BSM Physics Opportunities with Far-Forward Experiments at a 100 TeV Proton Collider

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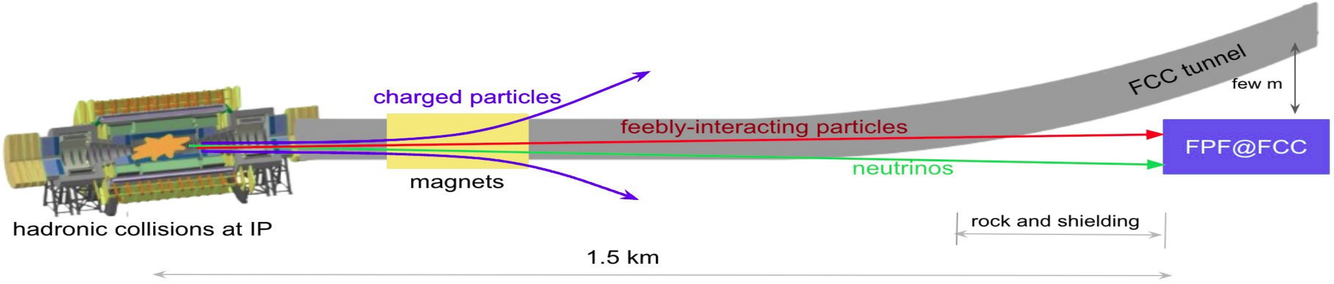
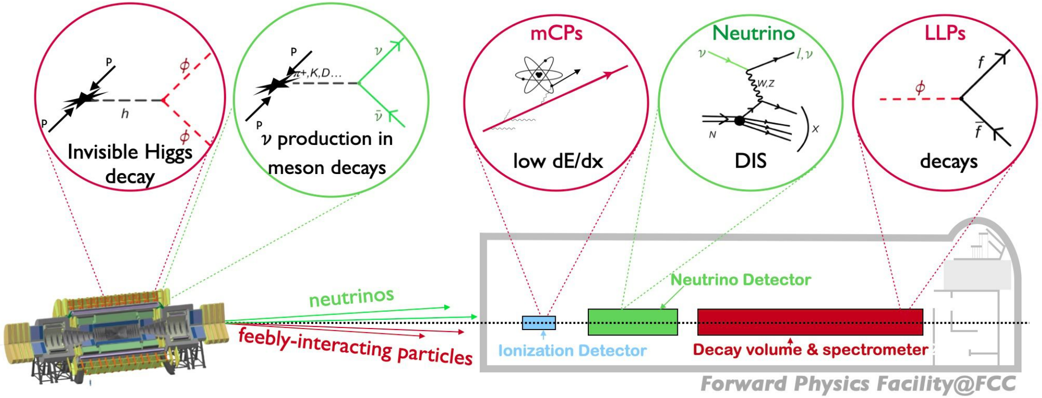
Forward Physics facility@FCC



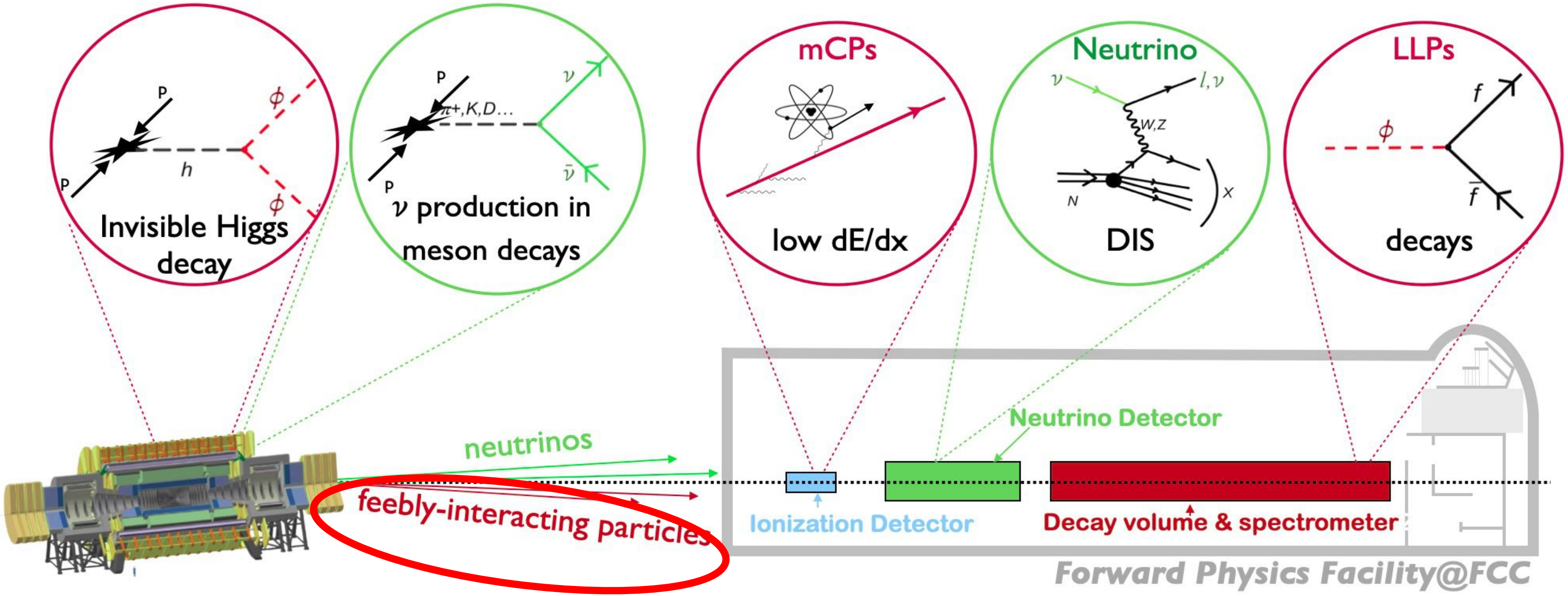
FCC-hh era

- ❑ COM energies of 100 TeV and beyond
- ❑ Expected integrated luminosity of 30 ab^{-1}



