The MilliQan Experiment and More Searches for Milli-charges

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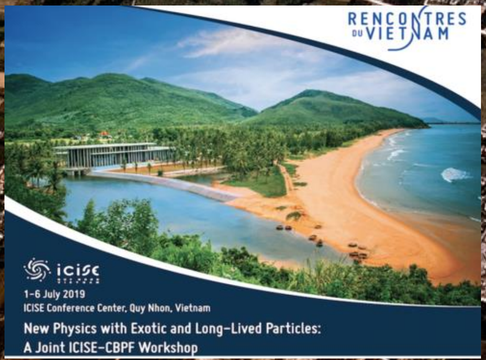
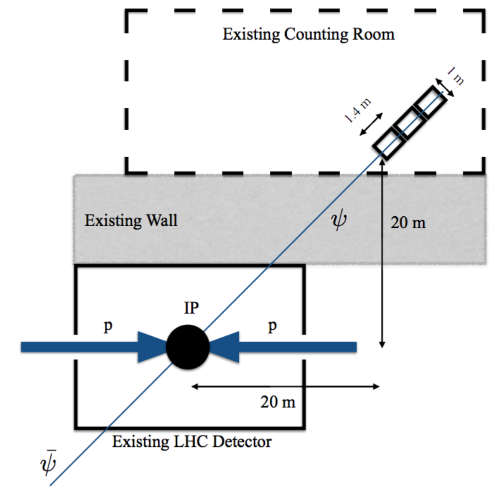
NTU, Singapore

3rd Julky 2019



Particles with Milli-Charges?

Idea -> Hunting for particles with charges ~ 0.3-0.001e
Baseline paper: arXiv:1410.6816
Proposal for a new experiment/CMS subdetector.
Demonstrator (1%) taking data since mid-2017

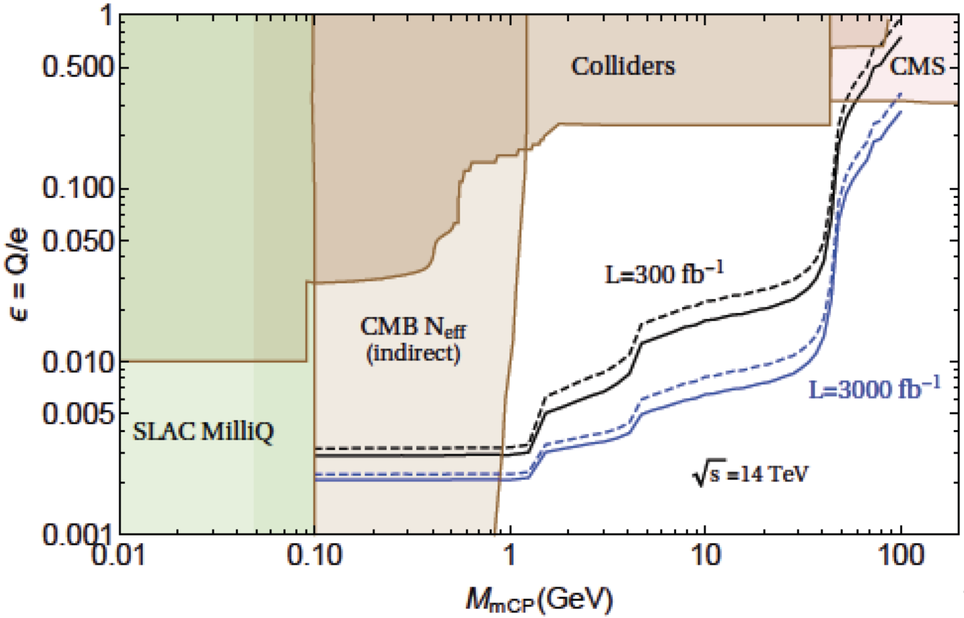


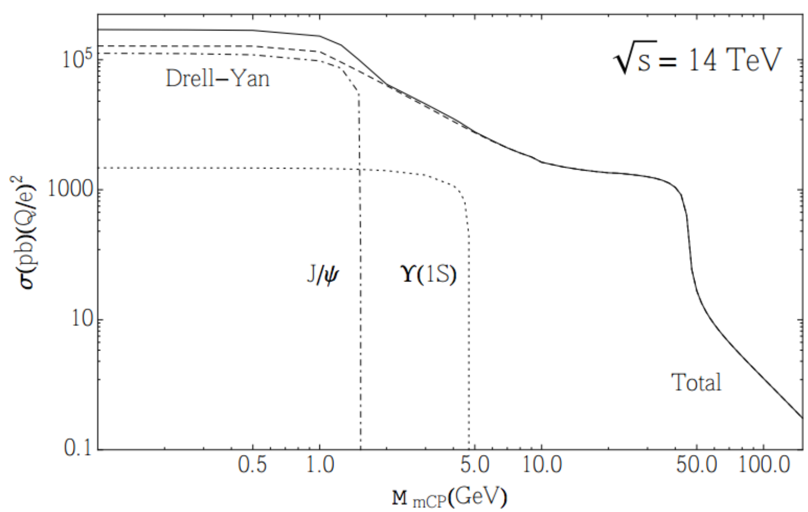
MilliQan Experiment

A Letter of Intent to Install a Milli-charged Particle Detector at LHC P5

arXiv:1607.04669

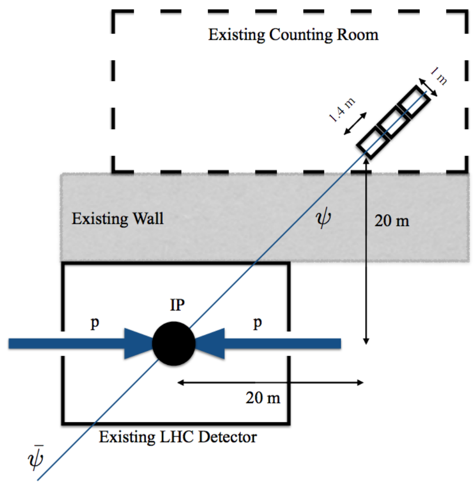
Austin Ball,[1] Jim Brooke,[2] Claudio Campagnari,[3] Albert De Roeck,[1] Brian Francis,[4] Martin Gastal,[1] Frank Golf,[3] Joel Goldstein,[2] Andy Haas,[5] Christopher S. Hill,[4] Eder Izaguirre,[6] Benjamin Kaplan,[5] Gabriel Magill,[7,6] Bennett Marsh,[3] David Miller,[8] Theo Prins,[1] Harry Shakeshaft,[1] David Stuart,[3] Max Swiatlowski,[8] and Itay Yavin[7,6]



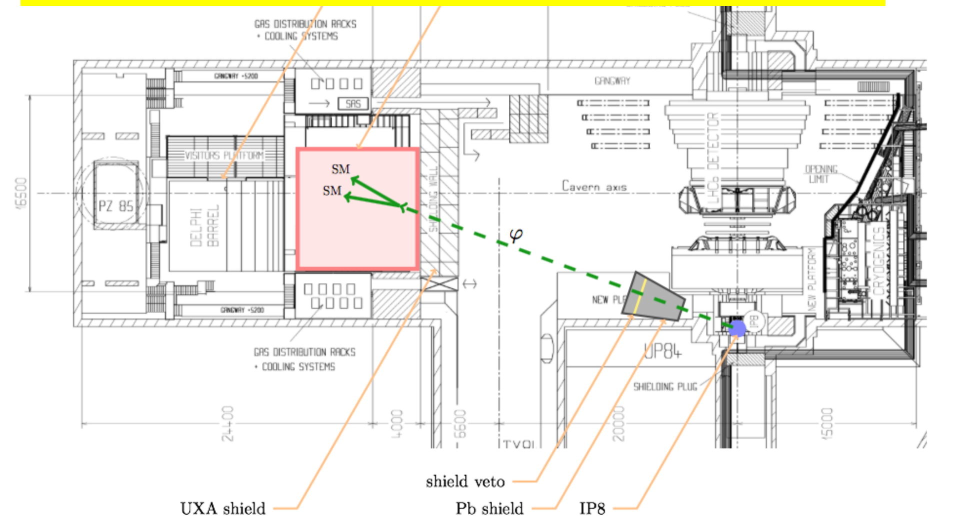


Proposals for New Experiments @LHC

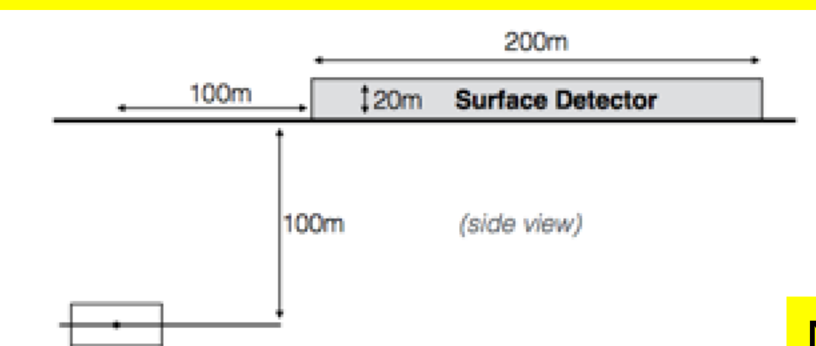
MilliQan: searches for millicharged particles
MAPP: Same from MoEDAL



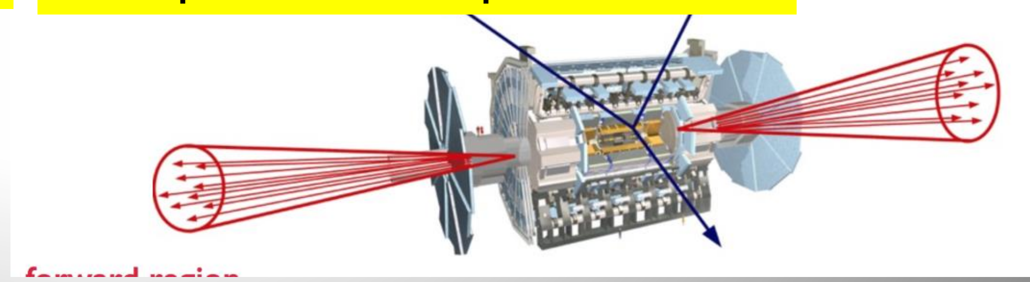
CODEX-b: searches for long lived weakly interacting neutral particles



