Feebly-interacting particles at future colliders

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National Centre for Nuclear Research (NCBJ), Poland

Corfu2024 – Workshop on Future Accelerators

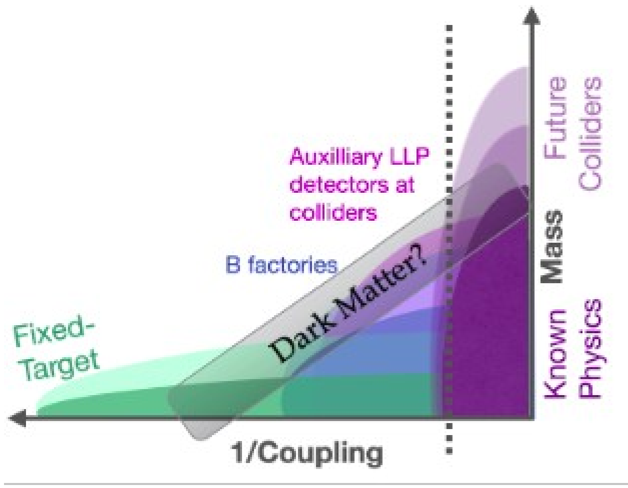
May 22, 2024

NATIONAL SCIENCE CENTRE POLAND

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

FIMPs (& neutrinos)

FIPs 2022 Workshop Report, 2305.01715



- Feebly-Interacting Massive Particles

- **This talk: ~MeV- to GeV-scale new physics (only selection of topics)**

- Motivation:

- Cosmology (DM, inflation, baryogenesis)

- Hierarchy (relaxion,…), ...

- Experimentally accessible:

- Intensity frontier

- Auxiliary collider detectors

- Prototype feebly-interacting particles: neutrinos

- FIMP detectors can offer additional ν physics opportunities

EXPERIMENTAL LANDSCAPE (NOT FULL)

Experiment	Facility	Beam Config	Beam Energy	Det Signature	Timeline
			US-based		
HPS	CEBAF @ JLab	electron FT	1-6 GeV	LLP	running
COHERENT	SNS @ ORNL	proton FT	1 GeV	rescattering	running
CCM	LANSE @ LANL	proton FT	0.8 GeV	rescattering	running
SpinQuest/DarkQuest	MI @ FNAL	proton FT	120 GeV	LLP	construction, proposed upgrade
LDMX	LESA @ SLAC	electron FT	4-8 GeV	Missing X	R&D funding, 2024
BDX	CEBAF @ JLab	electron BD	11 GeV	rescattering, Millicharged	proposed
JPOS	CEBAF @ JLab	positron FT	11 GeV	Missing X	proposed
PIP-II BD	PIP-II @ FNAL	proton FT	1 GeV	rescattering, LLP	proposed (2029)
SBN-BD	Booster @ FNAL	proton BD	8 GeV	rescattering	proposed (2029)
REDTOP	TBD	proton FT	1-5 GeV	Missing X, LLP, Prompt	proposed
M^3	MI @ FNAL	muon FT	15 GeV muons	Missing X	proposed
FNAL-μ	muon campus @ FNAL	muon FT	3 GeV	LLP	proposed
			International		
Belle-II	SuperKEKB @ KEK	e+e- collider	150 MeV	Missing X, LLP, Prompt	running
CODEX-β	LHC @ CERN	pp collider	6.5-7 TeV	LLP	construction (2023)
CODEX-b	LHC @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2026)
LHCb	LHC @ CERN	pp collider	6.5-7 TeV	LLP, Prompt	running, future upgrade planned
NA62	SPS-H4 @ CERN	proton BD	400 GeV	LLP	dedicated running planned
FASERnu	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running
milliQAN	LHC @ CERN	pp collider	6.5-7 TeV	Millicharged	running
DarkMESA	MESA @ Mainz	Electron FT	150 MeV	rescattering, LLP	construction (2023)
NA64-e	SPS-H4 @ CERN	electron FT	100-150 GeV	Missing X, Prompt	running
NA64-mu	SPS-M2 @ CERN	muon FT	100-160 GeV	Missing X	commissioning
NA64/POKER	SPS-H4 @ CERN	positron FT	100 GeV	Missing X	planned (2024)
PIONEER	πE5 @ PSI	proton FT	10-20 MeV pions	Prompt	planned (2028)
FASER2	FPF @ CERN	pp collider	6.5-7 TeV	LLP	proposed (2029)
FORMOSA	FPF @ CERN	pp collider	6.5-7 TeV	Millicharged	proposed (2029)
FASERnu2	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)
FLArE	FPF @ CERN	pp collider	6.5-7 TeV	rescattering	proposed (2029)
SND@LHC	LHC @ CERN	pp collider	6.5-7 TeV	rescattering	running
Advanced SND@LHC	FPF	pp collider	6.5-7 TeV	rescattering	proposed (2029)

FIMP DECAYS

PORTALS

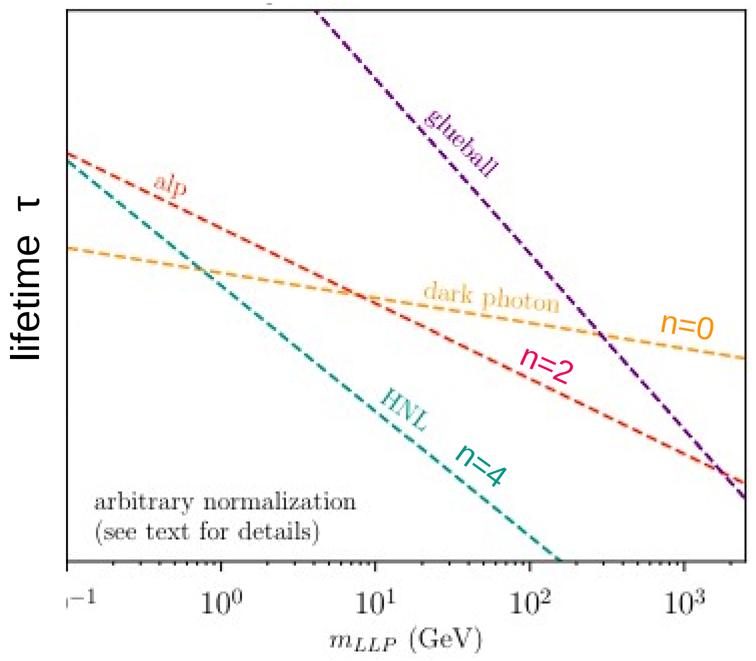
Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$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

& many more variants

Large lifetime

$$\Gamma \sim g^2 \frac{m}{(8\pi)^{a-1}} \times \left(\frac{m}{M}\right)^n \times (Add.\,phase - space\,suppr.)$$

S. Knapen, S. Lowette, 2212.03883



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S. Knapen, S. Lowette, 2212.03883

Large lifetime

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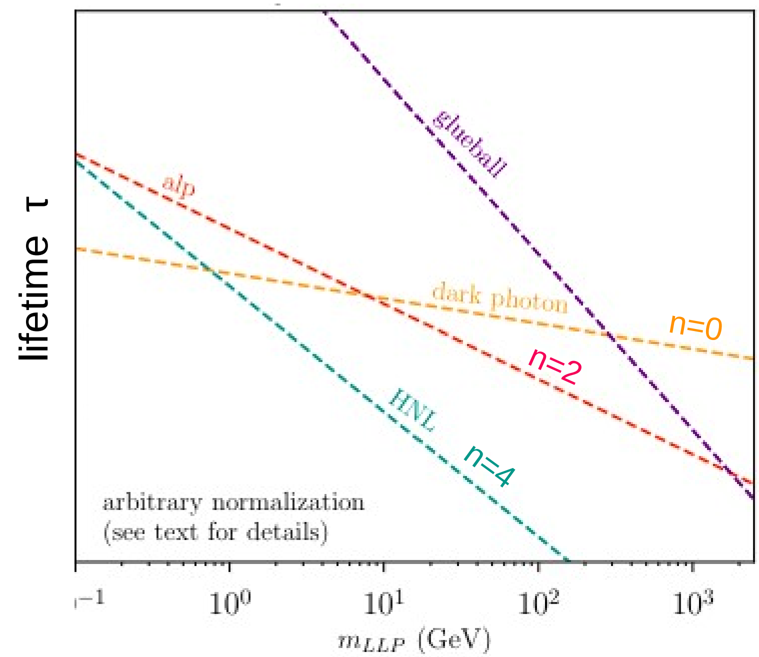
small couplings, e.g. kinetic mixing

$$\epsilon = -\frac{g' g_X}{16\pi^2} \sum_i Y_i q_i \ln \frac{M_i^2}{\mu^2}$$

B. Holdom (1986)
C. Cheung, etal, 0902.3246
T. Gherghetta, etal, 1909.00696

Dark photon

$$\Gamma_{A' \to ee} \sim \varepsilon^2 m_{A'}$$



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Dark photon

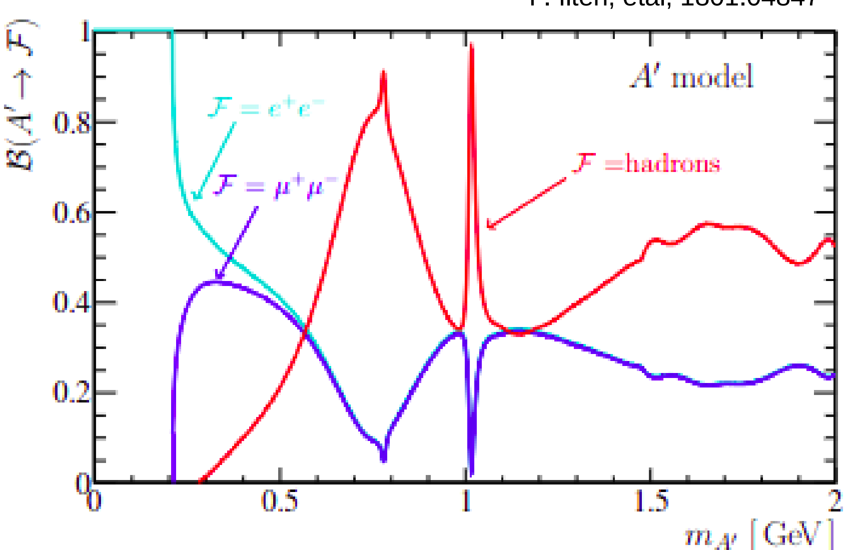
$$\Gamma_{A' \to f\bar{f}} \sim \varepsilon^2 m_{A'}$$

data-driven

$$\Gamma_{A' \to hadrons} \sim \Gamma_{A' \to \mu\mu} R_\mu(m_{A'})$$

$$R_\mu = \frac{\sigma(ee \to hadrons)}{\sigma(ee \to \mu\mu)}$$

P. Ilten, etal, 1801.04847



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& many more variants

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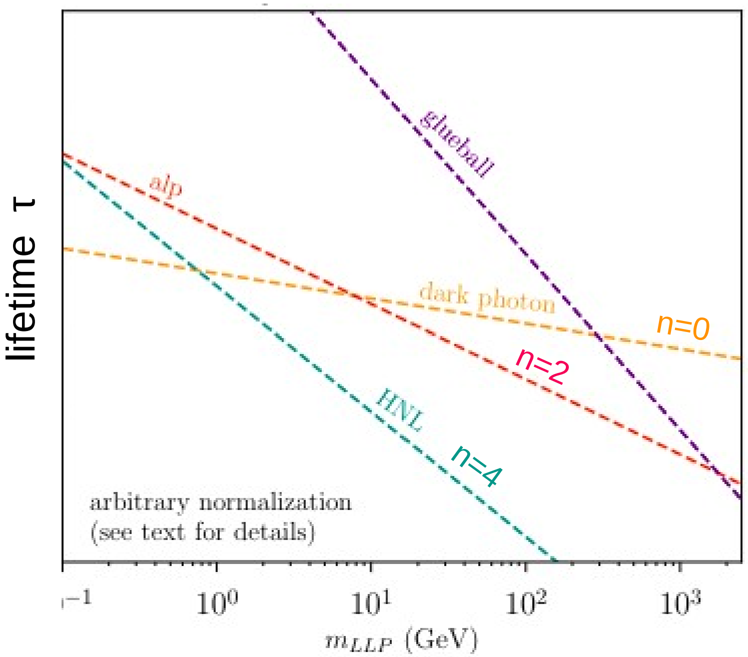
ALPs

$$\Gamma \sim \frac{m_a^3}{f_a^2}$$

HNLs

$$\Gamma \sim |U|^2 \frac{m_N^5}{m_{W,Z}^4}$$

S. Knapen, S. Lowette, 2212.03883



- low FIMP mass: large lifetime,
- quickly drops down at higher masses

→ impact on detection strategies

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& many more variants

Large lifetime

$$\Gamma \sim g^2 \frac{m}{(8\pi)^{a-1}} \times \left(\frac{m}{M}\right)^n \times (Add.\,phase - space\,suppr.)$$

Example: inelastic DM (iDM)

(dark photon mediator)

