New physics in the forward kinematic region of the FCC

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Laboratoire d'Annecy de physique des particules

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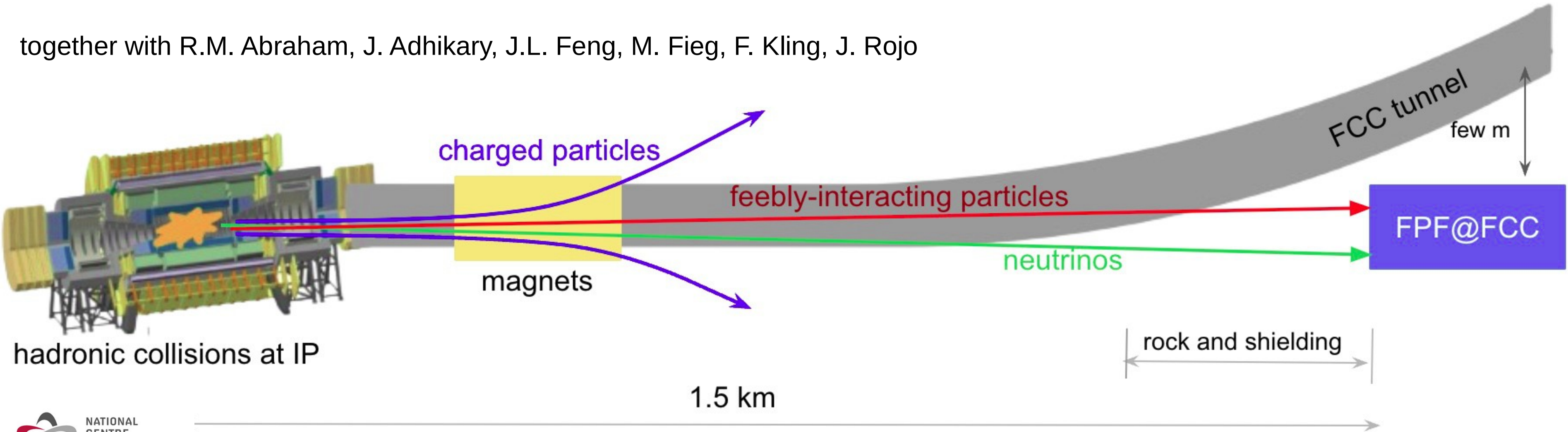
together with R.M. Abraham, J. Adhikary, J.L. Feng, M. Fieg, F. Kling, J. Rojo



NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

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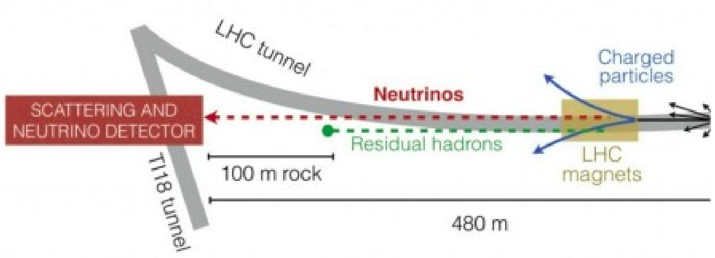
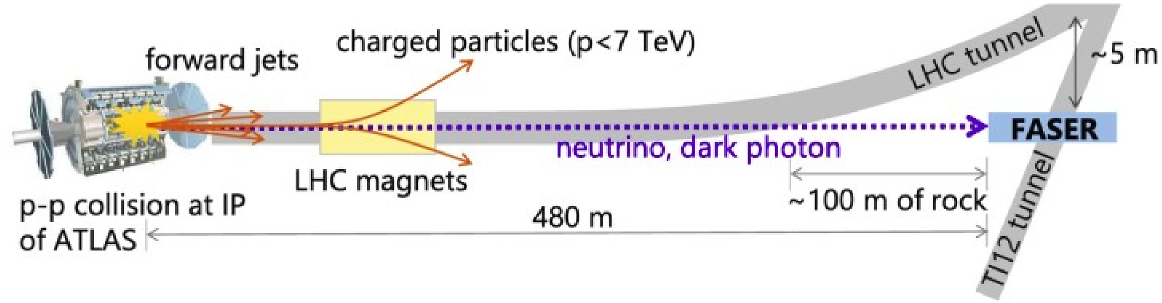
FAR-FORWARD SEARCHES AT THE LHC



