November 27, 2023

Searching for Scalars in Neutrino Facilities

Duncan Rocha

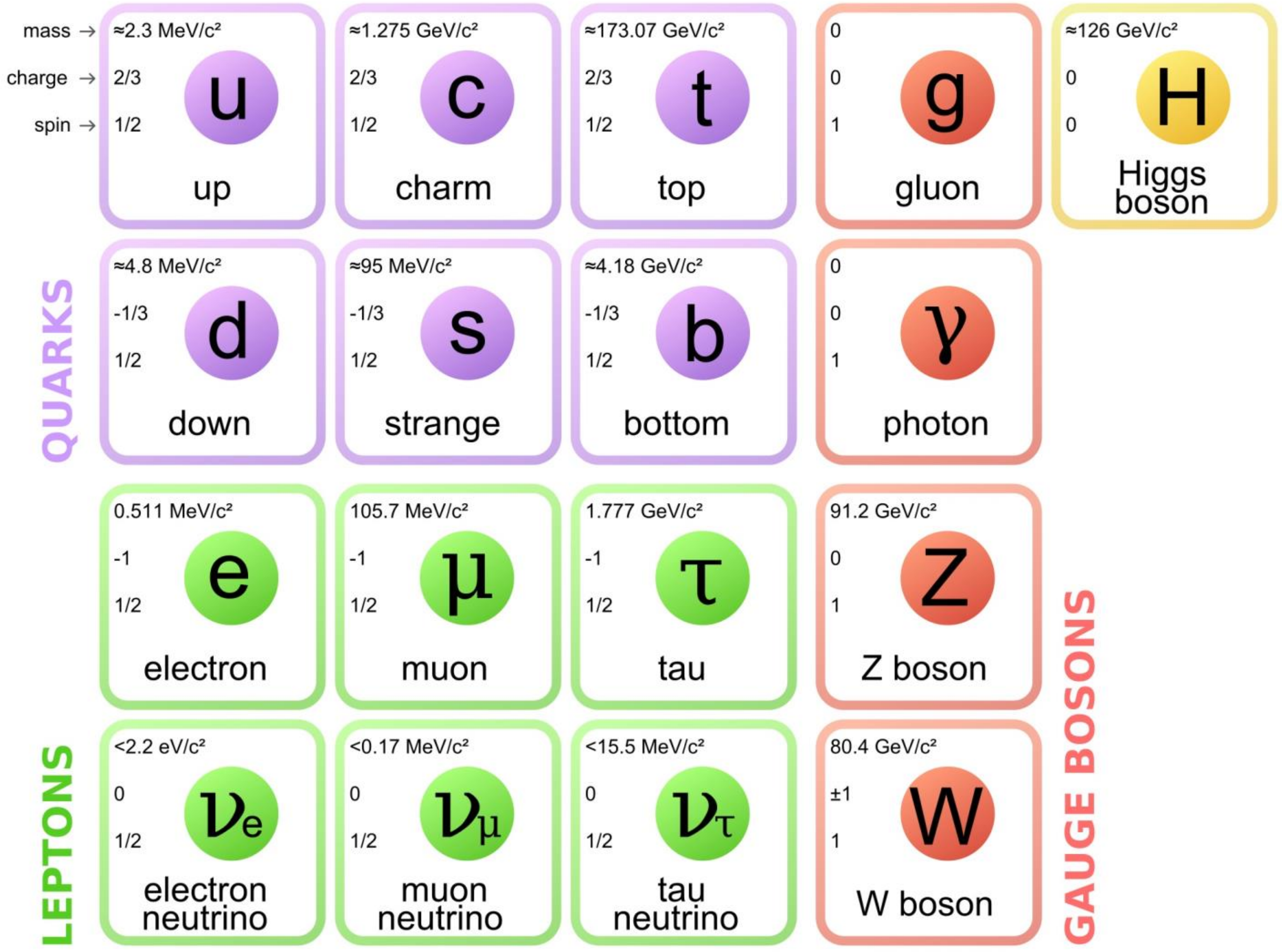
Outline

1. Background – The Standard Model (SM) and open questions

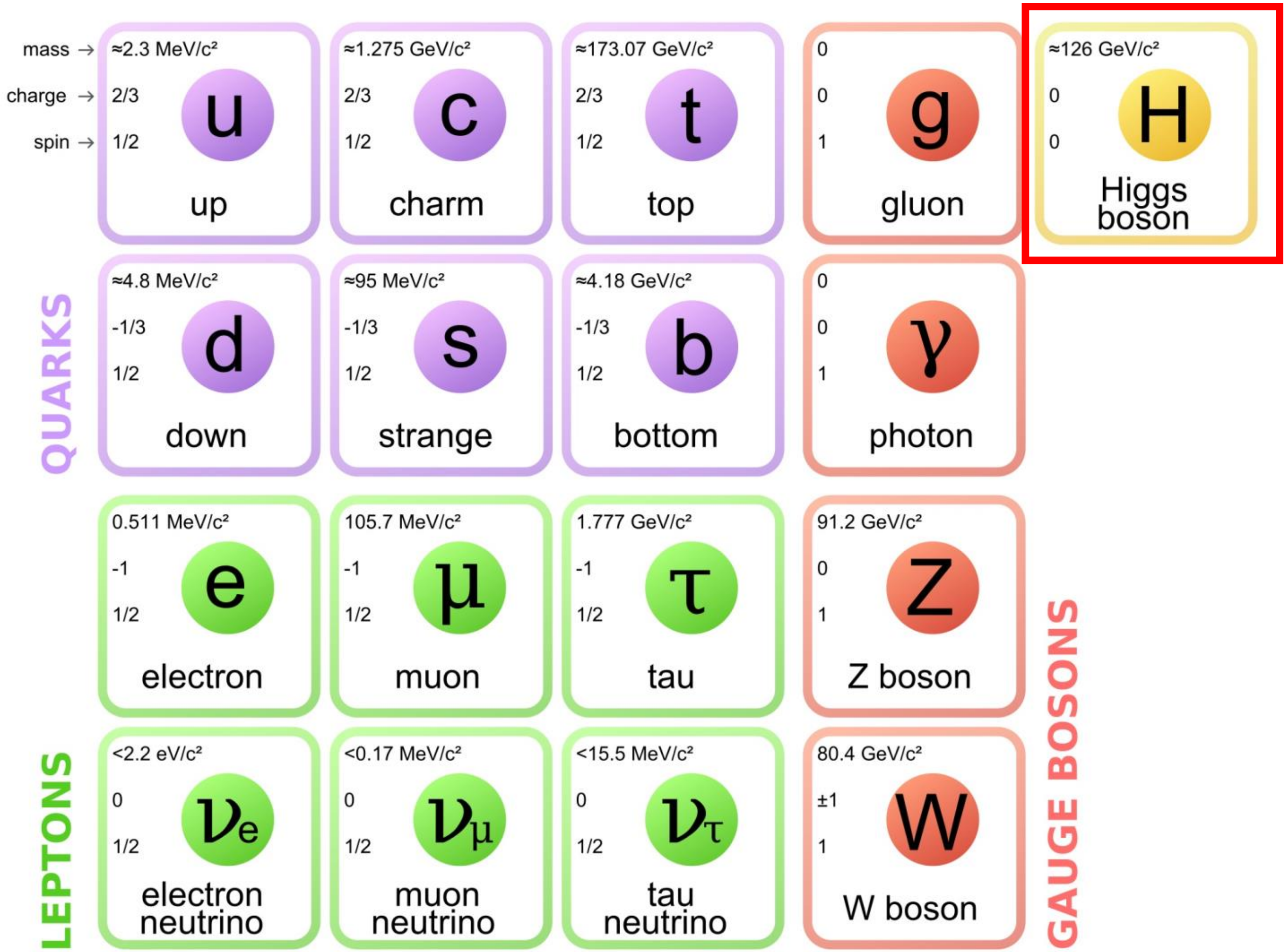
2. Model Construction

3. Muonphilic scalars at MiniBooNE/MicroBooNE

Standard Model – A Recap

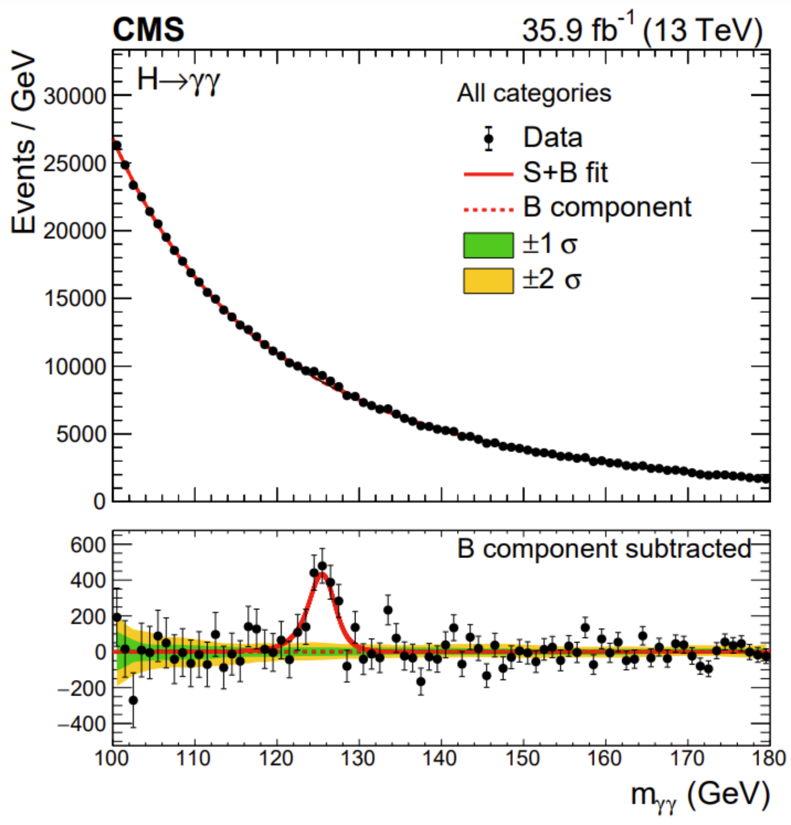


Standard Model – A Recap

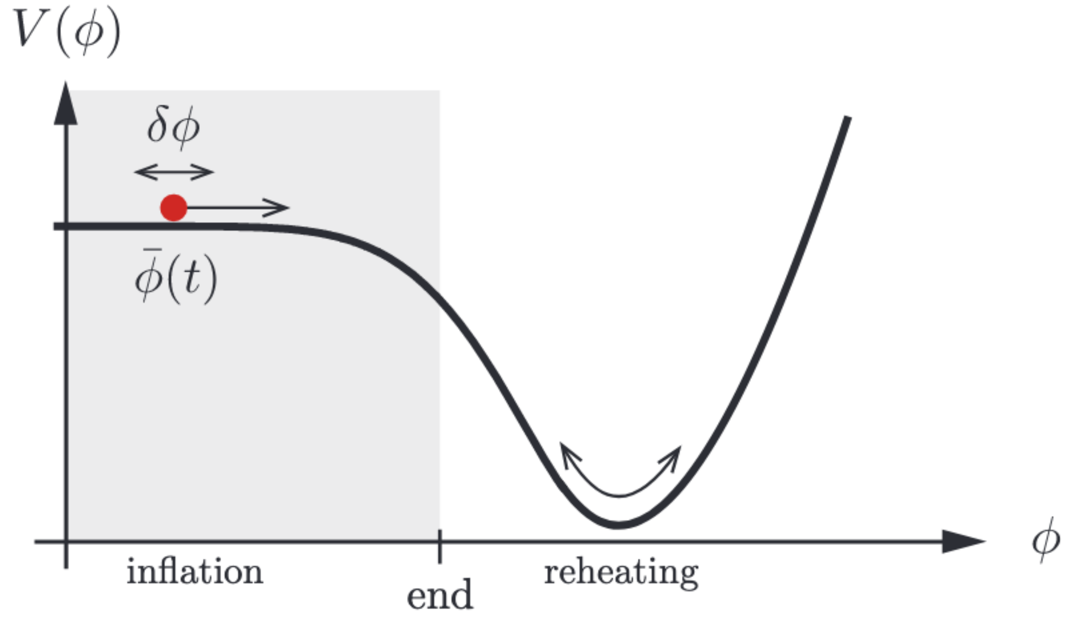


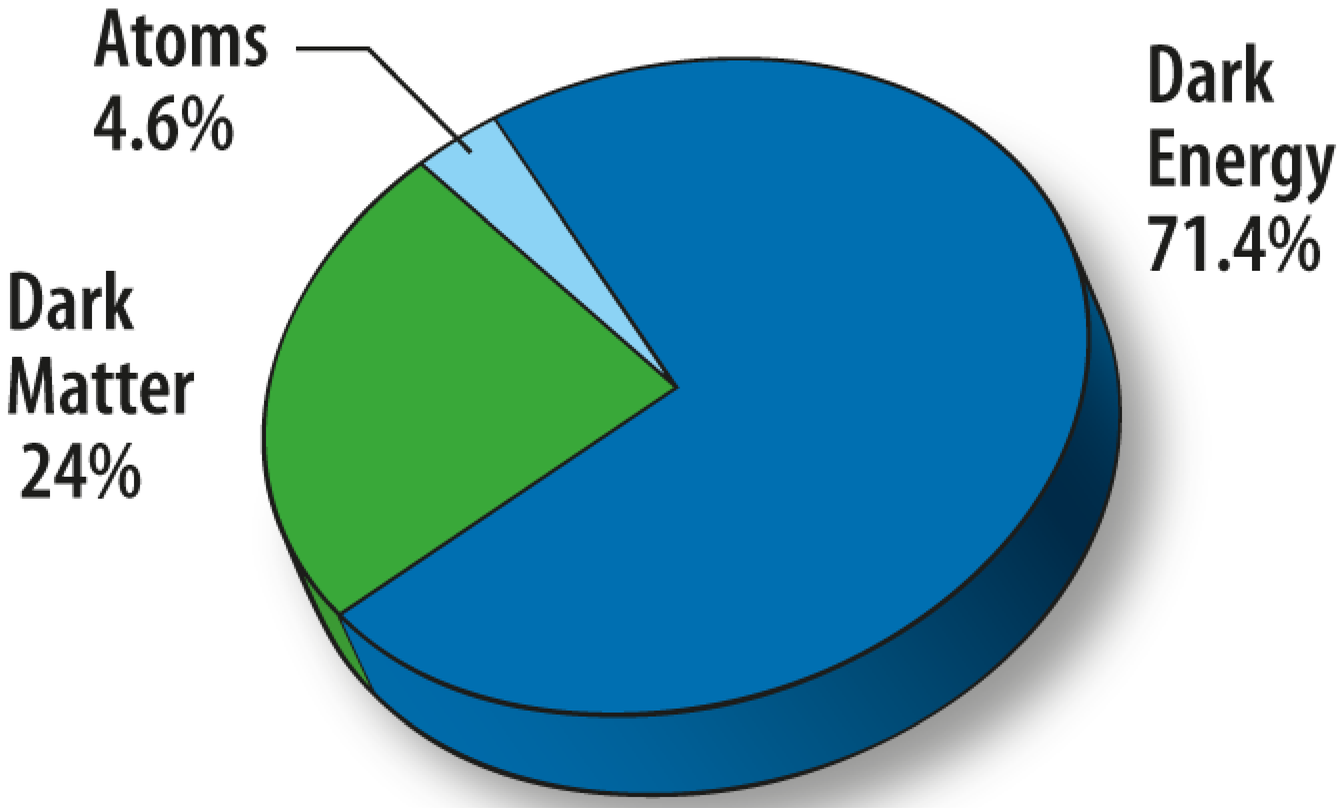
In standard physics there are two known (ish) scalars:

