MilliQan, the quest for millicharged particles

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UCLOUVAIN Talk

Electric charge: evolution

- Thales of Miletus: Amber

  Attraction without contact

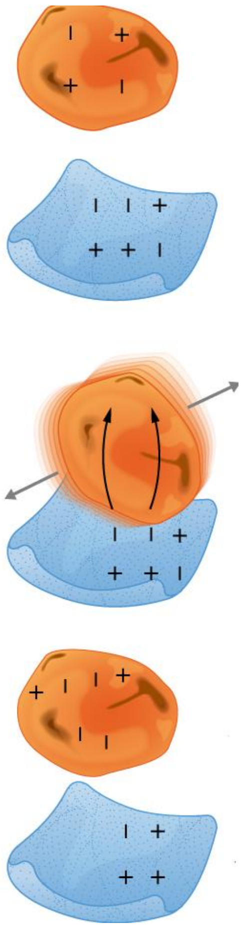
  (Charge Discovery)

- William Gilbert: Attraction and repulsion can be observed (Polarity)

- Charles Augustine de Coulomb: forces are repulsive when the same type of charge exists on two interacting objects and attractive when the charges are of opposite types. (Charge quantitative)

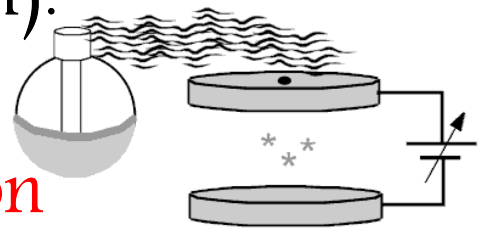
Electric charge: classical understanding

- Total charge conservation: no creation of charges upon rubbing an amber, it is just charge separation
- Force between charged particles is a kind of "action at a distance"
- Motion of electric charges produces current
- Motion of electric charges produces magnetism
- Charge in motion: electro-magnetic field production
- Link between charge and "electromagnetic waves"



The move from charged objects to particles

- **Charge quantization**: Robert A. **Millikan** and Harvey Fletcher
- Ratio of the charges of different drops is a fraction of two integers?
- The charge of the electron, now (2019 redefinition of SI base units) an exact set values −1.602176634×10−19 C.
- Charge Conservation: globally, locally (continuity equation).
- Relativity: Issues with action at a distance
- Quantum mechanics, wave nature, …, probabilities, photon
- New discoveries where particles are created and annihilated?



Q: how to reconcile all that?

Fields and particles

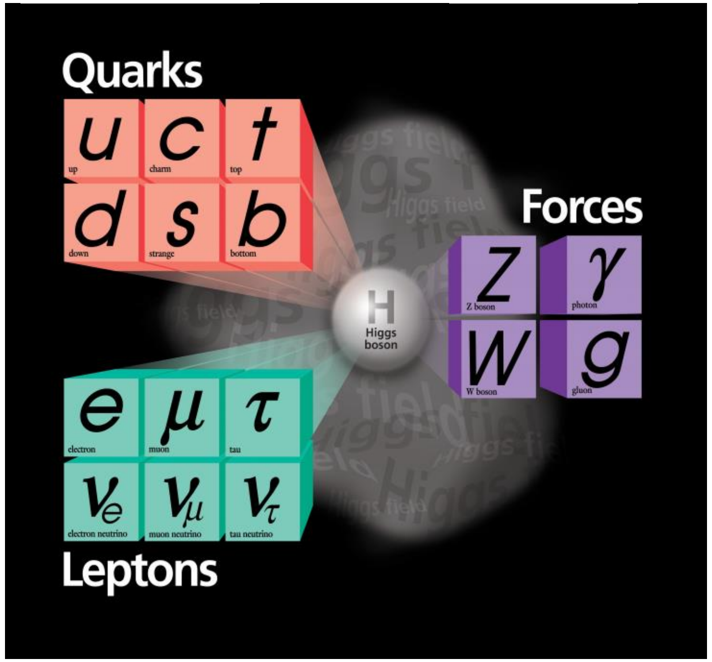
- Quantum field theory: nature is described by fields: combination of Quantum Mechanics and Special Theory of relativity
- The electron has a field and the electromagnetic field has a particle interpretation: the photon.
- Field are interacting among each others and even sometimes with themselves. This leads to particle creation and annihilation.
- Even with this "creation and annihilation" we can still define a kind of stable particles.
- Over the last 100 years: along with all new particles discovered has led to the Standard Model of Particle Physics. With the Minimal set of input parameters and imposed conservation laws.

The standard model

- The new (final?) "Periodic Table" of fundamental elements:

Fermions Bosons

Matter particles



Force particles

Fermions: particles with spin ½
Bosons: particles with integer spin

Combinations (non-elementary) of Fermions Can be fermions or Bosons

Charge: are multiple of e/3, Why?

Conservation laws, symmetries

- Quantum field dynamics is constructed via a: Lagrangian/action which is a functional of field(s). $L(A, \psi, \ldots.)$
- The mathematical functional L is chosen to satisfy some basic rules: respecting relativity, producing some known classical properties: e.g. Maxwell's equations, and indirectly charge conservation…..
- Conservation laws are obtained from symmetries of Lagrangian/action, then Noether theorem will give the conserved current, hence charge. (charge need not be electric)
- So charge is defined from the construction of the Lagrangian

Conservation laws, symmetries

- Interaction between photon and any other field respecting some symmetry will give the electric charge.
- Electron/muon/tau/quarks/…. Couples/interact with photon, hence should have electric charge.
- Neutrino/photon/Z-Boson … do not couple to photon: electrically neutral.
- Electron/muon/tau: e-charged
- Quarks: $\pm e/3$, $\pm 2e/3$, why? Naïve answer: To make baryons (example proton 3 quarks). Still not happy!

Lagrangian, symmetries, Gauge theory

- The standard model is built using symmetries that is packed by the so called symmetry group/algebra $SU_c(3) \otimes SU_L(2) \otimes U_Y(1)$

- Then there is a spontaneous symmetry breaking

$$SU_c(3) \otimes U_{EM}(1)$$

with the One massless (γ) and three massive $(Z, W^{\pm})$ EW gauge bosons.

- Hence the electric charge is coming from a Lagrangian that respect the $U_{EM}(1)$ (local) symmetry.

New symmetry, gauge only

- Even interaction (higher order correction), with just $SU_c(3) \otimes U_{EM}(1)$ can not lead effectively (effective theory) to fractional **e** other than e/3 multiples: renormalization/Ward identity.
- Need to modify the Standard model: new symmetry groups. Simplest just add another $U(1)$. :

$$\underbrace{SU_c(3)}_{\text{Non Abelian Gauge field: Gluons}} \otimes \underbrace{SU_L(2) \otimes U_Y(1)}_{W_\mu^{1,2,3},\, B_\mu} \otimes \underbrace{U(1)}_{\gamma'}$$

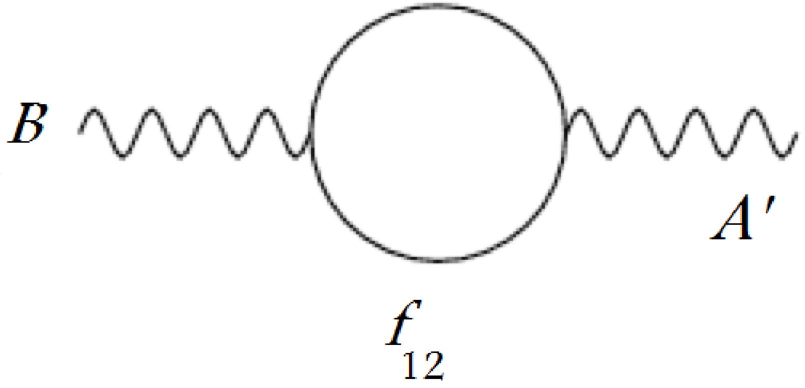
Non Abelian
Gauge field:
Gluons

$W_\mu^{1,2,3}, B_\mu$
The ancestors
of $W^{\pm}, Z^0, \gamma$
$W_\mu^{\pm}, Z_\mu, A_\mu,$

γ'
A'_μ

Coupling to fermions

- We can couple then B_μ, A'_μ to fermions. In different ways, couple exclusively to each (f_1, f_2, f_{12}), or couple to both. Assume the field that couples to both is a heavy fermion. (Holdom, 1986)
- If we work at an energy scale small compared to the fermion coupling to both fields then we can then approximate the f_{12} contribution



Kinetic Mixing

- Approximate theory: with kinetic mixing

$$= L_{SM} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i\bar{\Psi}(\partial_\mu \gamma^\mu + ie' A'_\mu \gamma^\mu + iM_{mcp})\Psi - \frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu}$$

$\kappa \ll 1$ and as usual in SM $B_\mu = \cos\theta_w A_\mu - \sin\theta_w Z_\mu$

- Redefinition of the new gauge boson:

$A'_\mu \to A'_\mu - \kappa B_\mu$ will get rid of gauge fields mixing/interaction