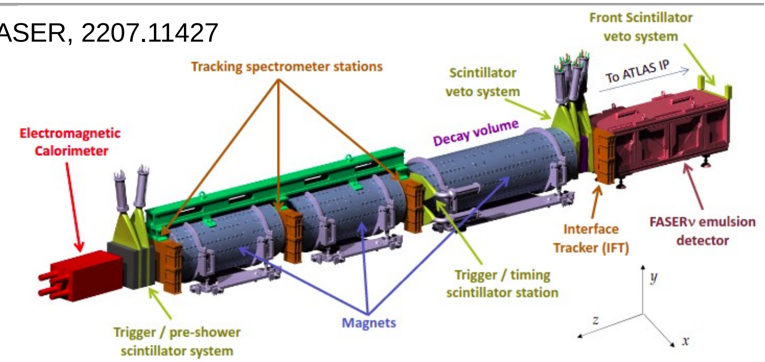


- Forward direction: lots of activity down the beam pipe
- Far-forward detectors:
  – well-screened from pp collisions
  – only neutrinos and muons survive
- **Current Run 3**: FASER, SND@LHC
- **HL-LHC**: proposed Forward Physics Facility (FPF)

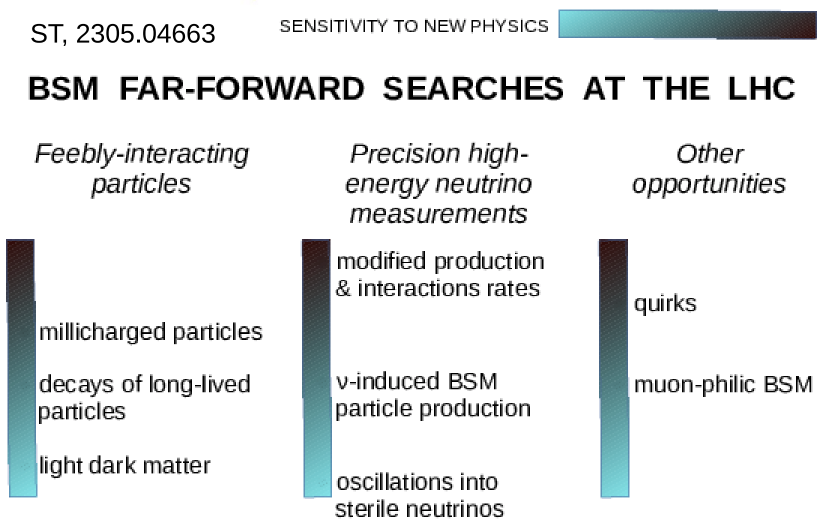
J.L. Feng etal, 2203.05090
L.A. Anchordoqui etal, 2109.10905

- Physics:
  – "Precision" high-energy neutrino physics
  – Implications for QCD & cosmic-ray physics
  – New physics searches

