Long-lived particles at accelerators (& neutrinos @ colliders)

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NATIONAL SCIENCE CENTRE POLAND

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

FIMPS (& NEUTRINOS)

- Feebly-Interacting Massive Particles
- **This talk: ~MeV- to GeV-scale new physics (only selection of topics)**
- Motivation:

- Cosmology (DM, inflation, baryogenesis)

- Hierarchy (relaxion,…), ...

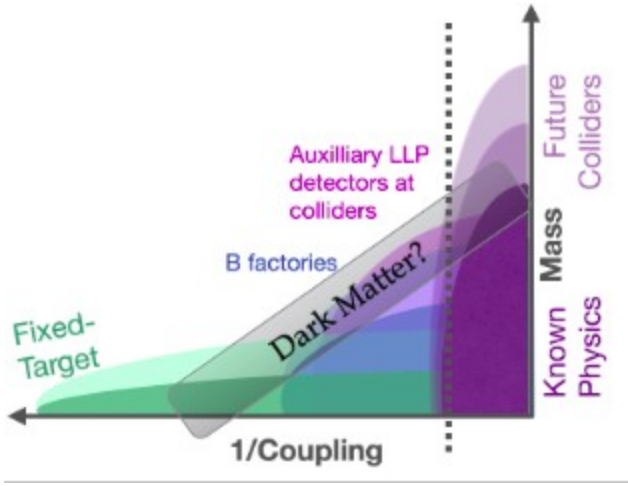
- Experimentally accessible:

- Intensity frontier

- Auxiliary collider detectors

- Prototype feebly-interacting particles: neutrinos
- FIMP detectors can offer additional ν physics opportunities

FIPs 2022 Workshop Report,



Outline of the talk:

1) FIMPs

2) Neutrinos @ LHC

3) FIMPs & ν @ FCC-hh

FIMPs

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)	$y_N L H N$

& many more variants

LIFETIME

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
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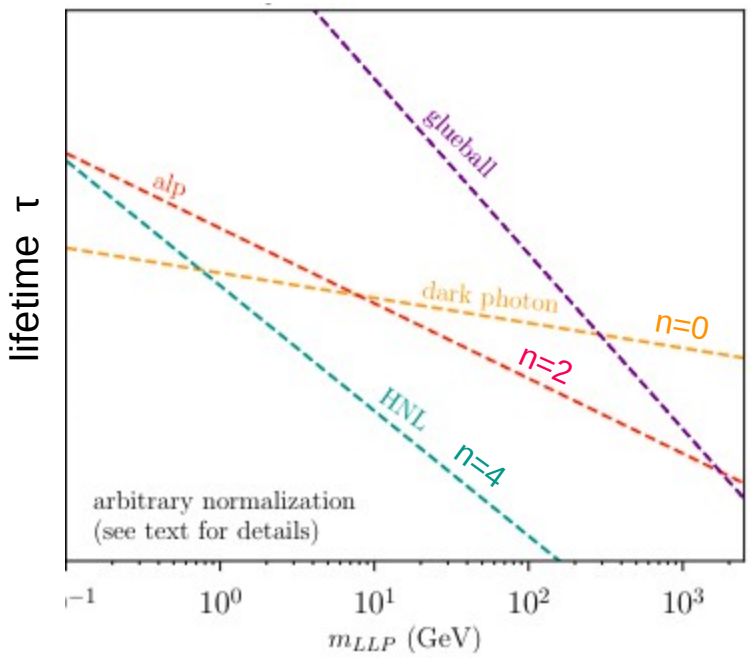
Sterile Neutrino, N	$y_N L H N$

(Heavy Neutral Lepton, HNL)

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



DARK PHOTON

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
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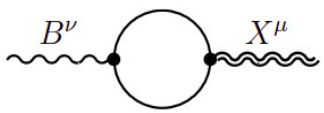
small couplings, e.g. kinetic mixing



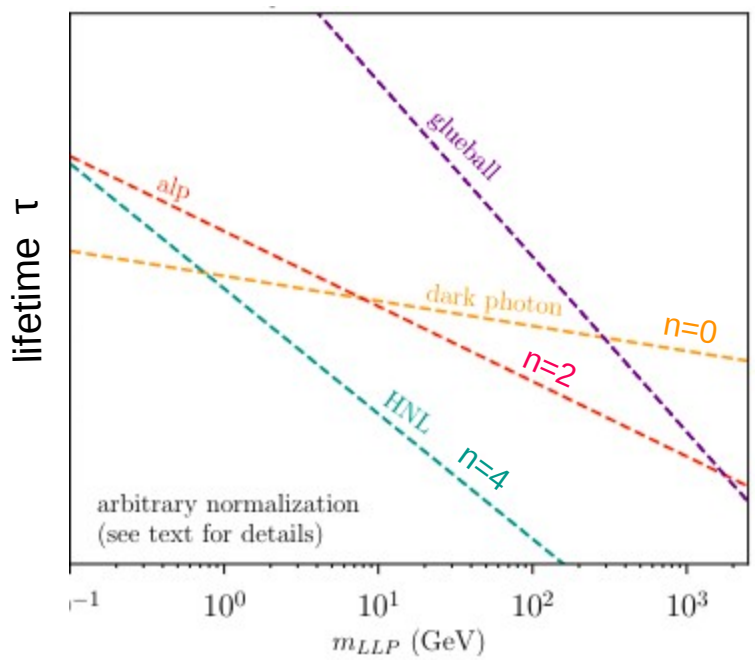
$$\epsilon = -\frac{g' g_X}{16\pi^2} \sum_i Y_i q_i \ln \frac{M_i^2}{\mu^2}$$

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

Dark photon

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

S. Knapen, S. Lowette, 2212.03883



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(Heavy Neutral Lepton, HNL)

Lifetime

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

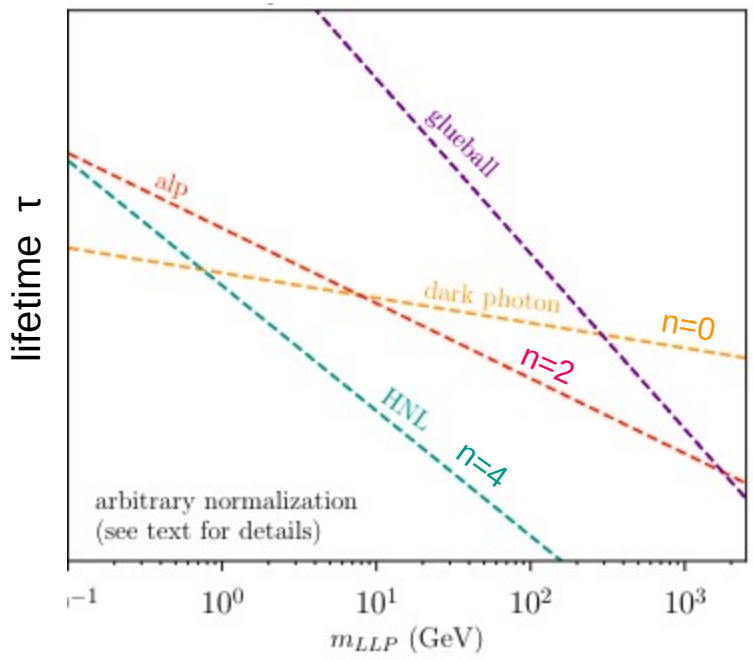
ALP

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

HNL

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

S. Knapen, S. Lowette, 2212.03883



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

→ impact on detection strategies

PORTALS

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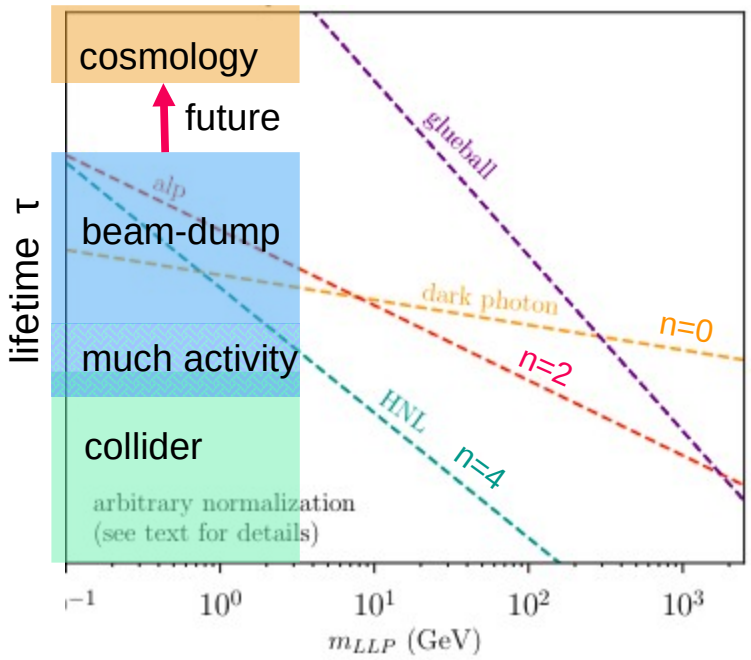
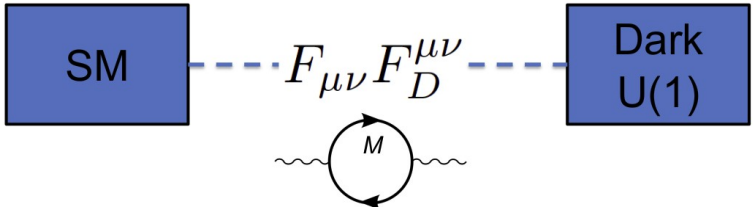
Schematic view on detection strategies

- lots of activity to bridge the (traditional) gap between Beam-dump & collider searches
- future: close the gap to cosmology

S. Knapen, S. Lowette, 2212.03883

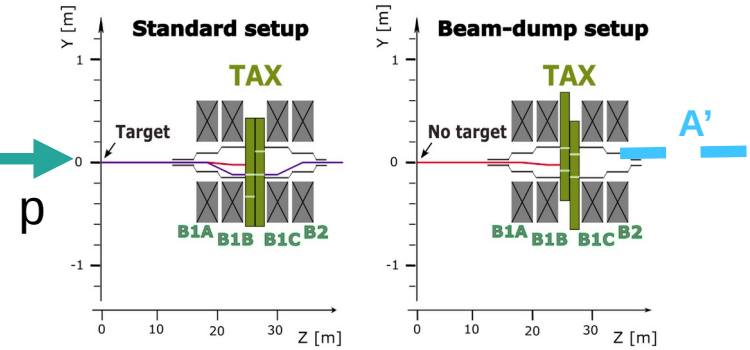


DARK PHOTON – EXPERIMENTAL STATUS (1)

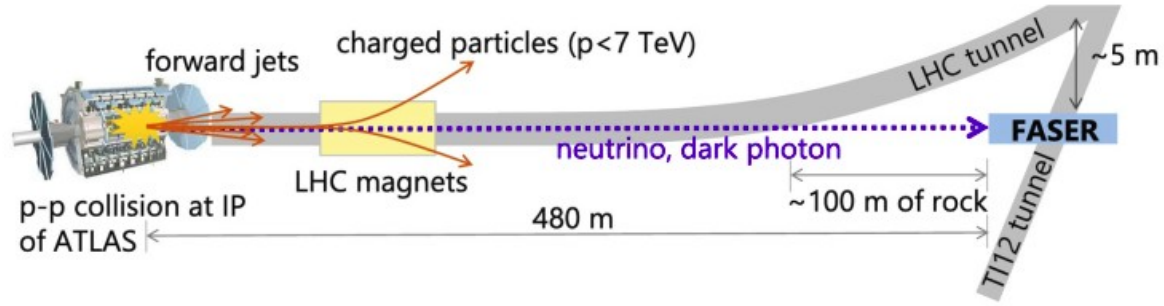


$$\mathcal{L} \supset \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e \sum_f q_f \bar{f} \not{A}' f$$

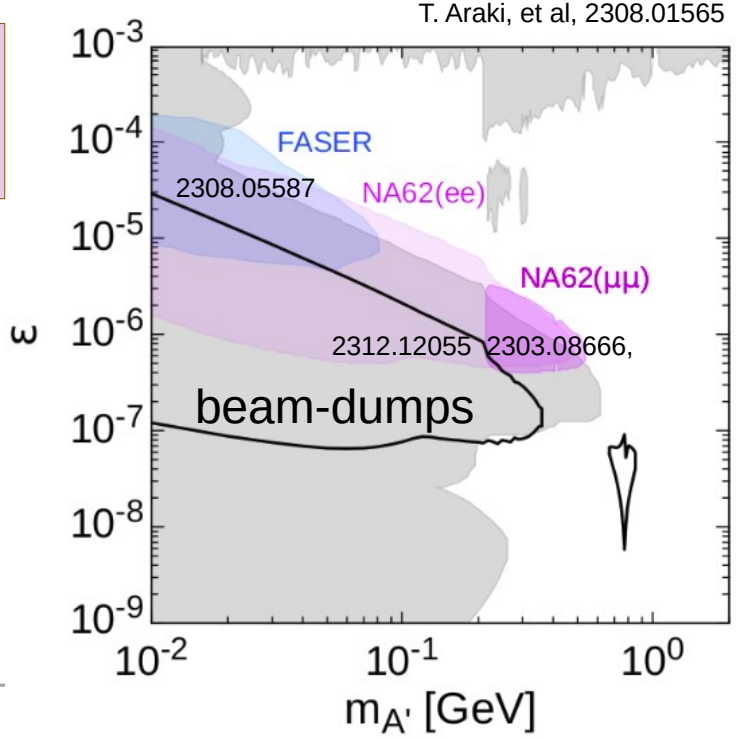
Beam-dump searches @ NA62



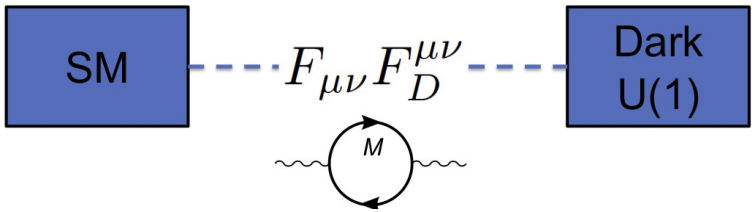
FASER



T. Araki, et al, 2308.01565



DARK PHOTON – EXPERIMENTAL STATUS (2)



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

Future:

- BDF/SHiP proposal endorsed by CERN Research Board on March 6th
- LHCb improvements & searches @ other central detectors

  electron identification in the high-level trigger allows to study A' → e+e downstream algorithm

  D. Craik, etal, 2203.07048
  LHCb, 2211.10920
  V. Gorkavenko, etal, 2312.14016

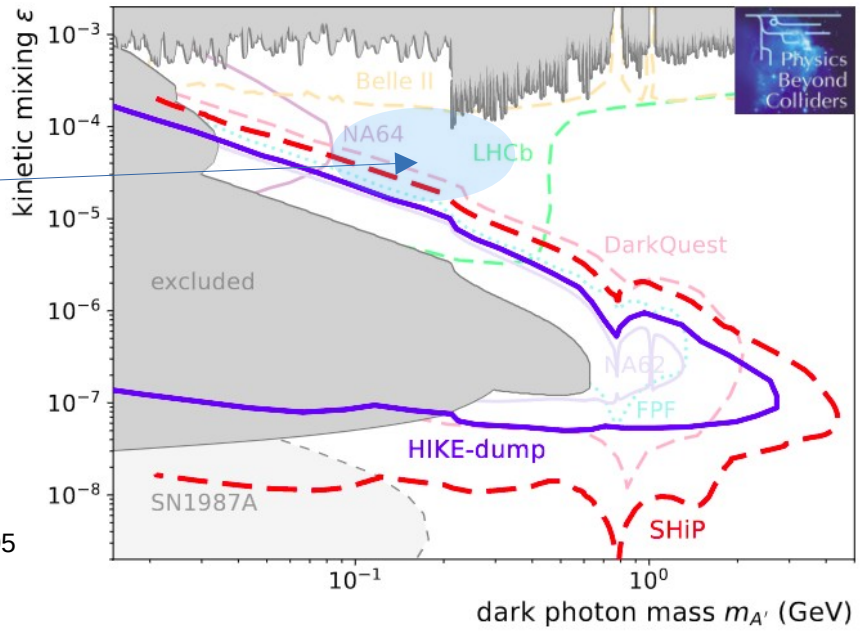
- Belle-II – displaced search

  T. Ferber, etal, 2202.03452
  J. Jaeckel, A.V. Phan, 2312.12522

- Proposed searches
  - FASER2 @Forward Physics Facility (FPF)
  - multiple other proposals...

