Dark Matter@ Accelerators Lecture 4

P.Harris

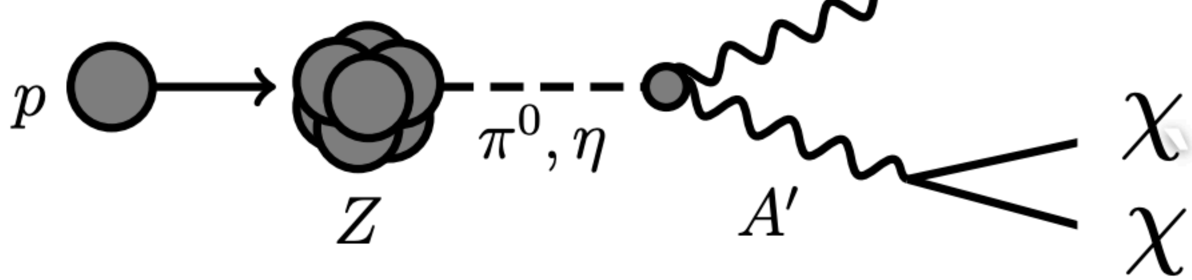
Anomalous DM Models+LHC Future

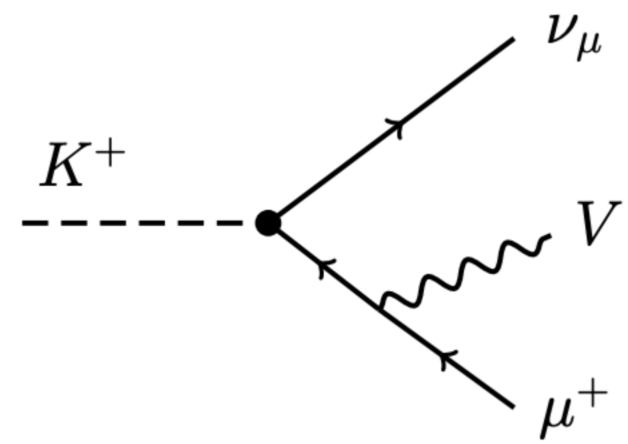
P. Harris

This Lecture

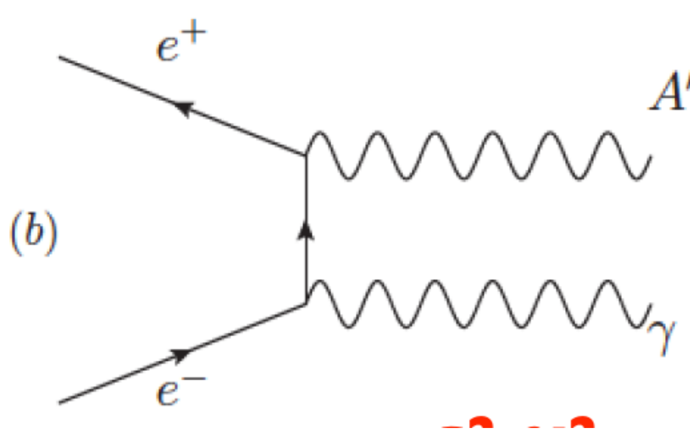
- Last Lecture we went to the wild world of low mass DM
  - Learned about many new and exciting ways to search for DM
    - Out of this emerged a picture of signatures
    - Also we are starting to think about the dark sector
- This lecture we ask what is going to become of the future
  - How sensitive do we expect future experiments to be
  - Let’s deep dive into the crazy cooky world of the dark sector
    - If we have a rich dark sector, what can we do?
- Finally, lets recap everything

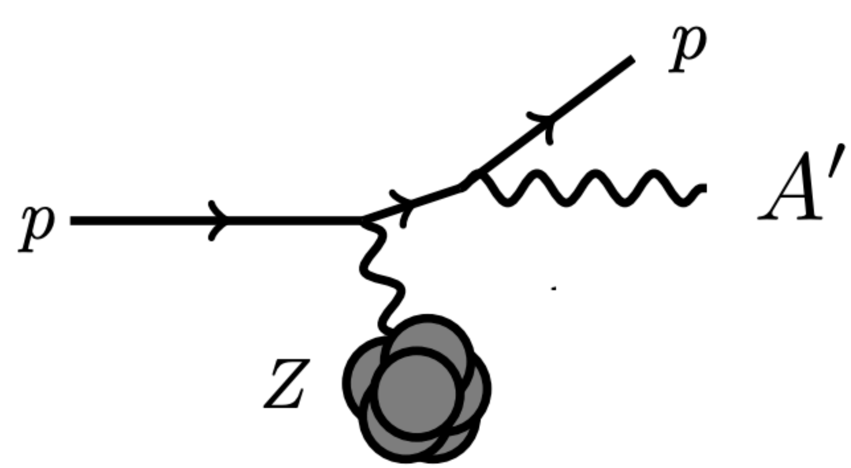
How do you produce a light particle?

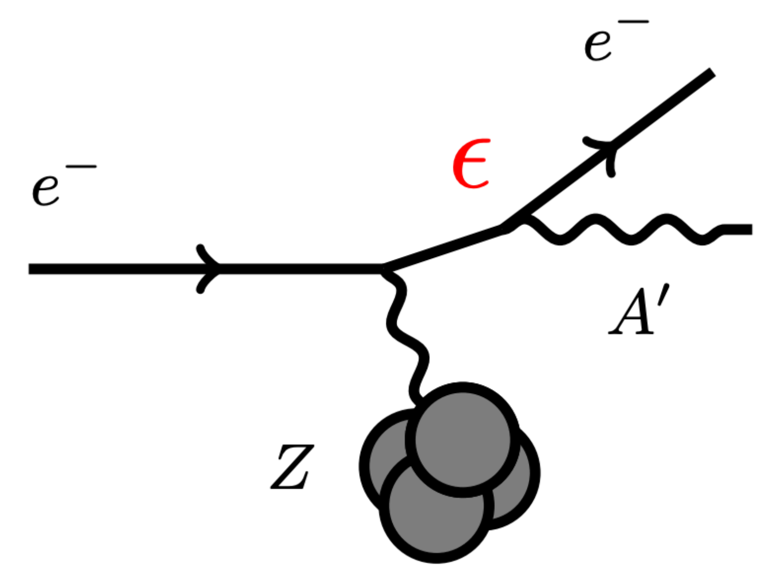




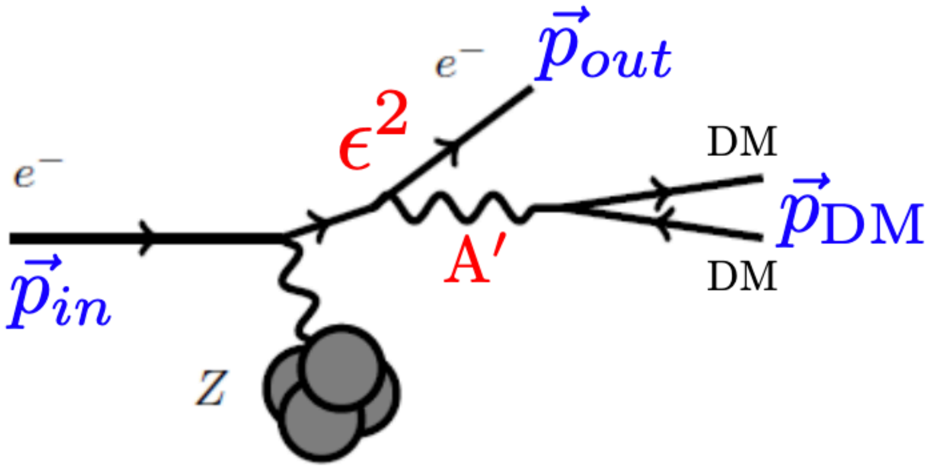
$$K^+ \to \mu^+ \nu_\mu V, \quad V \to \chi\chi$$



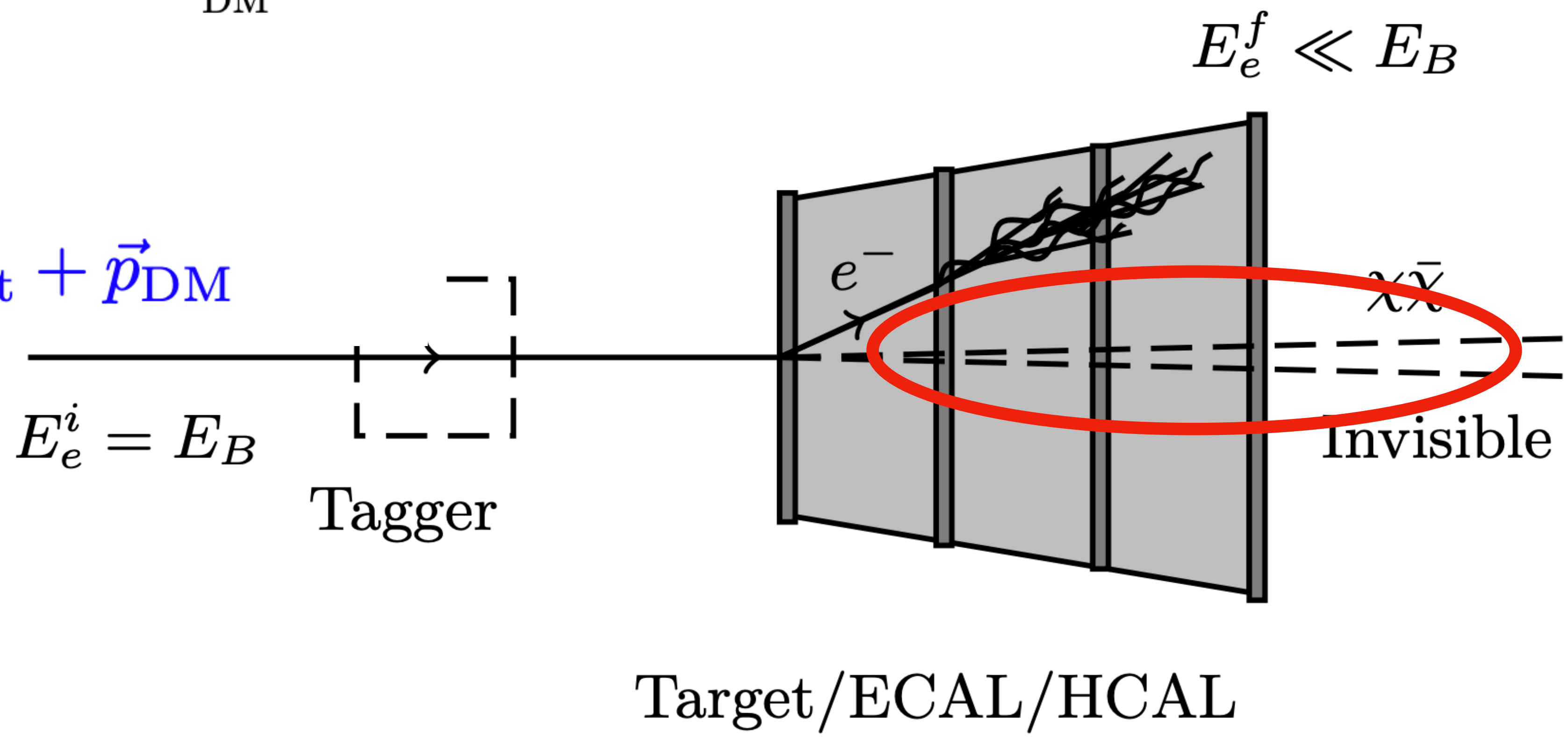




Missing Energy



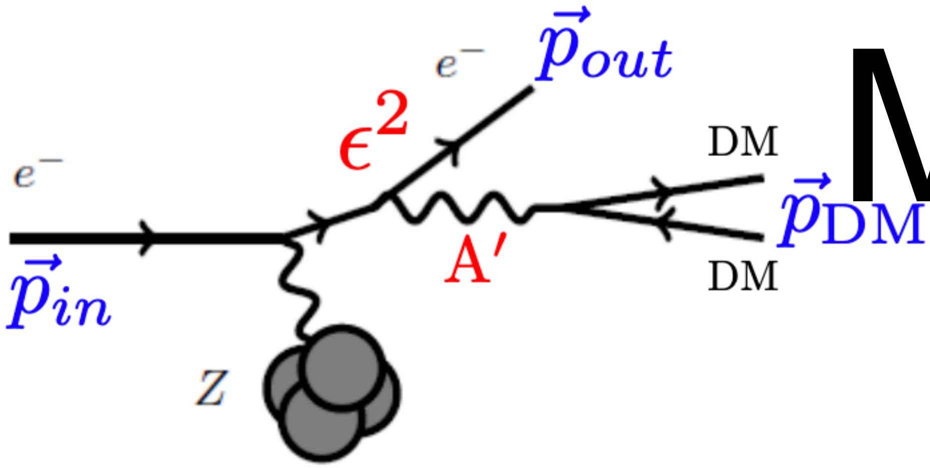
$$\vec{p}_{\rm in} = \vec{p}_{\rm out} + \vec{p}_{\rm DM}$$

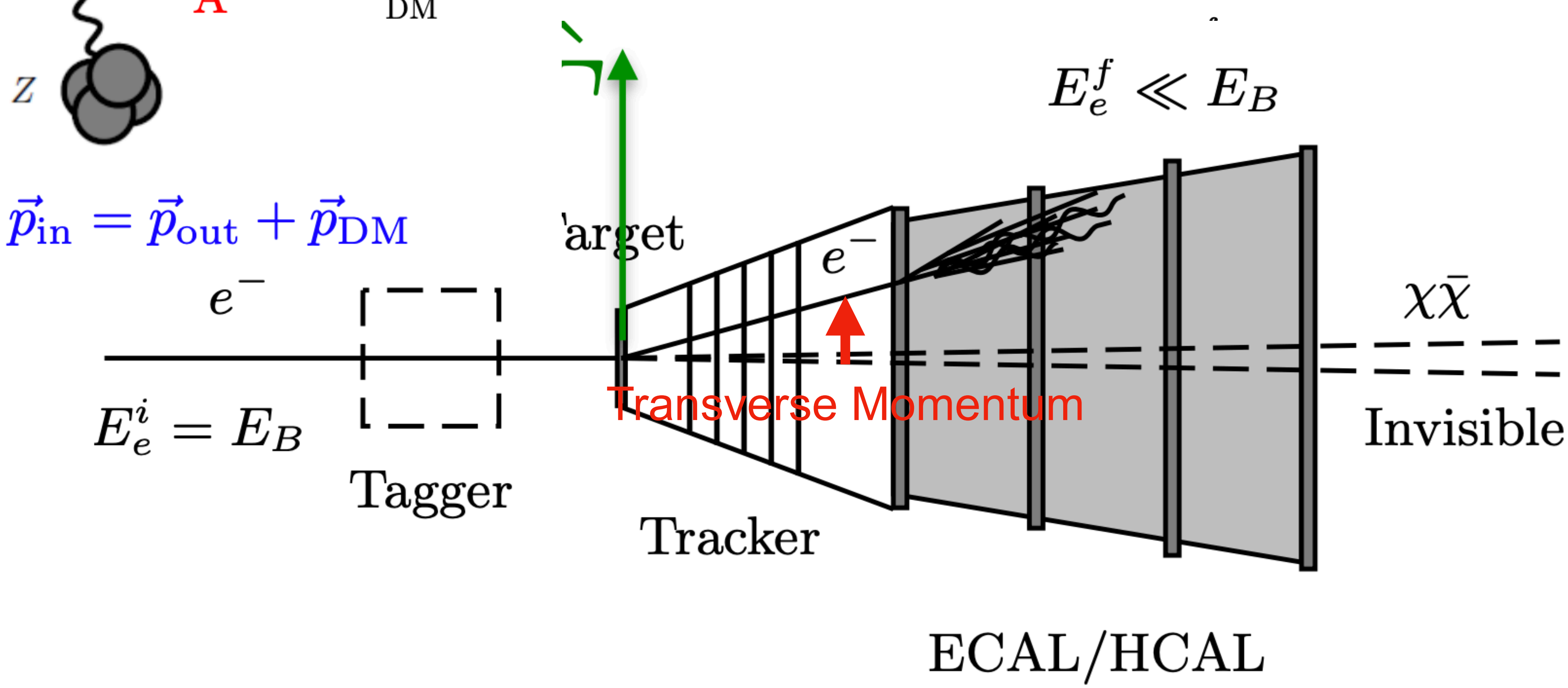


- Idea is to fire an electron on a target and measure energy
  - Clean signature if we ensure there is no visibly radiated object
  - Change in the energy will tell us we have radiated a dark photon

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

Missing Momentum





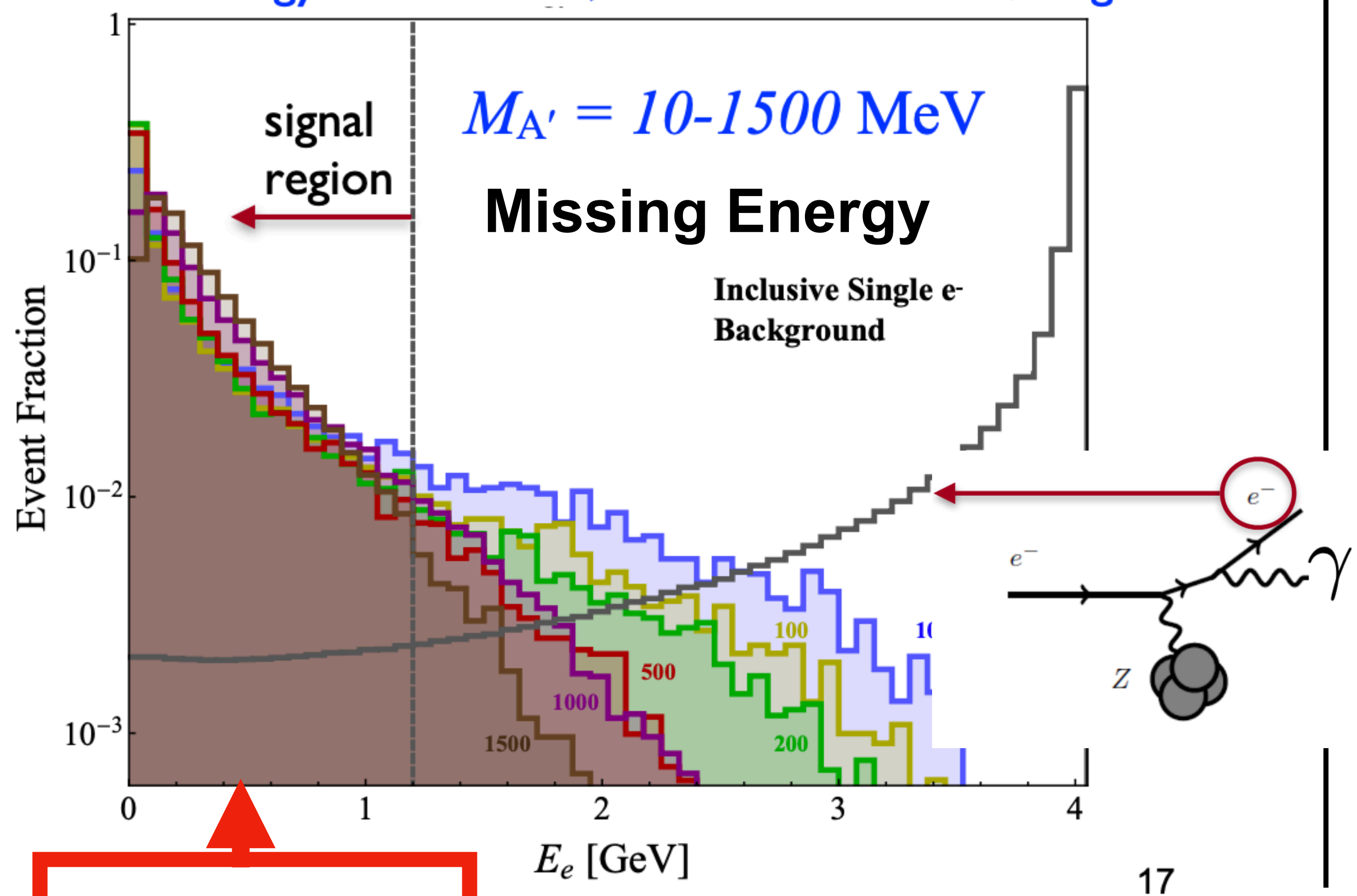
- Idea is to fire an electron on a target and measure momentum
  - On top of calorimeter, have a tracker that gives electron momentum
  - The addition of the tracker allows us to do e vs γ separation

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

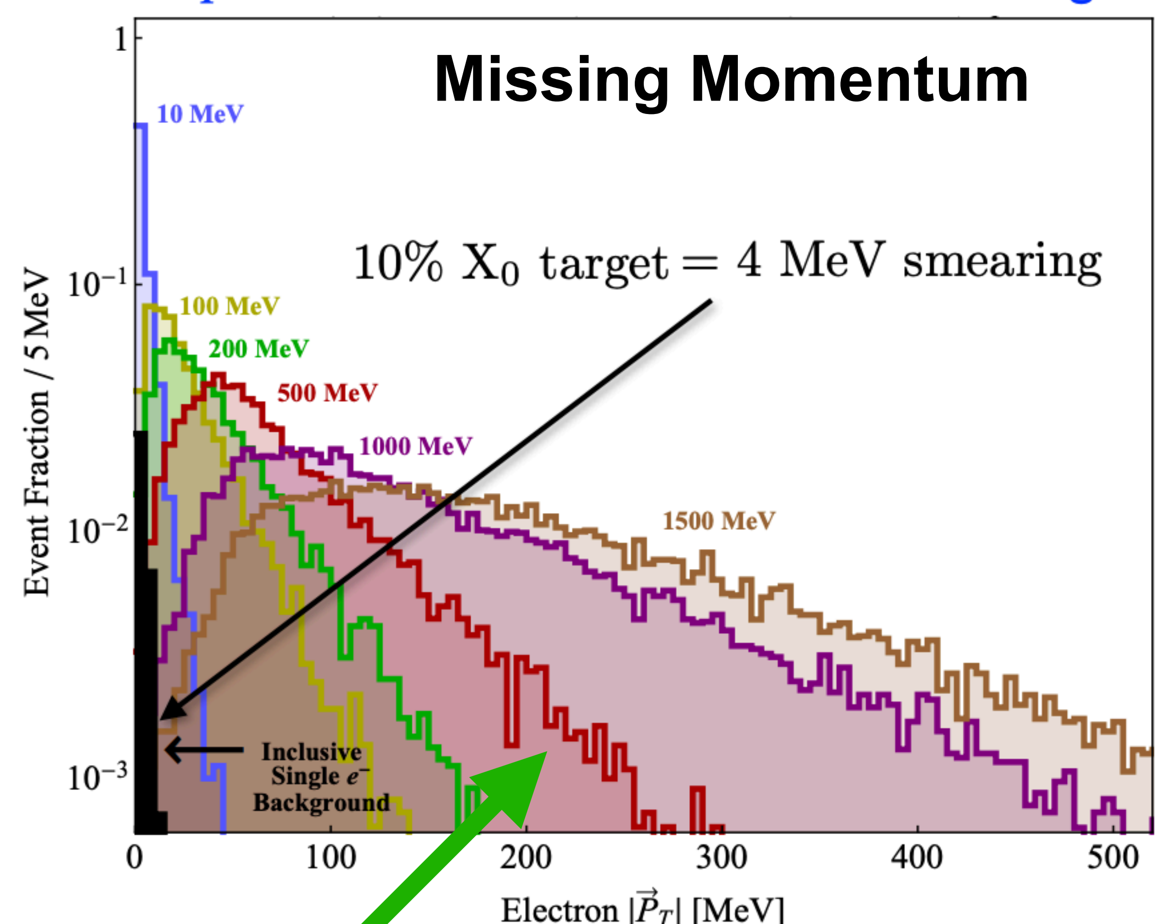
Transverse Momentum

Momentum vs Energy

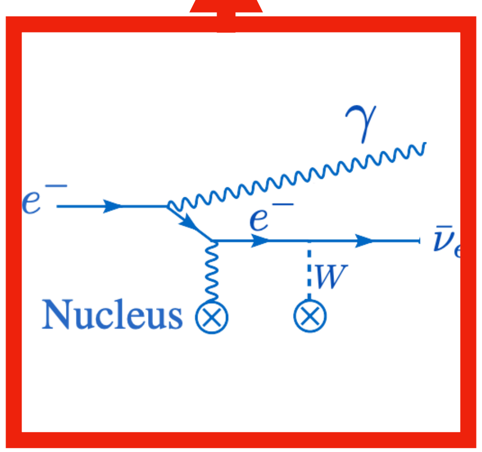
recoil energy distributions, 4 GeV e^- on 10% X_0 target



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



No Irreducible Background b/c of electron id



Irreducible Background

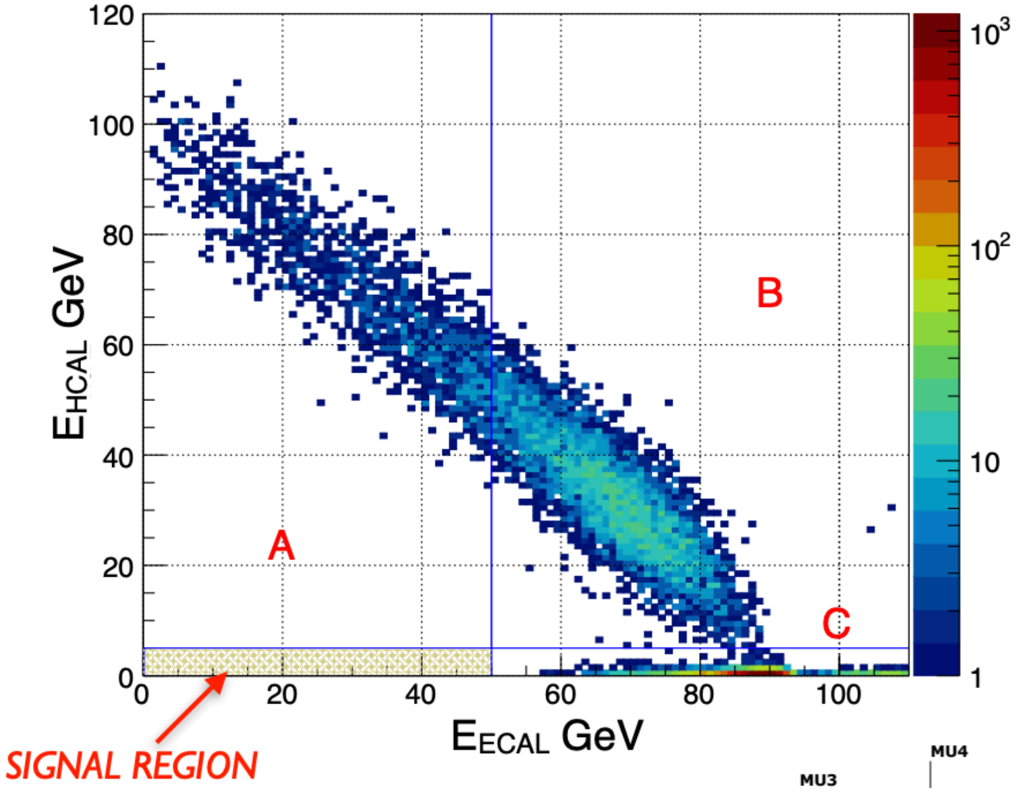
$$\frac{d\sigma}{dx} \propto \frac{\alpha^3}{\pi} \frac{\epsilon^2}{m_e^2 \cdot x + m_A^2 (1-x)/x}$$

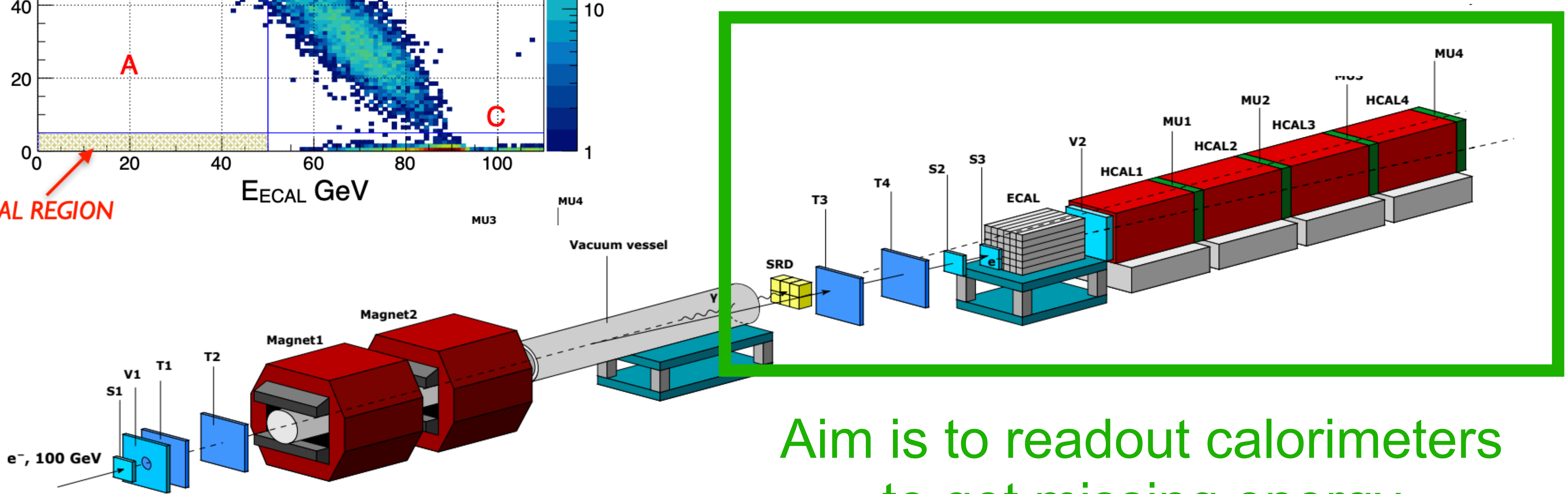
$$x = \frac{E_A}{E}$$

Kinematics **very different** from massless photon bremsstrahlung

Heavy object arries away the beam energy

Missing Energy Experiment: NA64

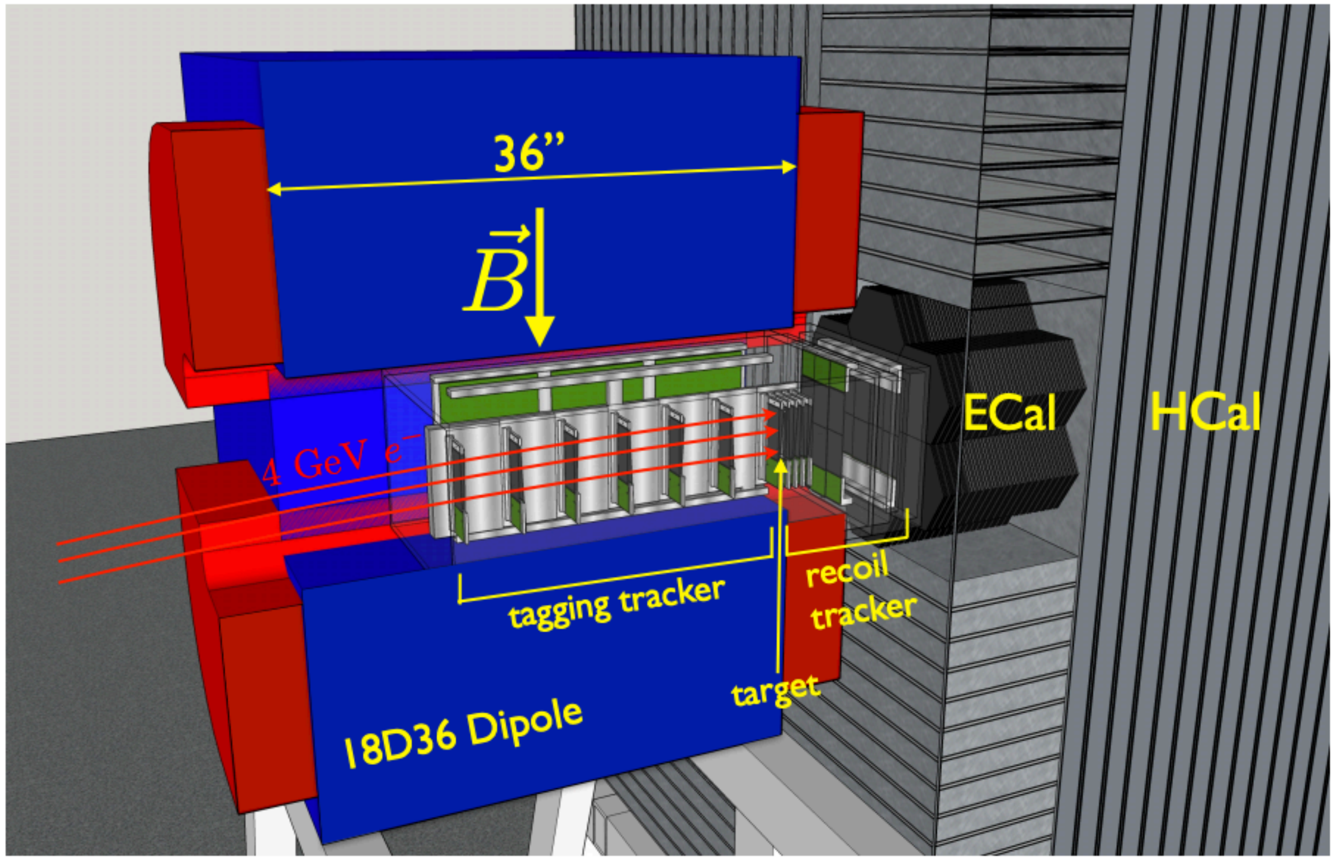


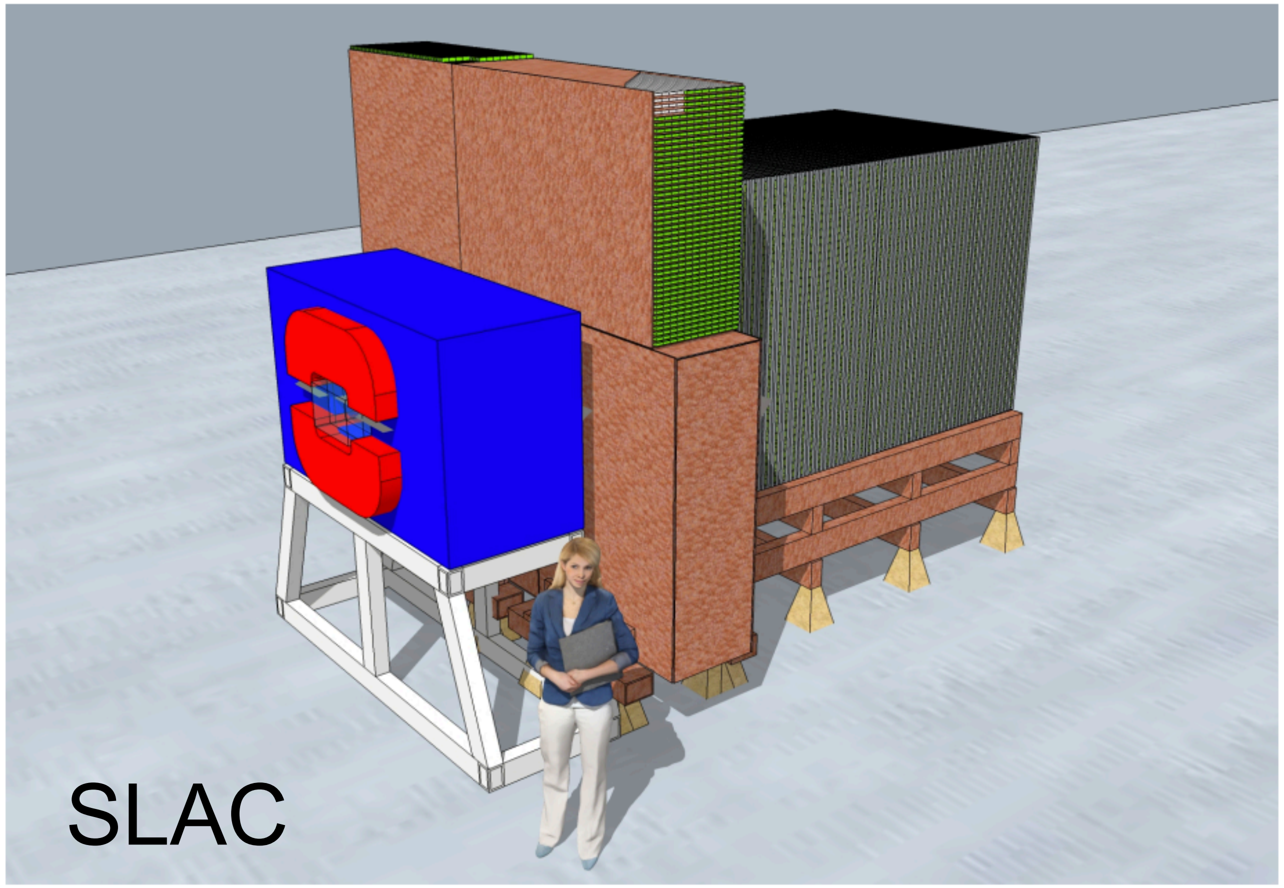


Aim is to readout calorimeters to get missing energy

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

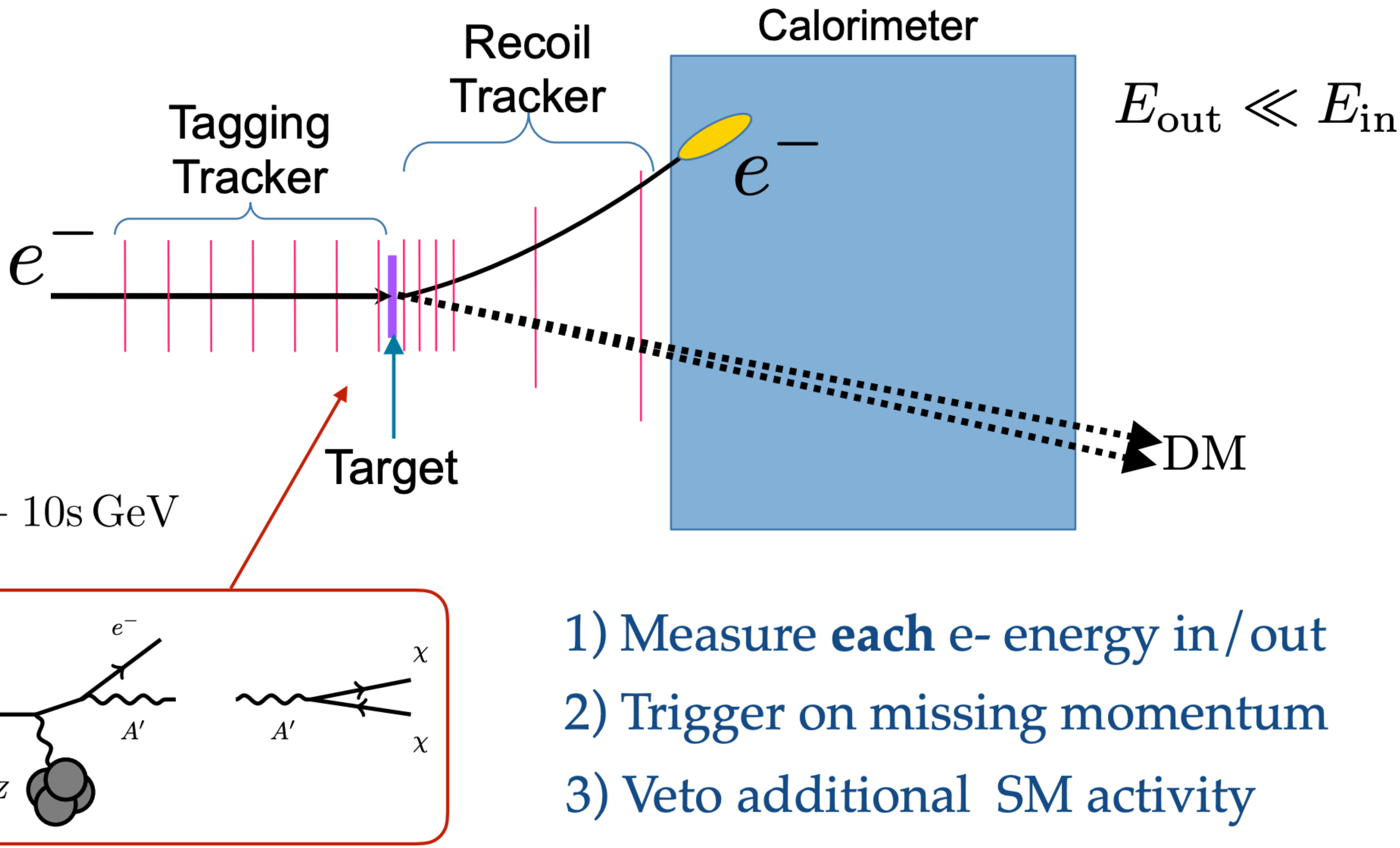
Missing Momentum Experiment: LDMX





- 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



$N_e \sim 10^{16}$

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

1) Measure **each** e- energy in/out

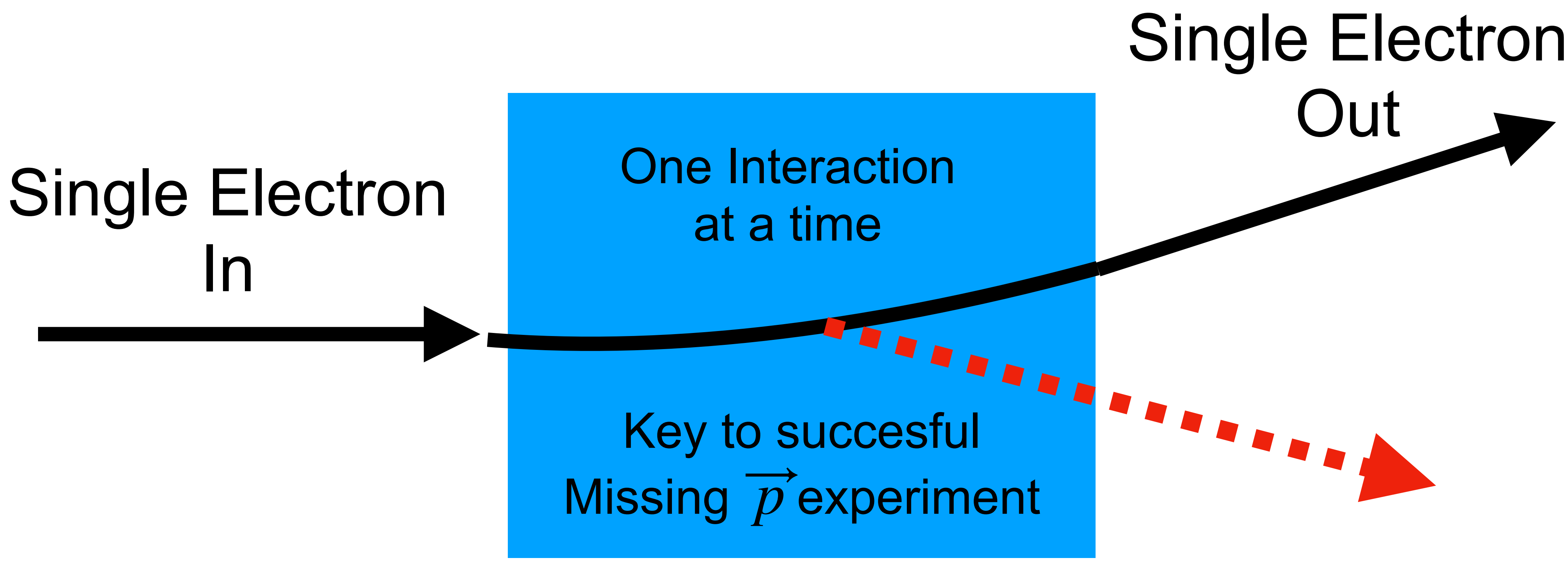
2) Trigger on missing momentum

3) Veto additional SM activity

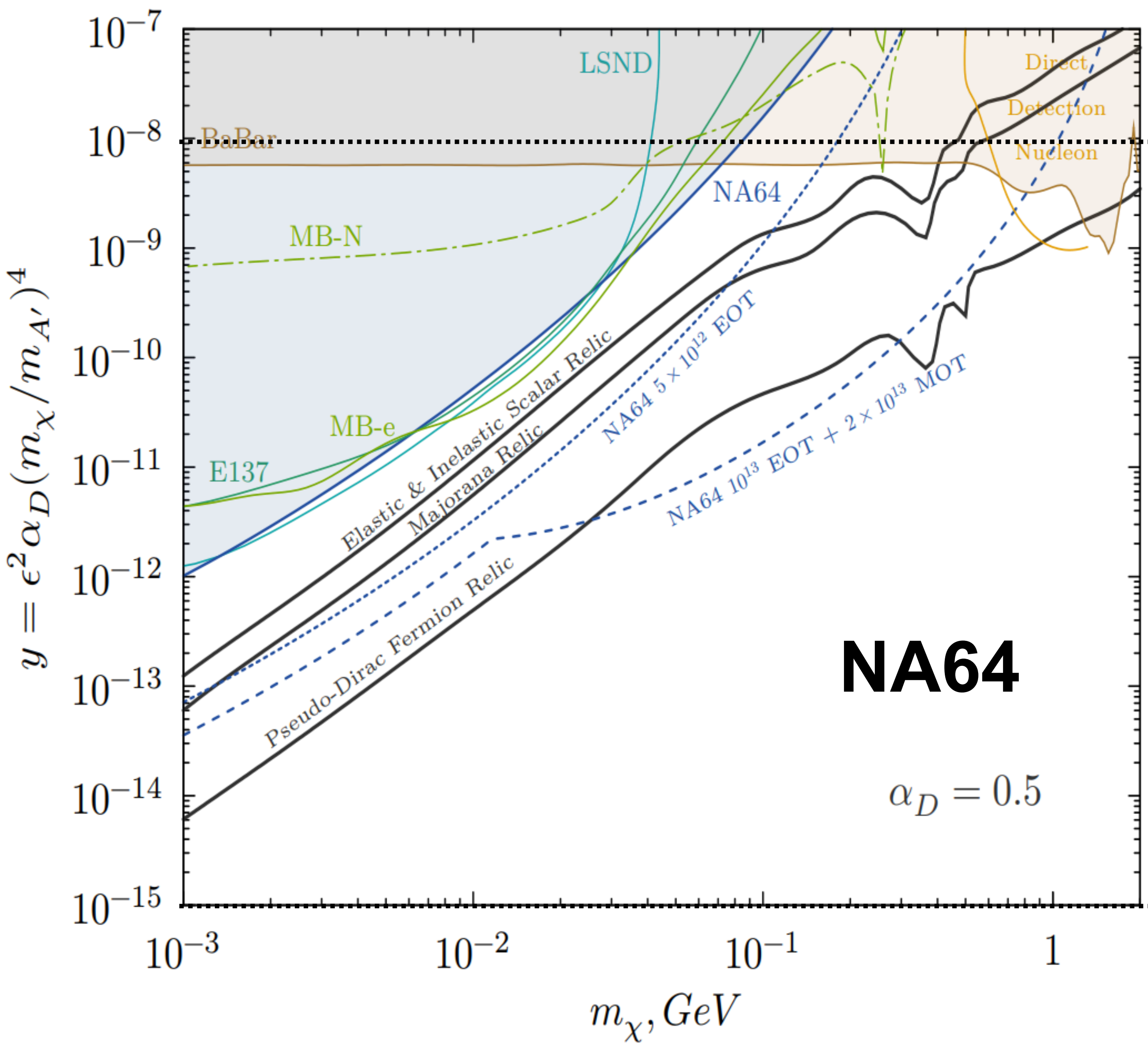
One particle at a time

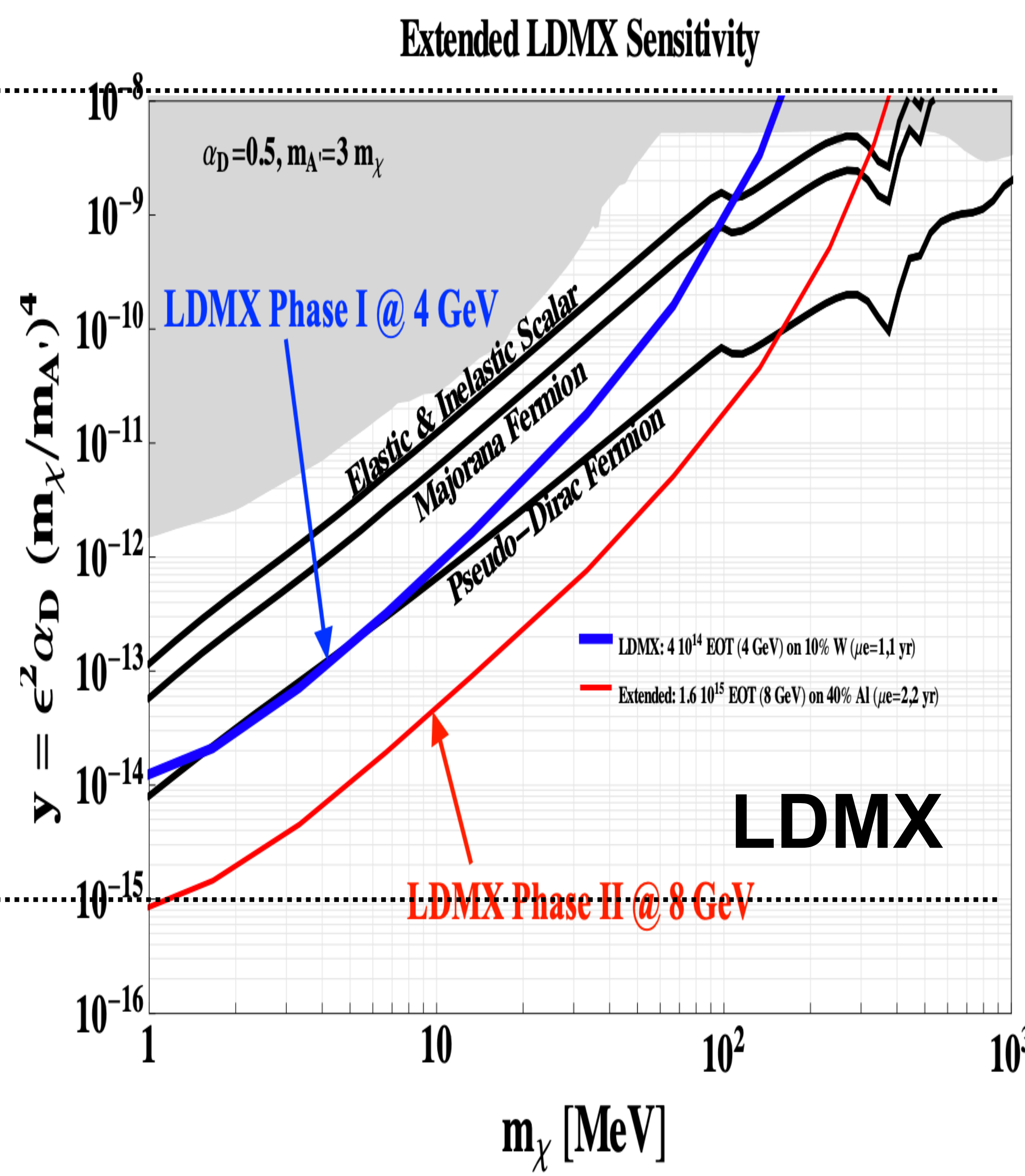
- An important component of running with each experiment
  - Only read out one electron at a time

Multiple Electrons at the same time will limit missing energy meas



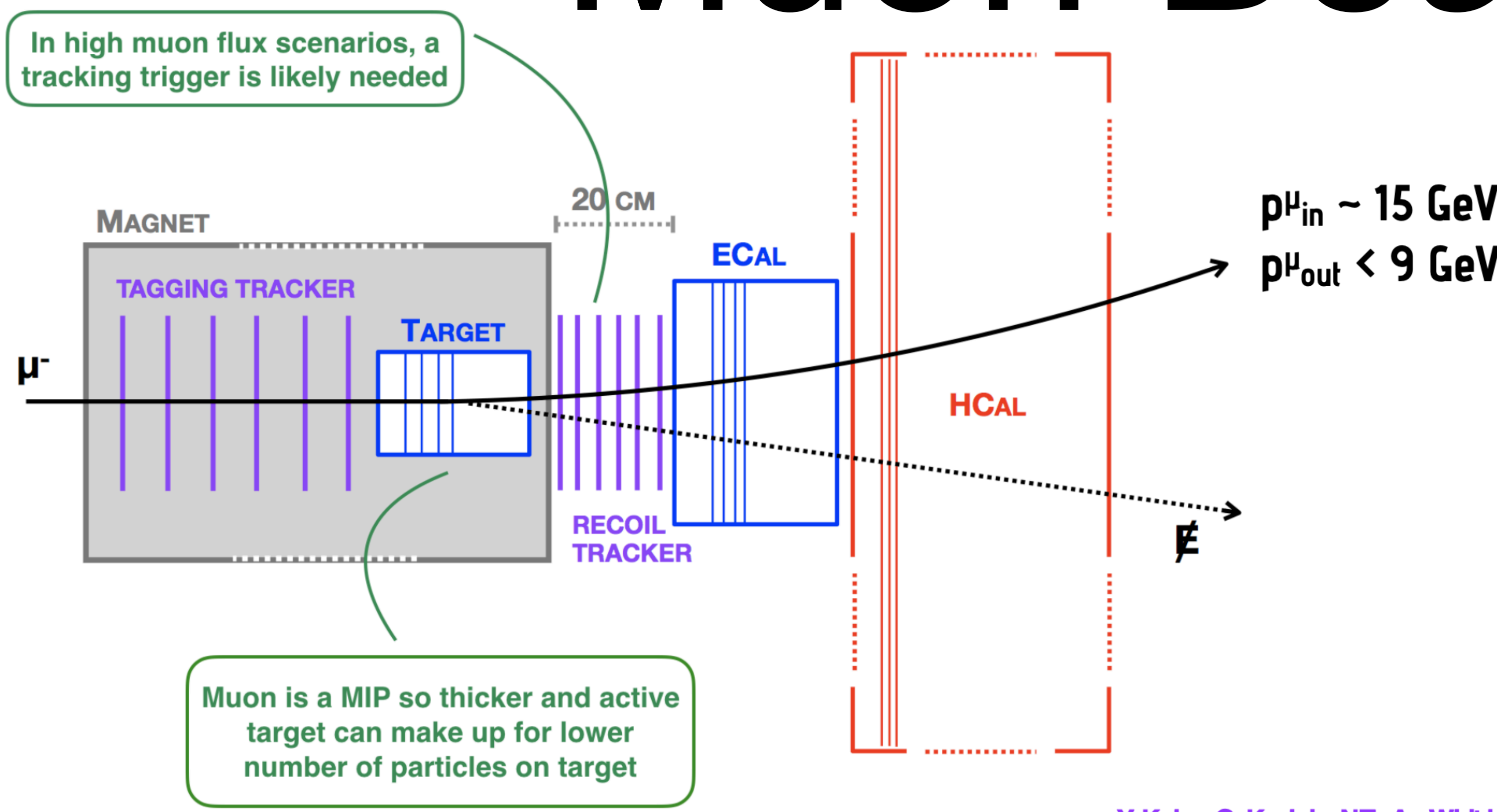
Sensitivity



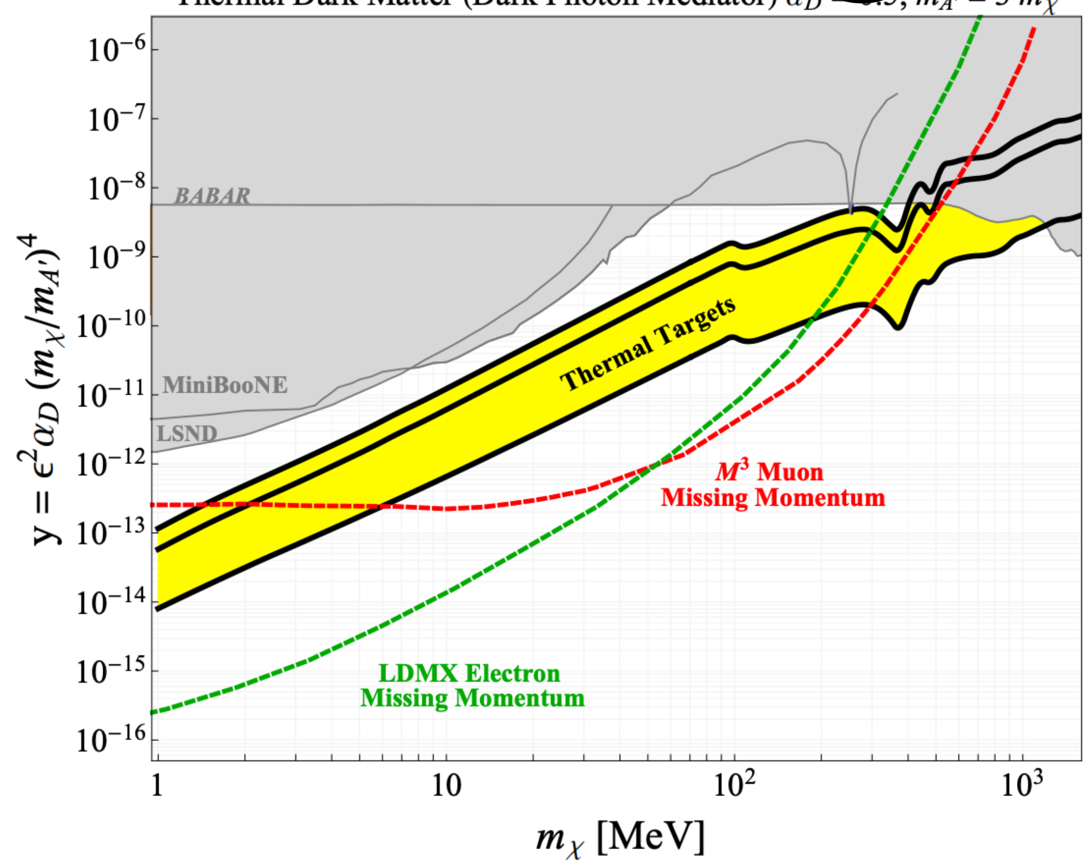


- NA64 can reach some of the relic limits
- LDMX can reach all of the limits of the detectors