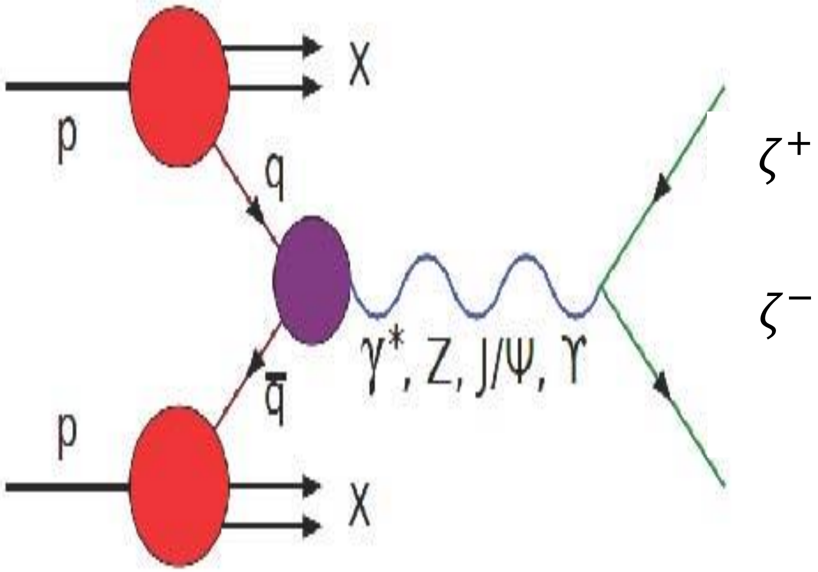
$$L = L_{SM} - \frac{1}{4} A'_{\mu\nu} A'^{\mu\nu} + i\bar{\Psi}(\partial_\mu \gamma^\mu + ie' A'_\mu \gamma^\mu + iM_{mcp} - i\kappa e' \cos\theta_w A_\mu \gamma^\mu - i\kappa \sin\theta_w Z_\mu \gamma^\mu)\Psi$$

Dark photon (massless)

Millicharge: mCP $\boldsymbol{Q = \varepsilon e}$

Basic production mechanism:

- QCD inspired production of mCP



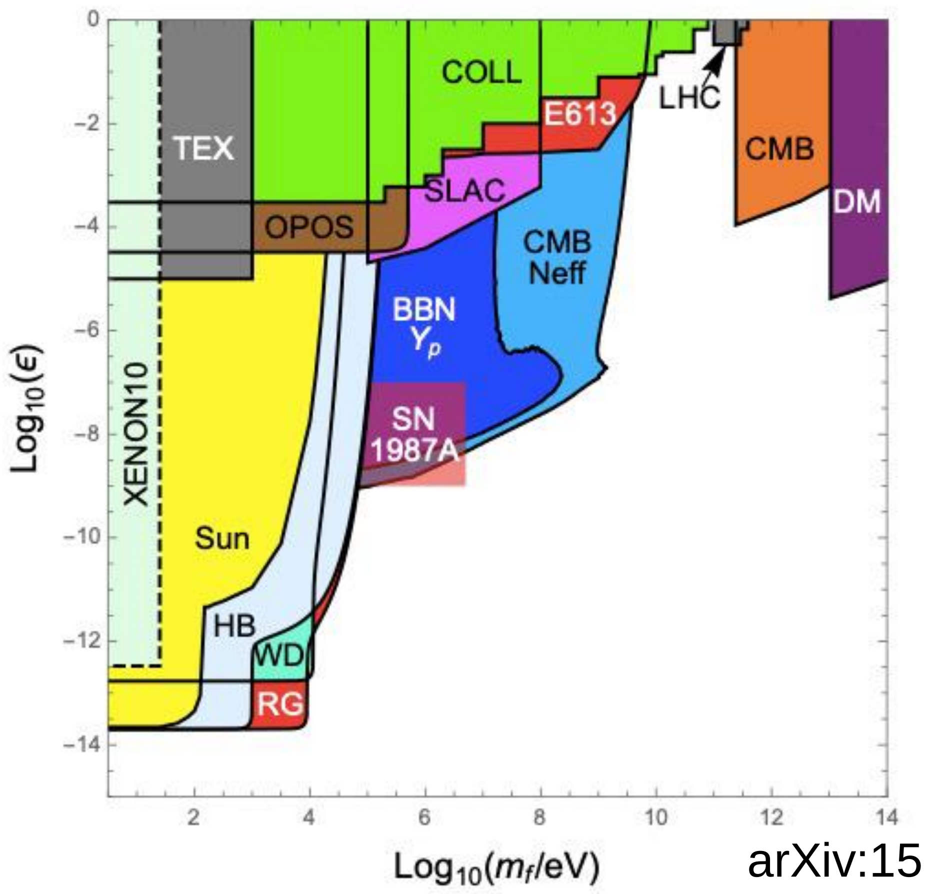
$$\eta, \eta', \pi^o \to \zeta^-\zeta^+\gamma; \rho \to \zeta^-\zeta^+; \phi, J/\psi, \ldots. \to \zeta^-\zeta^+;$$

The challenge:

- Small charge → low interaction with detectors. General purpose detectors $\frac{dE}{dx} \sim Q^2 \cdots$
- Main parameters for millicharge (ζ): Mass, Charge
- Searches using indirect searches: effects on sun, stars and supernovae, cosmological bounds,
- Searches using direct methods: colliders, beam dump
- Already covering wide range in masses/charges

Previous bounds

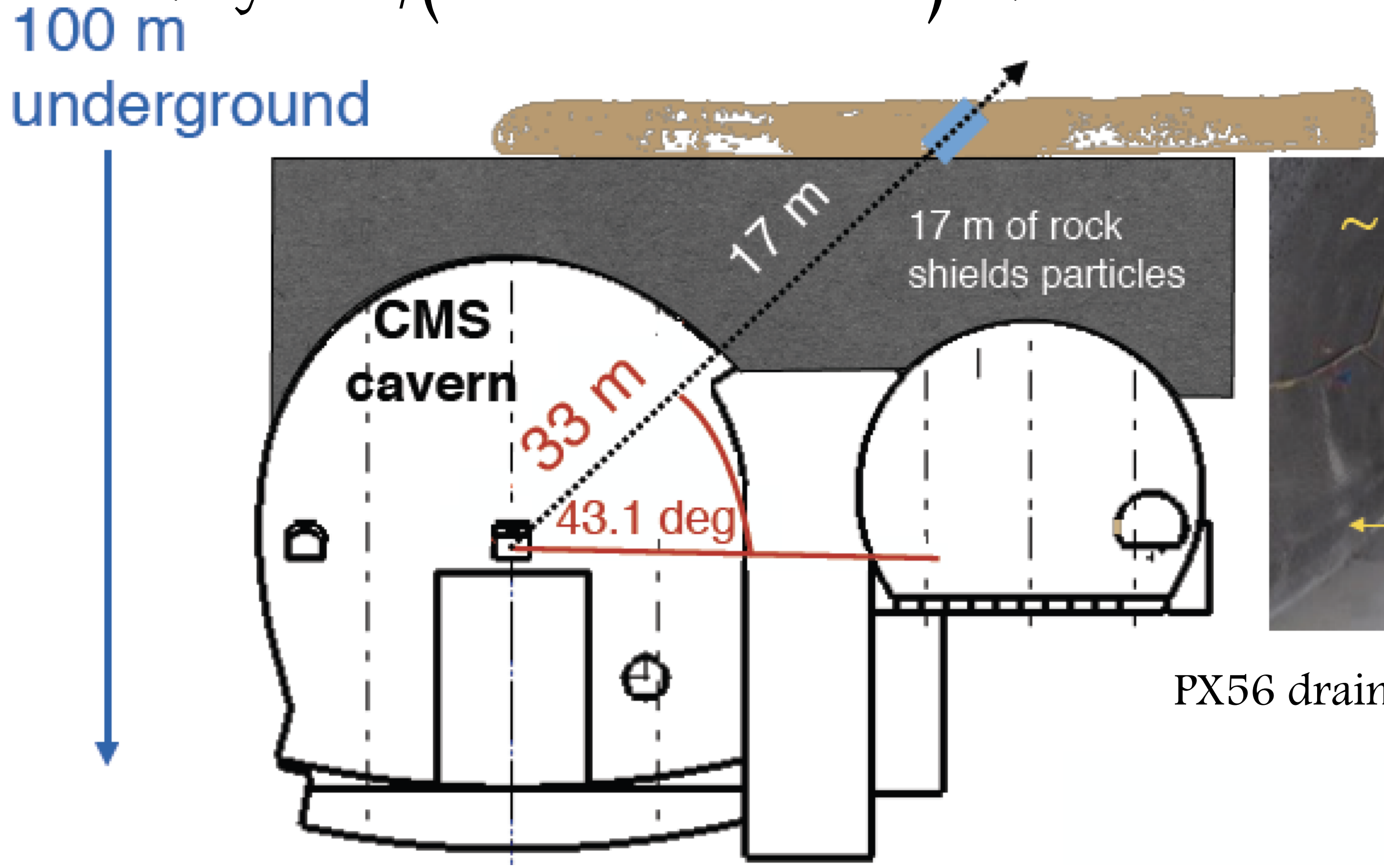
- LHC: mCP production rate well understood
- Milliqan proposal to fill Gap for heavier (~ GeV) low charged particles
- Using LHC beam to look for mCP.
- CMS is the hosting institute
- To become a subdetector

