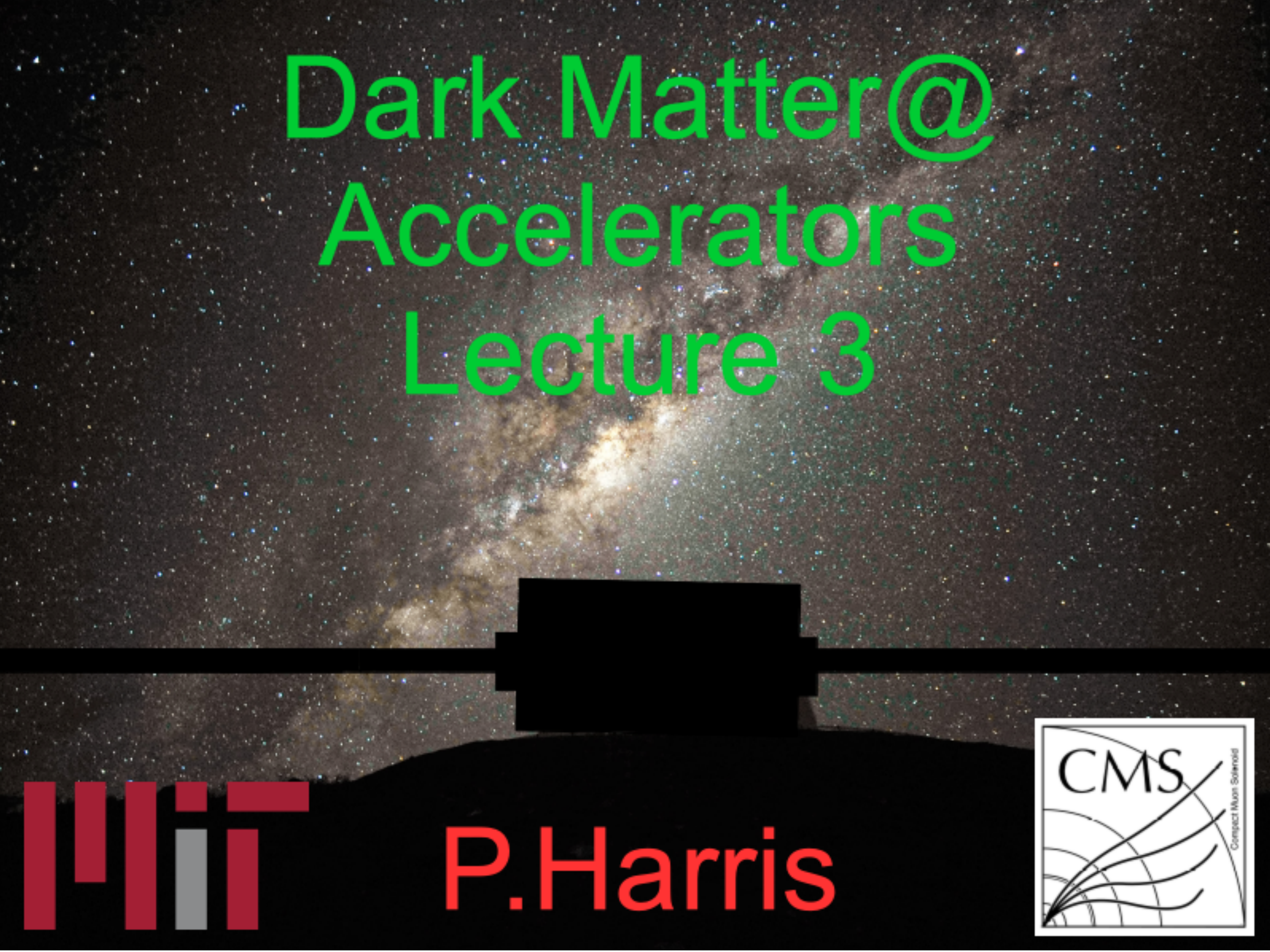
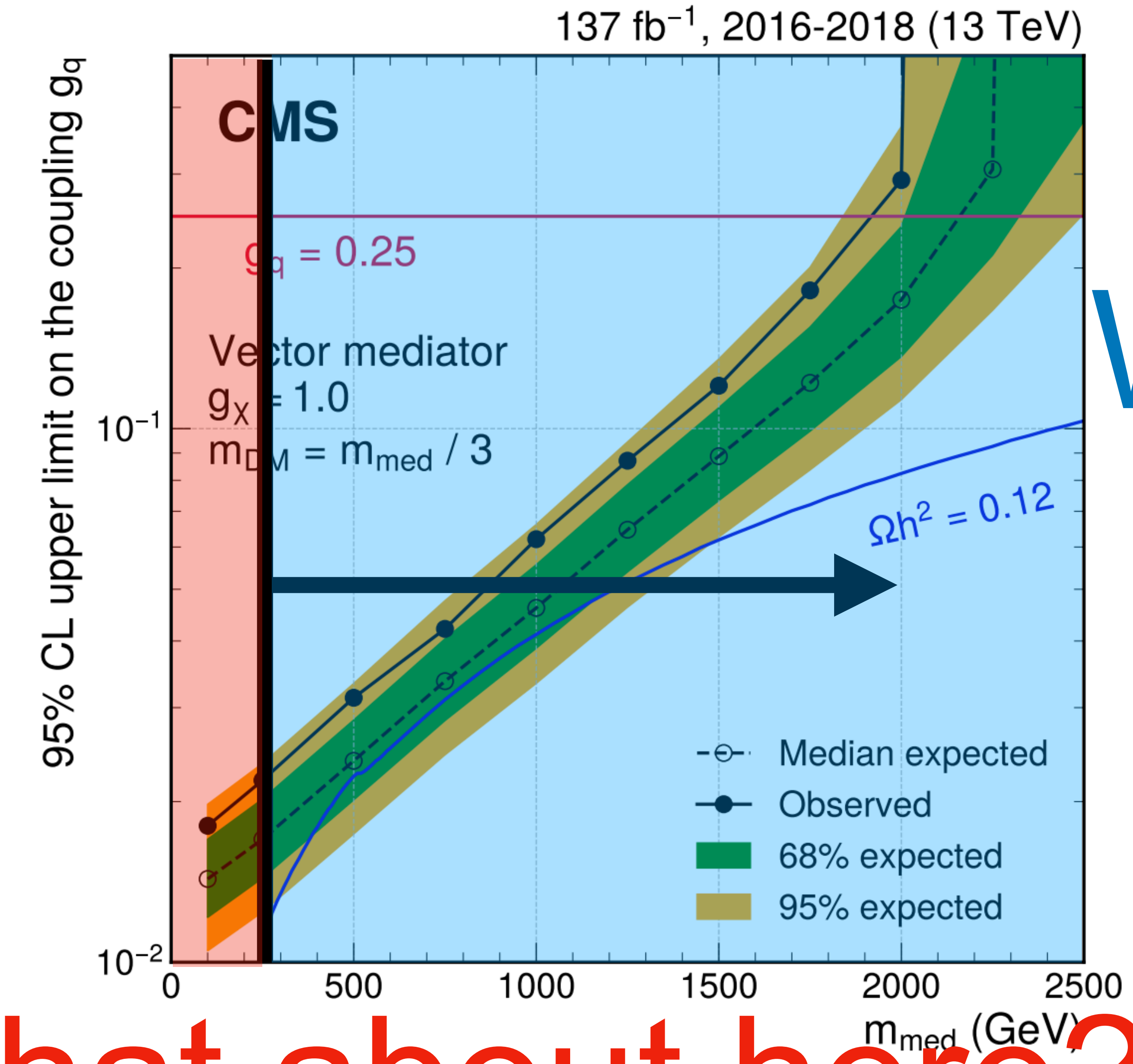


Dark Matter@ Accelerators
Lecture 3

P.Harris

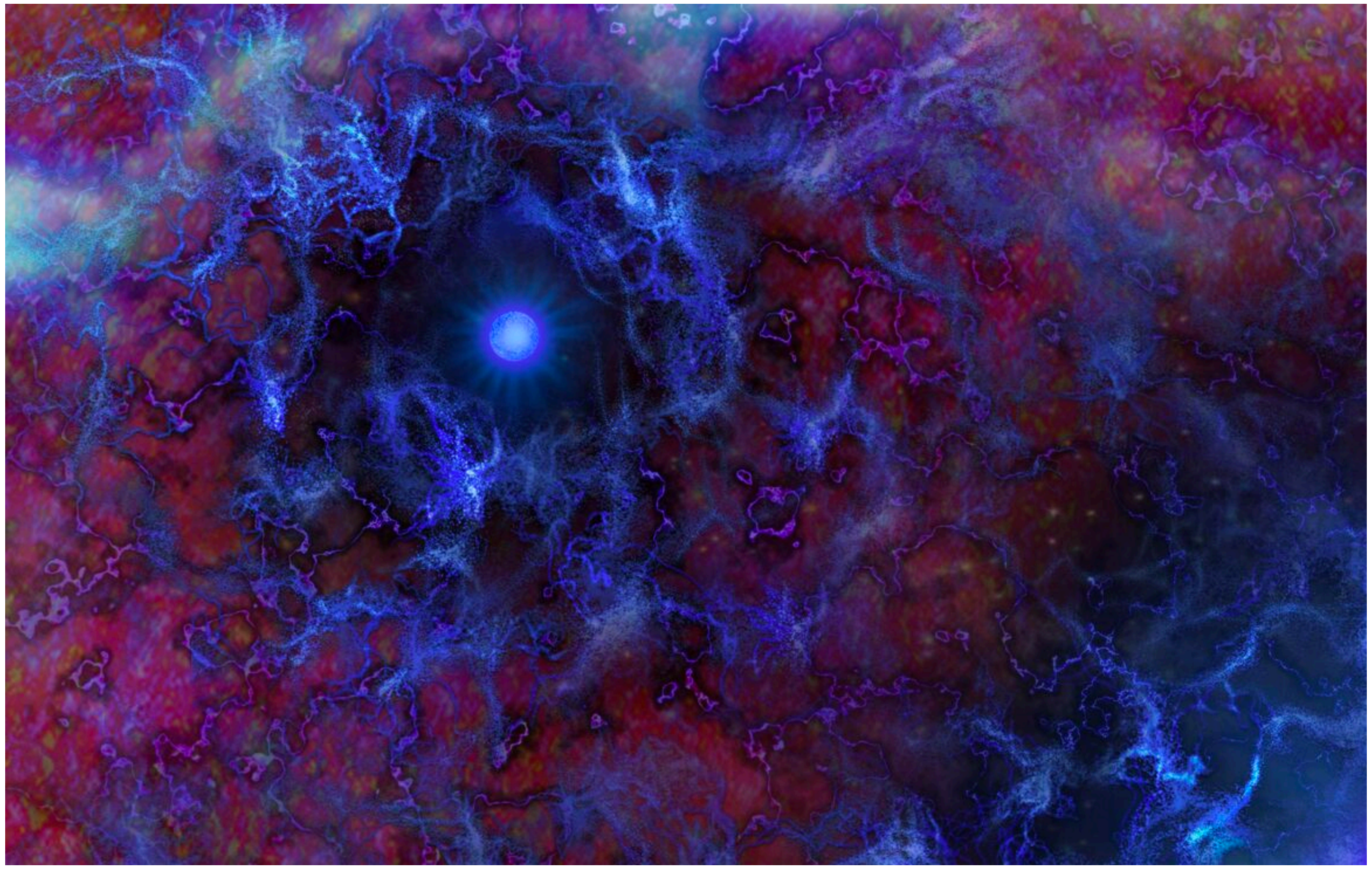
From LHC

- We said that we basically got the high mass covered



We got this

But what about here?



Low Mass DM Bonanza

Phil Harris

Start at Big Bang (again)

Following the Big Bang Dark Matter froze out and remained in universe

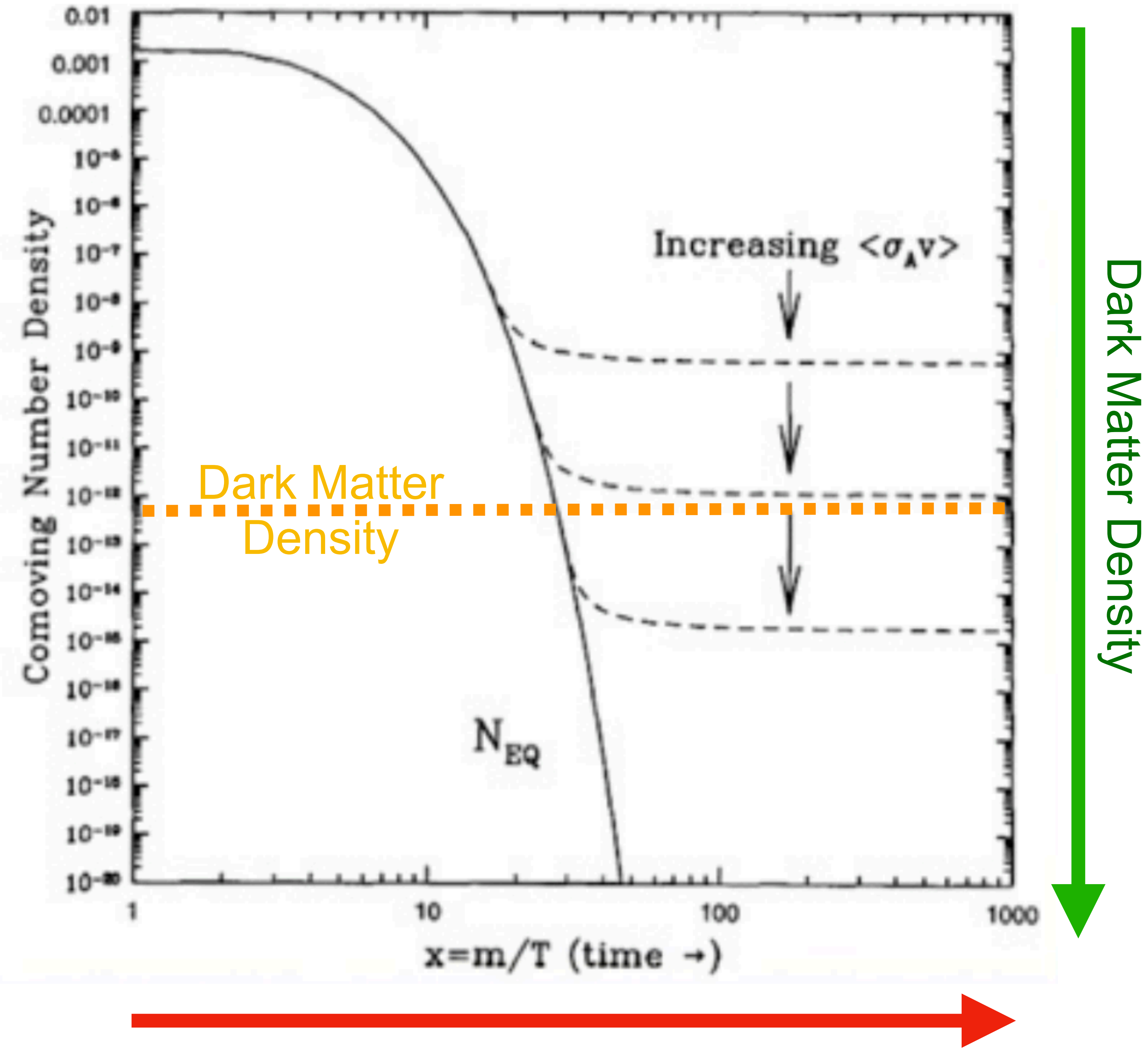
Before the LHC/Direct Detection we inclined to think DM from SUSY

SUSY fit too many pieces in the puzzle too elegantly

It made sense at the time

BTW the Higgs was also like this

WIMP Miracle



Time (age and/or Temp of universe)

If we calculate the rate of SUSY to matter interactions

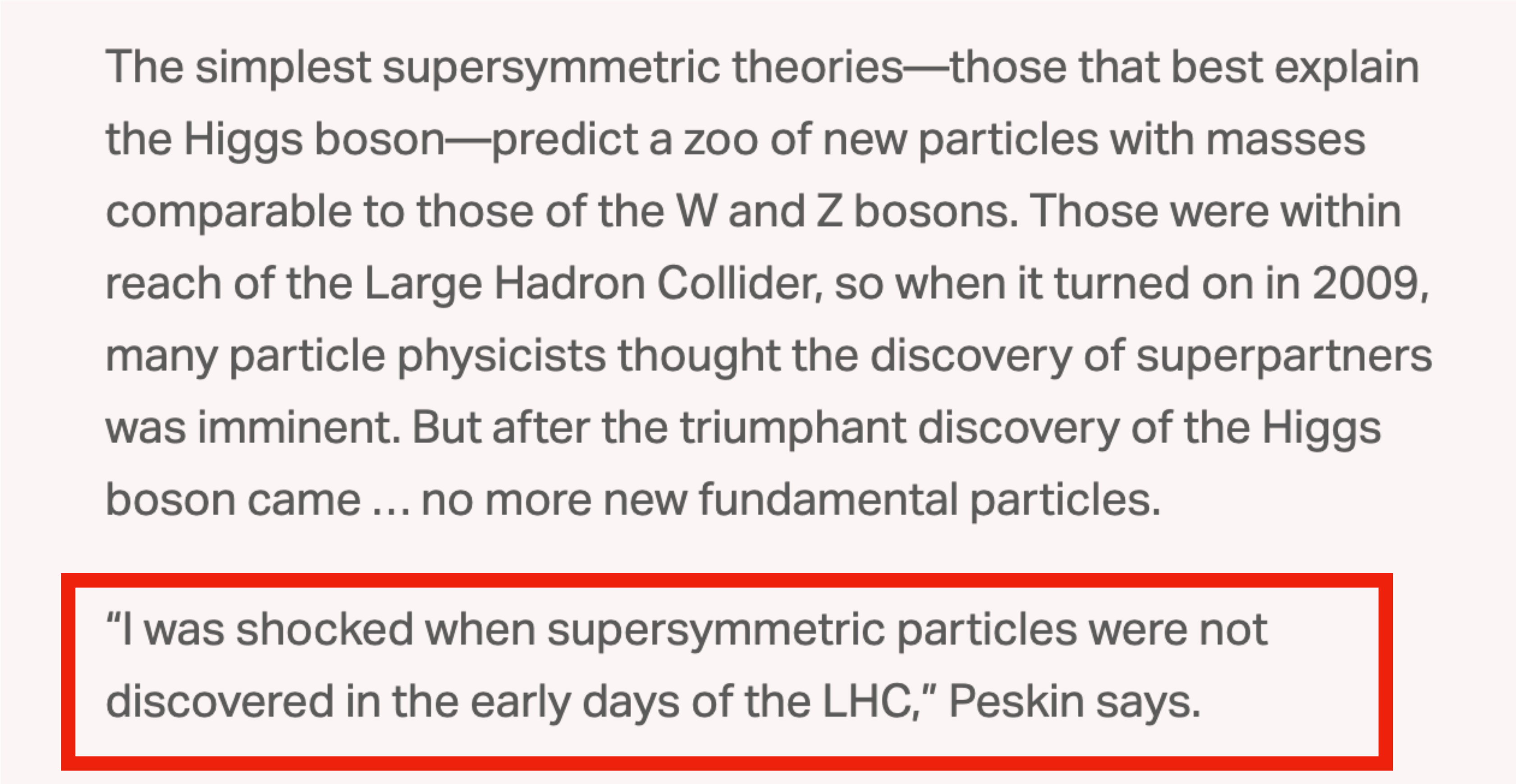
we get the right DM density

- Is it a miracle? or is it a coincidence?

However

However

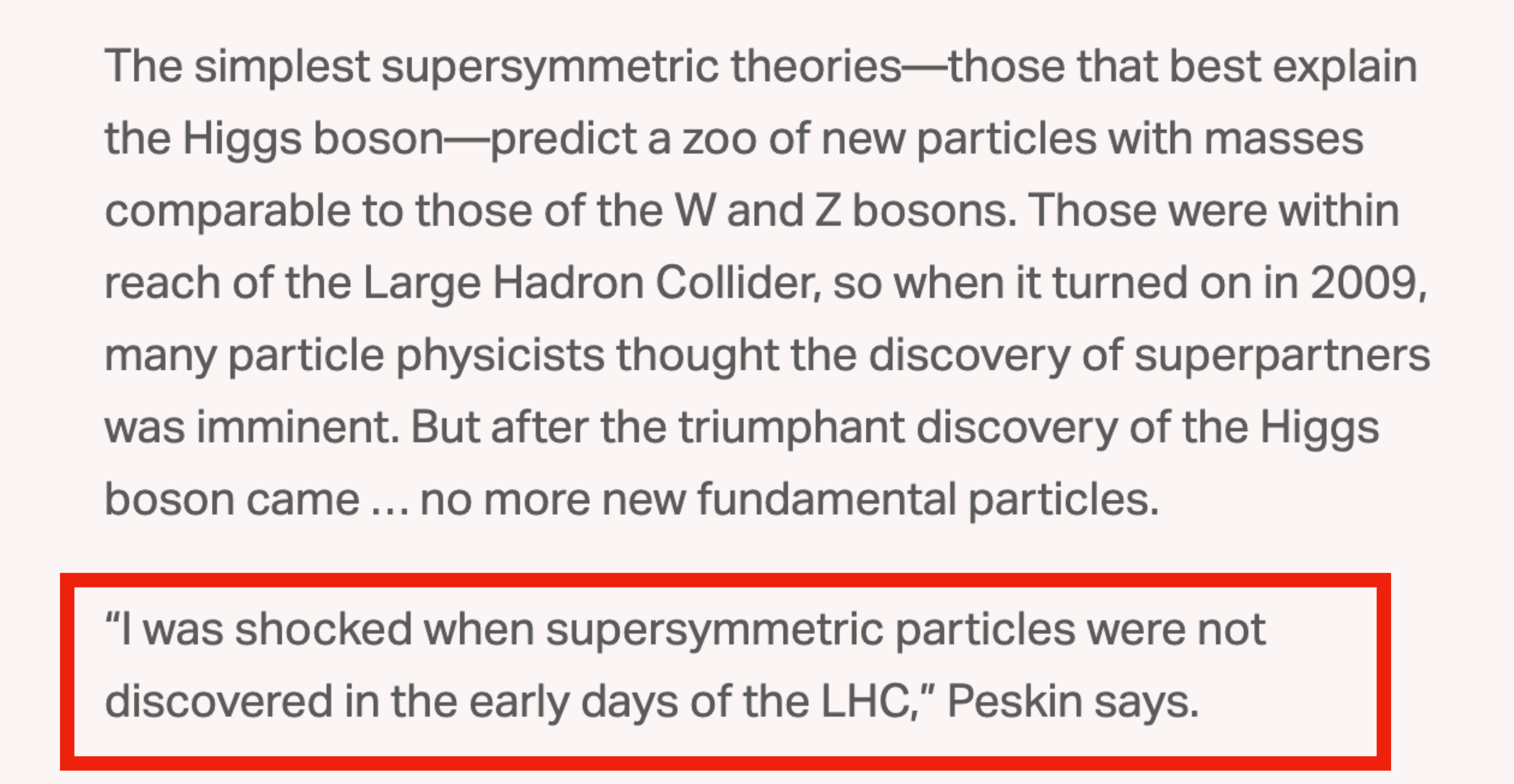
People were Excited



The simplest supersymmetric theories—those that best explain the Higgs boson—predict a zoo of new particles with masses comparable to those of the W and Z bosons. Those were within reach of the Large Hadron Collider, so when it turned on in 2009, many particle physicists thought the discovery of superpartners was imminent. But after the triumphant discovery of the Higgs boson came … no more new fundamental particles.

“I was shocked when supersymmetric particles were not discovered in the early days of the LHC,” Peskin says.

People were Excited



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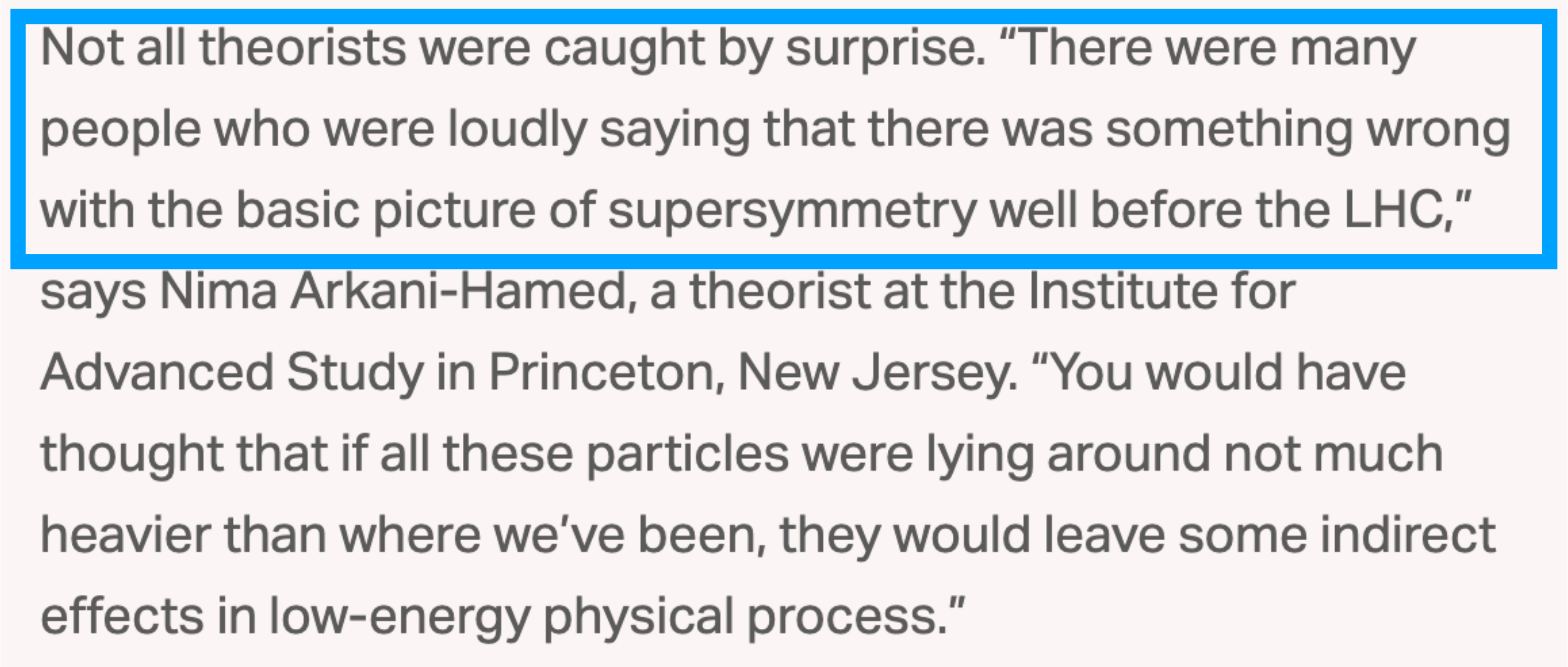
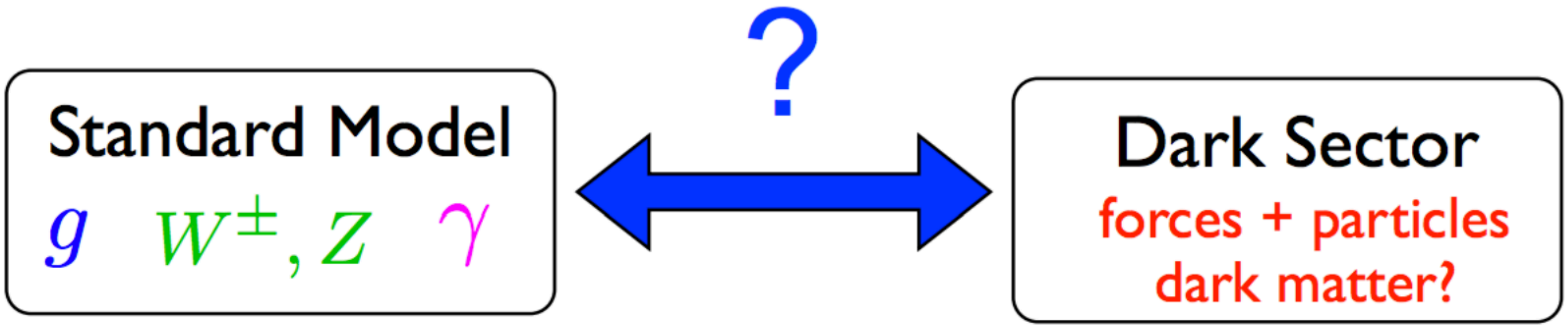
“I was shocked when supersymmetric particles were not discovered in the early days of the LHC,” Peskin says.



Not all theorists were caught by surprise. “There were many people who were loudly saying that there was something wrong with the basic picture of supersymmetry well before the LHC,” says Nima Arkani-Hamed, a theorist at the Institute for Advanced Study in Princeton, New Jersey. “You would have thought that if all these particles were lying around not much heavier than where we’ve been, they would leave some indirect effects in low-energy physical process.”

The Dark Sector

The dark sector



Standard Model

$g \quad W^{\pm}, Z \quad \gamma$

?

Dark Sector

forces + particles

dark matter?

Protons
Electrons
Muons
Gluons and More

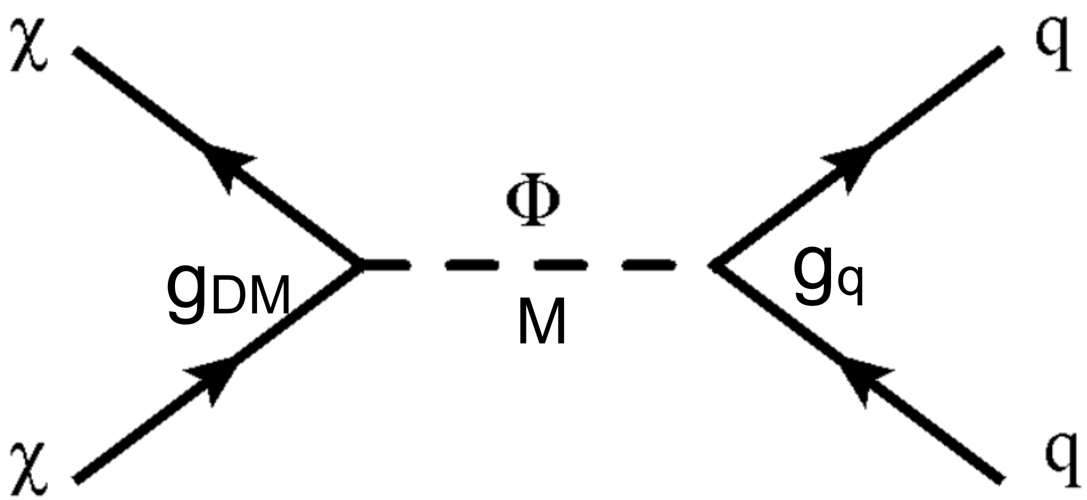
Dark Gluons
Dark Protons
Dark Pions
Dark Everything….

- Dark sector has the possibility to be rich
  - Lots of new interactions
  - Potential for a broad range of complex dynamics
- Only fundamental constraint is that it interacts gravitationally

Go back to DM annihilation

There a few critical elements here

In the limit where m_{DM} not $M_{med}/2$



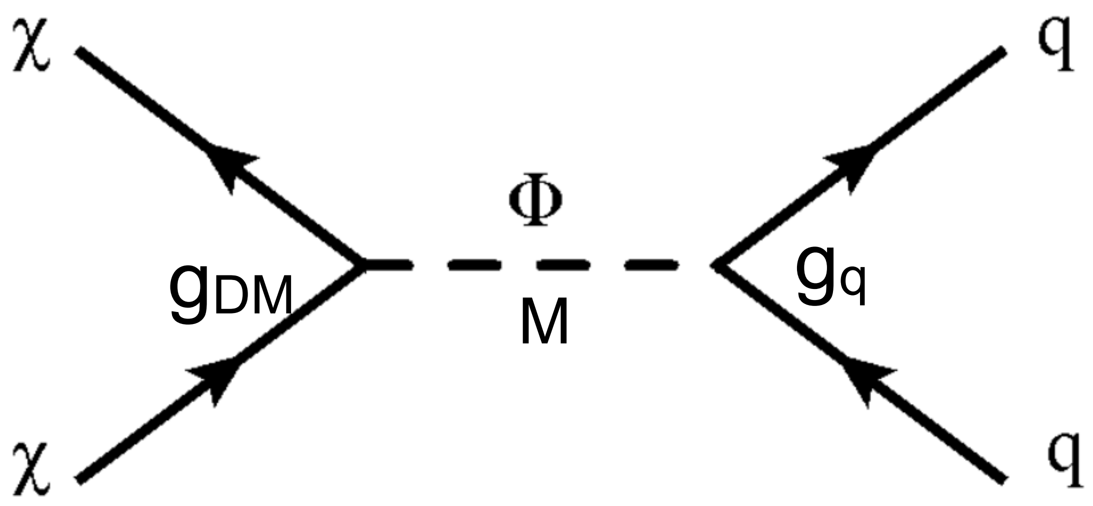
$$\boxed{\sigma^{V}_{\mathrm{ann},s} \cdot v} = \sum_q \frac{N_c^q \boxed{g_{\mathrm{DM}}^2 g_q^2} \beta_q}{2\pi} \frac{2m_{\mathrm{DM}}^2 + m_q^2}{\boxed{\left(M_{\mathrm{med}}^2 - 4m_{\mathrm{DM}}^2\right)^2} + M_{\mathrm{med}}^2 \Gamma_{\mathrm{med}}^2}$$

Gets our rate of DM production; needs to be roughly constant

To simplify things, we fix the ratio of $\frac{m_{DM}}{m_{med}} = \frac{1}{3}$

Go back to DM annihilation

To get the right relic density



$$\frac{(g_q g_{DM})^2}{M^2} = C$$

Fix to 1

For fixed m_{DM}/M_{med}

Large couplings &
Large masses or

Small couplings &
Small masses

$$\tilde{\mathcal{L}} = -\frac{\varepsilon}{2\cos\theta_W}\tilde{F}'_{\mu\nu}B^{\mu\nu}$$

Dark Photon

$$\begin{pmatrix} W^3_\mu \\ B_\mu \\ \tilde{A}'_\mu \end{pmatrix} = \begin{pmatrix} c_W & s_W & -s_W\varepsilon \\ -s_W & c_W & -c_W\varepsilon \\ t_W\varepsilon & 0 & 1 \end{pmatrix} \begin{pmatrix} \boxed{Z_\mu} \\ \boxed{A_\mu} \\ \boxed{A'_\mu} \end{pmatrix}$$

Z boson
Photon
Dark Photon

- Dark photon is a spin-1 portal mediator to the dark sector
  - For the minimal model we take the case of a vector mediator
- Dark photon differs from the simplified model in that it mixes
  - Kinetic mixing with the visible photon adds some differences
    - Mostly this modifies the DM content near Z poll
- Dark Photon has quickly become the standard benchmark
  - Nearly every low mass experiment uses it as a proxy

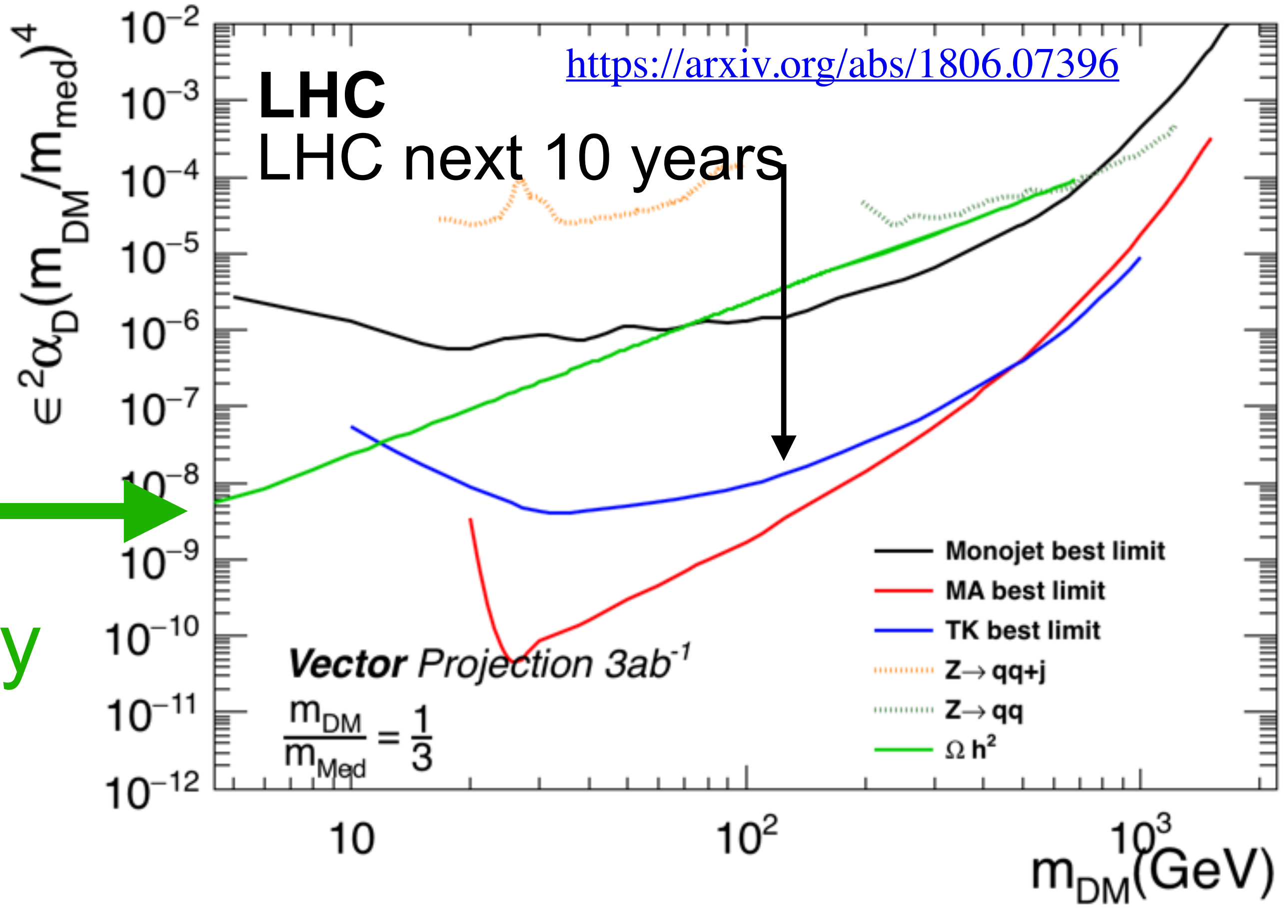
Story of Dark Matter

One Plot

Coupling axis

$$\alpha_D = \frac{g_{DM}^2}{4\pi}$$

$$\epsilon = g_q$$



https://arxiv.org/abs/1806.07396

LHC

LHC next 10 years

This is the dark matter density

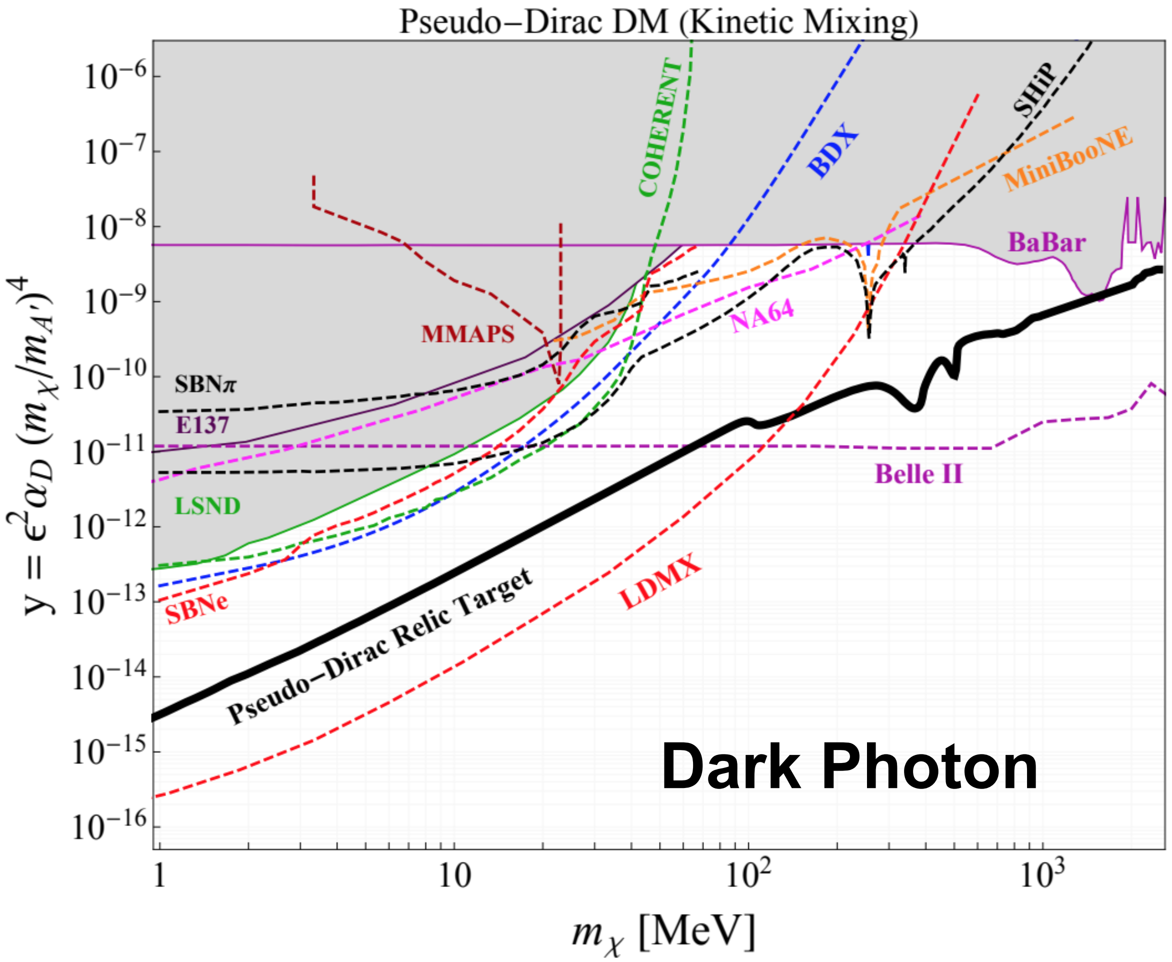
Weakly Coupled

Light Dark Matter

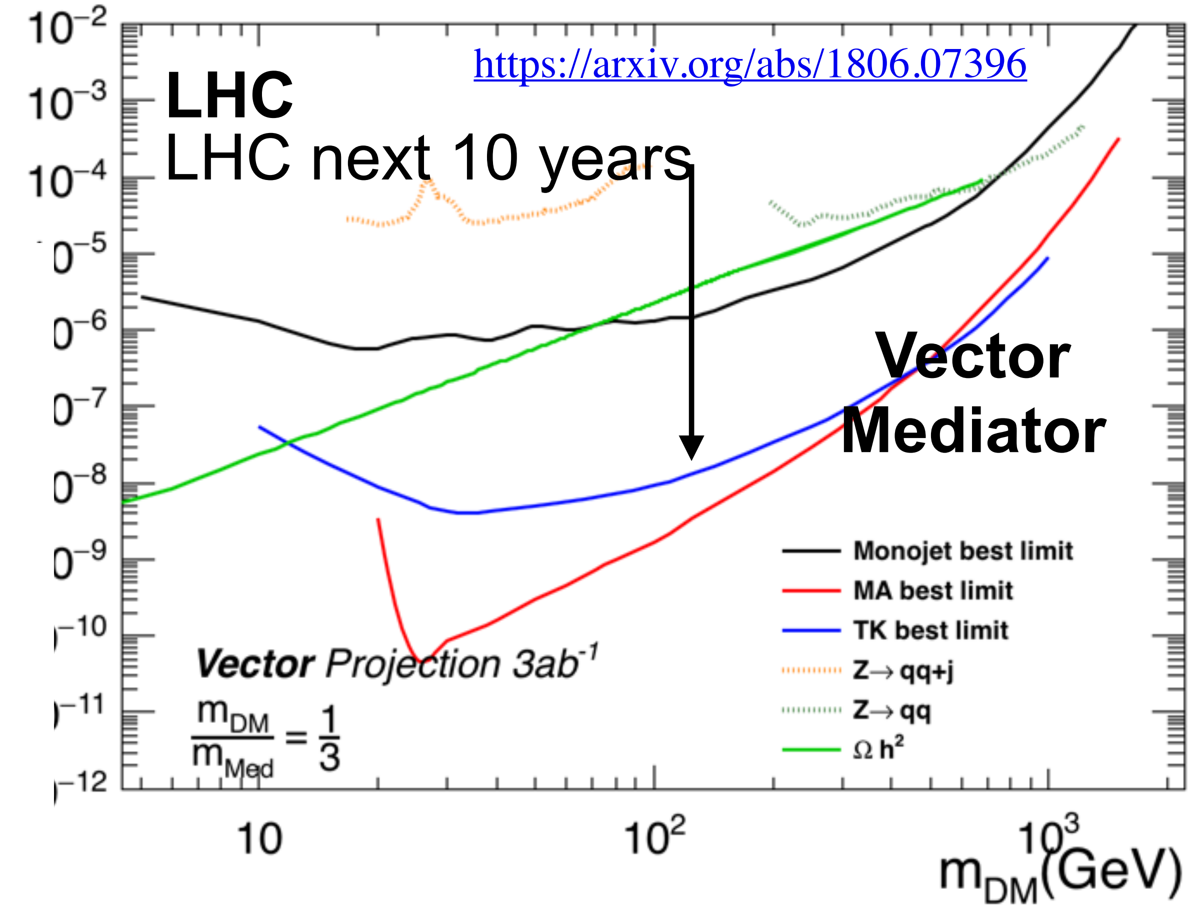
Story of Dark Matter

One Plot

US Cosmic visions report
https://arxiv.org/pdf/1707.04591.pdf



Dark Photon



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LHC next 10 years

Vector Mediator

Weakly Coupled

Light Dark Matter

Story of Dark Matter

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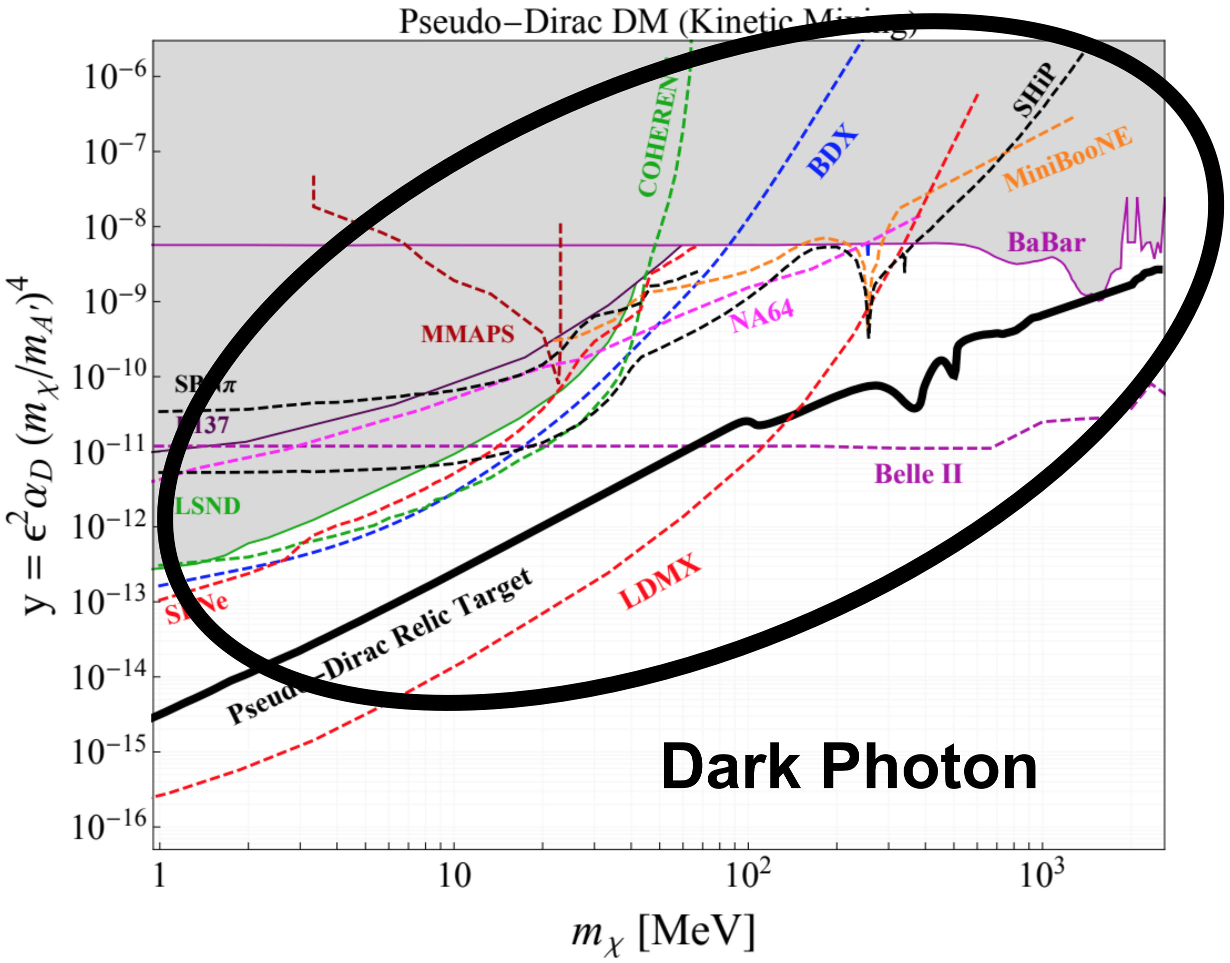


What are all
of these experiments?

Weakly Coupled

Light Dark Matter

What do we get with small couplings?

https://www.sciencedirect.com/science/article/pii/S2405428320300058

- Small couplings means interaction strength is weak
  - This also means the rate of decay will be weak
  - This also means the lifetime will be long

$$c\tau = \frac{1}{\Gamma} = \frac{3}{N_{eff} m_{A'} \alpha \epsilon^2} \sim \frac{80\ \mu\text{m}}{N_{eff}} \left(\frac{10^{-4}}{\epsilon}\right)^2 \left(\frac{100\ \text{MeV}}{m_{A'}}\right)$$

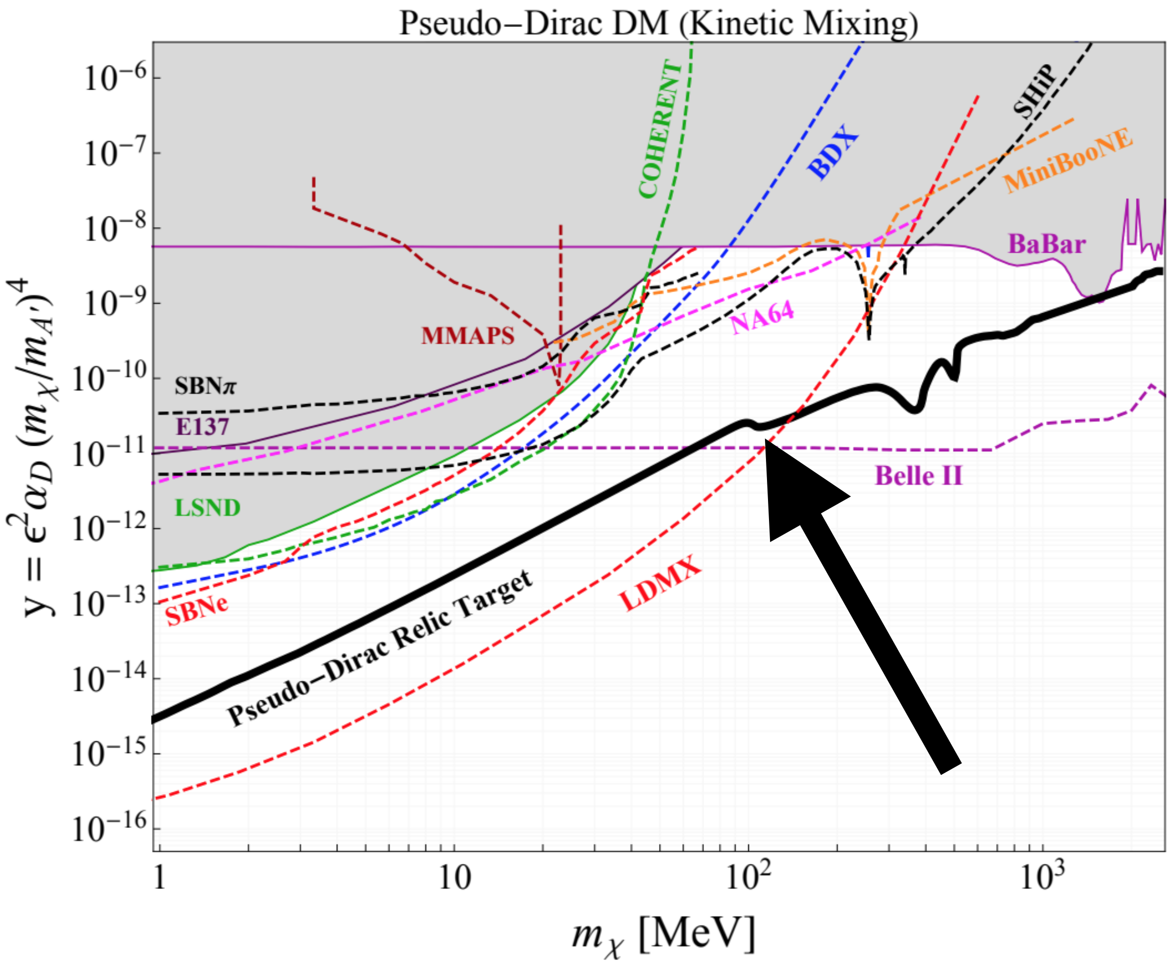
Quick estimaterelic gives $\epsilon \sim 10^{-4}$ Dark Photon mass of 100 MeV

Going lighter we have lifetime grows quickly 80x10 μm at 10 MeV
Thats a lifetime of 1 mm at 10 MeV

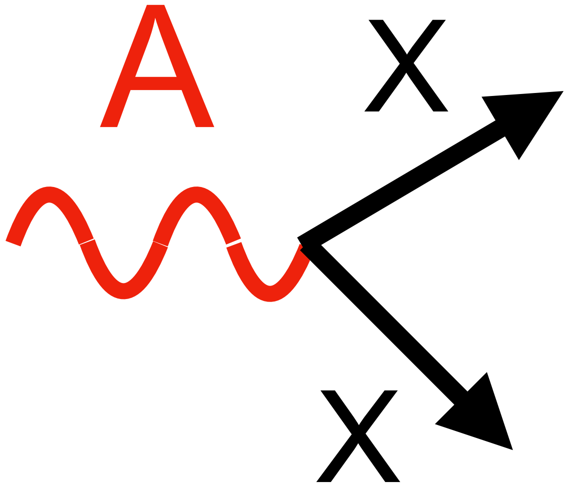
How do light mediators decay?