MATHUSLA: searches for long lived weakly interacting neutral particles



FASER: searches for long lived dark photons-like particles



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

Milli-Charges

Fractionally charged particles

Posit the existence of a new hidden $U(1)$ with **massless** field A'_μ:

$$\begin{aligned}\mathcal{L} &= \mathcal{L}_{\rm SM} + \mathcal{L}_{\rm dark-sector} \\ \mathcal{L}_{\rm dark-sector} &= -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} - \frac{\kappa}{2}A'_{\mu\nu}B^{\mu\nu} + \frac{1}{2}m^2_{A'}(A'_\mu)^2 \\ &\quad + i\bar{\psi}\left(\partial\!\!\!/ + ie'A\!\!\!/' + iM_{\rm mCP}\right)\psi\end{aligned}$$

- ψ is a Dirac particle of mass $M_{\rm mCP}$, charged under a new $U(1)$ with charge e', and field-strength $A'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$
- ψ is charged under hypercharge with charge $\kappa e'$, **a milli-charge**
- ψ couples to γ and Z^0 with $\kappa e' \cos\theta_W$ & $-\kappa e' \sin\theta_W$, respectively.
- Fractional charge is therefore $\epsilon \equiv \kappa e' \cos\theta_W / e$, where $\epsilon << 1$

→milli-charged particles (mCP) are a natural consequence of extra $U(1)$

Basic Idea for the MilliQan Experiment

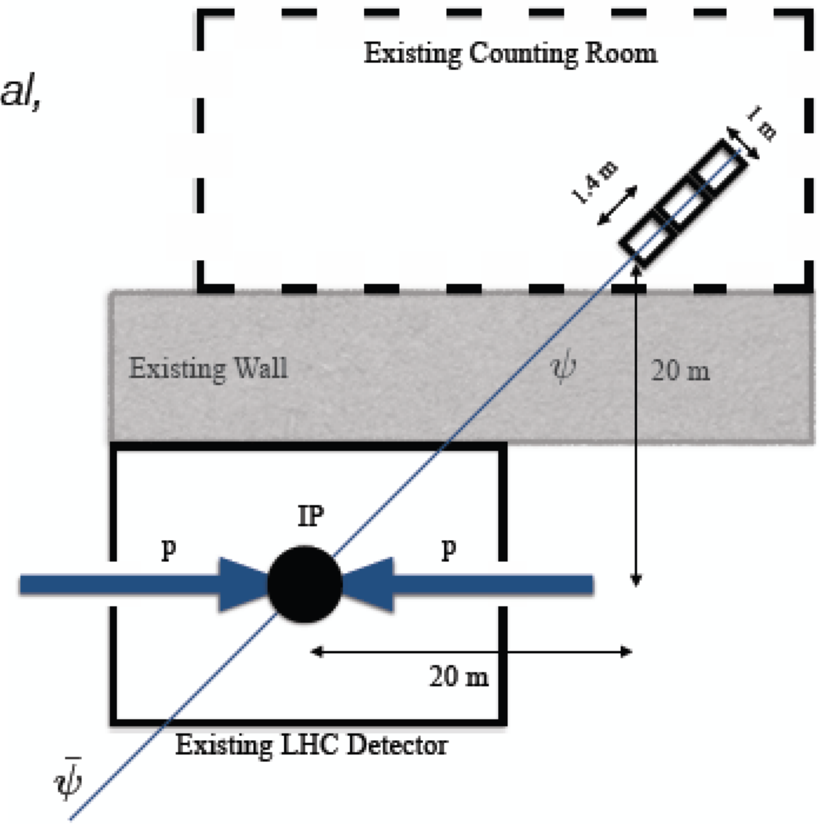
- Proposal to add detector that would be sensitive to milli-charged particles produced in LHC collisions
  - *With Q down to ~10^{-3}e, dE/dx is 10^{-6} MIP -> need long, sensitive, active length to see signal, $\mathcal{O}(1)$ PE.*
- Install ~1 m x 1 m x 3 m scintillator array, pointing back to IP, in well shielded area of Point 5
- With triple coincidence, random background is controlled

Looking for milli-charged particles with a new experiment at the LHC

Andrew Haas,[1] Christopher S. Hill,[2] Eder Izaguirre,[3] and Itay Yavin[3,4]
[1]Department of Physics, New York University, New York, NY, USA
[2]Department of Physics, The Ohio State University, Columbus, OH, USA
[3]Perimeter Institute for Theoretical Physics, Waterloo, Ontario, Canada
[4]Department of Physics, McMaster University, Hamilton, ON, Canada

We propose a new experiment at the Large Hadron Collider (LHC) that offers a powerful and model-independent probe for milli-charged particles. This experiment could be sensitive to charges in the range $10^{-3}e - 10^{-1}e$ for masses in the range $0.1 - 100$ GeV, which is the least constrained part of the parameter space for milli-charged particles. This is a new window of opportunity for exploring physics beyond the Standard Model at the LHC.

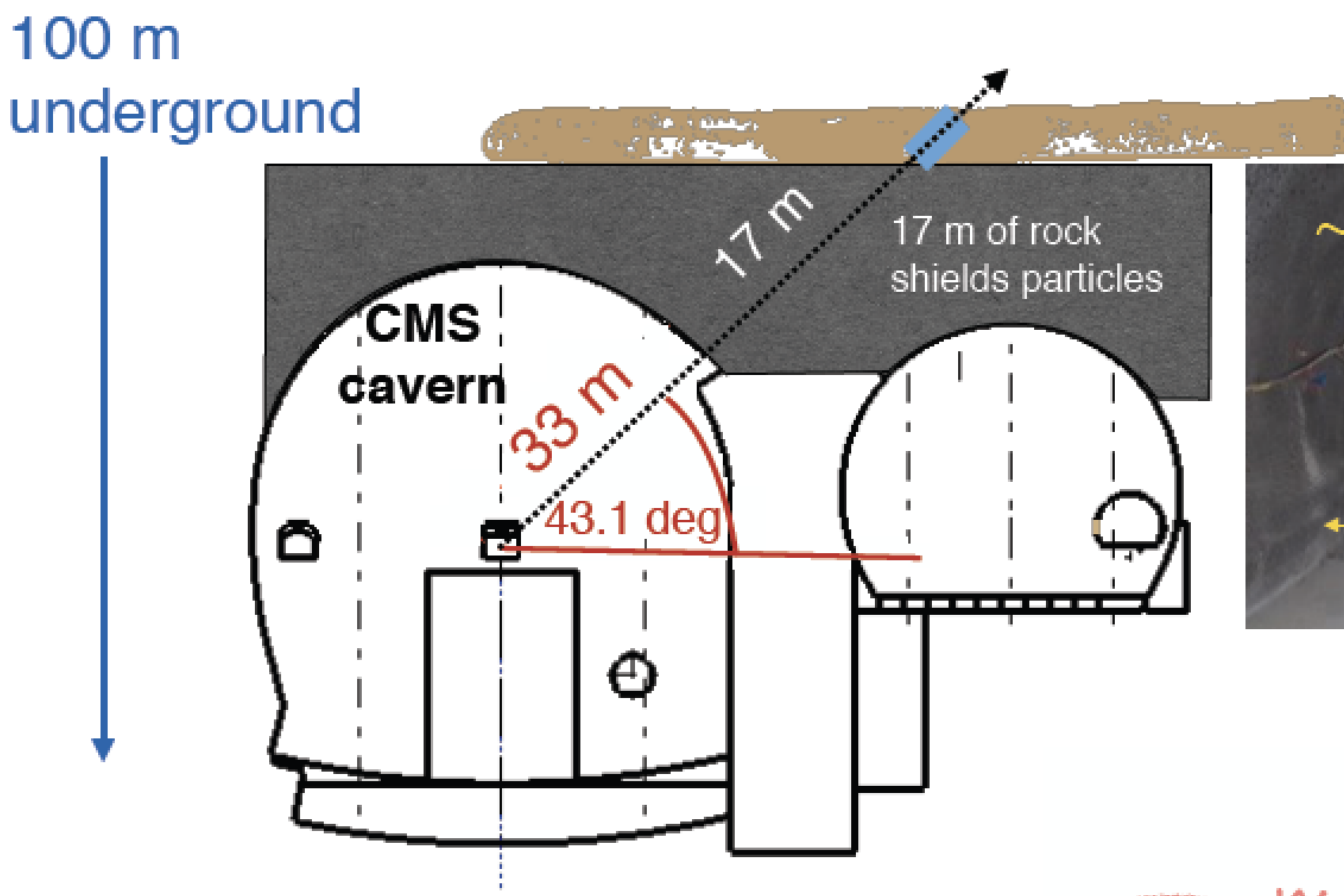
arXiv:1410.6816v1 [hep-ph] 24 Oct 2014

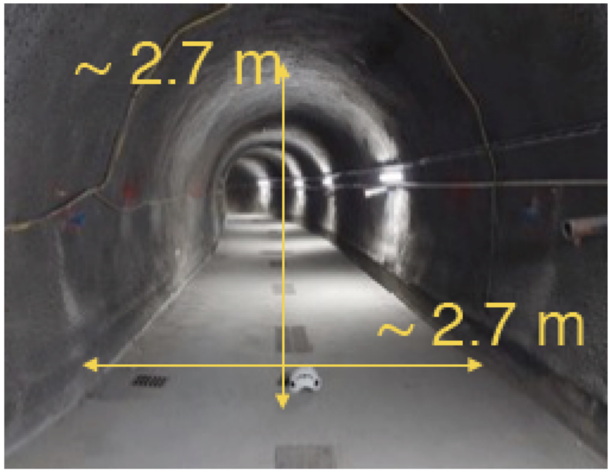


Where to put such a Detector

- **Constraints:**
  - *Behind at least 5 m of concrete/rock from the IP*
  - *Space to accommodate the detector (~1m x 1m x 3m)*
  - *Floor loading compatible with detector+support structure (up to 6000 kg)*
  - *Power available, with possibility to add other services*
  - *Selected experimental area should remain clear of "visitors" during data taking*
- **ATLAS did not have an adequate space**
- MoEDAL experiment (based on our paper) is planning on placing a similar detector at LHC Point 8 (opposite LHCb), **but this location receives only a small fraction of the luminosity delivered by the LHC** But more favorable acceptance..
- With help of CMS physicists in technical roles in early 2016 we identified/selected an appropriate site at LHC Point 5
  - *PX56 observation and drainage "gallery" (aka tunnel)*

