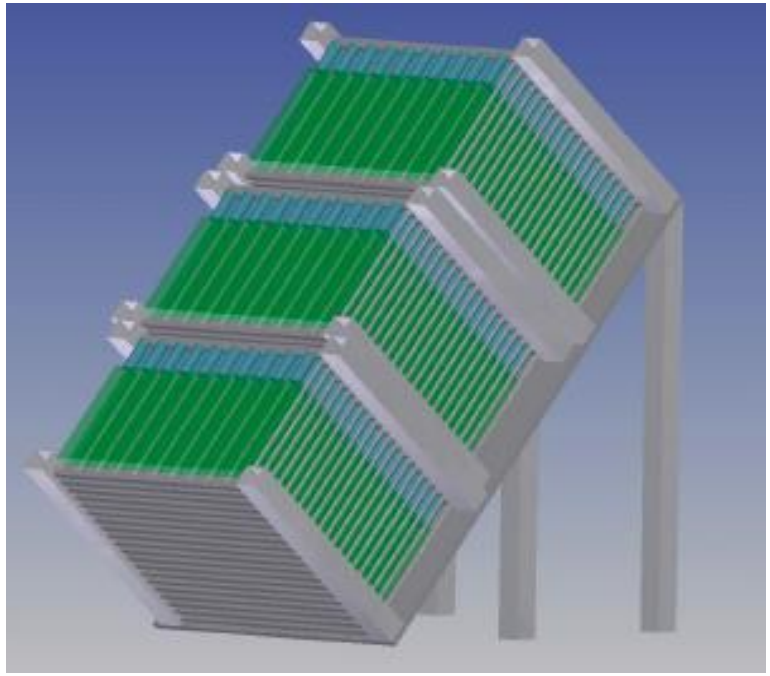
MilliQan : A new detector for milli-charged particles at the LHC

Andy Haas (NYU)
on behalf of the milliQan collaboration

Physics Beyond Colliders
Working Group Meeting

CERN
Jun. 14, 2018
https://indico.cern.ch/event/706741/



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Introduction

Stable particles with charge < ~0.3e are invisible to current LHC detectors – they deposit too little charge, so are below noise thresholds.

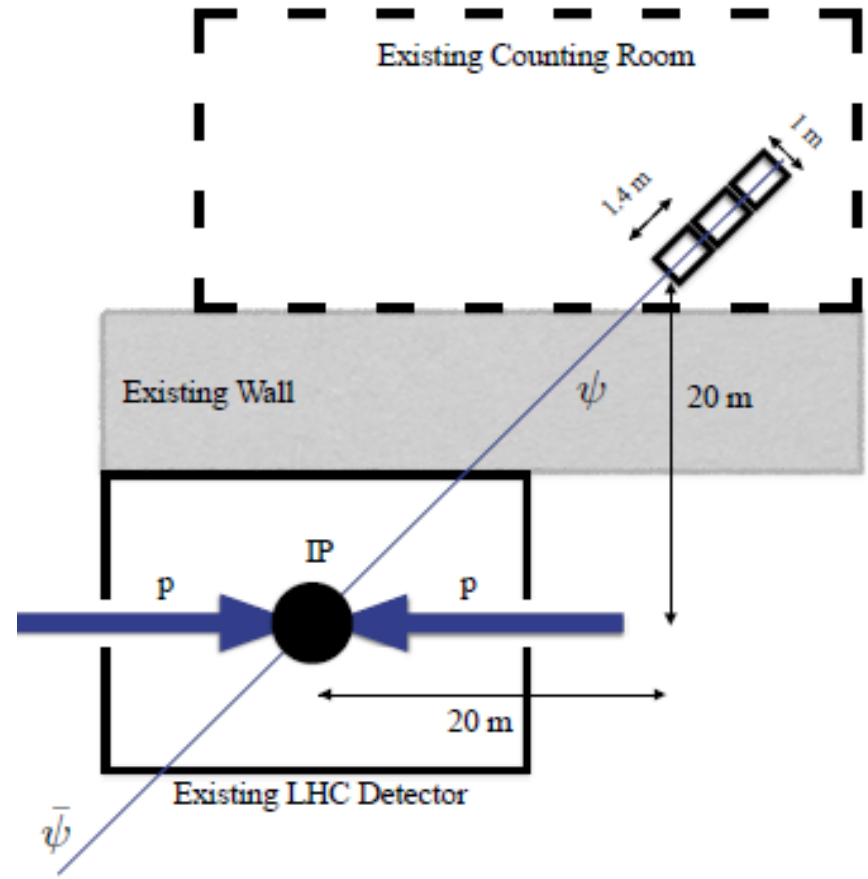
MilliQan is a new detector that will probe for particles down to ~0.001e, for masses of ~0.1 – 100 GeV

Produced via Drell-Yan and interact with detector via Bethe-Bloch

Cross-section and ionization $\propto$ charge^2

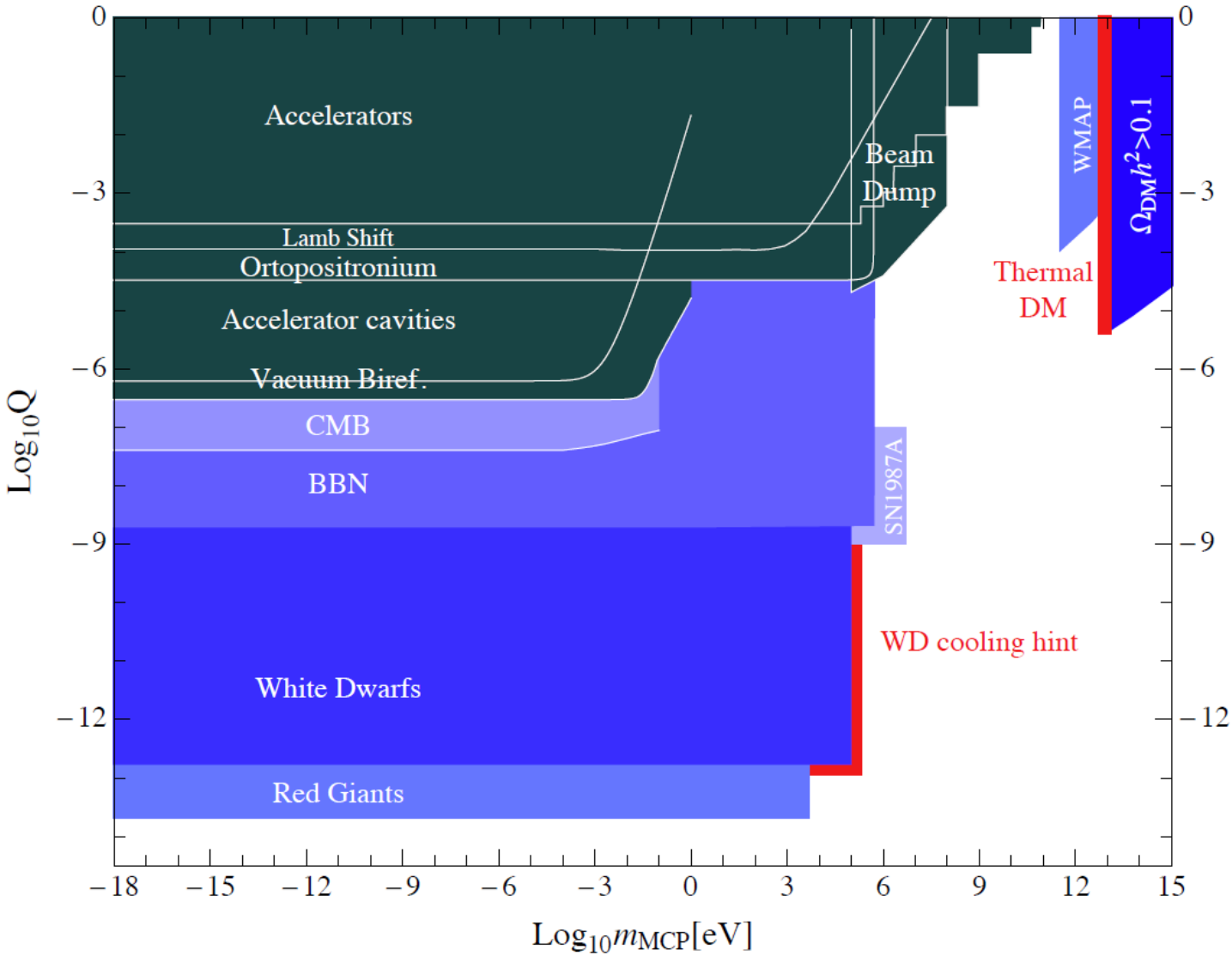
Simple and model-independent

- With Q down to ~10^{-3}e, dE/dx is 10^{-6} MIP -> need large, sensitive, active area 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



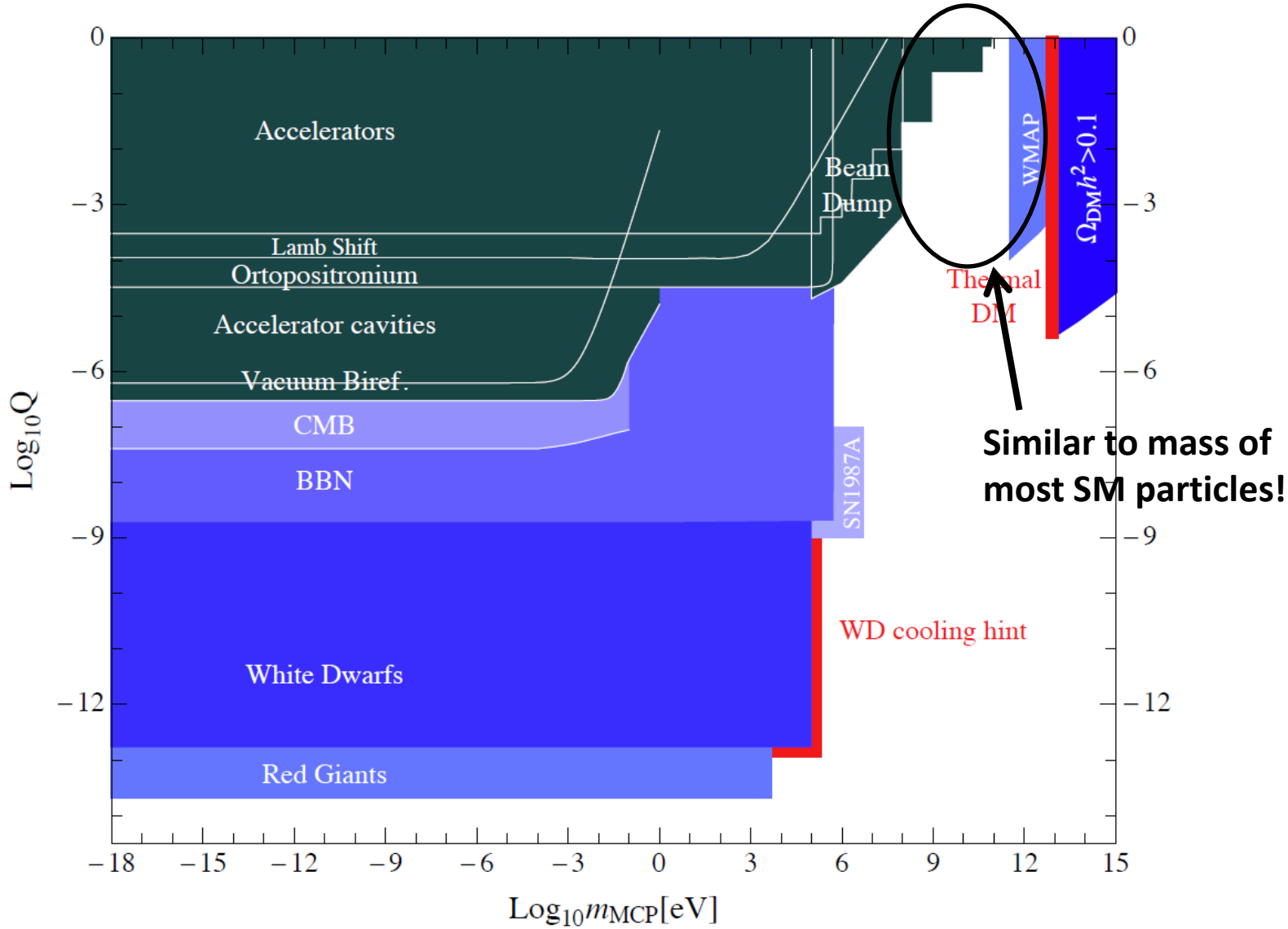
Letter of intent: arXiv:1607.04669

Long history of experimental searches for milli-charged particles, from terrestrial searches, to accelerator searches, to effects on stars!



Long history of experimental searches for milli-charged particles, from terrestrial searches, to accelerator searches, to effects on stars!

Very weak limits on the existence of <u>heavy</u> low-charged particles.



Do Non-Quantized Charges Make Sense?

