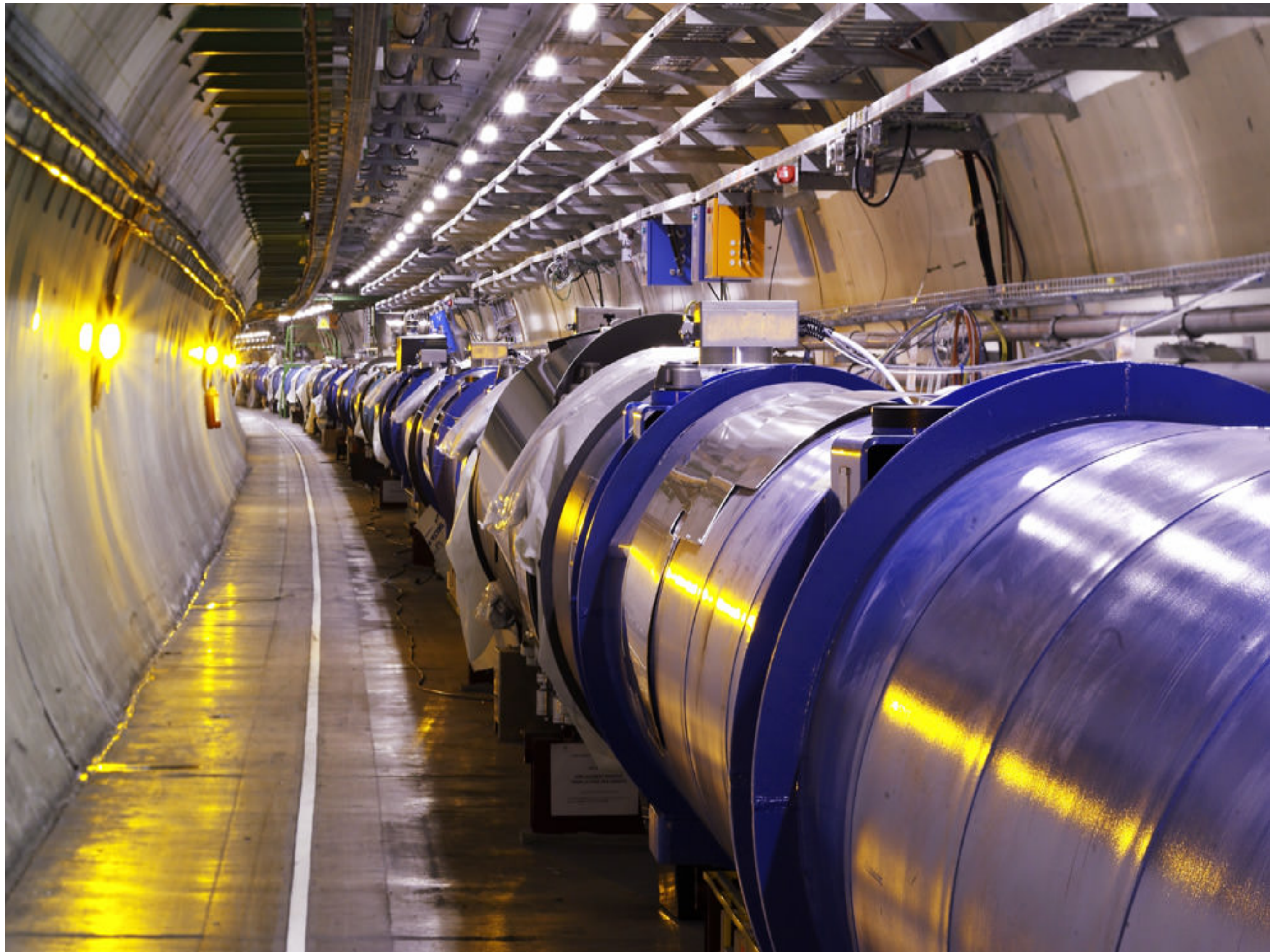
New Far Detectors at the LHC

Jamie Boyd (CERN)

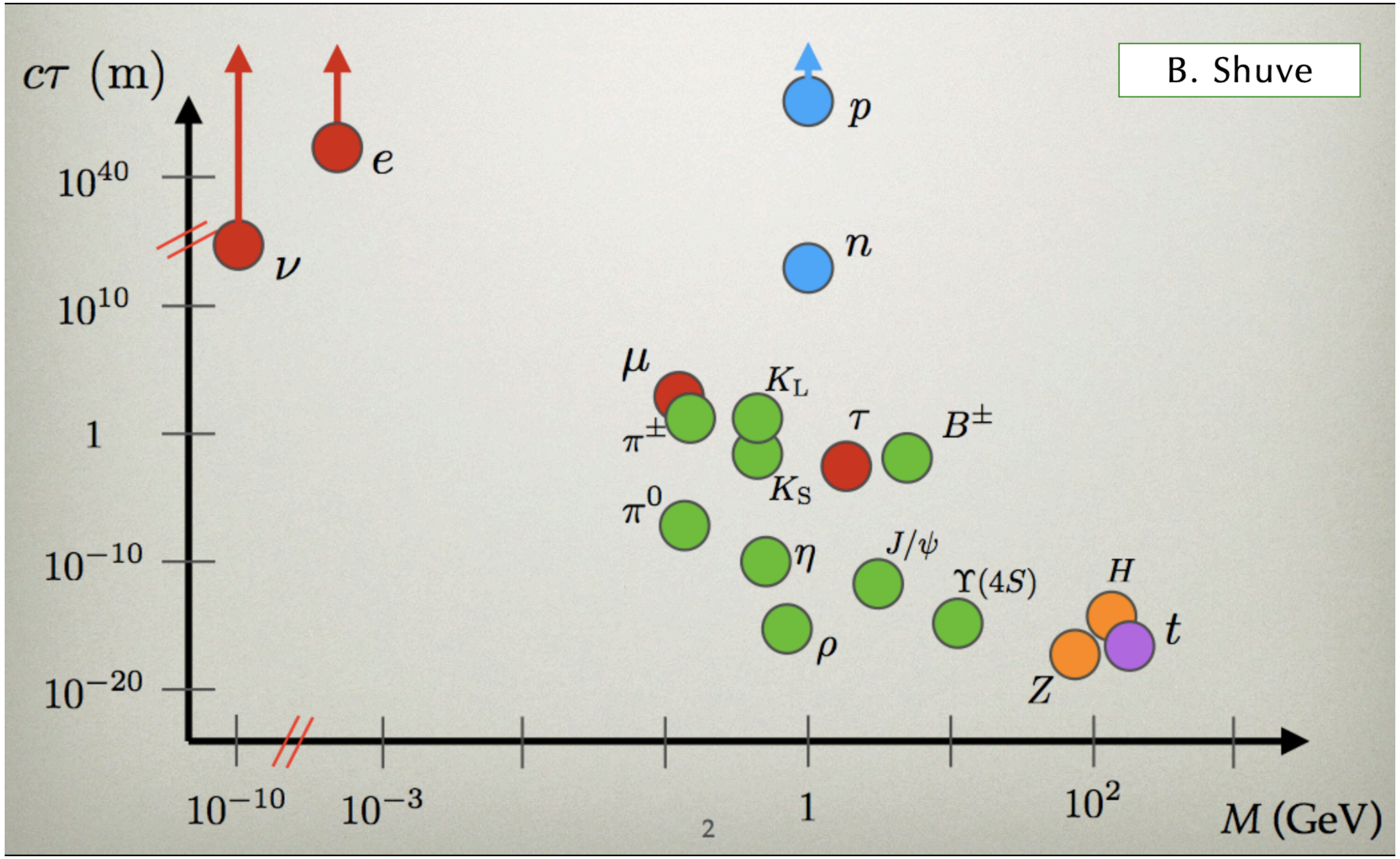
May 4th 2021



Introduction

- Despite excellent performance of the machine and detectors, the LHC experiments have not found any hints of new physics
- BSM long lived particles (LLPs) are theoretically well motivated and less well studied, and maybe one of the best remaining options for a new physics discovery at the LHC
- Current LHC experiments are putting increasing emphasis on such searches but in addition a number of new dedicated LLP search experiments at the LHC have been proposed to increase the coverage for theoretically motivated scenarios
  - New experiments can be considered good value as they maximize the scientific output from the (expensive to build / operate) LHC
  - Most of these are searching for neutral LLP decaying into charged SM particles
- Proposals cover a wide range of detector sizes/costs and hence there is a broad spectrum in “where the proposals are” in terms of approval, funding and readiness

Why search for new LLP at the LHC?



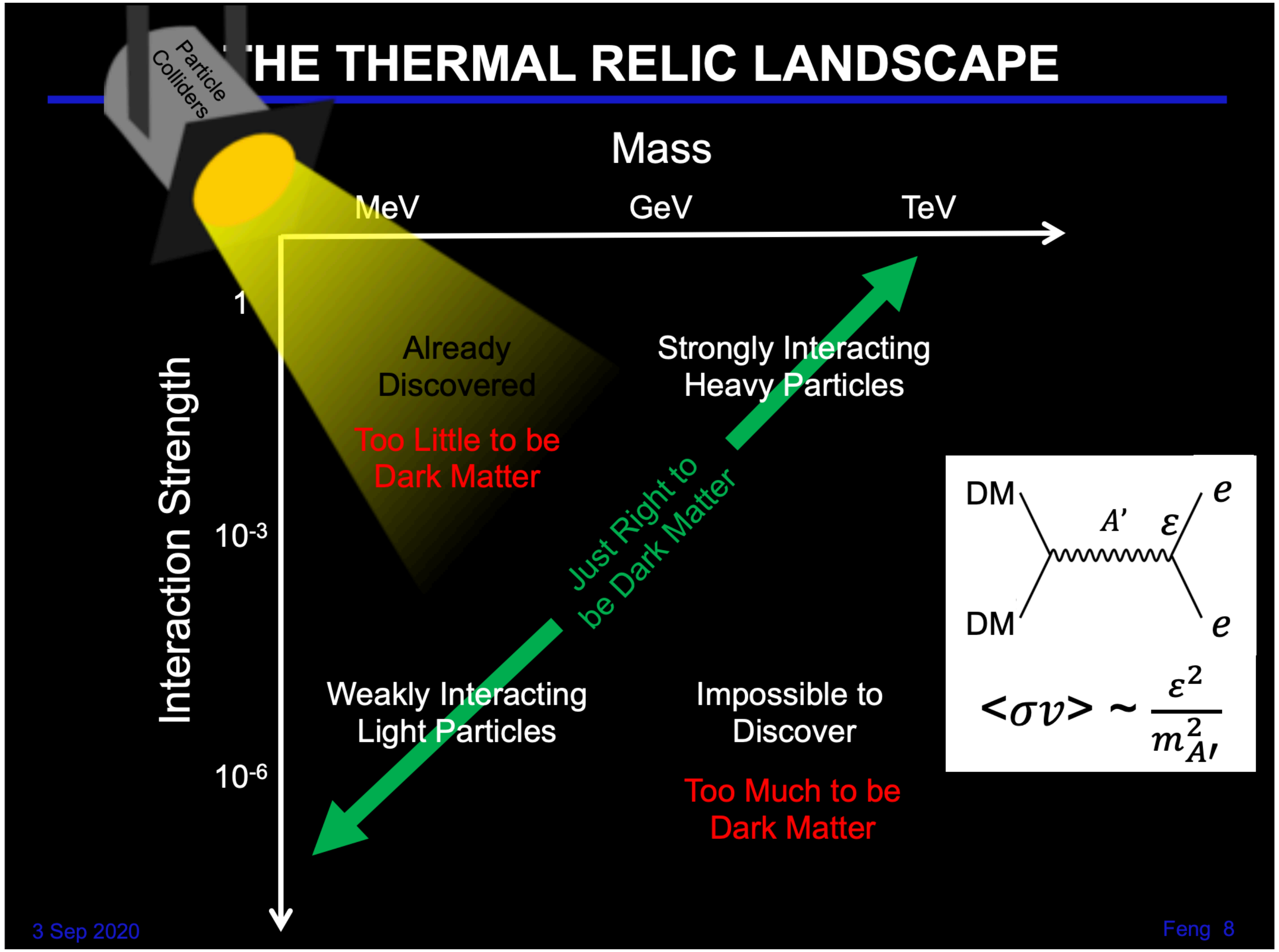
SM particles span a large range of lifetimes – why not BSM particles too?

In SM, particles lifetime usually stems from an approximate symmetry which would make the particle stable. In this case a small symmetry breaking parameter suppresses the decay rate -> long lifetime.

Brief motivation for BSM LLPs

- LLPs can naturally occur in many BSM theories
  - Weak couplings (gravity, RPV couplings)
  - Phase space suppressed decays
  - Heavy intermediate mediator particles (e.g. split-SUSY)
- Dark Sectors with light mediators naturally have weak couplings
  - Mixing with SM through loop induced processes
  - To give correct dark matter relic density

Slide fom J.L.Feng



Brief motivation for BSM LLPs at the LHC

Slide fom A. Hoecker

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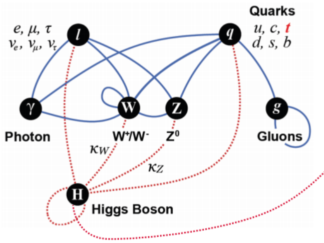
The Higgs boson as a *portal* to beyond the SM physics

Higgs is narrow: 4.1 MeV

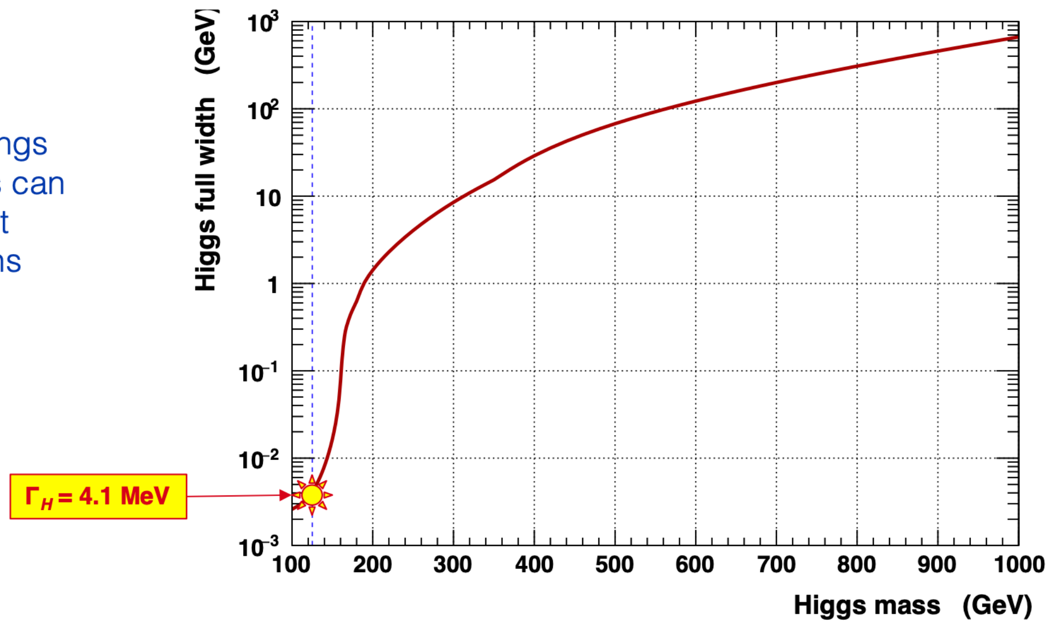
For comparison:

Γ_W = 2.1 GeV
Γ_Z = 2.5 GeV
Γ_{top} = 1.3 GeV

Even small couplings to new light states can measurably distort branching fractions



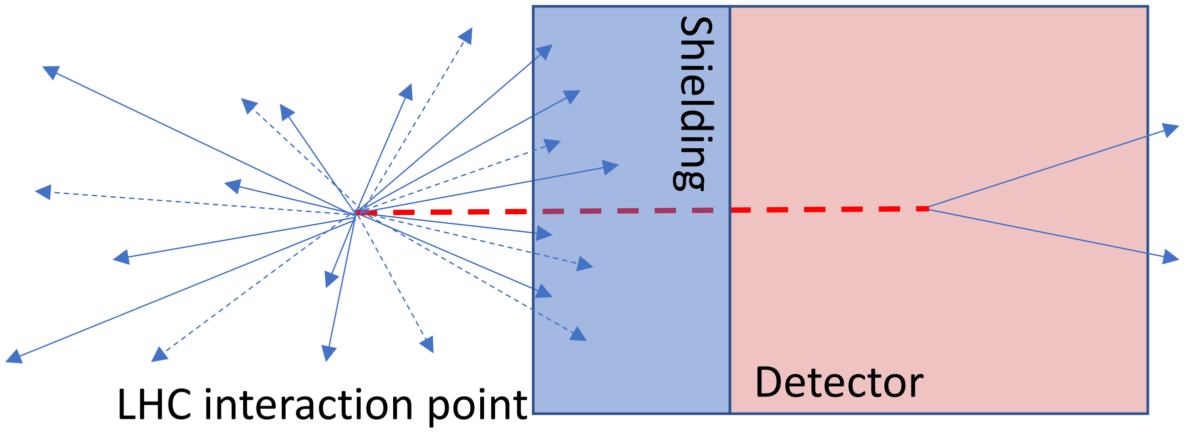
Invisible dark matter?



Given the very narrow width of the Higgs Boson.
Room for relatively large branching fractions of:
Higgs -> LLP BSM particles (can only be probed at LHC).
Current limits on H->inv from ATLAS/CMS at ~10% level.

Main Experiment Design goals

- Background free:
  - Need shielding/distance from high rate of SM particles produced in LHC collisions
  - Often “light-shining-through-wall” type of experiment
- Probe interesting/complementary lifetimes:
  - Often far from IP (~10s – 100s of metres)
- Good acceptance:
  - Cover substantial part of solid angle, or placed where signal flux is maximized
- Not too expensive:
  - Take advantage of existing infrastructure where possible
    - Tunnels, caverns, galleries, surface space etc…
    - Non-dedicated space does lead to its own complications!



