PASCOS 2023

BSM PHYSICS
IN THE FAR-FORWARD REGION
OF THE LHC

NATIONAL CENTRE FOR NUCLEAR RESEARCH ŚWIERK

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PASCOS 2023
UC Irvine

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Whitepapers:
J.L. Feng, F. Kling, M.H. Reno, J. Rojo, D. Soldin etal, 2203.05090
L.A. Anchordoqui etal, 2109.10905
+ many other papers

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952480
Dark Wave
European Funds Smart Growth
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FNP Foundation for Polish Science
European Union European Regional Development Fund
NATIONAL SCIENCE CENTRE POLAND

IT ALL STARTED AT UCI…

PHYSICAL REVIEW D **97,** 035001 (2018)

ForwArd Search ExpeRiment at the LHC

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(Received 13 October 2017; published 5 February 2018)

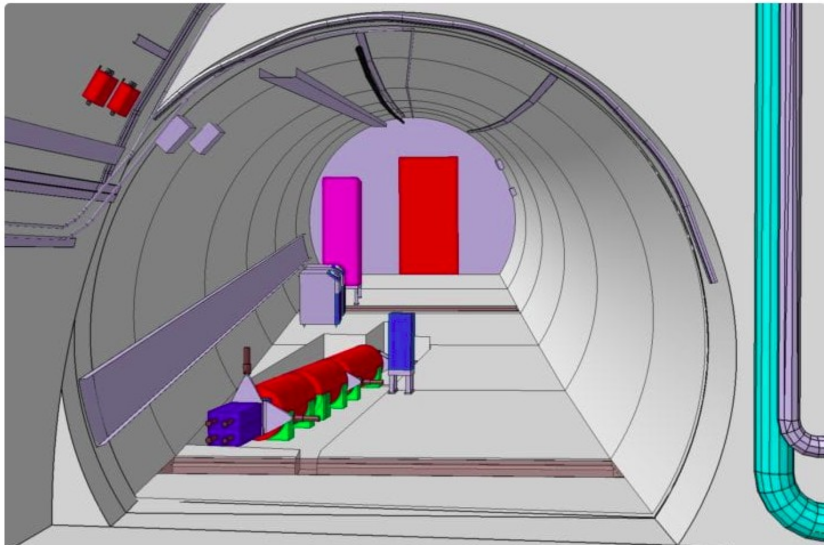
November 28, 2017

UCI physics debuts in prime time

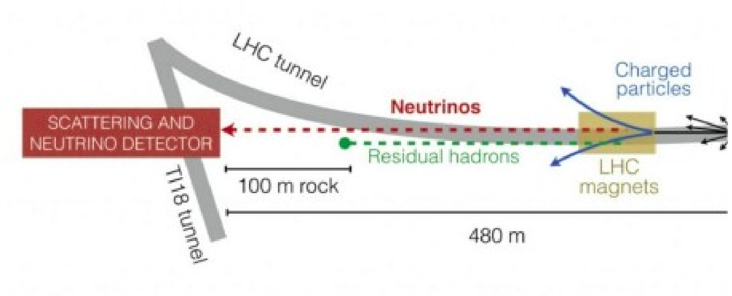
March 5, 2019

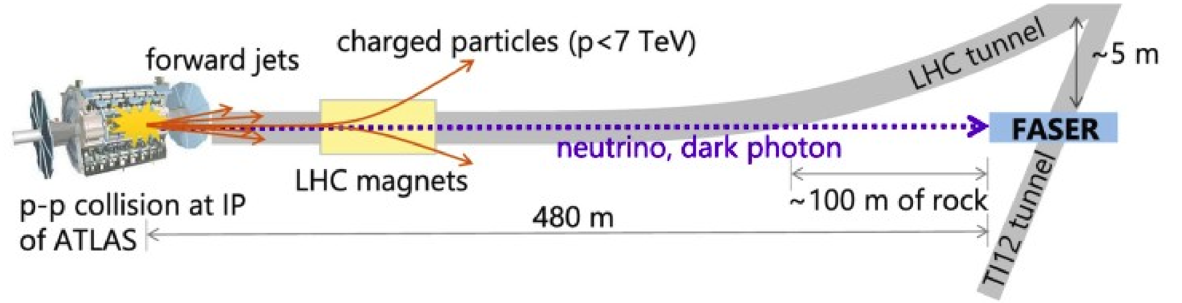
CERN approves UCI-initiated hunt for new particles at the Large Hadron Collider

