New proposals for LHC experiments and Options for Neutrino Measurements

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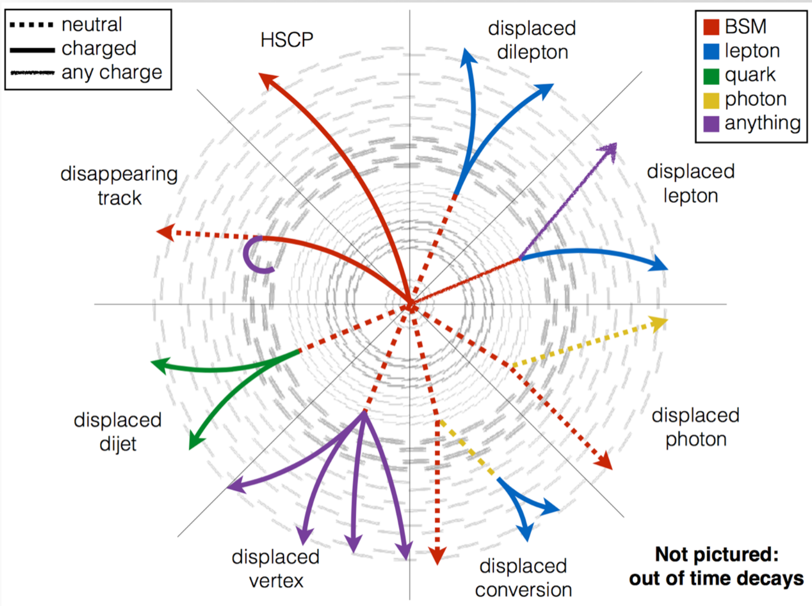
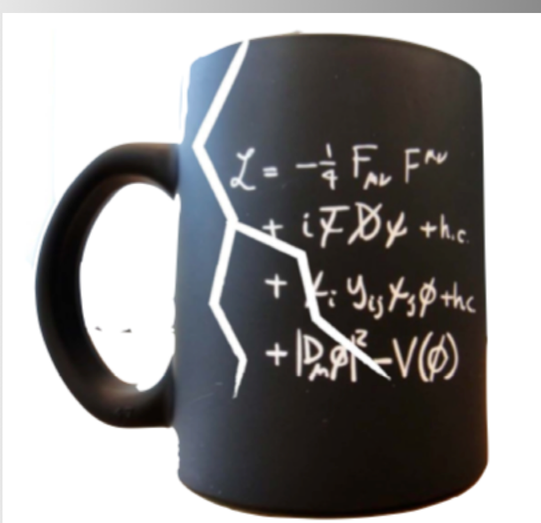
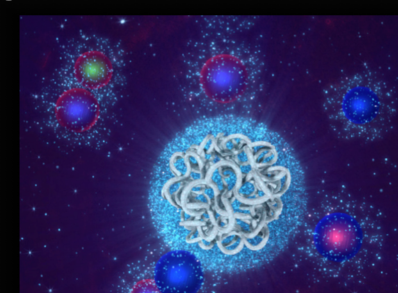
8th August 2019



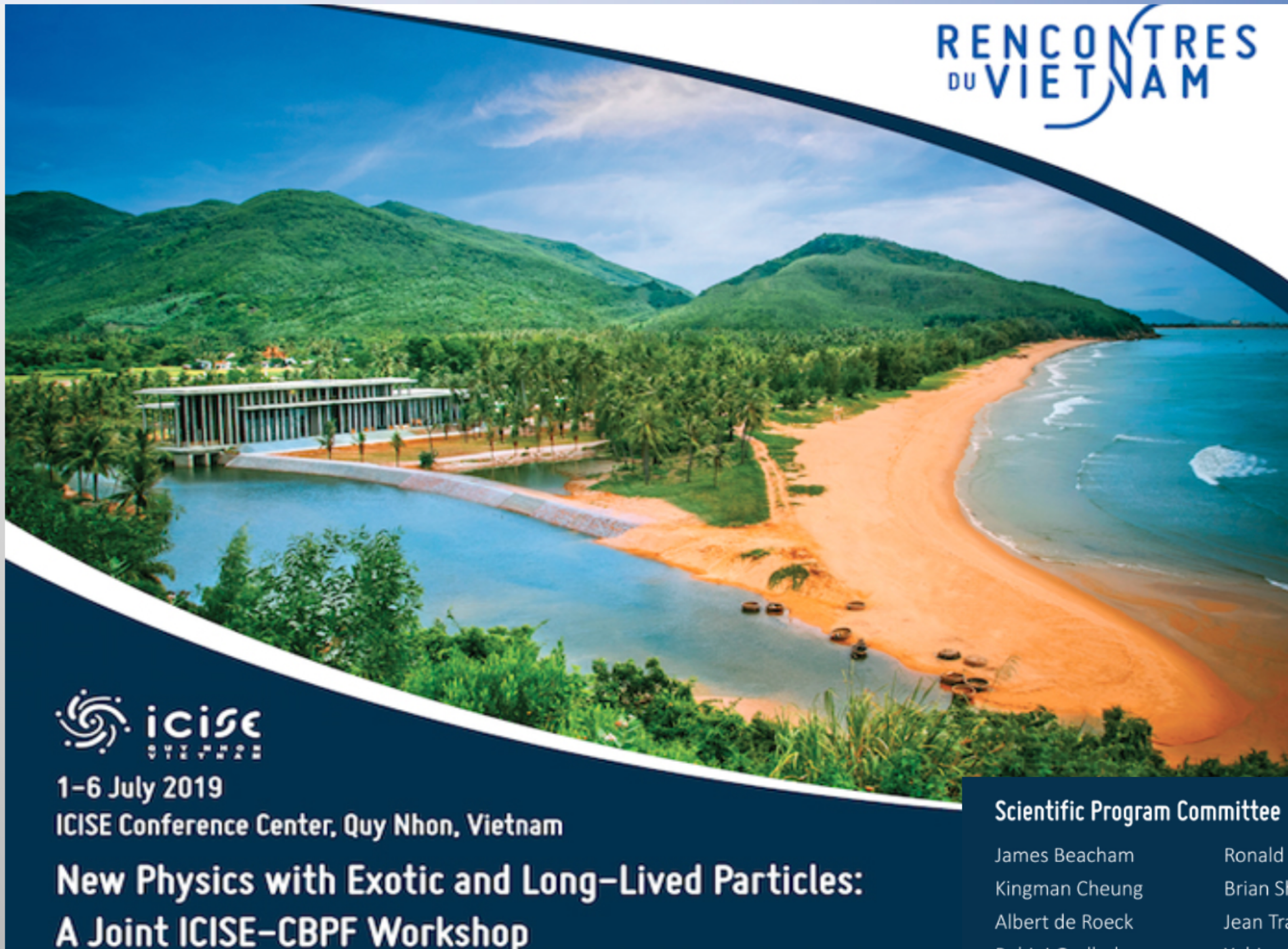


Outline

- Introduction
- Dedicated experiments @ LHC
- Several new proposals/ideas
  - MilliQan, MAPP, MATHUSLA, FASER, CODEX-b, AL3X
  - XSEN Experiment for neutrino physics at the LHC
- Summary & Outlook



One Month Ago…



Scientific Program Committee

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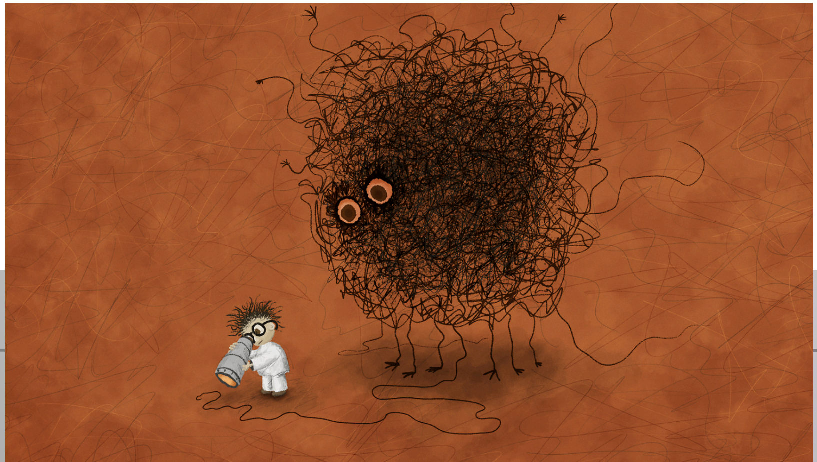
Up to date information by J. Feng, H. Lubatti, …

Are we leaving no stones unturned?

- No New Physics found yet at the LHC. The LHC BSM searches are indispensable and should be continued in the new energy regime and with increasing statistics (higher mass, lower couplings)
- But are we looking at the right place and do we leave not stones unturned? -> Recent focus on long lived particles
- Time for more effort in thinking of complementary searches: -> What could the LHC miss with the present detectors?

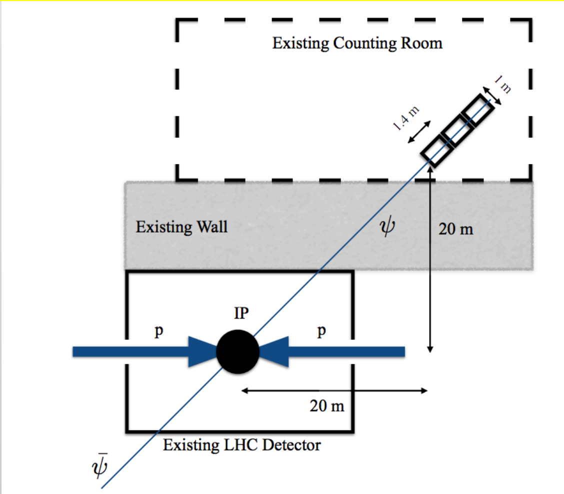
Are we looking at the right place?



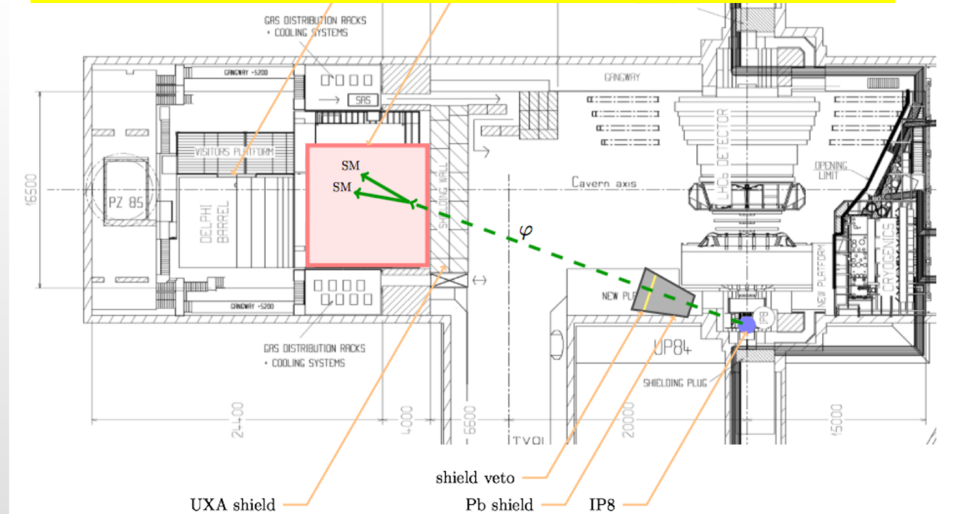
Leave no stone unturned!!

