

Experimental Perspectives: Near and Far Future projects

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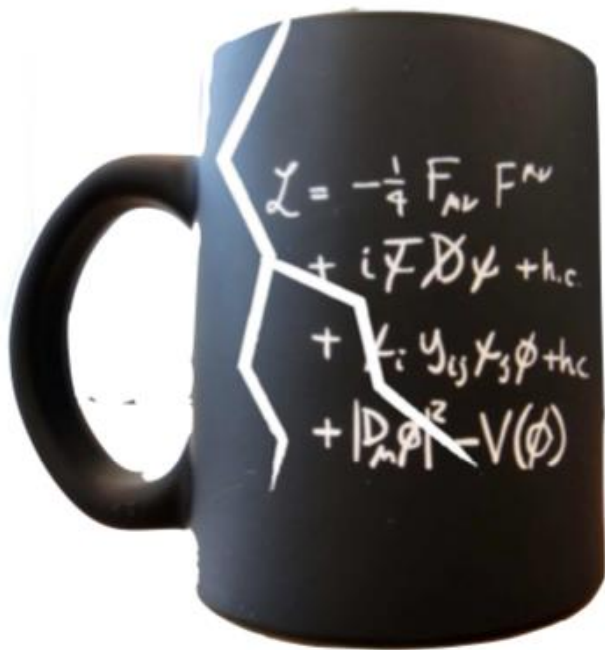
19th August 2022

Rencontres du Vietnam — Flavour Physics Conference 2022



Outline

In search of:



- Introduction & LHC program
- New directions at the LHC
- Physics beyond colliders
- Neutrinos
- Energy Frontier projects
- (Other topics)
- Summary

Comments

- personal selection of topics
- Not specially emphasizing flavor program (Many talks already included most info)

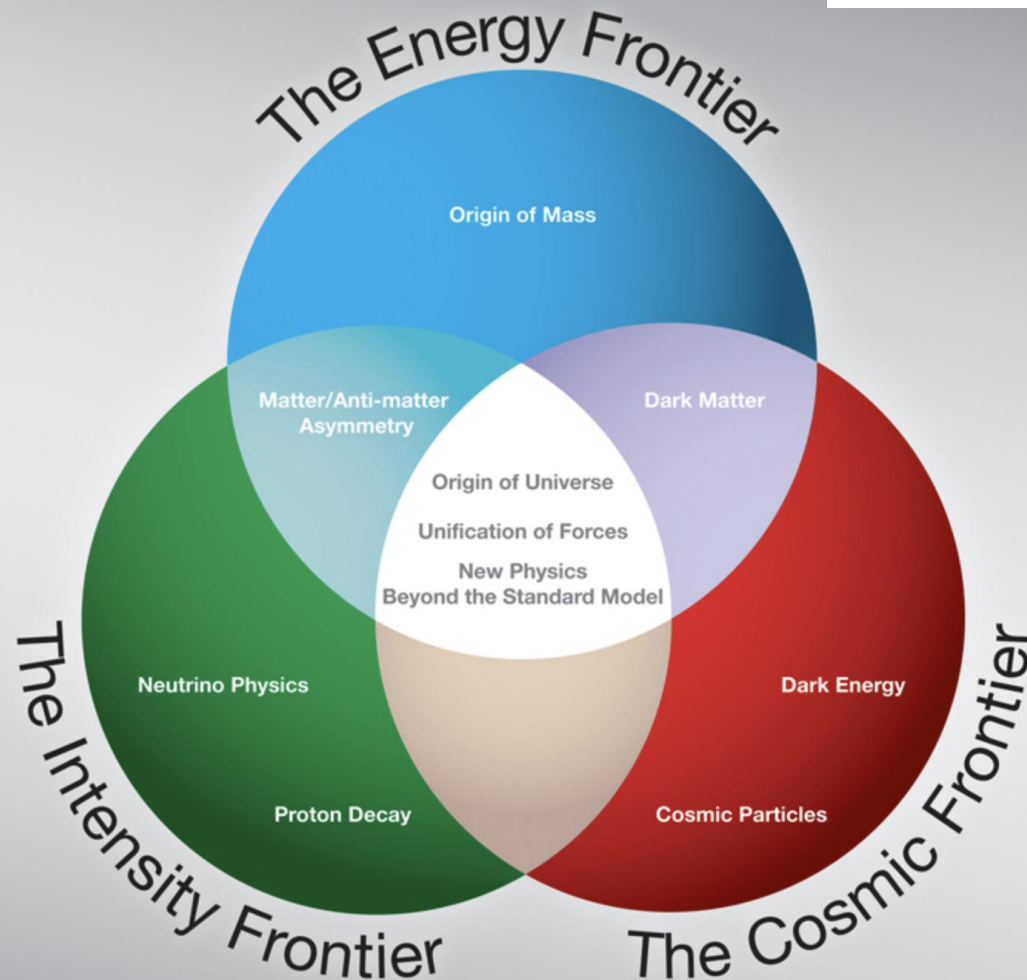
Recent Particle Physics Strategy Updates

NB: Snowmass 2021
had 9 frontiers...

European Strategy for
Particle Physics
2019-2020

Snowmass 2021
Still being finalized:
-SM-2021 book to be
completed by 10/22

P5 panel will follow
-Start fall 2022 and
aim for report late
spring/early summer
2023



Setting the Stage...

M. Carena @ Snowmass 2021

A lot of Particle Physics is Missing in the Standard Model

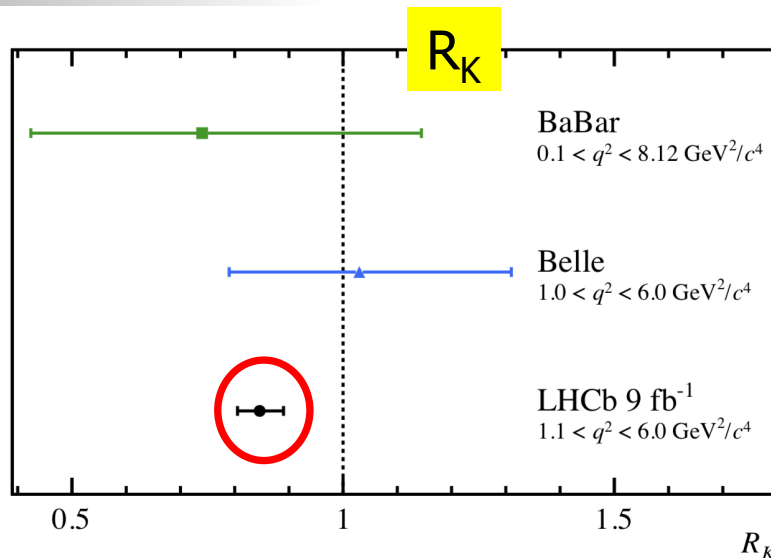
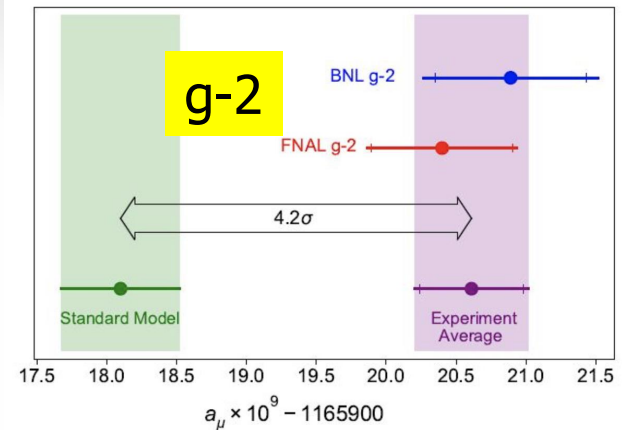
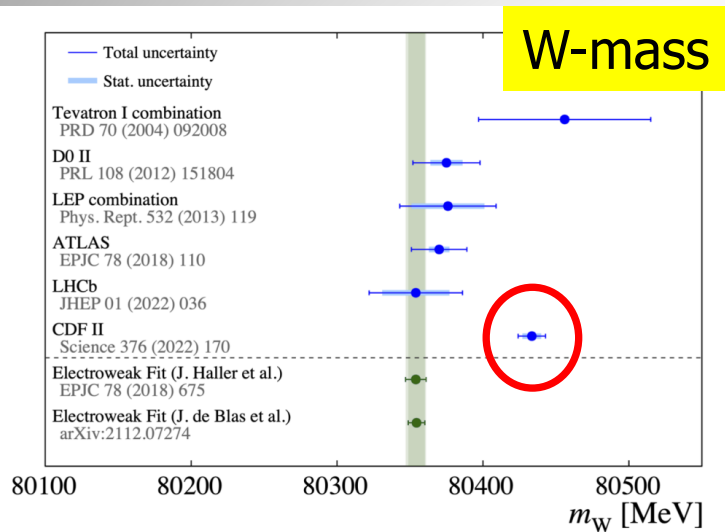
- Why Electroweak Symmetry Breaking occurs?
What is the history of the Electroweak Phase Transition ?
- The reason for the Hierarchy in Fermion Masses and their Flavor Structure
- The Nature of Dark Matter
- The origin of the Matter-Antimatter Asymmetry
- The generation of Neutrino Masses
- The cause of the Universe's accelerated expansion - Dark Energy
- What are the quantum properties of Gravity?
- What caused Cosmic Inflation after the Big Bang?

The SM is silent about all the above, BSM physics is at the core of it all

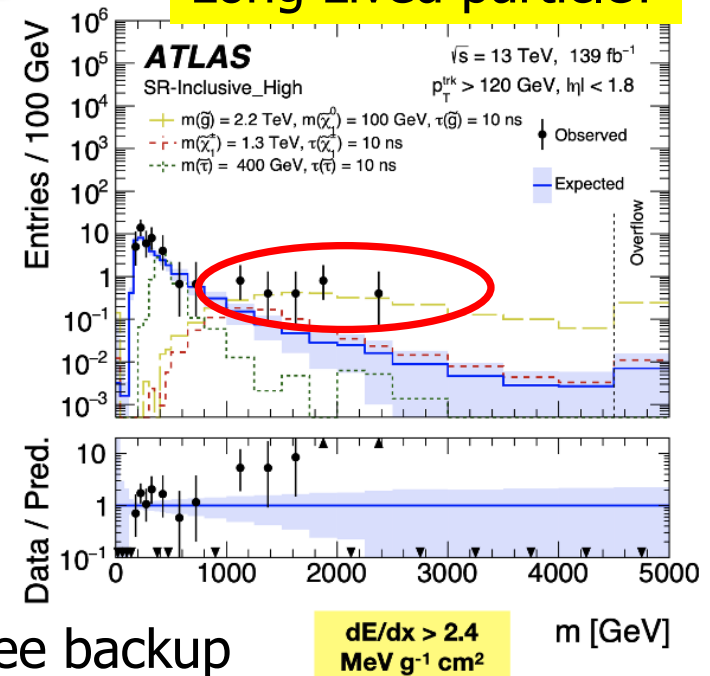
Each Frontier physics highlights aims at deciphering many of these mysteries and their approaches are in many ways complementary to each other

Tackle with direct & indirect searches for BSM effects

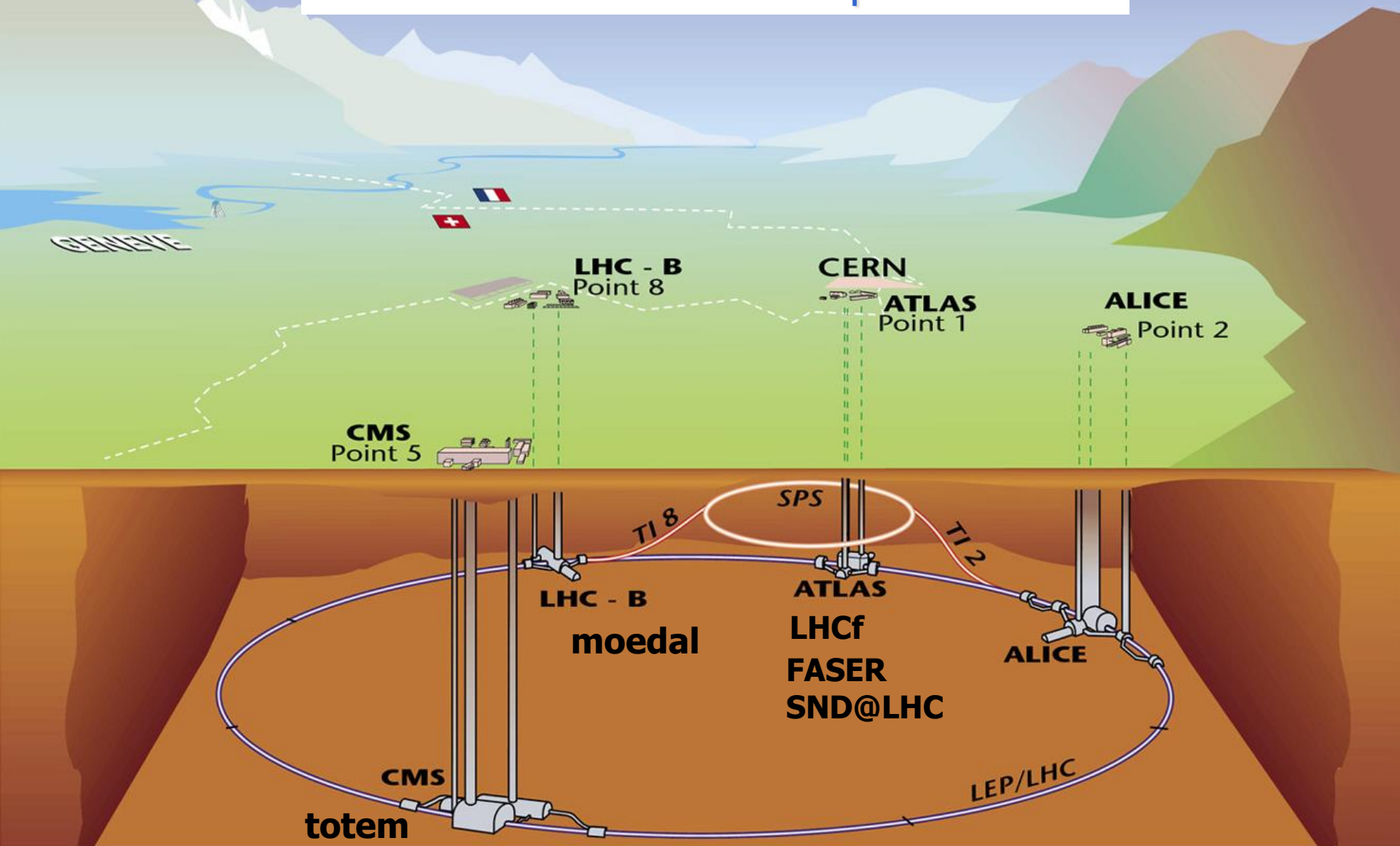
Examples of Anomalies...



Long Lived particle?



The LHC Machine and Experiments



9 experiments

LHC Operations

- 2010-2012: Run-1 at 7/8 TeV CM energy: Collected $\sim 25 \text{ fb}^{-1}$ /Exp
- 2015-2018: Run-2 at 13 TeV CM energy: Collected $\sim 140 \text{ fb}^{-1}$ /Exp
- 2012-2025: Run-3 at 13.6 TeV CM energy: Collect $> 250 \text{ fb}^{-1}$ /Exp

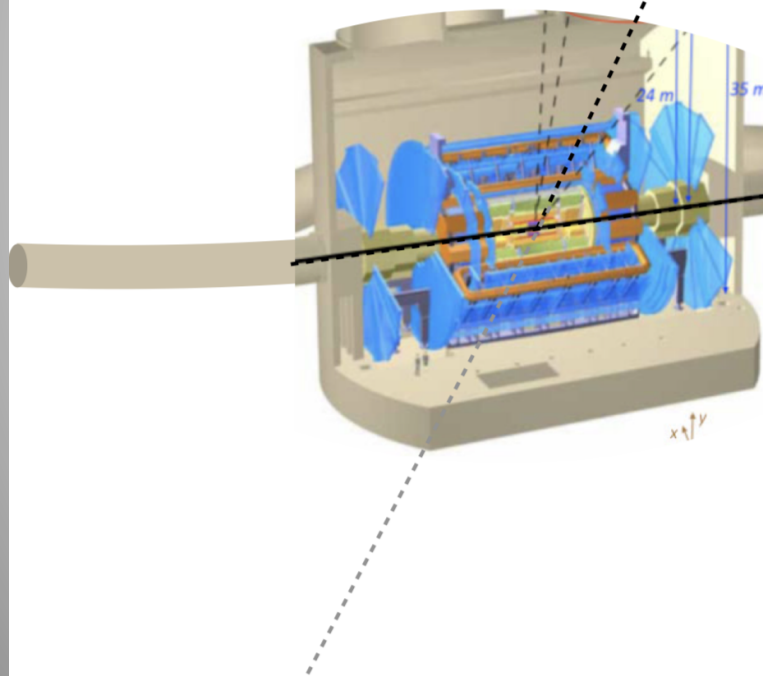


>2029 HL-LHC: 3000 fb^{-1} /Exp

New Directions/Detectors

Searches for new long lived
Particles

orthogonal



ANUBIS
MATHUSLA
CODEX-b
MILLIQAN
MAPP
(AL3X)

along the beam line

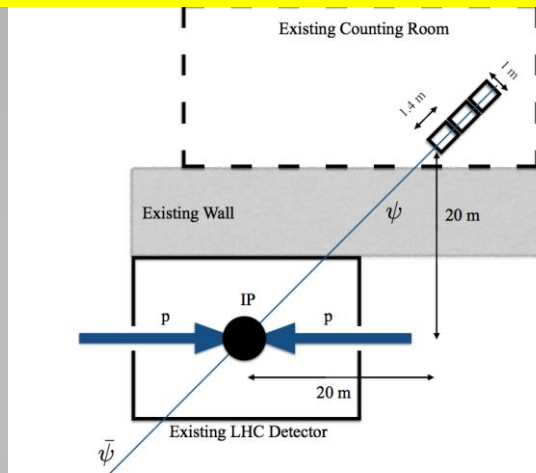
FASER(Nu)
SND@LHC
FACET
FPF

Examples:

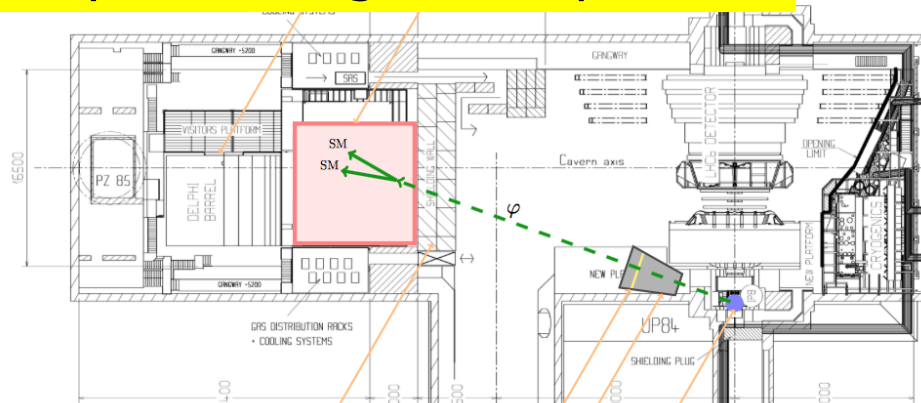
- Axions/Axion-like particles
- Heavy Neutral Leptons
- Millicharged particles
- Dark Sector scalars
- Light Dark Matter ...

New Transverse Experiment Proposals

MilliQan: searches for millicharged particles
MAPP: MoEDAL upgrade

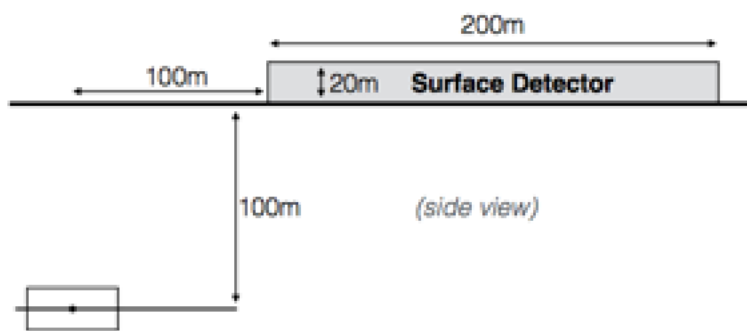


CODEX-b: searches for long lived weakly interacting neutral particles

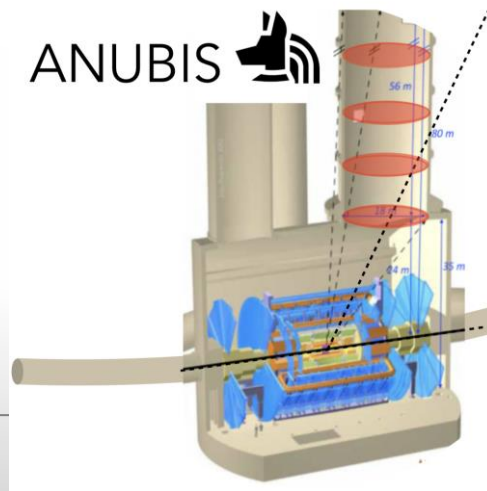


Also: **AL3X** ('ALICE' for LLP arXiv.1810.03636).