Higgs

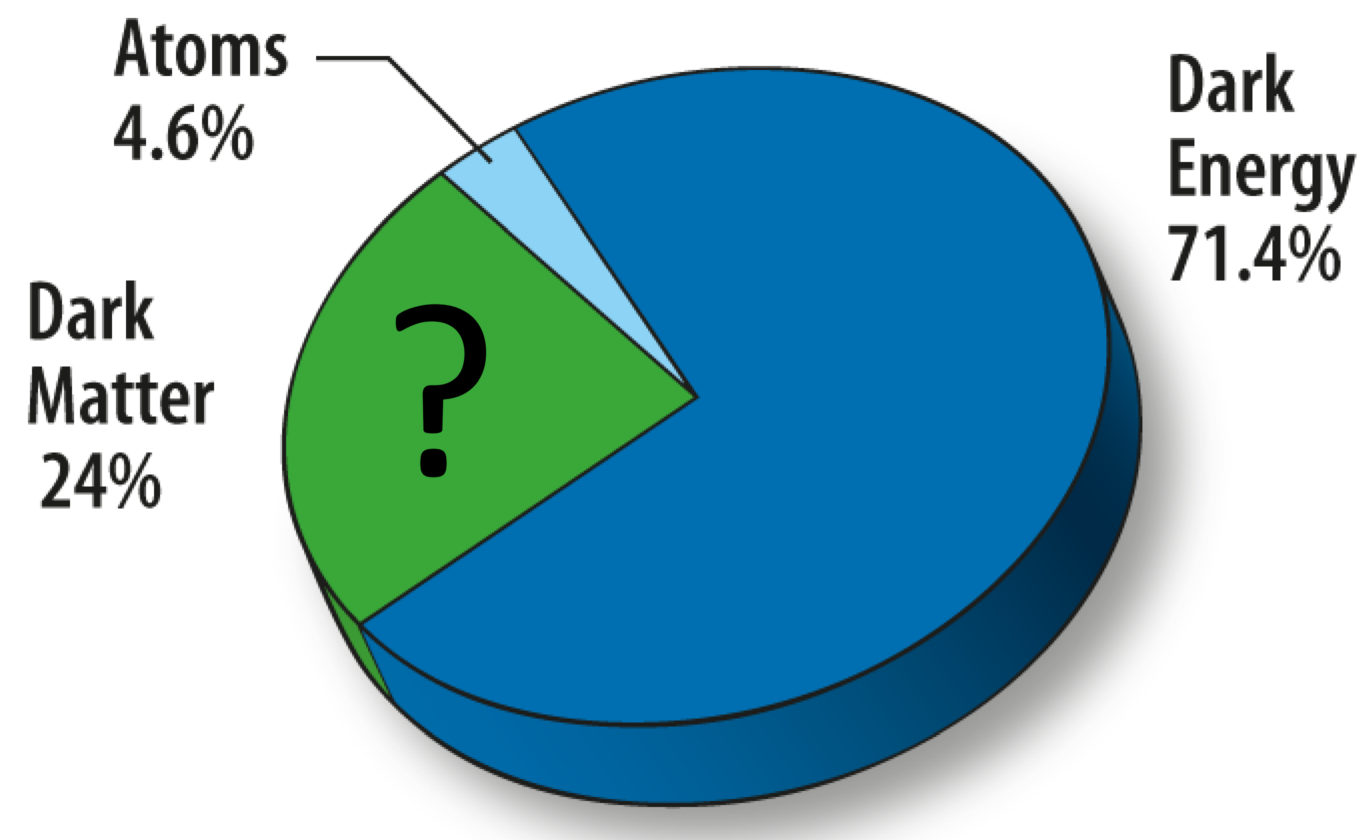


Inflaton

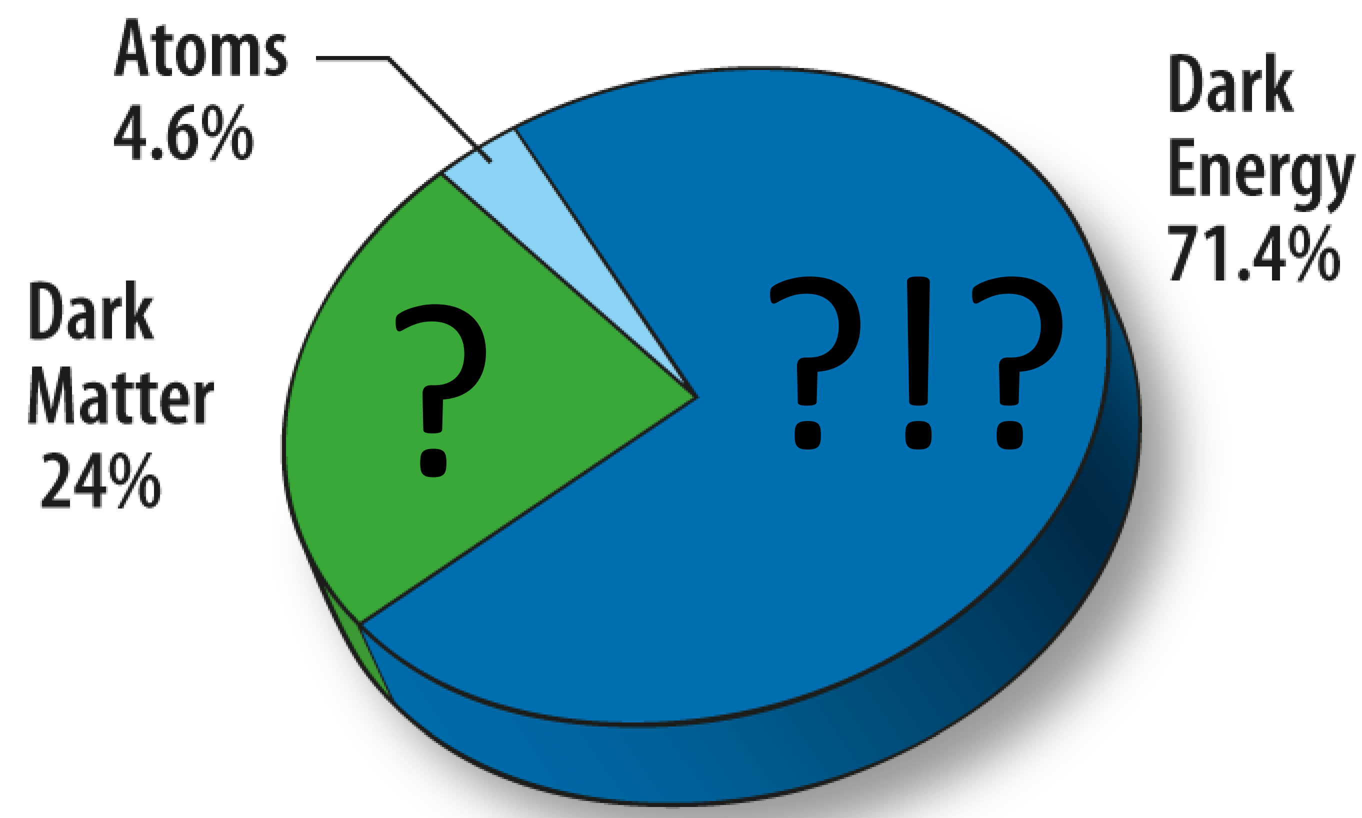




TODAY

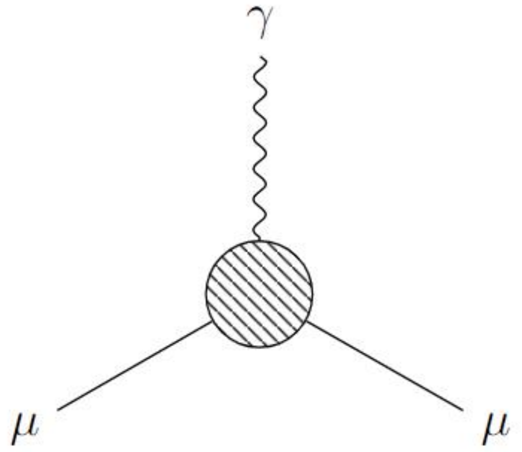


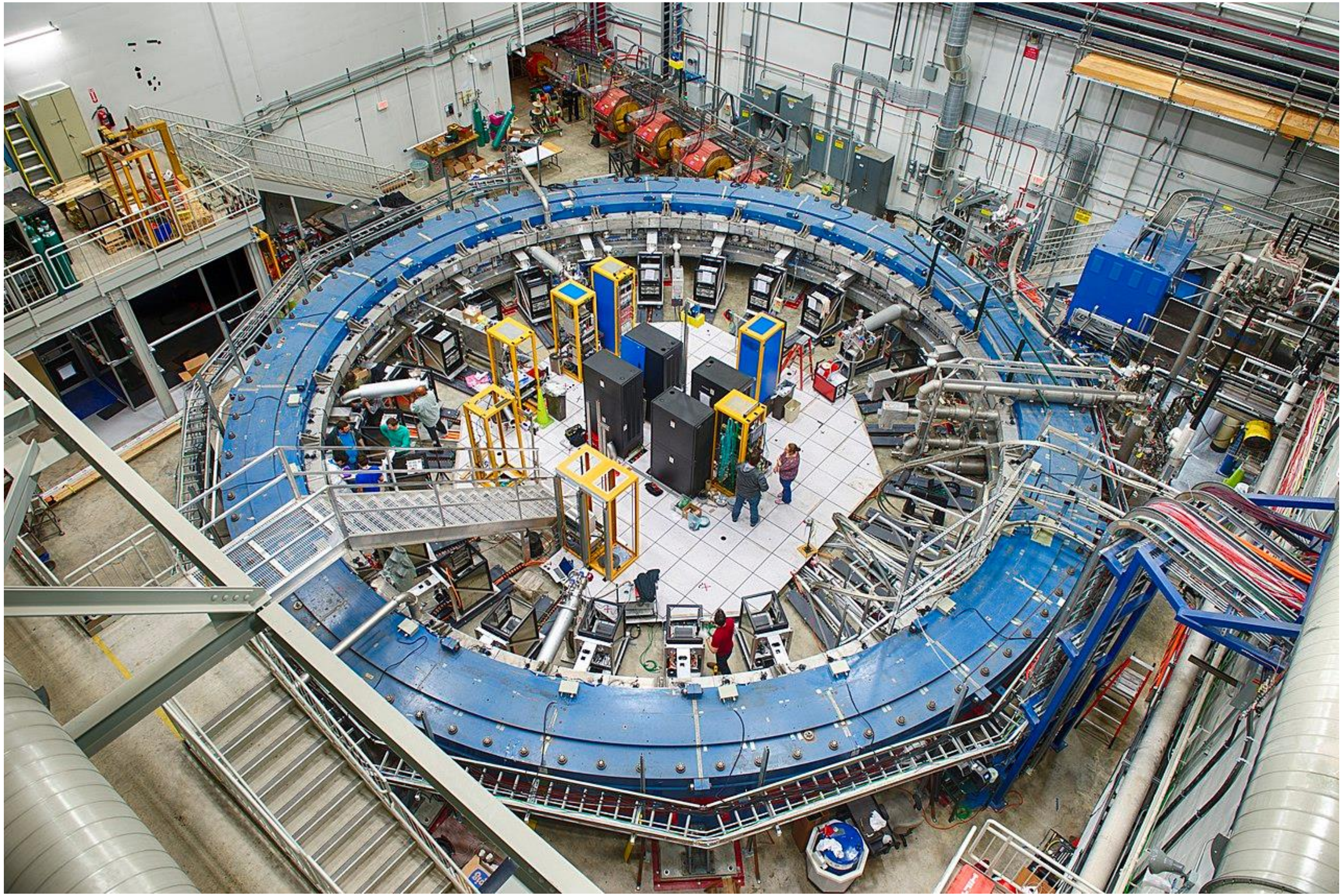
TODAY



TODAY

Muon g-2

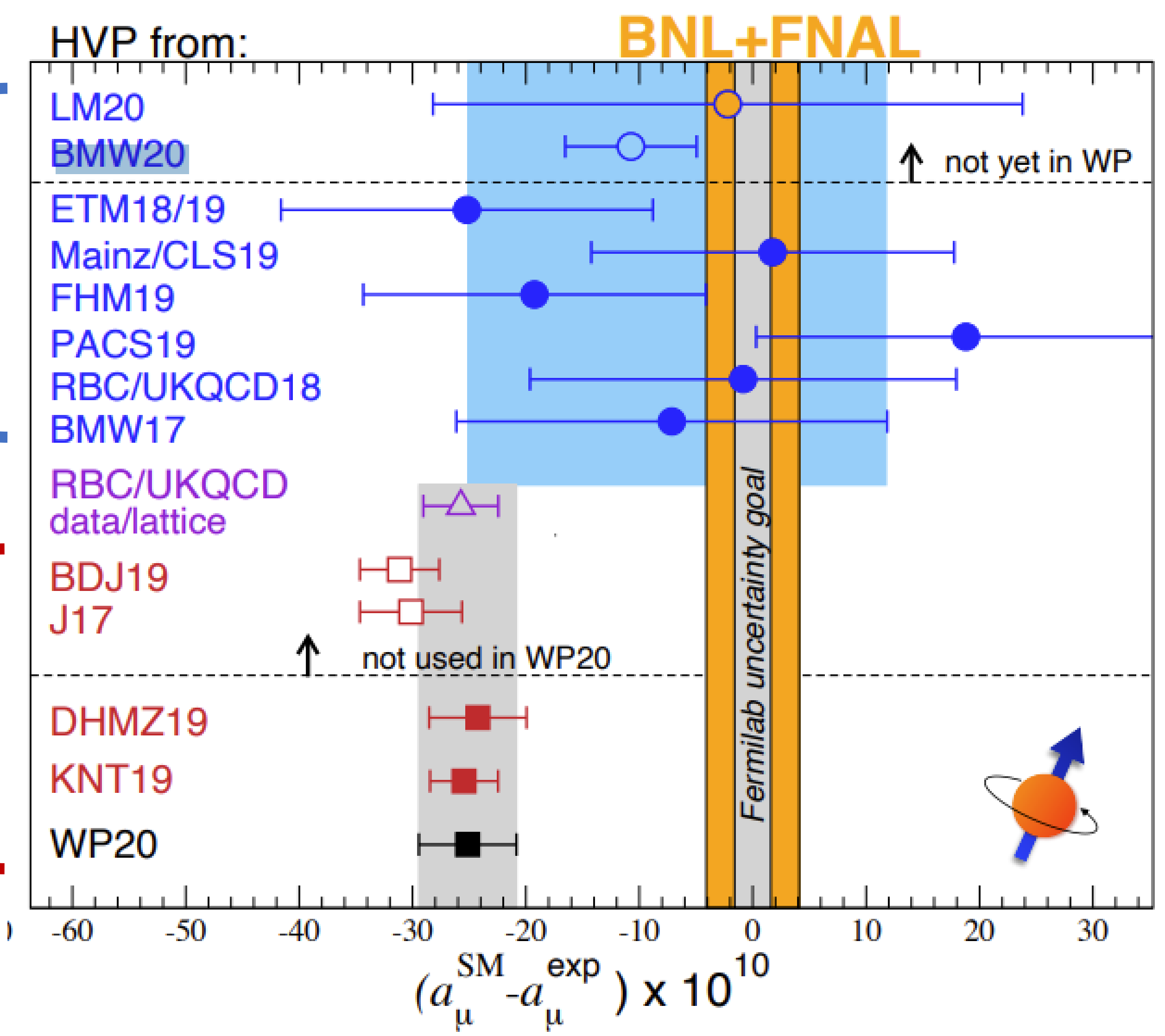




Experimental

Blue: Lattice

Red: R-Value (data driven)



Constructing a Model

What is a Scalar?

- Dimension-1 field
- Can have any charge

Yukawa Interaction

$$\phi\bar{\psi}\psi$$