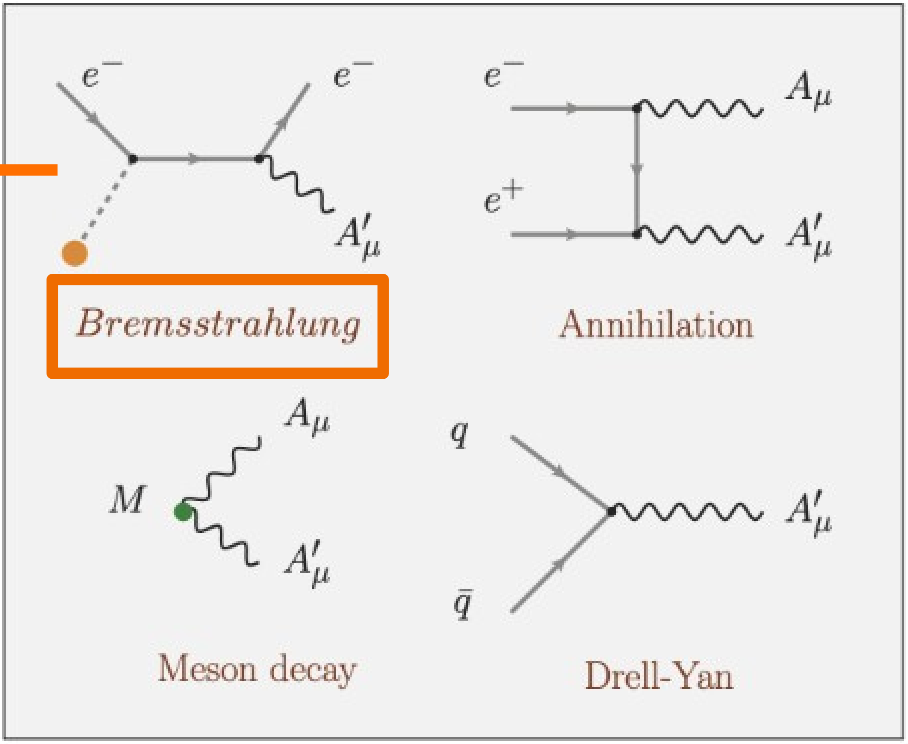
$$\mathcal{L} \supset i e_D A'_\mu \bar{\chi}_1 \gamma^\mu \chi_2,$$

$$\Gamma\left(\chi_2 \to \chi_1 \ell^+ \ell^-\right) \simeq \frac{4\epsilon^2}{15\pi} \alpha_{\rm em} \alpha_D \frac{m_1^5}{m_{A'}^4} \Delta^5.$$

$$\Delta \equiv \frac{m_2 - m_1}{m_D}$$

MODELING UNCERTAINTIES – A' PRODUCTION

M. Fabbrichesi, etal 2005.01515



- Electron beam-dumps,

conventional to use Weizsacker-Williams approximation

J.D. Bjorken, etal, 0906.0580

Cross section decomposition

$$\frac{d\sigma(p+P_i \to p'+k+P_f)}{dE_{A'}\,d\cos\theta_{A'}} = \left(\frac{\alpha\chi}{\pi}\right)\left(\frac{E_0 x \beta_{A'}}{(1-x)}\right) \times \frac{d\sigma(p+q\to p'+k)}{d(p\cdot k)}\bigg|_{t=t_{min}},$$

(effective) Photon flux

$$\chi \equiv \int_{t_{min}}^{t_{max}} dt \frac{t-t_{min}}{t^2} G_2(t).$$

Inelastic form factor

$$G_{2,in}(t) = \left(\frac{a'^2 t}{1+a'^2 t}\right)^2 \left(\frac{1+\frac{t}{4m_p^2}(\mu_p^2-1)}{(1+\frac{t}{0.71\,\mathrm{GeV}^2})^4}\right)^{2} Z,$$

typo

MODELING UNCERTAINTIES – A' PRODUCTION

M. Fabbrichesi, etal 2005.01515

- Electron beam-dumps,

conventional to use Weizsacker-Williams approximation

J.D. Bjorken, etal, 0906.0580

- Proton beam-dumps,

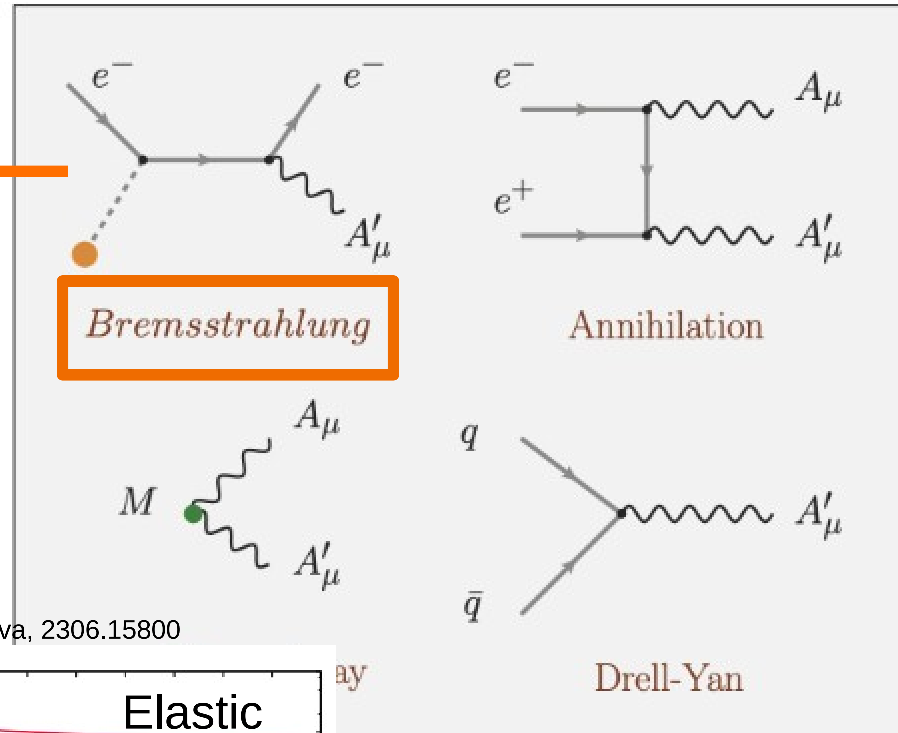
- widely used analogous approximation,
exchange of hypothetical massless vector boson b

J. Blümlein, J. Brunner, 1311.3870

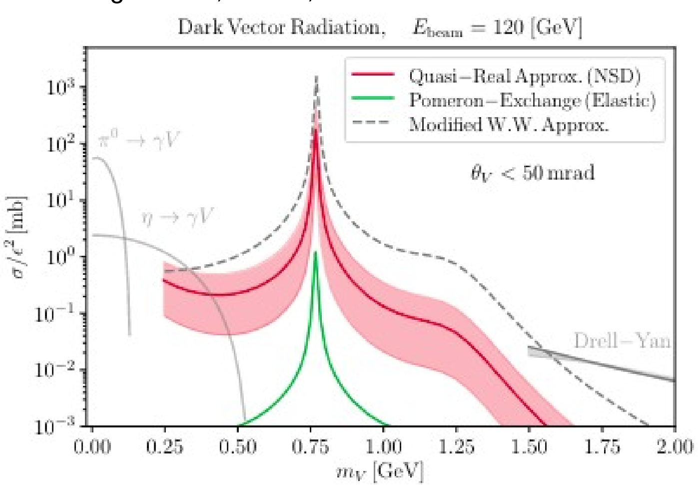
- Pomeron exchange – different propagators

- vector Pomeron (Donnachie-Landshoff) exchange result;

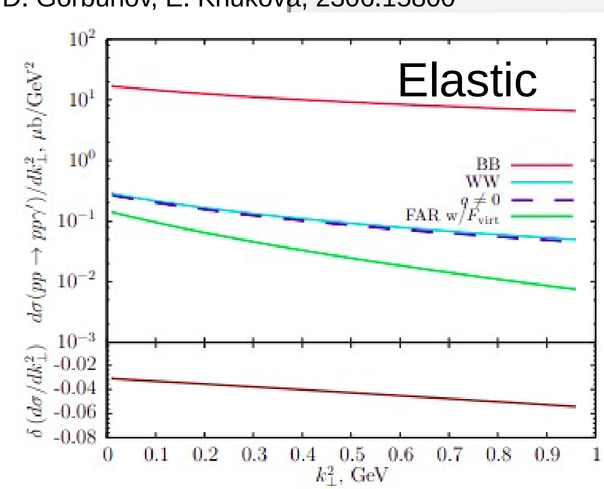
- need to consider proton momentum exchange



S. Foroughi-Abari, A. Ritz, 2108.05900



D. Gorbunov, E. Kriukova, 2306.15800



Theory effort needed

- inelastic brem. with general p momentum exchange

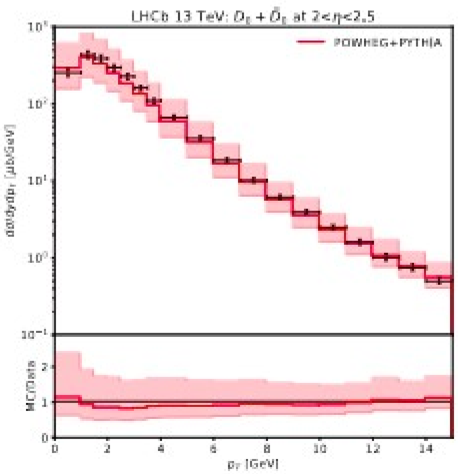
- going beyond vector Pomerons

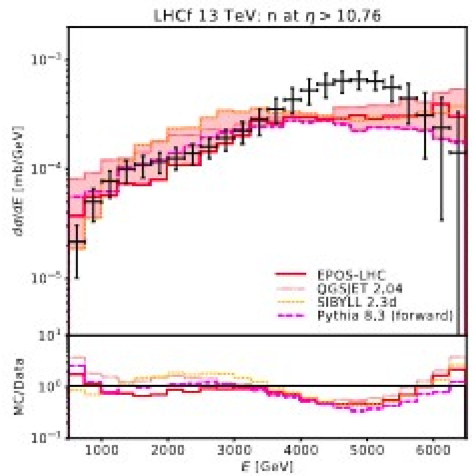
MODELING UNCERTAINTIES – A' PRODUCTION

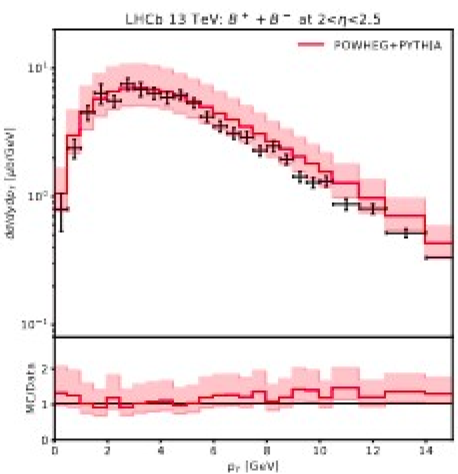
M. Fabbrichesi, etal 2005.01515

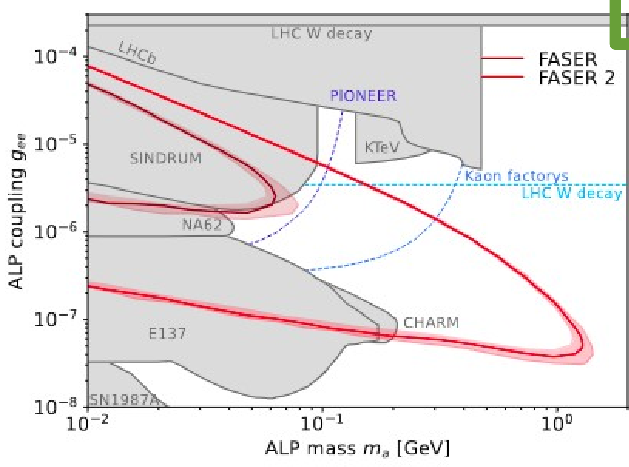
- Careful treatment of uncertainties needed to derive bounds

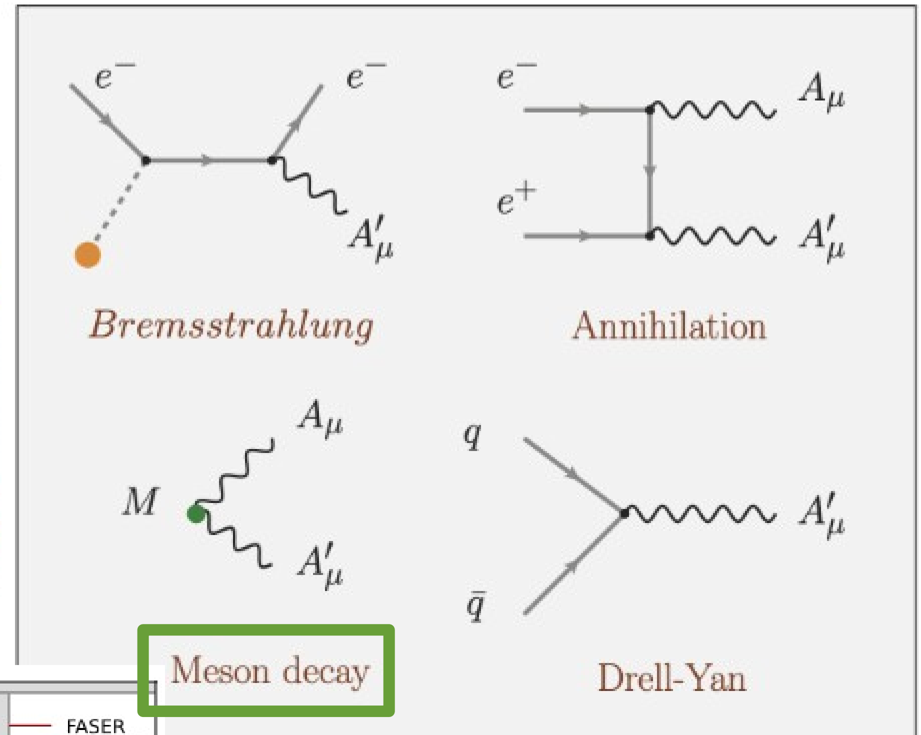
L. Buonocore, etal, 2309.12793
FASER, 2402.13318









