A New Detector at the LHC to Search for Millicharge Particles

Gabriel Magill

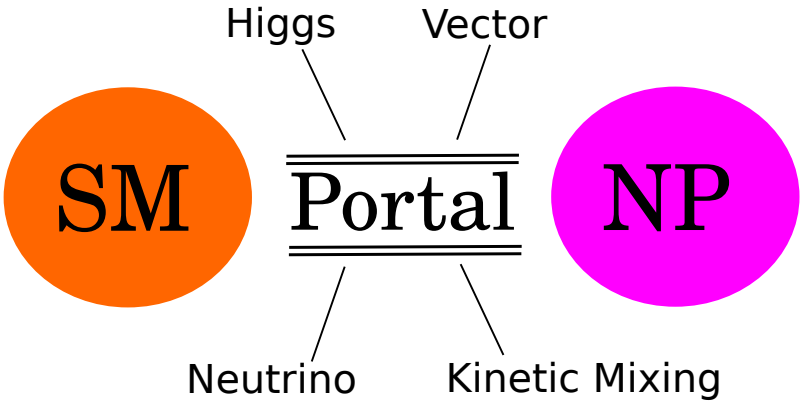
On Behalf of the milliQan Collaboration

Perimeter Institute for Theoretical Physics
McMaster University
gmagill@perimeterinstitute.ca

12th Patras Workshop on Axions, WIMPs and WISPs
Jeju Island, South Korea

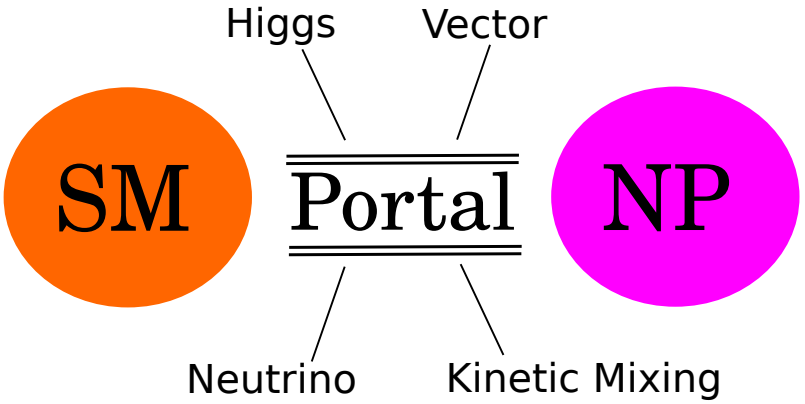
June 24th, 2016

Portals to New Physics: Kinetic Mixing



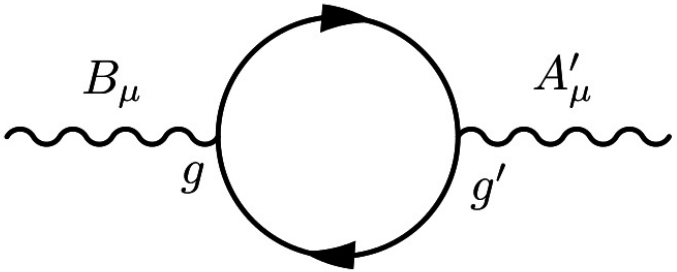
B. Holdom, Phys.Lett. B166, 196 (1986)

Portals to New Physics: Kinetic Mixing



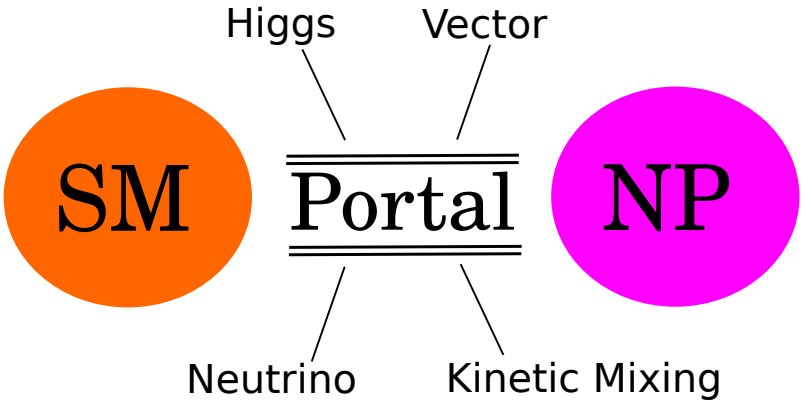
B. Holdom, Phys.Lett. B166, 196 (1986)

A **heavy** χ gauged under $U_Y(1) \times U'(1)$ induces $-\frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu}$



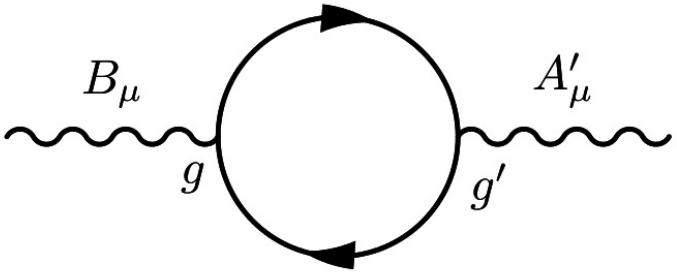
$$\left(\kappa \equiv \frac{gg'}{16\pi^2} < 1\right)$$

Portals to New Physics: Kinetic Mixing



B. Holdom, Phys.Lett. B166, 196 (1986)

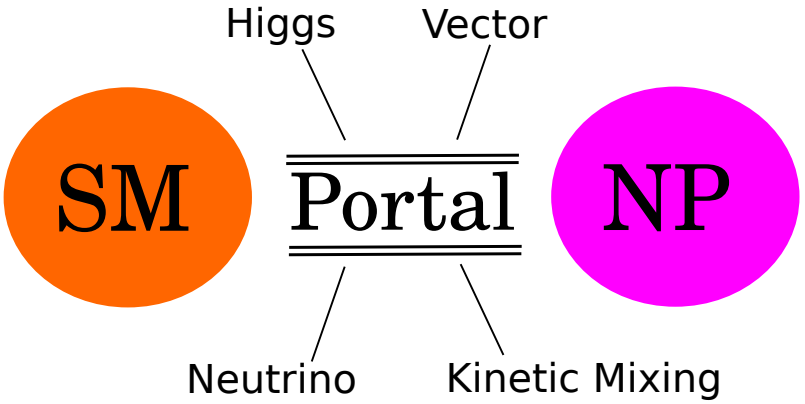
A **heavy** χ gauged under $U_Y(1) \times U'(1)$ induces $-\frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu}$



$$\left(\kappa \equiv \frac{gg'}{16\pi^2} < 1\right)$$

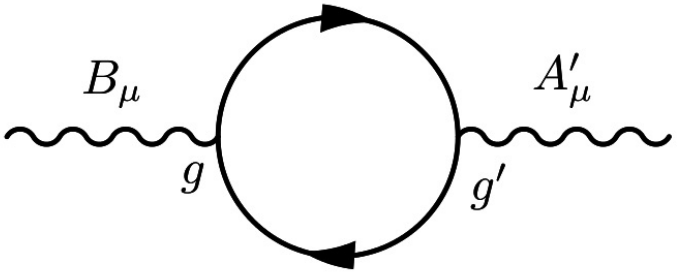
After redefining A'_μ, a **lighter** Ψ charged under $U'(1)$ will feel

Portals to New Physics: Kinetic Mixing



B. Holdom, Phys.Lett. B166, 196 (1986)

A **heavy** χ gauged under $U_Y(1) \times U'(1)$ induces $-\frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu}$

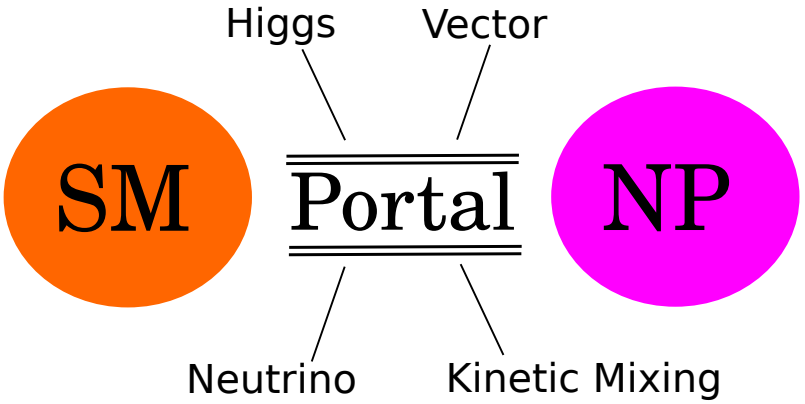


$$\left(\kappa \equiv \frac{gg'}{16\pi^2} < 1\right)$$

After redefining A'_μ, a **lighter** Ψ charged under $U'(1)$ will feel

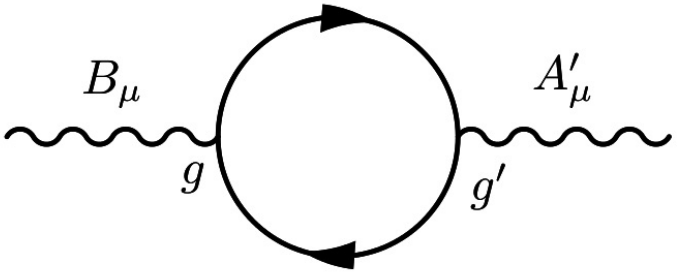
$\kappa g' \bar{\psi} \not{B} \Psi$

Portals to New Physics: Kinetic Mixing



B. Holdom, Phys.Lett. B166, 196 (1986)

A **heavy** χ gauged under $U_Y(1) \times U'(1)$ induces $-\frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu}$

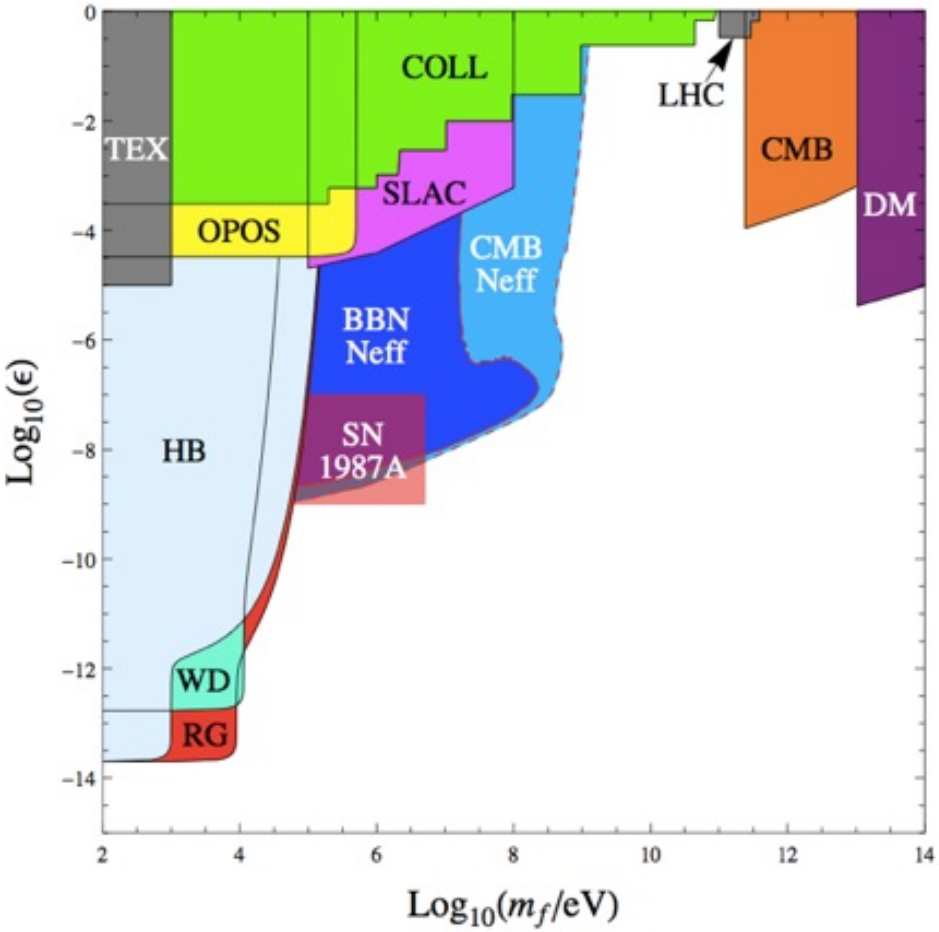


$$\left(\kappa \equiv \frac{gg'}{16\pi^2} < 1\right)$$

After redefining A'_μ, a **lighter** Ψ charged under $U'(1)$ will feel

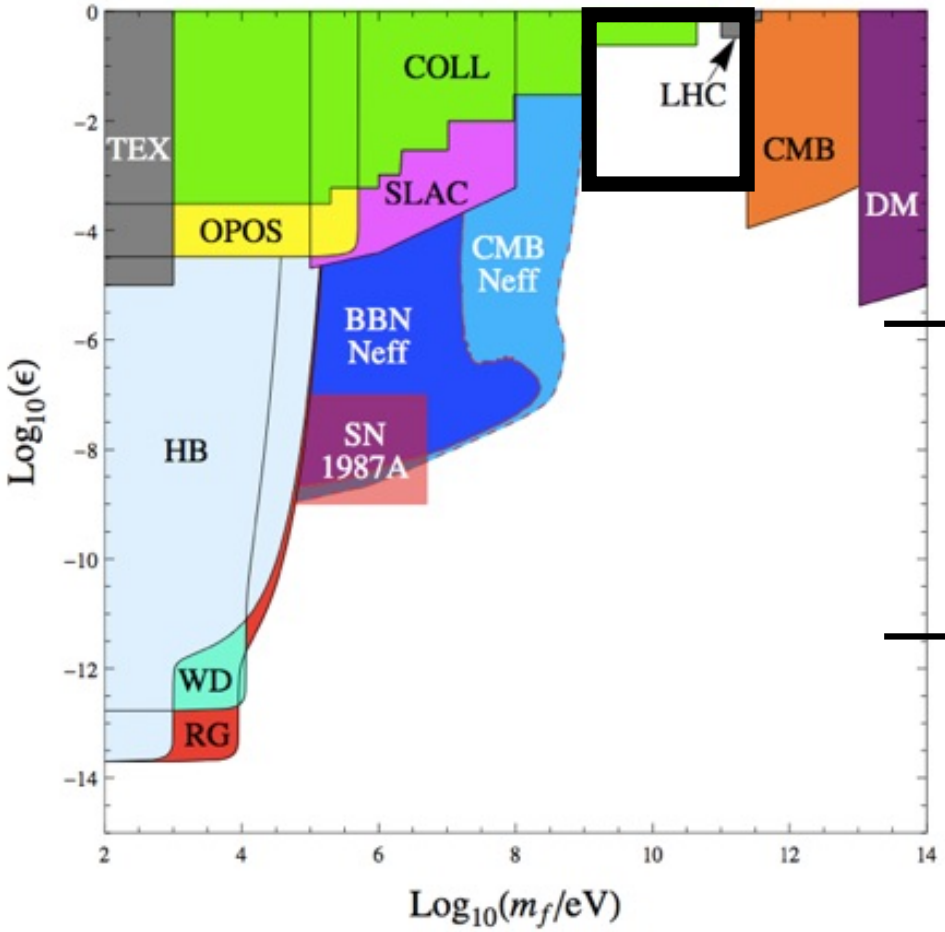
$\kappa g' \bar{\psi} \not{B} \Psi$ Ψ is now "milli-charged" as seen by B_μ!