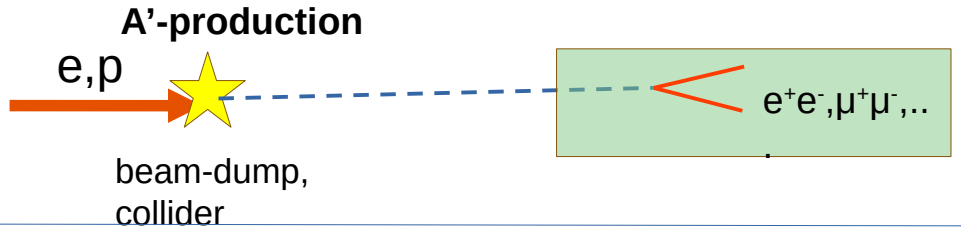
  J.L. Feng, et al, 2203.05090
  L.A. Anchordoqui, 2109.10905

CERN-PBC Report-2023-003

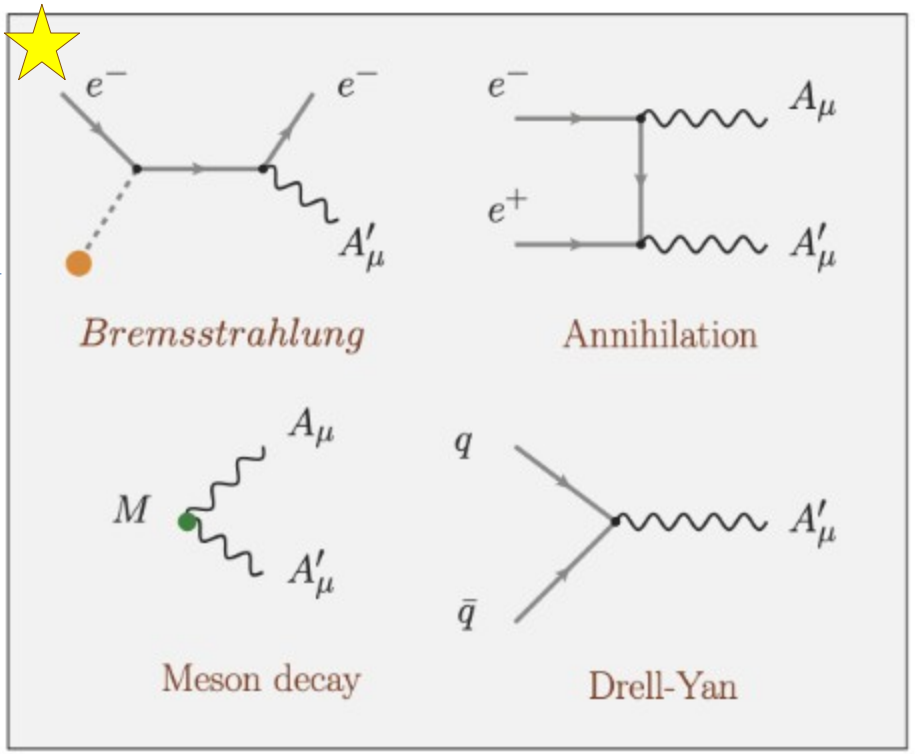


THEORY UNCERTAINTIES – A' PRODUCTION

Schematic – search for displaced decays



M. Fabbrichesi, etal 2005.01515



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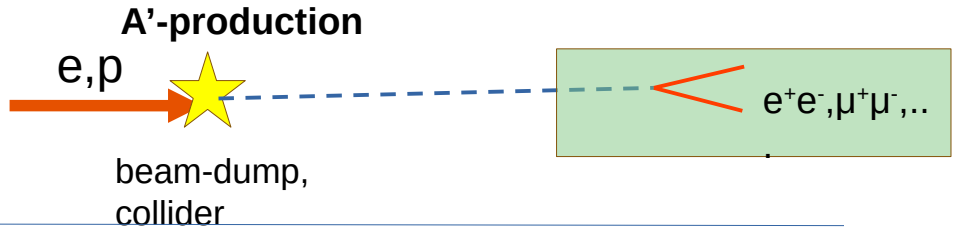
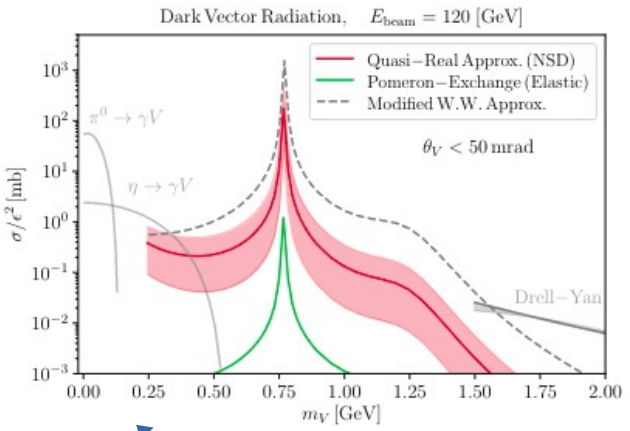
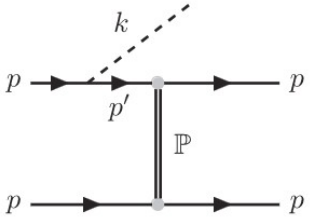


S. Foroughi-Abari, A. Ritz, 2108.05900





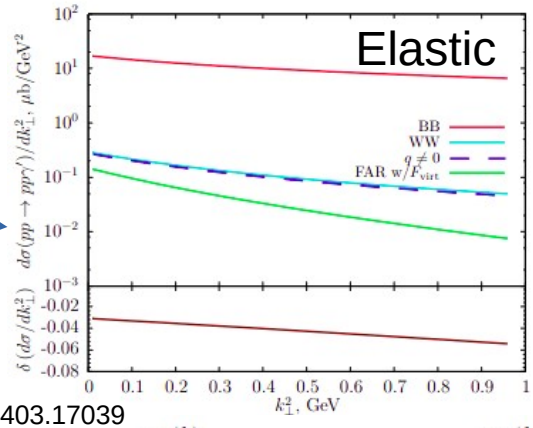
- Proton bremsstrahlung

- widely used FWW-like approximation, exchange of hypothetical massless vector boson

J. Blümlein, J. Brunner, 1311.3870

- vector Pomeron (Donnachie-Landshoff) exchange

D. Gorbunov, E. Kriukova, 2306.15800



- need to consider proton momentum exchange

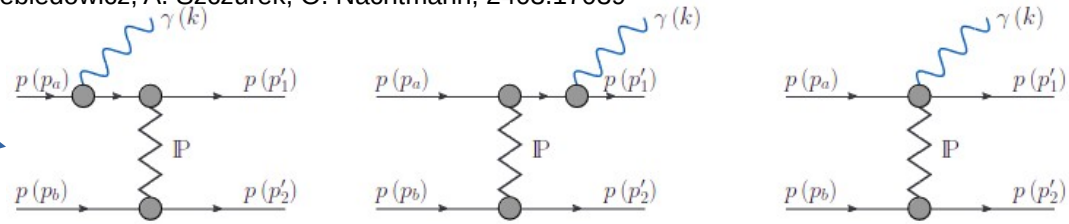
Theory effort needed

- inelastic brem. with general momentum exchange

P. Lebiedowicz, A. Szczurek, O. Nachtmann, 2403.17039

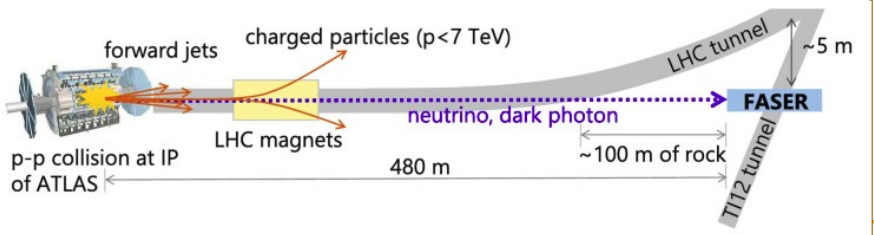
- going beyond vector Pomerons

Photon bremsstrahlung; tensor-Pomeron exchange

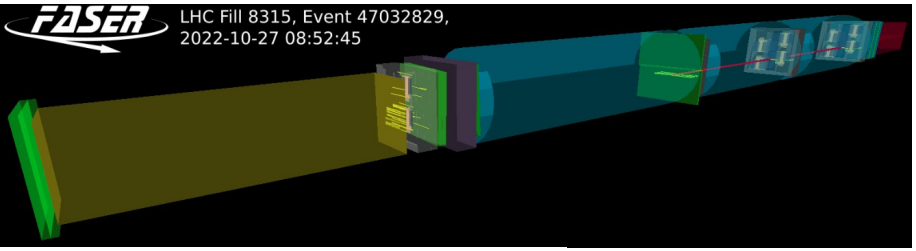


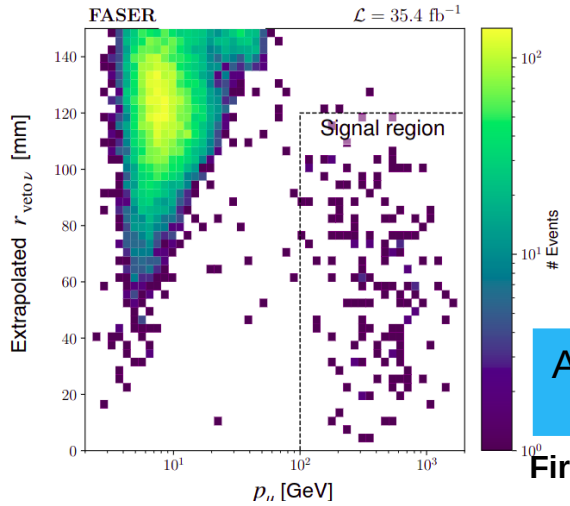
FORWARD NEUTRINOS @ LHC

FORWARD LHC NEUTRINOS



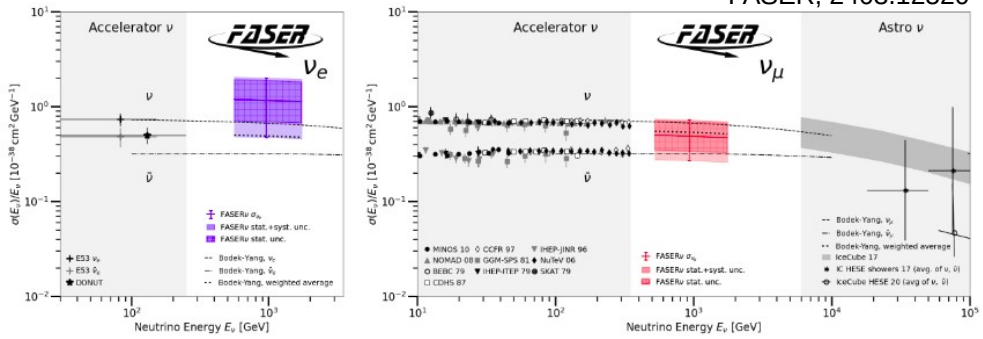
First ν observation at the LHC
FASER, 2303.14185; SND@LHC, 2305.09383





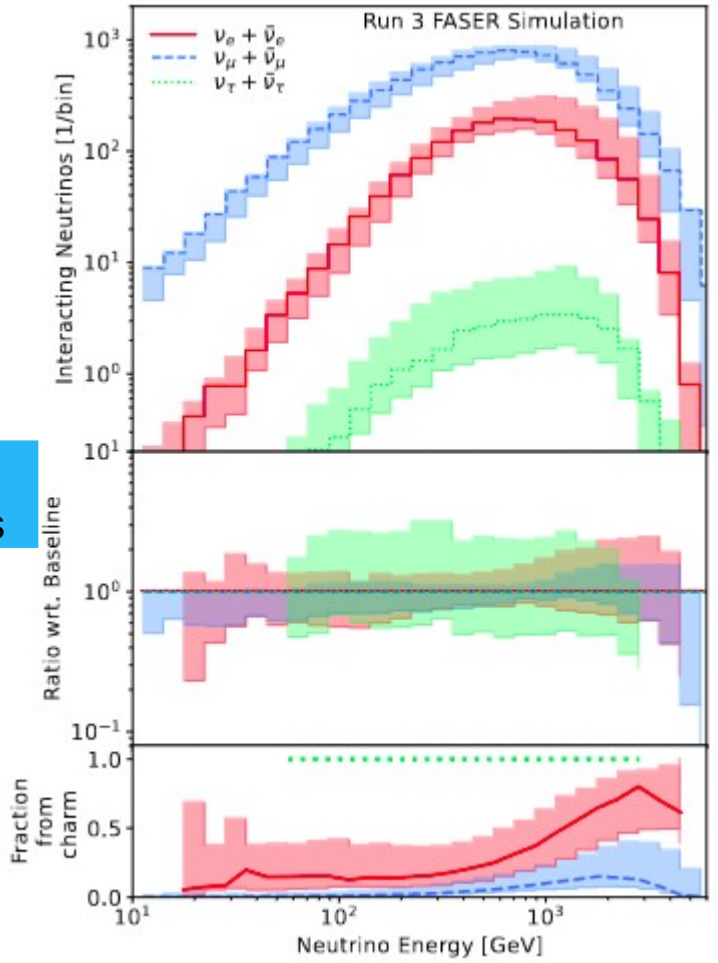
Aim: fill in the gap
in cross section measurements