Detector Location





maximize

- Sensitivity of experiment ∝ length of scintillator
- Sensitivity of experiment ∝ 1/(distance from IP)^2,

minimize

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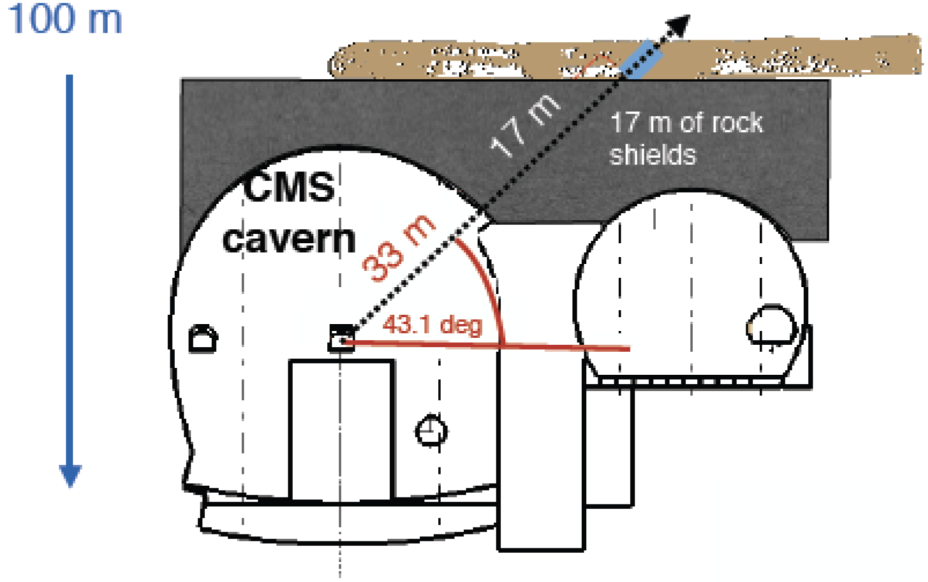
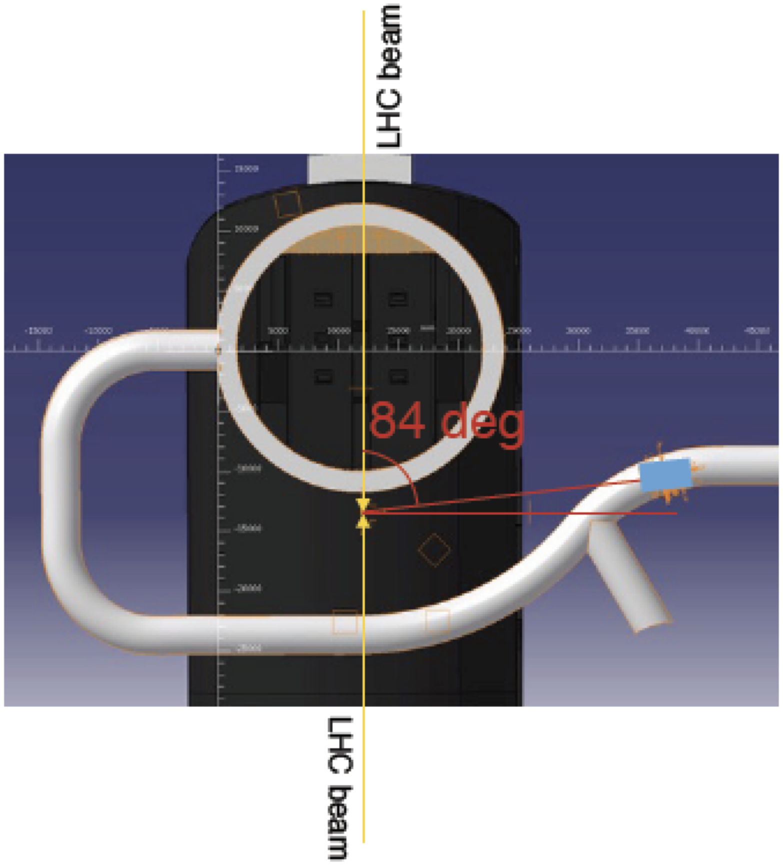
Detector Location



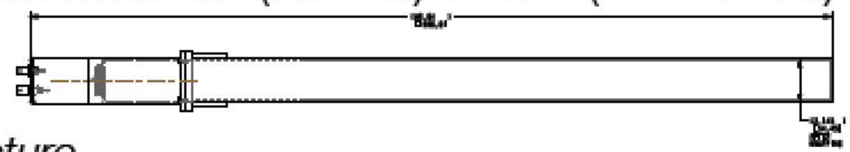


maximize

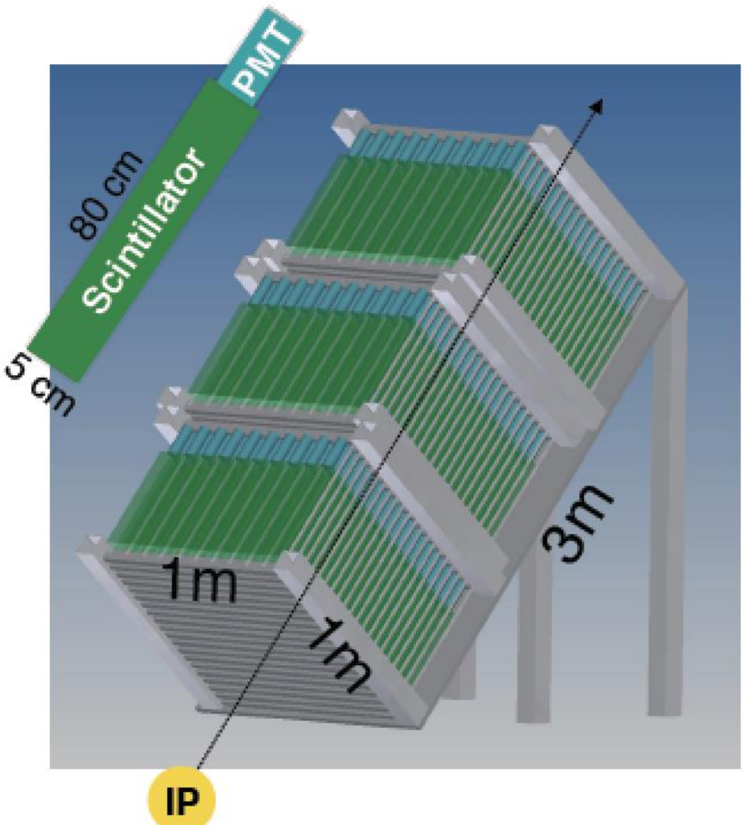
- Sensitivity of experiment ∝ length of scintillator
- Sensitivity of experiment ∝ 1/(distance from IP)^2, ← minimize

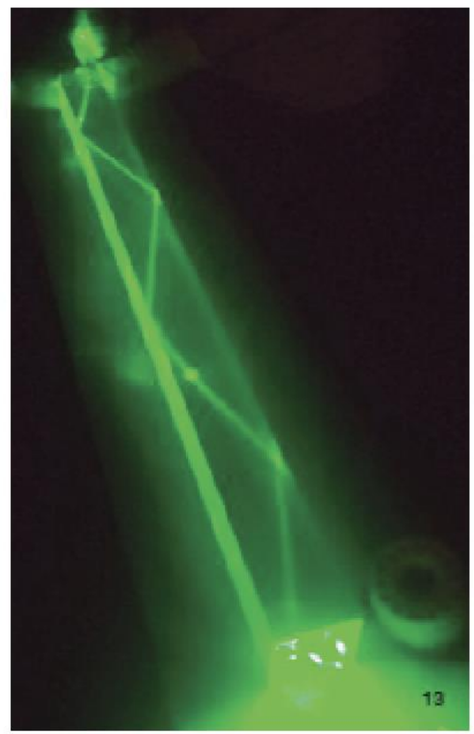
Detector Concept

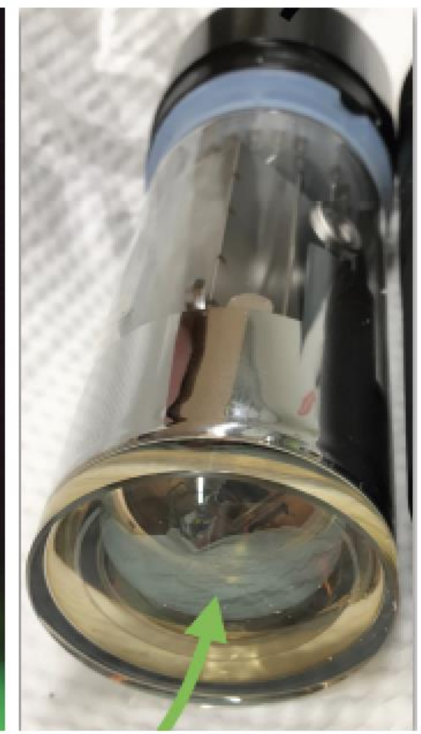
- Basic element is a 5 cm² x 80 cm bar pf plastic scintillator (BC 408) + PMT (HPK R7725)



- Arranged in a 20 x 20 x 3 array
  - *Supported by movable mechanical structure*
    - **Alignment to IP + retraction to allow passage through gallery**







