Looking forward to new physics and neutrinos at the LHC and beyond

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High Energy Physics seminar

Faculty of Physics, University of Warsaw

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ASTROCENT

NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

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FNP Foundation for Polish Science

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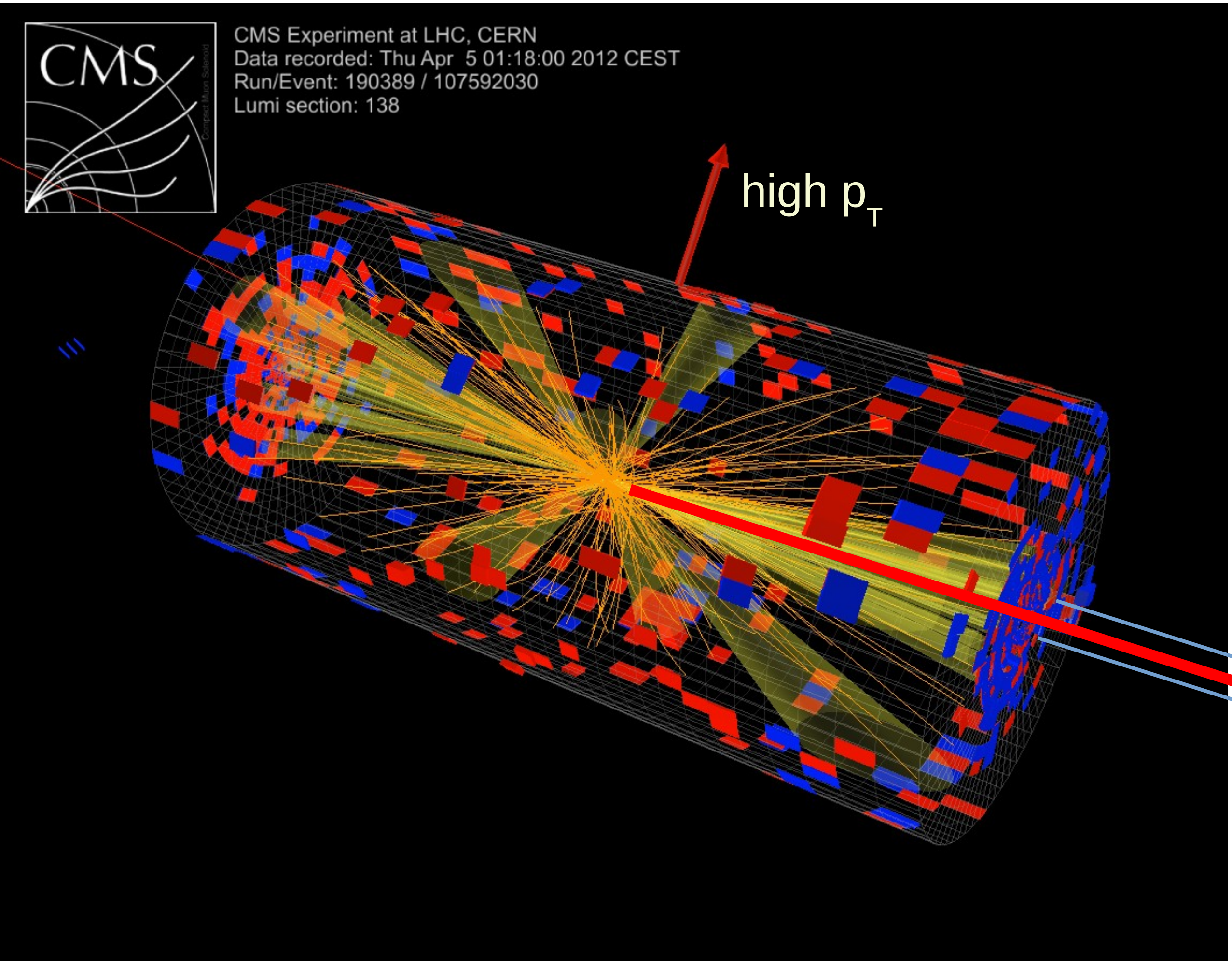
INTRODUCTION

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)

(NEAR-)FORWARD SEARCHES AT THE LHC

- Active area of interest from basically the beginning of the LHC

- Experiments:
  ATLAS-ALFA, AFP, LHCf, (CMS-)TOTEM,...
  but also measurements at
  ALICE, ATLAS, CMS, LHCb

- Physics case:
  – measurement of the composition of the total pp cross section in terms of elastic, diffractive and inelastic contributions
  – distributions of forward products (π^0,n)

- Impact on:
  – cosmic-ray physics (data to improve modeling, MC tools)
  – QCD in the low-x regime
  – heavy ion physics, PDFs,...

CERN-PH-LPCC-2015-001
SLAC-PUB-16364
DESY 15-167
September 3 2015

1611.05079 [hep-ph]

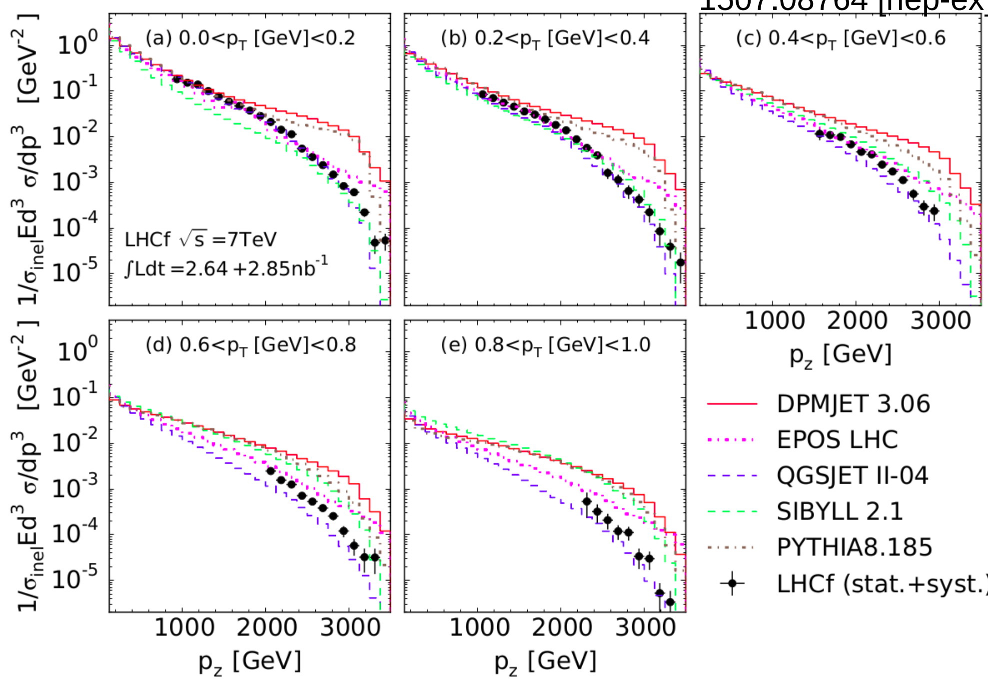
LHC Forward Physics

(184 authors)

Editors: N. Cartiglia, C. Royon
The LHC Forward Physics Working Group

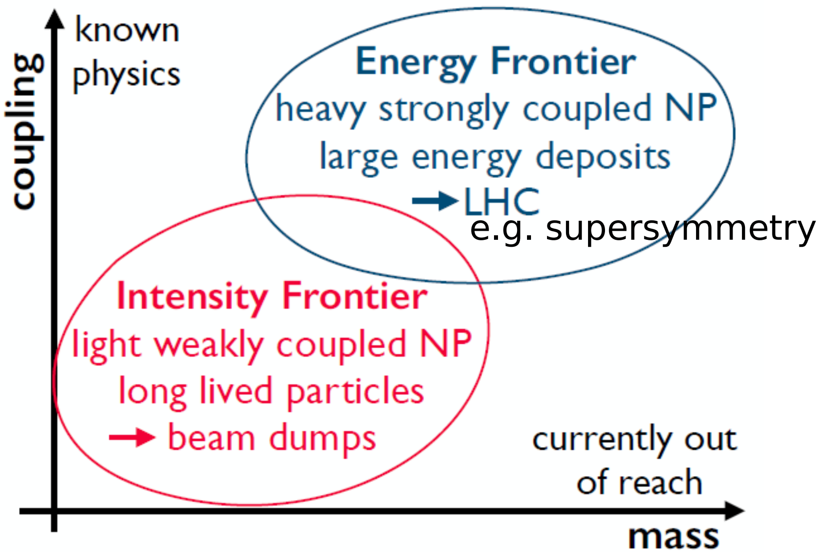
Neutral pion momentum distribution (LHCf)

1507.08764 [hep-ex]



MOTIVATION TO GO FAR FORWARD

LIGHT NEW PHYSICS



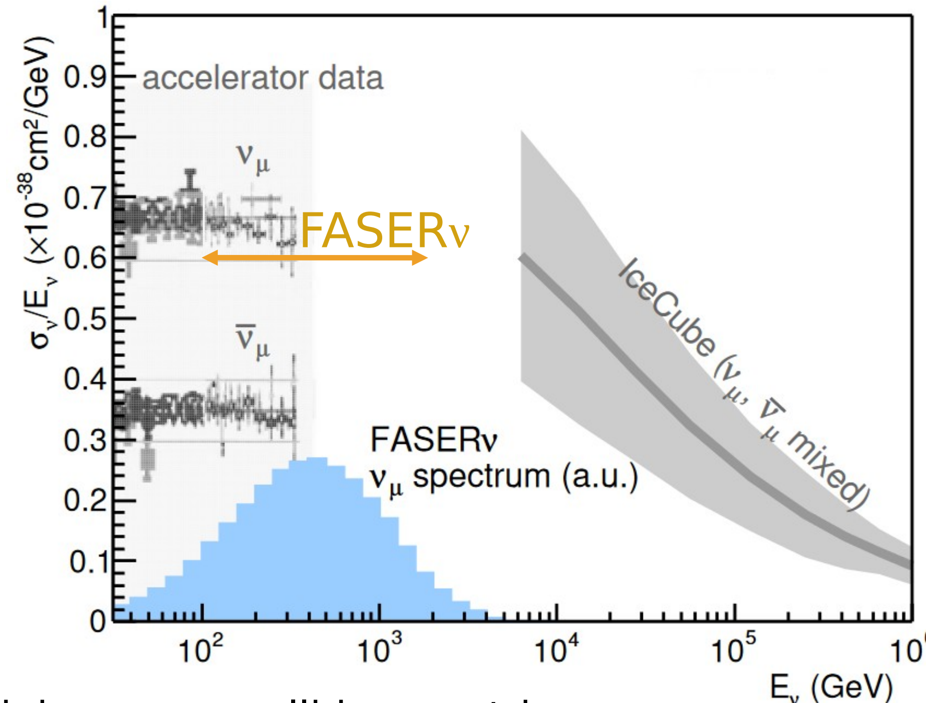
-- "leave no stone unturned"

-- cosmology
(dark matter, inflation, bariogenesis,...)

-- neutrino masses
(GeV-scale heavy neutral leptons)

-- anomalies

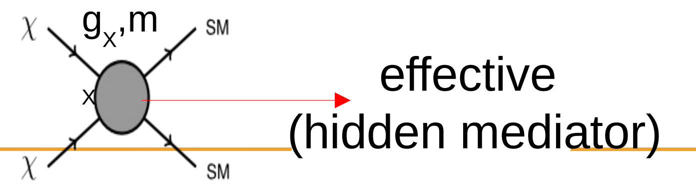
LIGHT „KNOWN" PHYSICS



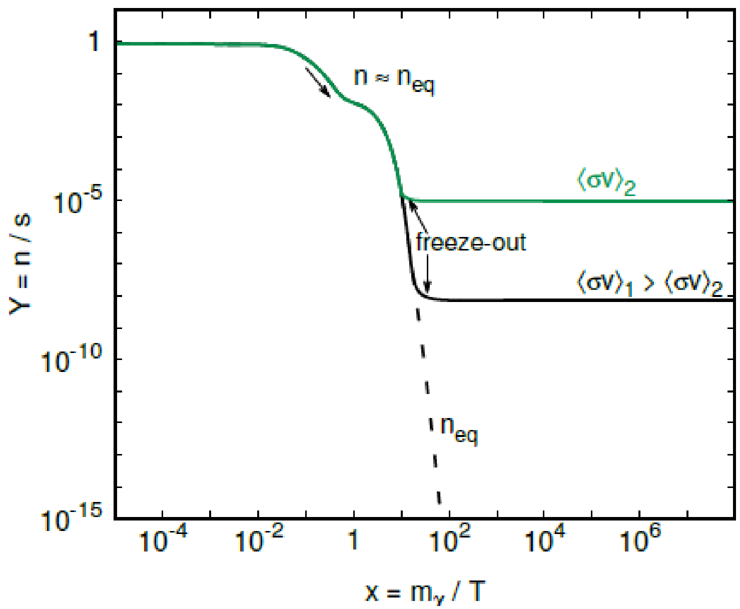
High-energy collider neutrinos:
-- first neutrino measurements at the LHC
(candidate events) FASER collaboration: 2105.06197

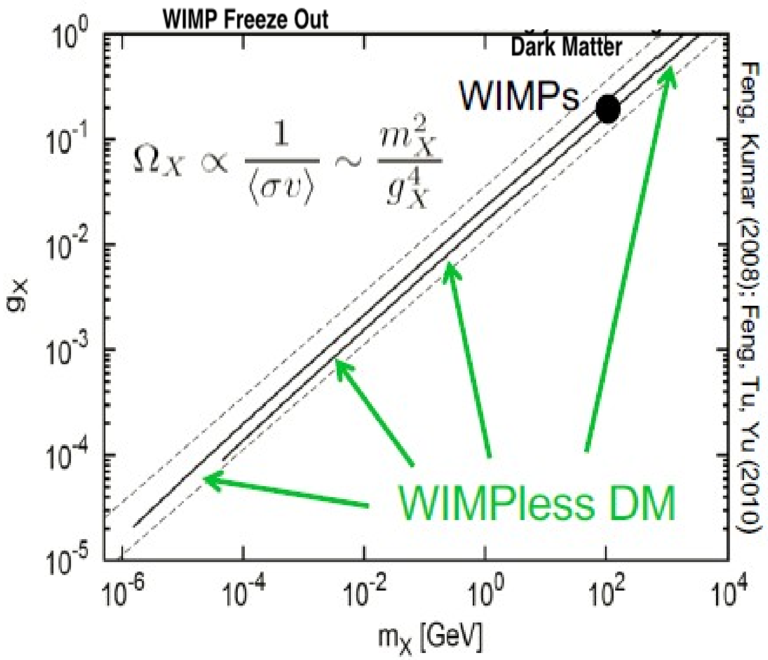
-- TeV-energy neutrinos remain less explored
-- any new tau neutrinos ν_τ highly welcome
-- other possibilities: charm-associated ν interactions, new physics

