BSM PHYSICS AT THE FORWARD PHYSICS FACILITY AT THE LHC

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XXIX Cracow EPIPHANY Conference

January 18, 2023

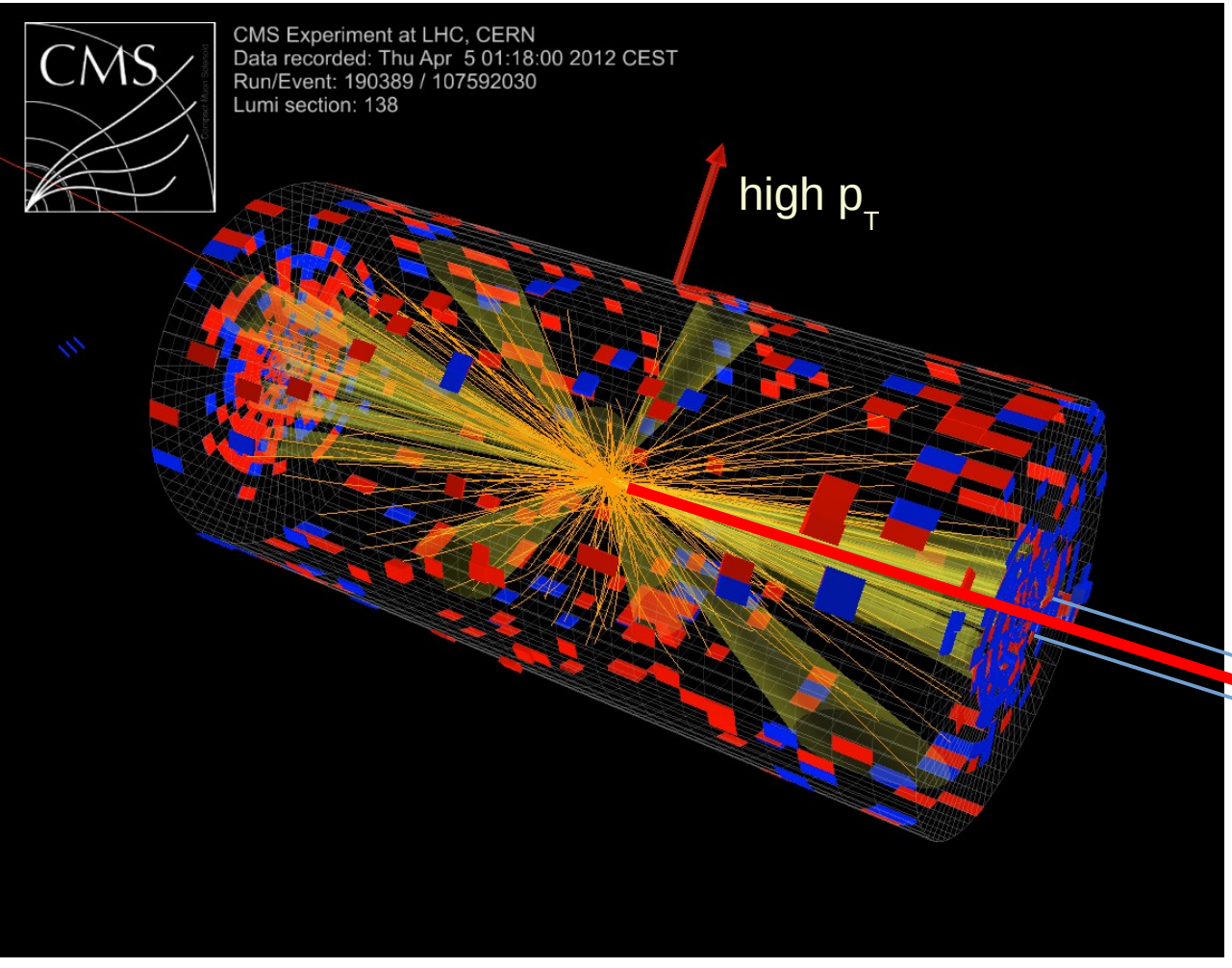
Whitepapers:
J.L. Feng, F. Kling, M.H. Reno, J. Rojo, D. Soldin etal, 2203.05090
L.A. Anchordoqui etal, 2109.10905
+ many other papers

LHC: HIGH p_T AND LOW p_T SEARCHES

Heavy new physics preferentially searched for in the high p_T region, but...

LHC is also a factory of light particles

(e.g. light mesons, mostly dismissed as not interesting)



σ_{inel} ~ 75 mb,

e.g., $N_\pi \sim 10^{18}$ at 3 ab^{-1}

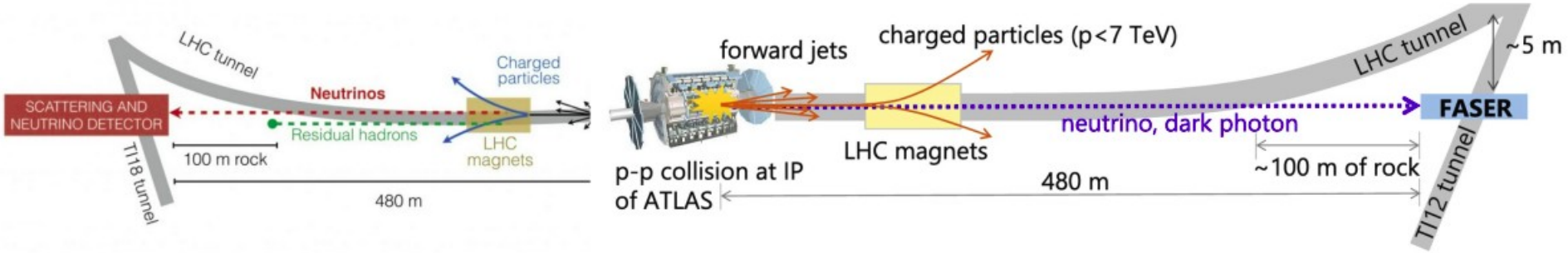
(for comparison **σ ~ fb – pb** and $N_H \sim 10^8$ Higgs bosons at 3 ab^{-1} in high-p_T searches)

Forward physics

down the beam pipe

FORWARD PHYSICS FACILITY

FAR-FORWARD SEARCHES AT THE LHC



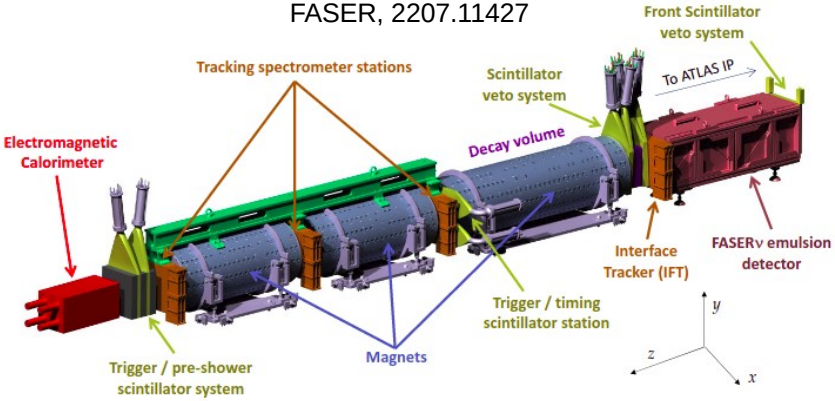
- Forward direction: lots of activity down the beam pipe

- Far-forward detectors:
  - well-screened from pp collisions
  - only neutrinos and muons survive
  - can search for rare BSM events