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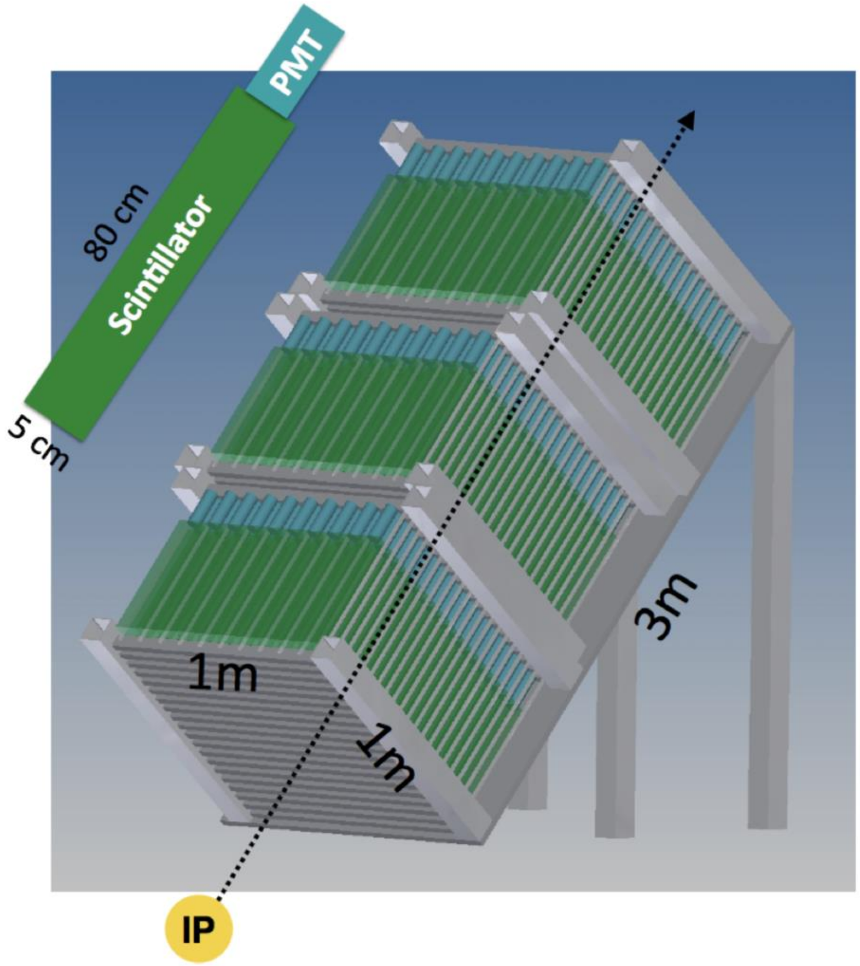
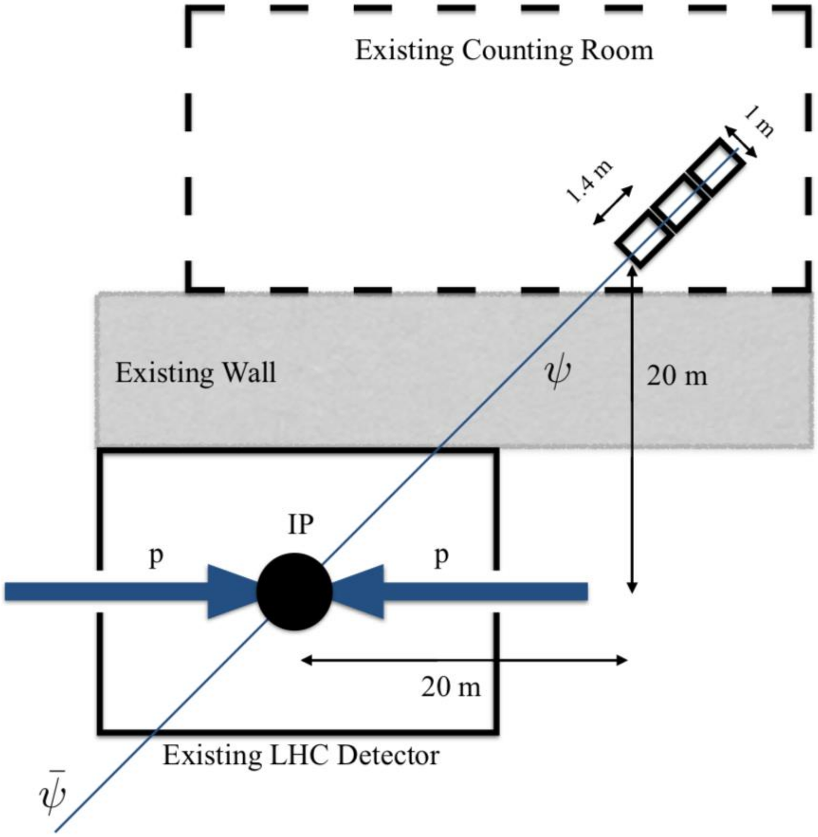
Experimental Set-up

- Basic element is a 5 cm² x 80 cm bar pf plastic scintillator (BC 408) + PMT (HPK R7725)

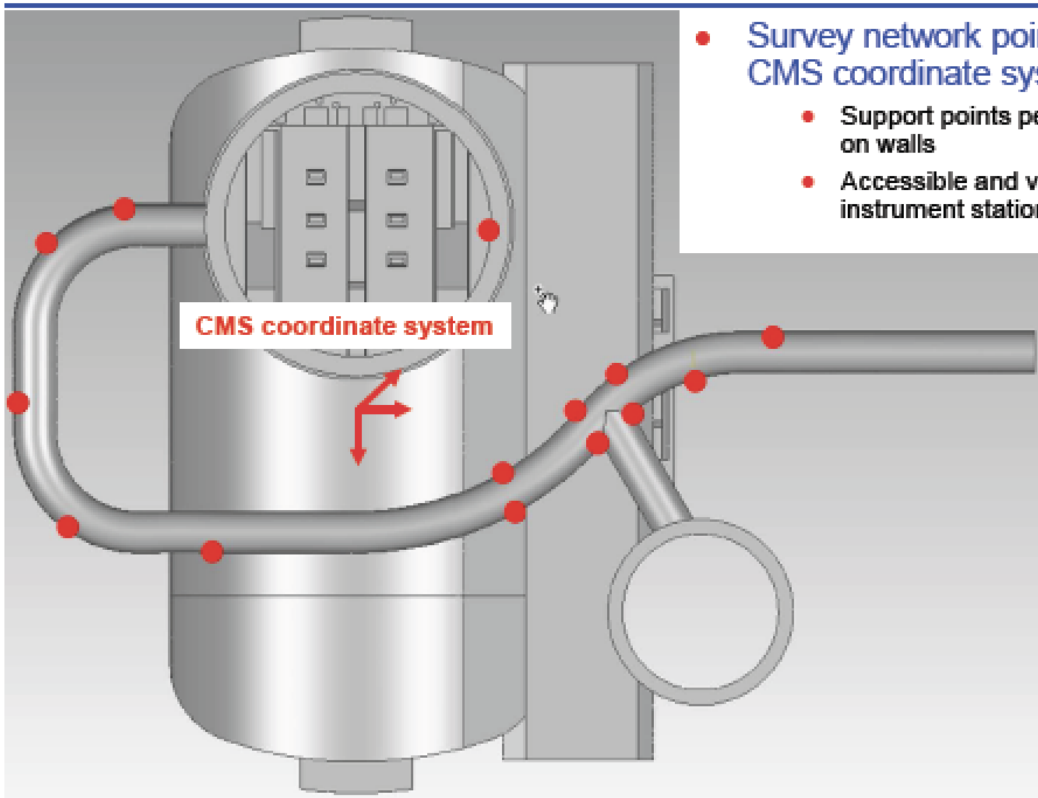




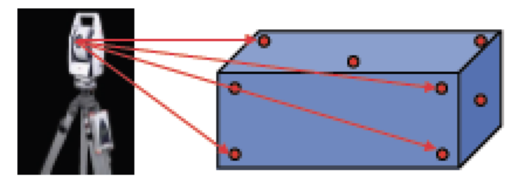
- Projective scintillator array requiring **multi-layer coincidence and ToF**
- Located in tunnel above CMS experiment (33m, $\phi \sim 43^\circ$, $\eta \sim 0.7$)

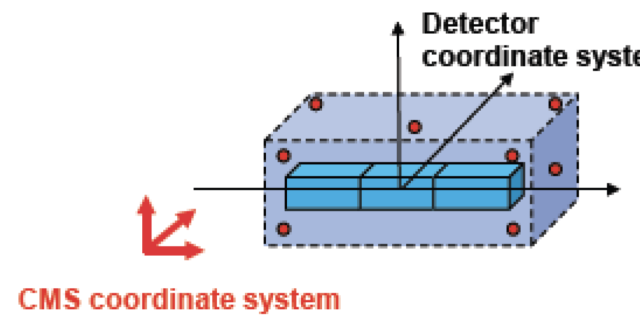
Allignment to CMS

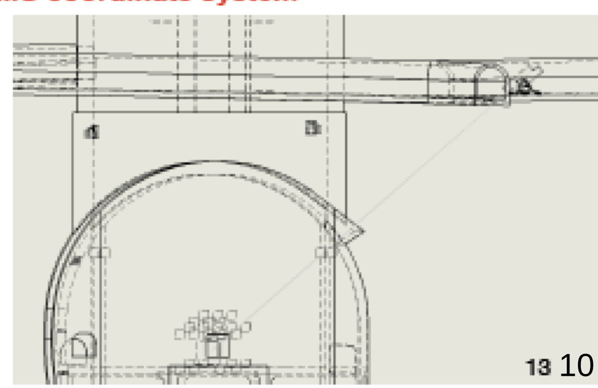
Survey network points installed in drainage gallery



- Survey network points known in CMS coordinate system
  - Support points permanently fixed on walls
  - Accessible and visible from instrument station



