Long-lived particle experiments Of The Ring

Sam Meehan on behalf of
3 June 2020 at DM@LHC 2020

MATHUSLA
CODEX-B
AL3X
ANUBIS
MilliQan
MAPP
FASER

In the spirit of a similar talk last year at DM@LHC2019 by C. Alpigiani ➜ orthogonal view & highlight points of progress

An Unexpected Journey

HCP 2002 Proceedings

- Pre-LHC : How do we tell SUSY #1 from SUSY #2?
- Post-Run2 : Where is everything (other than the Higgs)?

3 Supersymmetry (SUSY)

...

the missing E_T plus jets signal. The task of the LHC and LC will then be to untangle the supersymmetric spectroscopy and to verify that the new particles are indeed the result of an underlying supersymmetric theory.

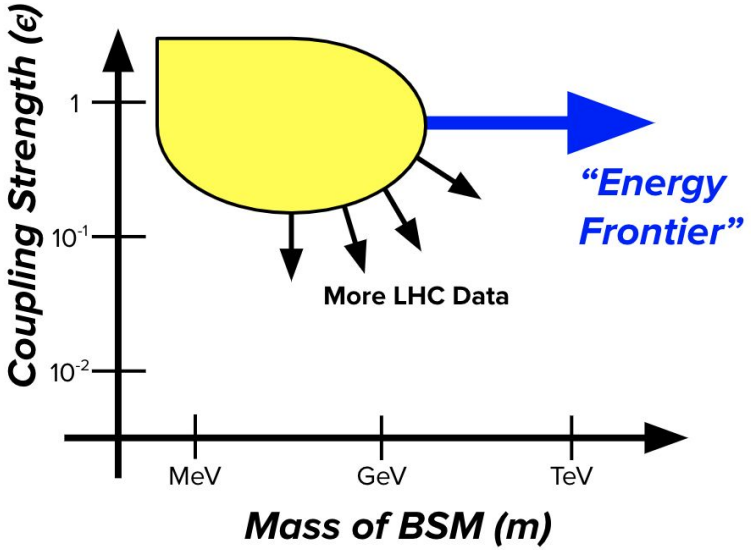
A New Intuition

(for Sam at least)

What are we searching for?

1911.00481

- LHC experiments built/operated with (necessary) biases about new physics
  - [1] Heavy particles ➔ energy-based triggers
  - [2] Charged particles ➔ choice of detector technology
  - [3] Strongly coupled ➔ instrumentation close to IP
- Need to rethink these biases to search for ***neutral ultra-long-lived*** particles



$$L = v\tau\gamma \sim c \times \frac{1}{\epsilon^2 m} \times \frac{E}{m}$$

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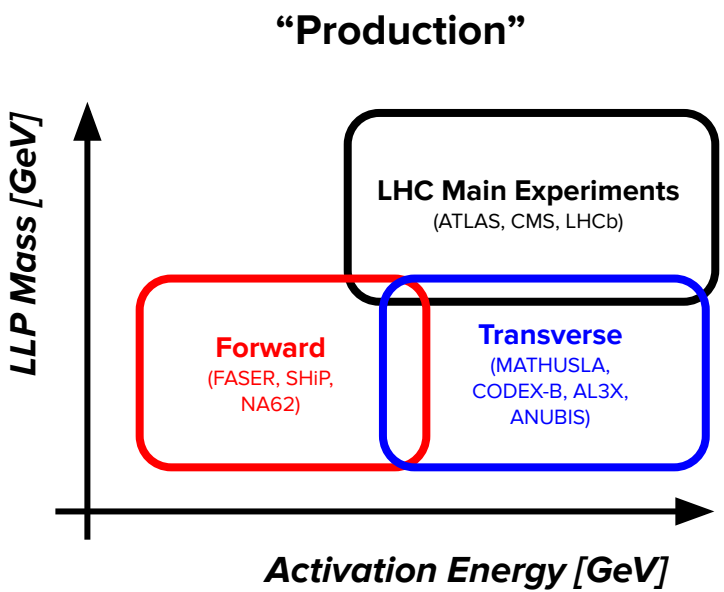
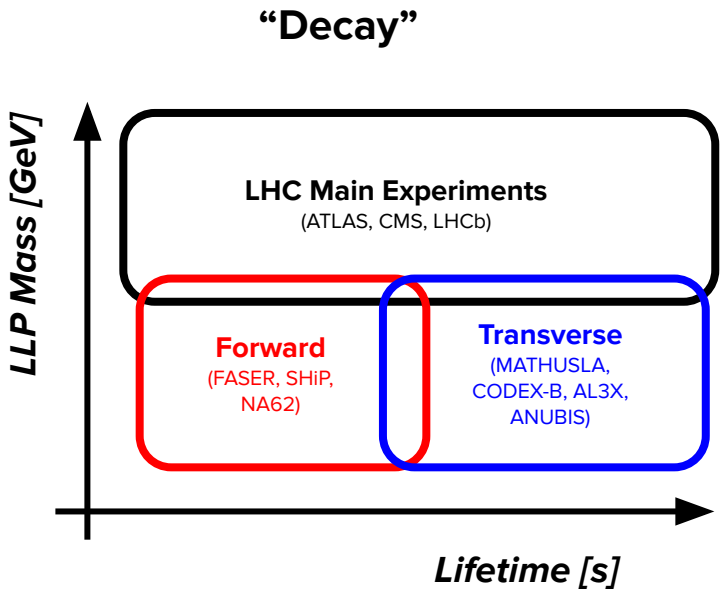
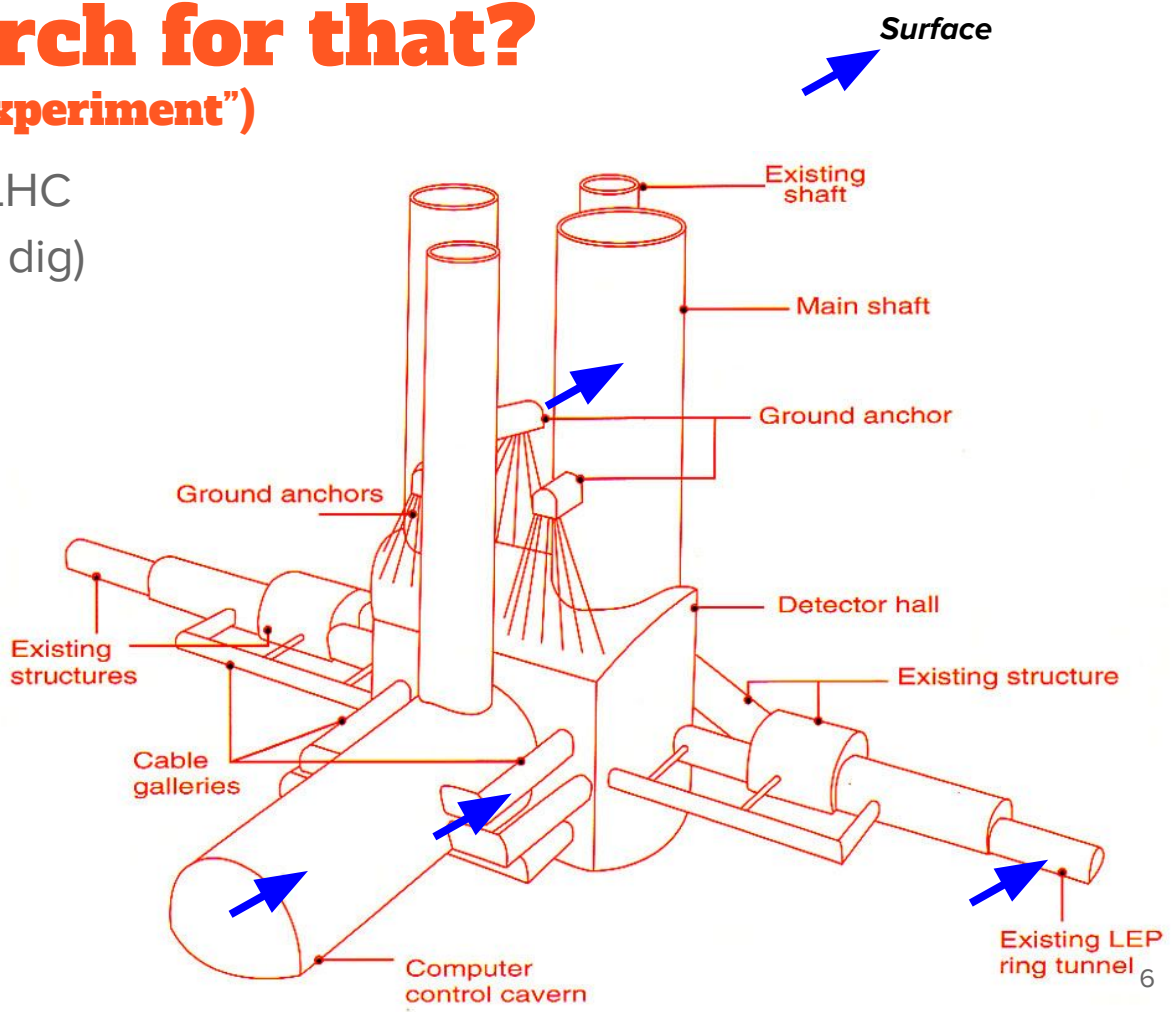




How do we search for that?

(aka "How to build an LLP experiment")

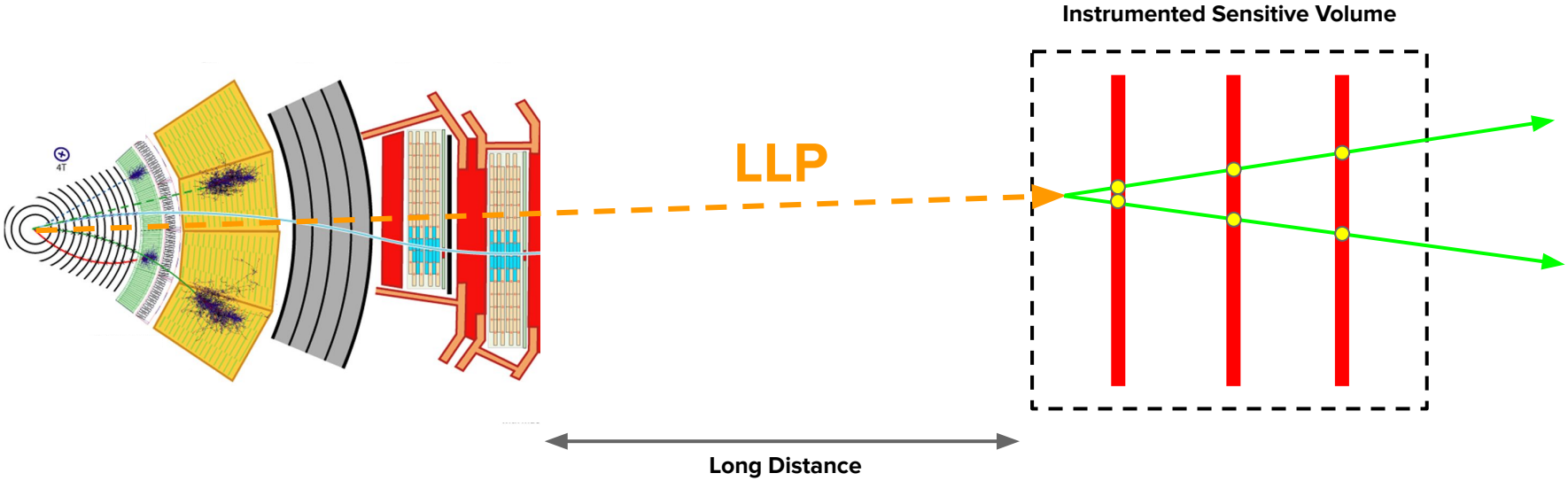
- **[1]** Find a place near an LHC interaction point (try not to dig)
  - Counting rooms
  - Service tunnels
  - Access shafts
  - Surface areas



How do we search for that?

(aka "How to build an LLP experiment")

- **[2]** Instrument the ***largest 3D volume*** with a set of "simple" subsystems
  - "Simple" : Nchan, availability/cost of hardware, complexity of operation
- Driving necessity : charged particle reconstruction
  - RPCs (muon systems), precision silicon detectors (ATLAS/CMS LHCb ID), extruded scintillators



How do we search for that?

(aka "How to build an LLP experiment")

1980s @ CERN

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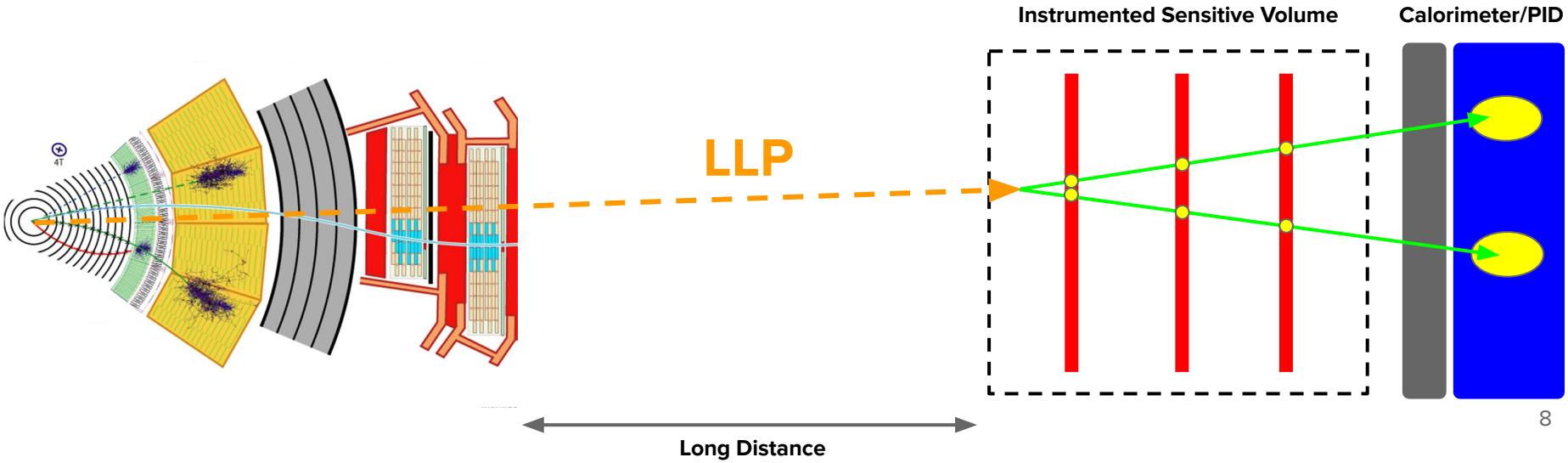
  - RPCs (muon systems), precision silicon detectors (ATLAS/C
- Would be nice : e/γ/μ/h discrimination ➔ calorimeter

Lepton detection at LHC is crucial. Small rates are expected for many potential signals

⇒ detection of e and μ



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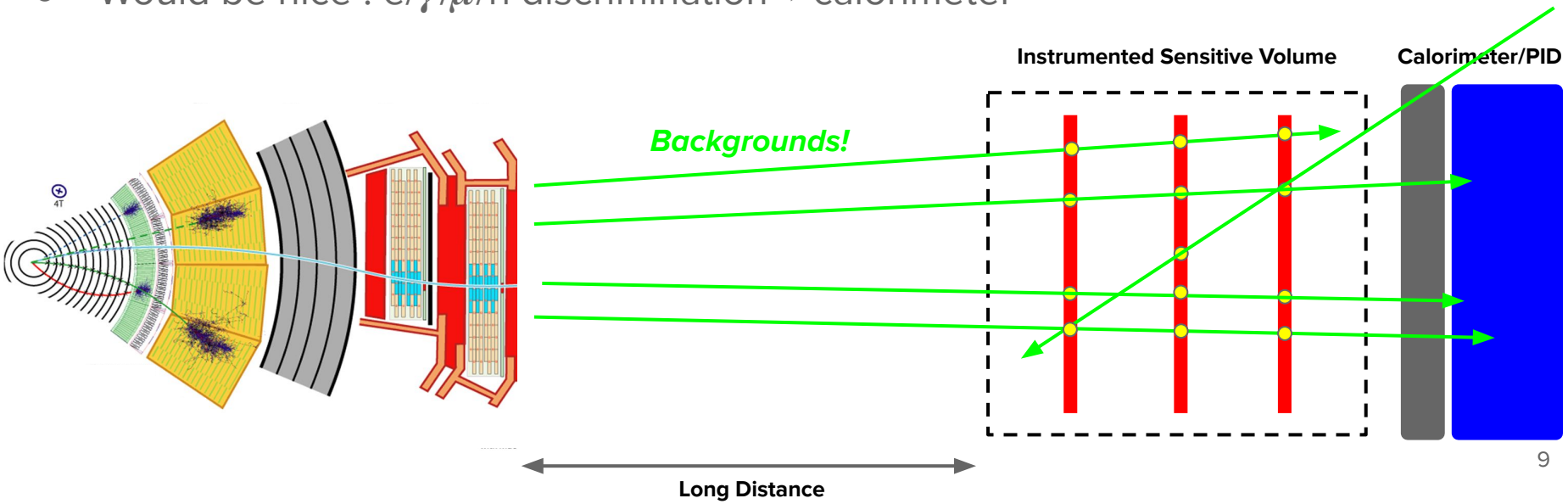
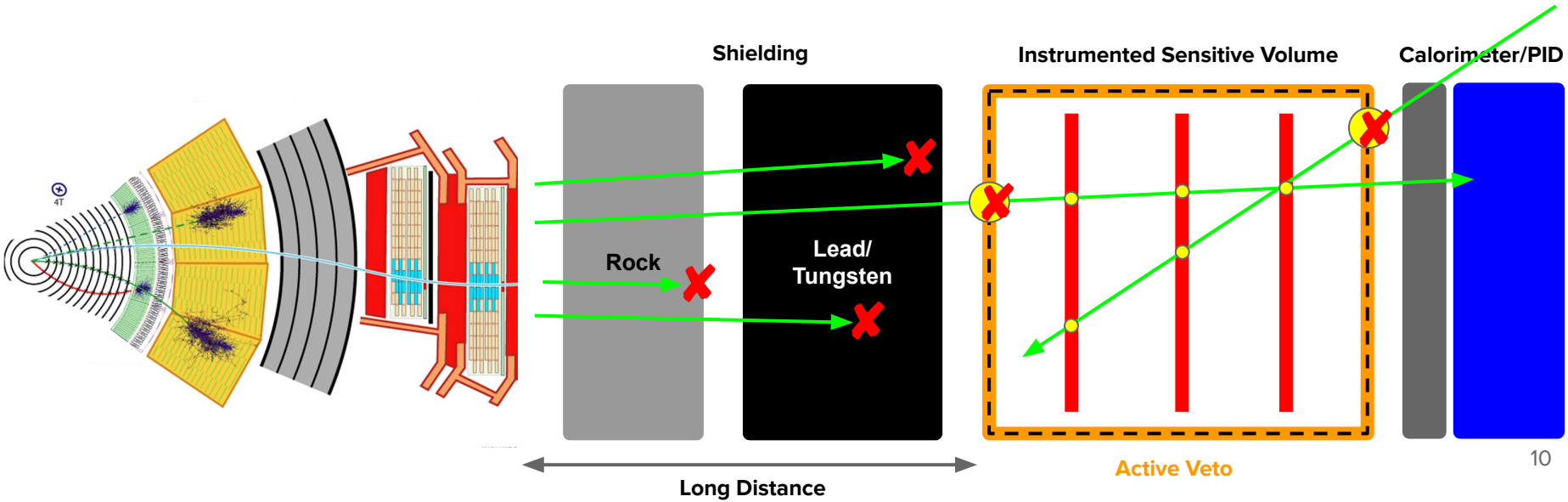


How do we search for that?