Common in SM!

With SU(2) and hypercharge – two higgs doublet model

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

$$\mathscr{L} \subset (\phi^\dagger\phi)(H^\dagger H) + (\phi^\dagger H)^2 + \ldots$$

Model Building Tutorial

Method 1: Top-down

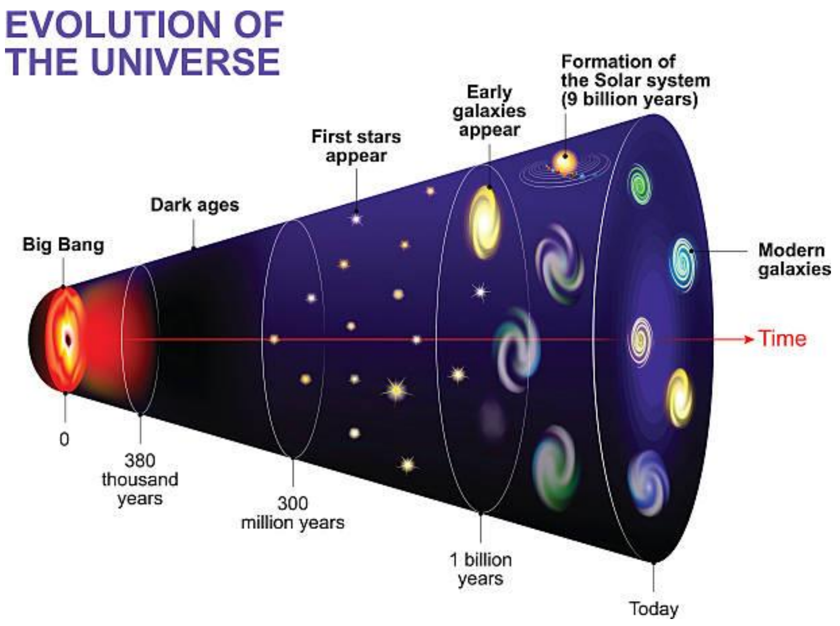
1. Choose **charges** under SM gauge groups (or new ones)
2. Write down **all renormalizable couplings** allowed in the UV SM
3. Break EW Symmetry

