Searches for particles with Q ≠ 1

Matthew Citron

millicharged (Q < 0.1e)

fractionally charged (0.1e < Q< 1e)

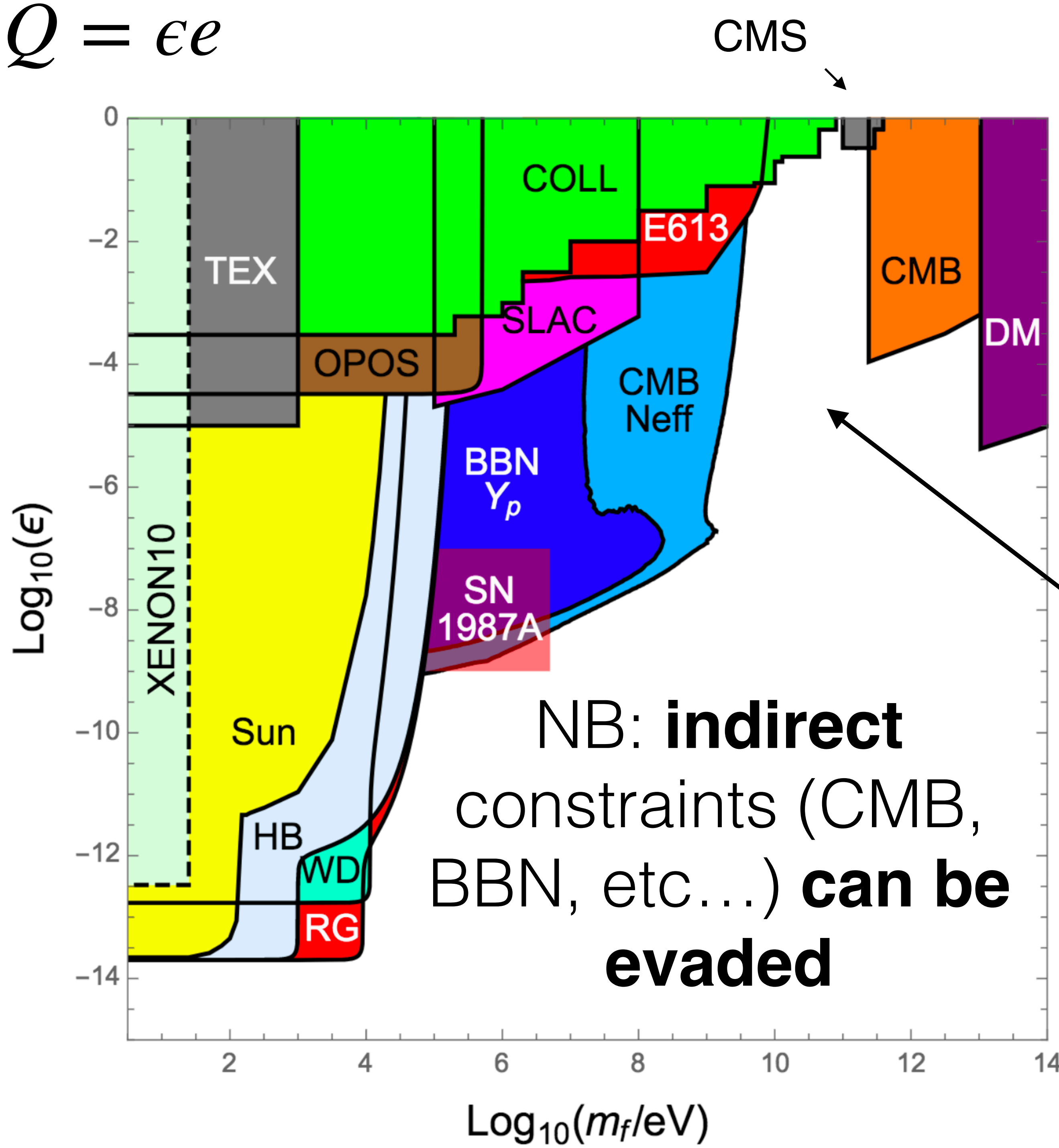
multiply charged (1e < Q)

Introduction

- Exotically charged particles theoretically well-motivated
- Focus in these slides on particles with Q < 1
  - Motivation from "**kinetic mixing**" of dark photon (link to the hidden sector)
- Many recent searches with a wide range of detectors
  - Interface of energy and intensity frontier
- Potentially many more detectors in near future - how can we **robustly** predict future sensitivity?

Searching for millicharged particles

$Q = \epsilon e$



NB: **indirect** constraints (CMB, BBN, etc…) **can be evaded**

Searches using colliders, effects on sun, stars and supernovae, cosmological bounds,… cover wide range in masses/charges

but

big gap for heavier (~ GeV) low charged particles

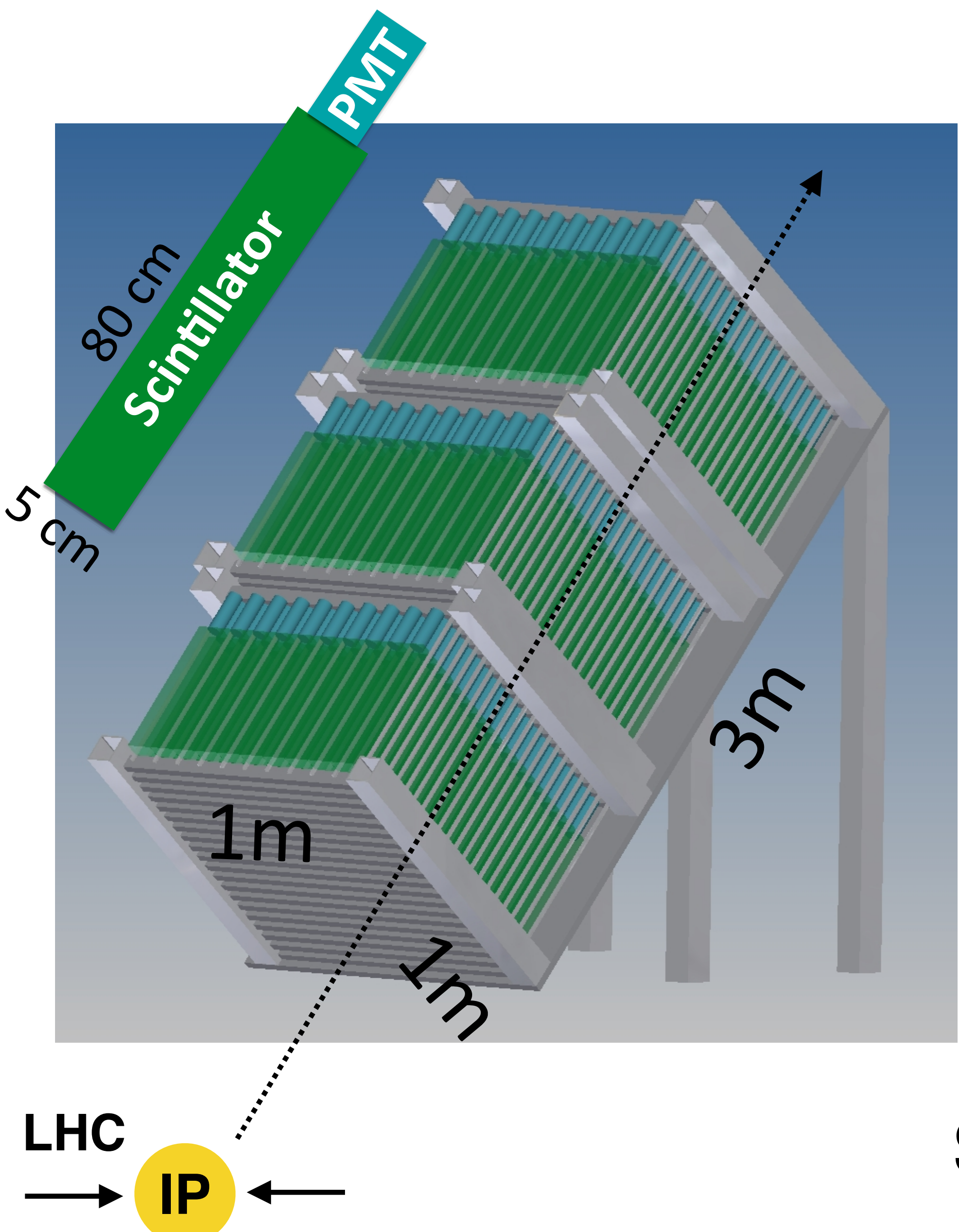
Focus on expanding reach with **new direct detection** experiments

arXiv:1511.01122

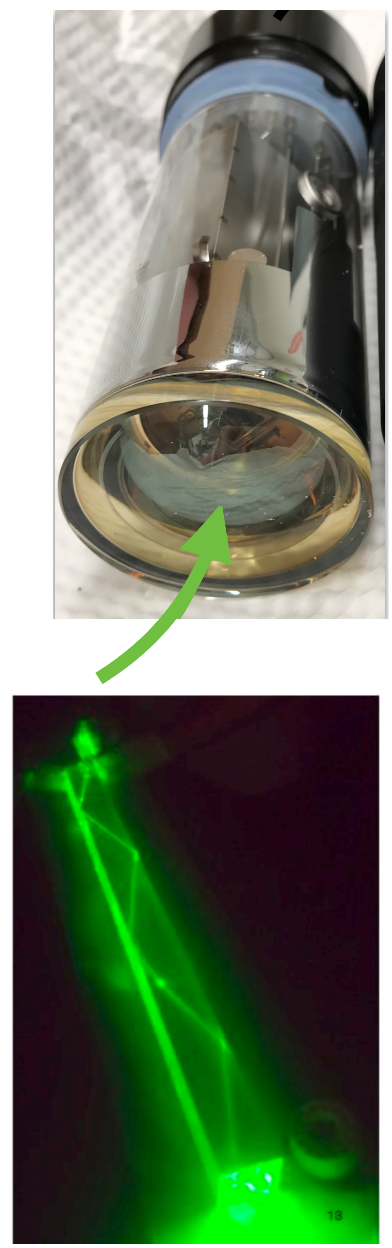
First: scintillation based detection

Scintillation based detection

Initial design in 2016 milliQan LOI: 1200 scintillating bars in three layers (400 pointing paths)



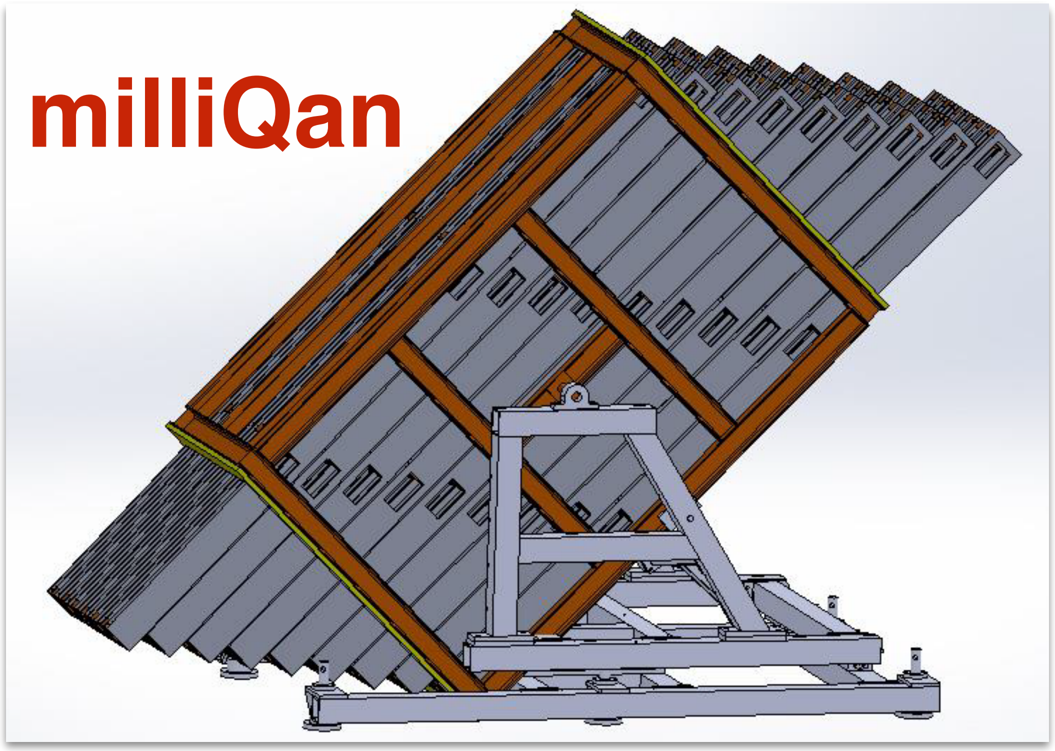
PMT



Scintillator bar

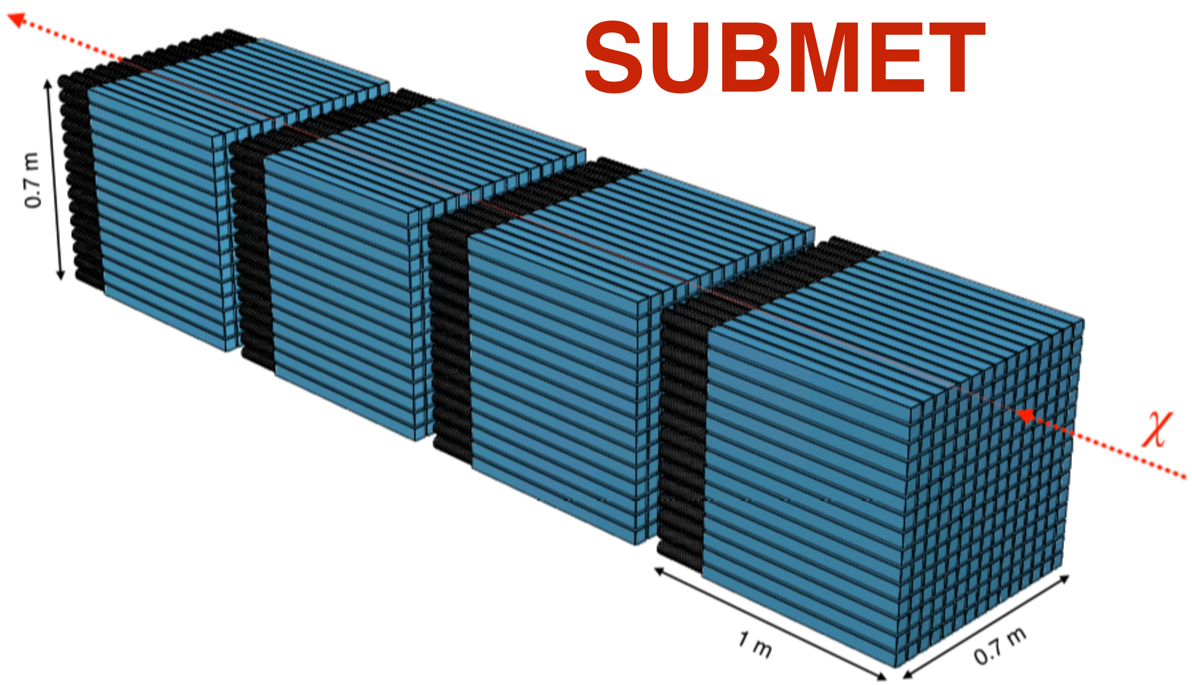
- **Key idea**: use scintillator bar array to detect (very) small ionisation from low charged particles
- Expected signal: few scintillation photons in multiple layers
- Each bar + PMT must be capable of detecting a single scintillation photon
- Control backgrounds: signal in each layer within small (~15 ns) time window and which points towards the IP
- Modular design is easy to scale and adapt!