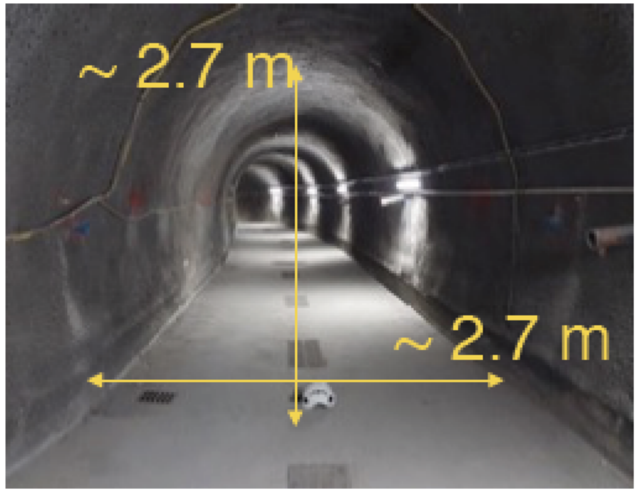


arXiv:1511.01122

Detector location

- Sensitivity ~ 1/(distance from IP)^2 & ~ scintillator length

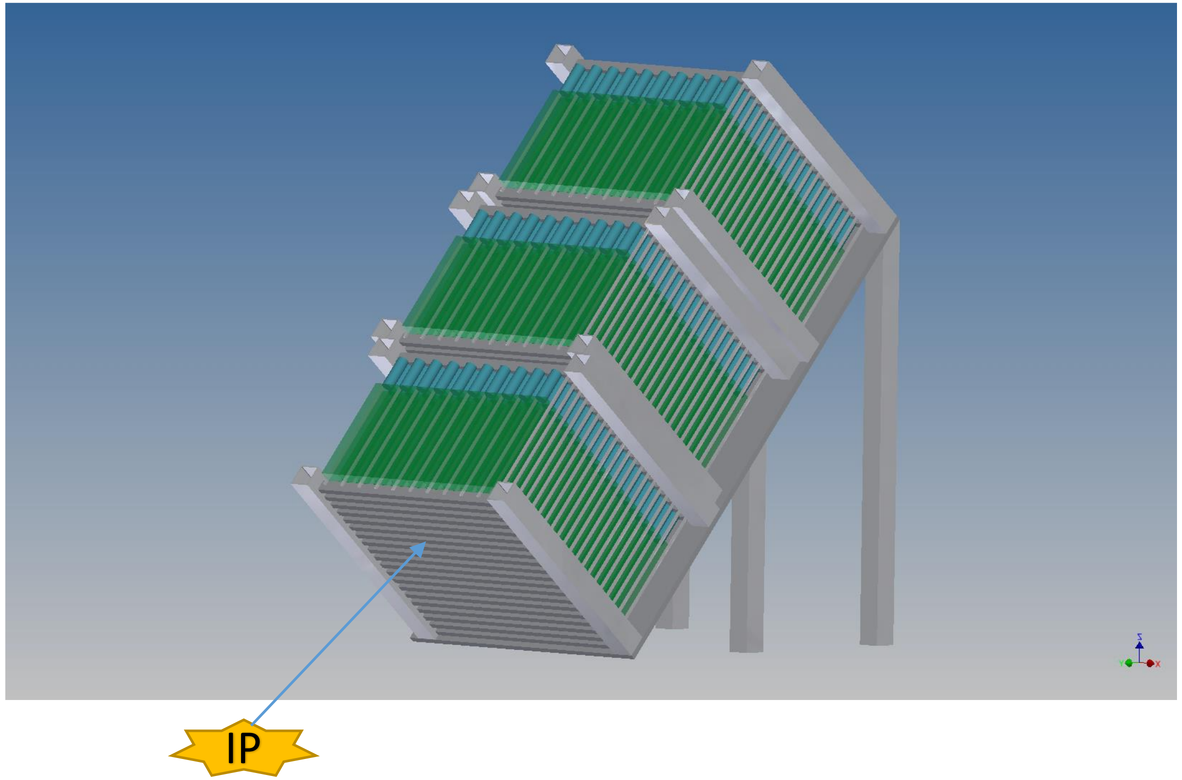




PX56 drainage gallery above CMS UXC

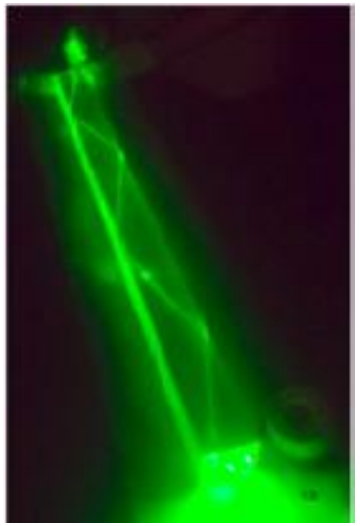
Detector Basic idea

- Scintillation array detector
- Initial proposal: LOI 2016



Key elements:

Scintillators



PMT

Detector Basic idea

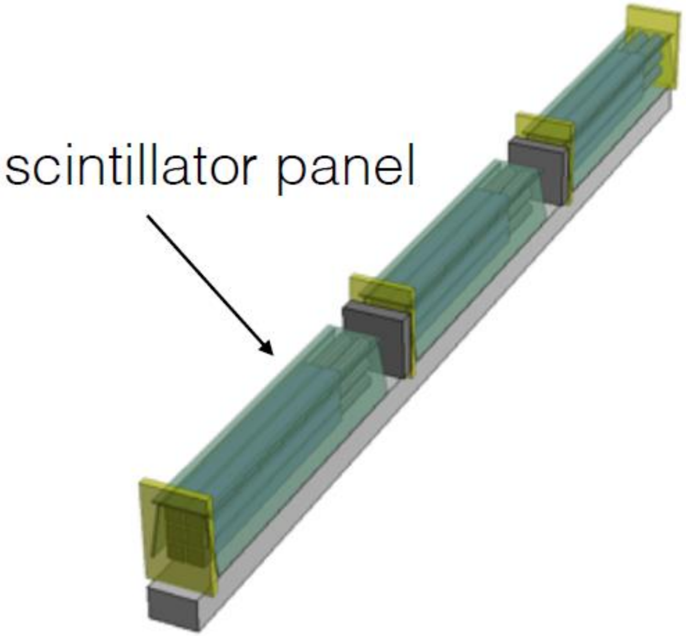
- Expected signal: few scintillation photons in multiple layers
- Each bar + PMT must be capable of detecting a single scintillation photon
- Control backgrounds: signal in each layer within small (~15 ns) time window and that points towards the IP
- Modular design is easy to scale
- Ionization $\sim \varepsilon^2 \rightarrow$ long bars boost sensitivity to charges as low as $0.001e$

Plan, and detector idea evolution

- A first prototype was installed (1% of the initial proposal), installed 2017, taking data 2018, published results 2020.
- A second modified detector was proposed, simulation done in 2020, sensitivity projections published 2021, installation fall 2021.
- Full detector ??

A prototype: demonstrator

- A first prototype was built to perform background studies and a proof of concept of the idea: Sept 2017 installed at point x56.

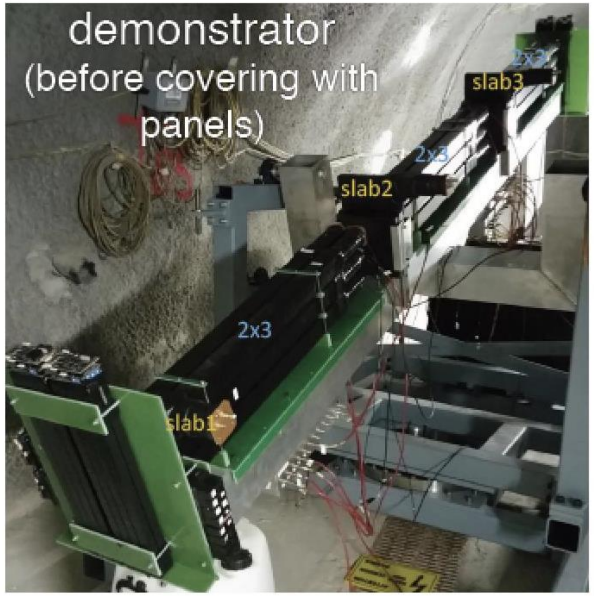


- 3 layers of 2X3 scintillators +PMT
- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation
- Scintillator panels to cover top +sides
  - Tag/reject cosmic muons + secondaries

Demonstrator installed

- milliQan demonstrator Installed and collected ~**37**fb-1 of data in 2018 (~2000h)

Installed demonstrator (before covering with panels)