Method 2: Bottom-up

1. Choose a coupling (can be non-renormalizable)
2. Pick a **mass range** of interest
3. Test away!

Cosmological Notes

- Scalars are a great candidate for a portal to a Dark Sector
- Scalar masses of less than a few MeV can interfere with big bang nucleosynthesis
- Additional scalars can cause the EWPT to be first-order, which is necessary for EW baryogenesis



Testing Muonphilic Models

FERMILAB-PUB-23-539-T
MIT-CTP/5649

New μ Forces From ν_μ Sources

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(Dated: November 21, 2023)

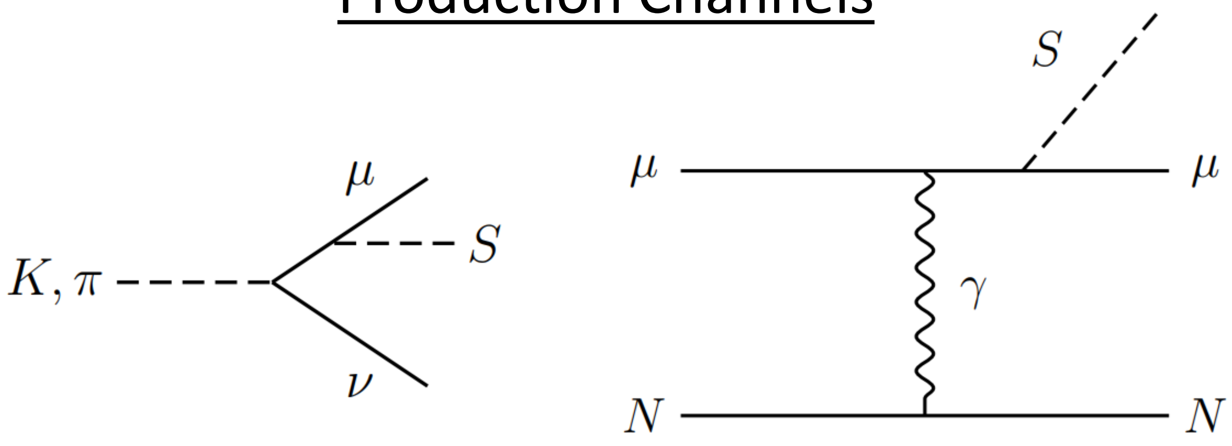
Muon-Philic Scalar

Scalar which couples only to muons

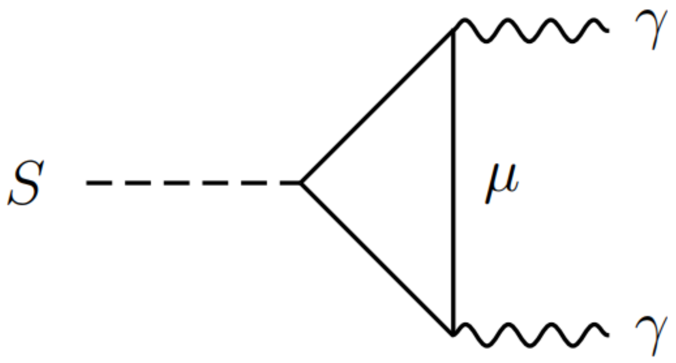
$$\mathscr{L}_{\text{int}} \supset y S \bar{\mu} \mu$$

$$\sim \text{MeV} < m_S < 2m_\mu \ (210\,\text{MeV})$$

Production Channels

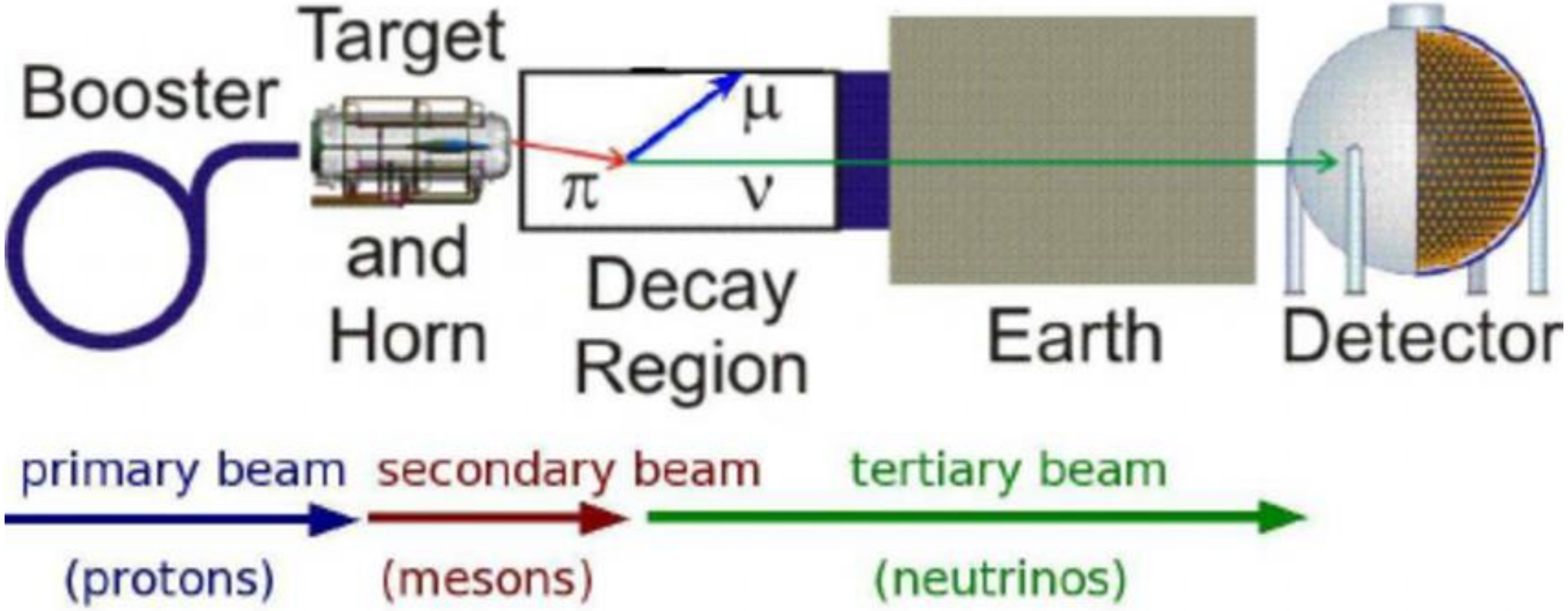


Decay Channels

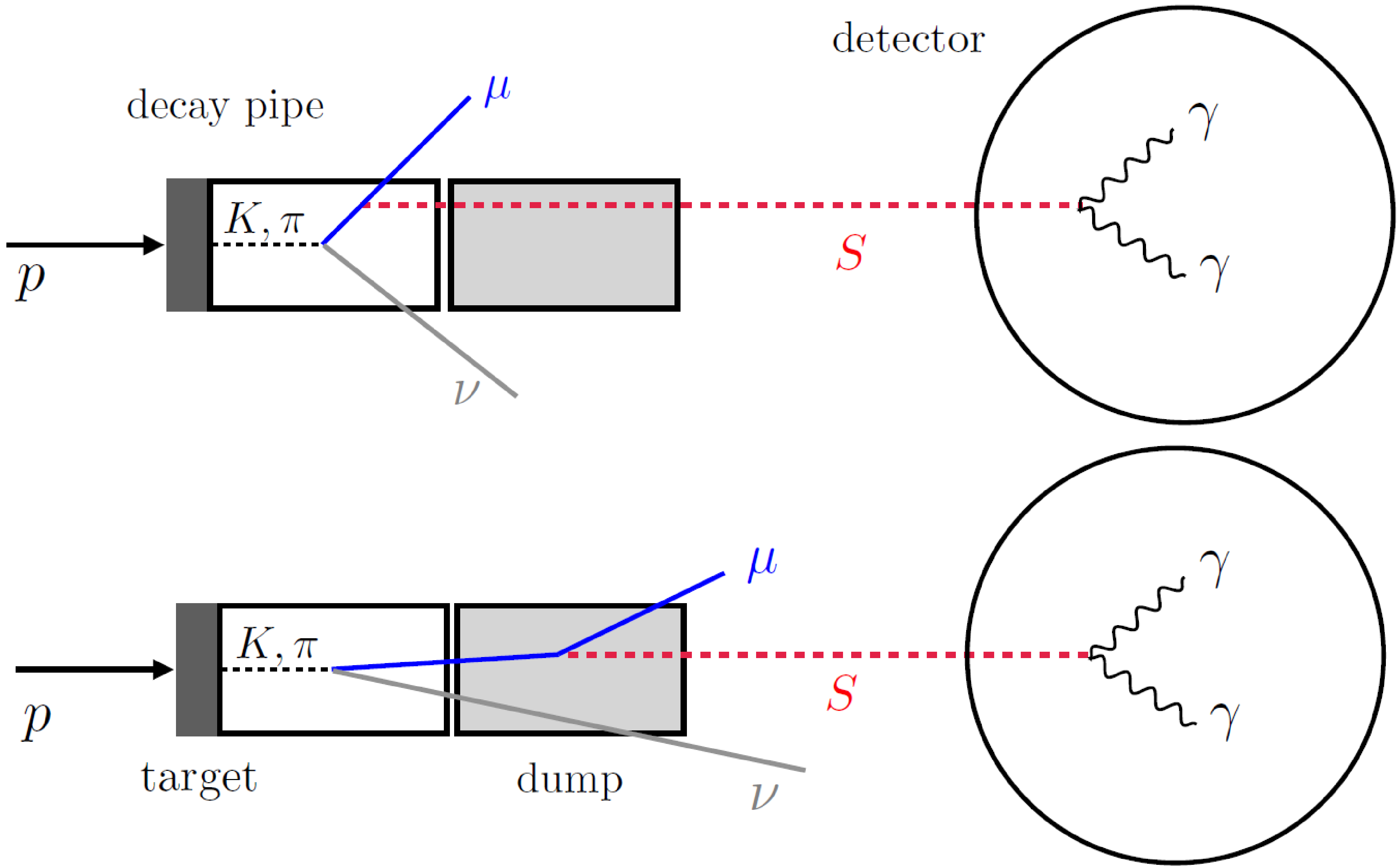


2311.10829
Me, Gordan Krnjaic, Cari Cesarotti, Josh Spitz, Yoni Khan

MiniBoone



Target
Booster
μ
π
ν
and
Horn
Decay
Region
Earth
Detector
primary beam
(protons)
secondary beam
(mesons)
tertiary beam
(neutrinos)


detector
decay pipe
μ
K, π
p
S
γ
γ
ν
μ
K, π
p
S
γ
γ
target
dump
ν

What does this look like?

Number of signal events can be written:

$$N_{\mathrm{signal}} \approx N_S \varepsilon_{\mathrm{geo}} P_{\mathrm{dec}} A_{exp}$$

What does this look like?

