Searching for New Physics with an Enhanced MoEDAL Detector

Guanajuato, Mexico November 2019

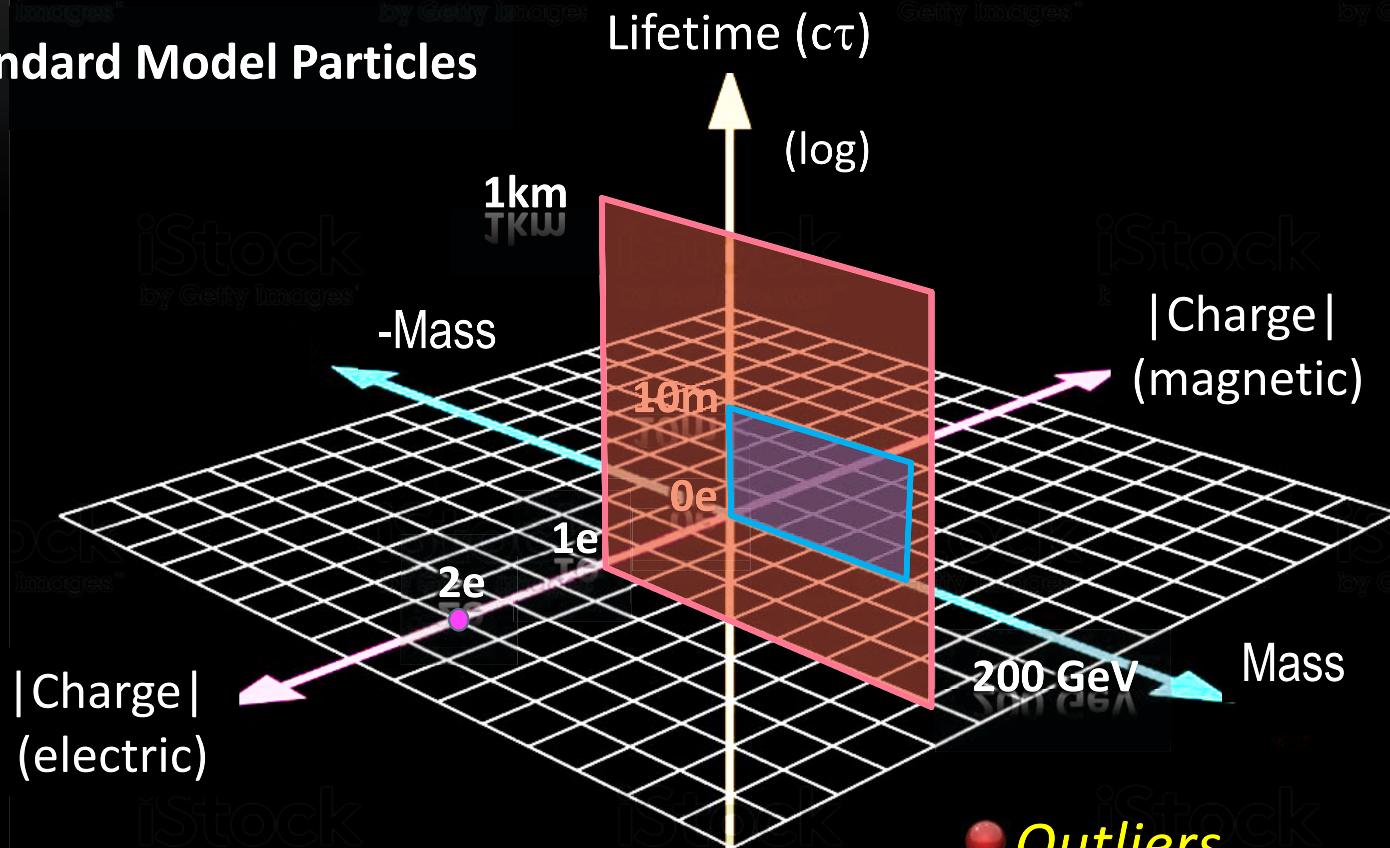
Workshop on Forward Physics and QCD at the LHC, the Future Electron-Ion Collider and Cosmic Ray Physics

James Pinfold, University of Alberta

The LHC – no new physics yet

Properties Standard Model Particle

Standard Model Particles

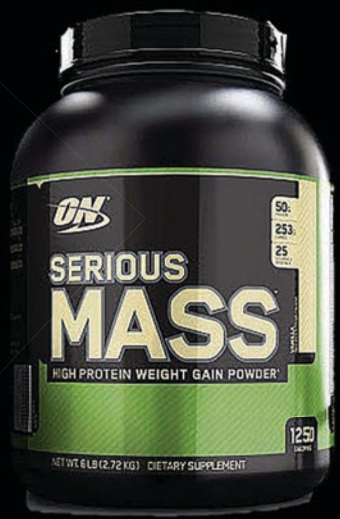


- *Stable Particles (?)*
  - *Proton*
  - *Electron*
  - *Neutrinos*
- *Outliers*
  - *Neutron lifetime 15min.*
  - *Lightest neutrino m < 0.1 eV*
  - *Top quark mass 173 GeV*
  - Δ^{++}, Ω_c^{*++}, Σ_c^{*++}, Ξ_c^{*++}

Clear Attributes of New Physics

Mass

$< \sim 0.1$ eV



Mass

$> \sim 180$ GeV/c^2

Lifetime ($c\tau$)

$> \sim 10$m

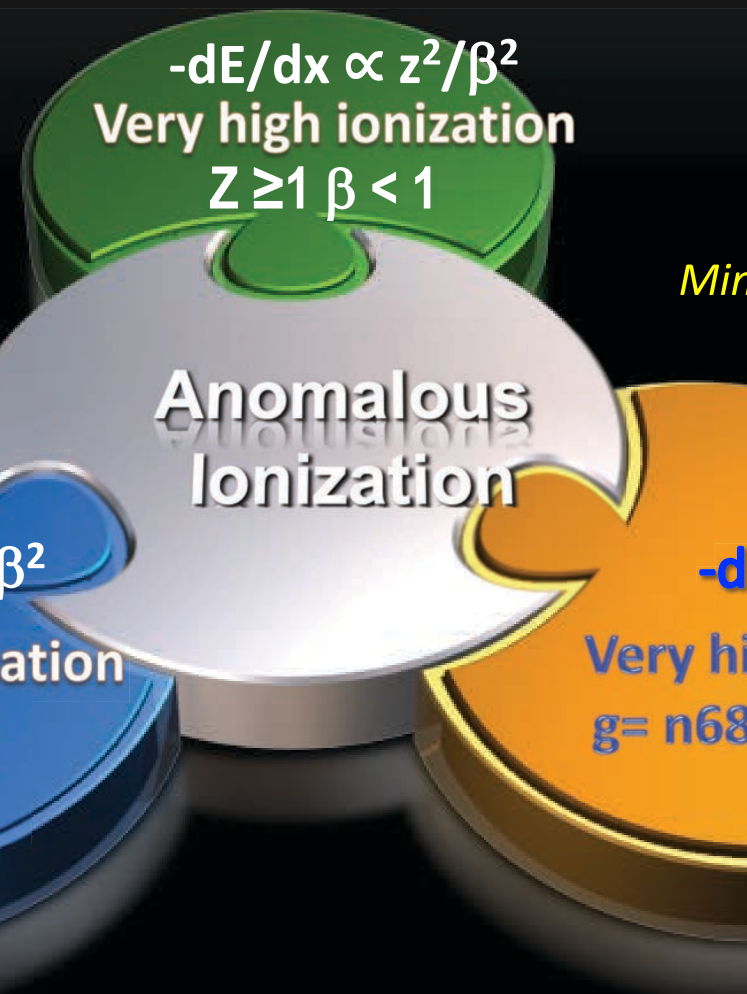
Fractional charge

Charge >2 or Magnetic charge

Anomalously Ionizing Avatars of New Physics

Highly ionizing particles (HIPs)

Mini-charged particles (mCPs)



*The velocity dep. of the Lorentz force cancels $1/\beta^2$ term

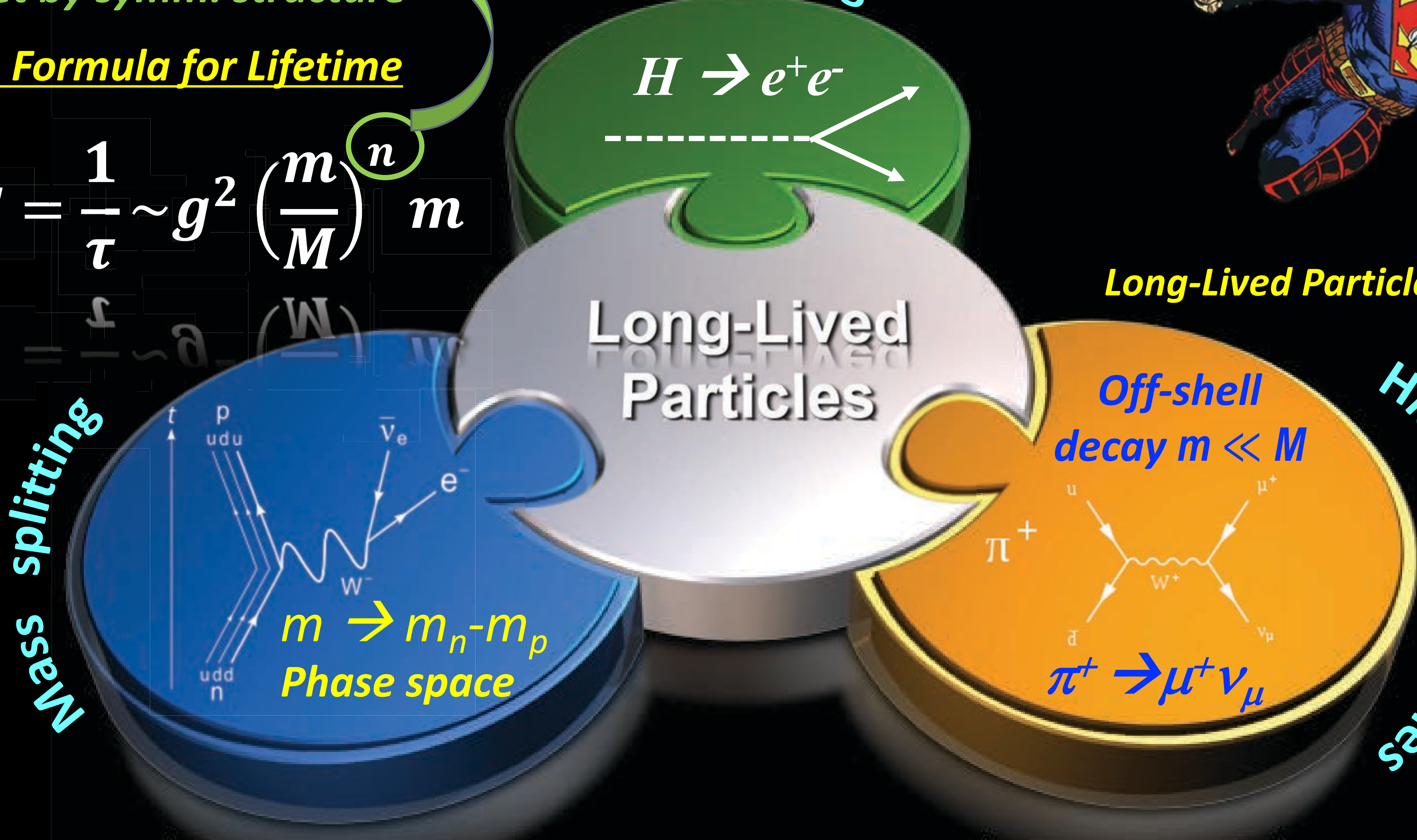
Long-Lived Avatars of New Physics

- *Besides: conservation of a quantum number (Charge, R-parity, KK-number; or partial conservation (RPV SUSY), we have →*

Typically n ≥ 4
(Set by symm. structure

The Formula for Lifetime

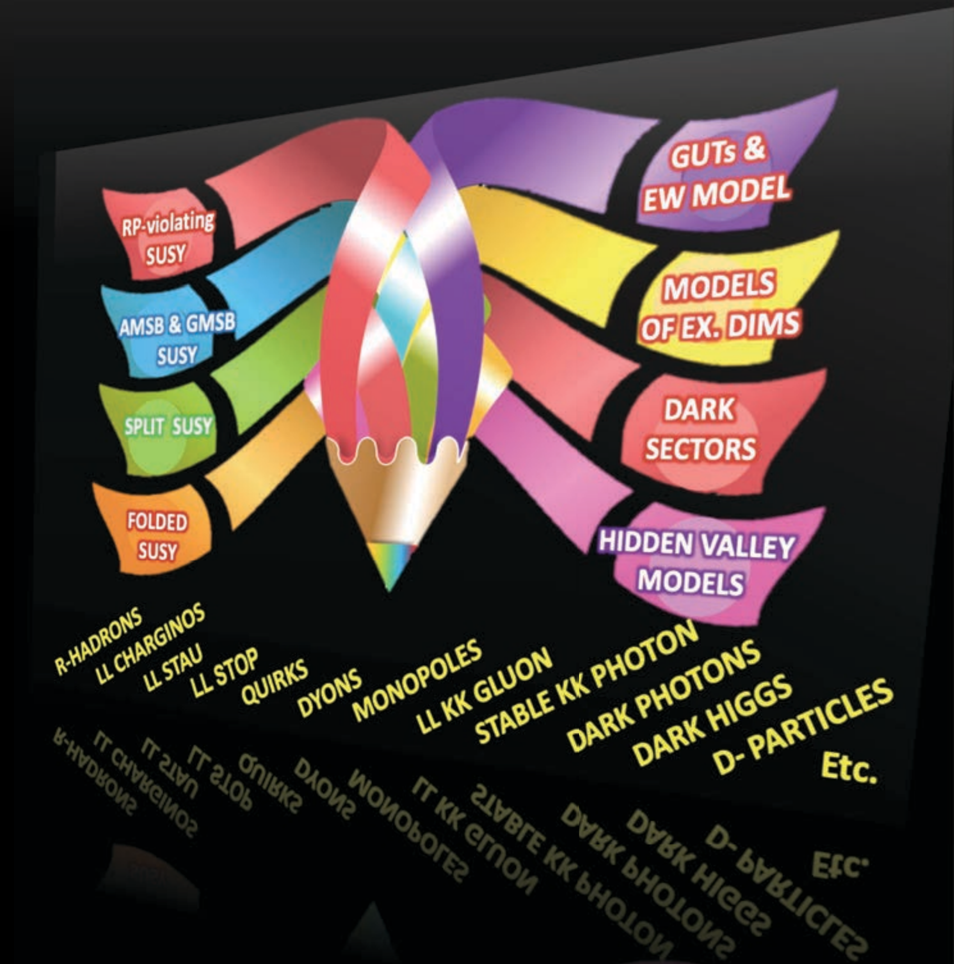
$$\Gamma = \frac{1}{\tau} \sim g^2 \left(\frac{m}{M}\right)^n m$$



Long-Lived Particles (LLPs)

Theory Origins

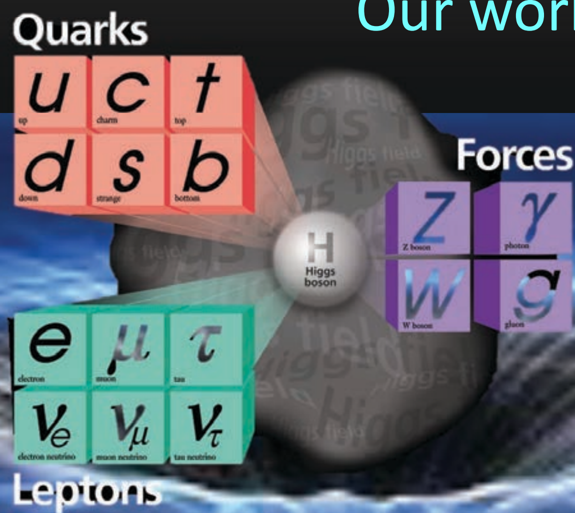
New LLPs & stable particles



Anomalously ionizing particles

Dark Sector Theory

Our world - the Standard Model



The dark sector may have a rich structure with matter and forces of its own

The Portal

The Hidden Sector

- *Main evidence so far for dark matter is gravitational. What are the " likely" non-gravitational interactions? Dark Sector theory attempts to answer this question*

Portals to the Dark Sector

- *To detect a dark sector, we must know how it interacts with us.*
  - *Interactions between the two sectors are via mediator particles crossing the portal*

The MoEDAL Experiment

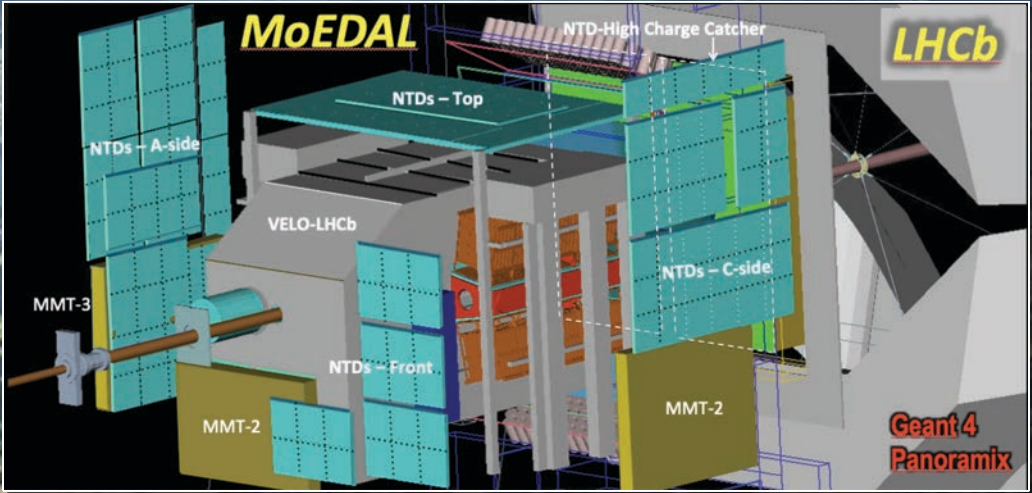
(Now 70 physicists Contributing)

The LHC's First Dedicated Search Experiment

An overview of the Run-2 MoEDAL Detector.