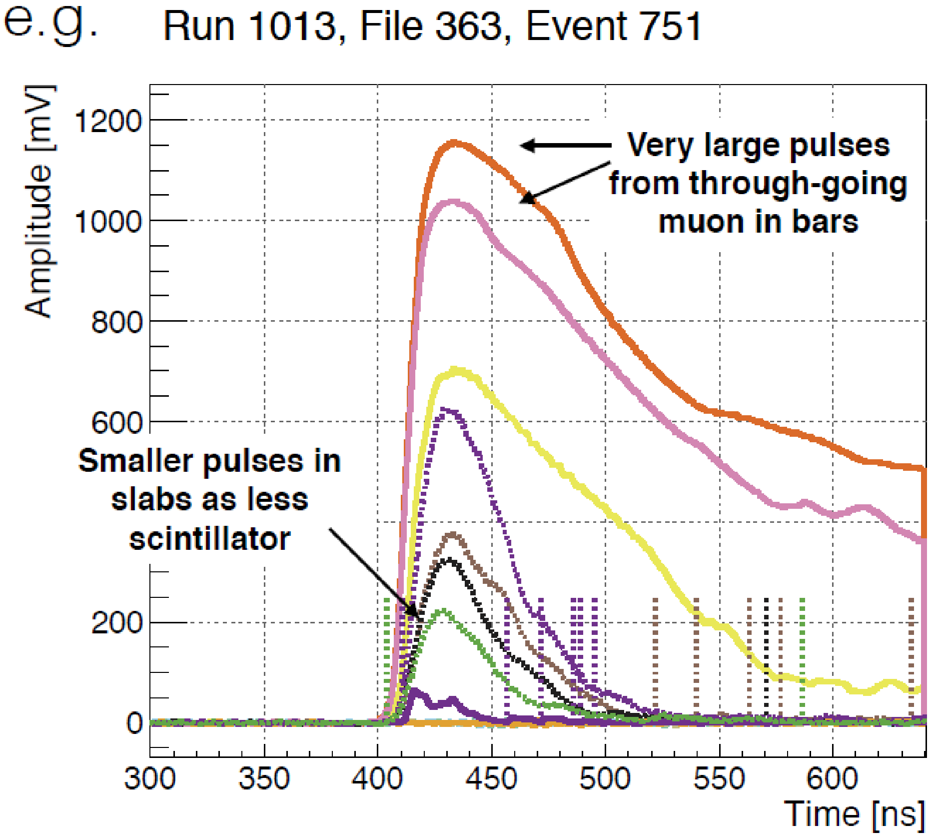


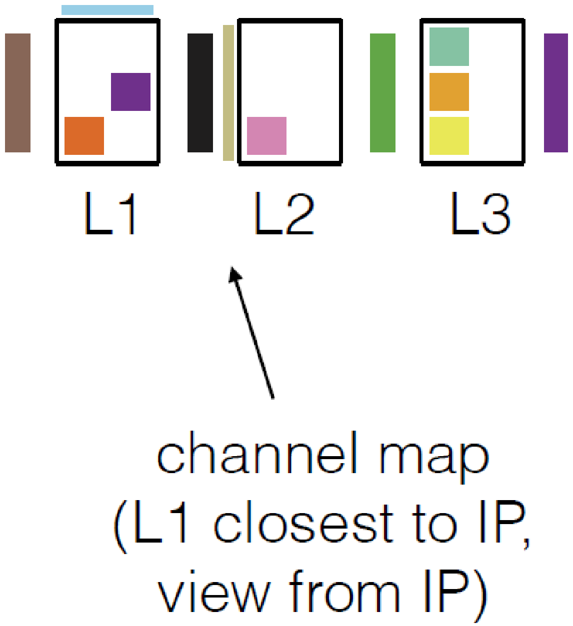
- Operational experience in difficult environment: triggering/DAQ/DQM
- Used for range of studies to prove feasibility and provide crucial insight for full detector
- Key results: alignment, calibrations, background measurements
- Fully simulated in GEANT4
- First search for millicharged particles at a hadron collider!
- Installed on mount designed for full detector

What kind of signals we could have

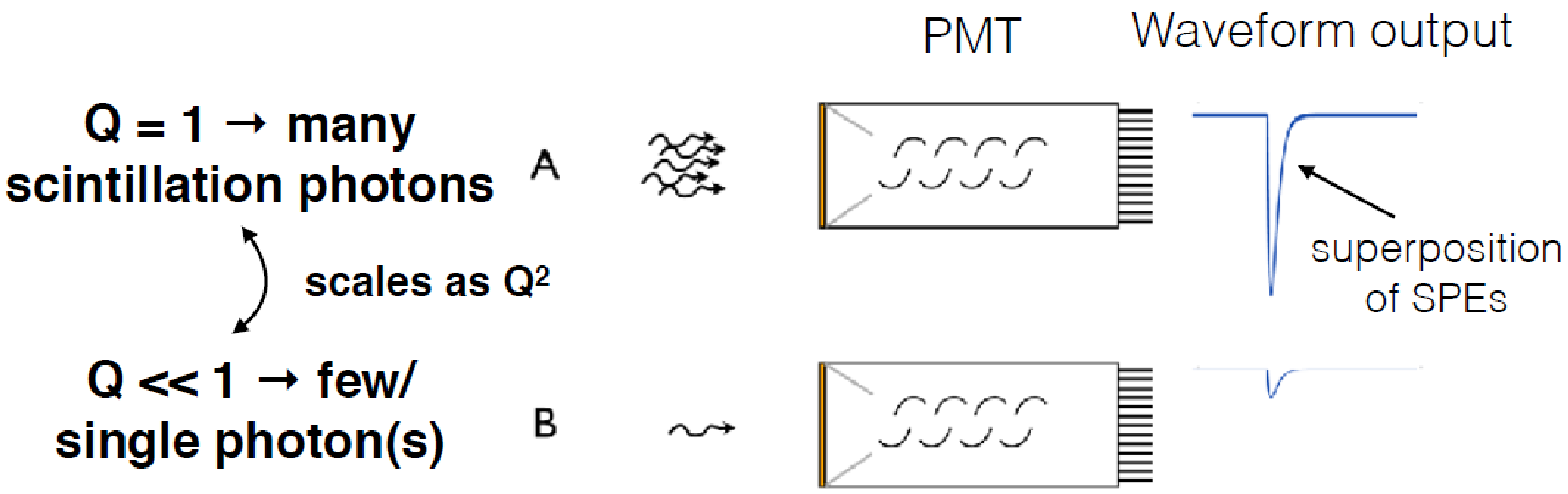
- We need to calibrate and synchronize

e.g.





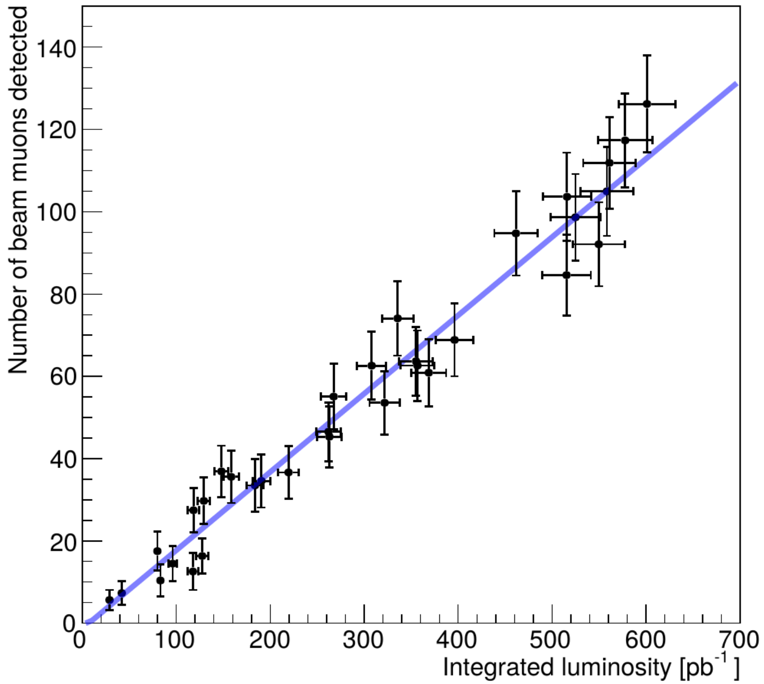
What kind of signals we could have



- Need to know number of photons (NPE) produced for a given Q
- First measure area of single photon events (SPE)
- Then use linearity: NPE(Q=1e) = pulse area (e.g. cosmic)/pulse area SPE
- Vital calibration for detector simulation

Good muons, bad muons: everywhere

- Good Muons: milliQan 'sees' muons from the CMS from interaction point. Check occupancy agreement with expectation
  - Simulate muon production at CMS interaction point
  - Propagate through CMS material and 17 m of rock considering multiple scattering and CMS magnetic field



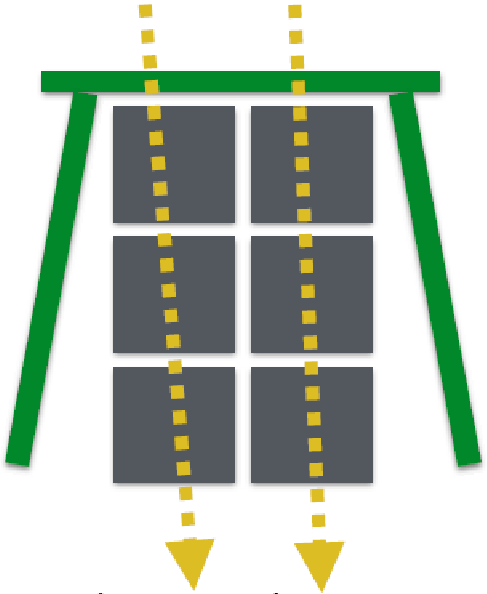
- Measured rate is 0.19=pb-1, consistent with the rate of 0.22=pb-1 predicted from simulation of particles from the IP, which is dominated by muons produced within jets.