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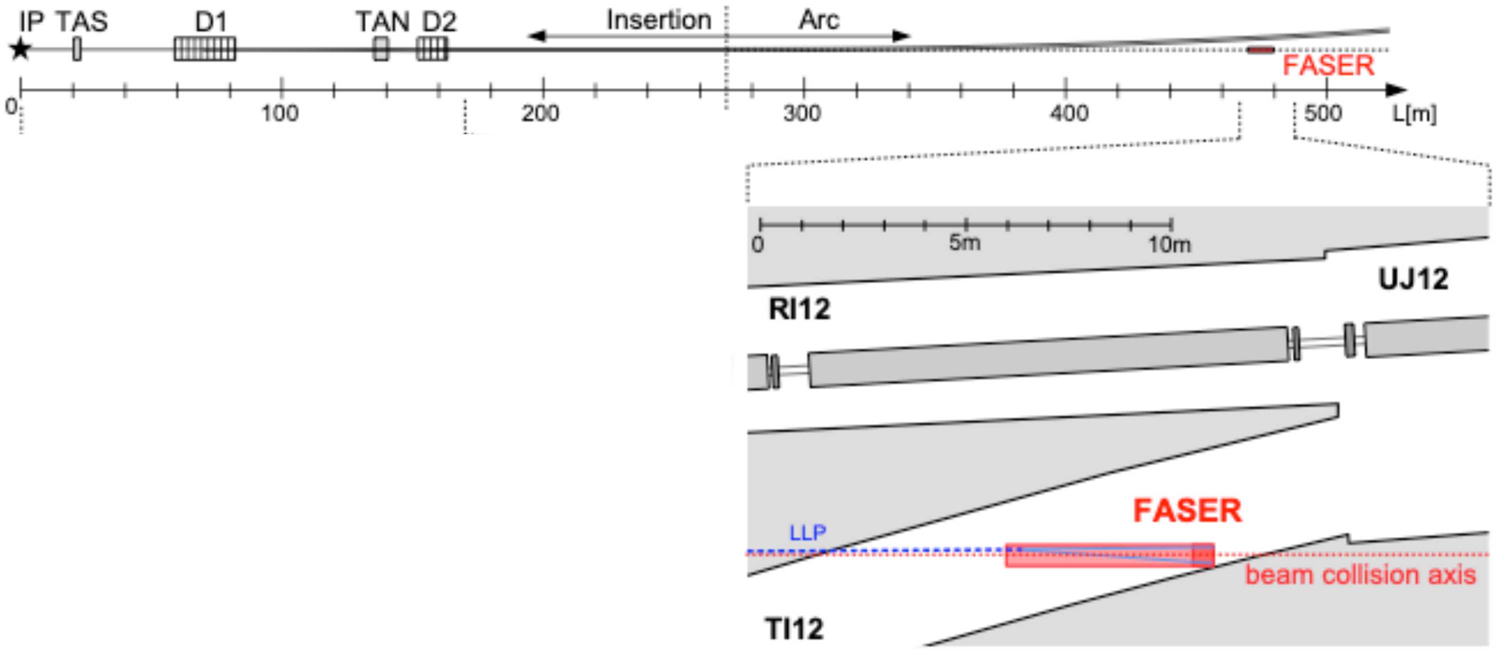
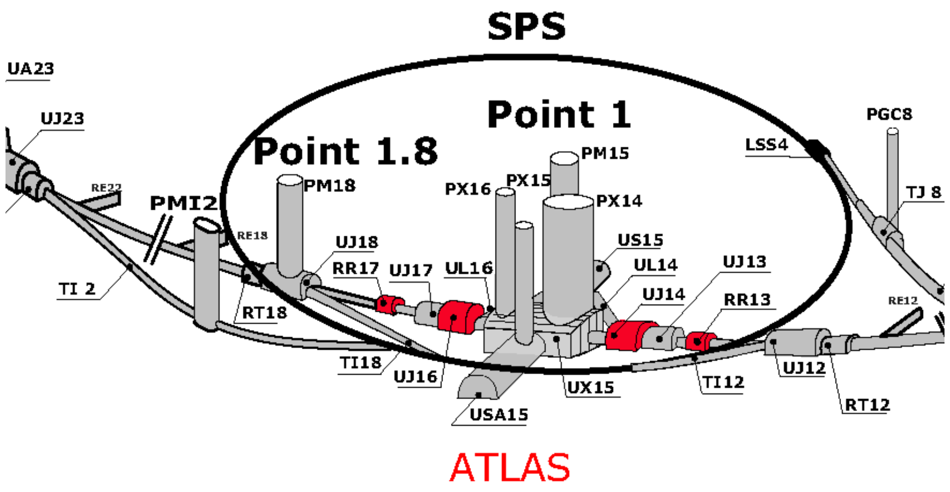
- CERN Physics Beyond Colliders study group has been very useful in helping to study proposed detectors
  - Including dedicated resources to look at possible civil engineering, installation of services, detector integration and safety aspects
- Final sensitivity a complex function of detector location, production process, background reduction capability, acceptance etc…

https://arxiv.org/abs/1812.09139

FASER

- FASER is a small experiment (5m x R=0.1m) to search for long lived, light particles produced in meson decay in the very forward region of LHC collisions ($|\eta|>9.1$)
- It sits in an unused tunnel TI12, ~500m from the ATLAS collision point, and directly aligned with the beam collision axis
- A small trench (~50cm deep) needed to be dug in TI12 to allow detector to be centred on the collision axis
- Particle rates and radiation measured in TI12 in 2018. General low, and OK for FASER physics and detector
    - Detector shielded by 100m of rock and charged particles from IP swept away by LHC magnets)





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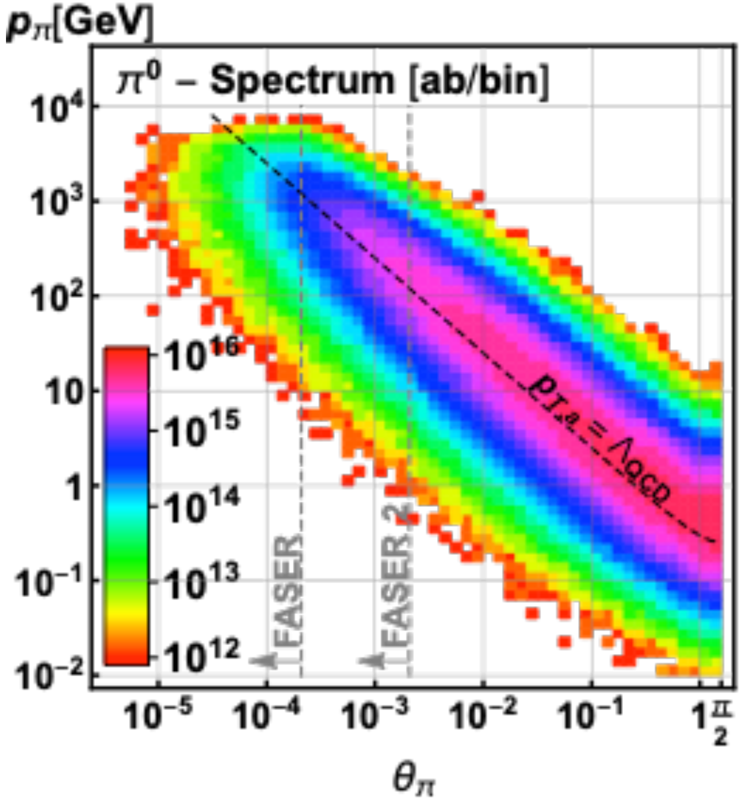
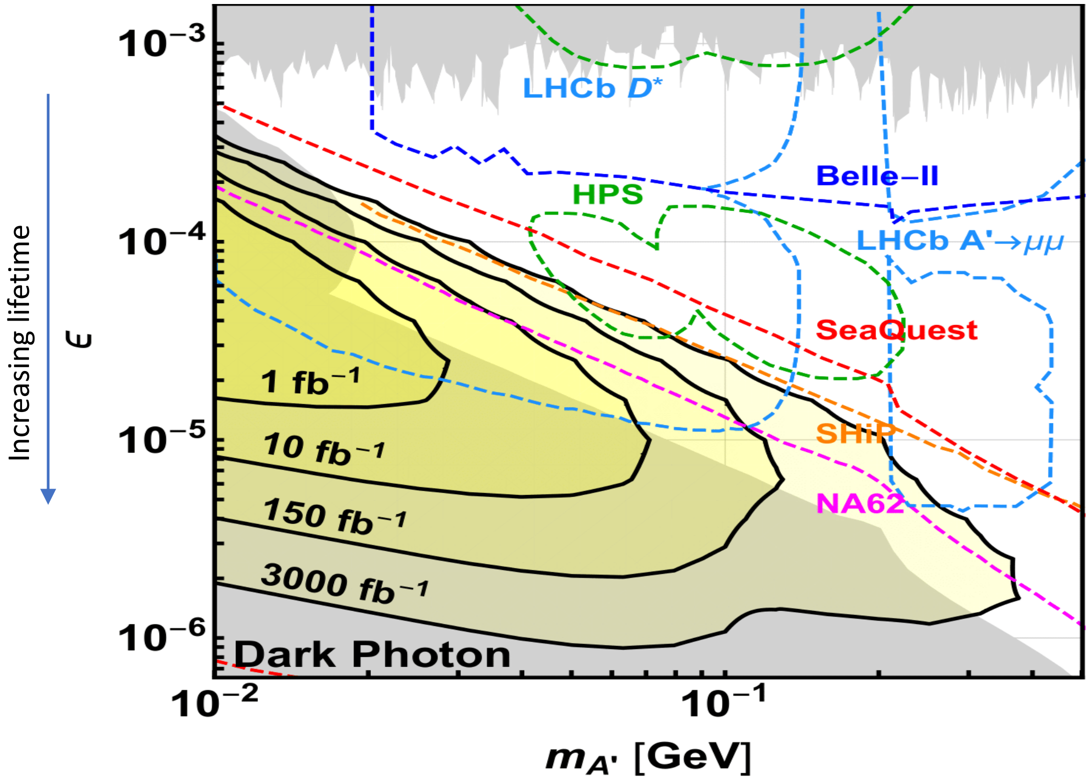
FASER

- FASER Covers only $(2\text{x}10^{-6})$% of the solid angle, but 2% of π^0's (with E>10GeV) are produced in the FASER angular acceptance
  - ~10^{15} π^0s in FASER angular acceptance during LHC Run-3 (150/fb)
- For dark sector particles produced very rarely in π^0 decays (e.g. BF ~ $O(10^{-10})$) FASER can still detect a significant number of signal events
- SM particles produced in FASER angular region have O(TeV) boost, means detector 500m from IP still sensitive to interesting lifetimes/couplings





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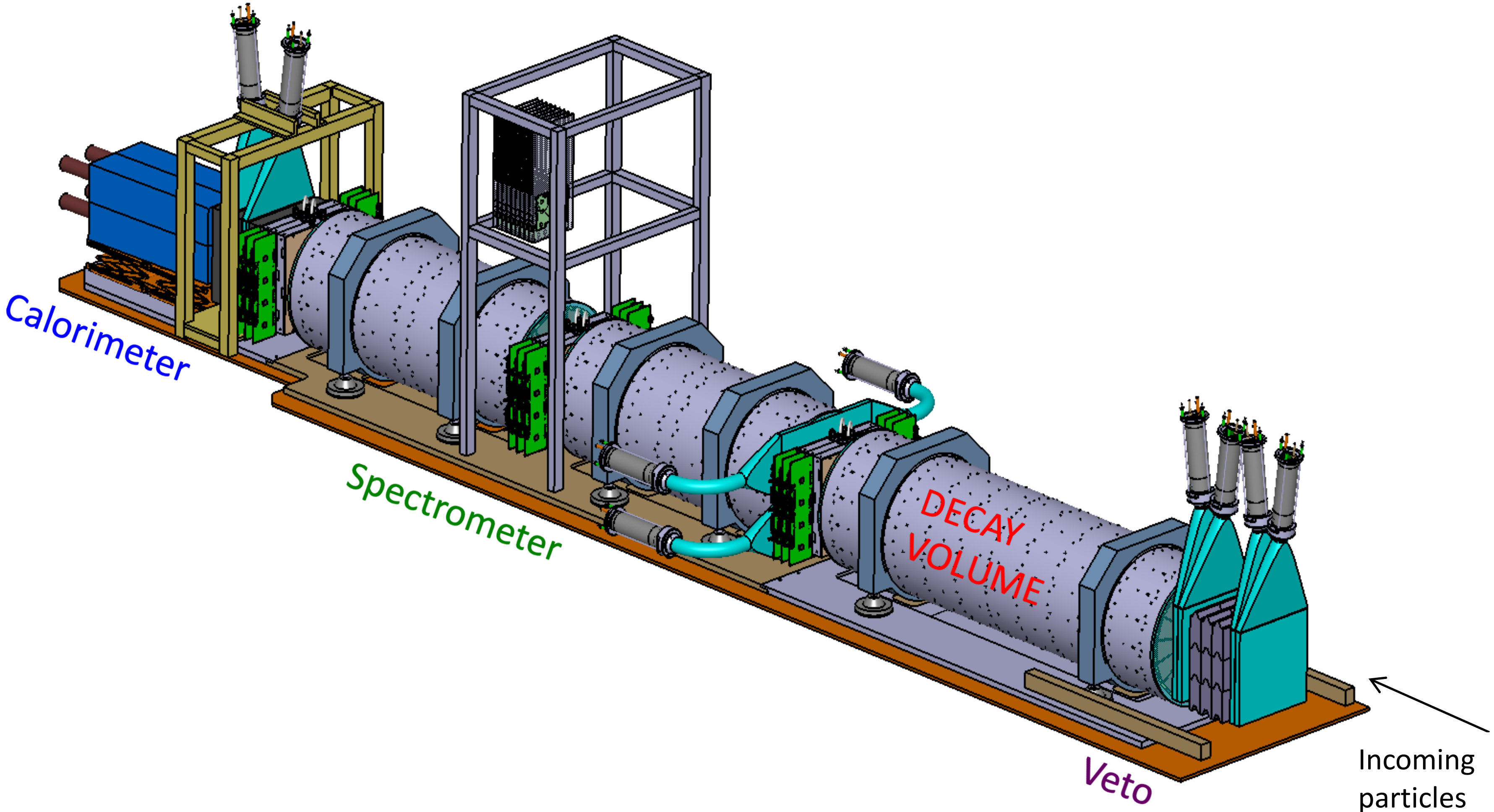
FASER Detector

The detector consists of:

- Scintillator veto
- 1.5m long decay volume
- 2m long spectrometer
- EM calorimeter



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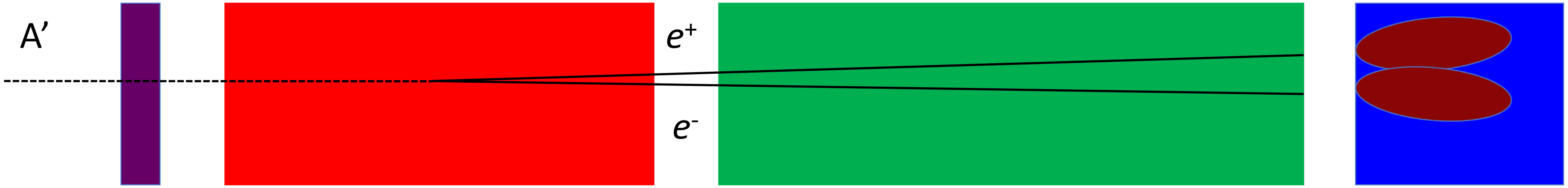
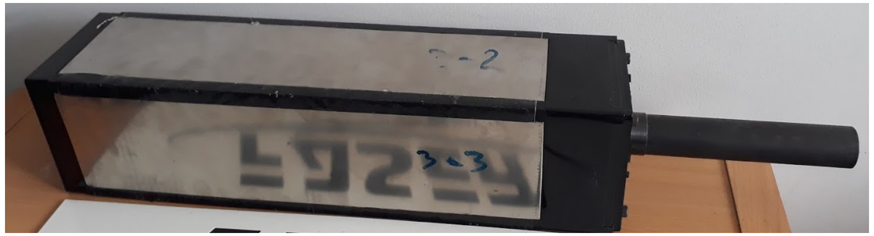
Signal signature



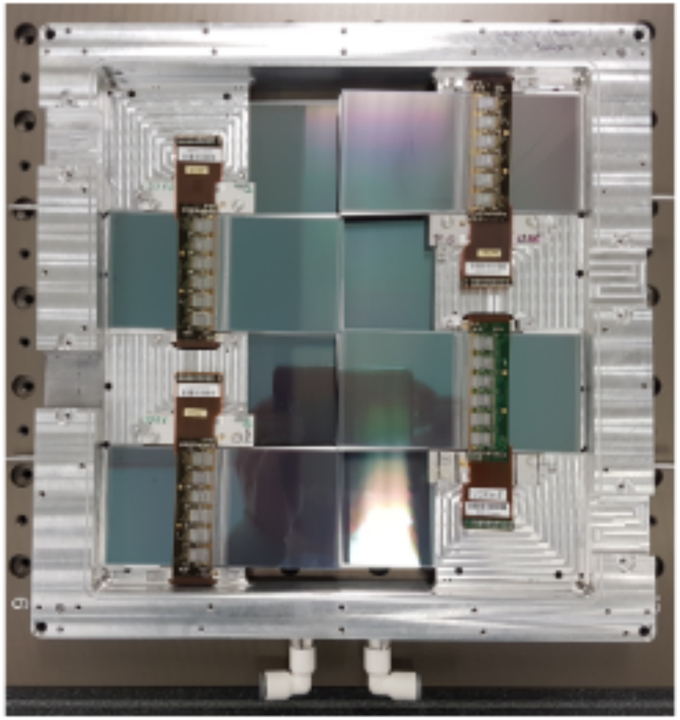
1. No signal in the veto scintillator;
2. Two high energy oppositely charged tracks, consistent with originating from a common vertex in the decay volume, and with a combined momentum pointing back to the IP;
3. For A'->e^+e^- decay: Large EM energy in calorimeter. EM showers too close to be resolved.

Magnets needed to separate the A' decay products sufficiently to be able to be resolved in tracker

FASER calorimeter module: 4 in final detector.



FASER tracking layer containing 8 ATLAS SCT modules. 9 layers in final detector.



FASER permenant dipole magnets. Constructed at CERN.

Detector installed in the tunnel in March 2021

Small detector size allows FASER to re-use spare detector components from other experiments:

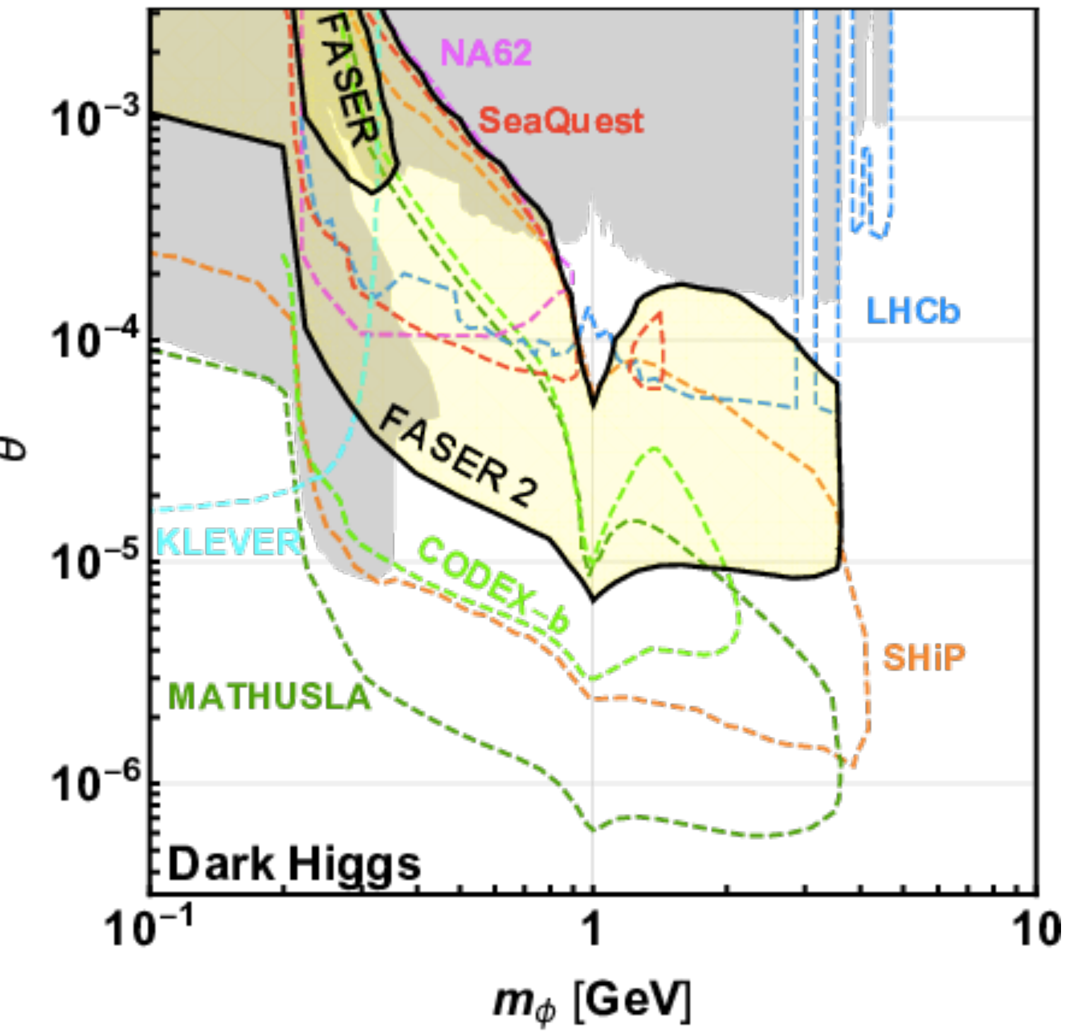
- Silicon strip tracker (SCT) modules from ATLAS
- ECAL modules from LHCb

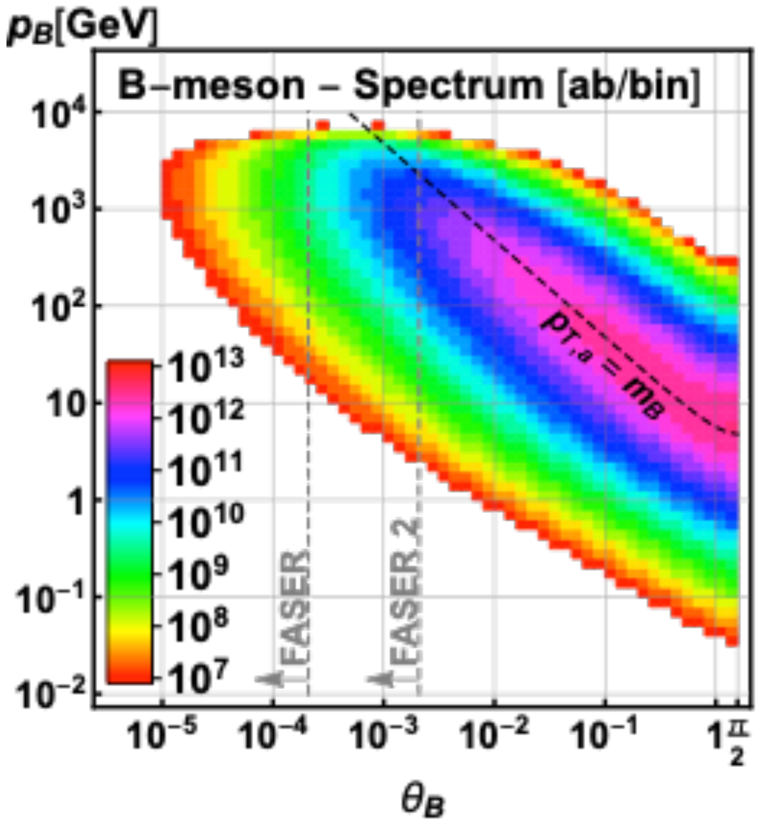
FASER went from a ‘theorists idea’ paper (summer 2017) to an installed experiment (early 2021) in ~3.5yrs

Demonstrating these experiments can be implemented quickly!