First FASERν observation (emulsion)
FASER, 2403.12520



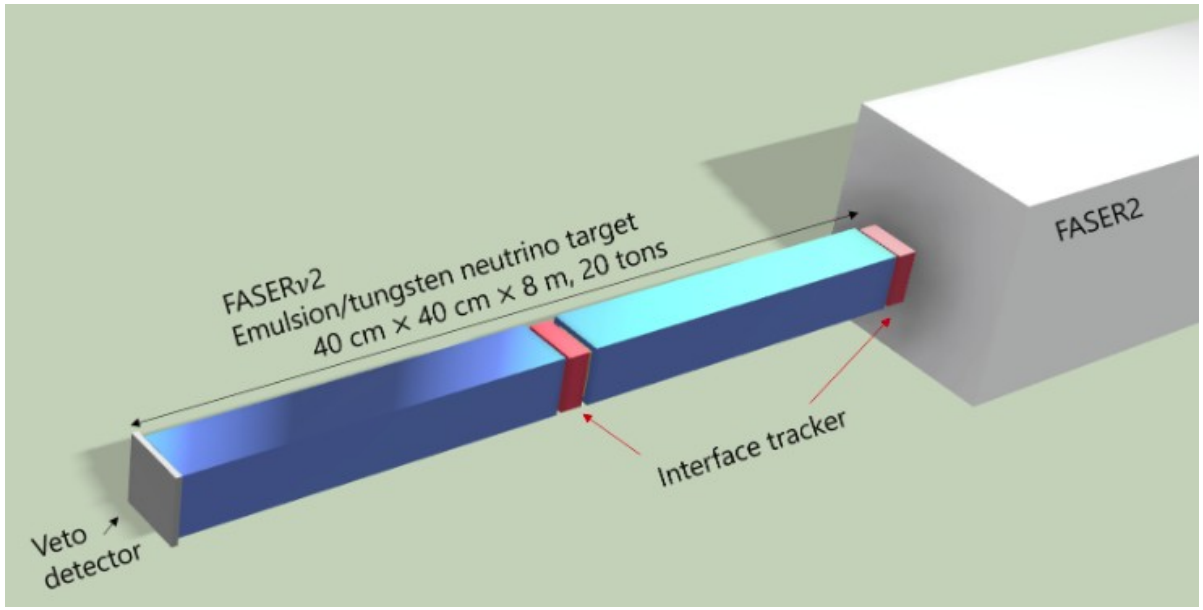
Aim: reduce uncertainties
enlight underlying QCD,
cosmic-ray physics,...

Forward LHC neutrino spectrum
FASER, 2402.13318



FORWARD NEUTRINOS @ HL-LHC

Proposed: FASERν2 (@ HL-LHC)



Aim: reduce uncertainties
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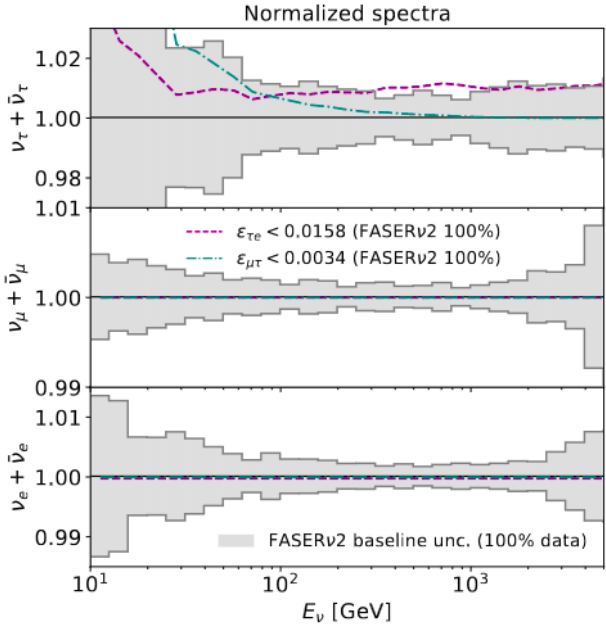
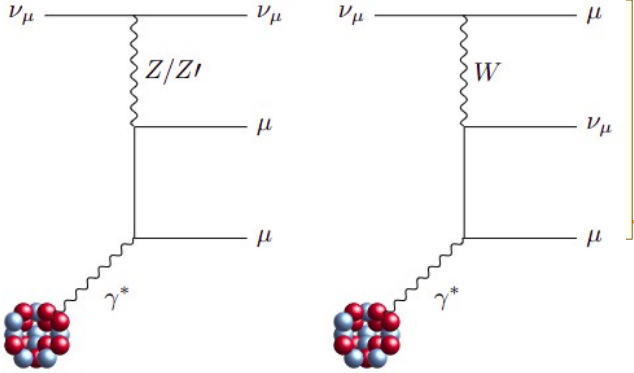
Forward LHC neutrino spectrum

F. Kling, T. Makela, ST, 2309.10417



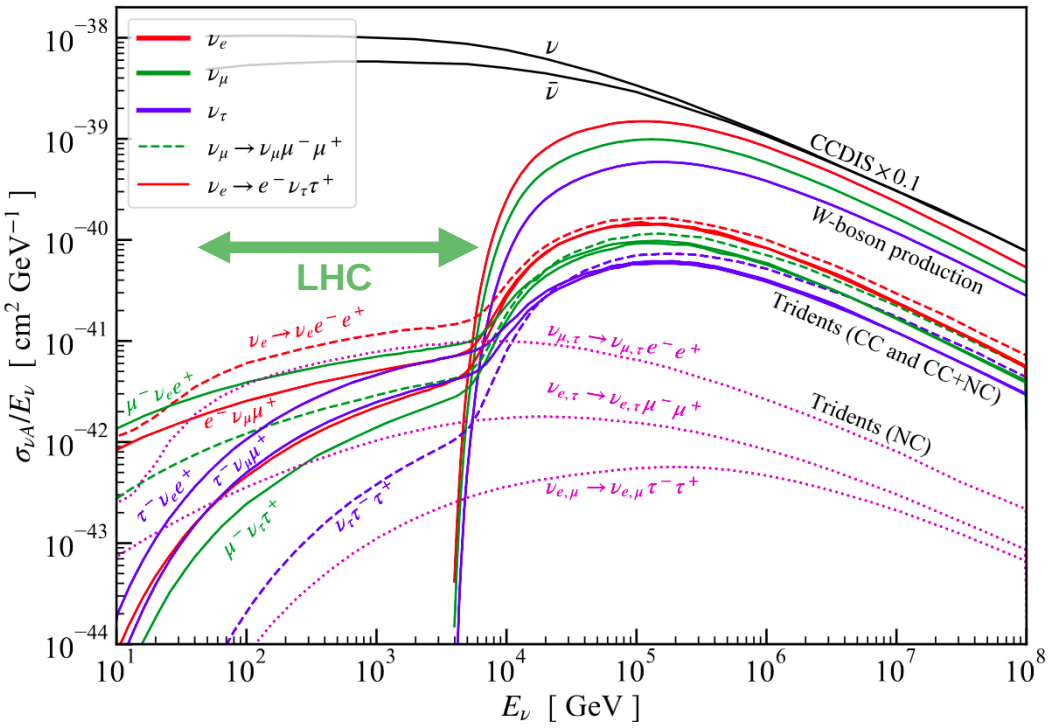
- ~1M expected ν-induced events (10k ν_τ)
- Flux uncertainties can be reduced to sub-percent level (for ν_μ)
- Implications for cosmic-ray physics (enahnced strangeness production, …)
- Opportunity to measure rare ν-induced events

NEUTRINO TRIDENT PRODUCTION



- test of electroweak theory (full $2 \to 4$ calculation needed); possible new physics contributions
- Past "measurements" only performed for a dimuon final state
  CHARM, CCFR (~3σ), later NuTeV (no conclusive signal; new BG sources identified)
- Proposals to measure tridents @ DUNE (2-4σ) and other facilities
  W. Altmannshofer, 1902.06765
- Challenges:
  - low statistics
  - backgrounds
    ν-induced charm production;
    single pion production (CC)
- Opportunity to use forward LHC νs
- Collimated flux & detailed event study
- No W-boson on-shell production, suppressed lepton FSR
  R. Plestid, B. Zhou, 2403.079

B. Zhou, J.F. Beacom, 1910.08090



NEUTRINO TRIDENT PRODUCTION @ LHC

- **μμ: ~10 ton forward detector – tens of dimuon trident events @ HL-LHC**
- μτ-channel could be studied with a larger detector (with τ→ μνν)
- μe-channel – even larger statistics, but challenging experimentally

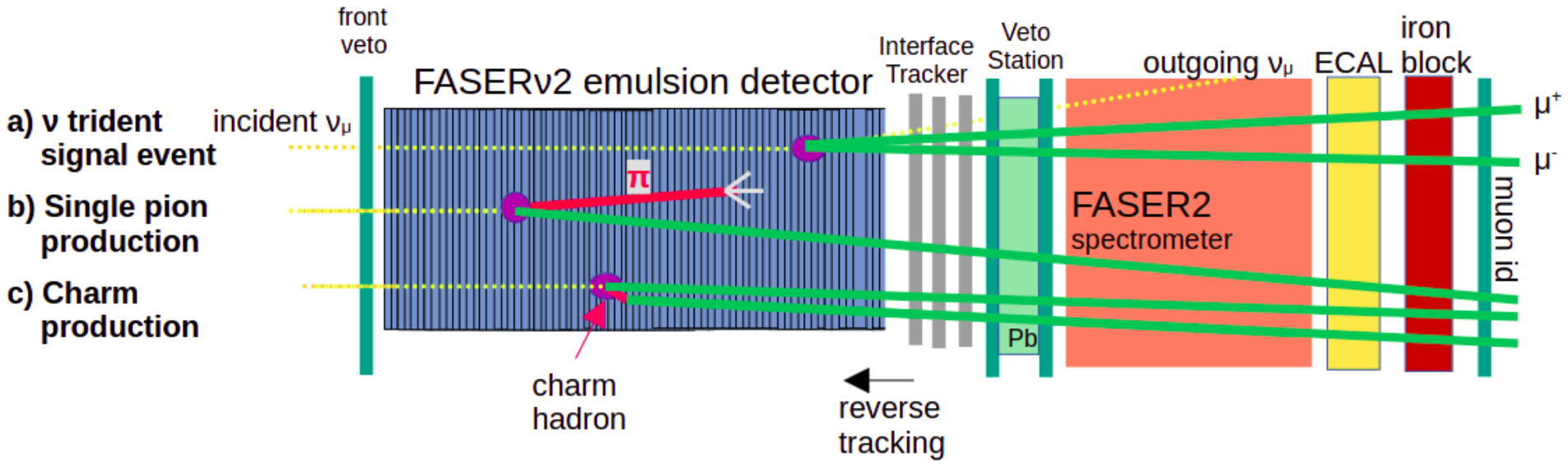
Name	Mass [tons]	Target nucleus	On(Off)--Axis	$L^{-1}_{\text{int,TeV}\nu\to\mu\mu}$ $\times 10^{17}$ [cm^{-1}]	Neutrino Tridents, $\nu N \to \nu N' \ell^+\ell^-$ $\mu^+\mu^-$	$\mu^+\mu^-_{f_s=0.5}$	e^+e^-	$\tau^+\tau^-$	$e^\pm\mu^\mp$	$e^\pm\tau^\mp$	$\mu^\pm\tau^\mp$
Run 3 (150 fb^{-1})											
FASERν	1.1	W	On	252	0.22	0.54	0.24	0.0029	0.83	0.035	0.060
SND@LHC	0.83	W	Off	252	0.024	0.06	0.03	0.0002	0.10	0.004	0.004
HL-LHC (3 ab^{-1})											
FASERν2	20	W	On	252	40	97	44	0.51	150	6.3	10
AdvSND@LHC (Far)	5	W	Off	252	2.2	5.3	2.7	0.02	9.0	0.3	0.4
FLArE	10	LAr	On	8.56	4.5	11	4.5	0.07	16	0.7	1.2
FLArE-100	100	LAr	On	8.56	26	63	27	0.37	91	4.1	6.8
NuTeV-like (Fe)	95	Fe	On	65.4	21	52	22	0.29	76	3.4	5.5
NuTeV-like (Pb)	135	Pb	On	154	48	116	57	0.45	190	7.0	10

NEUTRINO TRIDENT PRODUCTION @ FASERν2

- Example: FASERν2
- Mitigate backgrounds based on (mainly):

- muon ID
- charged track multiplicity in ν-N vertex

- Reverse tracking of muon pairs
- **Even >5σ can be achieved in the HL-LHC era**

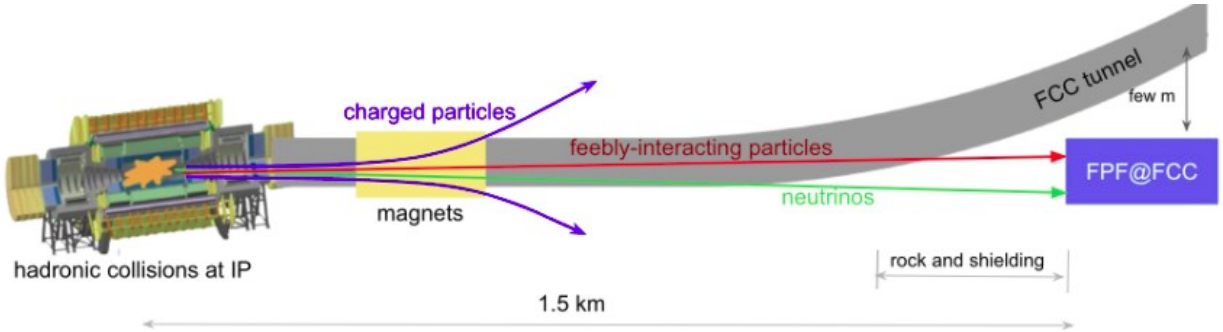


FORWARD STUDIES @ FCC-hh

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

FORWARD PHYSICS FACILITY (FPF) @ FCC-hh

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

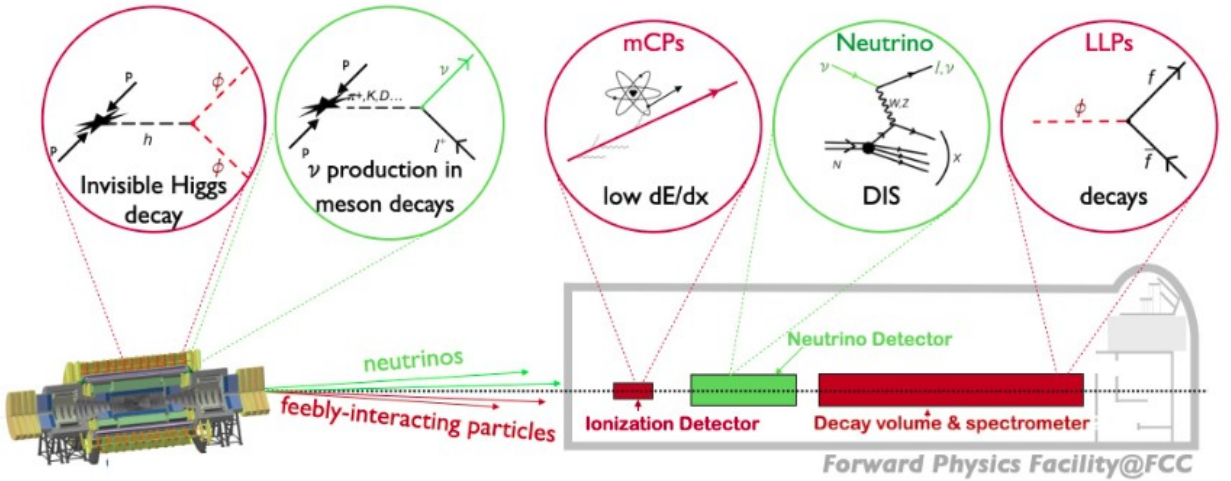


● Focus on FCC-hh:

– neutrino & QCD physics

– FIMP searches

– cosmic-ray physics...