Theoretically consistent to add new particles with electric charge $Q = \epsilon e$

Could in principle add a new fermion with hypercharge $Y = 2\epsilon$

Or

An elegant mechanism is that by Holdom, through the addition of a new massless U`(1) boson

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

- *BC3, Millicharged particles*: this is the limit of $m_{A'} \to 0$, in which case χ of $\bar{\chi}$ have an effective electric charge of $|Q_\chi| = |\epsilon g_D e|$ [4, 9]. The suggested choice of parameter space is $\{m_\chi, Q_\chi/e\}$, and χ can be taken to be a fermion.

*Pospelov, "Notes on benchmark models for the PBC evaluation", 2018

Adding Particles with Non-Quantized Charge

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

The last term generically appears in SM extensions with a new massive field (mass M) charged under hypercharge and the new U`(1)

Induces a mixing

$$\kappa \sim 10^{-3} - 10^{-2}$$

Adding Particles with Non-Quantized Charge

If there are new fermions charged under the new U`(1)

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4} B'_{\mu\nu} B^{\mu\nu\prime} - \frac{\kappa}{2} B'_{\mu\nu} B^{\mu\nu} + i\bar{\psi}(\not{\partial} + ie' B' + iM_{\rm mCP})\psi$$

Standard trick: Redefine the gauge field

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

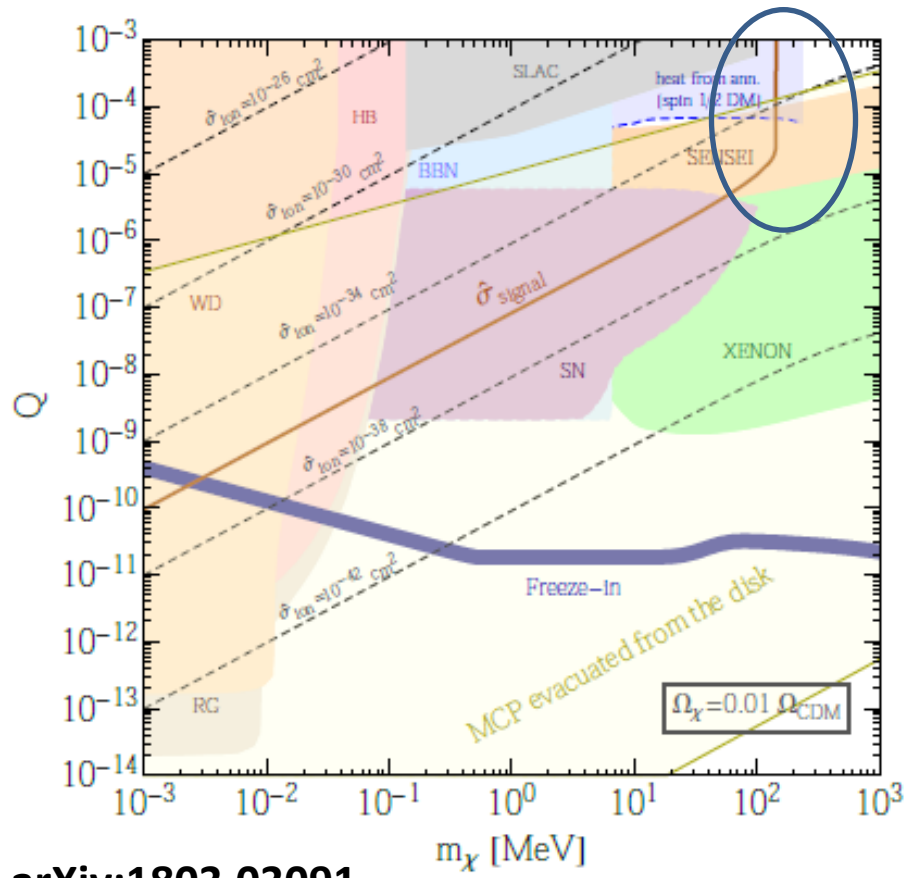
Gets rid of "mixing term" and generates a hypercharge for the new fermions

After electro-weak symmetry breaking fermions acquire an EM charge (normalized to e)

$$Q = \kappa e' \cos\theta_W$$

More Motivation?

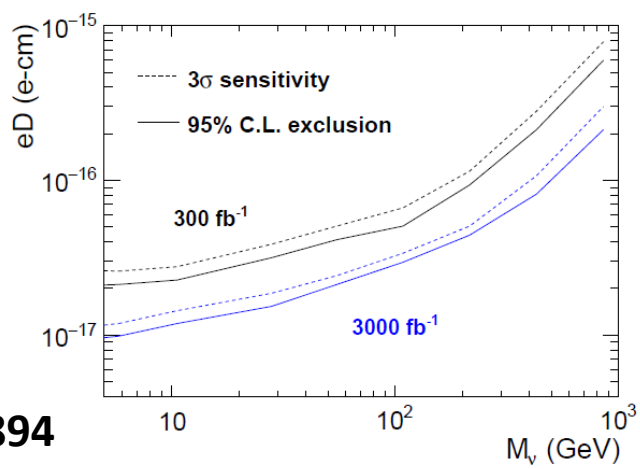
- Recent excitement that milli-charged dark matter at the 1% mass-density level is a leading explanation for the EDGES 21-cm result
- The mass/charge region favored is in a sweet-spot of milliQan sensitivity



arXiv:1803.03091

FIG. 4. Constraints on the charge, Q, of a millicharged particle as a function of the DM mass. The **red** line indicates the minimal cross section needed to explain the EDGES measurement, assuming the millicharged particle constitutes only 1% of the DM density. The **dashed-gray lines** show contours of constant $\hat{\sigma}$. Constraints from cooling of the supernova (SN) 1987A [6] (**purple**), direct detection limits from XENON10 [56, 63] (**green**) and SENSEI [74], SLAC millicharge experiment [22] (**gray**), BBN [7] (**light blue**) and cooling of white-dwarfs (WD), horizontal-branch (HB) stars and red-giants (RG) [8] (**pink and brown**) are shown in the shaded regions. We also add constraints from heating due to DM annihilation derived in [75] (**blue**). This bound only applies to fermionic DM for which the annihilation is *s*-wave. The shaded yellow band indicates where millicharge DM might be evacuated from the galactic disk [23, 29].

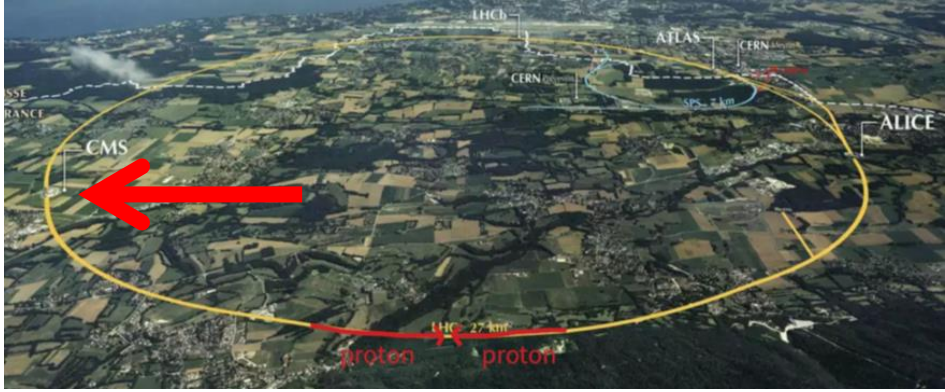
- Also other signals beyond mCP... like heavy neutrinos with large eDM:



arXiv:1710.06894

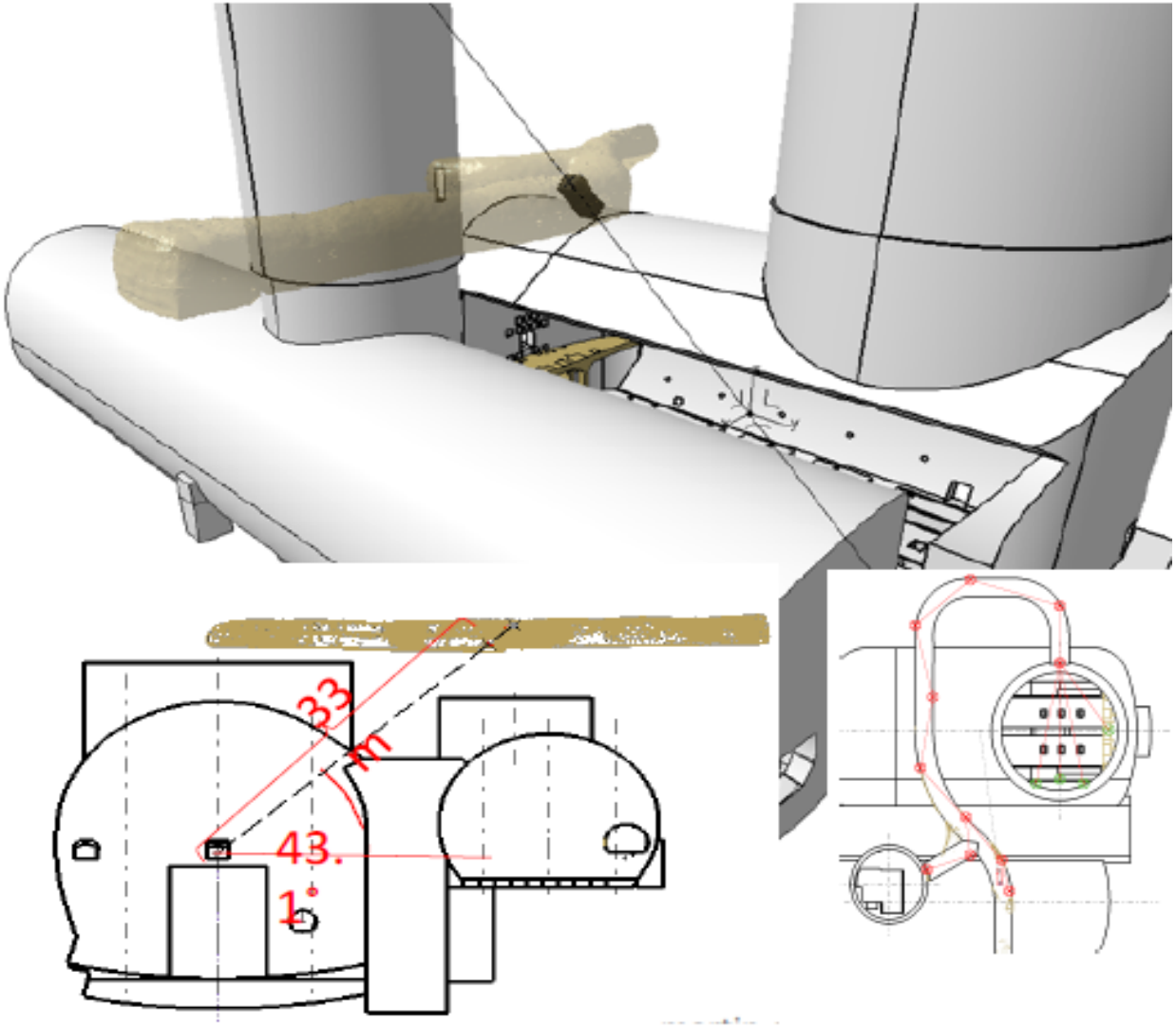
FIG. 1: The expected 95% C.L. exclusion (solid) and 3σ sensitivity (dashed) for heavy neutrino EDM detection using the milliQan experimental setup at $\sqrt{s} = 14$ TeV, assuming $\mathcal{L} = 300$ (3000) fb^{-1} integrated luminosity in black (blue).