Muon Beam Missing P

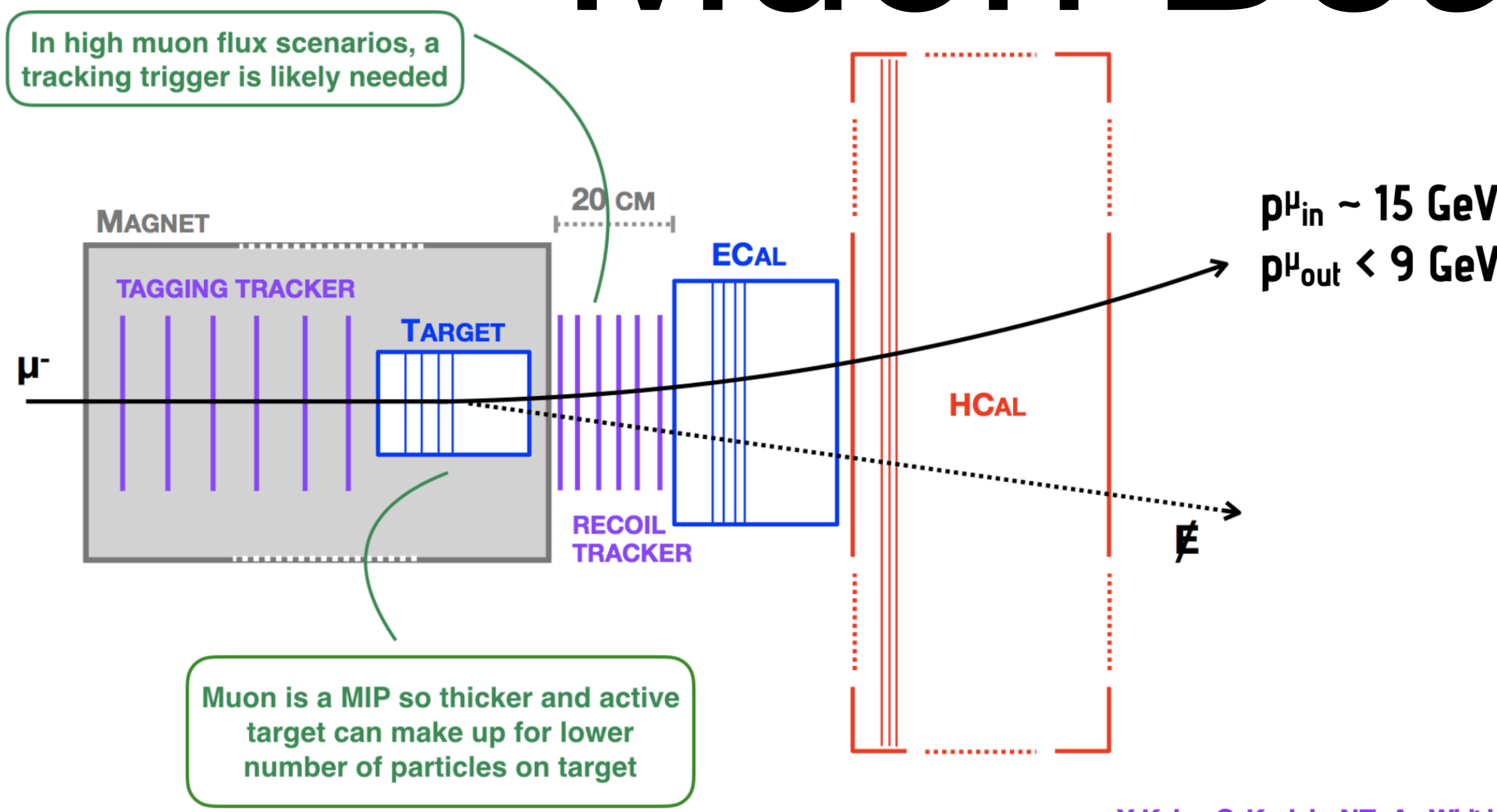


Y. Kahn, G. Krnjaic, N.T., A . Whitbeck
https://arxiv.org/abs/1804.03144



- 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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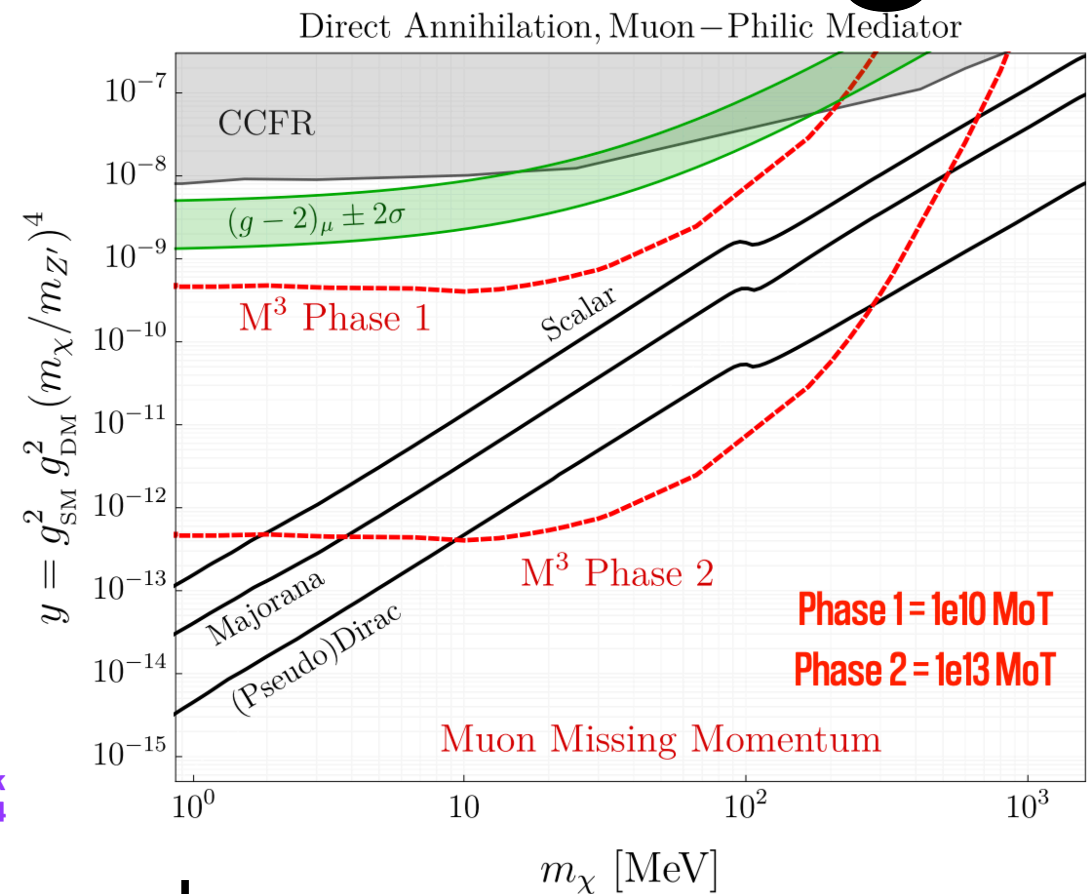

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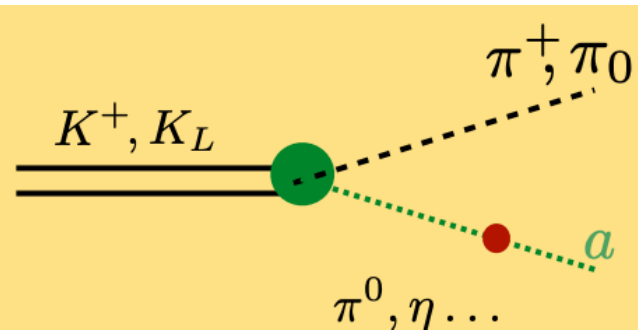
Probing Kaon Decays

Experiments		Main goal	SM value
			inputs from tree-level measurements of $V_{us}\,, V_{cb}\,, V_{ub}\,, \gamma$
NA62	CERN (running)	$K^+ \to \pi^+ \nu\bar{\nu}$	$\mathrm{BR} \simeq (8.4 \pm 1) \cdot 10^{-11}$ 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

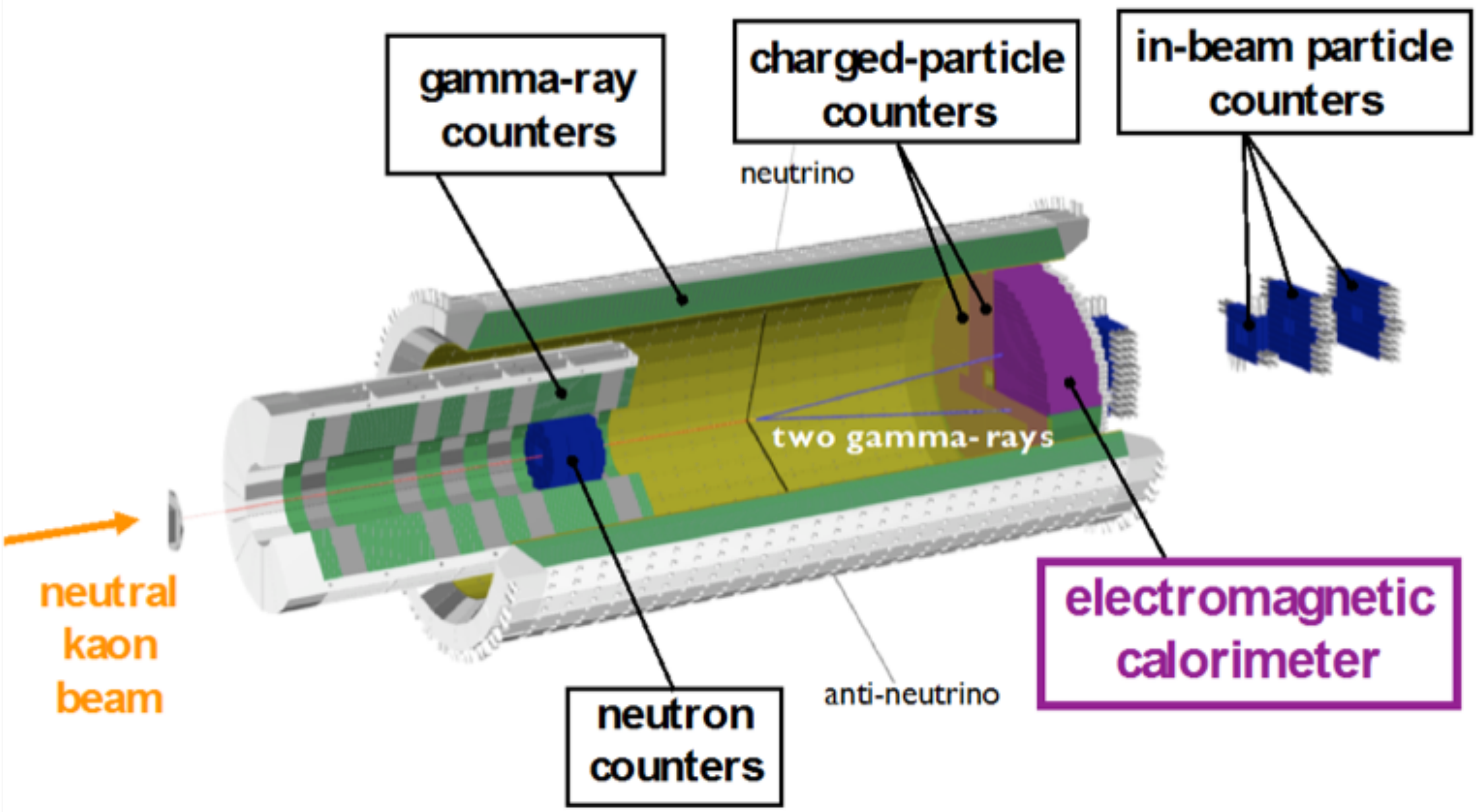
Vanilla axion, hadronic ALP

$$\frac{\alpha_s}{8\pi}\frac{Na}{f_a}G\tilde{G}$$

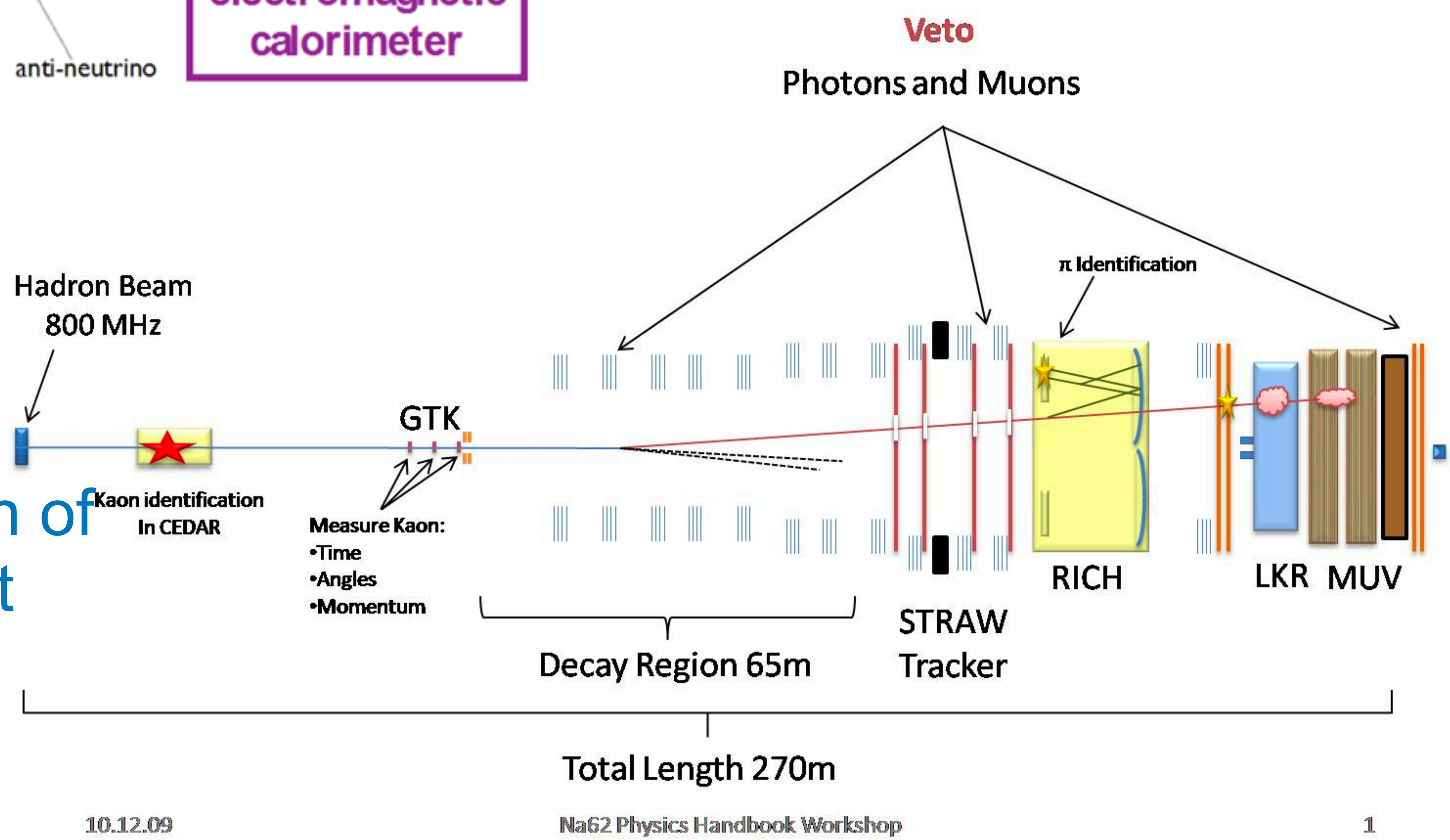


$$\sim \; 20\% \cdot \left(\frac{f_\pi}{f_a}\right)^2$$

KOTO/NA62

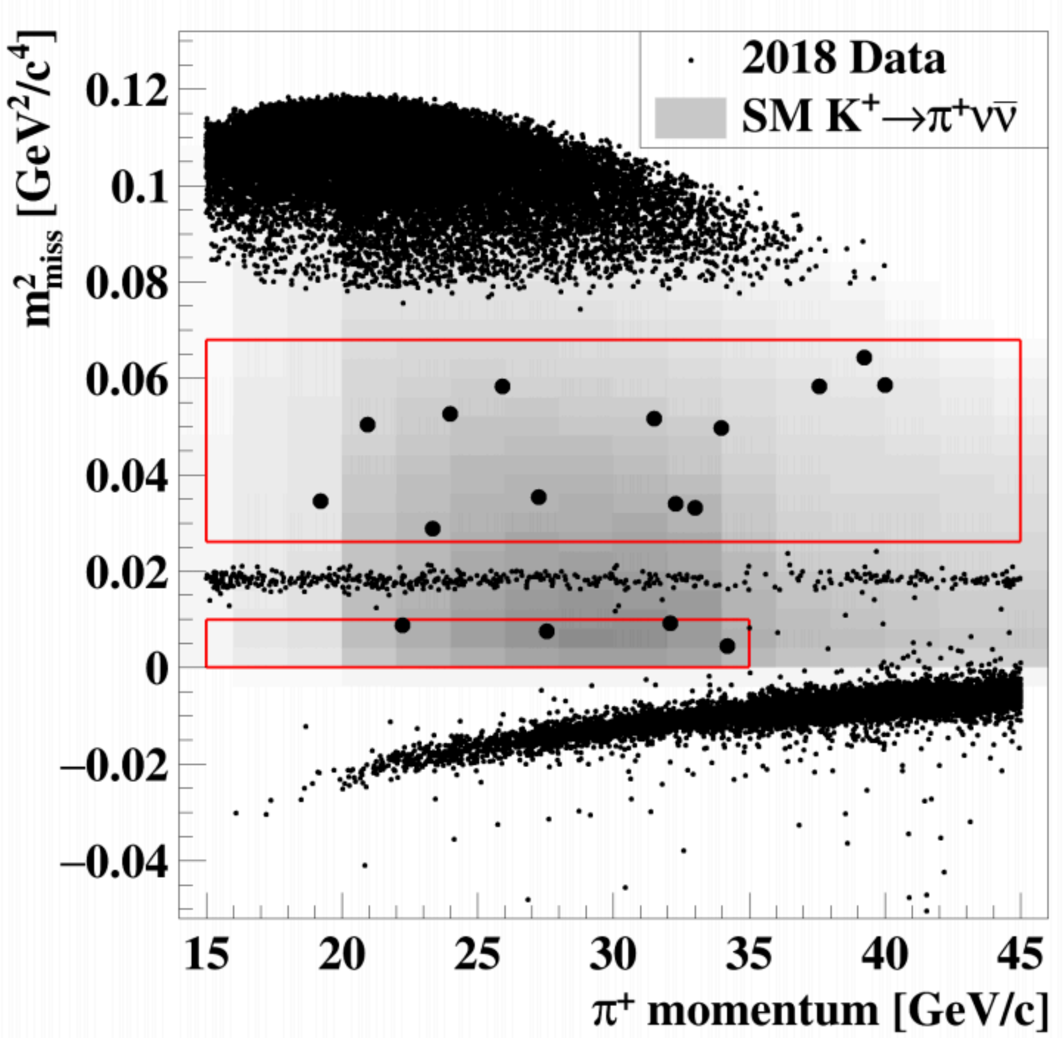


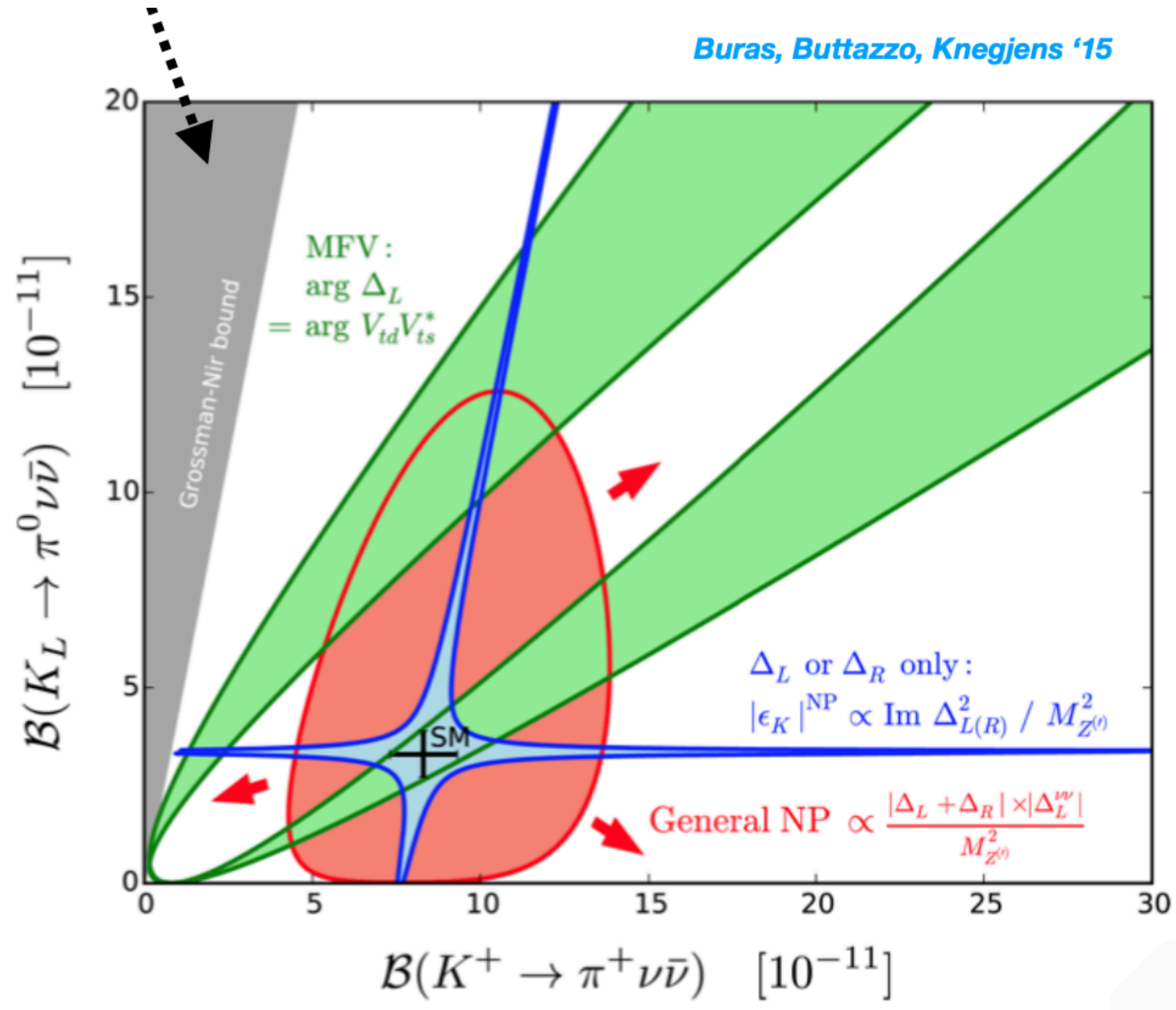
Fire a well measured Kaon beam to a detector and look for decays



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

Using Missing Mass

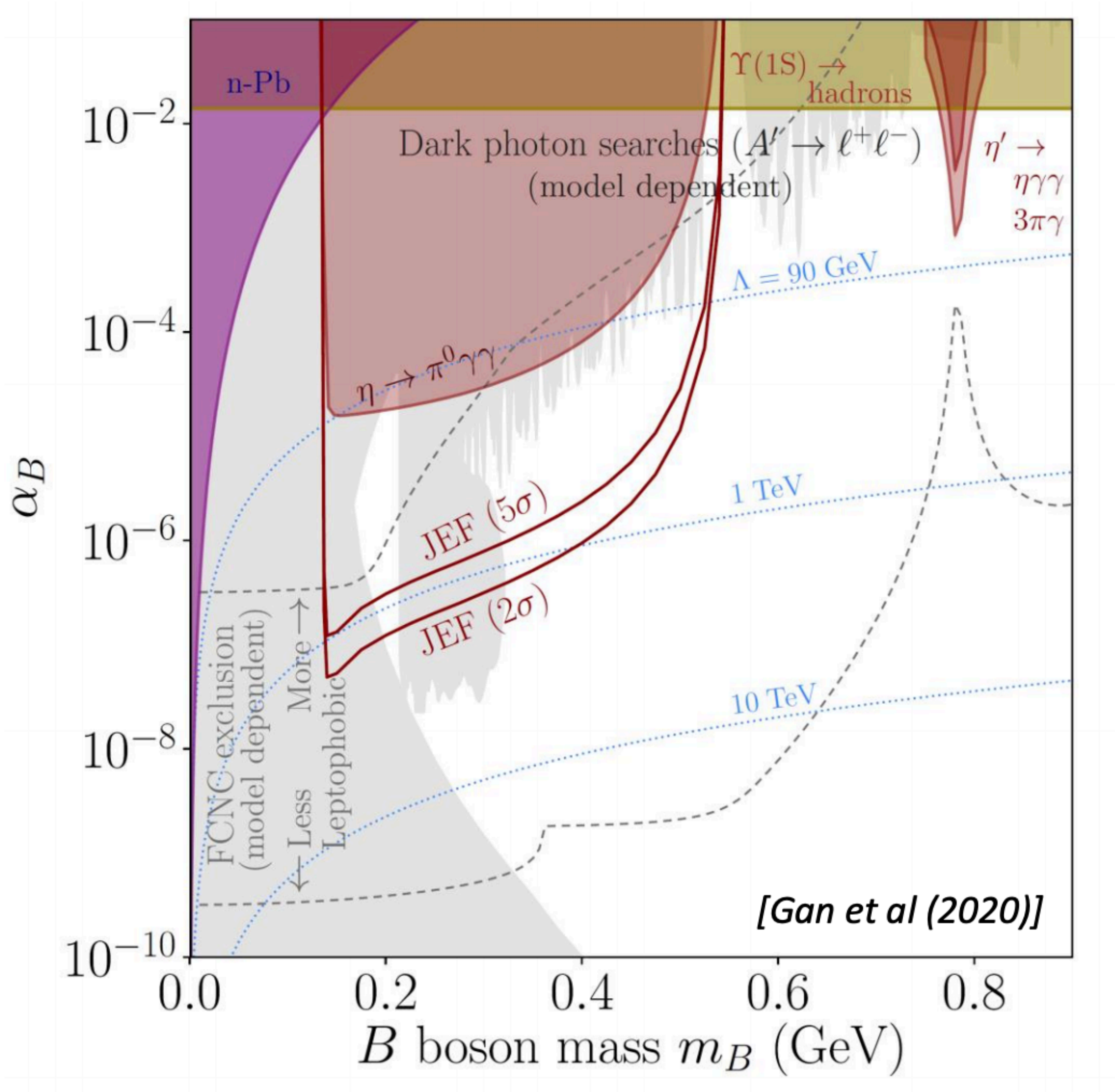




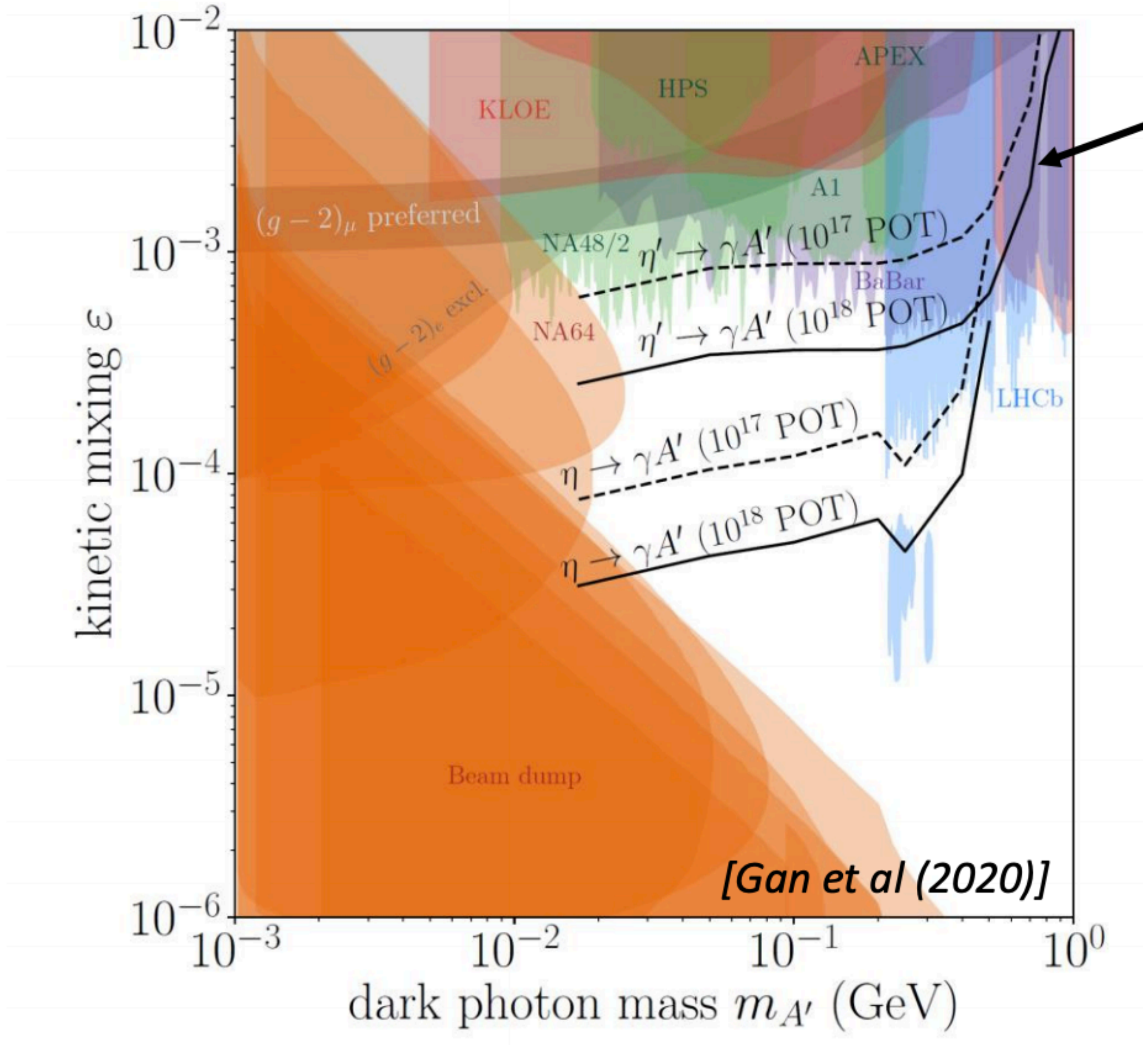
- Strategy: use missing mass to measure Kaon rate
  - Combination of π^0 and π^+ identified decays probes SM
- Decays allow for very precise probe

Probing Eta Decays

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

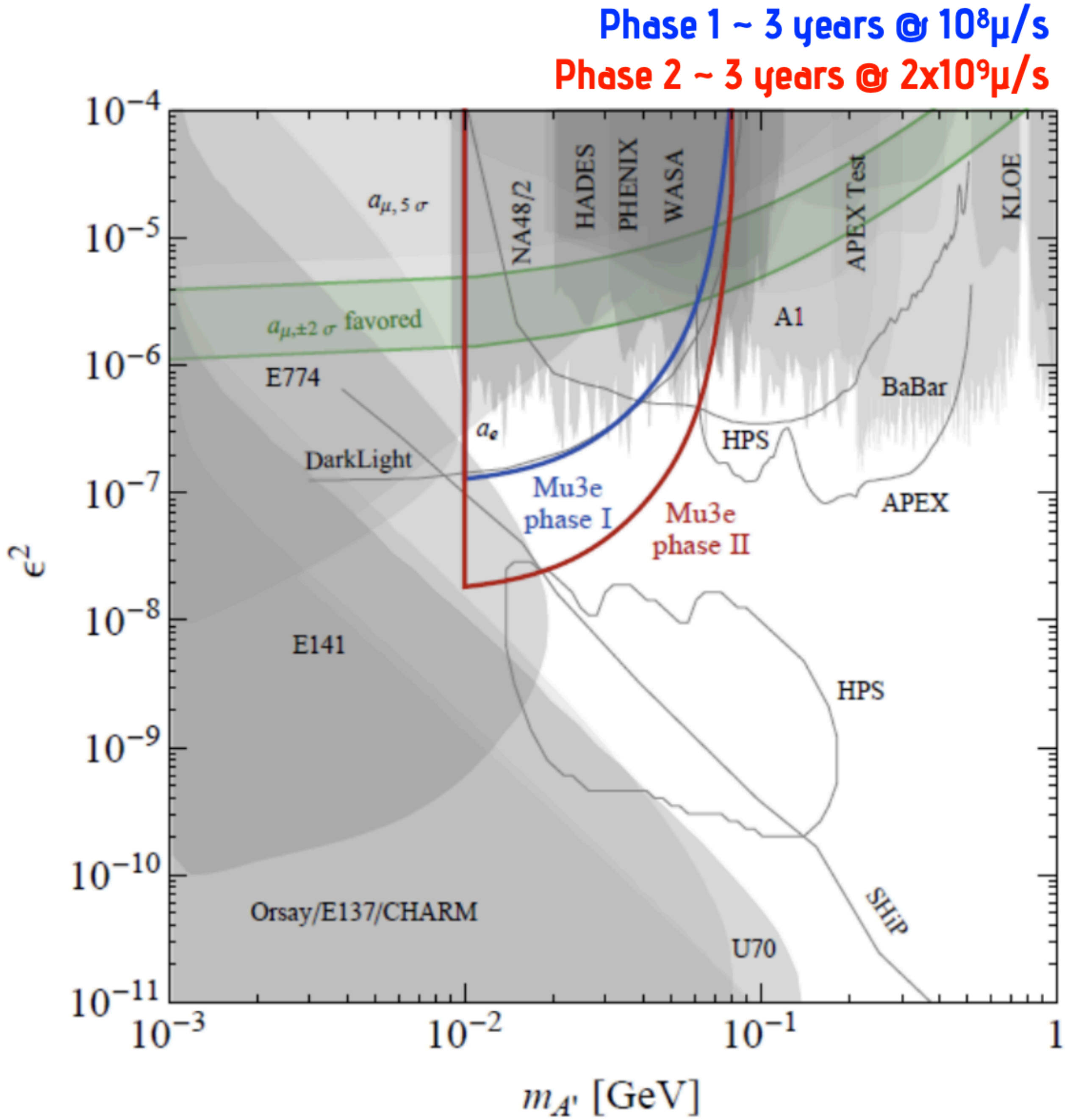


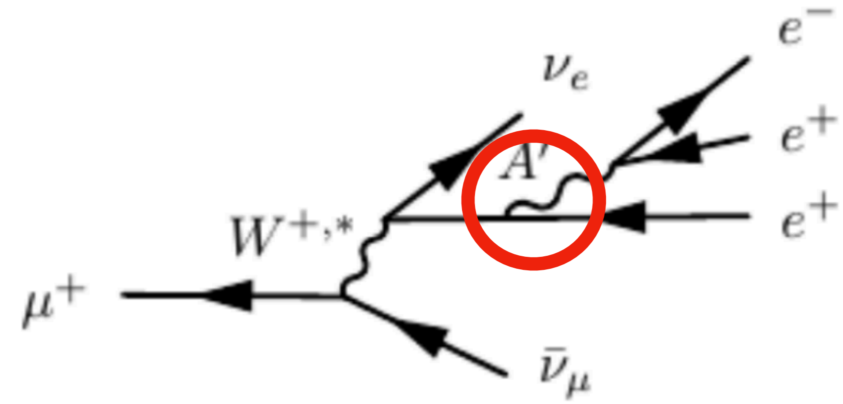
$\eta, \eta' \to \gamma A' \to \gamma \ell^+\ell^-$

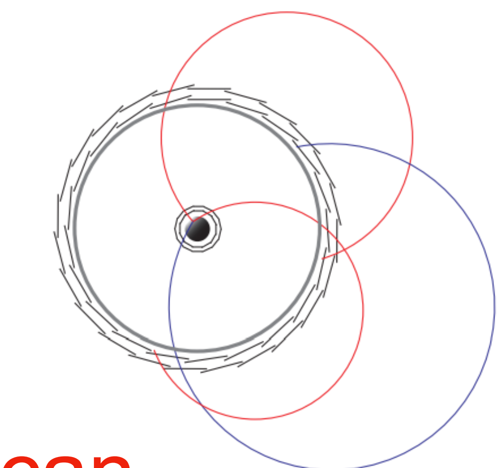


- Build a beam of η and η' particles using:
  - p+De→η/η' + $^3He^+$

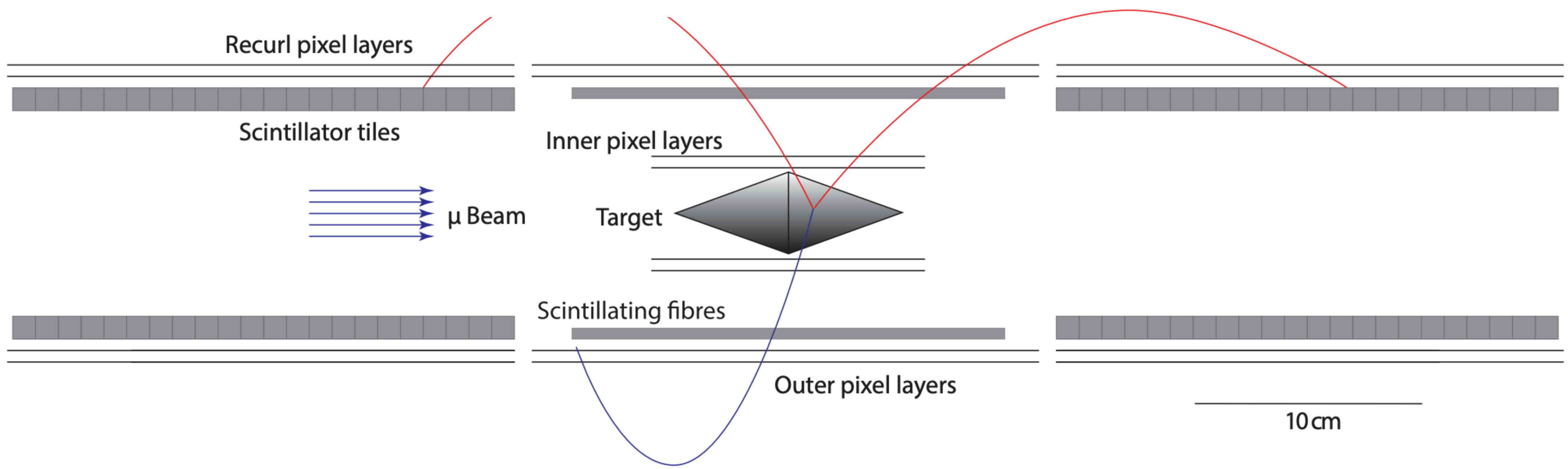
Other Ideas







- Muon to 3 lepton can probe a light dark photon



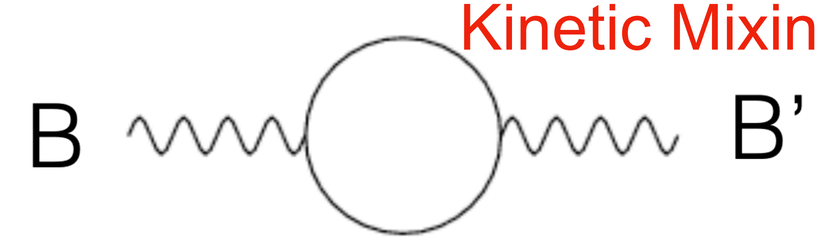
More Exotic Dark Photons

Milli-Charged Particles

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

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

$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} - \frac{\kappa}{2}B'_{\mu\nu}B^{\mu\nu} + \bar{\chi}\left(\not\partial + ie'\not B' + iM_{MCP}\right)\chi$$

$$B' \rightarrow B' + \frac{\kappa}{2}B$$

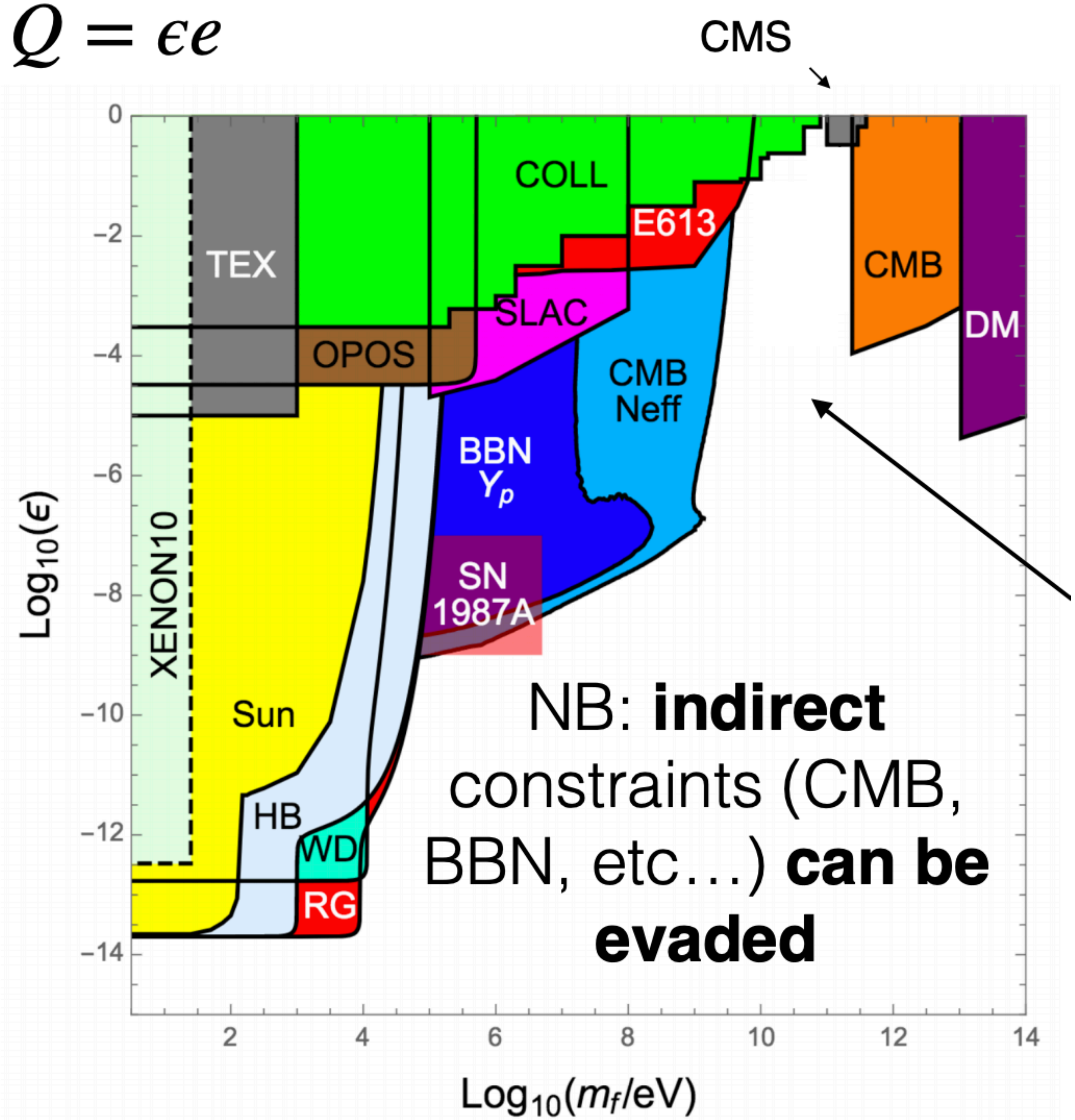
Usual Gauge Trick

Dark Sector Particle

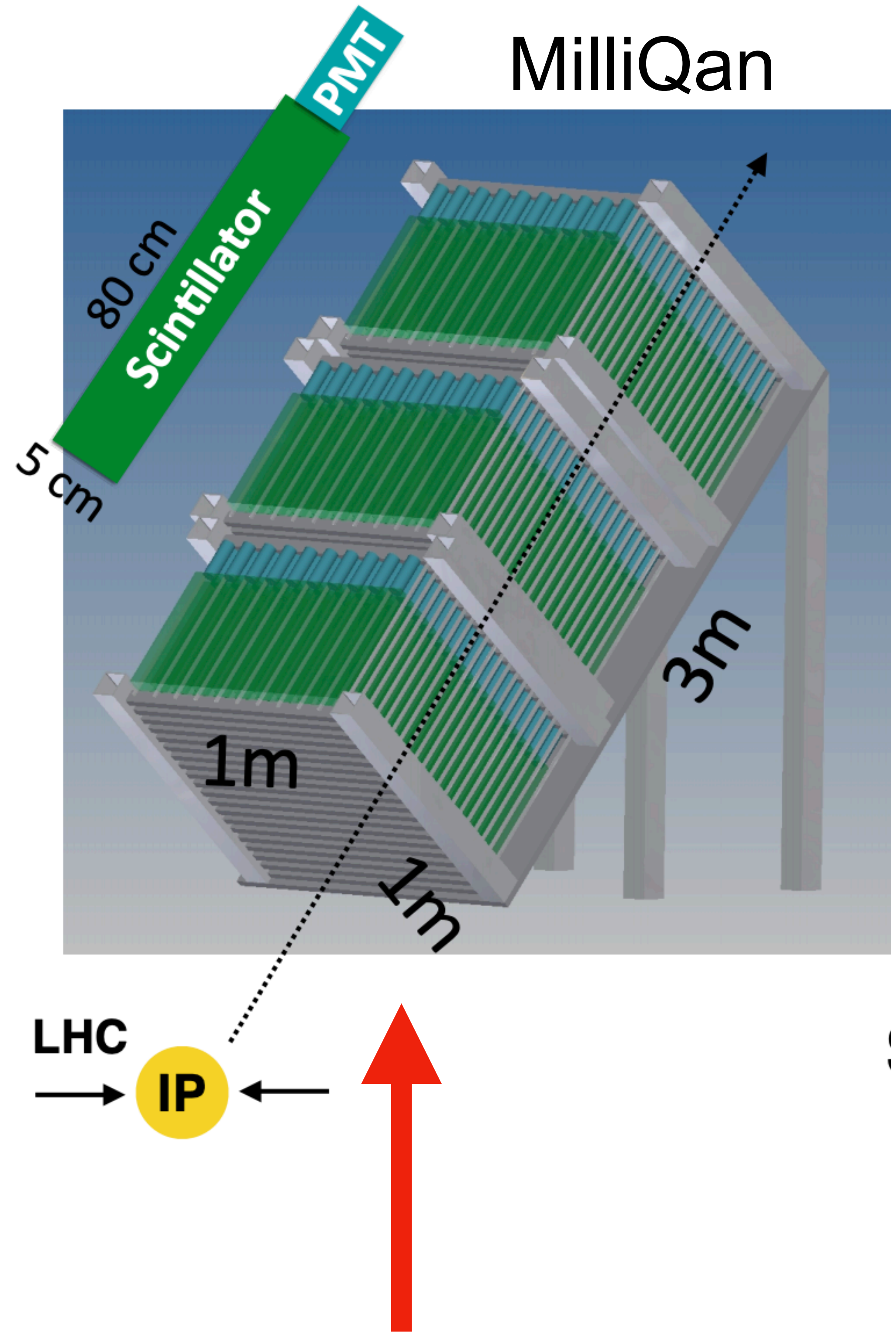
$$\mathscr{L} = \mathscr{L}_{\rm SM} - \frac{1}{4}B'_{\mu\nu}B'^{\mu\nu} + i\bar{\chi}\left(\not\partial + ie'\not B' + i\frac{\kappa}{2}e'\not B + iM_{MCP}\right)\chi$$

Milli-Charged Particles

$Q = \epsilon e$

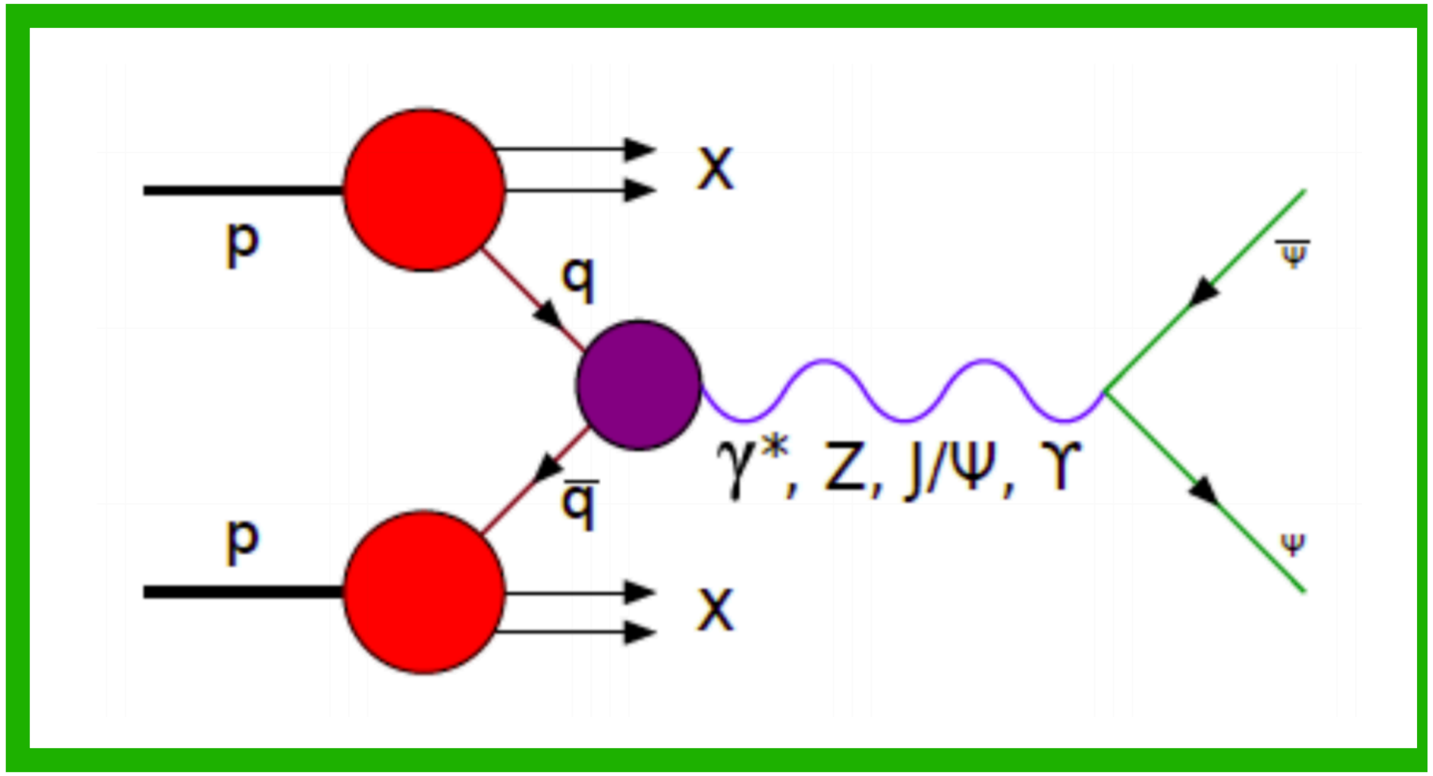


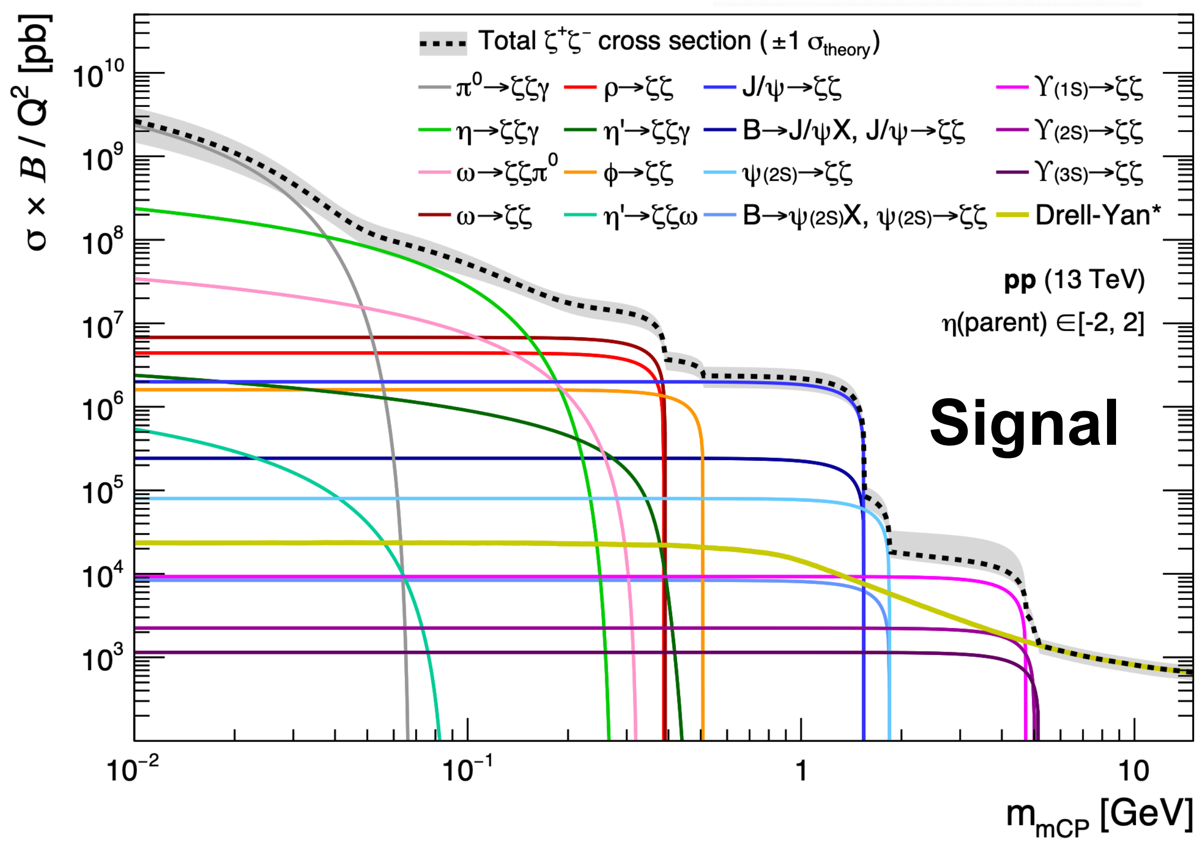
NB: **indirect** constraints (CMB, BBN, etc…) **can be evaded**