MATHUSLA: searches for long lived weakly interacting neutral particles



ANUBIS



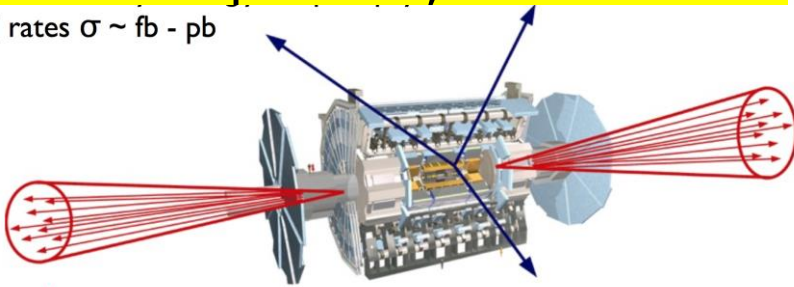
ANUBIS: searches for long lived weakly interacting neutral particles

+Recently (2021):
a new detector
for CMS cavern..

New Forward Detector Proposals

FASER: searches for long lived dark photons-like particles, neutrinos

- typical rates $\sigma \sim \text{fb} - \text{pb}$



SND@LHC: neutrino measurements and long lived particle searches

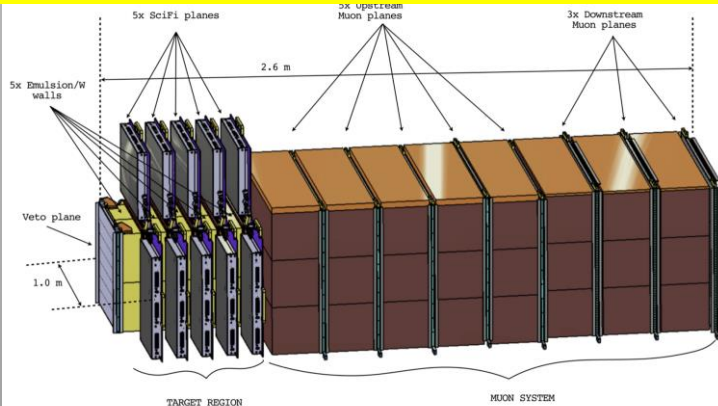
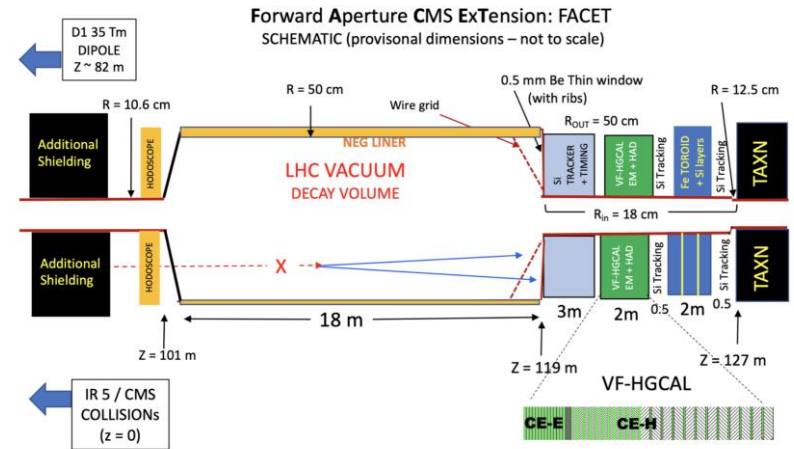


Figure 5: Layout of the proposed SND@LHC detector.

FACET: Instrumented Beampipe for CMS



FPS: A Facility for Forward Physics Containing several experiments



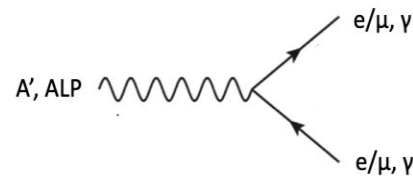
FASER and SND@LHC have been approved in 2019/2020 and are ready and take data during Run 3 which has just started.

BSM Searches in Forward Detectors

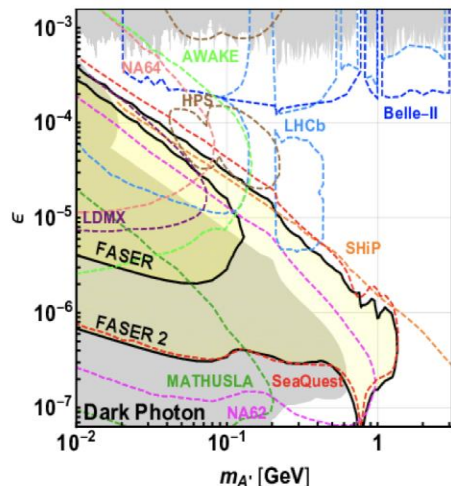
- LLP produced in pp collisions and then travels $O(100\text{ m})$ before being detected by experiment
 - Sensitive to masses in multi-MeV to low-GeV range

FASER

- LLP decays to SM
- ALPS, γ -dark (A'), ...

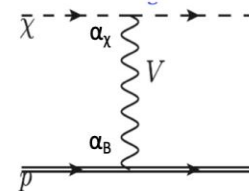


[arXiv:1811.12522](https://arxiv.org/abs/1811.12522)

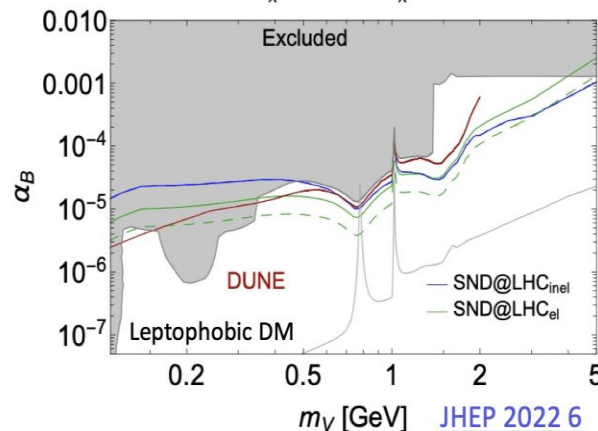


SND@LHC

- (In)elastic FIPS scattering or FIPS decay to $ee/\mu\mu$
- E.g. Light DM



$$m_\chi = 20 \text{ MeV}, \alpha_\chi = \alpha_B$$

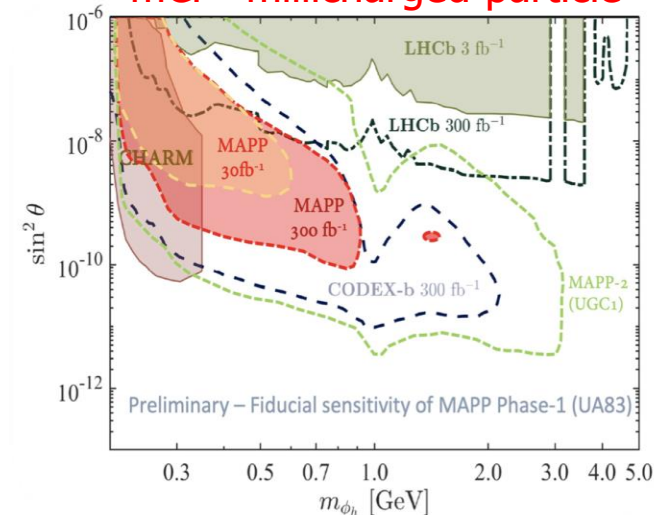


[JHEP 2022 6](https://arxiv.org/abs/2201.00001)

MoEDAL-MAPP

- LLP decays and mCP
- LLP \rightarrow mCP, Dark Higgs

mCP=millicharged particle



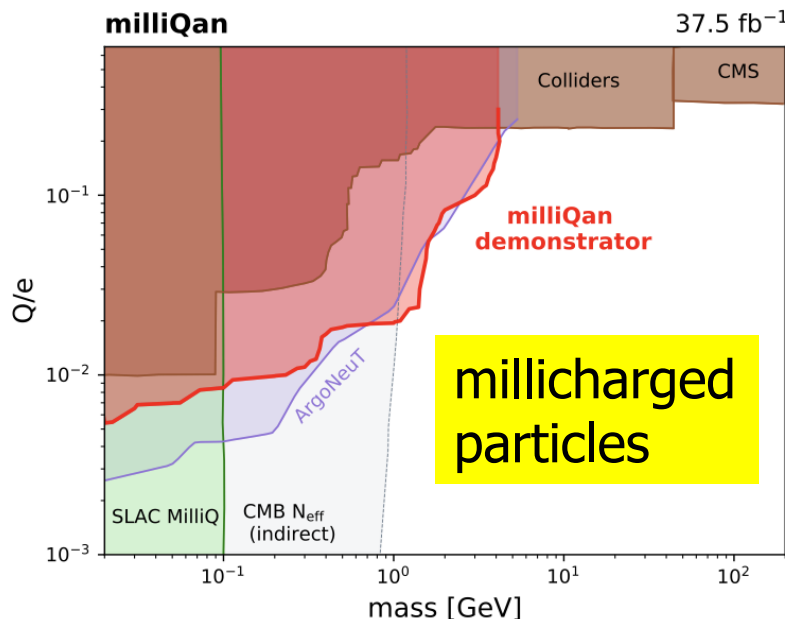
New Detectors with First Results

... based on prototypes/demonstrators installed during 2017-2018

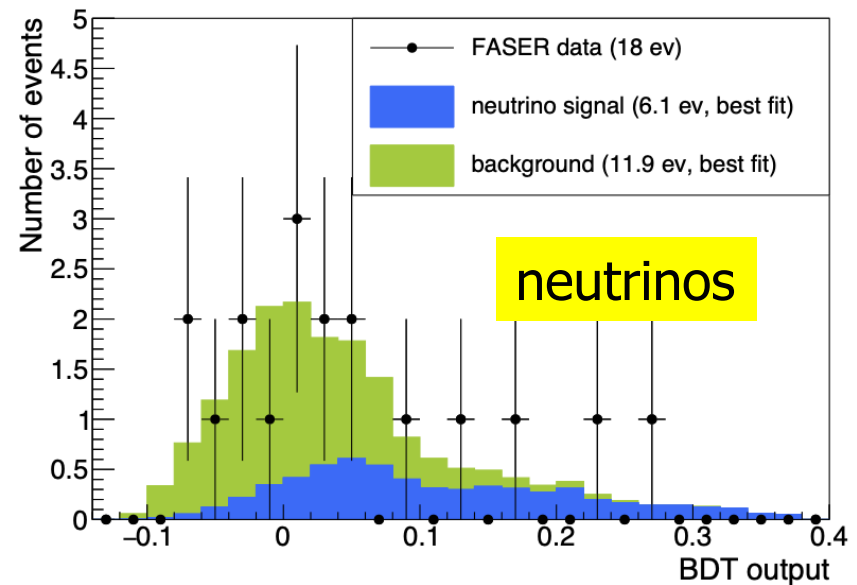
- First data from dedicated detectors that have already been funded (in test runs)



milliQan, 2005.06518 [PRD]



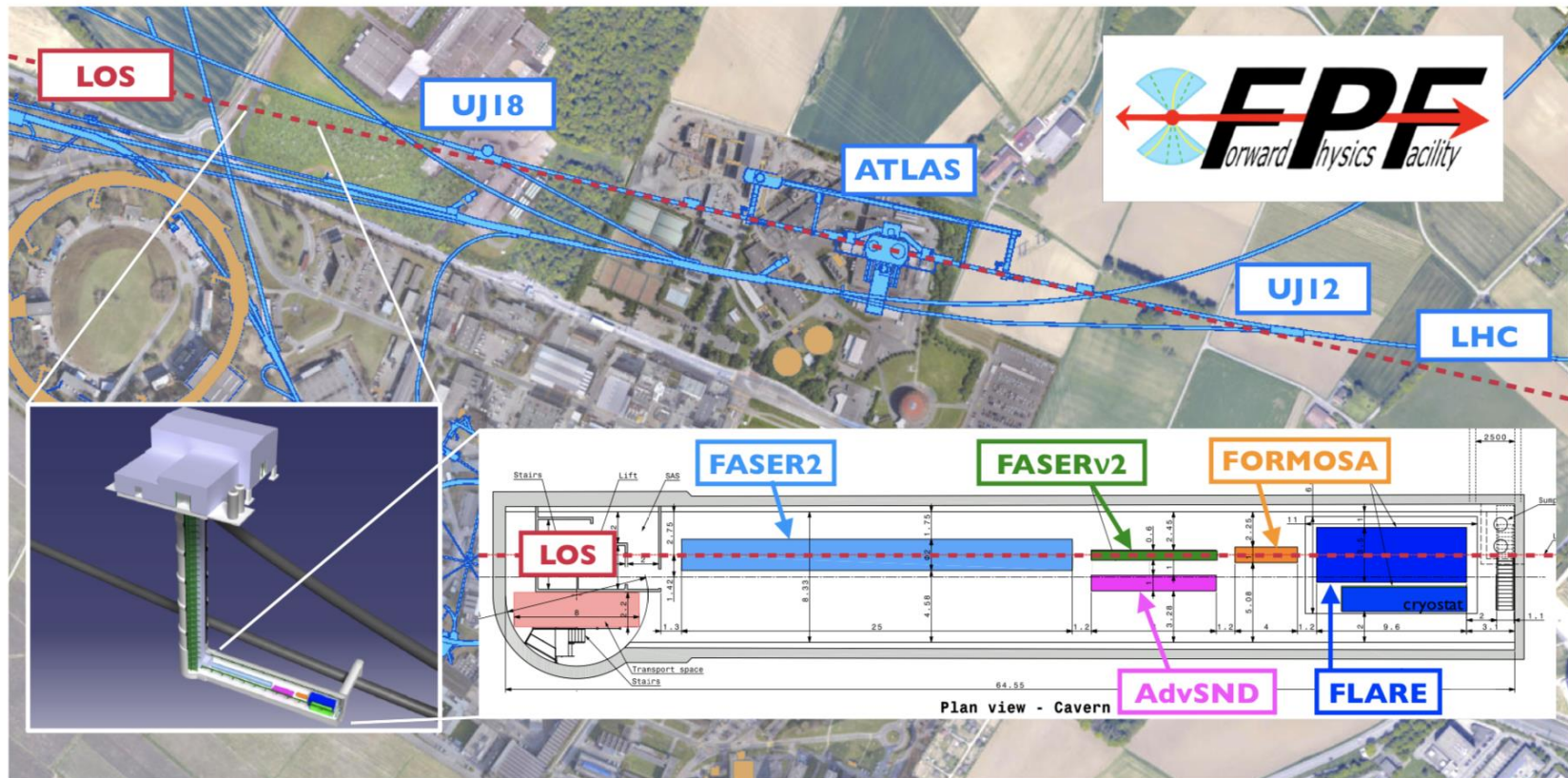
FASER, 2105.06197 [PRD]



The Forward Physics Facility

A Proposal for a New Large Underground Area $\sim 620\text{m}$ away from ATLAS
Based on the FASER experience and studies: propose to have a Forward Physics Facility (FPF) experimental hall with room to include forward detectors for new physics searches and neutrino measurements

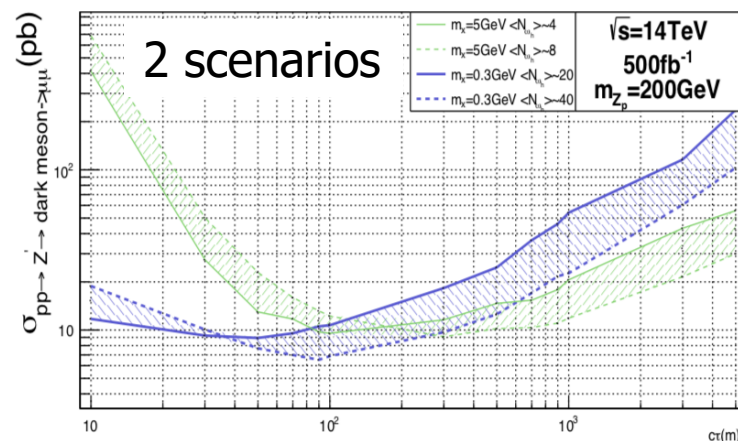
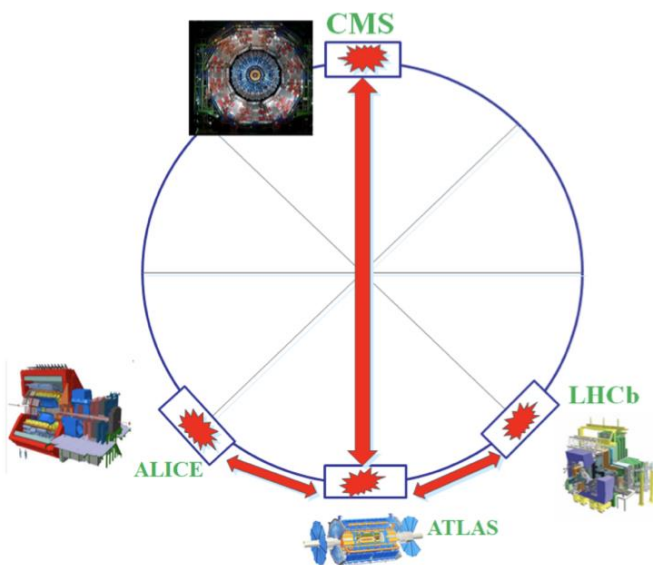
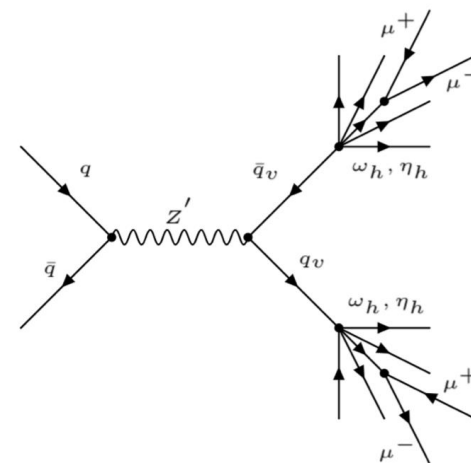
2203.05090



A Wild Idea?

- LLPs can escape the detector at the collision point and accidentally decay in the vicinity of detectors far away. Spooky?
- Estimates using ATLAS and ALICE for (favourable) Hidden Valley scenario, detecting the muons..

