Looking forward to new physics and neutrinos at the LHC

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High Energy, Cosmology and Astro-particle Physics (HECA)

May 25, 2021

AstroCeNT

NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES

European Funds Smart Growth

Republic of Poland

FNP Foundation for Polish Science

European Union European Regional Development Fund

OUTLINE

- Motivation & Fundamentals

- Far-forward BSM physics at the LHC
  - new physics production in the far-forward region of the LHC
  - selected BSM models
  - BSM particle production away from the ATLAS IP,
  - light dark matter (DM)

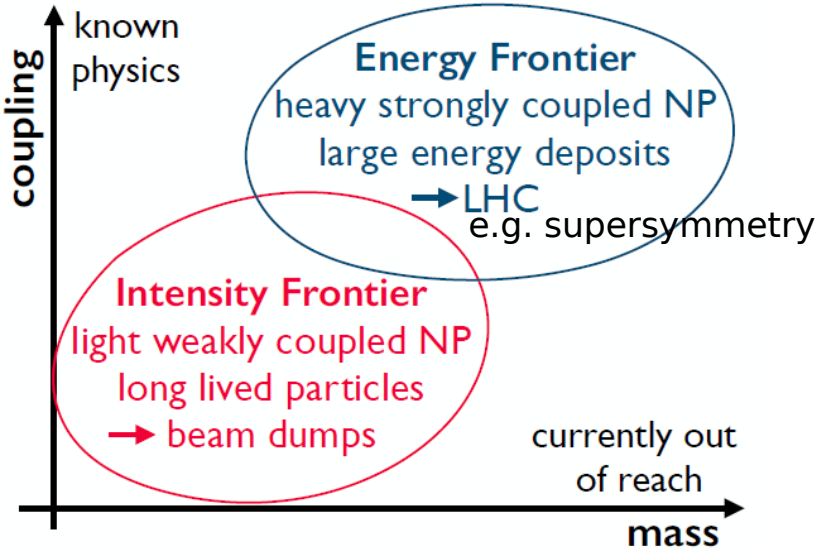
- High-Energy neutrino physics at the LHC

- Additional opportunites (QCD, connections to cosmic ray physics,...)

- Concluding remarks

MOTIVATION

LIGHT NEW PHYSICS



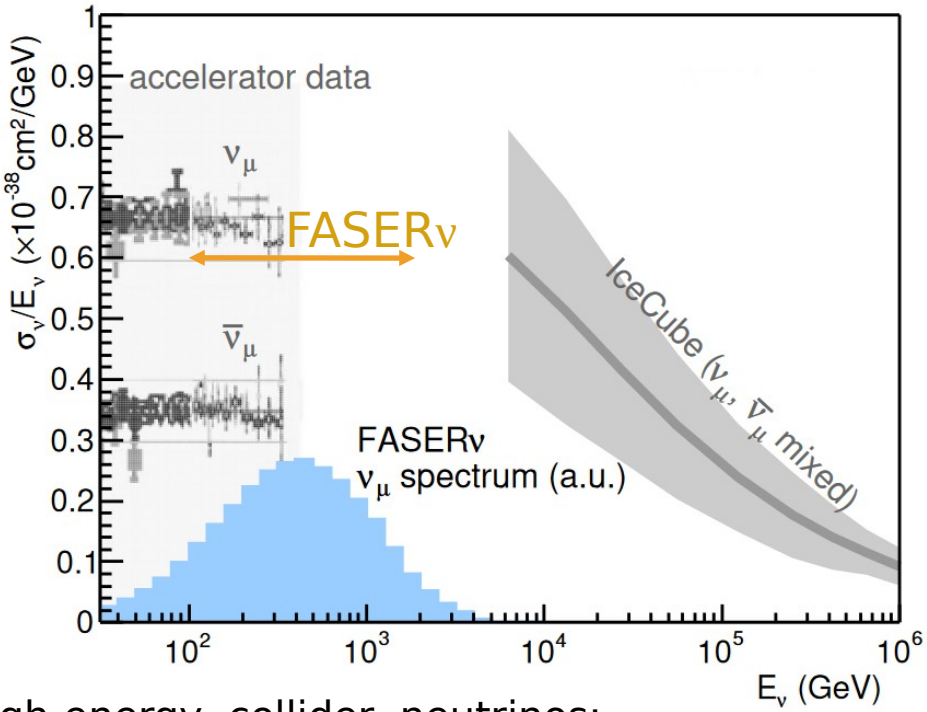
-- “leave no stone unturned”

-- 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

(SELECTED) BSM CONNECTIONS

a) gauging global symmetries of the SM e.g. **$U(1)_{Le-L\mu}$, $U(1)_{B-L}$,** ⟹ new dark vector

M. Bauer, P. Foldenauer, J. Jaeckel, **JHEP 1807 (2018) 094**

Additional U(1) groups might arise in extensions of the SM group,
typically light new gauge boson must be very weakly coupled to the SM

Mohapatra R N and Senjanovic G, Phys. Rev. D23:165 (1981

Kinetic mixing between the photon and new vector can also be loop-induced in secluded regime $U(1)_x$

b) mirror sector / Twin Higgs scenarios often predict new scalars coupled to the SM via Higgs

$$(H^\dagger H) \times m_H^2 \longrightarrow (H^\dagger H) \times (m_H^2 + c_1 S + c_2 S^2 + ...),$$

Lanfranchi etal, 2011.02157

c) Right-handed neutrinos e.g. **νMSM** (ν masses and oscillations, DM, baryon asymmetry)

T. Asaka, S. Blanchet and M. Shaposhnikov, *Phys. Lett.* **B631** (2005) 151–156
T. Asaka and M. Shaposhnikov, *Phys. Lett.* **B620** (2005) 17–26

d) Axion is an example of light weakly coupled particle postulated long time ago

later generalized to axion-like particles

HIDDEN SECTOR PORTALS

– new „hidden" particles are SM singlets (but gauged $U(1)_{B-L}$ 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

FAR-FORWARD BSM PROGRAM

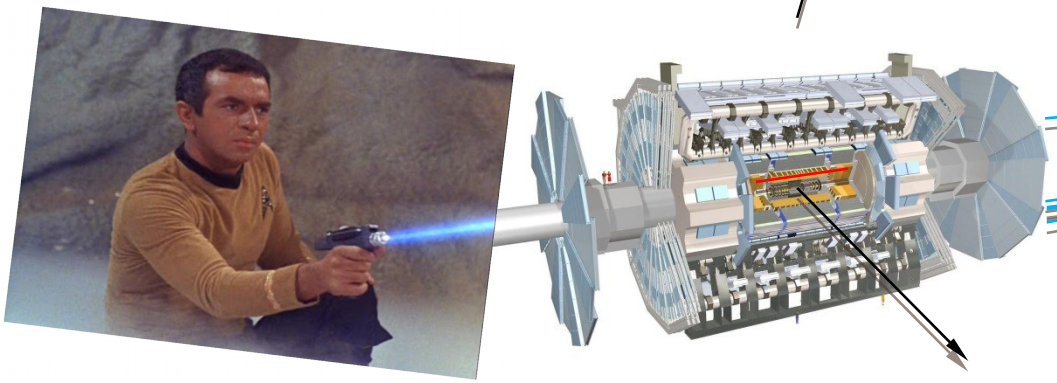
J.L. Feng, I. Galon, F. Kling, ST, 1708.09389
FASER Collaboration: 1811:10243, 1812.09139
1908.02310, 2001.03073

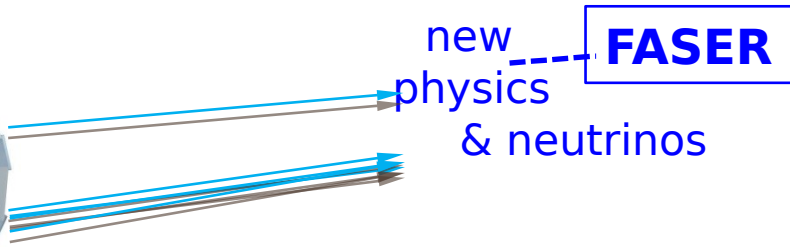
IDEA

ForwArd Search ExpeRiment (FASER) – small (**~0.05 m³**) and detector to be placed few hundred meters downstream the ATLAS IP

