Future dark sector searches at the LHC

Matthew Citron

Supported by funding from
DOE Office of Science

Brief overview of dark sectors

Standard model

We are here

Hidden sector

DM is here

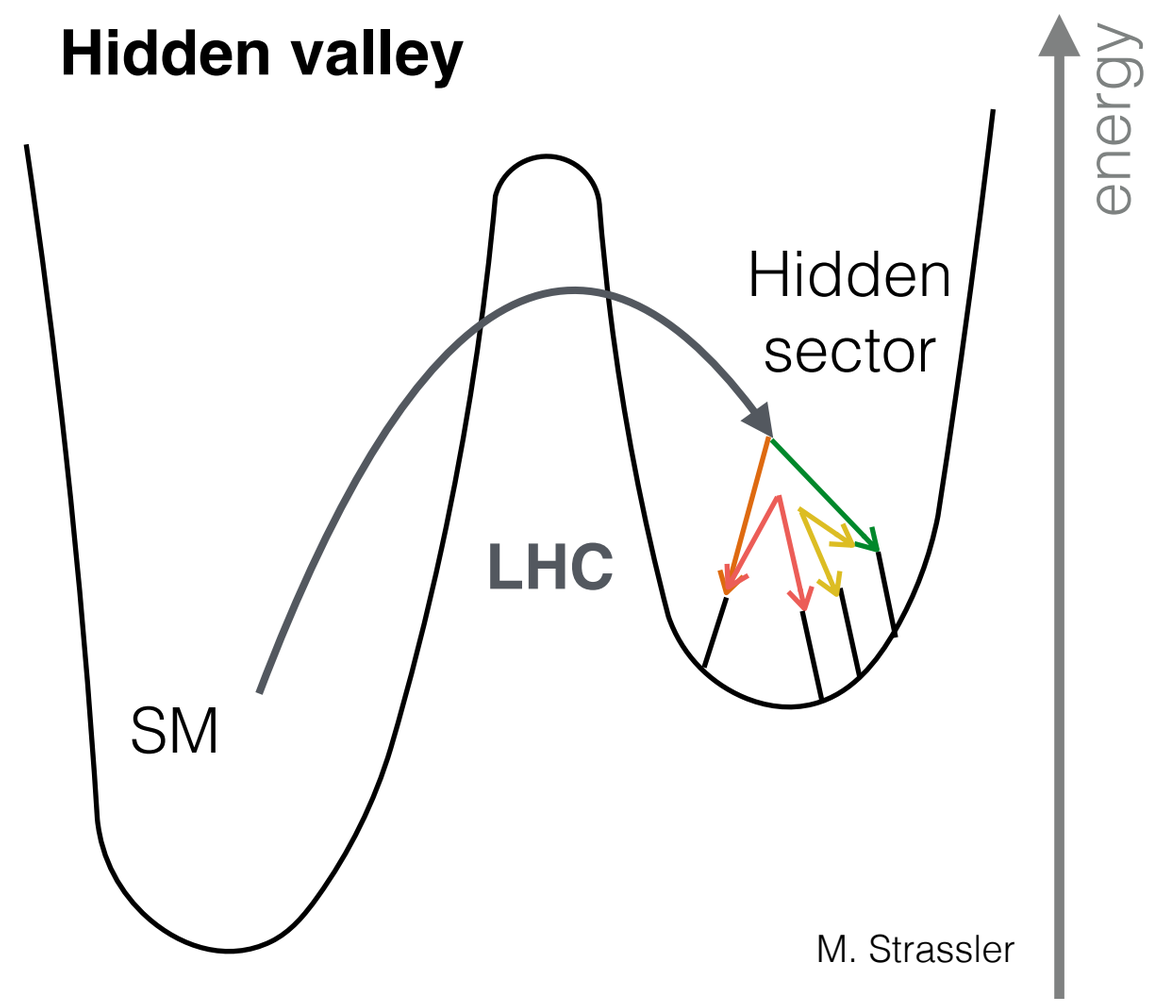
- Dark matter is part of a **“hidden” universe** with **no SM gauge interactions**

- Hidden universe can have **complex structure** and provide solutions to mysteries beyond DM

Connecting two worlds

- Hidden sector separated by heavy mediator and/or small couplings

- Intense high energy collisions at the LHC could **overcome the barrier** and produce hidden sector particles!

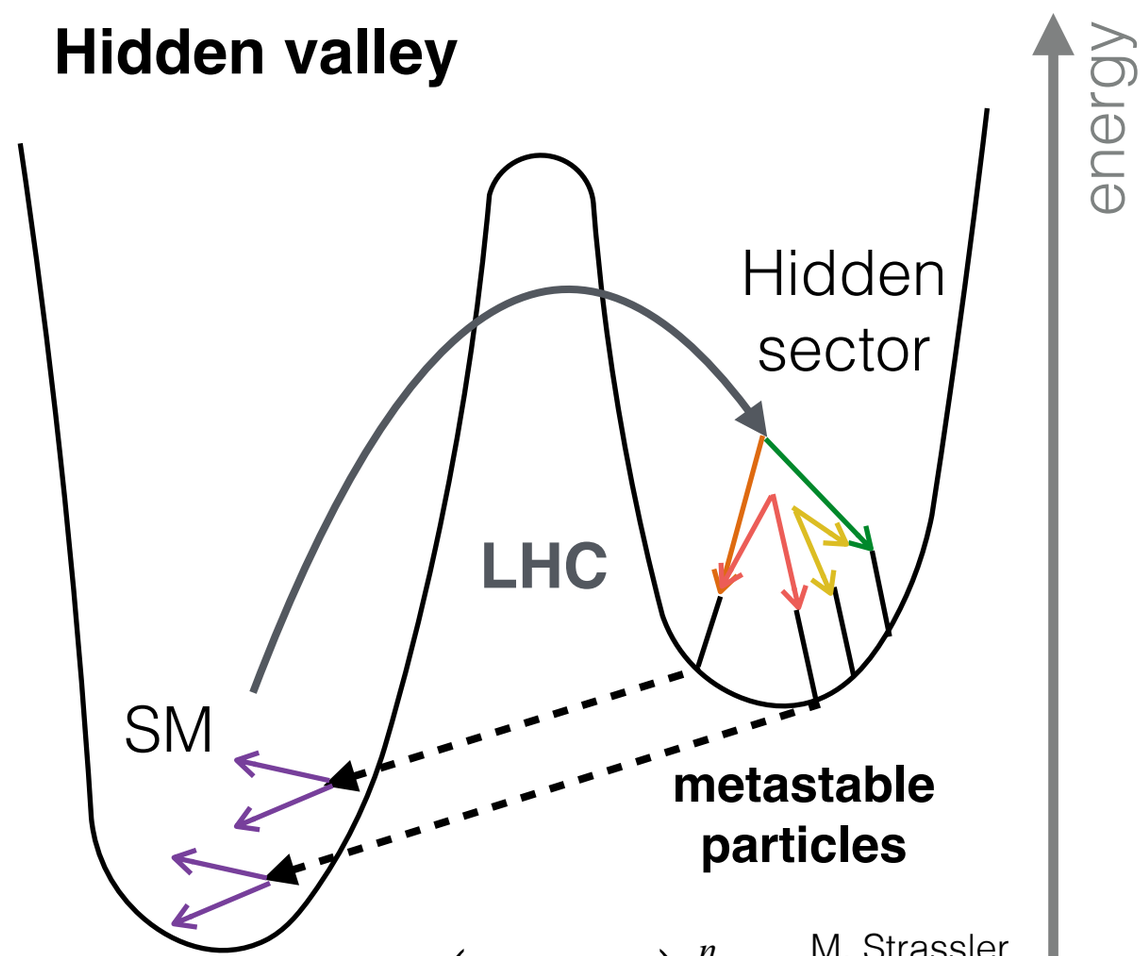


Signatures of the dark sector: decaying long-lived particles

Standard model ⟷ Hidden sector

- Dark sector particles could decay back to standard model "suppressed" by heavy mediator/small couplings → **metastable particles at the LHC**

- Stable dark sector particles could **directly interact** with detector material



M. Strassler

$$\Gamma \propto \frac{g^2}{8\pi}\left(\frac{m_{\mathrm{LLP}}}{m_{\mathrm{mediator}}}\right)^n m_{\mathrm{LLP}}$$

Signatures of the dark sector: stable long-lived particles

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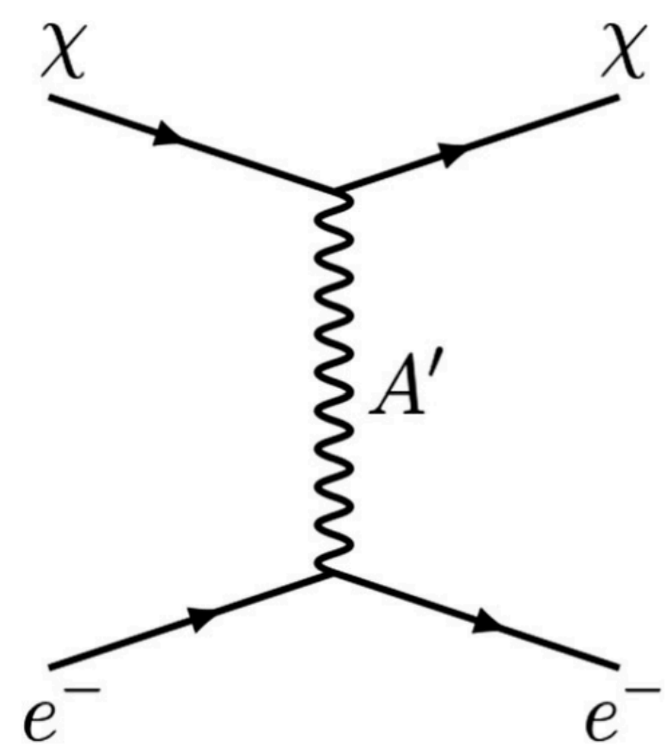
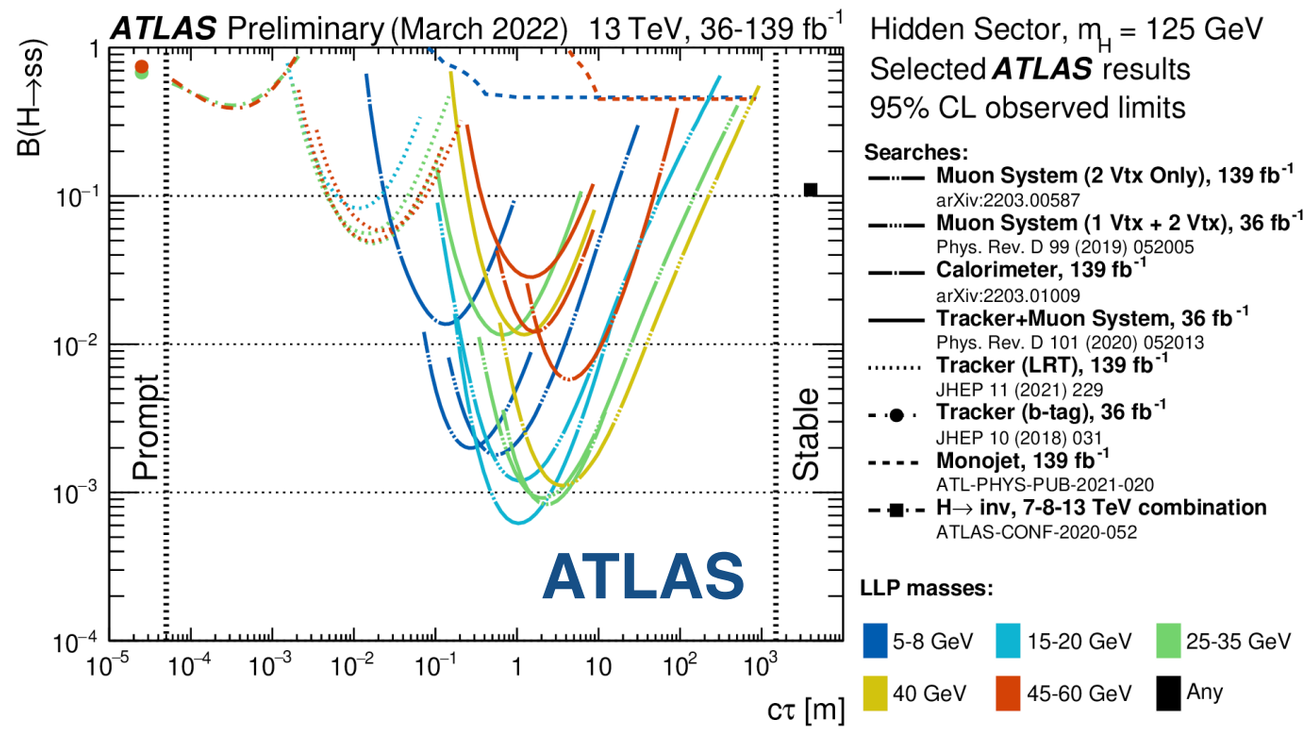
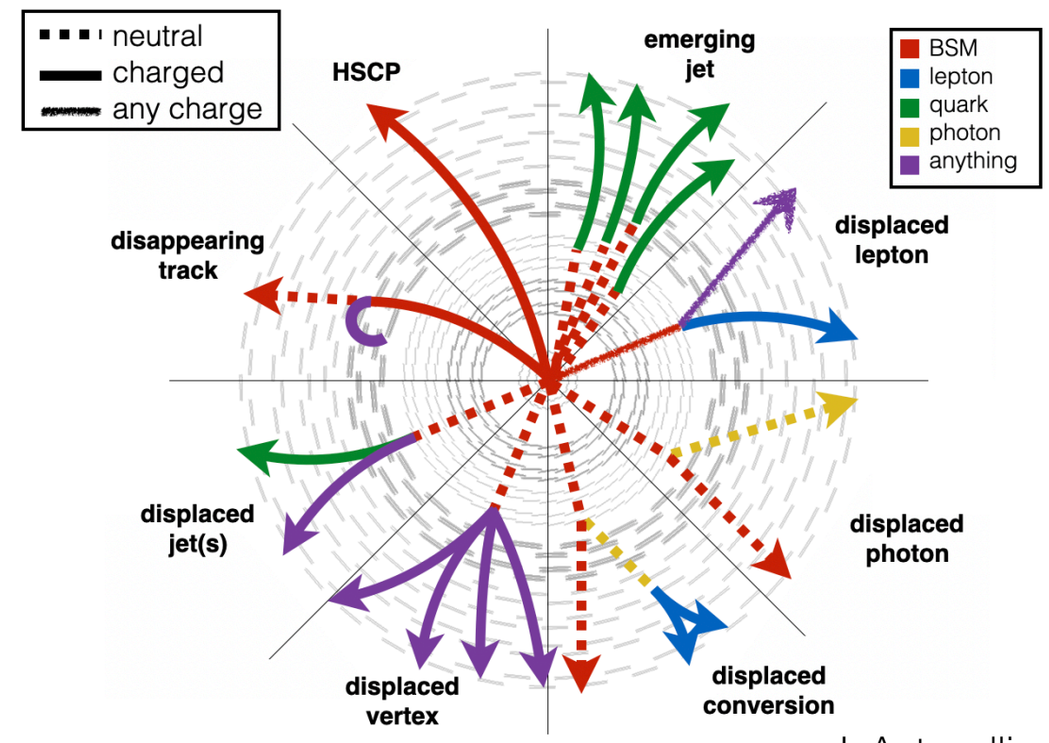


e.g. DM-electron scattering

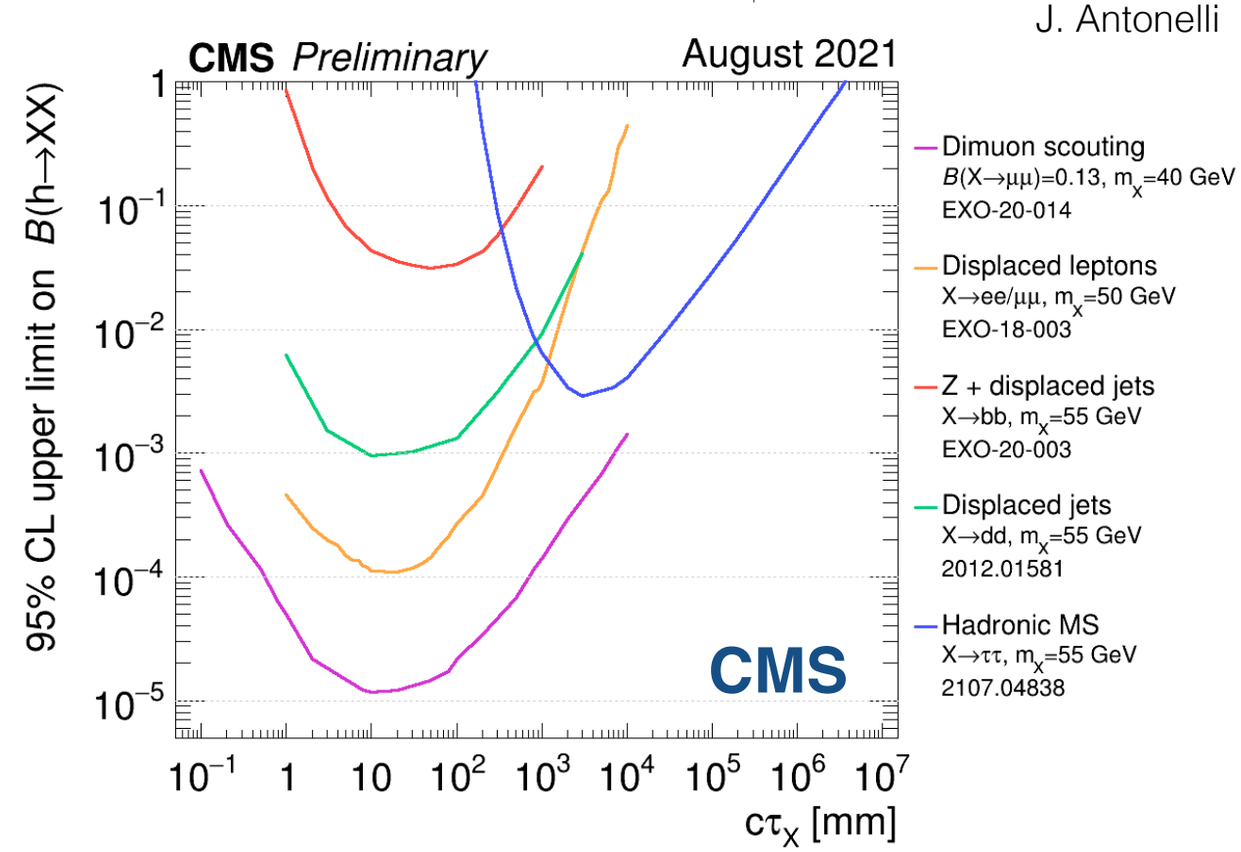
CMS/ATLAS/LHCb dark sector searches





J. Antonelli

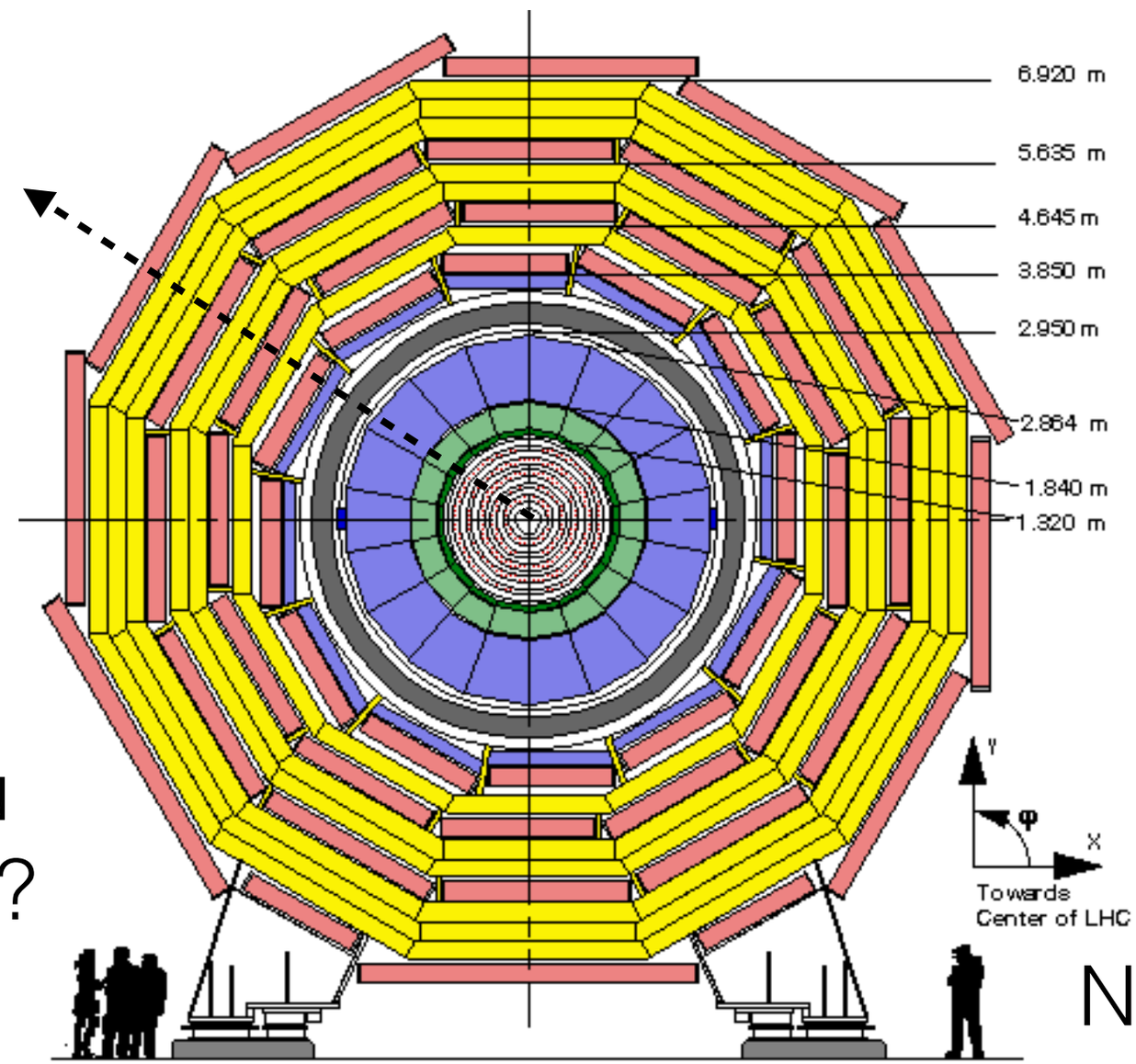
- Wide array of efforts looking for signatures in every detector subsystem!
- See other talks at CIPANP from ATLAS and CMS for more details on recent results!
- New triggers for Run 3 of the LHC and detector upgrades for the HL-LHC will greatly expand sensitivity (see backup)!



What about signatures that CMS/ATLAS can't see?

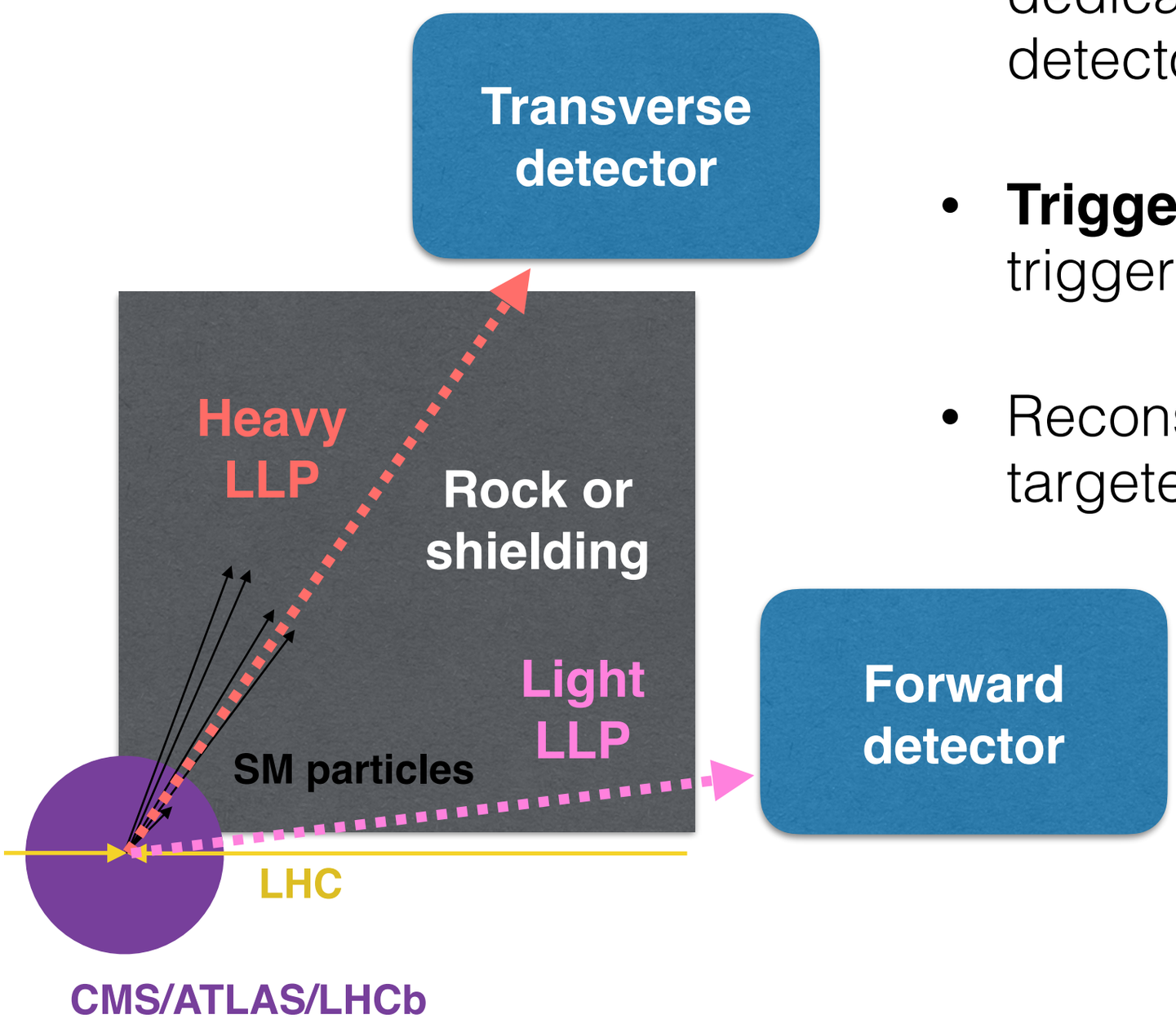
Soft signatures in particular face huge backgrounds, are very difficult to trigger and require highly non-standard reconstruction

Did you see that?