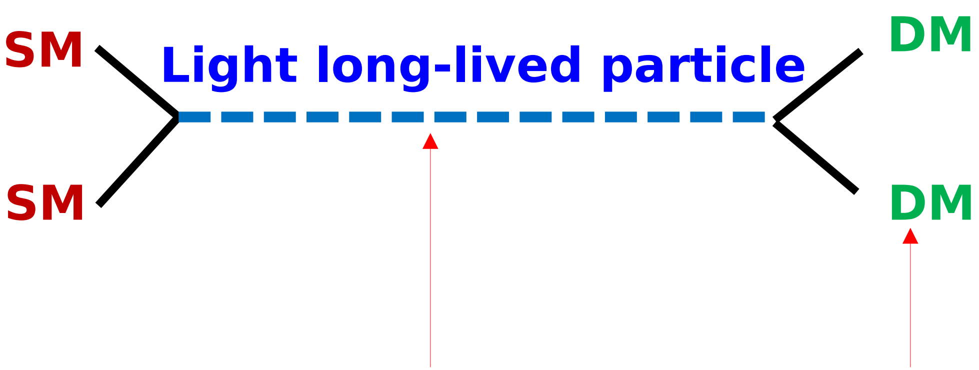
Example: WIMPless miracle



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



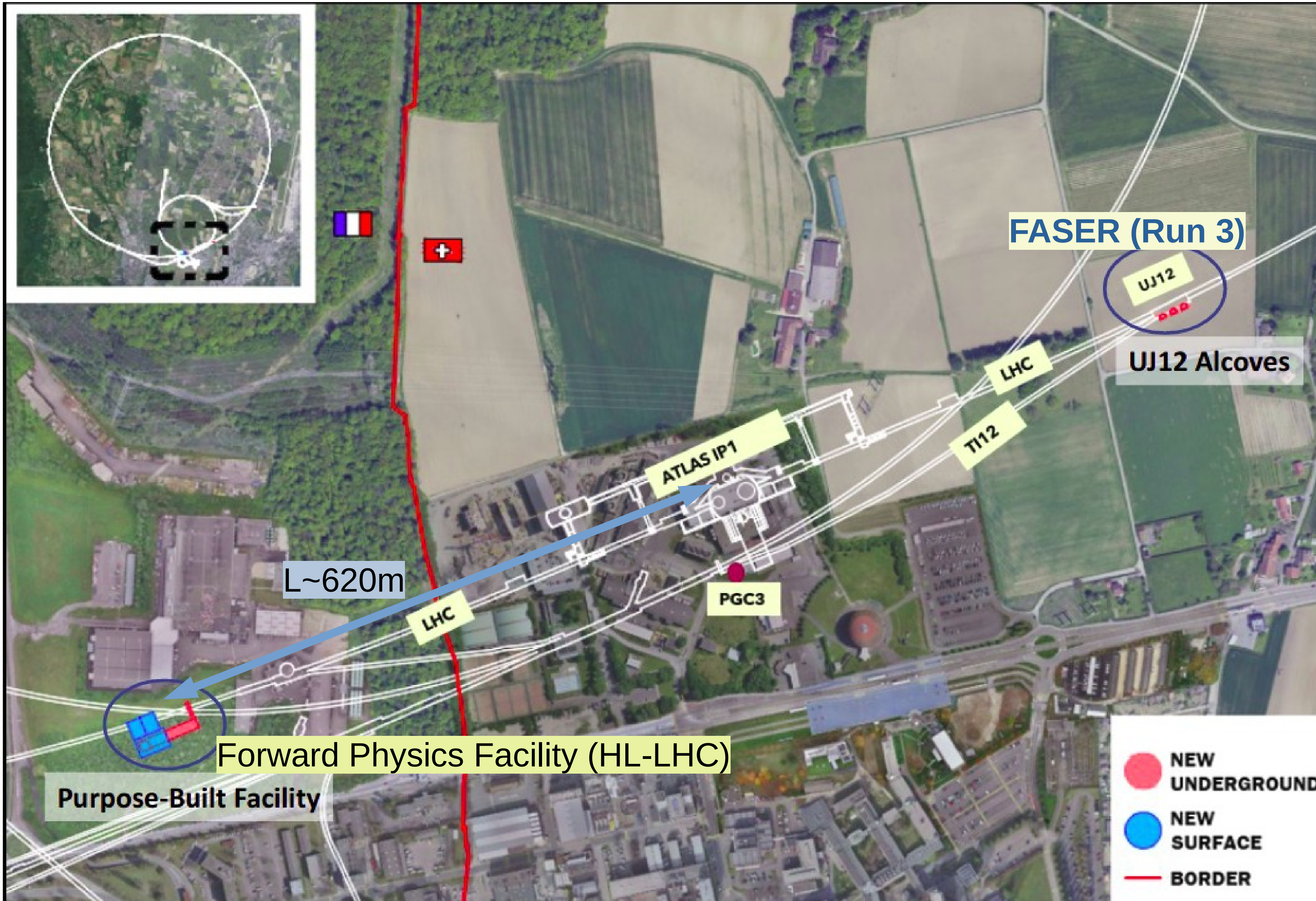




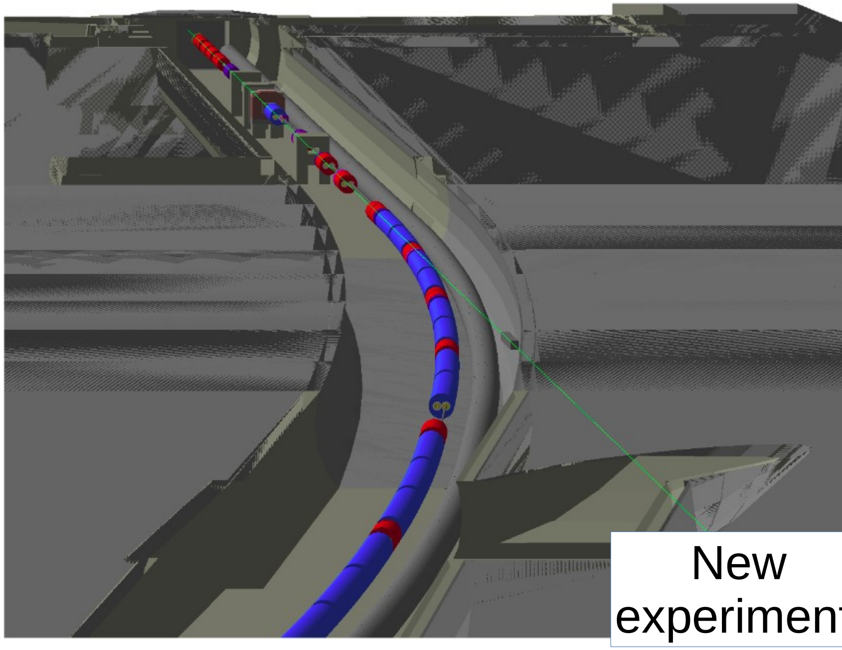
Search strategies: 1) search for light mediators, 2) search for light DM

FAR-FORWARD FACILITIES

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



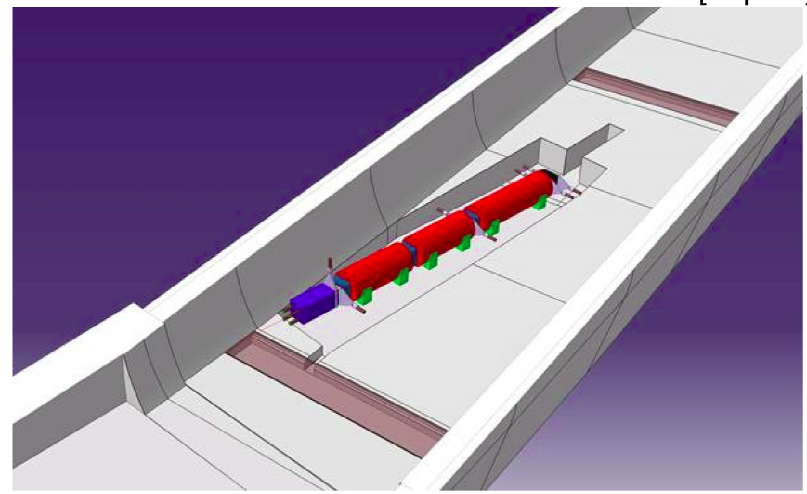
Far-forward searches at the LHC zoomed in



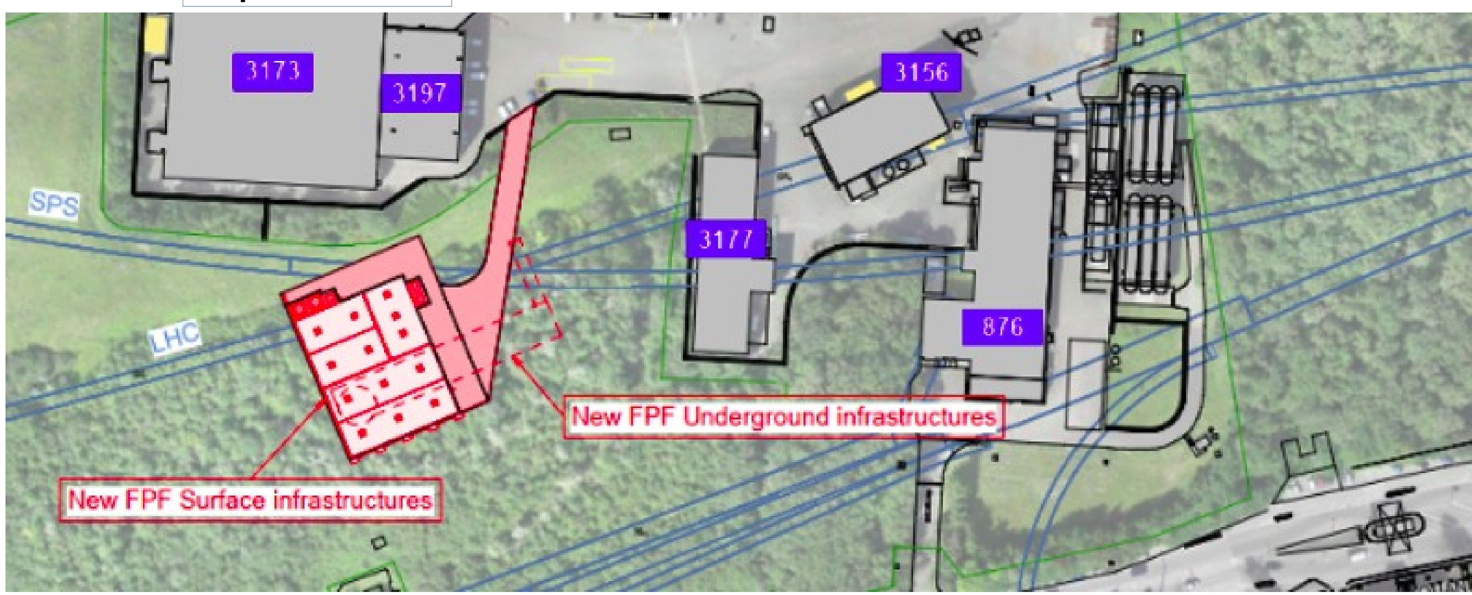
New experiments

1) FASER experiment (Run 3) (& SND@LHC experiment)

1812.09139 [hep-ex]



2) Forward Physics Facility (FPF) proposed for HL-LHC



2109.10905 [hep-ph]
2203.05090 [hep-ex]

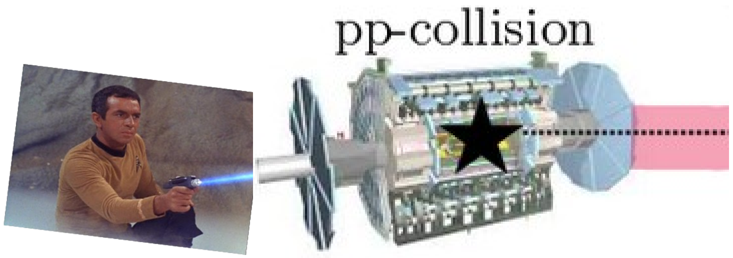
FASER LoI & TP: 1811:10243, 1812.09139
FASERν LoI & TP: 1908.02310, 2001.03073

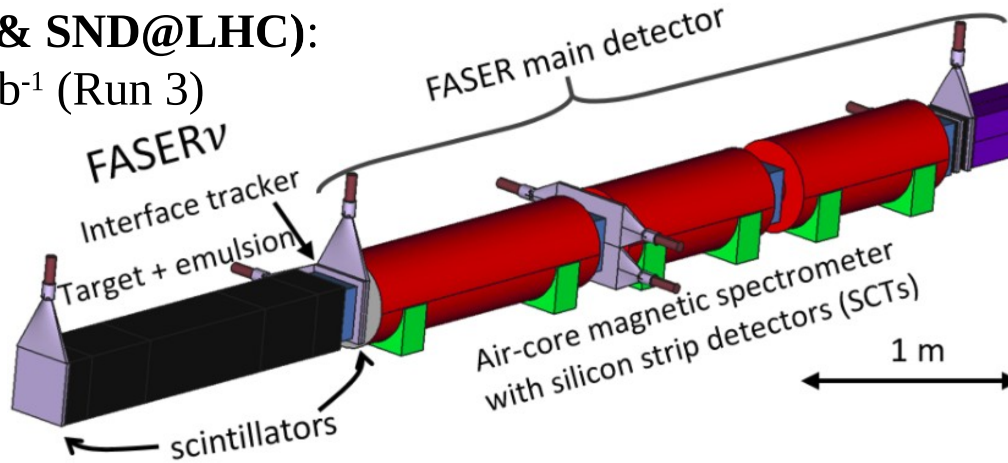
RUN 3 & HL-LHC PLANS

Run 3

main FASER -- cylindrical detector (& SND@LHC):

L = 1.5 m, R = 10 cm, V = 0.05 m^3, 150 fb^{-1} (Run 3)