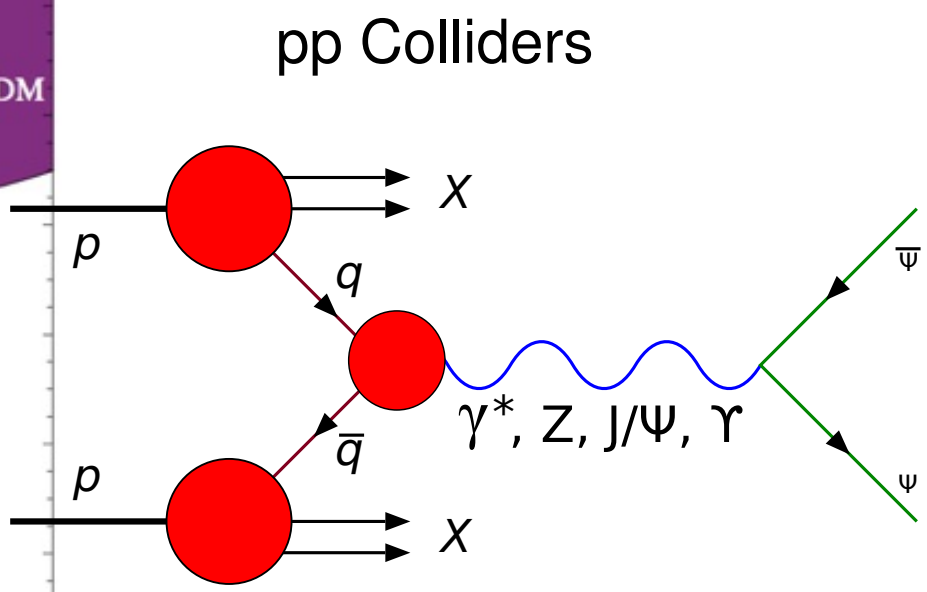
Existing Constraints



Many refs are in initial proposal: 1410.6816

Existing Constraints





Unconstrained

- $Q_{mCP} \in [0.001, 1]e$
- $M_{mCP} \in [0.1, 100]$ GeV

Many refs are in initial proposal: 1410.6816

Milli-Charged Particles at the LHC

An Expression of Interest to Install a Milli-charged Particle Detector at LHC P5

Austin Ball,[1] Jim Brooke,[2] Claudio Campagnari,[3] Albert De Roeck,[1] Brian Francis,[4] Martin Gastal,[1] Frank Golf,[3] Joel Goldstein,[2] Andy Haas,[5] Christopher S. Hill,[4] Eder Izaguirre,[6] Benjamin Kaplan,[5] Gabriel Magill,[7,6] Bennett Marsh,[3] David Miller,[8] Theo Prins,[1] Harry Shakeshaft,[1] David Stuart,[3] Max Swiatlowski,[8] and Itay Yavin[7,6]

[1] *CERN*

[2] *University of Bristol*

[3] *University of California, Santa Barbara*

[4] *The Ohio State University*

[5] *New York University*

[6] *Perimeter Institute for Theoretical Physics*

[7] *McMaster University*

[8] *University of Chicago*

(Dated: April 28, 2016)

Abstract

In this EOI we propose a dedicated experiment that would detect "milli-charged" particles produced by pp collisions at LHC Point 5. The experiment would be installed during LS2 in the vestigial drainage gallery above UXC and would not interfere with CMS operations. With 300 fb^{-1} of integrated luminosity, sensitivity to a particle with charge $\mathcal{O}(10^{-3})$ e can be achieved for masses of $\mathcal{O}(1)$ GeV, and charge $\mathcal{O}(10^{-2})$ e for masses of $\mathcal{O}(10)$ GeV, greatly extending the parameter space explored for particles with small charge and masses above 100 MeV.

CMS Note: CMS IN-2016/002

Milli-Charged Particles at the LHC

An Expression of Interest to Install a Milli-charged Particle Detector at LHC P5

Austin Ball,[1] Jim Brooke,[2] Claudio Campagnari,[3] Albert De Roeck,[1] Brian Francis,[4] Martin Gastal,[1] Frank Golf,[3] Joel Goldstein,[2] Andy Haas,[5] Christopher S. Hill,[4] Eder Izaguirre,[6] Benjamin Kaplan,[5] Gabriel Magill,[7,6] Bennett Marsh,[3] David Miller,[8] Theo Prins,[1] Harry Shakeshaft,[1] David Stuart,[3] Max Swiatlowski,[8] and Itay Yavin[7,6]

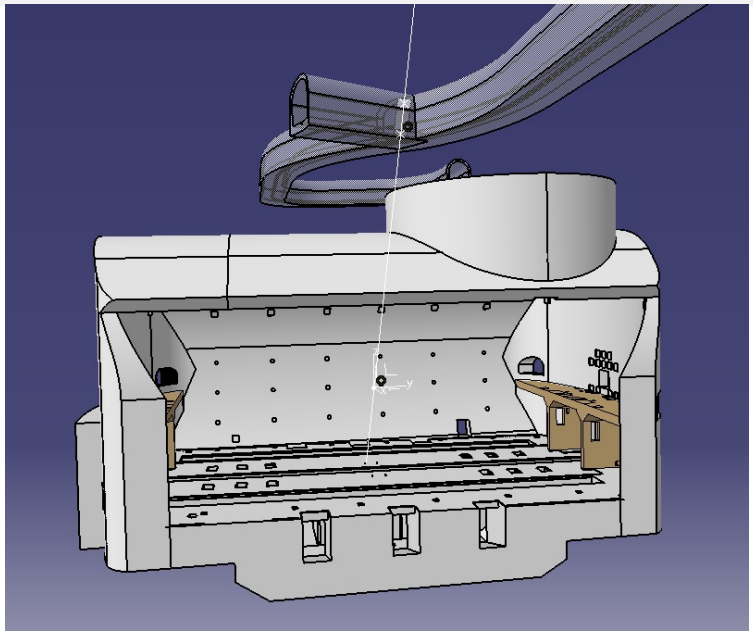
[1] *CERN*
[2] *University of Bristol*
[3] *University of California, Santa Barbara*
[4] *The Ohio State University*
[5] *New York University*
[6] *Perimeter Institute for Theoretical Physics*
[7] *McMaster University*
[8] *University of Chicago*

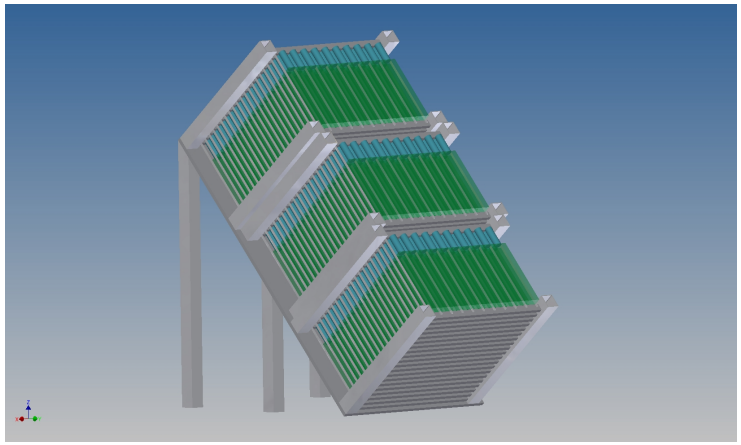
(Dated: April 28, 2016)

Abstract

In this EOI we propose a dedicated experiment that would detect "milli-charged" particles produced by pp collisions at LHC Point 5. The experiment would be installed during LS2 in the vestigial drainage gallery above UXC and would not interfere with CMS operations. With 300 fb^{-1} of integrated luminosity, sensitivity to a particle with charge $\mathcal{O}(10^{-3})$ e can be achieved for masses of $\mathcal{O}(1)$ GeV, and charge $\mathcal{O}(10^{-2})$ e for masses of $\mathcal{O}(10)$ GeV, greatly extending the parameter space explored for particles with small charge and masses above 100 MeV.

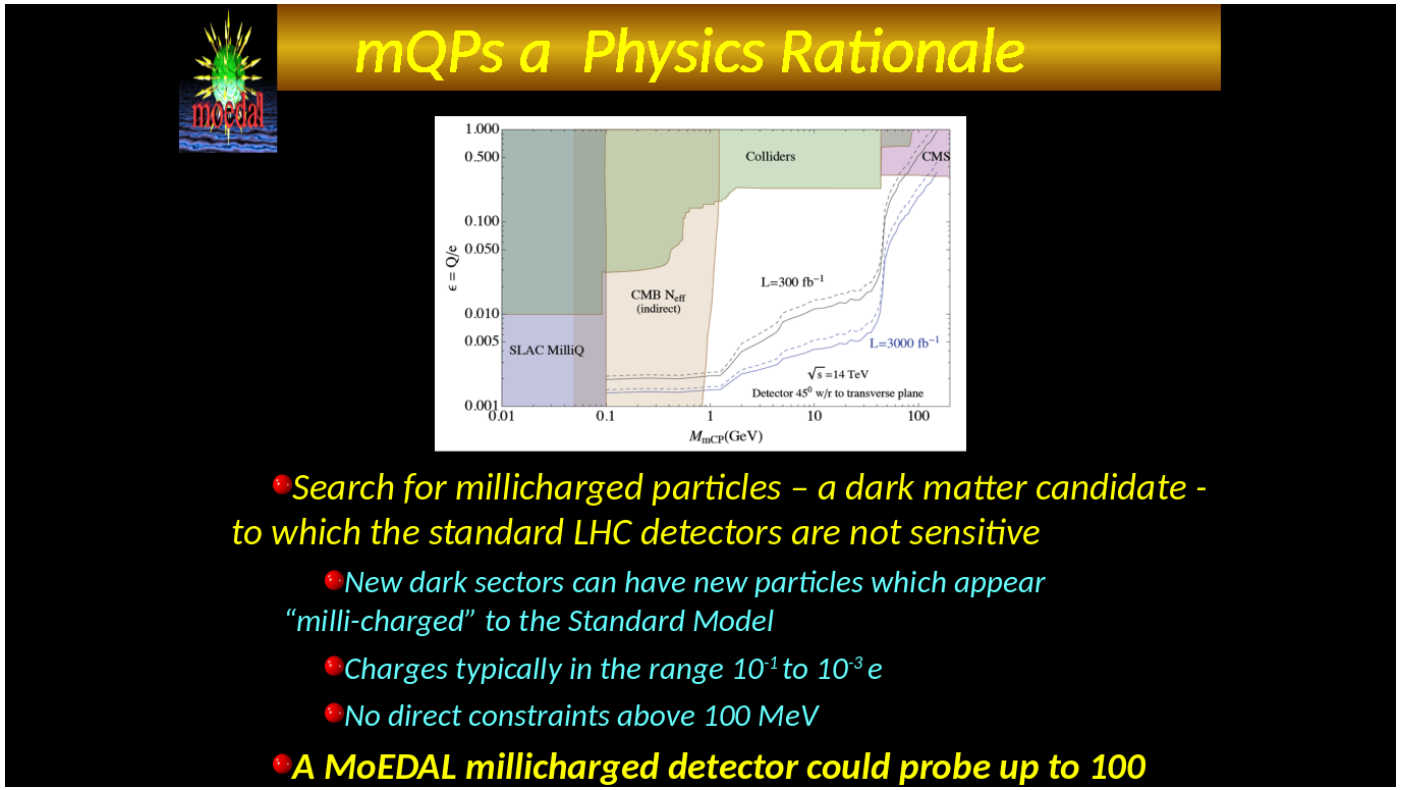
CMS Note: CMS IN-2016/002





Thanks to Martin Gastal for 3D scans!

Slide by James Pinfold, MoEDAL collaboration, Patras 2016



Sensitivity curve used by MoEDAL to motivate their experiment is actually from initial milliQan paper[1], based on much higher luminosity!

[1] Phys.Lett. B746 (2015) 117-120
Looking for milli-charged particles with a new experiment at the LHC
Andrew Haas, Christopher S. Hill, Eder Izaguirre, Itay Yavin

What are we looking for?