Nope

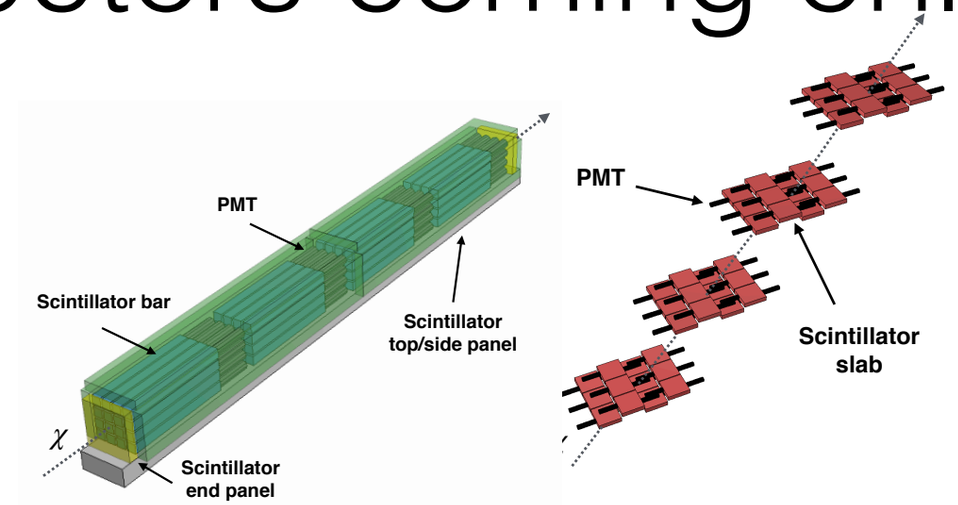
Solution: dedicated detectors!



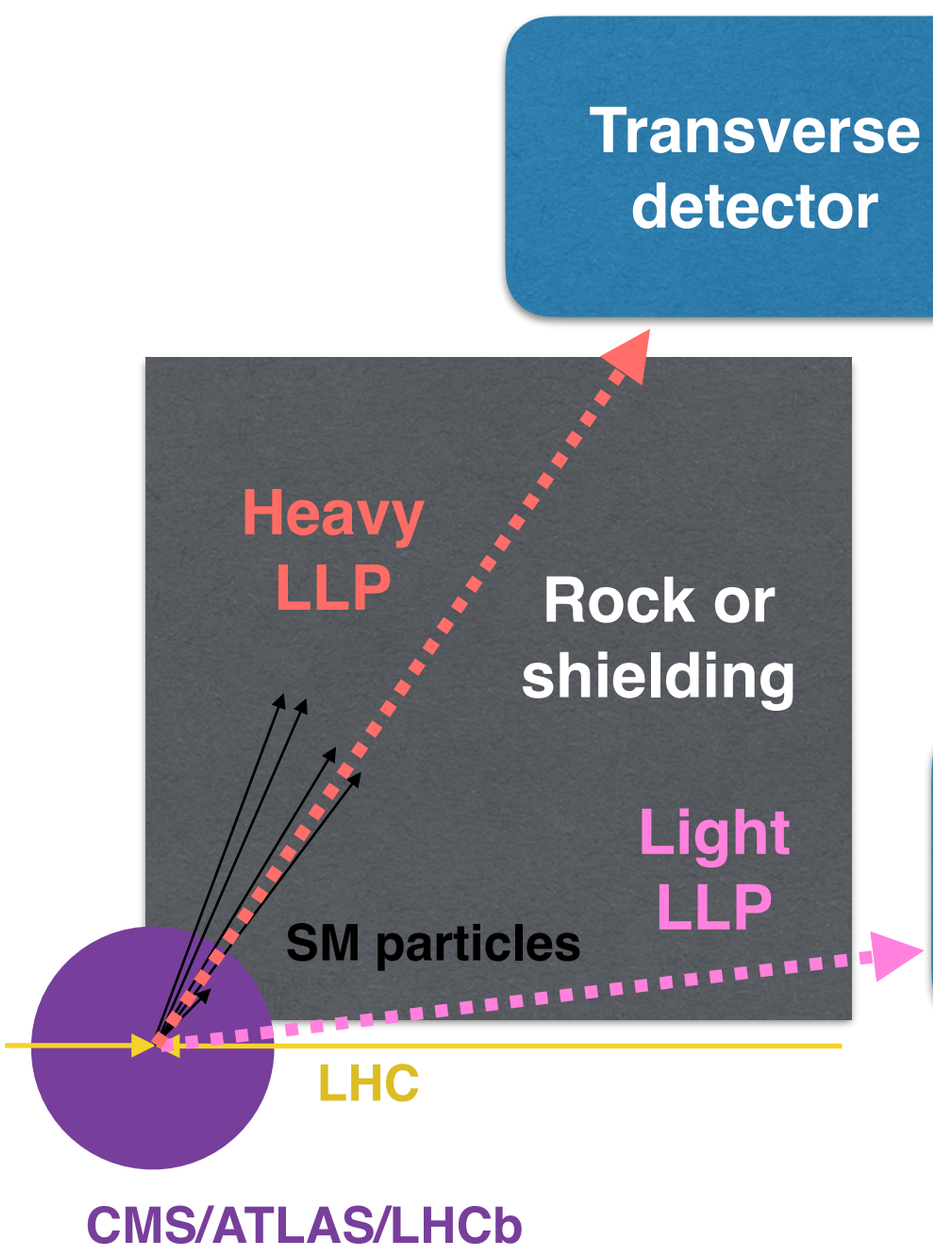
- **Backgrounds mitigated** by rock or dedicated shielding (or removing detector for readout)
- **Triggering simple** (or don't need trigger)
- Reconstruction **designed** for targeted LLP signature(s)
- Optimal **detector design** and **position** depend strongly on targeted signature: need **range** of different detectors!

Range of new detectors coming online for Run 3!

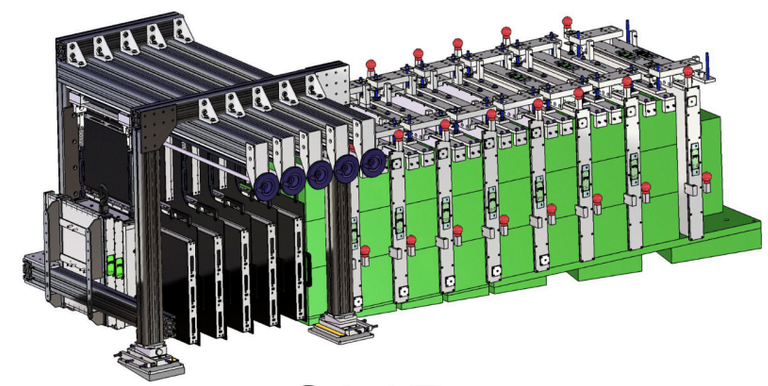
η ~ 0



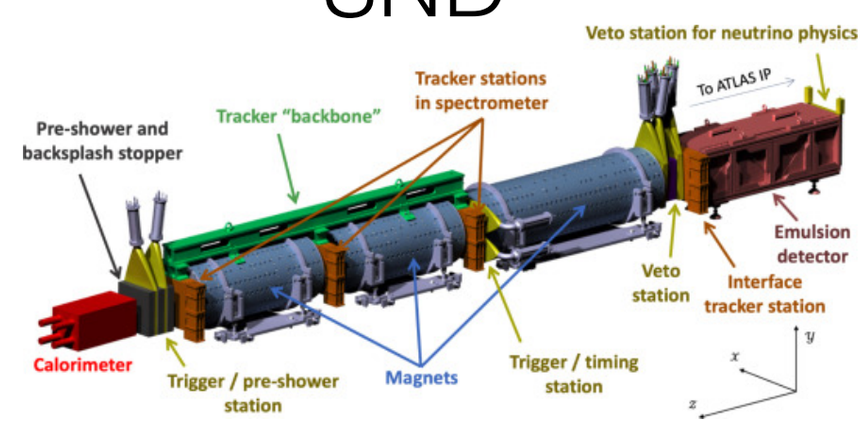
milliQan



7.2 < η < 8.6



SND

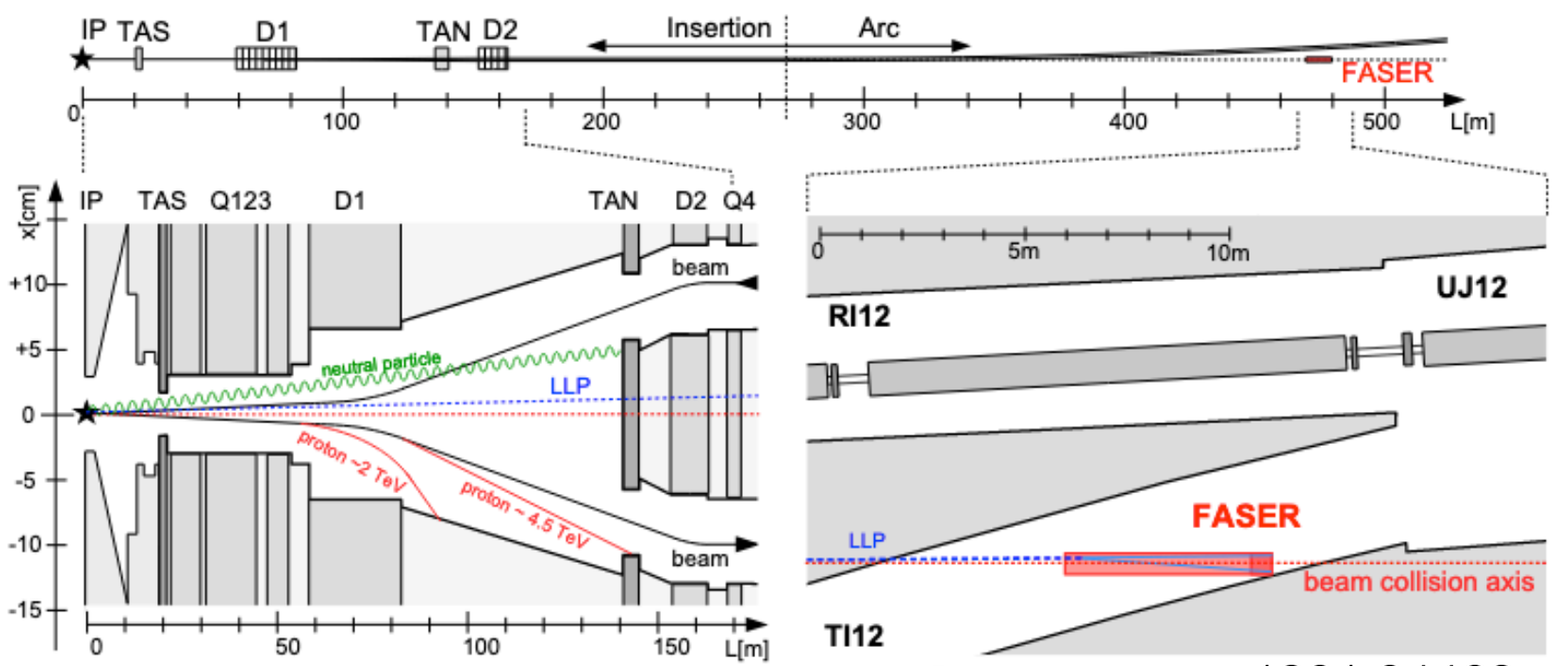


η > 9

FASER/FASERν

+ Moedal/MAPP

FASER detector

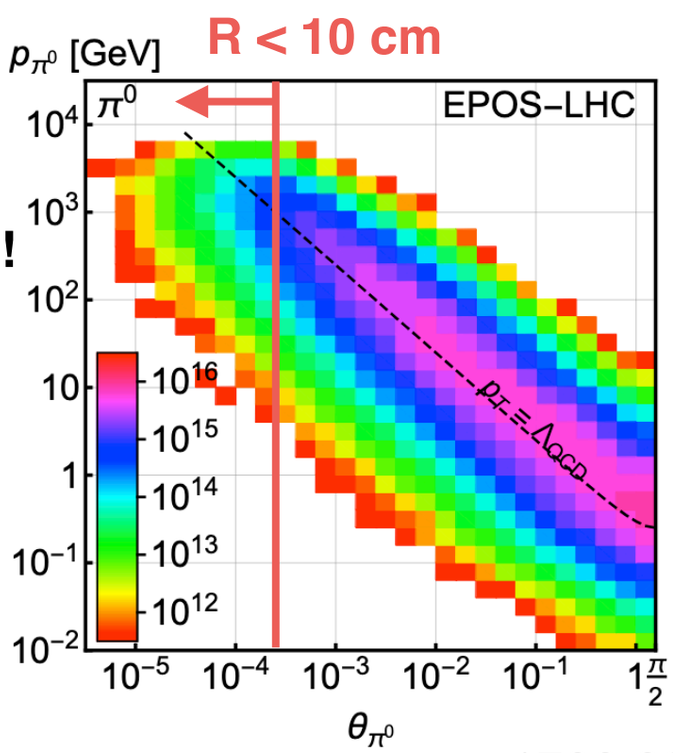


1901.04468

Located ~500m in front of ATLAS on the beam axis

SM particles deflected/blocked by B-field/rock

TeV scale momentum!



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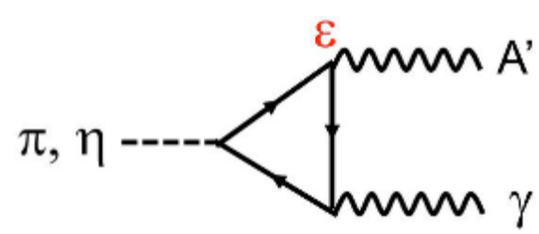
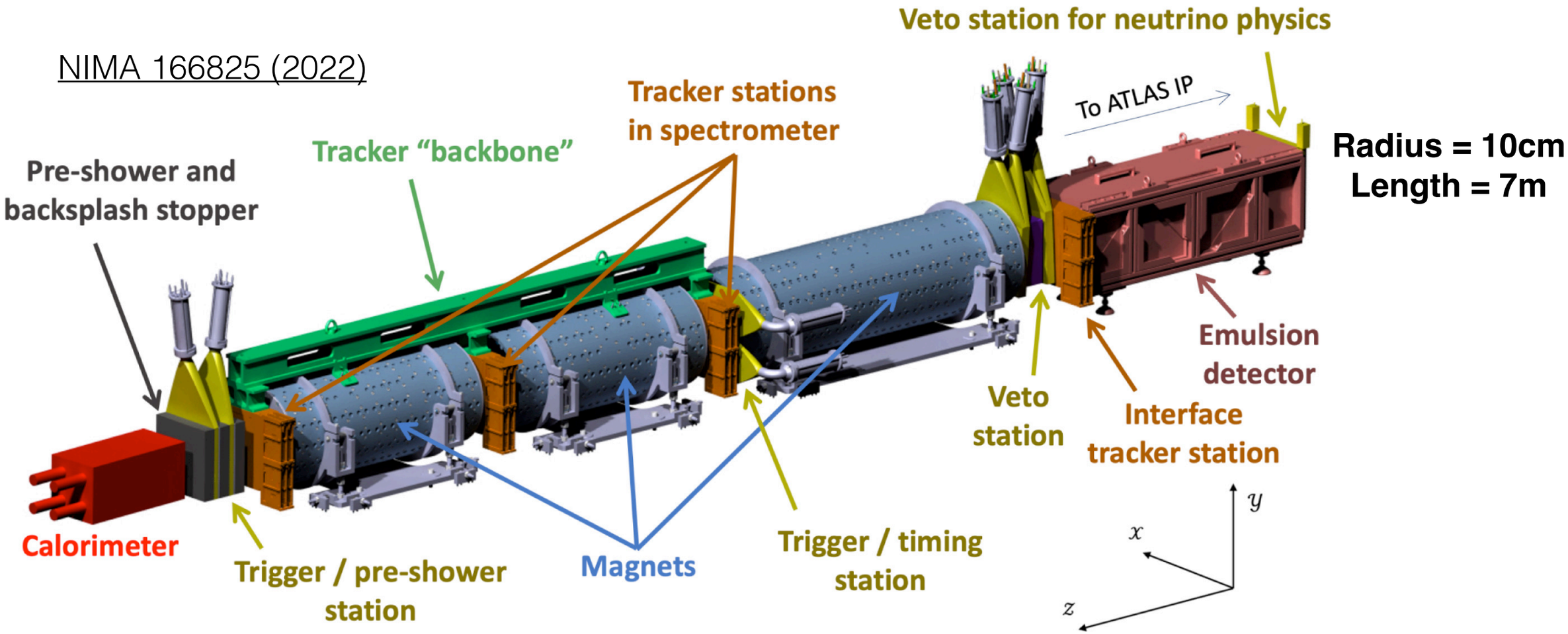


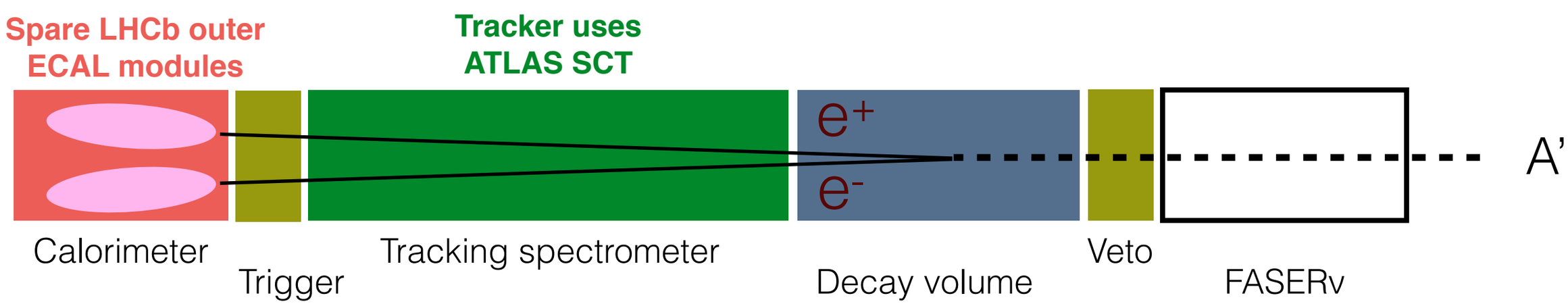
e.g. dark photon

Target low mass signatures (< ~GeV) → production mainly through decays of light mesons

FASER detector

NIMA 166825 (2022)



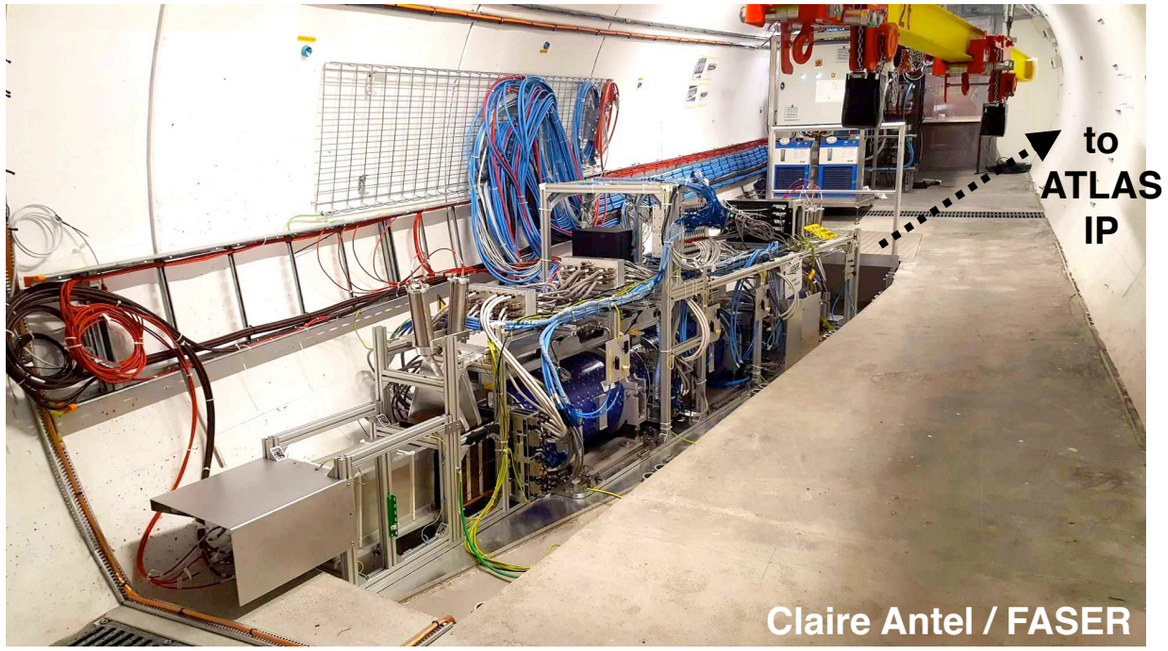


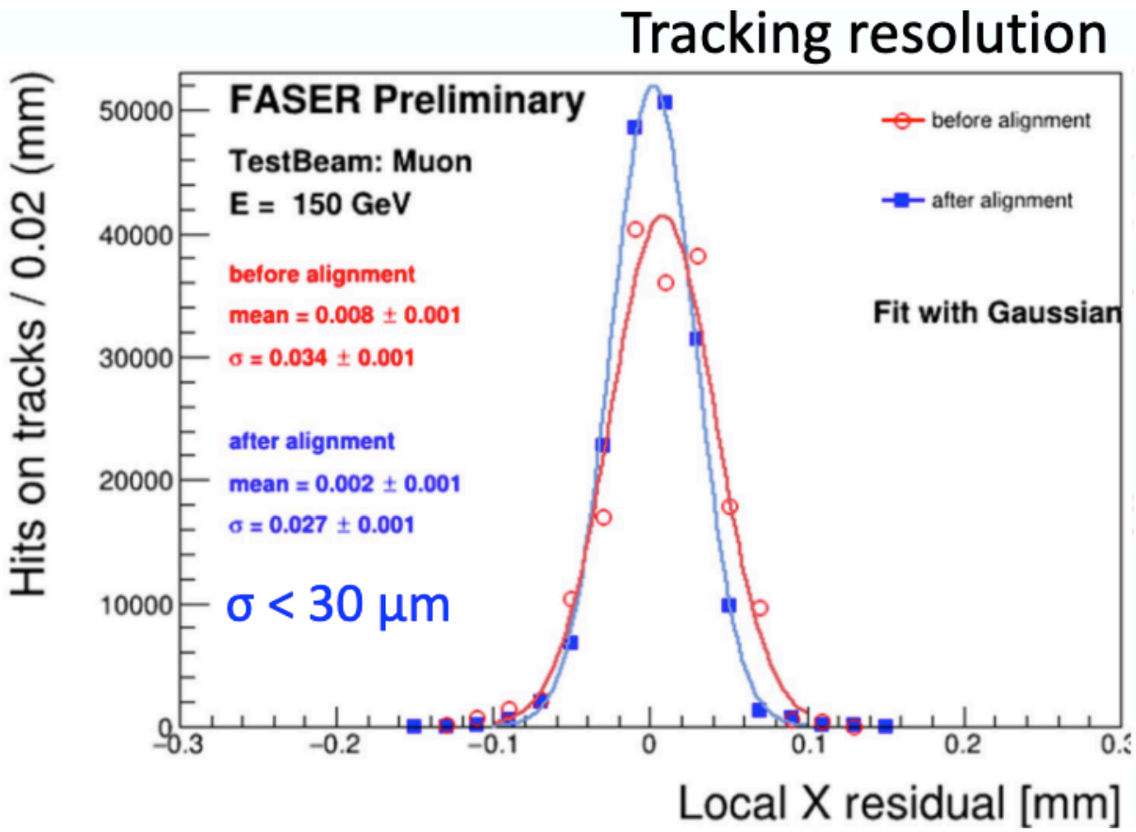
~1% energy resolution

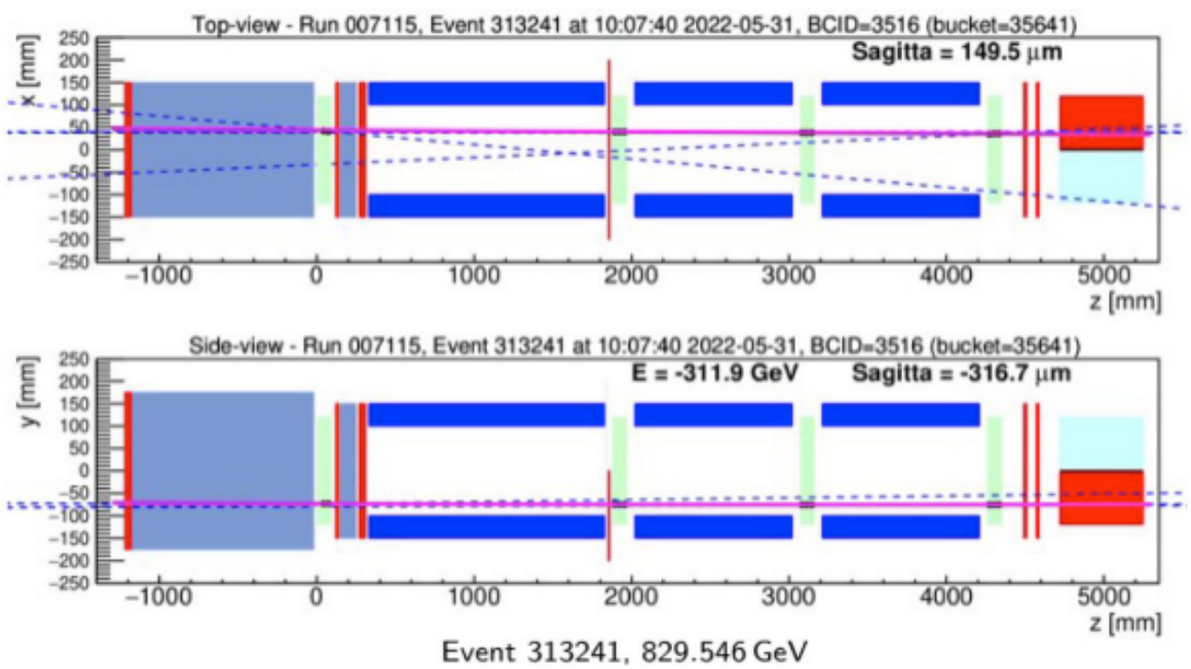
Resolution ~20 μrad

FASER status

- Detector installed in March 2021
- Commissioning with mix of cosmics, test beam and LHC collisions