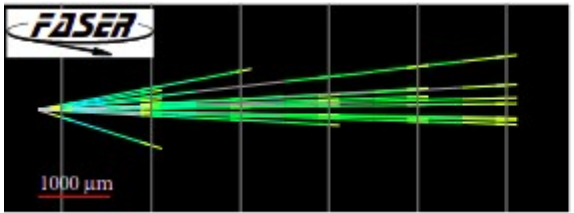
- **Current Run 3**: FASER, SND@LHC

- Physics:
  - "Precision" high-energy neutrino physics
  - New physics searches

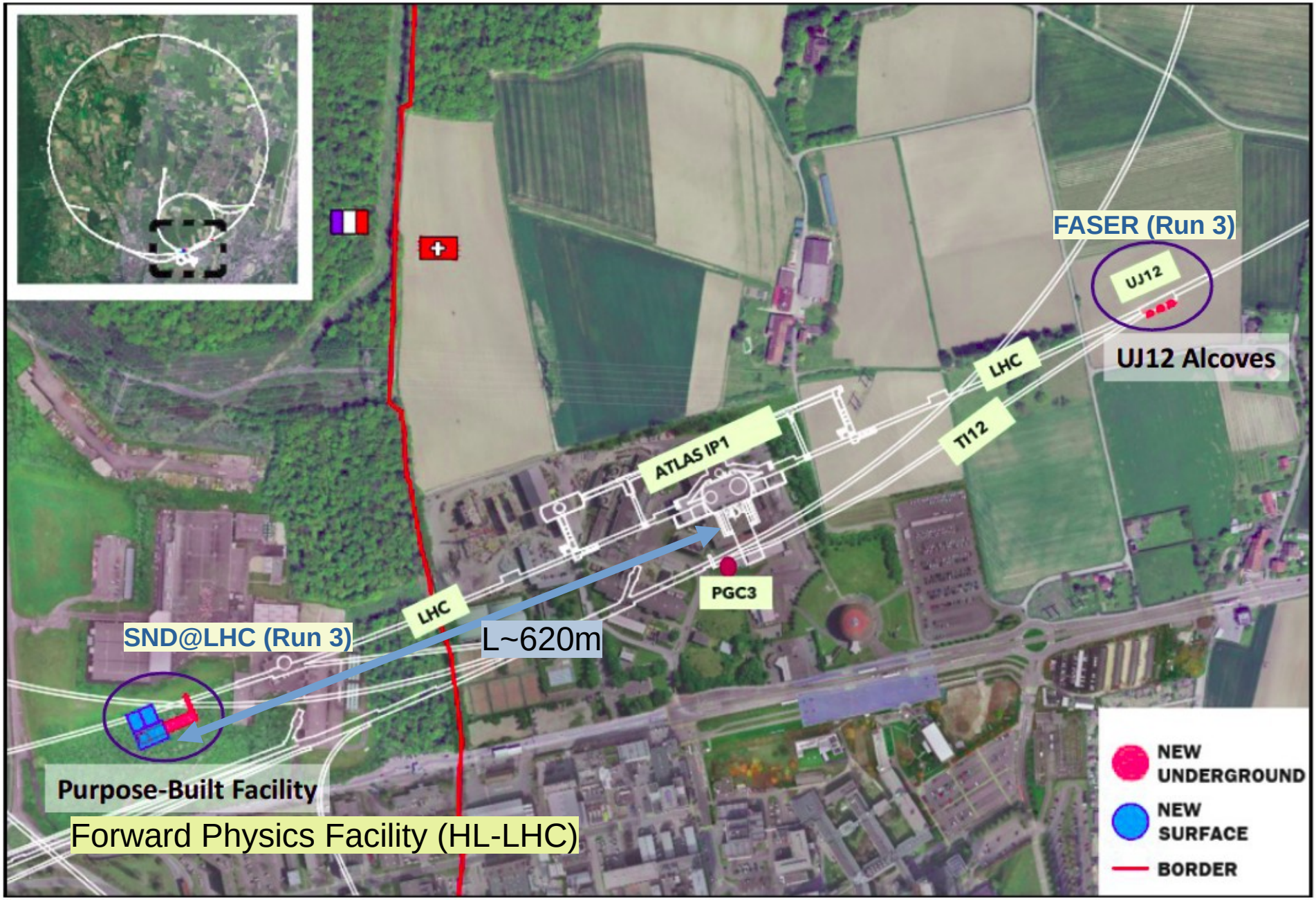
FASER, 2207.11427



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



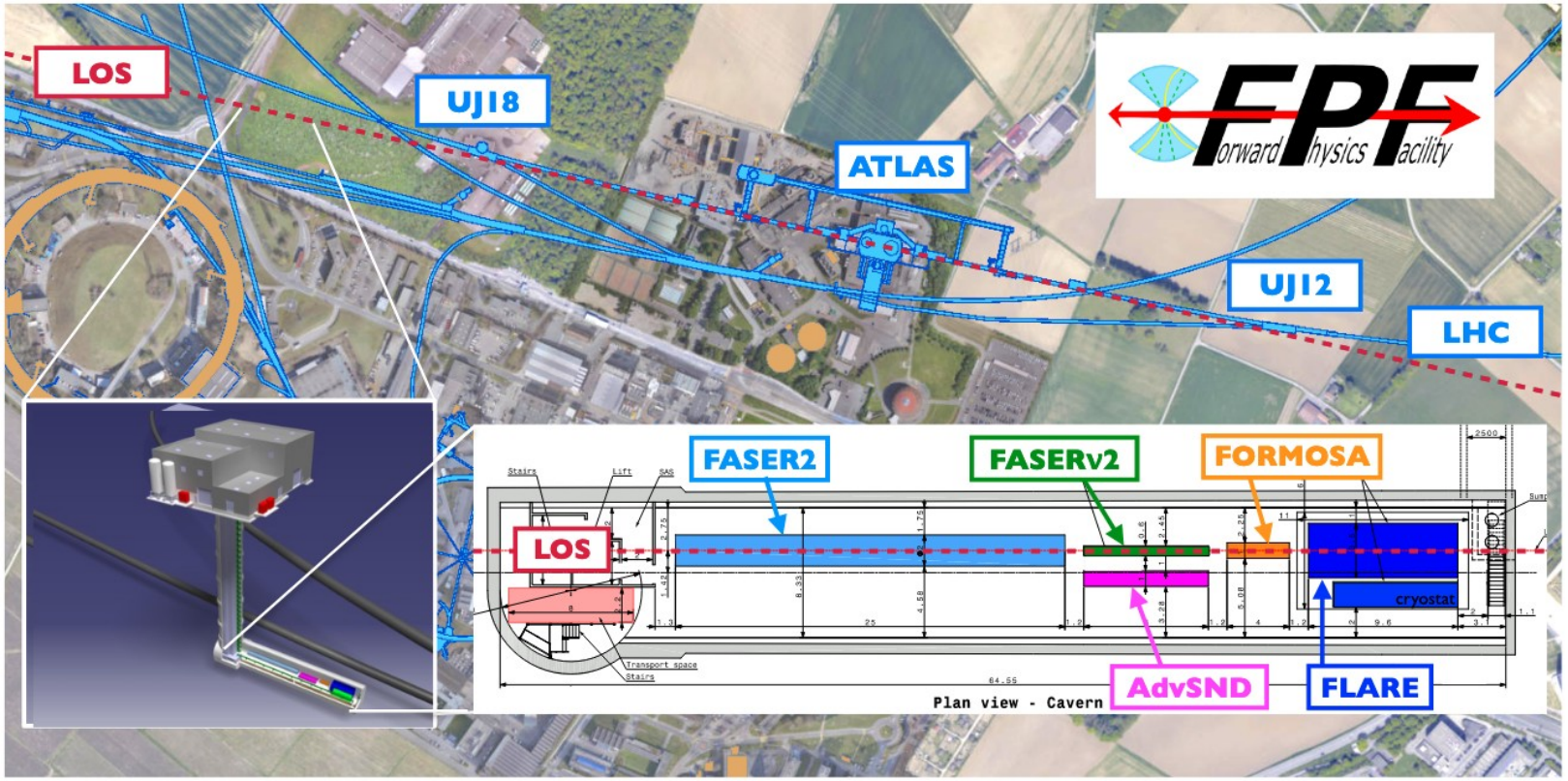
Far-forward searches at the LHC in a bird's eye view



PURPOSE-BUILT FACILITY

Underground facility:

- ~620 m far forward from the ATLAS IP,
- shielded by ~200 m concrete and rock.
- several experiments proposed (signatures: decay, scattering, ionization)
- up to ~1M neutrino events (of order 10k ν_τ CC events)



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 idea: **F**orward **L**iquid **Ar**gon **E**xperiment (**FLArE**) – BNL (lead), UCI, …

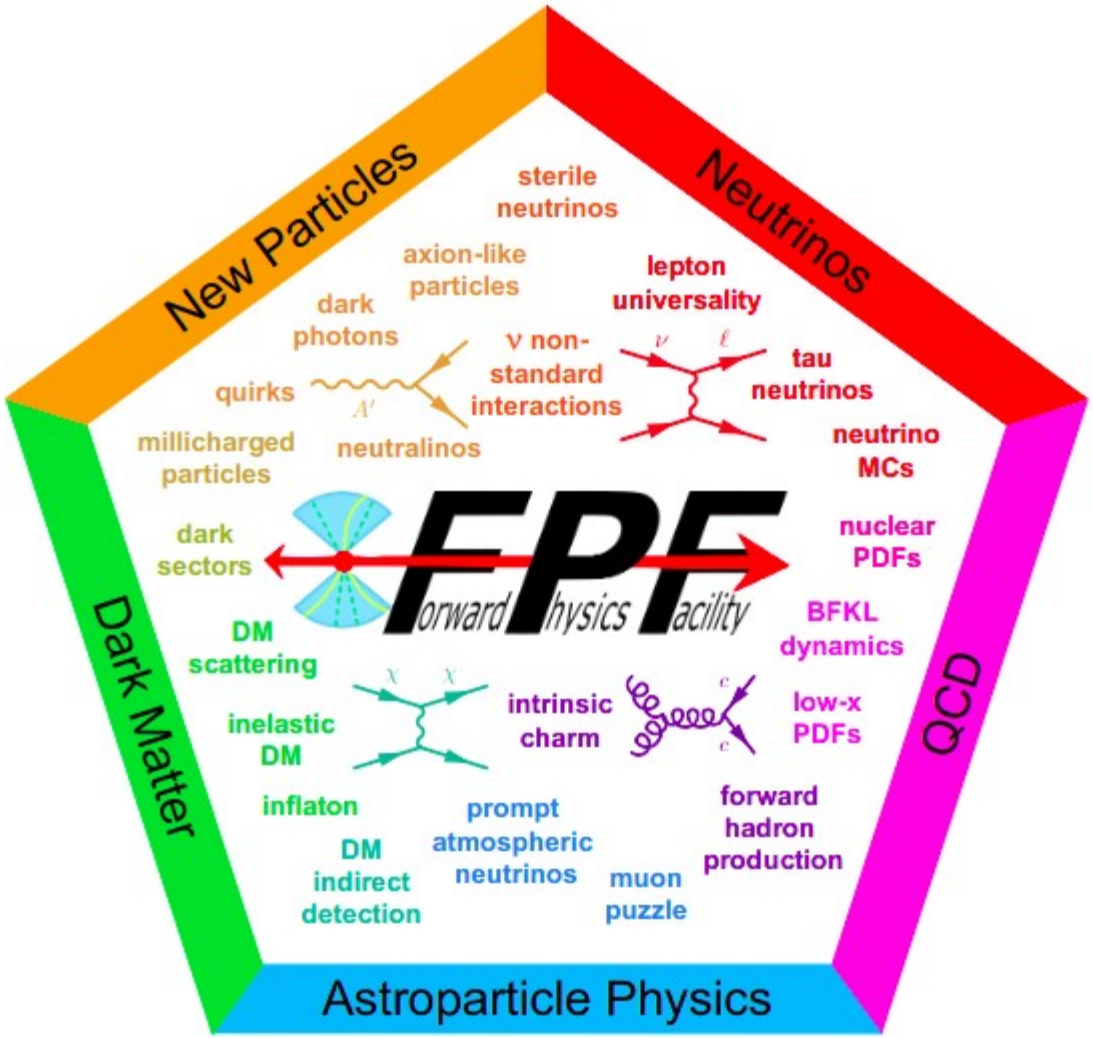
- The U.S. Snowmass process – strong endorsements of the FPF in the Energy Frontier, the Neutrino Frontier, the Rare Process Frontier, the Cosmic Frontier

- CERN:
  - Large progress in facility planning
  - Extensive simulations (CERN FLUKA team); BG and radiation safety, muons
  - Physics Beyond Colliders (PBC) at CERN allocated 75K CHF for site investigation

- Organization
  - Facility & experiments (Run 3 is running, HL-LHC: design)

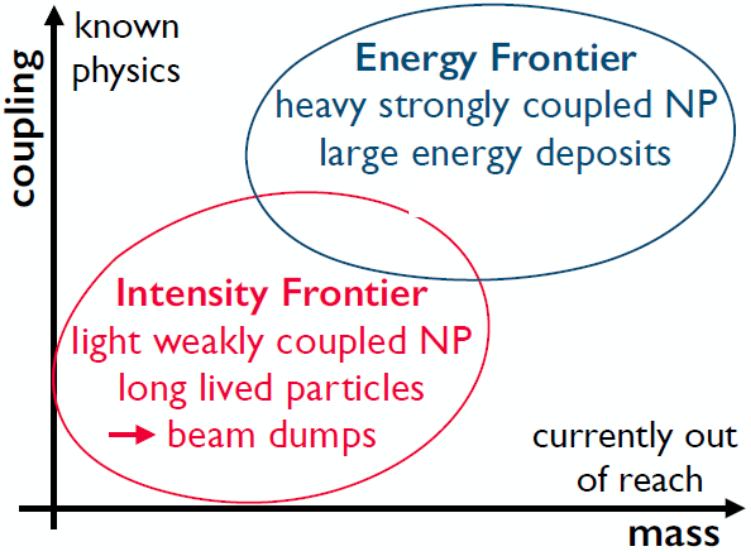
  - Physics – working groups (neutrino, BSM)

PHYSICS AT THE FPF

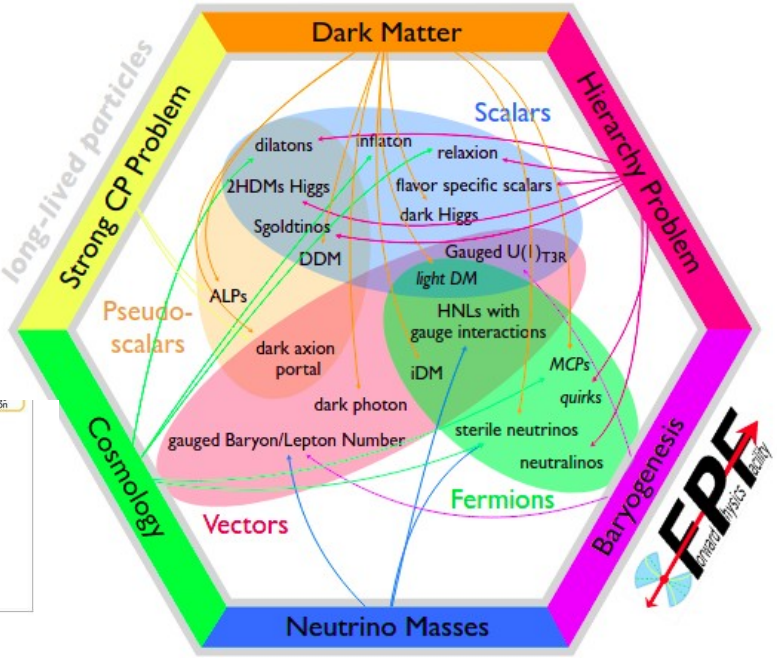


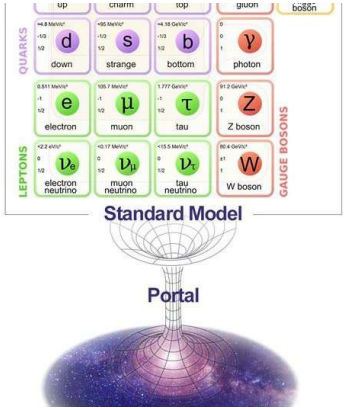
NEW PHYSICS PARTICLES
LIGHT LONG-LIVED (LLP) or STABLE

LIGHT LONG-LIVED PARTICLES



NEW PHYSICS & FPF





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	$y_N L H N$

PROTOTYPE SCENARIO – DARK PHOTON

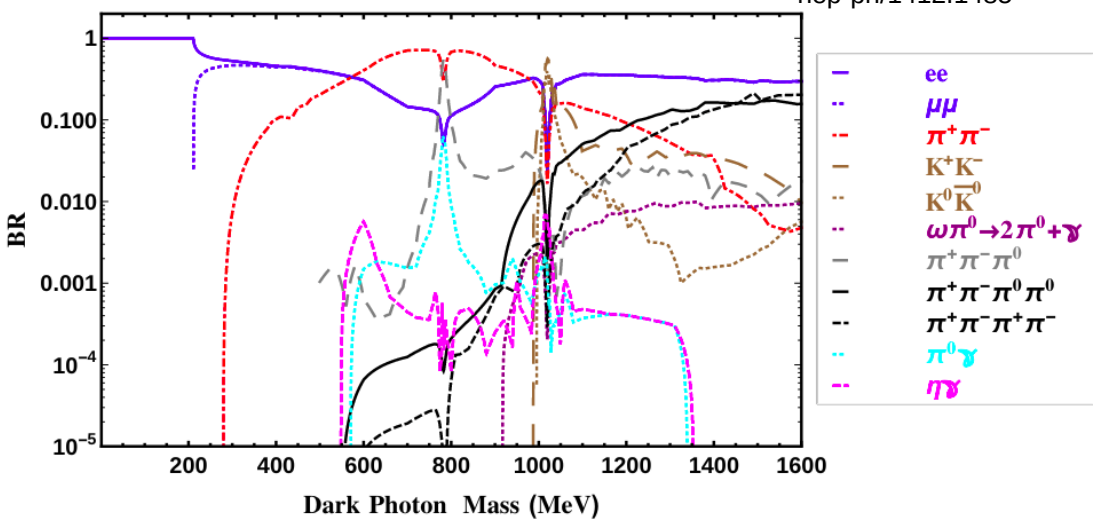
- New light (~sub-GeV) vector secluded from the SM, coupled via kinetic mixing
  (can be induced by heavy new fields at the loop level charged under both U(1) and $U(1)_D$)
- Suppressed couplings to SM fermions