2004.08820



LLPs @ Next Collider Projects

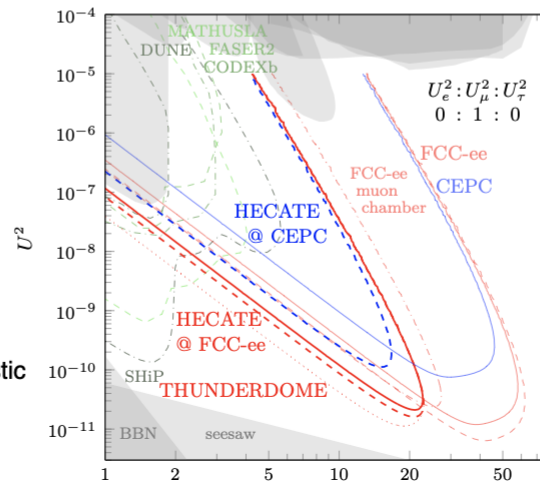
Important: take LLP requirements into account from the start (Snowmass2021)

LLPs @ FCC-hh, FCC-ee

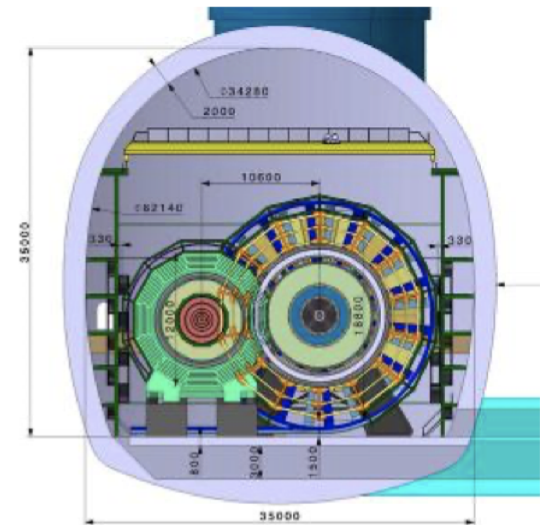
HECATE: **H**Ermetic **C**Avern **T**rack**E**R. A long-lived particle detector concept for FCC-ee or CEPC

- For FCC-hh / FCC-ee, main detector will be relatively smaller than the cavern
- Cover detector cavern walls with scintillator plates or RPCs
 - ≥ 2 layers of 1 m² separated by a sizeable distance — timing
 - ≥ 4 layers for good tracking
 - 4π coverage LLP detector
- FCC main detector as active veto
- Sensitive to a unique area of phase space

- Example: HNLs
- THUNDERDOME: Totally Hyper-UNrealistic DEtectoR in a huge DOME (maximum distance from IP=100m for comparison)



Proposal: [2011.01005](#)



- Cavern size: $r \sim 15$ m and $z \sim 50$ m
- Main detector size = (10m)

DELIGHT: idea for a LLP detector at FCC-hh

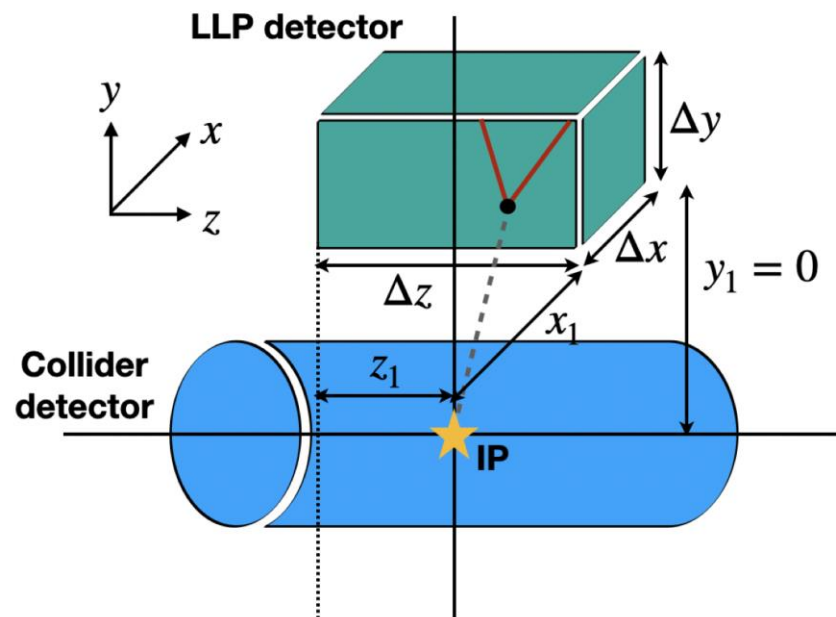
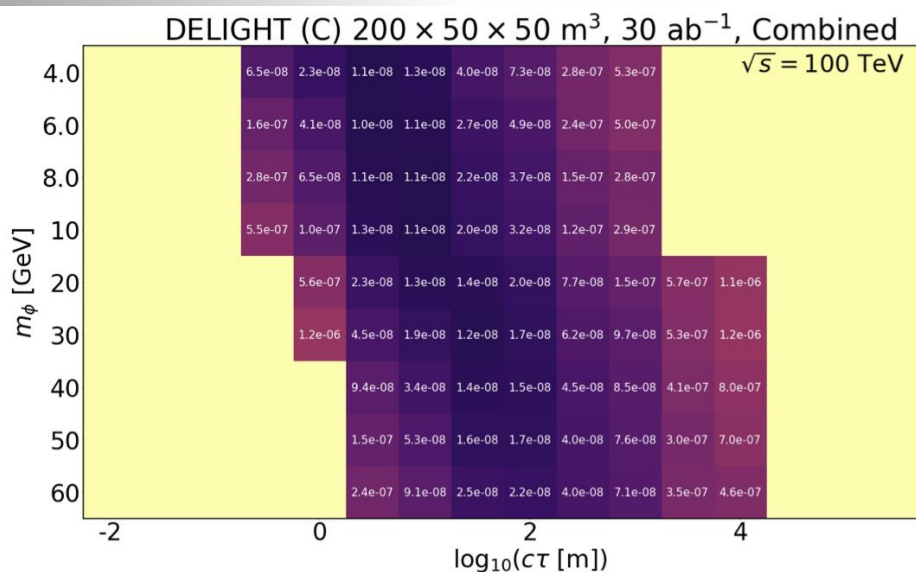
Long-Lived Light Mediators from Higgs boson decay studied for multiple decay modes of the scalars

2111.02437

DELIGHT
Detector for long-lived particles at
high energy of 100 TeV

DELIGHT (C): The same decay volume as the MATHUSLA detector with different dimensions, i.e. $\Delta x \times \Delta y \times \Delta z = 200 \times 50 \times 50 \text{ m}^3$.

$$\begin{aligned} x_1 &= 25 \text{ m} \\ y_1 &= 0 \text{ m} \\ z_1 &= -\Delta z/2 \end{aligned}$$



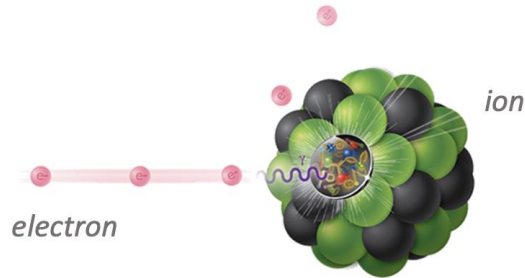
Electron Ion Collider EIC

A machine with –mostly– a QCD programme starting ~ 2030 at BNL

Electron-Ion Collider (EIC)

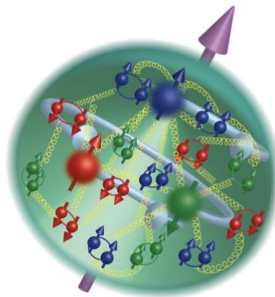
World's 1st polarized e-p/light-ion & 1st eA collider

User Group >1000 members: <http://eicug.org>

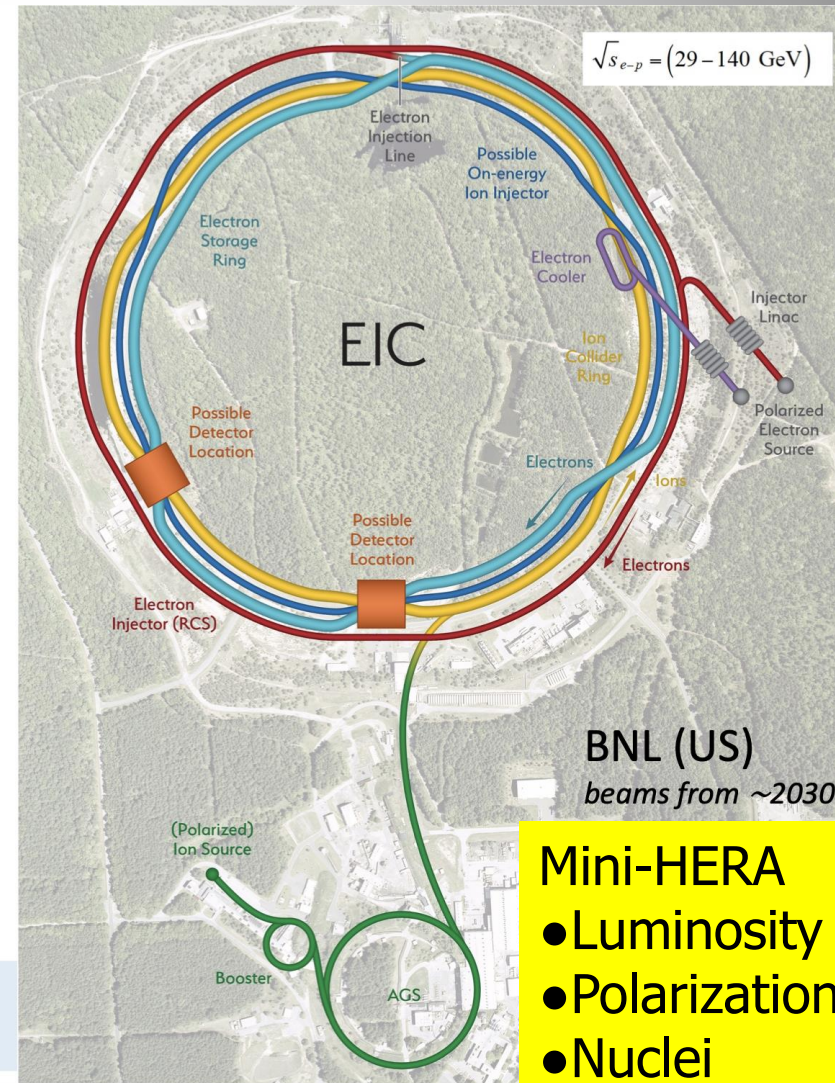


How do the properties of protons and neutrons arise from its constituents?

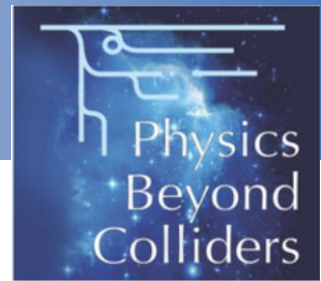
Towards a 3D partonic image of the proton



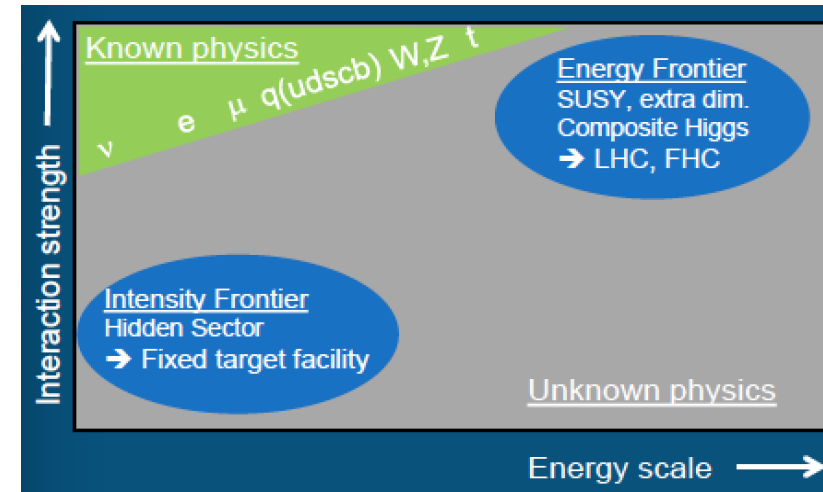
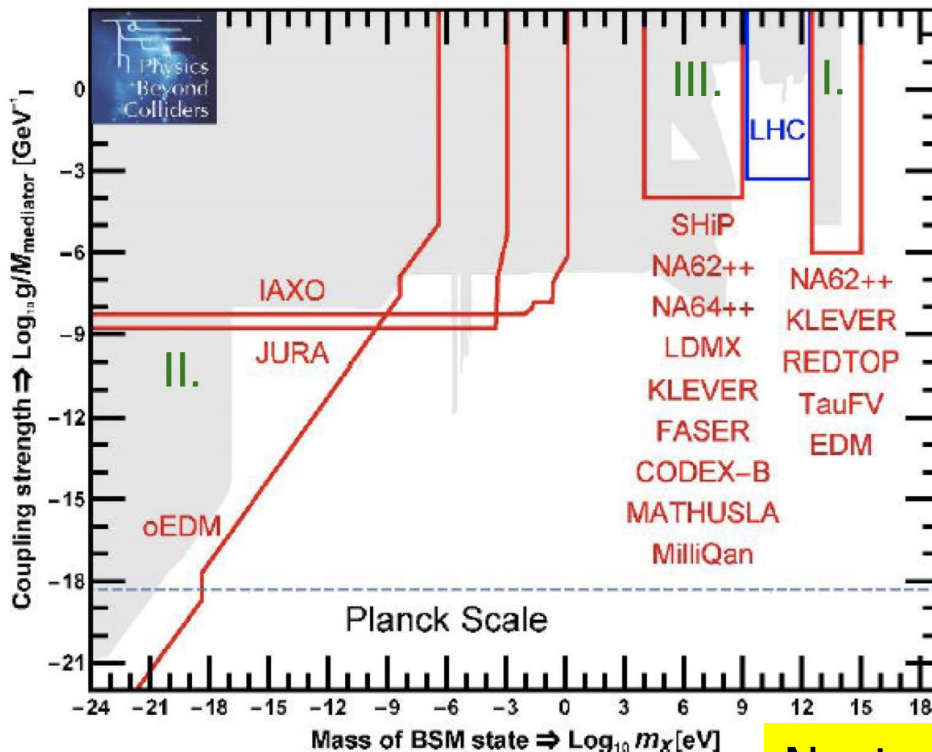
Many other running and emerging low-energy scattering facilities are key to understand the structure of hadrons



Physics Beyond Colliders



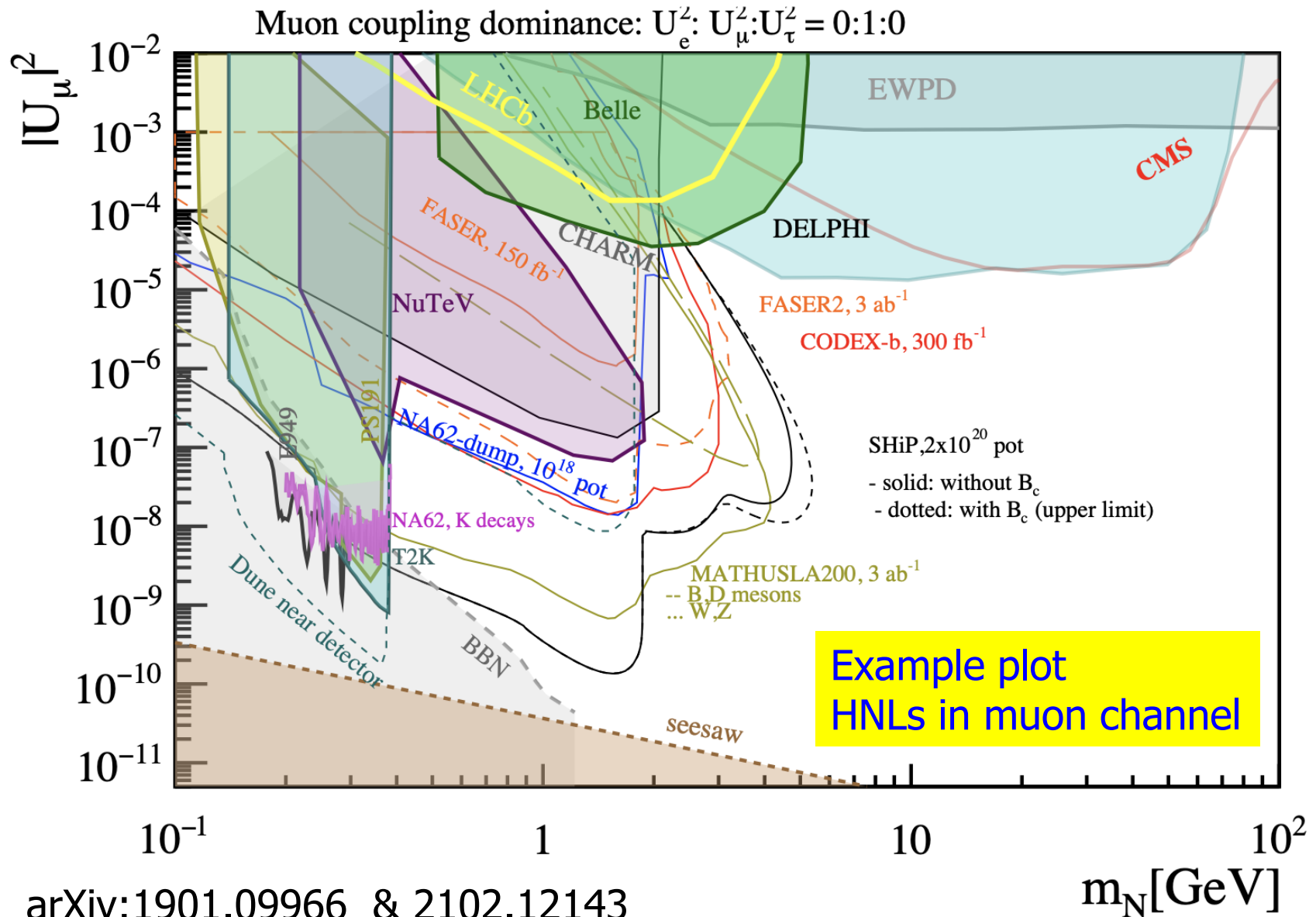
- Physics Beyond Colliders was a response at CERN to increasing interest in complementary methods to high energy frontier colliders to explore searches for BSM physics.
- It was a discussion forum for input to the 2019 European Strategy Update.
- It is continuing its activities..



Several FLAVOR experiments....

Next meeting 7/8 October 2022 @ CERN
<https://indico.cern.ch/event/1137276/>

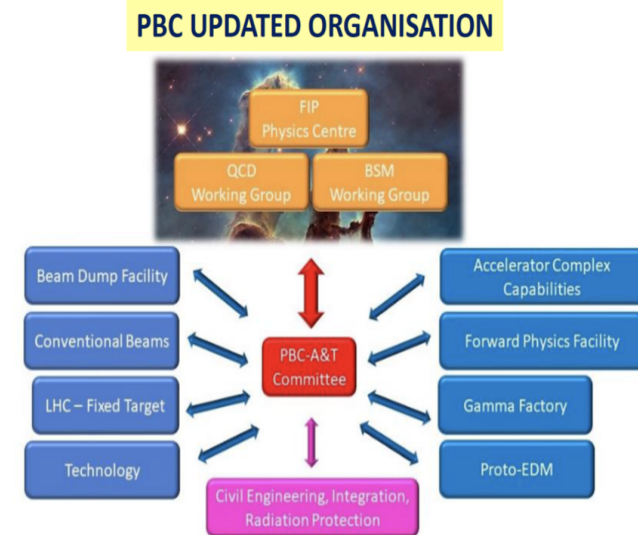
Physics Beyond Colliders



Physics Beyond Colliders

Recent ongoing PBC activities:

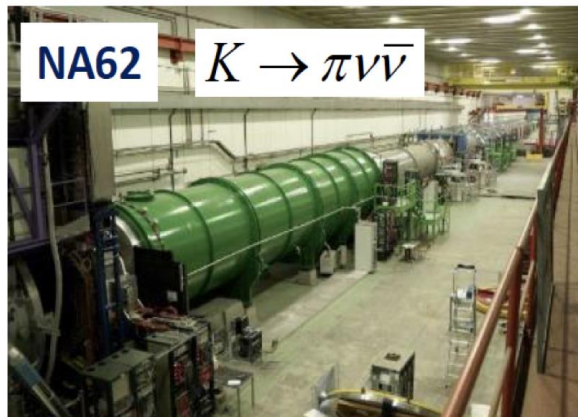
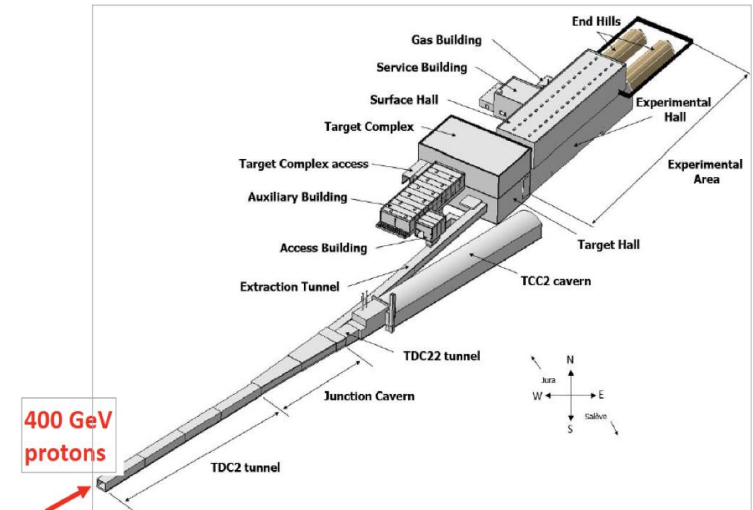
- PBC study extended with a mandate updated to take into account EPPSU recommendations
- Several projects studied for EPPSU are now in implementation phase:
 - IAXO at DESY
 - QCD projects for Run 3 (MUonE, COMPASS (Rp), NA61 heavy flavours)
 - LHC small forward detectors (FASER, SND, ...)
- Main developments for other projects:
 - NA60++ (caloric curve of QCD phase transition)
 - AMBER long-term QCD facility
 - pEDM prototype ring study under the lead of Jülich
 - Gamma Factory Proof of Principle experiment preparation
- Main new ideas:
 - Long term K^+ and K^0 rare decay physics ("HIKE") with higher intensity K beams in ECN3 (NA62++, KLEVER)
 - Completion of NA62 beam-dump mode with a small off-axis detector (SHADOWS) extending acceptance to higher-mass hidden particles
 - Possible relocation of BDF&SHiP in ECN3 to reduce the cost;
Dedicated ECN3 Task Force set up to address the competition issue
 - Forward Physics Facility at LHC to extend the reach of forward physics in the HL-LHC era



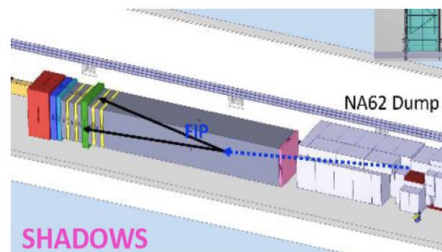
Physics Beyond Collider

CERN Proton Beam Dump Facility

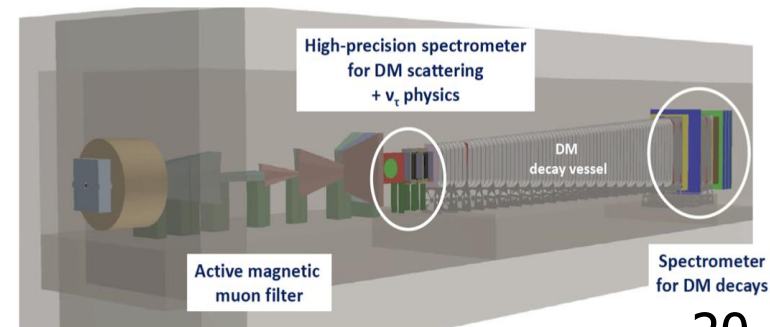
- Comprehensive Design Study of a new SPS facility done within PBC
- Promising option (lower cost) identified in existing **ECN3** underground hall in CERN North Area (currently used by NA62)
- Under evaluation with respect to alternative NA62 extension + SHADOWS option (new idea to search off-axis for feebly interacting particles)



Instrumentation of NA62 decay vessel well adapted to searches in visible decay mode



SHiP on the Beam Dump Facility



Feebly Interacting Particles FIPs

...Spin-off of the PBC forum...