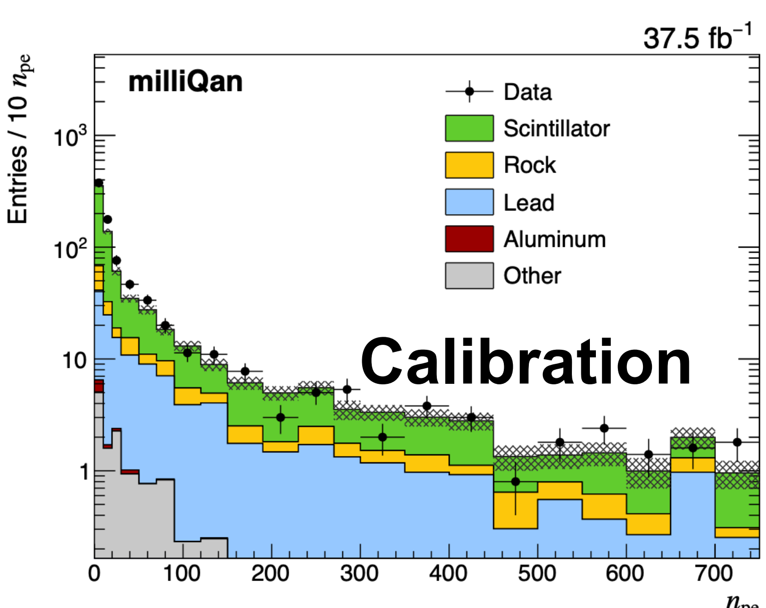
Scintillator capable of identifying a weakly charged object

Milli-Charged Particles

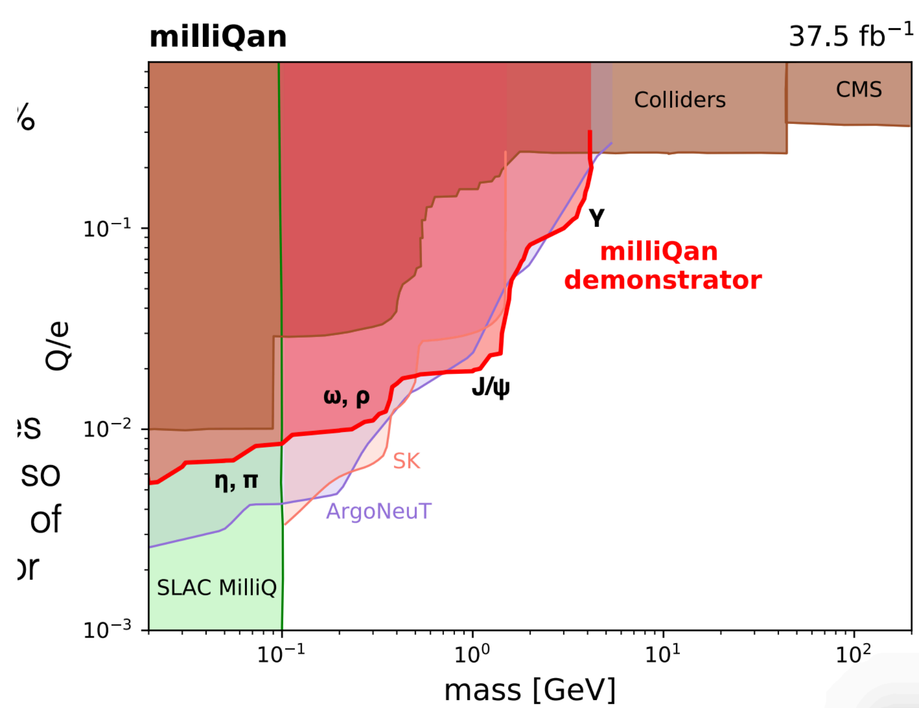




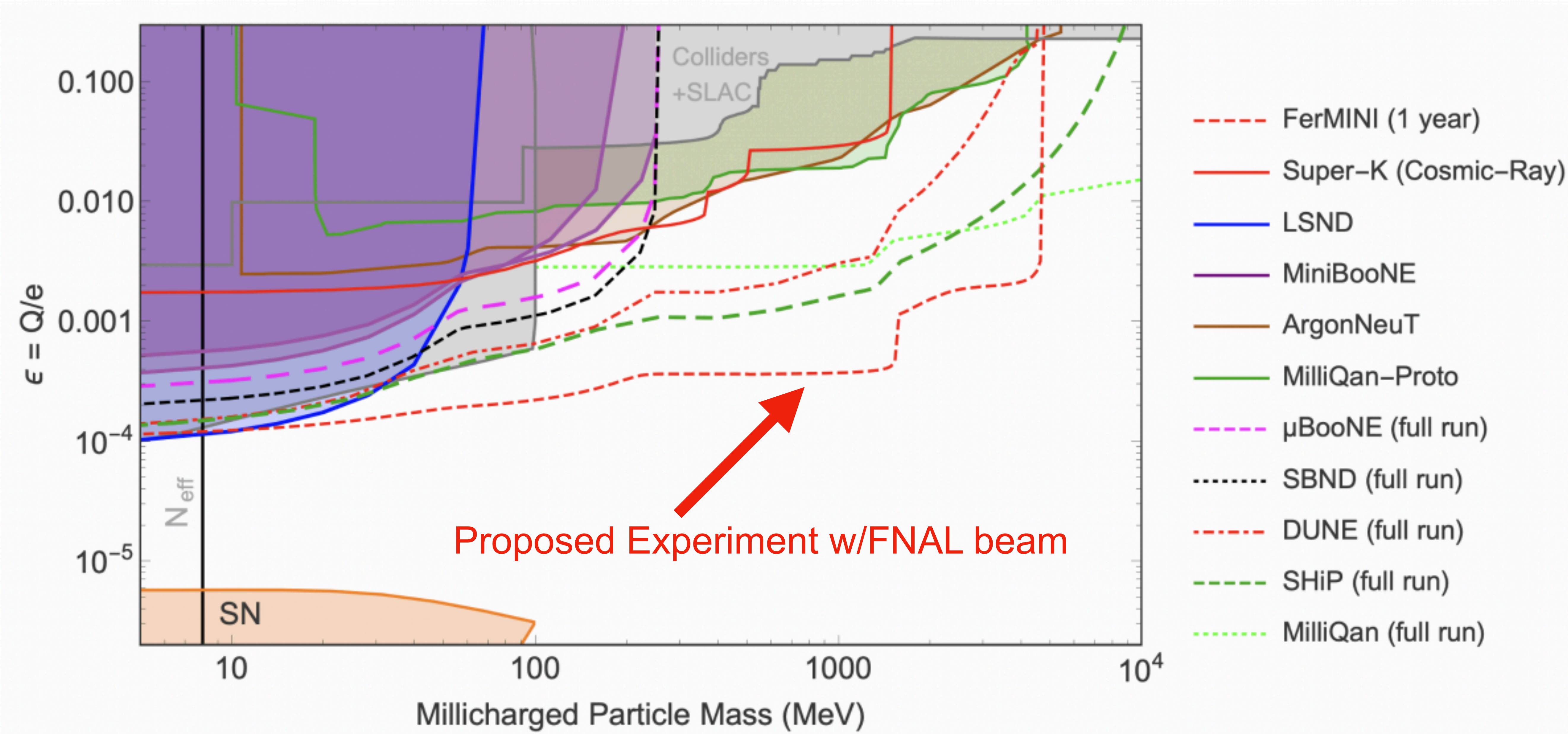
Since dark photon mixes with photon
Can produced weakly charged DM with drell-yan



Number of PE in bars due to muon shower products



Milli-Charged Particles

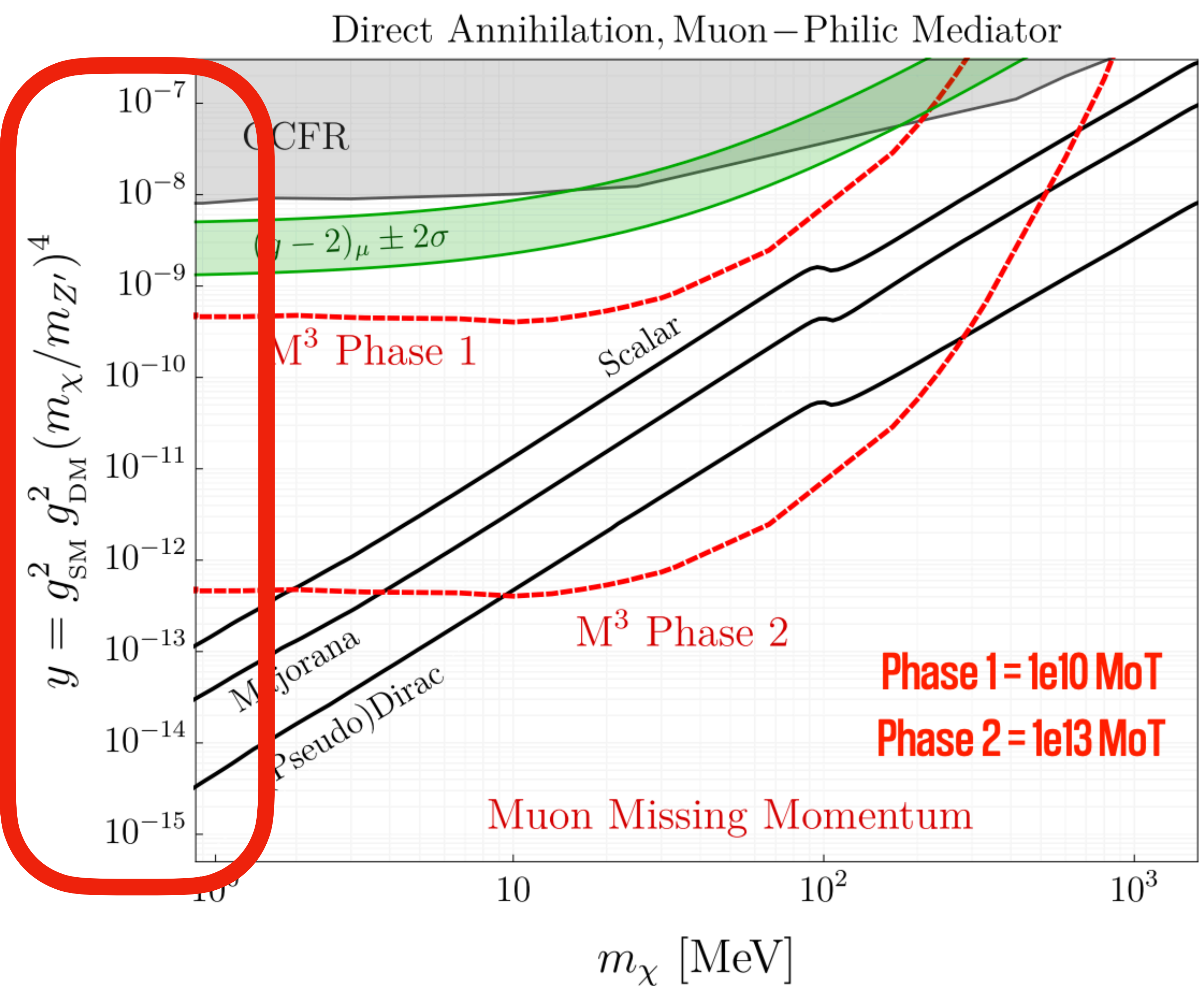


Yu-Dai Tsai

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

Lifetime Frontier

Weakly Interacting DM



Coupling values are very small

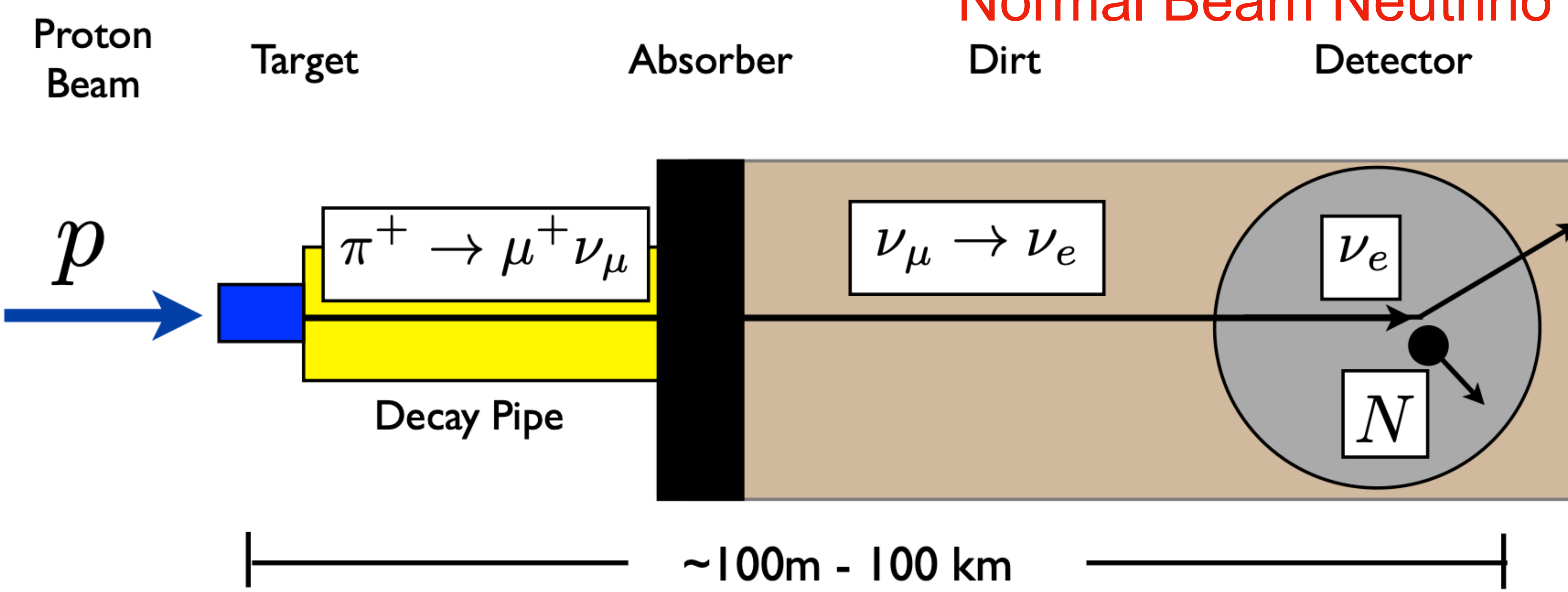
If DM is stable we can imagine using the beam to produced DM

Then we detect it with the same tools as direct detection

Turns out that neutrino detectors are quite similar to direct detection

Neutrino DM

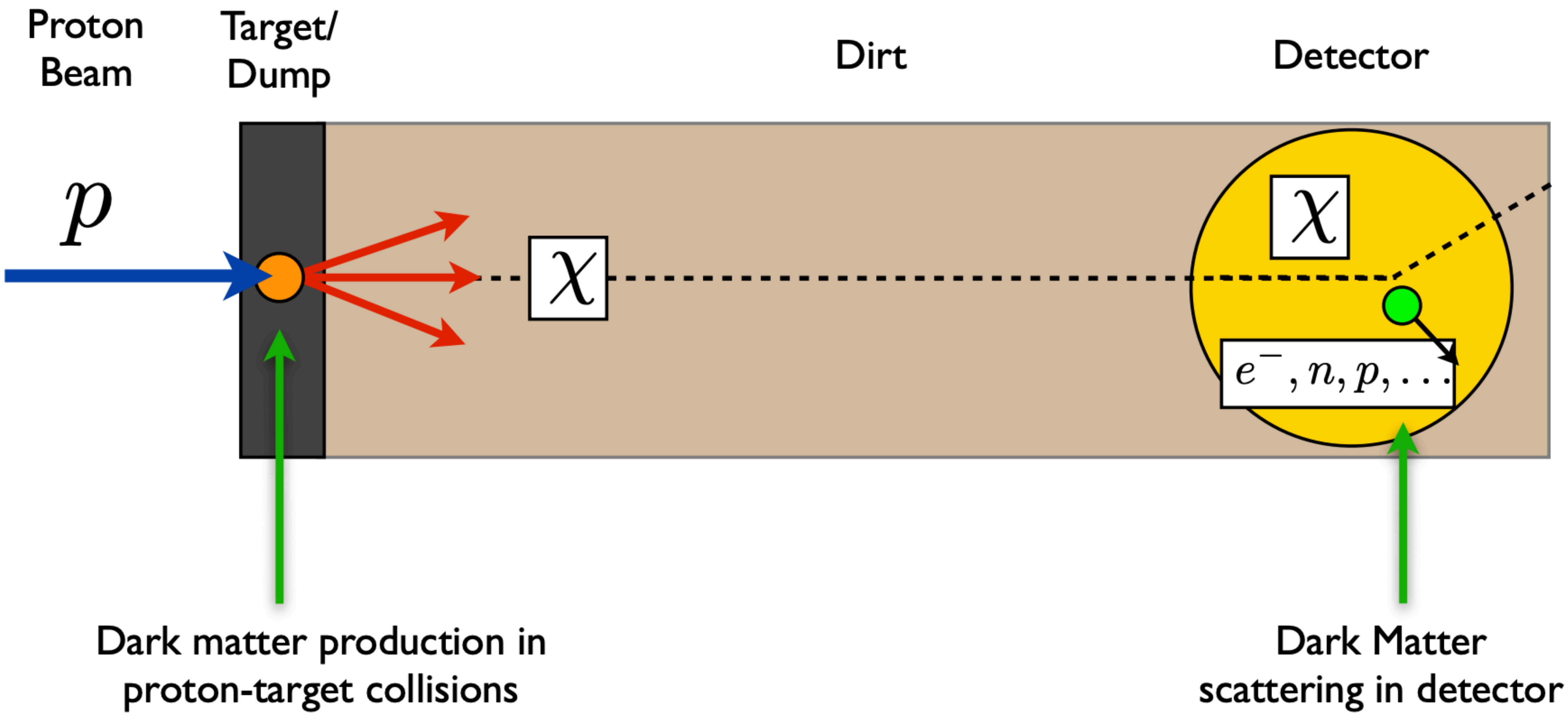
Normal Beam Neutrino Detector



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

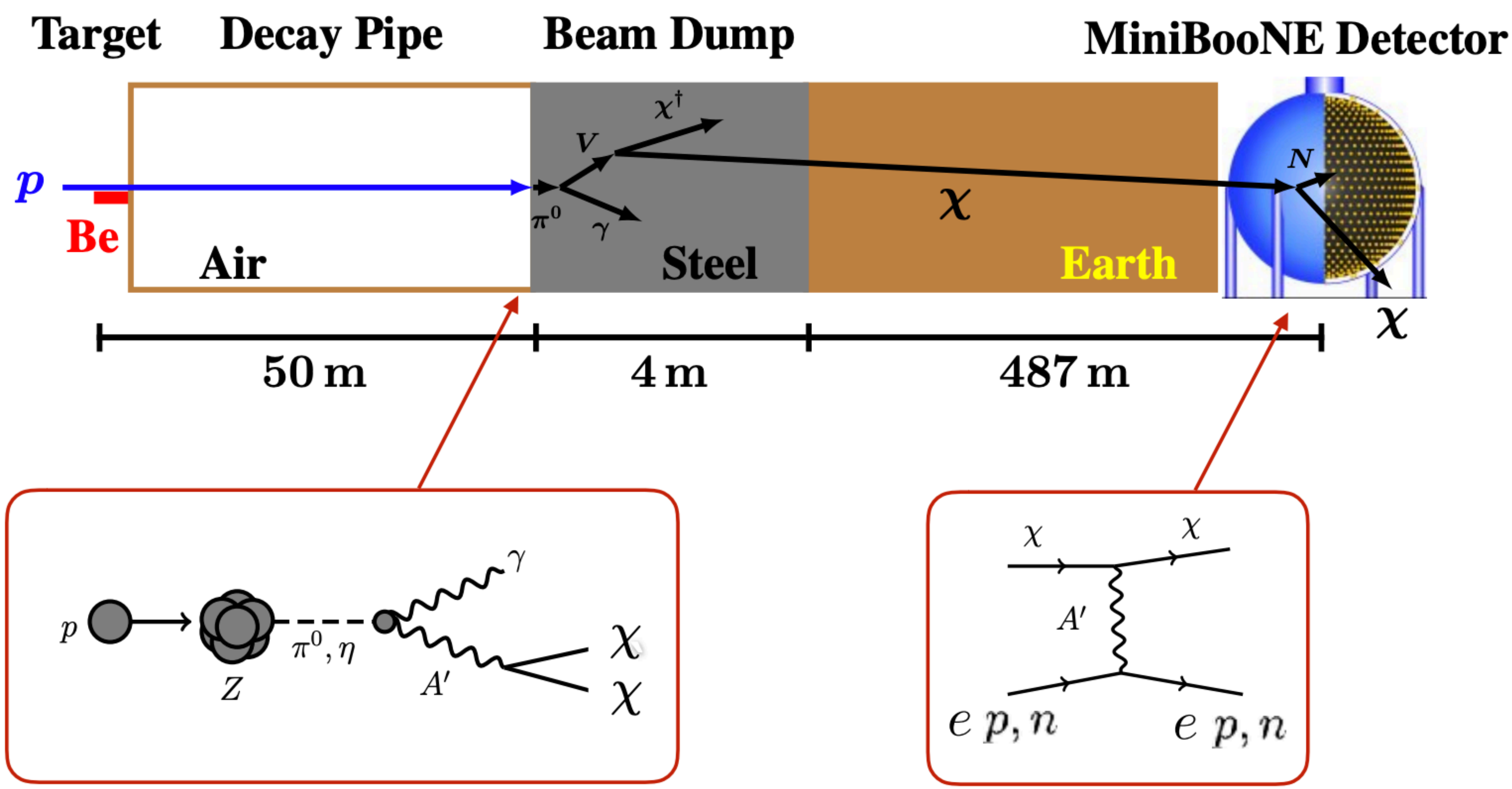
Neutrino DM

Normal Beam Neutrino Detector



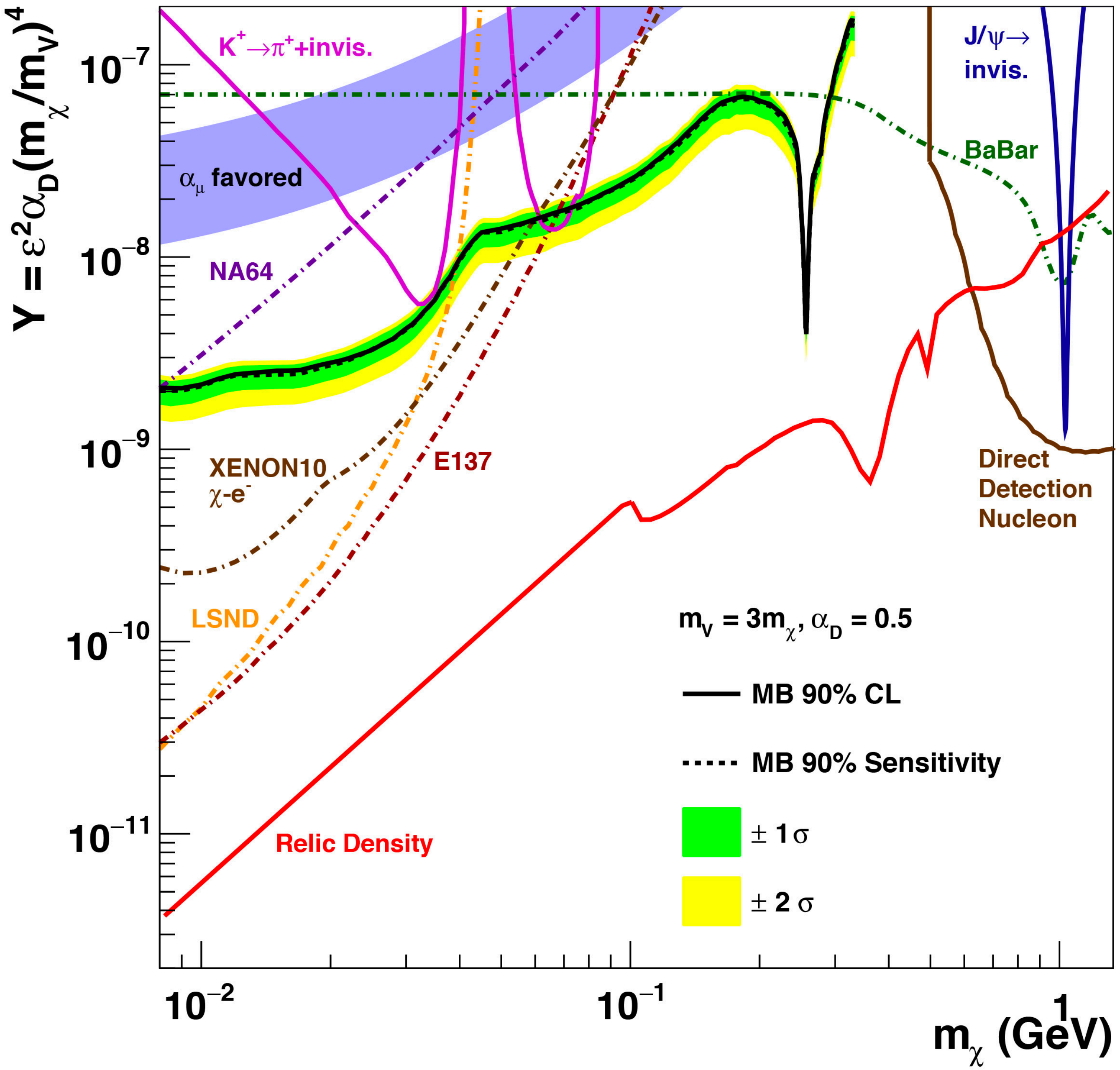
- Dark Matter produces DM from beam innteraction
- Use a large volume sensitive detector to see DM interaction

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

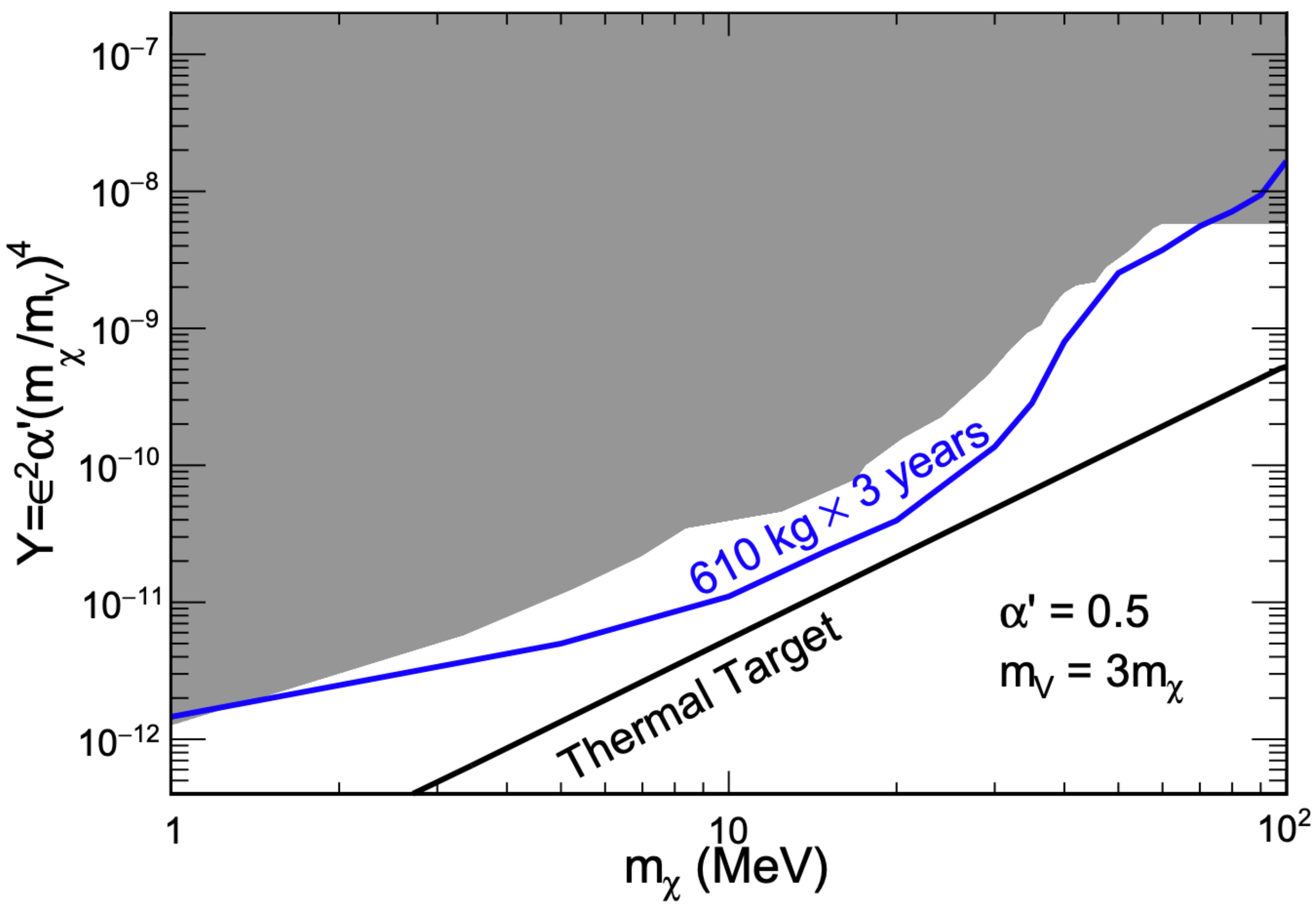
Experiments require really intense beams

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

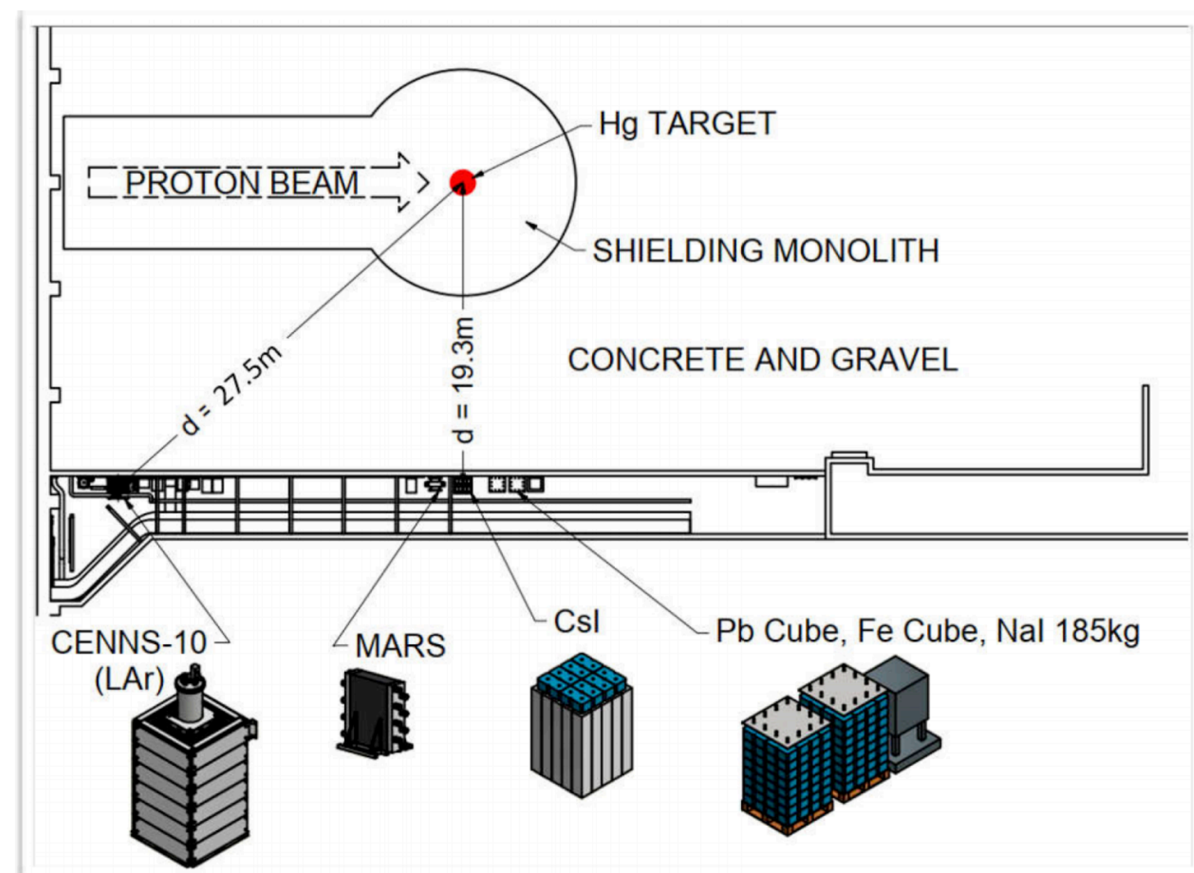
Suppression Factor

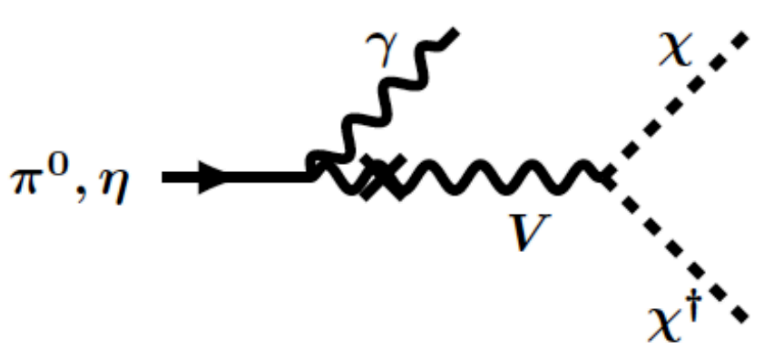
- Aim to parasitically use existing and future neutrino experiments

Bounds from COHERENT

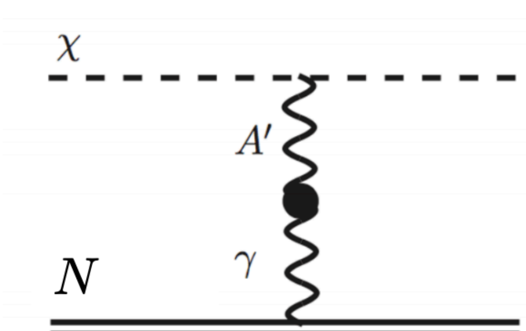


SNS Neutron beam @ORNL





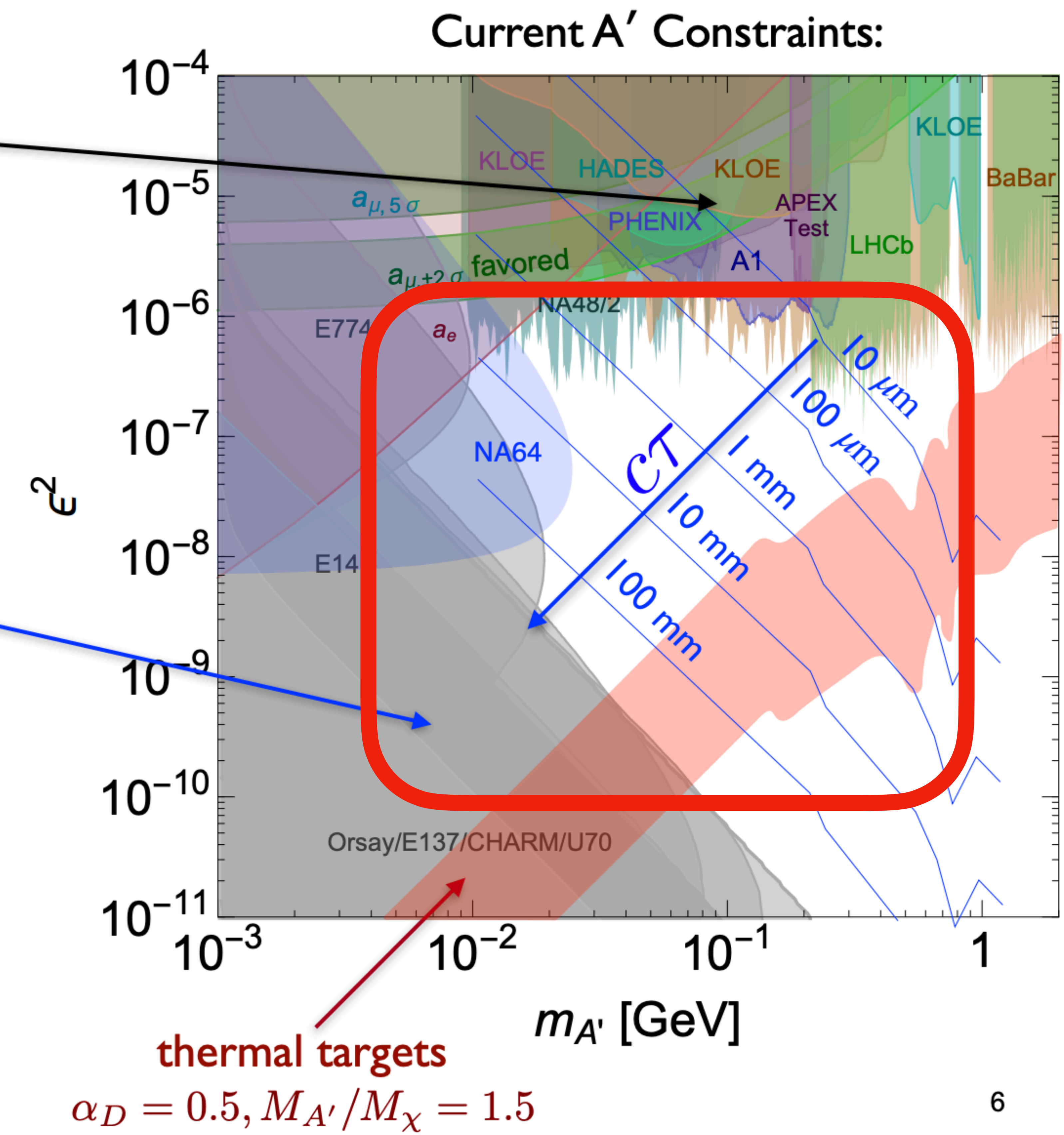
DM production



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?

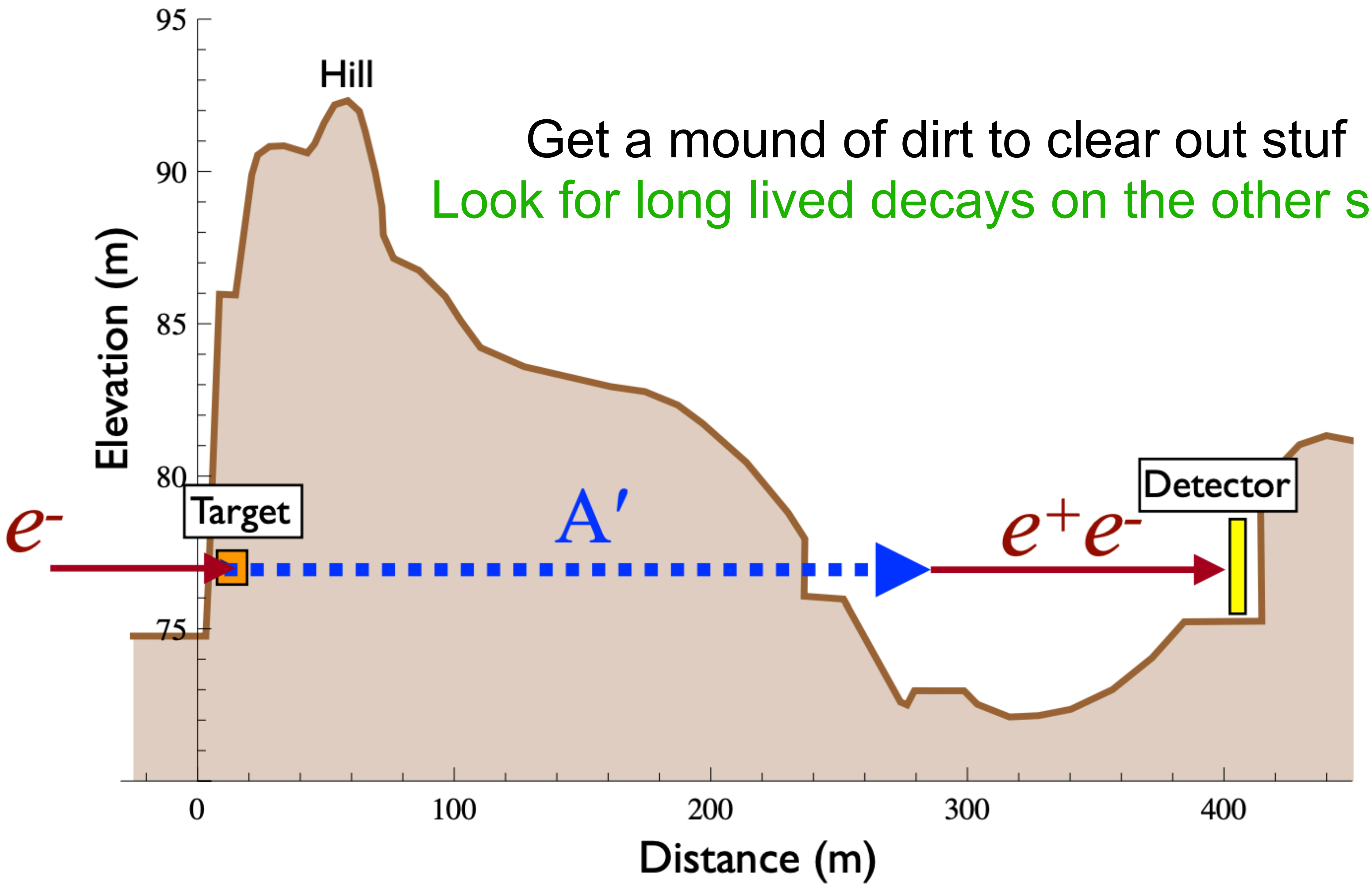
Limited amount of backgrounds w/such lifetimes

Unique signature

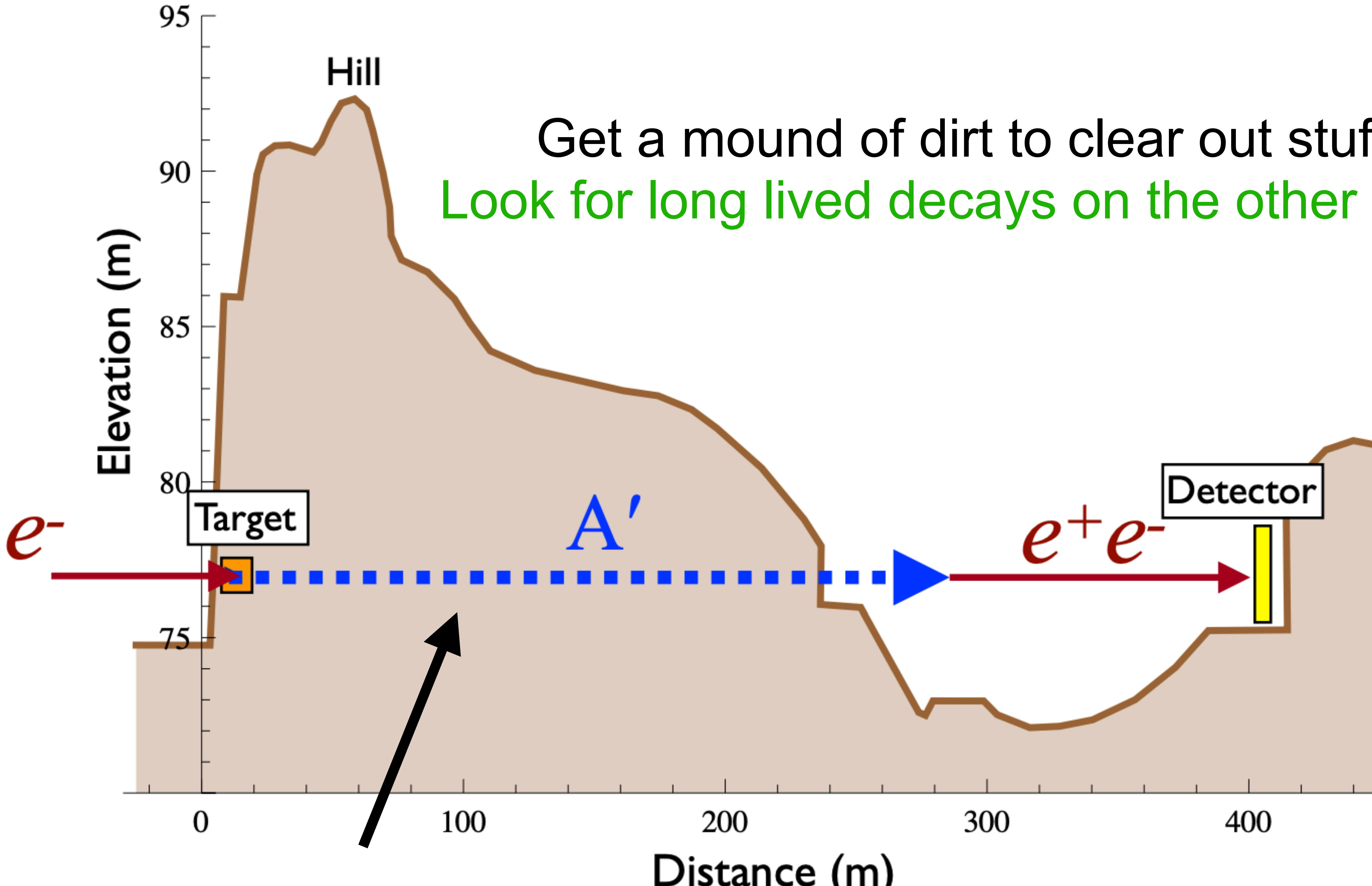
Long Lived DM

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

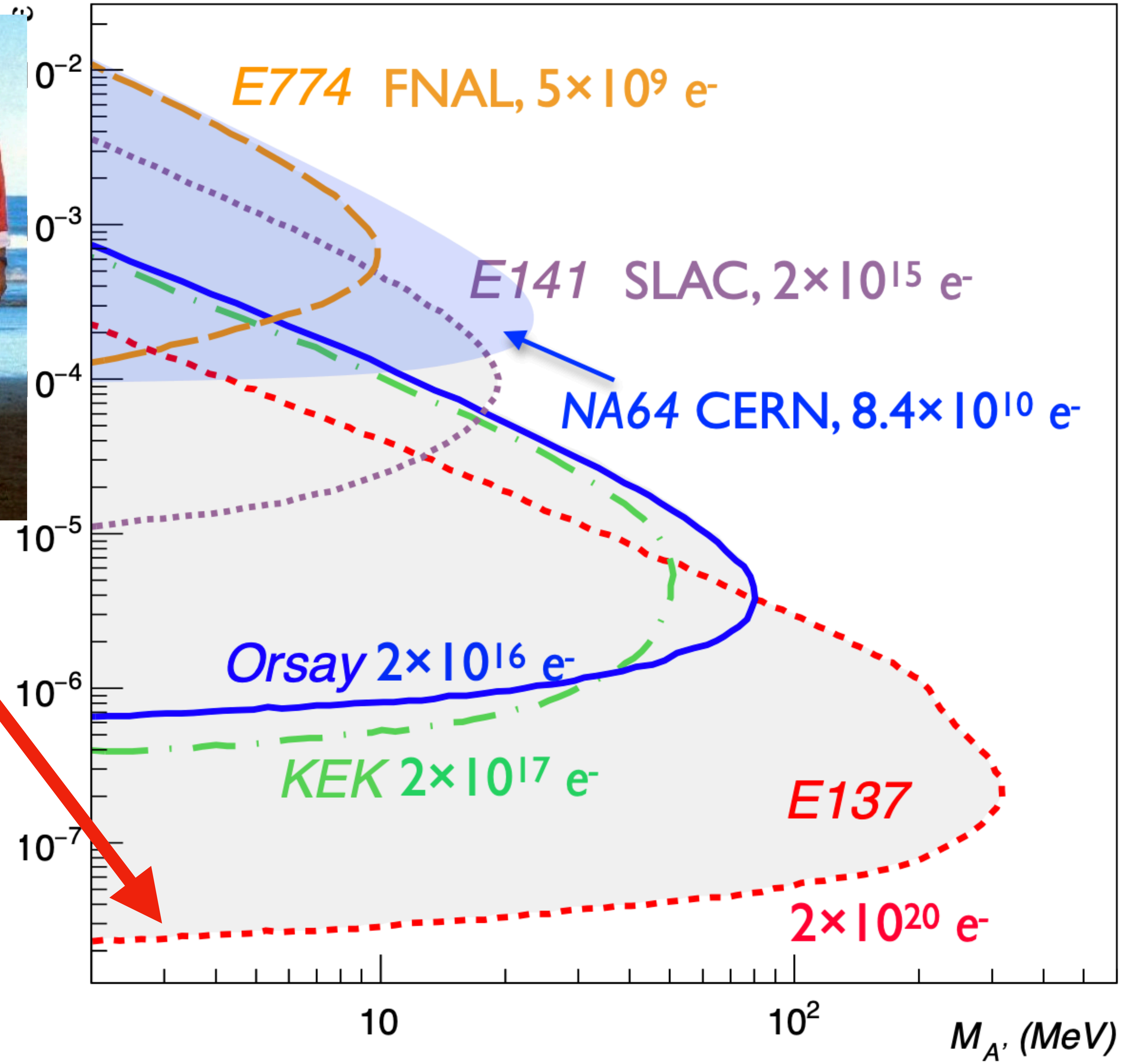
Look for long lived decays on the other side

What's the right lifetime?

Any lifetime from cτ = mm to the moon are possible

What are the bounds?