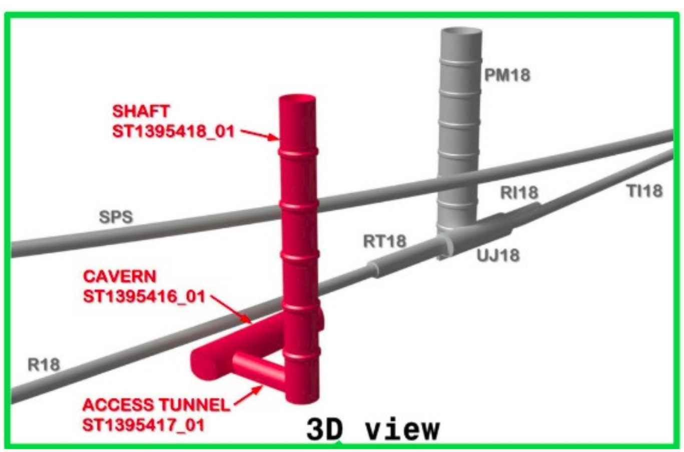


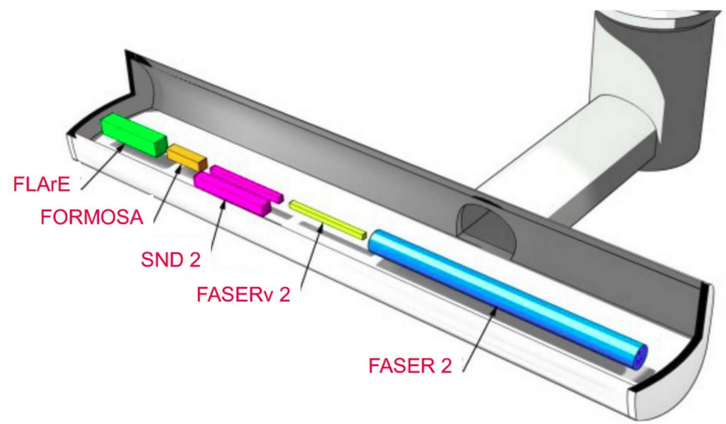
HL-LHC

(possible upgrade) FASER 2: L = 5 m ($\rightarrow$ 20 m), R = 1 m, V = 16 m^3, 3 ab^{-1} (HL-LHC)

Forward Physics Facility

2109.10905 [hep-ph]
2203.05090 [hep-ex]



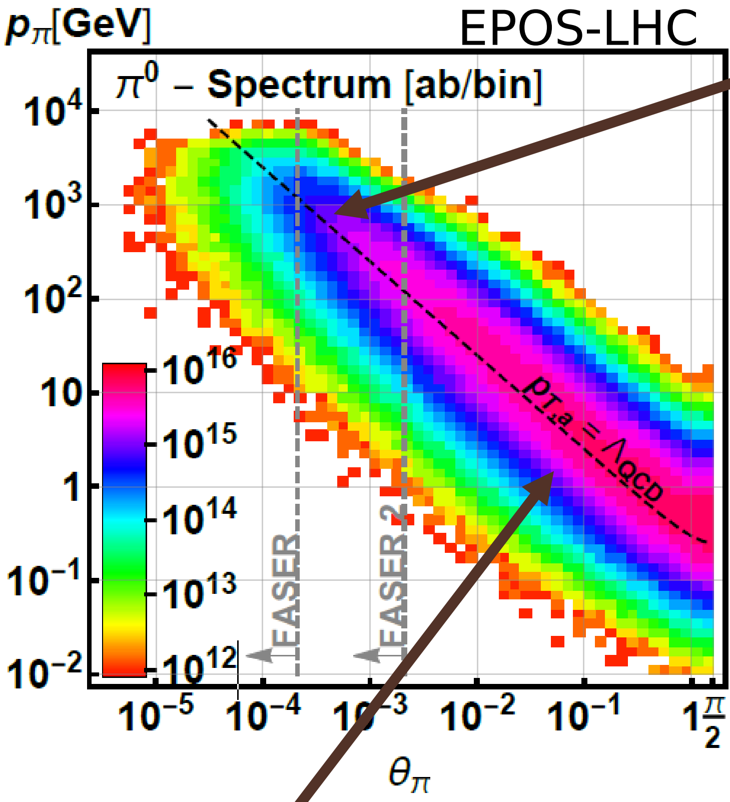


Credit: John Osborne, Kincso Balazs, Jonathan

SEARCH FOR DECAYS

NEW PHYSICS FROM PION DECAYS

J.L. Feng, I. Galon, F. Kling, ST, 1708.09389



Hard pions highly collimated along the beam axis since their $p_T \sim \Lambda_{QCD}$ e.g. for $E_{\pi 0} \geq 10$ GeV

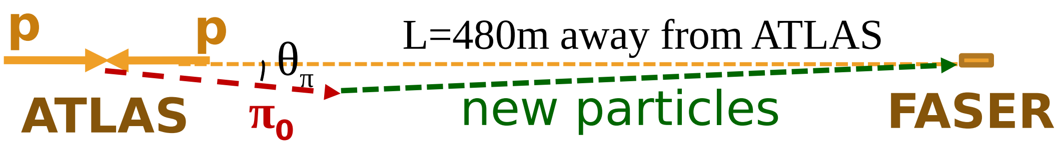
~ 1.7% of π_0s go towards FASER (10cm radius)

~ 24% of π_0s go towards FASER 2 (1m radius)

This can be compared to the angular size of both detectors with respect to the total solid angle of the forward hemisphere (2 π):

~ (2 × 10^{-6})% for FASER

~ (2 × 10^{-4})% for FASER 2



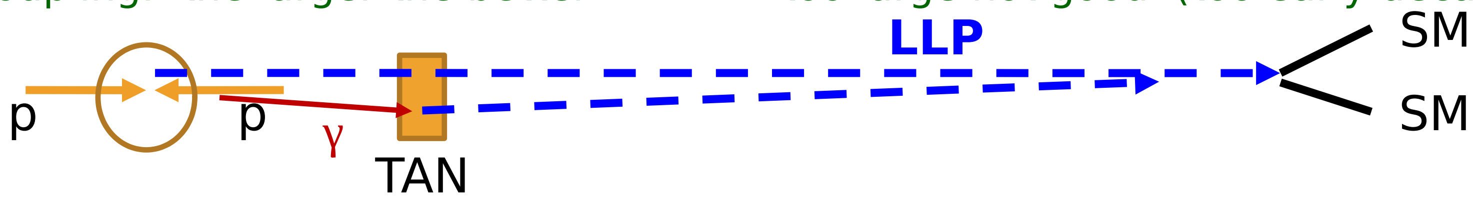
Soft pions going towards high-p_T detectors:

- produced LLPs would be too soft for triggers
- large SM backgrounds

SEARCH FOR HIGHLY DISPLACED DECAYS

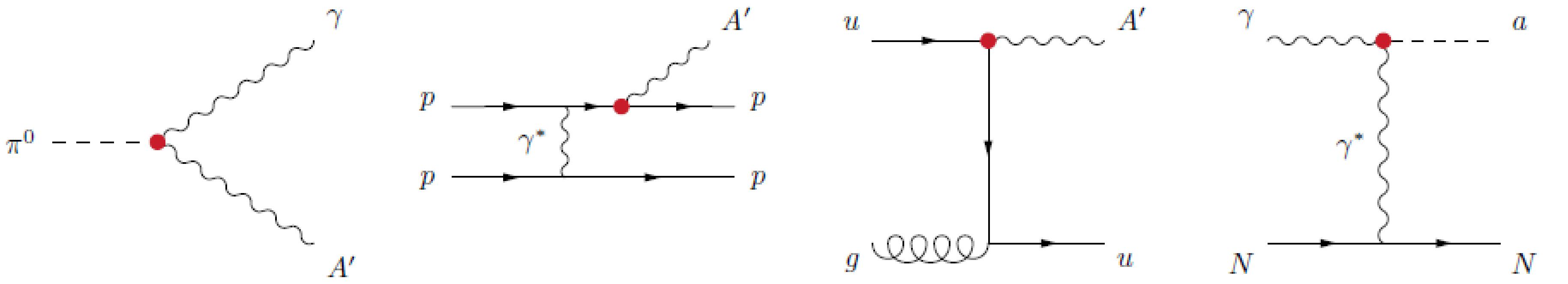
Production (ATLAS IP, ...) **Decay**

Coupling: the larger the better too large not good (too early decays)



Various production mechanisms:
-- meson decays (light & heavy)
-- bremsstrahlung
-- hard-scatterings,...

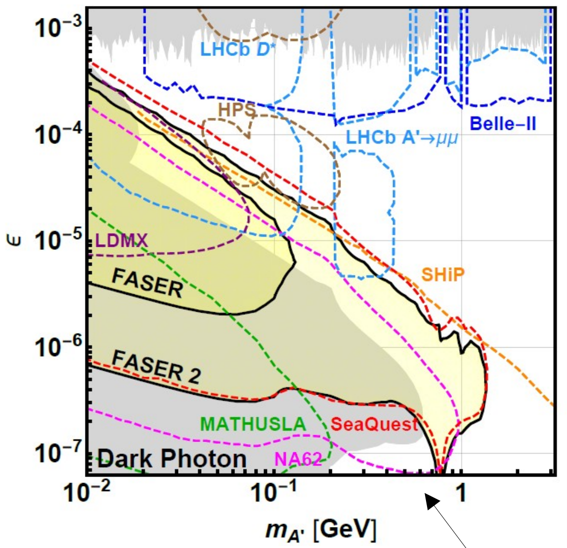
$$N_{\rm sig} \propto \begin{cases} \mathcal{L}^{\rm int}\,\epsilon^2\,e^{-L_{\rm min}/\bar{d}} & \text{for} \quad \bar{d} \ll L_{\rm min} \\ \mathcal{L}^{\rm int}\,\epsilon^2\,\frac{L_{\rm max}-L_{\rm min}}{\bar{d}} & \text{for} \quad \bar{d} \gg L_{\rm min}\,. \end{cases}$$



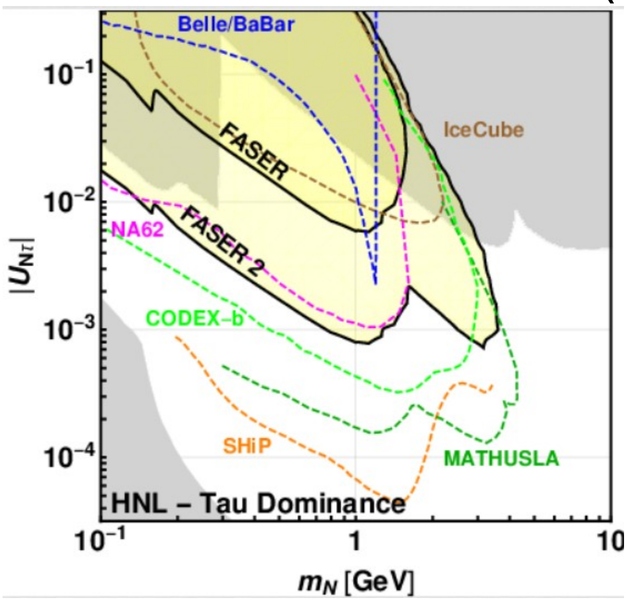
FASER Collaboration, 1811.12522

SELECTED SENSITIVITY REACH PLOTS

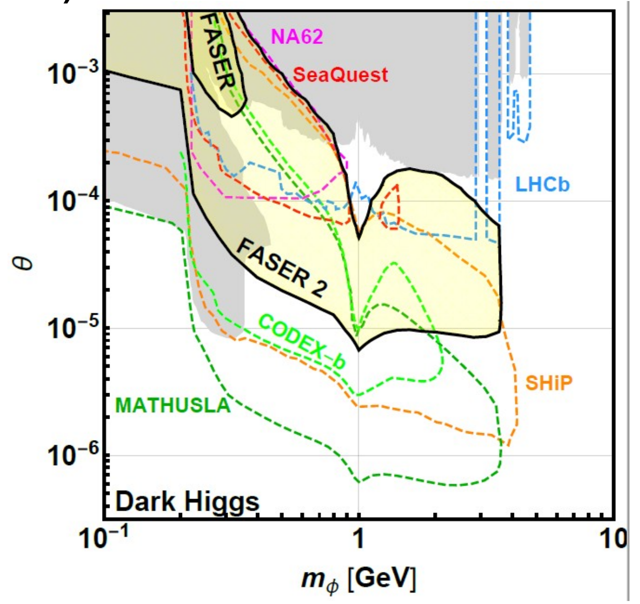
DARK PHOTON



HEAVY NEUTRAL LEPTON (TAU)

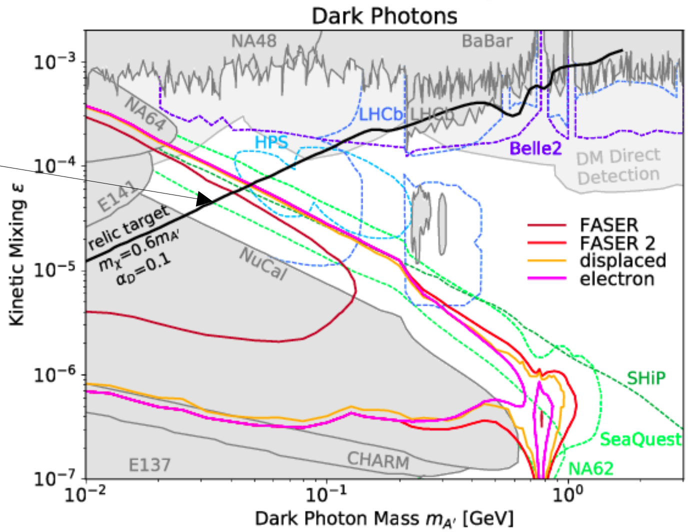


DARK HIGGS BOSON



complementarity
DM direct detection searches
complex scalar DM with A'

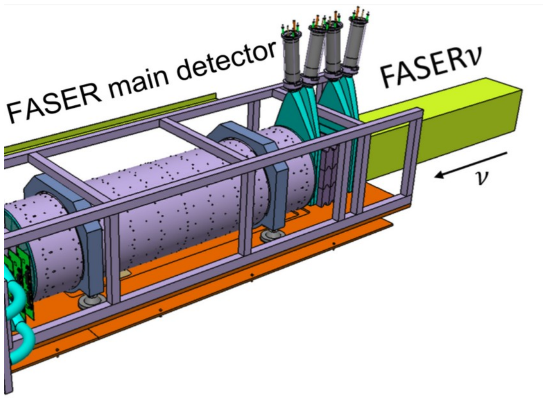
$$\mathcal{L}_D \supset (D^\mu \chi)^*(D_\mu \chi) - m_\chi^2 \chi^* \chi,$$

