Searching for millicharged particles at the LHC

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Towards discovery at LHC

Run 1: 2010-2012

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

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Run 2: 2015-2018

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

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Run 3: 2022-2024

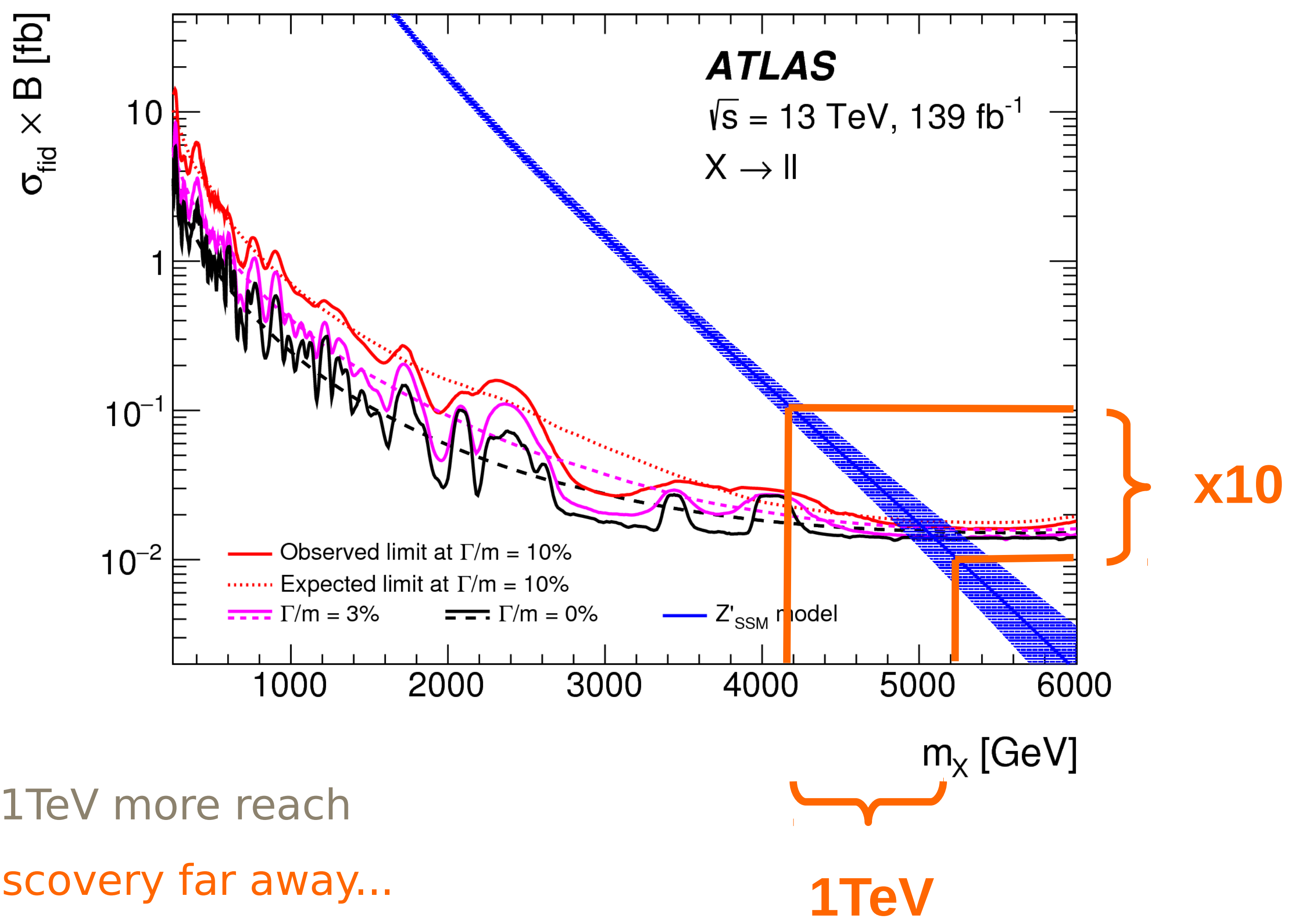
- 13-14 TeV, 300/fb
- aim for lower mass, lower cross section, difficult final states (eg. LL)
- BSM sensitivity? more lumi needed!

Towards discovery at LHC

Much more lumi – but how much?

- eg. new physics bump hunt on Drell-Yan background

arXiv:1903.06248 [hep-ex]



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

So what else?

The LHC is unique

- only player at the energy frontier
  - since a decade, more to come
- only player at the intensity frontier
  - at the EW scale

- whatever LHC is sensitive to should be done now or “never”
  - maximize return on investment
  - small investment can make big difference

- what else can we do with the LHC?
  - how can new physics still be hidden?

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 > physics > arXiv:1909.13022

Physics > Instrumentation and Detectors

ANUBIS: Proposal to search for long-lived neutral particles in CERN service shafts

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Leveraging the ALICE/L3 cavern for long-lived exotics

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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 F

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FASER: ForwArd Search ExpeRiment at the LHC

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

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High Energy Physics - Experiment

Physics Potential of an Experiment using LHC Neutrinos

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High Energy Physics - Phenomenology

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

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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

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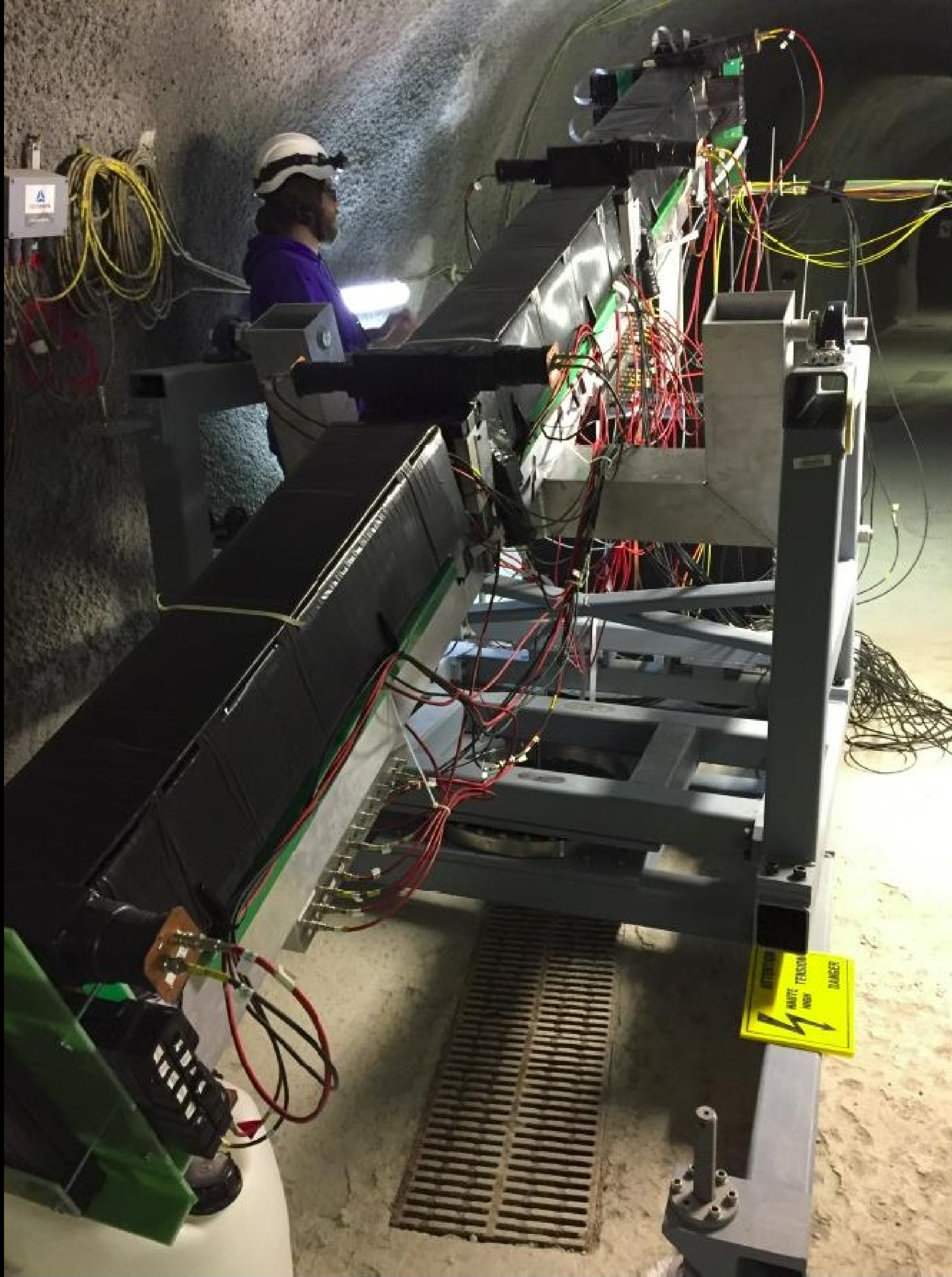
milliQan

New experiment to search for millicharged particles at the LHC



Millicharges?

Electric charge quantization

- all our elementary particles have an electric charge of N*e/3

- but… we don't know why electric charge appears quantized
  - explanations so far involve magnetic monopoles (never found) or SU(5) grand unified theories (ruled out)
  - it is theoretically entirely consistent to add new particles with small electric charge

Millicharges?

So how do millicharges then work?

- millicharged particles may actually arise rather naturally in extensions of the Standard Model

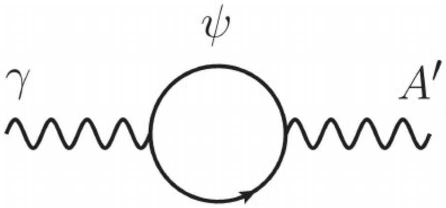
- suppose we add a U(1)' massless boson to the SM, a dark photon

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} B'_{\mu\nu} B^{\mu\nu\prime} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu}$$

kinetic mixing
[Holdom '86]

Millicharges?

- the kinetic mixing term can be generated through new heavy particles that couple both to hypercharge and to new U(1)'



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

  - generates coupling 10^{-3} for m_ψ ~ EW scale

- let's now add a new fermion only charged under U(1)'

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

- and redefine the field

$$B' \to B' + \kappa B$$

- mixing term disappears and new fermion gets hypercharge
- after EWSB new fermion has arbitrary electric charge: $Q = \kappa e' \cos\theta_W$

Motivation

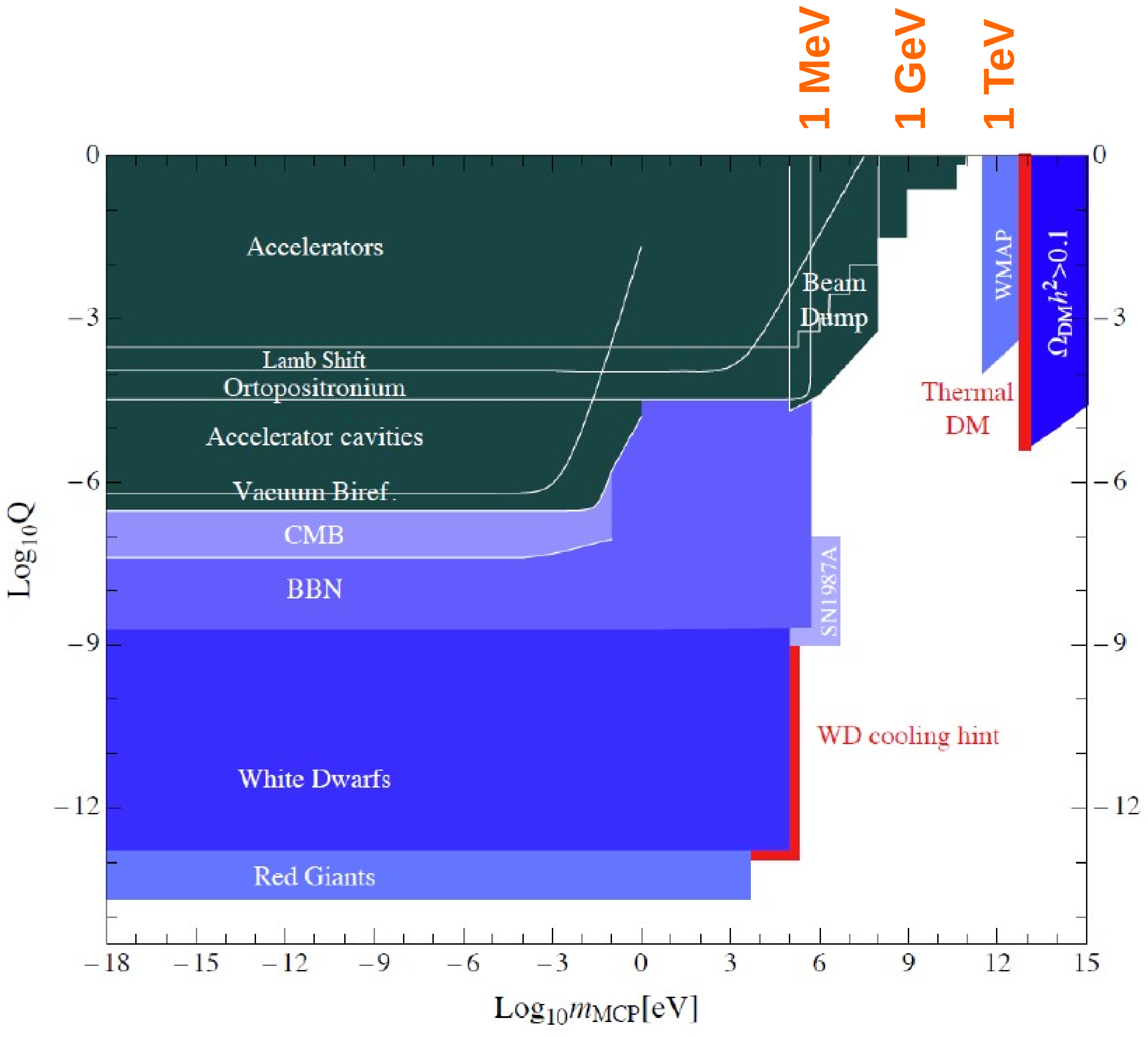
Theoretical

- kinetic mixing (a.k.a. vector portal) is 1 of 4 possible portals to dark sector
  - others go via Higgs, neutrinos, or axions
- dark sector can contain dark matter!
- extra U(1) groups rather generic feature of GUTs and other theories
- very economical BSM extension, easy to embed

Experimental

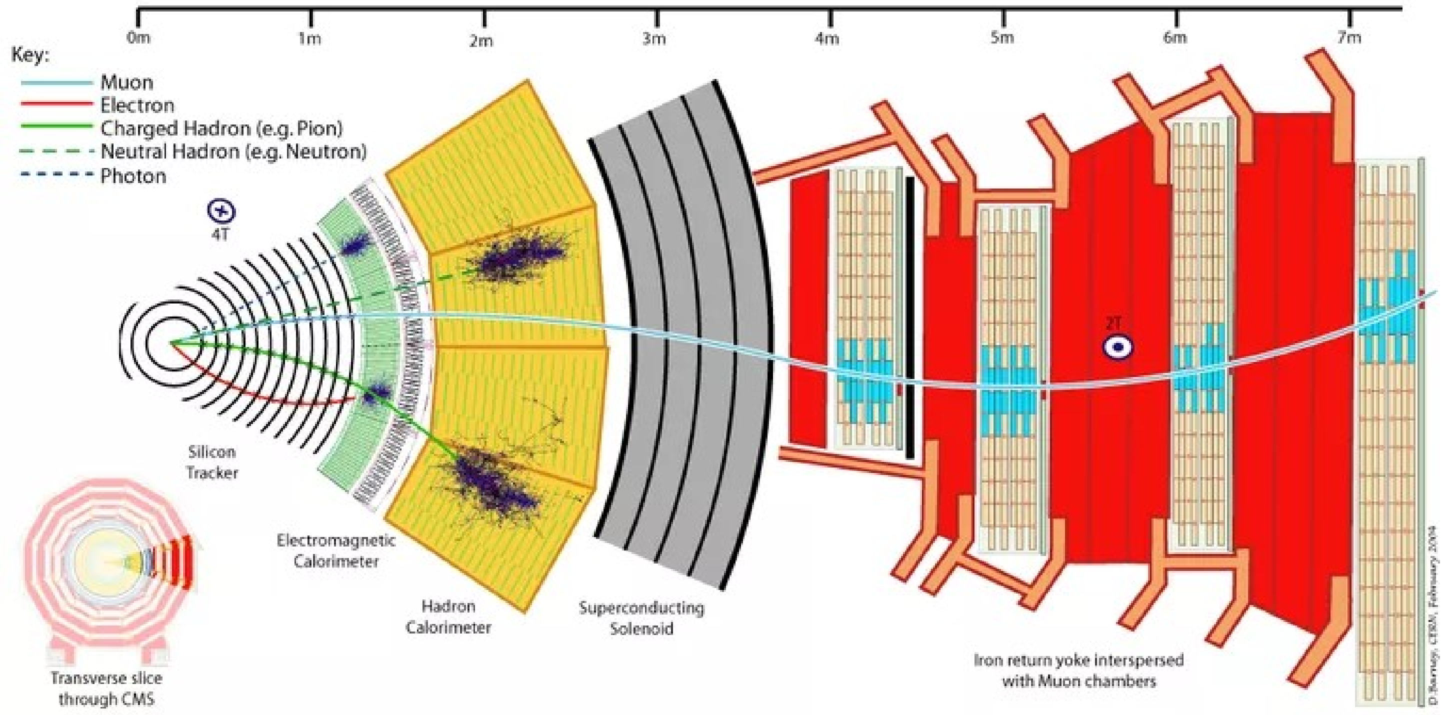
- opportunity: very weak limits above ~1GeV; unique role LHC
- EDGES 21cm result can be explained with subdominant millicharged DM (arXiv:1803.03091)

Existing bounds



How to detect millicharges?