- Single photoelectron
  - Minimally ionizing particles deposit about $2MeV/cm$ in materials of $1g/cm^3$

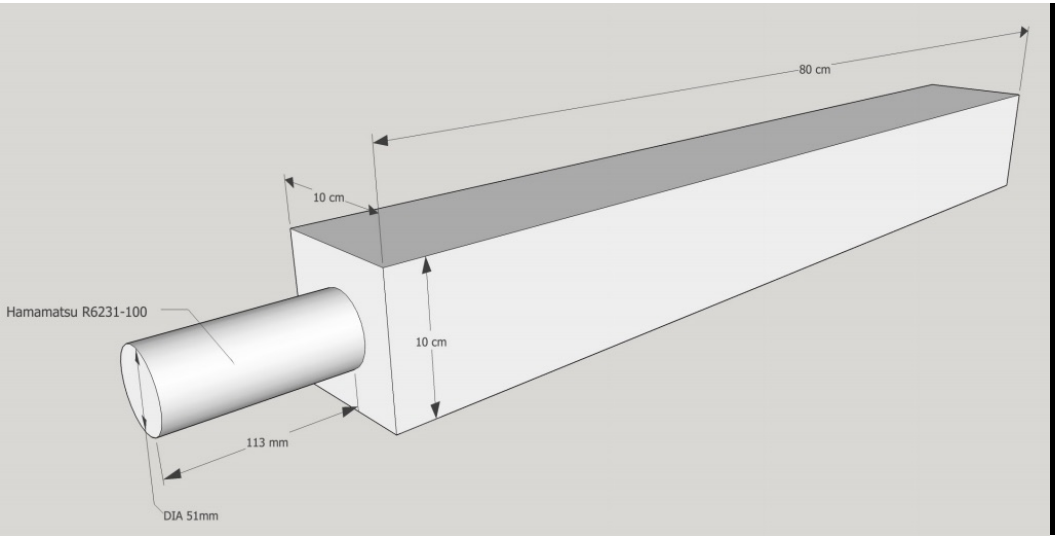
What are we looking for?

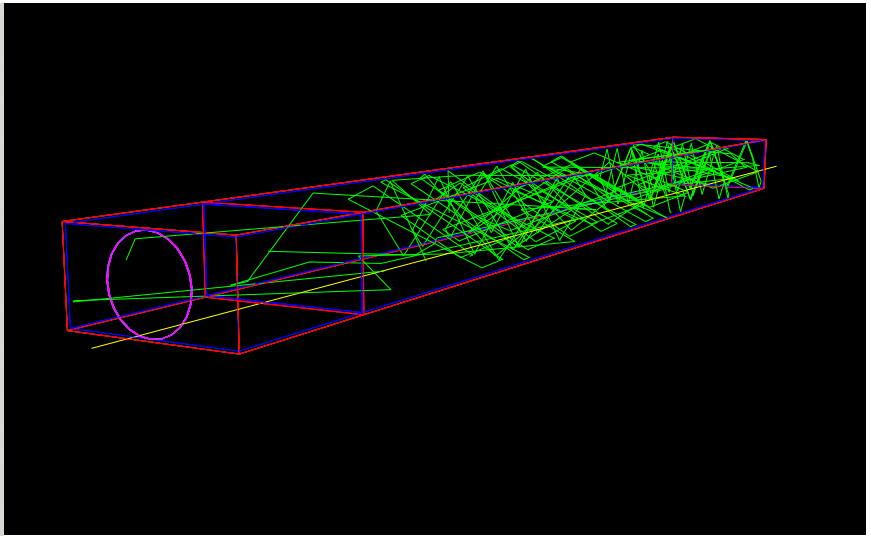
- Single photoelectron
  - Minimally ionizing particles deposit about $2MeV/cm$ in materials of $1g/cm^3$
  - 2×10^6 photons $\times Q_{mCP}^2$ where $Q_{mCP} \in [0.001, 1]e$

What are we looking for?

- Single photoelectron
  - Minimally ionizing particles deposit about $2MeV/cm$ in materials of $1g/cm^3$
  - 2×10^6 photons $\times Q_{mCP}^2$ where $Q_{mCP} \in [0.001, 1]e$
- Very precise timing information
- Trigger efficiently on signal

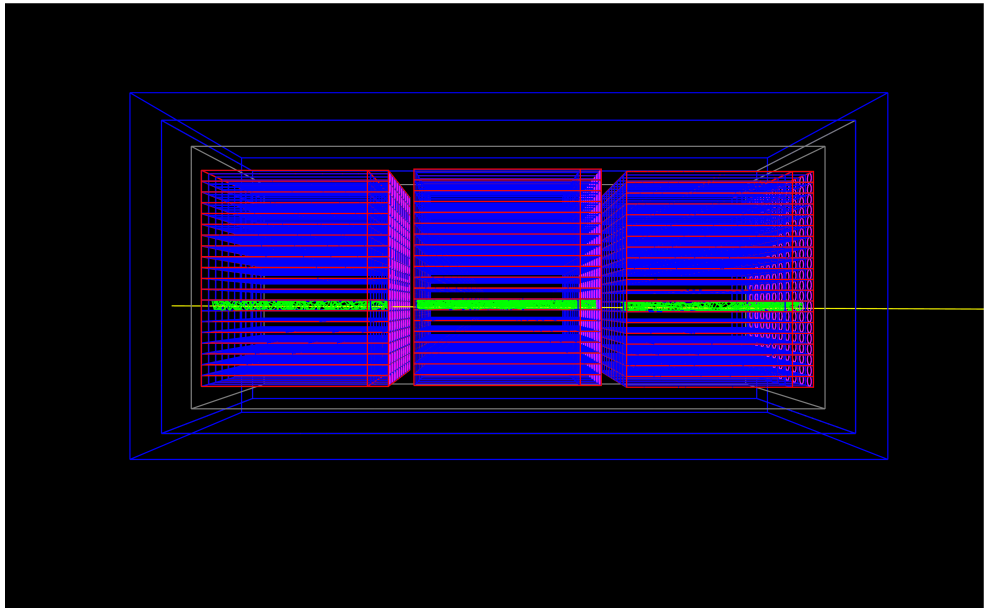
Detector Design





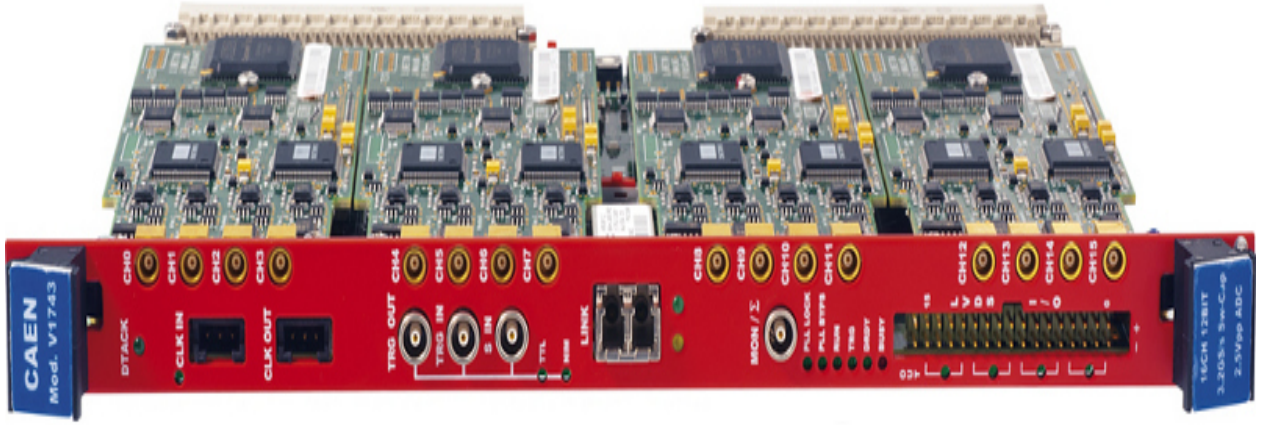
- 1 unit is made from polyvinyltoluene $5\times10\times90\text{cm}^3$ scintillator coupled to PMT, choose pastic scintillator for fast timing

Detector Design



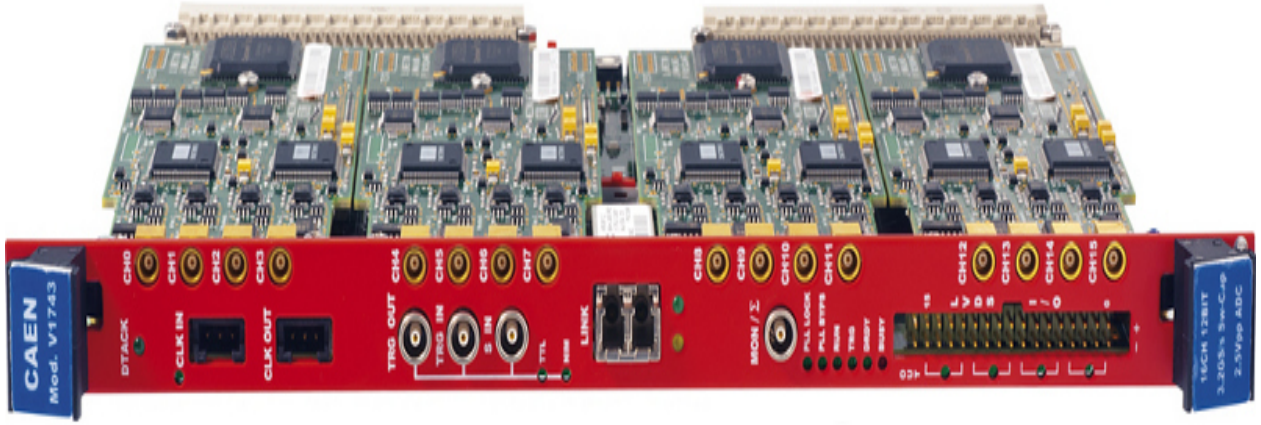
- 1 unit is made from polyvinyltoluene $5\times10\times90\text{cm}^3$ scintillator coupled to PMT, choose pastic scintillator for fast timing
- Detector made of 3 layers (coincidences), 200 units in each layer

Detector Design



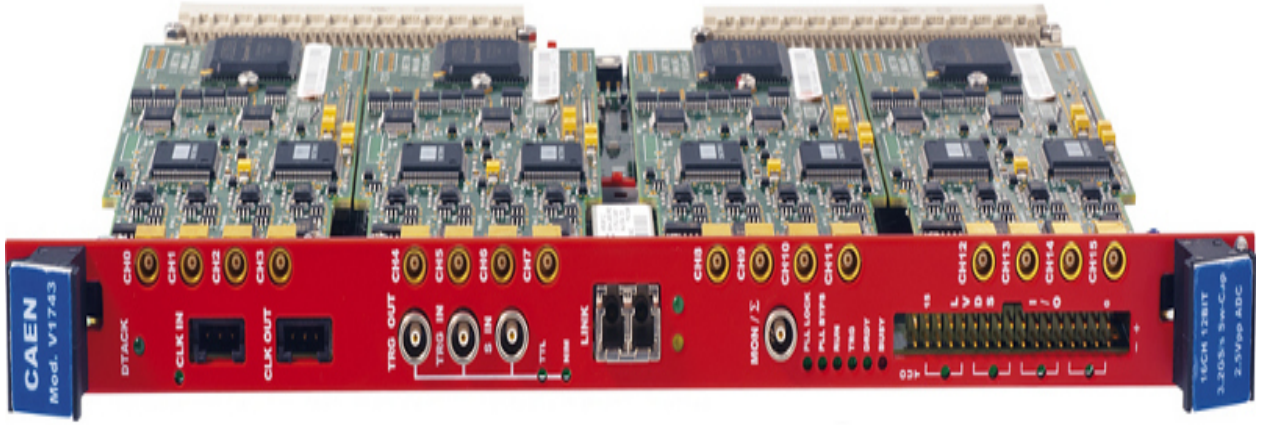
- 1 unit is made from polyvinyltoluene $5 \times 10 \times 90 cm^3$ scintillator coupled to PMT, choose pastic scintillator for fast timing
- Detector made of 3 layers (coincidences), 200 units in each layer
- Connect 4 PMTs in each layer to a CAEN V1743 digitizer (`http://www.caen.it/`)

Detector Design



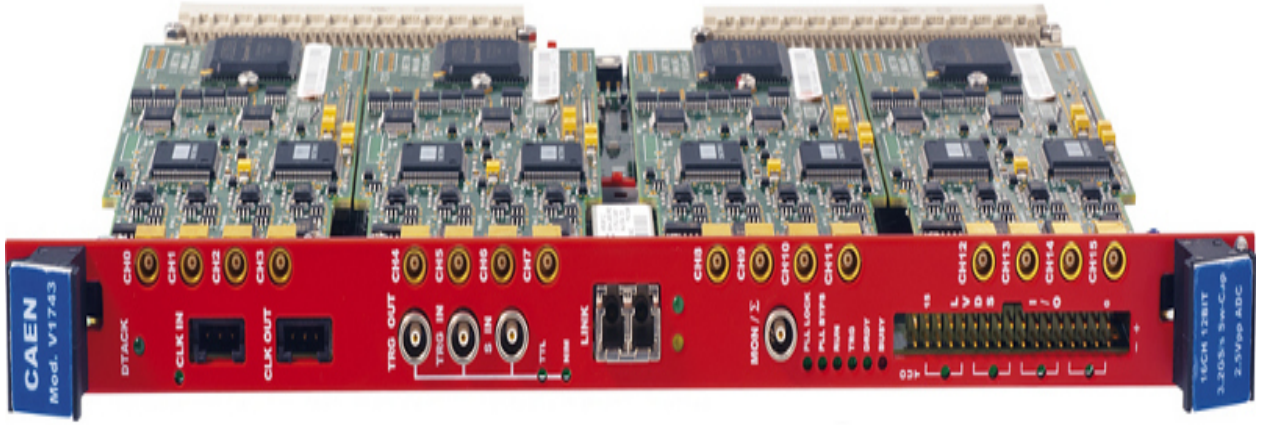
- 1 unit is made from polyvinyltoluene $5\times10\times90\text{cm}^3$ scintillator coupled to PMT, choose pastic scintillator for fast timing
- Detector made of 3 layers (coincidences), 200 units in each layer
- Connect 4 PMTs in each layer to a CAEN V1743 digitizer (`http://www.caen.it/`)
  - Stores analogue signal into 7 sample buffers, each of 1024×12-bit

Detector Design



- 1 unit is made from polyvinyltoluene $5\times10\times90\text{cm}^3$ scintillator coupled to PMT, choose pastic scintillator for fast timing
- Detector made of 3 layers (coincidences), 200 units in each layer
- Connect 4 PMTs in each layer to a CAEN V1743 digitizer (`http://www.caen.it/`)
  - Stores analogue signal into 7 sample buffers, each of 1024×12-bit
  - If 2 coincidences in 15ns, self-triggers to read out whole detector

Detector Design



- 1 unit is made from polyvinyltoluene $5\times10\times90\text{cm}^3$ scintillator coupled to PMT, choose pastic scintillator for fast timing
- Detector made of 3 layers (coincidences), 200 units in each layer
- Connect 4 PMTs in each layer to a CAEN V1743 digitizer (`http://www.caen.it/`)
  - Stores analogue signal into 7 sample buffers, each of 1024×12-bit
  - If 2 coincidences in 15ns, self-triggers to read out whole detector
  - Offline, require 3-fold coincidences

Backgrounds

Muons:

- CMS and milliQan separated by 14m of rock

Backgrounds

Muons:

- CMS and milliQan separated by 14m of rock
  - Muons get through

Backgrounds

Muons:

- CMS and milliQan separated by 14m of rock
  - Muons get through
- They look different: signal has Q^2_{mCP} suppression on number of photoelectrons in PMT

Backgrounds

Muons:

- CMS and milliQan separated by 14m of rock
  - Muons get through
- They look different: signal has Q^2_{mCP} suppression on number of photoelectrons in PMT

<u>However</u>

- Will the LHC (& cosmic muon) rates induce too much the digitizer dead time?

