OVERVIEW OF NEW PHYSICS SEARCHES AT THE FORWARD PHYSICS FACILITY AT THE LHC

Sebastian Trojanowski

Dark Interactions
New Perspectives from Theory and Experiment

November 15, 2022

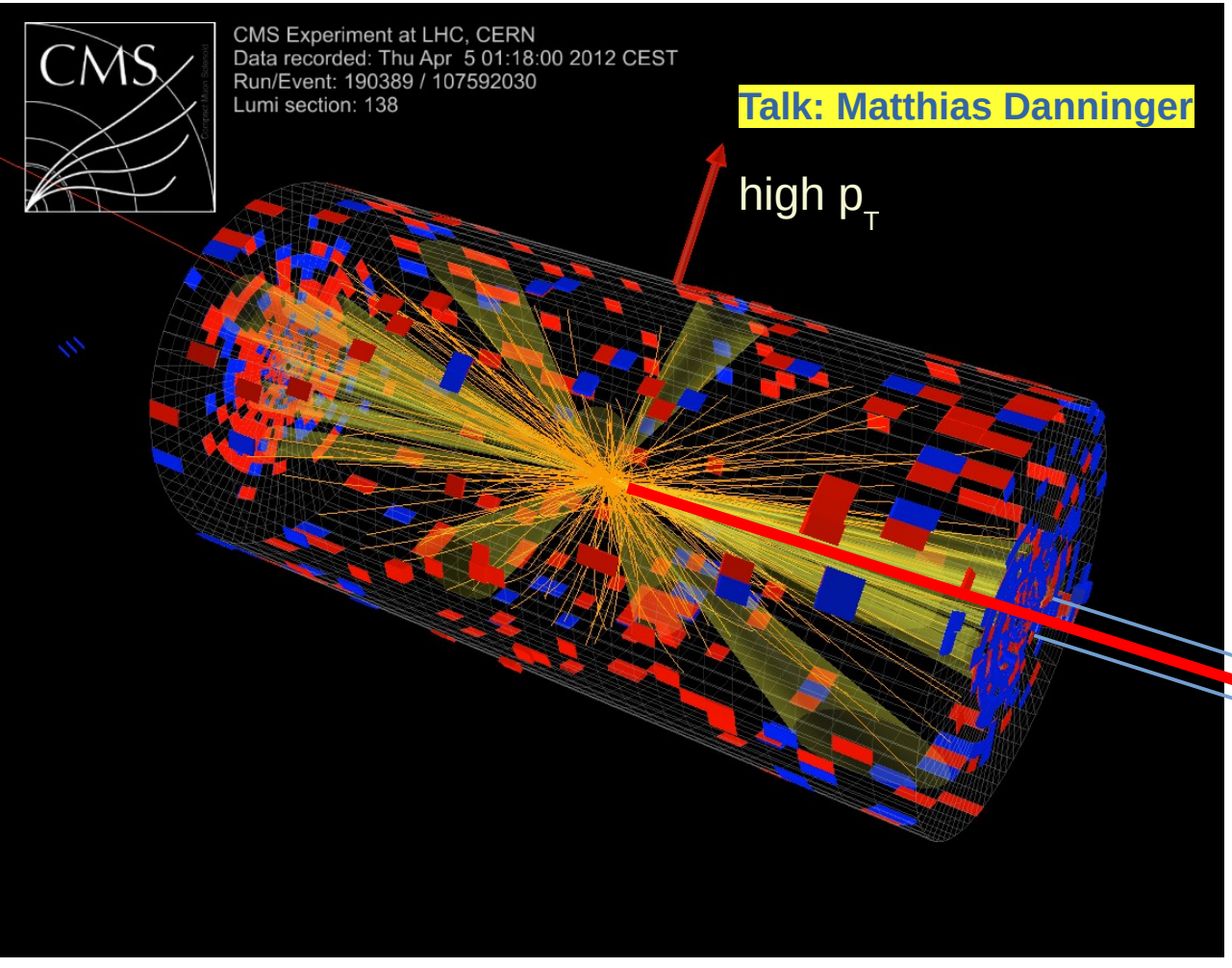
Whitepapers:
J.L. Feng, F. Kling, M.H. Reno, J. Rojo, D. Soldin etal, 2203.05090
L.A. Anchordoqui etal, 2109.10905
+ many other papers

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)

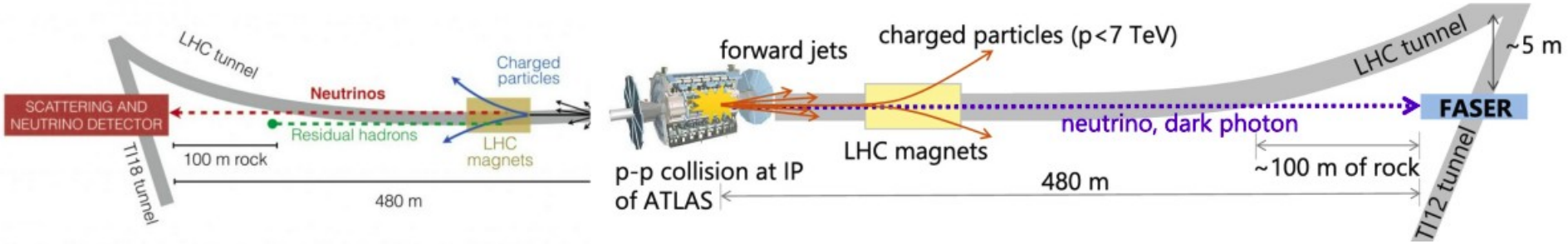
Forward physics

down the beam pipe

Also talk: Tobias Boeckh

FORWARD PHYSICS FACILITY

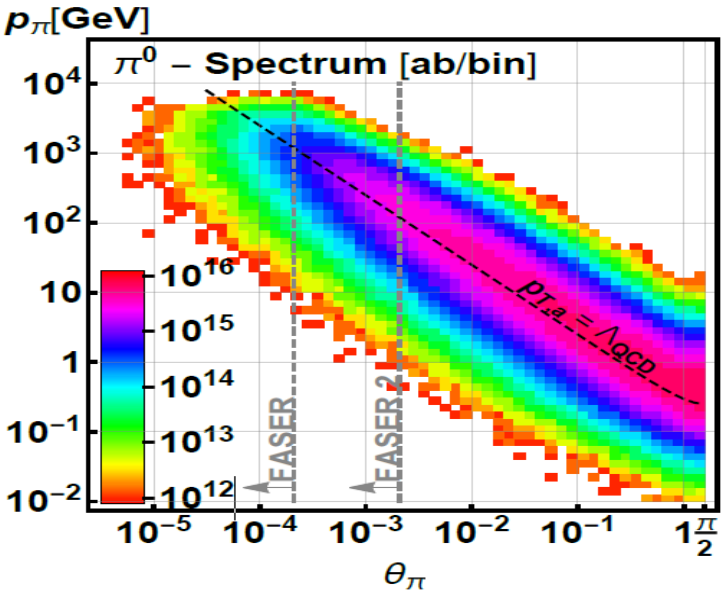
FAR-FORWARD SEARCHES AT THE LHC



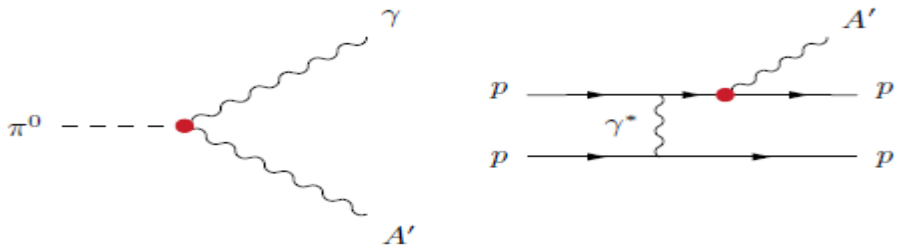
- Forward direction: lots of activity down the beam pipe

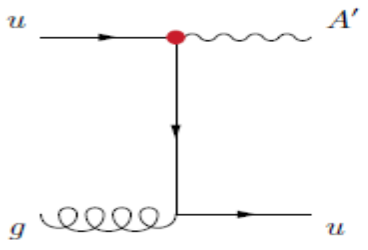
- Far-forward detectors:
  - well-screened from pp collisions
  - only neutrinos and muons survive
  - can search for rare BSM events

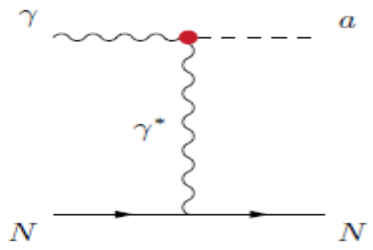
- Run 3: FASER, SND@LHC



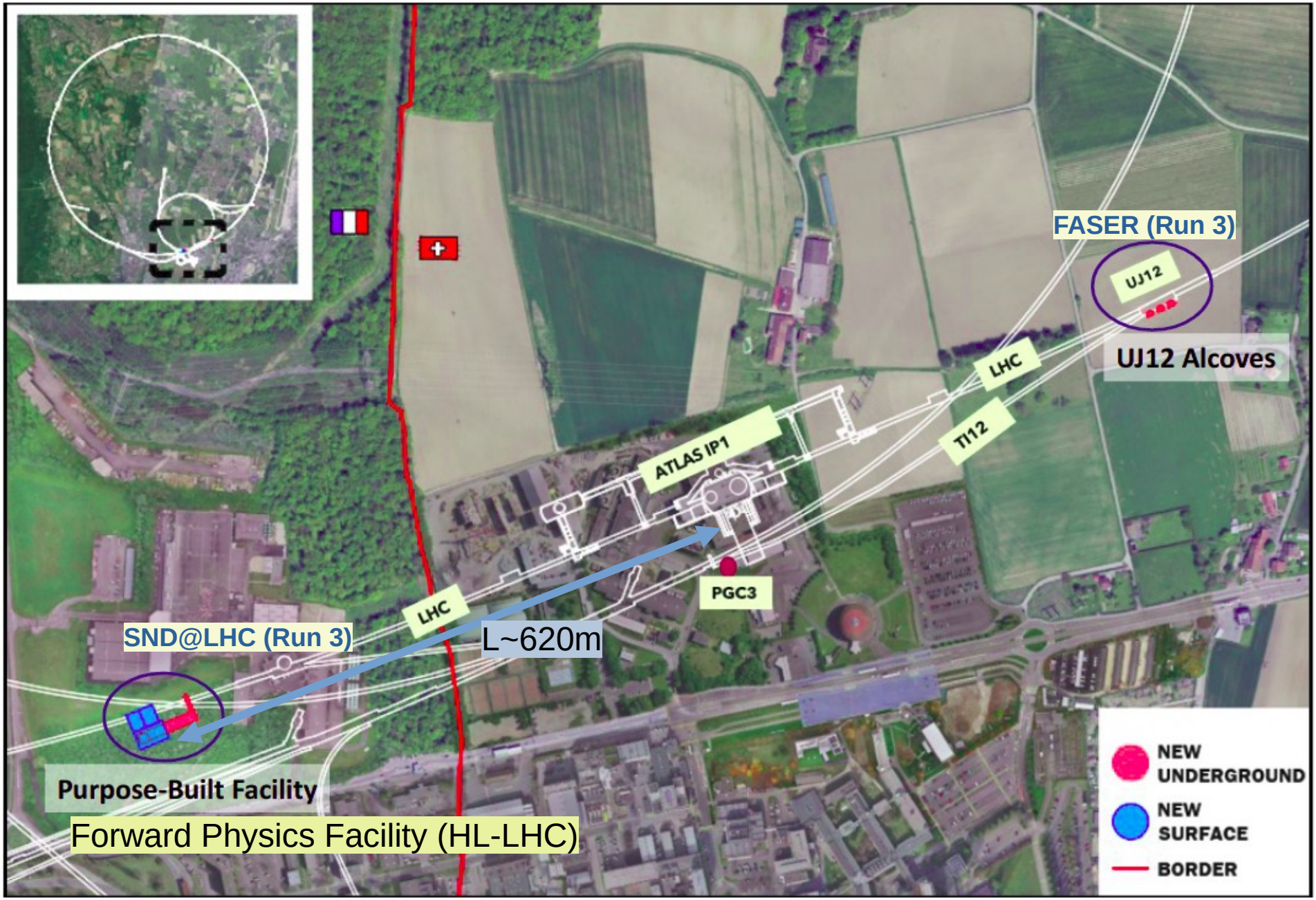
SAMPLE PRODUCTION MODES (DARK PHOTON)