- Dark photons can decay into SM fermions

- Lifetime depends on ε
Decays can be prompt
and DISPLACED

- Various final states are possible
Below 500 MeV mass di-lepton
final states e^+e^- & $\mu^+\mu^-$

hep-ph/1412.1485

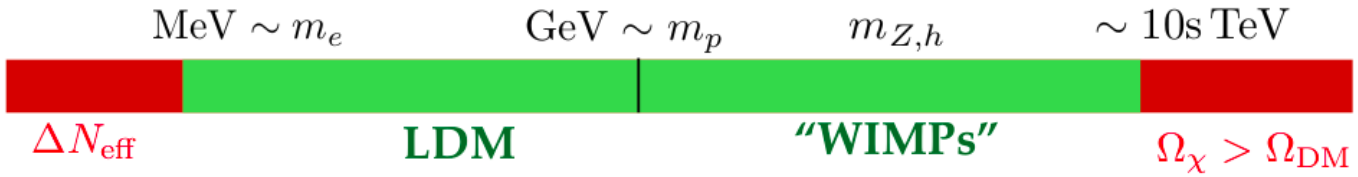


LIGHT DARK MATTER VIA DARK PHOTON

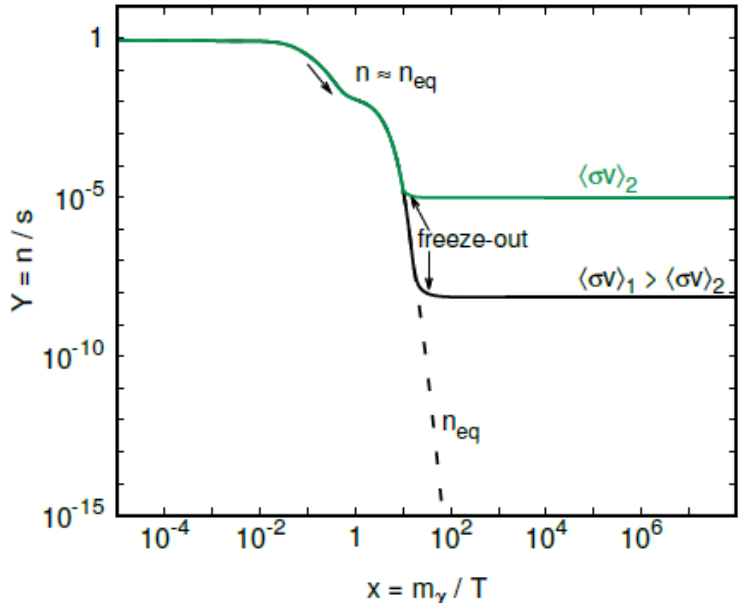
- Dark photon can also mediate interactions between the SM and a ``thermal'' DM relic χ

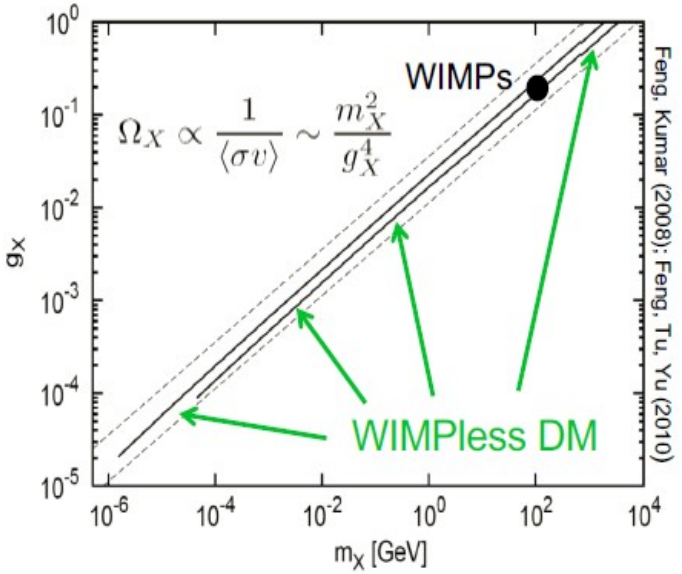
$$\mathcal{L} \supset A'_\mu(\epsilon\, e\, J^\mu_{EM} + g_D\, J^\mu_D) \qquad \mathcal{L} \supset \begin{cases} |\partial_\mu \chi|^2 - m_\chi^2 |\chi|^2 & \text{(complex scalar DM)} \\ \frac{1}{2}\overline{\chi} i\gamma^\mu \partial_\mu \chi - \frac{1}{2} m_\chi \overline{\chi}\chi & \text{(Majorana fermion DM)} \end{cases} \qquad J^\mu_D = \begin{cases} i\chi^* \overleftrightarrow{\partial_\mu} \chi & \text{(complex scalar DM)} \\ \frac{1}{2}\overline{\chi}\gamma^\mu\gamma^5\chi & \text{(Majorana fermion DM)} \,. \end{cases}$$

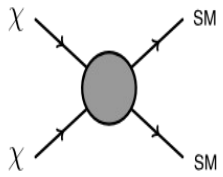
- Suppressed SM couplings of A' yield correct DM relic density for ~MeV-GeV χ **LDM**