Proposals for New Experiments @LHC

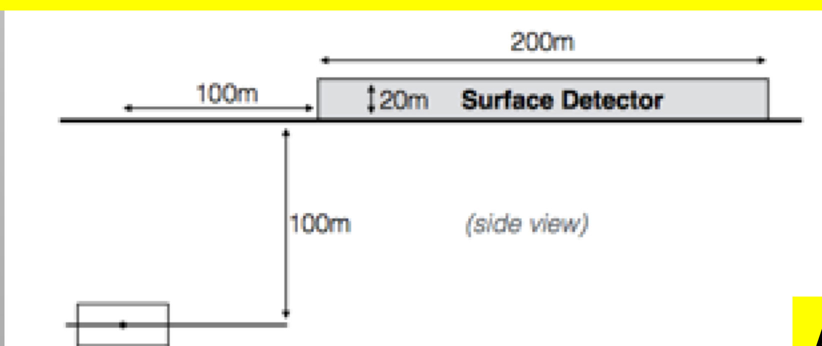
MilliQan: searches for milli-charged particles
MAPP: Same from MoEDAL



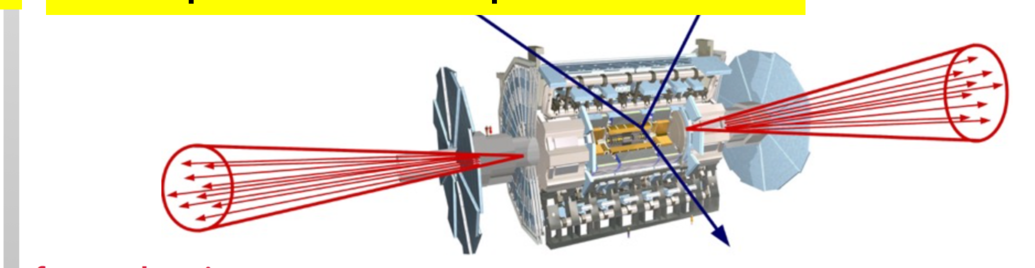
CODEX-b: searches for long lived weakly interacting neutral particles



MATHUSLA: searches for long lived weakly interacting neutral particles



FASER: searches for long lived dark photons-like particles



Also: AL3X ('ALICE' for LLP arXiv.1810.03636)...

MATHUSLA

A Letter of Intent for MATHUSLA: a dedicated displaced vertex detector above ATLAS or CMS

Cristiano Alpigiani,[a] Austin Ball,[o] Liron Barak,[c] James Beacham,[ah] Yan Benhammo,[c] Tingting Cao,[c] Paolo Camarri,[f,g] Roberto Cardarelli,[f] Mario Rodríguez-Cahuantzi,[h] John Paul Chou,[d] David Curtin,[b] Miriam Diamond,[e] Giuseppe Di Sciascio,[f] Marco Drewes,[x] Sarah C. Eno,[u] Erez Etzion,[c] Rouven Essig,[q] Jared Evans,[v] Oliver Fischer,[w] Stefano Giagu,[k] Brandon Gomes,[d] Andy Haas,[l] Yuekun Heng,[z] Giuseppe Iaselli,[aa] Ken Johns,[m] Muge Karagoz,[u] Luke Kasper,[d] Audrey Kvam,[a] Dragoslav Lazic,[ae] Liang Li,[af] Barbara Liberti,[f] Zhen Liu,[y] Henry Lubatti,[a] Giovanni Marsella,[n] Matthew McCullough,[o] David McKeen,[p] Patrick Meade,[q] Gilad Mizrachi,[c] David Morrissey,[p] Meny Raviv Moshe,[c] Karen Salomé Caballero-Mora,[j] Piter A. Paye Mamani,[ab] Antonio Policicchio,[k] Mason Proffitt,[a] Marina Reggiani-Guzzo,[ad] Joe Rothberg,[a] Rinaldo Santonico,[f,g] Marco Schioppa,[ag] Jessie Shelton,[t] Brian Shuve,[s] Martin A. Subieta Vasquez,[ab] Daniel Stolarski,[r] Albert de Roeck,[o] Arturo Fernández Téllez,[h] Guillermo Tejeda Muñoz,[h] Mario Iván Martínez Hernández,[h] Yiftah Silver,[c] Steffie Ann Thayil,[d] Emma Torro,[a] Yuhsin Tsai,[u] Juan Carlos Arteaga-Velázquez,[i] Gordon Watts,[a] Charles Young,[e] Jose Zurita.[w,ac]

A proposal for a large area surface array to detect ultra long-lived particles coming from the pp collisions

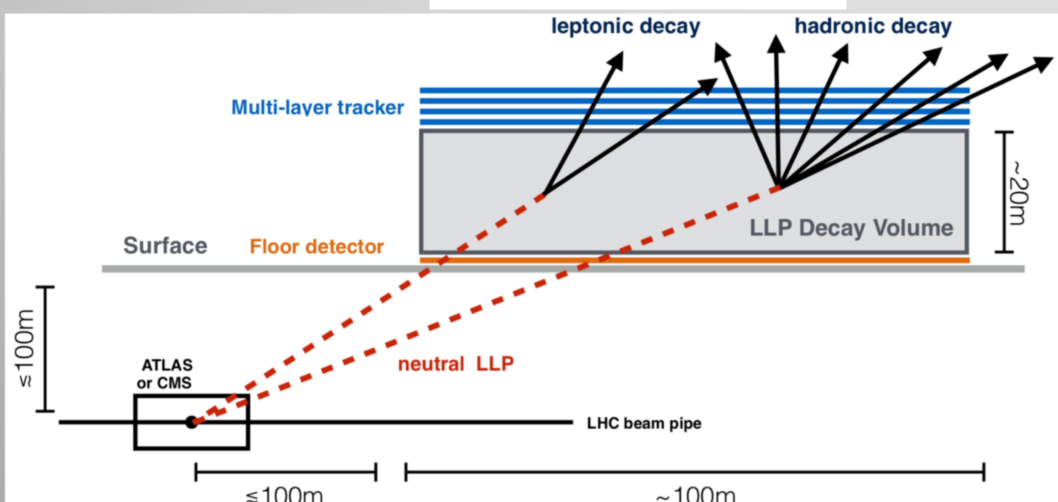
Aim to cover the range

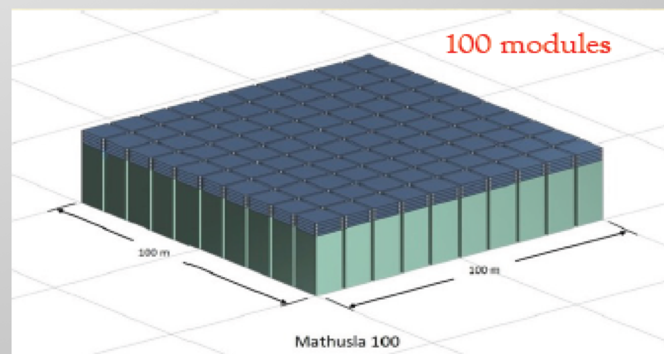
$$c\tau \lesssim 10^7 - 10^8\ \mathrm{m},$$

~ BBN constrained inspired

arXiv:1811.00927

Physic case arXiv:1806.07396





The Idea

- Going to BBN lifetime limit need to suppress SM backgrounds
- Put detector on surface above CMS or ATLAS detectors LHC O(90) meters of rock takes care of problem ☺
  - Requires large footprint (area) and large decay volume (height) for good acceptance.
- Exposed to cosmic rays and atmospheric neutrinos…☹
  - Requires veto of downward going cosmic rays (good timing)
- To establish decay vertex of Long-lived neutral particles to charged objects requires robust tracking for vertex reconstruction and good timing for separating upward going charged particles from downward going cosmic muons.

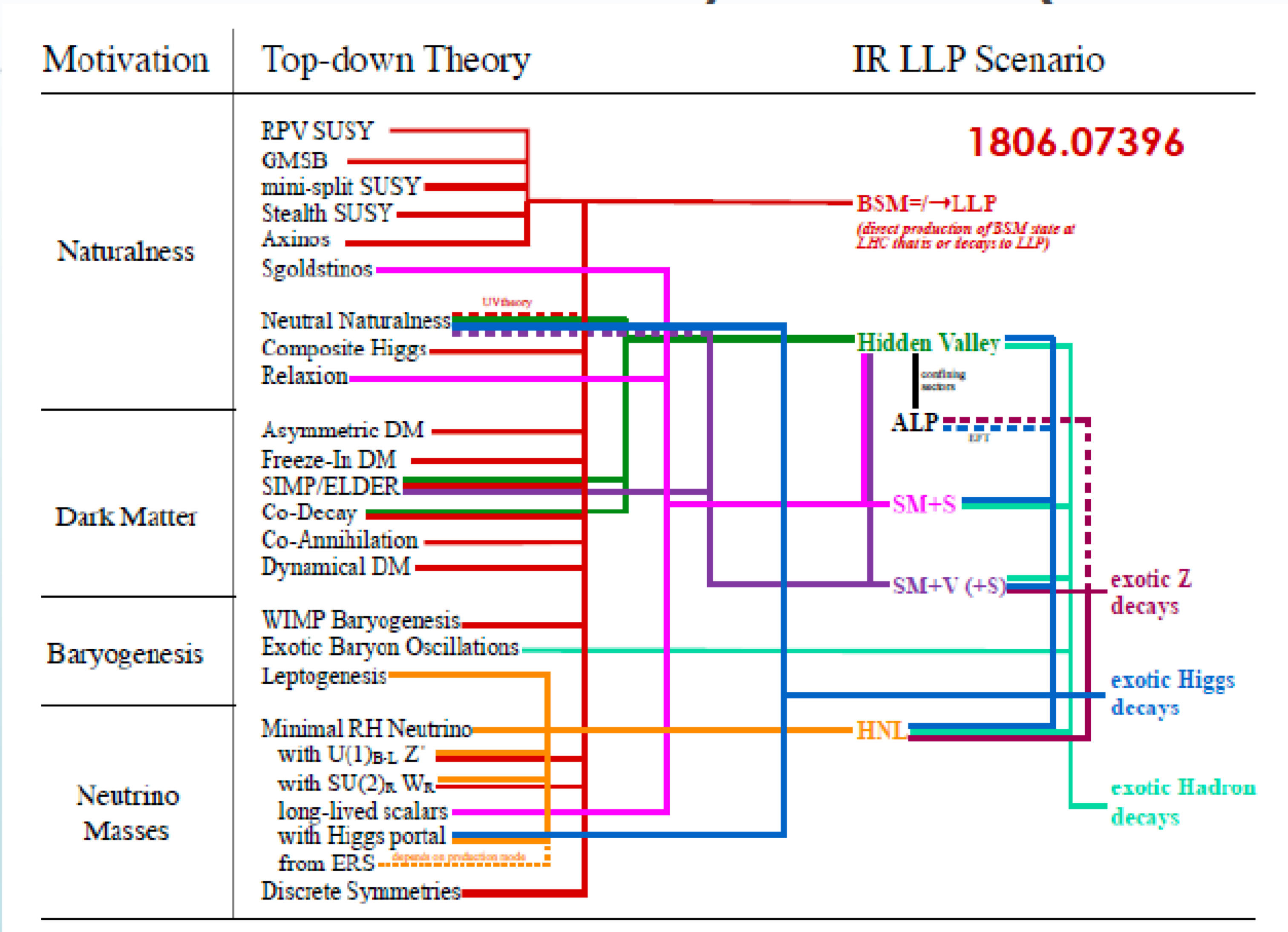
MATHUSLA

J.P Chou, D. Curtin, HL
arXiv:1606.06298

MAssive Timing Hodoscope for Ultra-Stable neutraL PArticles

MATHUSLA Physics Coverage

LLPs arise in most BSM theory constructs (1806.07396)