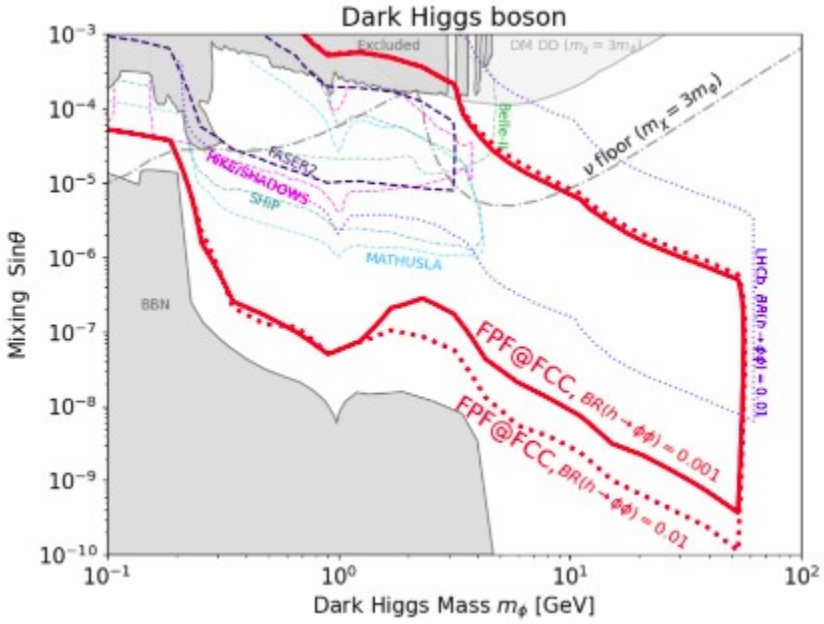
● Other proposals: HECATE@FCC-ee (2011.01005), FASER@FCC-hh (2105.07077), FOREHUNT@FCC-hh (2306.11803), BDF@ILC (1507.02809,2009.13790,2104.00888), proposal for the muon collider (2202.12302)

DARK HIGGS BOSON & FPF@FCC

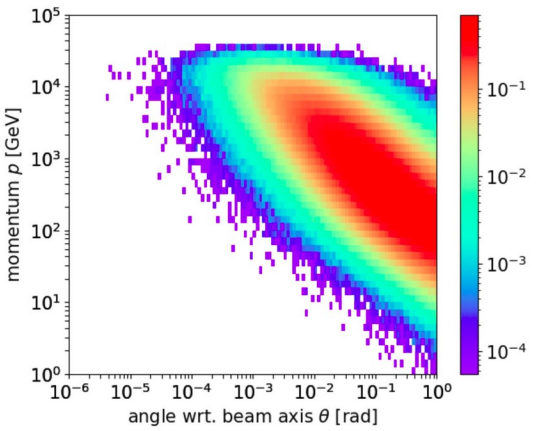
$$\mathcal{L} = -m_\phi^2\phi^2 - \sin\theta\frac{m_f}{v}\phi\bar{f}f - \lambda v h\phi\phi,$$

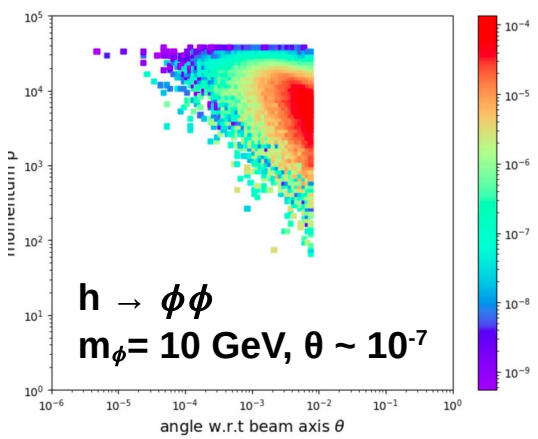
- Production: heavy meson decays ($B \to X_s\phi$), SM Higgs decay $h \to \phi\phi$ @ FCC

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, ST (in preparation)

DARK HIGGS BOSON & DARK MATTER

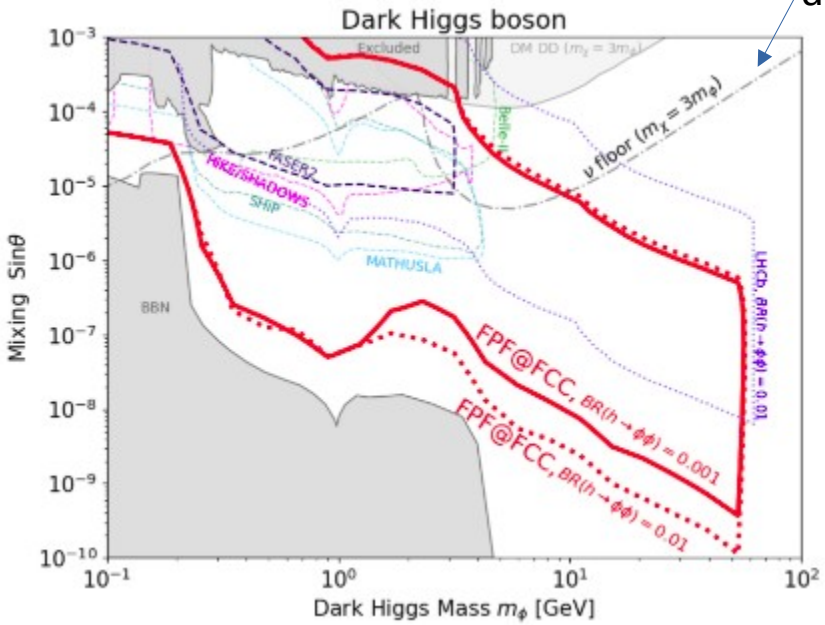
$$\mathcal{L} = -m_\phi^2\phi^2 - \sin\theta\frac{m_f}{v}\phi\bar{f}f - \lambda v h\phi\phi,$$

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

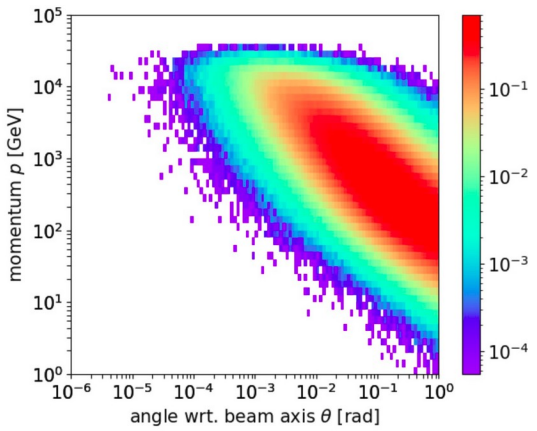
F. Kling, ST (FORESEE), 2105.07077

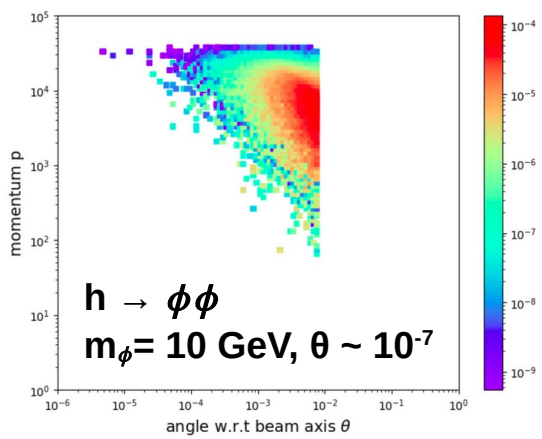
$$\mathcal{L} \supset -(1/2)\,\kappa\,\phi\,\bar{\chi}\chi$$

complimentarity:
DM direct detection



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



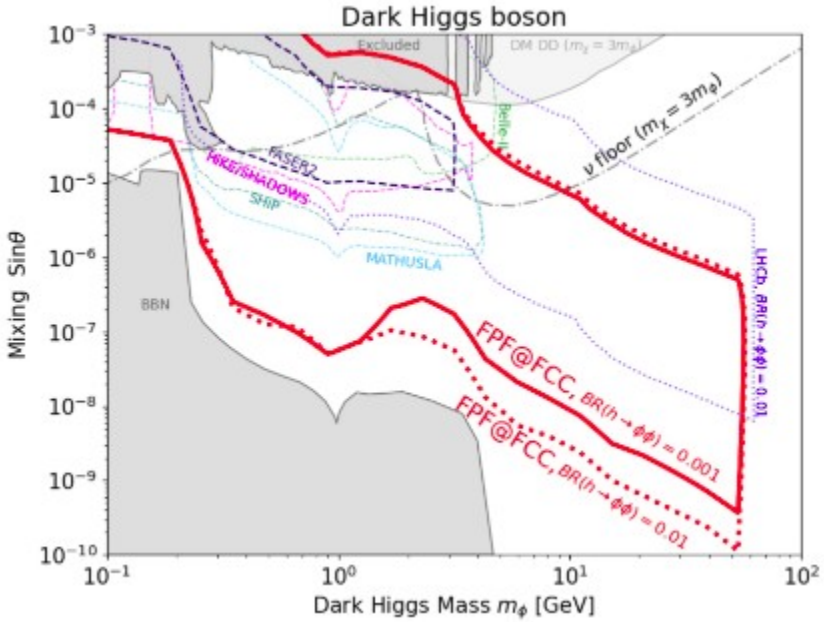


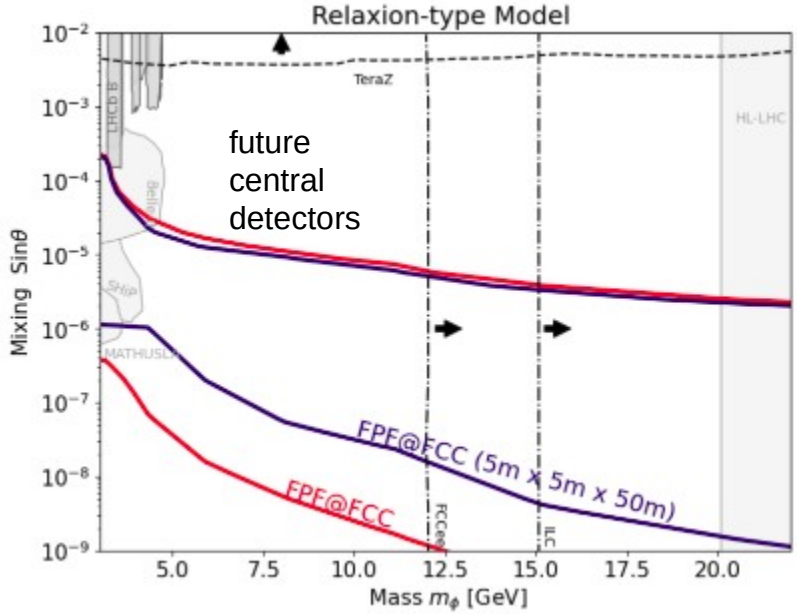
RELAXION & FPF@FCC

- 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, ST (in preparation)

MILLICHARGED PARTICLES AT FPF@FCC

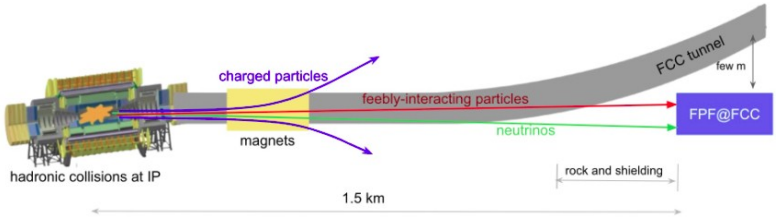
- Possible result of new unbroken gauge symmetries

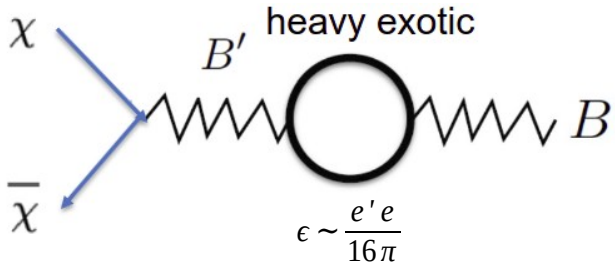
- Example: massless dark vector boson kinetically mixing with the hypercharge boson & additionally coupled to dark fermions χ

- χ acquires millicharge, Q_χ ~= εe
  & could be (a subdominant) DM component

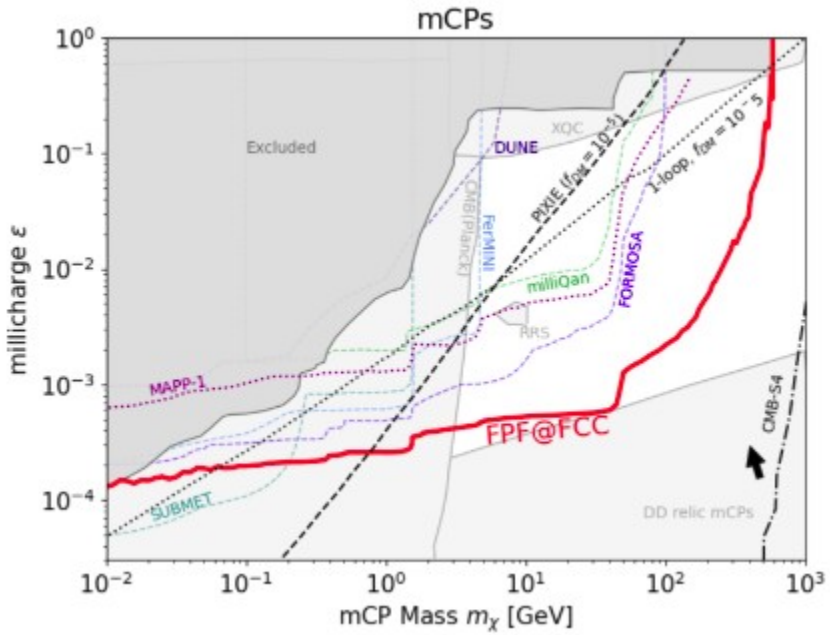
- χ detection via ionization (a-la-milliQan, FORMOSA@FPF, MAPP-1)

