Overview of New Physics Searches at the Forward Physics Facility

Roshan Mammen Abraham [1]
(On behalf of the FPF Working Groups)

LHCP 23, Belgrade
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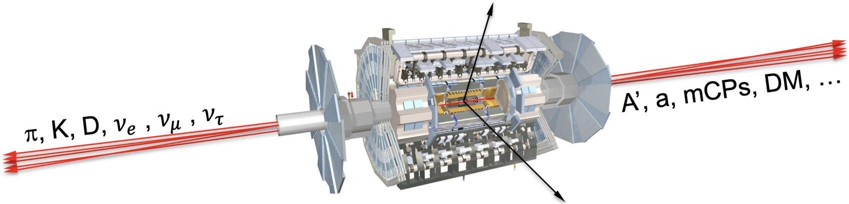
OKLAHOMA STATE UNIVERSITY

[1] rmammen@okstate.edu

Forward Region at the LHC



pp collisions at the LHC produce many light and weakly coupled particles in the forward direction.

They are currently being missed by the conventional detectors at LHC.

Forward Physics Facility

FPF is proposed to house many detectors in the forward direction to study SM and BSM physics, $\sim$ 500m downstream from ATLAS IP.

Currently, 5 experiments are being considered.

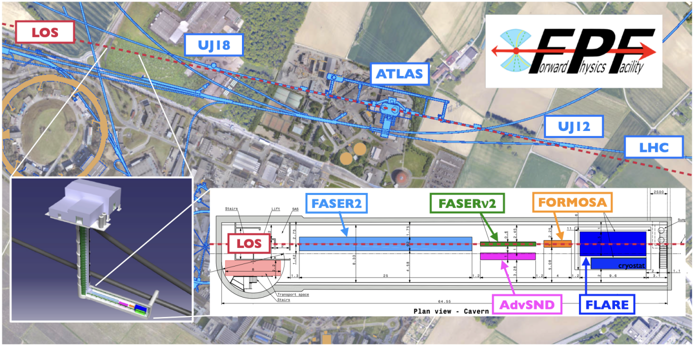


Figure 1: The preferred location for the Forward Physics Facility, a proposed new cavern for the High-Luminosity era. The FPF will be 65 m-long and 8.5 m-wide and will house a diverse set of experiments to explore the many physics opportunities in the far-forward region.

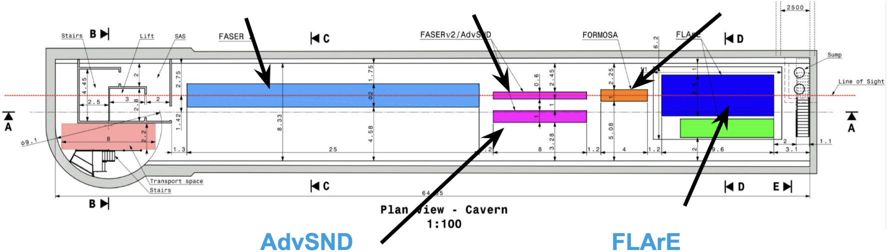
2109.10905, 2203.05090

Detectors at FPF

FASER2
magnetized spectrometer
for BSM searches

FASERν2
emulsion-based
neutrino detector

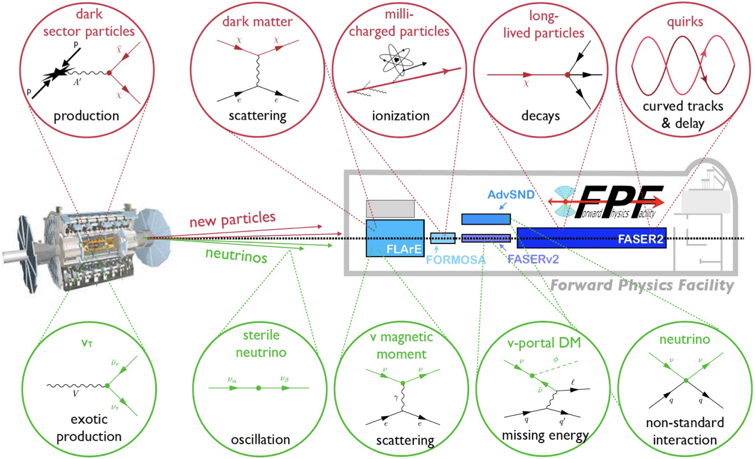
FORMOSA
plastic scintillator array
for BSM searches



AdvSND
electronic
neutrino detector

FLArE
LAr based
neutrino detector

Physics in the Forward Direction



DM, millicharged particles, LLPs, neutrinos, etc. can all be probed at the FPF.

