A search for millicharged particles at the LHC

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IIHE Seminar

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

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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

Towards discovery at LHC

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- many more limits on BSM physics

Run 3: 2021-2024

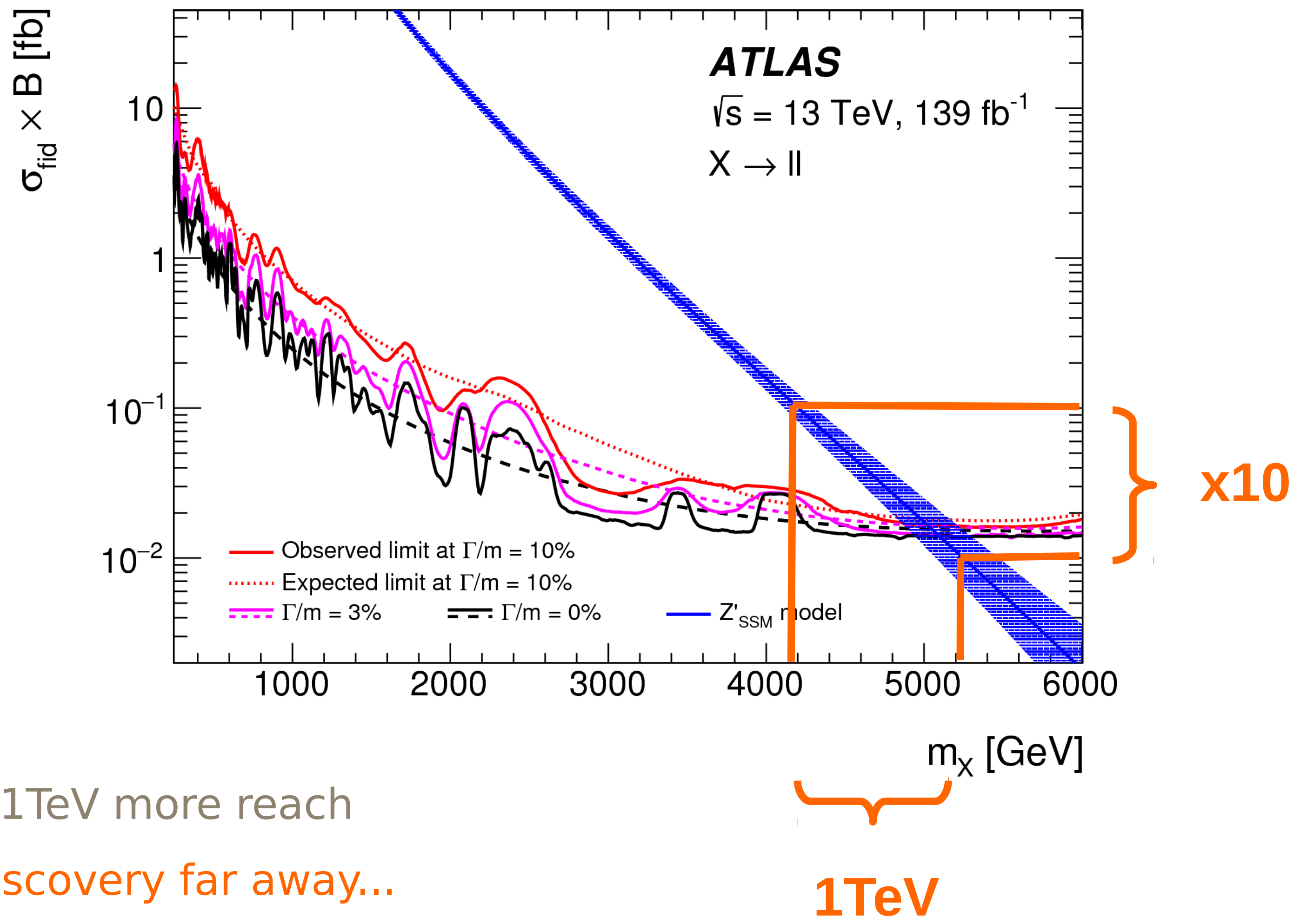
- 13-14 TeV, 300/fb
- aim for lower mass, lower cross section, difficult final states (eg. LL)
- BSM sensitivity? more lumi needed!

Towards discovery at LHC

Much more lumi – but how much?

- eg. 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...

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 > physics > arXiv:1909.13022

Physics > Instrumentation and Detectors

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

Martin Bauer, Oleg Brandt, Lawrence Lee, Christian Ohm

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 F

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

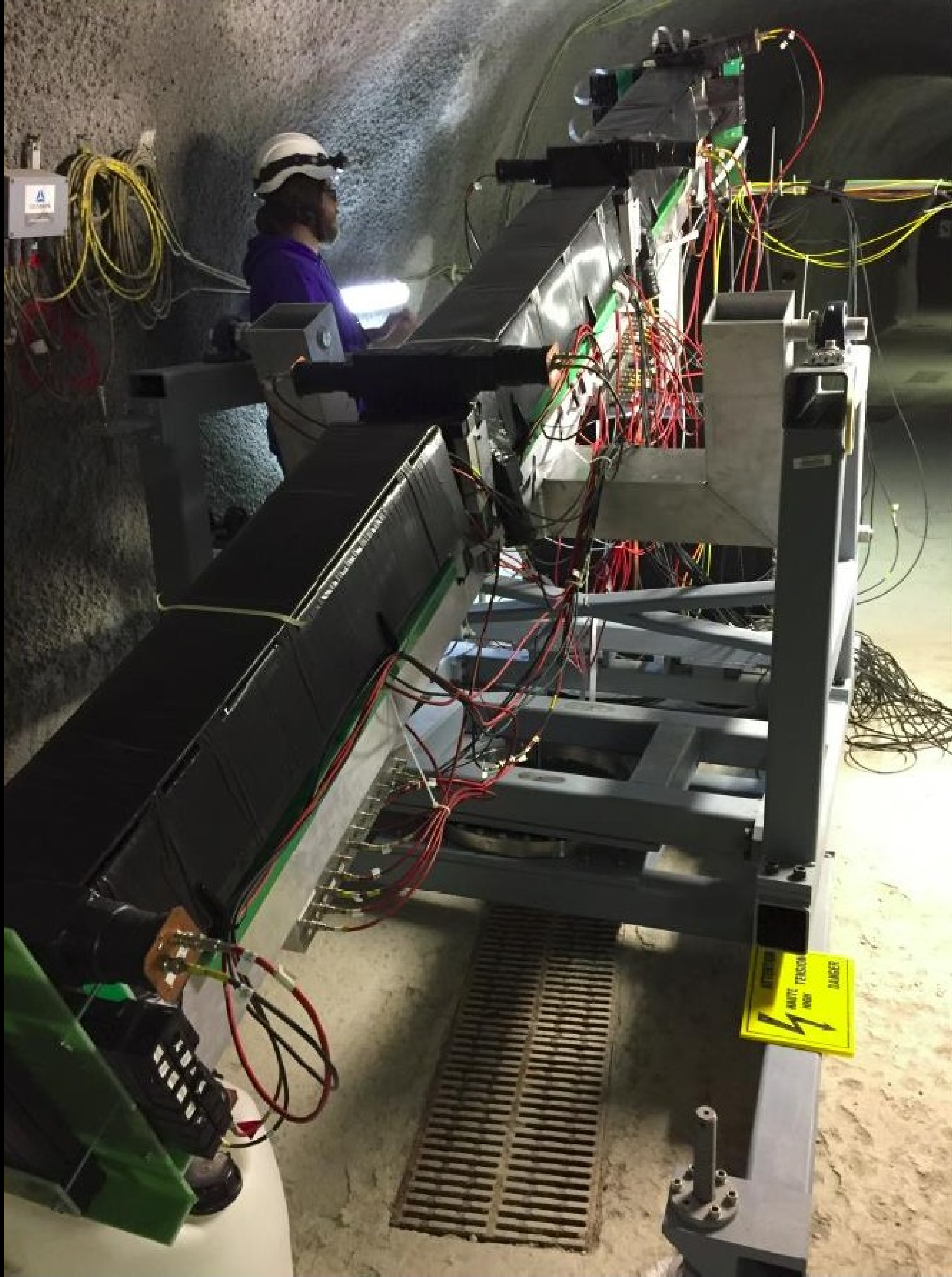
High Energy Physics - Experiment

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

milliQan

New experiment to search for millicharged particles at the LHC



Milli charges?

How does that even work?

- we actually don't even know why (or if) electric charge is quantized
  - only explanation so far involves monopoles, but unobserved (so far)
  - it is theoretically consistent to add new particles with small electric charge

- but it may actually arise rather naturally

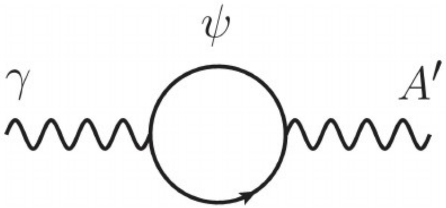
- suppose we add a U(1)' massless boson to the SM

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

kinetic mixing
[Holdom '86]

Milli charges?

- 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

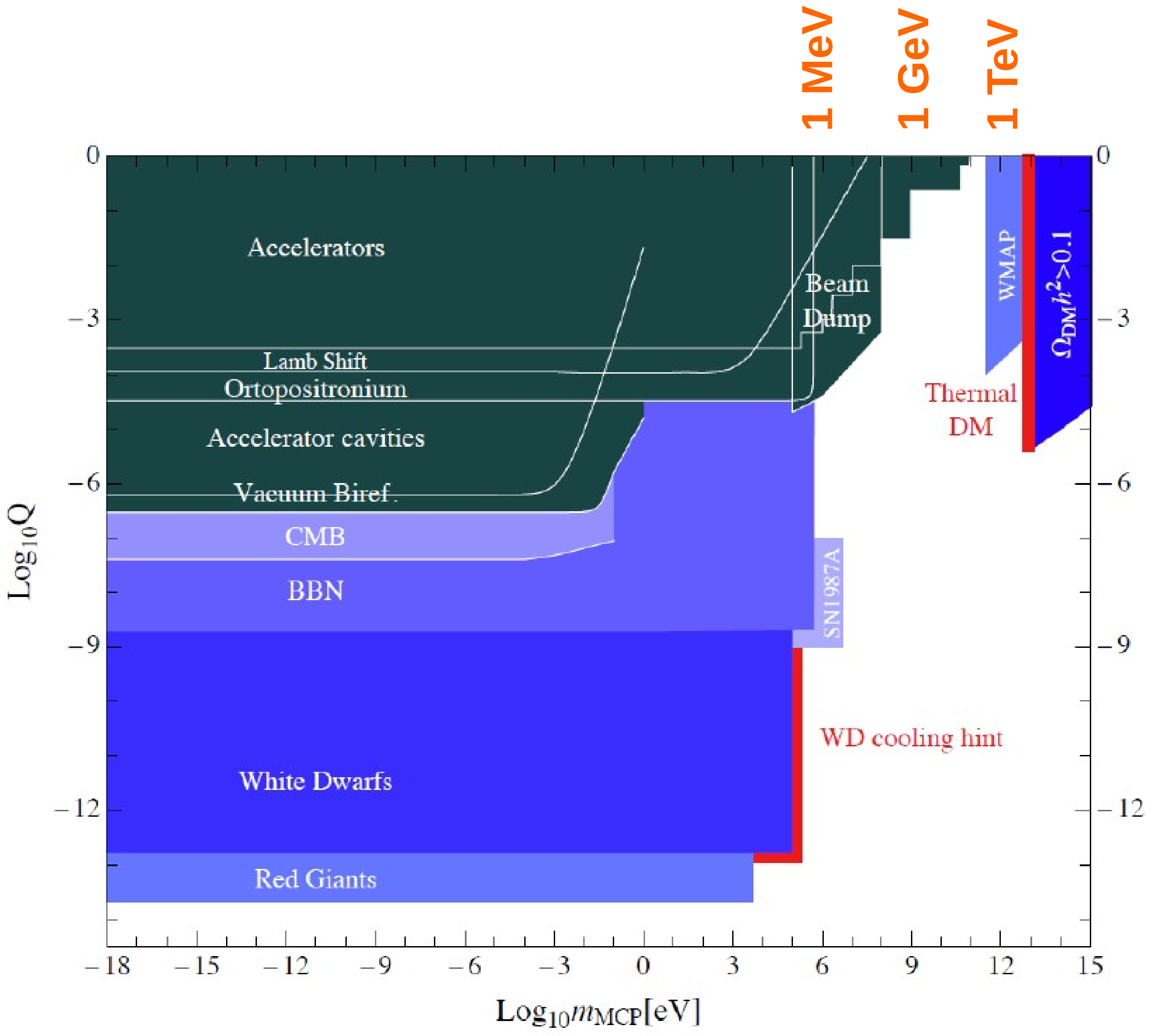
Theoretical

- kinetic mixing is 1 of 4 possible portals to dark sector
- dark sector can contain dark matter!
- extra U(1) groups rather generic feature of GUTs and other theories
- very economical setup, easy to embed

Experimental

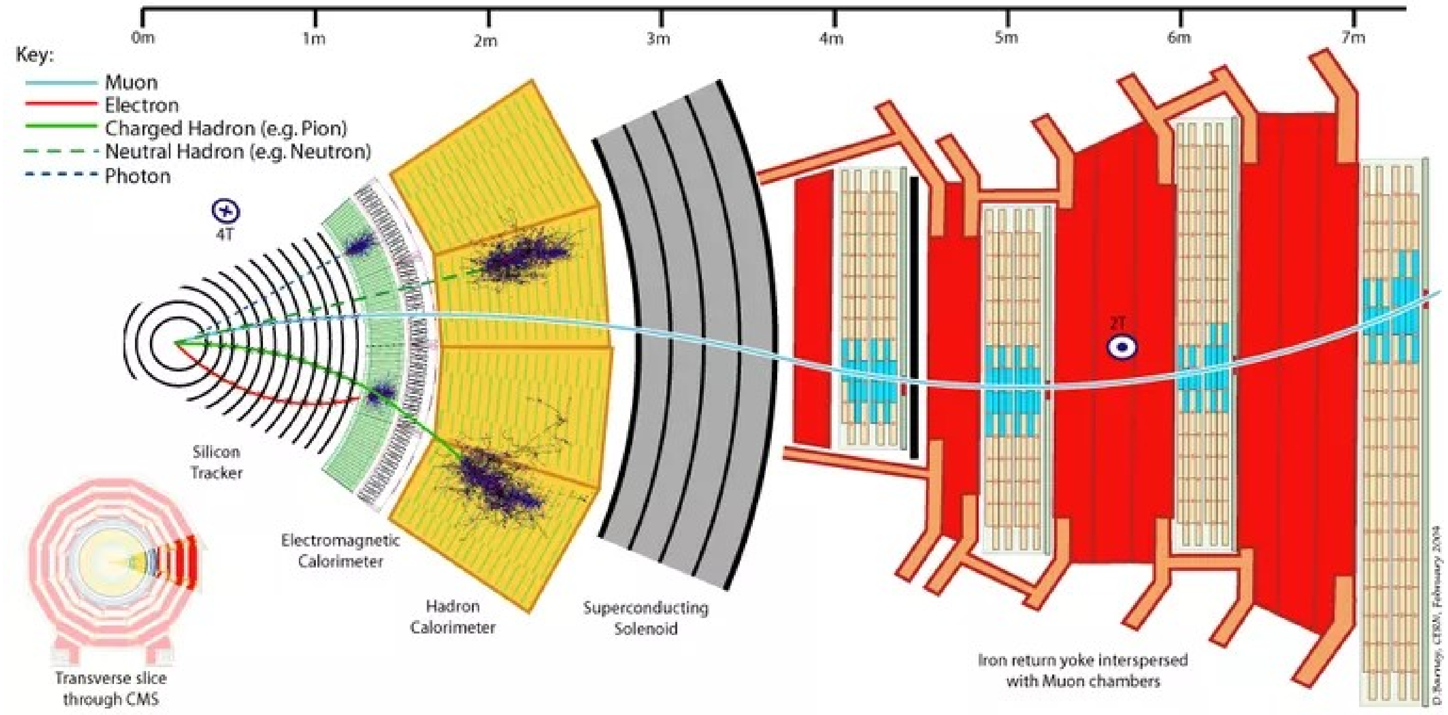
- opportunity: very weak limits above ~1GeV; unique role LHC
- EDGES 21cm result can be explained with subdominant millicharged DM (arXiv:1803.03091)

Existing bounds



How to detect milli charges?