A possible FASER upgrade: FASER-2

- A potential upgraded detector for HL-LHC running, would increase sensitivity further
- Increasing detector radius to 1m would allow sensitivity to new physics produced in heavy meson (B, D) decays increasing the physics case beyond just the increased luminosity

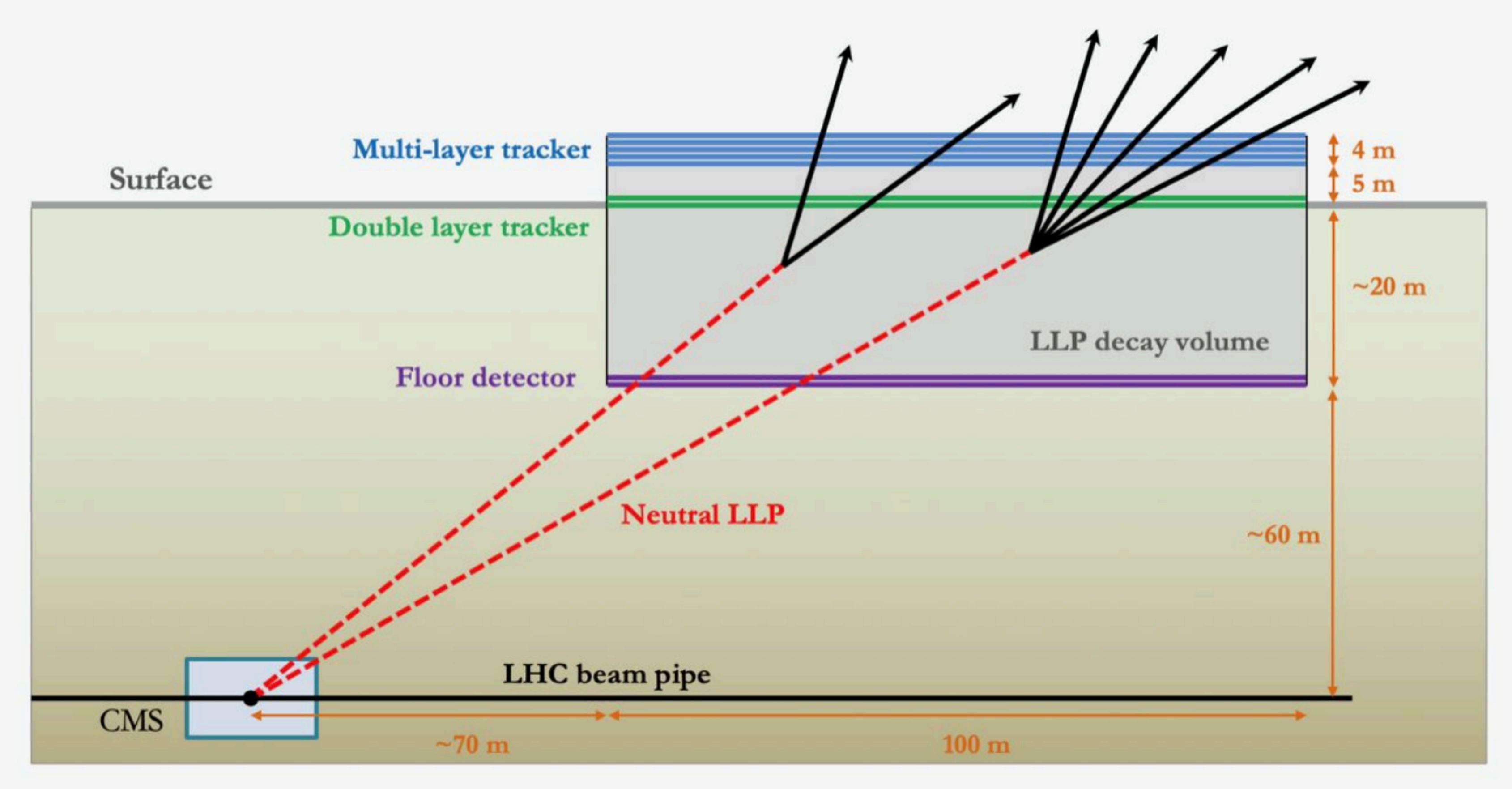




FASER 2 therefore becomes very strong compared to low energy experiments for certain models (dark Higgs), due to large B/D production rates at LHC:
N_B/N_π~10^{-2} (~10^{-7} at beam dump expts)

https://arxiv.org/abs/2009.01693

MATHUSLA



- MATHUSLA is a proposed large detector to sit close to the surface above CMS to search for LLP
  - 100m x 100m x 25m (O(5%) of solid angle)
- Search for neutral LLP decaying to charged particles in a ~20m decay volume
  - Sensitive to particles with very long lifetimes due to the distance from the IP

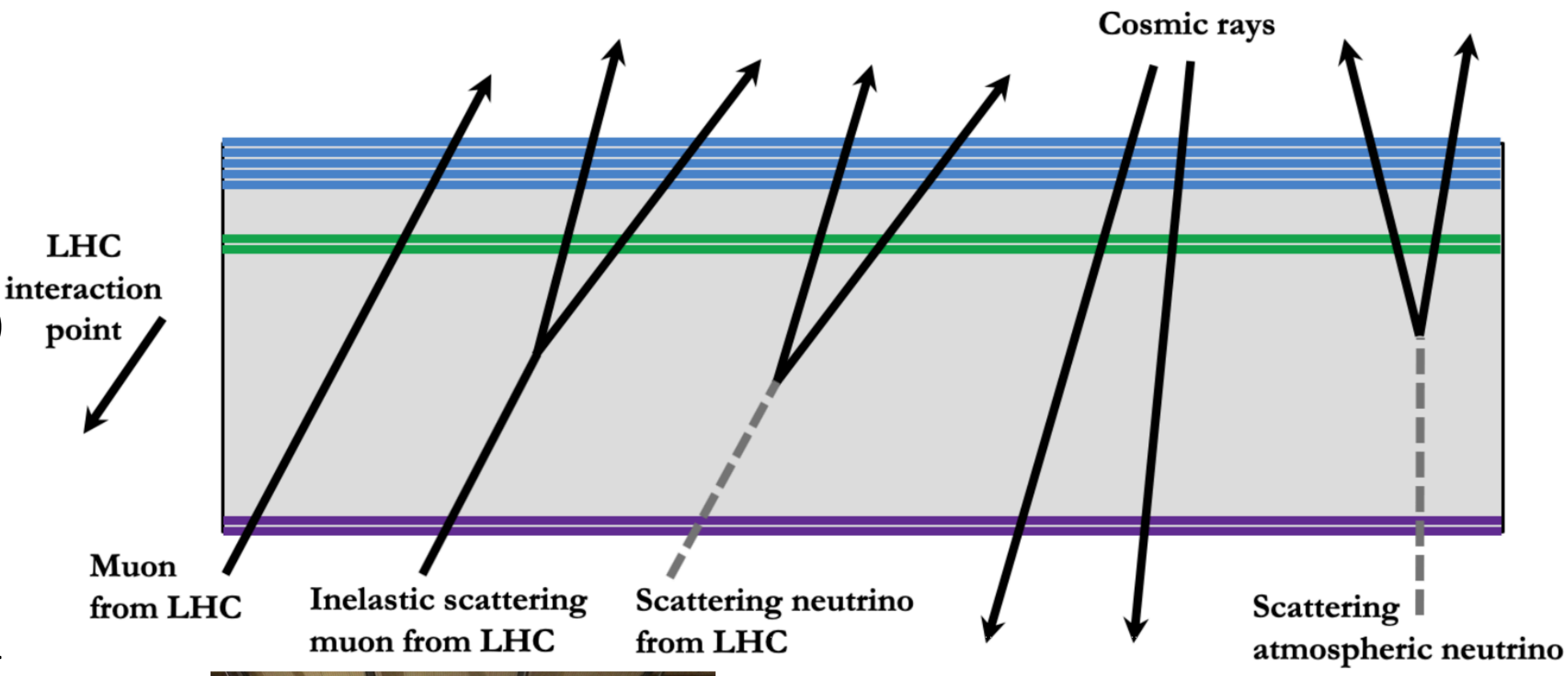
https://arxiv.org/abs/2009.01693

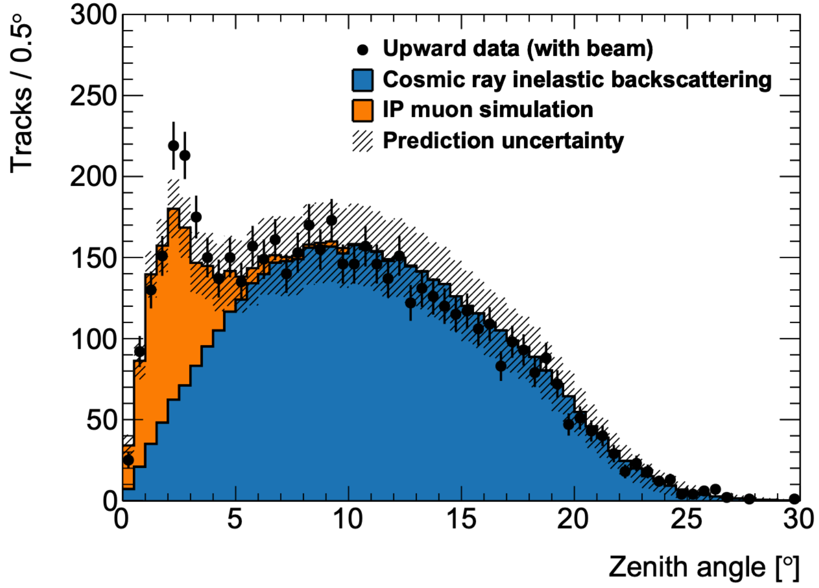
MATHUSLA

By combining precise timing (O(ns) resolution) and position (O(cm) resolution) measurements can effectively remove all backgrounds – at level of 1 background vertex / year.

Current tracking detector concept:
Extruded scintillator bars with wavelength-shifting fibers coupled to Silicon Photo Multipliers
Each scintillator bar ~ 5m x 4cm x 2cm, with readout at both ends
◦ Transverse resolution ~ 1 cm
◦ Δt between two ends gives longitudinal resolution: need sub-ns precision
Previously RPC detectors were considered.

A small test-stand (2.5 x 2.5 x 6.8 m^3) took data above ATLAS during 2018, important for validating the observed muon rate.





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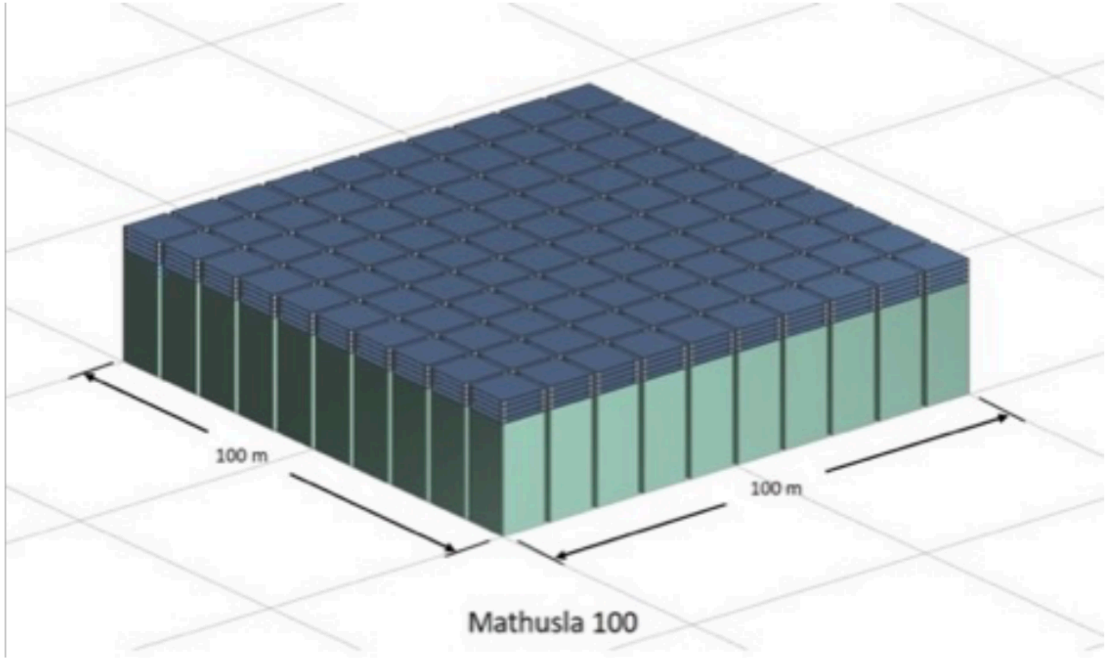
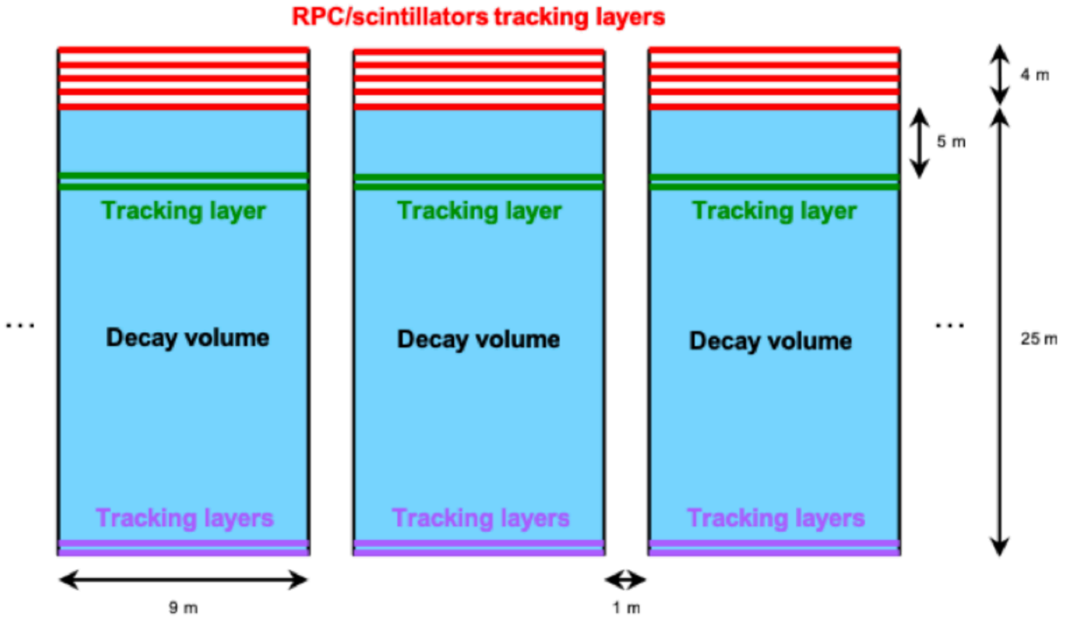
MATHUSLA

Detector segmented into 100: 9m x 9m x 29m (tall) modules.



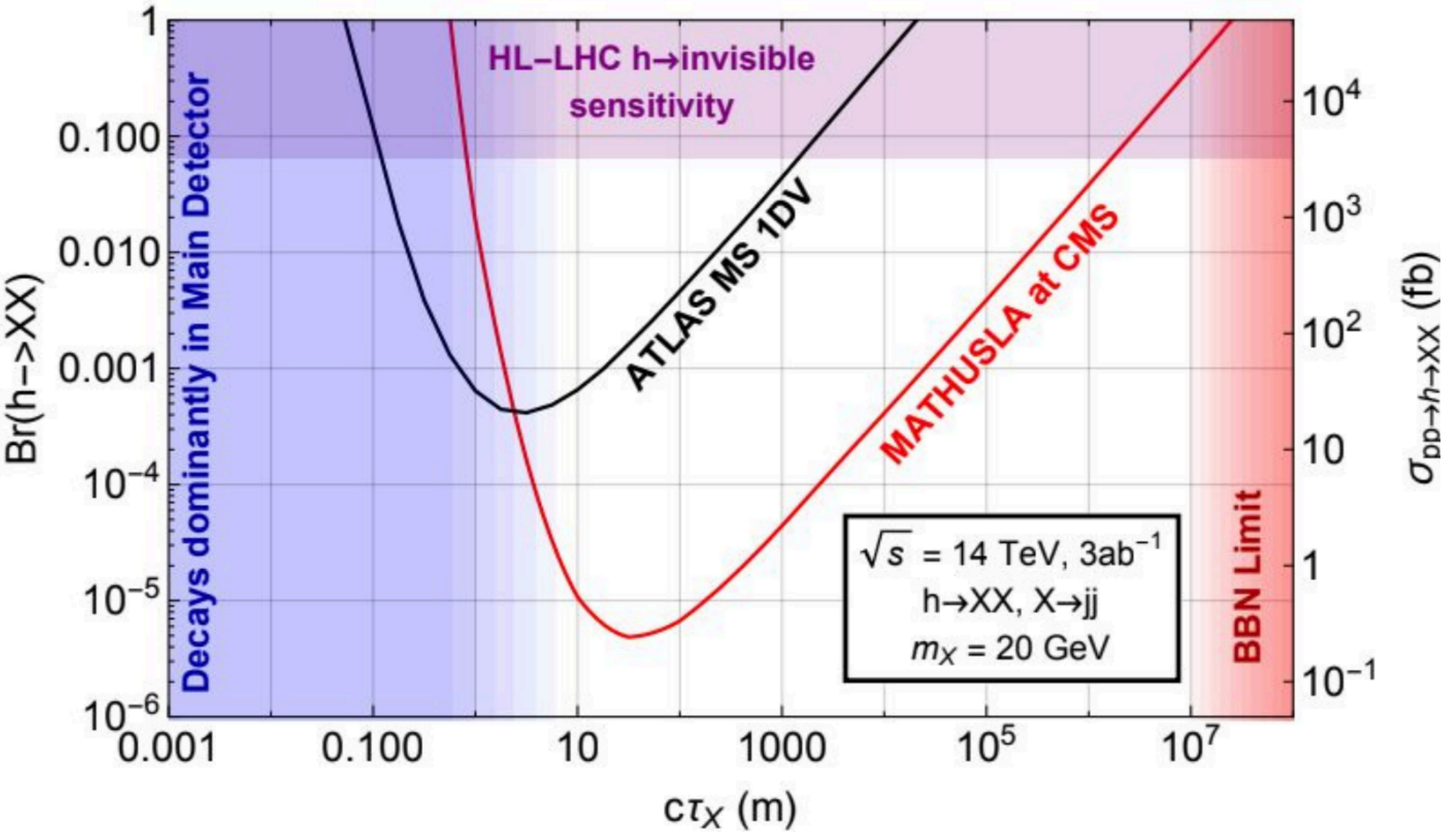


In total ~700k channels
Trigger rate ~2MHz
Trigger latency set to allow to combine triggers with CMS
CMS data can be used as an active ‘veto’ in the analysis, and also to provide information on production mechanism for any observed signal
For such a large detector cost of detector components and electronics crucial factor

https://arxiv.org/abs/2009.01693

MATHUSLA

Up to 3 orders of magnitude better sensitivity compared to LHC main detectors.
Shown here for exotic Higgs decays to LLPs.
Sensitivity studied in many models.
LLP from Higgs decays particularly relevant since these can not be probed at (future) beam dump experiments.
MATHUSLA also has a complementary cosmic ray physics case taking advantage of the large detector area to study cosmic ray showers.



LOI submitted to the LHCC in 2018 and revised in 2020.
Studies ongoing to finalize proposed detector design and cost estimate.