First Neutrino Events at FASERν and FASER

First neutrino interaction candidates at the LHC

Henso Abreu,[1] Yoav Afik,[1] Claire Antel,[2] Jason Arakawa,[3] Akitaka Ariga,[4,5] Tomoko Ariga,[6,*] Florian Bernlochner,[7] Tobias Boeckh,[7] Jamie Boyd,[8] Lydia Brenner,[8] Franck Cadoux,[2] David W. Casper,[3] Charlotte Cavanagh,[9] Francesco Cerutti,[8] Xin Chen,[10] Andrea Coccaro,[11] Monica D'Onofrio,[9] Candan Dozen,[10] Yannick Favre,[2] Deion Fellers,[12] Jonathan L. Feng,[3] Didier Ferrere,[2] Stephen Gibson,[13] Sergio Gonzalez-Sevilla,[2] Carl Gwilliam,[9] Shih-Chieh Hsu,[14] Zhen Hu,[10] Giuseppe Iacobucci,[2] Tomohiro Inada,[10] Ahmed Ismail,[15] Sune Jakobsen,[8] Enrique Kajomovitz,[1] Felix Kling,[16] Umut Kose,[8] Susanne Kuehn,[8] Helena Lefebvre,[13] Lorne Levinson,[17] Ke Li,[14] Jinfeng Liu,[10] Chiara Magliocca,[2] Josh McFayden,[18] Sam Meehan,[8] Dimitar Mladenov,[8] Mitsuhiro Nakamura,[19] Toshiyuki Nakano,[19] Marzio Nessi,[8] Friedemann Neuhaus,[20] Laurie Nevay,[13] Hidetoshi Otono,[6] Carlo Pandini,[2] Hao Pang,[10] Lorenzo Paolozzi,[2] Brian Petersen,[8] Francesco Pietropaolo,[8] Markus Prim,[7] Michaela Queitsch-Maitland,[8] Filippo Resnati,[8] Hiroki Rokujo,[19] Marta Sabaté-Gilarte,[8] Jakob Salfeld-Nebgen,[8] Osamu Sato,[19] Paola Scampoli,[4,21] Kristof Schmieden,[20] Matthias Schott,[20] Anna Sfyrla,[2] Savannah Shively,[3] John Spencer,[14] Yosuke Takubo,[22] Ondrej Theiner,[2] Eric Torrence,[12] Sebastian Trojanowski,[23] Serhan Tufanli,[8] Benedikt Vormwald,[8] Di Wang,[10] and Gang Zhang[10]

First Direct Observation of Collider Neutrinos with FASER at the LHC

FASER Collaboration

Henso Abreu,[1] John Anders,[2] Claire Antel,[3] Akitaka Ariga,[4,5] Tomoko Ariga,[6] Jeremy Atkinson,[4] Florian U. Bernlochner,[7] Tobias Blesgen,[7] Tobias Boeckh,[7] Jamie Boyd,[2] Lydia Brenner,[8] Franck Cadoux,[3] David W. Casper,[9] Charlotte Cavanagh,[10] Xin Chen,[11] Andrea Coccaro,[12] Ansh Desai,[13] Sergey Dmitrievsky,[14] Monica D'Onofrio,[10] Yannick Favre,[3] Deion Fellers,[13] Jonathan L. Feng,[9] Carlo Alberto Fenoglio,[3] Didier Ferrere,[3] Stephen Gibson,[15] Sergio Gonzalez-Sevilla,[3] Yuri Gornushkin,[14] Carl Gwilliam,[10] Daiki Hayakawa,[5] Shih-Chieh Hsu,[16] Zhen Hu,[11] Giuseppe Iacobucci,[3] Tomohiro Inada,[11] Sune Jakobsen,[2] Hans Joos,[2,17] Enrique Kajomovitz,[1] Hiroaki Kawahara,[6] Alex Keyken,[15] Felix Kling,[18] Daniela Köck,[13] Umut Kose,[2] Rafaella Kotitsa,[2] Susanne Kuehn,[2] Helena Lefebvre,[15] Lorne Levinson,[19] Ke Li,[16] Jinfeng Liu,[11] Jack MacDonald,[20] Chiara Magliocca,[3] Fulvio Martinelli,[3] Josh McFayden,[21] Matteo Milanesio,[3] Dimitar Mladenov,[2] Théo Moretti,[3] Magdalena Munker,[3] Mitsuhiro Nakamura,[22] Toshiyuki Nakano,[22] Marzio Nessi,[3,2] Friedemann Neuhaus,[20] Laurie Nevay,[2,15] Hidetoshi Otono,[6] Hao Pang,[11] Lorenzo Paolozzi,[3,2] Brian Petersen,[2] Francesco Pietropaolo,[2] Markus Prim,[7] Michaela Queitsch-Maitland,[23] Filippo Resnati,[2] Hiroki Rokujo,[22] Elisa Ruiz-Choliz,[20] Jorge Sabater-Iglesias,[3] Osamu Sato,[22] Paola Scampoli,[4,24] Kristof Schmieden,[20] Matthias Schott,[20] Anna Sfyrla,[3] Savannah Shively,[9] Yosuke Takubo,[25] Noshin Tarannum,[3] Ondrej Theiner,[3] Eric Torrence,[13] Serhan Tufanli,[2] Svetlana Vasina,[14] Benedikt Vormwald,[2] Di Wang,[11] Eli Welch,[9] and Stefano Zambito[3]