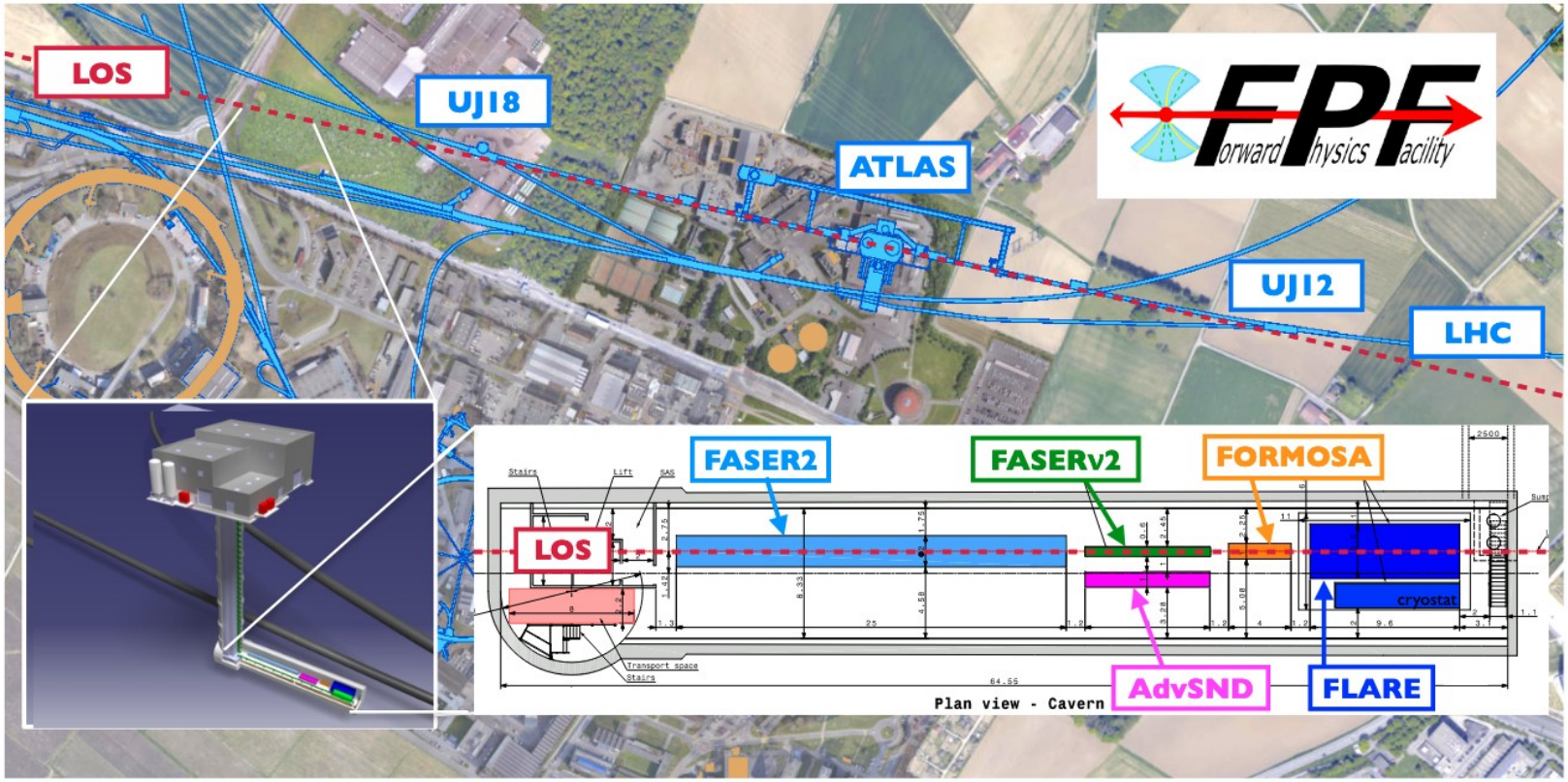
Far-forward searches at the LHC in a bird's eye view



PURPOSE-BUILT FACILITY

Underground facility:

- ~620 m far forward from the ATLAS IP,
- shielded by ~200 m concrete and rock.
- FPF experiments to detect neutrino interactions, energies up to a few TeV,
- and search for new physics
- Several experiments proposed so far (signatures: decay, scattering, ionization)



STATUS

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

- Forward Physics Facility (FPF)

In the U.S. the Snowmass process is concluding. From the Energy Frontier Executive Summary:

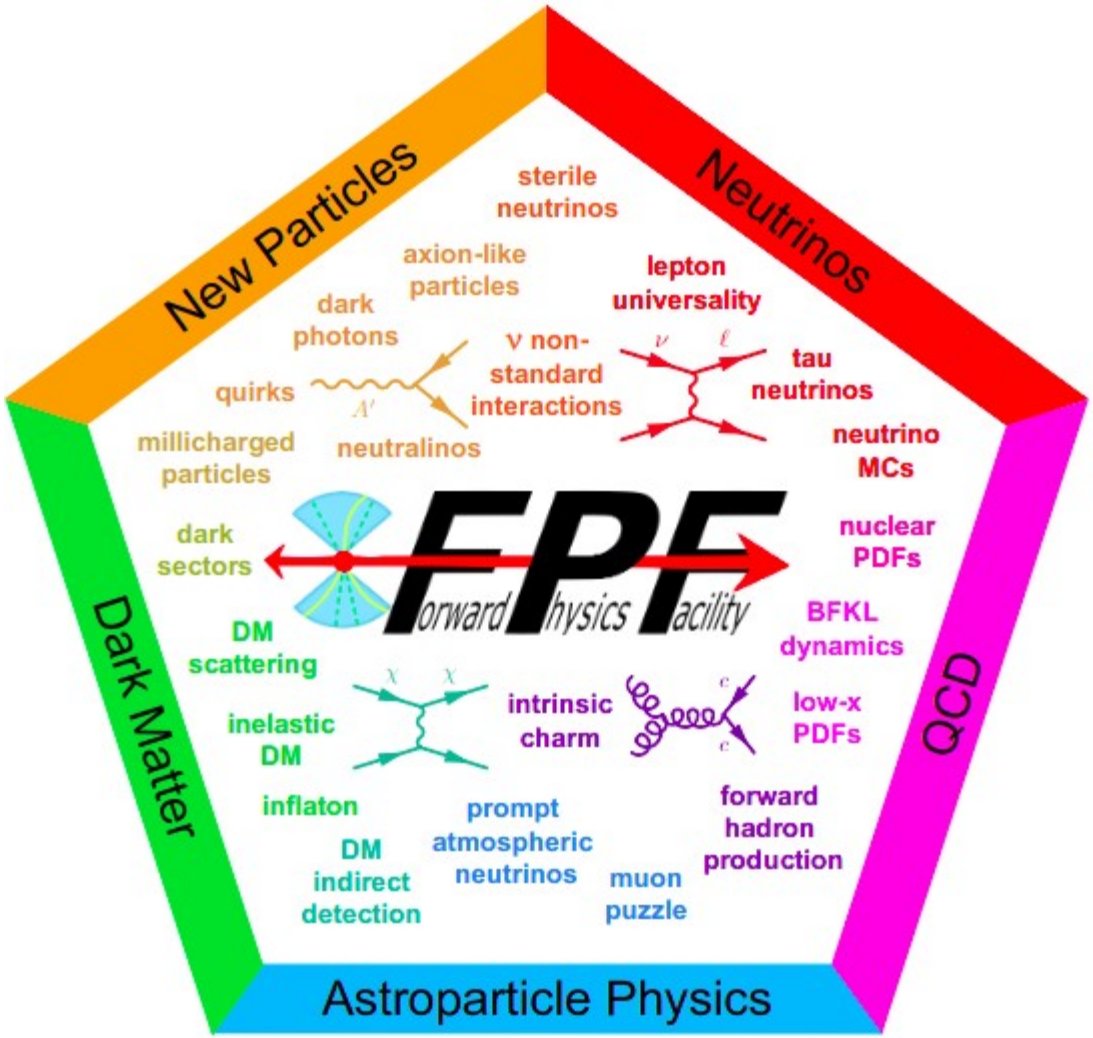
– "Our highest immediate priority accelerator and project is the HL-LHC, the successful completion of the detector upgrades, operations of the detectors at the HL-LHC, data taking and analysis, **including the construction of auxiliary experiments that extend the reach of HL-LHC in kinematic regions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

Also strong endorsements of the FPF physics case from the Neutrino Frontier, the Rare Processes Frontier, and the Cosmic Frontier.