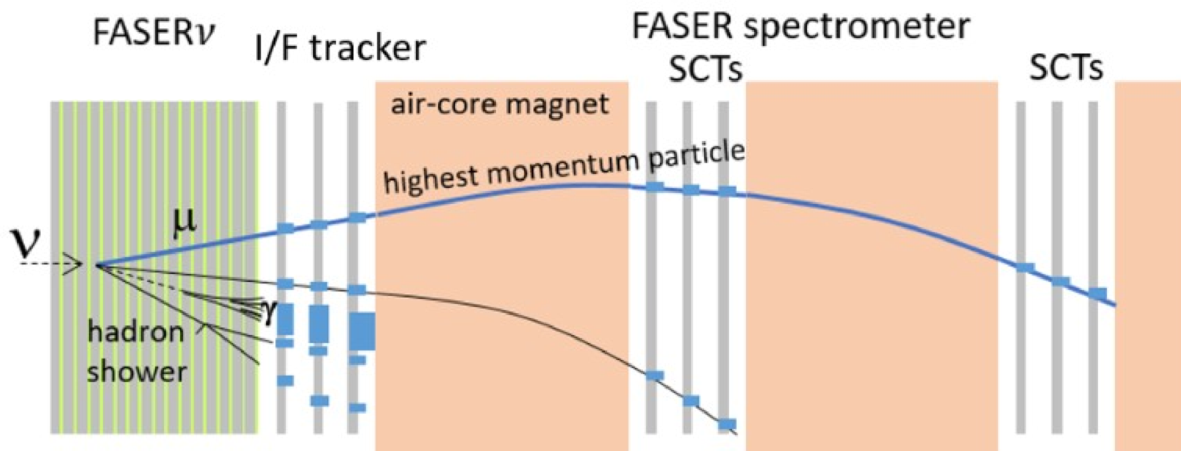


F. Kling, ST,

SEARCH FOR SCATTERINGS

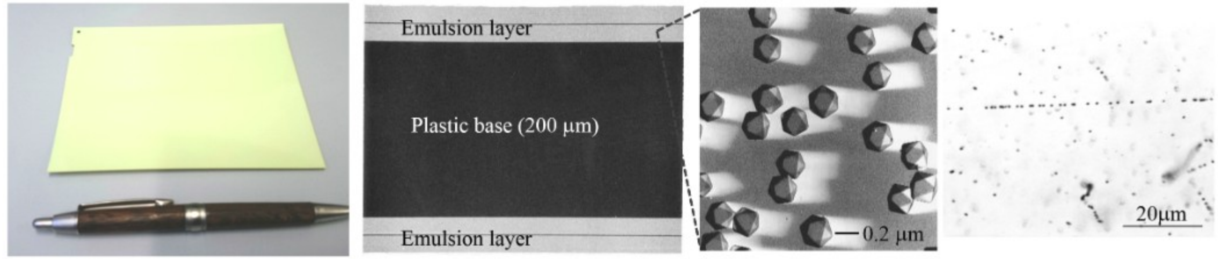
FASERν -- NEUTRINO SUBDETECTOR (RUN 3)

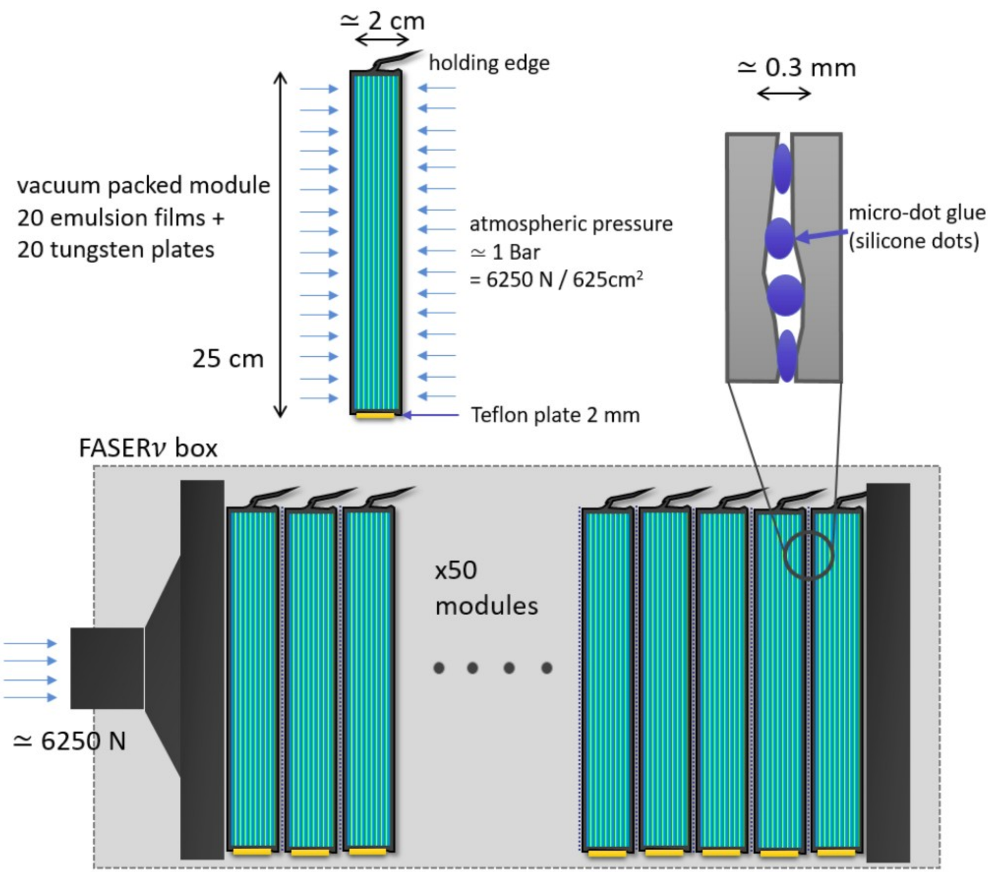




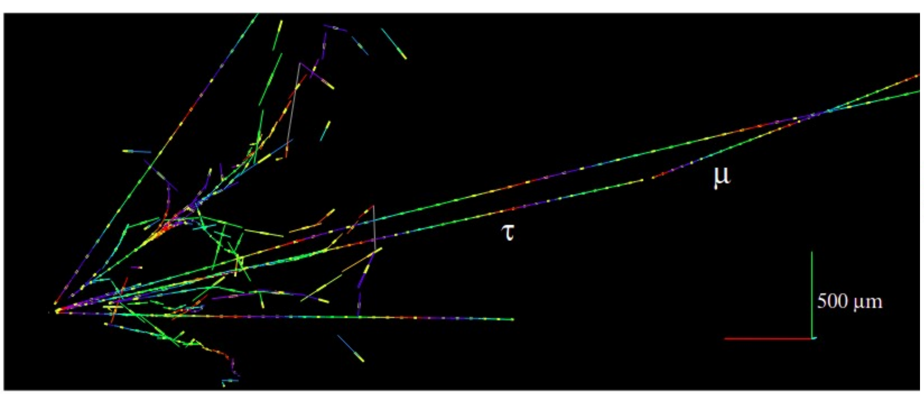
- FASERν (1908.02310, 2001.03073) and SND@LHC (2002.08722) emulsion detectors
- Excellent spatial resolution (even 50nm),
- Can deal with high track density (up to 10^6 tracks/cm^2),
- Study neutrino interaction vertices at TeV energies in great details
- Interface tracker – charge measurement disentangling ν_μ and $\bar{\nu}_\mu$

EMULSION DETECTOR (FASERν)





ν_τ CC scattering event display



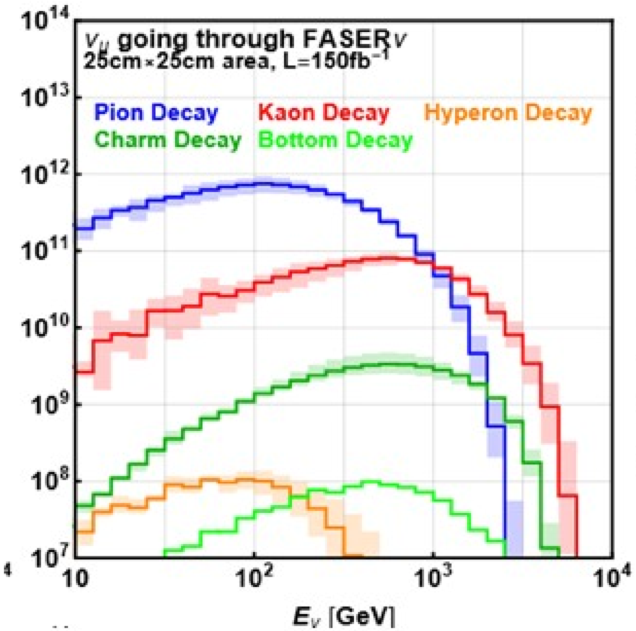
FASER Collaboration, 1908.02310

FAR-FORWARD NEUTRINOS

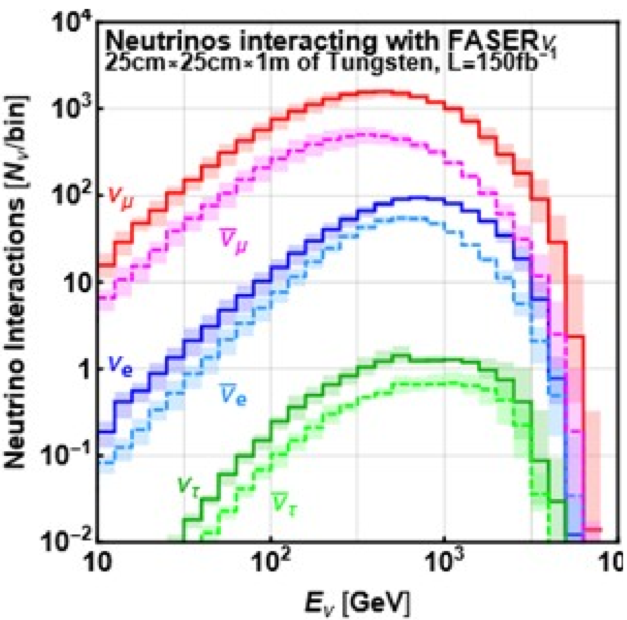
- LHC: lots of forward-going neutrinos from meson decays
- Measurement of the neutrino scattering cross section for E_ν ~TeV (currently poorly explored regime)
- Possible detection of 10-20 high-energy tau neutrino events

LHC Run 3

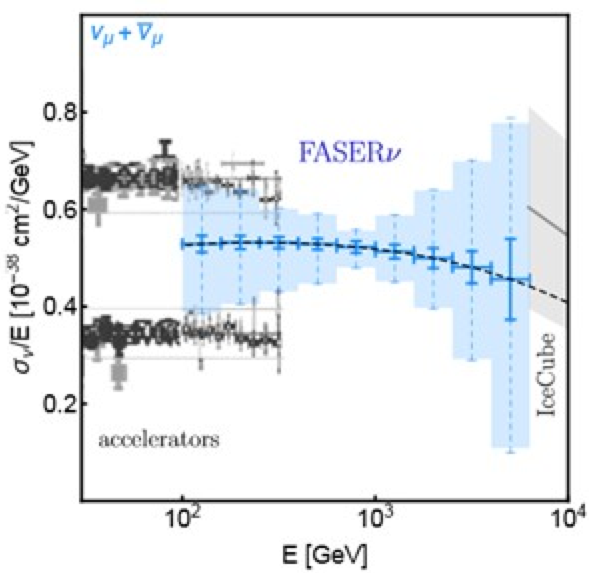
Going-through



Interacting



Scattering cross section



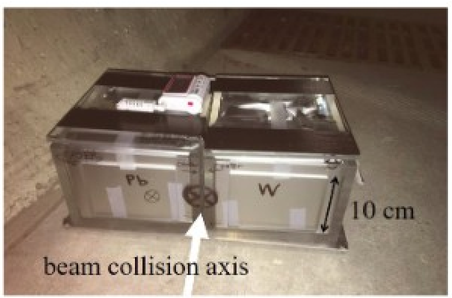
EXTREMELY POWERFUL DETECTION METHOD

- First neutrino candidate events has been observed already during Run 2...

FASER Collaboration, 2105.06197

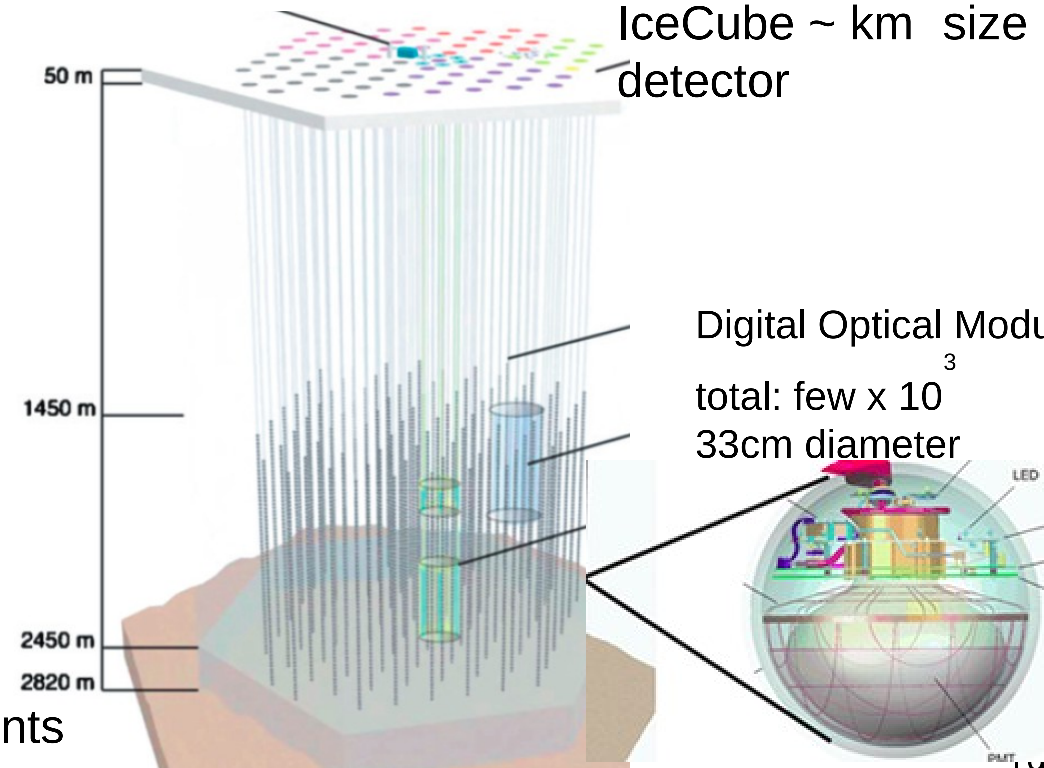
- ...with two handy boxes (10cm x 10cm x 12.5cm)

left in the far-forward place (480m) for 4 weeks (12.5 fb^{-1})



- several neutrino-like events (2.7σ over expected BG)
- proof-of-principle of detection strategy
- during Run 3 ~ 10^4 expected events