What are the decays?

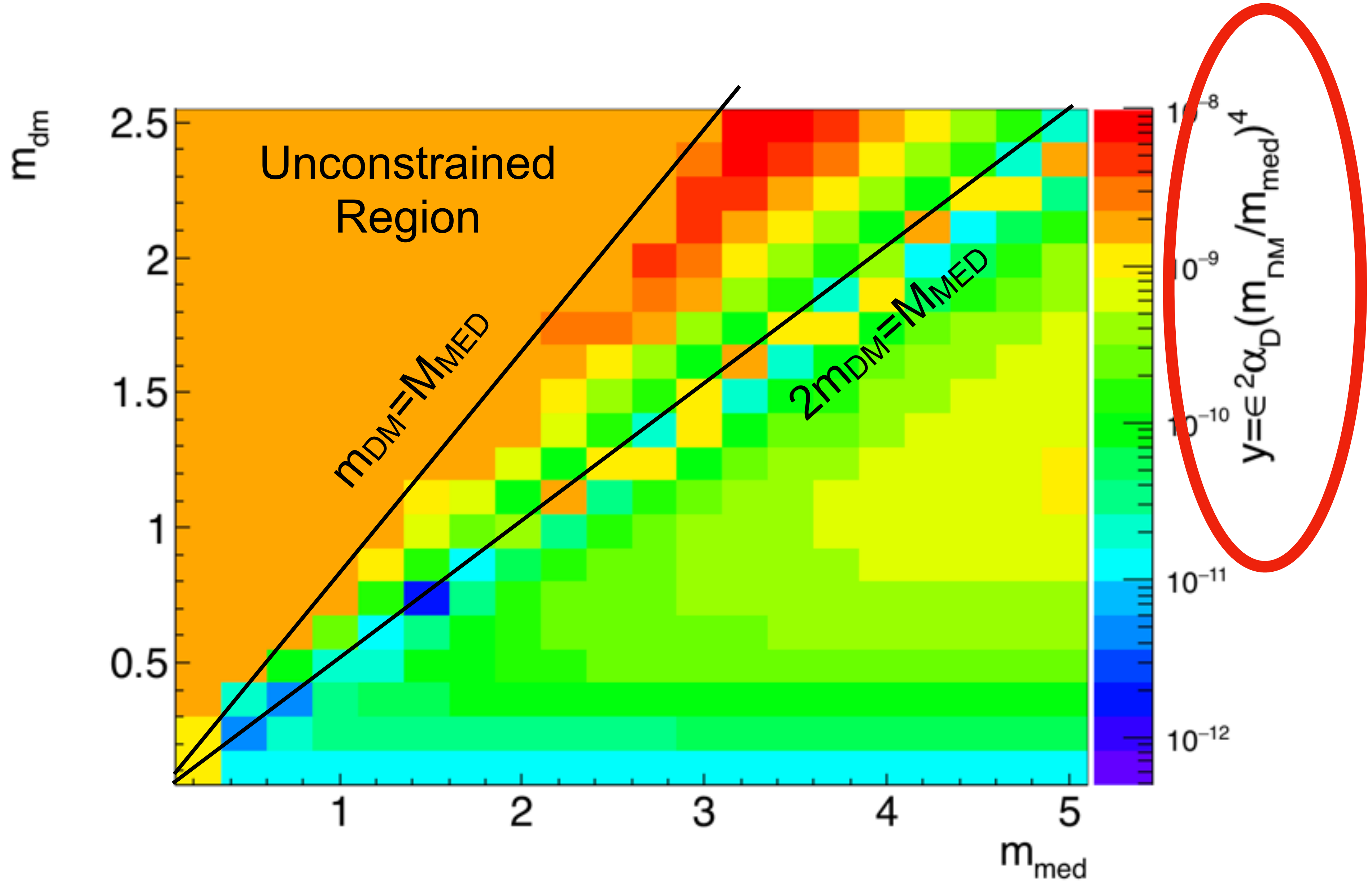
- Typically we assume a very large dark matter coupling
  - That means SM coupling to get relic is small
  - $10^{-11} = \epsilon^2 \alpha_D (m_{DM}/m_{A'})^4 = \epsilon^2 \alpha_D (1/3)^4 \approx 0.01 \epsilon^2 \alpha_D$
  - Taking $\alpha_D = \dfrac{1}{4\pi}$ we have $\epsilon^2 \approx 10^{-8}$



This means $\dfrac{\mathrm{BR}(\mathrm{A}' \to \chi\chi)}{\mathrm{BR}(\mathrm{A}' \to \mathrm{ee})} \approx \dfrac{1}{\epsilon^2}$



What about when DM is heavy?

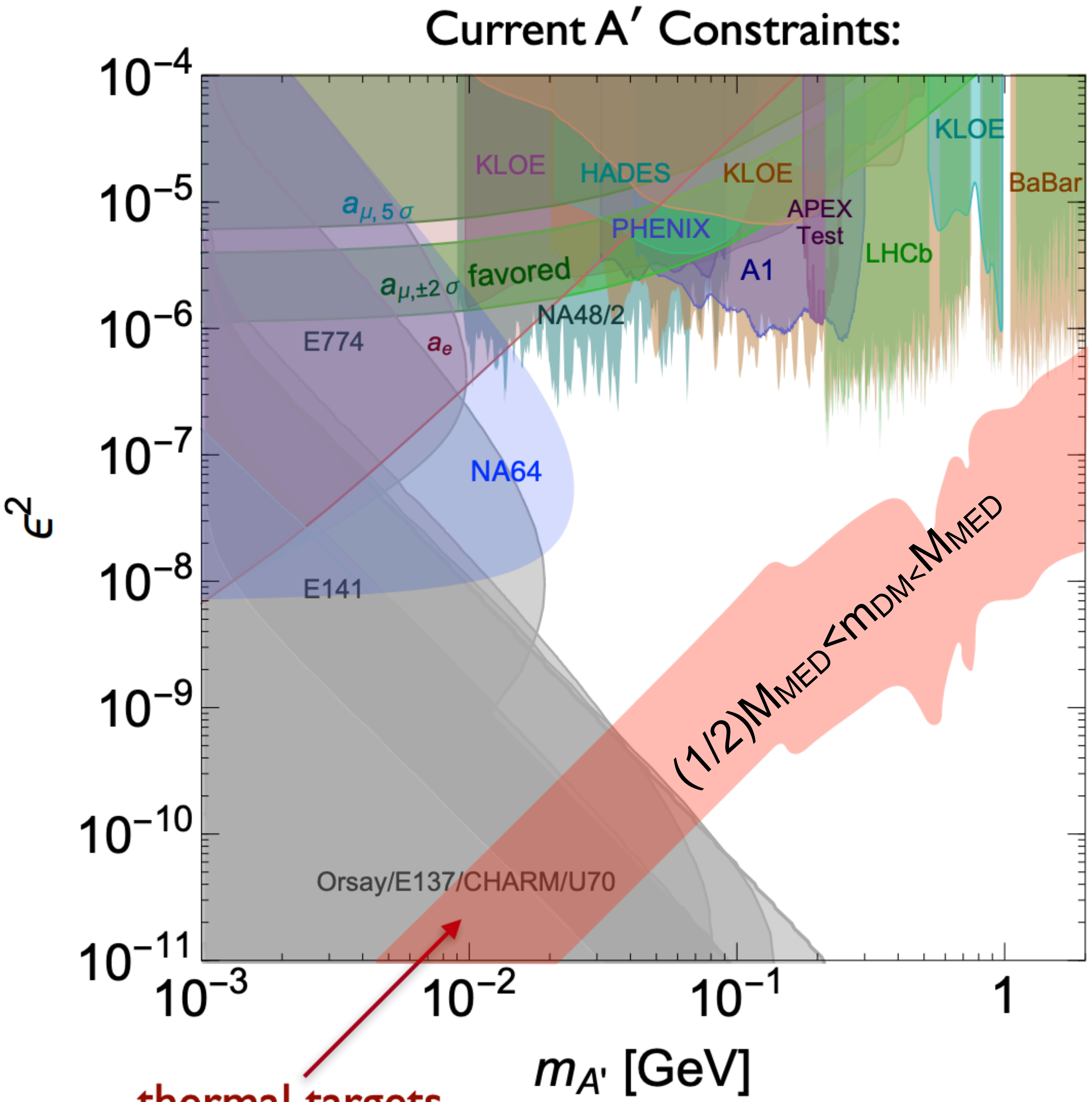


Minimum Coupling
To satisfy relic
constraints

In this region we typically don’t have strong constraints

However as a rule of thumb we aim to go for a similar coupling to invisible

General Rules of Thumb



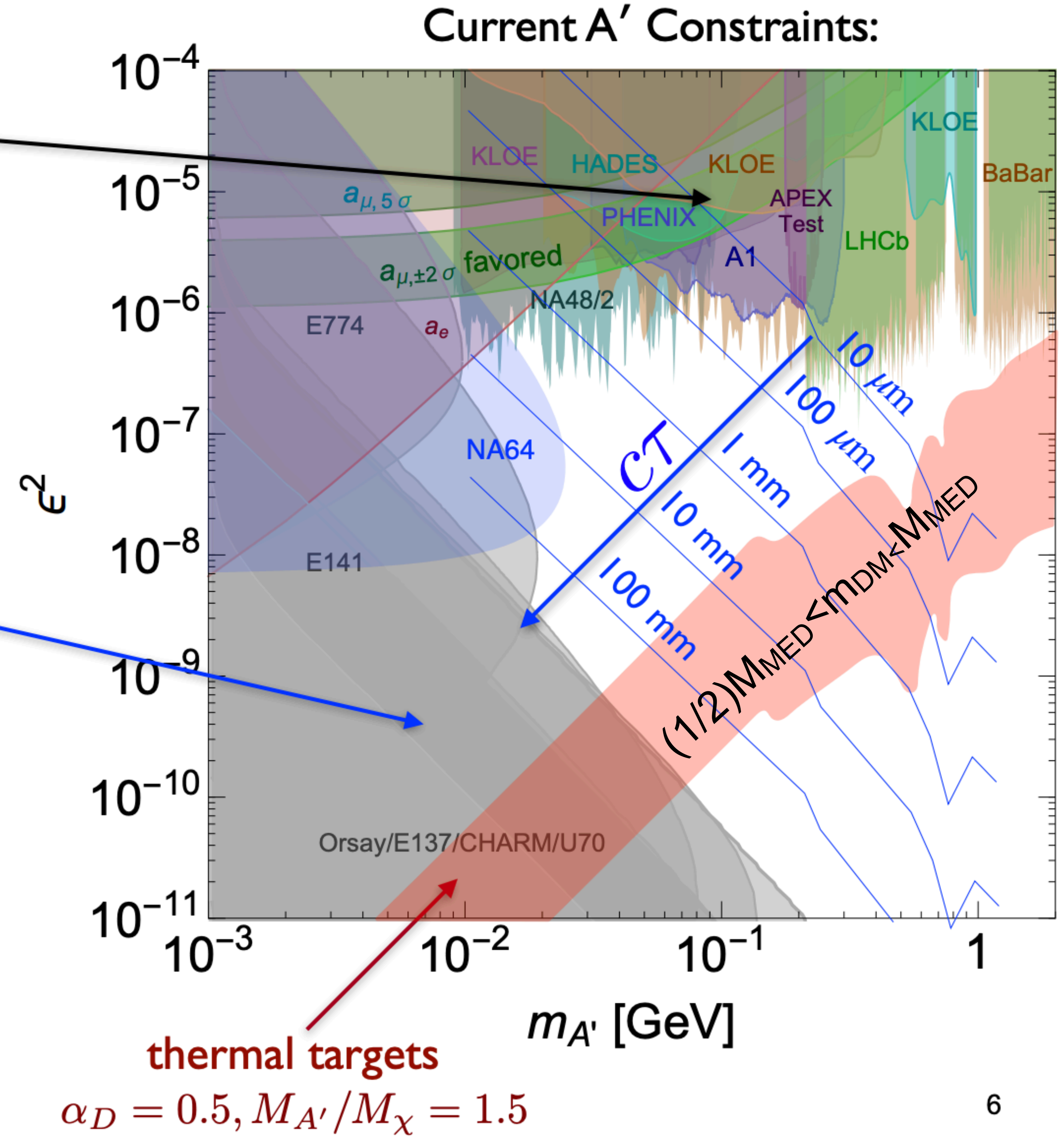
thermal targets

$\alpha_D = 0.5, M_{A'}/M_\chi = 1.5$

General Rules of Thumb

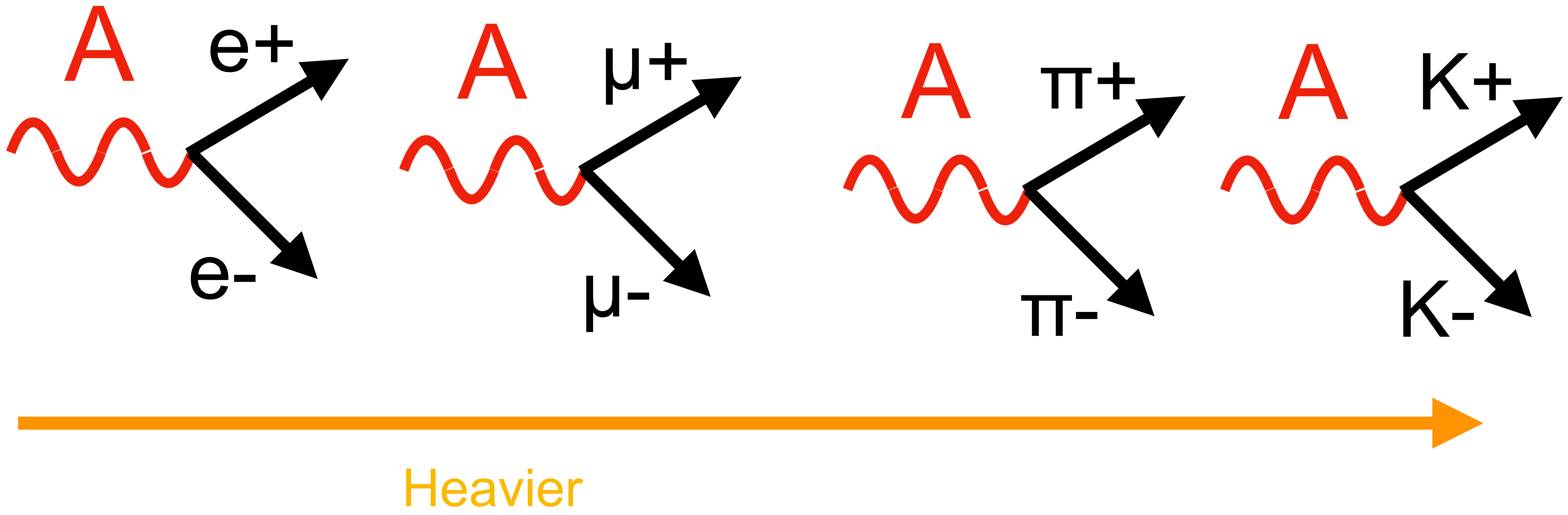
Prompt Region

Long Lived Region



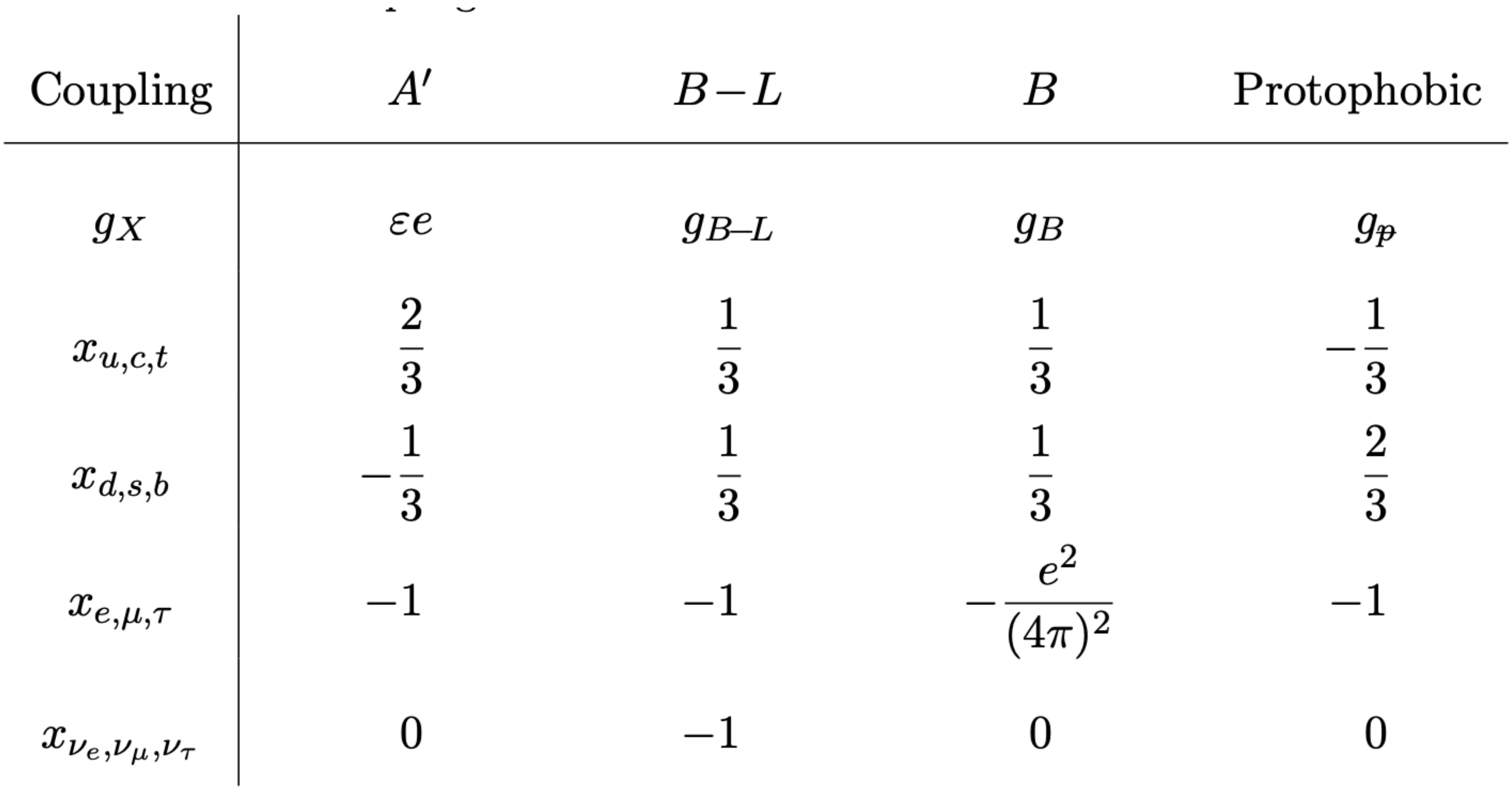
Decays of light DM?

For Light DM we are kinematically constrained



As the mediator gets heavy it opes the potential of many decays

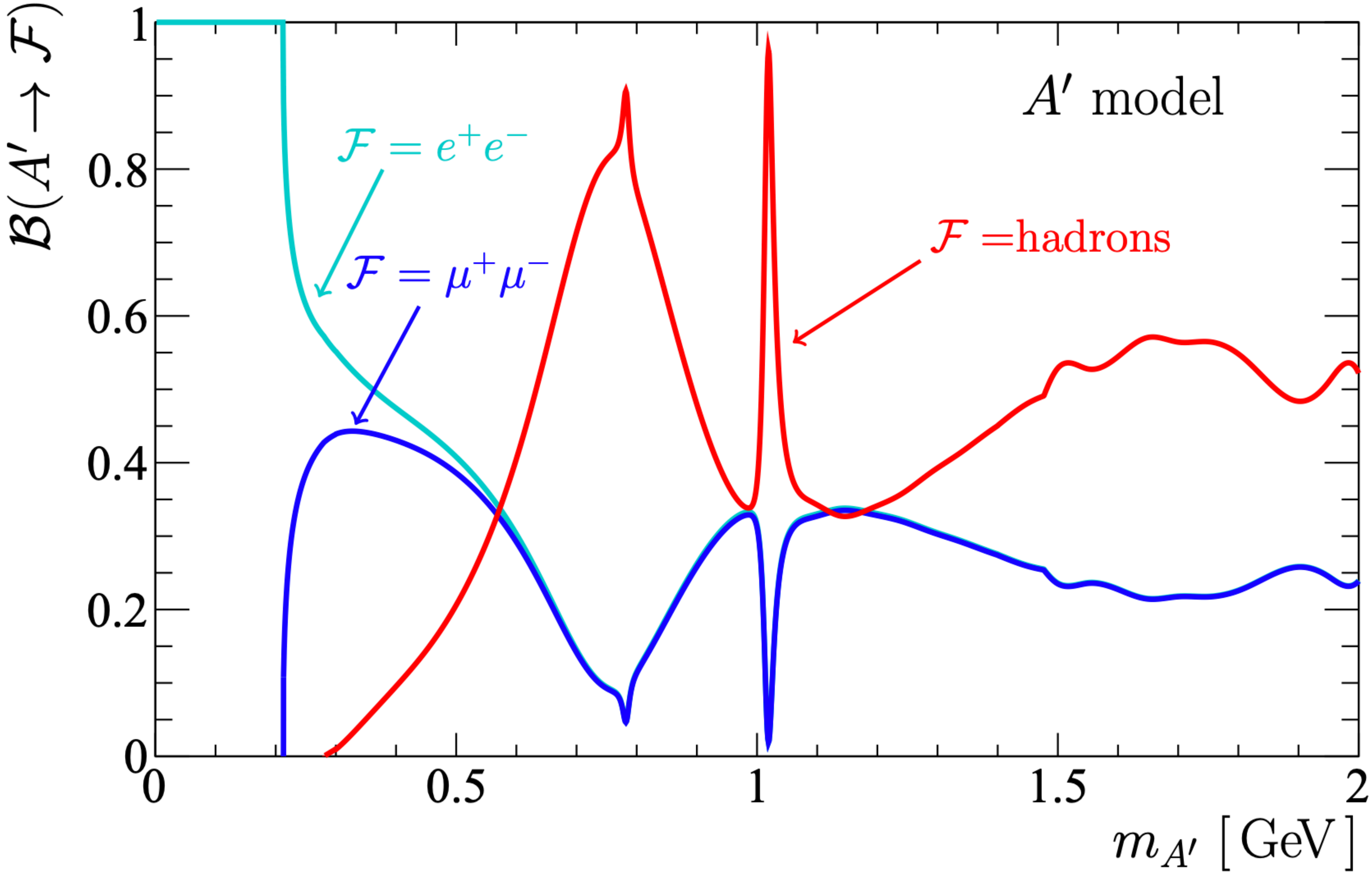
Key for Next Plots



Coupling	A'	$B{-}L$	B	Protophobic
g_X	εe	$g_{B\text{–}L}$	g_B	$g_{\not p}$
$x_{u,c,t}$	$\frac{2}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$-\frac{1}{3}$
$x_{d,s,b}$	$-\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{2}{3}$
$x_{e,\mu,\tau}$	-1	-1	$-\frac{e^2}{(4\pi)^2}$	-1
$x_{\nu_e,\nu_\mu,\nu_\tau}$	0	-1	0	0

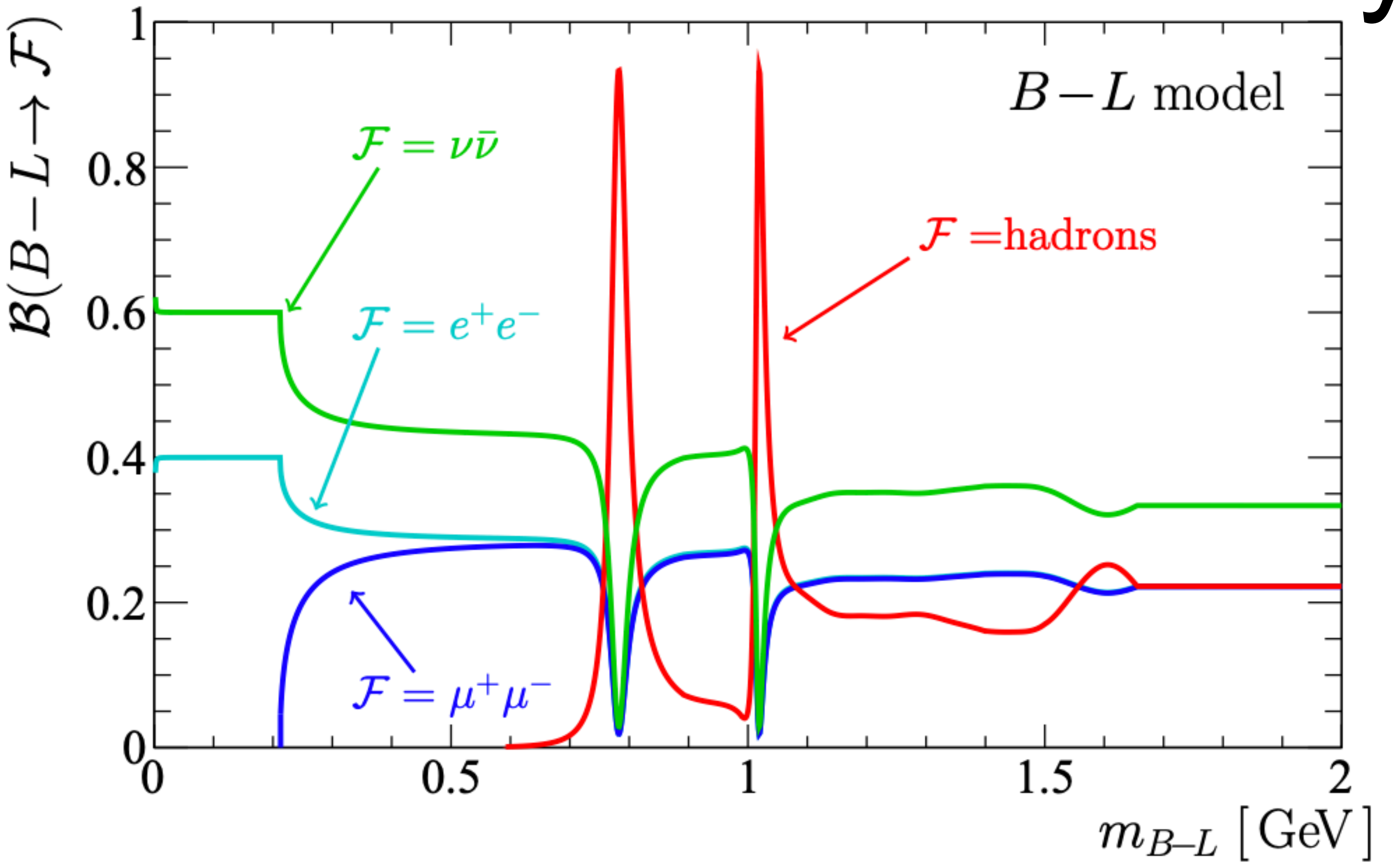
$$\mathcal{L} \subset g_X \sum_f x_f \bar{f} \gamma^\mu f X_\mu + \sum_\chi \mathcal{L}_{X\chi\bar{\chi}}$$

What are the decays?



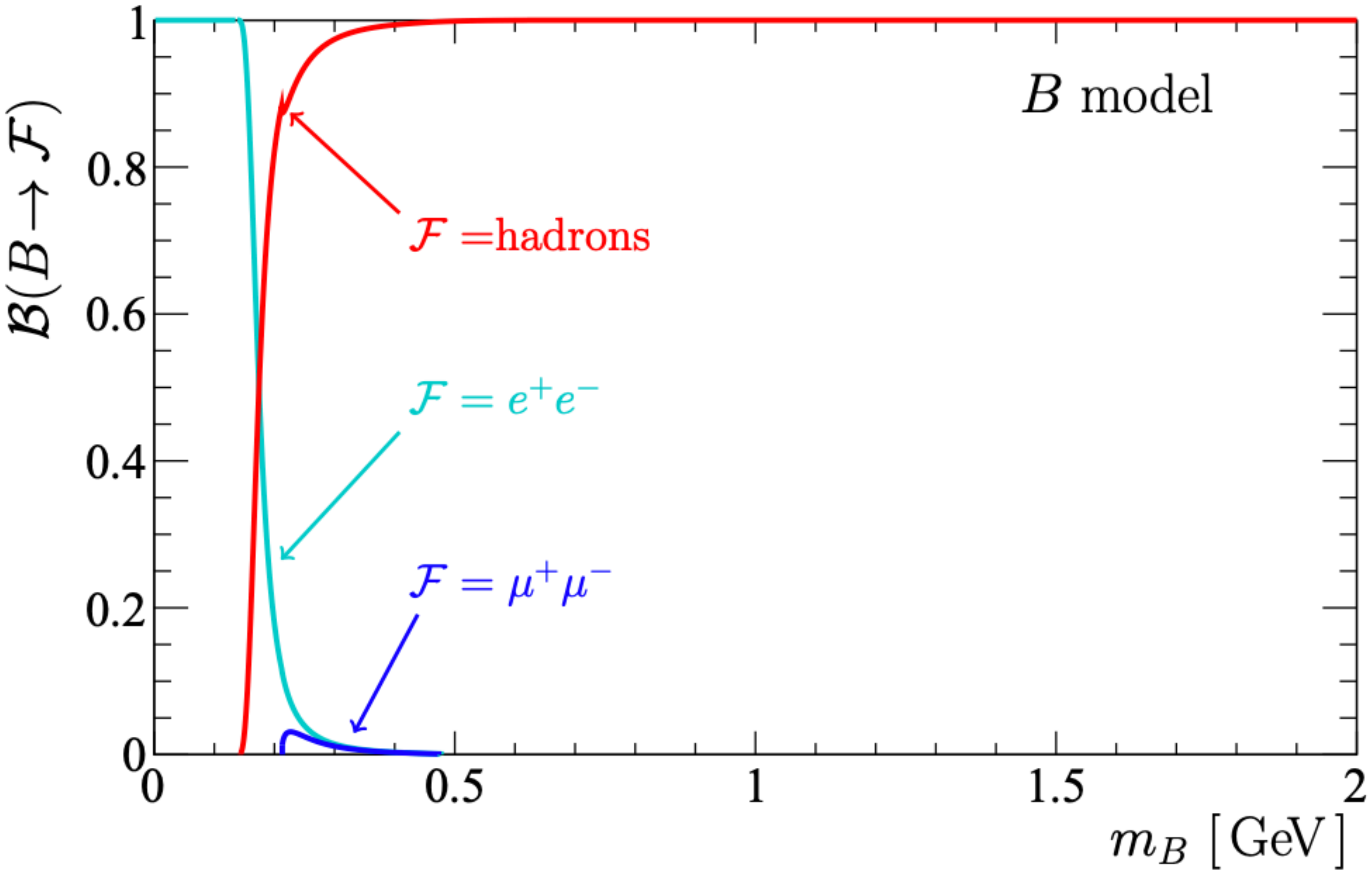
- Other thing to account for is the final state of these
  - Note that muons and electrons dominate at low mass

What are the decays?



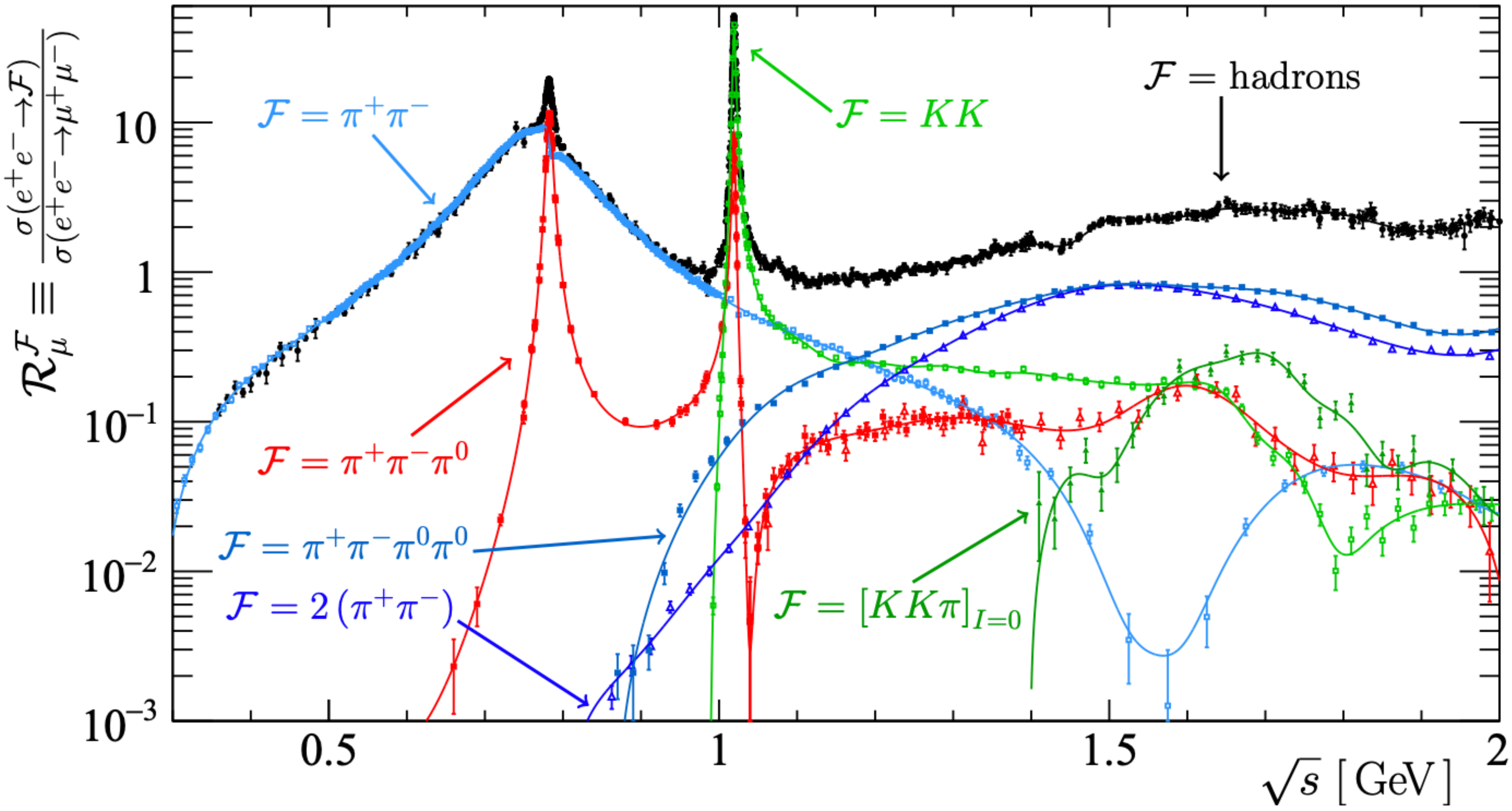
- We can add Neutrino decays

What are the decays?



- Even if we emphasize baryons, electrons dominate at low mass

How do we get this?

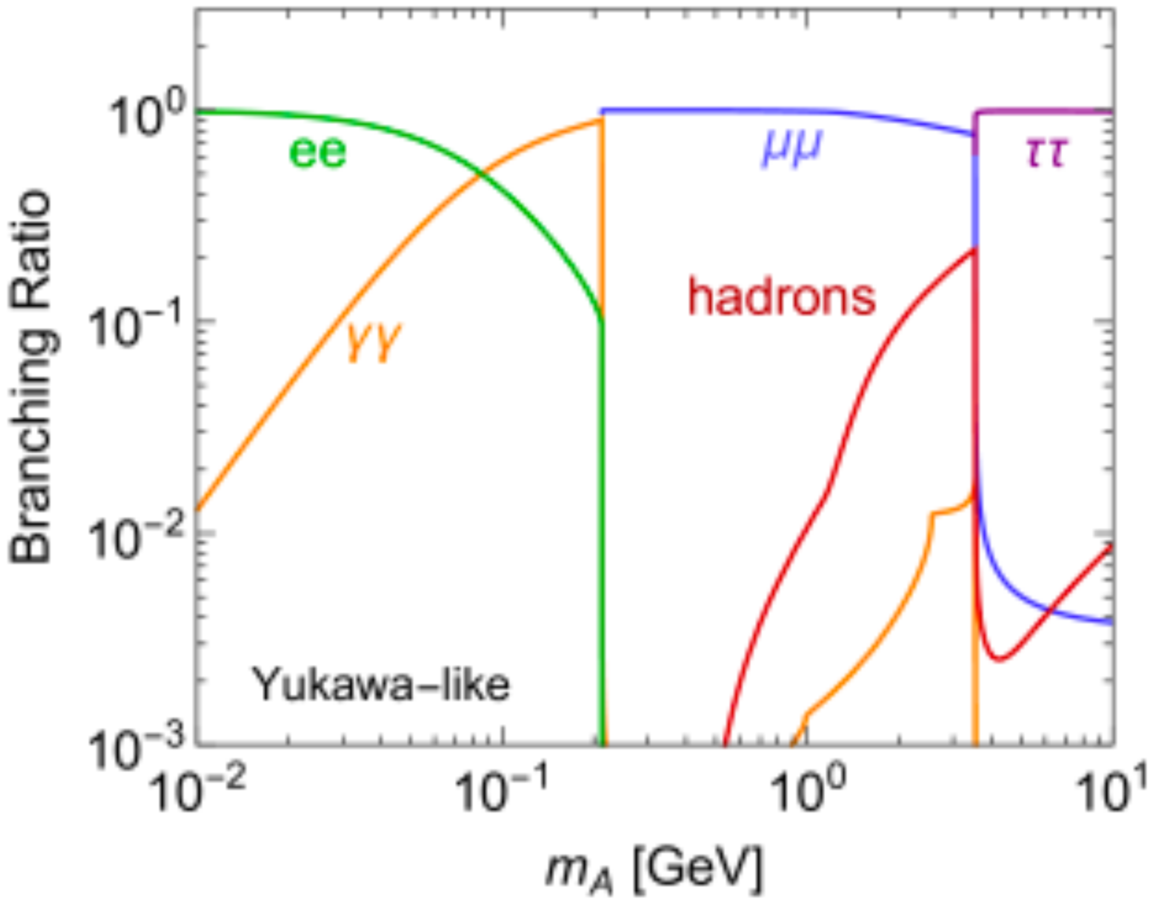


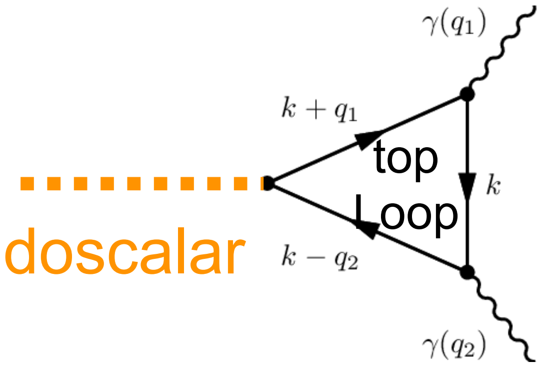
$$\mathcal{R}_\mu^{\mathcal{F}}(m) \equiv \frac{\sigma_{e^+e^-\to\mathcal{F}}}{\sigma_{e^+e^-\to\mu^+\mu^-}} = \frac{9}{\alpha_{\rm EM}^2}|\mathcal{A}_{\mathcal{F}}(m)|^2 \quad \Gamma_{X\to\text{hadrons}} = \frac{g_X^2 m_X}{12\pi}\left[\sum_V \mathcal{R}_X^V(m_X) + \mathcal{R}_X^{\omega\text{-}\phi}(m_X)\right]$$

Couplings to different final states change with model

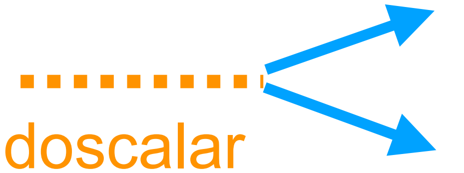
What about other signatures?

- So far we have been focusing on dark photons
  - Spin-1 mediators with equal, or close to equal lepton couplings
- To cover the diversity of thought lets consider ALPs
  - Axion Like Particles => Pseudoscalar mediators





Pseudoscalar



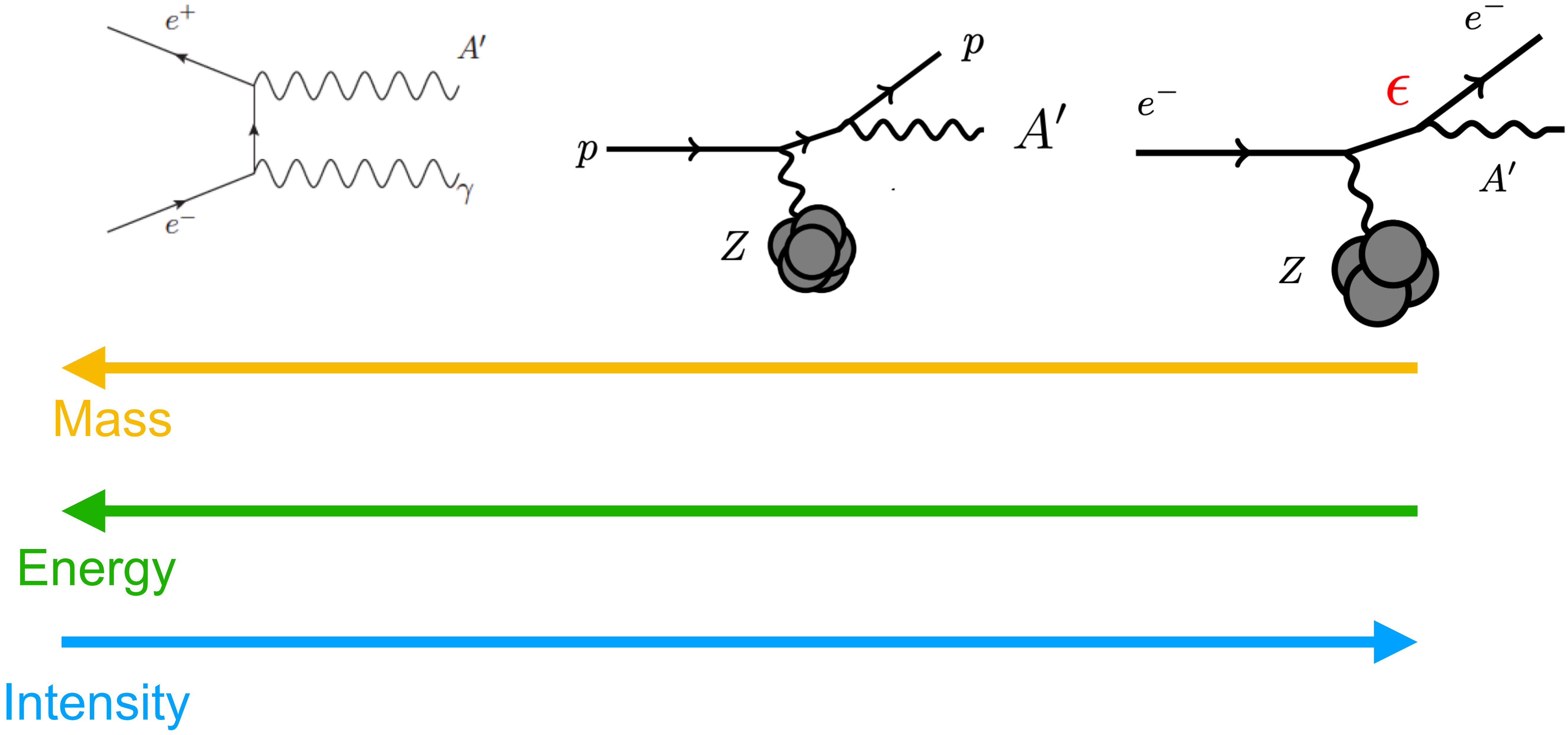
Pseudoscalar

Muons

For Yukawa-like Particles

Dominant decays typically are photons and muons

How do you produce a light particle?



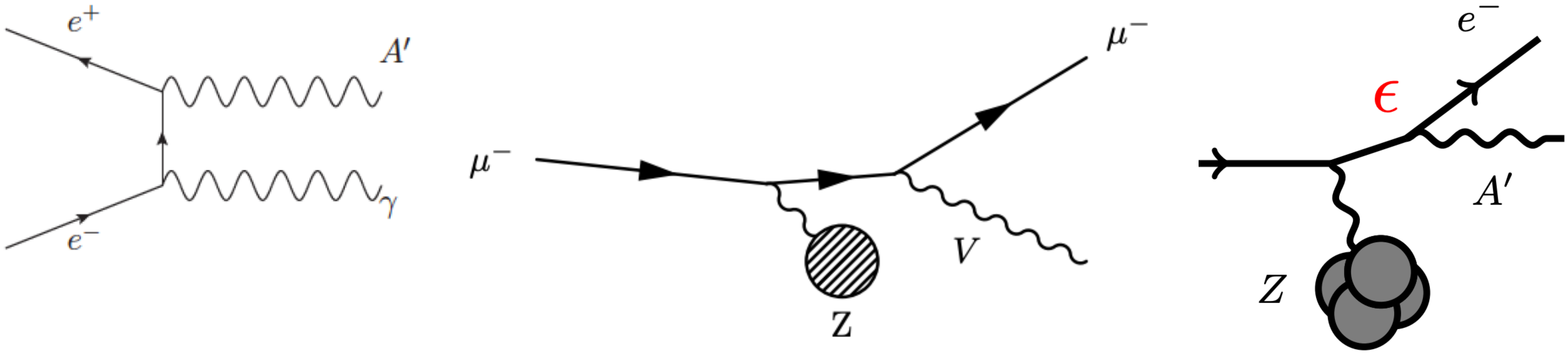
Mass

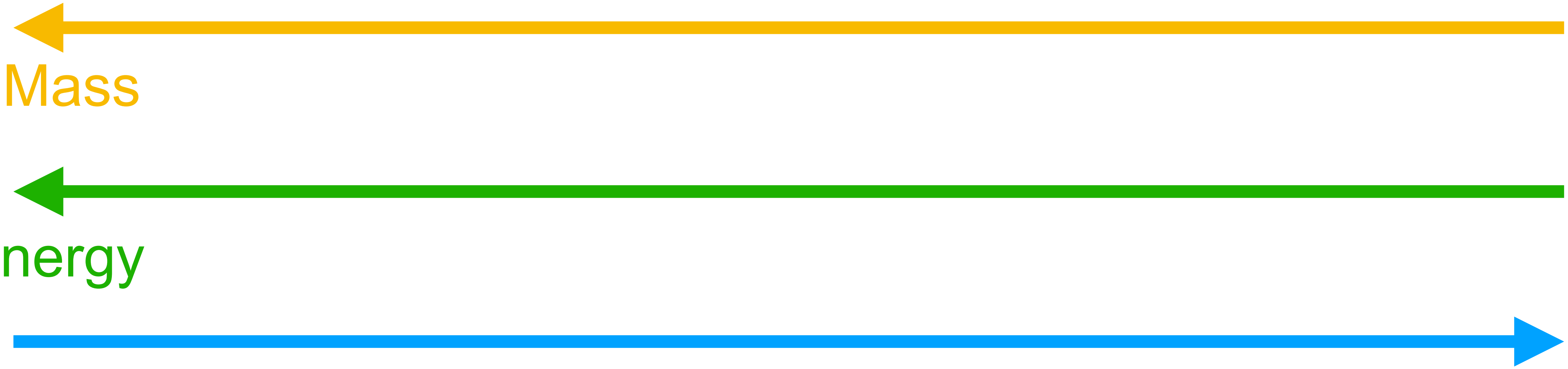
Energy

Intensity

- As we lighter in mass, we aim for higher intensity and lower E

How do you produce a light particle?





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Energy

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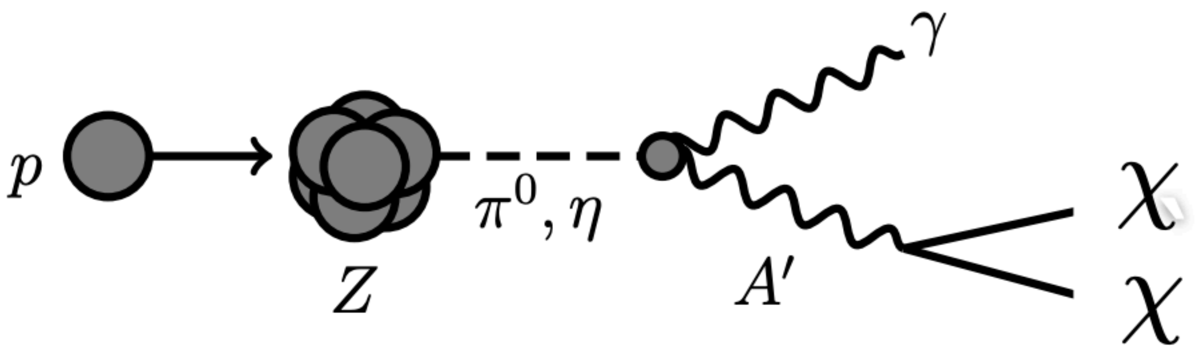
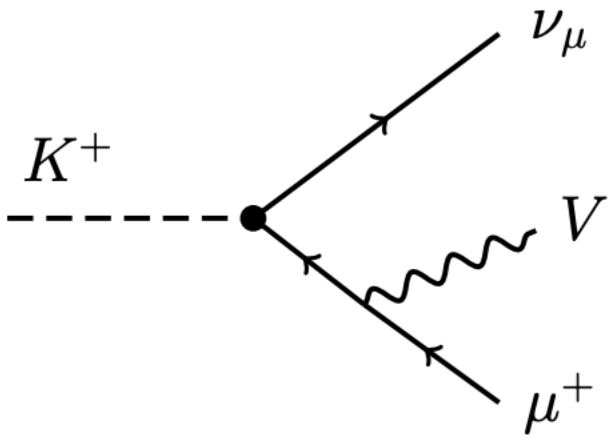




$$K^+ \to \mu^+ \nu_\mu V, \quad V \to \chi\chi$$

- When the mediator is very light we can decay into DM
  - The decay results from light mesons K, π, η
  - Sufficient freedom in particle decays to have these

Recap

- We need to look for simple signatures
- We know a few things:
  - As DM gets lighter we need to crank up the intensity
    - Allows us to go lighter coupling
  - For light DM, mediator likely decays invisibly
  - For heavy DM, mediator decays to SM that can be long lived
    - And then decay to light stuff (ie electrons or muons)

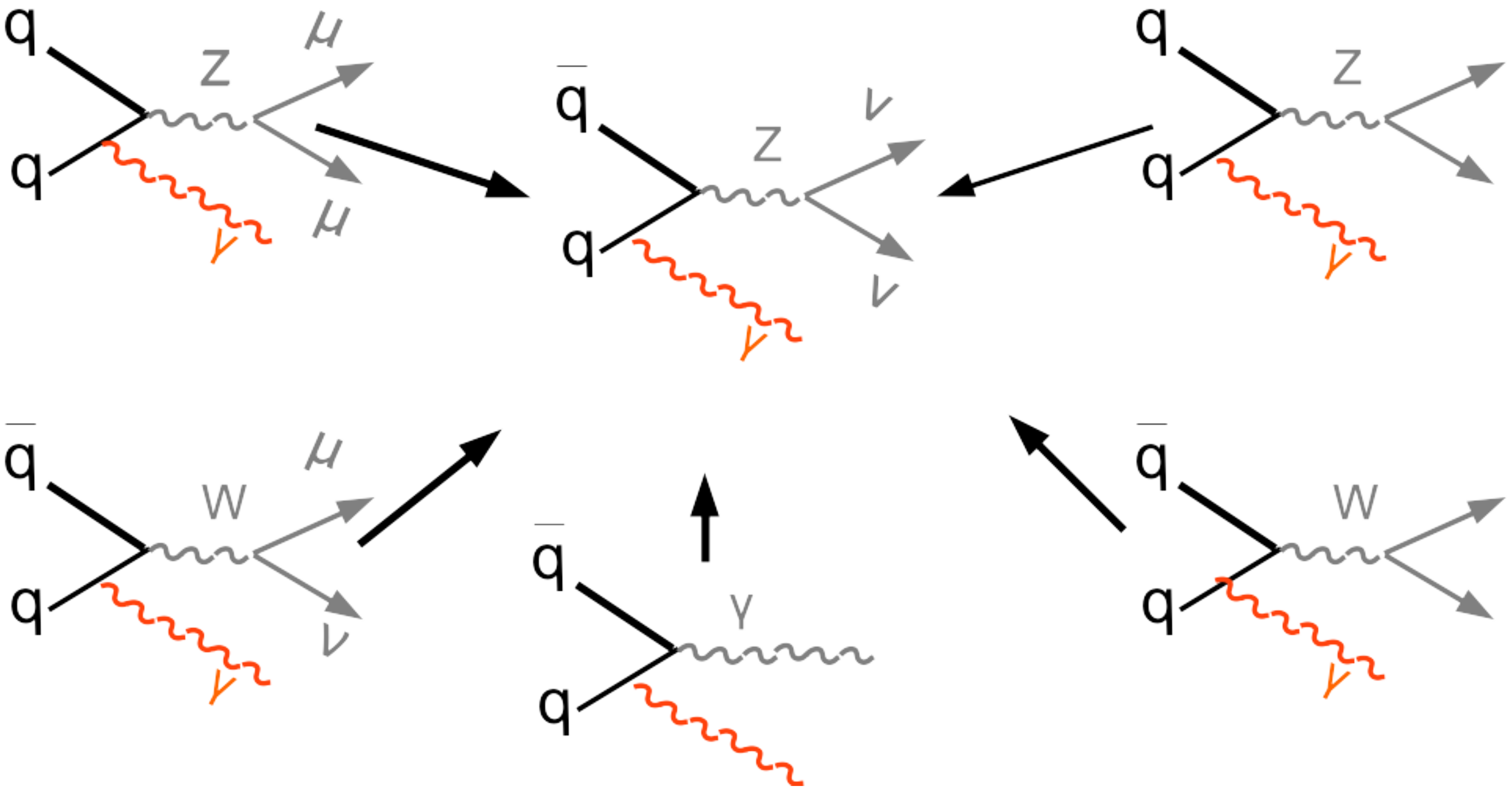
How to Find
Dark Photons

So…..How do we find them?