L. Roszkowski, E.M. Sessolo, ST, 1707.06277

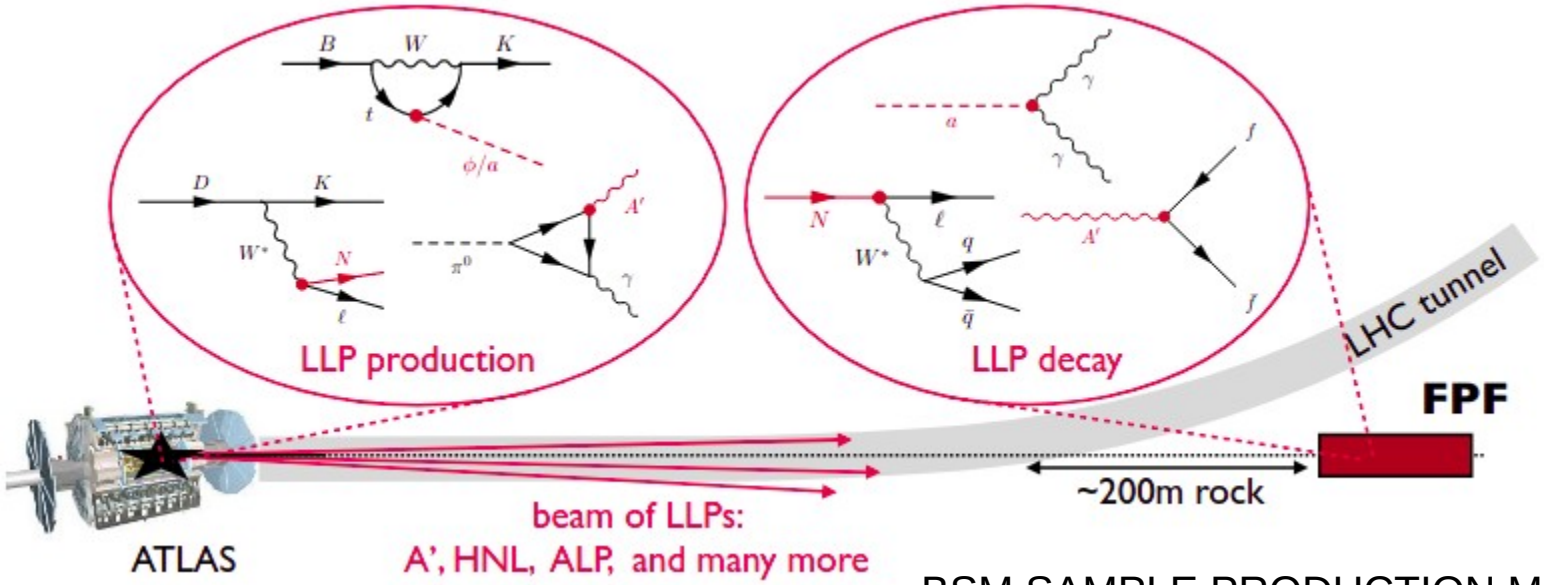


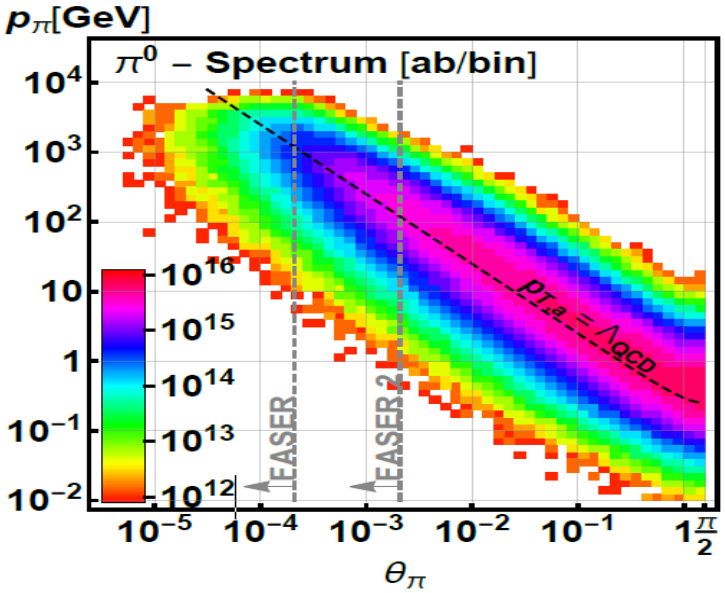




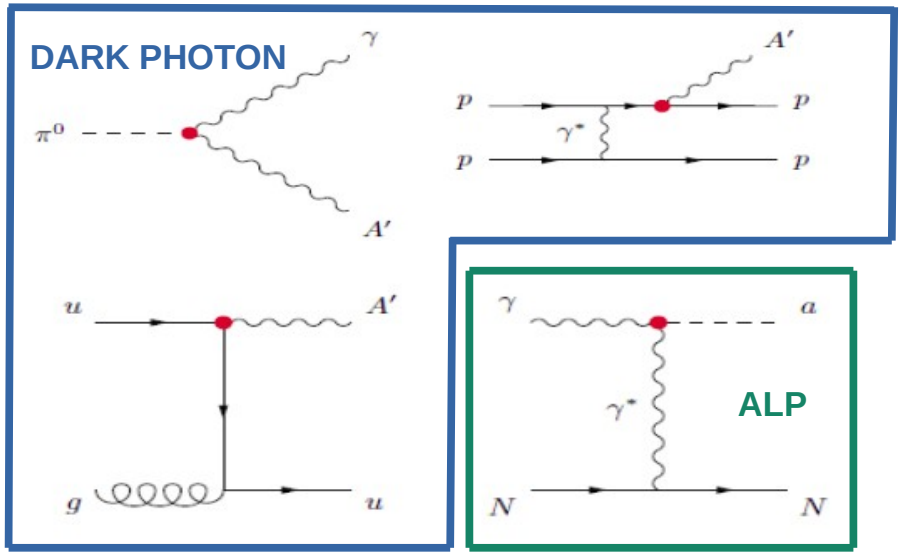
WIMP Freeze Out

LLP SEARCHES AT THE FPF



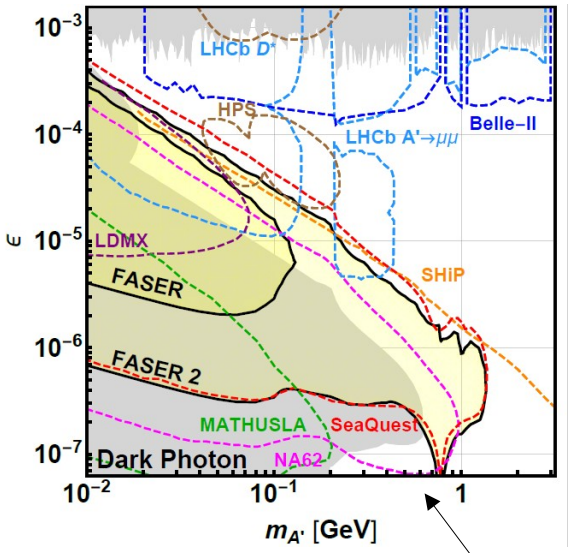


BSM SAMPLE PRODUCTION MODES

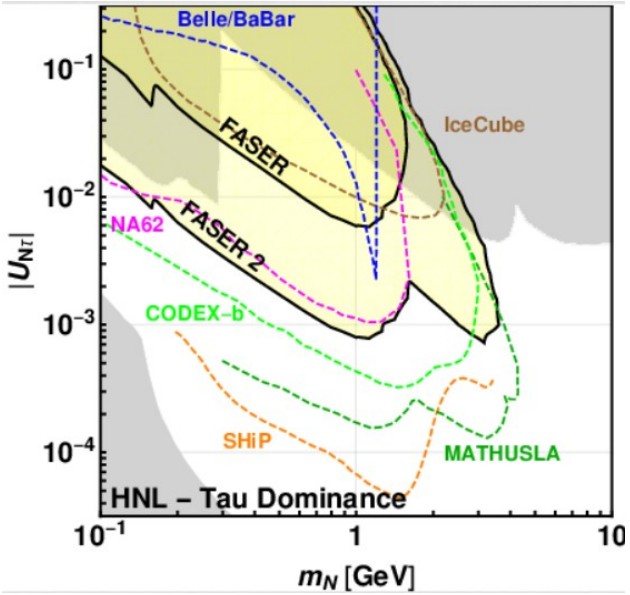


SELECTED SENSITIVITY REACH PLOTS

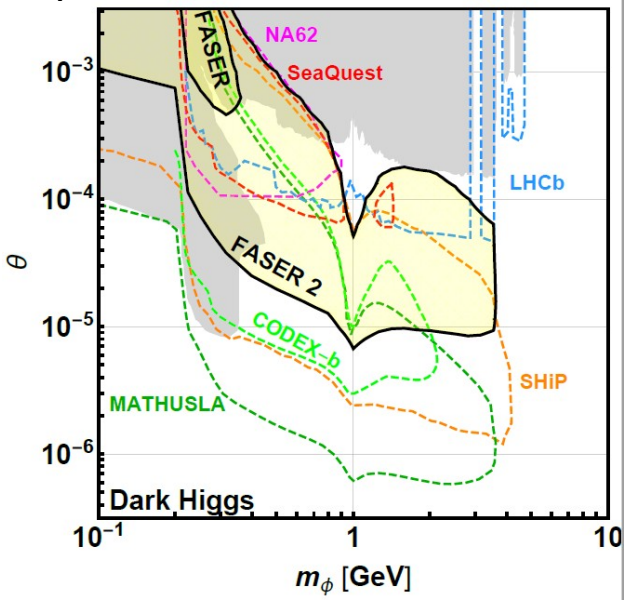
DARK PHOTON



HEAVY NEUTRAL LEPTON (TAU)



DARK HIGGS BOSON

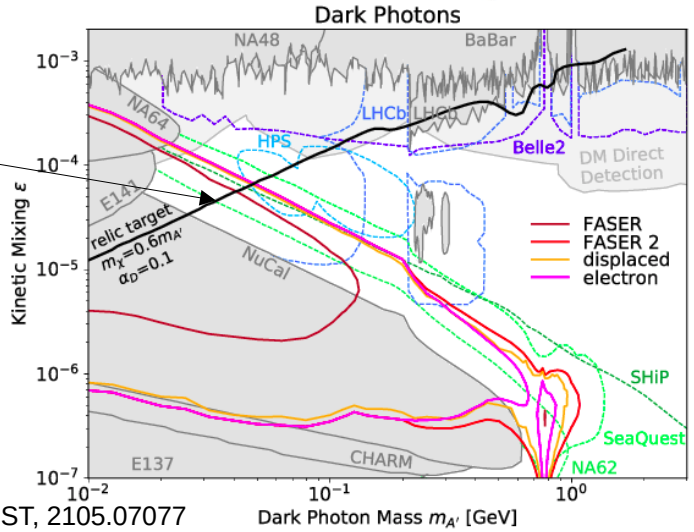


complementarity

DM direct detection searches

complex scalar DM with A' med

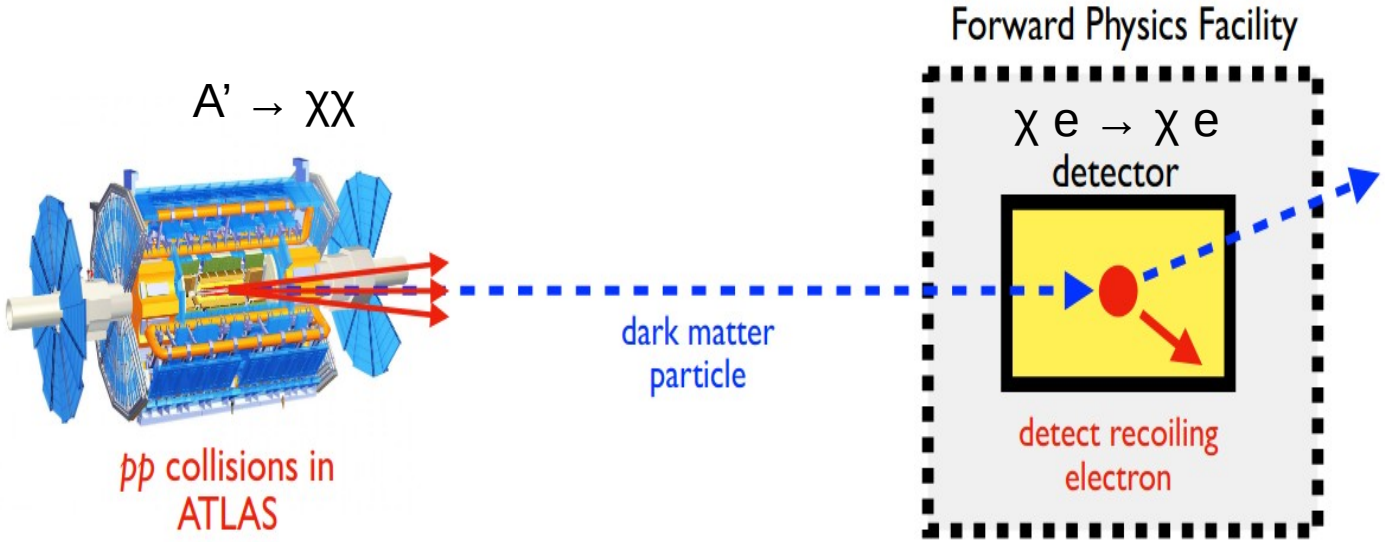
$$\mathcal{L}_D \supset (D^\mu \chi)^* (D_\mu \chi) - m_\chi^2 \chi^* \chi,$$



F. Kling, ST, 2105.07077

Direct light DM detection at the LHC

- We focus on LDM particles produced in the far-forward region of the LHC
  & their scattering in a distance detector



credit B. Batell

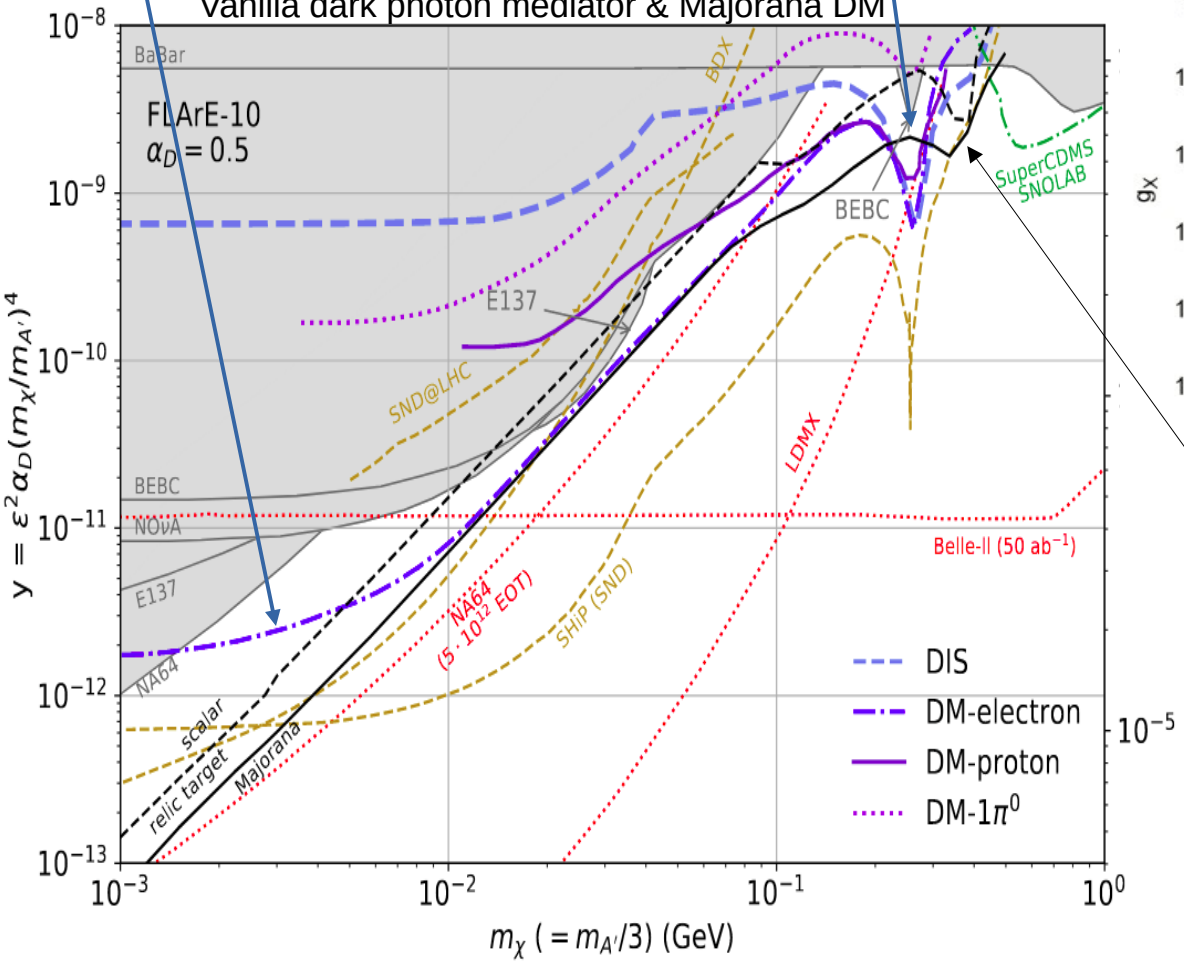
- This search is highly complementary to the traditional DM direct detection searches:
  – probe of relativistic interaction rates of LDM (DM energy ~ a few hundred GeV)
  [collider-boosted DM]
  – the search is not sensitive to the precise abundance of χ DM component
  (possible variations in cosmological scenario)
  [collider-produced DM]

Expected sensitivity reach

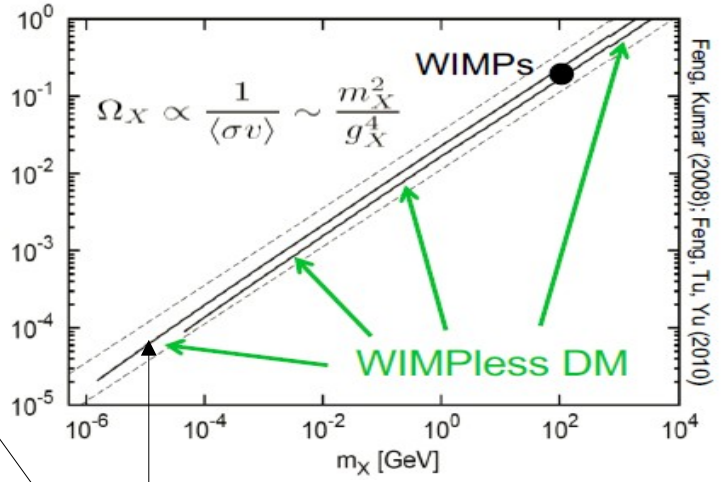
Nuclear scatterings also possible: elastic and DIS signatures

Electron scatterings

Vanilla dark photon mediator & Majorana DM



Thermal freeze-out for mDM << weak scale



DM relic target lines

For specific targets:
- non-relativistic (DM DD) rates low

- CMB bounds avoided
  p-wave suppressed <σv>

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

HEAVY PARTICLES
(UP TO TENS OR HUNDREDS GeV)

MILLICHARGED PARTICLES

Quantised Singularities in the Electromagnetic Field.