Number of signal events can be written:

Number of Scalars
(from all production channels)

Probability of decay $\sim \frac{w}{x_D} e^{-x/x_D}$

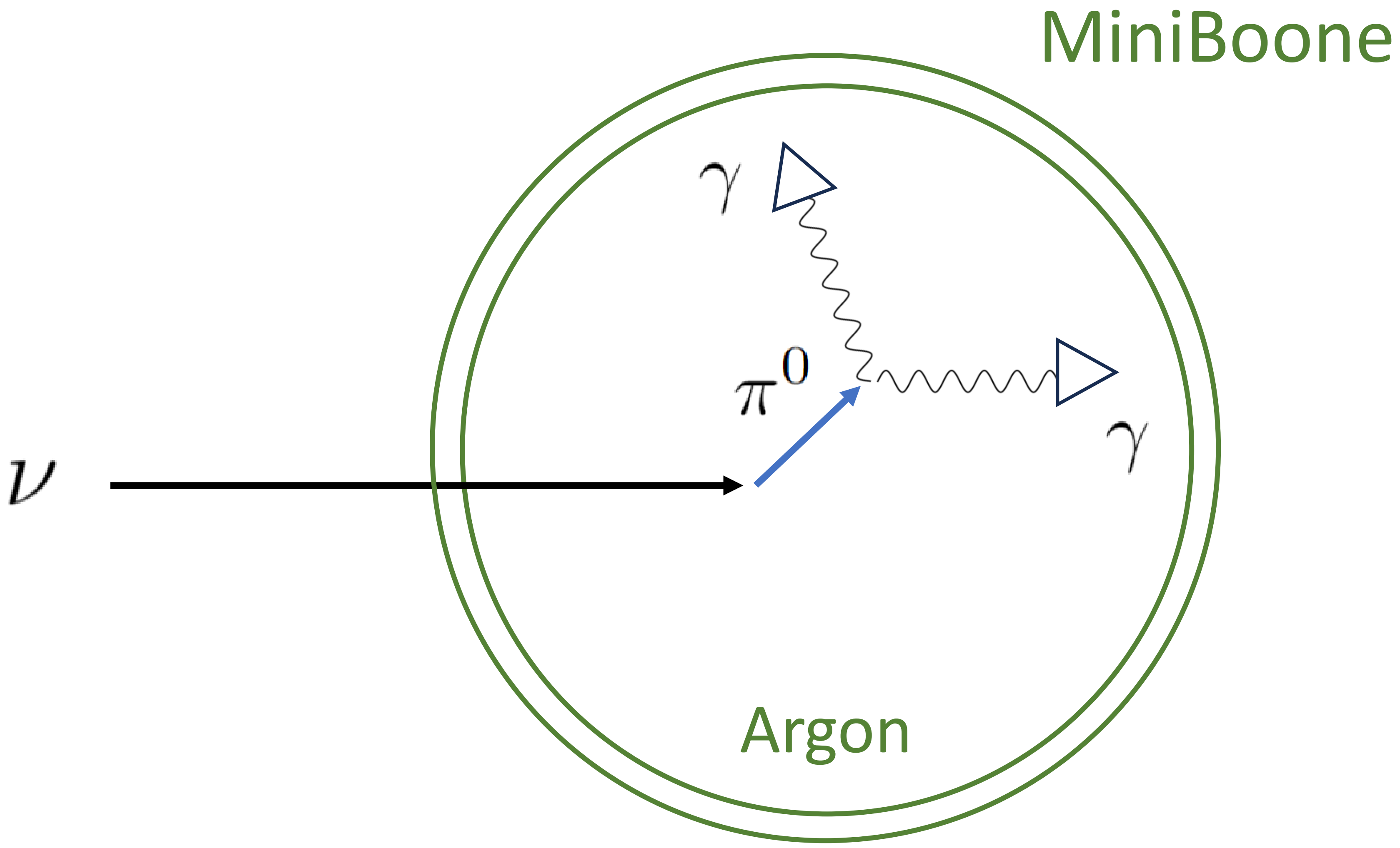
$$N_{\rm signal} \approx N_S \varepsilon_{\rm geo} P_{\rm dec} A_{exp}$$

Signal Events Observed

Geometric Acceptance

Detector Acceptance
(Analysis Specific)

Background: Pions

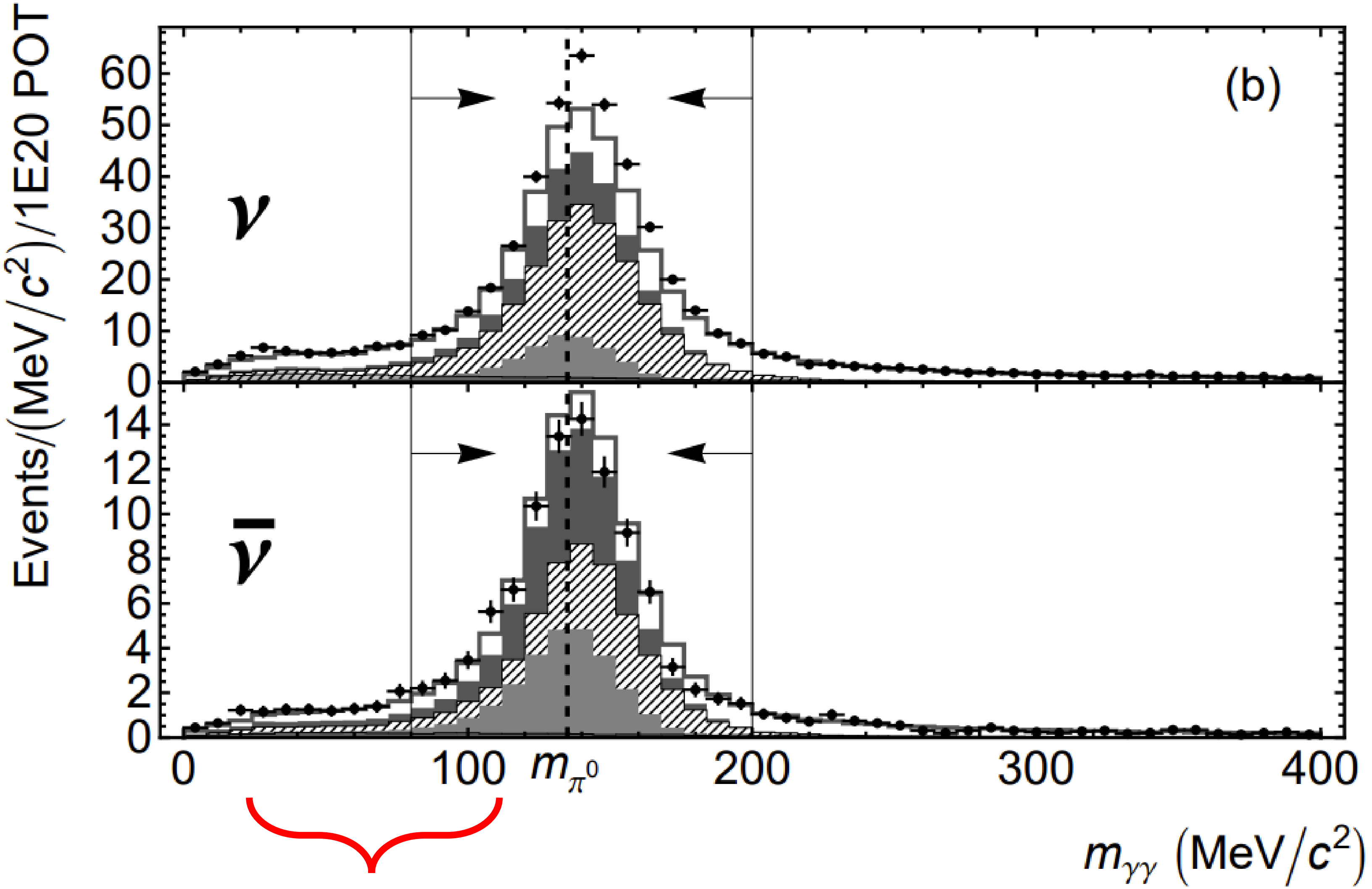


MiniBoone Background

40% Acceptance

~ 100-1000 Events/bin

500 m^3 Detector



Region of Interest

https://arxiv.org/abs/0911.2063

MiniBoone Background

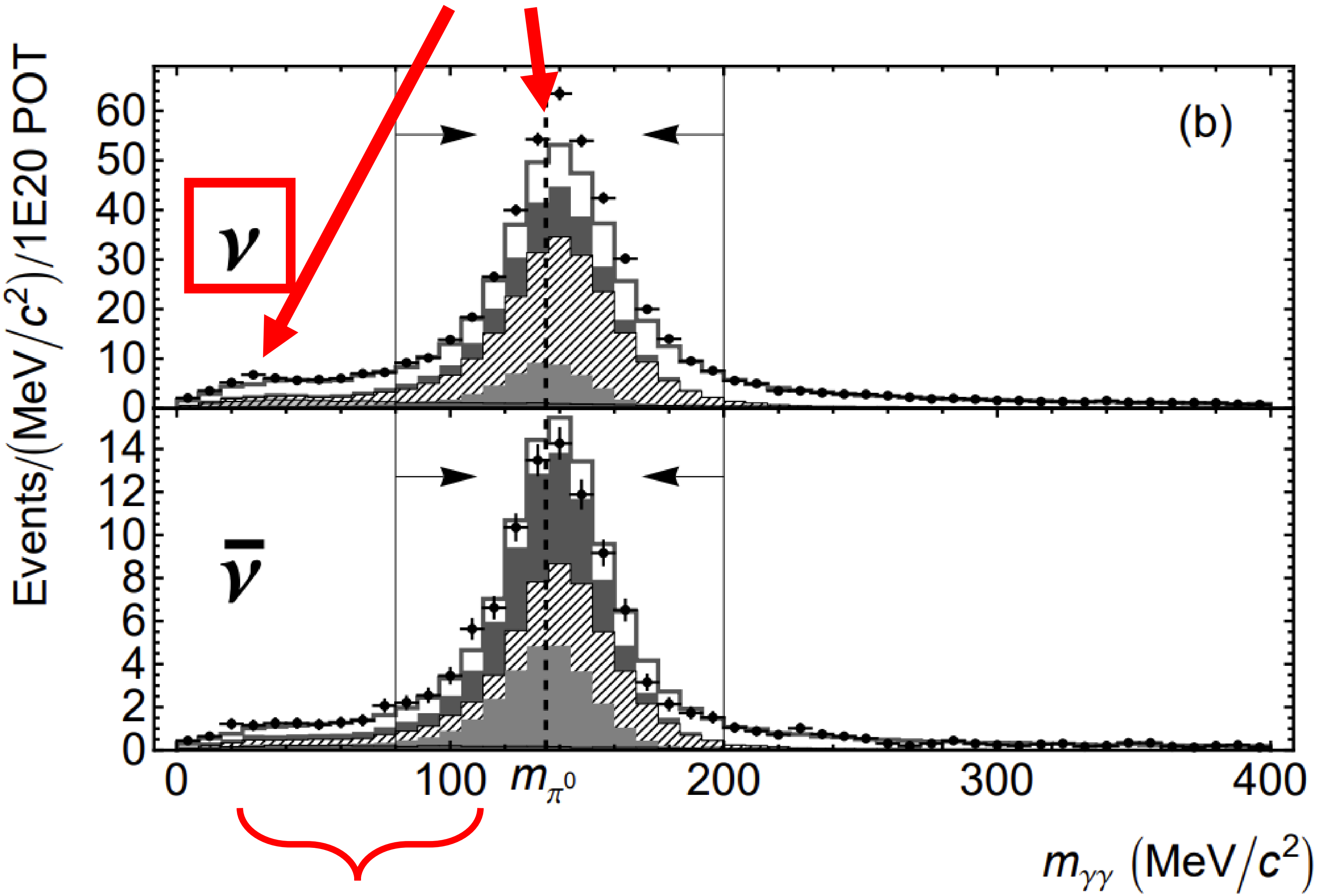
Excesses
(known to not be BSM…)