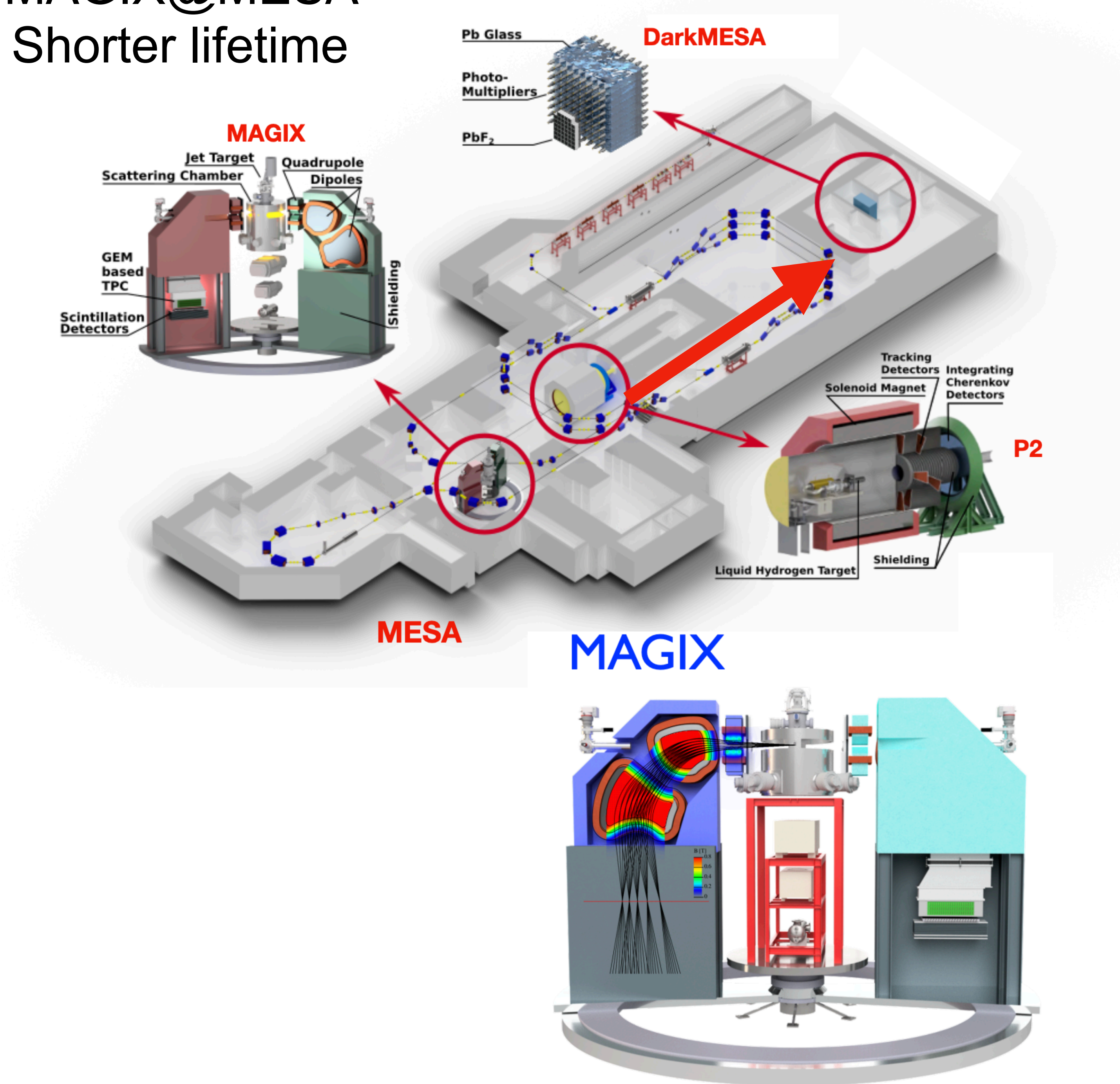
E137 was in 1980-82

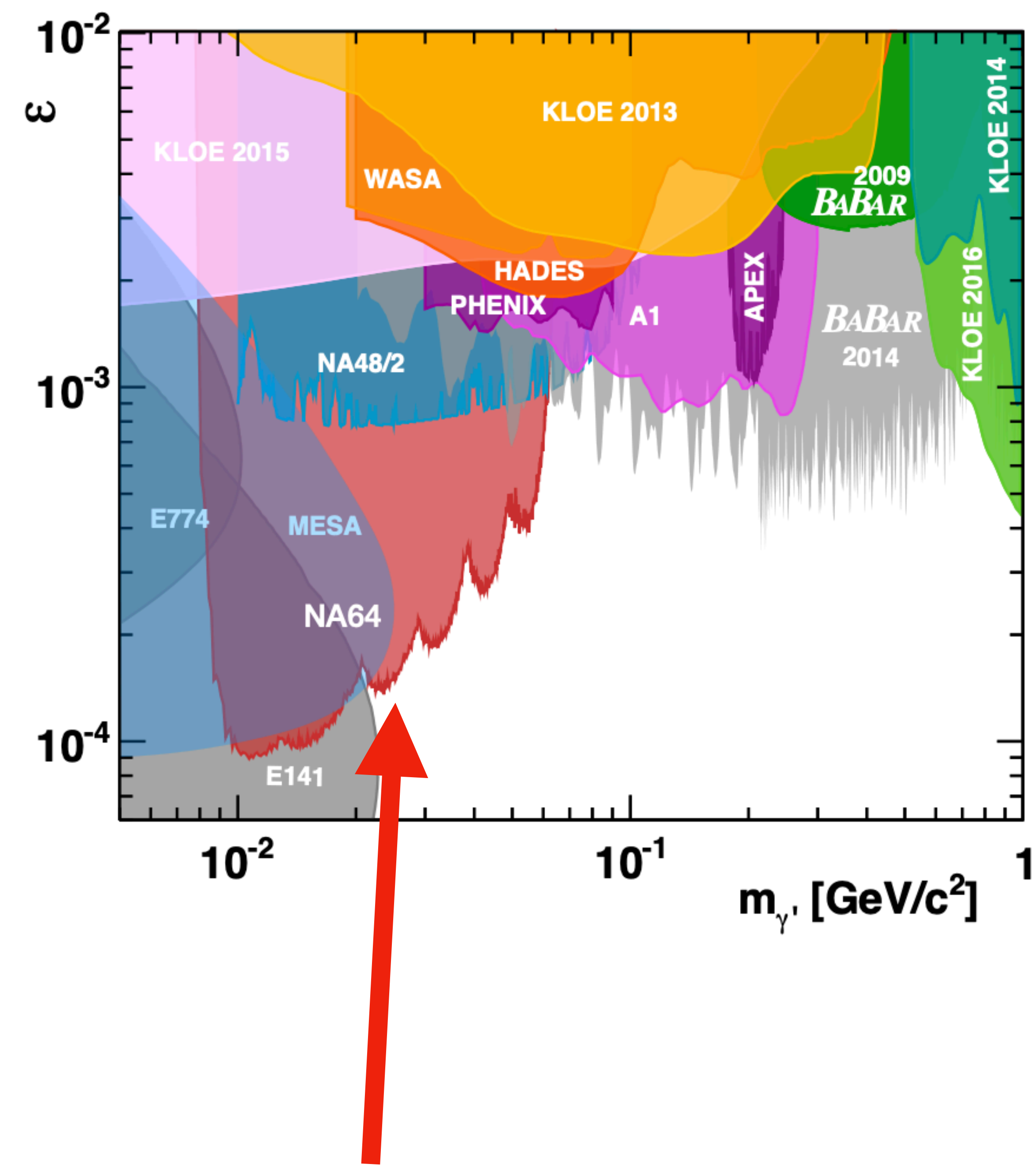


- Many experiments run in the 80s have strong bounds

Shorter lifetimes

MAGIX@MESA
Shorter lifetime

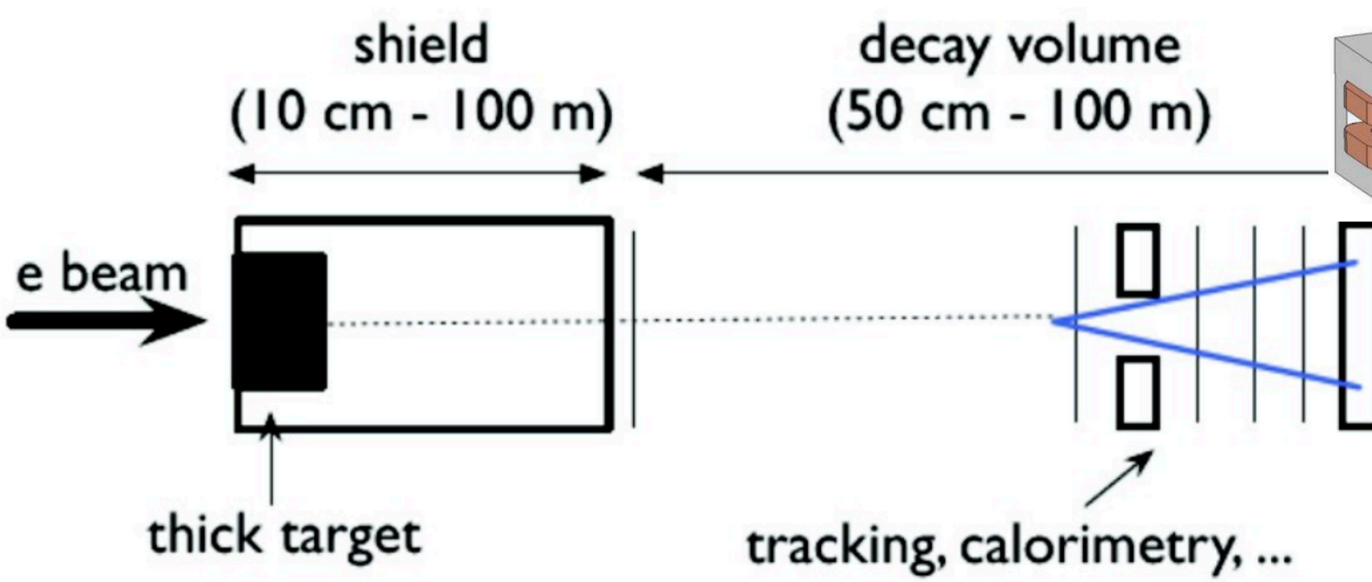


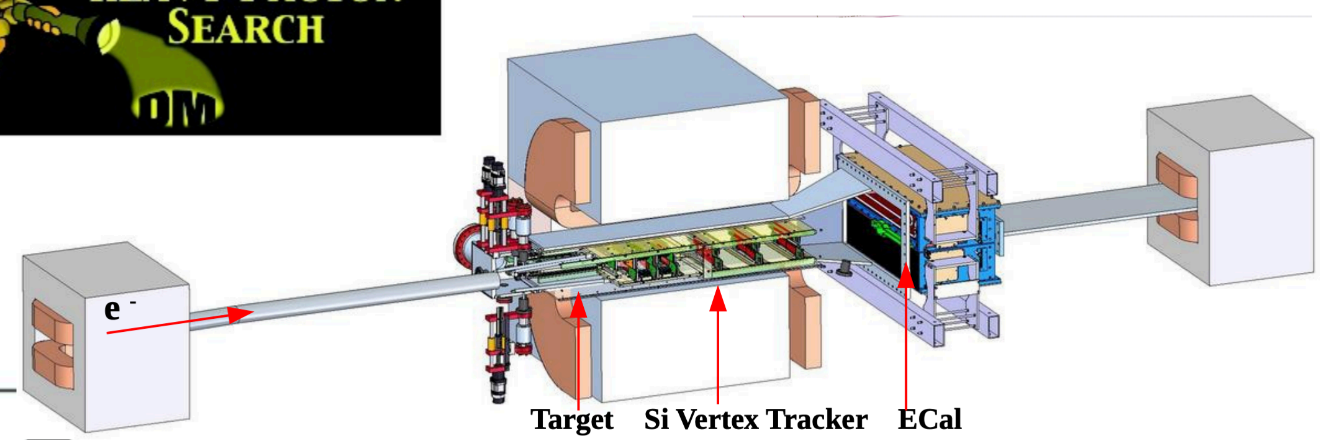


MAGIX beam produces a strong low E electron beam
Projected DM bounds can probe new territory

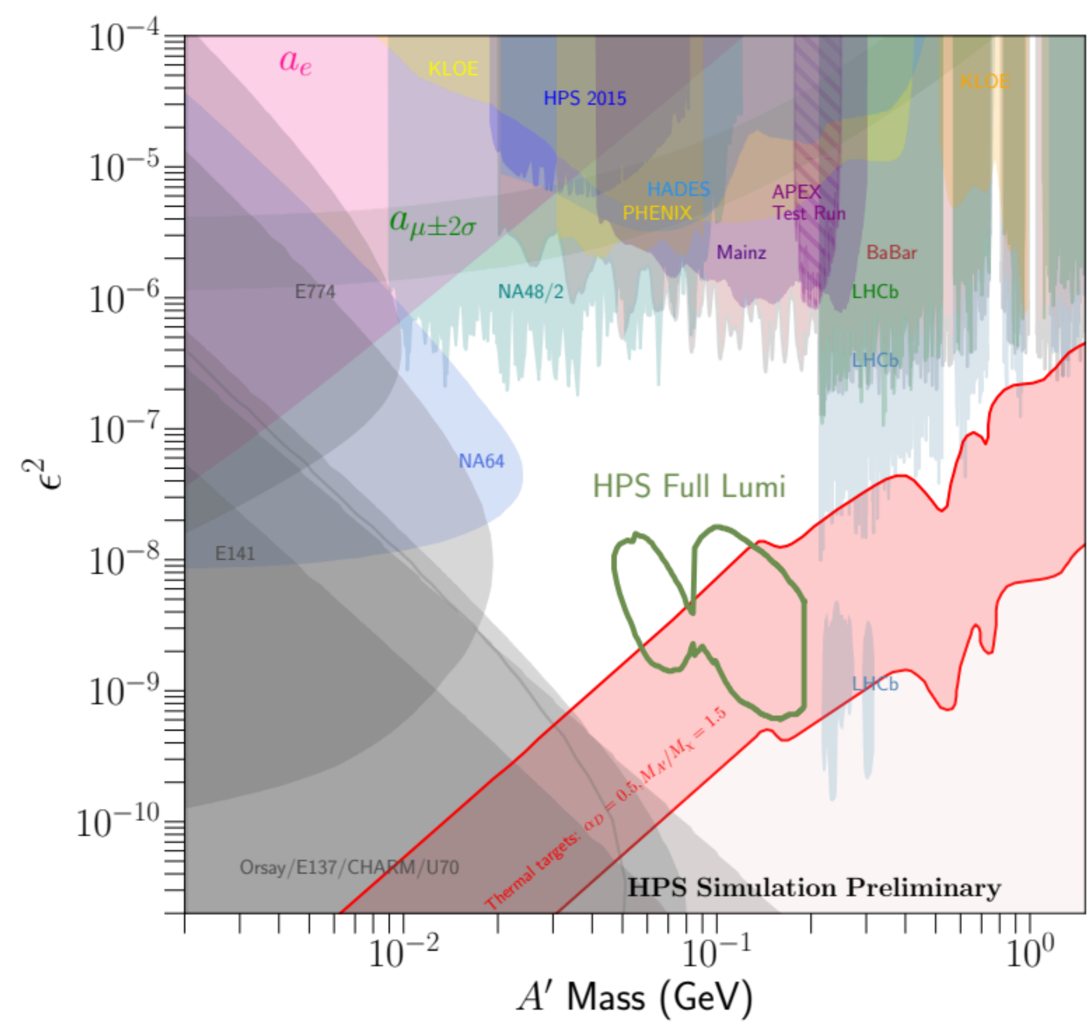
Heavy Photon Search

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



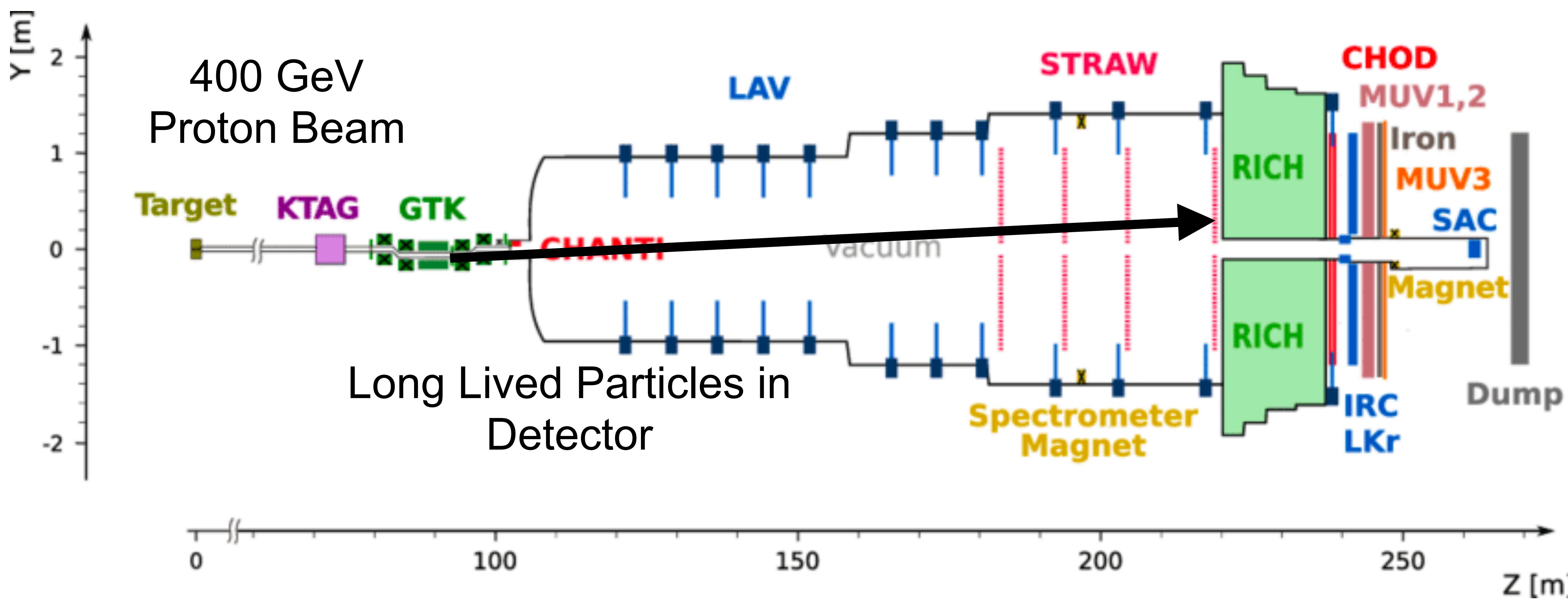


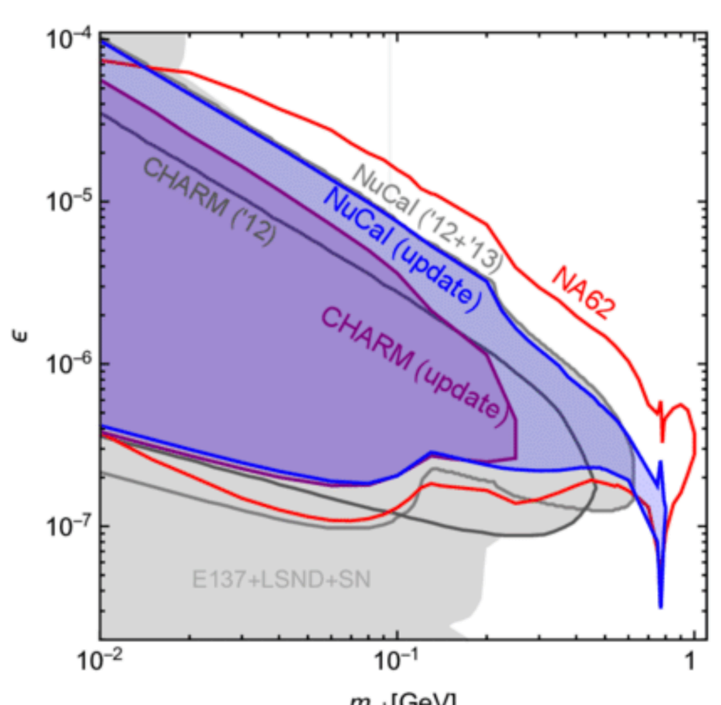
- Heavy Photon Search operating now
  - Expect some results soon



NA62

- Experiment currently focusing on kaon decays



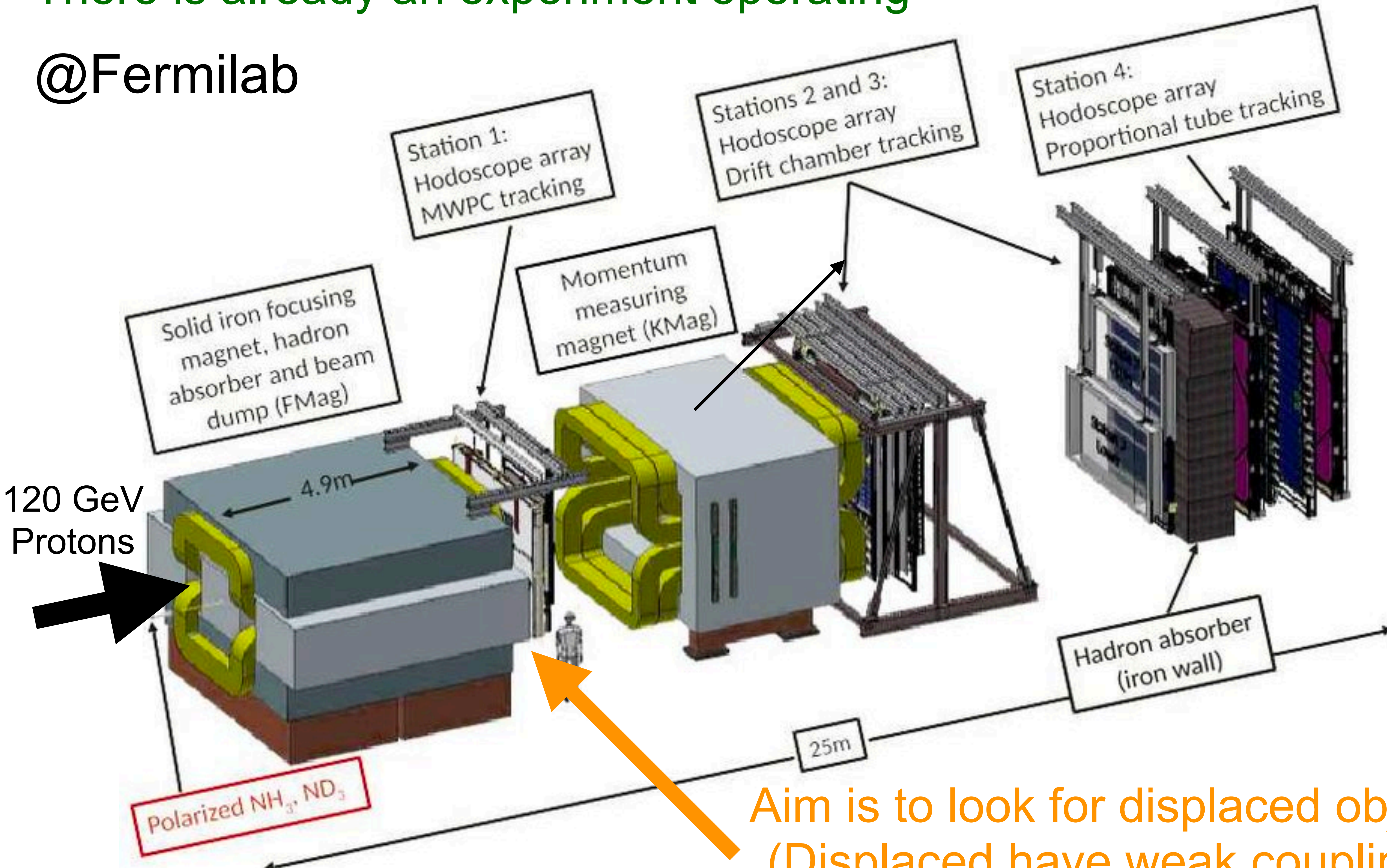


- Runs in various modes depending on beam
  - Left plot is from protons on a Be target

Spin Quest Experiment

There is already an experiment operating

@Fermilab

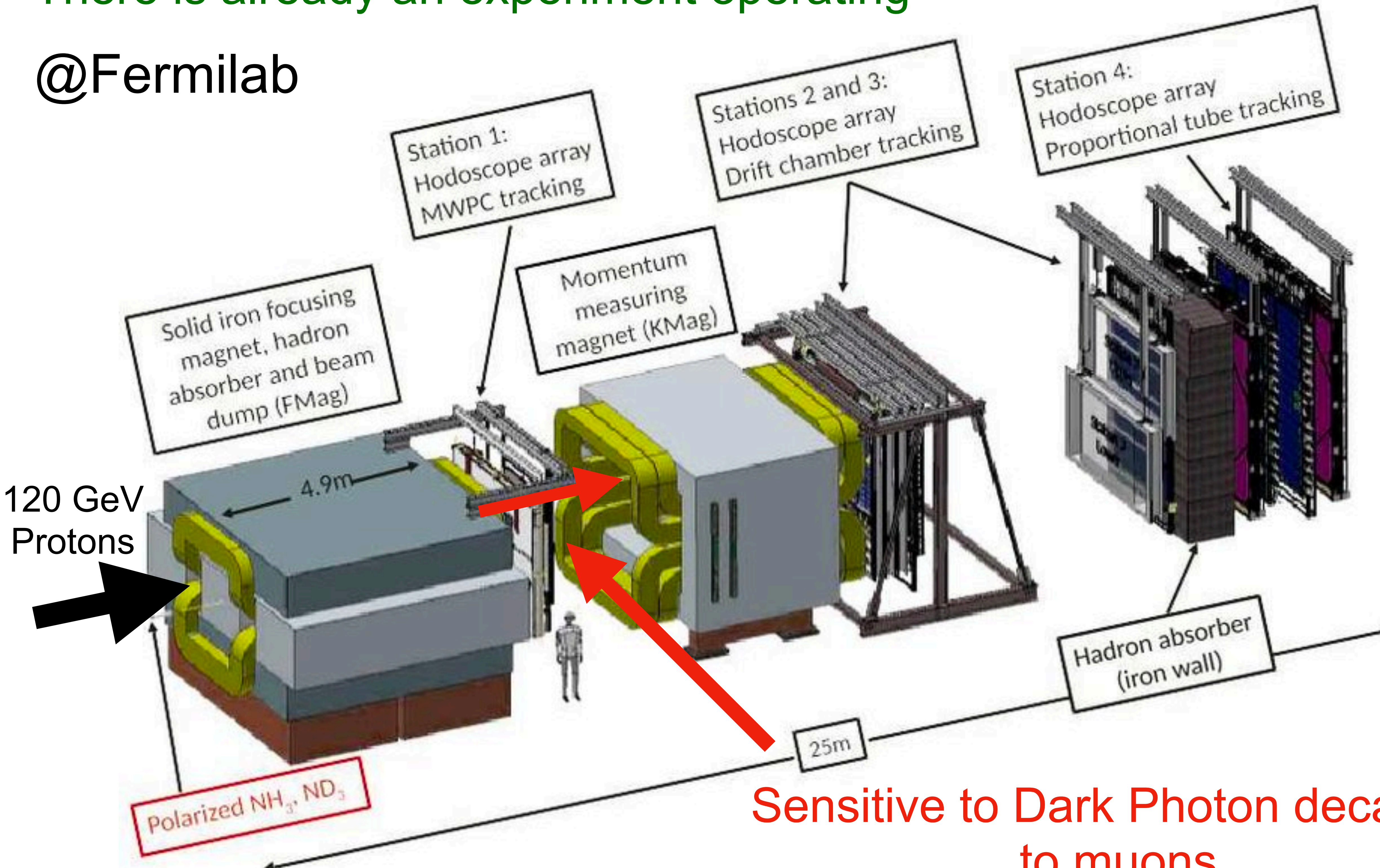


Aim is to look for displaced objects
(Displaced have weak couplings)

Spin Quest Experiment

There is already an experiment operating

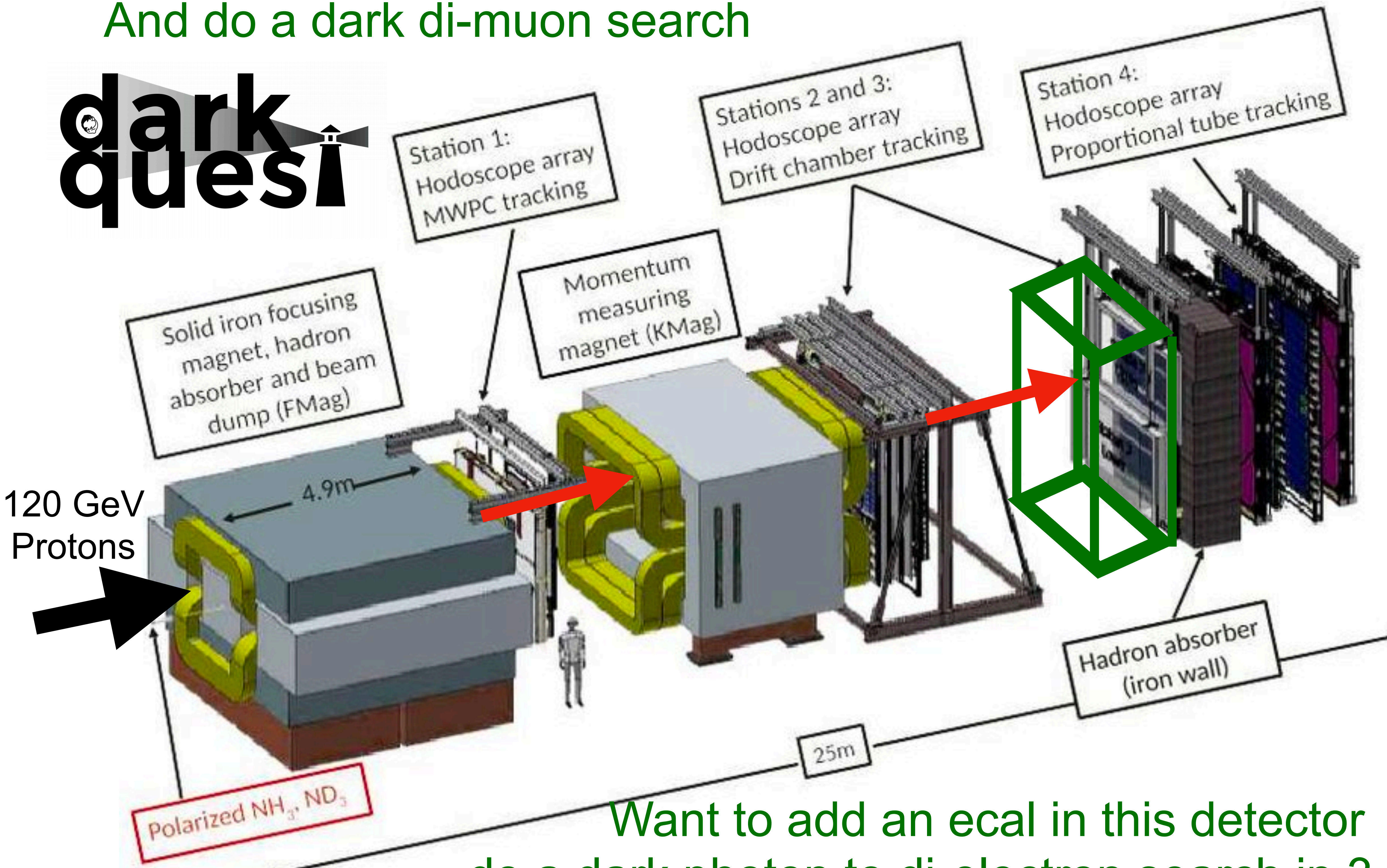
@Fermilab



Sensitive to Dark Photon decaying to muons

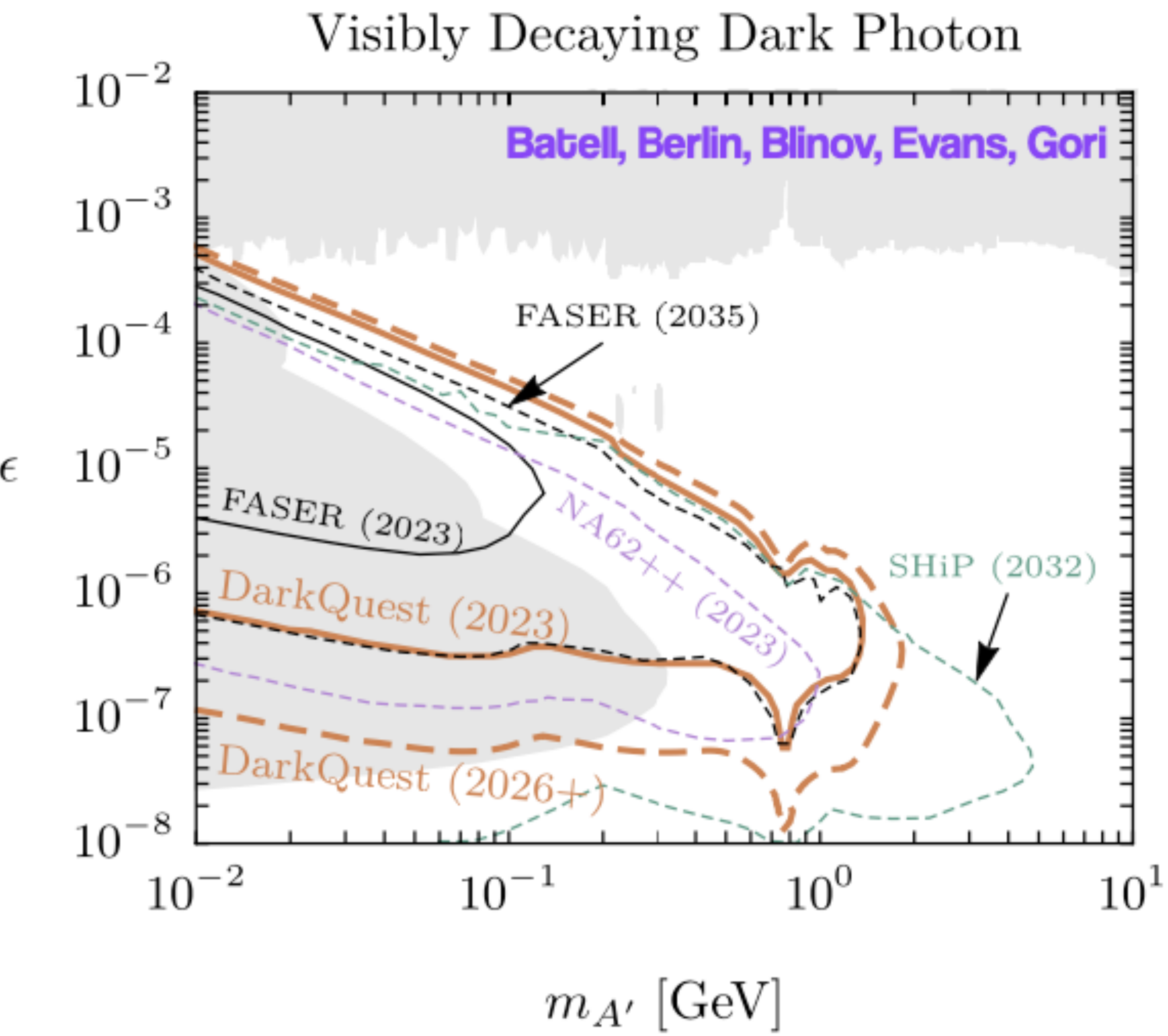
Dark Quest

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

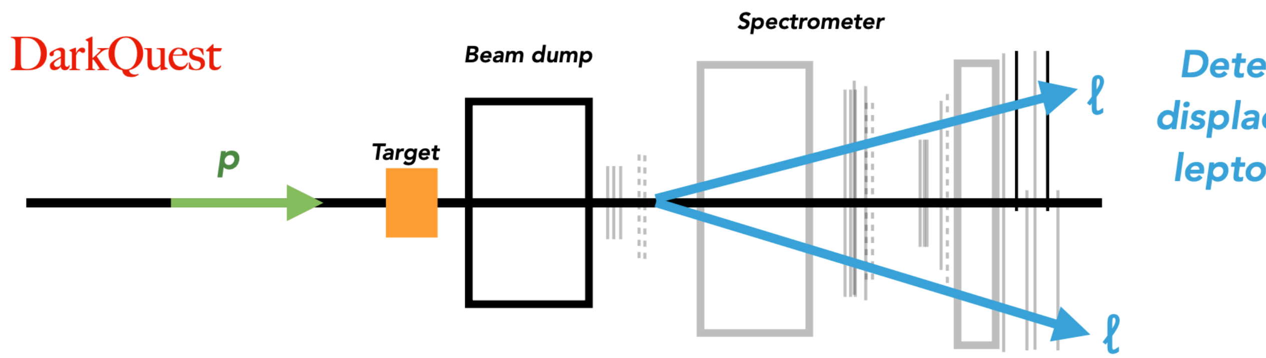


Want to add an ecal in this detector
do a dark photon to di-electron search in 3 years

Dark Quest



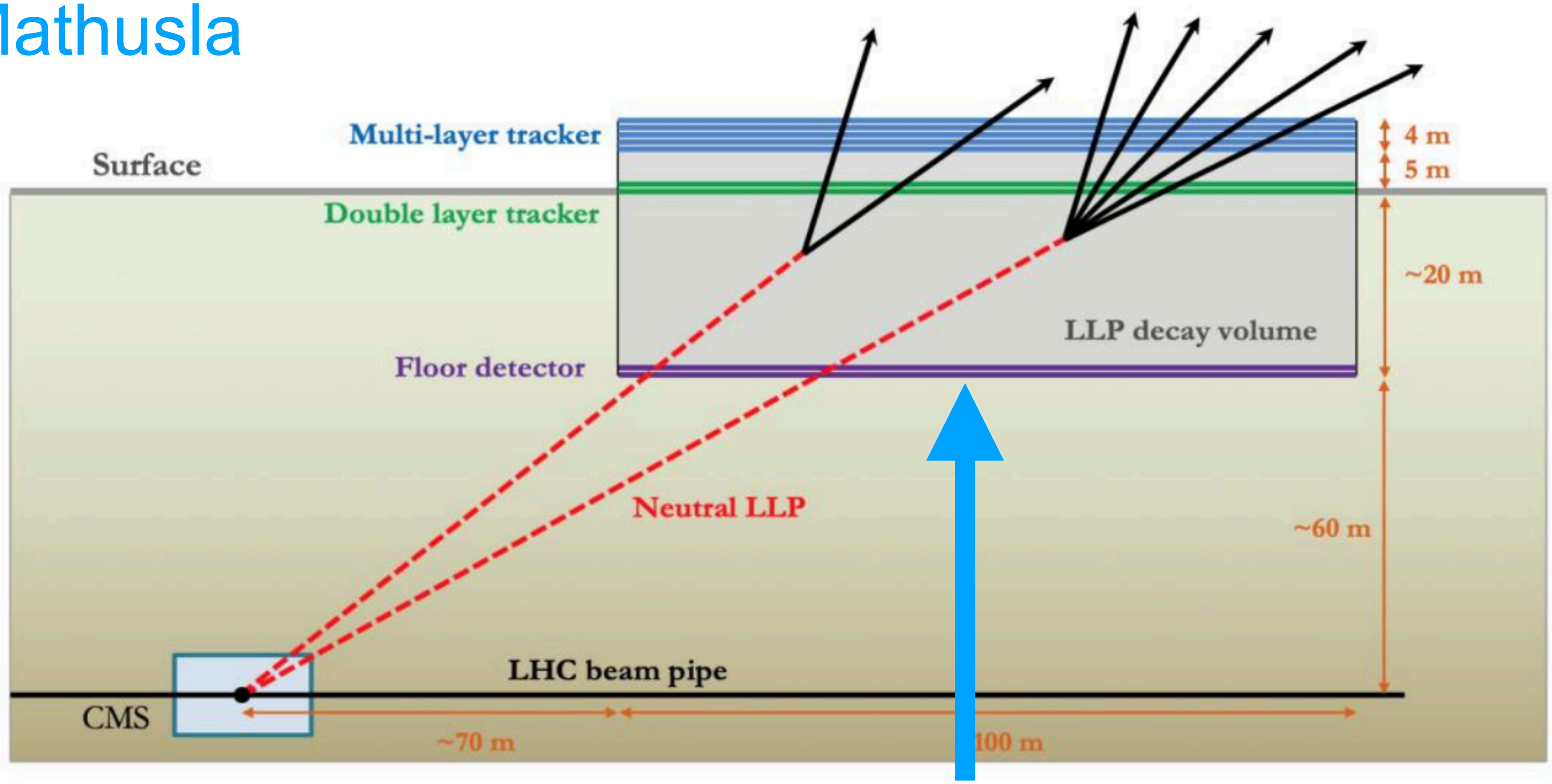
Sensitive to small couplings above the previous very long-lived searches



Addition of the Ecal
Allows for a broad range of other options

And @LHC

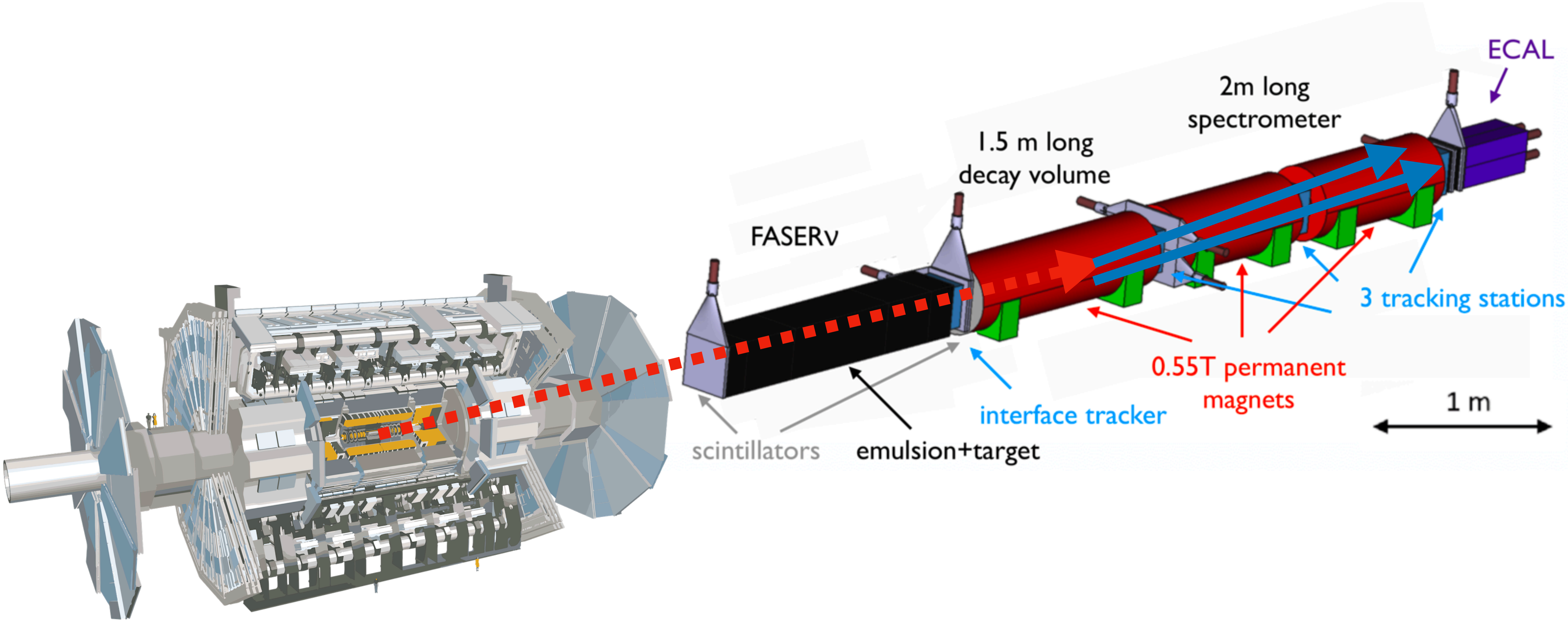
Mathusla



Giant Detector the size of an IKEA Store on the Surface

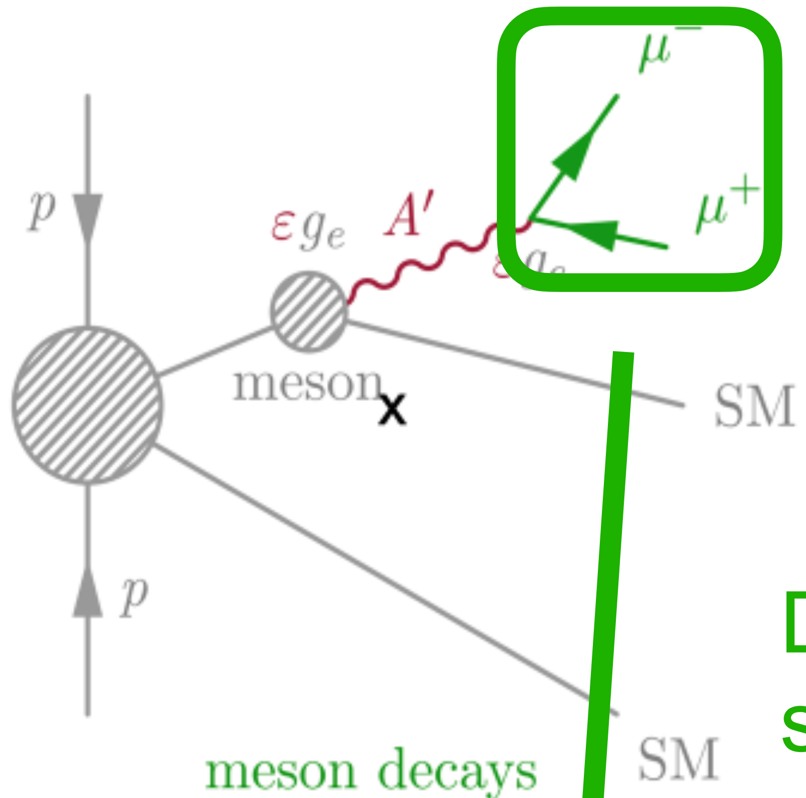
- Can also use the LHC collisions to look for long lived particles

FASER



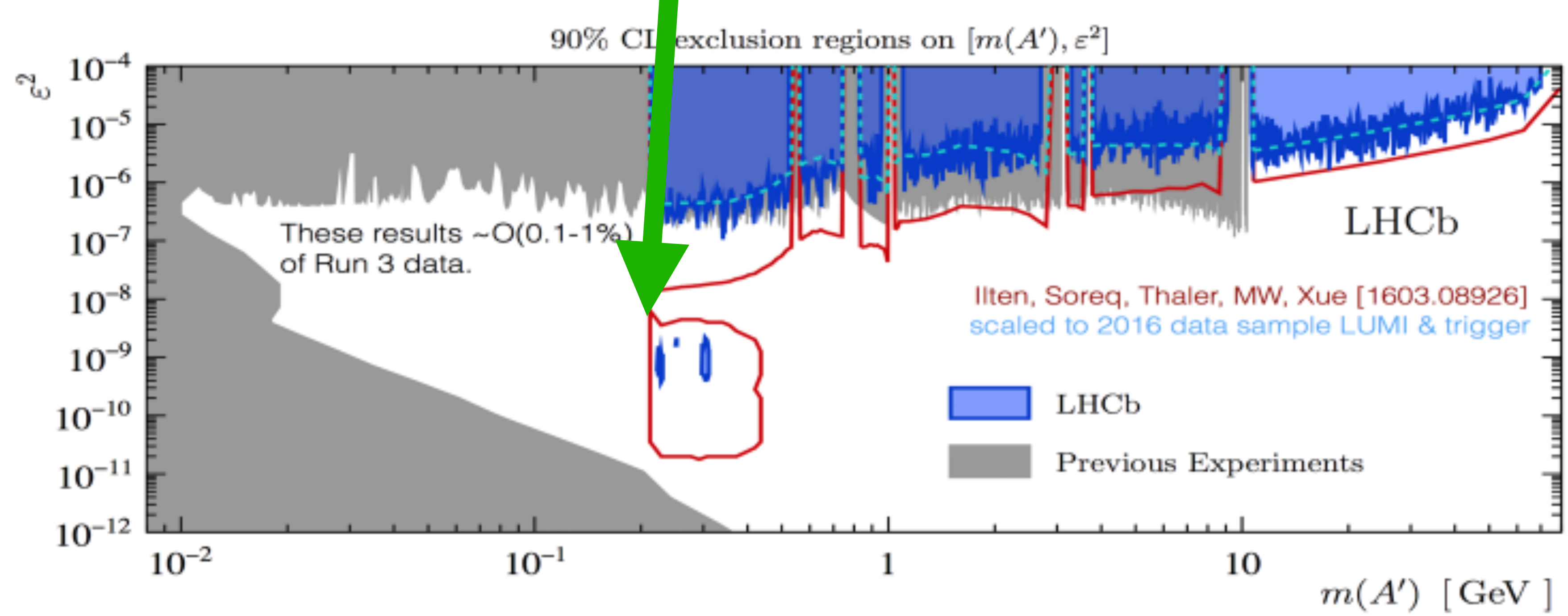
- FASER is a small detector along the beam near ATLAS
  - Can also look for collinear dark photons of ATLAS collisions

Dark Photon DM Heavy

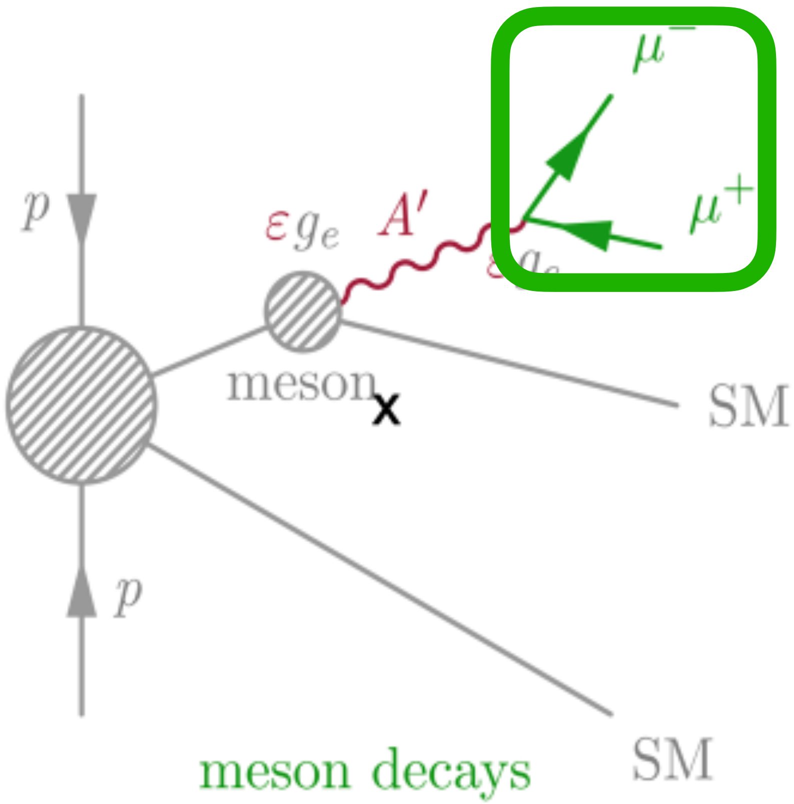


- As we saw before
  - Dark Photon can also be displaced
  - LHCb has used this effectively

Displaced selection can push to smaller couplings



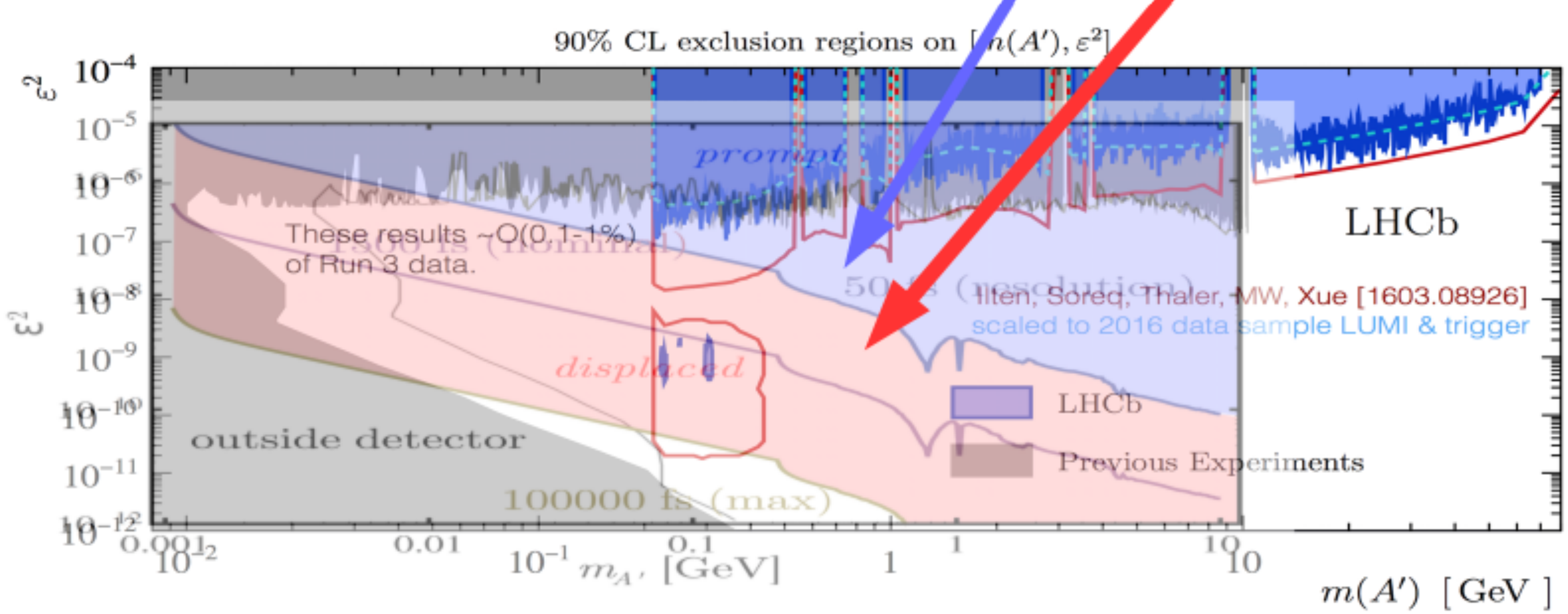
Dark Photon DM Heavy



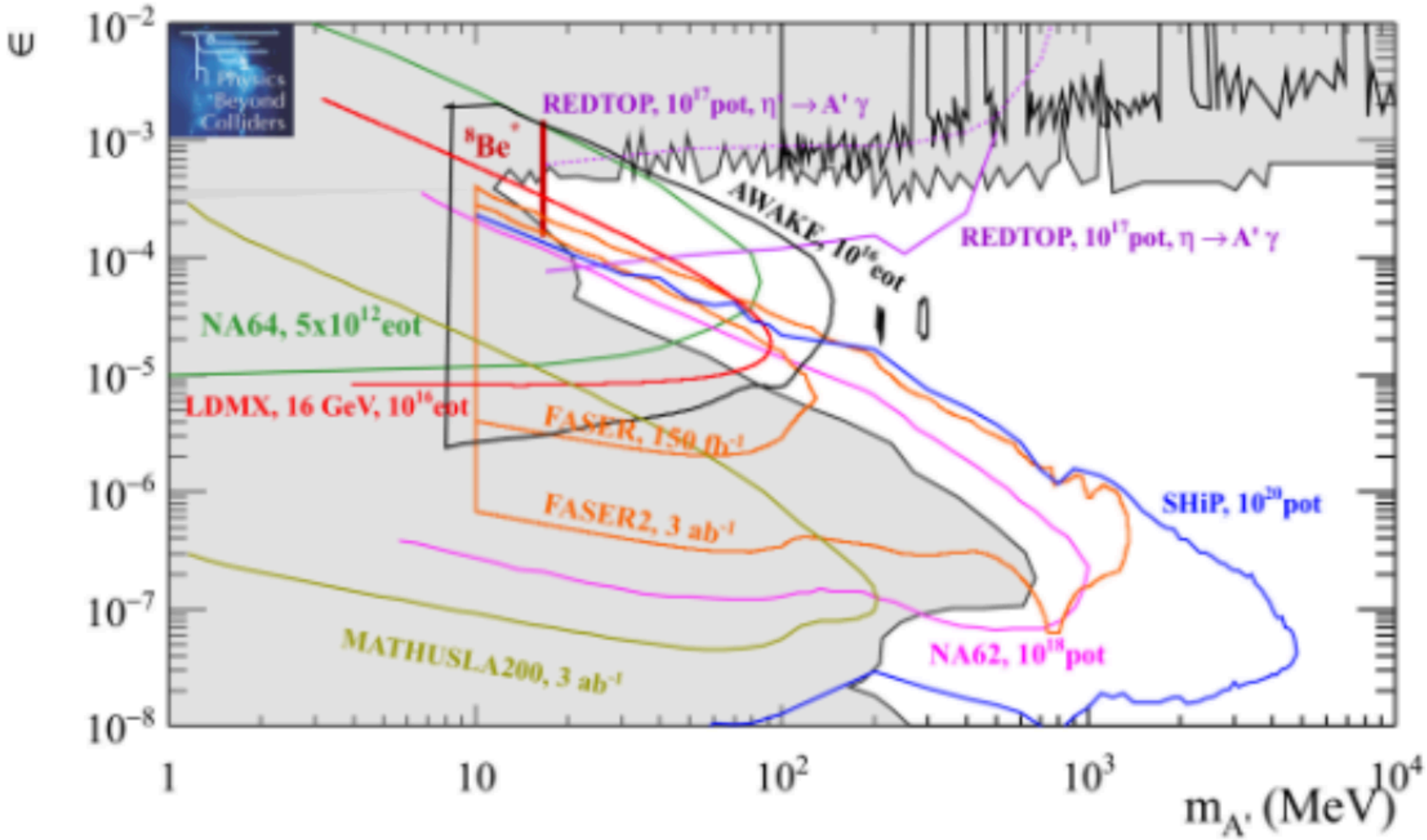
- As we saw before
  - Dark Photon can also be displaced
  - LHCb has used this effectively