MilliQan Location



"Drainage Gallery"
an existing tunnel just above CMS

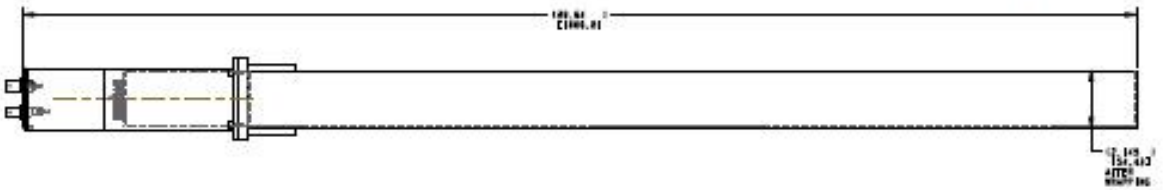
- Martin Gastal (CERN), and his team, have been particularly helpful
  - *3D drawings, surveys, B-field measurements, pictures, etc.*
- Now have precise details of location:
  - *33 m from IP*
  - *17 m through rock*
  - *Angle from horizontal plane is 43.1 deg*
  - *Clearance to gallery boundaries is ~30 mm!*

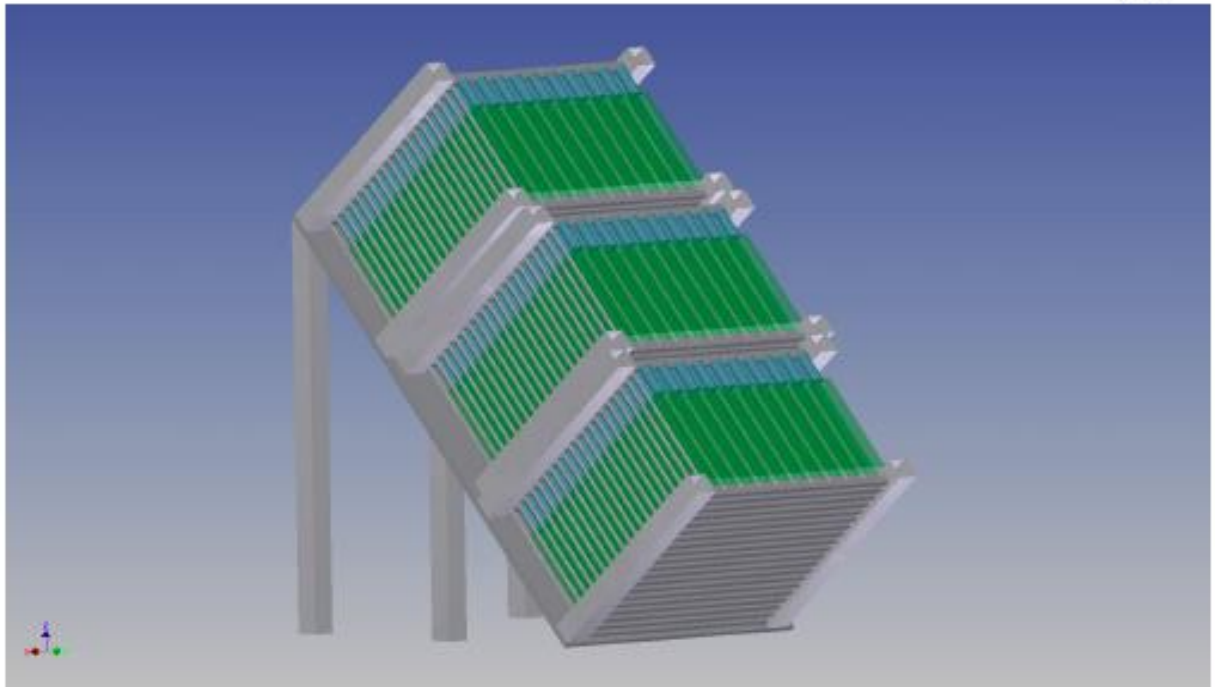


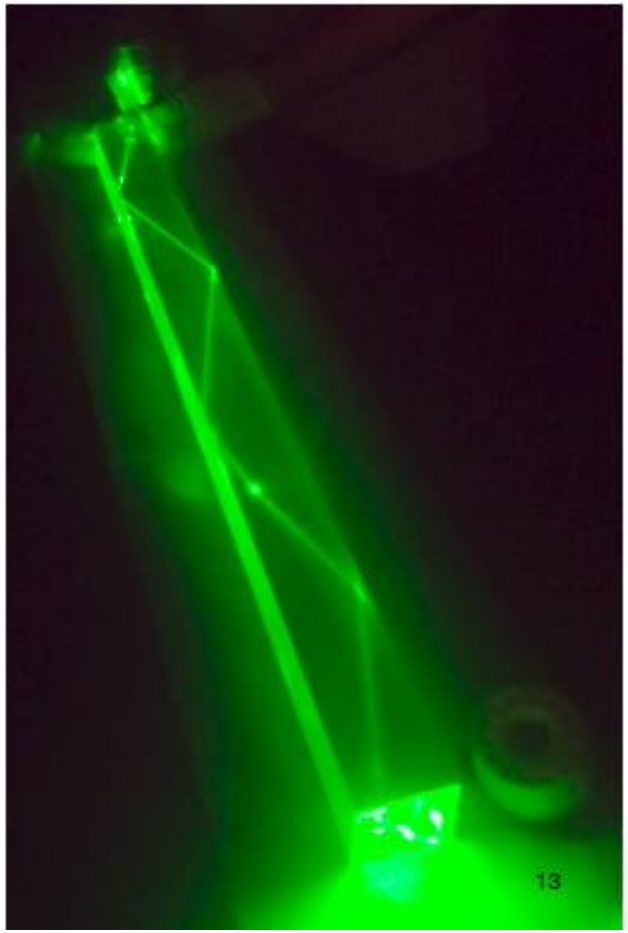
milliQan Detector

Aim to detect *single photons* in 3 long adjacent scintillators, pointing back to collision point, within a small time window (15 ns)

- Basic element is a 5 cm^2 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**

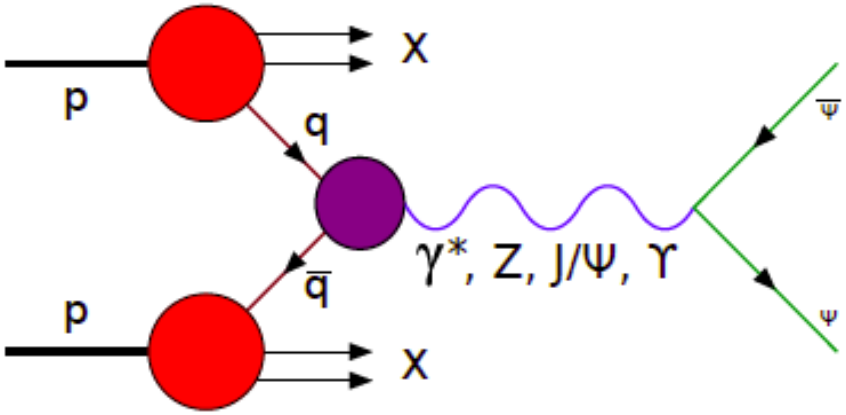






Signal simulation

Detailed simulation, including CMS magnetic field (small effect)



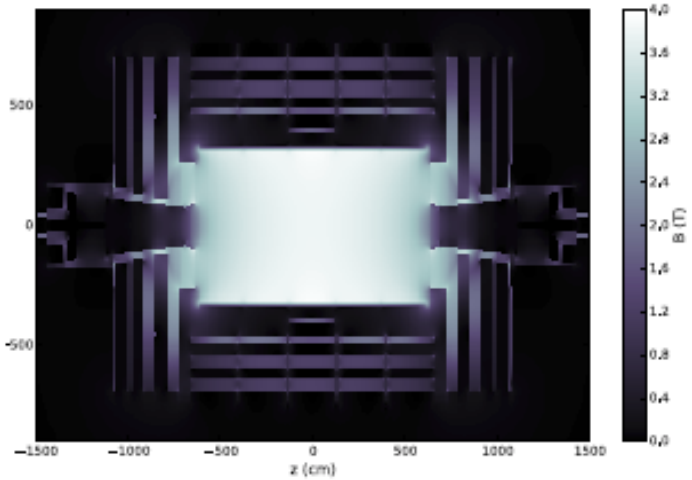
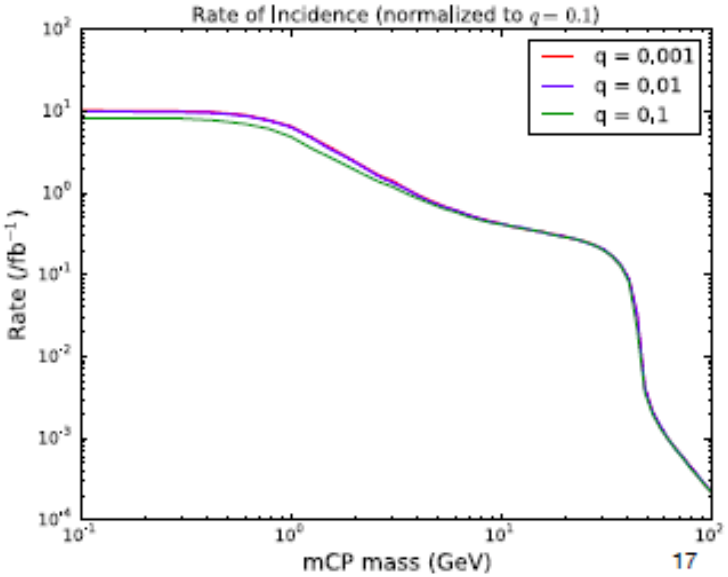


FIG. 2: Map of the CMS magnetic field in the r–z plane.

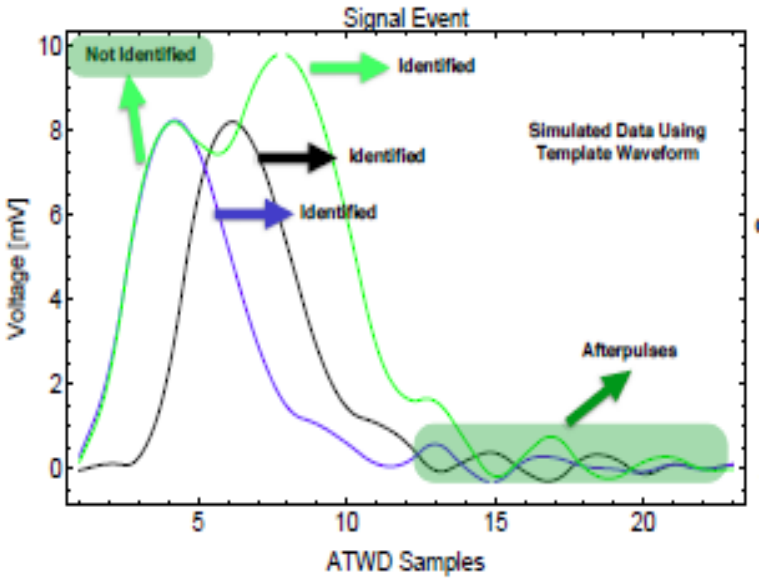
- Use madGraph + madOnia to simulate production via modified Drell-Yan
- Then propagate particles through parameterized simulation of material interactions with CMS & rock (full CMS simulation overkill)
  - *Used actual CMS B-field map though*
- Count rate of incidence on 1 m^2 face of milliQan detector

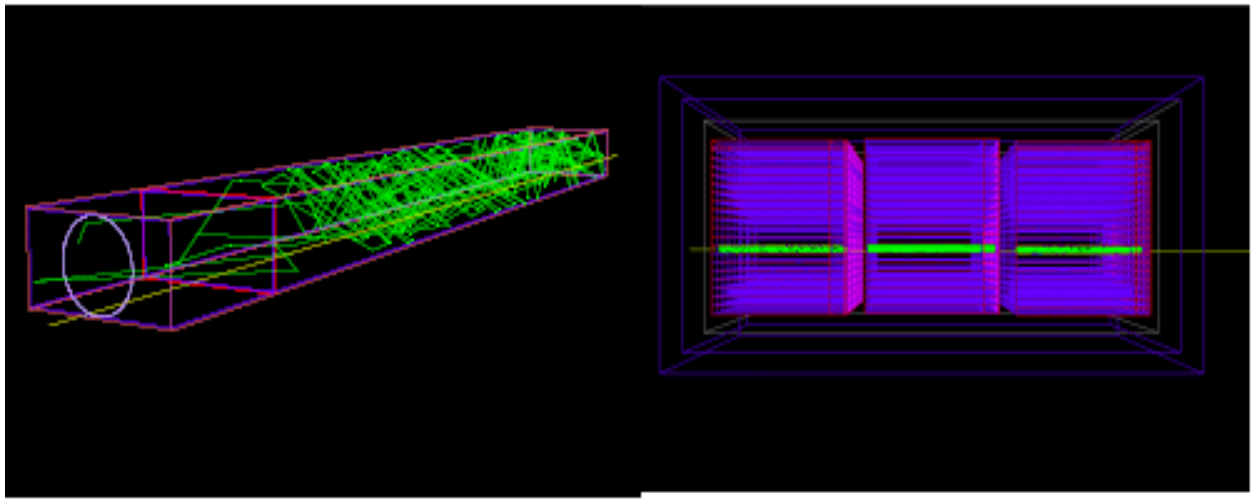


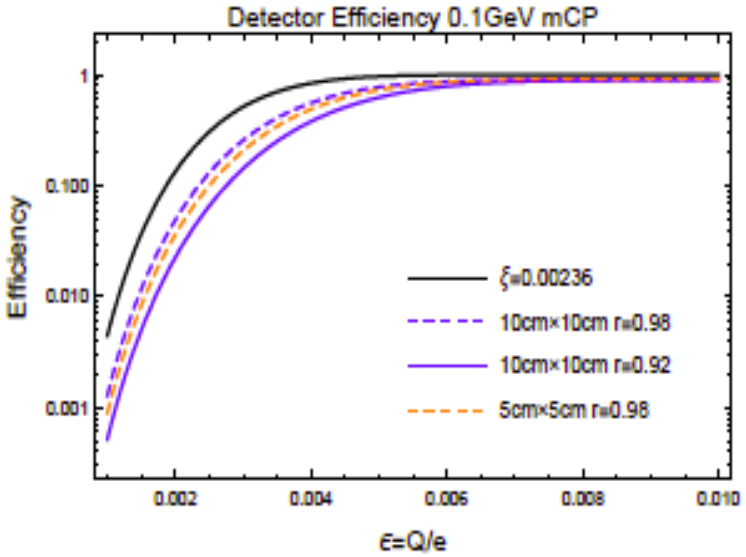
Signal simulation

Full Geant4 detector simulation

- Models reflectivity, the light attenuation length, and the shape of the scintillator. We input the PMT quantum efficiency, scintillator light emission spectrum, time constants, and digitized waveforms