Scintillation based detection



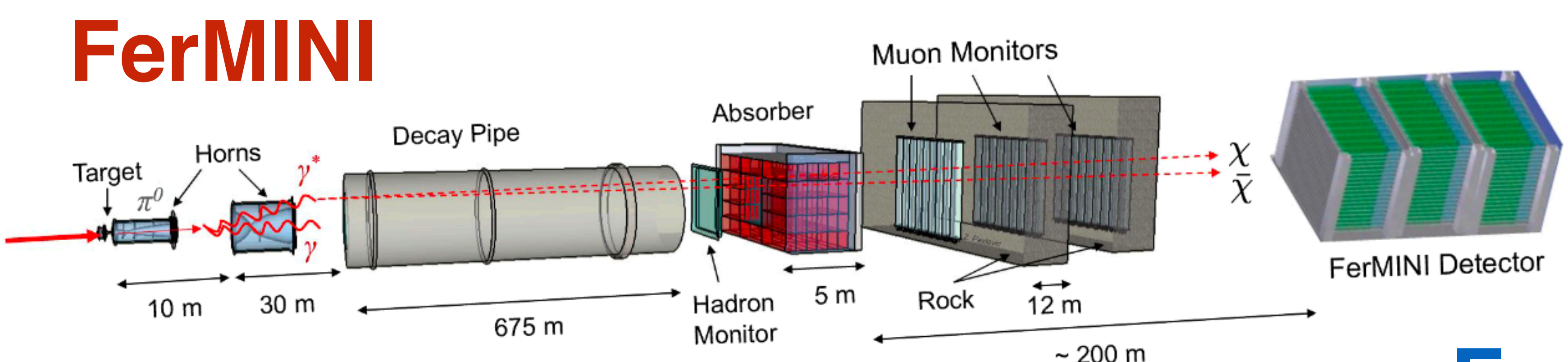
LHC with sensitivity for m < ~45 GeV

1607.04669



J-PARC with sensitivity for m < ~1.5 GeV

LOI to appear on arXiv soon



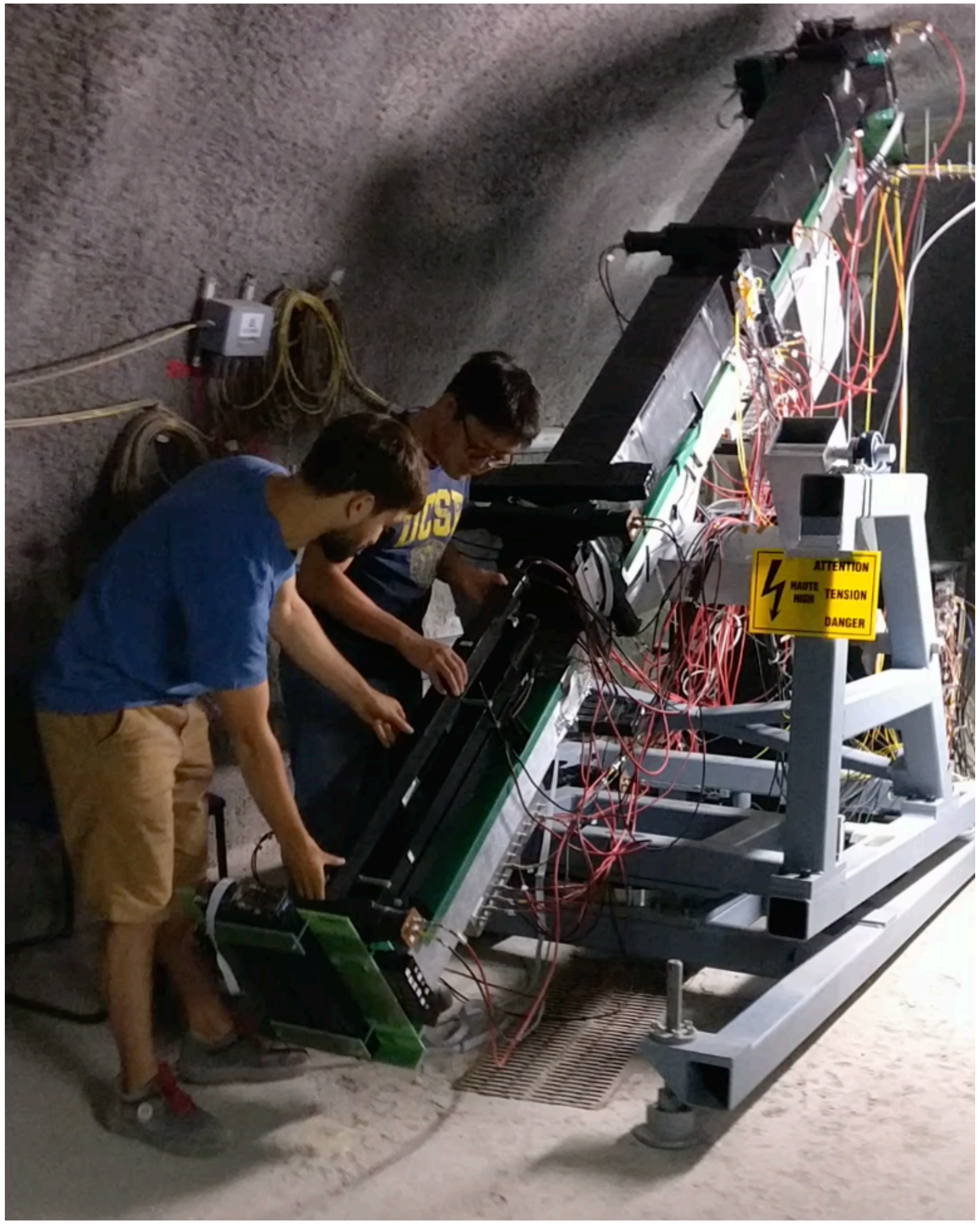
Fermilab with sensitivity for m < ~5 GeV

1812.03998

Range of detectors with complementary sensitivity

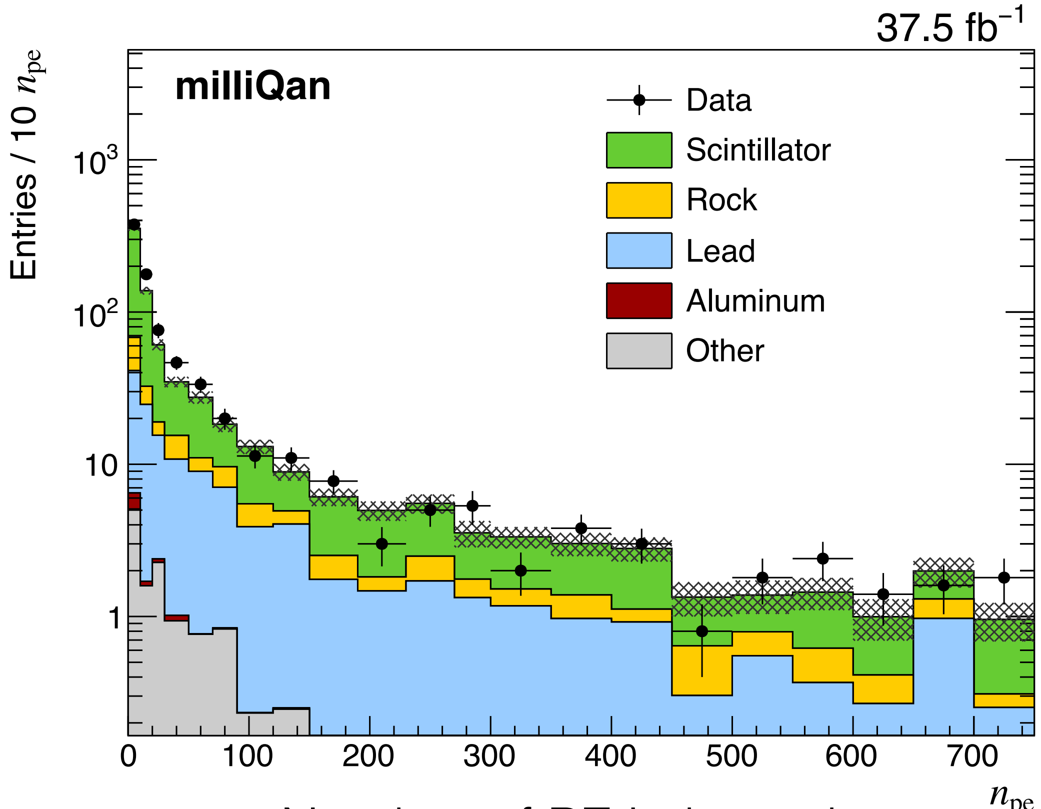
For milliQan: proof of concept "demonstrator" installed at CERN

milliQan demonstrator



Installed on mount designed to hold full detector

- Around 1% prototype of full milliQan detector working with ~40 collaborators
- Ran very successfully, collecting **~35/fb, 2000h** of data in 2018
- Operational experience in difficult environment: triggering/DAQ/DQM
- Used for range of studies to prove feasibility of full detector: **alignment, calibrations, background measurements**
- Fully simulated in GEANT4 (validated with data)



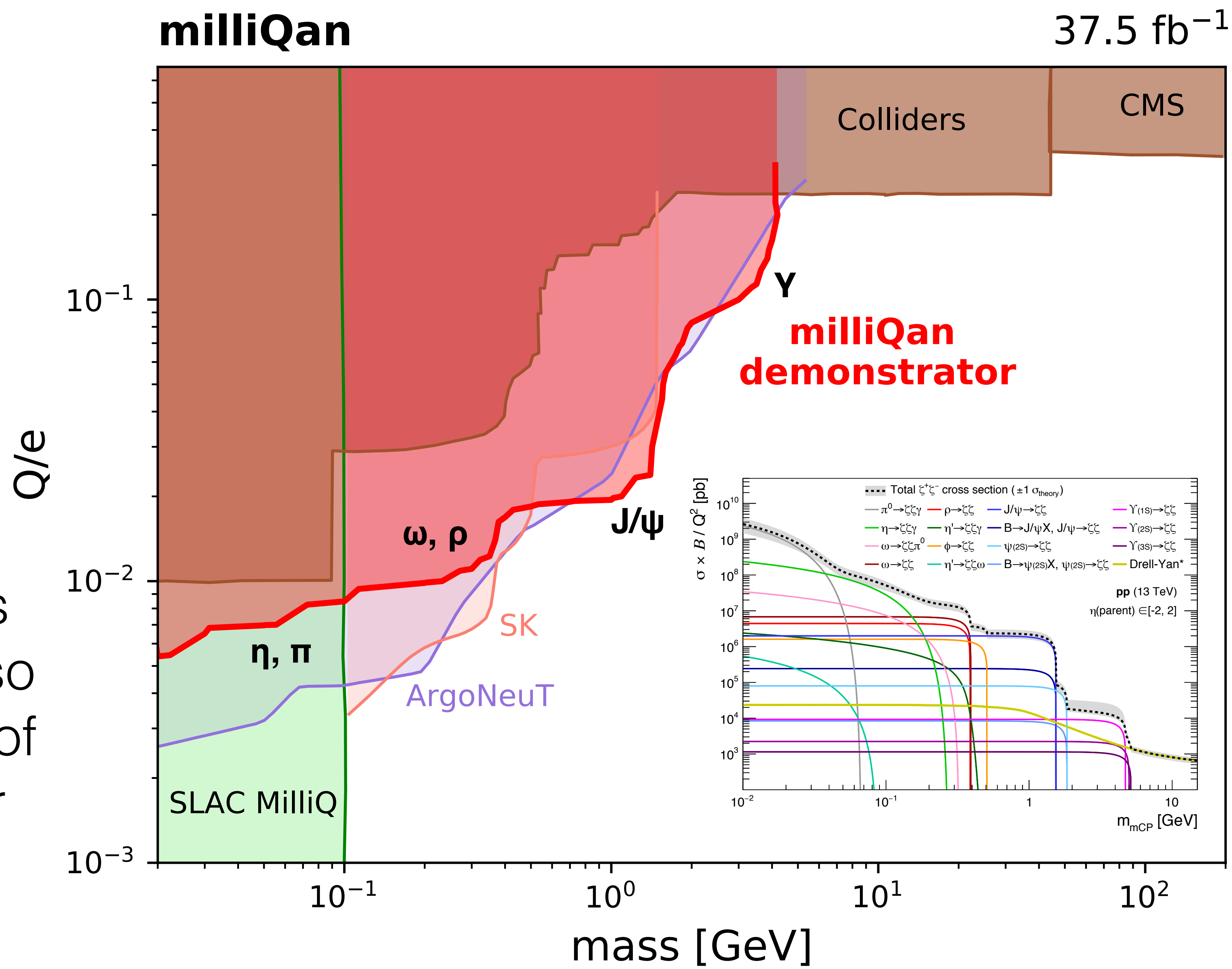
Number of PE in bars due to muon shower products

Search results

With only 37.5 fb^{-1} and 1% of the full detector, the milliQan demonstrator achieves competitive constraints on mCPs

The demonstrator provides new exclusion limits, but also quantitative understanding of backgrounds and detector performance

→ **Use this to guide future detectors!**

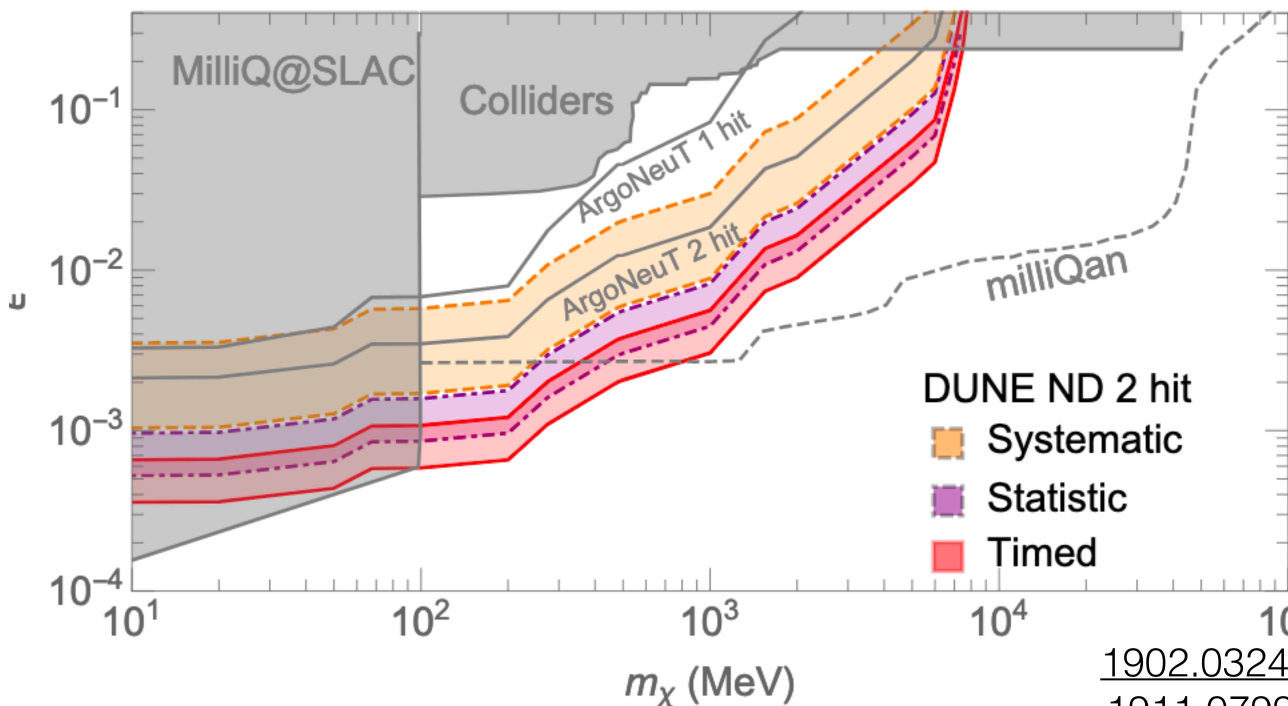


2005.06518

Snowmass plans

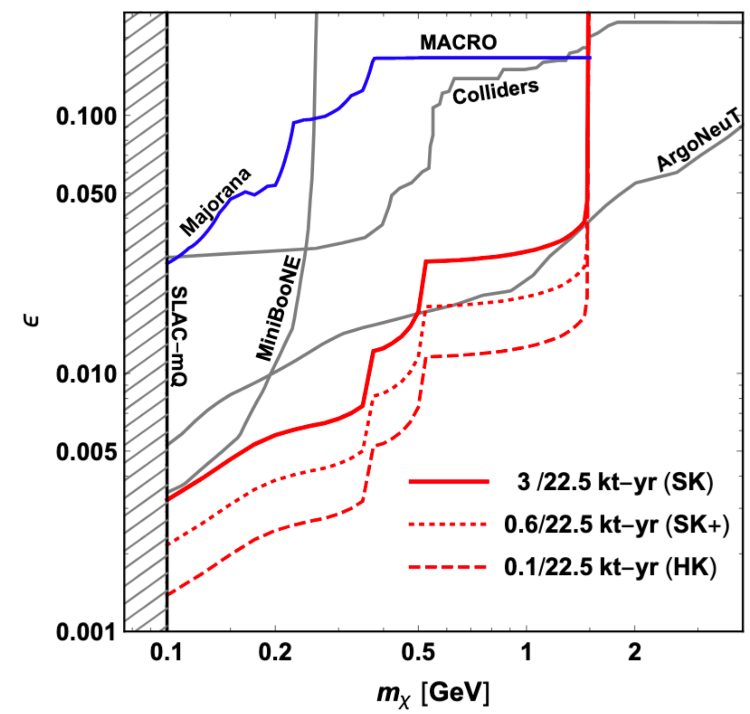
- EOI: Use data from demonstrator to make concrete sensitivity projections for scintillation based detectors at range of facilities: LHC, J-PARC, FERMILAB (and others?)
    - **Characterisation/understanding** of backgrounds (and how to reject them)
    - **Fully validated** simulation of signal/background
    - **Performance** of PMTs/scintillator
- Guide design of future detectors based on experience
    - Four layer design shown to be required using special runs of the demonstrator (see backup) - **necessary to reject correlated components of background**
    - Have complete mechanical design for four layer milliQan (see backup)