Prompt Search

Displaced Search

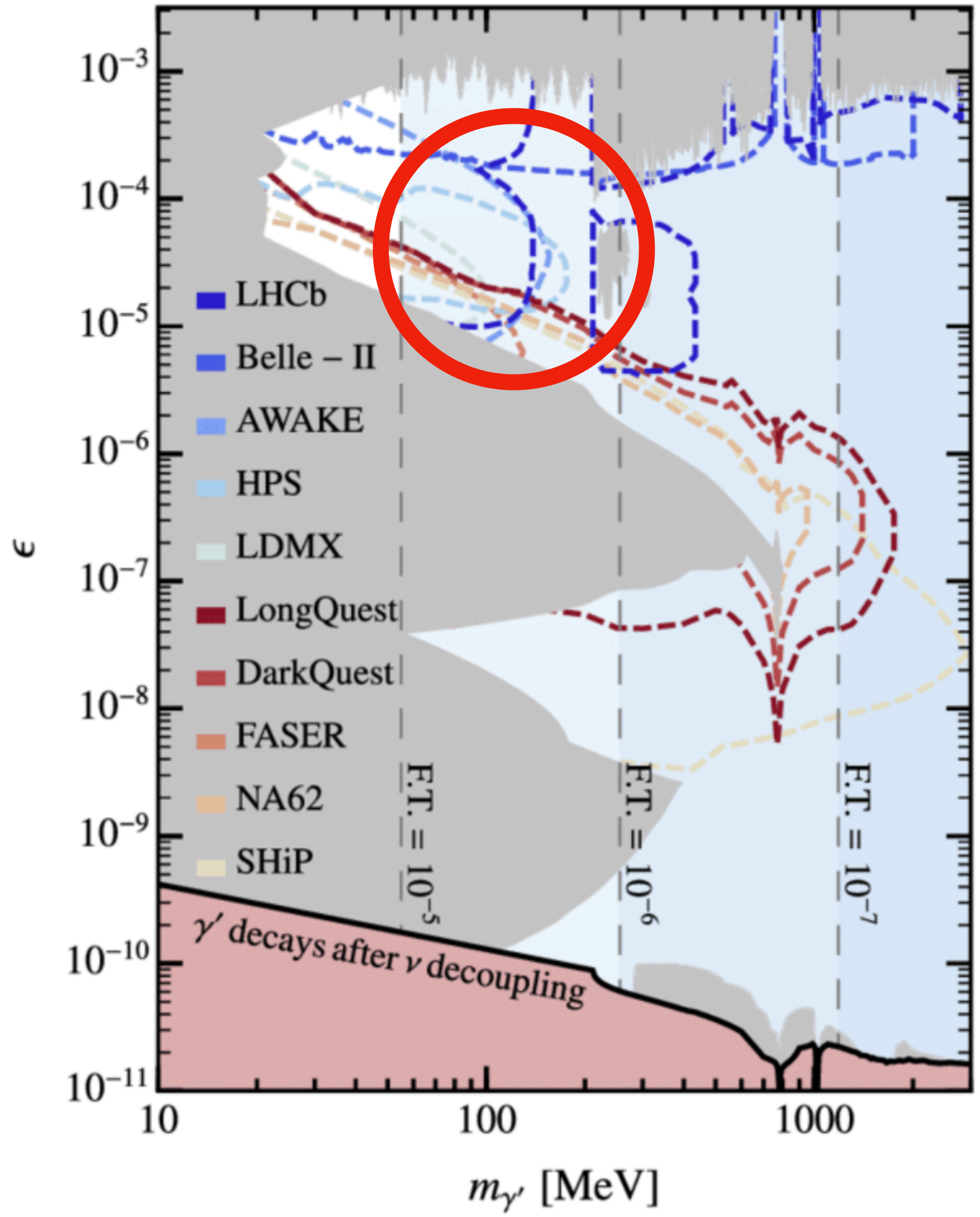


LHC on Dark Photon



- 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

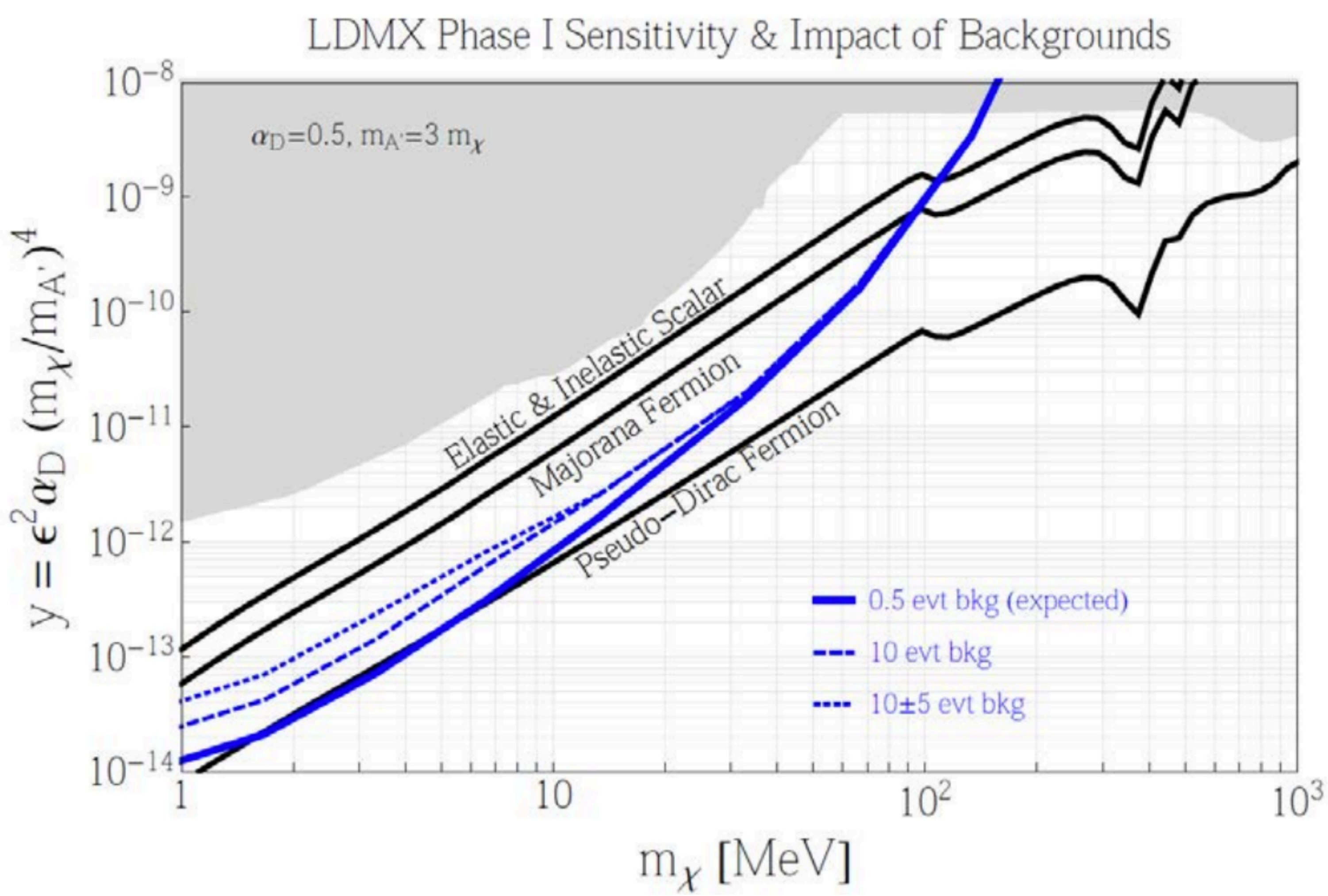
Overall each experiment covers slightly different territory

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

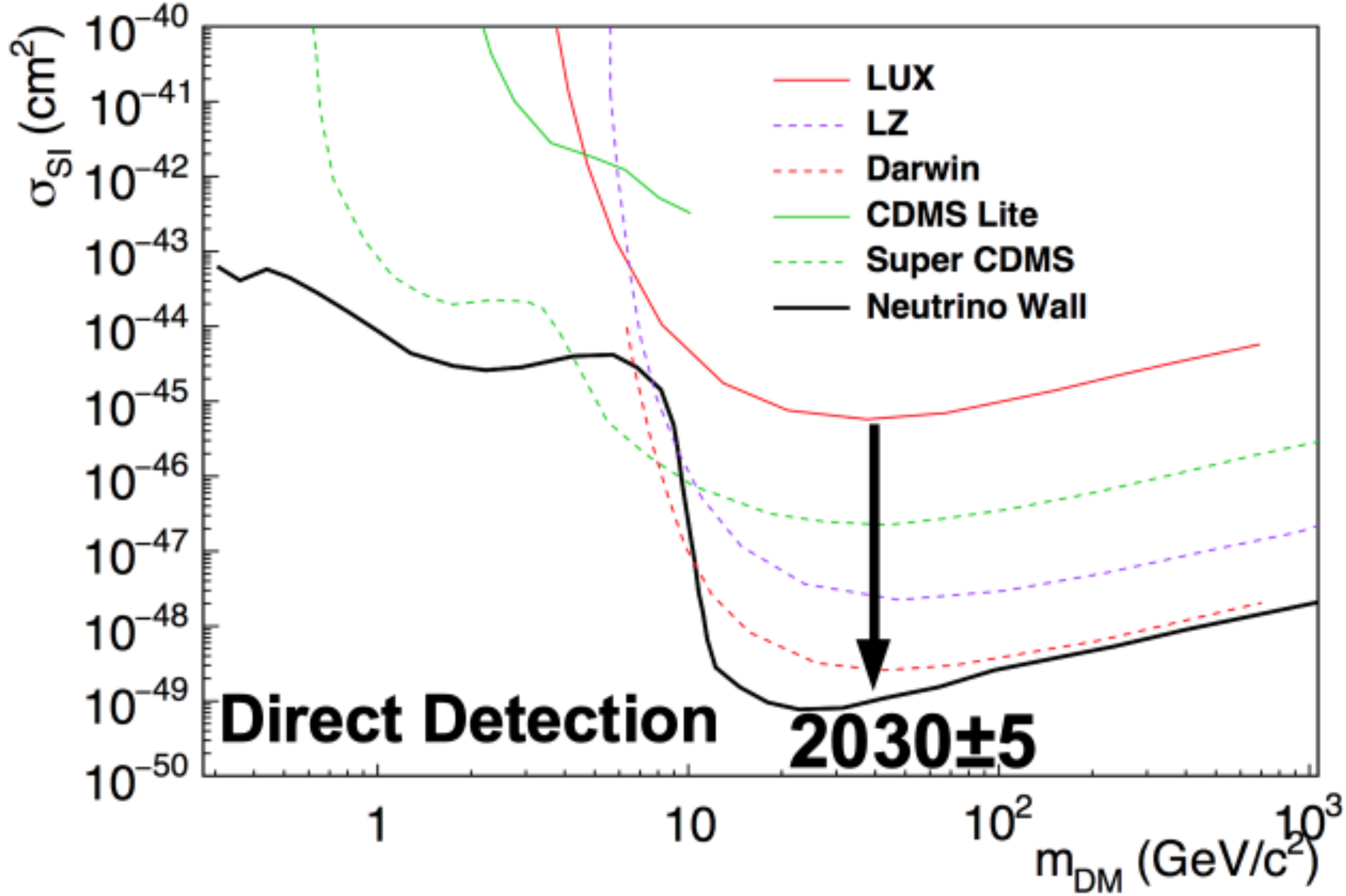
- Expect the most interesting region to be measured soon
  - Most projected experiment lines shown are likely to run

Disucucssion Questions

How do we find g-2?

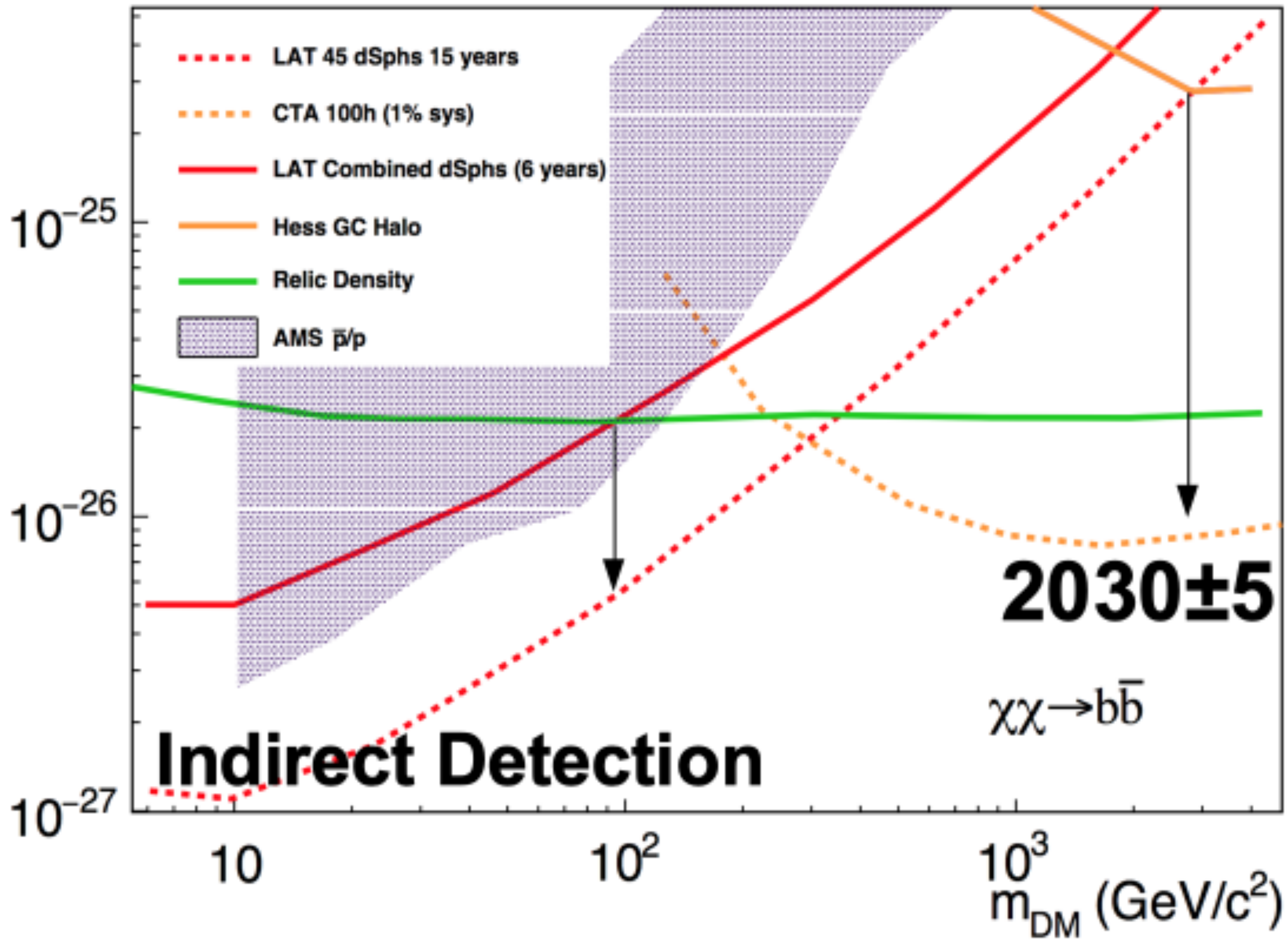
Drivers for the next 10 years

Dark Matter searches not @ collider



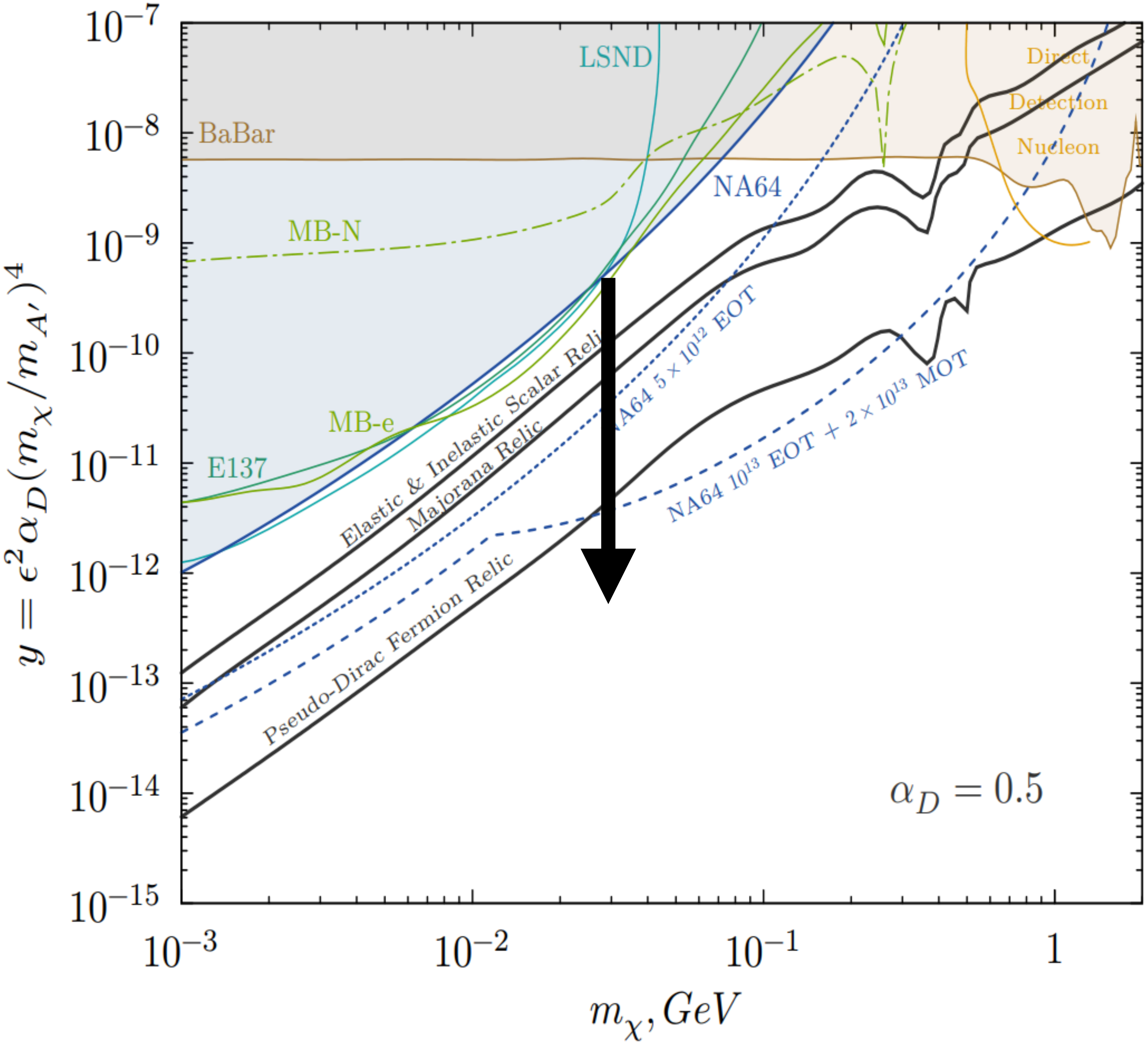
Goal: get to the Neutrino background wall

Dark Matter searches not @ collider



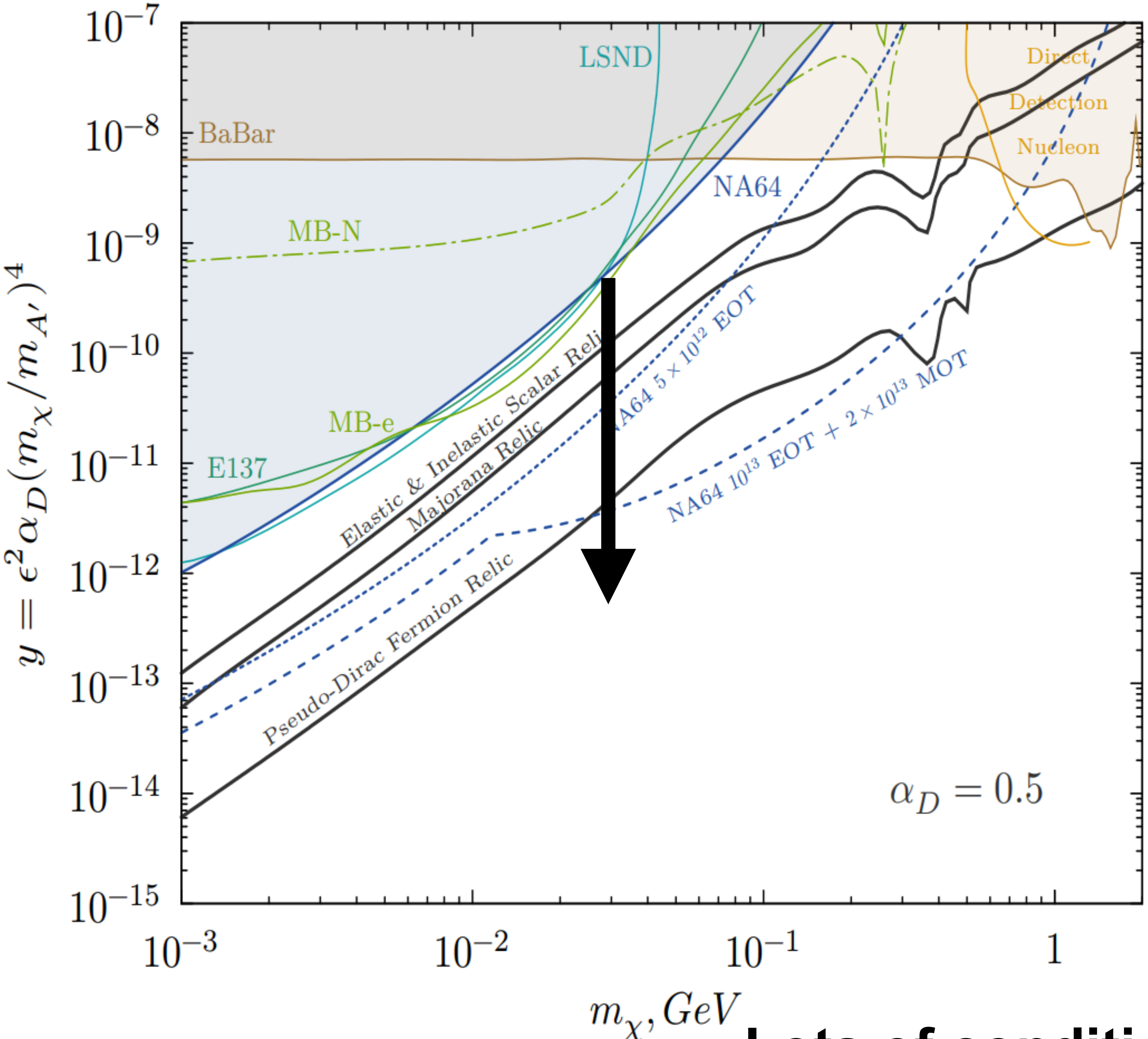
Goal: get to the Relic density

Light Dark Matter Goal



Can we make it to the relic line?

Light Dark Matter Goal



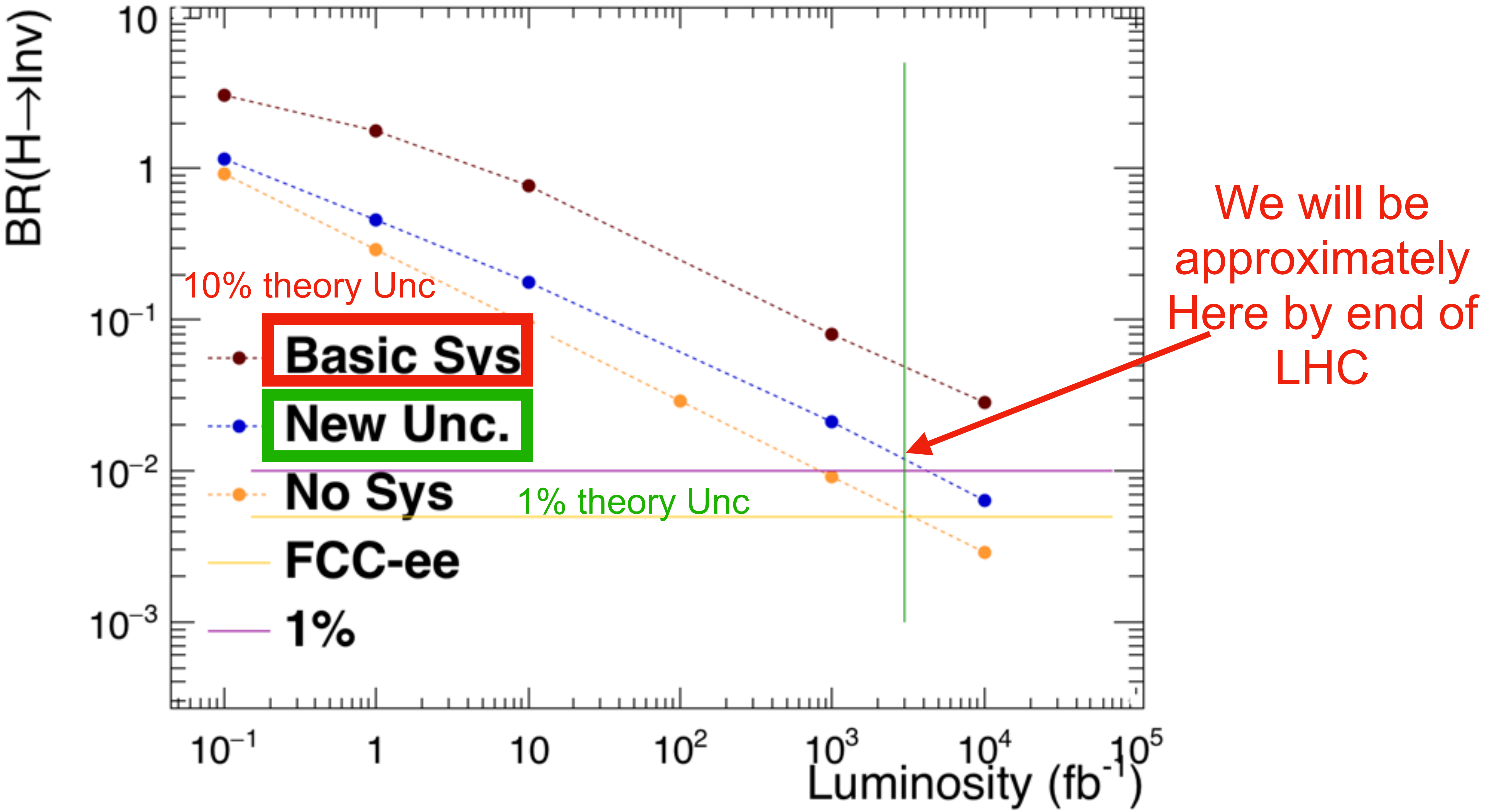
With invisible Searches
Can we make it to the relic line?
when $2m_{DM} < m_{MED}$

With visible Searches
Can we make it to the relic line?
when $m_{DM} < m_{MED}$

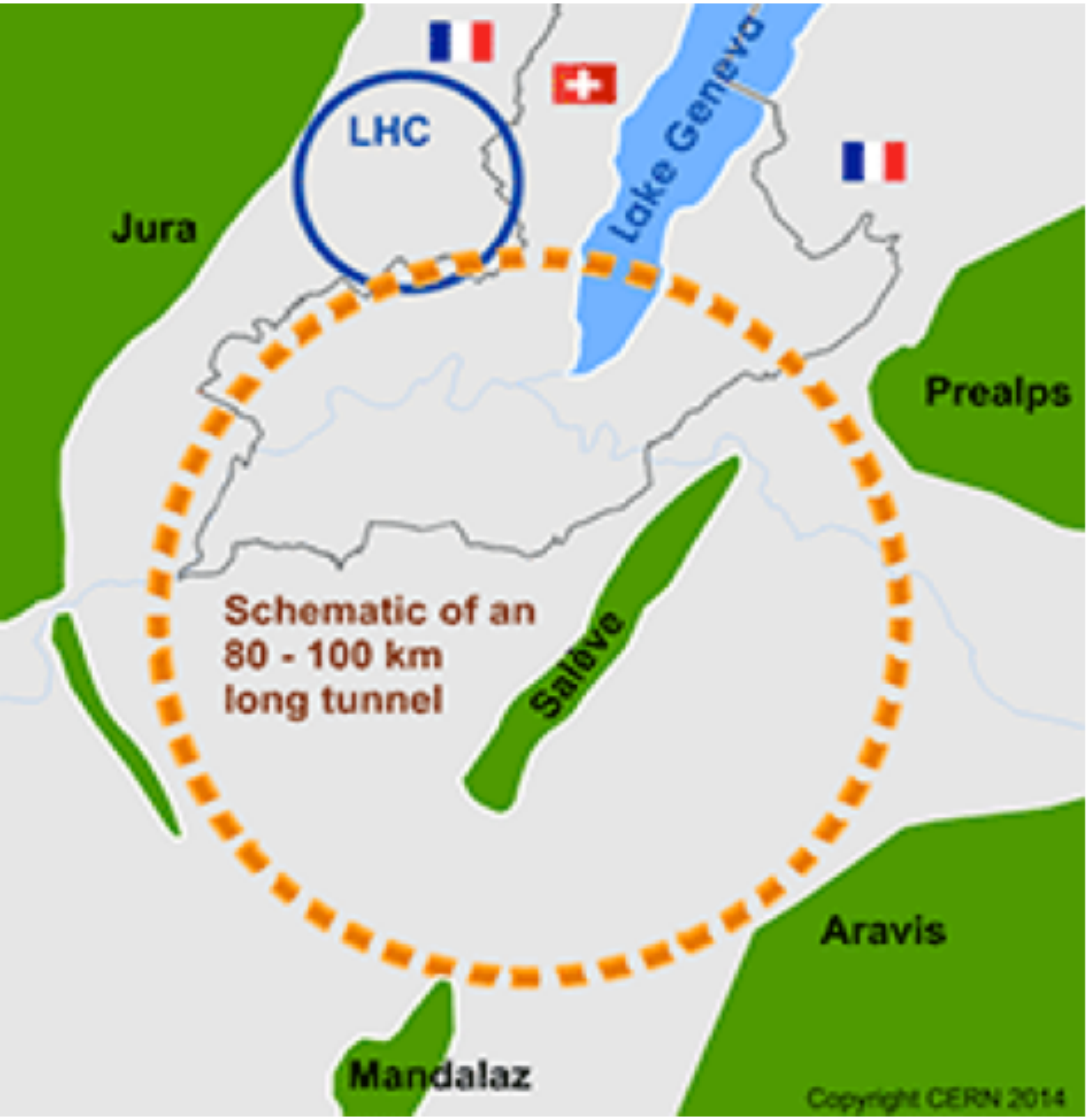
when $m_{DM} > m_{MED}$?
Gotta believe

Lots of conditions, but at least a target

Extrapolating to the full dataset



Up to 100 TeV?

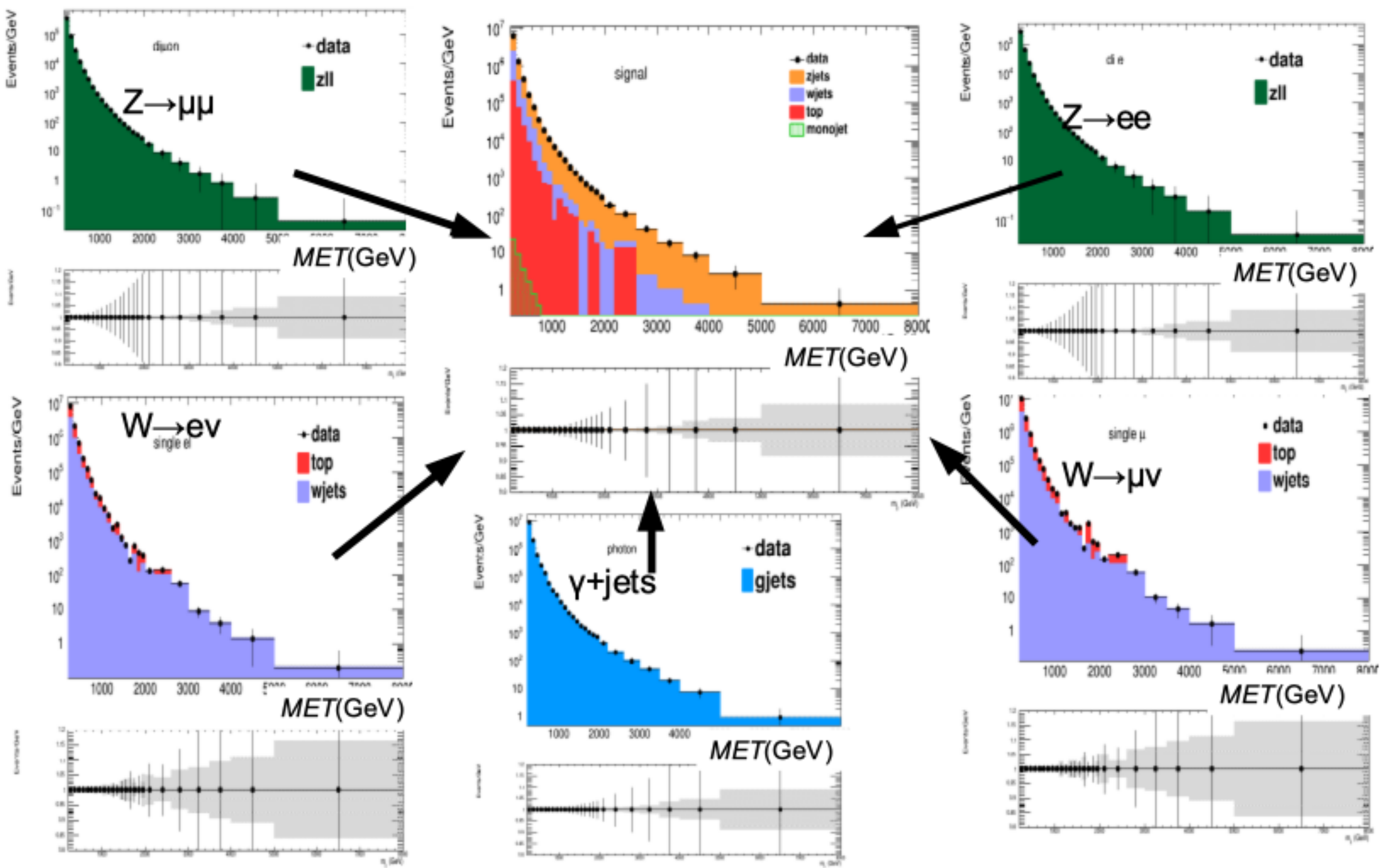


Current bound
yet to be determined

We take 100 TeV as a benchmark

Monojet@100 TeV?

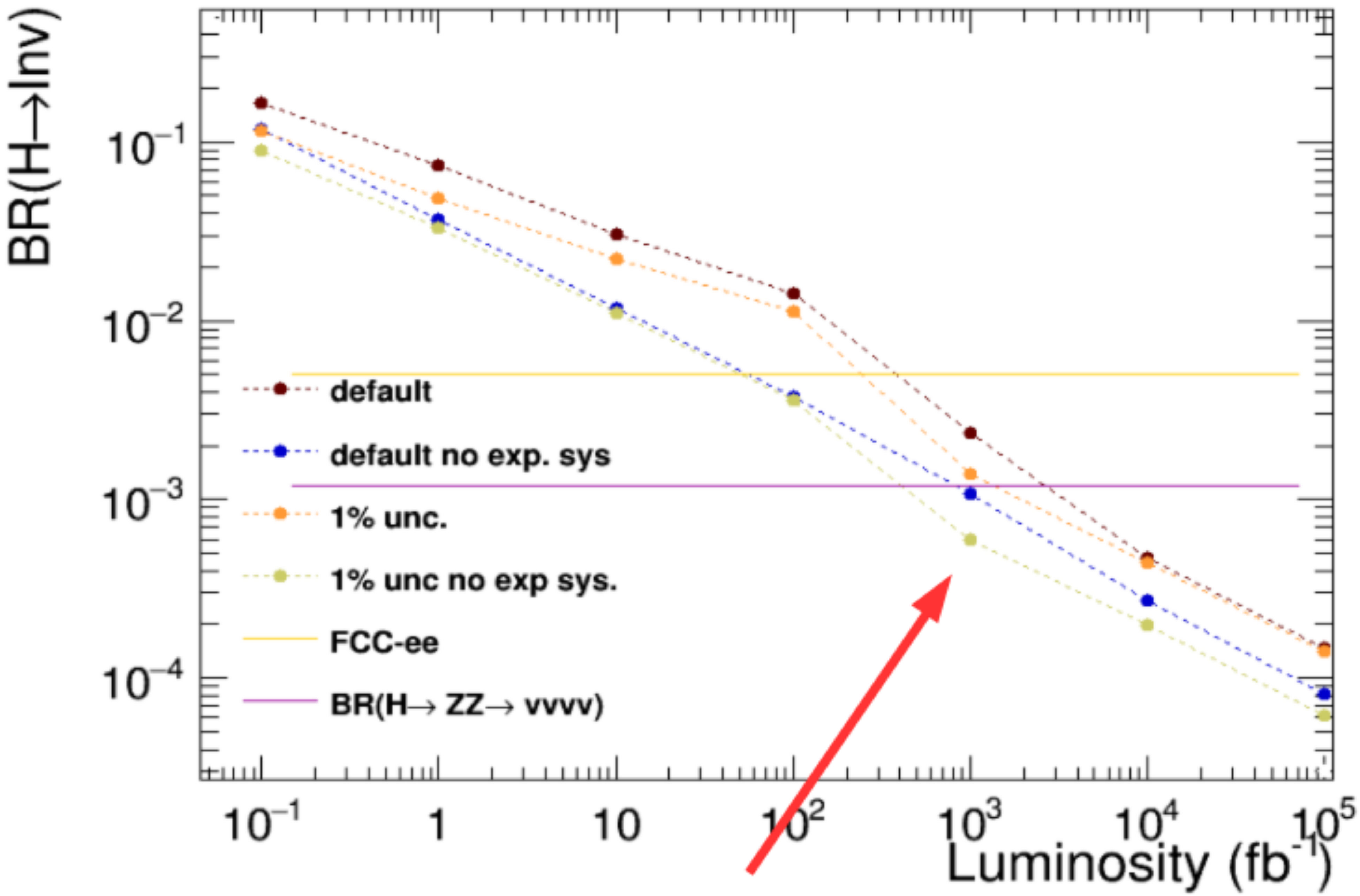
The same fitting scheme applies to 100 TeV (fits 1ab^{-1})



Straddling the lines of Precision

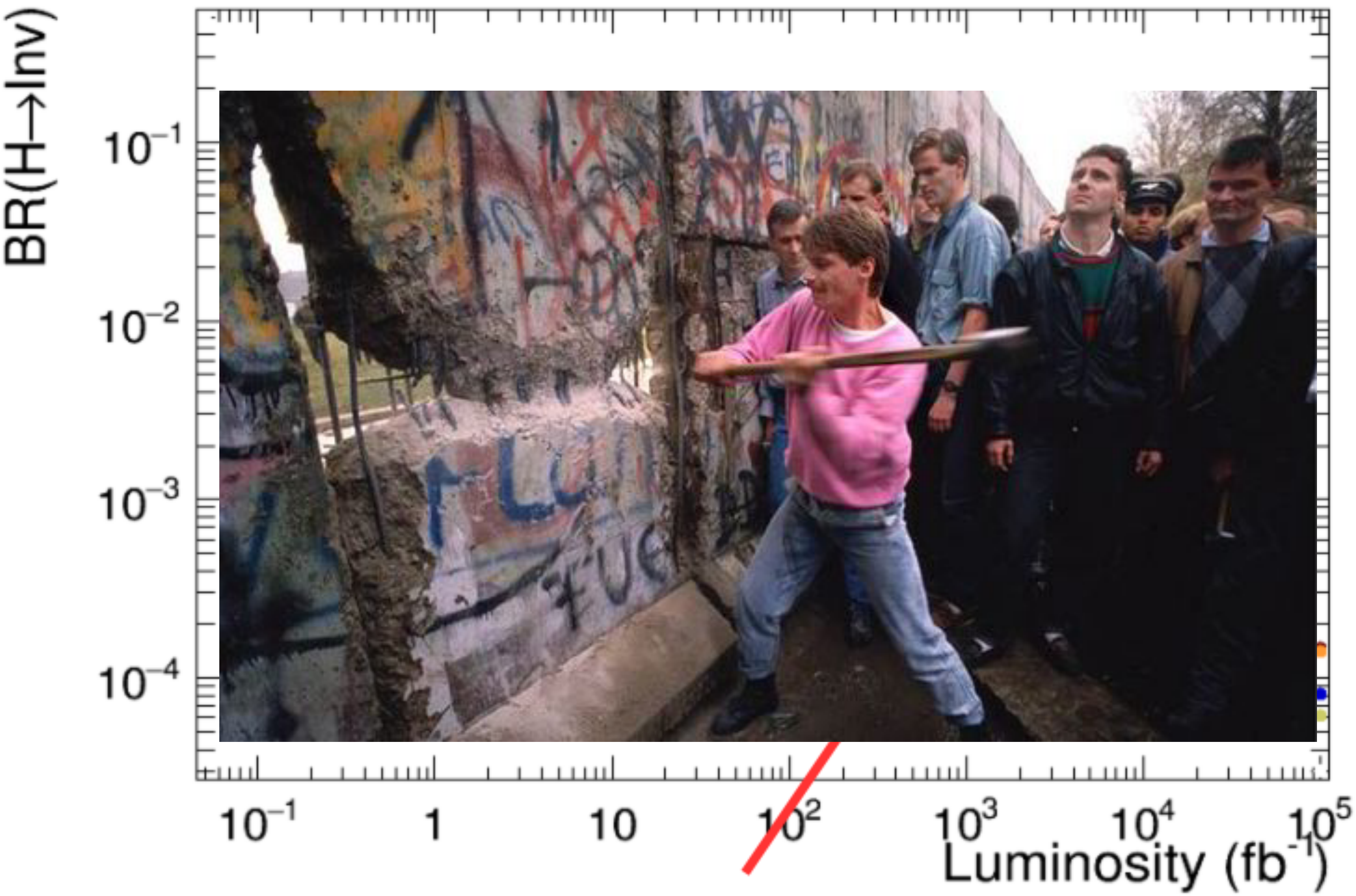
- The fit can constrain all the systematics simultaneously

No End in sight



There is no systematics wall

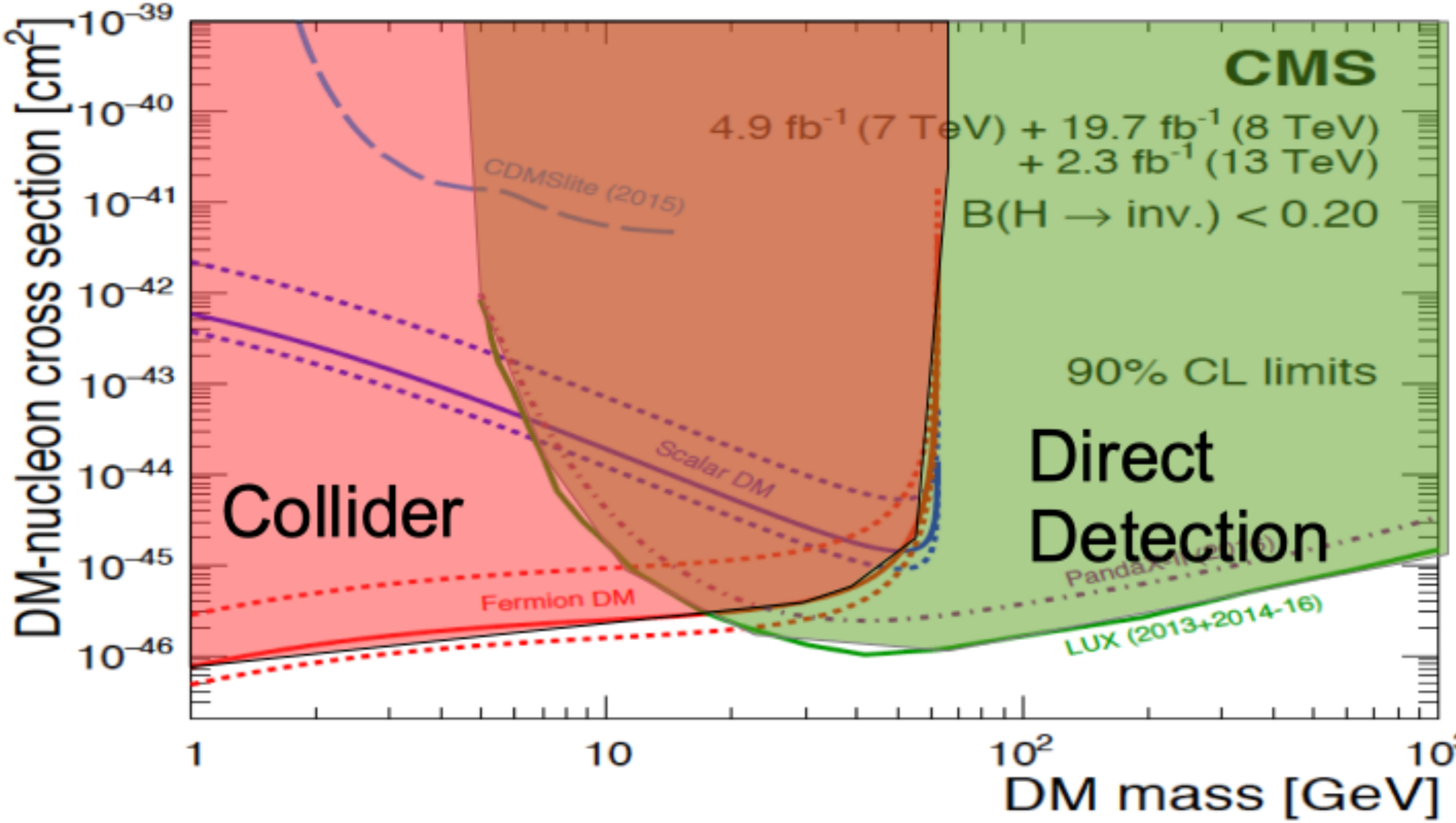
No End in sight



There is no systematics wall

Higgs Invisible Now

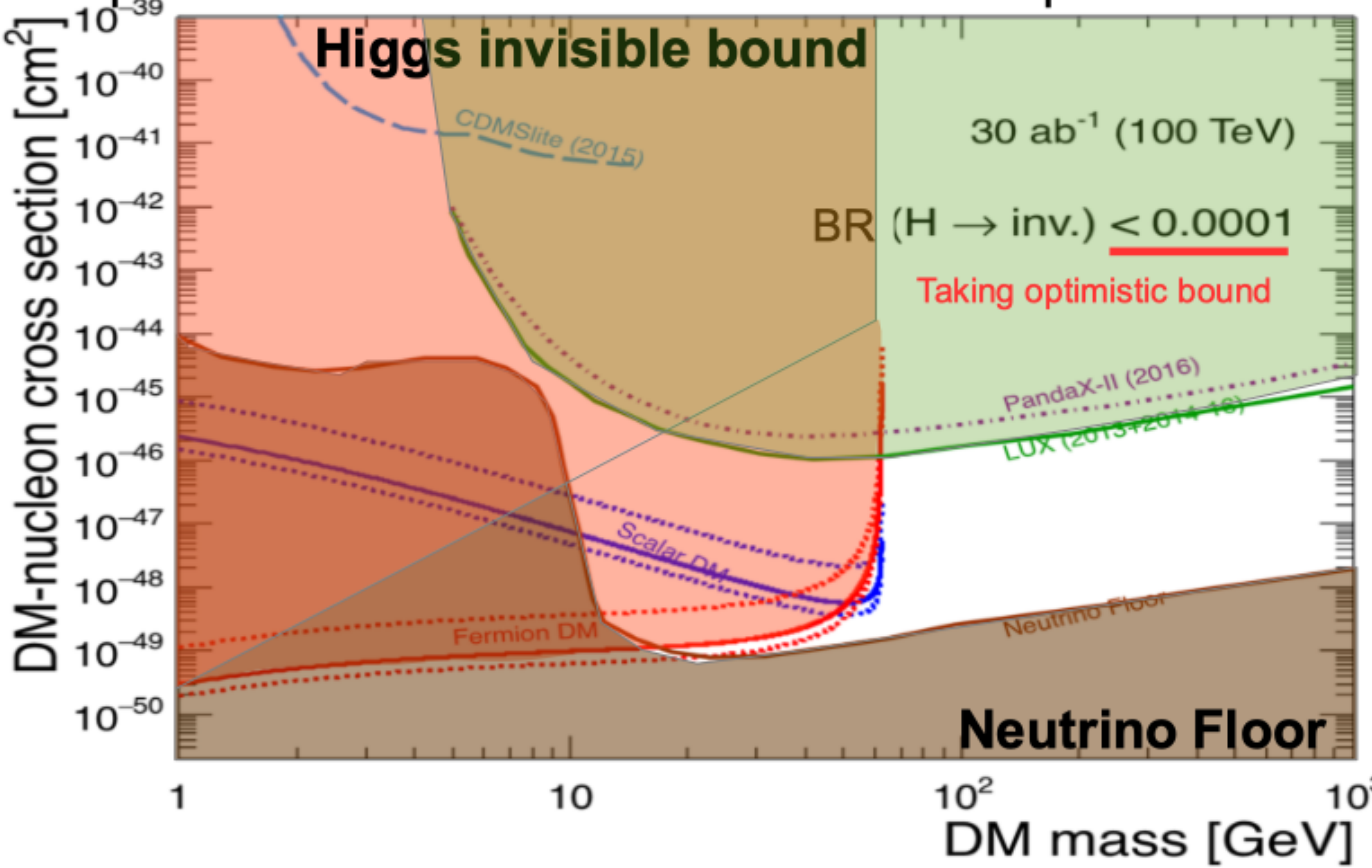
- Higgs to invisible :
  - Direct detection and collider are head to head



Competitive with the best direct detection experiments

Higgs Invisible 100 TeV

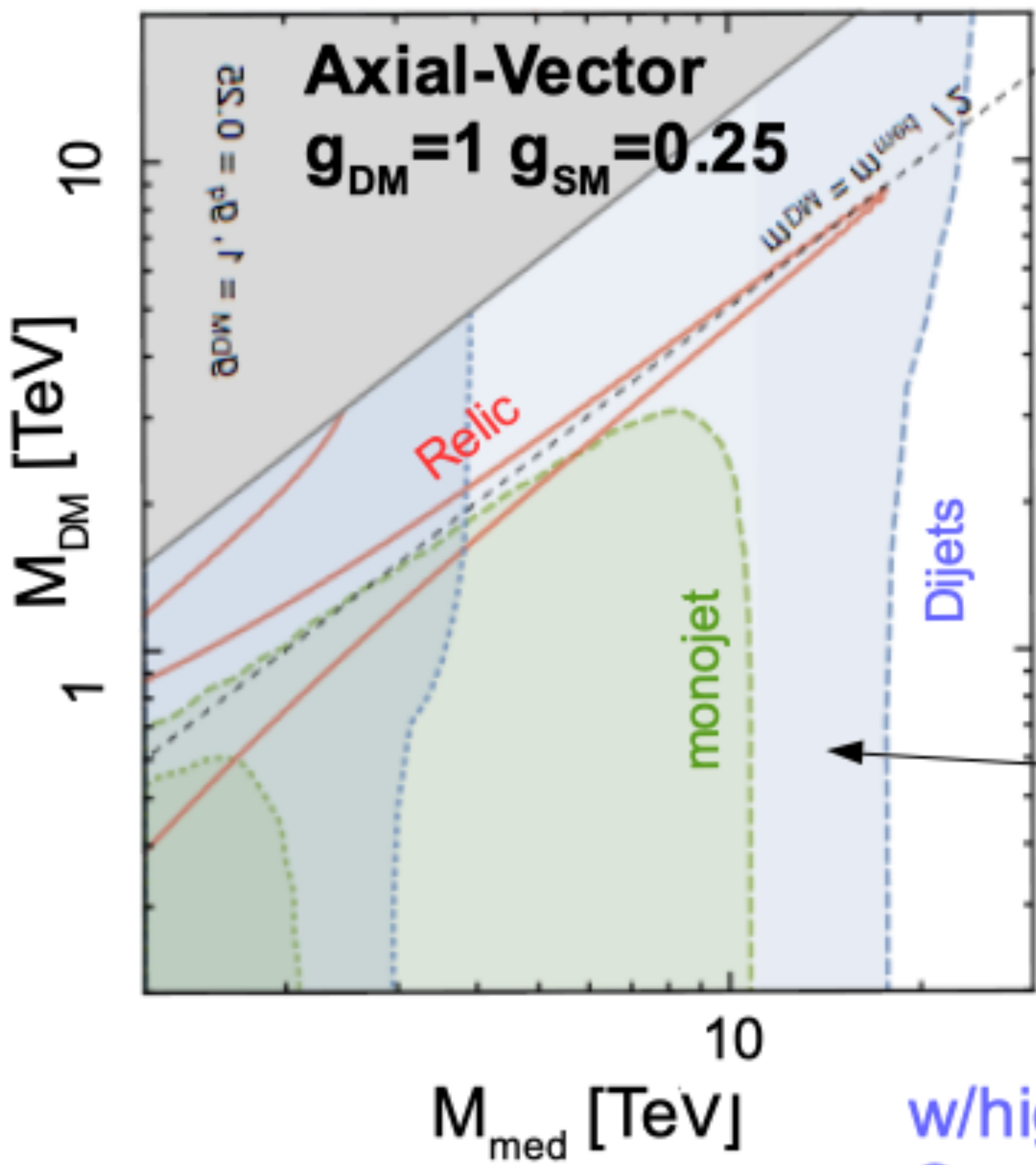
Competitive with the best direct detection experiments



Higgs invisible of 10^{-4} corresponds to g_{SM} from 10^{-3} to 10^{-2}

High Mass Reach

- Probing High mass reach



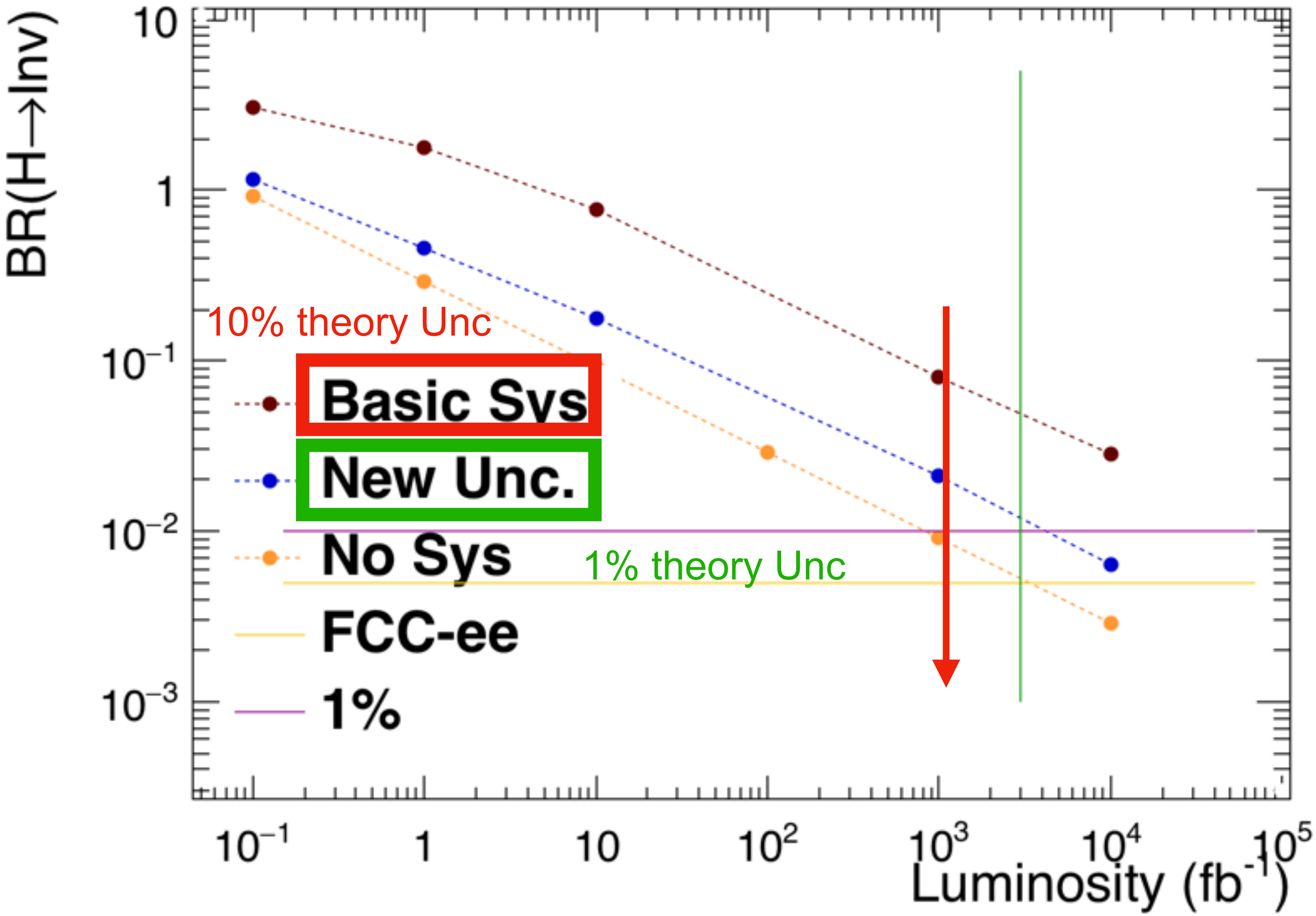
As with the LHC searches we find that Dijet searches are about 1.5x larger in mass range

We can cover the full allowed range of the relic density with a 100 TeV machine

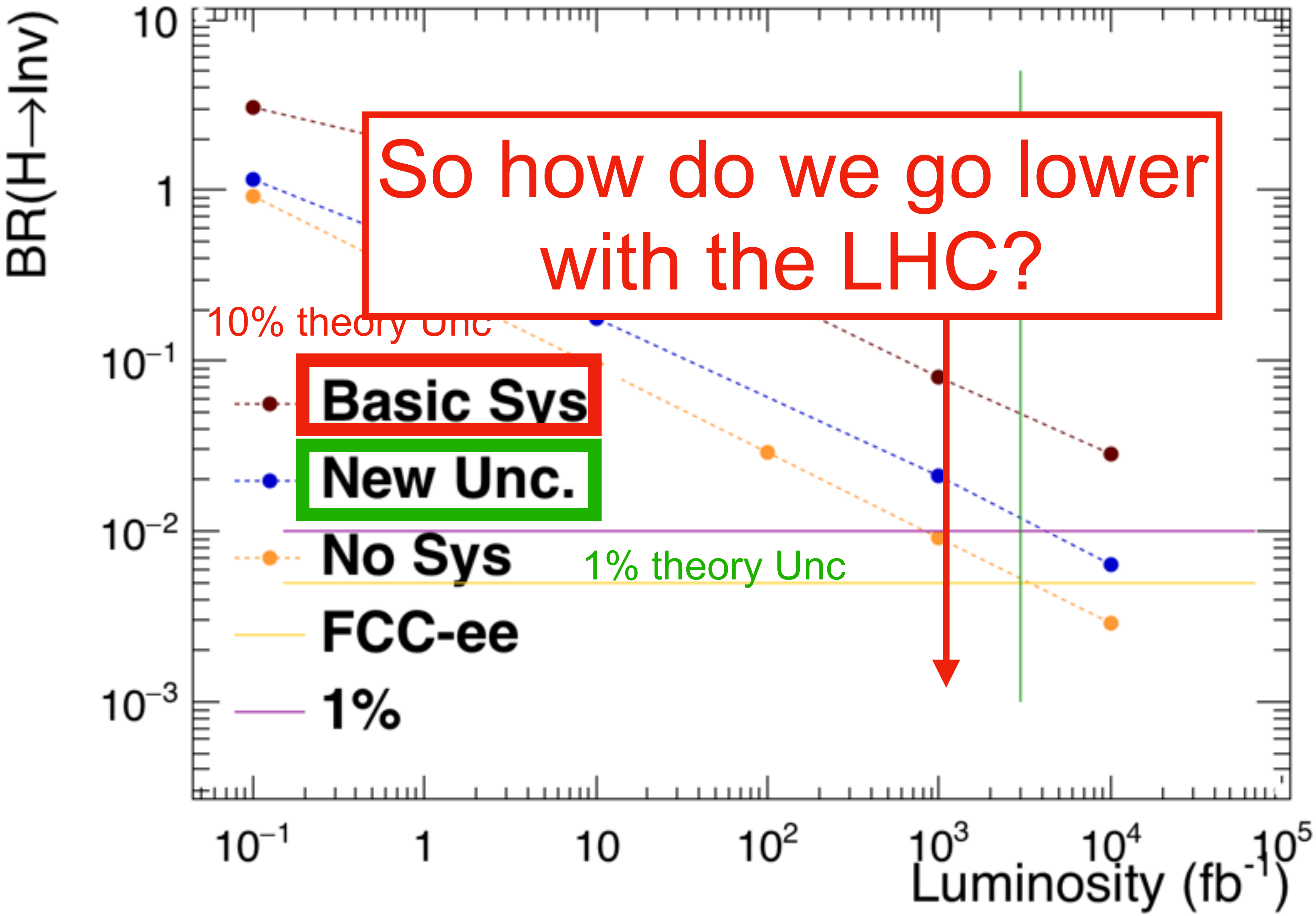
w/high mass mediators searches
Cover large most(if not all) allowed space)

Can Dark Matter Be More Complicated?