40% Acceptance

~ 100-1000 Events/bin

500 m^3 Detector

Look at neutrino-mode



Region of Interest

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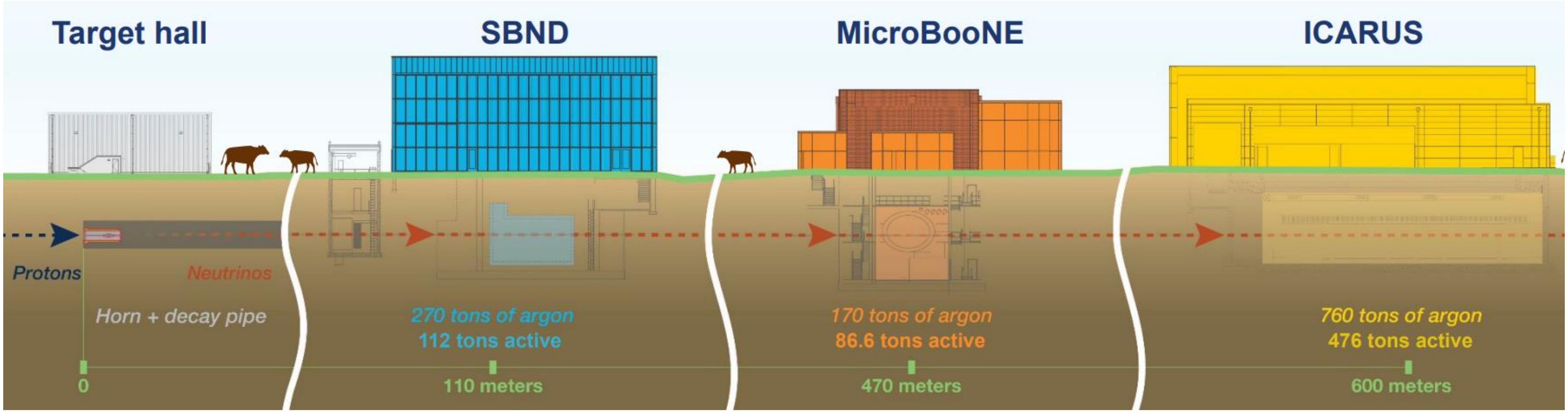
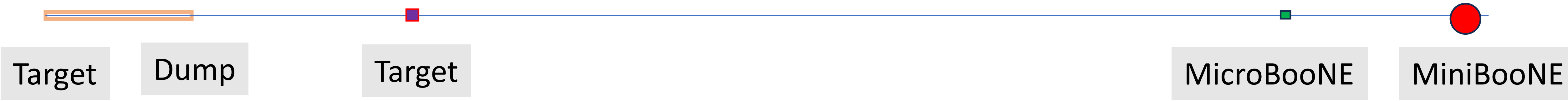
MiniBooNE/MicroBooNE/SBND



To Scale...



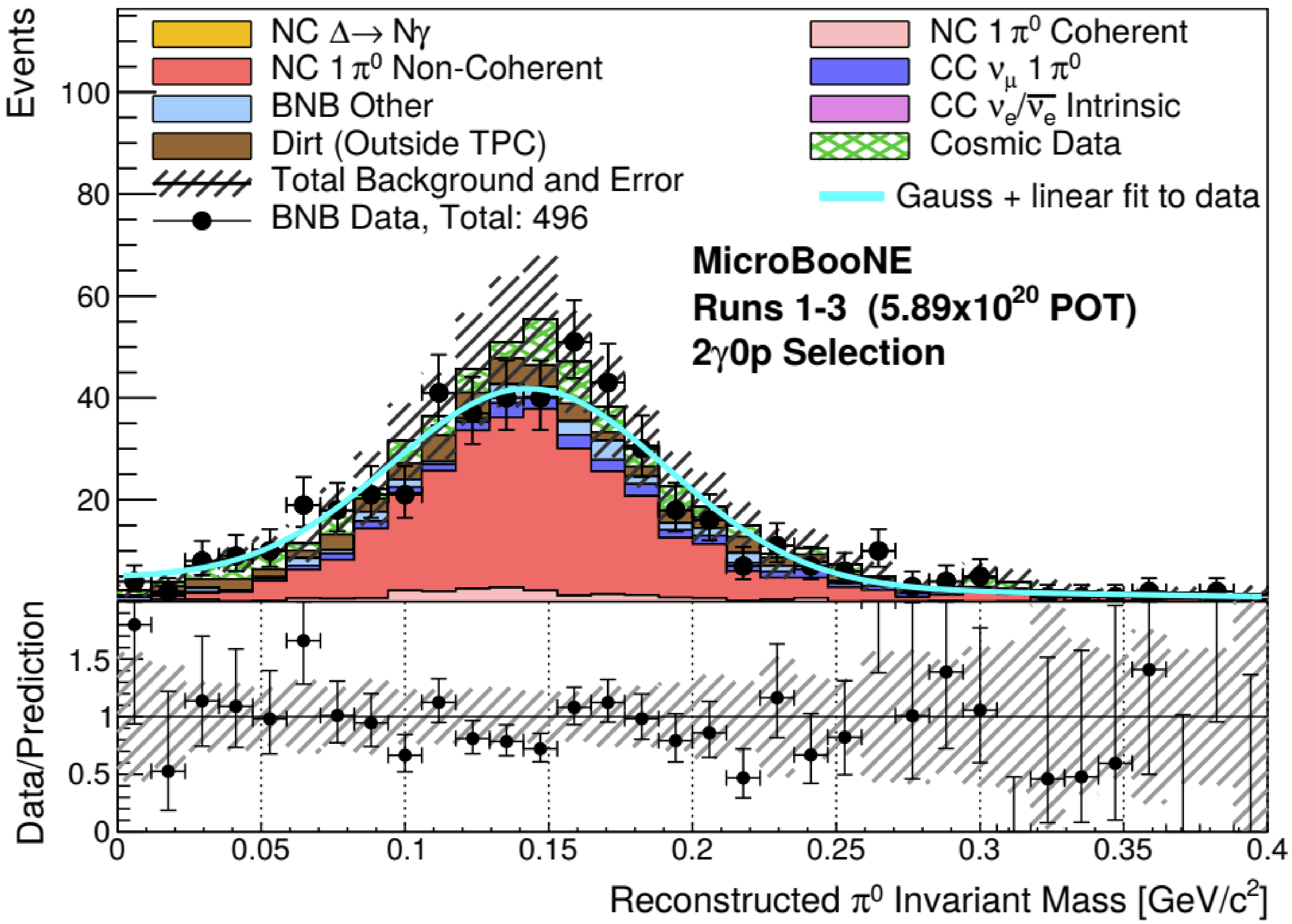
MicroBooNE

Data shows no excess

Diphoton is common signal for neutral scalars (ex. pion)