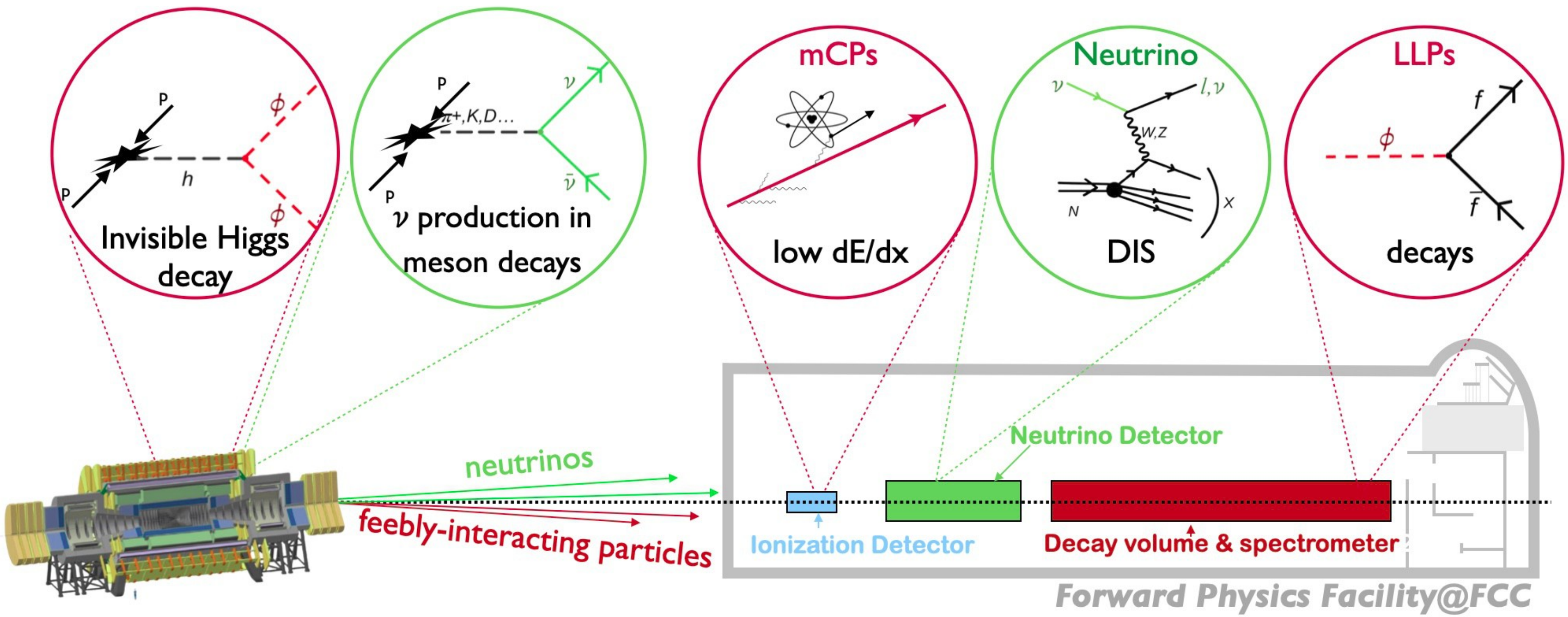
FASER, 2207.11427



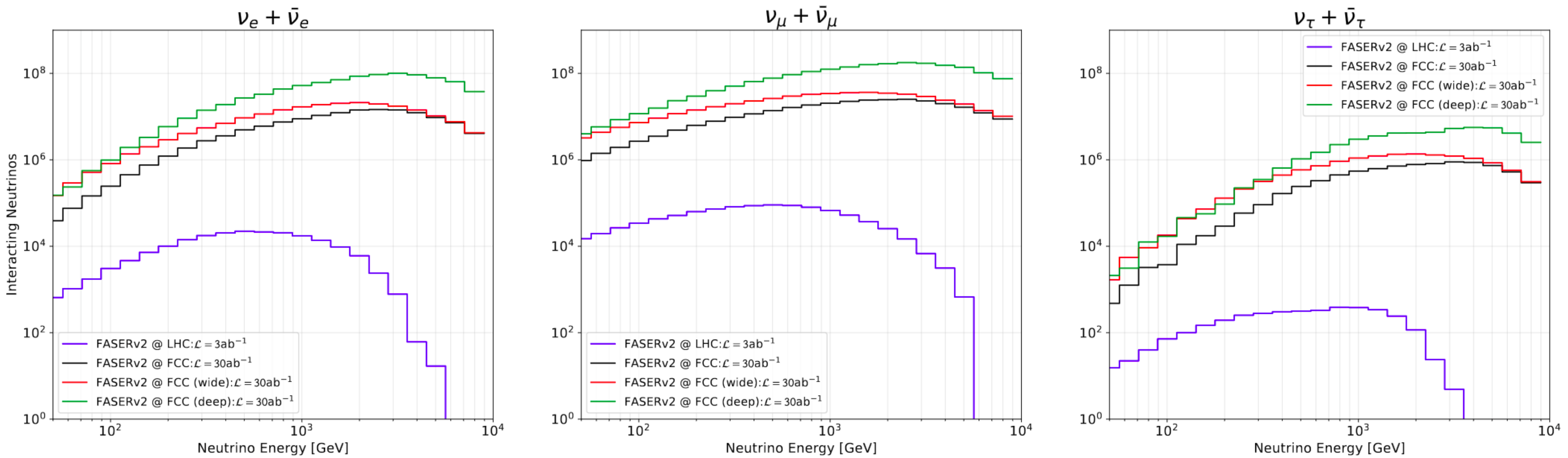
ST, 2305.04663



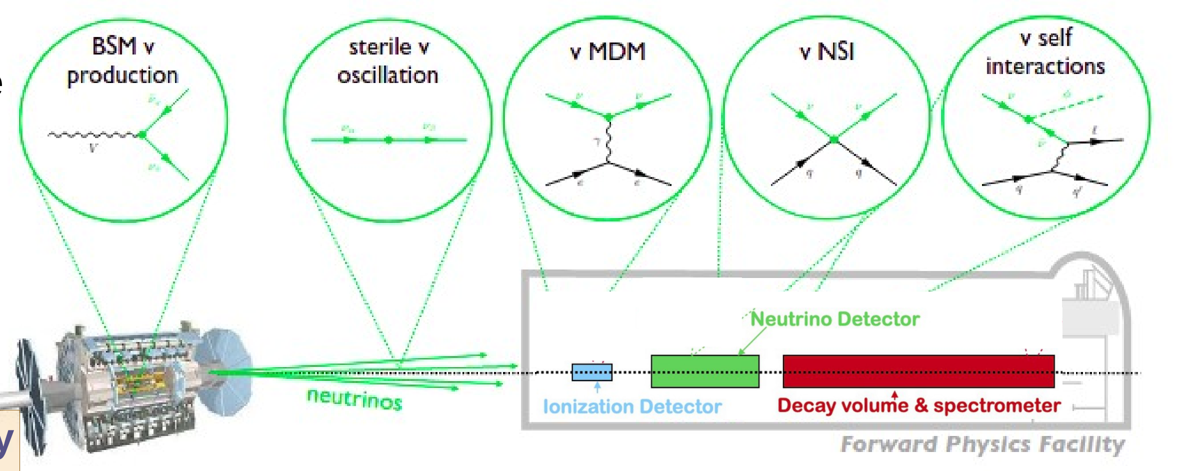
FORWARD PHYSICS FACILITY @ FCC



FORWARD NEUTRINOS @ FCC



- 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 (~100 ton detector; cf. DUNE 70kt mass)
- Collimated flux:
  - baseline: 40cm x 40cm transverse size
  - allows for detailed event studies
- No (SM) oscillations (~near detector)
- BSM opportunities
- Rich SM physics program

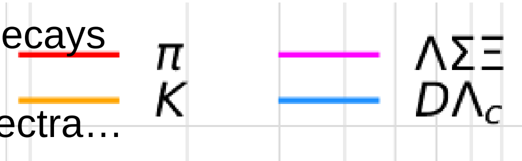


→ Juan Rojo talk on Thursday

F. Kling, L.J. Nevay, 2105.08270