Searching for millicharge particles with neutrino detectors



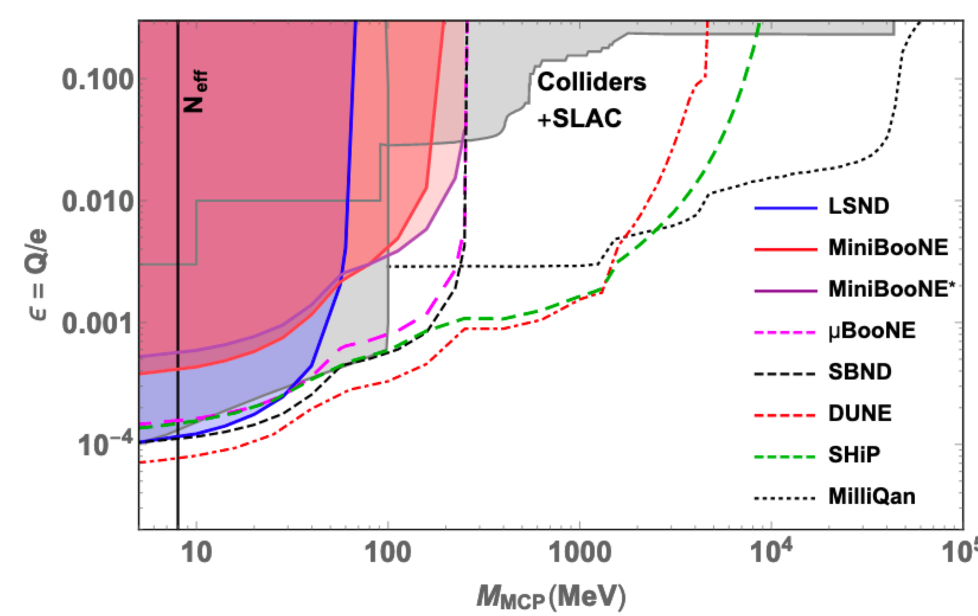
1902.03246, 1911.07996

Detection with LarTPC



Production in cosmic ray showers

2002.11732



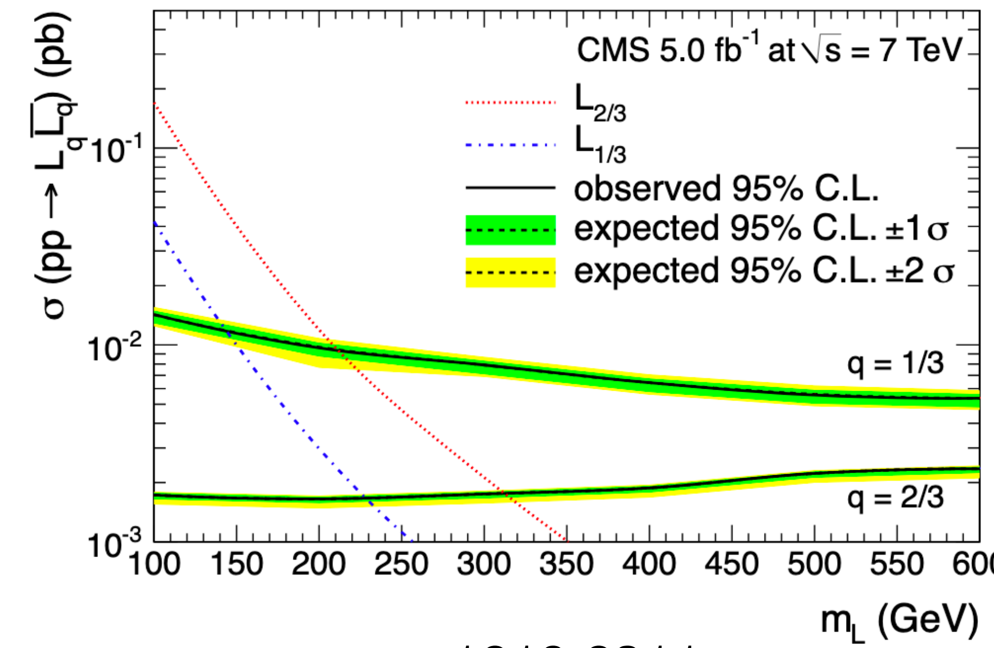
1806.03310

Fixed source neutrino experiments

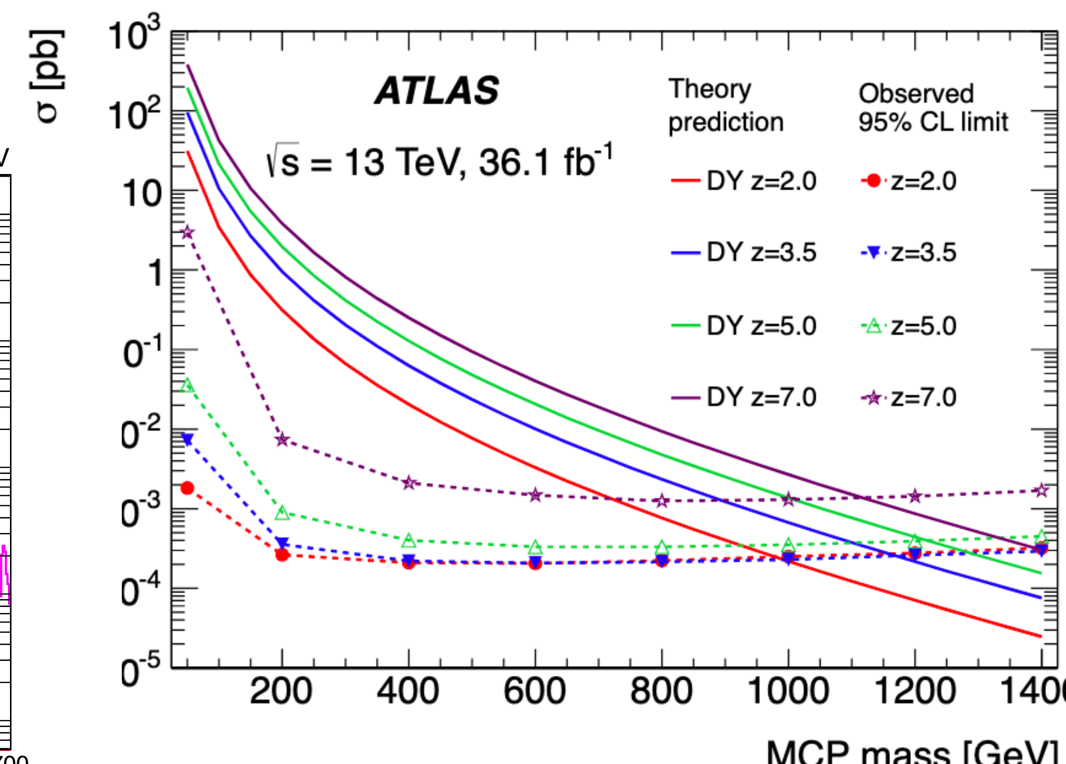
- Neutrino detectors provide sensitivity to millicharged particles through hard (> MeV recoil) electron scattering
- Many recent results!
- Would be interested in collaborating to expand scope of project: **full consideration of all complementary methods to search for mCPs**!

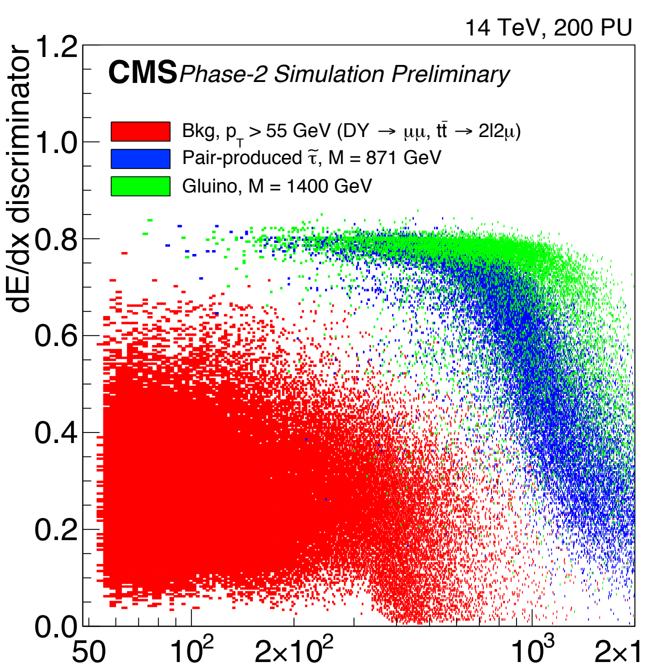
General purpose detectors at the LHC

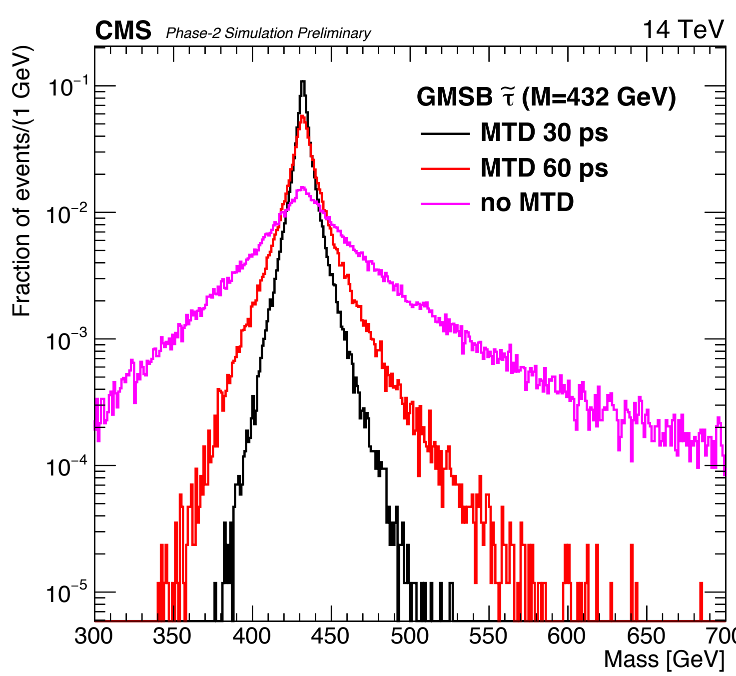
- ATLAS/CMS provide sensitivity to O(100) GeV particles with charges from 1/3e to 8e
    - Multiply charged has range of motivations e.g. H^{++} in left-right model
- Strategy: trigger on muons and look for low (high) dE/dx hits in tracker for low (high) charge models
    - For high charge also use muon system for timing (few ns resolution)
- HL-LHC provides opportunity to improve sensitivity
    - E.g. dedicated trigger with RPC timing (1 ns resolution), MTD timing offline for greatly improved mass resolution (30 ps resolution), improved muon system resolution



1210.2311







p (GeV)

TDR-17-001

TDR-19-002

1812.03673

More details in backup

Summary

- A large number of new potential detectors for millicharge particles coming online over the next years
- Benefit greatly from **experience with milliQan demonstrator**
- We plan to **robustly and consistently** evaluate reach for scintillation based detectors at wide range of sites
- Reach of **neutrino detectors complementary**: would also like to consider in projections
- General purpose detectors have sensitivity for Q 1/3 e → 8e but future needs further study

Who are we?

Matthew Citron
Andy Haas
Chris Hill
Yu-Dai Tsai
Jae Hyeok Yoo

Team includes proponents of milliQan/FERmini/SUBMET

Forming snowmass LOI and welcome collaborators!

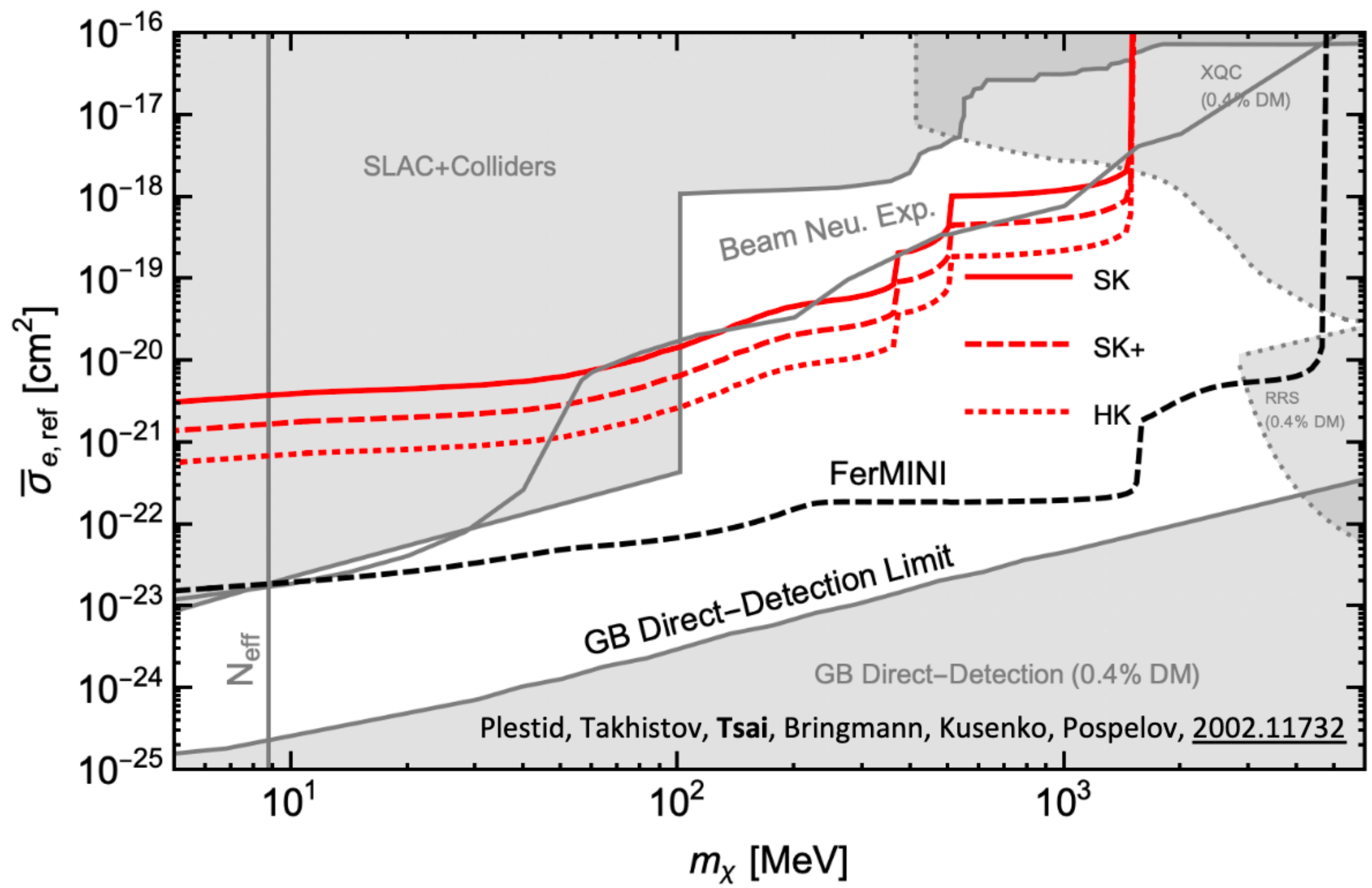
This speaker supported by funding from DOE Office of Science

Backup

FerMINI Probe of Millicharged SIDM

MCP / LDM with ultralight dark photon mediators

$$\bar{\sigma}_e \simeq \frac{16\pi\alpha^2\epsilon^2\mu_{\chi e}^2}{q_{ref}^2}, \; q_{ref} = \alpha m_e$$



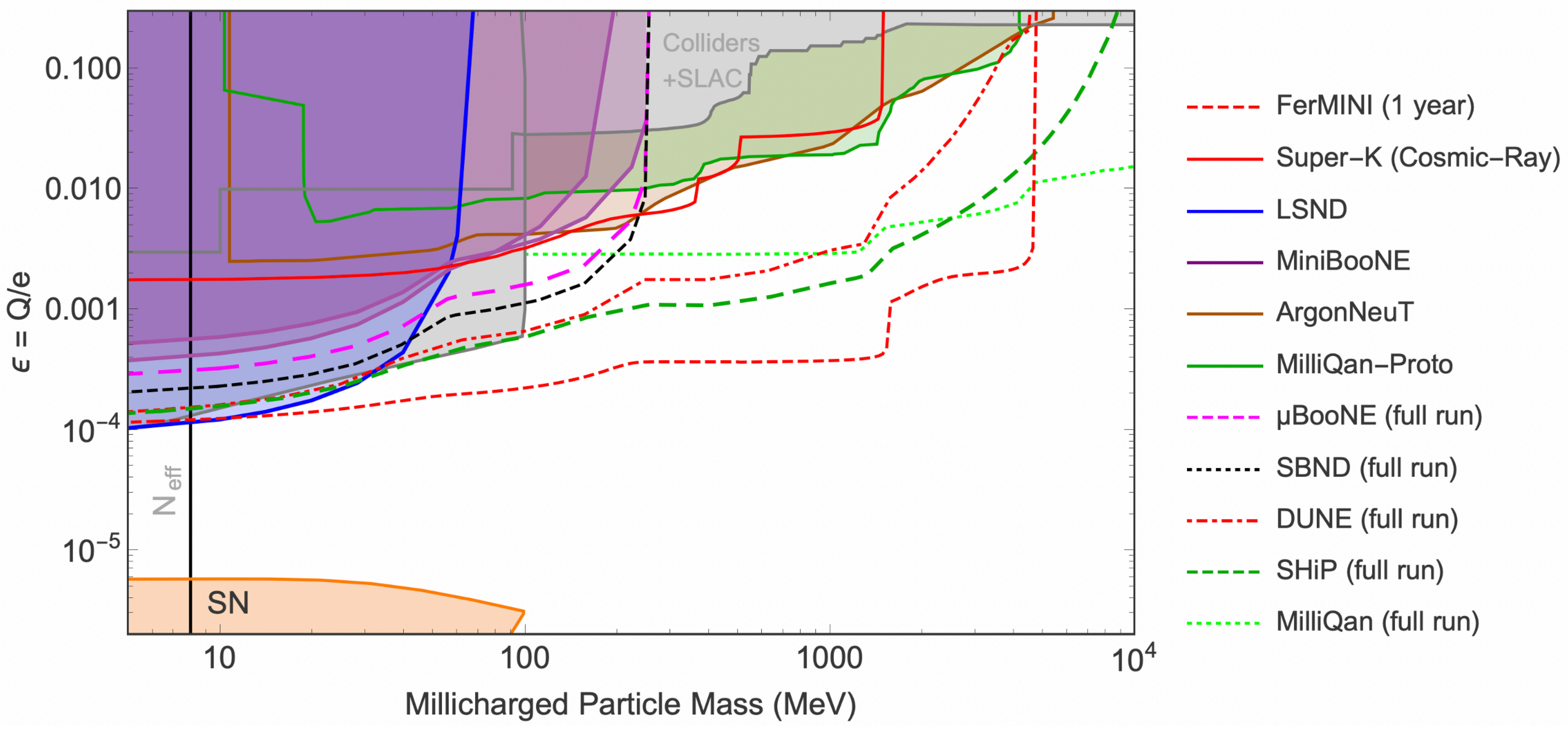
- Here we plot the **electron-scattering Millicharged SIDM** see 1905.06348 (Emken, Essig, Kouvaris, Sholapurkar)
- Cosmic-Ray Production/Super-K Detection 2002.11732 (our paper)
- **FerMINI can help close the Millicharged SIDM window!**

Yu-Dai Tsai, Fermilab

53

https://indico.cern.ch/event/910753/contributions/3831616/attachments/2053034/3441892/Tsai_MCP_FerMINI.pdf

Current projections



Why milli-charged?