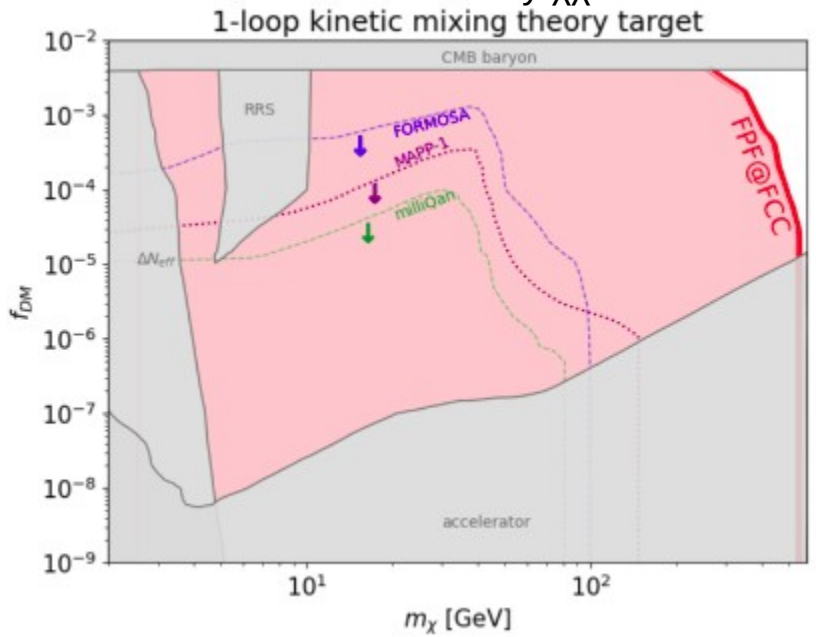
- FPF@FCC – assumed similar to FORMOSA (size 5m x 5m x 4m)





+ relic density χχ → A' A'

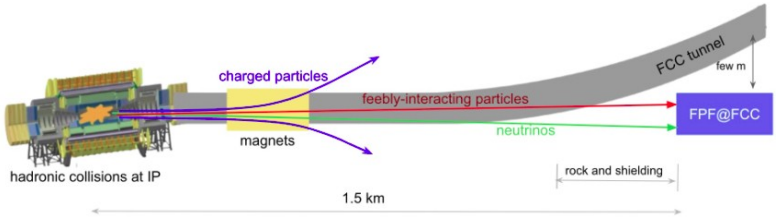


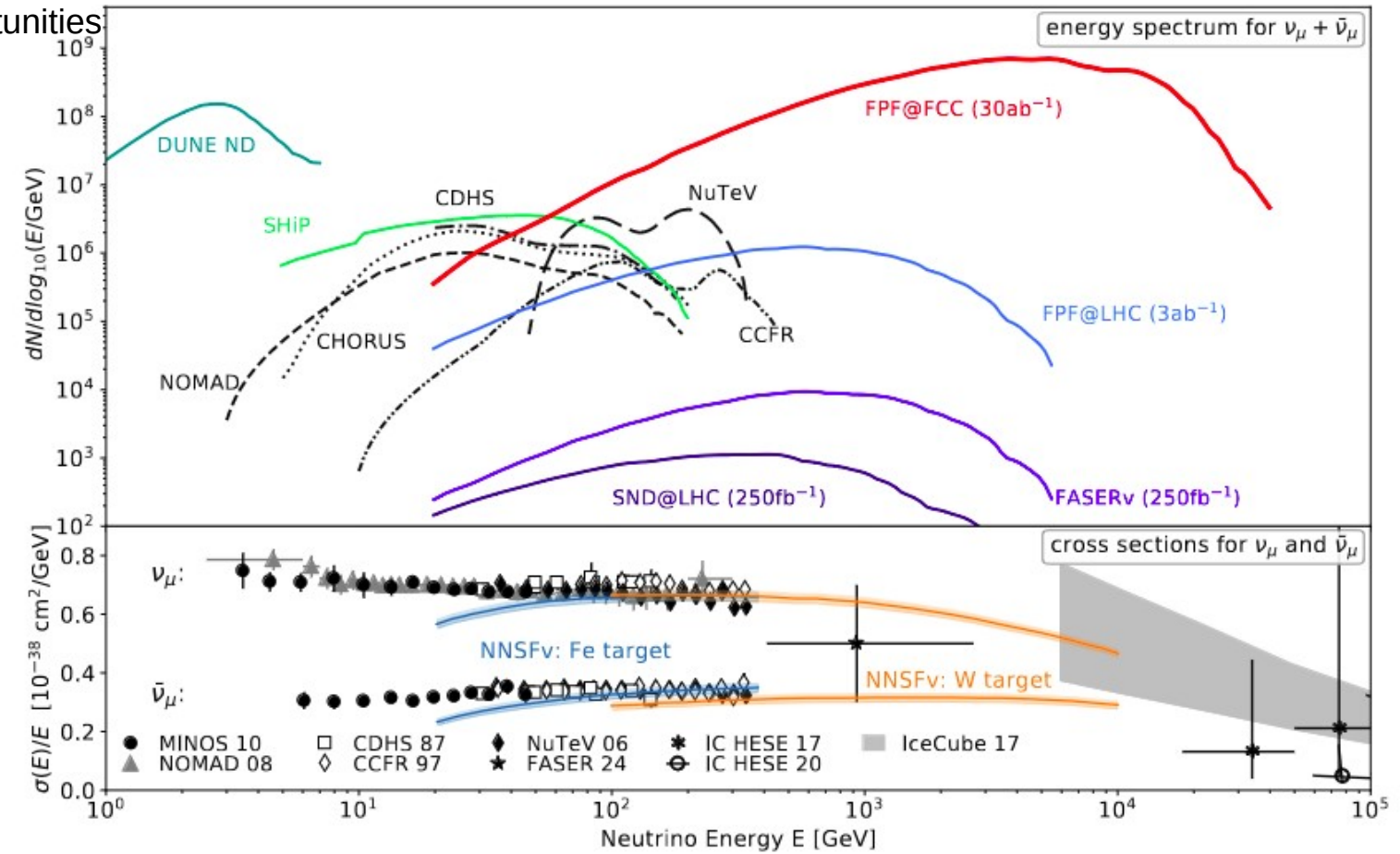


R.M. Abraham, J. Adhikary, J.L. Feng, F. Kling, T.R. Rabemananjara, J. Rojo, ST (in preparation)

HIGH-ENERGY NEUTRINOS & FPF@FCC

- 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 (FASERν2-like detector geometry)
- Rich physics opportunities





SUMMARY

- Light long-lived particles – rich experimental program & enormous pheno activity
- Lots of ideas how to bridge the gap between collider & beam-dump searches (target for coming years)
- 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 – precision measurements
- Forward LHC neutrinos can allow for the first dimuon trident measurement
- Neutrino physics – natural guaranteed physics case for FIMP-focused experiments

THANK YOU !

BACKUP

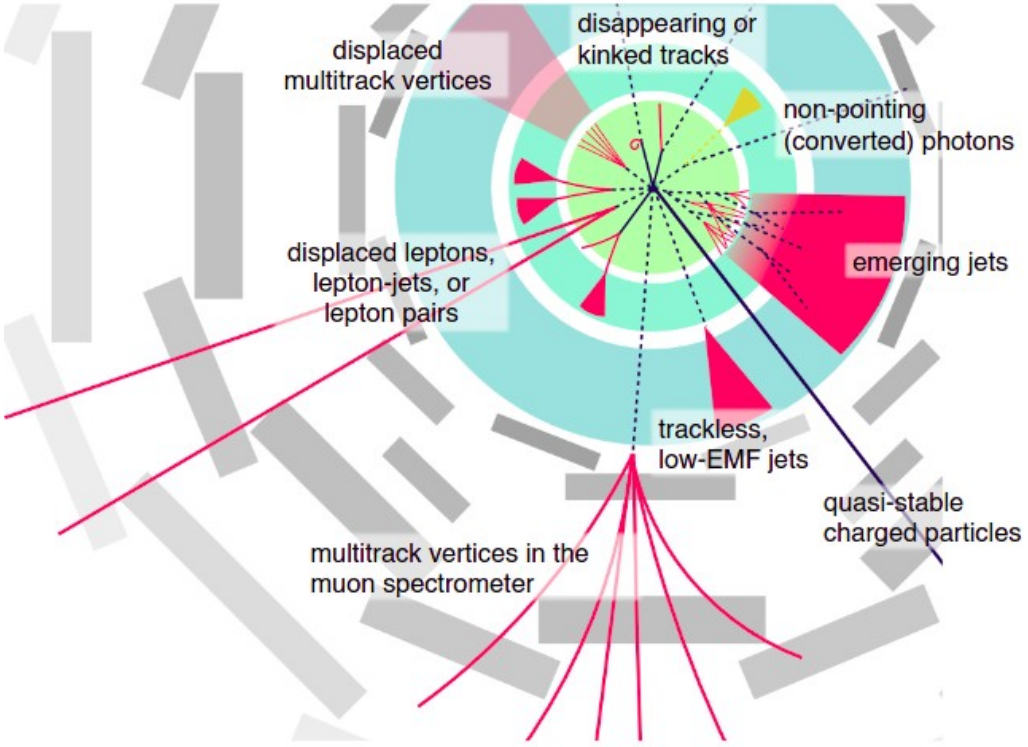
EXPERIMENTAL LANDSCAPE (NOT FULL)

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	160-160 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)

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

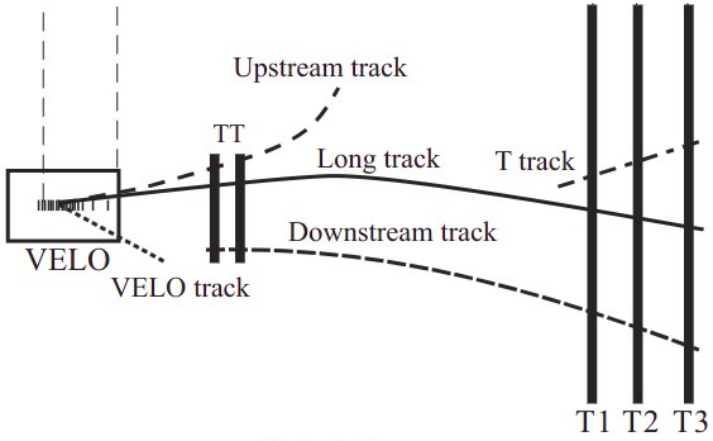
- Inclusive A' production
  + decay into di-muon pairs A' → μ+μ-

- Search for A' resonance excess over expected SM μ+μ- backgrounds

- LHCb: improved prospects expected

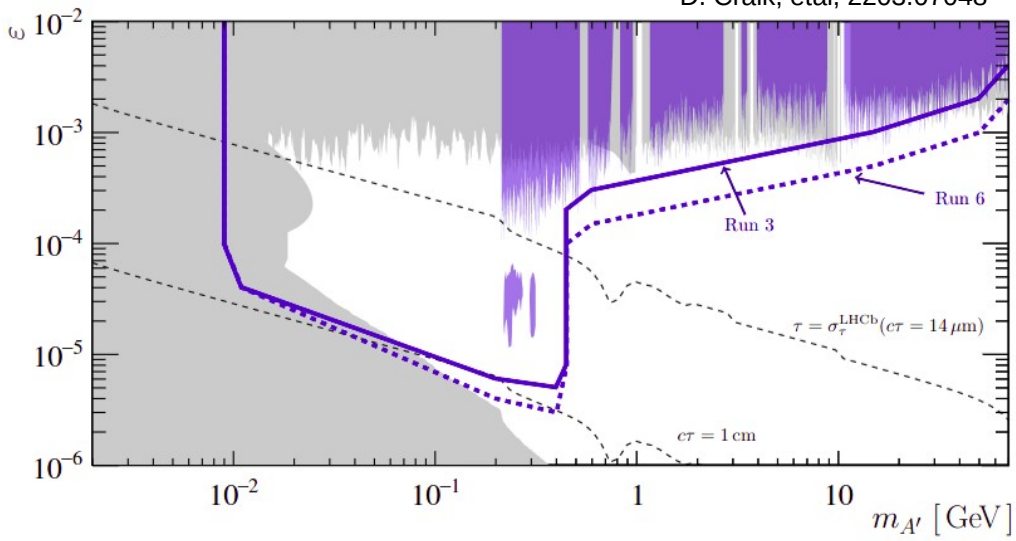
Downstream algorithm

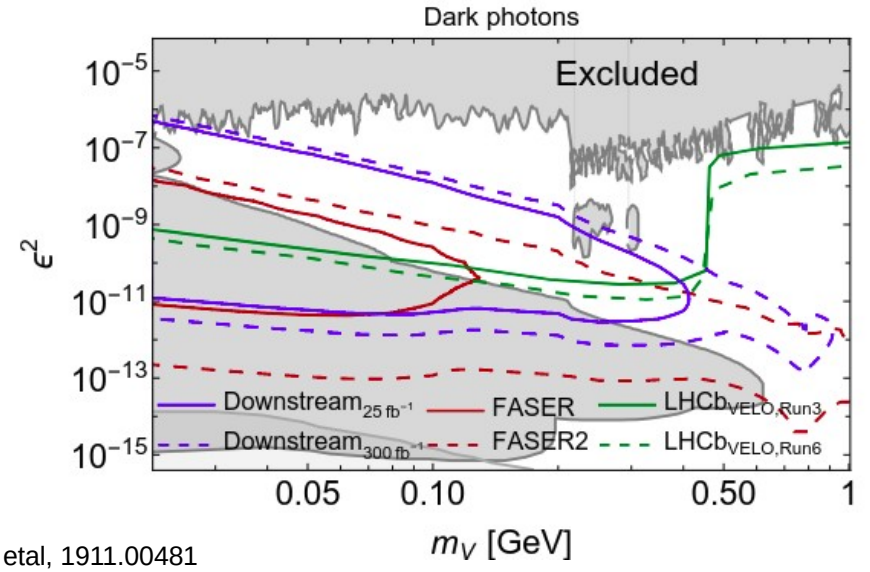
LHCb, 2211.10920
V. Gorkavenko, etal, 2312.14016



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

D. Craik, etal, 2203.07048





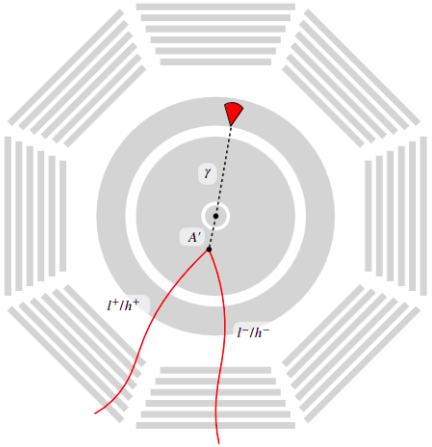
- Codex-b auxiliary detector for FIMP searches