2105.06197 (FASERν), 2303.14185 (FASER), 2305.09383 (SND@LHC)
See Thursday's talk by Tobias Boeckh (FASER) and by Simona Ilieva (SND).

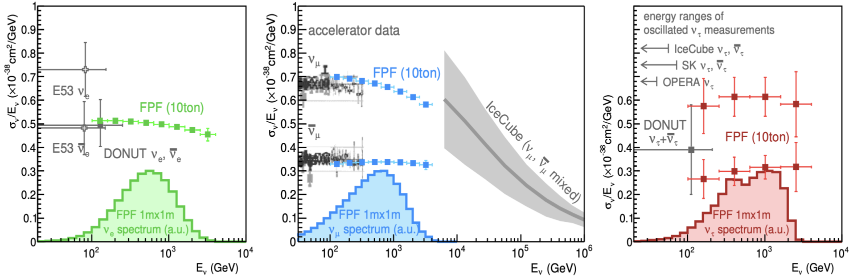
Neutrinos at the FPF

Neutrinos are produced in the forwards direction from the weak decays of mesons.

ν_e: $K \longrightarrow \pi e \nu_e$, $D \longrightarrow K e \nu_e$

ν_μ: $\pi^\pm \longrightarrow \mu\nu_\mu$, $K^\pm \longrightarrow \mu\nu_\mu$

ν_τ: $D_s \longrightarrow \tau\nu_\tau$



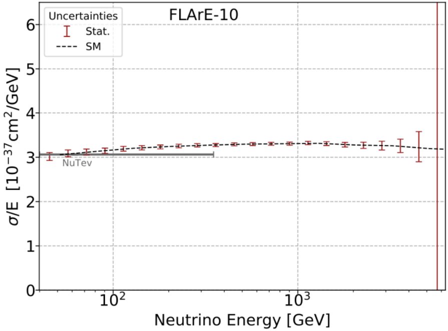
FLArE10 can see $\sim 10^4\ \nu_e,\ 10^5\ \nu_\mu,\ 10^3\ \nu_\tau$ interactions in the 100 GeV - few TeV range. FASERν2 can see more ($\sim$ 10X).

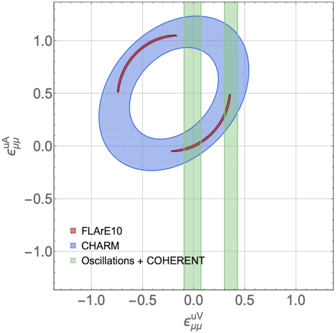
2109.10905, 2203.05090, 2105.08270

NC cross-section and NSI at FLArE10

Neutral current interactions are slightly more difficulty to detect.

Using ML techniques, they are also measurable at the FPF.