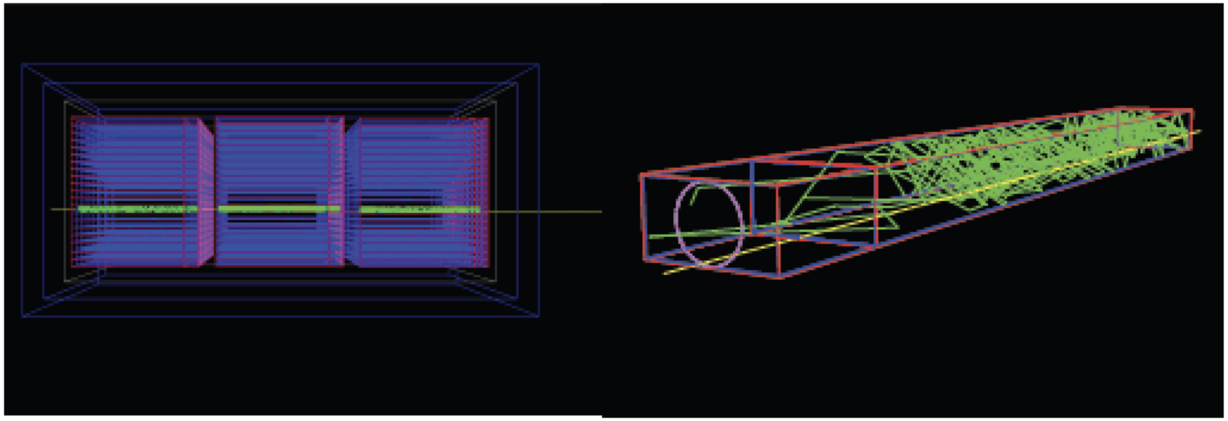


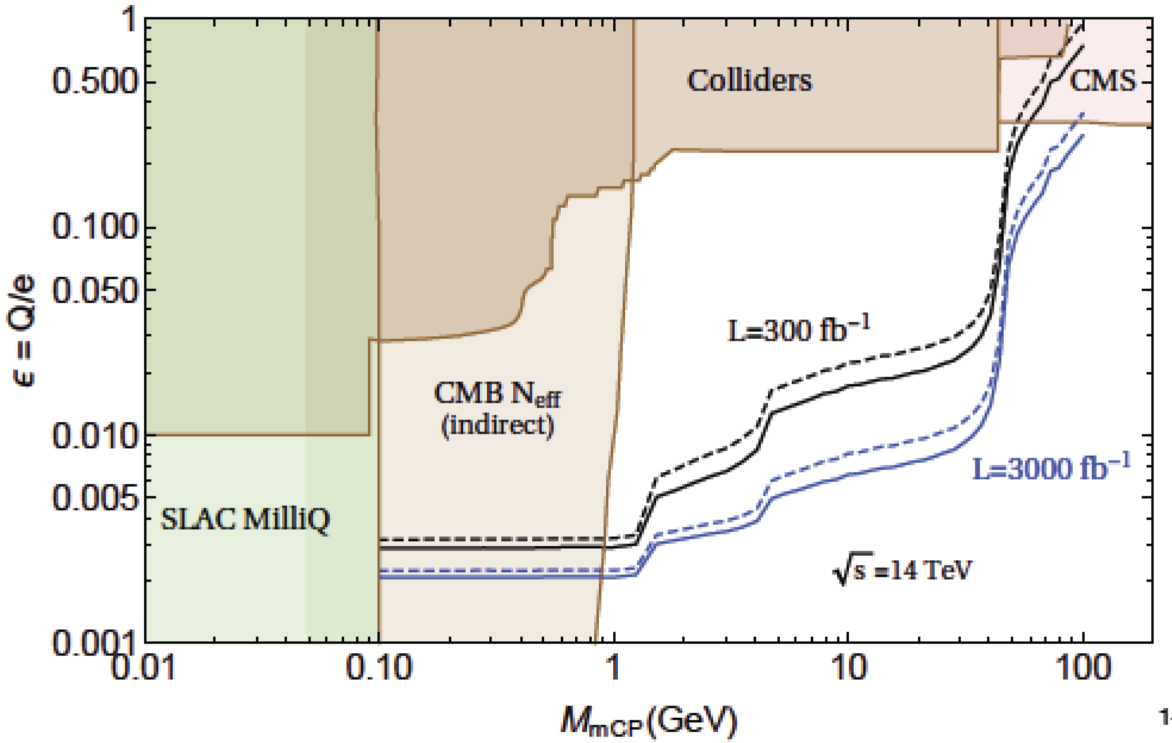


- Allows initial alignment good to < ~cm (over 33 m!)
  - *Final alignment using muons from IP*

Simulation and Expected Sensitivity

- Use madGraph + madOnia to **simulate production via modified Drell-Yan**
- Propagate particles through parameterized simulation of material interactions with CMS & rock
- Count rate of incidence on 1 m² face of milliQan detector
- **GEANT simulation of milliQan detector** response
- Sensitive to wide range of well-motivated, unexplored, parameter space
  - ***Q/e down to nearly 0.001***
  - ***Masses from 100 MeV to 100 GeV***





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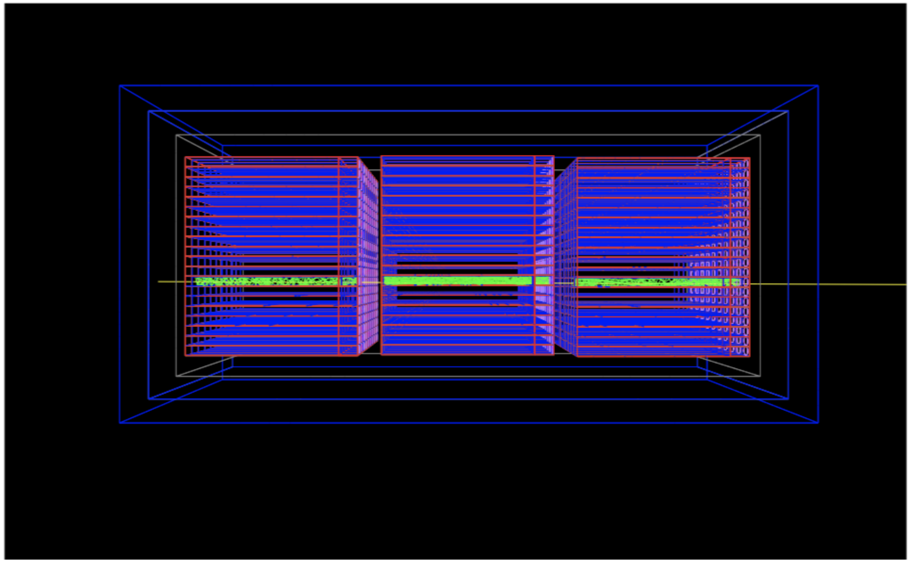
Expected Backgrounds

- Expect 17 m of rock will shield particles form pp collision (except muons) to negligible levels
- Muons (from LHC or cosmics) not actually a background since will be very bright (~1M photons in scintillator)
  - *They will be a small source of dead time though*
- Expect irreducible background to be from dark current pulses in PMTs
  - *Assuming dark rate of ~1kHz, triple-incidence in 15 ns window reduces this to ~10^{-6} Hz*
    - **$\mathcal{O}$(50) bkg events in 3000 fb^{-1}**
- Expect additional sub-dominant, reducible, backgrounds from activity in the scintillator, background radiation, and photo-multiplier after pulsing
- Background rate can be monitored *in situ* during beam-off periods
- Best way to understand backgrounds prior to this is via a concept "demonstrator" detector prototype in drainage gallery
  - *We installed a 1/100 scale such device about* *2 years ago*

Experimental Set-up

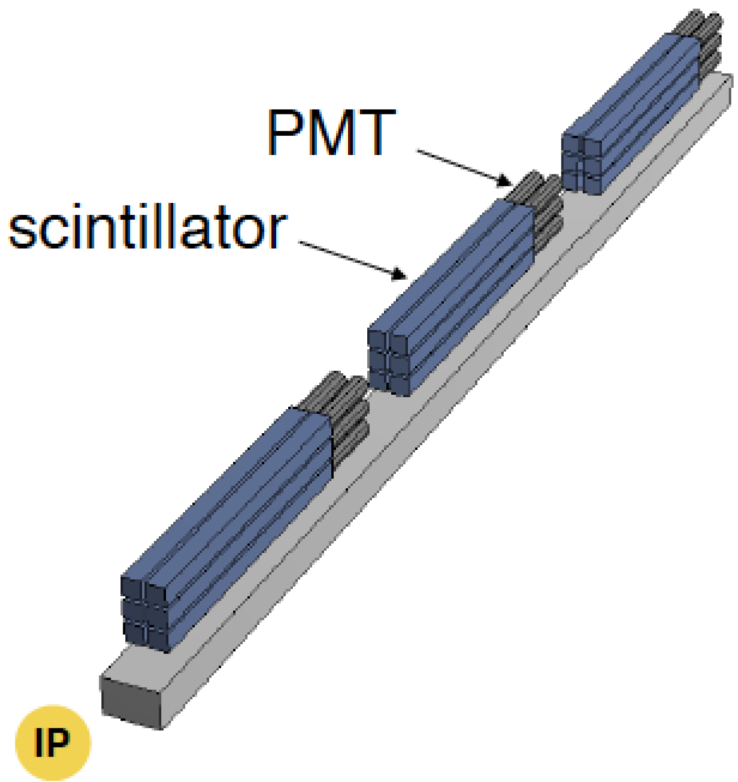
Detector must simultaneously operate as a very low background experiment, while also functioning as a sort of "beam telescope."

- Shielding from beam particles from LHC
- Long (0.6m – 0.8m) active material: $\frac{dE}{dx} \propto Q^2$
- Multi-layer coincidence in 15 ns to mitigate random tracks



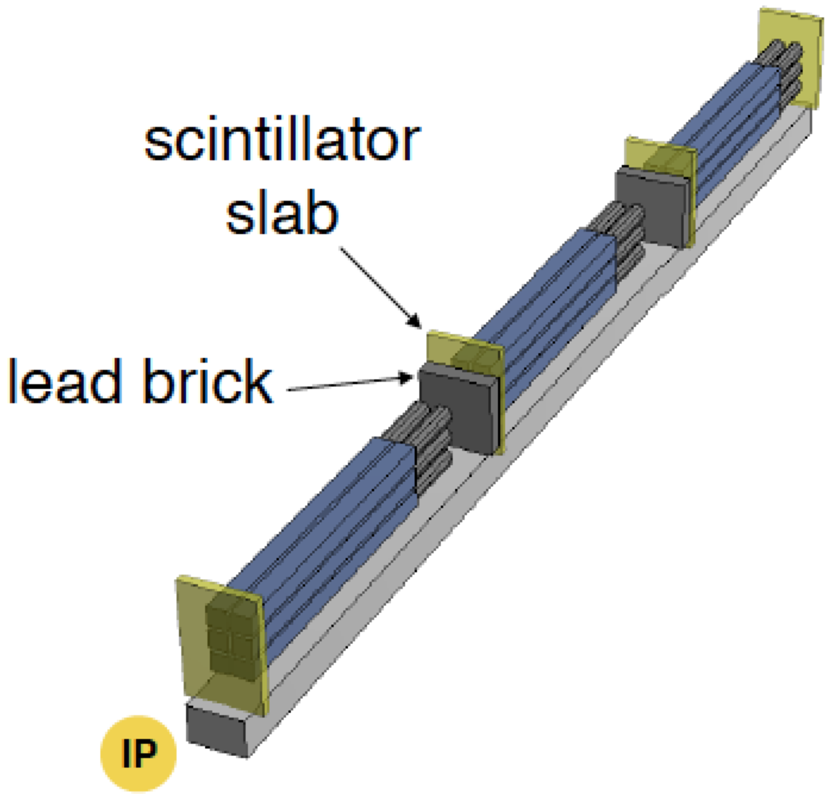
Dominant background: dark current pulses in the PMTs in coincidence with environmental radioactivity and cosmic rays
New design: 3 x 80cm → 4 x 60cm scintillator bars