FORWARD NEUTRINOS @ BSM

- Neutrinos produced in various meson decays



- Expected correlations between their spectra…
  (no impact of SM oscillations)

- Breakdowns in these correlations can be indicative of new physics effects
  F. Kling, T. Makela, ST, 2309.10417

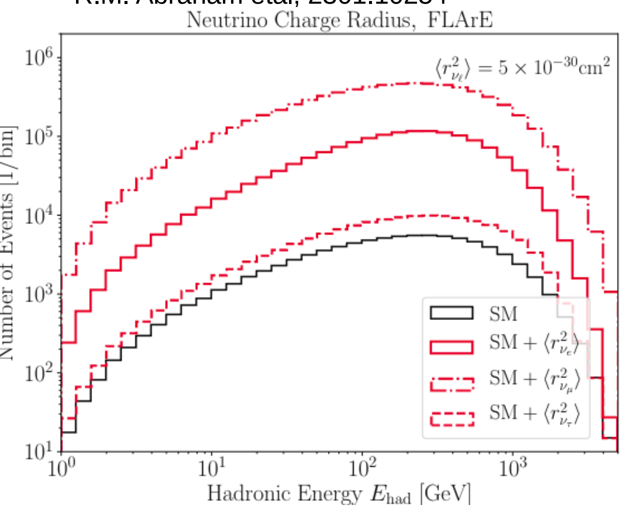
- Example: neutrino charge radius interaction

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

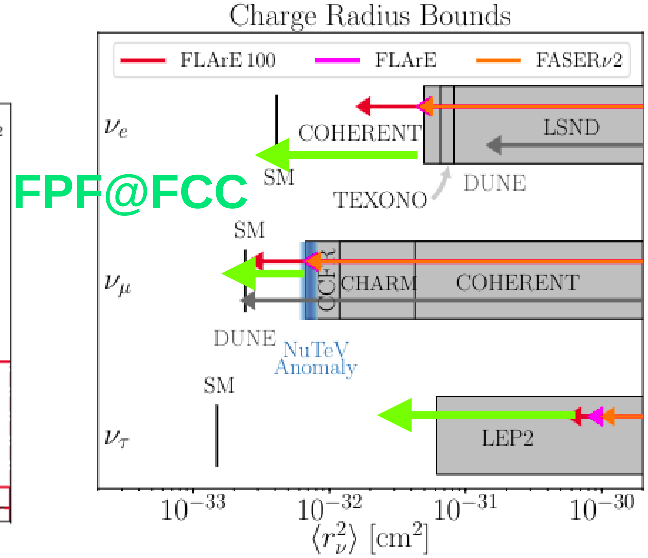
$$\Lambda^{\mu}_{fi}(q) = \gamma^{\mu}\left(Q_{fi} - \frac{q^2}{6}\langle r^2\rangle_{fi}\right) - i\sigma^{\mu\nu}q_{\nu}\mu_{fi}$$

