A Milli-window to Another World

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Beyond WIMPS workshop, May 2015

The Successful Standard Model

$SU(3) \times SU(2)_L \times U(1)_Y$ gauge symmetry

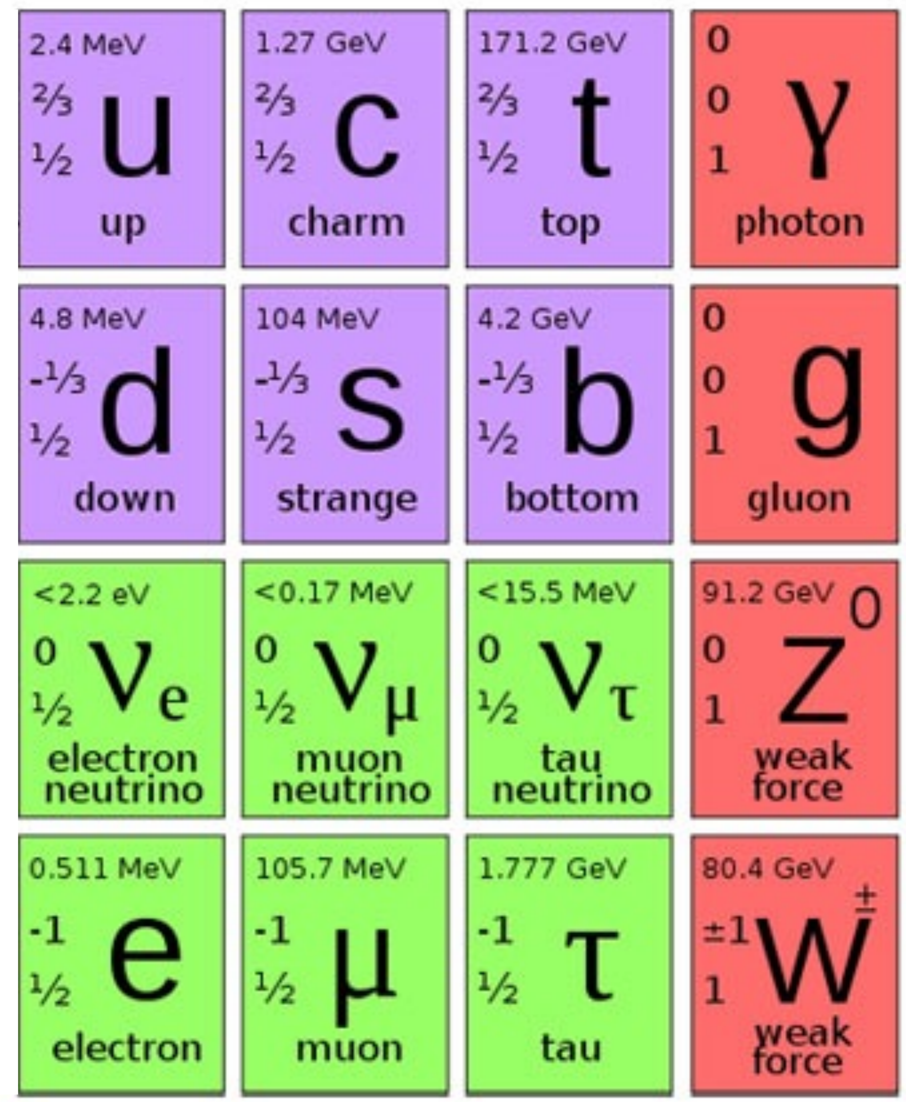
Incredibly predictive

With a few known shortcomings
Dark Matter, neutrino masses,…

This talk: Charge (non)-quantization

Does it make sense? And if so,
how to look for new
non-quantized charges

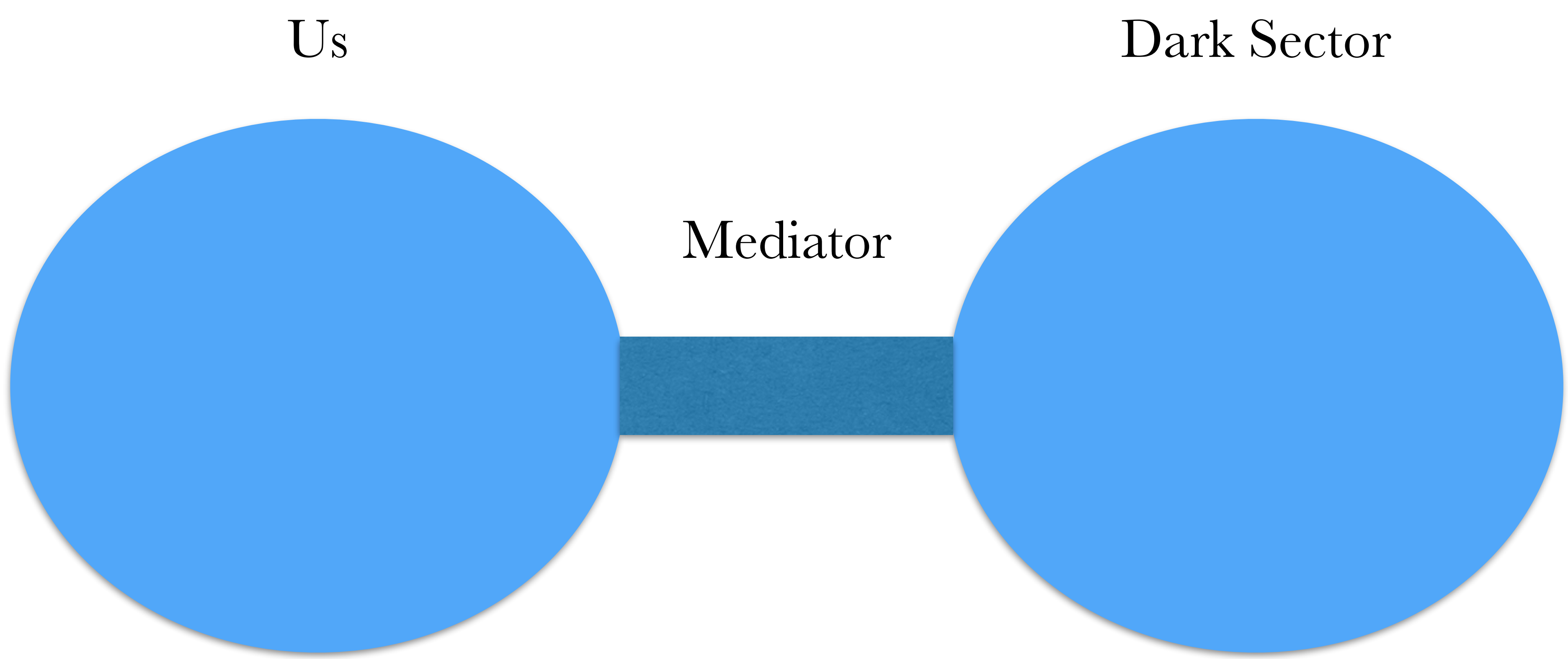
What the heck does charge
quantization have to do with DM?