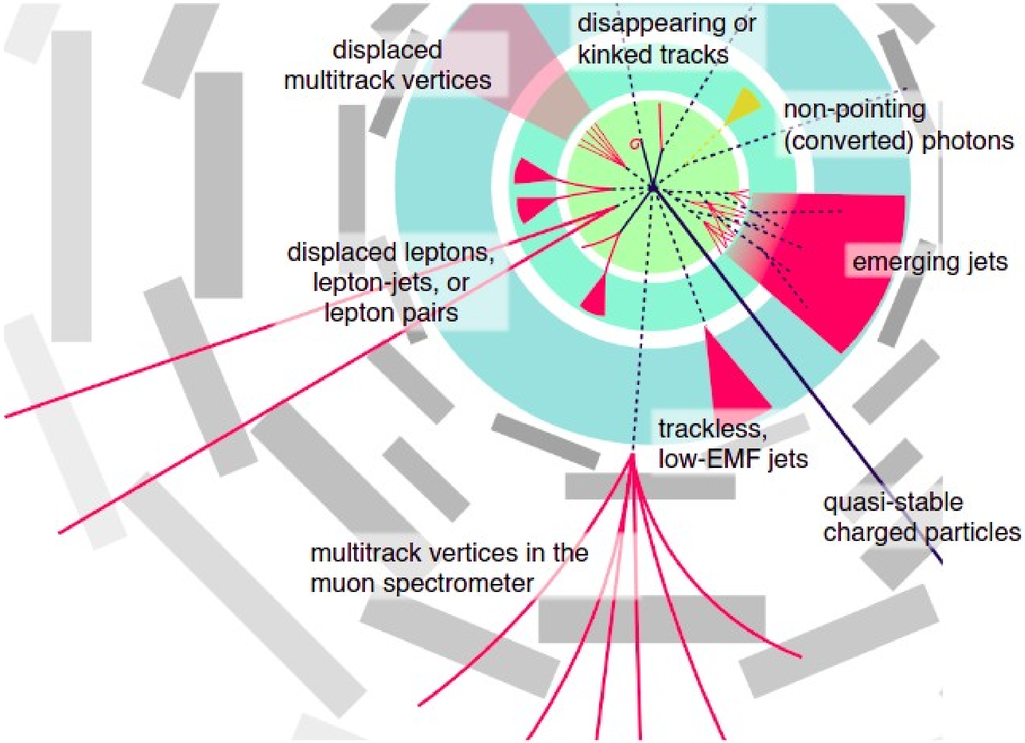


- ALP-ee $\mathcal{L} = \frac{g_{ee}}{2m_e} \partial_\mu a \; \bar{e}\gamma^\mu\gamma_5 e$
- Couplings to gauge bosons through chiral anomaly
- B-meson or kaon decays

Reviews: J. Alimena, etal, 1903.04497
J. Alimena, etal, 2110,14675
S. Knapen, S. Lowette, 2212.03883

LHC SEARCHES – CENTRAL DETECTORS

- Large activity to include displaced/delayed signatures in the analysis



- Future colliders will master these techniques

- Auxiliary detector proposal:
  MATHUSLA above CMS (LHC)

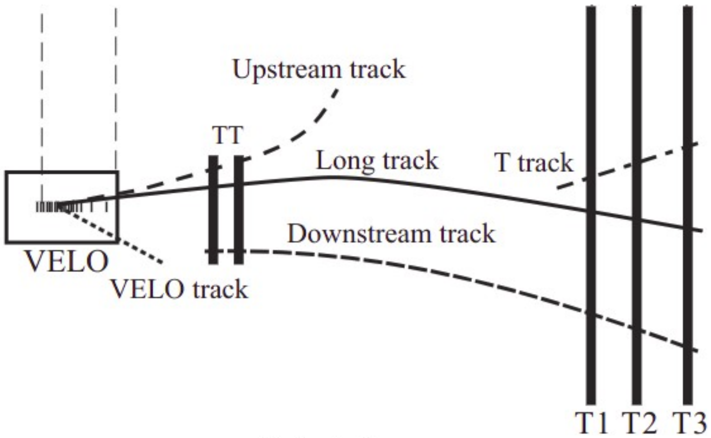
D. Curtin, etal, 1806.07396

LHCb

- Inclusive A’ production
  + decay into di-muon pairs A’ → μ+μ-
- Search for A’ resonance excess over expected
  SM μ+μ- backgrounds
- LHCb: improved prospects expected

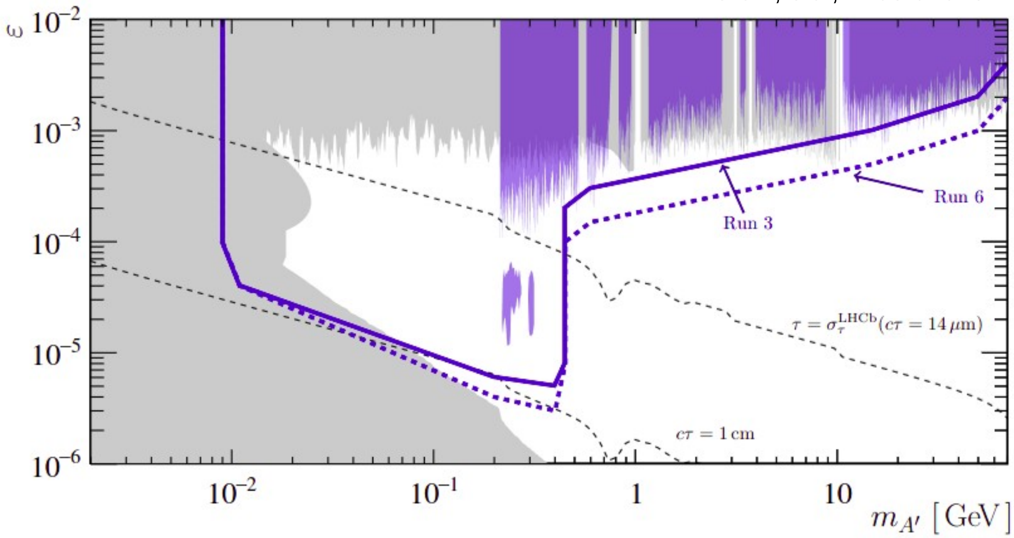
Downstream algorithm

LHCb, 2211.10920
V. Gorkavenko, etal, 2312.14016

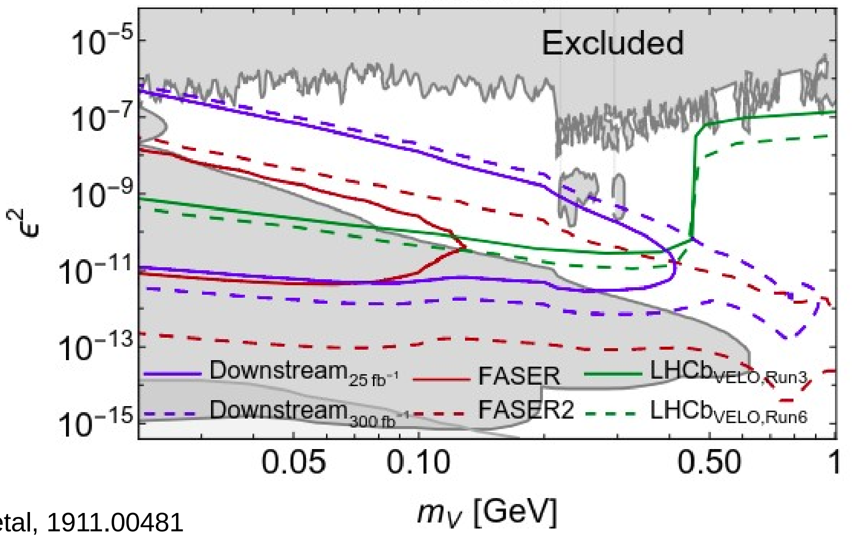


electron identification in the high-level trigger
allows to study A’ → e+e

D. Craik, etal, 2203.07048



Dark photons



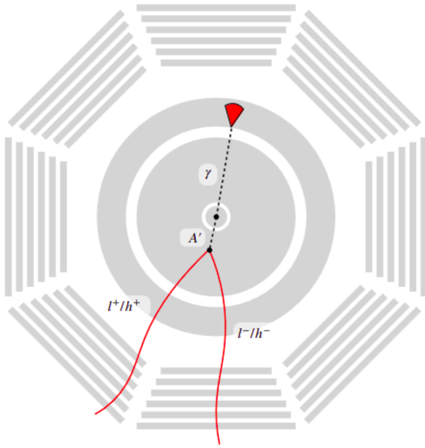
- Codex-b auxiliary detector for FIMP searches

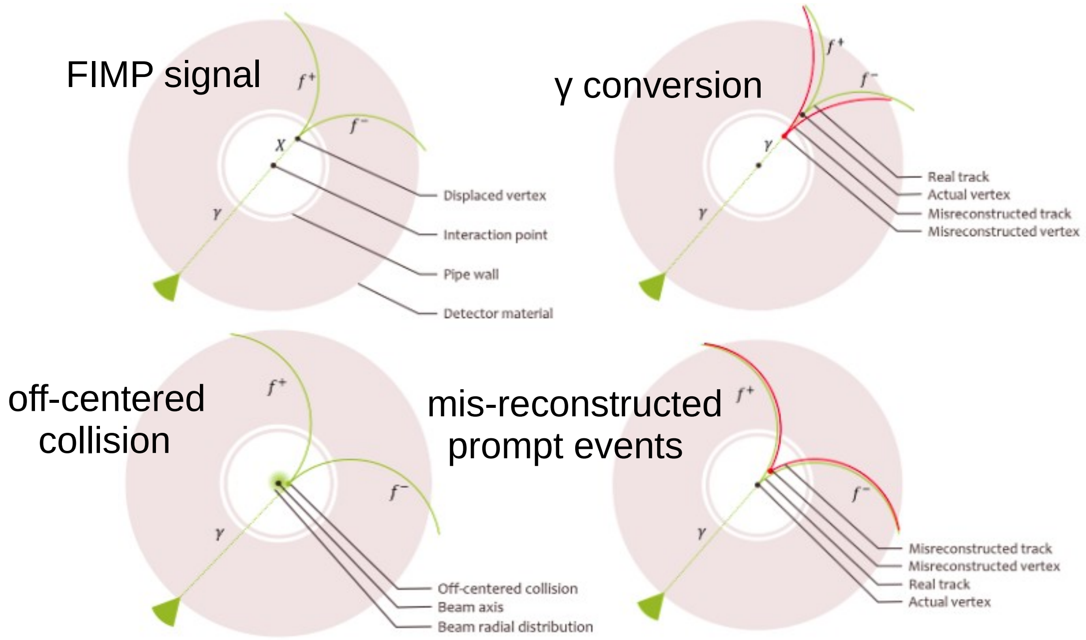
G. Aielli, etal, 1911.00481

Belle-II

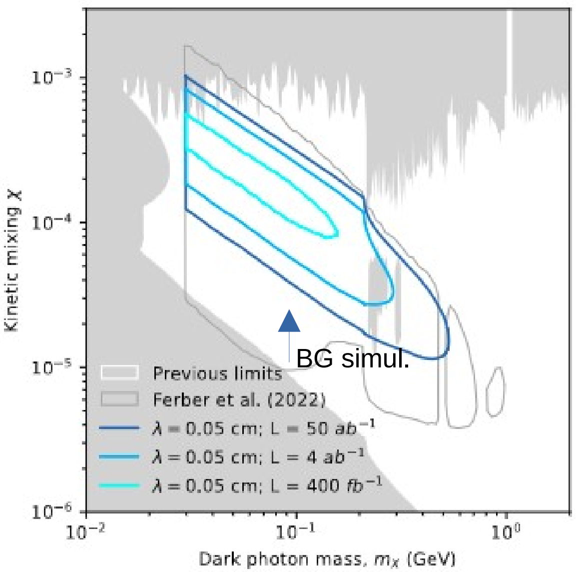
T. Ferber, etal, 2202.03452

- Displaced search proposed, O(1) - tens of cm
- Subject to backgrounds
- Recently updated background analysis





J. Jaeckel, A.V. Phan, 2312.12522



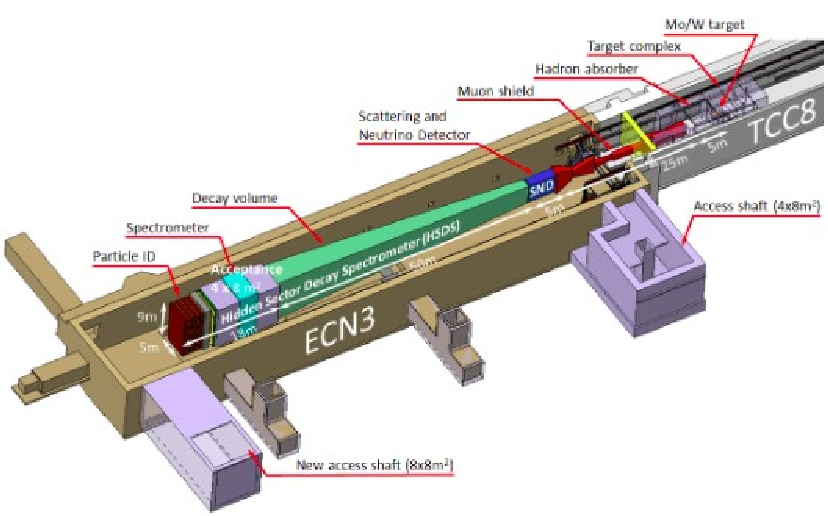
BEAM-DUMP EXPERIMENTS

- Past, present & future experimental program
- NA62 (proton), electron/muon beam-dump (NA64-e, NA64-μ), ...
- Future: SHiP, DarkQuest, beam-dumps at future collider facilities...