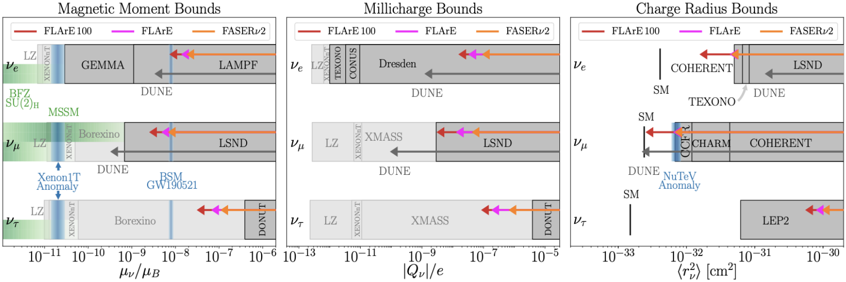
Ahmed Ismail, **R. Mammen Abraham**, Felix Kling; 2012.10500 (for FASERν)

Neutrino Electromagnetic (EM) Properties

Neutrino effective electromagnetic current:

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

Q_{fi} = Neutrino millicharge (NMC)
$\langle r^2\rangle_{fi}$ = Neutrino Charge Radius (NRC)
μ_{fi} = Neutrino Magnetic Moment (NMM)

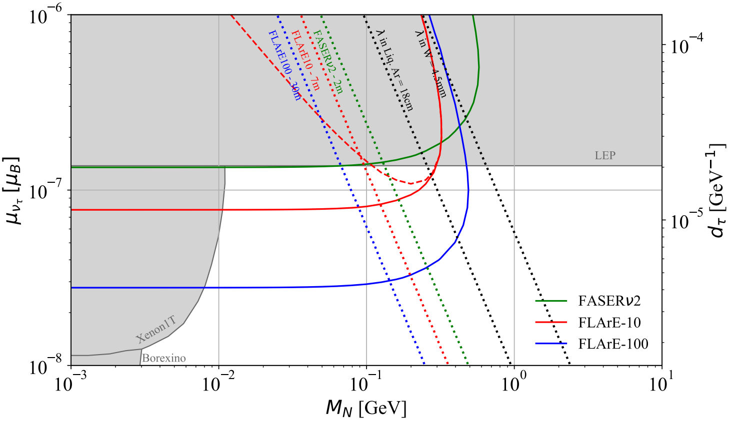


R. Mammen Abraham, Saeid Foroughi-Abari, Felix Kling, Yu-Dai Tsai, 2301.10254

Active to Sterile Neutrino Transition Magnetic Moment

SM neutrinos can couple to sterile neutrinos via a dipole portal.

$$\mathcal{L}_{dipole} \supset \frac{1}{2}\mu_\nu^\alpha \bar{\nu}_L^\alpha \sigma^{\mu\nu} N_R F_{\mu\nu}$$



The red dashed line is from considering only double bang events at FLArE10. Ahmed Ismail, Sudip Jana, **R. Mammen Abraham**, 2109.05032.

DM in the Forward Direction

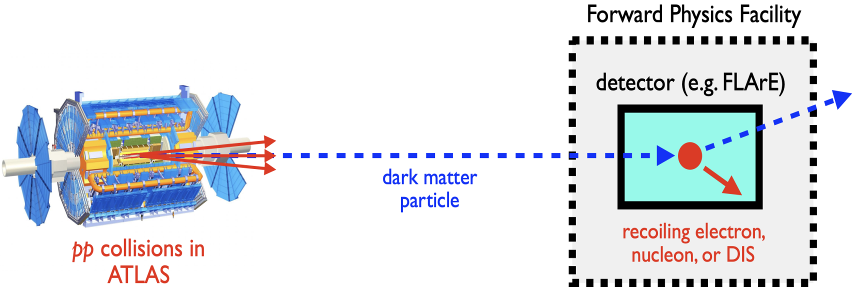


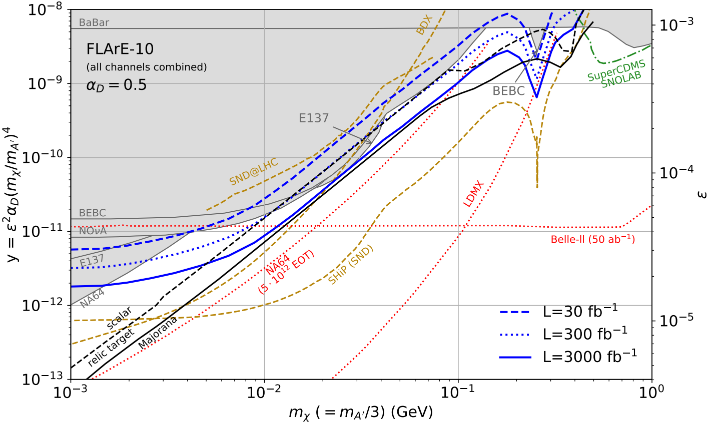
Image courtesy B. Batell

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'_\mu A'^\mu + A'_\mu \left(\varepsilon\, e\, J^\mu_{EM} + g_D\, J^\mu_D\right)$$

Dark photon models with $\epsilon \sim 10^{-3} - 10^{-4}$, and $M_{A',\chi} \sim$ MeV - GeV can produce the right thermal relic density via the freeze out mechanism.