IceCube ~ km^3 size detector



Digital Optical Module

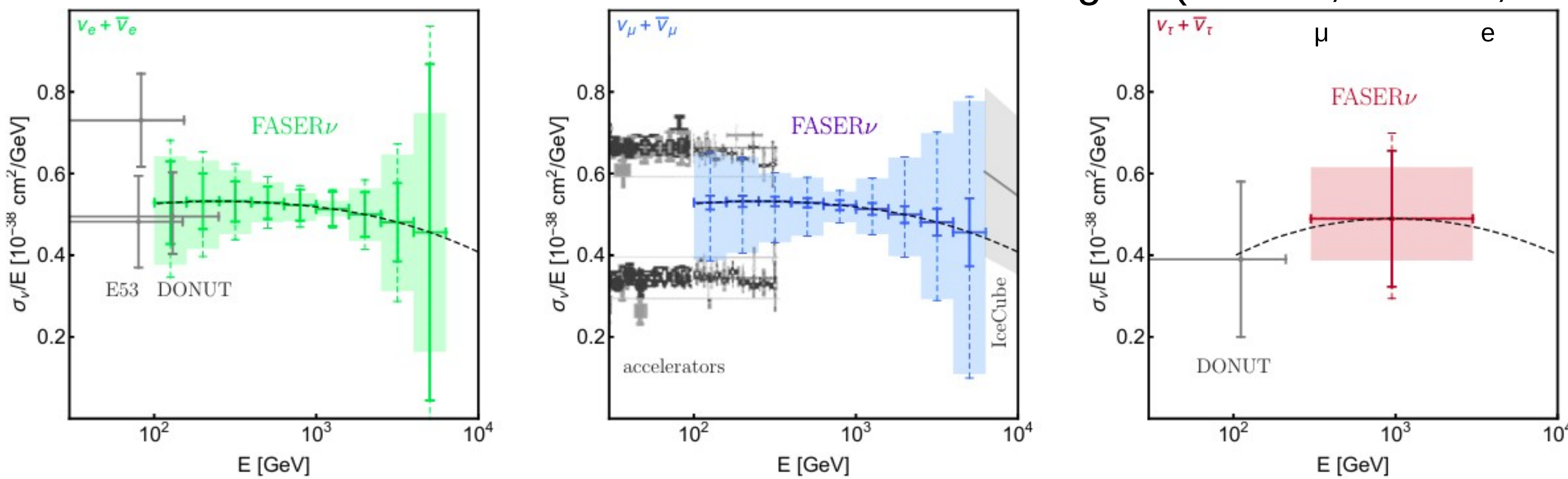
total: few x 10^3

33cm diameter

FASER Collaboration, 1908.02310

PROSPECTS FOR RUN 3

- Inclusive CC cross section measurements at TeV energies (~10^4 ν_μ , ~10^3 ν_e , ~10 ν_τ)



- NC cross section measurements

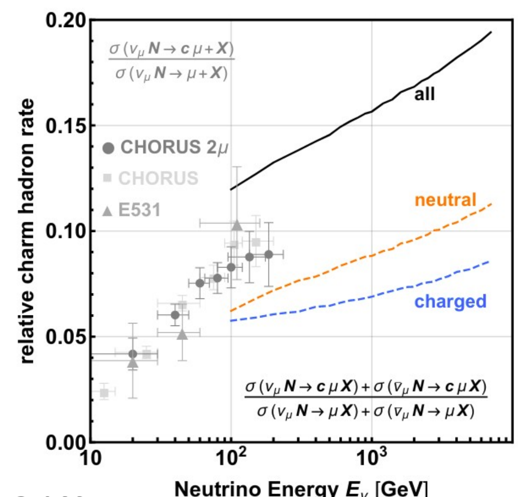
  (A. Ismail, R.M. Abraham, F. Kling, 2012.10500)

- specific neutrino interaction processes, e.g.,

  ν-induced charm production

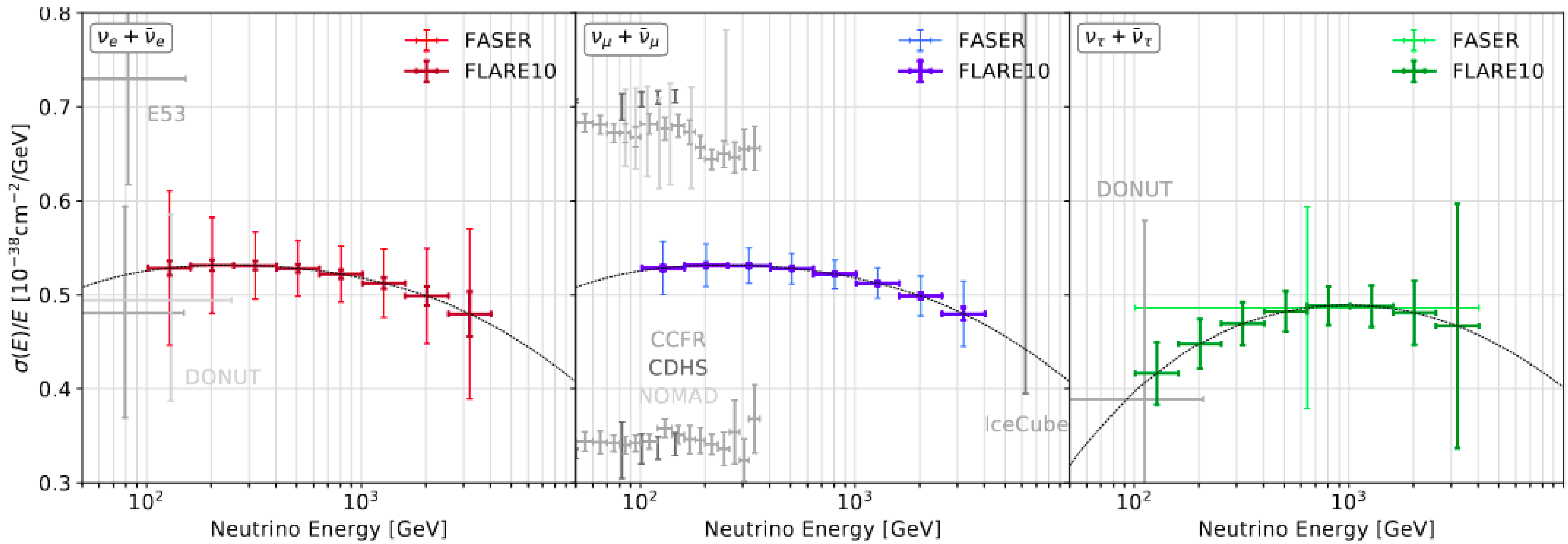
- Forward ν_e flux and spectrum:

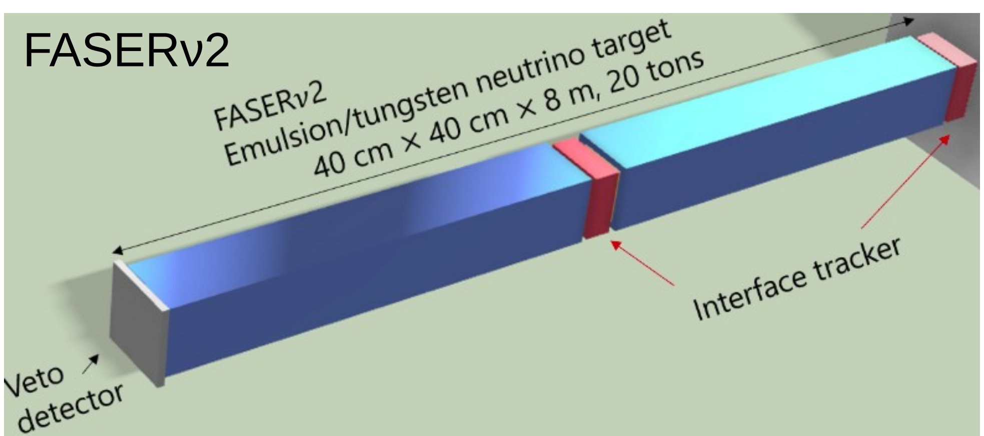
forward charm prod., gluon PDFs (gg→ cc), intrinsic charm

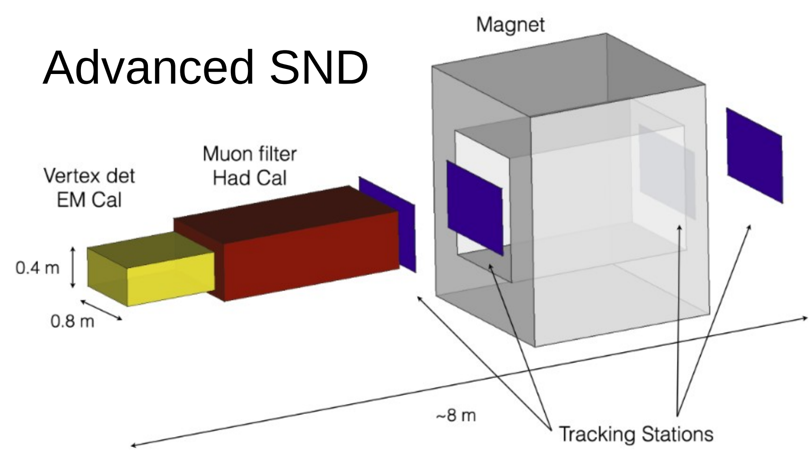


PROSPECTS FOR HL-LHC

- 10-tonne detector on beam collision axis
- Even better cross section measurements (few x 10^5 ν , few x 10^4 ν , ~10^3 ν)



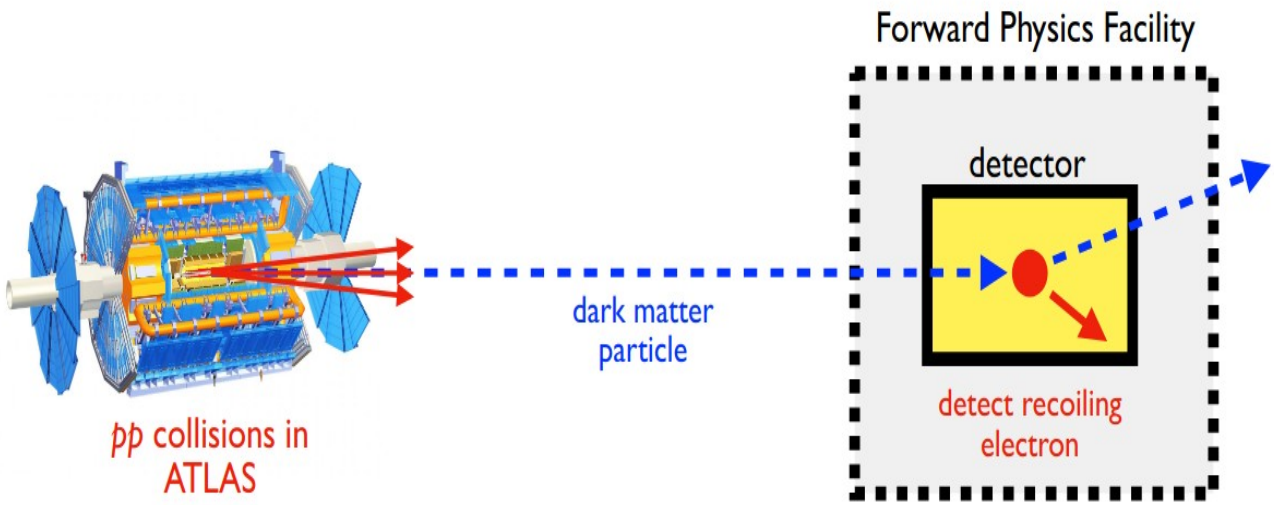




B. Batell, J. L. Feng, ST, 2101.10338
B. Batell, J.L. Feng, A. Ismail, F. Kling, R.M.Abraham, ST, 2107.00666

DM DIRECT DETECTION AT THE LHC

• Light DM particles can be efficiently produced in the far-forward region of the LHC & scatter in a distance detector



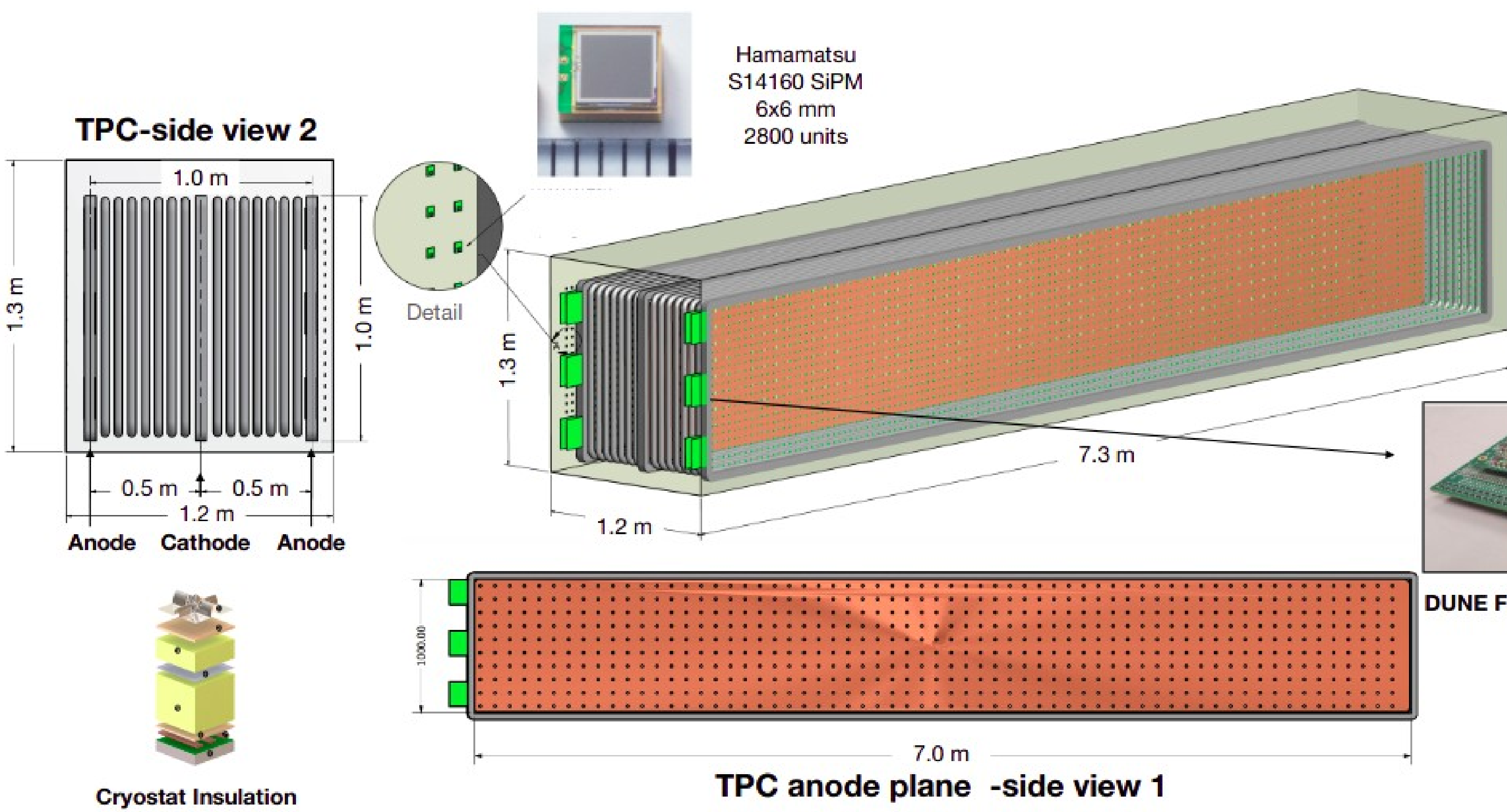
• This search is highly complementary to the traditional DM direct detection searches:
– probe of relativistic interaction rates of LDM (DM energy ~ a few hundred GeV) [collider-boosted DM]
– the search is not sensitive to the precise abundance of χ DM component (possible variations in cosmological scenario)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