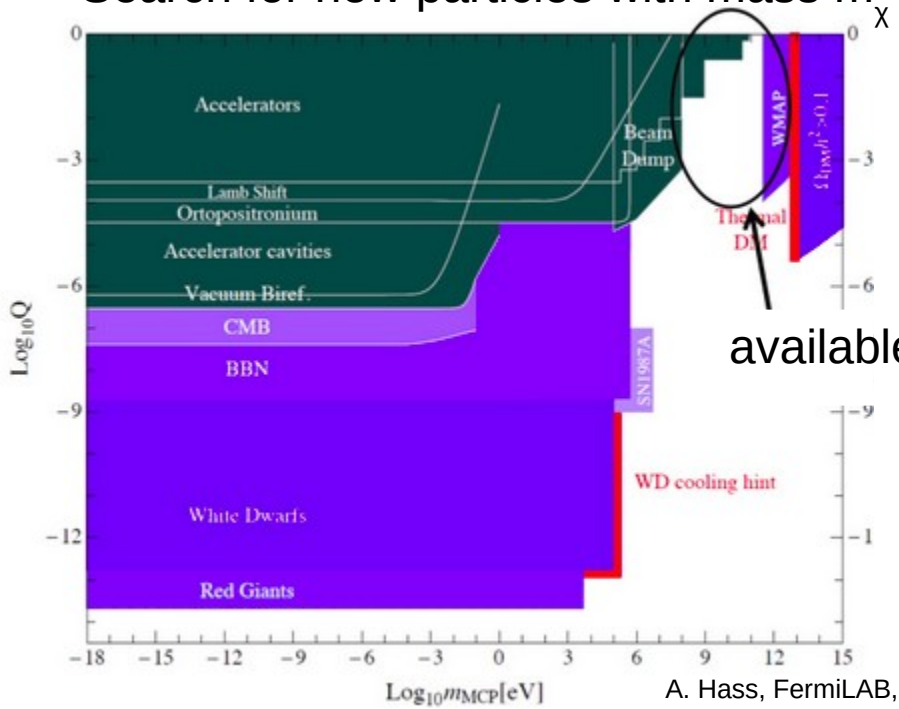
By P. A. M. Dirac, F.R.S., St. John's College, Cambridge.

(Received May 29, 1931.)

- Search for particles with a very small electric charge – test of charge quantization
- Some string theory motivations

Wen, Witten, Nucl. Phys. B 261 (1985) 651-677
Shiu, Soler, Ye, PRL '13

- Can also arise when SM is extended with a massless gauge boson (dark photon) kinetically mixed with the SM photon
- Search for new particles with mass m_χ & electric charge ε'e where ε'<<1



$$\mathcal{L}_{\mathrm{MCP}} = i\bar{\chi}(\not{\partial} - i\epsilon' e \not{B} + M_{\mathrm{MCP}})\chi$$

available window for new millicharge particles

A. Hass, FermiLAB, '17

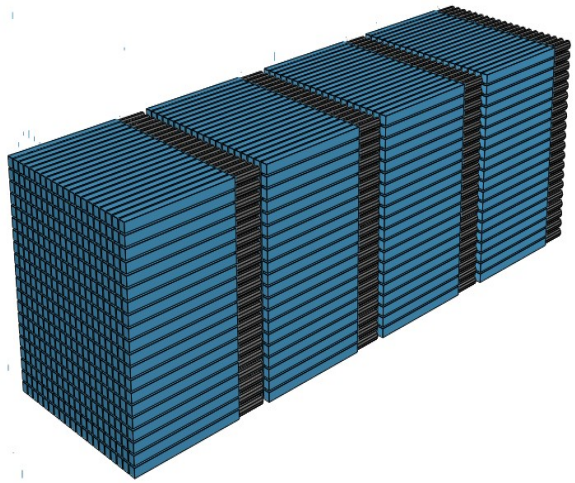
MILLICHARGED PARTICLES AT FPF

S. Foroughi-Abari, F. Kling, Y.-D. Tsai, FORMOSA 2010.07941
FPF whitepaper 2109.10905

- milliQan-like detector placed in the FPF

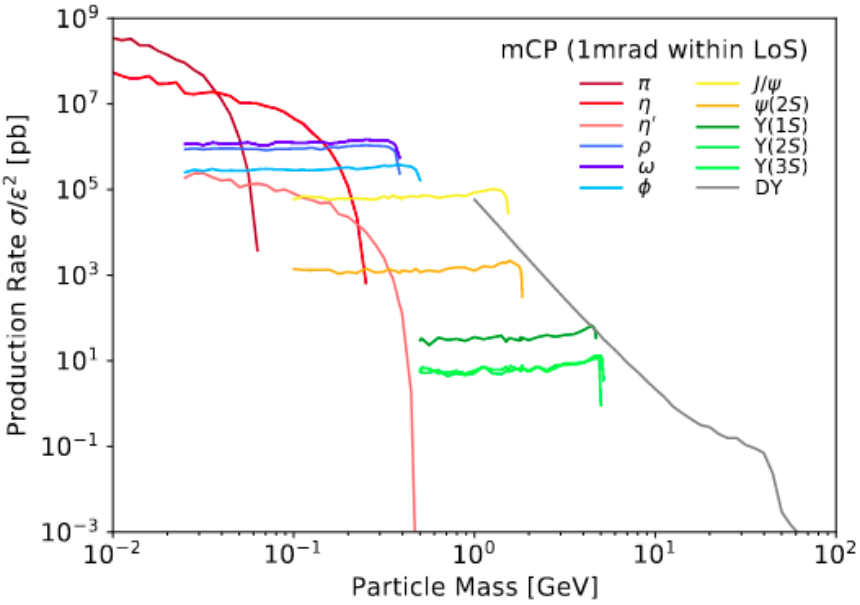
FORMOSA – **FOR**WARD **M**ICR**O**CHARGE **S**E**A**RCH

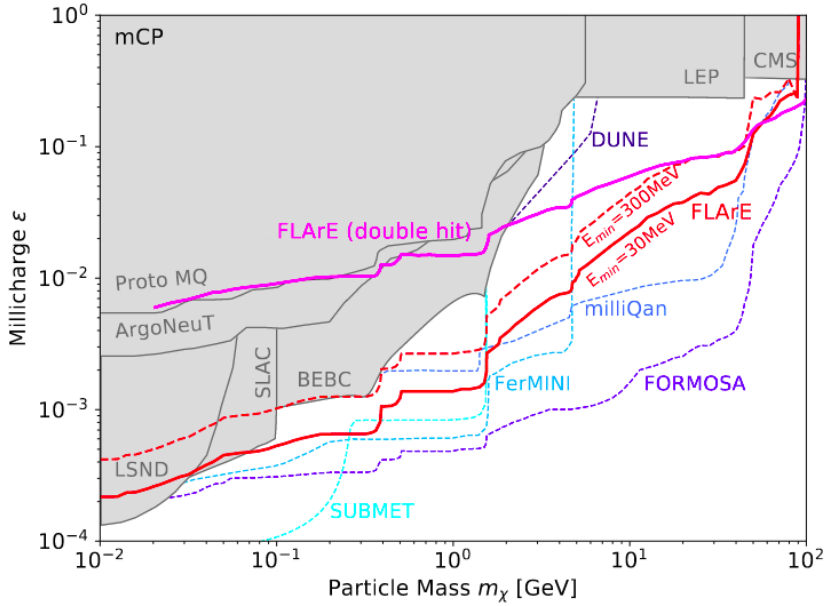
Sensitive to small energy depositions dE/dx of a particle with Q<0.1 e; plastic scintillator for detection



- 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





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

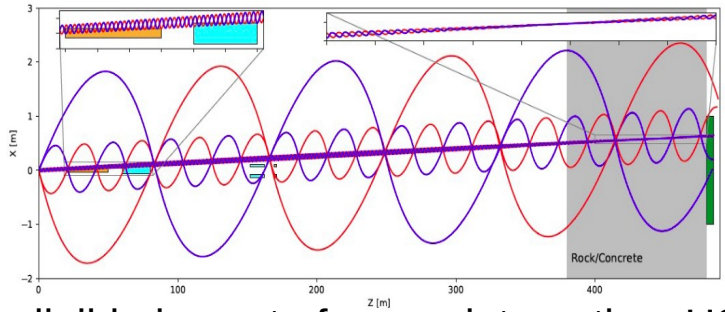
Λ

10 MeV — Rapid oscillations, energy loss via photon/glueball radiation, annihilation (SM resonances)

Un-resolvable oscillations (seen as neutral pair), low energy loss, straight highly ionizing track

10 keV — **Macroscopic oscillations (mm-m), pair of charged particles**

=> they leave fancy tracks



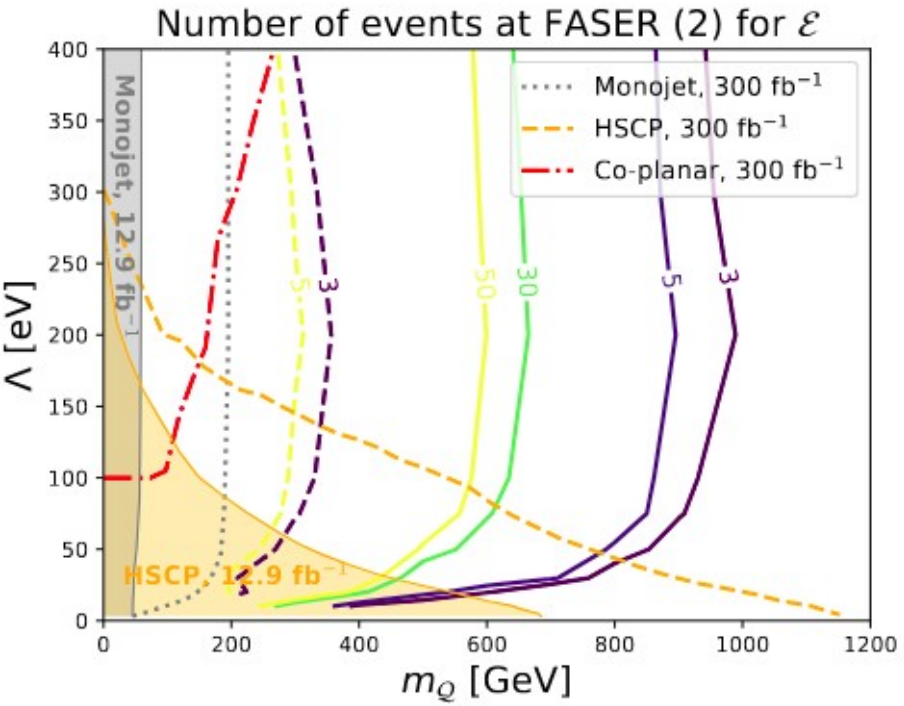
10 eV — Negligible impact of a new interaction, HSCP searches at the LHC

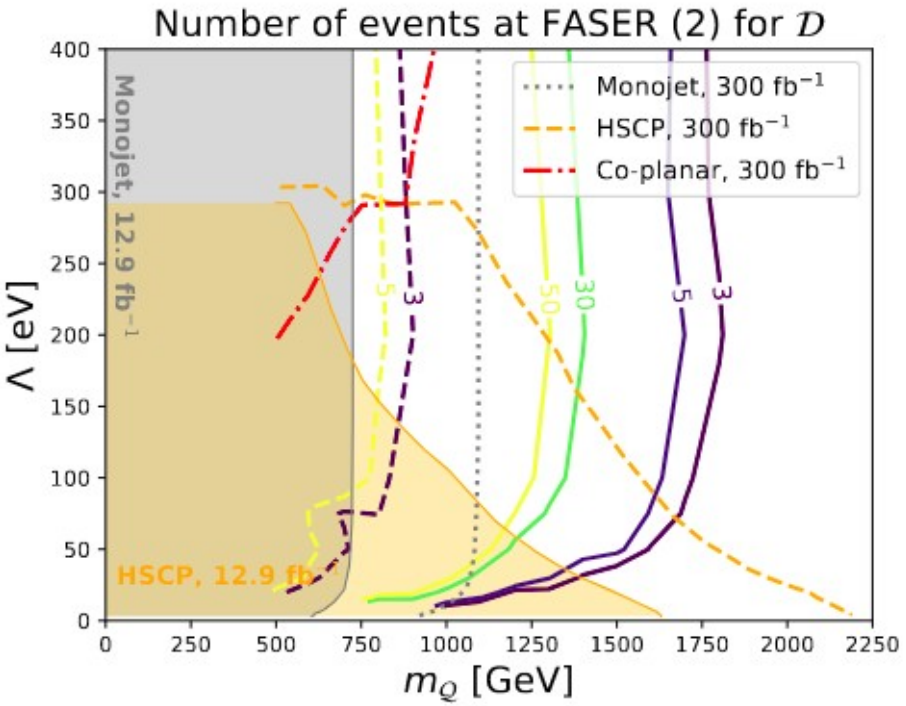
QUIRKS AT FPF

Li, Pei, Ran, Zhang, 2108.06748

- Quirk—anti-quirk system has low p_T → they travel forward (oscillating)
- Heavy (100 GeV - TeV) such quirks require LHC energies to be produced but often travel forward like light particles
- Sample projections for fermionic quirks

$$\mathcal{D} = (N_{\rm IC}, 3, 1, -1/3)\,,$$
$$\mathcal{E} = (N_{\rm IC}, 1, 1, -1)\,,$$