CERN:

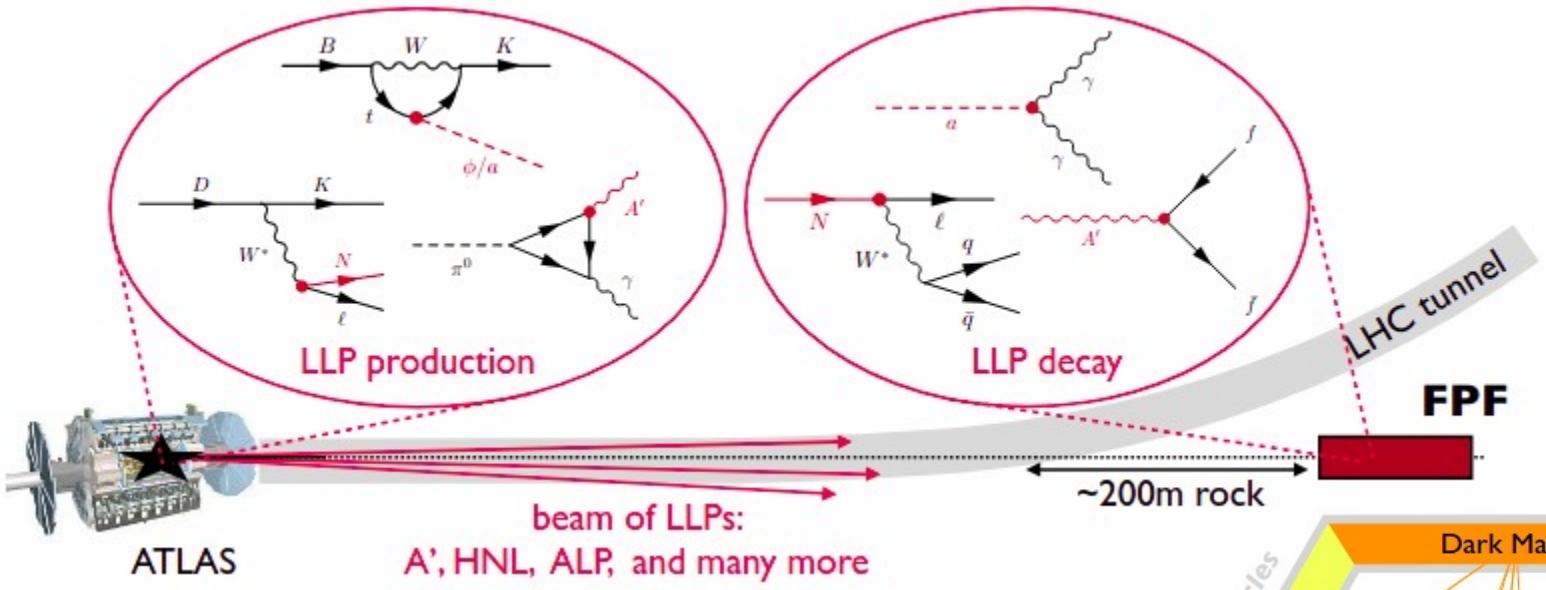
- large progress in facility planning (e.g. make sure that FPF installation and operation will not interfere with the LHC)
- extensive simulations (CERN FLUKA team); BG and radiation safety, **muons**
- first informal discussions with the LHCC chair
- Physics Beyond Colliders (PBC) at CERN allocated 75K CHF for site investigation

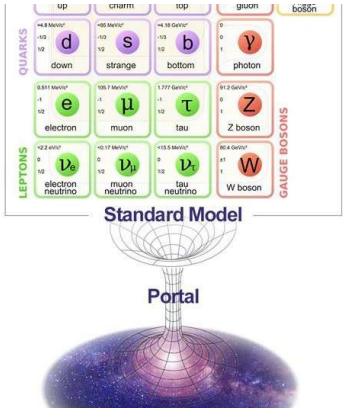
PHYSICS AT THE FPF



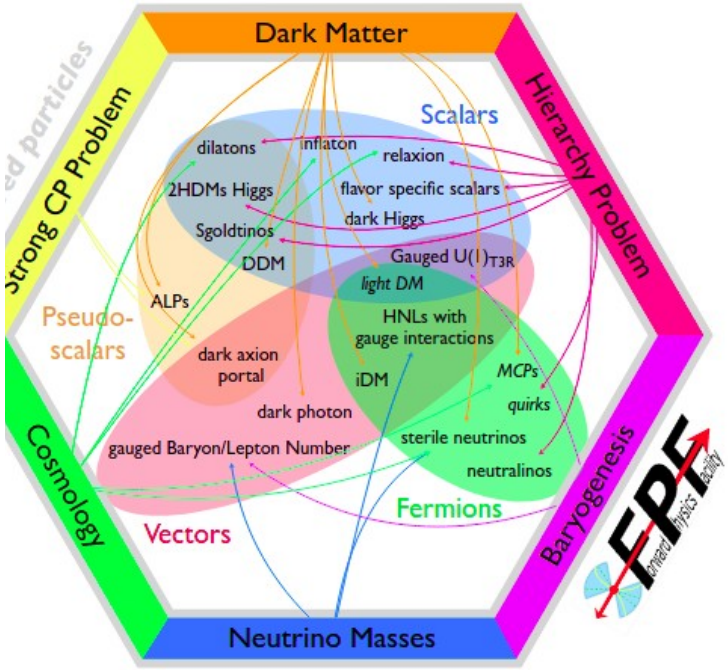
LIGHT LONG-LIVED PARTICLES (DECAYS)

MANY LLP STUDIES





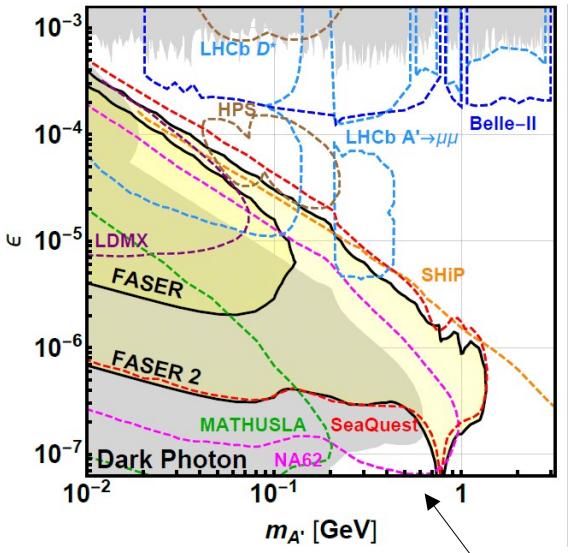
Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma$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



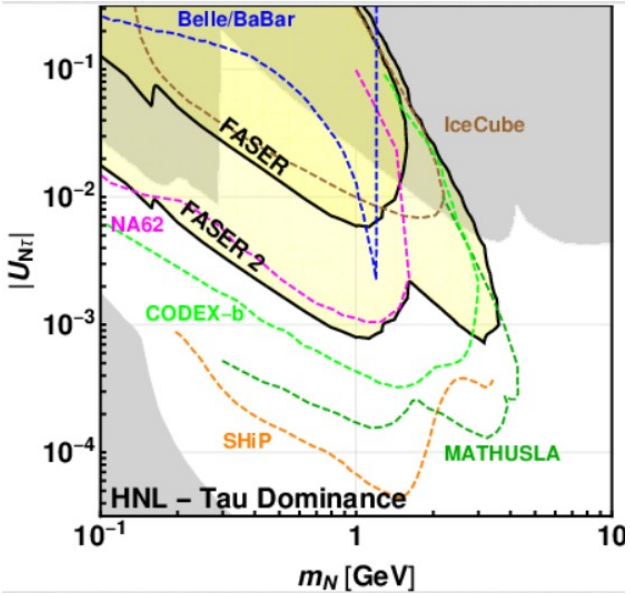
FASER Collaboration, 1811.12522

SELECTED SENSITIVITY REACH PLOTS

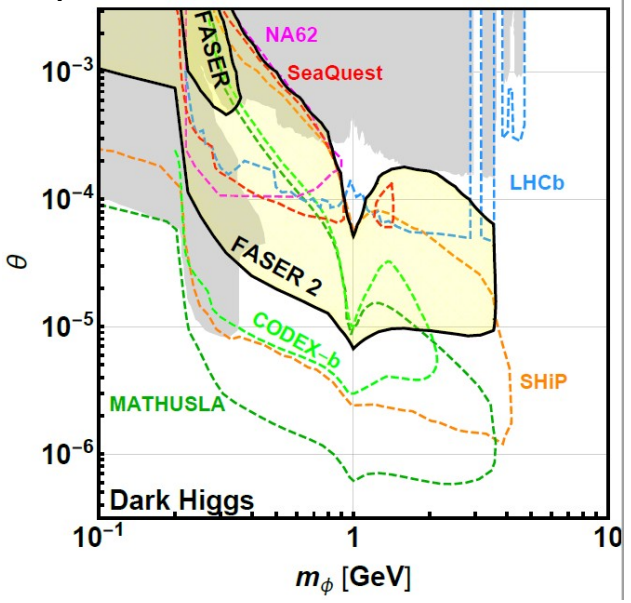
DARK PHOTON



HEAVY NEUTRAL LEPTON (TAU)



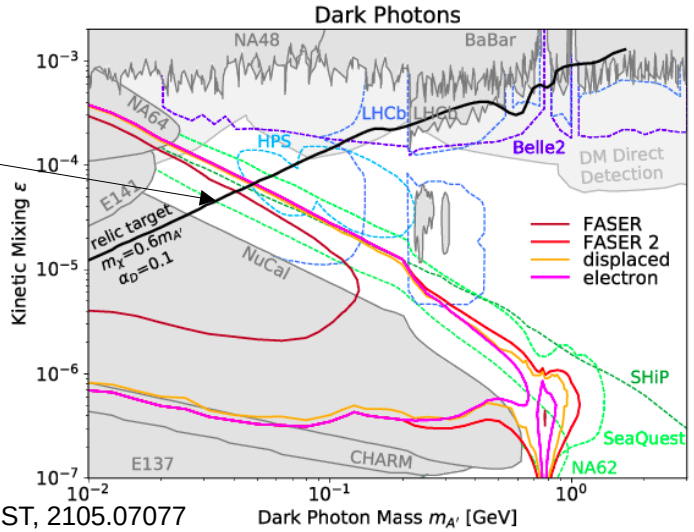
DARK HIGGS BOSON



complementarity

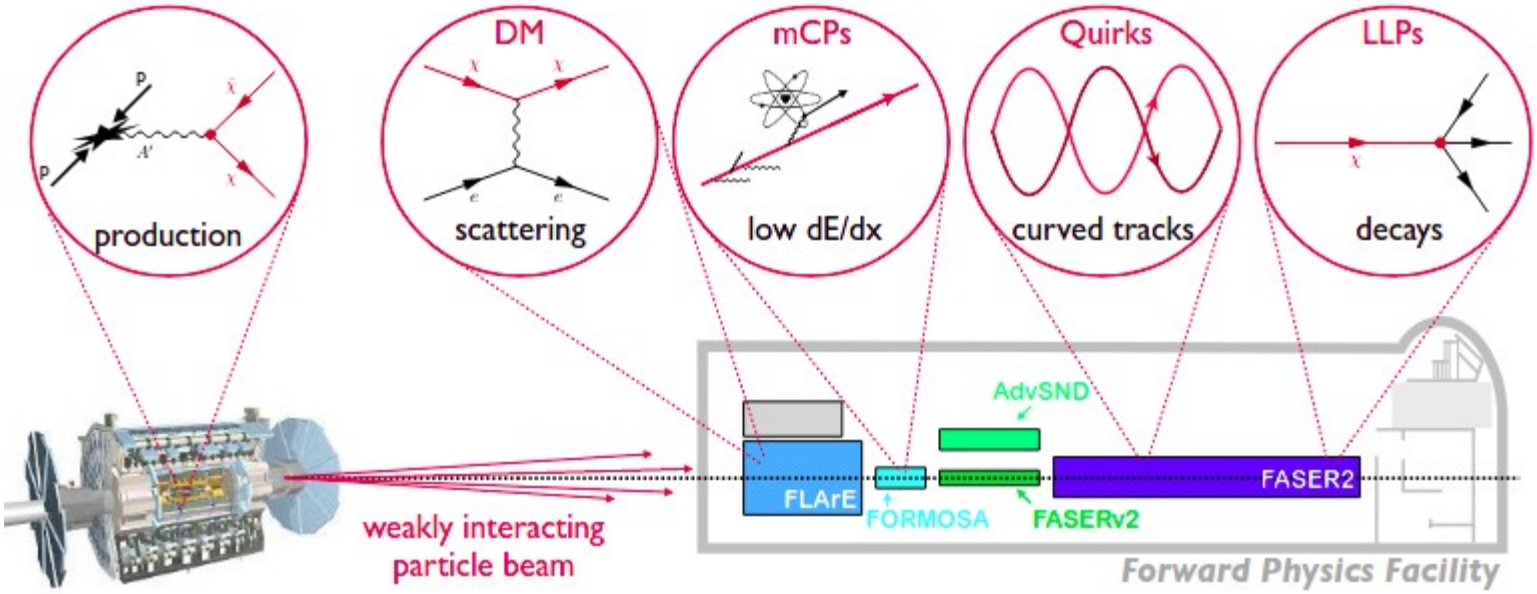
DM direct detection searches complex scalar DM with A' med

