The Hunt for Milli-Charged Particles at the Large Hadron Collider

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University of Pittsburgh

May 9$^{\mathrm{th}}$, 2016

Portals to New Physics

Many of the references are in initial proposal: 1410.6816

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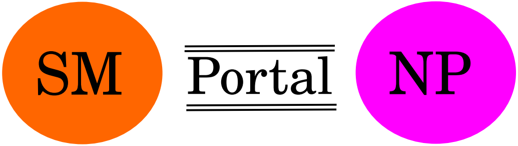

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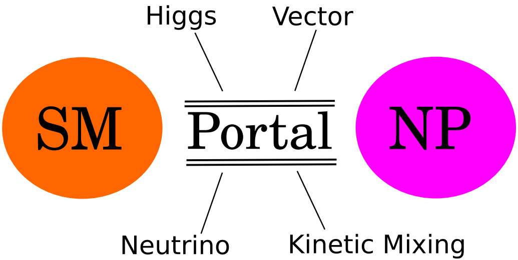

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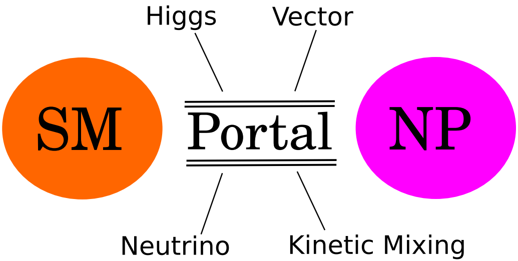

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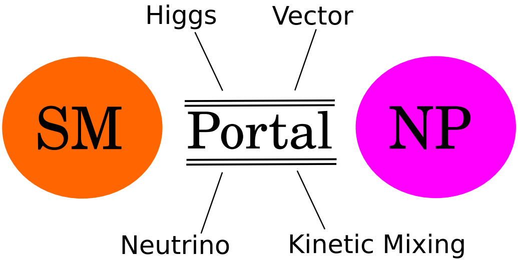

Kinetic Mixing

Can give rise to particles with fractional electric charge (milli-charged particles)

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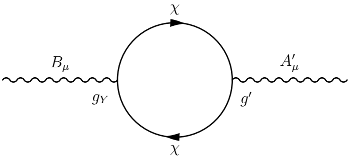
Kinetic Mixing: A Story

Given **heavy** χ gauged under $U_Y(1) \times U'(1)$



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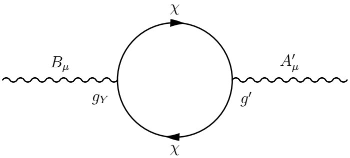

Effective operator: $-\frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu} \left(\kappa \equiv \frac{g_Y g'}{16\pi^2} < 1 \right)$

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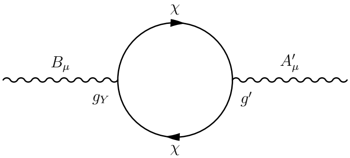

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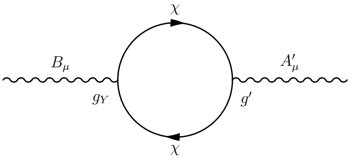

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$$\mathcal{L}_{SM+NP} \supset -\frac{\kappa}{2} A'_{\mu\nu} B^{\mu\nu} + i\bar{\psi}\partial\!\!\!/\psi - \bar{\psi} g' A\!\!\!/' \psi - M\bar{\Psi}\Psi$$

$$\rightarrow i\bar{\psi}\partial\!\!\!/\psi - \bar{\psi} g' A\!\!\!/' \psi - M\bar{\Psi}\Psi + \kappa g' \bar{\psi} B\!\!\!/ \Psi$$

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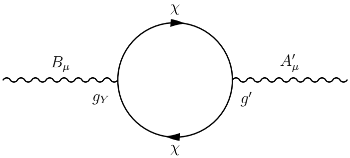