G. Aielli, etal, 1911.00481

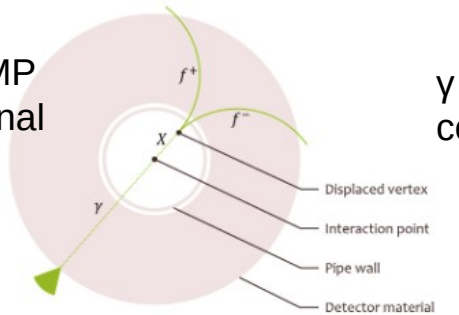
Belle-II

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

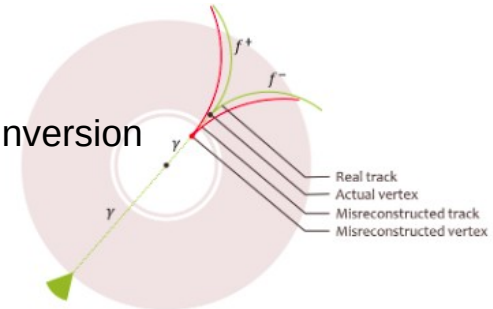
T. Ferber, etal, 2202.03452



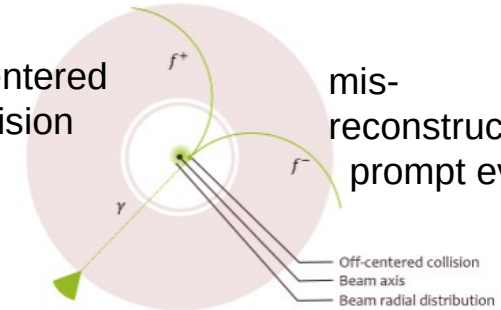
FIMP signal



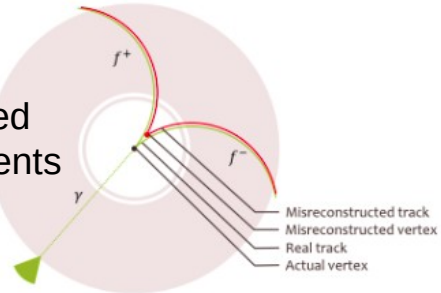
γ conversion



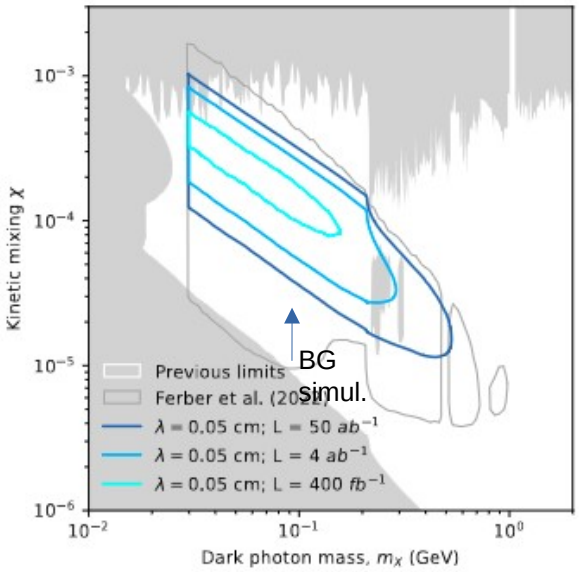
off-centered collision



mis-reconstructed prompt events



J. Jaeckel, A.V. Phan, 2312.12522



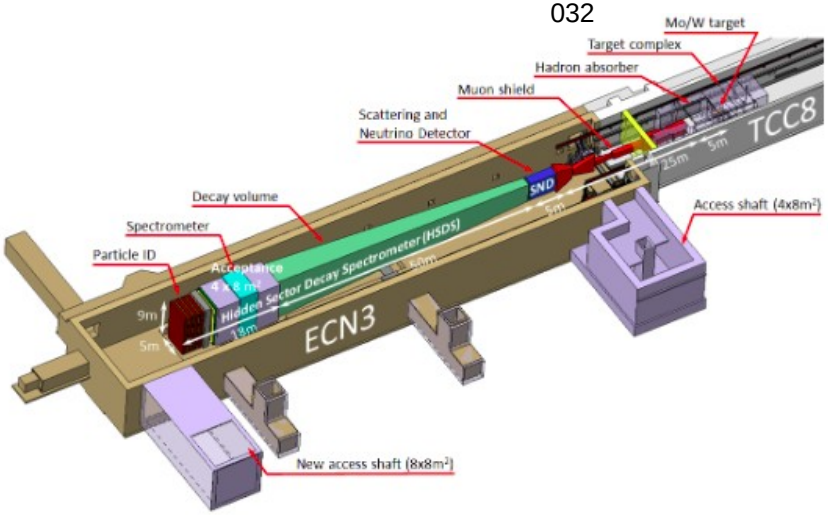
BEAM-DUMP EXPERIMENTS

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

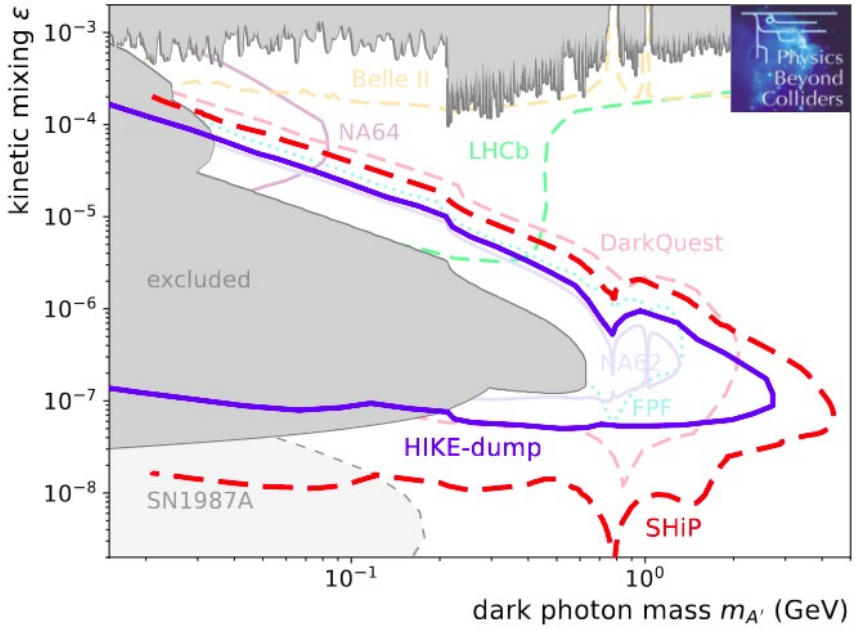
Daiki Ueda talk
(Saturday)

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

CERN-SPSC-2022-032



CERN-PBC Report-2023-003



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	$y_N L H N$

(Heavy Neutral Lepton, HNL)

Large lifetime

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

Dark photon

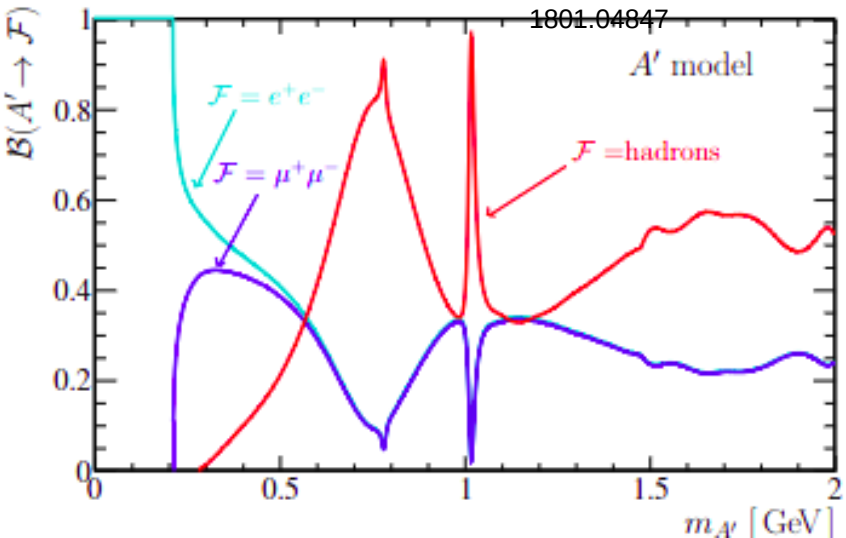
$$\Gamma_{A' \to f\bar{f}} \sim \varepsilon^2 m_{A'}$$

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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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	$y_N L H N$

(Heavy Neutral Lepton, HNL)

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)

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

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

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

MODELING UNCERTAINTIES – A' PRODUCTION

- 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

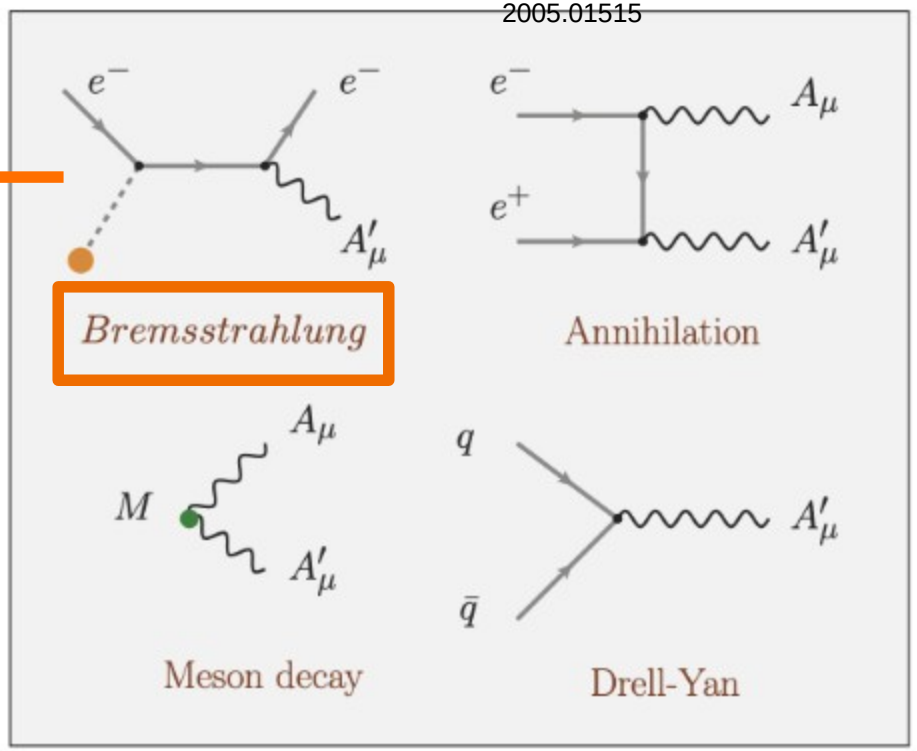
$$\chi\equiv\int_{t_{min}}^{t_{max}}dt\frac{t-t_{min}}{t^2}G_2(t).$$

Inelastic form factor

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

typo

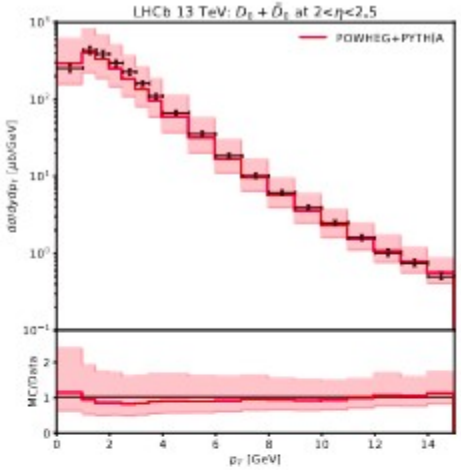
M. Fabbrichesi, etal 2005.01515

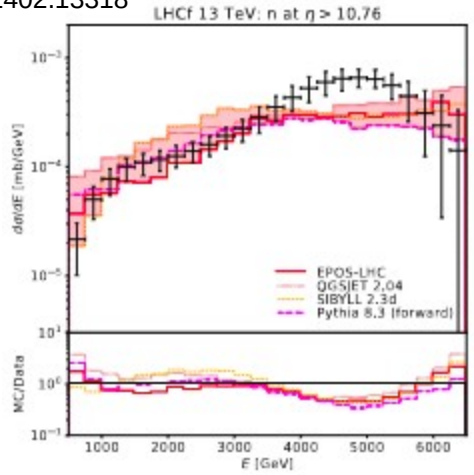


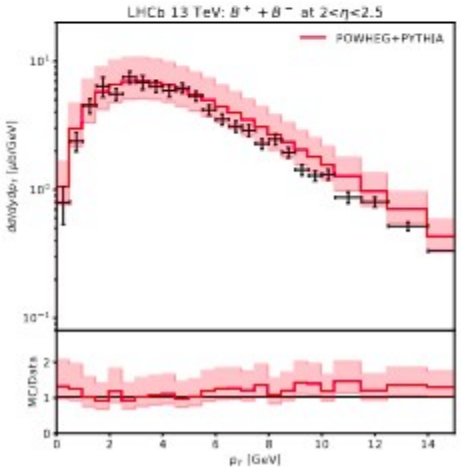
MODELING UNCERTAINTIES – A' PRODUCTION

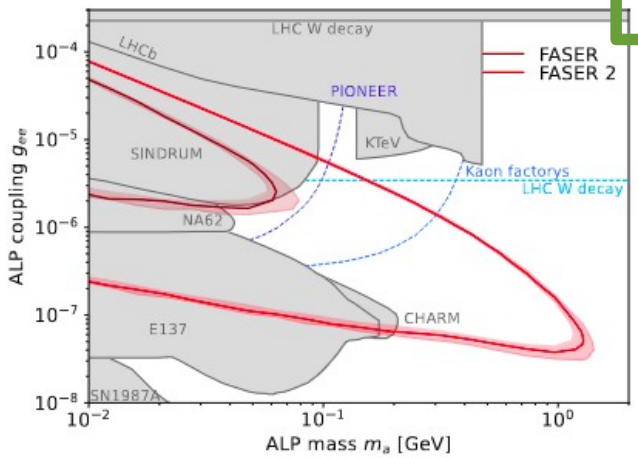
- Careful treatment of uncertainties needed to derive bounds