- There are a few nice features:
  - Small coupling means long lifetime, which is very distinct
    - There are not too many long lived non-interacting particles
  - Invisible decays means we don’t see anything
    - There are only a few invisible process
  - Weak interactions means a larger detector might see it
    - We can take advantage of neutrino physics

MonoPhoton Analysis

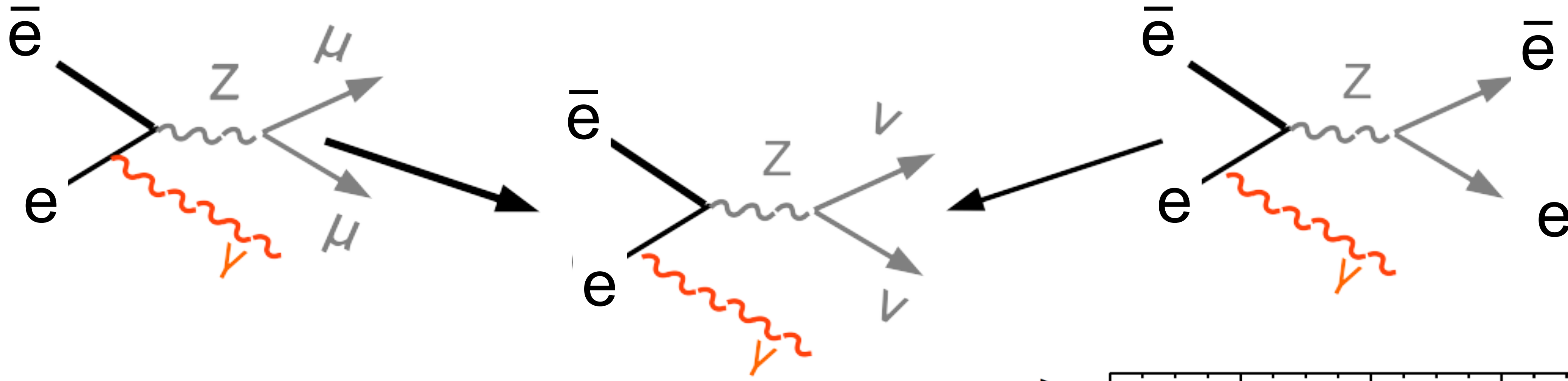
Recall from Lecture 1

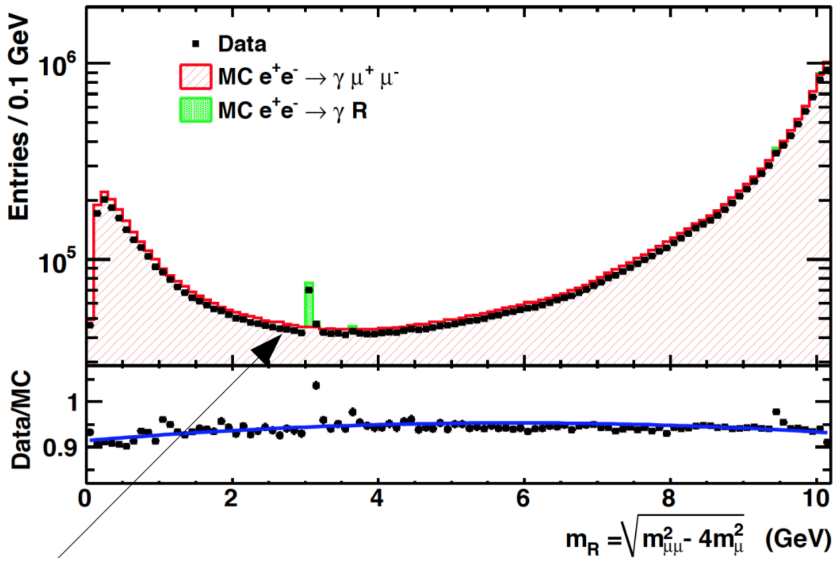


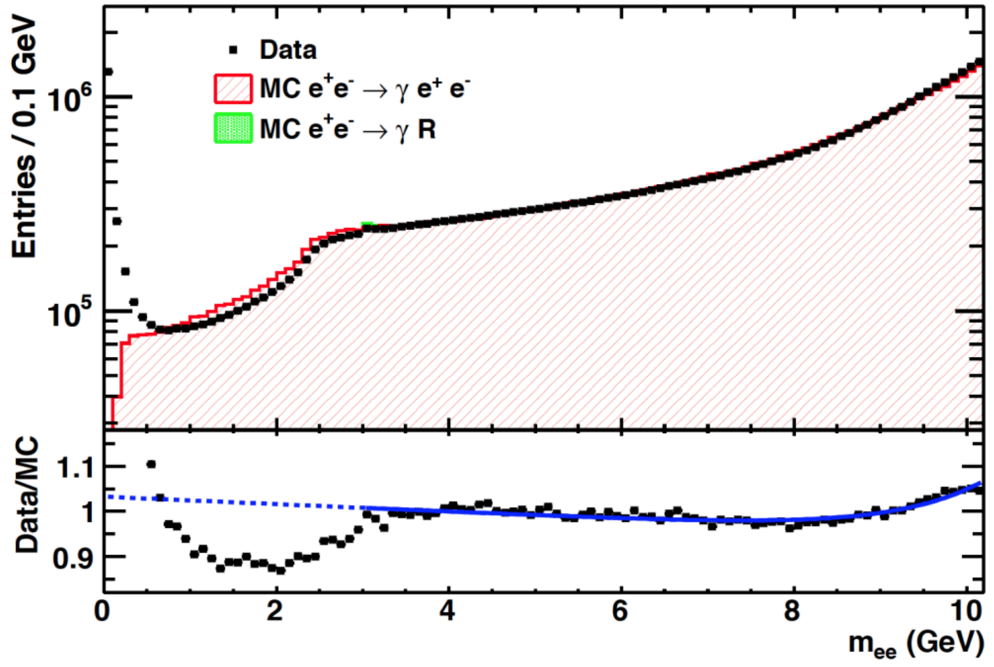
We used our simultaneous fit to search to do the photon analysis

MonoPhoton Analysis

We can replace this with electrons and use an electron positron collider



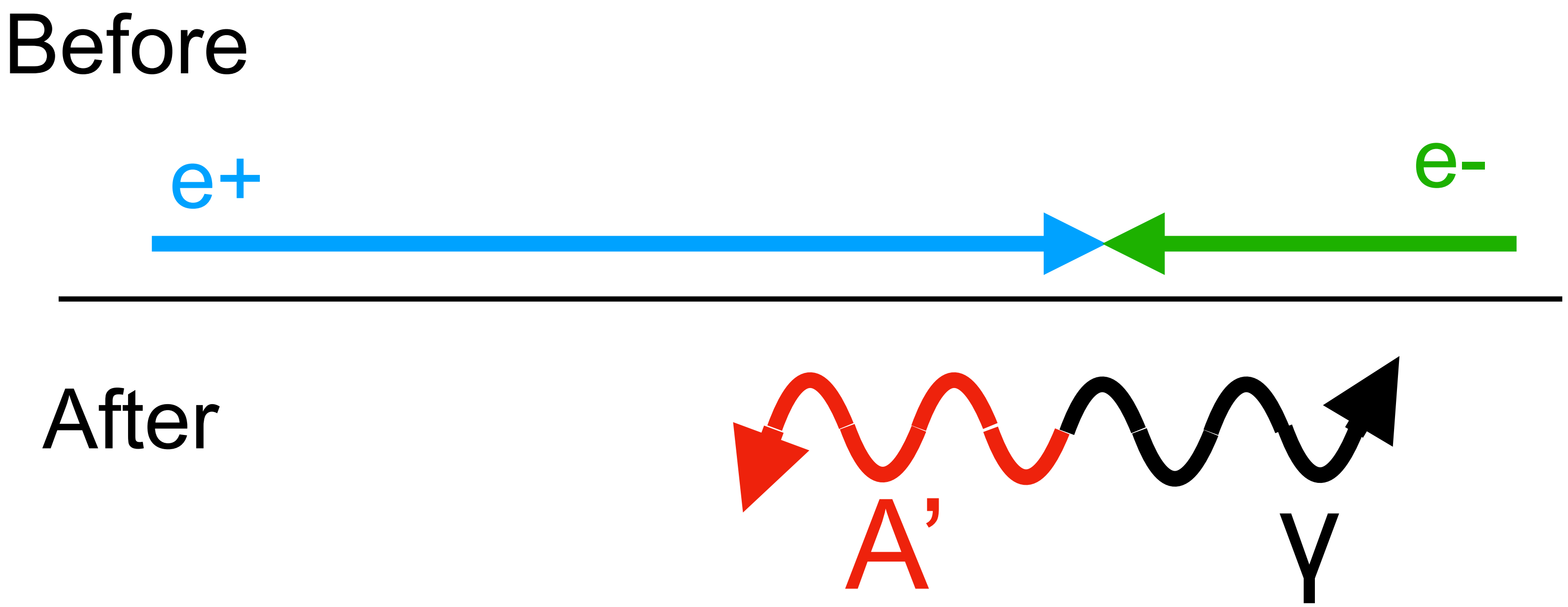


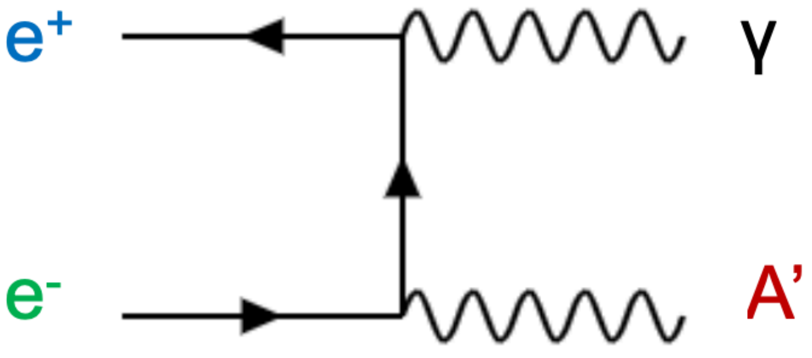


Here we now have additional variables that can help us

Missing Mass

- This was the first approach to these style of searches





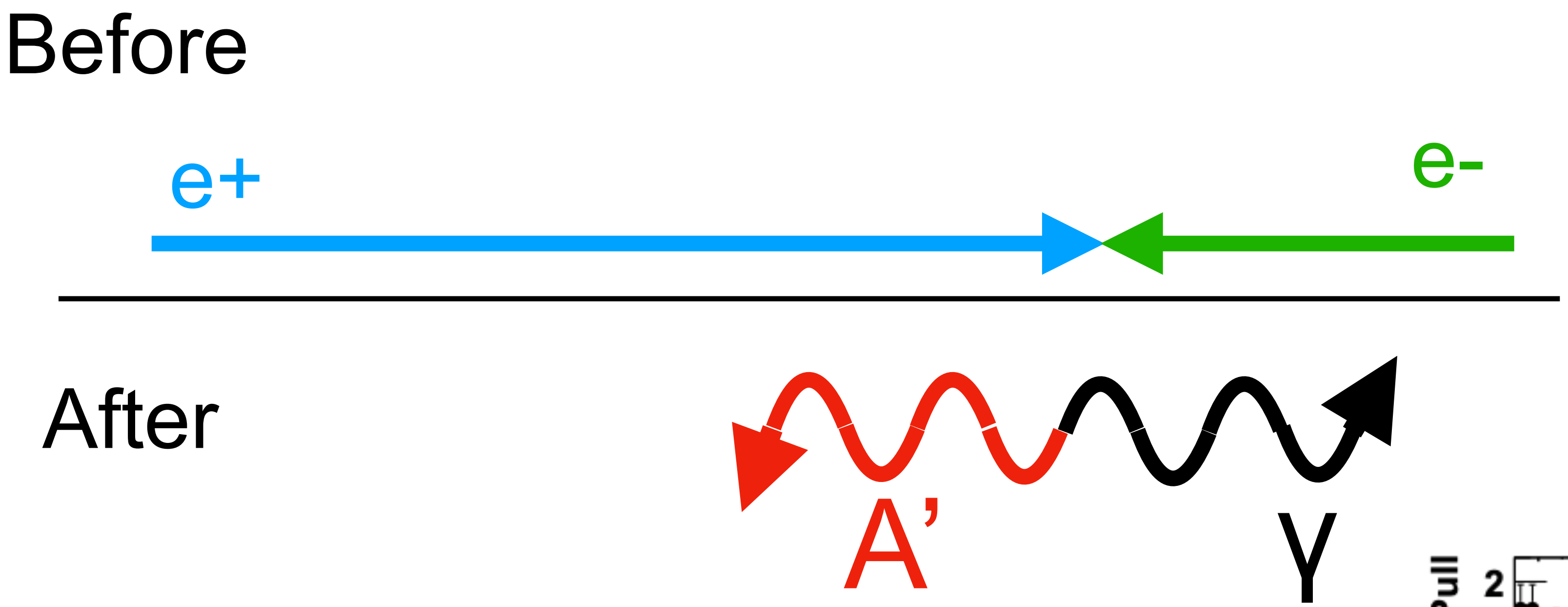
$$\overrightarrow{p_i^{e+}} + \overrightarrow{p_i^{e-}} = \overrightarrow{p_f^{\gamma}} + \overrightarrow{p_f^{A'}}$$

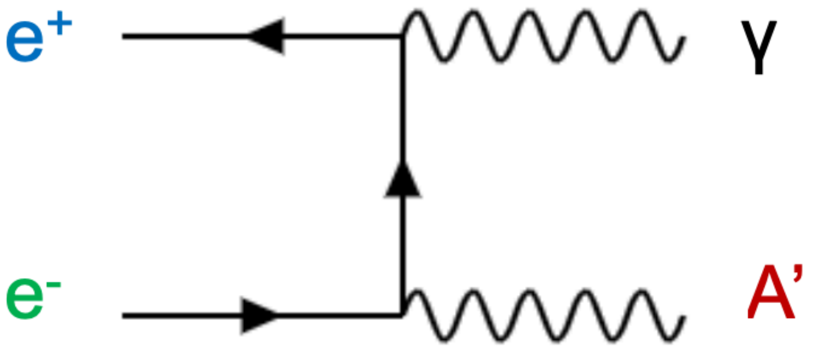
$$\overrightarrow{p_i^{e+}} + \overrightarrow{p_i^{e-}} - \overrightarrow{p_f^{\gamma}} = \overrightarrow{p_f^{A'}}$$

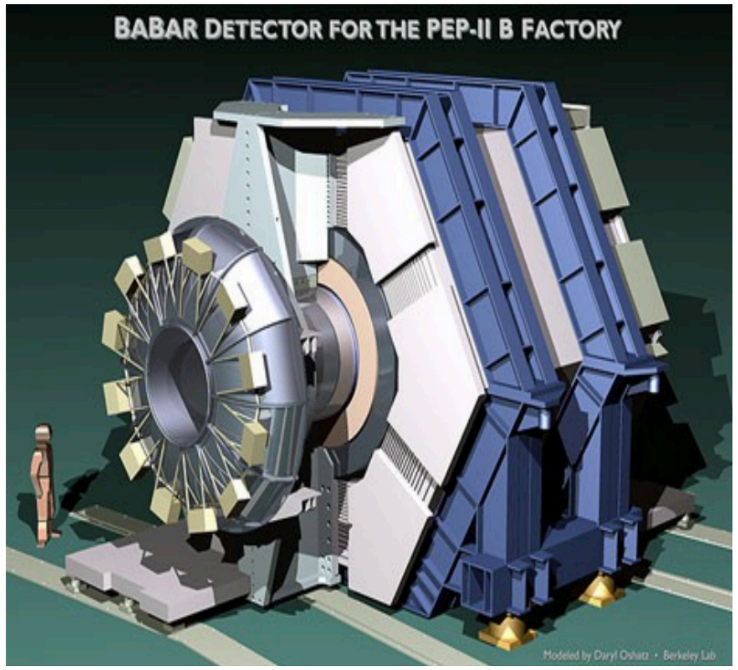
$$\left(\overrightarrow{p_i^{e+}} + \overrightarrow{p_i^{e-}} - \overrightarrow{p_f^{\gamma}}\right)^2 = \left(\overrightarrow{p_f^{A'}}\right)^2 = m_{A'}^2$$

Missing Mass

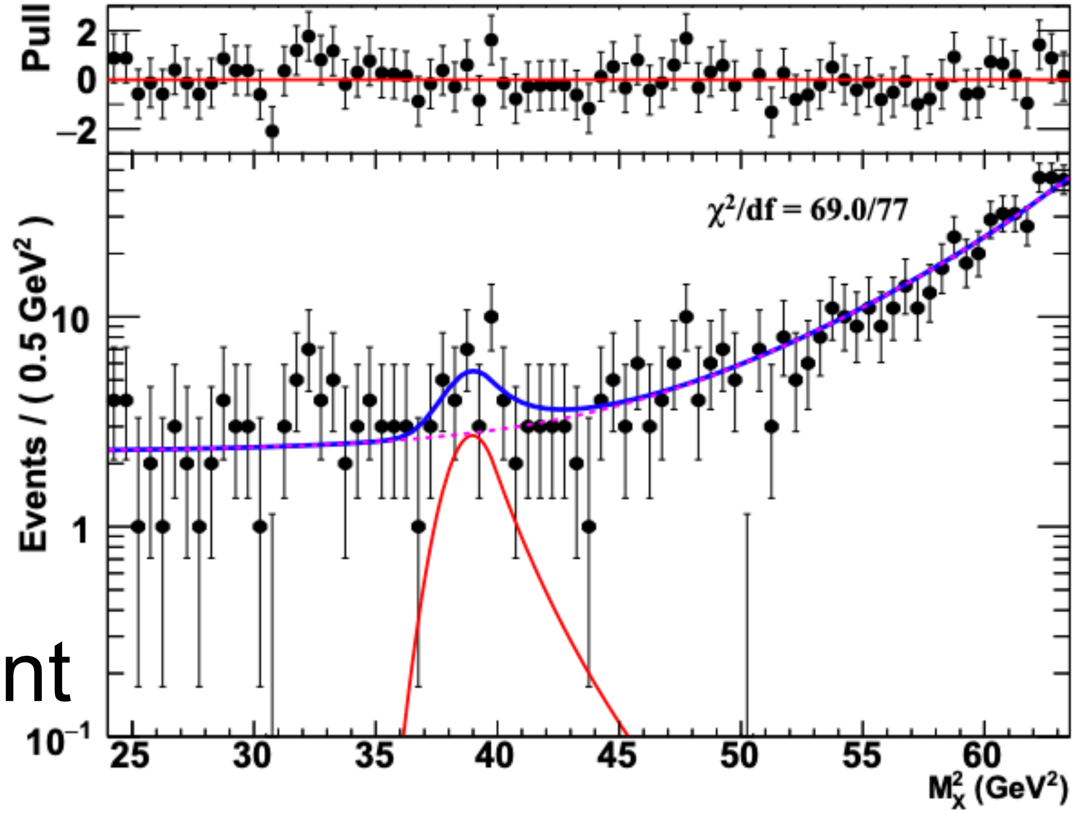
- This was the first approach to these style of searches



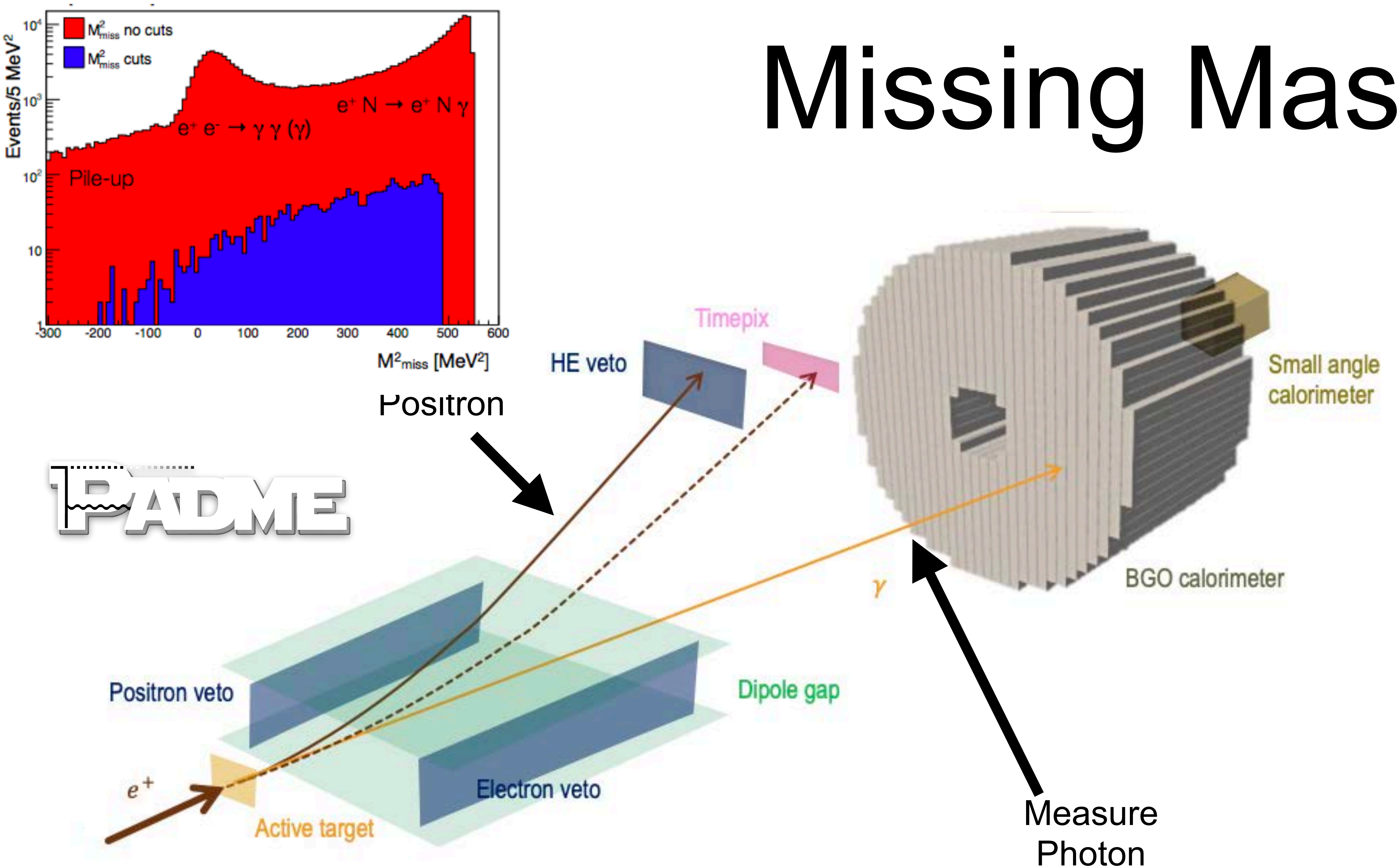




Babar Experiment



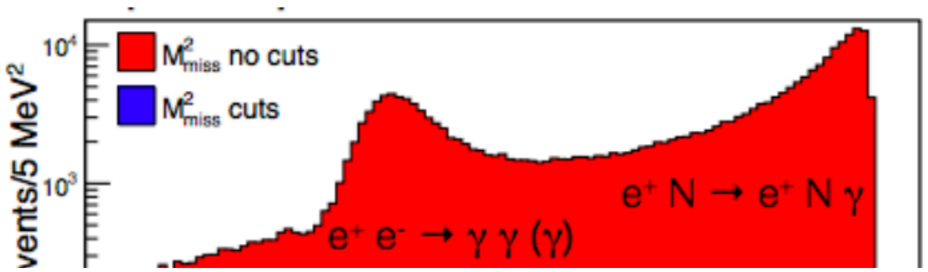
Missing Mass

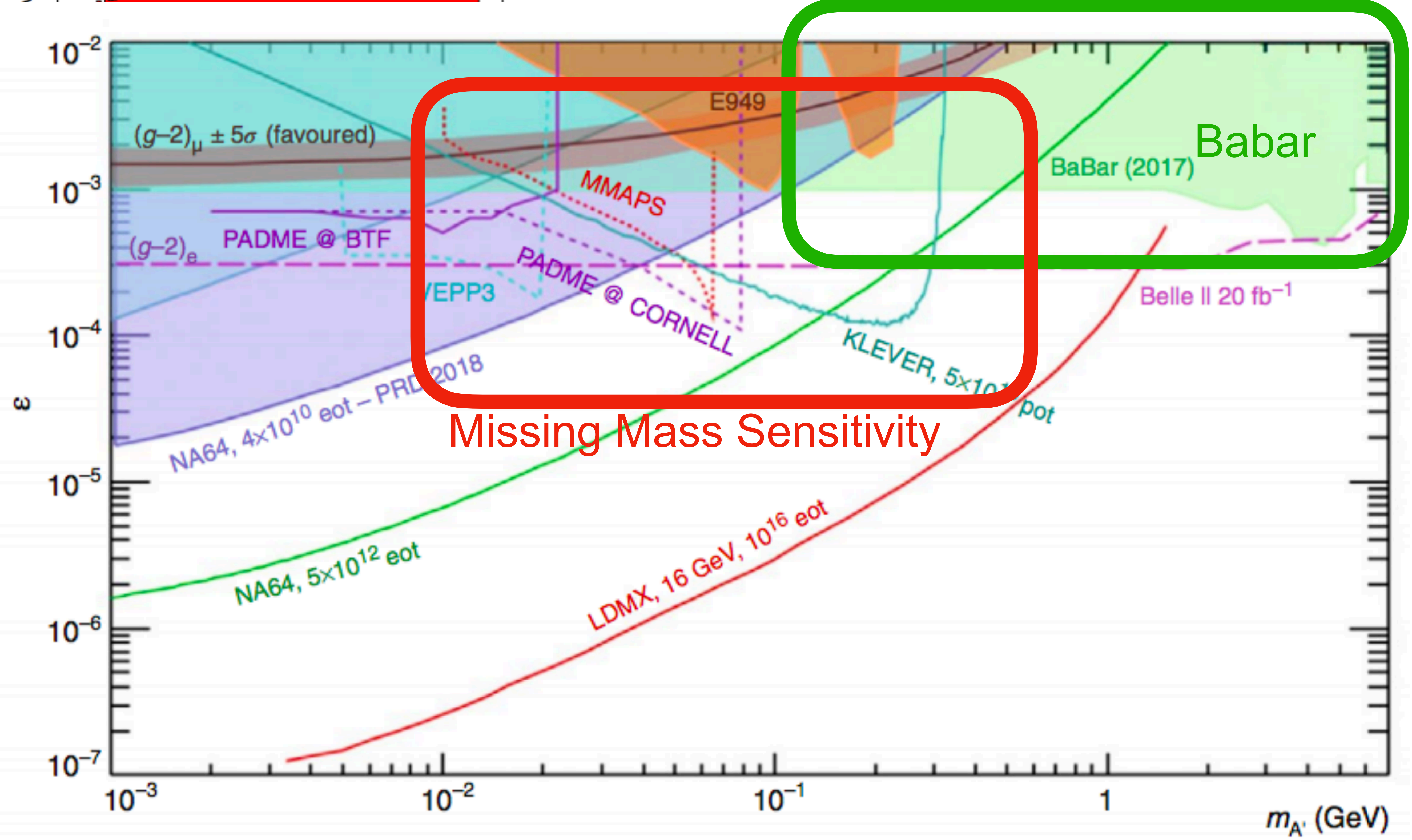


Positron

Measure
Photon

Missing Mass



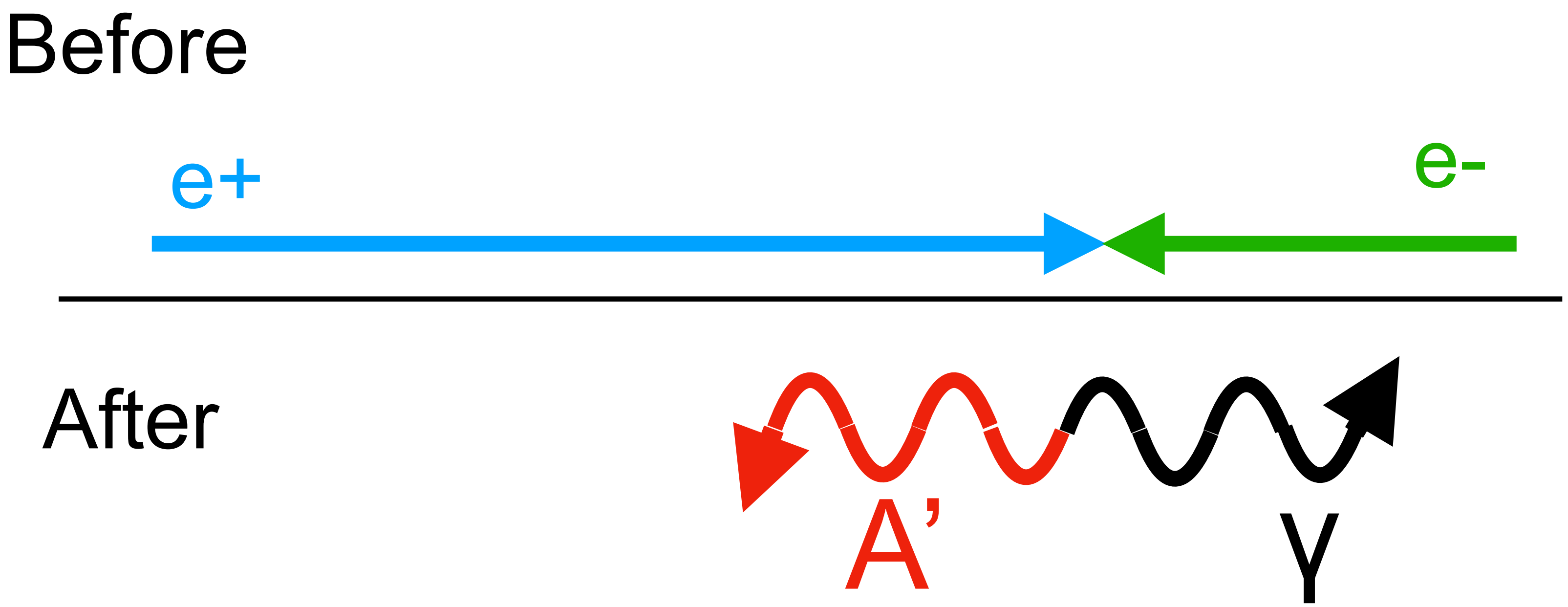


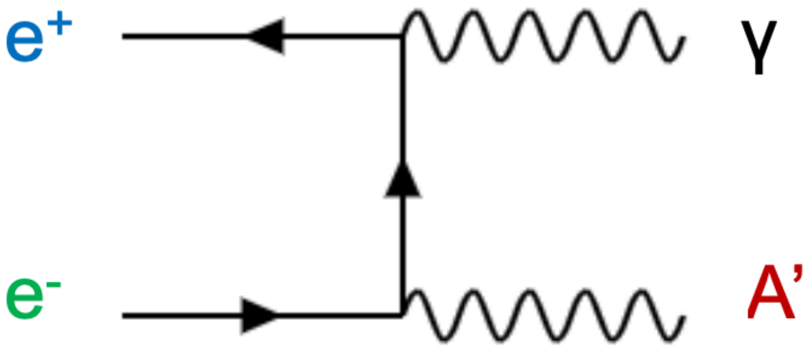
Babar

Missing Mass Sensitivity

Missing Mass

- This was the first approach to these style of searches





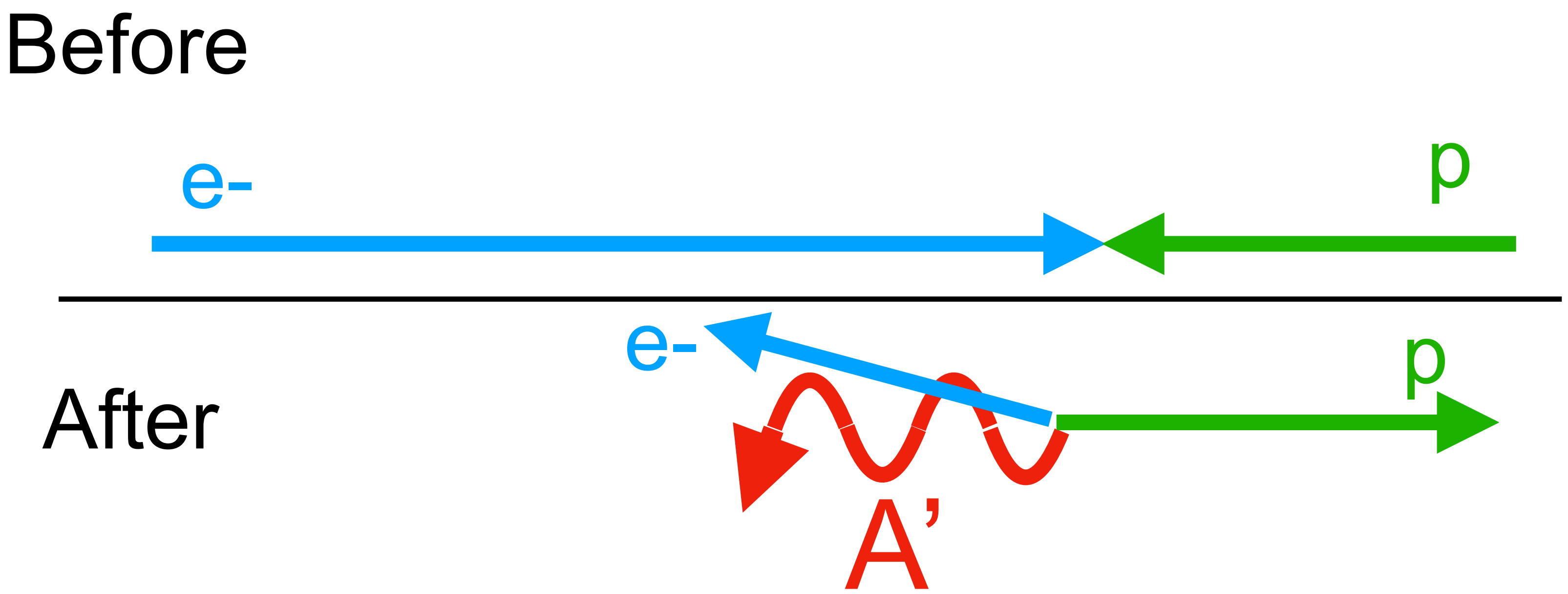
$$\overrightarrow{p_i^{e+}} + \overrightarrow{p_i^{e-}} = \overrightarrow{p_f^{\gamma}} + \overrightarrow{p_f^{A'}}$$

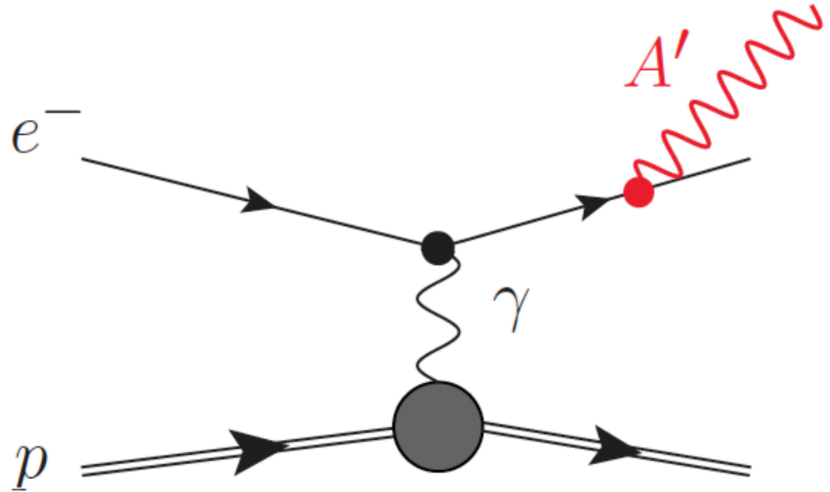
$$\overrightarrow{p_i^{e+}} + \overrightarrow{p_i^{e-}} - \overrightarrow{p_f^{\gamma}} = \overrightarrow{p_f^{A'}}$$

$$\left(\overrightarrow{p_i^{e+}} + \overrightarrow{p_i^{e-}} - \overrightarrow{p_f^{\gamma}}\right)^2 = \left(\overrightarrow{p_f^{A'}}\right)^2 = m_{A'}^2$$

Missing Mass

- This was the first approach to these style of searches





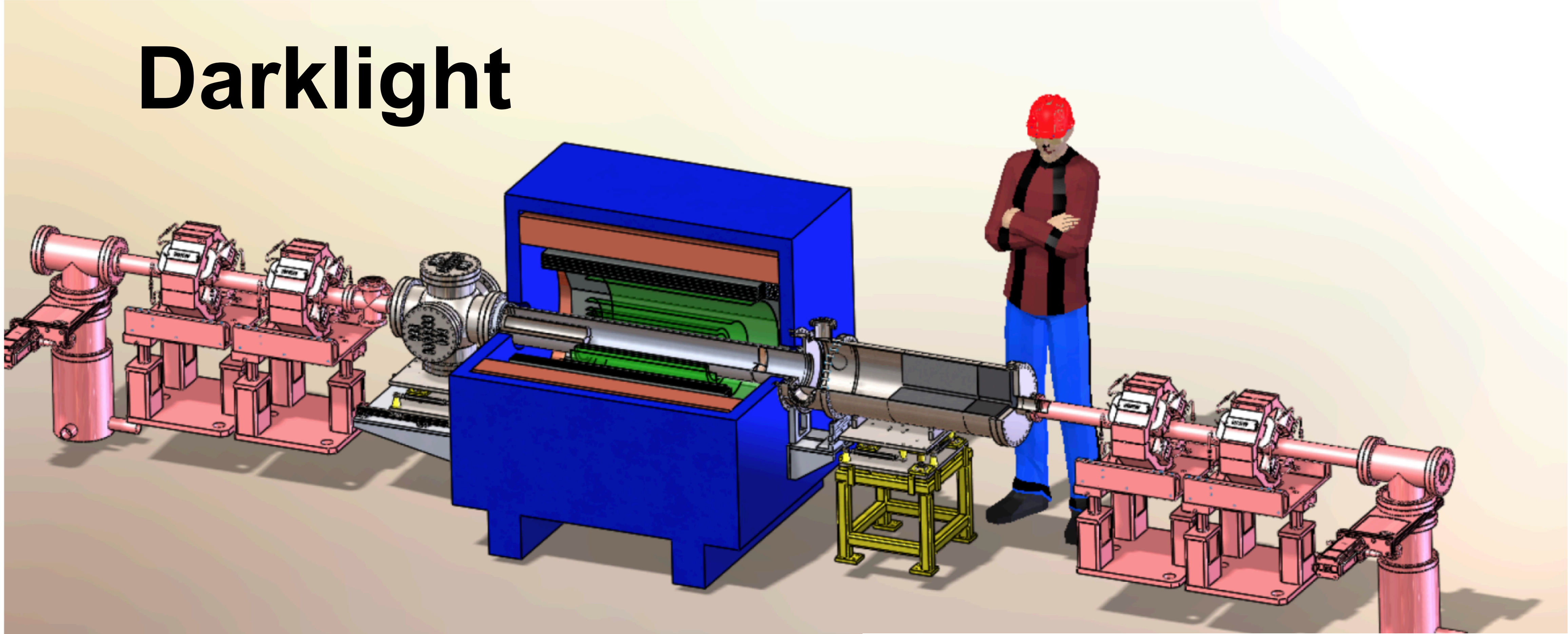
Elastic Scatter

$$\overrightarrow{p_i^p} + \overrightarrow{p_i^{e-}} = \overrightarrow{p_f^{e-}} + \overrightarrow{p_f^p} + \overrightarrow{p_f^{A'}}$$

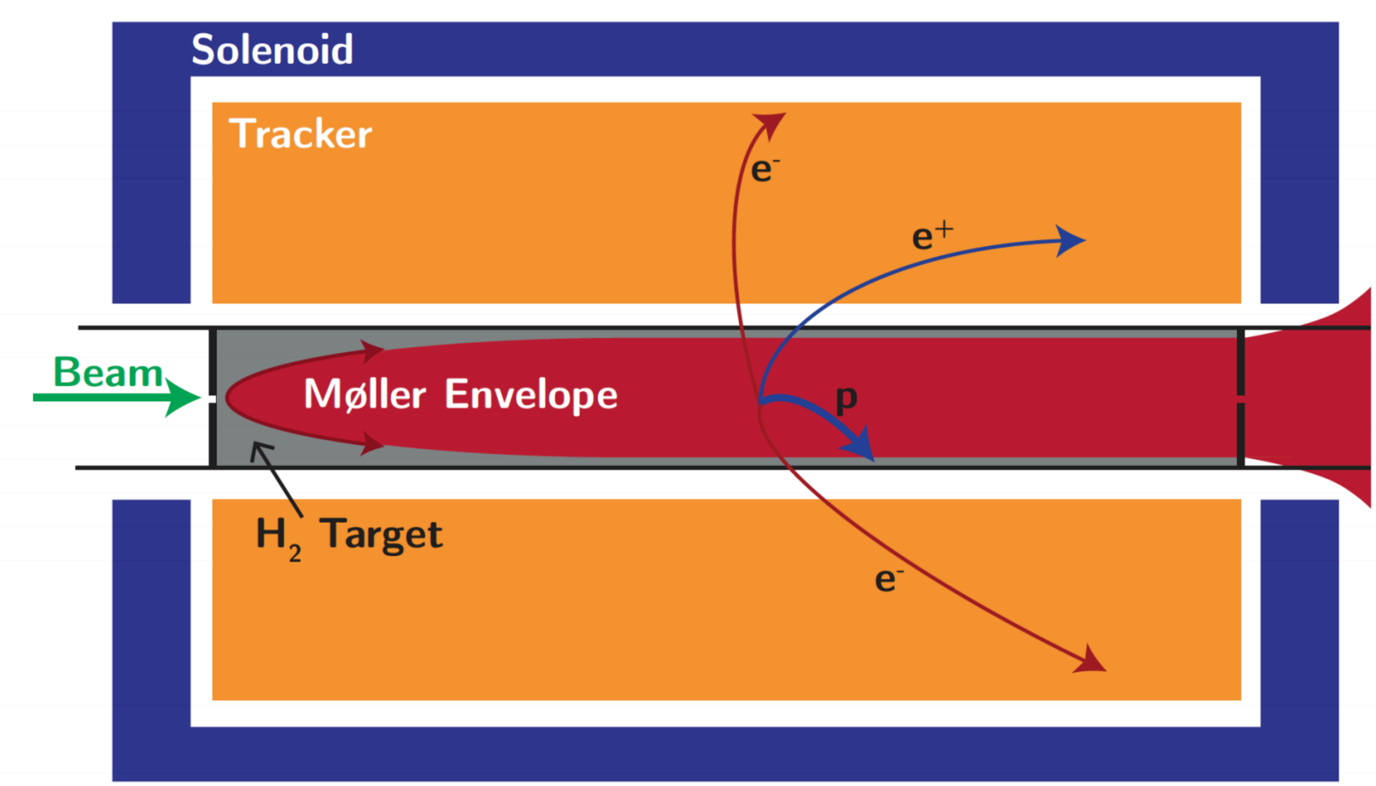
$$\overrightarrow{p_i^p} + \overrightarrow{p_i^{e-}} - \overrightarrow{p_f^{e-}} - \overrightarrow{p_f^p} = \overrightarrow{p_f^{A'}}$$

$$\left(\overrightarrow{p_i^p} + \overrightarrow{p_i^{e-}} - \overrightarrow{p_f^{e-}} - \overrightarrow{p_f^p}\right)^2 = \left(\overrightarrow{p_f^{A'}}\right)^2 = m_{A'}^2$$

Missing Mass

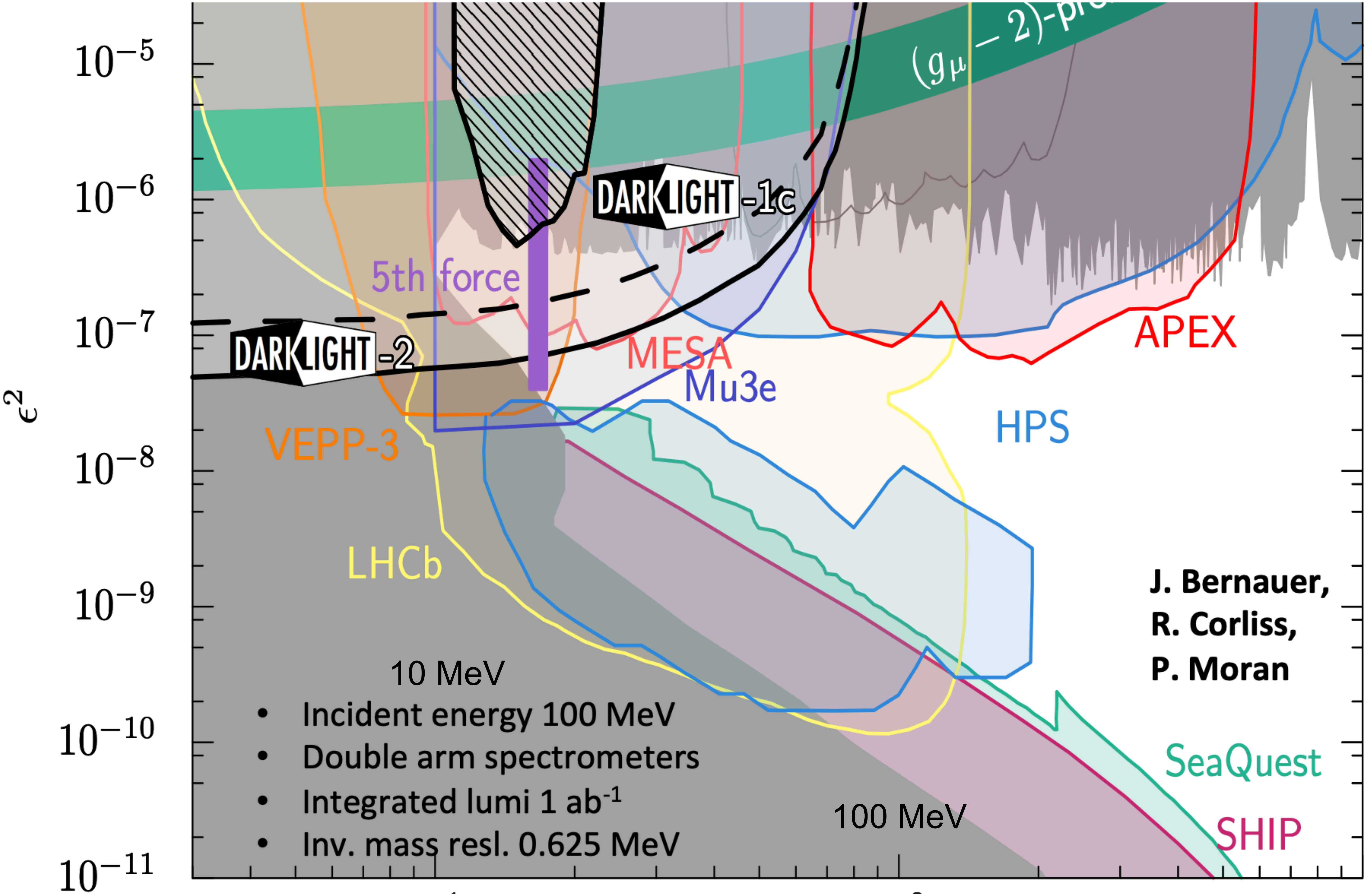


Use the known beam energy on the target



Tracking can allow us to reconstruct full info

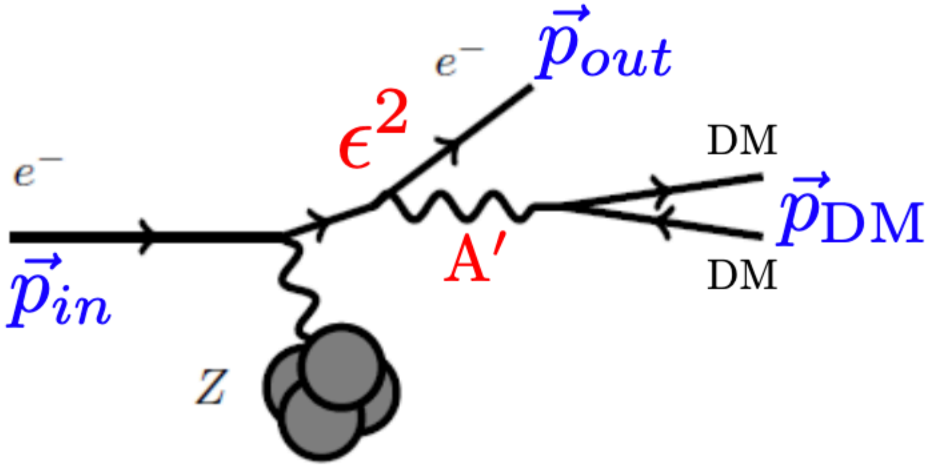
Missing Mass



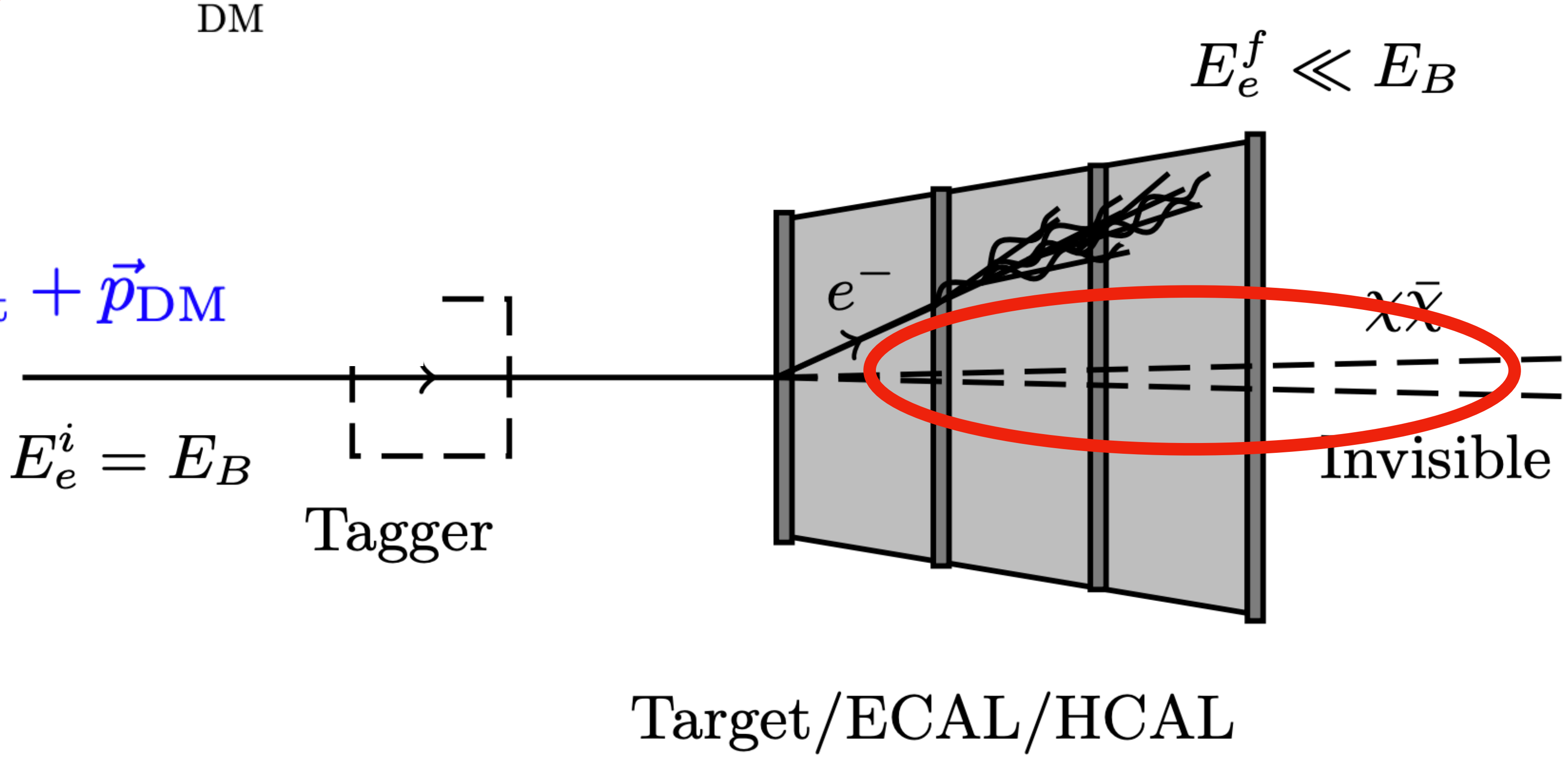
- Incident energy 100 MeV
- Double arm spectrometers
- Integrated lumi 1 ab^{-1}
- Inv. mass resl. 0.625 MeV