FASER detector will seek clues pointing to hidden matter in the universe

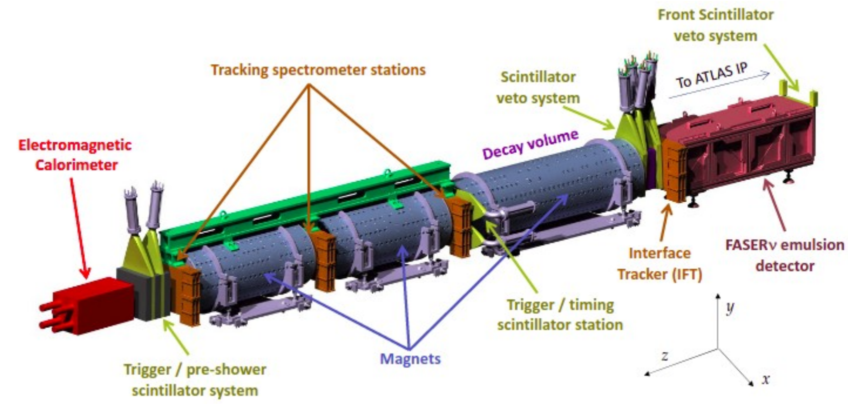


FAR-FORWARD SEARCHES AT THE LHC



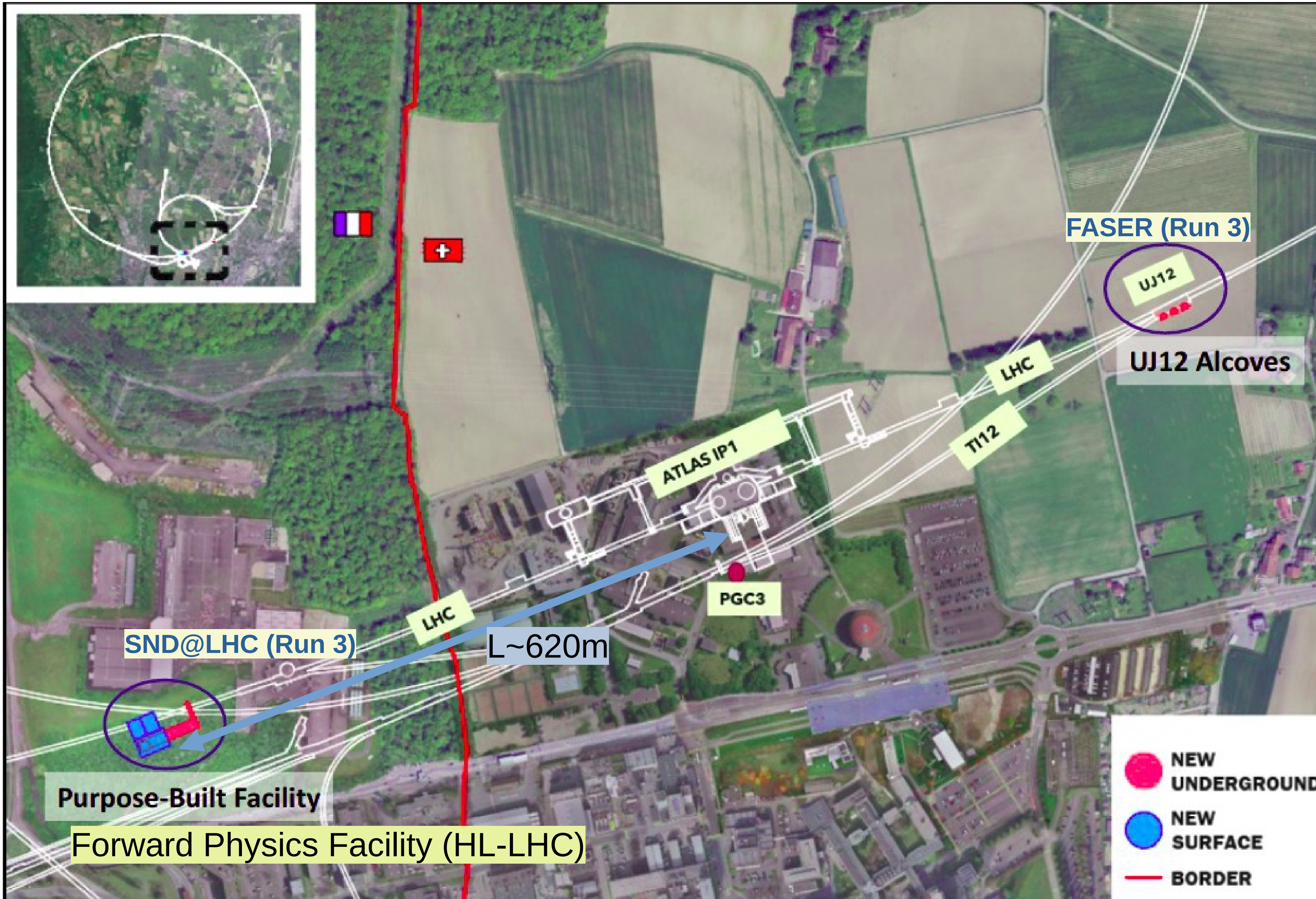


FASER, 2207.11427



- 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

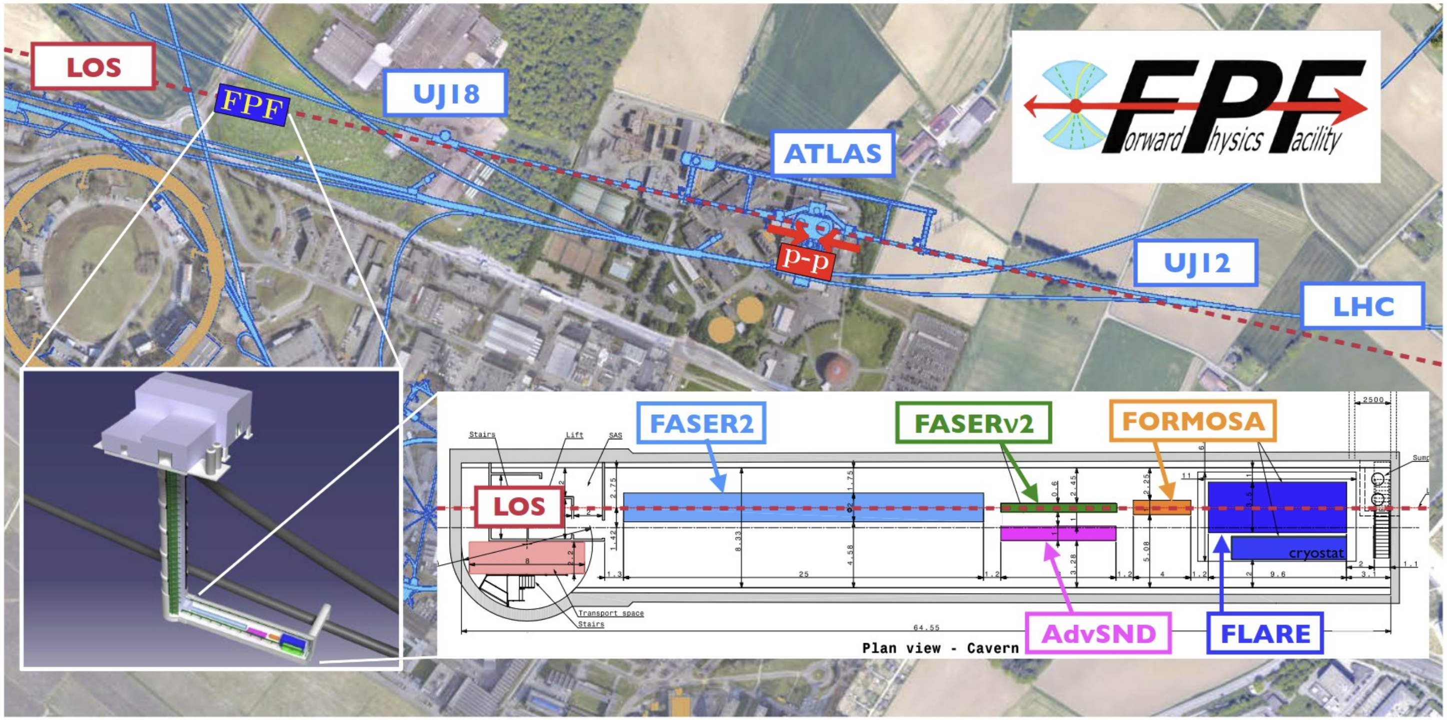
Far-forward searches at the LHC in a bird's eye view



FORWARD PHYSICS FACILITY (FPF)

Underground facility:

- ~620 m far forward from the ATLAS IP,
- shielded by ~200 m concrete and rock.
- several experiments proposed (signatures: scattering, decay, ionization)
- up to ~1M neutrino events (of order 10k ν_τ CC events)
- Main whitepapers: 2109.10905, 2203.05090
- Summary for P5 US fuding process, Recent technical update CERN-PBC-Notes-2023-002



STATUS

- FASER/FASERν and SND@LHC experiments are taking data

- Forward Physics Facility (FPF)
  - Experiments: largely based on existing collaborations (FASER, SND@LHC, MilliQan)
  - New ideas: **F**orward **L**iquid **Ar**gon **E**xperiment (**FLArE**) – BNL (lead), UCI, …
    FORward **M**icr**O**charge **S**e**A**rch (**FORMOSA**) – milliQan-based

- The U.S. Snowmass process – endorsed in several frontiers

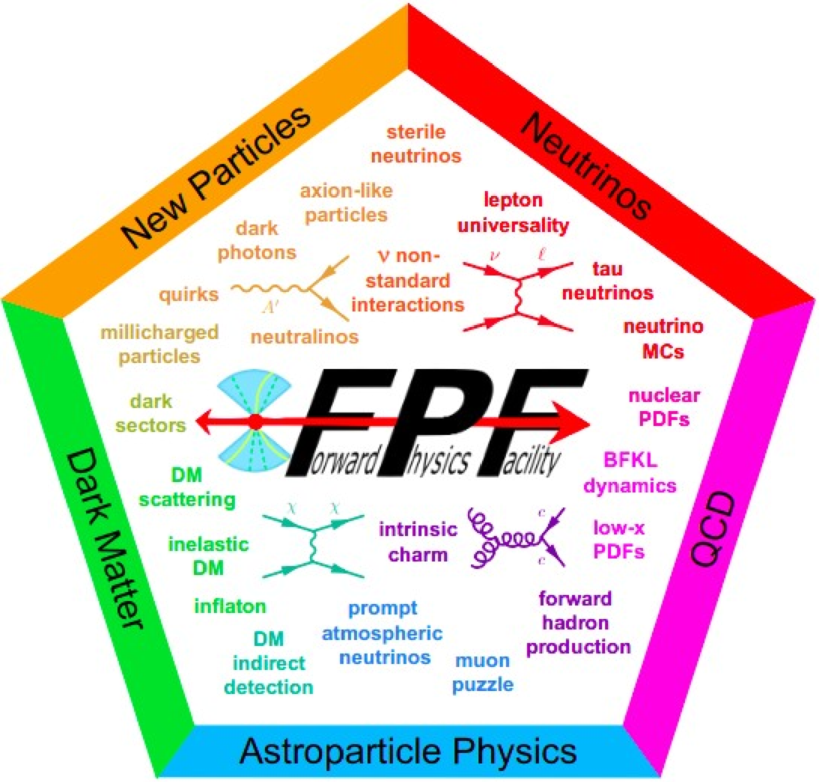
Energy Frontier, 2211.11084

In conclusion, our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions uncovered by the detector upgrades.

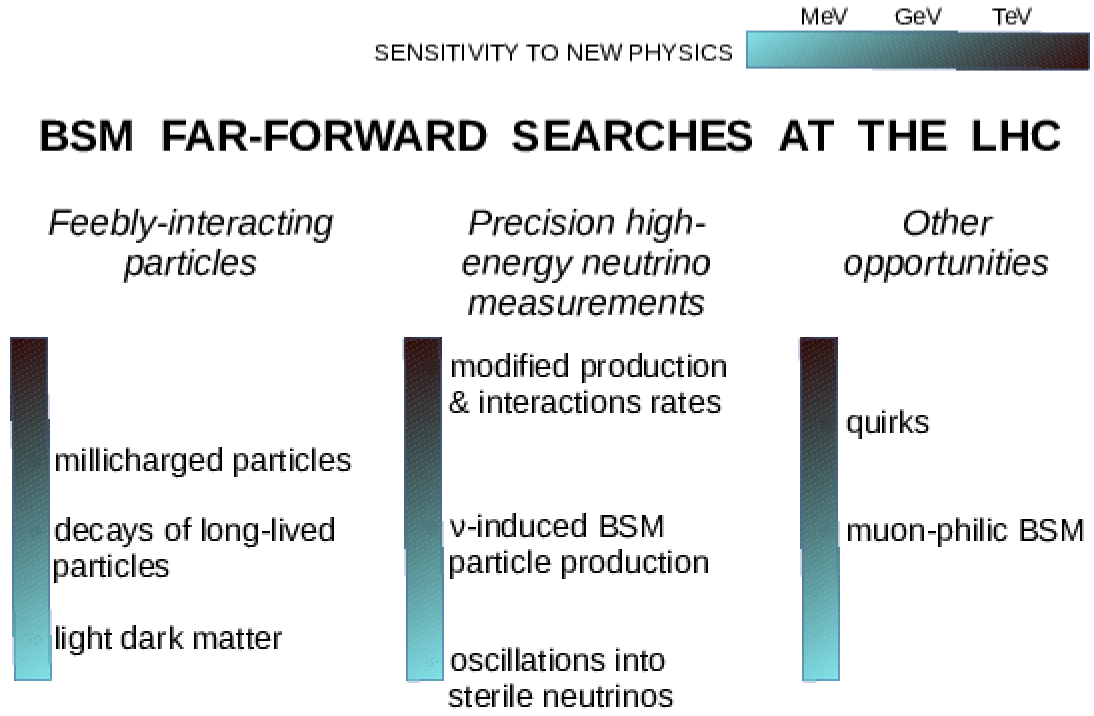
- CERN:
  - Large progress in facility planning & first site investigation
  - Extensive simulations (CERN FLUKA team); BG and radiation safety, muons

- Organization
  - Facility & experiments (Run 3 is running, HL-LHC: design)
  - 6th FPF workshop, June 8-9th **(link)**
  - Physics – working groups (neutrino/QCD, BSM)