<https://indico.cern.ch/event/1119695/>

This year the Workshop will be organized along three main directions:

1. MeV-GeV Dark Matter and its searches at accelerator, direct and indirect detection experiments;
2. Heavy neutral leptons and their connection to active neutrino physics;
3. Ultra-light (< 1 eV) FIPs in particle physics, astroparticle, and cosmology.

Neutrinos

Neutrino Program

The Questions to answer with present and future experiments

- What are the neutrino masses?
- Are neutrinos their own antiparticles?
- How are the masses ordered?
- What is the origin of neutrino mass and flavor?
- Do neutrinos and antineutrinos oscillate differently?
- Discovering new particles and interactions
- Neutrinos as messengers

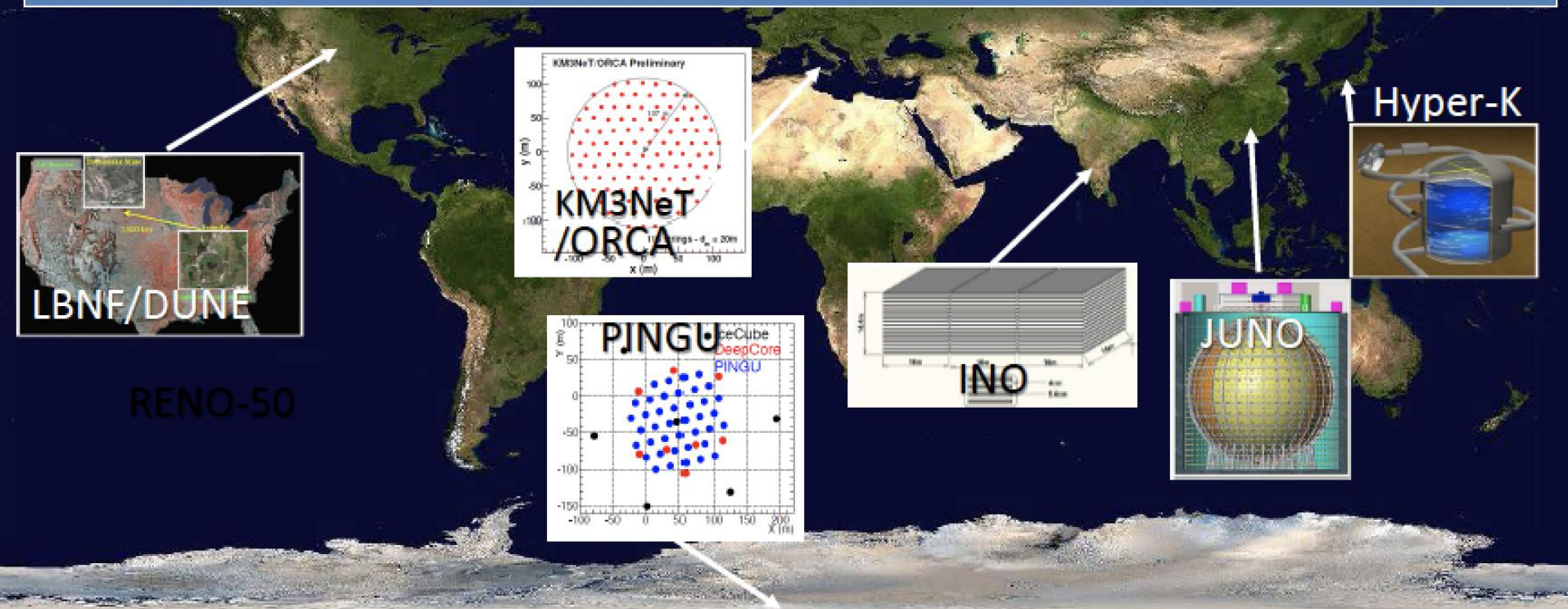
+ auxiliary measurements

M-C Chen + full session yesterday...

Future Neutrino Experiments

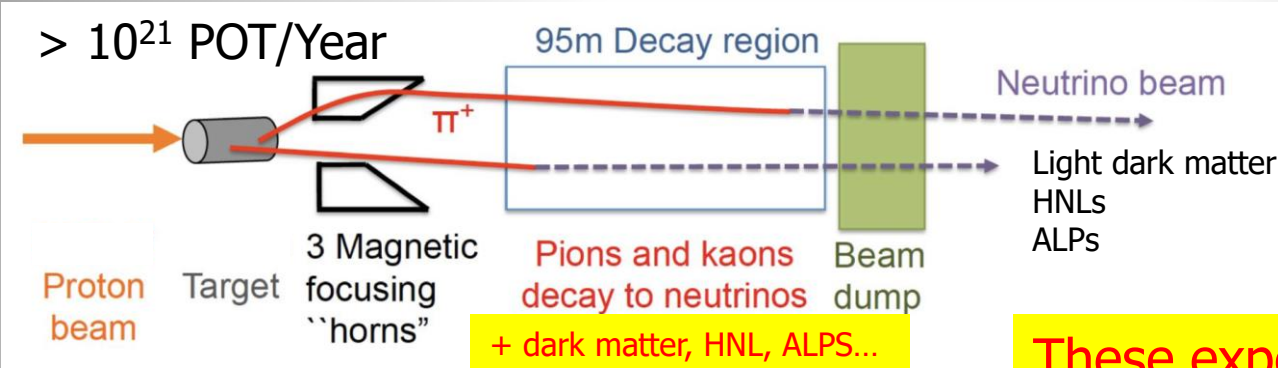
Eg. experiments that will contribute to the mass ordering question

We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with $> 3 \sigma$ CL from each exp.



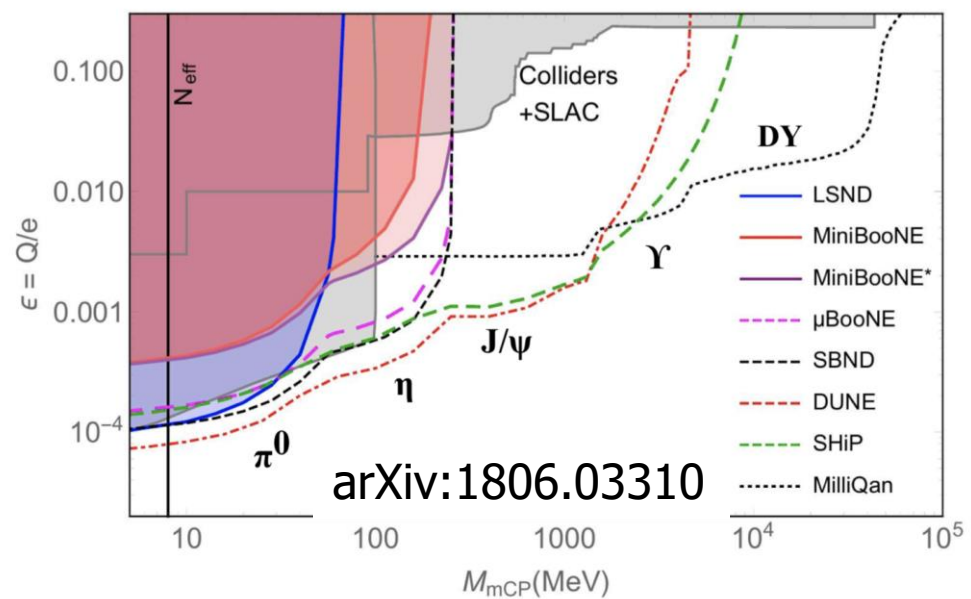
Neutrino Detectors as Beam Dump Experiments

High intensity frontier for low mass particles with very weak couplings
->upcoming neutrino experiments (SBL, LBL) foresee very high intensity beams



SBL or LBL Near Detectors are a few 100m away from the dump

Example millicharges:



These experiments can perform searches for low mass New Physics particles eg
-HNL/sterile neutrinos
-dark photons/light dark matter
-Axion-Like particles
-mini/millicharges
...

arXiv:1907.08311

NEXT-GENERATION NEUTRINO EXPERIMENTS
(PART 1: BSM NEUTRINO PHYSICS AND DARK MATTER)

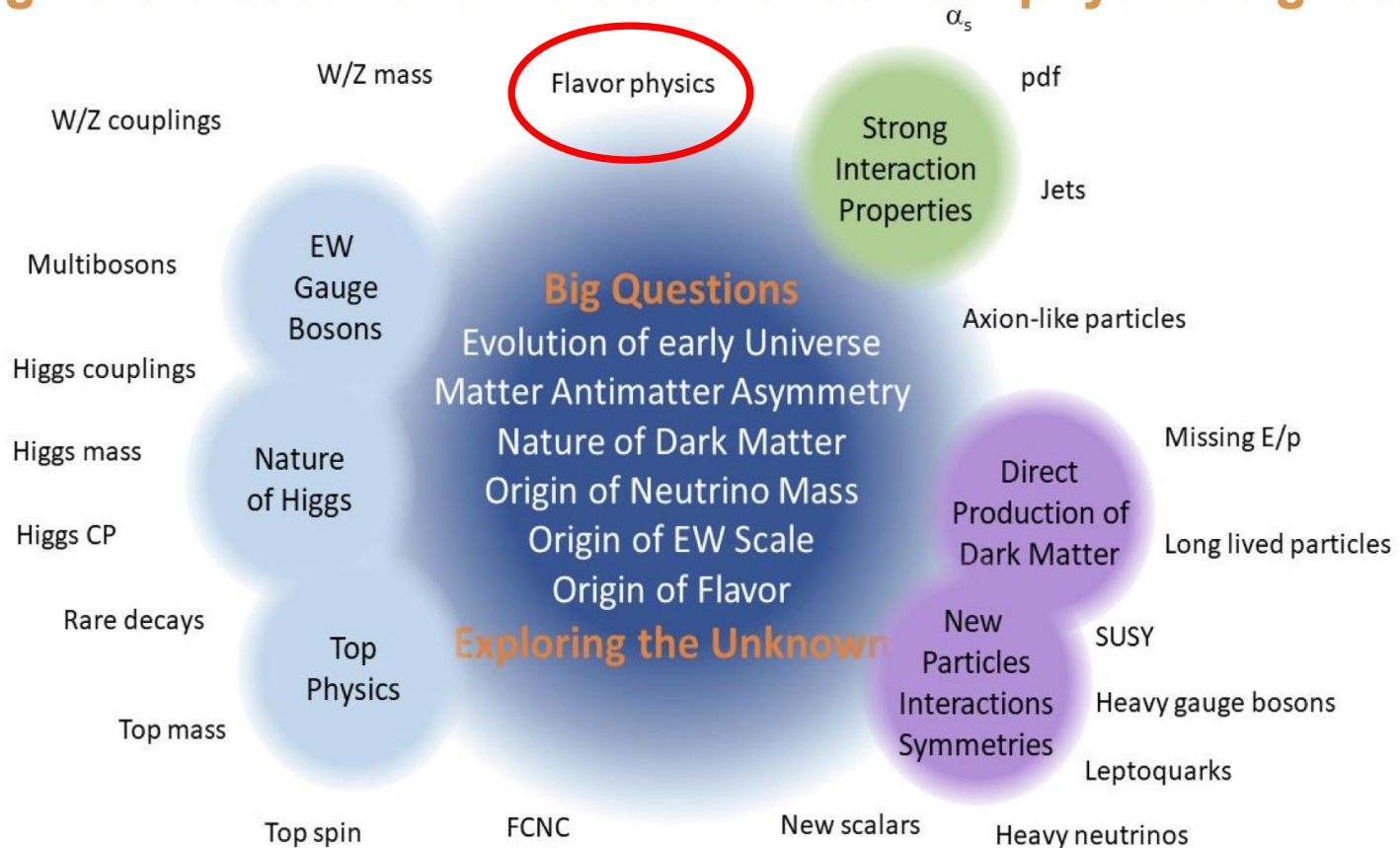
C.A. ARGÜELLES¹, A.J. AURISANO², B. BATELL³, J. BERGER³, M. BISHAI⁴, T. BOSCHI⁵, N. BYRNES⁶, A. CHATTERJEE⁶, A. CHODOS⁶, T. COAN⁷, Y. CUI⁸, A. DE GOUVÊA⁹, P.B. DENTON⁴, A. DE ROECK¹⁰, W. FLANAGAN¹¹, D.V. FORERO¹², R.P. GANDRAJULA¹³, A. HATZIKOUTELIS¹⁴, M. HOSTERT¹⁵, B. JONES⁶, B.J. KAYSER¹⁶, K.J. KELLY¹⁶, D. KIM¹⁷, J. KOPP^{10,18}, A. KUBIK¹⁹, K. LANG²⁰, I. LEPETIC²¹, P. MACHADO¹⁶, C.A. MOURA²², F. OLNES⁶, J.C. PARK²³, S. PASCOLI¹⁵, S. PRAKASH¹³, L. ROGERS⁶, I. SAFA²⁴, A. SCHNEIDER²⁴, K. SCHOLBERG²⁵, S. SHIN^{26,27}, I.M. SHOEMAKER²⁸, G. SINEV²⁵, B. SMITHERS⁶, A. SOUSA², Y. SUI²⁹, V. TAKHISTOV³⁰, J. THOMAS³¹, J. TODD², Y.-D. TSAI¹⁵, Y.-T. TSAI³², J. YU⁶, AND C. ZHANG⁴

The Future of the Energy Frontier

The Energy Frontier

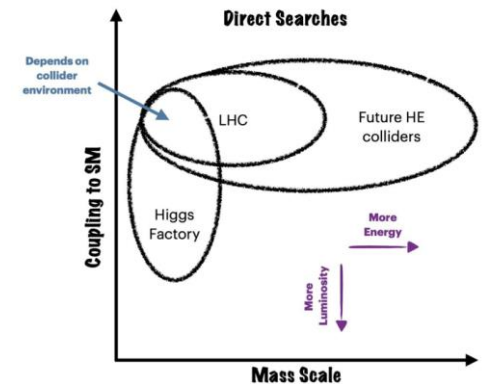
Snowmass 2021

Energy Frontier: explore the TeV energy scale and beyond
Through the breadth and multitude of collider physics signatures



The Energy Frontier

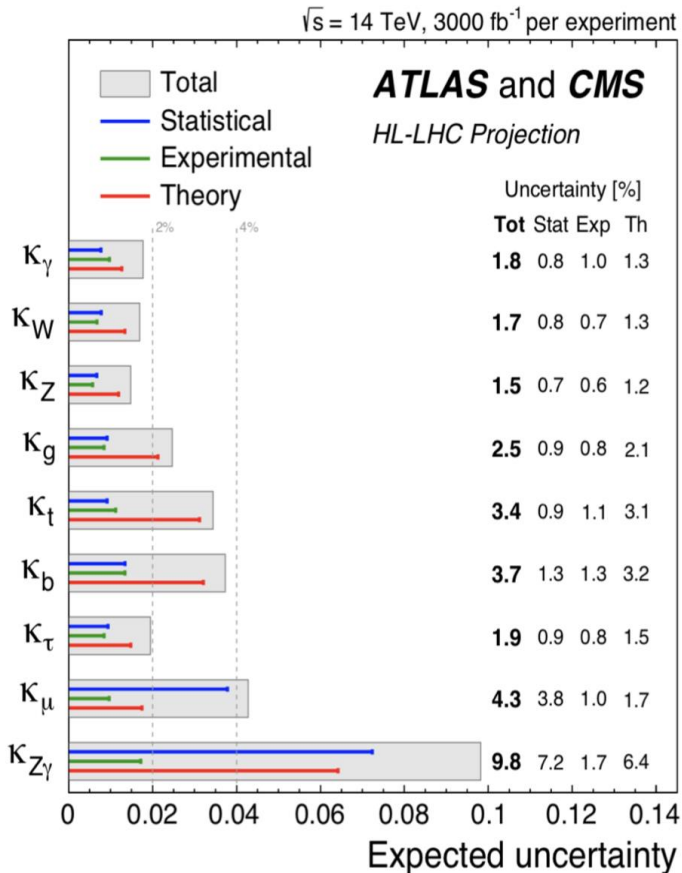
- Large interest in a wide variety of possible projects
- European Strategy Update 2020 & Snowmass 2022 conclusions come with clear community support for a
 - Higgs factory – possibly as part of a next big project
 - Multi TeV Colliders
- Opinions differ on which project and where...
- Optimism and enthusiasm in general is good^(*) but have to keep an eye on realism and “economics”, especially in the present dire times...



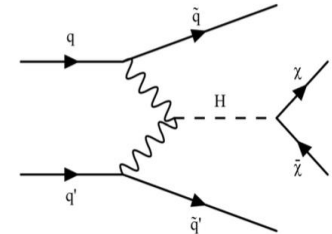
(*)remember Reagan in 1987: “Throw Deep” ... but finally Desertron was not to be...