Started data taking at the LHC in 2015

Permanent Physical record of new physics



No Standard Model Physics Backgrnds

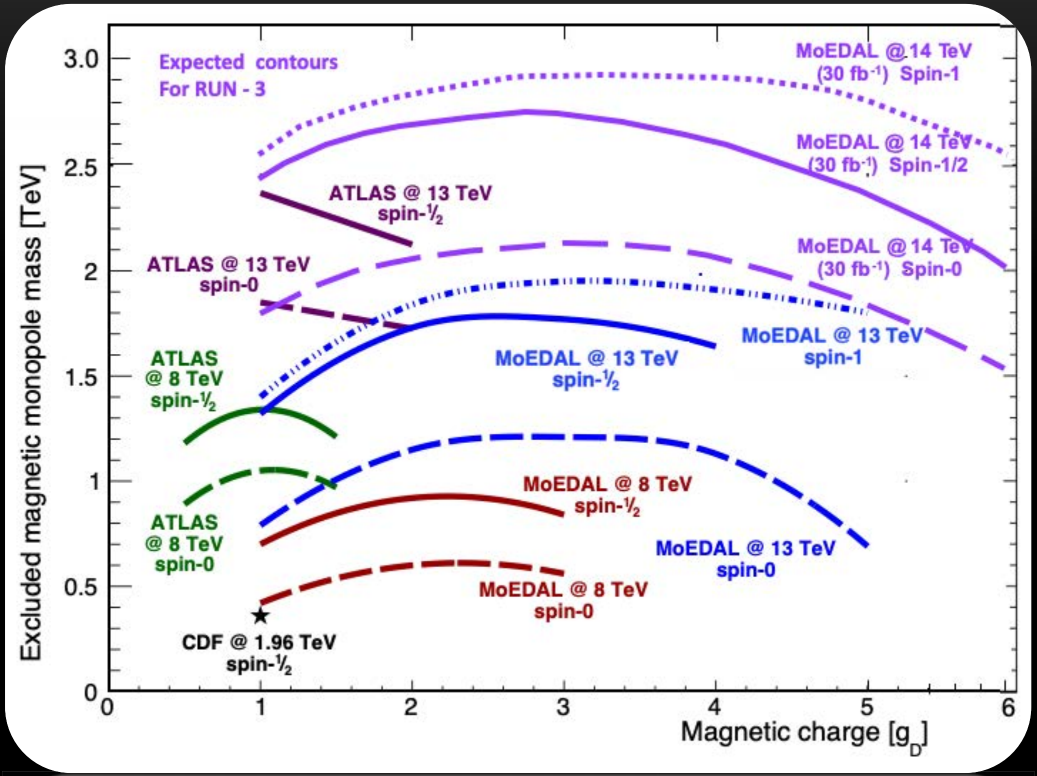
MoEDAL is largely passive made up of three detector system.

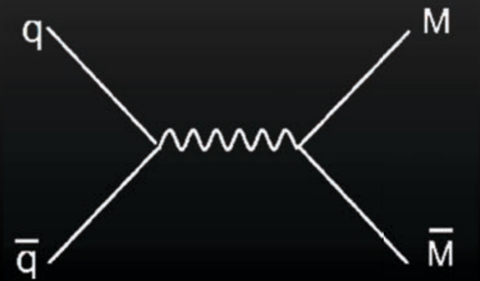
NUCLEAR TRACK DETECTOR
Plastic array (~200 sqm) – Like a Giant Camera

TRAPPING DETECTOR ARRAY
A tonne of Al to trap Highly Ionizing Particles for analysis

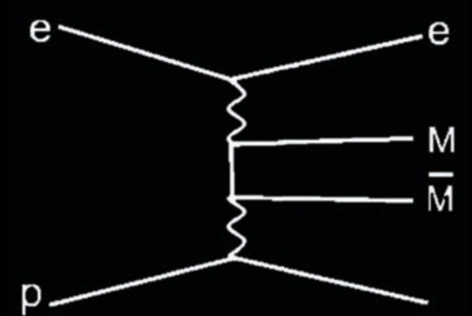
TIMEPIX Array a digital
Camera for real time radiation monitoring

Mass Limits on Multiply Charge Monopoles





Drell Yan mechanism



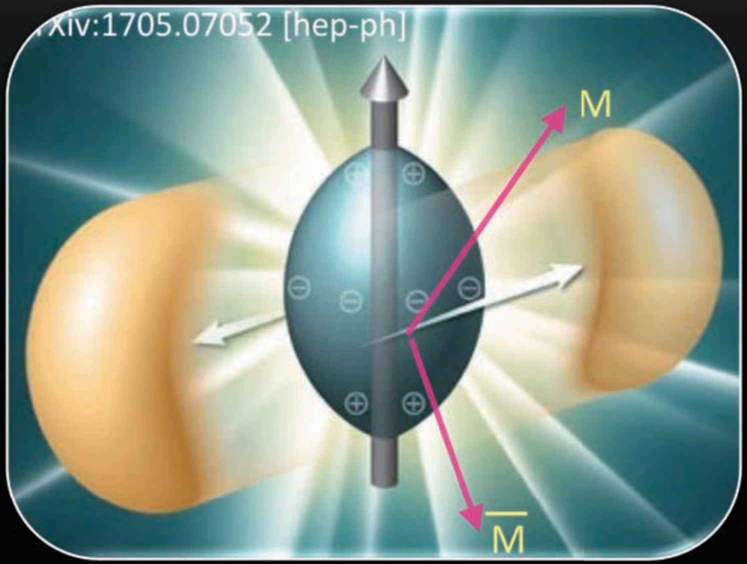
Photon fusion

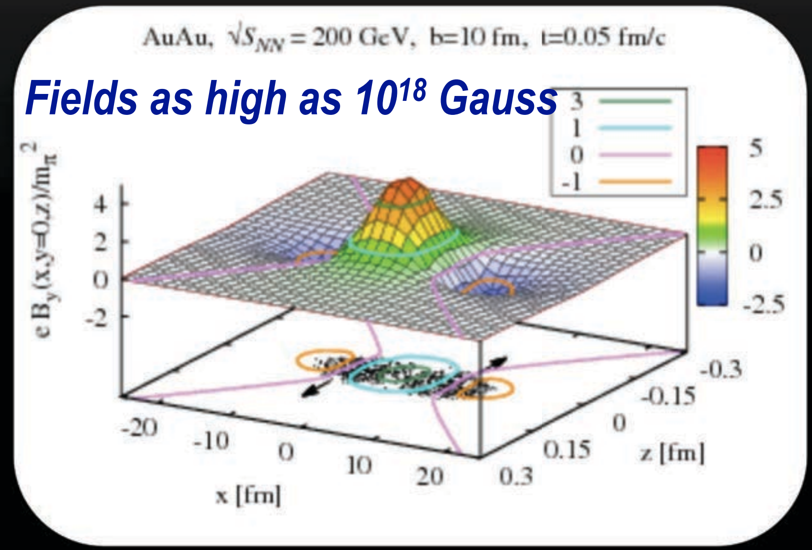
JHEP 1608 (2016) 067 PRL 118 (2017) 061801 Phys.Lett. B782 (2018) 510 PRL 123 (2019) 021802

- *So far MoEDAL has placed the world's best published direct limits on:*
  - *Multiply charged magnetic monopoles*
  - *Spin-1 monopoles*
  - *DY + Photon fusion production of monopoles*

MoEDAL

Monopoles From Heavy-ion Collisions
via the Thermal Schwinger Mechanism





- Probability of producing a monopole pair $\sigma_{MM} = \sigma_{Inl} V_{ST}\, \Gamma_T$ (where V_{st} is the space-time volume of the field, Γ_T is the rate/unit volume & σ_{inl} is the inelastic nuclear cross-section)
- Important benefits:
  - No exponential suppression for finite sized monopoles
  - X-sec calculation does not suffer from non-perturbative nature of coupling as in DY production
- Expect a MoEDAL result on this topic by Spring 2020.

Three Other Papers in Preparation

MONOPOLES

CMS beam pipe to be mined for monopoles

On 18 February the CMS and MoEDAL collaborations at CERN signed an agreement that will see a 6 m-long section of the CMS beam pipe c… into a SQUID in the n… research. The 4 cm … tube – which was i… 2008 until its repl… beampipe for LHC R…

CERN-PHOTO-201611-288-4

Pipe dreams *The original CMS beampipe, in use during LHC Run 1.*

Search for High Electrically Charge Objects and Magnetic Monopoles in 8 TeV *pp* Collisions at the LHC Using the Full MoEDAL Detector

B. Acharya,[1,*] J. Alexandre,[1] S. Baines,[1] P. Benes,[2] B. Bergmann,[2] J. Bernabéu,[3] A. Bevan,[4] H. Branzas,[5]
M. Campbell,[6] S. Cecchini,[7] Y. M. Cho,[8,†] M. de Montigny,[9] A. De Roeck,[6] J. R. Ellis,[1,10,‡] M. El Sawy,[6,§]
M. Fairbairn,[1] D. Felea,[5] M. Frank,[11] J. Hays,[4] A. M. Hirt,[12] J. Janecek,[2] D.-W. Kim,[13] A. Korzenev,[14]
D. H. Lacarrère,[6] S. C. Lee,[13] C. Leroy,[15] G. Levi,[16] A. Lionti,[14] J. Mamuzic,[3] A. Margiotta,[16] N. Mauri,[7]
N. E. Mavromatos,[1] P. Mermod,[14] M. Mieskolainen,[17] L. Millward,[4] V. A. Mitsou,[3,¶] R. Orava,[17]
I. Ostrovskiy,[18] J. Papavassiliou,[3] B. Parker,[19] L. Patrizii,[7] G. E. Păvălaş,[5] J. L. Pinfold,[9] V. Popa,[5]
M. Pozzato,[7] S. Posp…
S. Sarkar,[1] G. Seme…
M. Tenti,[23] V. To…

The search for Dyons with the full MoEDAL trapping detector in 13 TeV *pp* collisions

B. Acharya,[1,*] J. Alexandre,[1] P. Benes,[2] B. Bergmann,[2] J. Bernabéu,[3] A. Bevan,[4] H. Branzas,[5] M. Campbell,[6] S. Cecchini,[7] Y. M. Cho,[8,†] M. de Montigny,[9] A. De Roeck,[6] J. R. Ellis,[1,10,‡] M. El Sawy,[6,§] M. Fairbairn,[1] D. Felea,[5] M. Frank,[11] J. Hays,[4] A. M. Hirt,[12] J. Janecek,[2] M. Kalliokoski,[13] D.-W. Kim,[14] A. Korzenev,[15] D. H. Lacarrère,[6] S. C. Lee,[14] C. Leroy,[16] G. Levi,[17] A. Lionti,[15] J. Mamuzic,[3] A. Maulik,[7,9] A. Margiotta,[17] N. Mauri,[7] N. E. Mavromatos,[1] P. Mermod,[15] M. Mieskolainen,[18] L. Millward,[4] V. A. Mitsou,[3,¶] R. Orava,[18] I. Ostrovskiy,[19] P.-P. Ouimet,[9,**] J. Papavassiliou,[3] B. Parker,[20] L. Patrizii,[7] G. E. Păvălaş,[5] J. L. Pinfold,[9] V. Popa,[5] M. Pozzato,[7] S. Pospisil,[2] A. Rajantie,[21] R. Ruiz de Austri,[3] Z. Sahnoun,[7,††] M. Sakellariadou,[1] A. Santra,[3] S. Sarkar,[1] G. Semenoff,[22] A. Shaa,[9] G. Sirri,[7] K. Sliwa,[23] R. Soluk,[9] M. Spurio,[17] M. Staelens,[9] M. Suk,[2] M. Tenti,[24] V. Togo,[7] J. A. Tuszyński,[9] V. Vento,[3] O. Vives,[3] Z. Vykydal,[2] A. Wall,[19] and I. S. Zgura[5]

(THE MoEDAL COLLABORATION)

MoEDAL @ Run-3 – Desperately Seeking SUSY

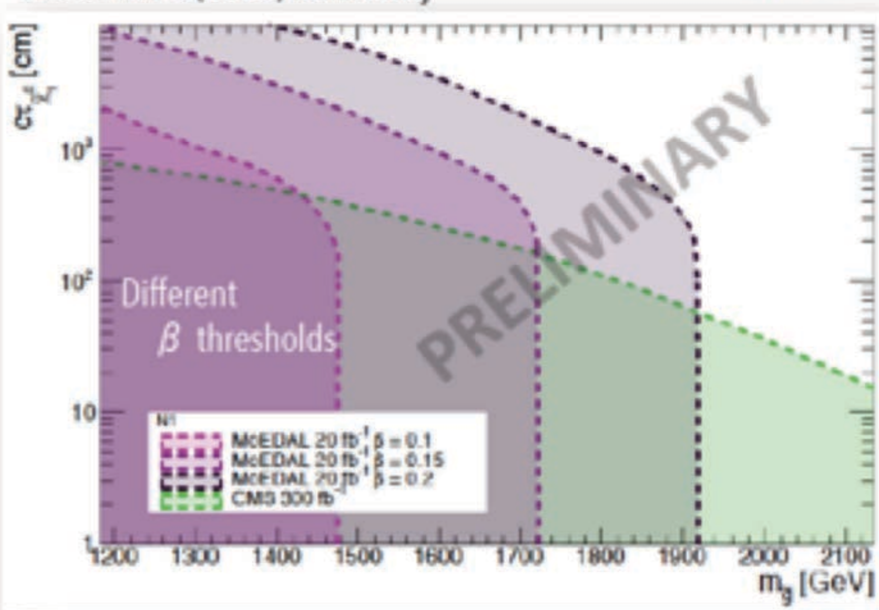
Results for $\tilde{g}\tilde{g}$, $\tilde{g}\rightarrow jj\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\rightarrow\tau^{\pm}\tilde{\tau}_1$

$\tilde{\chi}_1^0$ long-lived despite large mass split between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ ➜ decays in tracker