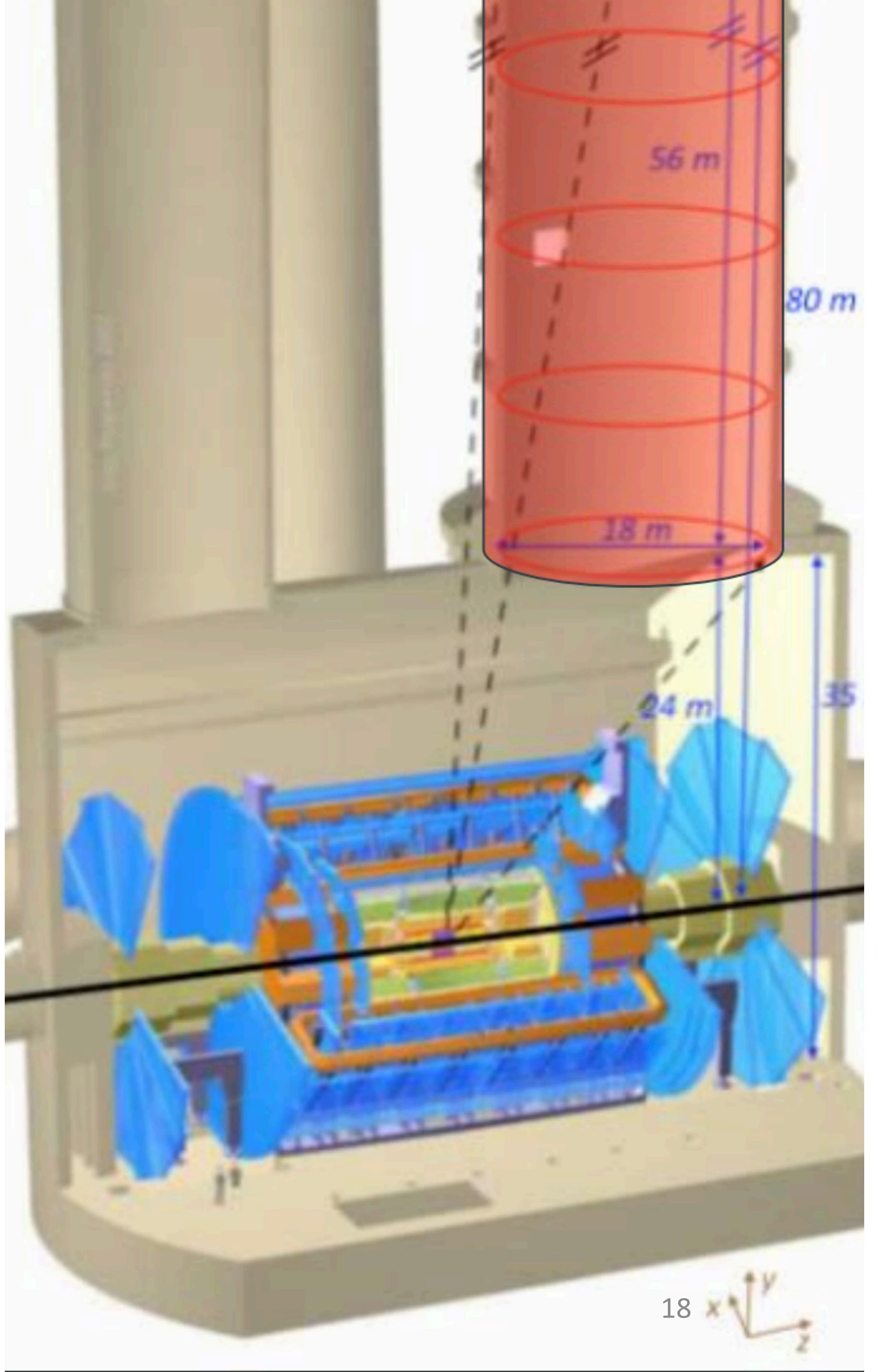
https://arxiv.org/abs/1909.13022

ANUBIS

ANUBIS is a more recent idea, for a detector with similar physics goals as MATHUSLA, but with the detector placed inside the ATLAS shaft (18m diameter, 56m high).
This allows to keep good solid angle coverage with a much smaller detector area (about 1% of MATHUSLA).
The plan is to use state of the art RPC layers (default detector has 4 tracking stations each made of 3 layers of RPCs).
ATLAS muon spectrometer and calorimeter can be used as an active veto for background reduction.

Detector requirements:

Parameter	Specification
Time resolution	$\delta t \lesssim 0.5$ ns
Angular resolution	$\delta\alpha \lesssim 0.01$ rad
Spatial resolution	$\delta x, \delta z \lesssim 0.5$ cm
Per-layer hit efficiency	$\varepsilon \gtrsim 98\%$



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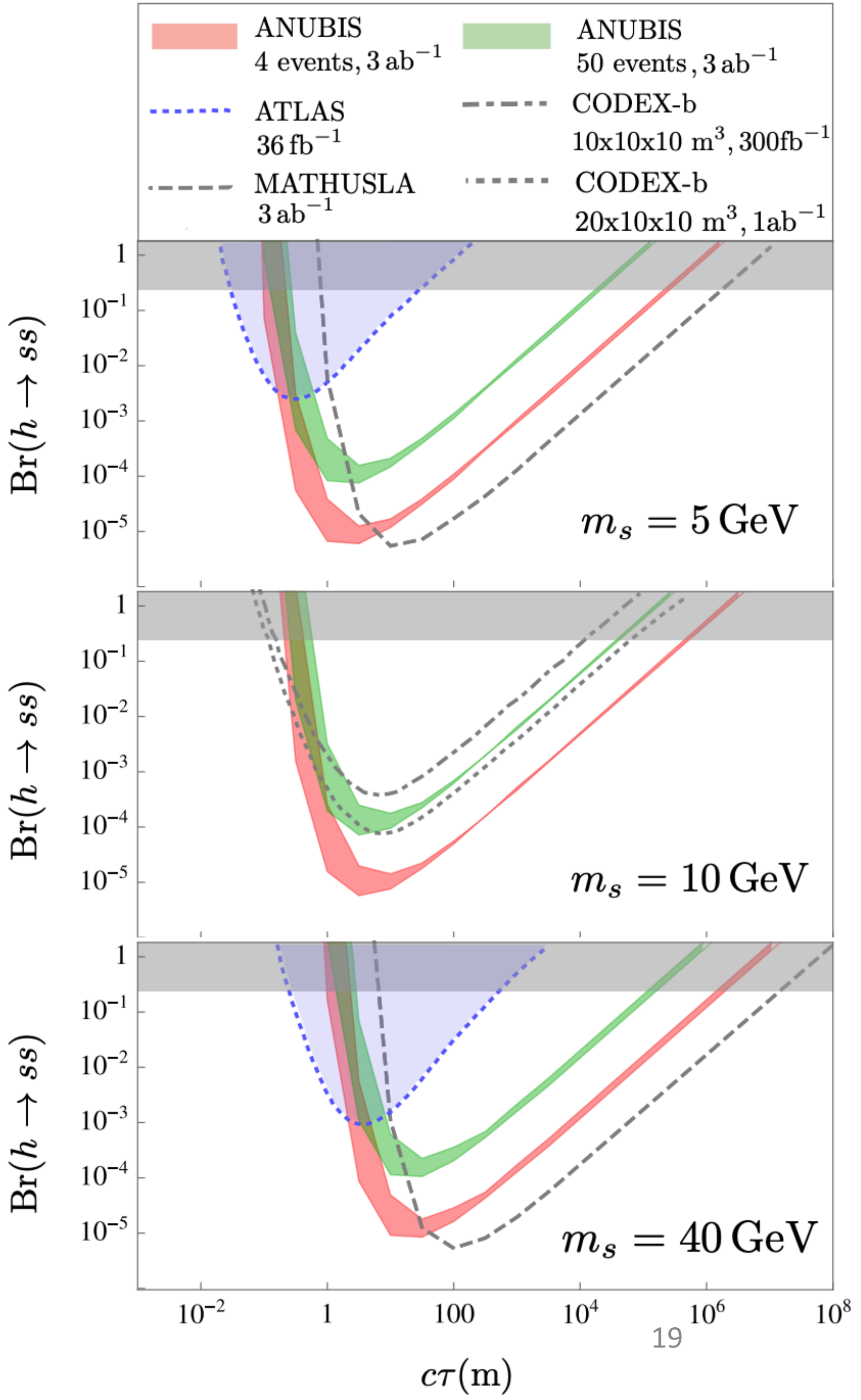
ATLAS muon spectrometer and calorimeter can be used as an active veto for background reduction.
Physics performance similar to MATHUSLA although with comparatively better sensitvity for slightly lower lifetimes.

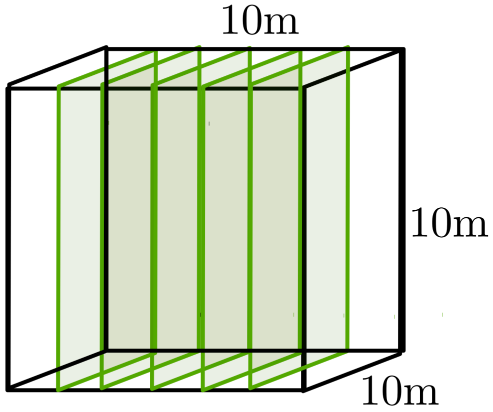


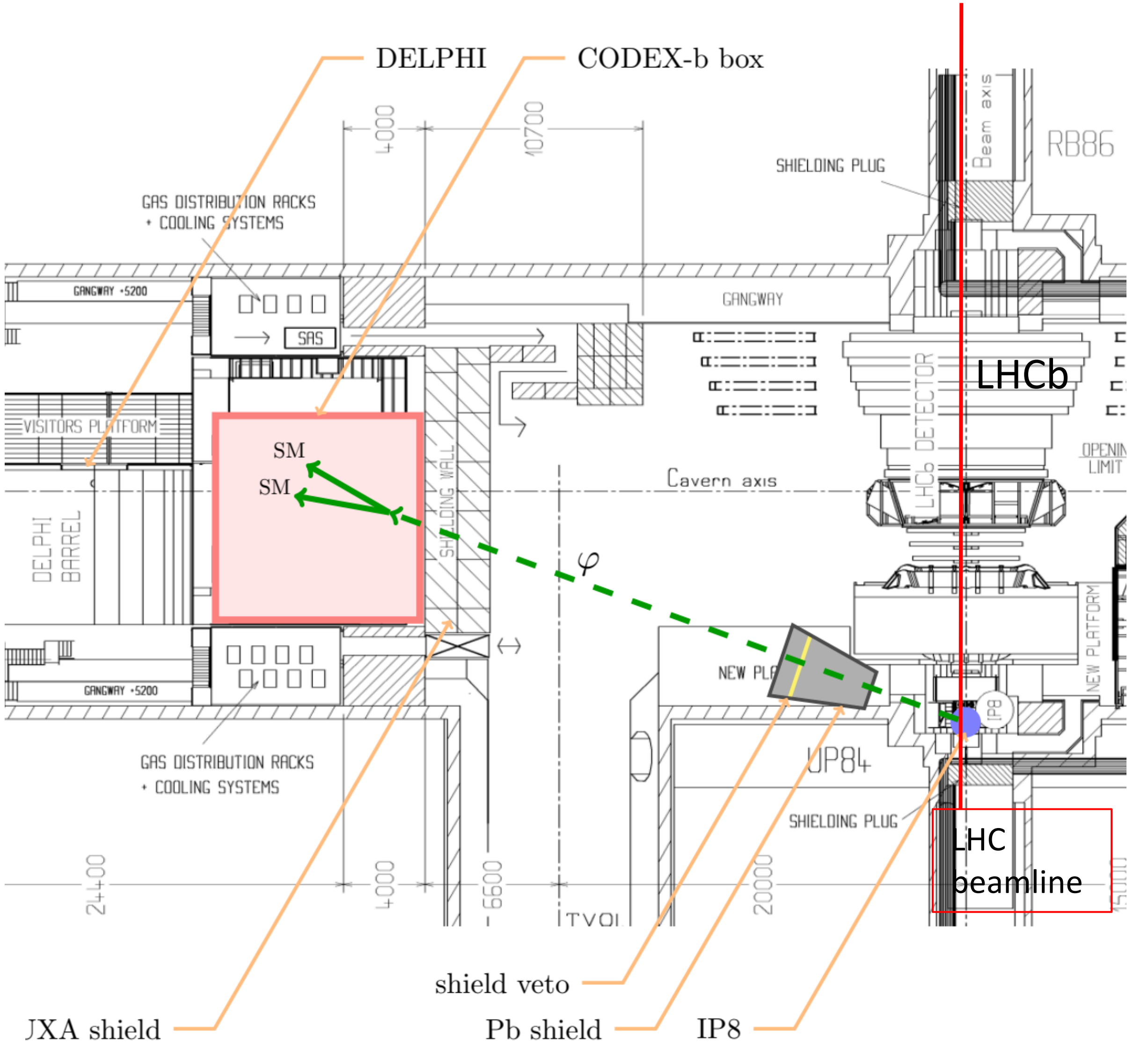
https://arxiv.org/pdf/1911.00481

CODEX-b

- Proposed medium sized experiment to be situated close to LHCb
  - ~25m from LHCb IP (behind active and passive shielding)
  - Detector size 10m x 10m x 10m
- Using space freed up by moving LHCb trigger CPUs to the surface
- Baseline design uses RPCs for tracking with good (100ps) timing resolution for background rejection
- To be implemented into the LHCb trigger/readout

Detector design:





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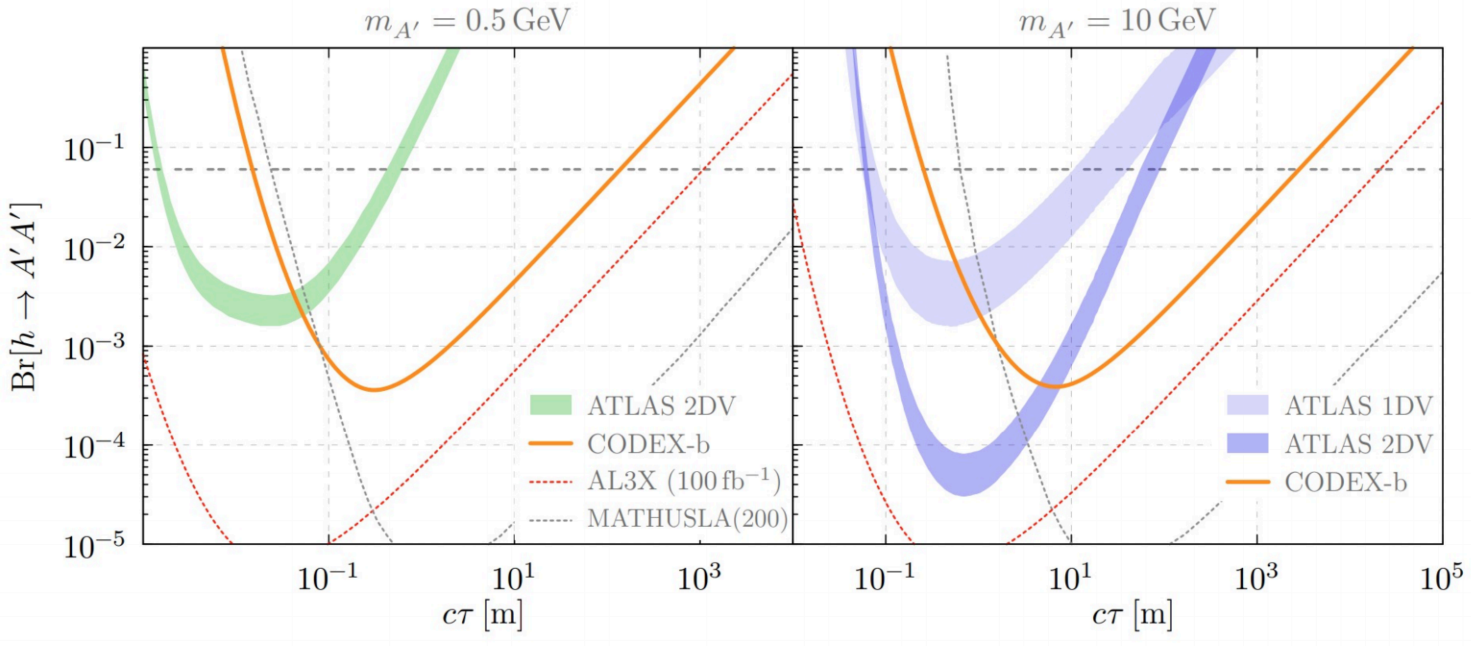
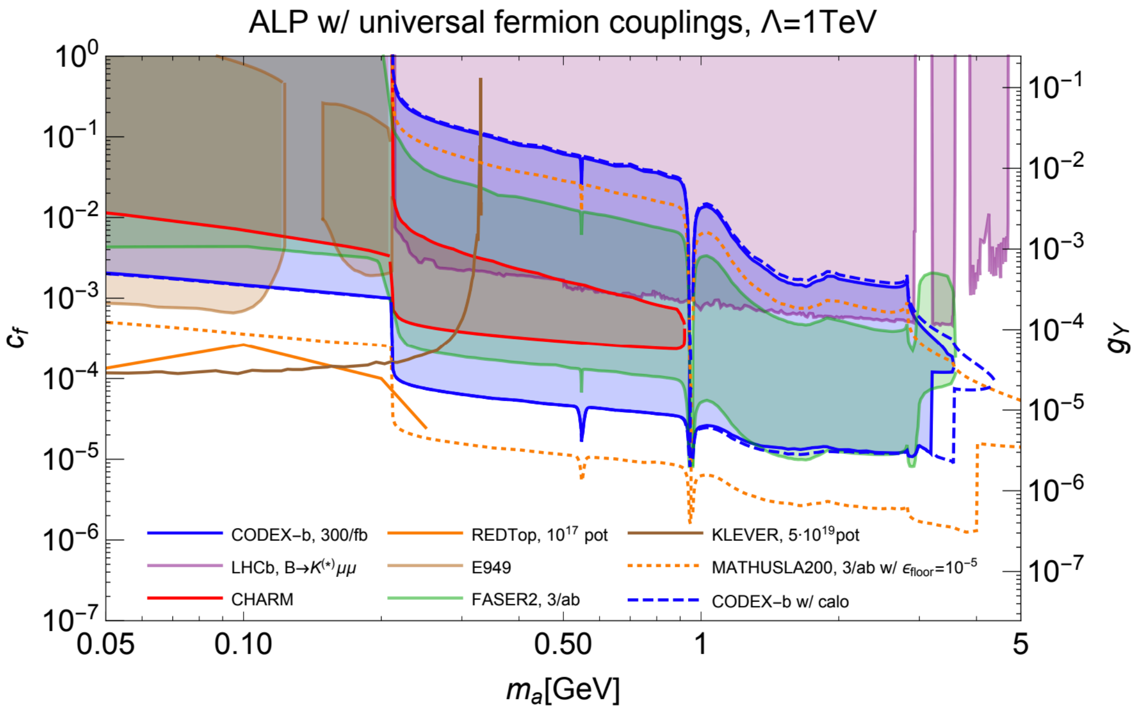
CODEX-b

- Example sensitivity e.g. for Higgs decay to (light/heavy) dark photons
- Good sensitivity in a large number of models
- Combined data taking with LHCb adds a number of interesting possibilities!





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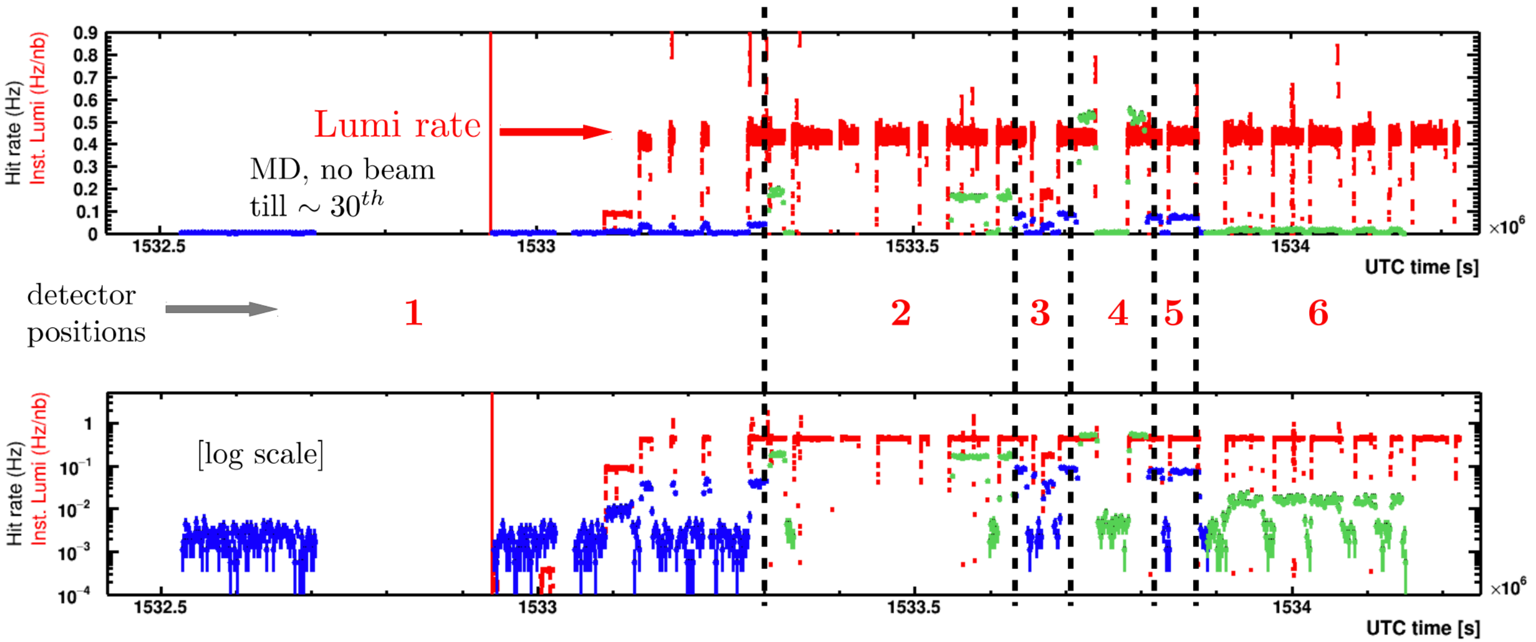
CODEX-$\boldsymbol{\beta}$

- Proposed small demonstrator: 2m x 2m x 2m (1/25th of final detector size)
- Allows to measure backgrounds, test detector technology, reconstruction etc..
- Plan to install in 2022 and take data during part of Run 3

During Run 2 background rates measured with a number of scintillator detectors showing rate estimates from GEANT4 simulation are conservative.