+ Higgs boson!

Hidden Sector Paradigm

An increasingly popular effort to probe beyond the SM physics that lives in a "dark sector"



Well-motivated by light DM
For light DM interactions between the DS and SM mediated by a light field

One organizing principle for probing it: focus on low-dimension operators:
vector portal, Higgs portal, neutrino portal

What are the generic properties one should expect from matter in the DS?
I will focus on the vector portal

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

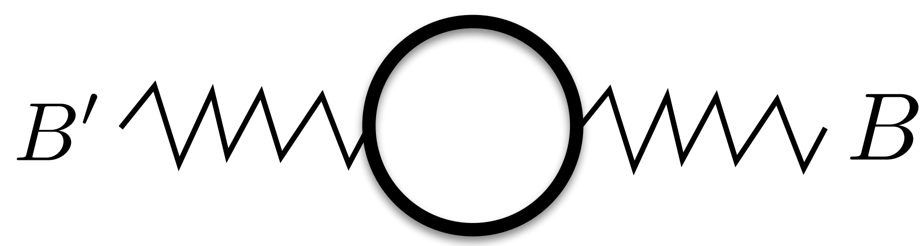
An elegant mechanism is that by Holdom, through the addition of a new massless U`(1) boson

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

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)

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

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)

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

Existing Constraints

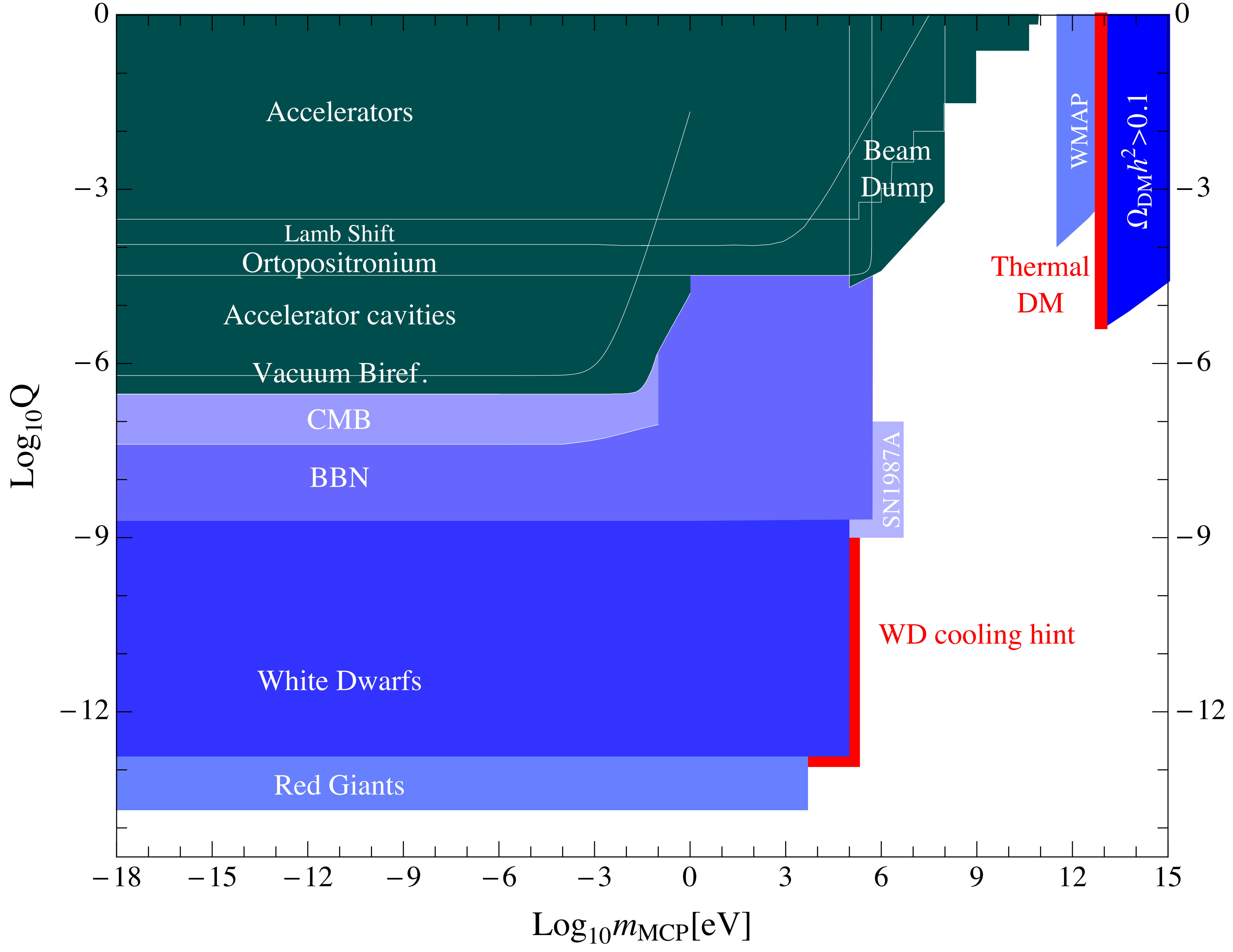
Status on Searches for Mini-charged Particles (mCPs)

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 (see work by local theorists)
Cosmology	BBN and CMB number of effective relativistic degree of freedom bounds
Laboratory	Direct bound from the invisible decay of ortho-positronium Direct bound from the Lamb shift Direct constraint from accelerators: SLAC Milli-Charge experiment, E613, ASP, LEP More later on this

Status on Searches for Mini-charged Particles (mCPs)