- Neutrino / QCD
- BSM physics

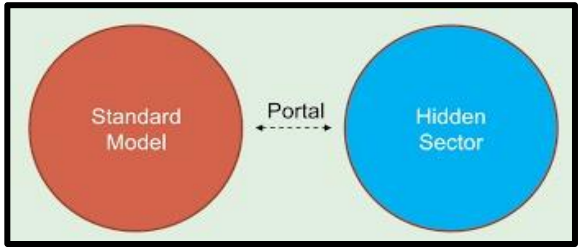
BSM physics Examples



P
P
h
ϕ
ϕ
Invisible Higgs decay
P
P
π+,K,D…
ν
ν̄
ν production in meson decays
mCPs
low dE/dx
Neutrino
ν
l,ν
W,Z
N
X
DIS
LLPs
ϕ
f
f̄
decays
neutrinos
feebly-interacting particles
Neutrino Detector
Ionization Detector
Decay volume & spectrometer
Forward Physics Facility@FCC

Dark Higgs Boson

The model



Dark Higgs, S $\quad (\mu S + \lambda S^2) H^\dagger H$

New scalar mixing with the SM Higgs ⟶ Dark higgs also inherits couplings to SM fermions

$$\mathcal{L} = -m_\phi^2 \phi^2 - \sin\theta \frac{m_f}{v} \phi \bar{f} f - \lambda v h \phi \phi,$$

Dark Higgs boson

Production and decay

Production:

- ❑ Heavy meson decays ($B \longrightarrow X_s \phi$) , ($B \longrightarrow X_s \phi\phi$)
- ❑ SM Higgs decay $h \rightarrow \phi\phi$ @ FCC

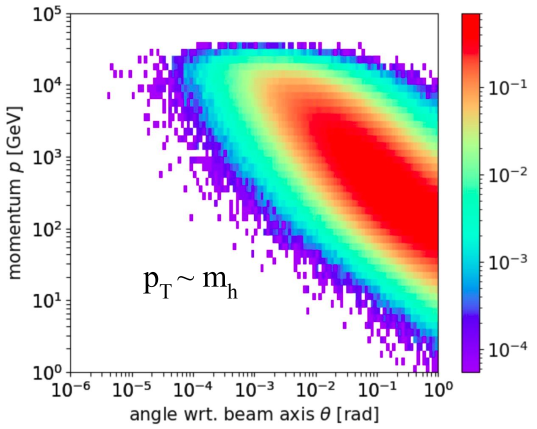
F. Kling, S.Trojanowski (FORESEE), 2105.07077

Decay:

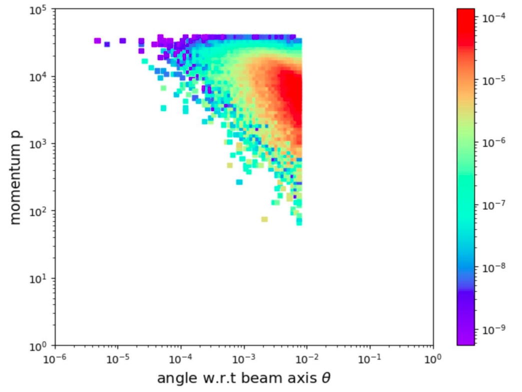
- ❑ mostly bb, $\tau^+\tau^-$, … final states

Large lifetime: TeV-energy $m_\phi = 10$ GeV, $\theta \sim 10^{-7} \rightarrow \tau_\phi \sim 100$ km

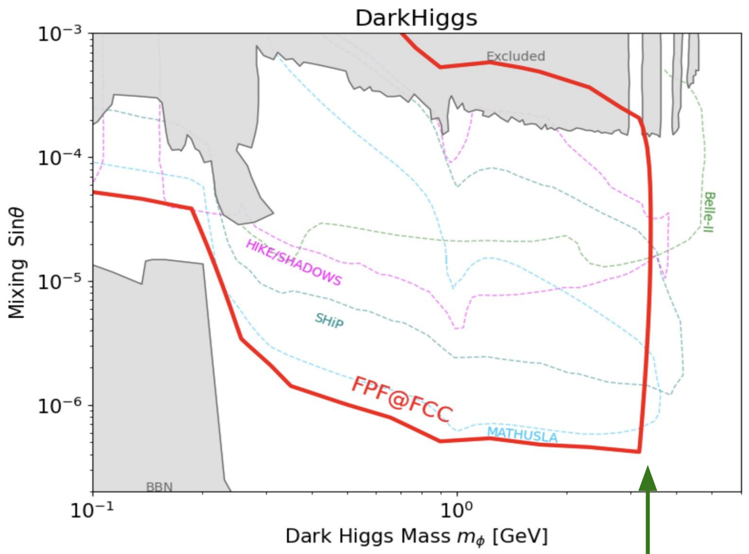
SM Higgs spectrum
Detector size ~0.003% of forward hemisphere
10% forward
85% E_h>10 TeV forward



Dark Higgs in FPF@FCC
$h \rightarrow \phi\phi$; $m_\phi = 10$ GeV,
$\theta \sim 10^{-7}$