Good muons now, bad muons later

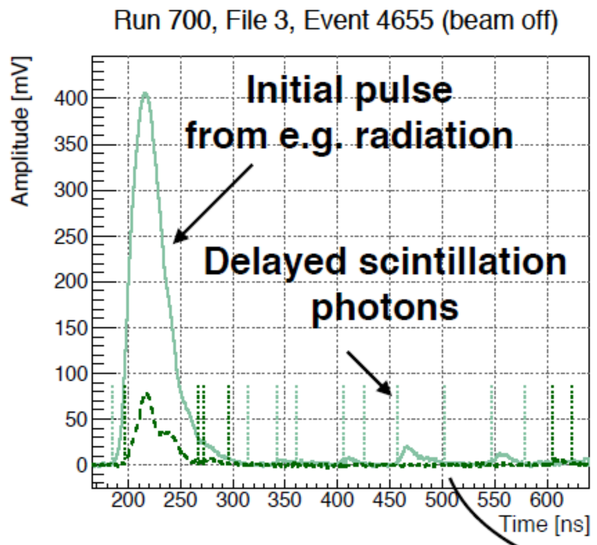
- Not so good Muons used for calibration: milliQan 'sees' cosmic muons, to be eliminated later.
- Select cosmic muon with vertical path
- Use delayed scintillation PEs to measure the SPE response (validated using an LED bench)

N_{PE} = Pulse Area Cosmic muons /pulse SPE

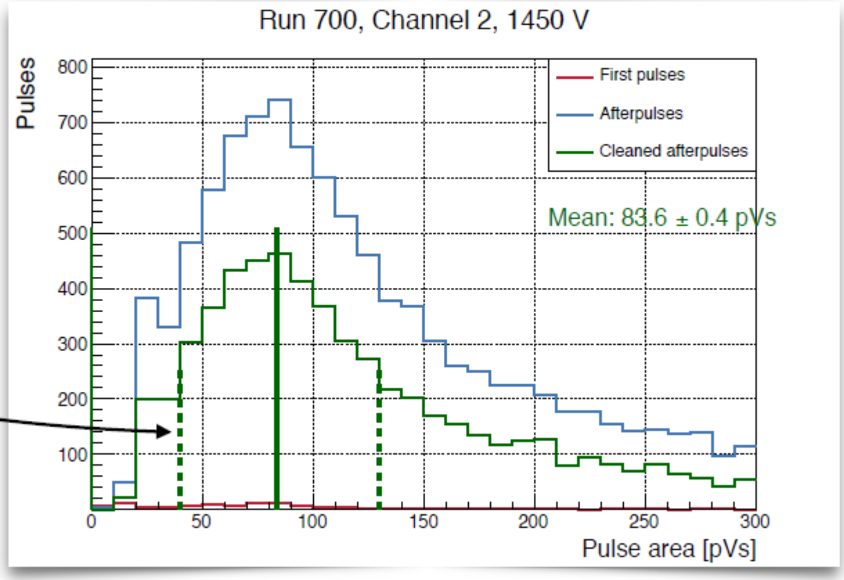
- Use cosmic showers simulation to predict background for Run 3 / HL-LHC



Good muons now, bad muons later



SPE measurement validated using LED on test bench (see backup)



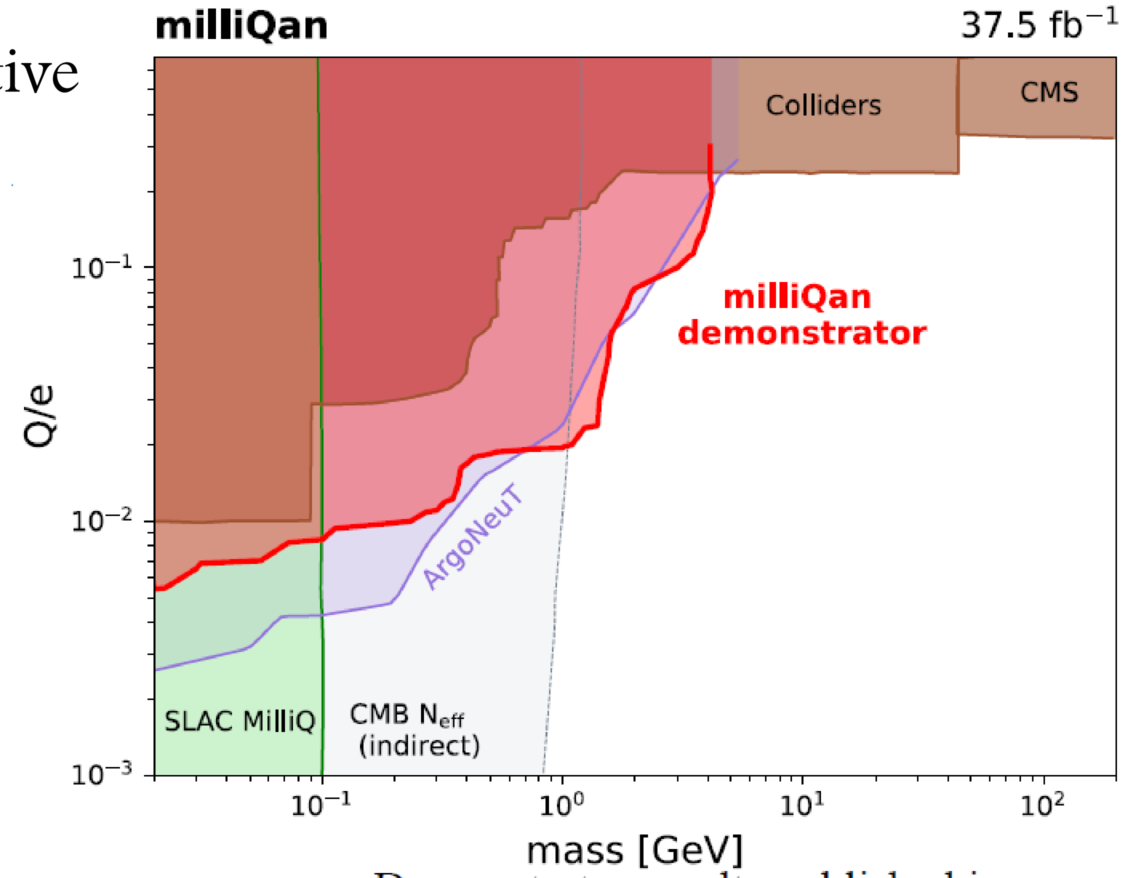
Build up pulse area distribution from 'cleaned afterpulses' (no pulse in preceding 20ns)

e.g. R878 PMT

Mean within half-width-max gives SPE pulse area

Results of demonstrator data

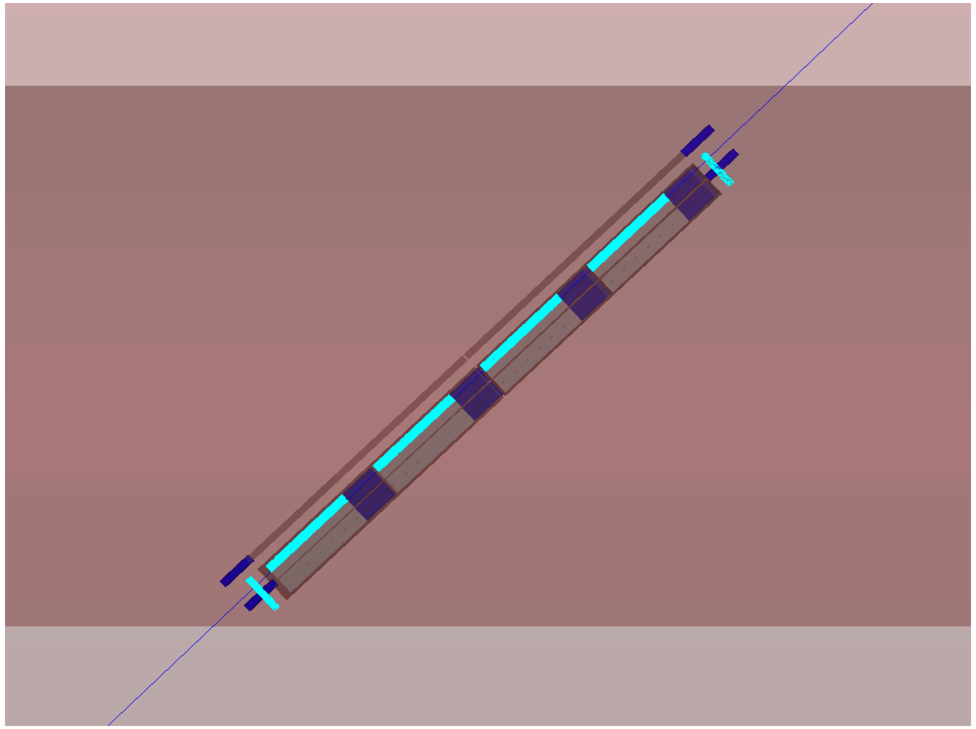
The demonstrator provided quantitative understanding of backgrounds and detector performance



Demonstrator results published in PhysRevD.102.032002.