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

kinetic mixing

massless U'(1) boson in the dark sector

'dark EM'

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

(naturally $\sim \alpha/\pi$)

Kinetic mixing with a new massless 'dark' boson **can provide link between SM and a hidden/dark sector**

Why milli-charged?

Now add fermion charged under new U'(1):

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

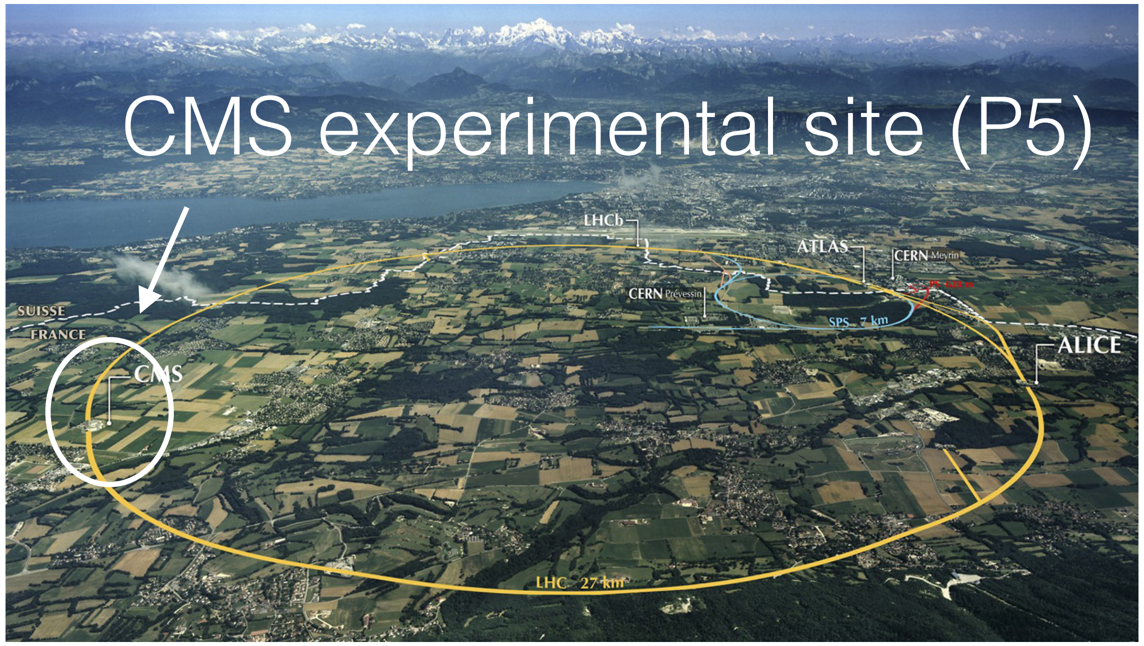
Standard trick - redefine gauge field B': $B' \rightarrow B' + \kappa B$

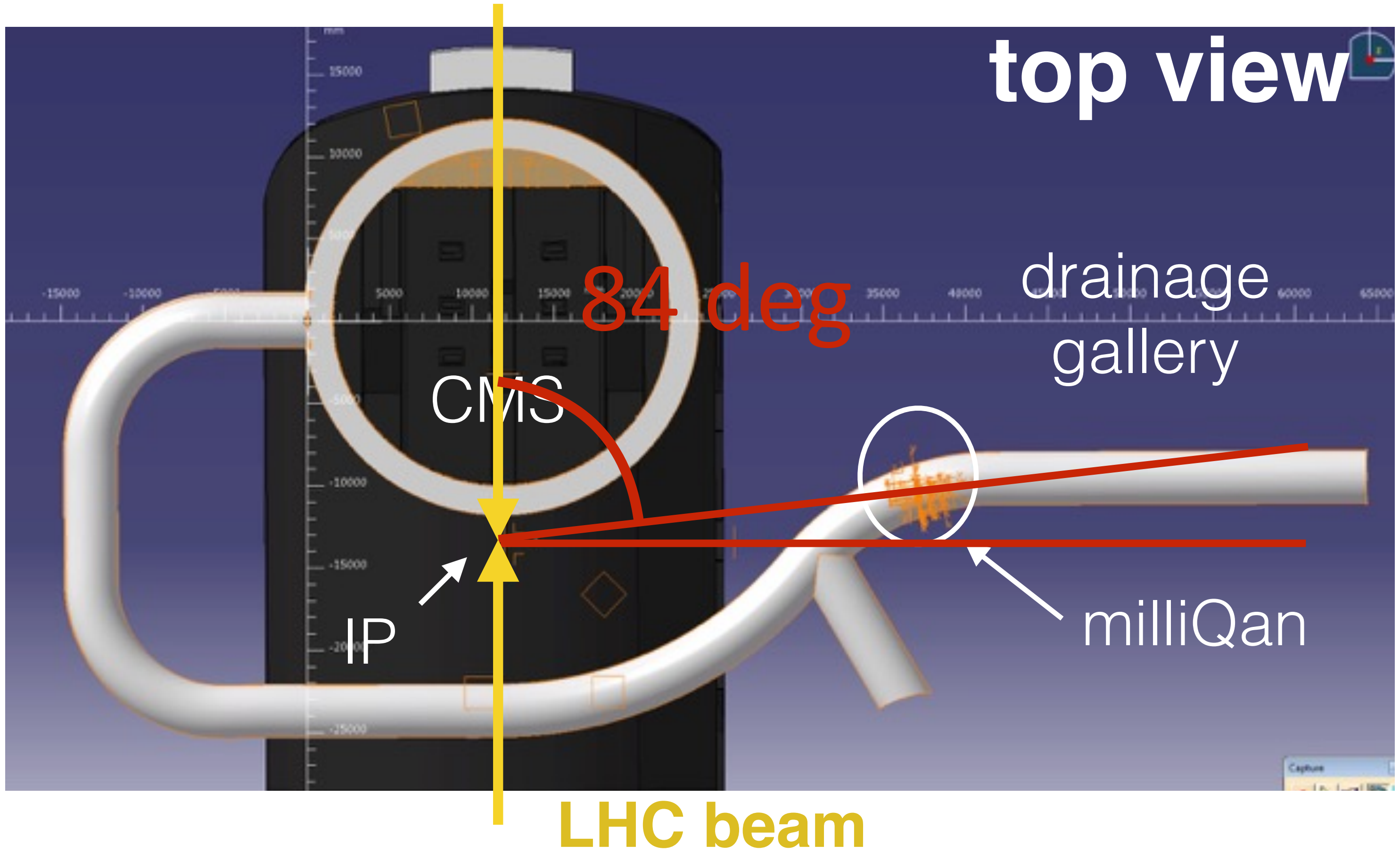
$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} + i\overline{\psi}(\partial\!\!\!/ + \underbrace{i\kappa e'B\!\!\!/} + ie'B\!\!\!/' + iM_{mCP})\psi$$

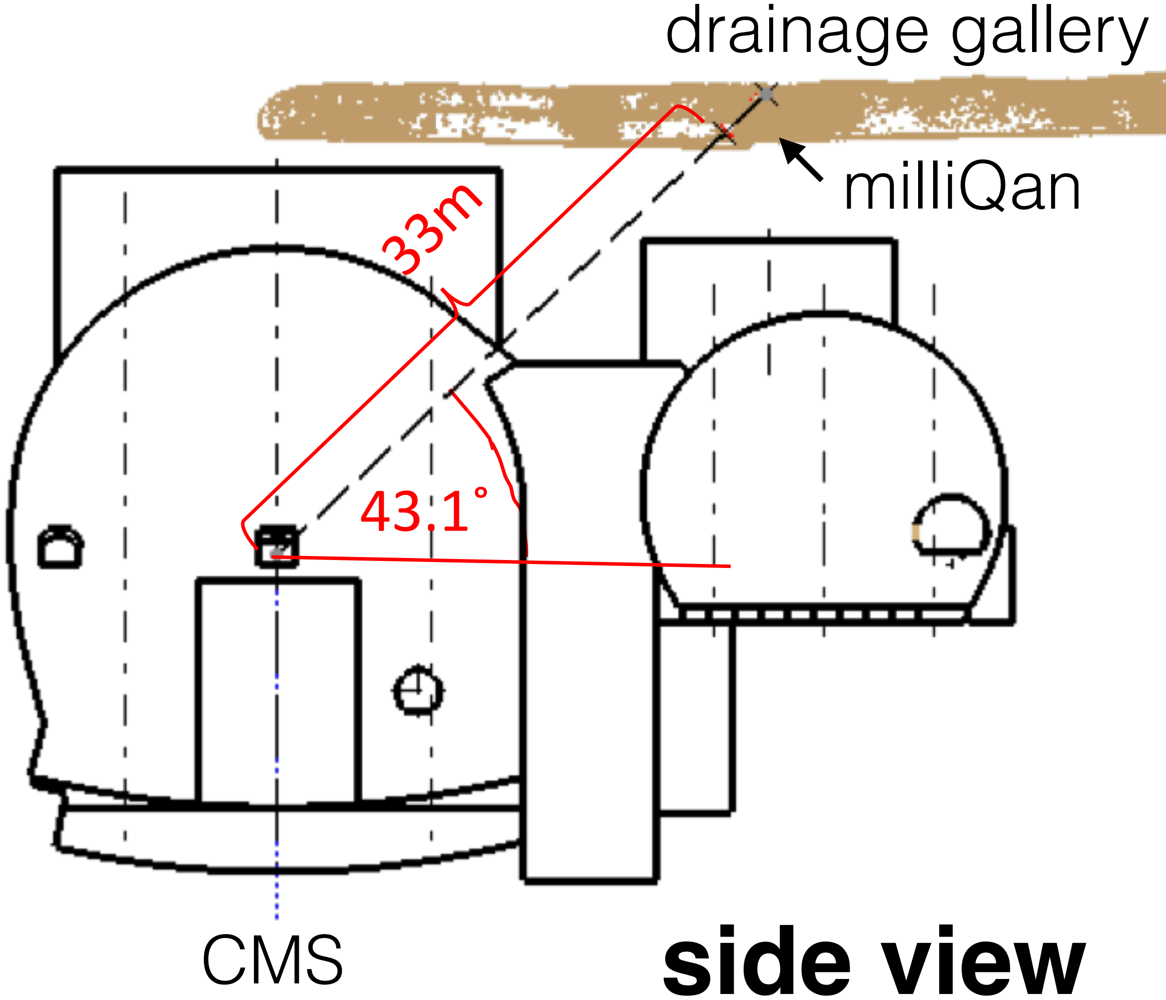
new fermion has small EM charge**: milli-charged particle**

Proposed milliQan location

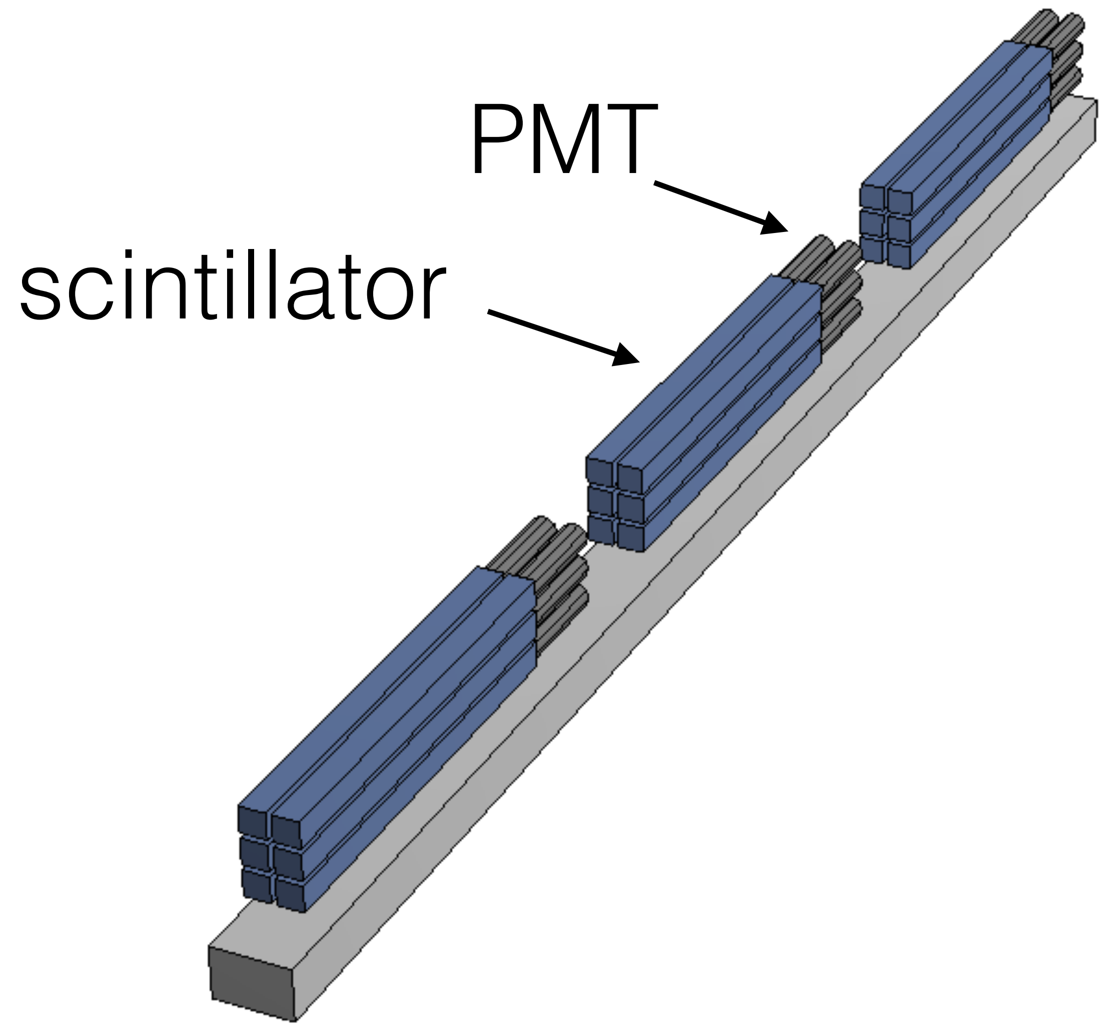
- Place detector in CMS experimental site within existing 'drainage gallery'
- Location 33 m from interaction point (including 17 m rock) → beam particles greatly suppressed