FAR-FORWARD PHYSICS



FPF whitepaper, 2203.05090

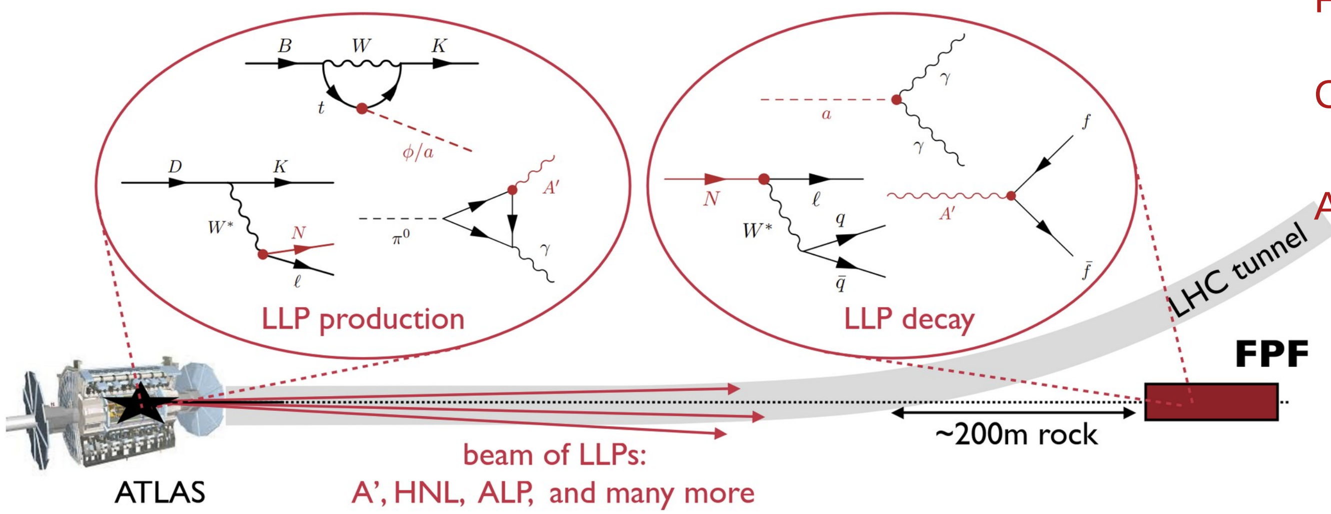


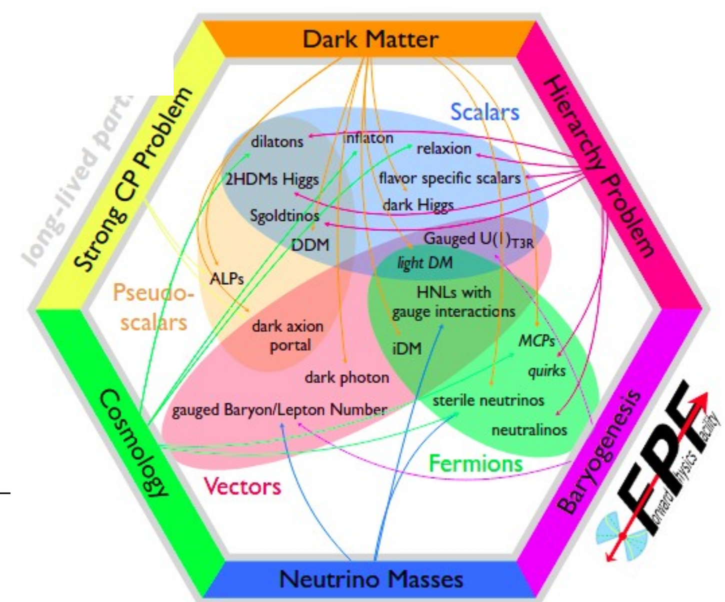
ST, 2305.04663

LIGHT LONG-LIVED PARTICLES

First FASER results
→ Dave
Casper

Also talks →
→ Shufang Su
Max Fieg

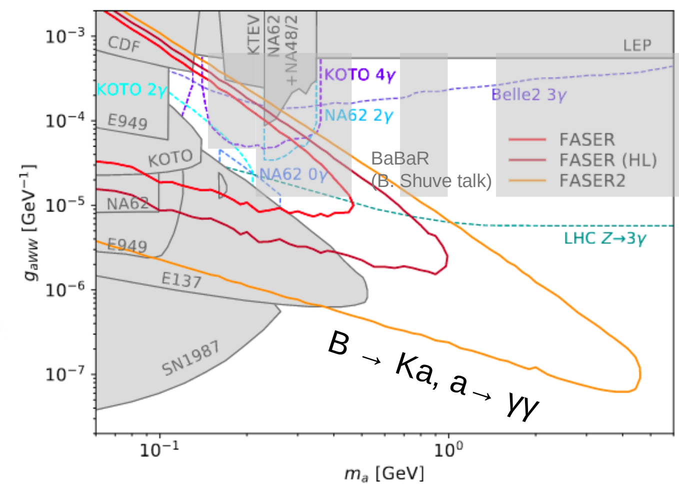




Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$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

LIGHT LONG-LIVED PARTICLES @ FPF

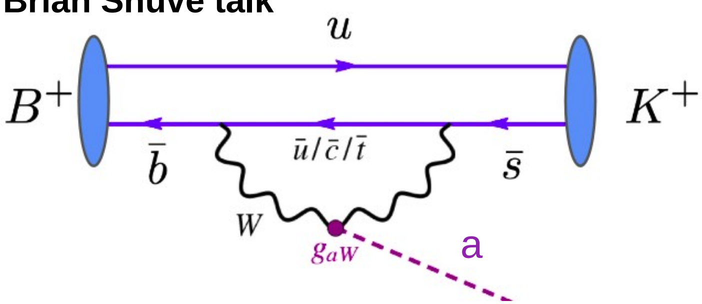
F. Kling, ST, 2006.10630



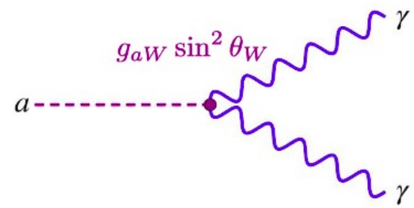
Large LHC energies:

- BSM species with the **mass up to tens of GeV** can be forward-focused

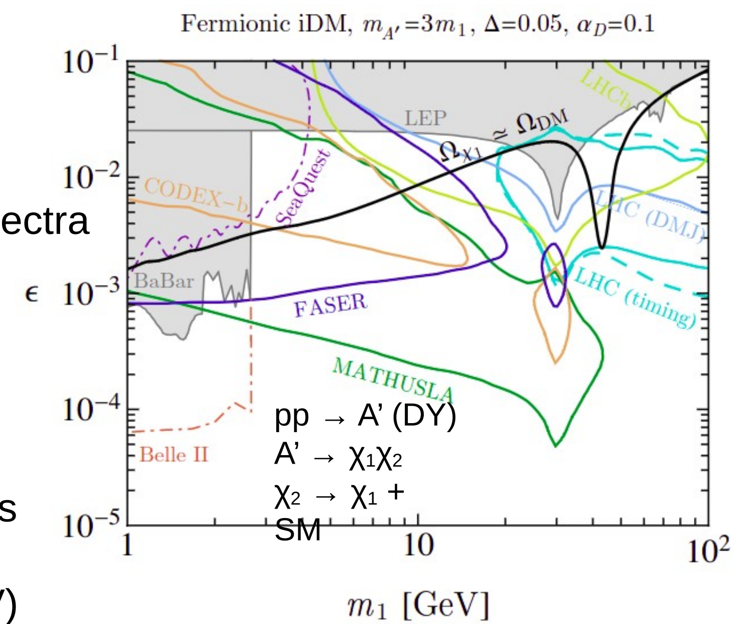
Brian Shuve talk



$$\mathcal{L} = -\frac{g_{aW}}{4} a\, W_{\mu\nu}\tilde{W}^{\mu\nu}$$



A. Berlin, F. Kling, 1810.01879



- Large boost factors:
  - – reach distant detectors before decaying
  - – enhanced signals in semi-visible decays with compressed spectra

K.R. Dienes etal, 2301.05252

- FPF detectors:
  - – larger transverse area than (current) FASER helps to catch heavier BSM species
  - – various detectors, possible low-energy thresholds (sub-GeV)

MILLICHARGED PARTICLES AT FPF

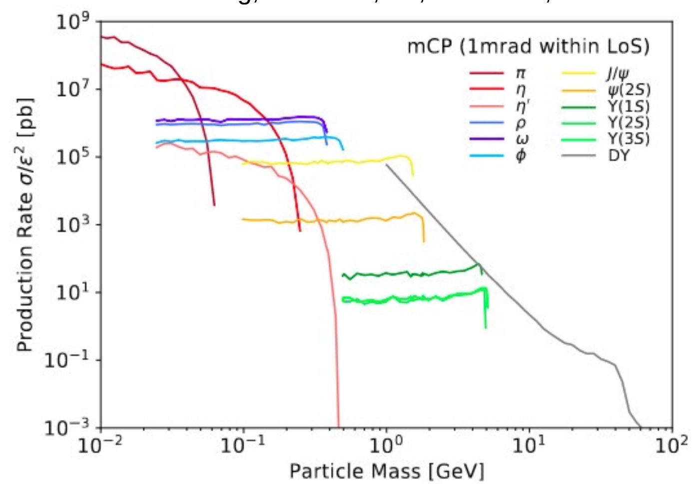
● milliQan-like detector placed in the FPF

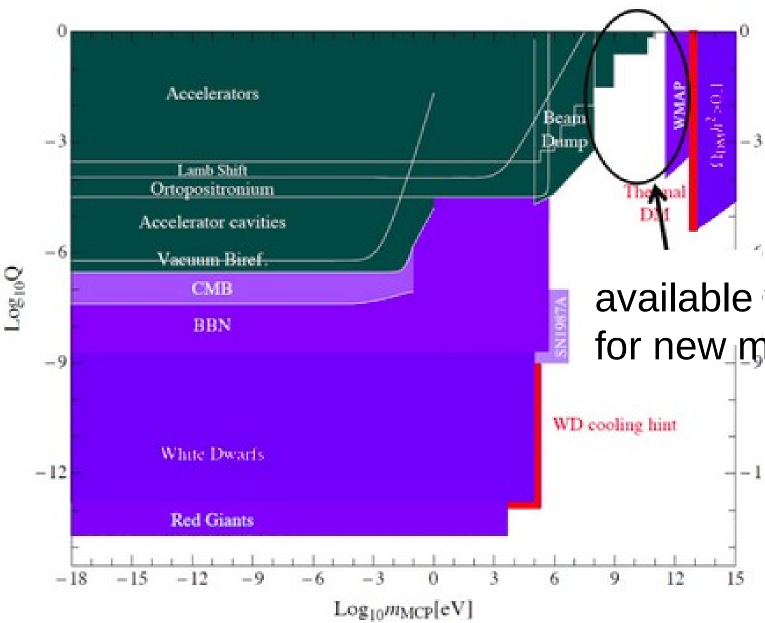
FORMOSA – **FOR**WARD **M**ICR**O**CHARGE **S**E**A**RCH