J. Bernauer,
R. Corliss,
P. Moran

Missing Energy



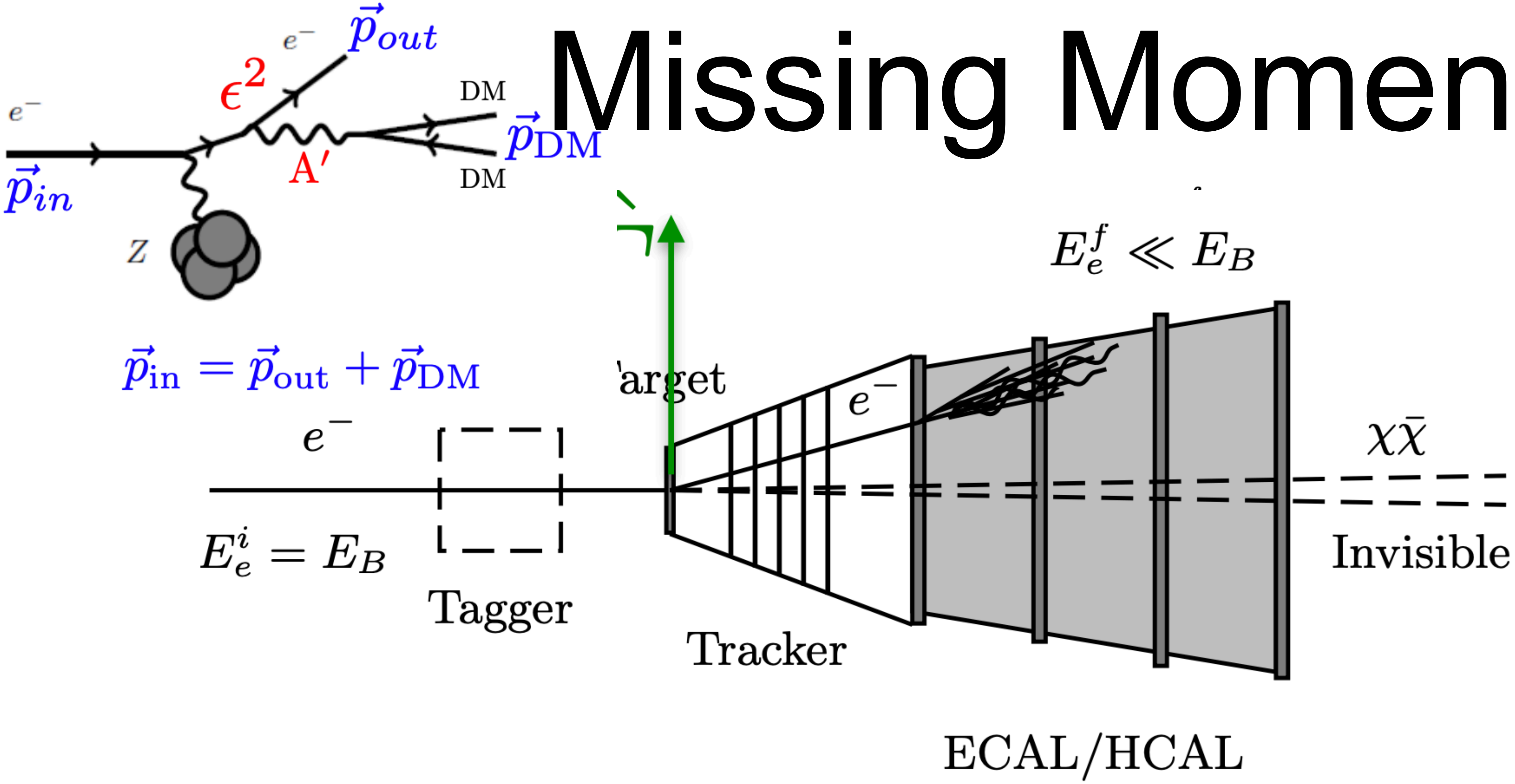
$$\vec{p}_{\rm in} = \vec{p}_{\rm out} + \vec{p}_{\rm DM}$$



- Idea is to fire an electron on a target and measure energy
  - Clean signature if we ensure there is no visibly radiated object
  - Change in the energy will tell us we have radiated a dark photon

$$\overrightarrow{p_i^{e-}} - \overrightarrow{p_f^{e-}} = \overrightarrow{p_f^{A'}} \rightarrow E_i - E_f = E_{A'}$$

Missing Momentum



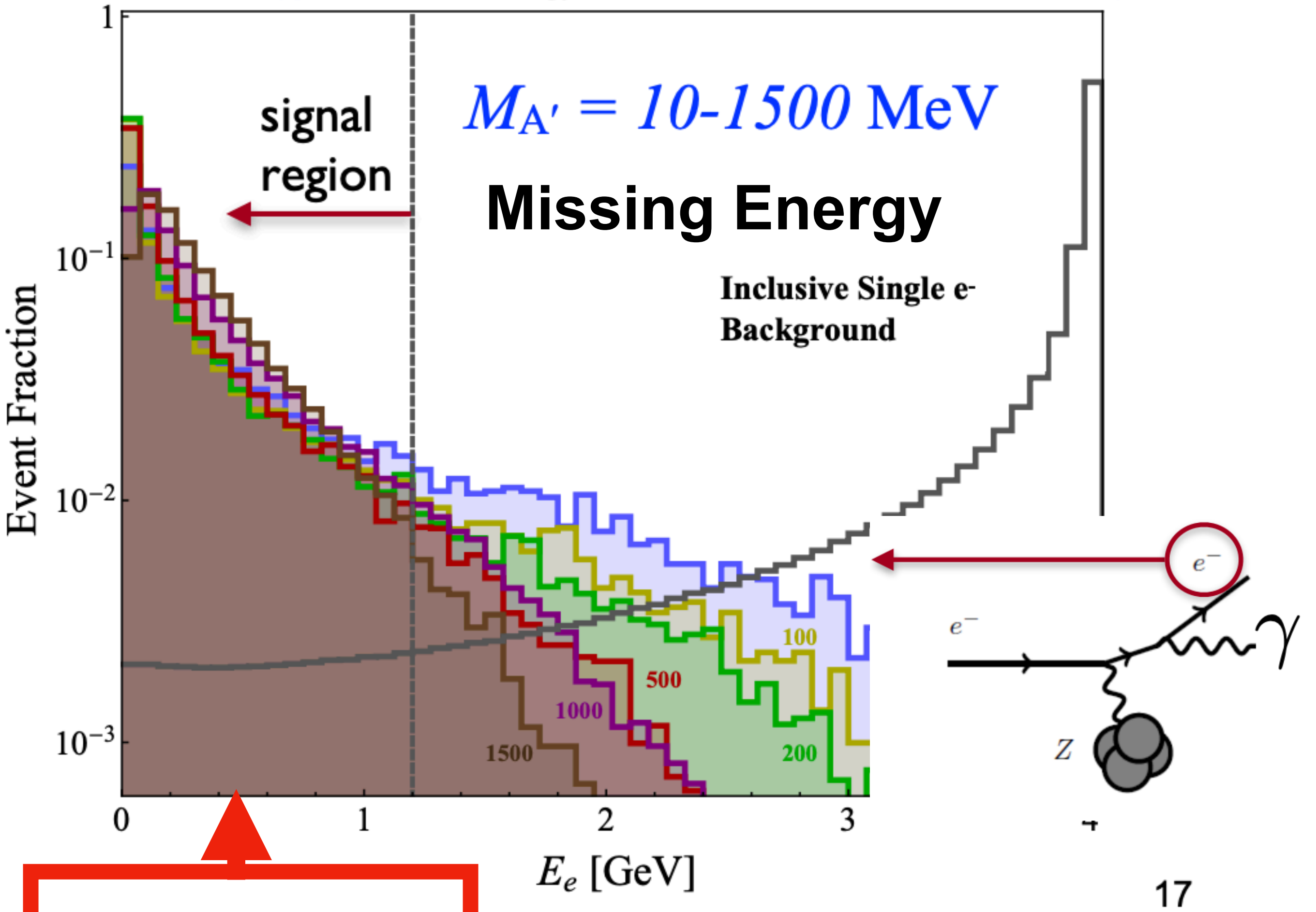
$$\vec{p}_{\rm in} = \vec{p}_{\rm out} + \vec{p}_{\rm DM}$$

- Idea is to fire an electron on a target and measure momentum
    - On top of calorimeter, have a tracker that gives electron momentum
    - The addition of the tracker allows us to do e vs γ separation

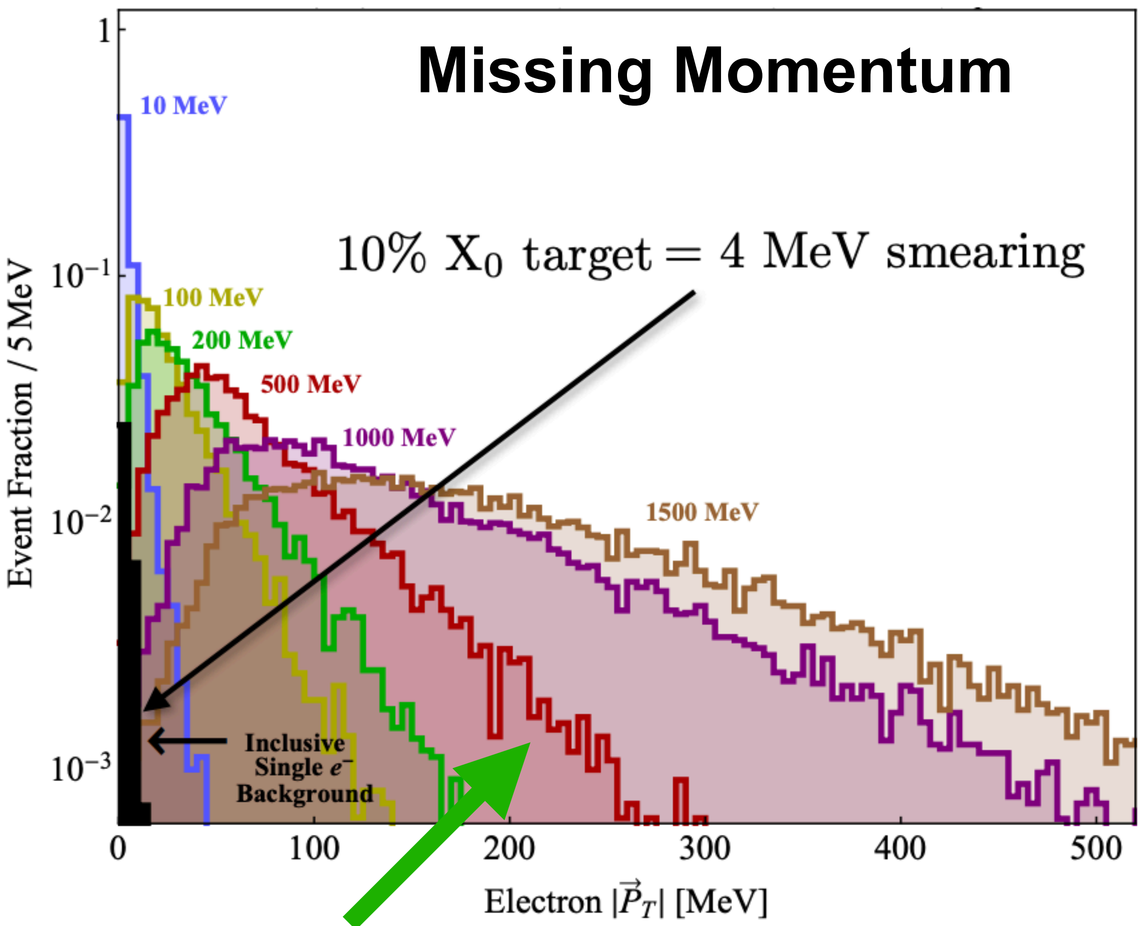
$$\overrightarrow{p_i^{e-}} - \overrightarrow{p_f^{e-}} = \overrightarrow{p_f^{A'}} \rightarrow \overrightarrow{p_T^{i}} - \overrightarrow{p_T^{f}} = \overrightarrow{p_T^{A'}}$$

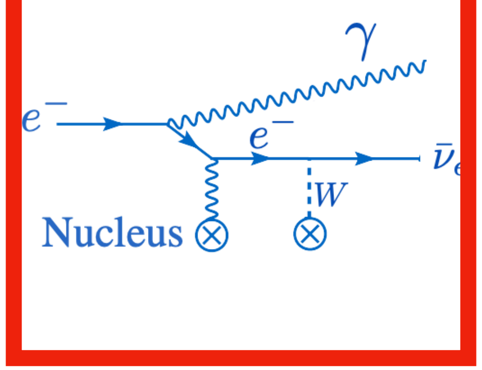
Momentum vs Energy

recoil energy distributions, 4 GeV e^- on 10% X_0 target



recoil p_T distributions, 4 GeV e^- on 10% X_0 target





Irreducible Background

No Irreducible Background b/c of electron id

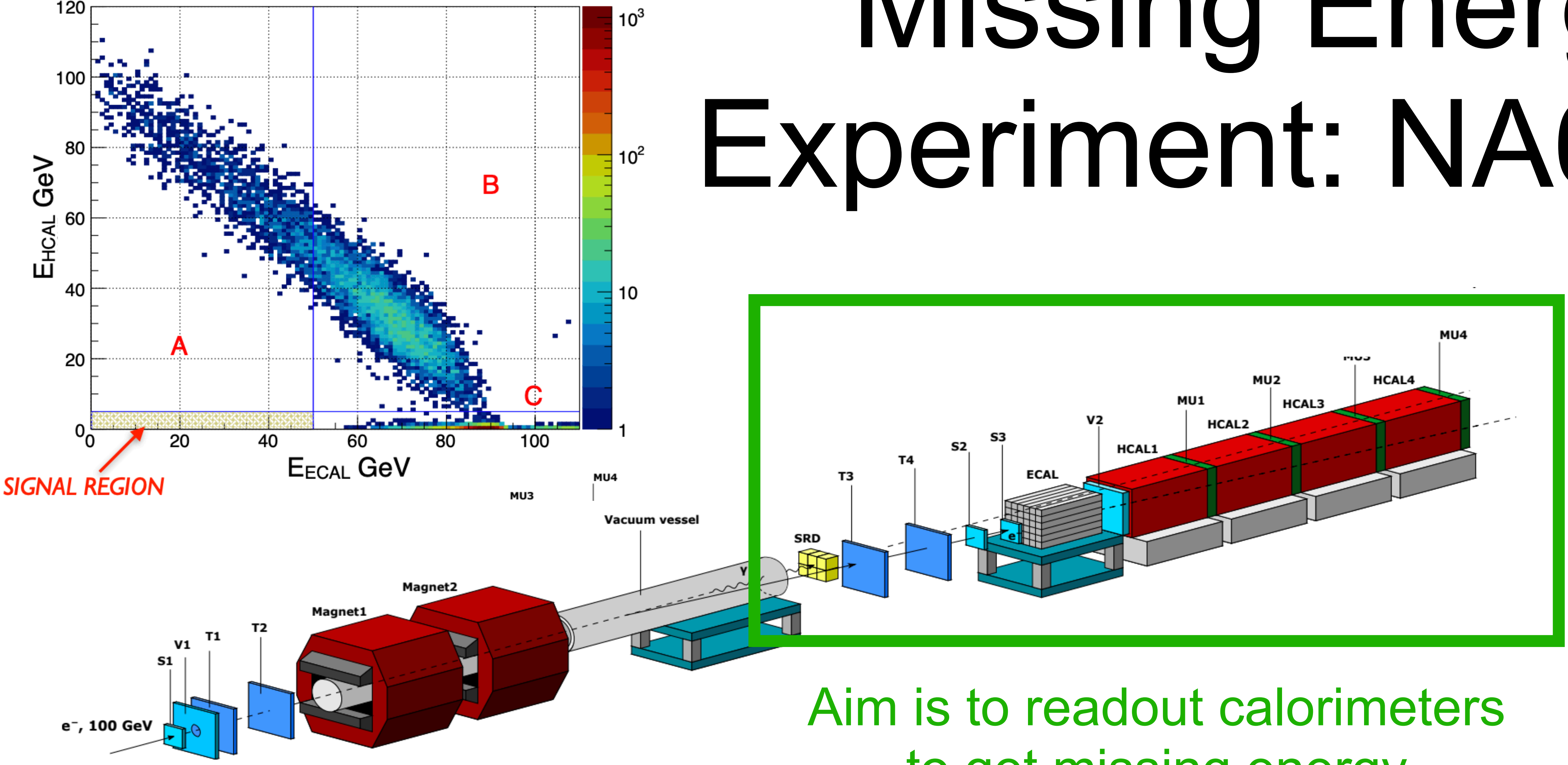
$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi}\,\frac{\epsilon^2}{m_e^2 \cdot x + m_A^2(1-x)/x}$$

Kinematics **very different** from massless photon bremsstrahlung

$$x = \frac{E_A}{E}$$

Heavy object arries away the beam energy

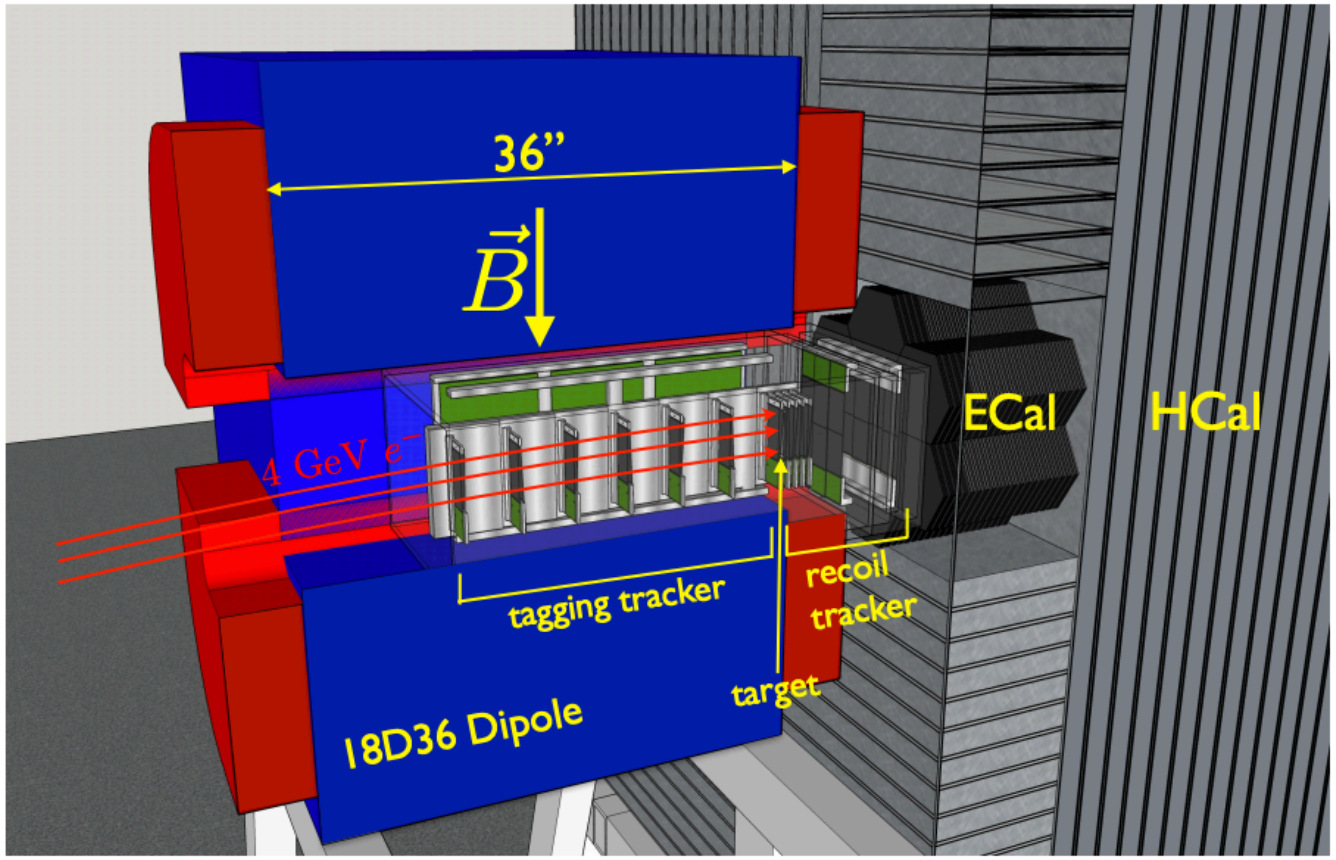
Missing Energy Experiment: NA64

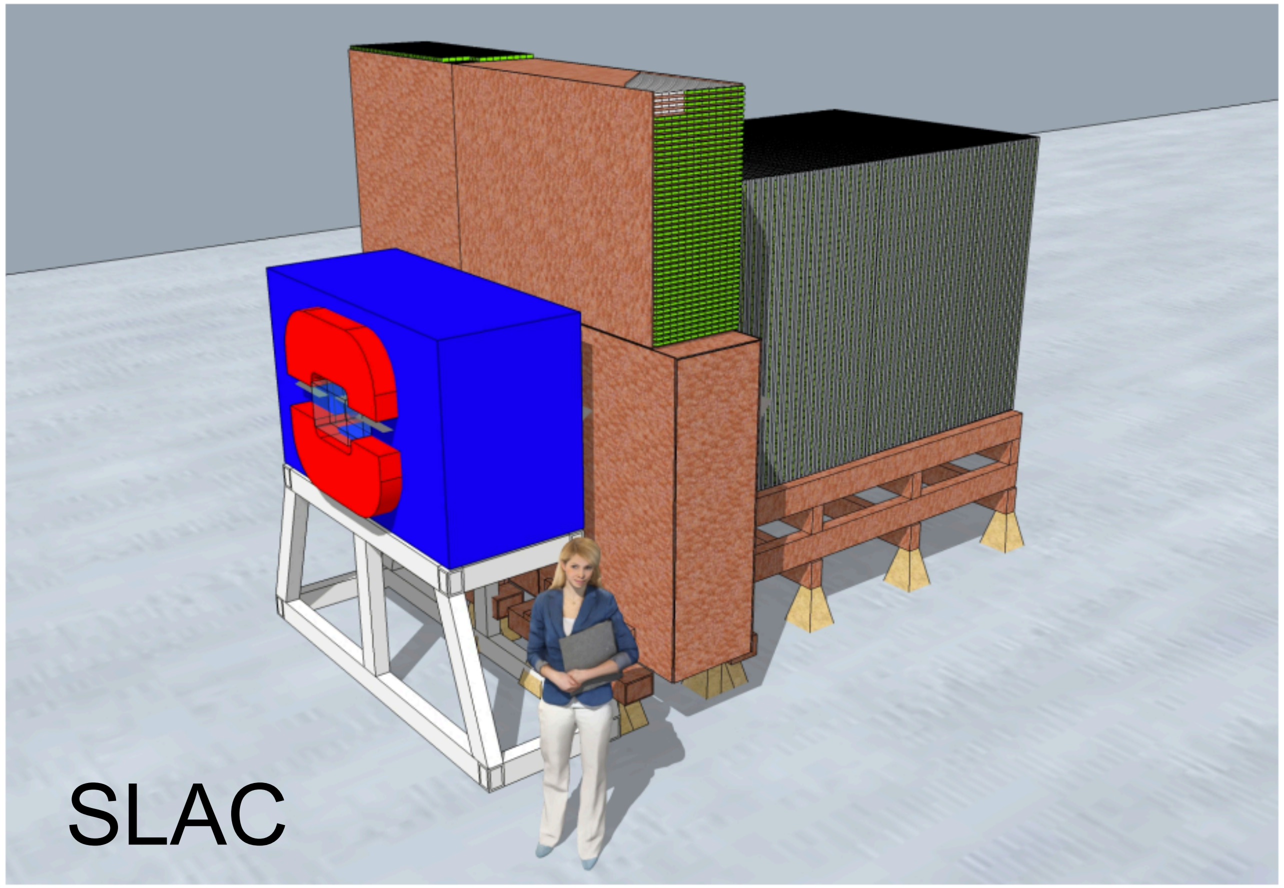


Aim is to readout calorimeters to get missing energy

- NA64 is up and running and taking data
  - 100 GeV electron beam on a target
  - Potential to also make a muon beam

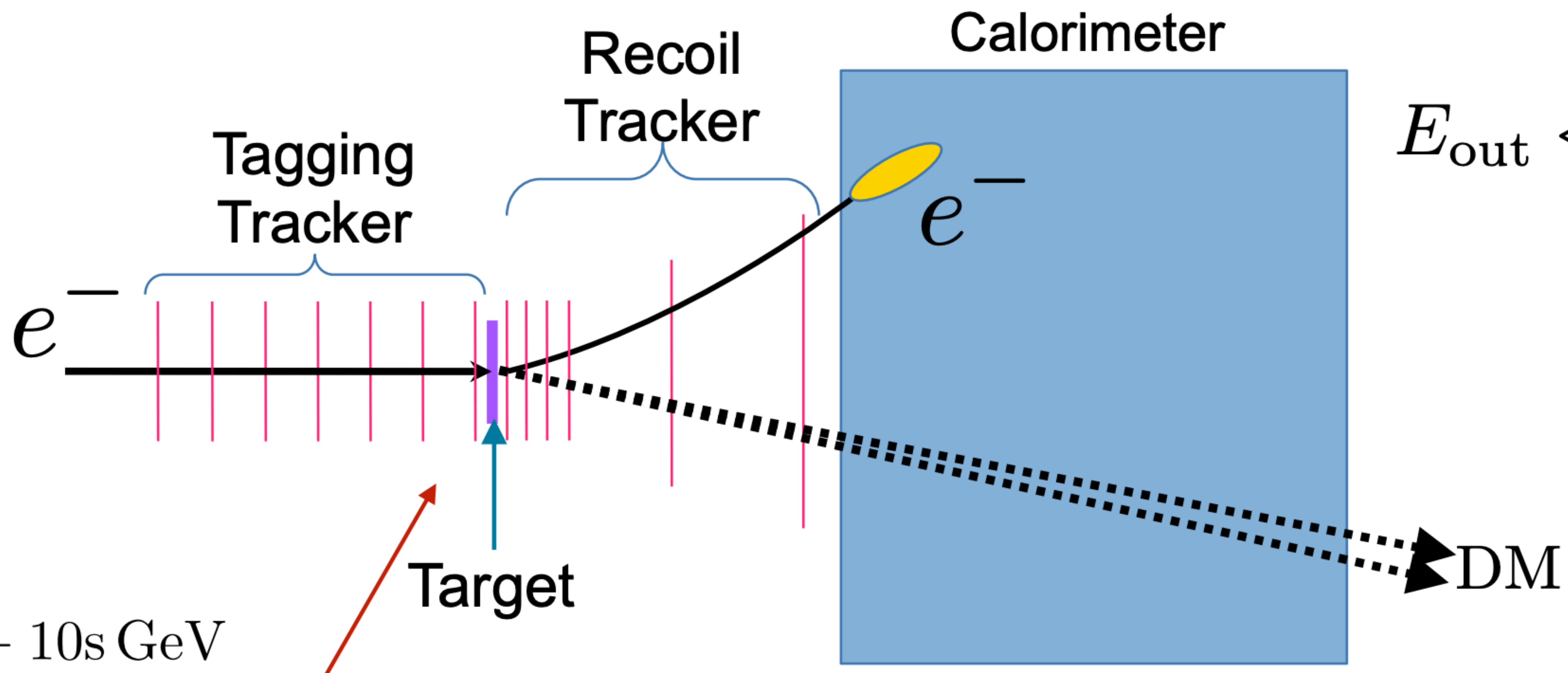
Missing Momentum Experiment: LDMX





- LDMX is in the design stage
  - Active effort to build up the project towards a large scale realization
  - Planning to start running in the late 2020s

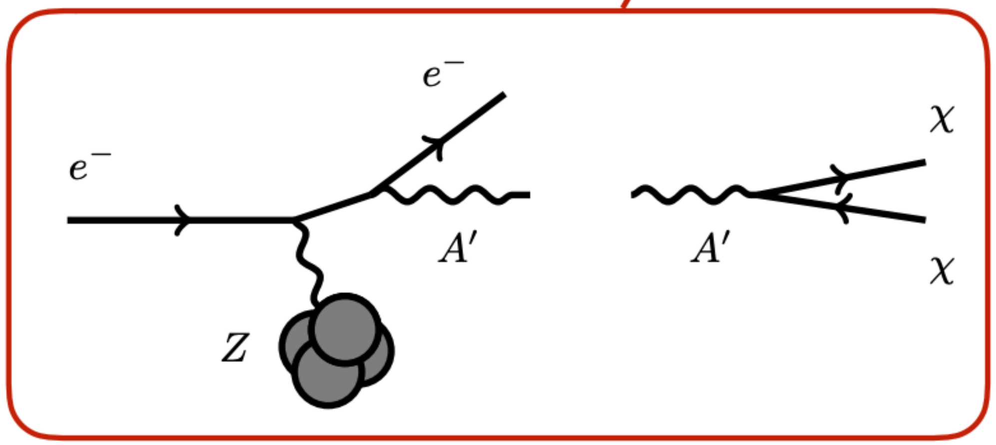
Missing Momentum Experiment: LDMX



$E_{\text{out}} \ll E_{\text{in}}$

$N_e \sim 10^{16}$

$E_e \sim \text{few} - 10\text{s GeV}$

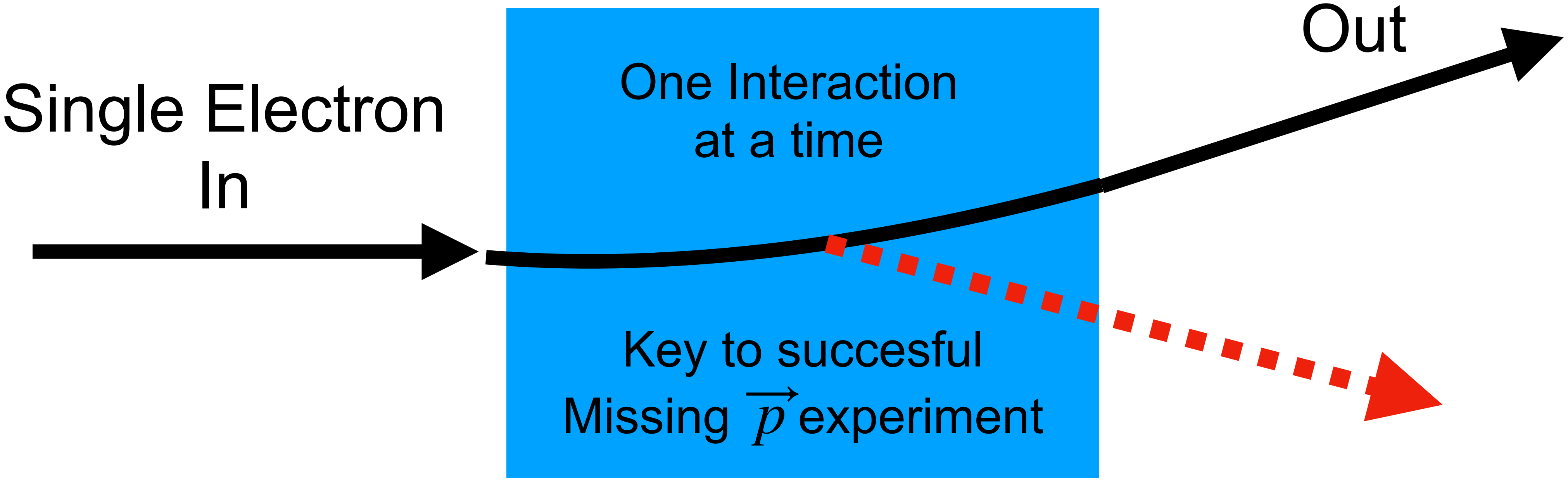


1) Measure **each** e- energy in/out
2) Trigger on missing momentum
3) Veto additional SM activity

One particle at a time

- An important component of running with each experiment
  - Only read out one electron at a time

Multiple Electrons at the same time will limit missing energy meas



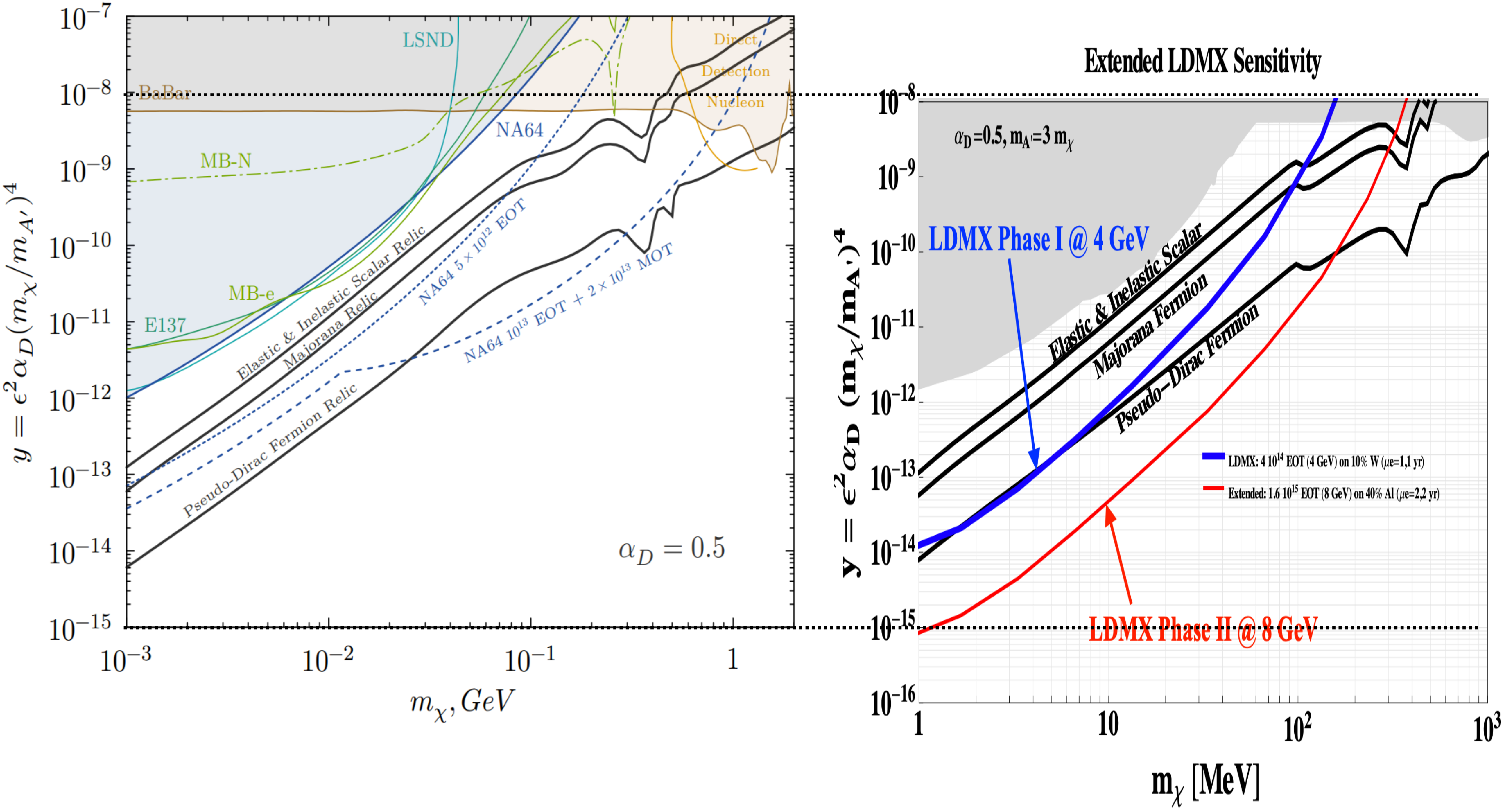
Single Electron In

One Interaction at a time

Key to succesful Missing $\vec{p}$ experiment

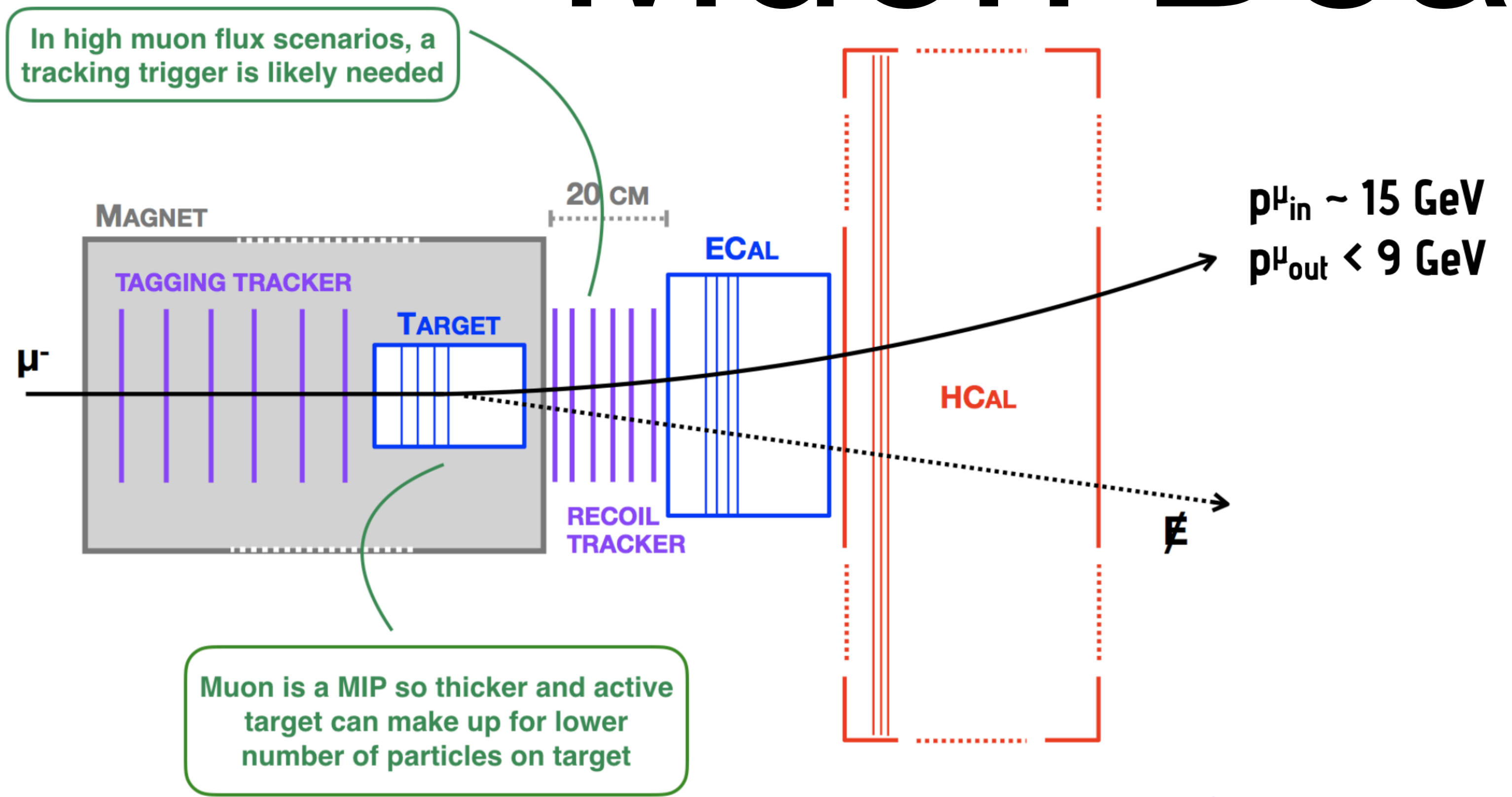
Single Electron Out

Sensitivity



- NA64 can reach some of the relic limits
- LDMX can reach all of the limits of the detectors

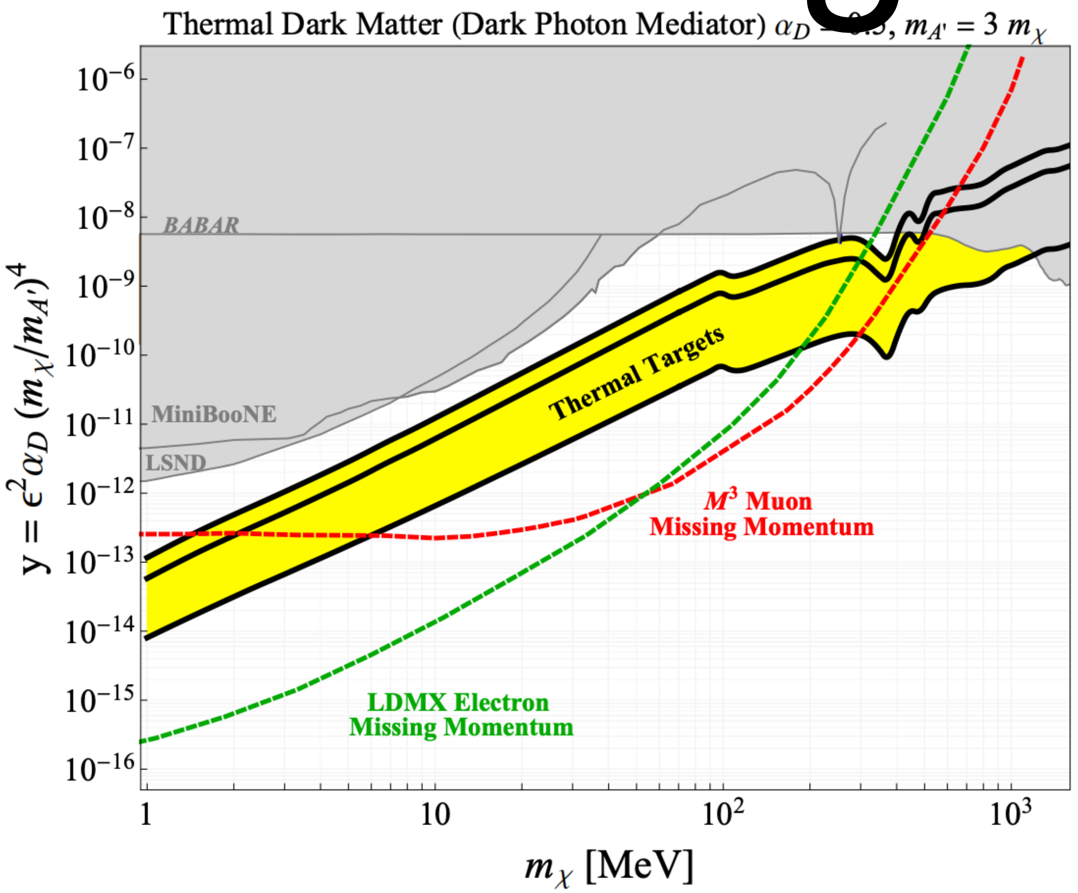
Muon Beam Missing E



In high muon flux scenarios, a tracking trigger is likely needed

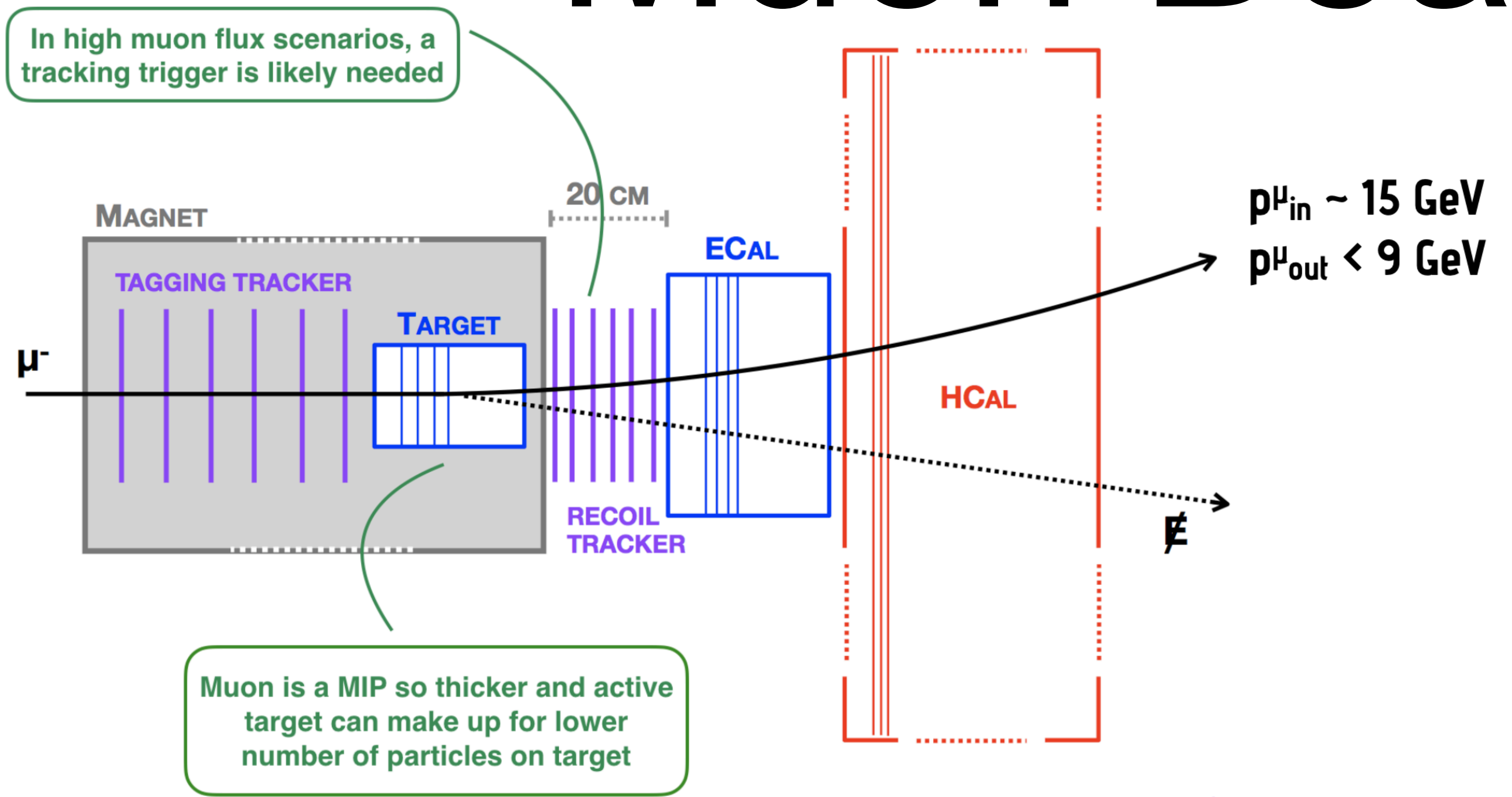
Muon is a MIP so thicker and active target can make up for lower number of particles on target

Y. Kahn, G. Krnjaic, N.T., A . Whitbeck
https://arxiv.org/abs/1804.03144



- Another variant on this is with a muon beam
    - A muon beam enables us to probe scalars (yukawa)
    - It also enables muo-philic models (that can explain g-2)
- M^3 is the current proposed experiment to perform this
- NA64 may also be able to do Muon beams

Muon Beam Missing E



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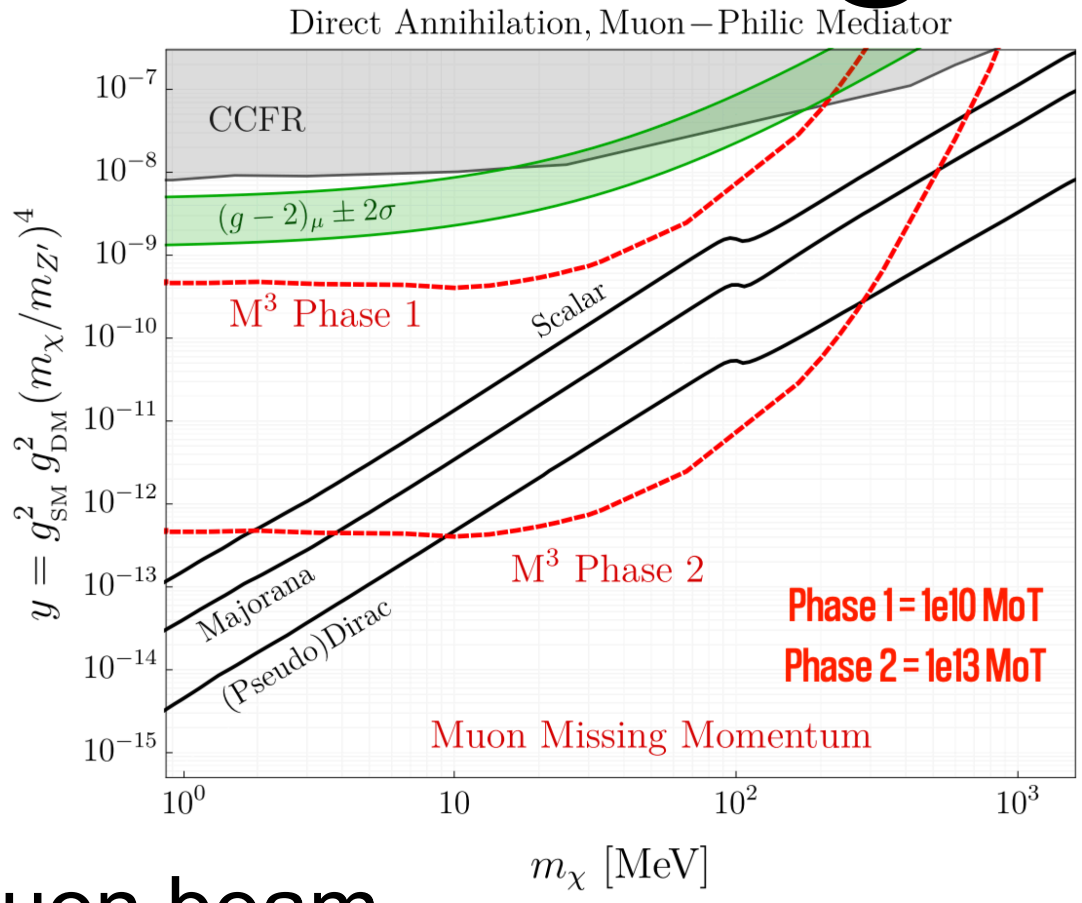

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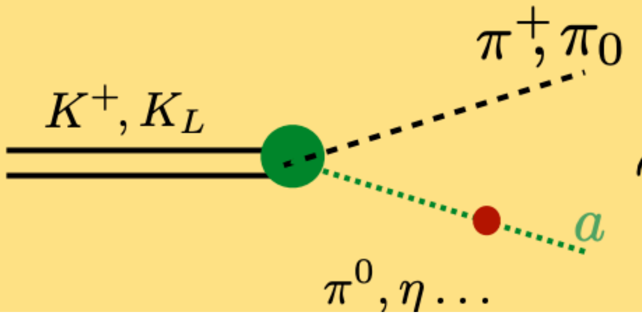
Probing Kaon Decays

Experiments		Main goal	SM value
NA62	CERN (running)	$K^+ \to \pi^+ \nu \bar{\nu}$	inputs from tree-level measurements of $V_{us}\,, V_{cb}\,, V_{ub}\,, \gamma$ $\mathrm{BR} \simeq (8.4 \pm 1) \cdot 10^{-11}$ *Brod, Gorbahn, Stamou 2011*
KOTO	J-PARC (running)	$K_L \to \pi^0 \nu \bar{\nu}$	$\mathrm{BR} \simeq (3.4 \pm 0.6) \times 10^{-11}$ *Buras, Buttazzo, Girrbach-Noe, Knegjens 2015*
KLEVER	CERN (proposal)	Kaon to invisible	error reduced using other observables $\epsilon_K\,, \Delta M_s\,, \Delta M_d\,, S_{\psi K_S}$ *Buras, Buttazzo, Girrbach-Noe, Knegjens 2015* *Brod, Gorbahn, Stamou 2019*