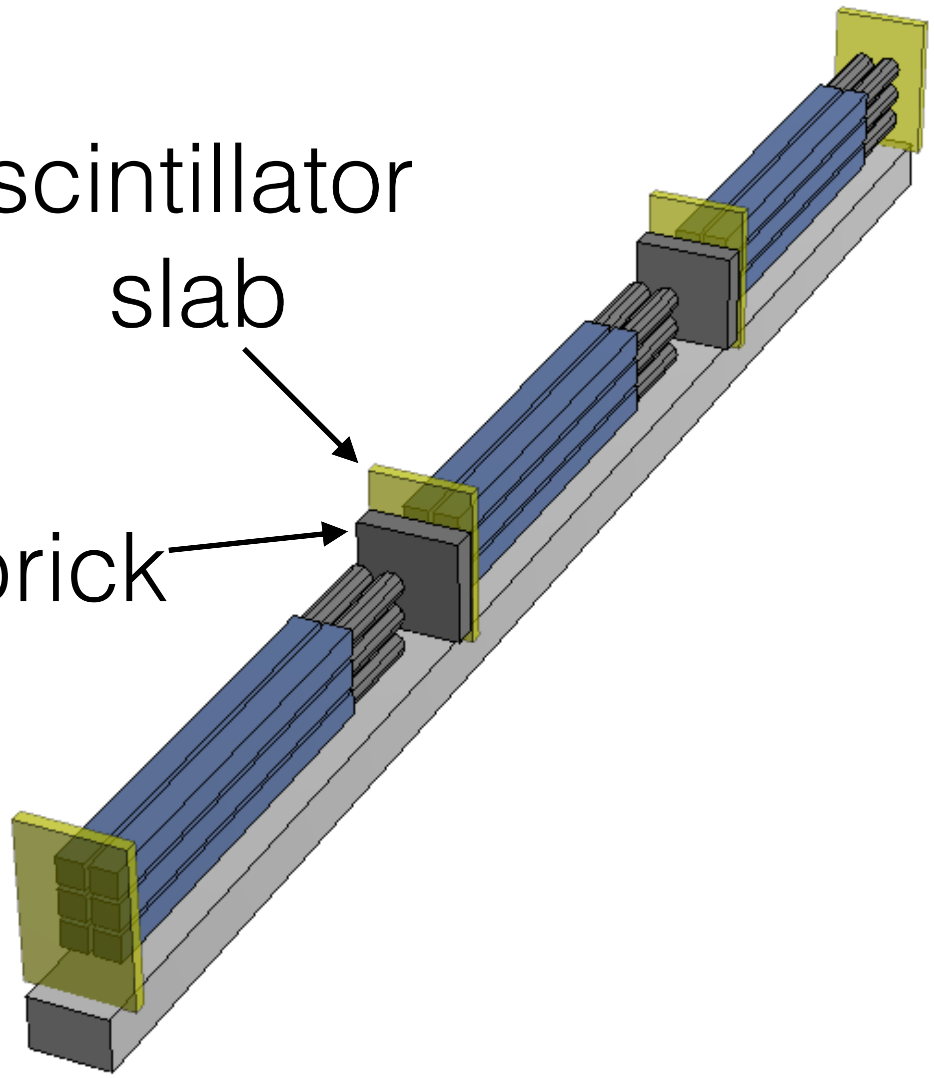
Demonstrator components



- 3 layers of 2x3 scintillator+PMT
  - ~ 1% prototype of full milliQan detector

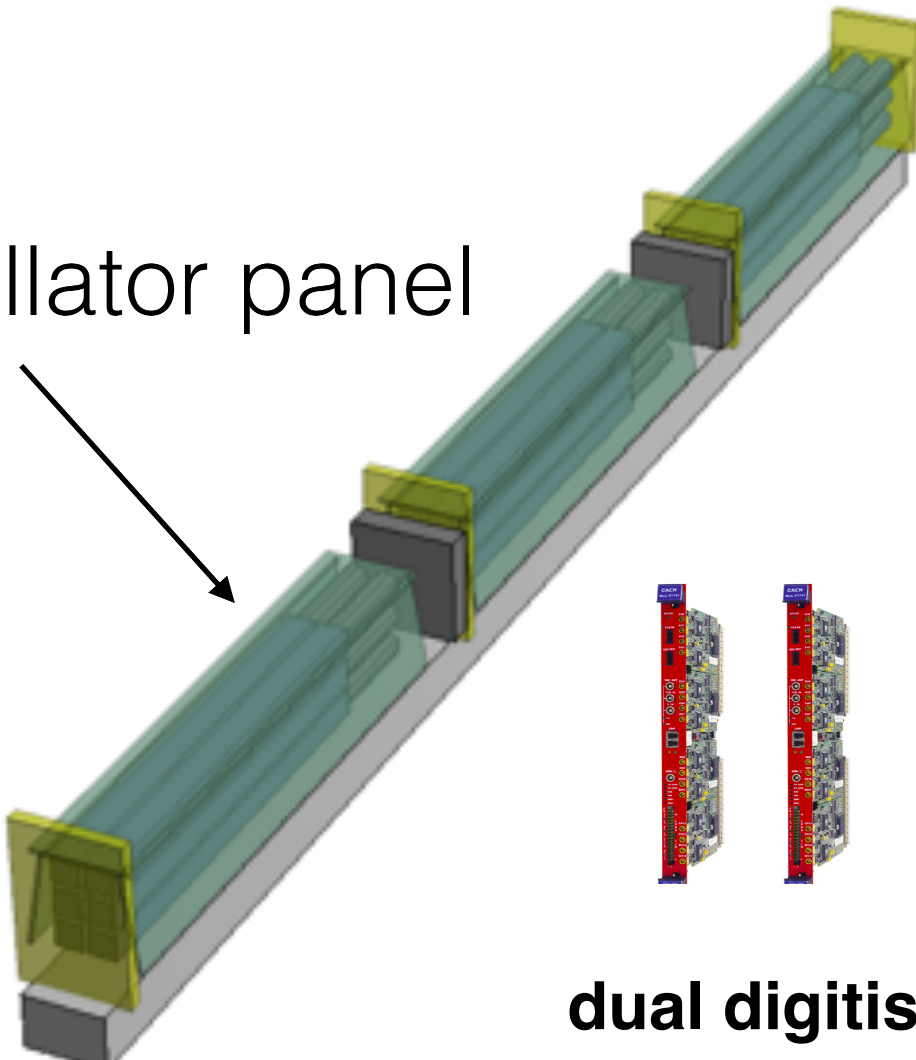
IP

Demonstrator components



- 3 layers of 2x3 scintillator+PMT
  - ~ 1% prototype of full milliQan detector
- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation

Demonstrator components



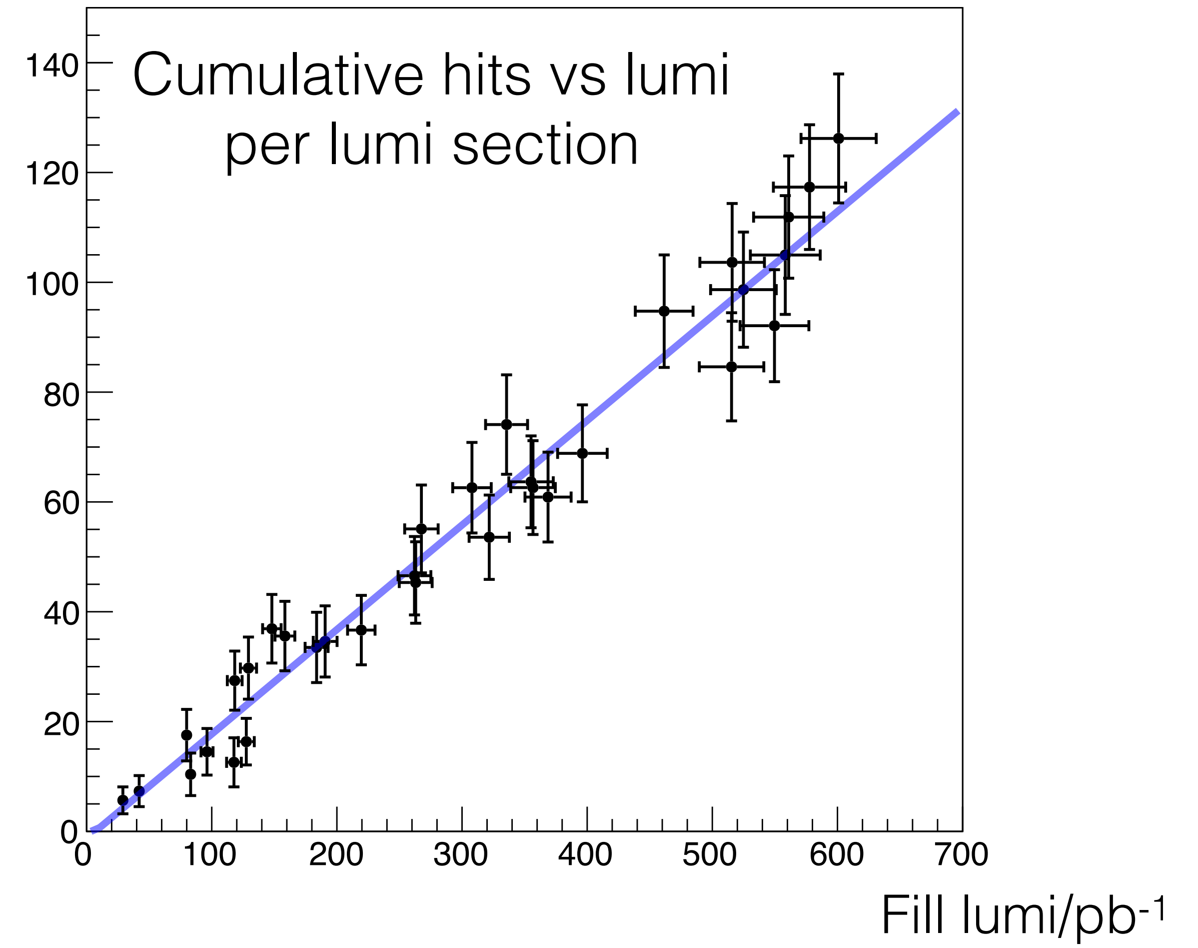
dual digitiser readout

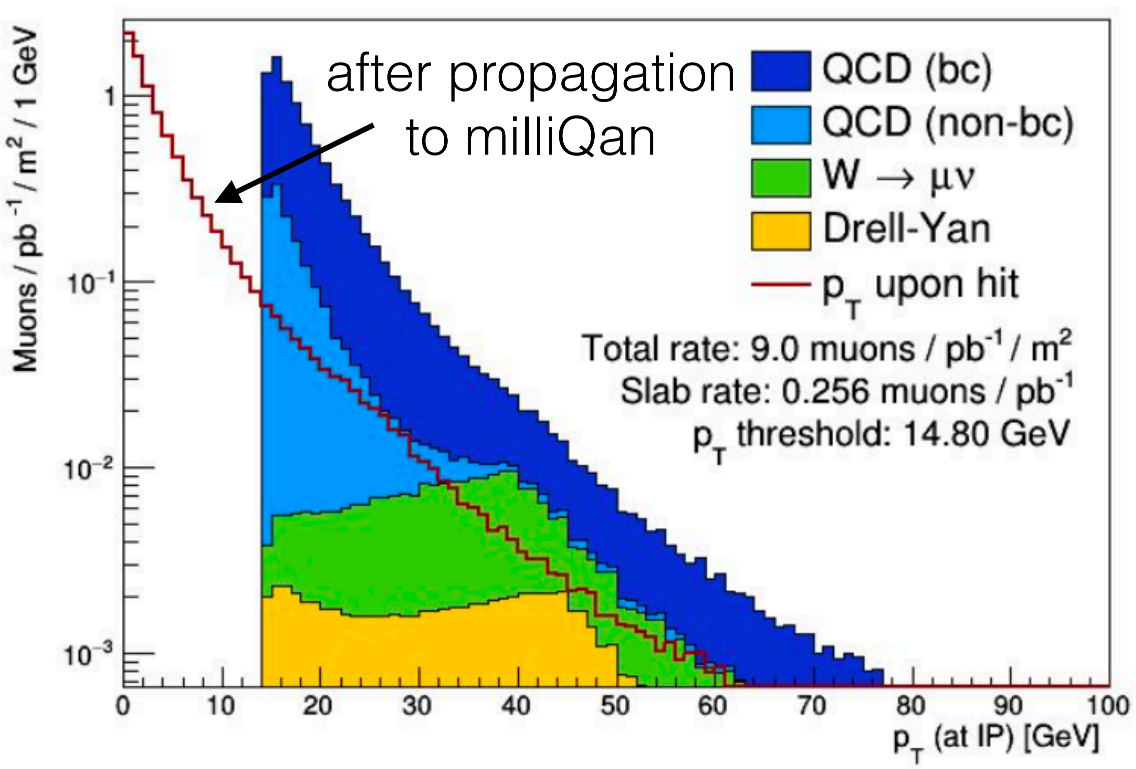
CAEN V1743 digitizer:
16 chan, 1.6 GS/s,
640 ns window

- 3 layers of 2x3 scintillator+PMT
  - ~ 1% prototype of full milliQan detector
- Scintillator slabs and lead bricks
  - Tag thru-going particles, shield radiation
- Scintillator panels to cover top + sides
  - Tag/reject cosmic muons

Alignment

- milliQan ‘sees’ muons from the CMS interaction point
- Check occupancy agreement with expectation
  - Simulate production at CMS interaction point
  - Propagate through CMS material and 17 m of rock considering **multiple scattering** and **CMS magnetic field**
- Expected rate: **0.28 ± 0.09/pb^{-1}**
- Measured rate: **0.19/pb^{-1}**

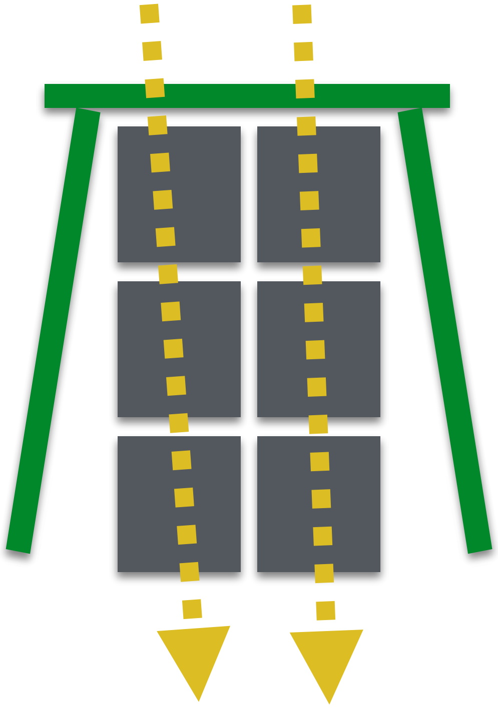




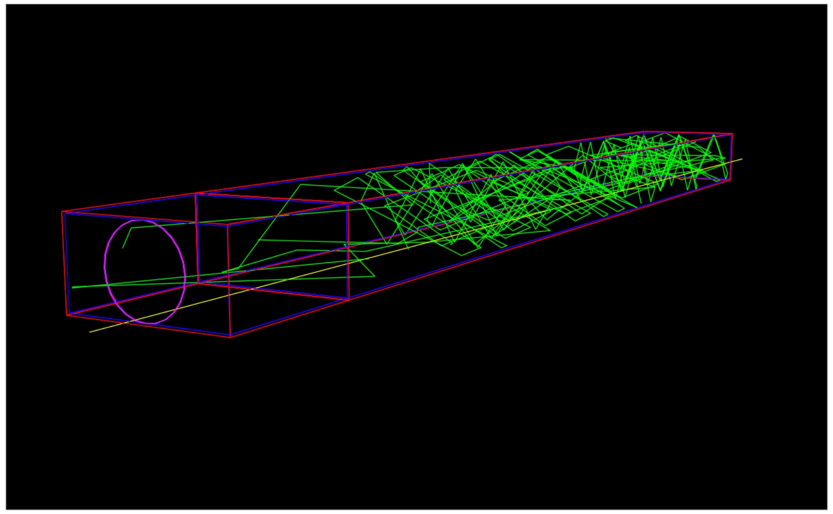
Calibrations

- In-situ charge calibration
  - Calculate N_{PE} produced by a cosmic muon (Q=1e) per PMT and scale (Q^2)
  - Find **N_{PE} = 1 for Q ~ 0.003e** → consistent with result from full GEANT4 simulation
- Timing calibration
  - Cable length, PMT rise time and geometric differences must be calibrated
  - Achieve ~4 ns resolution → easily sufficient for 15 ns window between hits in layers (as assumed in LOI)