Extrapolating to the full dataset



Extrapolating to the full dataset



Our Current models

- For the most part we have looked at simplified models
  - Spin-0 and Spin-1 mediators that couple to DM

$$\mathcal{L}_{\mathrm{vector}} = -g_{\mathrm{DM}}\, Z'_{\mu}\, \bar{\chi}\gamma^{\mu}\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_{\mu}\, \bar{q}\gamma^{\mu}q - g_{\ell} \sum_{\ell=e,\mu,\tau} Z'_{\mu}\, \bar{\ell}\gamma^{\mu}\ell$$

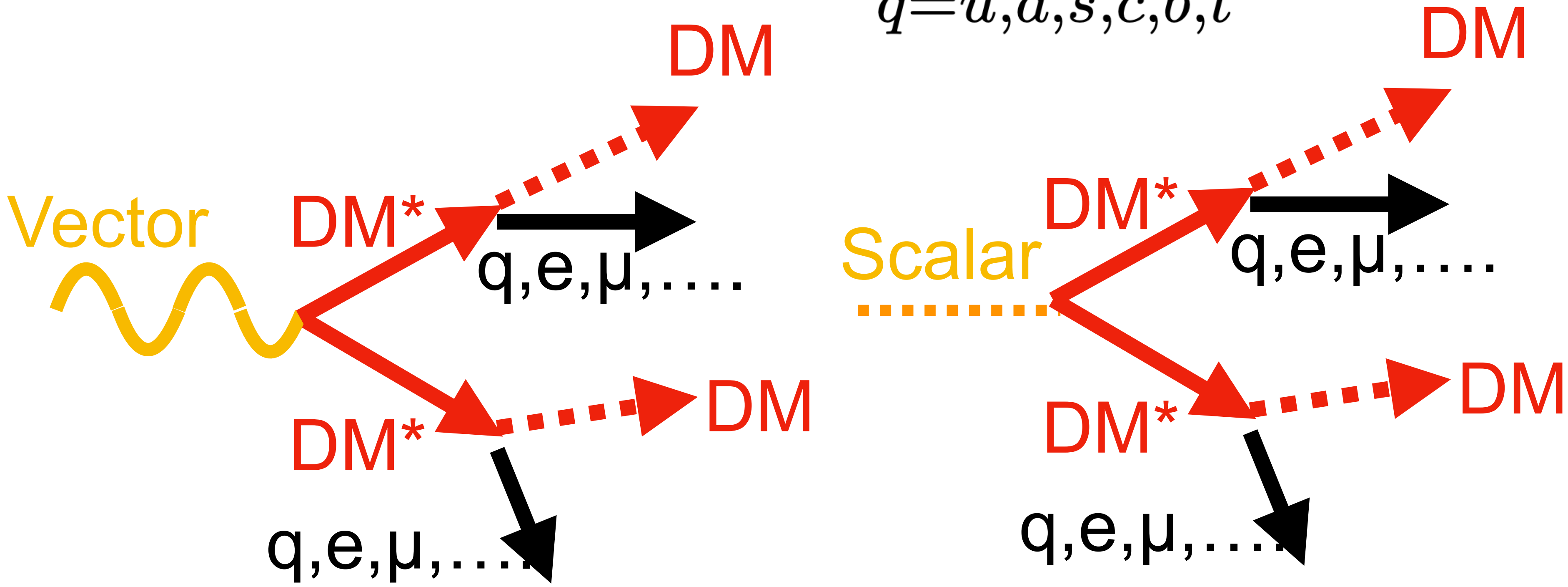
$$\mathcal{L}_{\mathrm{scalar}} = -g_{\mathrm{DM}}\, \phi\bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q\, \bar{q}q$$

This talk: What if we make things more complicated

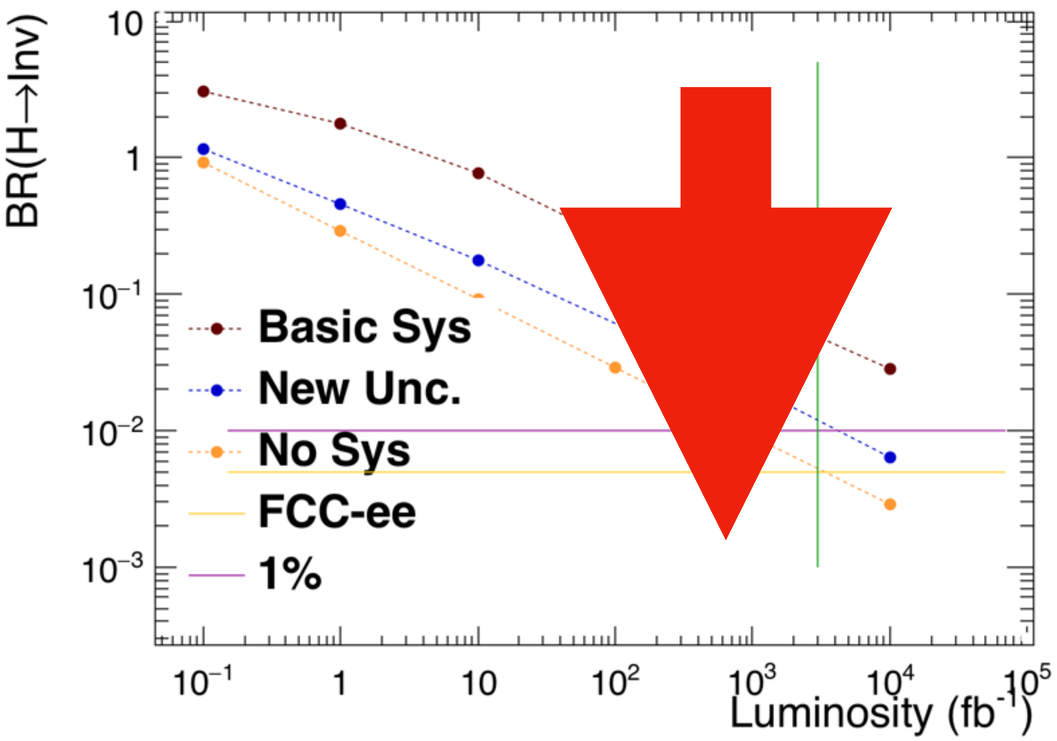
- What if we kept the same mediators?
  - But we make the dark matter unstable

$$\mathcal{L}_{\rm vector} = -g_{\rm DM}\, Z'_\mu\, \bar{\chi}\gamma^\mu\chi - g_q \sum_{q=u,d,s,c,b,t} Z'_\mu\, \bar{q}\gamma^\mu q - g_\ell \sum_{\ell=e,\mu,\tau} Z'_\mu\, \bar{\ell}\gamma^\mu \ell$$

$$\mathcal{L}_{\rm scalar} = -g_{\rm DM}\,\phi\bar{\chi}\chi - g_q \frac{\phi}{\sqrt{2}} \sum_{q=u,d,s,c,b,t} y_q \bar{q} q$$

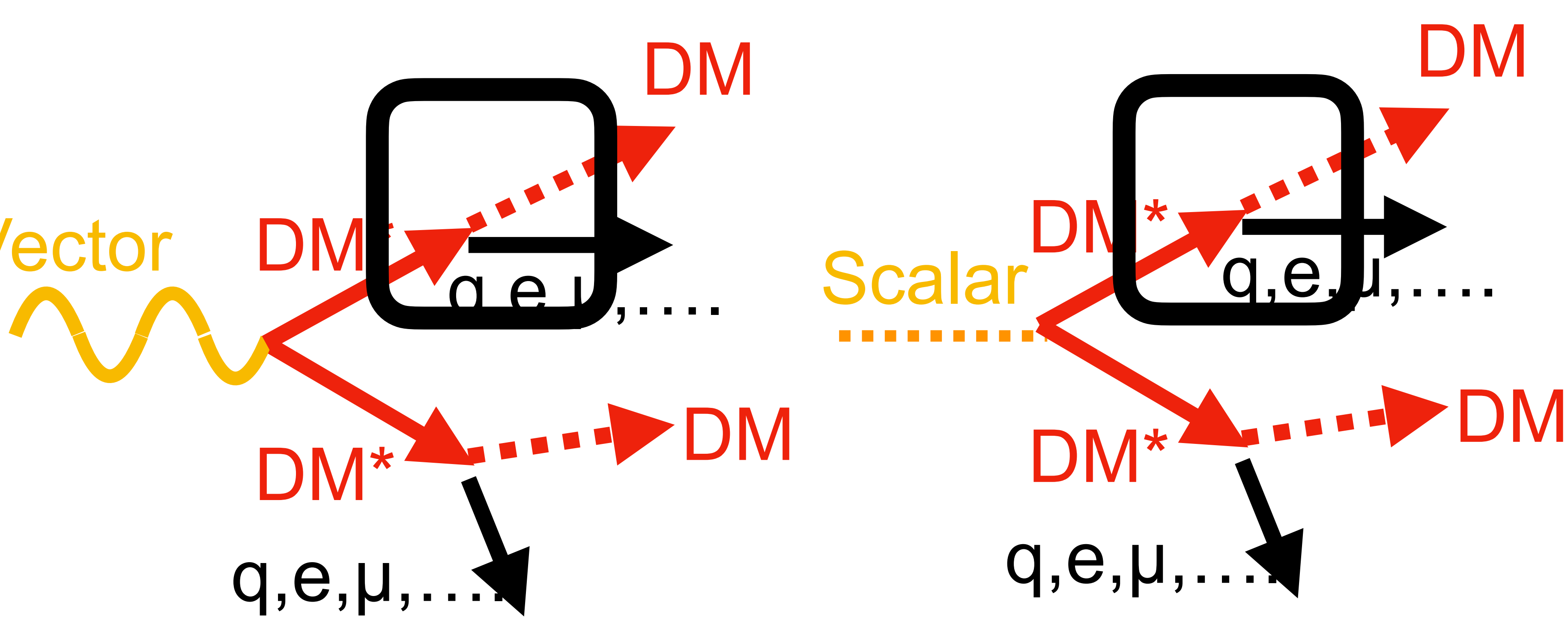


Beating down the Bkg

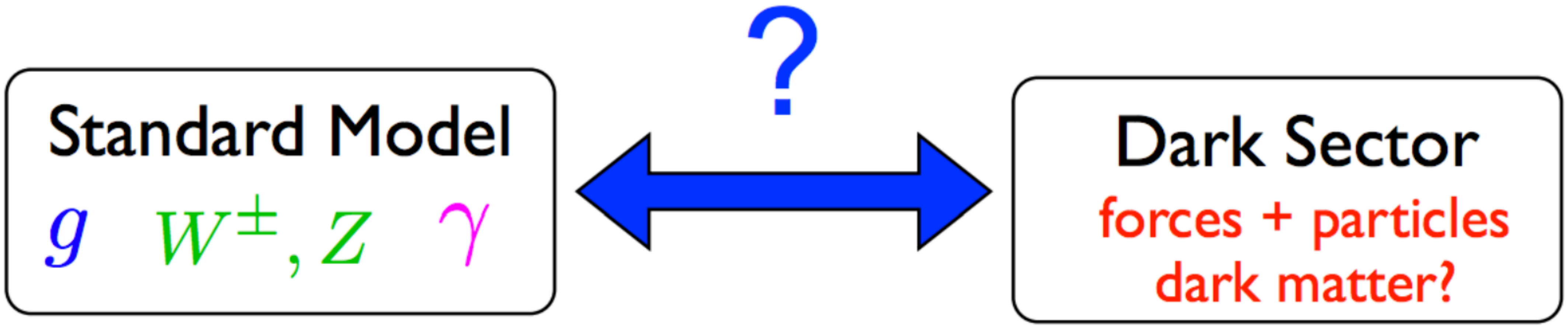


A displaced signature allows us to look for something distinct

This can significantly reduce backgrounds



Crazy Cooky Dark Sector



Protons
Electrons
Muons
Gluons and More

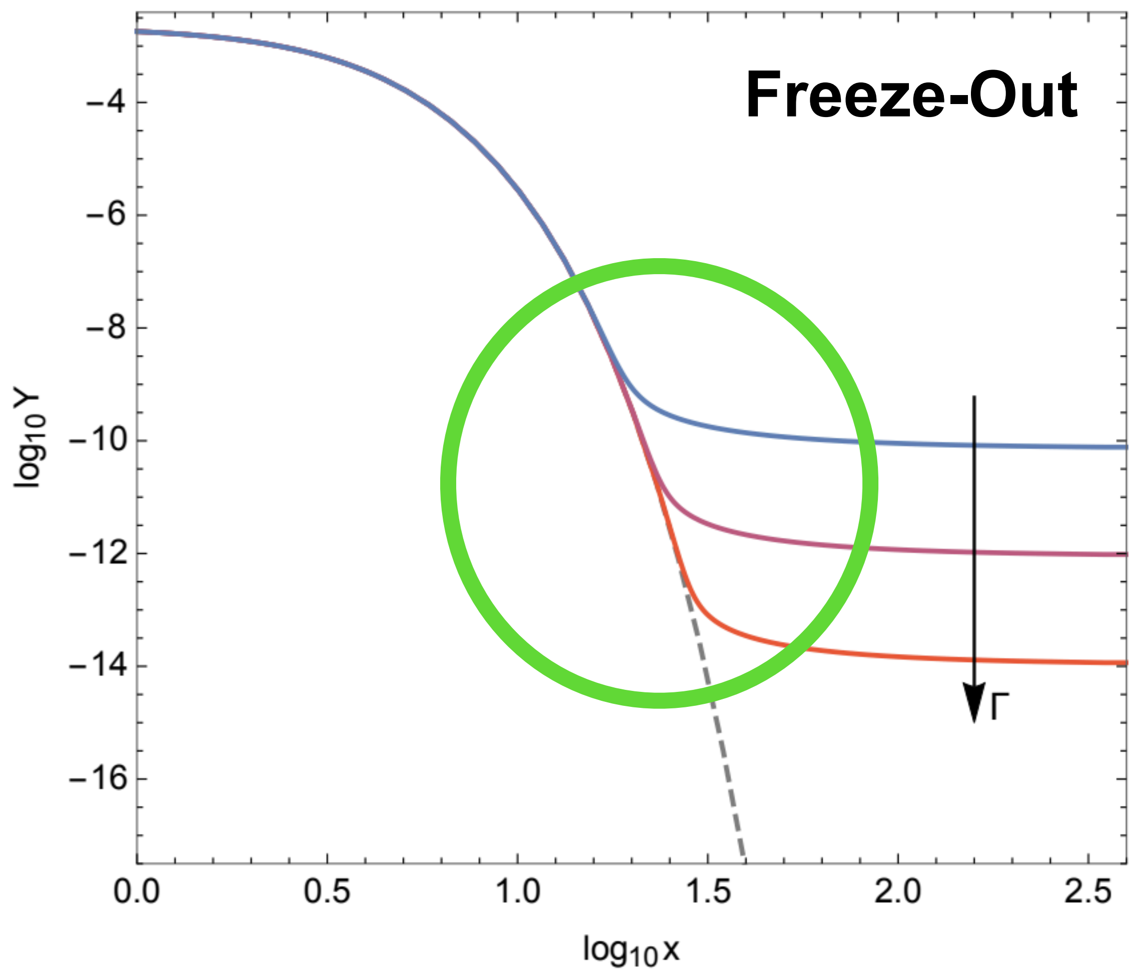
Dark Gluons
Dark Protons
Dark Pions
Dark Everything….

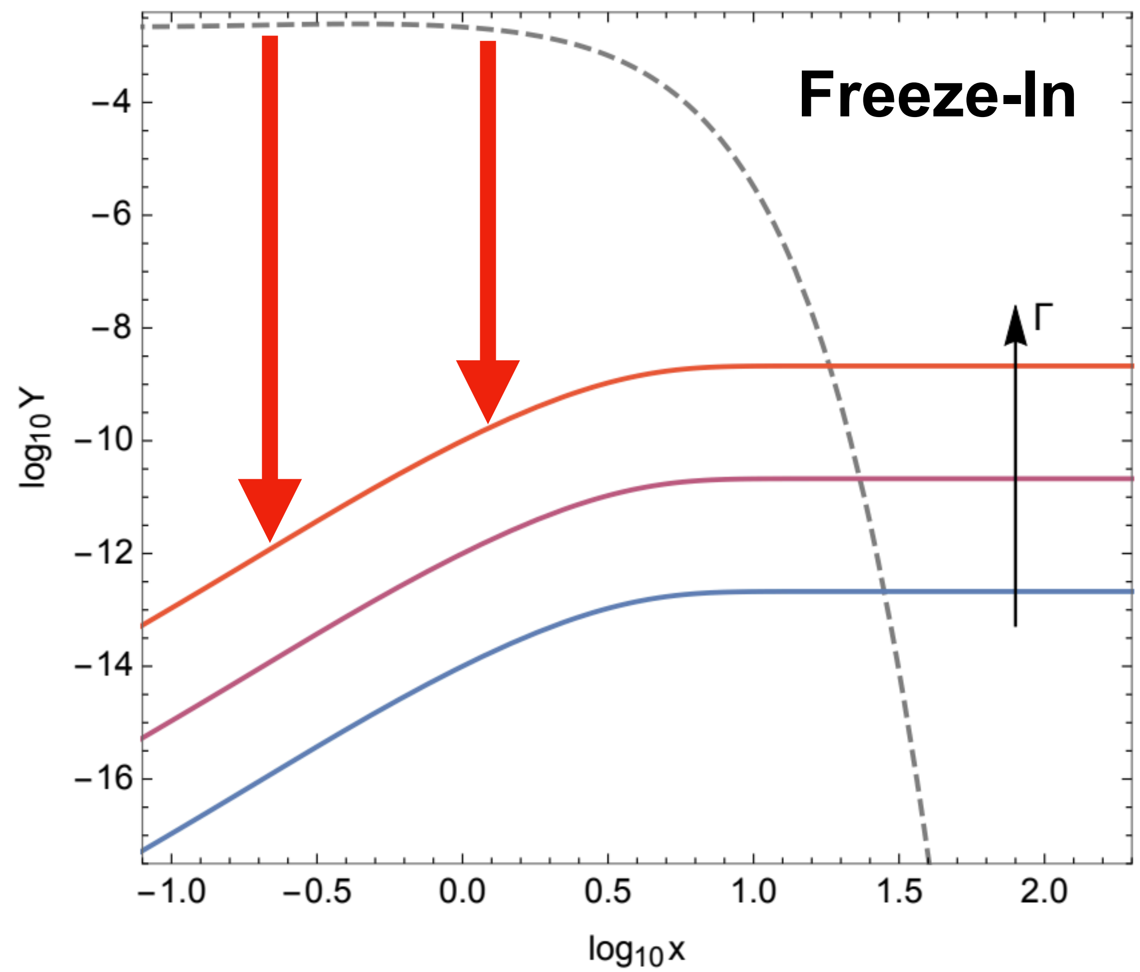
- Is there a Dark Les Houches?
  - If so are they talking about our Kaons as dark LL particles?

Quick (worrisome) Distraction

Freeze-in Mechanism

What else do we get?



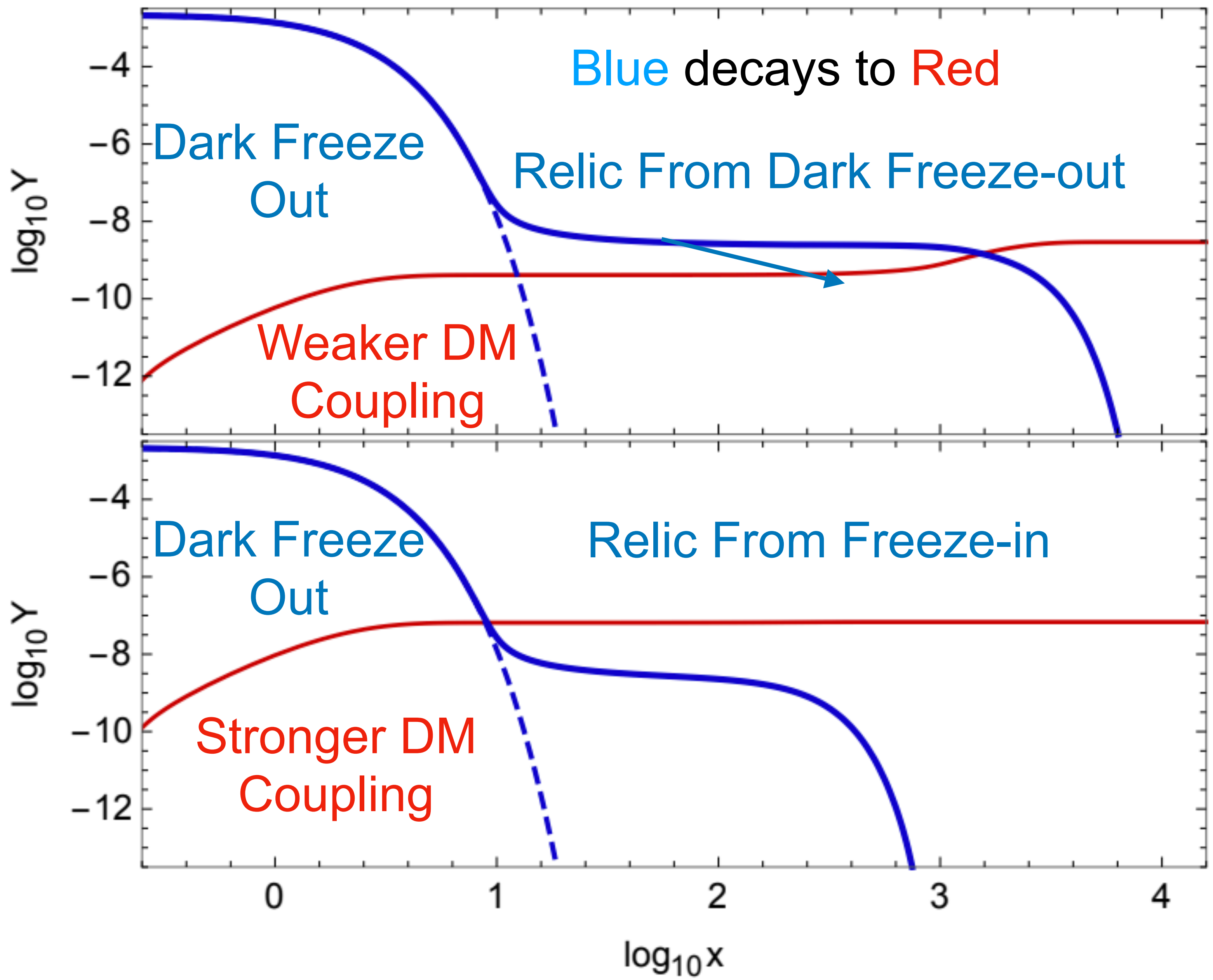


Dark Matter is thermal and at some point stops interacting due to expansion

Coupling between SM and DM is so weak it never thermalizes but builds up over time

- Dark Matter freeze-in can motivate alternative couplings
  - Long lifetime can allow for alternate production model

Variations of Freeze-in



Type of freeze-in
Depends on the DM model

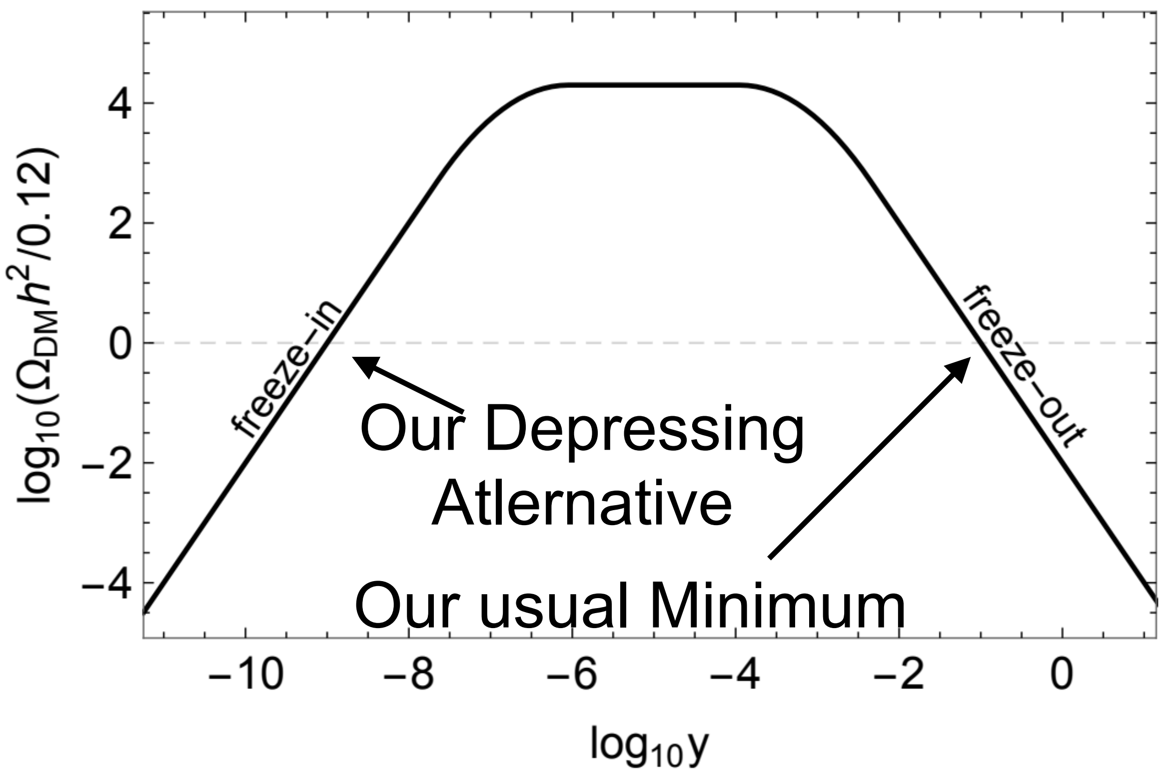
Interactions between DM
Can drive the DM production

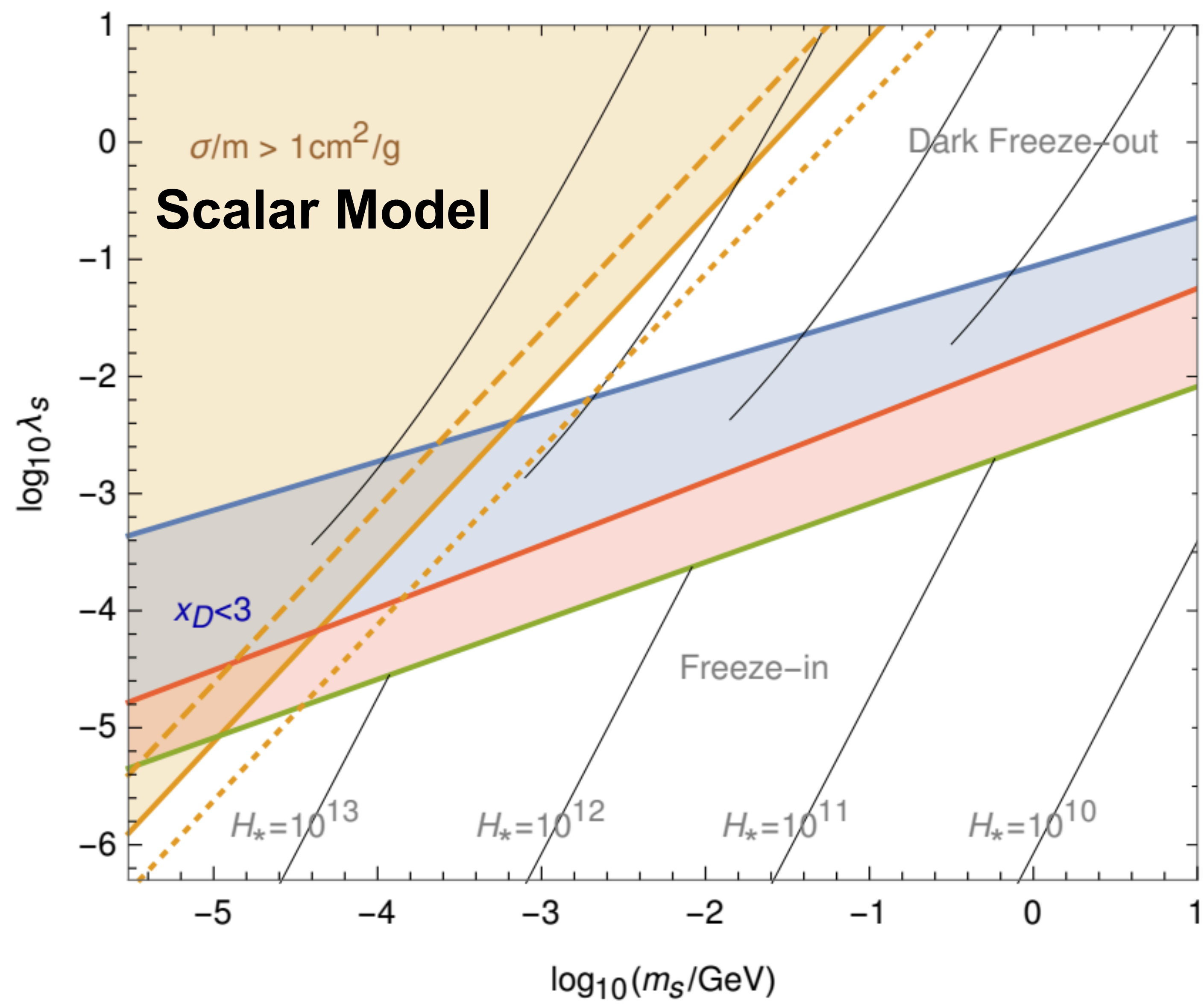
- With a complex dark sector there is a wide variety of options
  - In all cases they imply a weak coupling with SM early on

What results from this?

- Again we get very weak couplings between SM and DM

$$V(\Phi, s) = \mu_{\rm h}^2|\Phi|^2 + \lambda_{\rm h}(\Phi^\dagger\Phi)^2 + \frac{\mu_{\rm s}^2}{2}s^2 + \frac{\lambda_{\rm s}}{4}s^4 + \frac{\lambda_{\rm hs}}{2}|\Phi|^2 s^2,$$



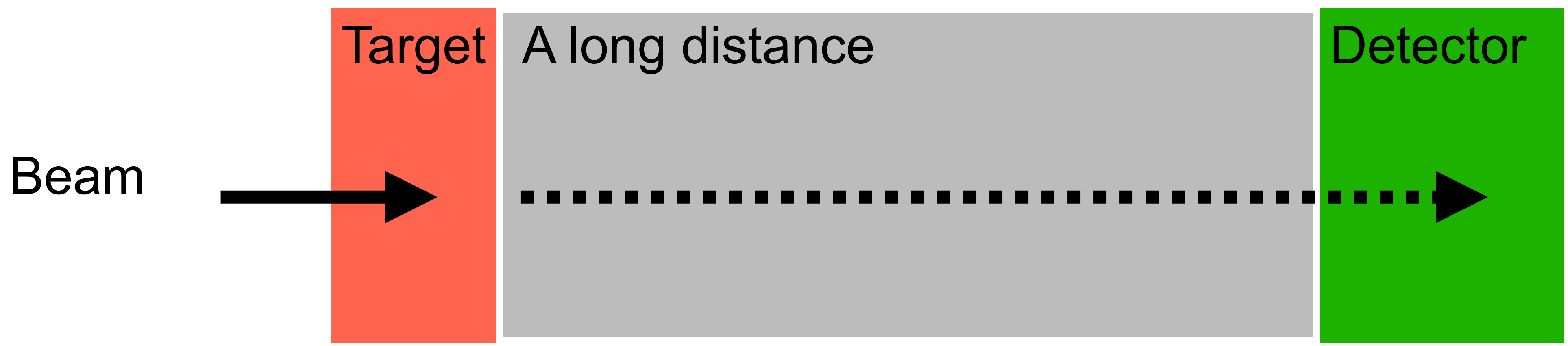


$$\frac{\Omega_{\rm s}h^2}{0.12} \simeq 5.3\times 10^{21}\,\lambda_{\rm hs}^2\left(\frac{m_{\rm s}}{\rm GeV}\right)$$

Super Weak Couplings

Couplings equate to a lifetime of cτ=1000 km (3.3ms) below BBN bound

Something to keep in Mind

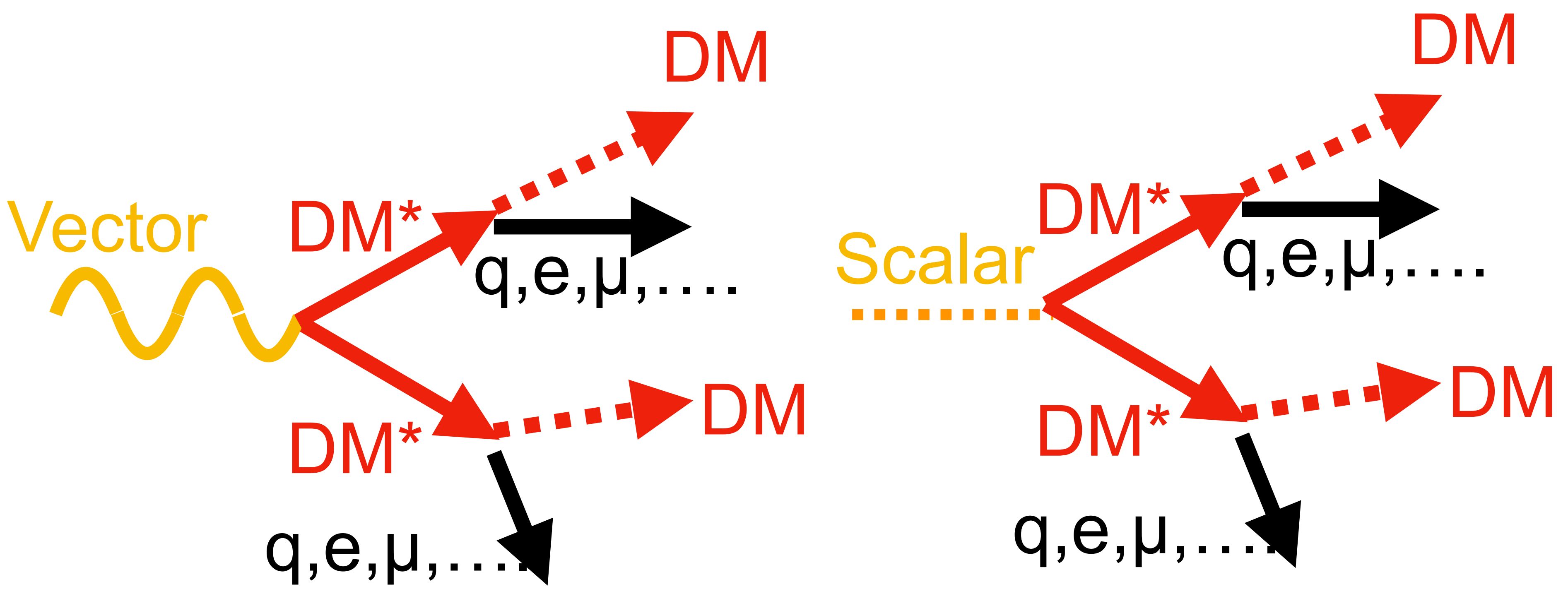


- Freeze in mechanism puts a wrench in everything
  - Allows for the possibility of very weak SM and matter couplings
  - Many different approaches to search for DM would be impossible
- Our best hope for understanding freeze-in is currently with CMB
  - Need to look for glimpse of dark sector motivated freeze
- The ultra long lifetimes make it possible at a high intensity beam to find it
  - However, the production cross section is tiny

Long-Lived Signatures

Inelastic Dark Matter

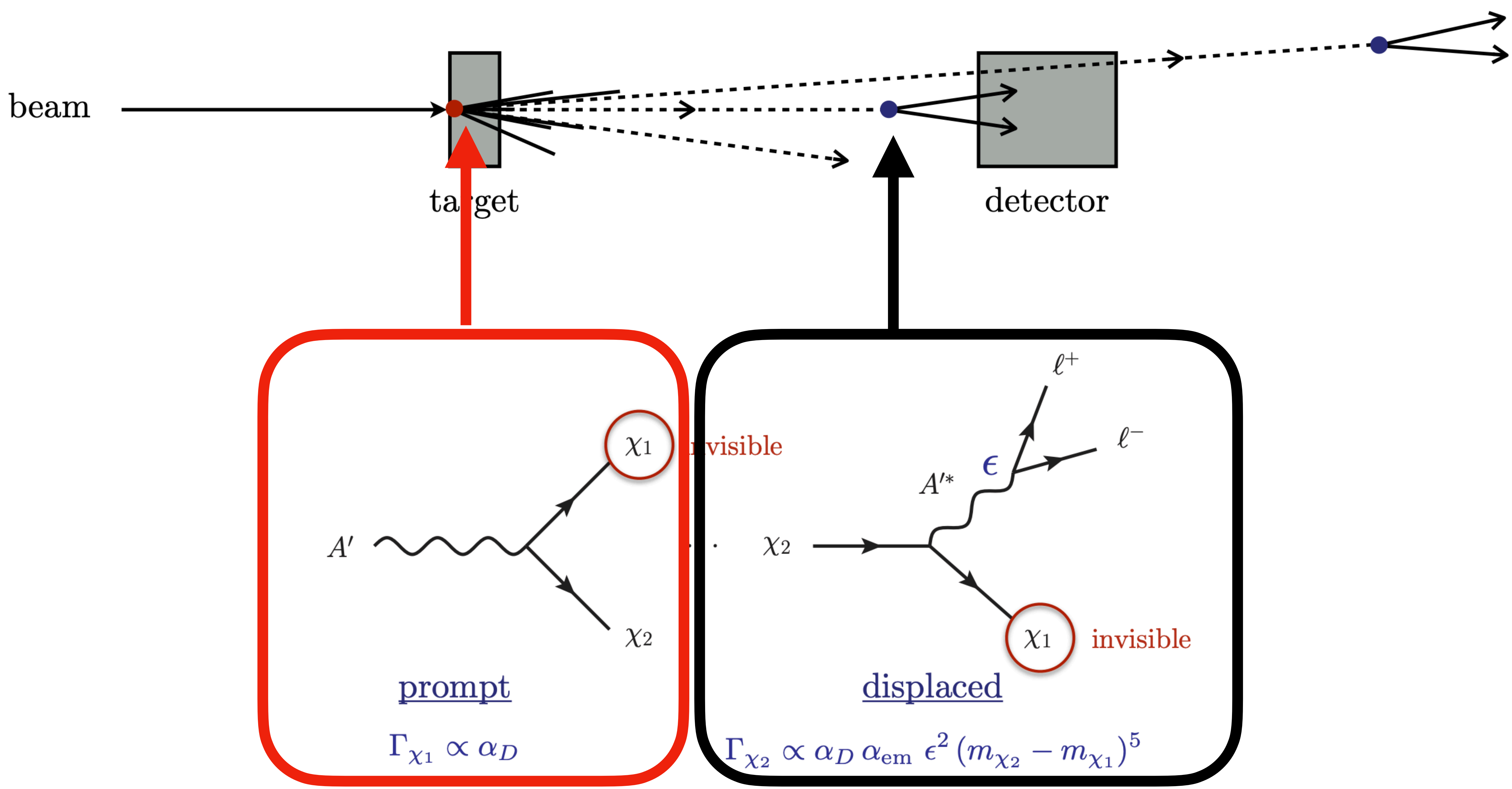
- What if we kept the same mediators?
  - We can add an unstable particle that will then decay to DM
  - This is a first, very simple complication to the DM
- Let's go through the exercise of how this changes things
  - Lets start with monojet



Inelastic DM

- Question 0: How do you build inelastic DM?
  - Any DM model and add an unstable particle the decays to DM
  - We can use the simplified models for reference here
- Question 1: What are the current model restrictions?
  - Inelastic has the freedom of lifetime
    - Lifetime can be almost anything
  - Does the relic density change?
    - In this case its not really impacted
    - Freeze-out is driven by the unstable particle (portal coupling)
      - Freeze-in mechansim is not relevant here
    - An upper bound in lifetime of $c\tau=10^7$km comes from BBN(nuclear composition)
- Lets use our knowledge of LHC to put together some bounds on inelastic DM

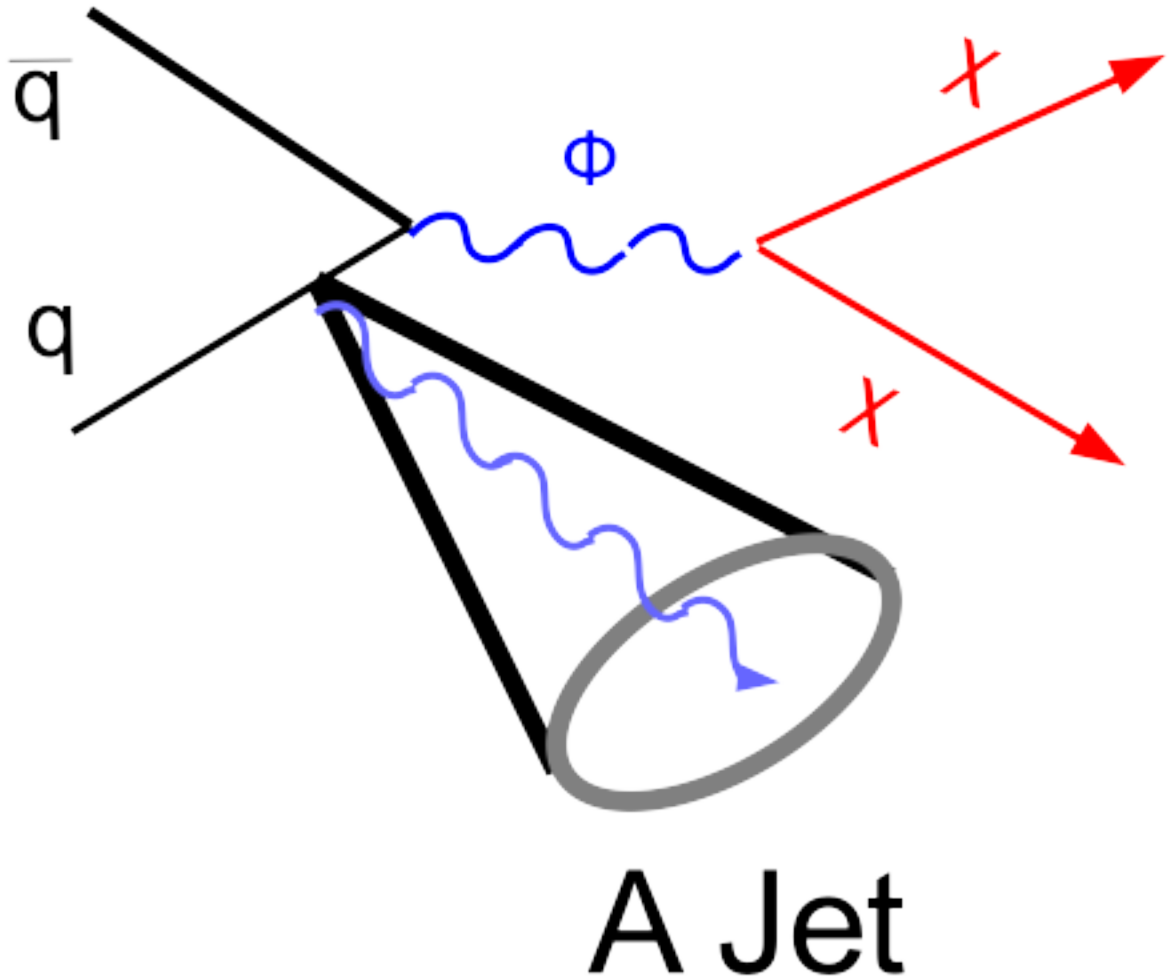
Inelastic DM Signature



How would you search for it?

Mono-jet

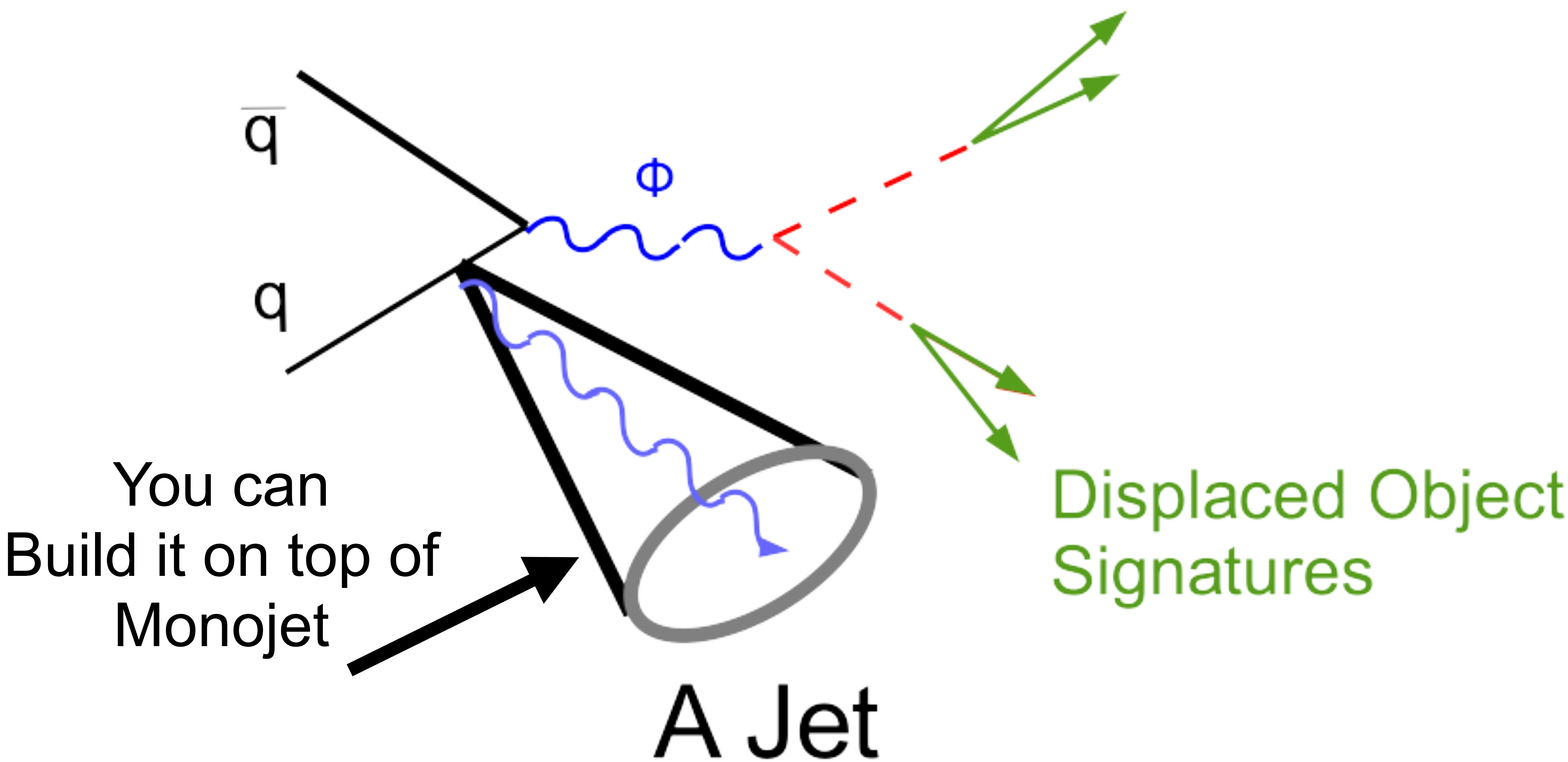
Simplified Models : Vector,Axial,Scalar,Pseudoscalar



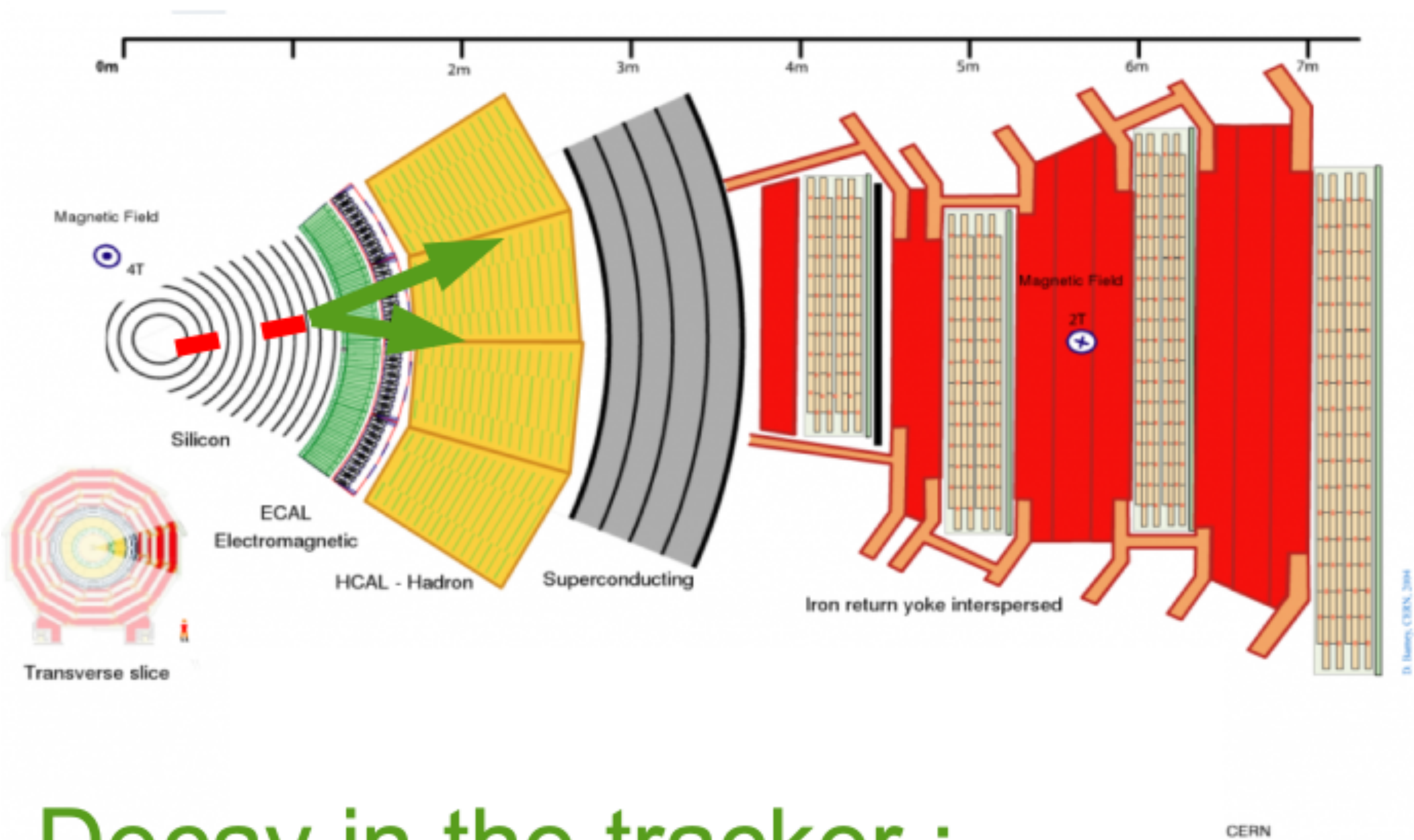
How would you search for it?