Sensitive to small energy depositions dE/dx
of a particle with Q<0.1 e; plastic scintillator for detection

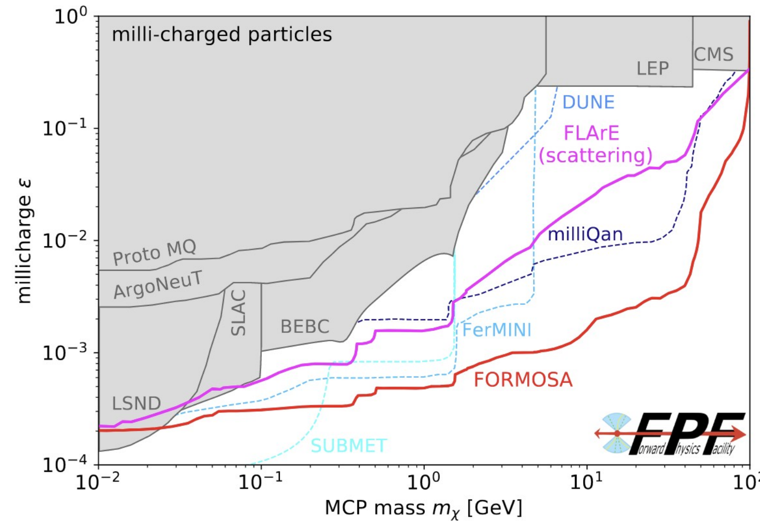
● leading projected bounds for m ~< 100 GeV
● complementary signature at FLArE scattering a-la-DM

F. Kling, J.-L. Kuo, ST, Y.-D. Tsai, 2205.09137





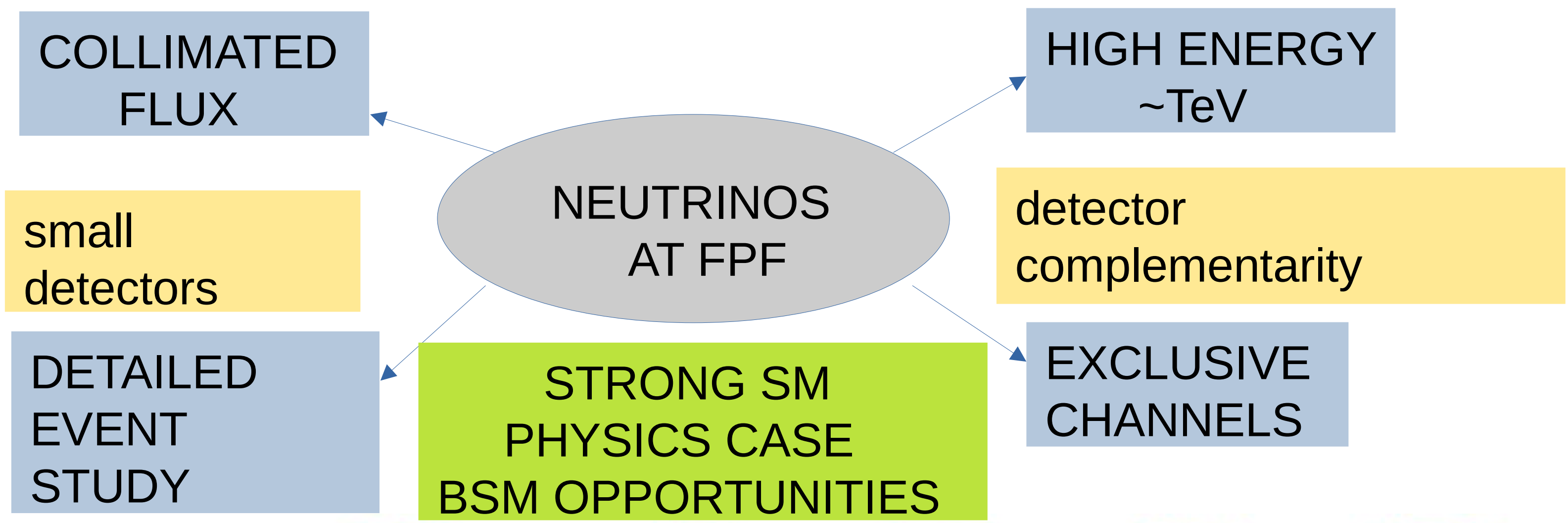
available window
for new millicharged particles



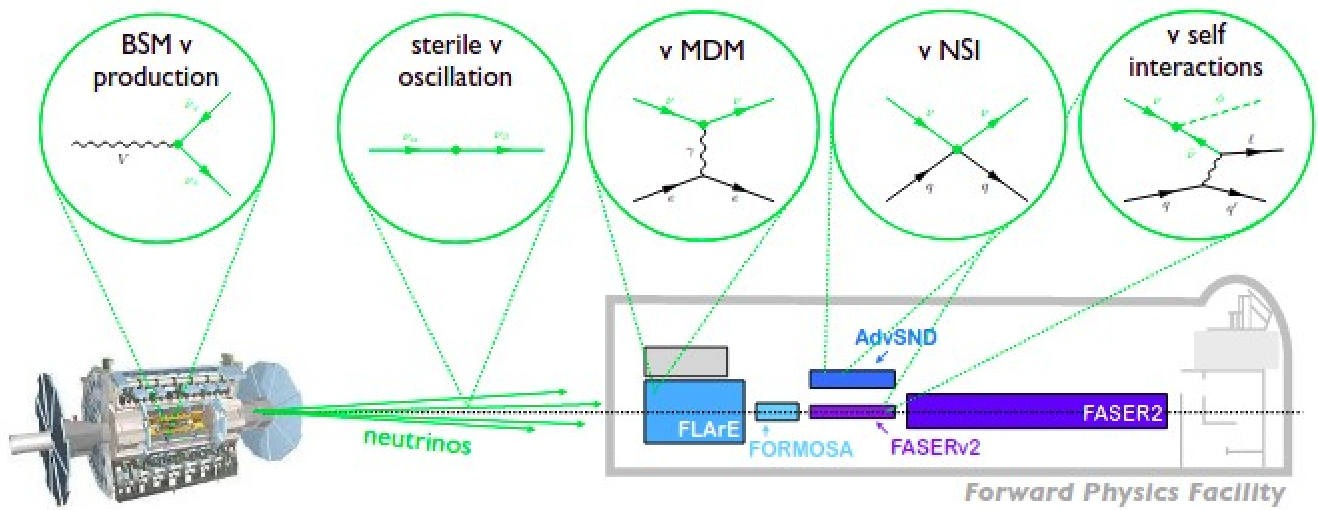
NEUTRINO PHYSICS PROGRAM

Forward LHC Neutrinos

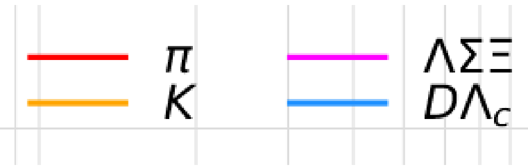
High-energy neutrinos at the LHC are preferentially produced in the forward direction



Neutrino BSM effects:
- Production rates
- Propagation (oscillations)
- Interaction rates
  (different channels)
- Event characteristics



FORWARD NEUTRINOS

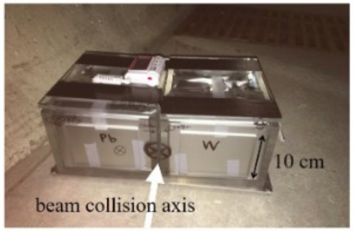


- Production: different meson decays dominate depending on the neutrino flavor and energy

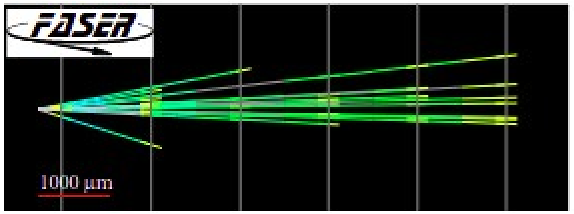
- Detection: expected CC event rates (FPF)

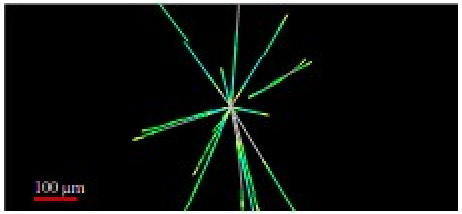
~10^6 ν_μ, few x 10^5 ν_e, ~(10^3-10^4) ν_τ