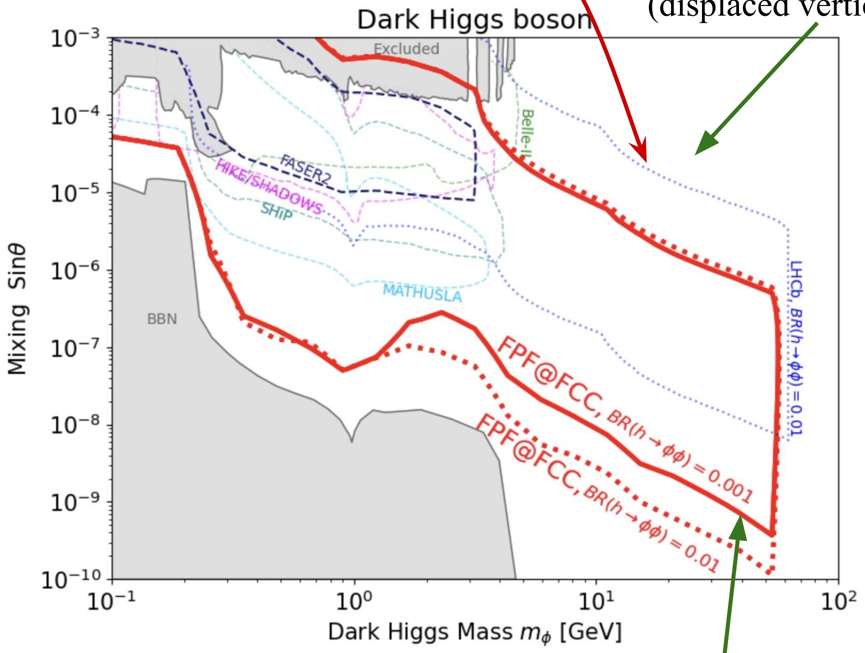
Dark Higgs sensitivity reach without or with trilinear coupling



Reach comparable to projections of proposed future experiments

Maksym Ovchynnikov's talk

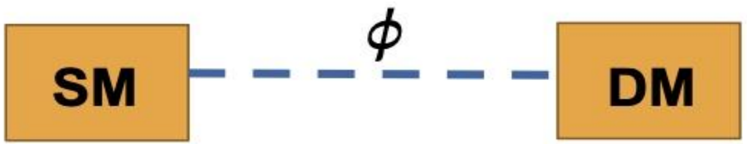
complementarity: central detectors (displaced vertices)



Advantage of high COM energy

Detector size: 20m x 20m x 400m

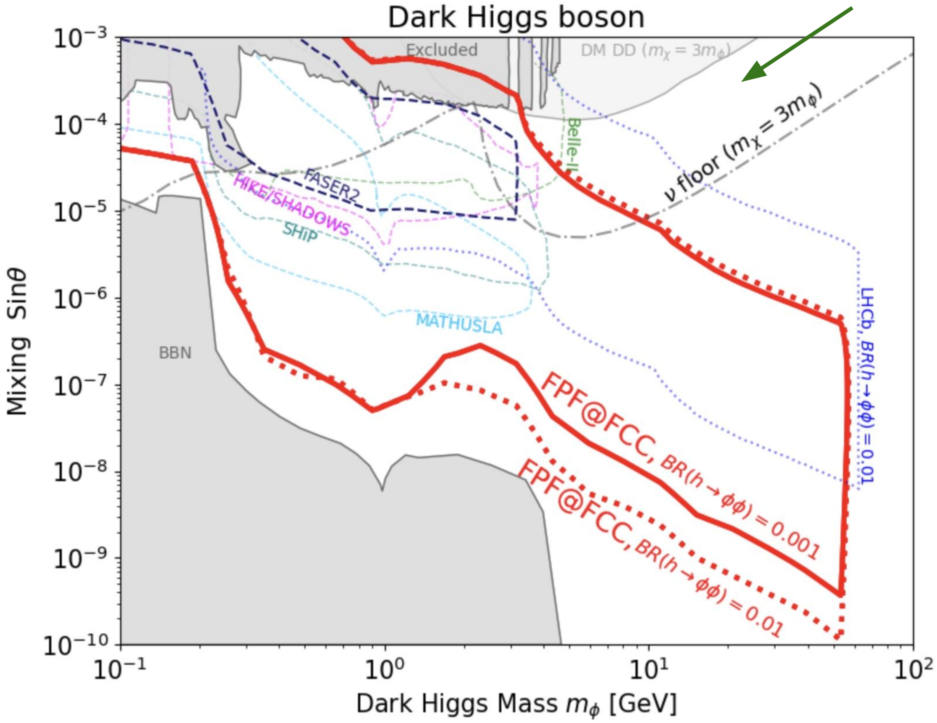
Dark Higgs and cosmology



$$\mathcal{L} \supset -(1/2)\,\kappa\,\phi\,\bar{\chi}\chi$$

Relic density, $\chi\chi \rightarrow \phi\phi$ (driven by κ)

complementarity:
DM direct detection



Millicharged particles

- ❑ Possible result of new unbroken gauge symmetries.