Just use CMS!?

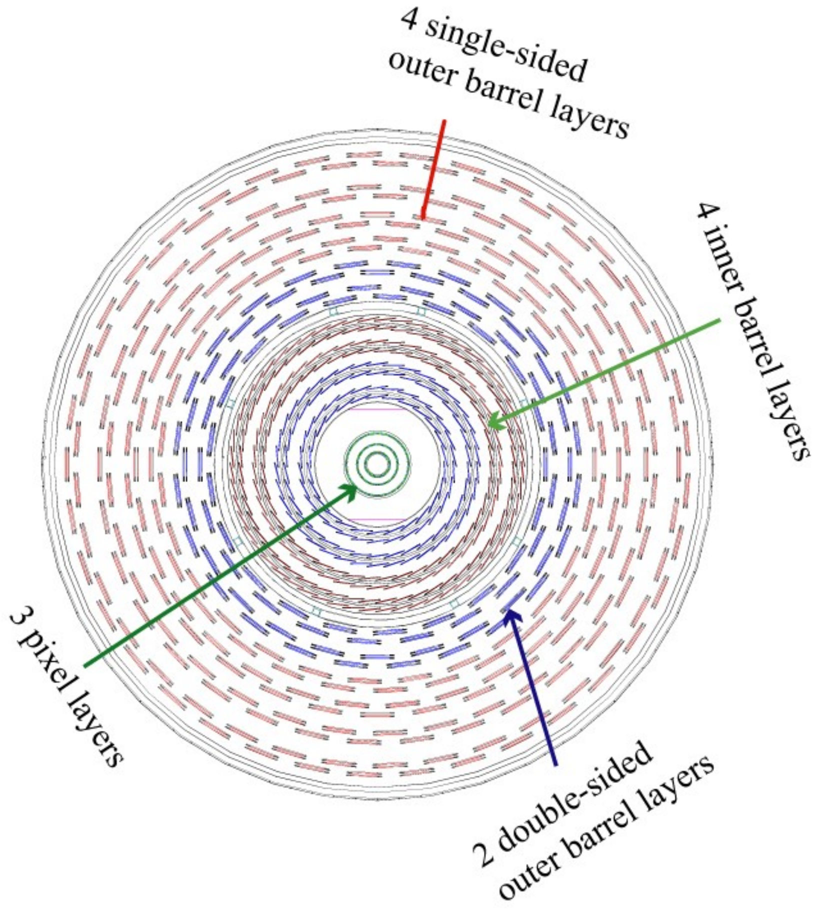


- at lower charge
  - tracks become straighter → momentum ~ 1/Q
  - energy loss becomes smaller → dE/dx ~ Q^2

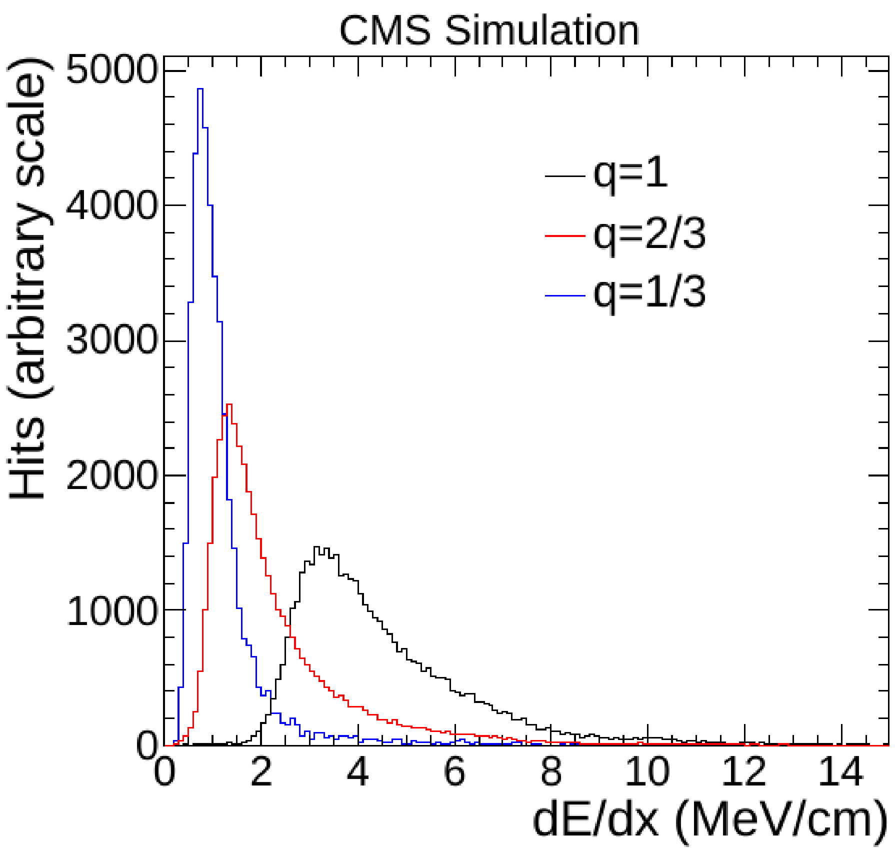
Milli charges in CMS

Search for tracks with many low-dE/dx hits

- 1 track brings many independent measurements of ionization loss



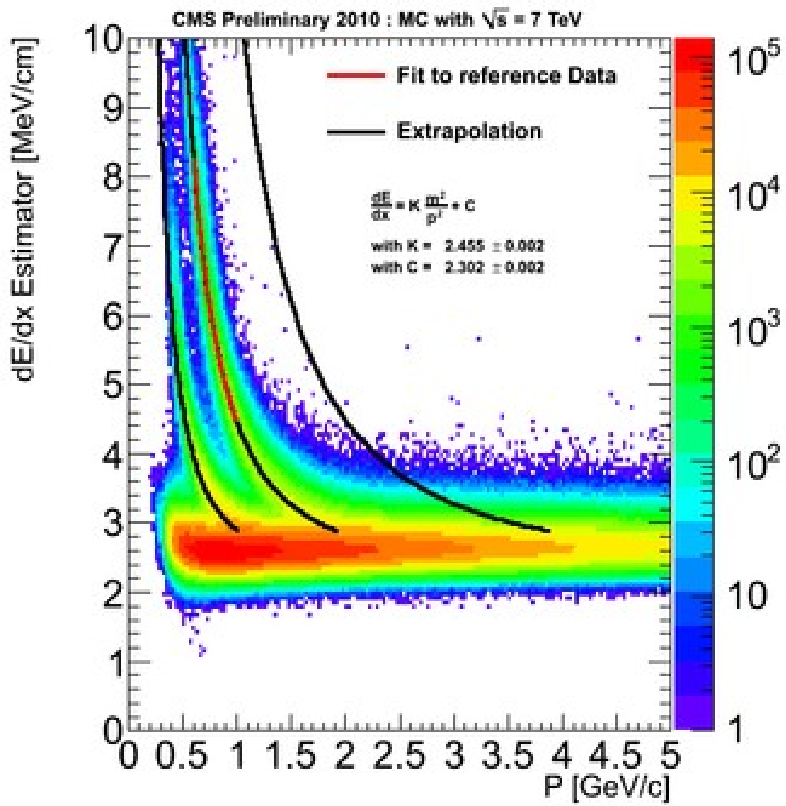
CMS-PAS-EXO-11-074



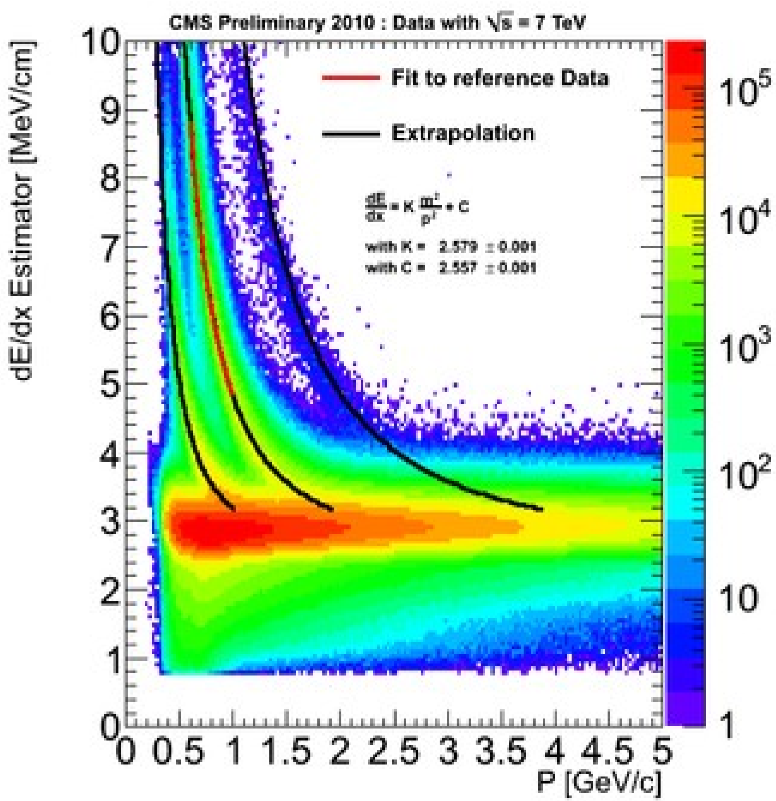
Milli charges in CMS

dE/dx performance in CMS

area of interest: difficult!



simulation



data

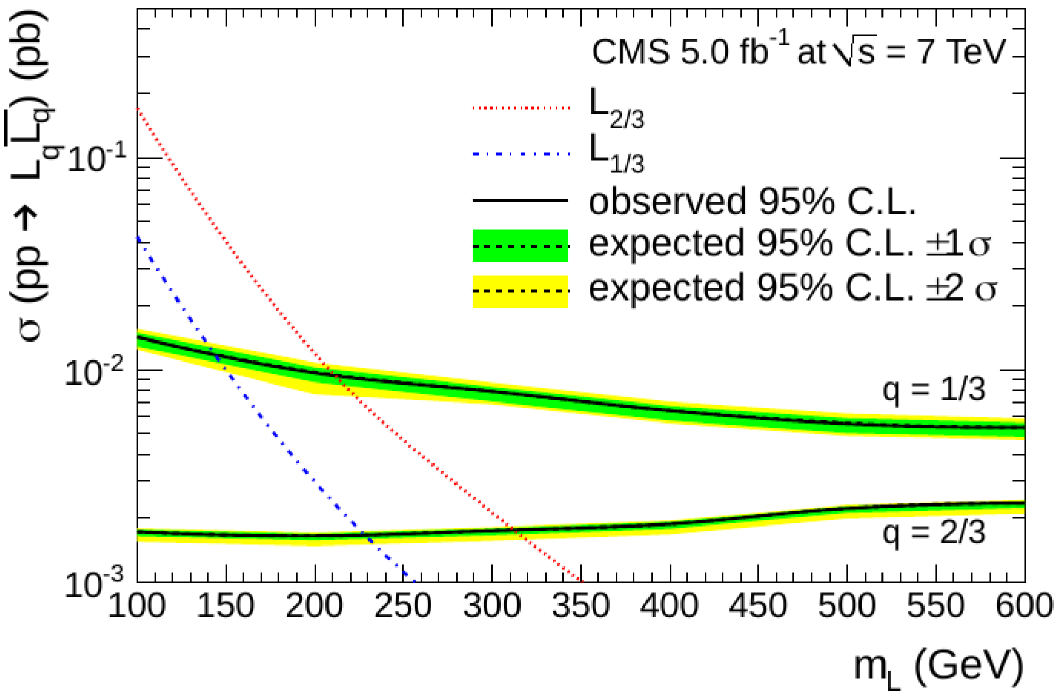
- also very sensitive to detector aging

Milli charges in CMS

Current analysis reach

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

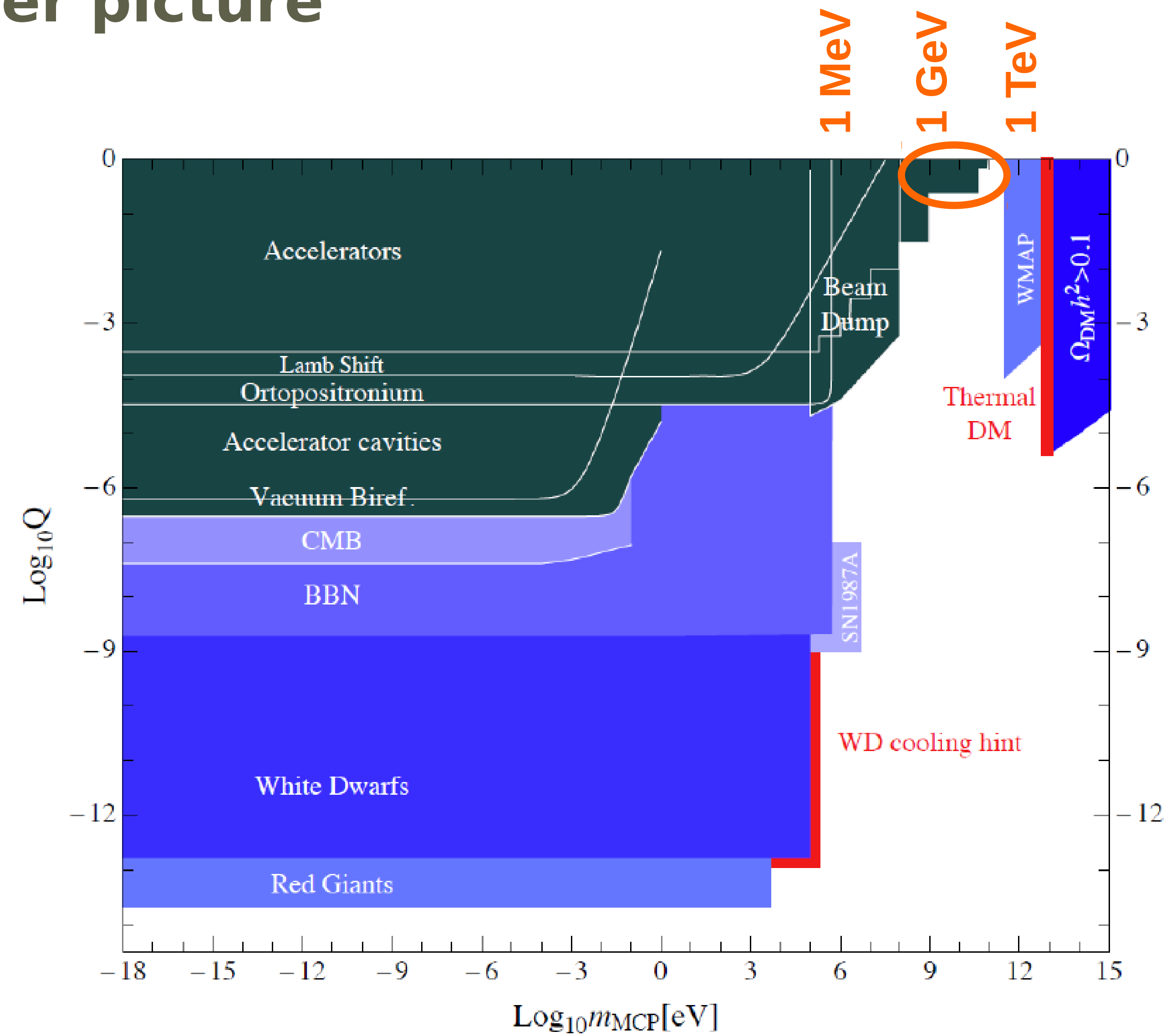
Phys. Rev. D 87 (2013) 092008



- update almost public!