Backgrounds

Muons:

- CMS and milliQan separated by 14m of rock
  - Muons get through
- They look different: signal has Q^2_{mCP} suppression on number of photoelectrons in PMT

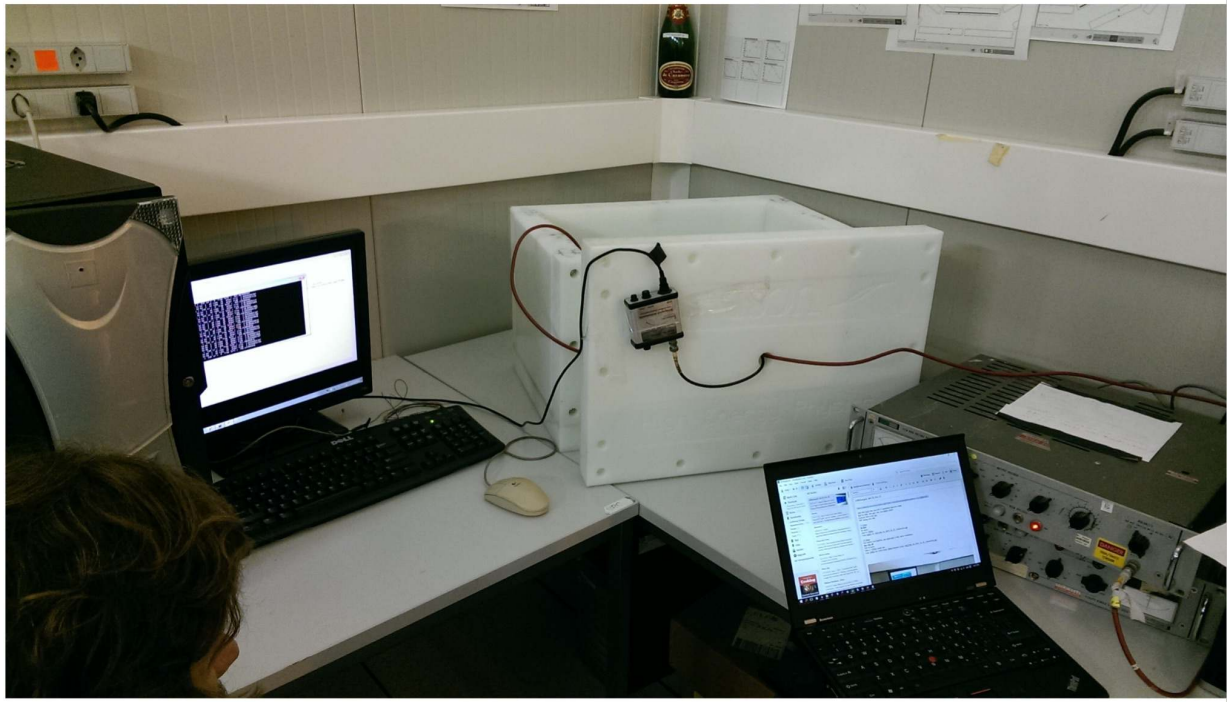
<u>However</u>

- Will the LHC (& cosmic muon) rates induce too much the digitizer dead time?
  - What are the muon rates at milliQan?

Backgrounds

Muon Rates at milliQan

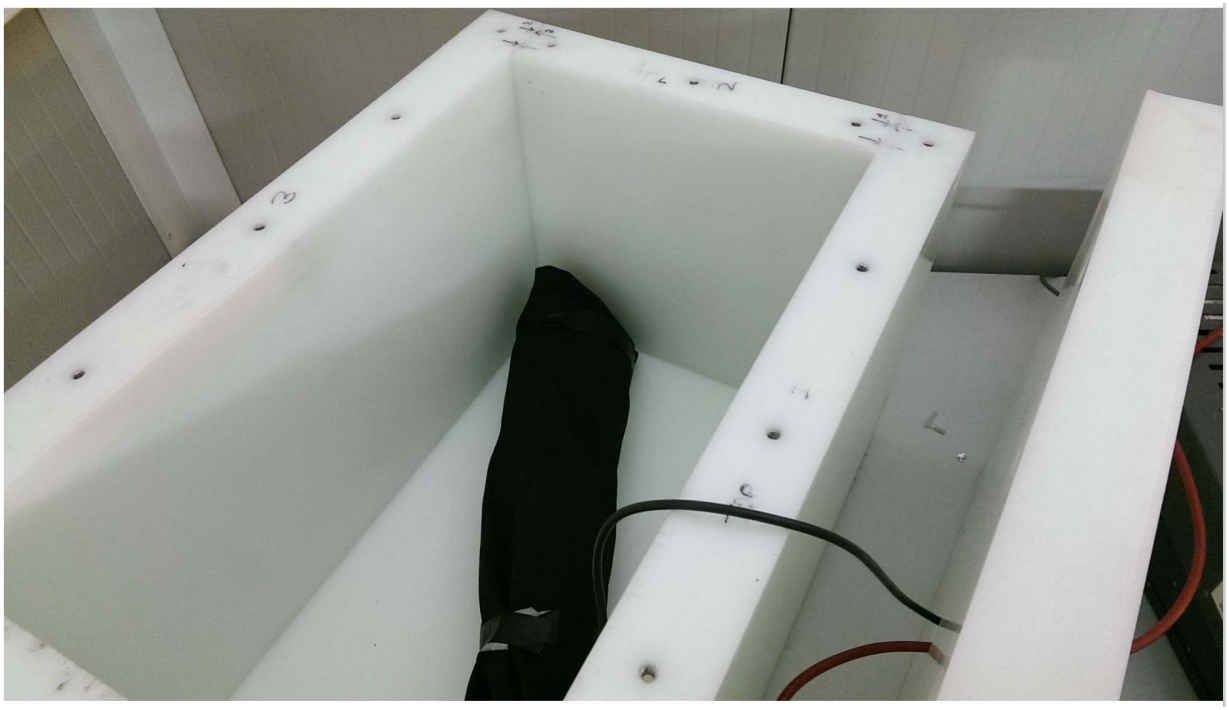
- Andy Haas & Frank Golf placed R329 scintillator and BC412 PMT in counting room with / without polyethylene box and lead bricks
- Measured rates with / without LHC beam



Backgrounds

Muon Rates at milliQan

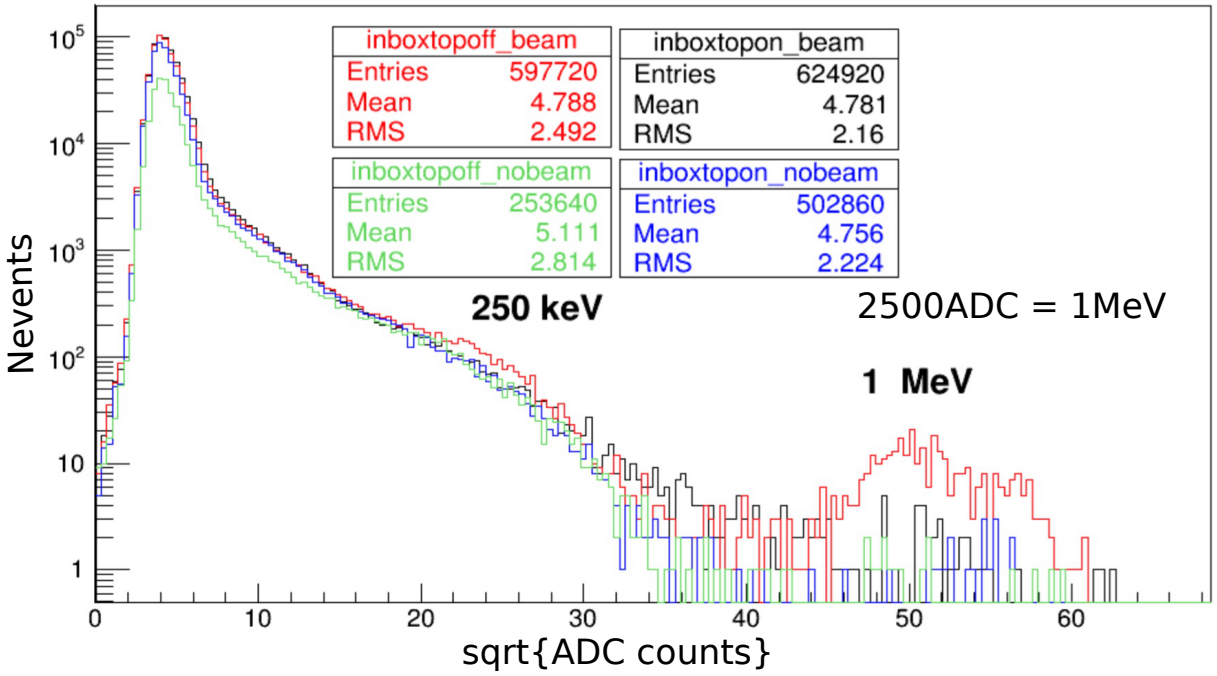
- Andy Haas & Frank Golf placed R329 scintillator and BC412 PMT in counting room with / without polyethylene box and lead bricks
- Measured rates with / without LHC beam



Backgrounds

Muon Rates at milliQan

- Andy Haas & Frank Golf placed R329 scintillator and BC412 PMT in counting room with / without polyethylene box and lead bricks
- Measured rates with / without LHC beam



Backgrounds

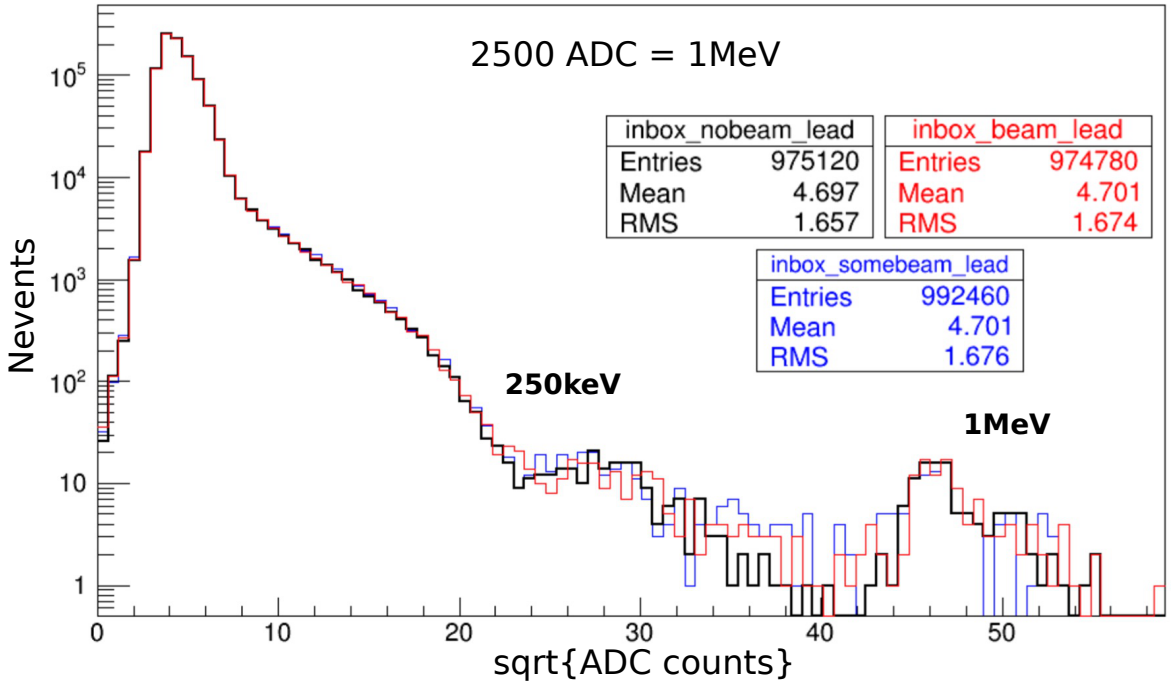
Muon Rates at milliQan

- Andy Haas & Frank Golf placed R329 scintillator and BC412 PMT in counting room with / without polyethylene box and lead bricks
- Measured rates with / without LHC beam