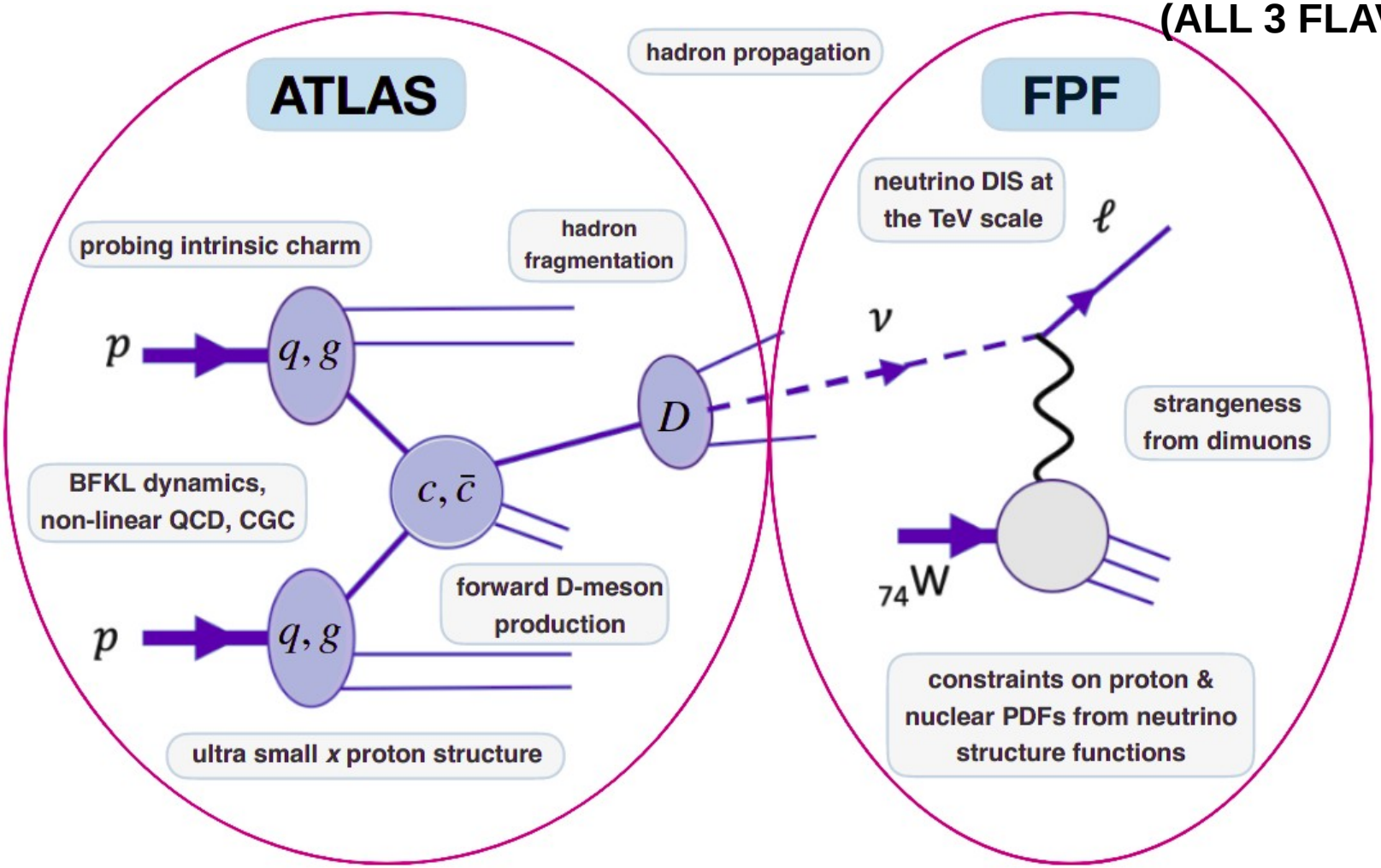


NEUTRINO PHYSICS PROGRAM

NEUTRINO PRODUCTION & DETECTION

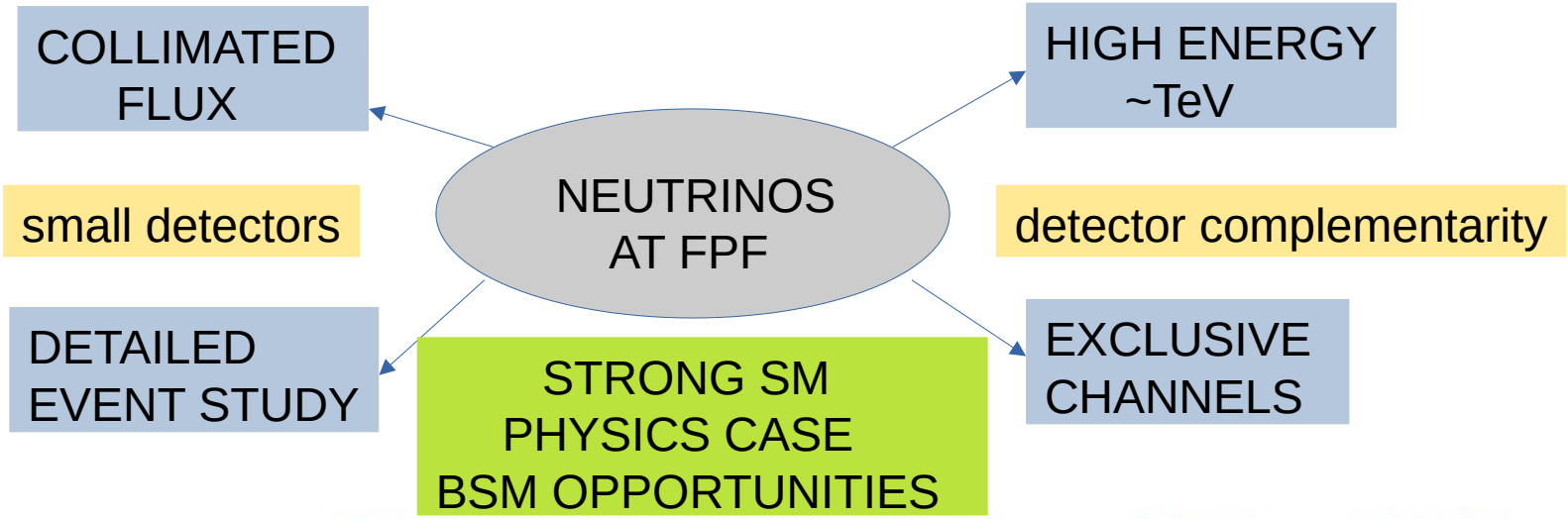
LIGHT HADRON & CHARM MESON DECAYS

NEUTRINO INTERACTIONS ON NUCLEAR TARGETS (ALL 3 FLAVORS)

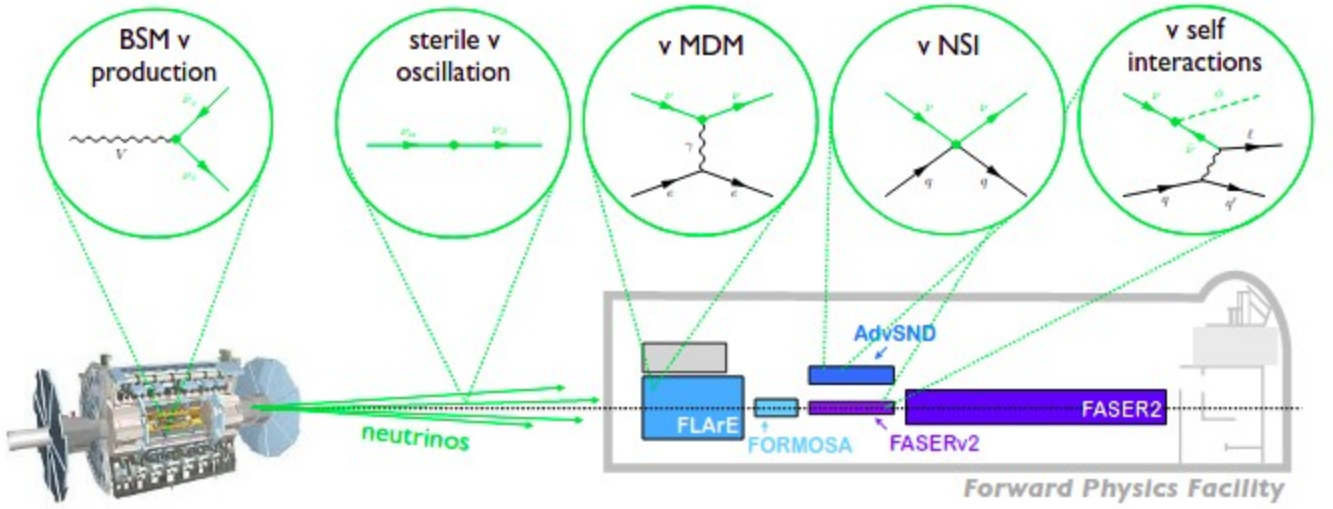


Forward LHC Neutrinos

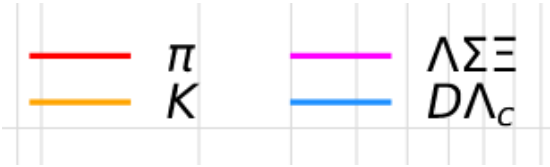
High-energy neutrinos at the LHC are preferentially produced in the forward direction



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



FORWARD NEUTRINOS



- Pions (for ν_μ) & kaons (ν_e)
  dominate at energies up to few hundred GeV

- Charm dominates at larger energies
  (also all ν_τ from charm)

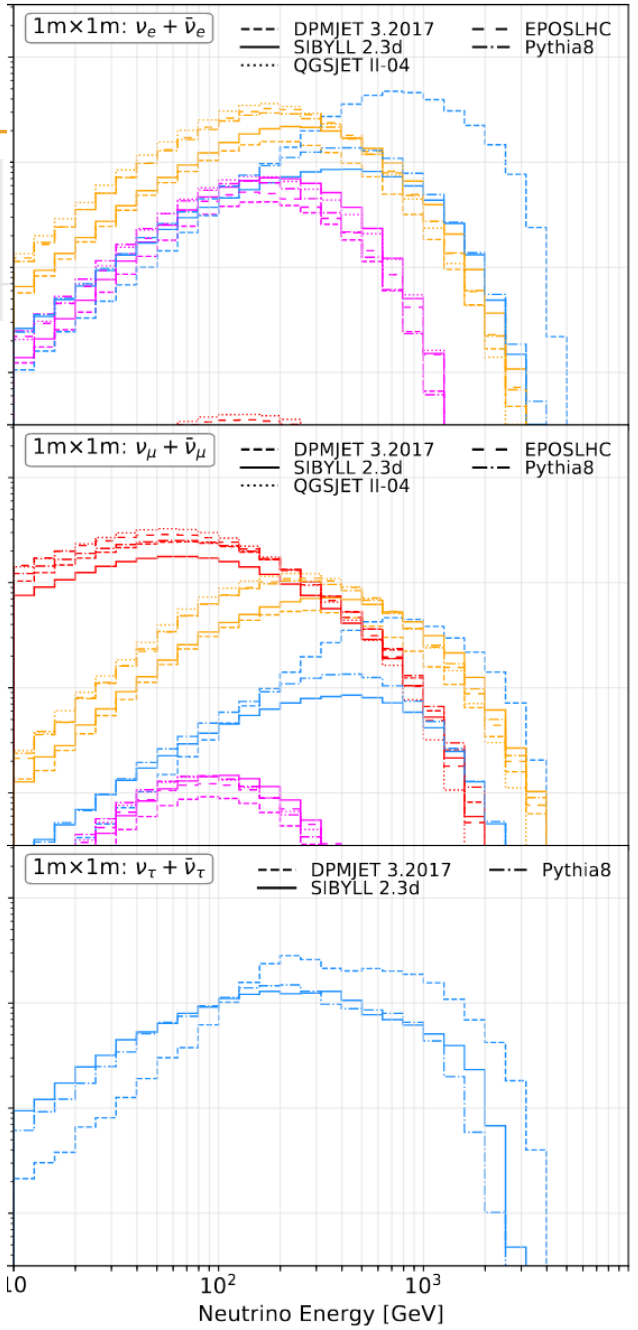
Here – larger uncertainties, further studies ongoing