Milli charges

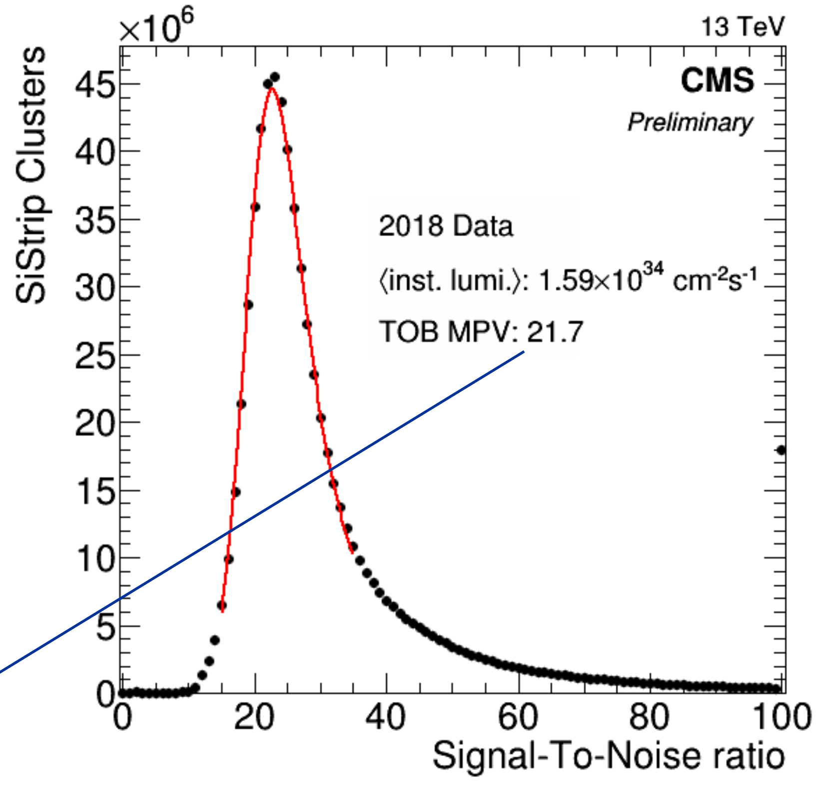
The bigger picture



Going lower

What about lower charges?

- fundamental limitation of the CMS/ATLAS detectors



CMS DP-2018/052

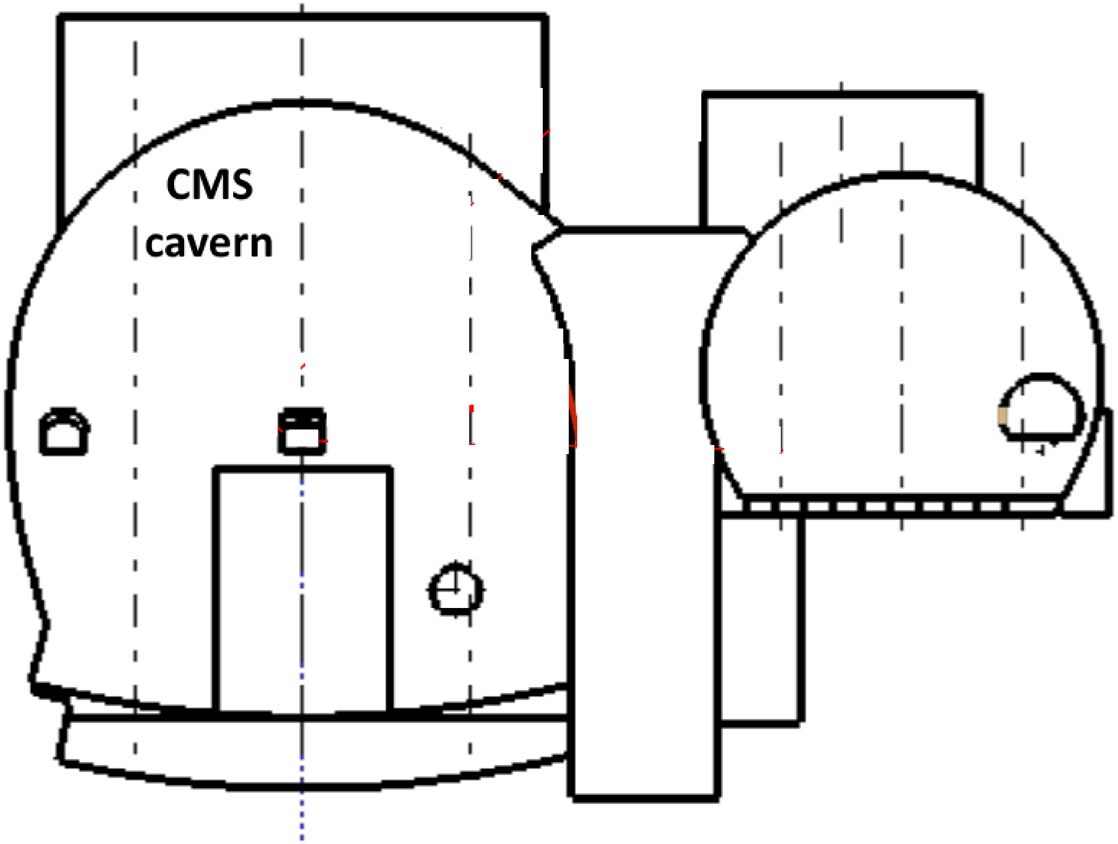
- $1/Q^2 \sim 21.7$
  → cluster charge from particle with Q = 0.2 has MPV ~ noise level