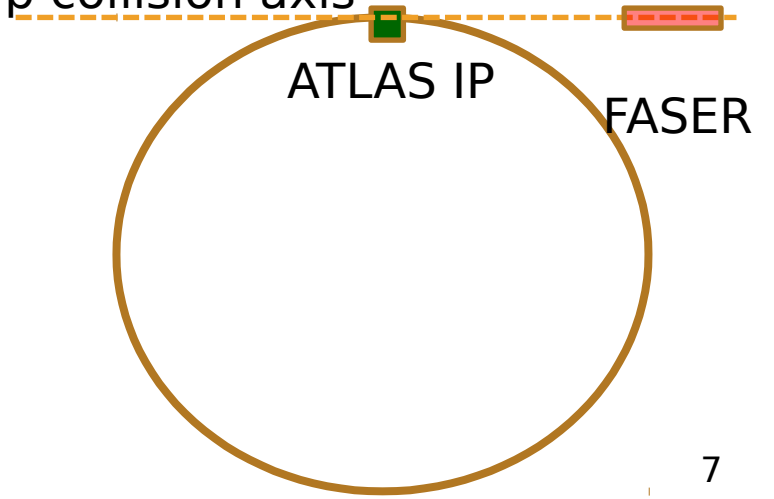
to harness large, currently „wasted" forward LHC cross section

σ_{inel} **~ 75 mb,** e.g., $N_\pi \sim 10^{17}$ at 3 ab^{-1} (for comparison **σ ~ fb - pb,** e.g., $N_H \sim 10^7$ at 300 fb^{-1} in high-p_T searches)





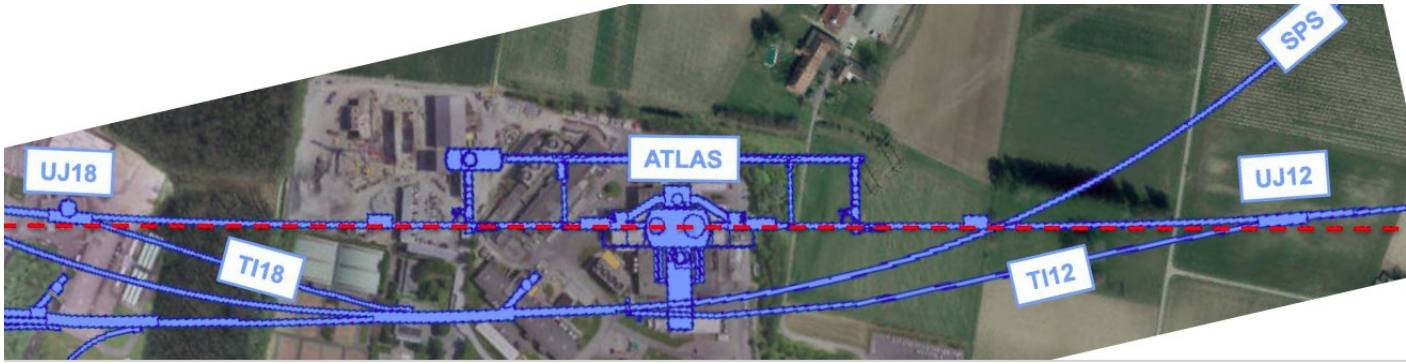
VERY SCHEMATICALLY



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

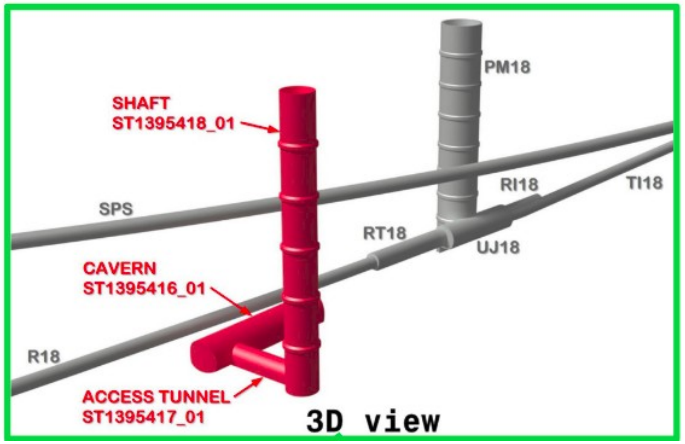
RUN 3 & HL-LHC PLANS

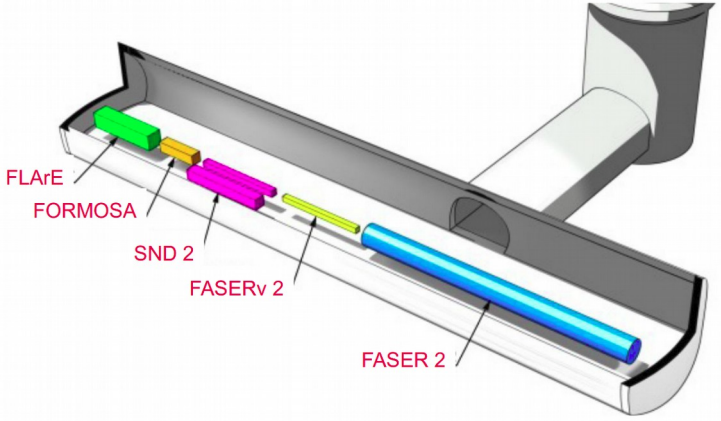
Run 3
main FASER -- cylindrical detector:
L = 1.5 m, R = 10 cm, V = 0.05 m^3, 150 fb^{-1} (Run 3)



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

Forward Physics Facility R.M.Abraham etal, Snowmass 2021 LoI



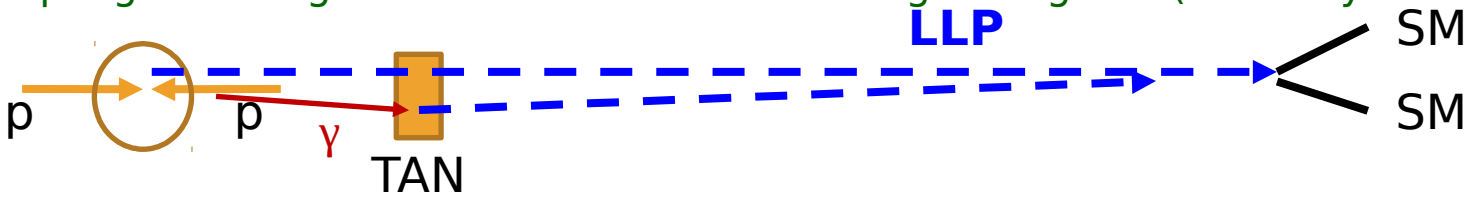


Credit: John Osborne, Kincso Balazs, Jonathan Gall

SEARCH FOR HIGHLY DISPLACED DECAYS

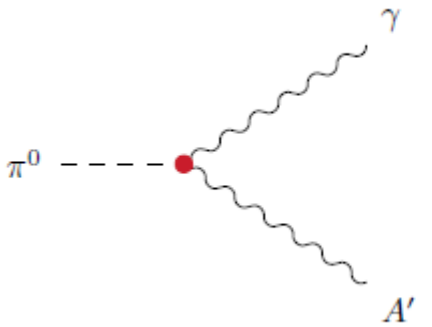
Production (ATLAS IP, …) **Decay**

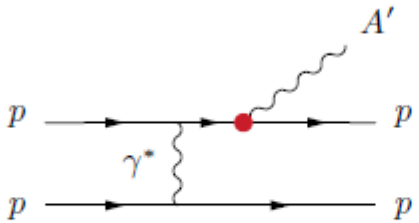
Coupling: the larger the better too large not good (too early decays)

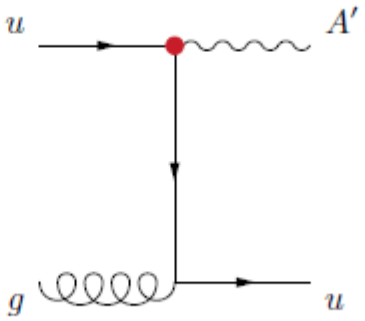


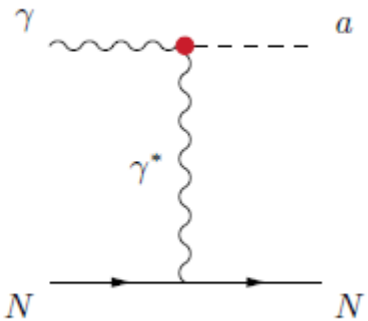
Various production mechanisms:
-- meson decays (light & heavy)
-- bremsstrahlung
-- hard-scatterings,…