DM in these models are dominantly produced in the forward direction.

DM result at FLArE10



DIS ($M_\chi \gtrsim 100$ MeV) and DM-e ($M_\chi \lesssim 10$ MeV) scattering are important.

Brian Batell, Jonathan L. Feng, Ahmed Ismail, Felix Kling, **R. Mammen Abraham**, Sebastian Trojanowski, 2107.00666

Hadrophilic Models

Hadronic collisions could be particularly sensitive to hadrophilic mediators; $U(1)_B$ (x=0) and $U(1)_{B-3\tau}$ (x=1).

$$J^\mu_{\rm SM} = g_V [J^\mu_B - 3x(\overline{\tau}\gamma^\mu\tau + \overline{\nu}_\tau\gamma^\mu P_L \nu_\tau)] + \varepsilon\, e\, J^\mu_{\rm EM}$$

Many signatures at FPF:

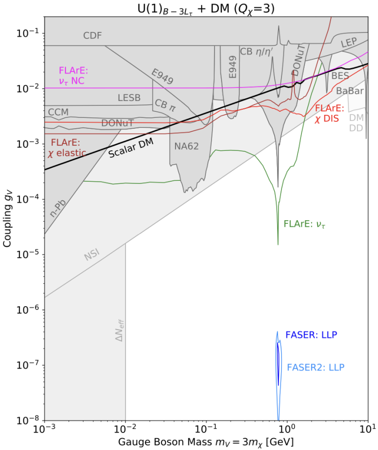
LLP searches: V $\rightarrow$ hadrons.

Excess of ν_τ: V $\rightarrow \nu_\tau\ \overline{\nu}_\tau$.

Neutrino NC scattering: ν_τ N $\rightarrow \nu_\tau$ N.

DM scattering: χ N $\rightarrow \chi N$.

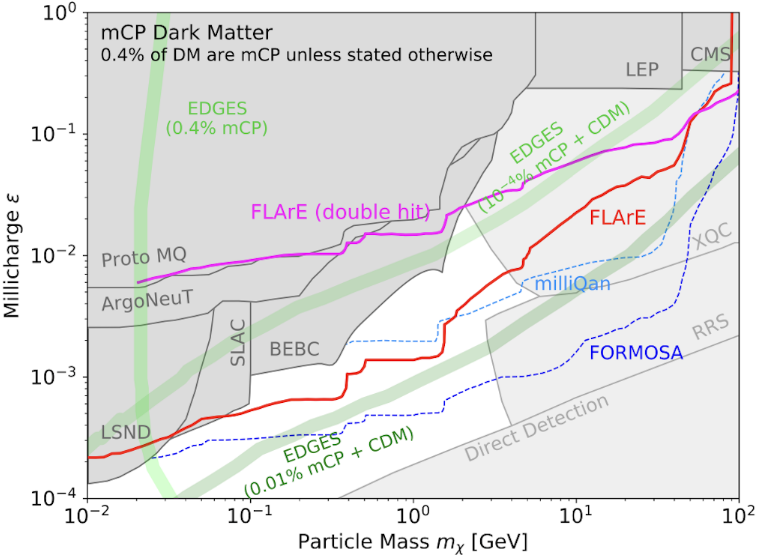
DM annihilation: $\chi\chi \rightarrow$ SM SM.



Brian Batell, Jonathan L. Feng, Max Fieg, Ahmed Ismail, Felix Kling, **R. Mammen Abraham**, Sebastian Trojanowski, 2111.10343

Milli-Charged Particles (mCP)

mCPs passing through the detector can result in scattering, and ionization signatures. 2010.07941, 2205.09137