(aka "How to build an LLP experiment")

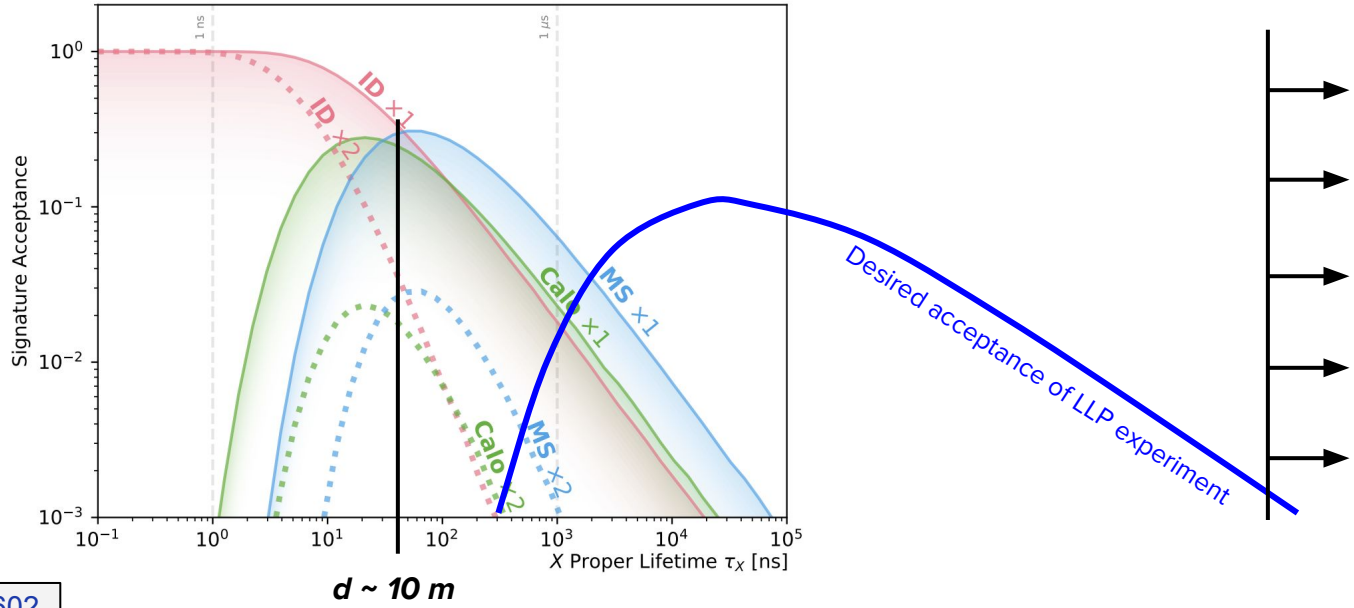
- **[3]** Shield the experiment from everything
  - Passive shielding : rock (λ=40cm), lead (λ=20cm), tungsten (λ=10cm)
  - Active shielding : Scintillator (integrated with passive shielding)
- Leverage reconstructed track topology : vertexing/pointing to IP
  - Assumed/biased towards fully visible decays of LLP



Sensitivity

trometer (i.e. ≈10 m away from the interaction point), and we assume that backgrounds can be brought under control in this region. In this case the discovery reach for LLP scenarios with $c\tau \lesssim 100$ m is significantly extended, cf. Fig. 5.

- It's all about signal yield (acceptance)
  - Key assumption : … so long as you can remove all backgrounds
- Existing (ATLAS/CMS/LHCb) experiments cover the "prompt" (<10m) region
  - Ultimate goal is to reach big bang nucleosynthesis bound at ~10^7 m



1810.12602

Sensitivity

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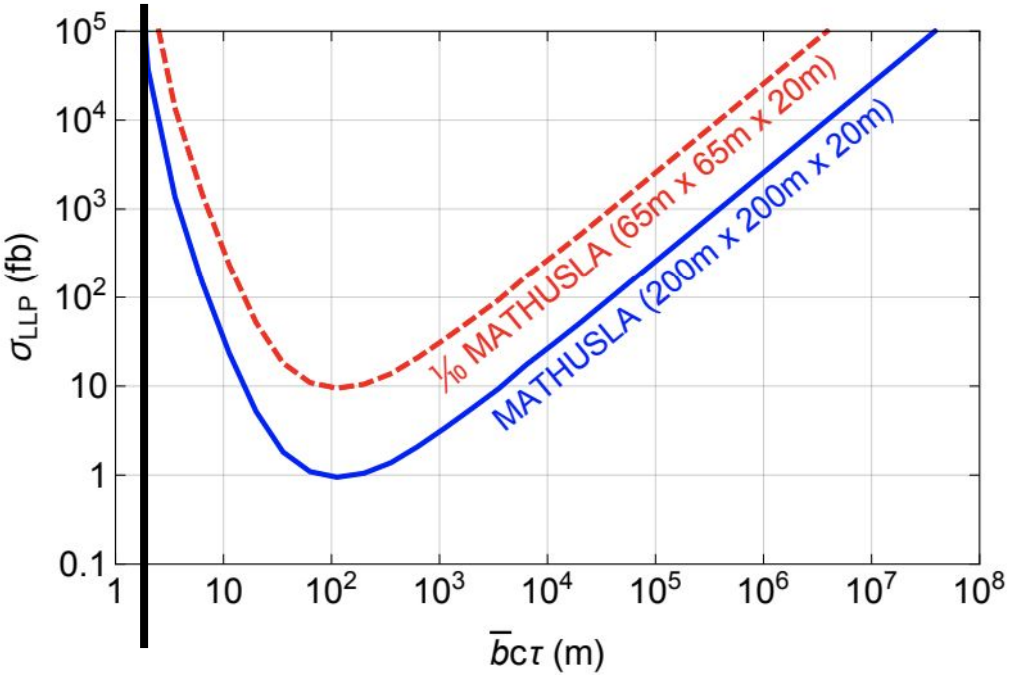
- It's all about acceptance
  - ... so long as you can remove all backgrounds
- **[1]** Hard boundary created by physical proximity to production
  - If particle decays too soon (strongly coupled) we won't see it



1806.07396

Sensitivity

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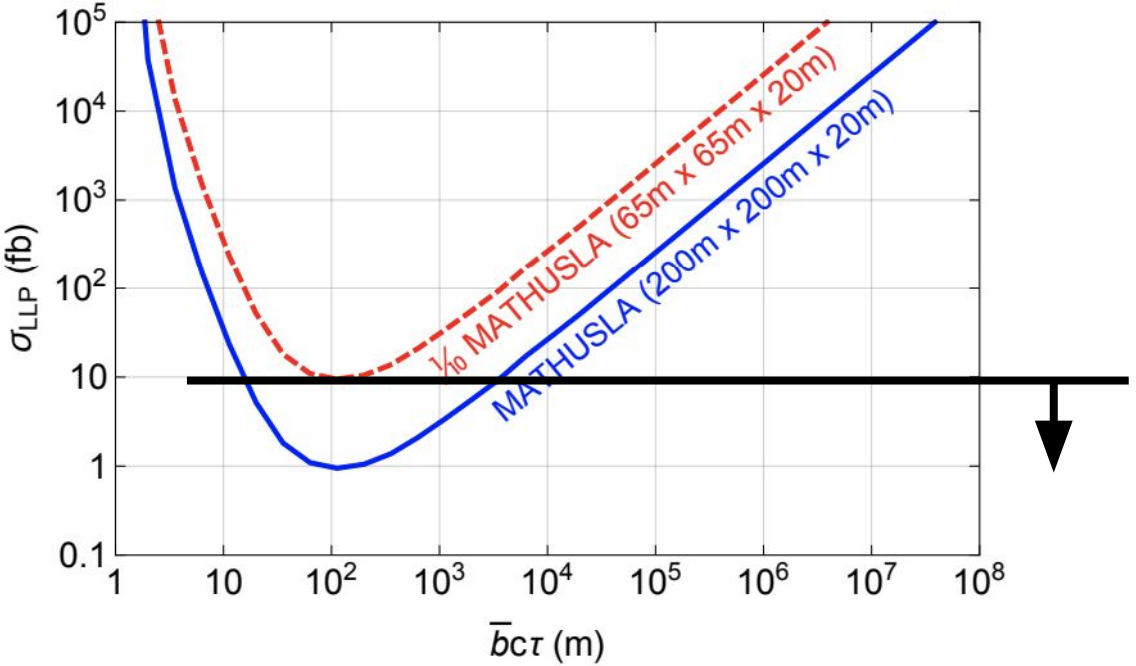
- It's all about acceptance
  - ... so long as you can remove all backgrounds
- **[2]** Depth of sensitivity increases with exposure : **Time (L_{int})** × **Volume** × **Efficiency**
  - Think like direct dark matter "kg*years"

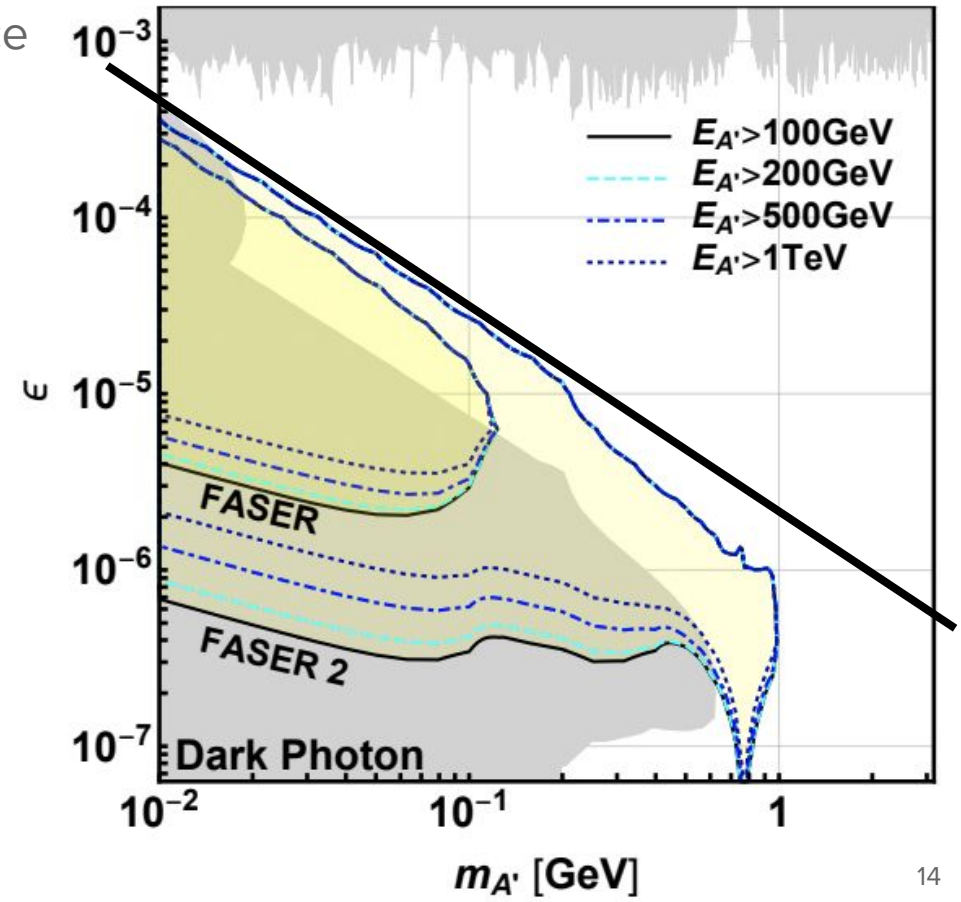


1806.07396

Sensitivity : Part Deux

1811.12522 (Physics Rev.)

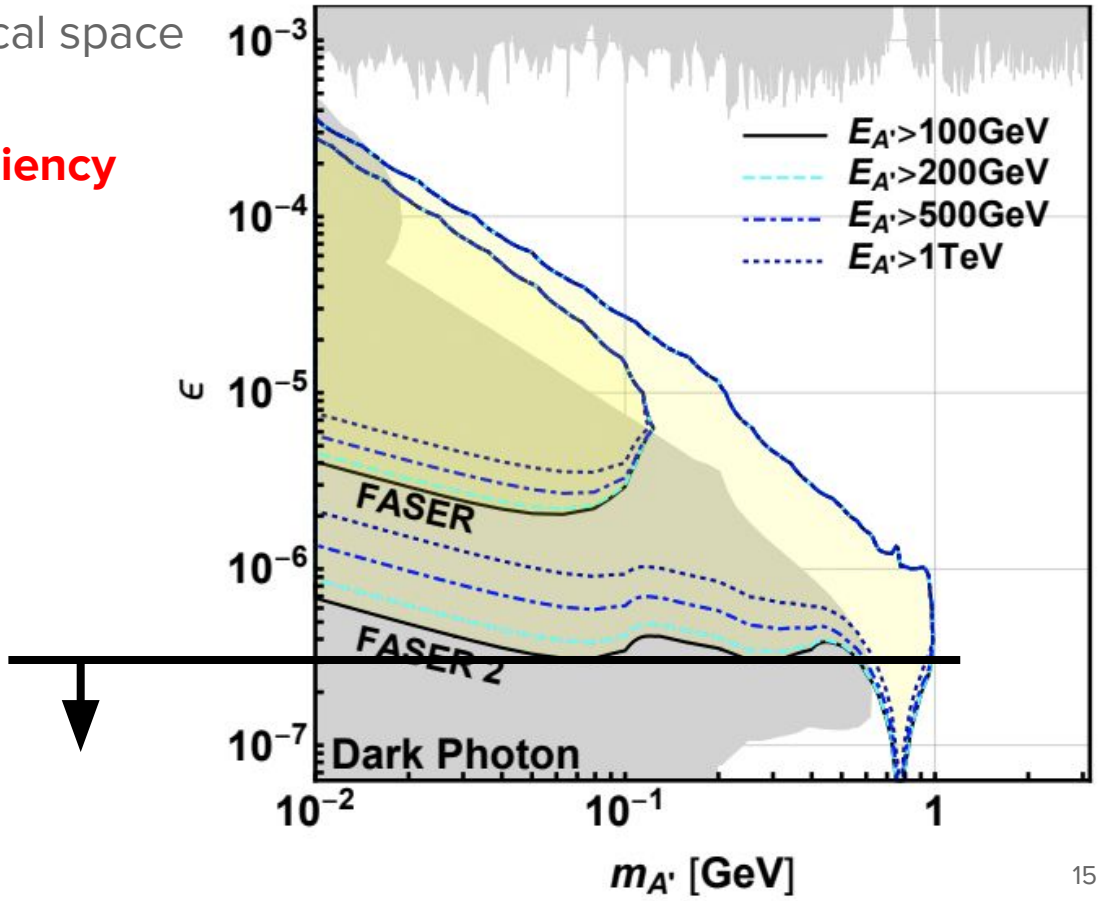
- Translate to “meaningful” physical space
- **[1]** Top boundary
  - Set by the “sensitivity wall” created by proximity to experiment



Sensitivity : Part Deux

1811.12522 (Physics Rev.)

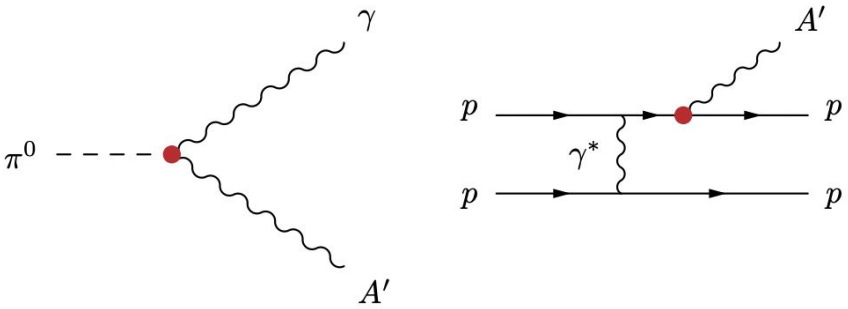
- Translate to “meaningful” physical space
- [2] Bottom boundary
  - **Time (L_{int}) × Volume × Efficiency**
    - Bigger detector
    - Lower thresholds
    - Higher luminosity

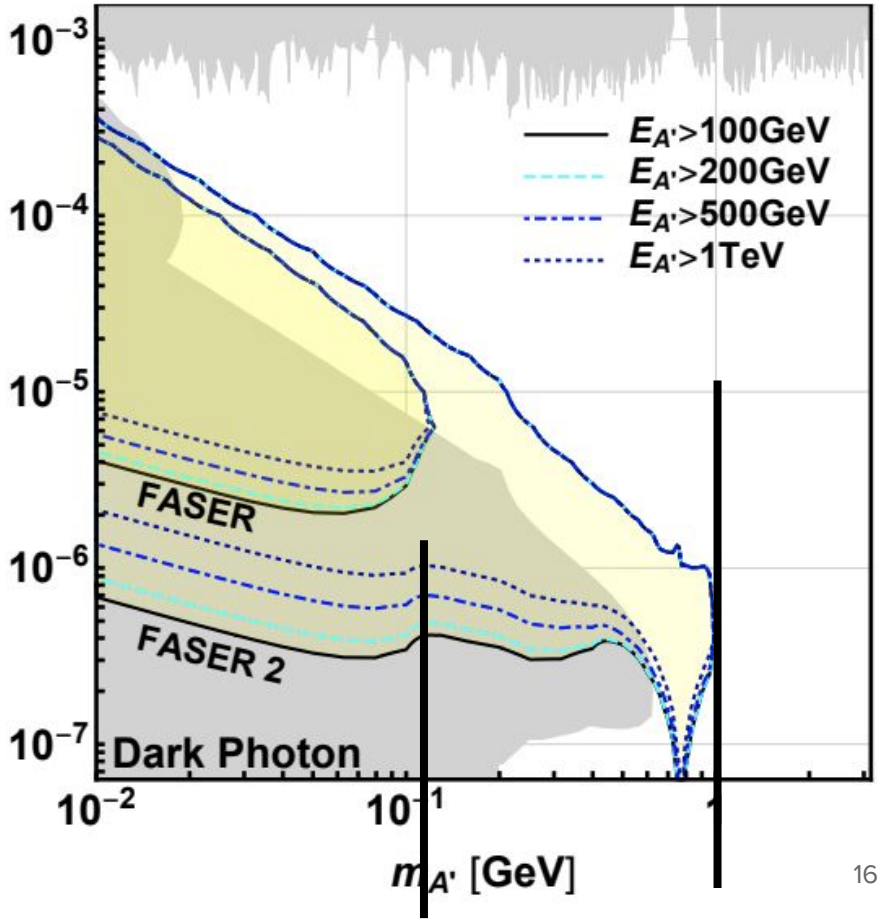


Sensitivity : Part Deux

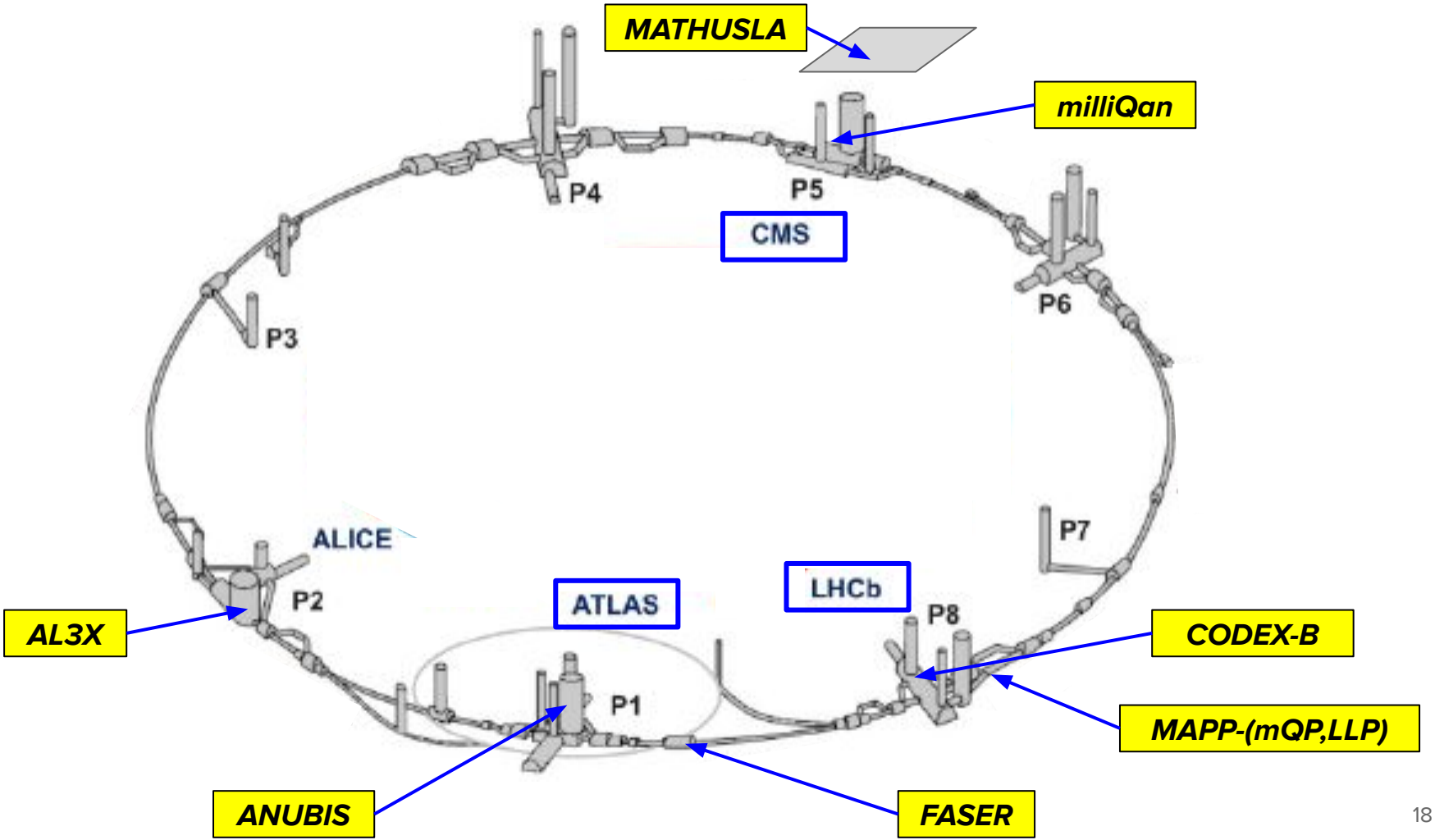
1811.12522 (Physics Rev.)