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



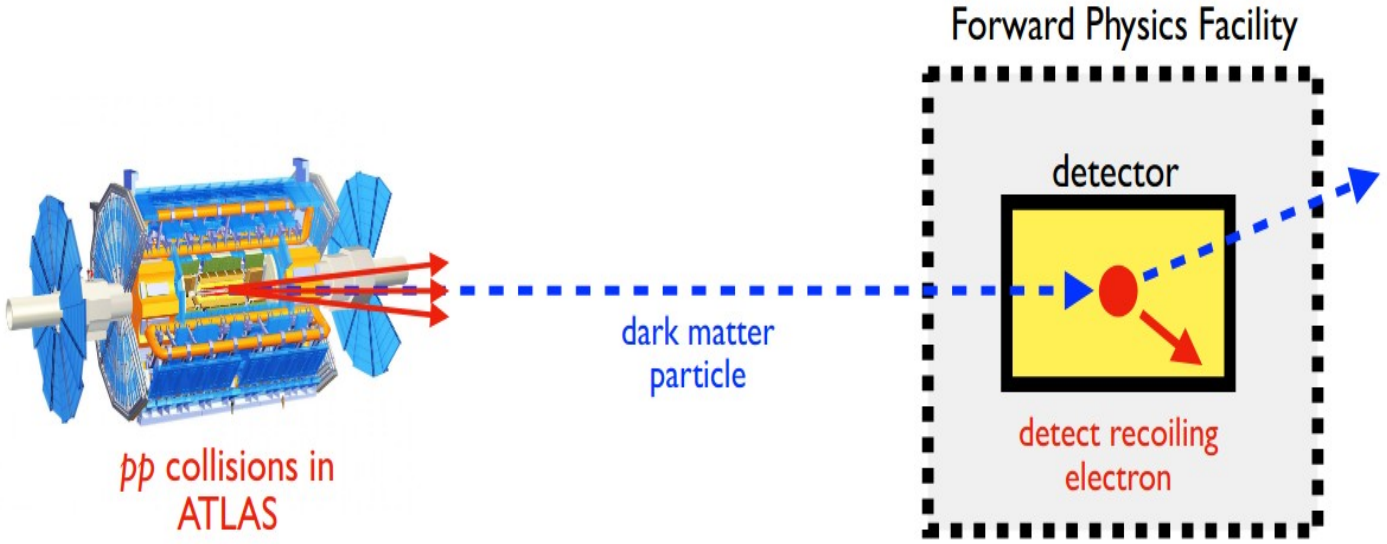
F. Kling, ST, 2105.07077

OTHER SIGNATURES



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

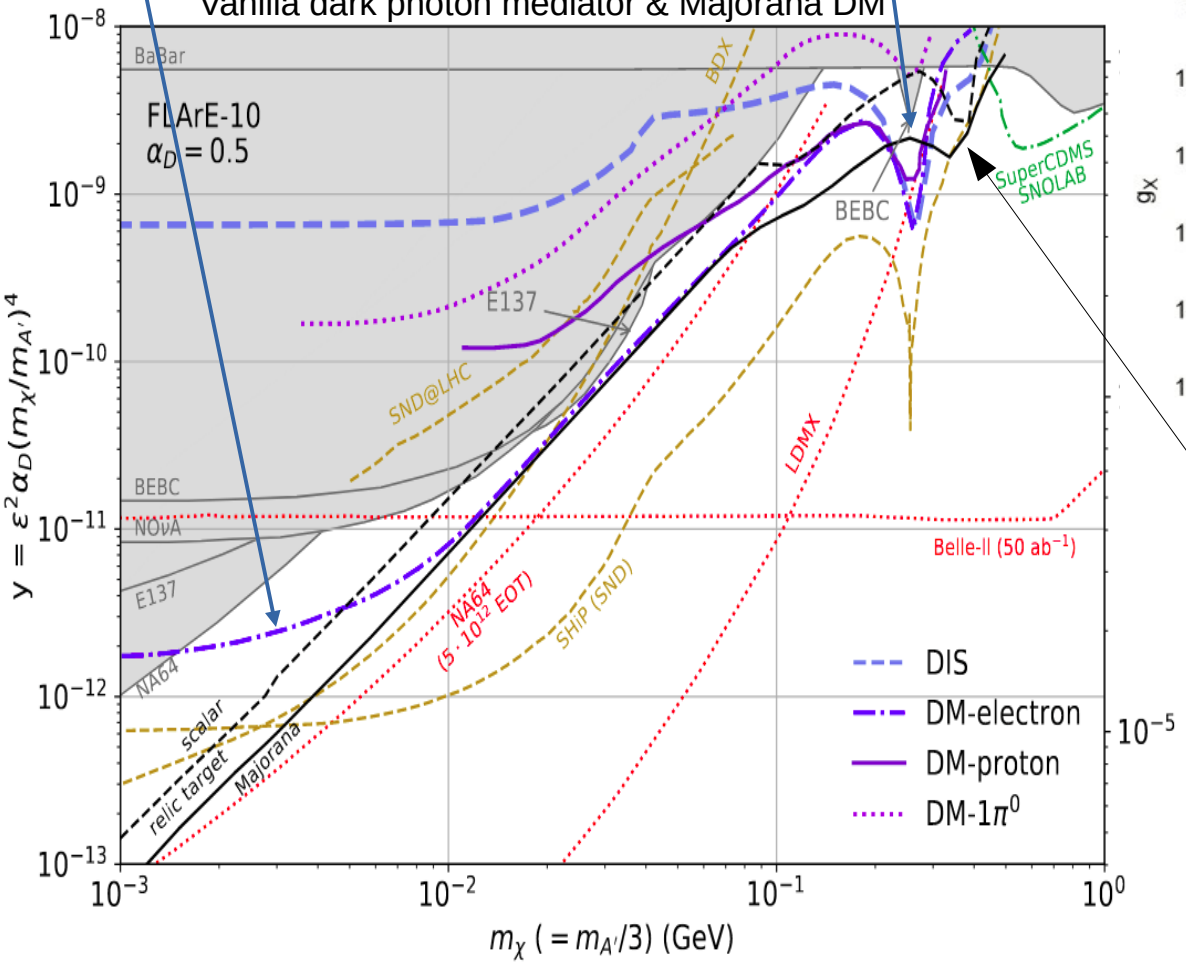
- This search is highly complementary to the traditional DM direct detection searches:
  – probe of relativistic interaction rates of LDM (DM energy ~ a few hundred GeV)
  [collider-boosted DM]
  – the search is not sensitive to the precise abundance of χ DM component
  (possible variations in cosmological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

Expected sensitivity reach

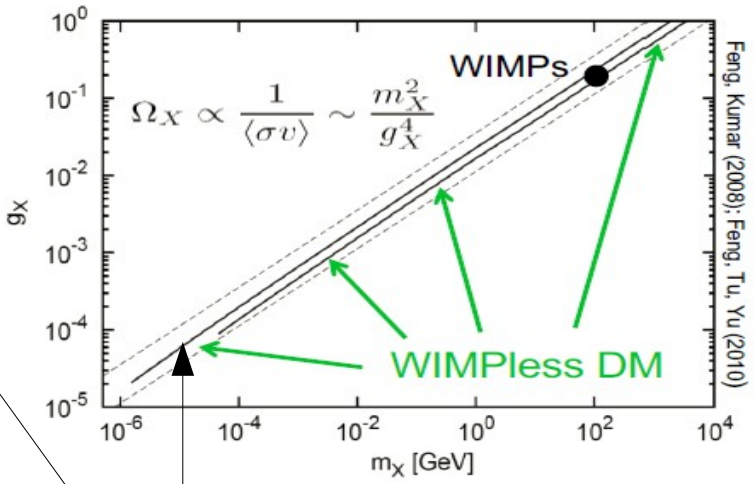
Nuclear scatterings also possible: elastic and DIS signatures

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>

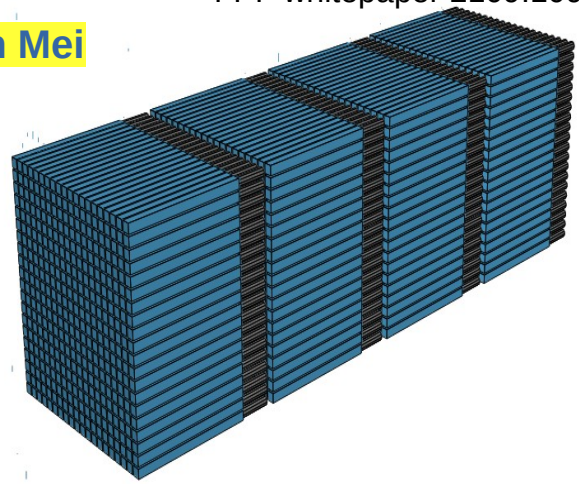
B. Batell, J.L. Feng, A. Ismail, F. Kling, R.M. Abraham, ST, 2107.00666