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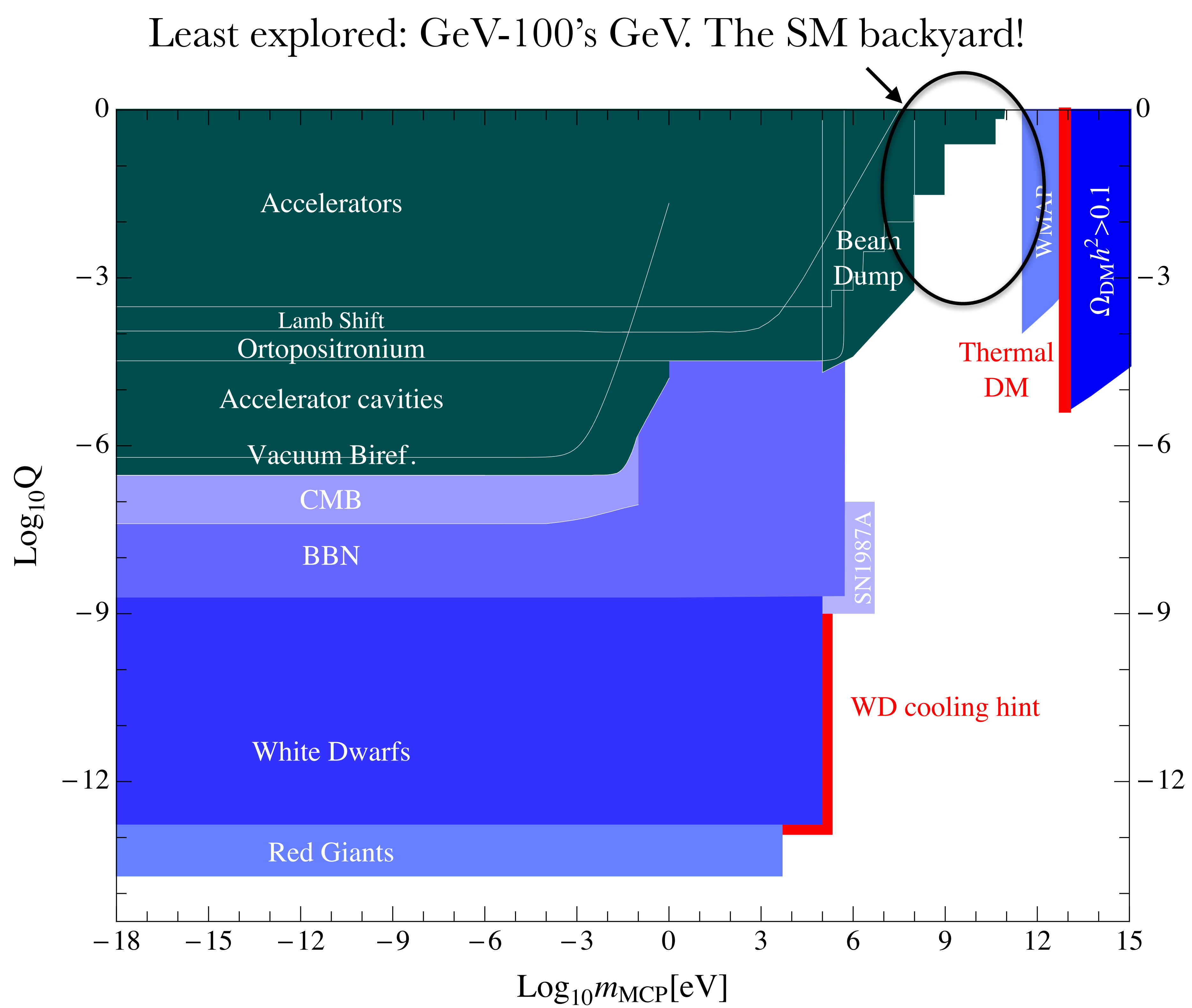
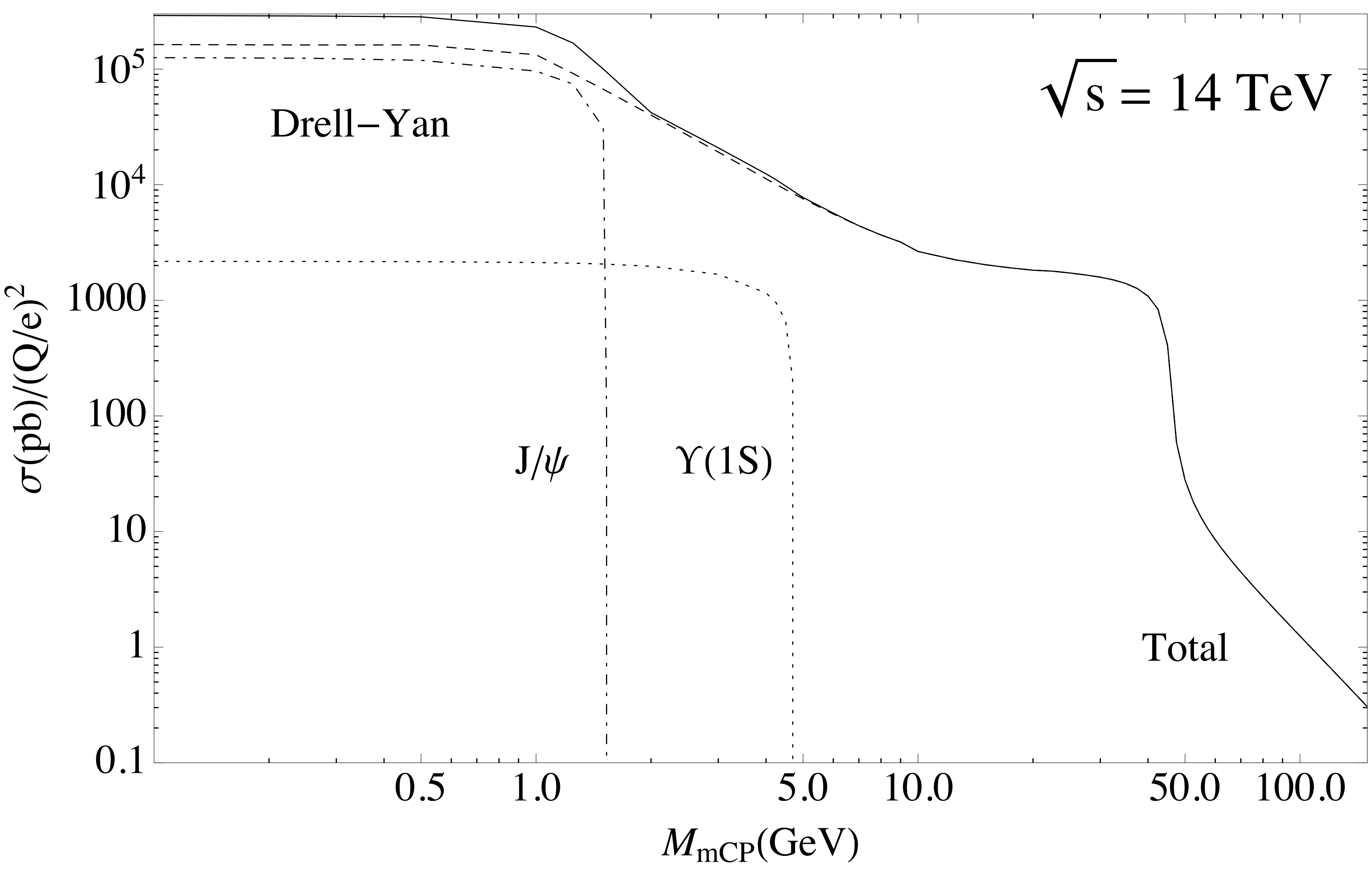