- Extremely collimated flux of neutrinos



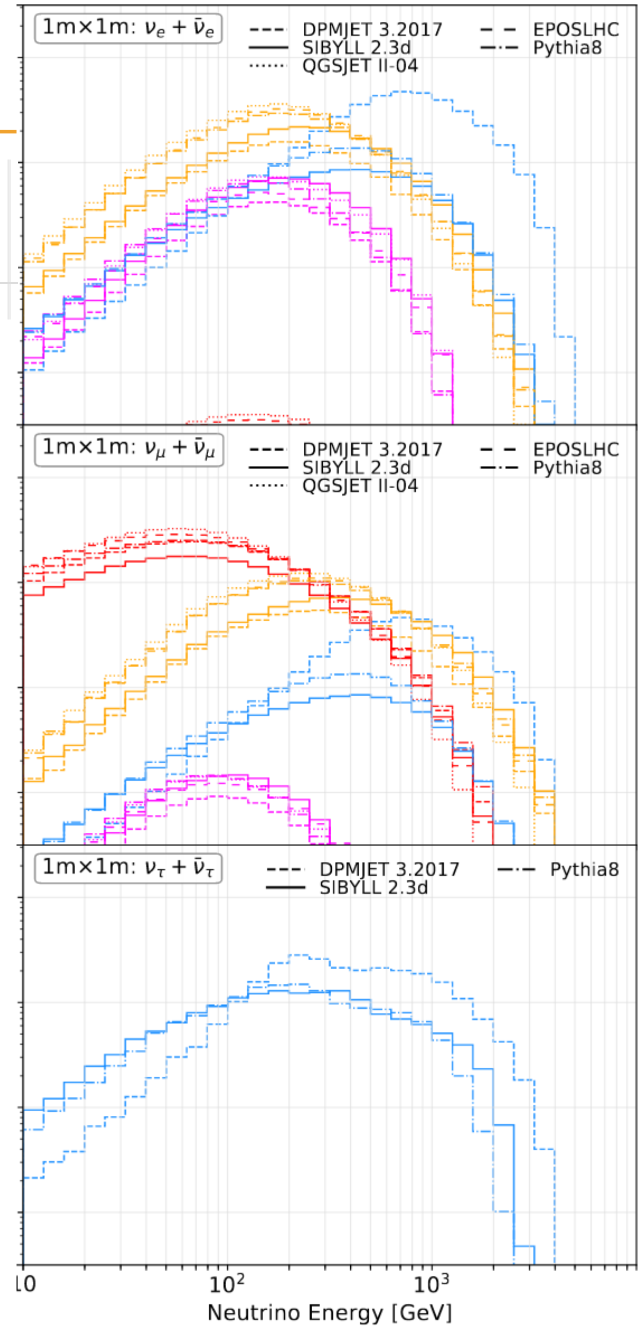
FASER, Phys.Rev.D 104 (2021) 9, L091101





First FASER ν observations

→ Dave Casper



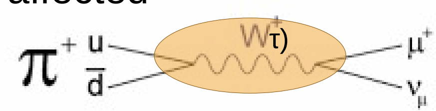
NEUTRINO NSI – CHARGED CURRENT

- Effective description Weak Effective Field Theory (WEFT), obtained from SMEFT below EWPT
- W, Z, H, t integrated out; WEFT Wilson coefficients to be matched onto SMEFT parameters at $\mu \sim m_W$
- $[\epsilon_X^{ud}]_{\alpha\beta}$ coefficients: X = L,R,S,P,T Lorentz structure; α – charged lepton, β – neutrino of different flavors

$$\mathcal{L}_{\rm WEFT} \supset -\frac{2V_{jk}}{v^2}\Big\{[\mathbf{1}+\epsilon_L^{jk}]_{\alpha\beta}(\bar{u}^j\gamma^\mu P_L d^k)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta) + [\epsilon_R^{jk}]_{\alpha\beta}(\bar{u}^j\gamma^\mu P_R d^k)(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)$$
$$+\frac{1}{2}[\epsilon_S^{jk}]_{\alpha\beta}(\bar{u}^j d^k)(\bar{\ell}_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P^{jk}]_{\alpha\beta}(\bar{u}^j\gamma_5 d^k)(\bar{\ell}_\alpha P_L\nu_\beta)$$
$$+\frac{1}{4}[\epsilon_T^{jk}]_{\alpha\beta}(\bar{u}^j\sigma^{\mu\nu}P_L d^k)(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{h.c.}\Big\}.$$

- Both production and detection probability for different neutrino flavors can be affected

$[\varepsilon_X^{ud}]_{\mu(e/\mu/\tau)}$



- Example: BSM contributions to $\pi^+ \to \ell_\alpha^+ \nu$; decays
- Constrained by $\Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$ & individual decay widths
- Measured values might already be contaminated by NSI – compare with “theory” predictions
- Also, bounds can also be significantly weakened by tuning different Wilson coefficients

→ **essential to detect the outgoing neutrino flavor**

- Neutrino detection rate can also be modified in CC DIS, e.g., ν_μ N → (e/μ/τ) N* $[\varepsilon_X^{ud}]_{(e/\mu/\tau)\mu}$

NEUTRINO NSI AT FPF

Characteristic for the FPF neutrino physics:

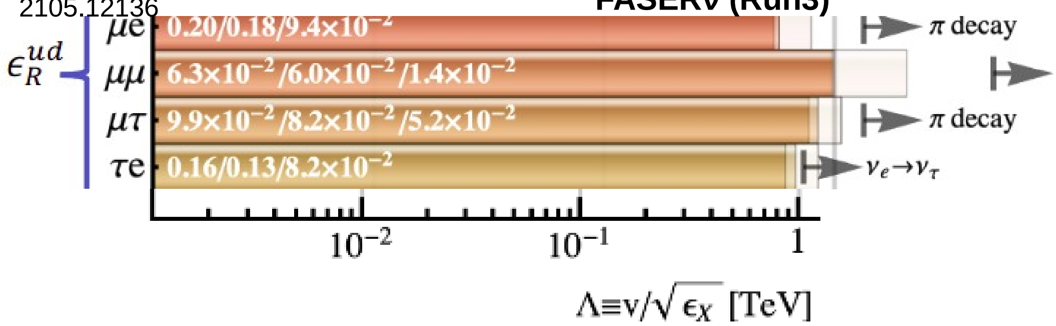
non-negligible ν_τ flux from charm, not affected by (SM) oscillations & measured directly

- Forward charm production affects ν_τ and high-energy ν_e; can be distinguished from neutrino NSI

- Example neutrino CC NSI analyses:

Combine energy and flavor information for all the ν data

A. Falkowski etal, 2105.12136

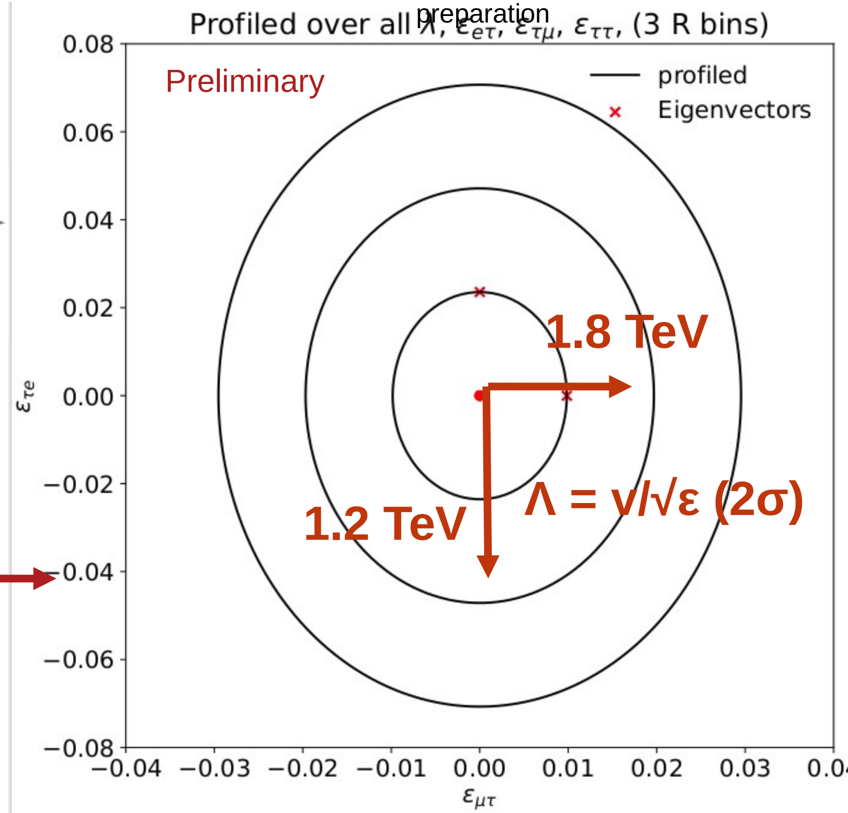


Additionally consider spatial distribution (radial)

Cramer-Rao bound based on information matrix (**FPF**)