MILLICHARGED PARTICLES

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

- milliQan-like detector placed in the FPF

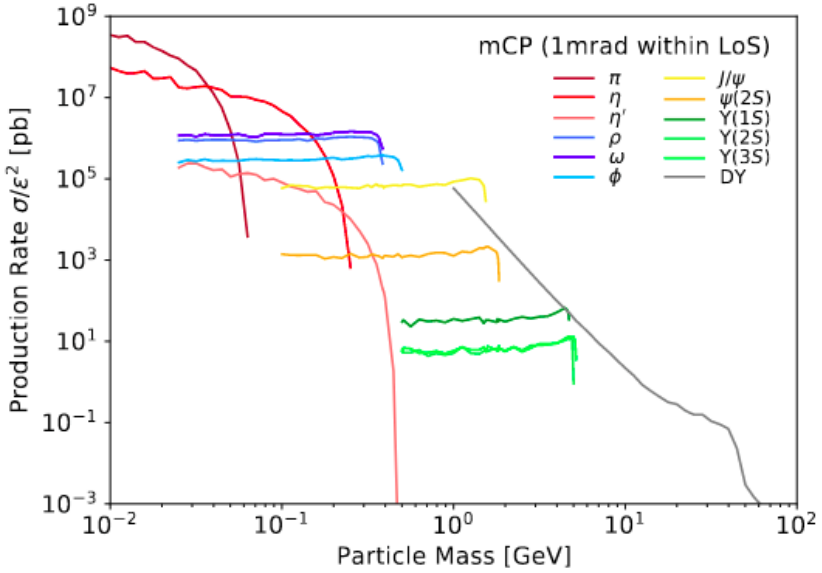
MilliQan talk: Hualin Mei



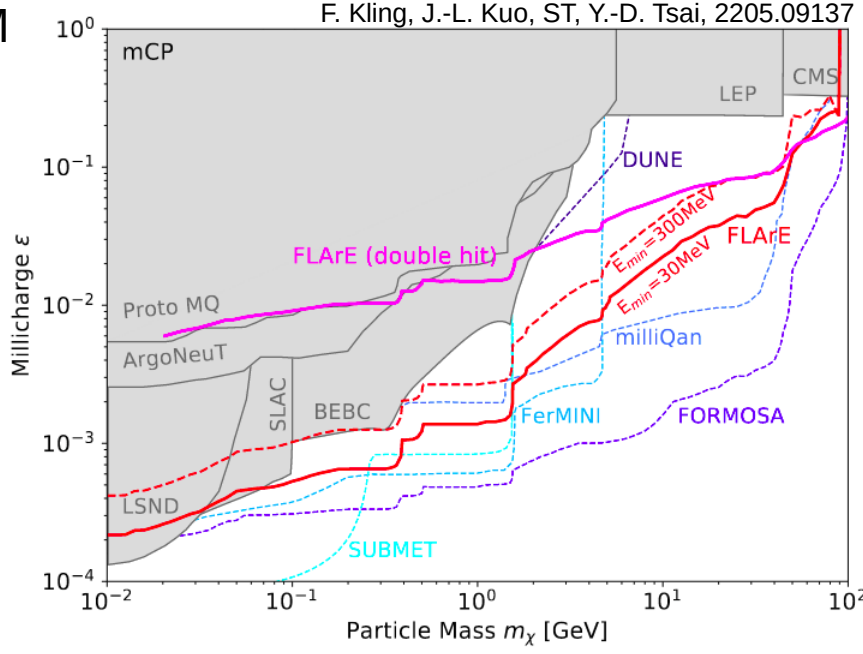
FORMOSA – **FOR**WARD **M**ICR**O**CHARGE **S**E**A**RCH

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



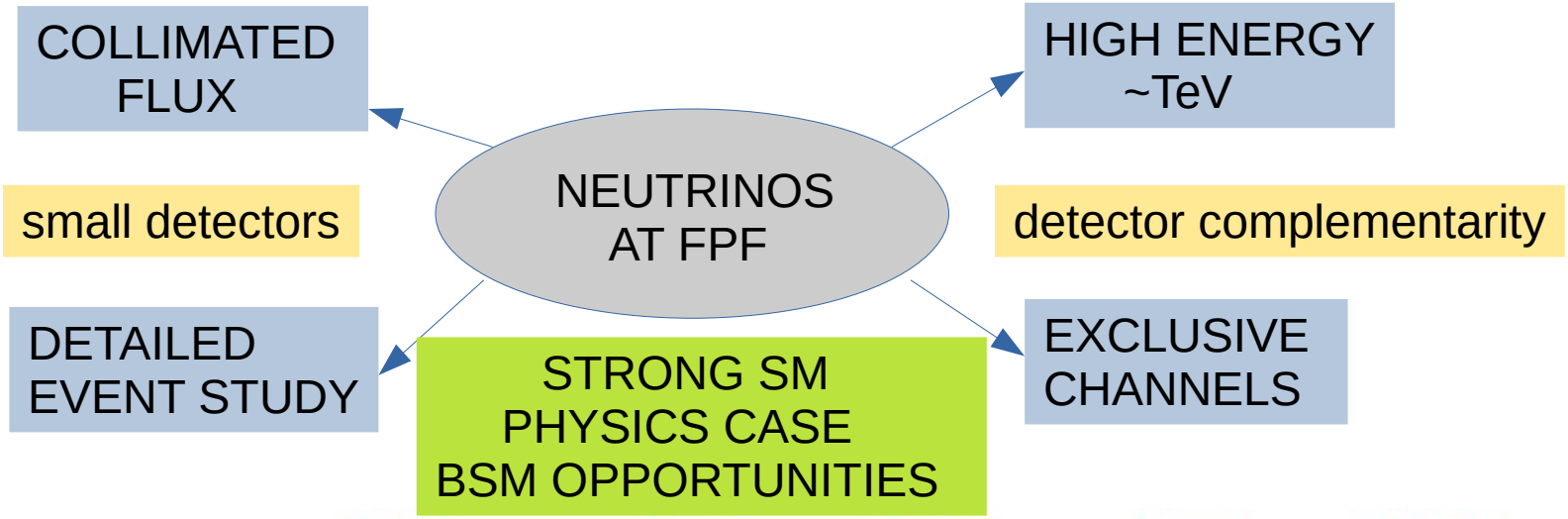
F. Kling, J.-L. Kuo, ST, Y.-D. Tsai, 2205.09137



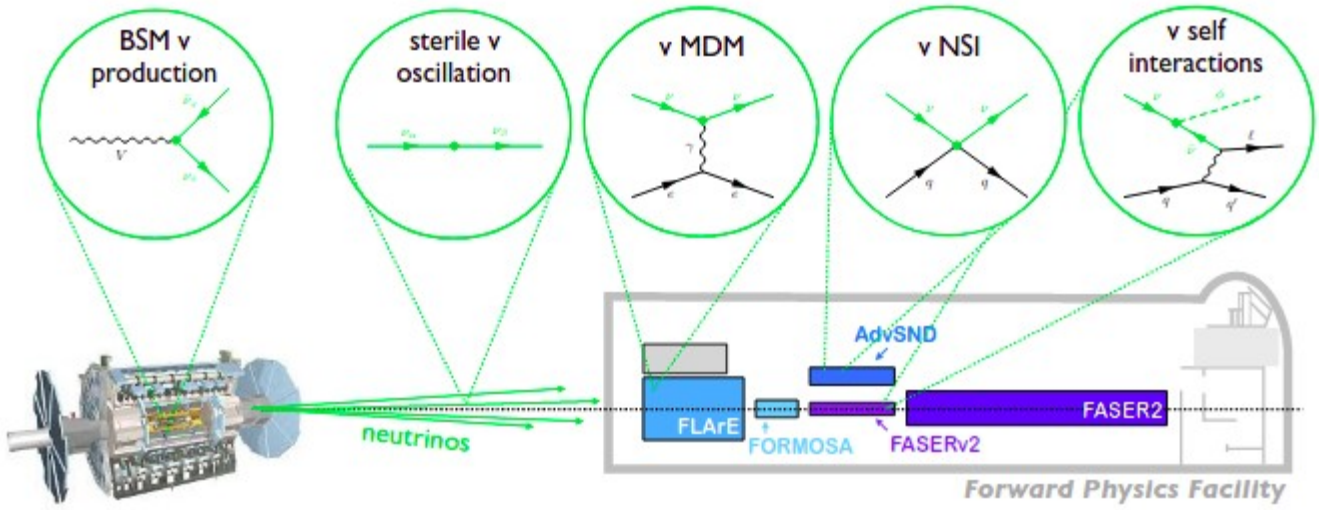
NEUTRINO BSM

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



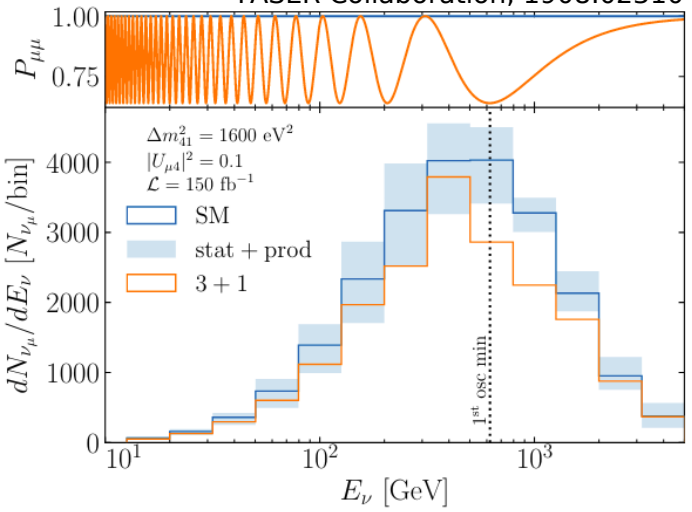
NEUTRINO BSM HIGHLIGHTS

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

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

(also e.g. Gallium anomaly)

FASER Collaboration, 1908.02310



- Non-standard neutrino interactions

Example: dipole portal to heavy neutral leptons

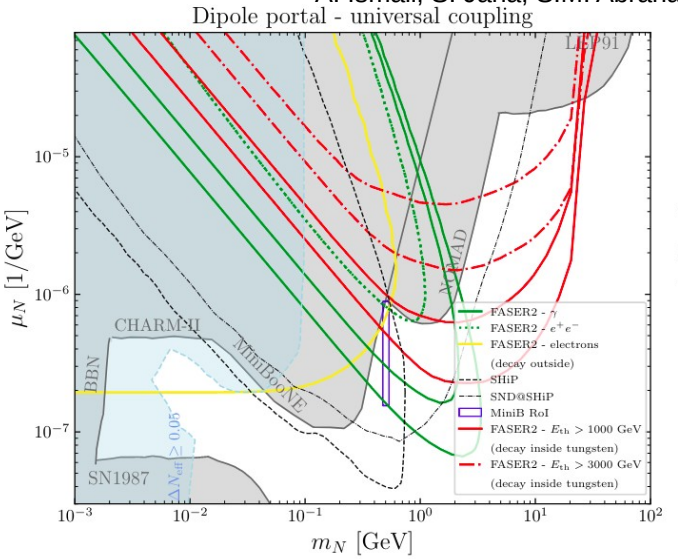
Magill etal, 1803.03262

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

Transition magnetic moments of neutrinos Before EWSB

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

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



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, Sebastian Trojanowski)

WG4 (BSM) goals:

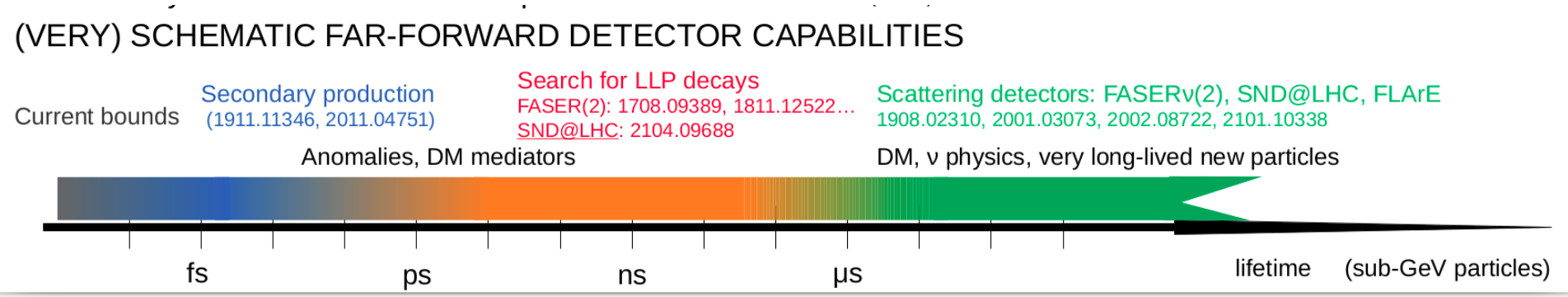
a) **trigger further discussions about possible unique BSM physics opportunities of the FPF**,

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 IDE

SUMMARY OF FAR-FORWARD LHC PHYSICS PROGRAM



- For BSM and neutrino physics, the program starts at Run 3 FASER(ν), SND@LHC
- For HL-LHC: proposed dedicated **Forward Physics Facility** (add light DM, mCPs,...)
- Best reach for masses<GeV, but even ~100 GeV new particles can be probed
- Further (B)SM opportunities: non-DIS & rare ν scat., neutrino NSI, oscillations, quirks,...
- Tool for BSM simulations: FORESEE F. Kling, ST, 2105.07077

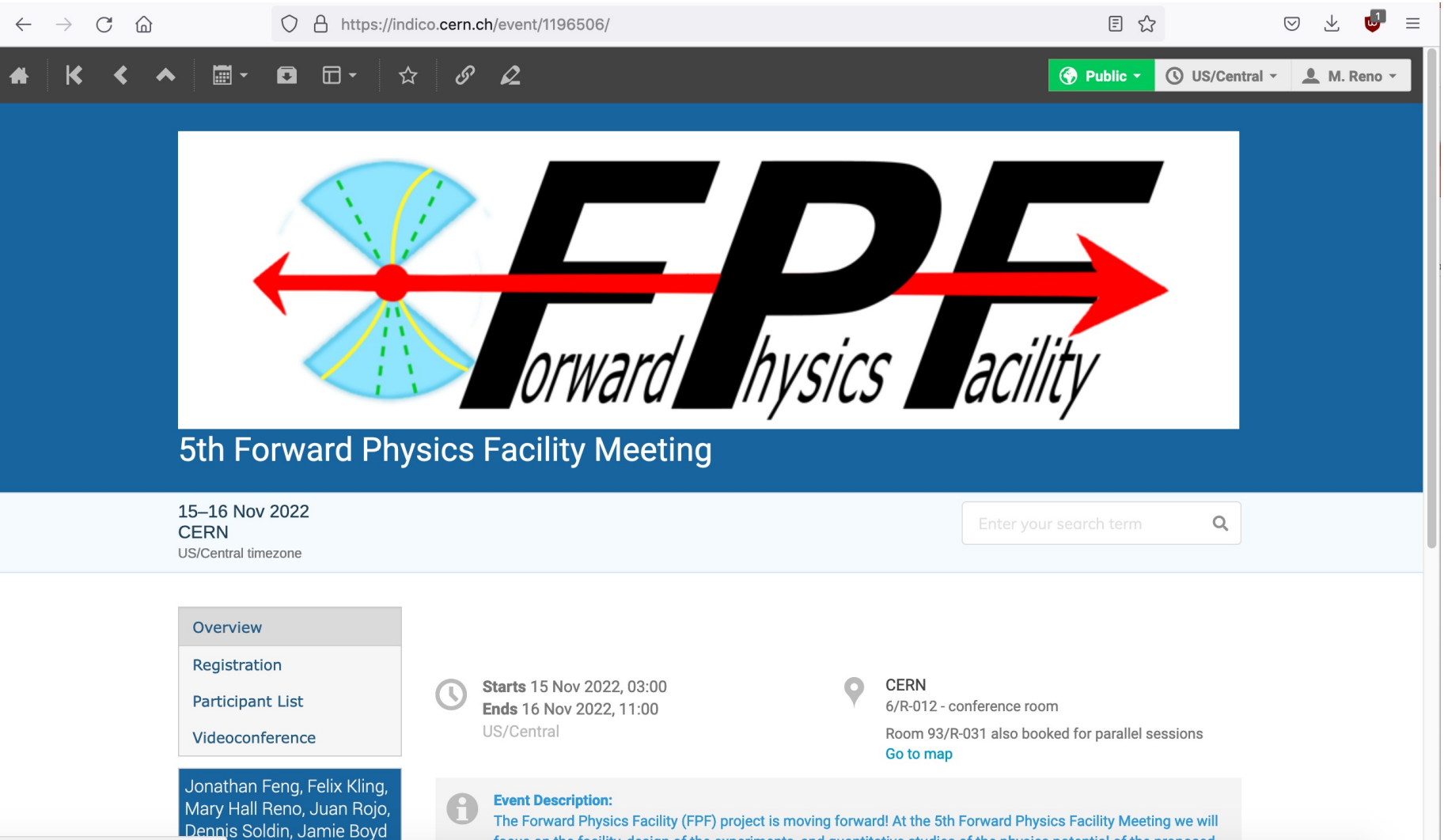
THANK YOU !

BACKUP

5TH FORWARD PHYSICS FACILITY WORKSHOP

Primary focus this time: facility, experiments, next steps

https://indico.cern.ch/event/1196506/



QUIRKS

Li, Pei, Ran, Zhang, 2108.06748

Postulated particles charged under a hidden strong force
If they mass exceeds the hidden scale m >> Λ_{hidden}, they do not hadronize

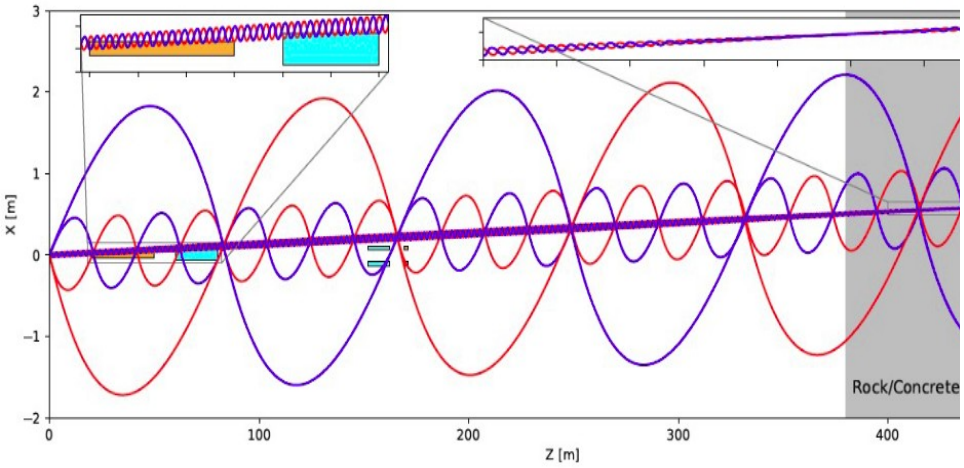
Instead, they are pair produced and remain bounded => they leave very strange tracks

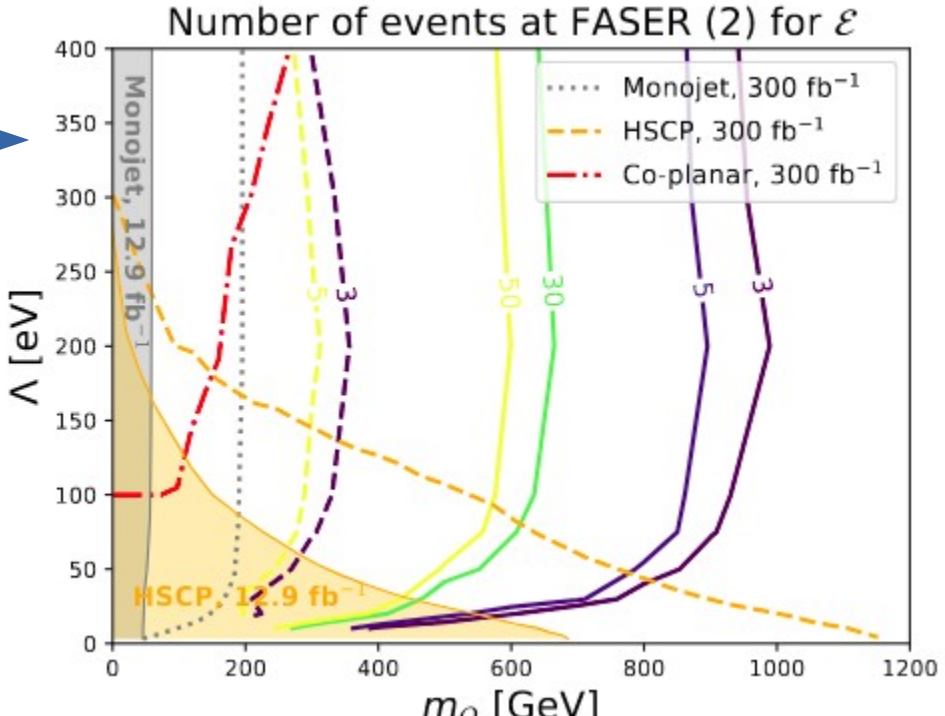
bosonic

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

fermionic

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





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

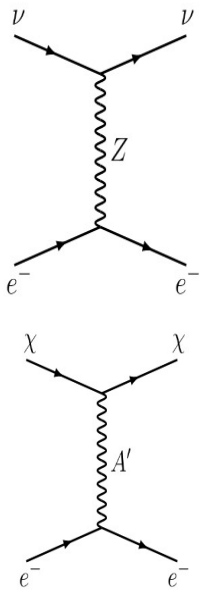
$y = E_e/(E_x,E_\nu)$

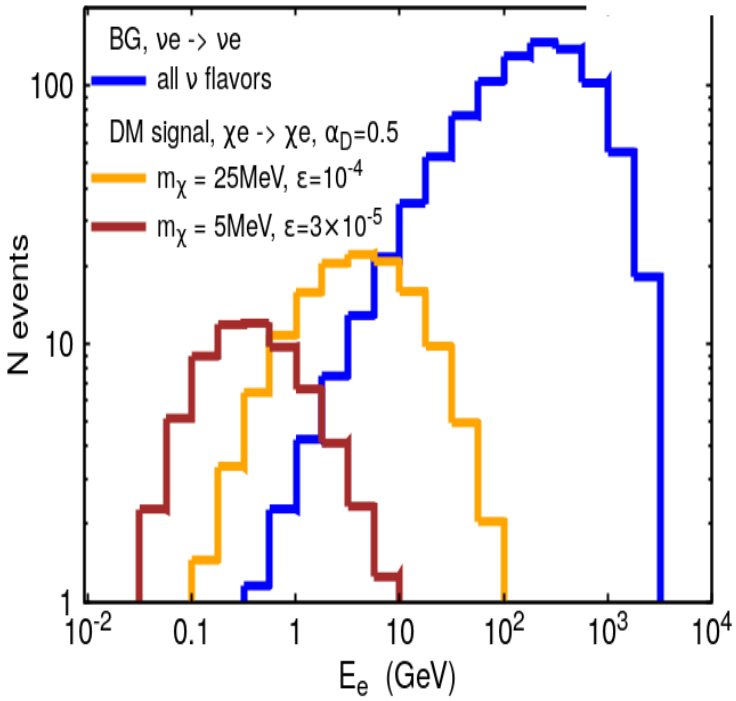
$$\frac{d\sigma(\nu_l e \to \nu_l e)}{dy} = \frac{2m_e G_F^2 E_\nu}{\pi} \frac{1}{(1+2m_e E_\nu y/M_Z^2)^2} \left(g_L^2 + g_R^2(1-y)^2\right),$$