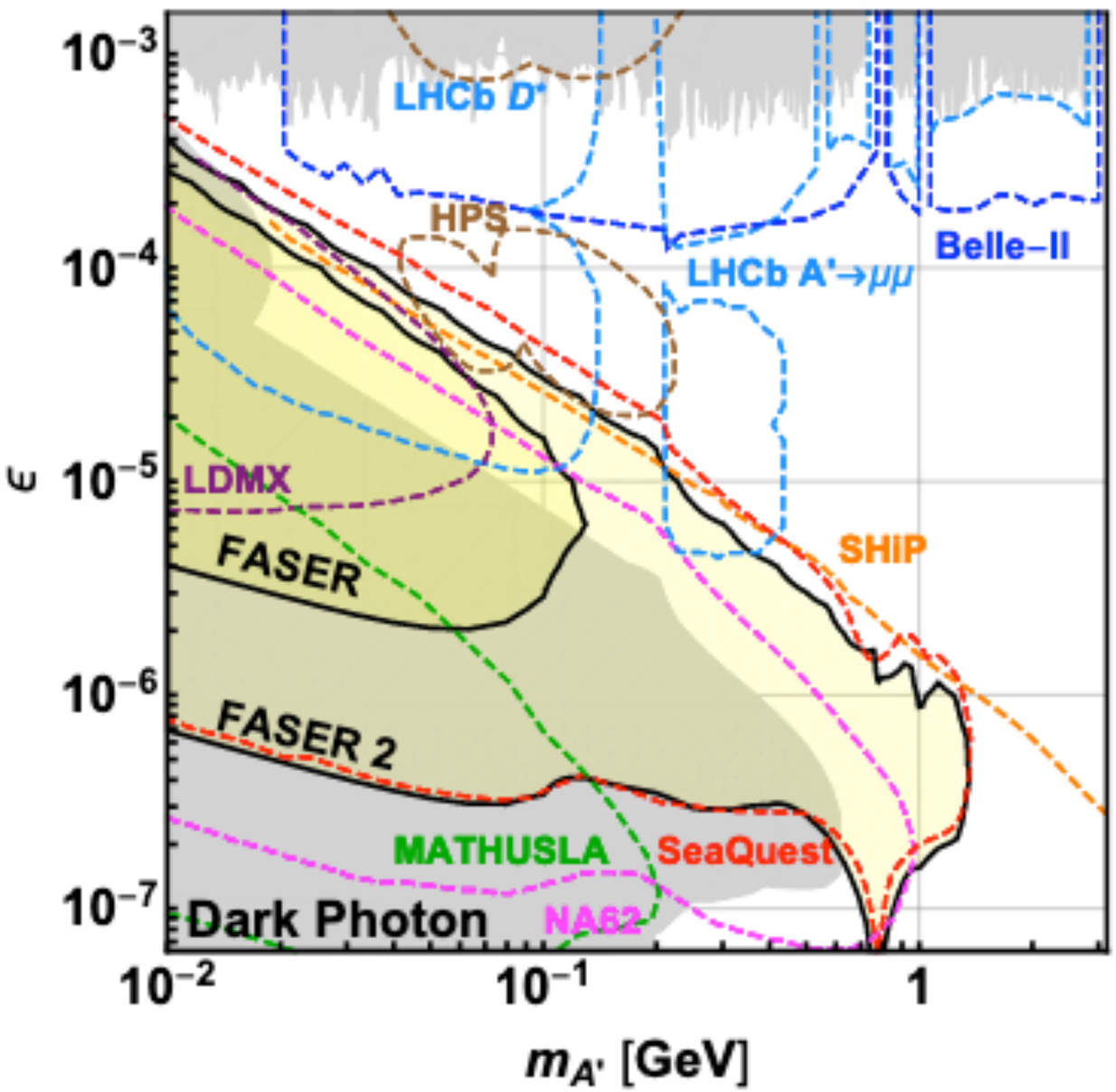


Through-going muons from LHC collisions (6.8 TeV beams)

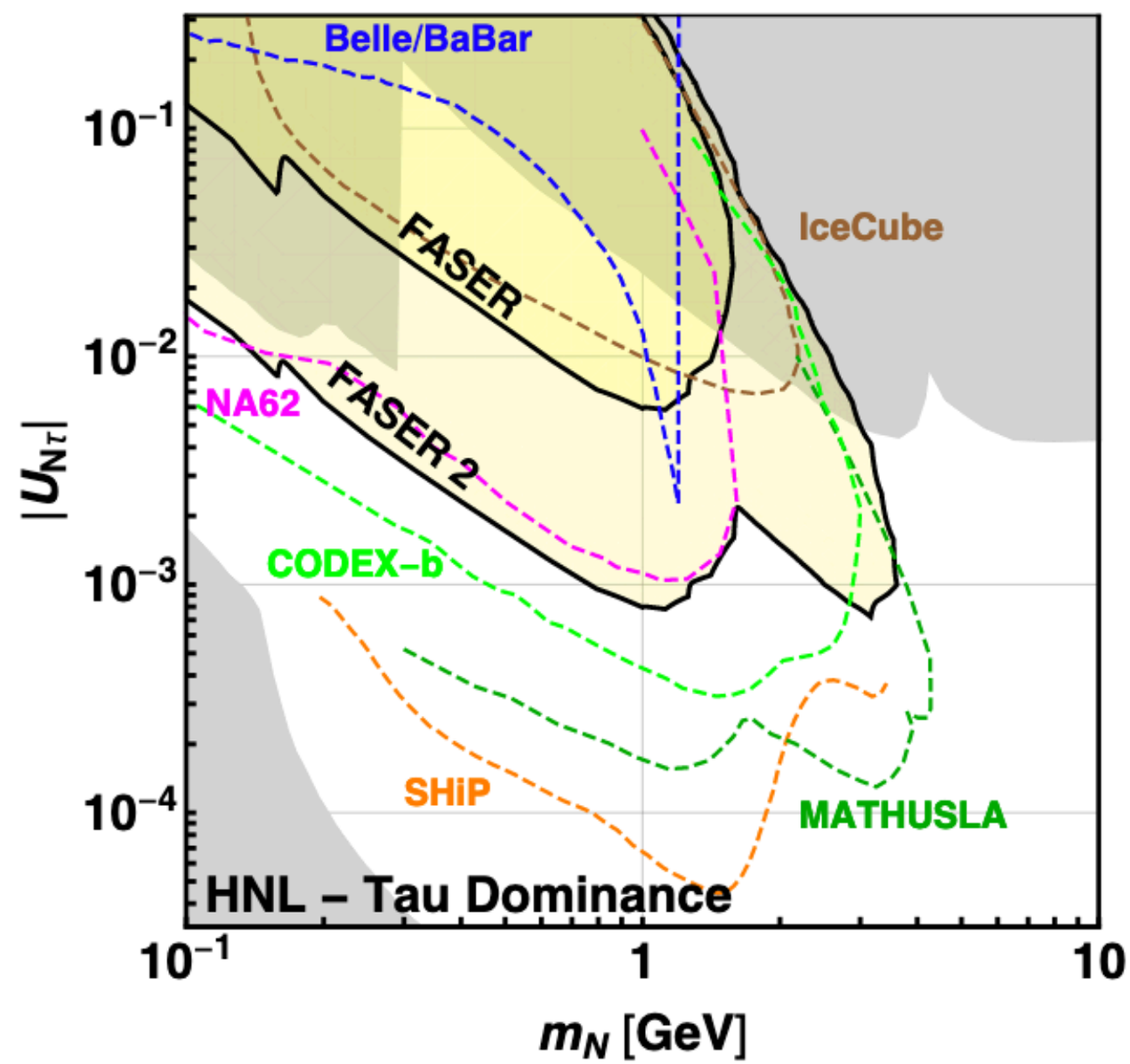
S. Shivley

FASER dark sector sensitivity

A' → l^+l^-, h^+h^-

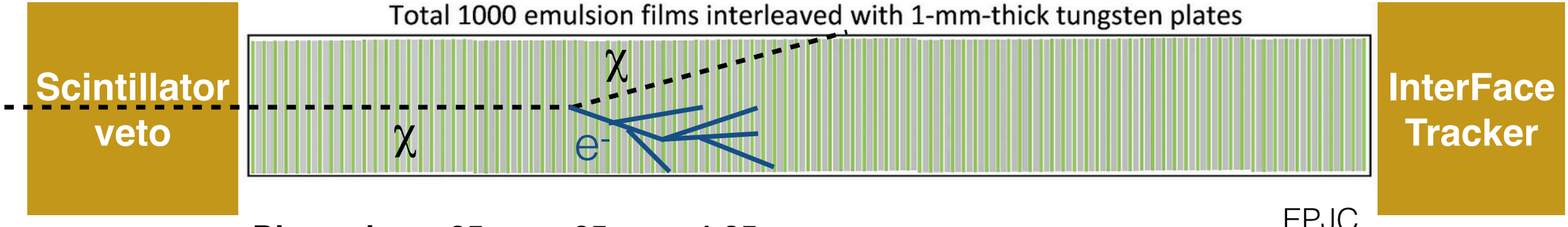


Heavy Neutral Lepton



+ dark Higgs, ALP, ...

FASERν detector

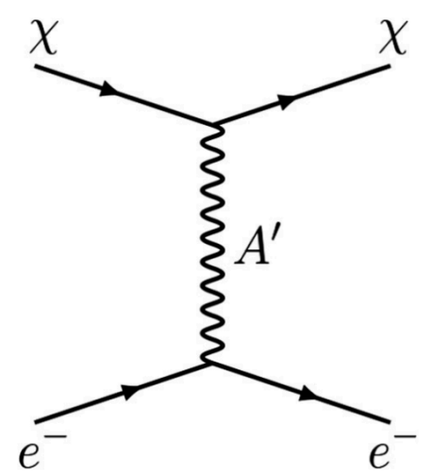


Dimensions: 25 cm x 25 cm x 1.35 m

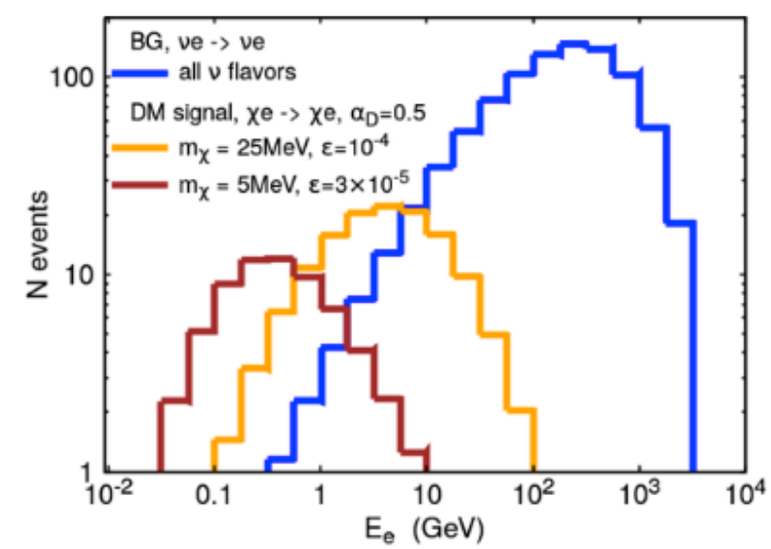
EPJC

Interface with FASER

- Emulsion detector designed for neutrino physics is sensitive to DM scattering from electrons/nucleons
- Capable of efficient reconstruction of low p_T tracks with ~mrad resolution
- Backgrounds from neutrinos rejected using kinematic cuts (mediated by heavy electroweak bosons)



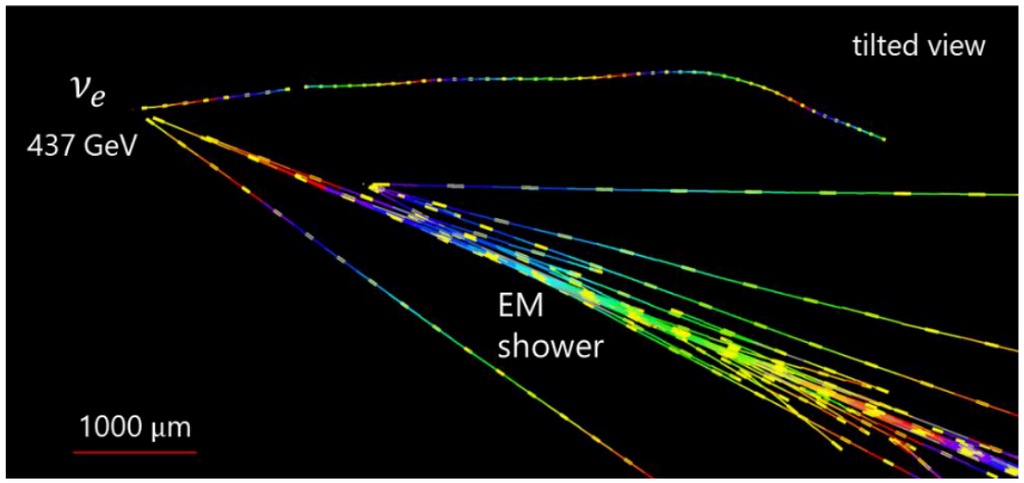
DM-electron scattering via dark photon



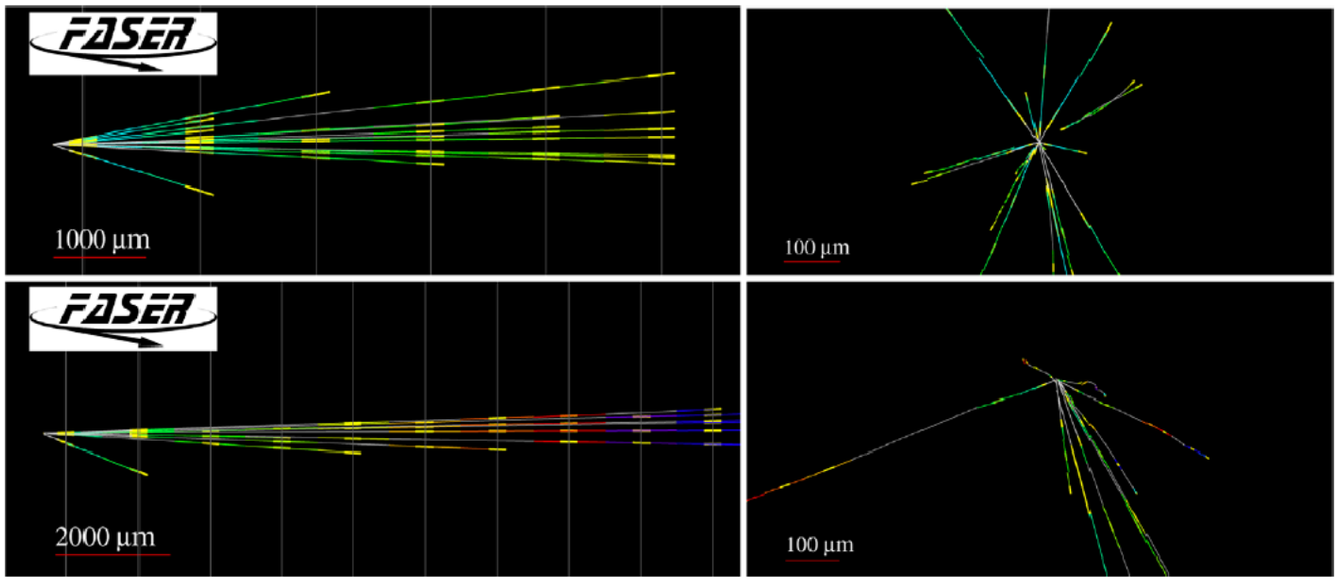
Recoil energy spectra

PhysRevD.103.075023

FASERν status

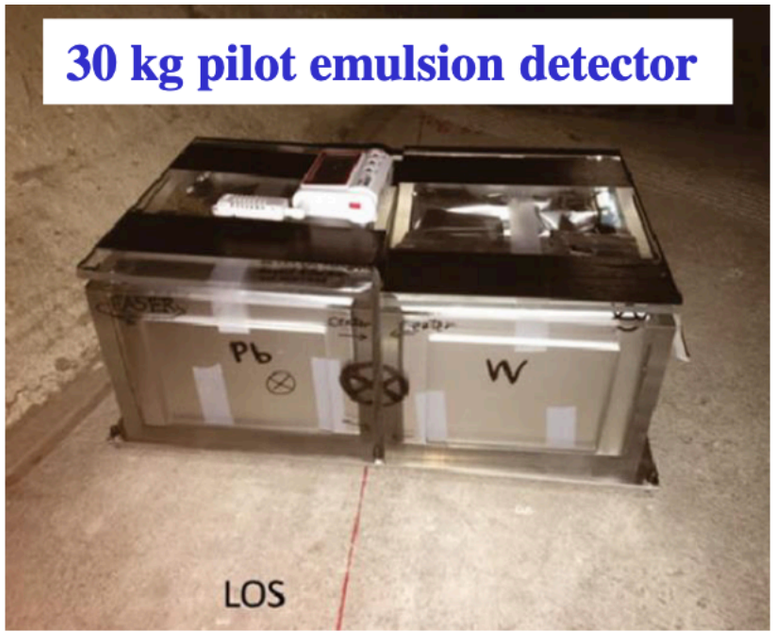


Simulated ν_e event



Neutrino candidate events

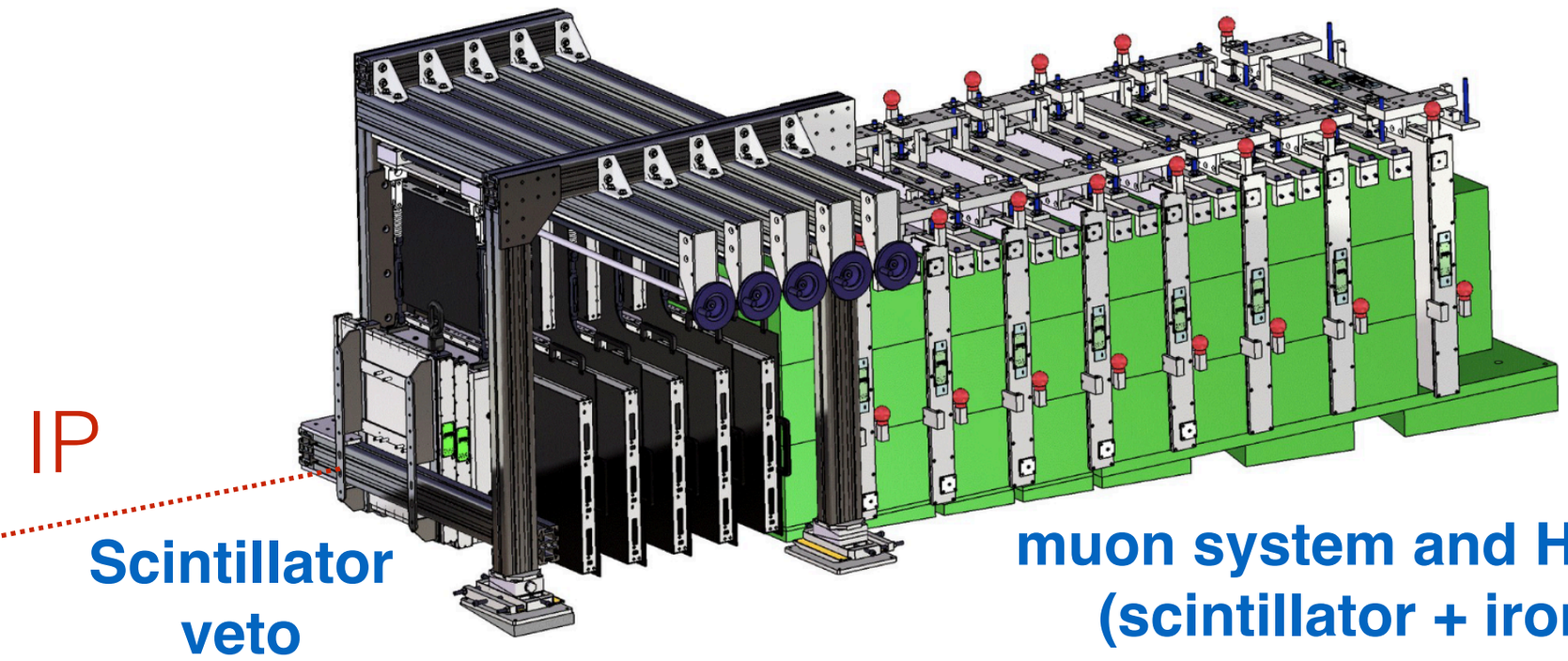
- Successful 2018 run with pilot detector observed neutrino candidates
- Full detector taking data since July 2022
- Need to remove emulsion plates for readout every 30-50 fb^{-1} for manageable pileup



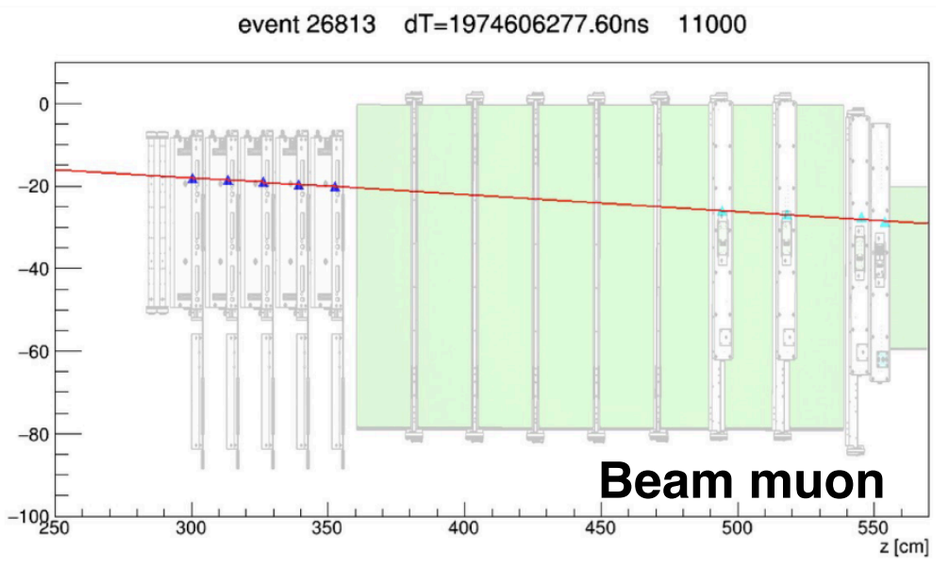
Y. Takubo

Scattering Neutrino Detector (SND)

Vertex detector and calorimeter (emulsion/tungsten and SciFi)

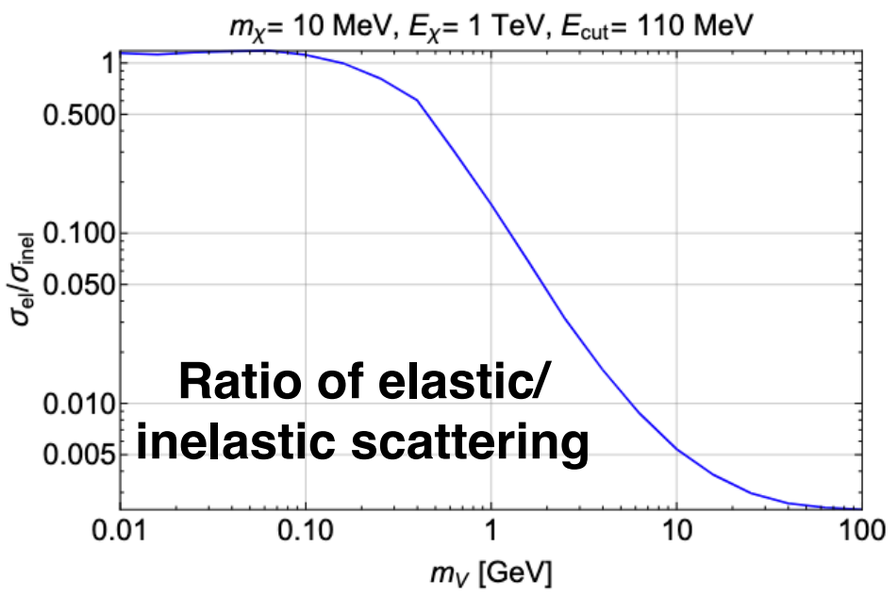


- Off-axis ($7.2 < \eta < 8.6$) hybrid emulsion/electronic detector
- Match candidates from electronic detector to emulsion detector for full event reconstruction
- Commissioning detector with beam muons/neutrino candidate interactions