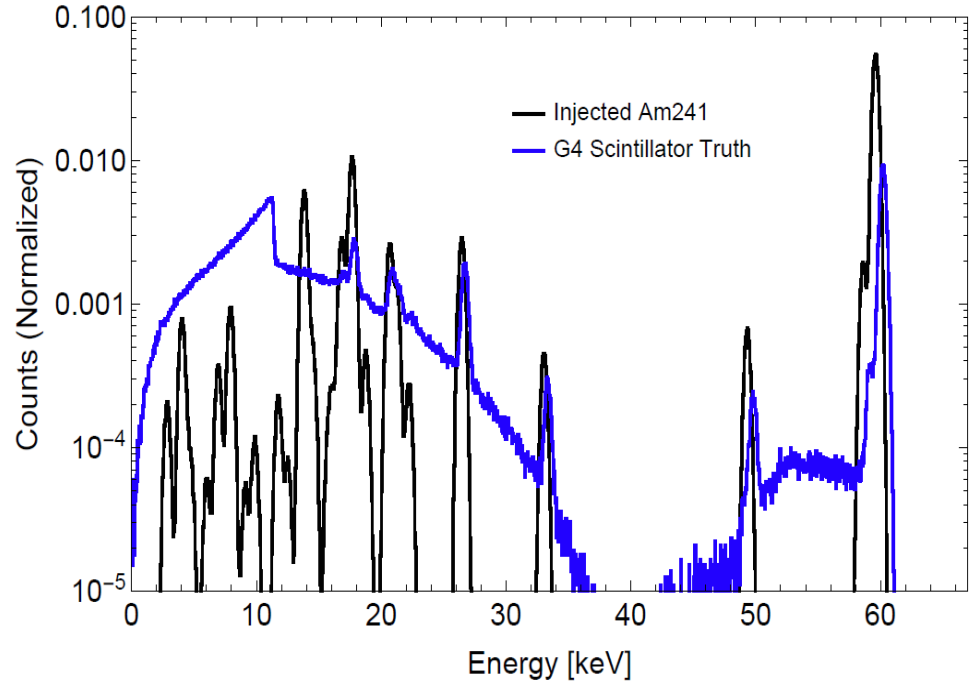




Efficiency Calibration

Am^{241}

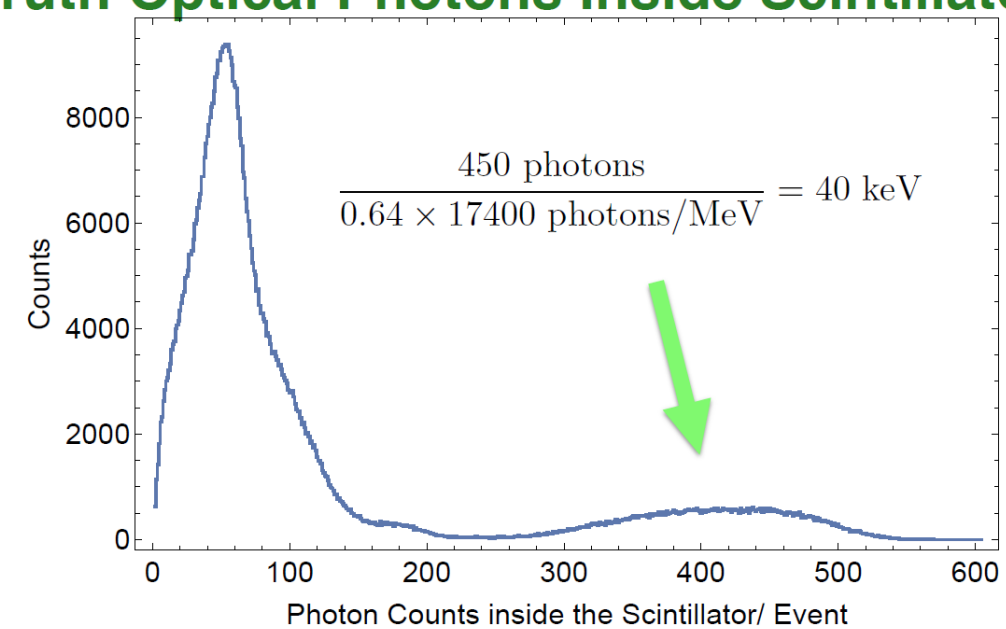
- Absolute calibration done using radioactive source, with known X-ray spectrum, at multiple points along each scintillator bar
- Full Geant4 simulation of X-rays in scintillator and creation / propagation of photons in bar
- By comparing to number of photo-electrons observed by PMT, can measure efficiency to ~25% accuracy
- Only done during accesses



Cosmic Landau peak

- PMT response monitored between calibrations via natural background energy peaks
- Can check *relative* efficiency during running periods, to ~10% accuracy

Truth Optical Photons Inside Scintillator



Backgrounds

17m of rock removes all Standard Model background from LHC collisions

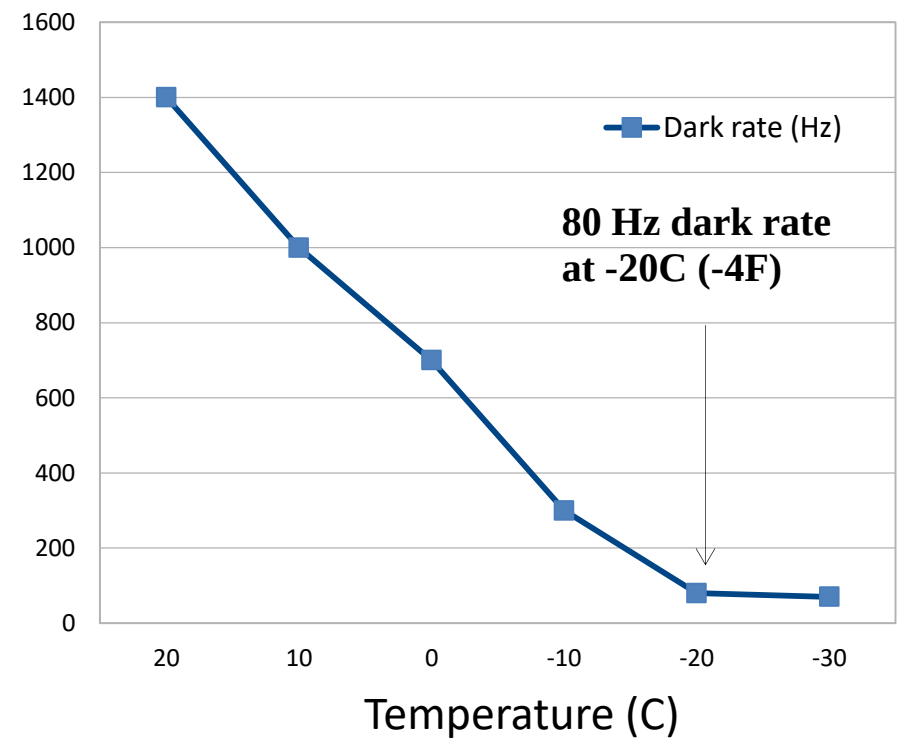
- ~15 muons / minute make it through the rock, but they're clearly not milli-charged (~1M photons actually saturates the detector!)
  - Can be used for rough check of alignment
- Middle layer slightly offset to avoid glancing muons on edge of 3 bars

Cosmic muon rate ~100x smaller in tunnel than on surface

- Comparable to collider muon rate
- Worry about showers in rock with n, γ, etc. but will have *active vetos* and self-shielding from outer layer

Random dark-pulse background

- Need 3 coincident pulses
- ~50 events per year at room temp
- Greatly reduced by cooling to -20C



Backgrounds being studied in situ from data: beam on/off, time relative to bunch crossing, pointing to IP or not, etc.

Put milliQan here!

milliQan "demonstrator" prototype

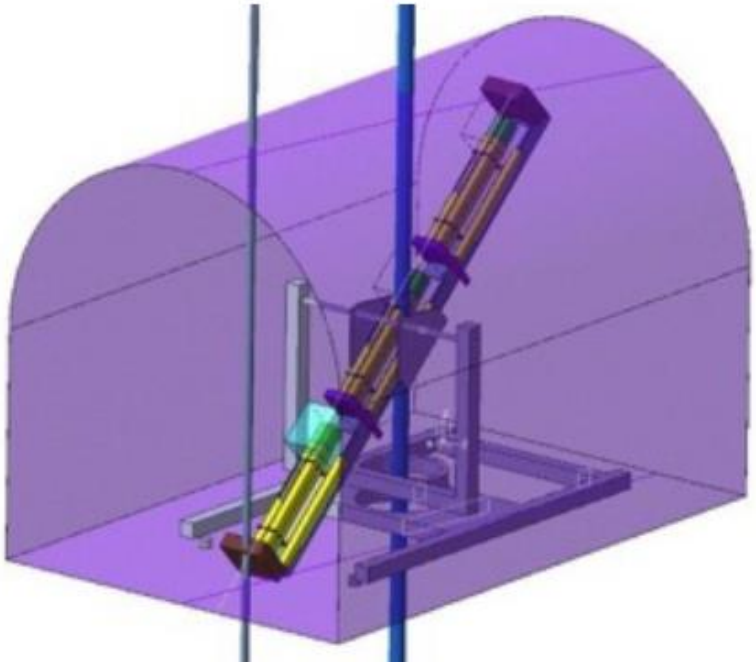
~1% size test of milliQan in tunnel, with 15 scintillators/PMTs, plus 2 hodoscopes for alignment

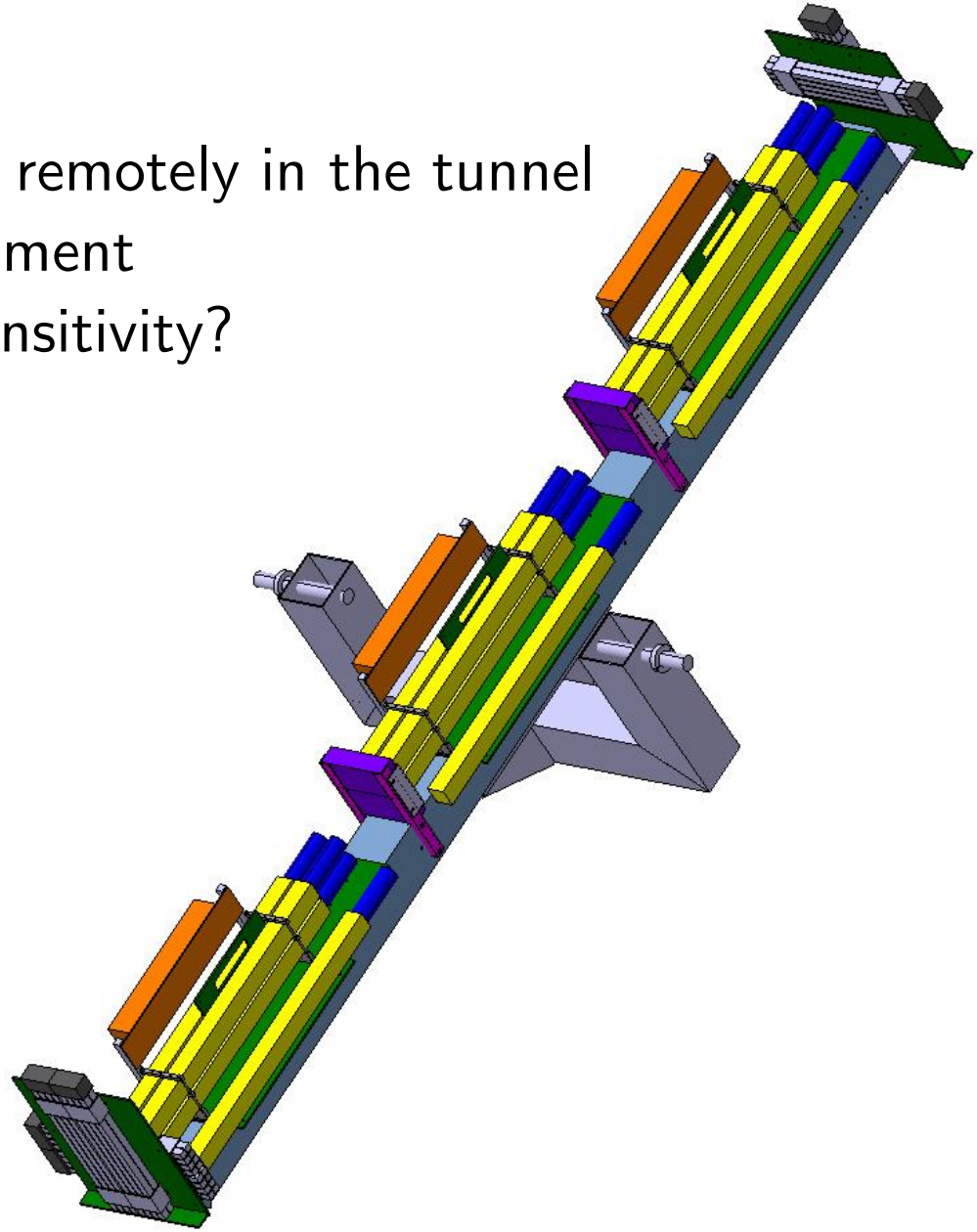
Installed in tunnel Sept., 2017!