Millicharges at the LHC

Looking for mCPs above GeV

Surely the LHC?
Can produce them analogously to SM charged fermions
i.e. Drell Yan production, rare meson decays



Energy Loss of mCPs

The problem: mCPs will deposit very little energy

The LHC general experiments designed to measure very energetic objects such as photons, jets, leptons

Comparison

dE/dx for muons ~ MeV/cm

dE/dx for mCP ~ (Q/e)^2 MeV/cm

and R ~ 1/Q

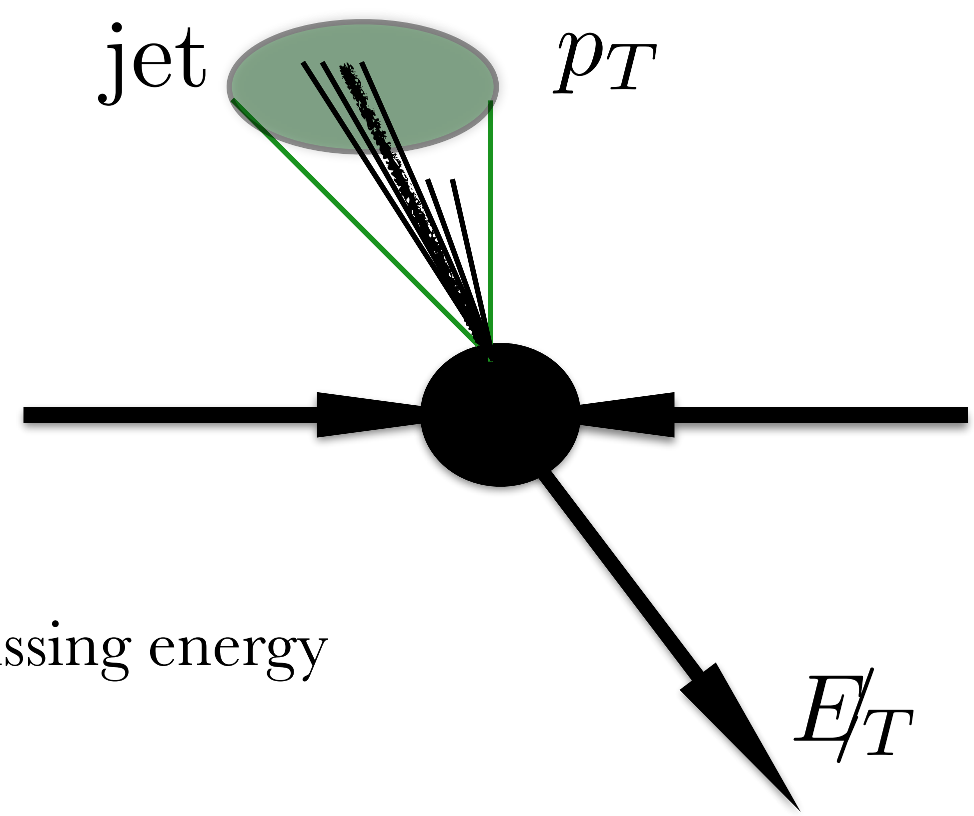
So, mCP might not register at the LHC detectors sub-components…

Missing Energy to the rescue?

The mCPs could appear as missing energy instead

Momentum conservation implies $\vec{P}_{T,\mathrm{vis}} = -\vec{P}_{T,\mathrm{invis}}$

Can look for visible-energy + missing energy $pp \to j/\gamma/\ell + \bar{\psi}\psi$



Example: 1 jet + missing energy

Darn Neutrinos

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

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 $S \gtrsim 0.1B$

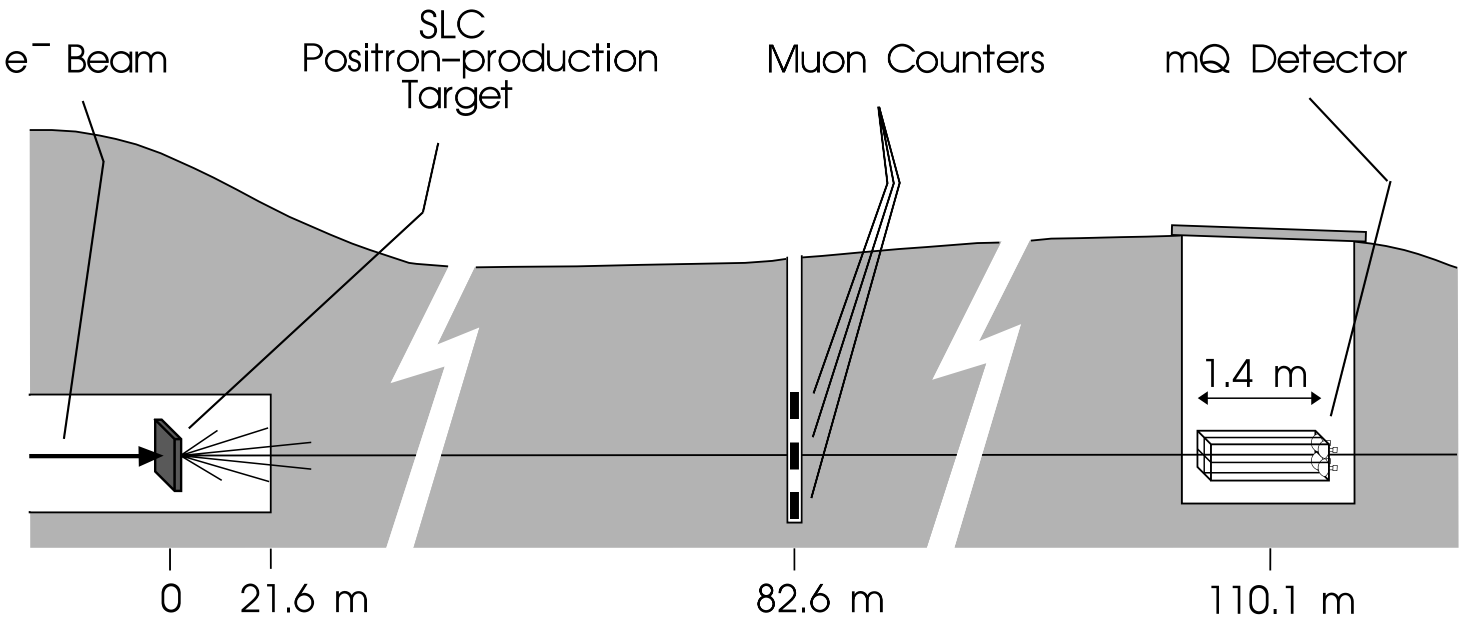
Punchline: LHC jet + missing energy unlikely to improve sensitivity to mCPs beyond current bounds