6% Acceptance
~ 10-50 Events/bin

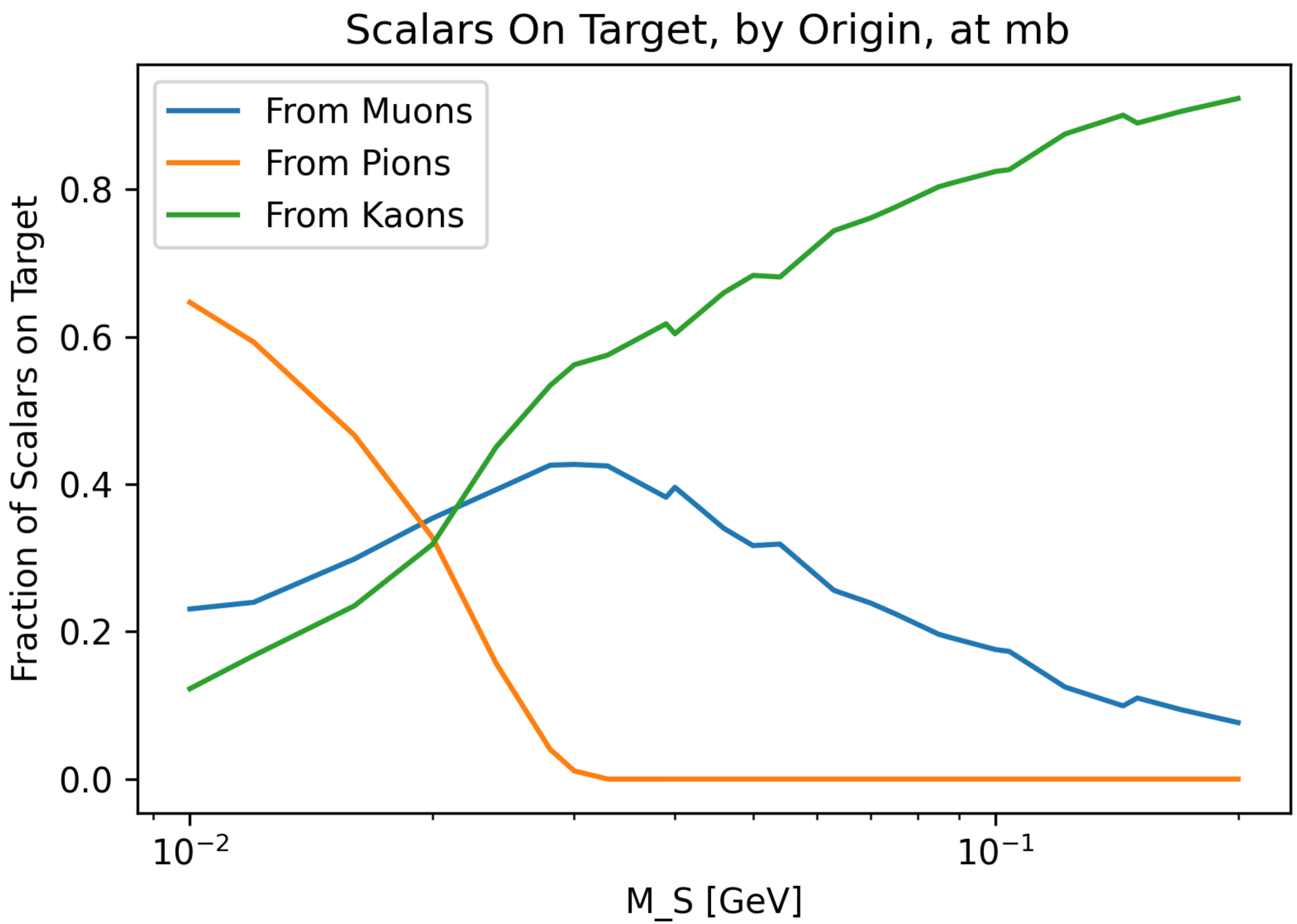
~60 m^3 Detector



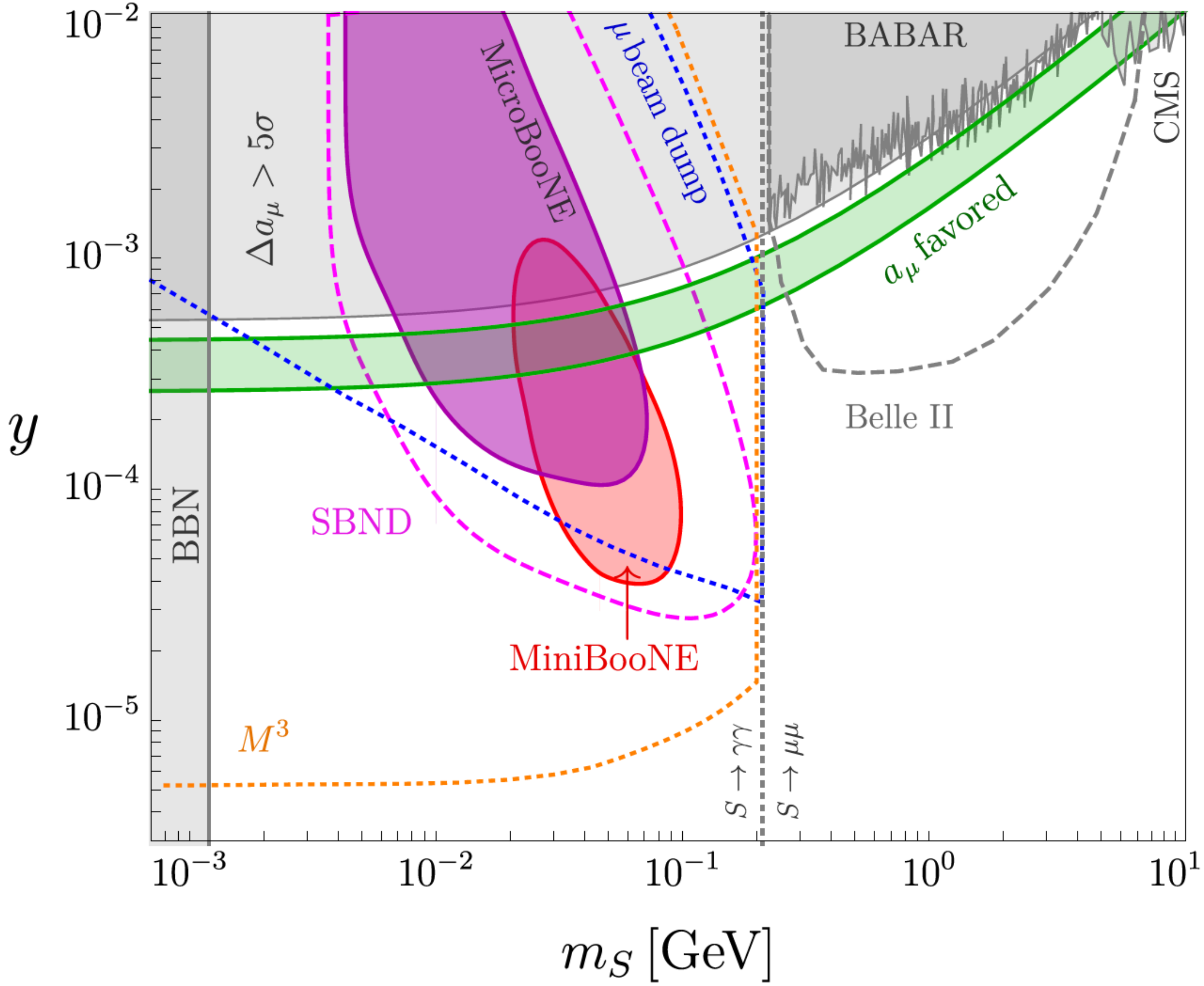
https://arxiv.org/abs/2205.07943

Detector Comparison

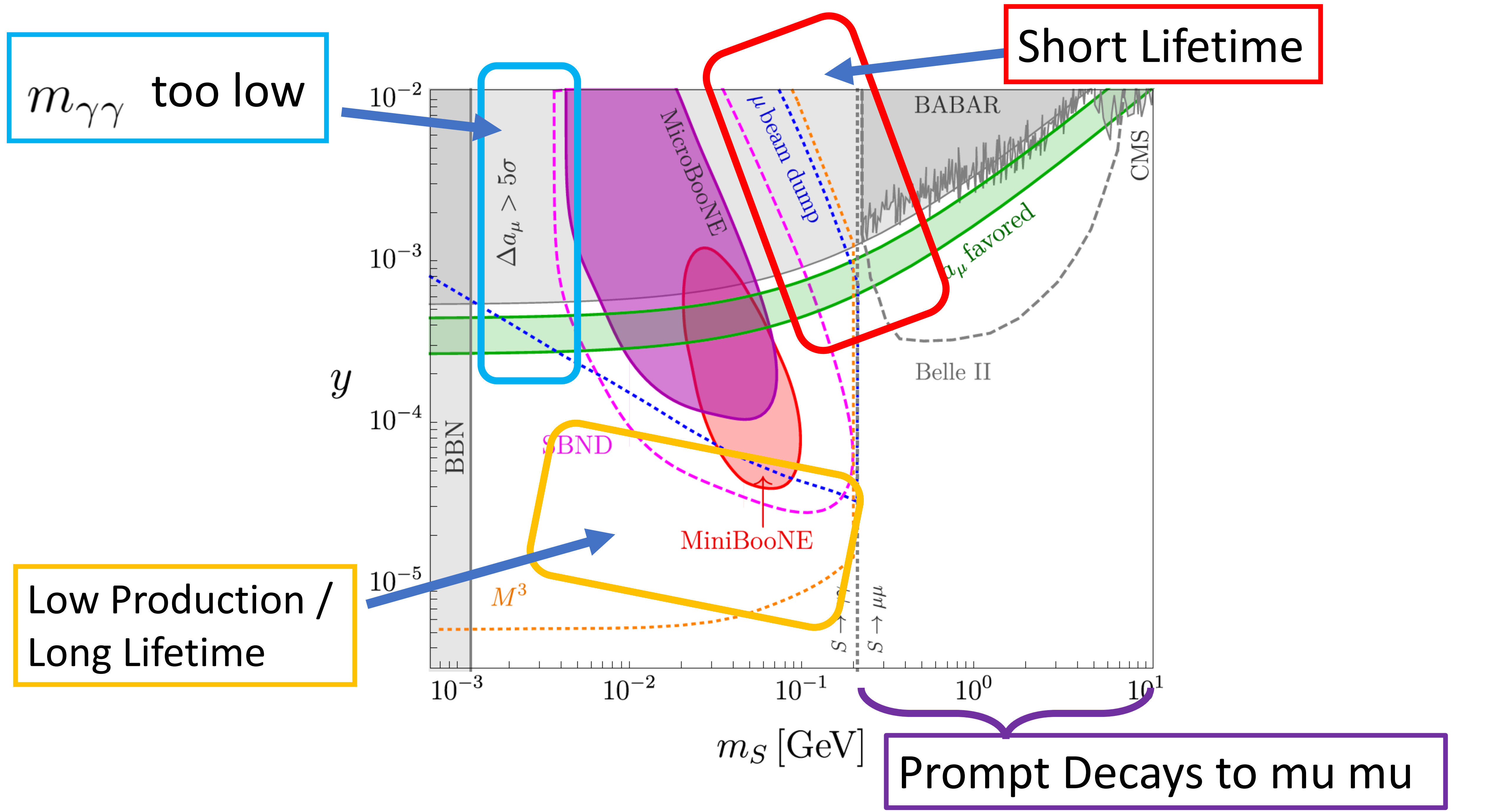
	MiniBooNE	MicroBooNE	SBND
Protons On Target	6.5×10^{20}	5.9×10^{20}	Same as μB
Baseline	491 m	420 m	60 m
Volume	520 m^3	60 m^3	80 m^3
Signal Events Required	$\sim$ 1000 Events	$\sim$ 50 Events	$\sim$ 4500 Events
Angular Width (at beam dump)	1.2°	0.4°	4°
Acceptance Requirement	$m_{\gamma\gamma}^{\text{Smear}} \gtrsim 32$ MeV	$m_{\gamma\gamma}^{\text{Smear}} > 10$	Same as μB
Analysis Efficiency	40%	6%	$\sim$ 6%



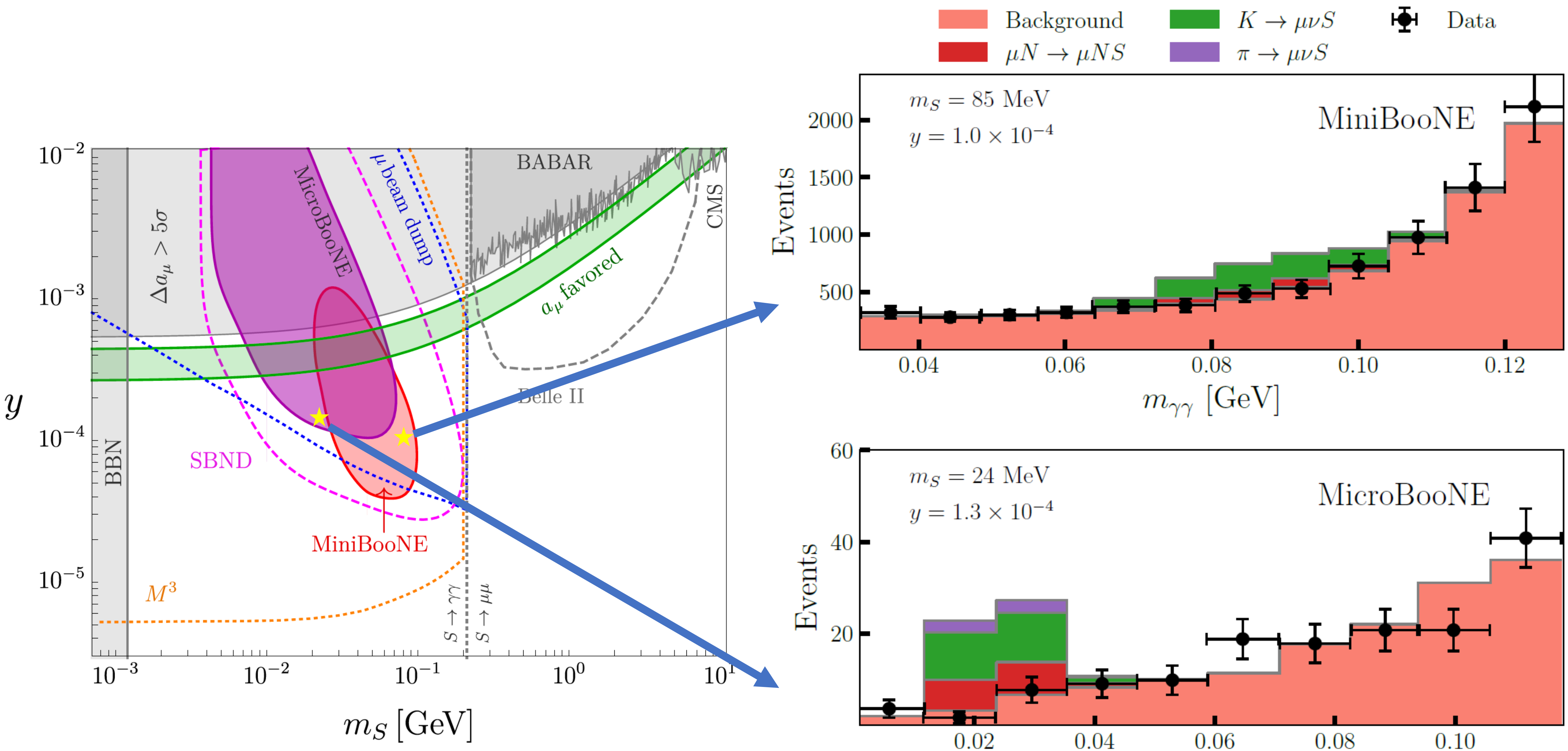
Scalars On Target, by Origin, at mb
From Muons
From Pions
From Kaons
Fraction of Scalars on Target
0.0
0.2
0.4
0.6
0.8
10^{-2}
10^{-1}
M_S [GeV]