- Translate to “meaningful” physical space
- **[3]** Mass reach
  - Which production mechanism (“activation energy”) falls into your acceptance
    - Higgs vs. Hadron decays
    - 2 body vs. 3 body
    - Production energy (“boost”)
  - Largely dictated by location wrt collision point and beamline





But what about the actual experiments?


MATHUSLA
milliQan
P4
P5
CMS
P6
P3
P7
ALICE
P2
ATLAS
LHCb
P8
AL3X
CODEX-B
P1
MAPP-(mQP,LLP)
ANUBIS
FASER

LHC-LLP Workshop #7
(“The Council of Elrond”)

MATHUSLA (Gandalf)

1606.06298 (Initial idea)
1705.06327 (Reco Ideas)
1806.07396 (Thorough Review)
1811.00927 (Letter of Intent)

- Surface-based detector near CMS (200×200×20) m^3 @ 100m
  - Box of scintillators + 5 planes of charged particle identification (cm-sized hit resolution) ➔ tracking
    - Considering : resistive plate chambers (“muon detectors”) or extruded scintillators
  - No magnet / No calorimetry ➔ possible extension upgrade

In the Mines of Moria (youtube)

“I wish it need not have happened in my time," said Frodo. "So do I," said Gandalf, "and so do all who live to see such times. ***But that is not for them to decide. All we have to decide is what to do with the time that is given us.***”

In the MATHUSLA Physics Case

“***The collider to produce LLPs is already in place***. ***A relatively incremental upgrade*** … ***is not only feasible, but highly motivated*** …”

MATHUSLA

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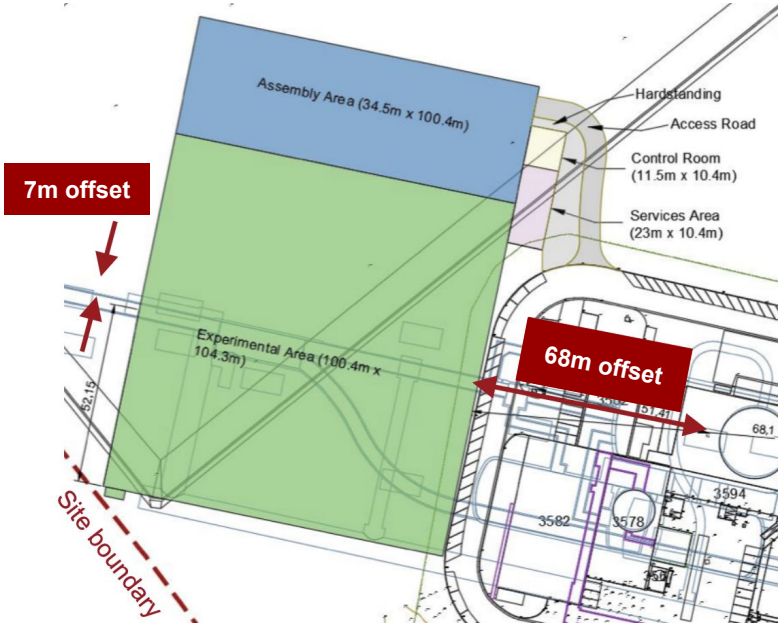

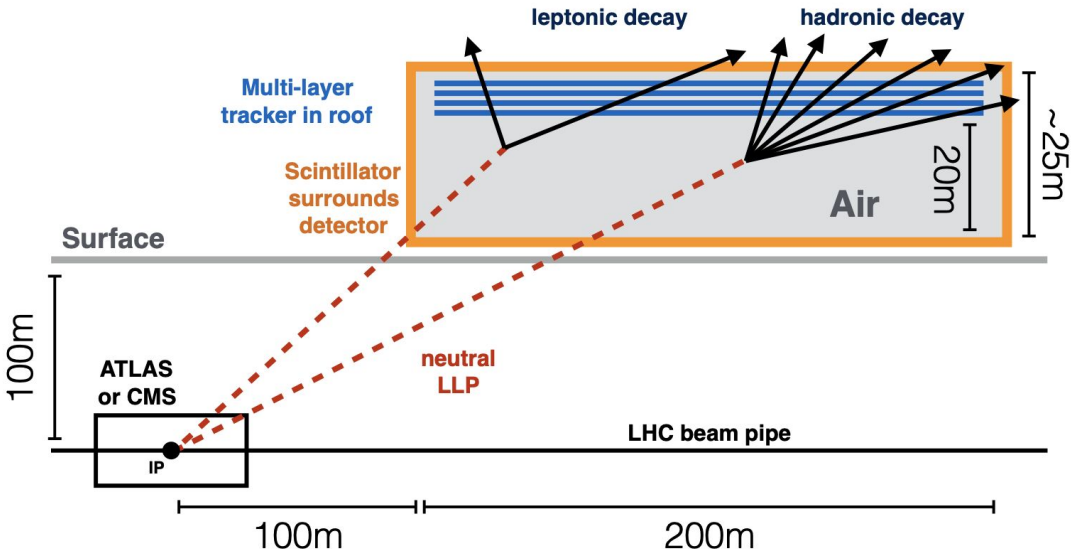

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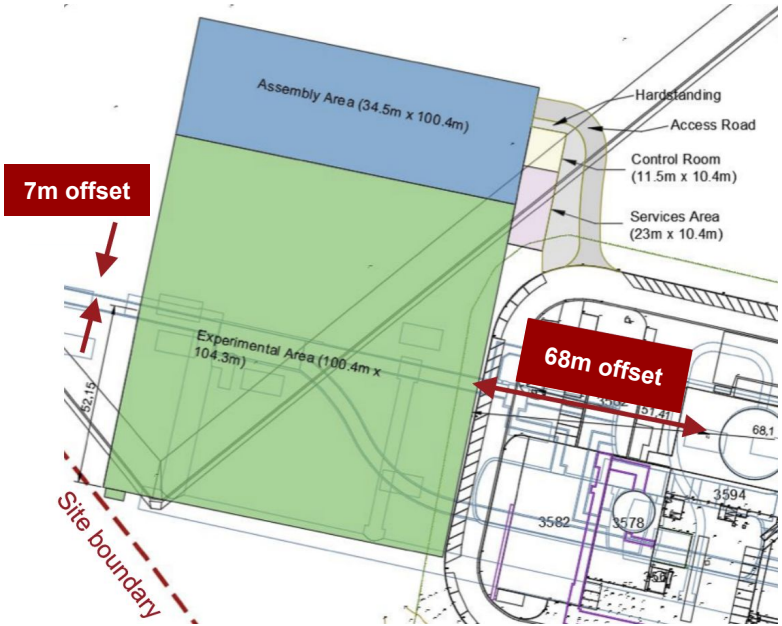
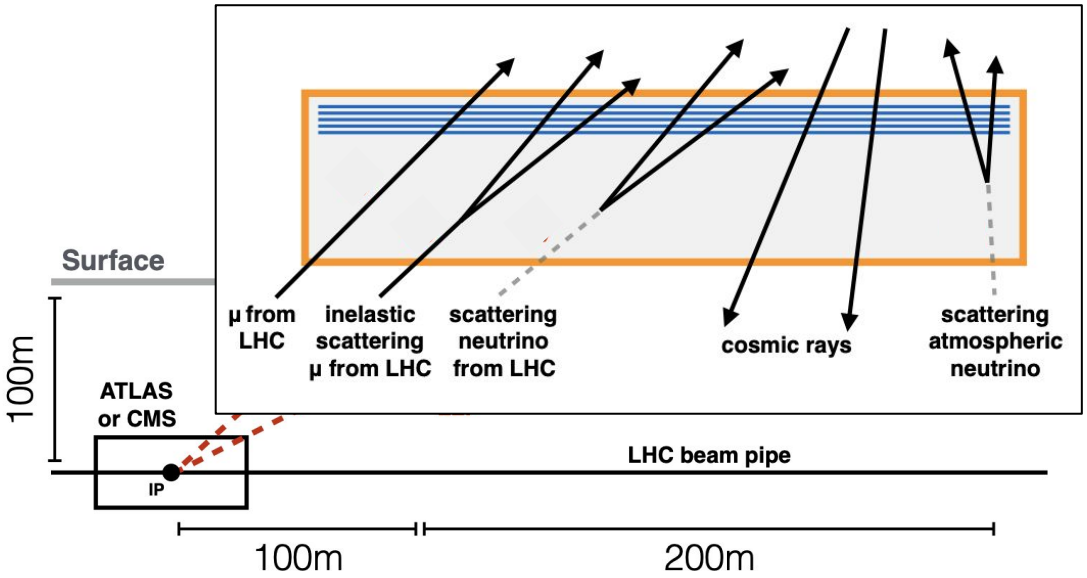
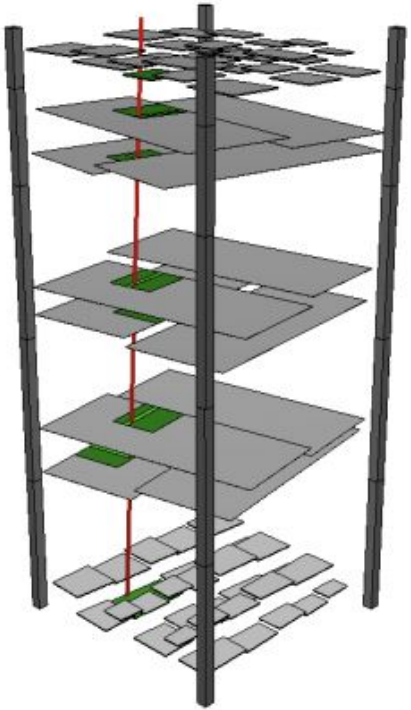


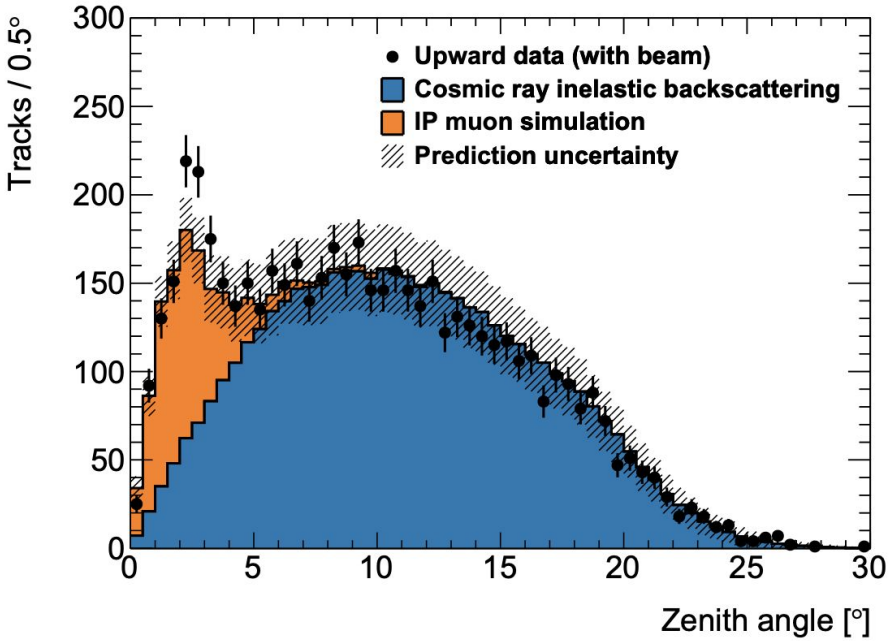


MATHUSLA

2005.02018 (Data!!!!)

- Test stand operated during Run2 near ATLAS during 2018
  - RPC+scintillators, (2.5m×2.5m×3m) @ 80m directly above ATLAS
- Promising description of cosmic background (especially backscattering!)

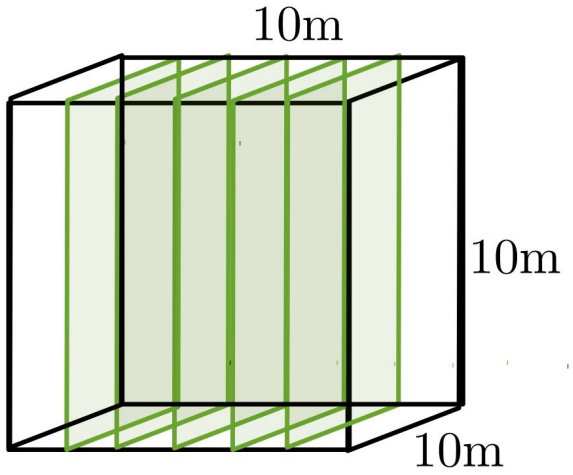


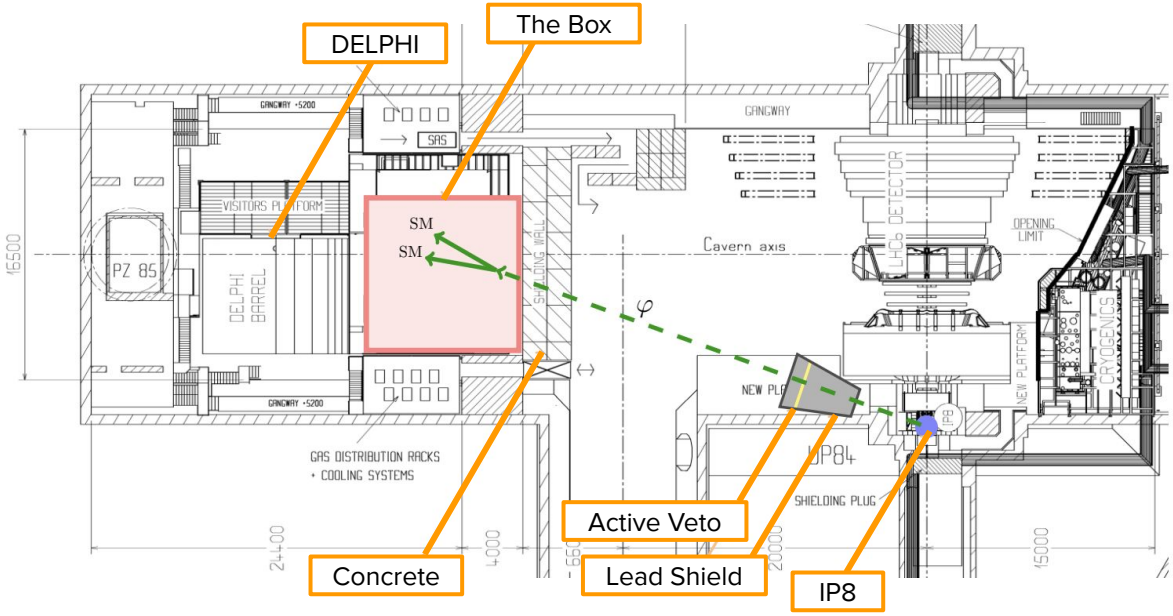


CODEX-B (Aragorn)

1708.09395 (Initial Idea)

- Located underground in old LHCb HLT farm "box" : (10×10×10) m^3 @ 25m
  - Box of resistive plate chambers with 5 inner layers
  - No magnet / No calorimetry ➡ possible extension upgrade
  - Additional passive (lead) shielding (25**λ**) with embedded active scintillator veto
- Reminder : IP8 runs at much lower lumi (factor of 10)





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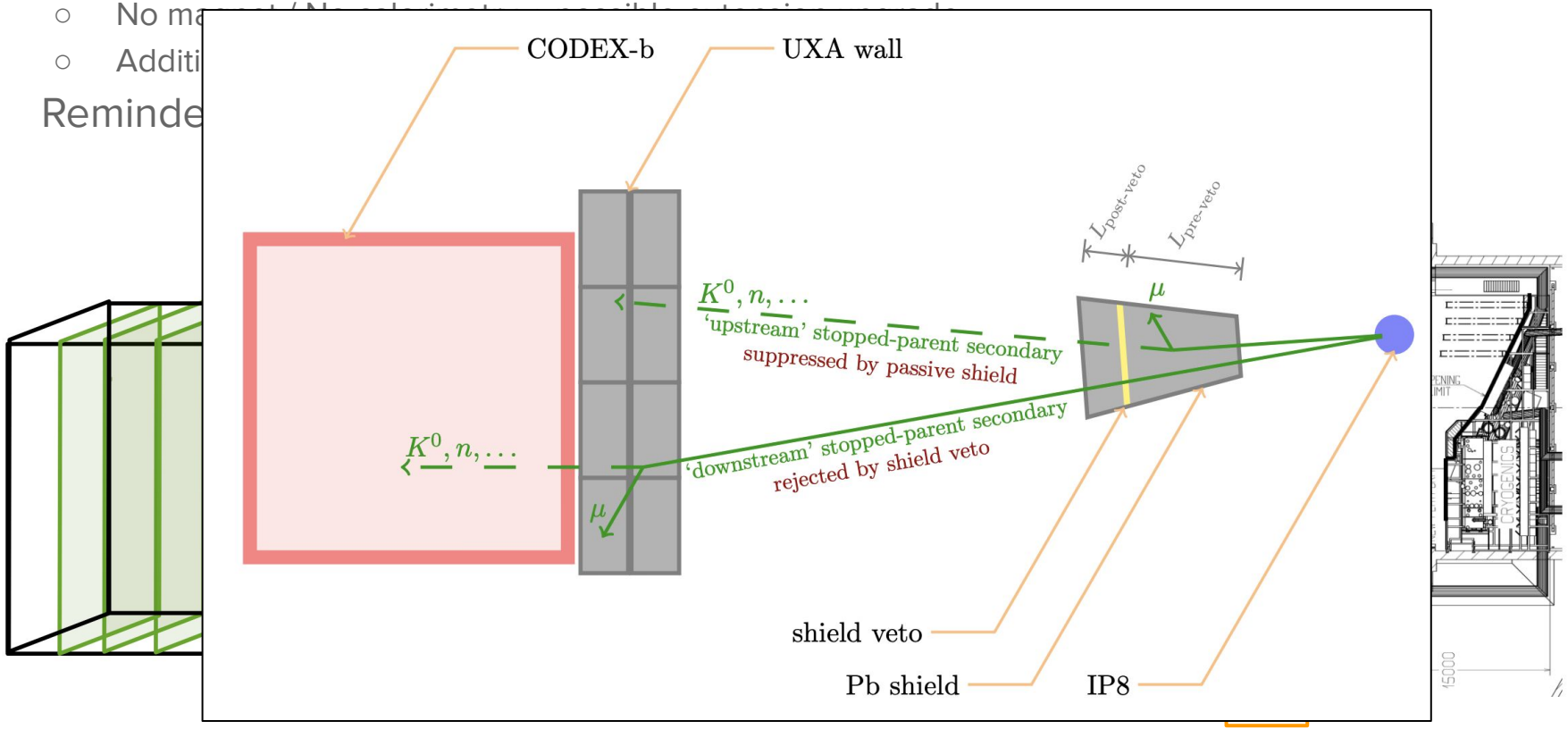
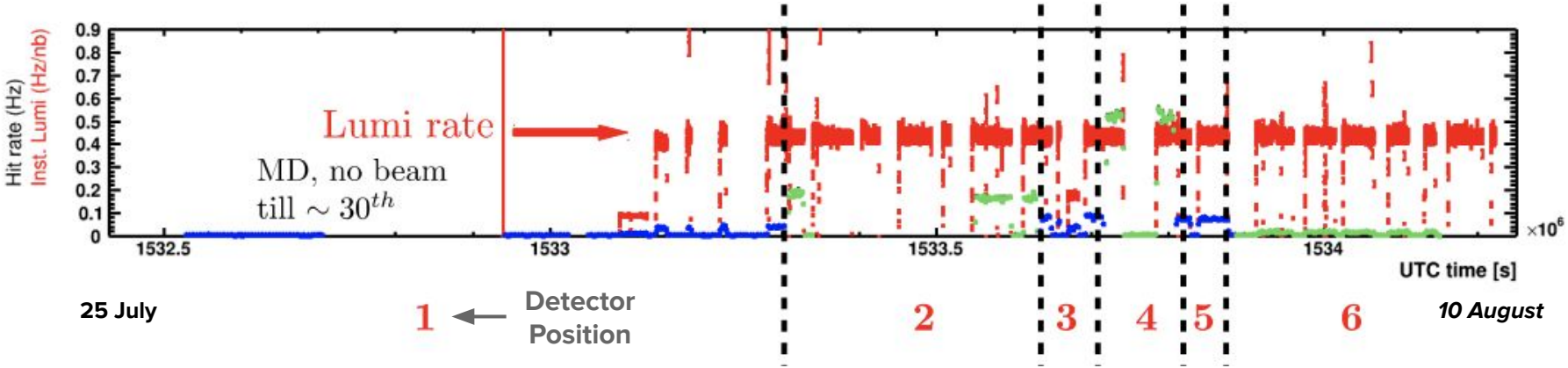