Just use CMS!?

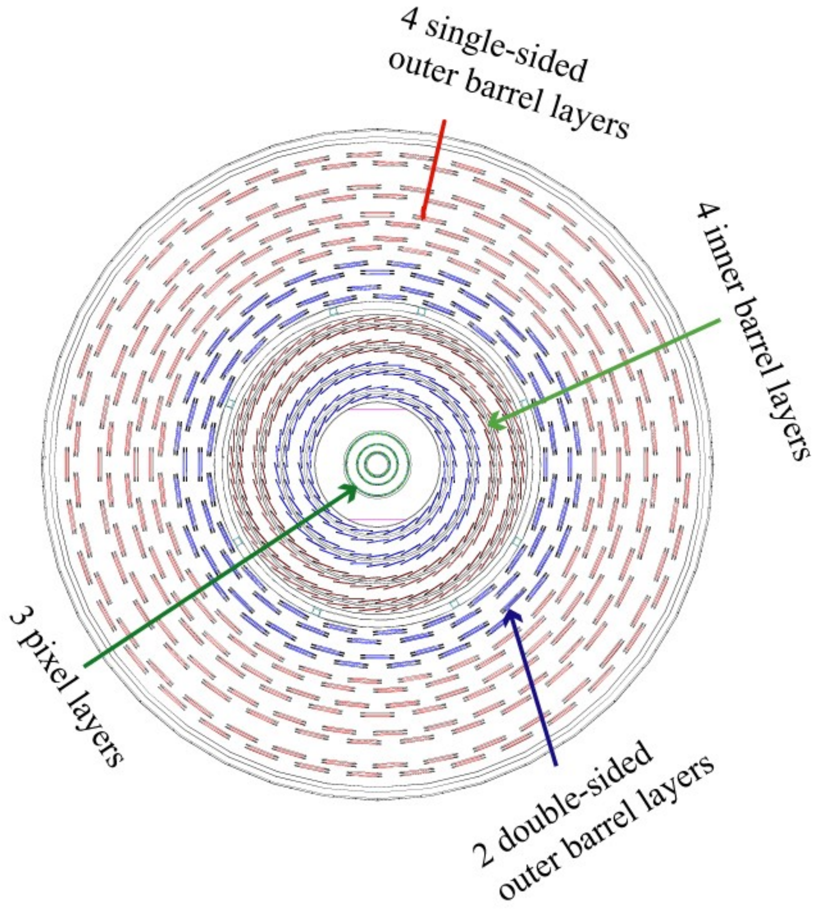


- at lower charge
  - tracks become straighter → momentum ~ 1/Q
  - energy loss becomes smaller → $dE/dx \sim Q^2$

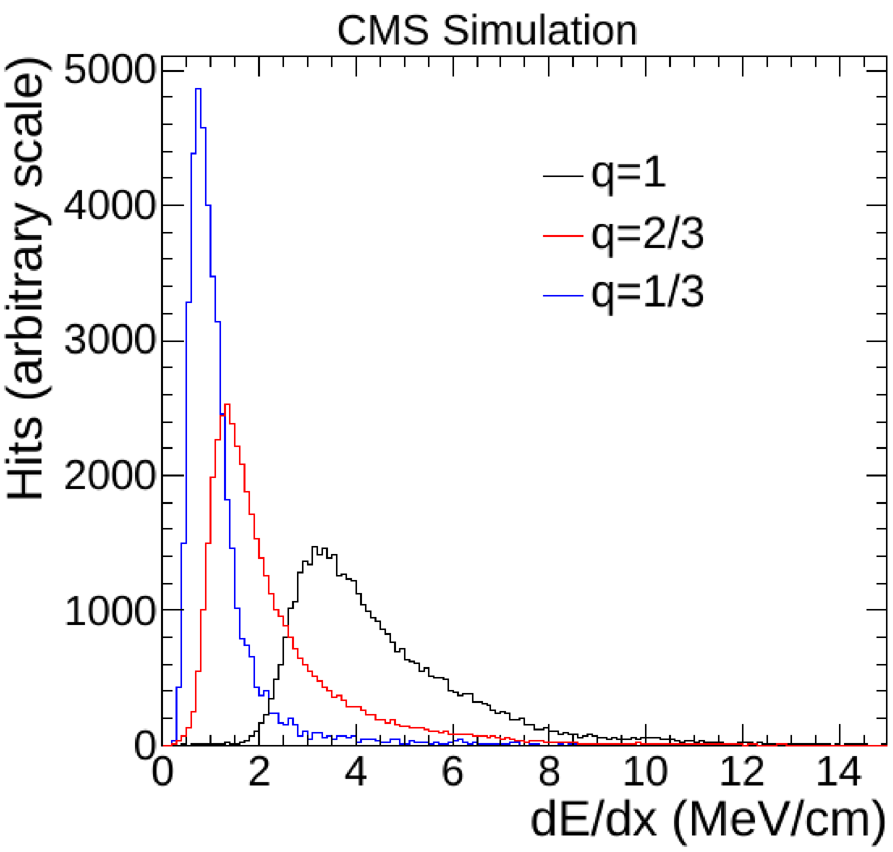
Millicharges in CMS

Search for tracks with many low-dE/dx hits

- 1 track brings many independent measurements of ionization loss



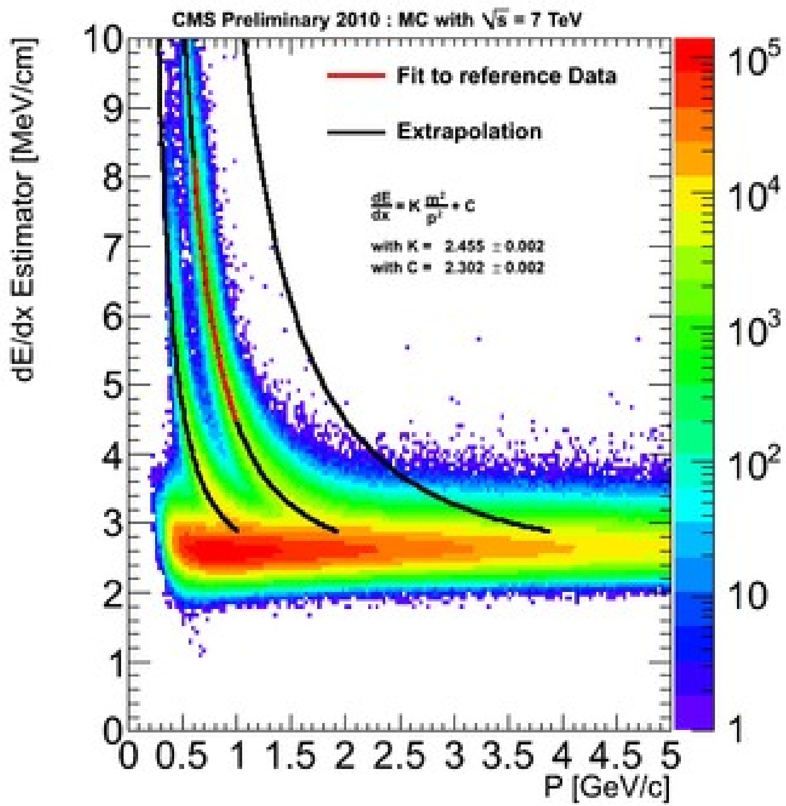
CMS-PAS-EXO-11-074



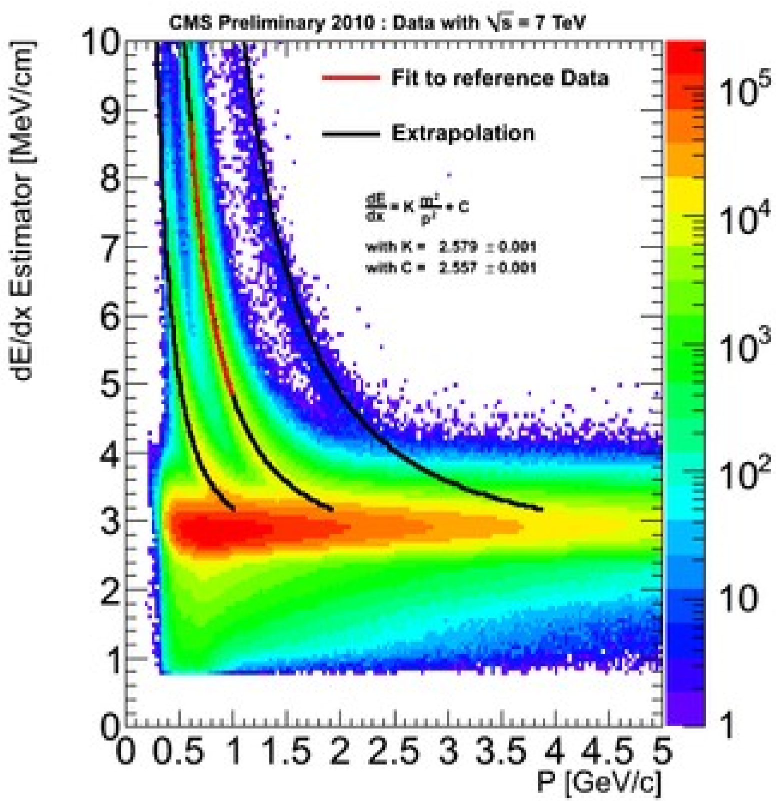
Millicharges in CMS

dE/dx performance in CMS tracker

area of interest: difficult!



simulation



data

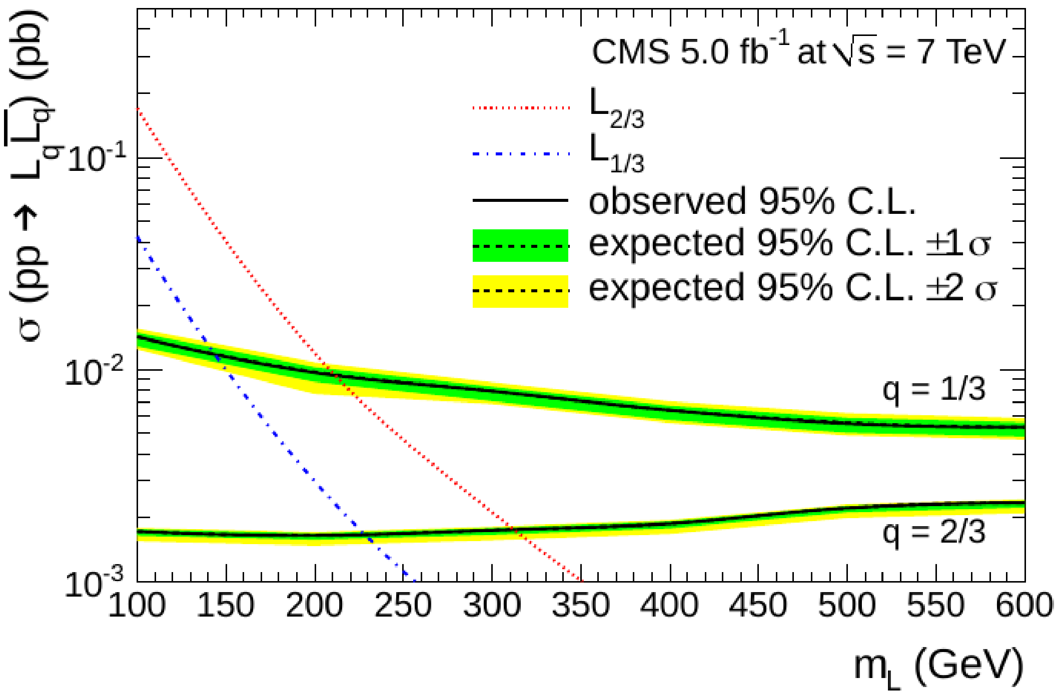
- also very sensitive to detector aging

Millicharges in CMS

Current analysis reach

- predict background fully from data
- can suppress all backgrounds above ~6 hits with low dE/dx

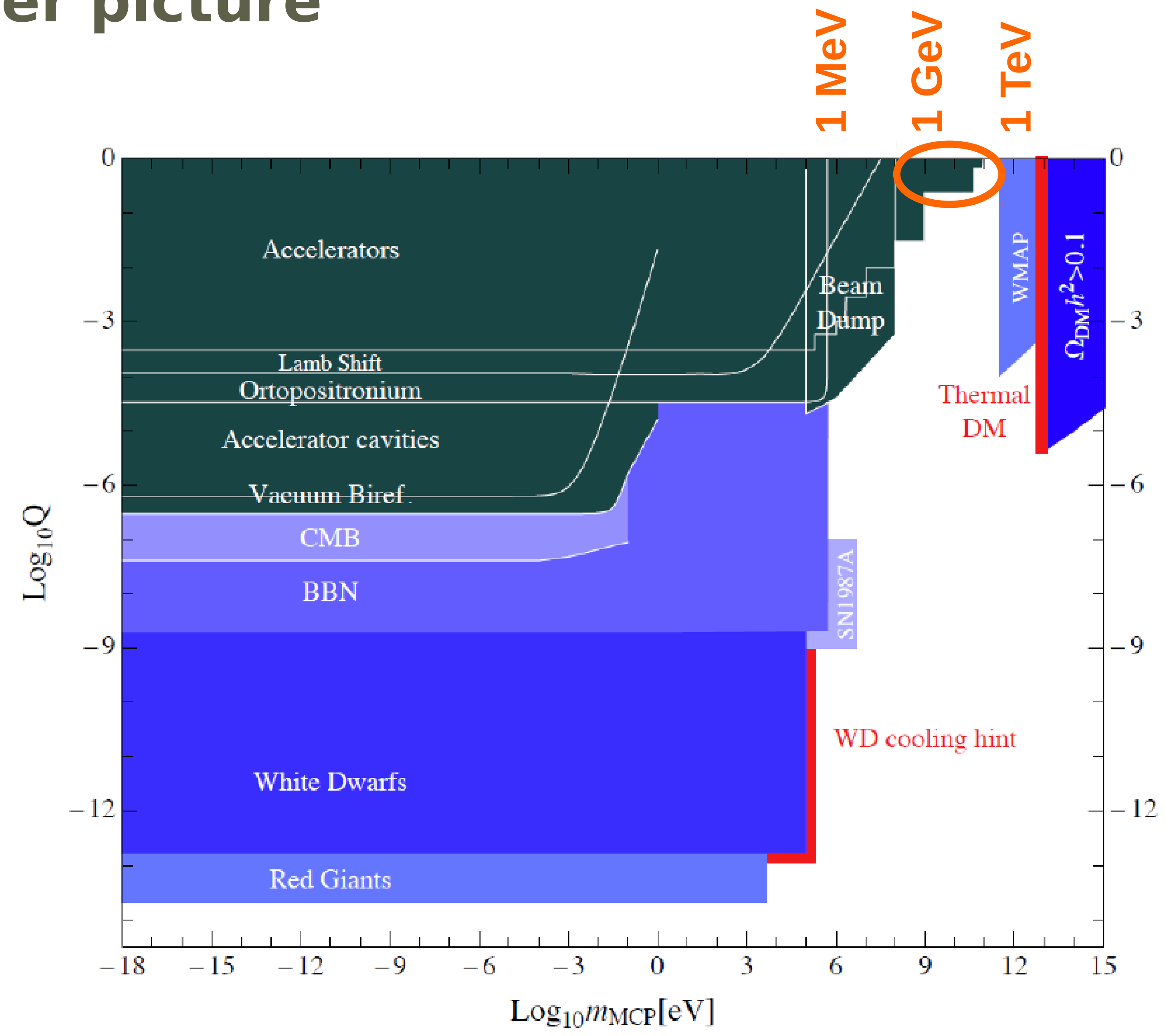
Phys. Rev. D 87 (2013) 092008



- LHC Run2 update almost ready!

