A search for millicharged particles at the LHC

Steven Lowette
Vrije Universiteit Brussel – IIHE

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Introduction

The LHC is unique

- only player at the energy frontier
  - since a decade, two more decades to come
- only player at the intensity frontier
  - except well below EW scale, eg. NA62, HPS, Belle2,,…
- whatever LHC is sensitive to should be done now or “never”

The LHC is costly

- maximize return on investment
- what else can we do with the LHC?
  - small investment can make big difference

Plenty of proposals

arXiv.org > hep-ph > arXiv:1708.09395

High Energy Physics - Phenomenology

Searching for Long-lived Particles: A Compact Detector for Exotics at LHCb

Vladimir V. Gligorov, Simon Knapen, Michele Papucci, Dean J. Robinson

arXiv.org > hep-ph > arXiv:1810.03636

High Energy Physics - Phenomenology

Leveraging the ALICE/L3 cavern for long-lived exotics

Vladimir V. Gligorov, Simon Knapen, Benjamin Nachman, Michele Papucci, Dean J. Robinson

arXiv.org > hep-ph > arXiv:1405.7662

High Energy Physics - Phenomenology

The Physics Programme Of The MoEDAL Experiment At The LHC

B. Acharya, J. Alexandre, J. Bernabéu, M. Campbell, S. Cecchini, J. Chwastowski, M. De Montigny, D. Derendarz, A. De Ro

arXiv.org > hep-ph > arXiv:1708.09389

High Energy Physics - Phenomenology

FASER: ForwArd Search ExpeRiment at the LHC

Jonathan L. Feng, Iftah Galon, Felix Kling, Sebastian Trojanowski

arXiv.org > hep-ex > arXiv:1903.06564

High Energy Physics - Experiment

Physics Potential of an Experiment using LHC Neutrinos

N. Beni (1 and 2), M. Brucoli (2), S. Buontempo (3), V. Cafaro (4), G .M. Da
Crescenzo (3), V. Giordano (4), C. Guandalini (4), D. Lazic (5), S. Lo Meo (

arXiv.org > hep-ph > arXiv:1410.6816

High Energy Physics - Phenomenology

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

Andrew Haas, Christopher S. Hill, Eder Izaguirre, Itay Yavin

arXiv.org > hep-ex > arXiv:1901.04040

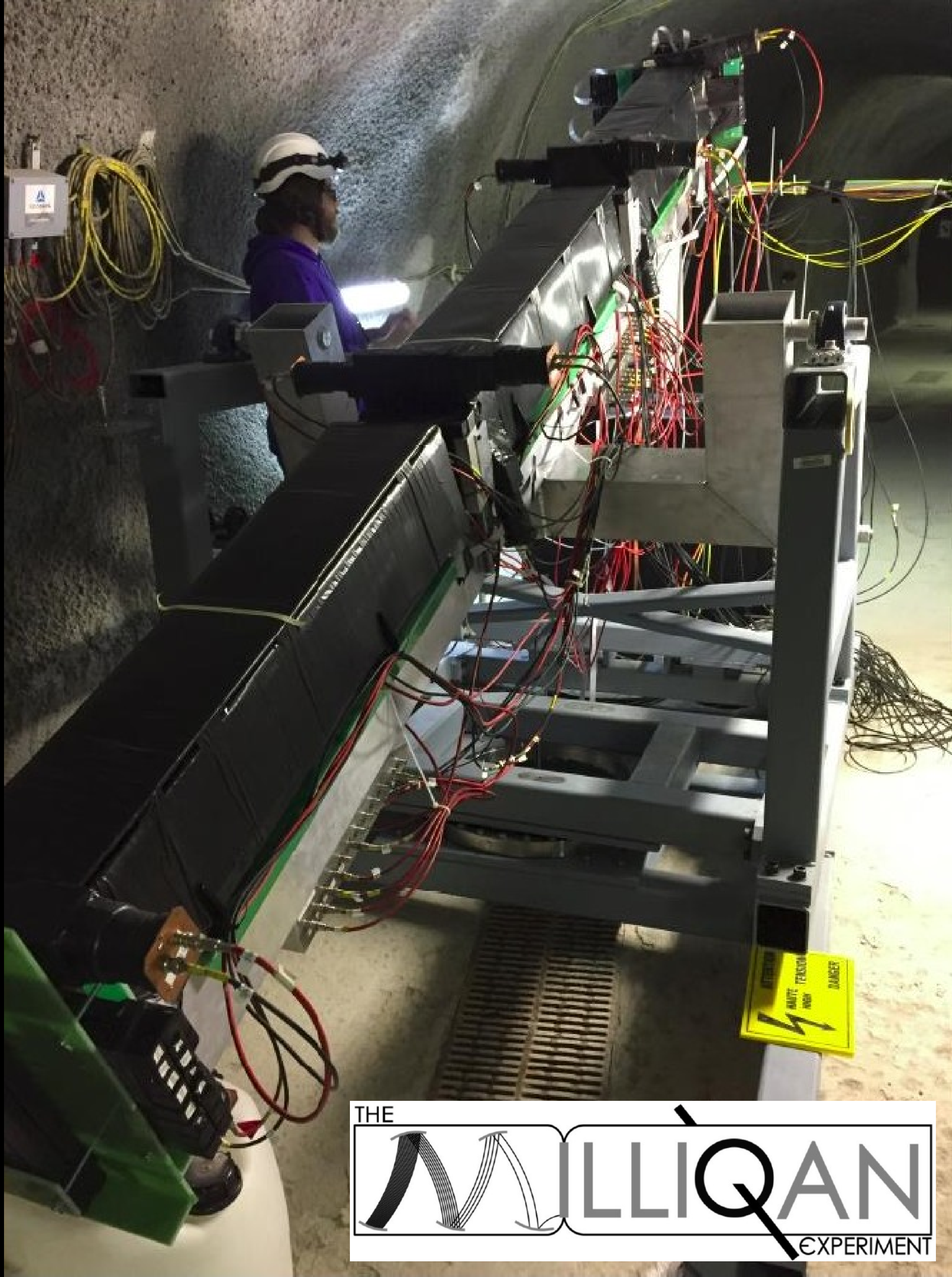
High Energy Physics - Experiment

MATHUSLA: A Detector Proposal to Explore the Lifetime Frontier at the HL-LHC

Henry Lubatti, Cristiano Alpigiani, Juan Carlos Arteaga-Velázquez, Austin Ball, Liron Barak James Beacham, Yan Benhammo, Karen Salomé Caballero-Mora, Paolo Camarri, Tingting Cao, Roberto Cardarelli, John Paul Chou, David Curtin, Albert de Roeck, Giuseppe Di

milliQan

New experiment to search for millicharged particles at the LHC



Milli charges?

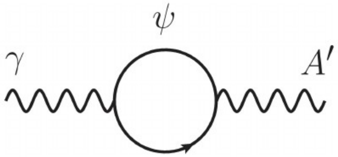
How does that even work?

- we take charge quantization for granted, but it's actually not understood
  - non-unity charges may actually arise rather naturally
- toy model: add to the SM
  - a U(1)' massless boson
  - a new fermion only charged under U(1)'

kinetic mixing [Holdom '86]

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} B'_{\mu\nu} B^{\mu\nu\prime} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} + i\bar{\psi}(\partial\!\!\!/ + ie'B' + iM_{\rm mCP})\psi$$

- after a field redefinition $B' \to B' + \kappa B$ and EWSB, we now “feel” the new fermion to have electric charge $Q = \kappa e' \cos\theta_W$
- note: kinetic mixing via new particle loop gives Q ~ 10^{-3} for m_ψ ~ EW scale