L. Buonocore, etal, 2309.12793
FASER, 2402.13318

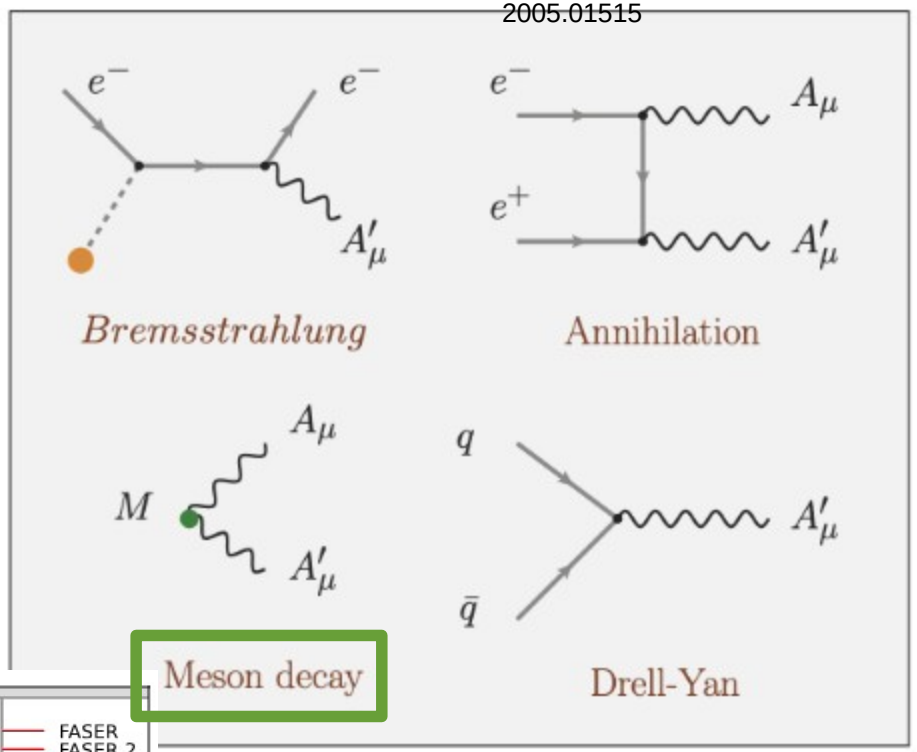








M. Fabbrichesi, etal
2005.01515

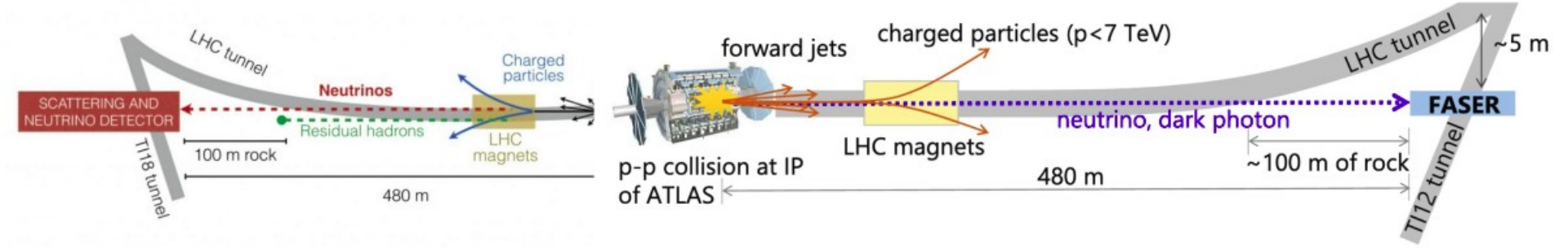


- ALP-ee $\mathcal{L} = \frac{g_{ee}}{2m_e}\,\partial_\mu a\;\bar{e}\gamma^\mu\gamma_5 e$

- Couplings to gauge bosons
through chiral anomaly

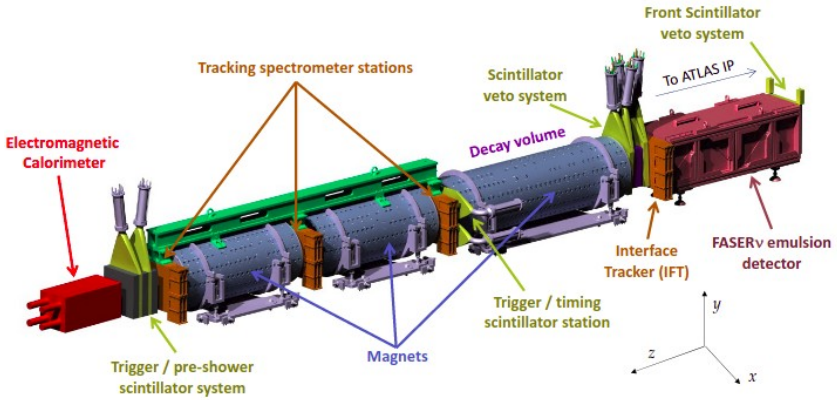
- B-meson or kaon decays

FAR-FORWARD SEARCHES AT THE LHC



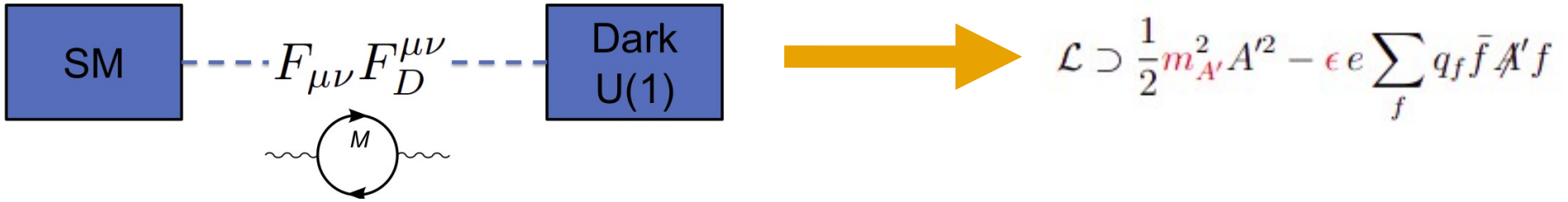
- Forward direction: lots of activity down the beam pipe
- Far-forward detectors:
  - well-screened from pp collisions
  - only neutrinos and muons survive
- **Current Run 3**: FASER, SND@LHC
- **HL-LHC**: proposed Forward Physics Facility (FPF)
- Physics:
  - "Precision" high-energy neutrino physics
  - Implications for QCD & cosmic-ray physics
  - New physics searches

FASER, 2207.11427

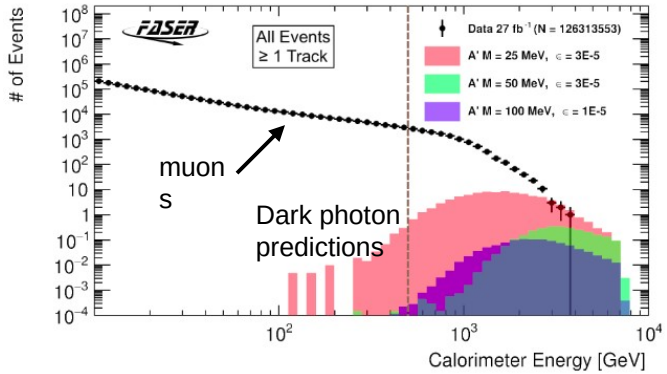


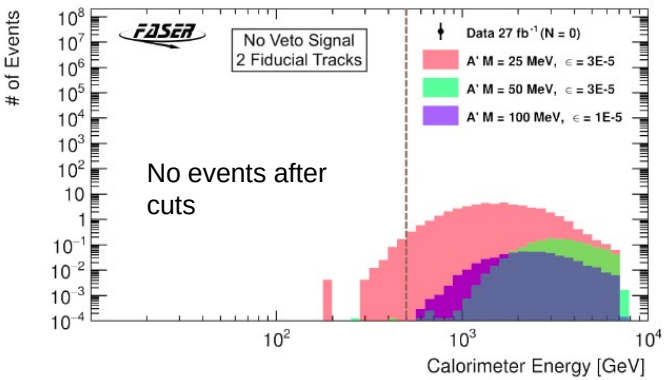
DARK PHOTONS @ FASER

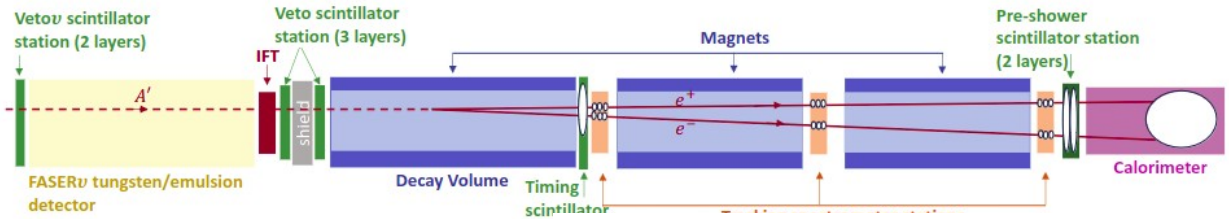
- New light (~sub-GeV) vector secluded from the SM, coupled via kinetic mixing
  (can be induced by heavy new fields at the loop level charged under both U(1) and $U(1)_D$)



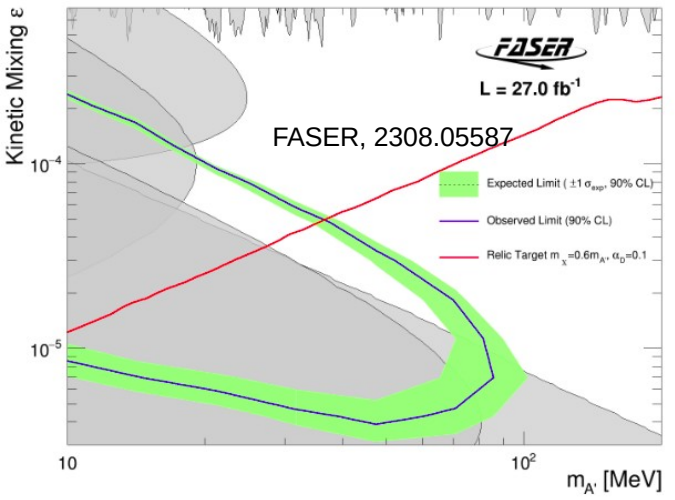
- Suppressed couplings to SM fermions, A' can decay into, e.g., e+e- pairs





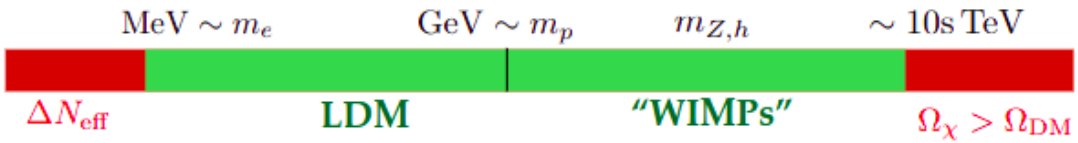


Dark photon bounds



DARK MATTER SEARCHES

LIGHT DARK MATTER SEARCH



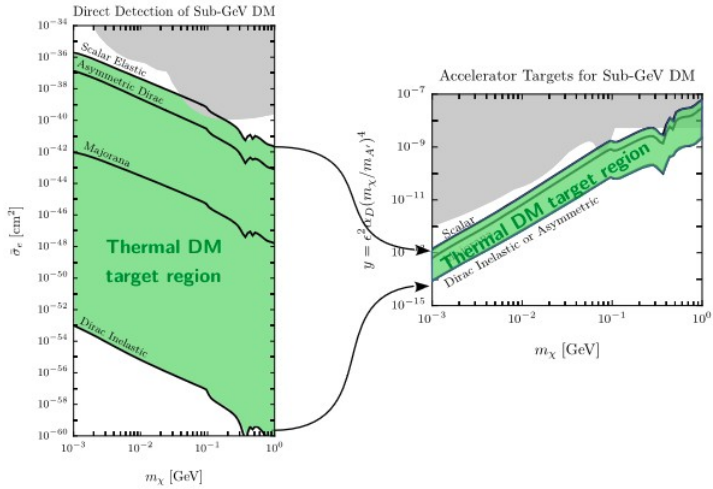
- Probing thermal DM target

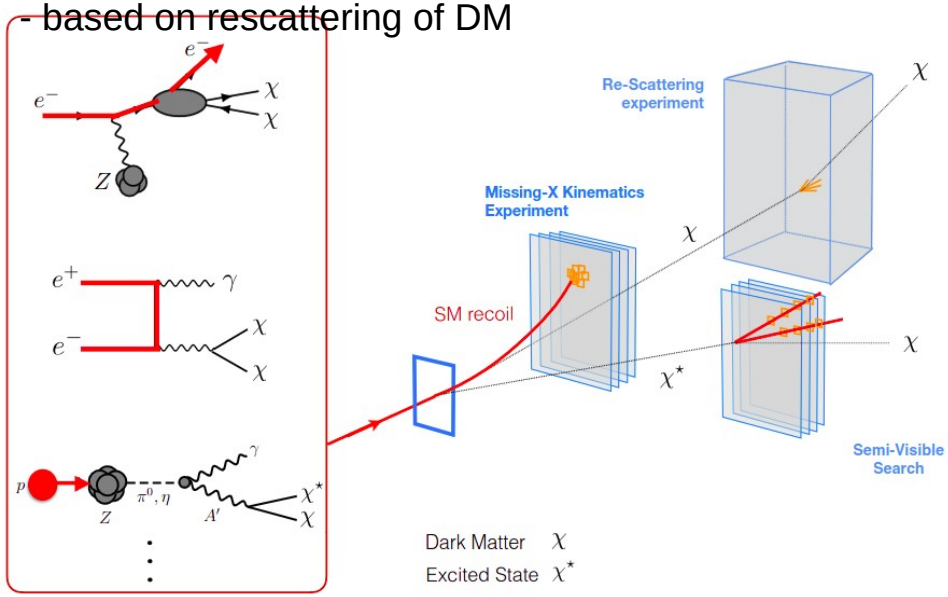
- In the relativistic regime, life becomes easier…

- Various detection strategies proposed

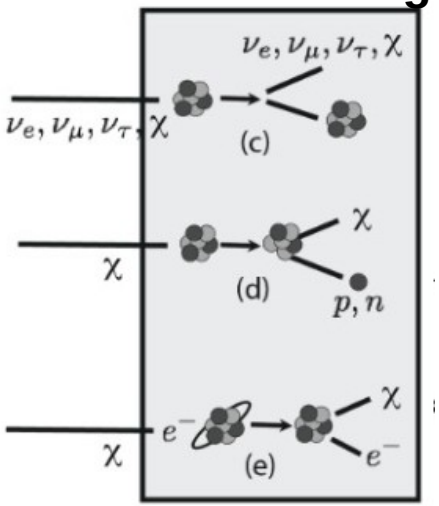
- based on missing momentum, energy, mass
- based on rescattering of DM