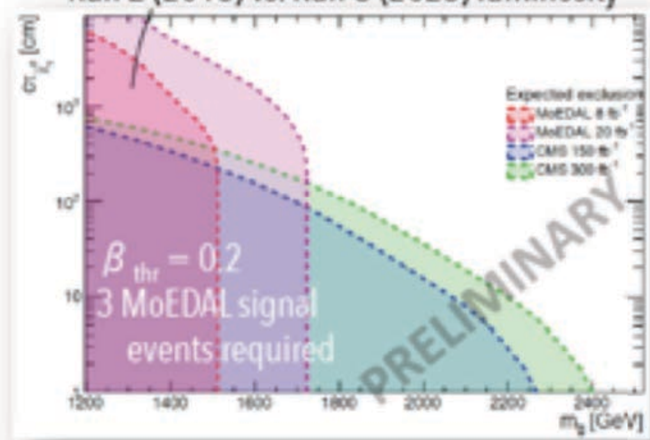
(massive) $\tau^{\pm}$ produces a kink between $\tilde{\chi}_1^0$ and $\tilde{\tau}_1$ tracks ⇒ large impact parameter d_{xy}, d_z

$\tilde{\tau}_1$ metastable, e.g. gravitino LSP ➜ detected by MoEDAL

End-of-run-3 (2023) luminosity



Run 2 (2018) vs. Run-3 (2023) luminosity



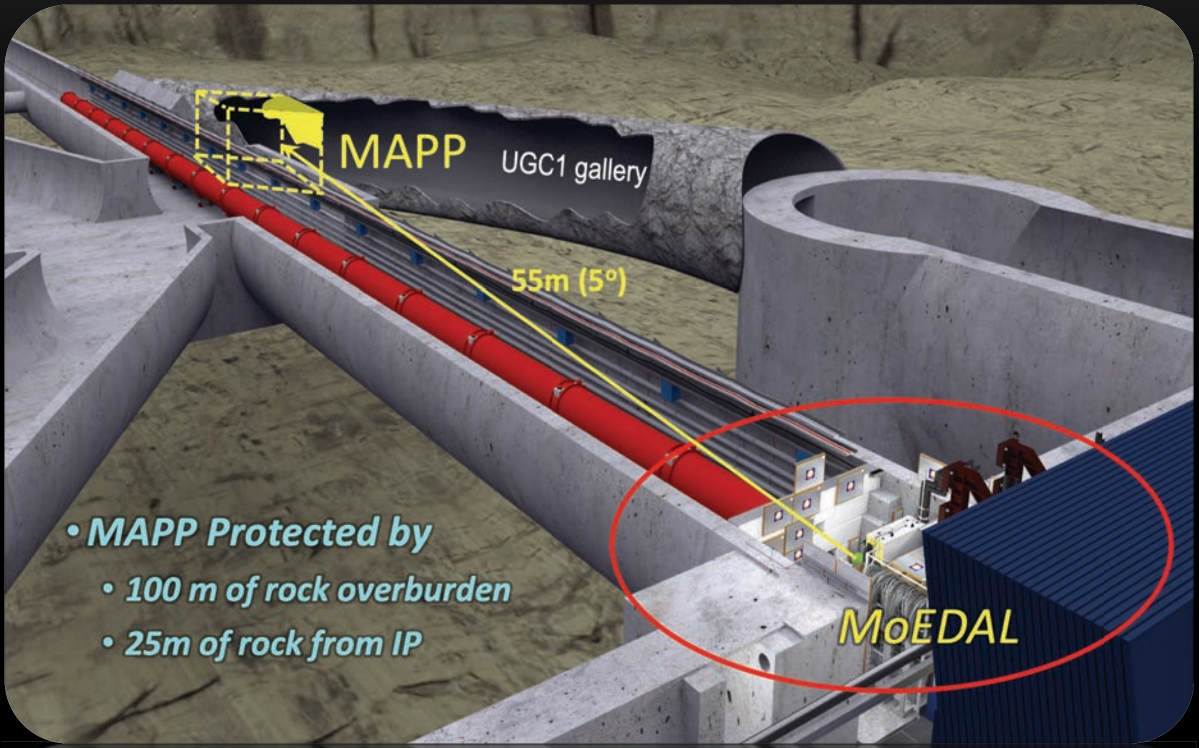
- CMS suffers twice:
  - a) no pixel hit
  - b) too large impact parameters

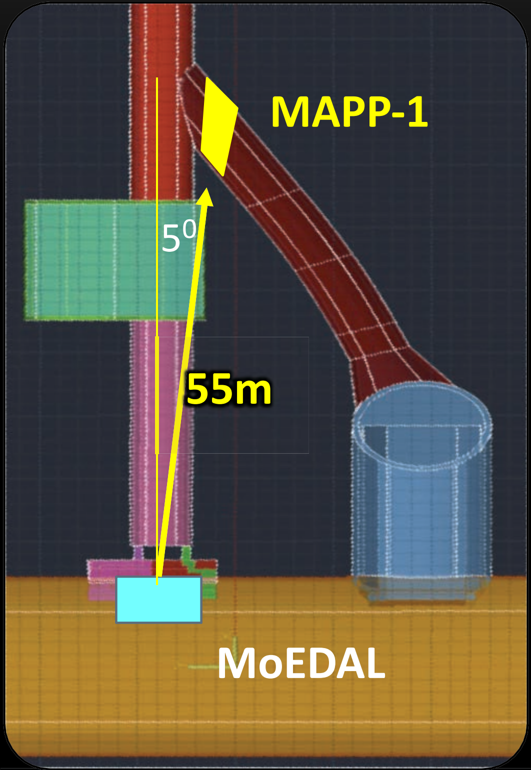
- MoEDAL can cover long-lifetime region inaccessible by ATLAS/CMS even with a *moderate* NTD performance **$z/\beta > 10$**

Comparison of CMS exclusion with MoEDAL discovery potential requiring 1 event

MAPP-1 – MoEDAL Upgrade for RUN-3

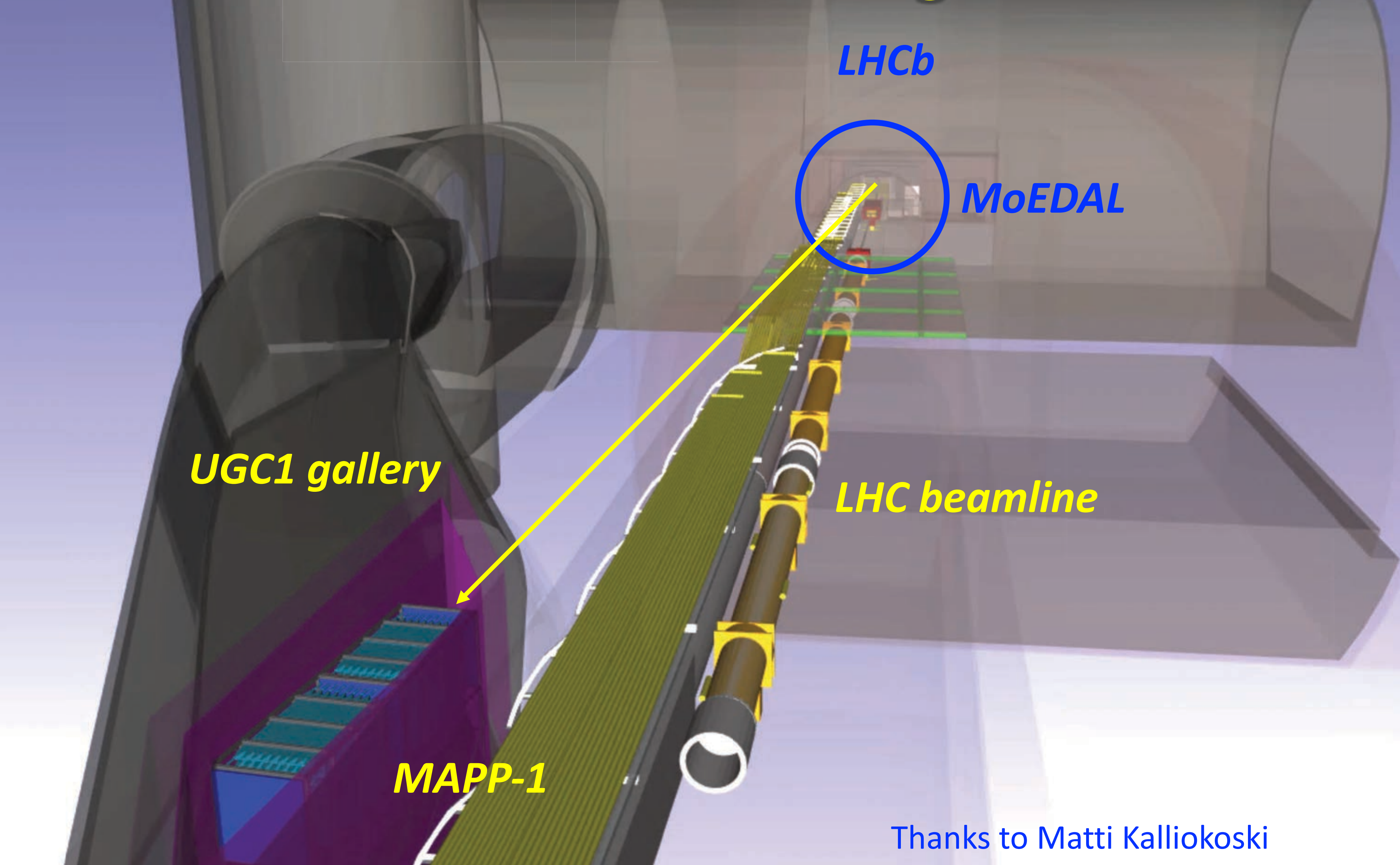
(MoEDAL Apparatus for Penetrating Particles)





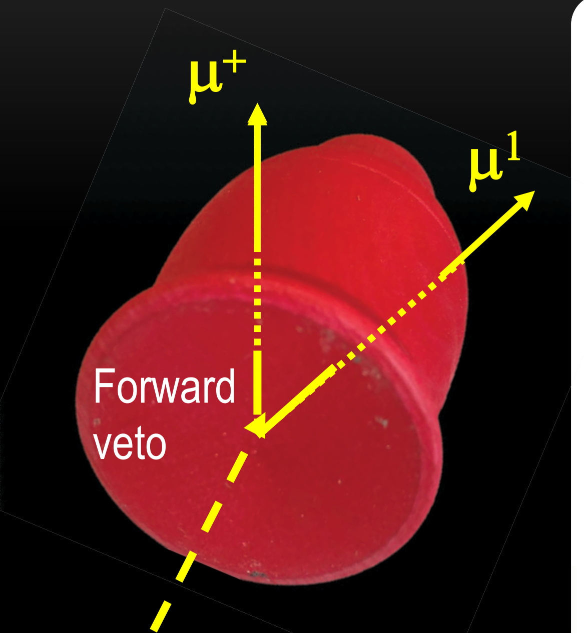
- MAPP (to be installed for Run-3 of the LHC) has 2 motivations
  - To search for particles with charges <<1e (ATLAS & CMS limited to searches with particles of charge around e ≥ 1/3)
  - To search for new weakly interacting neutrals with long lifetime

A Fully Simulated (GEANT4) View of the MoEDAL-MAPP Region

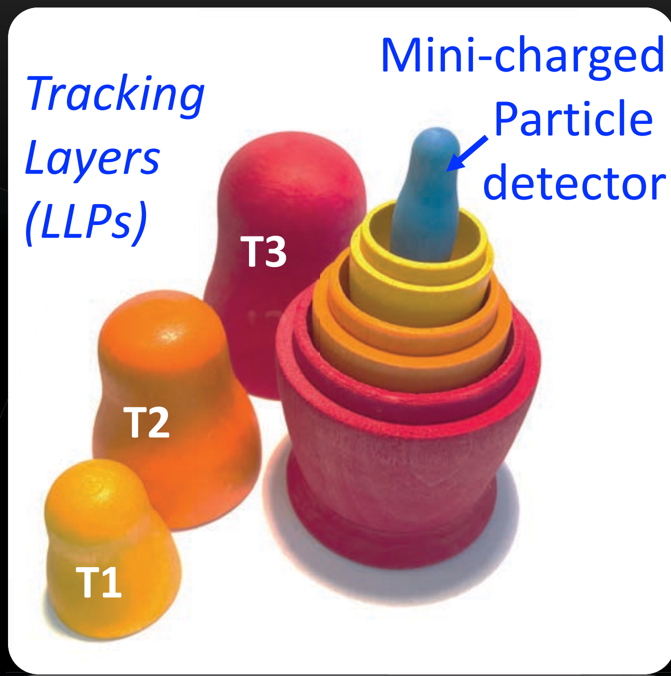


Thanks to Matti Kalliokoski

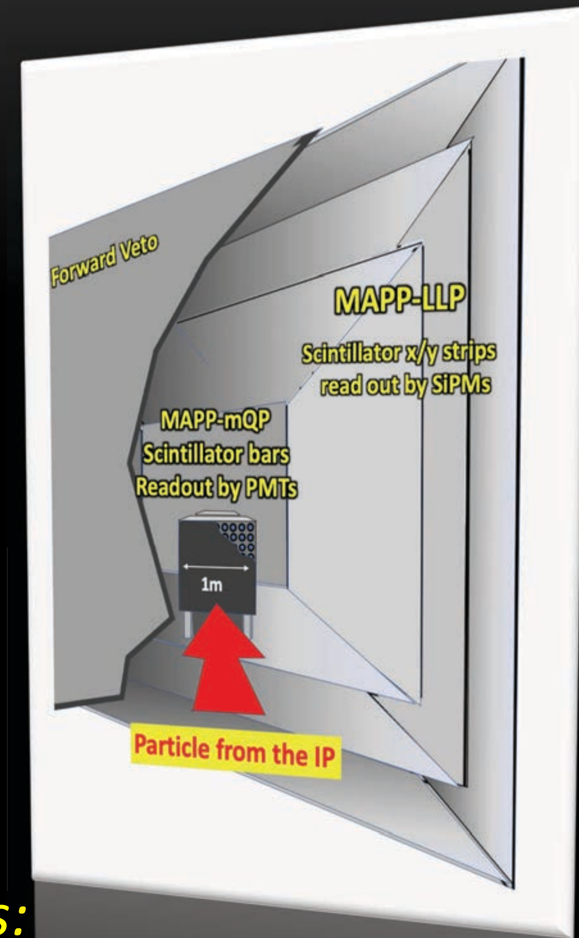
The MAPP Detector Concept



Long-lived neutral decay in MAPP

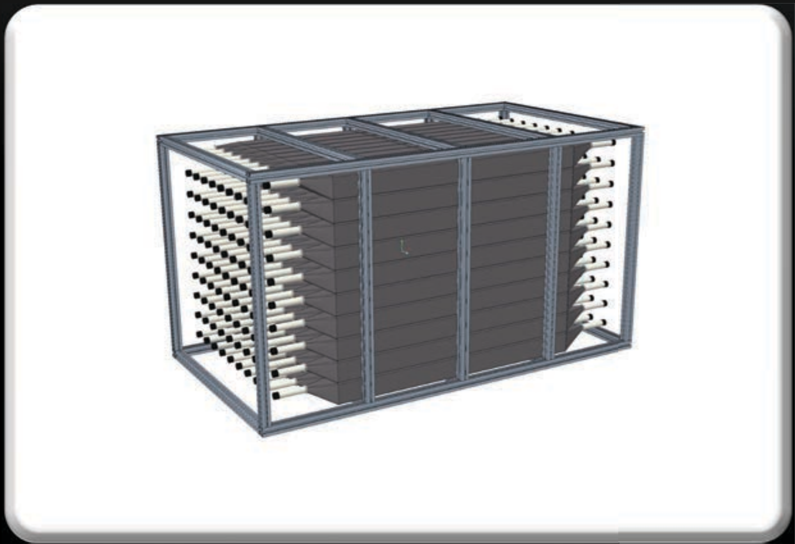


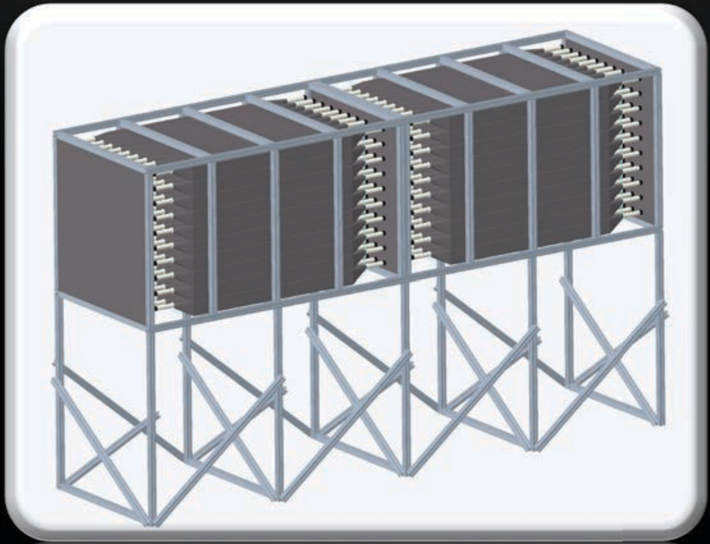
"Russian Doll" configuration



- *The MAPP detector is comprised of two parts:*
  - *The Long-lived particle (MMP-LLP detector) that consists of three X/Y scintillator hodoscope layers in a nested "Russian Doll" configuration (tracking eff. ~ 80%/trk)*
  - *A central mini-charged particle detector (MMP-mCP)*