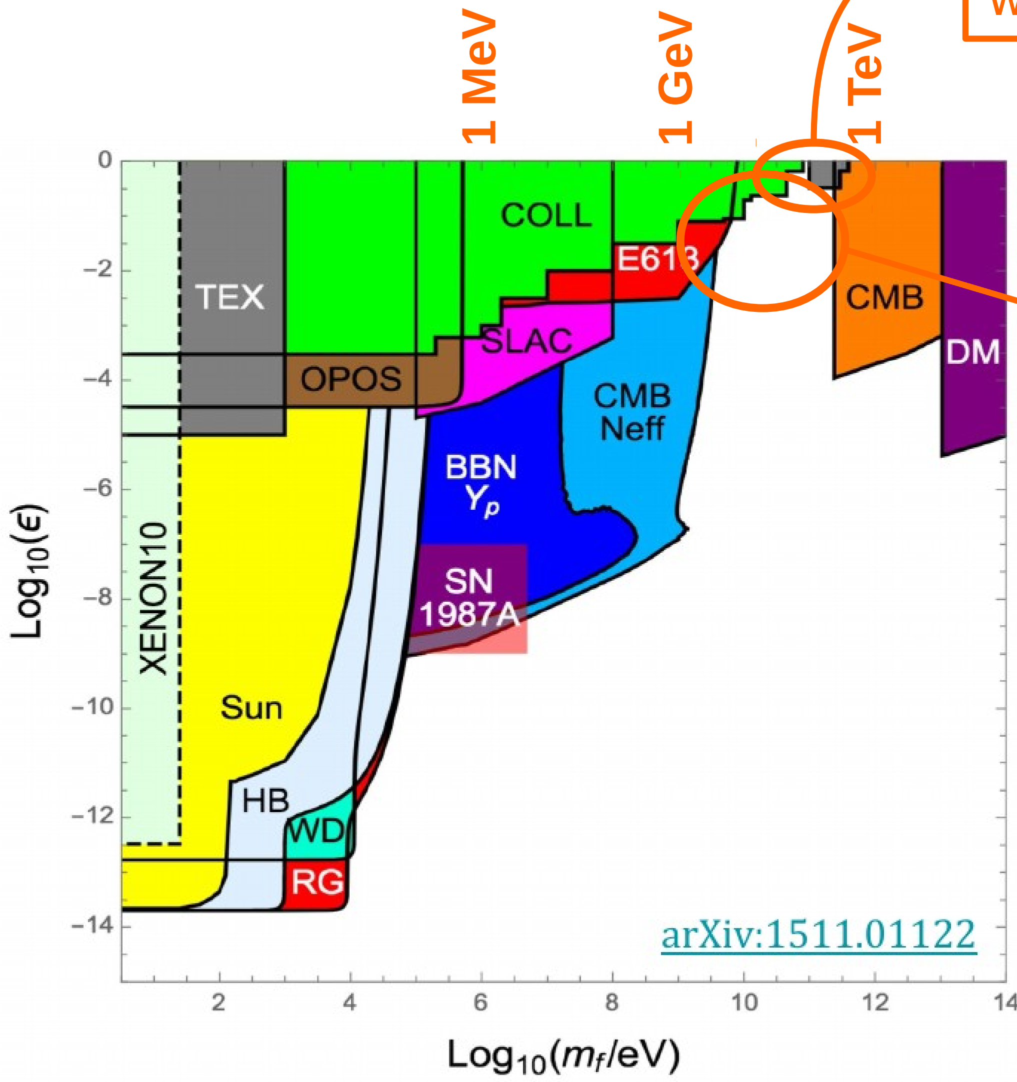


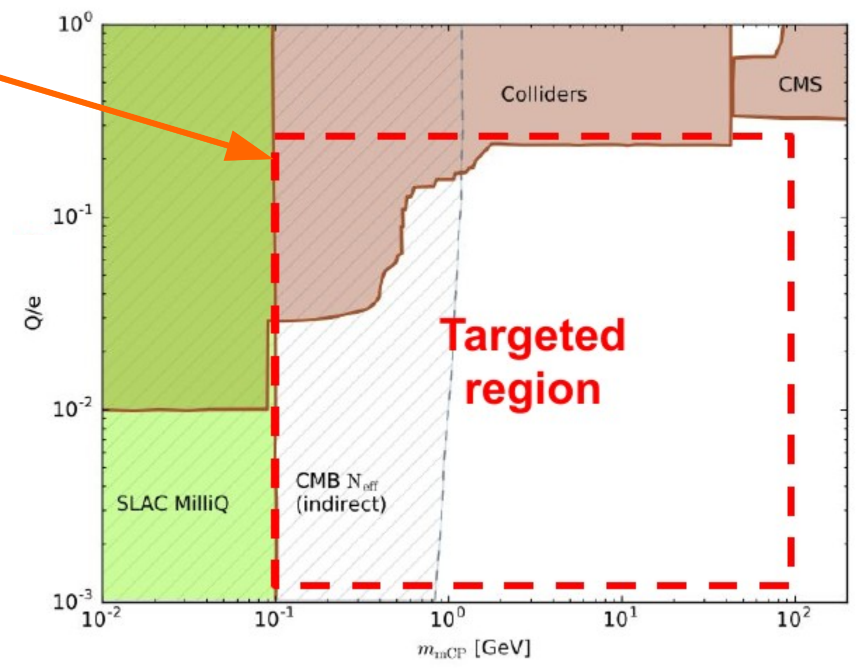
$$\sim \frac{e\, g_D}{16\pi^2} \log \frac{m_\psi}{M_*}$$