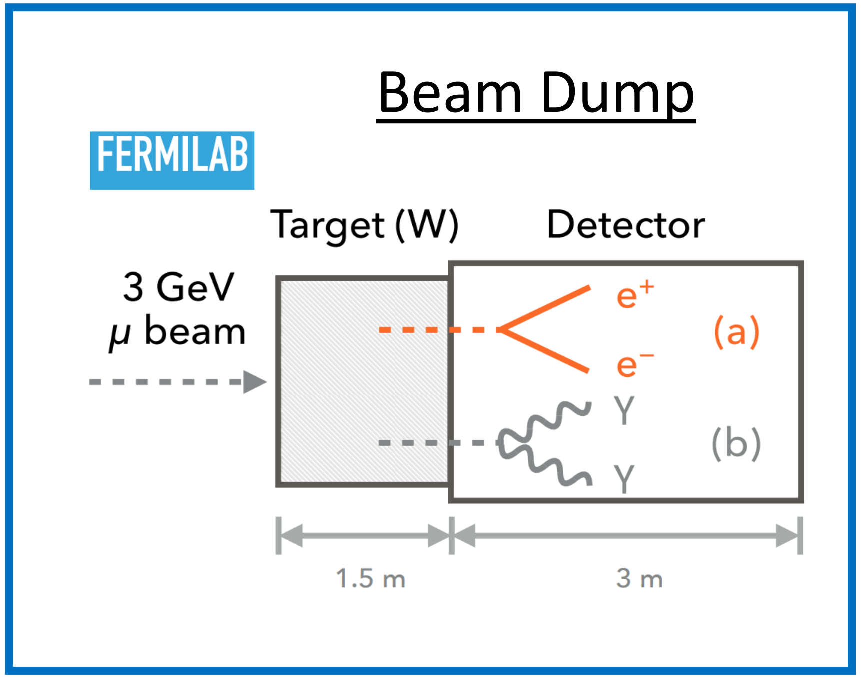
BABAR
CMS
MicroBooNE
μ beam dump
$\Delta a_\mu > 5\sigma$
a_μ favored
Belle II
BBN
SBND
MiniBooNE
M^3
$S \to \gamma\gamma$
$S \to \mu\mu$
y
m_S [GeV]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

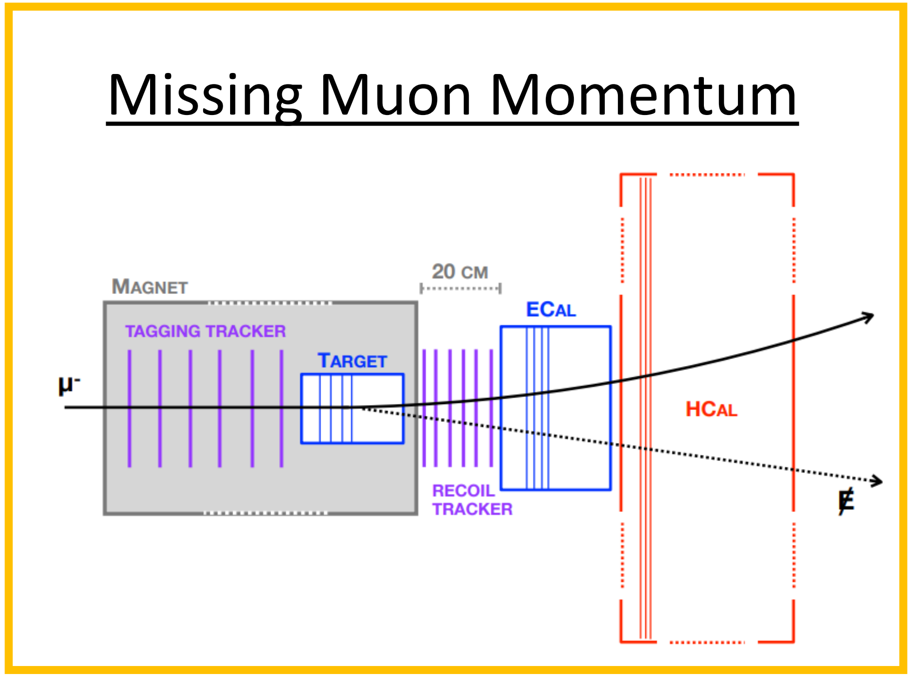


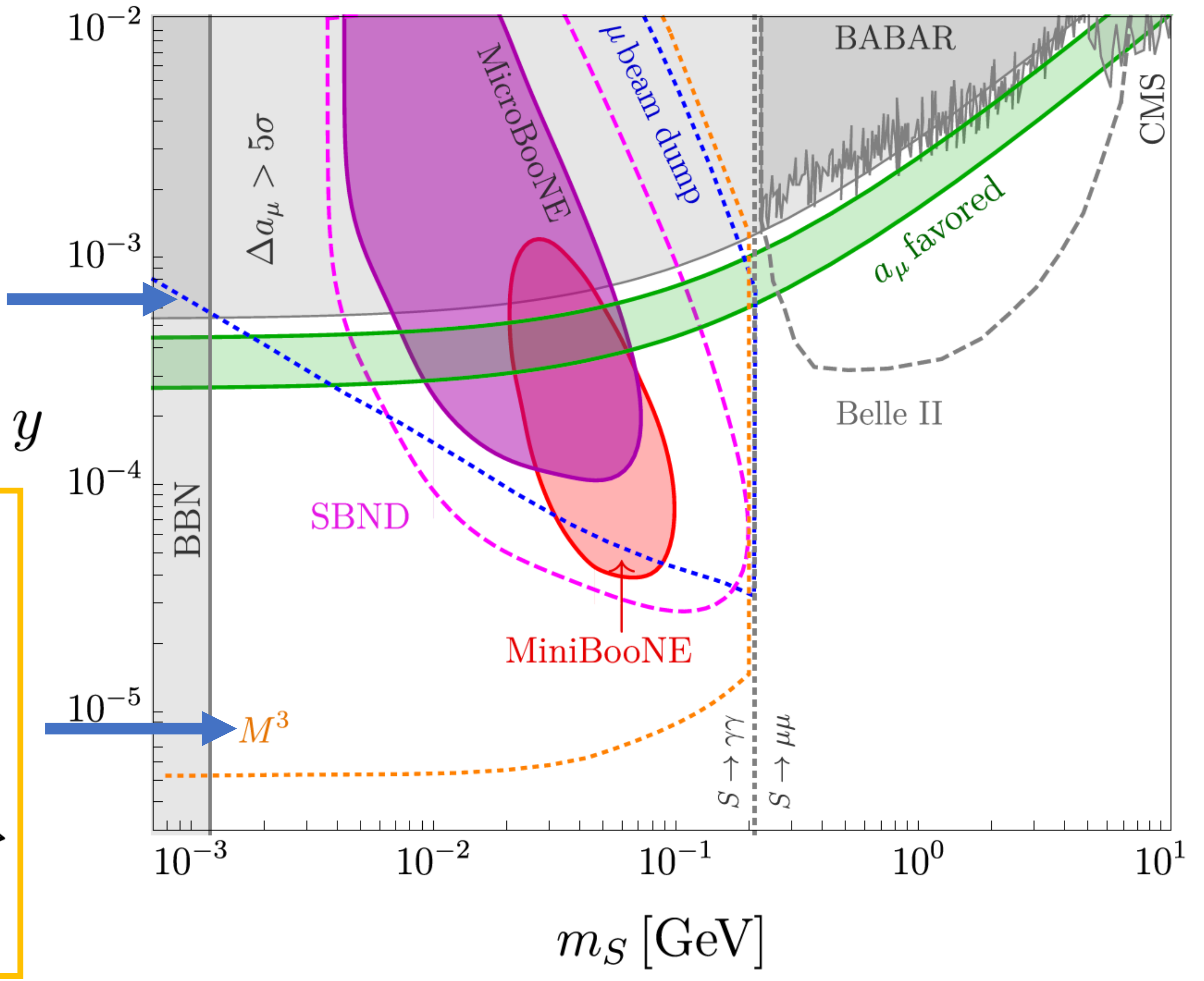
$m_{\gamma\gamma}$ too low
Short Lifetime
Low Production / Long Lifetime
Prompt Decays to mu mu
BABAR
CMS
Belle II
MicroBooNE
MiniBooNE
SBND
BBN
μ beam dump
a_μ favored
$\Delta a_\mu > 5\sigma$
M^3
$S \to \mu\mu$
y
m_S [GeV]



Background
$K \to \mu\nu S$
Data
$\mu N \to \mu N S$
$\pi \to \mu\nu S$
$m_S = 85$ MeV
$y = 1.0 \times 10^{-4}$
MiniBooNE
Events
$m_{\gamma\gamma}$ [GeV]
$m_S = 24$ MeV
$y = 1.3 \times 10^{-4}$
MicroBooNE
Events
$m_{\gamma\gamma}$ [GeV]
BABAR
MicroBooNE
μ beam dump
CMS
$\Delta a_\mu > 5\sigma$
a_μ favored
Belle II
BBN
SBND
MiniBooNE
M^3
$S \to \gamma\gamma$
$S \to \mu\mu$
y
m_S [GeV]


Beam Dump
FERMILAB
Target (W)
Detector
3 GeV
μ beam
e+
e−
(a)
γ
γ
(b)
1.5 m
3 m


Missing Muon Momentum
MAGNET
TAGGING TRACKER
TARGET
20 CM
ECAL
HCAL
RECOIL
TRACKER
μ-


BABAR
CMS
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$\Delta a_\mu > 5\sigma$
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M^3
$S \to \gamma\gamma$
$S \to \mu\mu$
y
m_S [GeV]
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

Conclusions

- Neutrino facilities happen to be very suitable to search for muonphilic scalar models.
- A dedicated diphoton search in SBND could potentially produce fairly strong bounds on these models
- I would encourage all experiments to think about how they might generate “bonus physics”