Higgs @HL-LHC Expectations

HL-LHC reach: Higgs

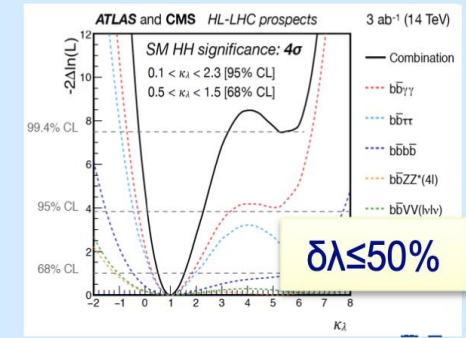
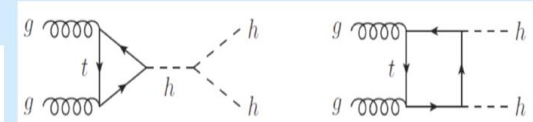
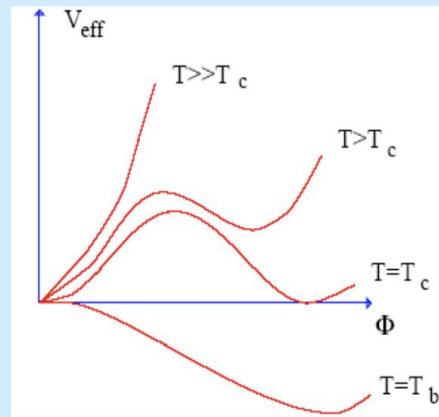


H width to invisible:
 $h(125) \rightarrow XX$.
Includes BSM decays
and rare SM decays: $\leq 4\%$



The ultimate frontier: Higgs self-coupling

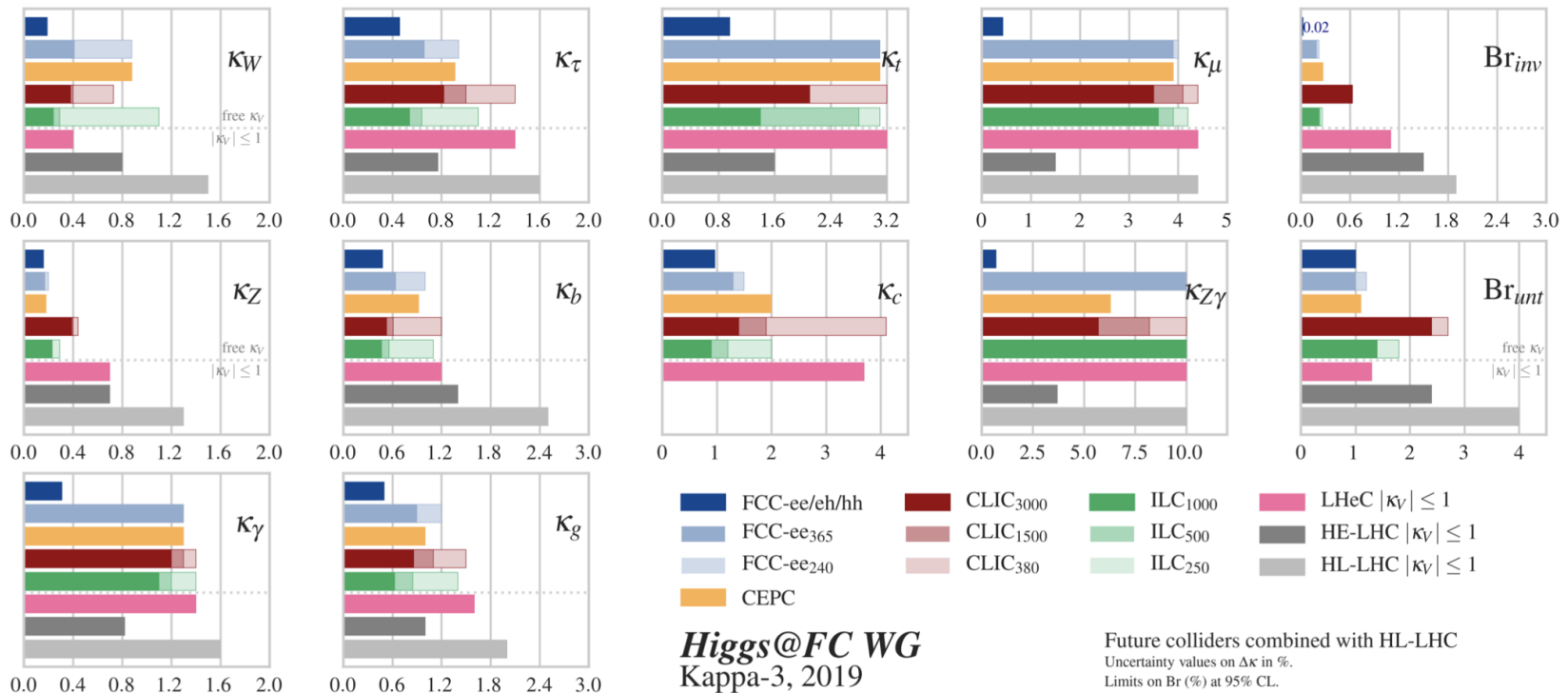
$$V_h = \frac{m_h^2}{2} h^2 + (1 + \kappa_3) \lambda_{hhh}^{\text{SM}} v h^3 + \frac{1}{4} (1 + \kappa_4) \lambda_{hhhh}^{\text{SM}} h^4$$



by $\sim 2040(+)$

New Projects Expectations

- Higgs Coupling Modifiers in Kappa Framework.
- Results for Future Collider+ HL-LHC



% and sub-% level precision..

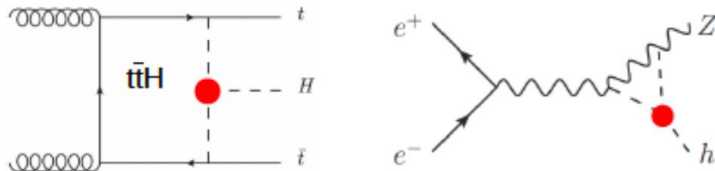
Kappa framework: Can show deviation from SM, but gives no real further information on nature of source of deviation

New Projects Expectations

Higgs Self Coupling

Single-H production

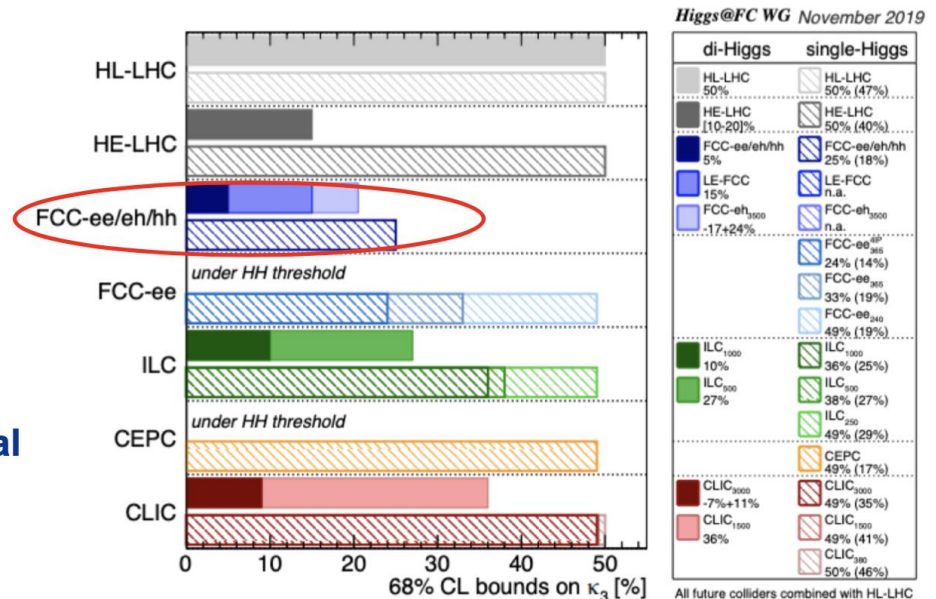
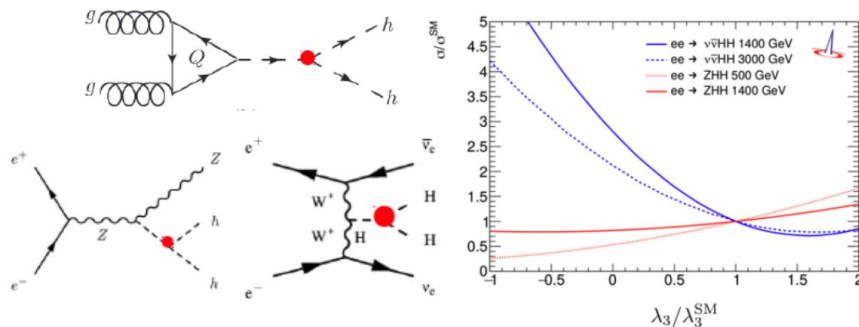
Sensitivity via loop diagrams



For $k_\lambda=2$, hh: 3%; ee: 1%.

HH production

- hh: $\sigma(\text{HH}) \sim 0.01\sigma(\text{H})$; must use differential measurements;
- ee: Complementarity of ZHH and VBF production



Single-H: FCC-ee or ILC ~ 35% (global analysis)

HH production:

HL-LHC: ~50% (can probably do better)?

HE-LHC: ~15%

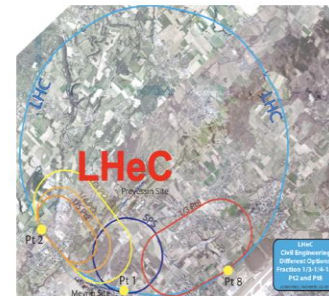
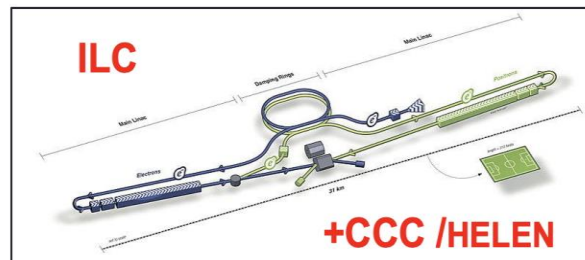
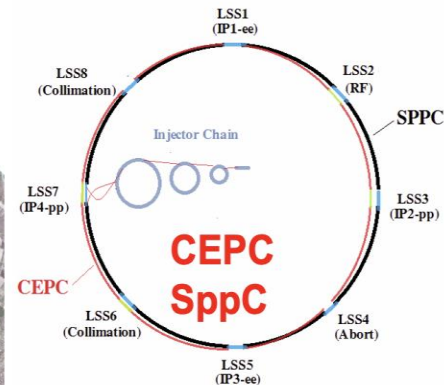
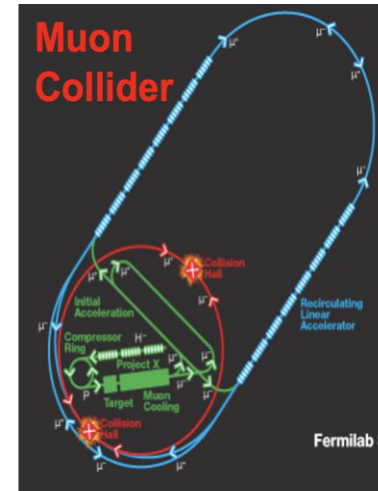
ILC500: ~27%; CLIC1500 ~36%

CLIC3000: ~9%; FCC-hh ~5%

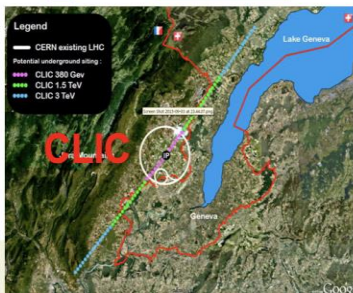
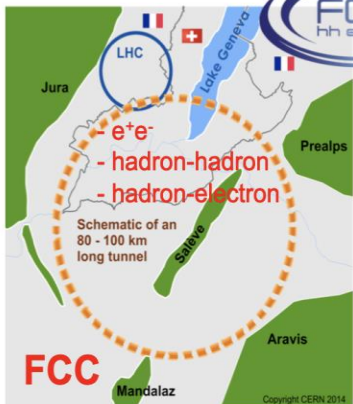
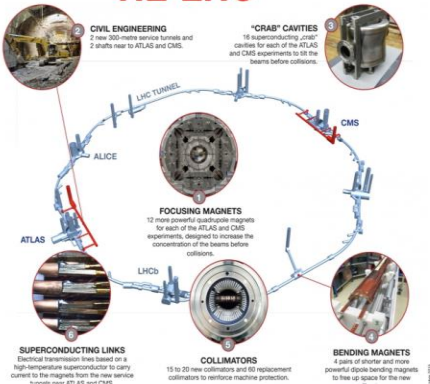
The Energy Frontier

Which machines?

- Looking for indirect evidence of BSM physics
 - Need **factories of Higgs bosons** (and other SM particles) to probe the TeV scale via precision measurements
- Search for direct evidence of BSM physics at the energy frontier
 - Need to directly reach the **multi-TeV scale**



HL-LHC



The Energy Frontier

Energy Frontier Benchmark Scenarios

Higgs-boson factories
(up to 1 TeV c.o.m. energy)

Collider	Type	\sqrt{s}	$\mathcal{P}[\%]$	\mathcal{L}_{int} ab^{-1}/IP	Start Date	
			e^-/e^+		Const.	Physics
HL-LHC	pp	14 TeV		3		2027
ILC & C ³	ee	250 GeV	$\pm 80/\pm 30$	2	2028	2038
		350 GeV	$\pm 80/\pm 30$	0.2		
		500 GeV	$\pm 80/\pm 30$	4		
		1 TeV	$\pm 80/\pm 20$	8		
CLIC	ee	380 GeV	$\pm 80/0$	1	2041	2048
CEPC	ee	M_Z		50	2026	2035
		$2M_W$		3		
		240 GeV		10		
		360 GeV		0.5		
FCC-ee	ee	M_Z		75	2033	2048
		$2M_W$		5		
		240 GeV		2.5		
		$2 M_{\text{top}}$		0.8		
μ -collider	$\mu\mu$	125 GeV		0.02		

Multi-TeV colliders
(> 1 TeV c.o.m. energy)

Collider	Type	\sqrt{s}	$\mathcal{P}[\%]$	\mathcal{L}_{int} ab^{-1}/IP	Start Date	
			e^-/e^+		Const.	Physics
HE-LHC	pp	27 TeV		15		
FCC-hh	pp	100 TeV		30	2063	2074
SppC	pp	75-125 TeV		10-20		2055
LHeC FCC-eh	ep	1.3 TeV		1		
		3.5 TeV		2		
CLIC	ee	1.5 TeV	$\pm 80/0$	2.5	2052	2058
		3.0 TeV	$\pm 80/0$	5		
μ -collider	$\mu\mu$	3 TeV		1	2038	2045
		10 TeV		10		

C³= "Cool Copper Collider" A US development with copper RF cavities at 80 K, gradients 70-120 MV/m, Lumi $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, no full design available yet..

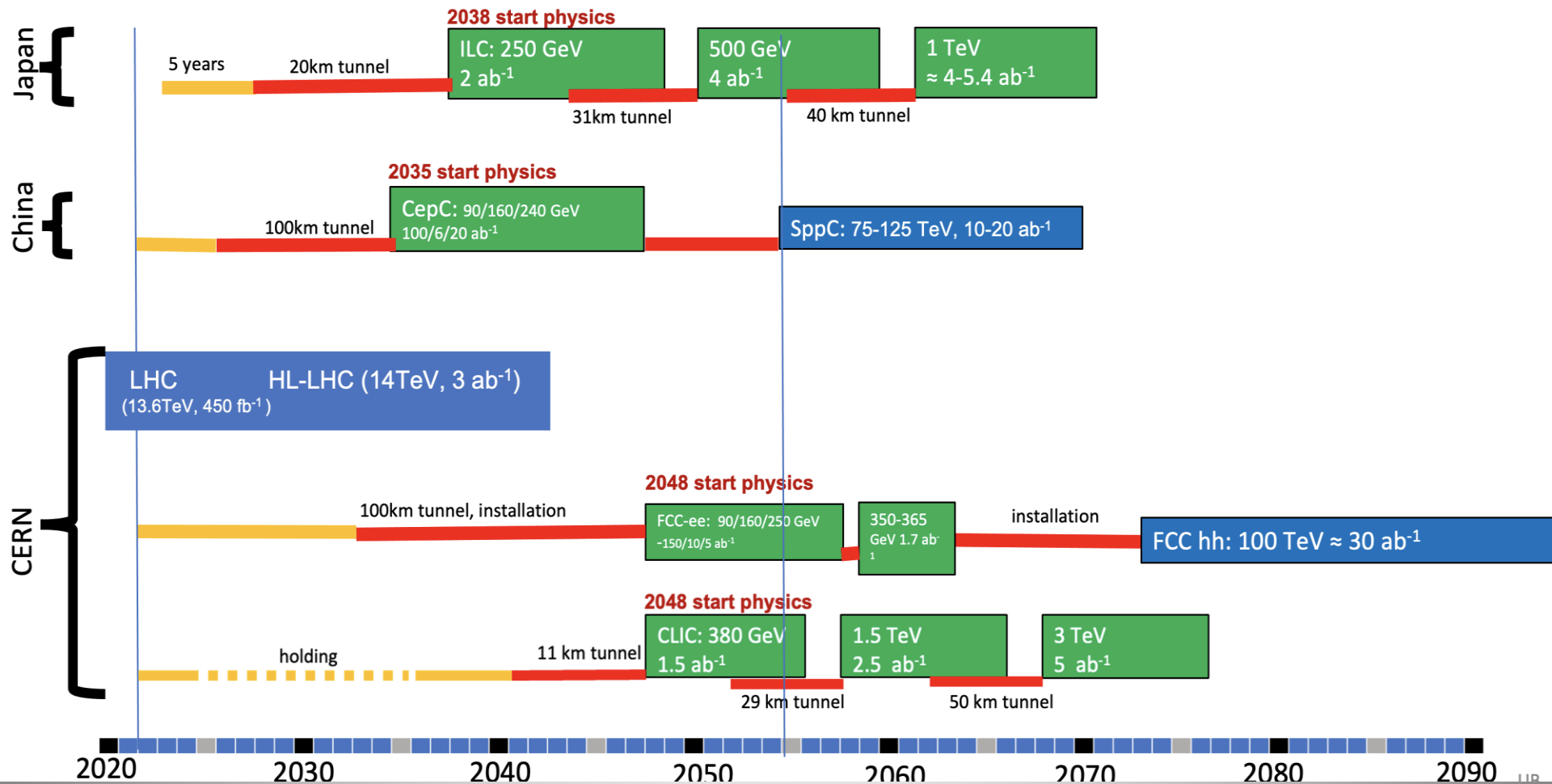
The Energy Frontier

Indicative scenarios of future colliders [considered by ESG]

■ Proton collider
■ Electron collider
■ Muon collider

■ Construction/Transformation
■ Preparation / R&D

Original from ESG by UB
Updated July 25, 2022 by MN



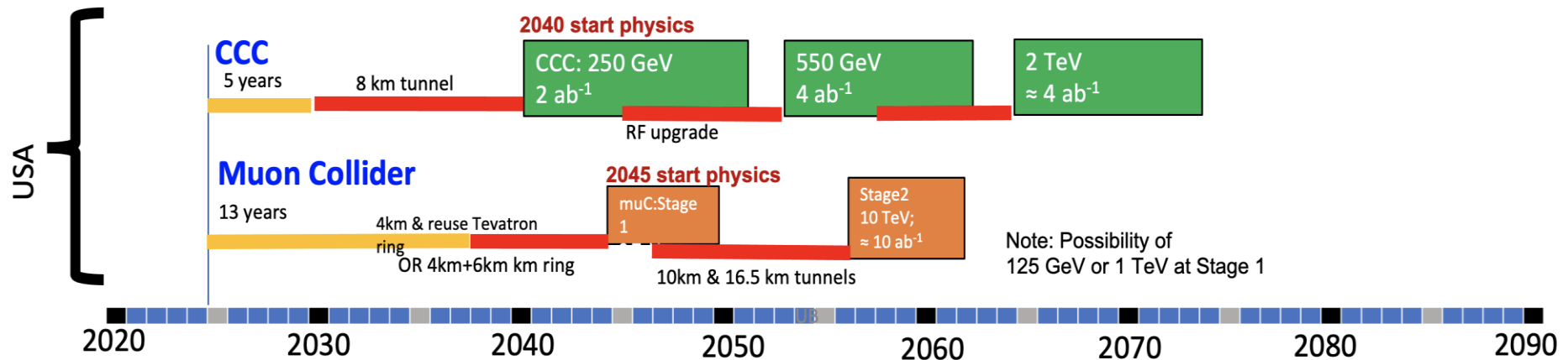
The Energy Frontier

Possible scenarios of future colliders



Original from ESG by UB
Updated July 25, 2022 by MN

Proposals emerging from this Snowmass for a US based collider



- **Timelines technologically limited**
- Uncertainties to be sorted out
 - Find a contact lab(s) ...Snowmass 2021 discussion
 - Successful R&D and feasibility demonstration for CCC and Muon Collider
 - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
 - International Cost Sharing

The Energy Frontier

Large Projects

Project	Construction Start date (yr)	Construction End date (yr)	Construction Cost B\$
Higgs Factories			
CepC	2026	2035	12-18
CCC (higgs Fac)	2030	2040	7-12
ILC (higgs Fac)	2028	2038	7-12
CLIC	2041	2048	7-12
FCC-ee	2033	2048	12-18
Multi-TeV Colliders			
Muon Collider (3 TeV)	2038	2045	7-12
Muon Collider (10 TeV)	2042	2052	12-18
SppC	2043	2055	30-80
HE CCC	2055	2065	12-18
HE CLIC (3 TeV)	2062	2068	18-30
FCC-hh	2063	2074	30-50

Snowmass 2021

-> From the Accelerator Frontier Report

Cost estimates from the ITF report by AF. Please refer to the document for explanations now they were estimated and associated caveats

[Link](#) to the report on AF wiki

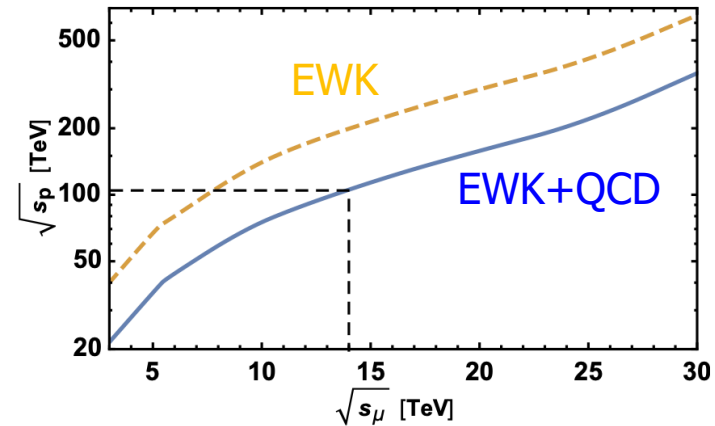
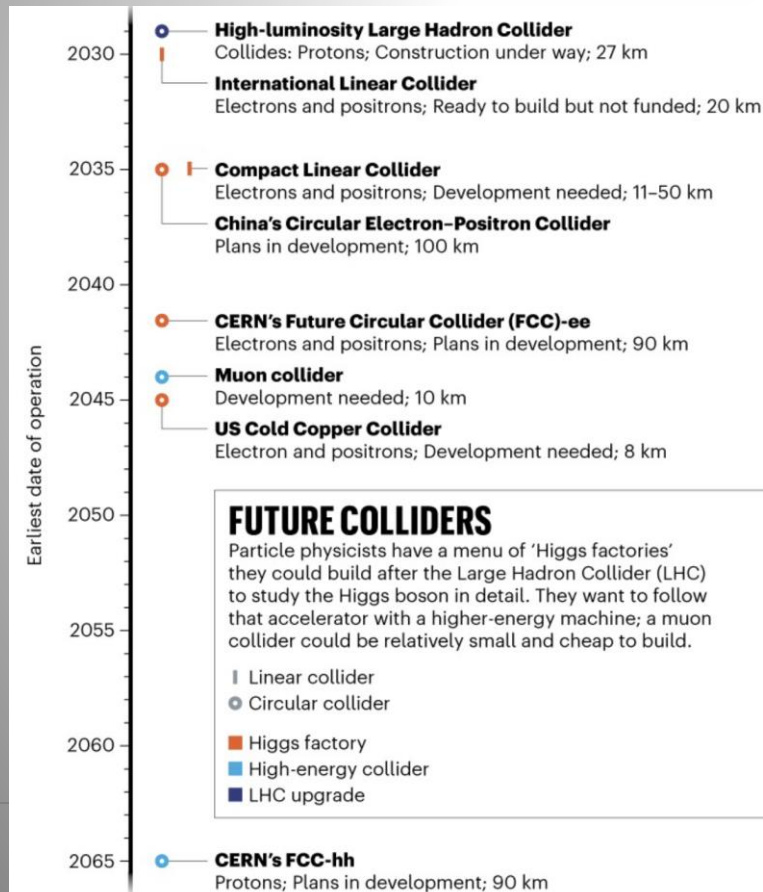
A Muon Collider...

nature

A week ago...