Learn about operating experiment remotely in the tunnel

Measure backgrounds, check alignment

New heavy milli-charge particle sensitivity?





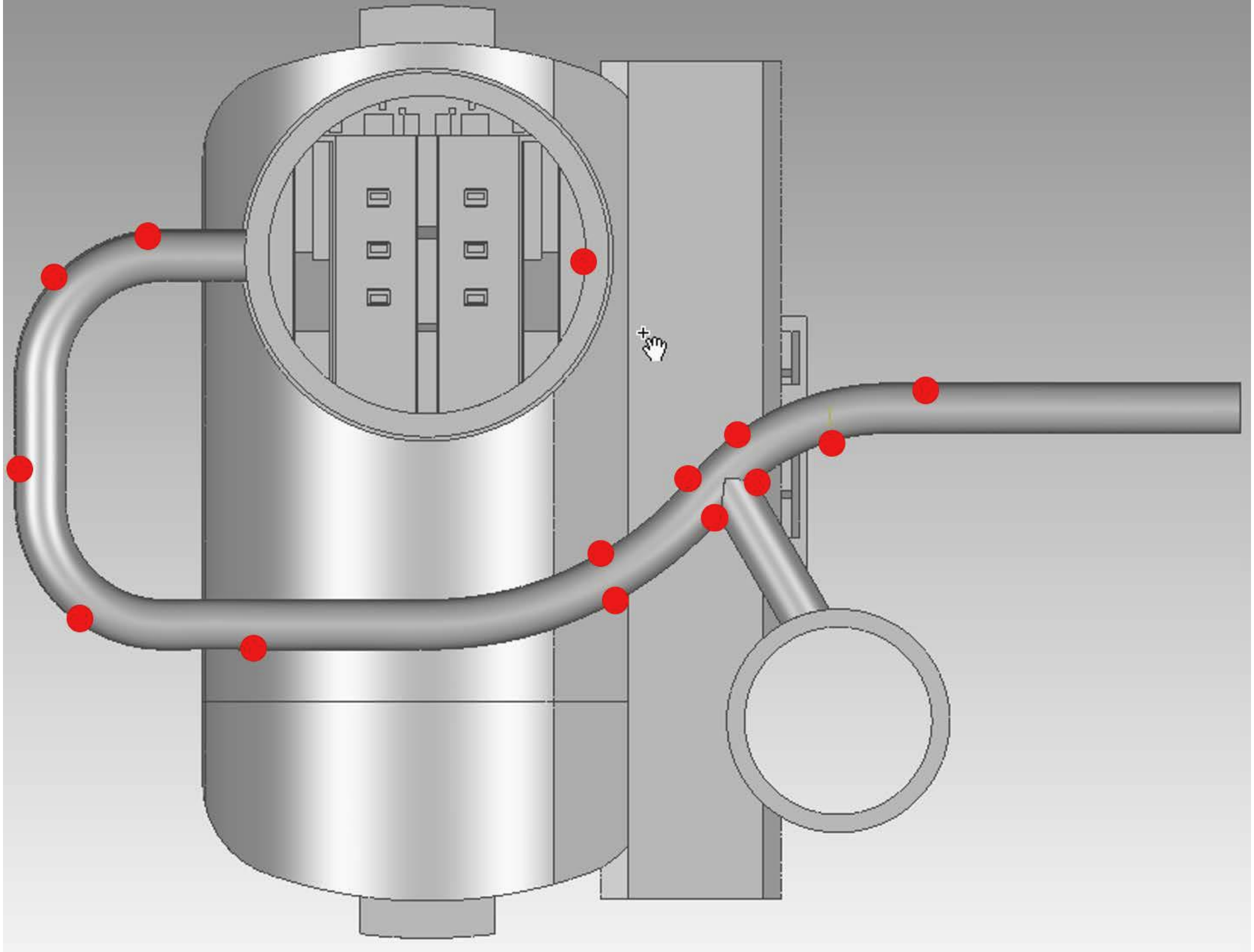
Demonstrator upgraded during 2017-18 YETS

- Now have 18 milliQan bars
- 9 thin scintillator veto sheets
- 4 scintillator slabs between bars
- Expanded hodoscope
- Timing information from CMS
- 4 magnetic field sensors
- Temperature & humidity sensors
- Fire protection system

Alignment

Special challenge, since far from collision point with no line-of-sight!

CERN team has heroically extended the CMS coordinate system into the tunnel, with ~µm precision

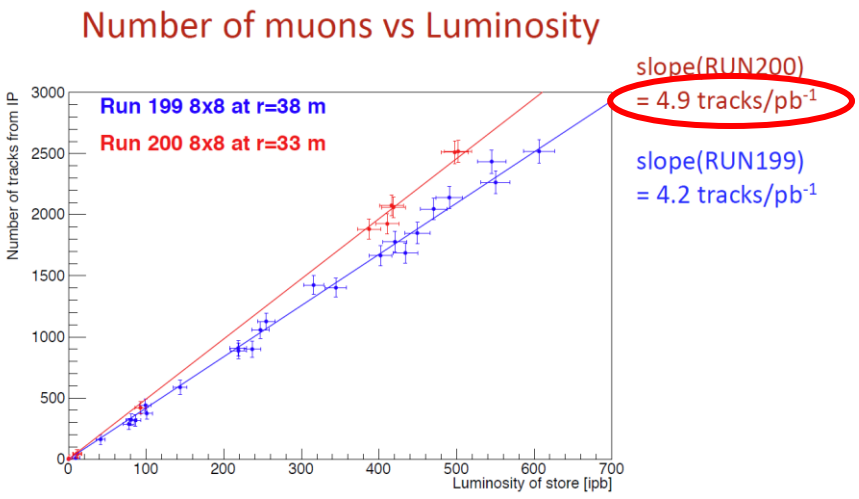


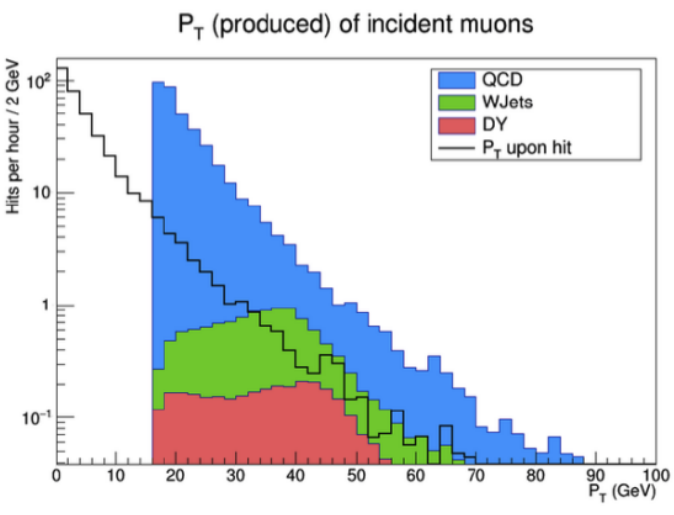
Alignment cross-check: **Measure muons from LHC proton collisions**

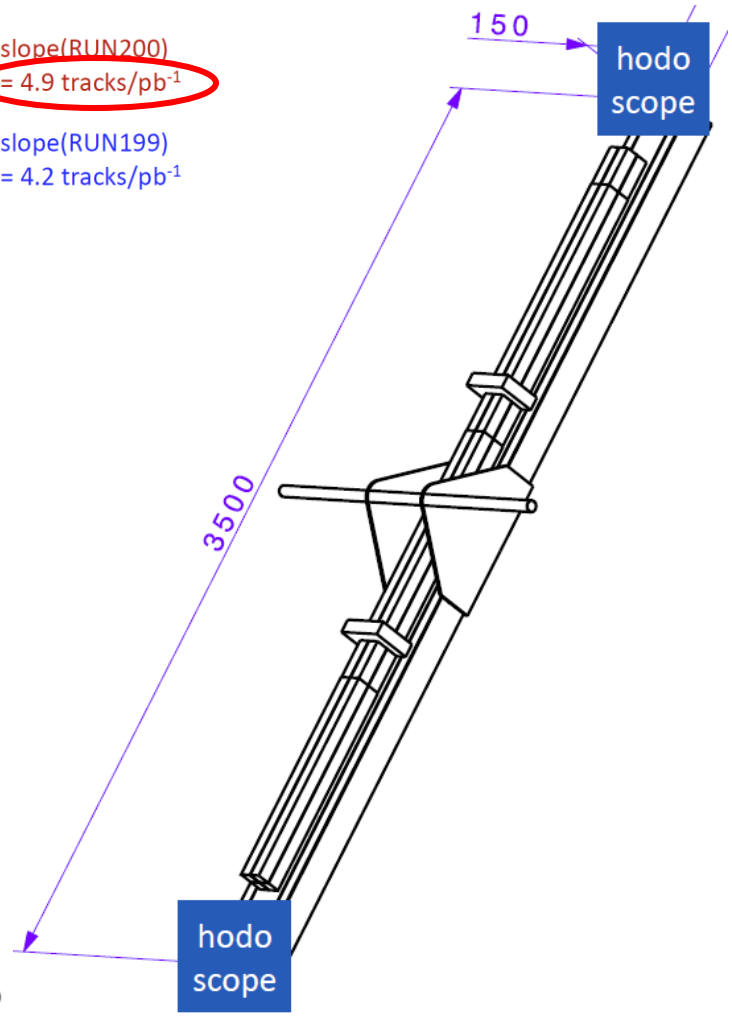
Two muon hodoscope detectors with arrays of 2x2x50 cm scintillator bars and SiPM readout

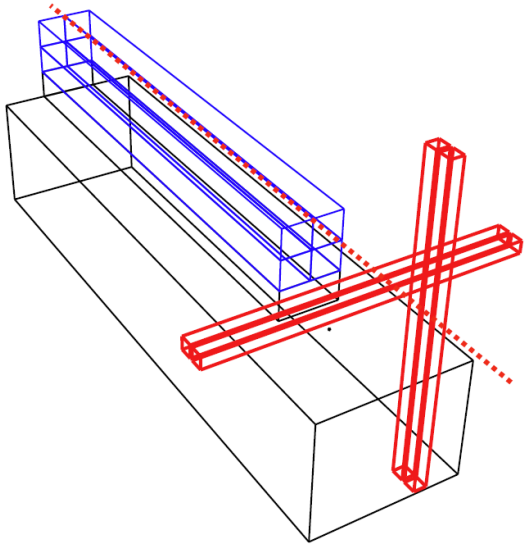
About 1000/hour will hit full milliQan at standard LHC interaction rate

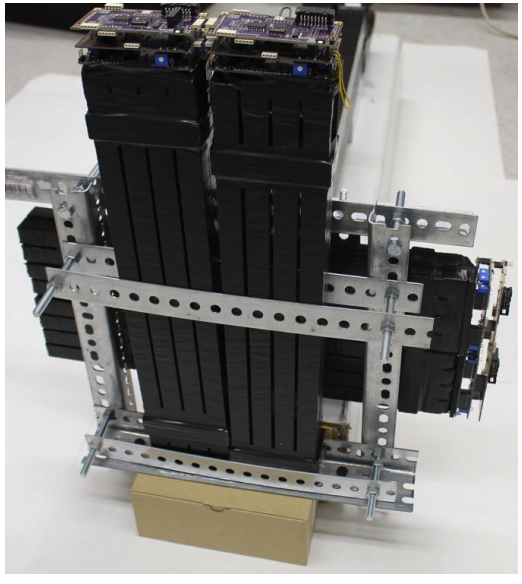
Also can be used to "time-in" detector w.r.t. LHC collisions