- ❑ Massless dark vector boson A' kinetically mixes with hypercharge boson.

$$(\epsilon'/2\cos\theta_W)B^{\mu\nu}X_{\mu\nu}$$

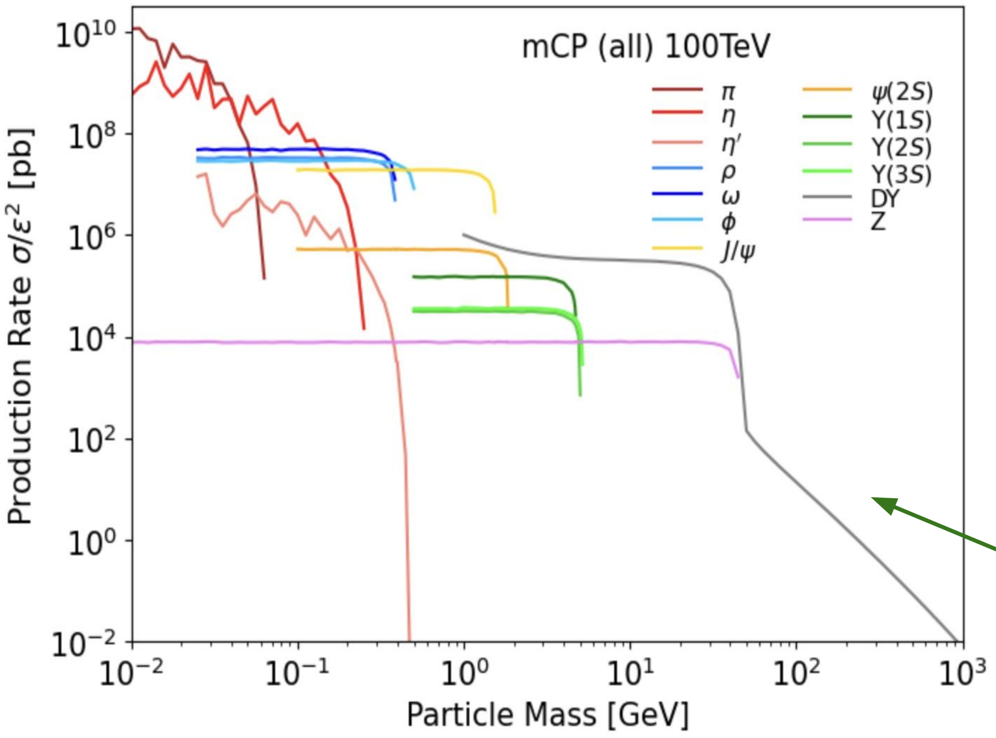
If dark fermion χ couples to A' ➡ □ can also interact with hypercharge boson

$$(\epsilon' e'/\cos\theta_W)\bar{\chi}\gamma^\mu\chi B_\mu.$$

After EWSB, χ couples to photon and Z boson.

- ❑ Gains millicharge, ε~= ε′e′/e

Millicharged particles production and detection



Stable particle

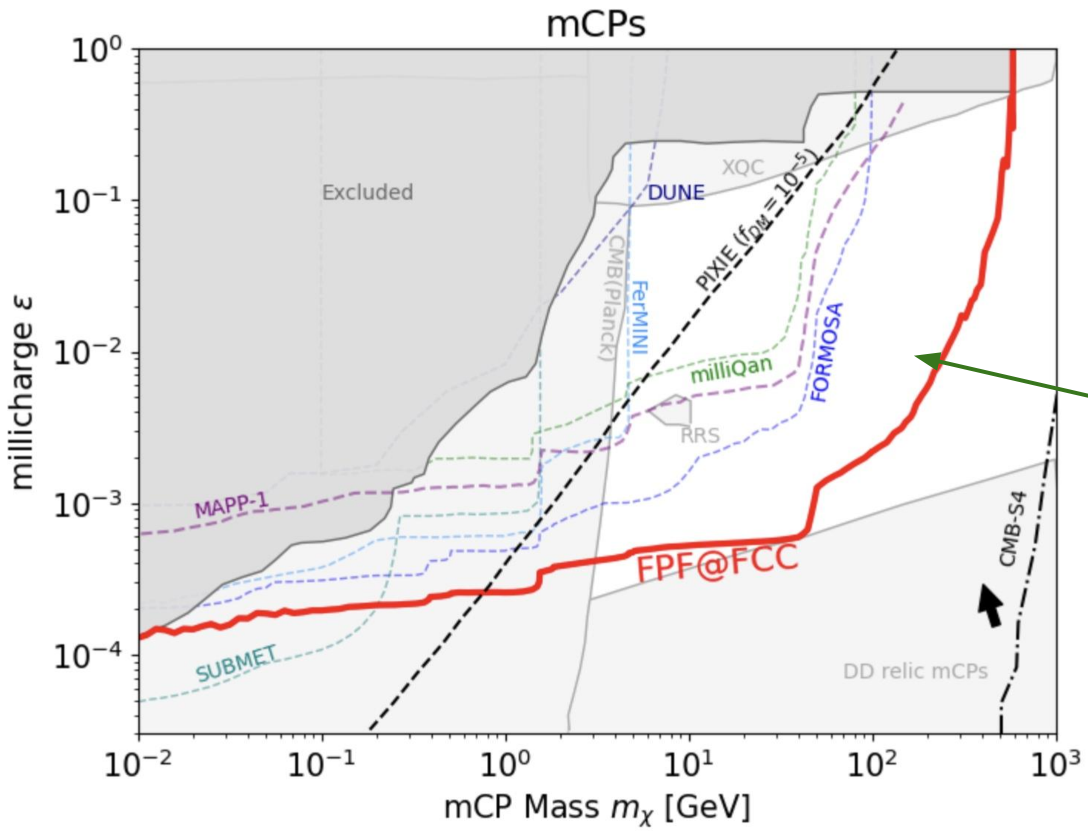
possibility of detection with ionization signals

Drell Yan production becomes dominant at higher masses

χ detection via ionization (a-la-milliQan, FORMOSA@FPF)