Demonstrator Design



- In order to verify the feasibility and optimize the design of the experiment thoroughly, ~1% of the detector is installed as a "demonstrator"
- 3 layers of 2x3 scintillator+PMT

Demonstrator Design



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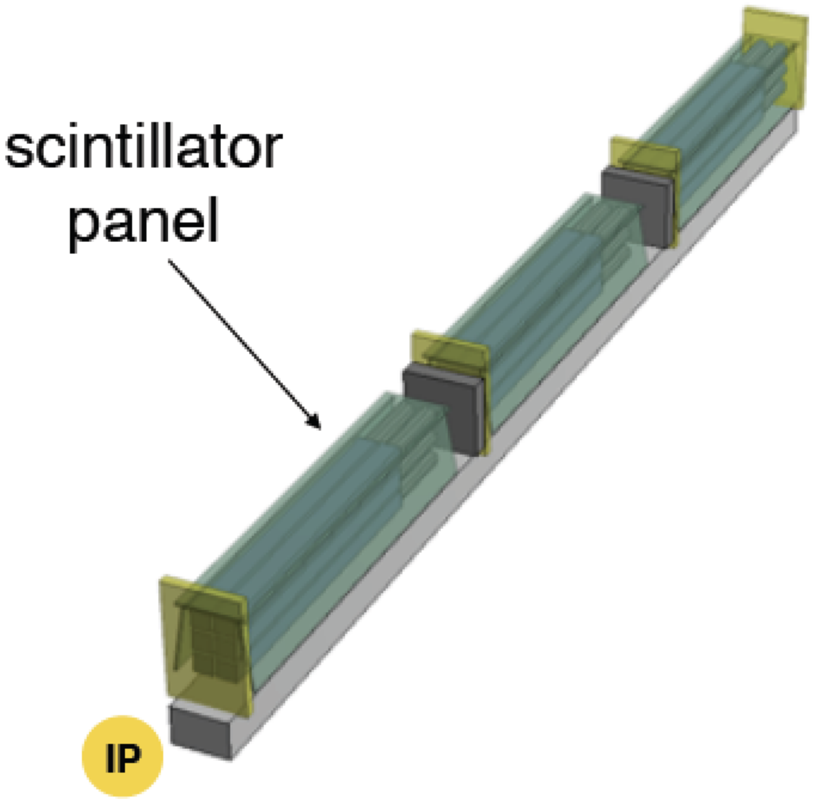
- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
    - *Tag thru-going particles, shield radiation*

Demonstrator Design



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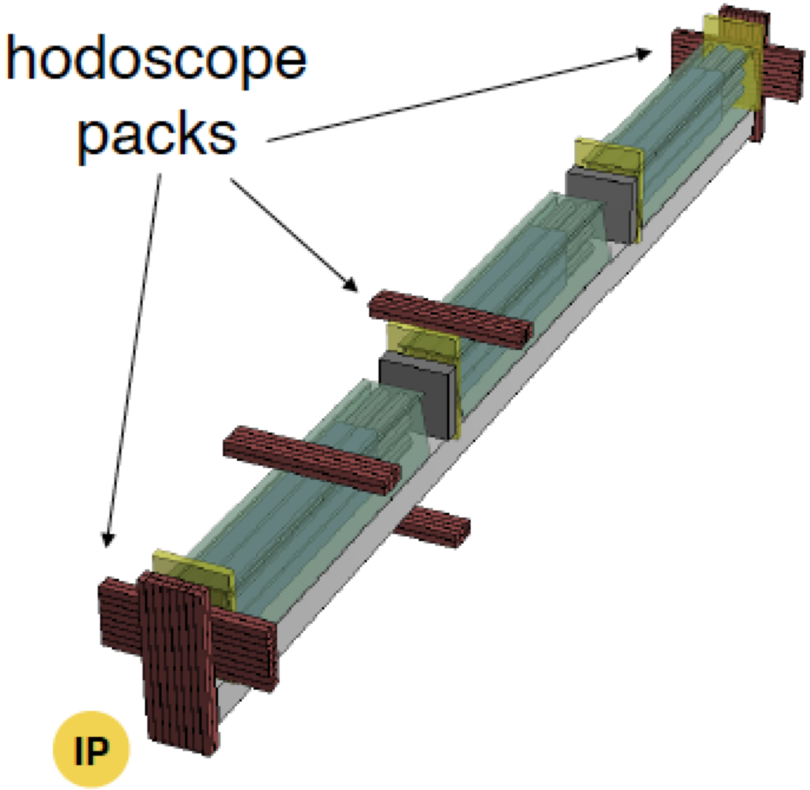
- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
  - *Tag thru-going particles, shield radiation*
- Scintillator panels to covering top and sides
  - *Tag/reject cosmic muons*

Demonstrator Design



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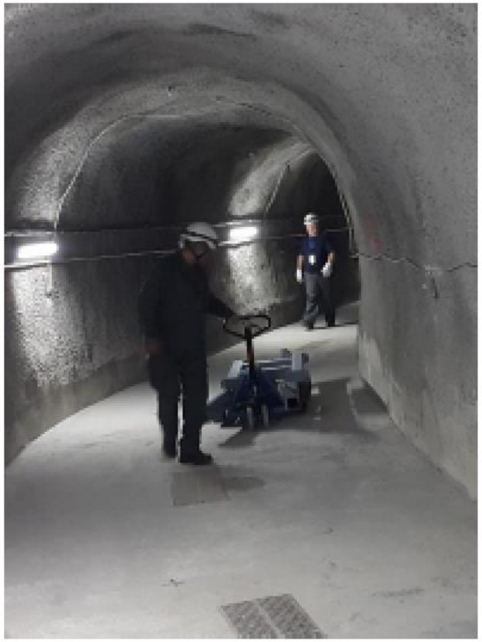
- 3 layers of 2x3 scintillator+PMT
- Scintillator slabs and lead bricks
  - *Tag thru-going particles, shield radiation*
- Scintillator panels to covering top and sides
  - *Tag/reject cosmic muons*
- Hodoscope packs
  - *"Tracks" of beam/cosmic muons*