Milli charges

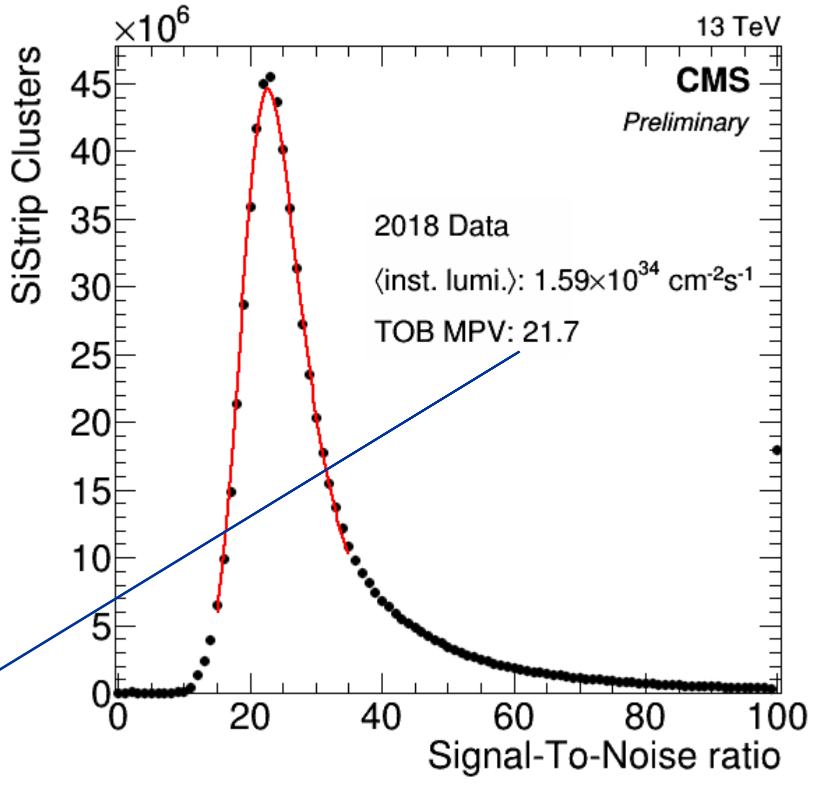
The bigger picture



Going lower

What about lower charges?

- fundamental limitation of the CMS/ATLAS detectors



CMS DP-2018/052

- $1/Q^2 \sim 21.7$

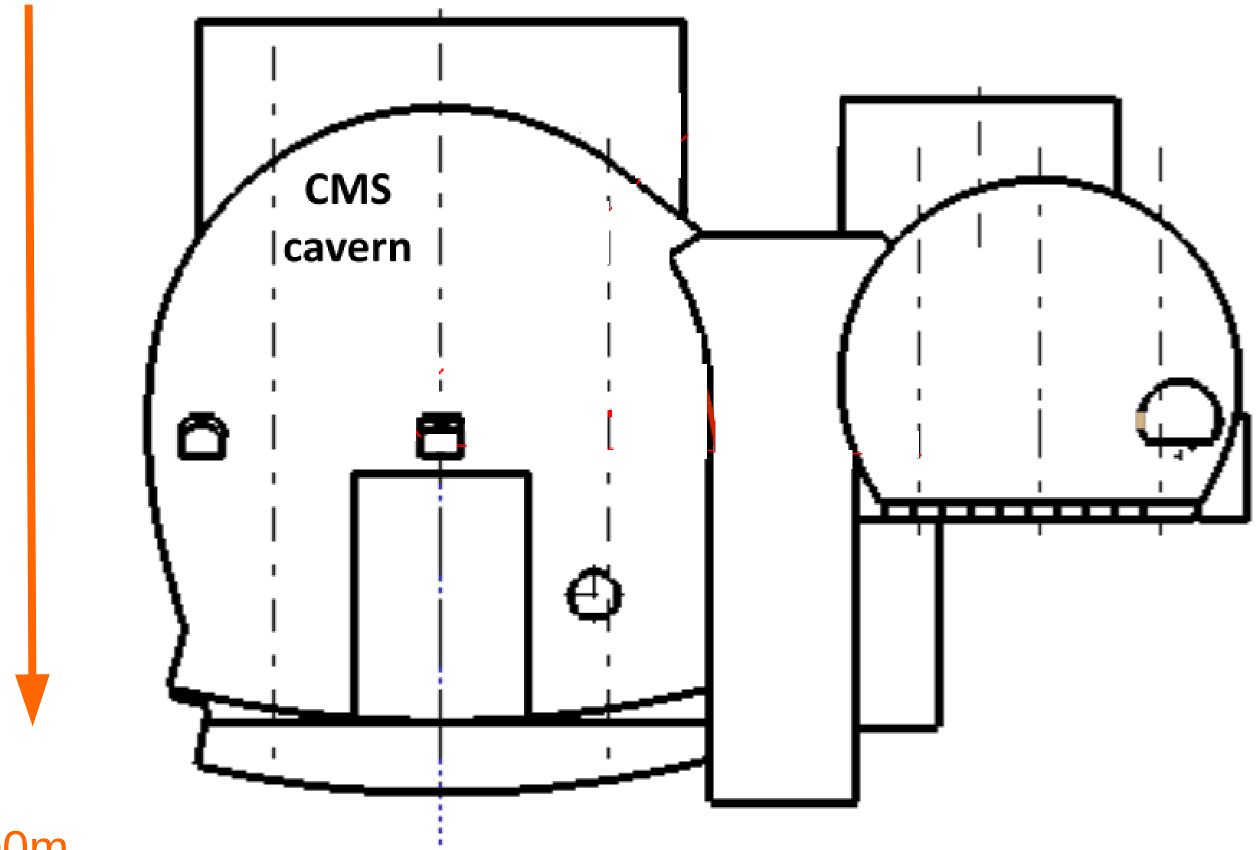
  → cluster charge from particle with Q = 0.2 has MPV ~ noise level

Going lower

Facing the Q^2 suppression

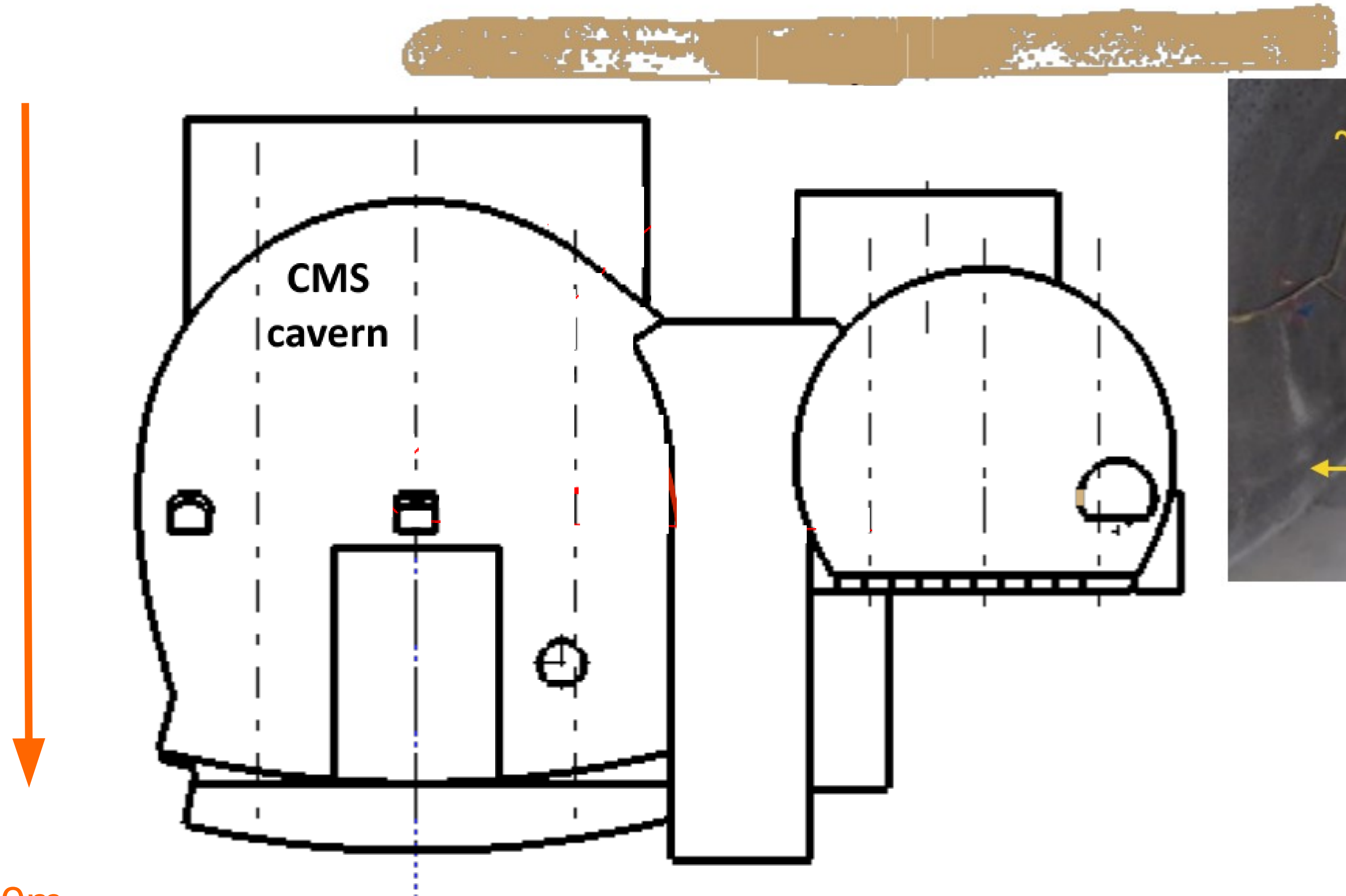
- need much more sensitive detection technique
  - with charge down to 10^{-3}, dE/dx suppressed by 10^{-6}
  - counting of single photons in “large” scintillator volume
- need to go to a low-background area
  - out of the CMS cavern, to suppress radiation backgrounds
  - still shielded from cosmic muons by ~100m overburden
- stay relatively close to the interaction point
  - minimize r^2 suppression of flux