DM scattering (dark photon mediator)

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

$m_{A'} << M_Z$





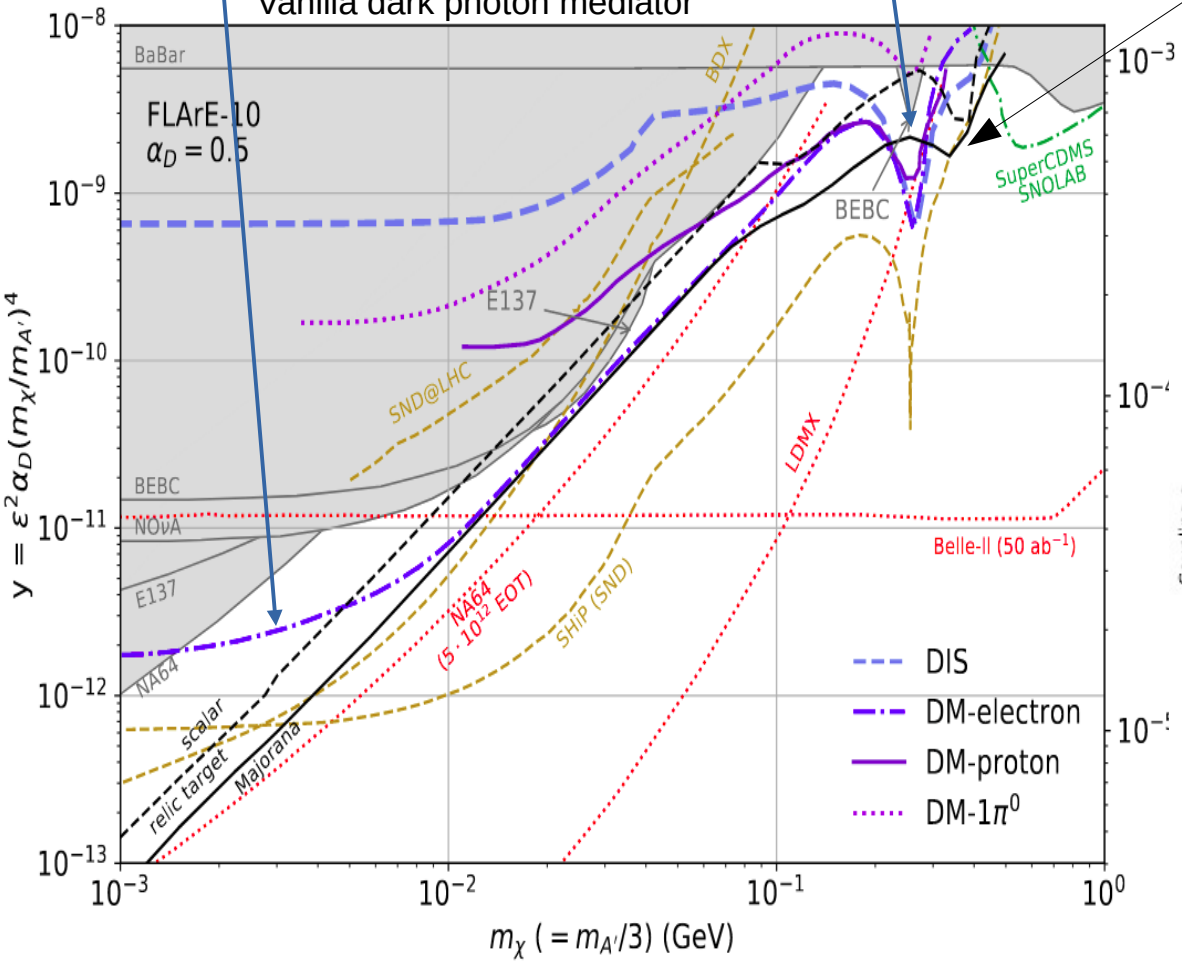
Expected sensitivity reach

Nuclear scatterings also possible: elastic and DIS signatures

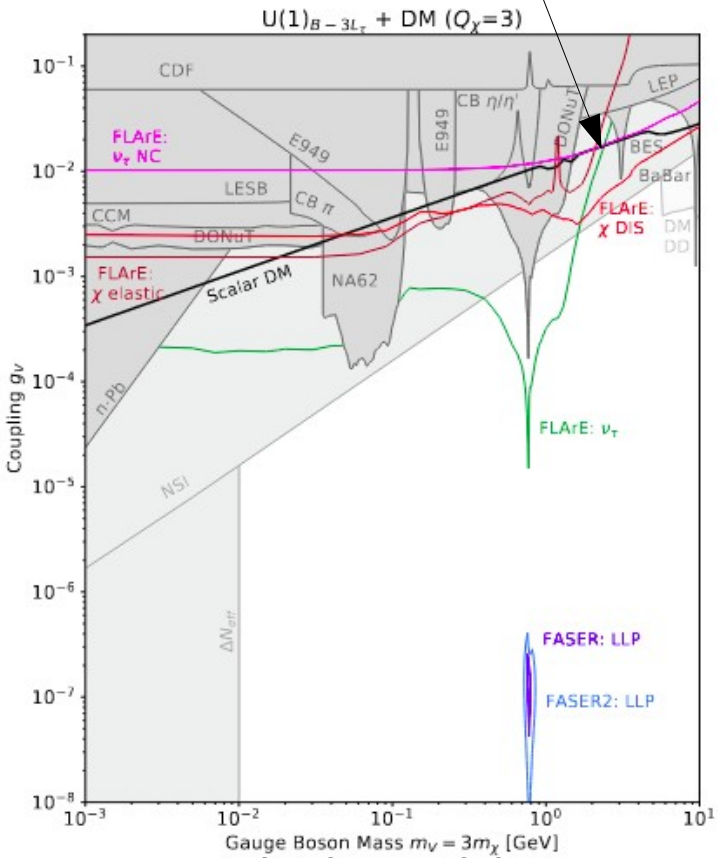
relic target lines

Electron scatterings

Vanilla dark photon mediator



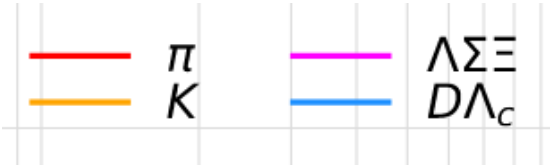
B- 3Lτ mediator
Multiple signatures

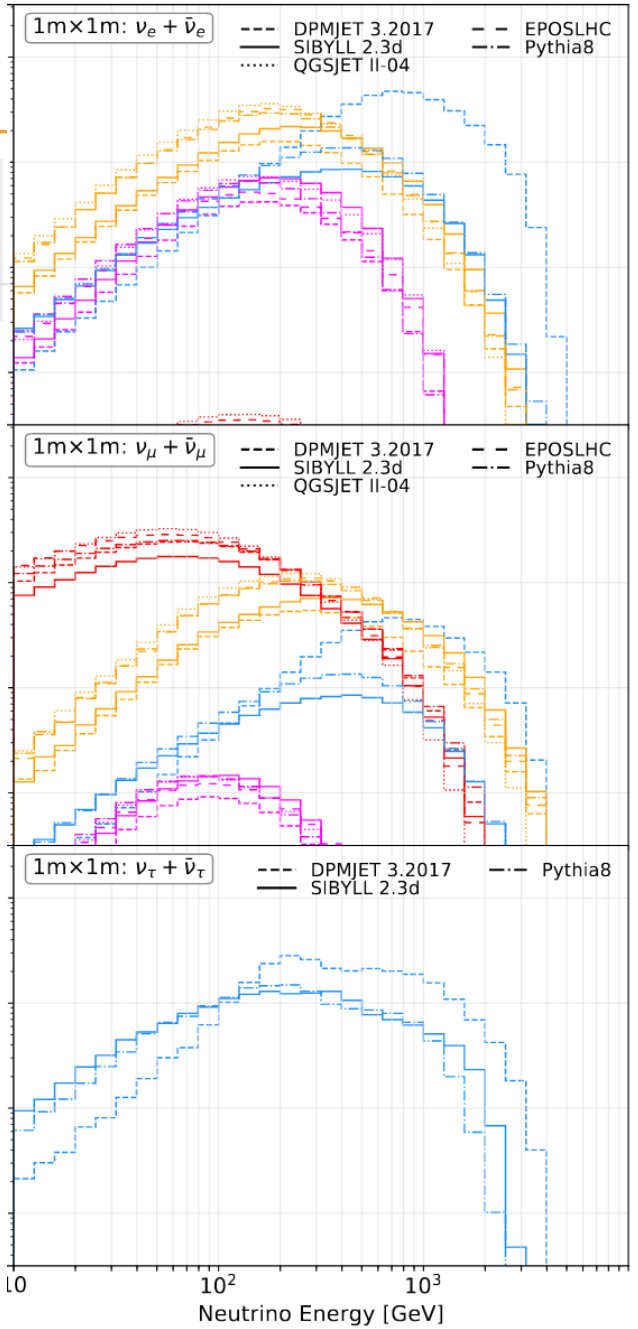


B. Batell, J.L. Feng, A. Ismail, F. Kling, R.M. Abraham, ST, 2107.00666

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

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

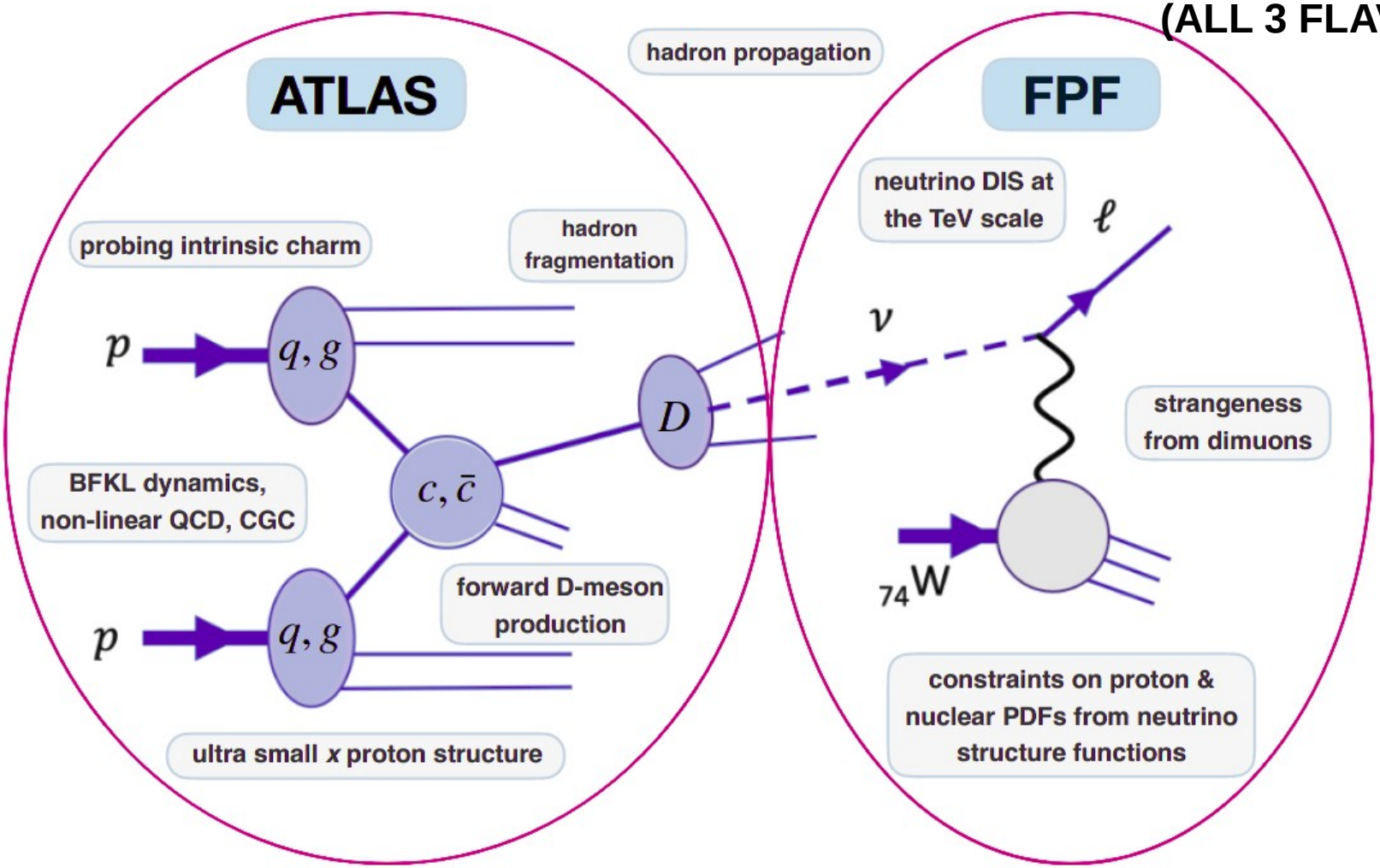
- Expected CC event rates (HL-LHC)

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