Snowmass 2021, G. Krnjaic, etal, 2207.00597



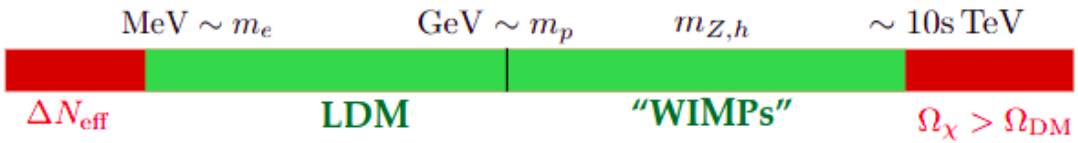


DM rescattering

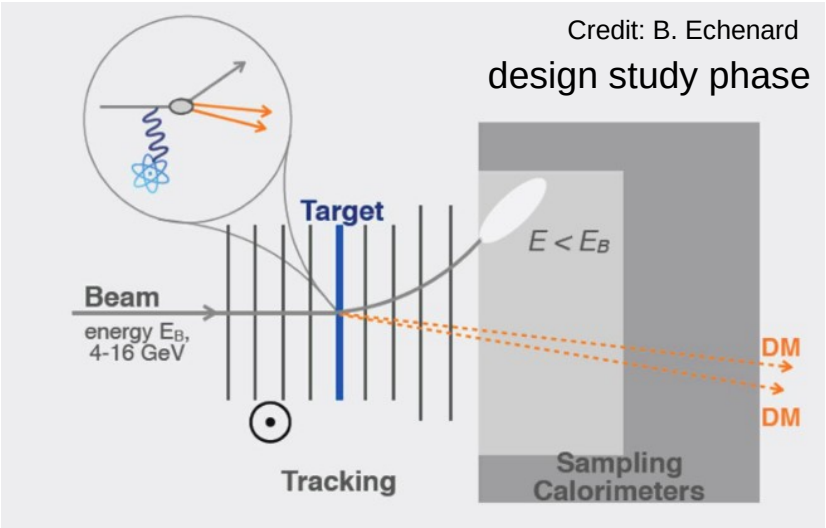


T. Åkesson, etal (LDMX), 1808.05219
A. Berlin, etal, 1807.01730

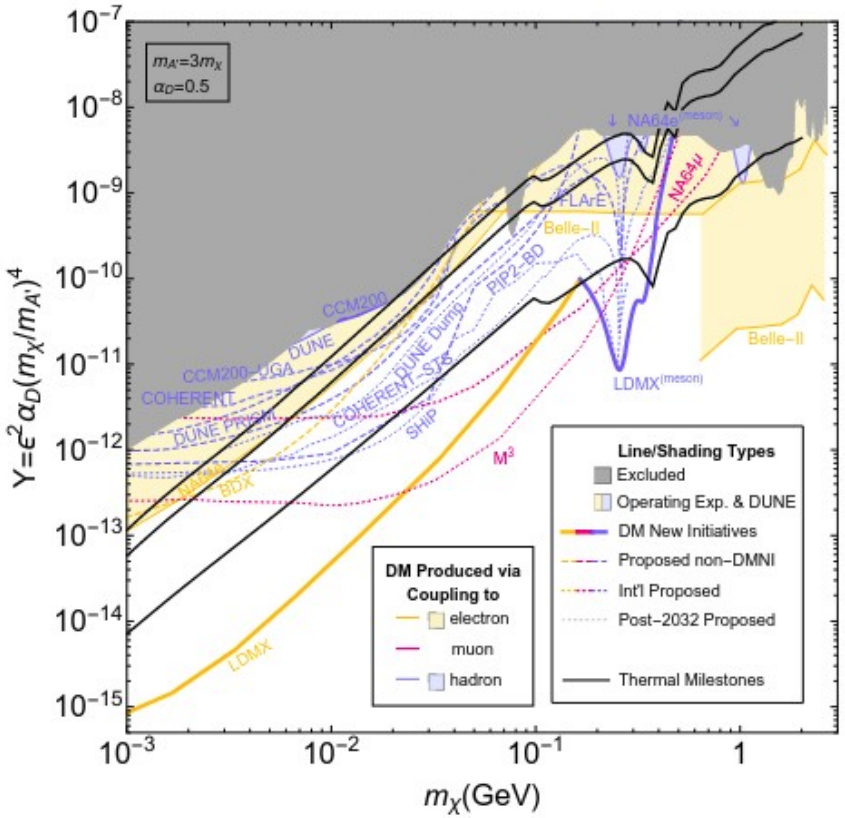
LDMX



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

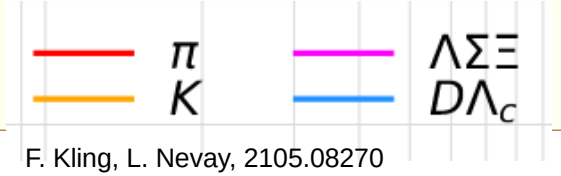


Snowmass 2021, G. Krnjaic, etal, 2207.00597



FORWARD NEUTRINOS
(at LHC & FCC-hh)

CONSTRAINING NEUTRINO FLUXES



F. Kling, L. Nevay, 2105.08270

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

F. Kling, T. Makela, ST, 2309.10417

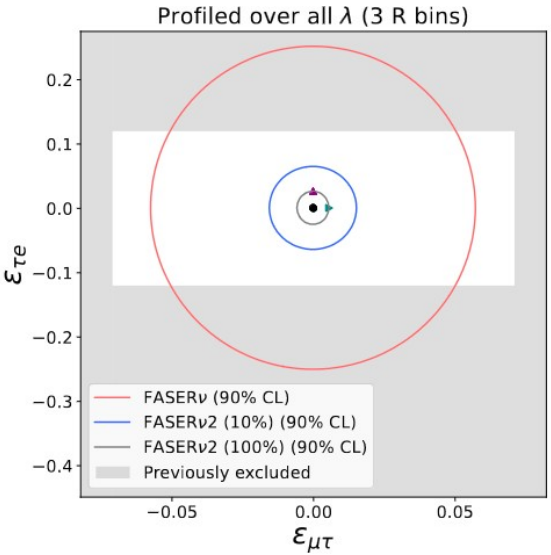
  - energy spectrum & pseudurapidity (differential prod. σ)

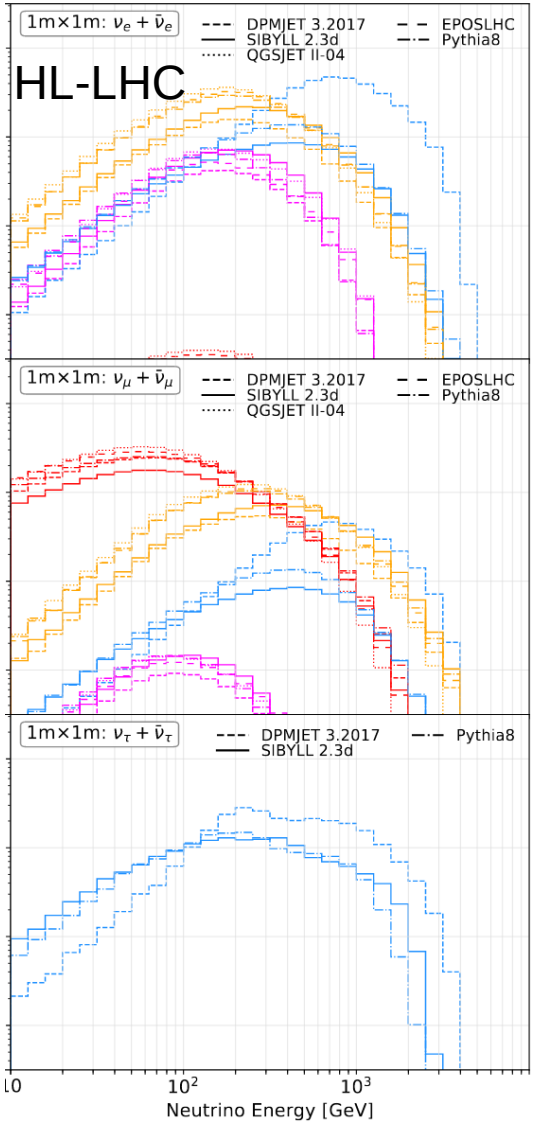
- Variations in parent meson spectra → correlations in ν spectra

- New physics can be searched for if correlations are broken

Effective right-handed operators

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

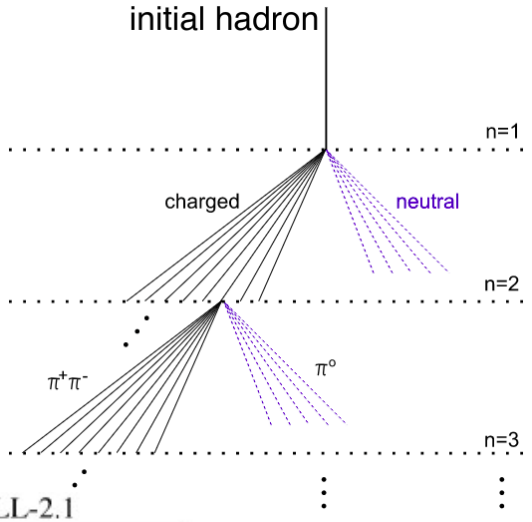


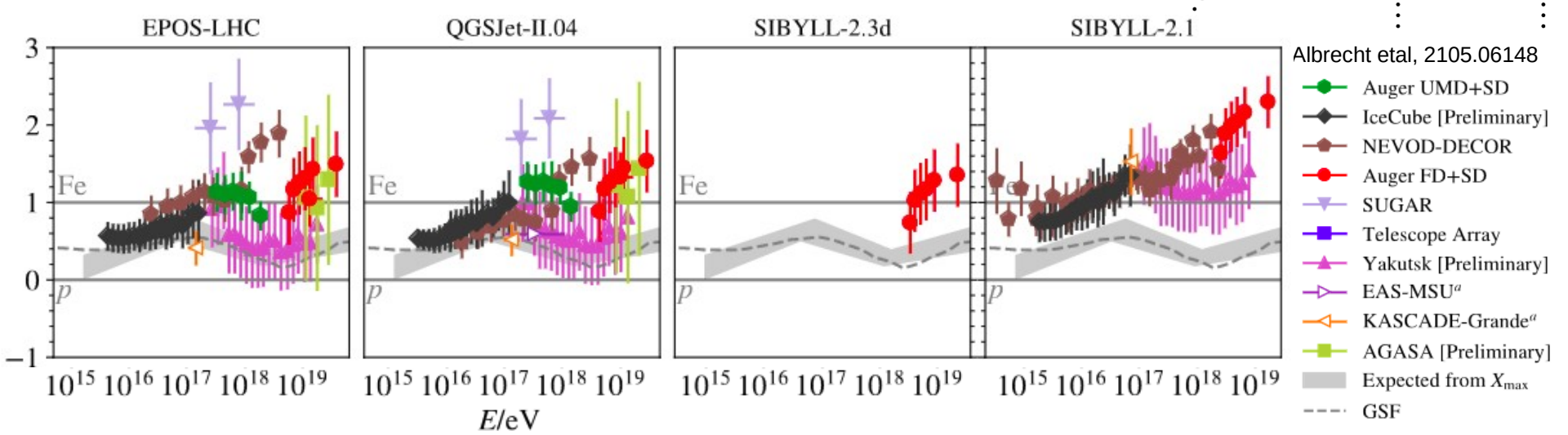


COSMIC-RAY MUON PUZZLE

- 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





L.A. Anchordoqui etal, 2202.03095

MUON PUZZLE & FPF@LHC

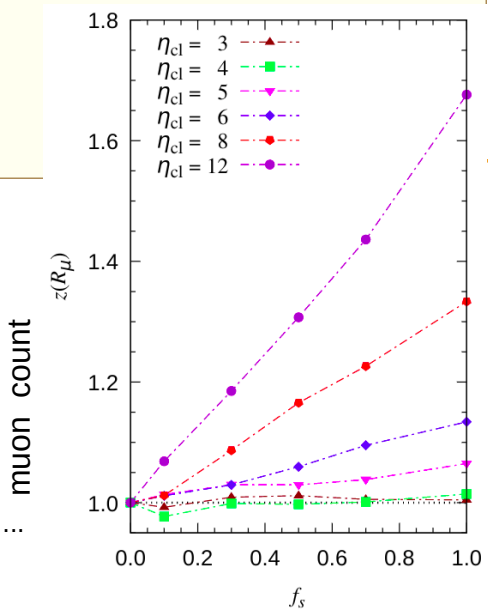
- Possible explanation: enhanced strangeness, K/π ratio ↑
- Might be motivated by ALICE mid-rapidity data…

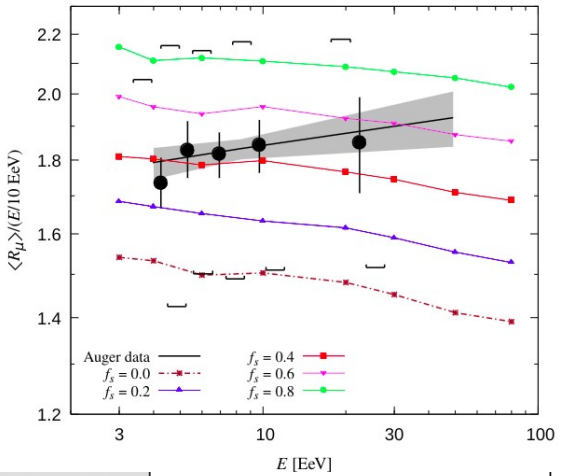
P. Palni (for ALICE), 1904.00005

- Simple modeling – introduce K → π swapping probability $0 < f_s < 1$
- Underlying physics might be related to QGP formation, strange fireballs,...

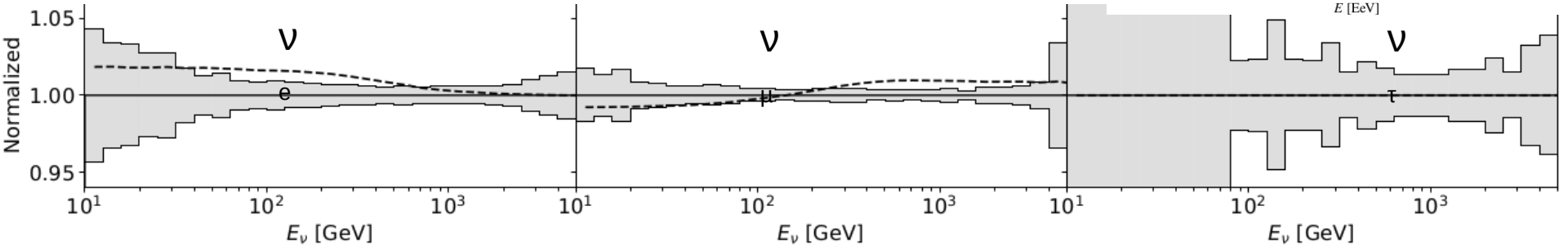
L. A. Anchordoqui etal, 1907.09816; 1612.07328; ...

- 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**



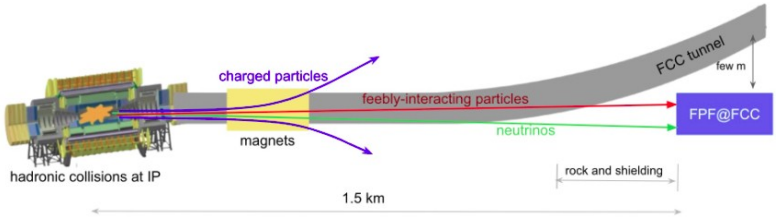


F. Kling, T. Makela, ST, 2309.10417



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
- 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