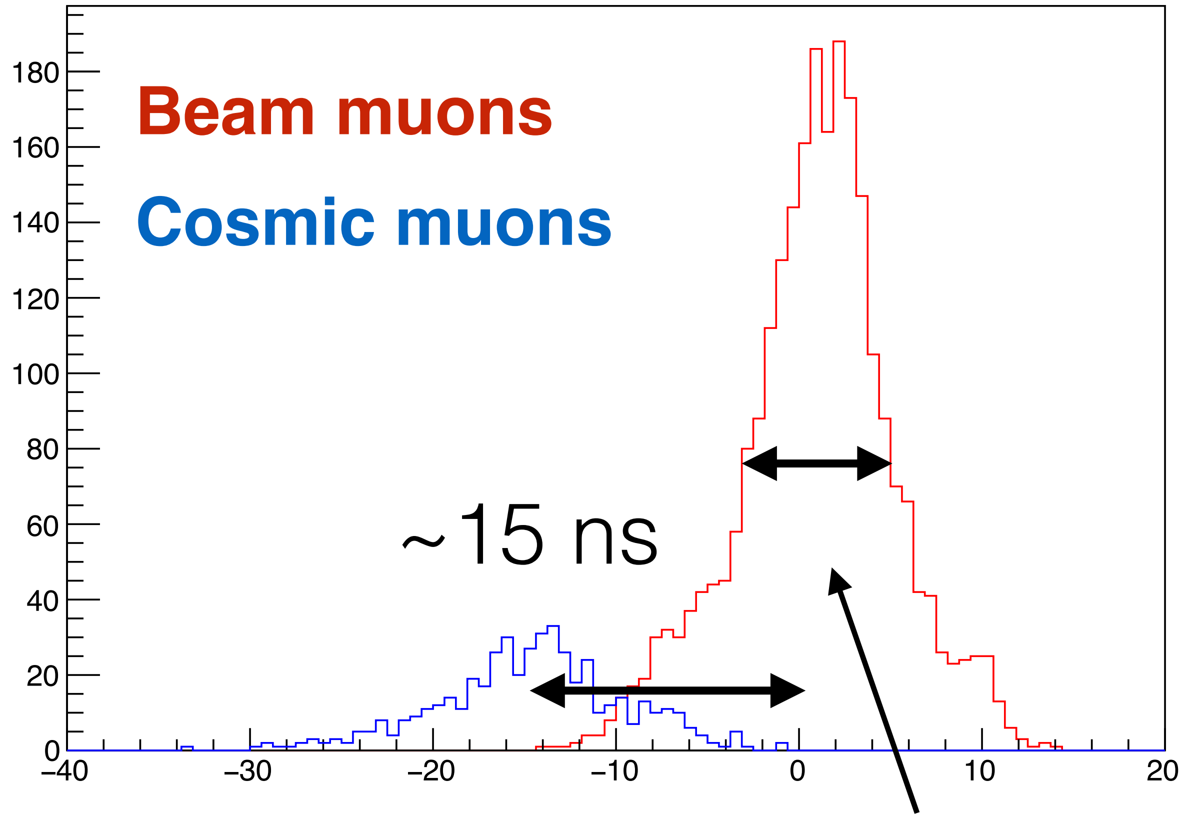
Downgoing cosmics used for charge calibration



GEANT4 simulation



Calibrated time difference between L3 and L1



resolution ~ 4 ns

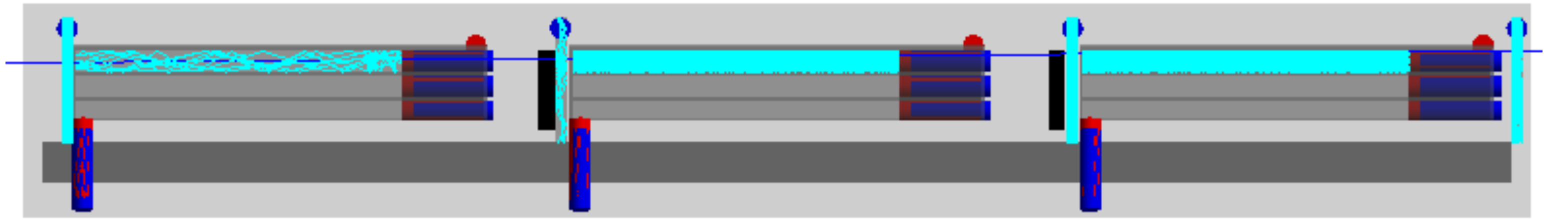
Background Sources

- The following components potentially contribute to background:
  - **PMT Dark Counts**: overlap of dark rate from three in-line PMTs, or one PMT and two correlated background hits
  - **Cosmic and beam muon shower secondaries**, especially electrons and gammas, can cause a pulse in each layer of the demonstrator
  - **Radiation** from the cavern, bars, or surrounding material (mostly Pb shielded)
  - **Afterpulses**: Small, delayed pulses in PMTs caused by ionization of residual gases following an initial detection
- A detailed detector simulation allows us to **understand these sources in detail**

milliQan signal selection

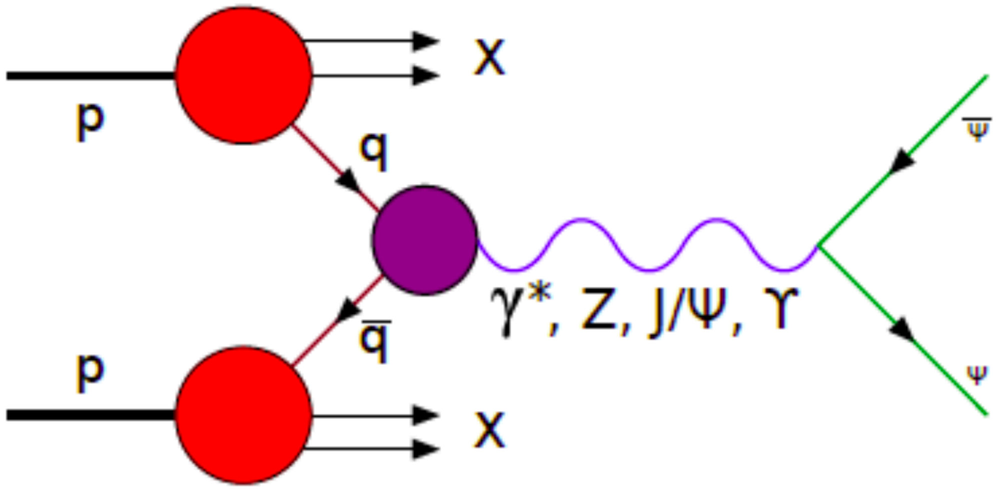
- Selections: event must have exactly 3 hits, at the right time, in a straight path (all with well-behaved signal amplitudes)
- Under these selections, backgrounds are reduced by 5 orders of magnitude
- We categorize signal using # of PE and slab deposits to optimize sensitivity for a wide range of charges

	Selection	Data Beam-on $t = 1106$ h	Data Beam-off $t = 1042$ h	Signal $m_\chi = 0.05$ GeV $Q/e = 0.007$	Signal $m_\chi = 1.0$ GeV $Q/e = 0.02$	Signal $m_\chi = 3.0$ GeV $Q/e = 0.1$
Common	≥ 1 hit per layer	2 003 170	1 939 900	136.4	34.2	5.7
Selections	Exactly 1 hit per layer	714 991	698 349	123.1	31.0	5.0
	Panel veto	647 936	632 494	122.5	30.8	4.9
	First pulse is max	418 711	409 296	114.3	30.6	4.8
	Veto early pulses	301 979	295 040	113.9	30.6	4.8
	max n_{pe} / min $n_{\mathrm{pe}} < 10$	154 203	150 949	104.2	29.6	4.7
	$\Delta t_{\mathrm{max}} < 15$ ns	5 284	5 161	72.8	28.4	4.4
	Slab muon veto	5 224	5 153	72.8	28.4	4.4
	Straight path	350	361	68.4	28.1	4.2
	$\mathrm{N_{slab}} = 0$	332	339	64.8	16.9	0.0
	$\mathrm{N_{slab}} \geq 1$	18	22	3.6	11.2	4.2
SR 1	$\mathrm{N_{slab}} = 0$ & min $n_{\mathrm{pe}} \in [2, 20]$	129	131	47.4	0.4	0.0
SR 2	$\mathrm{N_{slab}} = 0$ & min $n_{\mathrm{pe}} > 20$	52	45	0.0	16.5	0.0
SR 3	$\mathrm{N_{slab}} = 1$ & min $n_{\mathrm{pe}} \in [5, 30]$	8	9	1.1	0.5	0.0
SR 4	$\mathrm{N_{slab}} = 1$ & min $n_{\mathrm{pe}} > 30$	4	4	0.0	8.7	0.0
SR 5	$\mathrm{N_{slab}} \geq 2$	1	1	0.0	2.0	4.2

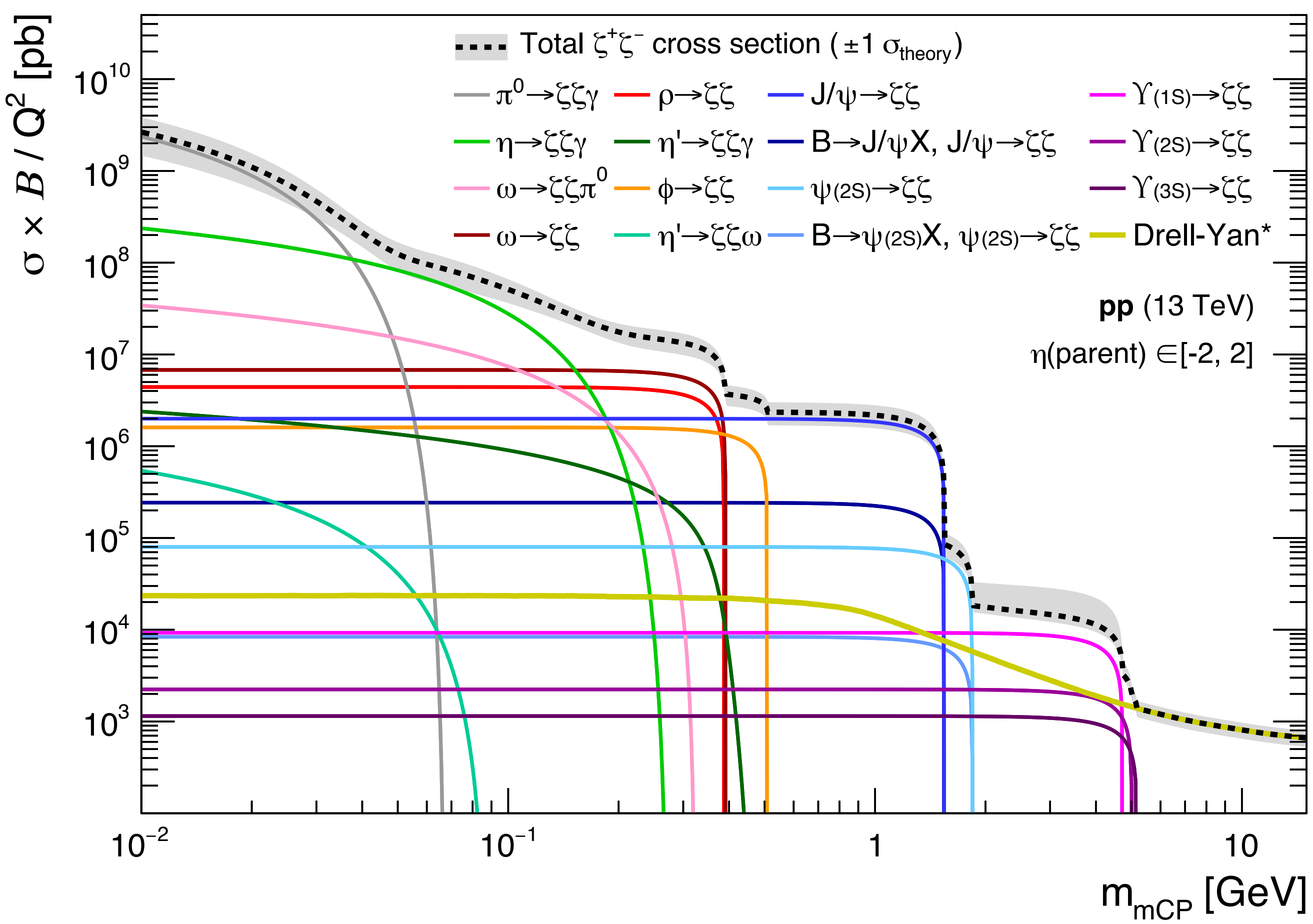


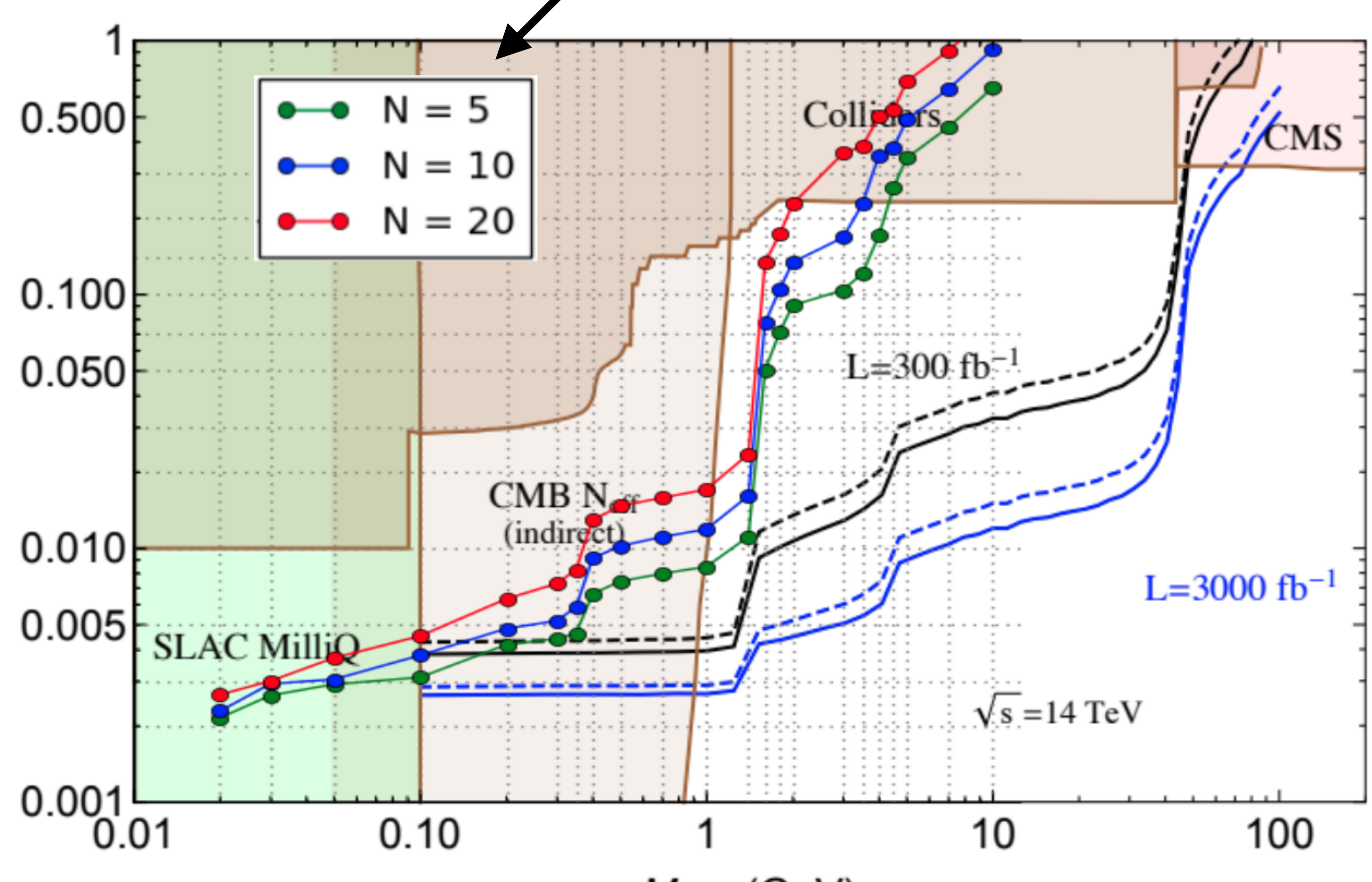
Signal simulation

- Wide range of production mechanisms considered!
- Propagate to detector with response **fully simulated** in GEANT4
- Expect **new sensitivity** already using demonstrator data