Milli charges

Experimental status

CMS results from David's thesis will go here

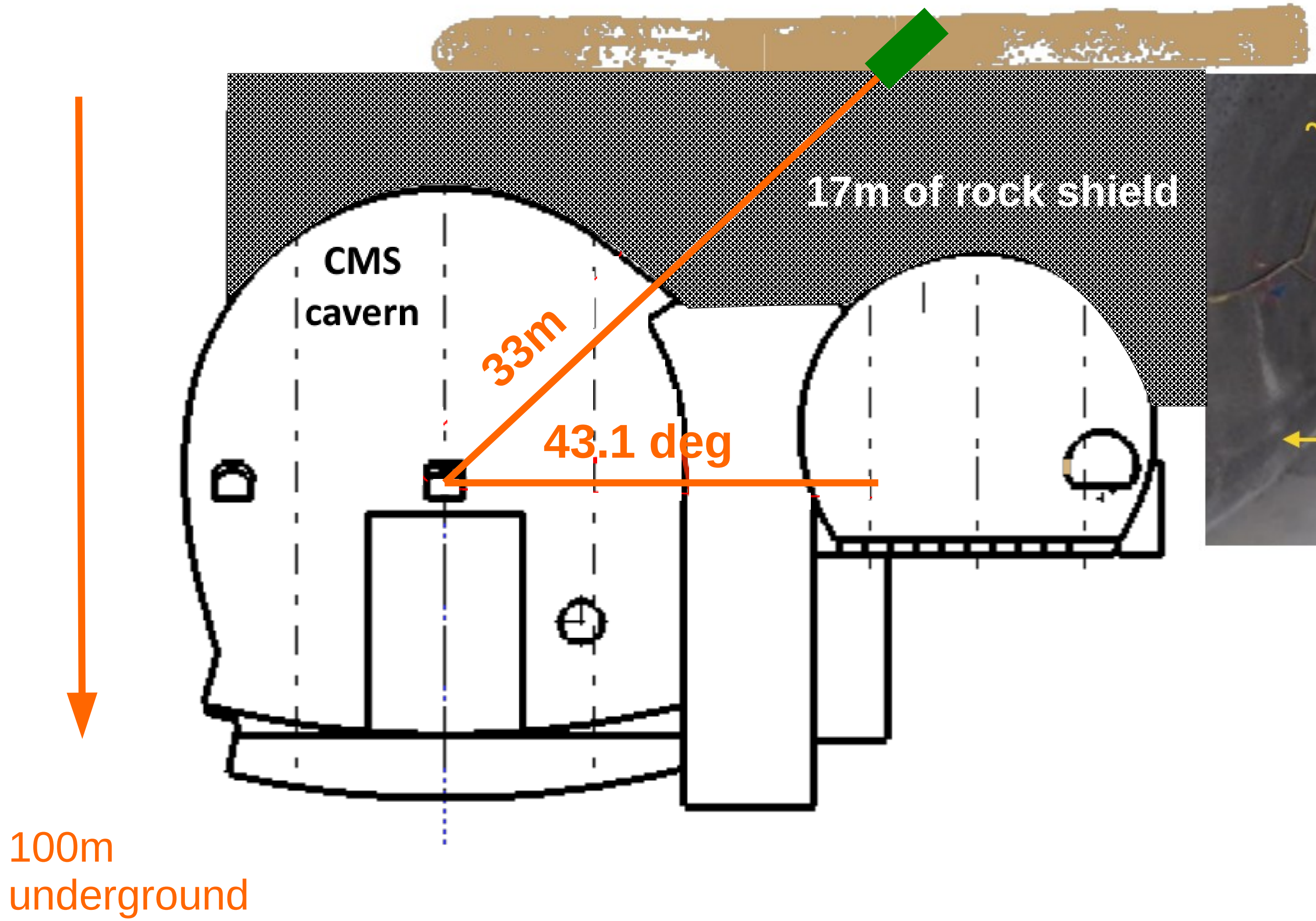


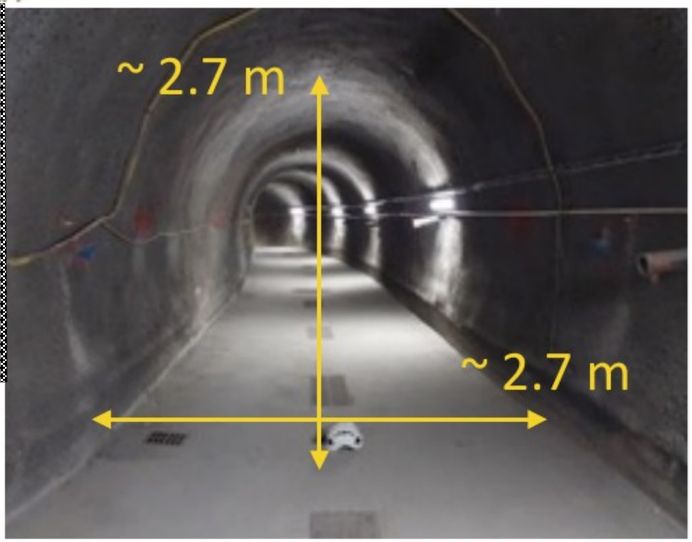


Going low in charge

- needs very sensitive detection technique
  - for Q ~ 10^{-3}, ionization energy loss suppressed by 10^{-6}
  - counting of single photons in “large” scintillator volume
- need to go to a low-background area
  - out of the CMS cavern, to suppress radiation backgrounds (eg. neutrons)
  - still shielded from cosmic muons by ~100m overburden
- stay relatively close to the interaction point
  - r^2 dependence of flux

milliQan location

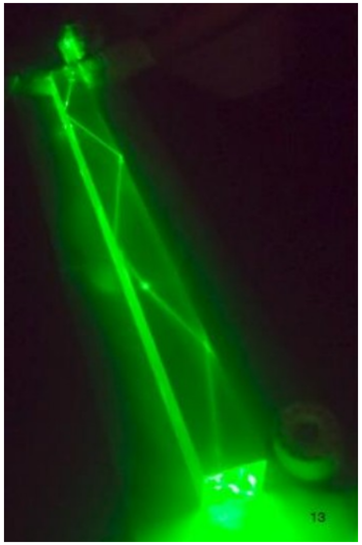


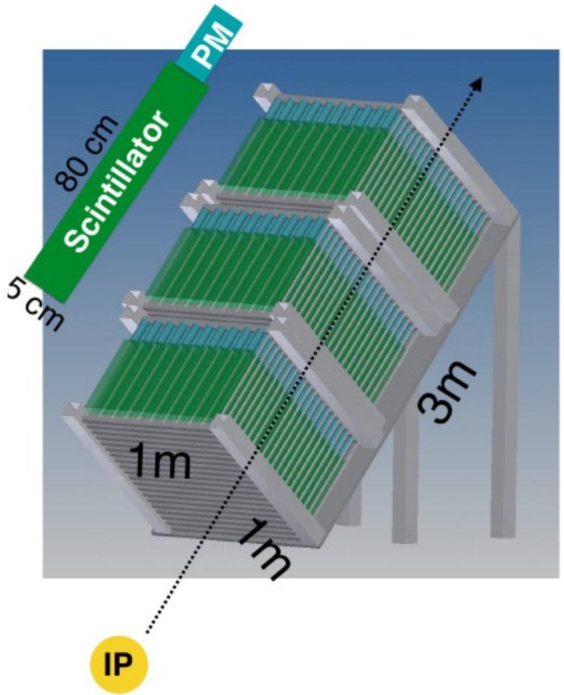


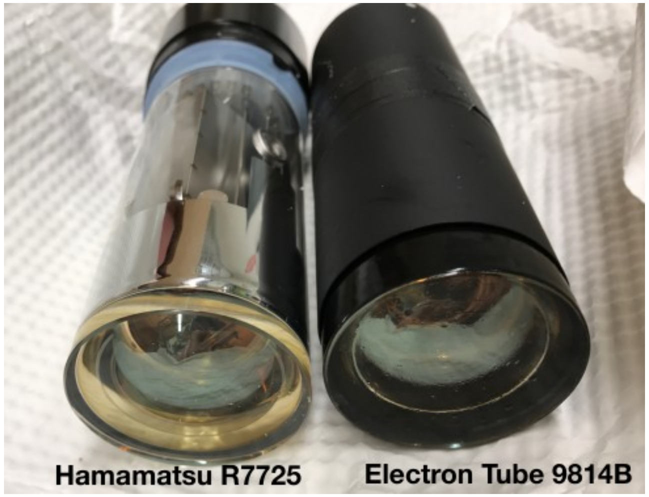
milliQan detector principle

Single photons in scintillators

- basic element is 5x5x60 cm³ plastic scintillator
- attached to photomultiplier tube
- 1x1x3 m³ in 3 or 4 length-layers
- full simulation available



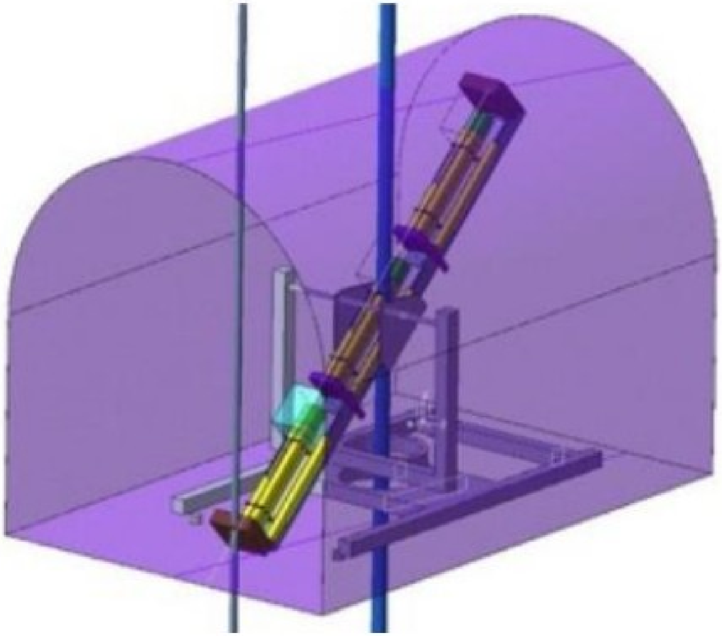


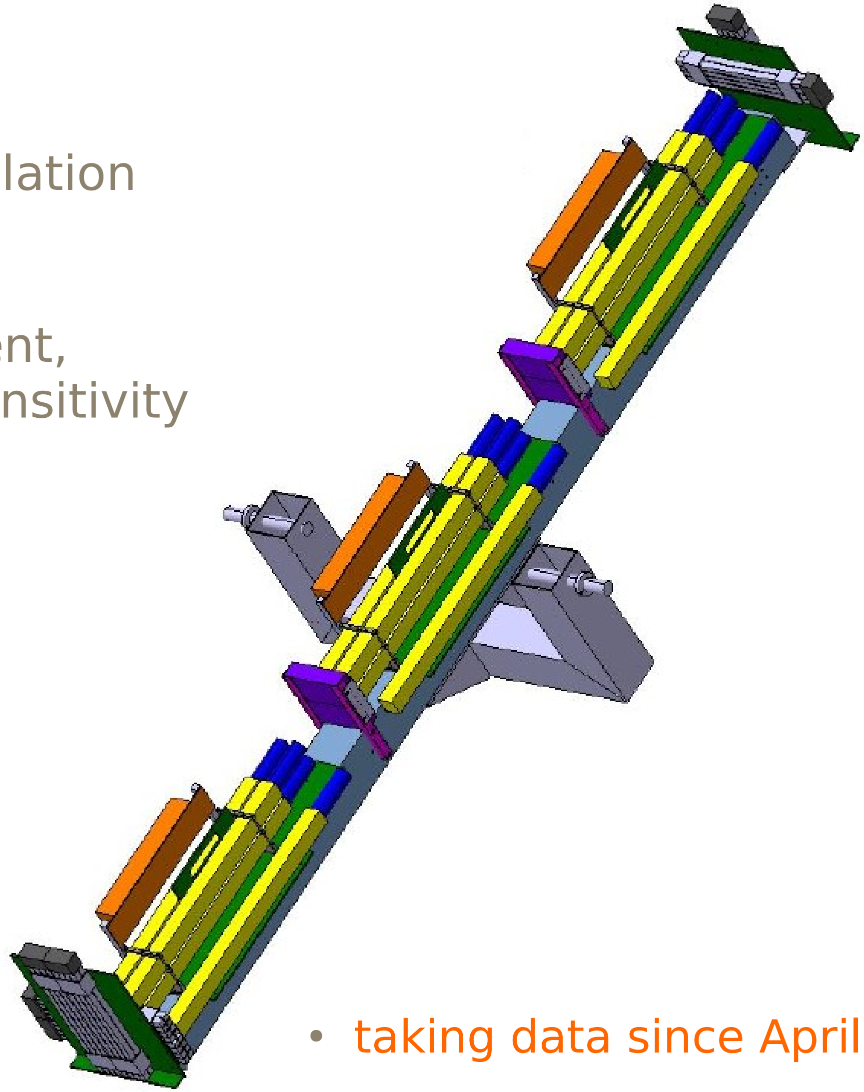


Demonstrator

1% prototype test

- exercise detector assembly and installation
- operate experiment remotely
- measure backgrounds, check alignment, calibrations, simulation, determine sensitivity
- input for final design