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



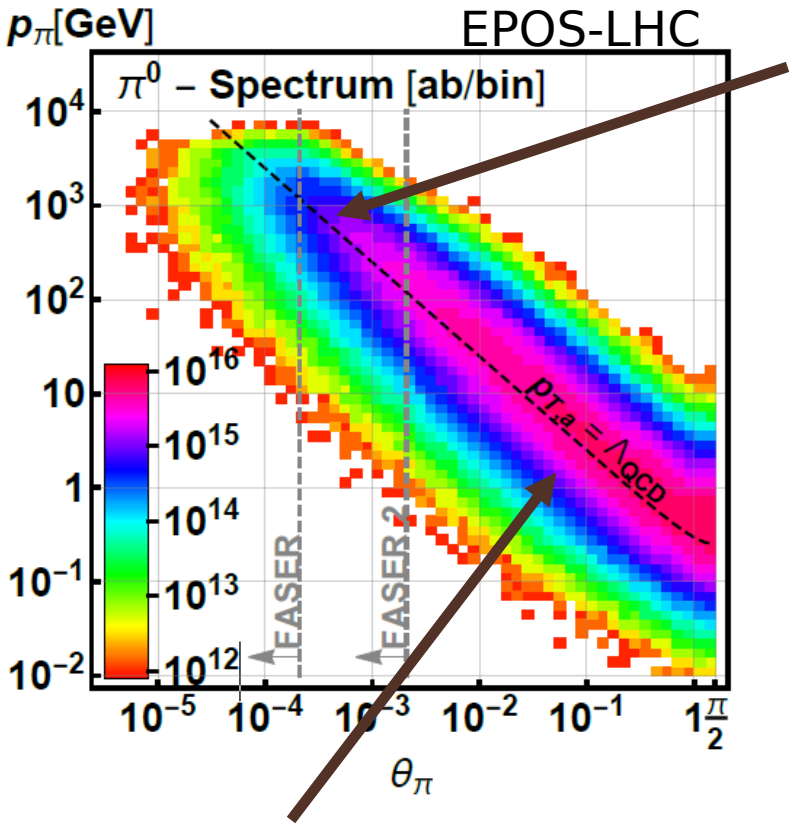






NEW PHYSICS FROM PION DECAYS AT THE ATLAS IP

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

~ 24% of π_0s go towards FASER 2

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

~ (2×10^{-6})% for FASER

~ (2×10^{-4})% for FASER 2

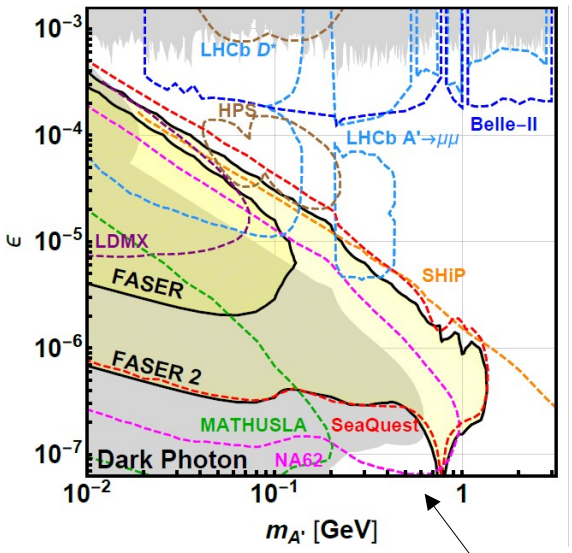
Soft pions going towards high-p_T detectors:

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

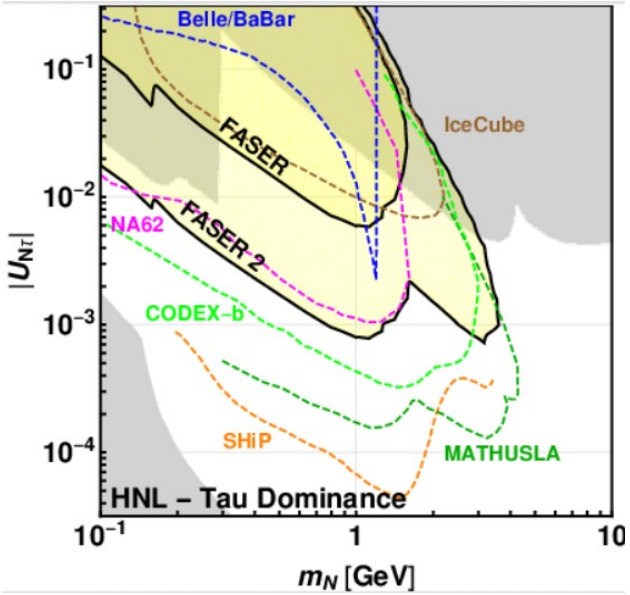
FASER Collaboration, 1811.12522

SELECTED SENSITIVITY REACH PLOTS

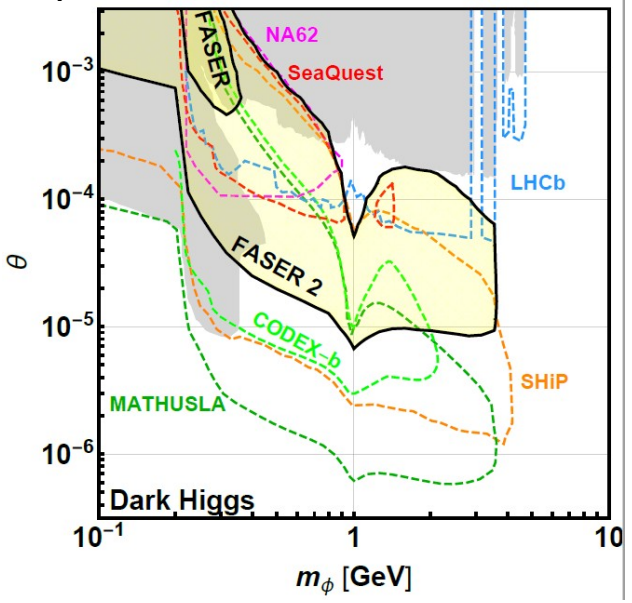
DARK PHOTON



HEAVY NEUTRAL LEPTON (TAU)



DARK HIGGS BOSON

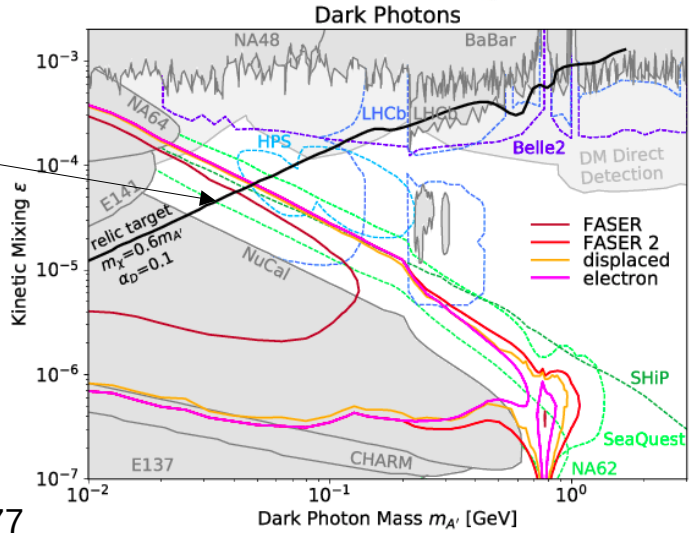


complementarity

DM direct detection searches

complex scalar DM with A' med

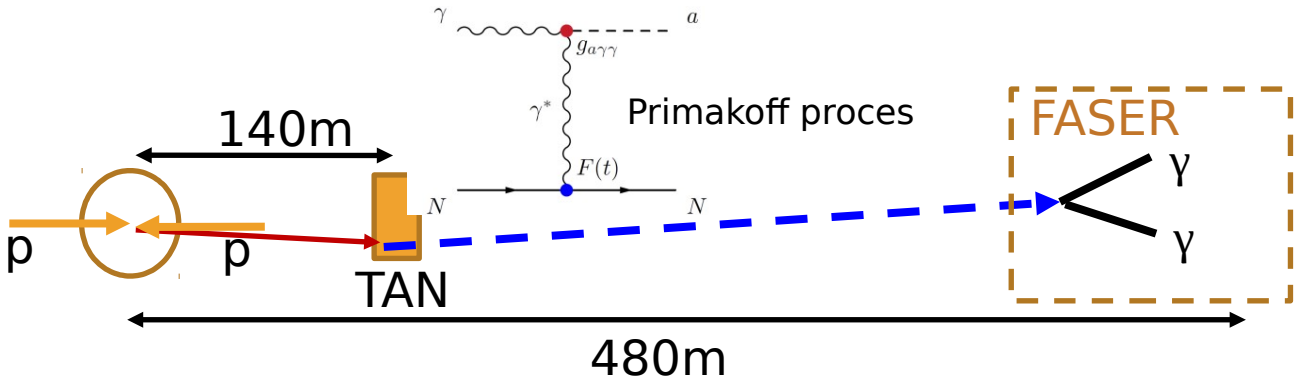
$$\mathcal{L}_D \supset (D^\mu \chi)^* (D_\mu \chi) - m_\chi^2 \chi^* \chi,$$