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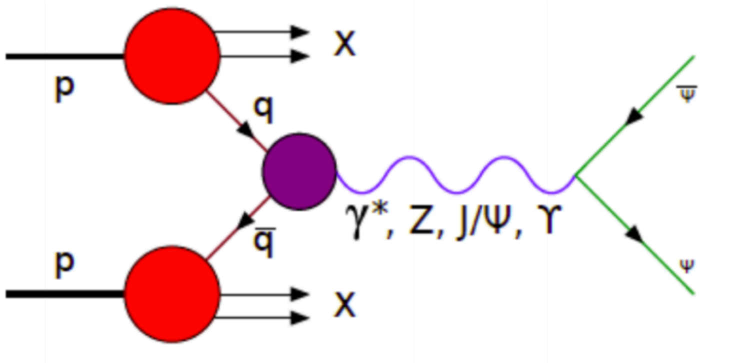
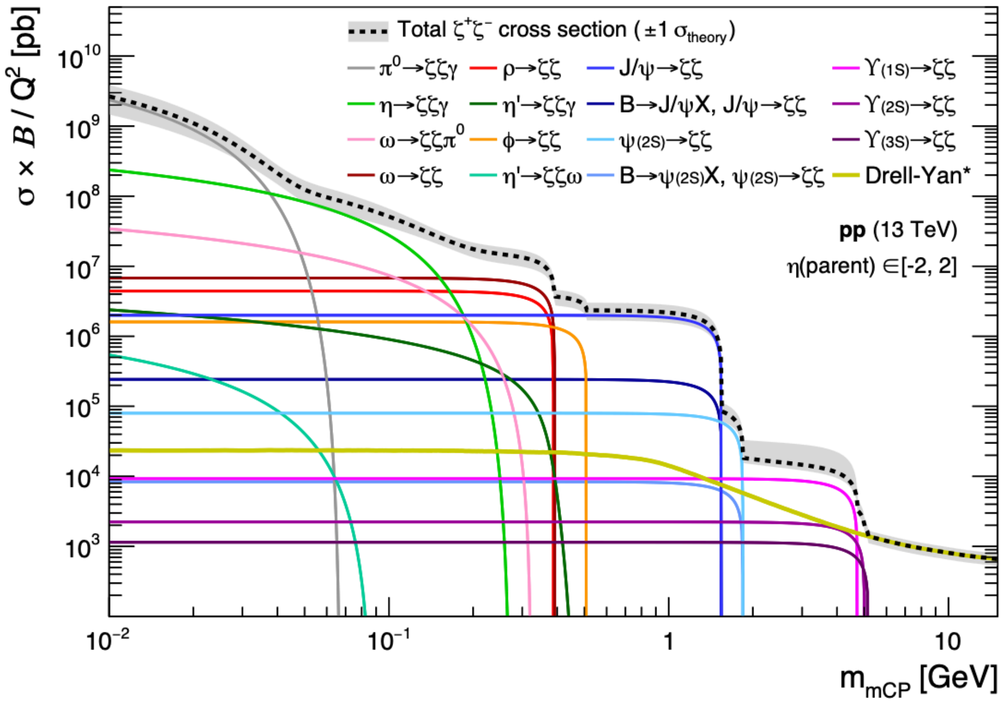
milliQan

- Designed to search for charged particles with low electric charge, in range:
  - $10^{-3} – 10^{-1}$ e
  - With masses of 10 MeV – 10’s of GeV
- Relies on scintillator bar array to detect (very) small ionisation from low charged particles
  - Expected signal has very few scintillation photons in multiple layers
  - Detector pointing at IP to give needed signature
- Control background from cosmic rays and dark rate with timing, and pointing requirements
- Detector placed in unused drainage gallery close to CMS cavern 33m from the IP (shielded by 17m of rock)

Possible millicharged particle LHC production processes considered





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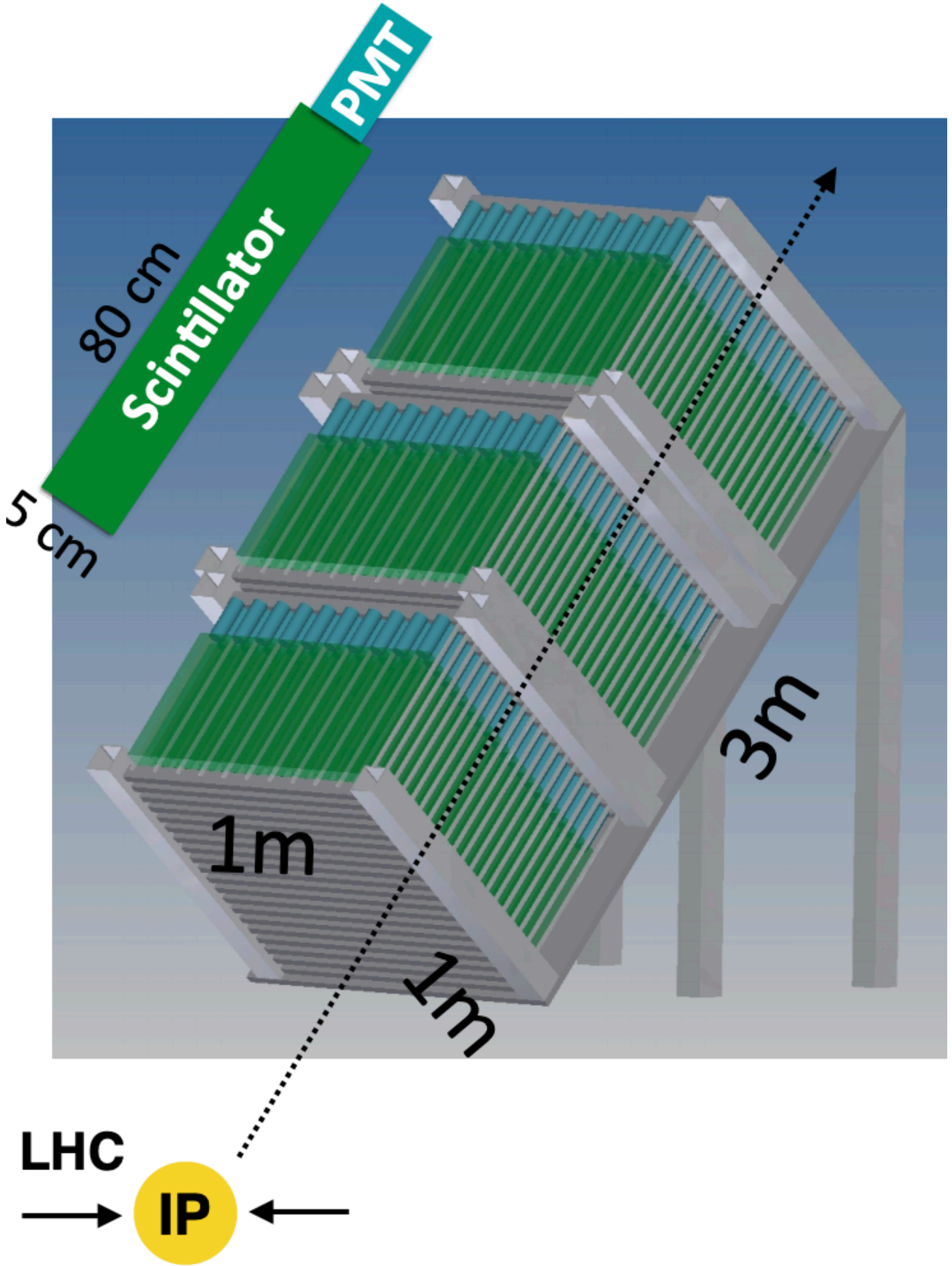

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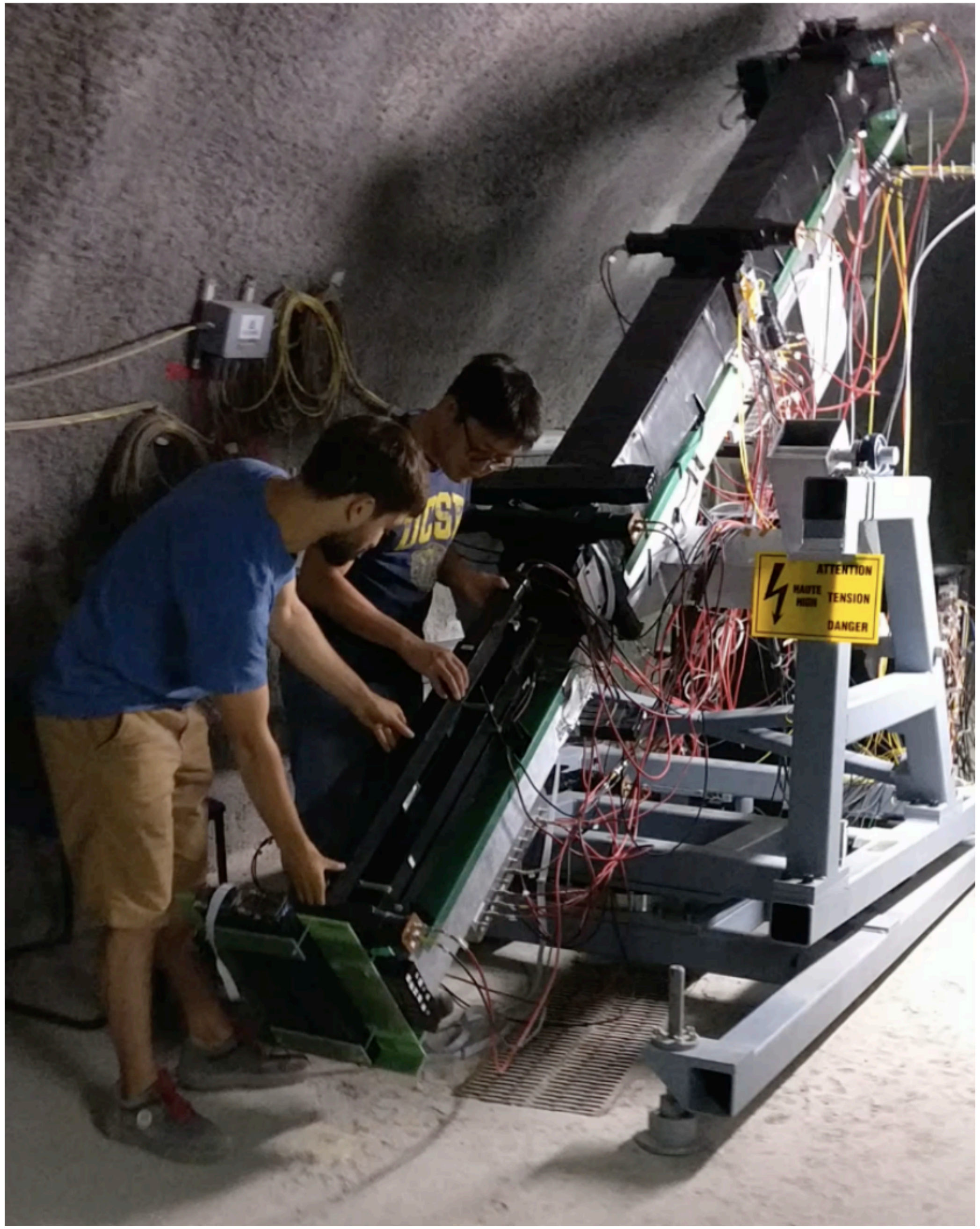
milliQan Demonstrator

- Small demonstrator installed (~1% of final detector) for 2018 LHC run
- Collected ~35/fb of 13 TeV data
- Very useful for understanding backgrounds, and used for first physics result



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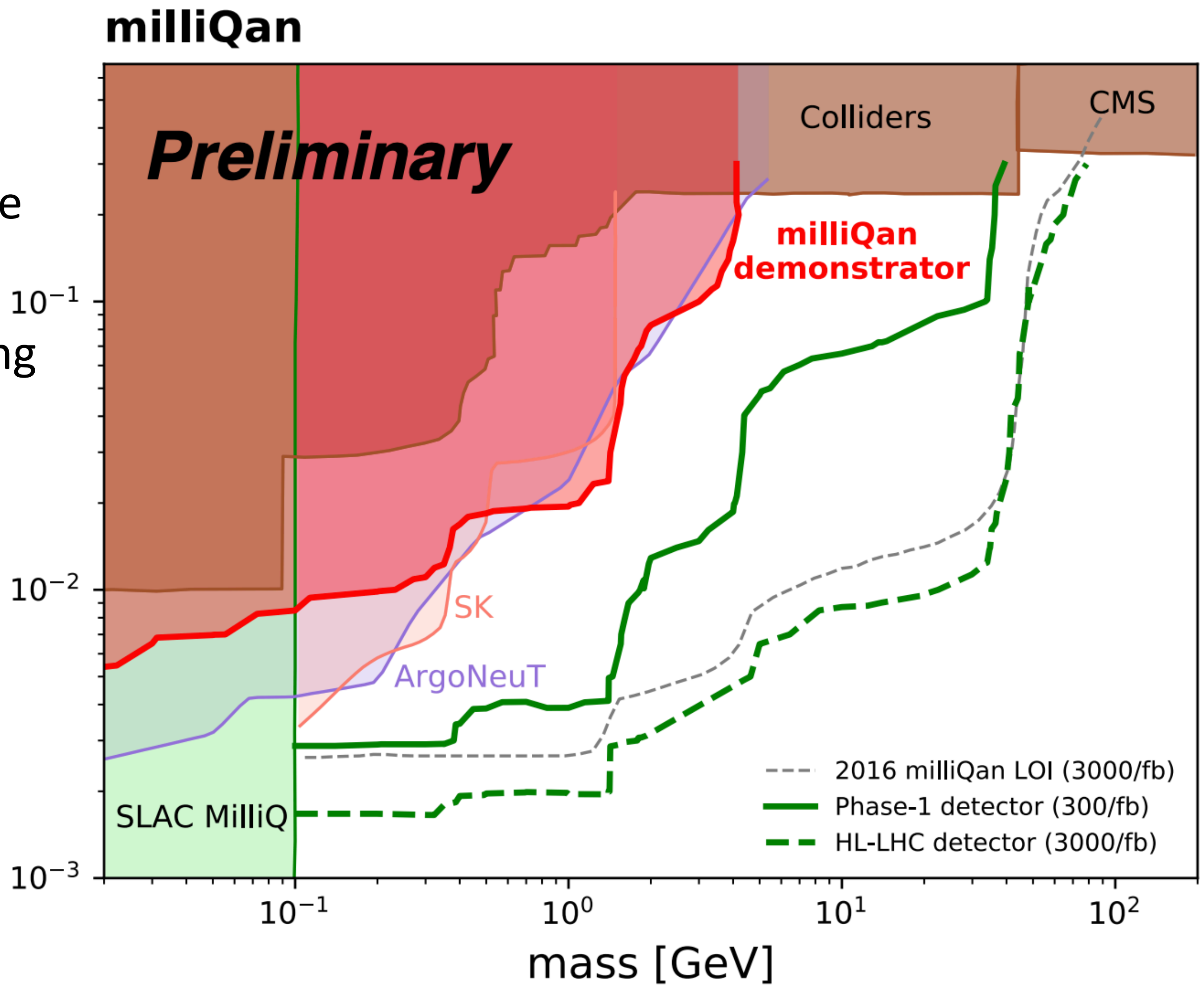
milliQan

- Demonstrator already showed competitive sensitivity
- Phase-1 and HL-LHC detector will significantly expand sensitivity over existing limits



Contrasting proposed experiments

	FASER	FASER2	Codex-b	MATHUSLA	milliQan
Distance from IP [m]	500	500	25	~100	33
Detector size [m^3]	0.1x0.1x6 = 0.2	1x1x10 = 30	10x10x10 = 1e3	100x100x30 = 3e5	1x1x3= 3
Solid Angle coverage	1e-6%	1e-4%	~1%	~5%	1e-2%
Interaction point (lumi in HL-LHC)	IP1 (ATLAS) 3000/fb	IP1 (ATLAS) 3000/fb	IP8 (LHCb) 300/fb	IP5 (CMS) 3000/fb	IP5 (CMS) 3000/fb
Sensitive to particles produced in decay of	Light mesons (π, η)	Heavy mesons (B,D)	Higgs, or light/heavy mesons	Higgs, or light/heavy mesons	~0.1 - 10 GeV
Rough Cost (by me!)	Cheap	Medium	Medium	Expensive	Cheap
Status	Installed awaiting Run-3 data	Planning started	Prototype Codex-β for Run-3?	R&D studies ongoing	Prototype installed for Run 2 being updated during R3

(In most of these experiments) lack of magnet to allow to reconstruct LLP mass can be seen as a weak point

https://arxiv.org/abs/2001.03073
http://cds.cern.ch/record/2750060

Neutrino Detectors at the LHC

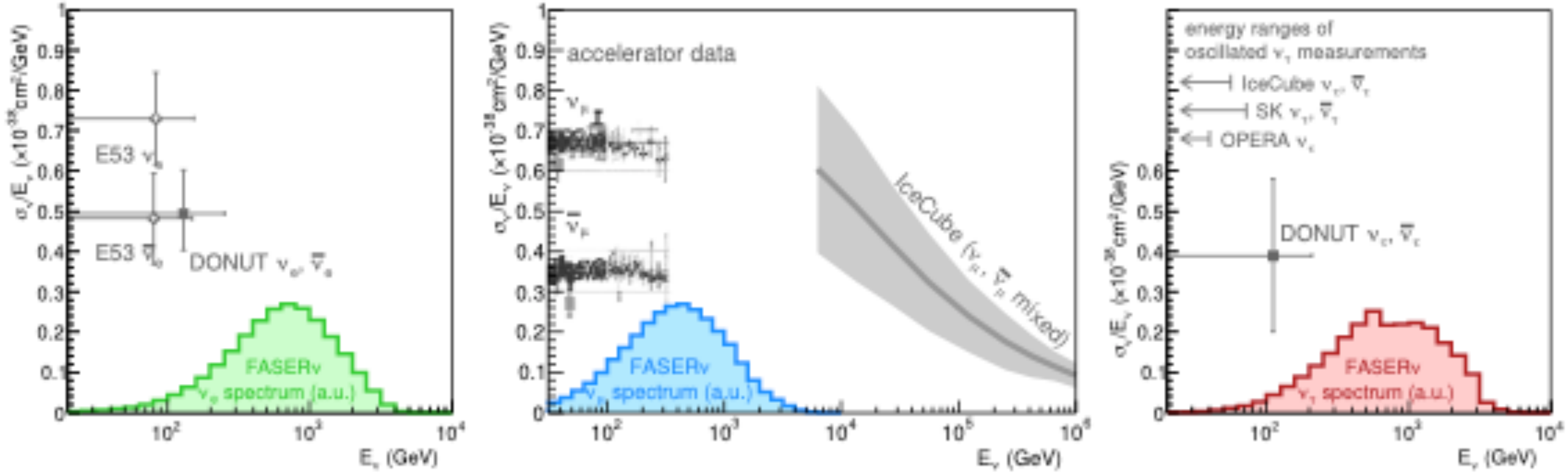
In addition to the BSM LLP search experiments there has also been an interest in experiments to detect and study neutrinos produced in the LHC collisions

A huge flux of high energy neutrinos are produced in hadron decay in the very forward region of the LHC collisions

FASERnu and SND are two emulsion based experiments, recently approved, designed to take advantage of this.