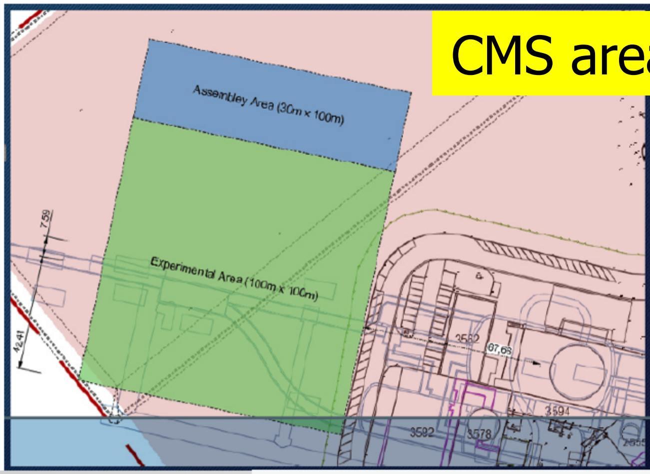


MATHUSLA

- **MATHUSLA: MAsive Timing Hodoscope for Ultra Stable neutraL pArticles**

- The current MATHUSLA detector concept is 100x100 m^2 located at the surface of CMS
- Currently working with CERN civil engineers to:
  - determine the feasibility of excavating to install MATHUSLA slightly below surface
  - and feasibility of building a structure (building) with crane coverage to house MATHUSLA

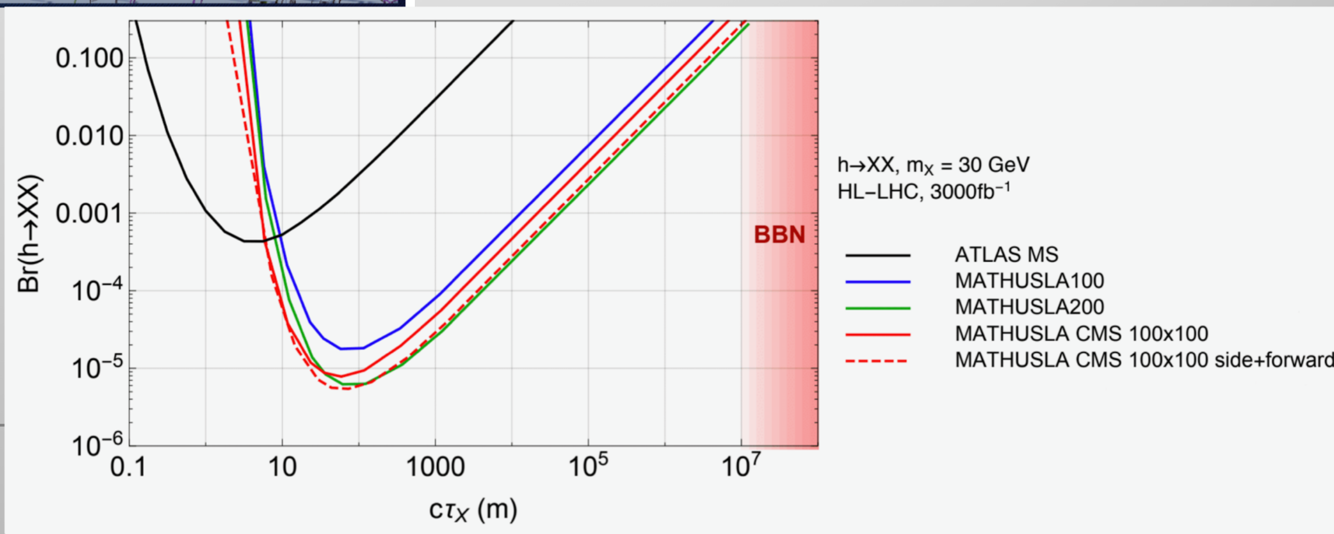
- 100m x 100m experimental area
- 30m x 100m assembly area
- ~7.5m offset to center of beam
- ~68m to IP



Recent developments

- Not on surface but make 5-10m deep hole to put it in.
- Size to 100mx100m
- Use scintillators instead of RPCs for the tracking stations

MATHUSLA physics white paper arXiv:1806.07396



MATHUSLA: Backgrounds

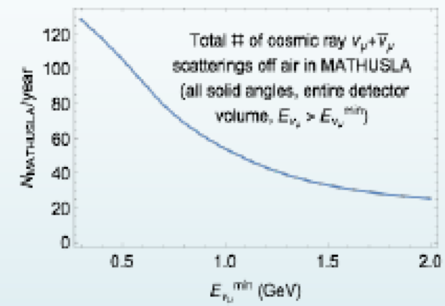
- Cosmic muon rate ~7MHz for 200mx200m and 1.6MHz for 100mx100m detector

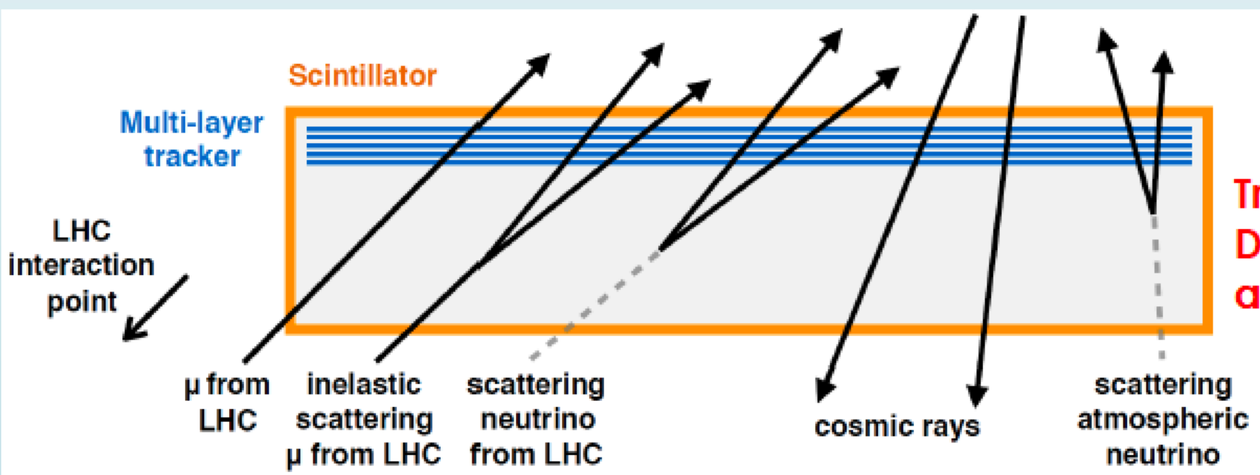
In 20 m gives $\Delta t \approx 70$ ns in 20m - top to bottom

- LHC collision backgrounds

Reject with timing and entrance hit position

  - LHC muons about 10 Hz
- Upward atmospheric neutrinos that interact in air decay volume
  - Estimate Low rate ~ 10-100 per year above 300 MeV
  - Most have low momentum proton (~ 300 MeV - reject with time of flight)-





Tracking/timing Detectors (2) at bottom and no side/back vetoes

MATHUSLA Test stand

Test Stand at PI above ATLAS IP

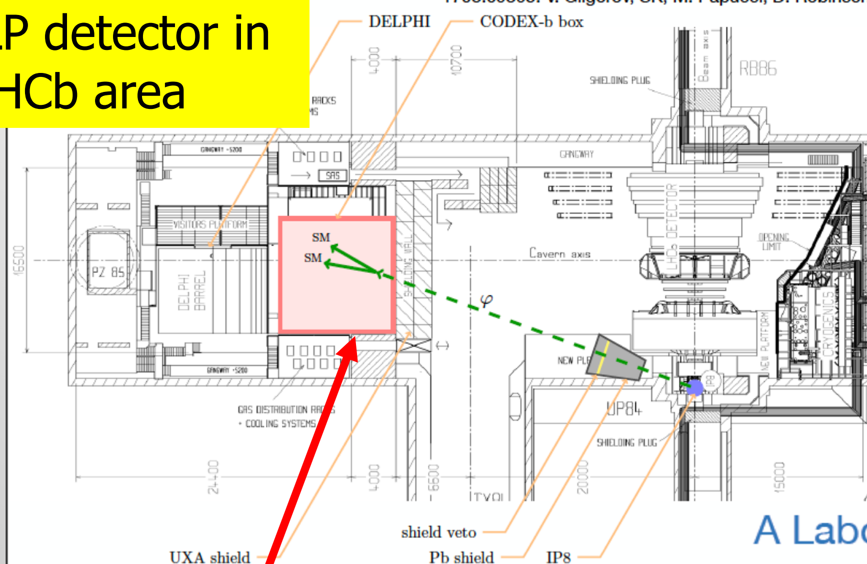
- Built a ~ 2.5x2.5x6 m^3 test stand with three layers of RPCs and top and bottom scintillator layers
  - RPCs from Rinaldo Santonico Rome, Tor Vergata – spares from ARGO experiment
  - Scintillators are recycled from D0 forward muon trigger wall - thanks to Dmitri Denisov.
- Goal to get some idea of upward LHC backgrounds (muons)
- Photo at right shows the structure installed at LHC point-1, above ATLAS IP.

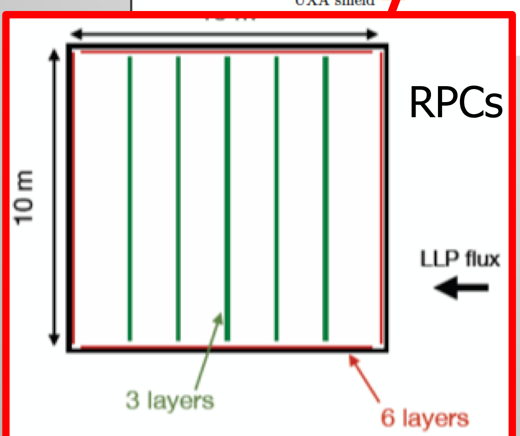
- Make technology choices early 2020
- Prepare full Technical Design Report by end 2020

CODEX-b & AL3X Proposal

An LLP detector in the LHCb area

1708.09395: V. Gligorov, SK, M. Papucci, D. Robinson





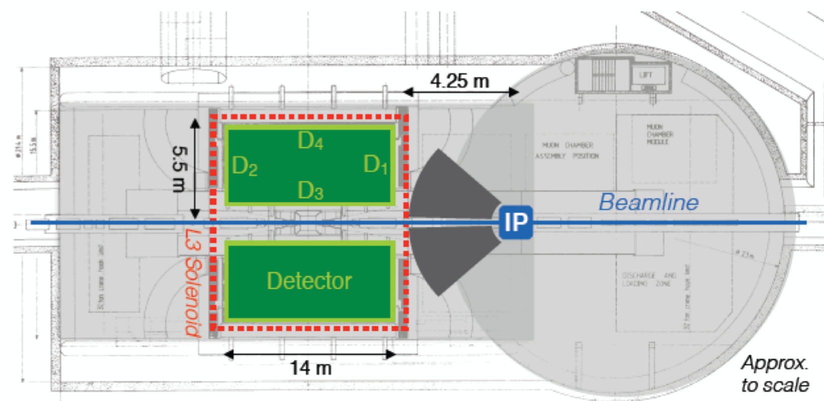
EOI being prepared for LHCb (Sept 2019?)