CODEX-B

- Shielding reduces IP and secondary backgrounds
  - Studied in refined GEANT sim. ➔ Most challenging background (secondary neutrals) is manageable
- Validated during Run2 using scintillator measurement of fluxes
  - Rate is 50 times lower than expected from GEANT ➔ estimation is conservative
- Planning to install CODEX-**β** (10×10×10 m^3) demonstrator in Run3

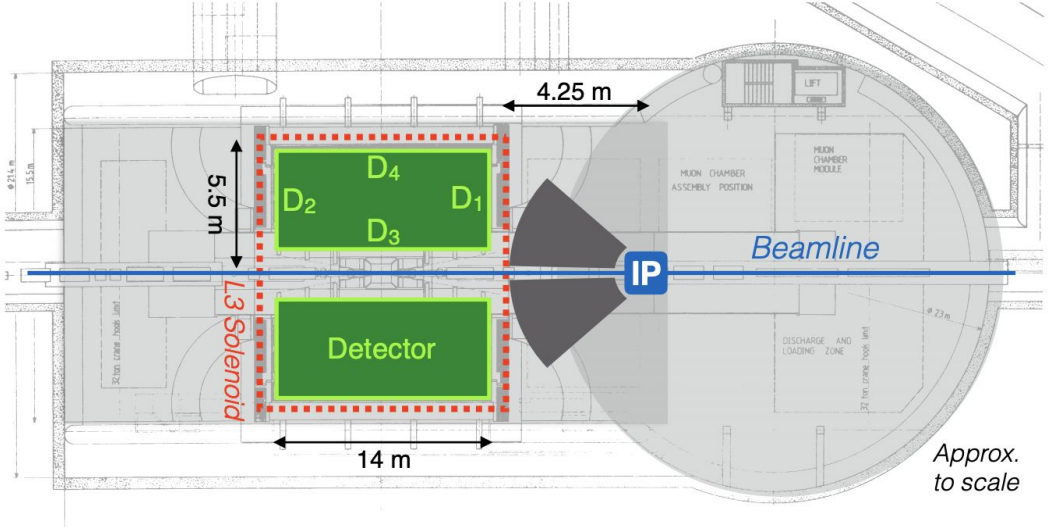
Predicted : 10 Hz ***Observed :*** 0.2 Hz

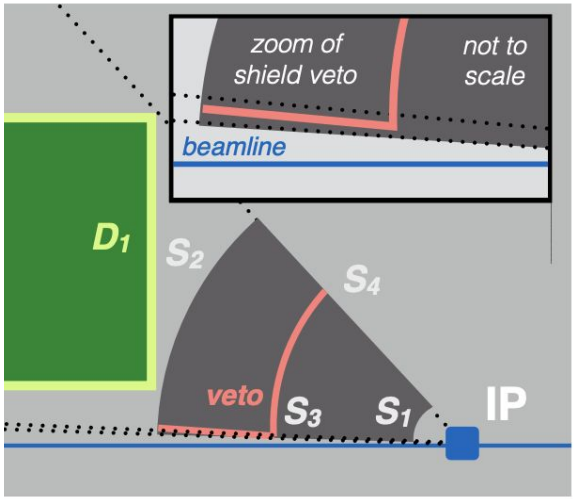


AL3X (Boromir)

1810.03636 (Initial Idea)

- Targeting IP2 (ALICE) in Run5 (assumed no Run5 ALICE ➔ unclear 1902.01211)
- "augmented ALICE" : (12 × r=[0.85,5]) m^3 annulus @ 10m with full 2π azimuth
  - ALICE time projection chamber (with magnet!) + scintillator shell + passive(40λ)/active veto
  - LHC machine modifications near IP2 would be sizeable
    - Move IP by ~10m ➔ needs new magnet infrastructure
    - Increase luminosity ➔ secondary effects to other experiments

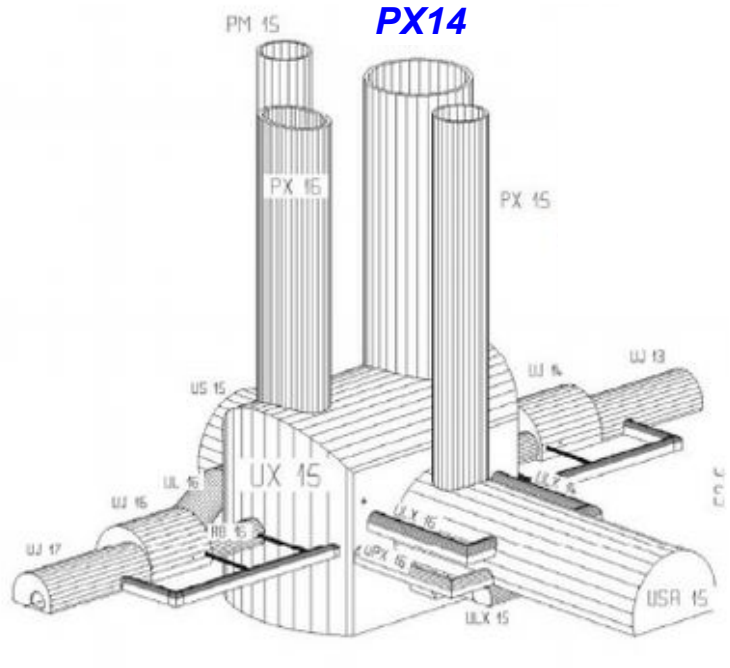




ANUBIS (Legolas)

1909.13022 (Initial Idea)

- “smaller/closer/cheaper MATHUSLA” : (60 × r=10) m^3 cylinder @ 20m
  - Instrumented in ATLAS PX14 access shaft
  - Hang 4 layers of resistive plate chambers spaced 18m apart into PX14 shaft
  - No magnet / No calorimeter / No veto scintillators ➡ room for exploration



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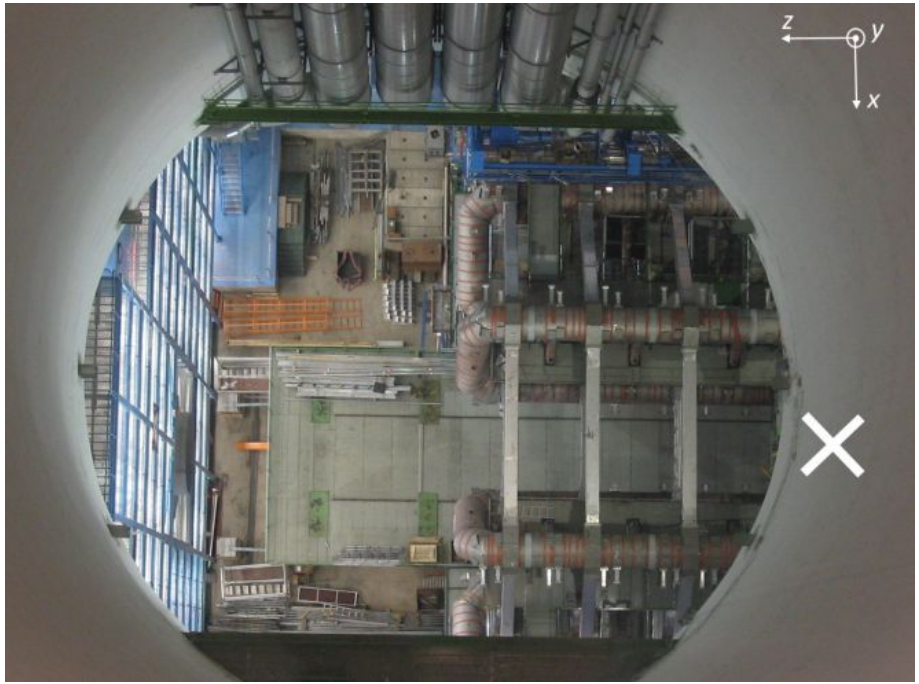
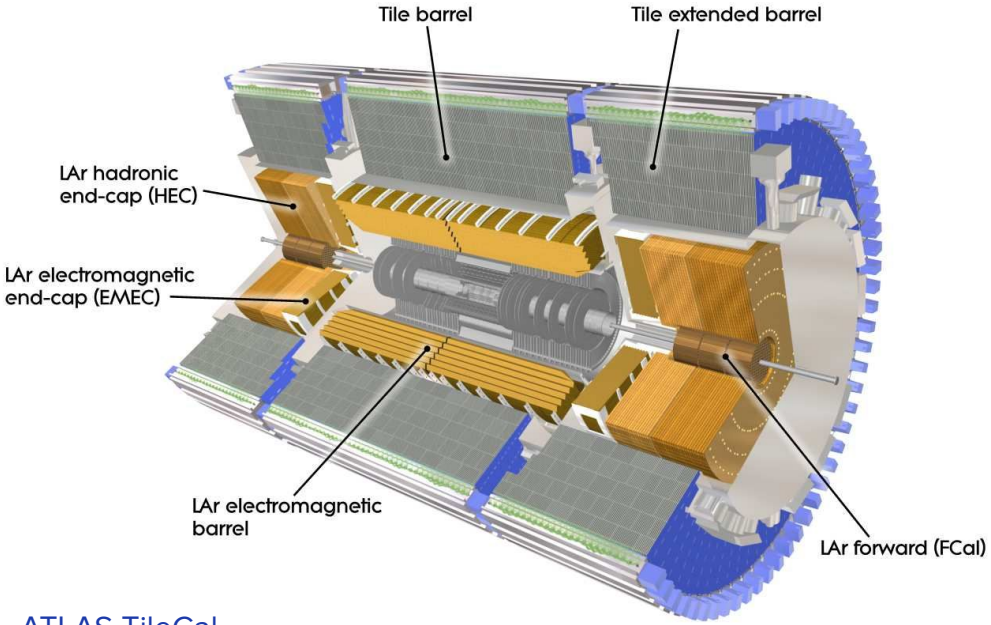
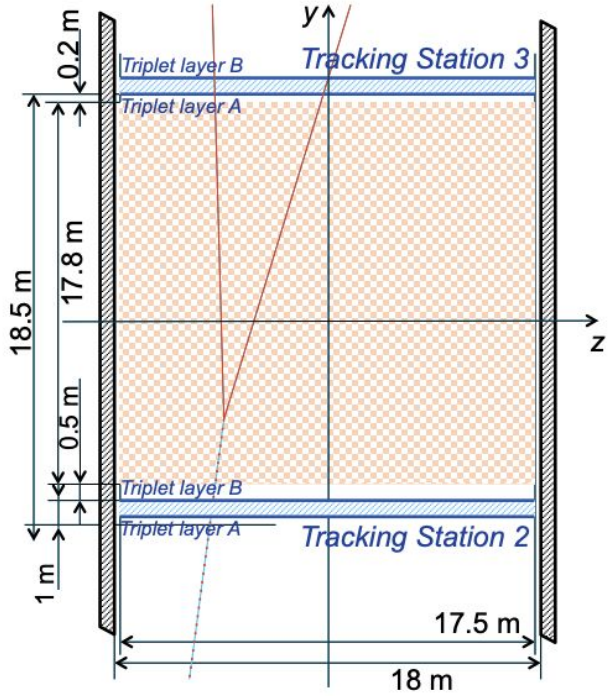


ANUBIS

- Critically relies on ATLAS calorimeter system (10λ) for shielding and active veto
  - (seemingly) not possible without interfacing to main ATLAS detector
  - ATLAS L1 muon rate is many kHz from IP ➡ not really background free - can it be vetoed/measured?



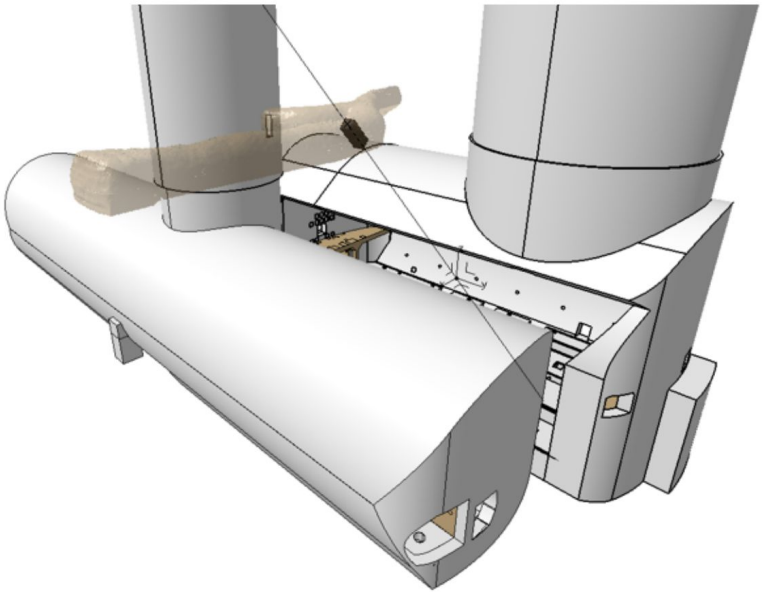


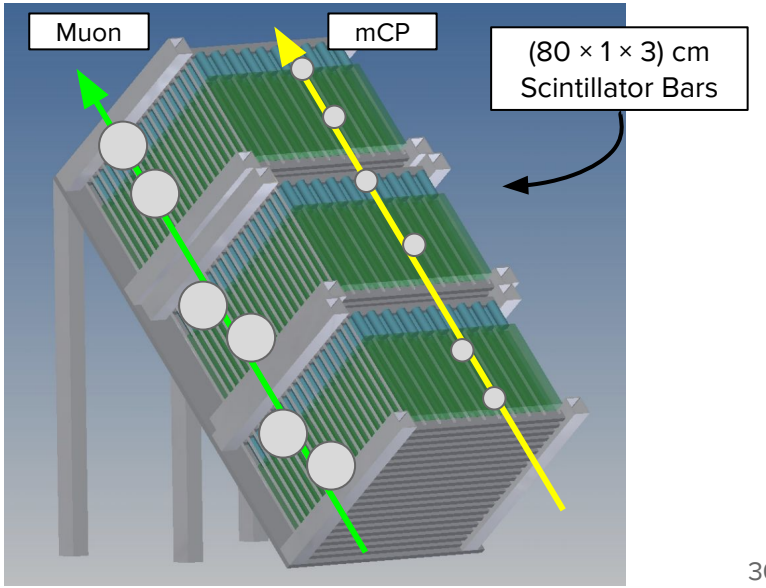
ATLAS TileCal

MilliQan (Gimli)

1410.6816 (Initial Idea)
1607.04669 (Letter of Intent)

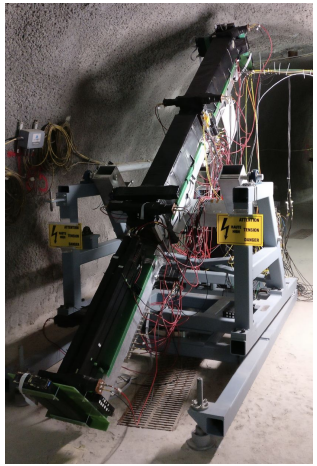
- Grid of plastic scintillators : (1×1×3) m^3 @ 33m with 17m of rock
  - Installed in drainage gallery above CMS at IP5
  - 400 scintillators per layer ➡ triple coincidence to identify origin at CMS IP
- Searching for millicharged particle scintillation light
  - milli-charged ➡ few photo-electrons



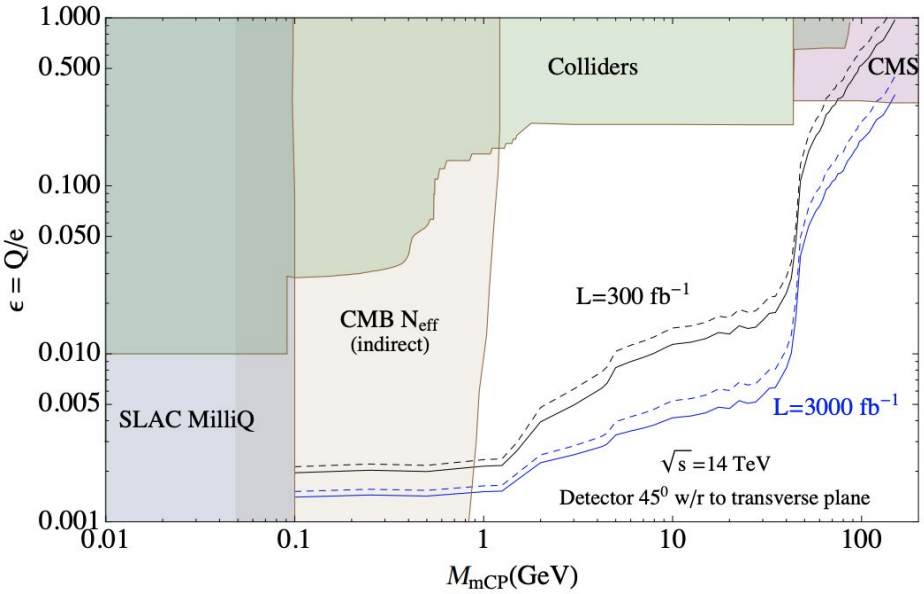


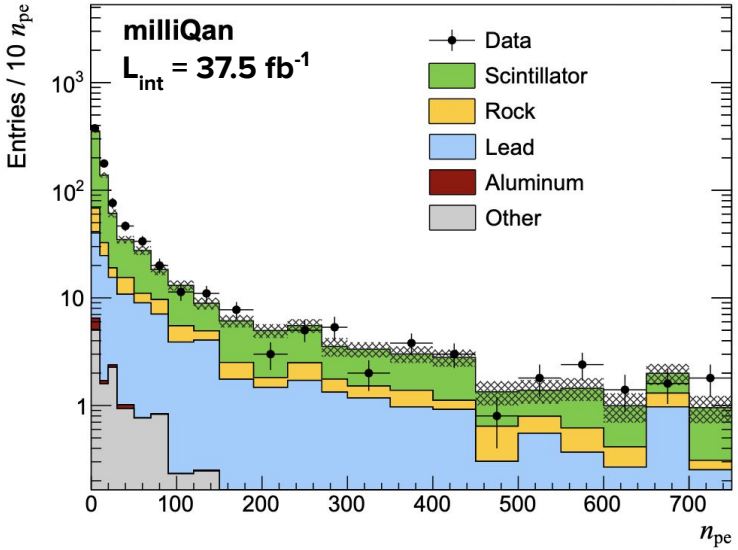
MilliQan

2005.06518 (Data!!!)