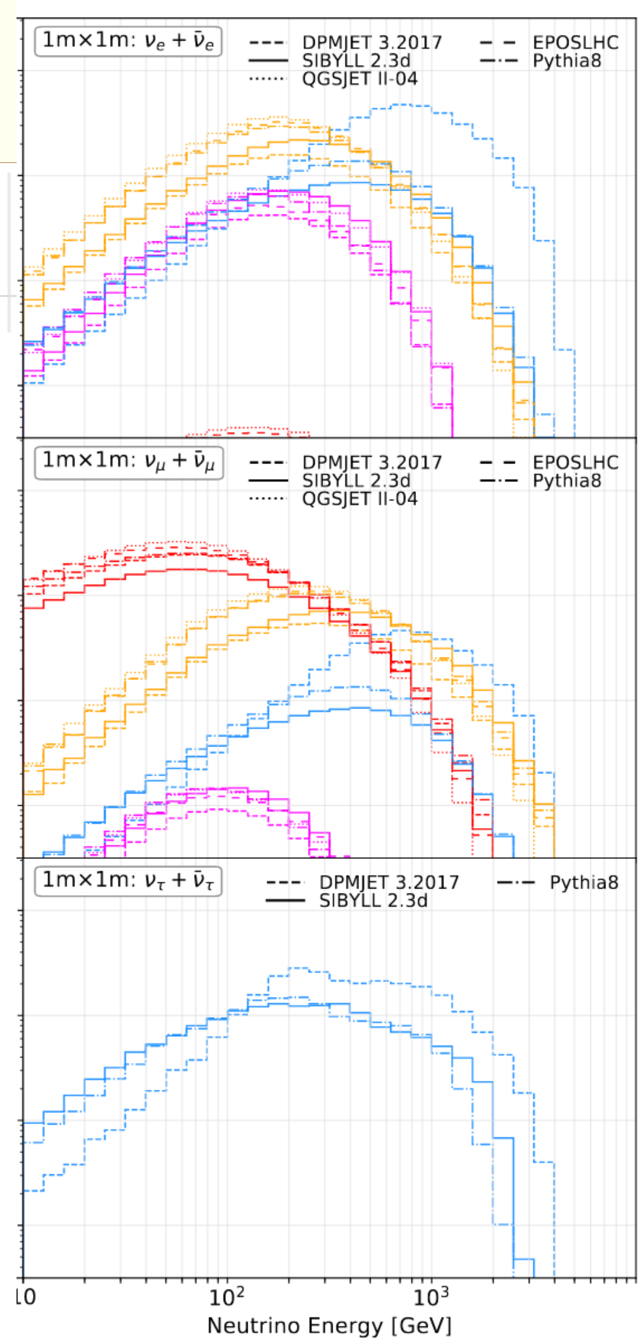
$$g^q_V \to g^q_V - \frac{2}{3}Q_q m^2_W \langle r^2_{\nu_e}\rangle \sin^2\theta_w.$$

R.M. Abraham etal, 2301.10254



Preliminary



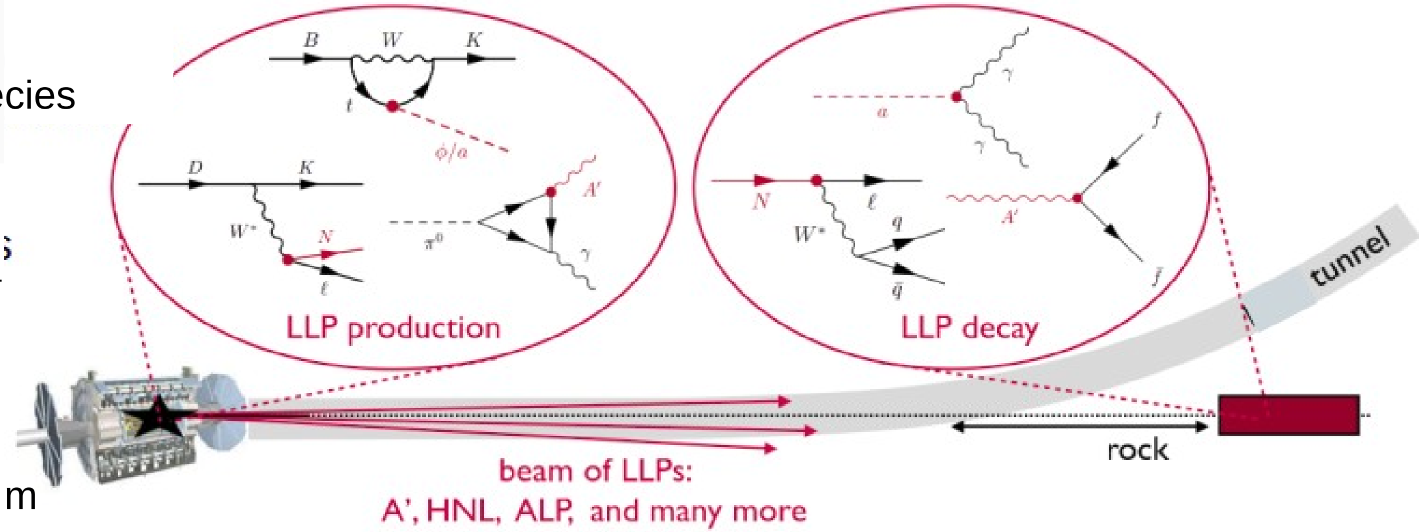


FORWARD LONG-LIVED PARTICLES

● Rare meson decays can also produce BSM particles

● Other production modes:
- decays of heavier SM species
- bremsstrahlung
- Drell-Yan
- secondary processes