Mono-jet

Simplified Models : Vector,Axial,Scalar,Pseudoscalar



Searching for DM*at LHC

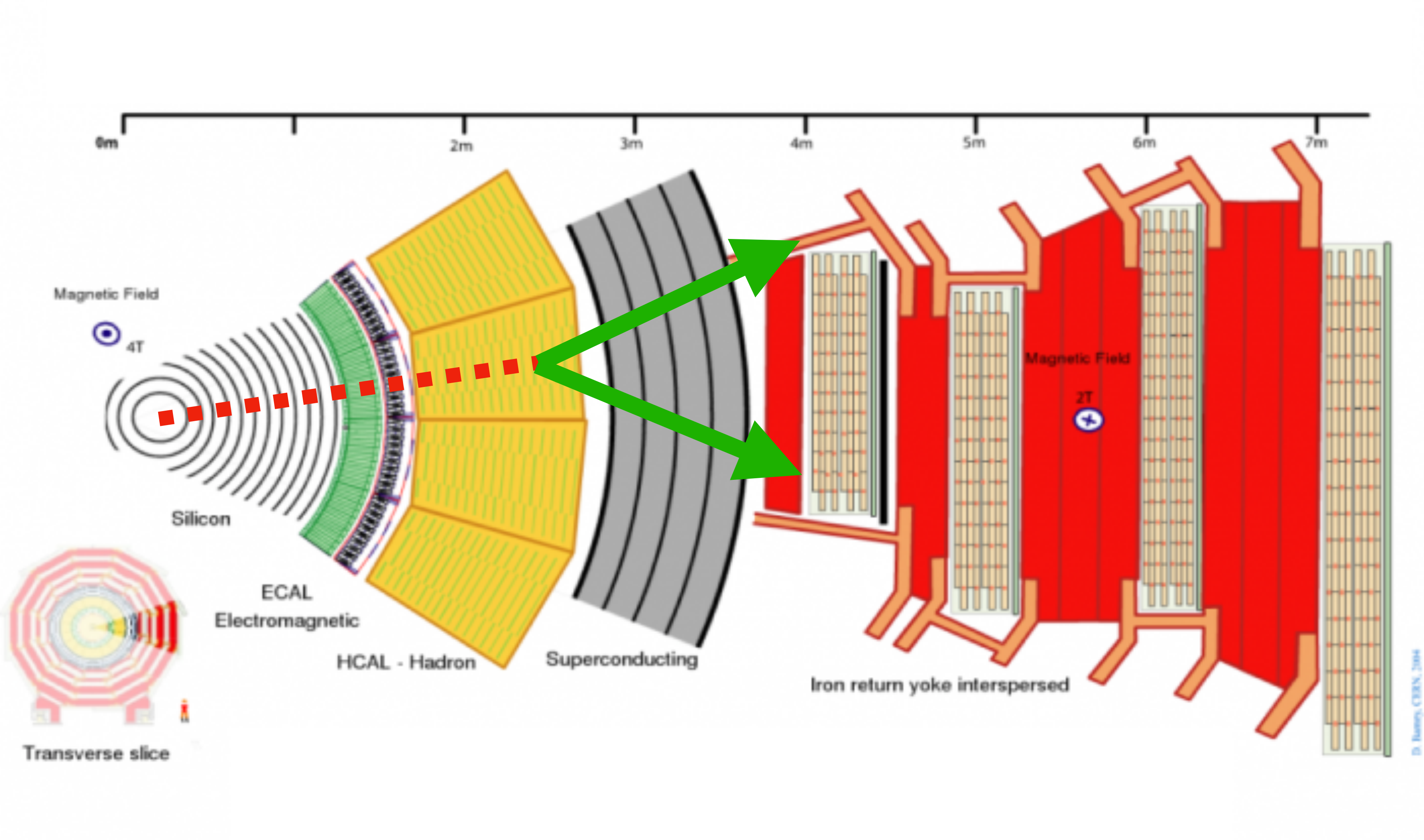


Decay in the tracker :

Displaced track signature

No missing transverse energy

Searching for DM* at LHC

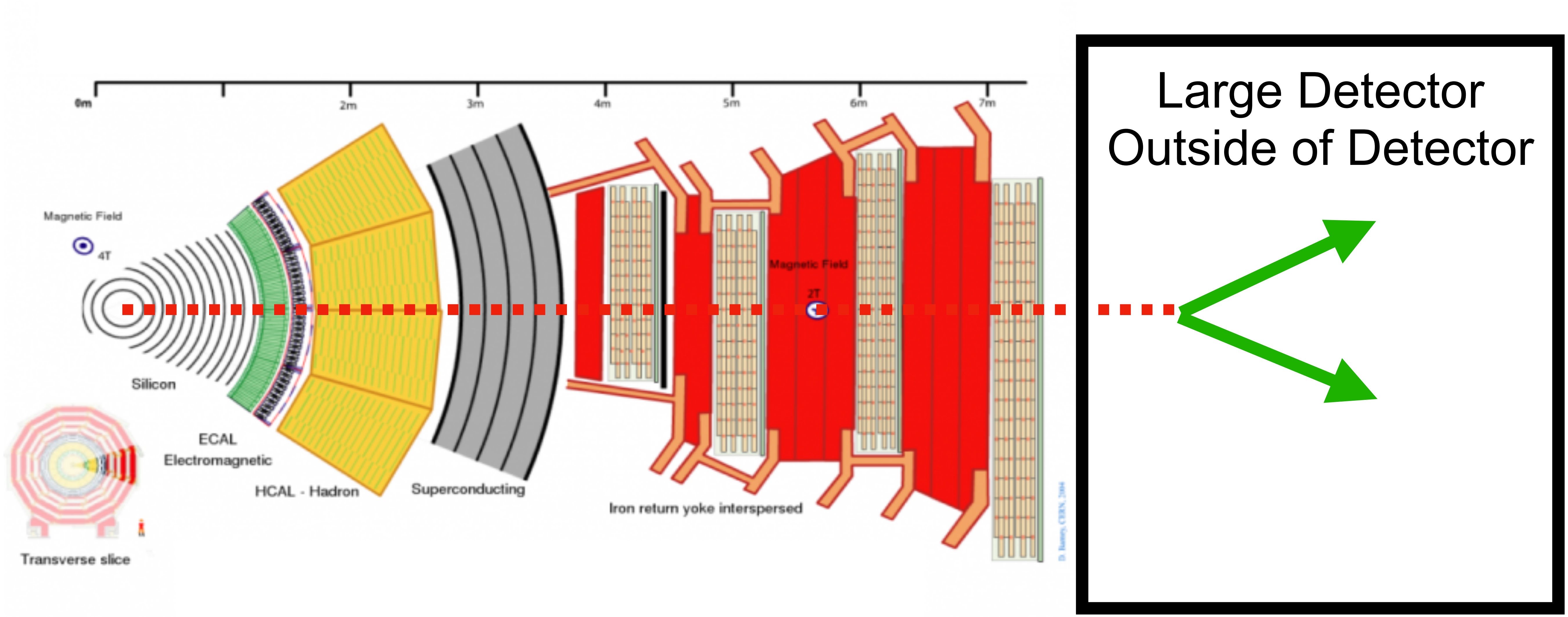


Decay in Calorimeter:

Calorimeter/Muon Signature

Missing Transverse Energy

Searching for DM* at LHC

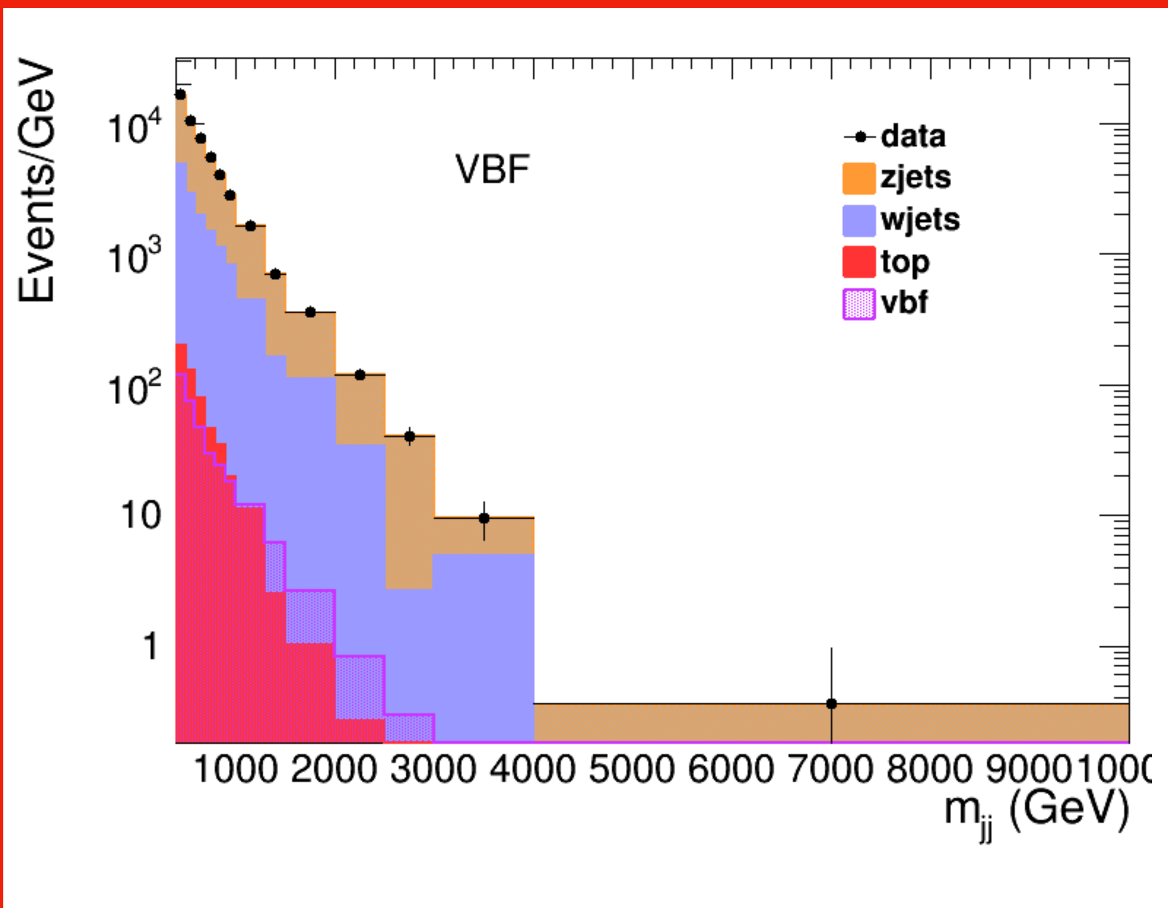


Decay Outside of the Detector:

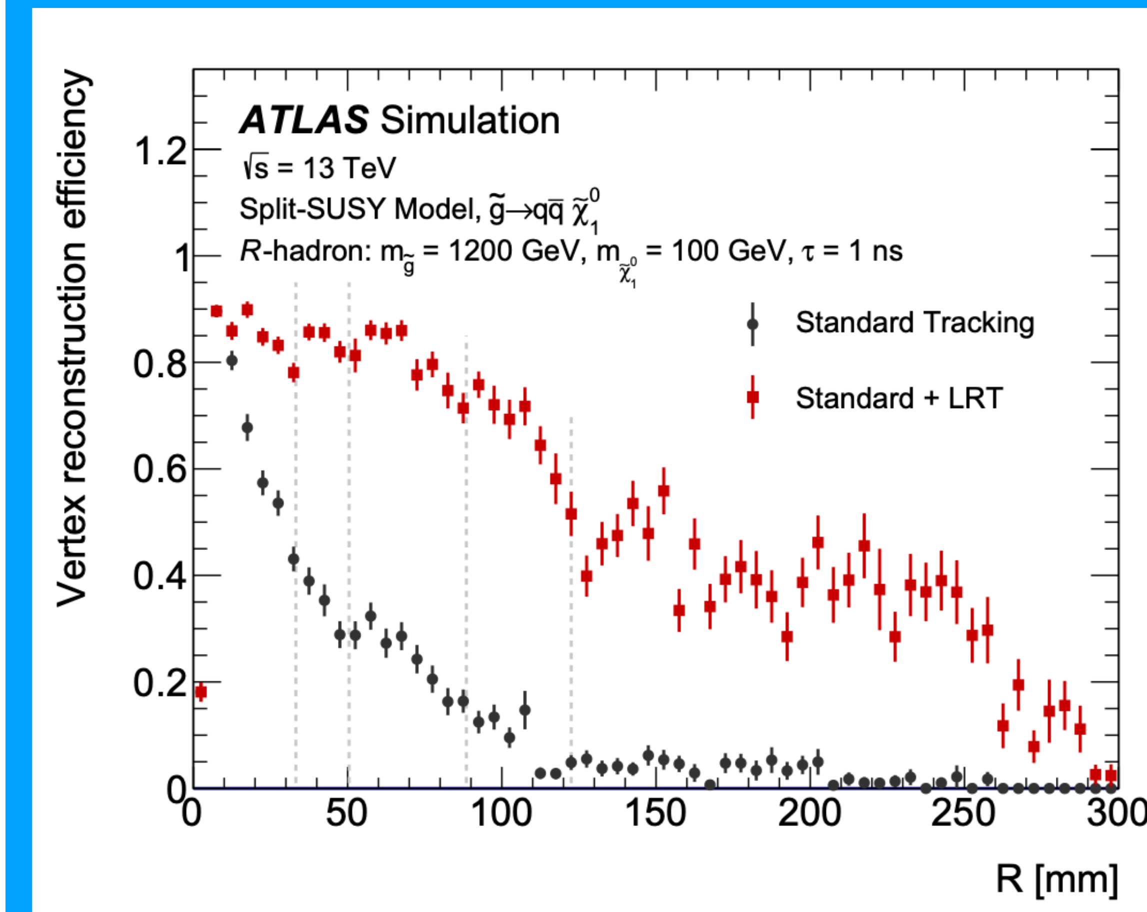
Missing Transverse Energy in Detector
Many proposals for new detectors (i.e. Mathusla)

A simple example

- What if perform a search for a displaced vertex



+



Monojet

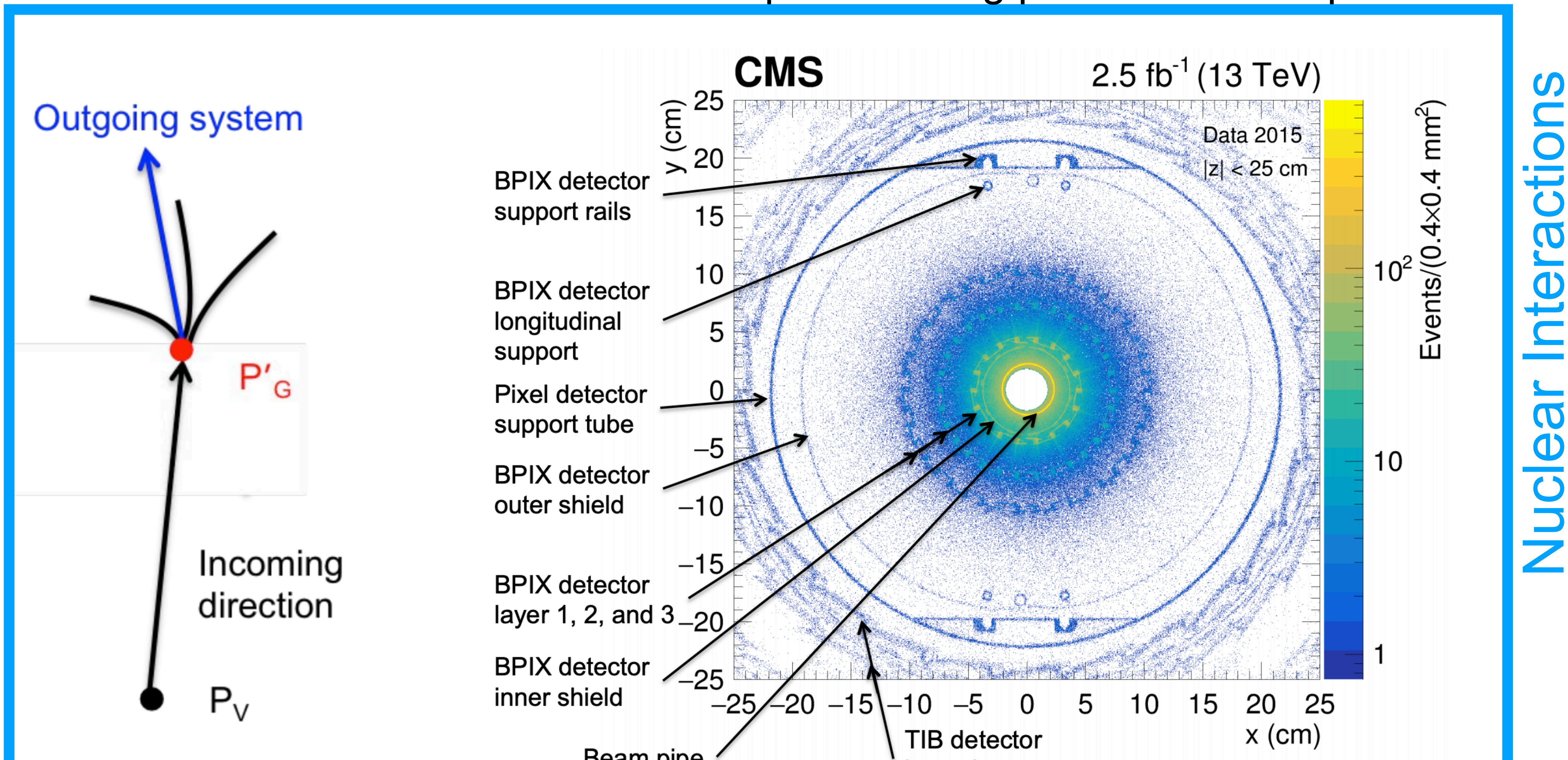
Displaced Vertex

By combining the monojet search with a displaced vertex search
Can continue to search for long lived DM and scale it to $3ab^{-1}$

What are backgrounds?

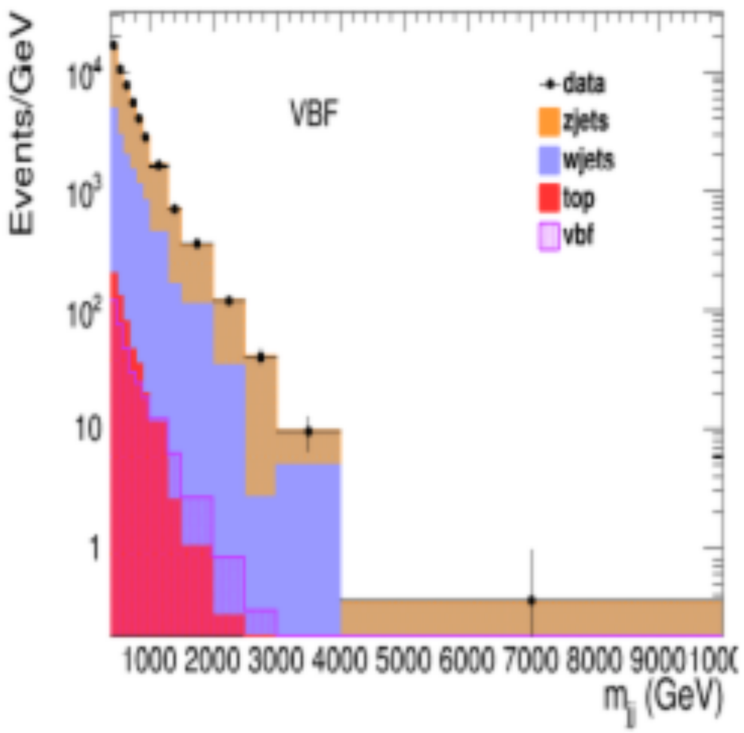
- Can have Nuclear interactions:
  - Also Kaon and Pion decays can give long lived vertex
    - We can often easily remove these guys

https://arxiv.org/pdf/1807.03289.pdf



Constructing an LL analysis

- Can recast the dark matter searches

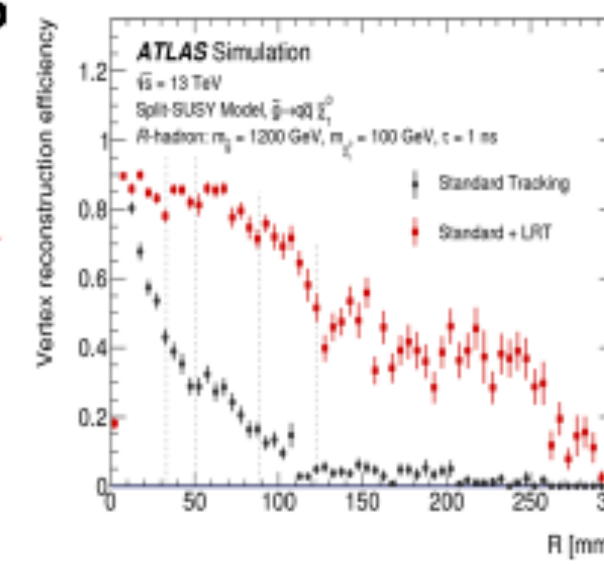


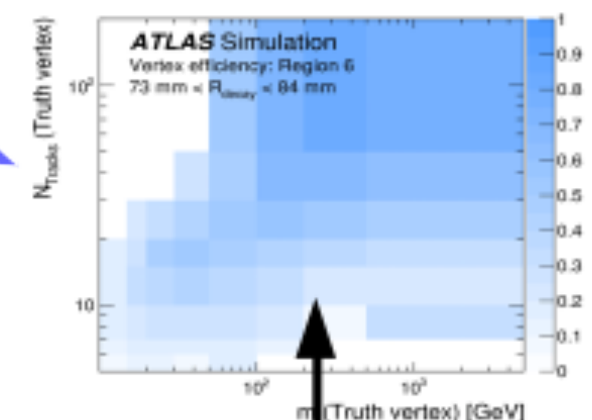
X 10^{-2}

10^{-4}

X

Preselection

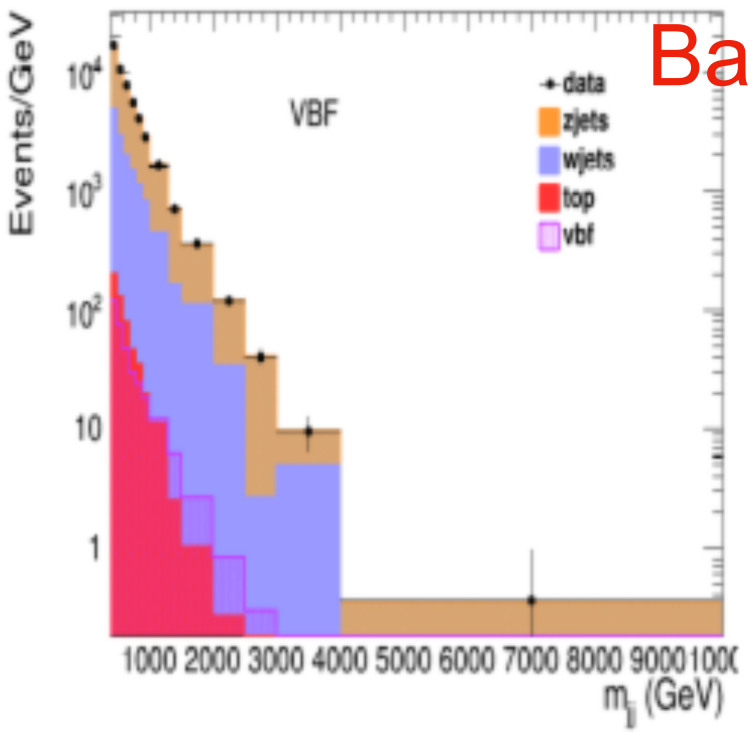




Run analysis on reduce background and correct for eff
(Approximates right scale)

Constructing an LL analysis

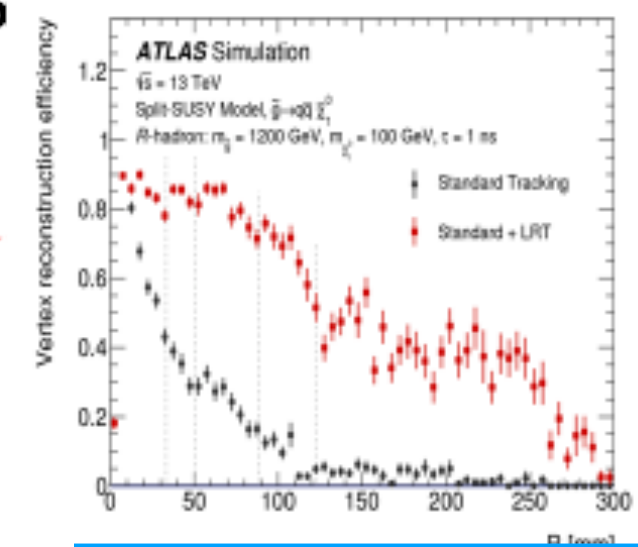
- Can recast the dark matter searches

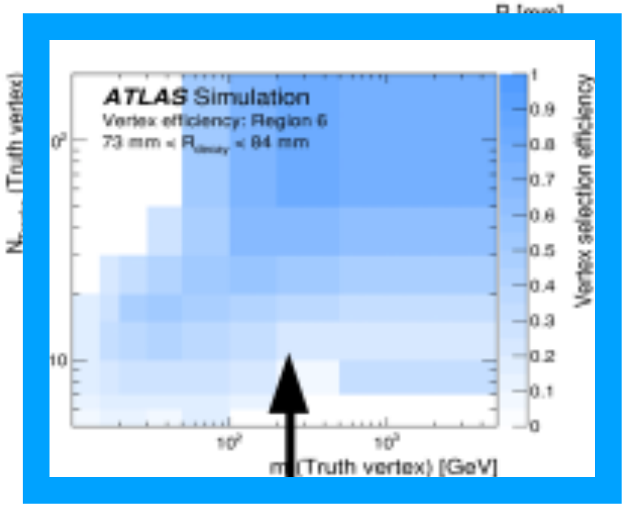


Background Efficiency Rate

X 10^{-2} 10^{-4} X

Preselection



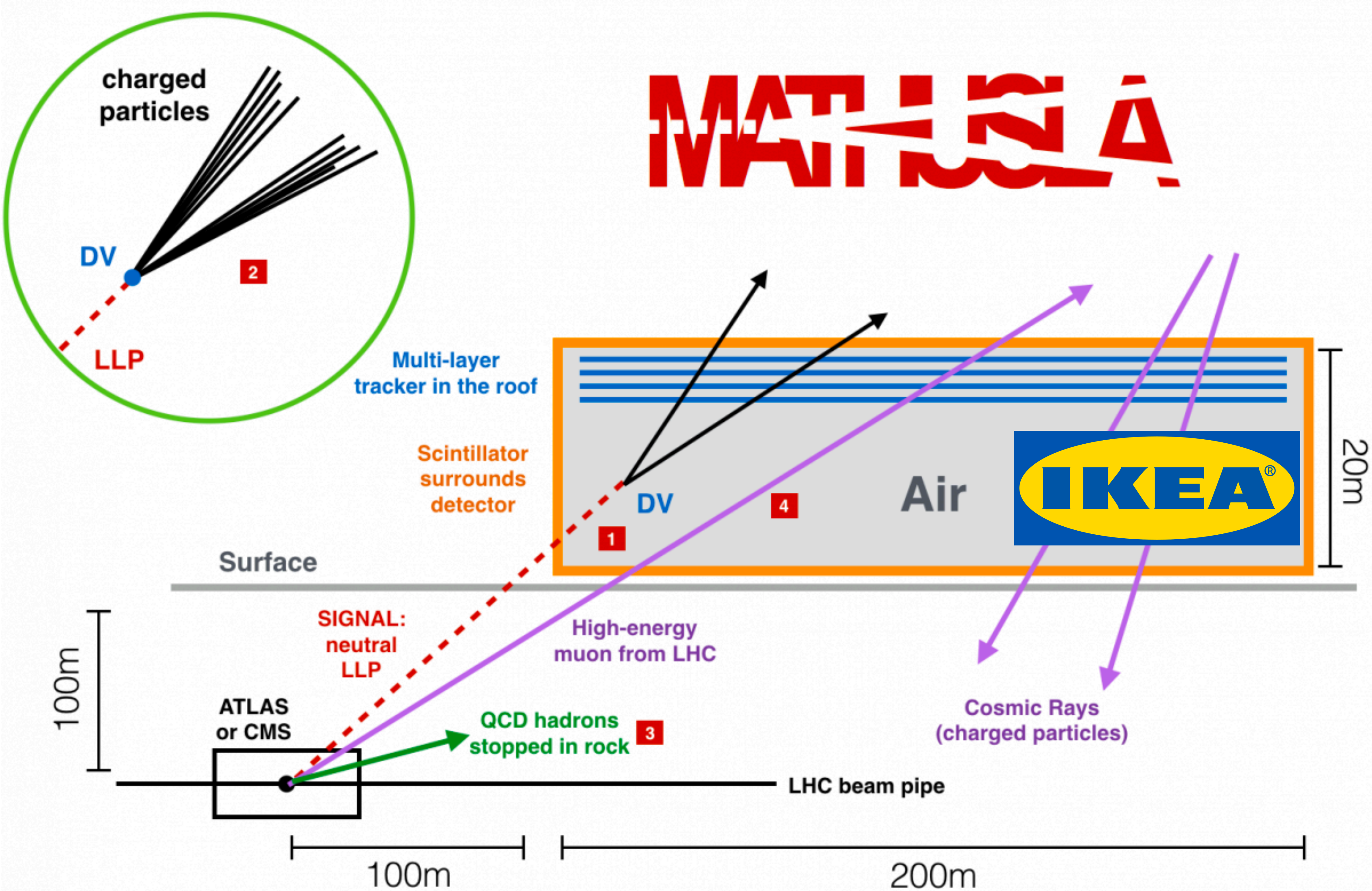


Signal Efficiency Rate

Following displaced vertex analysis we can envision doing monojet with a secondary vertex cut and using the same simultaneous fit background method

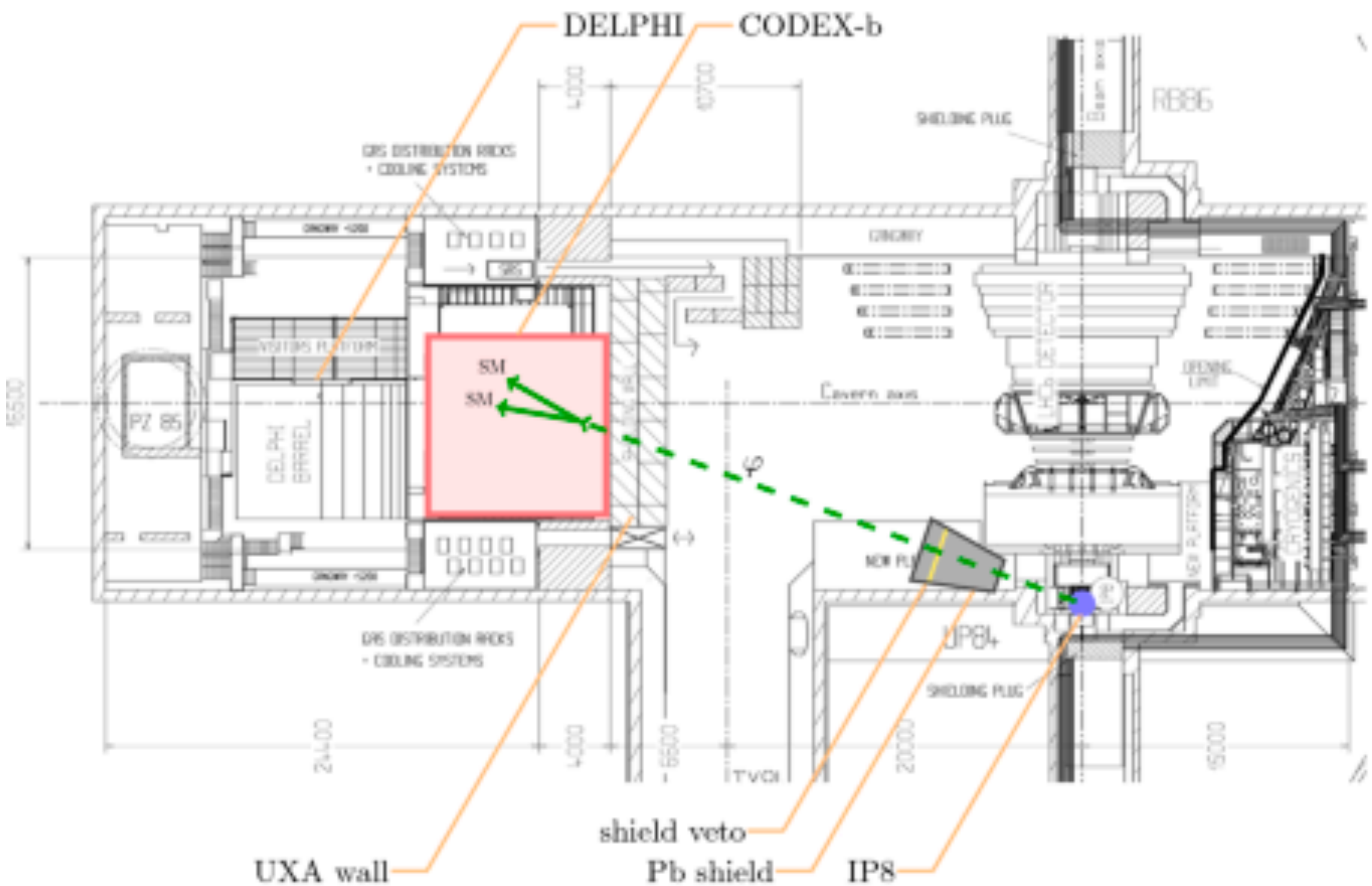
ATLAS released an efficiency map to allow for a recast of results

Now for Variety

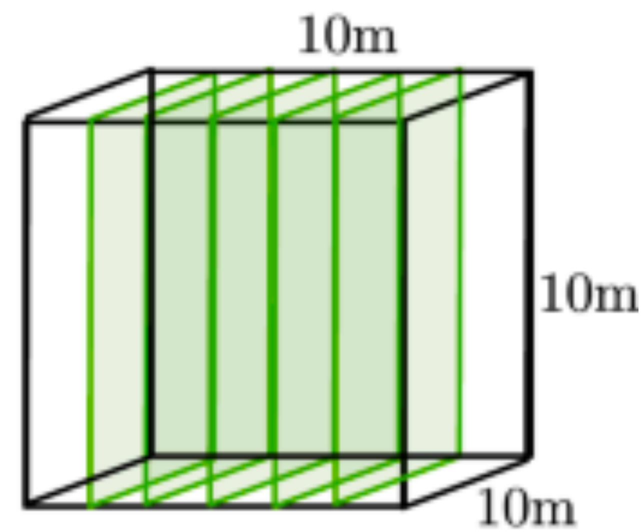


- Lets compare this with a large volume detector

Codex-b



(a) Location in the cavern

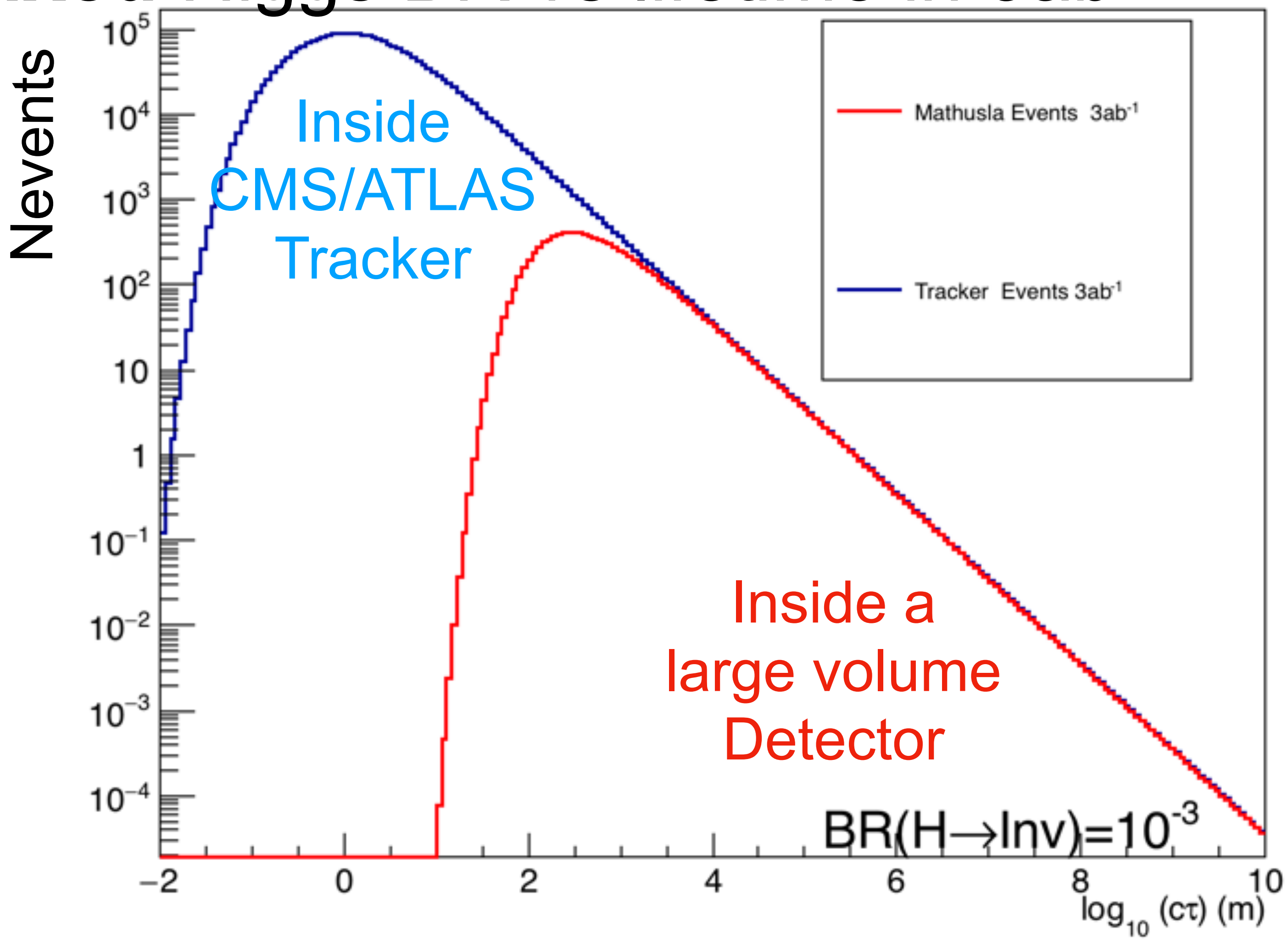


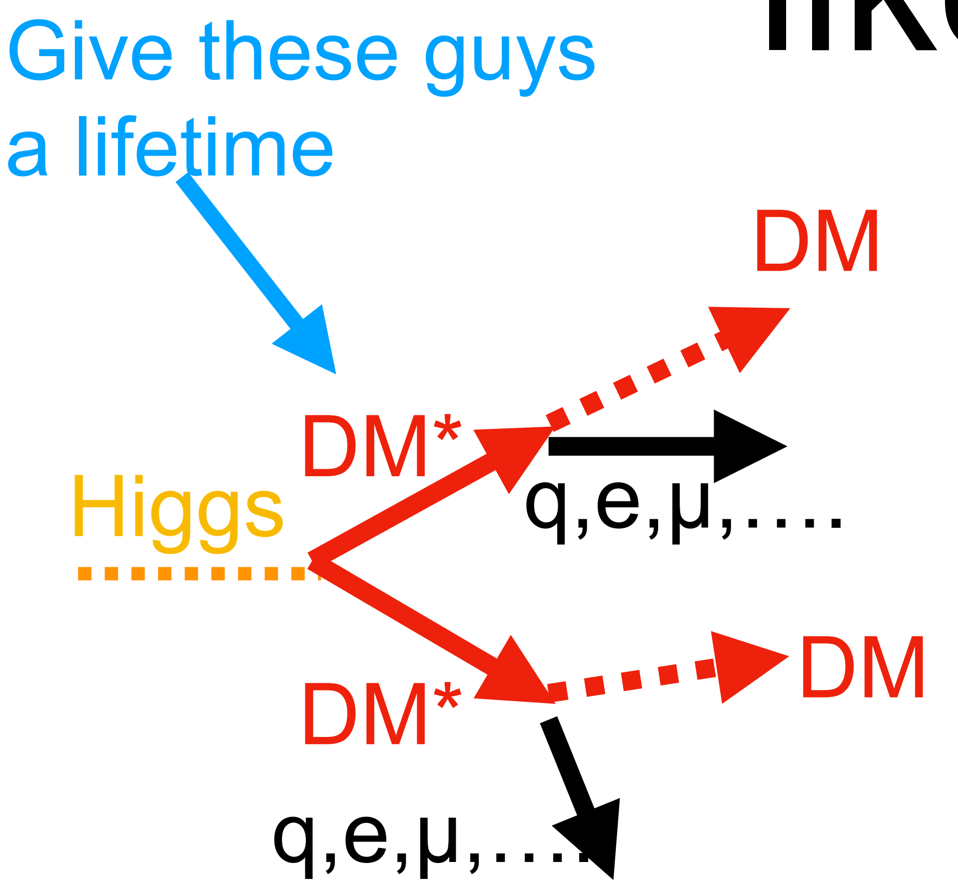
(b) Detector geometry

- Similar idea to Mathusla, but a lot smaller

What do these events look like?

Number of Decays in a volume for a **fixed** Higgs BR vs lifetime in 3ab^{-1}



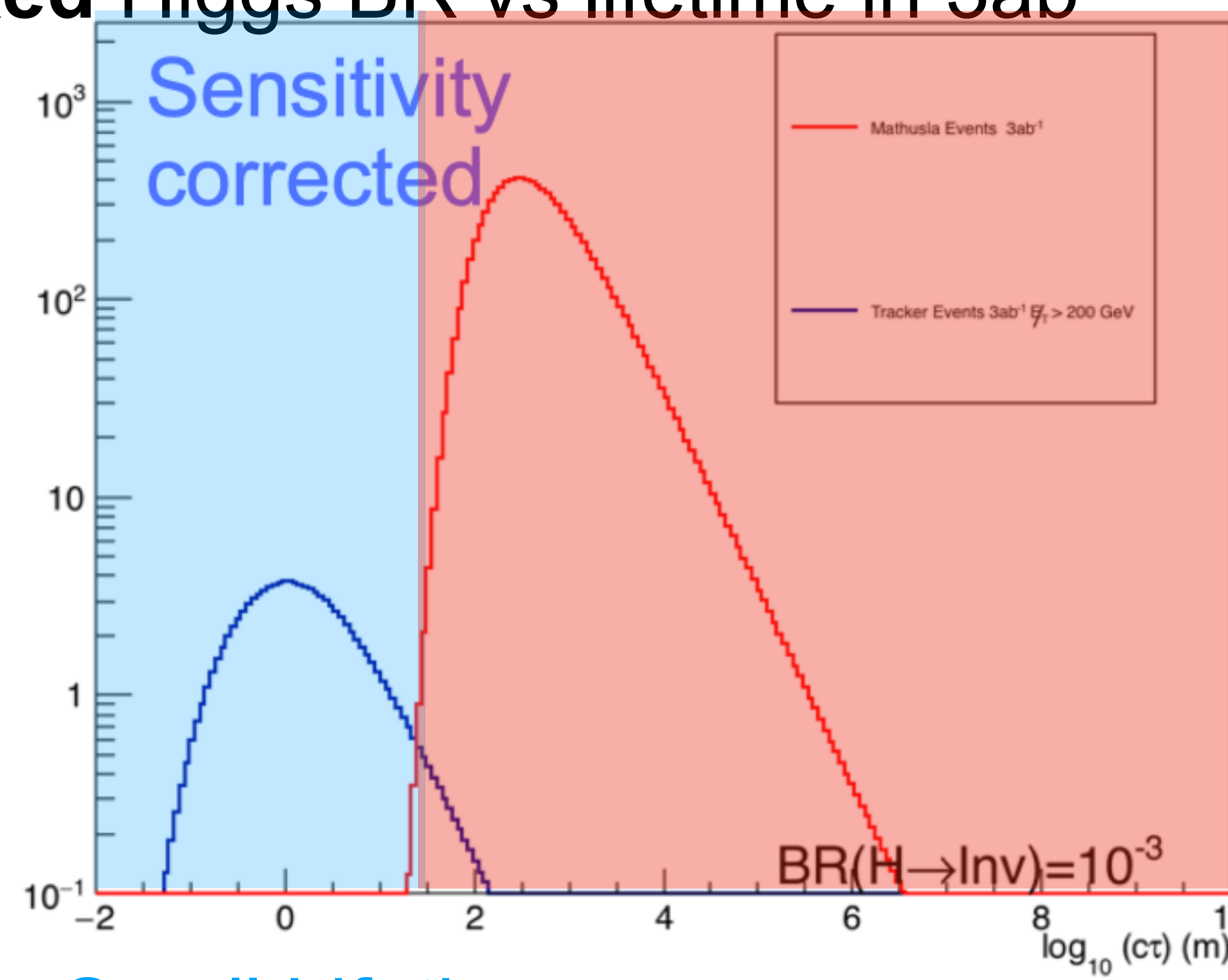


To simulate the signal we can take Higgs events and decay them

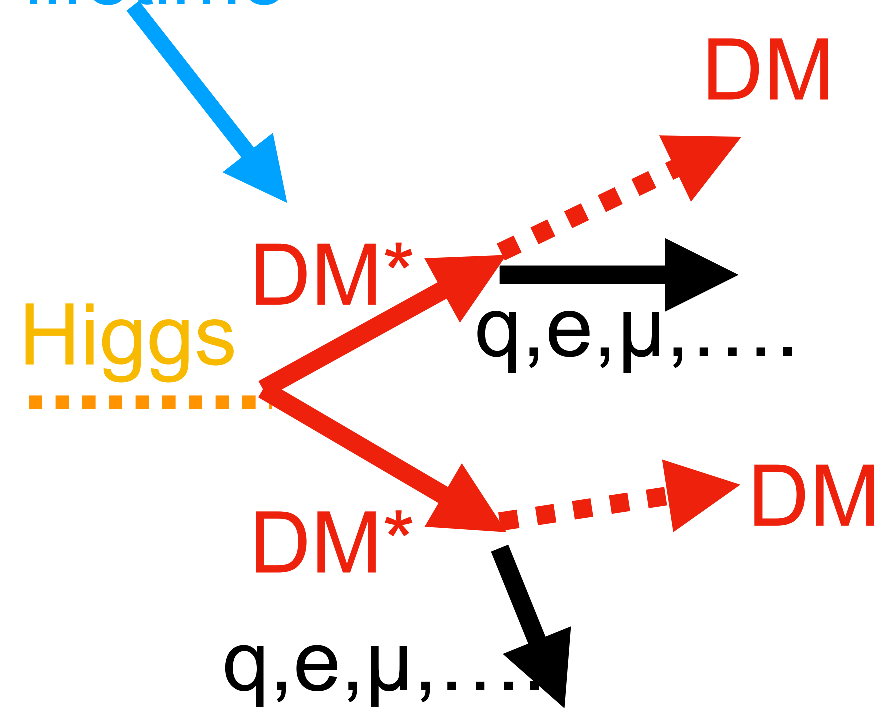
The large boost pushes liftetimes to small values

What do these events look like?