Lessons from the SLAC MilliCharge Experiment

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

29.5 GeV pulsed electron beam

~ 10^{19} electrons on target



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

Sensitivity to single-incitation photo electron (PE) pulses

Note: Significant single-few-PE backgrounds from dark current

Why not deploy a similar setup near the LHC interaction points?

LHC Interaction Points

Two main purpose detectors: ATLAS and CMS

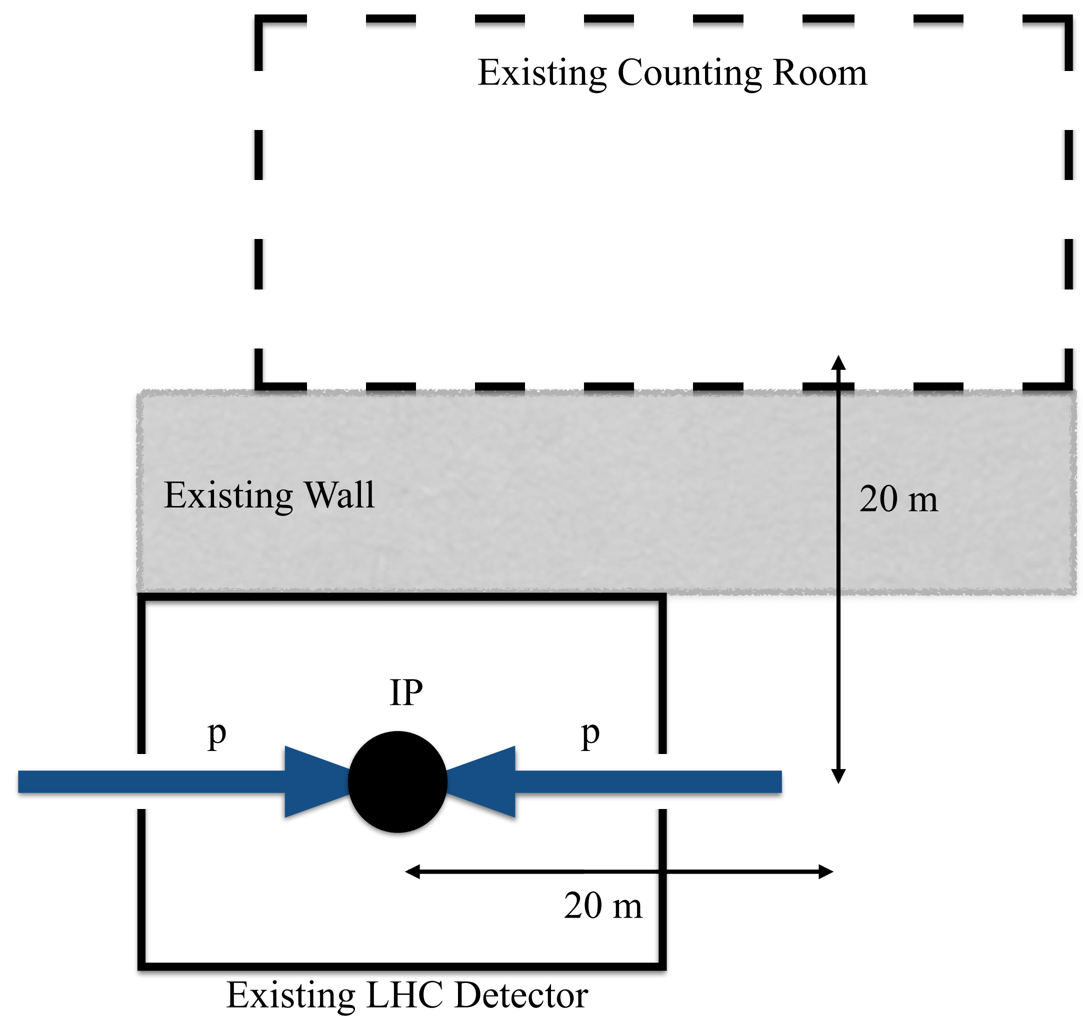
Typical layout

Both ATLAS and CMS feature a `counting room'
or older control rooms

Stores equipment, electronics, etc

Conveniently shielded
Personnel allowed during normal beam running

A promising location for deploying a detector
near the IP
Existing shielding will reduce
beam-related backgrounds too!



Efficient Detection

Why not deploy a similar version of the mQ detector in the counting (or control) room?