- taking data since April '18
  - 2000h, 37/fb
  - many no-beam runs

Demonstrator

Backgrounds

- collisions
  - 17m of rock removes all SM background from LHC collisions
  - ~15 muons / min make it through the rock, but they're clearly not milli-charged

    actually, they emit so many photons that they saturate the detector
- cosmic muons
  - rate ~100 times smaller than on surface
  - comparable to collider muon rate
  - induce showers in rock with neutrons, γ's, etc

    use the active vetos / outer layer to suppress this background
- random dark-pulse background
  - need 3 coincident pulses
  - can be reduced with cooling
- radiation within PMTs and cavern walls

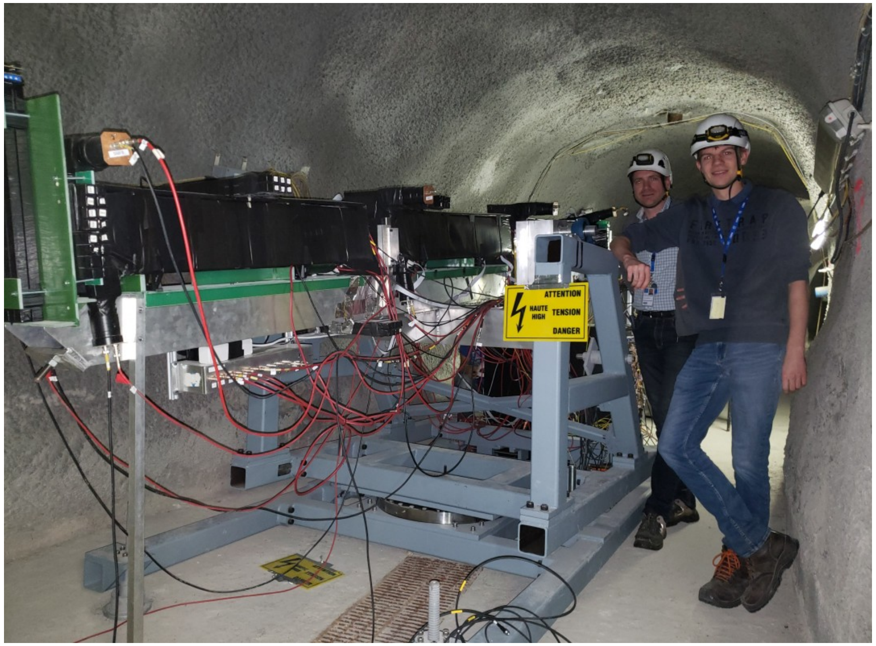
muons easy to reject

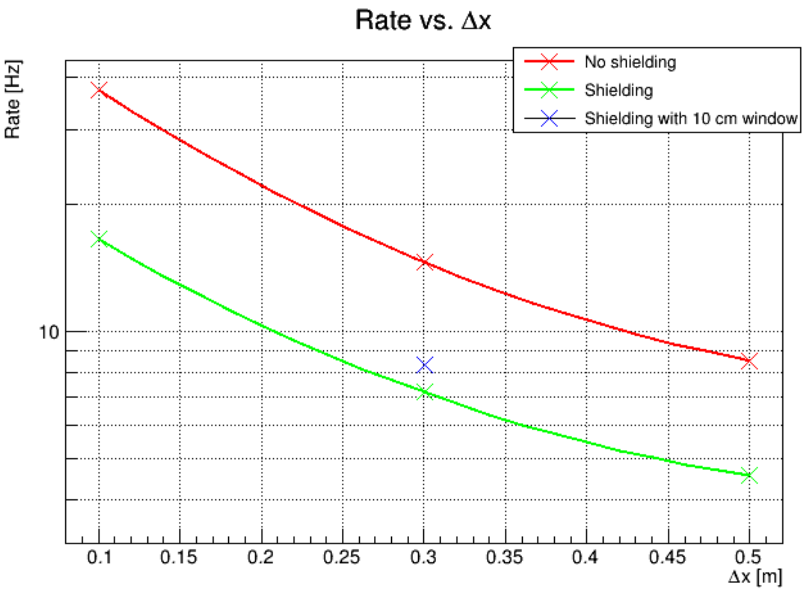
reject using vetos, timing, correlations neighbouring scintillators, etc

Demonstrator

Deepen background studies

- we (with Yens Elskens, VUB MA2) took up studying background in situ when no beam
  - measuring coincidences when between 2 scintillators
- identify sources, whether problematic and what can be done about it
  - identify cosmic (showers)
  - rejection of noisy periods
  - time difference studies
  - dependence on shielding / separation
  - ...
  - simulation!
- study cosmics: rates, multiplicities and angular distributions

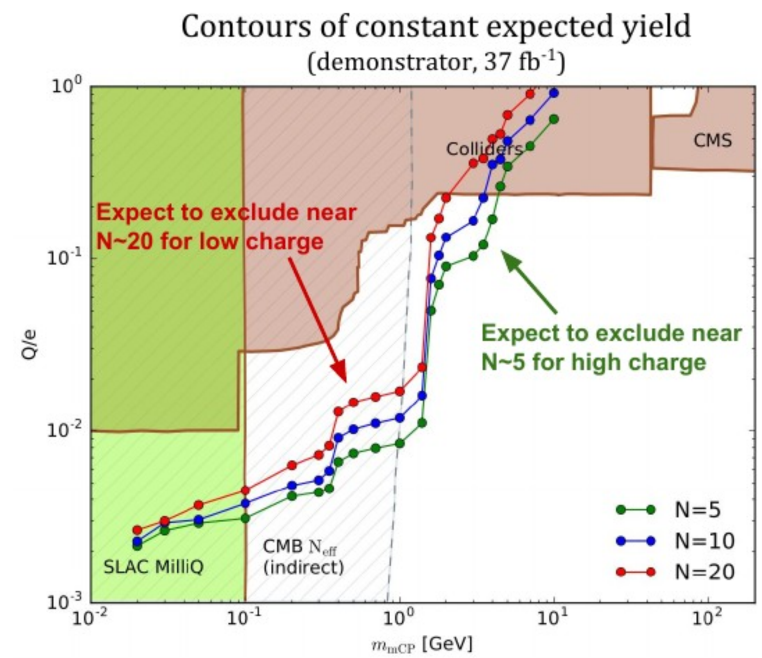




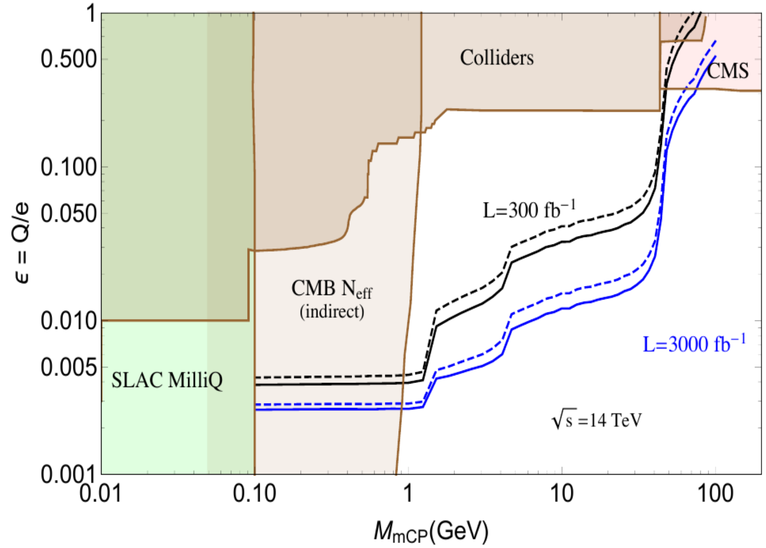
Sensitivity

Background control is key

- demonstrator analysis wrapping up
  - publication goal this winter
- preview:
  expected limits versus number of B
  - expect to exclude along red line for low charge
  - expect to exclude along green line for high charge