Backgrounds

Muon Rates at milliQan

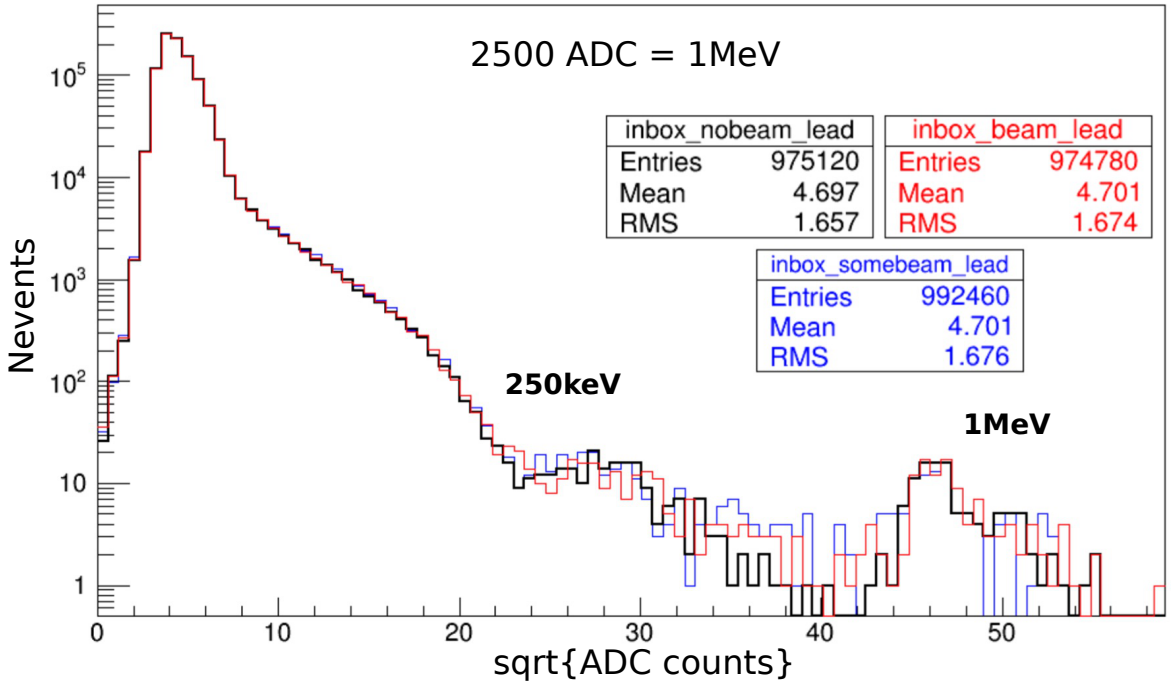
- Andy Haas & Frank Golf placed R329 scintillator and BC412 PMT in counting room with / without polyethylene box and lead bricks
- Measured rates with / without LHC beam



Backgrounds

Muon Rates at milliQan

- Andy Haas & Frank Golf placed R329 scintillator and BC412 PMT in counting room with / without polyethylene box and lead bricks
- Measured rates with / without LHC beam



- Conclusions: PMT rates underground with polyethylene box + led shielding consistent with electronic noise + dark current

Backgrounds

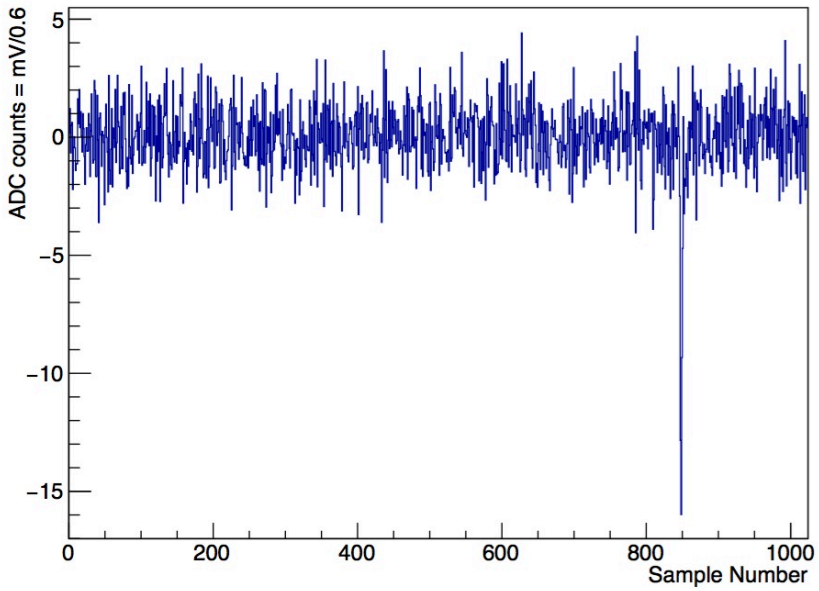
Dark Current

- Main background! Rate of $\sim$1kHz per PMT, $\sim$500Hz with cooling

Backgrounds

Dark Current

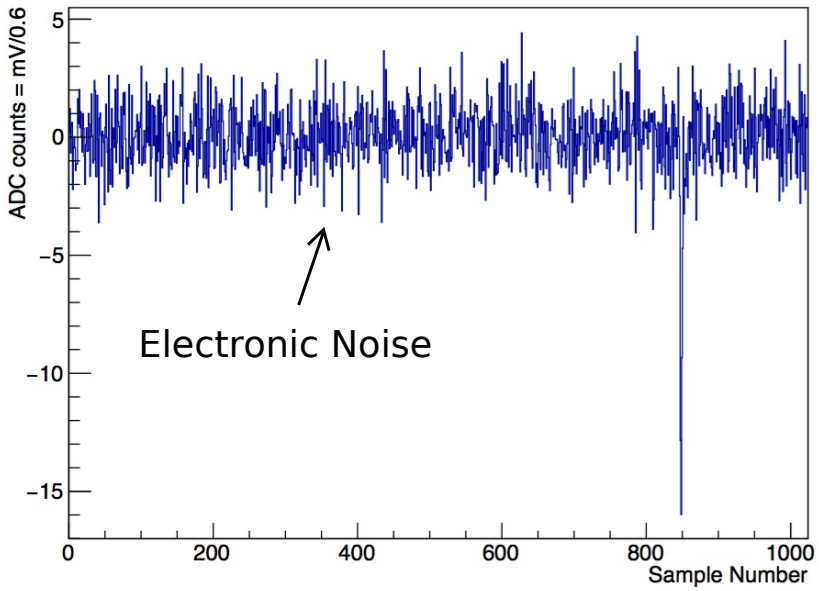
- Main background! Rate of ∼1kHz per PMT, ∼500Hz with cooling
  Plots produced by Andy Haas and Benjamin Kaplan (NYU)



Backgrounds

Dark Current

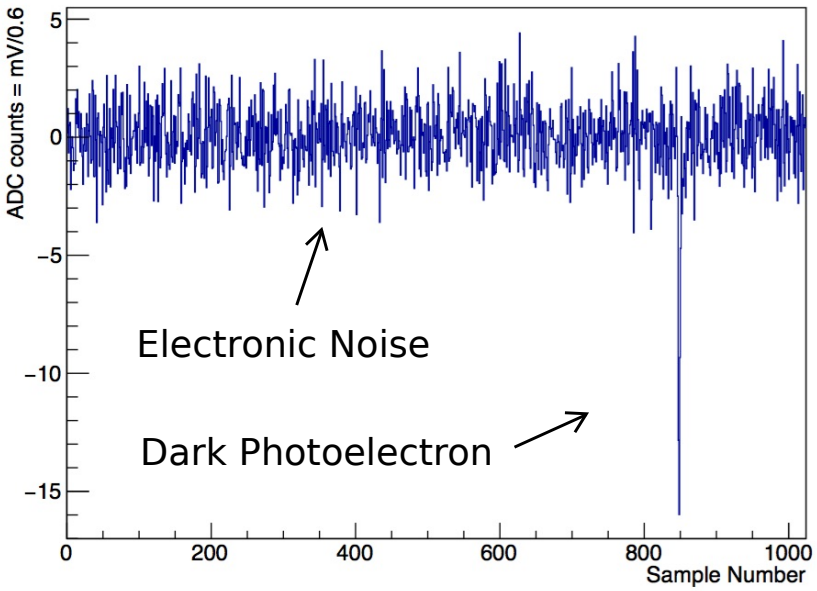
- Main background! Rate of ∼1kHz per PMT, ∼500Hz with cooling
  Plots produced by Andy Haas and Benjamin Kaplan (NYU)



Backgrounds

Dark Current

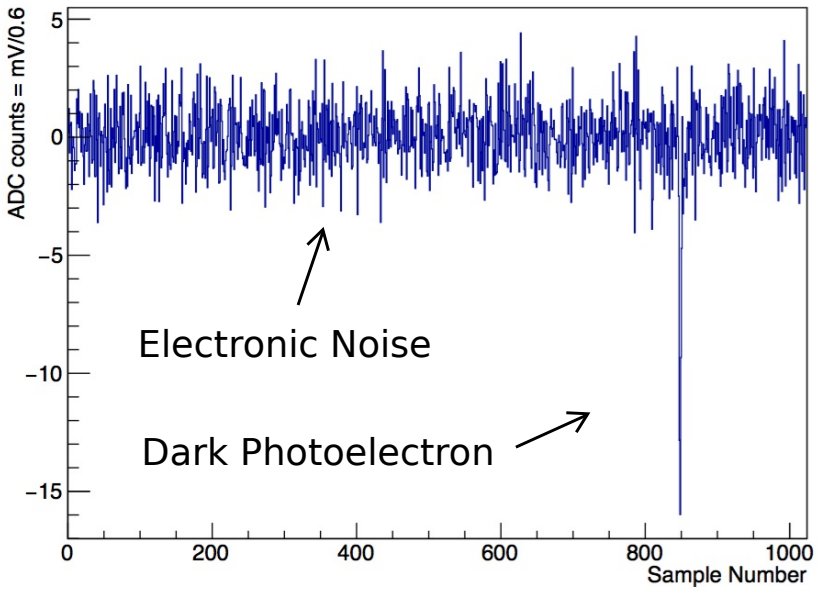
- Main background! Rate of ∼1kHz per PMT, ∼500Hz with cooling
  Plots produced by Andy Haas and Benjamin Kaplan (NYU)

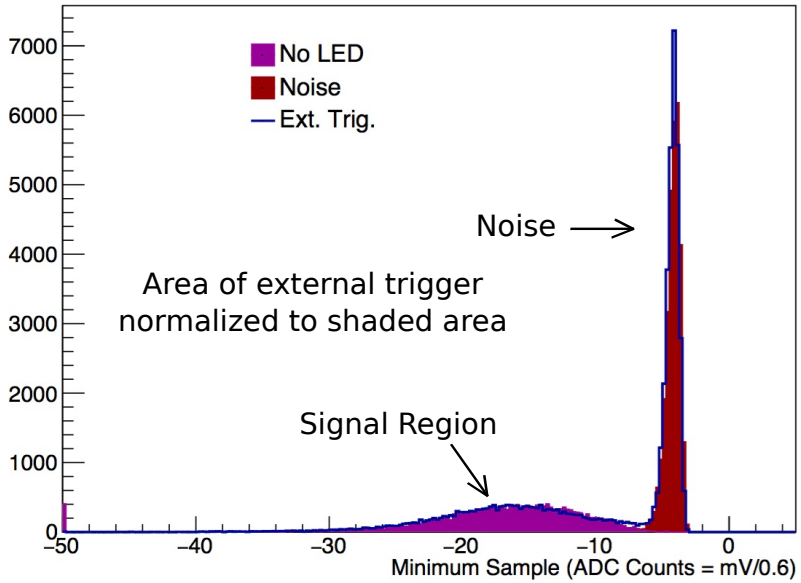


Backgrounds

Dark Current

- Main background! Rate of ∼1kHz per PMT, ∼500Hz with cooling
  Plots produced by Andy Haas and Benjamin Kaplan (NYU)

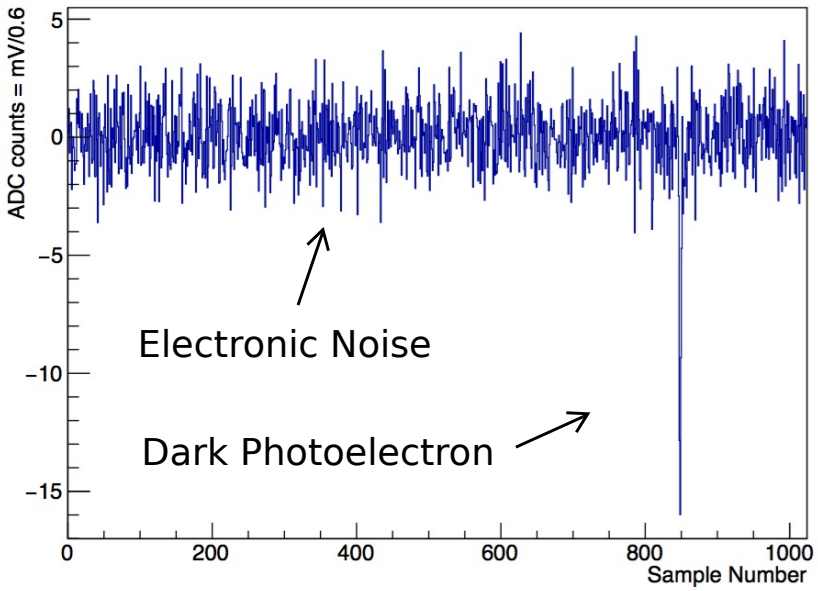


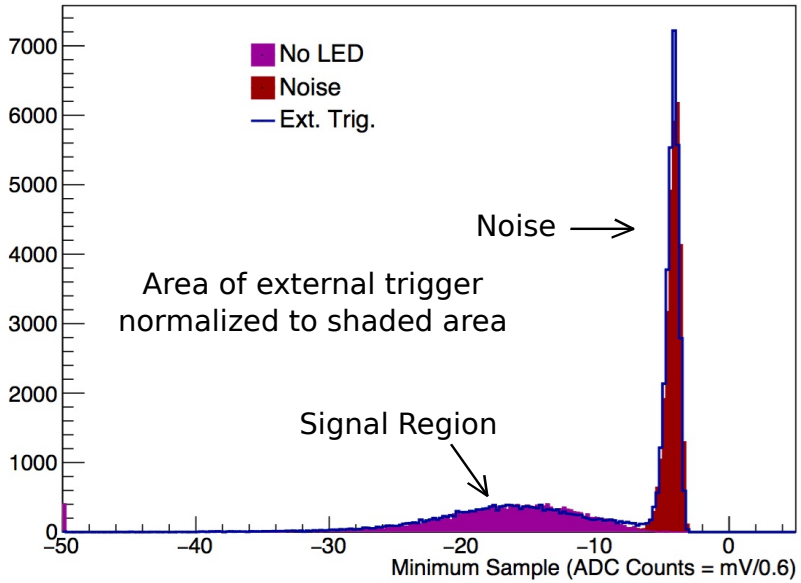


Backgrounds

Dark Current

- Main background! Rate of ∼1kHz per PMT, ∼500Hz with cooling
  Plots produced by Andy Haas and Benjamin Kaplan (NYU)