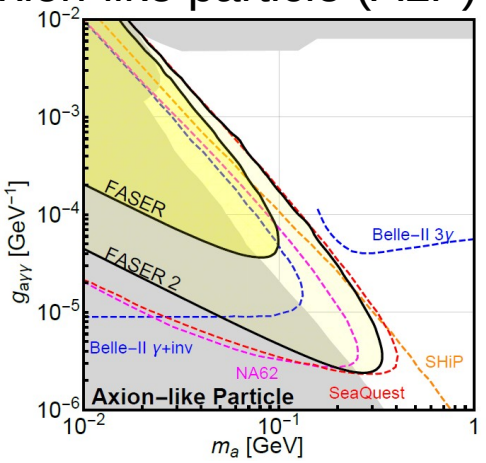
F. Kling, ST, 2105.07077

NOT ONLY ATLAS IP

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

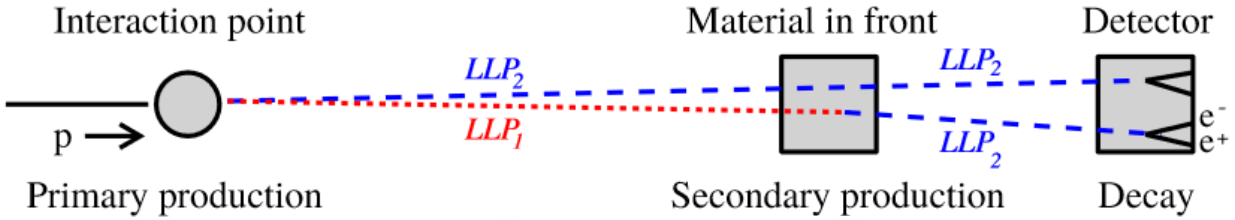


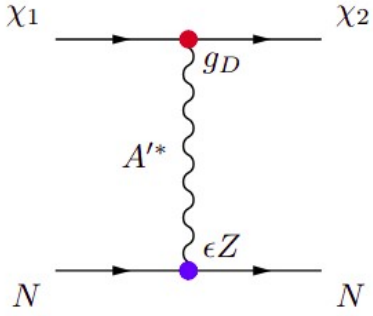
Axion-like particle (ALP)



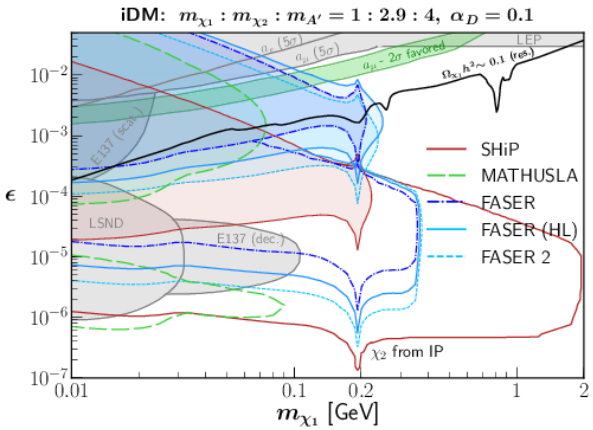
J. L. Feng, I. Galon, F. Kling, ST, 1806.02348

Secondary production in front of the detector





Inelastic DM

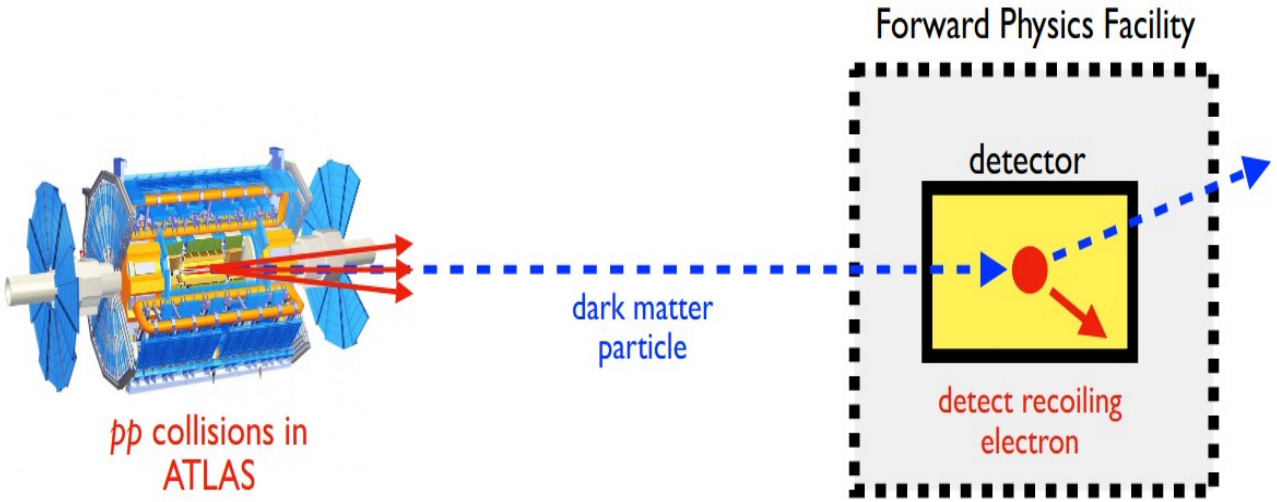


K. Jodłowski, F. Kling, L. Roszkowski, ST, 1911.11346

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

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]

EXAMPLE DM REACH PLOTS

- Useful for probing DM models with suppressed non-relativistic scattering rates

- Sample results for two benchmark models:
dark photon mediator & Majorana or (inelastic) complex scalar DM

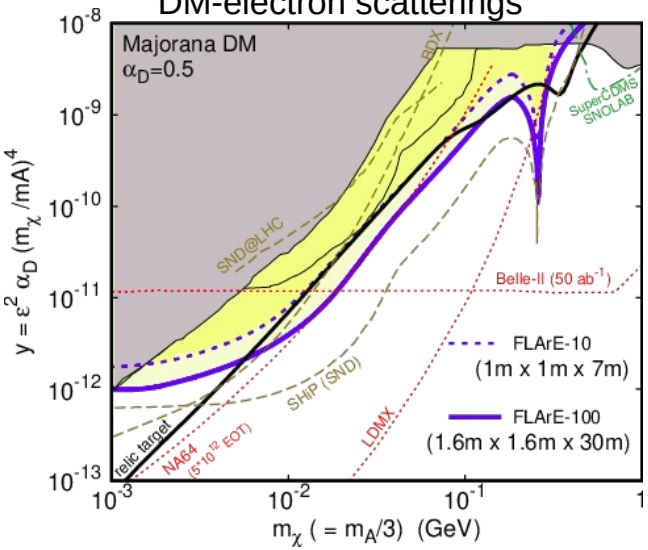
$$\mathcal{L} \supset A'_\mu(\epsilon\, e\, J^\mu_{EM} + g_D\, J^\mu_D) \qquad \mathcal{L} \supset \begin{cases} |\partial_\mu \chi|^2 - m_\chi^2 |\chi|^2 & \text{(complex scalar DM)} \\ \frac{1}{2}\overline{\chi} i\gamma^\mu \partial_\mu \chi - \frac{1}{2} m_\chi \overline{\chi}\chi & \text{(Majorana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

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

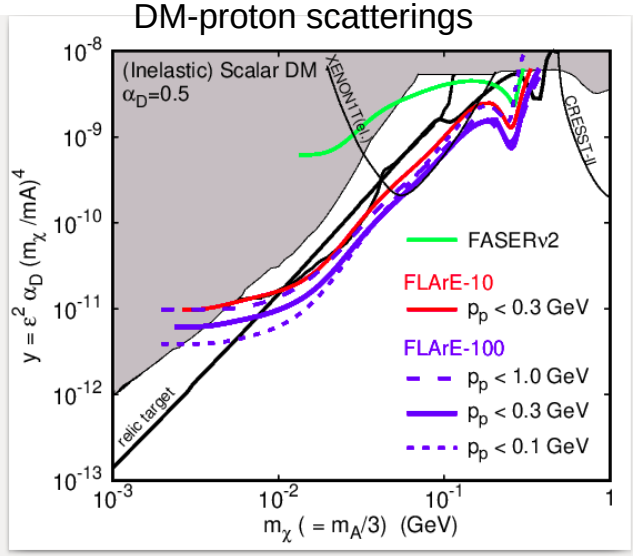
- They avoid stringent bounds from CMB

- Possible detection method: **F**orward **L**iquid **Ar**gon **E**xperiment **FLArE** (a la MicroBooNE…)
(or emulsion detector FASERv2)