V. Gligorov, SK, B. Nachman, M. Papucci, D. Robinson: 1810.03636

A Laboratory for Long-Lived eXotics (AL3X)

Reuse the L3 magnet and (perhaps) the ALICE TPC

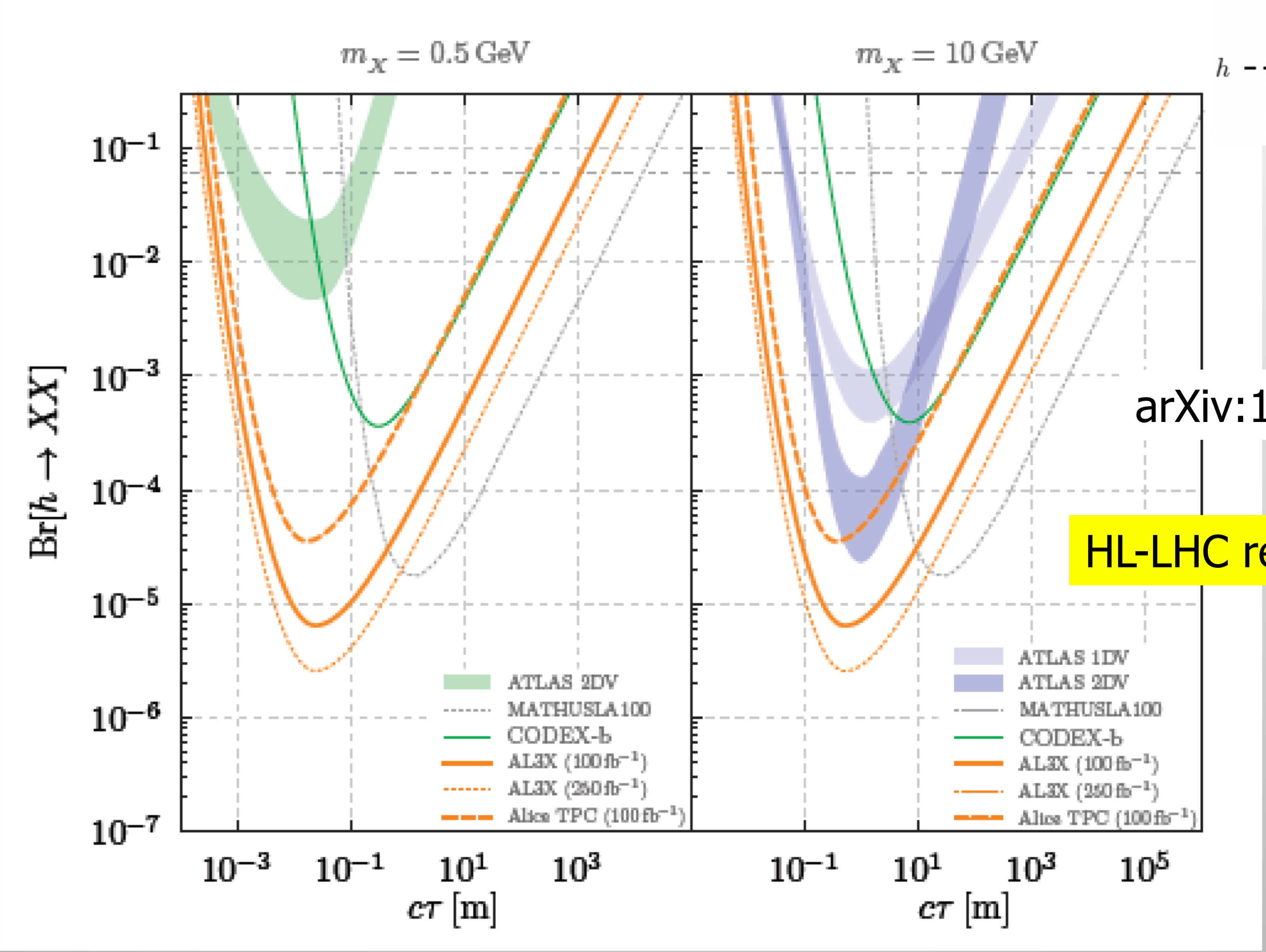
For LHC Run 5 or later??

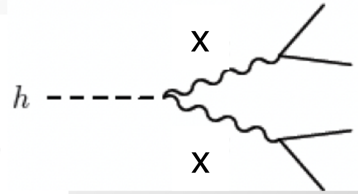


Similar strategy as for CODEX-b: use thick shield with active veto to reduce the backgrounds

So far just an idea

Physics Reach: Example





arXiv:1810.03636

HL-LHC reach

For low masses: MATHUSLA, CODEX-b and AL3X have a leading edge

FASER

Forw**A**rd **S**earch **E**xpe**R**iment at the LHC

FASER will search for light, extremely weakly-interacting particles at the LHC

The FASER Collaboration: 45 collaborators, 17 institutions, 8 countries

Supported by:

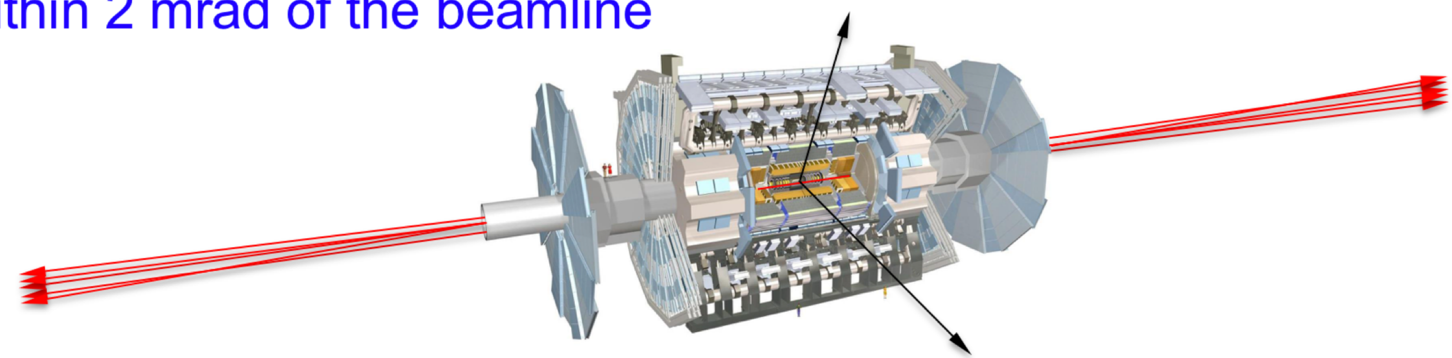
HEISING-SIMONS FOUNDATION

SIMONS FOUNDATION

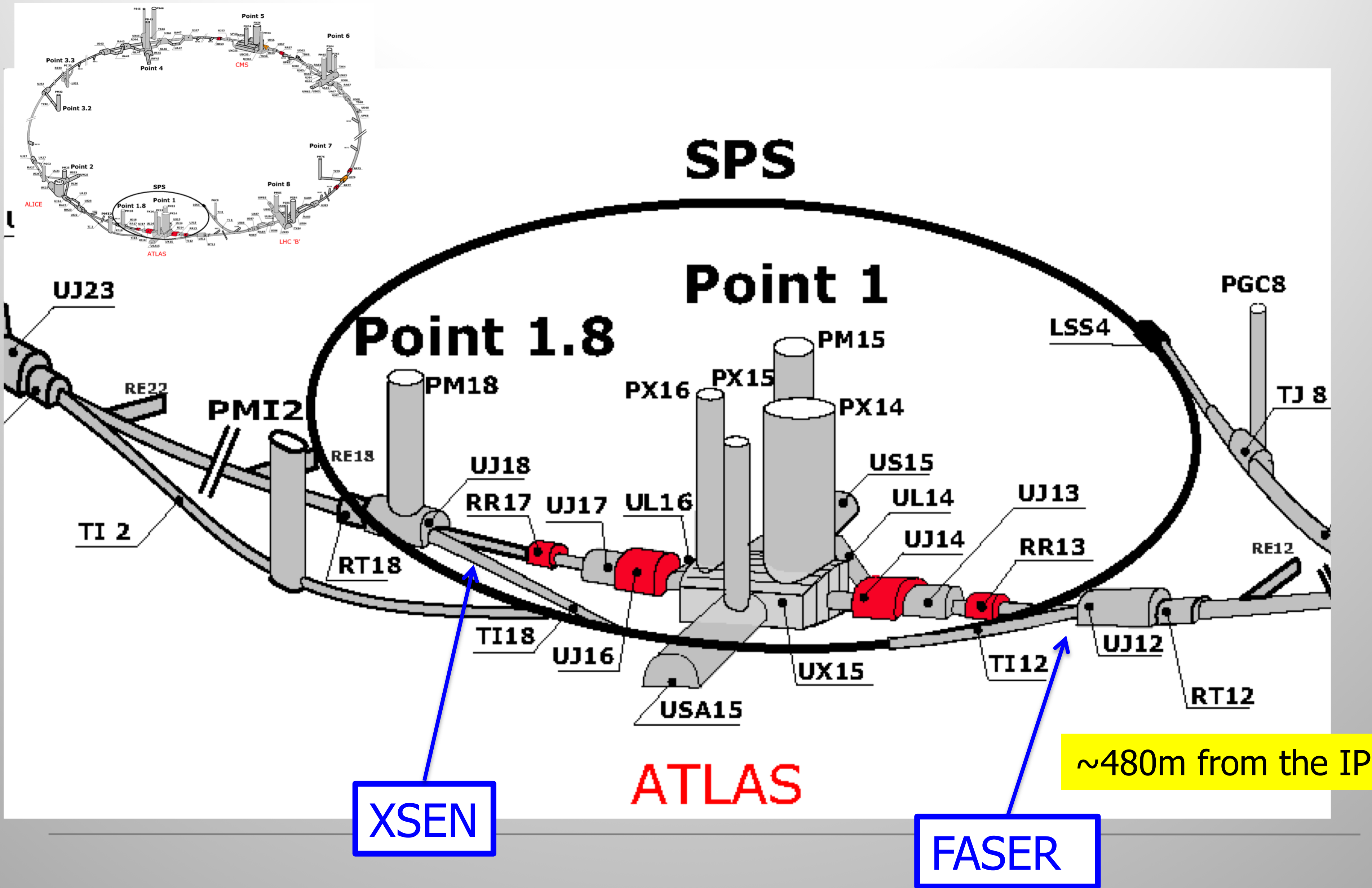
FASER website:
https://twiki.cern.ch/twiki/bin/view/FASER/WebHome