milliQan location

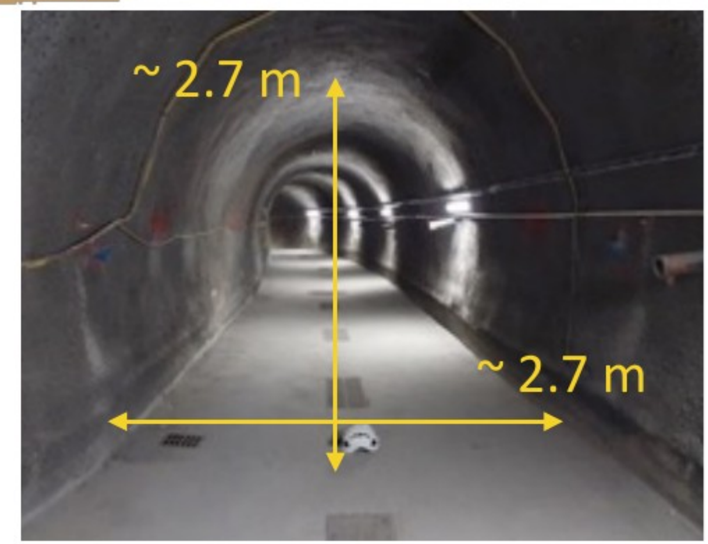


100m
underground

milliQan location

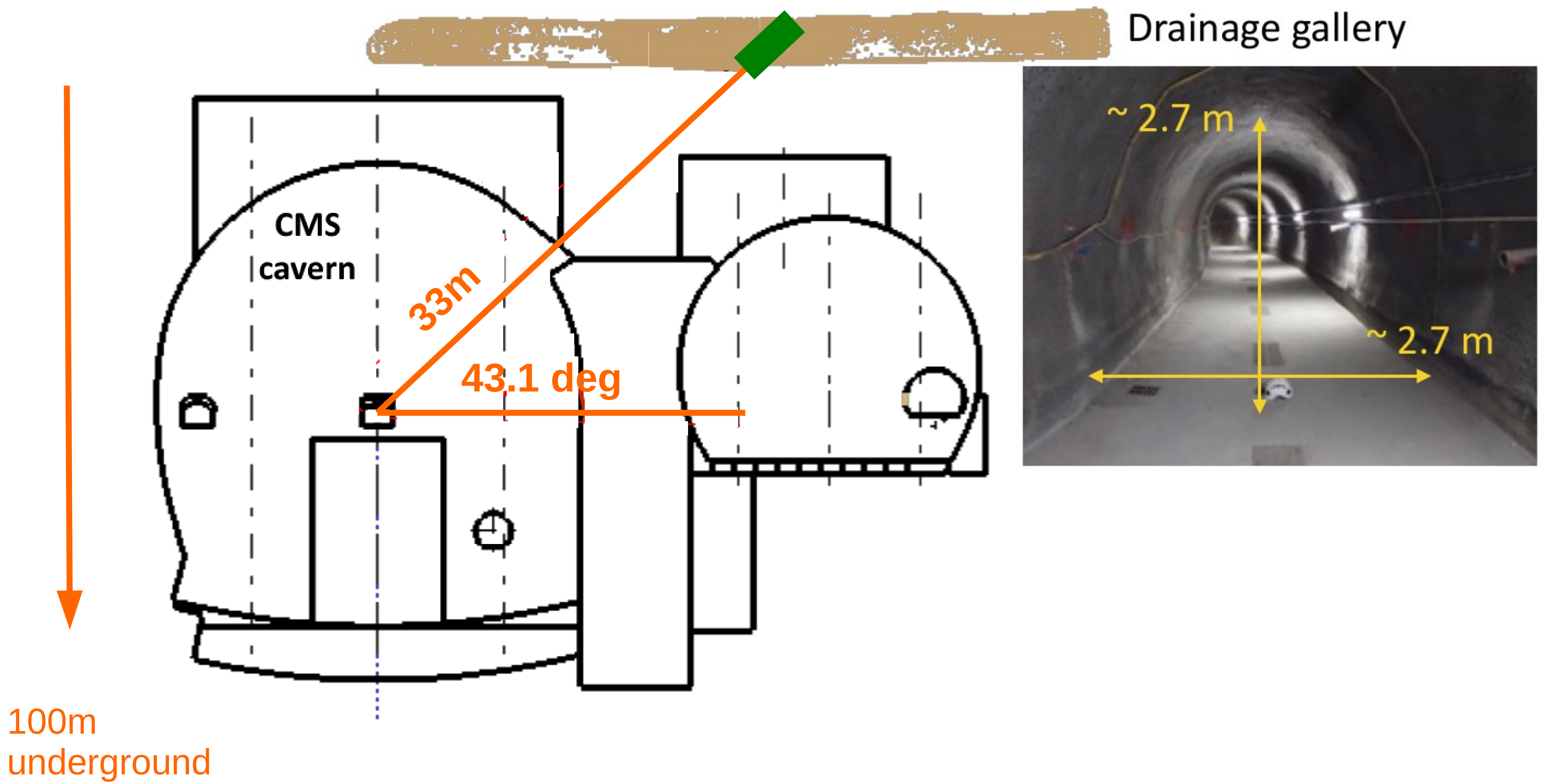


Drainage gallery

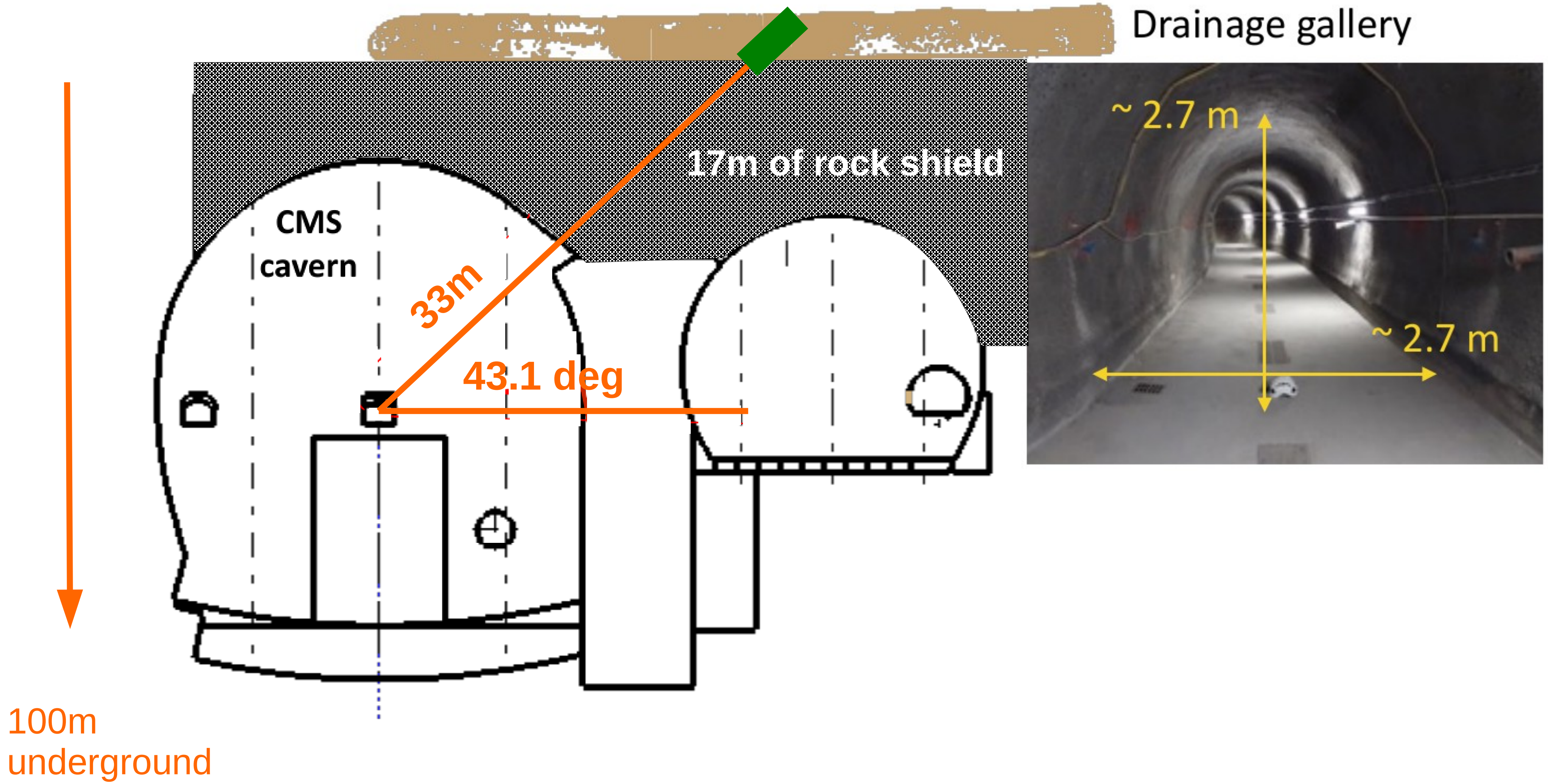


100m
underground

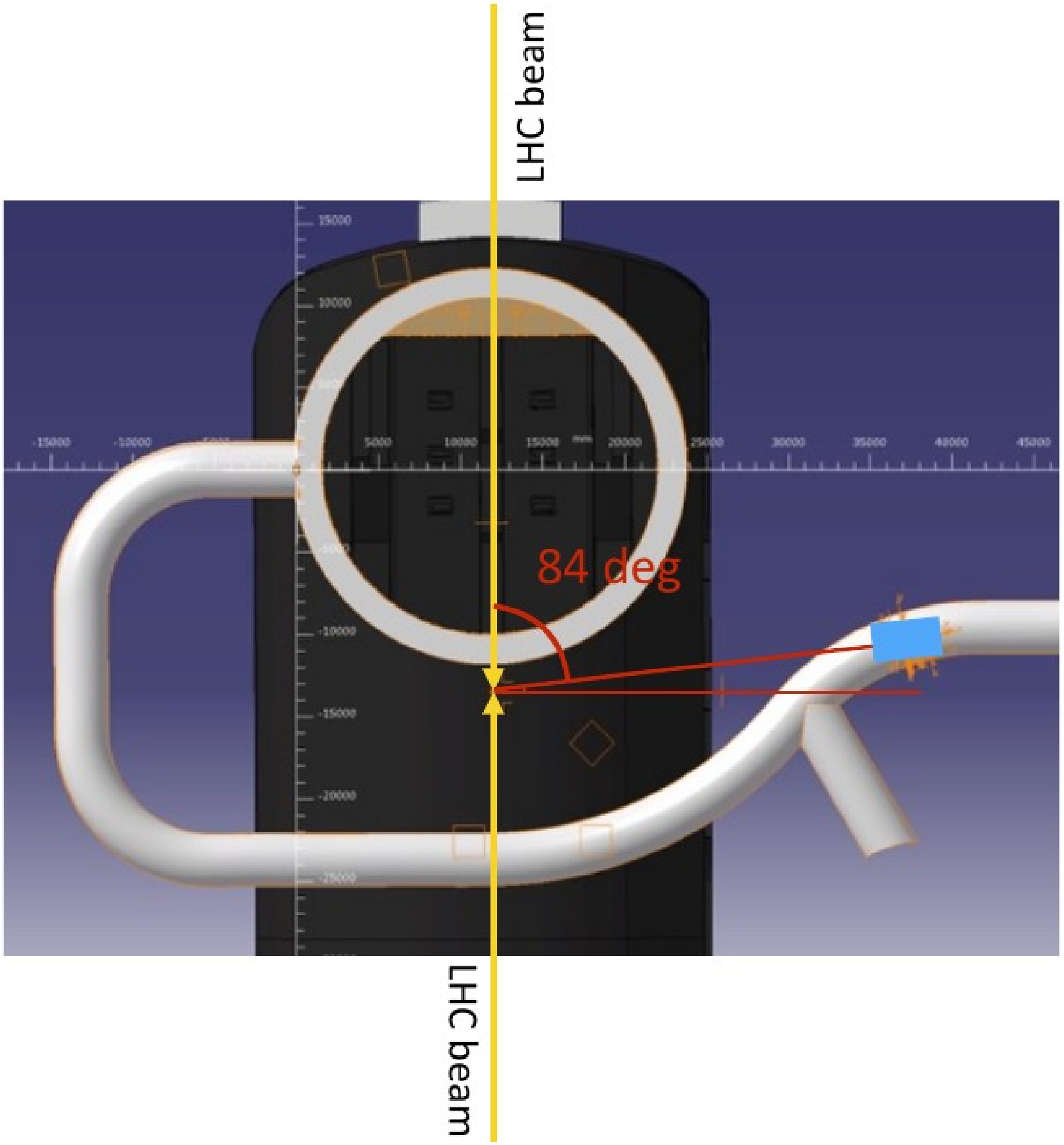
milliQan location



milliQan location

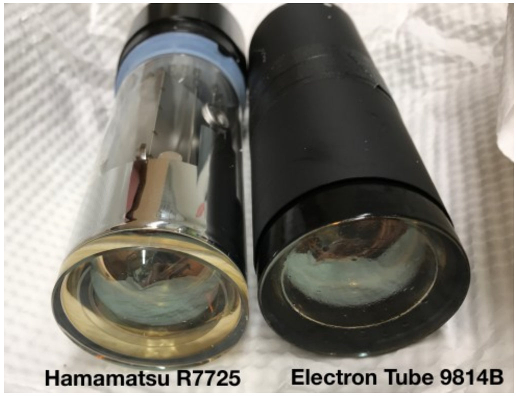


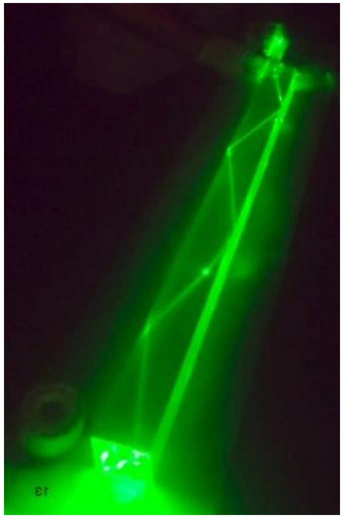
milliQan location

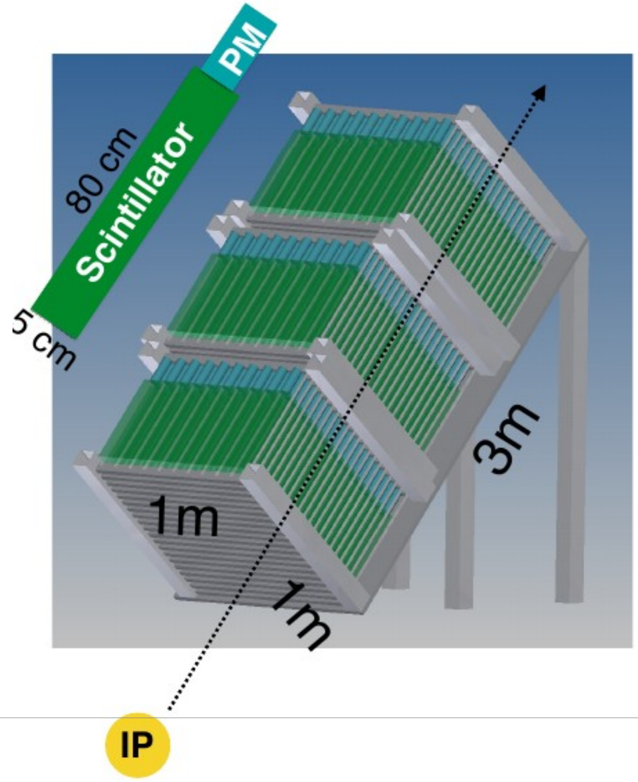


milliQan detector principle

- concept: arXiv:1410.6816; LOI: arXiv:1607.04669
- basic element is 5x5x80 cm³ plastic scintillator
- attached to photomultiplier tube
- 1x1x3 m³ in 3 length-layers
- search coincidence of few photons in consecutive scintillators pointing to IP



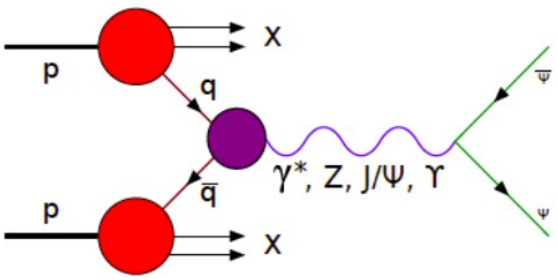




Simulation

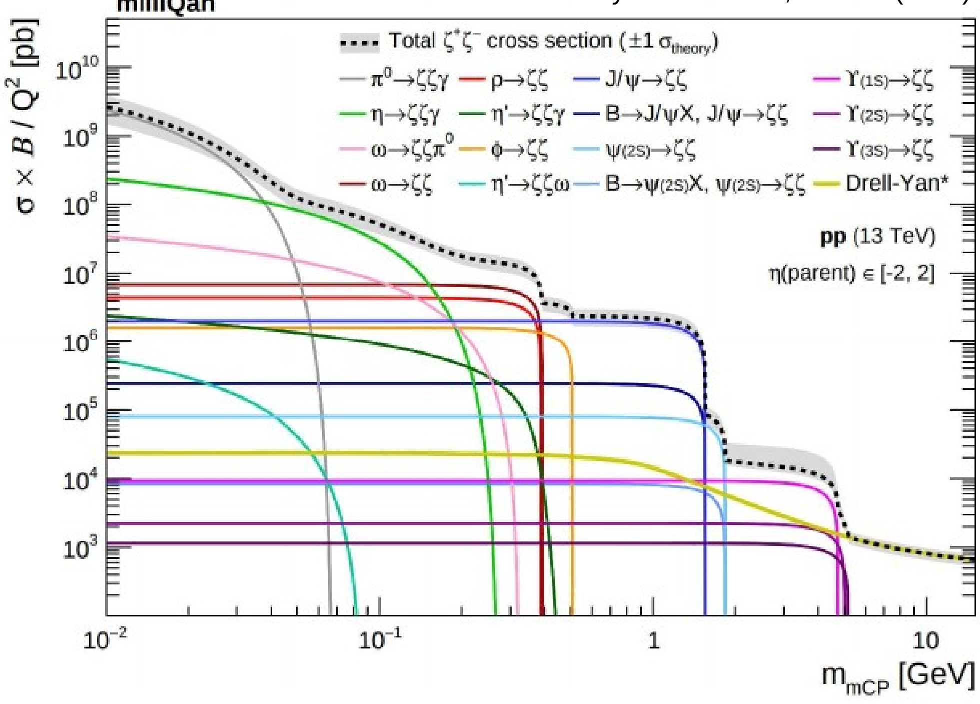
Production and transport simulation

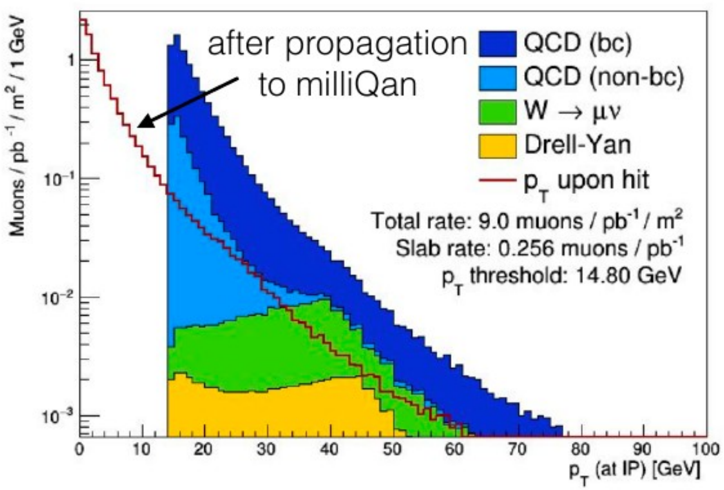
- any process that can make e^+e^- can make millicharged particles
  - low masses dominated by QCD production of π^0, η, ρ, ω, ϕ, then J/ψ and Υ
  - above 5GeV it's all Z/γ^*



- propagate through CMS material and 17m of rock
  - with multiple scattering and CMS magnetic field

Phys. Rev. D 102, 032002 (2020)