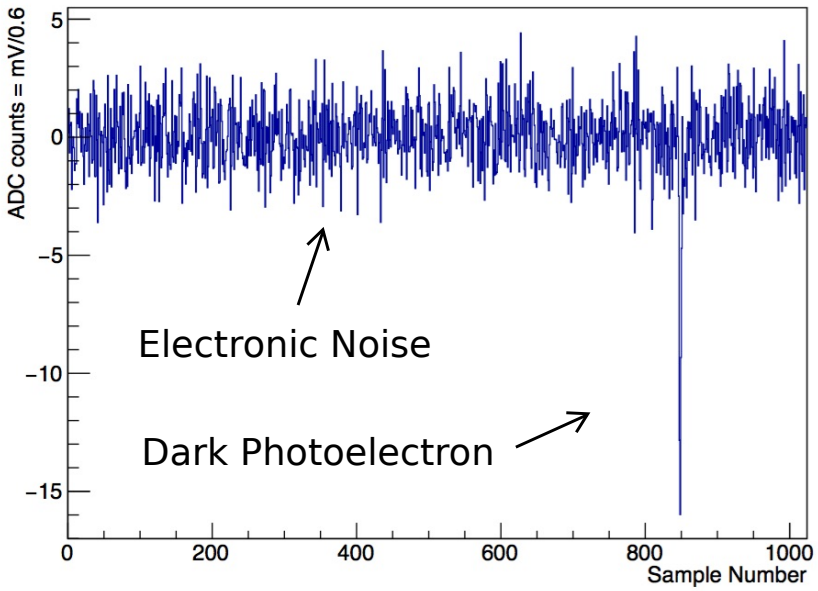


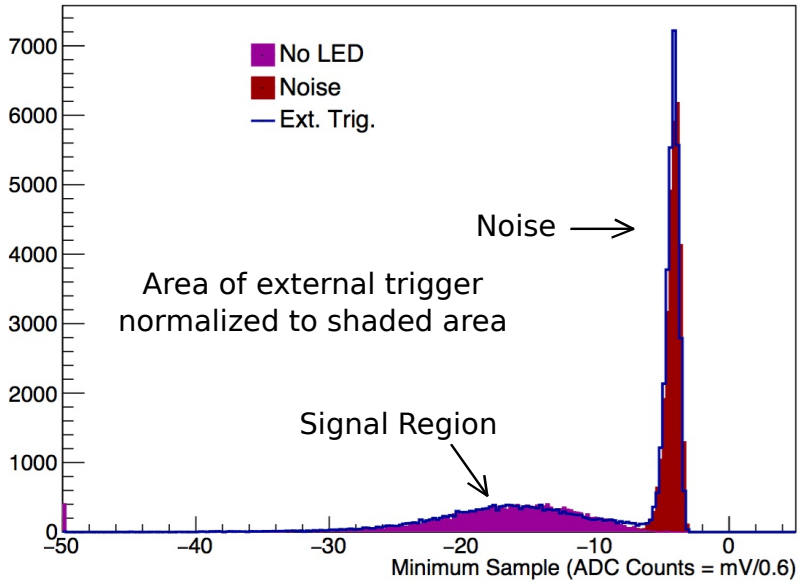
- Digitizer triggers and 3-fold coincidence in 15ns reduce background rates to $\sim 10^{-6}$Hz (see backup slide)

Backgrounds

Dark Current

- Main background! Rate of ∼1kHz per PMT, ∼500Hz with cooling
  Plots produced by Andy Haas and Benjamin Kaplan (NYU)





- Digitizer triggers and 3-fold coincidence in 15ns reduce background rates to $\sim 10^{-6}$Hz (see backup slide)
- Results in $O(50)$ background events for 3000fb^{-1}, look for excess

Sensitivity

Of all the mCP produced in LHC, how many make it to our detector?

Sensitivity

Of all the mCP produced in LHC, how many make it to our detector?

- To calculate acceptance

Sensitivity

Of all the mCP produced in LHC, how many make it to our detector?

- To calculate acceptance
  - Simulated mCP production in Madgraph5 and Madonia

Sensitivity

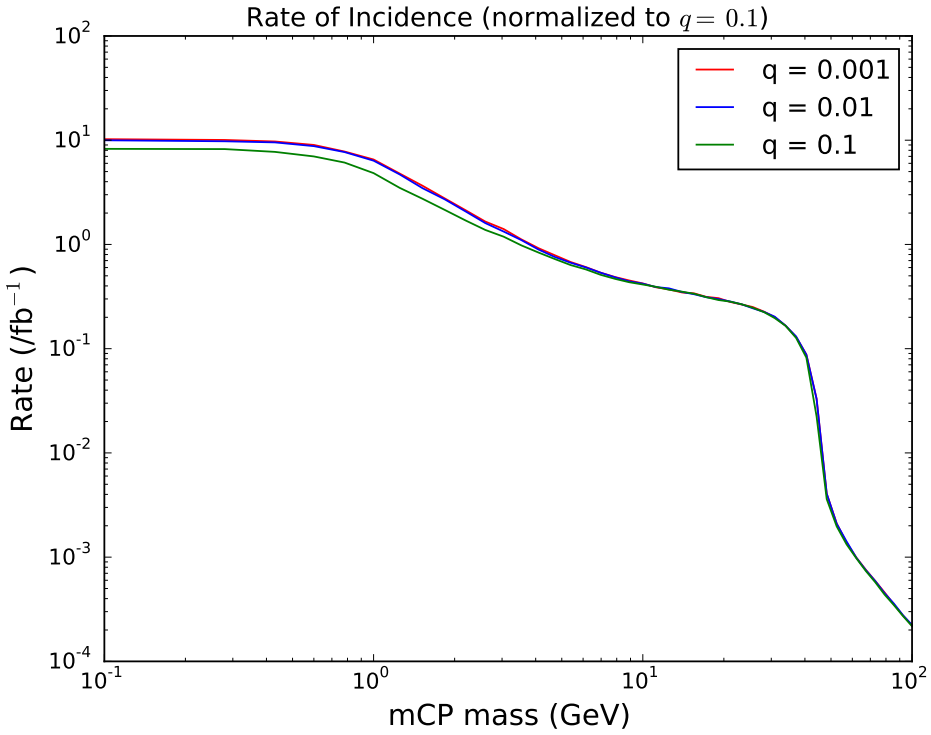
Of all the mCP produced in LHC, how many make it to our detector?

- To calculate acceptance
  - Simulated mCP production in Madgraph5 and Madonia
  - Simulated mCP interaction with CMS magnetic field and passage of mCP through 14m of rock (Frank Golf and Bennett Marsh)

Sensitivity

Of all the mCP produced in LHC, how many make it to our detector?

- To calculate acceptance
  - Simulated mCP production in Madgraph5 and Madonia
  - Simulated mCP interaction with CMS magnetic field and passage of mCP through 14m of rock (Frank Golf and Bennett Marsh)



Dip due to falling σ with increasing mass

Bump is Z enhancement

Sensitivity

Of all the mCP that make it to our detector, how many are actually recorded?

Sensitivity

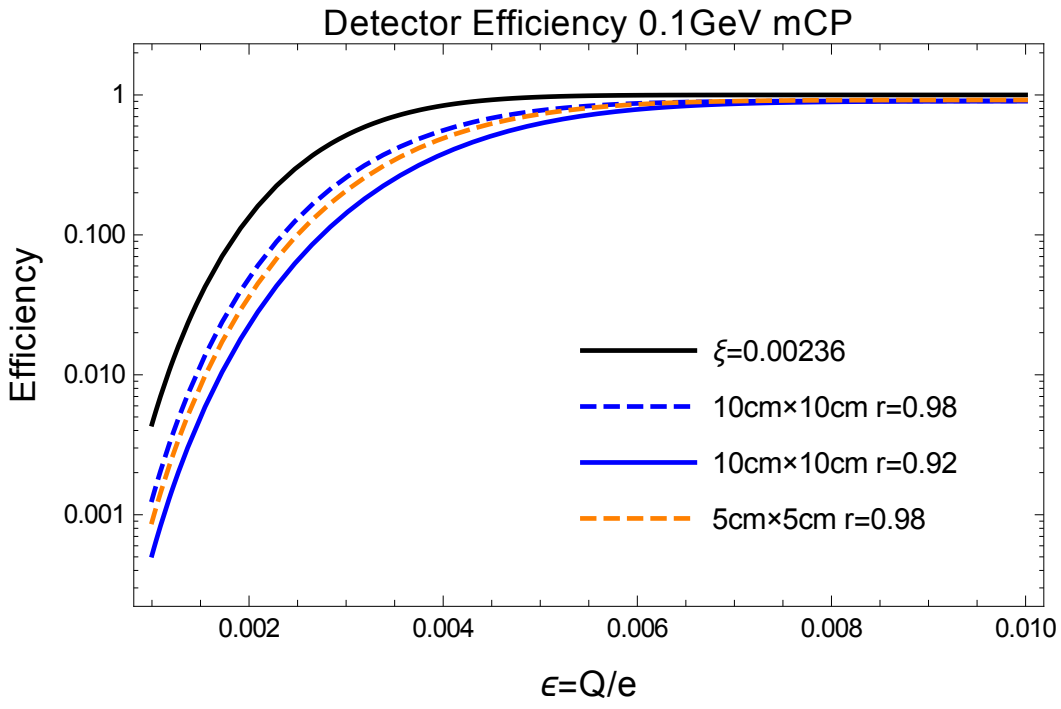
Of all the mCP that make it to our detector, how many are actually recorded?

- With James London (OSU), made full Geant4 simulation of the detector!

Sensitivity

Of all the mCP that make it to our detector, how many are actually recorded?

- With James London (OSU), made full Geant4 simulation of the detector!



Black line:
Analytic estimate

Other lines:
Geant4
Varying scintillator dimensions

How many signal events?

Collecting info from previous slides for 0.1GeV / 0.002e mCP,

$$\text{\# signals} = 0.1 \times 10^3 \left(\frac{0.002e}{0.1e}\right)^2 fb \times 3000 fb^{-1} = 12$$

Detector Efficiency

How many signal events?

Collecting info from previous slides for 0.1GeV / 0.002e mCP,

$$\text{\# signals} = 0.1 \times 10^3 \left(\frac{0.002e}{0.1e}\right)^2 fb \times 3000 fb^{-1} = 12$$

Detector Efficiency

Acceptance

How many signal events?

Collecting info from previous slides for 0.1GeV / 0.002e mCP,

$$\text{\# signals} = 0.1 \times 10^3 \left(\frac{0.002e}{0.1e}\right)^2 fb \times 3000 fb^{-1} = 12$$

Detector Efficiency

Acceptance

Luminosity

How many signal events?

Collecting info from previous slides for 0.1GeV / 0.002e mCP,

$$\text{\# signals} = 0.1 \times 10^3 \left(\frac{0.002e}{0.1e}\right)^2 fb \times 3000 fb^{-1} = 12$$