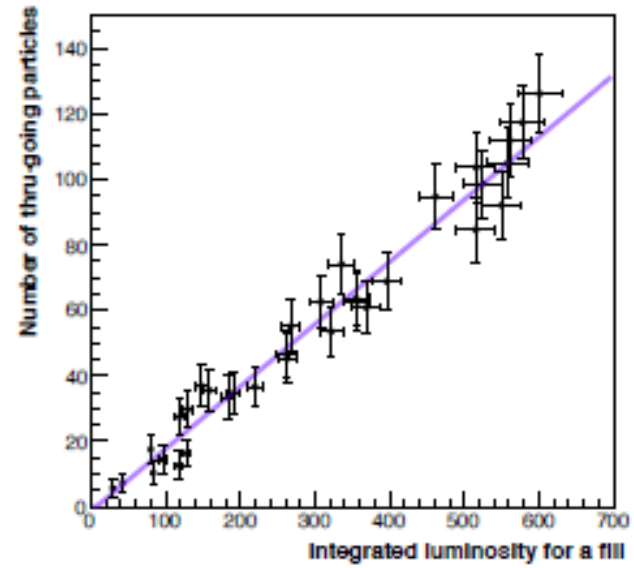


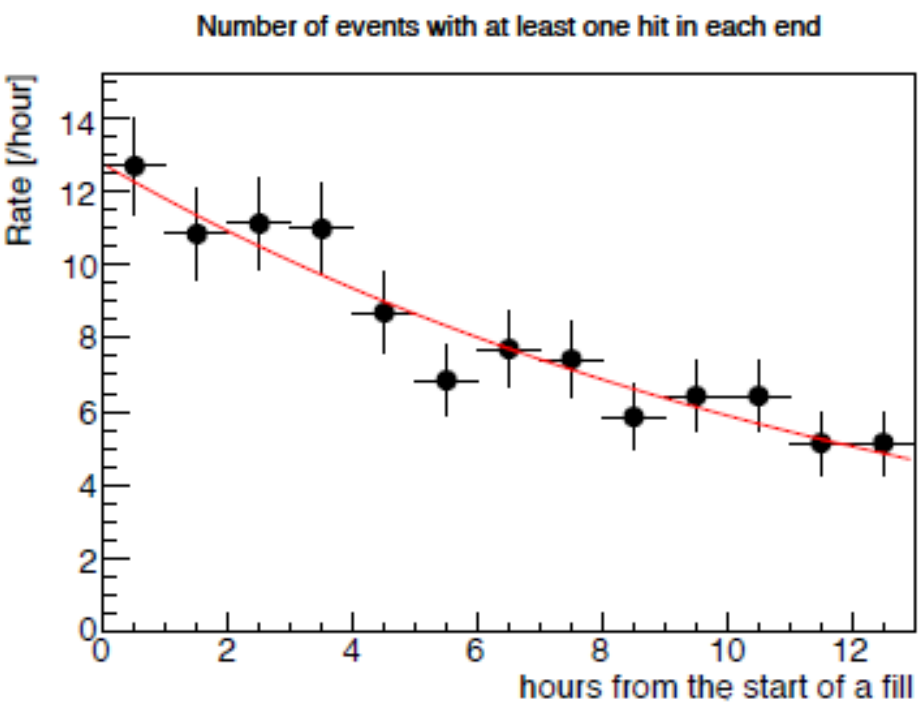


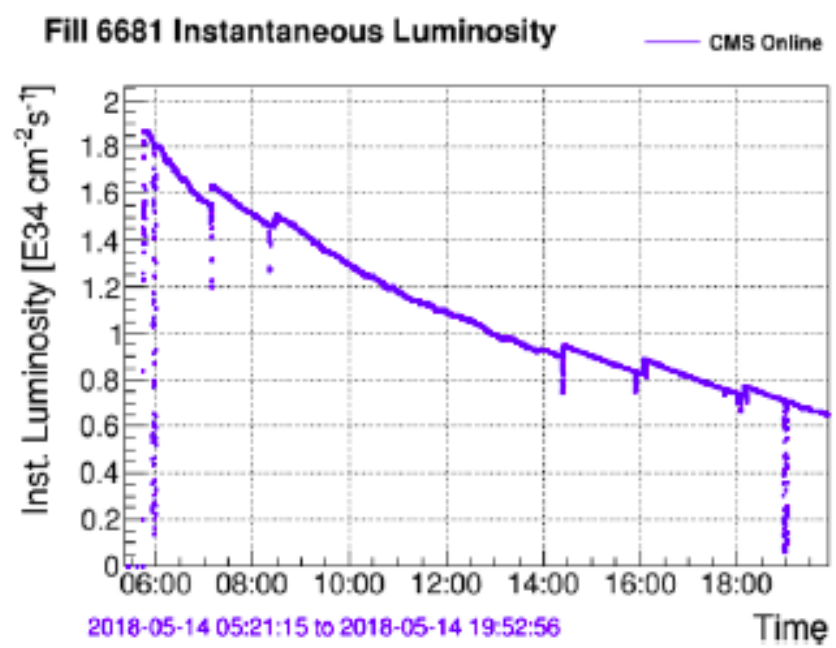
Data from Upgraded Demonstrator

THE OHIO STATE UNIVERSITY

- Have confirmed muon rate observed in 2017
- Observe luminosity structure within a fill
  - *Measured time constant of 13 ± 2 h*
  - *Consistent with beam lifetime of fill of 14 h*
- Study of *in situ* background with additional handles provided by upgrades is ongoing



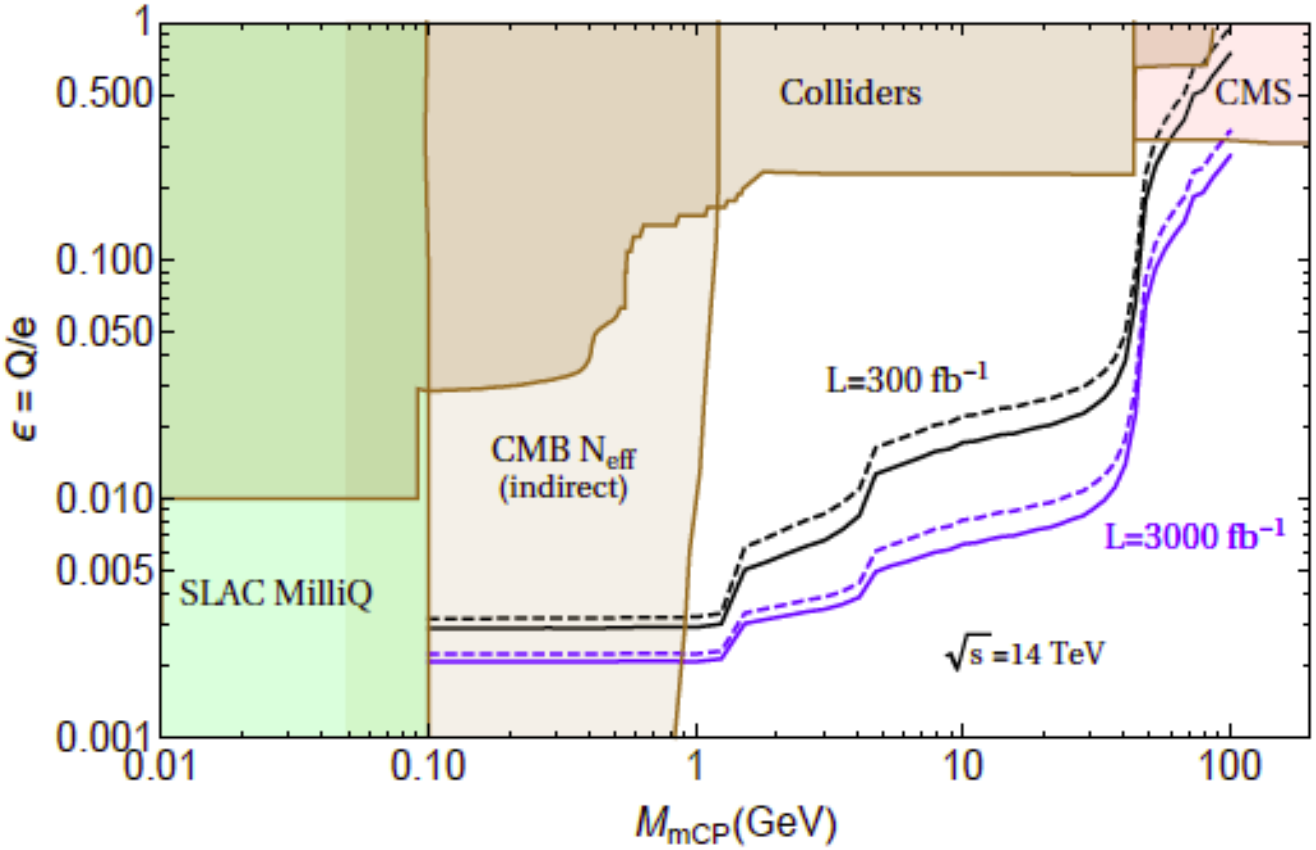




Final 1200 bar detector

Specifications

Location: LHC mCP distributions
Bar #: 2 x 2 x 3
Bar dim: 80cm x 5cm x 5cm
2nd layer offset: None
Inter-Scintillator Space: 1cm
Backgrounds: Same * 1%
Shield: 1mm G4_AIR, 1mm G4_AIR
Reflectivity/Wrapping: 0.99/tyvek
Scintillator: BC-408
PMT: R329-02
Lumi: 5,10, 50, 300, 3000/fb
Backgrounds: 1, 1, 1, 3, 5
Coincidence Threshold: 15ns
Dark-Current Rate: 700
Strategy: Back-to-Back

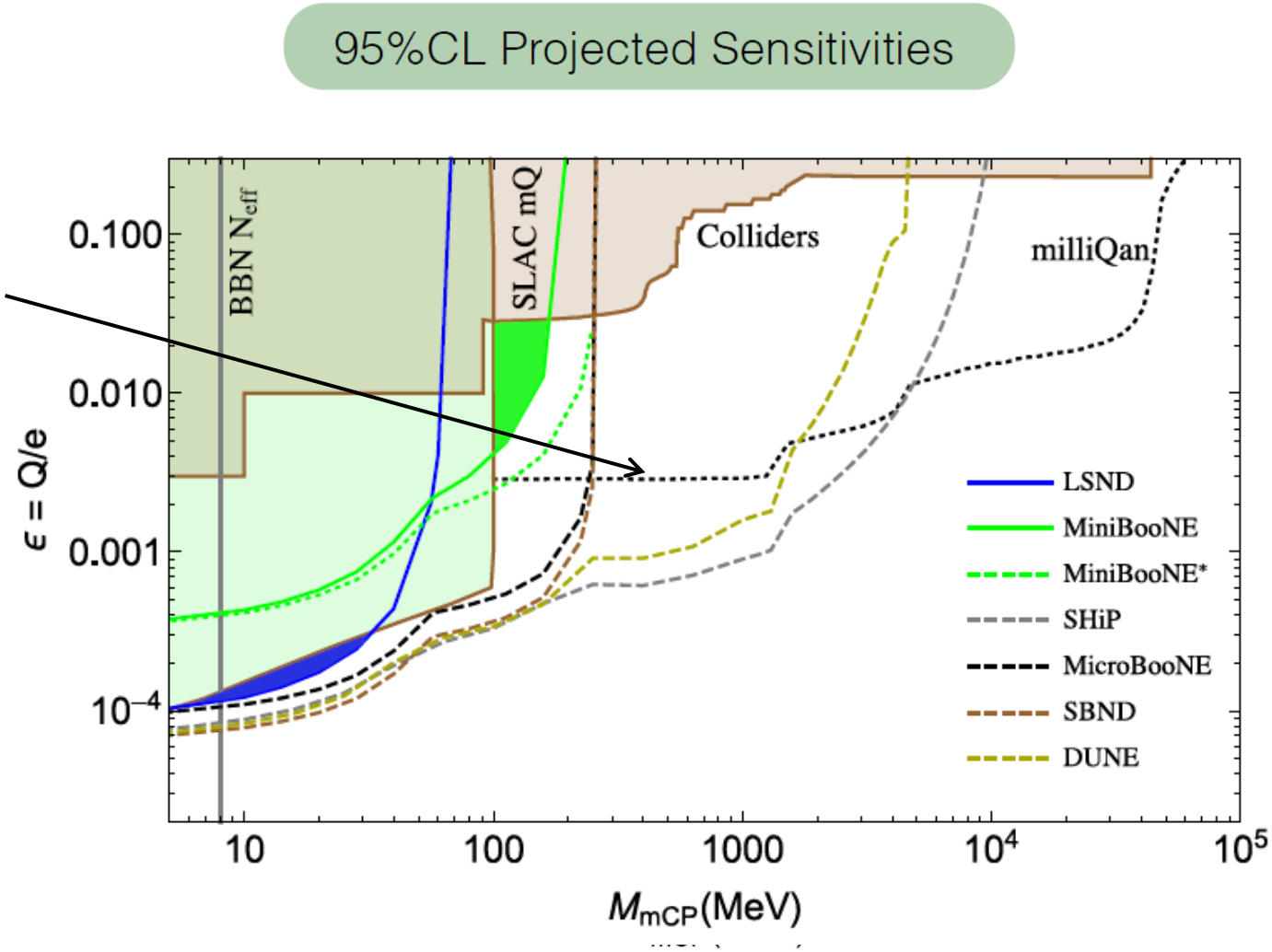


More generally, milliQan is the first detector sensitive to small ionization at the LHC (or any collider?)

Potentially sensitive to other signals from other new particles as well?