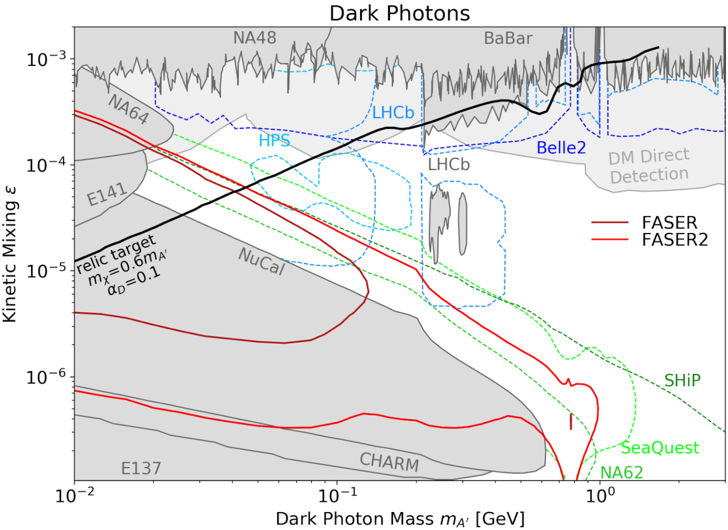


Long Lived Particles

Dark photon mixing with SM photon.

$\mathcal{L} \sim \frac{1}{2} m_{A'}^2 A'^2 - \epsilon e q_f \bar{f} \gamma^\mu f A'_\mu$

2105.07077



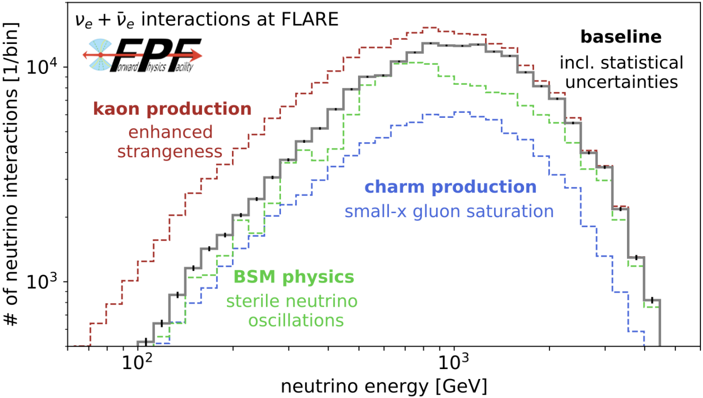
See Noshin Tarannum's previous talk on dark photon searches at FASER.

QCD at FPF

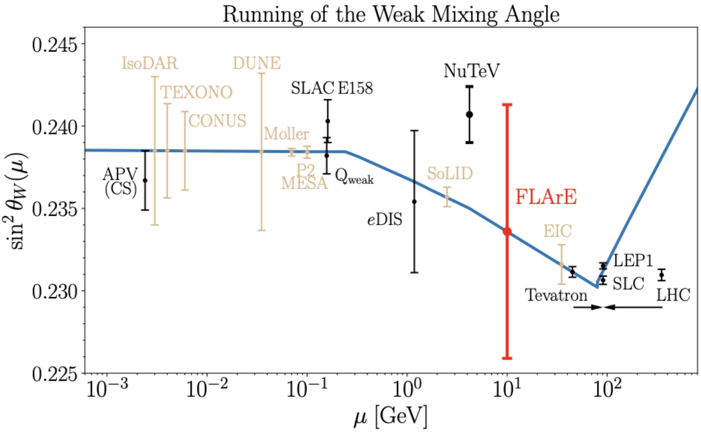
Neutrino flux is a novel and complementary probe of forward hadron production.

Muon puzzle (observed excess of muons in high-energy cosmic ray air showers) could be solved by enhanced rate of forward strangeness production. 2202.03095

Probe PDFs at low small-x (for example, gluon saturation).



SM Physics: Weak Mixing Angle at FPF



$\sin^2\theta_W$ could be measured to 3% precision at FLArE10.

R. Mammen Abraham, Saeid Foroughi-Abari, Felix Kling, Yu-Dai Tsai, arXiv:2301.10254

Summary

Many physics opportunities exist in the forward direction at LHC.

FASER, FASERν, SND are all currently taking data in the forward direction.

The FPF is proposed to significantly enlarge the scope of physics that can be studied at the LHC.

Neutrinos, DM, QCD Physics, mCPs, LLPs, etc. can all be probed at the FPF.

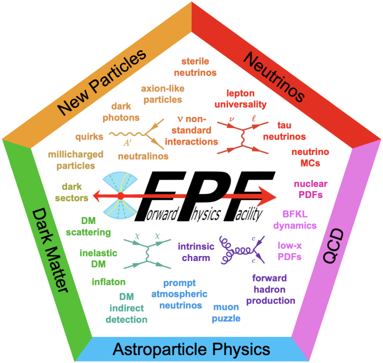
Much more physics remains to be studied. We invite the LHC community to join this program.