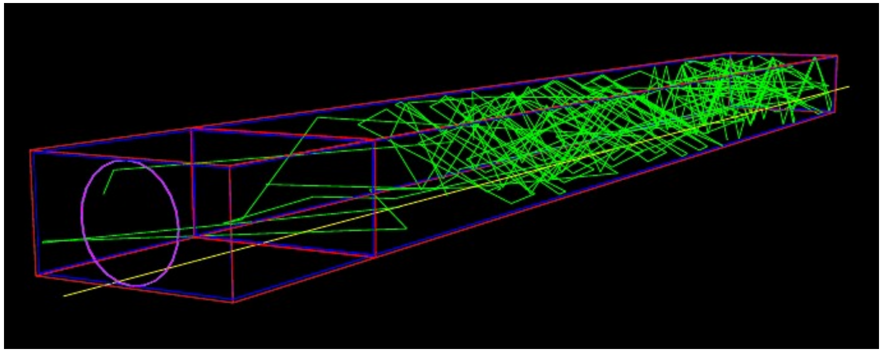


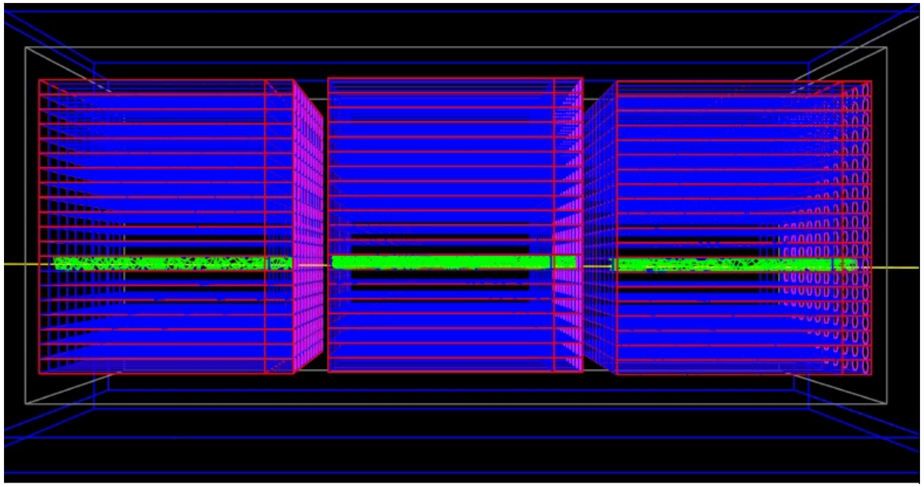


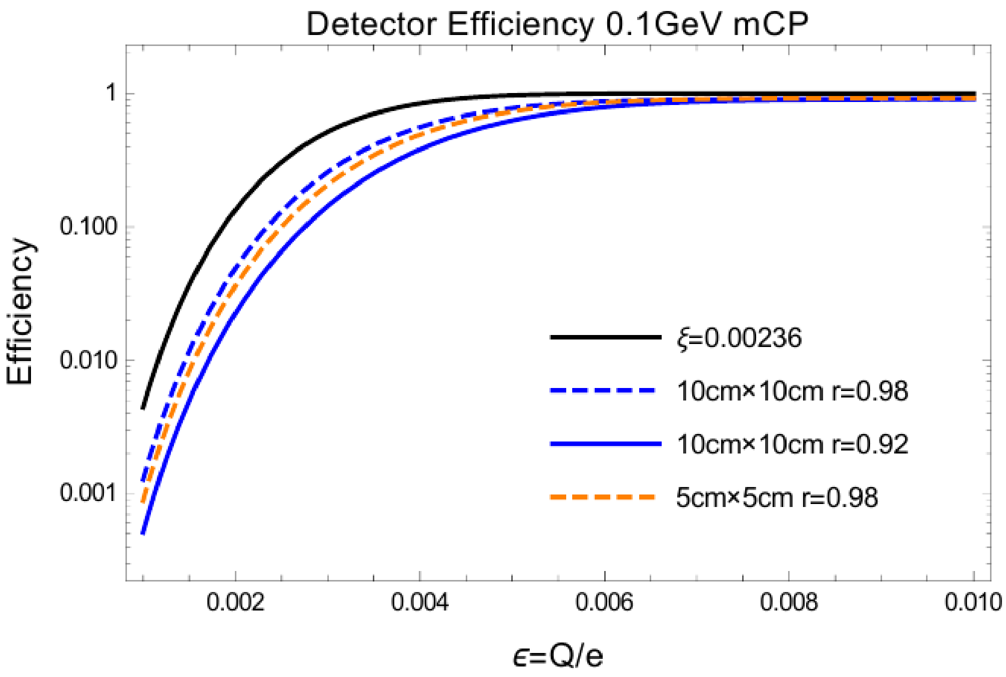
Simulation

Full Geant4 detector simulation

- models reflectivity, the light attenuation length, and the shape of the scintillator
- PMT parameters as input



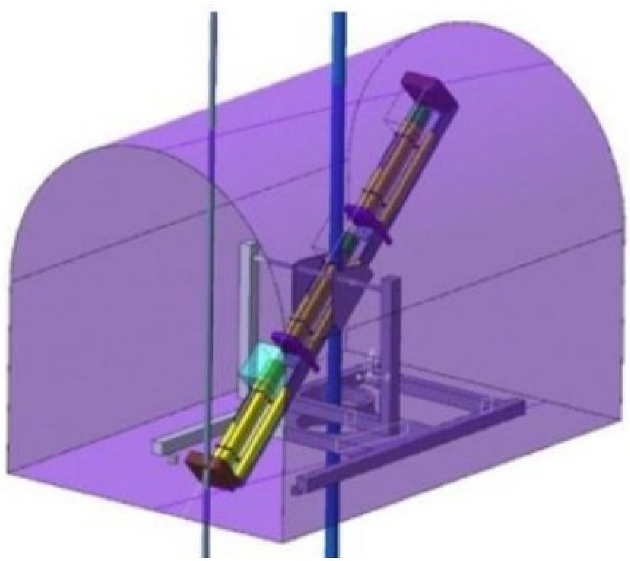


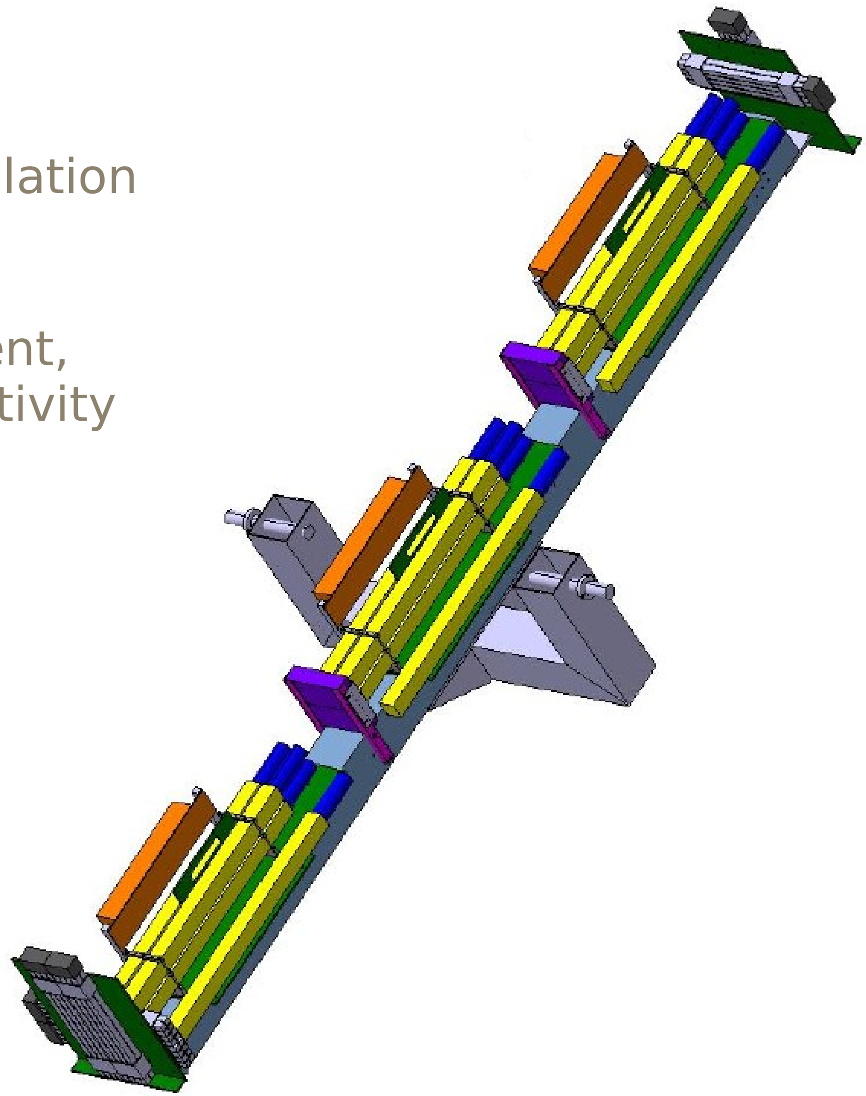


Demonstrator

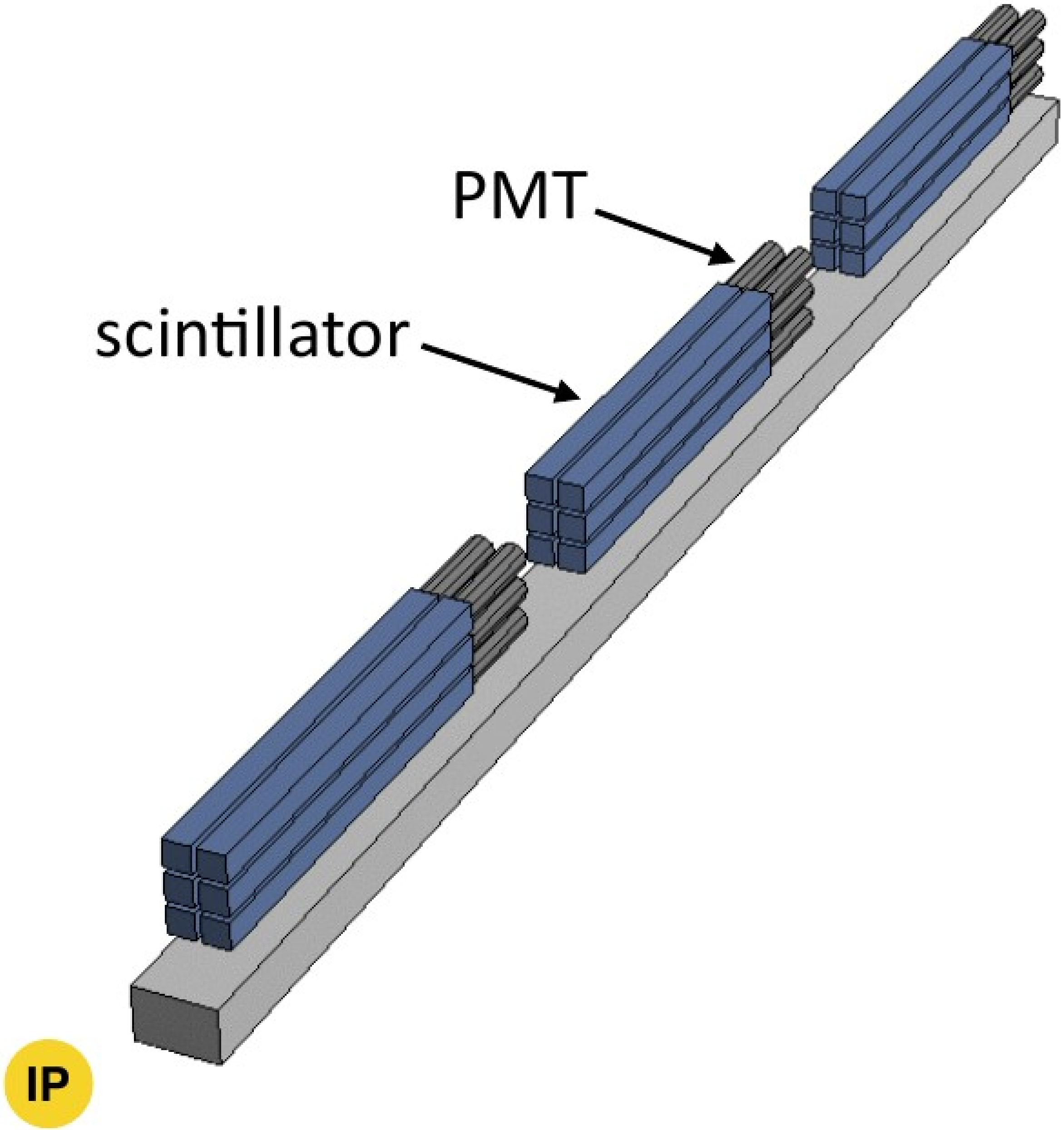
1% prototype test

- exercise detector assembly and installation
- establish remote operation
- measure backgrounds, check alignment, perform calibrations, determine sensitivity
- input for full detector design