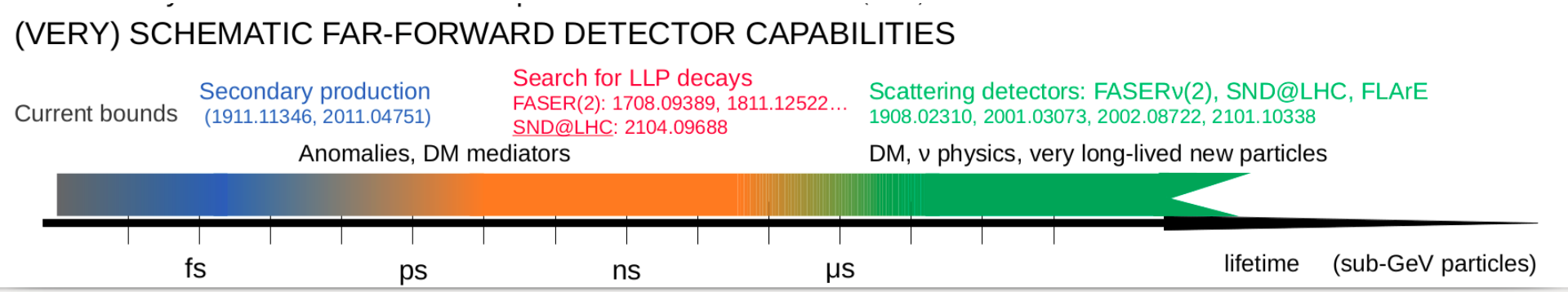
DM-electron scatterings



DM-proton scatterings



SUMMARY OF FAR-FORWARD BSM PROGRAM



- Search for highly-displaced decays of light new particles
  (boosted decay lengths d~100-1000 m)

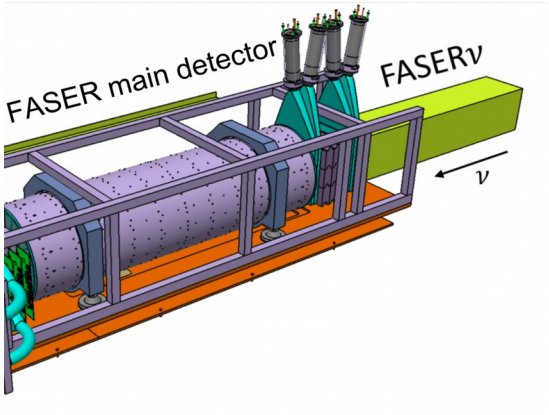
- Secondary production in front of the detector allows for probing even d~meters
  (or less inside the scattering detectors)

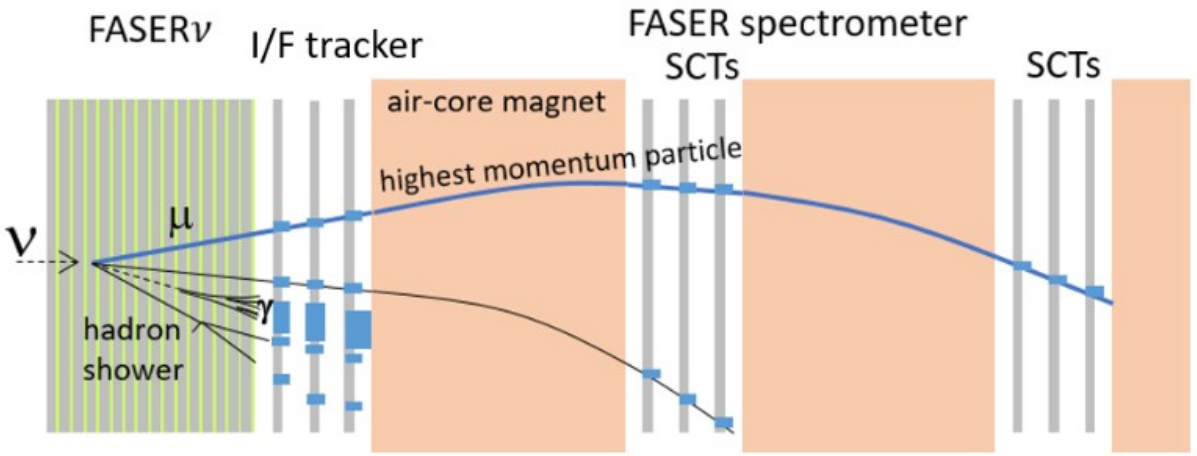
- Scattering detectors:
especially important if decays not possible (stable species like ν and DM)
can also open new detection channels for very long-lived particles

- Typically best reach for masses<GeV, but even ~10 GeV particles can be probed

FAR-FORWARD NEUTRINO PROGRAM

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 $\bar{\nu}_\mu$

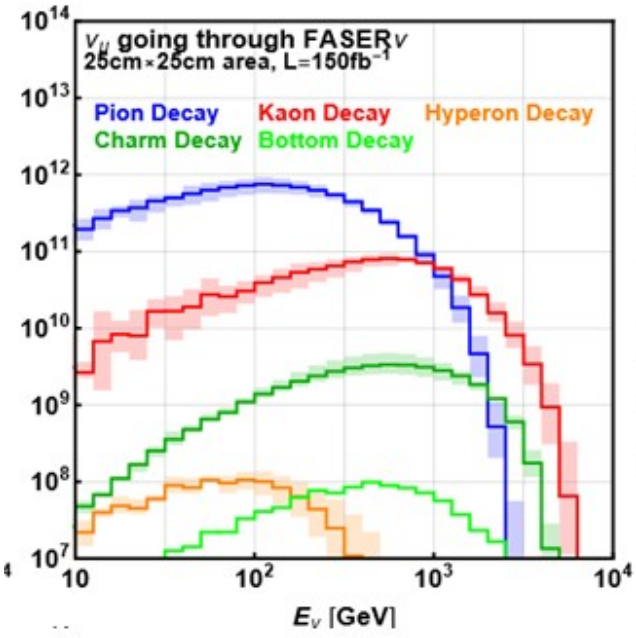
FASER Collaboration, 1908.02310

FAR-FORWARD NEUTRINOS

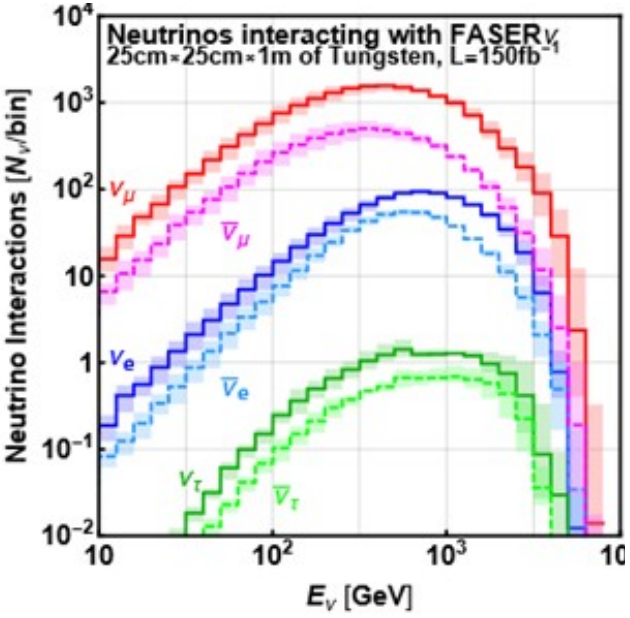
- LHC: lots of forward-going neutrinos from meson decays
- Measurement of the neutrino scattering cross section for $E_\nu \sim$TeV (currently poorly explored regime)
- Possible detection of 10-20 high-energy tau neutrino events

LHC Run 3

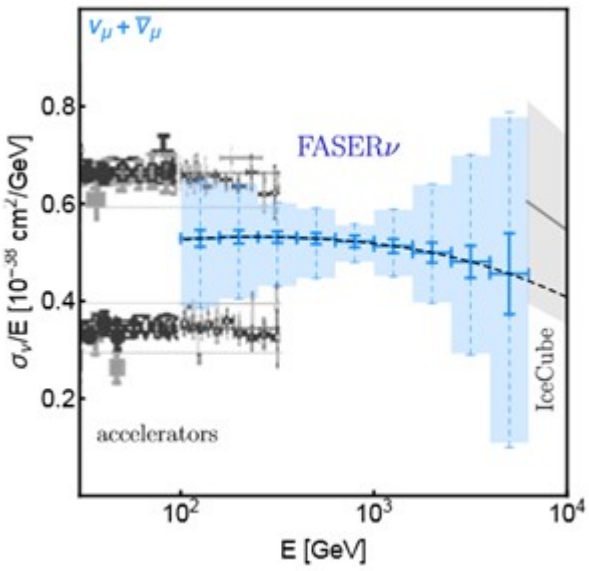
Going-through



Interacting



Scattering cross section

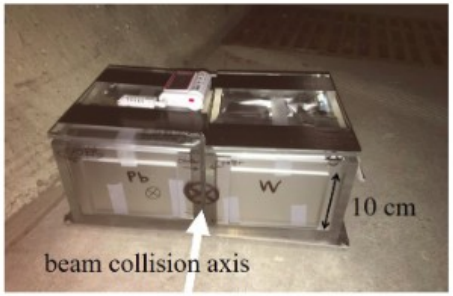


EXTREMELY POWERFUL DETECTION METHOD

- 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})