The Idea

- New physics searches at the LHC focus on high p_T. This is appropriate for heavy, strongly interacting particles
  - σ ~ fb to pb → N_{events} ~ $10^3 – 10^6$, produced ~isotropically
- However, if new particles are light and weakly interacting, this may be completely misguided
  - Light → we can produce them in π, K, D, B decays
  - Weakly-interacting → need extremely large SM event rate to see them
- Conclusion: we should go where the pions are: at low p_T along the beamline
  - σ_{inel} ~ 100 mb → N_{events} ~ 10^{17}, and 10% of the pions are produced within 2 mrad of the beamline



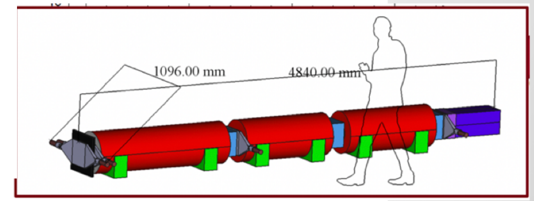
FASER Location

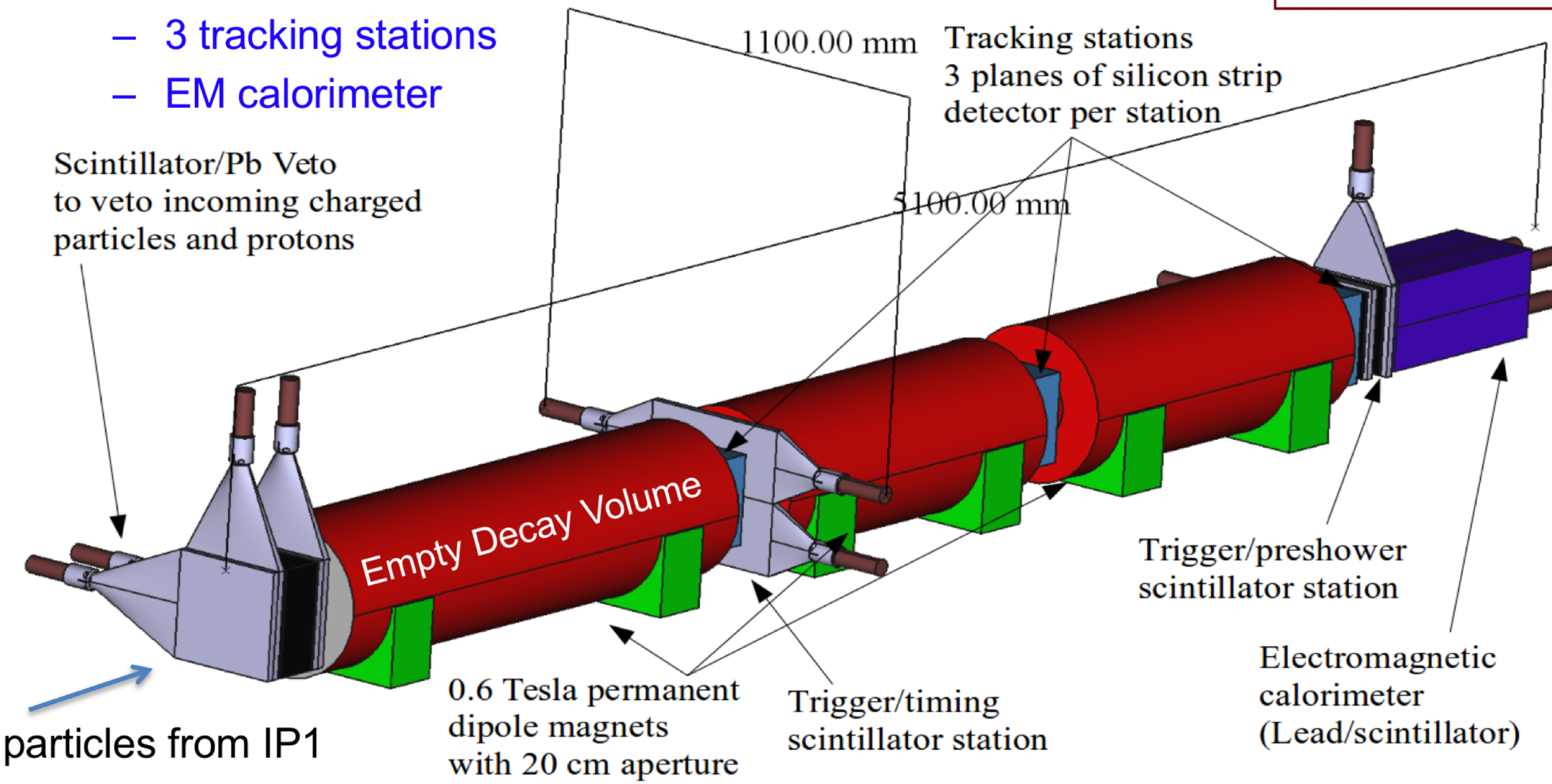


The FASER Detector

- The entire detector is 5.5 m long. It consists of
  - Scintillator veto
  - 1.5 m-long decay volume
  - 2 m-long spectrometer
  - 3 tracking stations
  - EM calorimeter

Re-use spare ATLAS SCT silicon tracking modules and LHCb EM calorimeter modules



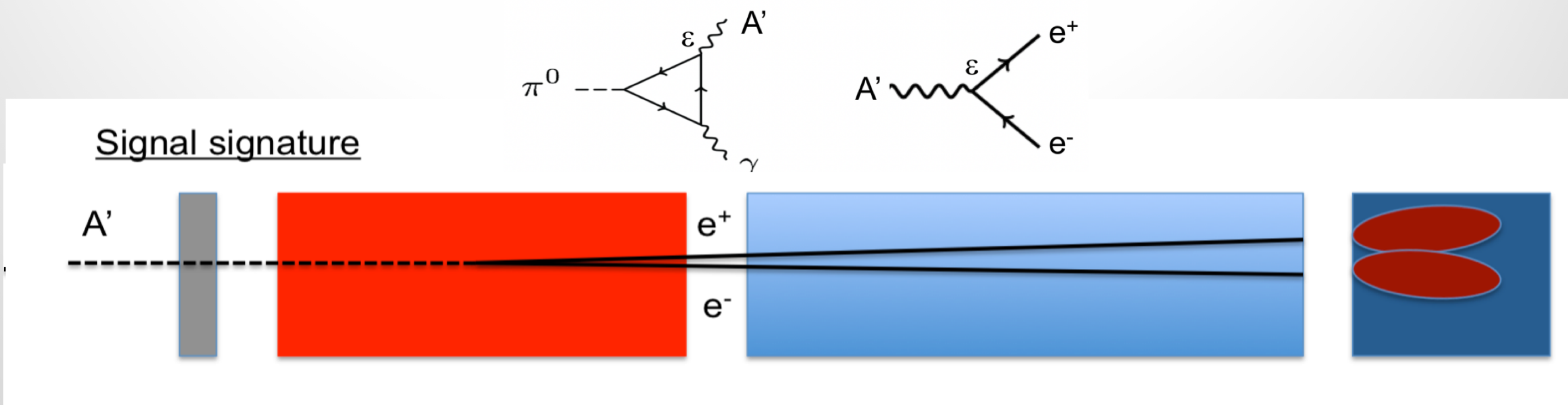


"Tabletop" experiment for about 2M USD ☺

FASER Timeline

- September 2017: First theory paper
- July 2018: Submitted LOI to CERN LHCC
- October 2018: Approval from ATLAS SCT and LHCb Collaborations for use of spare detector modules
- November 2018: Submitted Technical Proposal to LHCC
- November – December 2018: Construction fully funded by the Heising-Simons and Simons Foundations
- March 2019: FASER fully approved by CERN Research Board along with support for infrastructure costs
- April 2019: 1st FASER Collaboration Meeting
- 2019-20: Install FASER in Long Shutdown 2
- 2021-23: Collect data in Run 3 with the potential to discover new particles starting with the first fb^{-1} of luminosity

Dark Photon Detection



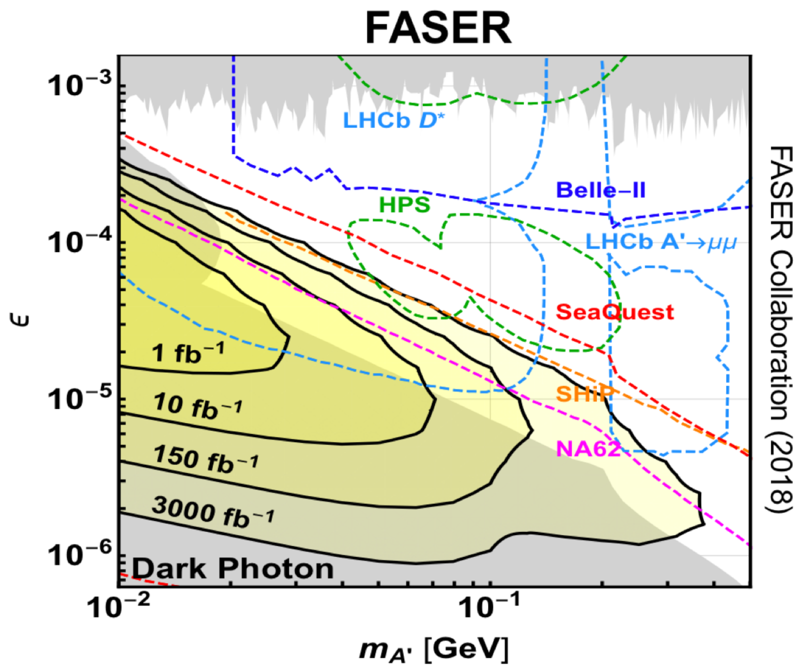
- The signal is spectacular: 2 ~TeV-energy, oppositely-charged tracks originating in the decay volume and pointing back to IP
- Initial scintillators: veto entering tracks
- Tracker: detect charged tracks
- Magnets: separate the 2 charged tracks sufficiently to resolve them in the tracker

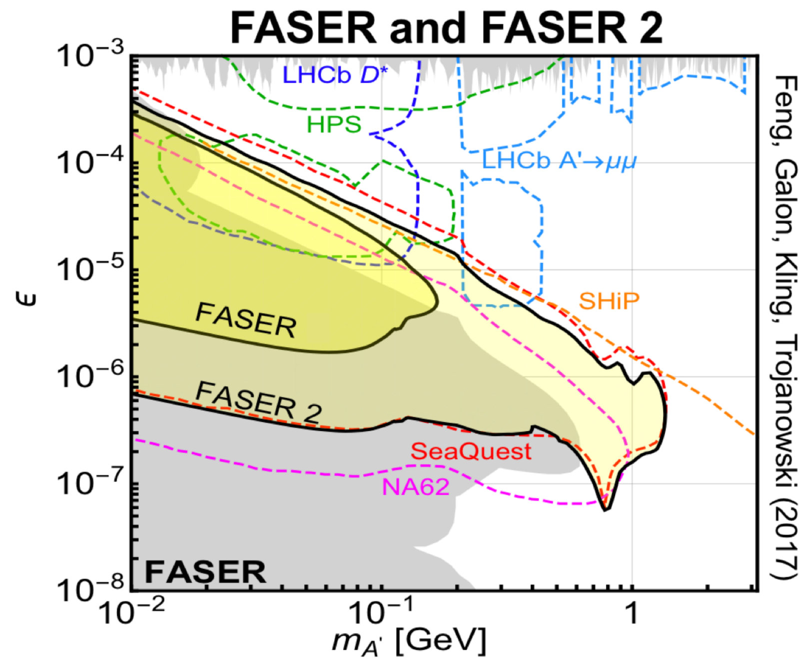
$$h_B \approx \frac{ec\ell^2}{E} B = 2 \text{ mm} \left[\frac{1 \text{ TeV}}{E}\right] \left[\frac{\ell}{3 \text{ m}}\right]^2 \left[\frac{B}{0.6 \text{ T}}\right]$$

- Calorimeter: differentiate e from μ, detect γ, measure energy

Dark Photon Sensitivity Reach

- FASER: R=10cm, L=1.5m, Run 3;   FASER 2: R=1m, L=5m, HL-LHC





- FASER probes new parameter space with just 1 fb^{-1} starting in 2021

- Without upgrade, HL-LHC extends (L*Volume) by factor of 3000; with possible upgrade to FASER 2, HL-LHC extends (L*Volume) by ~10^6

FASER Phase 2

For the HL-LHC run..