Mechanical Structure

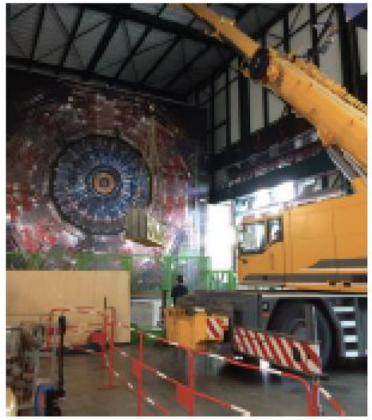






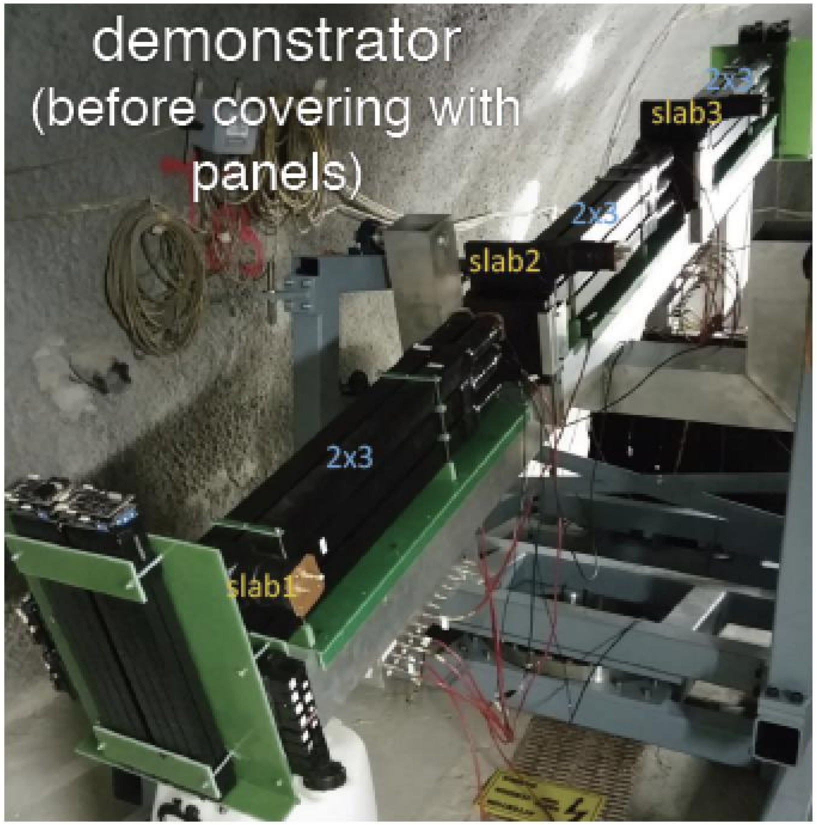

- Supports weight of “final” milliQan
- Rotates out of position to allow passage

Demonstrator Installed in TS2 of 2017



- Upgraded during 2017 YETS

Installed

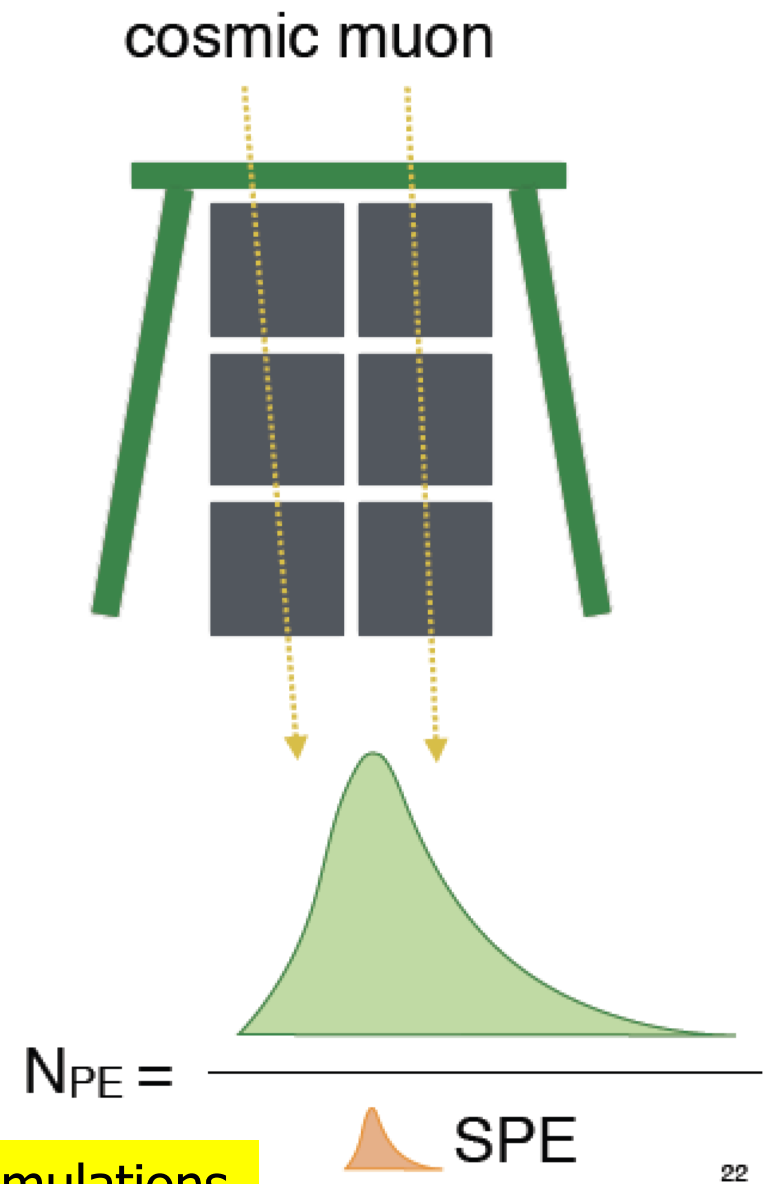


- Been taking data ~continuously since then (during and between fills)

In the Gallery

In Situ Charge Calibration

- Important because it allows us to study efficiency for small charge depositions
  - Is it sufficient to be able to see milli-charged pls?
  - Want to know number of photoelectrons (N_{PE}) that mCP will produce
- Two ingredients:
  - *Select cosmic muons from vertical paths*
  - *Get single photoelectron (SPE) charge from afterpulses*
    - *(SPE pulse area measurement also done on the bench as a validation)*
- With these can calculate N_{PE} for cosmic muon (Q=1e)
  - *N_{PE} (Q=1e) = Pulse area (cosmic muon) / Pulse area (SPE)*
- Extrapolate this to N_{PE} for fractional charges by Q^2

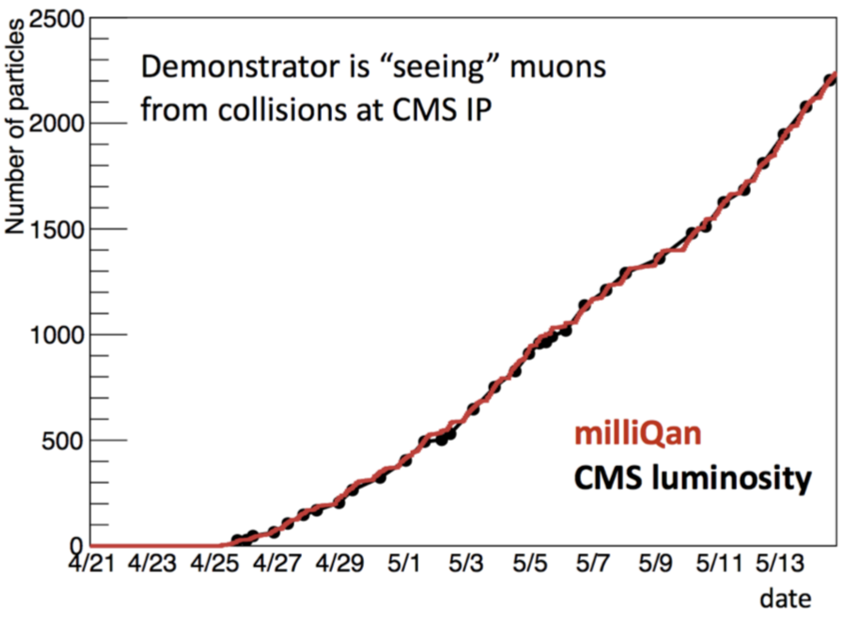


Results are consistent with full Geant4 simulations

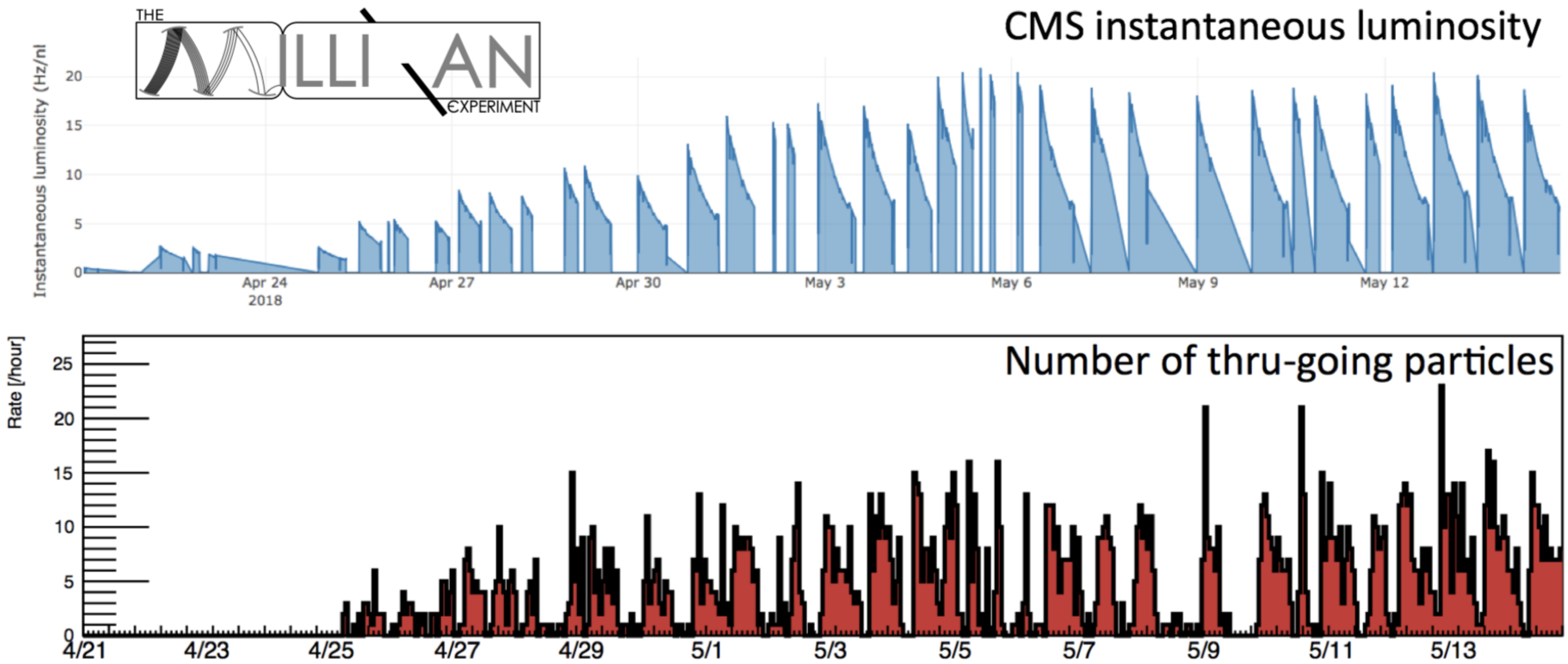
Demonstrator Analysis

Have performed multiple *in situ* measurements important to inform the full detector design and operation.

- Charge calibration using ratio of cosmic muon pulse to single photo-electrons
- Angular resolution and timing using LHC *pp* muons
- Beam muon occupancy and luminosity dependence



Demonstrator Analysis



Directly verified milli*Q*an capabilities as a charged particle telescope for particles produced in the CMS IP. Next stop, fractionally charged particles!

Collaboration

- ~20 people, 12 institutes, 6 countries
- 9 "CMS" groups
  - *The Ohio State University* (**C. Hill***, *B. Francis*)
  - *University of California, Santa Barbara* (**D. Stuart, C. Campagnari**)
  - *The University of Nebraska* (**F. Golf**)
  - *CERN* (**A. Ball, A. De Roeck, M. Gastal**)
  - *The University of Bristol* (**J. Brooke, J. Goldstein**)
  - *Karlsruhe Institute of Technology* (**R. Ulrich**)
  - *Lebanese University* (**H. Zaraket**)
  - *University of Virginia (C. Neu)*
  - *FNAL (J. Hirschauer)*

+VUB, Brussels (S. Lowette)

- 2 "ATLAS" groups
  - *New York University* (**A. Haas***, *B. Kaplan*)
  - *University of Chicago* (**D. Miller,** *M. Swiatlowski*)

C. Hill 2018:
not quite complete
person list

More Milli-Charge Hunting

A proposal for milli-charges at FNAL @ MINOS near detector

FerMINI: Fermilab Search for Milicharged Particle

J. F. Hirschauer, (Principle Investigator) and Y.-D. Tsai (Co-Investigator)

Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

A. Haas (Co-Investigator)

New York University, New York, NY 10003, USA

C. Hill (Co-Investigator)

Ohio State University, Columbus, OH 43210, USA

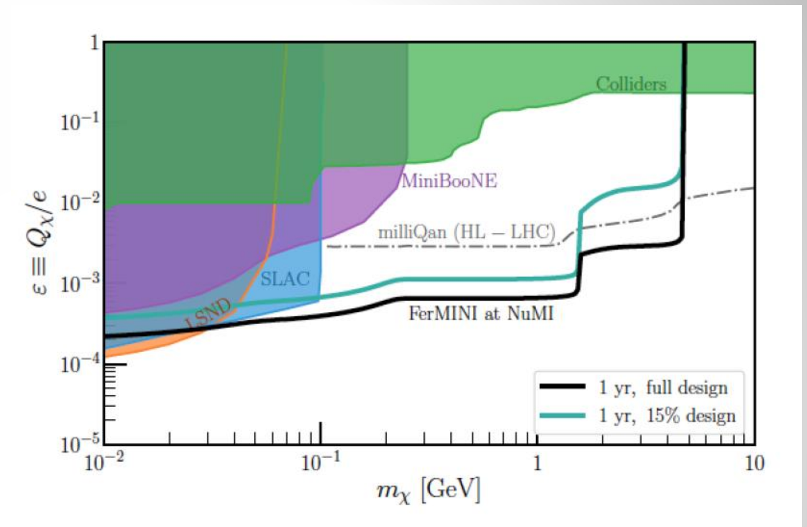
D. Miller (Co-Investigator)