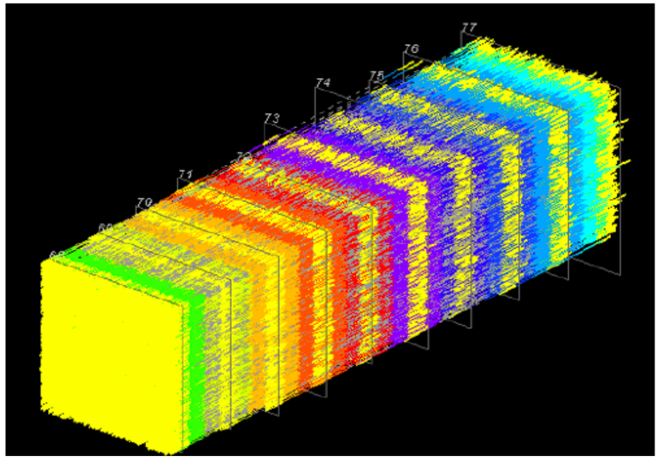
150/fb @14TeV	ν_e	ν_μ	ν_τ
Main production source	kaon decay	pion decay	charm decay
# traversing FASERnu 25cm x 25cm	$O(10^{11})$	$O(10^{12})$	$O(10^{9})$
# interacting in FASERnu (1.2tn Tungsten)	~1300	~20000	~20

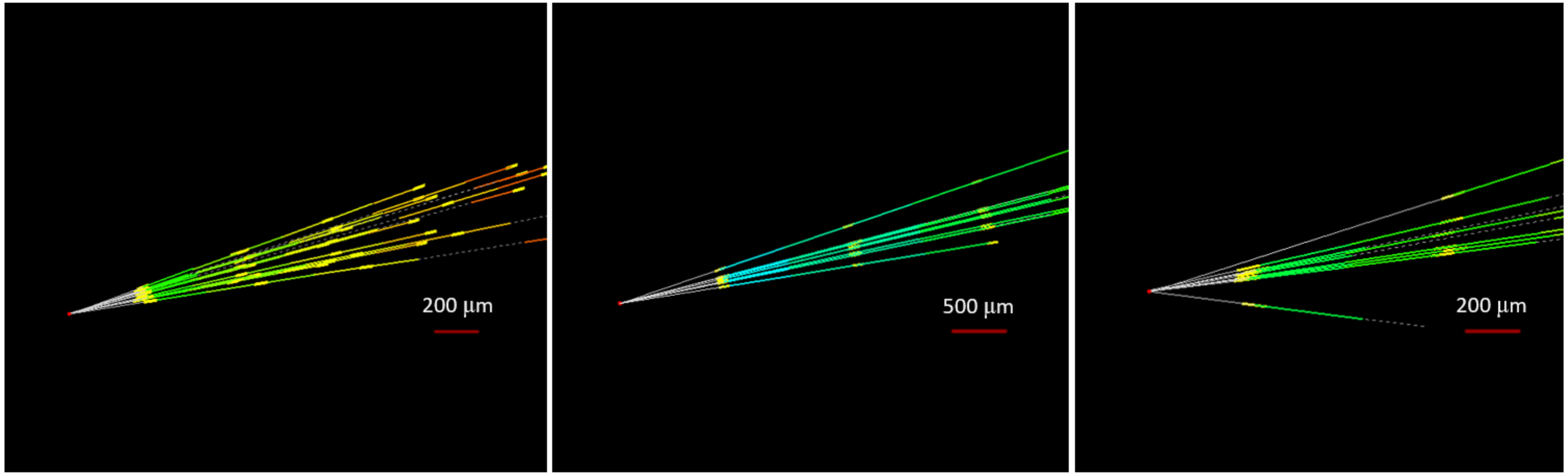
FASERnu (approved in 2019) is situated with FASER in the TI12 tunnel directly on the collision axis (covering |η|>9).
SND (approved in 2021) will be installed in TI18, a symmetric tunnel on the other side of the ATLAS IP, slightly offset from the collision axis (covering 7.2<η<8.6).



FASERnu Pilot Detector

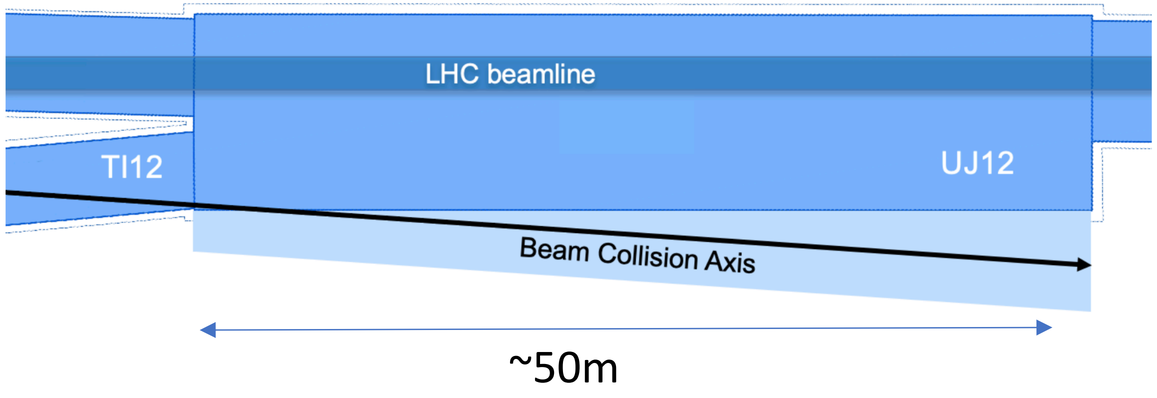
- A 30 kg emulsion detector was installed in FASER location during 2018 LHC running
    - 12.5/fb data collected, ~10 neutrino interactions expected in detector
- Emulsion data developed, reconstructed and analysis ongoing
- Several neutral vertices identified, likely to be neutrino interactions, but could also be neutral hadrons – analysis ongoing…

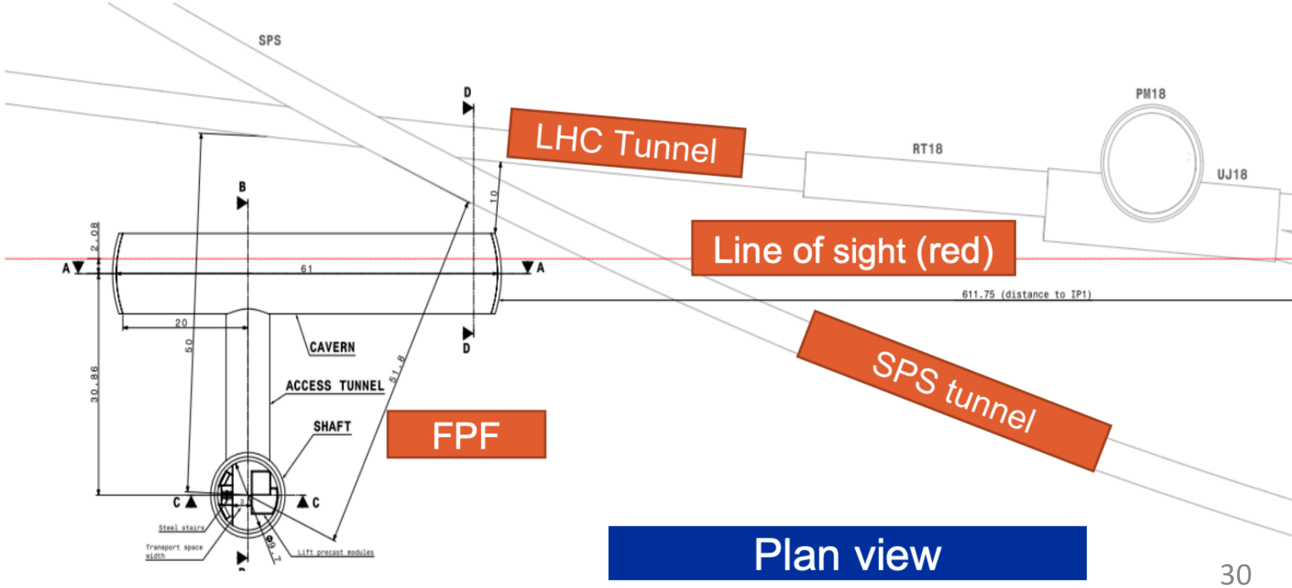




A very recent idea: The Forward Physics Facility (FPF)

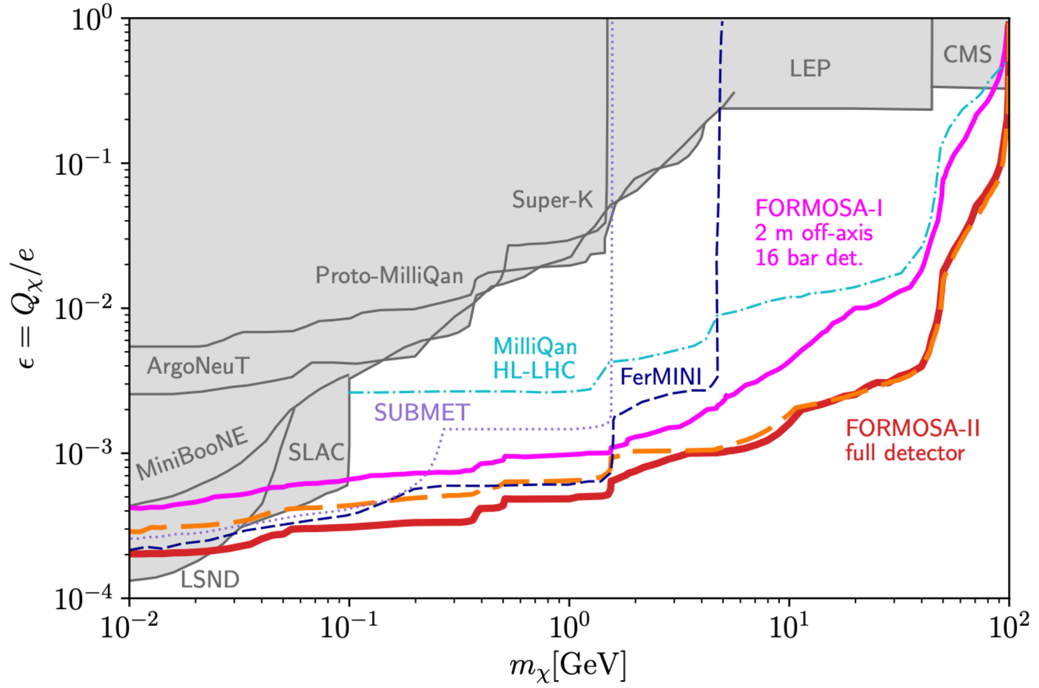
- Studies for FASER(nu) have demonstrated that there is a lot of interesting physics in the very forward region of the LHC collisions which could be exploited by having space for more experiments on the collision axis line of site
- The FPF is a proposed new facility to house such experiments (including FASER-2)
- Different options are being looked at by CERN civil engineering experts:
  - Widen the LHC junction cavern (UJ12) close to FASER
  - Dig a completely new cavern on the LOS (~600m from the IP)

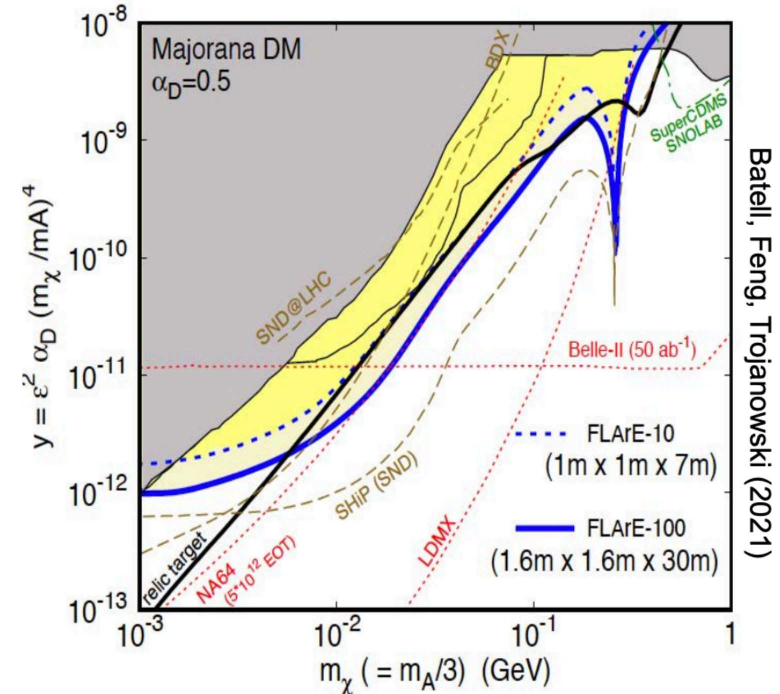




A very recent idea: The Forward Physics Facility (FPF)

- Studies of physics potential for FPF just starting but some examples:
- 10tn neutrino detector would have a few thousand high energy tau neutrino interactions in HL-LHC dataset
  - "Discover" tau anti-neutrino / Constrain tau neutrino EDM / Study tau neutrino interactions to heavy flavour
- Dark matter scattering with a LArTPC detector (FLArE)
  - Initial studies suggest can probe most of the favoured/allowed relic target region: https://arxiv.org/abs/2101.10338
- Milicharge particle searches (FORMOSA)
  - Studies suggest relocating MilliQan to FPF could increase sensitivity significantly: https://arxiv.org/abs/2010.07941





FPF Neutrino studies can gives new constraints on proton pdfs, forward QCD, and have important relevance for cosmic ray physics.

A very recent idea: The Forward Physics Facility (FPF)

Benchmark Model	Underway	FPF	References
BC1: Dark Photon	FASER	FASER 2	Feng, Galon, Kling, Trojanowski, 1708.09389
BC1': $U(1)_{B-L}$ Gauge Boson	FASER	FASER 2	Bauer, Foldenauer, Jaeckel, 1803.05466 FASER Collaboration, 1811.12522
BC2: Dark Matter	–	FLArE	Batell, Feng, Trojanowski, 2101.10338
BC3: Milli-Charged Particle	–	FORMOSA	Foroughi-Bari, Kling, Tsai, 2010.07941
BC4: Dark Higgs Boson	–	FASER 2	Feng, Galon, Kling, Trojanowski, 1710.09387 Batell, Freitas, Ismail, McKeen, 1712.10022
BC5: Dark Higgs with hSS	–	FASER 2	Feng, Galon, Kling, Trojanowski, 1710.09387
BC6: HNL with e	–	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC7: HNL with μ	–	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC8: HNL with τ	FASER	FASER 2	Kling, Trojanowski, 1801.08947 Helo, Hirsch, Wang, 1803.02212
BC9: ALP with photon	FASER	FASER 2	Feng, Galon, Kling, Trojanowski, 1806.02348
BC10: ALP with fermion	FASER	FASER 2	FASER Collaboration, 1811.12522
BC11: ALP with gluon	FASER	FASER 2	FASER Collaboration, 1811.12522

Summary

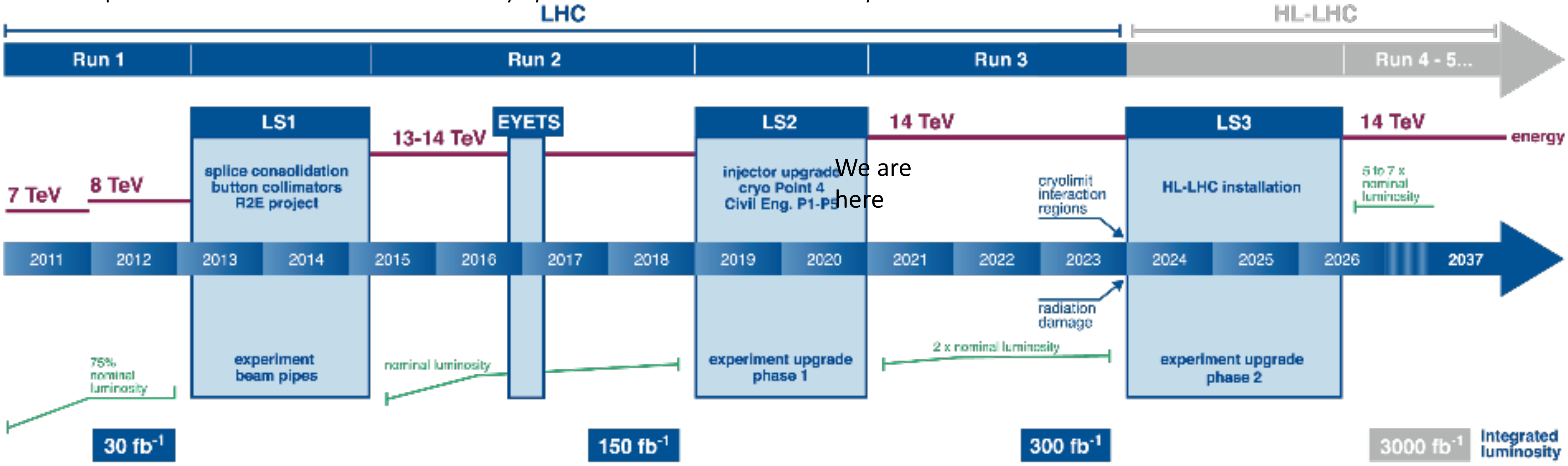
- Several interesting proposals for new far detectors at the LHC
  - FASER, MATUSLA (ANUBIS), CODE—b and MiliQan discussed
  - Did not have time to cover some others: MoEDAL and AL3X – apologies….
- Such new detectors are theoretically well motivated and good-value to increase the physics reach of the LHC
- As well as BSM (especially dark-sector) LLP searches, new experiments targeting neutrinos produced in LHC collisions
  - To date no neutrino produced at a collider has been detected
  - LHC neutrinos are in an unexplored energy regime
- Forward Physics Facility a new idea to allow multiple new experiments to increase sensitivity in several important areas

Some useful references…

- The LHC LLP Community white paper (2019):
  - https://arxiv.org/abs/1903.04497
- CERN Physics Beyond Colliders BSM study group report (2019):
  - https://iopscience.iop.org/article/10.1088/1361-6471/ab4cd2
- Latest CERN Physics Beyond Colliders workshop (March 2021):
  - https://indico.cern.ch/event/1002356
- Latest LLP at the LHC workshop (Nov 2020):
  - https://indico.cern.ch/event/922632/
- Neutrinos at the LHC workshop:
  - https://indico.cern.ch/event/977827
- Upcoming FPF workshop (May 2021):
  - https://indico.cern.ch/event/1022352/

HL-LHC Timeline

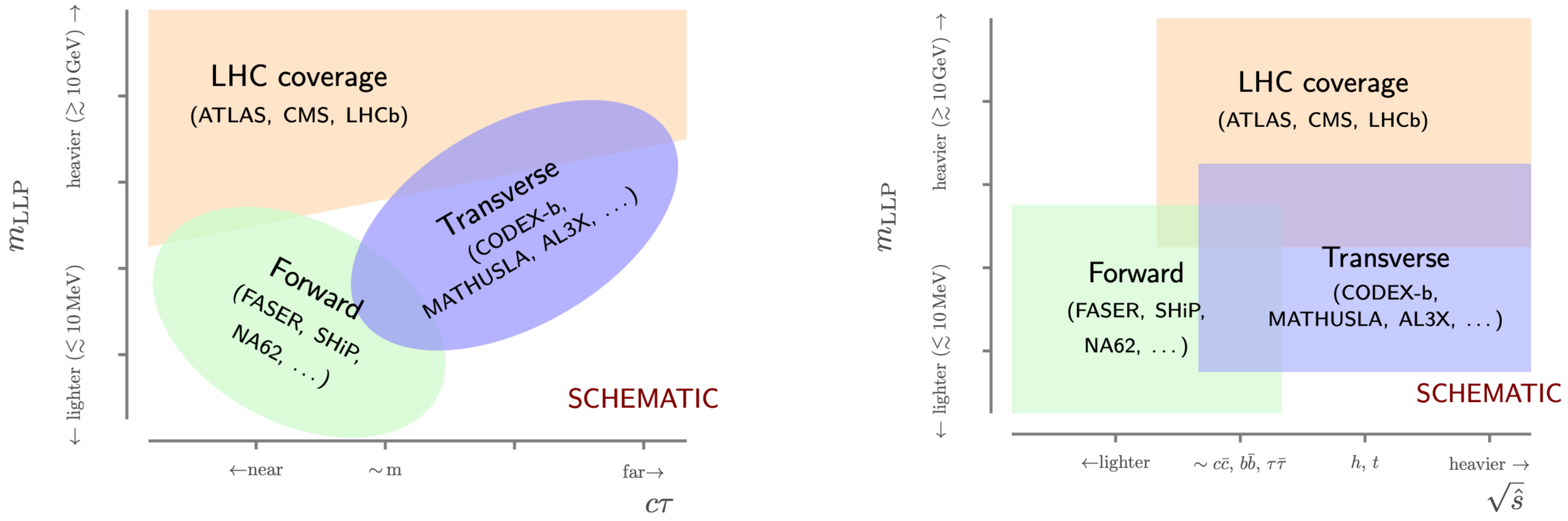
Note compared to what is shown schedule shifted by 1yr in LS2 due to COVID related delays



LHC timeline sees Run-3 at ~14 TeV for 2022-2024 (collecting >150/fb more data).
Long shutdown 3 (LS3) – for installation of HL-LHC components (and upgrades to ATLAS/CMS) after which the instantaneous luminosity will increase to ~5x nominal. Giving a dataset of ~3000/fb within ~10yrs.
LS3 is the obvious moment to install new experiments into the LHC to allow them to collect the full HL-LHC dataset.