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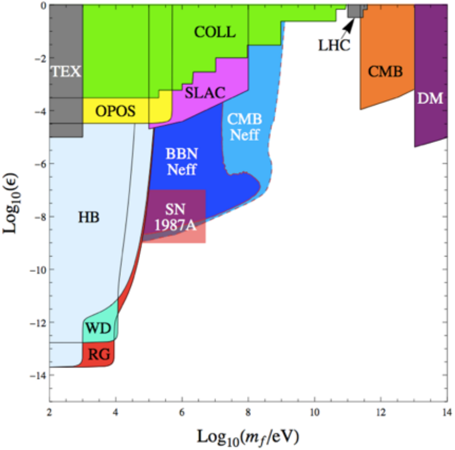
$$\to i\bar{\psi}\not{\partial}\psi - \bar{\psi} g' \not{A}' \psi - M\bar{\Psi}\Psi + \kappa g' \bar{\psi} \not{B} \Psi$$

Ψ is now "milli-charged" as seen by B_μ!

Existing Constraints



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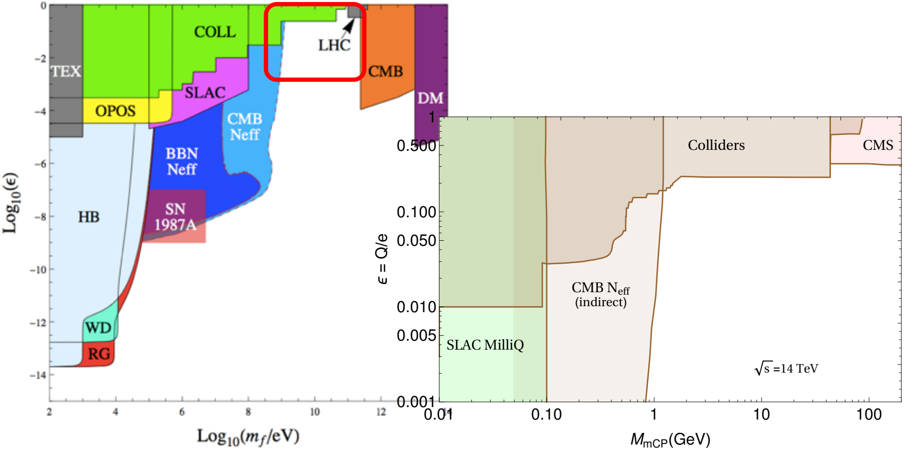

Milli-Charged Particles at the LHC

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]

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(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

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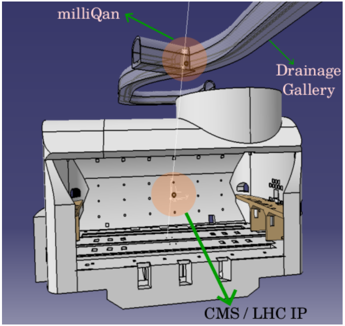
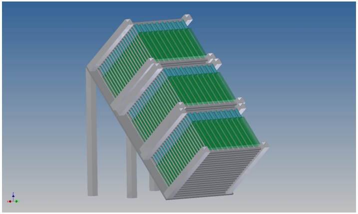
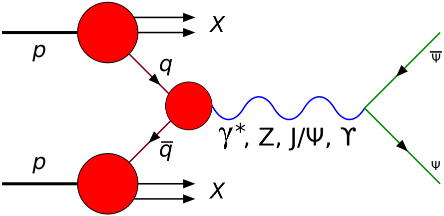




Credit: Martin Gastal for 3D scans

Signature of mCP at LHC

Production Mechanism



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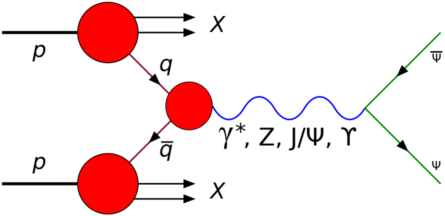