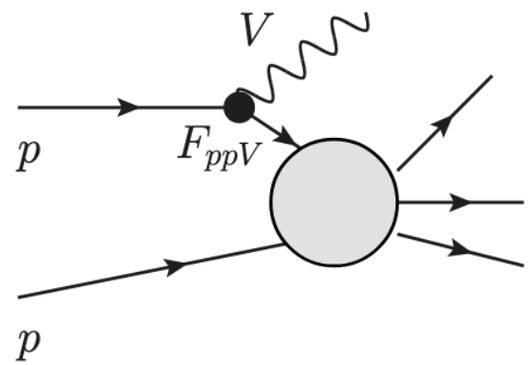


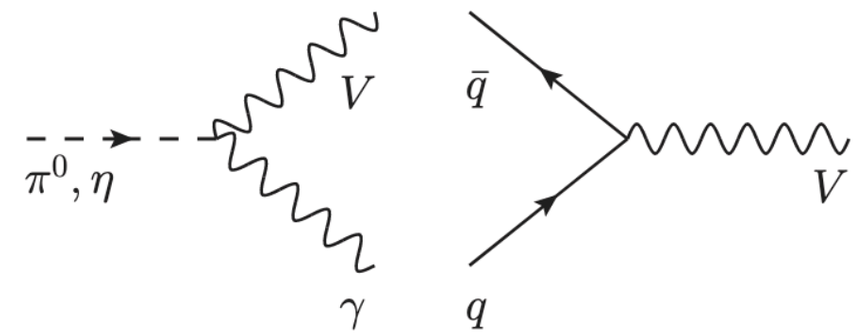
E. Zaffaroni

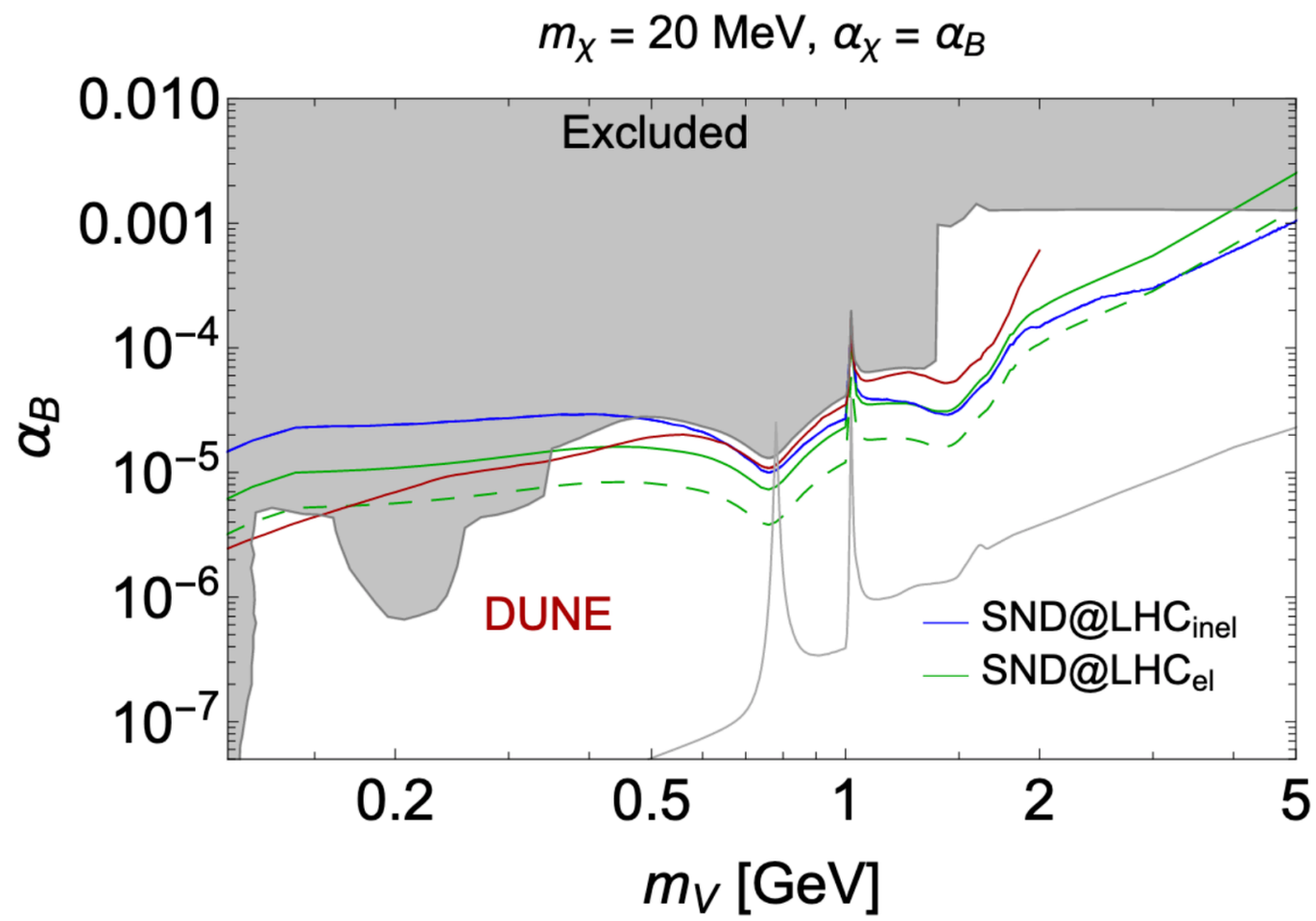
SND dark sector sensitivity



Production





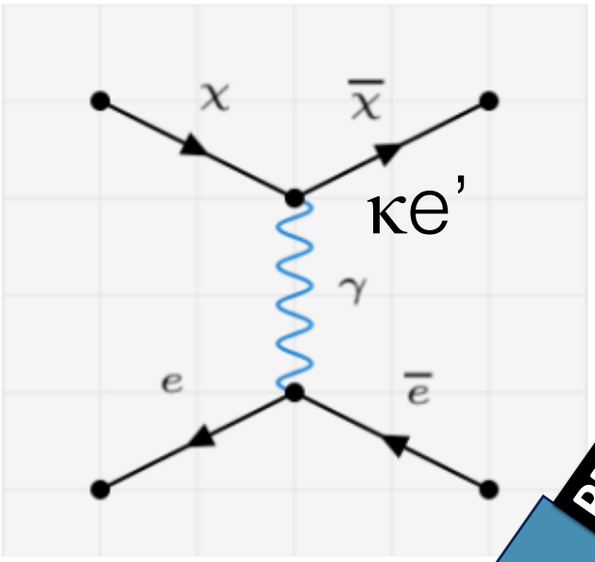


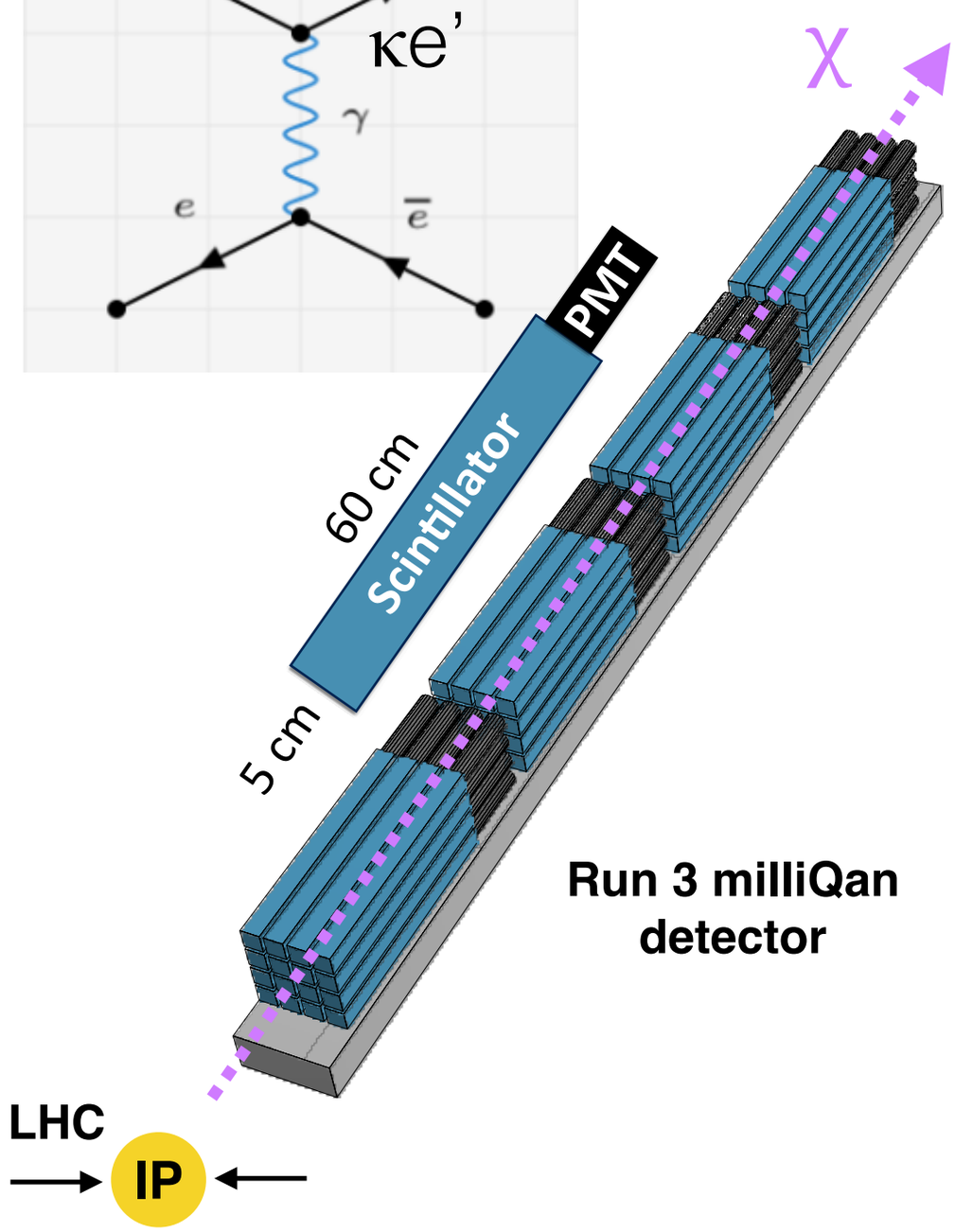
- Sensitivity to elastic nucleon scattering (mediator < ~GeV) through kinematics (as for electron scattering)
- Sensitivity to inelastic scattering (mediator > ~GeV) requires measuring NC/CC interaction ratio

Leptophobic DM benchmark

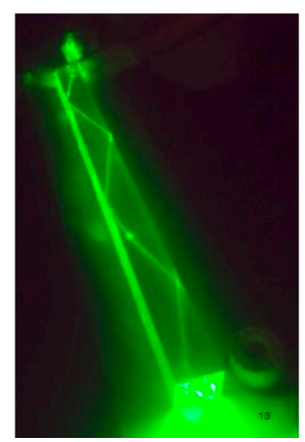
JHEP03(2022)006

milliQan search for millicharged particles





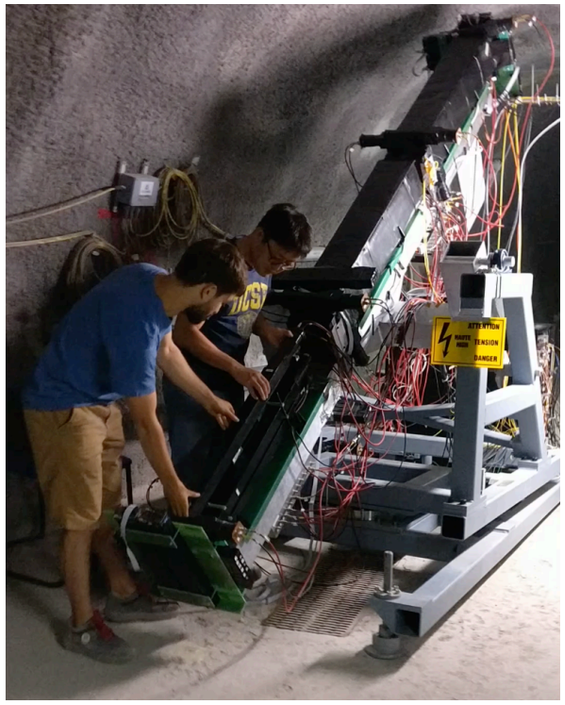
Run 3 milliQan detector



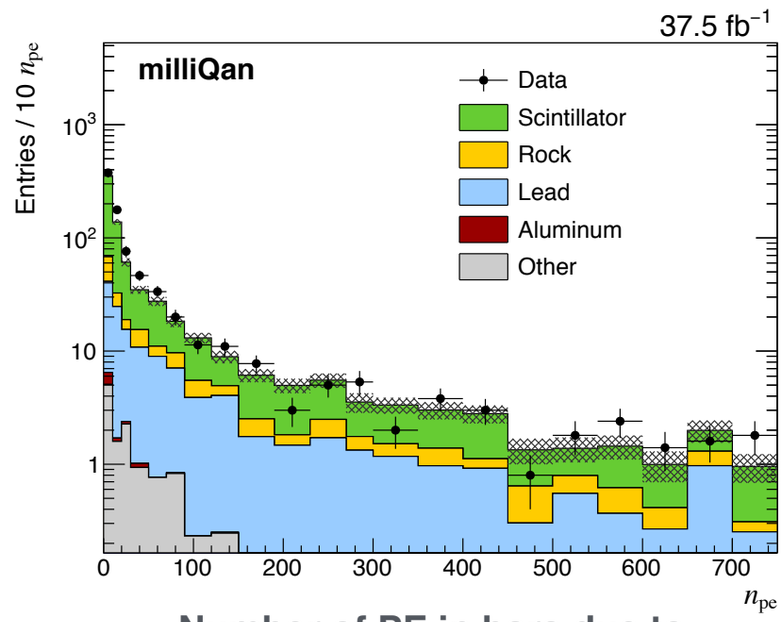
Scintillator bar

- Use long scintillator bar array to detect (very) small ionisation from low charged particles
- Expected signal: few scintillation photons in multiple layers
- Each bar + PMT must be capable of detecting a single scintillation photon
- Require hits in multiple layers for stringent background rejection
- Modular design is easy to scale and adapt!

The milliQan demonstrator



Installed on mount designed to hold full detector in CMS cavern: 33m from IP (17m of rock shielding)

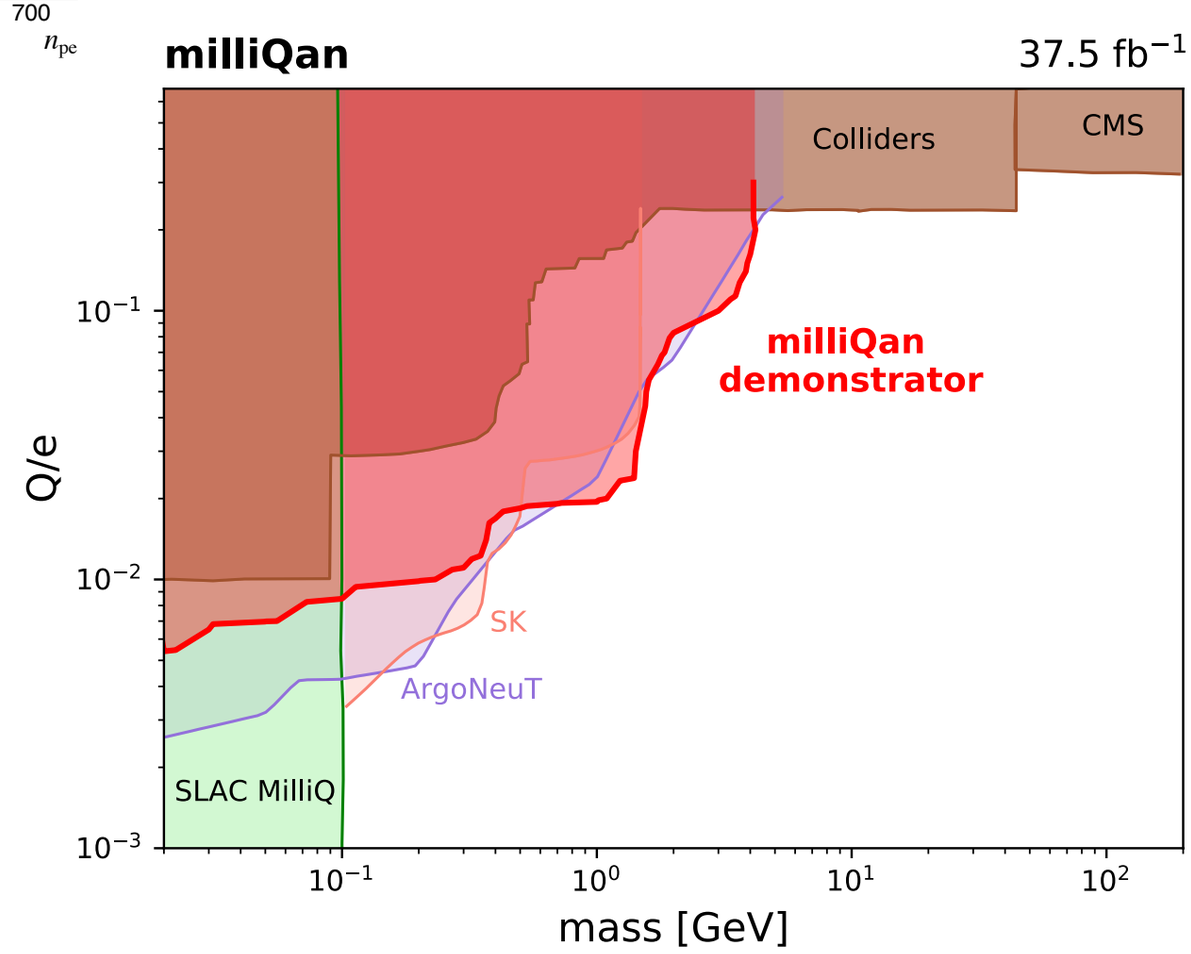


Number of PE in bars due to muon shower products

- Demonstrator ran very successfully, collecting **~35/fb, 2000h** of data in 2018
- Used for range of studies to prove feasibility of full detector: **alignment, calibrations, background measurements**

- **First search** for millicharged particles at a hadron collider with new sensitivity
- **Quantitative understanding** of backgrounds and detector performance

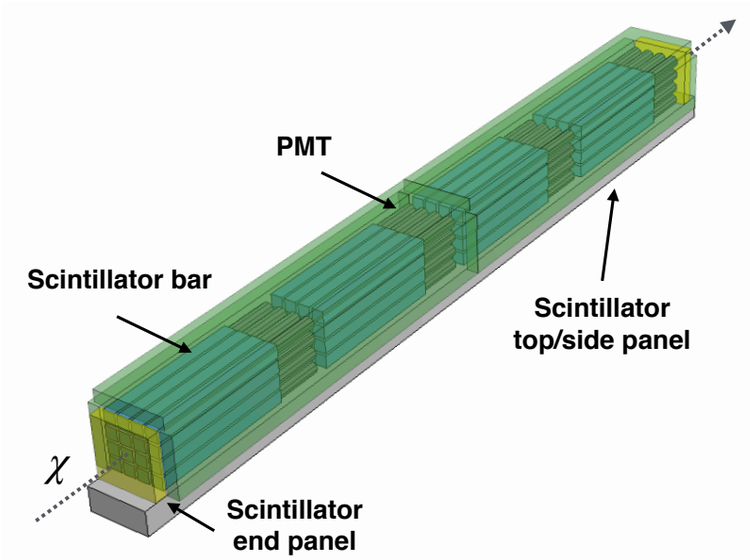
→ **Use this to guide future detectors!**

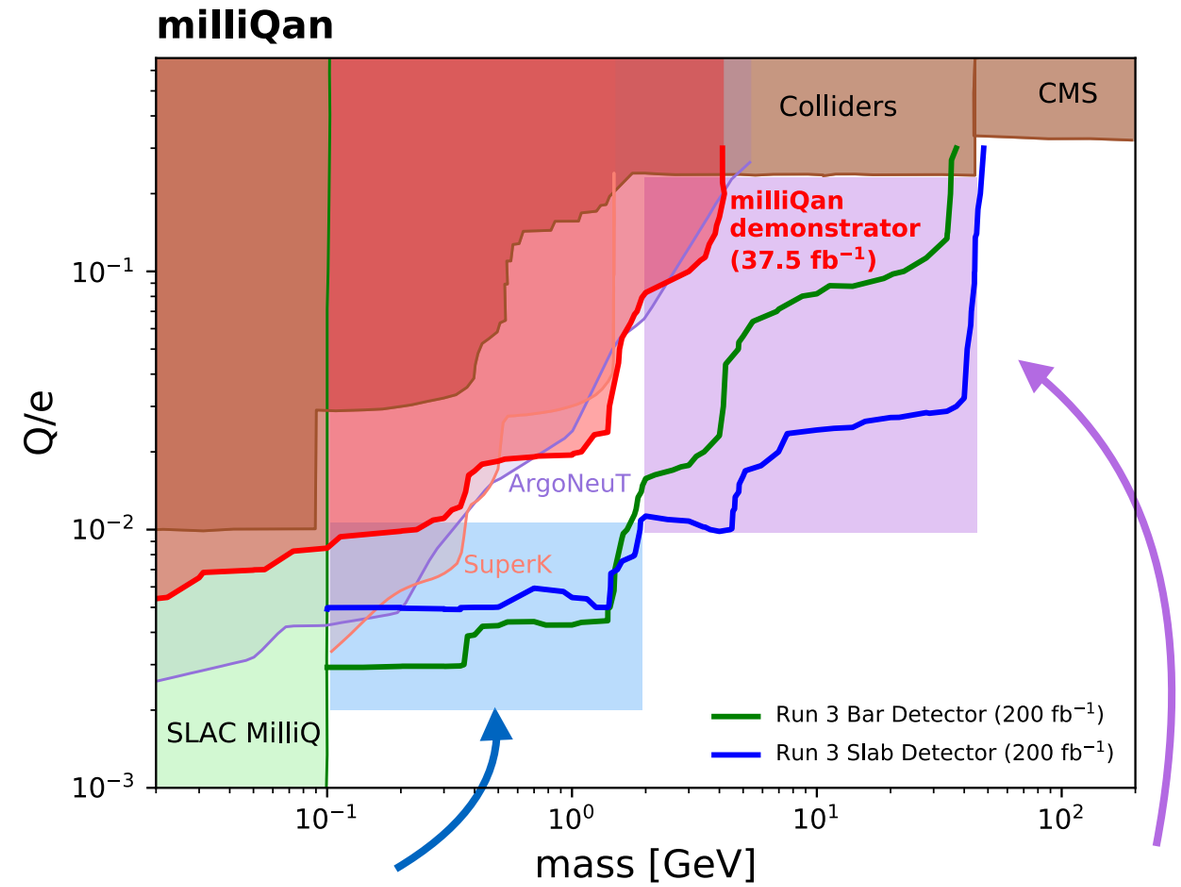


Published in PRD: PhysRevD.102.032002

Run 3 milliQan experiment

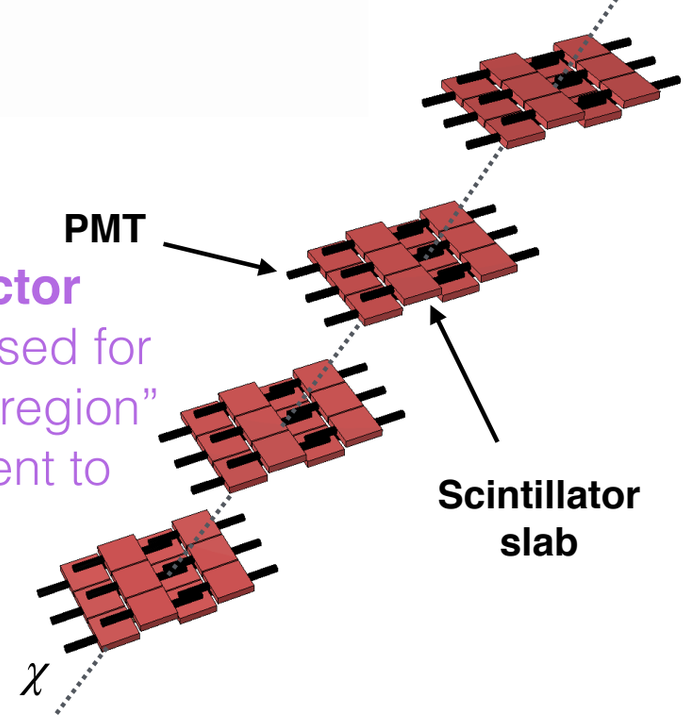
Run 3 bar detector
design based on lessons from demonstrator: expanded size (4x4 bars), four layers, thicker veto panels, signal amplification





Charge limited region: very high mcp flux but low efficiency

Acceptance limited region: high efficiency but low mcp flux



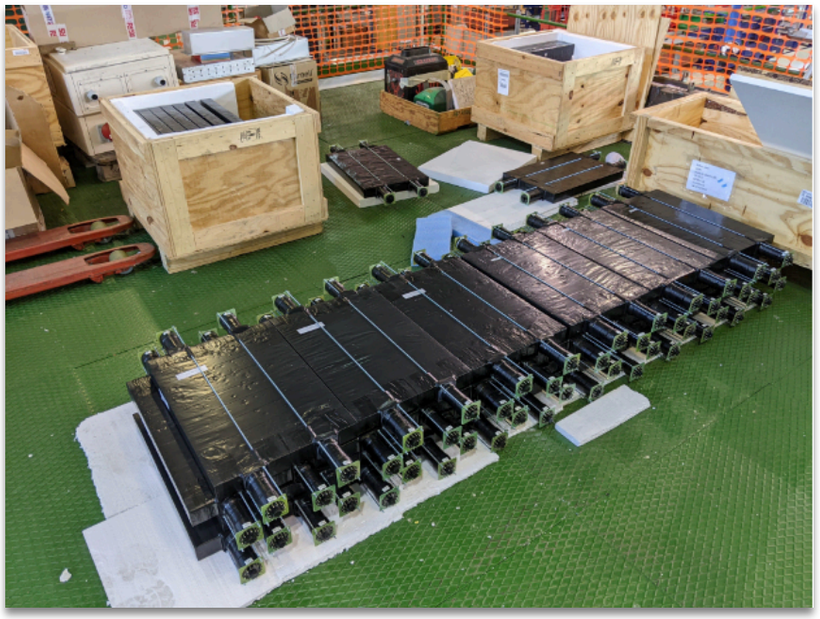
Run 3 slab detector
thinner slabs optimised for "acceptance limited region" (total area equivalent to >1000 bars!)

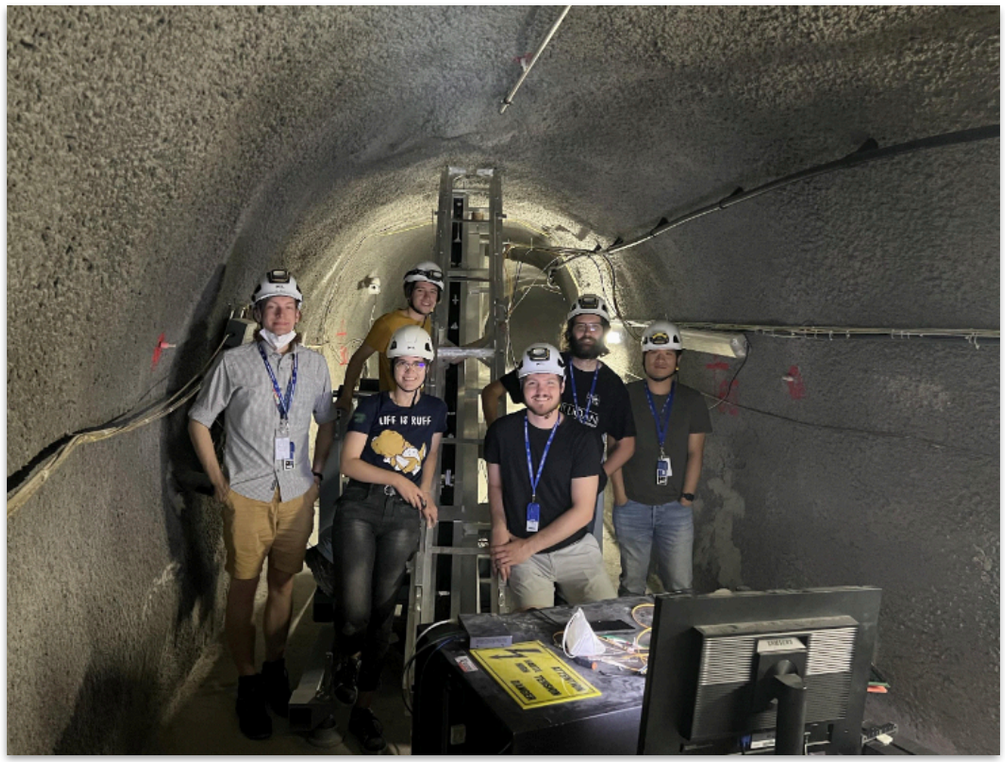
Backgrounds/signal efficiencies estimated using **data collected by demonstrator**

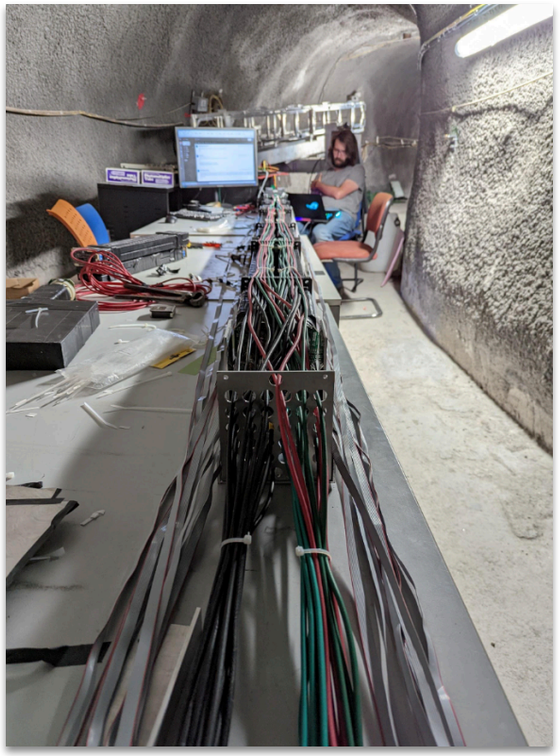
Expect world leading sensitivity for **0.1 < m < 45 GeV** using **combination** of **slab and bar** detector