Consider several operators simultaneously

F. Kling, T. Makela, ST, in preparation



- Neutrino NSI based on NC interactions in the FPF has also been studied

A. Ismail, R.M. Abraham, F. Kling, 2012.10500

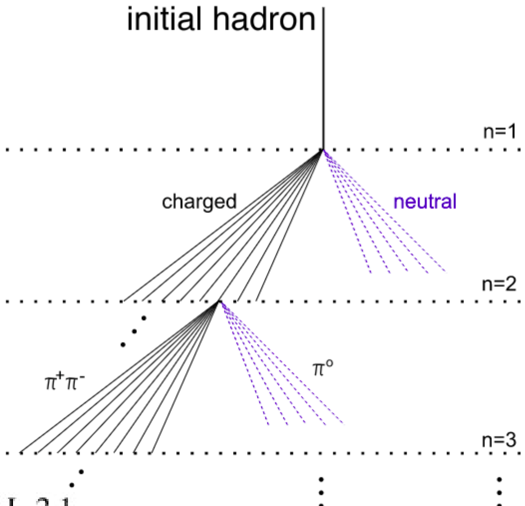
COSMIC-RAY MUON PUZZLE

- 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

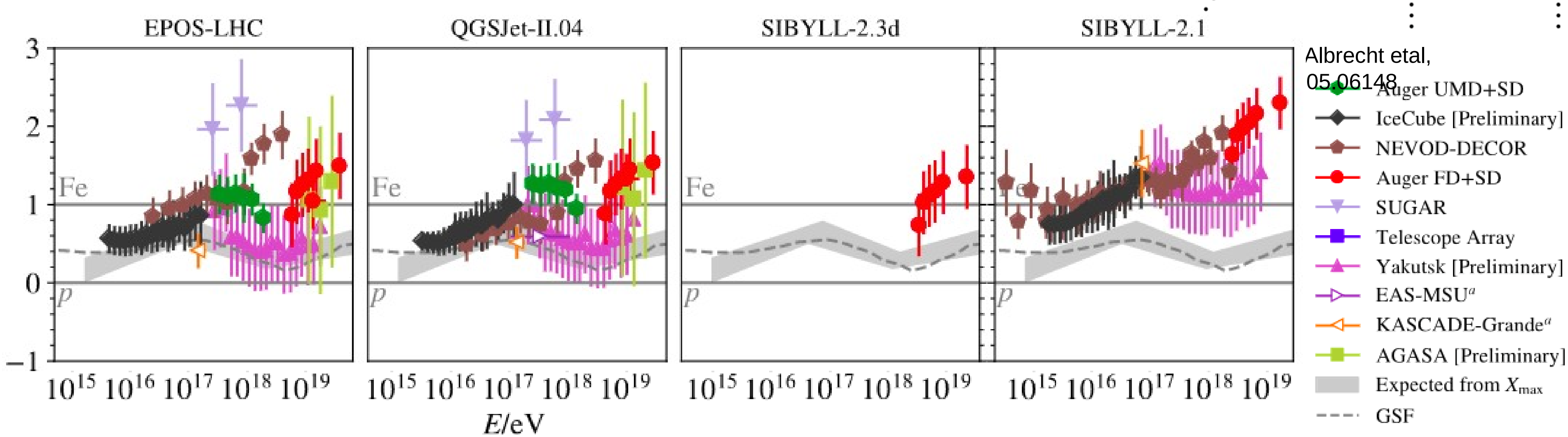
J.D. Allen, G.R. Farrar, 1307.7131



- 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

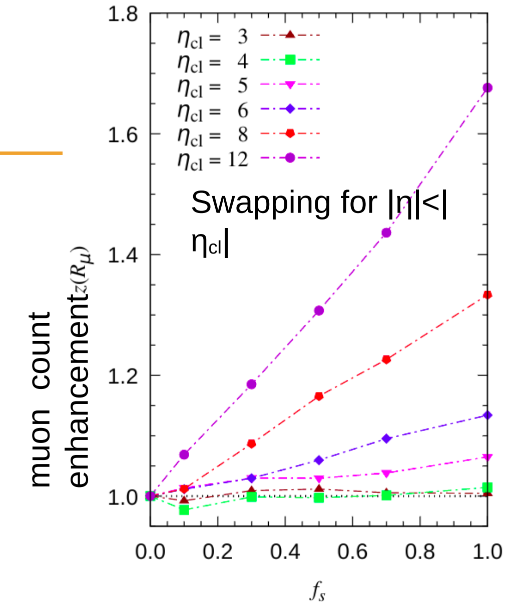


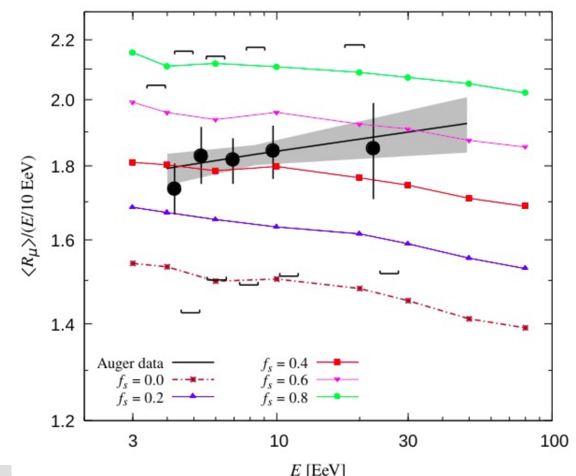
Albrecht etal, 05.06148

MUON PUZZLE & FPF

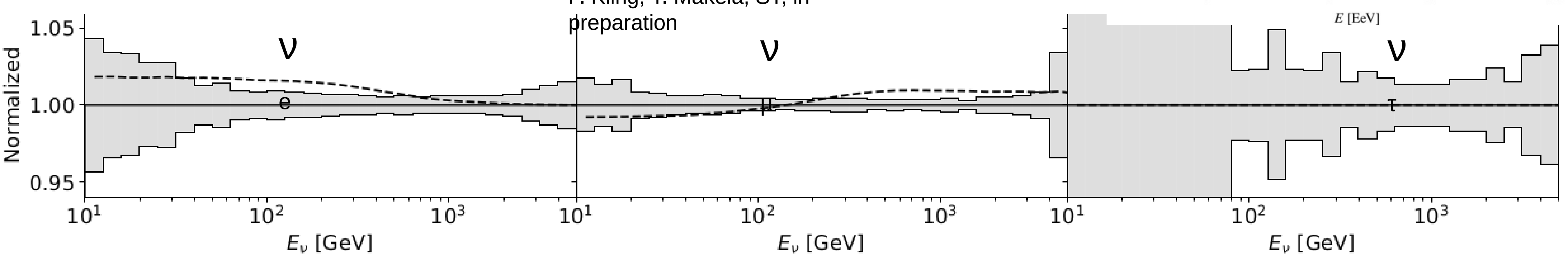
- Possible explanation: enhanced strangeness, K/π ratio ↑
- Might be motivated by ALICE mid-rapidity data… P. Palni (for ALICE), 1904.00005
- Simple modeling – introduce K → π swapping probability $0 < f_s < 1$
- Underlying physics might be related to QGP formation, strange fireballs,... L. A. Anchordoqui 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 bounds f_s < 0.01**

L.A. Anchordoqui etal, 2202.03095





F. Kling, T. Makela, ST, in preparation

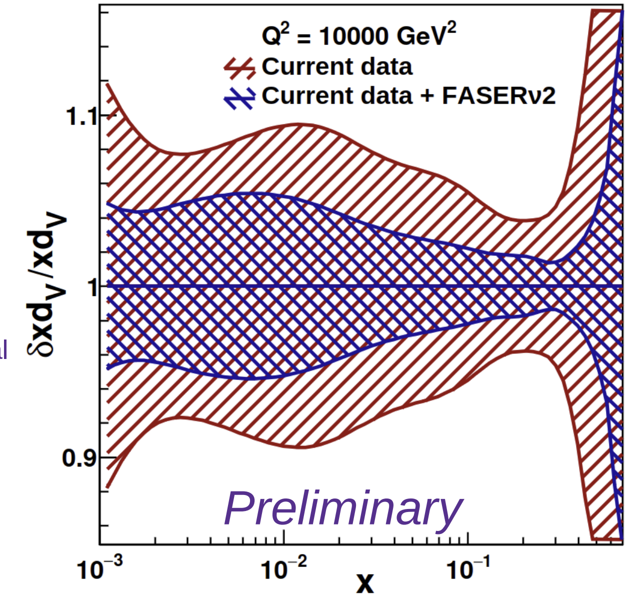


NEUTRINO “SM” PHYSICS AT FPF

- PDF measurements

– high-energy νs → extended kinematic coverage

– possible measurements for various nuclear targets (Ar, W)

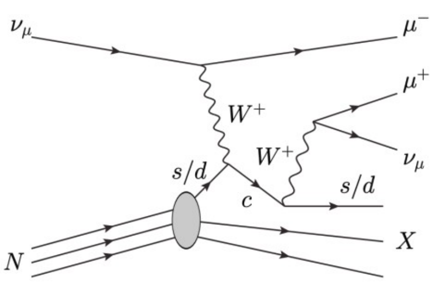


Projected impact on down quark valence PDF from the PDF4LHC21 set

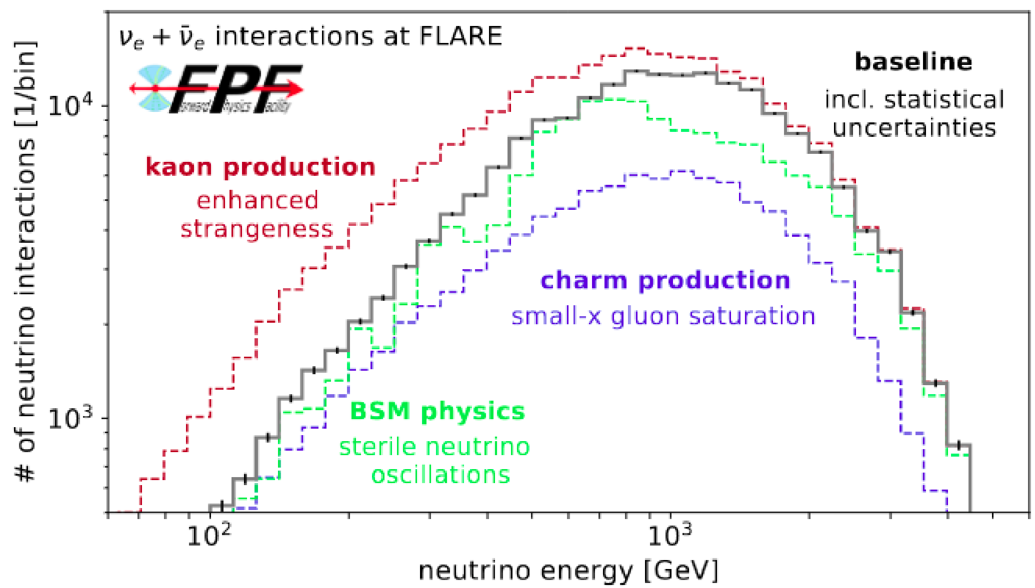
FPF WG1, J. Rojo etal

- Forward charm production (determines ν_τ flux & spectrum at FPF)
  - – currently largest uncertainties
  - – sensitive to gluon saturation, intrinsic charm,...