The MAPP Mini-charged Particle Detector (MAPP-mCP)



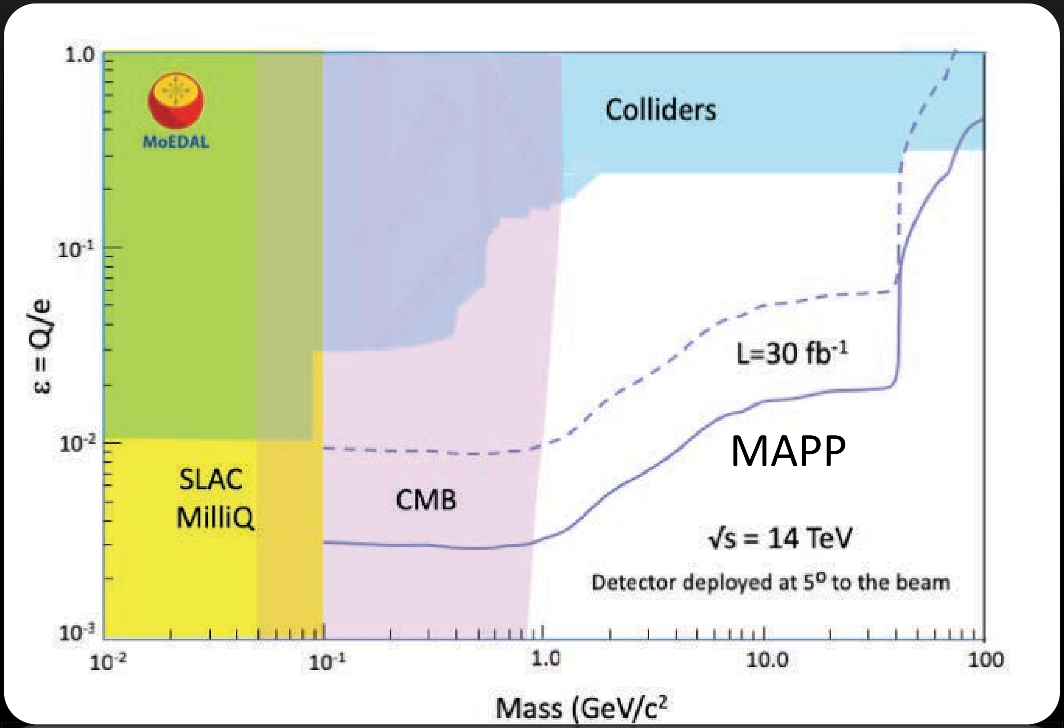


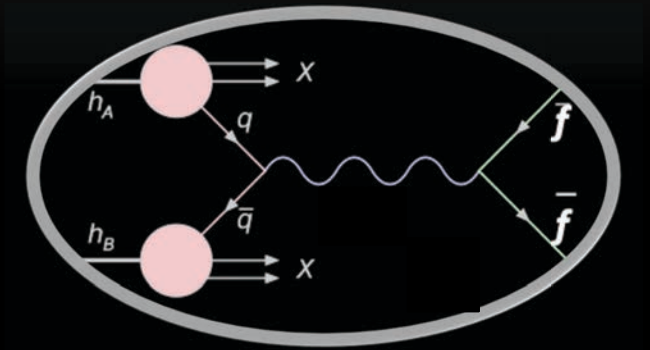
- Central Milli-Charged (mQP) Detection Sections:
  - 100 x (10cm x 10cm x 75cm) scintillator bars in 4 lengths, 2 lengths/section readout by 4 low noise 3.1” PMTs, in coincidence
  - No background from dark counts and radiogenic backgrounds
  - Protected from cosmics by 100m of rock overburden + surrounding active veto system (not shown)
  - Protected by 25-26m of rock/concrete (~65 Nuclear Interaction Lengths) from SM particles from the Intercation Point)

The MAPP LLP Detector

- The above shows one wall of the "box-within-a-box" or "Russian Doll" structure of the MAPP LLP detector
- The baseline readout structure are scintillator strips in an x-y configuration readout by SiPMs resolutions ~1cm x 1cm on each hit.

Example of MAPP Sensitivity for mQP

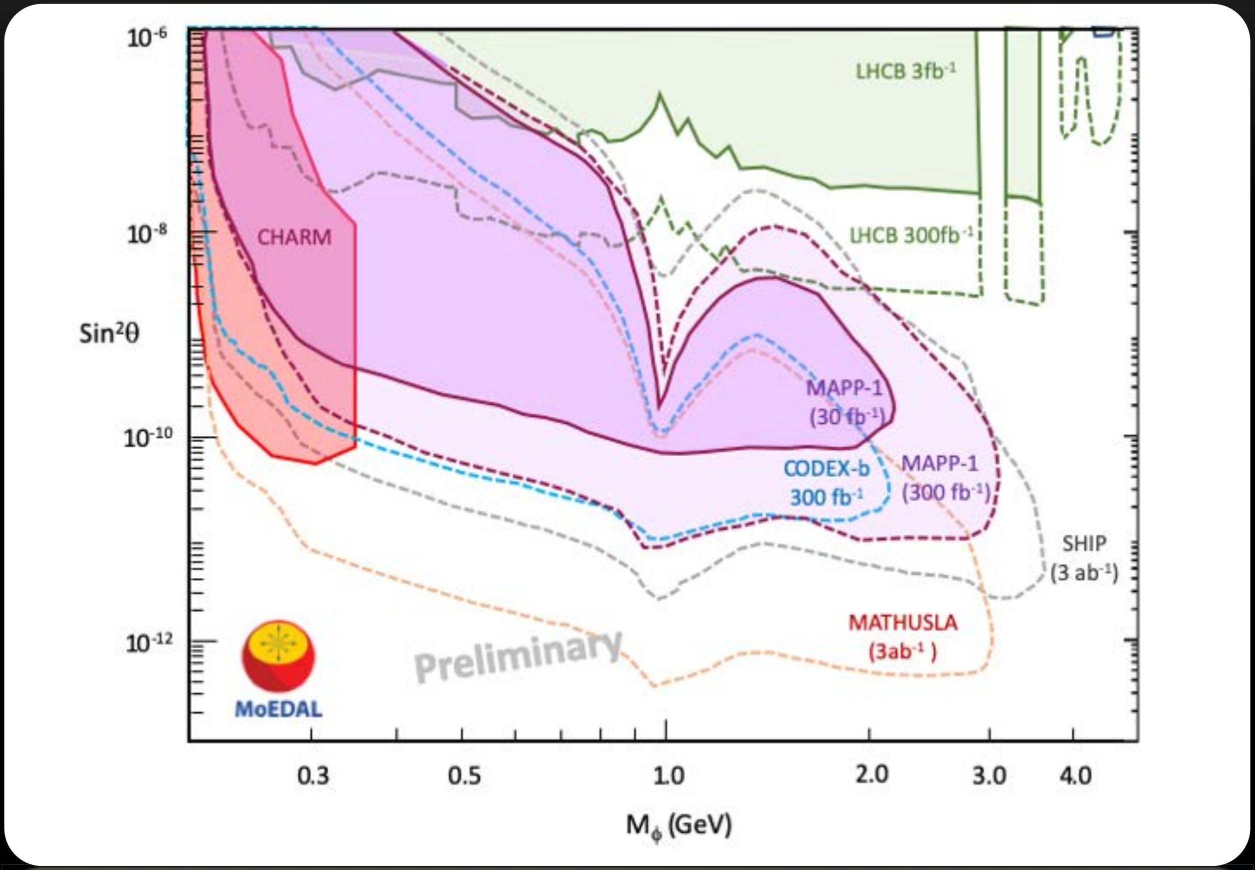




The direct and indirect bounds on mQPs for models with a massless dark photon qnd the max. projected reach of MAPP for RUN-3 (---line 10% overall MAPP eff.)

- *MAPP will enable the search for particles with charge as low as ~10^{-3}e & masses above ~100 MeV.*
  - *In the dark photon search we have sensitivity to a charge of $\mathcal{O}(10^{-2})$ - $\mathcal{O}(10^{-3})$e for mass of $\mathcal{O}$(1) GeV & charge $\mathcal{O}(10^{-2})$ e for mass of $\mathcal{O}$(10) GeV.*

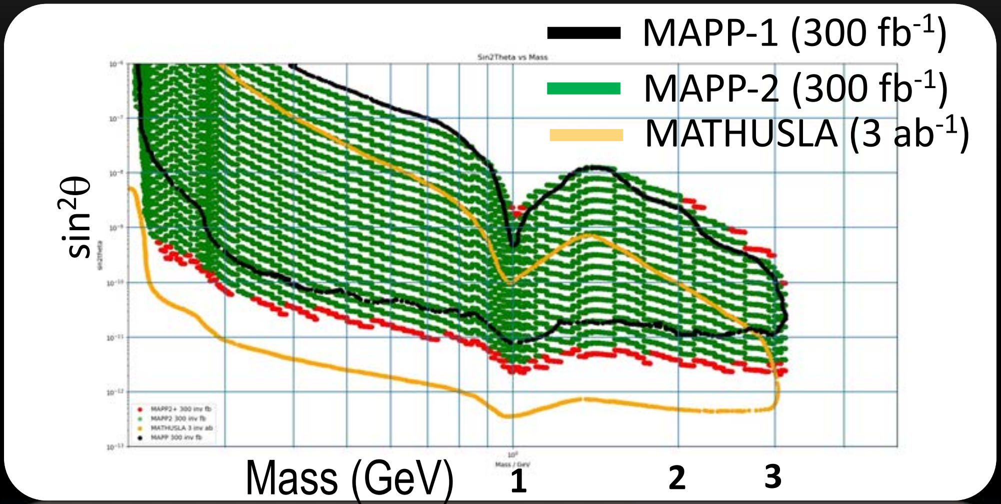
Example of MAPP Sensitivity for LLPs

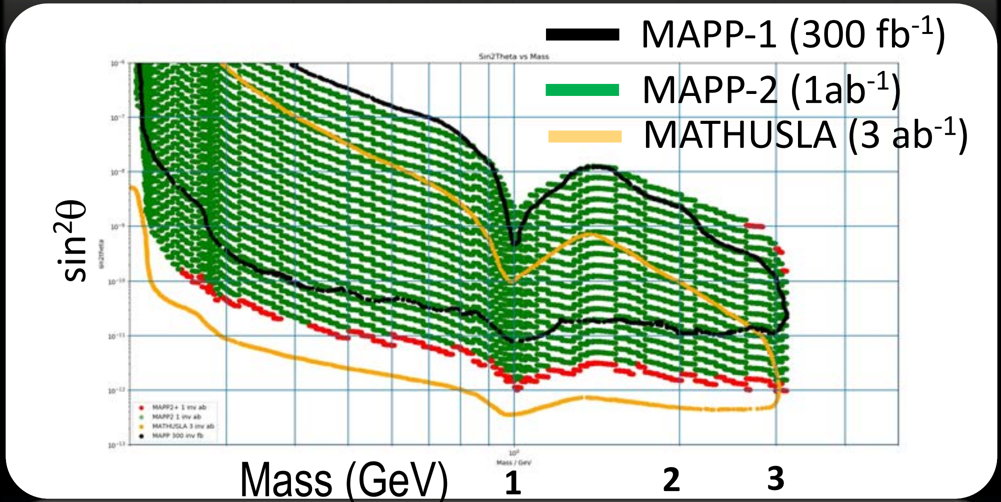


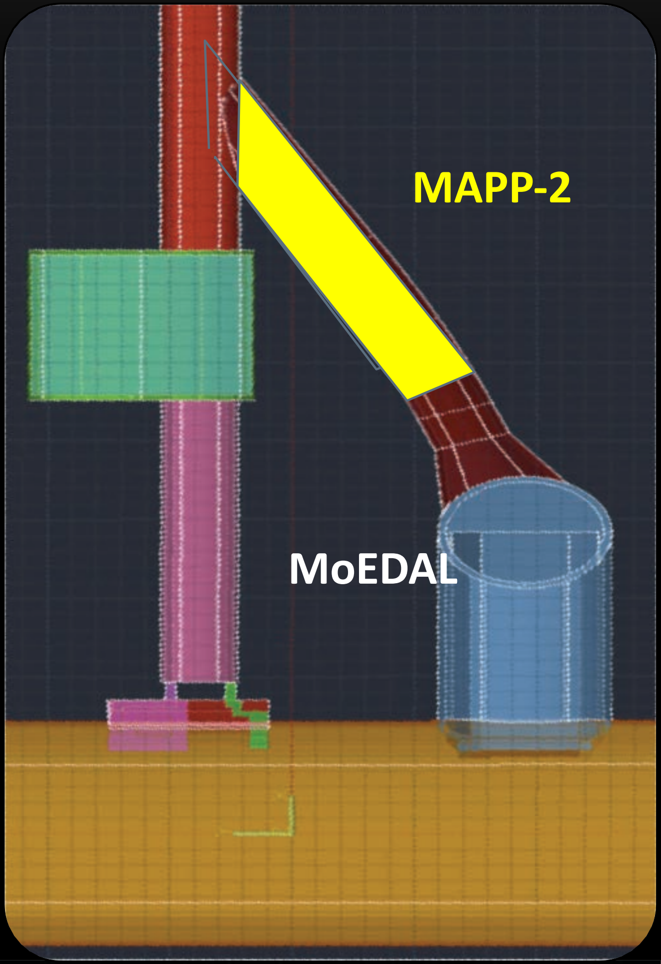
The figures shows MAPP's reach for 30 fb^{-1} and 300 fb^{-1} for the scenario where a Higgs mixing portal admits exotic inclusive $B \rightarrow Xs\phi$ decays, in which φ is a light CP-even scalar that mixes with the Higgs, with mixing angle $\vartheta \ll 1$

- *We envisage the full MAPP detector will operate in RUN-3 (2021-24)*
  - *Our max. fid. eff. for $B \rightarrow X_s\phi$ is ~ 5 x 10^{-4}*
  - *For comparison 100% tracking efficiency is assumed with no background.*