Lessons learnt: extra layer, larger angles

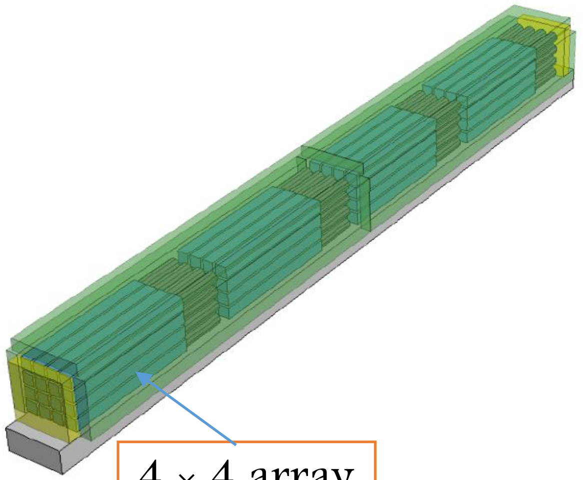
- Calibration of cosmic rate and modelling of crucial variables was performed with four-layer demonstrator data
- Studies with four layer configuration show background is well modelled and under control



Limitation of the bar detector due to the Angular acceptance: → need for large ngle → the new slab detector

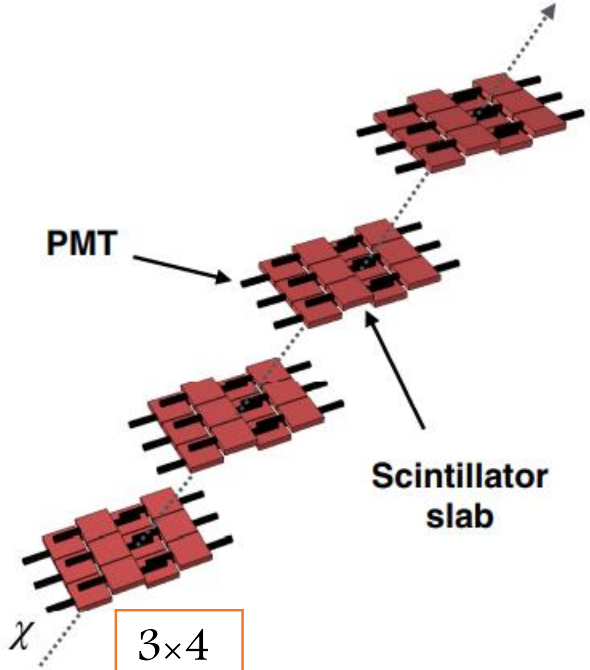
Run 3 detector, Milliqan detector

- Two detectors parts: Bar detector (4 layers), Slab detector



4 × 4 array

Each 5×5×60 cm3 scintillator

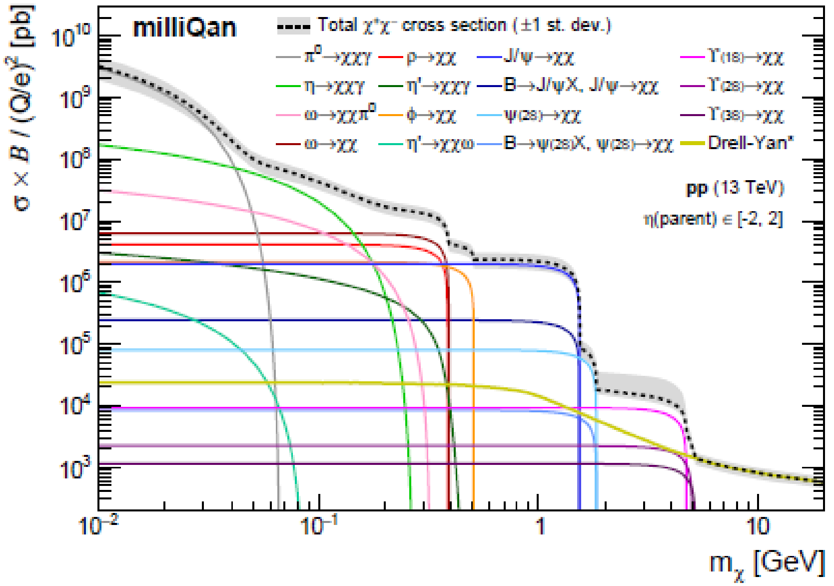


3×4

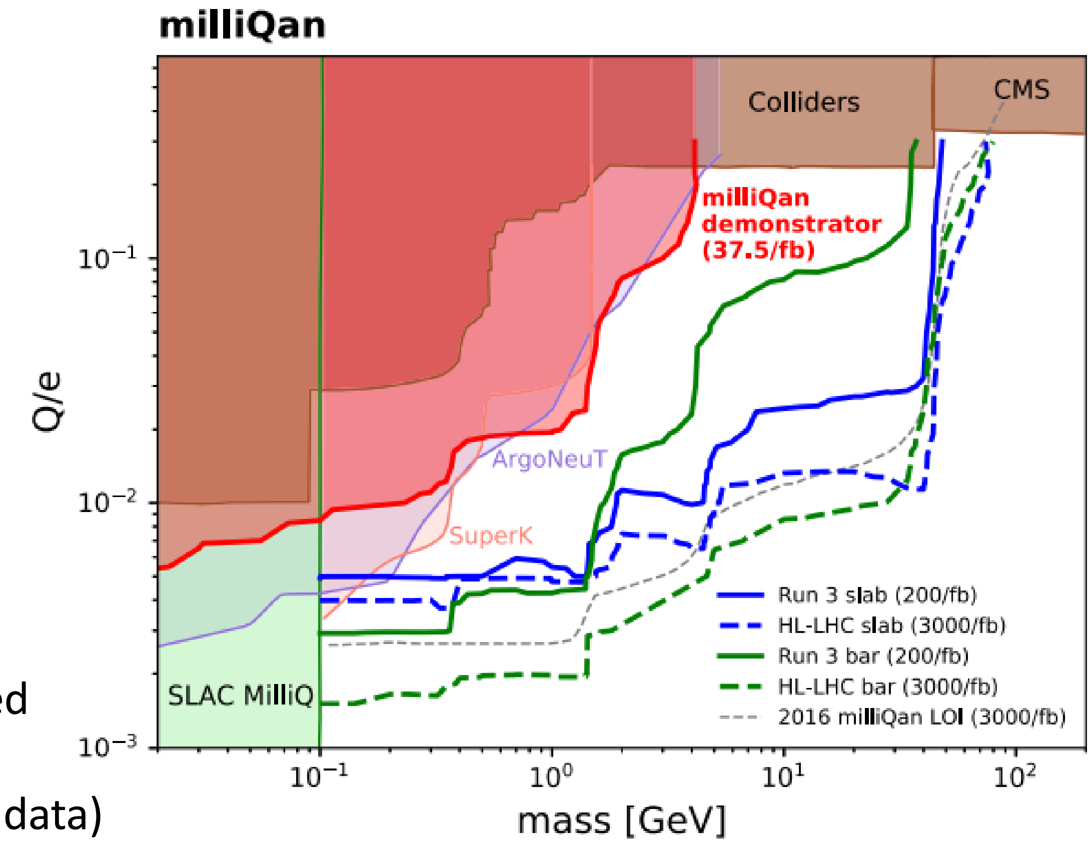
Each: 40 × 60 × 5 cm3 scintillator

Run 3 detector

- Sensitivity projection



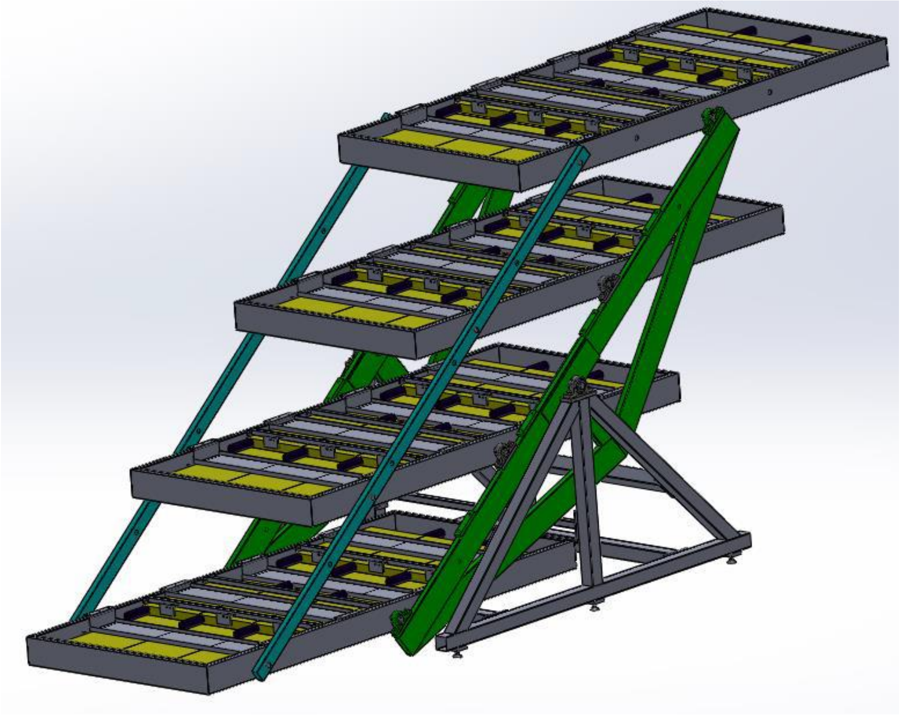
- Wide range of signal production modes considered
- Signal efficiency evaluated with full GEANT4 detector simulation (calibrated with demonstrator data)



PHYS. REV. D 104, 032002 (2021)

Ongoing activities

- Funding already available
- Scintillators-PMT-DAQ under test and packaging
- Mechanics: design almost done
- Easy to install, easy to upgrade:

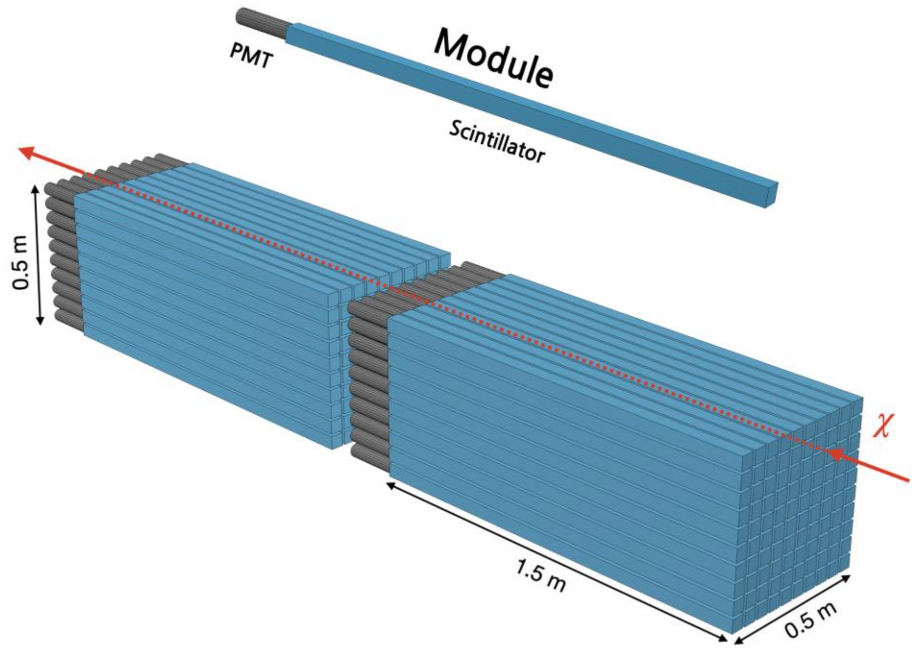


Expectations-Conclusions

- Be ready for run3
- Down to $\varepsilon \sim 10^{-3}$
- significantly extend the parameter space explored for new particles with small charges, and masses above 100 MeV.
- A recent excitement regarding the mCP search is its connection to the explanation to the anomaly reported by the Experiment to Detect the Global EoR Signature (EDGES) collaboration.
- A fraction of dark matter being millicharged would provide a possible explanation of the cooling of gas and thus the enhanced absorption of the 21-cm spectral light, which was observed by the EDGES collaboration.
- A discovery of a mCP? Why not?

Beyond milliqan

- SUBMET (SUB-Millicharge ExperimenT): submitted to JPARC, already funded, awaiting approval, first round positive feedback received recently



Milliqan collaboration

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J. Brooke,
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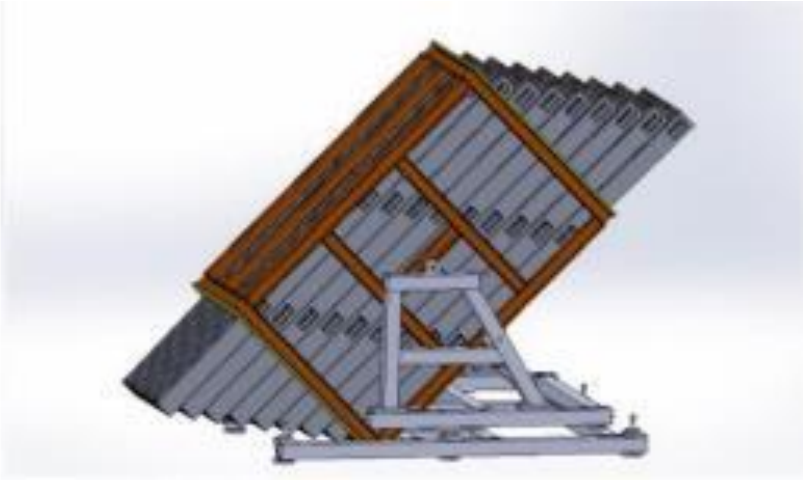
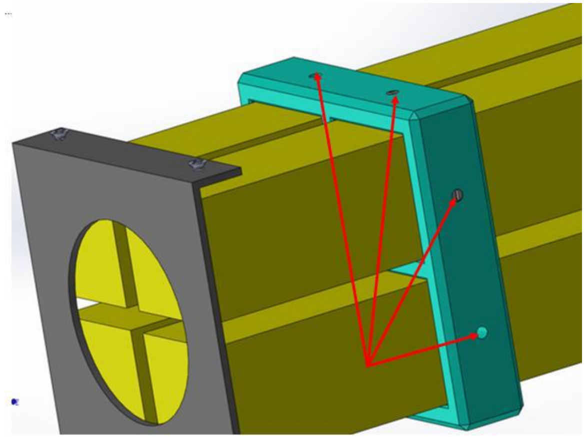
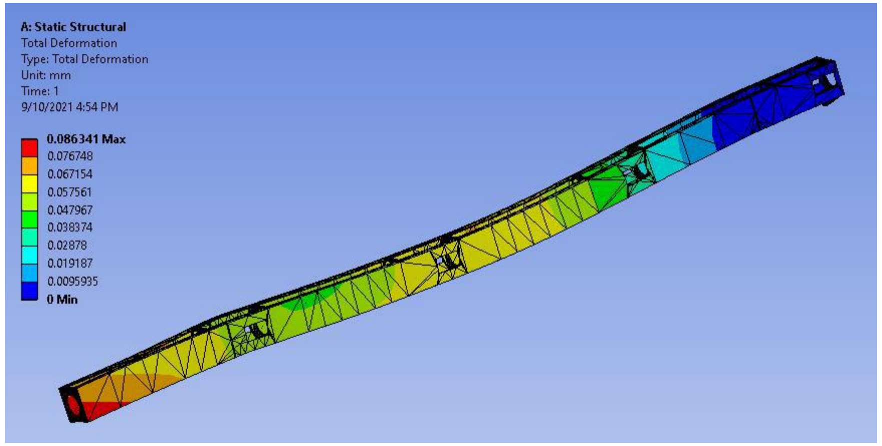
Backup slides

Full CAD

- Full structure Bar design:

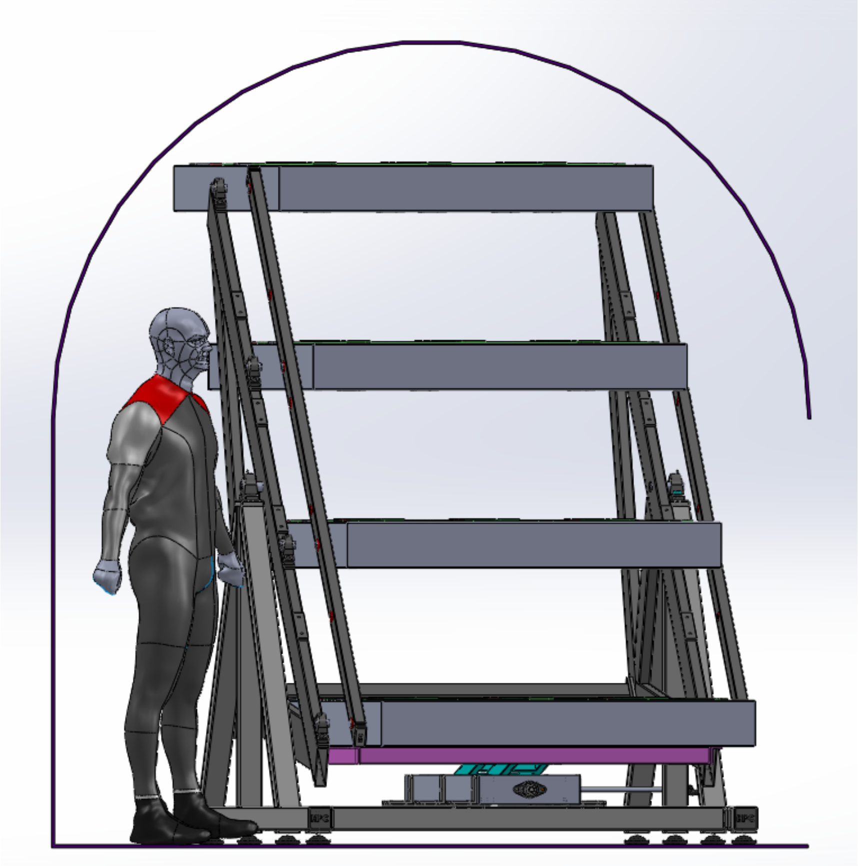


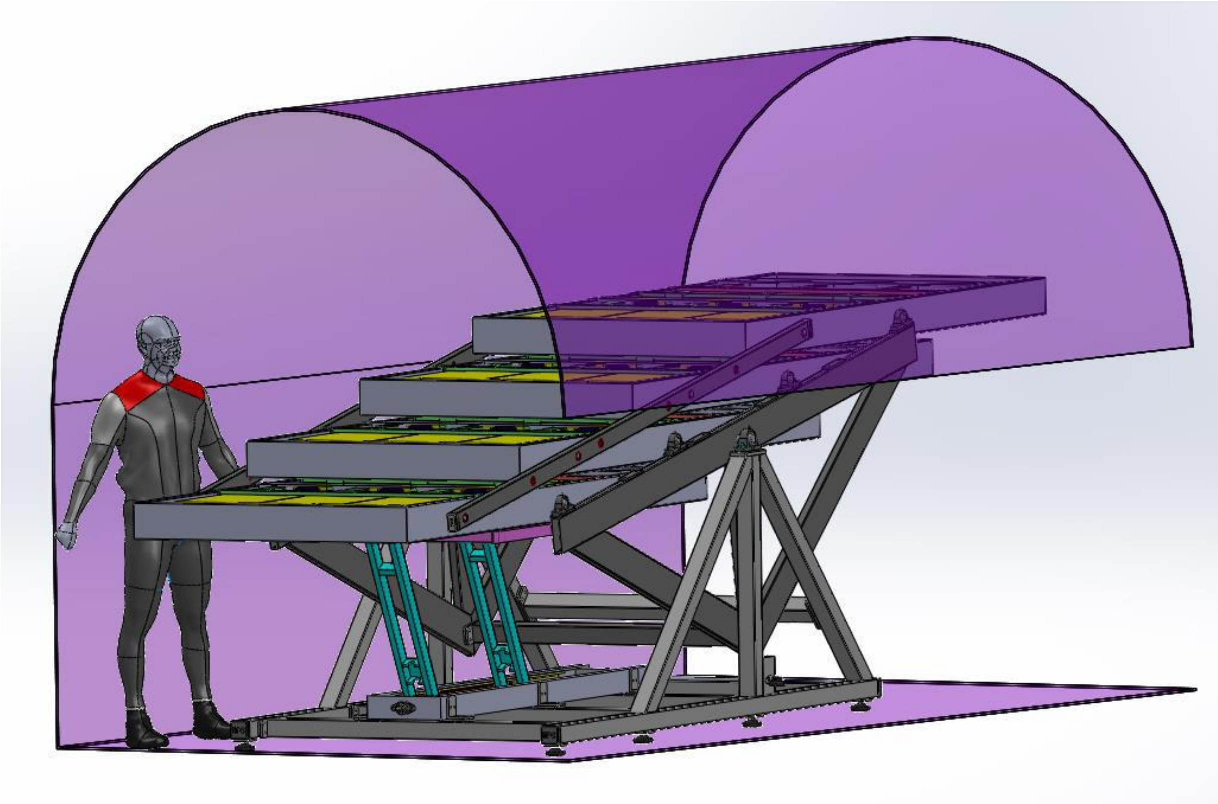




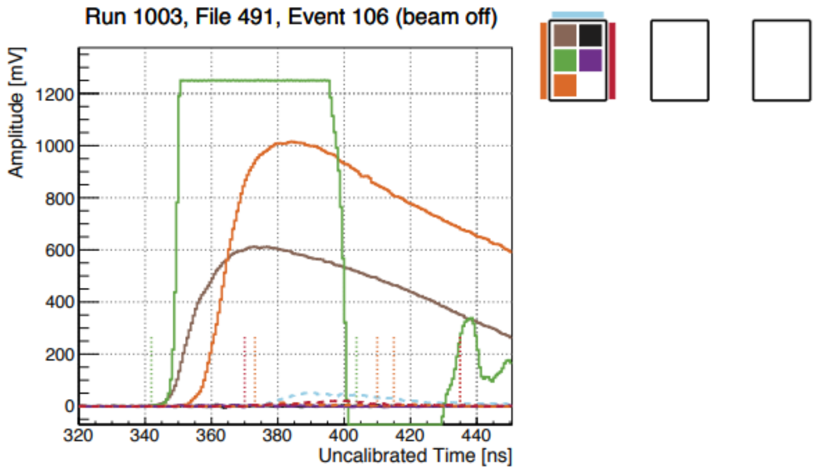
Full CAD

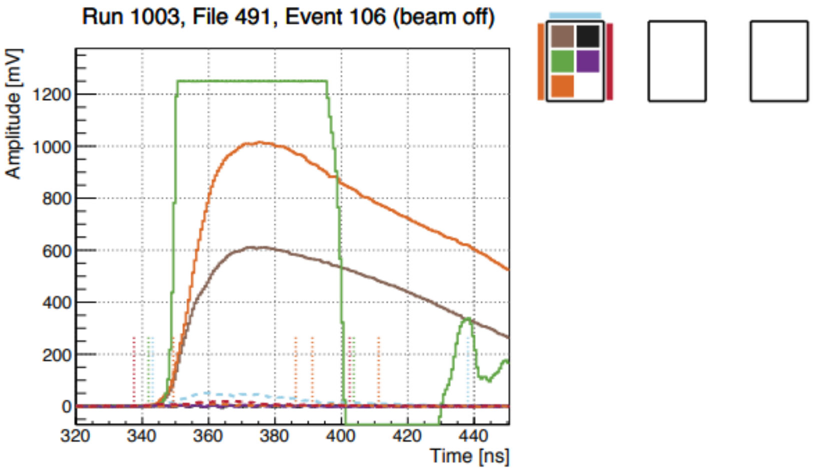
- Full structure design:

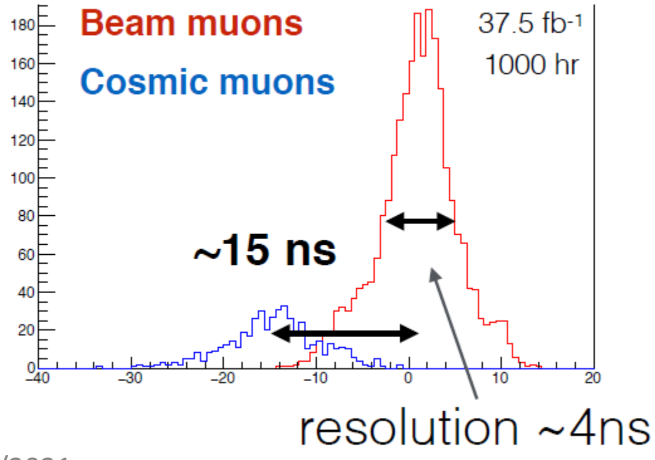


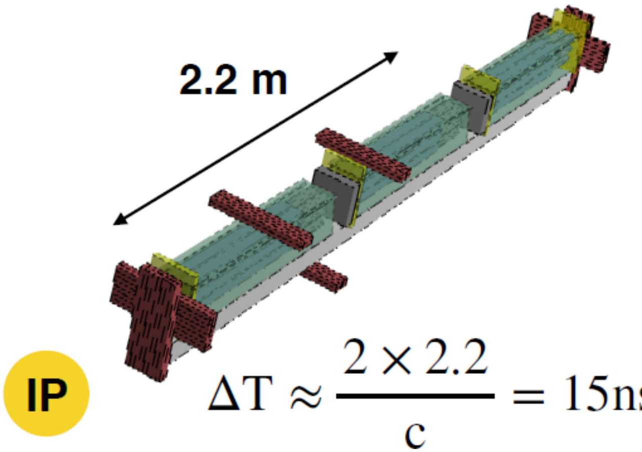


Through going particles









$$\Delta T \approx \frac{2 \times 2.2}{c} = 15\text{ns}$$