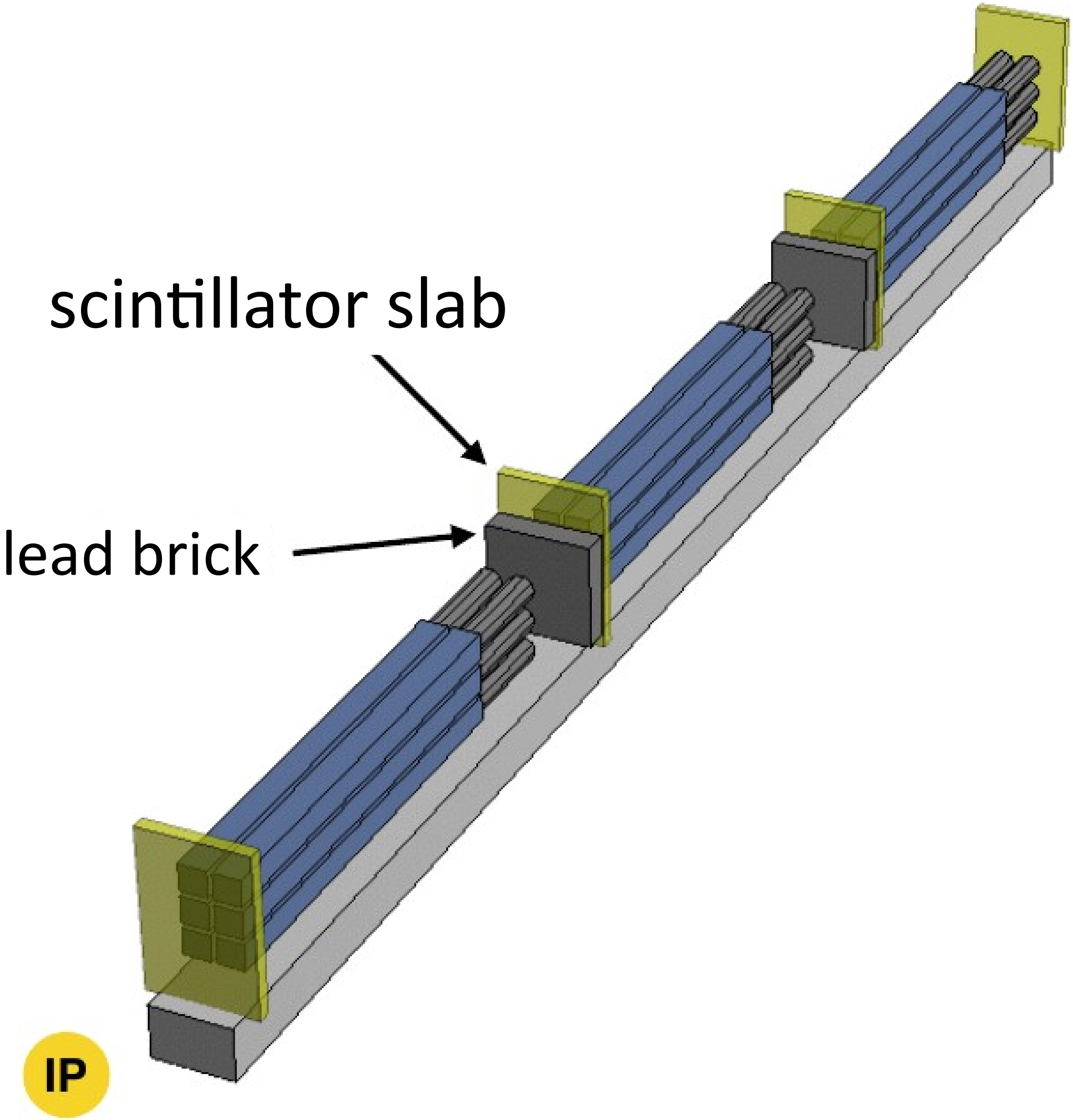


Demonstrator



- 3 layers of 2x3 scintillator+PMT

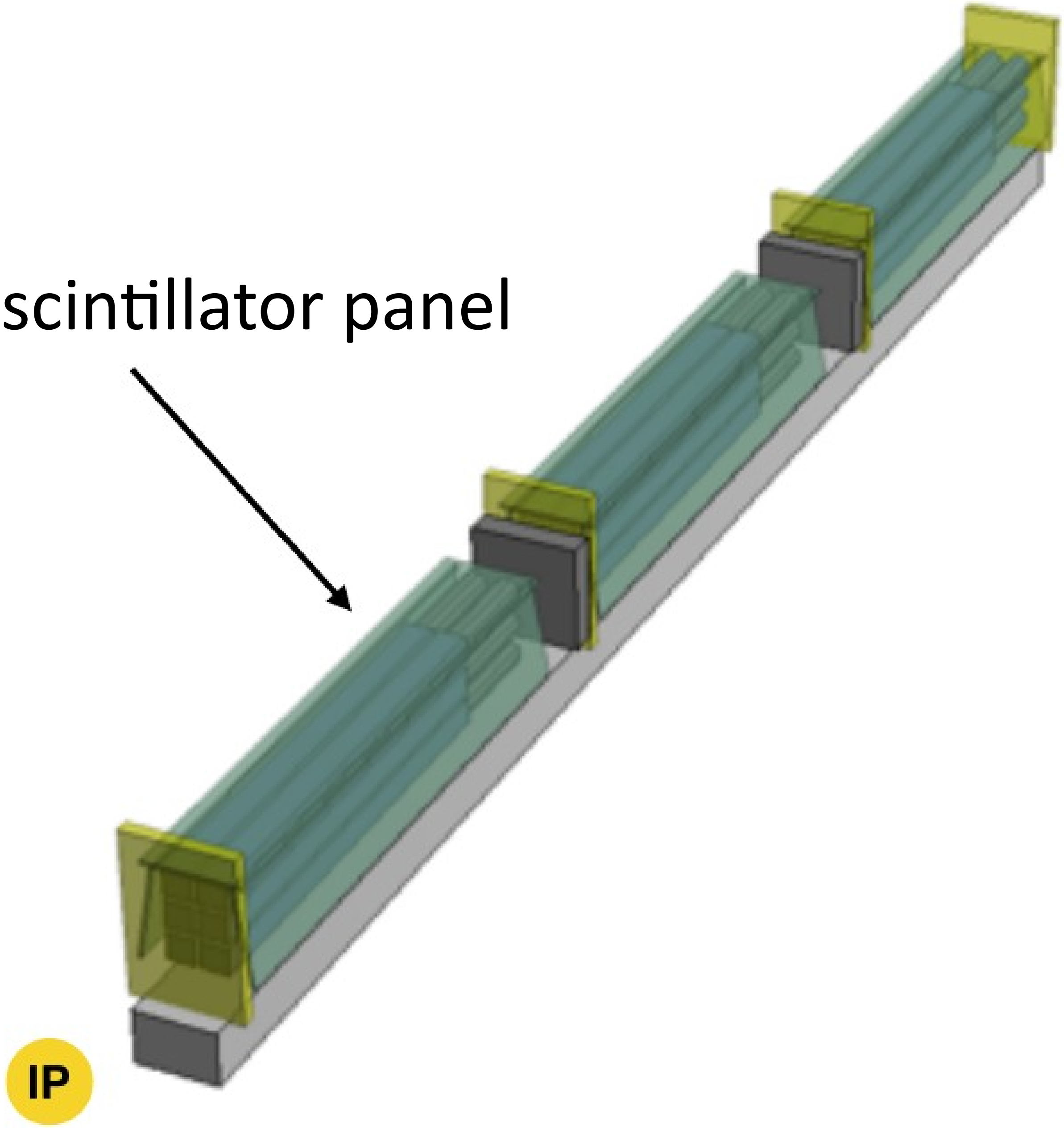
Demonstrator



- 3 layers of 2x3 scintillator+PMT
- scintillator slabs and lead bricks
  - tag thru-going particles, get time info, shield radiation

Demonstrator

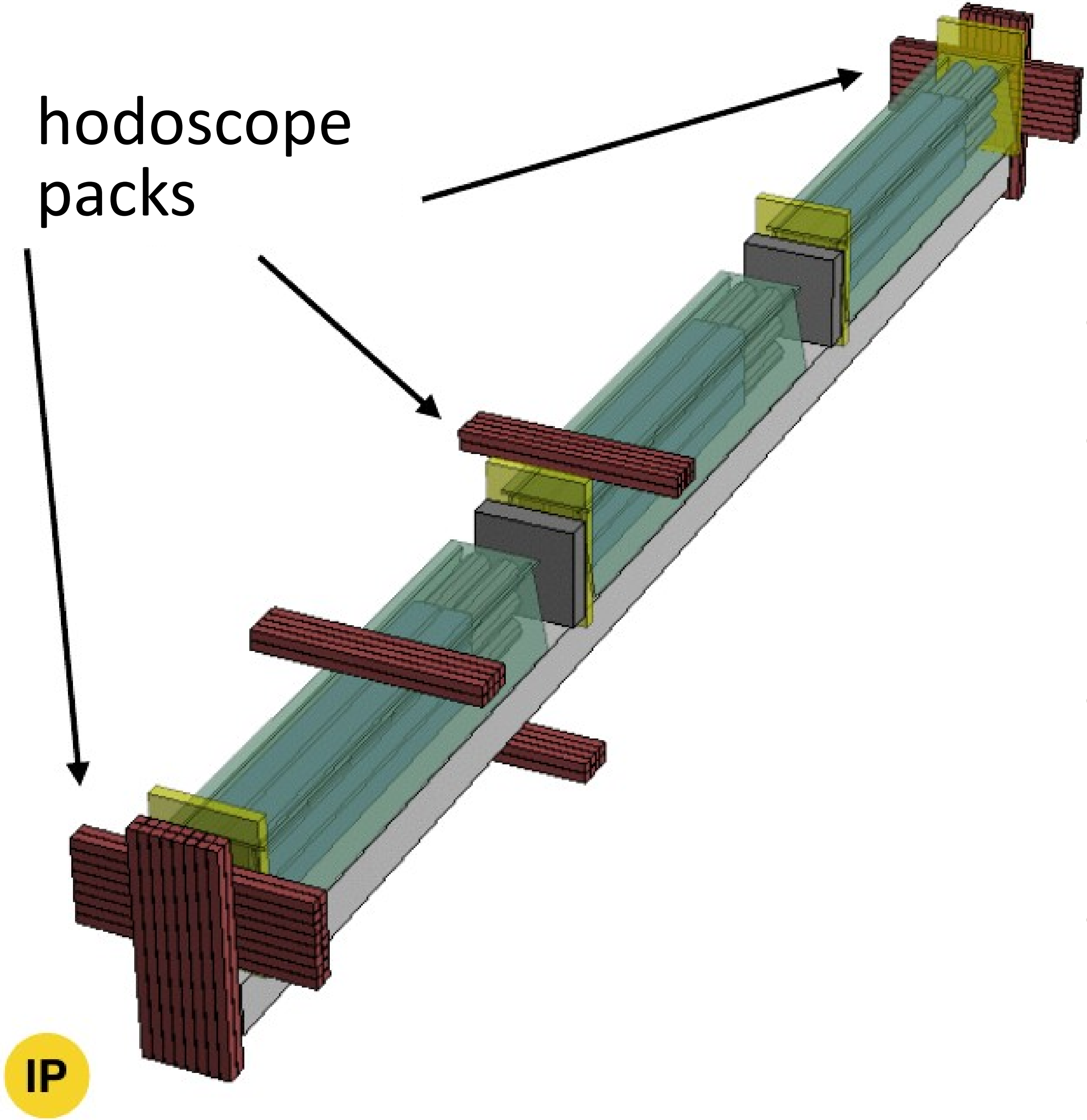
scintillator panel



- 3 layers of 2x3 scintillator+PMT
- scintillator slabs and lead bricks
  - tag thru-going particles, get time info, shield radiation
- scintillator panels to cover top and sides
  - tag/reject cosmic muons

Demonstrator

hodoscope
packs



- 3 layers of 2x3 scintillator+PMT
- scintillator slabs and lead bricks
  - tag thru-going particles, get time info, shield radiation
- scintillator panels to cover top and sides
  - tag/reject cosmic muons
- hodoscope packs
  - tracking of beam/cosmic muons

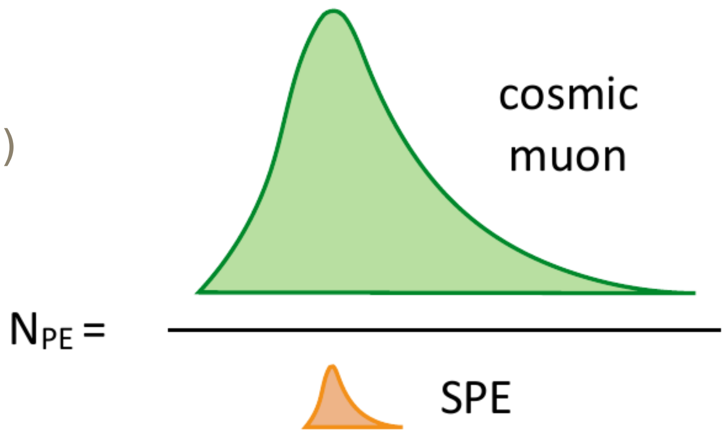
Demonstrator

- took data since April '18
  - 2000h, 37/fb
  - and lots beam-off data
- 3 layers of 2x3 scintillator+PMT
- scintillator slabs and lead bricks
  - tag thru-going particles, get time info, shield radiation
- scintillator panels to cover top and sides
  - tag/reject cosmic muons
- hodoscope packs
  - tracking of beam/cosmic muons

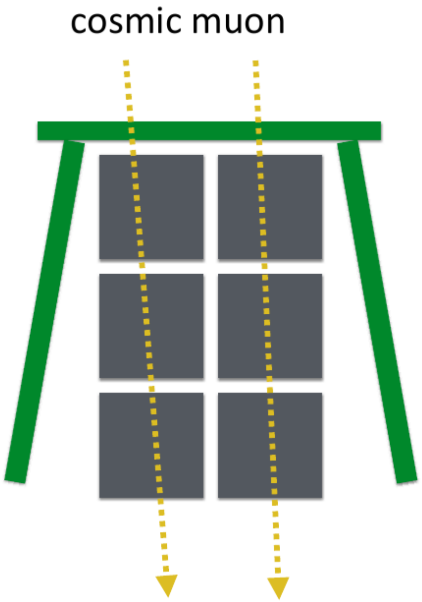
Demonstrator results

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

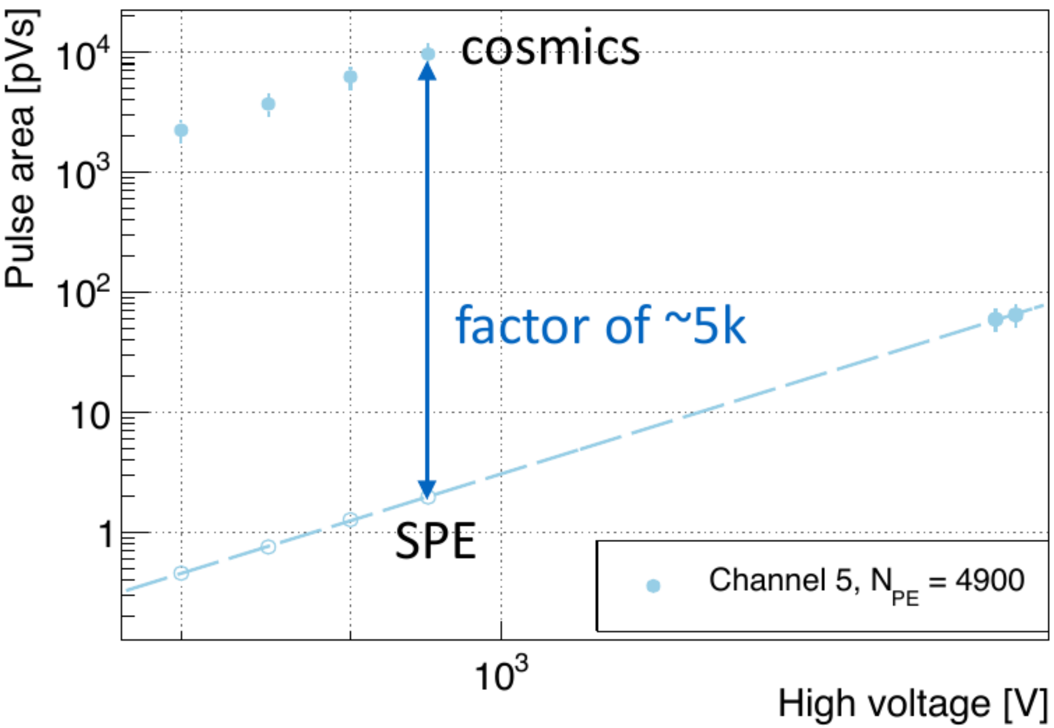


- cosmic muons taken from vertical path
- Single PhotoElectron (SPE) from afterpulses
  - validated with LED on bench

Demonstrator results

In situ charge calibration

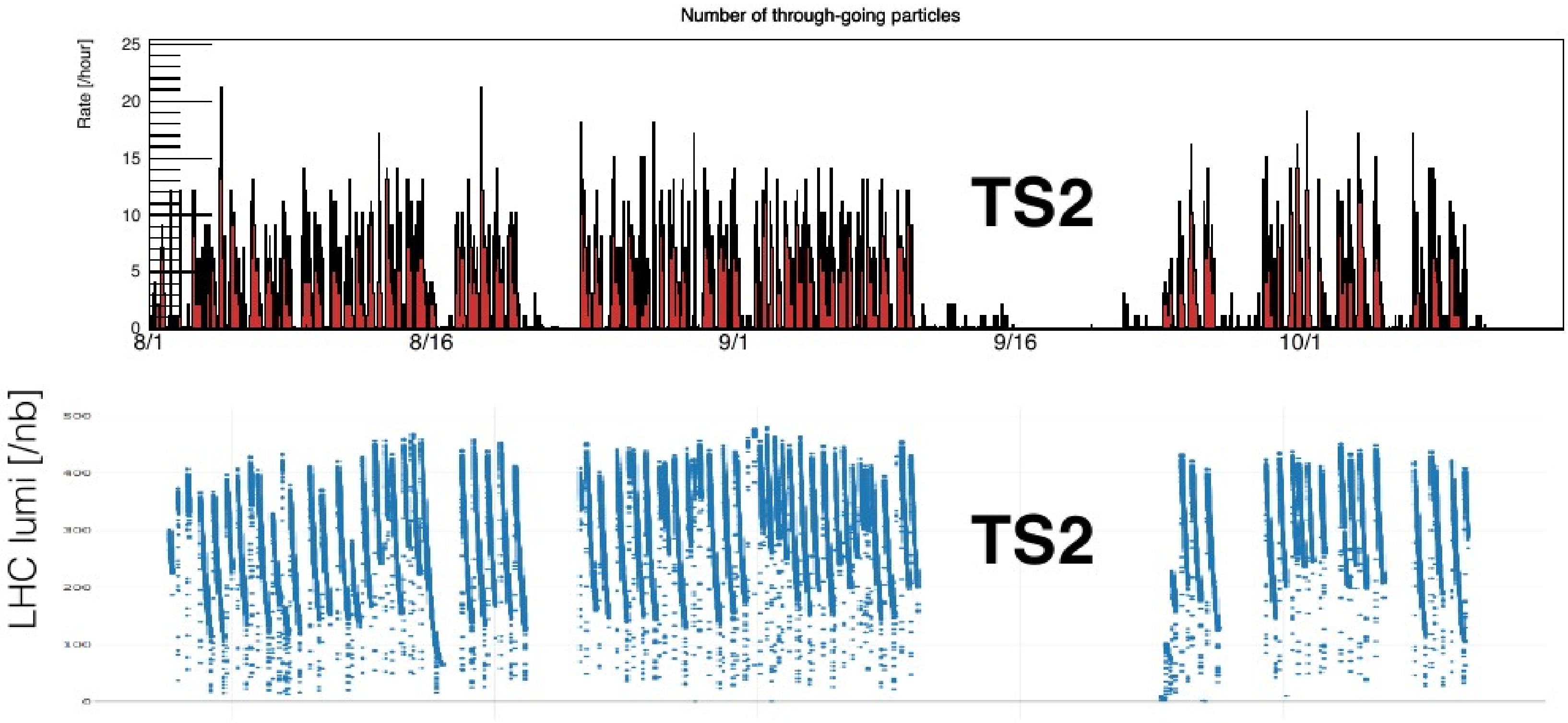
- pulse area as function of HV for a PMT
- N_{PE} for Q = 1e is ~5k
- flight distance of cosmic muons arriving perpendicular to scintillator is 5cm
  - for through-going muons the flight distance is 80cm
  - N_{PE} for through-going muons is 5k x 80/5 = 80k
- N_{PE} ~ Q^2
  - N_{PE} = 1 for Q ~ 0.003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