S. Foroughi-Abari etal, 2010.07941

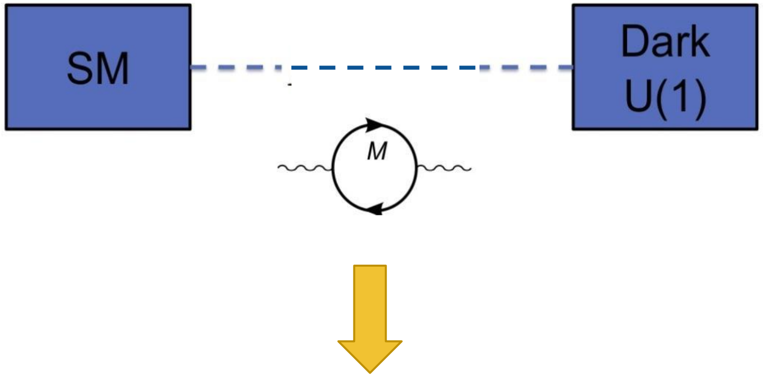
Millicharged particles sensitivity reach



Complementarity:
Direct probe for mCPs only tested by indirect cosmological constraints

Detector size: 5m x 5m x 4m (4 layers 1m each)

Millicharged particles theory target



$$\epsilon' = ee'/16\pi^2$$

A. Berlin et. al 2211.05139

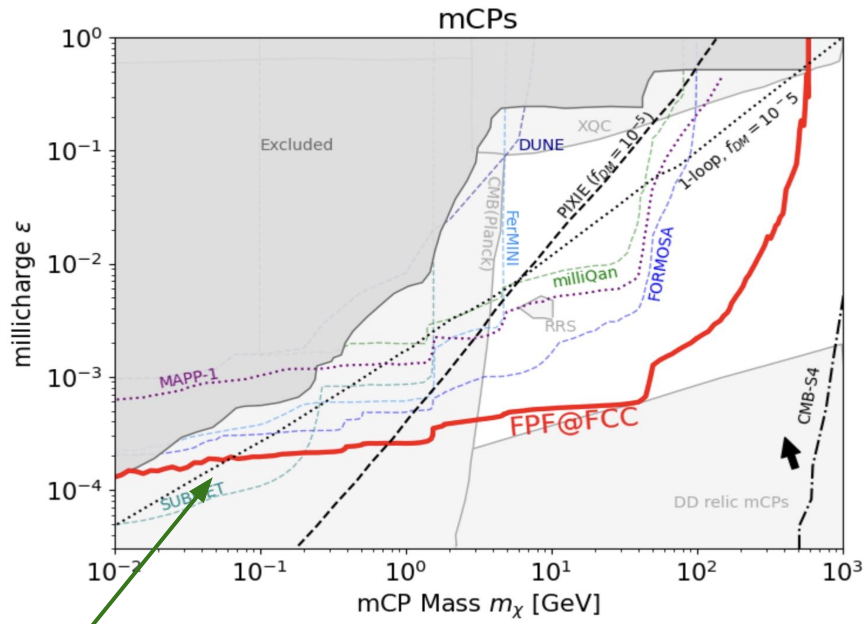
Tony Gherghetta et. al. 1909.0069

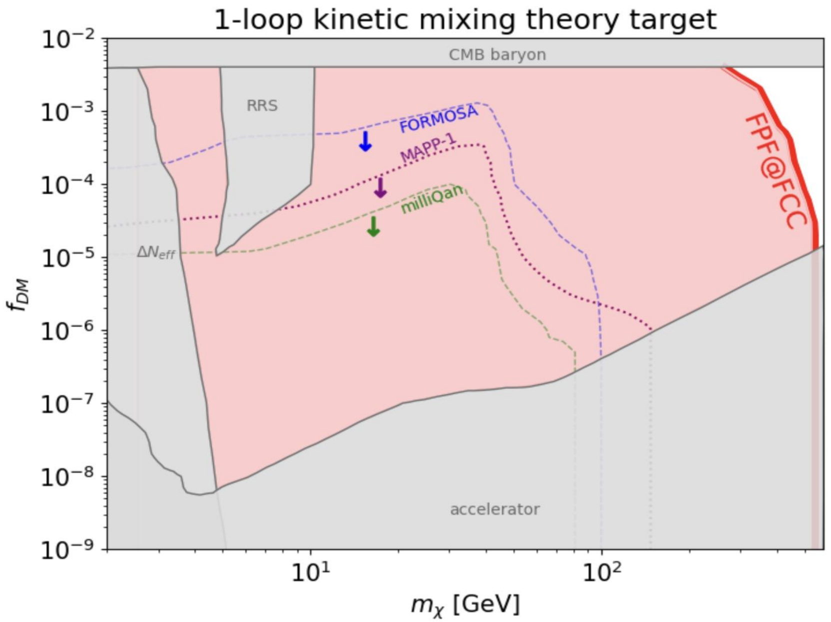
B.Holdom doi:https://doi.org/10.1016/0370-2693(86)91377-8