- Can extend sensitivity reach by orders of magnitude
- First results from demonstrator ➔ more in Ryan Schmitz talk next
  - Study backgrounds, guide full design, already probing new coupling regime

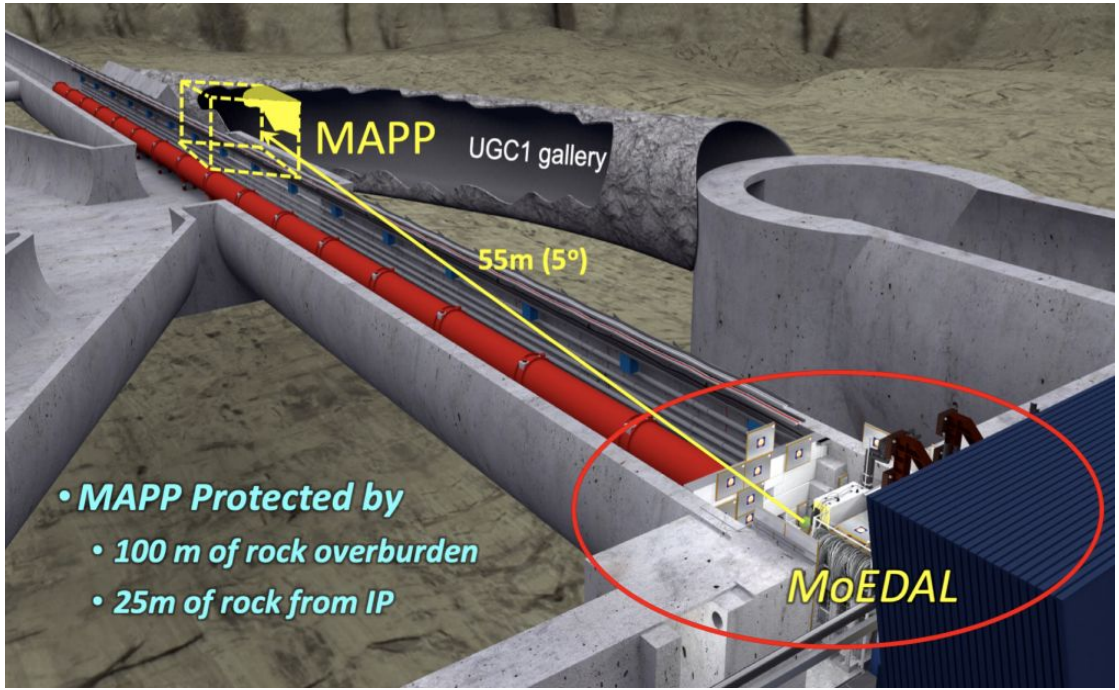




MAPP-(mQP,LLP)

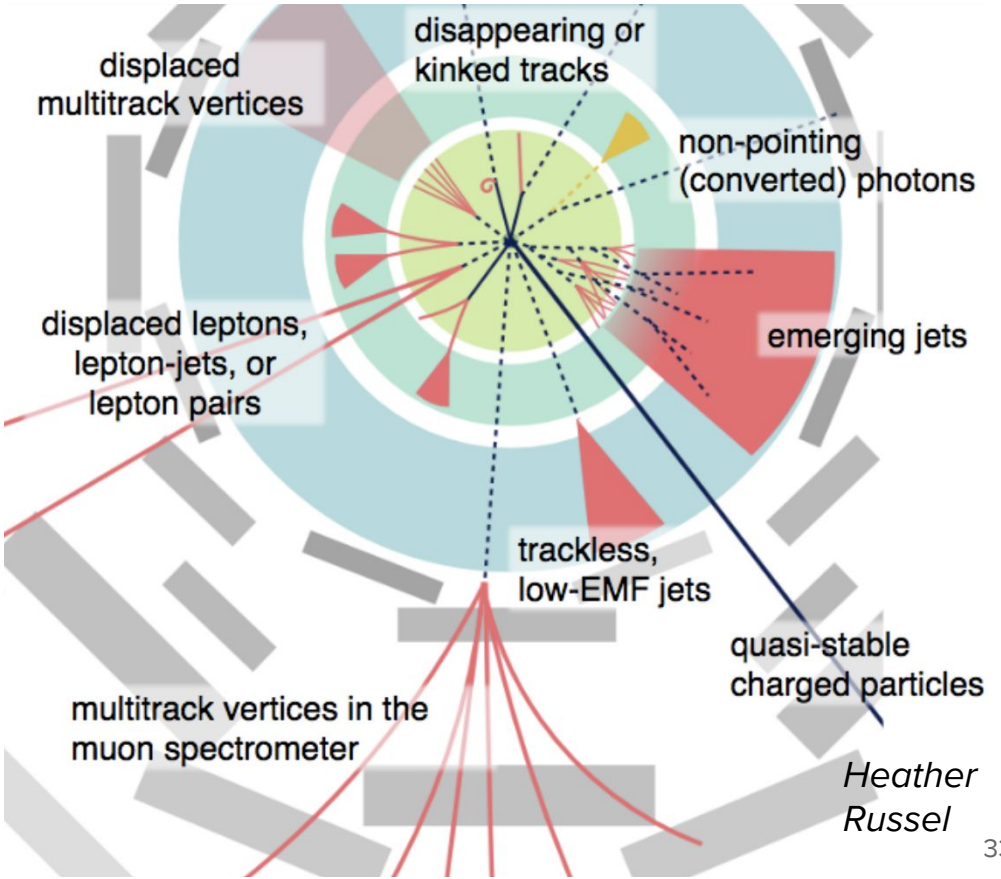
LHCP (Full MoEDAL Overview)
MoEDAL Review Article

- Upgrade to existing MoEDAL : instrumented near LHCb (reminder : low lumi)
- Detector configuration : “put MilliQan inside of CODEX-b”
  - Scintillator bar arrays + (x,y) grid of scintillator bars for tracking



ATLAS/CMS, LHCb (Merri, Pippin, Samwise)

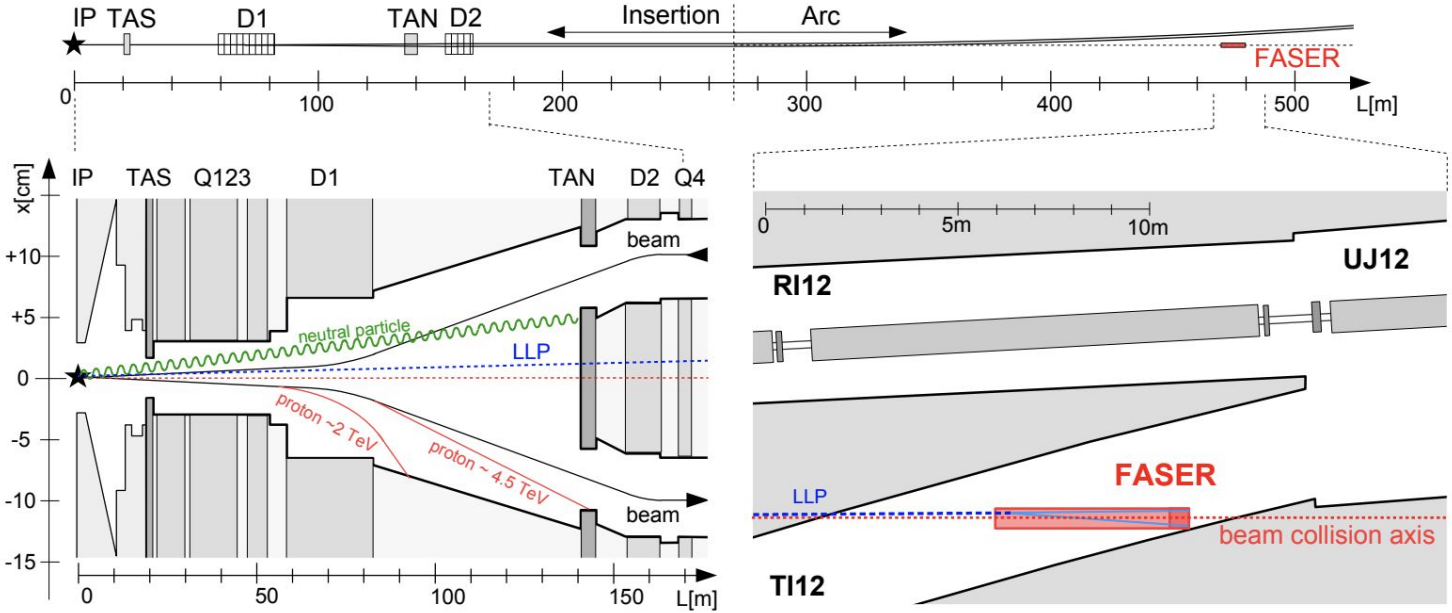
- Data can be “repurposed” in creative ways from primary general purpose experiments
  - ATLAS/CMS
  - LHCb
- … even between experiments
  - Cool idea by Yue Zhao @ LLP workshop!



FASER (Frodo)

[1708.09389](1708.09389) (Initial Idea)
[1811.10243](1811.10243) (Letter of Intent)
[1812.09139](1812.09139) (Tech Proposal)
[1811.12522](1811.12522) (Physics Rev.)

- Alternative approach : down the beamline
  - Targets radically different LLP production mechanism : hadron decays
  - Akin to beam dump experiments (i.e. SHiP, NA62)
- **Approved and on track to take data in Run3** (thanks to Simons/Heising-Simons!)

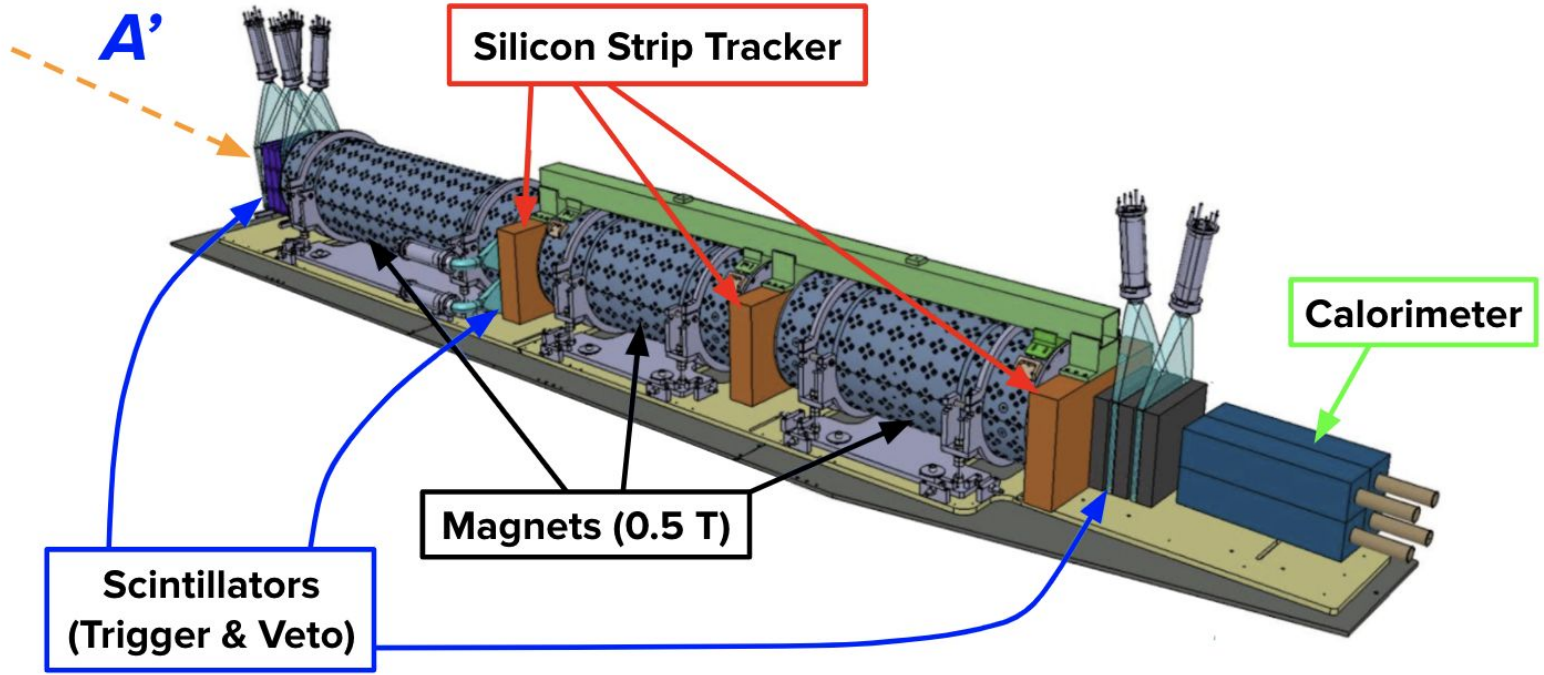


SIMONS FOUNDATION

HEISING-SIMONS FOUNDATION

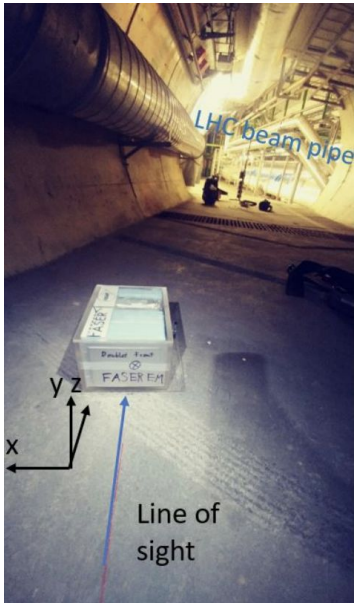
FASER

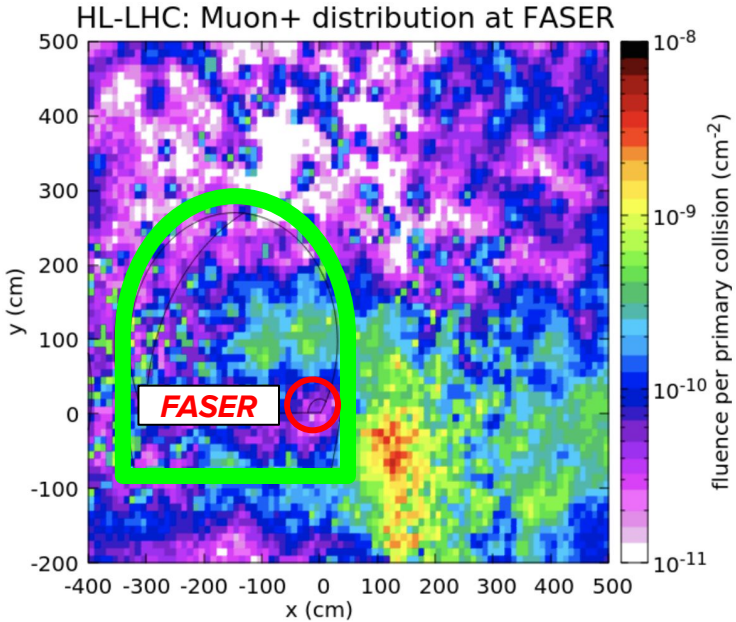
- Design : LHCb without the VELO/RICH ➔ (3 × r=0.1) m^3 @ 480 m
  - Precision silicon tracking (from ATLAS), electromagnetic calorimeter (from LHCb), permanent dipole magnet for charged particle ID, fast scintillators for trigger/timing/active veto



FASER

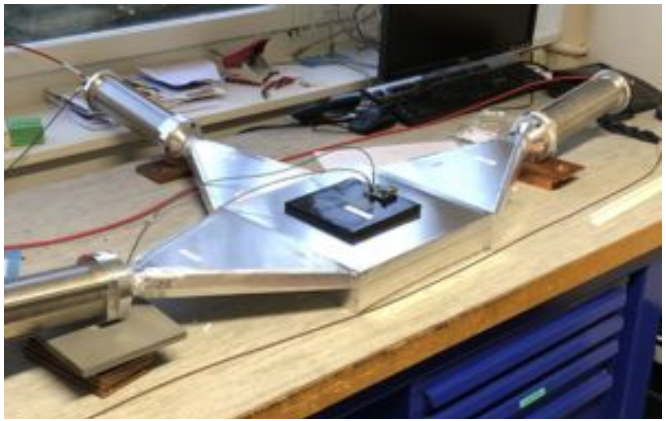
- Expected background modeled with FLUKA
  - Primarily from IP and secondary muons ➔ ~600 Hz
  - Verified using emulsion detector in 2018 - very good agreement
- Civil engineering/space preparation ongoing
  - Services, over-LHC crane, digging the trench!

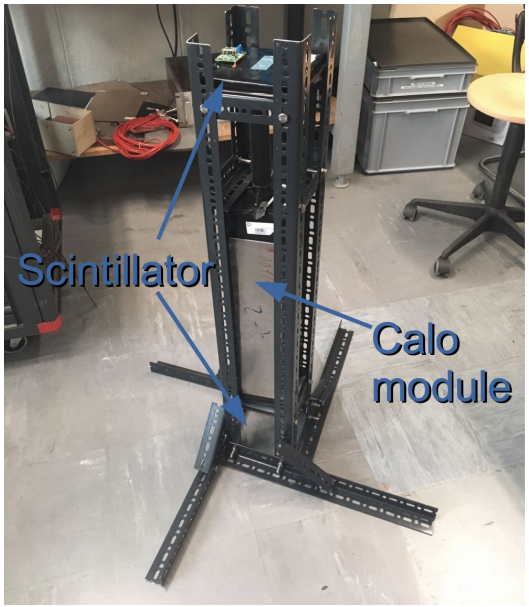


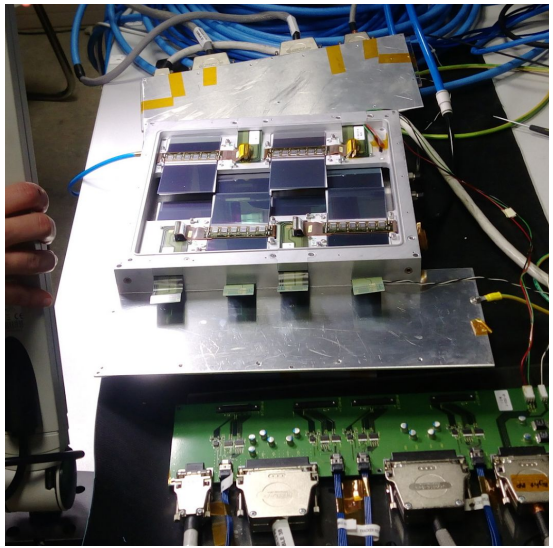


FASER

- Construction/commissioning of all detector components ongoing
  - Starting to ramp back up from Covid safe mode
- Plan for surface assembly near ProtoDUNE in ENH1

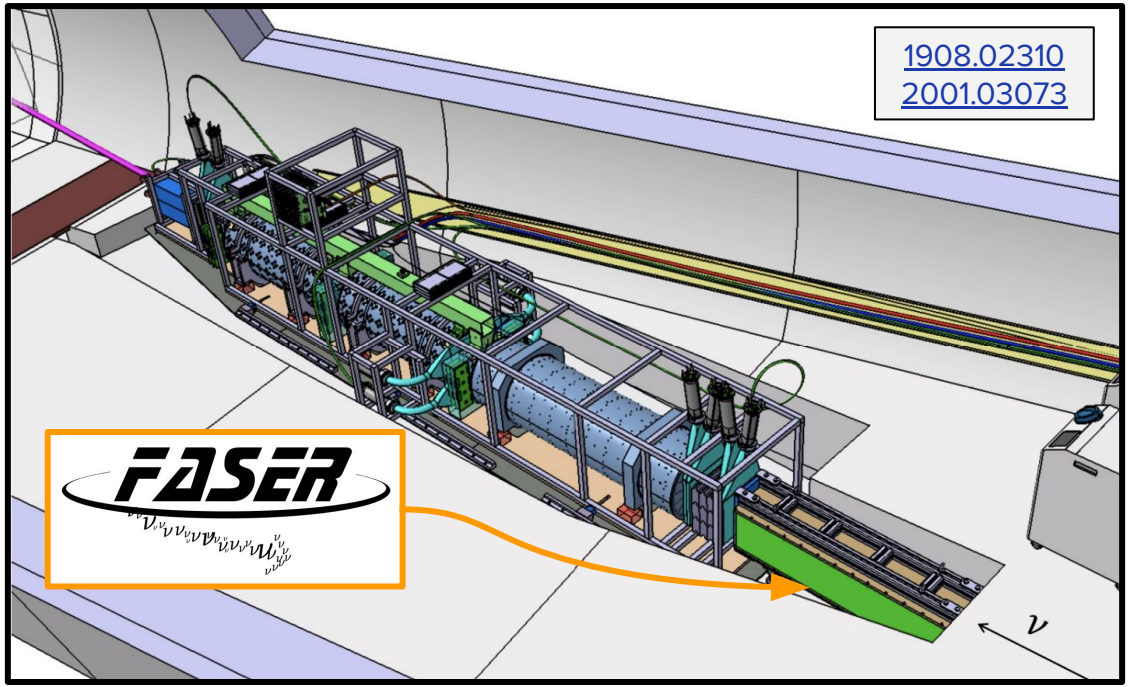






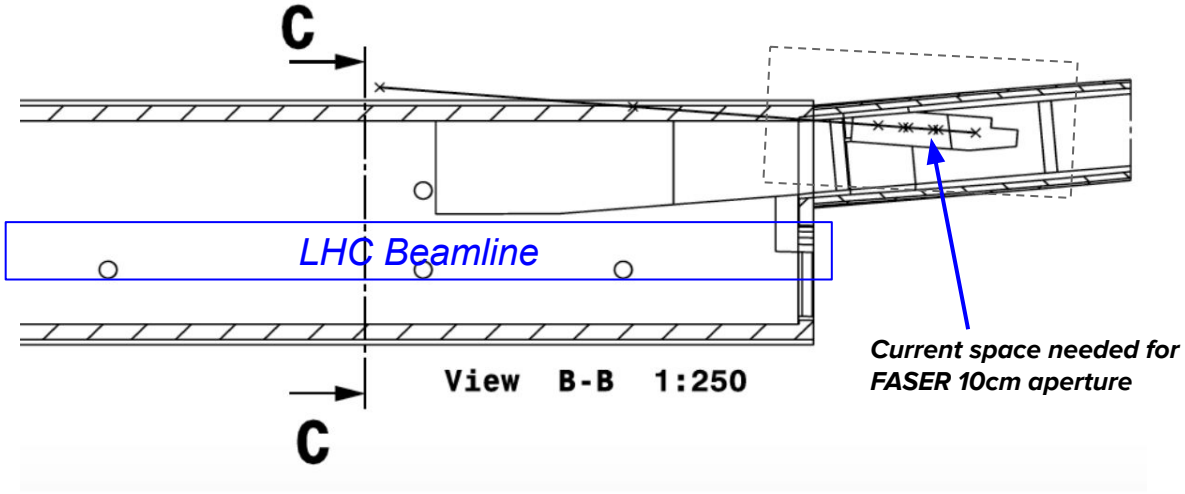
FASER (Frodo+Smeagol)