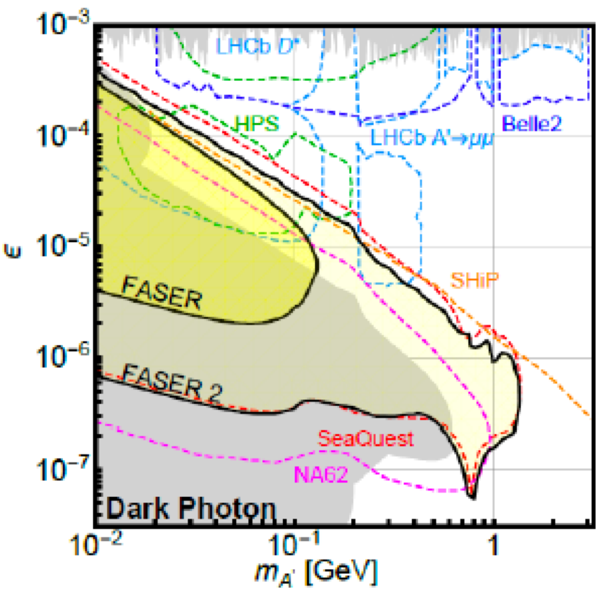
- FASER2 is a potential upgrade to run in HL-LHC with bigger dimensions of the detector.
  - Radius: 1 m
  - Decay volume length: 5 m

To open the acceptance for decays from Ds & Bs

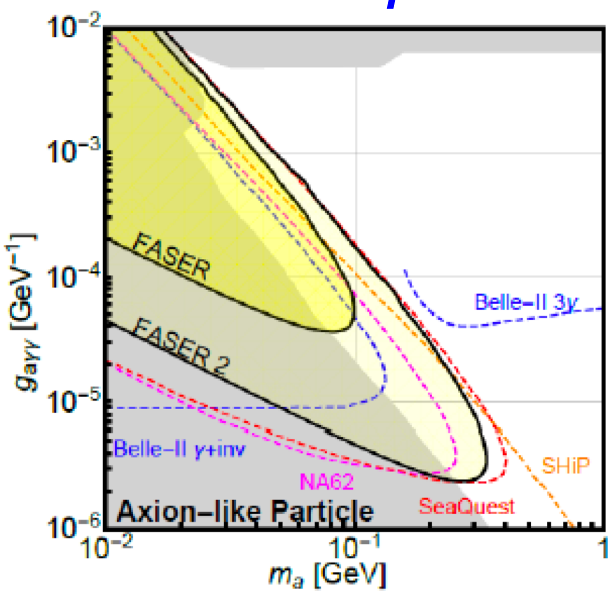
arXiv:1901.04468

- FASER2 can explore much larger parameter space in dark sectors.

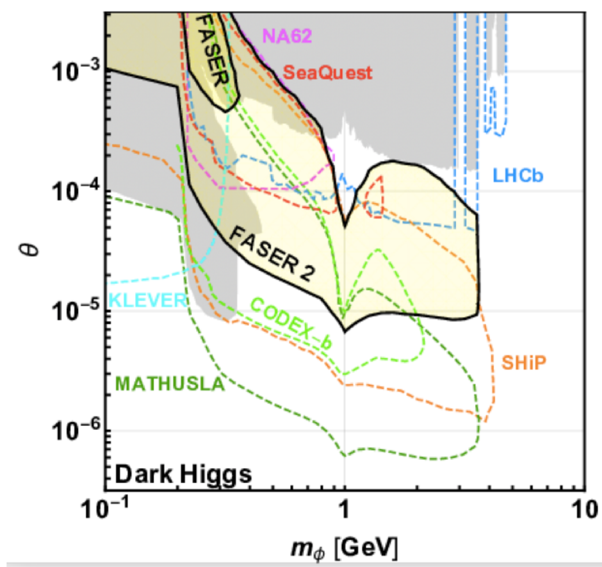
Dark Photon



Axion like particle



Dark Higgs



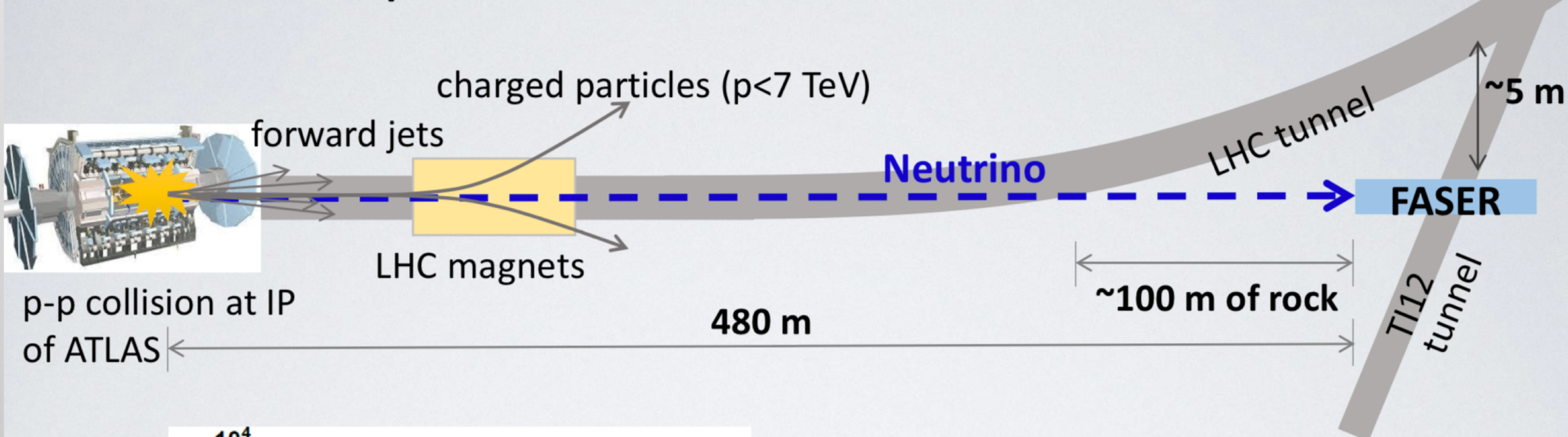
FASER Physics Goals Summary

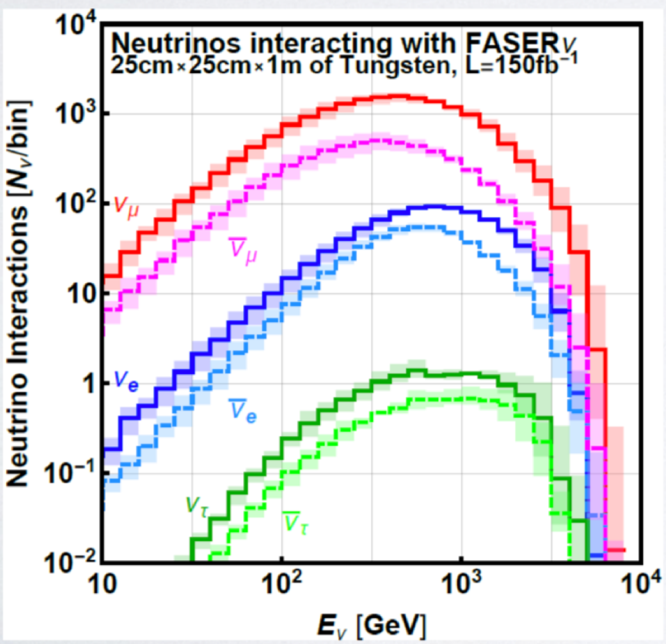
- FASER and FASER 2 have full physics programs: can discover all candidates with renormalizable couplings (dark photon, dark Higgs, HNL); ALPs with all types of couplings (γ, f, g); and many other examples.

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

Neutrinos

Expected neutrino rates at FASER





Expected yields in Run 3 (2021-2023)

	# of CC interactions	Mean energy (GeV)
$\nu_e + \bar{\nu}_e$	1296	827
$\nu_\mu + \bar{\nu}_\mu$	20439	631
$\nu_\tau + \bar{\nu}_\tau$	21	965

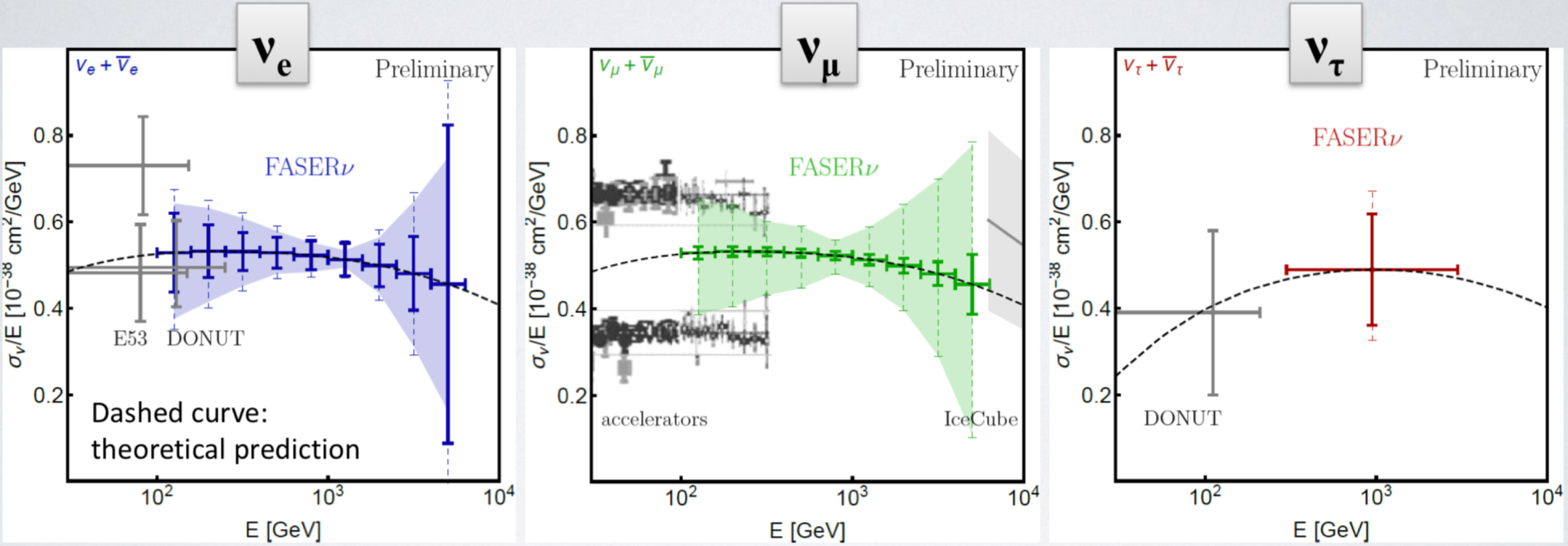
E.g., ν_μ CC cross section in unexplored region 400 GeV < E < 6 TeV, and ν_τ events.