Comparisons

This flattening is artificial, as we did not include the more complicated production of mCP from QCD/hadronic physics … (only DY and prompt resonances).



arXiv: 1806.03310 [hep-ph] 8 Jun 2018

milliQan Collaboration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Itay Yavin

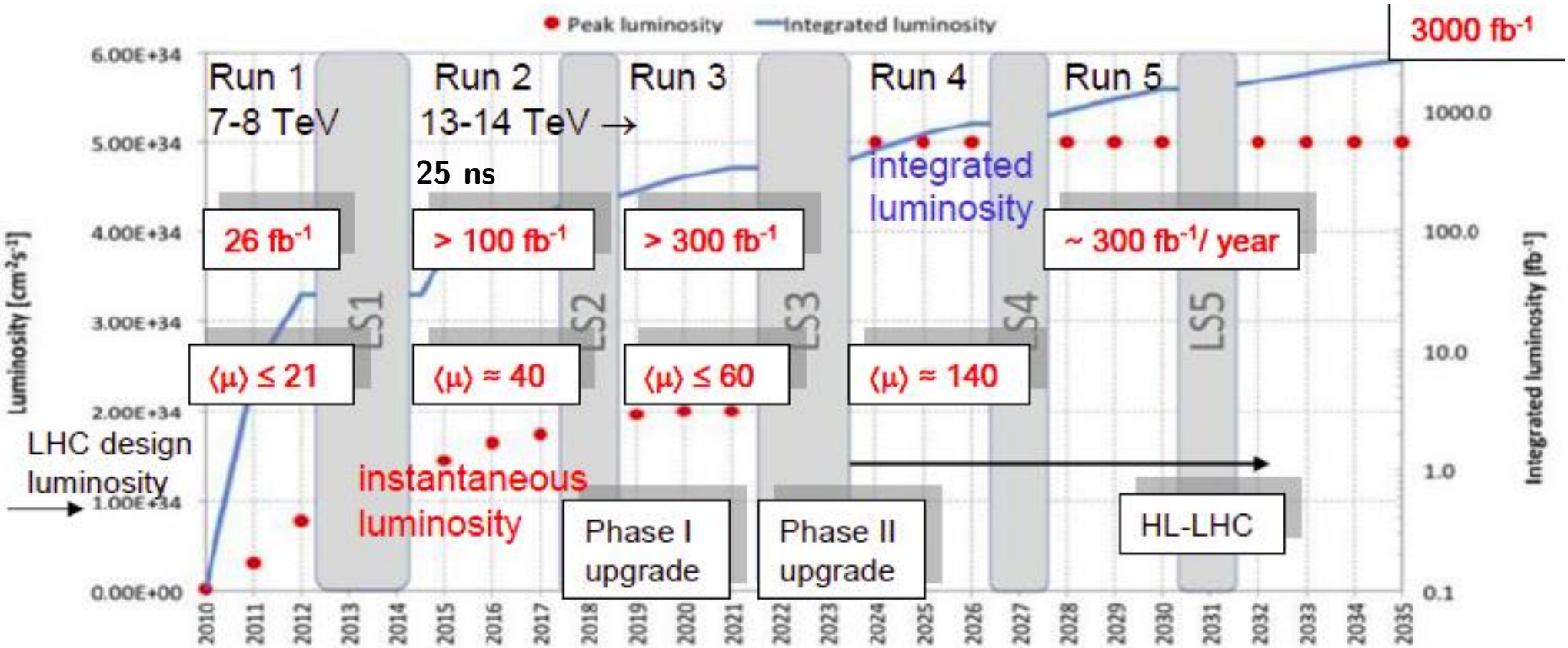
…plus many fantastic postdocs and students!

LHC and milliQan Schedule

Collected ~10/fb of data in 2017 and ~20/fb so far this year with 1% prototype detector – excellent uptime and efficiency! (until recently :)

Complete full milliQan detector for LHC Run3, collect ~300/fb

Then a milliQan upgrade in time for HL-LHC?



Backup

Status on Searches for Mini-charged Particles (mCPs)

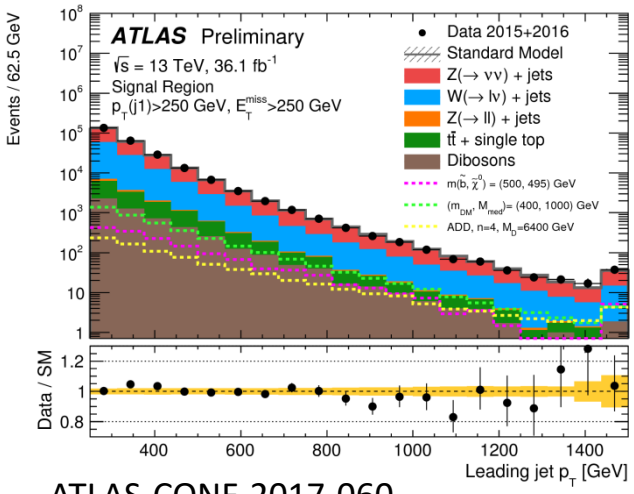
A long history of direct and indirect searches for mCPs

For mCPs with mass below m_e one finds strong bounds from astrophysics and cosmology

Astrophysics	Cooling and energy loss bounds from stars and SN
Cosmology	BBN and CMB number of effective relativistic degree of freedom bounds
	Direct bound from the invisible decay of ortho-positronium
Laboratory	Direct bound from the Lamb shift
	Direct constraint from accelerators: SLAC Milli-Charge experiment, E613, ASP, LEP More later on this

Darn Neutrinos

The limitations of looking for weakly-coupled new physics with missing energy: neutrinos (and mis-measured jets)



ATLAS-CONF-2017-060

Irreducible background from Z+jets

$$Z \to \nu\bar{\nu}$$

Additionally, from dijet production

Occasionally a jet's momentum is mis-measured giving missing energy + jet

Systematic uncertainties on these processes (jet energy scale, etc)

Unlikely to see a signal unless $S \gtrsim 0.1B$

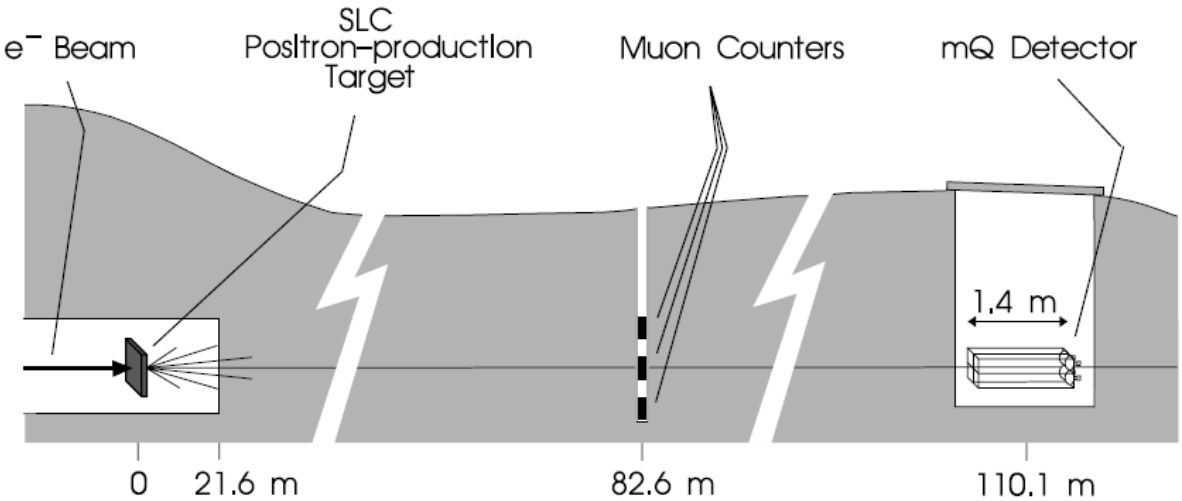
Punchline: LHC jet + missing energy unlikely to improve sensitivity to mCPs beyond current bounds

Lessons from the SLAC MilliCharge Experiment

Phys.Rev.Lett. 81 (1998) 1175-1178

29.5 GeV pulsed electron beam

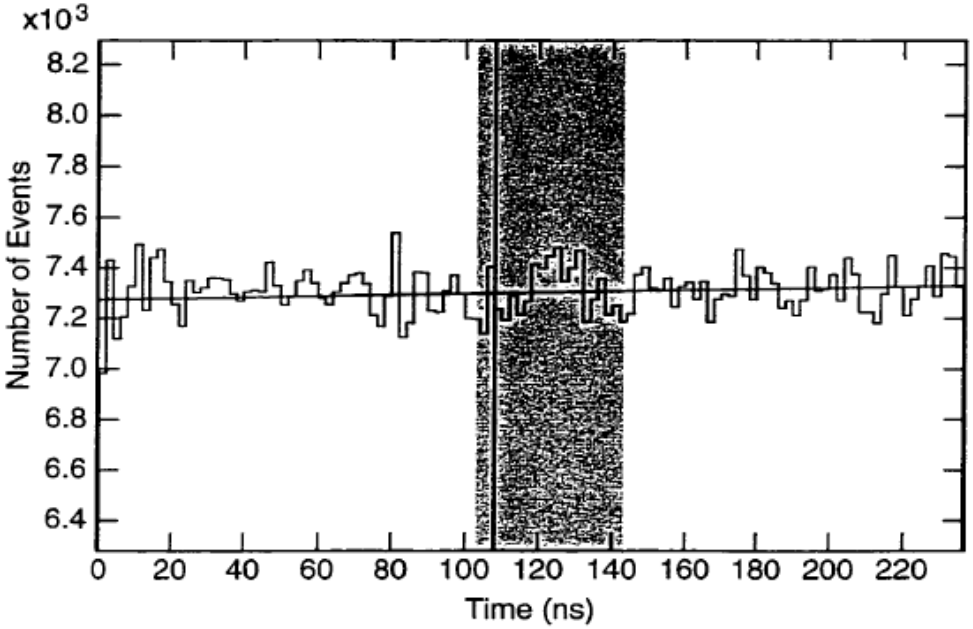
~ 10^{19} electrons on target

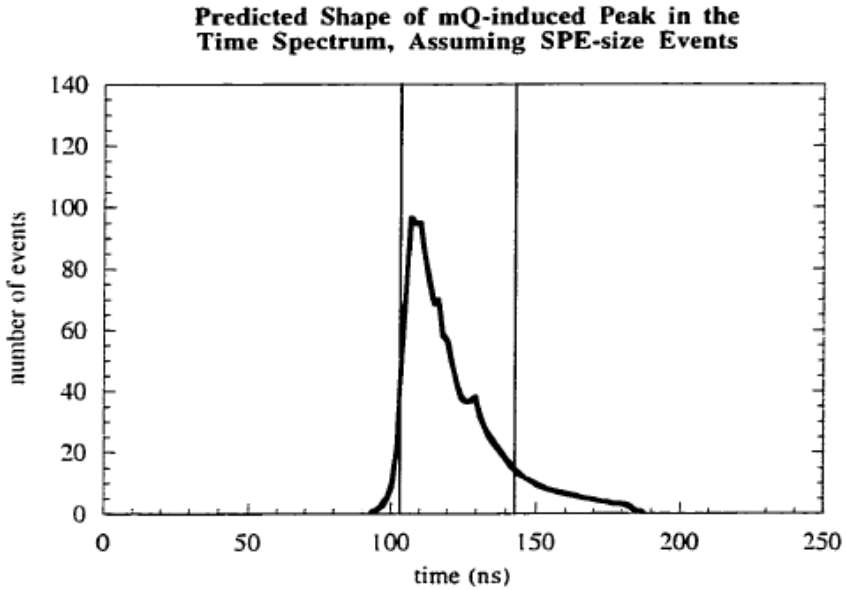


Good time resolution is essential, and tricky for small (SPE) pulses!

mQ detector

2x2 blocks of 21 cm x 21 cm x 130 cm plastic scintillator





What's in the Dark Sector?

EI, Itay Yavin, 1506.04760

Recall: Kinetic mixing communicating our sector with Dark Sector (DS)

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

Two cases studied in the literature

$$\frac{1}{2} m_{B'}^2 B'^2$$

$m_{B'} = 0$ matter in DS is mCP: "Massless phase"

$m_{B'}$ non − zero matter in DS is DM: "Massive phase"

What's in the Dark Sector?

Our hyper-charge is a linear combination of a massless and a massive boson

What if that also is realized in the DS?
i.e. a "mixed phase"

$$B' = \cos\theta_{W'} A' - \sin\theta_{W'} Z'$$

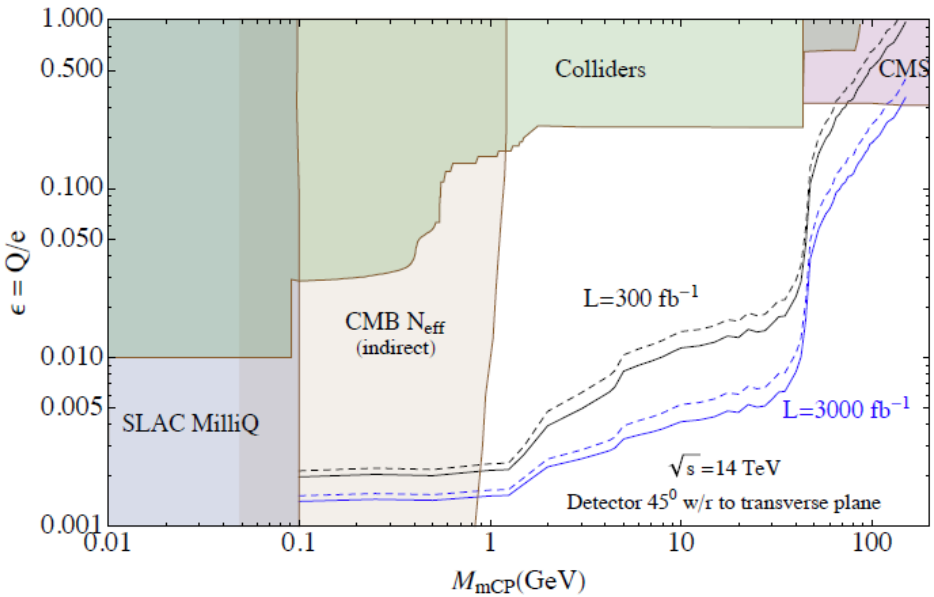
Opens up a new window into the DS
Produce the Z' on-shell
Z' decays to matter in the DS
Matter in the DS is still mCP!