Demonstrator results

Alignment

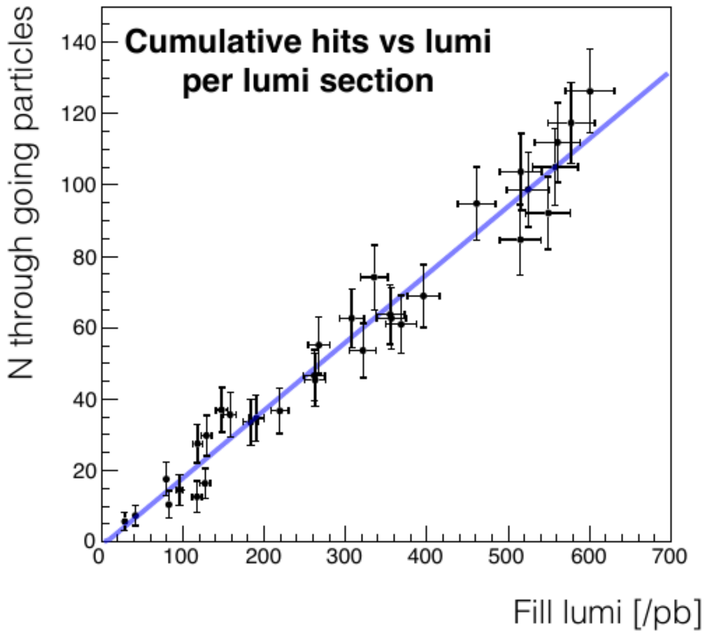
- check alignment with LHC beam
- plot rate of events with muon hit in all 4 slabs

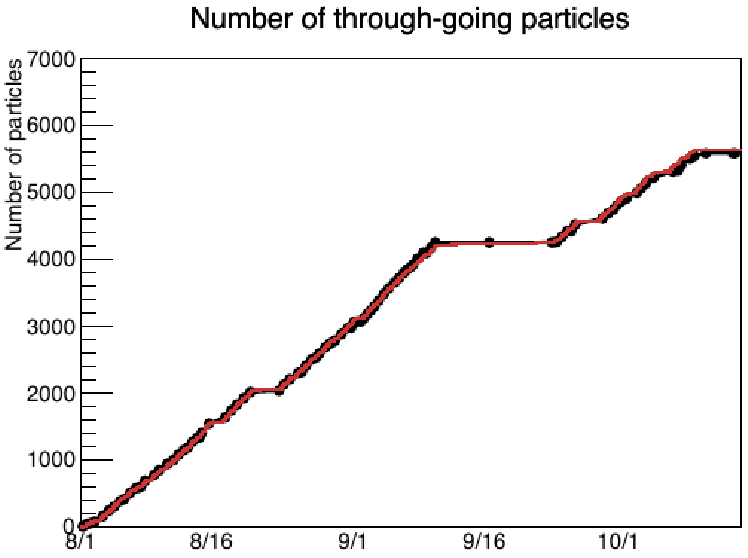


- agrees well with LHC fill / lumi data

Demonstrator results

Alignment





Black points - through-going milliQan particles

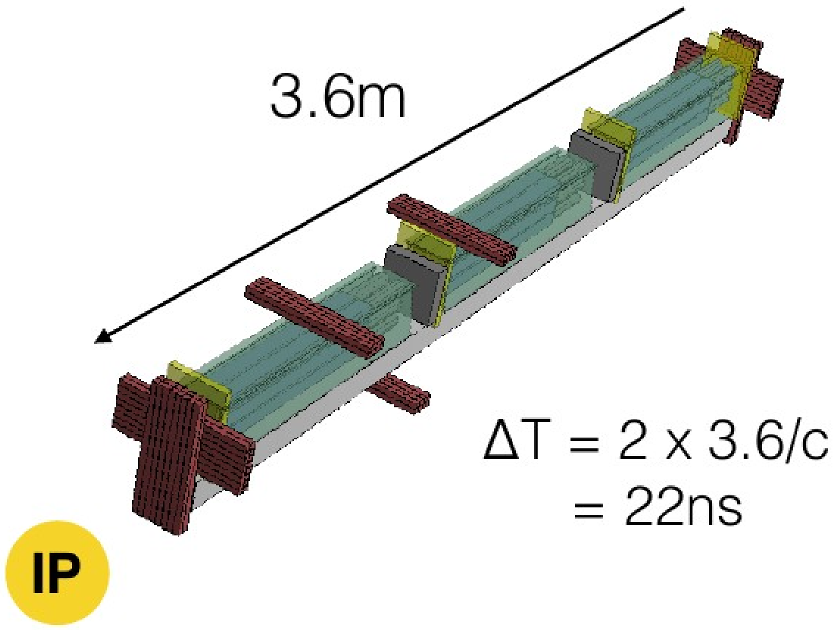
Red line - LHC cumulative lumi

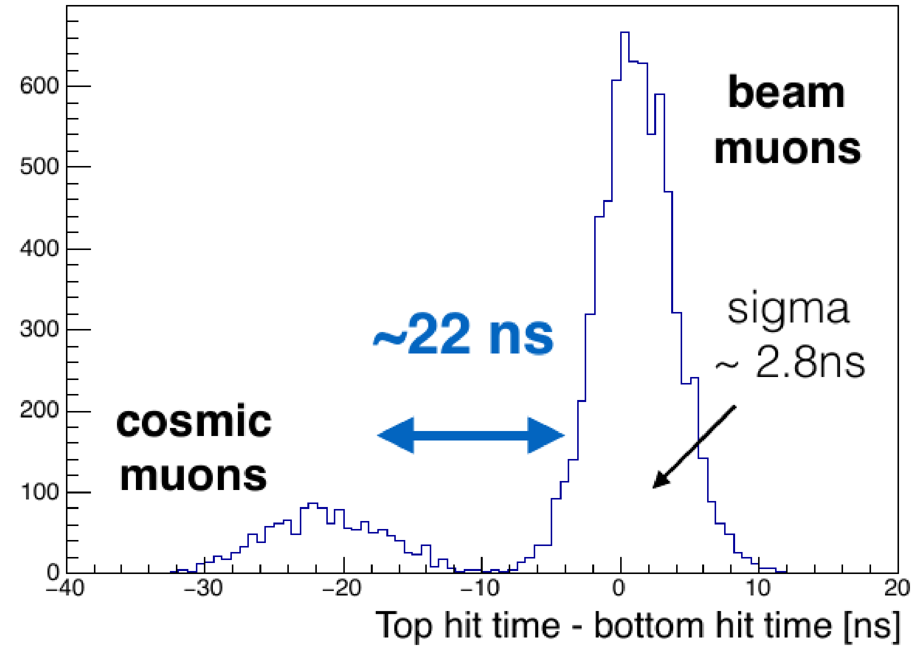
- measured rate: 0.20 ± 0.01 / pb^{-1} predicted rate: 0.25 ± 0.08 / pb^{-1}
  - very good match data – simulation!
    - uncertainties from B-hadron cross section and amount of material to cross
- in principle precision from survey is sufficient, no need for angular scan

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

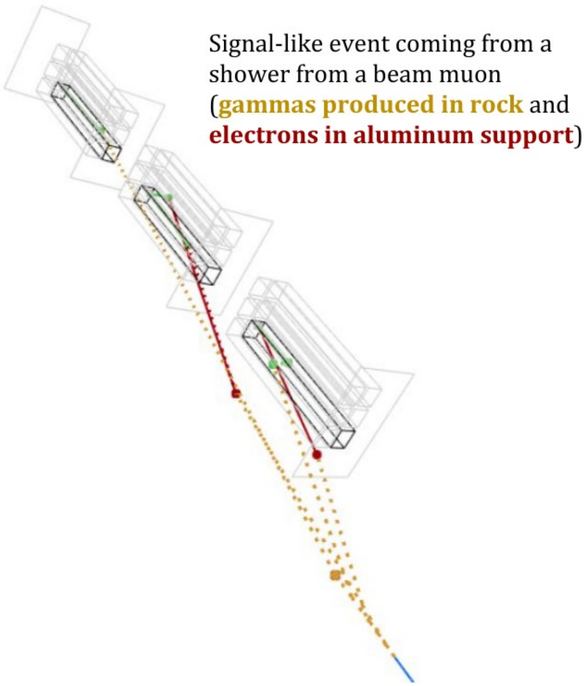


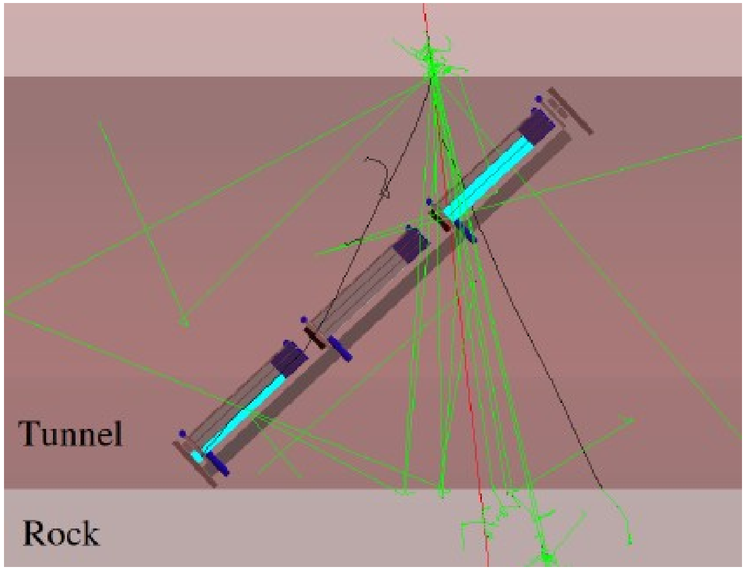


Demonstrator results

Backgrounds

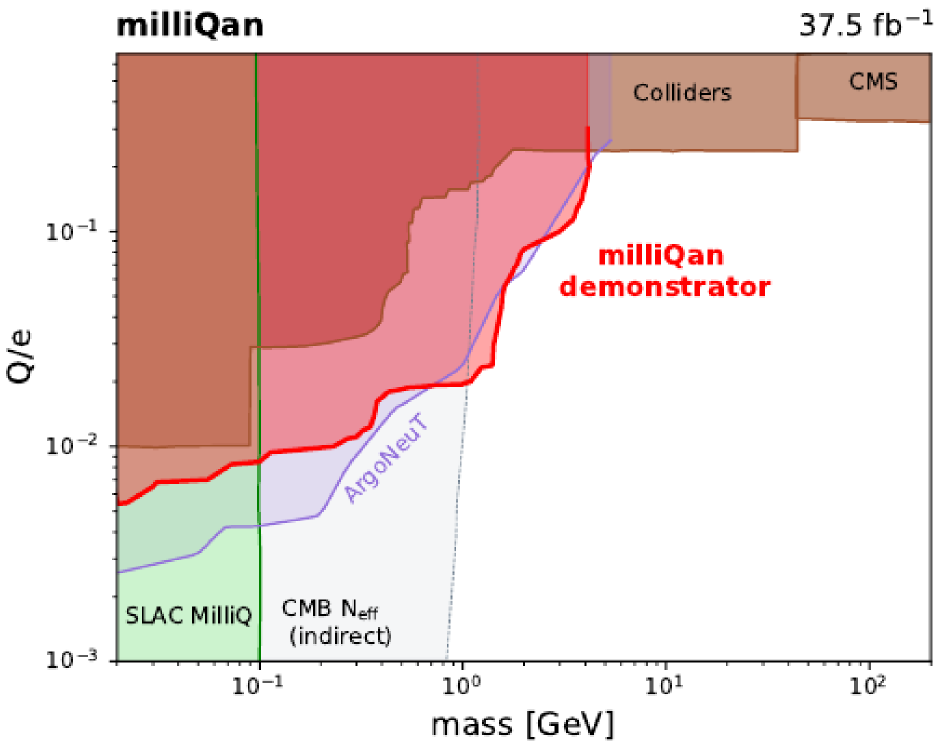
- sources of 3 in-time hits
  - PMT dark rate
  - afterpulses
  - radiation
  - showers from beam/cosmic muons
- important lesson from demonstrator
  - background from PMT dark rate subdominant
- further background suppression can be achieved
  - extra shielding
  - tagging of external sources
  - going to 4-layer design





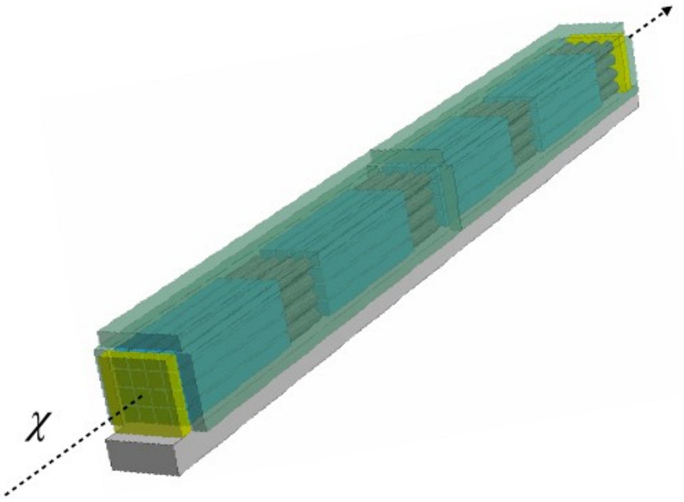
Demonstrator sensitivity

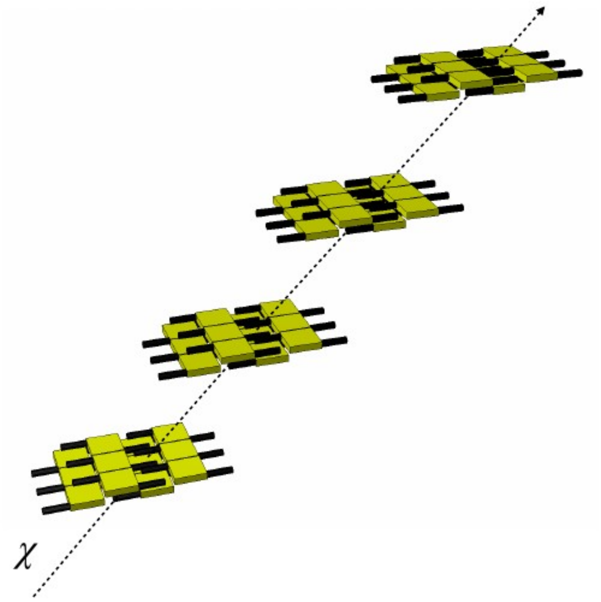
- analysis with demonstrator data published: Phys.Rev.D 102, 032002 (2020) arXiv:2005.06518 [hep-ex]
- new sensitivity already with demonstrator data!
  - new particles with masses between 20 and 4700 MeV are excluded for charges between 0.006 and 0.3 e