Neutrinos

Prospects for cross section measurements at 14-TeV LHC

in Run3 (150 fb^{-1}) using a 1.2-ton tungsten/emulsion detector

arXiv:1908.02310

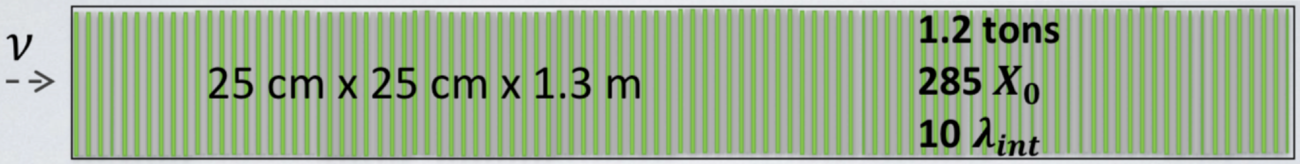


Solid error bars: statistical uncertainties.

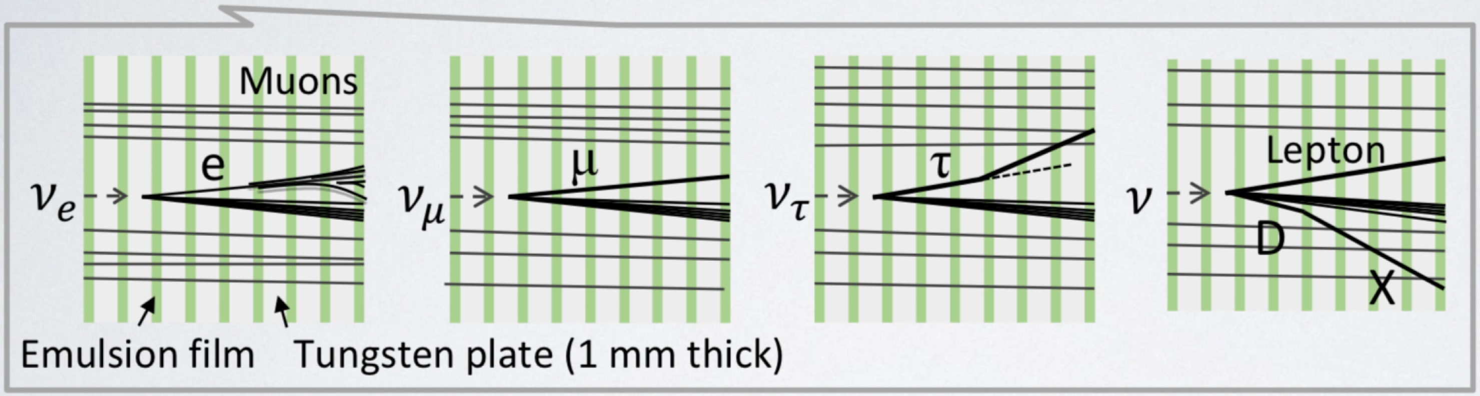
Dashed error bars: also include uncertainties from neutrino production rate corresponding to the range of predictions obtained from different Monte Carlo generators.

Neutrinos

Total 1000 emulsion films interleaved with 1-mm-thick tungsten plates



Muon ID: muons are identified by their track length in the detector

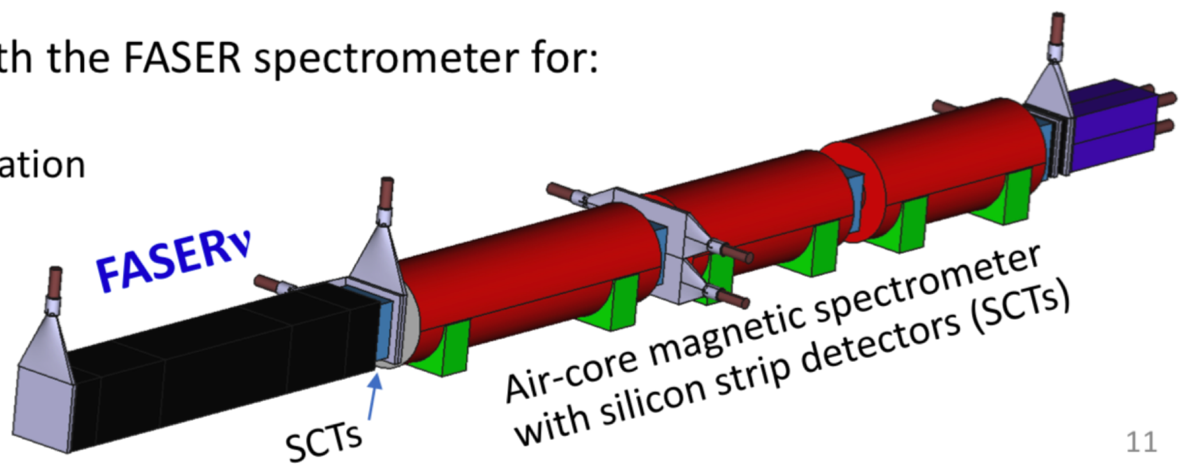


Expected yields in Run3

	# of CC int.
$\nu_e + \bar{\nu}_e$	1296
$\nu_\mu + \bar{\nu}_\mu$	20439
$\nu_\tau + \bar{\nu}_\tau$	21

Possibly upgraded to couple with the FASER spectrometer for:

- charge measurement
- improvement of the energy estimation
- background suppression



Neutrino Experiments at LHC

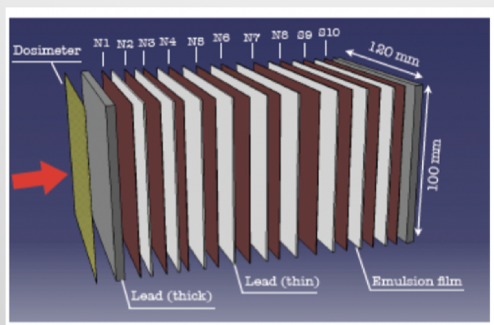
arXiv:1903.06564: a proposal for an emulsion neutrino experiment

Physics Potential of an Experiment using LHC Neutrinos

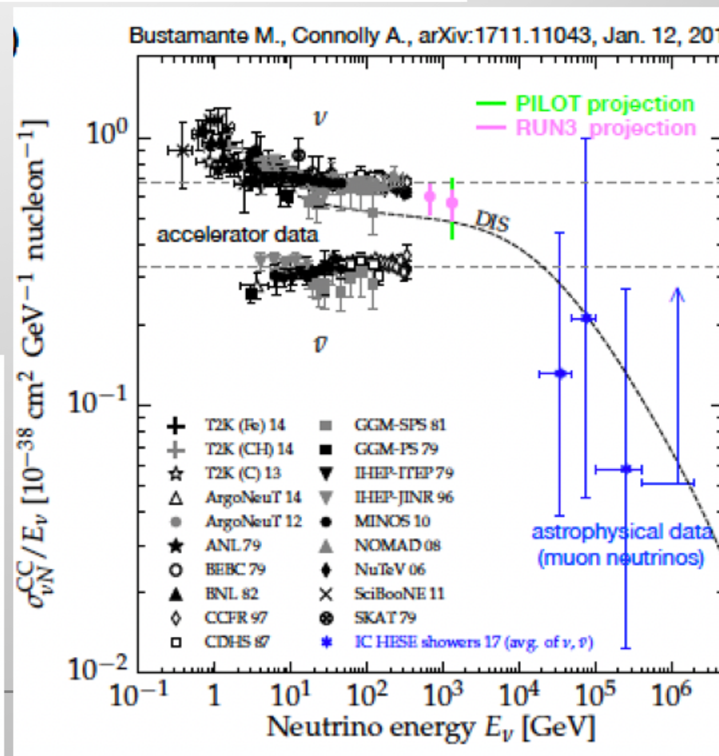
The XSEN experiment

N. Beni[1], M. Brucoli[2], S. Buontempo[3], V. Cafaro[4], G.M. Dallavalle[4], S. Danzeca[2], G. De Lellis[5], A. Di Crescenzo[3], V. Giordano[4], C. Guandalini[4], D. Lazic[6], S. Lo Meo[7], F. L. Navarria[4], and Z. Szillasi[1]