- old background estimate in LoI:
  - 165 events in Run-3 (300/fb)
  - 330 events during HL-LHC (3000/fb)
- update soon



arXiv:1607.04669 [physics.ins-det]

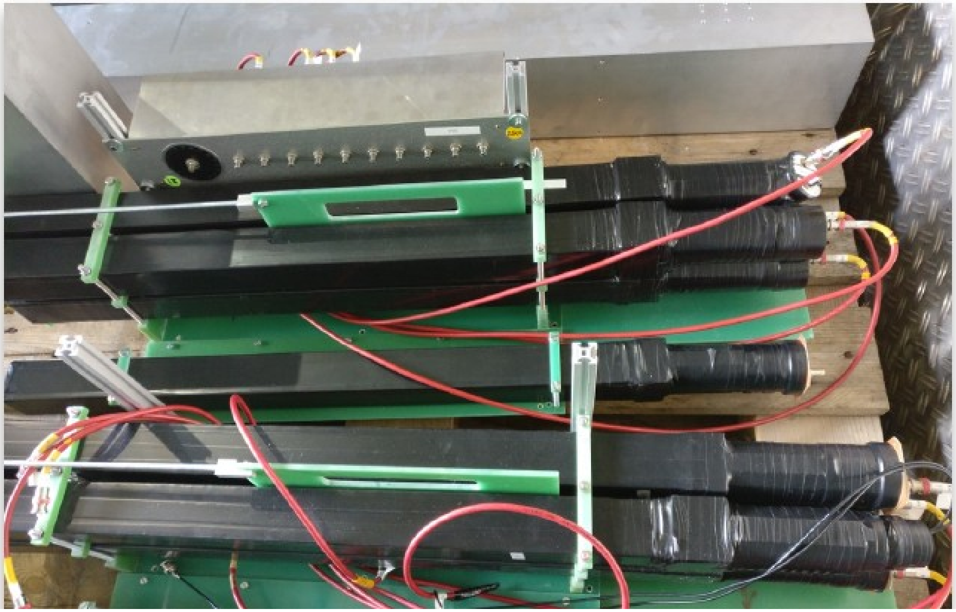
Next steps

Detector assembly “easy”

- R&D done, ready to build – when funded…

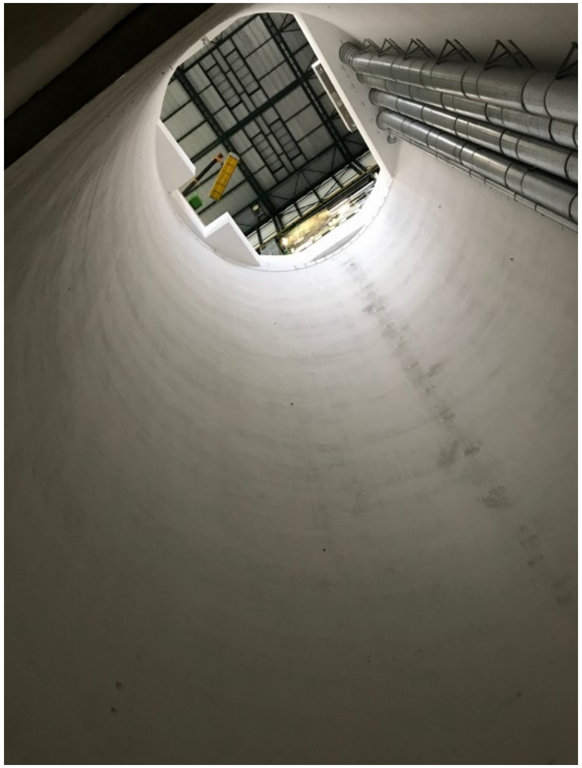
3D printed
PMT casing

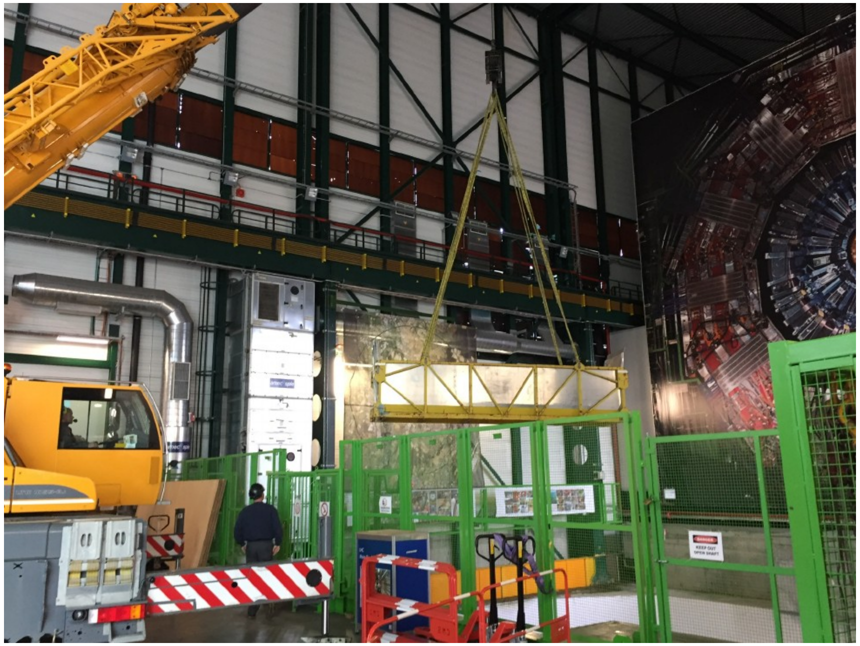
Bars wrapped in layers of reflective
and light blocking materials
(including tyvek, tinfoil, electrical tape)