NEWS | 08 August 2022

Particle physicists want to build the world's first muon collider



...As Multi-TeV discovery machine

- Would become operational after a Higgs factory start-up
- Smaller and cheaper than eg a 100 TeV collider

But still significant R&D required

- Technology (cooling)...
- Neutrino backgrounds...
- ..

Realistic timeline?

A Far, Far Future Project...??

Circular Collider on the Moon (CCM)

[arXiv:2106.02048](https://arxiv.org/abs/2106.02048)

7 June 2021

A very high energy hadron collider on the Moon

James Beacham^{1,*} and Frank Zimmermann^{2,†}

¹*Duke University, Durham, N.C., United States*

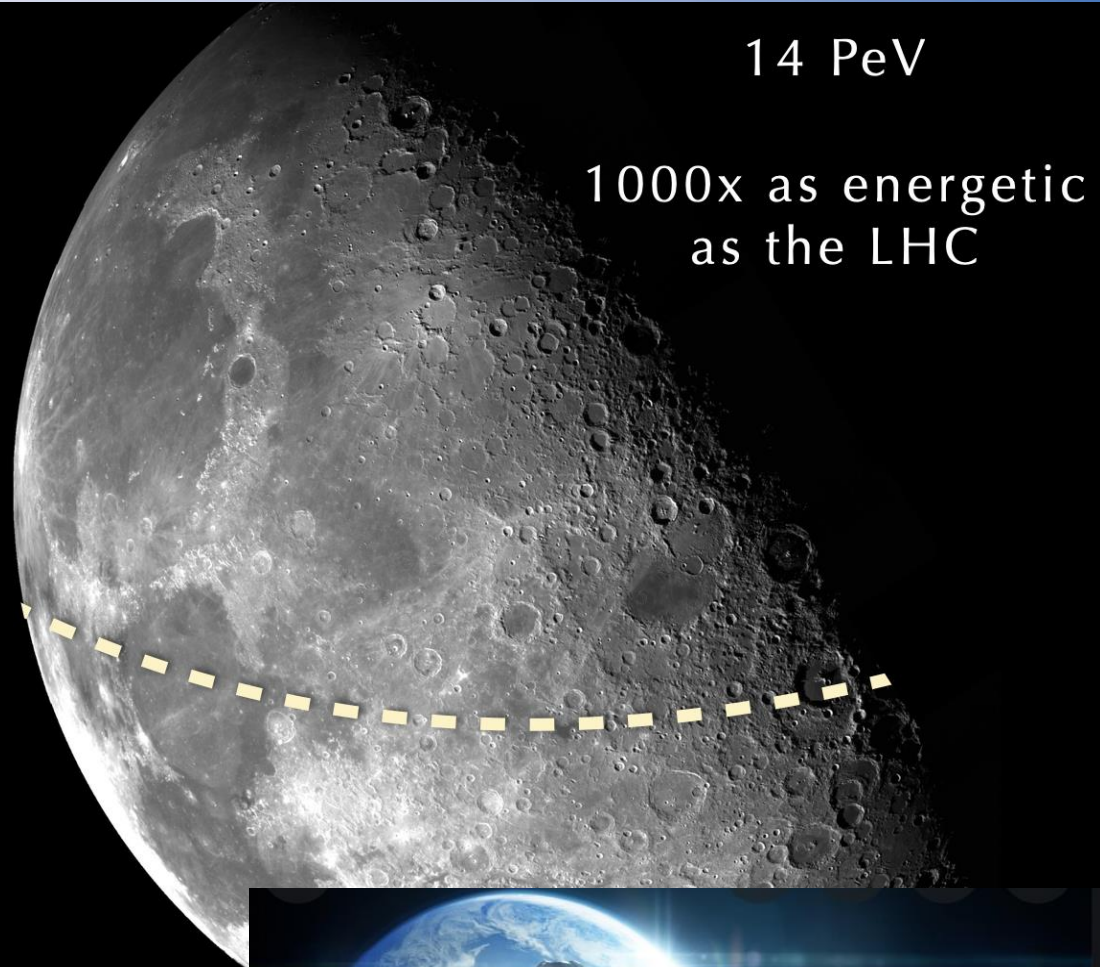
²*CERN, Meyrin, Switzerland*

(Dated: June 7, 2021)

The long-term prospect of building a hadron collider around the circumference of a great circle of the Moon is sketched. A Circular Collider on the Moon (CCM) of ~ 11000 km in circumference could reach a proton-proton center-of-mass collision energy of 14 PeV — a thousand times higher than the Large Hadron Collider at CERN — optimistically assuming a dipole magnetic field of 20 T. Siting and construction considerations are presented. Machine parameters, powering, and vacuum needs are explored. An injection scheme is delineated. Other unknowns are set down. Through partnerships between public and private organizations interested in establishing a permanent Moon presence, a CCM could be the (next-to-) next-to-next-generation discovery machine and a natural successor to next-generation machines, such as the proposed Future Circular Collider at CERN or a Super Proton-Proton Collider in China, and other future machines, such as a Collider in the Sea, in the Gulf of Mexico. A CCM would serve as an important stepping stone towards a Planck-scale collider sited in our Solar System.

14 PeV

1000x as energetic
as the LHC



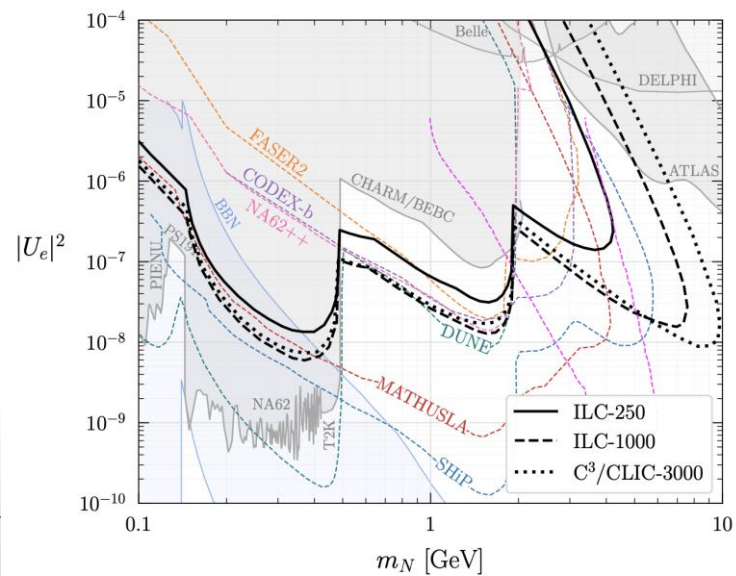
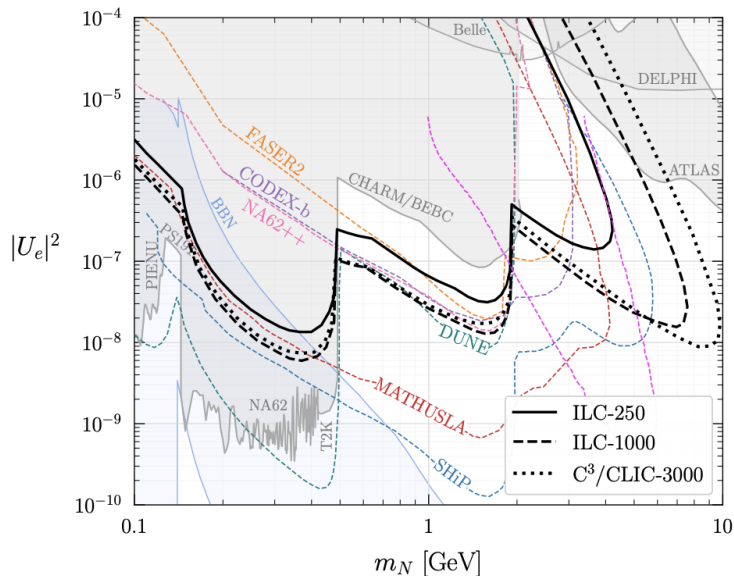
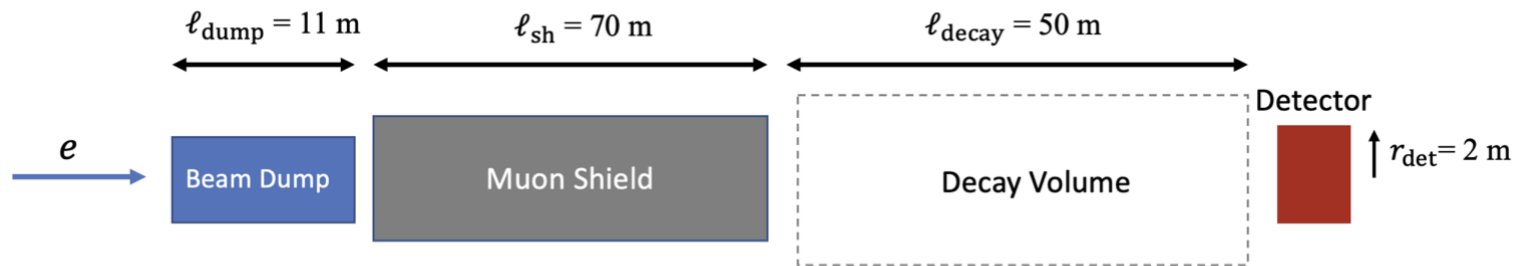
Having grand dreams is of course allowed!

Beam Dump at Future Colliders

...making use the high intensity facility beams...

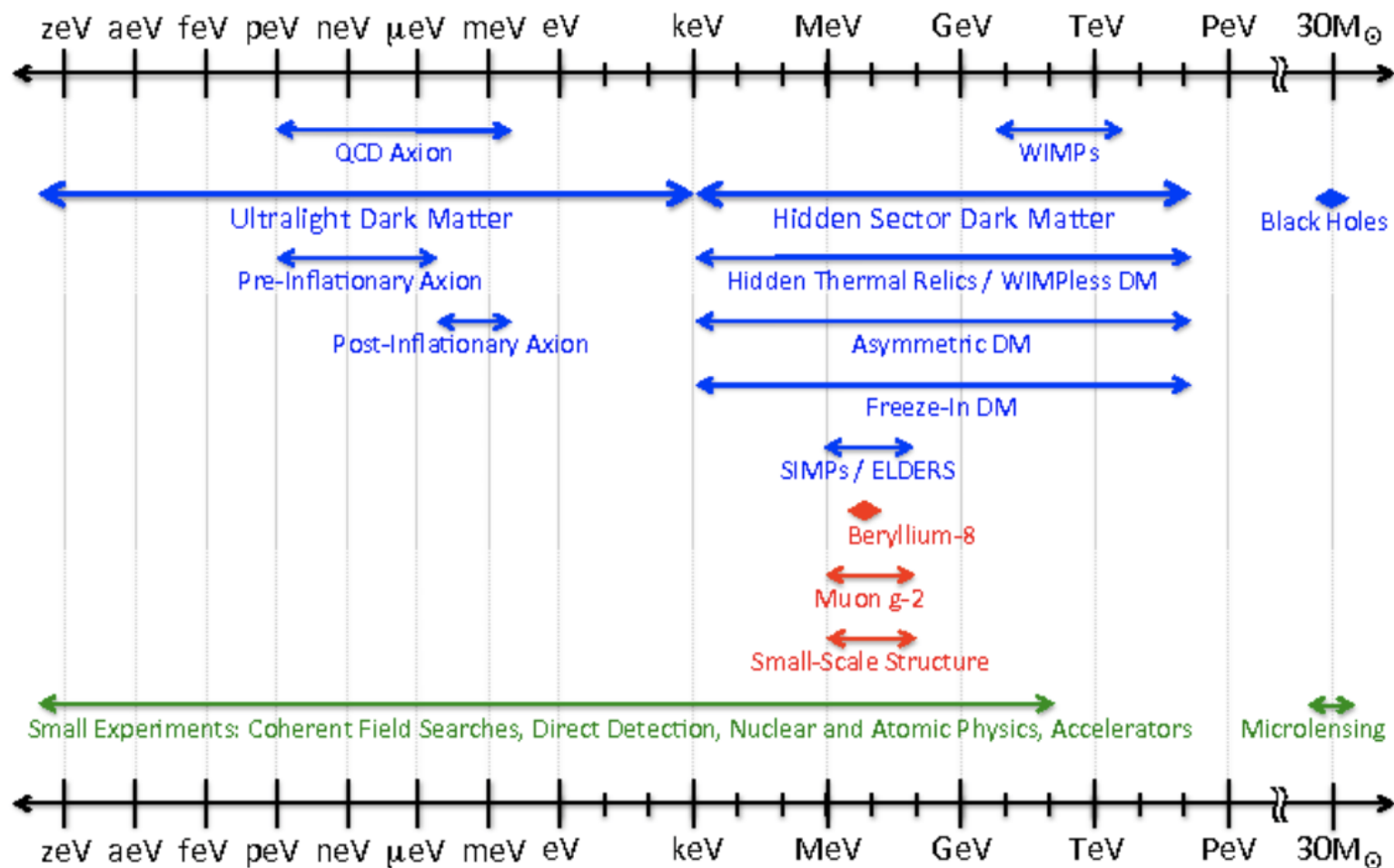
Heavy Neutral Leptons at Beam Dump Experiments of Future Lepton Colliders

2206.13745



Dark Matter Searches

Dark Sector Candidates, Anomalies, and Search Techniques



Search region $10^{-22} eV \leftrightarrow 10^{-18} GeV$

Xenon Detectors

XENON 10 (LNGS)
ZEPLIN (Boulby)

10 kg

2010

Xenon100



XENON 100 (LNGS)

LUX (250 kg,
SURF),

PANDA-X

(500 kg, CJPL)

XMASS

(0.8t, Kamioka)

2015

1,000 kg

XENON 1T

(1t, LNGS)

PandaX-4:(4t, CJPL)

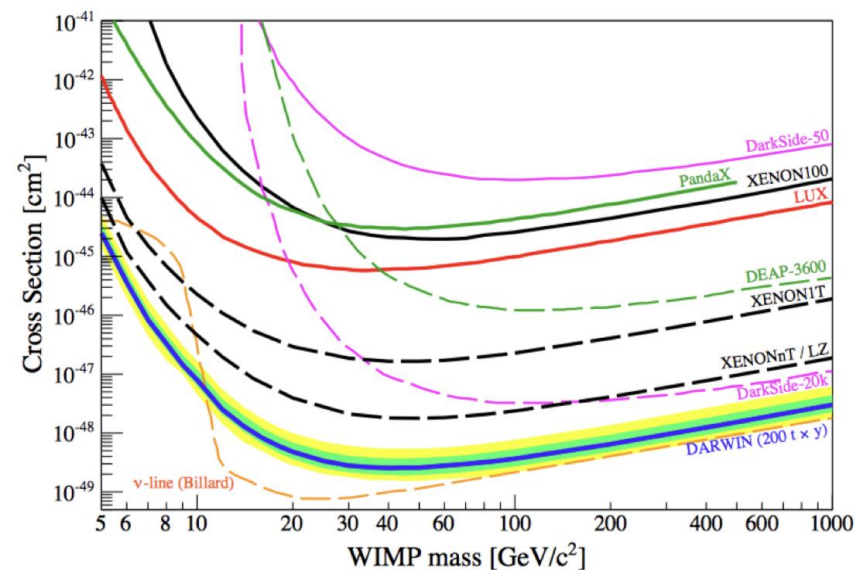
XENONnT: (6t, LNGS)

LZ: (7t, SURF)

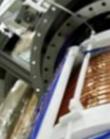
2020

10,000 kg

Future: DARWIN: 50 t -> XLZD ?



DARWIN, JCAP 1611 (2016) no.11, 017, arXiv:1606.07001



A photograph of the Xenon100 detector assembly. It features a large, cylindrical copper coil (the cryostat) mounted within a white support structure. Below the coil, numerous small, cylindrical photomultiplier tubes (PMTs) are arranged in a circular pattern, connected by blue and orange cables. The entire assembly is housed within a larger, metallic structure.

2010

100 kg

ArDM
(1t, LSC)

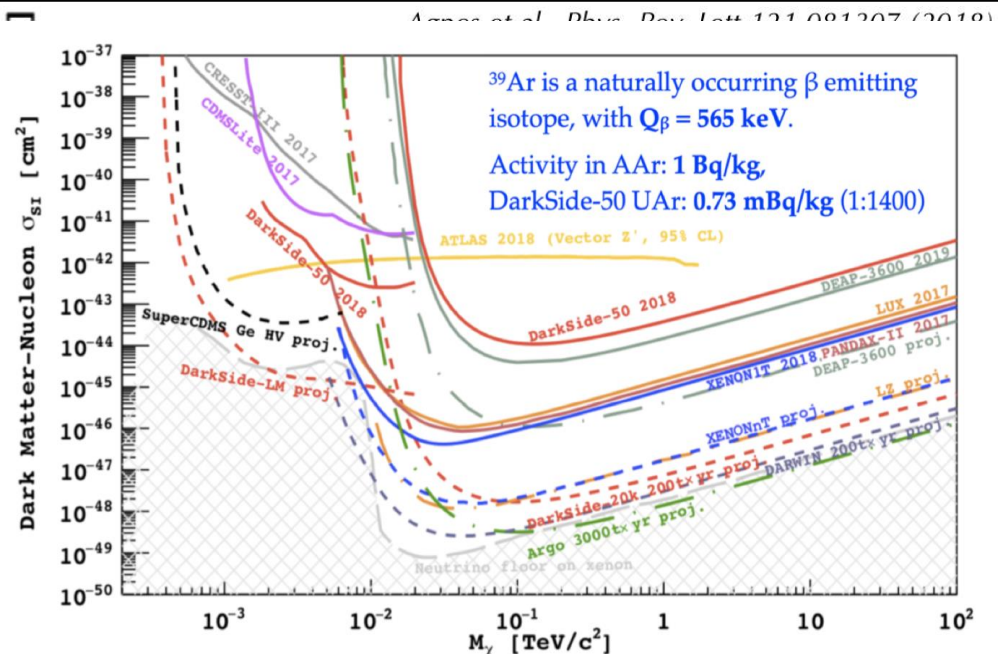
1,000 kg

2015

DEAP-3600 (3.6t,
SNOLAB)

DEAP-3600:
parts-per-billion level
"S1" particle ID,
ultrapure acrylic cryostat
Ajaj et al, Phys. Rev. D (2019)

50: leading SI limit at 1-5 GeV/c² for WIMP-nucleus and WIMP-e scattering



Global Argon Dark Matter Collaboration formed

10,000 kg

2020

DarkSide-20k (50t, LNGS)