- Potential to study exclusive processes
  - – charm tagging for ν-induced di-muons (strange PDFs)



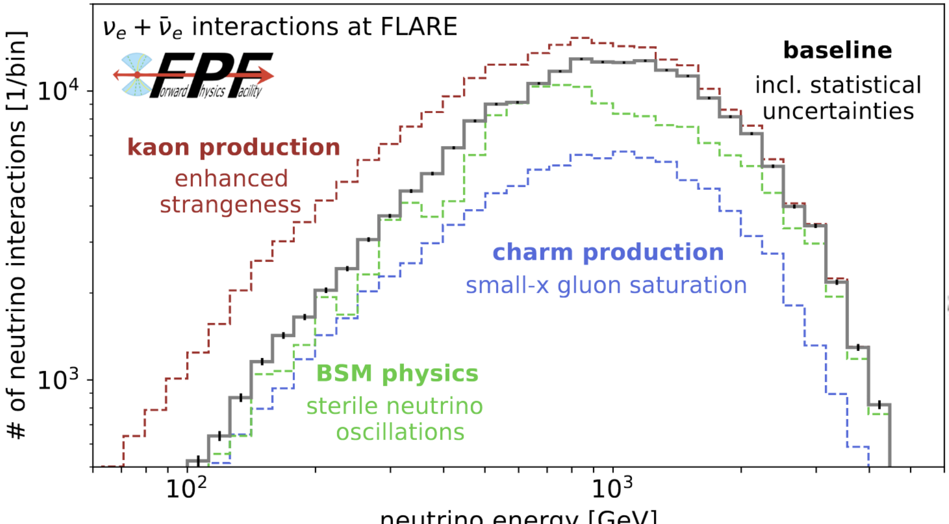
  - – neutrino tridents,...

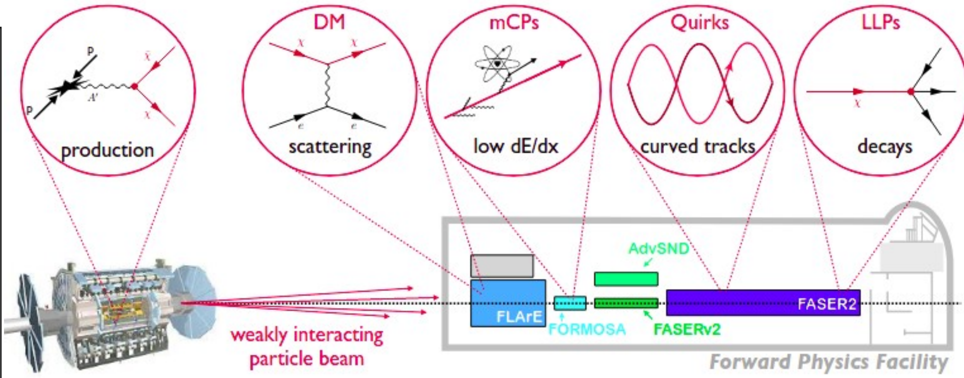


SUMMARY OF FAR-FORWARD LHC PHYSICS PROGRAM

νN collisions	pp collisions	μN collisions	NEW PHYSICS

- For BSM and neutrino physics, the program started with Run 3 **FASER(ν), SND@LHC**
- For HL-LHC: proposed extension **Forward Physics Facility**
- High-energy neutrino physics, connections to QCD & cosmic-rays, BSM
- Tool for BSM simulations: FORESEE F. Kling, ST, 2105.07077





THANK YOU !

BACKUP

FPF BSM WORKING GROUP

FPF physics working groups (+ different groups for facility and experiments)

WG1 – Neutrino Interactions (Leader: Juan Rojo)
WG2 – Forward Charm Production (Hallsie Reno)
WG3 – Light Hadron Production (Luis Anchordoqui, Dennis Soldin)
WG4 – BSM physics (Brian Batell, ST)

WG4 (BSM) goals:

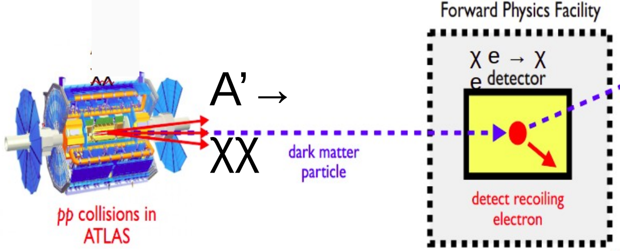
a) **trigger further discussions about possible unique BSM physics opportunities of the FPF**,

b) **studies for already proposed benchmarks**
(implementation, modeling uncertainties, new prod. and det. modes)

c) **facilitate exchange of (new) ideas** related to FPF BSM physics
(slack channel, community, feedback from experimental representatives)

WE INVITE CONTRIBUTIONS / HAPPY TO DISCUSS IDEAS

LIGHT DARK MATTER



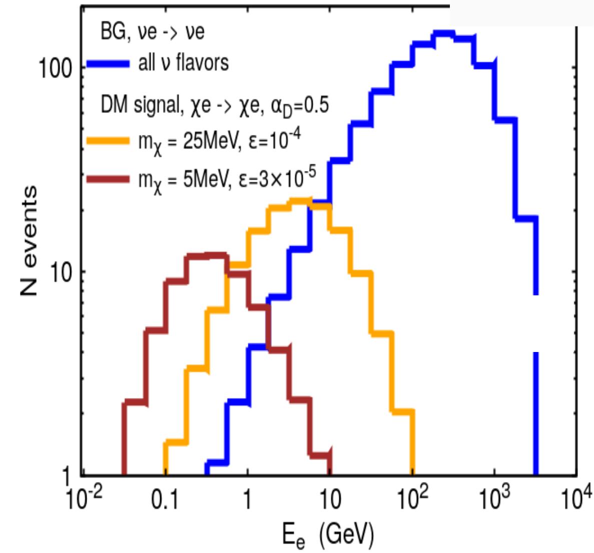
- Forward flux of light DM

- Signature: recoiled electron (recoil energy E_e)

Nuclear recoils also possible

- Light mediator favors low energy electron recoil

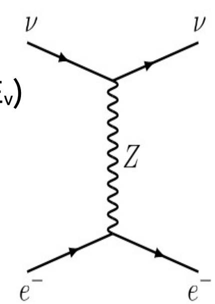
- Neutrino-induced backgrounds: larger recoils



Neutrino scattering example

y = E_e/(E_x,E_ν)

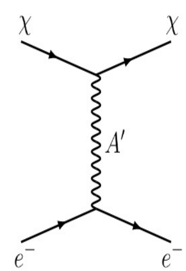
$$\frac{d\sigma(\nu_l e \to \nu_l e)}{dy} = \frac{2 m_e G_F^2 E_\nu}{\pi} \frac{1}{(1 + 2 m_e E_\nu y / M_Z^2)^2} \left(g_L^2 + g_R^2 (1-y)^2 \right),$$

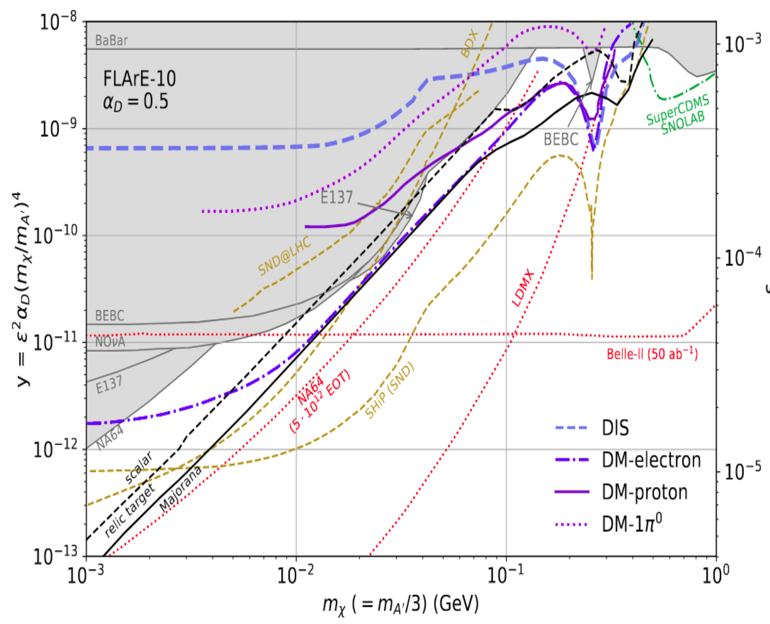


DM scattering (dark photon mediator)

$$\frac{d\sigma}{dy} \approx \frac{8\pi \epsilon^2 \alpha \alpha_D m_e E_\nu}{m_{A'}^4 (1 + 2 m_e E_\chi y / m_{A'}^2)^2}$$

$m_{A'} << M_Z$





B. Batell, J.L. Feng, ST, 2101.10338

B. Batell, J.L. Feng, A. Ismail, F. Kling, R.M. Abraham, ST, 2107.00666

B. Batell, J.L. Feng, M. Fieg, A. Ismail, F. Kling, R.M. Abraham, ST, 2111.10343

J. Li, J. Pei, L. Ran, W. Zhang, 2108.06748

QUIRKS WITH A LOW CONFINEMENT SCALE

- Postulated particles charged under a hidden strong force, QCD-like SU(N)

- If they carry also SM charge and color, they are pair produced at the LHC and connected by a “hidden” color string

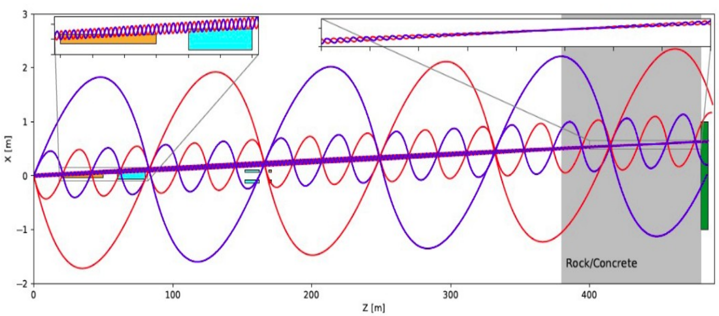
- If they mass exceeds the hidden scale m >> Λ_{hidden}, breaking the string is not energetically favorable and quirks **do not** hadronize