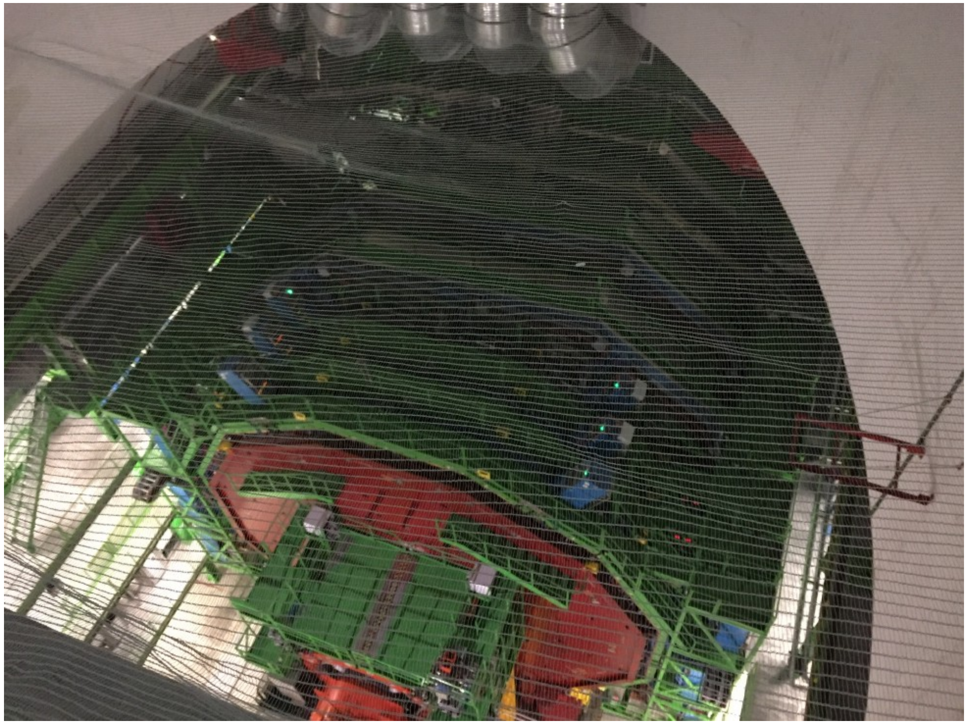


Next steps

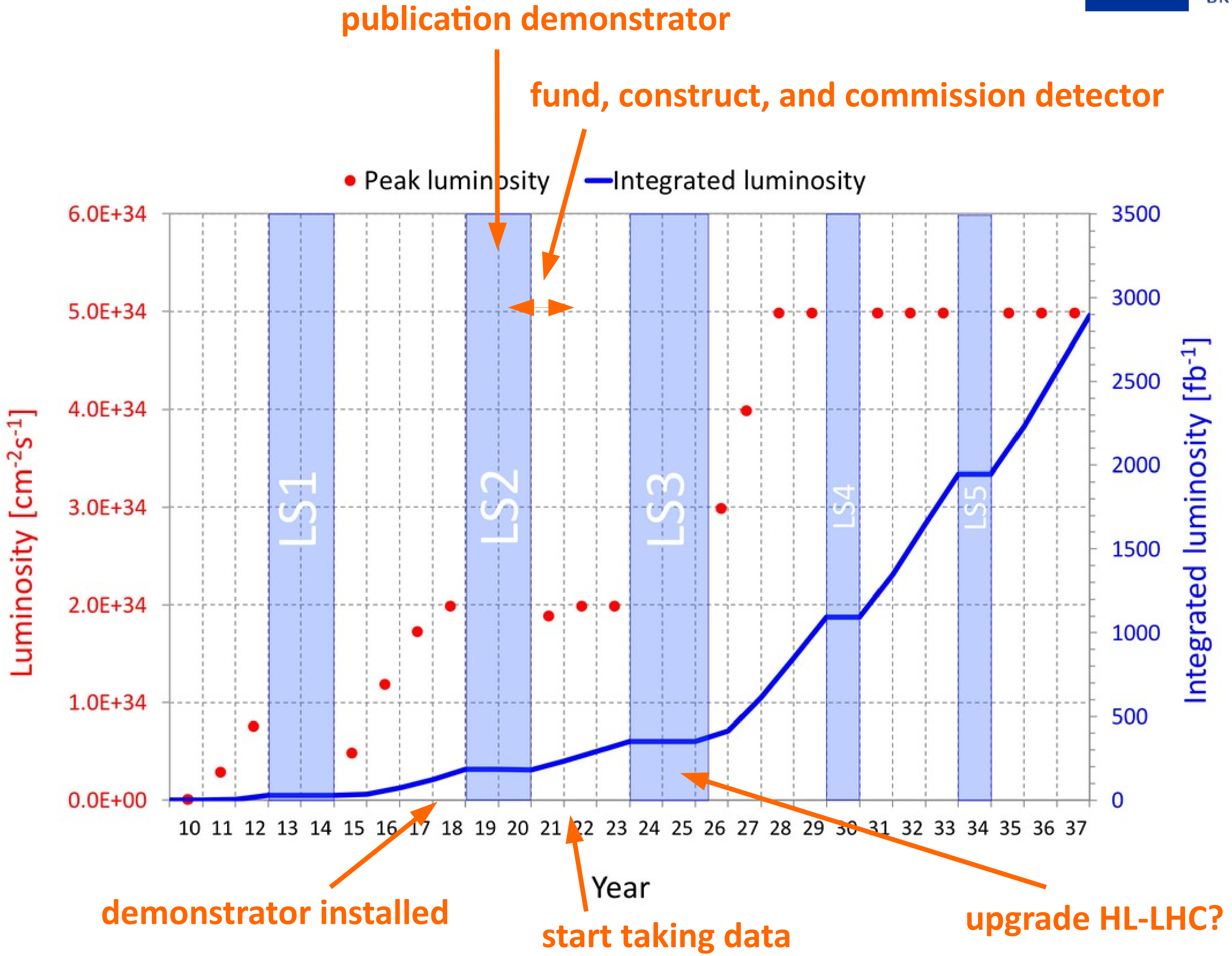
Installation







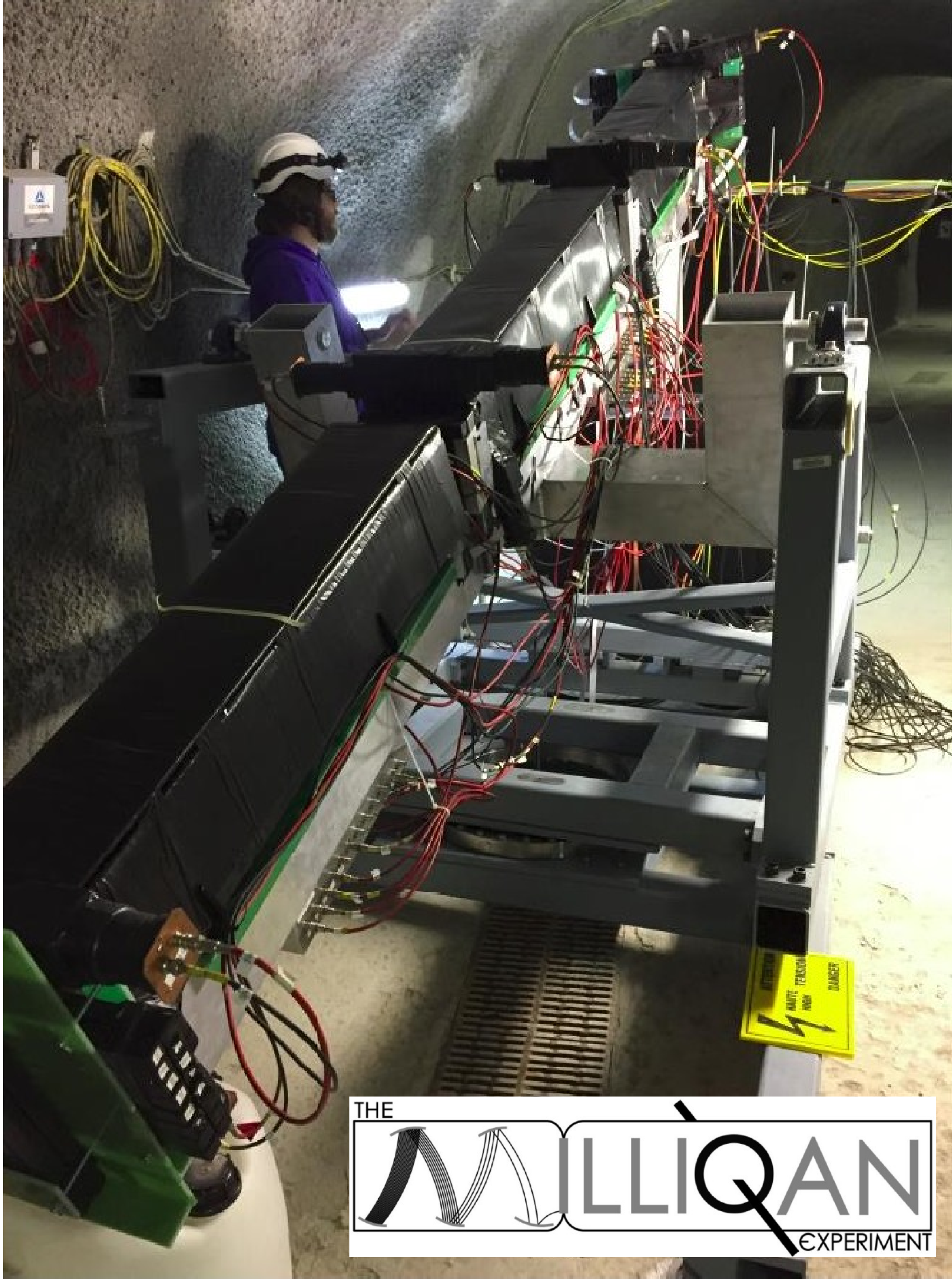
Next steps



publication demonstrator
fund, construct, and commission detector
Peak luminosity
Integrated luminosity
Luminosity [cm-2s-1]
Integrated luminosity [fb-1]
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
3500
3000
2500
2000
1500
1000
500
0
LS1
LS2
LS3
LS4
LS5
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
Year
demonstrator installed
start taking data
upgrade HL-LHC?