MAPP-2 – for High Luminosity LHC

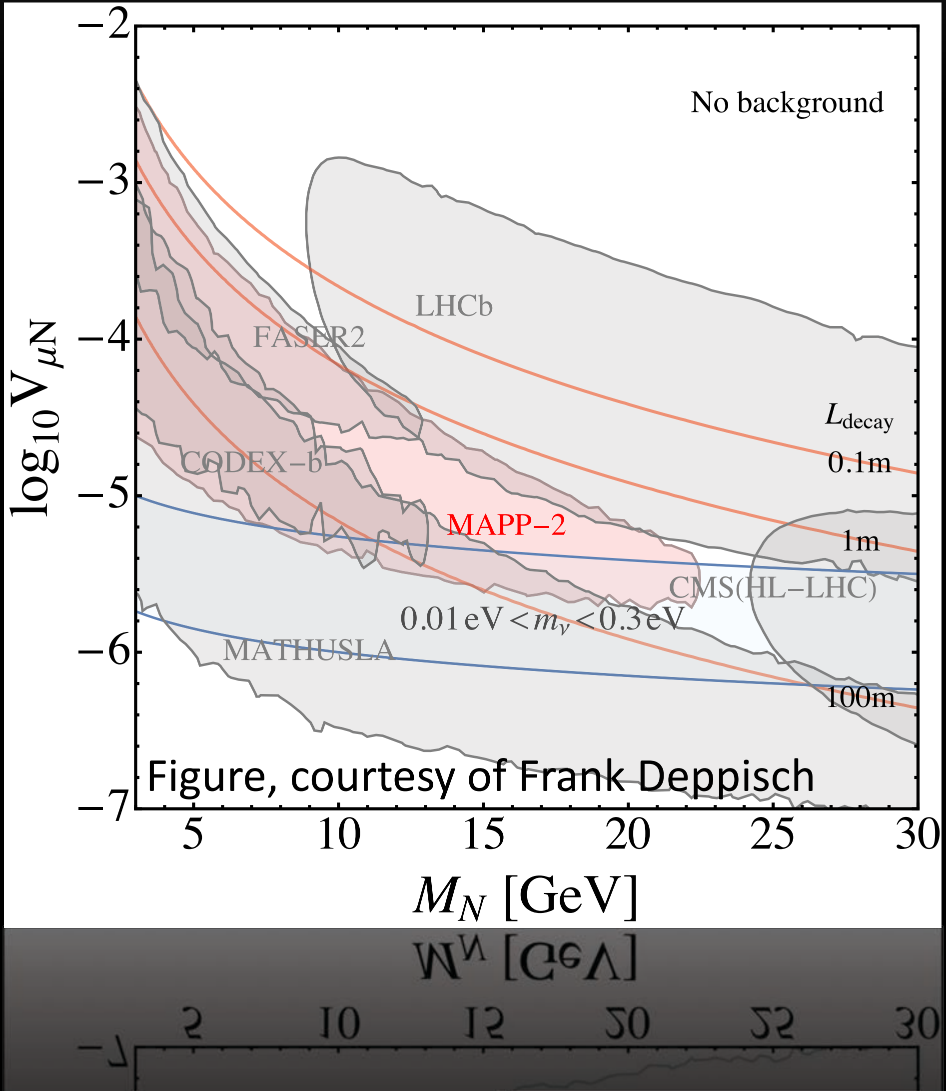




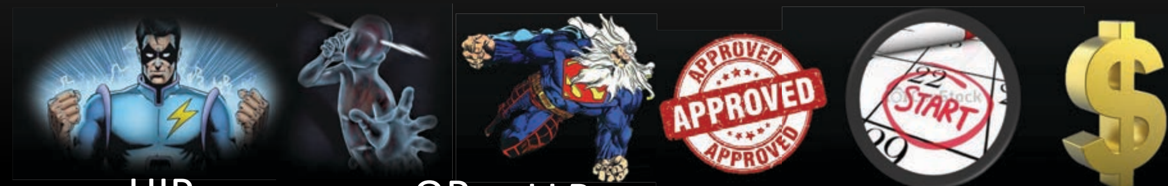


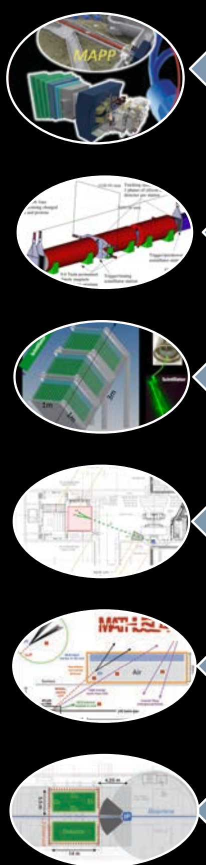
MAPP-2 Sensitivity to Heavy Neutrino Production via Z⁰ at the lifetime frontier

- *Pair production of right-handed neutrinos from the decay of an additional neutral **Z^0** boson in the gauged **B-L** model – Phys. Rev. D100 (2019), 035005.*
- *Luminosity assumed in figure:*
  - *MAPP-2 → 300 fb^{-1}*
  - *CODEX-b → 300 fb^{-1}*
  - *FASER-2 → 3000 fb^{-1}*
  - *MATHUSLA → 3000fb^{-1}*



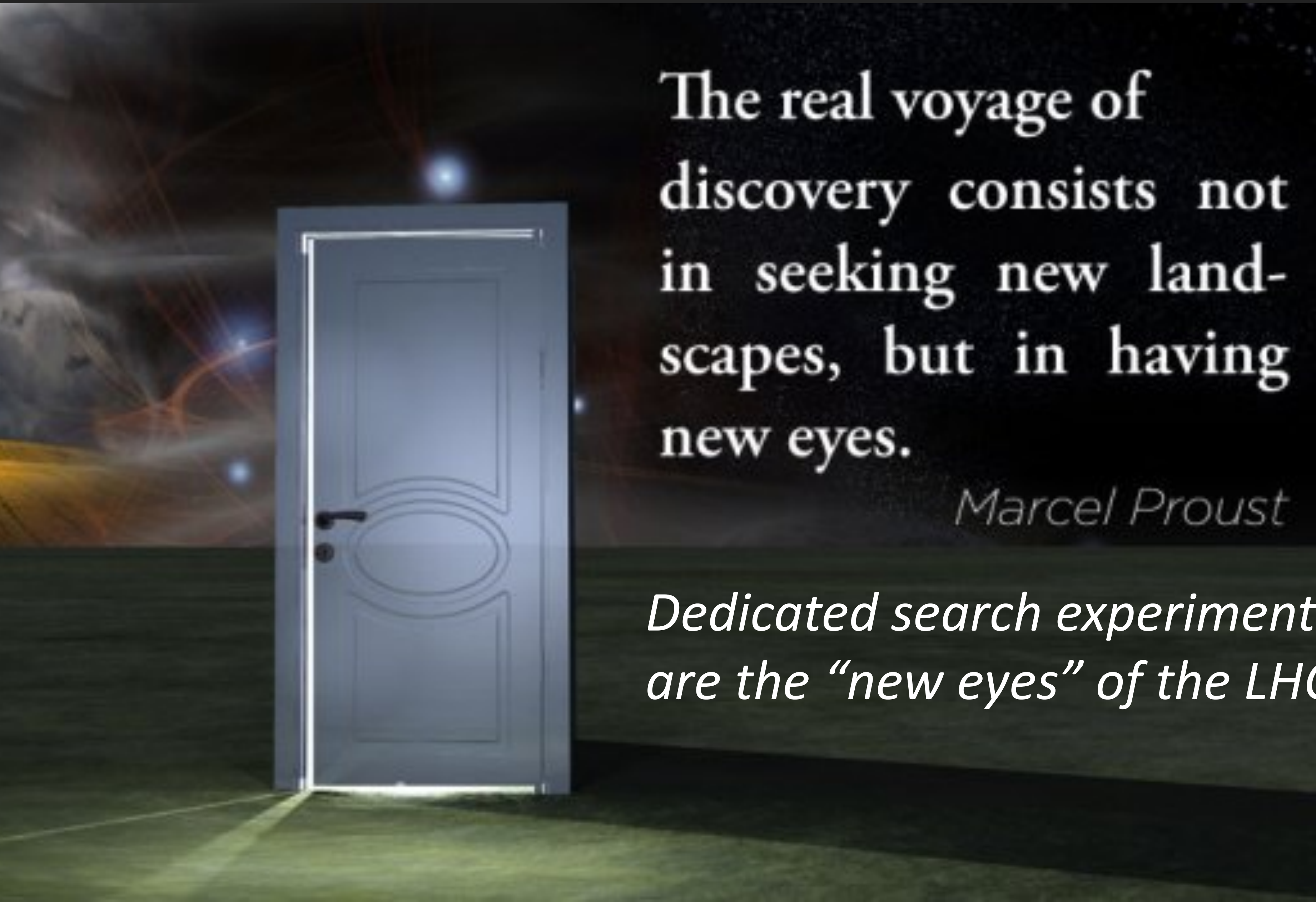
Summary of LHC's Dedicated Search Experiments





Experiment	HIPs	mQPs	LLPs	Approved	Start	$
MoEDAL+MAPP-1	✓	✓	✓	✓	2021	*
FASER-1/2	✗	✗	✓	✓	2021/26	*
MilliQan	✗	✓	✗	UNDER CONSTRUCTION	≳2021?	**
CODEX-B	✗	✗	✓	UNDER CONSTRUCTION	≳2026	*****
MATHUSLA	✗	✗	✓	UNDER CONSTRUCTION	≳2026	>50*
AL3X	✗	✗	✓	UNDER CONSTRUCTION	≳2026	?

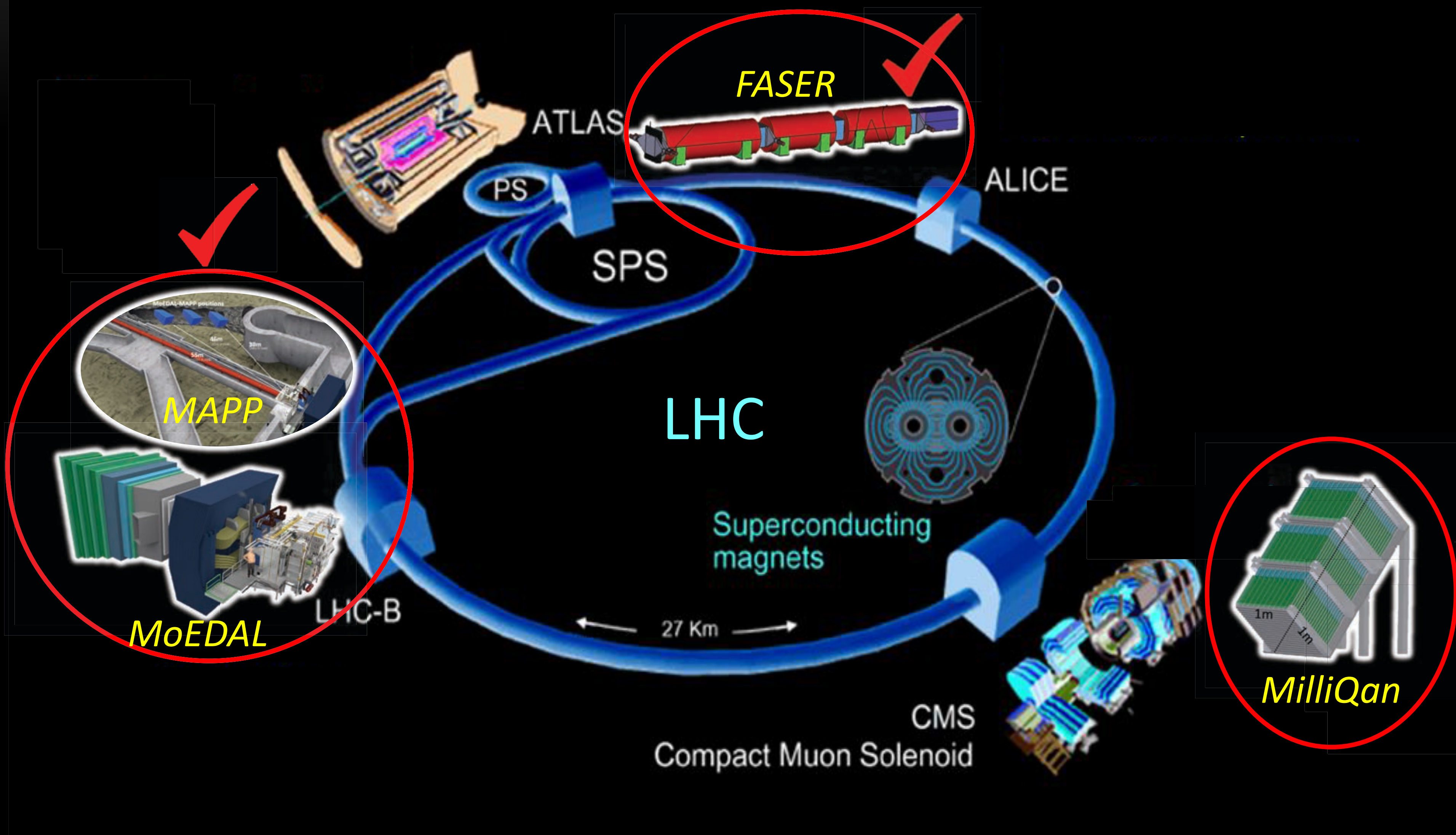
Final Words



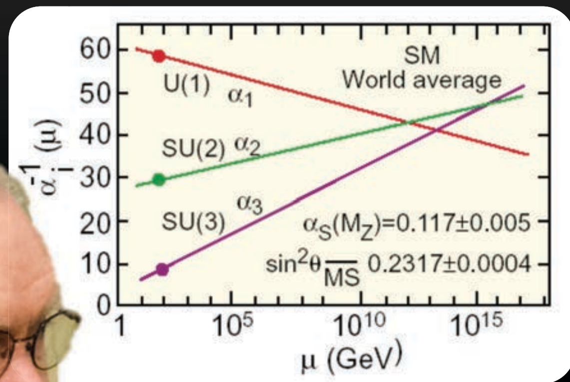
Dedicated search experiments are the “new eyes” of the LHC

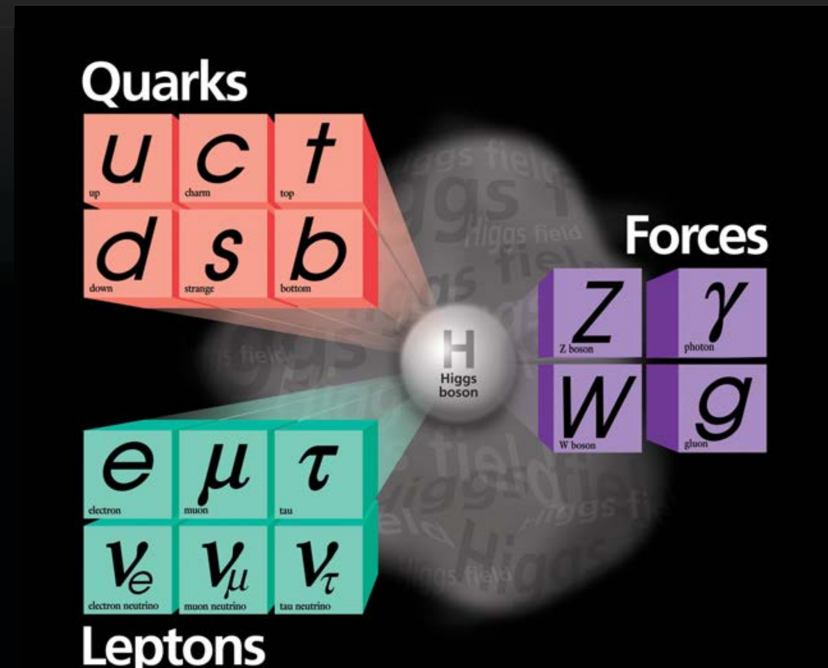
EXTRA SLIDES

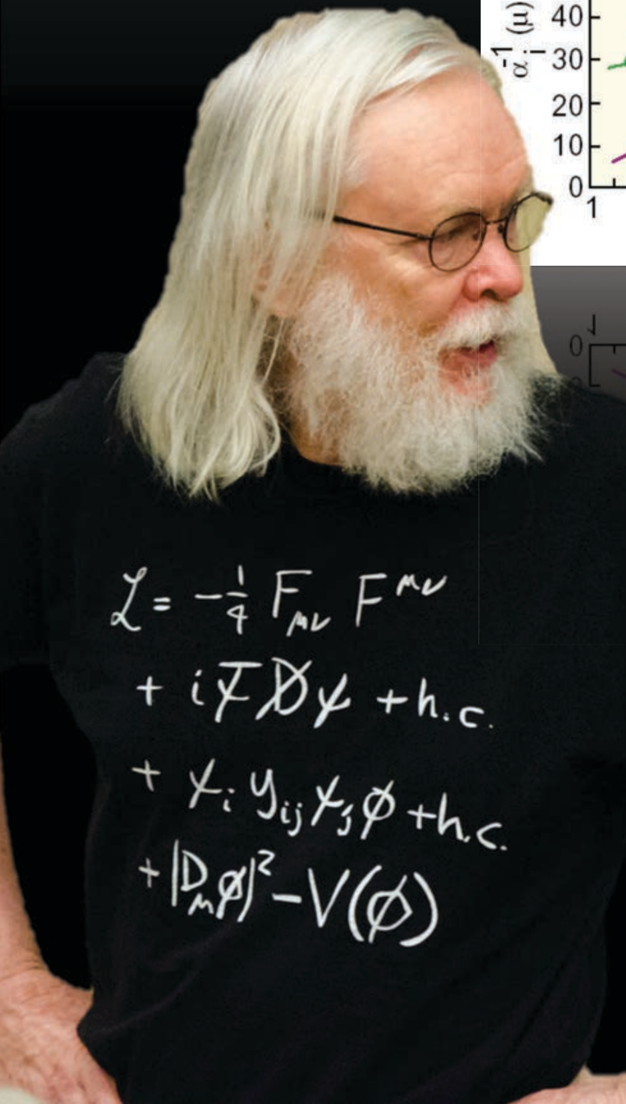
MoEDAL-MAPP, MilliQan and FASER Planned for Run-3 (2021-23)