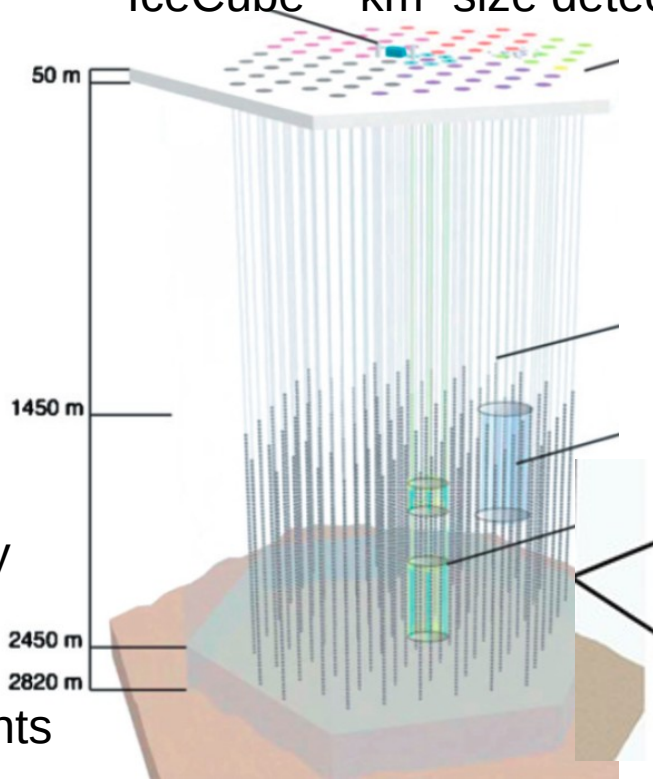


- several neutrino-like events (2.7σ over expected BG)

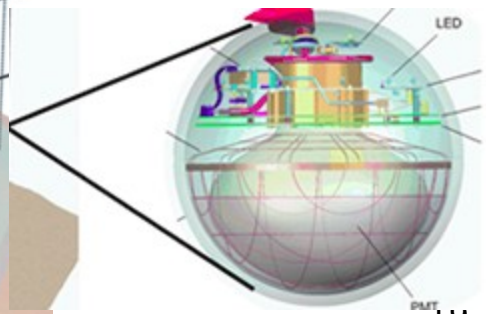
- proof-of-principle of detection strategy

- during Run 3 ~ 10^4 expected events

IceCube ~ km^3 size detector



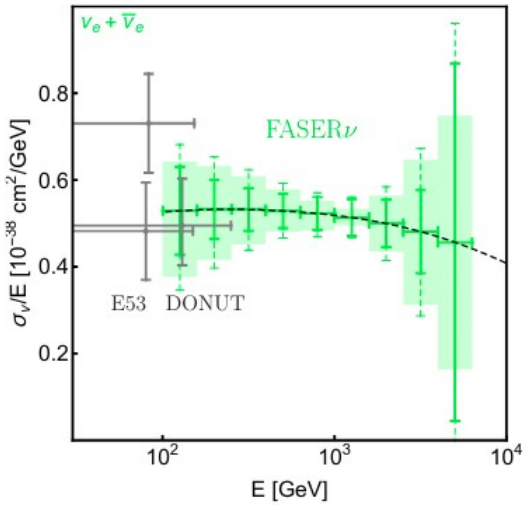
Digital Optical Module
total: few x 10^3
33cm diameter

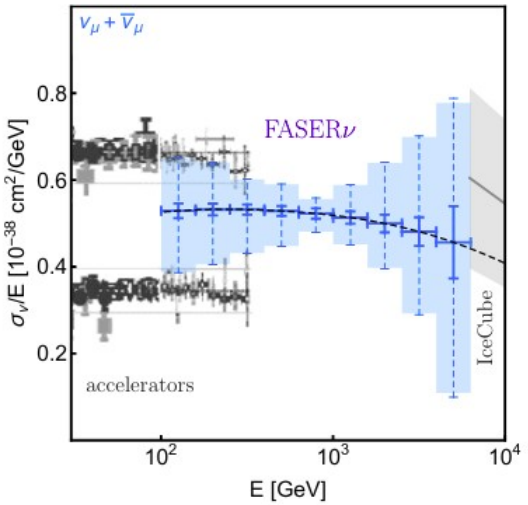


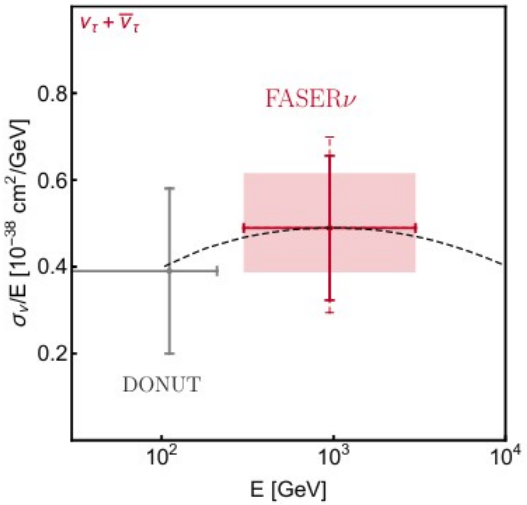
FASER Collaboration, 1908.02310

PROSPECTS FOR RUN 3

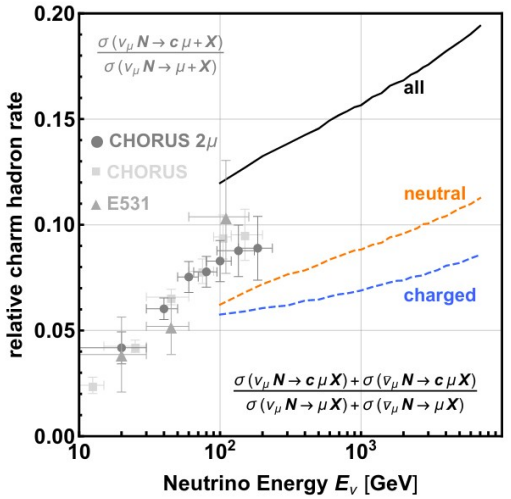
- Inclusive CC cross section measurements at TeV energies (~10^4 ν_μ, ~10^3 ν_e, ~10 ν_τ)







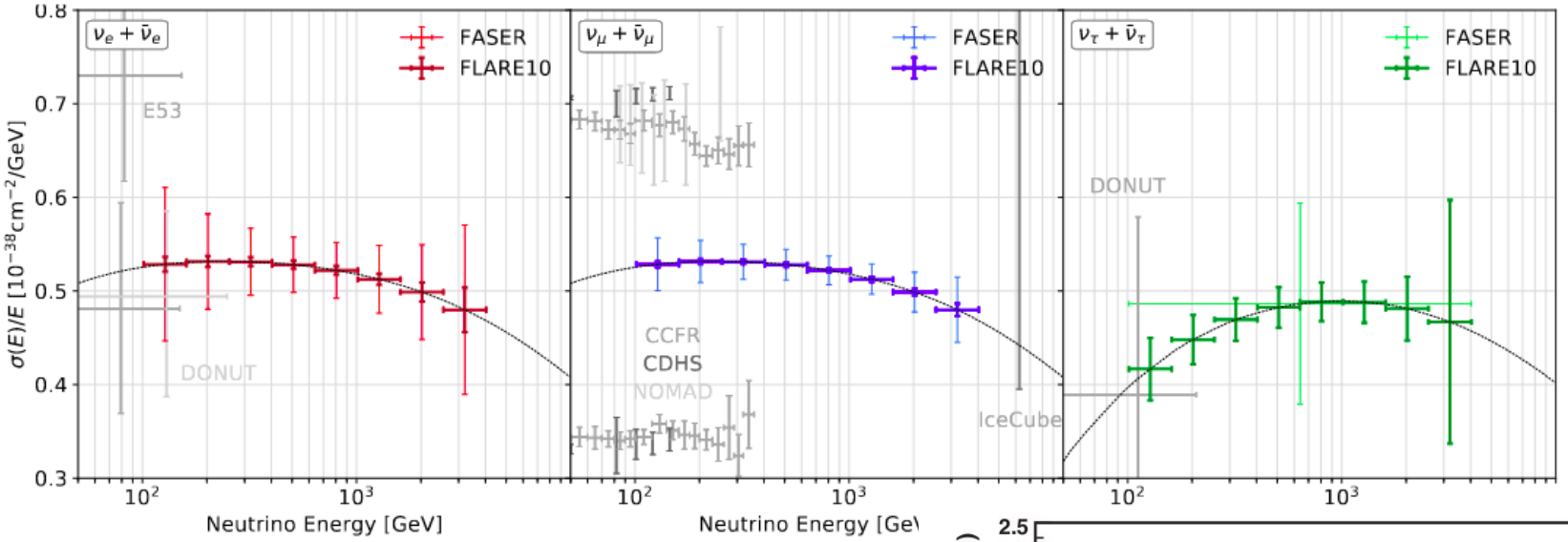
- NC cross section measurements
  (A. Ismail, R.M. Abraham, F. Kling, 2012.10500)