Conclusions

- the milliQan detector will provide unique sensitivity to millicharged particles
  - uncovered phase space
    $0.1 < m < 100$ GeV, $Q < .3e$
- 1% demonstrator successfully validates feasibility
  - successful construction and operation
  - upcoming paper with lessons learned and first sensitivity
- joined background studies
  - radiation dominant?
- ready to build the full detector



The MILLIQAN Collaboration

C. Hill,
B. Francis,
M. Carrigan

D. Stuart, C. Campagnari,
M. Citron, B. Marsh,
R. Schmitz, F. Setti, B. Odegard

A. Haas,
G. Beauregard

D. Miller,
M. Swiatlowski

S. Lowette
Y. Elskens

R. Ulrich

A. Ball, A. De Roeck,
M. Gastal, R. Loos

M. Ezzeldine,
H. Zaraket

F. Golf

J. Brooke,
J. Goldstein

Backup

Towards discovery at LHC

Run 1: 2010-2012

- 7-8 TeV, 25/fb
- long-standing targets: Higgs boson, $B_s \to \mu\mu$, QGP, …
- many limits on SUSY, ED, 4^{th} gen, etc

Run 2: 2015-2018

- 13 TeV, 140/fb
- hard / rare processes: tt/H/bb, B anomalies, $\not{CP}$ in charm, … [and γγ(750)…]
- many more limits on BSM physics

Run 3: 2021-2023

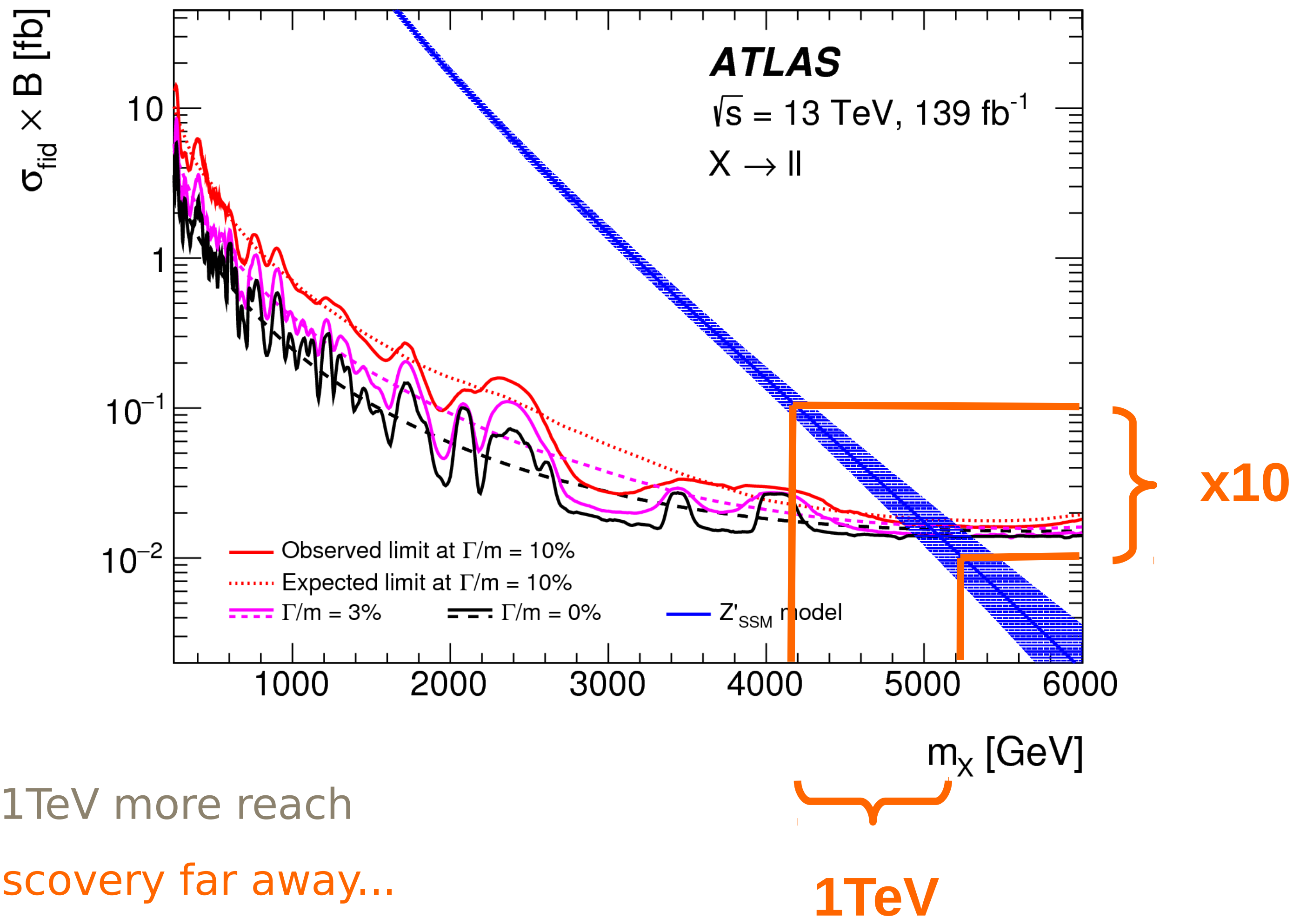
- 14 TeV, 220/fb
- aim for lower mass, lower cross section, difficult final states (eg. LL)
- BSM sensitivity? more lumi needed!

Towards discovery at LHC

Much more lumi – but how much?

- eg. Drell-Yan cross section ~ 1 / q^4

arXiv:1903.06248 [hep-ex]

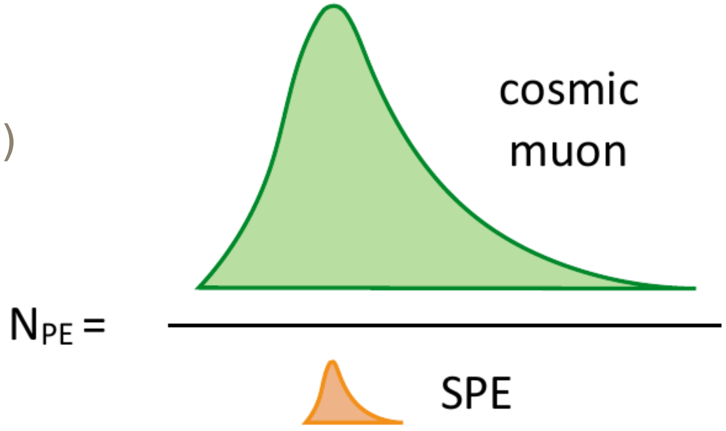


- factor 10 in lumi → 1TeV more reach
  - no hint yet → discovery far away...

Demonstrator results

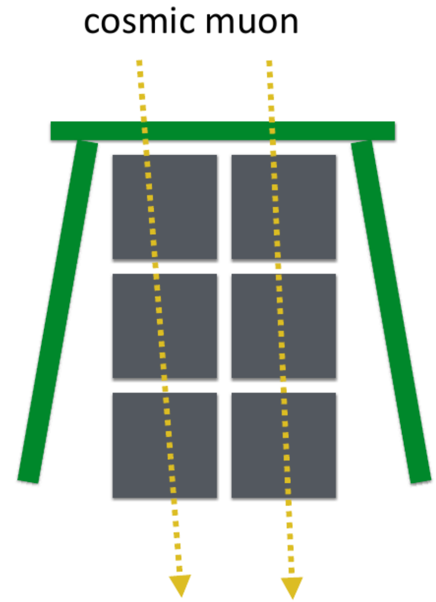
In situ charge calibration

- calculate N_{PE} for cosmic muons (Q = 1e)
  - N_{PE} = Pulse area (cosmic muon) / Pulse are (SPE)
- extrapolate it to fractional charges by Q^2



- this tells us how small a charge milliQan can detect

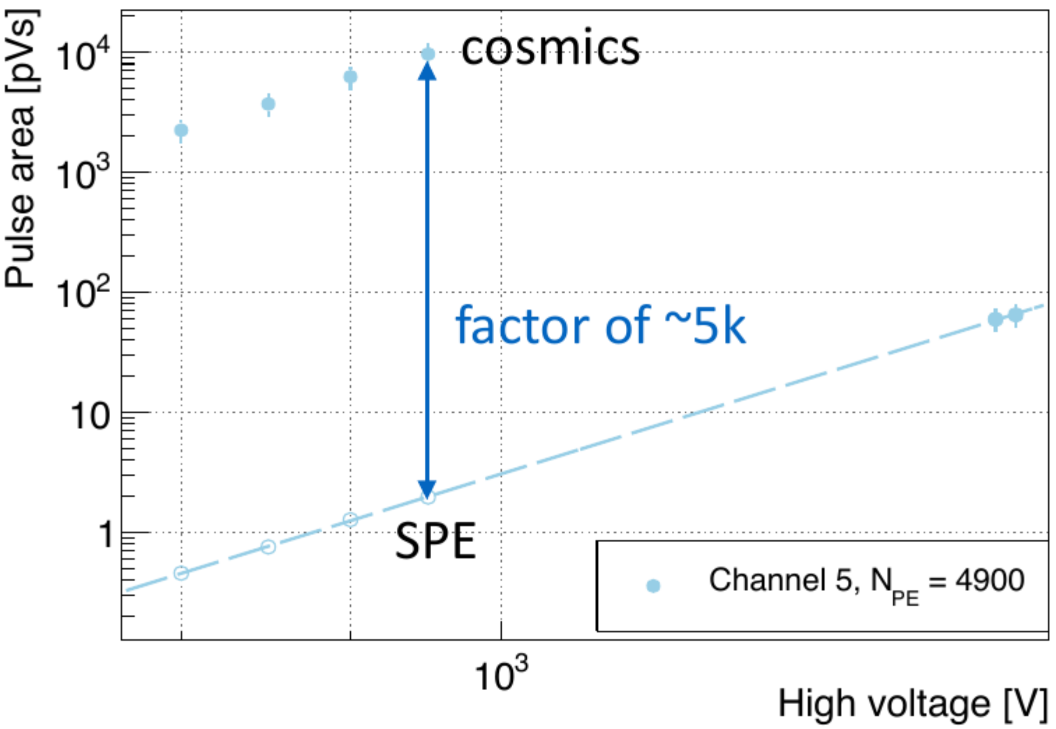
- cosmic muons taken from vertical path
- Single PhotoElectron (SPE) from afterpulses
  - validated with LED on bench