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
  - r^2 dependence of flux

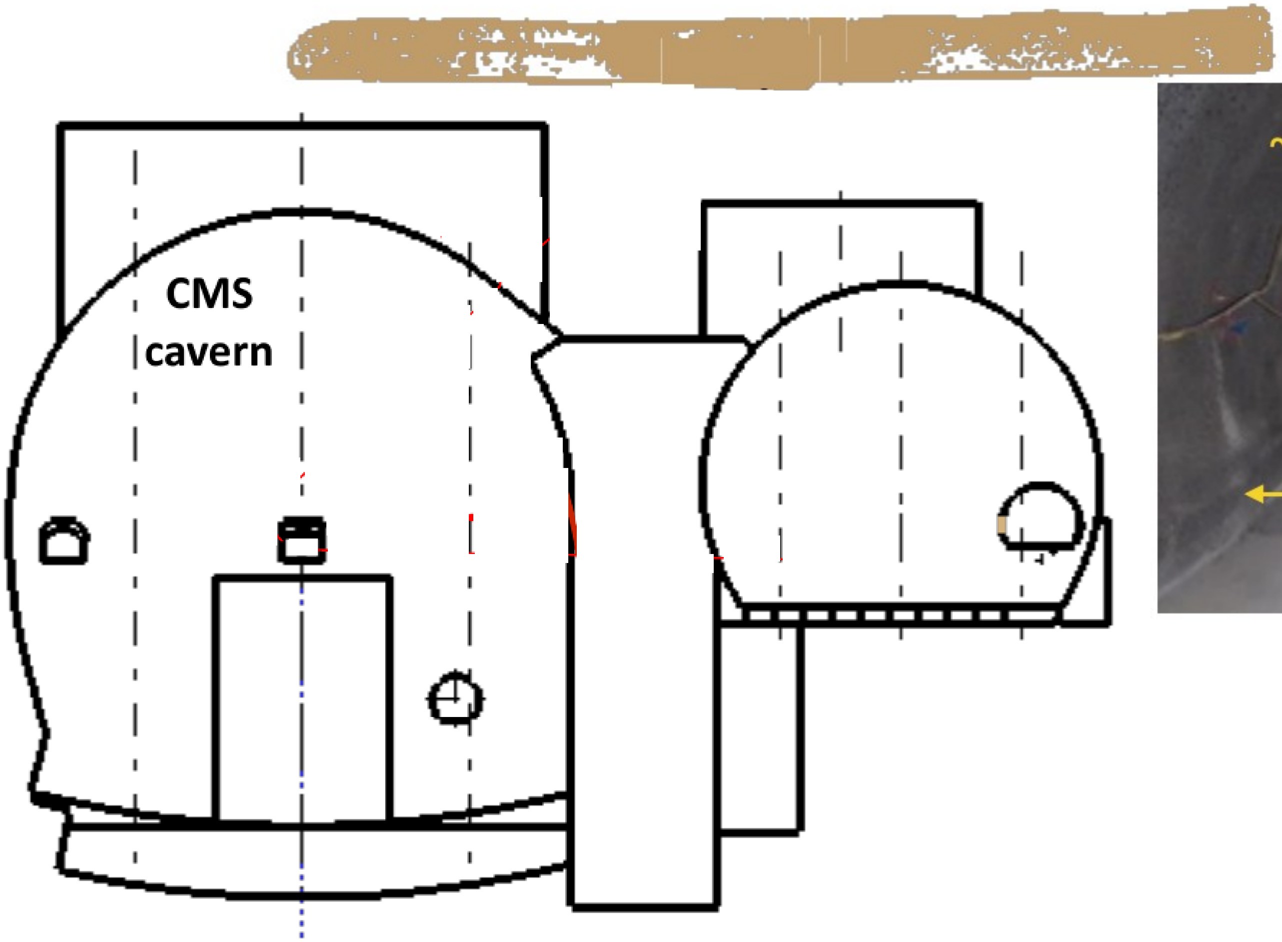
milliQan location

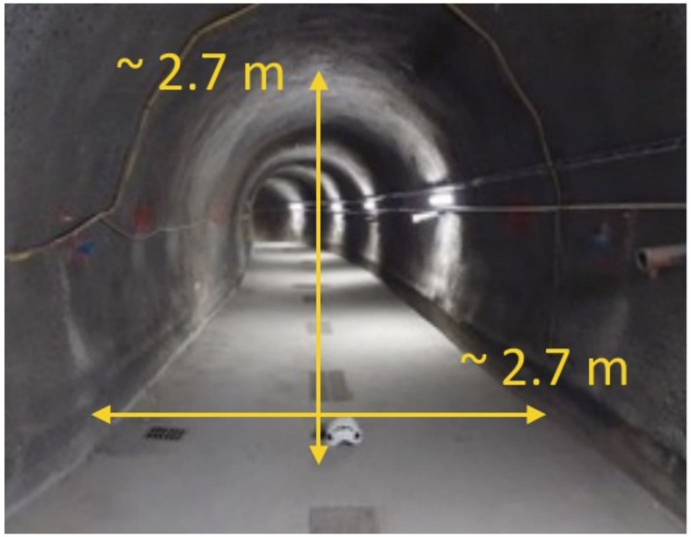


100m
underground

milliQan location

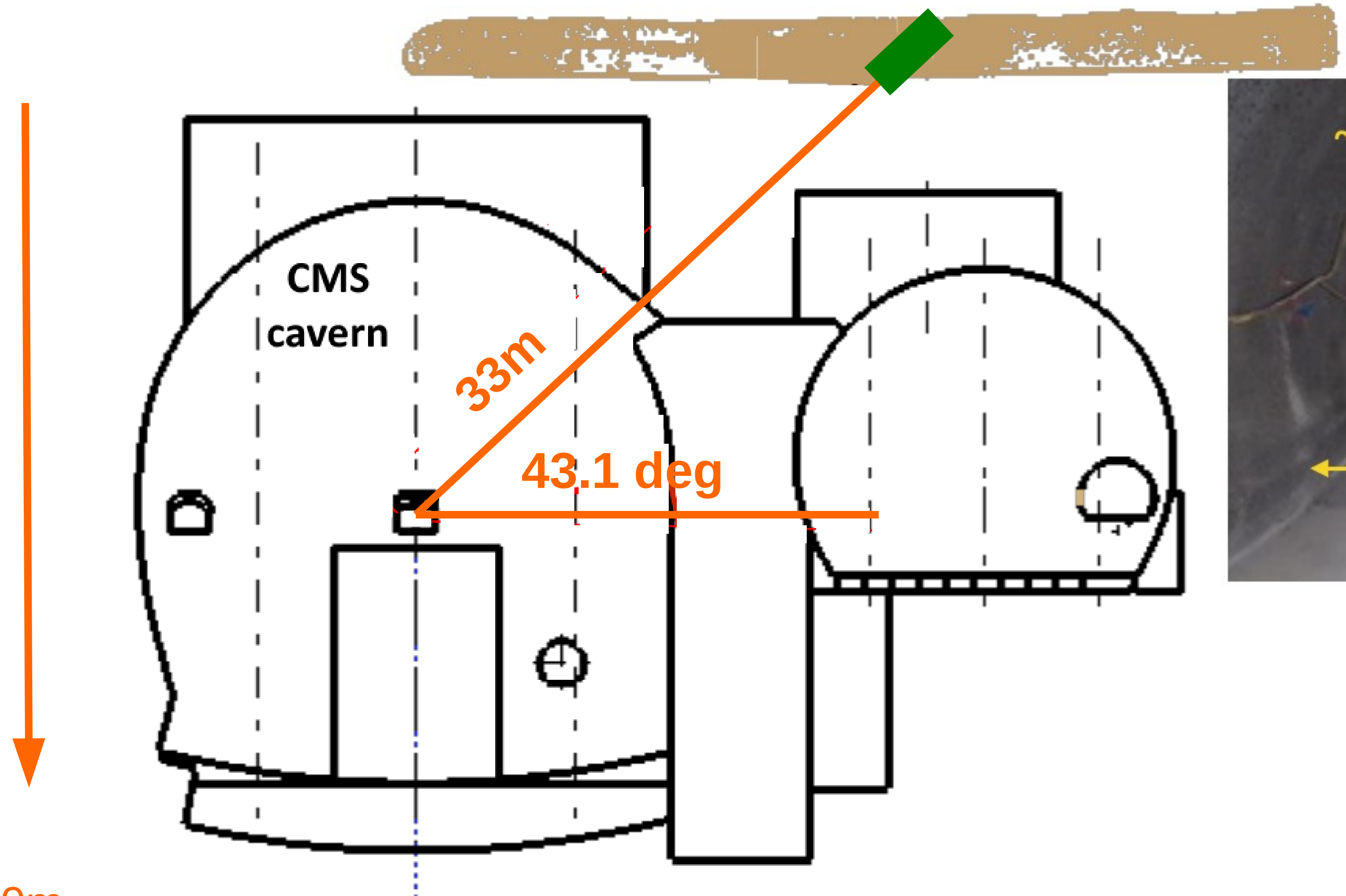
Drainage gallery



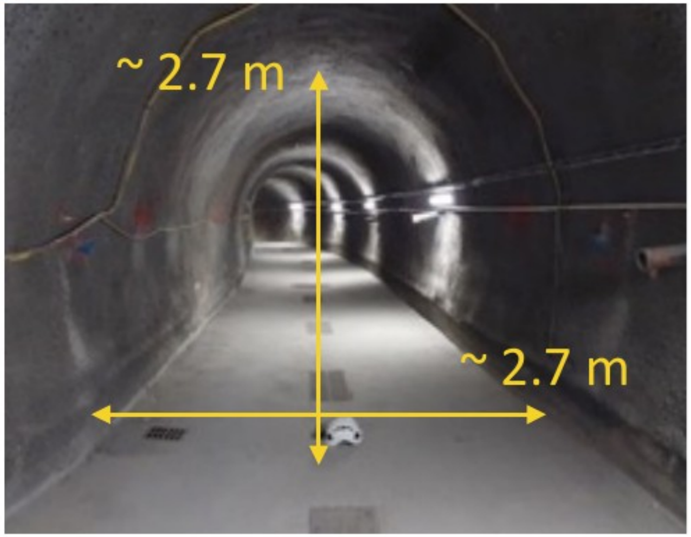


100m
underground

milliQan location

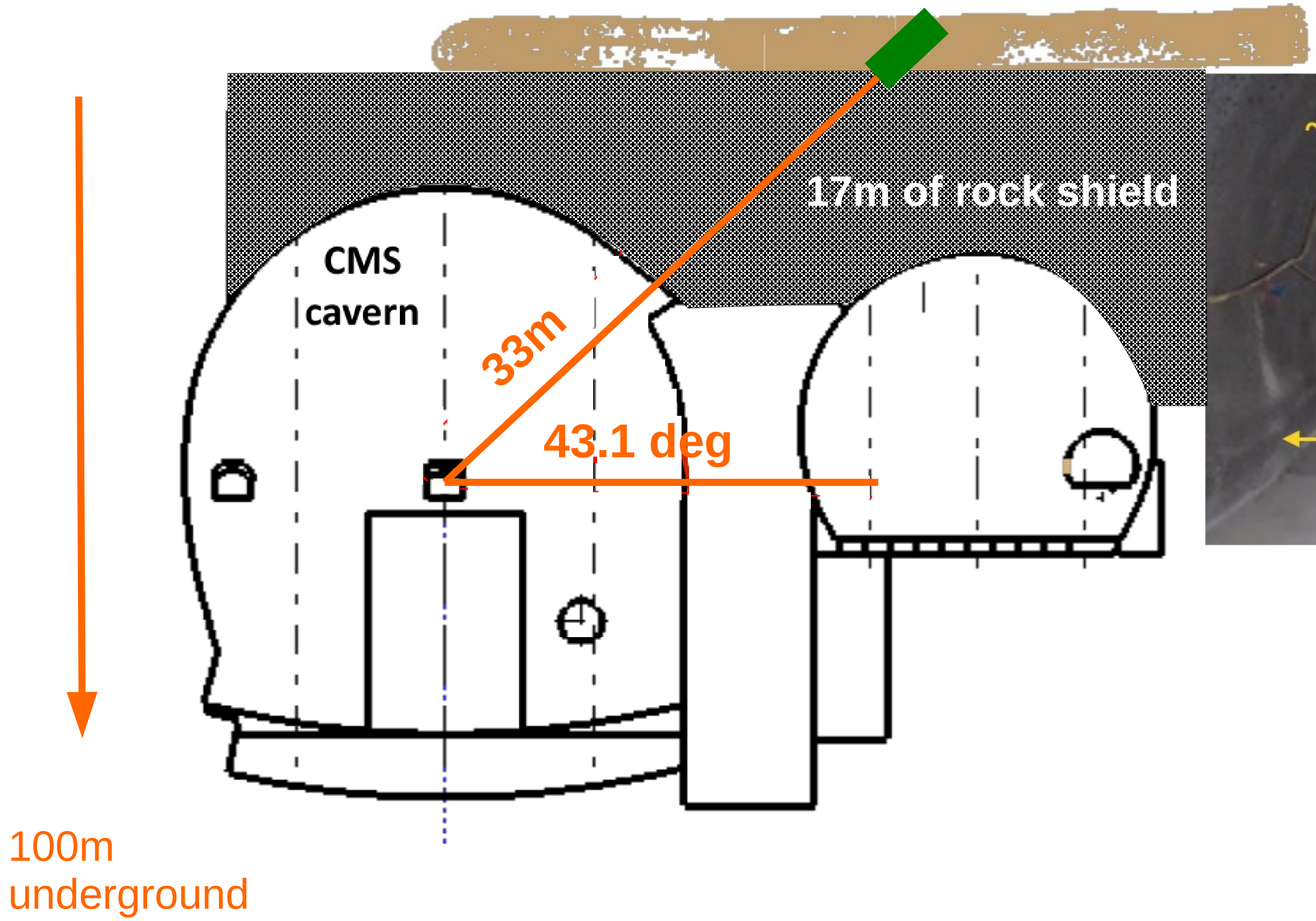


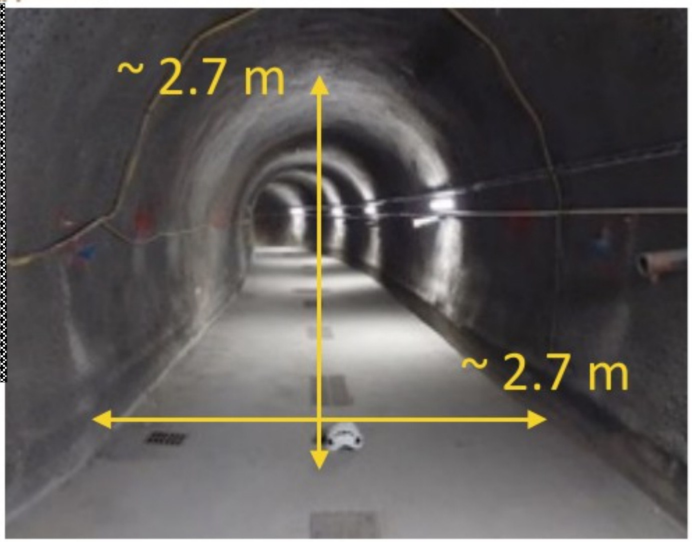
Drainage gallery



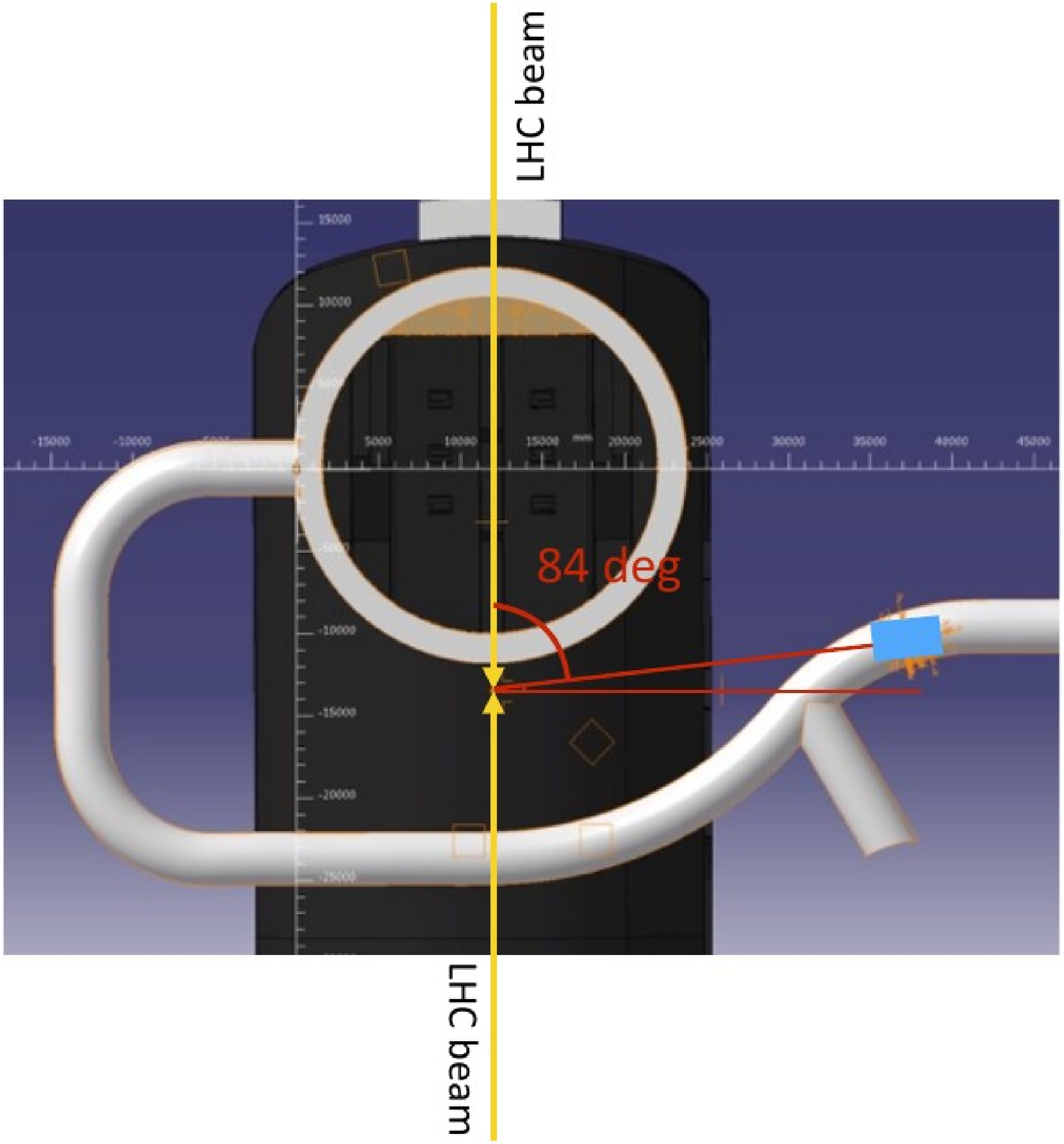
100m
underground

milliQan location



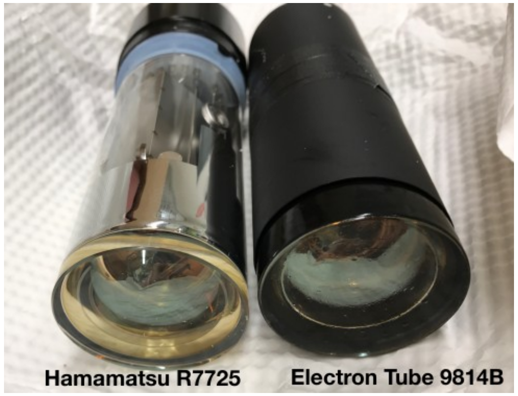


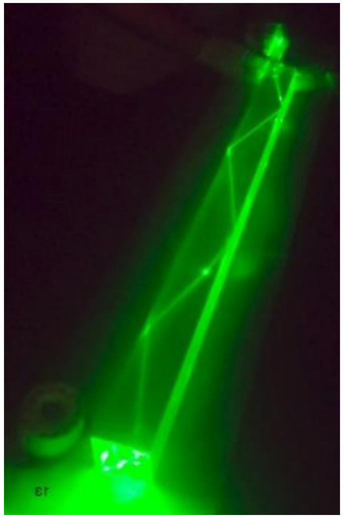
milliQan location

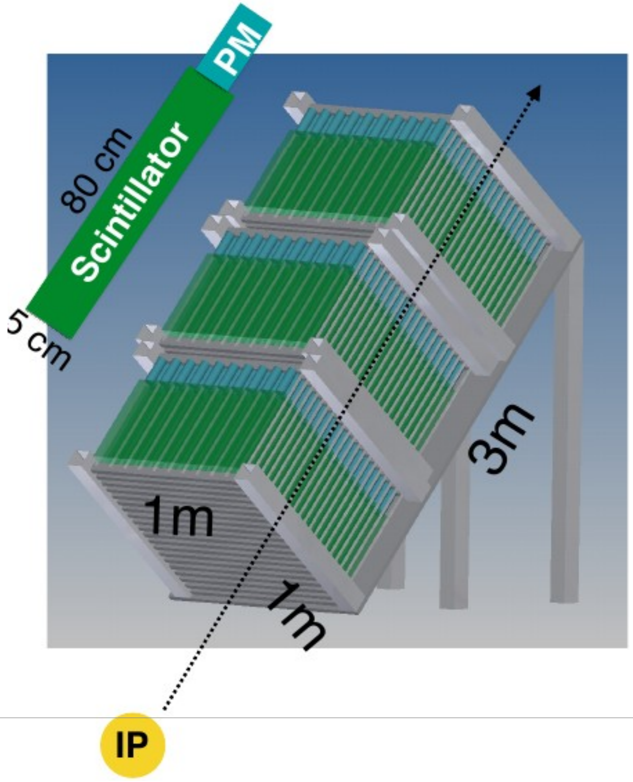


milliQan detector principle

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



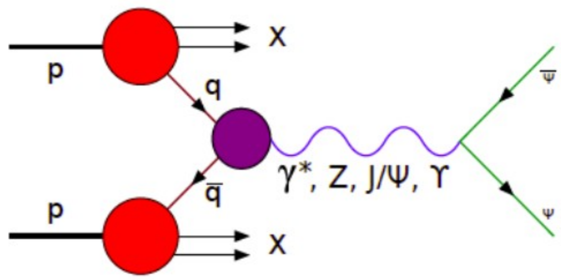




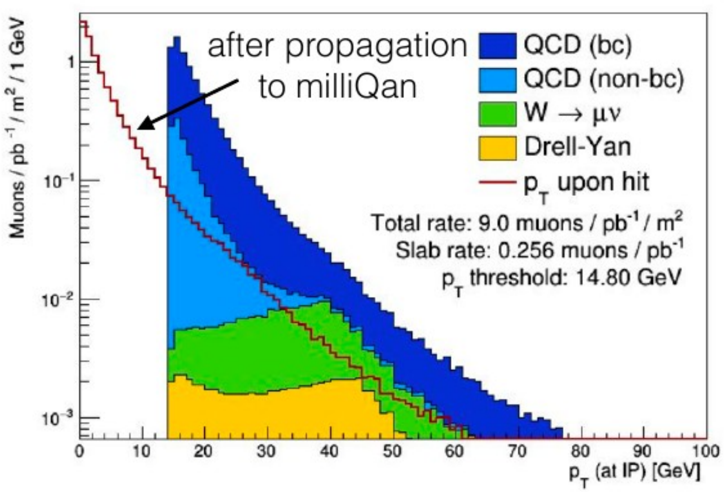
Simulation

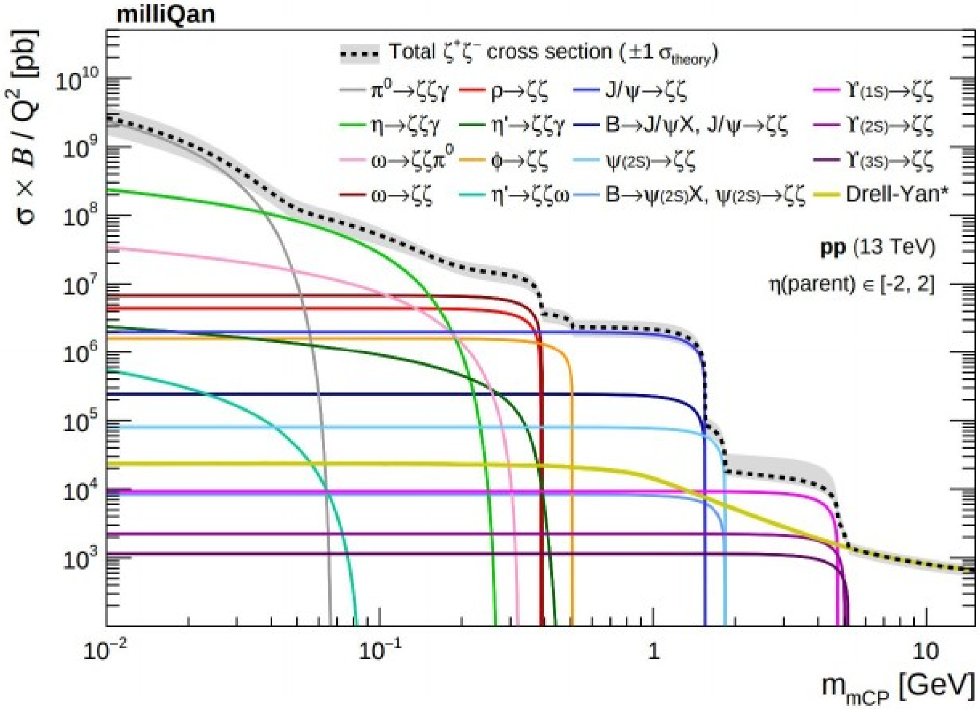
Production and transport simulation

- 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