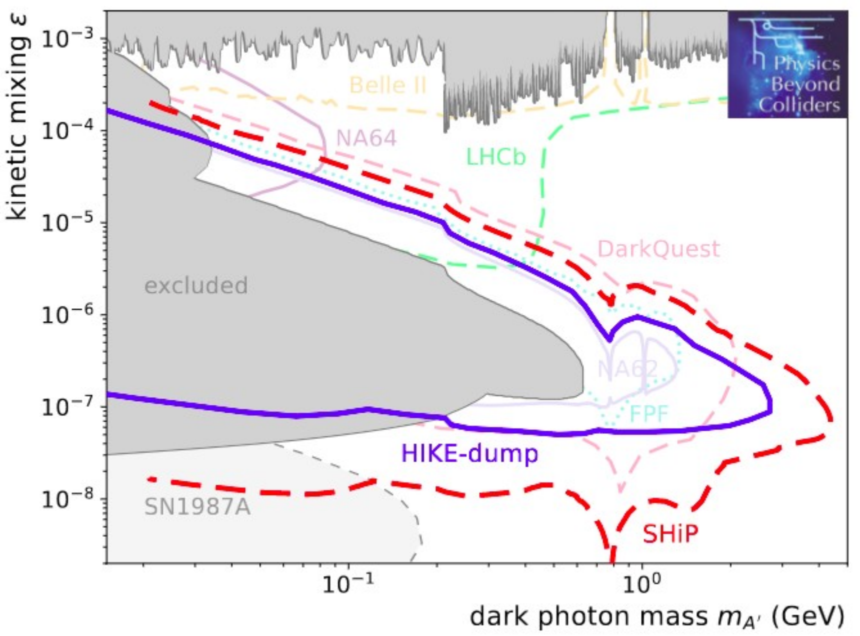
Daiki Ueda talk
(Saturday)

BDF/SHiP proposal endorsed by CERN Research Board on March 6th

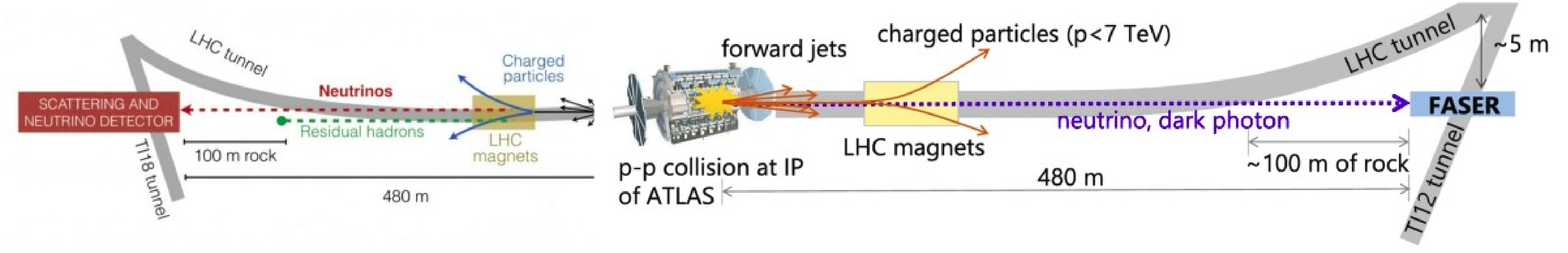
CERN-SPSC-2022-032



CERN-PBC Report-2023-003

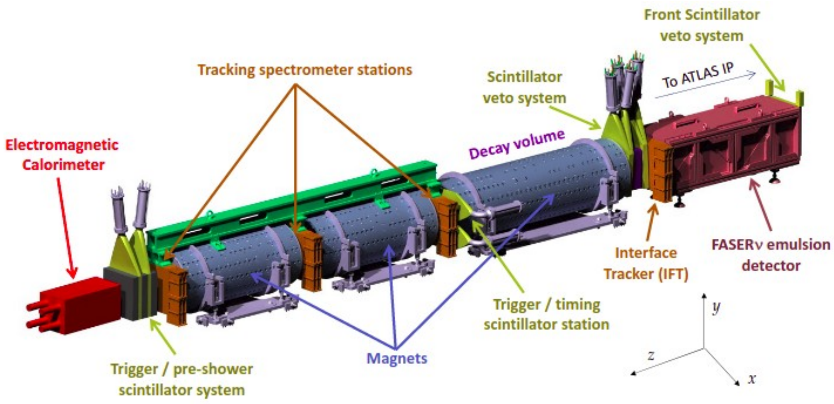


FAR-FORWARD SEARCHES AT THE LHC



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

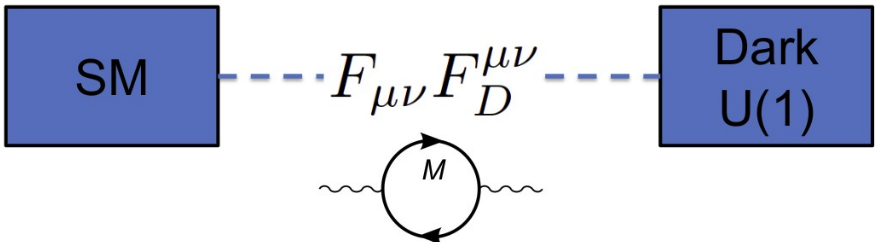
FASER, 2207.11427



DARK PHOTONS @ FASER

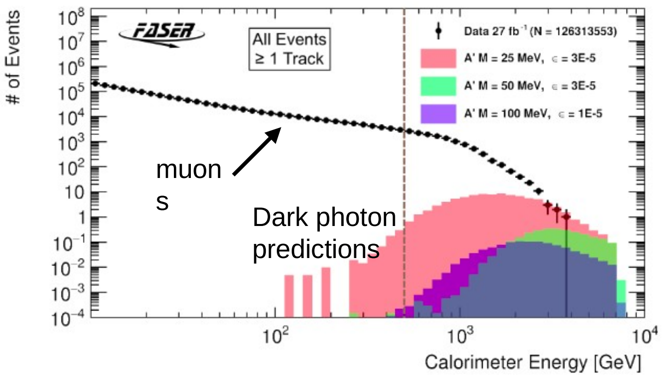
- New light (~sub-GeV) vector secluded from the SM, coupled via kinetic mixing

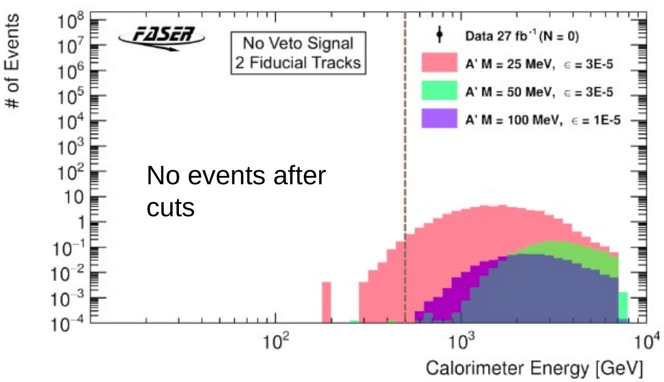
  (can be induced by heavy new fields at the loop level charged under both U(1) and $U(1)_D$)

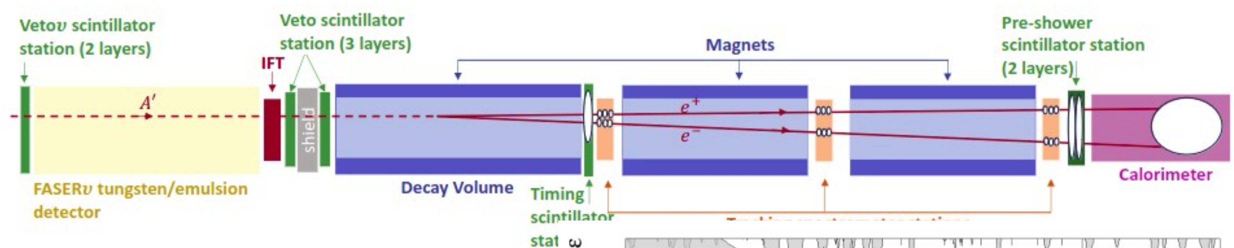


$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum_f q_f \bar{f} \not{A}' f$$

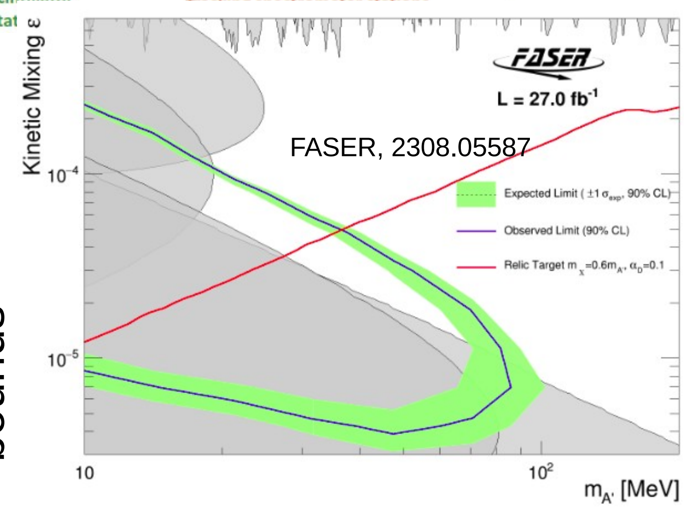
- Suppressed couplings to SM fermions, A' can decay into, e.g., e+e- pairs







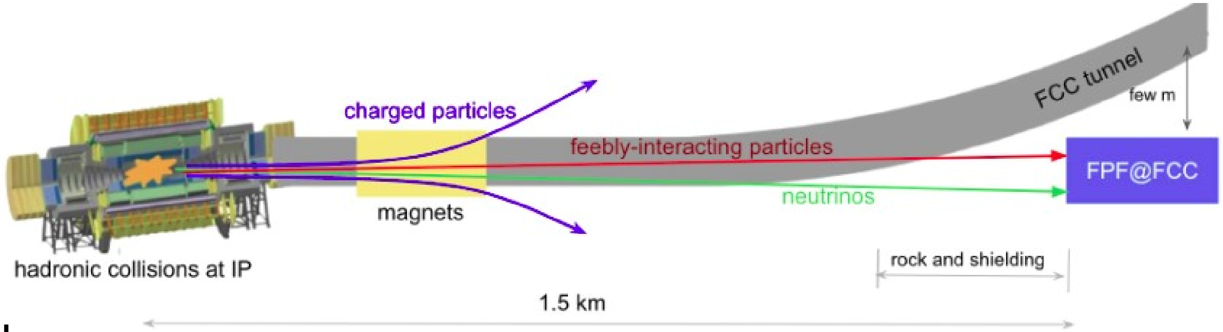
Dark photon bounds



R.M. Abraham, J. Adhikary, J.L. Feng, F. Kling, T.R. Rabemananjara, J. Rojo, S. Trojanowski (in preparation)

FORWARD PHYSICS FACILITY (FPF) @ FCC-hh

- Idea: continue & expand the forward physics program from LHC to FCC



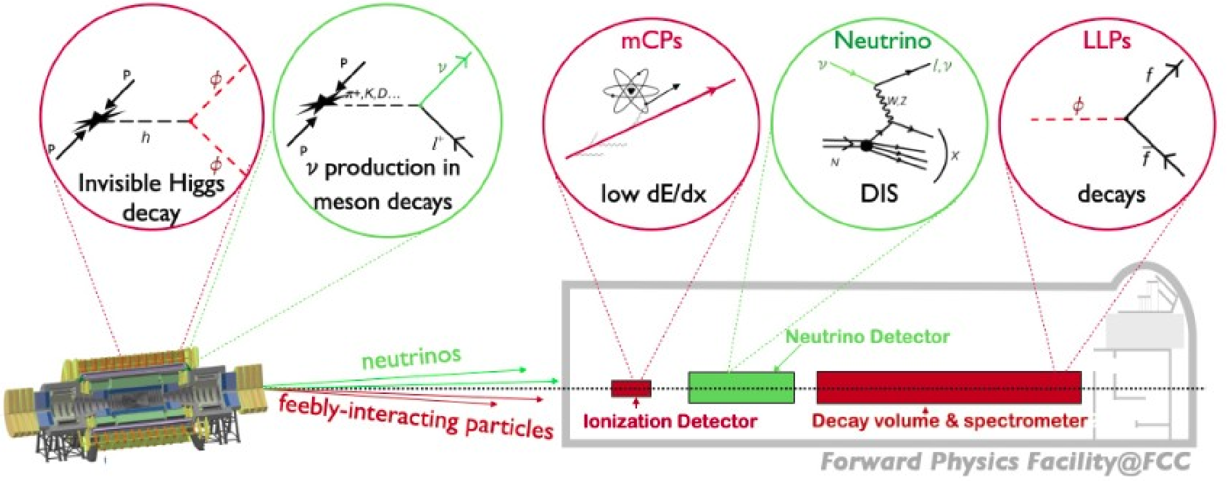
- Both FCC-ee & hh should be considered

- Focus on FCC-hh:

– neutrino & QCD physics

– FIMP searches

– cosmic-ray physics...