- Approved addition to FASER with dedicated aim of detecting neutrinos ➜ FASER-nu
  - More in Felix Kling's talk just after this



FASER2 (Frodo on steroids)

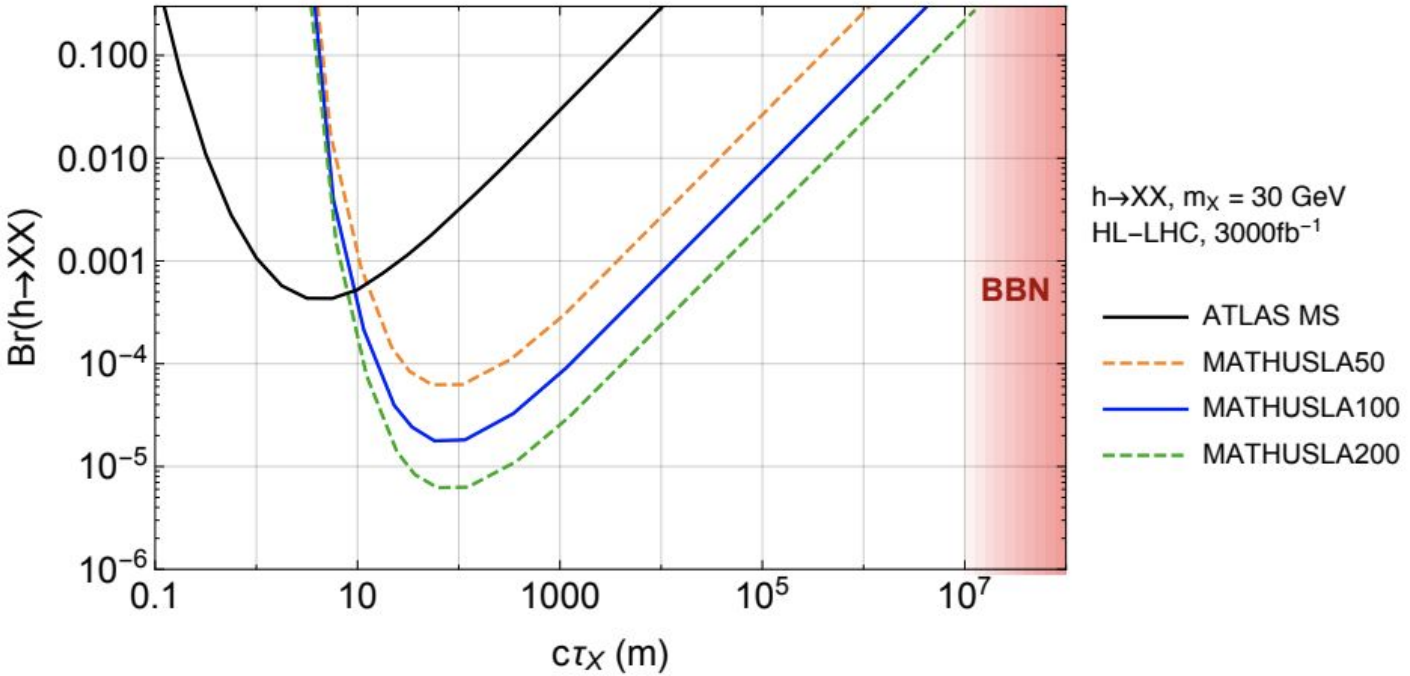
- Possibility to upgrade (replace) FASER experiment with FASER2
  - Main improvement : 100 times larger fiducial volume - 10cm radius ➔ 1m radius
- Requires non-negligible modifications
  - Physical space (civil engineering) ➔ expansion? :-/
  - Tracking (ATLAS SCTs not enough) ➔ SciFi technology?
  - Magnet (would need to be bigger)



So what can we learn?!?!

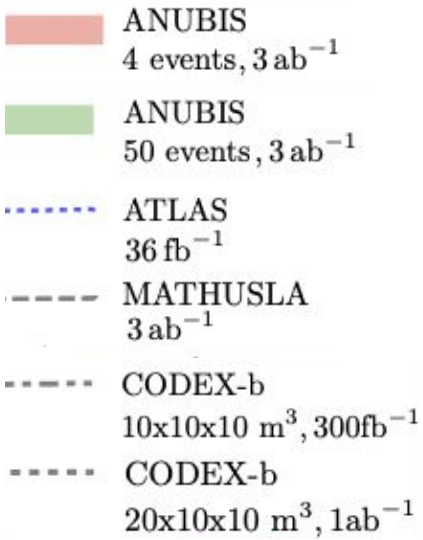
So many sensitivity curves! : Part I

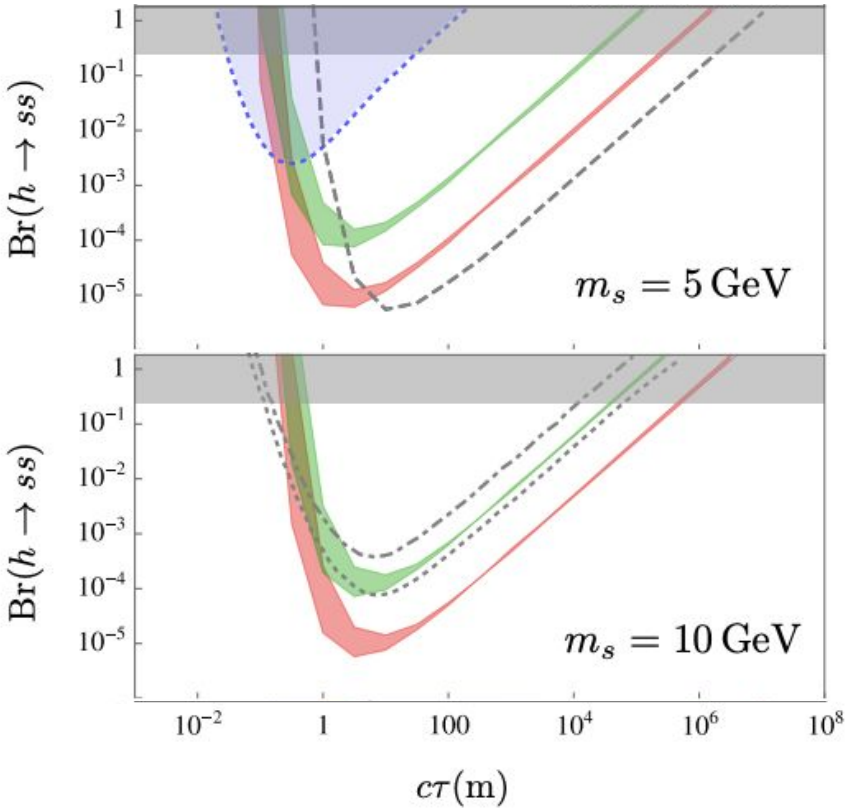
- We can now start to hone our LLP intuition : *MATHUSLA vs. ATLAS*
  - [1] Deep center point reaches out further ➔ location from IP
  - [2] Sensitivity scales with Time (L_{int}) × **Volume** × Efficiency



Part II

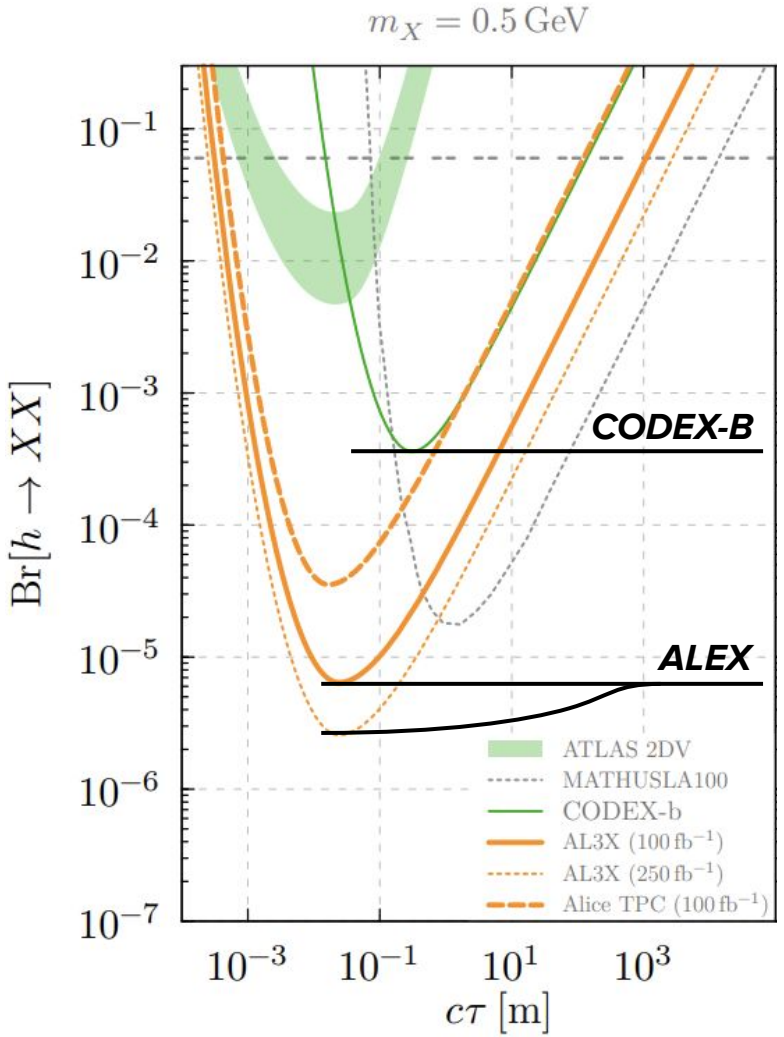
- *ANUBIS vs. MATHUSLA vs. CODEX-b* : geometrical themes persist
  - ANUBIS : 10000 m^3 @ ~30m
  - CODEX-B : 1000 m^3 @ ~25m
  - MATHUSLA : 1000000 m^3 @ ~100m





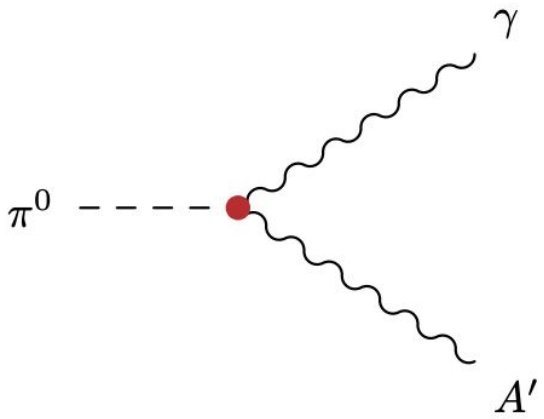
Part III

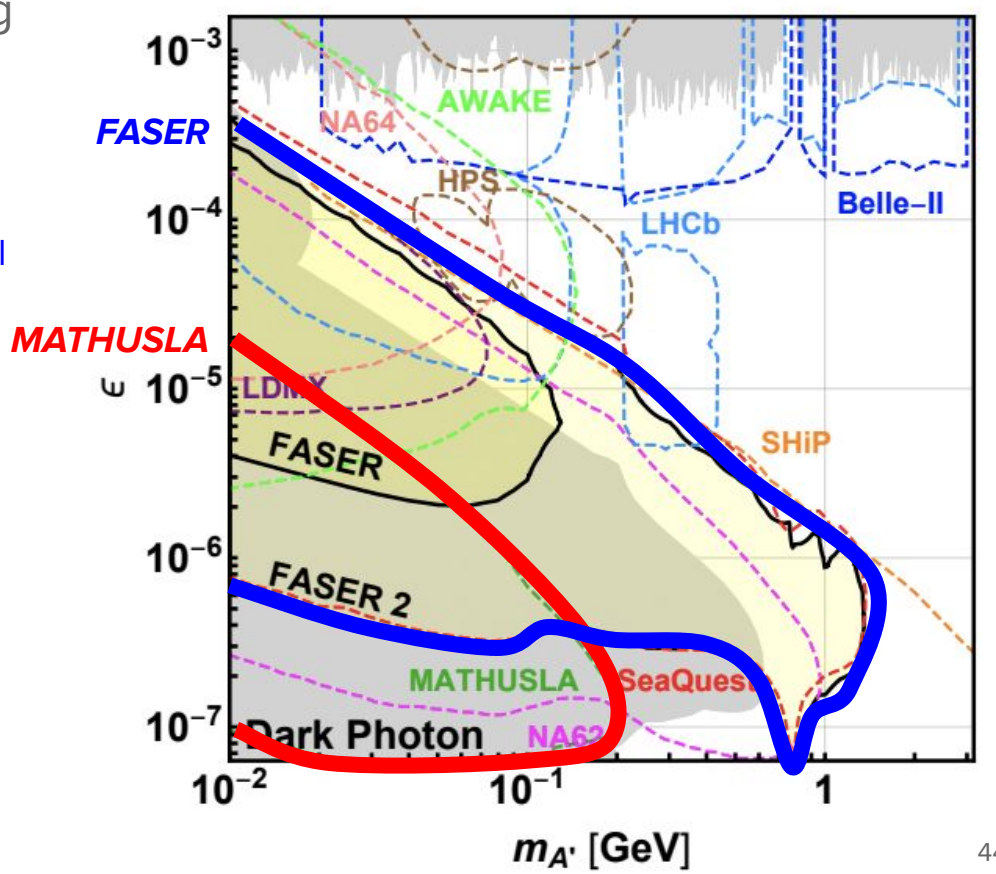
- *AL3X vs. CODEX-b*
  - Same geometrical themes ➜ AL3X dominates sensitivity due to 2π azimuthal coverage
- Recall : CODEX-b will be interfaced with LHCb DAQ ➜ unique trigger
  - Main experiment can provide information on the production mechanism
  - Perhaps not a novel idea but details fleshed out in CODEX-B LoI nicely



So much phase space to cover : Part I

- What do we learn when projecting into parameter space?
- *FASER2 vs. MATHUSLA*
  - Bigger is not always better
  - Rephrased : interpretations are model dependent!





So much phase space to cover : Part I

- What do we learn when projecting into parameter space?
- *FASER2 vs. MATHUSLA*
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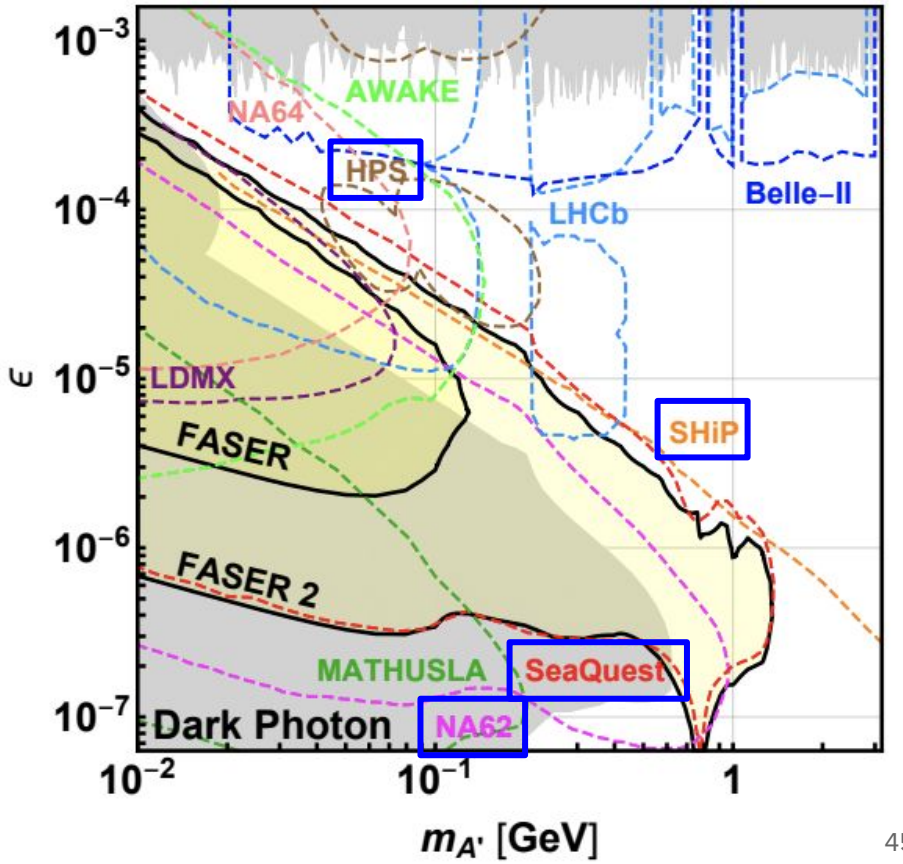
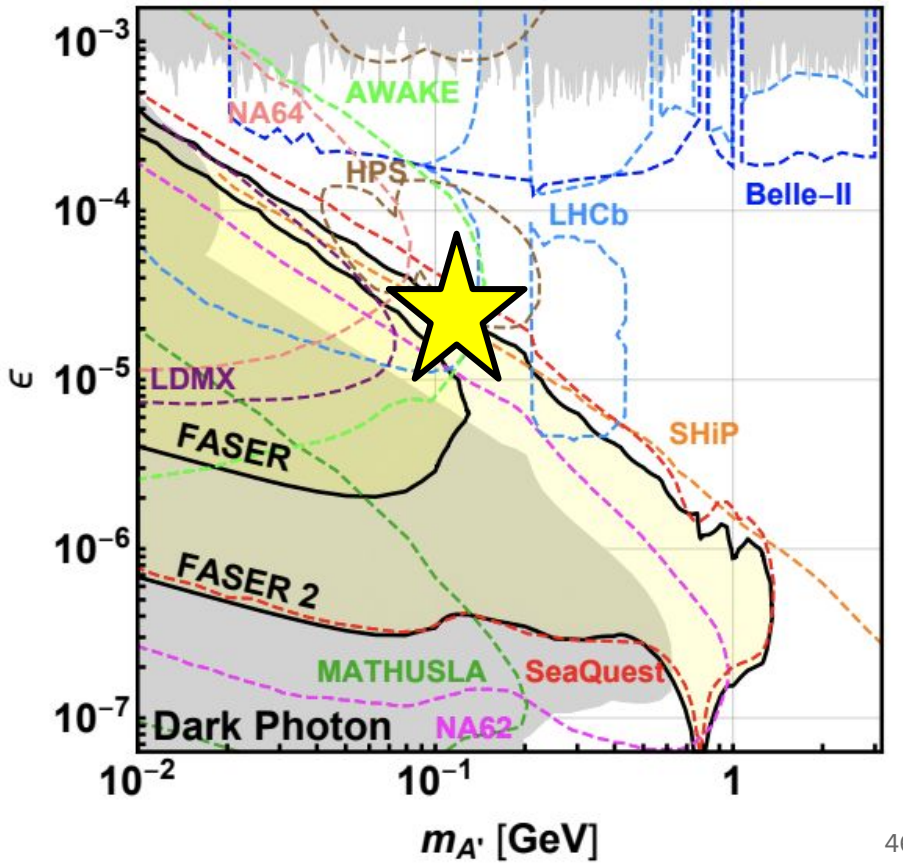
- Beam dump experiments
  - SHiP ➔ Mordor
  - NA62 ➔ Isengard
  - SeaQuest ➔ Pirates
  - HPS ➔ Olifants