C. Cheung et. al. 0902.3246

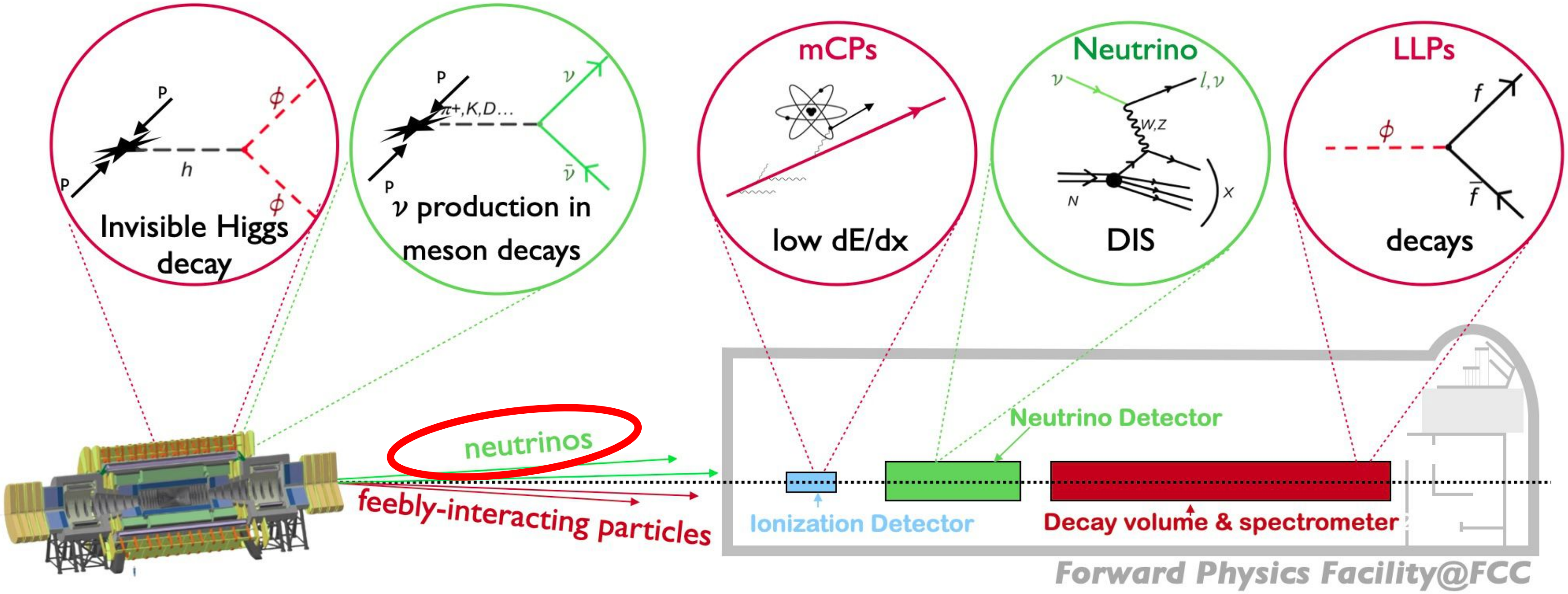
- mCP relic abundance is set by annihilations $\chi\ \chi \longrightarrow A'\ A'$
- e′ is fixed by relic density of mCPs set to be equal to $f_{DM} = 10^{-5}$.

Millicharged particles theory target





Theory target



Invisible Higgs decay
ν production in meson decays
π+,K,D…
mCPs
low dE/dx
Neutrino
DIS
LLPs
decays
neutrinos
feebly-interacting particles
Ionization Detector
Neutrino Detector
Decay volume & spectrometer
Forward Physics Facility@FCC

Neutrino charge radius

- Neutrino effective electromagnetic current:

$$\langle \nu_f(p_f)|j^{\mu}_{\nu,\mathrm{EM}}|\nu_i(p_i)\rangle = \overline{u}_f(p_f)\Lambda^{\mu}_{fi}(q)u_i(p_i)$$

For ultrarelativistic case with small momentum transfer

$$\Lambda^{\mu}_{fi}(q) = \gamma^{\mu}(Q_{fi} - \frac{q^2}{6}\langle r^2\rangle_{fi}) - i\sigma^{\mu\nu}q_{\nu}\mu_{fi}$$

Charge radius

- Presence of charge radius changes the vector coupling constant:

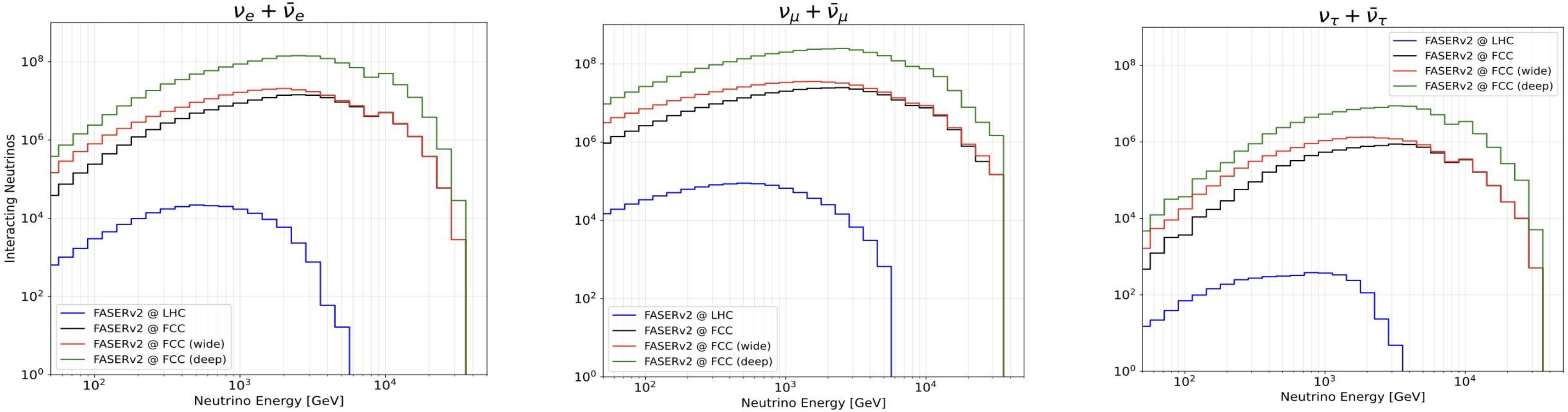
R.M. Abraham etal, 2301.10254

$$g^q_V \to g^q_V - \frac{2}{3}Q_q m^2_W \langle r^2_{\nu_\ell}\rangle \sin^2\theta_w .$$