Contrasting proposed experiments

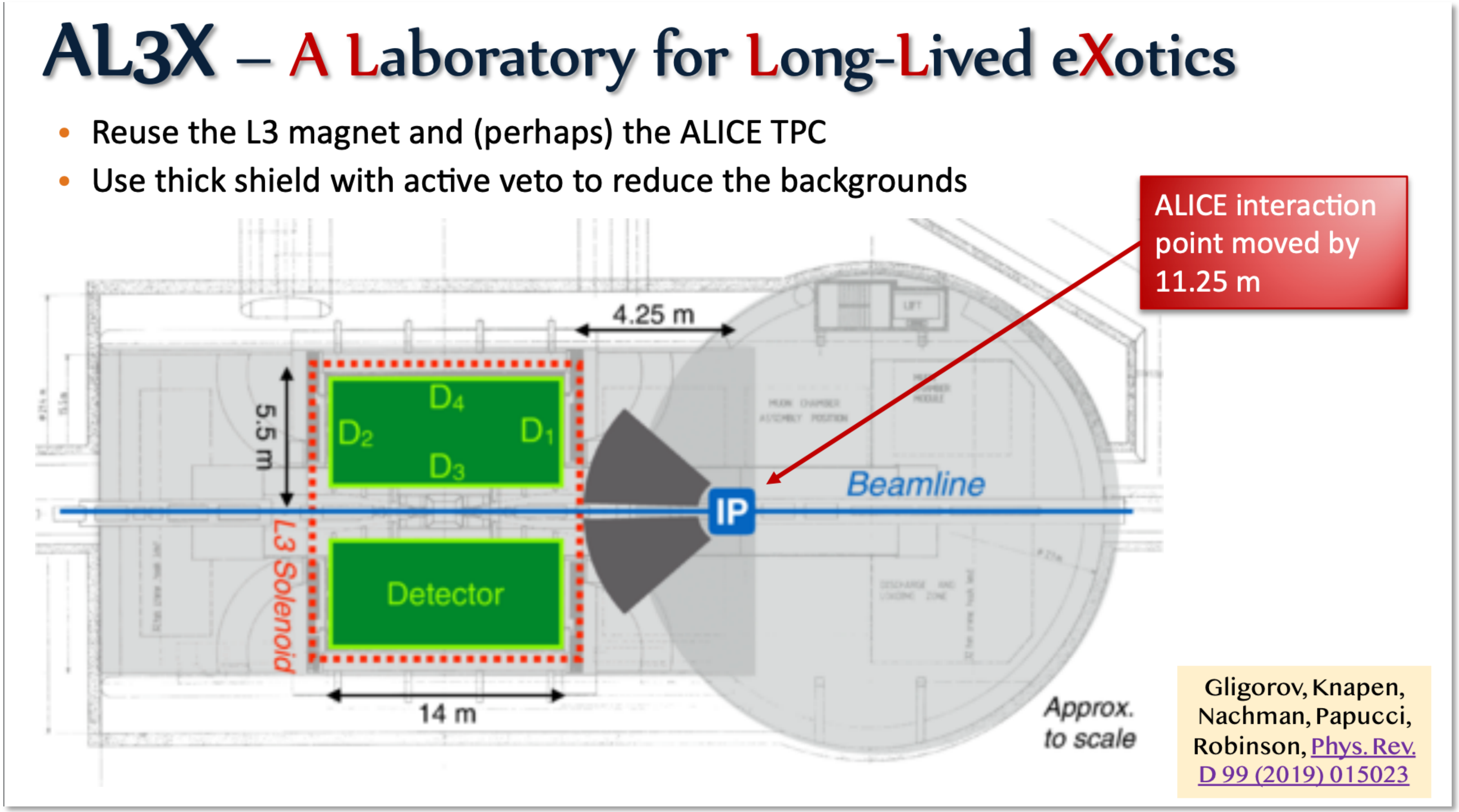
From Codex-b physics case paper: 1911.00481



https://arxiv.org/abs/1810.03636

AL3X

Slide from V.A. Mitsou



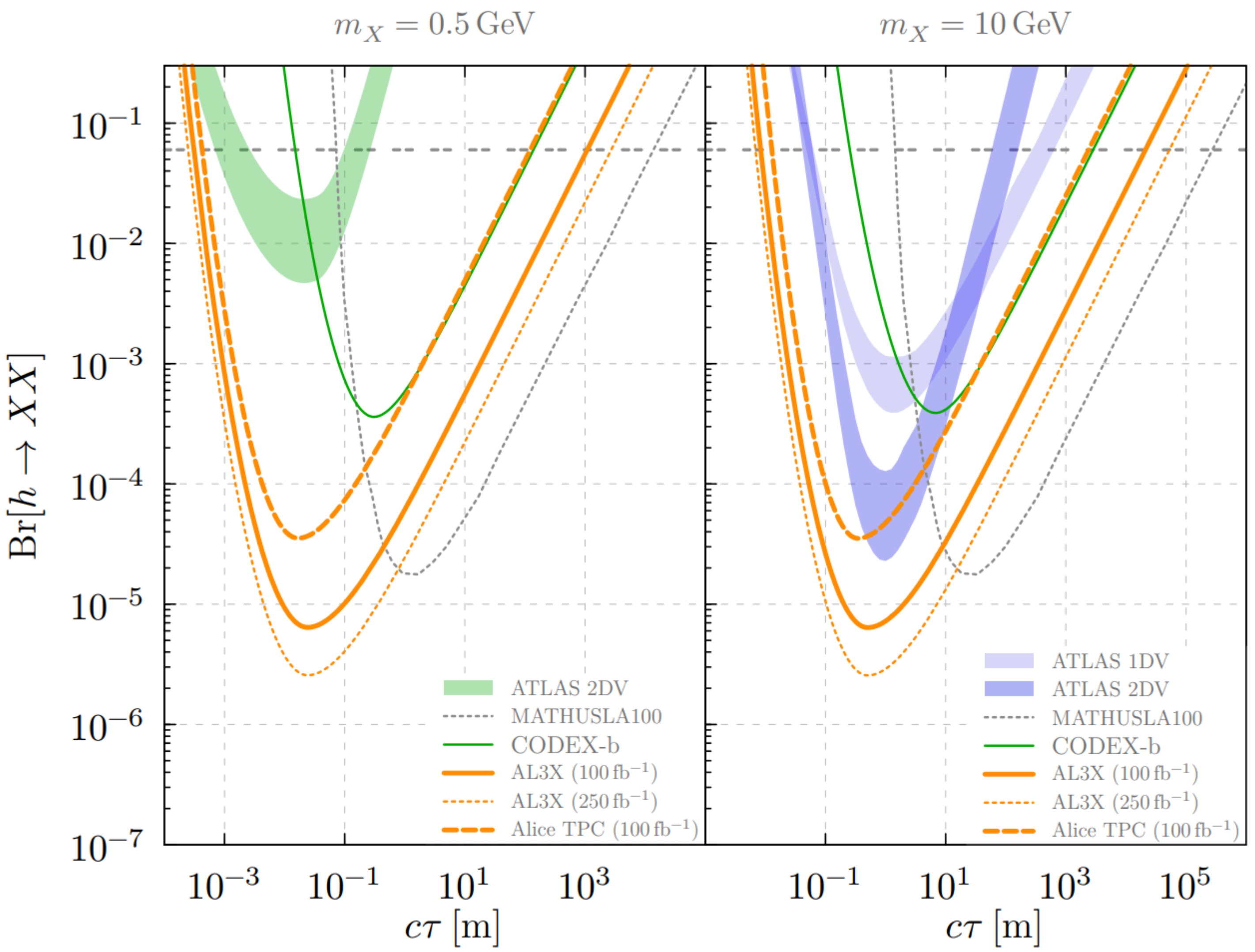
https://arxiv.org/abs/1810.03636

AL3X

Physics sensitivity very strong, due to large solid angle coverage (closeness to IP).
But a number of complications:

- Moving IP by 12.5m
- Upgrading LHC systems at P2 to be able to handle high luminosity running

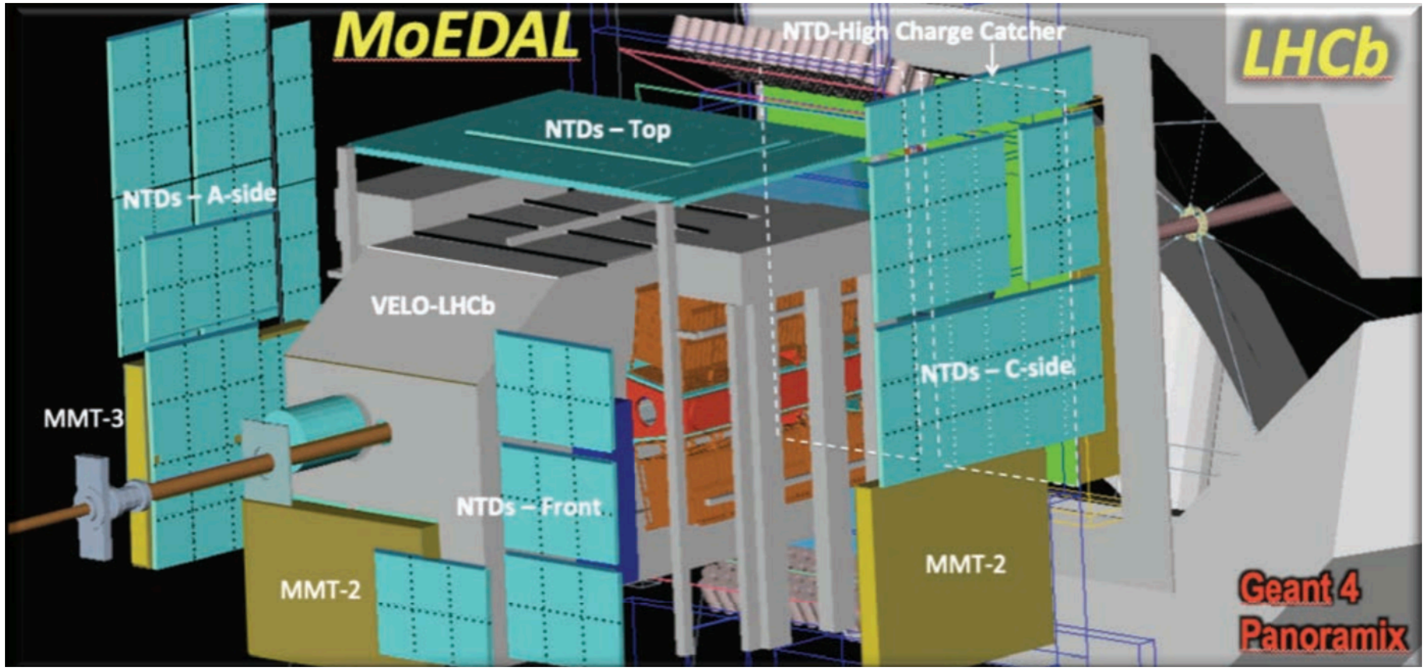
In addition it is not at all clear that IP2 will not continue to be used by an upgraded version of ALICE during the full HL-LHC.



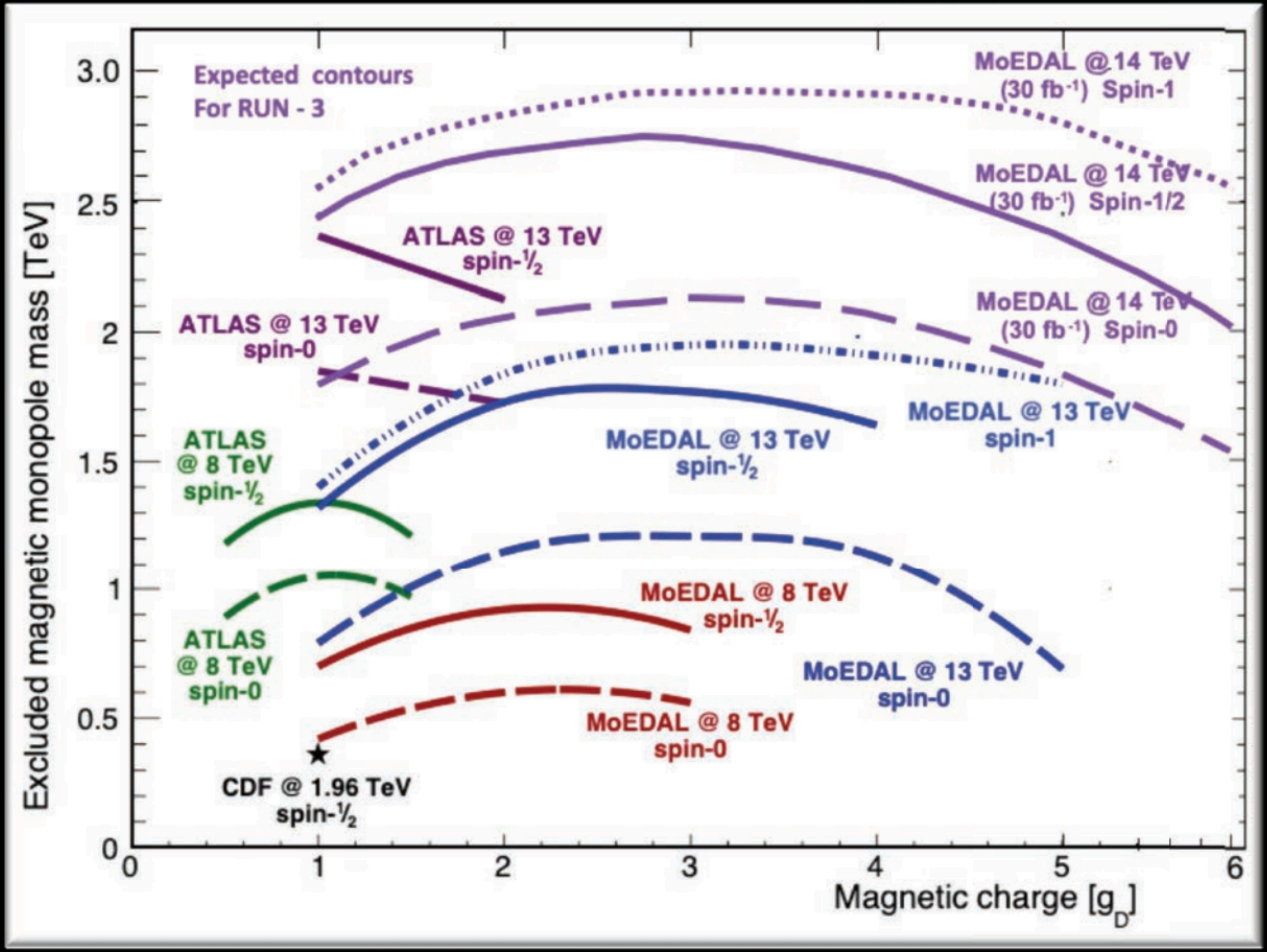
https://arxiv.org/abs/1604.06645

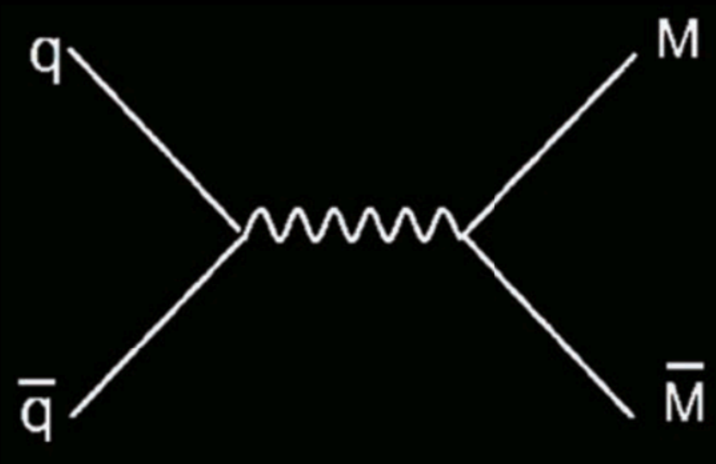
MoEDAL

- Originally purely passive detector searching for magnetic monopoles situated around LHCb IP, using 2 technologies
  - Nulcear Track Detectors
    - Analyzed offline with optical scanning microscope for signature of exposure to highly ionizing particle
  - Trapping detector
    - Trapping charged particles in aluminium samples. Monitored offline for the presence of trapped magnetic charge at a remote superconducting magnetometer facility

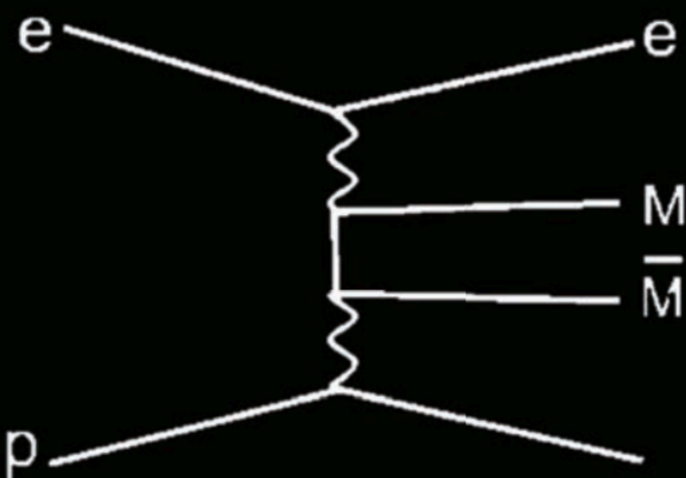


MoEDAL results for searches for magnetic monopoles (slide taken from J. Pinfold)





Drell Yan mechanism

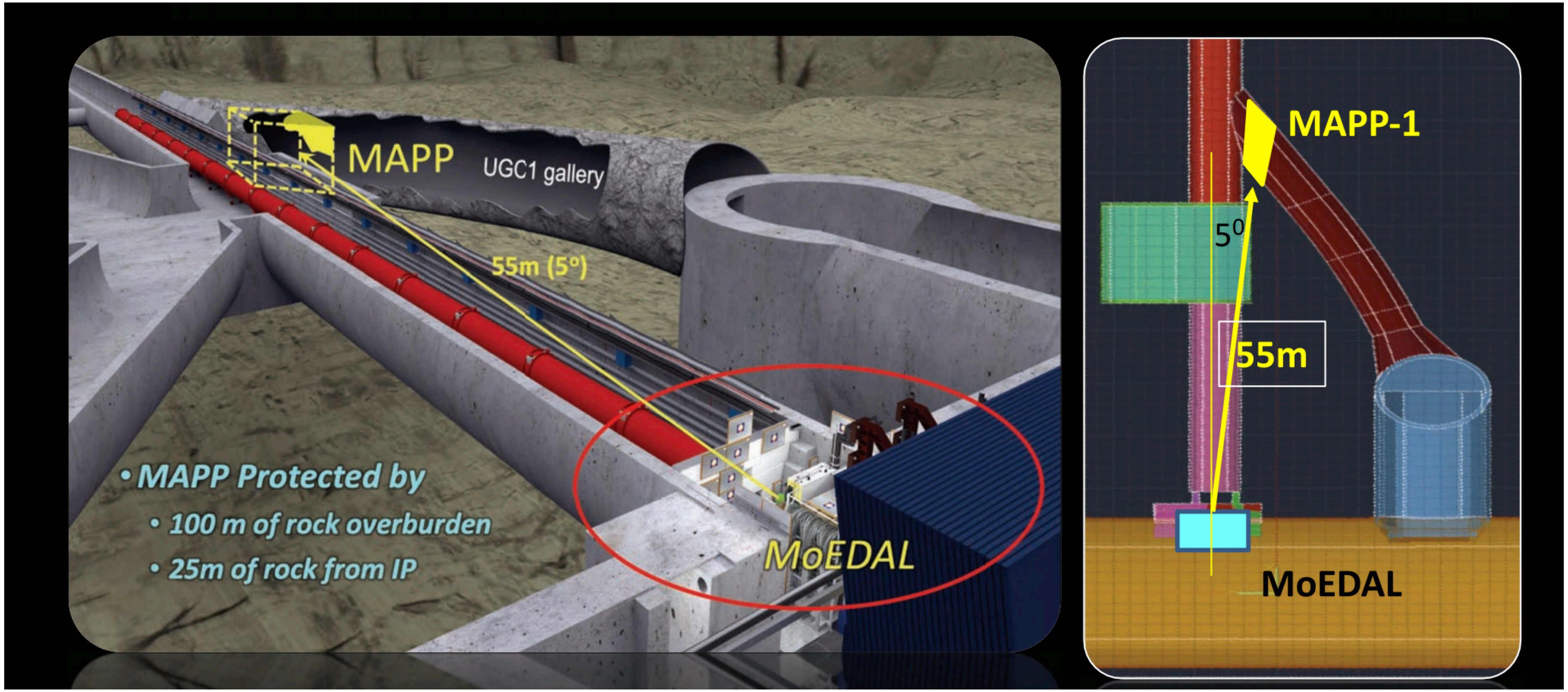


Photon fusion

JHEP 1608 (2016) 067 PRL 118 (2017) 061801 Phys.Lett. B782 (2018) 510 PRL 123 (2019) 021802 https://cds.cern.ch/record/2754178

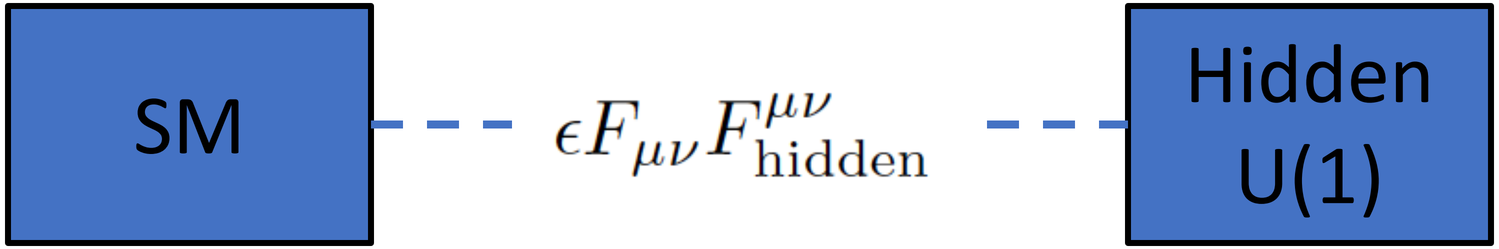
MoEDAL Upgrade

Recent proposal to add additional electronic detectors for LLP and millicharged particle searches. Detectors to be placed in unused drainage gallery at 5 degrees to the beam.