Measuring neutrino flux & spectrum

window to study forward hadron production in pp collisions at the LHC

- Expected CC event rates (HL-LHC)

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

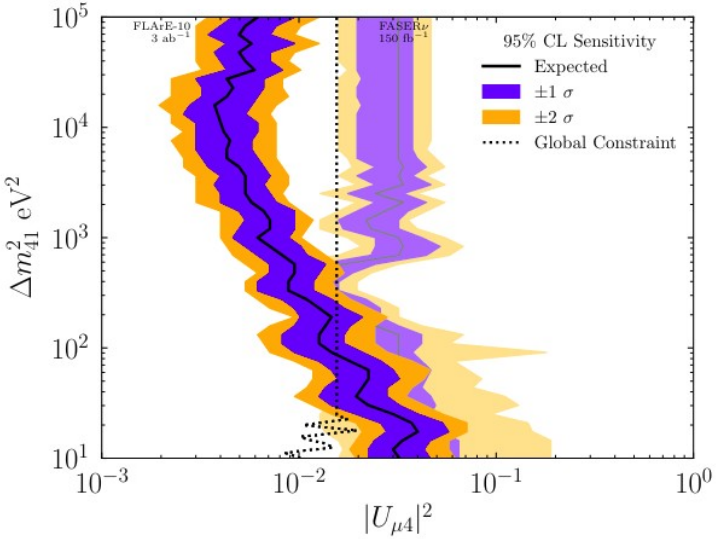


NEUTRINO BSM HIGHLIGHTS

- Neutrino oscillations into sterile neutrinos direct probes at larger mass differences than typical neutrino experiments

$$\Delta m^2 \sim 1000\ \mathrm{eV}^2$$

(also e.g. Gallium anomaly)



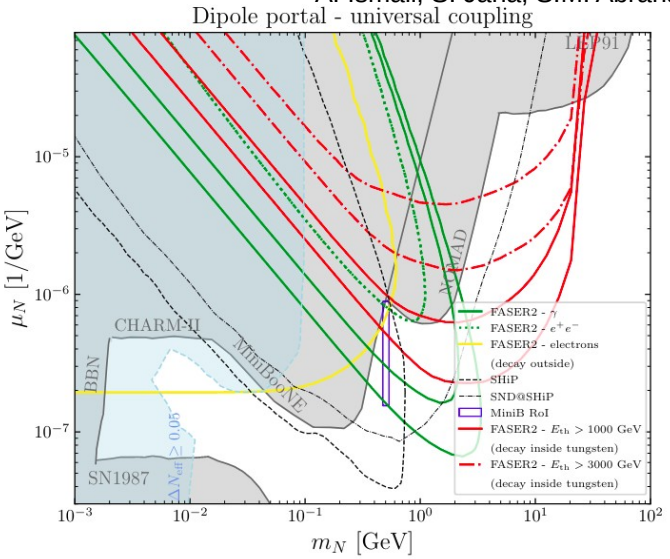
- Non-standard neutrino interactions

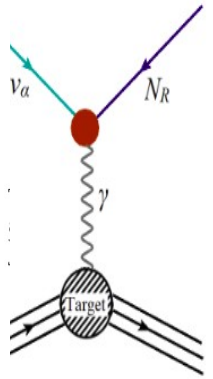
K. Jodłowski, ST, 2011.04751
A. Ismail, S. Jana, S.M. Abraham, 2109.05032

Example: dipole portal to heavy neutral leptons

Magill etal, 1803.03262

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





Transition magnetic moments of neutrinos before EWSB

$$\mathcal{L} \supset \bar{L}\left(d_W \mathcal{W}^a_{\mu\nu}\tau^a + d_B B_{\mu\nu}\right)\tilde{H}\sigma_{\mu\nu}N_D + h.c.$$

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)

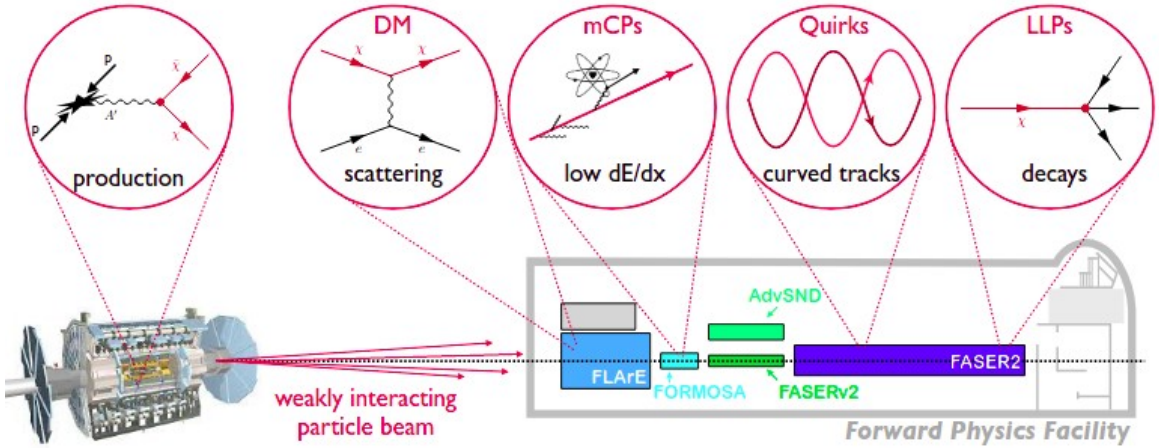
c) **facilitate exchange of (new) ideas** related to FPF BSM physics
(slack channel, community, feedback from experimental representatives)

WE INVITE CONTRIBUTIONS / HAPPY TO DISCUSS IDEAS

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



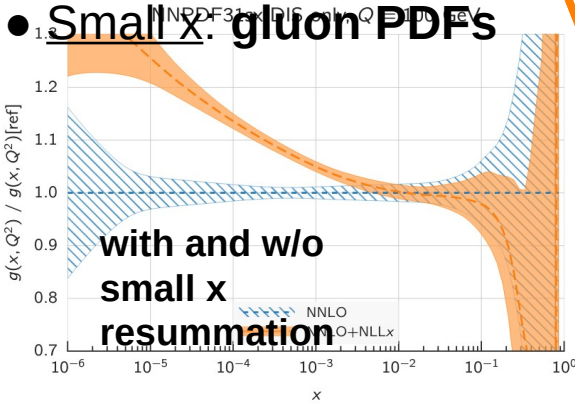
THANK YOU !

BACKUP

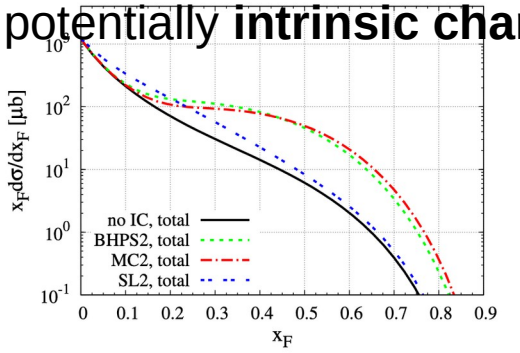
NEUTRINOS FROM CHARM DECAYS

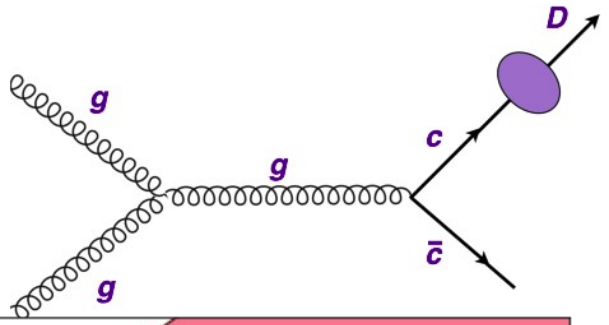
- probes of low-x (~10^{-7}) and high-x (~0.1-1) regimes at low Q

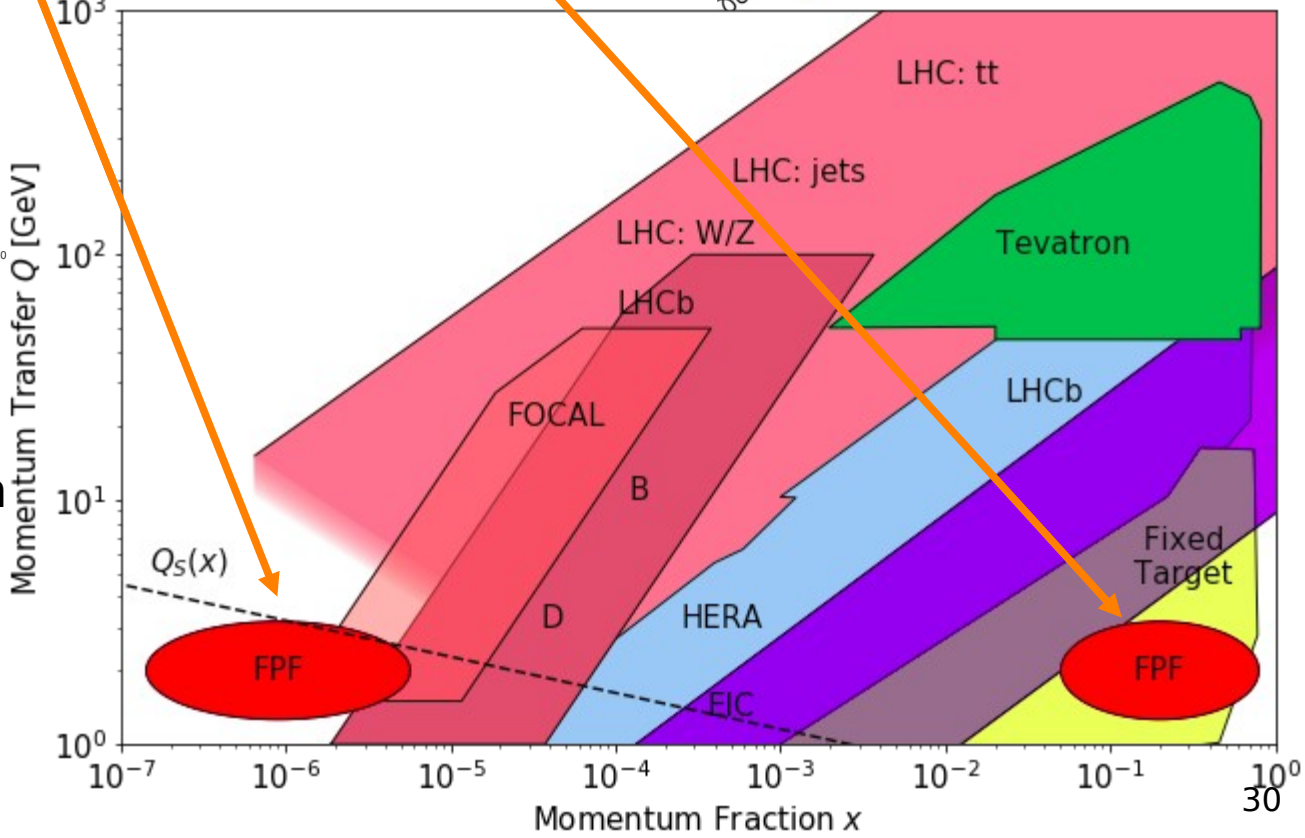
- Small x: **gluon PDFs**



- Large x: charm sea & potentially **intrinsic charm**







NEUTRINO DEEP INELASTIC SCATTERING

- Nuclear PDF measurements

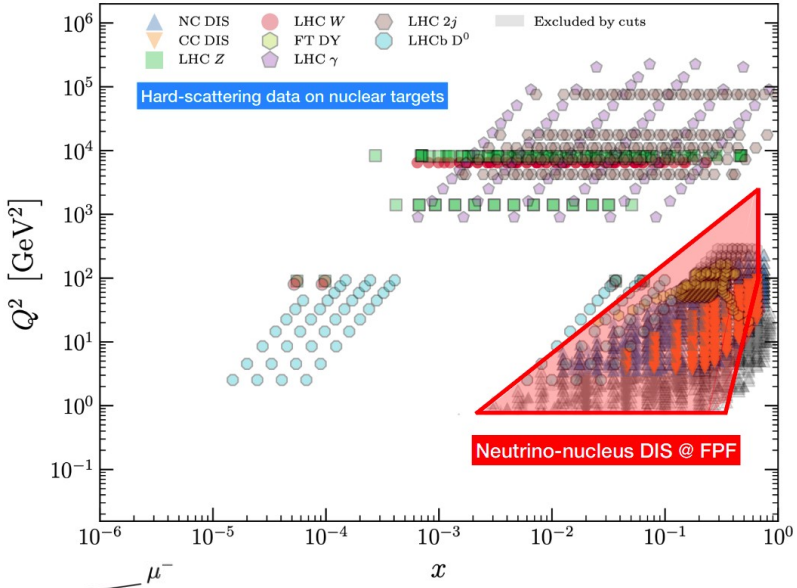
– high-energy νs → extended kinematic coverage