increased neutrino neutral current event rate

Neutrino charge radius

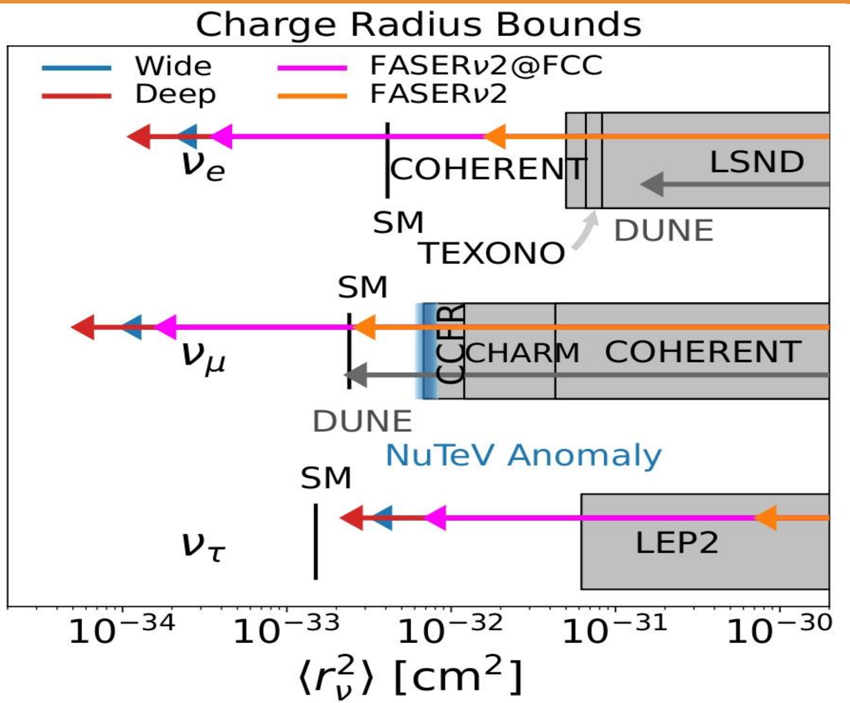
- Neutrinos are produced in various meson decays at IP.



- Large forward flux of high-energy (up to few tens of TeV) neutrinos of all 3 flavors
- Up to order 10^9 ν_μ and ν_e interactions, and few x 10^6 for ν_τ

Neutrino charge radius

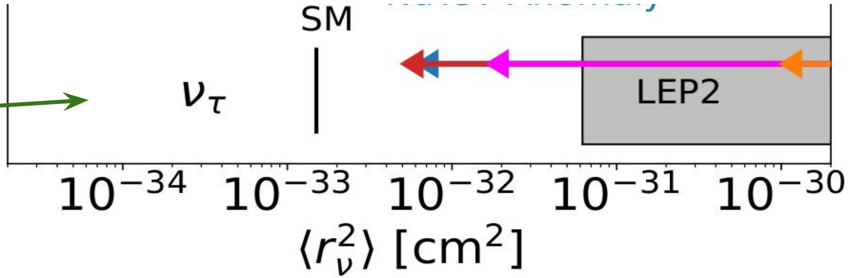
- Signal: Electron scatterings and neutral current DIS (dominant)
- Charge radius changes the normalization of the event rate



Systematics

- Flux uncertainties
- Modelling of the neutrino-nucleus interaction cross section
- Uncertainties arising from the experimental setup

With systematics



Conclusions

- FPF@FCC – out-of-the-box studies but updated for higher energies

  → Neutrino/ QCD- Juan Rojo's talk

- Predictions: high-energy neutrinos up to tens of TeV and billions of interactions

- Can be used to search for new physics (collimated flux)

- Long-lived particles with masses up to tens or hundreds of GeV can be probed (examples: dark Higgs, mCPs)