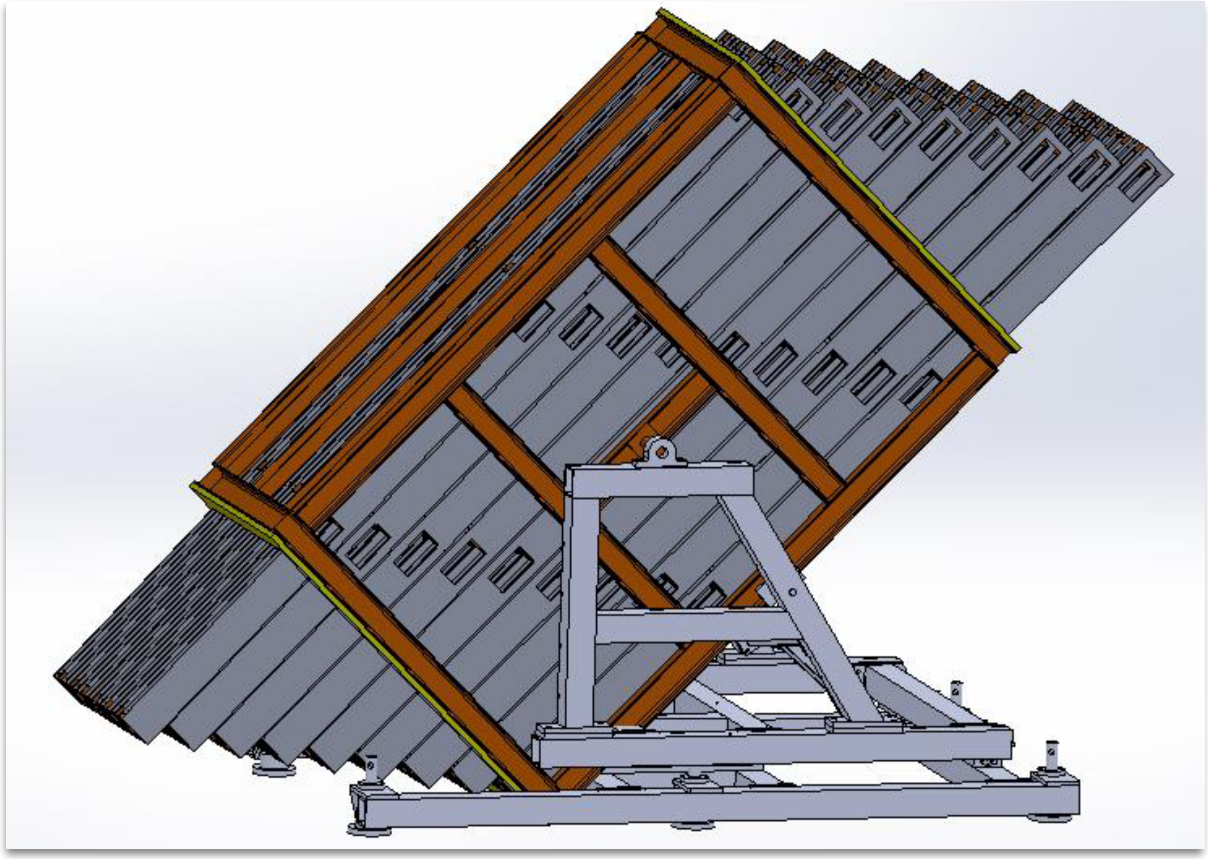
Constant yield contours for triple coincidence ($N_{PE} \geq 1$) from signal **+ demonstrator** simulation in 35/fb



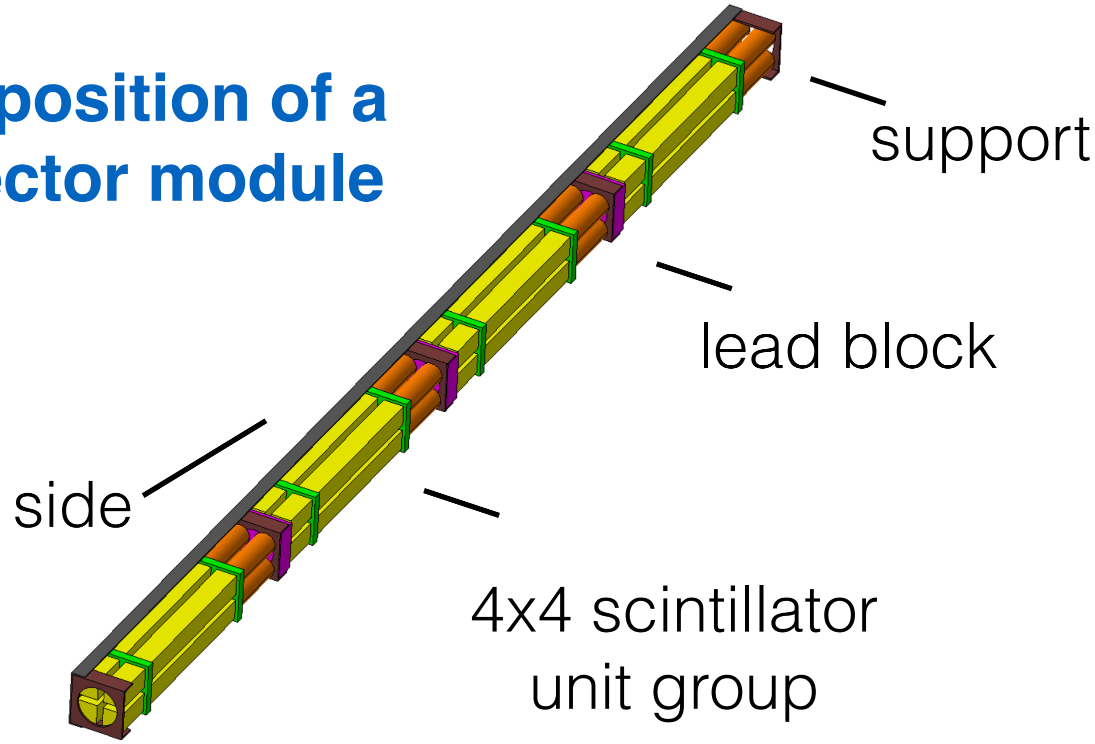


Mechanical structure for full detector

- Plans for mechanical structure finalised with **four layers**
- Constraints: maximum bars in minimal space: two adjacent detectors of 9x6x4x4 = 864 bars (1 x 1 x 3 m)
- Use mounts as in place in drainage gallery

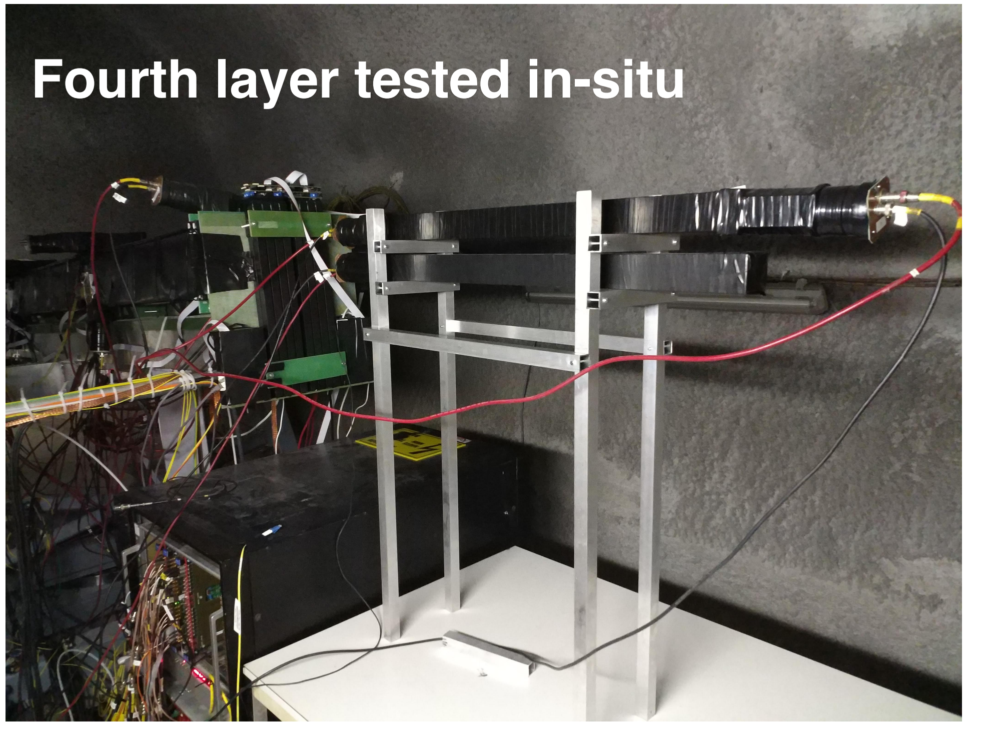


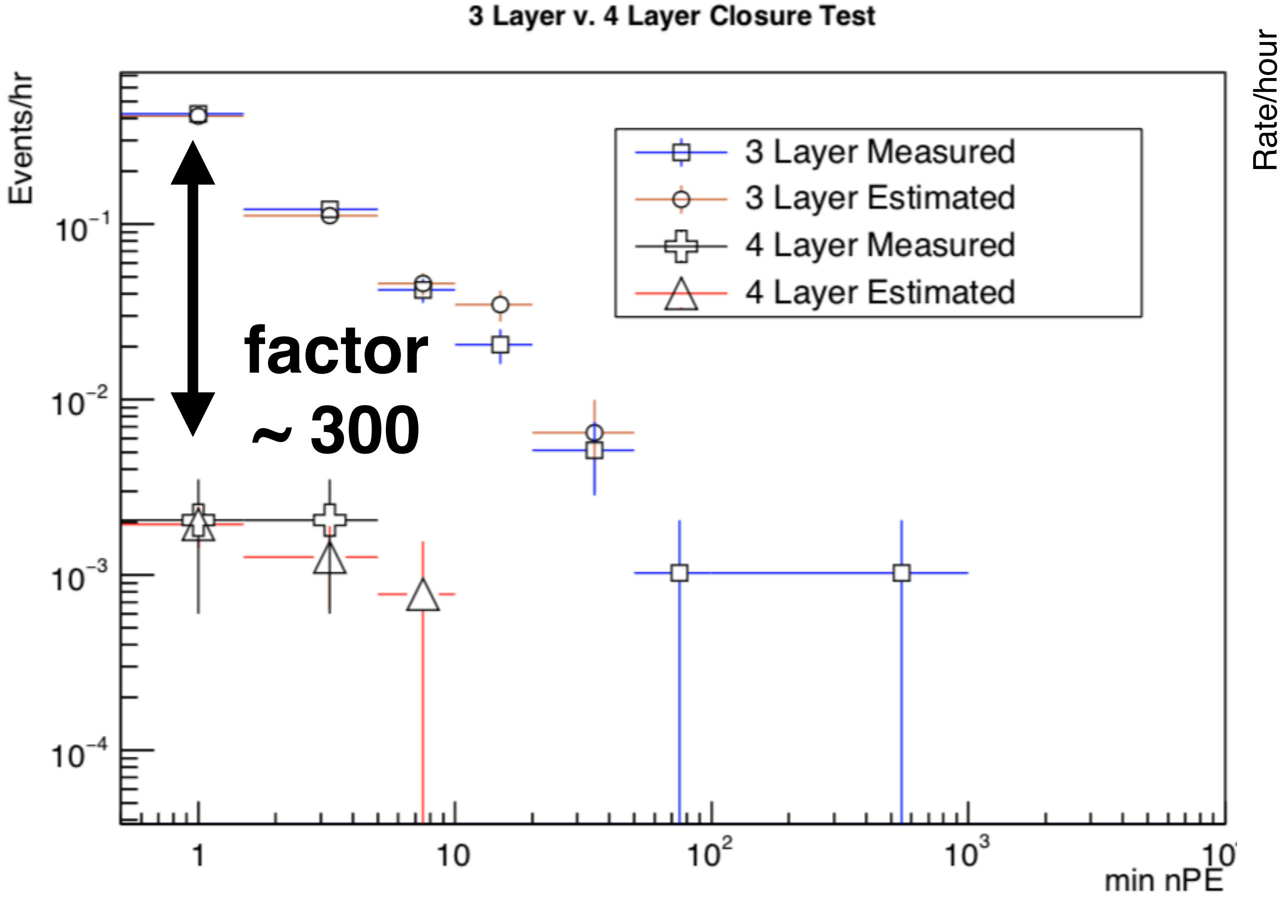
Composition of a detector module

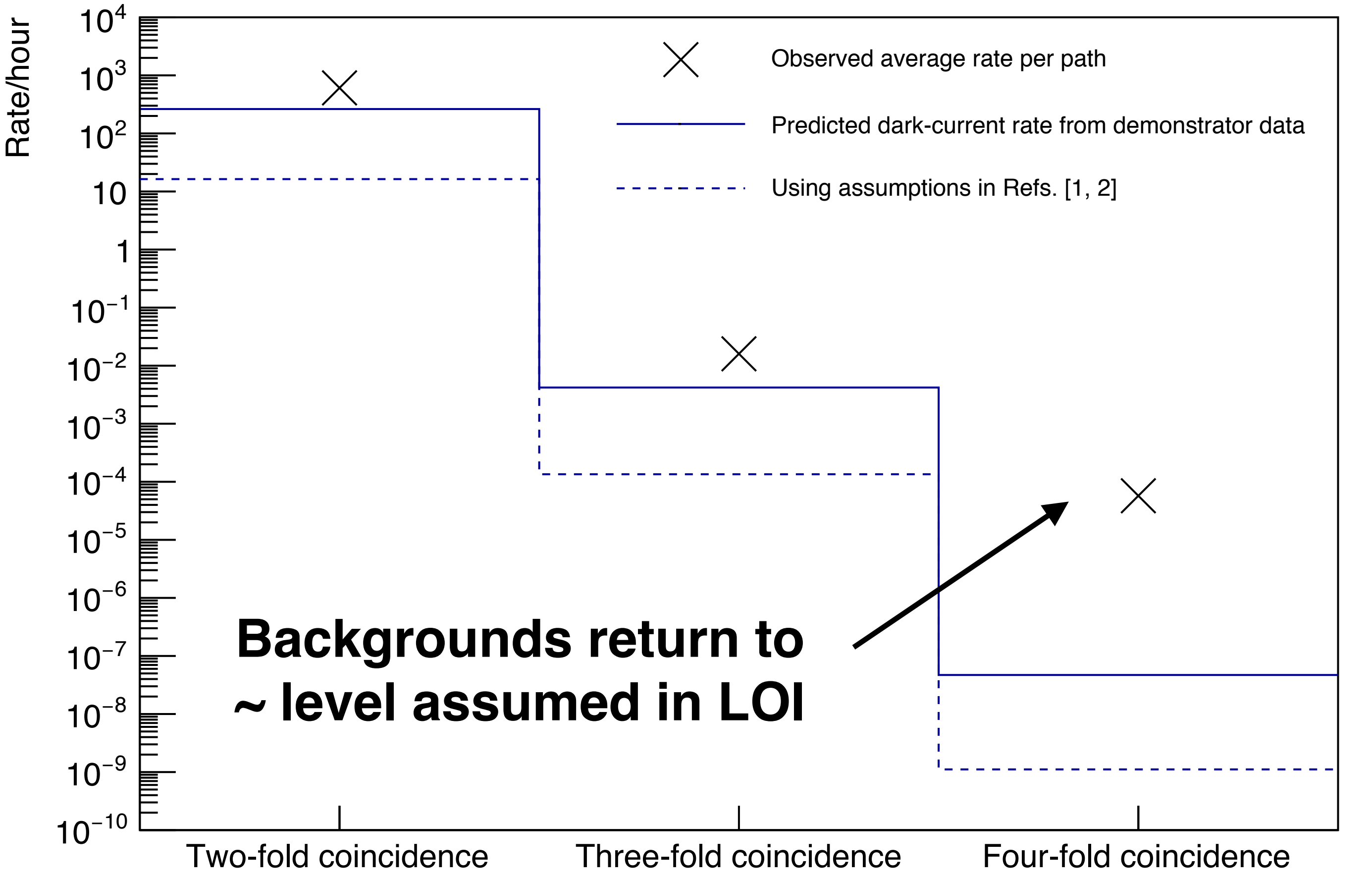


Background measurement

- Detector **aligned** and **calibrated** - measure backgrounds for full milliQan detector
- Major lesson from demonstrator: dark rate subdominant background source
- Motivates update to 'four layer' design → achieve targeted background rate