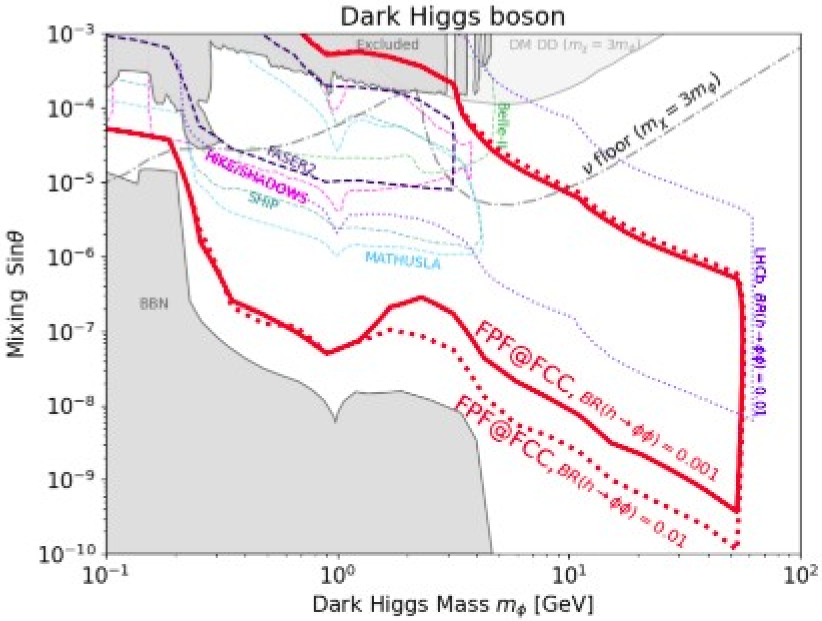
- Other proposals: HECATE@FCC-ee (2011.01005), FASER@FCC-hh (2105.07077), FOREHUNT@FCC-hh (2306.11803), BDF@ILC (1507.02809,2009.13790,2104.00888), proposal for the muon collider (2202.12302)

DARK HIGGS BOSON & FPF@FCC

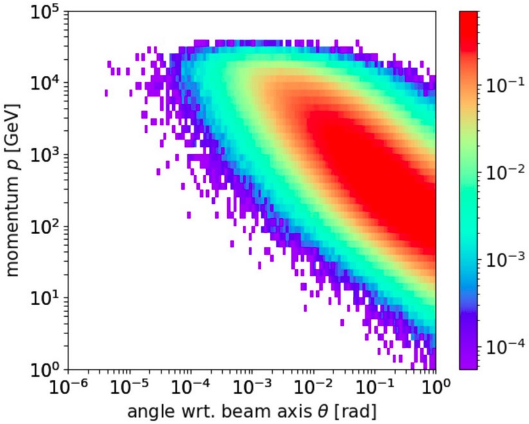
$$\mathcal{L} = -m_\phi^2 \phi^2 - \sin\theta \frac{m_f}{v} \phi \bar{f} f - \lambda v h \phi\phi,$$

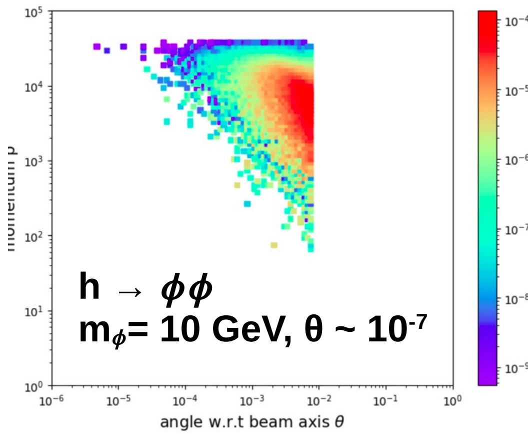
- Production: heavy meson decays ($B \to X_s \phi$), SM Higgs decay $h \to \phi\phi$ @ FCC

F. Kling, ST (FORESEE), 2105.07077



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





R.M. Abraham, J. Adhikary, J.L. Feng, F. Kling, T.R. Rabemananjara, J. Rojo, S. Trojanowski (in preparation)

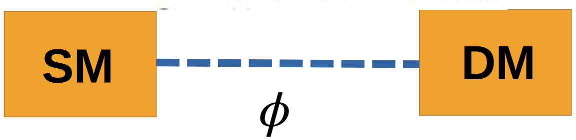
DARK HIGGS BOSON & DARK MATTER

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

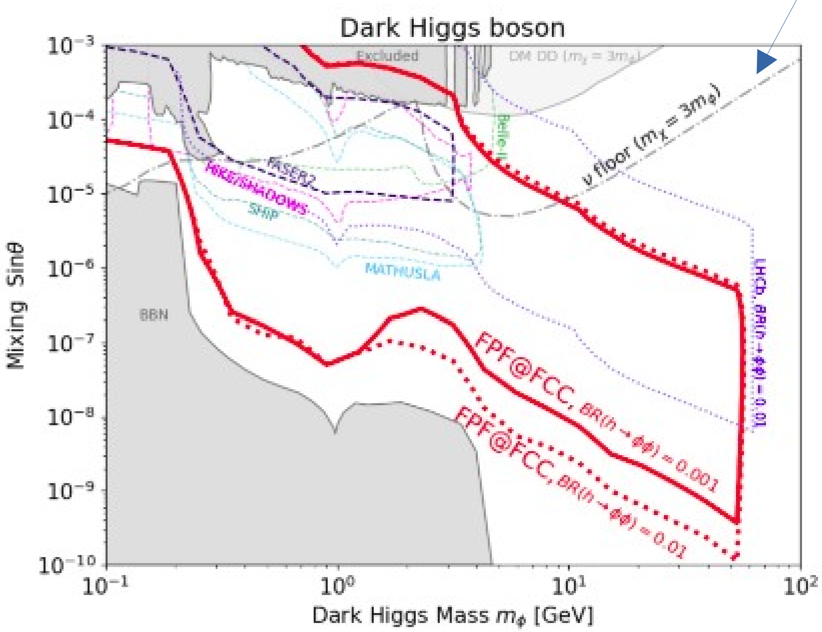
- Production: heavy meson decays ($B \to X_s \phi$), SM Higgs decay $h \to \phi\phi$ @ FCC

F. Kling, ST (FORESEE), 2105.07077

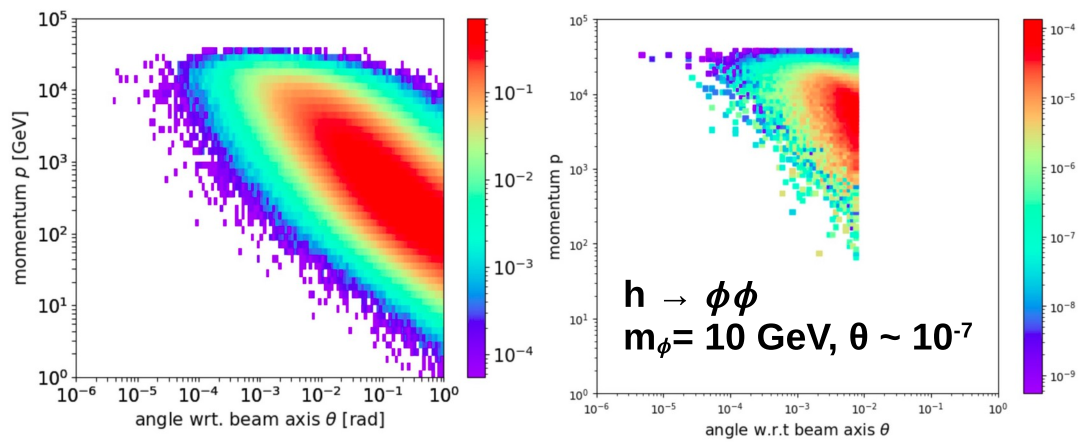
$$\mathcal{L} \supset -(1/2)\, \kappa\, \phi\, \bar{\chi} \chi$$



complimentarity:
DM direct detection



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

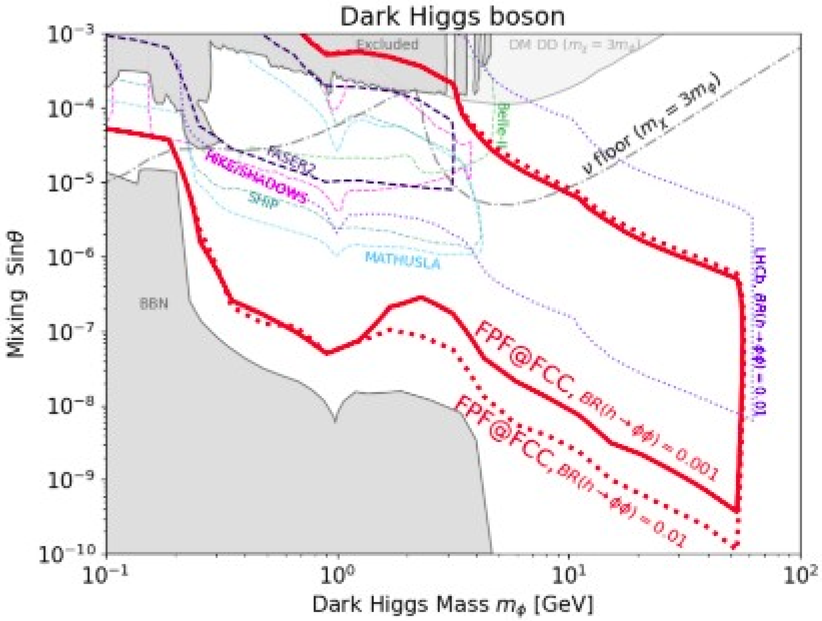


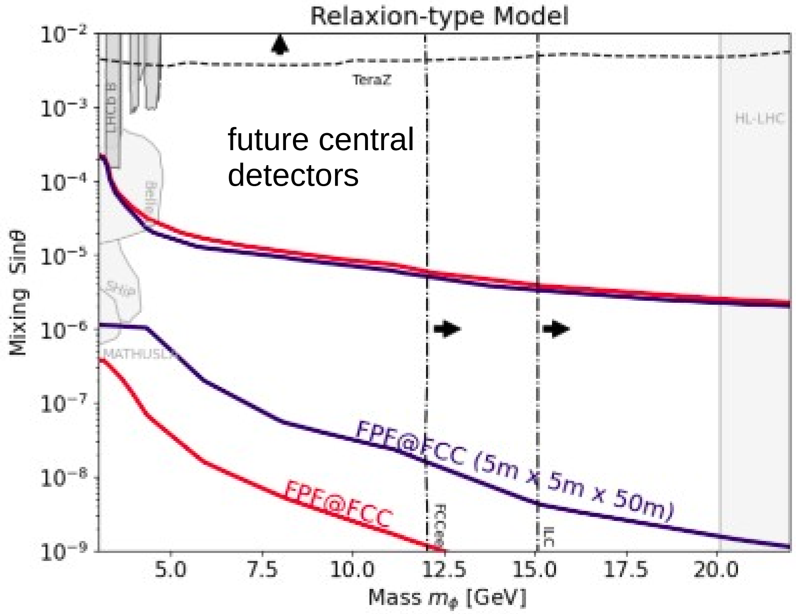
RELAXION & FPF@FCC

- 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, $\mathrm{BR}(h \to \phi\phi)$ decreases with the ϕ mass

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

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

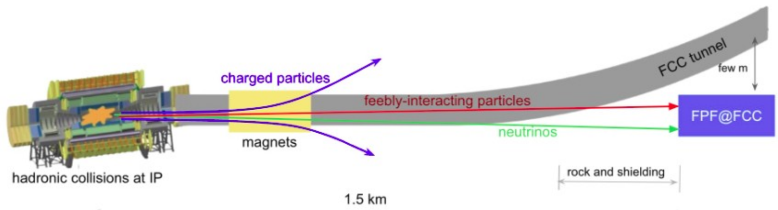


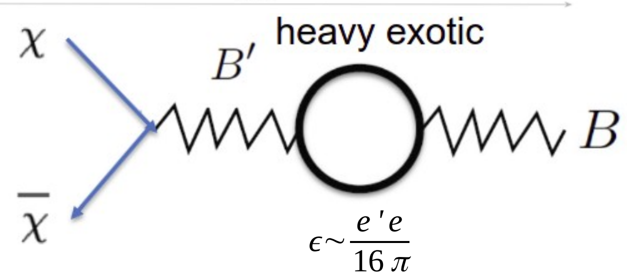


R.M. Abraham, J. Adhikary, J.L. Feng, F. Kling, T.R. Rabemananjara, J. Rojo, S. Trojanowski (in preparation)