100,000 kg

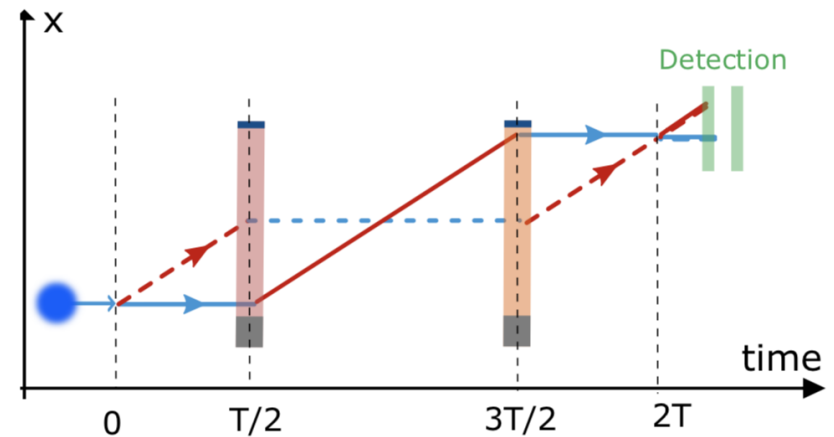
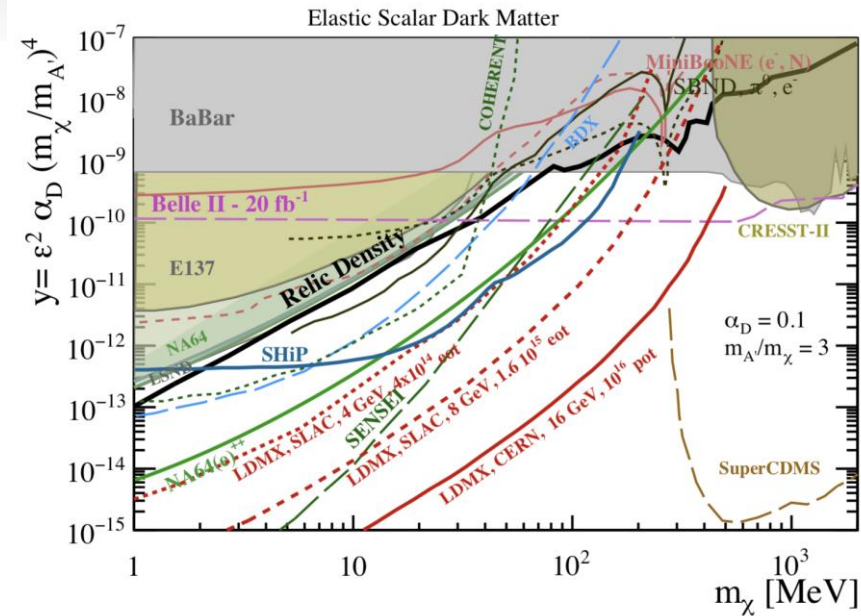
Future: ARGO: 400 t



More Examples of Ongoing Activities

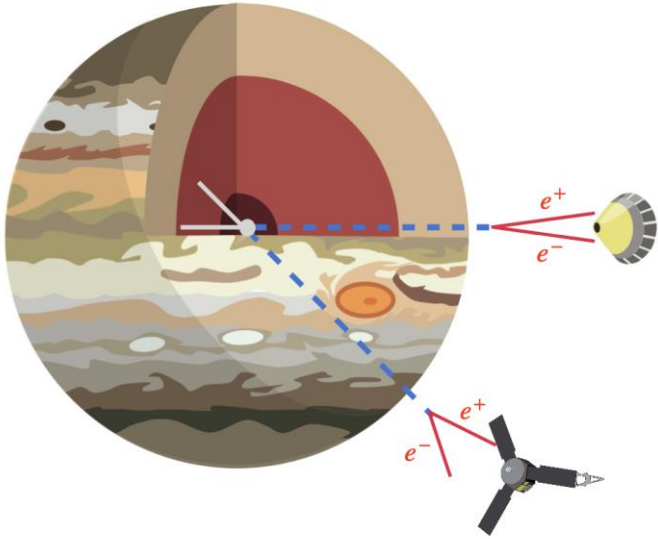
- New techniques for direct experiments eg directional detectors, bolometers, superheated liquids, crystals...
- Light Dark Matter searches at high intensity fixed target experiments
- Axion and ALP searches
- Quantum interference devices, eg cold atom interferometers
- ... And many more

The multi-prong attack on
Dark Matter is on!



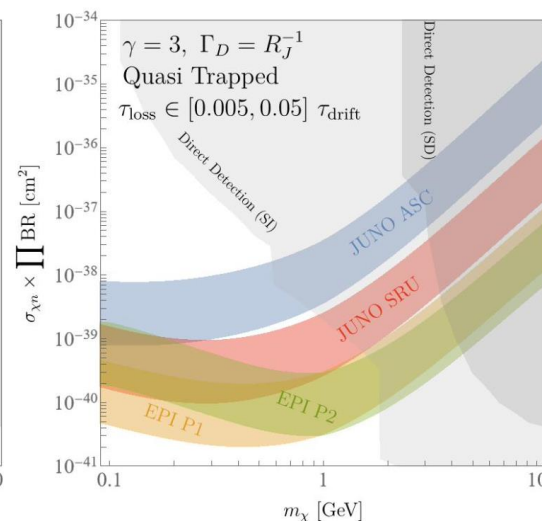
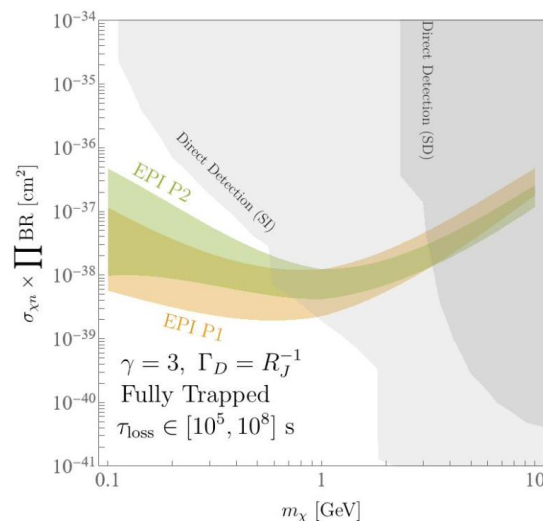
Searching dark matter on ... Jupiter

2207.13709



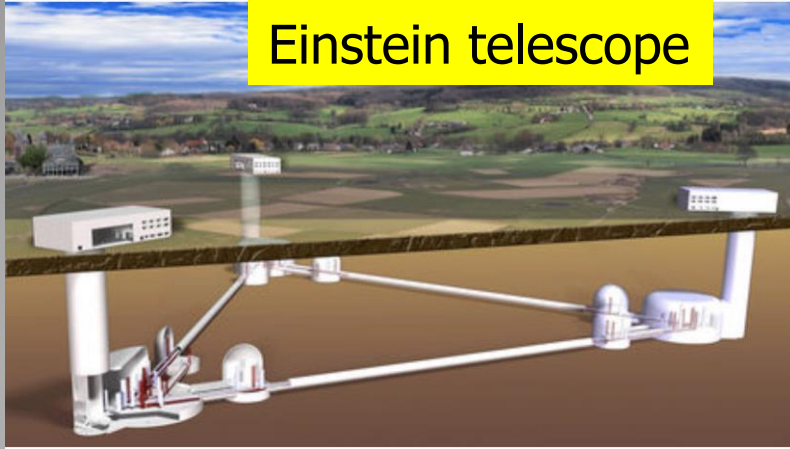
Using Jupiter missions as a probe for dark matter annihilation in the planet. Assume long lived dark photons that decay outside Jupiter into e^+e^-

The Galileo probe and Juno orbiter make in situ measurements of the relativistic electron fluxes trapped in Jupiter's large magnetic field

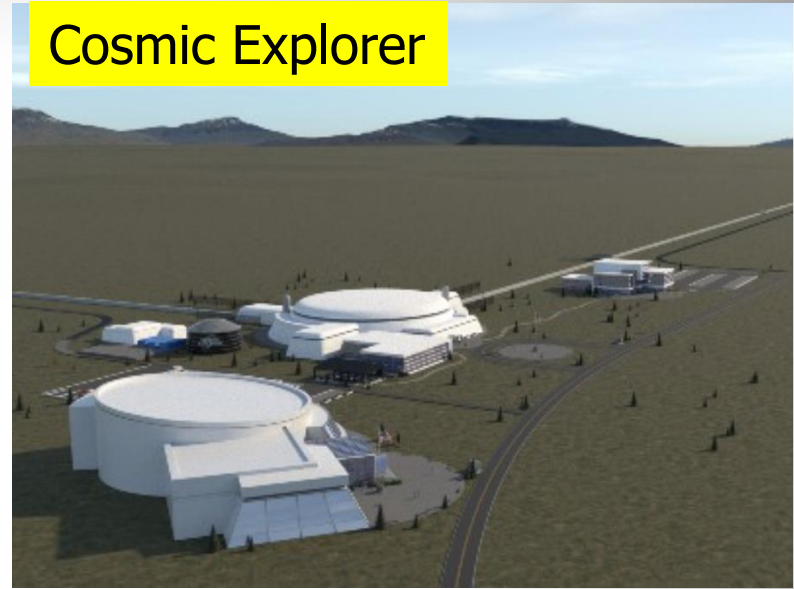


Gravitational Waves 2035-2040?

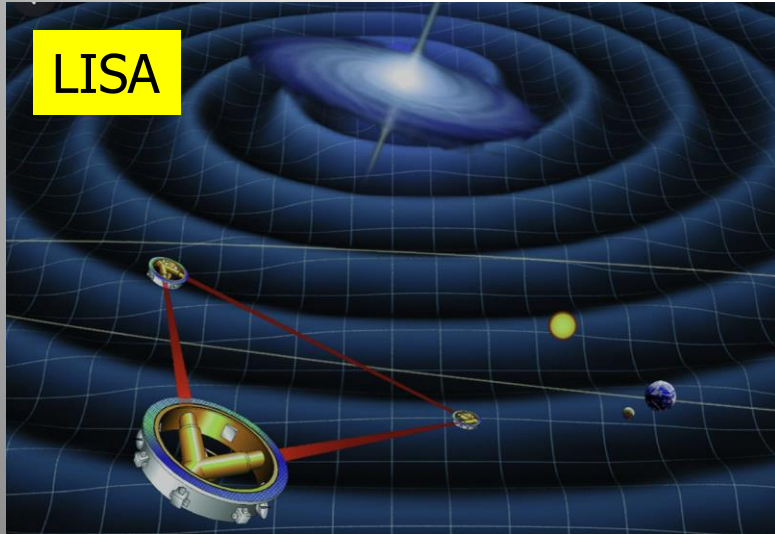
Einstein telescope



Cosmic Explorer

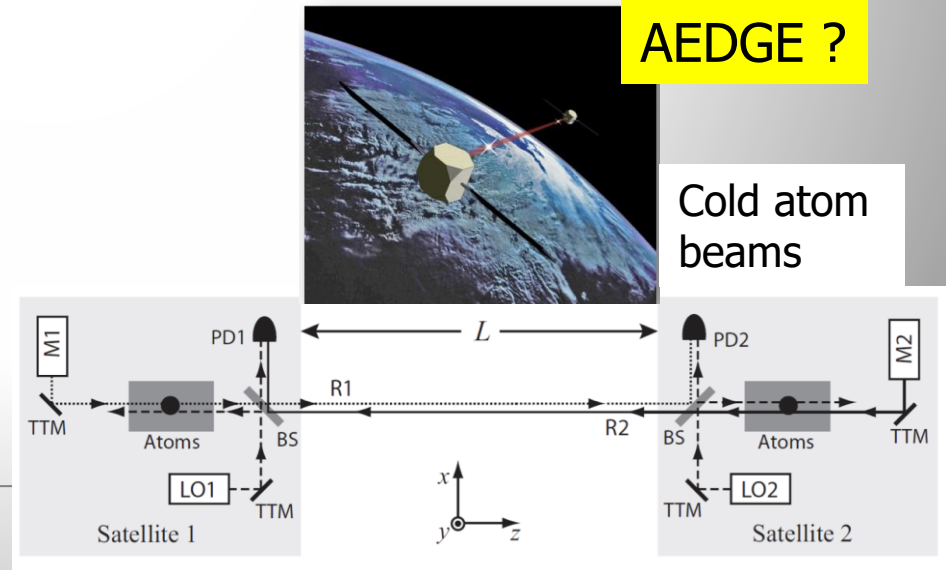


LISA



AEDGE ?

Cold atom beams



Final Words...

- Energy frontier: LHC will be the workhorse for the next 20 yrs
- No lack of ideas for a next new project.. (but funding...?)
 - Energy frontier clearly aiming for a Higgs Factory first. A multi-TeV collider next (?)
 - Neutrino/Dark Matter program well under way to answer important questions in the next 1-2 decades
 - Support for PBC program (re-)gaining momentum. Keeping opportunities eg for light BSM particles @ intense beam searches in mind.
- Connectivity/complementarity across frontiers is a regularly appearing target pursue...

Exciting future prospects and flavour Physics will be a strong part of it

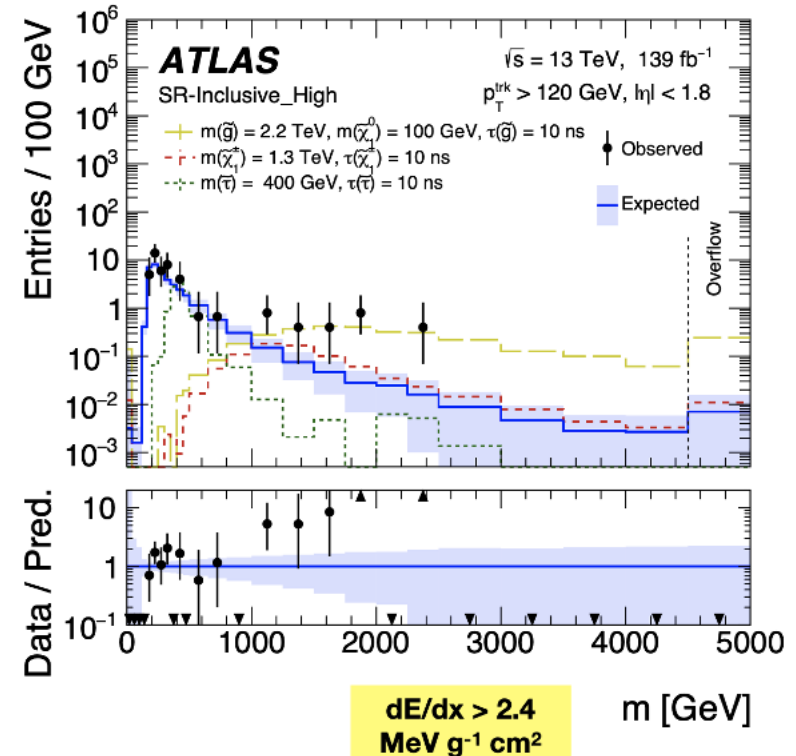
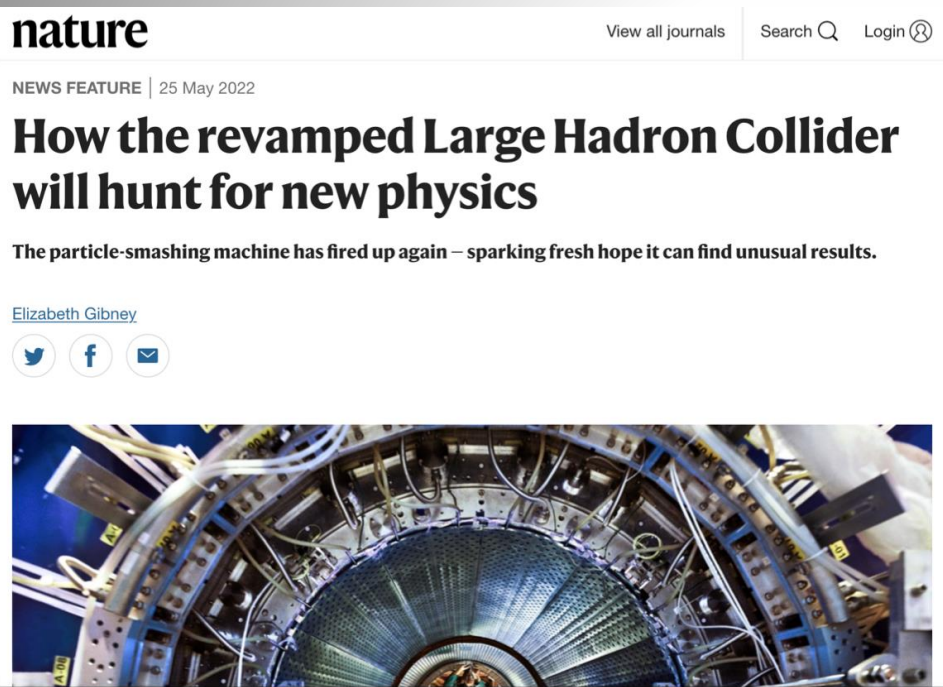
- No time today to cover interesting progress/directions in experimental techniques (quantum sensors, ML, etc...),

Backup

Excess of Events with High dE/dx

dE/dx measurement from the pixel detectors

2205.06013

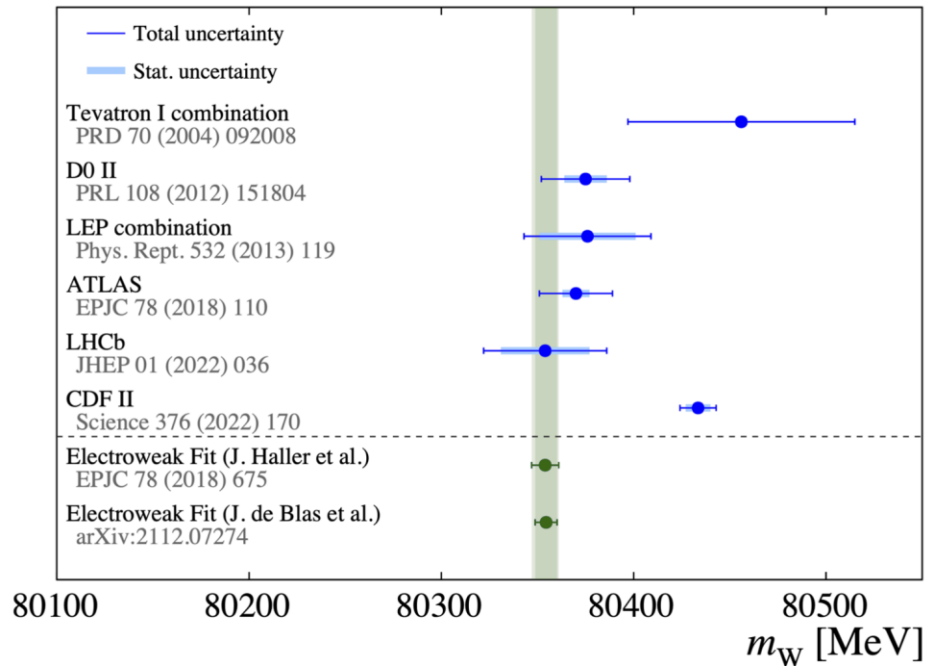


Another intriguing result comes from ATLAS, where Ismet Siral at the University of Oregon in Eugene and his colleagues looked for hypothetical heavy, long-lived charged particles. In trillions of collisions from 3 years of data they found 7 candidates at around 1.4 TeV, around 8 times the energy of the heaviest known particle⁴. Those results are 3.3 sigma, and the identity of the candidate particles remains a mystery. “We don’t know if this is real, we need more data. That’s where run 3 comes in,” says Siral.

7 events and expect **0.7 +/- 0.4**
Local (global) significance is **3.6 σ**
(3.3 σ)

W-mass

CDF W mass measurements (2022)



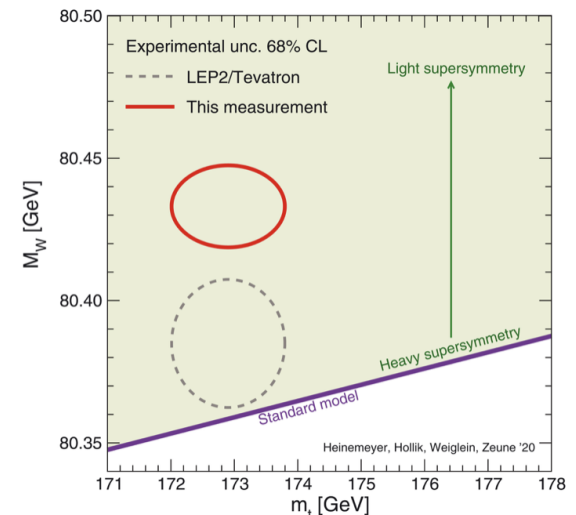
A 7σ discrepancy with the SM prediction ...