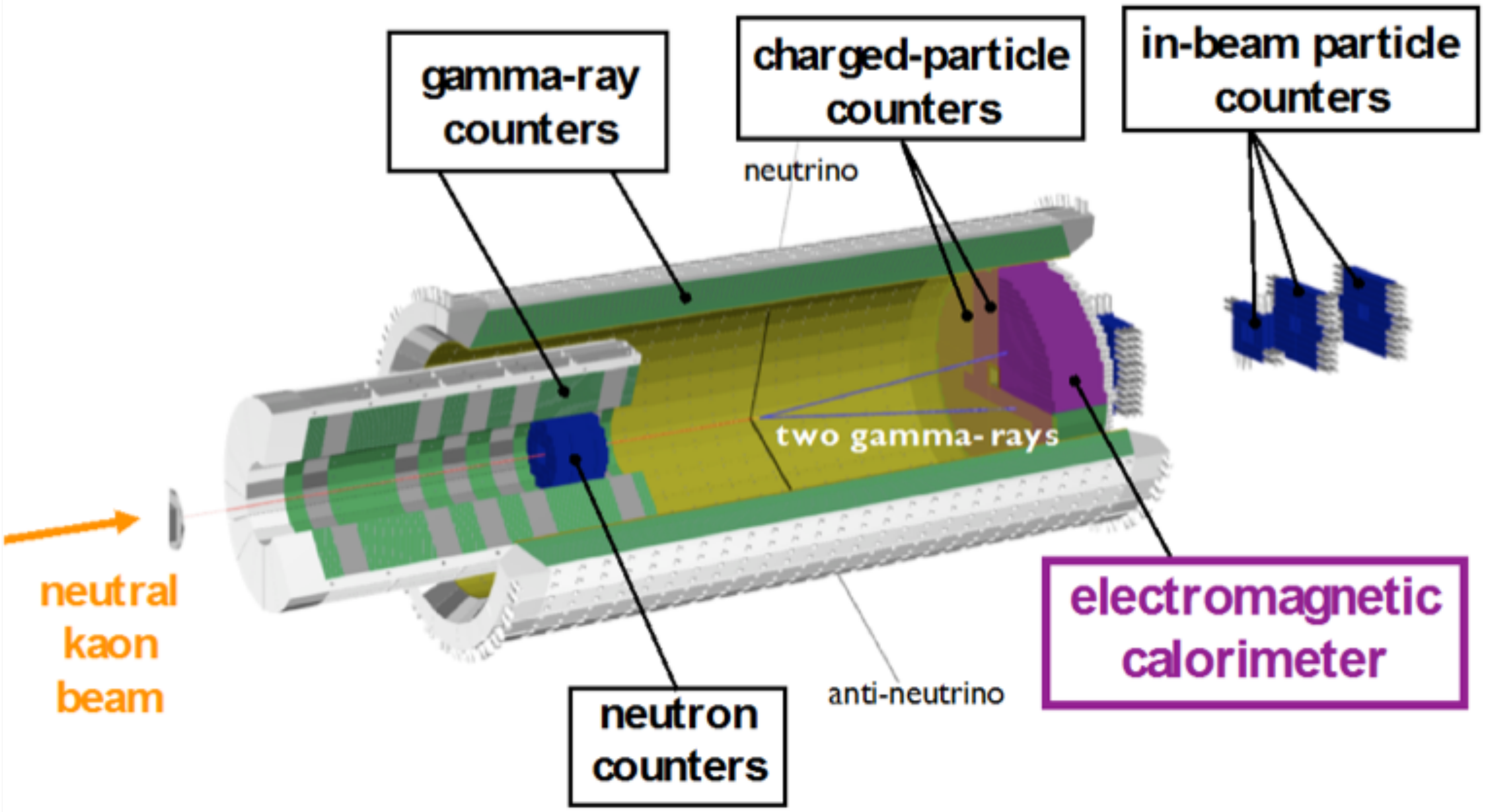
Vanilla axion,
hadronic ALP

$$\frac{\alpha_s}{8\pi}\frac{N a}{f_a} G\tilde{G}$$

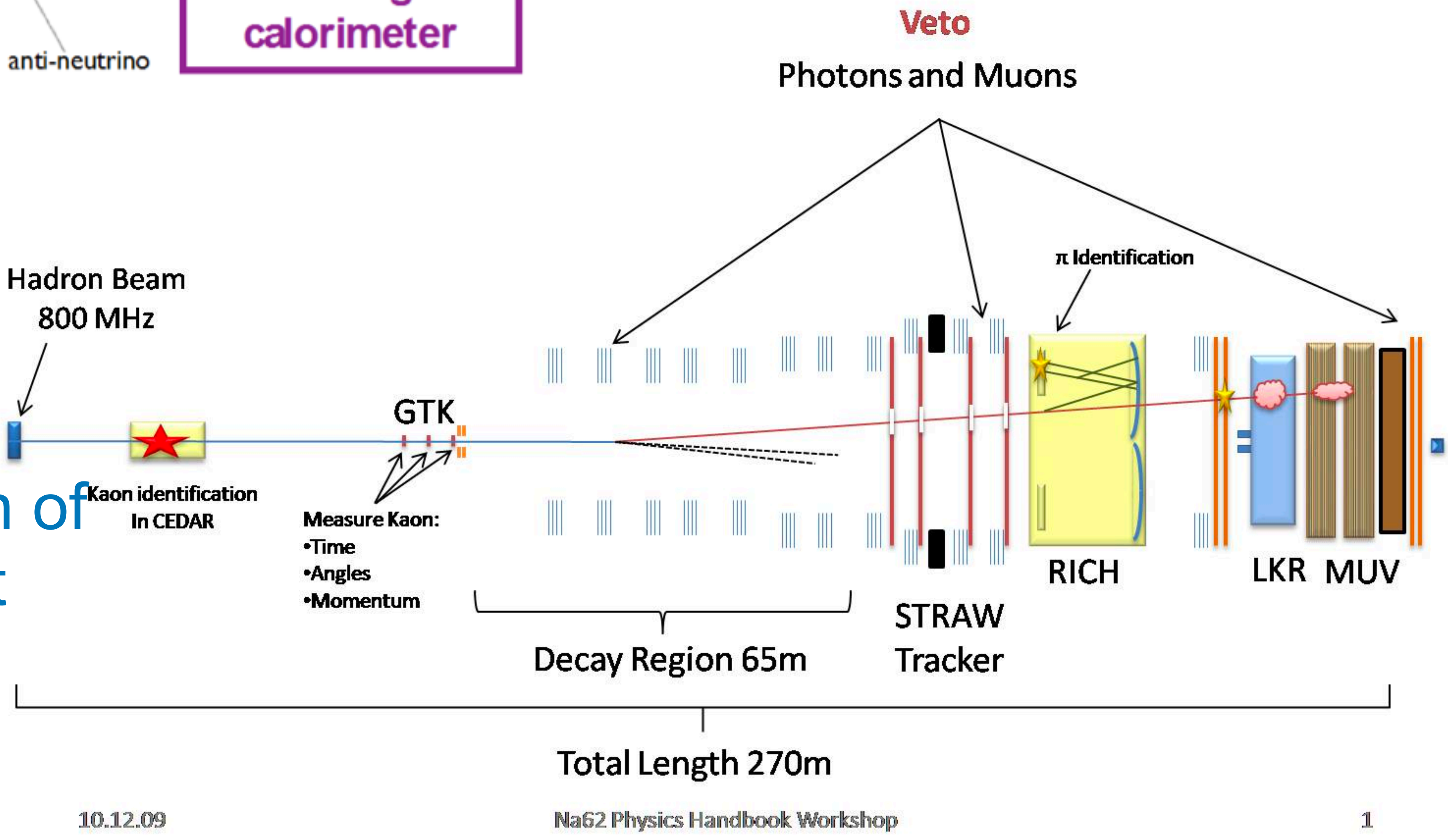


$$\sim \; 20\% \cdot \left(\frac{f_\pi}{f_a}\right)^2$$

KOTO/NA62

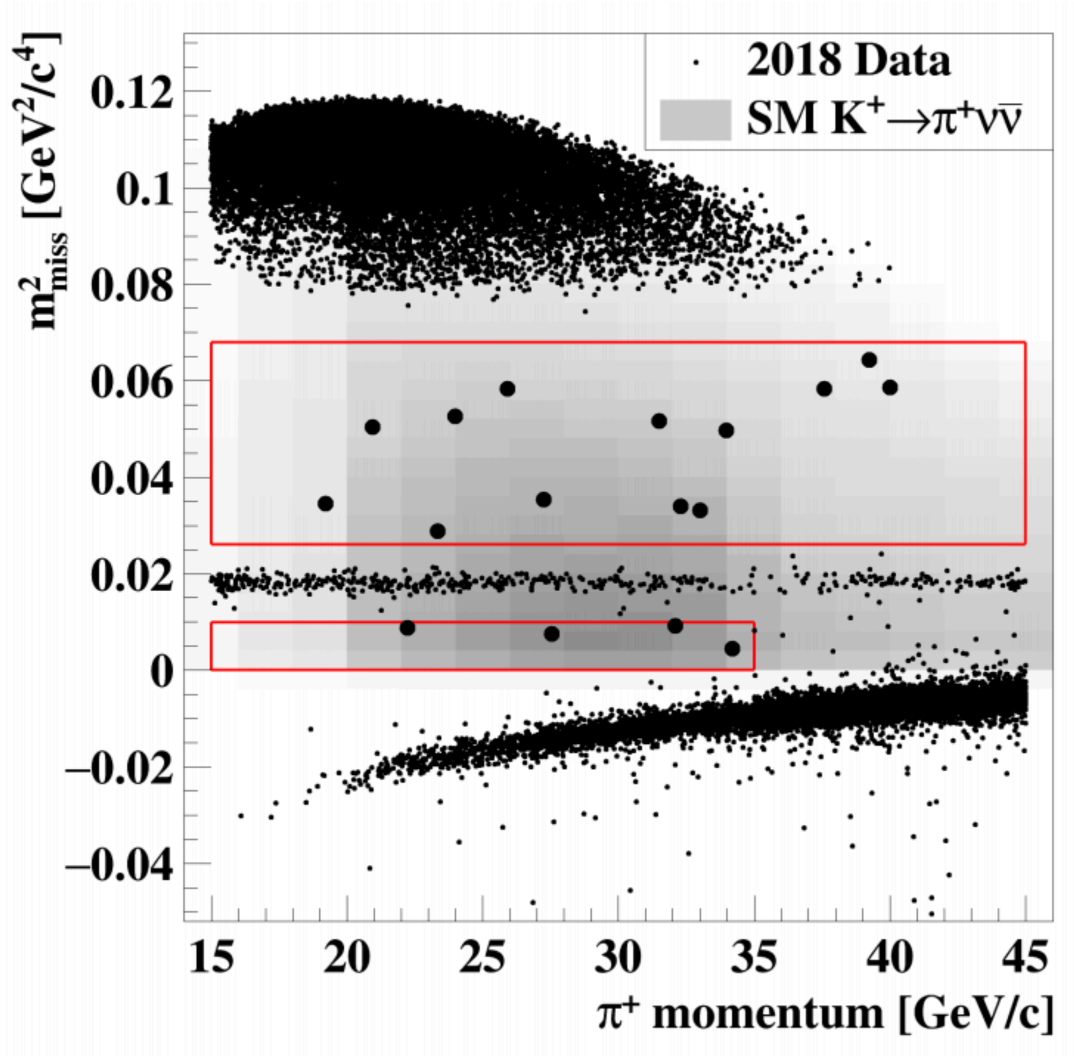


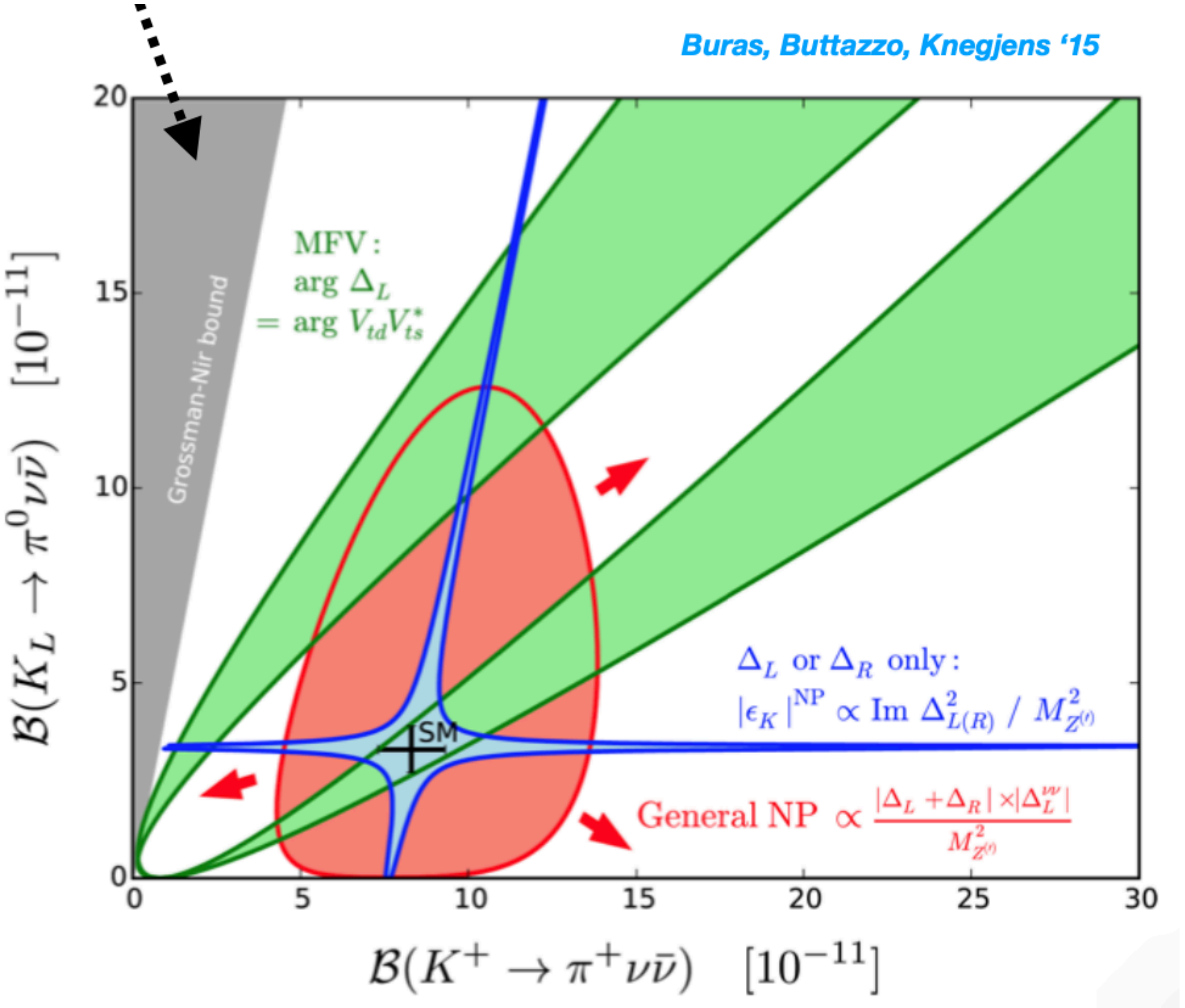
Fire a well measured Kaon beam to a detector and look for decays



Detector
Aimed at identification of all kaon decays to get missing mass

Using Missing Mass

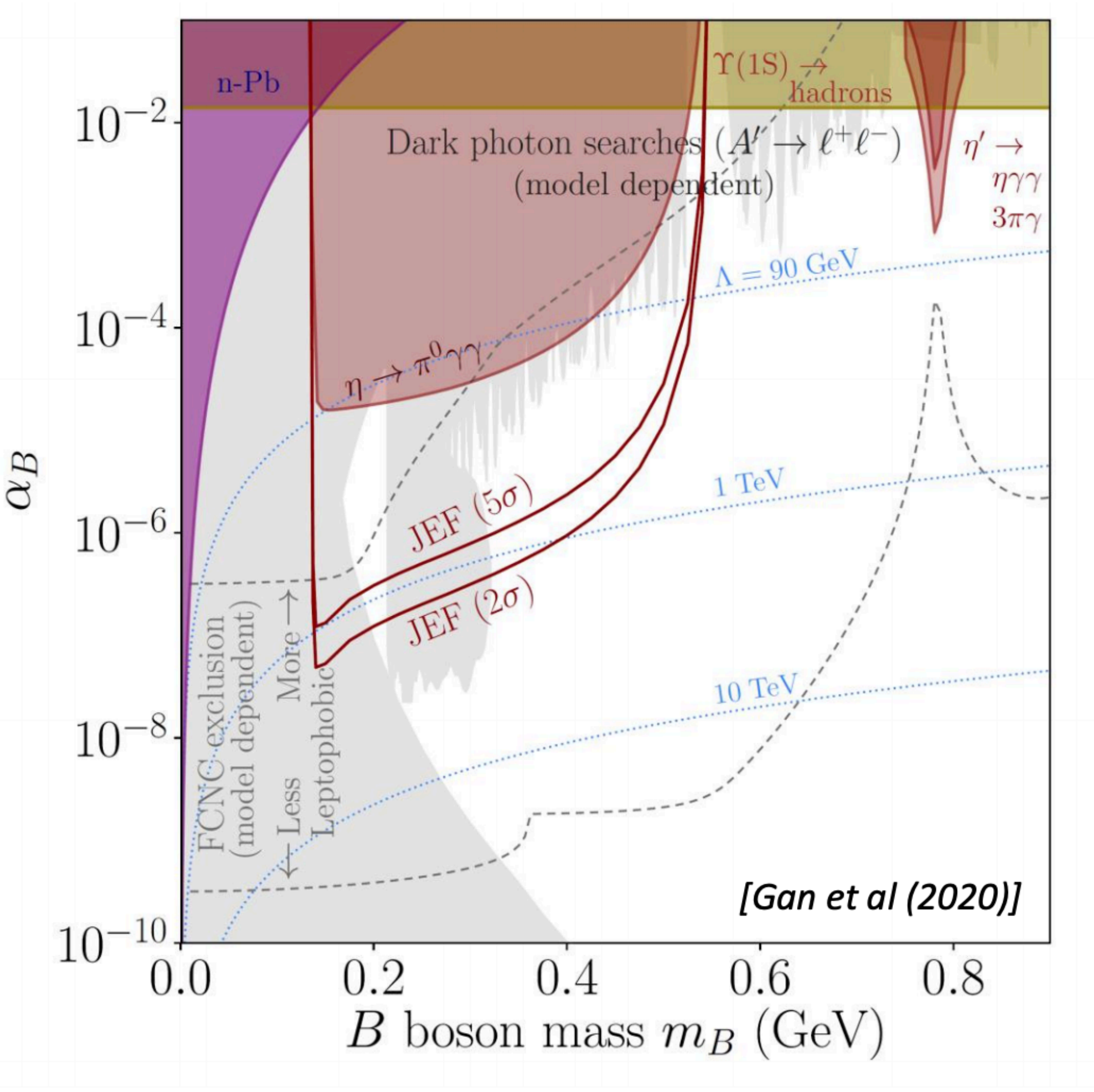




- Strategy: use missing mass to measure Kaon rate
    - Combination of π^0 and π^+ identified decays probes SM
- Decays allow for very precise probe

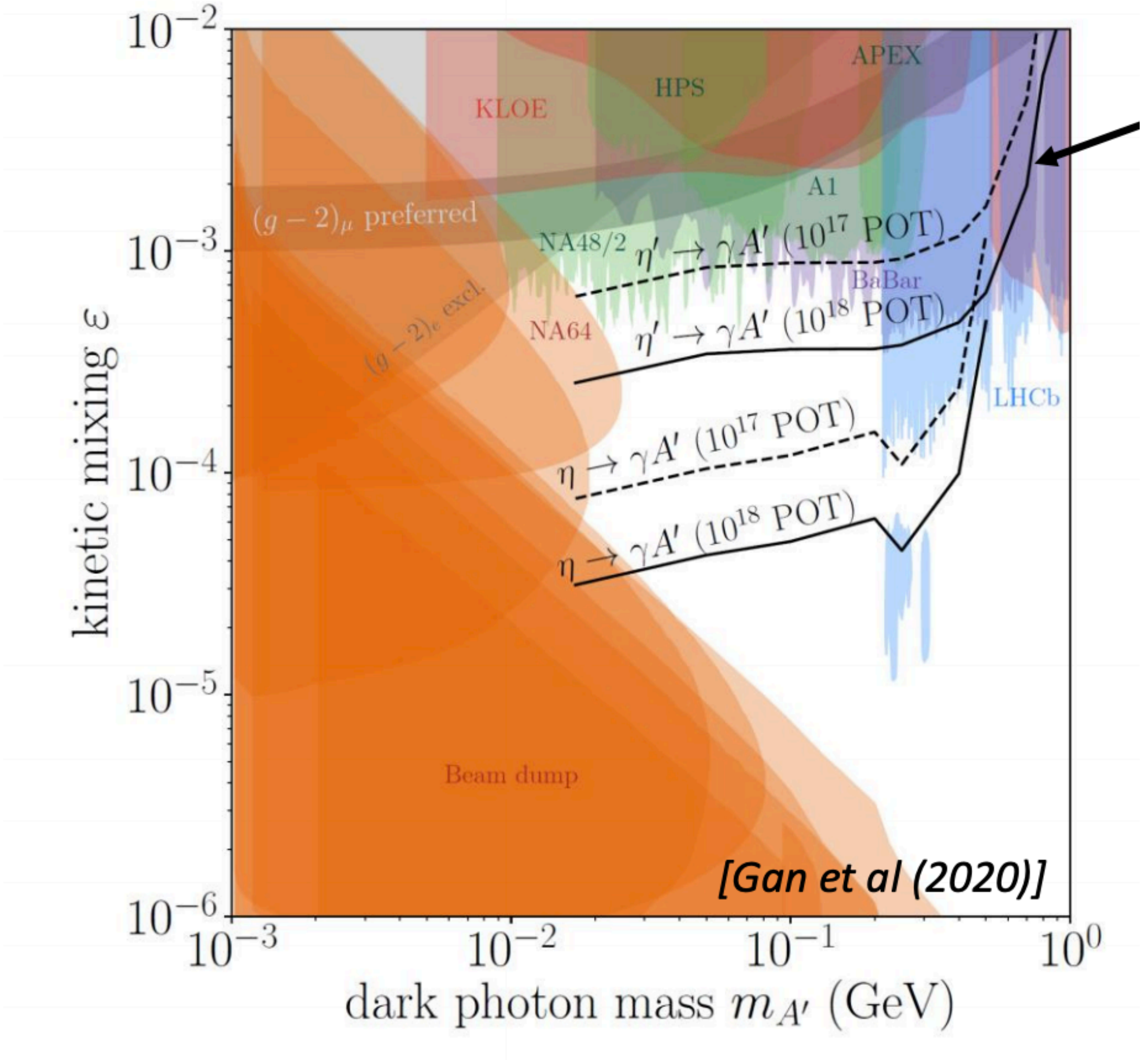
Probing Eta Decays

$\eta \to B\gamma \to \pi^0\gamma\gamma$



[Gan et al (2020)]

$\eta, \eta' \to \gamma A' \to \gamma \ell^+\ell^-$



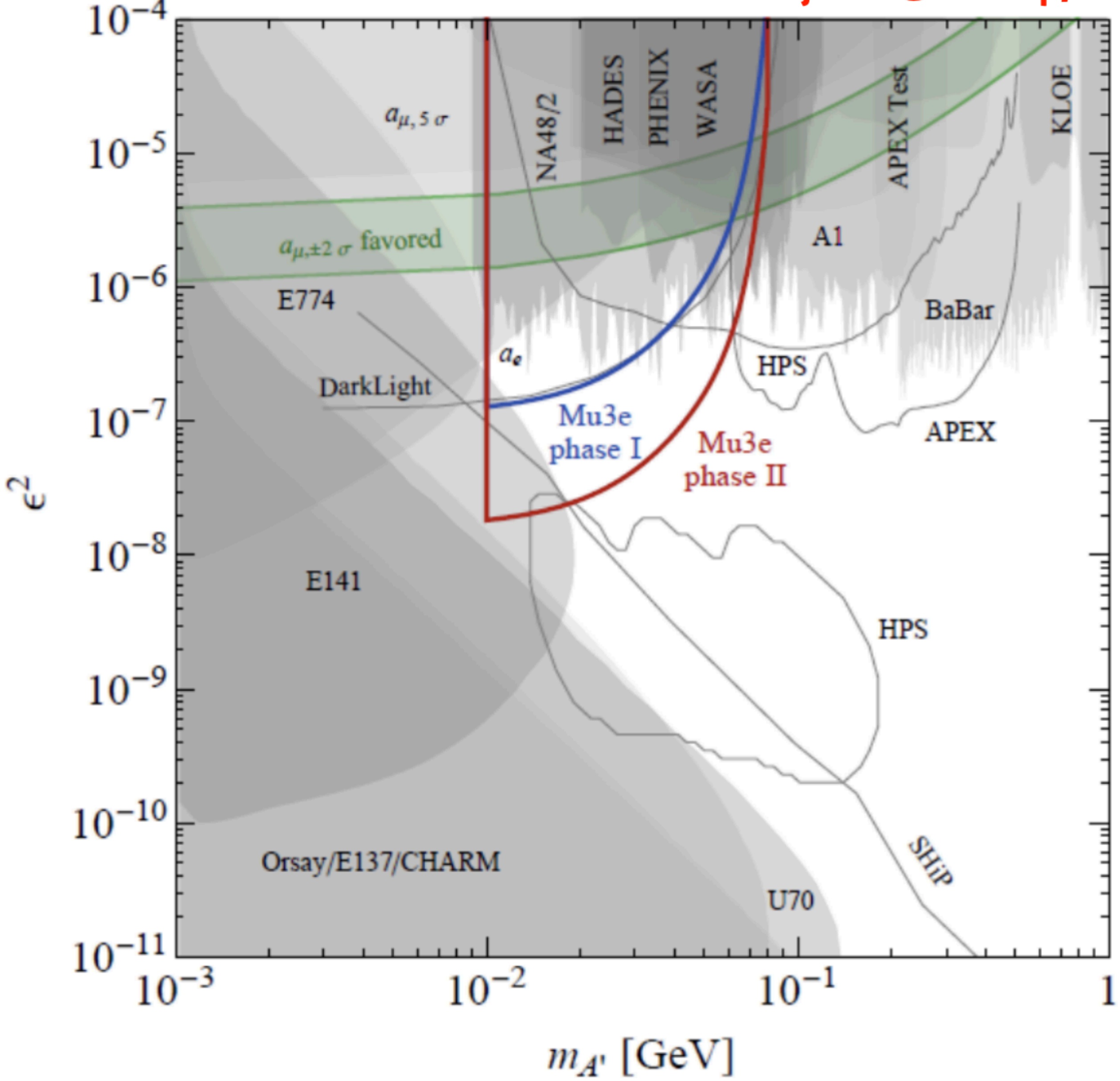
[Gan et al (2020)]

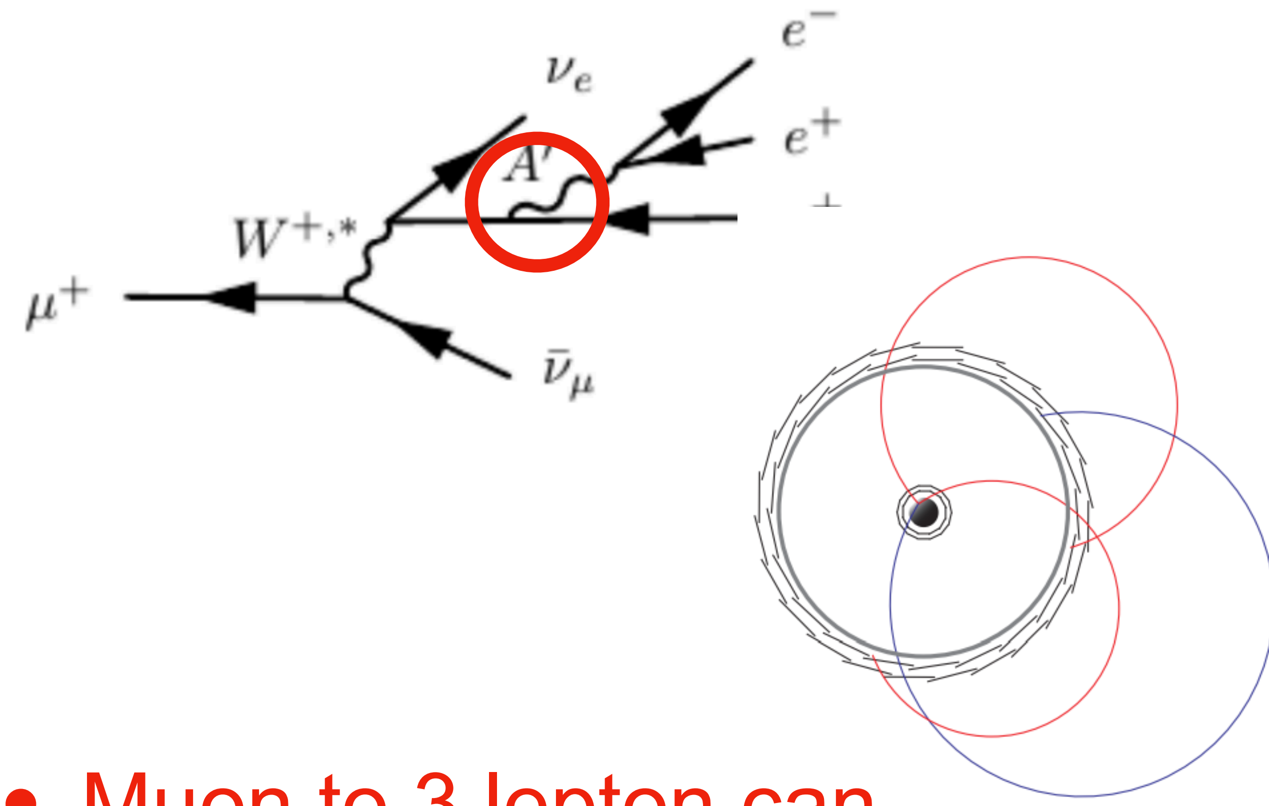
- Build a beam of η and η’ particles using:
    - p+De→η/η’ + $^3He^+$

Other Ideas

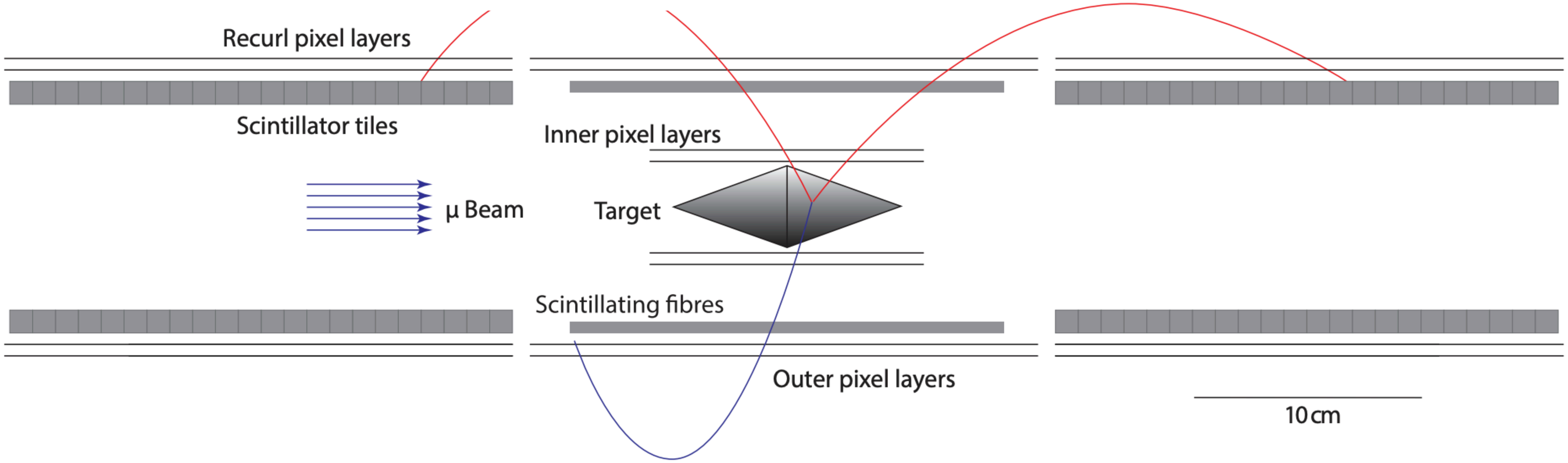
Phase 1 ~ 3 years @ $10^8 \mu/s$

Phase 2 ~ 3 years @ $2 \times 10^9 \mu/s$





- Muon to 3 lepton can probe a light dark photon



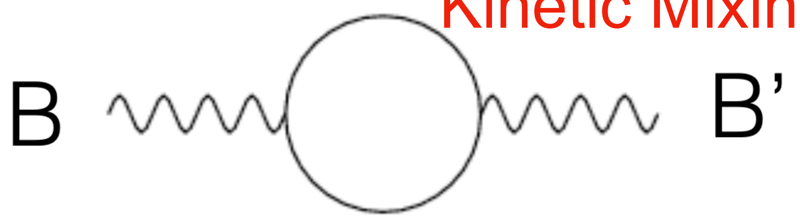
More Exotic Dark Photons

Milli-Charged Particles

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

Massless Dark Photon

Kinetic Mixing



SM

dark sector

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

- To get milli-charged particles, lets look at photon field mixing

$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + \boxed{\bar{\chi}\left(\partial\!\!\!/ + ie'B\!\!\!/' + iM_{MCP}\right)\chi}$$

$$\boxed{B' \to B' + \epsilon B}$$

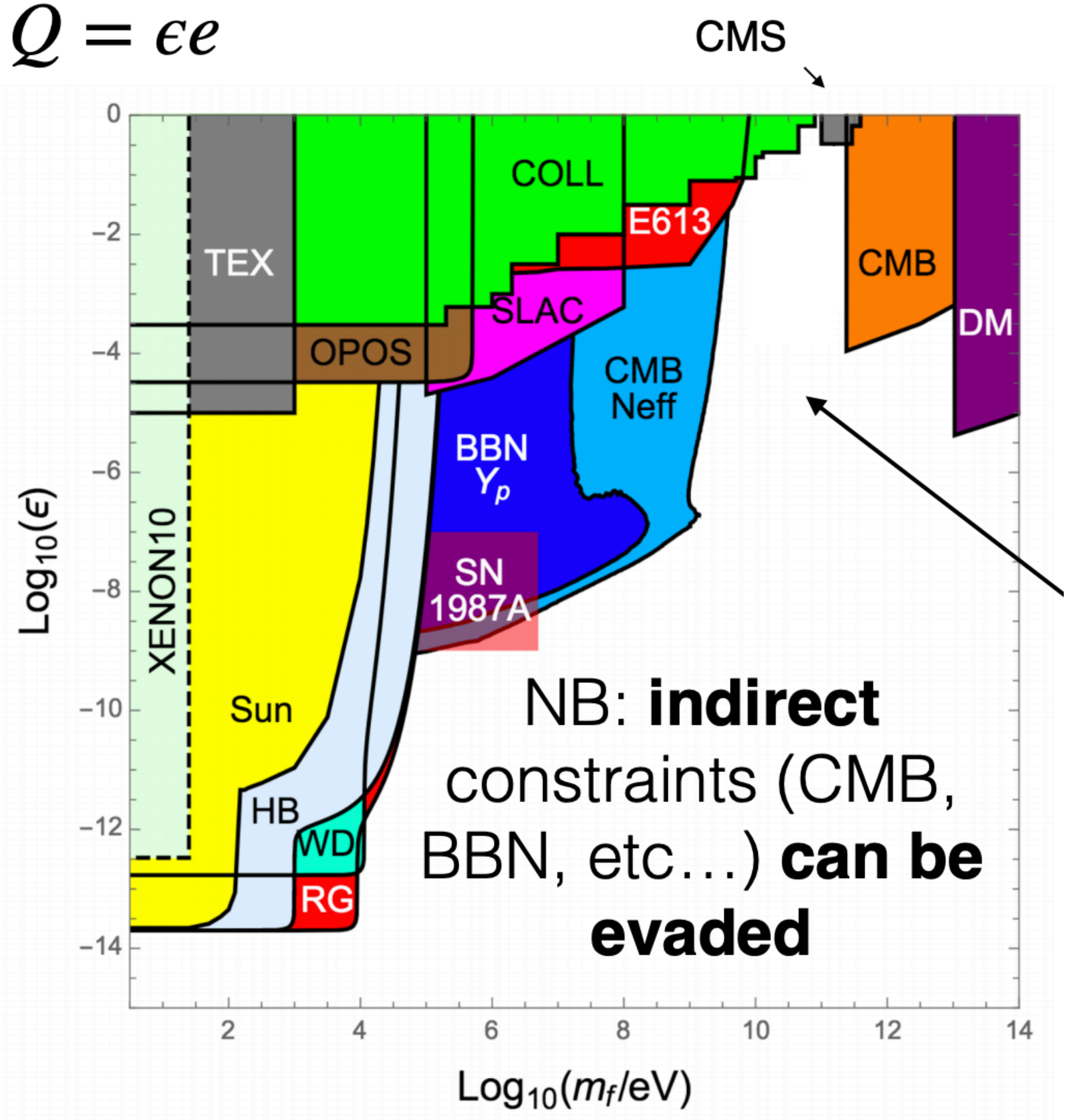
Usual Gauge Trick

Dark Sector Particle

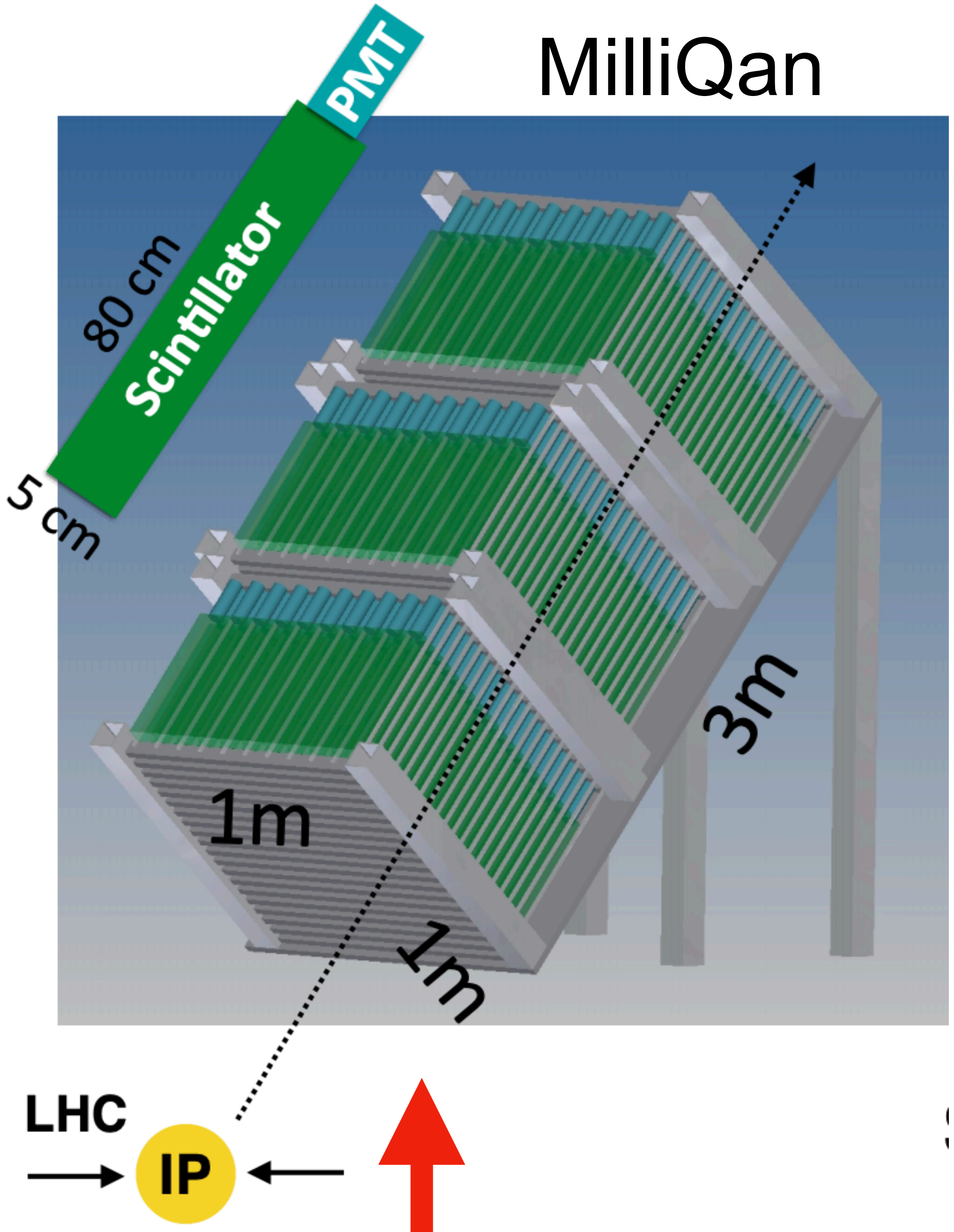
$$\mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} + i\bar{\chi}\left(\partial\!\!\!/ + ie'B\!\!\!/' + i\kappa e'B\!\!\!/ + iM_{MCP}\right)\chi$$

Milli-Charged Particles

$Q = \epsilon e$

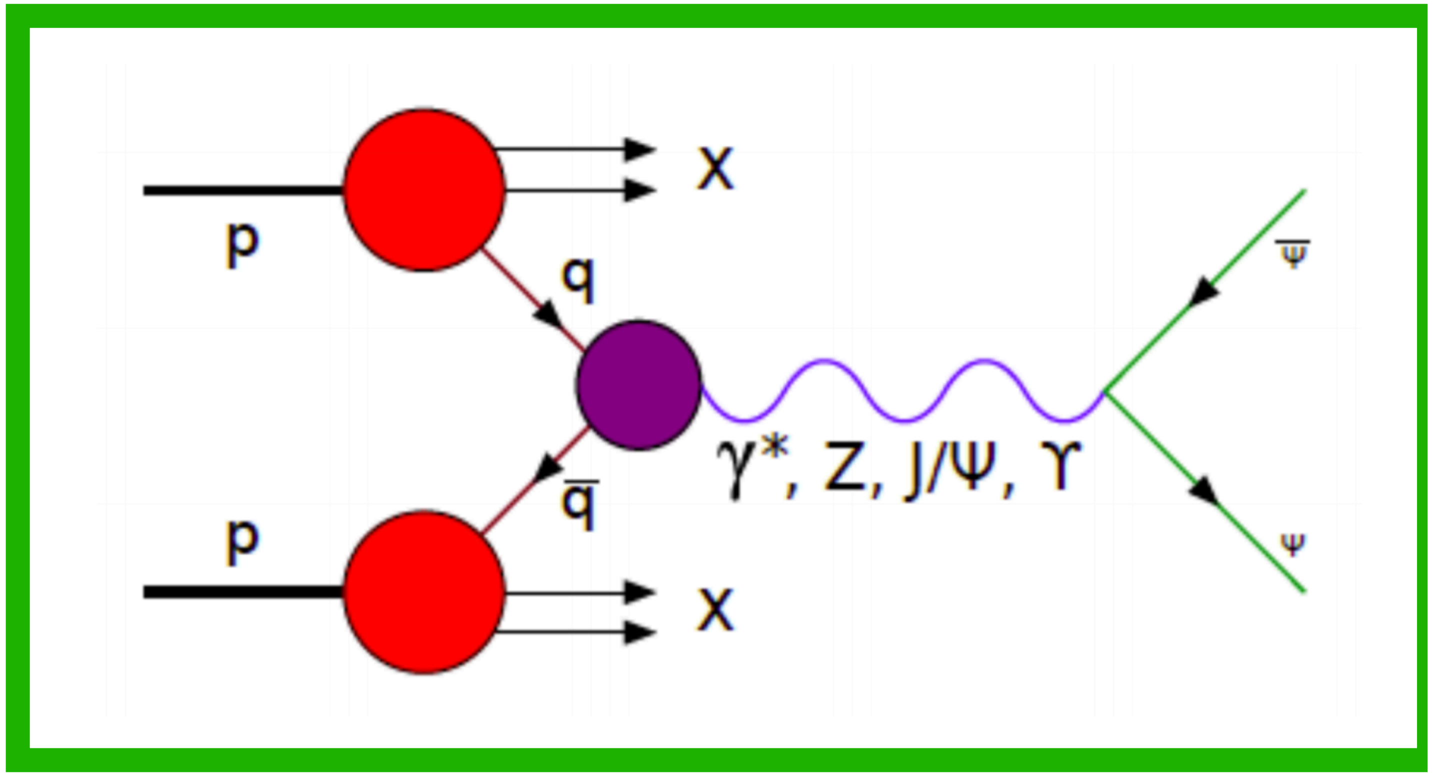


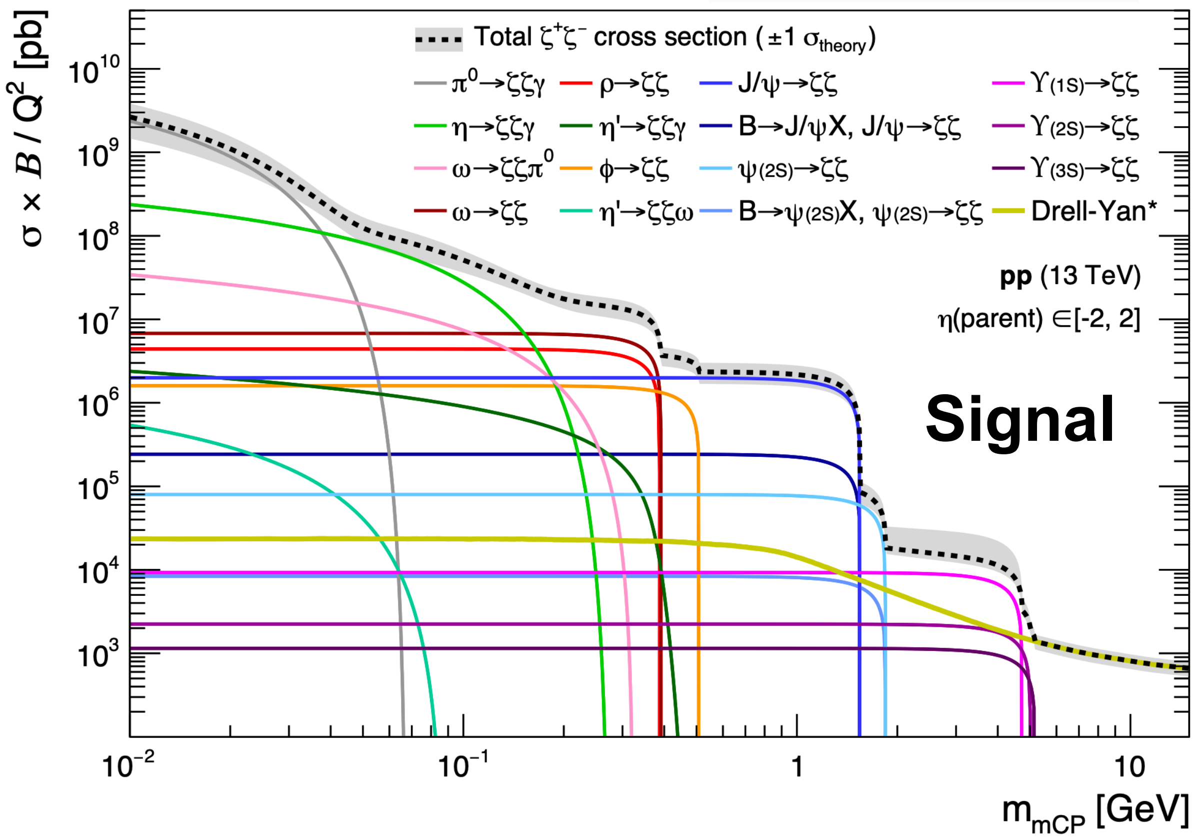
NB: **indirect** constraints (CMB, BBN, etc…) **can be evaded**



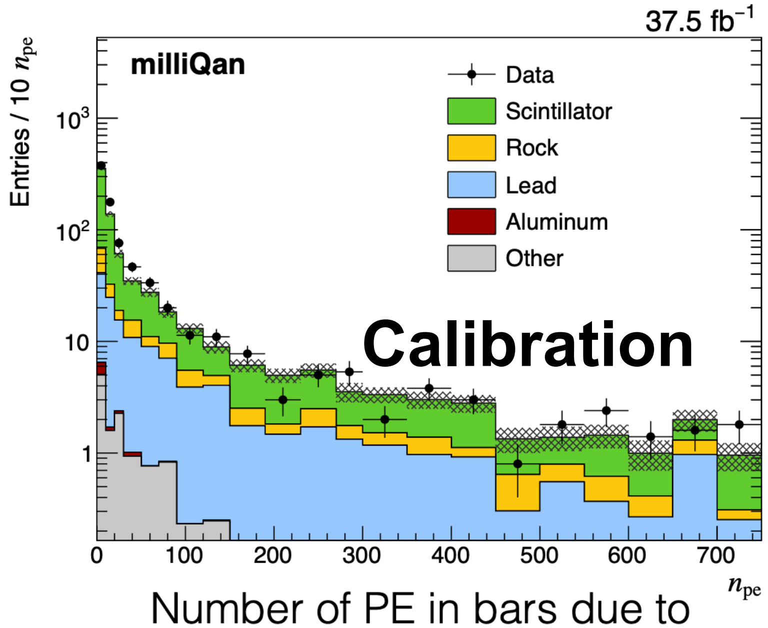
Scintillator capable of identifying a weakly charged object

Milli-Charged Particles





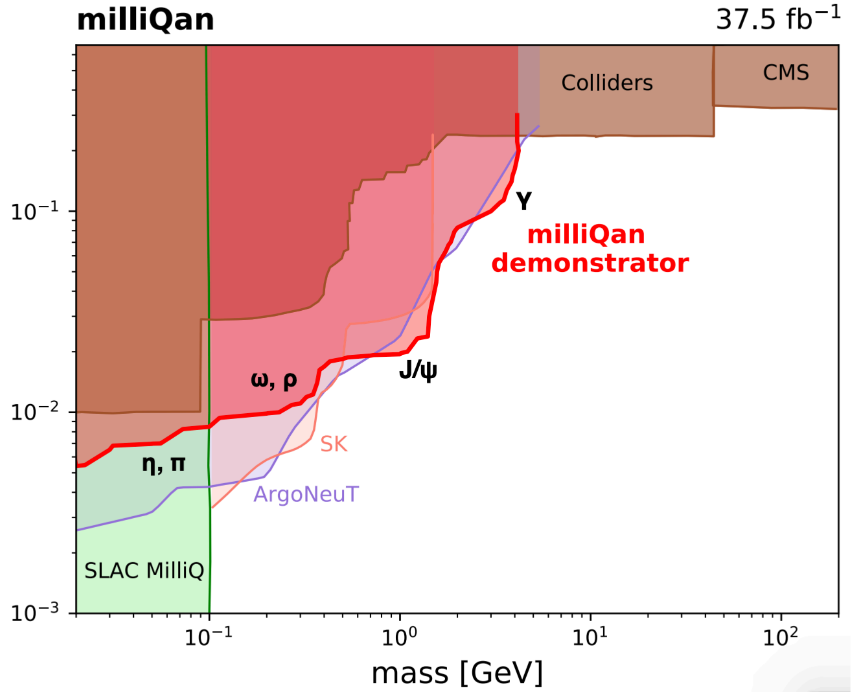
Since dark photon mixes with photon
Can produced weakly charged DM with drell-yan



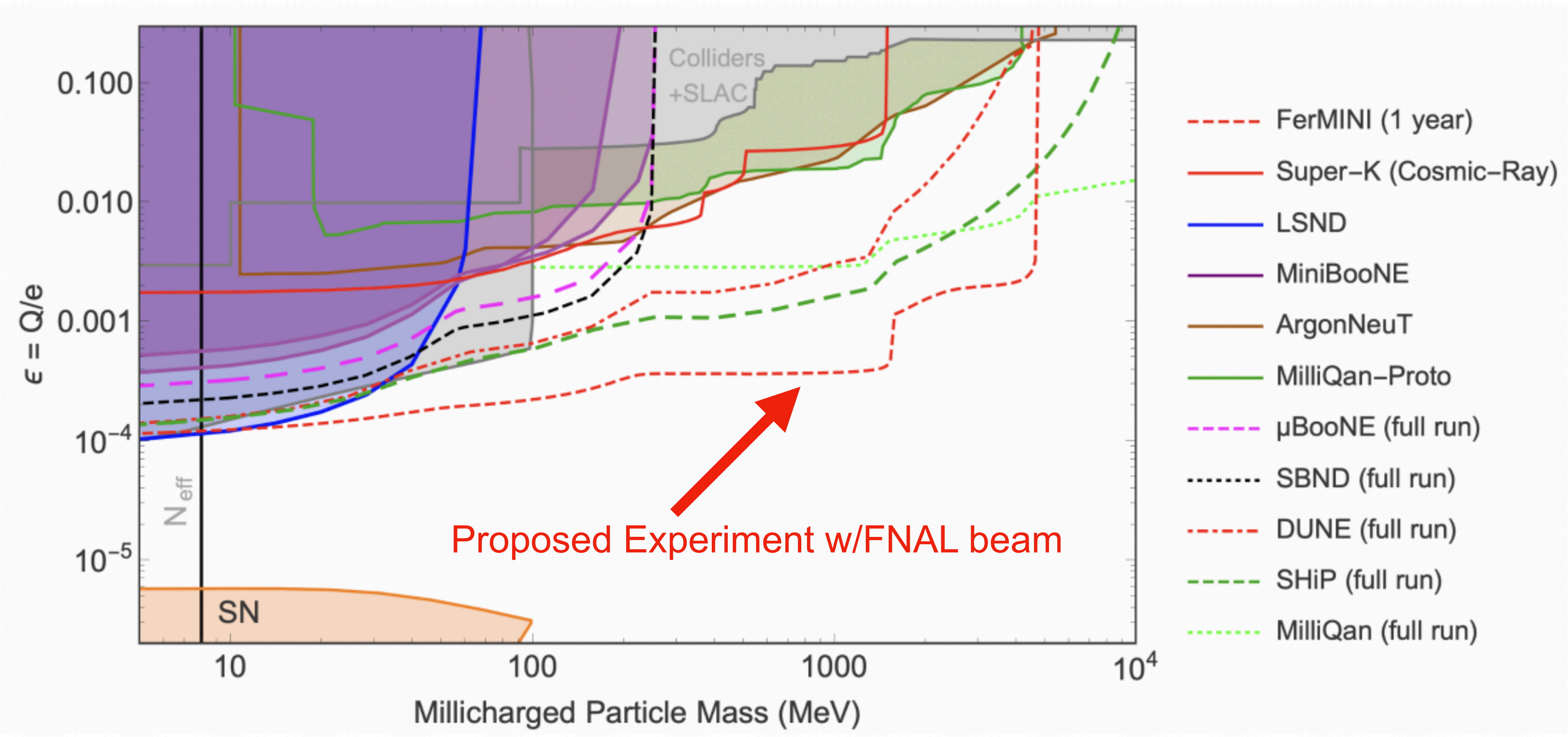
Number of PE in bars due to
muon shower products