The Problems of the Standard Model



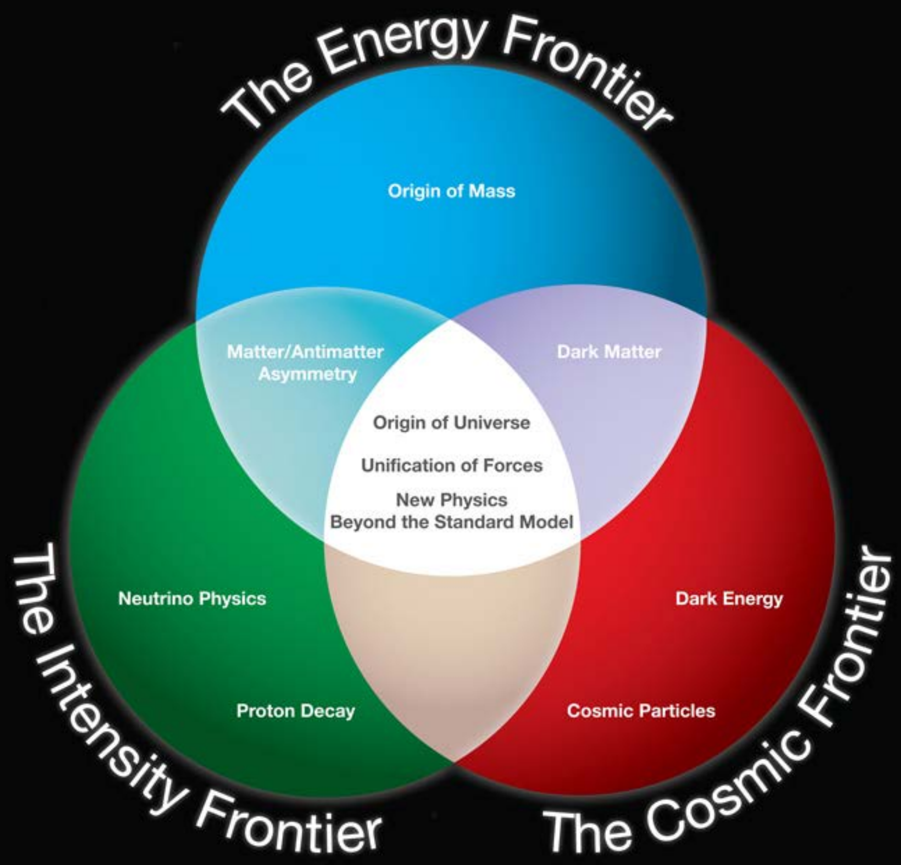




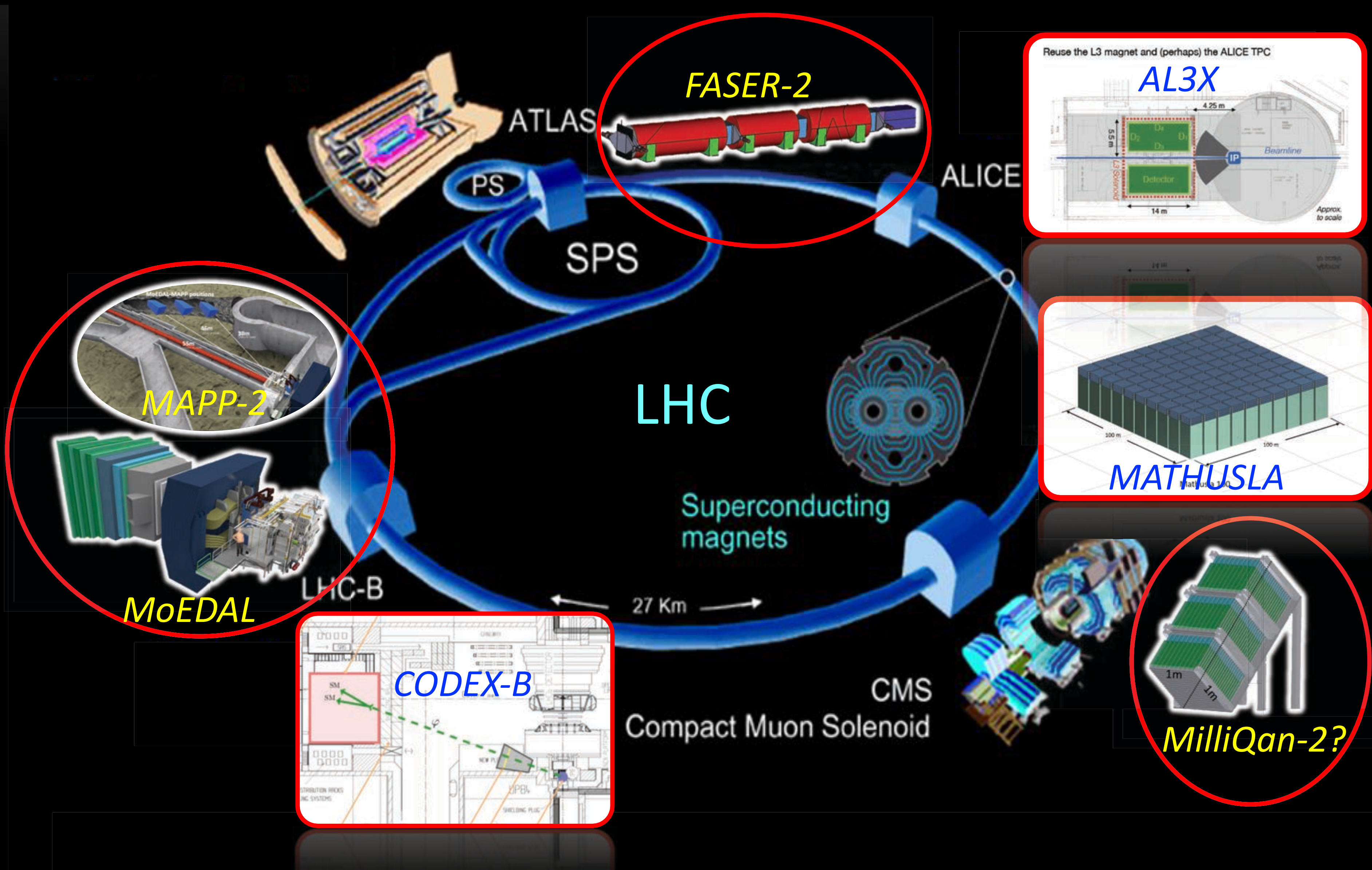
- *The SM has 21 free parameters to fix "by hand", from experiment*
- *No solution to the matter-antimatter asymmetry*
- *There is no candidate for cold dark matter*
- *No way to incorporate gravity*
- *Hierarchy problem - divergent quantum corrections to the Higgs boson mass*
- *Unification of coupling constants is not realized, etc.*

Conclusion

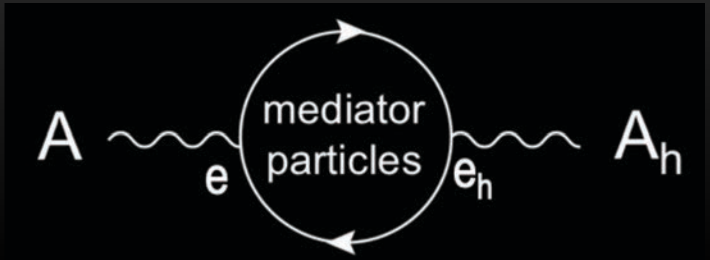
- *AT THE LHC*
  - *It seems that the if a discovery is to be made with conventional collider detectors it will be at the intensity frontier of the High luminosity LHC*
  - *However, there is some small chance of a discovery at the energy frontier with the increase from 13-14 TeV centre-of-mass-energy for RUN-3*
- *Dedicated search experiments bring back the chance of a discovery at the energy frontier at the LHC’s RUN-3 and beyond*



The Situation for High Luminosity LHC >2026



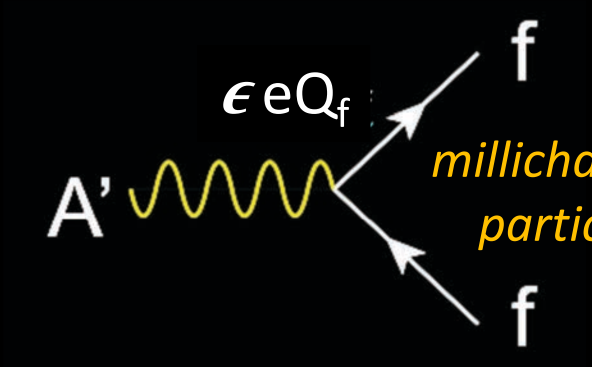
Kinetic Mixing



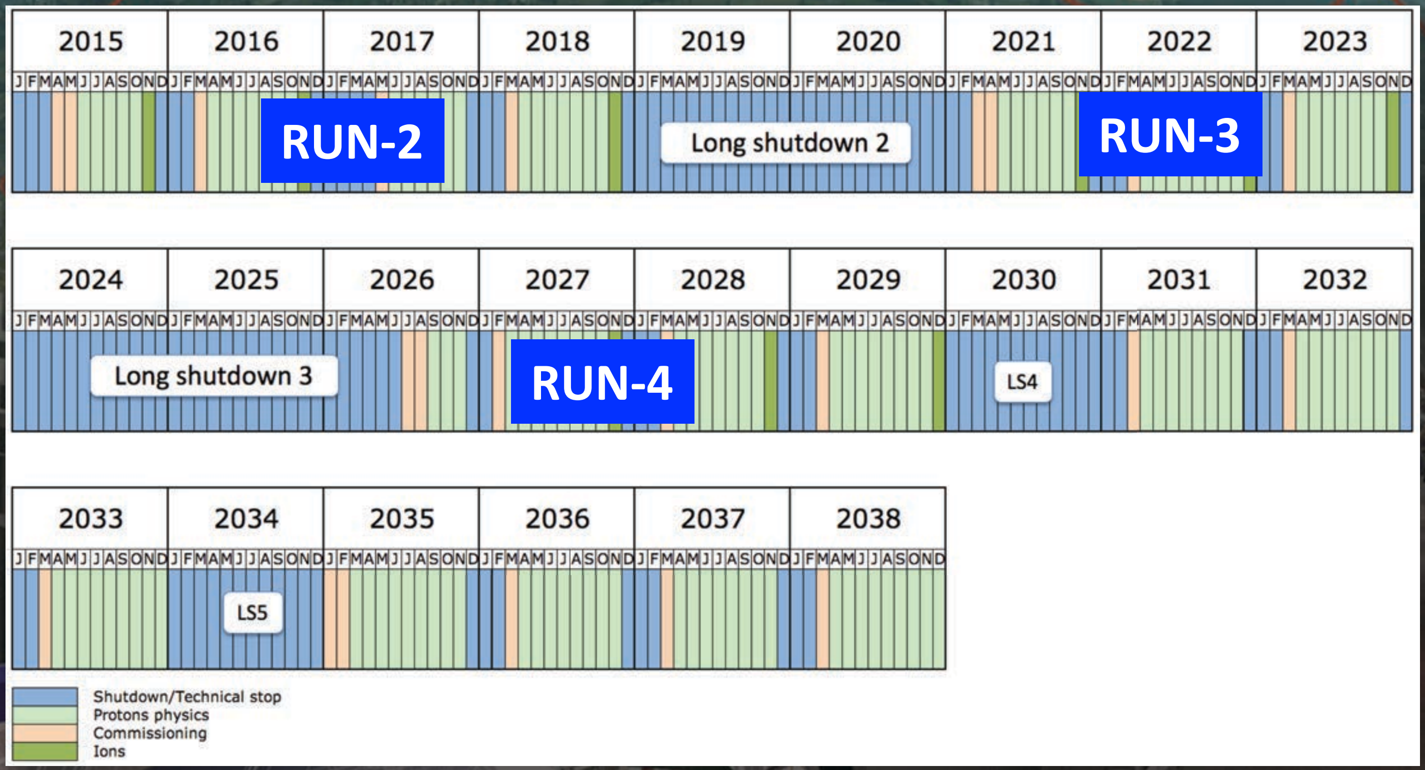
- *Suppose there are mediator particles with both dark sector and visible sector charges. This induces a kinetic mixing term , with $\epsilon \sim 10^{-3}\, e e_h$*

$$\epsilon F_{\mu\nu} F_h^{\mu\nu} \; e\, e_h$$

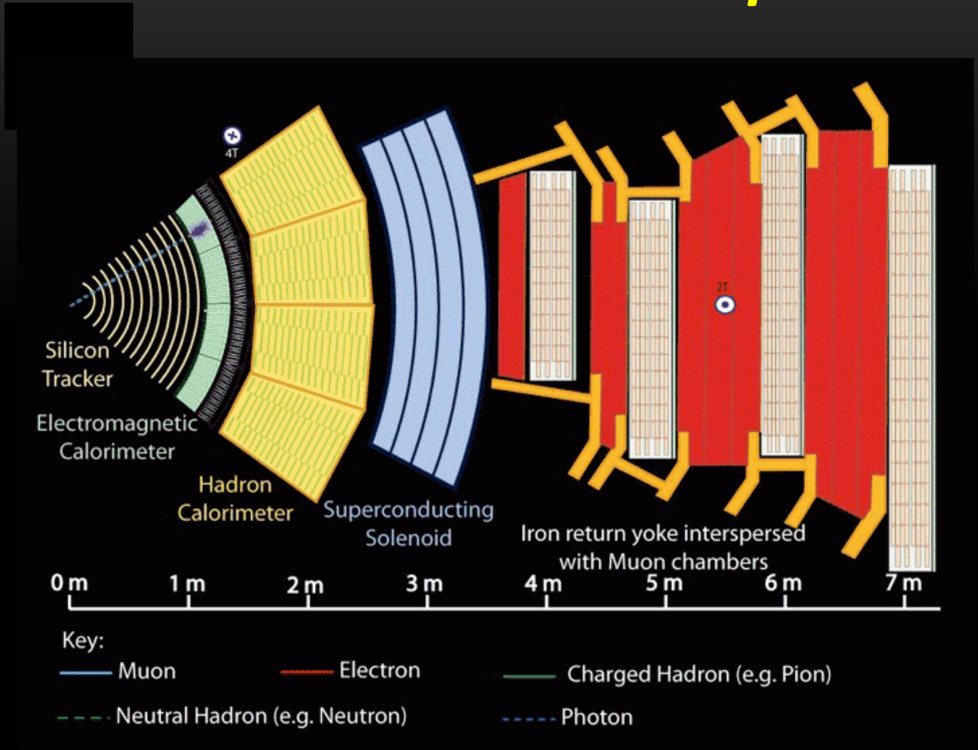
  - *The 10^{-3} arises from it being a 1-loop effect, and e & e_h are the visible and hidden sector charges*
- *The physical state is a massive dark photon A’ with the same couplings as the SM photon, but suppressed by ϵ*