Summary

FPF workshops: FPF1, FPF2, FPF3, FPF4, FPF5 (highly active community)

FPF6, Jun 8-9. (much more physics to be studied, invitation to join in this exciting venture.)

FPF Snowmass Whitepaper



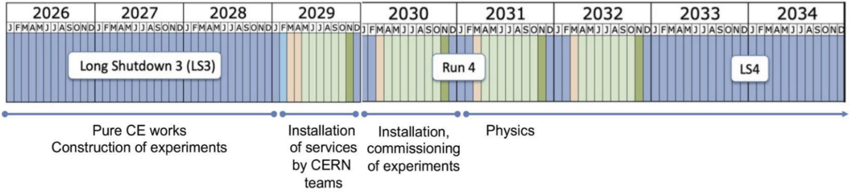
Contact: rmammen@okstate.edu

Backup slides - FPF Timeline

radiation protection studies indicate that there is no danger from working in the FPF while the LHC is running

vibration studies indicate that construction of the FPF, installation of services, experiments, will not interfere with LHC operations

possible timeline presented at Chamonix (Jan 2022)



conceptual designs for the FPF and its 5 experiments by mid-2023

Slide courtesy F. Kling

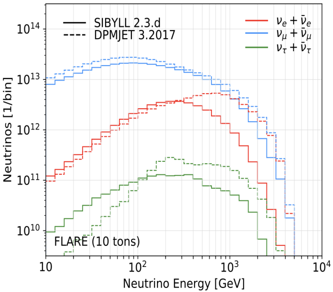
Backup slides - Neutrino Fluxes in the Forward Direction

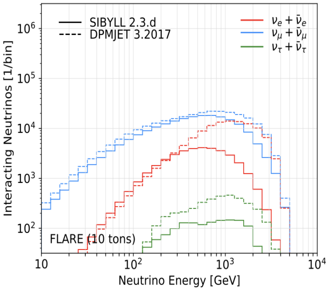
Neutrinos are produced in the weak decays of mesons.

ν_e: $K \longrightarrow \pi e \nu_e$, $D \longrightarrow K e \nu_e$

ν_μ: $\pi^\pm \longrightarrow \mu \nu_\mu$, $K^\pm \longrightarrow \mu \nu_\mu$

ν_τ: $D_s \longrightarrow \tau \nu_\tau$



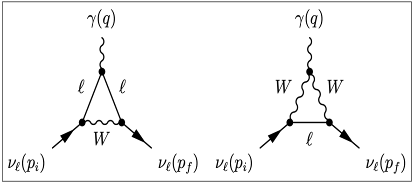


Neutrino flux and CC interactions at FLArE for $\mathcal{L} = 3\ \text{ab}^{-1}$.

2109.10905, 2203.05090, 2105.08270

Backup slides - Predictions for Neutrino EM properties

- $Q_{SM} = 0.$
- Non-zero neutrino mass $\Longrightarrow$ Non-zero NMM.
- NCR is generated at loop level within the SM, $\left\langle r^2_{\nu_\ell} \right\rangle_{\rm SM} = \frac{G_f}{4\sqrt{2}\pi^2}\left[3 - 2\log\frac{m_\ell^2}{m_W^2}\right].$



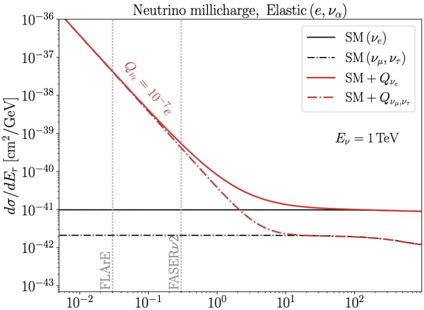
  - $\left\langle r^2_{\nu_e} \right\rangle_{\rm SM} = 4.1 \times 10^{-33} {\rm cm}^2$
  - $\left\langle r^2_{\nu_\mu} \right\rangle_{\rm SM} = 2.4 \times 10^{-33} {\rm cm}^2$
  - $\left\langle r^2_{\nu_\tau} \right\rangle_{\rm SM} = 1.5 \times 10^{-33} {\rm cm}^2$

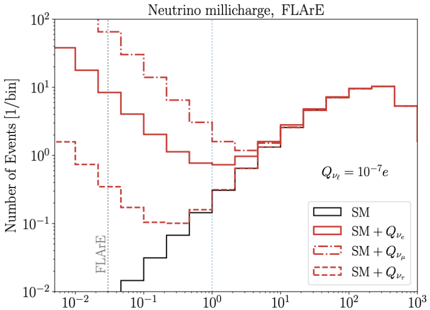
Backup slides - Modified Rates at FPF: $\nu - e$ elastic scattering

Neutrino Millicharge:

$\mathcal{L} \supset Q_\nu (\bar{\nu}\gamma_\mu \nu) A^\mu$. Adds coherently with SM amplitude.