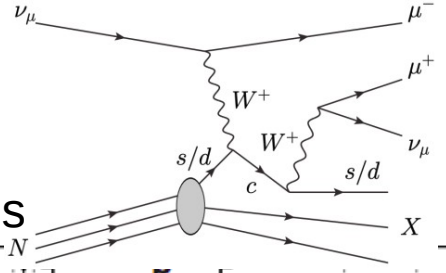
– possible measurements for various nuclear targets (Ar, W)

- Strange PDFs (separate s and anti-s)

Di-muon final state in CC DIS from intermediate charm, ν_μ s → c μ, and c → D → μ x

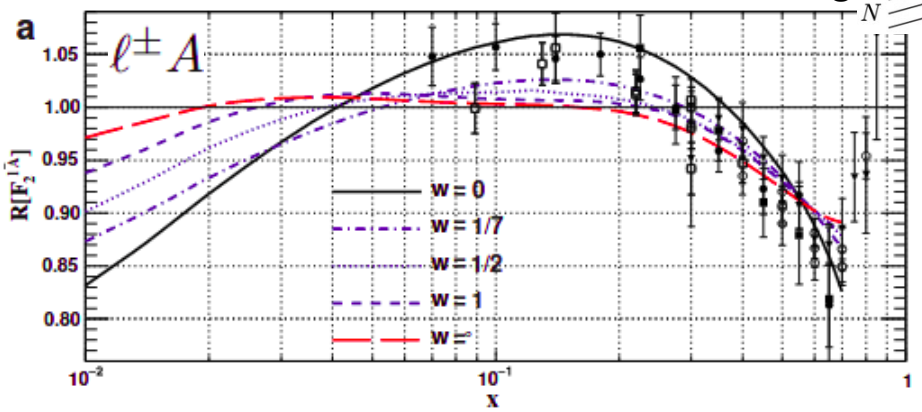
FPF: various expermients to tag charm and muons

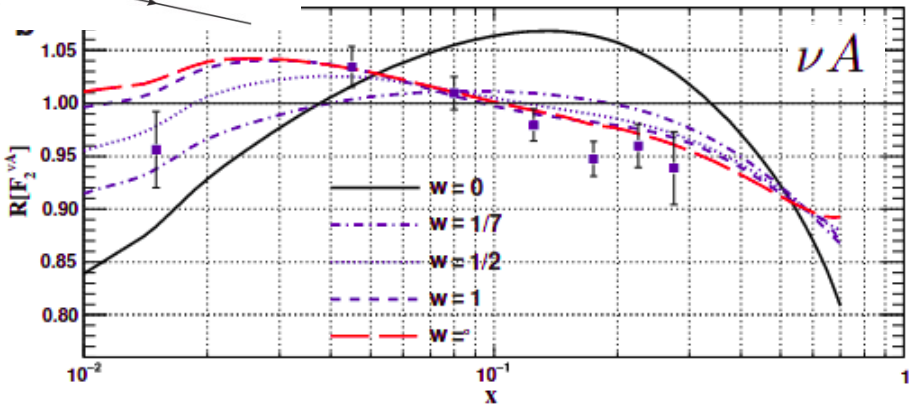




- nuclear effects in neutrino scatterings

hep-ph/





Example signature: DM scattering off electrons

- Signature: recoiled electron (recoil energy E_e)
- Light mediator favors low energy electron recoil
- Neutrino-induced backgrounds: larger recoils

Neutrino scattering example

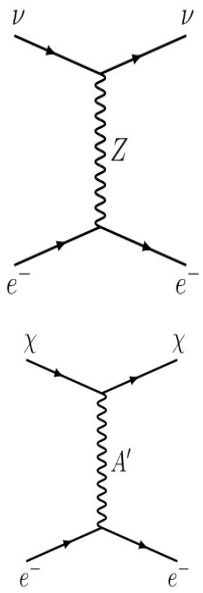
$$\frac{d\sigma(\nu_l e \to \nu_l e)}{dy} = \frac{2m_e G_F^2 E_\nu}{\pi} \frac{1}{(1+2m_e E_\nu y/M_Z^2)^2} \left(g_L^2 + g_R^2(1-y)^2\right),$$

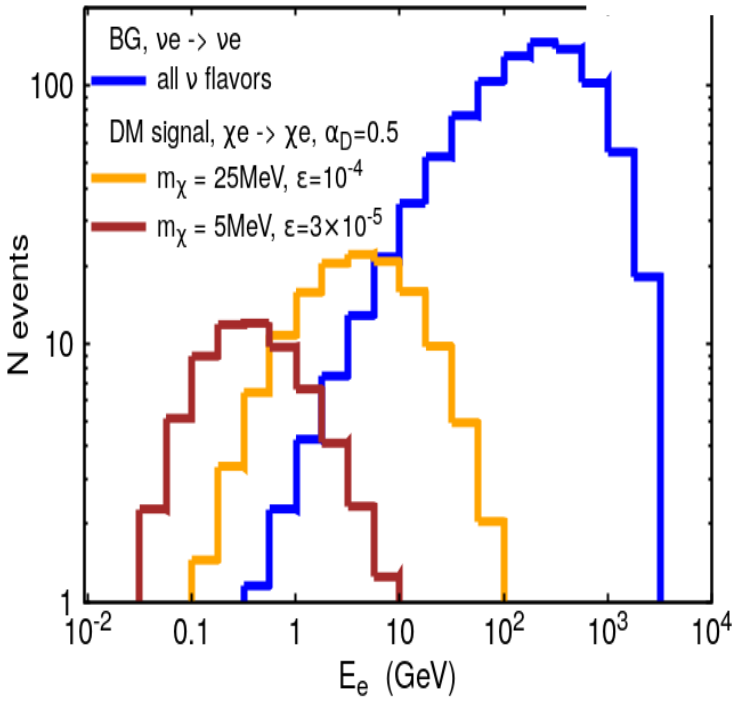
y = $E_e/(E_x,E_\nu)$

DM scattering (dark photon mediator)

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

$m_{A'} << M_Z$





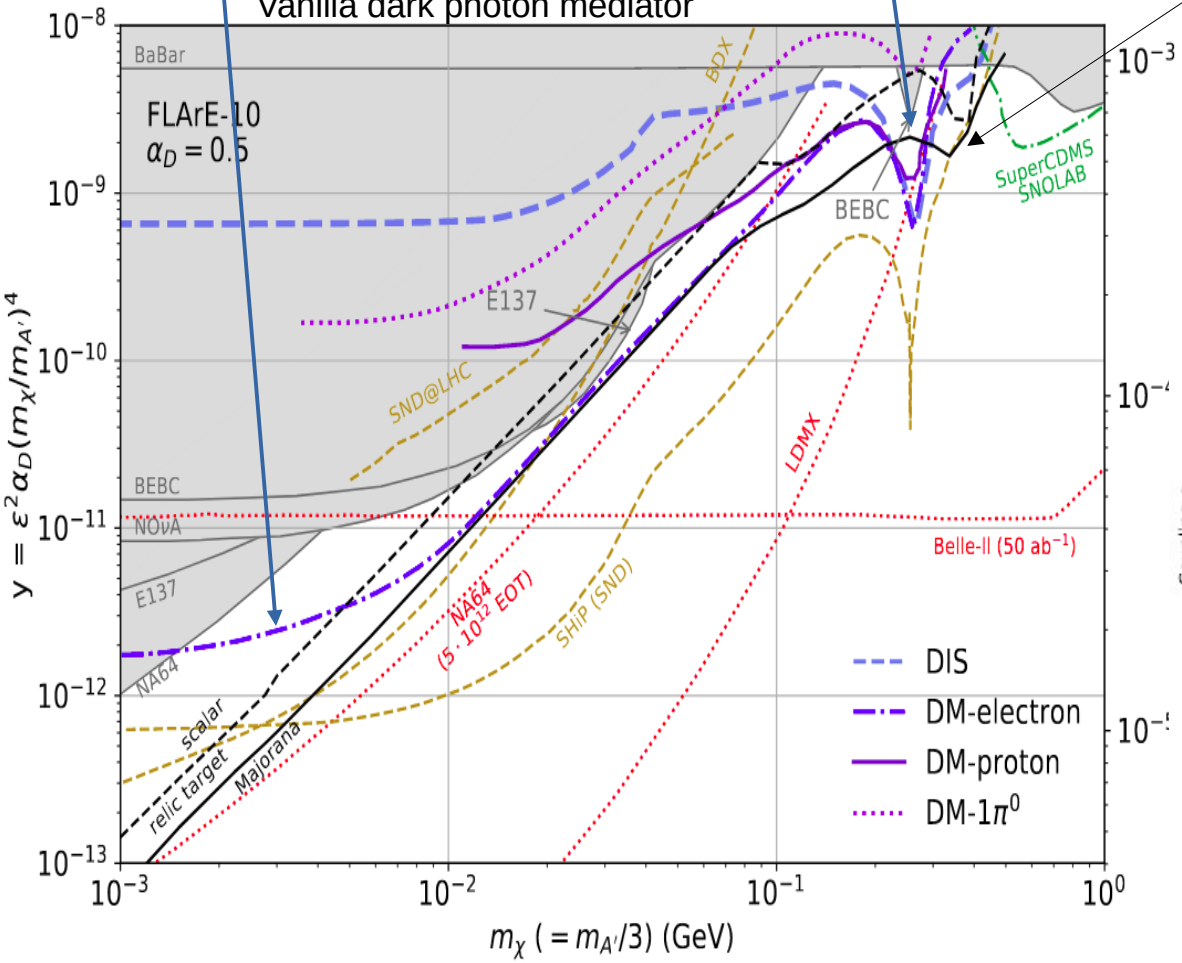
Expected sensitivity reach

Nuclear scatterings also possible: elastic and DIS signatures

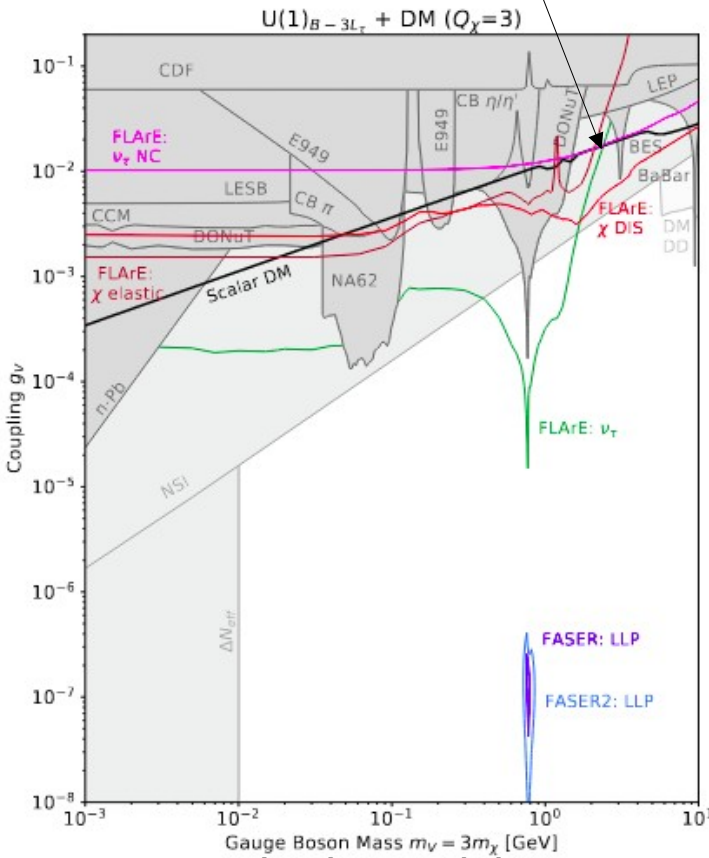
Electron scatterings

Vanilla dark photon mediator

relic target lines



B- 3Lτ mediator
Multiple signatures



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