Published in PRD: PhysRevD.104.032002

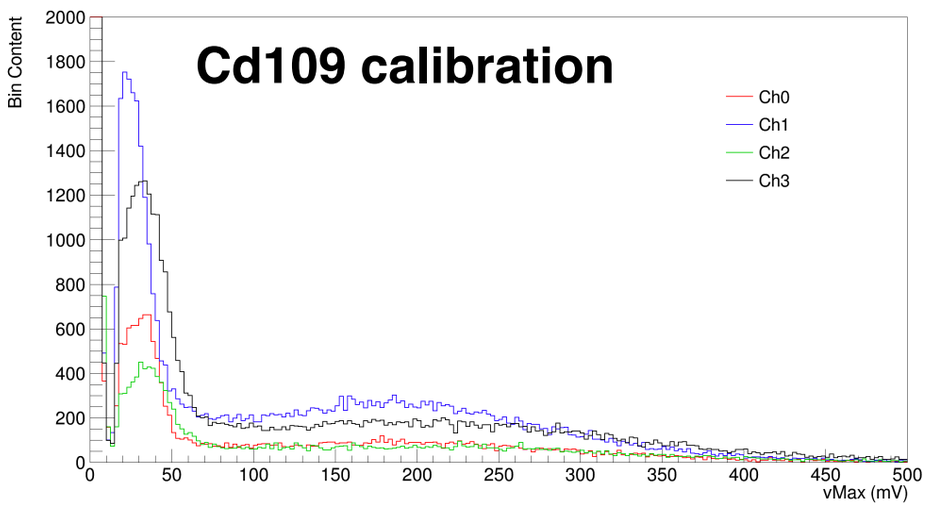
Run 3 milliQan detector status





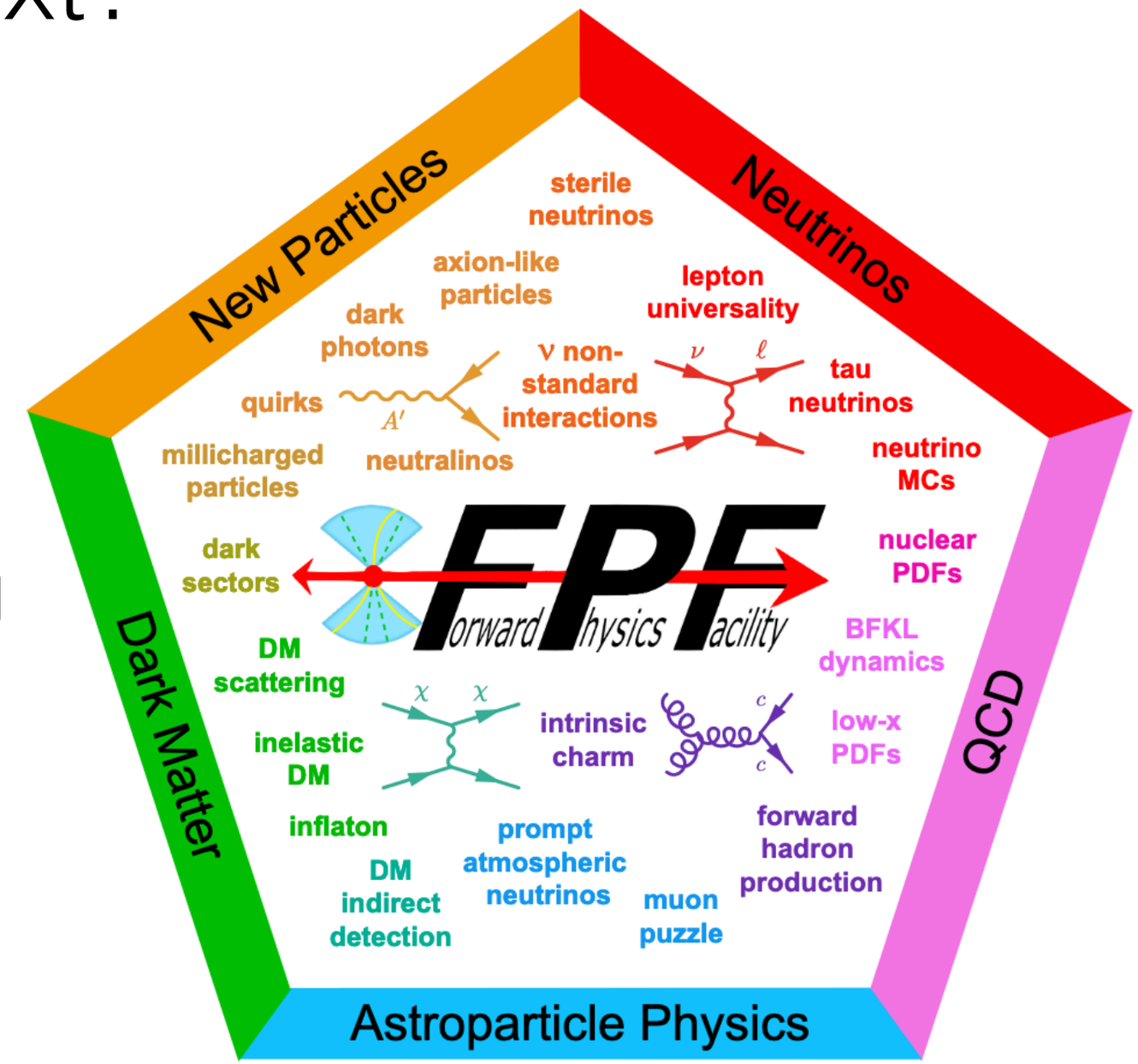


- Run 3 detectors being installed and commissioned using cosmics, radioactive sources and beam muons
- Experience from demonstrator allowing rapid progress



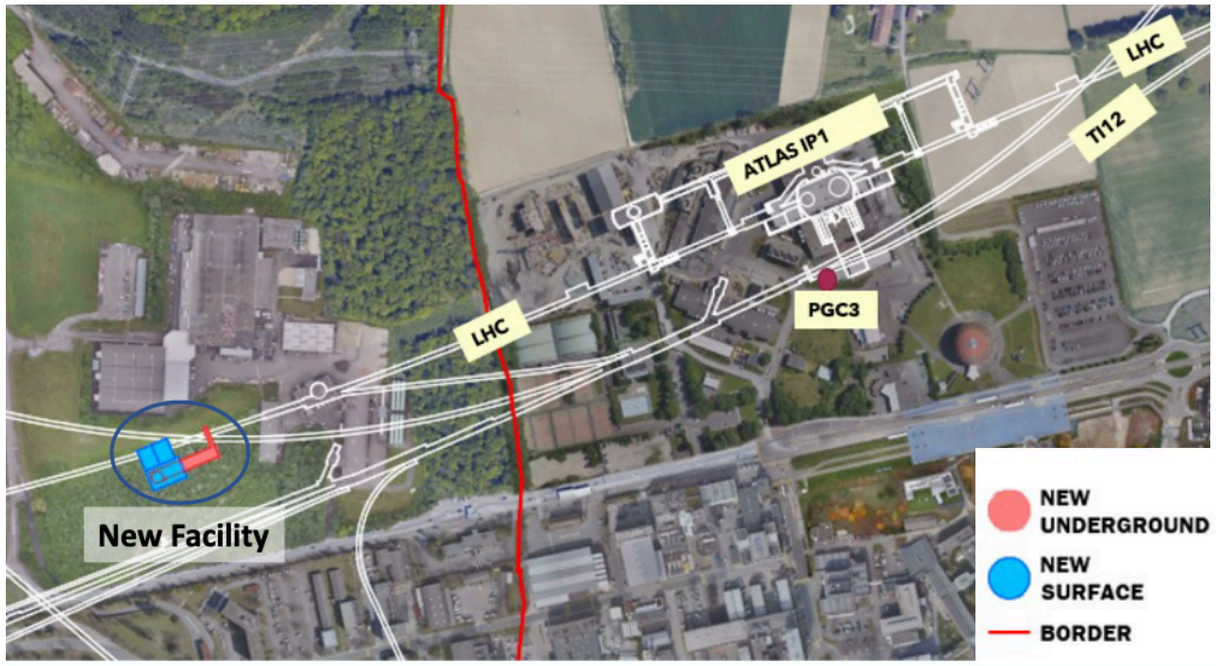
What could come next?

- The HL-LHC will provide over **3000 fb^{-1}** of p-p collisions
- Many proposals for dedicated detectors (see summary)!
- Focus on FPF: dedicated **forward physics facility** provides extensive probe of wide range of BSM (and SM) signatures to **fully exploit** physics potential of the LHC!
- Facility allows **longer**, **wider** and **new** detectors for optimal sensitivity!



Detailed white paper with > 200 authors released in March 2022

Forward Physics Facility



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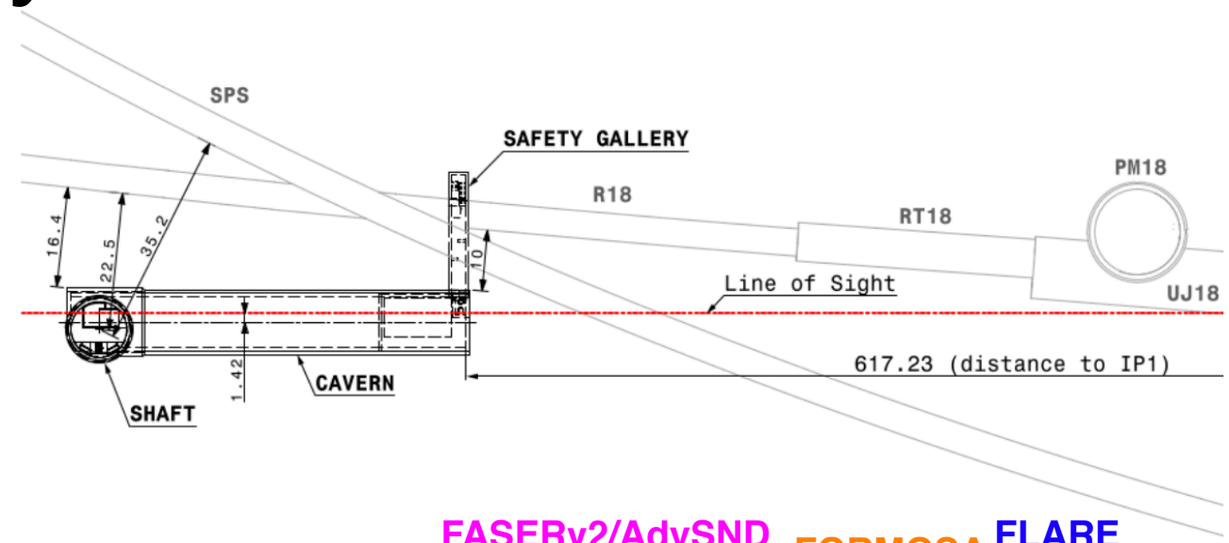
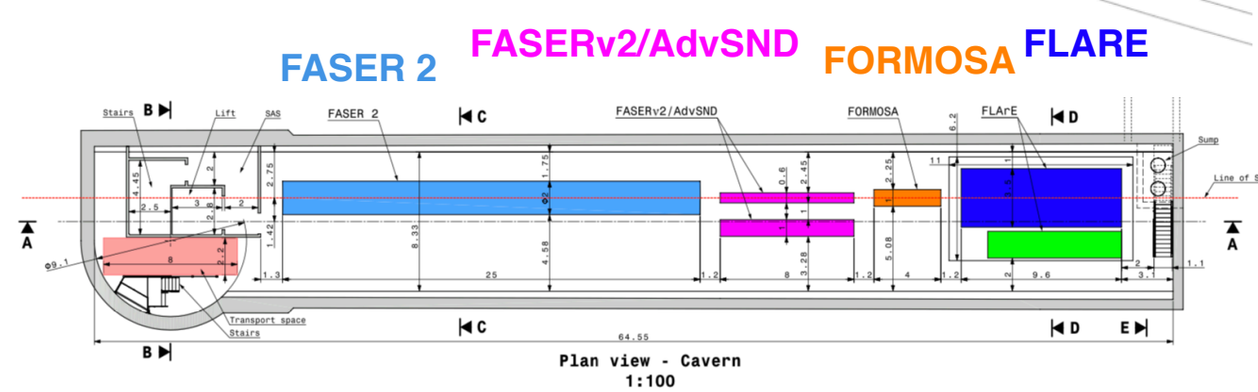
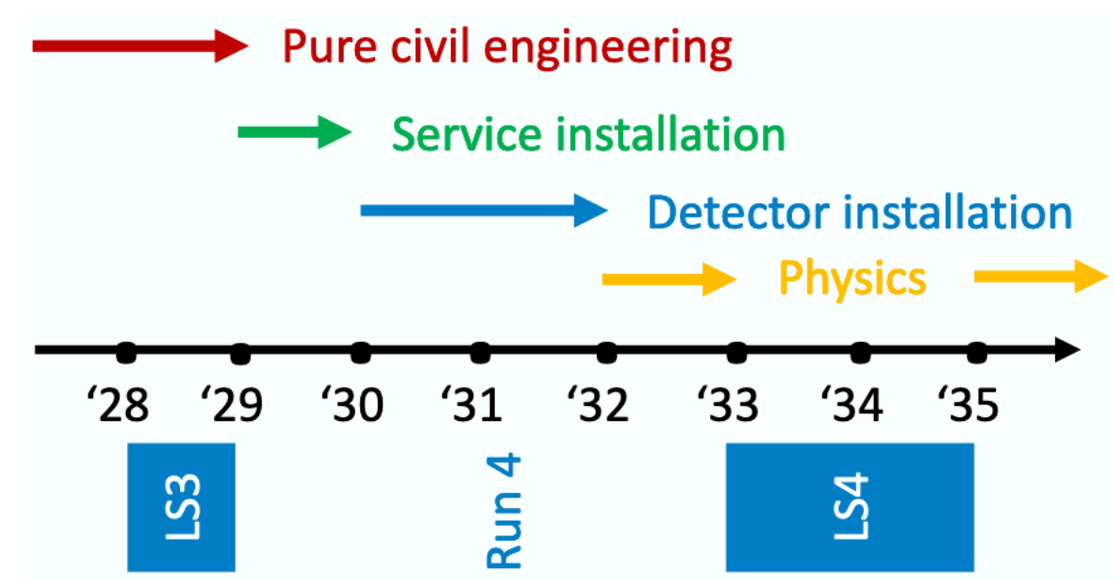


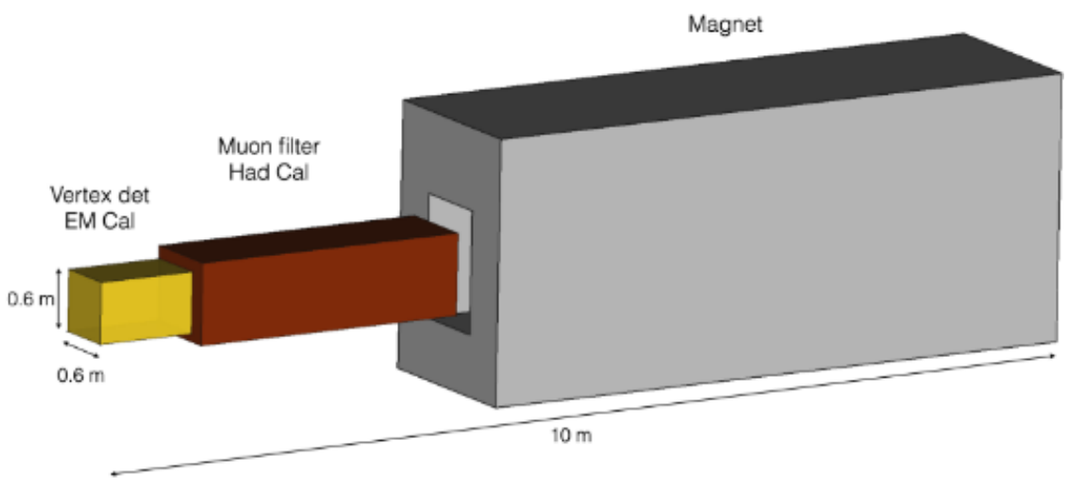


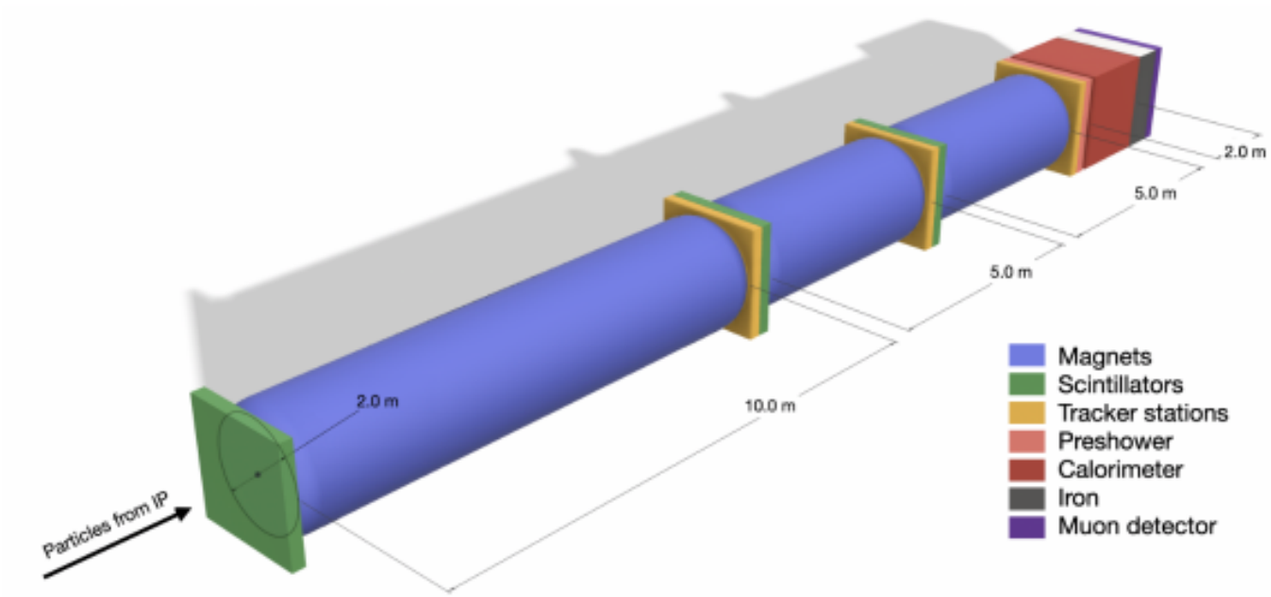
- Purpose built cavern ~600m in front of ATLAS IP
- Tight schedule to install in time for end of Run 4 (facility cost ~40 MCHF)
- Five detectors provide comprehensive coverage of BSM and SM physics

Timeline

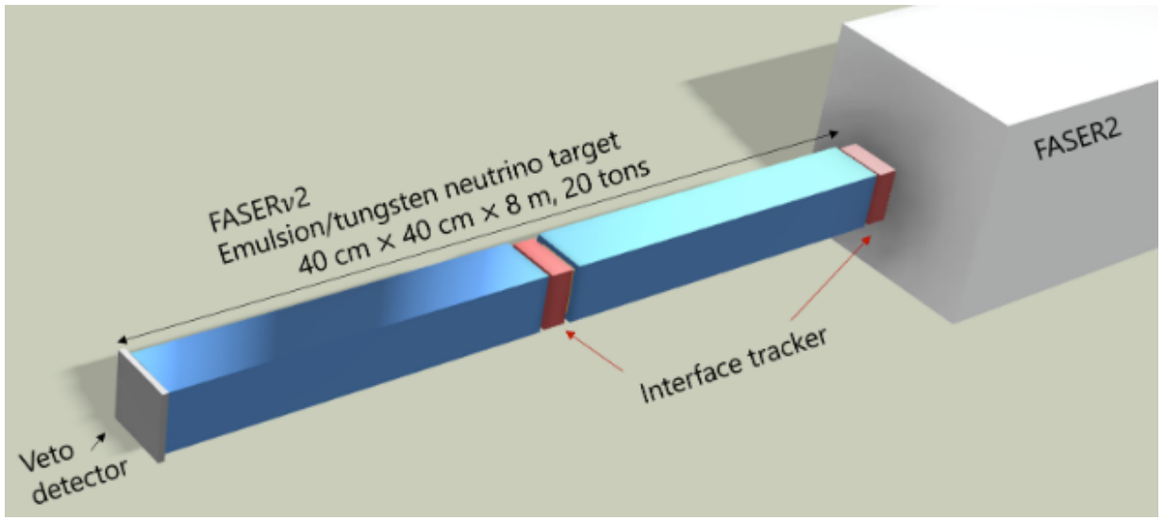


FPF detectors: AdvSND, FASER 2, FASERv2





- Similar designs to Run 3 detectors with main difference being scale: up to ~**10 times** larger in each dimension!
- Sensitivity to DM scattering and decaying LLPs
- Proponents exploring possible upgrades to designs



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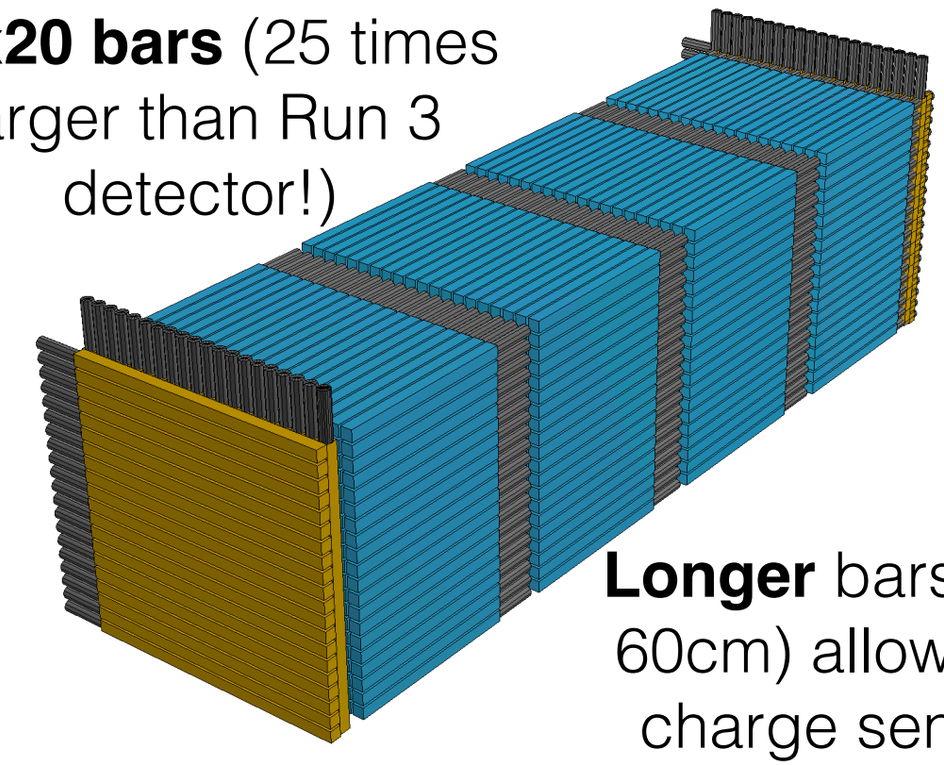
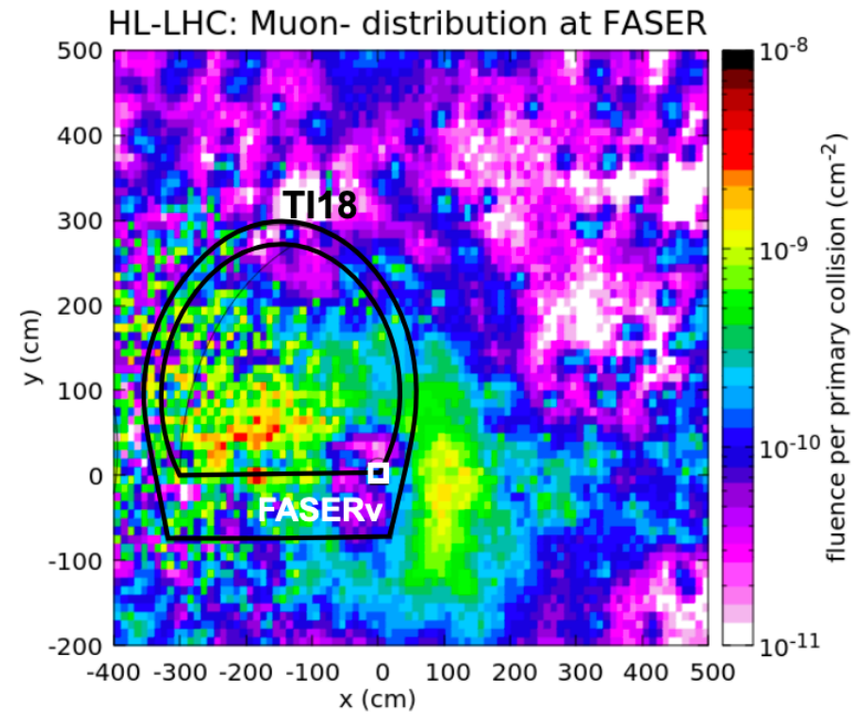
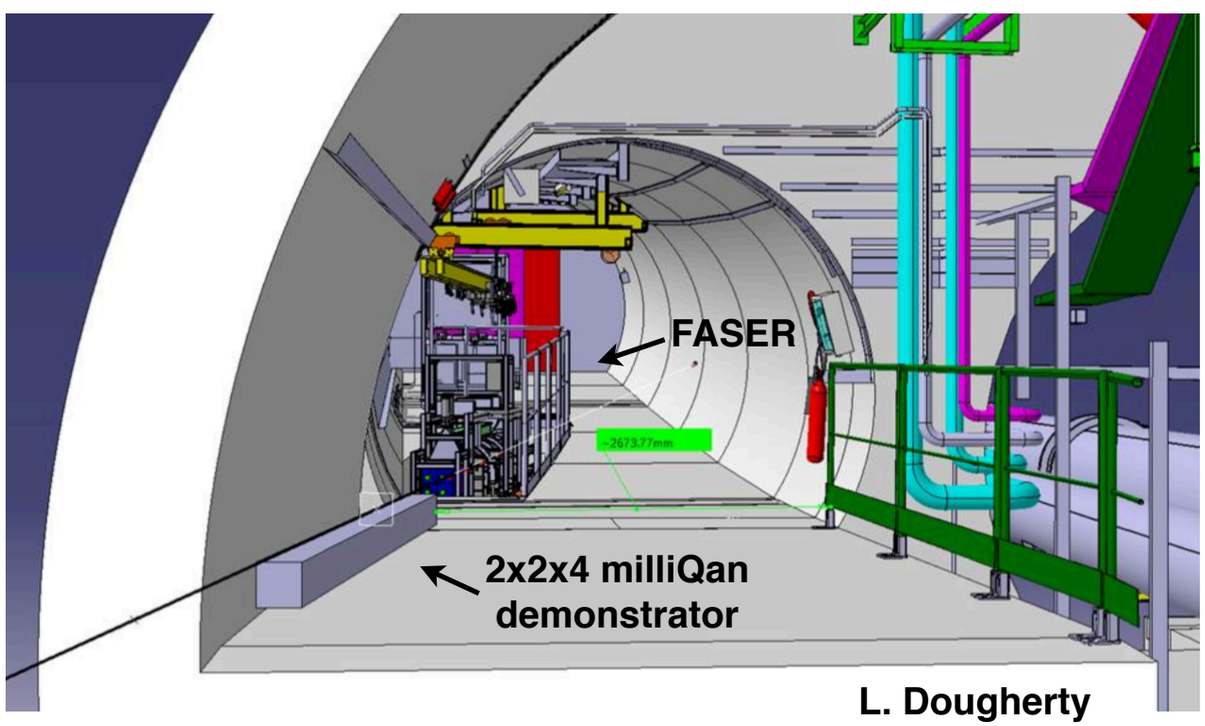
FPF detectors: FORMOSA

20x20 bars (25 times larger than Run 3 detector!)