FORWARD **L**IQUID **AR**GON **E**XPERIMENT

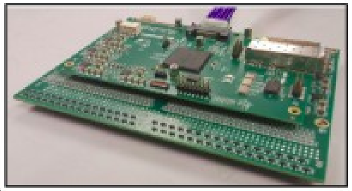
- LAr TPC detector (sensitivity to even low-energy signals, dynamical info)
- possible additional light collection system (triggering, helps with BG rejection, event rec.)
- also for neutrino physics

Brookhaven National Laboratory

FLArE Detector Preliminary Sketch



Volume	11.5 m^3
LAr	16 ton
LKr	27.5 ton
menbran	0.5 m
heat loss	290 W

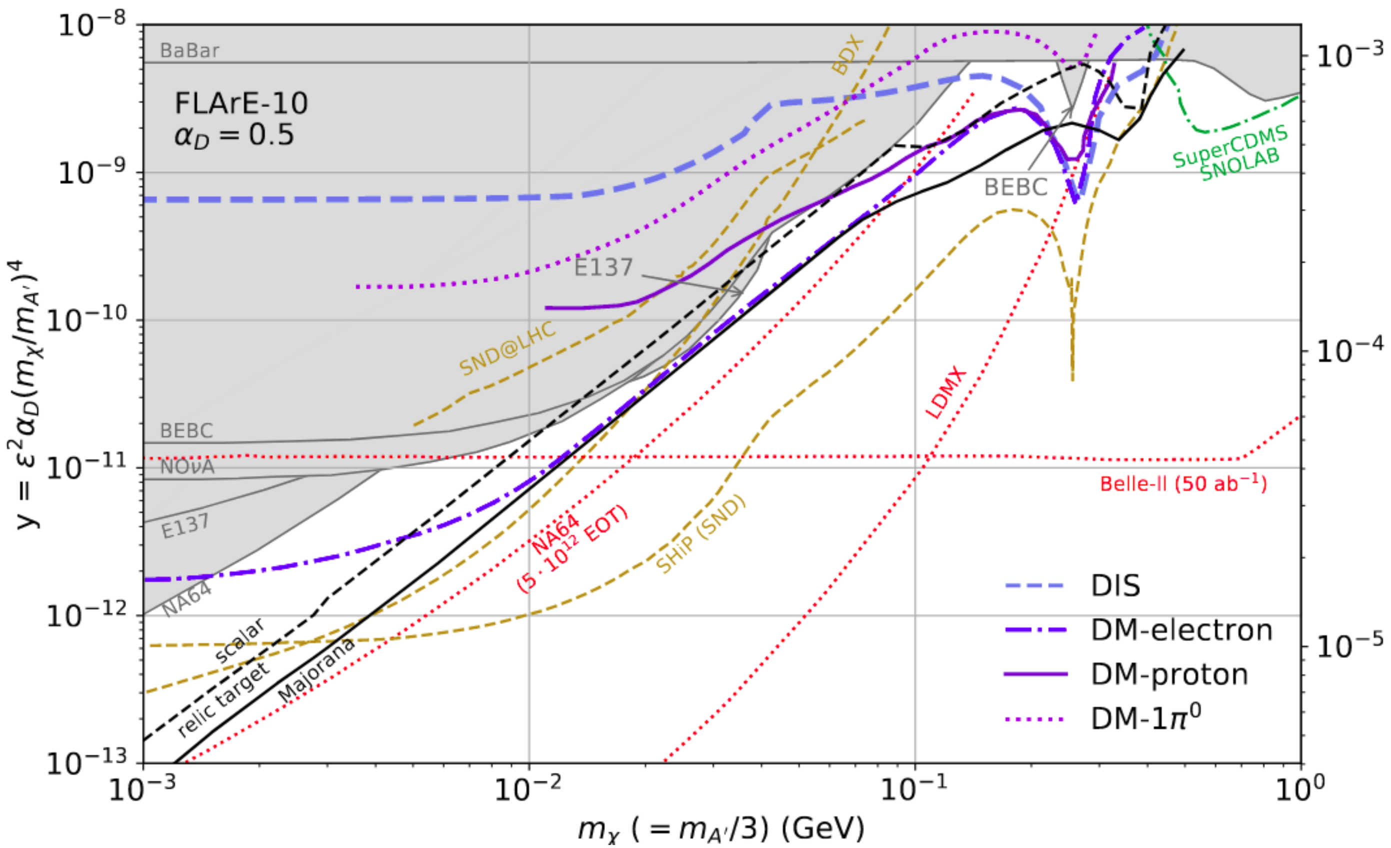


DUNE Front End Motherboard

EXAMPLE DM REACH PLOTS

- Useful for probing DM models with suppressed non-relativistic scattering rates
- Examples: dark photon mediator & Majorana or (inelastic) complex scalar DM

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



SCINTILLATION SIGNAL

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.)

a) important experimental test of charge quantization

Search for particles with a very small electric charge , $\varepsilon \equiv q/e \ll 1.$

b) motivated by GUT and string theories

c) also arise when SM is extended with a massless gauge boson (dark photon) kinetically mixed with the SM photon

d) rich literature: also dedicated detector at the LHC (milliQan)

e) one of the benchmark scenarios typically considered in light new physics searches (e.g. PBC,...)

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

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

- milliQan-like detector placed in the FPF

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

- size: 1m x 1m x 5m

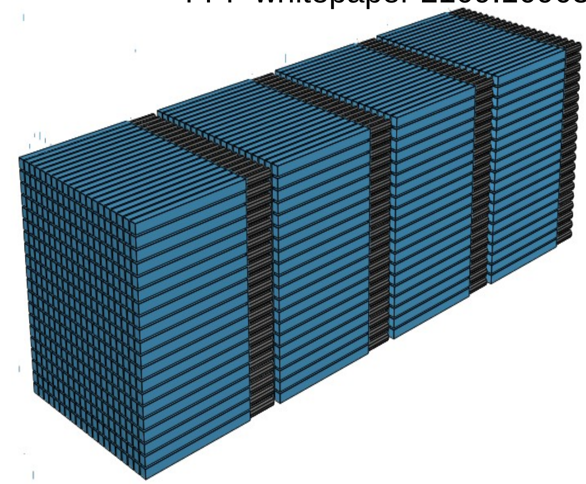
segmented into 4 longitudinal ``layers''
each layer contains 100 scintillator bars
(5cm x 5cm x 1m) organized in a 10 x 10 array

- signature (~eV):

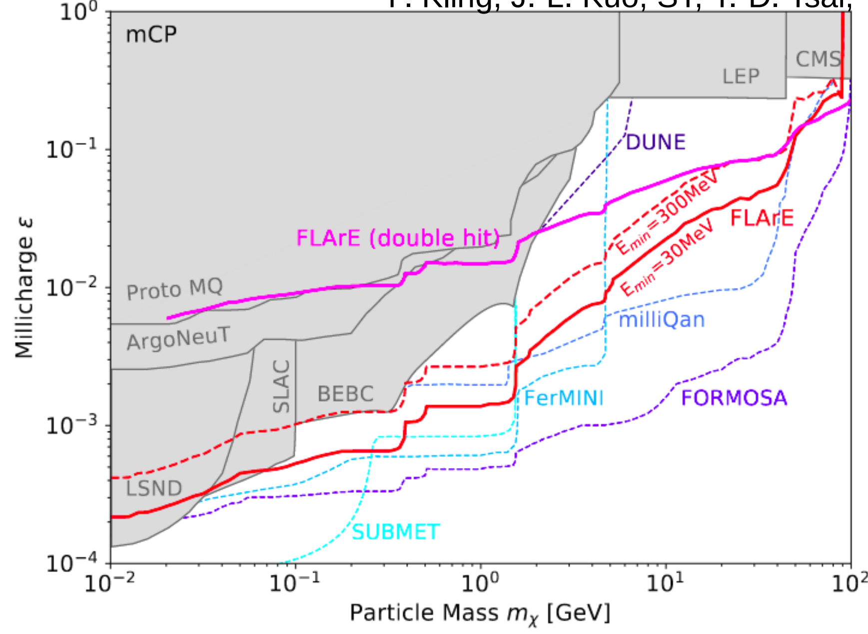
4 time-coincident hits (N_{PE}>1)

- complementary signature at FLArE

(>~30 MeV)
scattering a-la-DM



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



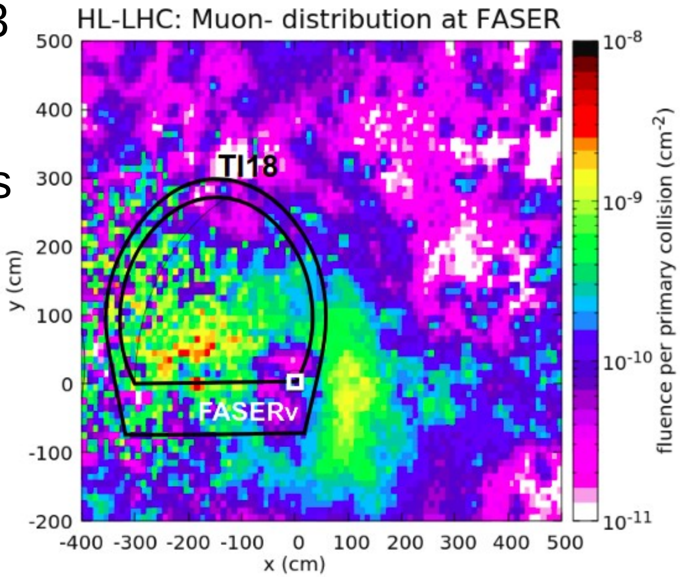
MUON BACKGROUNDS AND SWEEPER MAGNET

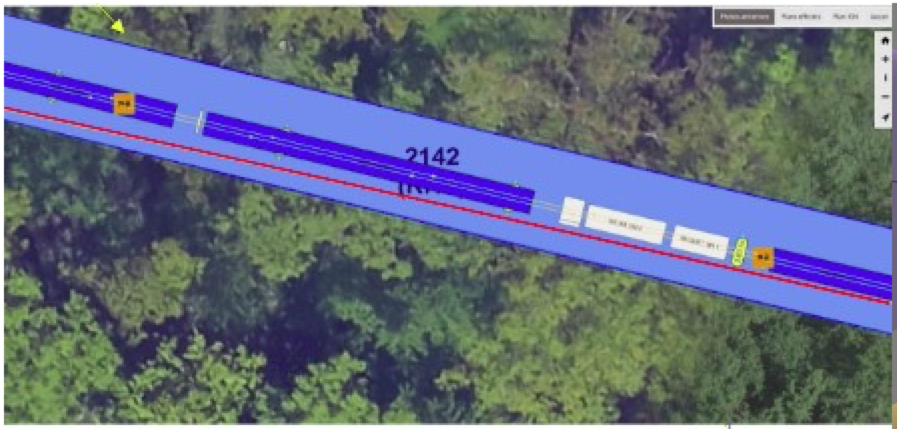
Run 3

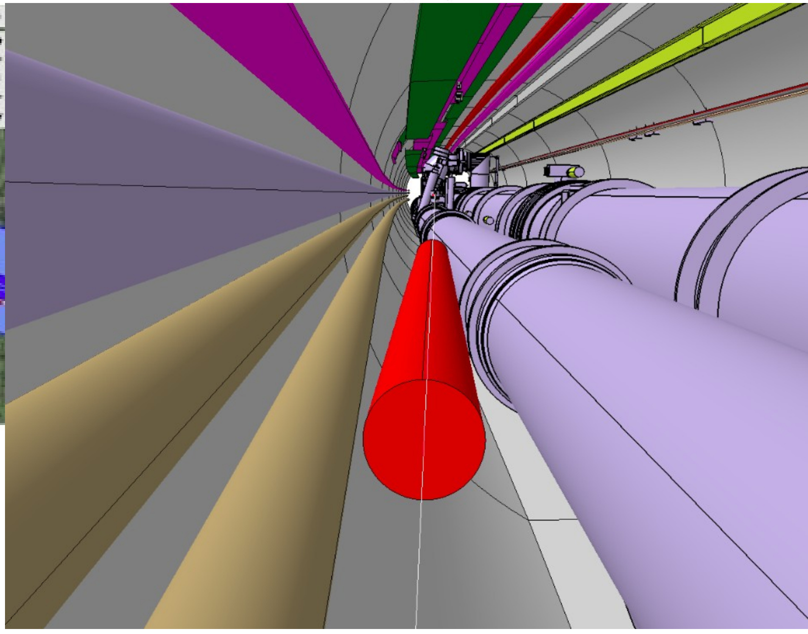
- High-energy muons from the ATLAS IP & collisions inside the beam-pipe can reach far-forward Detectors

- Run 3: (Fortunate) Impact of the LHC magnets

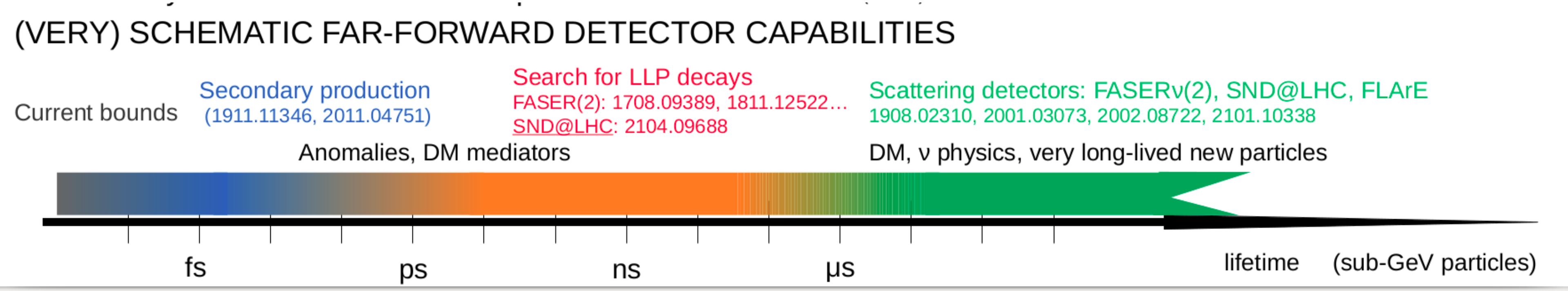
- HL-LHC: Idea to place a dedicated sweeper magnet in the LHC tunnel to deflect away forward muons