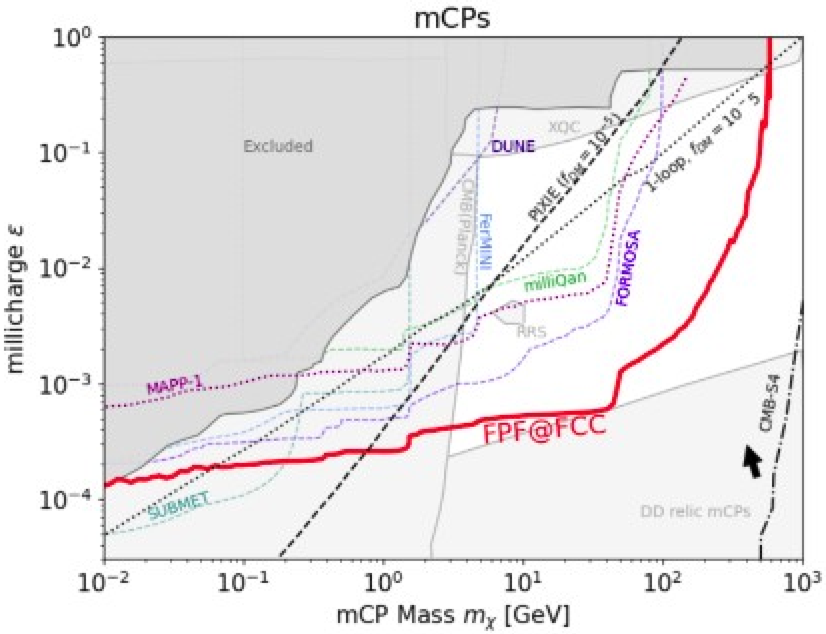
MILLICHARGED PARTICLES AT FPF@FCC

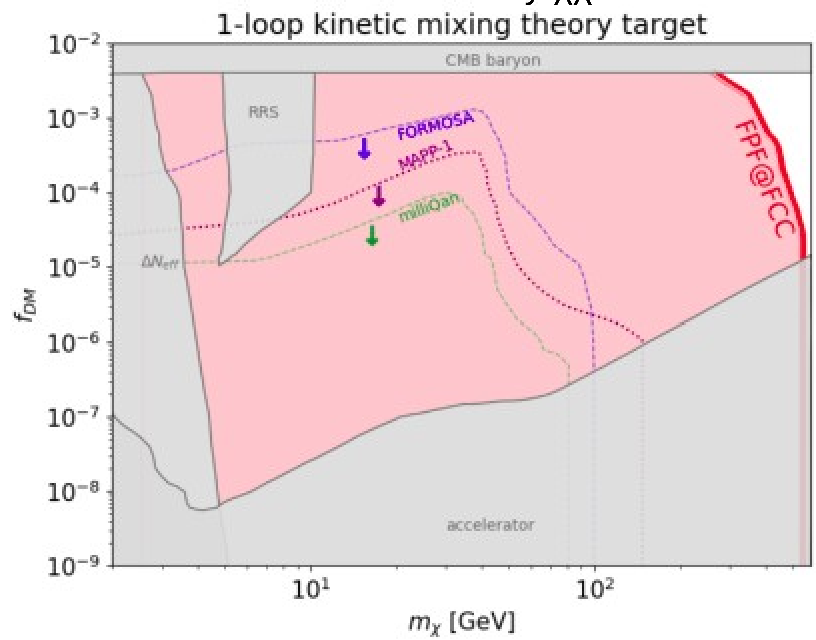
- Possible result of new unbroken gauge symmetries
- Example: massless dark vector boson kinetically mixing with the hypercharge boson & additionally coupled to dark fermions χ
- χ acquires millicharge, $Q_\chi \sim= \varepsilon e$ & could be (a subdominant) DM component
- χ detection via ionization (a-la-milliQan, FORMOSA@FPF, MAPP-1)
- FPF@FCC – assumed similar to FORMOSA (size 5m x 5m x 4m)





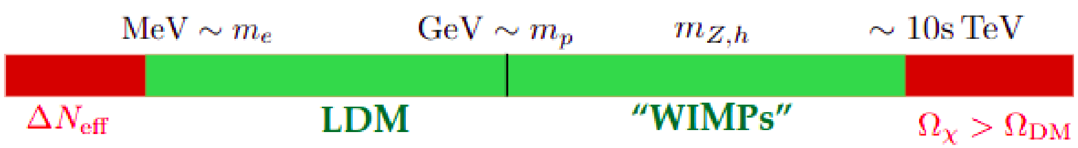
+ relic density χχ → A' A'



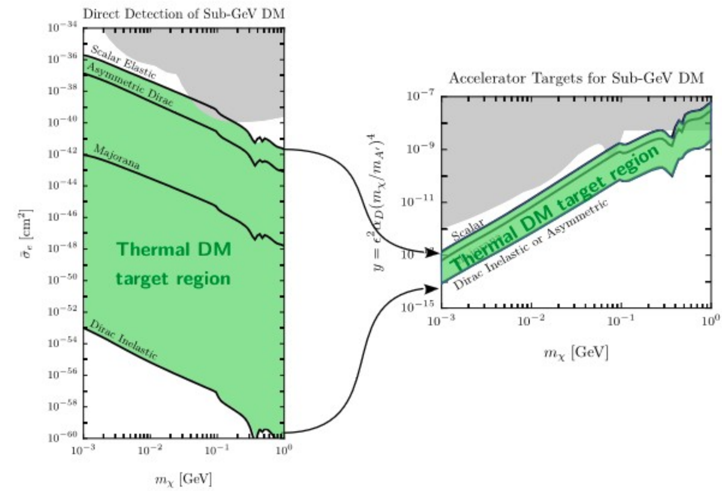


DARK MATTER SEARCHES

LIGHT DARK MATTER SEARCH

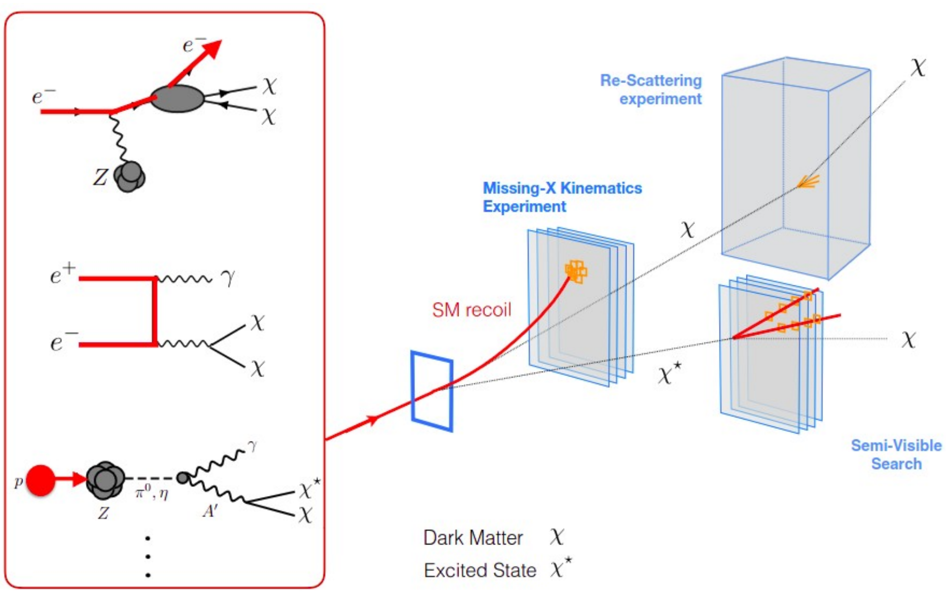


Snowmass 2021, G. Krnjaic, etal, 2207.00597

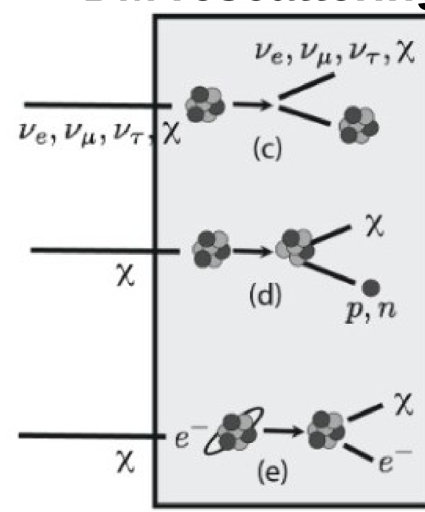


- Probing thermal DM target
- In the relativistic regime, life becomes easier…
- Various detection strategies proposed

- based on missing momentum, energy, mass
- based on rescattering of DM

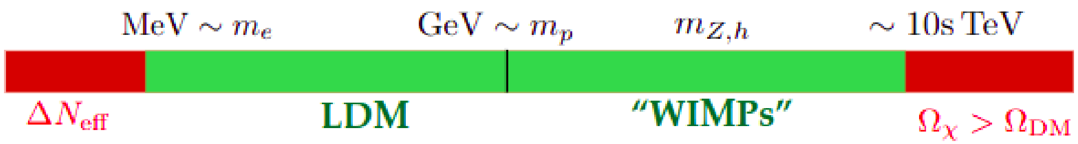


DM rescattering

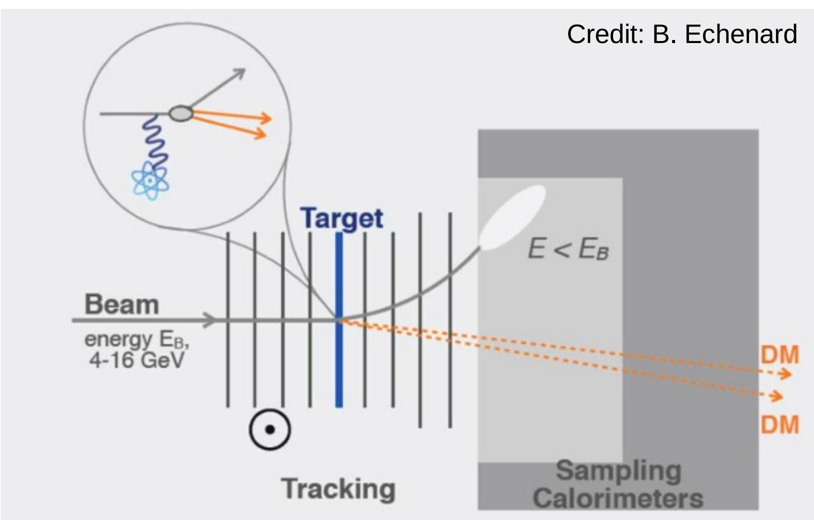


T. Åkesson, etal (LDMX), 1808.05219
A. Berlin, etal, 1807.01730

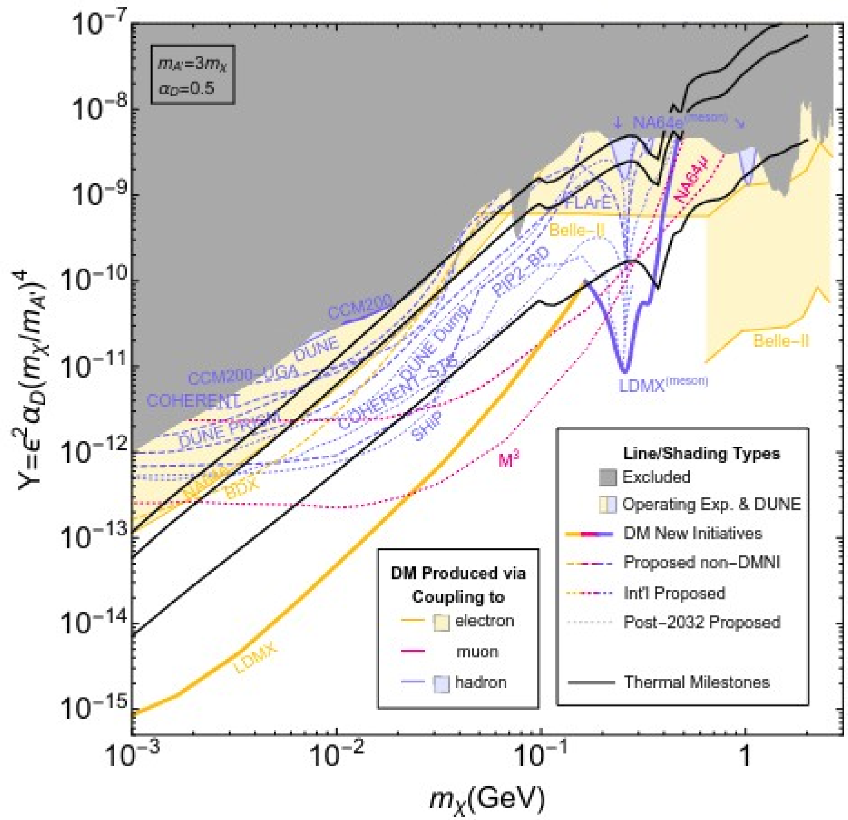
LDMX



- Probing thermal DM target
- In the relativistic regime, life becomes easier…
- Various detection strategies proposed
- LDMX – missing momentum search
  design study phase