Longer bars (1m vs 60cm) allows lower charge sensitivity



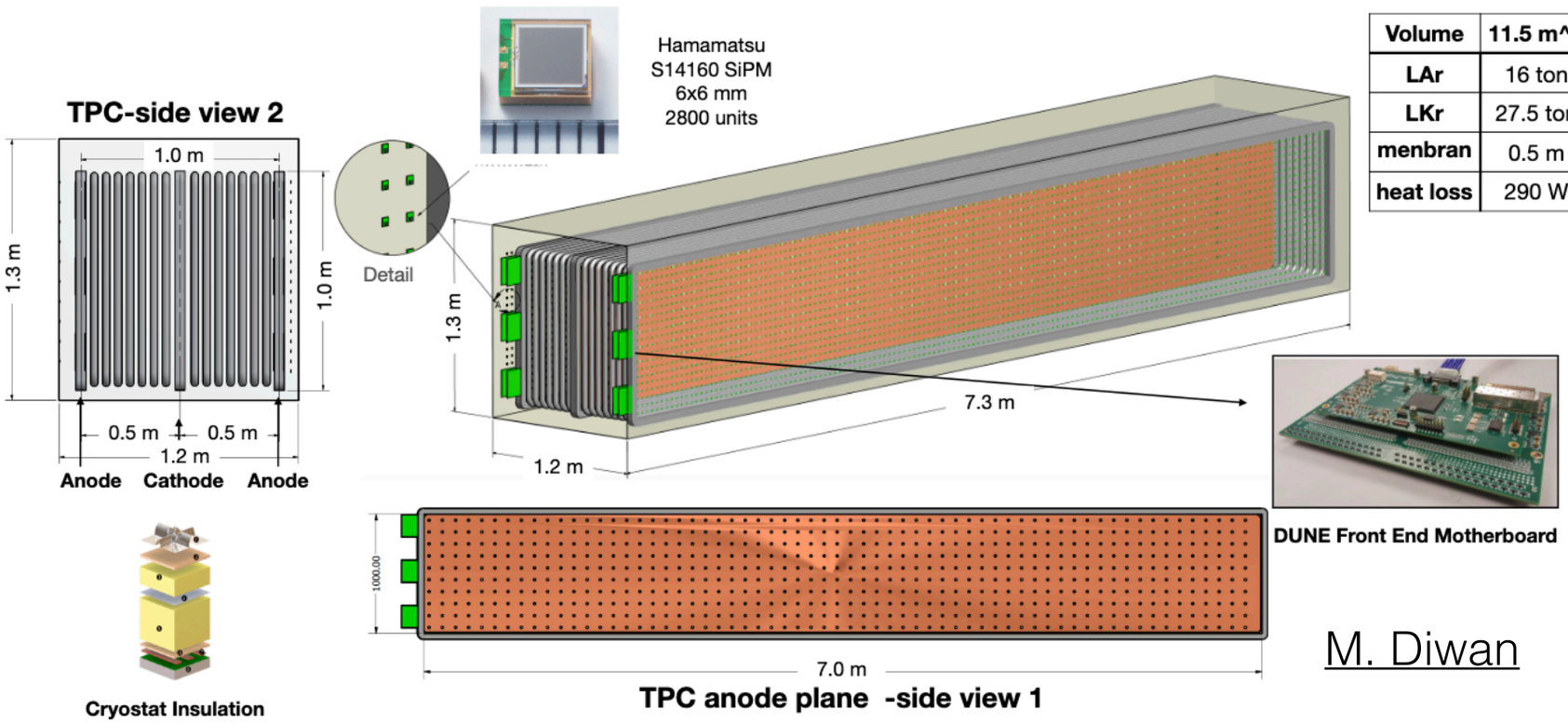


- FORMOSA: forward detector sees up to **factor ~ 250 higher** mcp rate compared to central location
- Challenging location → prove feasibility with **FORMOSA demonstrator** in Run 3!
- Provide **critical insights** into backgrounds/operation in forward environment

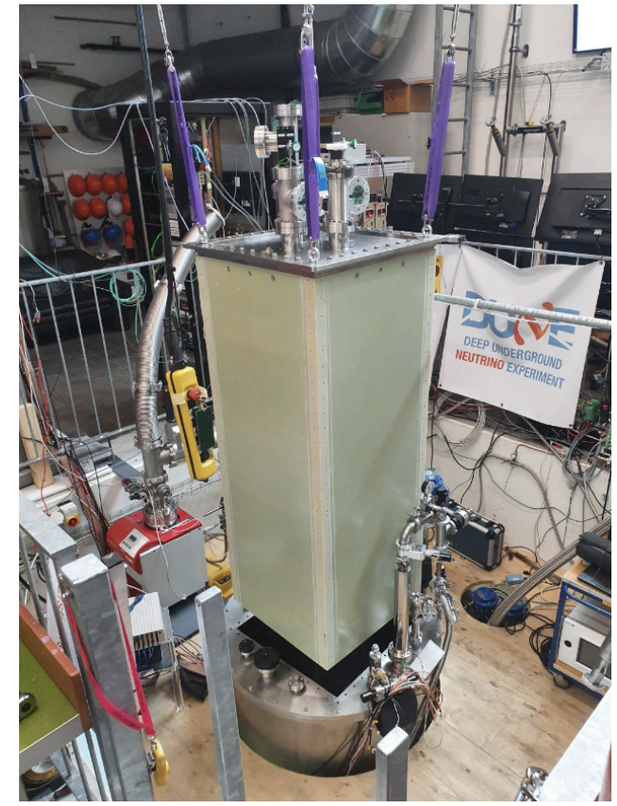
2203.05090

FPF detectors: FLArE

FLArE Detector Preliminary Sketch

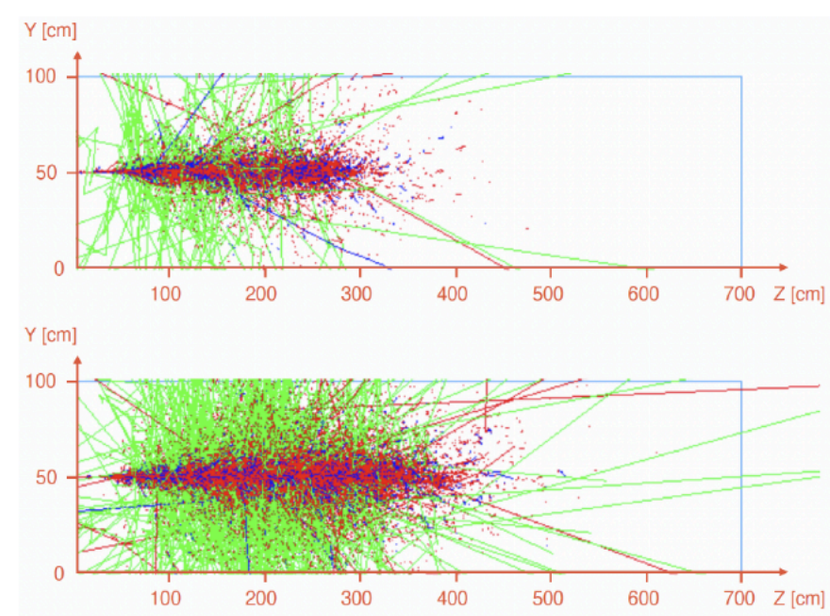


Volume	11.5 m^3
LAr	16 ton
LKr	27.5 ton
menbran	0.5 m
heat loss	290 W



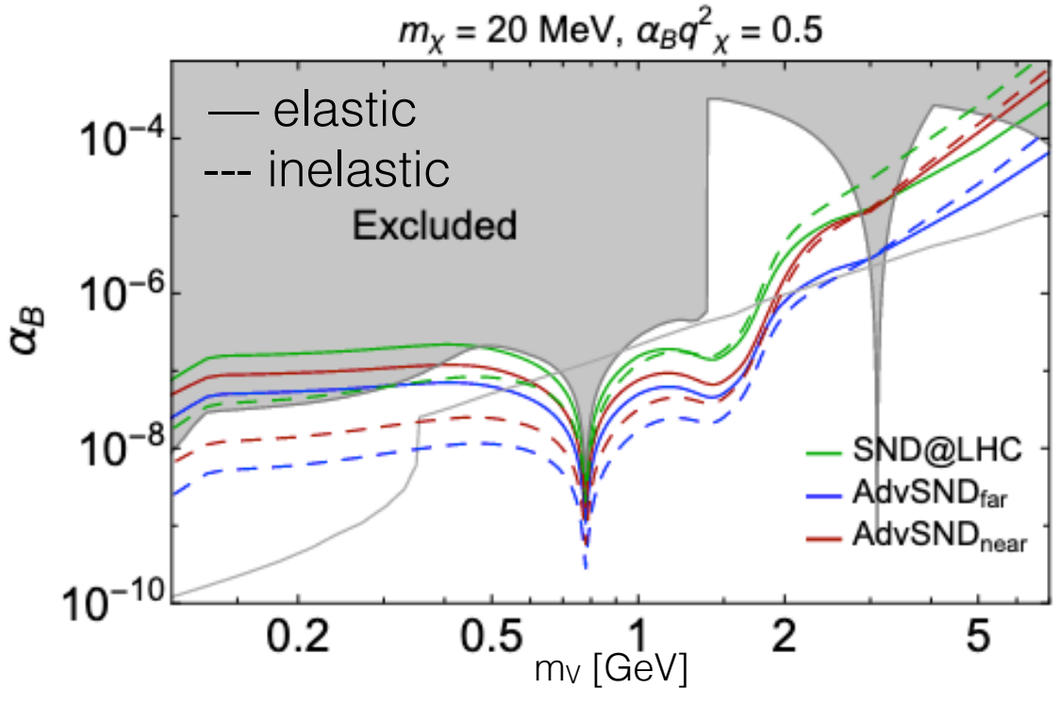
M. Diwan

- Measure showers from neutrinos/DM scattering with ~16 ton LArTPC (and exploring alternative Krypton option)
- Big advantage compared to emulsion for DM scattering: real-time readout!

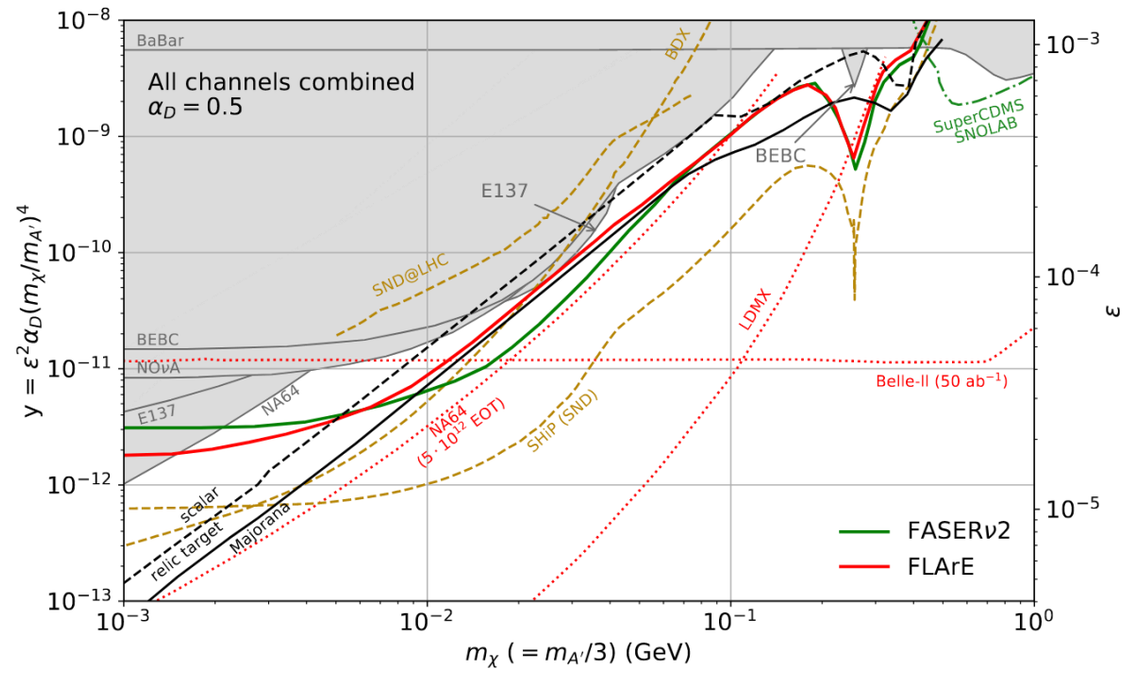


EM shower in LAr

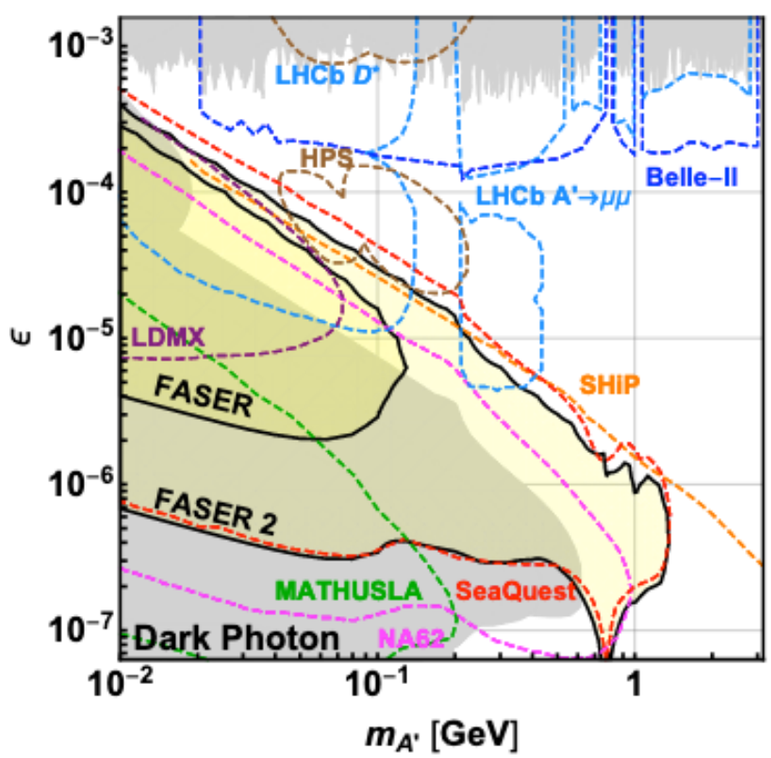
BSM sensitivity at the FPF



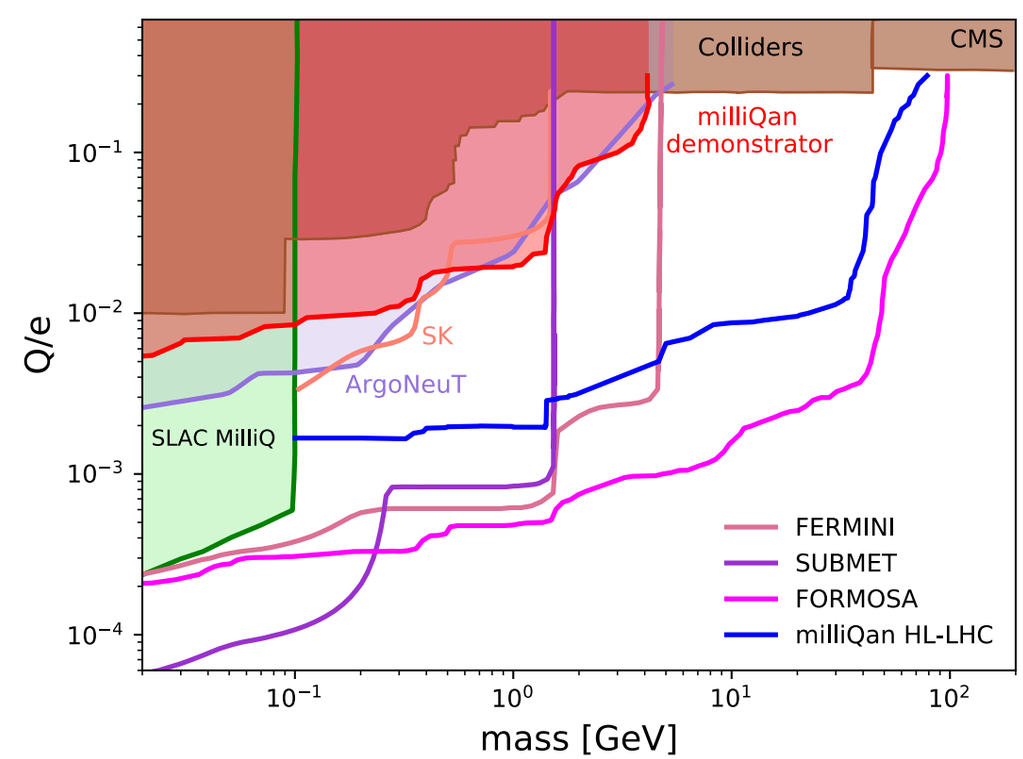
Leptophobic DM scattering



Dark photon mediated DM scattering



LL dark photon



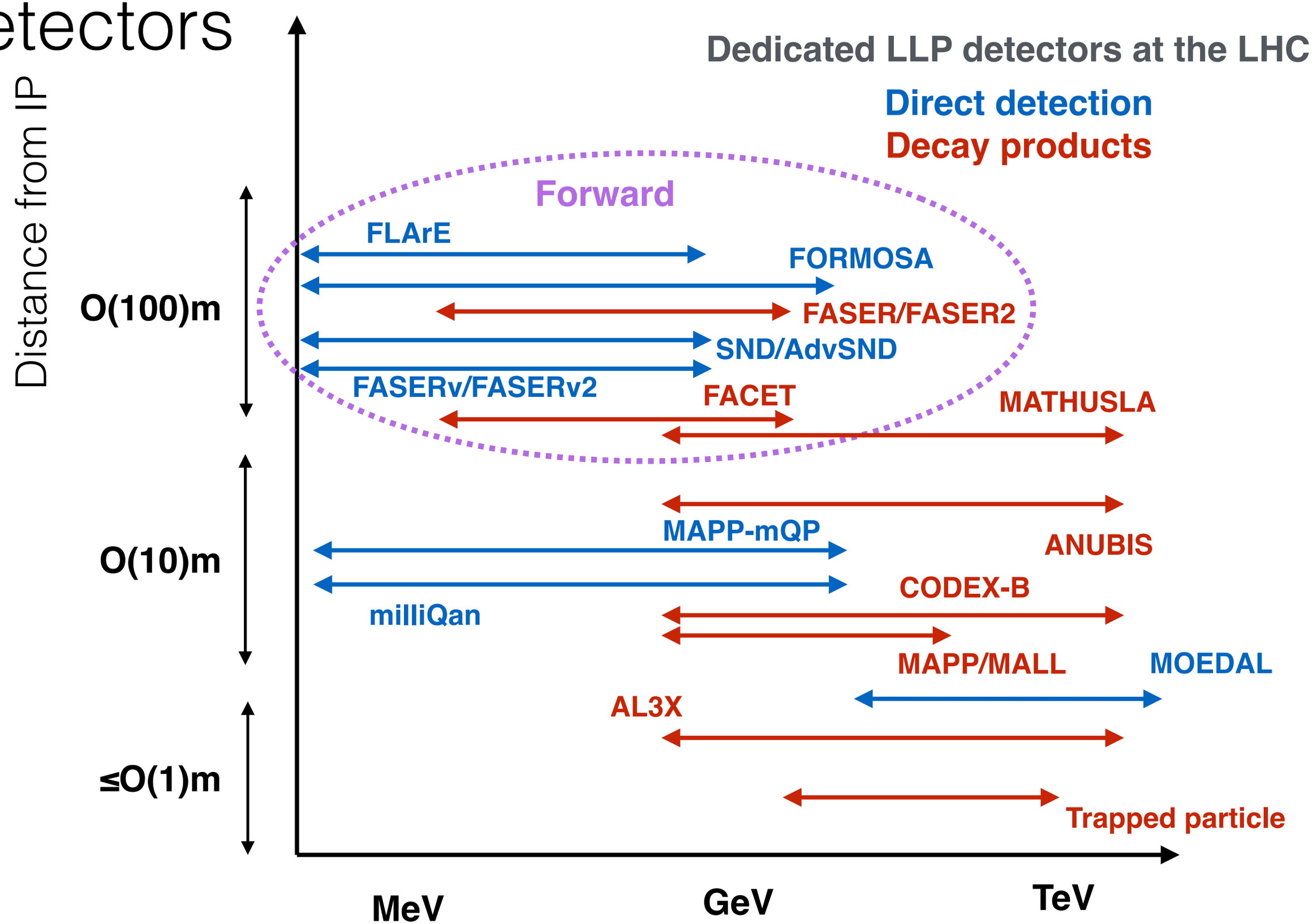
millicharged particle

NB: this is only a small subset!

Summary

- The LHC may be a dark sector factory but many **dark sector** signatures **invisible** to ATLAS/CMS/LHCb
- Need **eco-system of dedicated experiments** to fully exploit the physics potential of the LHC
- New detectors **taking Run 3 data now** and proposed detectors for the HL-LHC will provide excellent prospect for discovery!

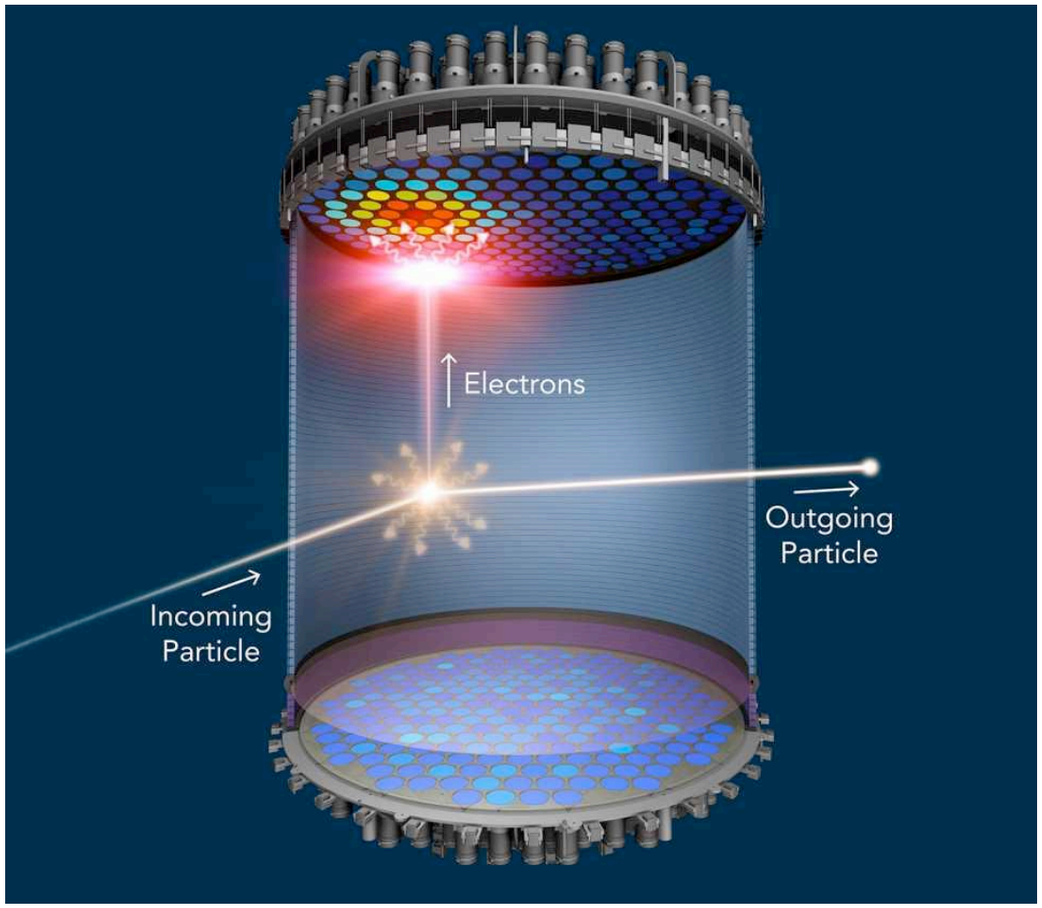
Qualitative summary of proposed detectors



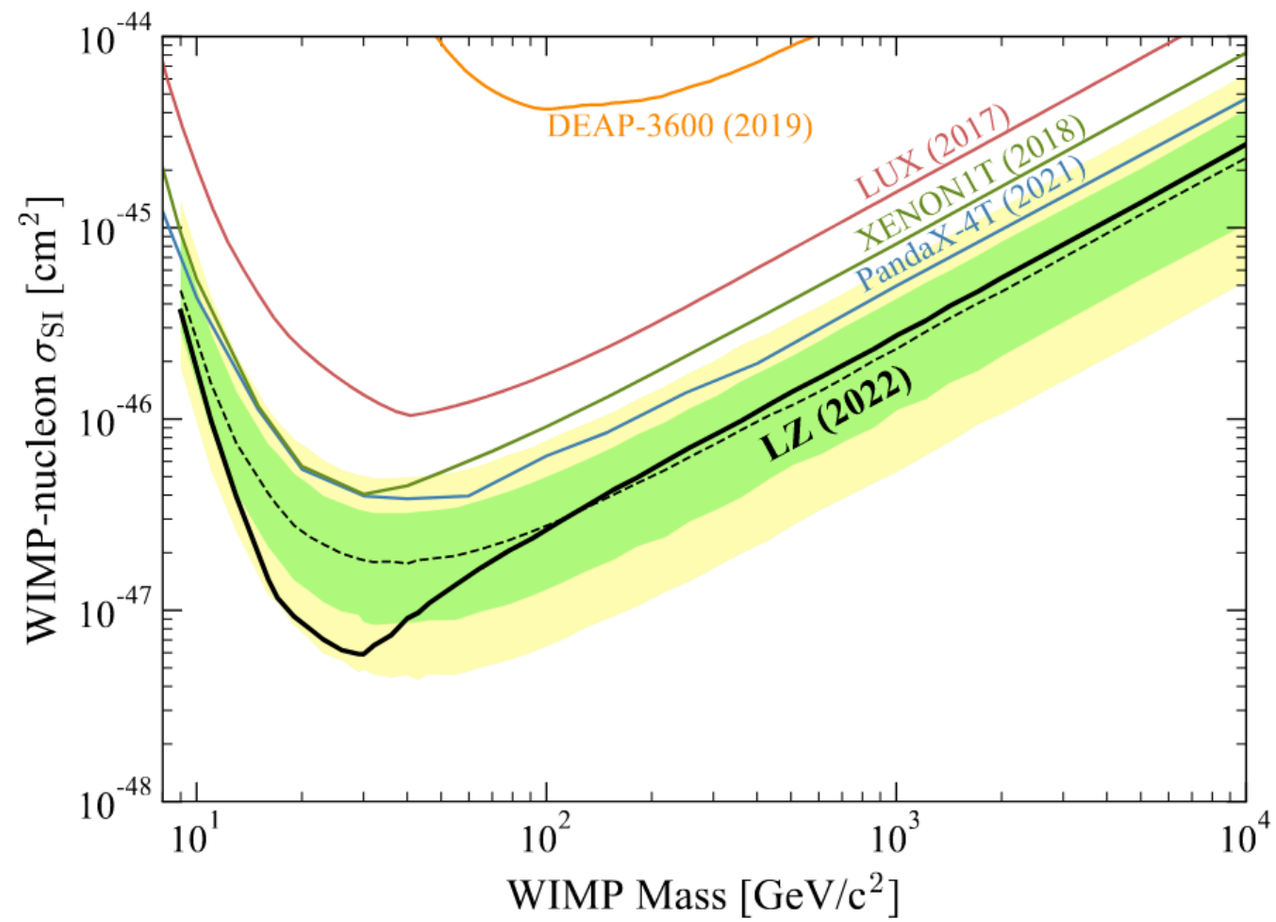
LLP mass range targeted

Backup

No evidence for WIMP DM (so far…)