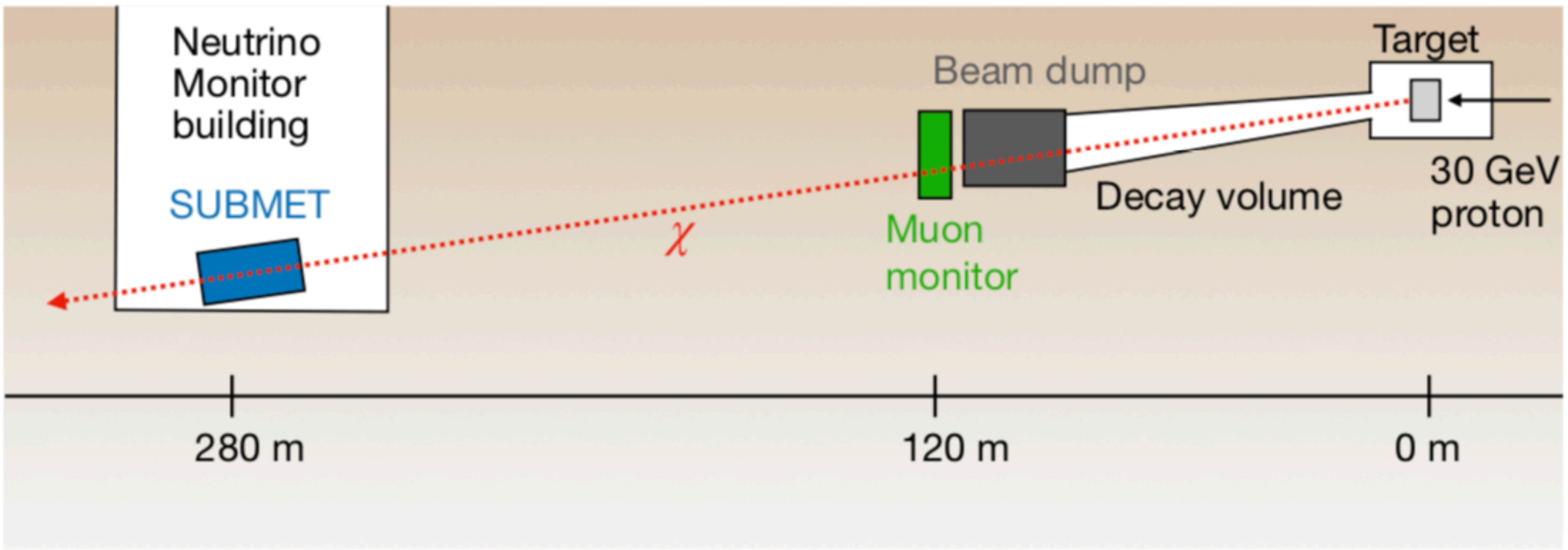




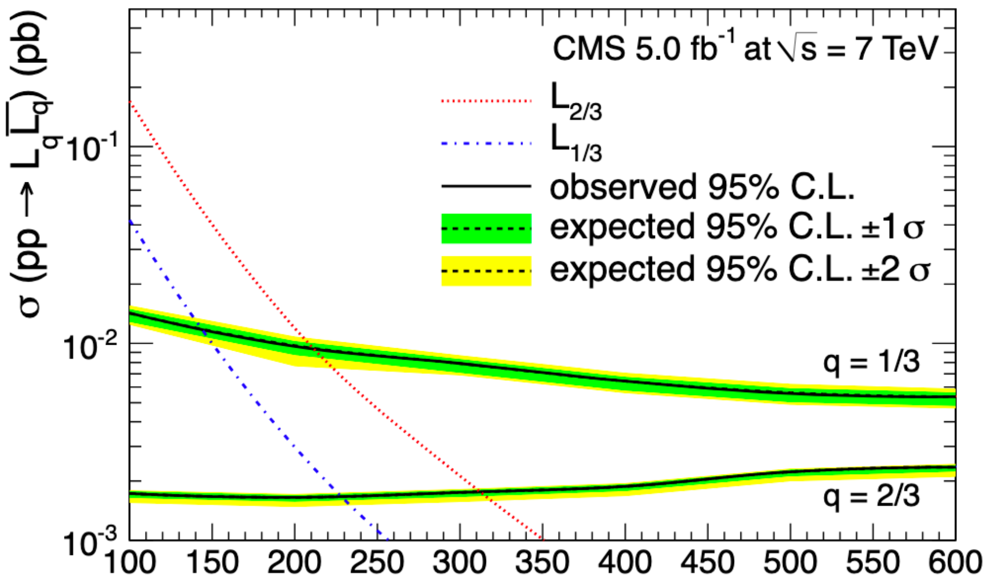


Signal selection: coincident hits within 15 ns (pointing to IP)

SUBMET location

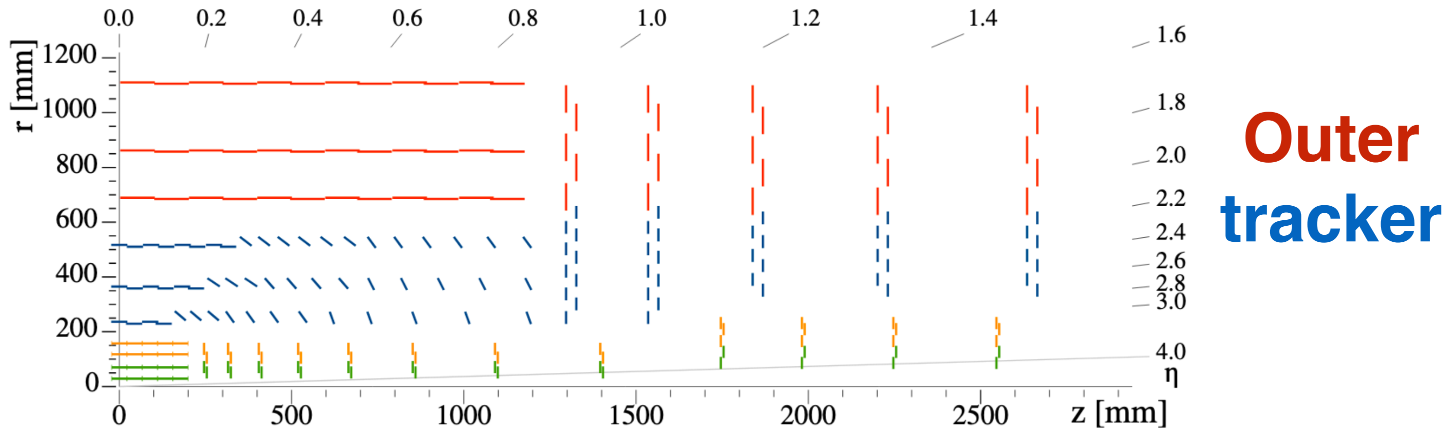


General purpose detectors at the LHC



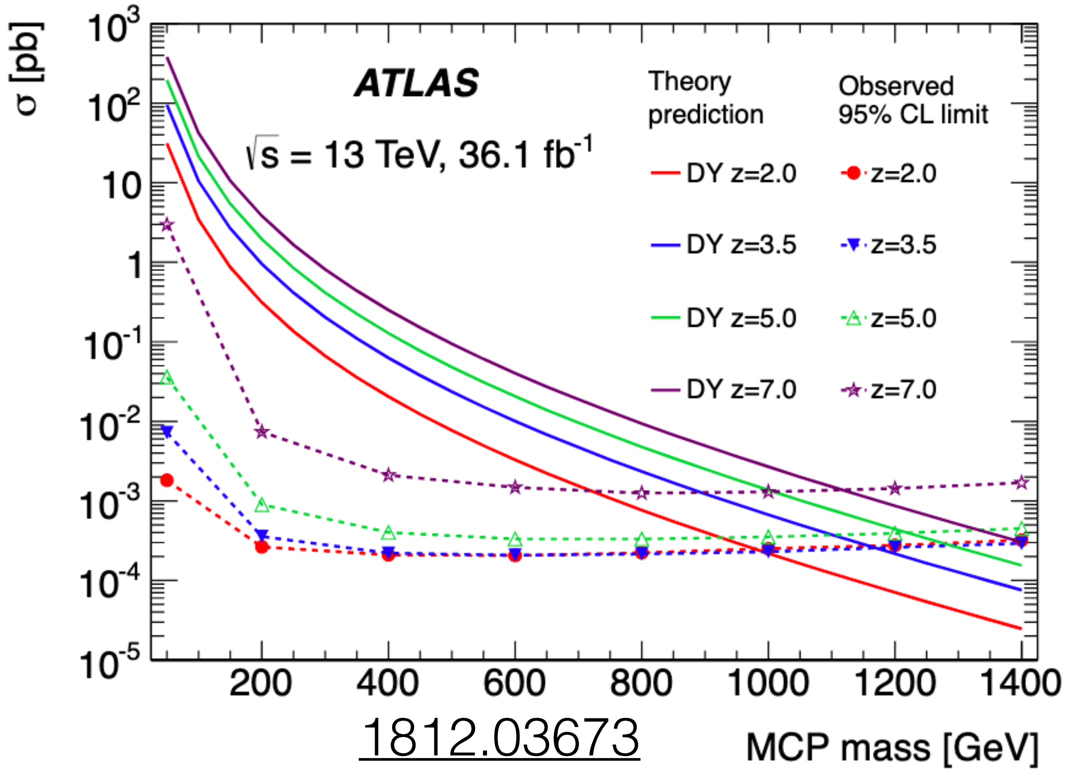
1210.2311

Phase 2 tracker



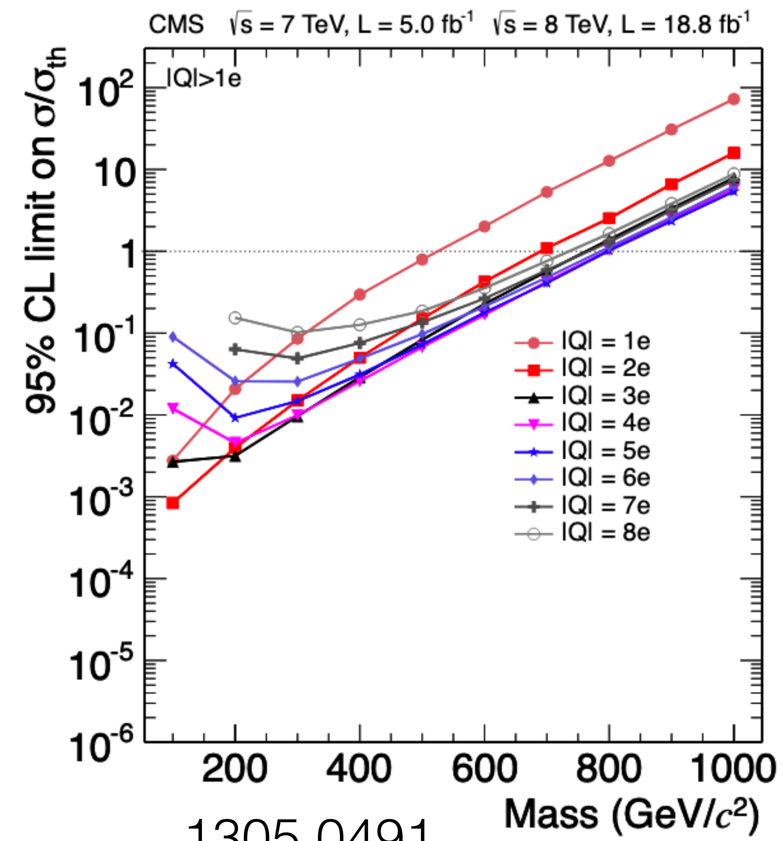
- Much larger angular coverage than external detector provides sufficient acceptance for models up to O(100s) GeV but **sensitivity only for Q > 1/3 (FCPs)**
- Strategies: trigger on muons and look for low dE/dx hits in tracker (1210.2311, 1305.0491)
- In phase 2, CMS outer tracker only provides binary output
- Searches with dE/dX from (upgraded) muon system? Dedicated triggers? Dedicated low dE/dx readout bit? Timing measurement from MTD? Considerations for ATLAS/future detectors?

Searching for multicharge



1812.03673

ATLAS: dE/dx of tracker, muon system

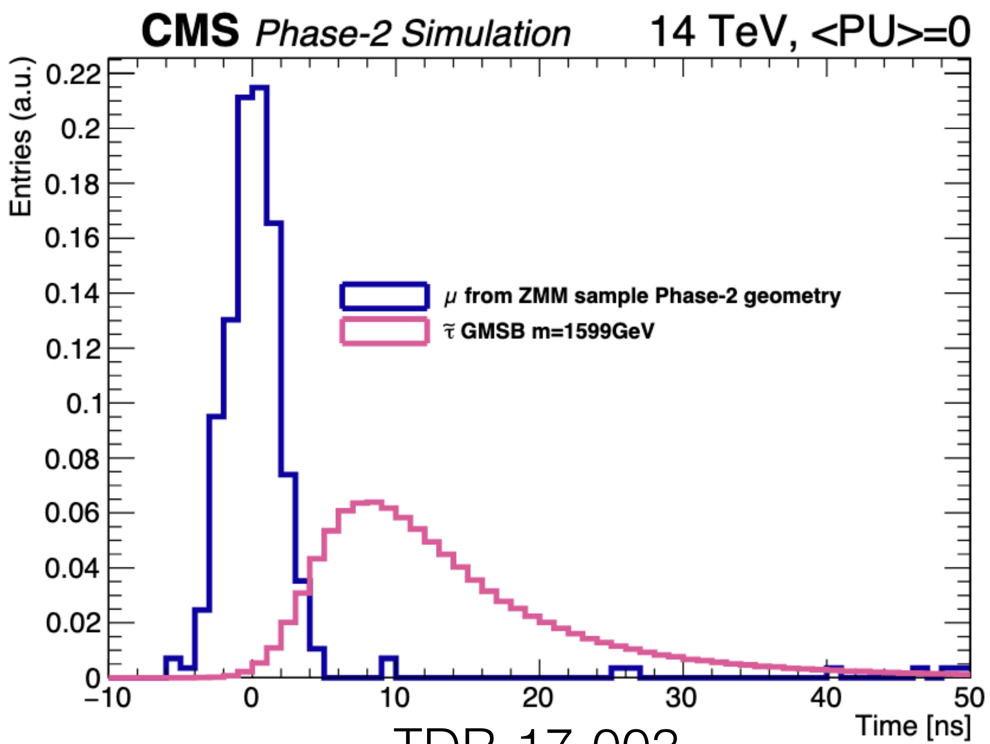


1305.0491

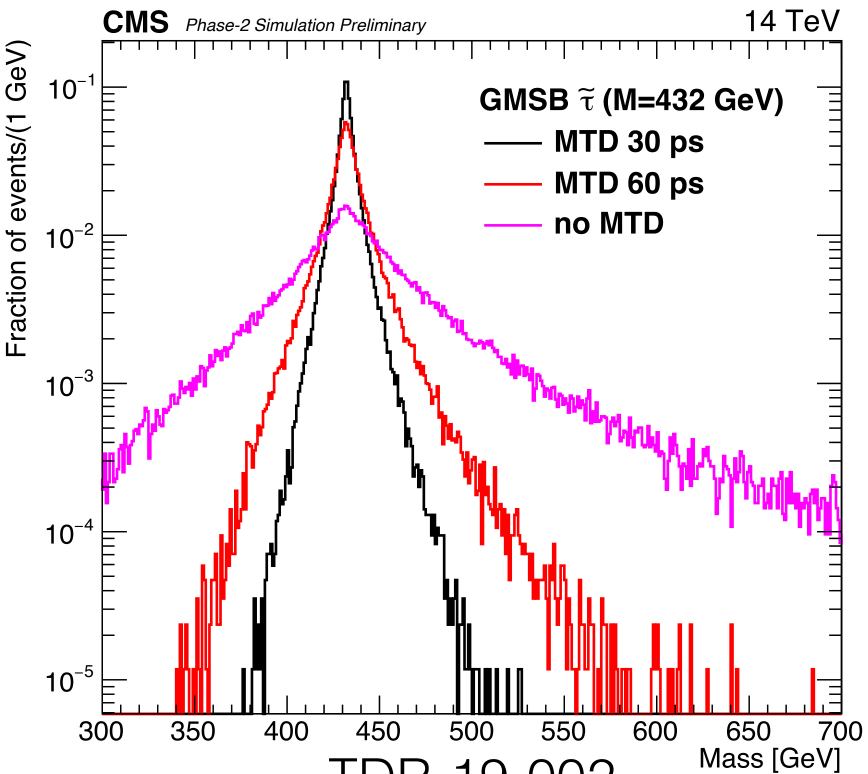
CMS: dE/dx of tracker, β measurement from muon system

- Range of theory motivations: AC leptons, doubly charged Higgs (left-right model), technibaryons
- Current searches rely on dE/dx and timing measurements from muon system
- Phase 2: improvements from resolution upgrades to muon system, timing measurements from MTD

Searching for multicharge: phase 2

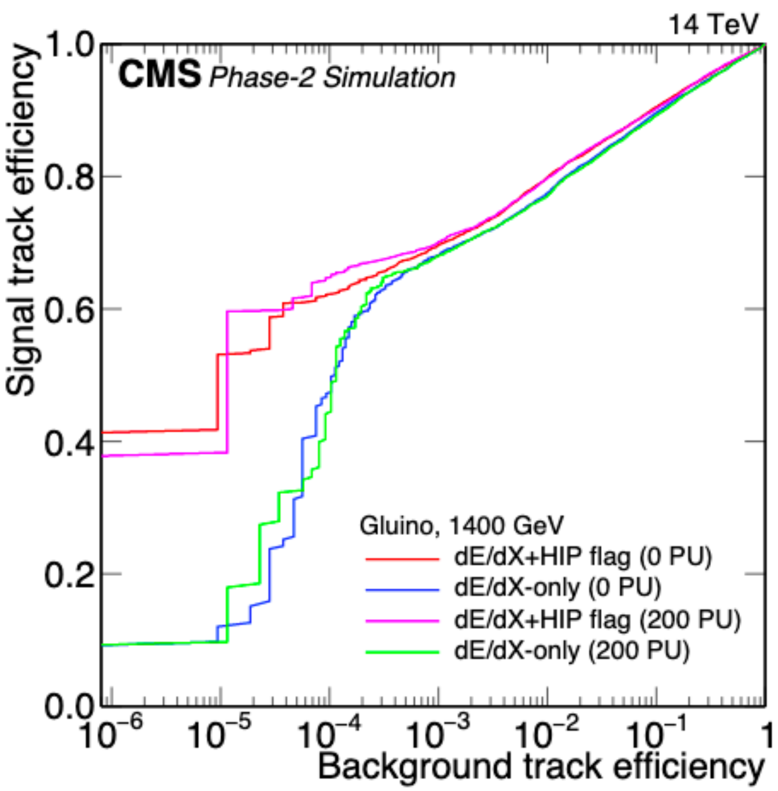


TDR-17-003



TDR-19-002

- Dedicated HSCP trigger using RPC timing (~ns resolution)
- Mass resolution improvement with MTD timing
- Dedicated HIP flag (no dE/dx info from outer tracker)
- Improved muon system resolution for higher charge models
- What about unstable multicharge particles: doubly charged vertex reconstruction with tracker/endcap?



TDR-17-001