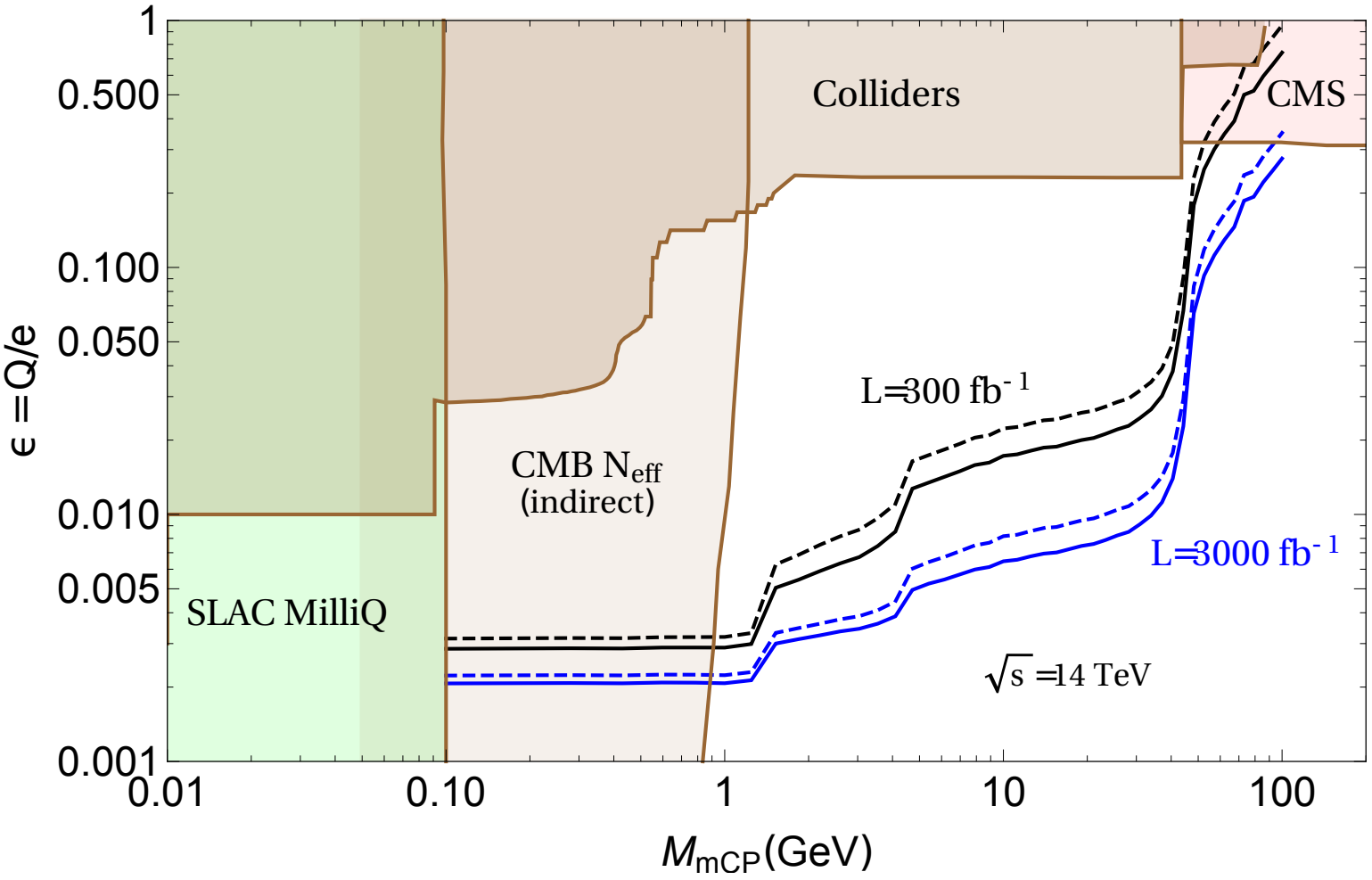
Detector Efficiency

Acceptance

Luminosity

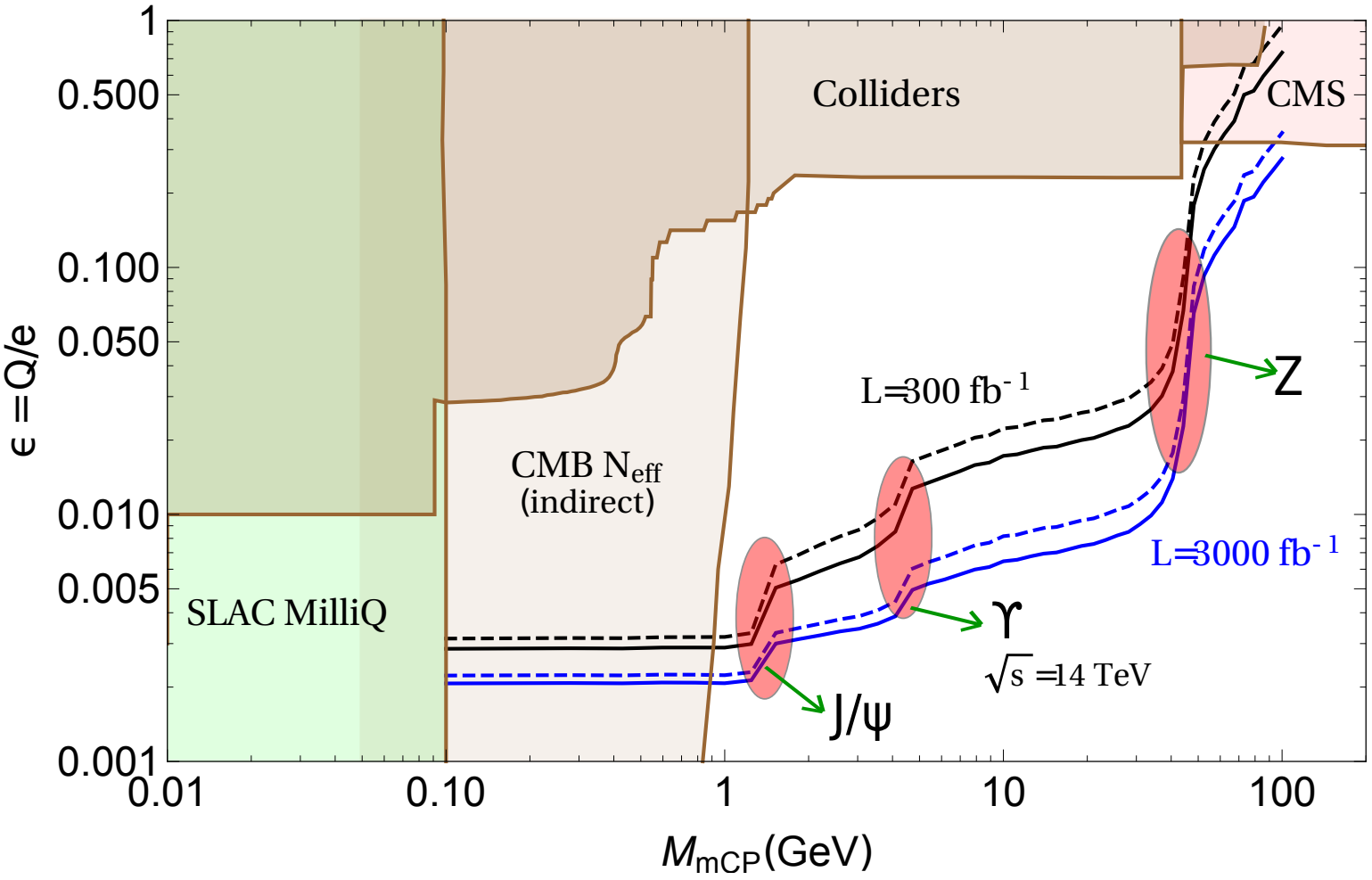
Compare this to $O(50)$ background events

LHC Reach with milliQan



With Geant4, CMS B-field and Bethe-Bloch energy loss!

LHC Reach with milliQan



With Geant4, CMS B-field and Bethe-Bloch energy loss!

Outlook

What's Next?

Outlook

What's Next?

- Currently in the R&D phase:
  - Testing scintillators, PMTs, writing software for CAEN digitizer, running simulations

Outlook

What's Next?

- Currently in the R&D phase:
  - Testing scintillators, PMTs, writing software for CAEN digitizer, running simulations
- New Simulations: Kinetic mixing with dark hypercharge produces milli-charged particles from massive resonance (Izaguirre, Yavin, 1506.04760)

Outlook

What's Next?

- Currently in the R&D phase:
  - Testing scintillators, PMTs, writing software for CAEN digitizer, running simulations
- New Simulations: Kinetic mixing with dark hypercharge produces milli-charged particles from massive resonance (Izaguirre, Yavin, 1506.04760)
- Pending external agency funding and CMS approval, we hope to have milliQan installed during LS2 and taking data by run 3 (2019-2020)

Outlook

What's Next?

- Currently in the R&D phase:
  - Testing scintillators, PMTs, writing software for CAEN digitizer, running simulations
- New Simulations: Kinetic mixing with dark hypercharge produces milli-charged particles from massive resonance (Izaguirre, Yavin, 1506.04760)
- Pending external agency funding and CMS approval, we hope to have milliQan installed during LS2 and taking data by run 3 (2019-2020)
- Special thanks to Tiziano, Austin, Wolfram and Martin Gastal who are helping us at CMS

Outlook

What's Next?

- Currently in the R&D phase:
  - Testing scintillators, PMTs, writing software for CAEN digitizer, running simulations
- New Simulations: Kinetic mixing with dark hypercharge produces milli-charged particles from massive resonance (Izaguirre, Yavin, 1506.04760)
- Pending external agency funding and CMS approval, we hope to have milliQan installed during LS2 and taking data by run 3 (2019-2020)
- Special thanks to Tiziano, Austin, Wolfram and Martin Gastal who are helping us at CMS

Exciting physics ahead!

Backup

Backup Slides

New Signals

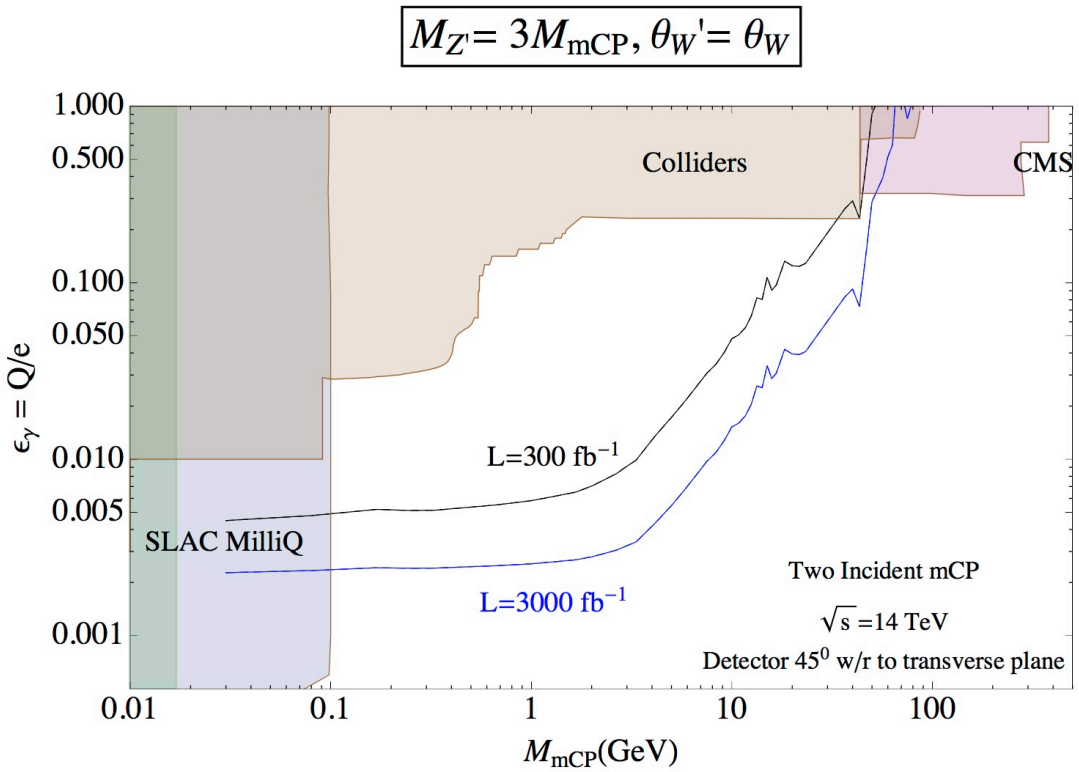
Production from Massive Z'

- $\mathcal{L} \supset -\frac{1}{4} B^{\mu\nu} B'_{\mu\nu}$ (B' is dark hypercharge) induces Z' decays to a milli-charged dark sector (Izaguirre, Yavin, 1506.04760)

New Signals

Production from Massive Z'

- $\mathcal{L} \supset -\frac{1}{4} B^{\mu\nu} B'_{\mu\nu}$ (B' is dark hypercharge) induces Z' decays to a milli-charged dark sector (Izaguirre, Yavin, 1506.04760)



($Z' \to$ mCP mCP)+jet where both mCP reach milliQan

Dark Photon Background Rates

Definitions

- PMT Dark Current ν = 500Hz
- Resolution time τ = 5ns
- Digitizing deadtime D = $125\mu s$
- Unit = 1 Scintillator + 1 PMT (600 units in detector)
- Group = 2 neighbouring units in a layer (100 groups / layer)
- Detector = 3 layers

Strategy

- Connect 2 neighbouring groups in each layer to 1 CAEN Board (need 50 boards)
- Readout detector if any 2 groups in board have coincidences
- Offline, require coincidence for 3 units in back-to-back layers

Dark Photon Background Rates

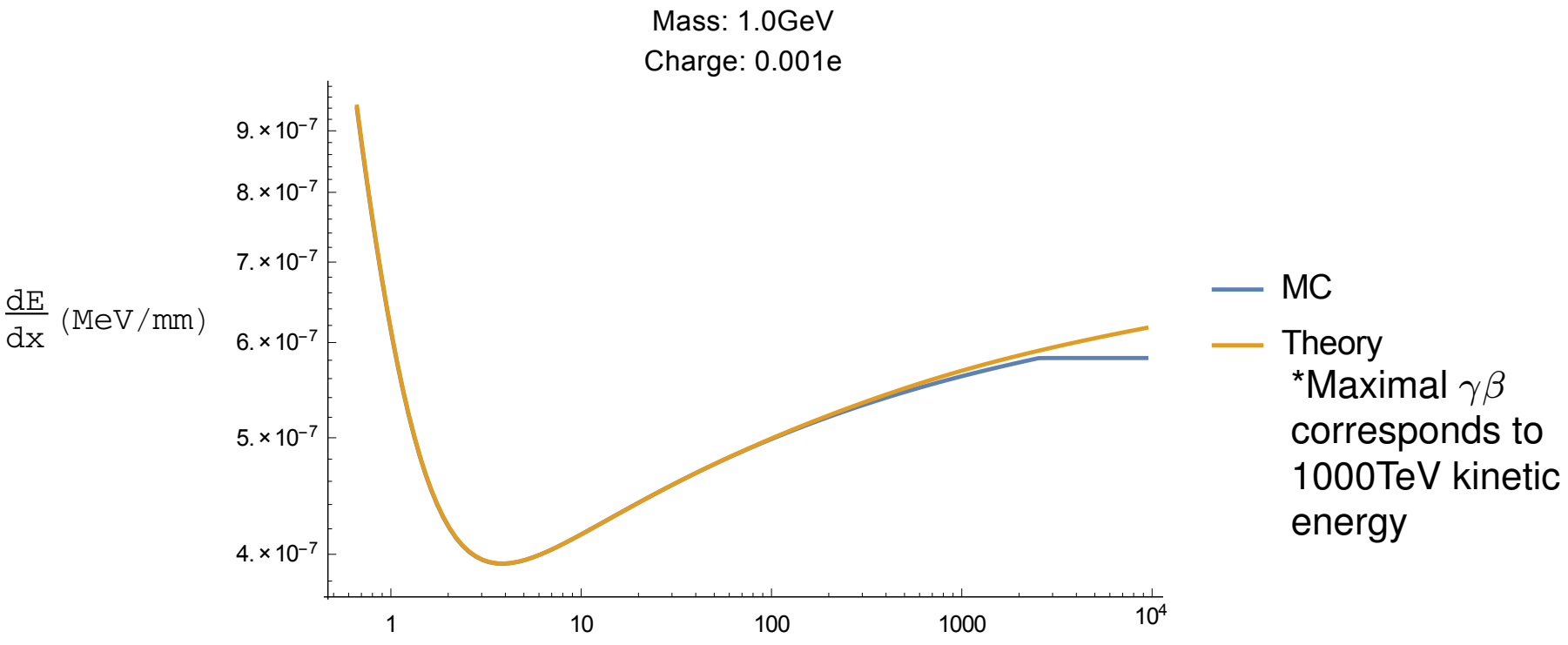
Following Grupen & Shwartz, Particle Detectors (eq. 2.21, 2.23, 2.25):