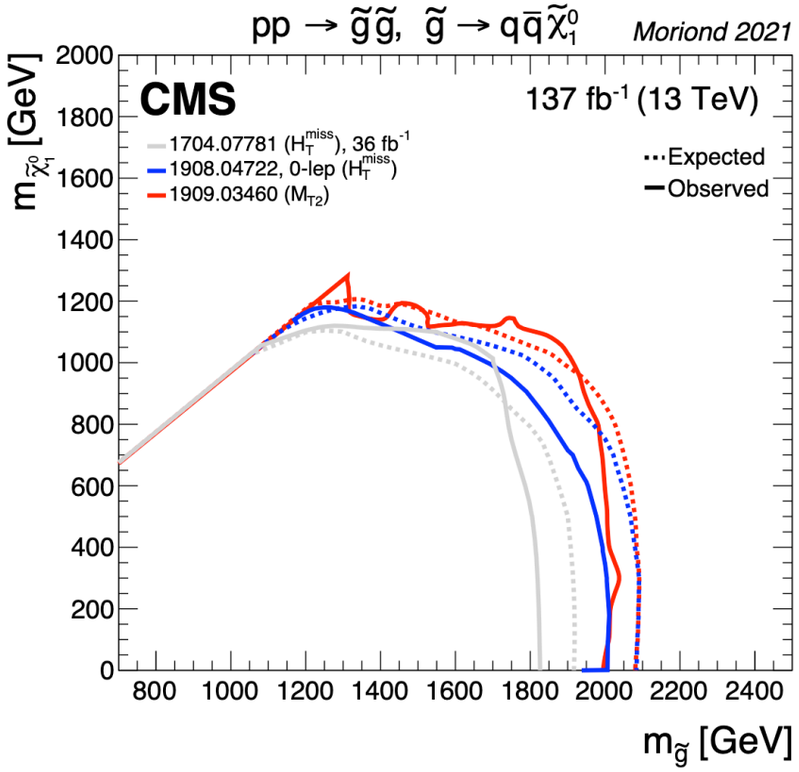


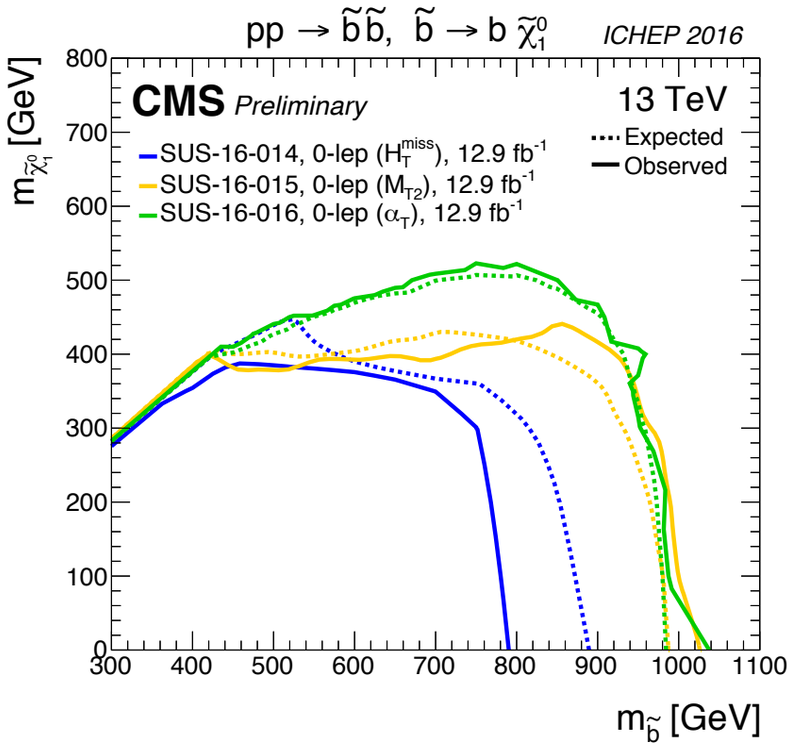
Direct detection experiments look for DM scattering

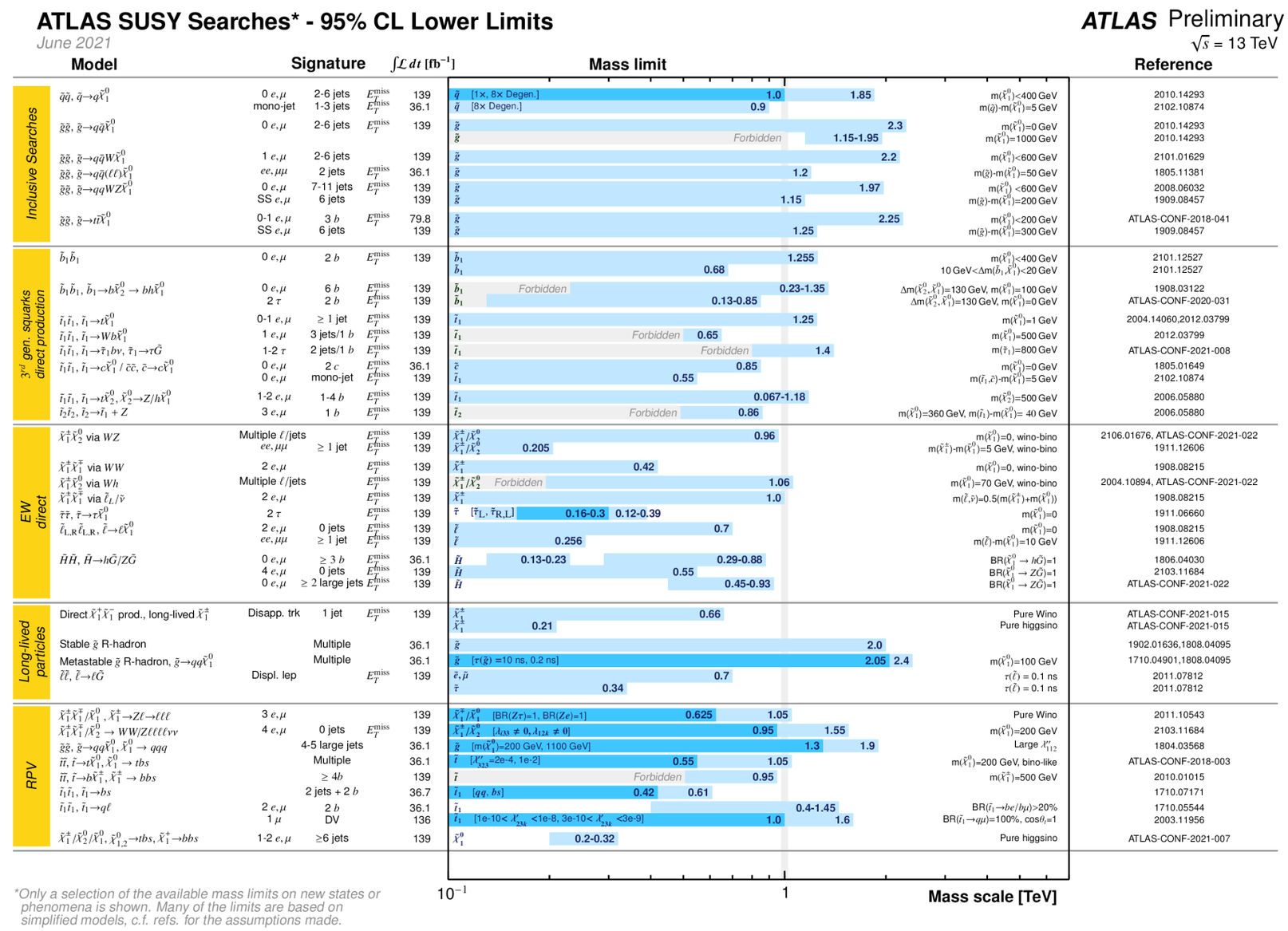


https://arxiv.org/abs/2207.03764

And no SUSY at the LHC







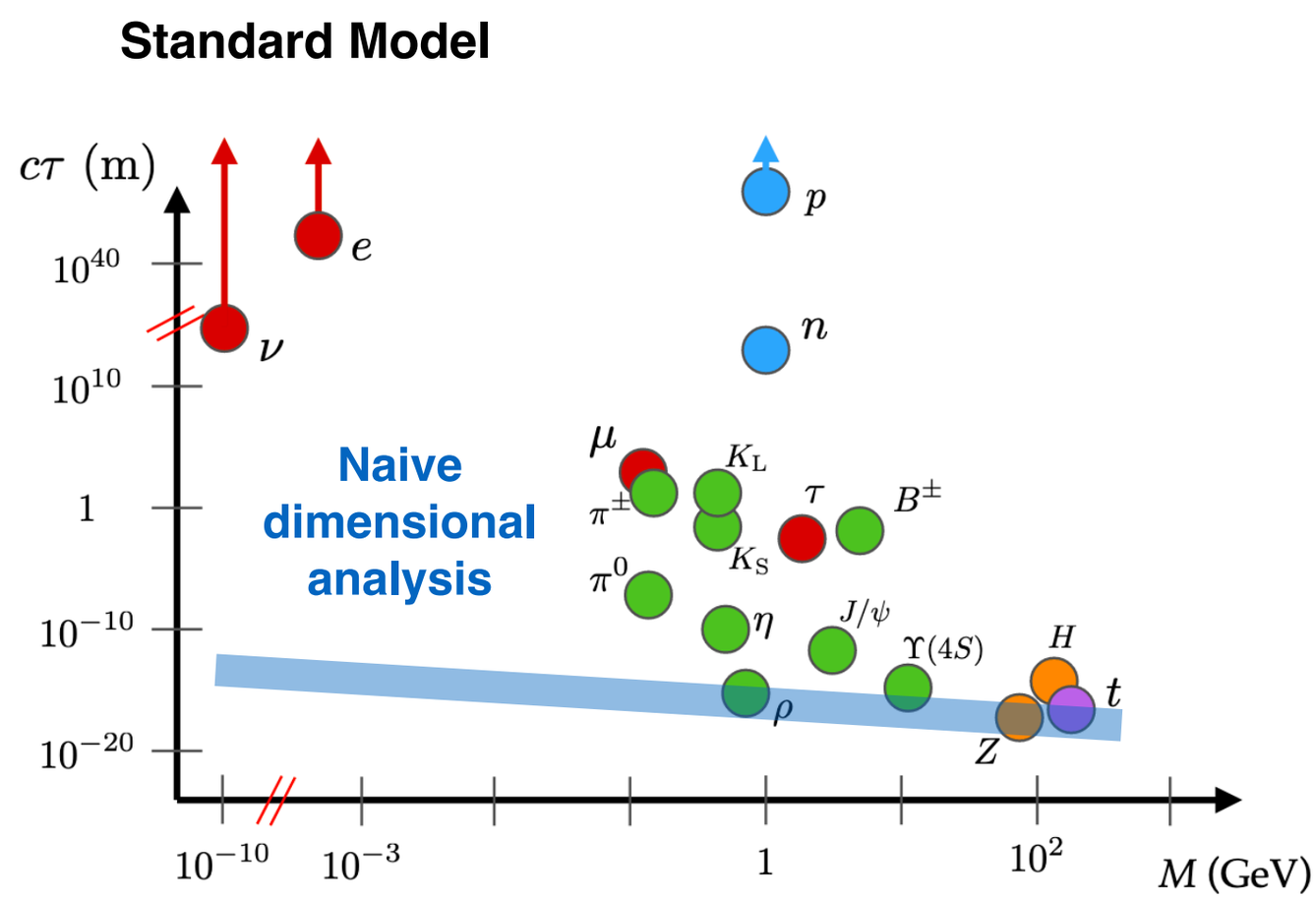
Long-lived particles in the Standard Model

e.g. π^- decay rate suppressed by **heavy W**

$$\Gamma \propto g^2 \left(\frac{m_{\pi^-}}{m_W} \right)^4 m_{\pi^-}$$

~0.1 GeV

~80 GeV



1903.04497

Why milli-charged?

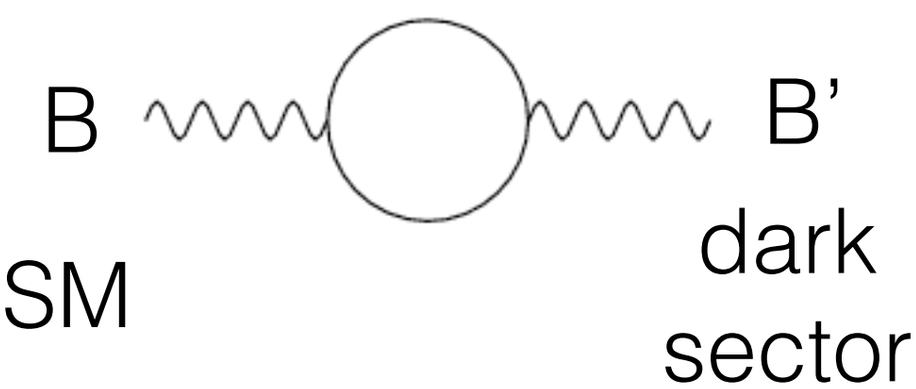
Consider a model with kinetic mixing with a new 'dark' boson **- link to the dark/hidden sector**

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu}$$

introduces mixing

massless U'(1) boson in the dark sector

'dark EM'



$\kappa \sim 10^{-3} - 10^{-2}$

(naturally $\sim \alpha/\pi$)

Why milli-charged?

Now add fermion charged under new U'(1):

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + i\overline{\psi}(\not{\partial} + ie'B' + iM_{mCP})\psi$$

Standard trick - redefine gauge field B': $B' \rightarrow B' - \kappa B$

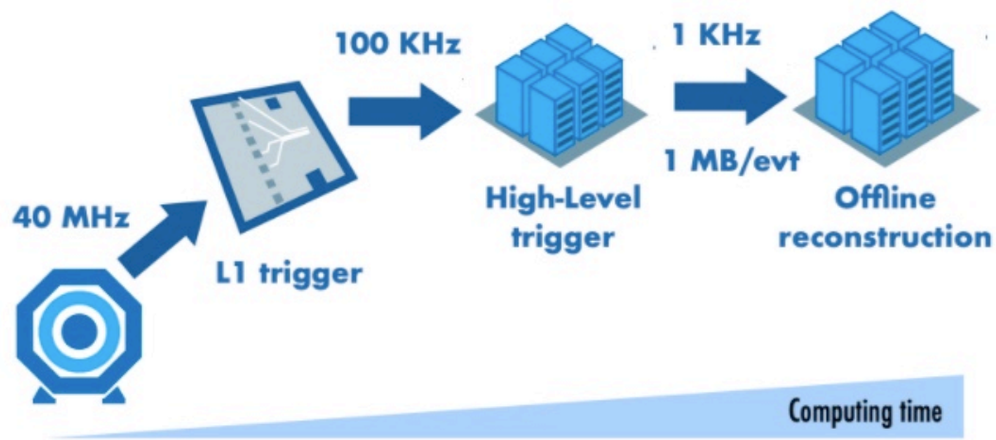
Removes mixing term and generates hypercharge for new fermion

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} + i\overline{\psi}(\partial + \underbrace{i\kappa e'B} + ie'B' + iM_{mCP})\psi$$

new fermion has small EM charge**: milli-charged particle**

Future searches at CMS/ATLAS

Rejected events are lost forever!



Review of opportunities for new long-lived particle triggers in Run 3 of the Large Hadron Collider

Produced for the LPCC Long-Lived Particles Working Group.

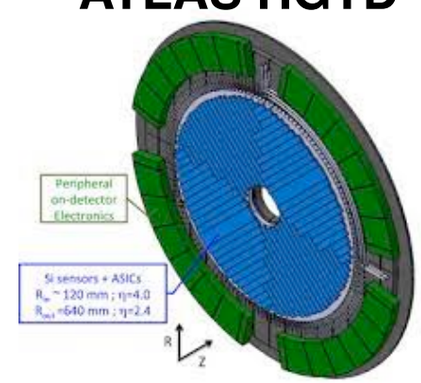
Editors:

Juliette Alimena,[5] James Beacham,[4] Freya Blekman,[3] Adrián Casais Vidal,[11] Xabier Cid Vidal,[11] Matthew Citron,[31] David Curtin,[36] Albert De Roeck,[5] Nishita Desai,[24] Karri Folan Di Petrillo,[8] Yuri Gershtein,[21] Louis Henry,[10,27,5] Tova Holmes,[35] Brij Jashal,[10] Philip James Ilten,[33] Sascha Mehlhase,[6] Javier Montejo Berlingen,[5] Arantza Oyanguren,[10] Giovanni Punzi,[28] Murilo Santana Rangel,[26] Federico Leo Redi,[9] Lorenzo Sestini,[13] Emma Torro,[10] Carlos Vázquez Sierra,[5] Maarten van Veghel,[37] Mike Williams,[17] José Zurita.[10]

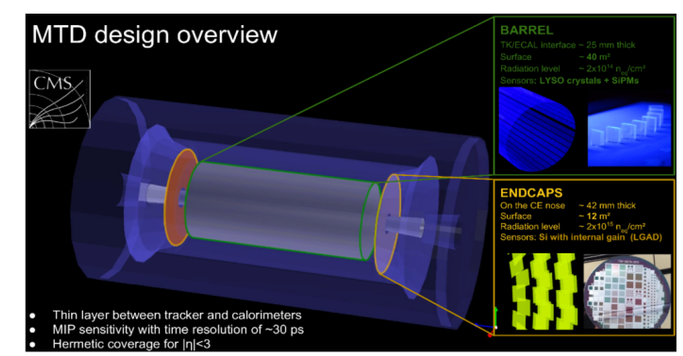
https://arxiv.org/abs/2110.14675

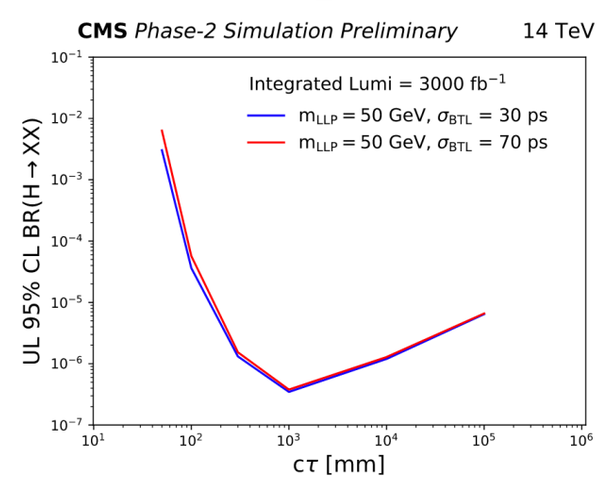
- **New trigger selections** significantly expand acceptance for Run 3 - **started July 2022**
  - e.g. CMS using calorimetry timing, “clusters” in the muon clusters to open new phase space
- **HL-LHC**: exciting **upgrades** and **new detectors** planned!
  - e.g. Timing detectors, high granularity calorimetry, …

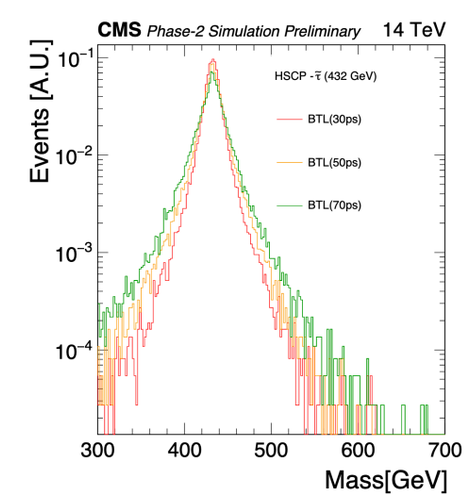
ATLAS HGTD



CMS MTD

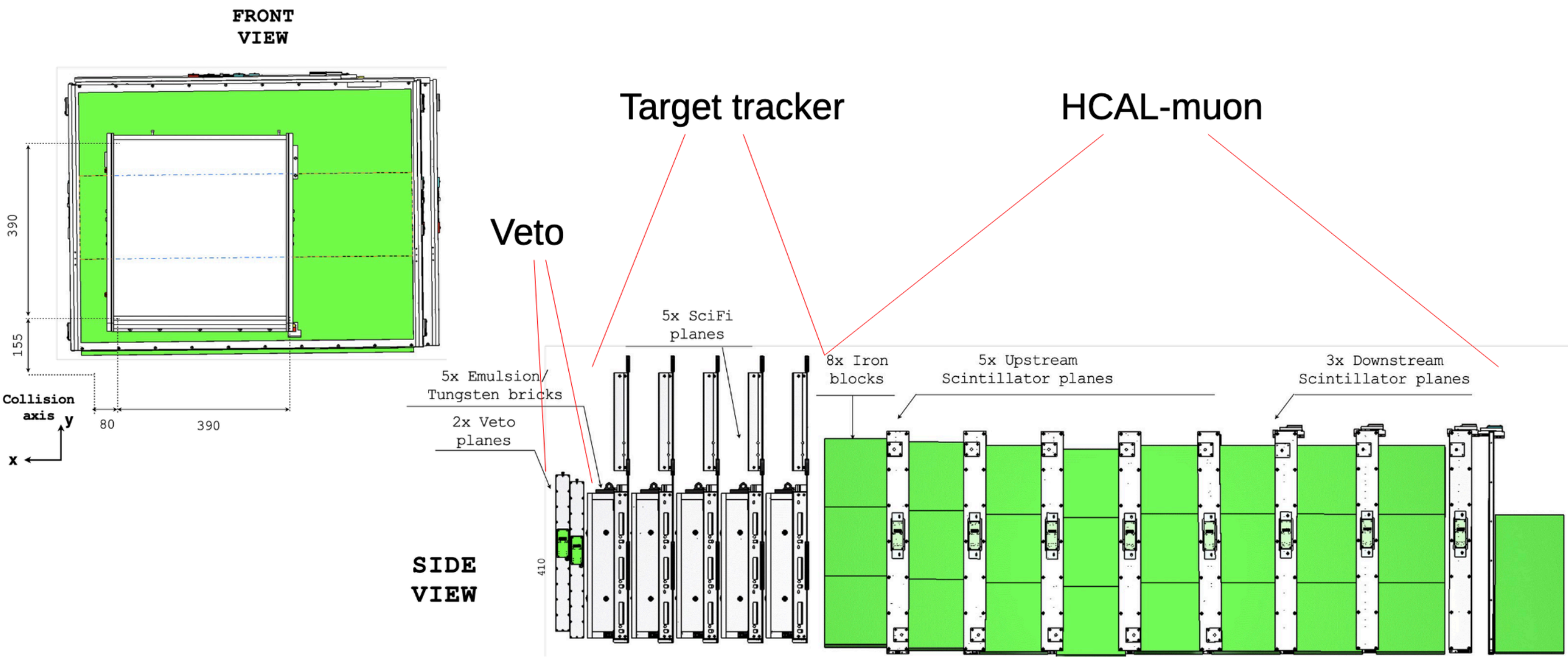






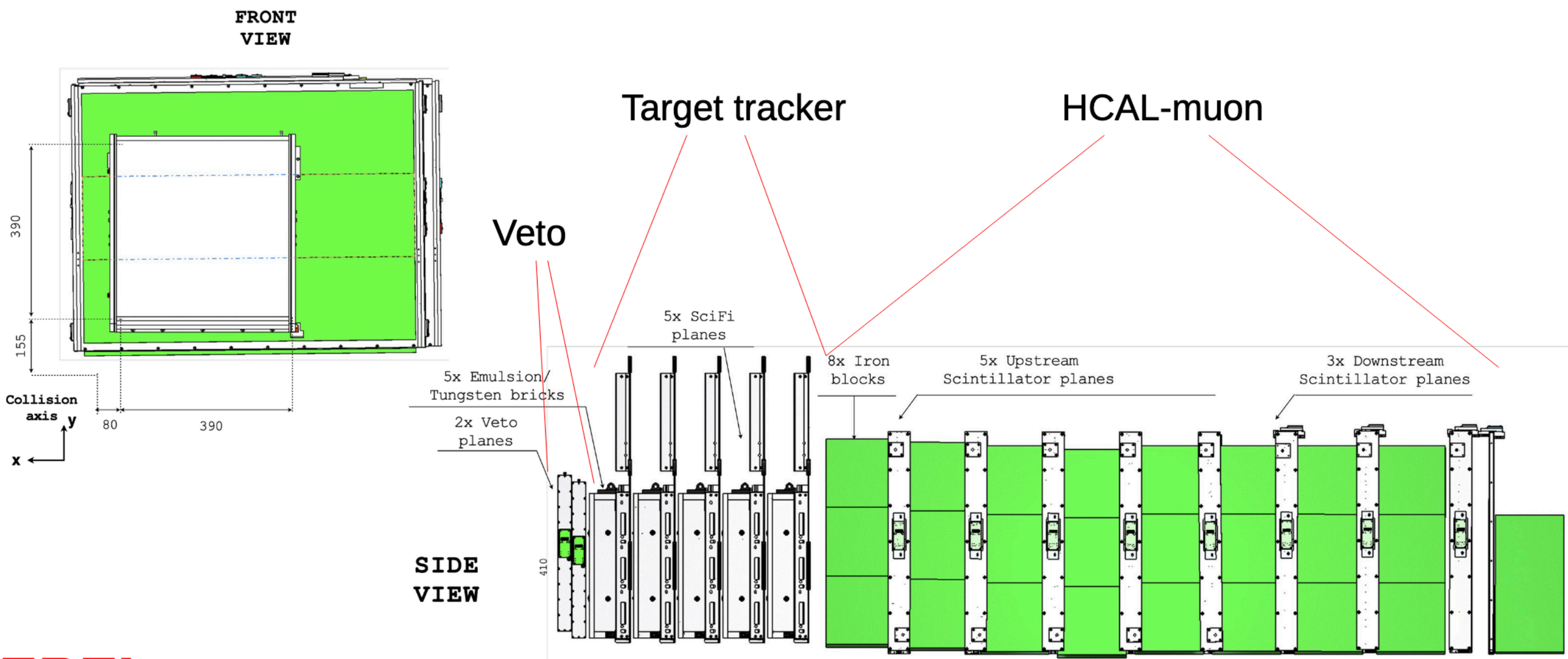
DP2022_025

SND in detail



Emulsion/tungsten bricks each comprised of 60 interleaved film + 59 tungsten layers