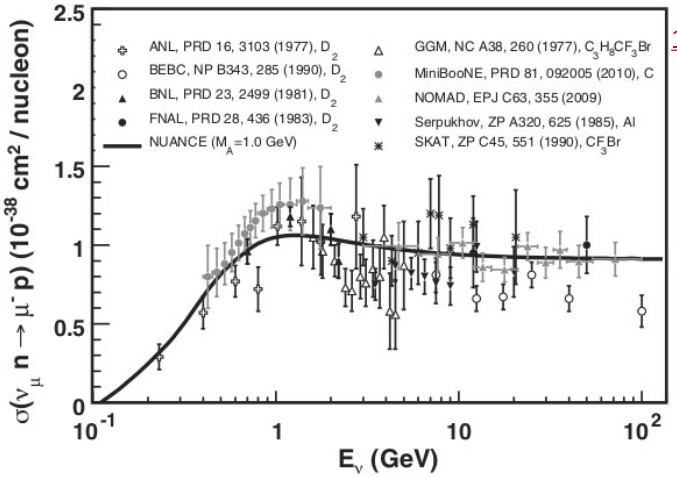


- specific neutrino interaction processes, e.g.,
  ν-induced charm production

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)





1305.7513

- Non-DIS type of processes, e.g., CCQE, CCRES, …
  expected ~10^3 events
  with mean energy of a few hundred GeV

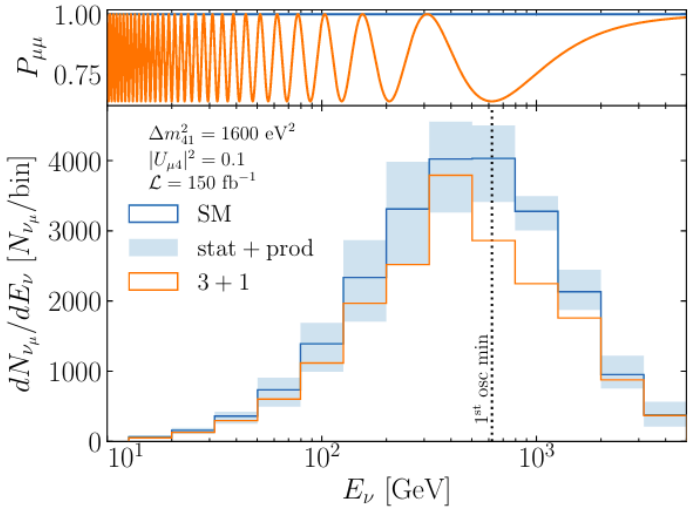
NEW PHYSICS & NEUTRINO INTERACTIONS

FASER Collaboration, 1908.02310

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

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

(also e.g. Gallium anomaly)



K. Jodłowski, ST, 2011.04751

- Non-standard neutrino interactions

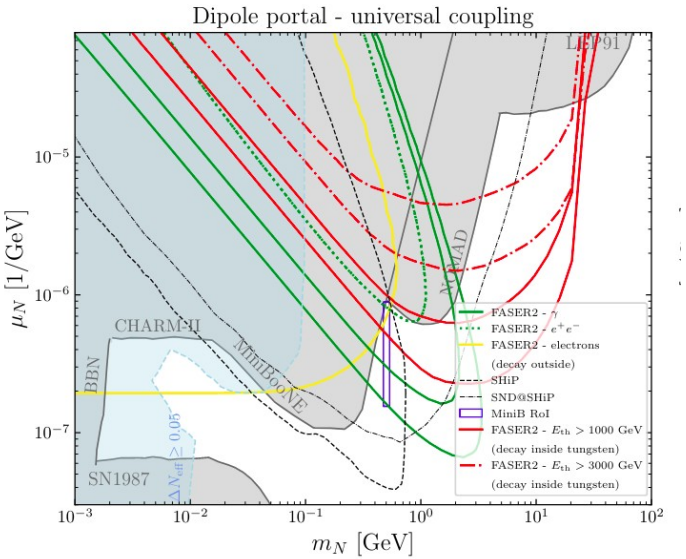
Example: dipole portal to heavy neutral leptons