Snowmass 2021. G. Krniaic. etal. 2207.00597

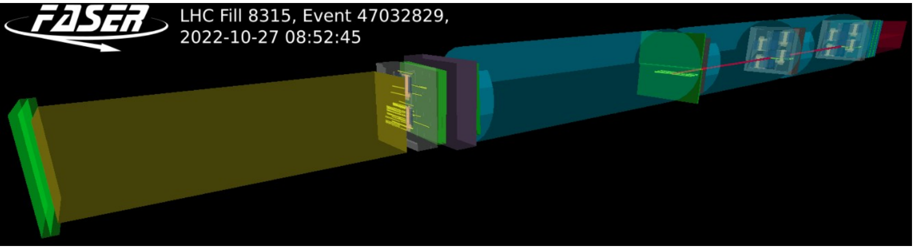


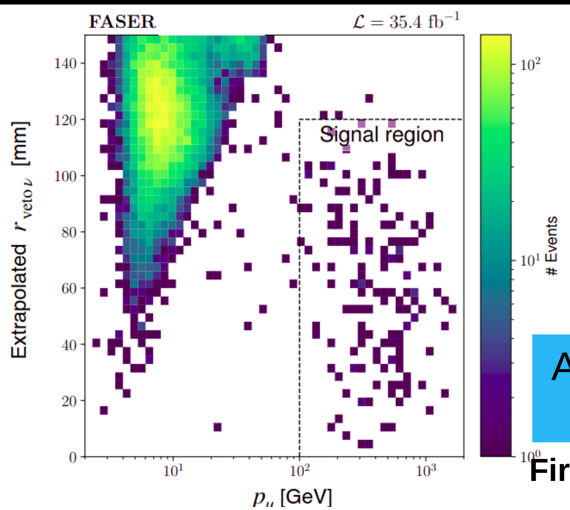
FORWARD NEUTRINOS
(at LHC & FCC-hh)

FORWARD LHC NEUTRINOS

First ν observation at the LHC

FASER, 2303.14185; SND@LHC, 2305.09383

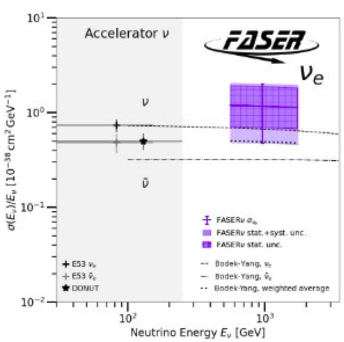


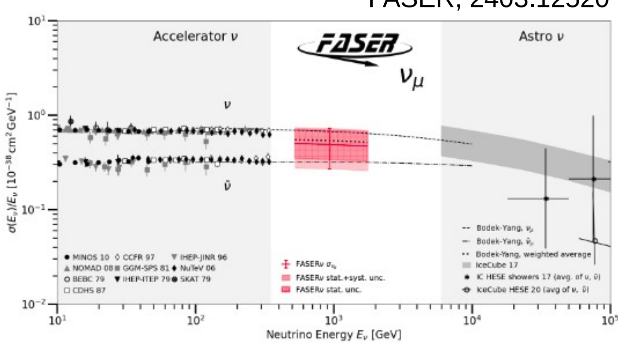


Aim: fill in the gap
in cross section measurements

First FASERν observation (emulsion)

FASER, 2403.12520

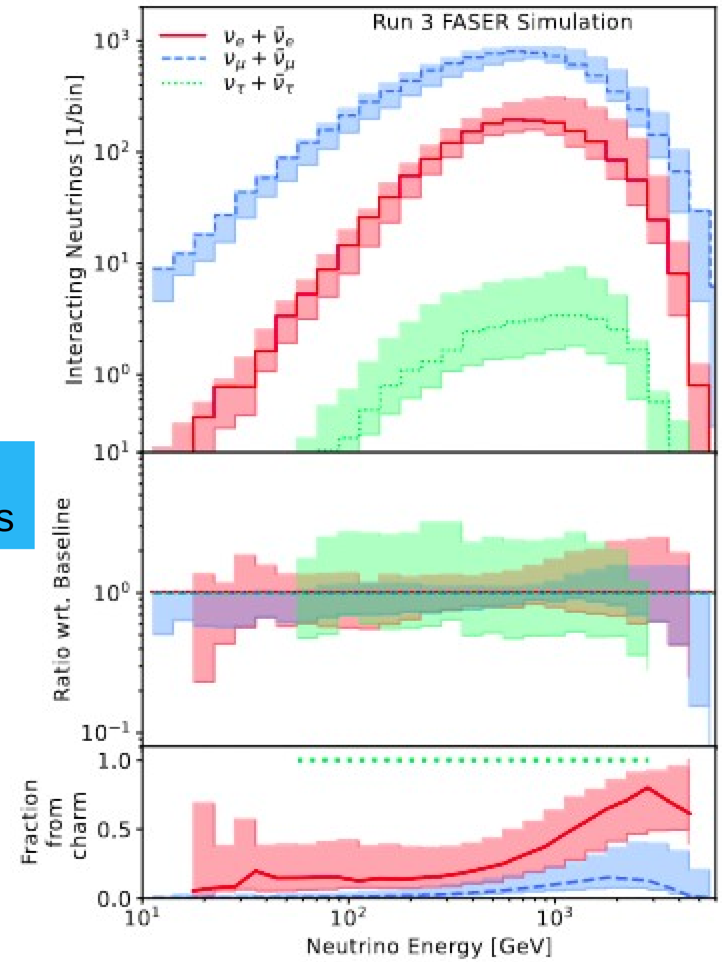




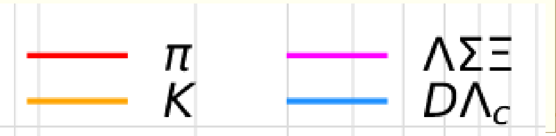
Aim: reduce uncertainties
enlight underlying QCD,
cosmic-ray physics,...

Forward LHC neutrino spectrum

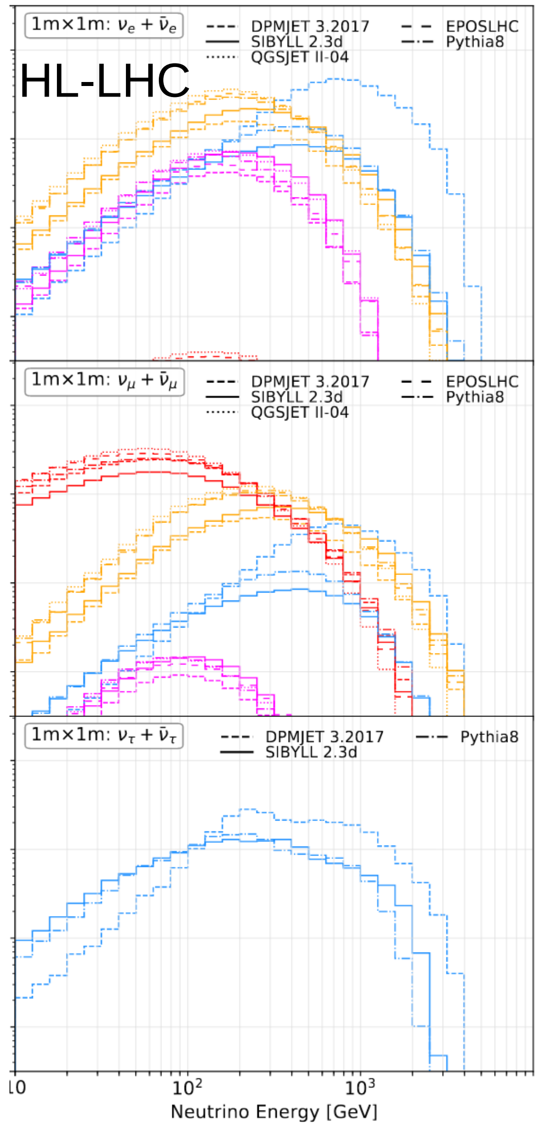
FASER, 2402.13318



CONSTRAINING NEUTRINO FLUXES



Kling, Nevay, 2105.08270



- Combine information from various neutrino flavors (different parent mesons)

F. Kling, T. Makela, ST, 2309.10417

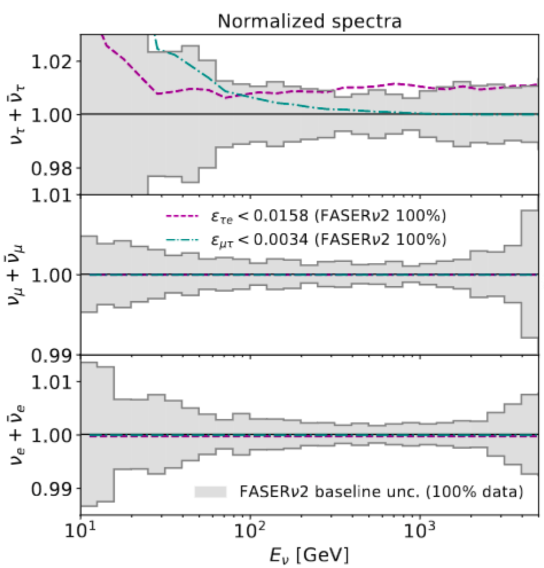
- energy spectrum & psedurapidity (differential prod. σ)

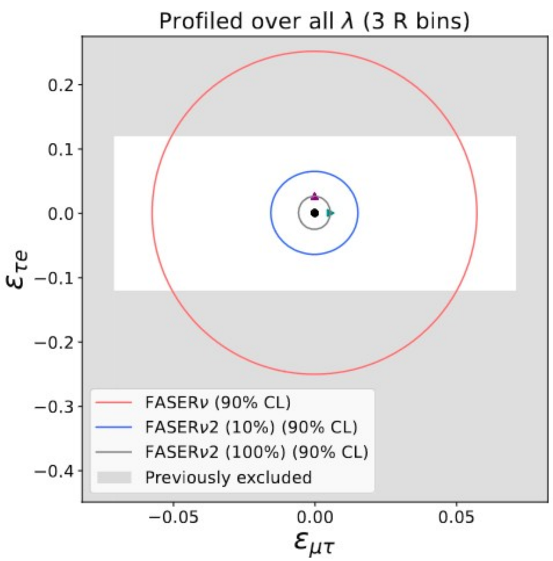
- Variations in parent meson spectra → correlations in ν spectra

- New physics can be searched for if correlations are broken

Effective right-handed operators

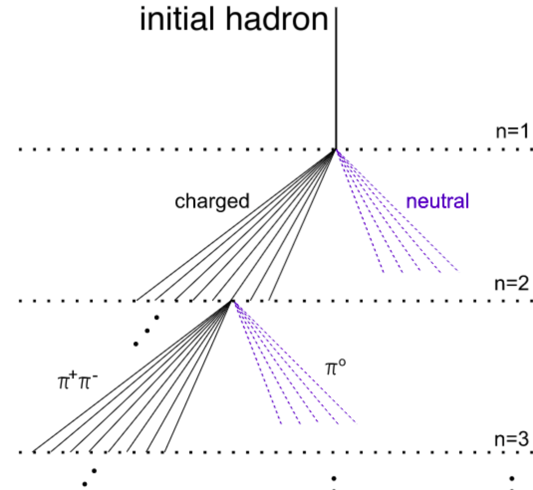
$$\mathcal{L} = -\frac{2V_{ud}}{v^2} \times (\bar{u}\gamma^\kappa P_R d) \times \left[\epsilon_R^{\mu\tau}\,(\bar{\ell}_\mu \gamma_\kappa P_L \nu_\tau) + \epsilon_R^{\tau e}\,(\bar{\ell}_\tau \gamma_\kappa P_L \nu_e)\right]$$