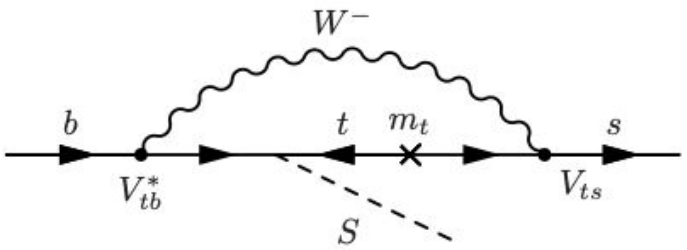
So much phase space to cover : Part I

- What do we learn when projecting into parameter space?
- *FASER vs. MATHUSLA*
  - Bigger is not always better
  - Rephrased : Model dependence
- Beam dump experiments
  - SHiP ➔ Mordor
  - NA62 ➔ Isengard
  - SeaQuest ➔ Pirates
  - HPS ➔ Olifants
- ***Having orthogonal views is great!***
  - We have a sense of the “ideal place” to discover an LLP

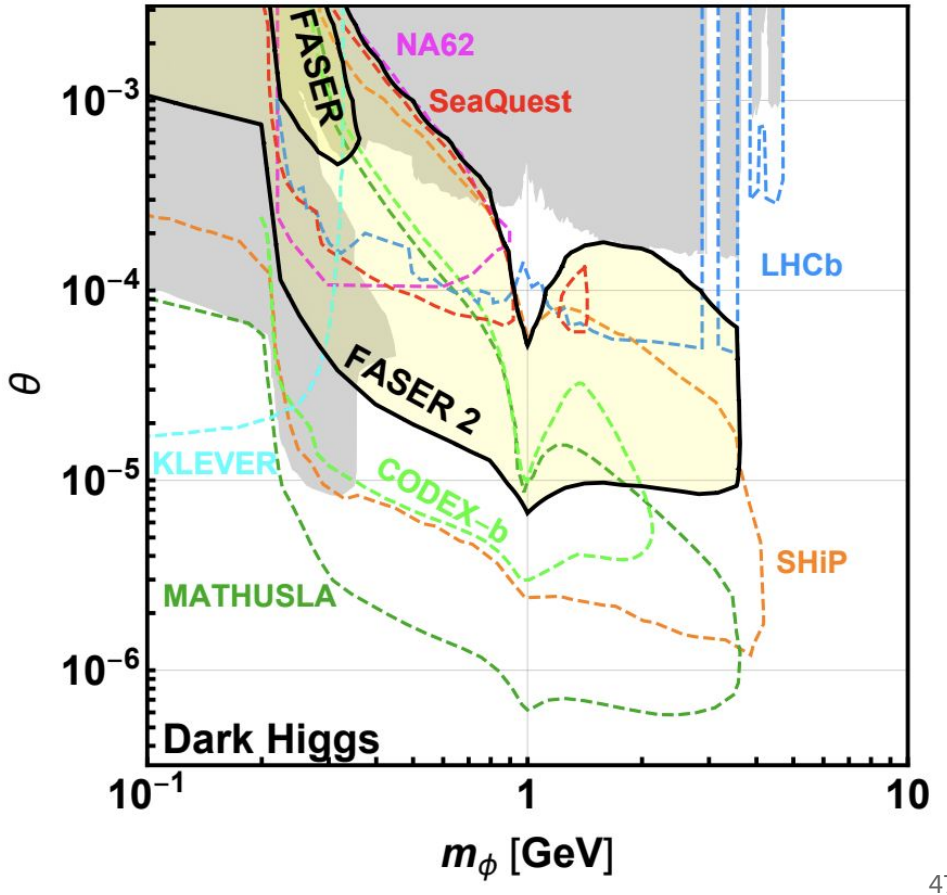


Model Dependence

- What do we learn when projecting into parameter space?
- *FASER2 vs. MATHUSLA*
  - We need them both!



$$L = v\tau\gamma \sim c \times \frac{1}{\epsilon^2 m} \times \frac{E}{m}$$

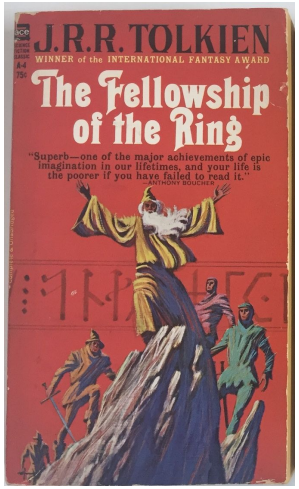


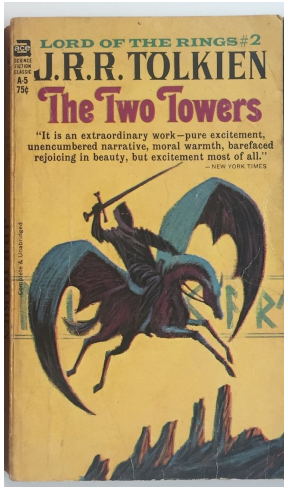
An Unexpected Journey

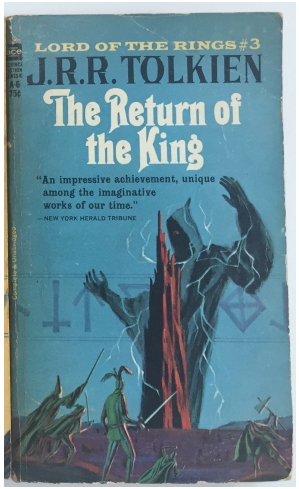
- Diverse array of experiments at various stages of progression
  - First results = milliQan
  - Construction = FASER/MAPP
  - Prototyping = CODEX-b/MATHUSLA
  - New Ideas = ANUBIS/AL3X
- It will require contributions from all to achieve the ultimate goal:

“top priority should be the exploitation of the full potential of the LHC”

- 2013 European Strategy





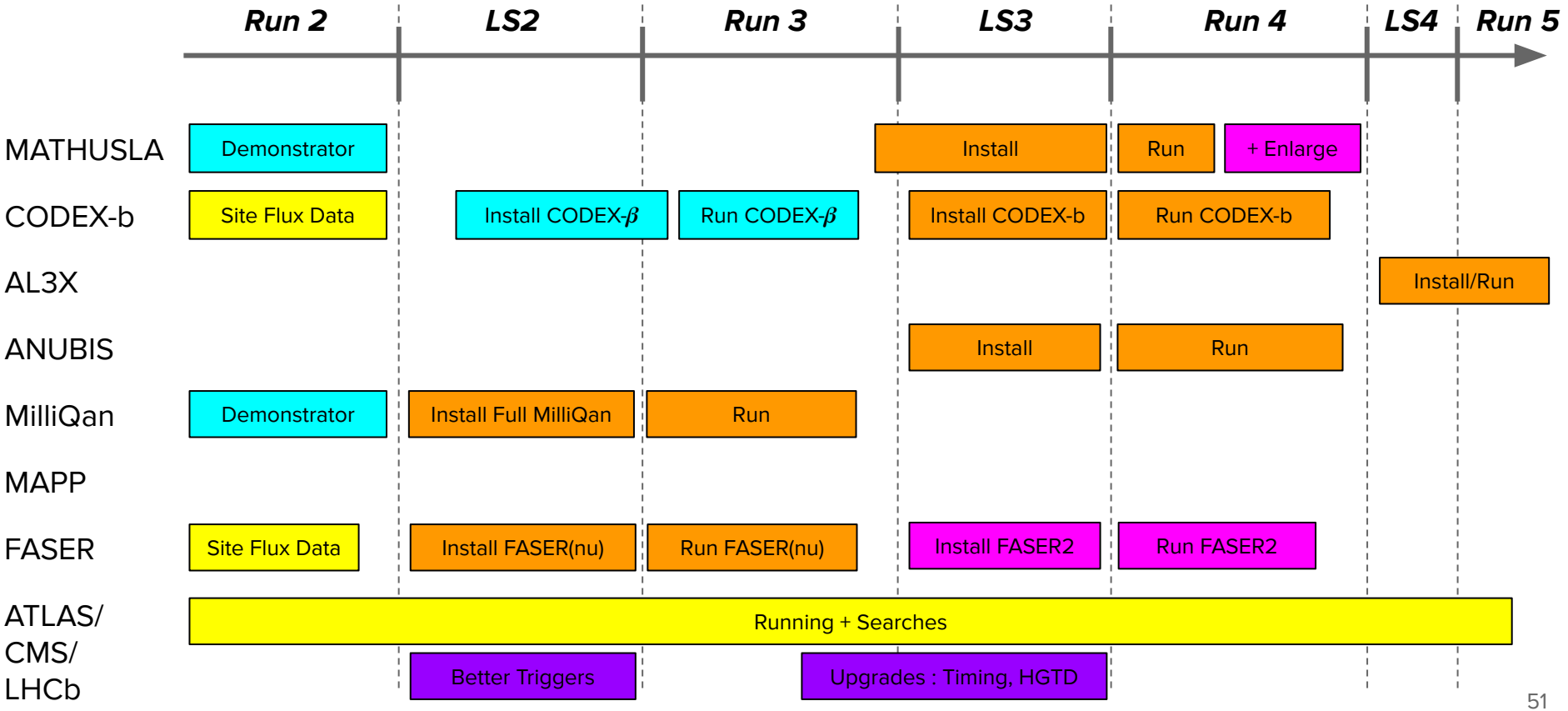


Backups

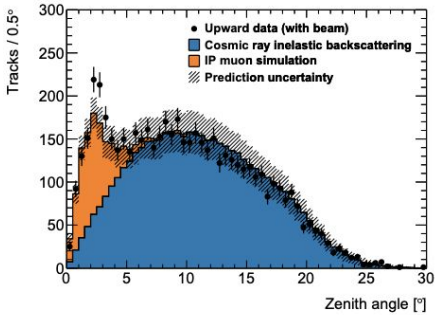
Literature/Refs

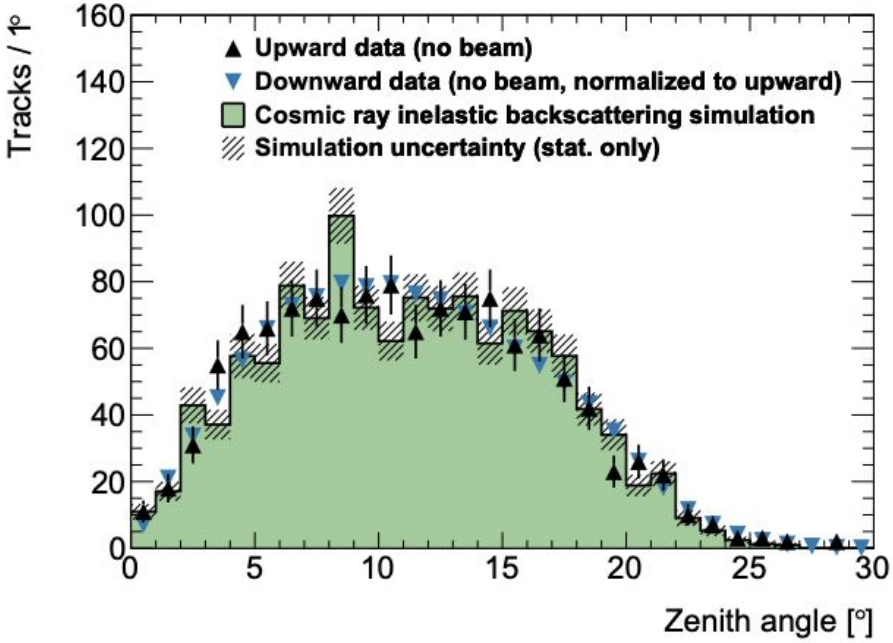
- Last years talk - https://indico.cern.ch/event/783977/timetable/?view=standard#63-new-experiment-proposals
- ATLAS, CMS, LHCb
  - Pippin, Merri, Samwise
- FASER - https://arxiv.org/abs/1811.12522, https://arxiv.org/abs/1812.09139
  - Frodo - the ring is heavy but we have the infrastructure in place [magnet]
  - Has inherited from others (mithril = calorimeter, sting = tracker)
  - (+Smeagol = fasernu)
- CodexB - https://arxiv.org/abs/1708.09395, https://cds.cern.ch/record/2699473?ln=en
  - Aragorn - inherits wisdom from gandalf and can do one better (interface with LHCb)
- Mathusla - https://arxiv.org/abs/1606.06298, https://arxiv.org/pdf/1705.06327.pdf, https://arxiv.org/abs/1806.07396, https://cds.cern.ch/record/2631491
  - Gandalf - the wisest, guidance given to all
- ANUBIS - https://arxiv.org/abs/1909.13022
  - Legolas - dances in the air and requires precision vetoing from ATLAS calorimeter
- MilliQan - https://arxiv.org/abs/1410.6816, https://arxiv.org/abs/1607.04669, https://arxiv.org/abs/2005.06518
  - Gimli - lives in a mine, a *mine*

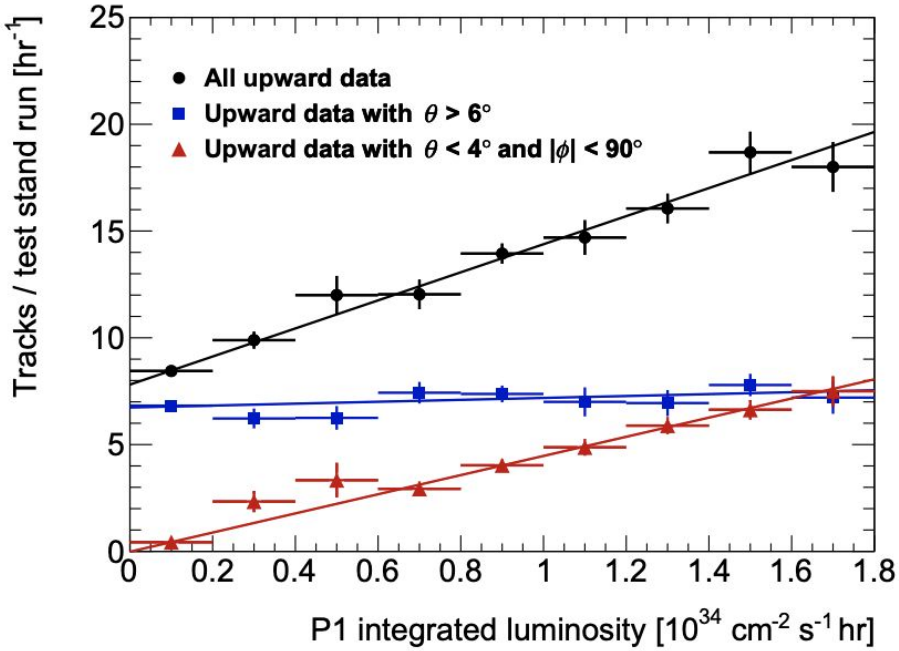
Timelines (not to scale)



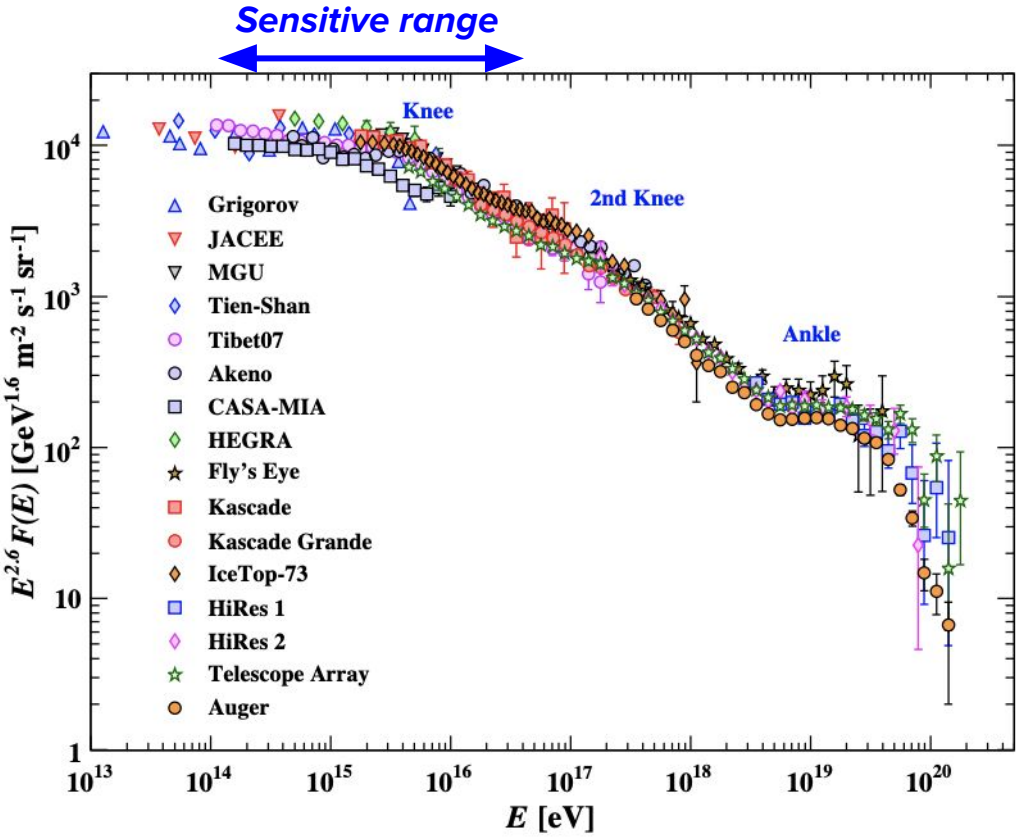
MATHUSLA - Demonstrator







Mathusla - Cosmic Ray Physics

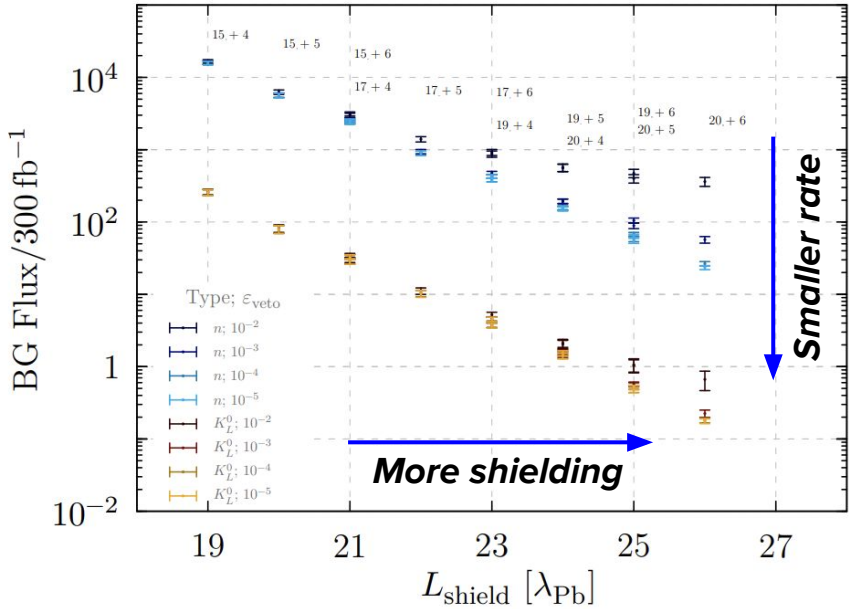


CODEX-B

1911.00481 (Letter of Intent)