An upset to the standard model

SCIENCE

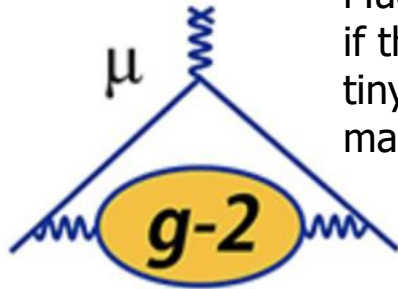
Latest measurement of the W boson digs at the most important theory in particle physics

CLAUDIO CAMPAGNARI AND MARTIJN MULDER

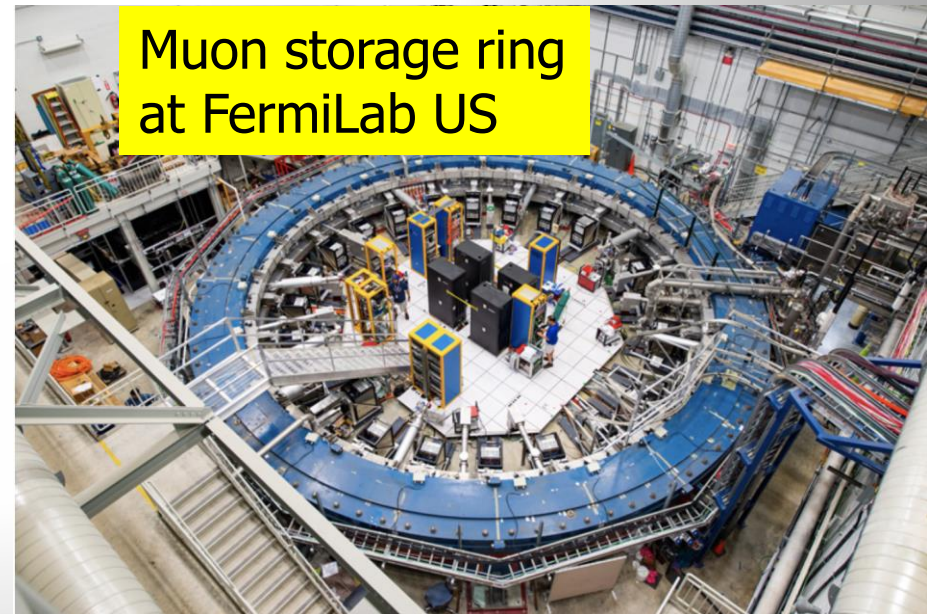
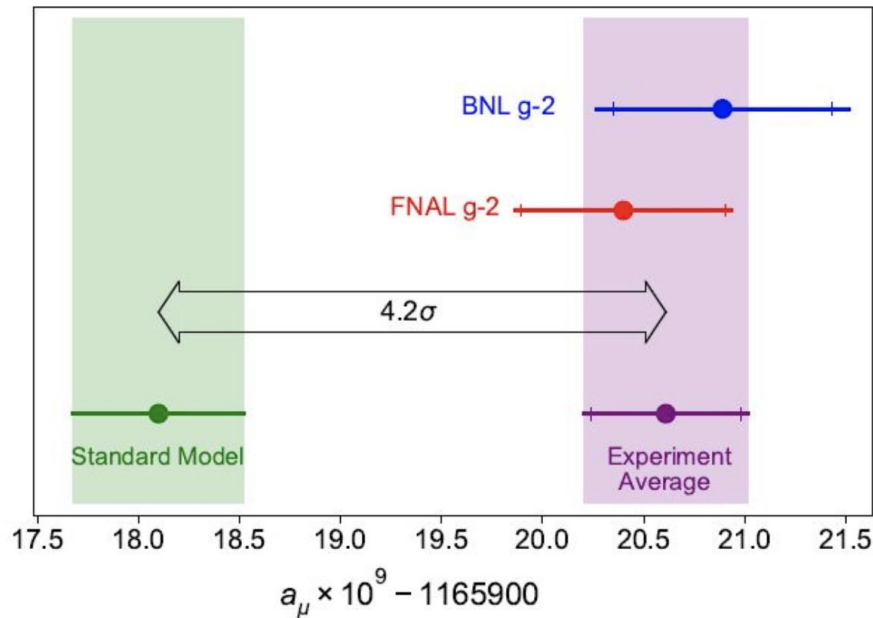
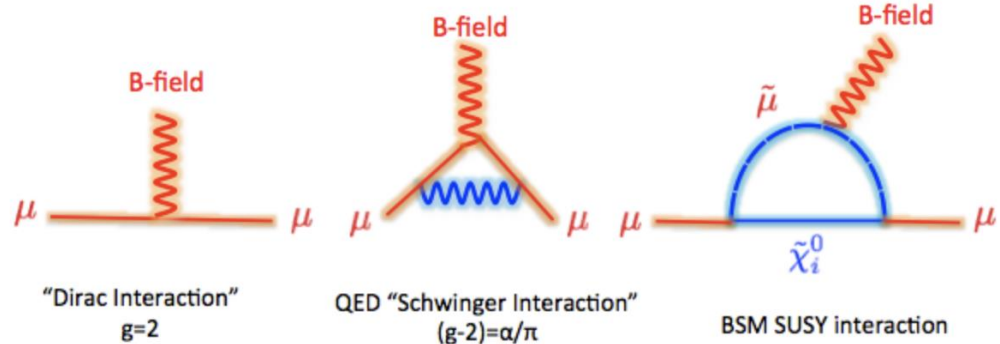


The Muon Anomalous Magnetic Moment

The muon anomalous magnetic moment can be precisely calculated in the SM



Muons act as if they have a tiny internal magnet



Muon storage ring at FermiLab US

A 4.2σ discrepancy with the SM prediction ... but lattice?

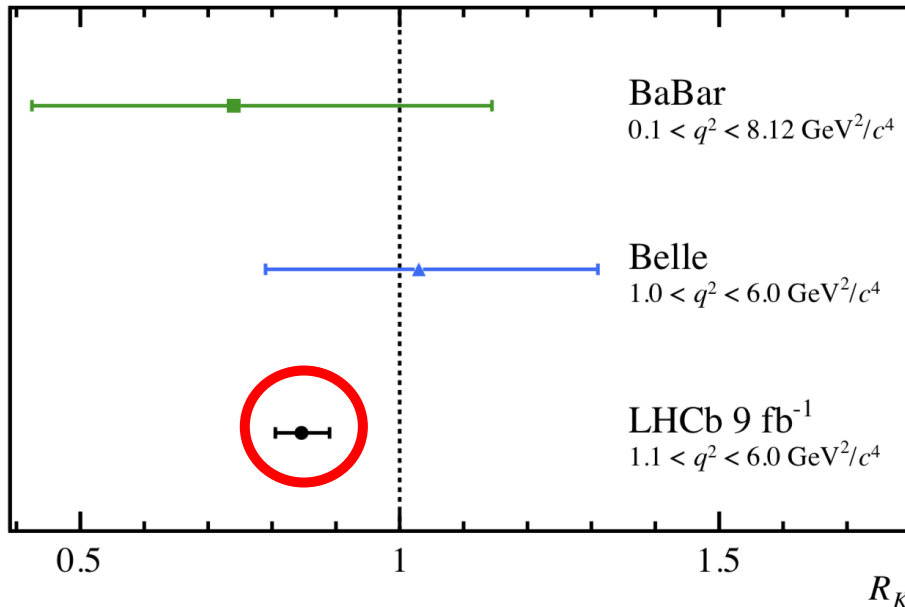
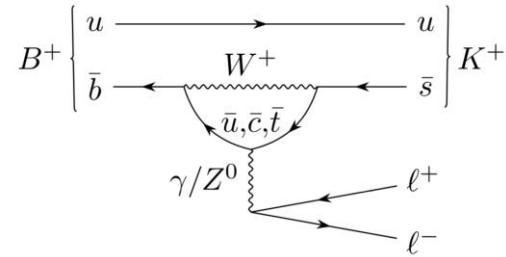
LHCb: Tests of Lepton Universality

Comparing the rates of $B \rightarrow H \mu^+ \mu^-$ and $B \rightarrow H e^+ e^-$

$H = K, K^*, \phi, \dots$

Standard
Model

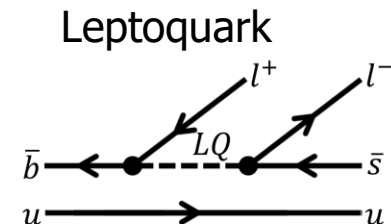
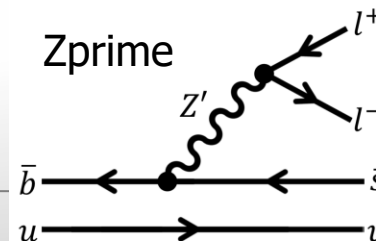
$$R_H = \frac{\int_{q_{min}^2}^{q_{max}^2} \frac{dB(B \rightarrow H \mu^+ \mu^-)}{dq^2} dq^2}{\int_{q_{min}^2}^{q_{max}^2} \frac{dB(B \rightarrow H e^+ e^-)}{dq^2} dq^2} \cong 1$$



New physics: latest results from Cern further boost tantalising evidence

19 octobre 2021, 13:04 CEST

Possible new physics



The Energy Frontier

Medium Project Scale R&D requests

Project	R&D Start date (yr)	R&D End Date (yr)	R&D cost M\$
Higgs Factory detector R&D	now	2035	~100-150
CCC higgs factory	2024	2028	~100
CCC High Energy	2045	2050	~200
Muon Collider (1-3 TeV)	now	2040	~300
Muon Collider (10 TeV)	2040	2047	~200

Estimated US Contributions
In the spirit of Snowmass numbers are very preliminary. They give an approximate scale.

Need to be vetted further.

LEP3/HE-LHC

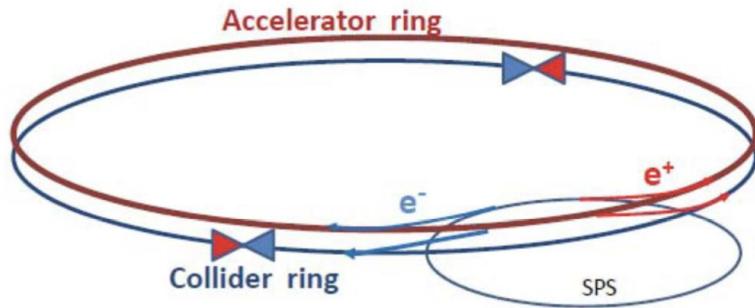
Reduced aspirations...

What can one still do in the largest tunnel we have already?

LEP3 proposal 2012: 1208.0504

e+e- collider in LHC/LEP tunnel

Note: -Max 240 GeV CM energy max
-LHC to be removed (>2040)



Accelerator →	LHC	HL-LHC	ILC	Full ILC	CLIC	LEP3, 4 IP	TLEP, 4 IP
Physical Quantity ↓	300 fb ⁻¹ /expt	3000 fb ⁻¹ /expt	250 GeV 250 fb ⁻¹	250+350+ 1000 GeV	350 GeV (500 fb ⁻¹) 1.4 TeV (1.5 ab ⁻¹)	240 GeV 2 ab ⁻¹ (*)	240 GeV 10 ab ⁻¹ 5 yrs (*)
			5 yrs	5yrs each	5 yrs each	5 yrs	350 GeV 1.4 ab ⁻¹ 5 yrs (*)
N _H	1.7 × 10 ⁷	1.7 × 10 ⁸	6 × 10 ⁴ ZH	10 ⁵ ZH 1.4 × 10 ⁵ Hvv	7.5 × 10 ⁴ ZH 4.7 × 10 ⁵ Hvv	4 × 10 ⁵ ZH	2 × 10 ⁶ ZH 3.5 × 10 ⁴ Hvv
m _H (MeV)	100	50	35	35	100	26	7
ΔΓ _H / Γ _H	—	—	10%	3%	ongoing	4%	1.3%
ΔΓ _{inv} / Γ _H	Indirect (30% ?)	Indirect (10% ?)	1.5%	1.0%	ongoing	0.35%	0.15%
Δg _{Hγγ} / g _{Hγγ}	6.5 – 5.1%	5.4 – 1.5%	—	5%	ongoing	3.4%	1.4%
Δg _{Hgg} / g _{Hgg}	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	< 3%	2.2%	0.7%
Δg _{HWW} / g _{HWW}	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	~1%	1.5%	0.25%
Δg _{HZZ} / g _{HZZ}	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	~1%	0.65%	0.2%
Δg _{HHH} / g _{HHH}	—	< 30% (2 expts)	—	~30%	~22% (~11% at 3 TeV)	—	—
Δg _{Htt} / g _{Htt}	< 30%	< 10%	—	—	10%	14%	7%
Δg _{Htt} / g _{Htt}	8.5 – 5.1%	5.4 – 2.0%	3.5%	2.5%	≤ 3%	1.5%	0.4%
Δg _{Hcc} / g _{Hcc}	—	—	3.7%	2%	2%	2.0%	0.65%
Δg _{Hbb} / g _{Hbb}	15 – 6.9%	11 – 2.7%	1.4%	1%	1%	0.7%	0.22%
Δg _{Htt} / g _{Htt}	14 – 8.7%	8.0 – 3.9%	—	5%	3%	—	30%

(*): the total luminosity is the sum of the integrated luminosity at four IPs

HE-LHC proposal: IPAC 2019

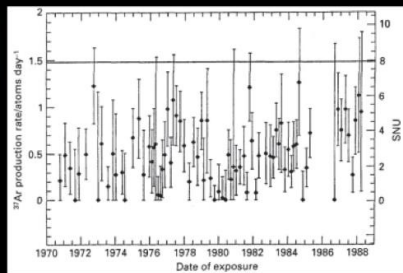
pp colider in LHC/LEP tunnel

Note: - Max 27 TeV CM energy max
- Needs 16 Tesla magnets

These options may be cheaper
but will not necesarilly faster...
(and more limited in reach)

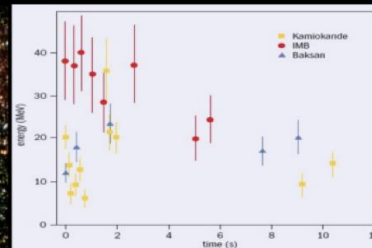
Neutrinos as messengers

Solar neutrinos



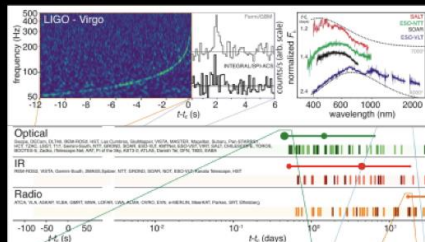
→ Neutrino oscillation

SN1987A



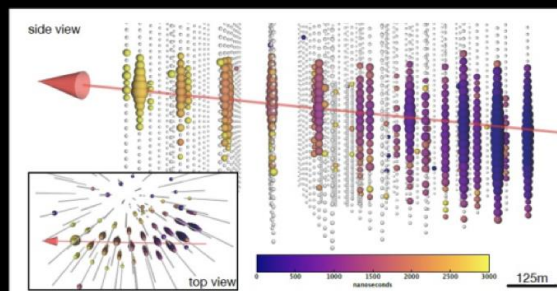
→ Weak interactions in core collapse
→ Eg axion limits

GW170817



→ Short GRB ↔ merger
→ Eg equivalence principle test

TSX 0506-056



→ Flare's hadronic component

Neutrinos are one leg of multi-messenger astronomy

Combination with photons from radio to gamma rays and gravitational waves

Figures from SNOWMASS neutrino colloquium by S. Horiuchi

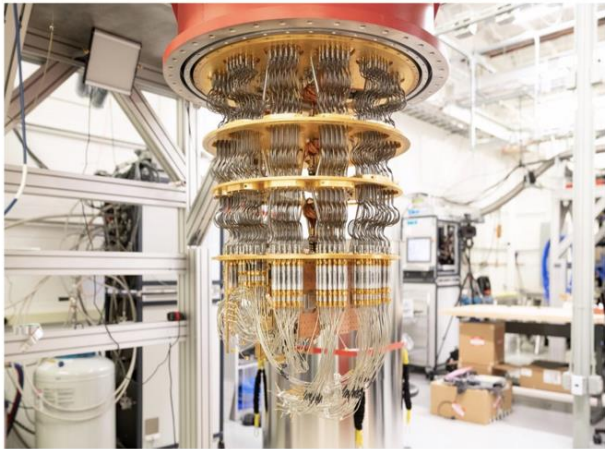
Quantum 2.0

The First Quantum Revolution: exploitation of quantum matter to build devices
Second Quantum Revolution: engineering of large quantum systems with full control of the quantum state of the particles, e.g. entanglement

Google's quantum supremacy is only a first taste of a computing revolution

"Quantum supremacy" is nice, but more broadly useful quantum computers are probably still a decade away.

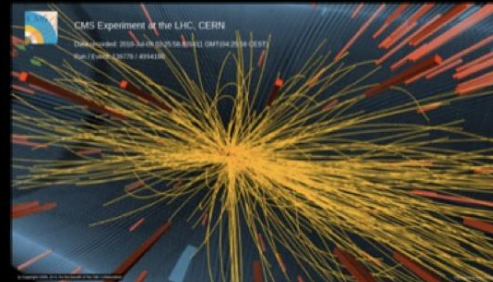
Stephen Shankland · October 25, 2019 6:20 AM PDT



One of five Google quantum computers at a lab near Santa Barbara, California.

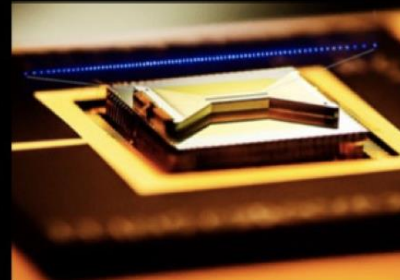
Stephen Shankland/CNET

AI, ML on Quantum annealer



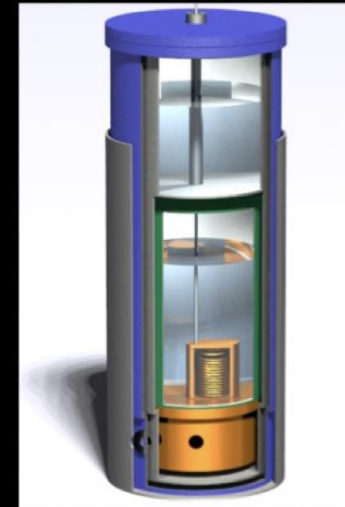
Nature 550 (2017) 375

IonQ >60-qubit



arXiv:1902.10171

Atomic clocks



Nature (564) 87 (2018)

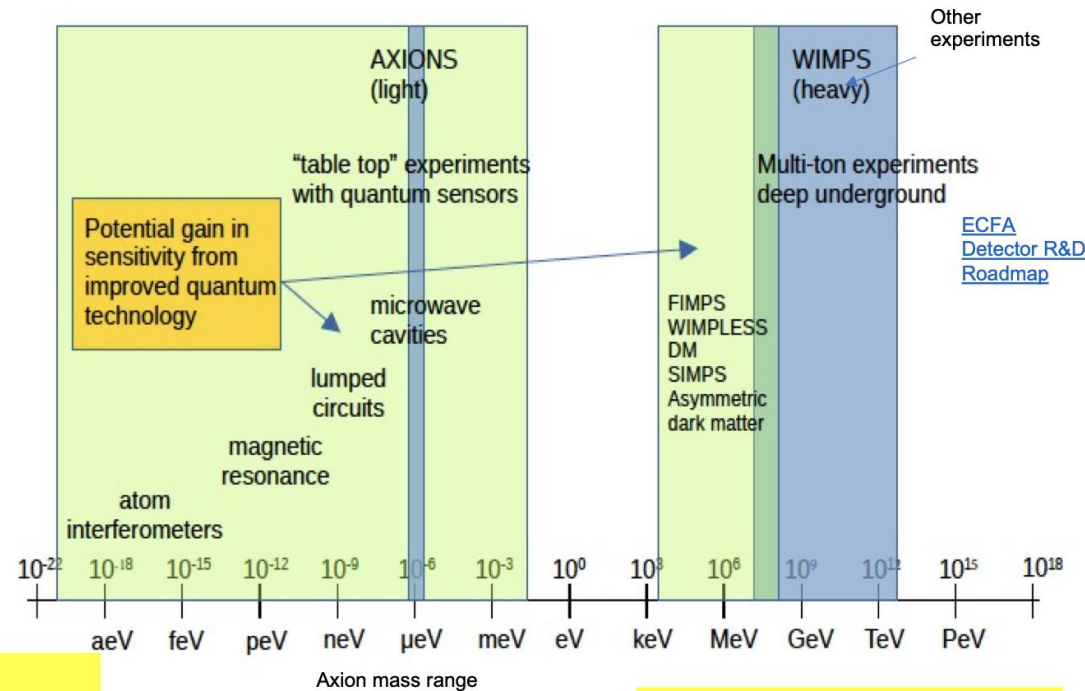
Quantum Technologies



Quantum and emerging technologies

- **Quantum Technologies are a rapidly emerging area** of technology development to study fundamental physics
- The ability to engineer quantum systems to improve on the measurement sensitivity holds great promise
- **Many different sensor and technologies being investigated:** clocks and clock networks, spin-based, superconducting, optomechanical sensors, atoms/molecules/ions, atom interferometry, ...
- Several initiatives started at CERN, DESY, FNAL, US (DOE QuantISED UK QTFP...)

Example: potential mass ranges that quantum sensing approaches open up for Axion searches



Blue: now
Light green: with quantum



Significant new funding
for HEP & spectacular opportunities
for interdisciplinary collaboration

Enablig-HEP-Snowmass 21 -- I. Shipsey