Deploy 10 cm x 5cm x 140 cm scintillating bars
Need 200 to cover 1m^2

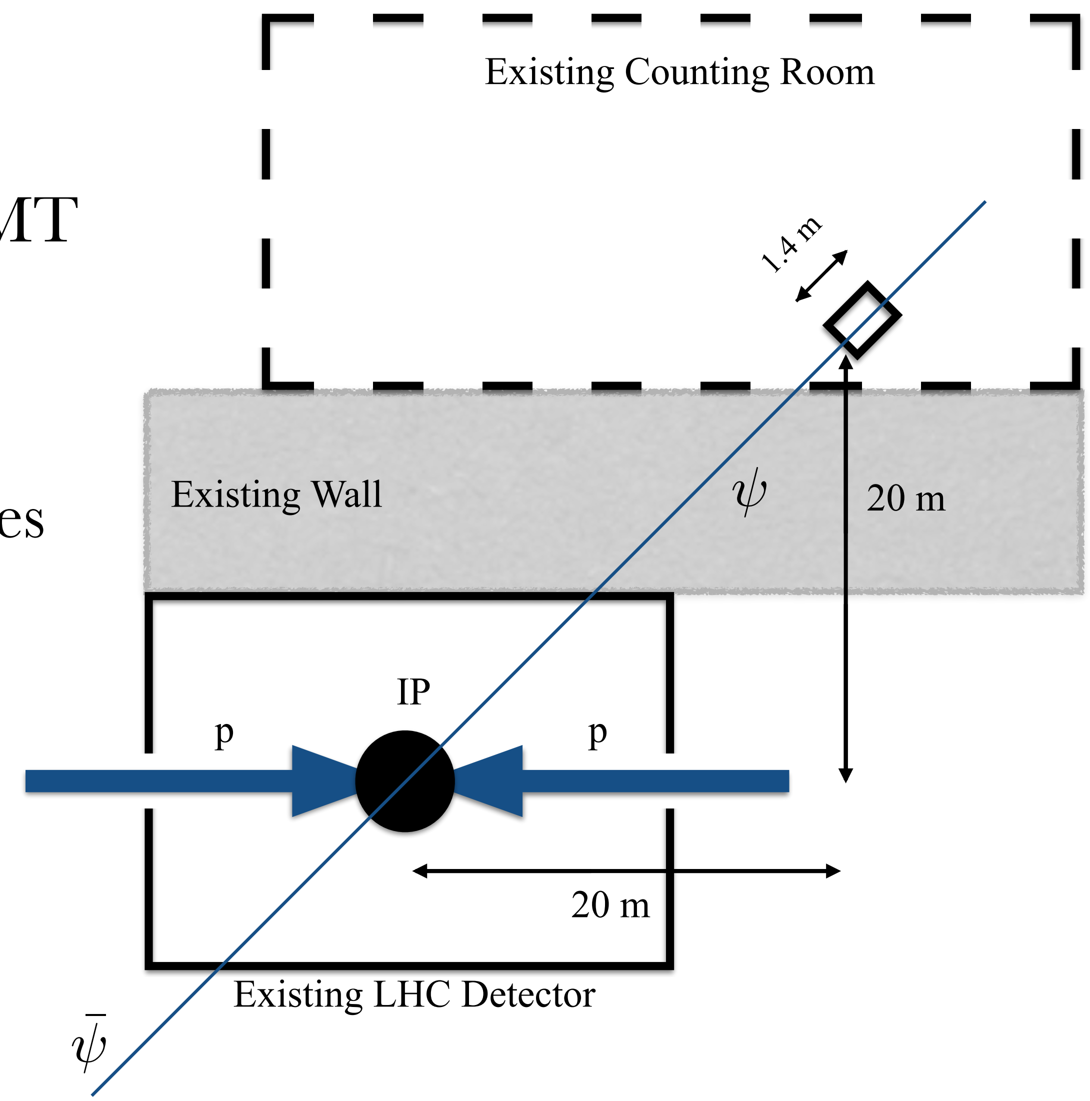
High detection efficiency
mCP with Q = 10^{-3}e gives ~ 1 PE in one PMT
(Assuming a 10% det. efficiency)

The problem
Not a pulsed beam. Large dark current rates

From PMT Handbook
Rate (1 PE) ~ 500 Hz

Livetime ~ 1 year

Background = 10^{10} events



Solution: Coincident hits

Look for single/few PEs in ~ 3 scintillator detector copies $\Delta t \approx 5\text{ns}$ apart

Dark noise background reduced dramatically!
coincidence prob = $\Delta t \times R_{\text{dark}}$

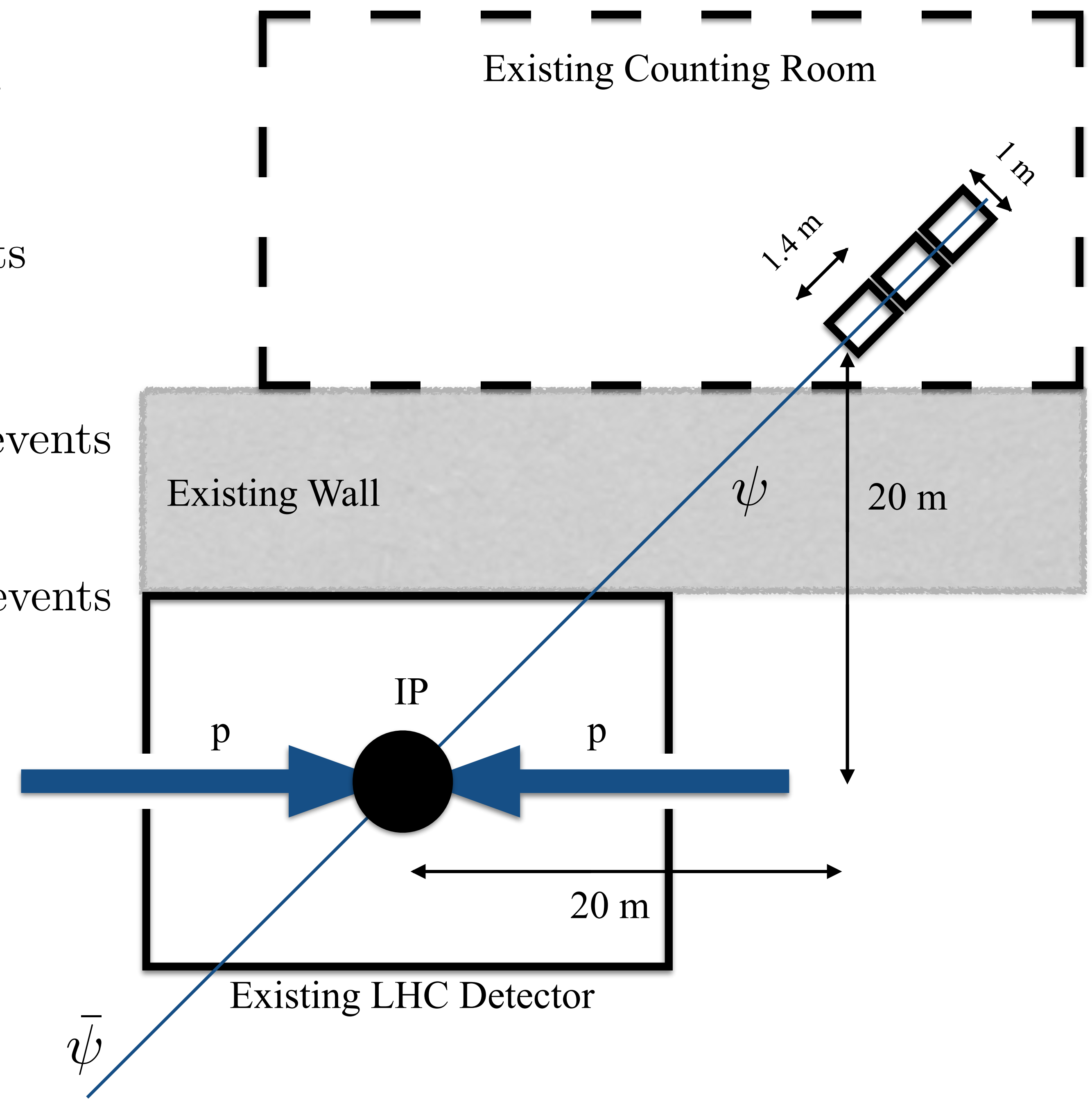
$N_{\text{PE}\geq 1}(1\text{ PMT}) = \text{livetime} \times \text{dark rate} \approx 10^{10}$ events