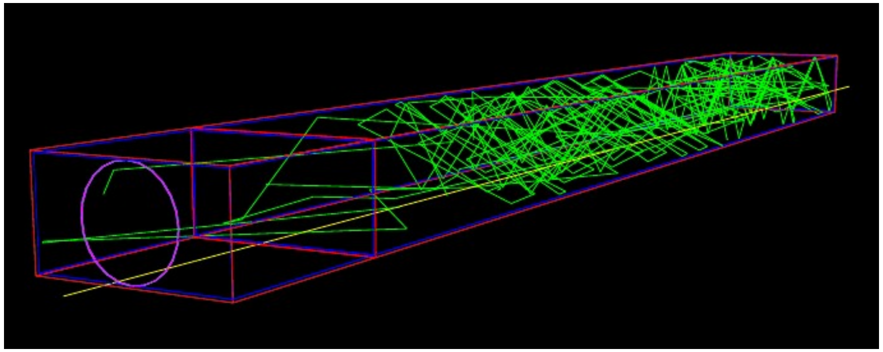


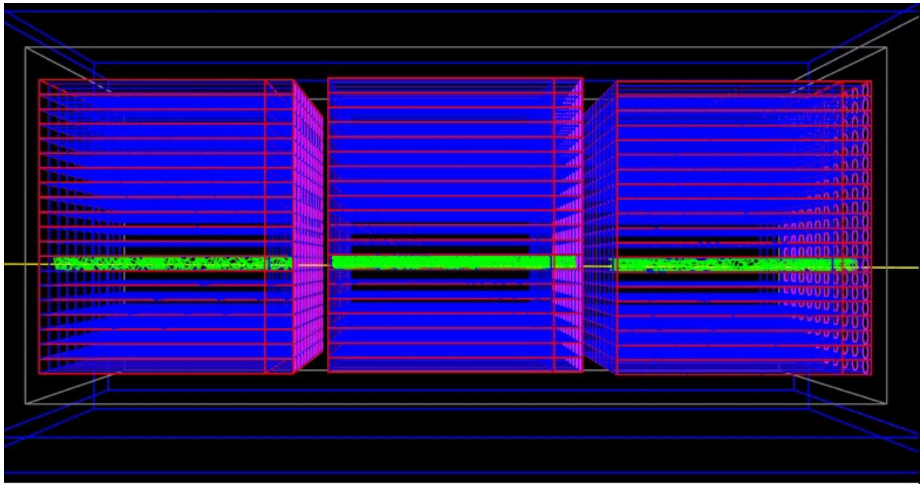


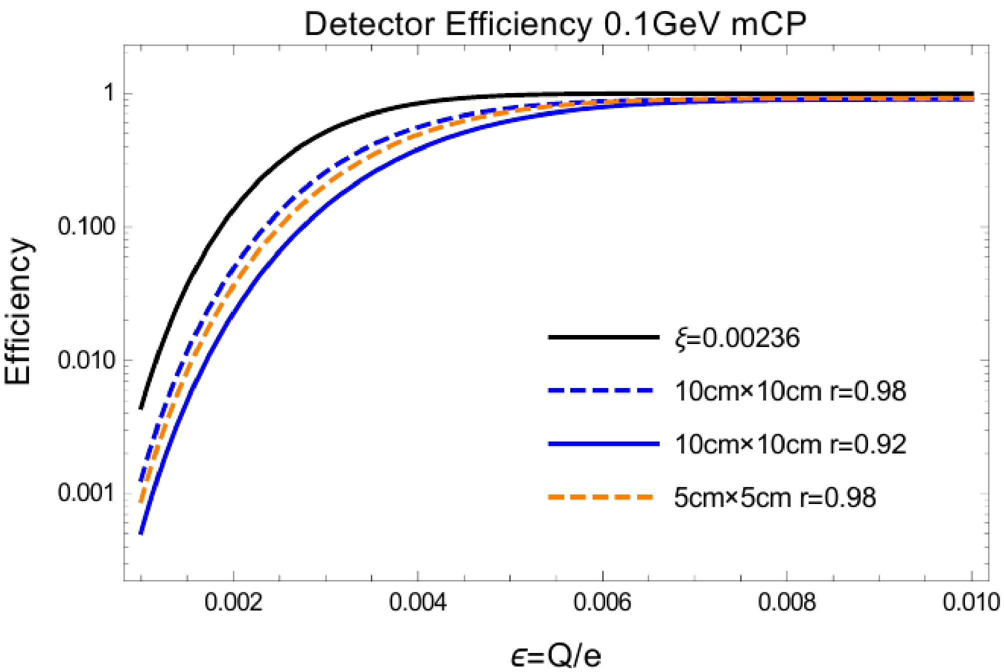
Simulation

Full Geant4 detector simulation

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



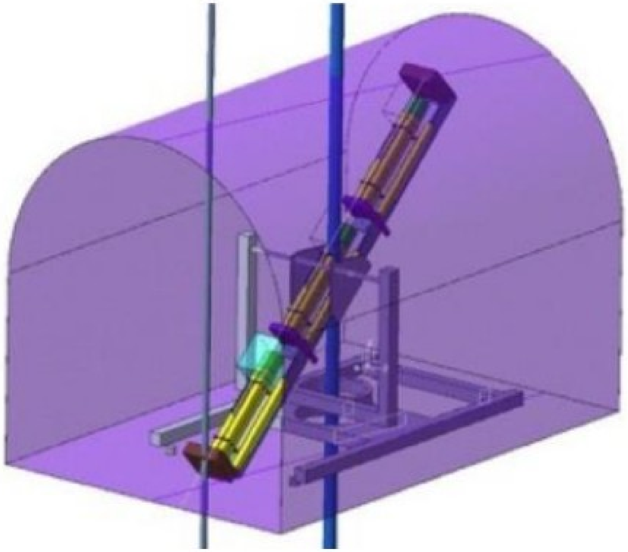


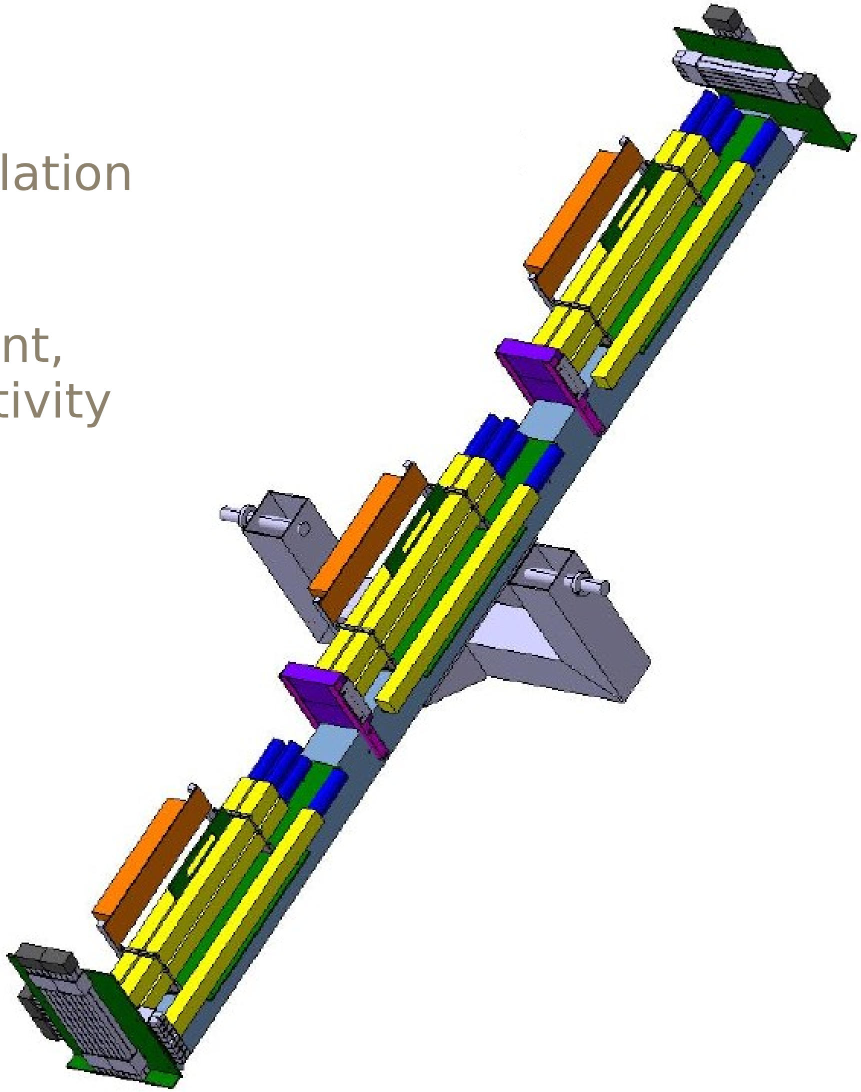


Demonstrator

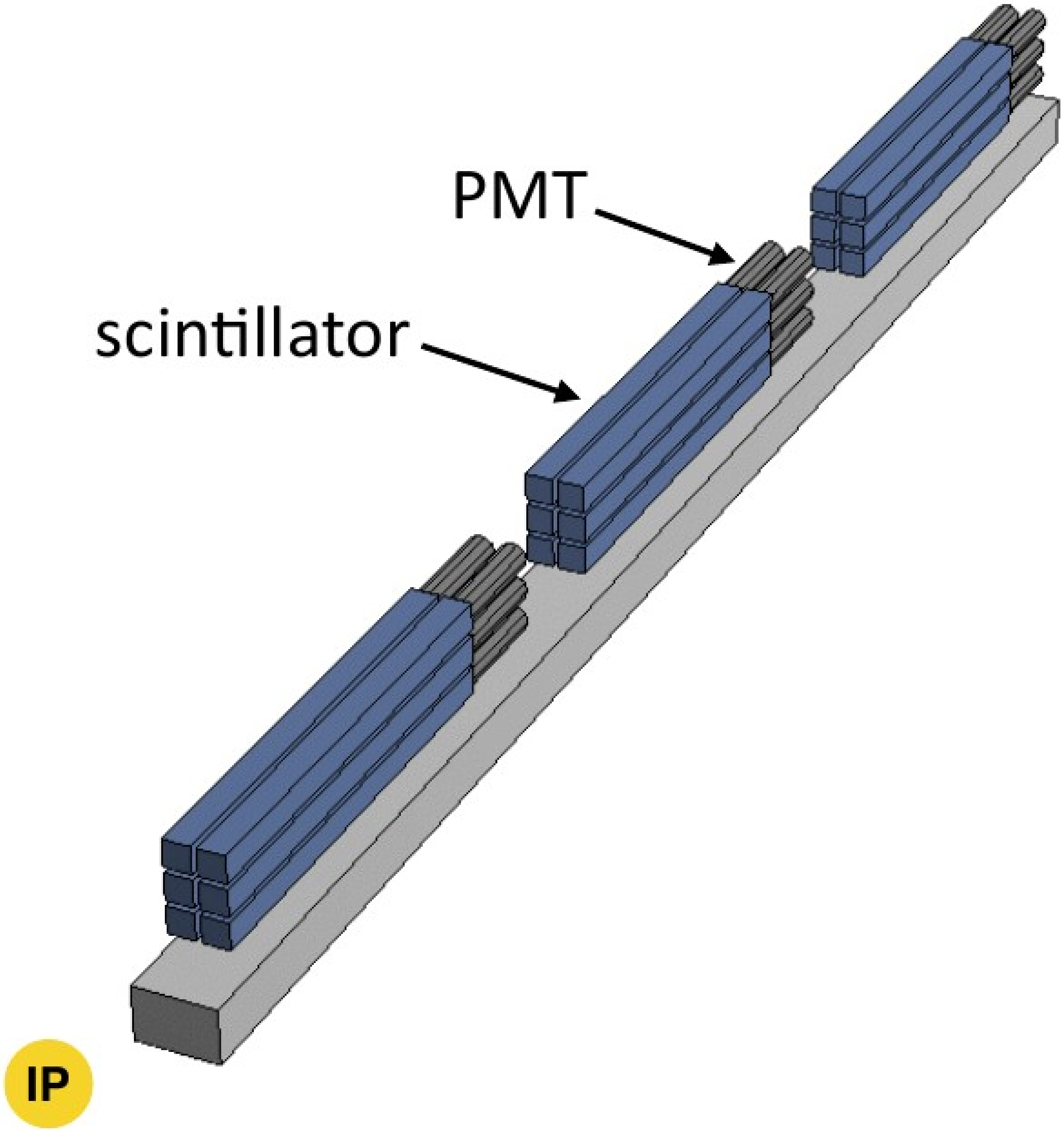
1% prototype test

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



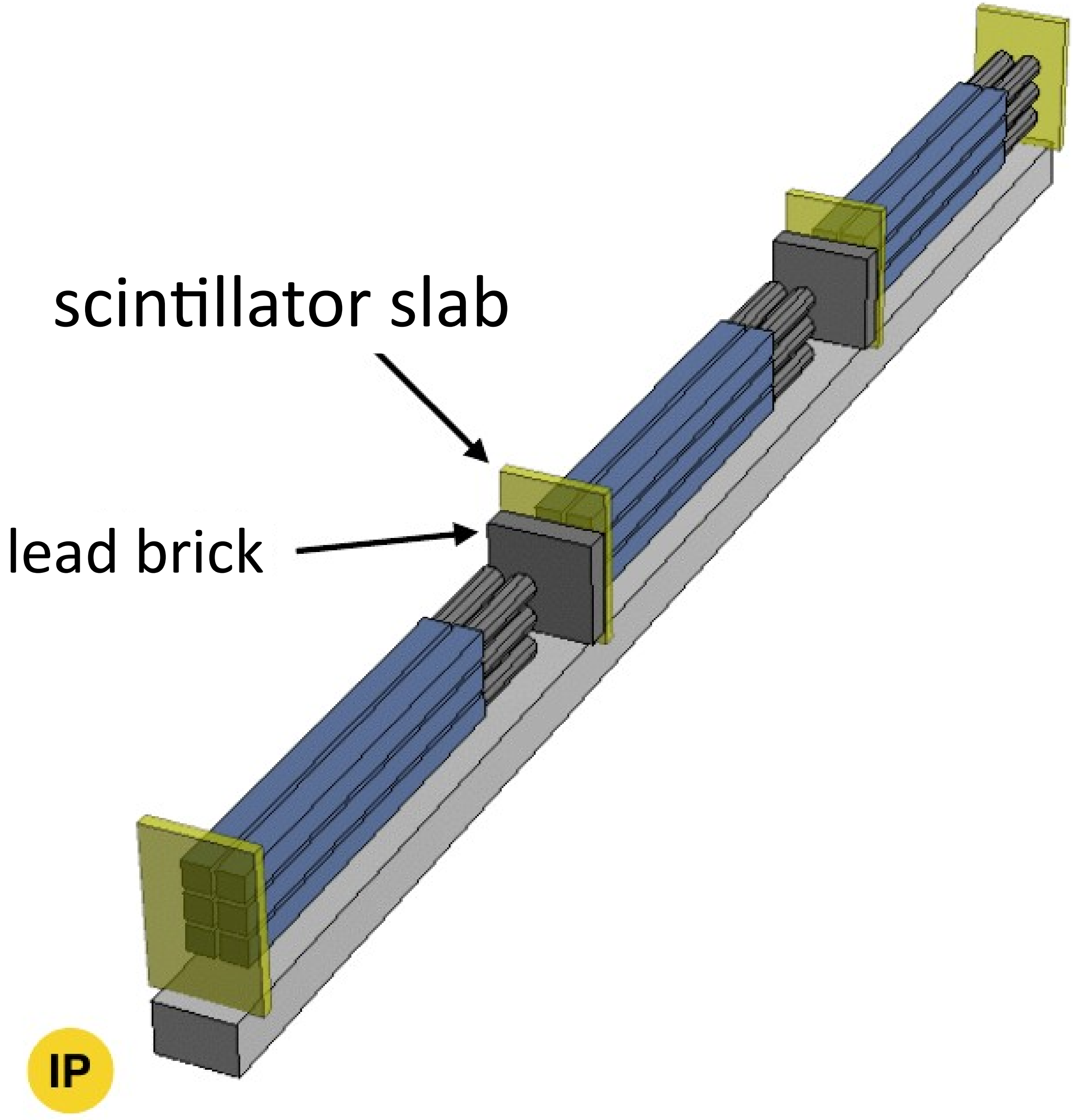


Demonstrator



- 3 layers of 2x3 scitillator+PMT

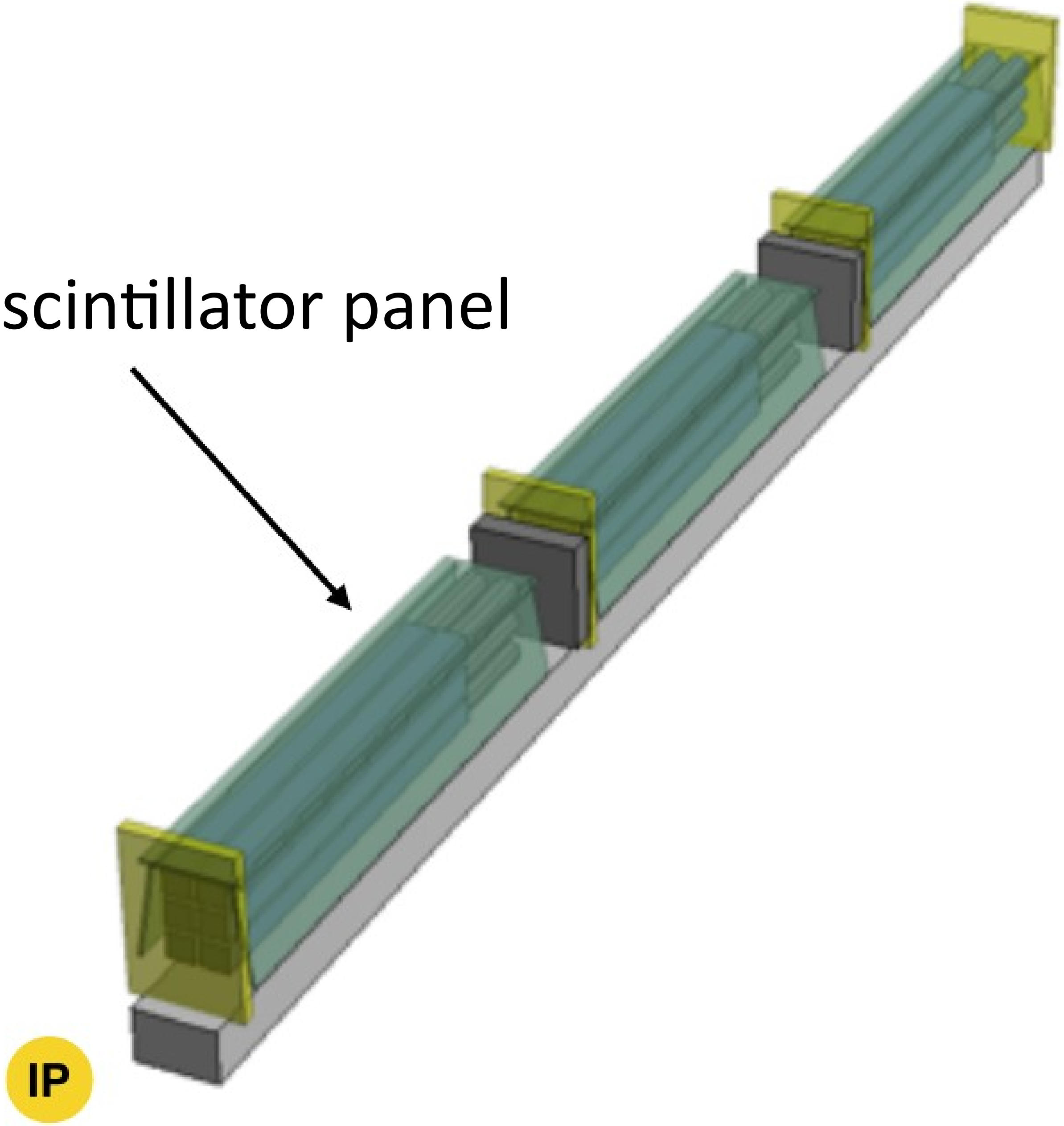
Demonstrator



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

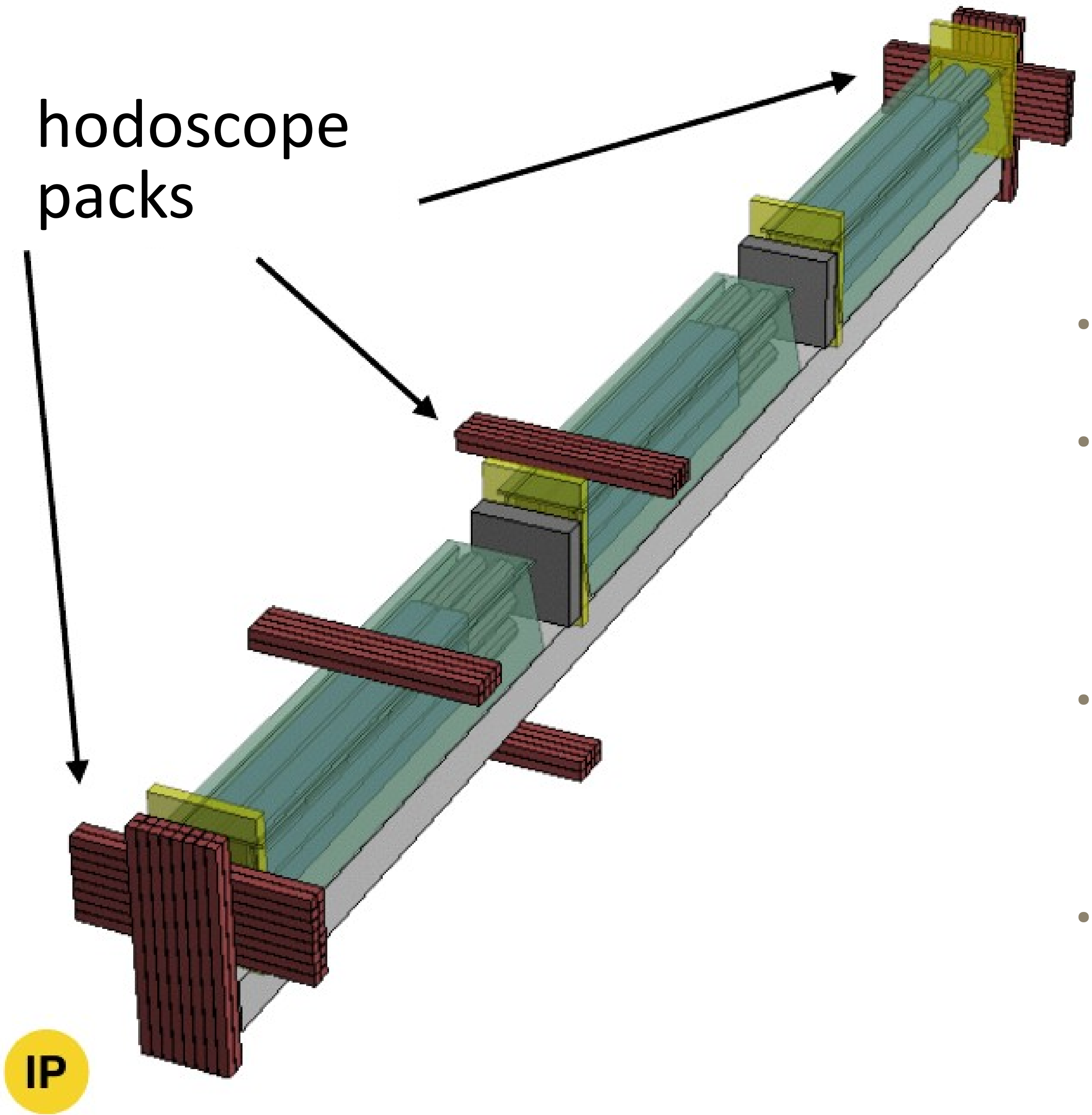
Demonstrator

scintillator panel



- 3 layers of 2x3 scitillator+PMT
- sinctillator 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



- 3 layers of 2x3 scitillator+PMT
- sinctillator 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

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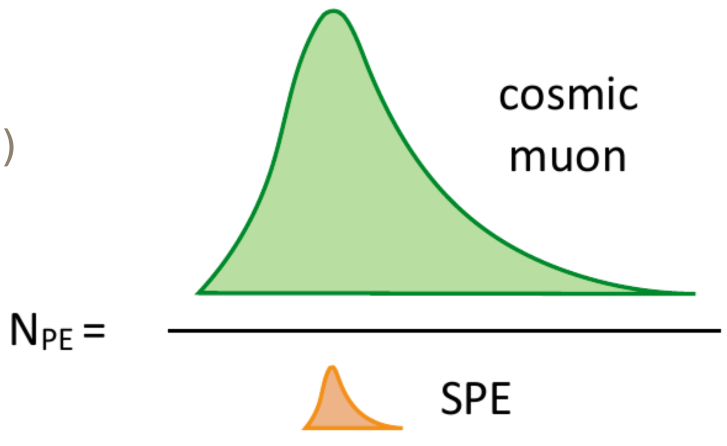