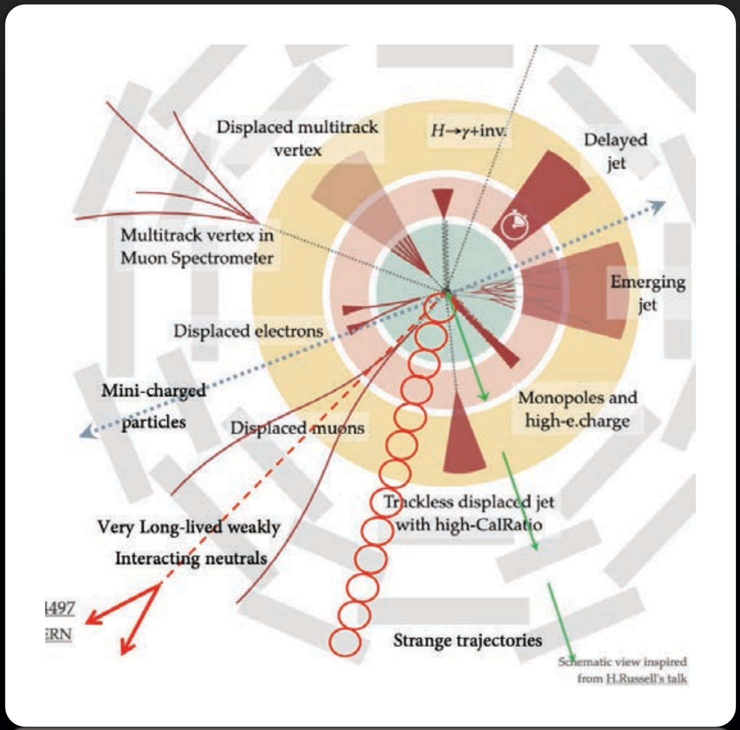


The LHC Schedule



The General Purpose LHC Experiments



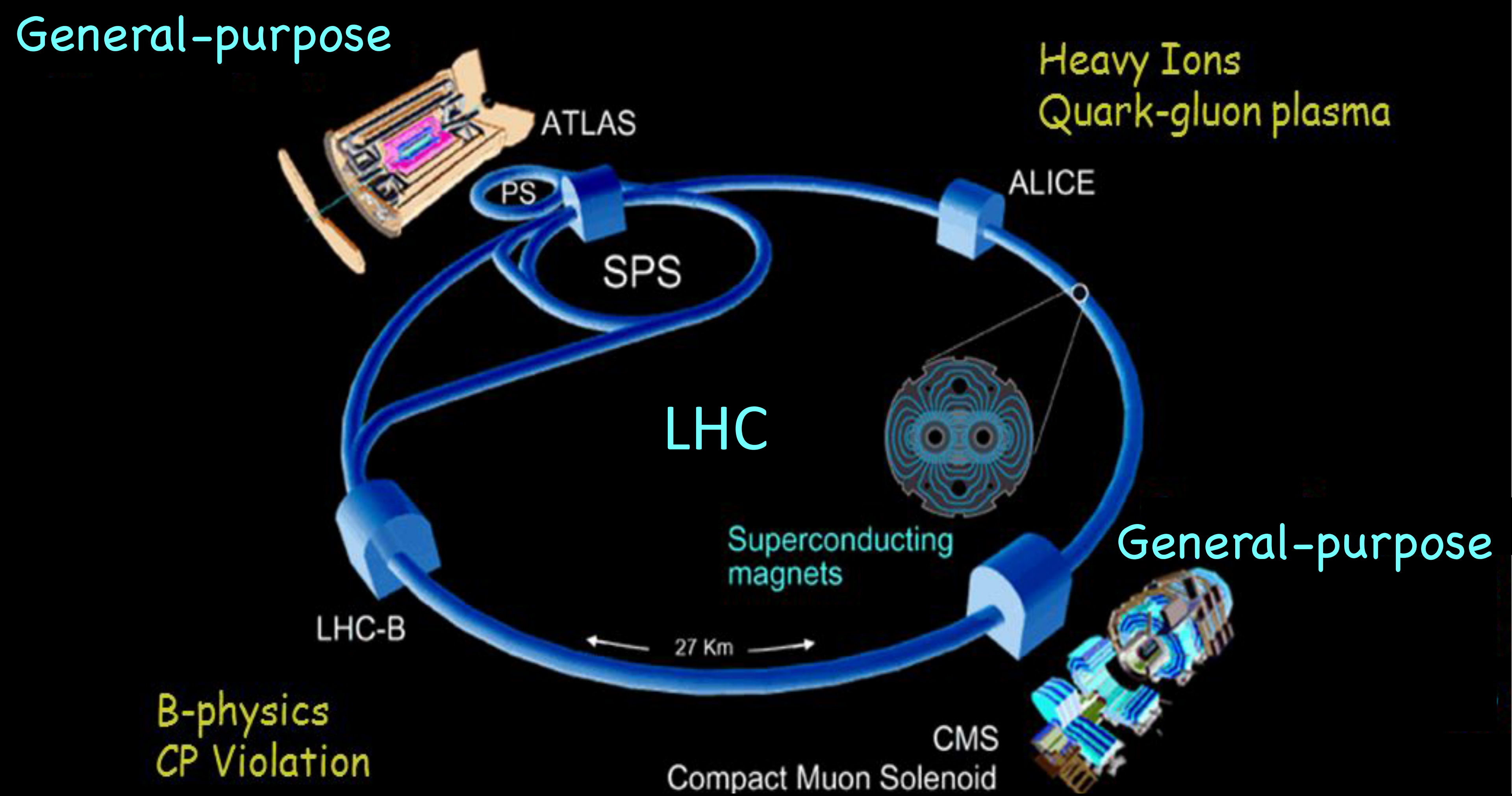


- *ATLAS/CMS detection and triggering assumptions optimized for relativistic Standard Model particles and topologies.*
  - *Triggering problems with detection of slow moving very massive charged particles*
  - *Detection challenging for very long-lived neutral weakly interacting particles*
  - *Detection of very highly ionizing objects problematic, calibration is not possible*
  - *Detection of fractionally charged particles with charge less than e/3 is impossible*
  - *Detection of particles with strange trajectories is very difficult, etc.*

Closing Thoughts

...to myself I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.   Isaac Newton

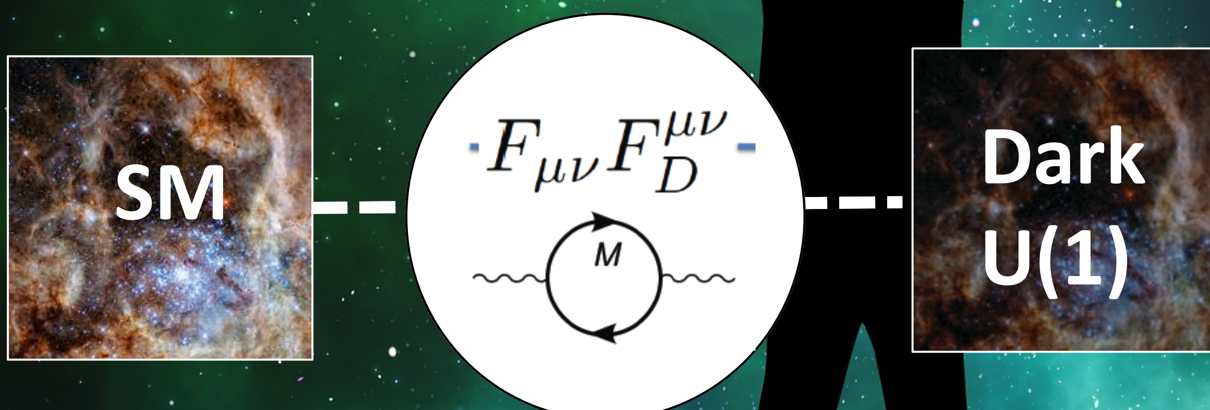
LHC's Search for New Physics – Run1 (2009-13)



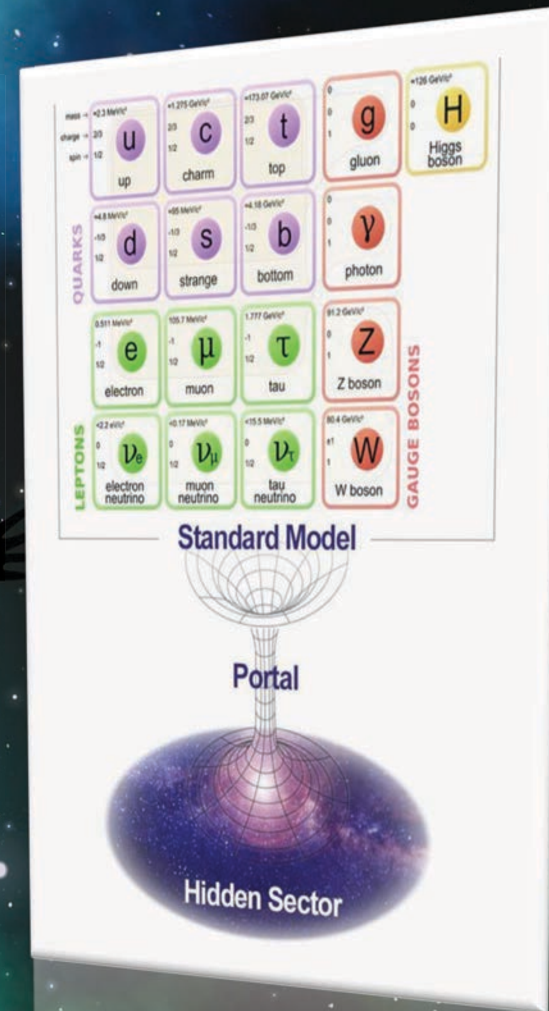
Roughly 1700 LHC physics papers on the search for new physics

Dark Sectors

- *Main evidence so far for dark matter is gravitational. What are the " likely" non-gravitational interactions? Dark Sector theory attempts to answer this question*
- *To detect a dark sector, we must know how it interacts with us.*
  - *Interactions between the two sectors are via mediator particles crossing the portal – in this case the vector portal*



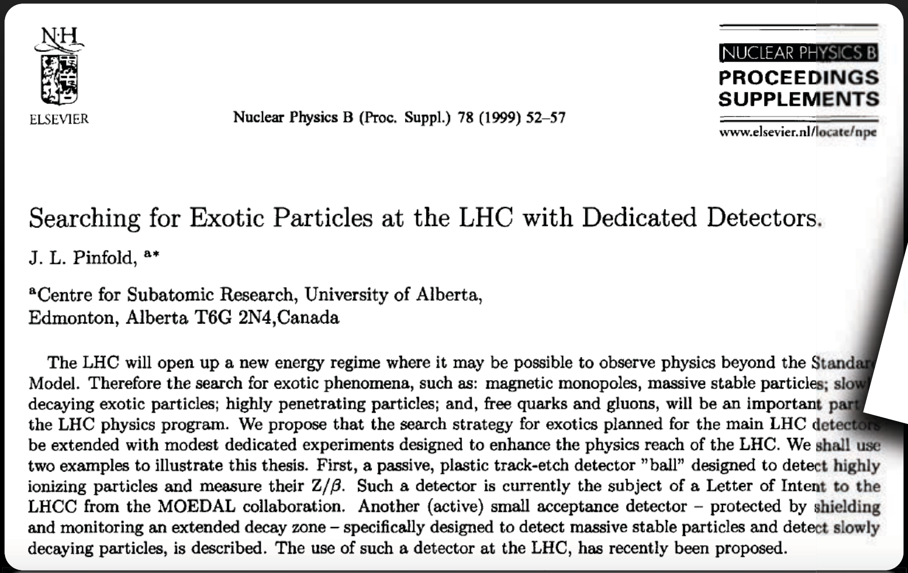
Mediator particles



The dark sector may have a rich structure with matter and forces of its own

We Should Leave No Stone Unturned in the Search for New Physics

Dedicated Search Experiments at Colliders



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Searching for Exotic Particles at the LHC with Dedicated Detectors.

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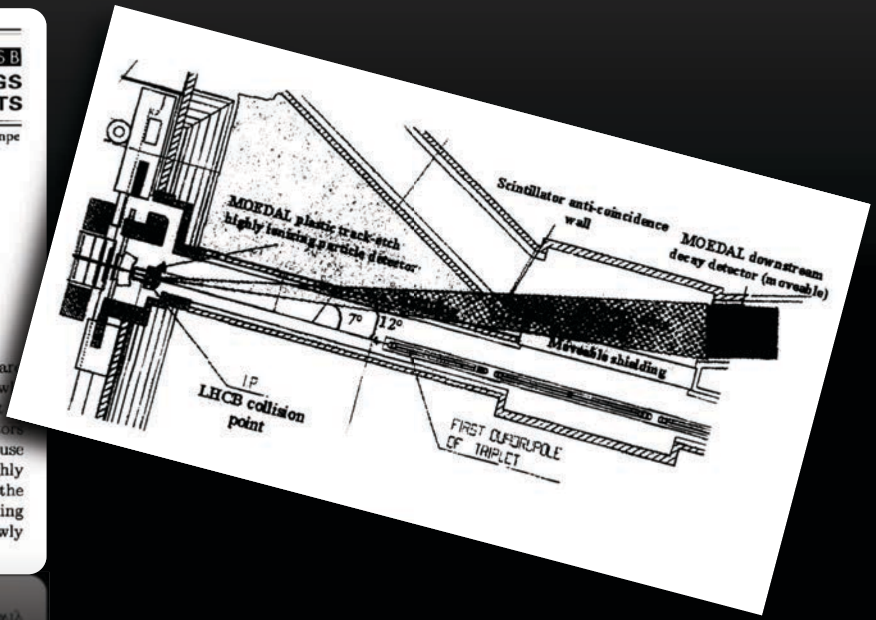
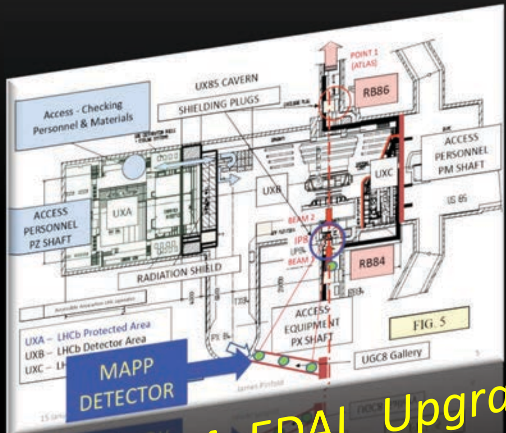
Edmonton, Alberta T6G 2N4,Canada

The LHC will open up a new energy regime where it may be possible to observe physics beyond the Standar Model. Therefore the search for exotic phenomena, such as: magnetic monopoles, massive stable particles; slow decaying exotic particles; highly penetrating particles; and, free quarks and gluons, will be an important part the LHC physics program. We propose that the search strategy for exotics planned for the main LHC detectors be extended with modest dedicated experiments designed to enhance the physics reach of the LHC. We shall use two examples to illustrate this thesis. First, a passive, plastic track-etch detector "ball" designed to detect highly ionizing particles and measure their Z/β. Such a detector is currently the subject of a Letter of Intent to the LHCC from the MOEDAL collaboration. Another (active) small acceptance detector – protected by shielding and monitoring an extended decay zone – specifically designed to detect massive stable particles and detect slowly decaying particles, is described. The use of such a detector at the LHC, has recently been proposed.