Emulsion detector
"OPERA" style



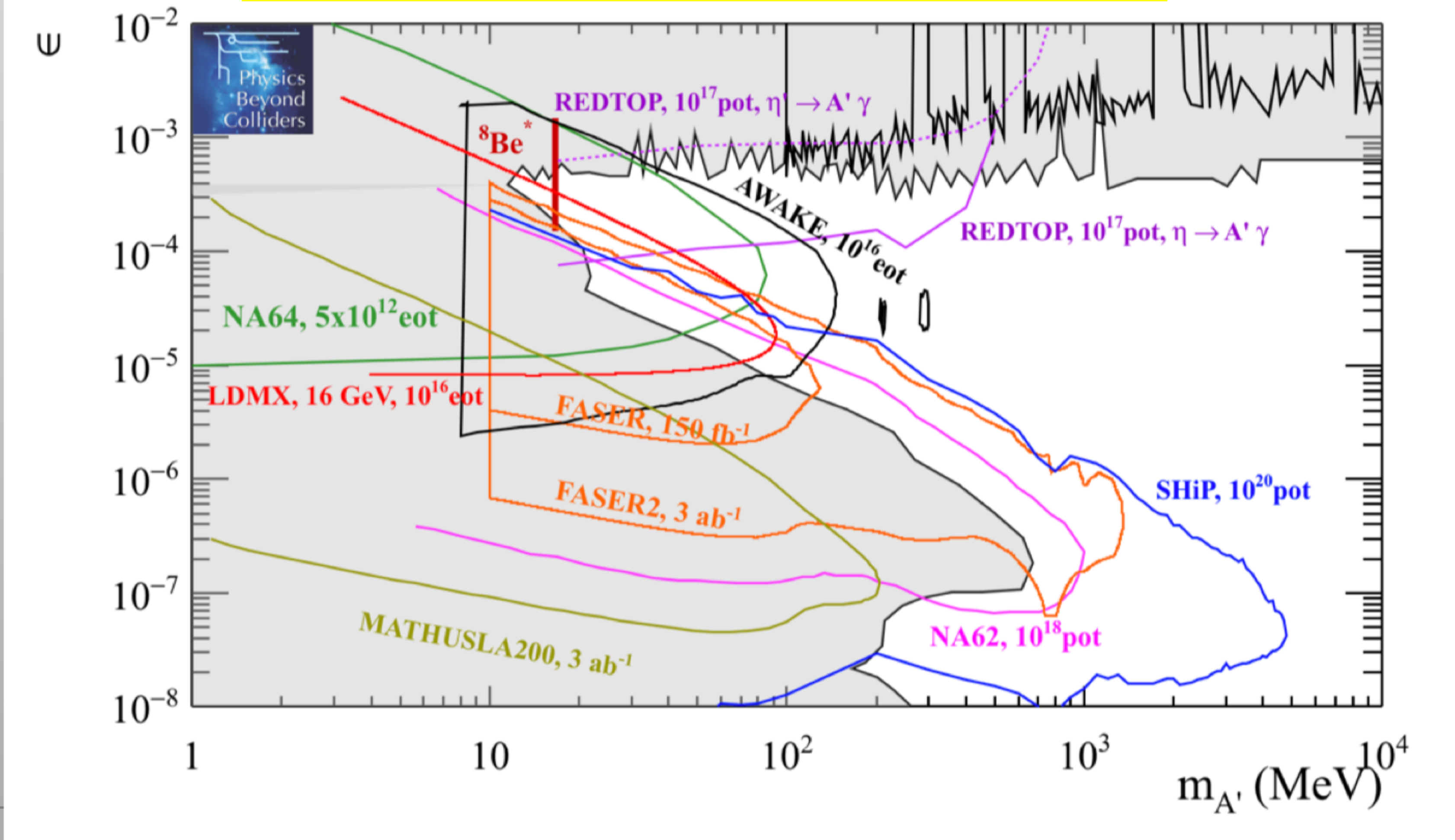
- Phase 1 (PILOT run): 2021, 0.4 ton detector for characterisation of the background, and set-up and tune emulsion handling infrastructure and analysis for 2022-23,
- Phase 2: 2022-23, 1.5 ton detector, 2 sections covering η ranges with different average energy (0.7, 1.2 TeV)
- with 150 /fb can record up to 2000 HE neutrino interactions, up to 100 ν_tau



Comparative Plots from PBC

PCB = Physics Beyond Colliders study: arXiv:1901.09966

Dark Photon Search (visible decay channel)



Comparative Plots from PBC

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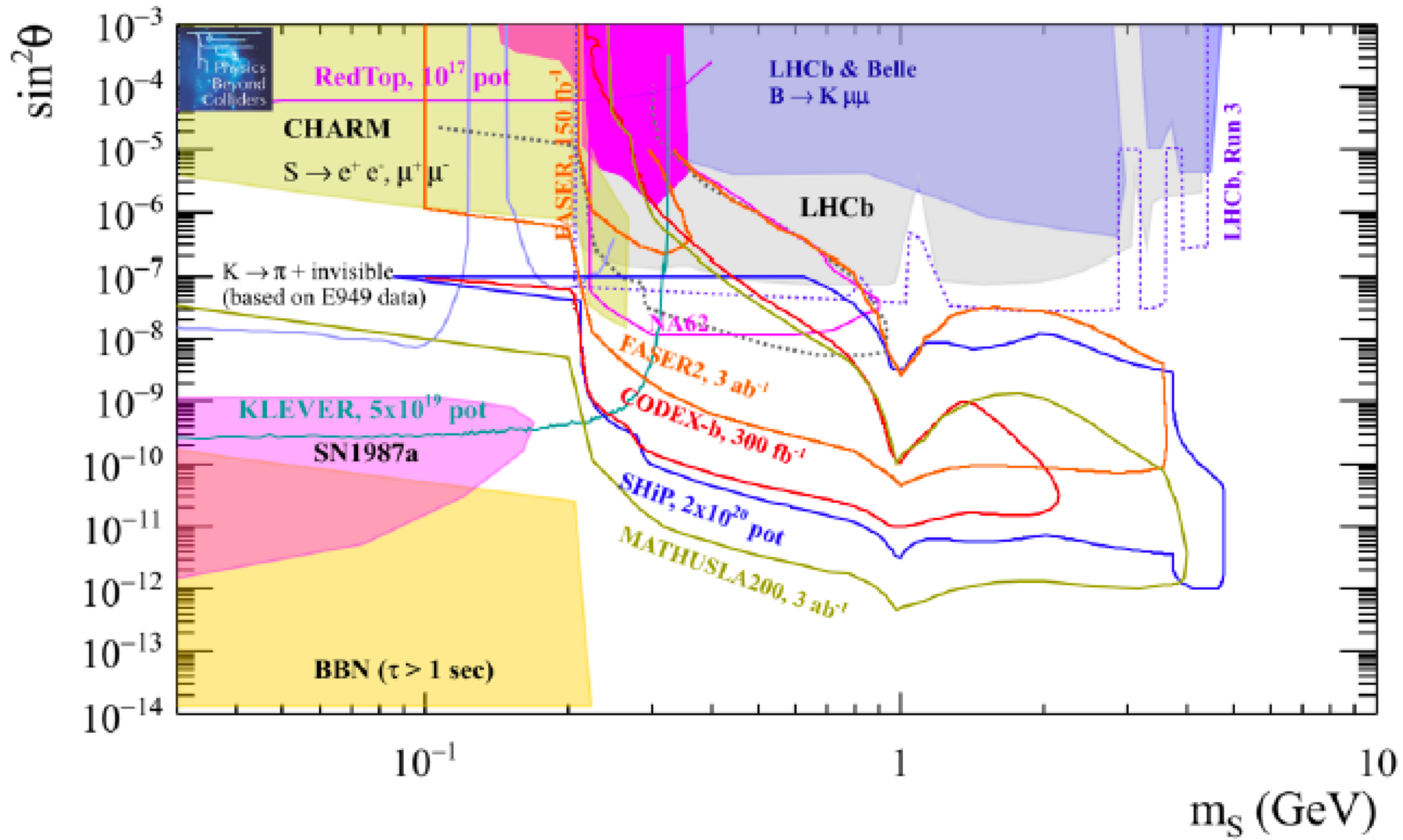
Dark Scalar Search (simplest version)



Comparative Plots from PBC

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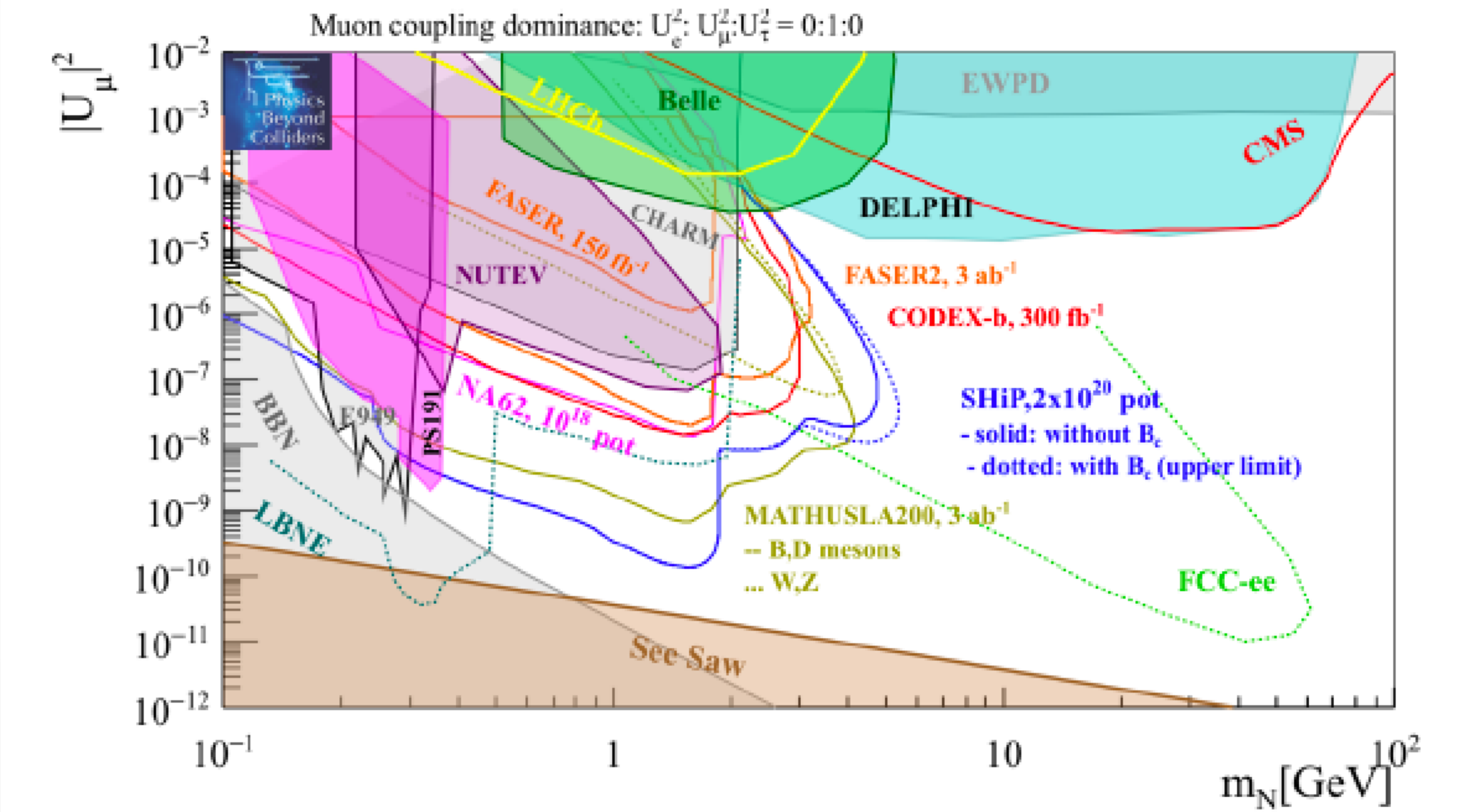
Heavy Neutral Lepton with strongest coupling to the muon flavor



Note: experiments have different NP identification capabilities

Summary

- New ideas for additional new experiments at the LHC to increase the LHC coverage: MilliQan, MAPP, MATHUSLA, CODEX-b, FASER, AL3X…
- MATHUSLA aims to search for ultra long-lived particles to cover lifetimes up to the BBN limit. It needs a huge volume detector.
- FASER aims to search for low mass new particles in the forward direction of the LHC phase space. FASER1 is approved and funded (8^{th} LHC experiment) and will start taking data in 2021
- FASER has a program to add an emulsion detector for the study of high energy neutrino interactions.
- A similar idea has been forwarded by XSEN (LOI under preparation): An emulsion detector for high energy neutrino interaction measurements at the LHC
- Among others, MATHUSLA and FASER (CODEX-b, AL3X) will hunt for Heavy Neutral Leptons in the ~ GeV range!