- hodoscope packs
  - tracking of beam/cosmic muons

Demonstrator results

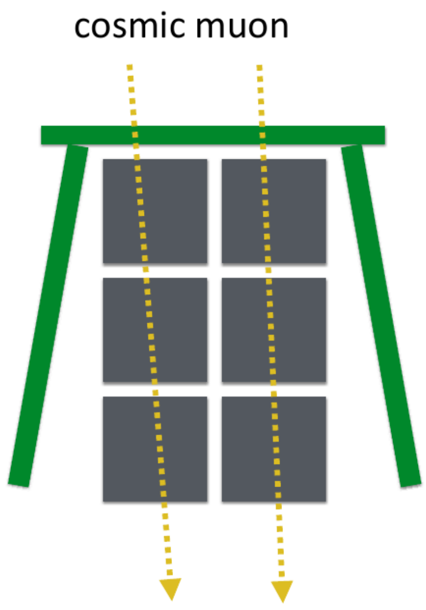
In situ charge calibration

- 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



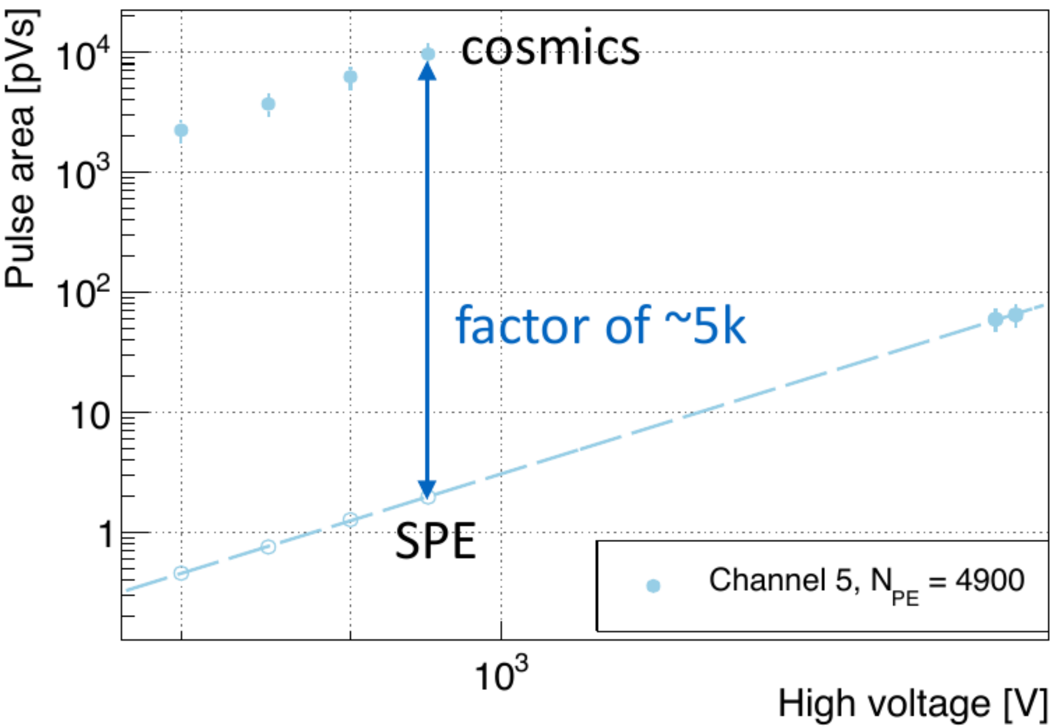
- cosmic muons taken from vertical path
- Single PhotoElectron (SPE) from afterpulses
  - validated with LED on bench



Demonstrator results

In situ charge calibration

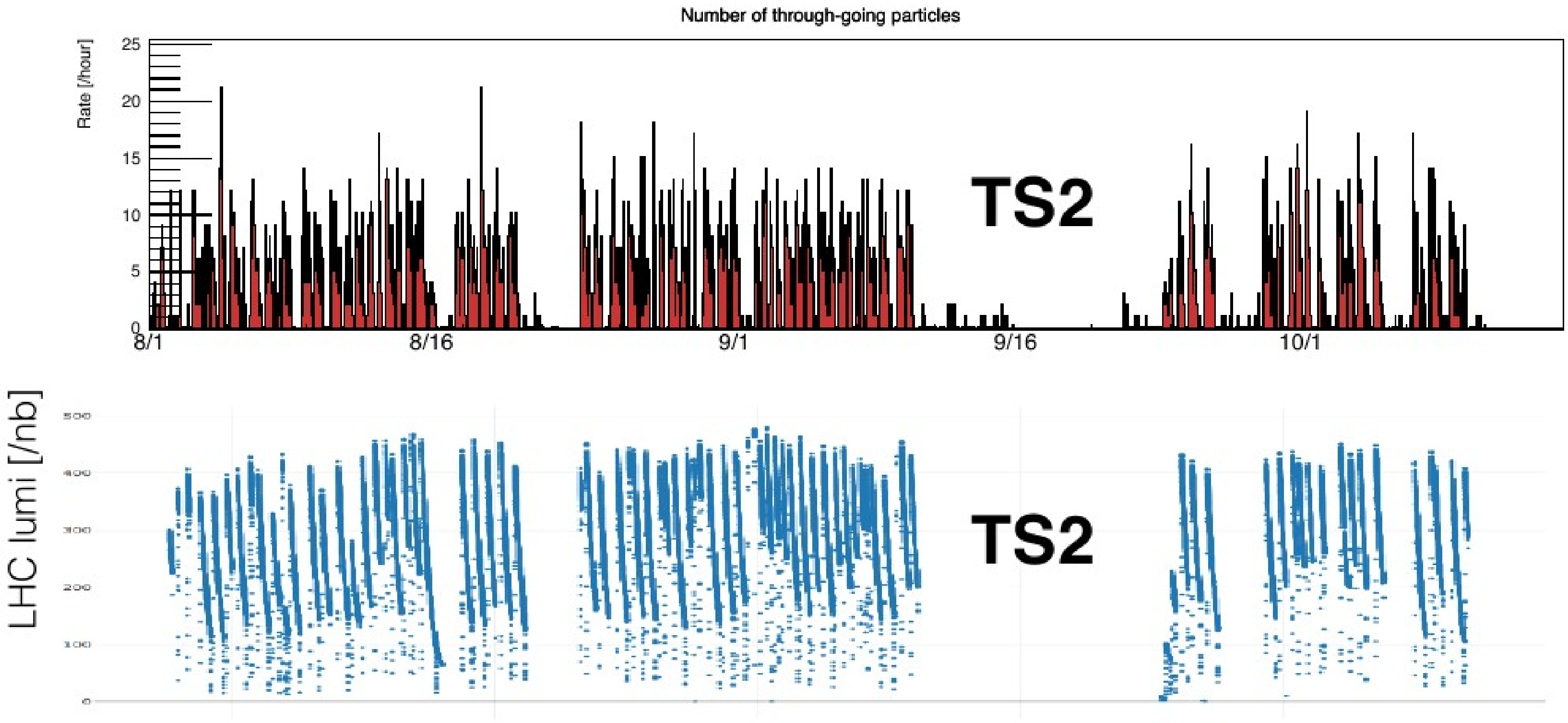
- pulse area as function of HV for a PMT
- N_{PE} for Q = 1e is ~5k
- flight distance of cosmic muons in scintillator is 5cm
  - for through-going muons the flight distance is 80cm
  - N_{PE} for through-going muons is 5k x 80/5 = 80k
- N_{PE} ~ Q^2
  - N_{PE} = 1 for Q ~ 0.003 e
- consistent with full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



Demonstrator results

Alignment

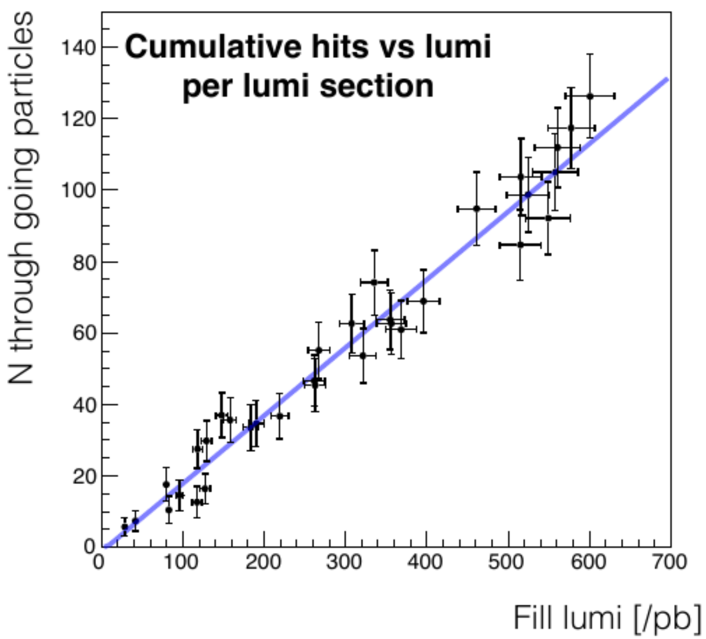
- check alignment with LHC beam
- plot rate of events with muon hit in all 4 slabs

