HELP4CERN collaboration

HELP4CERN collaboration focuses on the physics case for high-energy, high-luminosity lepton-hadron colliders at CERN.

- assess the physics potential of future lepton-hadron collider options,
- develop benchmark studies for Higgs, electroweak, top, QCD, and BSM physics,
- provide a common framework for phenomenology, detector studies, and future projections,
- new contributions and physics studies are very welcome,

Contact: help-4-cern@cern.ch
Visit: https://help4cern.web.cern.ch

White Paper on High Energy, High Luminosity Lepton-Hadron Colliders at CERN

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Next steps for HELP4CERN:

- turn the current benchmark studies into a coherent white-paper assessment of high-energy lepton-hadron options at CERN by the end of 2026;
- foster a worldwide study effort, in close coordination with the LHeC Study Group, aimed at preparing a dedicated HELP4CERN proposal by 2028.

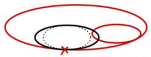
Exclusive $\gamma\gamma$ channels: electroweak, top, and BSM reach

$\gamma\gamma \to W^+W^-$

Strong aQGC sensitivity comes from the high-M_{WW} tail

$\gamma\gamma \to ZZ$

Loop-induced in the SM; clean probe of high-mass electroweak dynamics



Exclusive high-energy $\gamma\gamma$ programme

$\gamma\gamma \to t\bar{t}$

Probes heavy thresholds and top-sector dynamics in exclusive topology

Exclusive BSM pairs

Charged states such as higgsinos and sleptons

Beyond $\tau^+\tau^-$, the high-energy $\gamma\gamma$ programme at LHμC spans electroweak, top, and BSM-sensitive channels in a clean exclusive environment.

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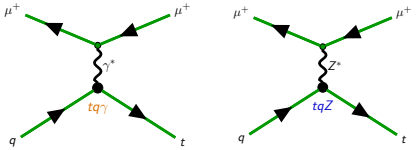
Top-FCNC probes at LHμC: $tq\gamma$ and tqZ

- In the Standard Model, top-FCNC transitions are forbidden at tree level and remain highly suppressed at loop level by the GIM mechanism; any observable signal would therefore be a clean indication of physics beyond the Standard Model.
- The key rare-top vertices are $tq\gamma$ and tqZ with $q = u, c$, naturally parameterized by anomalous couplings or SMEFT dimension-6 operators.
- At LHμC, the large top sample, harder kinematics, and characteristic μp topology make anomalous single-top and associated production natural benchmarks for converting top statistics into BSM reach.

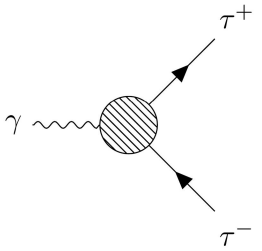
Top-FCNC at LHμC



Representative process: $\mu^+ q \to \mu^+ t$, with $q = u, c$. Neutral-current exchange probes anomalous $tq\gamma$ and tqZ couplings.

Improved sensitivity relative to the LHeC is expected at LHμC, but quantitative limits remain channel-dependent and require realistic event selections, detector modelling, and systematic-uncertainty estimates.

Current constraints on a_τ, d_τ



Benchmark topology

Photon-induced

$$\gamma\gamma \to \tau^+\tau^-$$

directly probes the $\gamma\tau\tau$ vertex. It is therefore a clean channel for anomalous magnetic and electric dipole moments, a_τ and d_τ.

Current 95% CL constraints on a_τ

Experiment	Channel	Dataset	a_τ interval
DELPHI	$e^+e^- \to e^+e^-\tau^+\tau^-$	650 pb^{-1}	$[-0.052,\ 0.013]$
ATLAS 2022	PbPb UPC	1.44 nb^{-1}	$[-0.057,\ 0.024]$
CMS 2022	PbPb UPC	1.34 nb^{-1}	$[-0.030,\ 0.017]$
CMS 2024	pp exclusive $\gamma\gamma \to \tau\tau$	138 fb^{-1}	$[-0.0022,\ 0.0041]$
ATLAS 2025	pp high-mass $\tau\tau$	140 fb^{-1}	$[-0.0024,\ 0.0047]$

- The SM expectation is

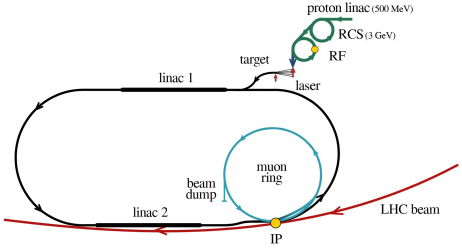
$$a_\tau^{\mathrm{SM}} \simeq 117721 \times 10^{-8} \simeq 1.18 \times 10^{-3}.$$

- CMS 2024 also reports

$$a_\tau = 0.0009^{+0.0032}_{-0.0031}, \qquad |d_\tau| < 2.9\times10^{-17}\, e\,\mathrm{cm} \quad (95\%\ \mathrm{CL}).$$

- Present LHC constraints are therefore already at the few-10^{-3} level for a_τ. The LHμC motivation is a much larger high-mass exclusive $\tau^+\tau^-$ sample.

Technical concept behind the LHμC proposal



Conceptual layout of the proposed LHμC configuration.

- The LHμC proposal aims to re-use key elements of the LHeC infrastructure to make high-energy, high-luminosity μ^+p collisions.
- The basic ingredients are:
  - an ultra-cold positive-muon source,
  - acceleration / booster stages for the μ^+ beam,
  - a dedicated μ^+ storage ring.

See talk by Krzysztof Piotrzkowski

References

(1) μTRISTAN: Y. Hamada *et al.*, *Prog. Theor. Exp. Phys.* **2022** (2022) 053B02.

(2) μLHC: Antimuon Ring and High Luminosity-LHC-Based μ^+p Collider: D. Akturk *et al.*, *Prog. Theor. Exp. Phys.* **2026** (2026) 033C04.

(3) HELP4CERN White Paper (in preparation)