%

es
so
of
or



Milli-Charged Particles



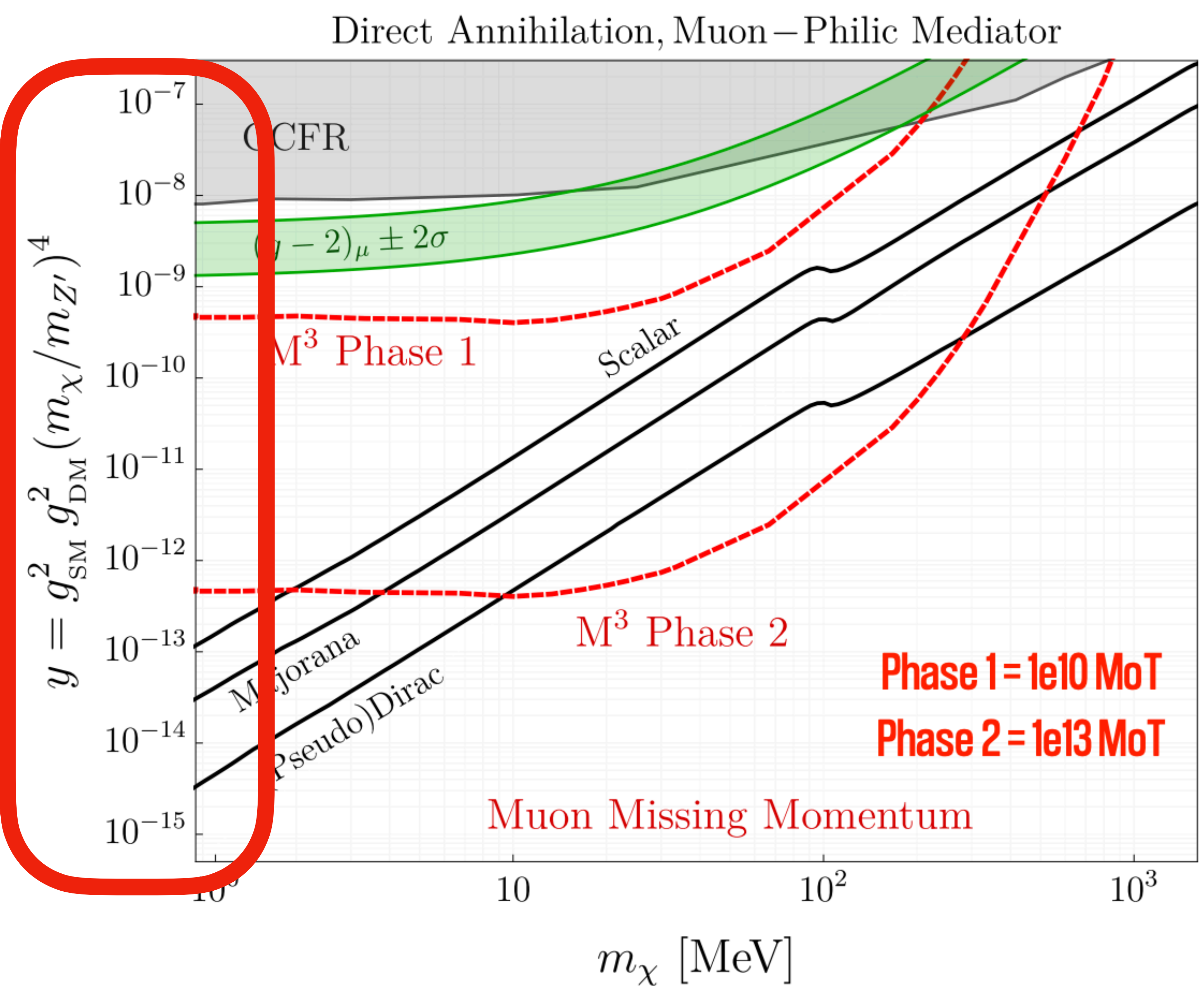
Proposed Experiment w/FNAL beam

Yu-Dai Tsai

Potential for large improvements over current bounds with a number of new (+small) experiements

Lifetime Frontier

Weakly Interacting DM



Coupling values are very small

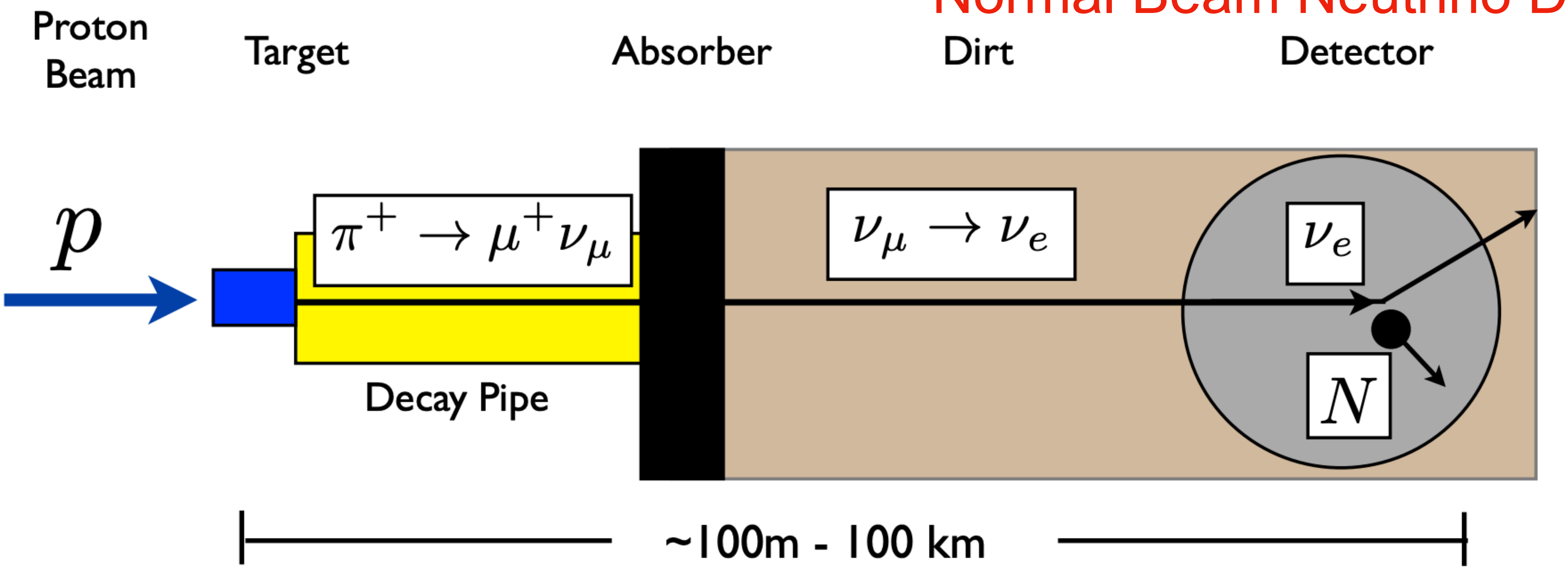
If DM is stable we can imagine using the beam to produced DM

Then we detect it with the same tools as direct detection

Turns out that neutrino detectors are quite similar to direct detection

Neutrino DM

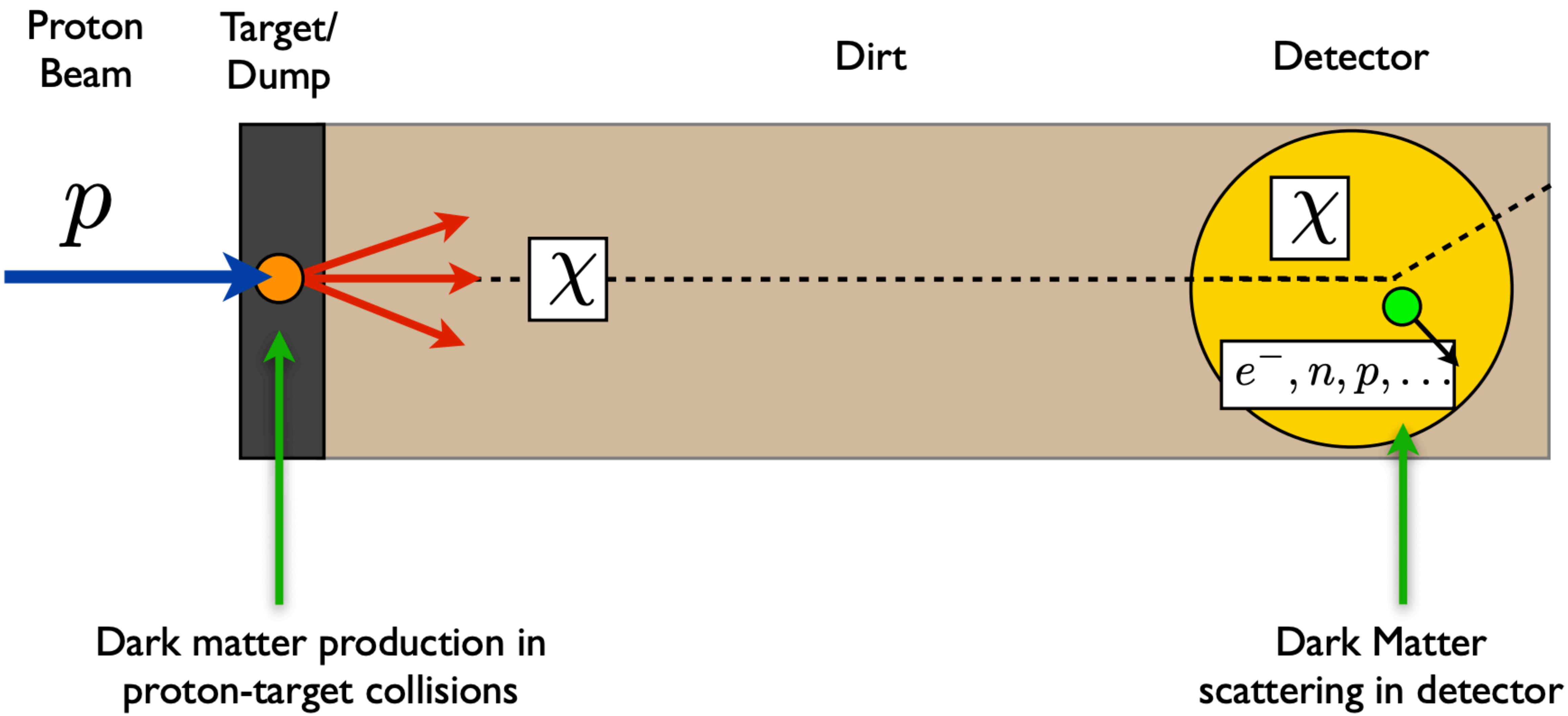
Normal Beam Neutrino Detector



- Neutrino physics produces neutrinos from Pion/Kaon decays
- Use a large volume sensitive detector to see neutrino

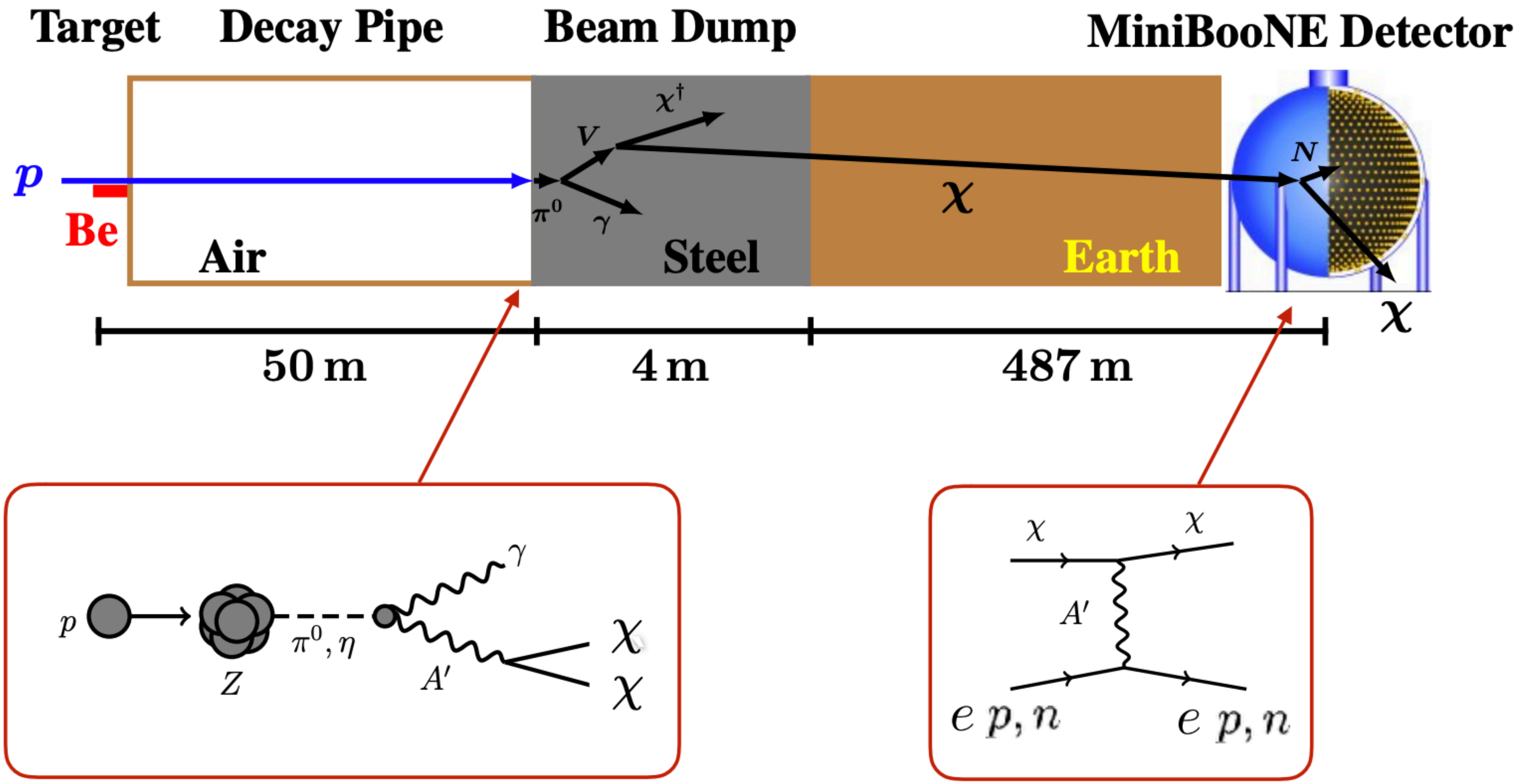
Neutrino DM

Normal Beam Neutrino Detector



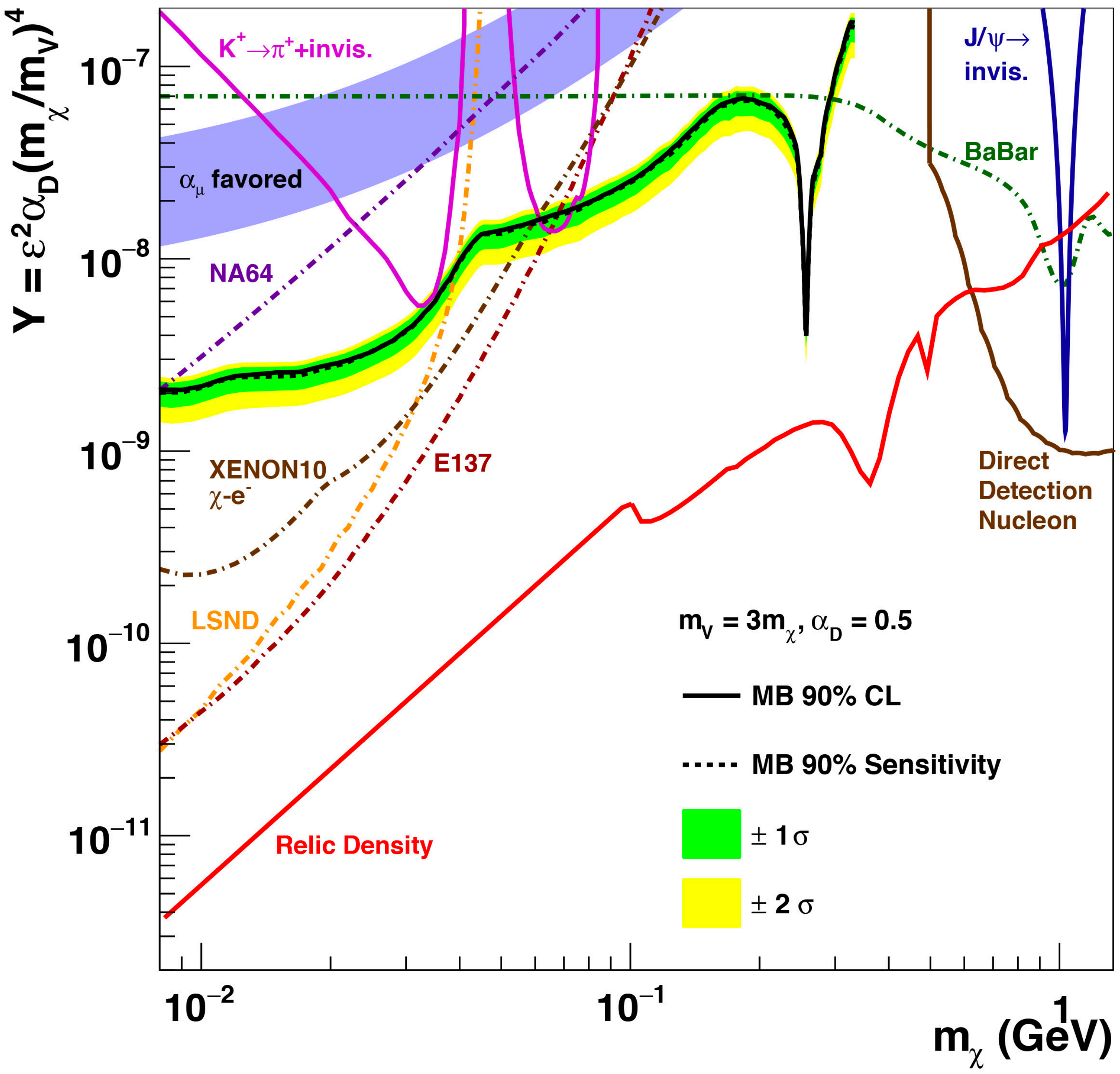
- Dark Matter produces DM from beam innteraction
- Use a large volume sensitive detector to see DM interaction

Typical Example:MiniBoone



- Miniboone is a good example of how to observe DM

Bounds form MiniBoone



MiniBoone is able to cover regions that had been unexplored

Dark Matter interactions are weak Approaches the relic line

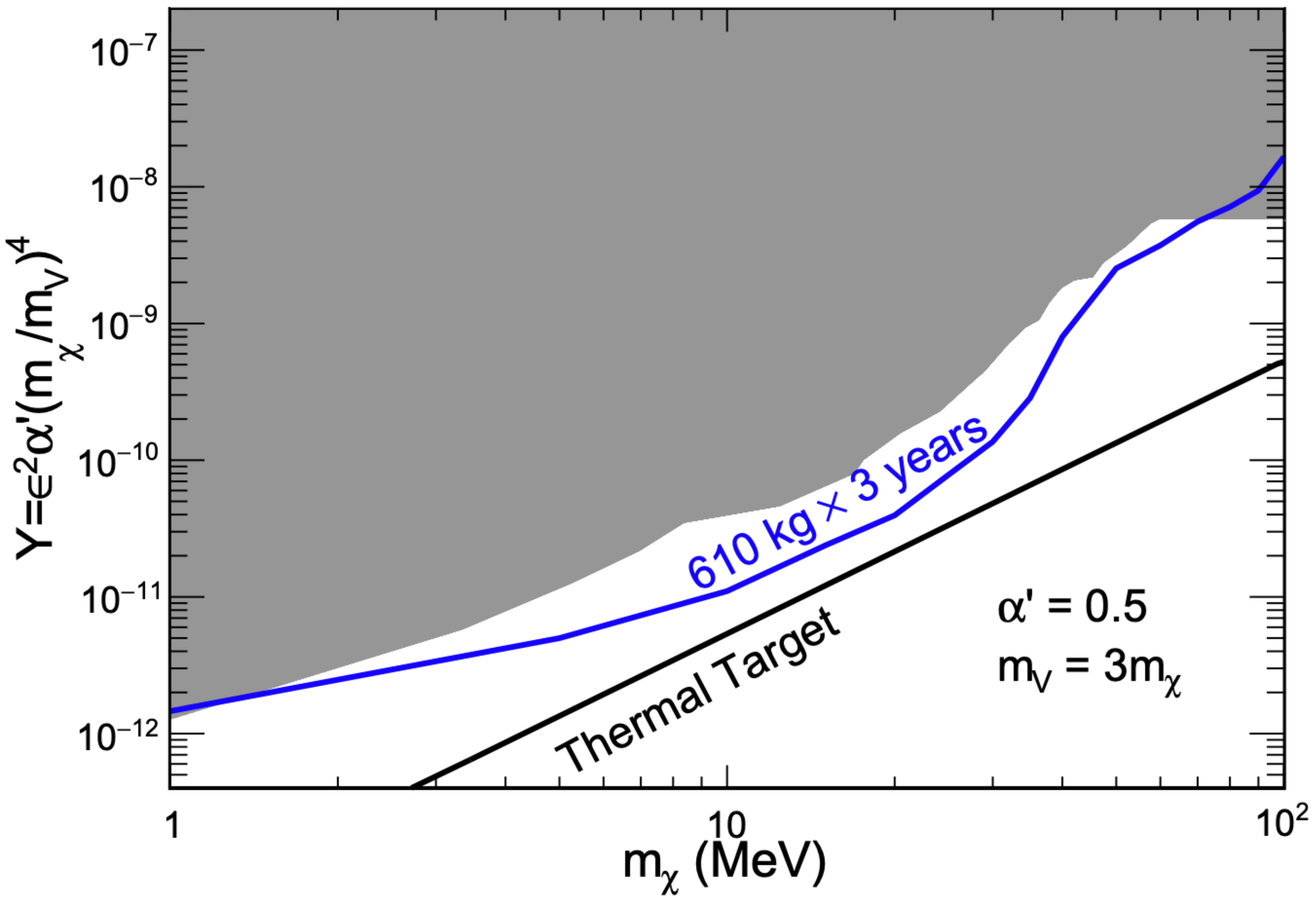
Experiments require really intense beams

$$[\text{production}] \times [\text{detection}] \propto \boxed{\epsilon^4}$$

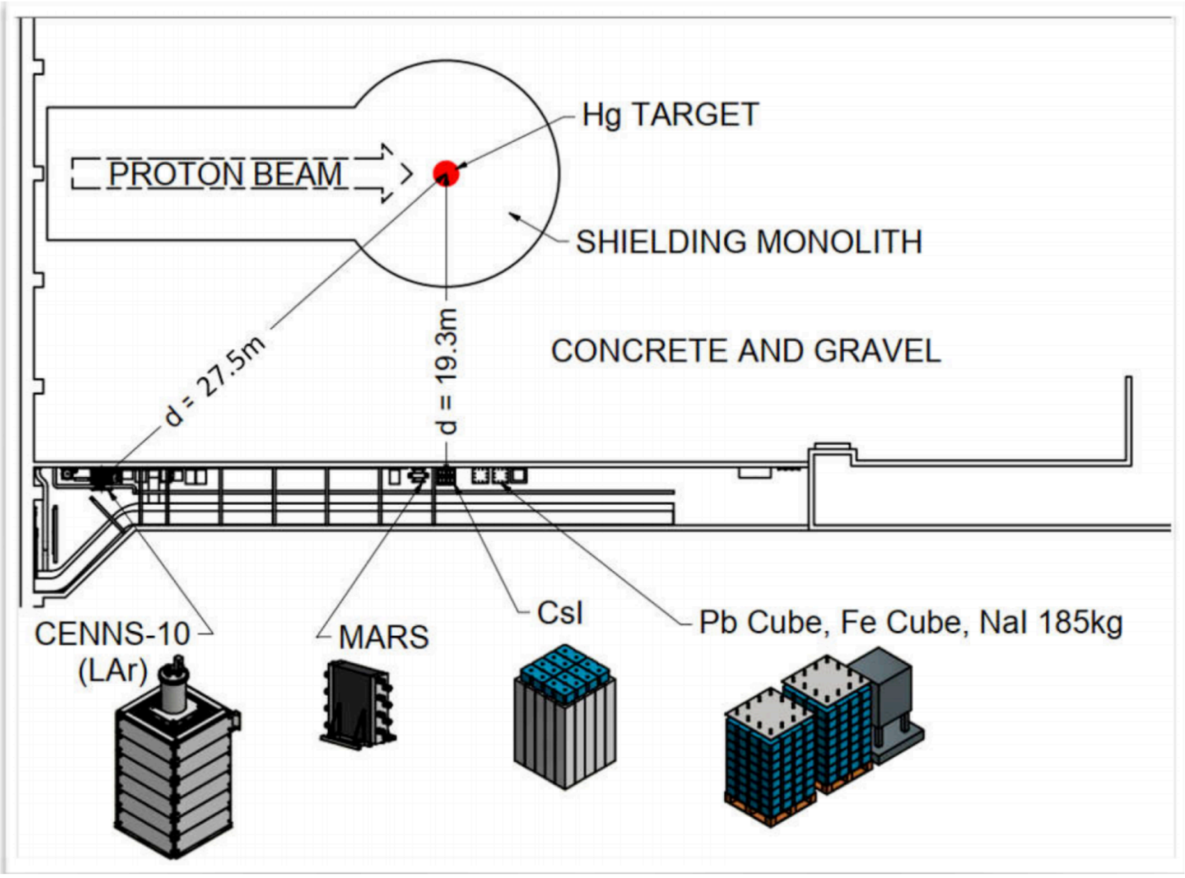
Suppression Factor

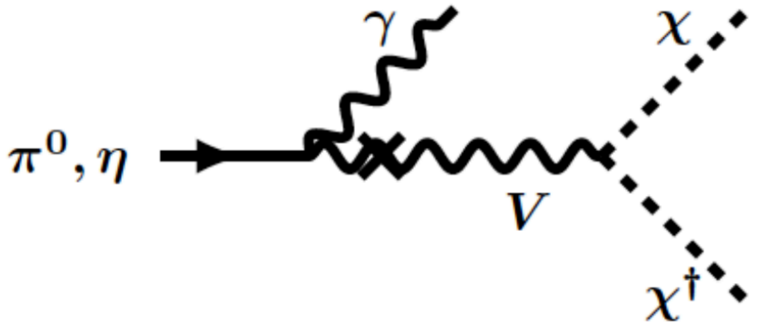
- Aim to parasitically use existing and future neutrino experiments

Bounds from COHERENT

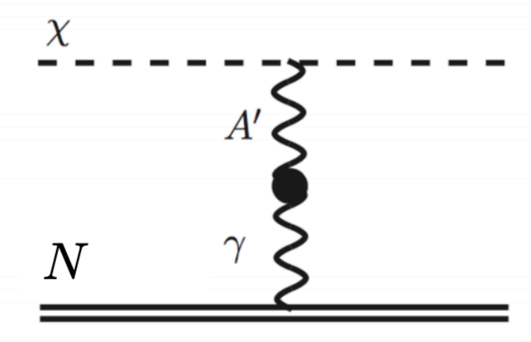


SNS Neutron beam @ORNL





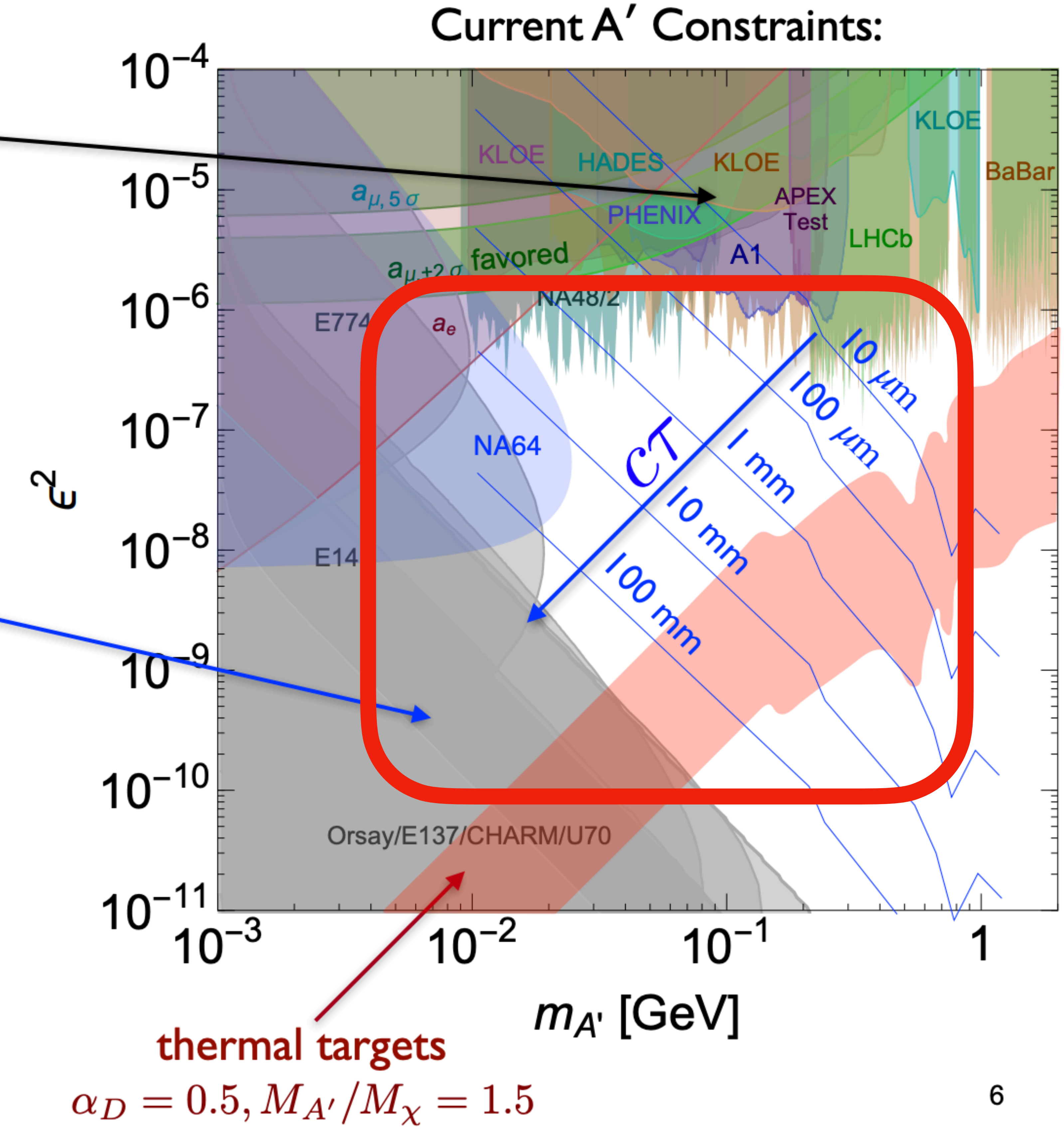
DM production



Coherent DM-nucleus scattering

- Neutron source at Oak ridge is a good source pions and eta

Long Lived DM



How do we exploit the long lifetimes to look for dark matter?

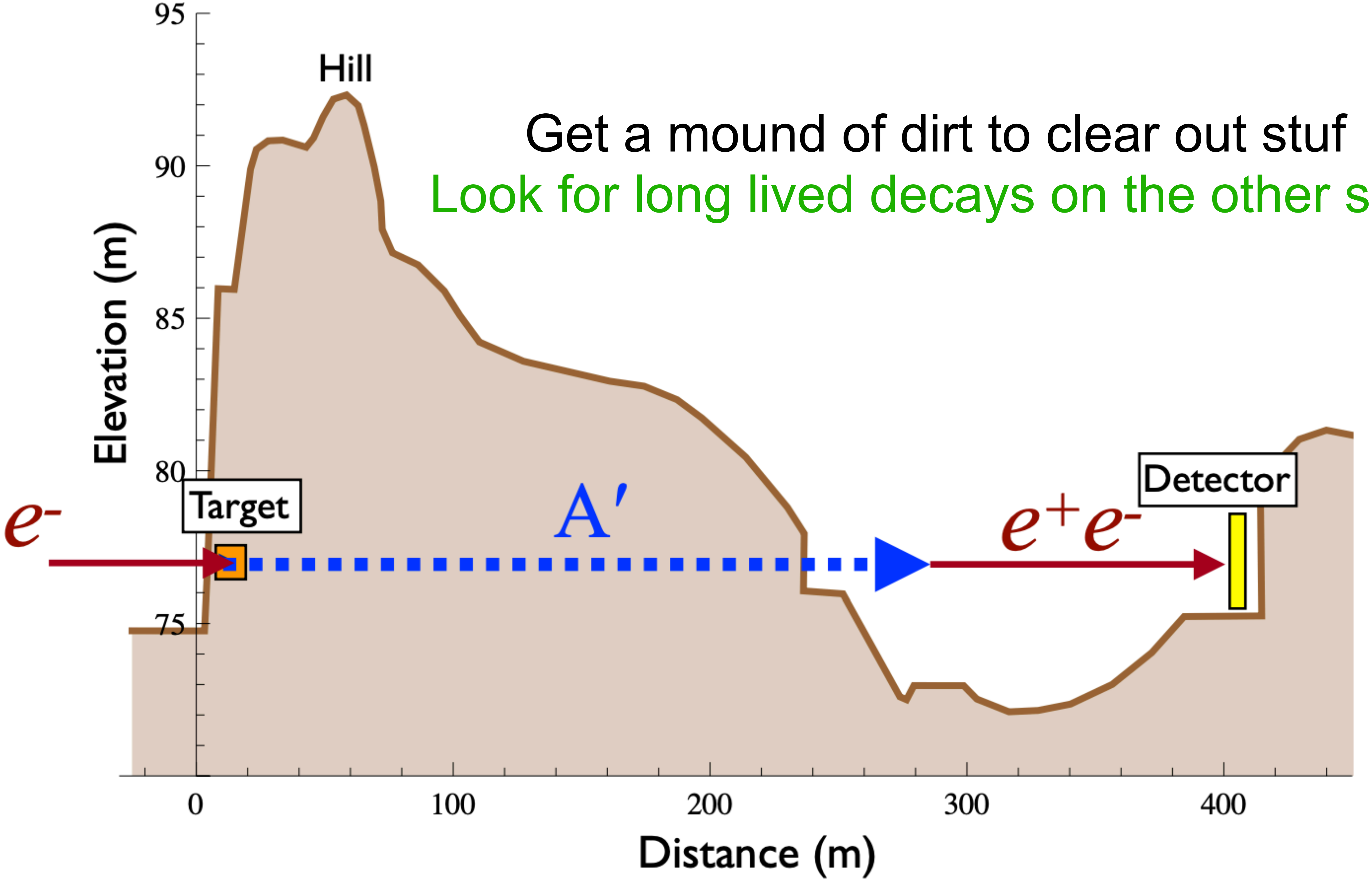
Limited amount of backgrounds w/such lifetimes

Unique signature

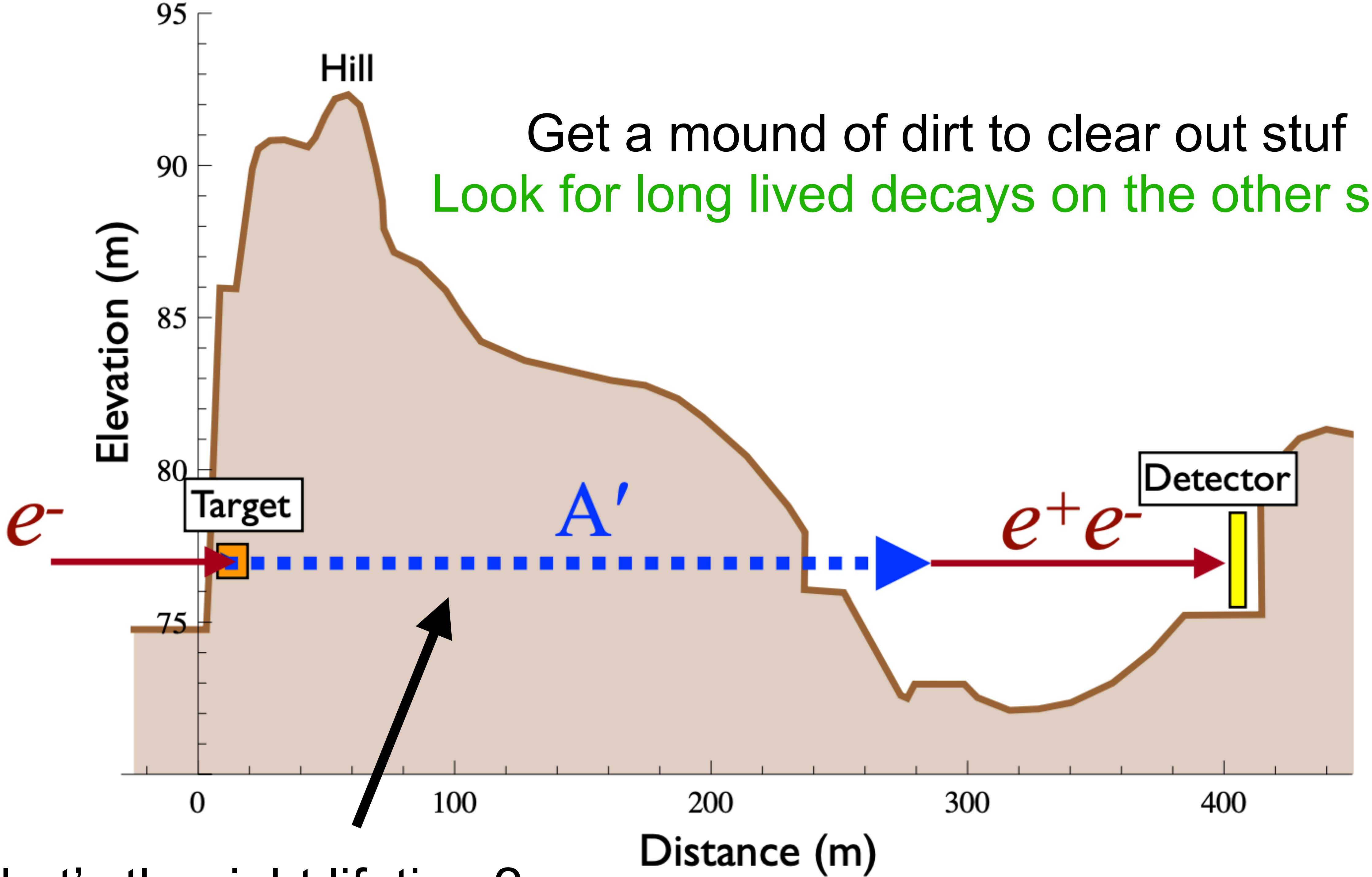
Long Lived DM

Get a mound of dirt to clear out stuf

Look for long lived decays on the other side



Long Lived DM



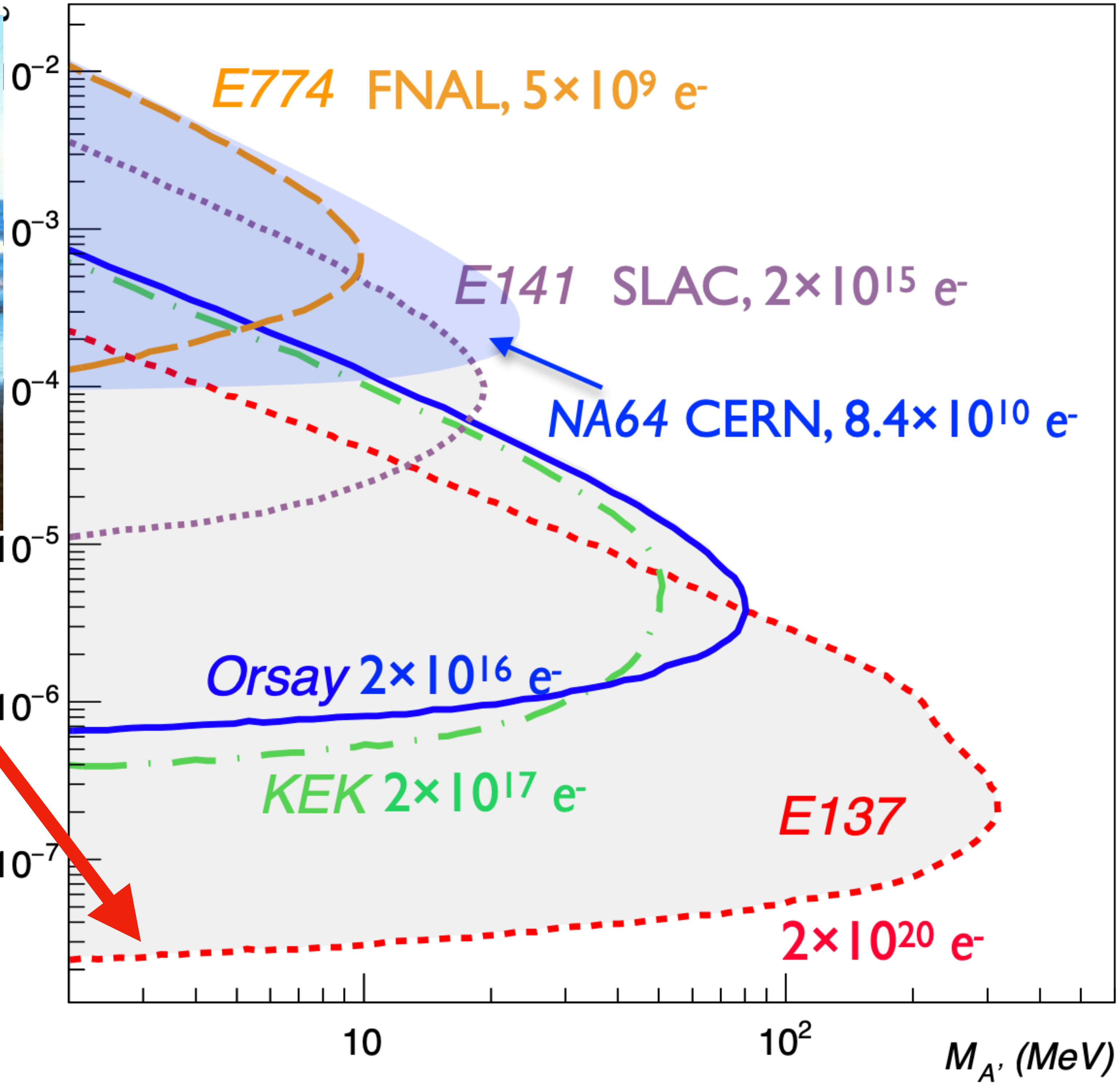
Get a mound of dirt to clear out stuf

Look for long lived decays on the other side

What’s the right lifetime?

Any lifetime from cτ = mm to the moon are possible

What are the bounds?

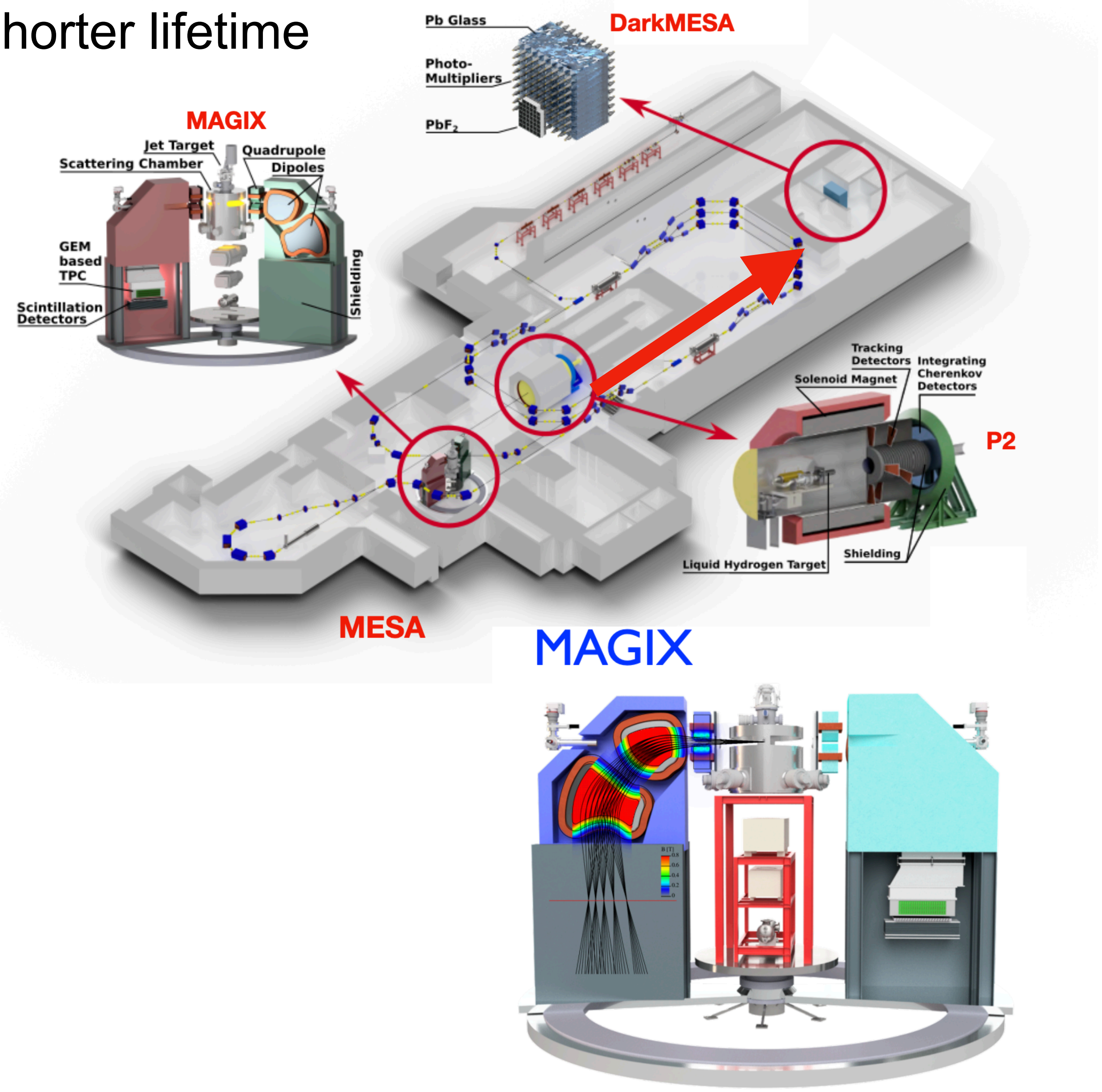


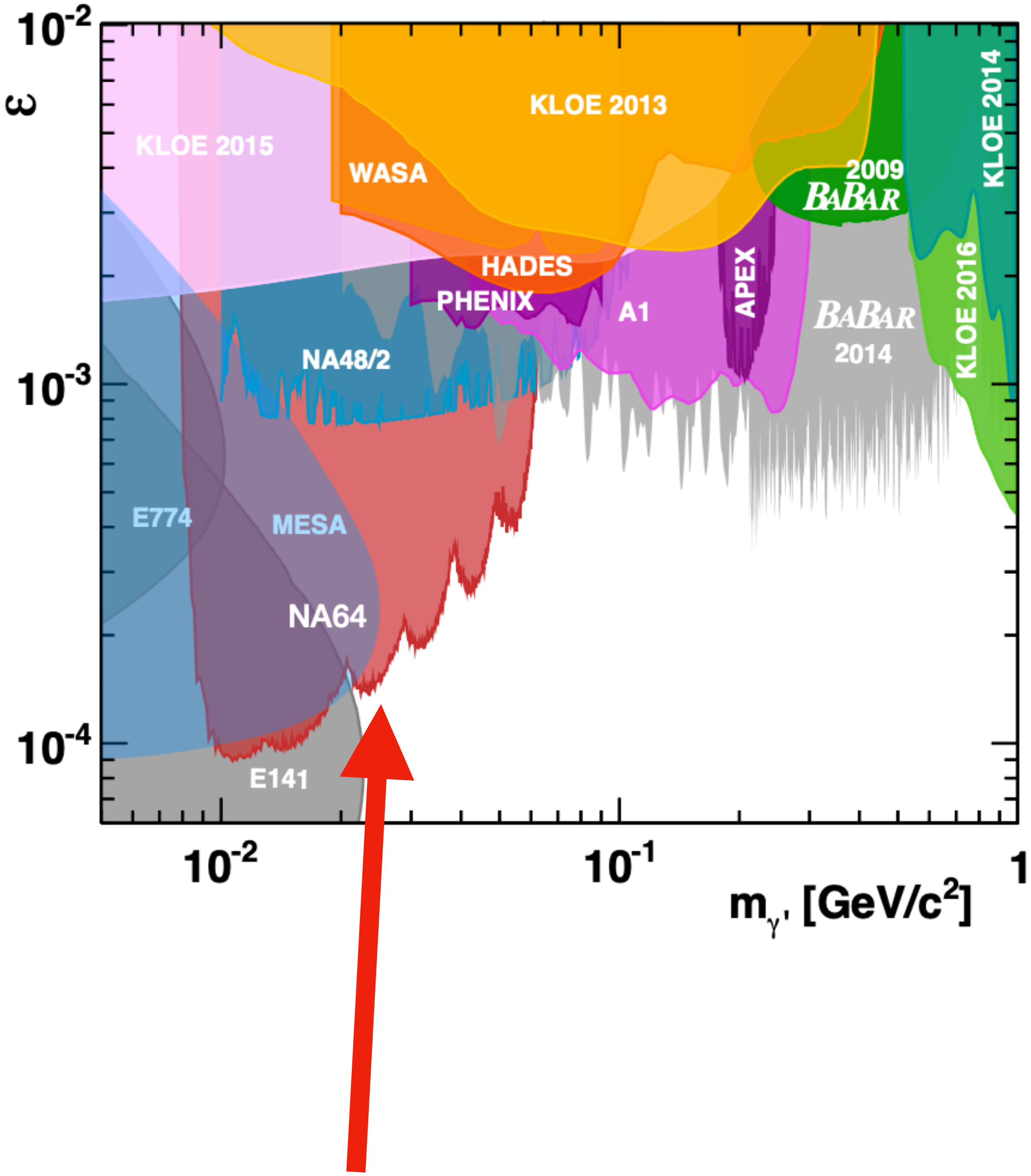
E137 was in 1980-82

- Many experiments run in the 80s have strong bounds

Shorter lifetimes

MAGIX@MESA
Shorter lifetime

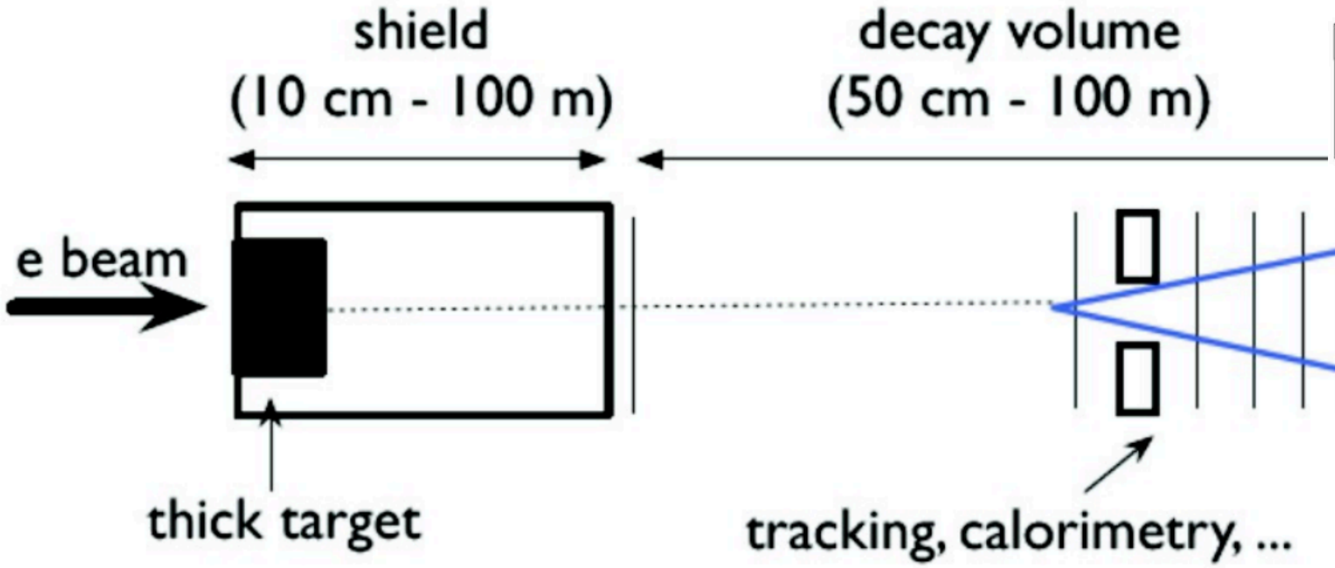


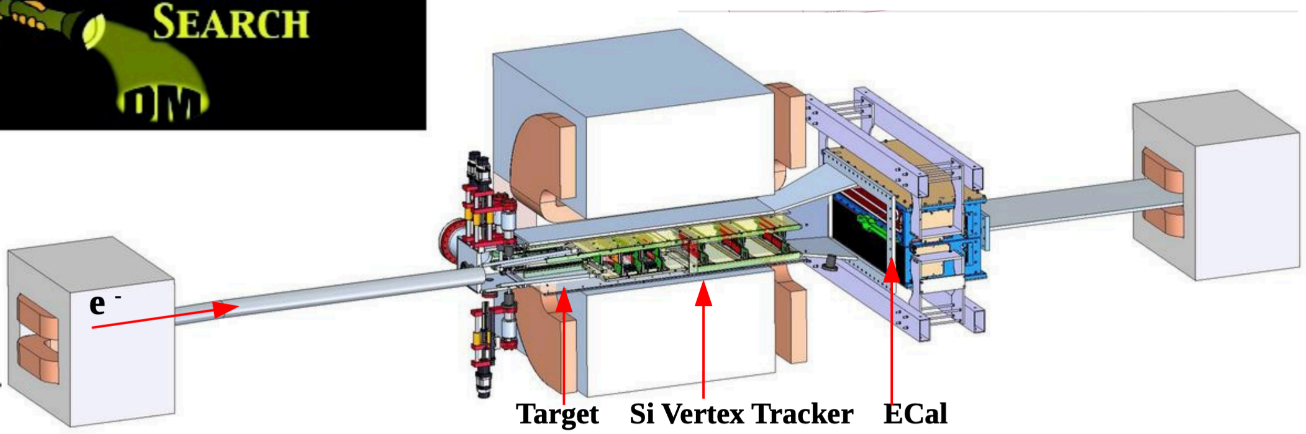


MAGIX beam produces a strong low E electron beam
Projected DM bounds can probe new territory