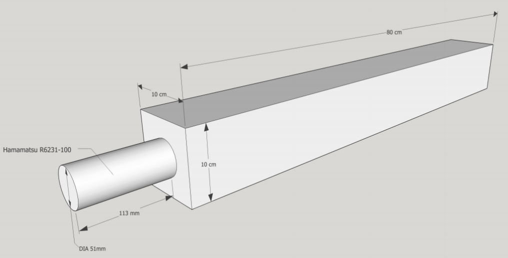
Final State

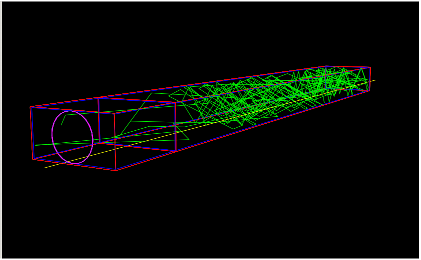
- $Q_{mCP} \in [0.002, 1]e$
- $M_{mCP} \in [0.1, 100]$ GeV

Need sensitivity to very small electric charge, precise timing information!

Detector Design

- Basic unit is a plastic scintillator coupled to PMT





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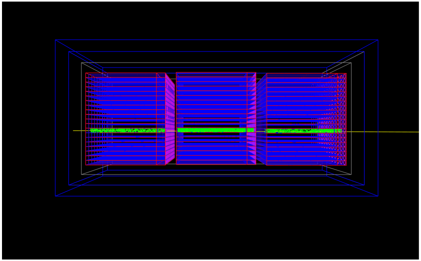
- 3 layers, each containing 200 5cm$\times$10cm$\times$90cm scintillators (precise details under study)



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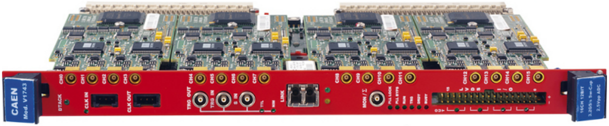

`http://www.caen.it/`

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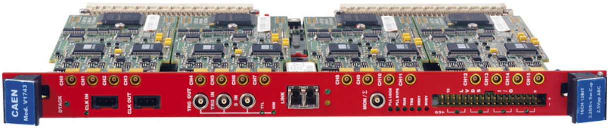

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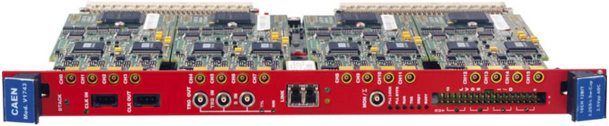
  - Offline, require 3-fold coincidences



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LHC Backgrounds:

- 14m of rock between end of CMS and beginning of milliQan

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- Given digitizer triggers and offline requirements (3-fold coincidence in 15ns), reduce the background rate to $\sim 10^{-6}$Hz
- Results in $\sim O(50)$ background events for 3000fb^{-1}

Sensitivity

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

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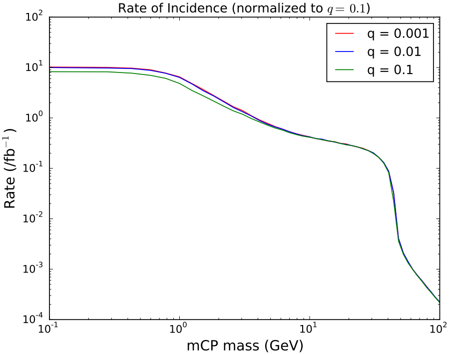

Dip due to falling σ with increasing mass

Bump is Z enhancement

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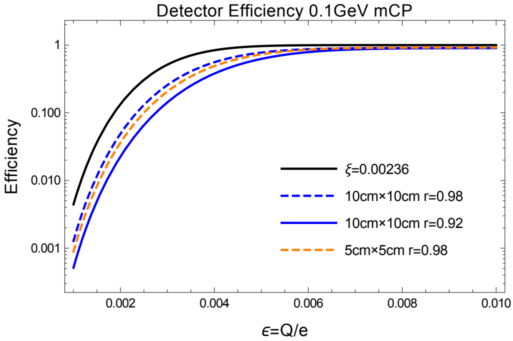

Black line:
Analytic estimate

Other lines:
Geant4
Varying scintillator dimensions

How many signal events?