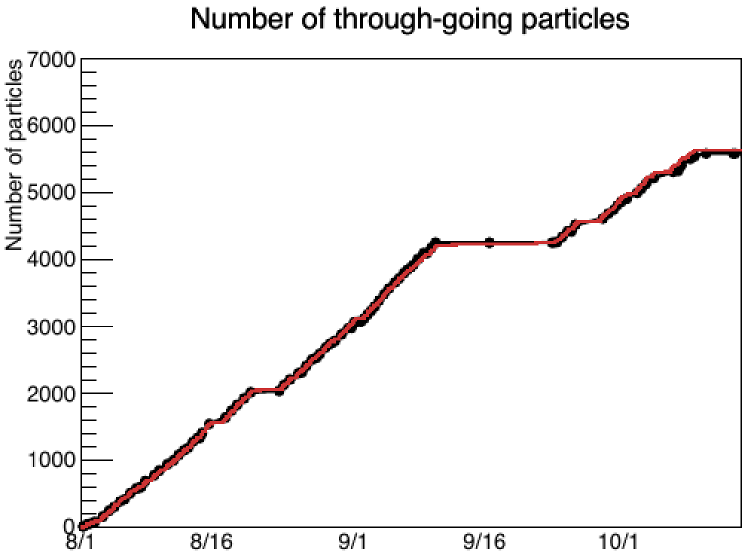


- agrees well with LHC fill / lumi data

Demonstrator results

Alignment





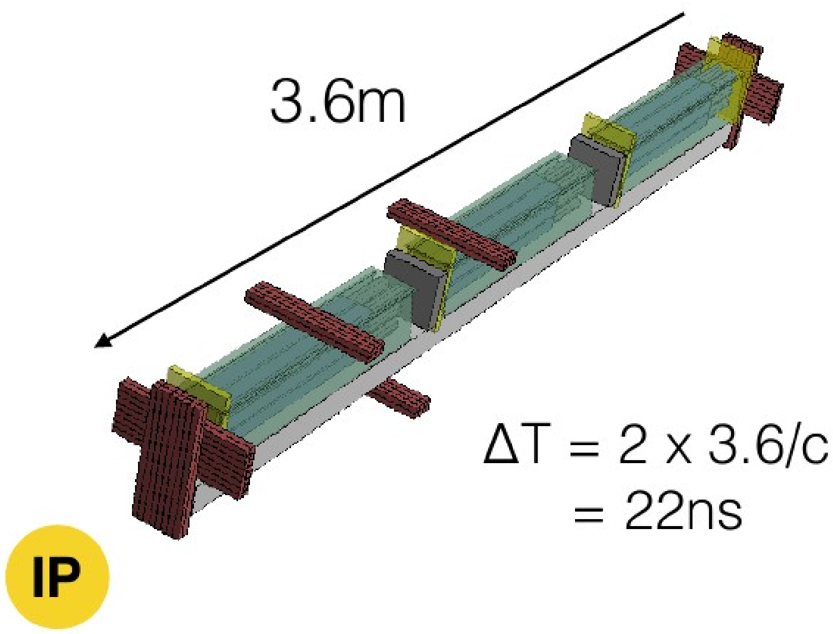
Black points - through-going milliQan particles
Red line - LHC cumulative lumi

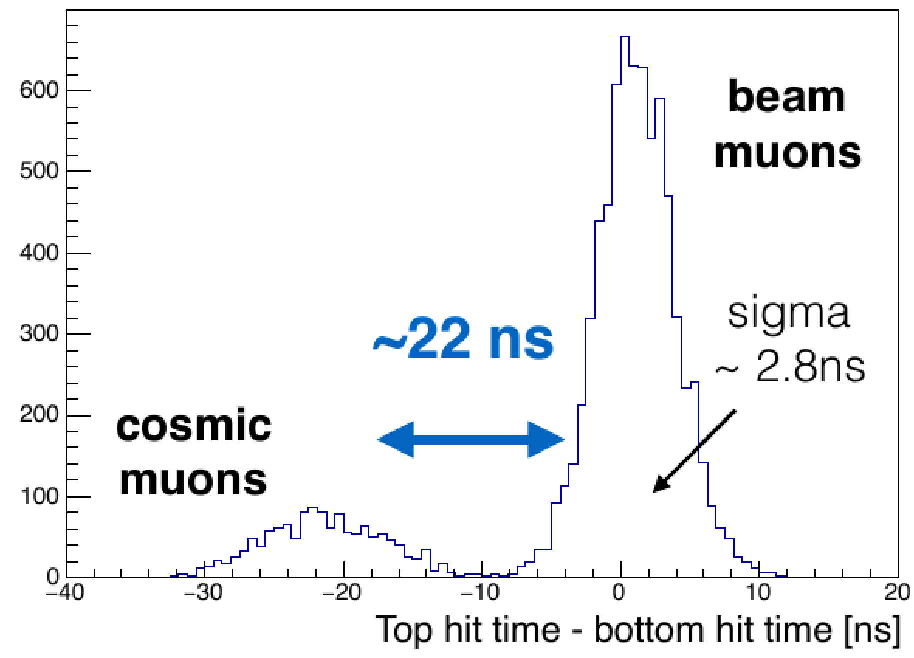
- measured rate: 0.19 / pb^{-1} predicted rate: 0.25 ± 0.08 / pb^{-1}
  - very good match data – simulation!
- uncertainties from B-hadron cross section and amount of material to cross
- in principle precision from survey is sufficient, no need for angular scan

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

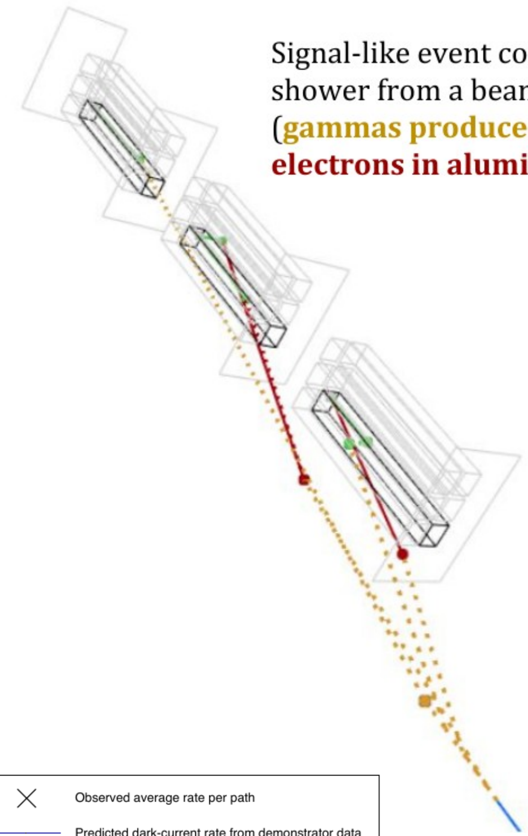




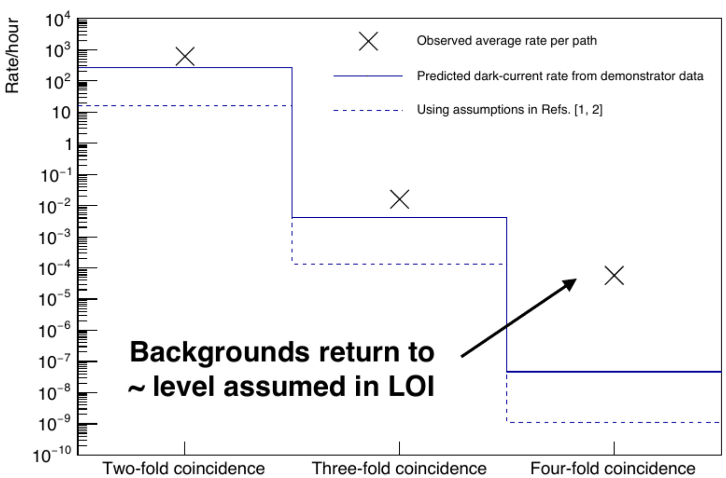
Demonstrator results

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



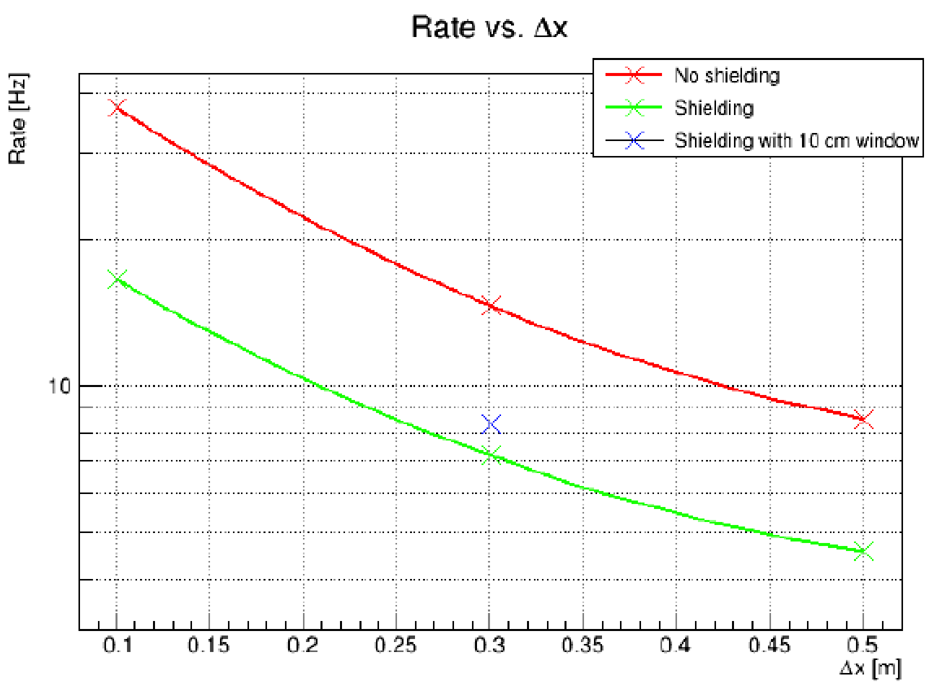
Signal-like event coming from a shower from a beam muon (gammas produced in rock and electrons in aluminum support)

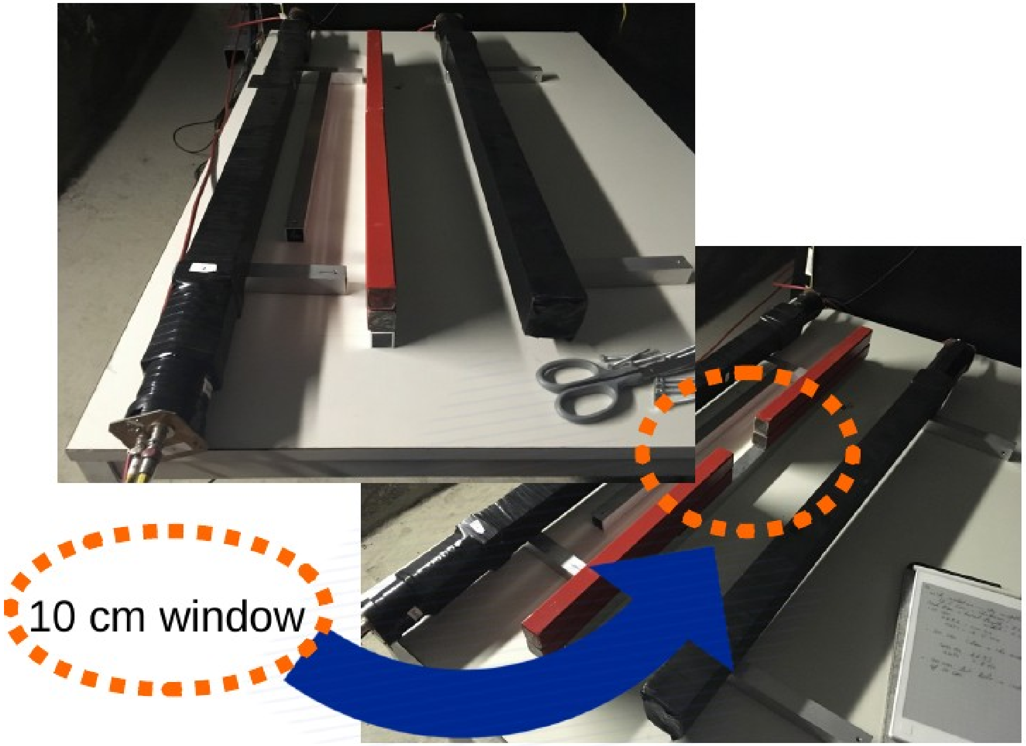


Demonstrator results

Backgrounds

- observation of rate decrease with bar separation
- observation of rate decrease with inter-bar shielding
- shown not to be cosmic showers



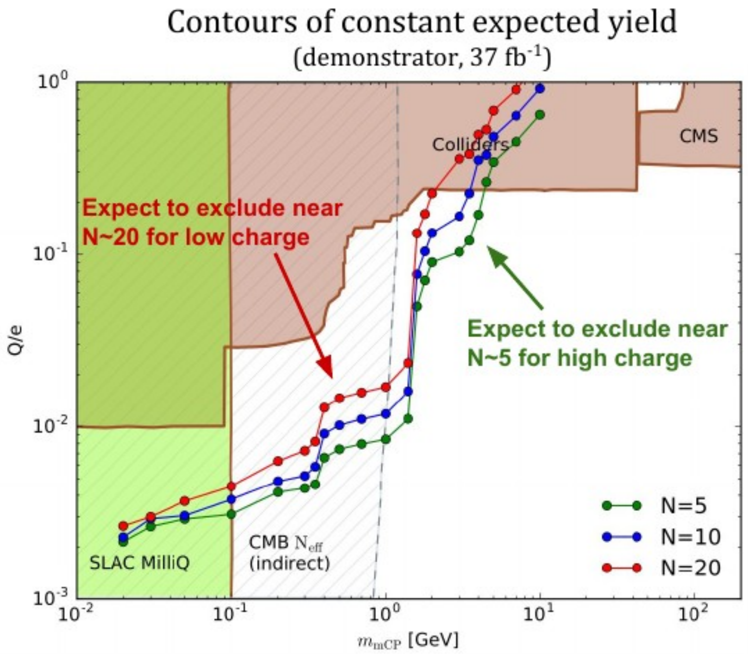


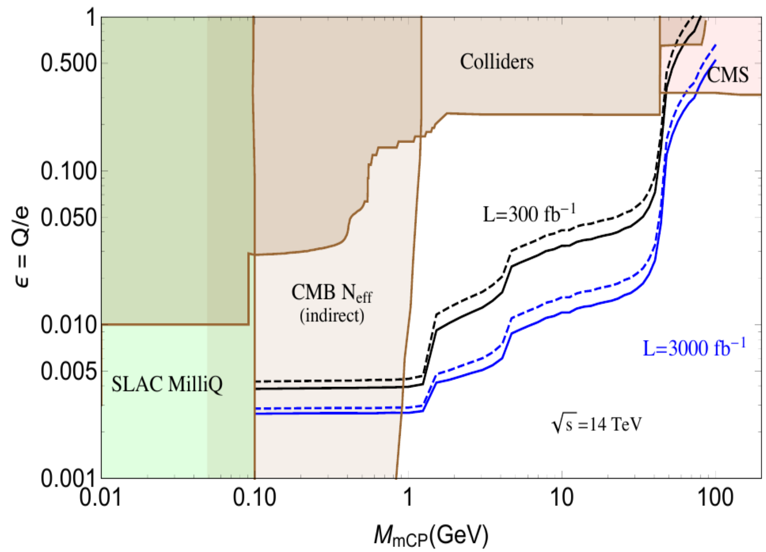
also studying cosmics in-situ with hodoscope

Sensitivity

- demonstrator analysis coming along
- 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
- expect new sensitivity already with demonstrator data
  - publication in preparation!