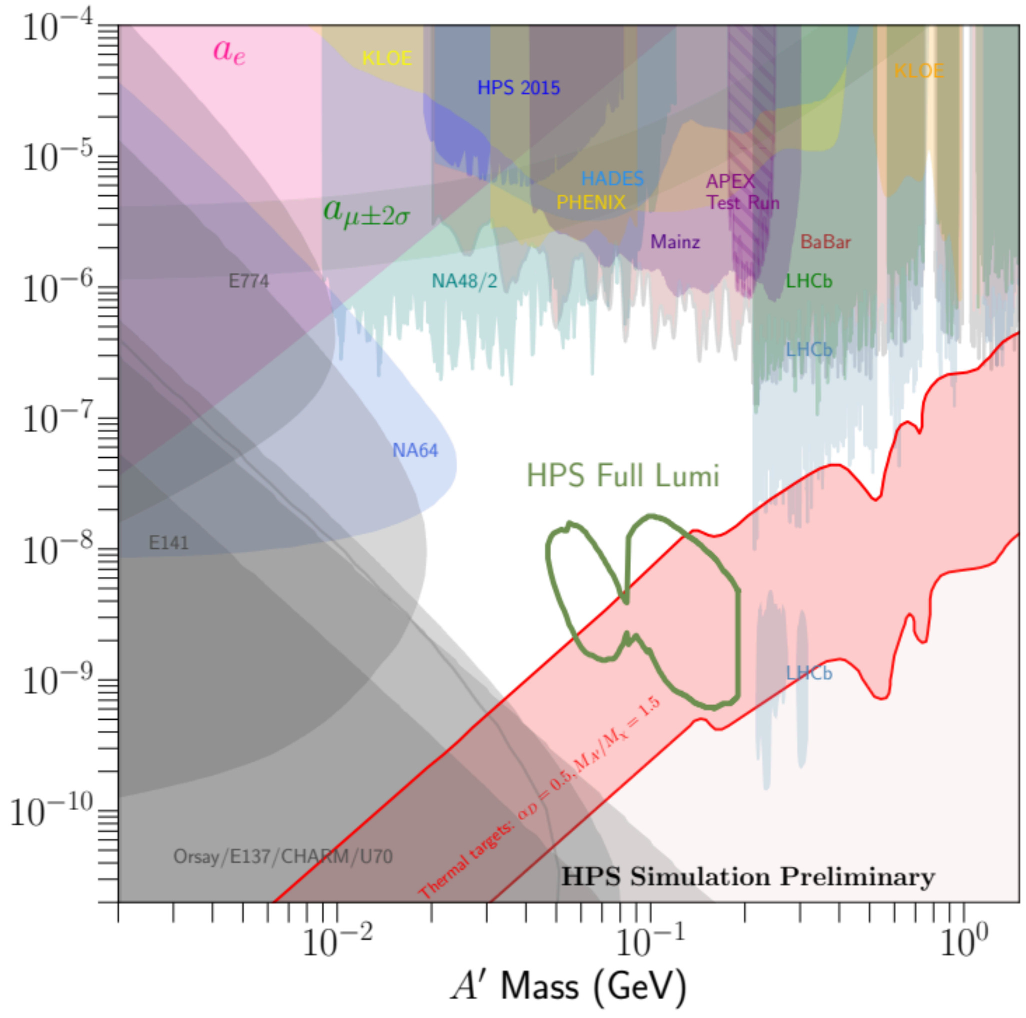
Heavy Photon Search

$$\gamma c\tau \approx 1\ \text{mm}\,(\gamma/10)\,(10^{-8}\alpha/$$
$$\times\,(100\ \text{MeV}/m_{A'})$$



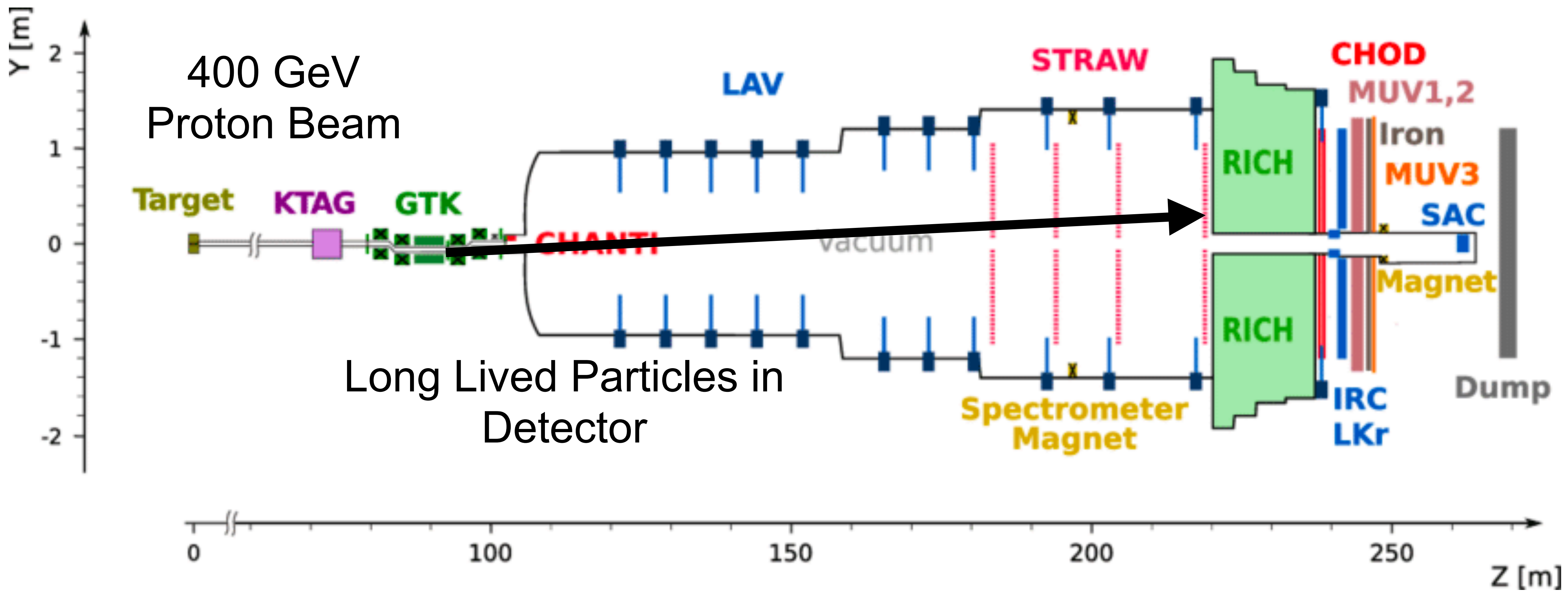


- Heavy Photon Search operating now
  - Expect some results soon

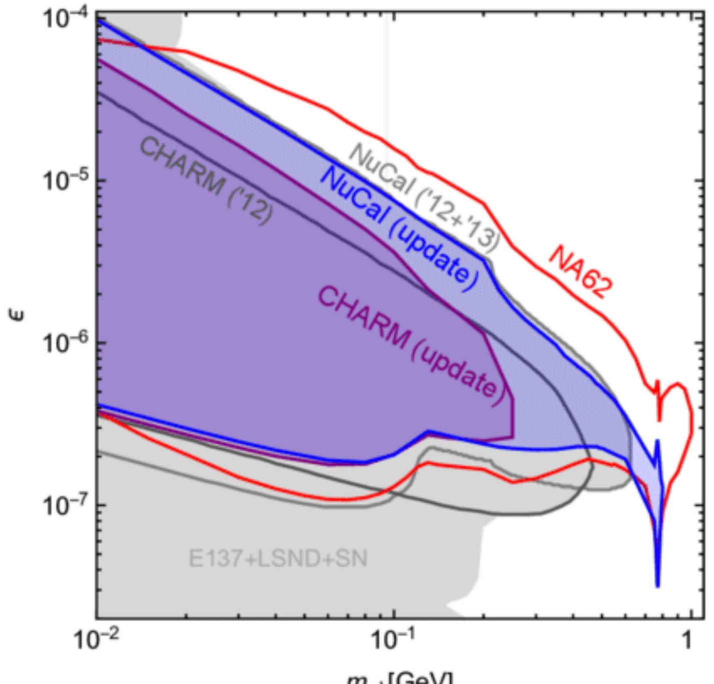


NA62

- Experiment currently focusing on kaon decays


400 GeV
Proton Beam

Long Lived Particles in
Detector

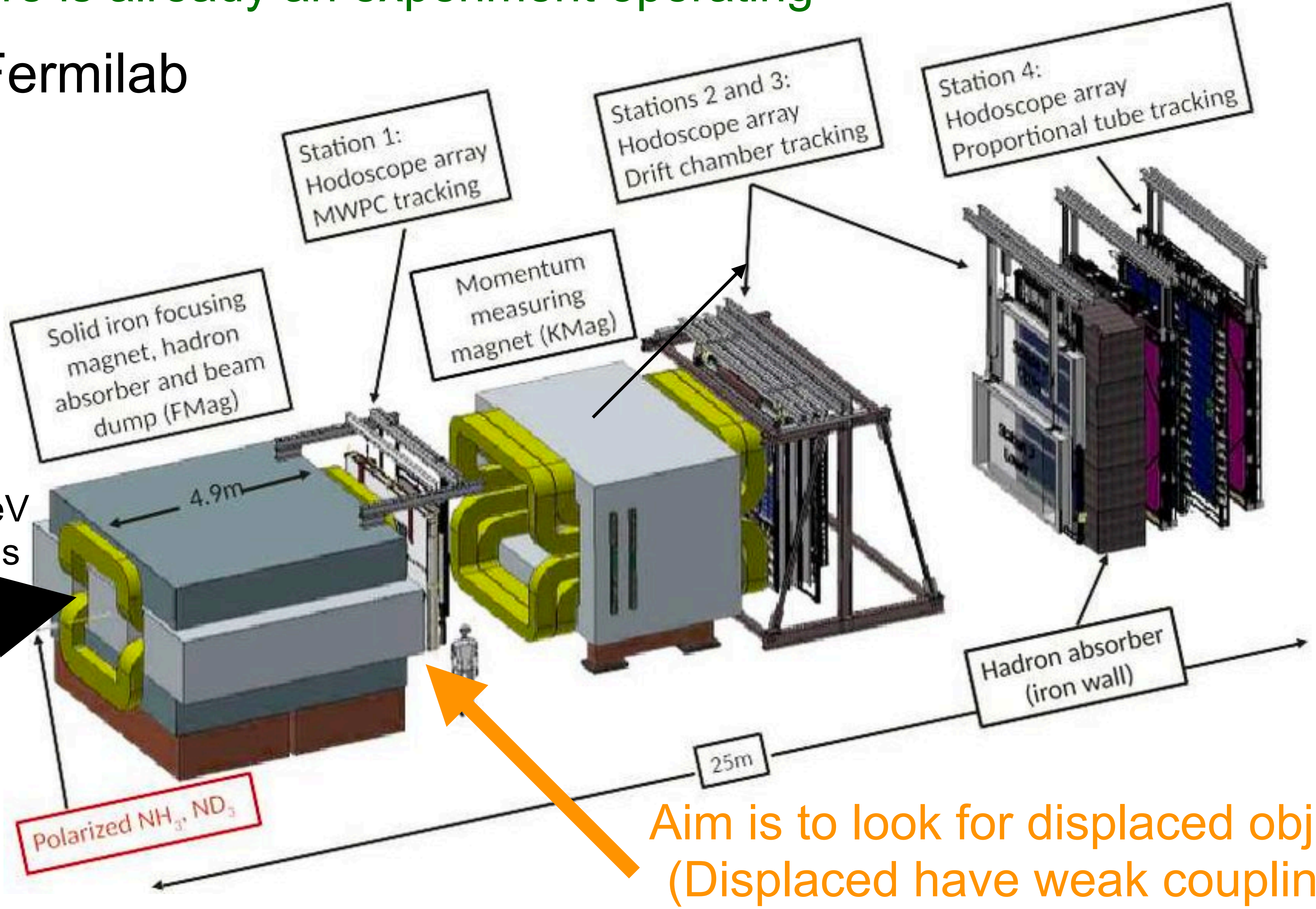


- Runs in various modes depending on beam
  - Left plot is from protons on a Be target

Spin Quest Experiment

There is already an experiment operating

@Fermilab



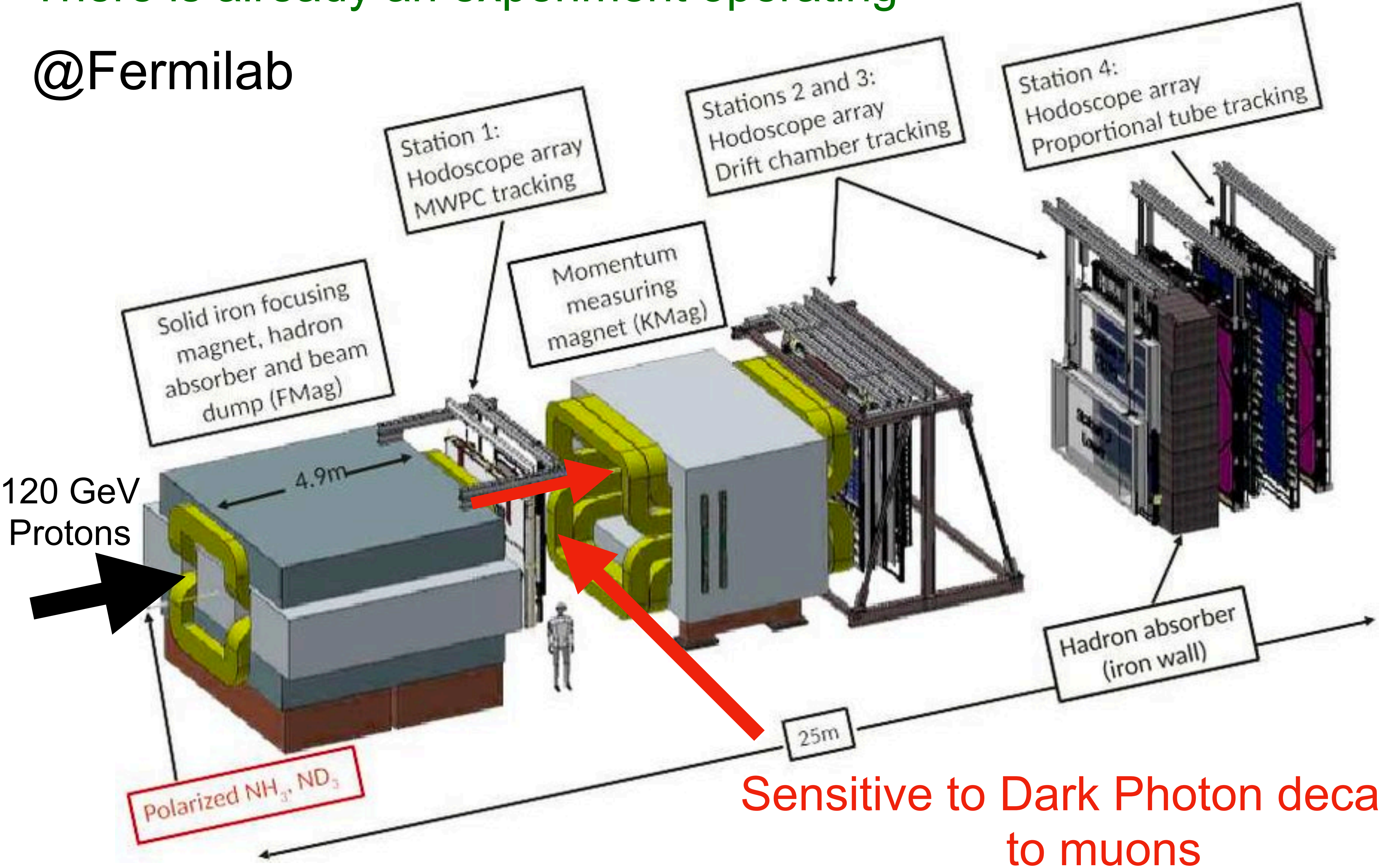
120 GeV Protons

Aim is to look for displaced objects
(Displaced have weak couplings)

Spin Quest Experiment

There is already an experiment operating

@Fermilab

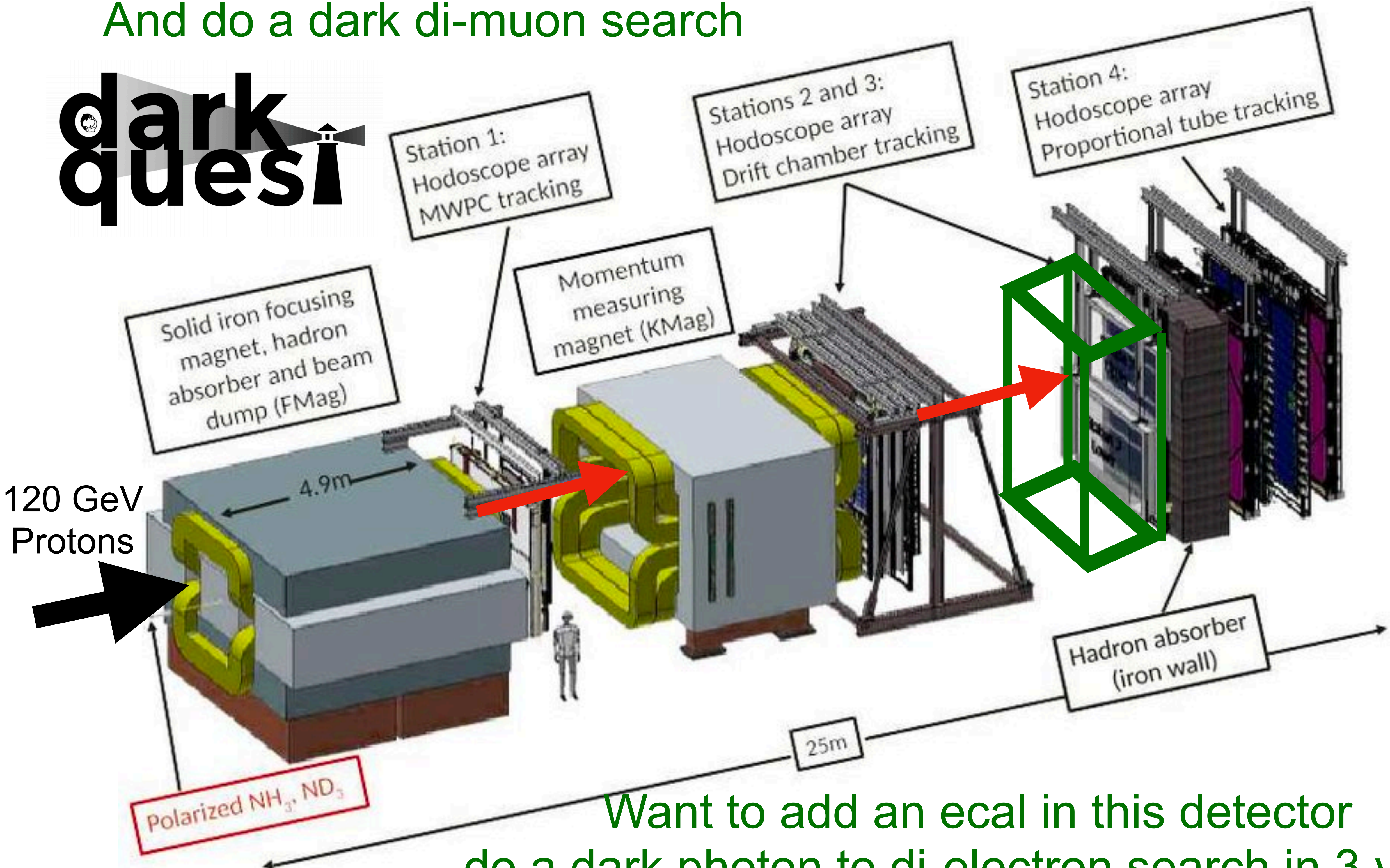


120 GeV Protons

Sensitive to Dark Photon decaying to muons

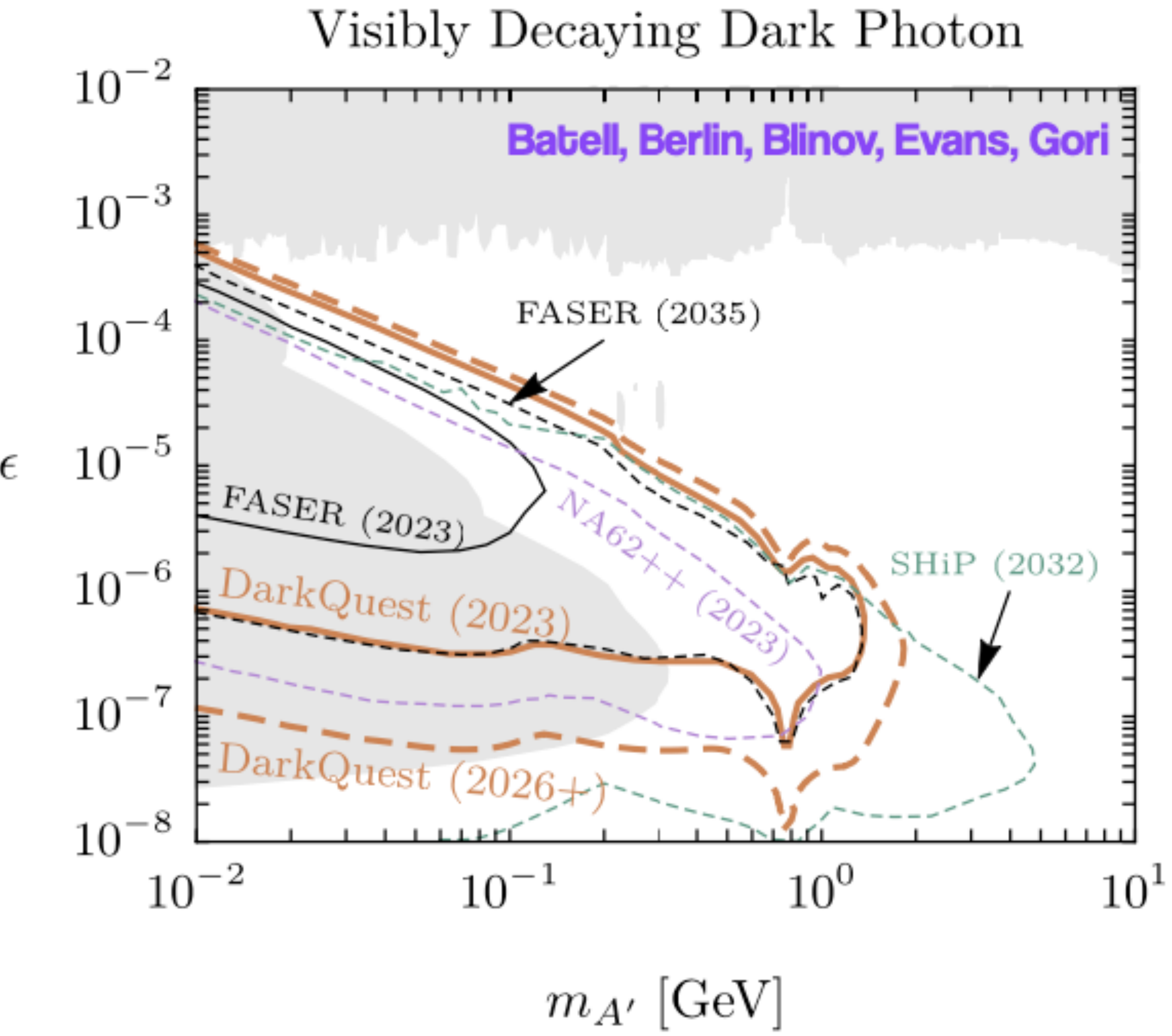
Dark Quest

Want to add an ecal in this detector
And do a dark di-muon search

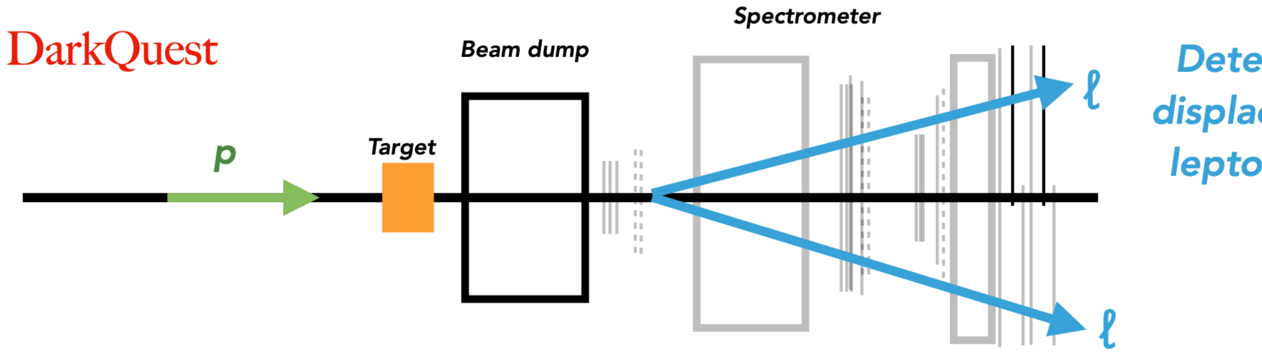


Want to add an ecal in this detector
do a dark photon to di-electron search in 3 years

Dark Quest



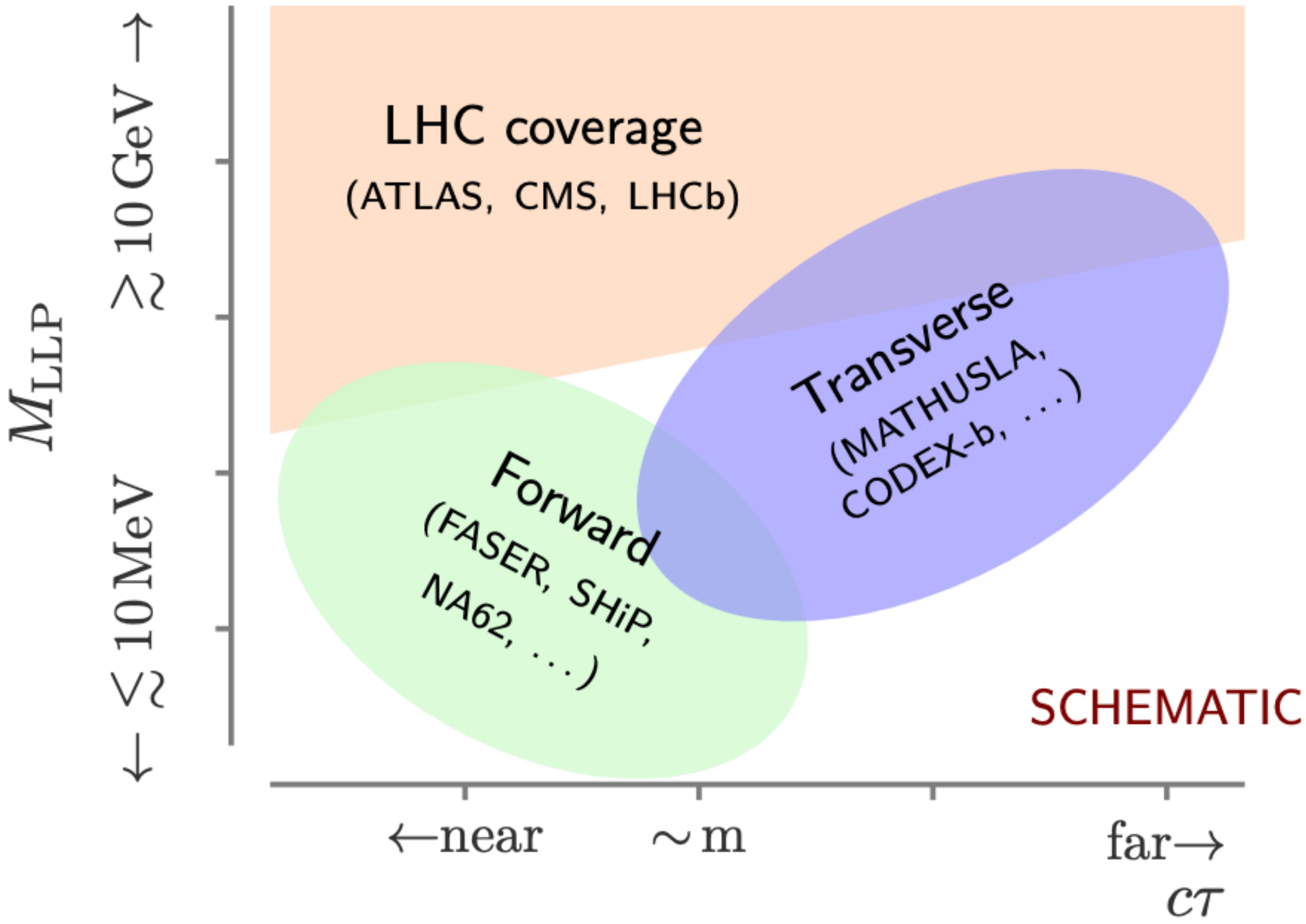
Sensitive to small couplings above the previous very long-lived searches



Addition of the Ecal

Allows for a broad range of other options

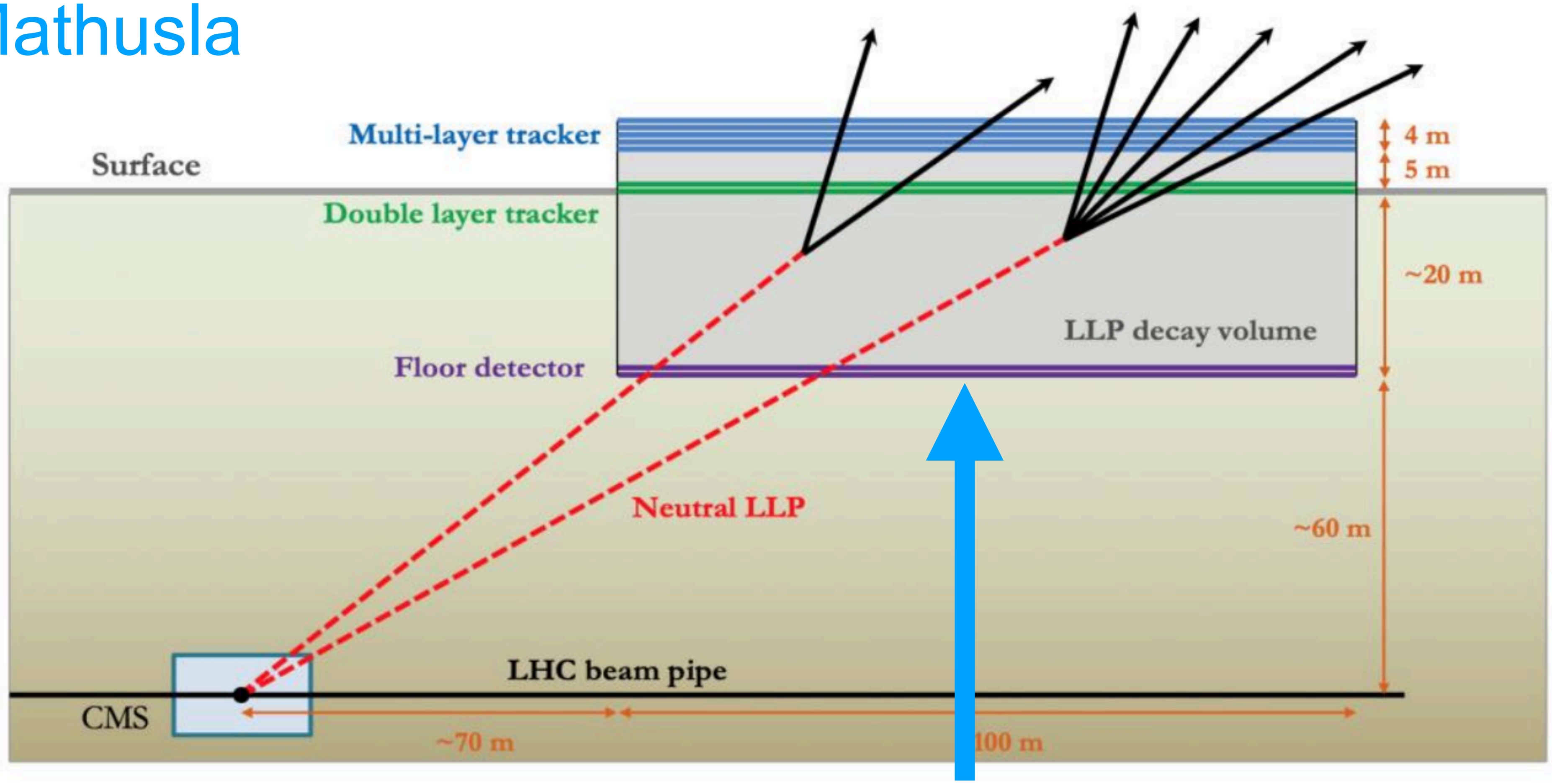
And @LHC



- We can also use the LHC beam to look for long lived particles

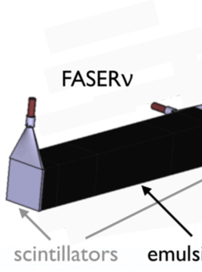
And @LHC

Mathusla



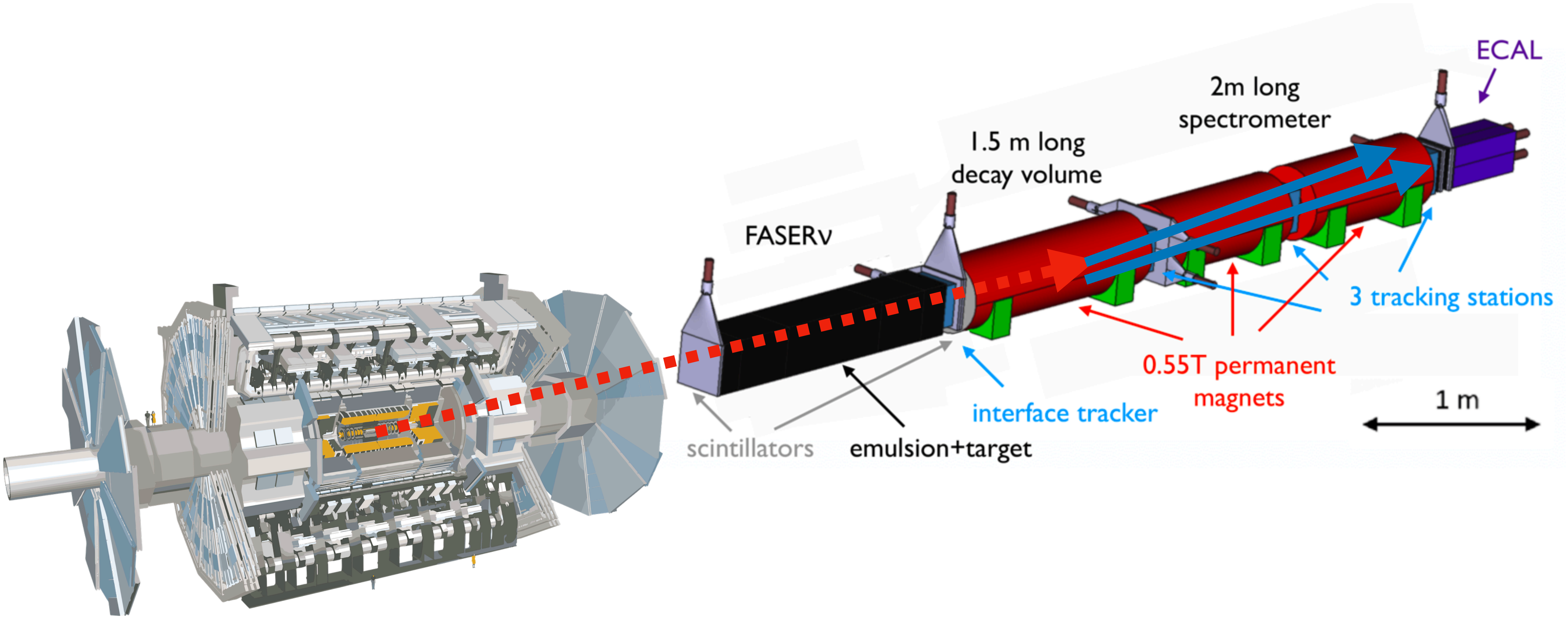
IKEA®

Giant Detector the size of an IKEA Store on the Surface



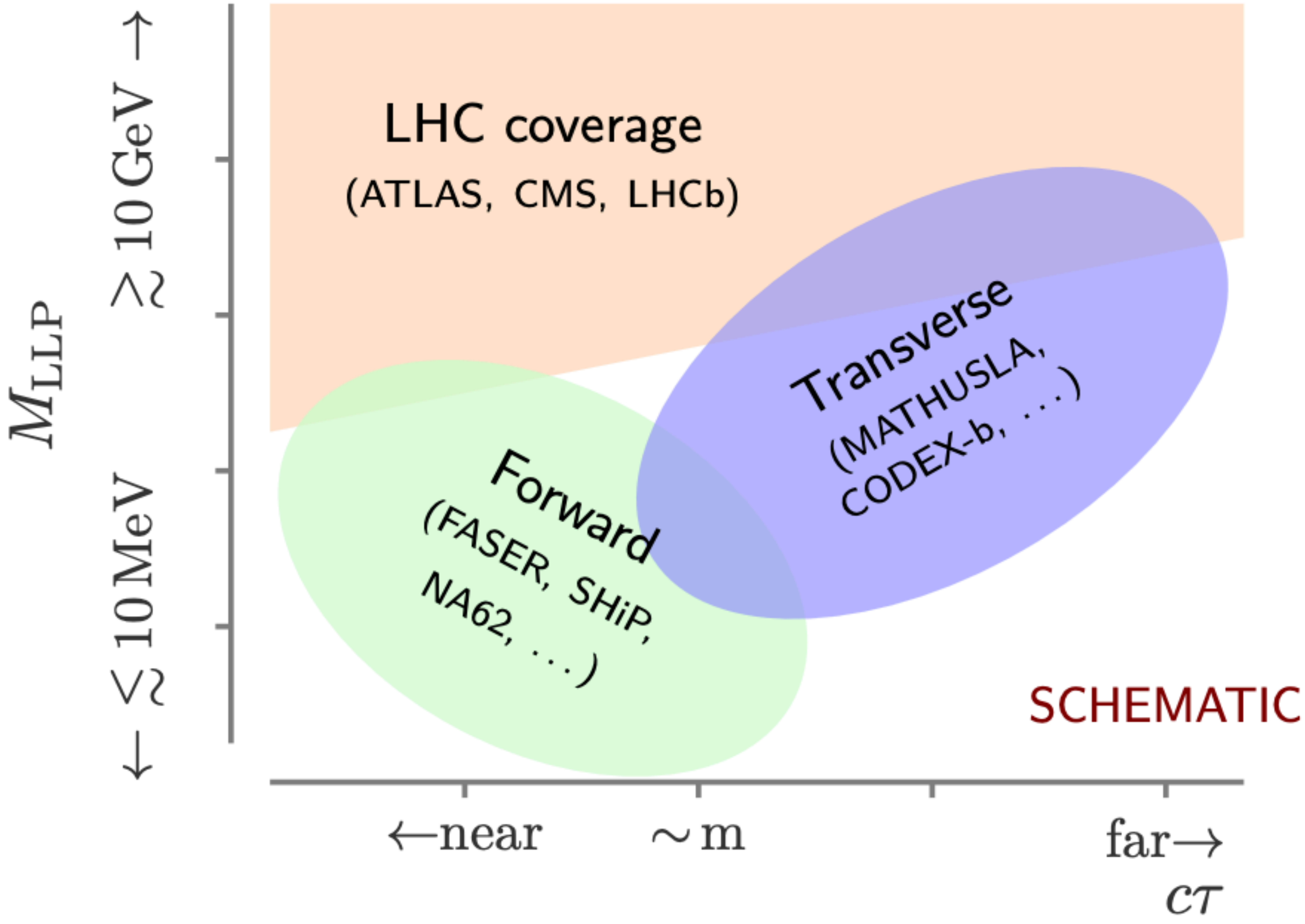
- Can also use the LHC collisions to look for long lived particles

FASER



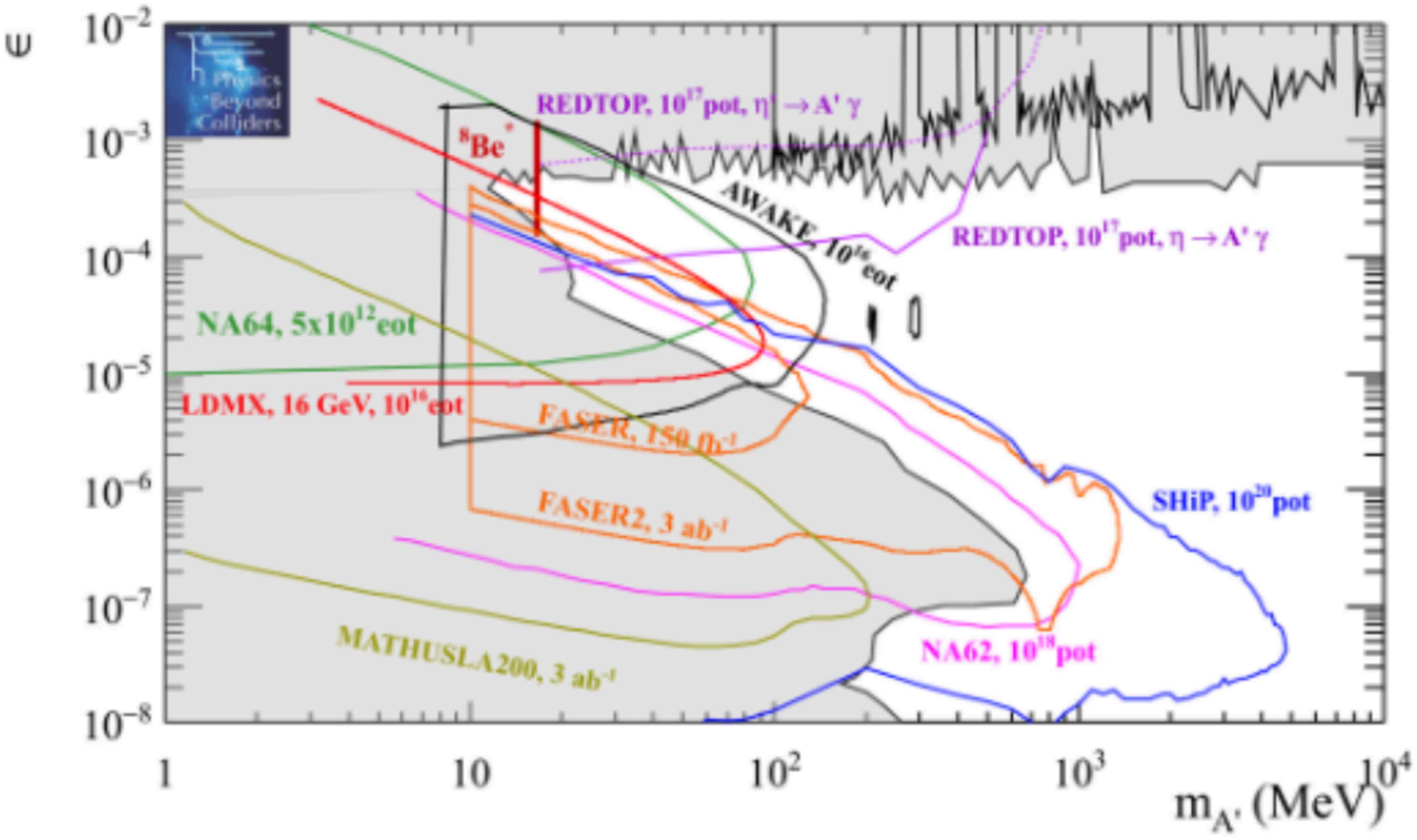
- FASER is a small detector along the beam near ATLAS
  - Can also look for collinear dark photons of ATLAS collisions

@LHC



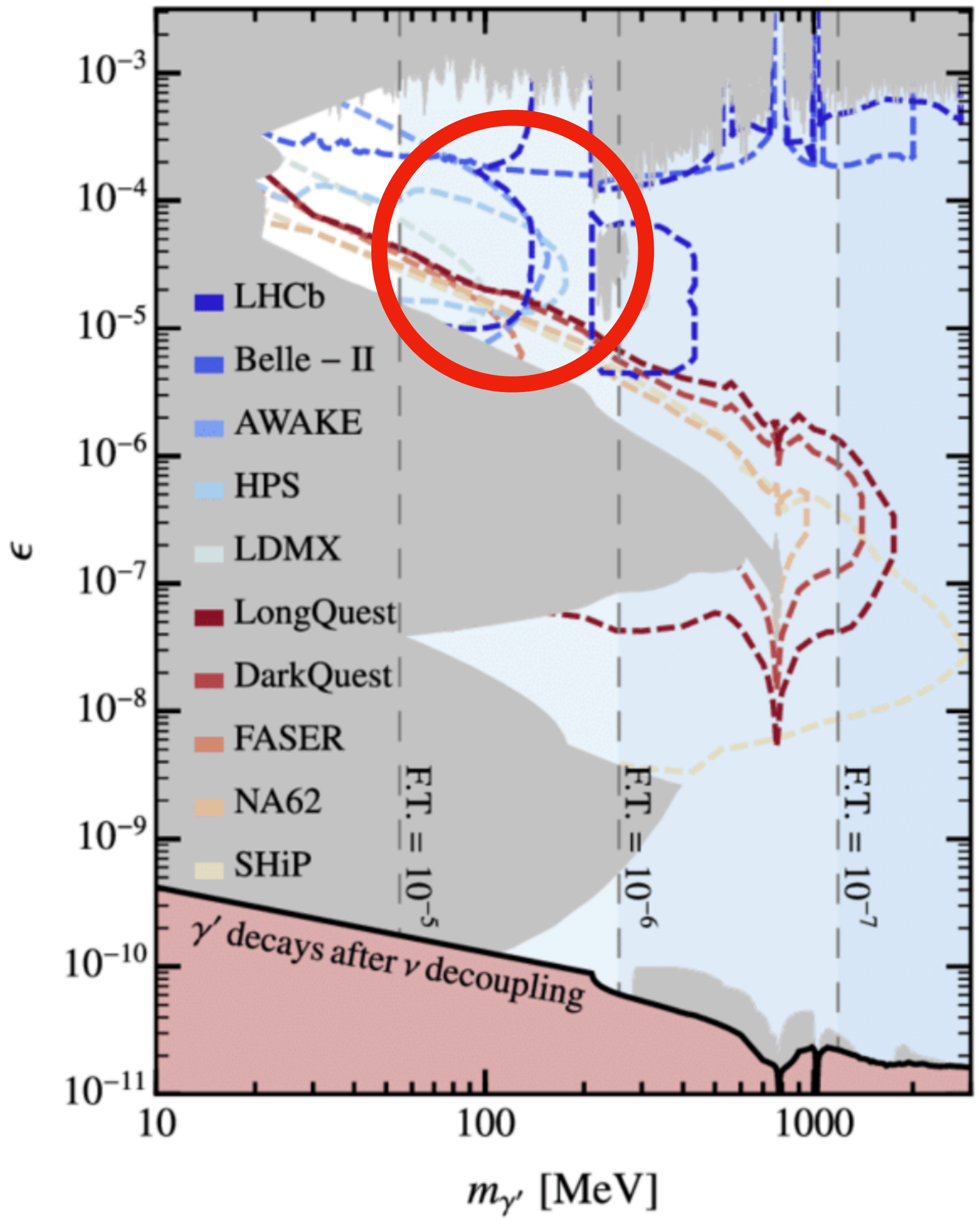
- LHC long lived experiments probe very high COM collisions
  - There are many other things we can explore (see later)

LHC on Dark Photon



- FASER probes similar region to DarkQuest
    - Mathusla bounds are not as sensitive as older experiments

Putting it All Together



Region where the relic is approximately satisfied

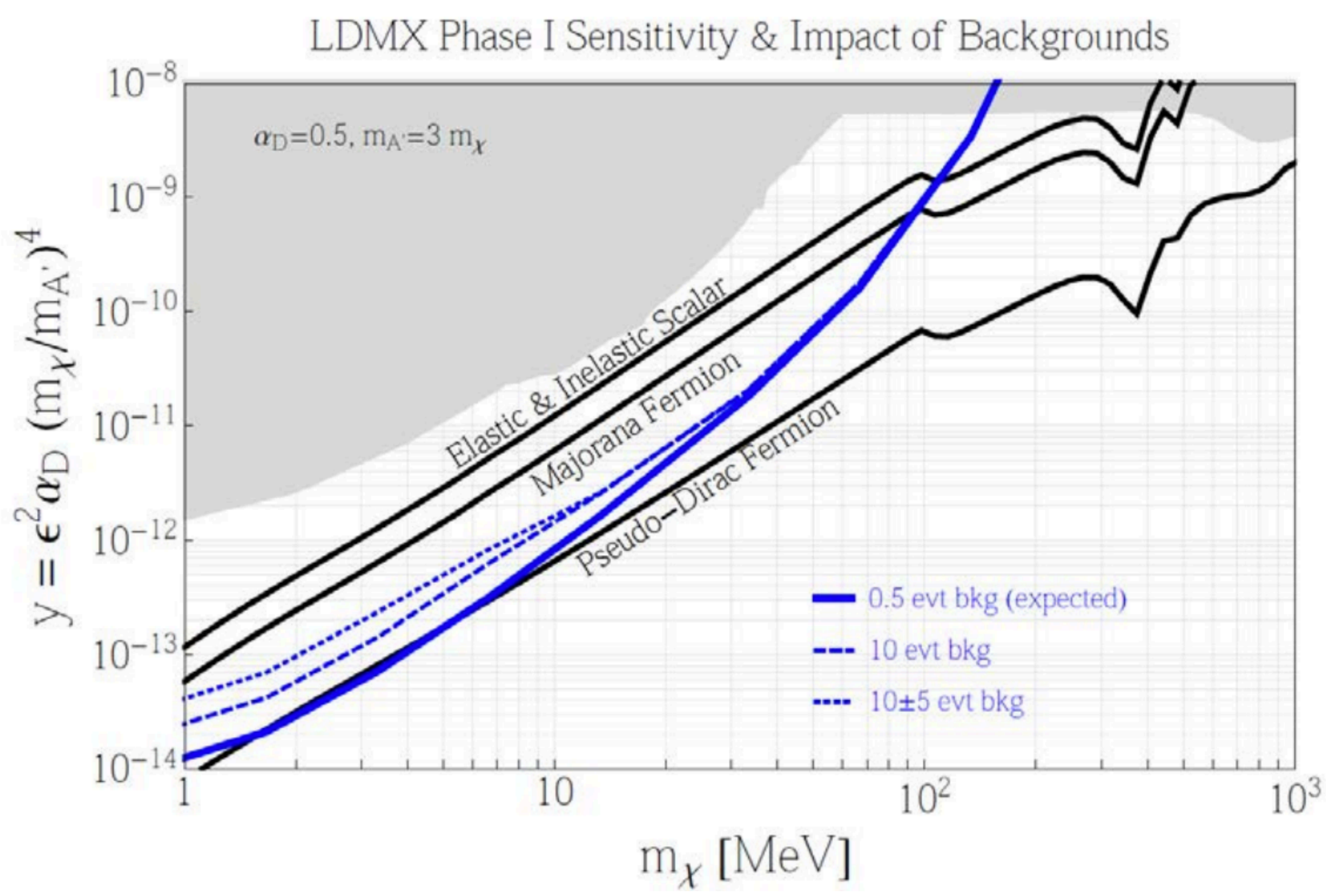
Overall each experiment covers slightly different territory

Its very hard to have a light dark photon with mass below 10 MeV

Broad range of different experiments all contribute

- Expect the most interesting region to be measured soon
    - Most projected experiment lines shown are likely to run

Putting it All Together



Invisible searches

experment overs slightly different

to have a light dark photon
low 10 MeV

range of different
nents all contributie

- Expect the most interesting region to be measured soon
  - Most projected experiment lines shown are likely to run

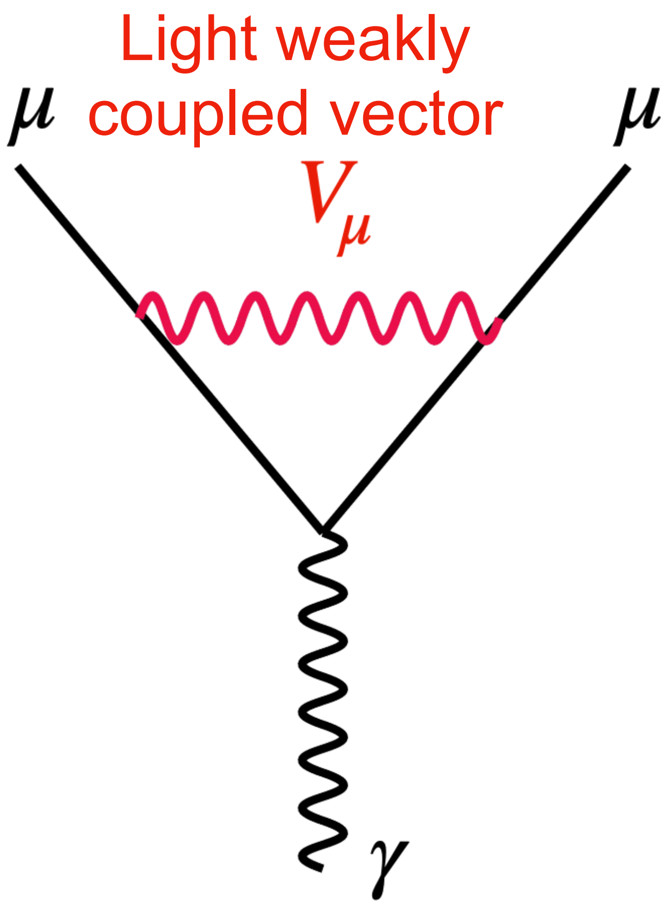
A hypothetical

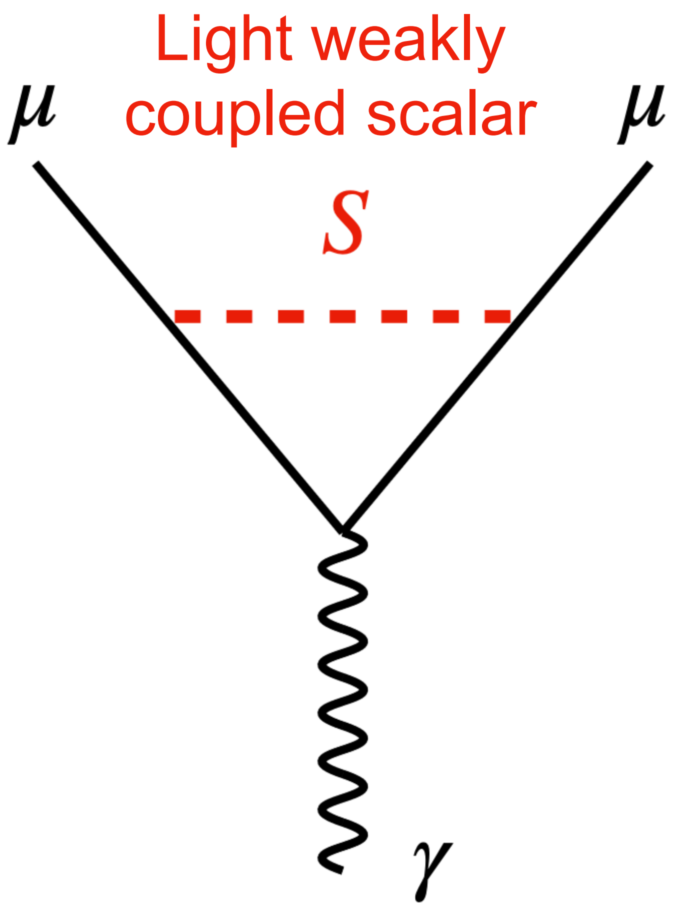
How do we find g-2?