Z' couples to SM matter with strength $\epsilon_Z e = \kappa \cos\theta_W \sin\theta_{W'} e$

Matter in the DS charged under A' acquires mill-charge $\epsilon_\gamma e = \kappa \cos\theta_W \cos\theta_{W'} e'$

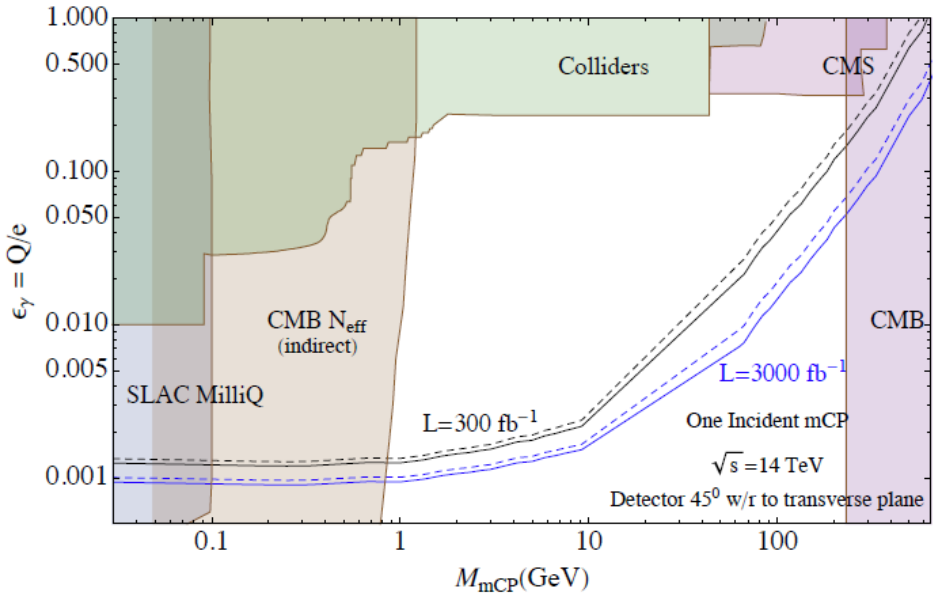
Looking for mCPs above GeV

Massless phase



Mixed phase

$M_{Z'} = 3M_{mCP}, \theta_{W'} = \theta_W$



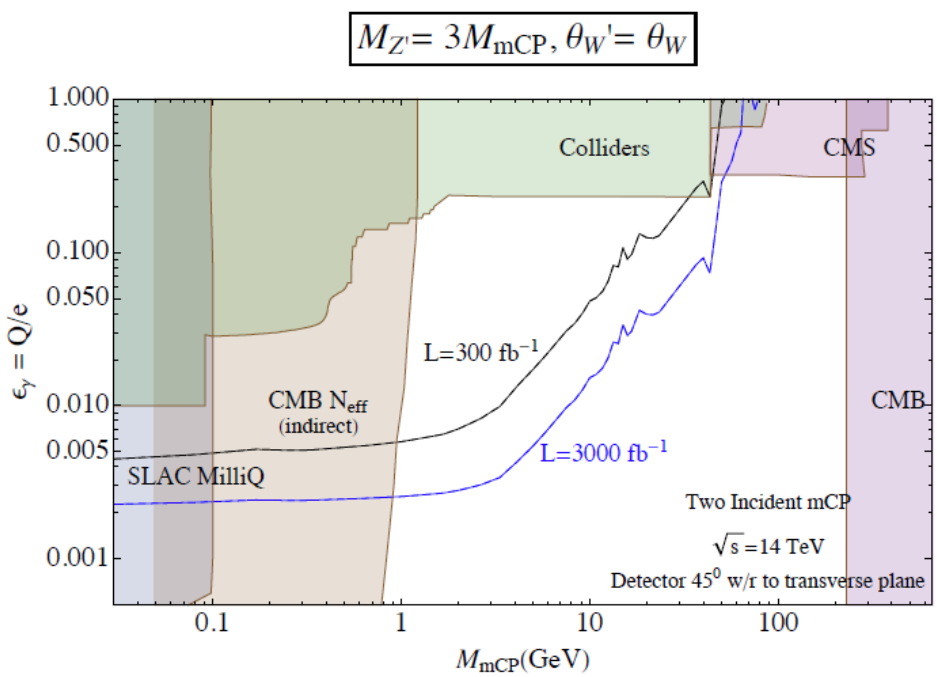
Note that mixed phase constraints at LHC experiment primarily sensitive to $\kappa_Z \kappa_\gamma$

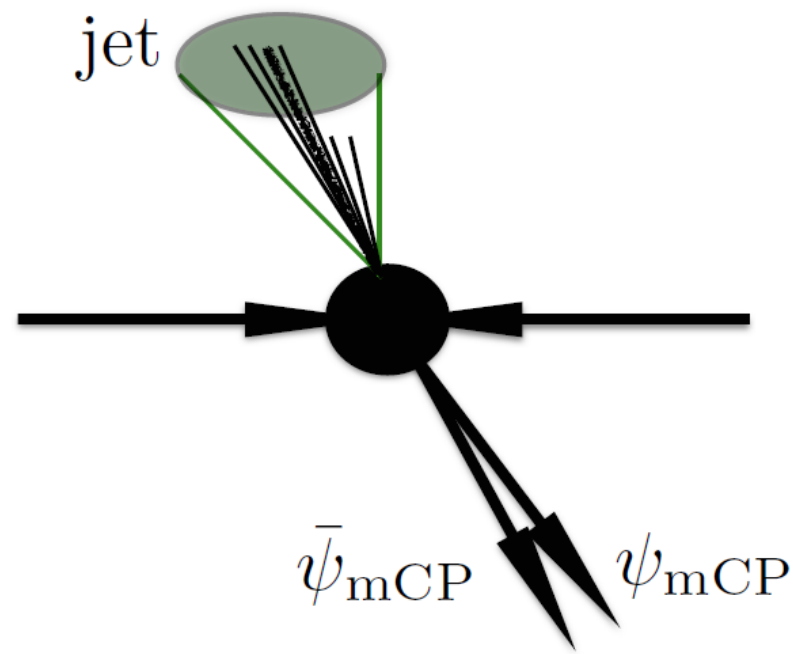
Unique Signature of the Mixed Phase

Mixed phase offers new striking signatures

Two incident mCPs for boosted Z' when:

$$\Delta\theta(\bar{\psi}_{\rm mCP}, \psi_{\rm mCP}) < \Delta\theta_{\rm det}$$





Other Scintillators Considered

Light yield in bar given by (photon yield / energy) * density * length

- Want high photon yield / energy -> can go to lower charge (but limited by production cross-section too…)
- Want high density -> can go to shorter bars / more layers
- Want it fast -> lower backgrounds from smaller coincidence time window
- Want it cheap -> can afford more bars / acceptance area

Material	Photons/keV	Density (g/cm^3)	* Length needed (cm)	Speed (ns)	Cost for 5x5 cm ($)	Notes
Plastic BC408	10	1.03	145	~2	~200	Current choice
NaI	38	3.67	11	~230	~800	Slow, fragile
LaBr3(Ce)	63	5.08	5	~16	~3000	Radioactive
Liquid Xe	62	2.95	8	~2 / ~34	~1000?	Cryogenic, ultraviolet

* Length needed to get 3 photons for charge 1/1000 e

Readout and trigger

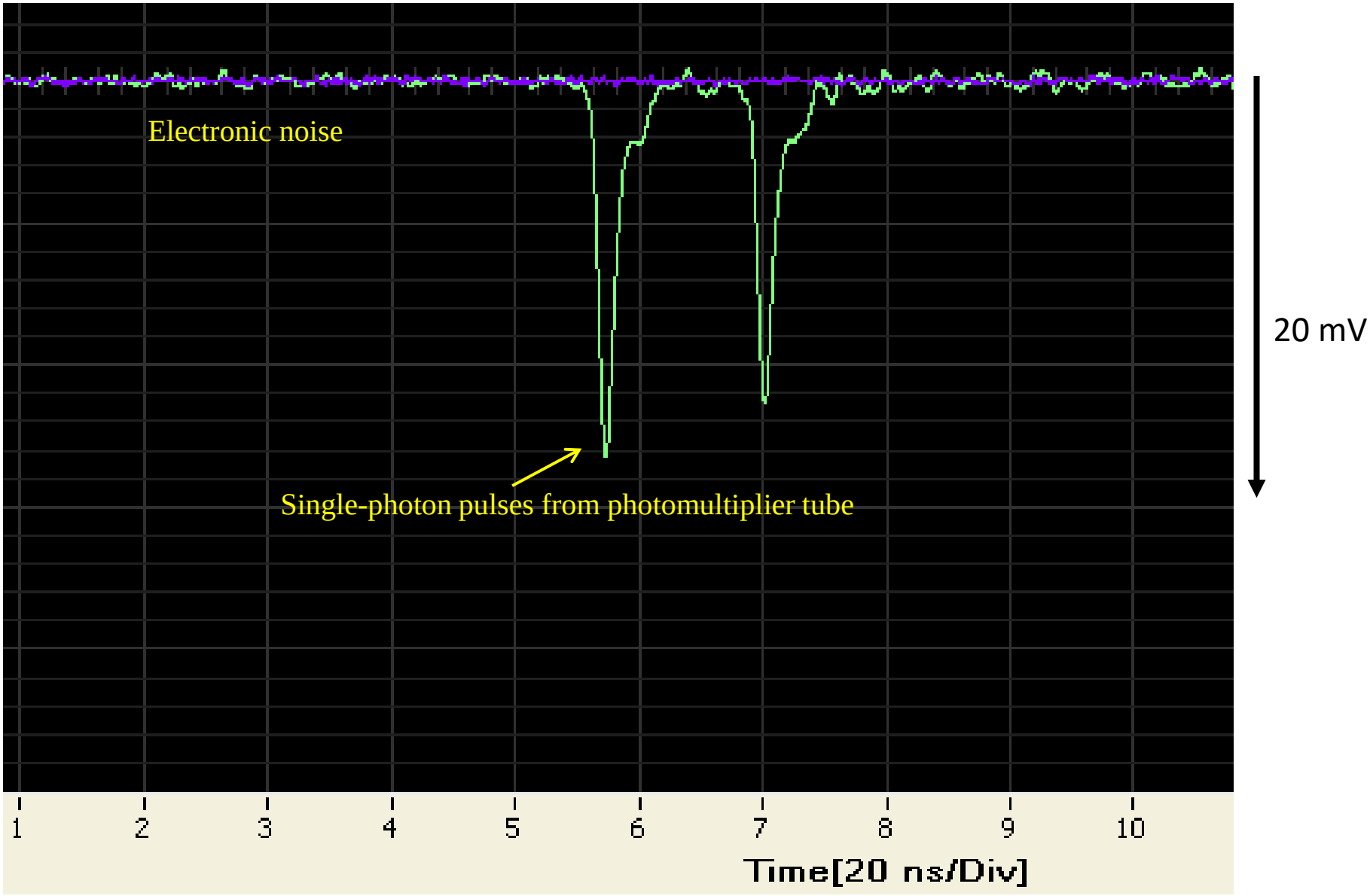
Fantastic detail of each photomultiplier pulse from a triggered event
~1 ns timing resolution, even for tiny (single photon) pulses

- Readout via CAEN V1743 12 bit digitizer
- 16 channels
  - *Sampled at 3.2 GS/s (a sample each 312.5 ps)*
  - *1024 analog buffer ring (320 ns long).*
  - *Analog noise is about 0.75 mV per channel, allowing good identification of and triggering on single PE signals*
- Trigger
  - *If 2 of 3 bars coincident in 15 ns window, self-triggers to read out whole detector*
    - **Completely separate from CMS trigger**
  - *Data will be read out via CAEN CONET 2 over 80 Mbps optical fiber to a PCI card in dedicated DAQ*
    - **Completely separate from CMS DAQ**

Will also interface with LHC clock to time-stamp events with bunch-crossing info!

Readout and trigger

Fantastic detail of each photomultiplier pulse from a triggered event
~1 ns timing resolution, even for tiny (single photon) pulses



1% milliQan

Current Prototype

Specifications

Location: LHC mCP distributions
Bar #: 2 x 2 x 3
Bar dim: 80cm x 5cm x 5cm
2nd layer offset: None
Inter-Scintillator Space: 1cm
Backgrounds: Same * 1%
Shield: 1mm G4_AIR, 1mm G4_AIR
Reflectivity/Wrapping: 0.99/tyvek
Scintillator: BC-408
PMT: R329-02
Lumi: 5,10, 50, 300, 3000/fb
Backgrounds: 1, 1, 1, 3, 5
Coincidence Threshold: 15ns
Dark-Current Rate: 700
Strategy: Back-to-Back

95%CL Projected Sensitivities