Demonstrator results

In situ charge calibration

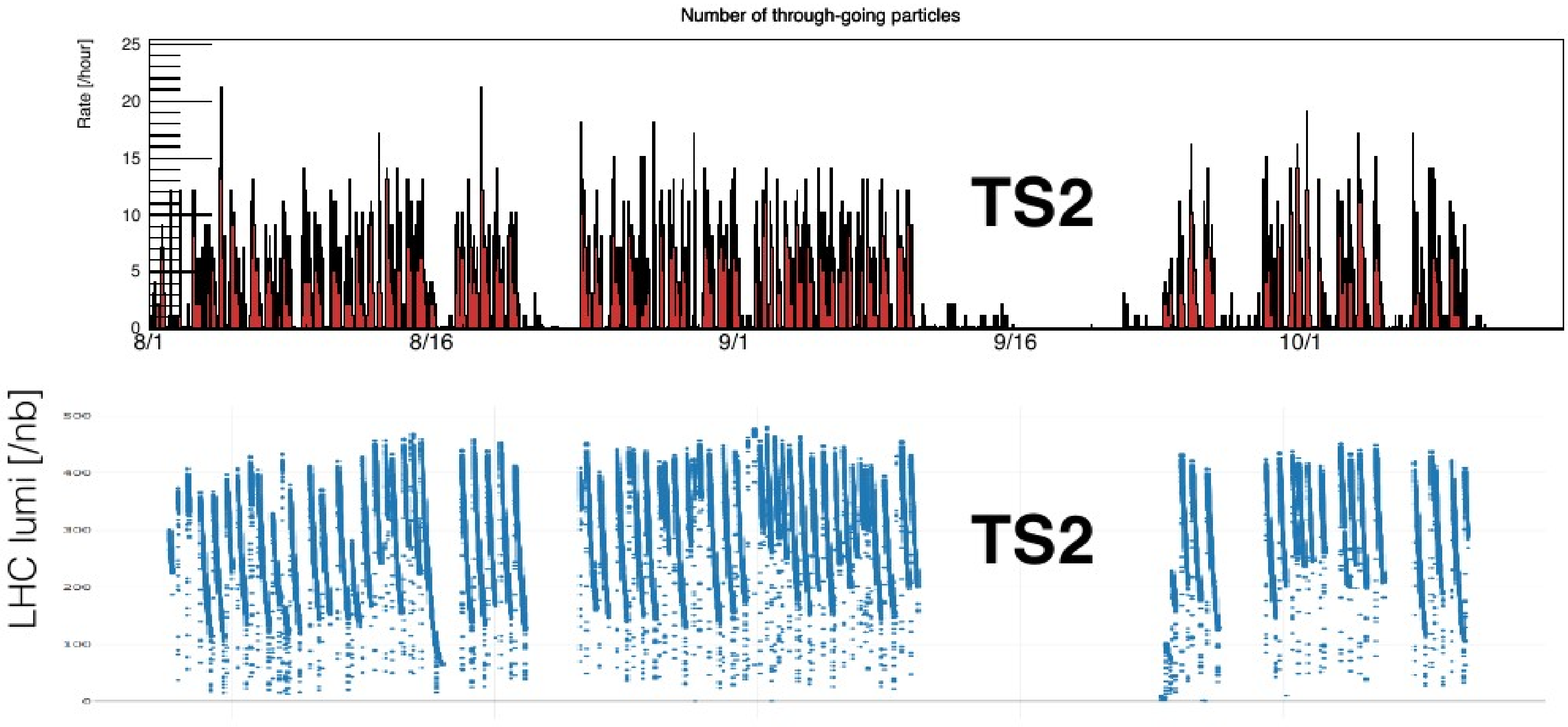
- pulse area as function of HV for a PMT
- N_{PE} for Q = 1e is ~5k
- flight distance of cosmic muons in scintillator is 5cm
  - for through-going muons the flight distance is 80cm
  - N_{PE} for through-going muons is 5k x 80/5 = 80k
- N_{PE} ~ Q^2
  - N_{PE} = 1 for Q ~ 0.003 e
- consistent with full Geant4 simulation results



Demonstrator results

Alignment

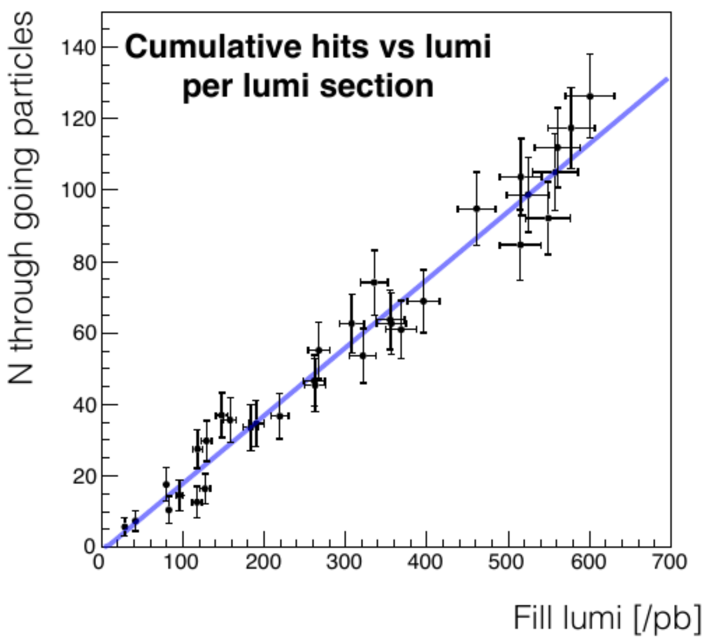
- check alignment with LHC beam
- plot rate of events with muon hit in all 4 slabs

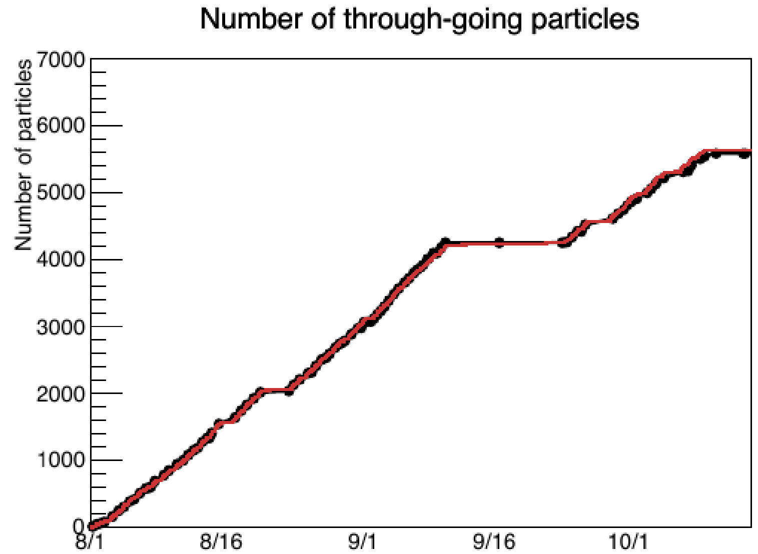


- agrees well with LHC fill / lumi data

Demonstrator results

Alignment





Black points - through-going milliQan particles

Red line - LHC cumulative lumi

- measured rate: 0.19 / pb^{-1} predicted rate: 0.22 / pb^{-1}
  - very good match data – simulation!
- in principle precision from survey is sufficient, no need for angular scan

Demonstrator results

Timing

- need good timing resolution
  - mCP resolution limited by length of scintillator ~2ns
- when timed-in use time-coincidence to suppress backgrounds
  - eg. cosmics