Dark Photons

- Dark matter is our most solid evidence for new particles. In recent years, the idea of dark matter has been generalized to dark sectors
- Dark sectors motivate light, weakly coupled particles (WIMPless miracle, SIMP miracle, small-scale structure, ..)
- A prominent example: vector portal, leading to dark photons

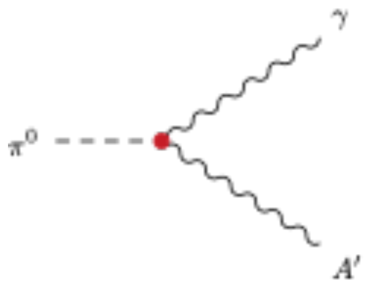


- The resulting theory contains a new gauge boson A' with mass $m_{A'}$ and εQ_f couplings to SM fermions f

Dark Photon Properties

- Produced (very rarely) in meson decays, e.g.,

$$B(\pi^0 \to A'\gamma) = 2\epsilon^2 \left(1 - \frac{m_{A'}^2}{m_{\pi^0}^2}\right)^3 B(\pi^0 \to \gamma\gamma)$$



and also through other processes

- Travels long distances through matter without interacting, decays to e^+e^- , $\mu^+\mu^-$ for $m_{A'} > 2\ m_\mu$, other charged pairs

$$\bar{d} = c\frac{1}{\Gamma_{A'}}\gamma_{A'}\beta_{A'} \approx (80\ \mathrm{m})\ B_e \left[\frac{10^{-5}}{\epsilon}\right]^2 \left[\frac{E_{A'}}{\mathrm{TeV}}\right] \quad E_{A'} \gg m_{A'} \gg m_e$$

- TeV energies at the LHC → huge boost, decay lengths of ~100 m are possible for viable and interesting parameters

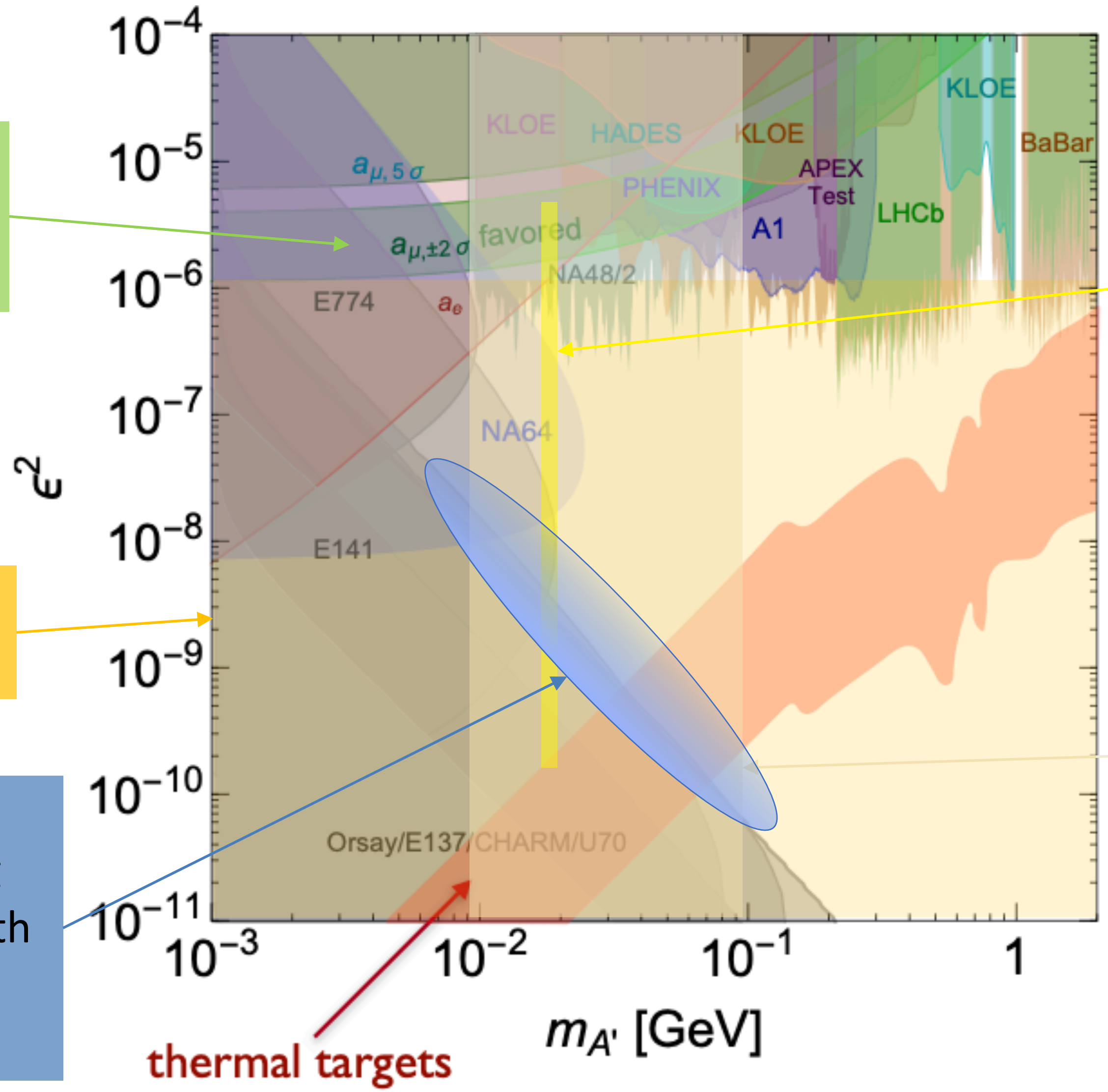
Slide from J. Feng

Targets in Dark Photon parameter space

Muon g-2 Anomaly

Loop-induced Coupling

FASER probes an interesting region, even with the 1st fb^{-1} of Run 3 data



$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$

^{8}Be and ^{4}He ATOMKI Anomalies

Self-interacting Dark Matter

Tim Nelson, Snowmass RP6 (2020)

https://arxiv.org/abs/1812.09139

Evolution of FASER Location

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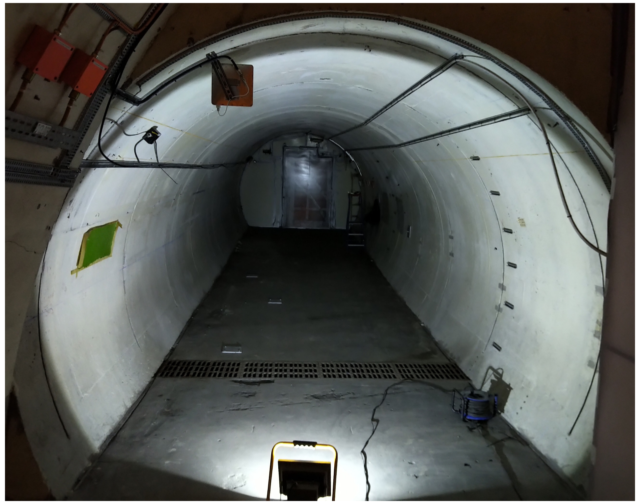

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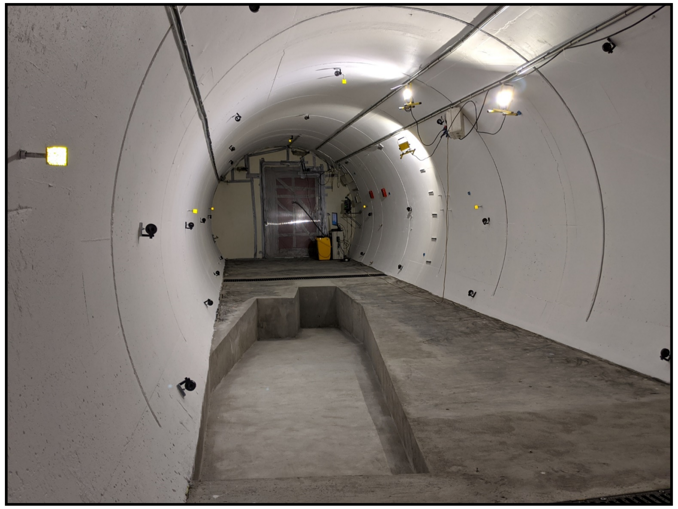

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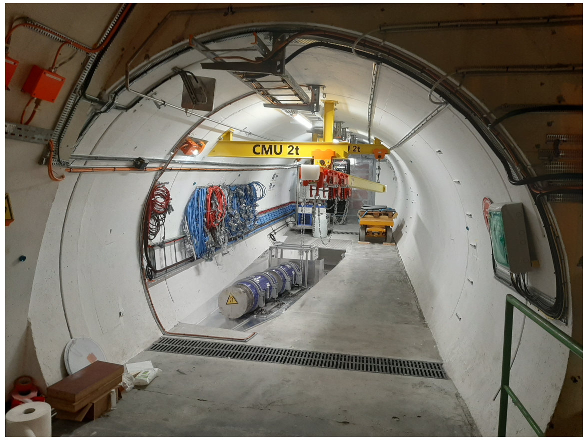

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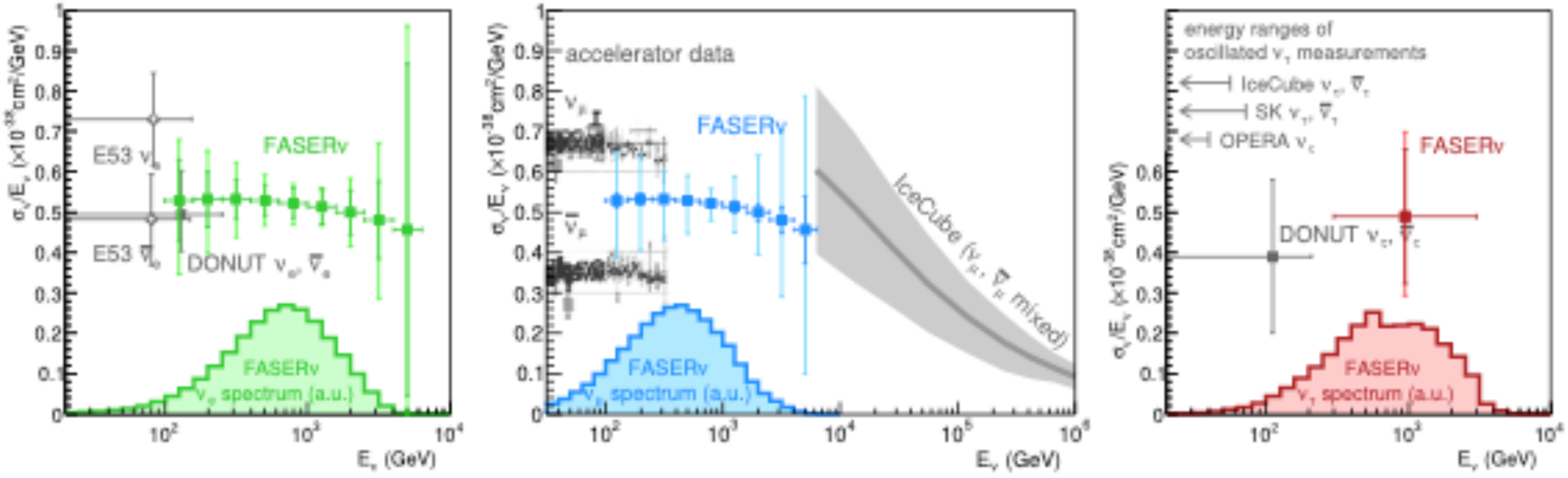
FASERnu cross section projections

Primary physics goal – cross section measurements at high energy.
Projected results:

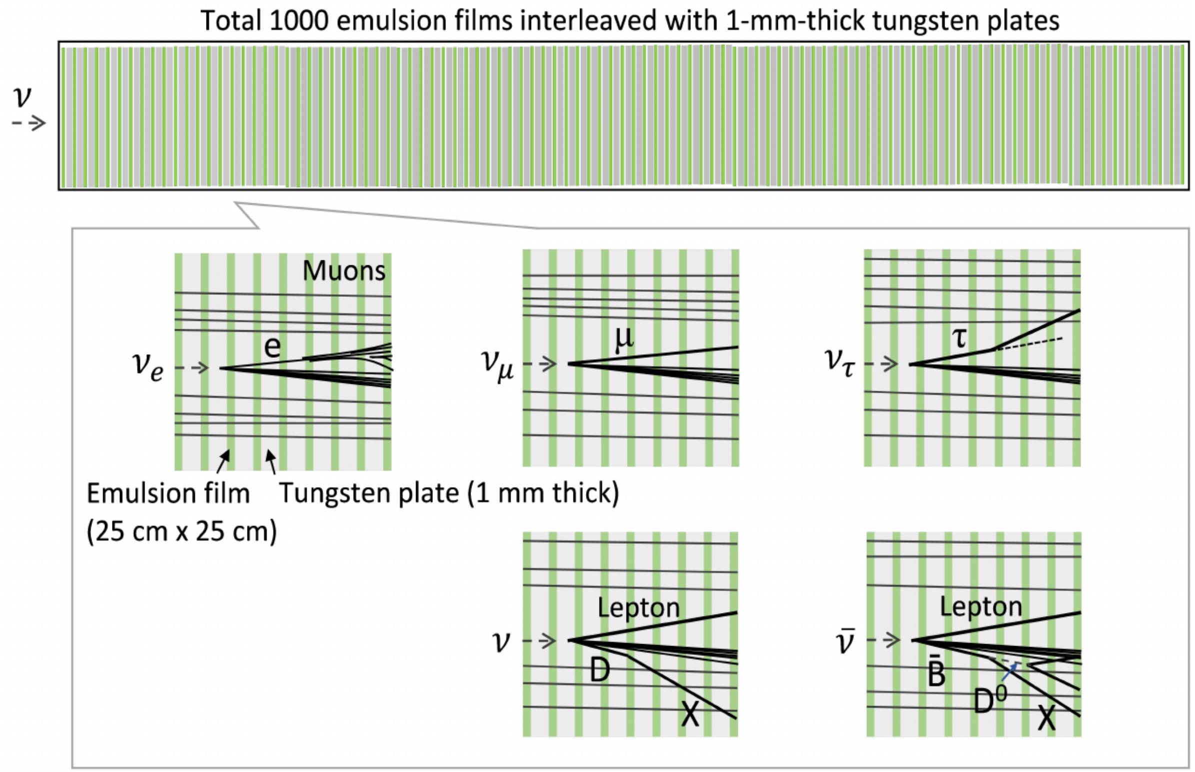


Uncertainty from neutrino production important
Neutrino energy reconstruction with resolution ~30% expected from simulation studies

Highest energy measurements for electron and tau nuetrinos.
Bridges gap between accelerator measurements (<400GeV) and very high energy measurements from ICECUBE

The FASERnu Detector

- FASERnu detector is 1.3m long, 25x25cm 1.2tn detector
- Made from 1000 x 1mm tick tungsten plates, interleaved with emulsion films
- Allows to distinguish all flavour of neutrino interactions and neutral hadron vertices
- Emulsion film has excellent position/angular resolution for charged particle tracks
- But no time resolution…
- Detector needs to be replaced every 30-50/fb to keep the track multiplicity manageable
- Will be replaced during Technical Stops during LHC running
    - Take advantage of transport infrastructure installed in UJ12/TI12 for FASER



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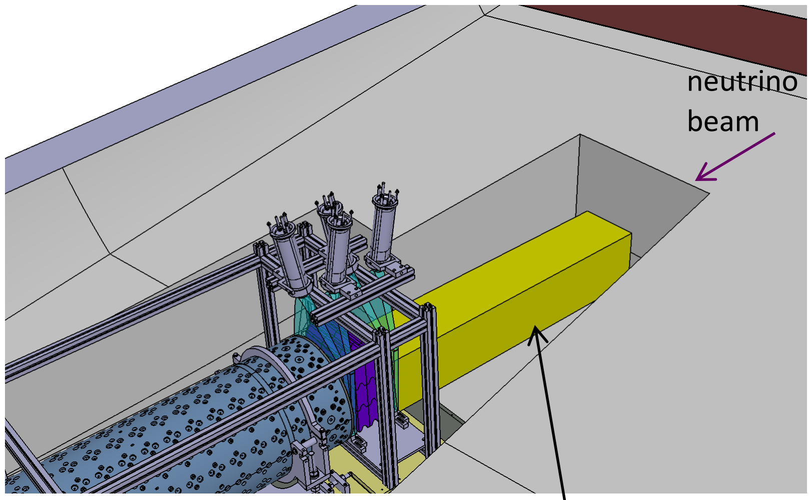
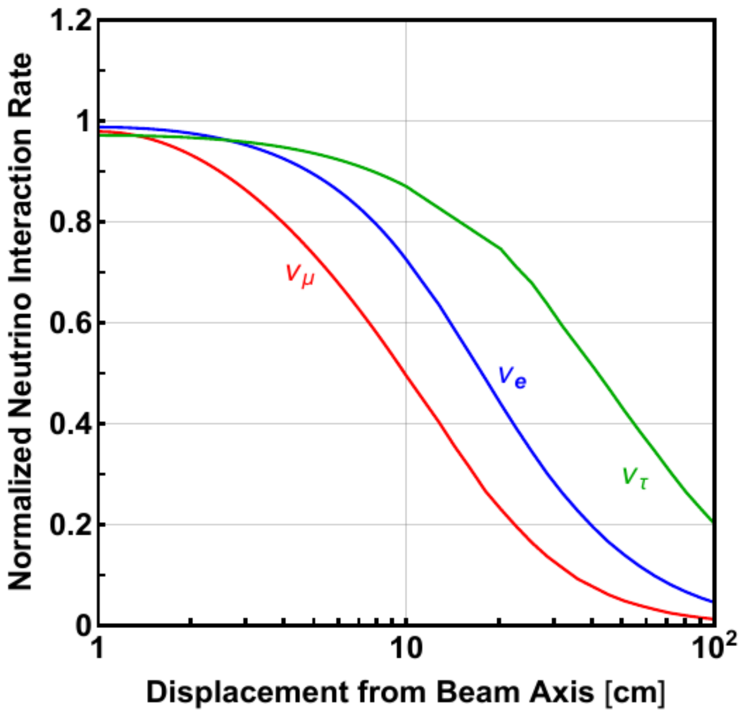
- Will be replaced during Technical Stops during LHC running
    - Take advantage of transport infrastructure installed in UJ12/TI12 for FASER
- FASERnu will be centered on the LOS (in the FASER trench)
    - Maximises flux of all neutrino flavours



FASERnu



The SND Experiment

- SND is 830tn neutrino detector installed in TI18 tunnel 500m from ATLAS IP (the other side from FASER(nu))
- The detector uses
  - tungsten/emulsion target interleaved with tracking (scintilator fiber tracker)
  - followed by a iron/scintilator-fiber detector (muon ID and hadronic calorimeter)
- SND is slightly off the collision axis, meaning it sees less neutrino flux than FASERnu, and probes different neutrino production processes
- Plans to:
  - Measure neutrino cross sections
  - Constrain gluon PDF at low x
  - Constrain lepton flavour universality in neutrino interactions
  - Measure neutral / charge current ratio
- The detector is under construction now, and will be installed in the tunnel from Oct-Dec 2021 for physics data taking in LHC Run 3