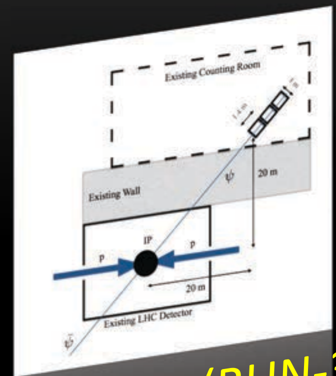


- What are dedicated search experiments at the LHC?
  - They concentrate on some particular clear experimental signature of new physics eg long-lived particles or anomalously ionizing particles
  - Their physics reach is complementary to the main collider detectors – extending the LHC's discovery horizon
  - They are usually stand alone, smaller & needs-be lower cost with small teams
- MoEDAL is the 1st dedicated LHC search experiment - proposing in 1999 the search for highly ionizing & long-lived particles at the LHC

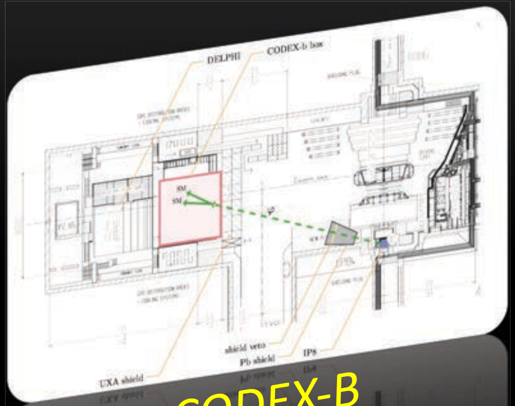
CERN's Dedicated Search Expts



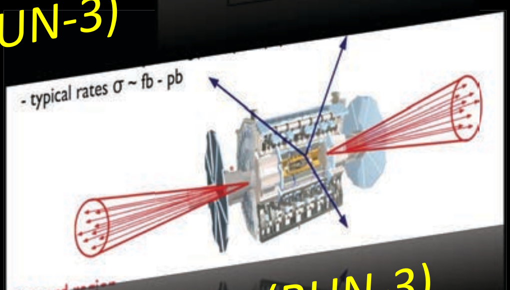
MAPP (MoEDAL Upgrade)
Extending the search for HIPs to the search for mQP & LLNPs(RUN-3)



MilliQan (RUN-3)
Search for mQP

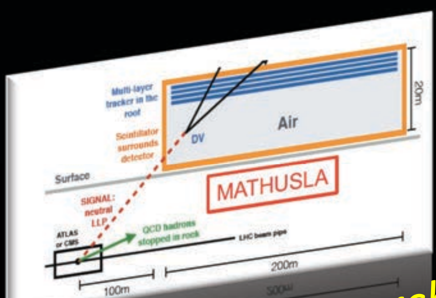


CODEX-B
Search for LLNPs



FASER (RUN-3)
Search for very LLNPs

AL3X Search for LLPs



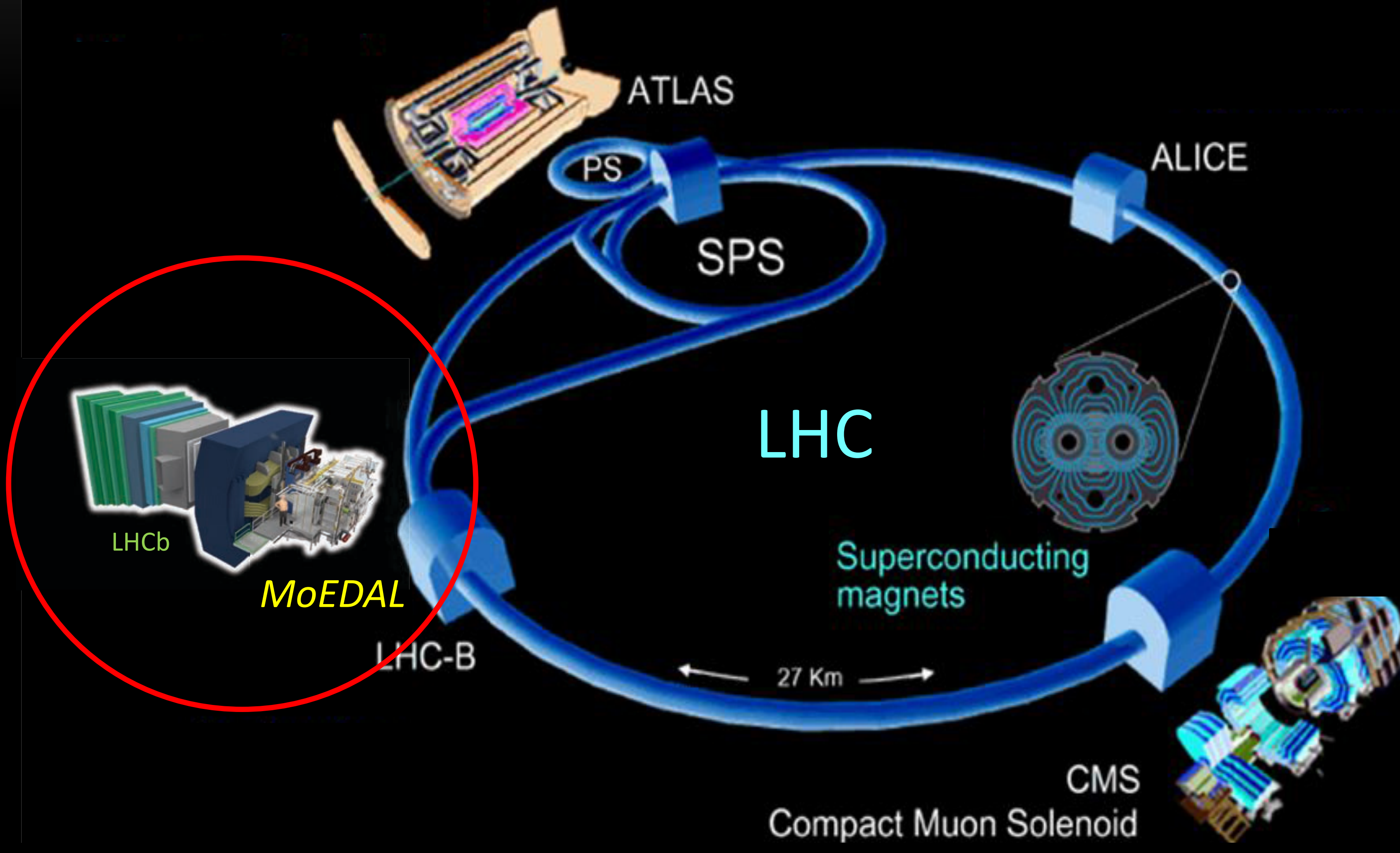
MATHUSLA Search for very LLNPs

SHIP (Intensity frontier) Search f0r new neutral particles

Concluding Remarks

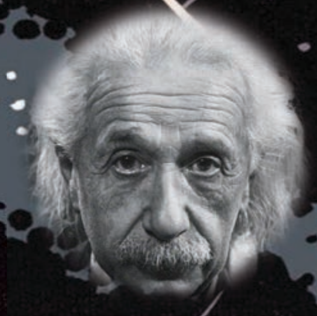
- *The next breakthrough in particle physics is likely to involve New Long-Lived Particles (LLPs) and Anomalously Ionizing Particles (AIPs):*
  - *LLPs & AIPs are ubiquitous in BSM theories, especially those with cosmological significance*
  - *LLPs and AIPs can be detected through a variety of signatures*
  - *Many of these signals are truly spectacular – a few events can be a discovery*
  - *For existing experiments, we have not yet reached the full LLP & AIP discovery potential*
  - *LLPs and AIPs present many opportunities for new and clever experiments – some of which we have seen in this talk.*

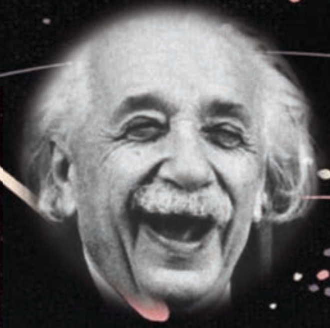
MoEDAL the LHC's 1st Dedicated Search Expt is Deployed for Run2 (2015-18)



Roughly 1300 LHC physics papers on the search for new physics

What are the Possibilities?





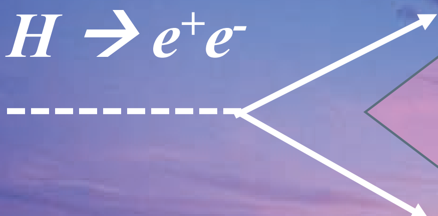
- *The Standard Model is it - there is no New Physics*
- *The Physics exists but a mass scale we can't ever reach*
- *The physics exist at our mass scale but it has extremely small cross-section*
- *The Physics exists but we can only see something at a future (100 TeV?) collider*

- ***New physics is right under our noses – but we can't see it with our existing "standard" detectors***

What Gives Stability or Long Life?

- **Besides: conservation of charge; conservation of some new quantum number (R-parity, KK-number; or partial conservation (RPV SUSY), we have →**

$H \rightarrow e^+e^-$



Coupling

Typically $n \geq 4$

Set by symmetry structure

$$\Gamma = g^2 \left(\frac{m}{M}\right)^n m$$

Phase space

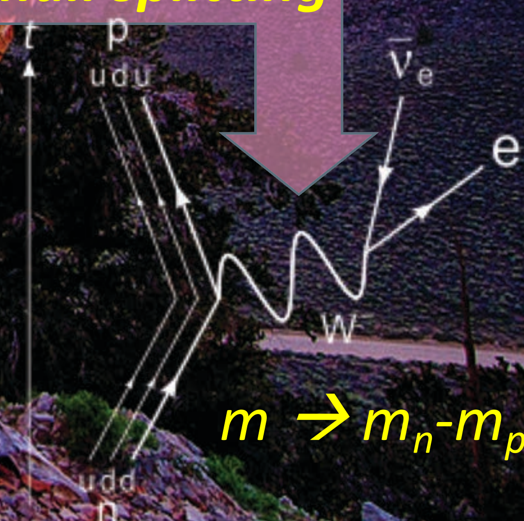
Small splitting

$m \ll M$

$\pi^+ \rightarrow \mu^+ \nu_\mu$

Hierarchy of scales

Off-shell decay



$m \rightarrow m_n - m_p$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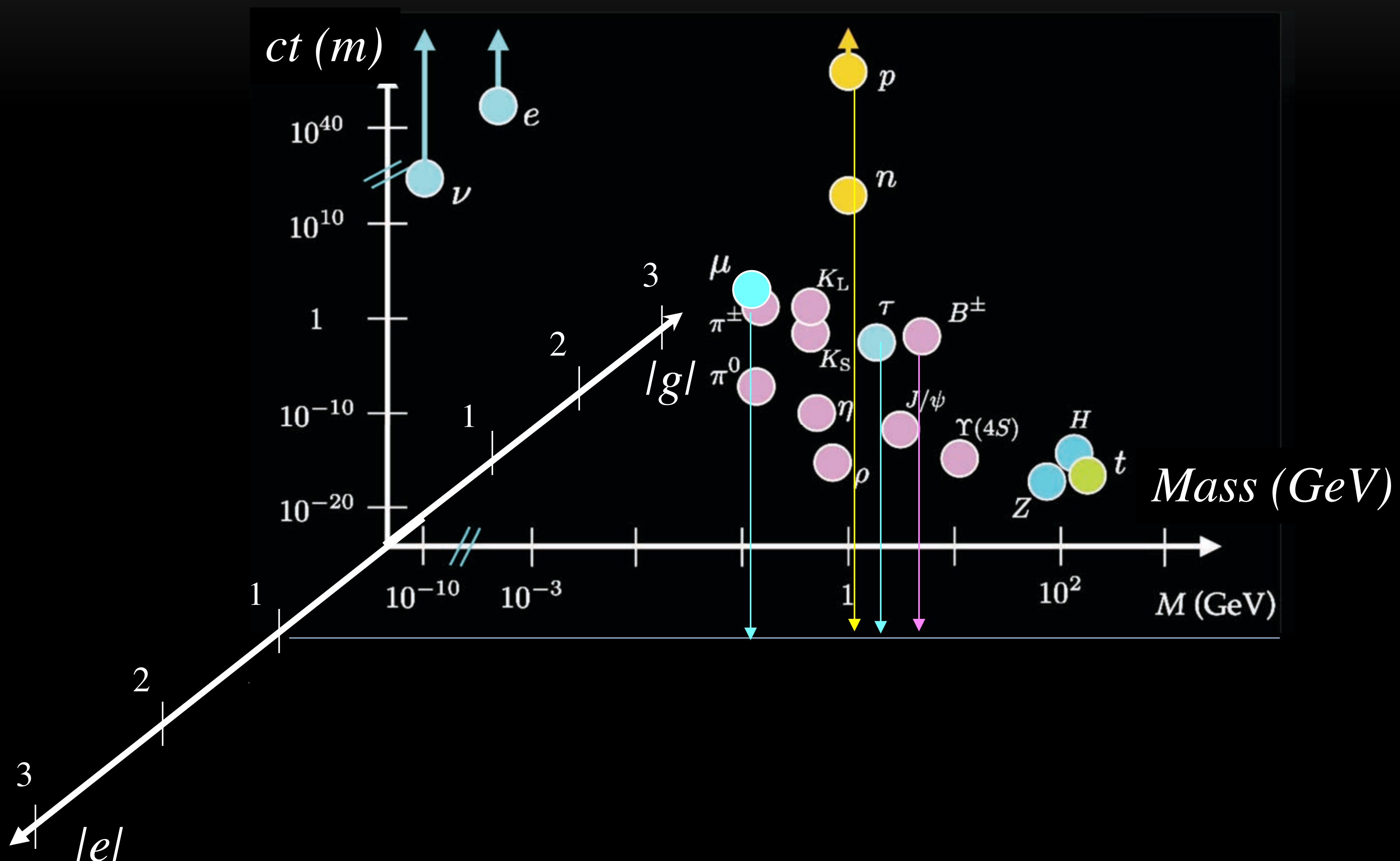
THE
MAGNIFICENT
SEVENTH
They fought on the high energy frontier
MoEDAL was fully installed in 2014/15 and started to take data in p-p and p-A running at ~13 TeV in 2015
ATLAS
STEVE MCQUEEN
JAMES COBURN
"BRITT"
CMS
LHCb
HORST BUCHHOLZ
"CHICO"
YUL BRYNNER
"CHRIS ADAMS"
ALICE
TOTEM
BRAD DEXTER
"HARRY LUCK"
ROBERT VAUGHN
"LEE"
LHCf
MoEDAL
CHARLES BRONSON
"BERNARDO O'REILLY"

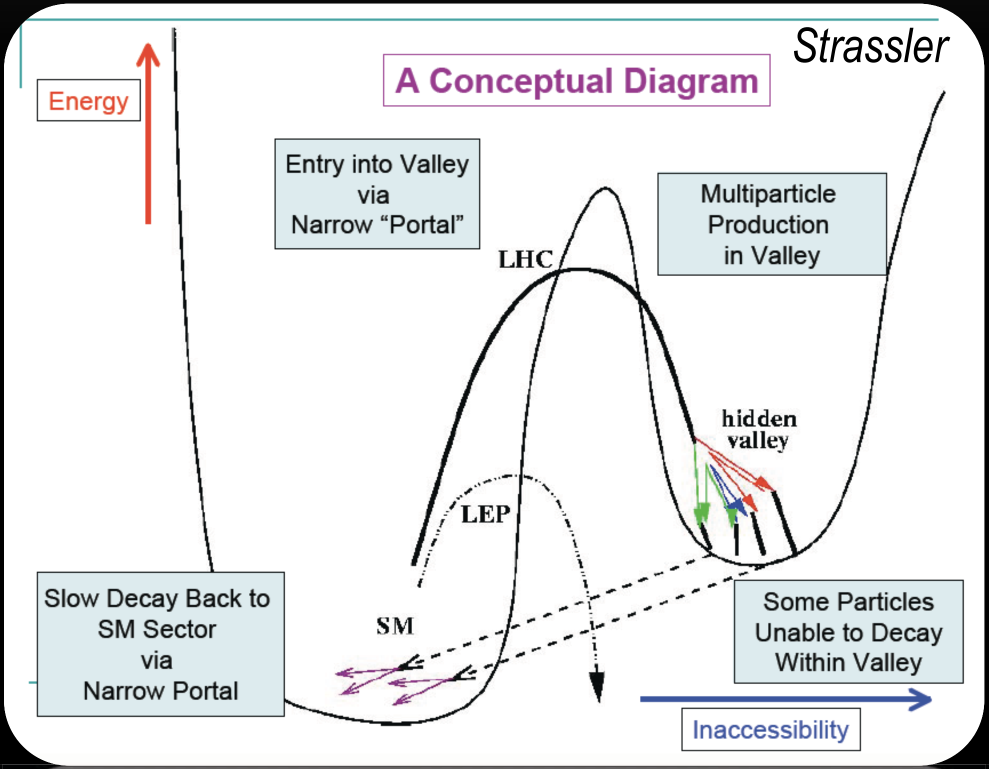
Clear Experimental Signals for New Physics:

Large Mass , Long lifetime & Anomalous Charge



Hidden Valley Scenarios

In hidden-valley models, the hidden sector confines in a way analogous to QCD, i.e. there are some quarks lighter than the confinement scale.



Heavy connectors are represented by the peak(s)

the light hidden sector is represented as a valley

The connector sectors could be many things eg new heavy states

- *In the presence of a Hidden Valley (HV) partner particles might decay to HV particles & some HV particles might decay to SM particles*