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

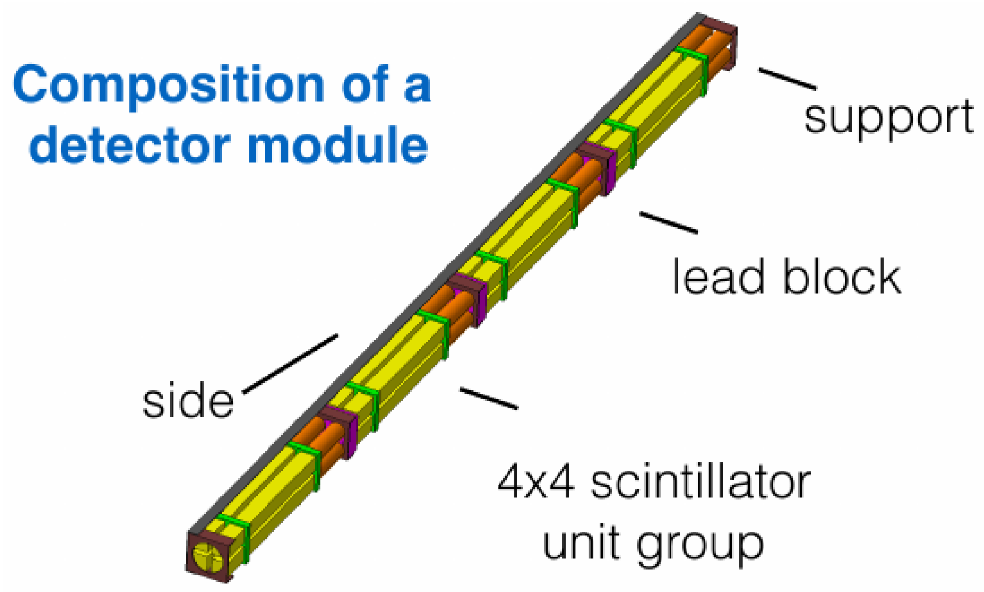


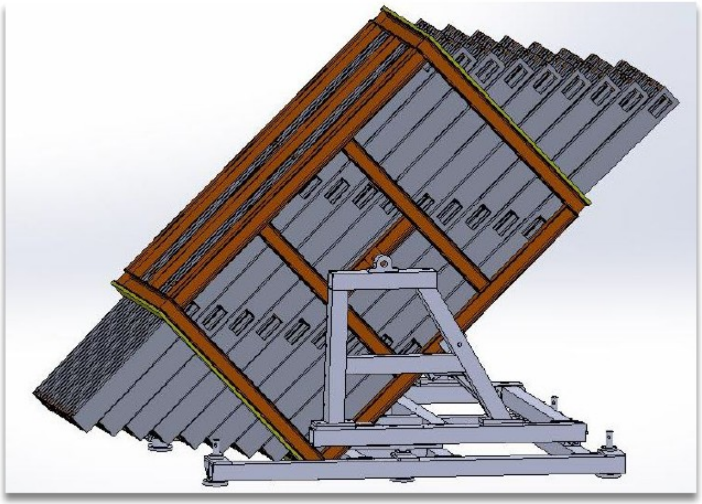


arXiv:1607.04669 [physics.ins-det]

Towards Full Detector

- plans for final mechanical structure finalized with four layers
- due to space constraints, use two adjacent detectors
  - composed of a 9x6 array of “modules” of 4x4 “bars” each
  - 1728 bars total



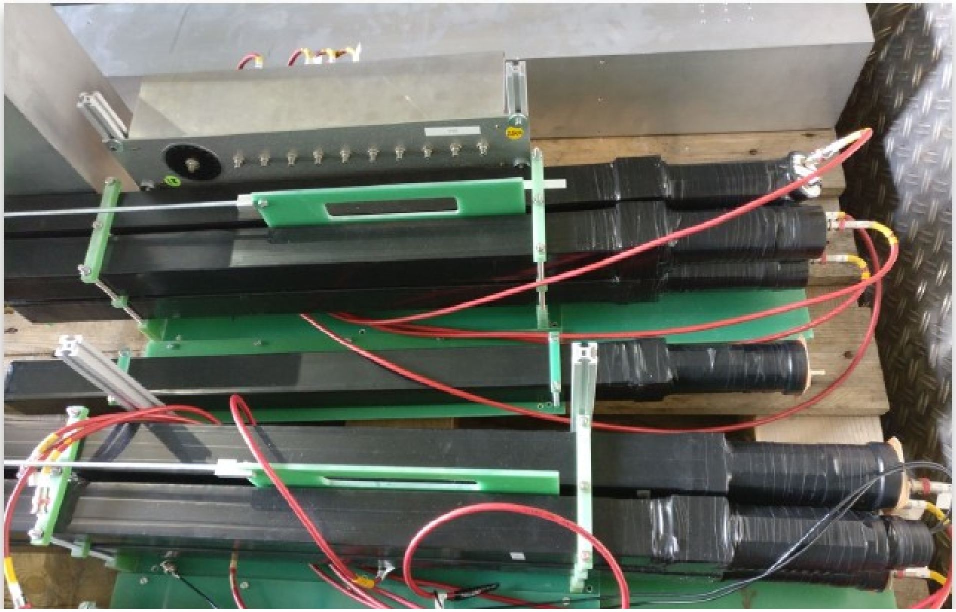


Next steps

Building modules: “easy”!

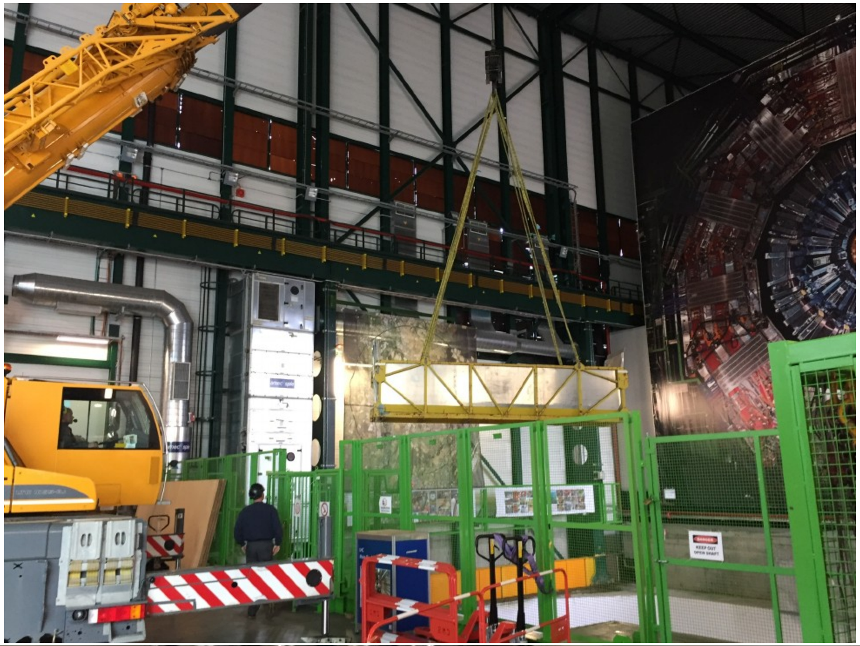
3D printed
PMT casing

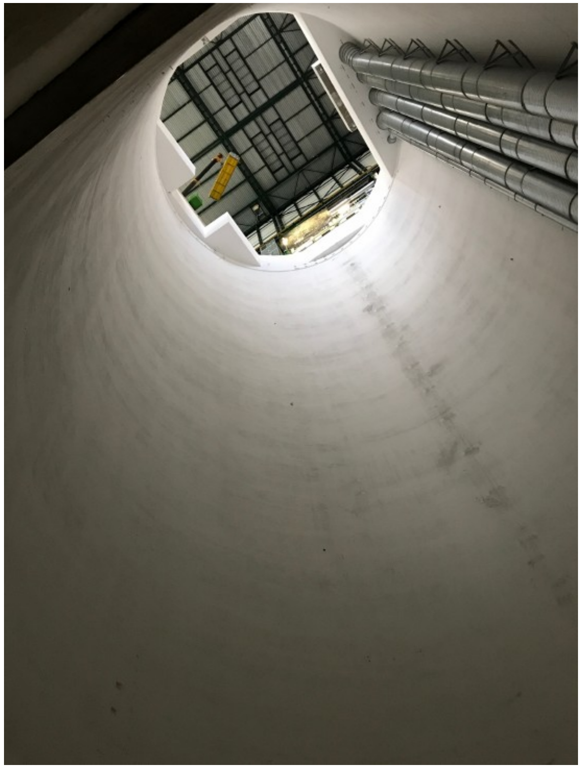
Bars wrapped in layers of reflective
and light blocking materials
(including tyvek, tinfoil, electrical tape)



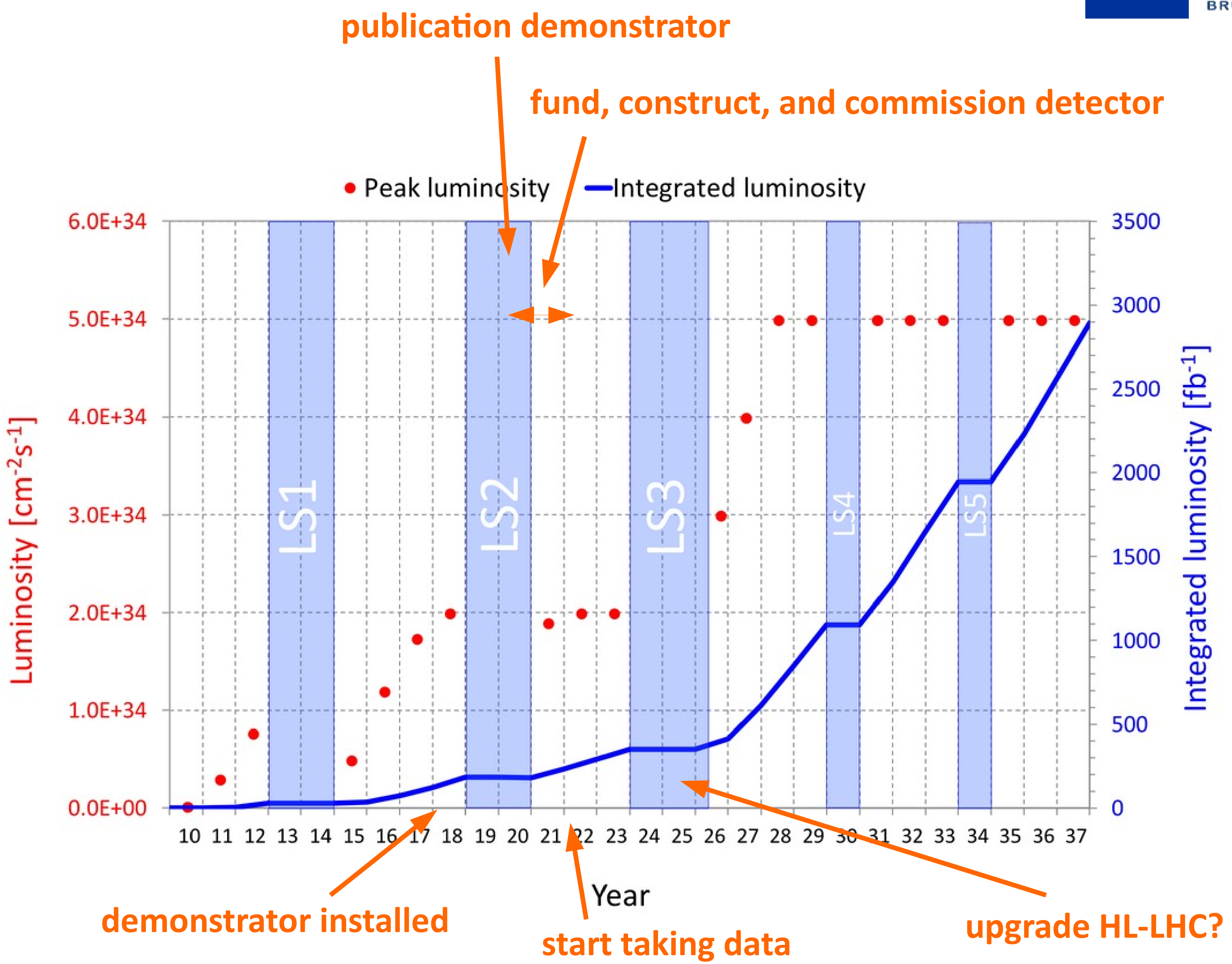
Next steps

Installation





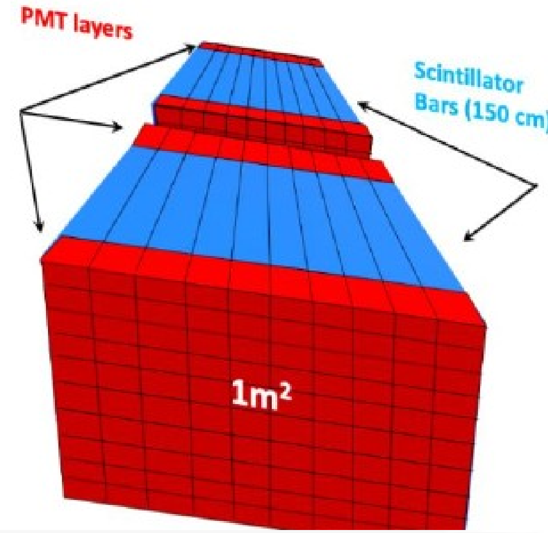
Next steps



publication demonstrator
fund, construct, and commission detector
Peak luminosity
Integrated luminosity
Luminosity [cm-2s-1]
Integrated luminosity [fb-1]
Year
LS1
LS2
LS3
LS4
LS5
demonstrator installed
start taking data
upgrade HL-LHC?

Competitors?

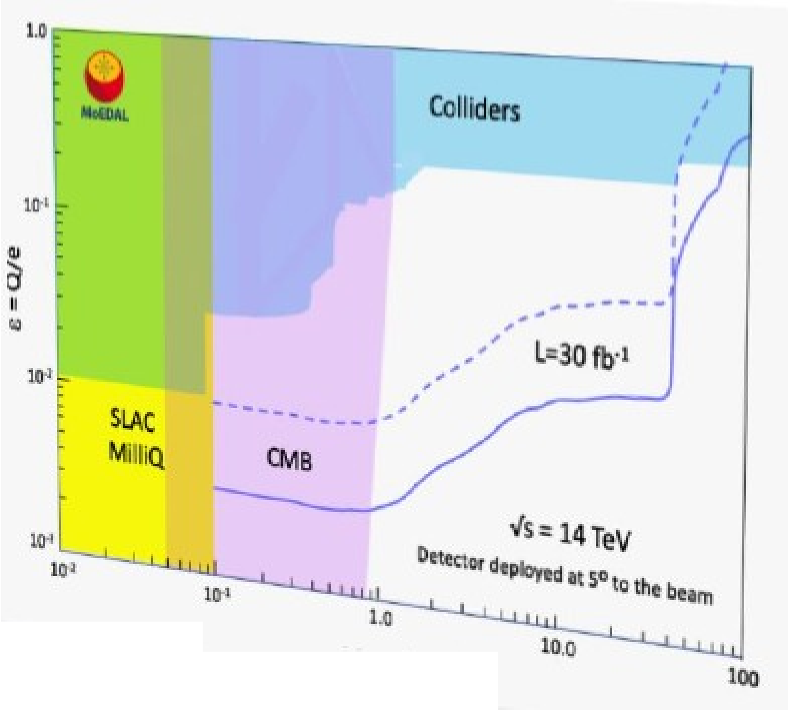
MAPP (part of MoEDAL)



- 55m from LHCb IP, 50m of rock shielding
- much more forward (5° from beam)
- 2 scintillators with 2 PMTs each
  - quadruple coincidence to suppress dark rate
- active veto against showers in rock

- currently under construction
  to take data in Run 3

- slightly less sensitivity than milliQan
- no demonstrated background control
  - no data from a prototype...



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
  - many lessons learned from commissioning and in-situ background studies
- upcoming paper with lessons learned and first sensitivity
- the collaboration is ready to build the full detector

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