Collecting info from previous slides for 0.1GeV 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

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Detector Efficiency → 0.1

Acceptance → $10^3 \left(\frac{0.002e}{0.1e}\right)^2 fb$

Luminosity → $3000 fb^{-1}$

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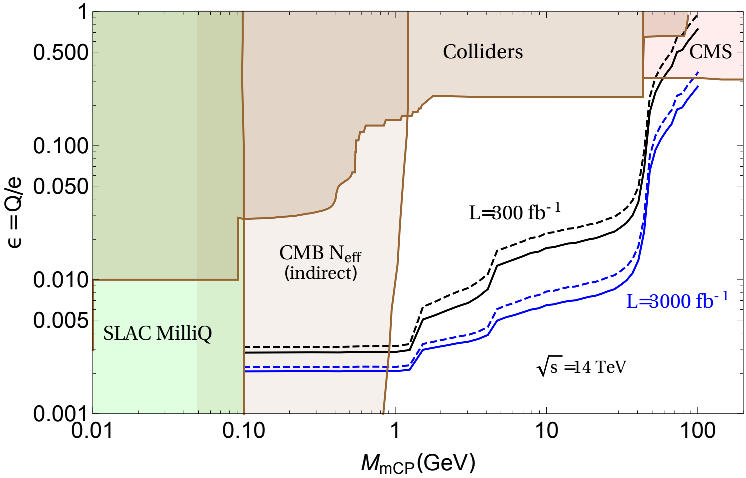
LHC Reach with milliQan



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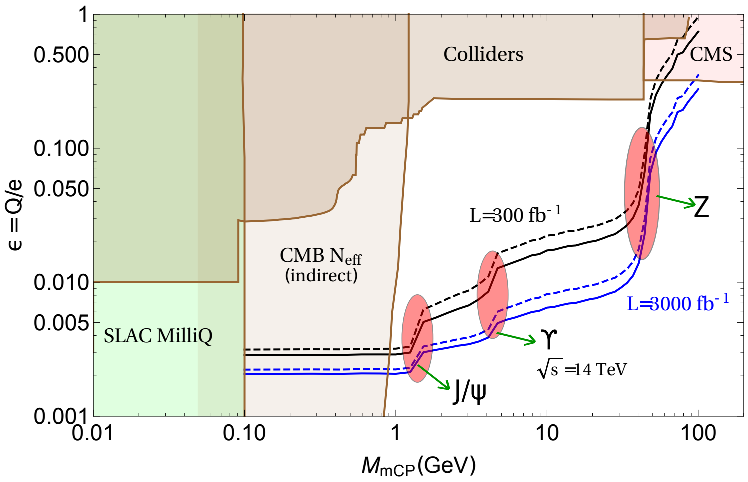

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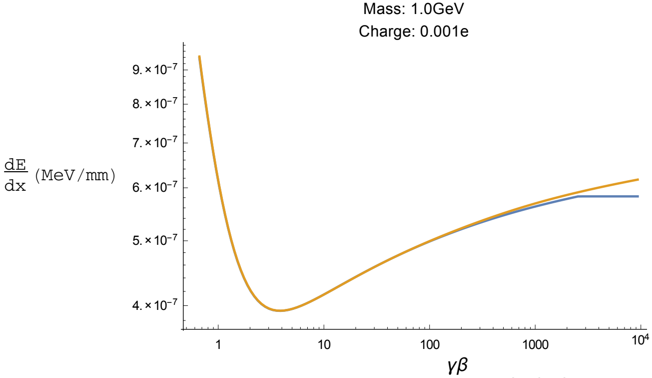
Exciting physics ahead!