K. Jodlowski etal, 1911.11



● Forward production: $p_T \sim m$

● Long-lived species can decay inside FPF@FCC detectors

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu \gamma^5 \psi$
Sterile Neutrino, N	$y_N L H N$

R.M. Abraham, J. Adhikary, J.L. Feng, M. Fieg, F. Kling, J. Rojo, ST (in preparation)

EXAMPLE: DARK HIGGS BOSON

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

- New scalar mixing with the SM Higgs; inherits also couplings to SM fermions

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

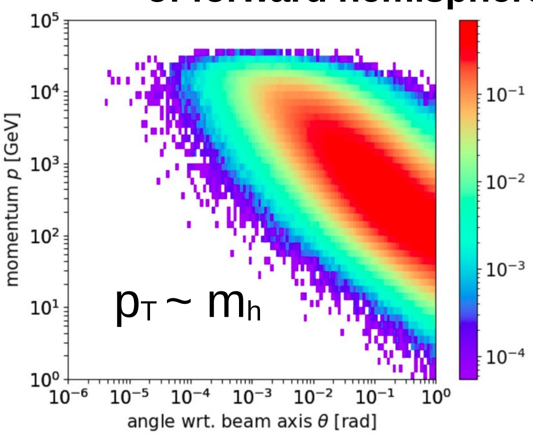
- Production: heavy meson decays ($B \to X_s \phi$), SM Higgs decay h $\to$ $\phi\phi$ @ FCC

F. Kling, ST (FORESEE), 2105.07077

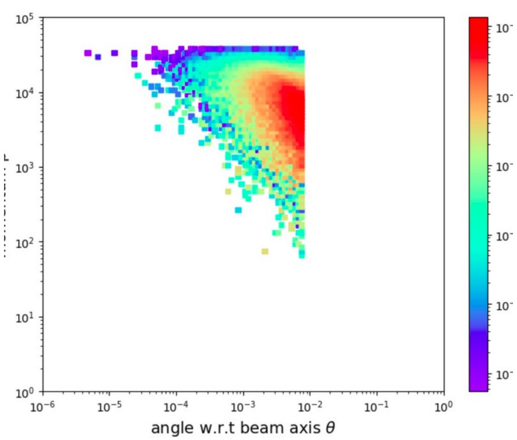
- Decay: mostly bb, $\tau^+\tau^-$, … final states
- Large lifetime: TeV-energy m_ϕ= 10 GeV, $\theta \sim 10^{-7}$ $\to$ $\tau_\phi \sim$ 100 km

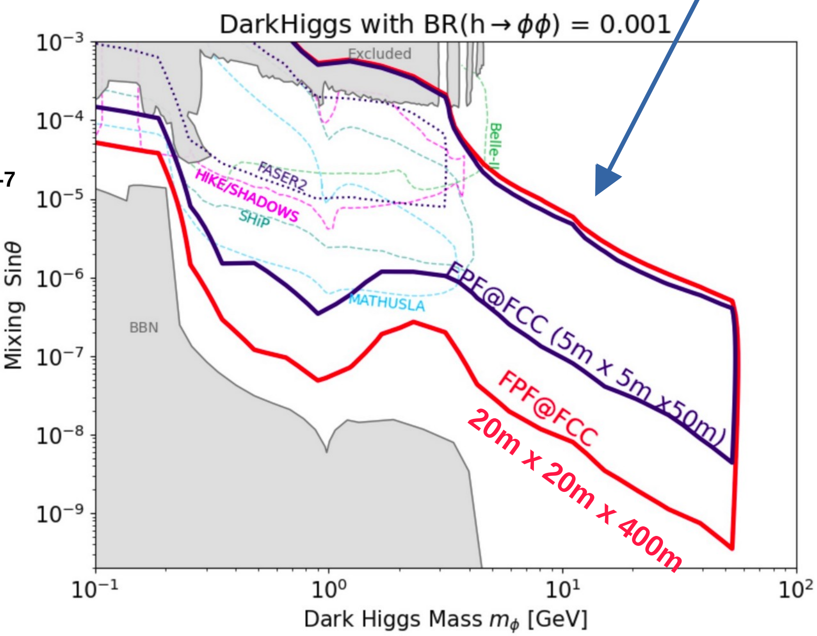
complimentarity:
central detectors
(displaced vertices)

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



Dark Higgs in FPC@FCC
h $\to$ $\phi\phi$; m_ϕ= 10 GeV, $\theta \sim 10^{-7}$





R.M. Abraham, J. Adhikary, J.L. Feng, M. Fieg, F. Kling, J. Rojo, ST (in preparation)