Towards Run-3 Detector

- collaboration is gearing up towards a detector for LHC Run-3
- use the knowledge from the demonstrator to build a 4x4x4 bar detector
  - 5x5x60 cm^3 scintillator bars to fit 4 layers
  - thicker 5cm scintillator panels for active veto
- additionally, add a 4-layer slab detector
  - bar detector good for low charge, but at high mass limitation is angular acceptance
  - 4 layers of 40x60x5 cm^3 scintillator slabs
- preparing construction this Fall
- installation and commissioning at CERN in time for LHC Run-3 operations in Spring 2022



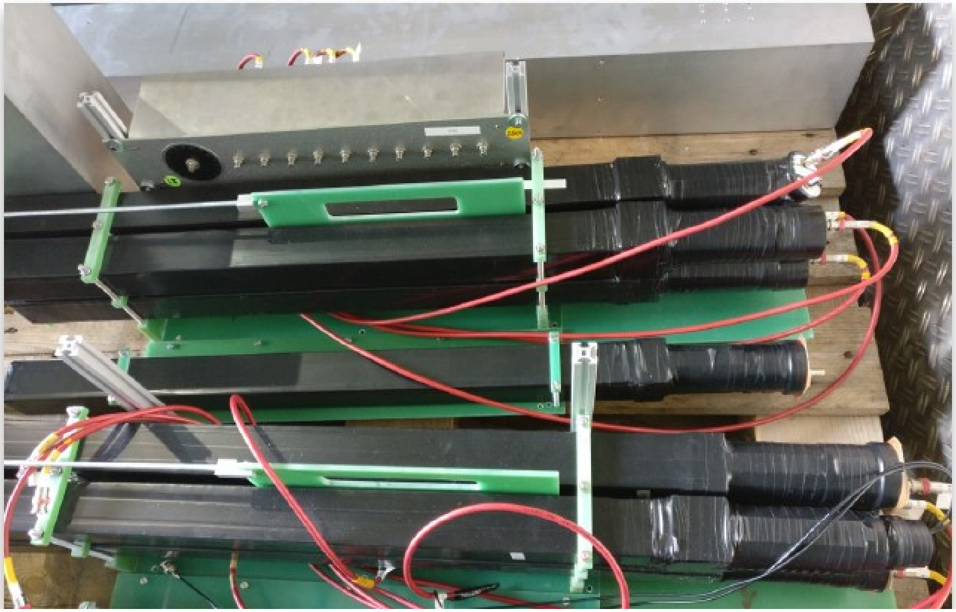


Towards Run-3 Detector

Building bars: “easy”!

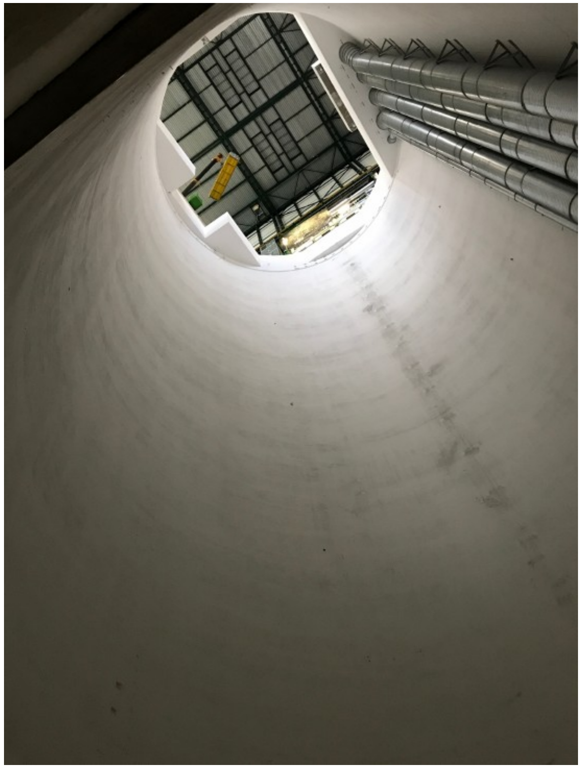
3D printed
PMT casing

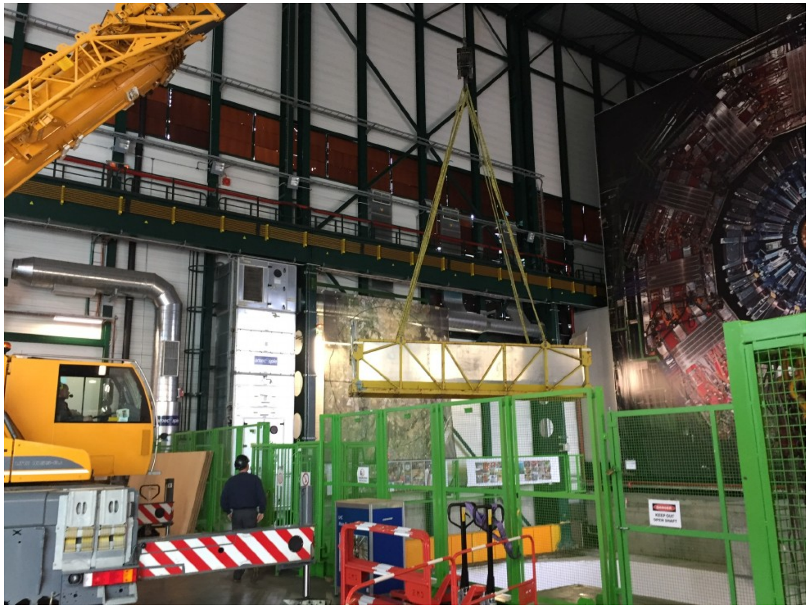
Bars wrapped in layers of reflective and light blocking materials (including tyvek, tinfoil, electrical tape)



Towards Run-3 Detector

Installation



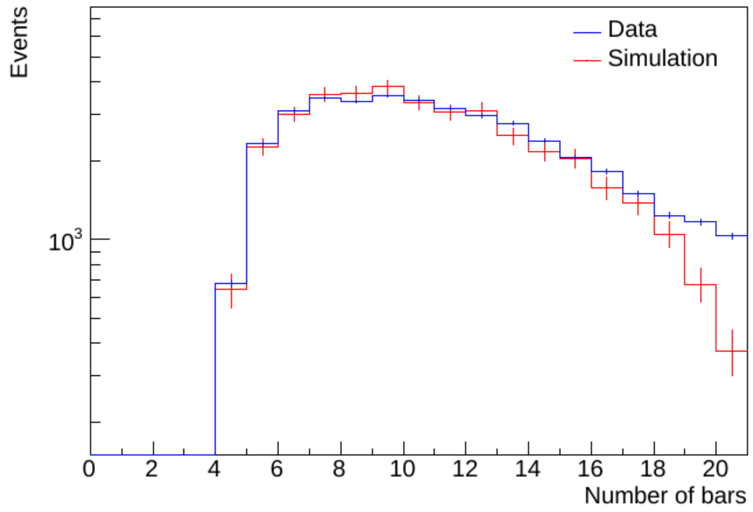


Towards Run-3 Detector

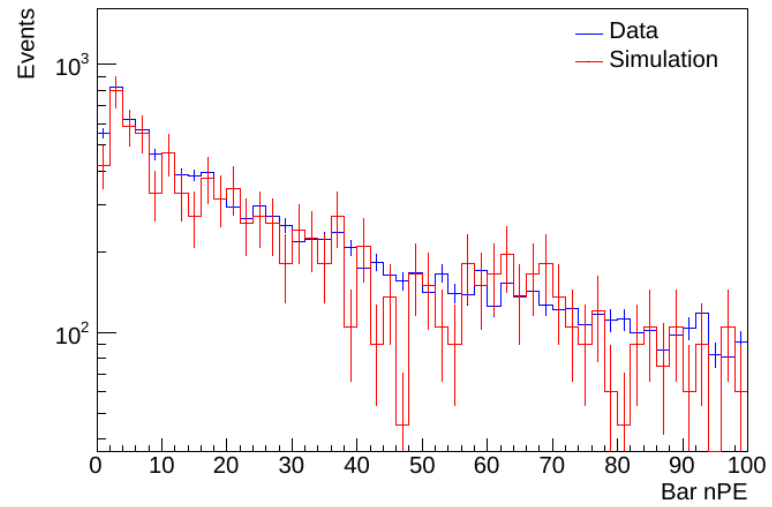
Detector simulation

- cosmic shower simulation refined using demonstrator data
- examples of well predicted quantities: (see arXiv:2104.07151)

number of bars with detected pulse from cosmic muons



number of photoelectrons in pulses from cosmic muons



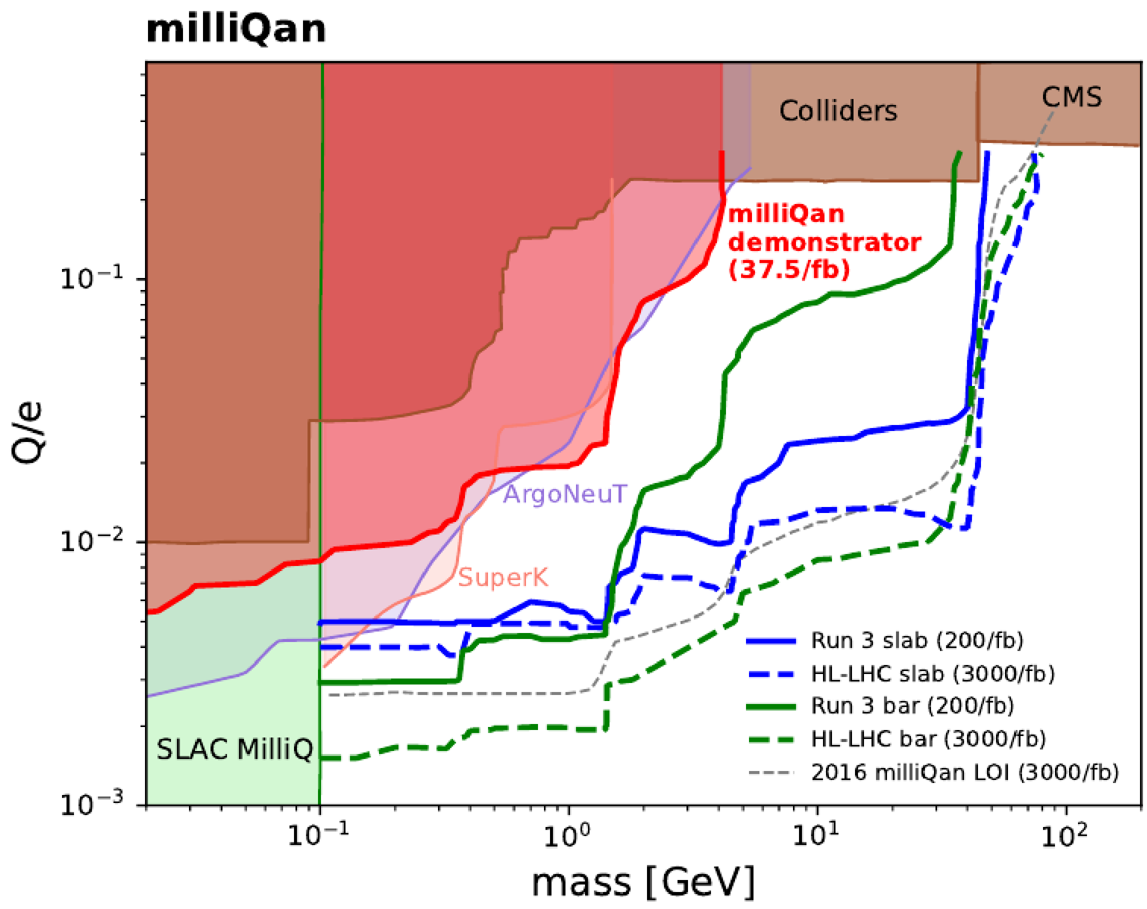
- main expected background very well predicted in simulation

  → optimize design for best sensitivity

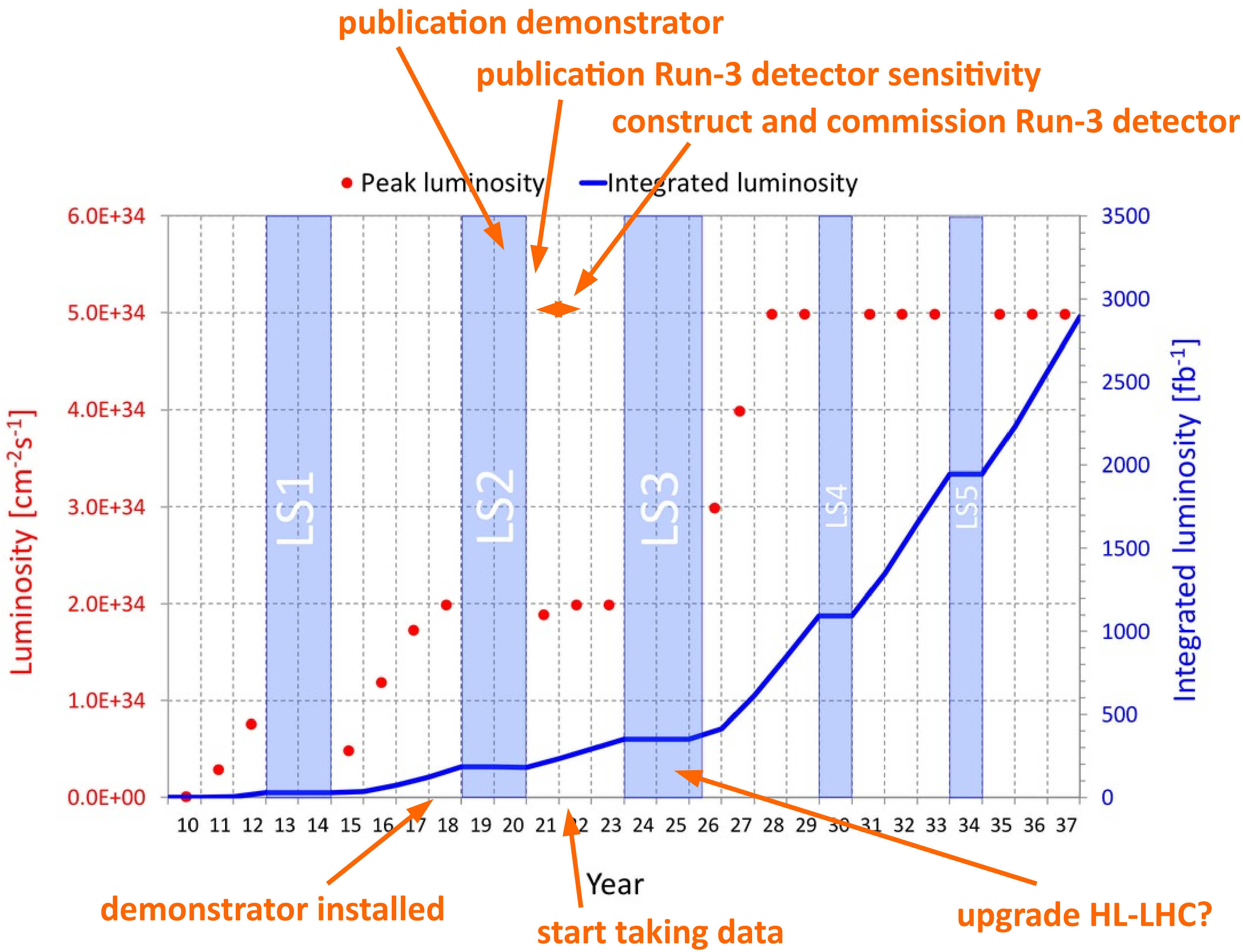
Towards Run-3 Detector

Sensitivity projection

- expect to rapidly enter new discovery territory



milliQan timeline



Conclusions

- the milliQan detector provides unique sensitivity to millicharged particles
  - uncovered phase space $0.1 < m < 100$ GeV, $Q < .3e$
- 1% demonstrator successfully validates feasibility
  - successful construction and operation; first sensitivity
  - many lessons learned from commissioning and in-situ background studies
- Run-3 detector is underway
  - 4x4x4 bar detector complemented with 4-layer slab detector
  - large new sensitivity projected

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