University of Chicago, Chicago, IL 60637, USA

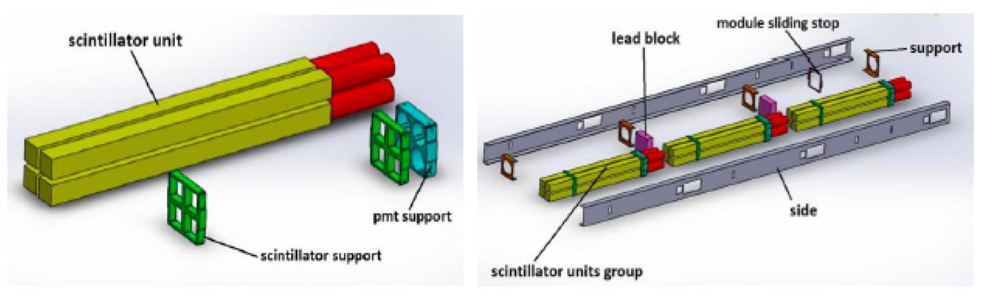
D. Stuart (Co-Investigator)

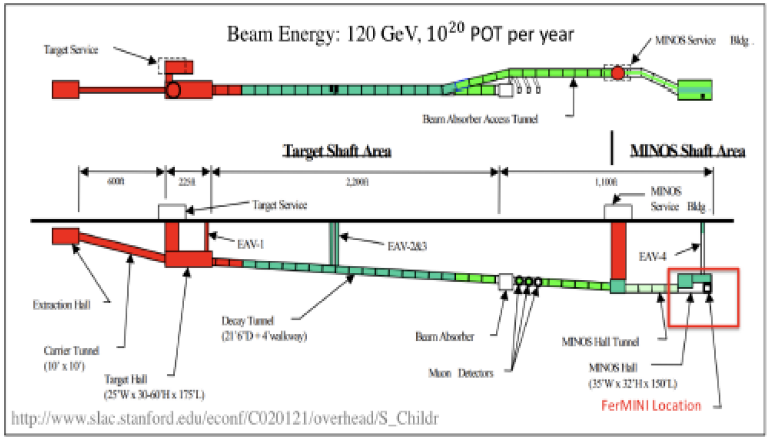
University of California, Santa Barbara, CA 93106-9530, USA

See also: arXiv:1806.03310



Based on the MilliQan design





See also MoEDAL talk for another proposal

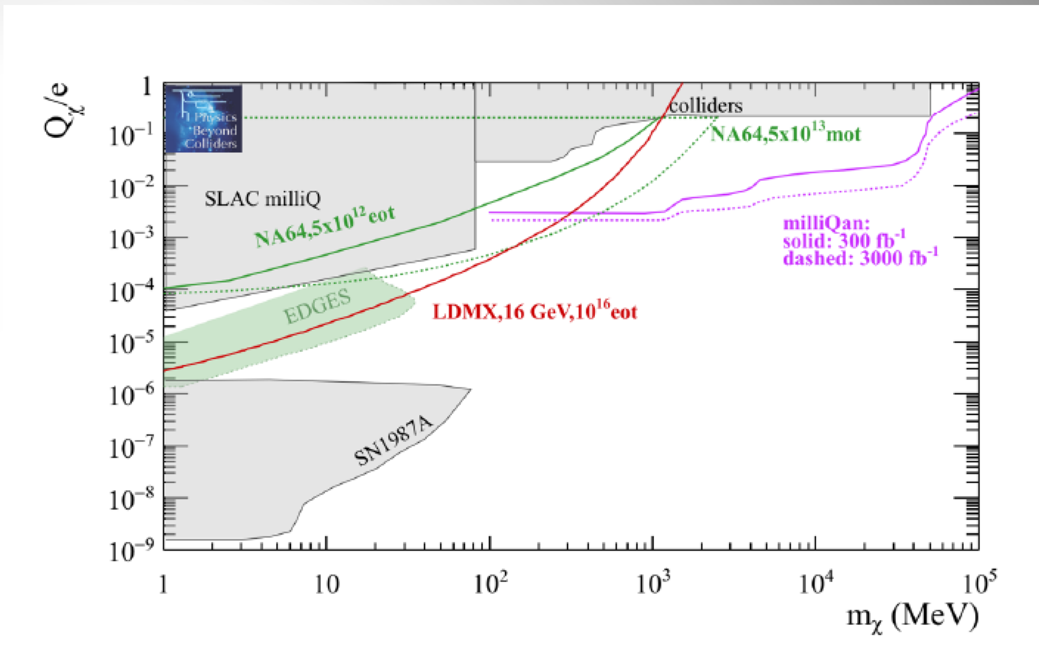
More Milli-charge Activities

Physics Beyond Collider Study

arXiv:1901.09966

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

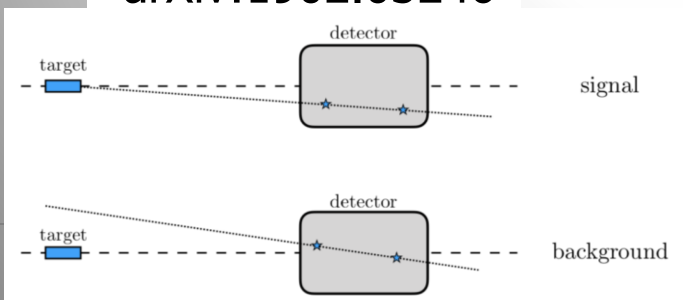
J. Beacham[1], C. Burrage[2,*], D. Curtin[3], A. De Roeck[4], J. Evans[5], J. L. Feng[6], C. Gatto[7], S. Gninenko[8], A. Hartin[9], I. Irastorza[10], J. Jaeckel[11], K. Jungmann[12,*], K. Kirch[13,*], F. Kling[6], S. Knapen[14], M. Lamont[4], G. Lanfranchi[4,15,*,**], C. Lazzeroni[16], A. Lindner[17], F. Martinez-Vidal[18], M. Moulson[15], N. Neri[19], M. Papucci[4,20], I. Pedraza[21], K. Petridis[22], M. Pospelov[23,*], A. Rozanov[24,*], G. Ruoso[25,*], P. Schuster[26], Y. Semertzidis[27], T. Spadaro[15], C. Vallée[24], and G. Wilkinson[28].



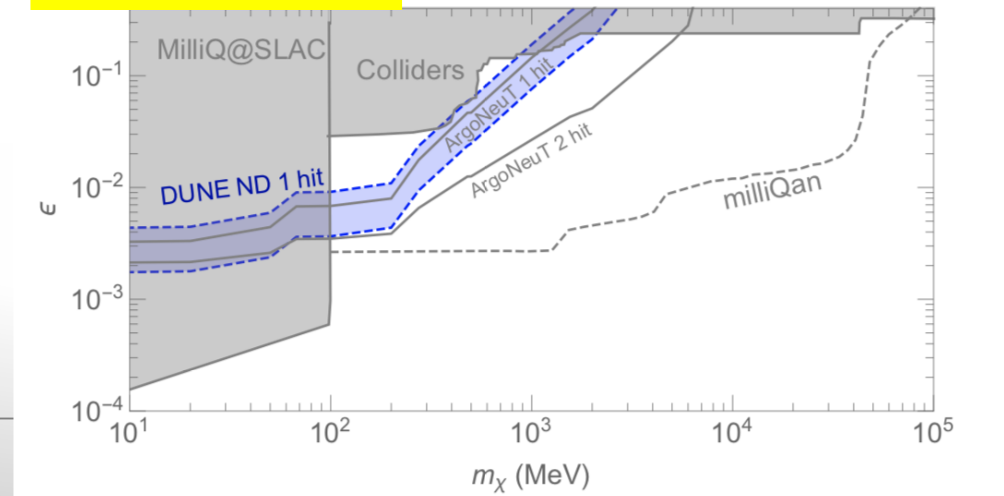
Millicharged Particles in Liquid Argon Neutrino Experiments

Roni Harnik[1], Zhen Liu[2], and Ornella Palamara[1]
[1] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[2] Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, MD 20742-4111 USA

arXiv:1902.03246



LArTPC study



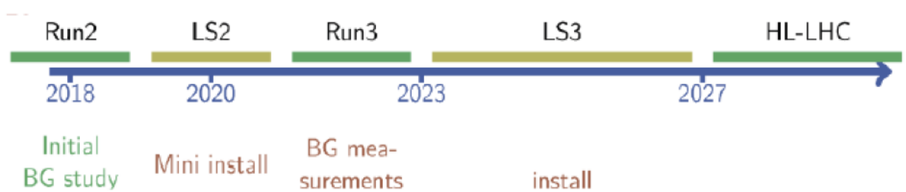
Status of the Various Projects

Based on Simon Knapen FNAL seminar fall 2018 (*)

Lifetime frontier

Supplementary detectors

	Higgs Decay	B meson decay	π, η- decay dark photon	Progress	Cost
FASER		(✓)	✓	First phase approved and funded	$
CODEX-b	✓	✓		Sub-collaboration formed	$
MilliQan		(✓)		Sub-collaboration formed	$
AL3X	✓	✓	✓	Proof of concept	$$
MATHUSLA	✓	(✓)		Letter of Intent	$$
SHIP		✓	✓	Conceptual design report	$$$



- FASER1/MilliQan(?) installation by 2021
- MATHUSLA, CODEX-b, FASER2 for HL-LHC

(*) Experiments have different capabilities for measuring the LLPs

Summary

- MilliQan aims to search for milli-charges in the regime $0.1 < Q < 0.003$
- MilliQan demonstrator installed in mid-2017 and taking data since (1% of a full module). First physics with the demonstrator results?
- Funding requests under evaluation (NSF-MRI, European requests). Expect outcome soon.
- Detector ready to be constructed, as soon as funding becomes available, for run-III
- More initiatives for milli-charge searches, at CERN and FNAL in progress