EXAMPLE: DARK HIGGS BOSON & COSMOLOGY

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

- New scalar mixing with the SM Higgs; inherits also couplings to SM fermions

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

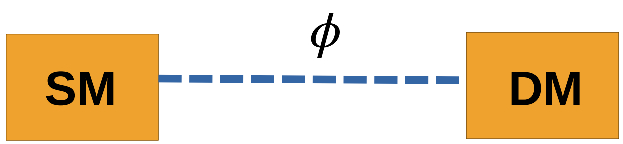
- Production: heavy meson decays ($B \to X_s \phi$), SM Higgs decay h → $\phi\phi$ @ FCC

F. Kling, ST (FORESEE), 2105.07077

- Decay: mostly bb, $\tau^+\tau^-$, … final states
- Large lifetime: TeV-energy m_ϕ= 10 GeV, θ ~ 10^{-7} → $\tau_\phi \sim 100$ km

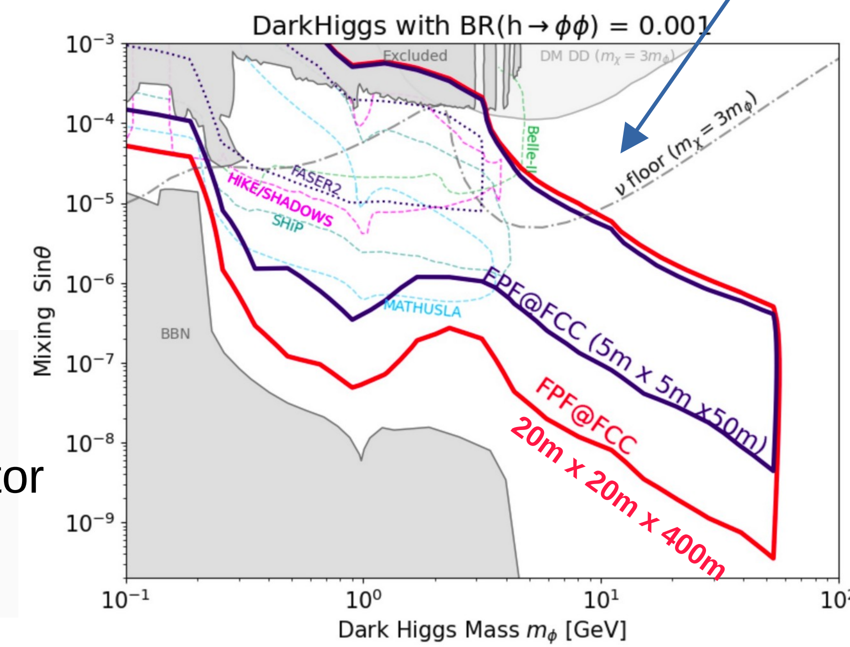
complimentarity:
DM direct detection

Portal to dark matter (DM)



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

- relic density, χχ → $\phi\phi$ (driven by κ)
- indirect search for the dark Higgs mediator goes significantly below the ν floor



EXAMPLE: RELAXION-TYPE MODEL

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

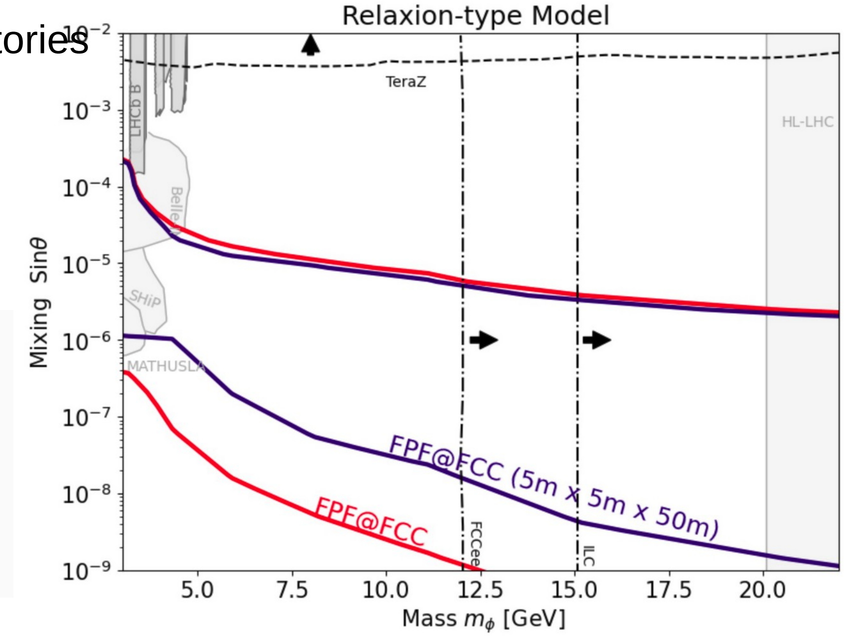
P.W. Graham, D.E. Kaplan, S. Rajendran, 1504.07551