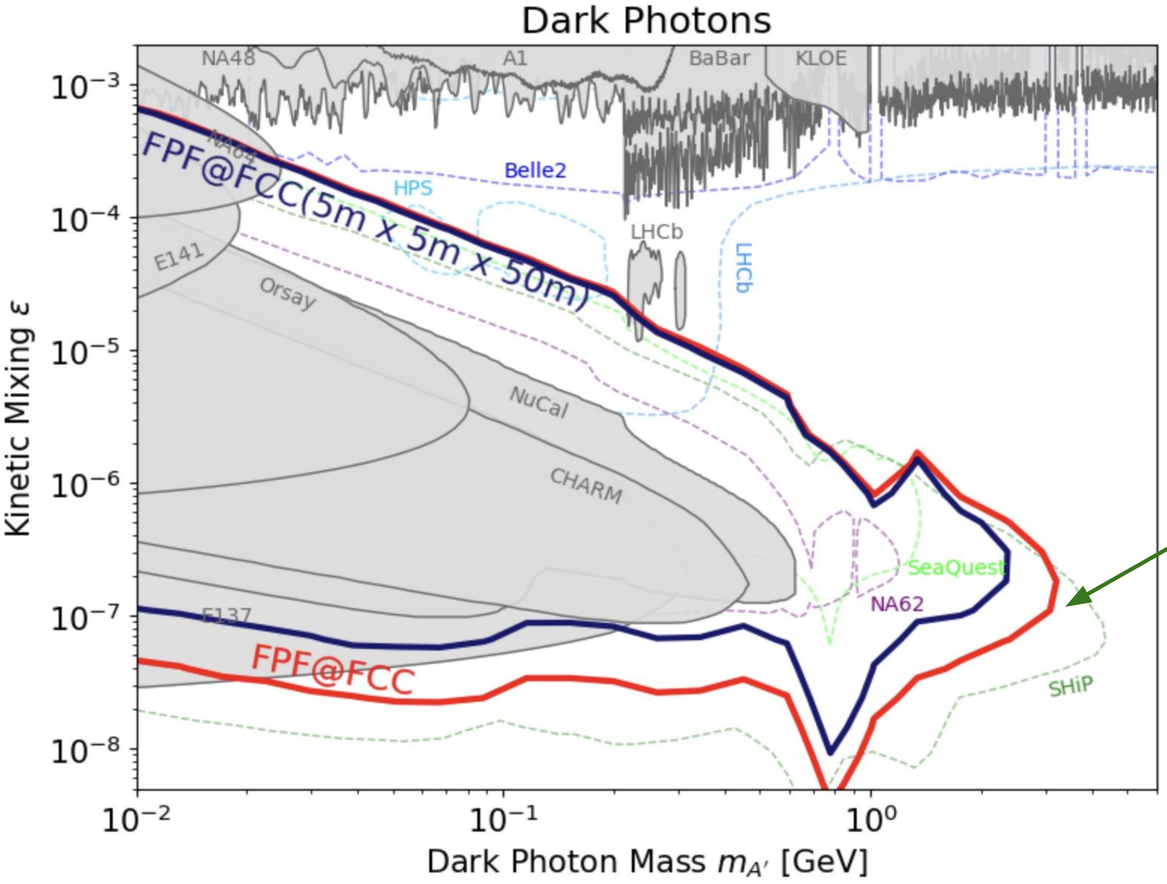
- **Convenient simulation tool FORESEE** F. Kling, ST (FORESEE), 2105.07077
  (initial forward BSM studies for FCC-hh, HE-LHC, SppC)

  → Roshan's talk

Thank you!

Supplementary material

Dark photon model results



Production rate for lower values of epsilon are suppressed

Relaxion type model

The model

P.W. Graham, D.E. Kaplan, S. Rajendran, 1504.07551

Relaxion solution to the hierarchy problem: stabilizing the Higgs mass dynamically.

$$V(H,\phi) = \mu^2(\phi)H^\dagger H + \lambda(H^\dagger H)^2 + V_{\rm sr}(\phi) + V_{\rm br}(h,\phi)\,,$$
$$\mu^2(\phi) = -\Lambda^2 + g\Lambda\phi + \dots\,,$$

Slow roll potential

Back reaction potential

In the limit of small relaxion-Higgs mixing-

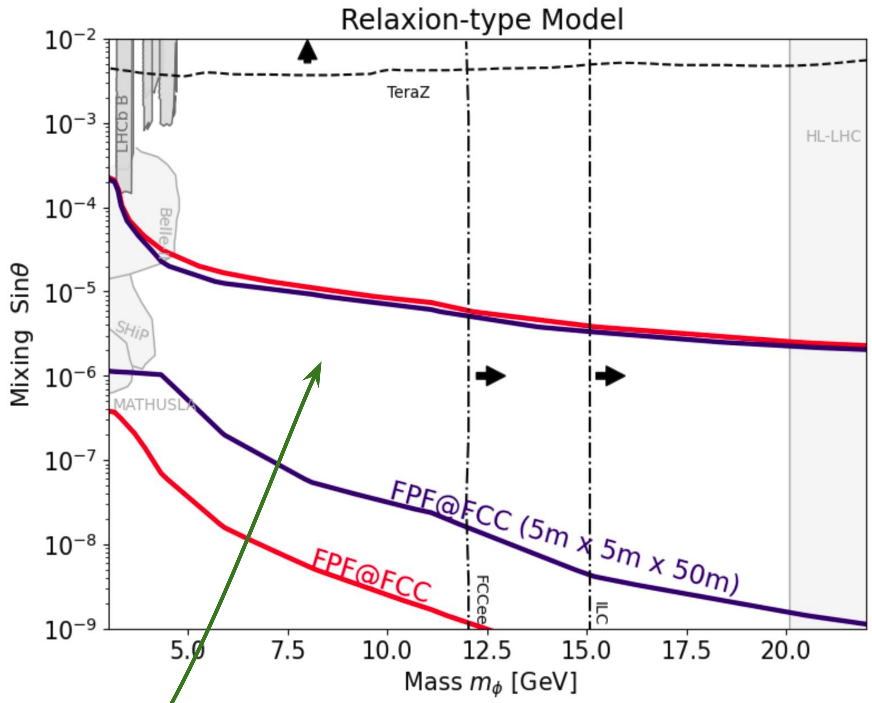
$$\mathcal{L} = -m_\phi^2\phi^2 - \sin\theta\frac{m_f}{v}\phi\bar{f}f - \lambda v h\phi\phi,$$

T. Flacke etal, 1610.02025
C. Frugiuele etal, 1807.10842

$$\lambda = \frac{(m_\phi)^2}{v^2}$$

Relaxion type model sensitivity reach

- ❑ BR(h→ $\phi\phi$) becomes suppressed for low m_ϕ
- ❑ Sensitivity gap between beam-dump and B-meson factories & invisible Higgs decay search
- ❑ Requires detecting ϕ decays
- ❑ Complementarity between the central and forward detectors to bridge the gap



Detector size: 20m x 20m x 400m