Backup

Backup Slides

Energy Loss

Energy loss of mCP through carbon



*Maximal $\gamma\beta$ corresponds to 1000TeV kinetic energy

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

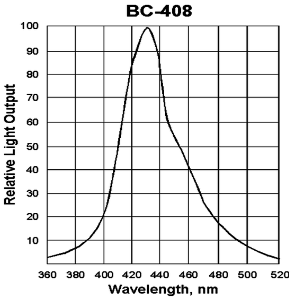
$\delta(\beta\gamma)$ follows Sternheimers parameterization (function by parts fitted to material)

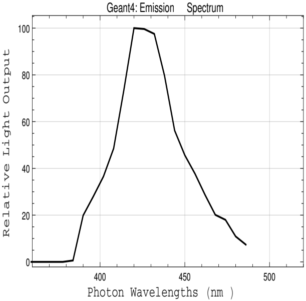
W_{max} max E transfer to e- I: mean excitation energy

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*:

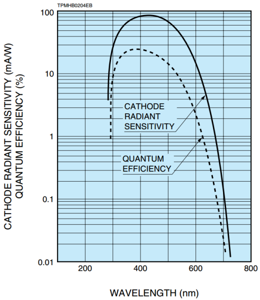




*www.crystals.saint-gobain.com/document.aspx?docId=274290

PMT -Hamamatsu R329-02

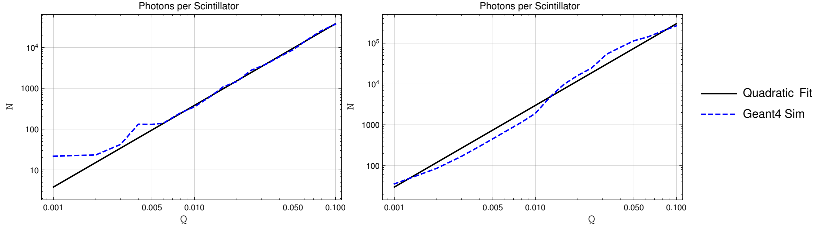
- Real active area pmt dimensions (23mm radius)
- Spacing between layers for PMT length (12.7cm)
- Quantum efficiency profile* for Geant4 photocathode efficiency



*http://www.hamamatsu.com/resources/pdf/etd/R329-02_TPMH1254E.pdf

Number of Photons Emitted

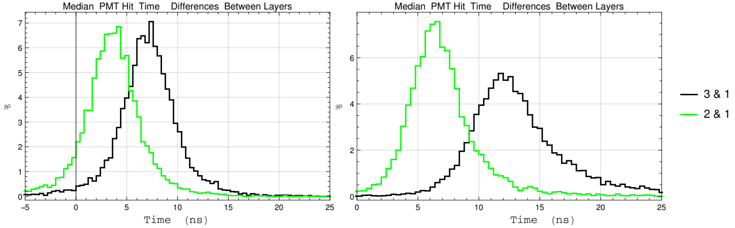
- Simulated light output in the scintillator as a function of electric charge for mCP masses of 0.1GeV (left) and 100GeV (right)



- 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

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

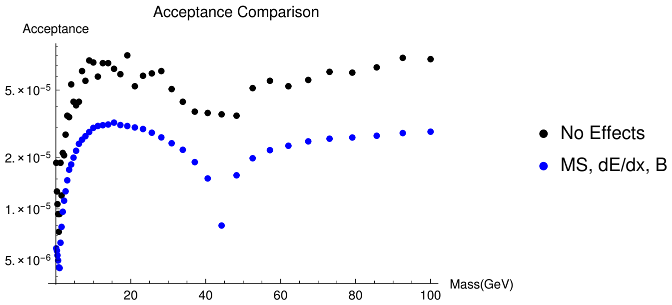
$$\text{Block Efficiency} = 1 - \exp\left[-\left(\frac{q}{\xi}\right)^2\right] \quad (2)$$

- 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