A hypothetical Example

- With of the discussion of g-2 lets consider a simple model
  - Lets try to explain how to search for DM that solves g-2

Two Simple Explanations

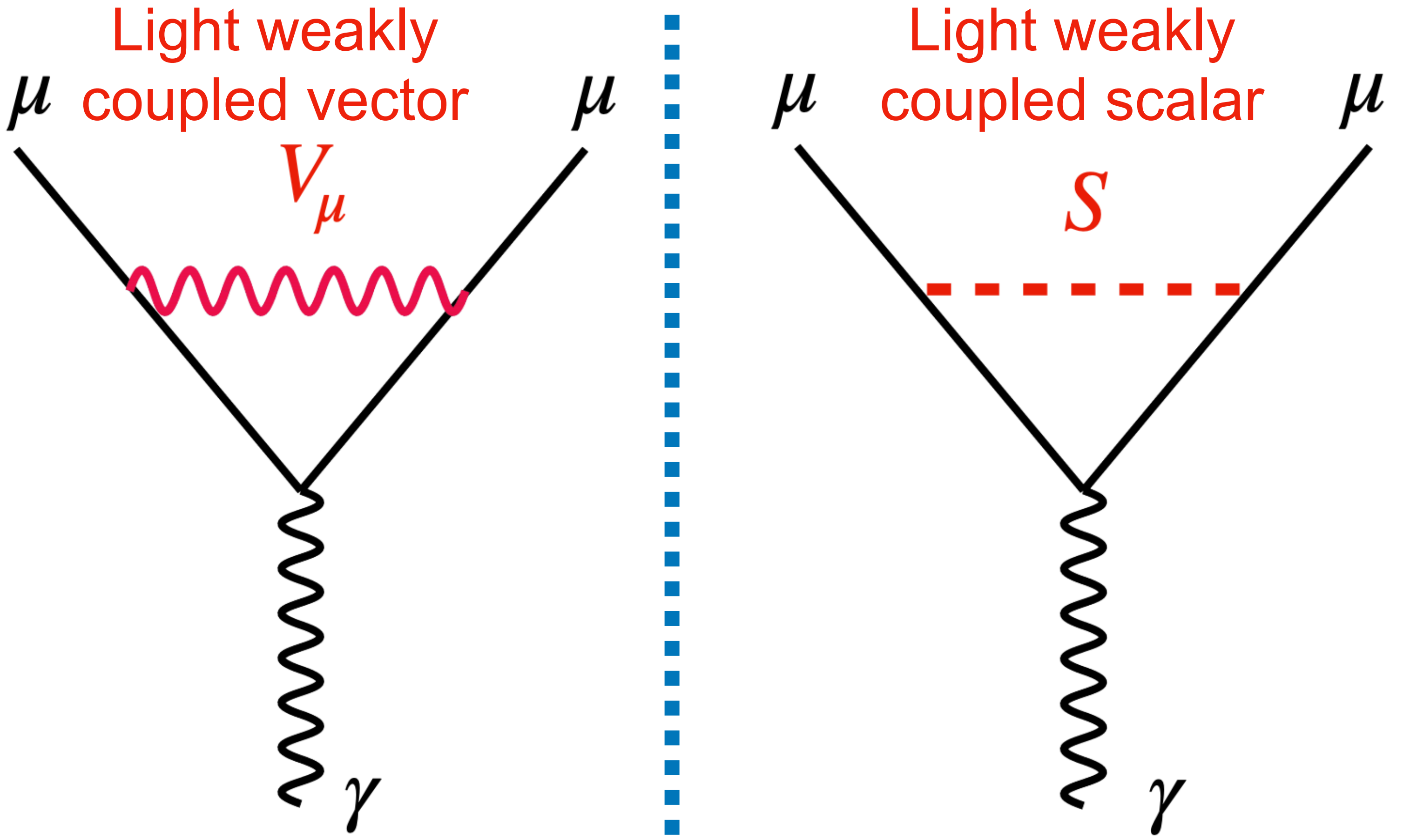




A hypothetical Example

- Discussion Question?
  - What are the different ways we can search for this guy

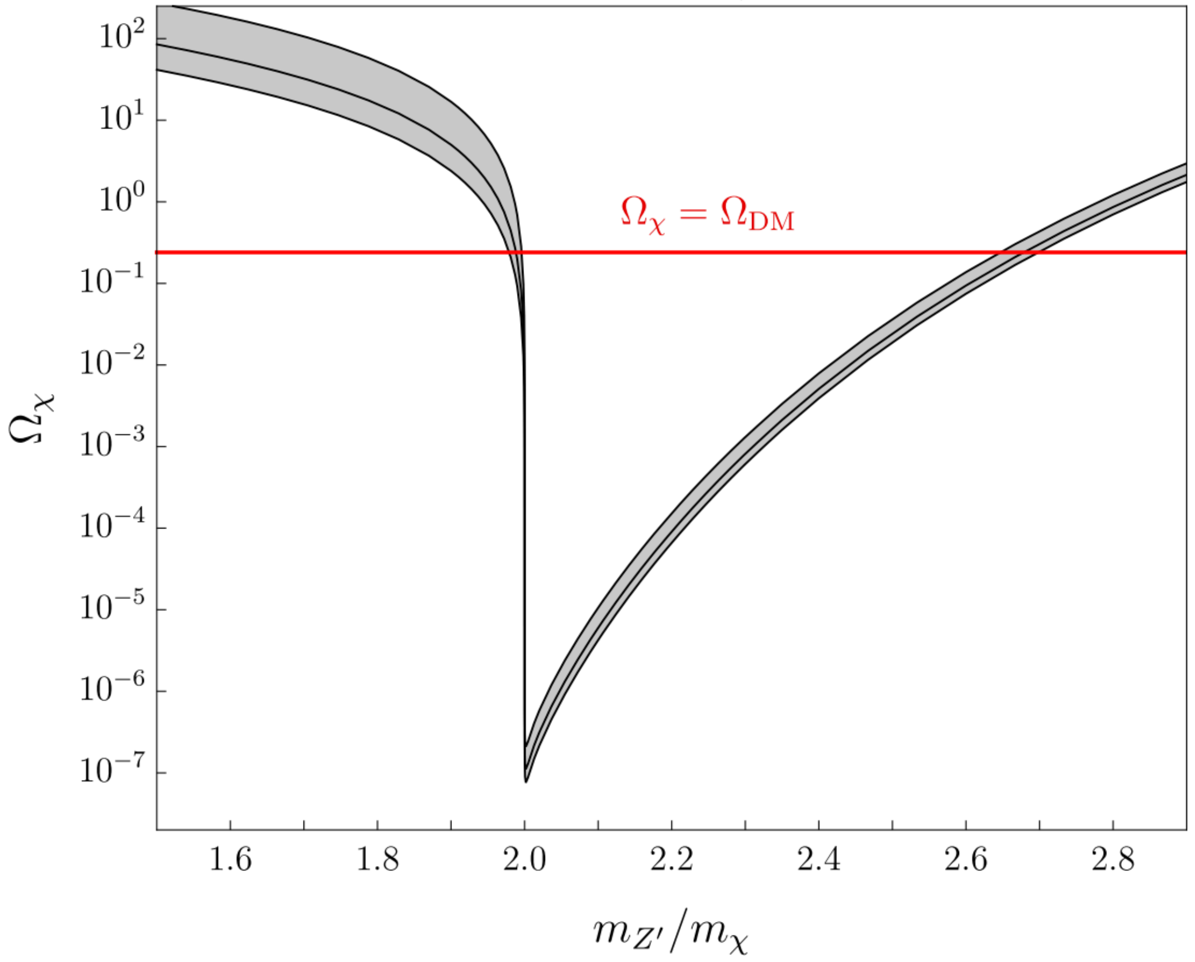
Two Simple Explanations



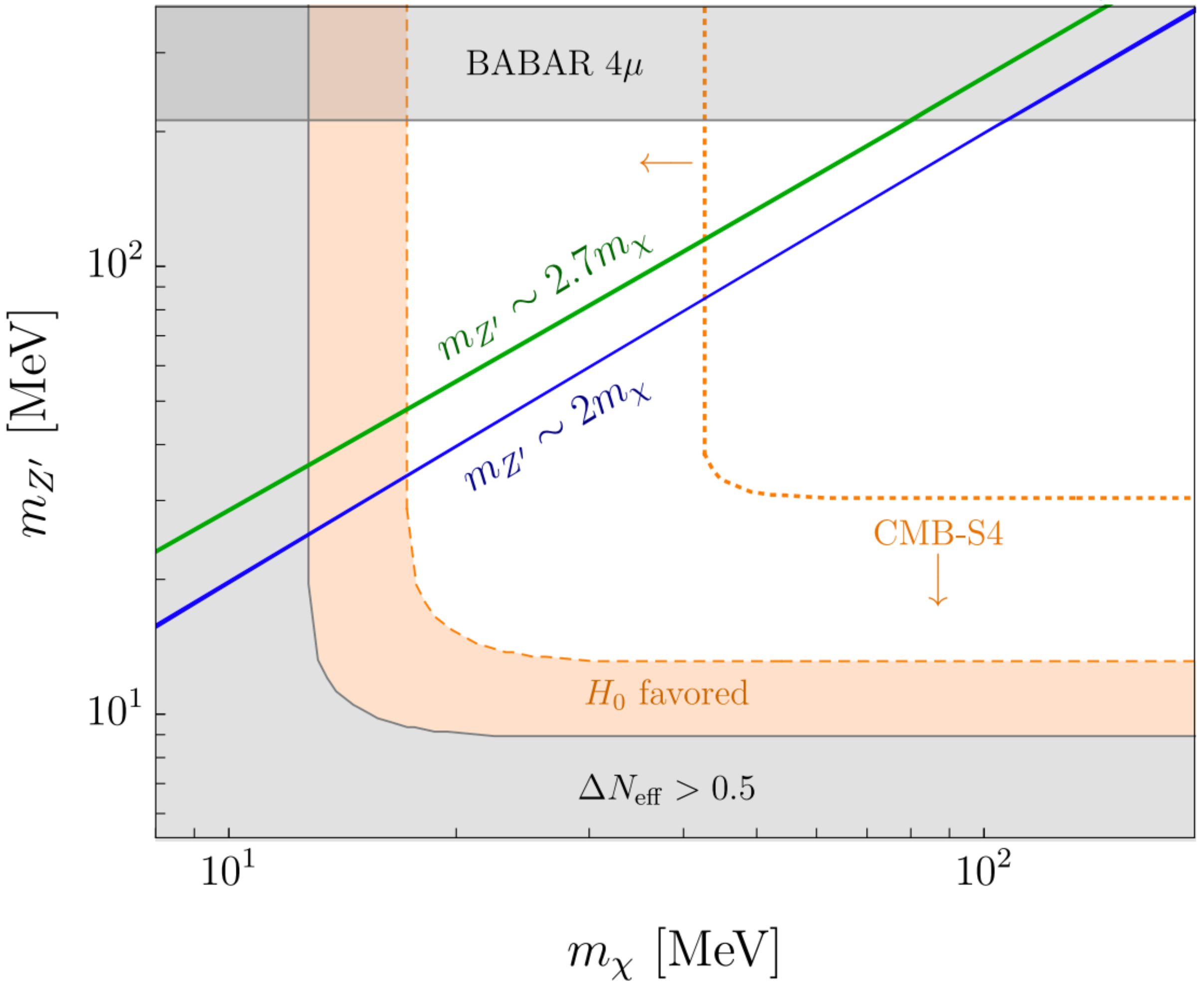
The impact of the g-2 deviation gives a measure of coupling

Some Model Constraints

- Before we develop an experiment:
  - Think about the constraints on g-2 that impact our measurement



Relic density for $m_\chi = 50$ MeV



Dirac DM relic density with g' that resolves Δa_μ

Mediator needs to be quite light ~100 MeV

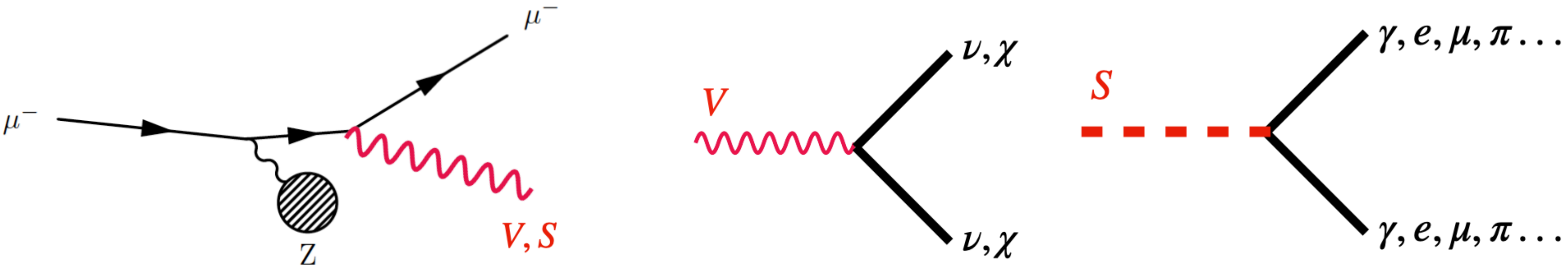
DM needs to be lighter to satisfy the relic density

A rubric of final states

	Invisible			**Visible**			
final state/ mediator	Long-lived	neutrinos $\nu\nu$	DM $\chi\chi$	photons $\gamma\gamma$	electrons e^+e^-	muons $\mu^+\mu^-$	hadrons $\pi\pi, \ldots$
vector							
scalar							
signature	missing momentum			prompt or displaced resonance			

Lets try to search for it

- What are some ways to find it?



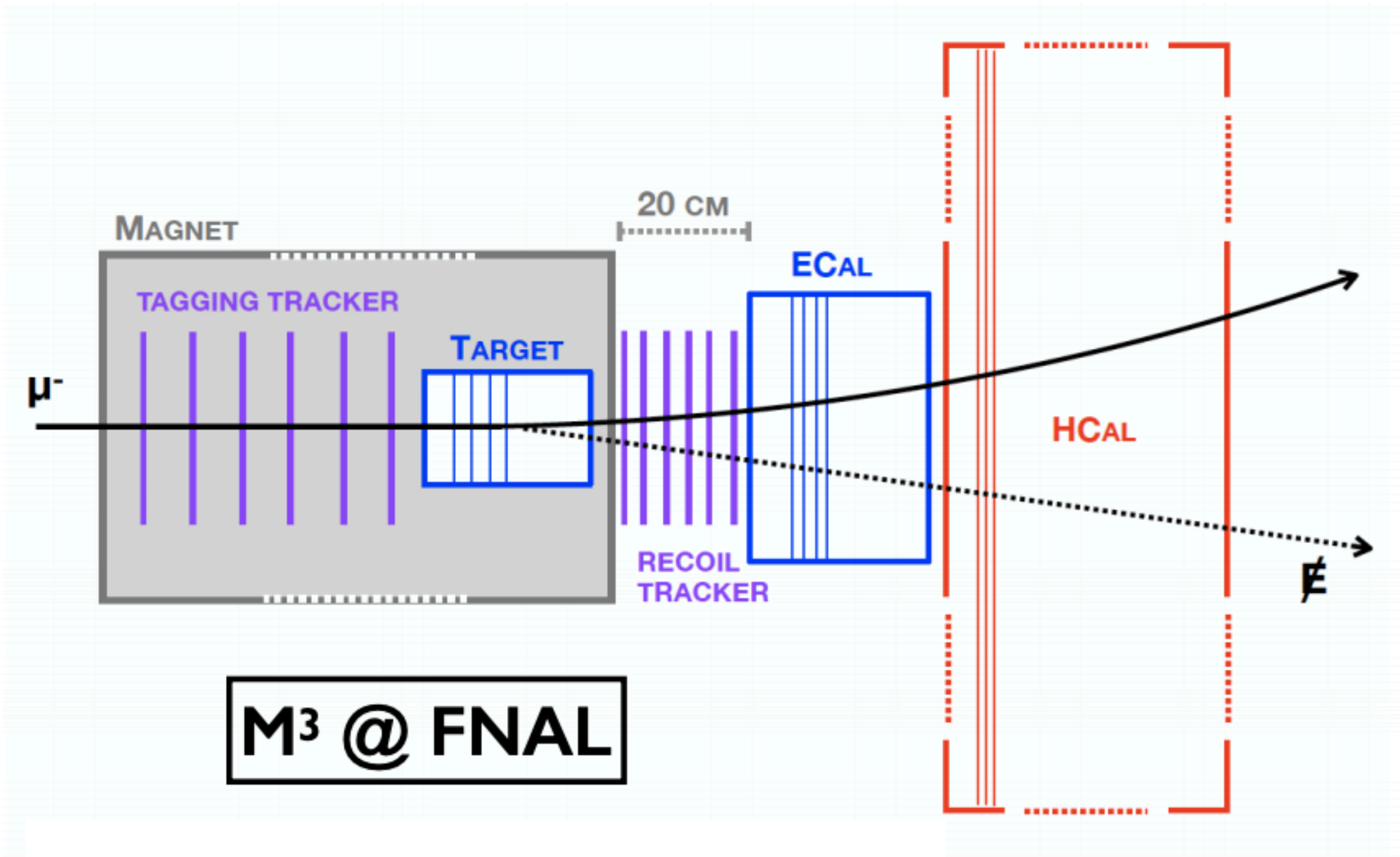
We can look for invisible decays when DM is light

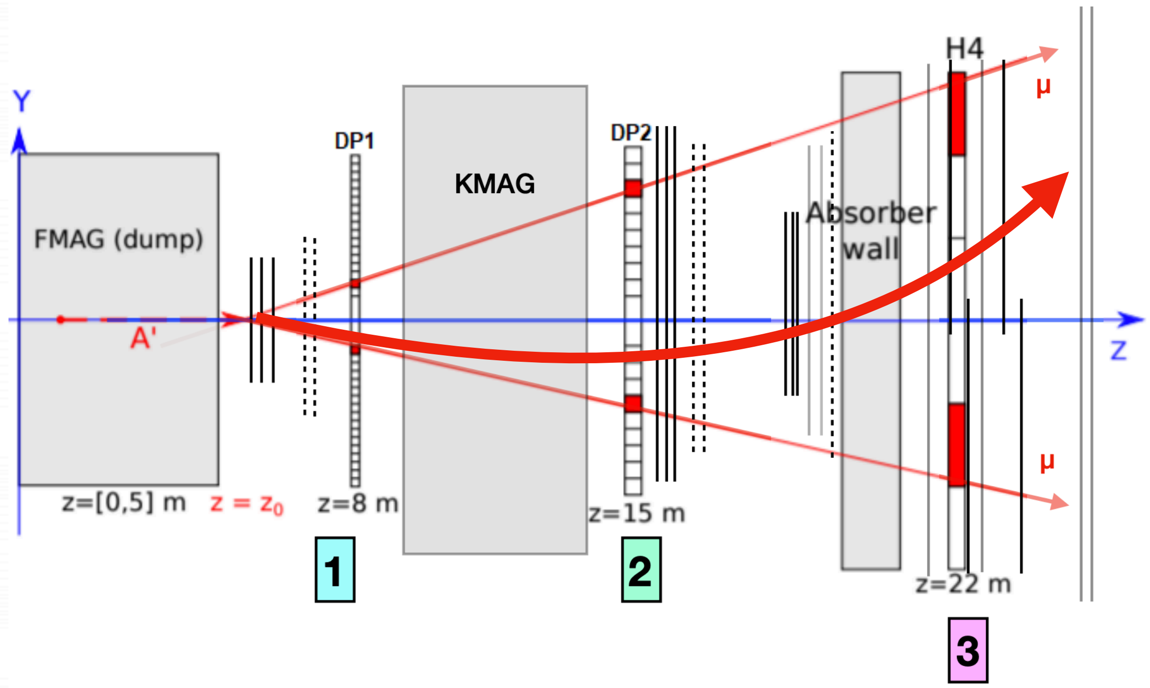
Can look for visible decays, this could be muons (minimal) or electrons/photons

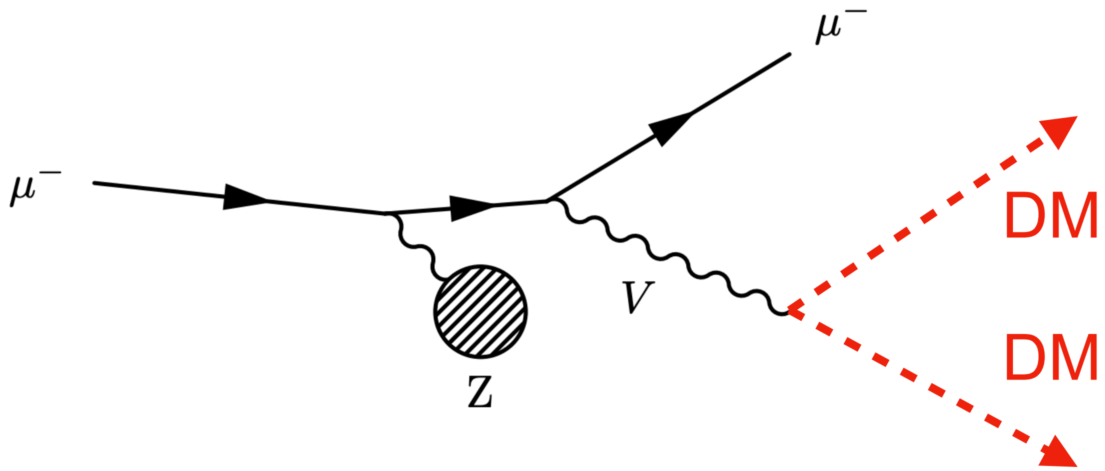
The key to all of this is being able to get a muon beam

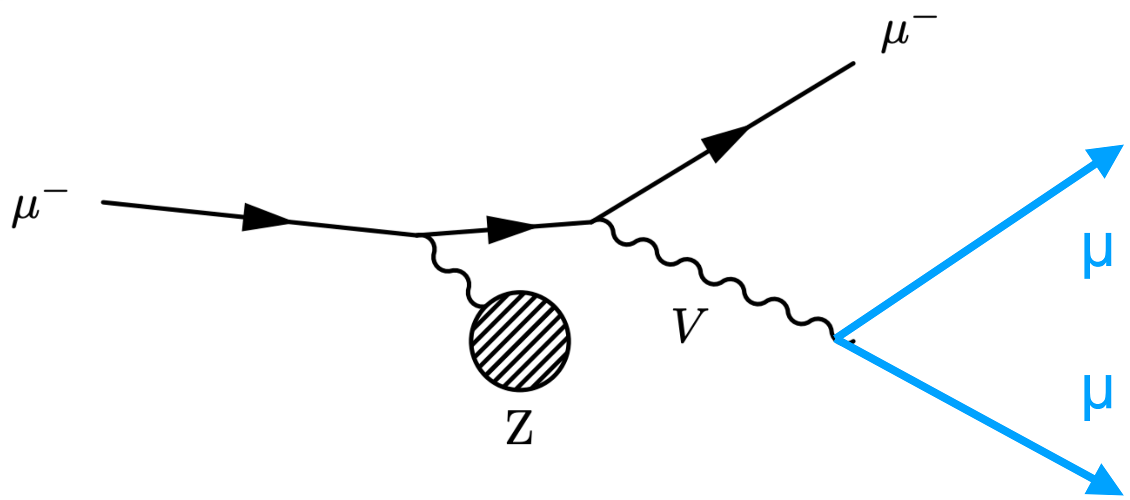
What do we do?

- Build a detector from a muon beam:



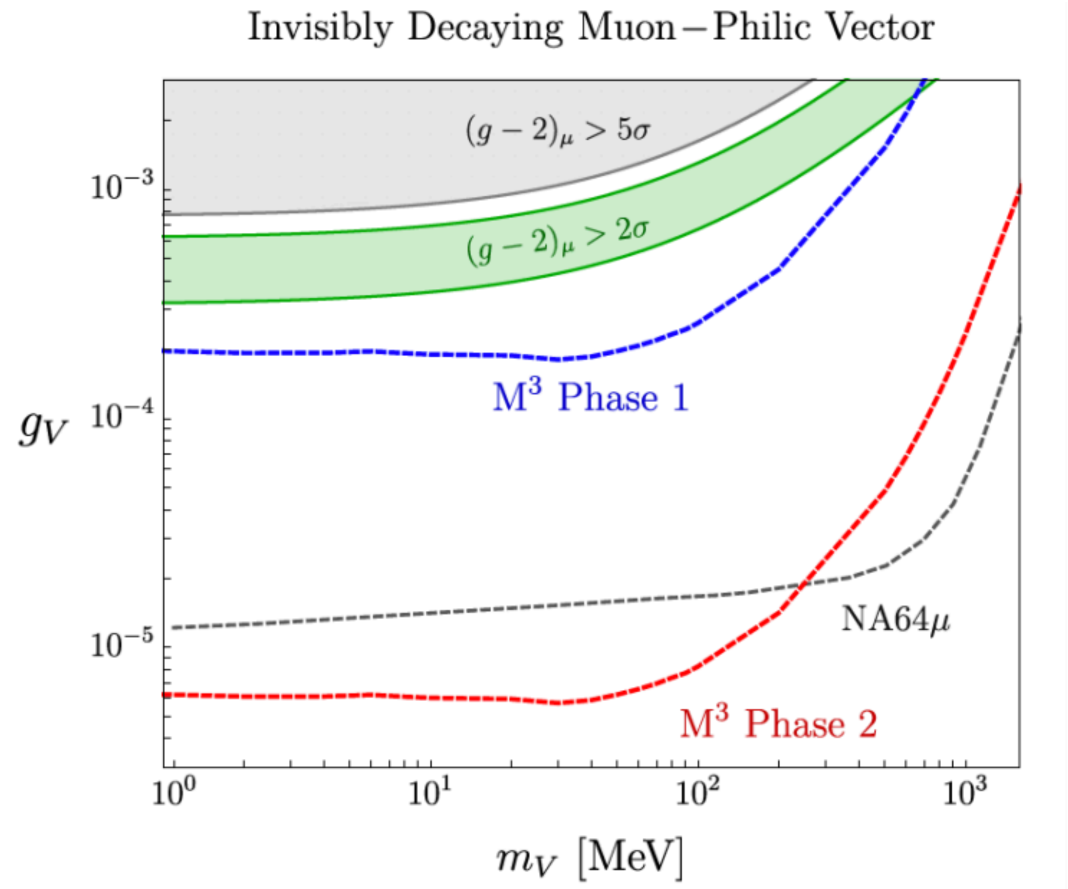


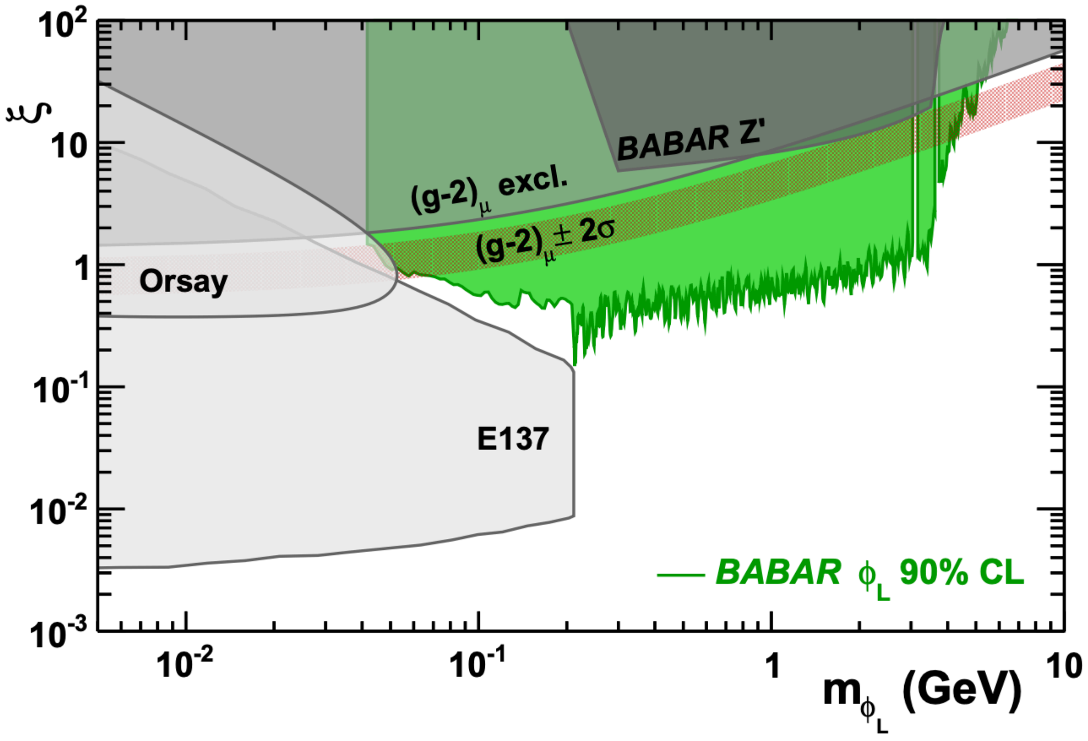


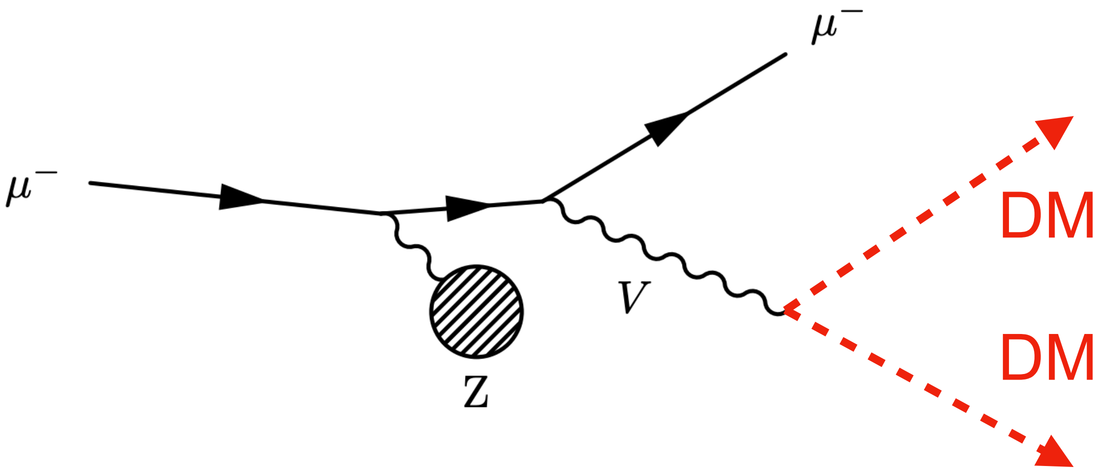


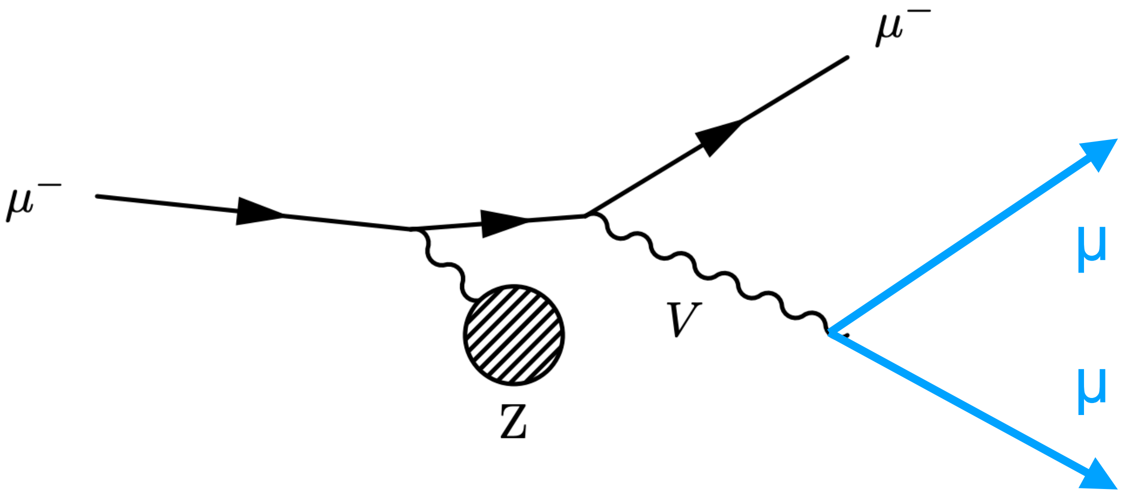
What do we do?

- Build a detector from a muon beam:









What do we do?

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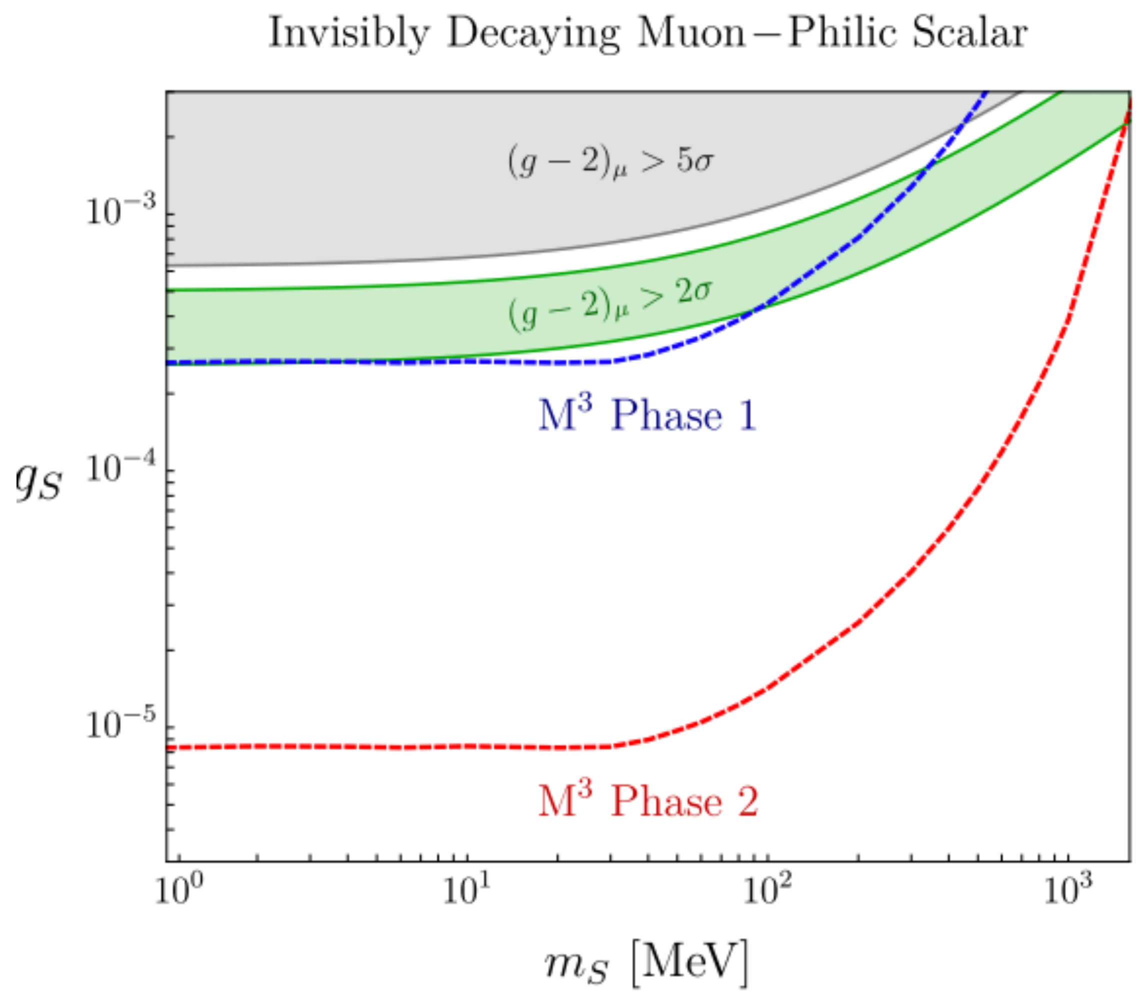
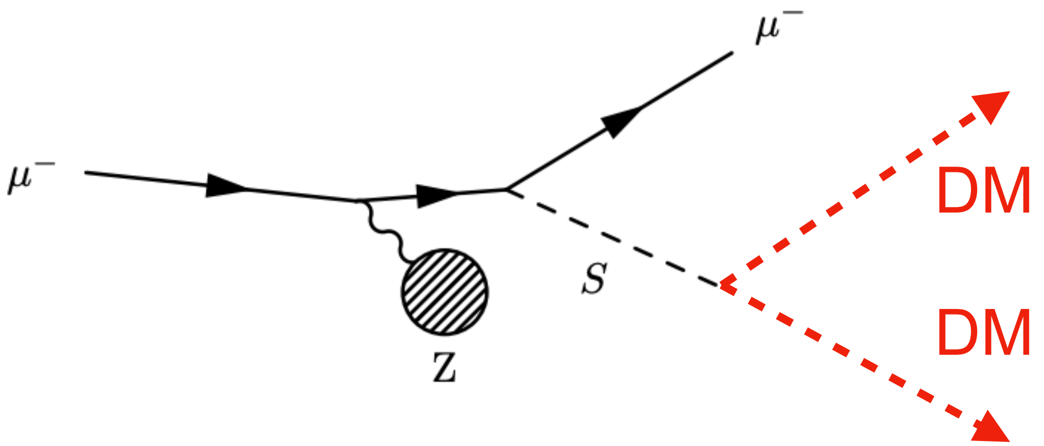
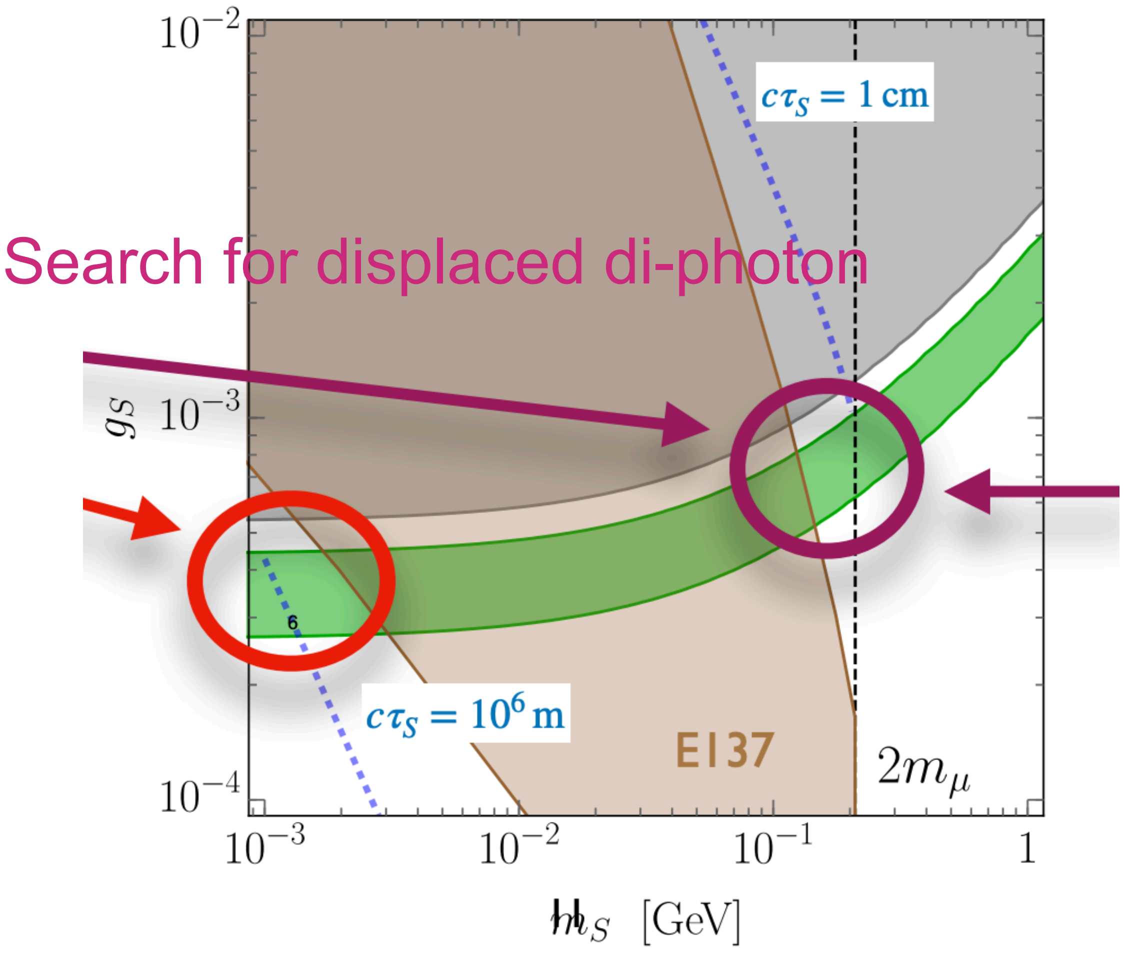
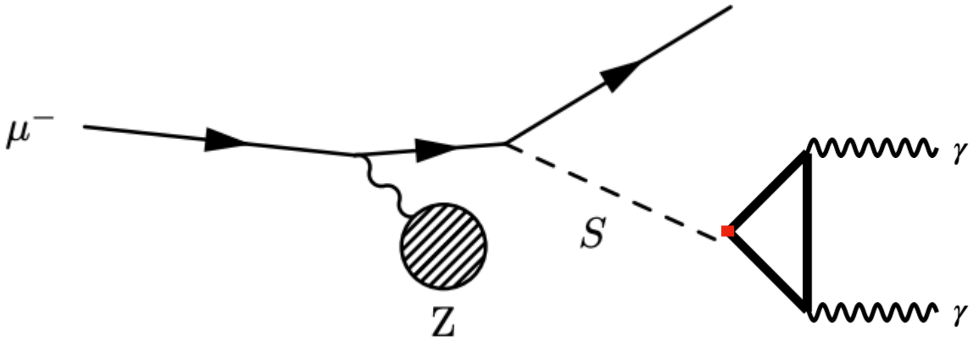






Search for displaced di-photon



Summary

- Given the diverse heavy mediator program at the LHC/ID/DD
    - We have largely constrained possibility of heavy DM
- This pushes Dark matter to have different types of signatures
    - Light dark matter with weaker couplings satisfies these rules
    - Super weak DM from freeze-in is another alternative
- Light dark matter has the advantage that it requires a small COM
    - However the weak coupling pushes light DM to intensity frontier
    - Many creative ways to probe for light DM models

Discussion Problem:

For SM decays, when is the coupling too small?

Thanks!

Dark Matter Density

- To get the current dark matter density:
  - Assume that dark matter density $\rho = m_{DM}n_{DM}$
  - Now lets consider the Hubble's constant
    - Noting the distance at freeze-out is $d = \dfrac{1}{n\sigma}$
    - and noting that $v = Hd \rightarrow H = \dfrac{v}{d} \propto v(n\sigma)$
- Now writing out the densities in terms of temperature
  - $\rho_i = \dfrac{\pi^2}{30} g^i T^4$ for relativistically moving particles (high temp)
  - $n_i = \dfrac{\zeta(3)}{\pi^2} g^i_{DM} T^3$ noting the number density is roughly $n_{DM} \propto e^{\frac{-m_{DM}}{T}}$

Expanding Further

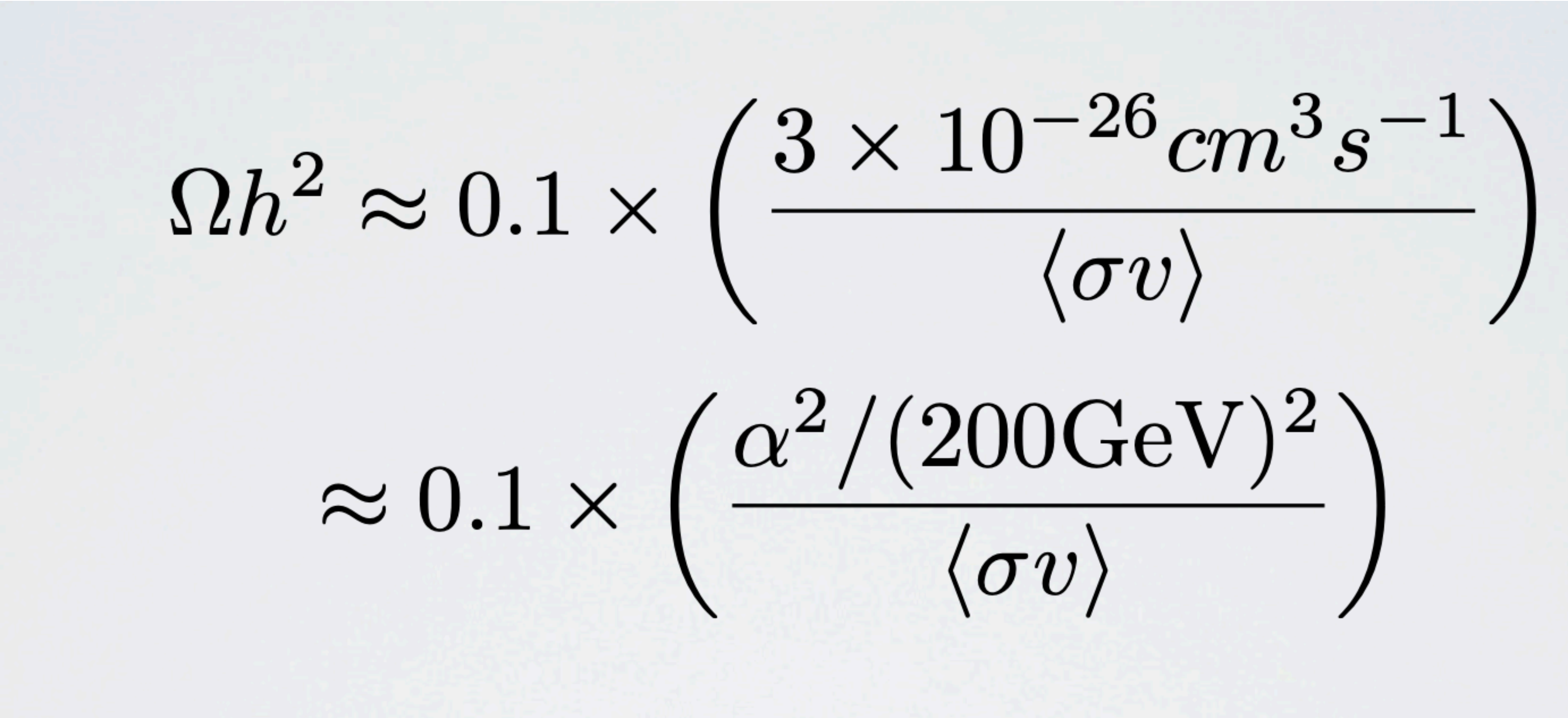
- Now from Friedmann's equations we have Hubble's constant
  - $H^2 = \frac{8\pi G_N}{3}\rho$
  - $\rho = \frac{\pi^2}{30} g_*(T) T^4 \rightarrow H^2 \simeq 1.66^2 g_*(T) \frac{T^4}{M_P^2}$
  - Now combining we have $n\sigma v \propto H \propto \frac{T^2}{M_{pl}} \rightarrow n_{DM} \propto \frac{T^2}{\langle \sigma v \rangle M_{pl}}$
- Now evolving this to current conditions we have
  - $\Omega h^2 \approx \left(\frac{\frac{\alpha^2}{200 \text{ GeV}}}{\langle \sigma v \rangle} \right) = \left(\frac{3 \times 10^{-26} \text{cm}^2/\text{s}}{\langle \sigma v \rangle} \right)$

Expanding Further

- Now from Friedmann's equations we have Hubble's constant
    - $H^2 = \frac{8\pi G_N}{3}\rho, \rho = \frac{\pi^2}{30} g_*(T) T^4 \to H^2 \simeq 1.66^2 g_*(T) \frac{T^4}{M_P^2}$
    - Now combining we have $n\sigma v \propto H \propto \frac{T^2}{M_{pl}} \to n_{DM} \propto \frac{T^2}{\langle \sigma v \rangle M_{pl}}$
- So we have taking the ratio of photon to matter constant $\frac{n_{DM}}{n_\gamma} \approx C$
    - $\frac{n_\gamma^f}{n_{DM}^f} \propto \frac{1}{\langle \sigma v \rangle T M_{pl}} = \frac{1}{\langle \sigma v \rangle m_{DM} M_{pl}}$
    - $\frac{n_\gamma^{now}}{n_{DM}^{now}} \propto \frac{1}{\langle \sigma v \rangle m_{DM} M_{pl}} \to \rho_{DM}^{now} = \frac{T^3}{\langle \sigma v \rangle M_{pl}}$

Dark Matter Density

- Gets us to a standard formula for the dark matter density



$$\Omega h^2 \approx 0.1 \times \left(\frac{3 \times 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle} \right)$$

$$\approx 0.1 \times \left(\frac{\alpha^2/(200\mathrm{GeV})^2}{\langle \sigma v \rangle} \right)$$

So the right dark matter density (0.12) corresponds to a
200 GeV mass for SM like coupling