Rates and Deadtime

- Rate in a board is: $R = \binom{6}{2} 2(2\nu)^2\tau = 0.15Hz$
- Rate in detector is: $0.15Hz \times 50 = 7.5Hz$
- % of Deadtime in detector is 7.5Hz $\times D = 0.09\%$
- Offline rate: $3\nu^3\tau^2 \times 50 = 4.7 \times 10^{-7}$Hz
- Number of events in 300fb^{-1}: $4.7 * 10^{-7}Hz \times 1.5 * 10^7 s = 7$

Energy Loss

Energy loss of mCP through carbon



$$\left.\frac{dE}{dx}\right|_{Theory} = \rho K \epsilon^2 \frac{Z}{A}\frac{1}{\beta^2}\left(\ln\left[\frac{2m_e c^2\beta^2\gamma^2 W_{max}}{I^2}\right] - \beta^2 - \frac{\delta(\beta\gamma)}{2}\right)$$

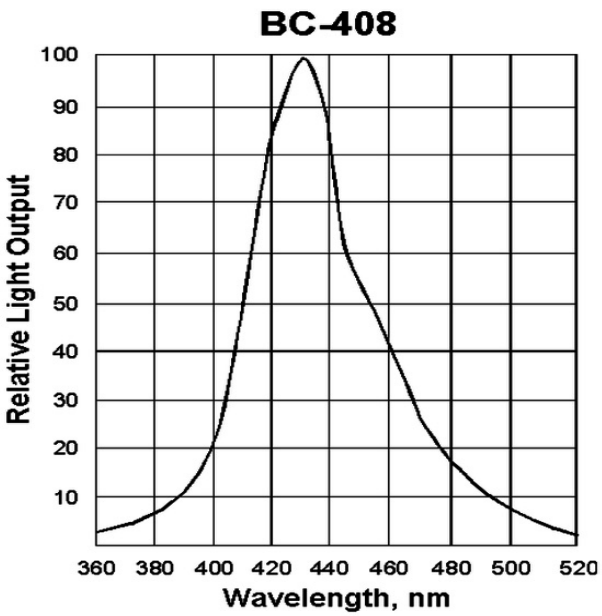
$\delta(\beta\gamma)$ follows Sternheimers parameterization (function by parts fitted to material)

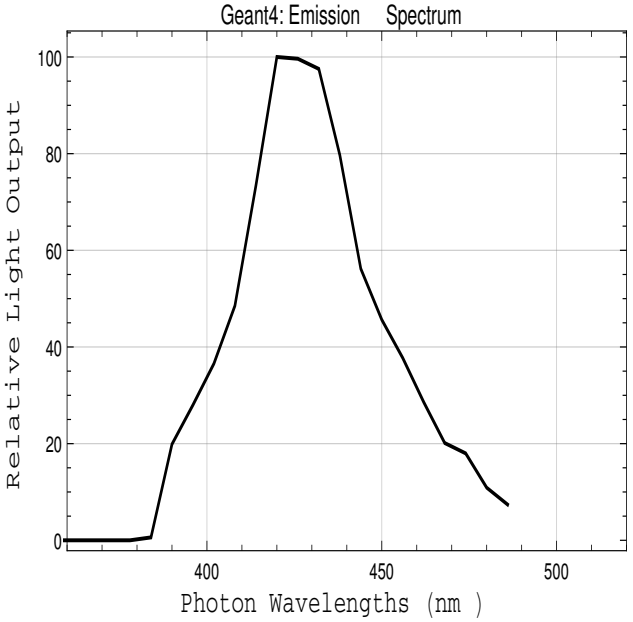
W_{max} max E transfer to e- I: mean excitation energy

dedx[i]$_{MC}$ = ‘G4EmCalculator’.ComputeElectronicDEDX(ekin[i], mCP, matName);

Scintillator - Bicron BC-408

- Real rise time (0.9ns), decay time (2.1ns), index of refraction (1.58), Birk's constant (0.111mm/MeV)
- Detector stack offset, real emission spectra*:

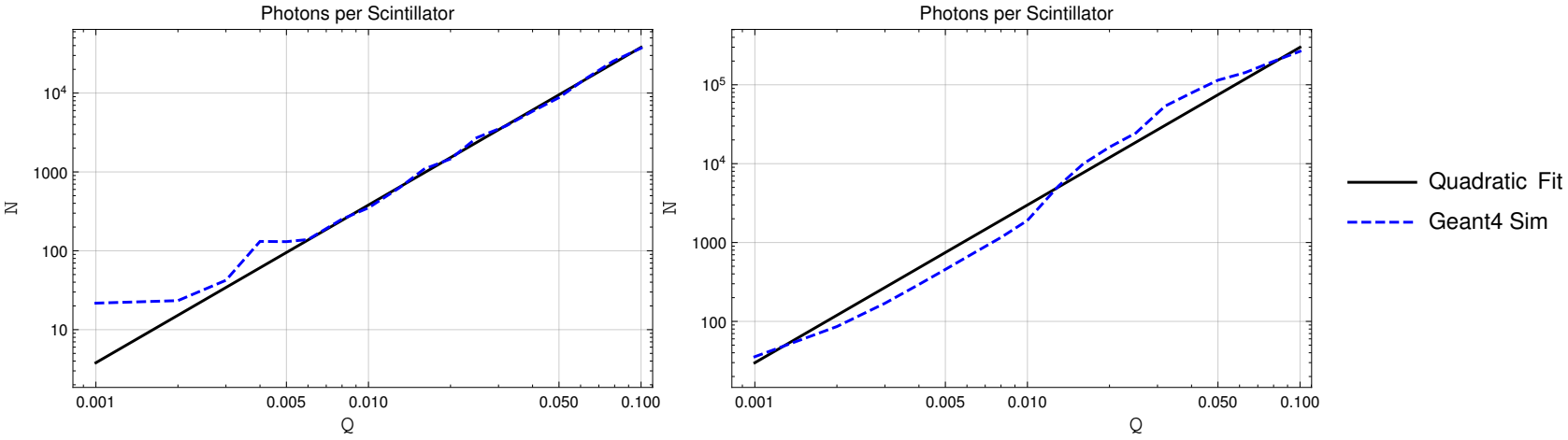




*www.crystals.saint-gobain.com/document.aspx?docId=274290

Number of Photons Emitted

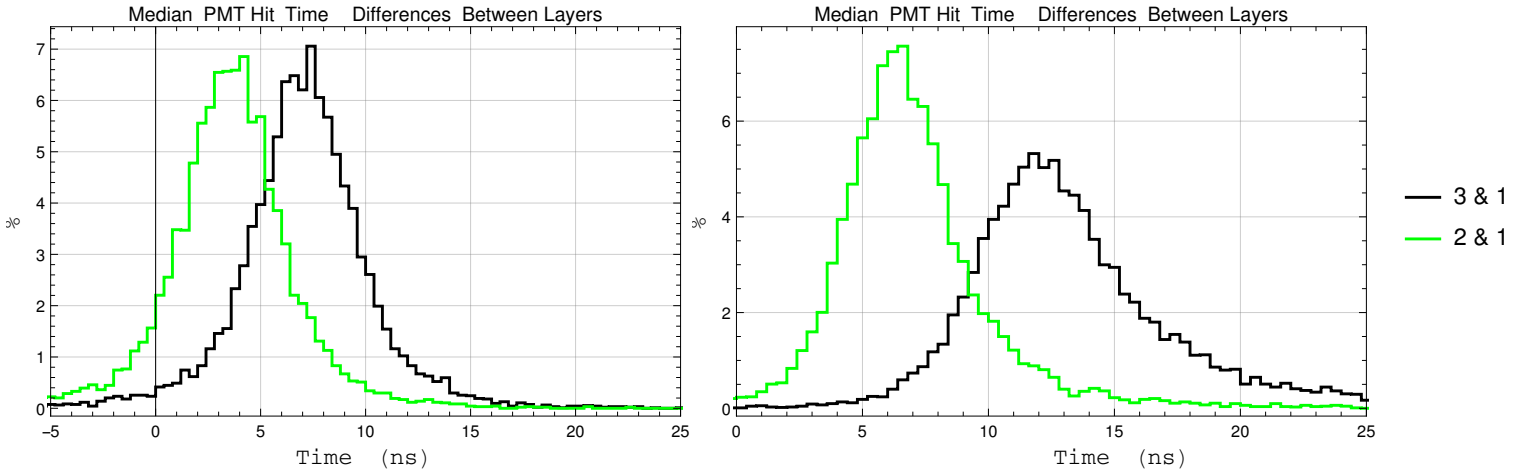
- Simulated light output in the scintillator as a function of electric charge for mCP masses of 0.1GeV (left) and 100GeV (right)



- Mean E deposit (q=0.01, m=0.1GeV) is 0.031MeV $\Rightarrow$ 350 photons
- Mean E deposit (q=0.01, m=100GeV) is 0.099MeV $\Rightarrow$ 1100 photons
- Note: these two plots are done for different energy distributions

PMT Peak Time

- For all photons recorded by pmt, take median time. Take only events with 3 consecutive PMTs in each layer activated. I have readout information for each PMT.
- Plot for q=0.01, and for 0.1GeV (left) + 100GeV (right).



- SC: $(\text{ScintLength} + \text{PMTLength})/c$=3.4ns
- SC: $(2 \times \text{ScintLength} + 2 \times \text{PMTLength})/c$=6.8ns

Detector Efficiencies

- Settings: Light output (64% anthracene), attenuation length (210cm), specular polished reflector with reflectivity = 0.98*
- 2nd layer offset of 0.5cm, layer separation of 12.7cm (pmt length), 10cm polyethylene + 10cm led shielding starting at r=33m, require all coincidences within 15ns

$$\text{Detector Efficiency} = \left(1 - \exp\left[-\left(\frac{q}{\xi}\right)^2\right]\right)^3 \tag{1}$$

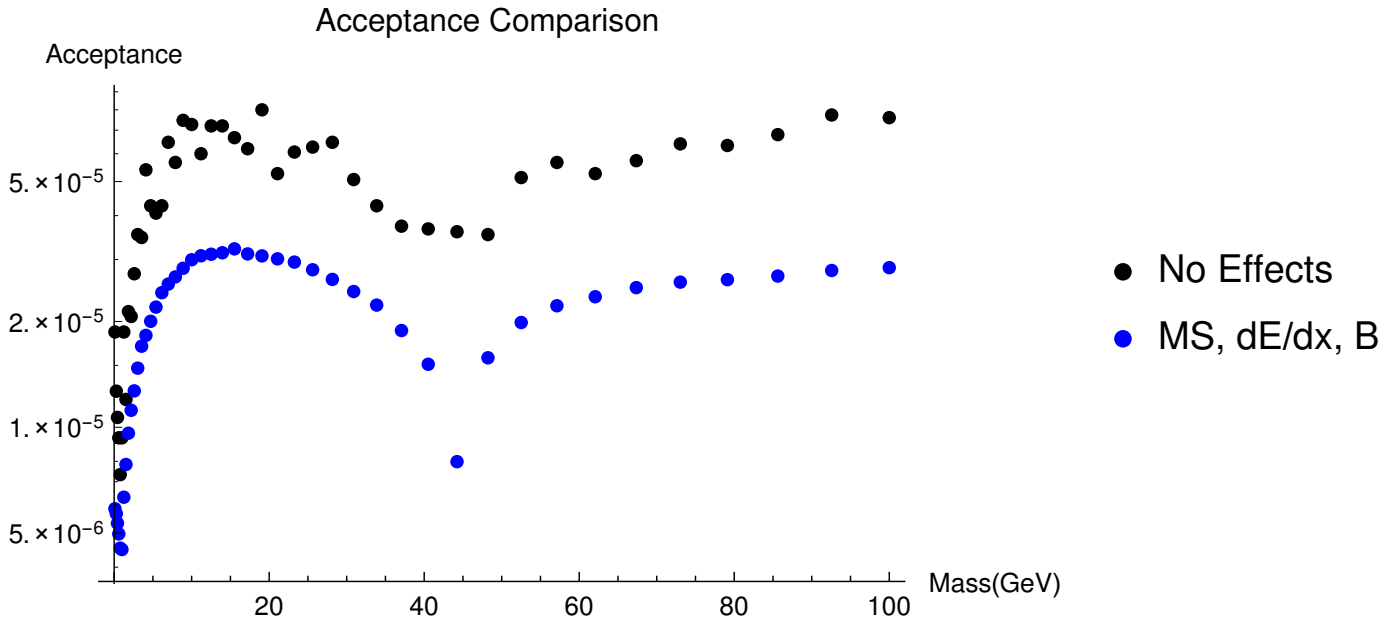
$$\text{Block Efficiency} = 1 - \exp\left[-\left(\frac{q}{\xi}\right)^2\right] \tag{2}$$

- 1410.6816 estimate: $2\frac{\text{MeV}}{\text{cm}} \times 90\text{cm} \times 10^4 \frac{\text{photons}}{\text{MeV}} \times 10\% \times \xi^2 = 1$ $\Rightarrow \xi = 0.00236$
- In following, large mCP charges not considered in fits

*Reflectivity Spectra for Commonly Used Reflectors, M. Janecek, 2012, IEEE Transactions on Nuclear Science

Acceptances (with Frank Golf and Bennett Marsh)

- Comparison of acceptance before and after multiple scattering, dE/dx and magnetic field effects.



- Rise up until ∼15GeV, contribution from Z boson increases
- Dip at ∼45GeV, on-shell Z production, mCP produced at rest, acceptance relies on ISR boost to escape magnetic field
- Rise afterwards since Z is off-shell again