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,...)
- Decays: Search for highly-displaced decays of light new particles (boosted decay lengths d~100-1000 m) FASER (2)
- Scatterings: neutrinos (high-energy), light DM (low-energy) FASERν(2), FLArE, AdvSND@LHC
- Scintillation: millicharged particles (mCPs) FORMOSA
- 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

BACKUP

HIDDEN SECTOR PORTALS

– new „hidden” particles are SM singlets (but gauged $U(1)_{B\text{-}L}$ etc. are also considered)

– interactions between the SM and „hidden” sector arise due to mixing through some SM portal

$$\mathcal{L}_{\rm portal} = \sum O_{\rm SM} \times O_{\rm DS}$$

B. Patt, F. Wilczek, 0605188
B. Batell, M. Pospelov, A. Ritz, 0906.5614

Renormalizable

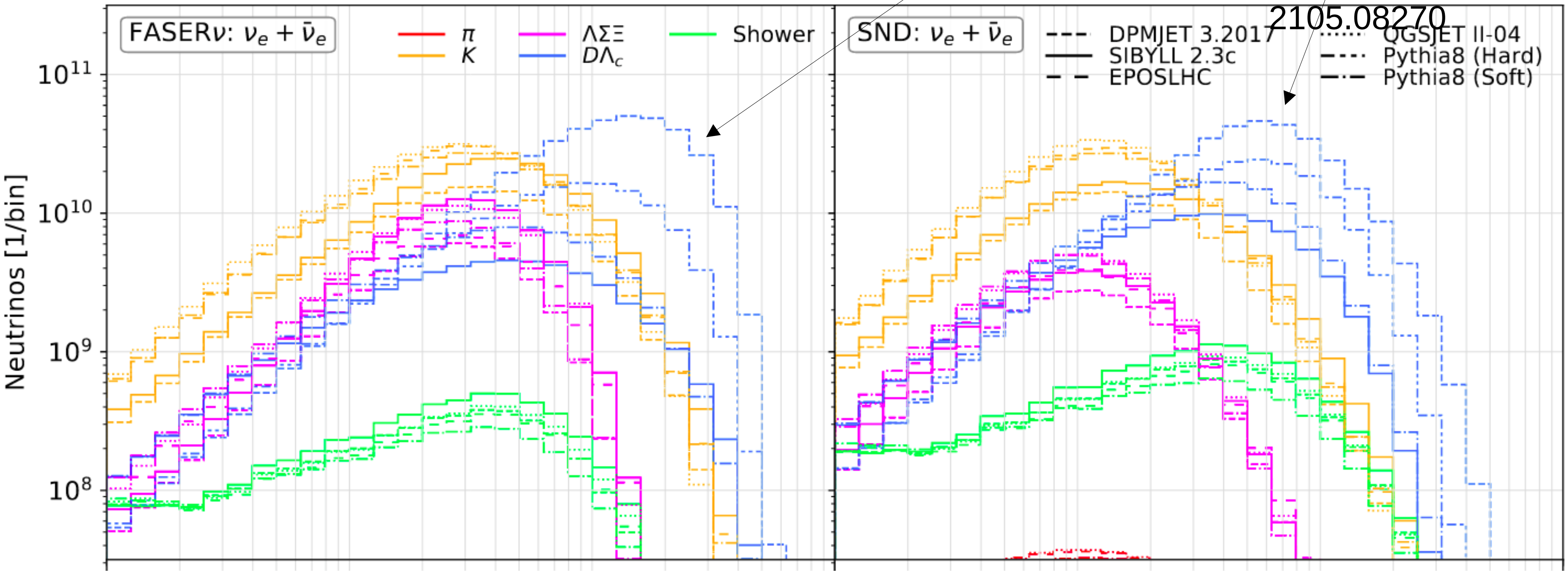
Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu} \tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a} \overline{\psi} \gamma^\mu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

PBC report, 1901.09966

QCD – FORWARD CHARM

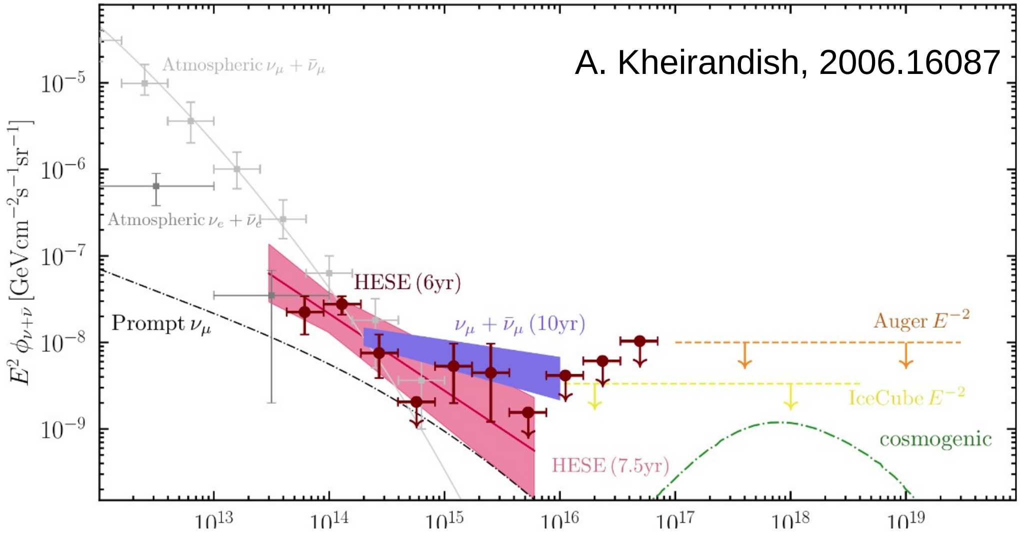
- Measuring neutrino flux and spectrum: further tuning of forward MC tools
- Large differences in electron neutrino spectrum at high energies from charm decays
- ν_e main production at high energies: gg → cc, D → K l ν
- probe of gluon PDFs at low x, intrinsic charm,...

F. Kling, 2105.08270



COSMIC RAYS AND MORE

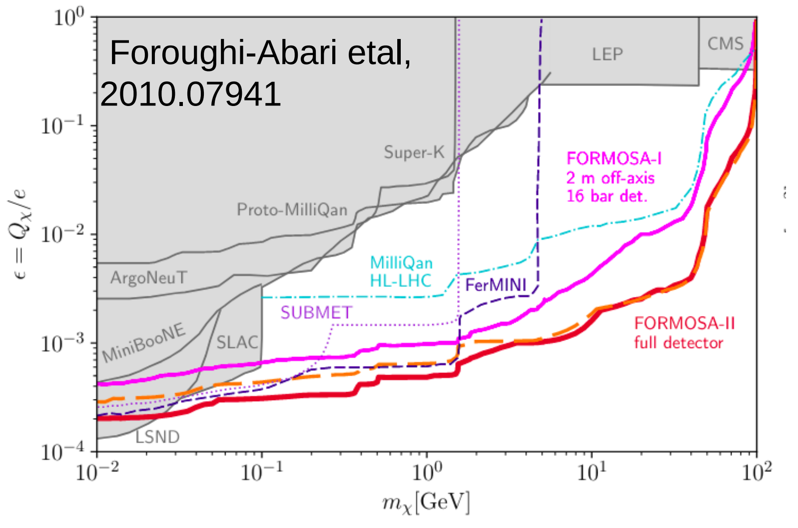
- Forward charm production → constrain ``prompt'' atmospheric neutrino flux
(relevant for measurements of the astrophysical neutrino flux at IceCube)



- Cosmic-ray muon problem
(observed excess of high-energy muons, better high-energy forward kaon production measurement remains essential here)

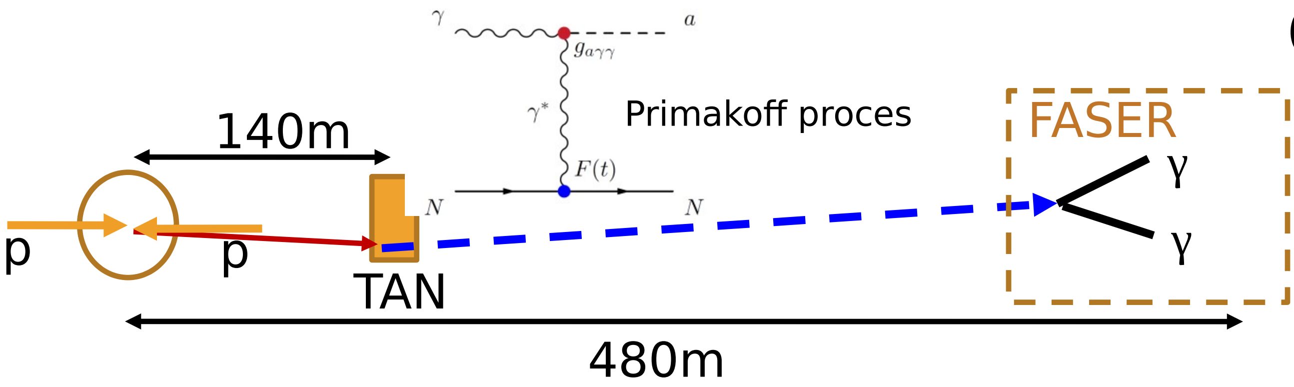
- Opportunities in muon physics
(SM measurements, new physics)

- millicharged particles
– tests of charge quantization
– motivations from GUTs, strings, massless A',.

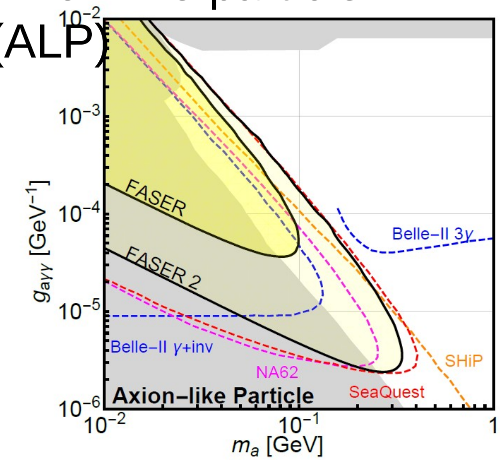


NOT ONLY ATLAS IP

LHC as a **high-energy photon beam-dump**

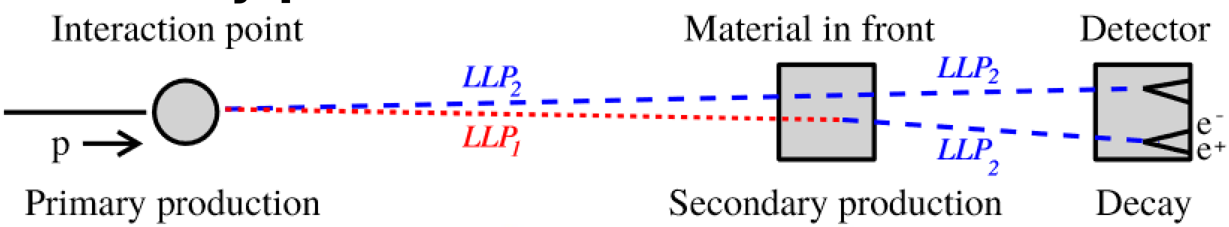


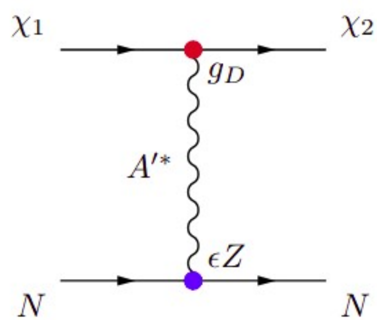
Axion-like particle (ALP)



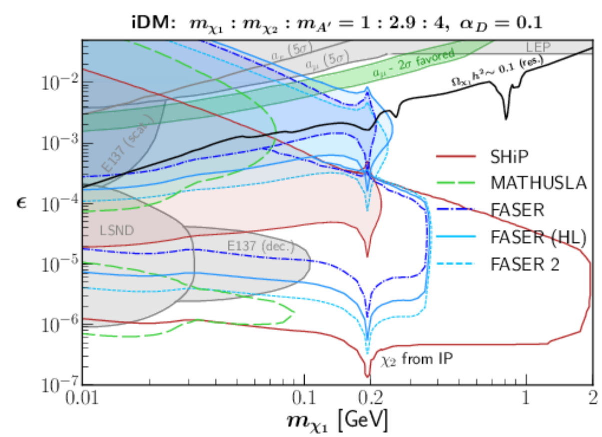
J. L. Feng, I. Galon, F. Kling, ST, 1806.02348

Secondary production in front of the detector





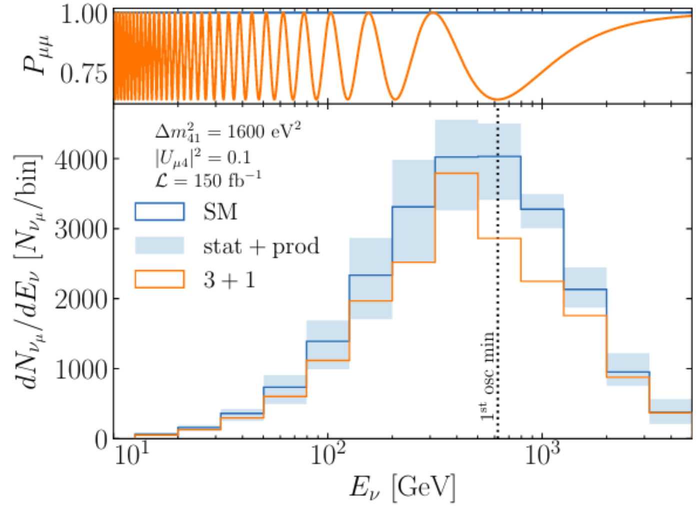
Inelastic DM



K. Jodłowski, F. Kling, L. Roszkowski, ST, 1911.11346

NEW PHYSICS & NEUTRINO INTERACTIONS

FASER Collaboration, 1908.02310



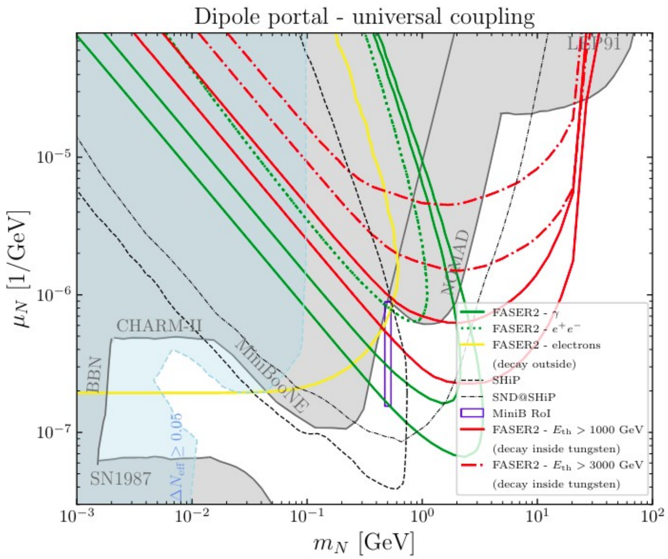
- Neutrino oscillations into sterile neutrinos direct probes at larger mass differences than typical neutrino experiments