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

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

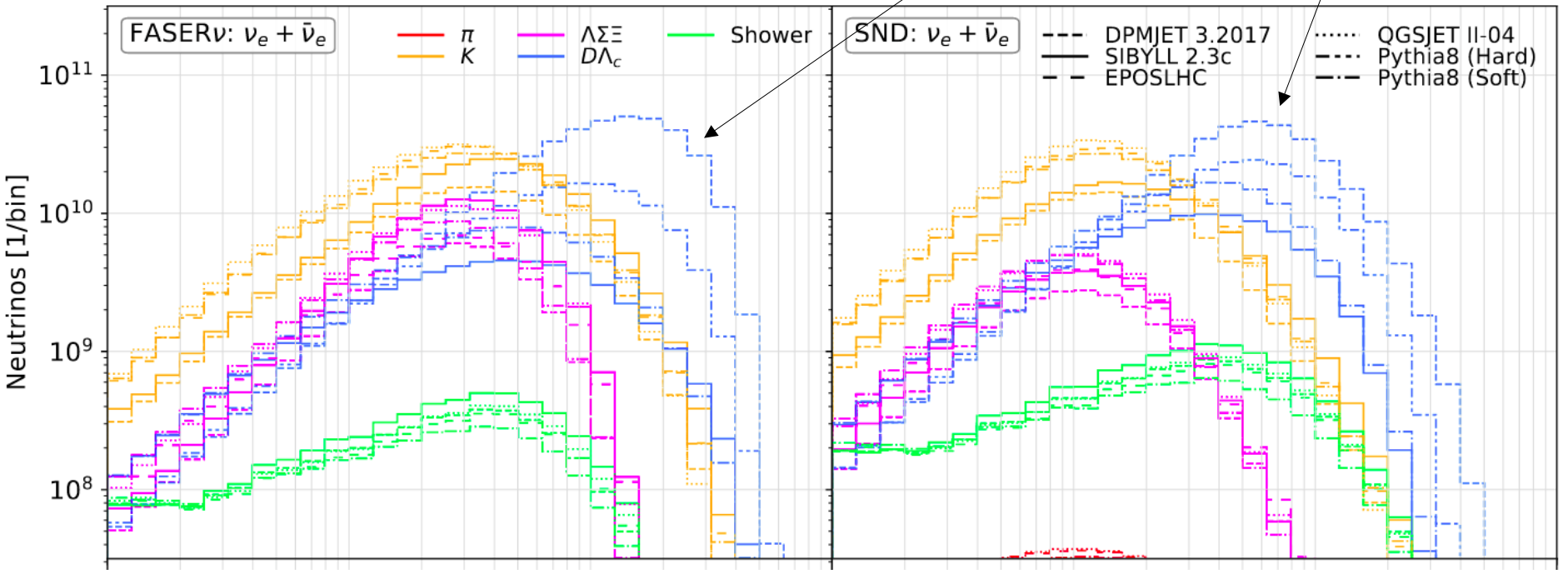


FURTHER OPPORTUNITIES

QCD – FORWARD CHARM

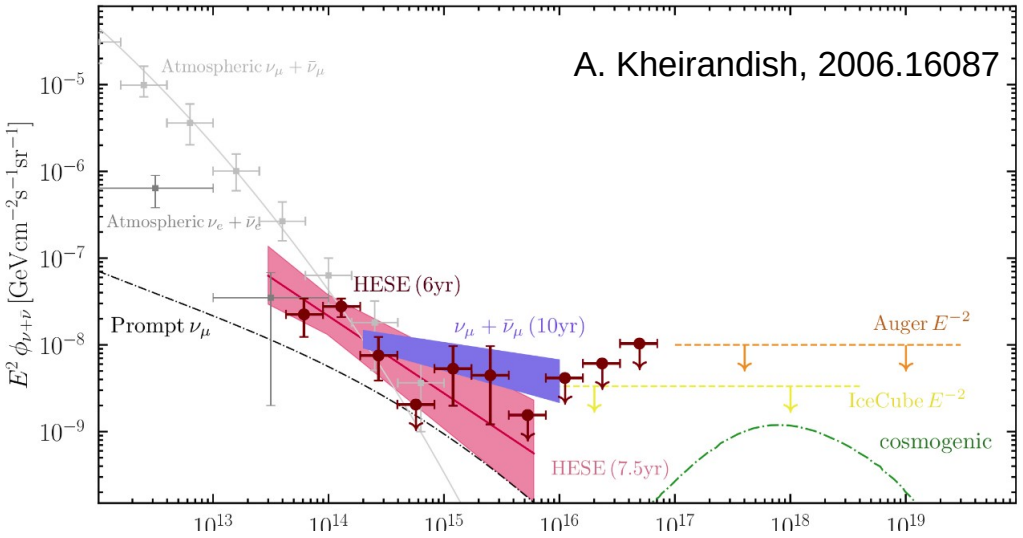
- Measuring neutrino flux and spectrum: further tuning of forward MC tools
- Large differences in electron neutrino spectrum at high energies from charm decays
- ν_e main production at high energies: gg → cc, D → K l ν
- probe of gluon PDFs at low x, intrinsic charm,...

F. Kling, 2105.08270



COSMIC RAYS AND MORE

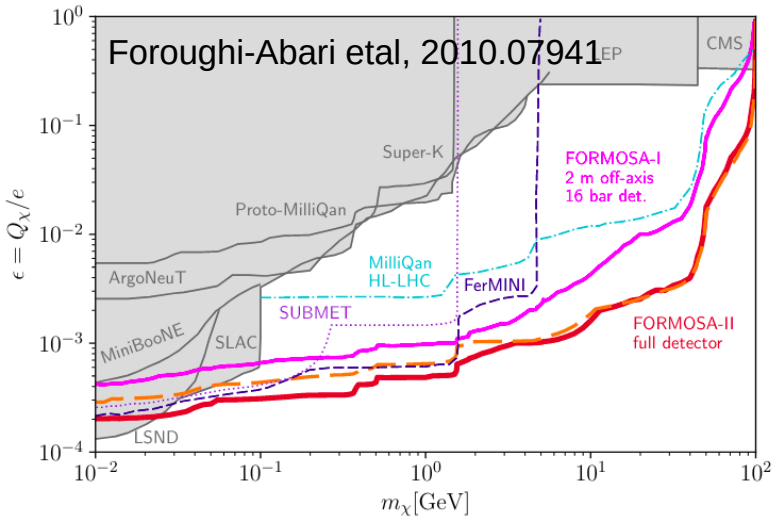
• Forward charm production ➡ constrain ``prompt'' atmospheric neutrino flux (relevant for measurements of the astrophysical neutrino flux at IceCube)



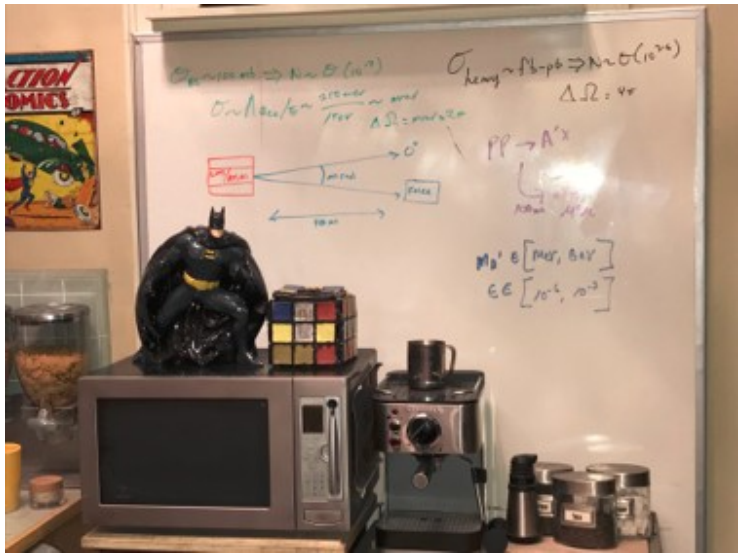
• Cosmic-ray muon problem (observed excess of high-energy muons, better high-energy forward kaon production measurement remains essential here)

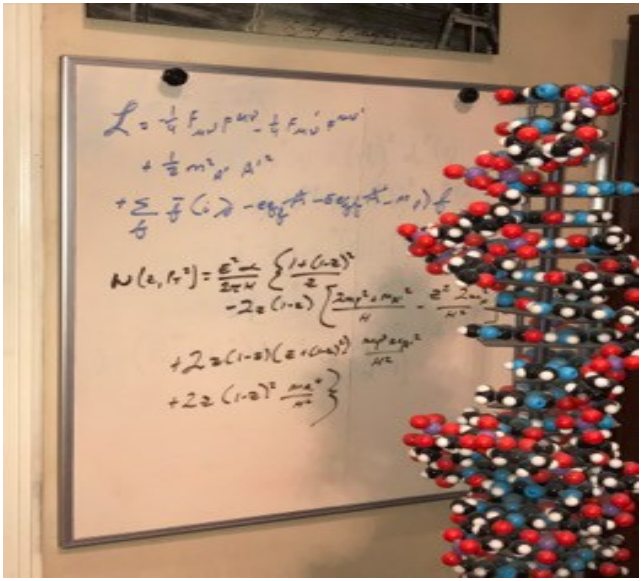
• Opportunities in muon physics (SM measurements, new physics)

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



FASER IN POPULAR CULTURE



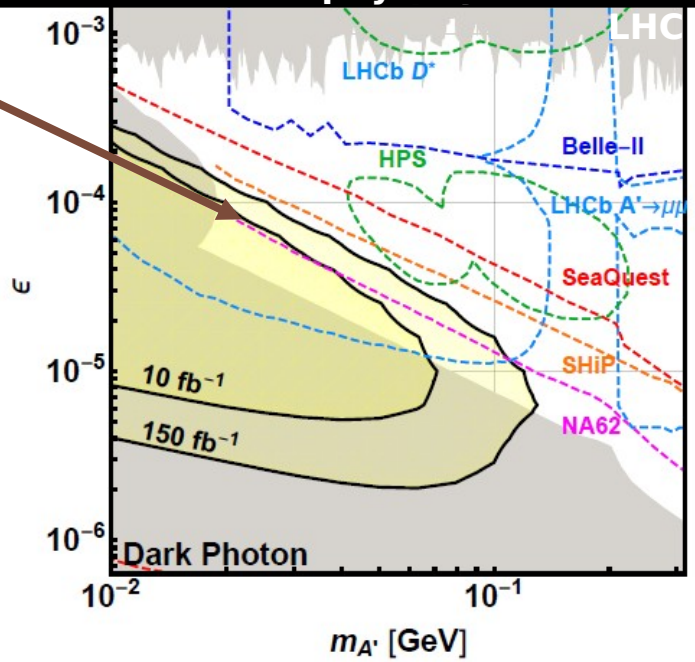


related article

LA Times

New physics reach even after first 10fb^{-1}

CONCLUSIONS



- Far-forward LHC physics – new research agenda at the LHC

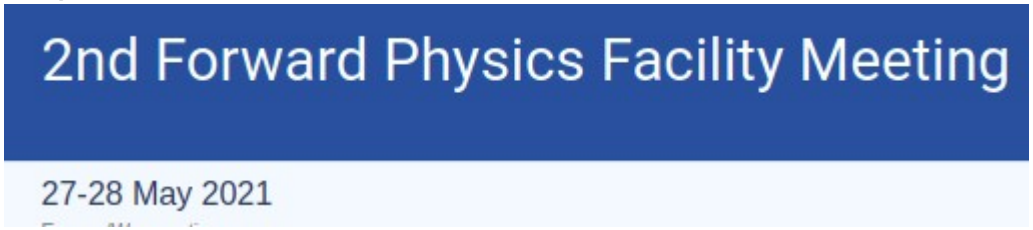
- **FASER** experiment will initiate it during Run 3 (light long-lived particles & high-energy neutrinos)

- It could be continued towards HL-LHC: **Forward Physics Facility**
  - further prospects: light DM, QCD and other SM measurements...

- For pheno BSM studies: useful tool **FORESEE** (F. Kling, ST, 2105.07077)

- 2nd Forward Facility Meeting starts just in two days! (>100 participants)

https://indico.cern.ch/event/1022352/overview



THANK YOU !