$N_{\text{PE}\geq 1}(2\text{ PMT}) = \text{N}_{\text{PE}\geq 1} \times \text{coincidence prob.} \approx 10^{4}$ events

$N_{\text{PE}\geq 1}(3\text{ PMT}) = \text{N}_{\text{PE}\geq 2} \times \text{coincidence prob.} \approx 10^{-2}$ events

Need 200 scintillating bars to cover ~ 1 m^2

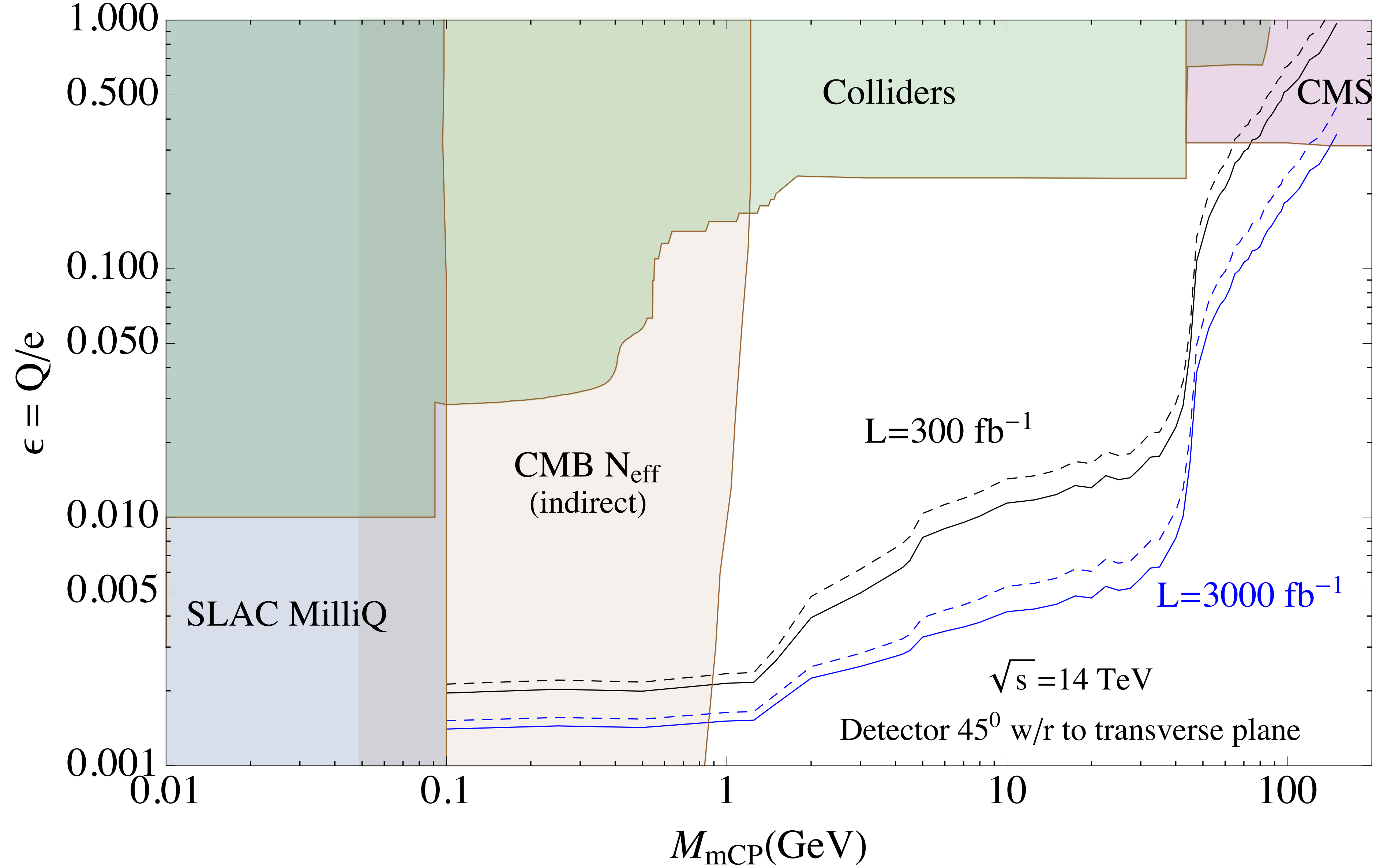
Three coincident 1 PE hits gives O(1) events expected!



Sensitivity

mCP@LHC Potential

Model-independent (direct) bounds on mCPs



Another Phase

What's in the Dark Sector?