$\Delta m^2 \sim 1000$ eV^2

(also e.g. Gallium anomaly)

- Non-standard neutrino interactions

K. Jodłowski, ST, 2011.04751



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

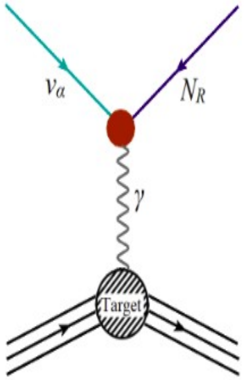
$$\mathcal{L} \supset \bar{L} \left(d_W \mathcal{W}^a_{\mu\nu} \tau^a + d_B B_{\mu\nu} \right) \tilde{H} \sigma_{\mu\nu} N_D + h.c.$$

DM scattering: 2101.10338 (el. scat.), 2107.00666 (nuclear scat.), 2111.10343 (hadrophilic DM)

Other interesting ideas (possibly different signatures)

a) Neutrino up-scattering into heavy neutral lepton

Possible subsequent decay (double-bang): $N_R \rightarrow \nu\gamma$



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

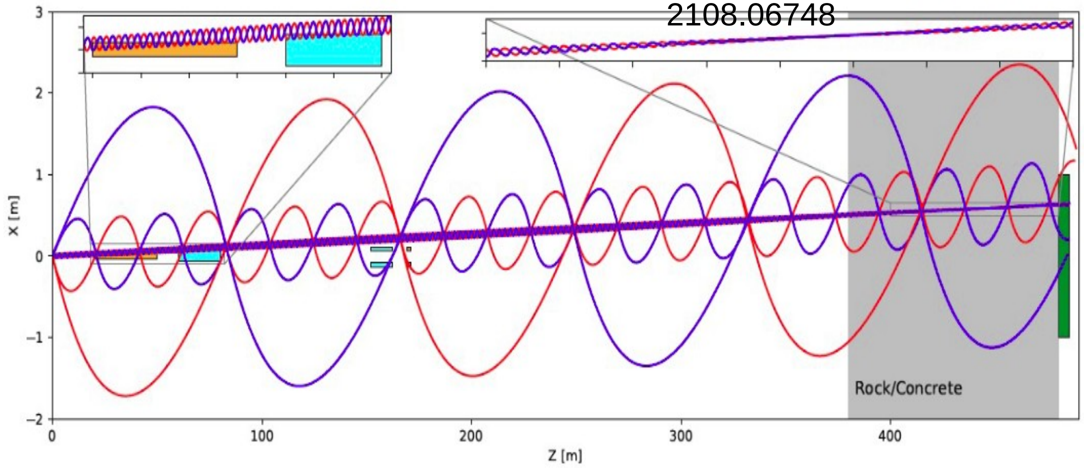
b) Quirks (J. Kang, M.A. Luty, 0805.4642)

Postulated particles charged under a hidden strong force

If they mass exceeds the hidden scale $m >> \Lambda_{hidden}$, they do not hadronize

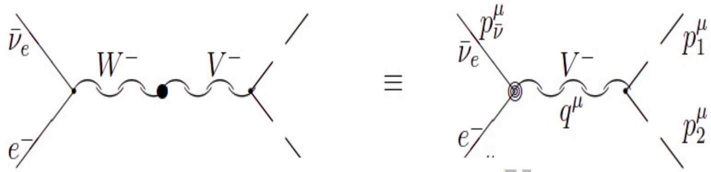
Instead, they are pair produced and remain bounded => they leave very strange tracks

Li, Pei, Ran, Zhang, 2108.06748



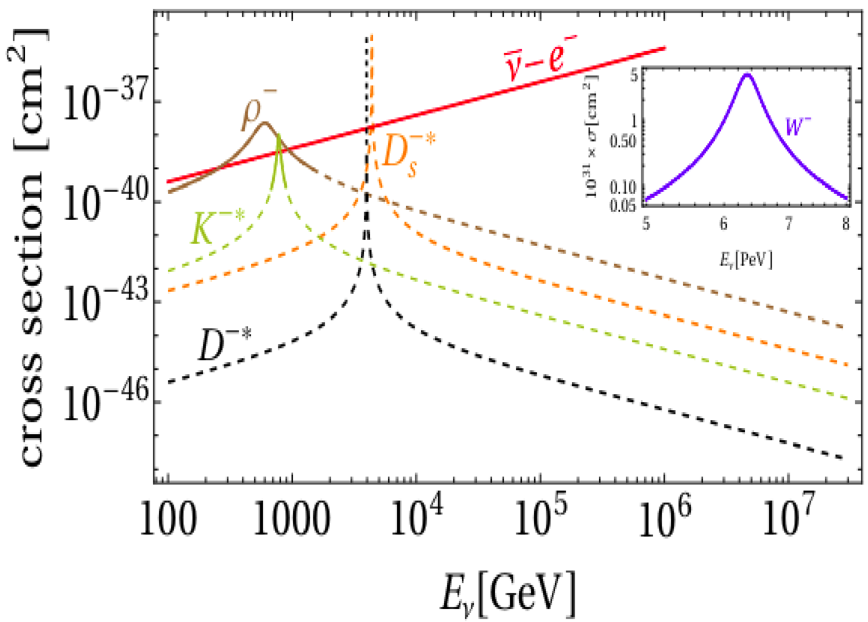
Other interesting ideas (possibly different signatures) (2)

c) Rare neutrino scattering process in the SM



$\bar{\nu}_e e^- \to \mathfrak{m} \to X$

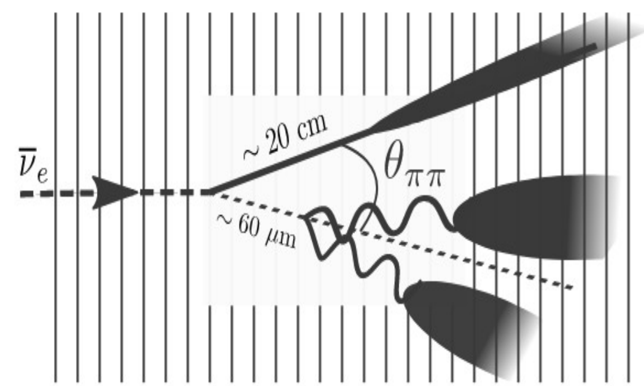
Total absorption of the electron anti-neutrino



Resonances in $\bar{\nu}_e - e^-$ scattering below a TeV

Vedran Brdar, André de Gouvêa, Pedro A. N. Machado, Ryan Plestid

2112.03283



Most promising channel: $\rho \to \pi^- \pi^0$

Overlapping forward charged pion and γγ EM shower

Experiment	ρ^-, $\pm\Gamma/2$	ρ^-, $\pm 2\Gamma$	K^{-*}, $\pm\Gamma/2$	K^{-*}, $\pm 2\Gamma$
FASERν	0.3	0.5	–	–
FASERν2	23	37	0.7	3
FLArE-10	11	19	0.3	2
FLArE-100	63	103	2	8
DeepCore	3 (1)	5 (2)	–	–
IceCube	8 (40)	(17, 83)	–	–

Other interesting ideas (possibly different signatures) (3)

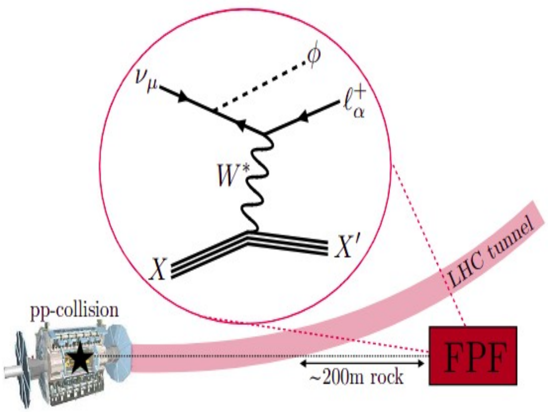
d) Neutrino-philic DM – neutrino CC scatterings with large MET

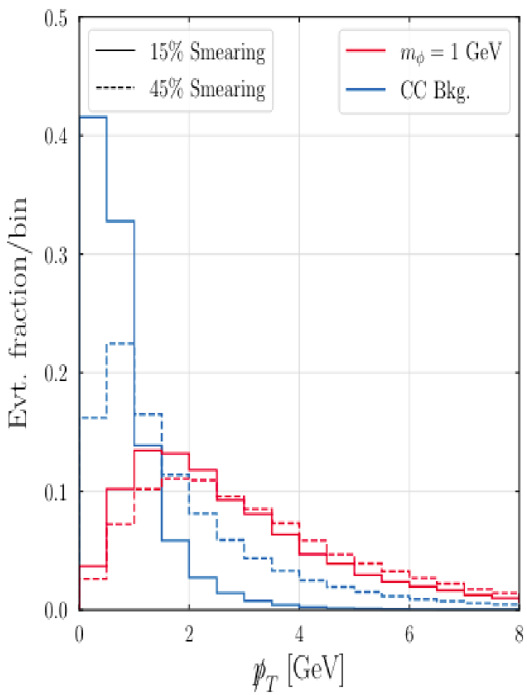
2111.05868

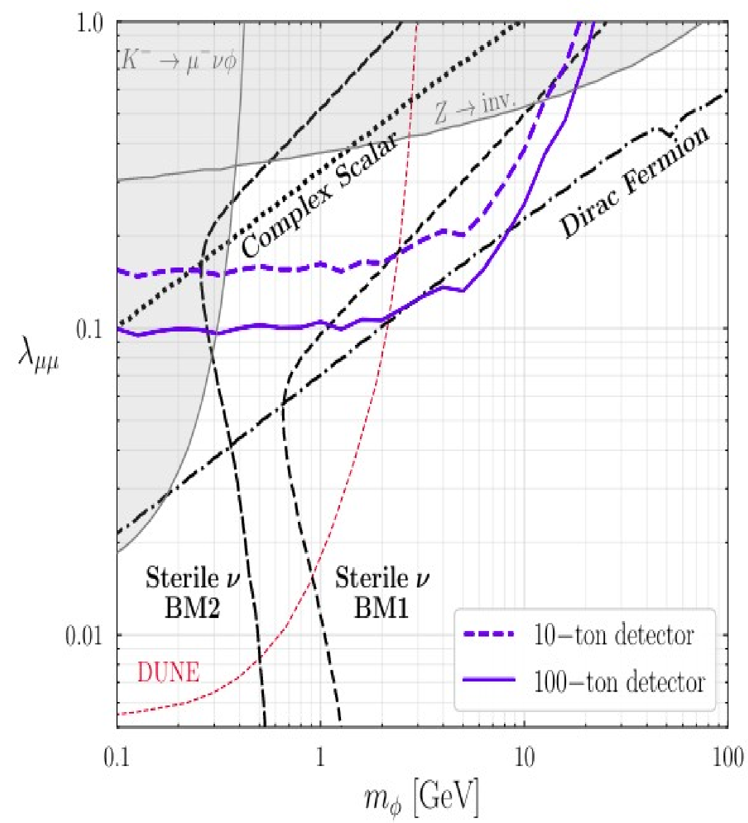
Probing Neutrino-Portal Dark Matter at the Forward Physics Facility

Kevin J. Kelly,[1,2,*] Felix Kling,[3,4,†] Douglas Tuckler,[5,‡] and Yue Zhang[5,§]

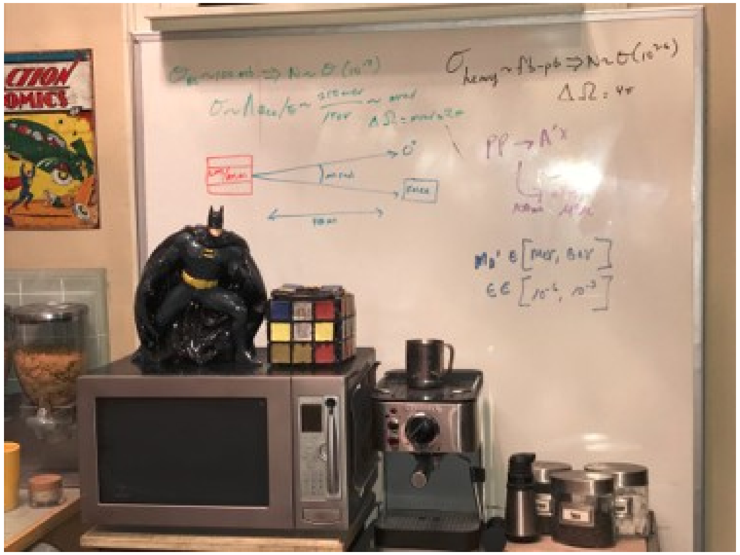
$$\mathcal{L} \supset \frac{1}{2}\lambda_{\alpha\beta}\nu_\alpha\nu_\beta\phi + \text{h.c.} \,,$$

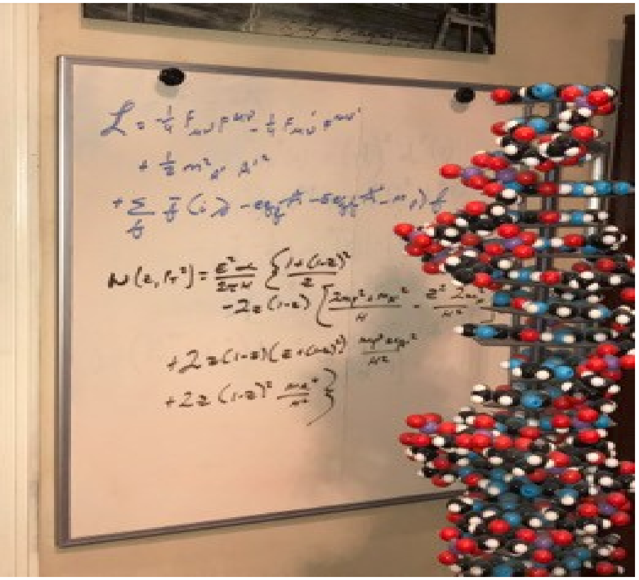






FASER IN POPULAR CULTURE





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LA Times