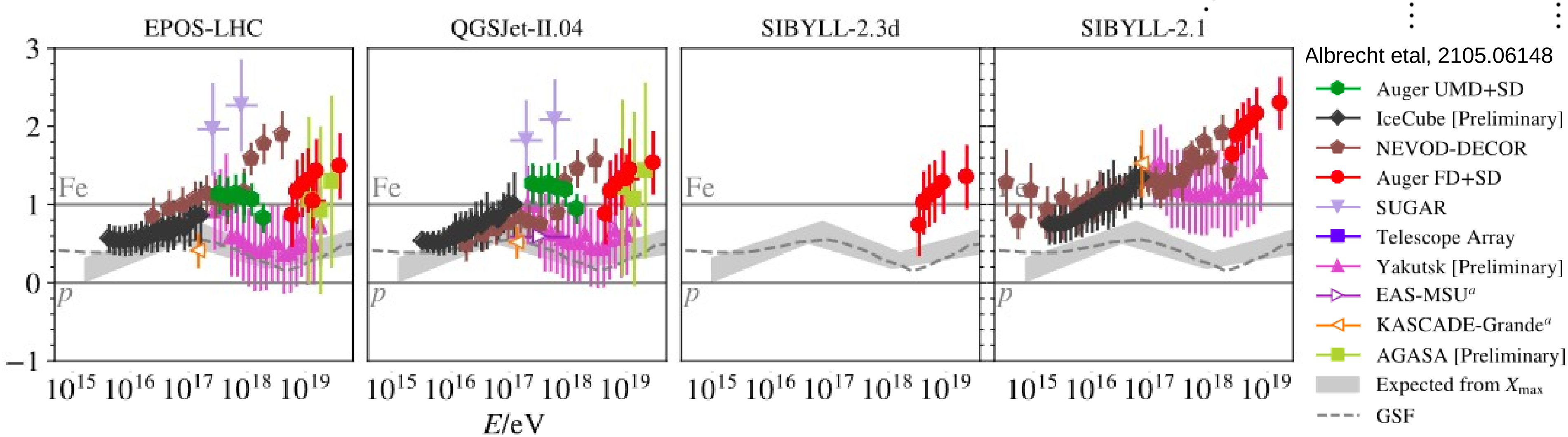


COSMIC-RAY MUON PUZZLE

- Observed more muons (30-60%) in ultrahigh-energy cosmic ray (UHECR) data than expected based on air-shower simulations (significance ~8σ)
- Task: simultaneously fit the (excess) number of muons N_μ and the depth of the shower maximum X_{max}
- Preferred solution: reduced energy transfer from hadronic to EM shower
  J.D. Allen, G.R. Farrar, 1307.7131

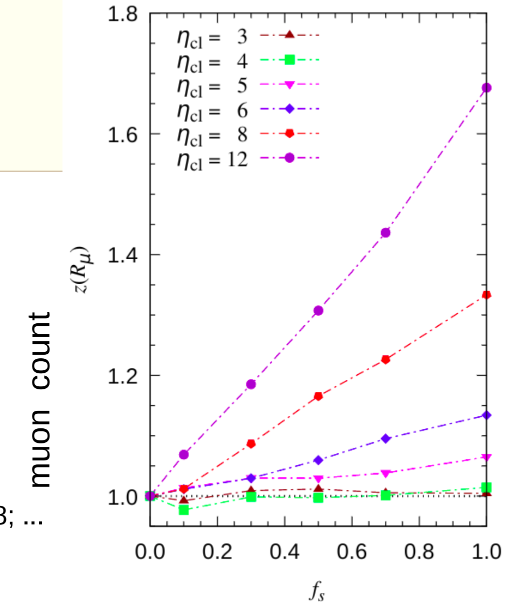


- EM shower initiated by neutral pions π^0
- Muons come from charged pions and kaons
- The difference could be explained by a modified **production** or decay rate of π^0



MUON PUZZLE & FPF@LHC

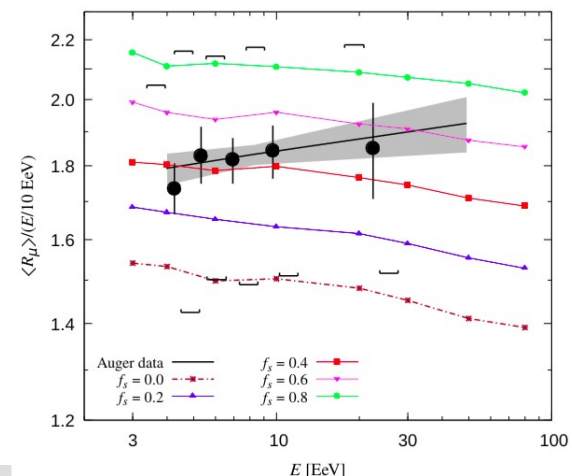
L.A. Anchordoqui etal, 2202.03095



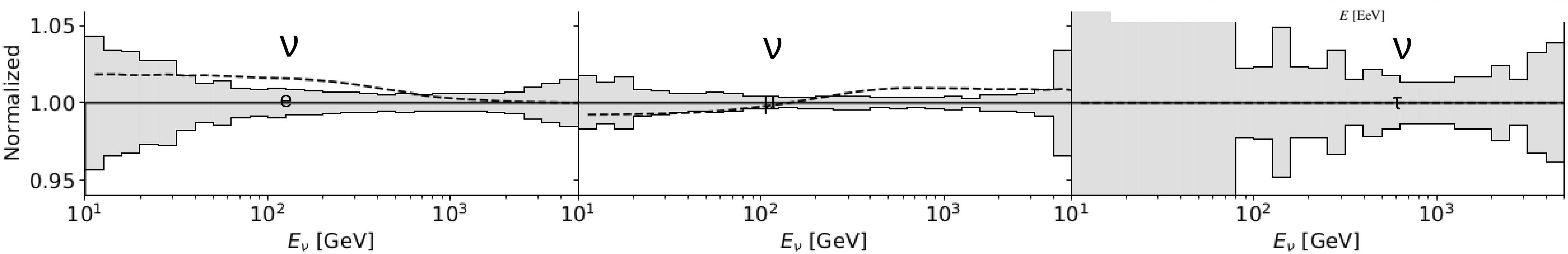
- Possible explanation: enhanced strangeness, K/π ratio ↑
- Might be motivated by ALICE mid-rapidity data…

  P. Palni (for ALICE), 1904.00005
- Simple modeling – introduce K → π swapping probability $0 < f_s < 1$
- Underlying physics might be related to QGP formation, strange fireballs,...

  L. A. Anchordoqui etal, 1907.09816; 1612.07328; ...
- The effect is most pronounced for **large η**, **best fit f_s ~0.5 or so**
- Increased K/π ratio:
  - – increased ν_e rate for E_ν < TeV
  - – increased ν_μ rate for E_ν > few hundred GeV
  - – reduced ν_μ rate for lower energies
  - – no impact on ν_τ rate
- **Projected FPF@LHC bounds f_s < 0.01**



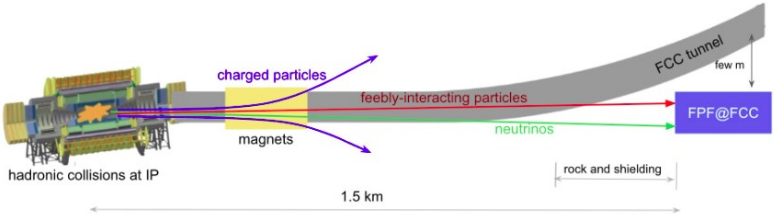
F. Kling, T. Makela, ST, 2309.10417



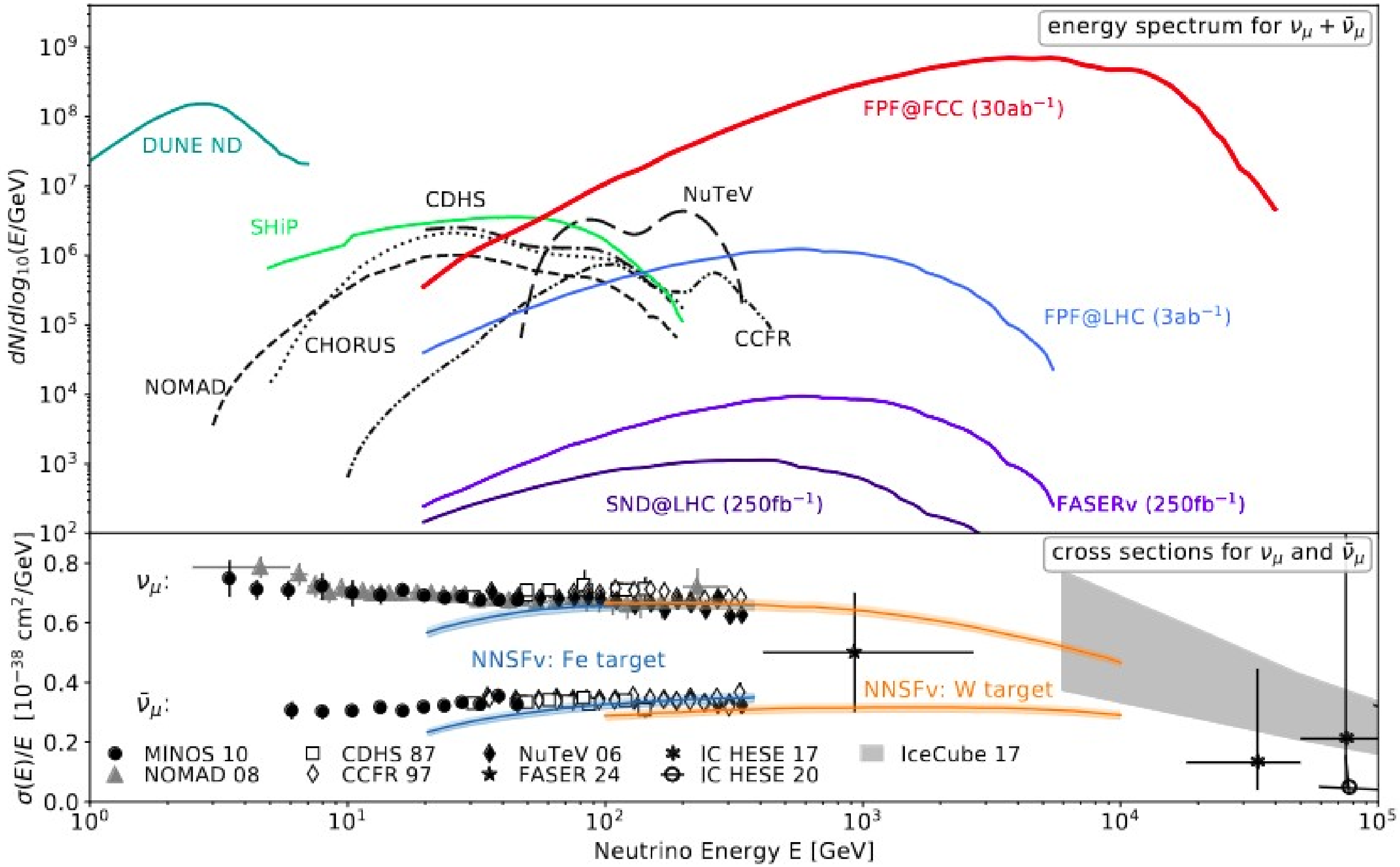
R.M. Abraham, J. Adhikary, J.L. Feng, F. Kling, T.R. Rabemananjara, J. Rojo, S. Trojanowski (in preparation)

HIGH-ENERGY NEUTRINOS & FPF@FCC

- assumed FASERν2-like detector geometry
  (proposed for HL-LHC; 40cm x 40cm x 6.6m)



- collimated flux of ν with E_ν up to tens of TeV



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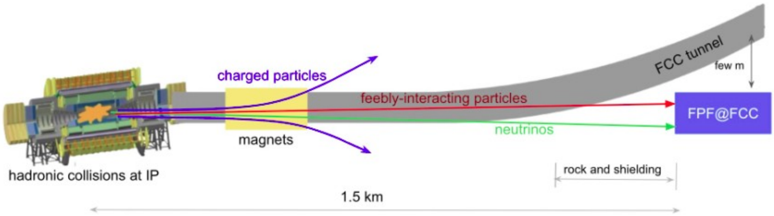


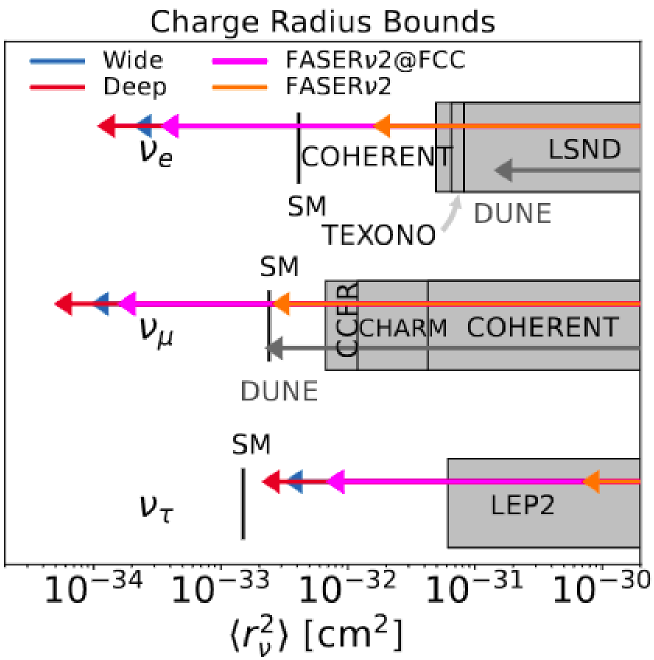
- collimated flux of ν with E_ν up to tens of TeV
- Expected ν scattering rates from O(100M) for ν_μ to O(1 M) for ν_τ
- Rich physics opportunities: PDFs, polarized targets, p-Pb → ν, Pb-Pb → ν
- Example: neutrino charge radius

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

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

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

- SM predictions can be confirmed for ν_e, ν_μ



SUMMARY

- FIMPs – rich experimental program & enormous pheno activity
- New proposals for dedicated detectors,…
- … but the central LHC detectors strike back
- Future colliders will benefit from all these – dedicated ideas already discussed (pheno)
- Closing the gap to cosmological bounds (BBN) will require future accelerators & ideas
- Colliders are also high-energy neutrino factories
- Rich physics prospects, complimentary to large-scale neutrino telescopes,...
- … but substantially smaller ν detectors needed at colliders – precision measurements

THANK YOU !