NEUTRINO PRODUCTION & DETECTION

LIGHT HADRON & CHARM MESON DECAYS

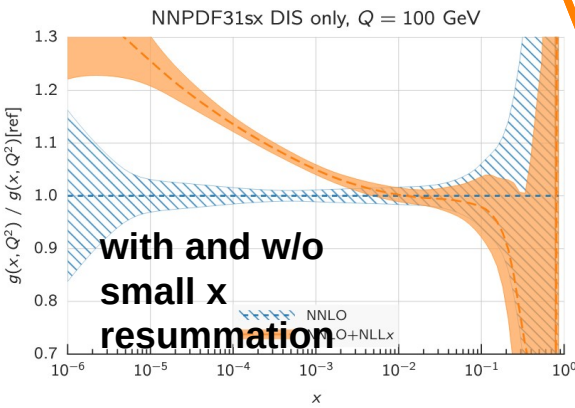
NEUTRINO INTERACTIONS ON NUCLEAR TARGETS (ALL 3 FLAVORS)



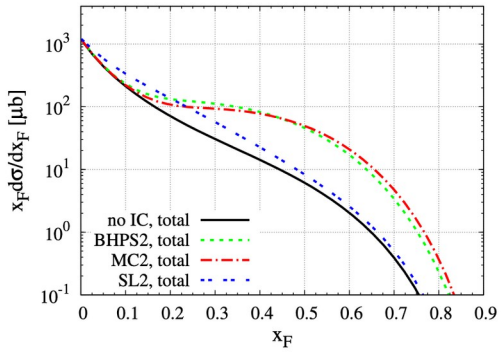
NEUTRINOS FROM CHARM DECAYS

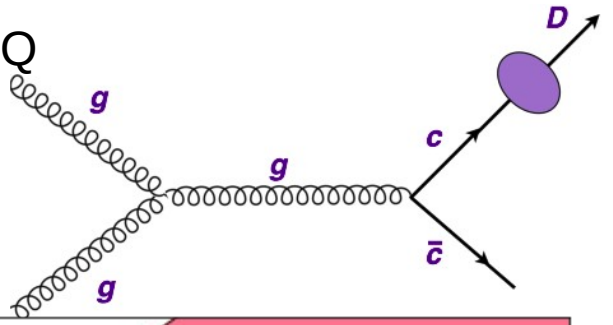
- probes of low-x (~10^{-7}) and high-x (~0.1-1) regimes at low Q

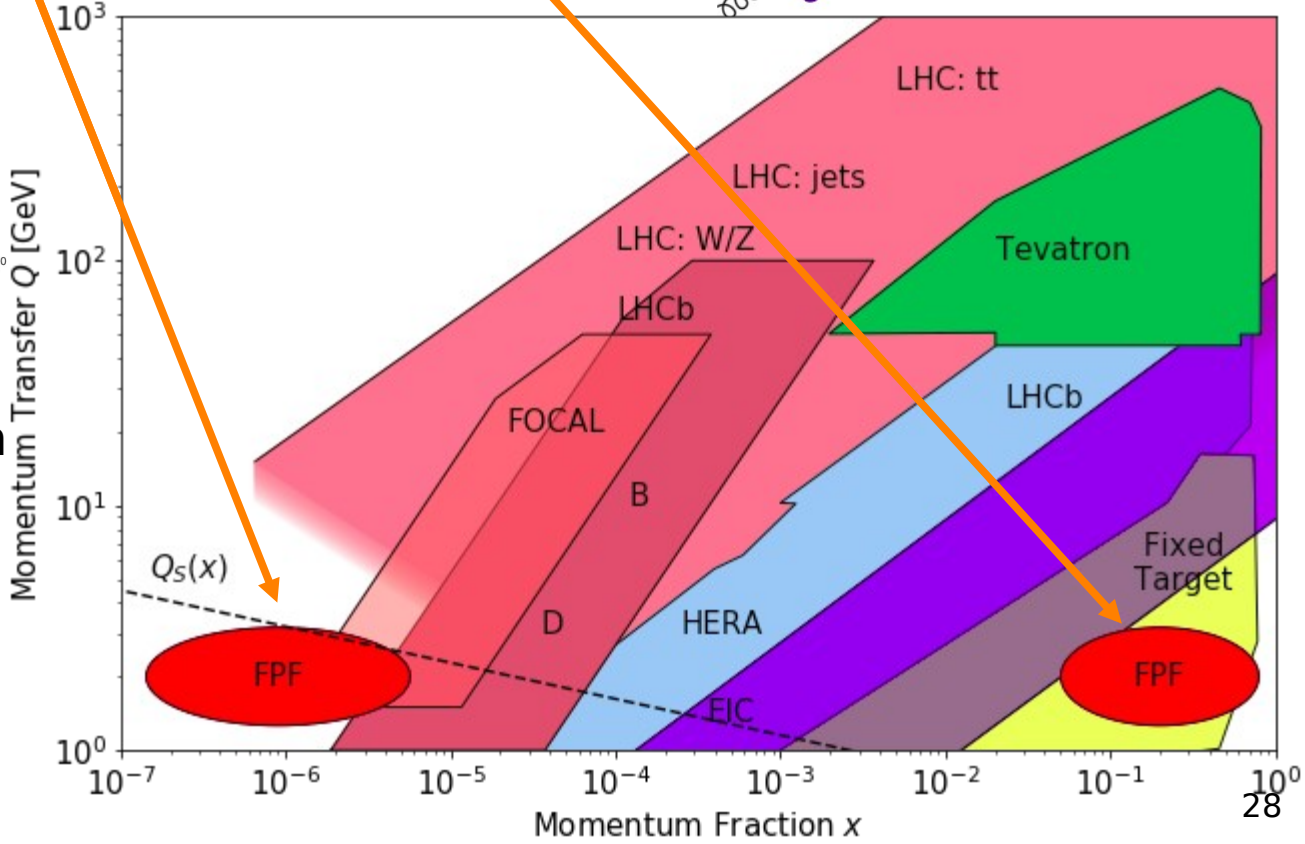
- Small x: **gluon PDFs**



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







NEUTRINO DEEP INELASTIC SCATTERING

- Nuclear PDF measurements

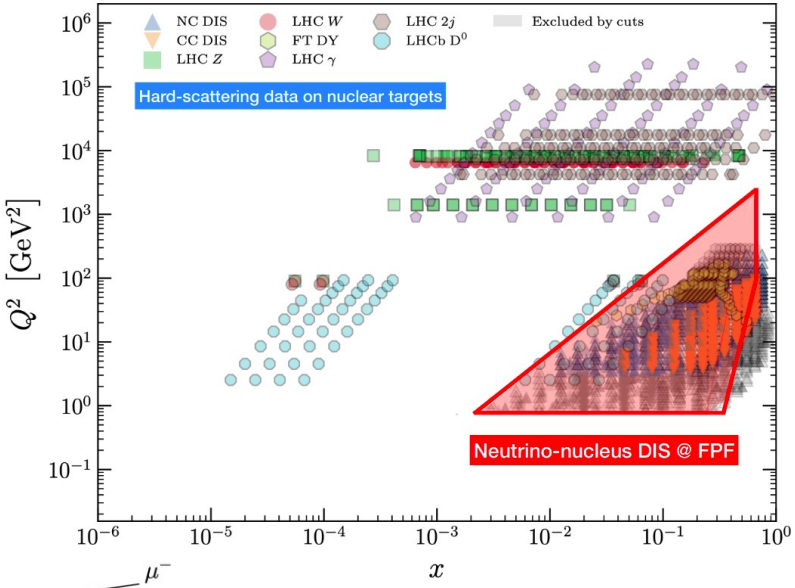
– high-energy νs → extended kinematic coverage

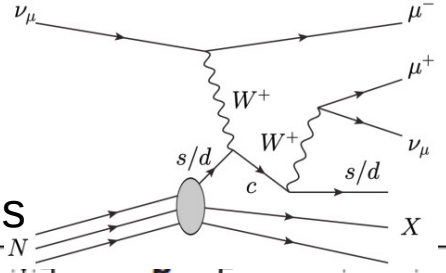
– possible measurements for various nuclear targets (Ar, W)

- 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/1012.0286