- Relaxion phenomenology resembles dark Higgs boson with m_ϕ and sinθ ...
- ...but the h$\phi\phi$ coupling is not a free parameter and becomes non-zero in the low-θ regime

$$c_{\phi\phi h}\big|_{\theta\to 0} \simeq \frac{r_{\rm br}^4 v^3}{f^2} c_0 c_\theta^3 \simeq \frac{m_\phi^2}{v}$$

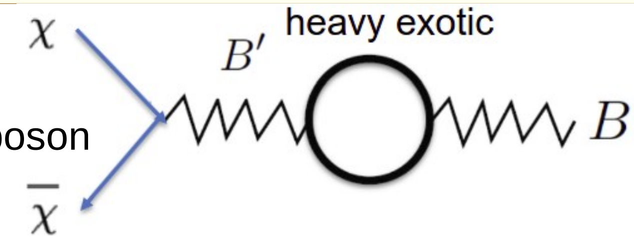
T. Flacke etal, 1610.02025
C. Frugiuele etal, 1807.10842

- 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
- Complimenatarity between the central and forward detectors to bridge the gap



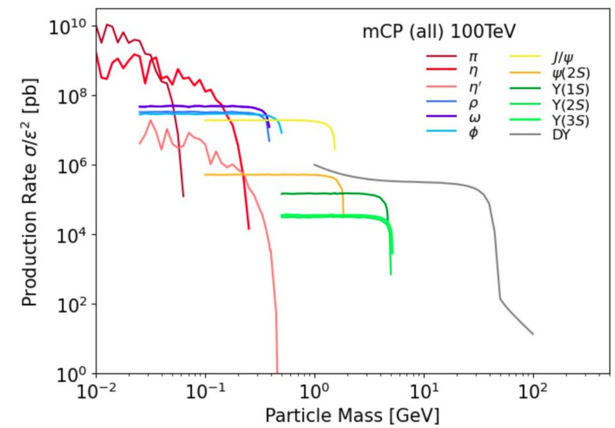
EXAMPLE: MILLICHARGED PARTICLES

- Possible result of new unbroken gauge symmetries
- Massless dark vector boson kinetically mixing with the hypercharge boson



- Massless dark photons additionally coupled to dark fermions χ...

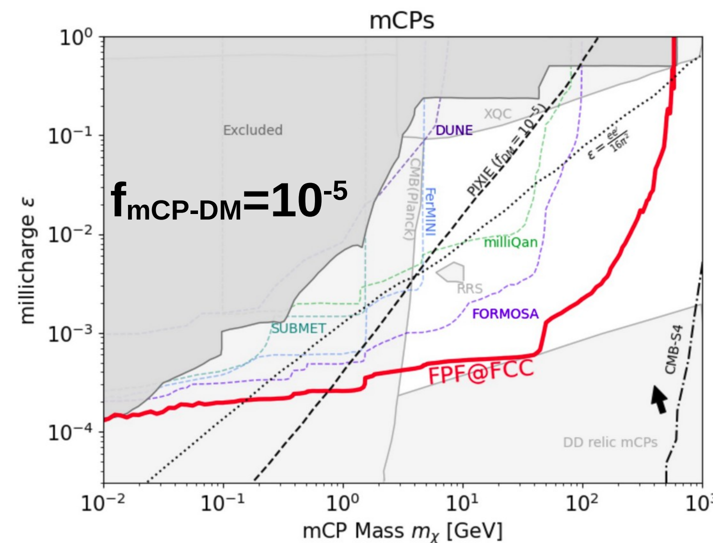
$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\varepsilon}{2}B'_{\mu\nu}B^{\mu\nu} + i\bar{\chi}(\partial\!\!\!/ + ie'B\!\!\!/' + iM_{\rm MCP})\chi$$



- ...they acquire millicharge, $Q_\chi \sim= \varepsilon e$
- χ could be (a subdominant) DM contribution
- χ production @ FCC: hadron decays, Drell-Yan, …
- χ detection via ionization (a-la-milliQan, FORMOSA@FPF)

S. Foroughi-Abari etal, 2010.07941

- Complimentary DM direct detection searches & cosmological probes



CONCLUSIONS

- Forward BSM & neutrino physics program at the LHC (running: FASER, SND@LHC)
- Proposed extension for HL-LHC: Forward Physics Facility (FPF)

J.L. Feng etal, 2203.05090
L.A. Anchordoqui etal, 2109.10905

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

(initial forward BSM studies for FCC-hh, HE-LHC, SppC)

F. Kling, ST (FORESEE), 2105.07077

THANK YOU !