EI, Itay Yavin, 1506.xxxxx

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

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

Two cases studied in the literature

$$\frac{1}{2} m^2_{B'} B^{'2}$$

$m_{B'} = 0$ 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 $\epsilon_\gamma e = \kappa \cos\theta_W \cos\theta_{W'} e'$

Existing constraints on Mixed Phase

The mixed phase still constrained by limits from Holdom and Okun phases
Each experiment more or less applicable depending on dark Weinberg angle

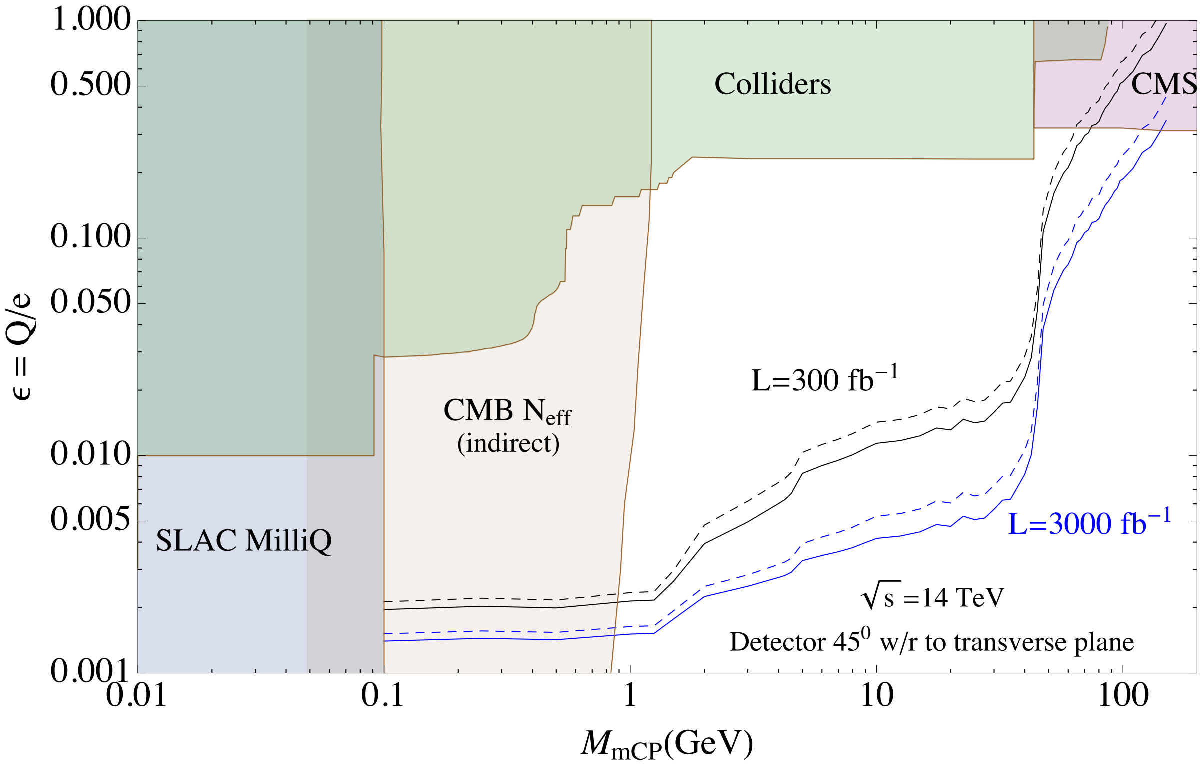
Massless phase searches constrain ϵ_γ

Massive phase searches constrain ϵ_Z

One exception: Mass of the Z-boson primarily constrains κ

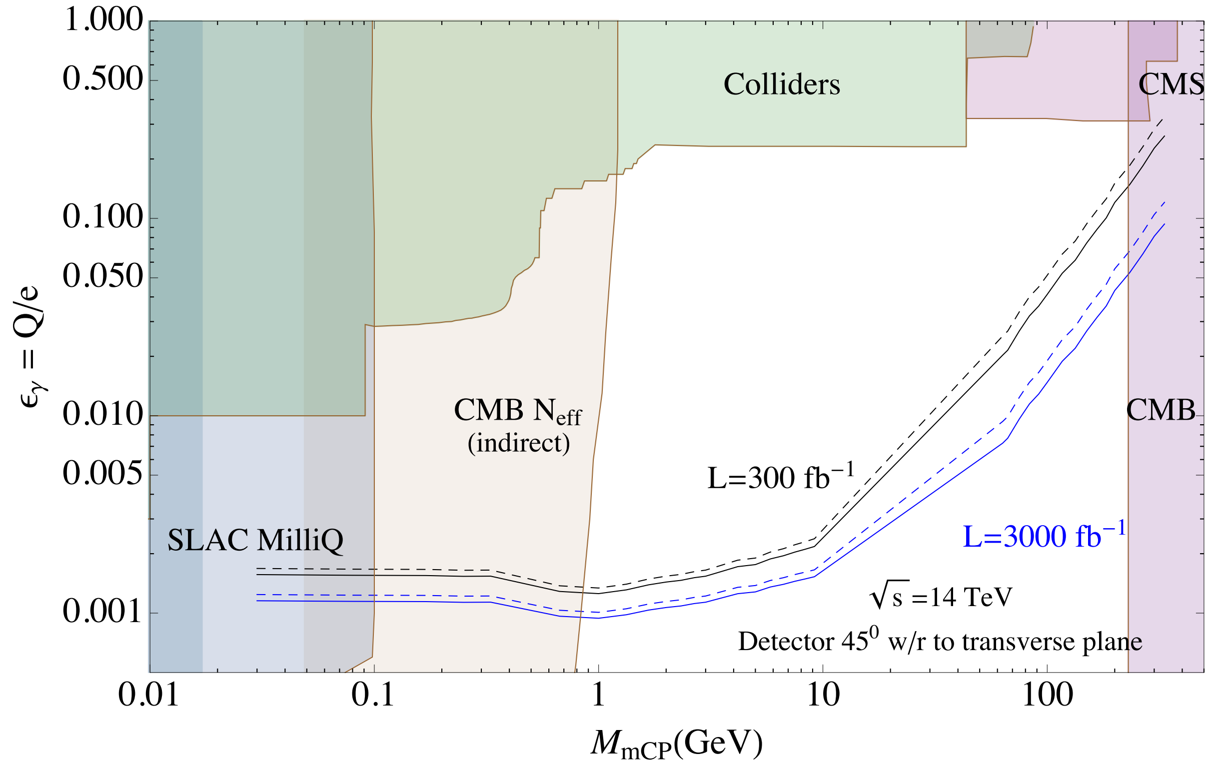
Looking for mCPs above GeV

Massless phase



Mixed phase

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



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

Mixed phase offers new striking signatures
milli-jets, two-mCP signal from boosted Z'

Conclusions

Gave an example of a basic question about Nature that can be probed at the LHC:
Are there particles with non-quantized charges?

Progress in the past made by high intensity systems (stars, fixed target low energy, etc)
Neat new application for the LHC!

Could potentially shed light on mCPs in the 100 MeV - 100 GeV
Least constrained part of the parameter space by direct searches
precisely in the regime where our SM lives

mCPs could offer a new window into an intricate DS that may contain Dark Matter
Dark neutrinos? Dark QCD?

Plan to measure backgrounds in-situ this summer during Run 2!