Due to the interference term, we are sensitive to the sign of neutrino millicharge.





R. Mammen Abraham, Saeid Foroughi-Abari, Felix Kling, Yu-Dai Tsai, arXiv:2301.10254

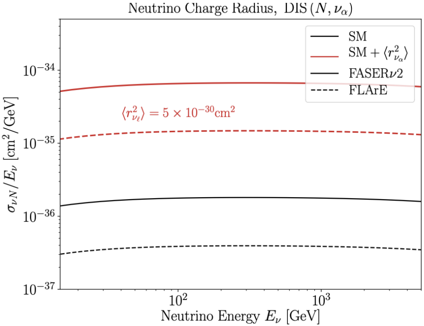
Backup slides - Modified Rates at FPF: $\nu-$nuclear scattering

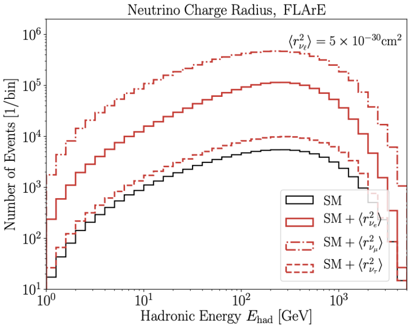
Neutrino Charge Radius:

Vector coupling in the NC DIS is modified as,

$g_V^q \to g_V^q - \frac{2}{3} Q_q m_W^2 \langle r_{\nu_\ell}^2 \rangle \sin^2 \theta_w$ — Vogel and Engel, 89

We use a heavier target (nuclear scattering) for higher signal event rates.





Backup slides - Light Dark Matter Models

SM connected to the dark sector via a GeV scale dark photon A'

$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + A'_\mu \left(\varepsilon\, e\, J^\mu_{EM} + g_D\, J^\mu_D\right)$$

Dark Currents

$$J^\mu_D = \begin{cases} \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{(Majorana fermion DM)} \\ i\chi^*\overset{\leftrightarrow}{\partial^\mu}\chi & \text{(complex scalar DM)}\ . \end{cases}$$

DM Lagrangian

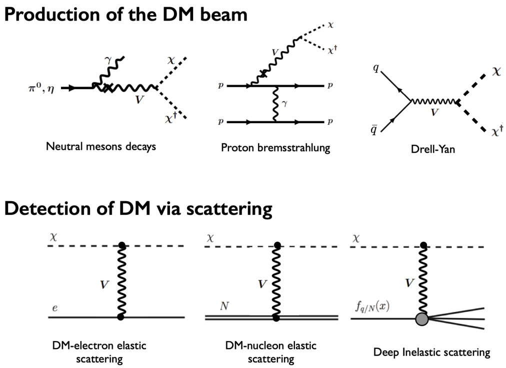
$$\mathcal{L} \supset \begin{cases} \frac{1}{2}\overline{\chi}i\gamma^\mu\partial_\mu\chi - \frac{1}{2}m_\chi\overline{\chi}\chi & \text{(Majorana fermion DM)} \\ |\partial_\mu\chi|^2 - m^2_\chi|\chi|^2 & \text{(complex scalar DM)}\ , \end{cases}$$

2101.10338
Brian Batell, Jonathan L. Feng, Ahmed Ismail, Felix Kling, **R. Mammen Abraham**, Sebastian Trojanowski, arXiv:2107.00666

Backup slides - Hadrophilic Models

- Hadronic collisions could be particularly sensitive to hadrophilic mediators.
- We also consider $U(1)_B$ (x=0) and $U(1)_{B-3\tau}$ (x=1) models.

$$J^\mu_{\rm SM} = g_V [J^\mu_B - 3x(\overline{\tau}\gamma^\mu\tau + \overline{\nu}_\tau\gamma^\mu P_L\nu_\tau)] + \varepsilon\, e\, J^\mu_{\rm EM}$$



Brian Batell, Jonathan L. Feng, Max Fieg, Ahmed Ismail, Felix Kling, **R. Mammen Abraham**, Sebastian Trojanowski, arXiv:2111.10343

image courtesy B. Batell