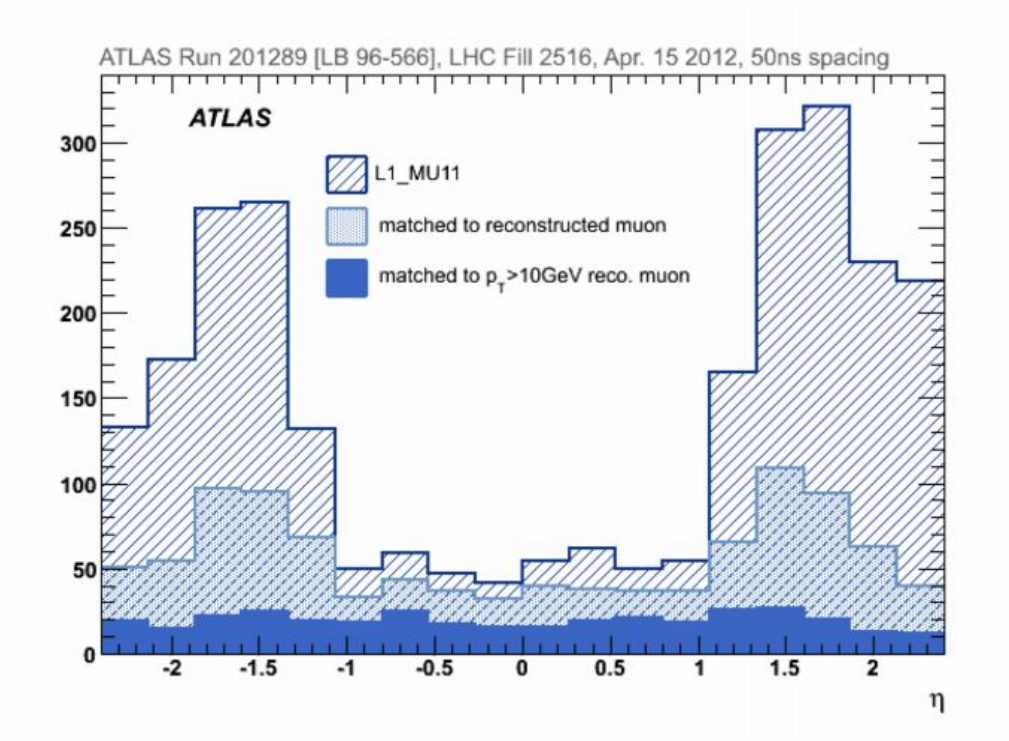
- Shielding reduces IP and secondary backgrounds
  - Studied in refined GEANT sim. ➔ Most challenging background (secondary neutrals) is manageable
- Validated during Run2 using scintillator measurement of fluxes
  - Rate is 50 times lower than expected from GEANT ➔ estimation is conservative
- Planning to install CODEX-β (10×10×10 m^3) demonstrator in Run3

BG species	Particle yields: Net ($E_{kin}^{neutral} > 0.4\,GeV$)	Shield veto rejection (total)	Shield veto rejection (±/0 correlation)	Net yield
γ	0.54 ± 0.12	$(8.06 \pm 0.60) \times 10^4$	$(2.62 \pm 1.03) \times 10^3$	–
n	58.10 ± 4.63	$(4.59 \pm 0.15) \times 10^5$	$(3.45 \pm 0.51) \times 10^4$	–
n ($> 0.8\,GeV$)	2.78 ± 0.25	$(1.03 \pm 0.06) \times 10^5$	$(7.45 \pm 1.92) \times 10^3$	$\lesssim 1$
$\bar{n}$ (no cut)	$(3.24 \pm 0.72) \times 10^{-3}$	34.40 ± 25.80	$(7.44 \pm 2.20) \times 10^{-2}$	$\ll 1$
K_L^0	0.49 ± 0.05	$(1.94 \pm 0.74) \times 10^3$	55.00 ± 19.30	$\lesssim 0.1$
K_S^0	$(6.33 \pm 1.39) \times 10^{-3}$	93.90 ± 45.80	0.74 ± 0.19	$\ll 1$
$\nu + \bar{\nu}$	$(5.69 \pm 0.00) \times 10^{13}$	$(7.35 \pm 0.12) \times 10^6$	$(5.69 \pm 0.00) \times 10^{13}$	–
$p^{\pm}$	$(2.07 \pm 0.26) \times 10^2$	$(9.24 \pm 0.36) \times 10^5$	$(9.24 \pm 0.36) \times 10^5$	–
$e^{\pm}$	$(4.53 \pm 0.02) \times 10^3$	$(4.38 \pm 0.02) \times 10^7$	$(4.38 \pm 0.02) \times 10^7$	–
π^+	34.70 ± 2.27	$(2.96 \pm 0.20) \times 10^5$	$(2.96 \pm 0.20) \times 10^5$	–
π^-	31.40 ± 2.12	$(2.68 \pm 0.19) \times 10^5$	$(2.68 \pm 0.19) \times 10^5$	–
K^+	0.83 ± 0.30	$(3.08 \pm 1.24) \times 10^3$	$(3.08 \pm 1.24) \times 10^3$	–
K^-	0.23 ± 0.12	$(1.12 \pm 0.63) \times 10^3$	$(1.12 \pm 0.63) \times 10^3$	–
μ^+	$(1.04 \pm 0.00) \times 10^6$	$(1.04 \pm 0.00) \times 10^{10}$	$(1.04 \pm 0.00) \times 10^{10}$	–
μ^-	$(8.07 \pm 0.01) \times 10^5$	$(8.07 \pm 0.01) \times 10^9$	$(8.07 \pm 0.01) \times 10^9$	–



ANUBIS

- Muon rate in endcap : [ATLAS-TDR-020]



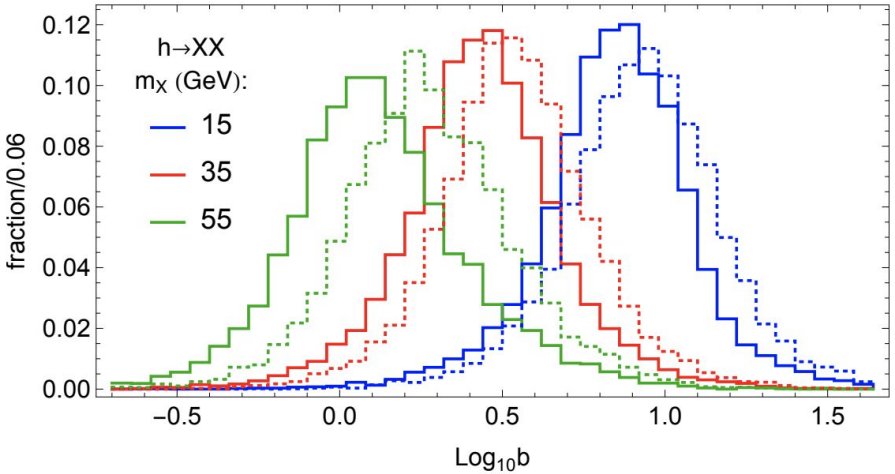
Basic Physics Stuff

- MilliQan/MAPP : Bethe-Bloch Formula

$$-\left\langle \frac{dE}{dx} \right\rangle = \frac{4\pi}{m_e c^2} \cdot \frac{nz^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0} \right)^2 \cdot \left[\ln\left(\frac{2m_e c^2 \beta^2}{I \cdot (1-\beta^2)} \right) - \beta^2 \right]$$

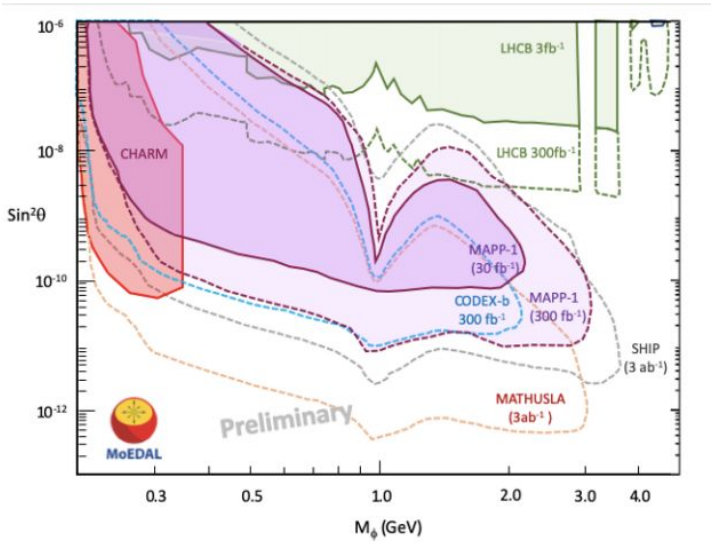
- Mass measurement in MATHUSLA : 1705.06327

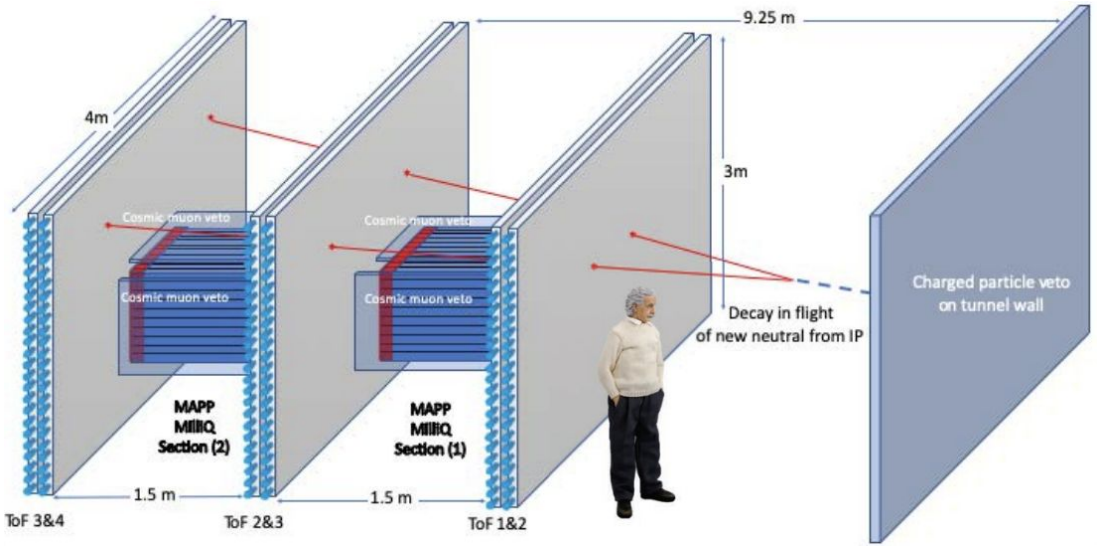
$$\beta_X = \frac{\beta_1 \beta_2 \sin(\theta_1 + \theta_2)}{\beta_1 \sin\theta_1 + \beta_2 \sin\theta_2}$$



MoEDAL-MAPP

- Two different review talks
  - https://www.mdpi.com/2218-1997/5/2/47
  - http://vietnam.in2p3.fr/2019/longlived/transparencies/02_wednesday/01_morning/06_pinfold.pdf
- Suffers primarily from low integration (due to IP8 luminosity)

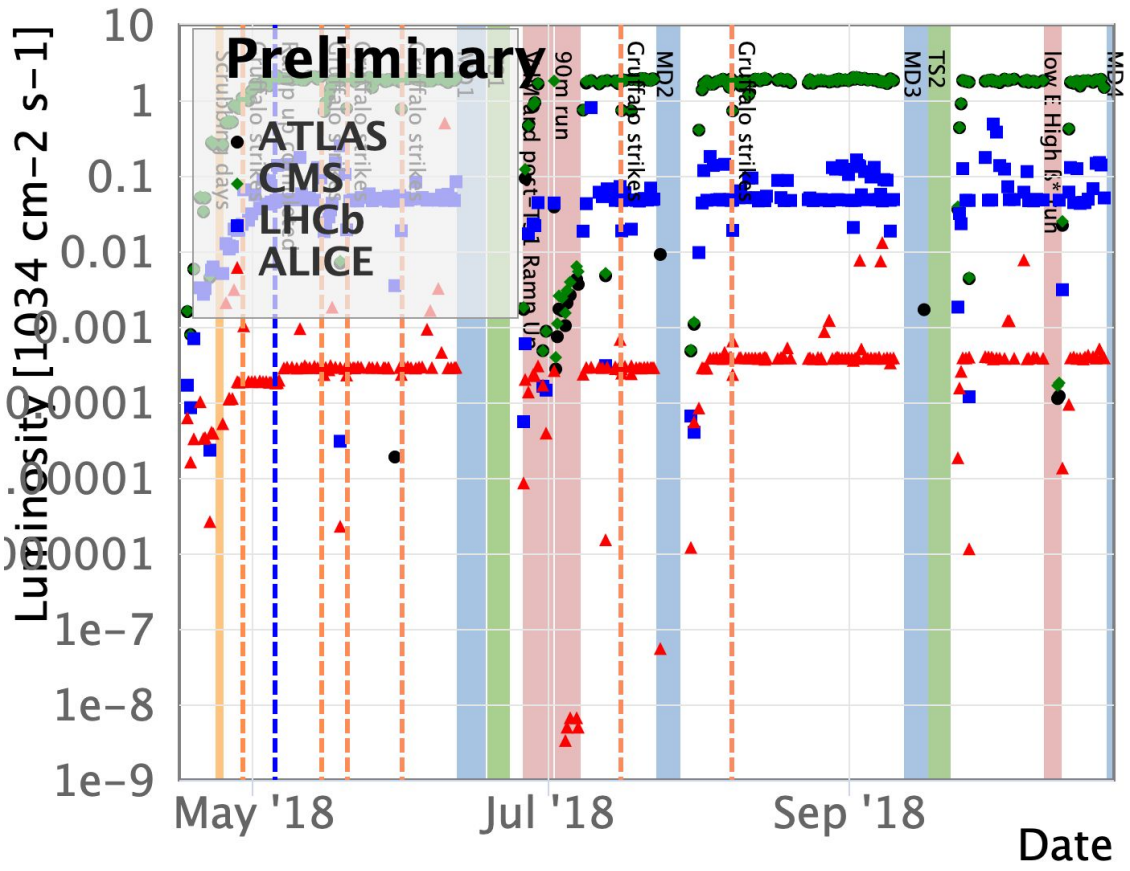




LHC Lumi

Taken from :

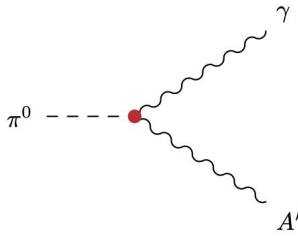
http://lpc.web.cern.ch/cgi-bin/plots.py



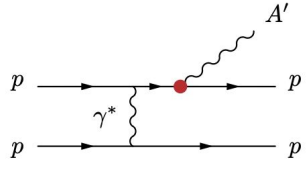
Production Mechanisms

- Reach can be highly dependent on the assumptions about the production mechanism
  - Same LLP “model”
  - Model dependence ➔ “theoretical uncertainties”

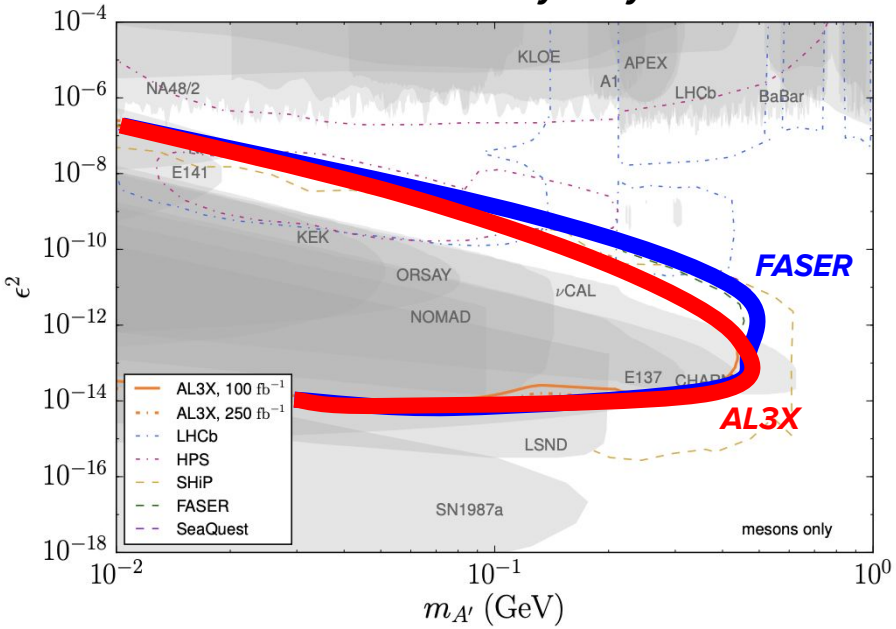
Meson Decay



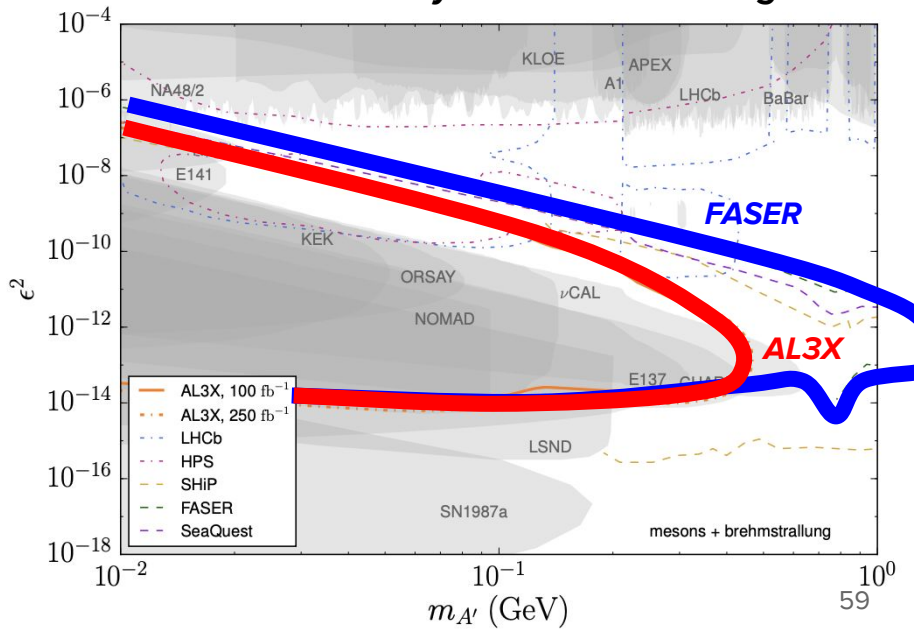
Brehmstrahllung



Meson Decay Only



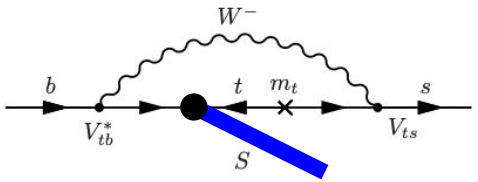
Meson Decay & Brehmstrahllung



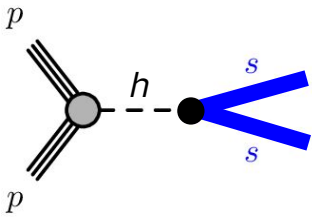
Model Dependence

- Within a single model, the exclusion is highly parameter dependent
  - Dark Higgs Model with and without the trilinear coupling for h ➔ ss decays

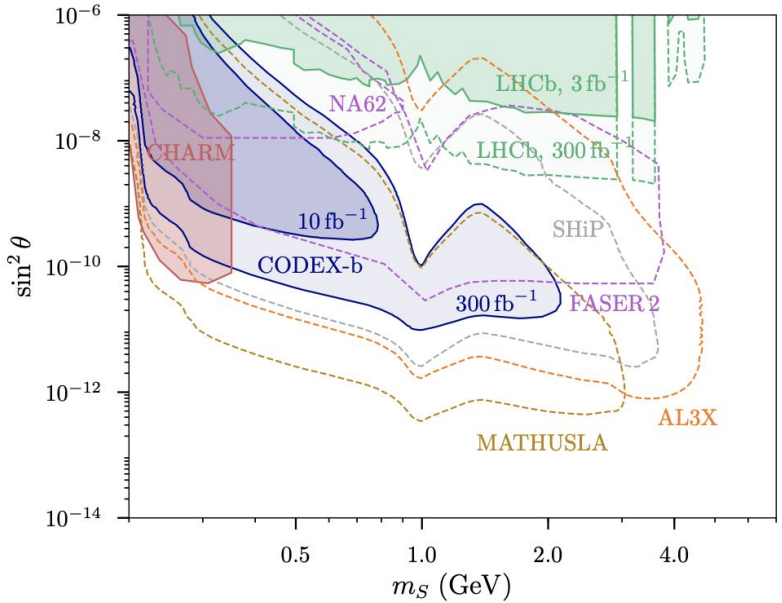
b-Hadron Decay



Exotics Higgs Decay



λ = 0 : b-Hadron Decay Only



λ > 0 : b-Hadron Decay + h ➔ ss