SND status



now with beam muon and neutrino candidate interactions

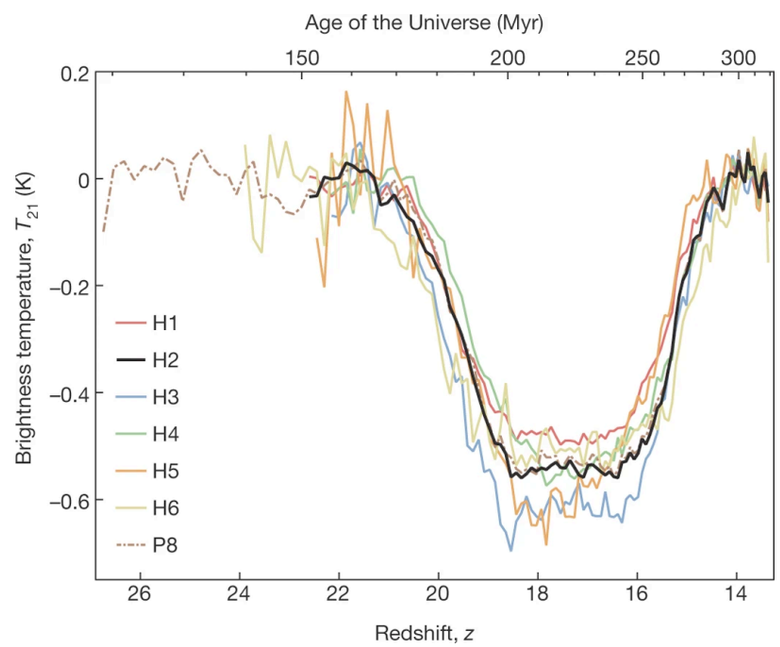
- Analysing data from 1/20 scale emulsion detector extracted July 2022

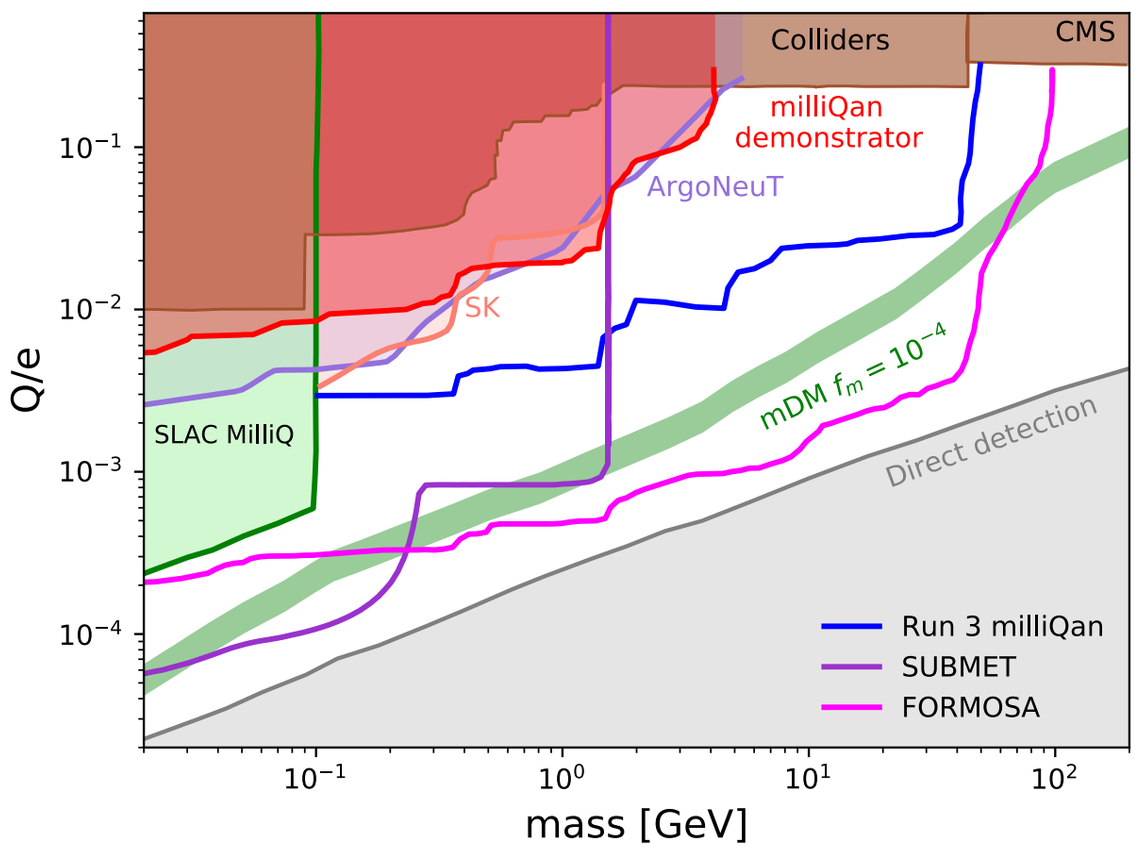
E. Zaffaroni

EDGES and millicharged dark matter

EDGES 21cm absorption spectrum

Bowman et al

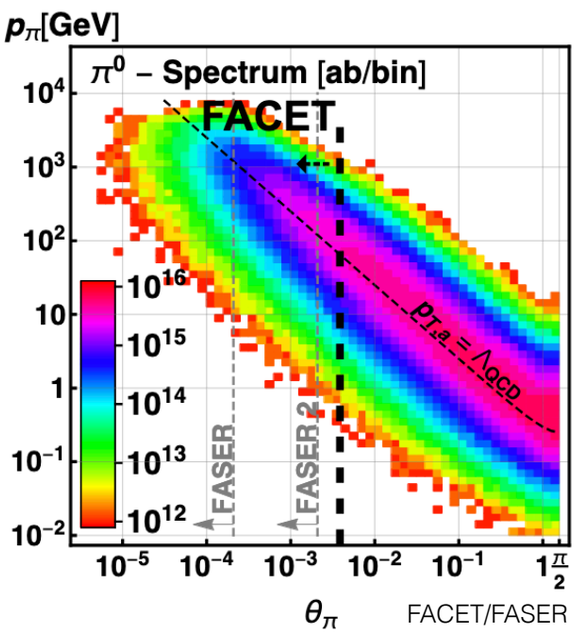




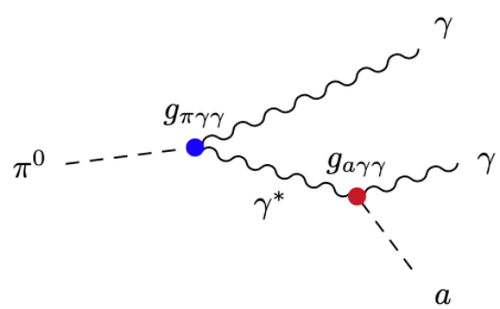
Motivated by EDGES

- EDGES observes anomalous **deepening in absorption spectrum** → anomalous cooling of baryons in the early universe
- Could be explained by **fraction of DM being millicharged** (1908.06986)
- Dedicated millicharged detectors can **close the gap to direct DM detection!**
- Exciting **cosmological** probe in **accelerator setting!**

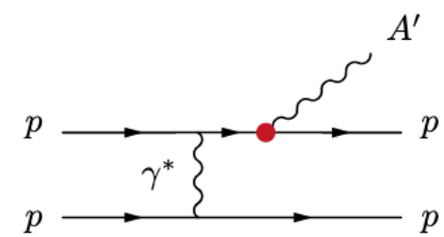
Low mass decaying LLPs

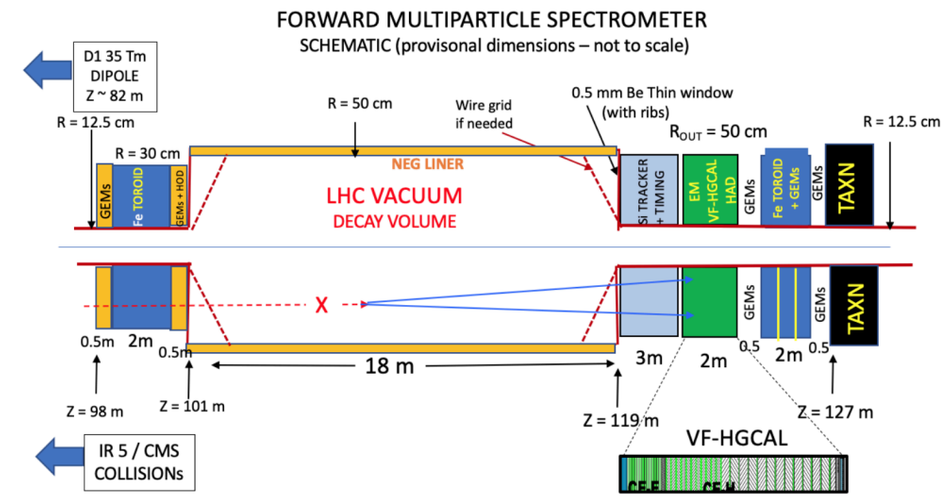


e.g. ALP from pion decay



e.g. dark bremsstrahlung





FACET: ~100m in front of CMS

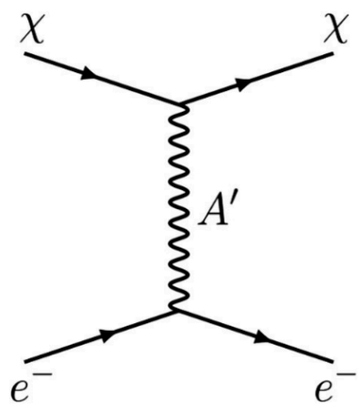
- The lower the mass of the LLP (typically) the higher the **forward** production
- Far forward detectors target m_{LLP} < ~GeV to provide sensitivity to e.g. ALPs, dark photons, dark higgs, …
- Forward physics facility (FPF) designed to **comprehensively cover** forward BSM/SM signatures

FASER: installed ~400m from ATLAS IP

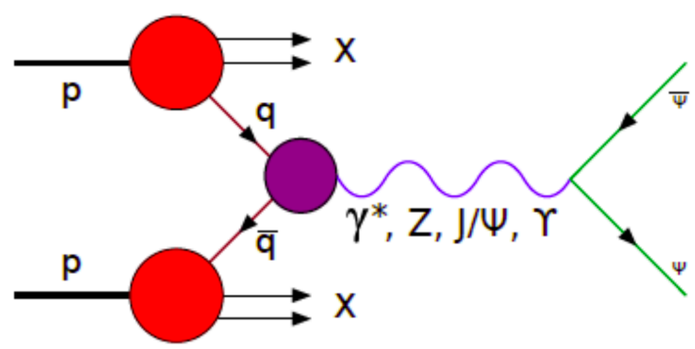
Disclaimer: not comprehensive summary of physics reach!

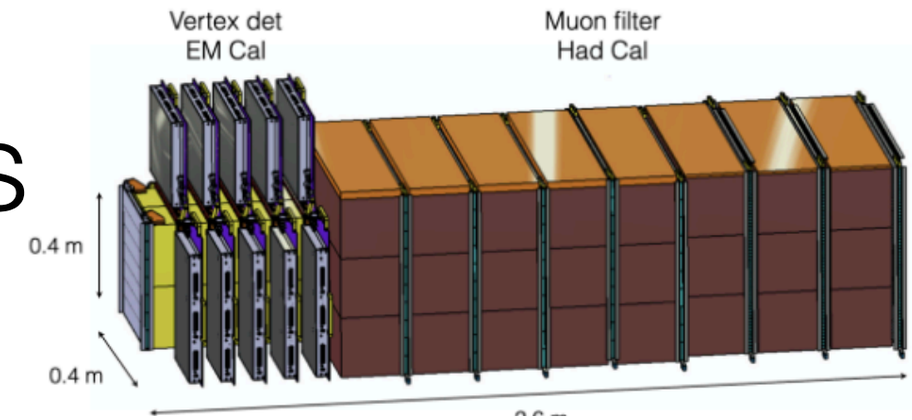
Direct detection: stable FIPs

e.g. DM scattering

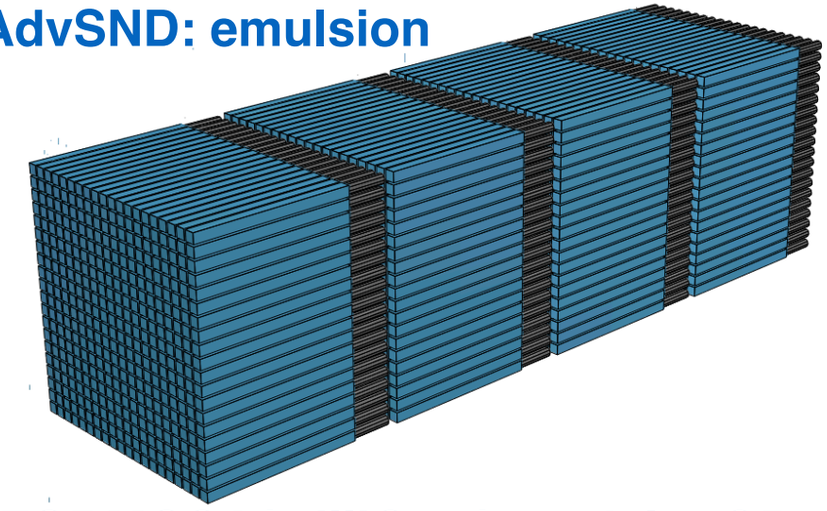


e.g. millicharged particles

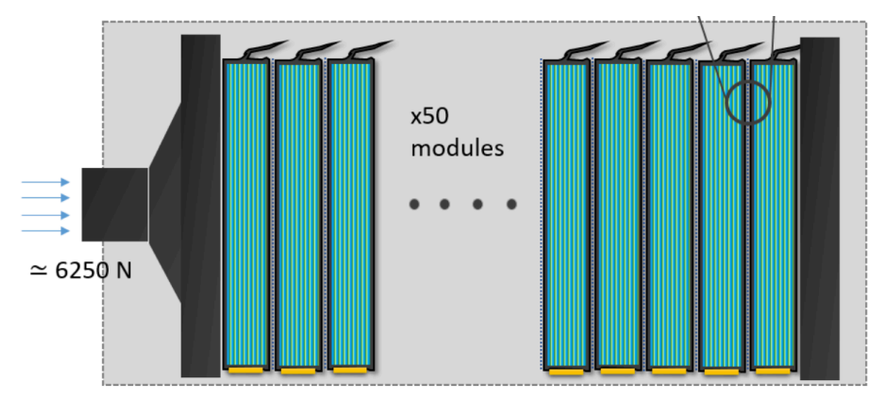




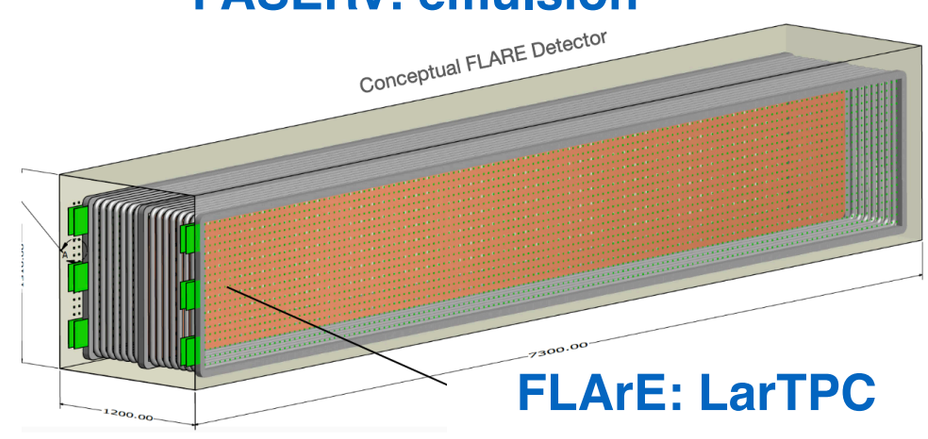
SND/AdvSND: emulsion



FORMOSA/milliQan/moedal-mQP: scintillator



FASERv: emulsion



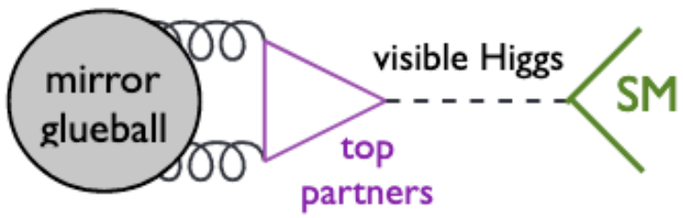
FLArE: LarTPC

- Interactions of many LLPs **too weak** to observe with general purpose detectors: e.g. light DM, millicharged particles, …
- Require dedicated detectors with **large volume** of active material
- Range of detector designs provides comprehensive coverage (including several at FPF)

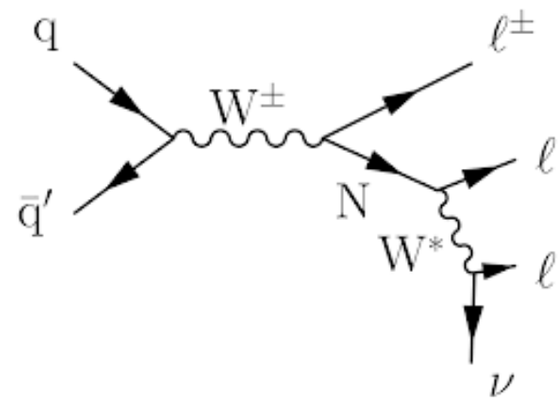
Disclaimer: not comprehensive summary of physics reach!

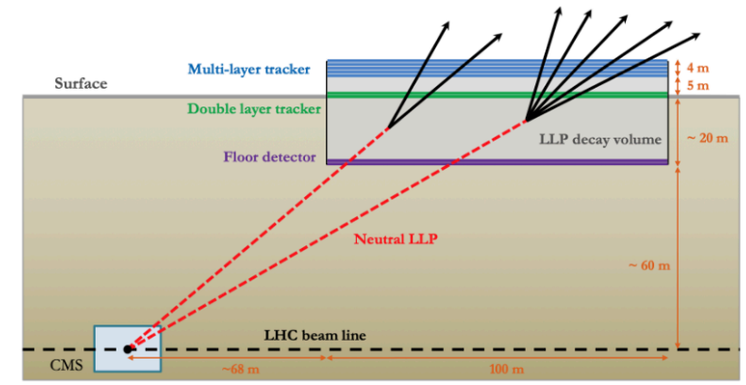
Heavy(ish) decaying LLPs

e.g. Twin Higgs

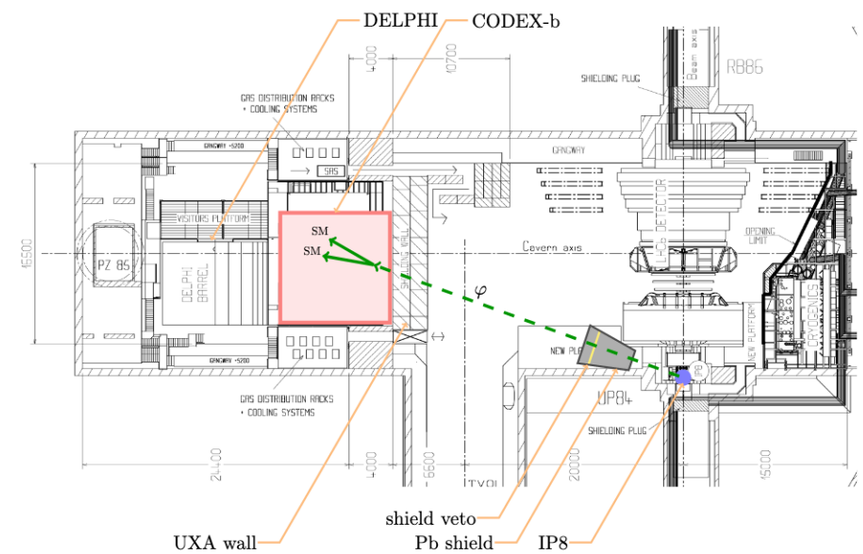


e.g. HNL



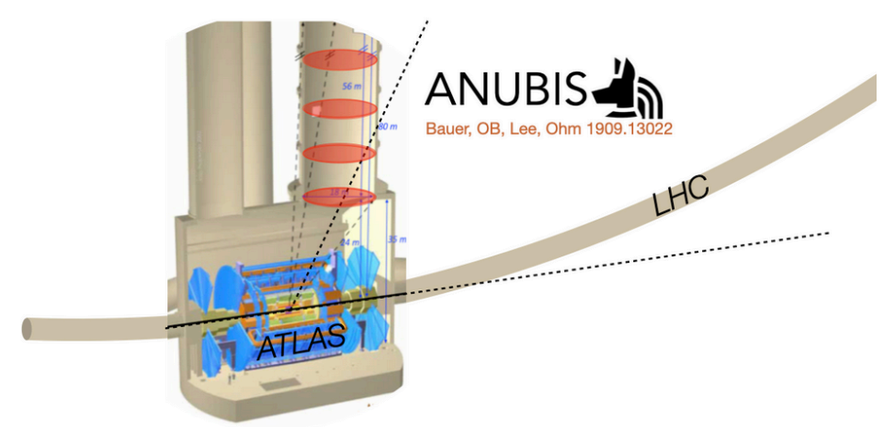


MATHUSLA: ~ IKEA at CMS IP surface



CODEX-b: detector + Pb shield at LHCb IP

- **Centrally produced** LLPs arise in wide range of well motivated models: Twin Higgs, HNL, …
- Wide mass range: from ~ GeV to ~TeV
- Range of detectors proposed: optimal lifetime coverage ~ distance from detector to IP

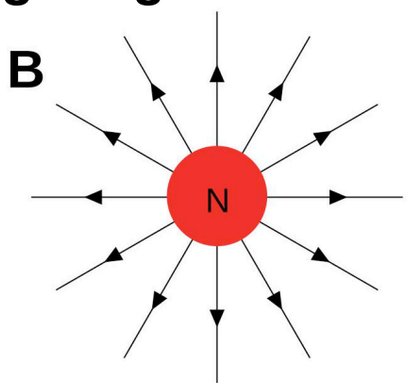


ANUBIS: instrument ATLAS shaft

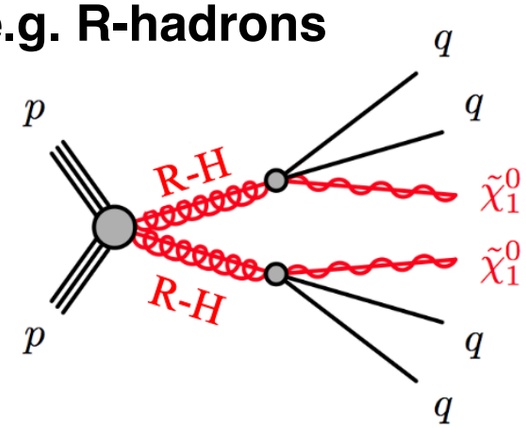
Disclaimer: not comprehensive summary of physics reach!

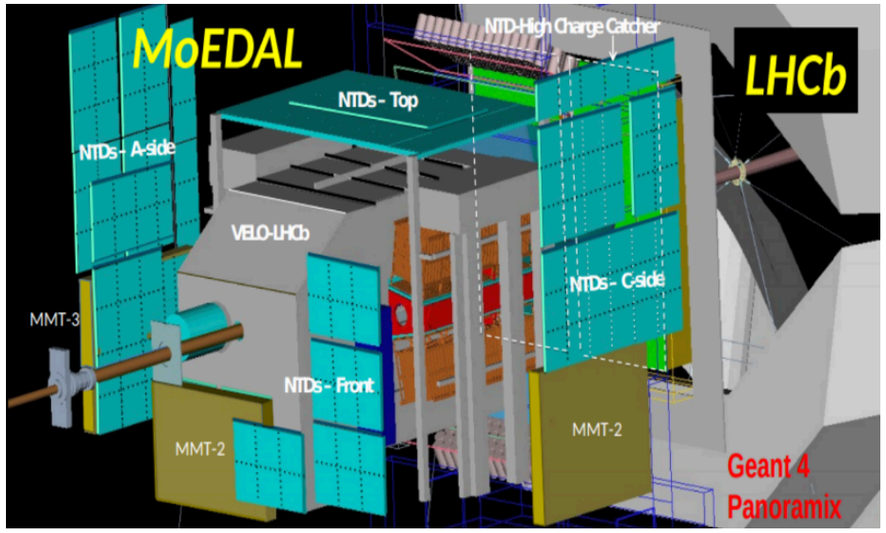
Direct detection: highly interacting LLPs

e.g. magnetic monopoles



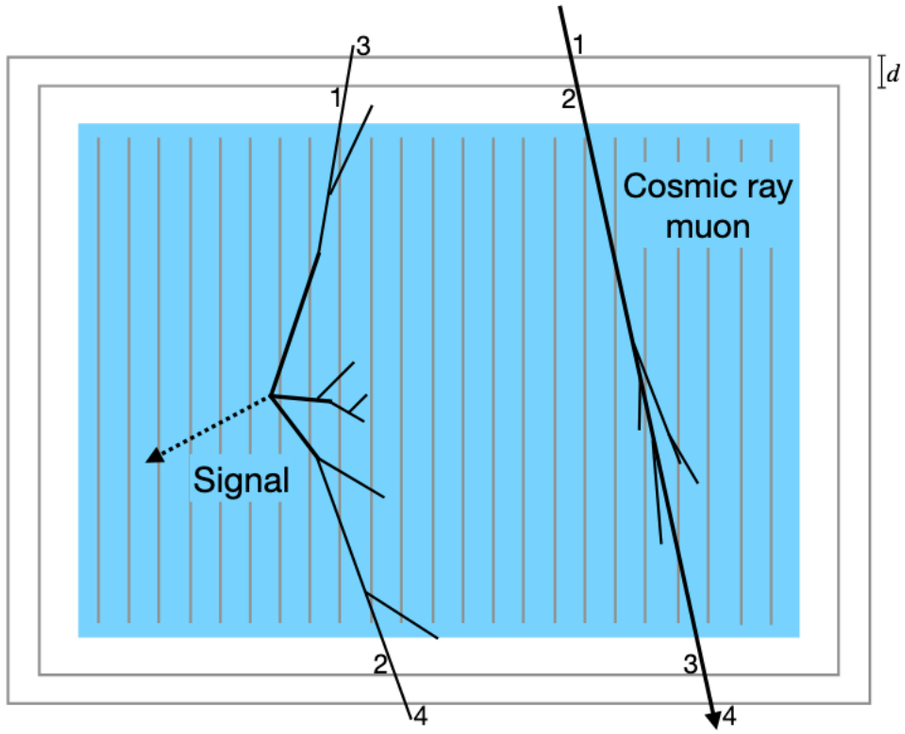
e.g. R-hadrons





MoEDAL/MoEDAL-MALL: search for magnetic monopoles, dyons and charged particles

- Highly interacting LLPs can produce highly ionising tracks and/or get trapped in detector material: e.g. magnetic monopoles, dyons, R-hadrons, …
- Scan detector material for evidence of LLPs or place material in detector and wait for decays



Trapped particle detector: embed within CMS

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