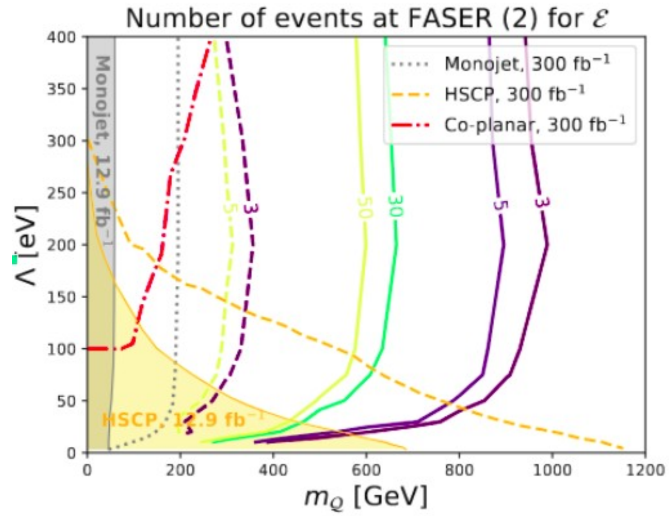
- For Λ_{hidden} ~ 10 keV, macroscopic oscillations (mm-m), pair of charged tracks leaving fancy tracks

- Quirk—anti-quirk system has low p_T

- Heavy (100 GeV - TeV) such quirks require LHC energies to be produced but often travel forward like light particles

$$\mathcal{E} = (N_{\text{IC}}, 1, 1, -1)$$

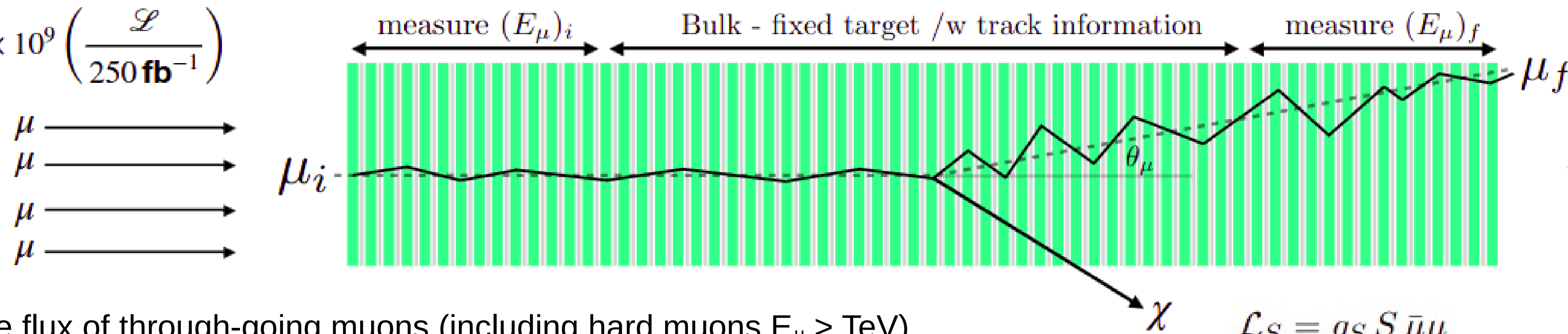




A. Ariga, R. Balkin, I. Galon, E. Kajamovitz, Y. Soreq,
2305.03102

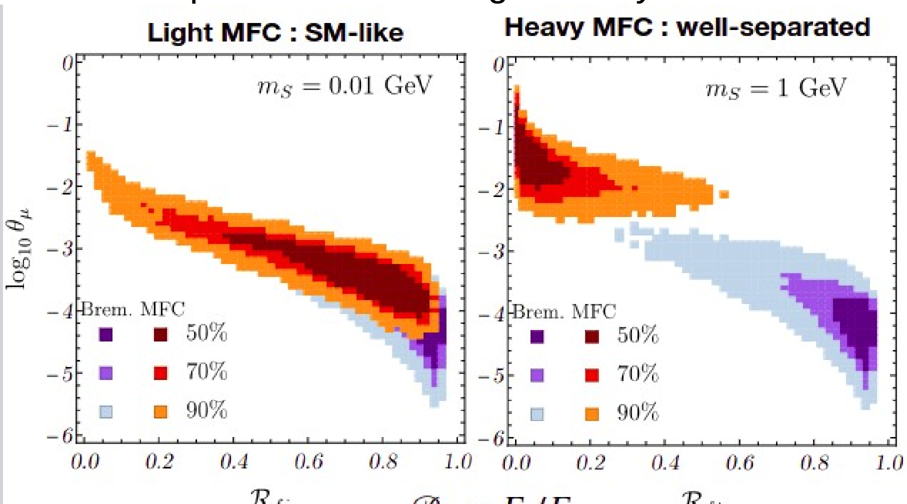
MUON-PHILIC DARK SECTORS

$$N_\mu \sim 2 \times 10^9 \left(\frac{\mathscr{L}}{250\,\mathbf{fb}^{-1}} \right)$$

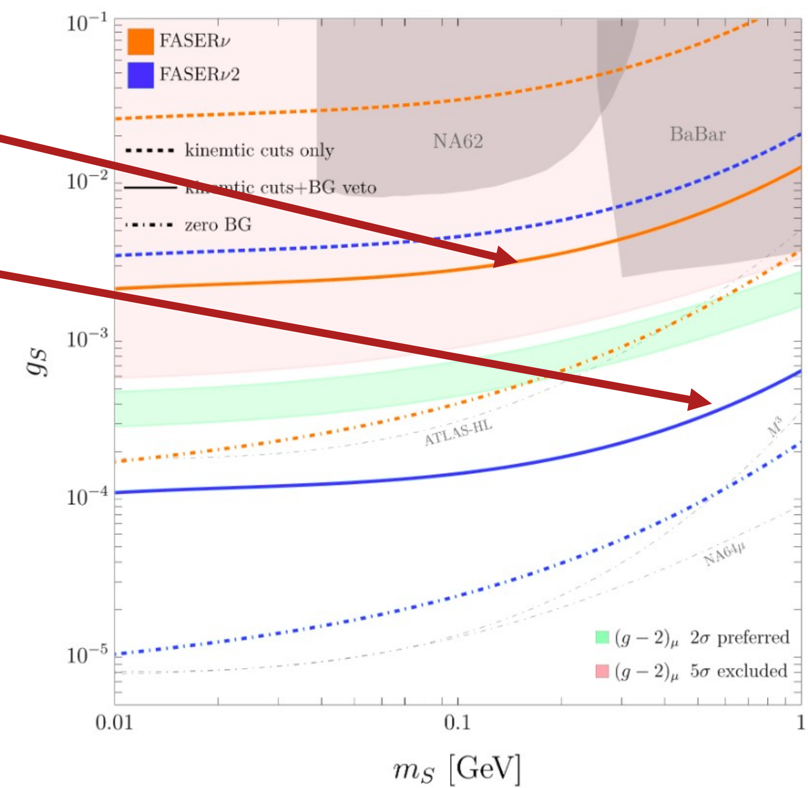


$$\mathcal{L}_S = g_S\, S\, \bar{\mu}\mu$$

- Large flux of through-going muons (including hard muons E_μ > TeV)
- Bremsstrahlung background is a challenge if the search relies only on kinematic cuts
- Novel strategies to identify displaced SM energy depositions could improve the reach significantly



$\mathscr{R}_{fi} \equiv E_f/E_i$



OTHER NEUTRINO-INDUCED BSM SIGNALS

- High-energy LHC νs + precise FPF detectors

  ~GeV-scale ν-induced particles can be produced in neutrino interactions

R.M. Abraham etal, 2301.10254

- Scatterings off electrons, νe → νe

Neutrino EM properties

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

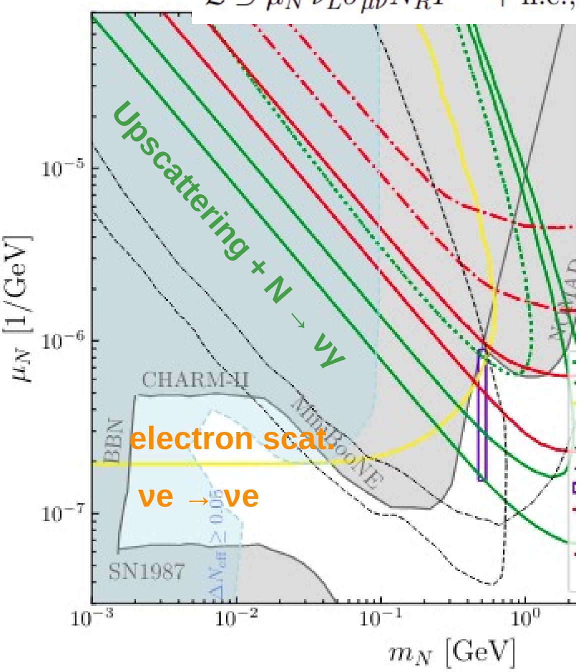
$$\Lambda^{\mu}_{fi}(q) = \gamma^{\mu}(Q_{fi} - \frac{q^2}{6}\langle r^2\rangle_{fi}) - i\sigma^{\mu\nu}q_{\nu}\mu_{fi}$$

- Neutrino oscillations into sterile neutrinos $\Delta m^2_{41} \sim 100 - 1000\ \mathrm{eV}^2$

K. Jodłowski, ST, 2011.04751

Dipole portal to HNLs

$$\mathcal{L} \supset \mu_N \bar{\nu}_L \sigma_{\mu\nu} N_R F^{\mu\nu} + \mathrm{h.c.},$$



K.J. Kelly etal, 2111.05868

Neutrinophilic DM

$$\mathcal{L} \supset \frac{1}{2}\lambda_{\alpha\beta}\nu_\alpha\nu_\beta\phi + \mathrm{h.c.}$$