Number of Decays in a volume for a **fixed** Higgs BR vs lifetime in $3ab^{-1}$



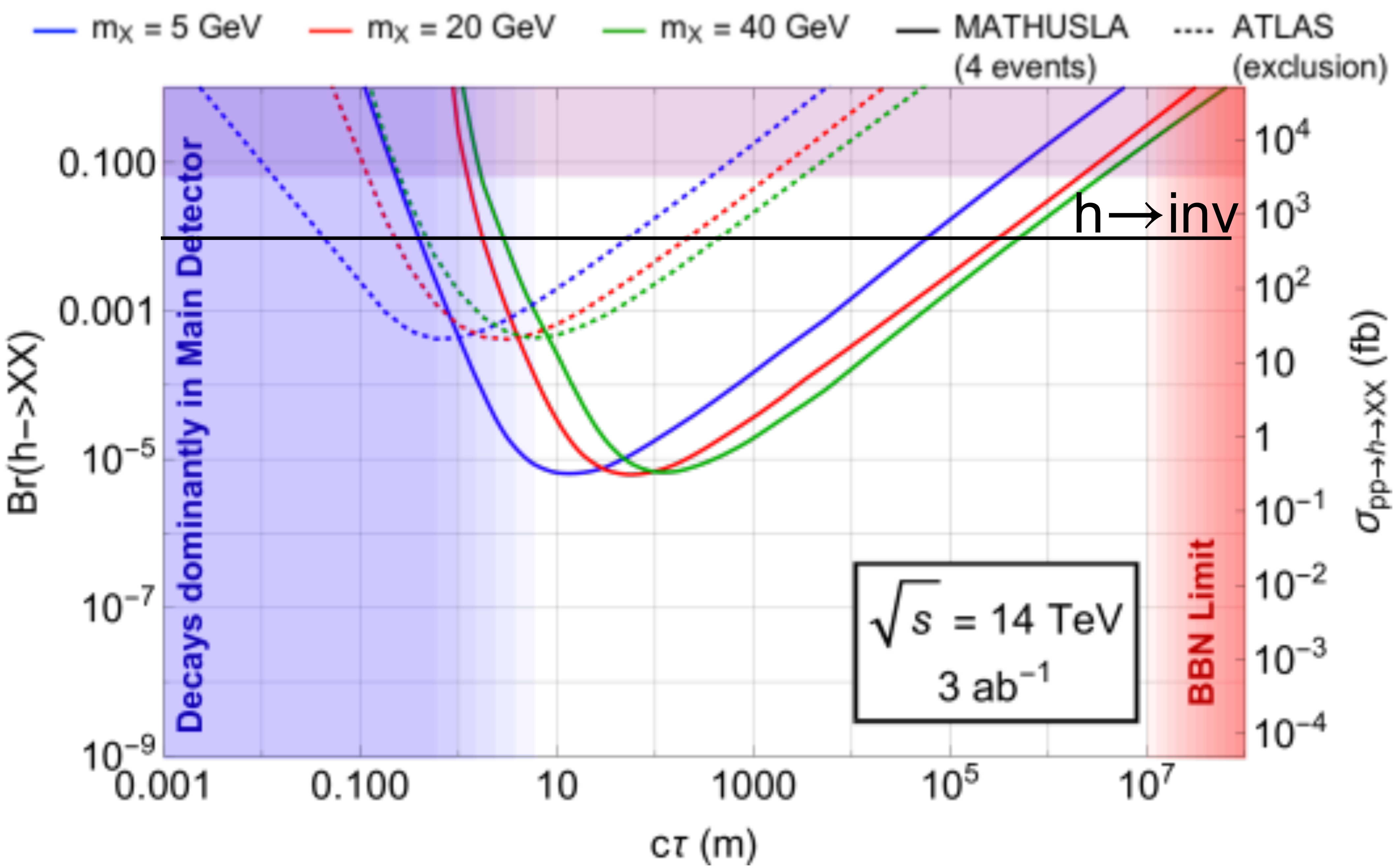
Give these guys a lifetime



Small Lifetimes
Using existing detectors works well

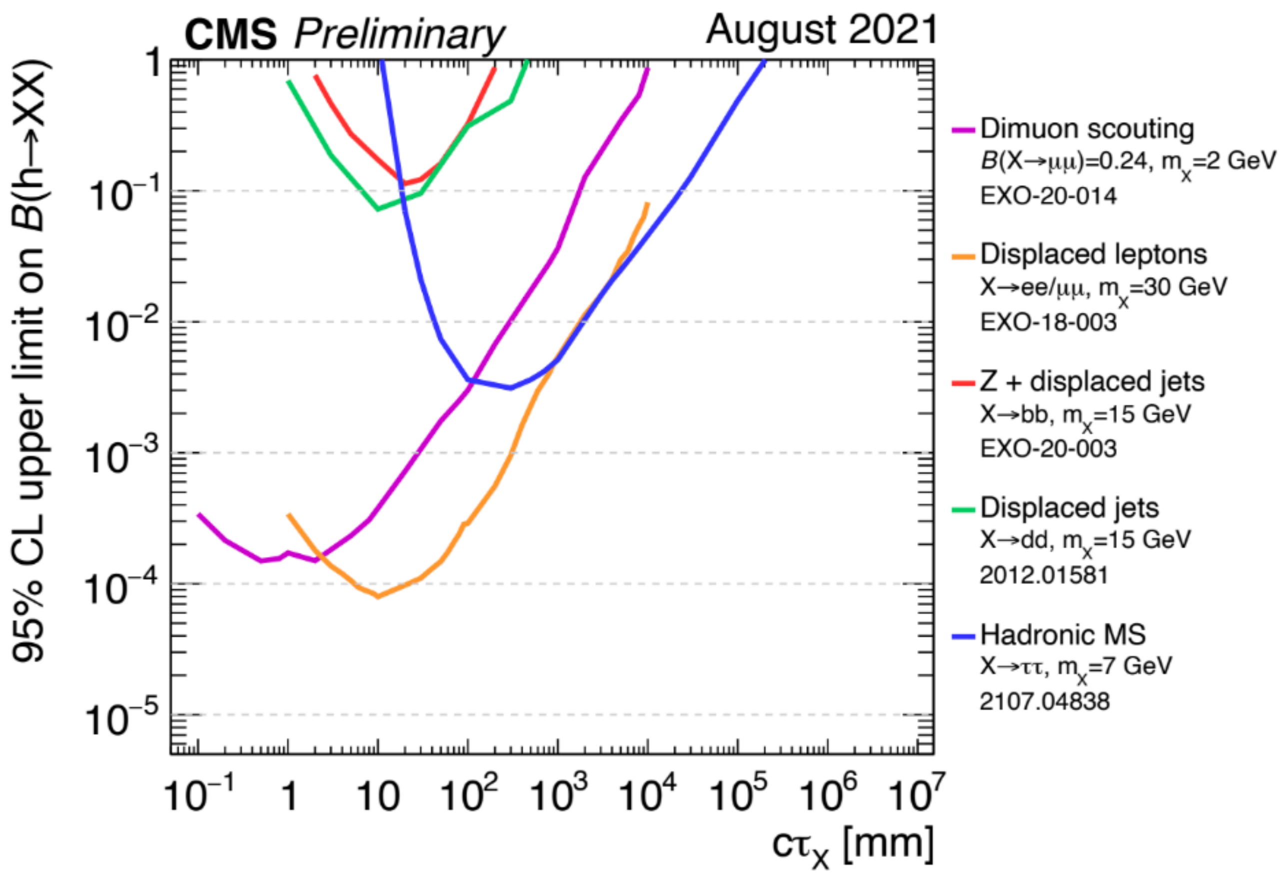
Large Lifetimes
Using existing detectors works well

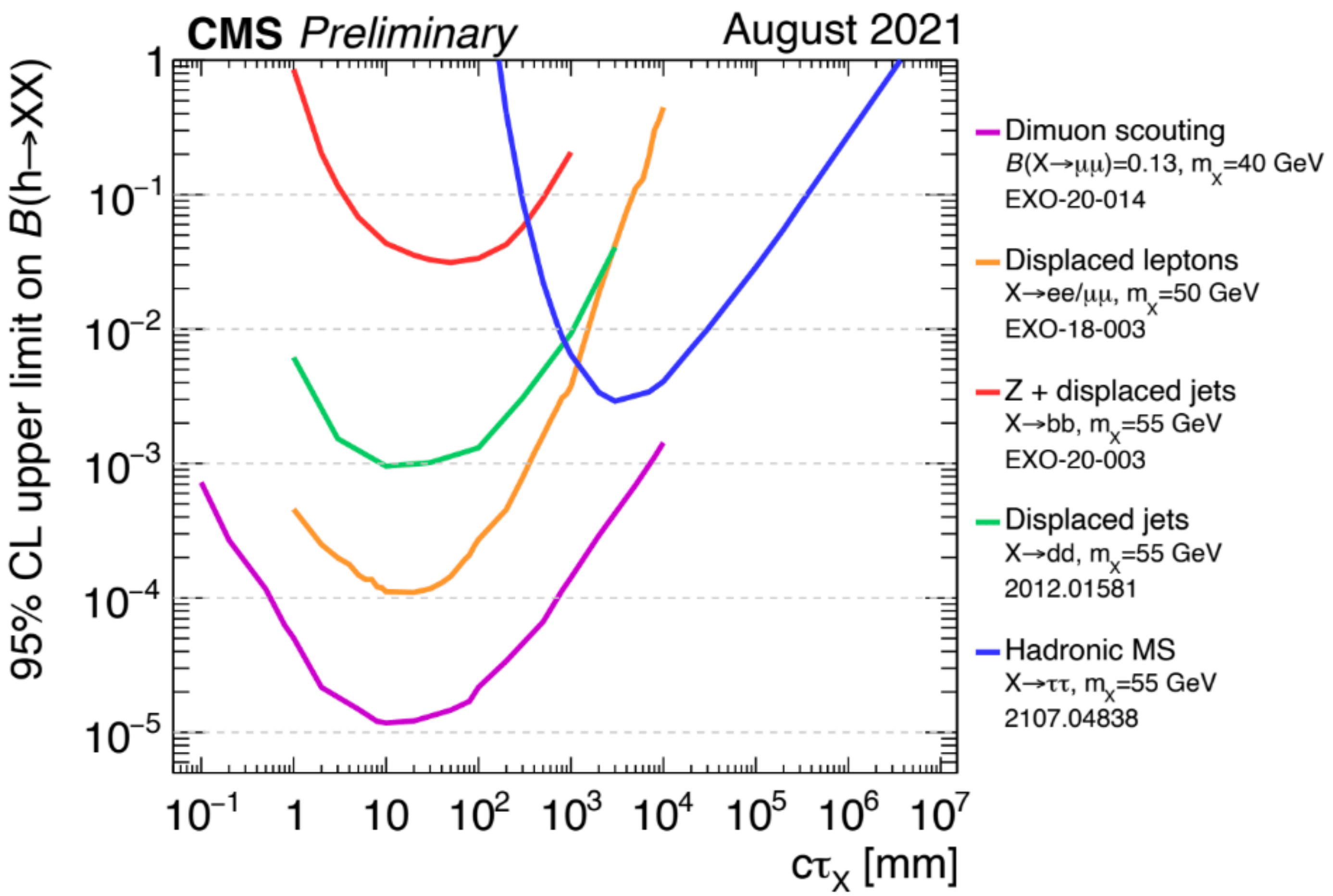
Another way to view it



- Detectors far away allow us to probe much longer lifetimes
  - Open unexplored space @LHC lots of new territory to probe

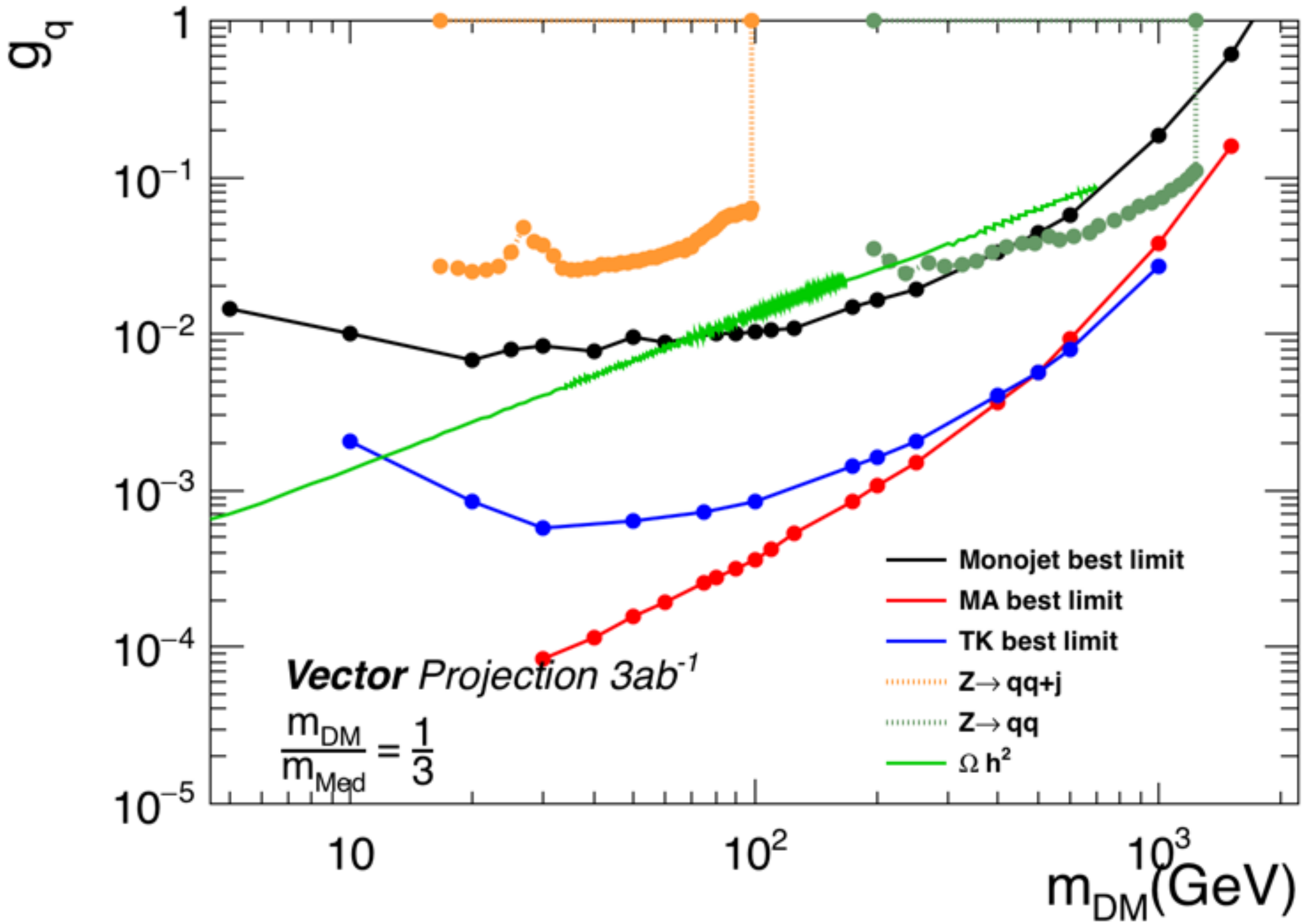
Current Analyses



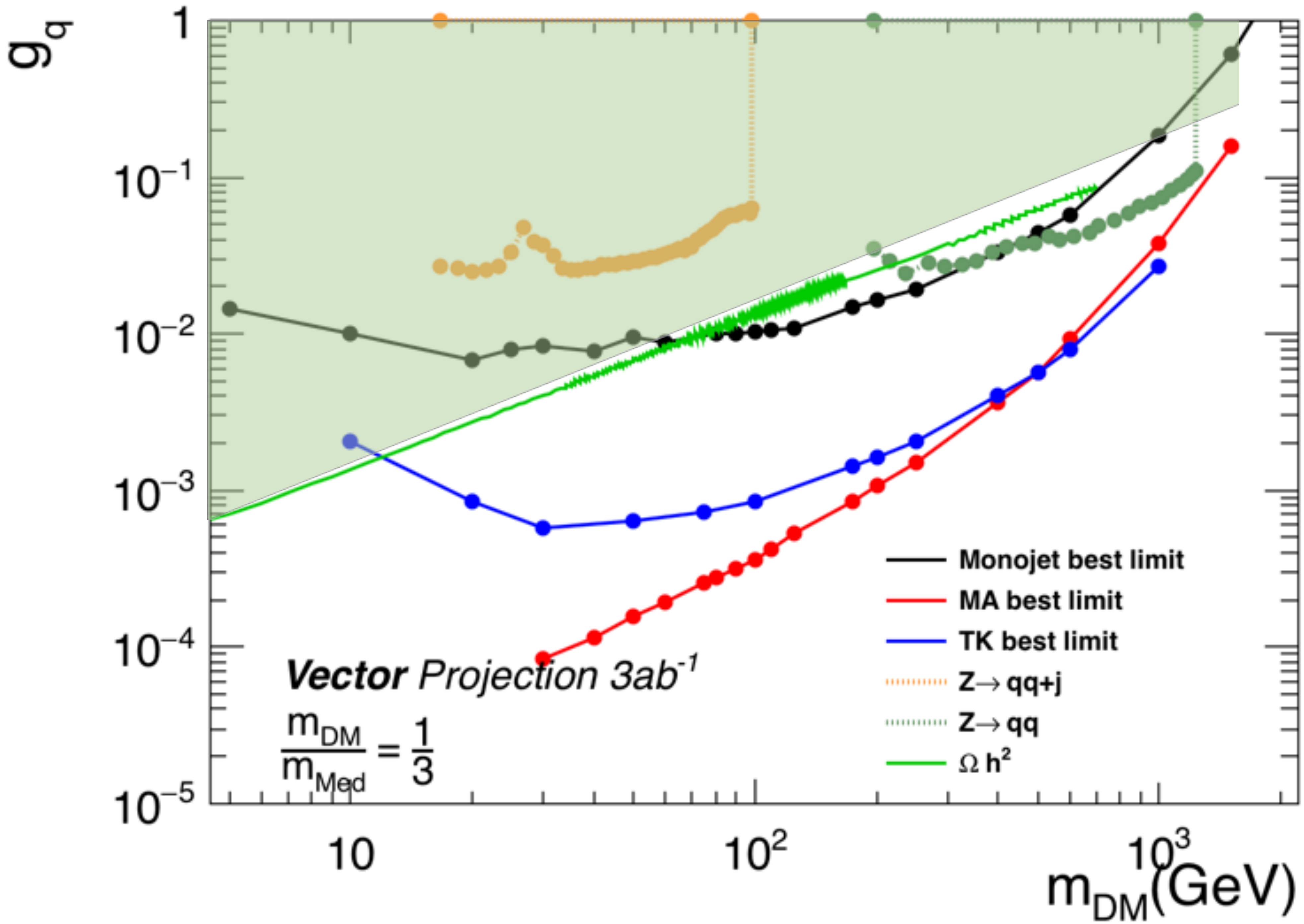


- Several final states we have already reached 10^{-4} benchmark
  - An interesting note: best bounds are coming from trigger scouting

Condensing into one plot

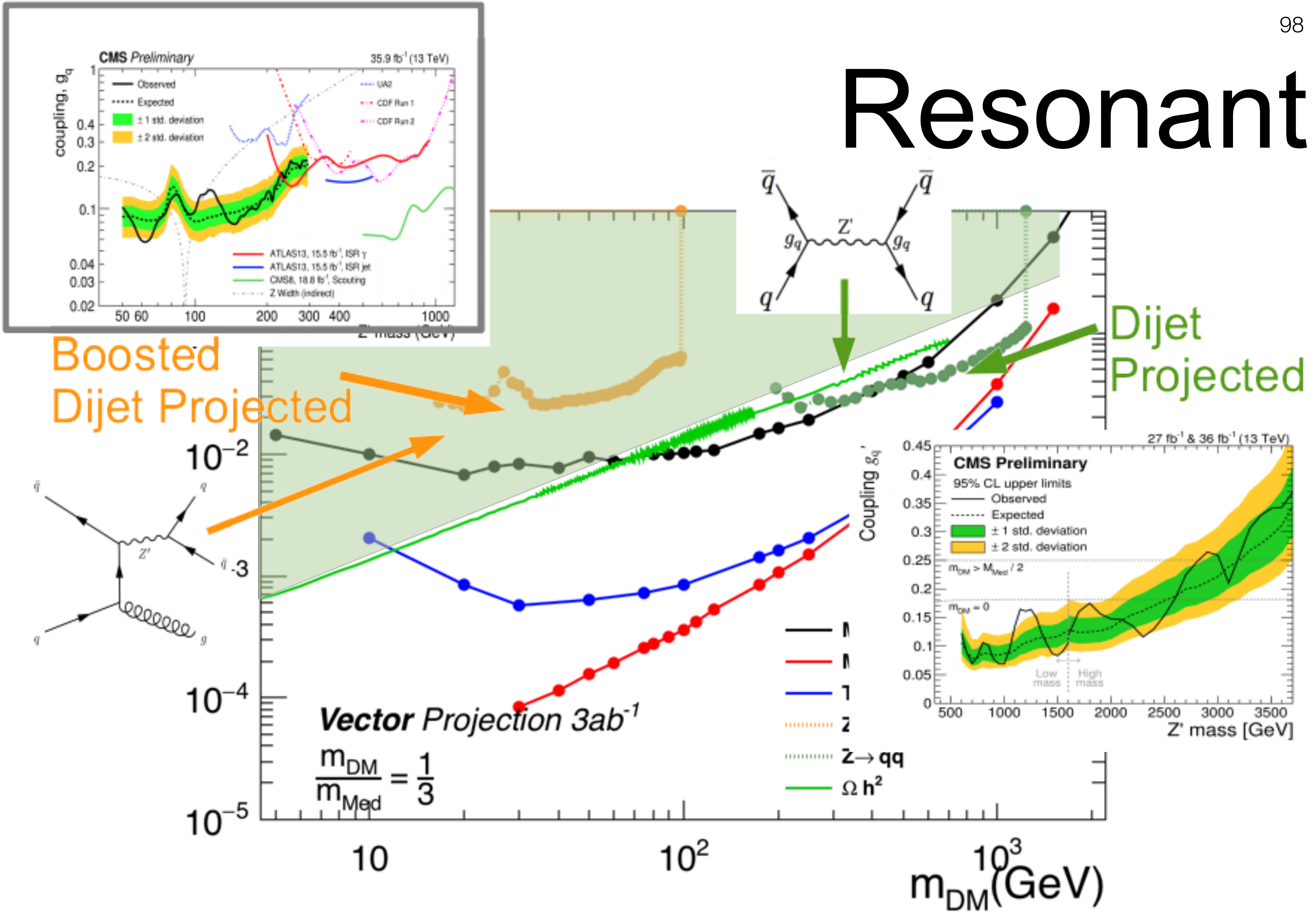


Condensing into one plot



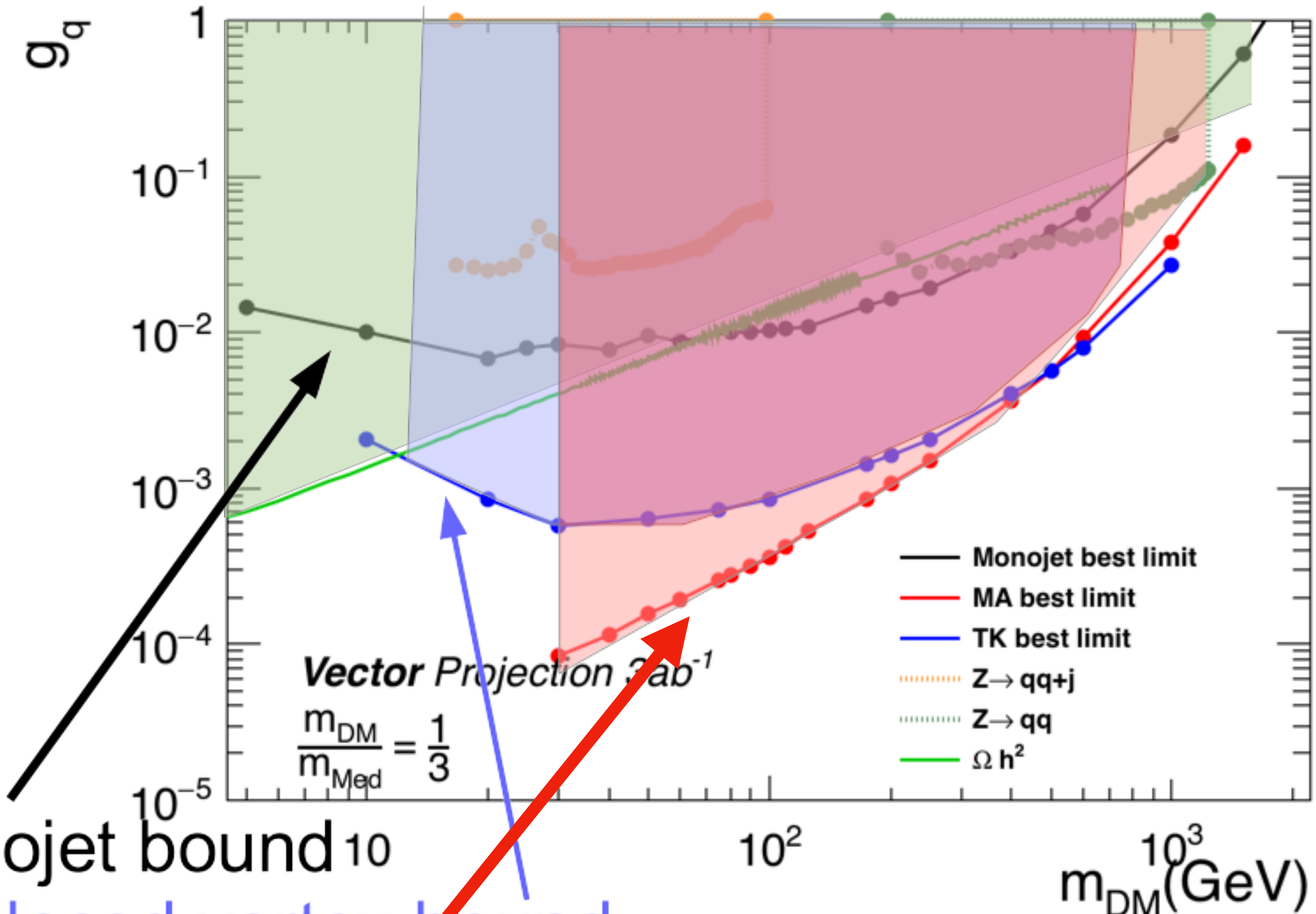
- Relic Density bounds are the same as previous models

Resonant



- Relic Density bounds are the same as previous models

MET+Displaced searches



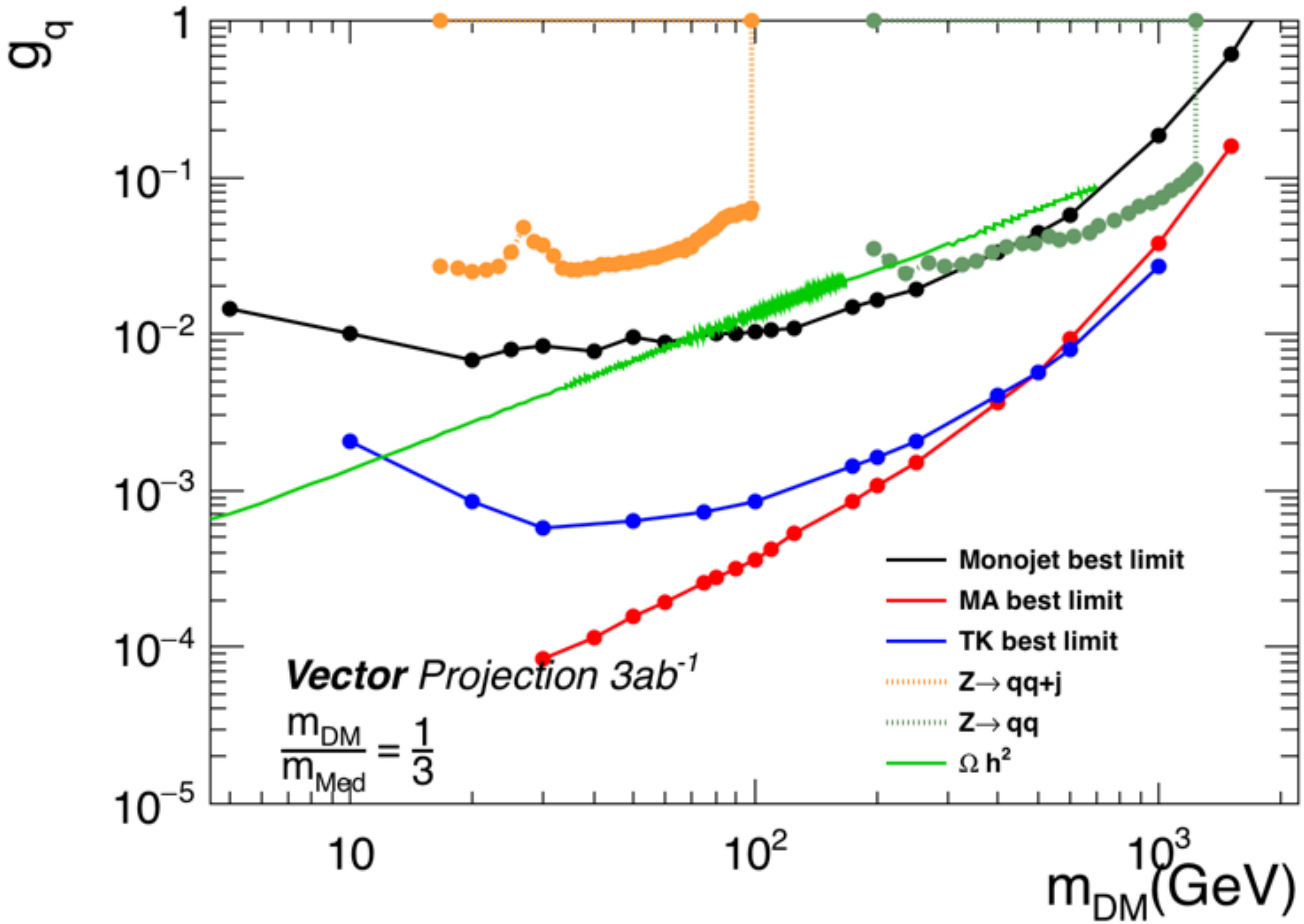
Monojet bound

Displaced vertex bound

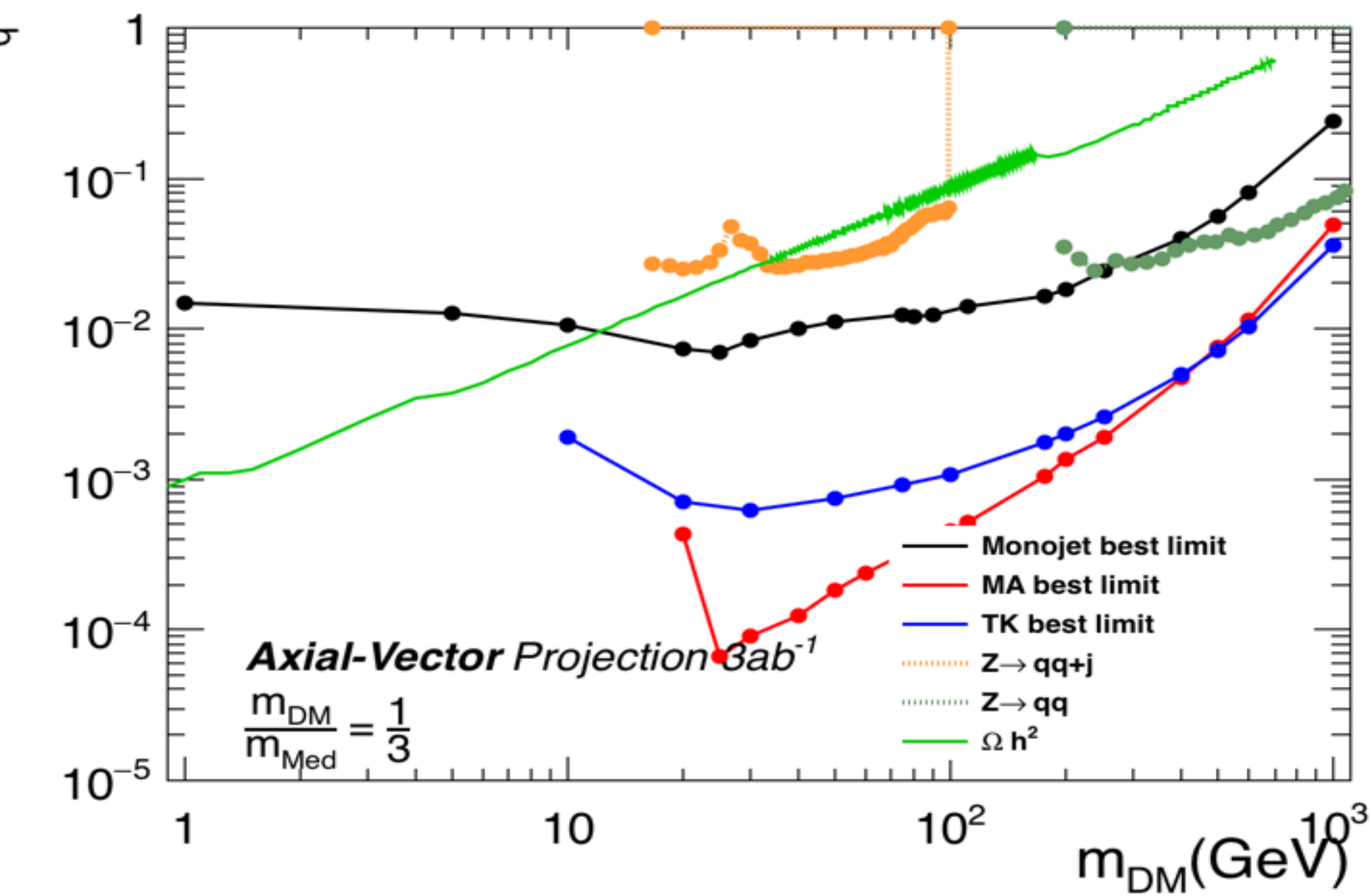
Mathusla bound

For Long Lived projects
take **Lowest possible bounds**

Condensing into one plot

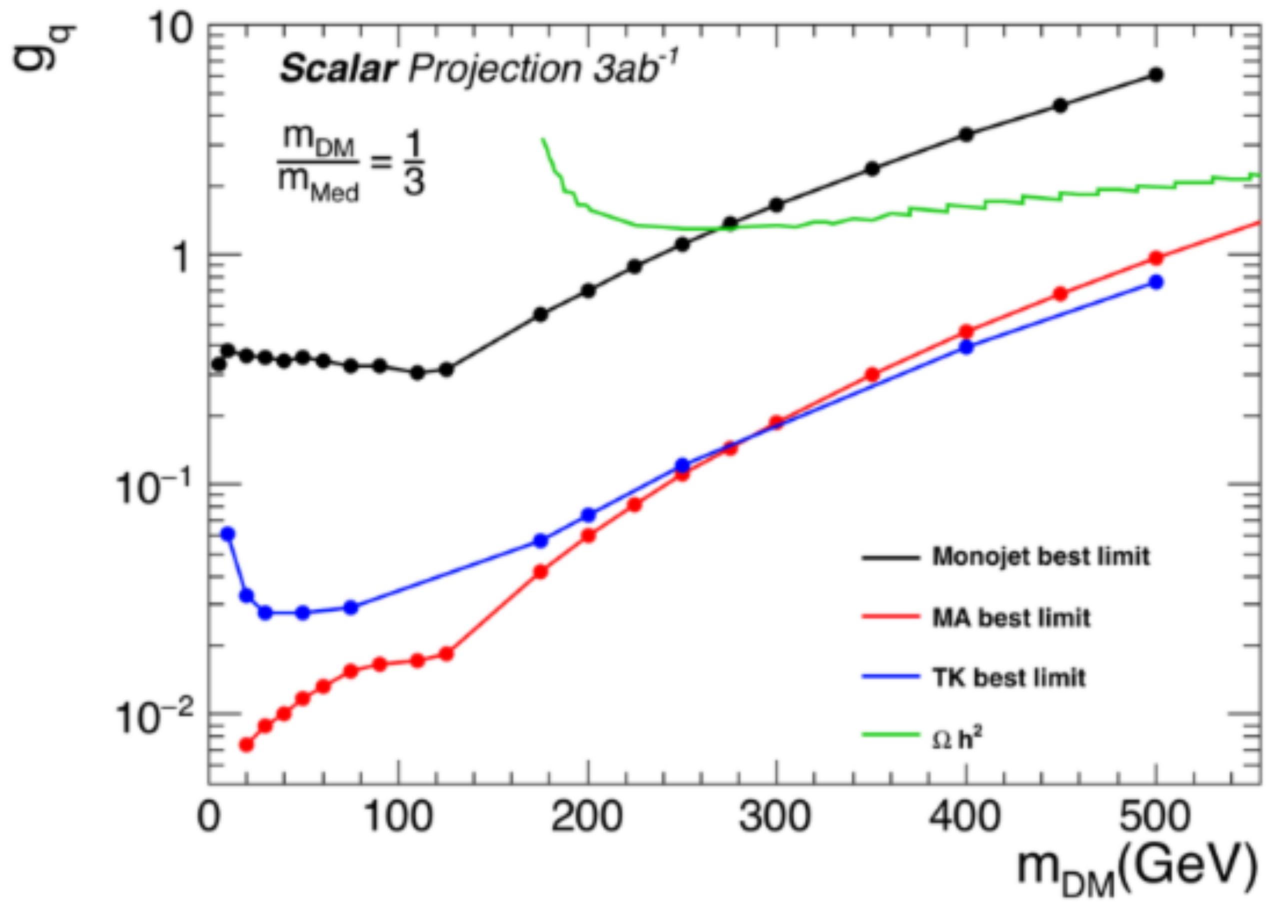


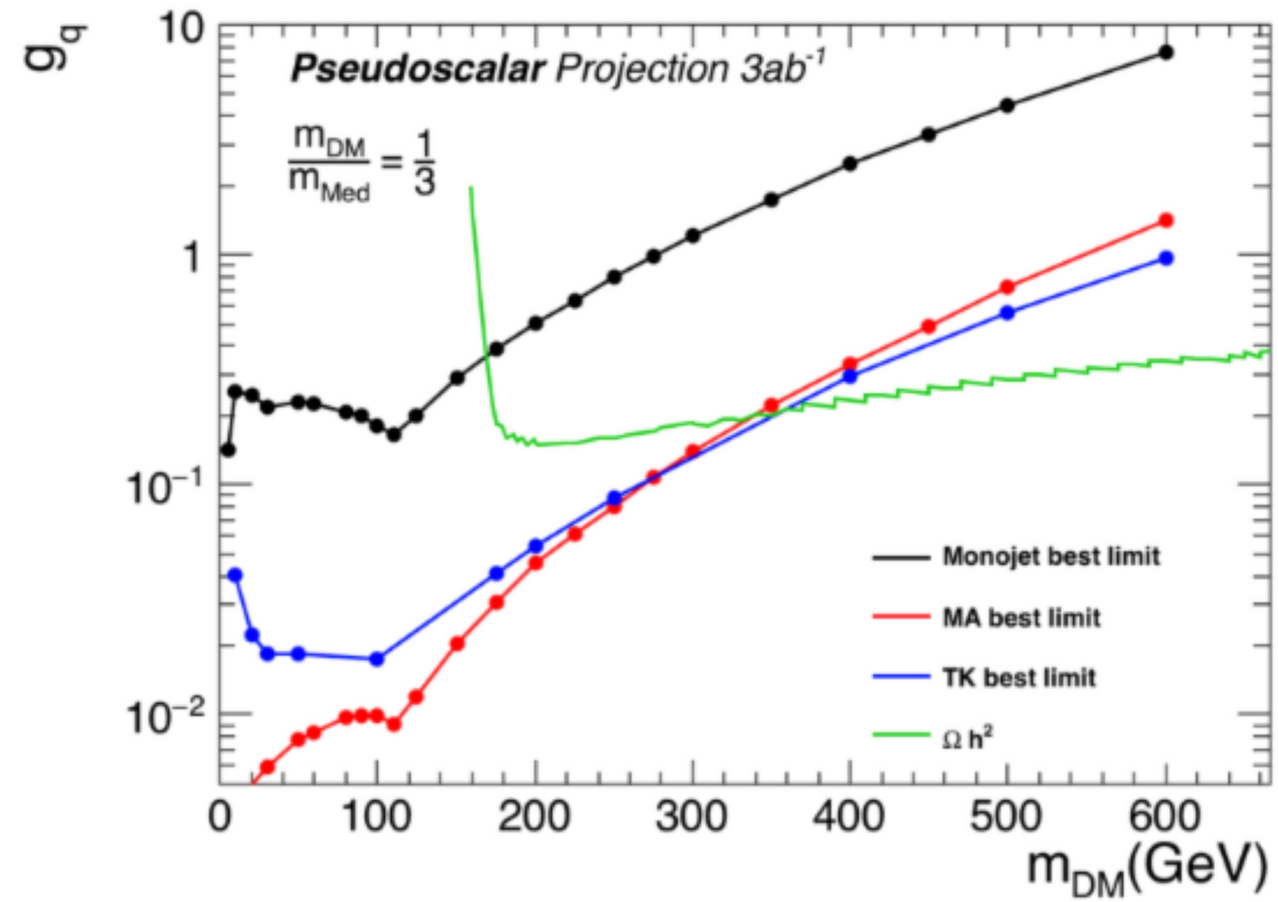
Axial Coupling Bound



- With Axial-vector model Relic density requires larger coupling

(Pseudo)Scalar



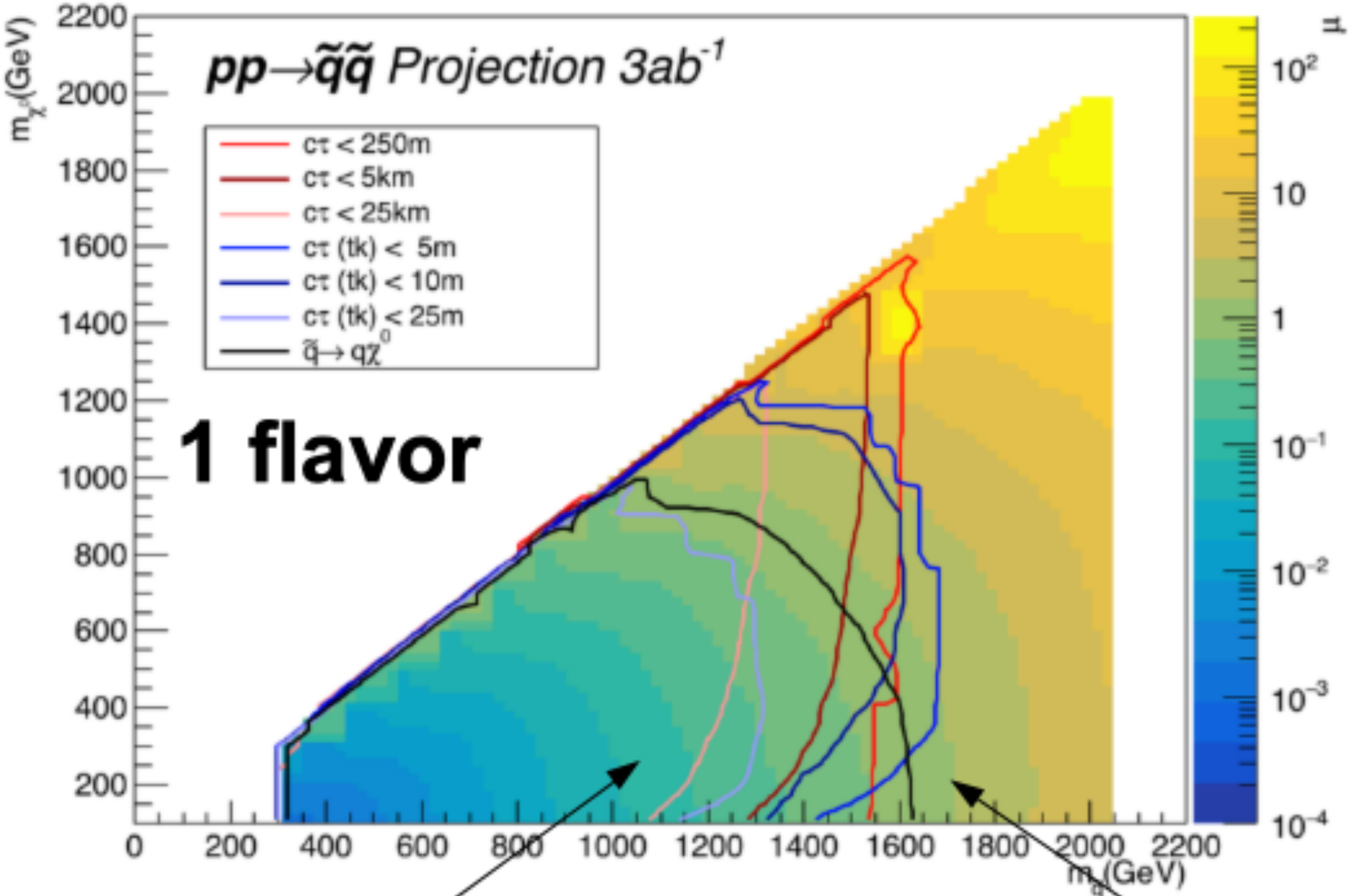


- Similar Large improvements insensitivity
  - How this plays into DM is a more complicated question

A SUSY example

- SUSY bounds
  - Lots of heavy objects

With heavy objects its harder to win



Project CMS bound

LL and MATHUSLA bring less

Other Long-Lived Models

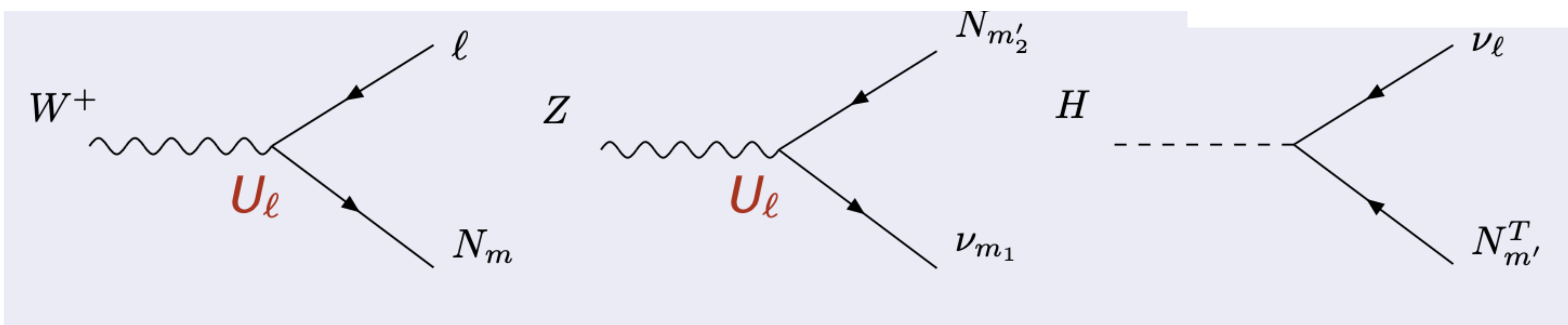
Heavy Neutral Lepton

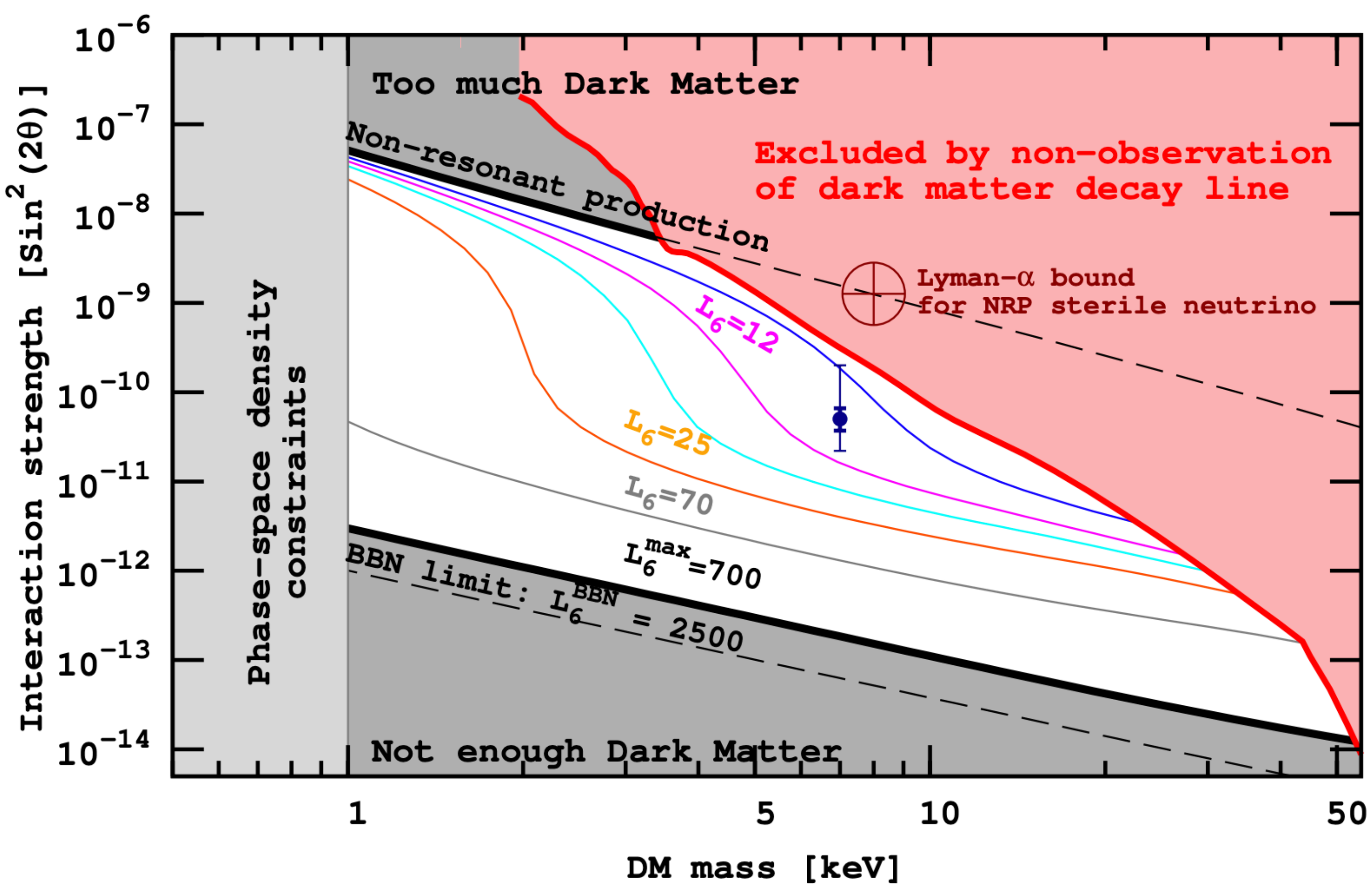
Heavy Neutral Leptons

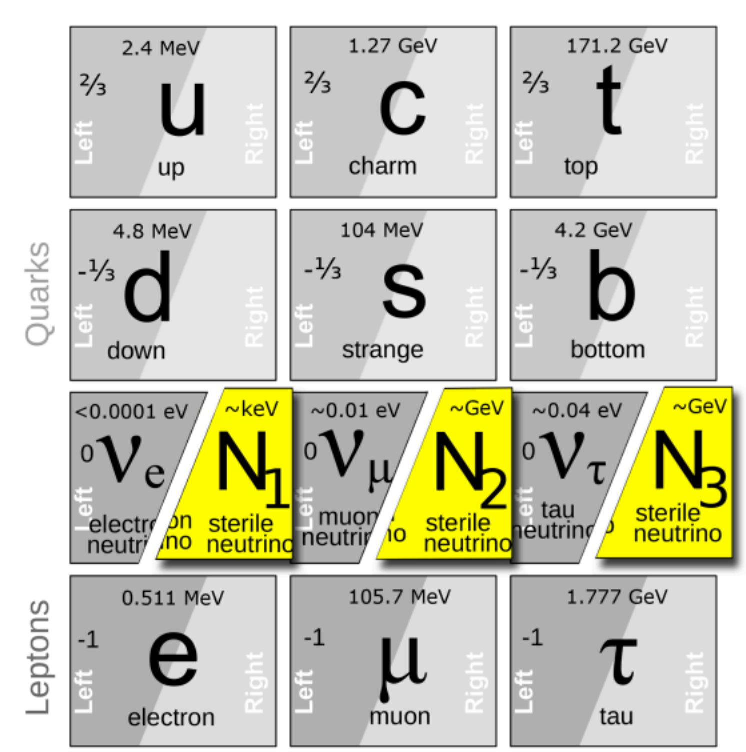
- Explanation for DM comes from heavy neutral letpons

$$\mathcal{L} = y\bar{L}\tilde{H}N = M_D\bar{\nu}N + yh\nu N$$

$$m_\nu \simeq \frac{(M_D)^2}{M} = U^2 M$$

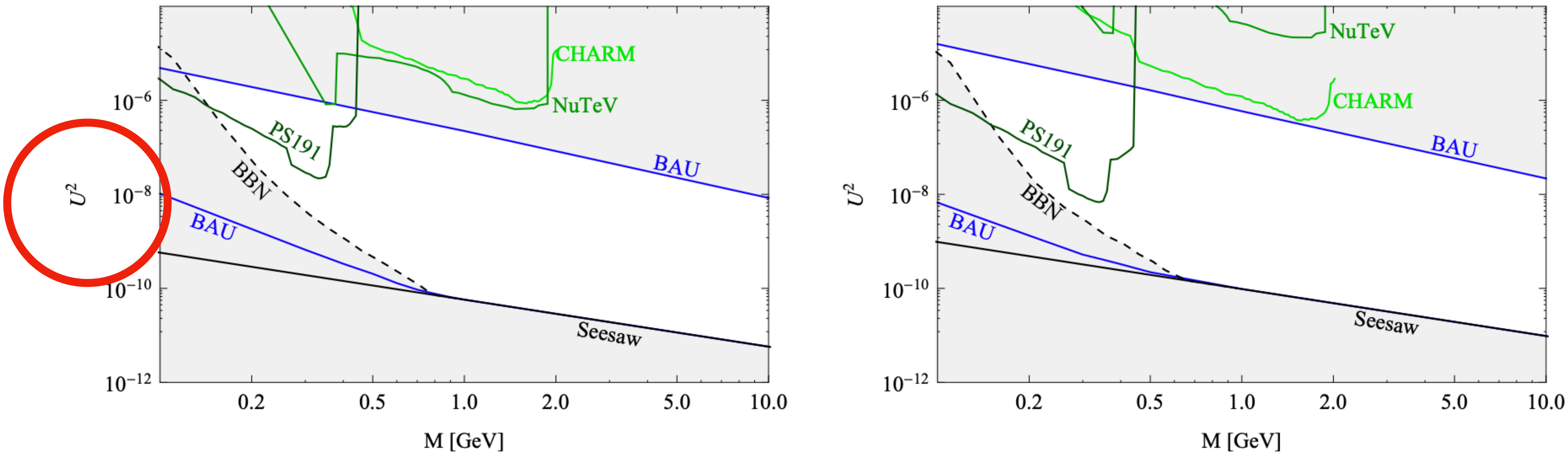






Heavy Neutral Leptons

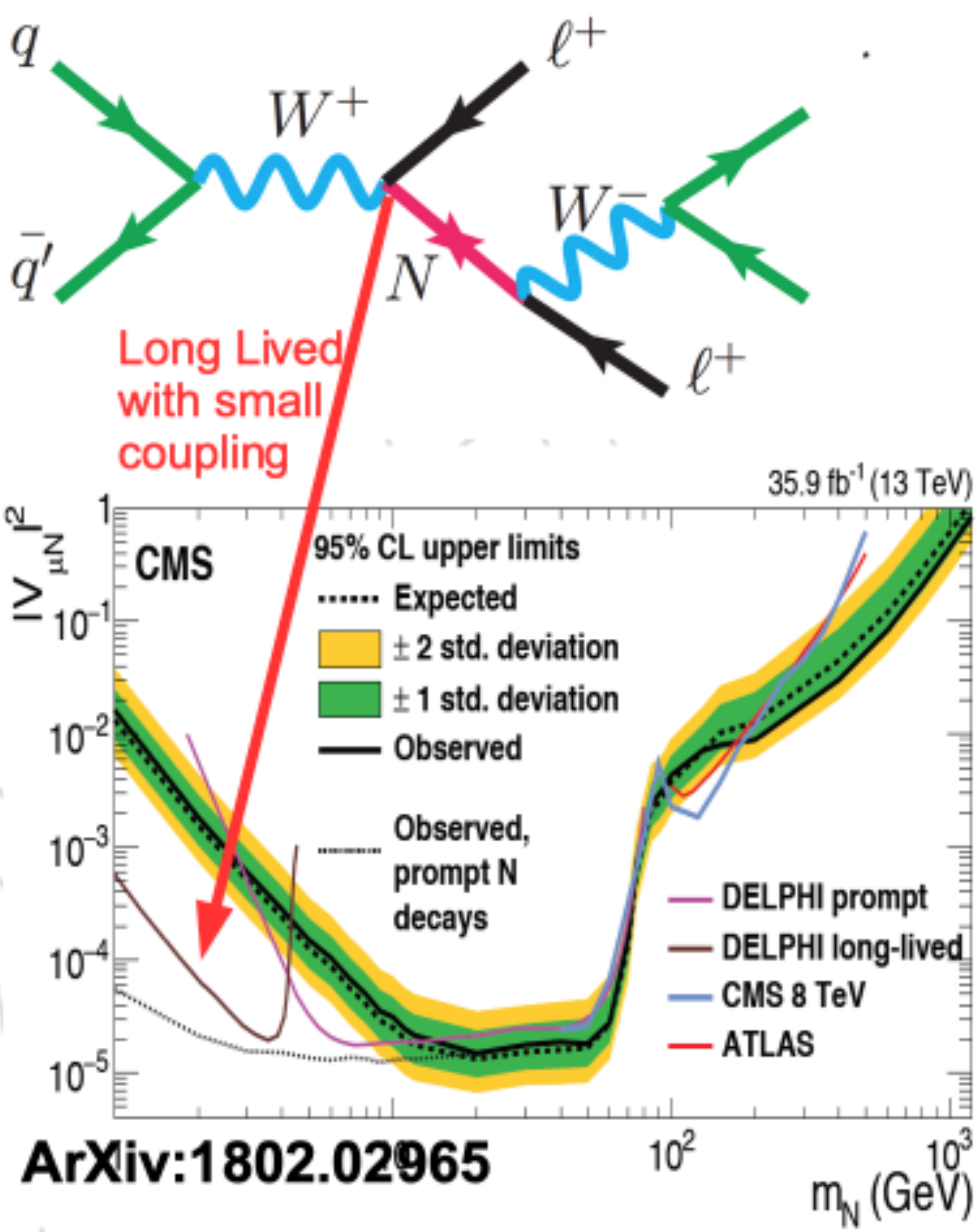
- Explanation for DM comes from heavy neutral leptons
  - Minimal version gives up to 3 leptons for each flavor
  - In the minimal version 2 heavier leptons are a few GeV in mass



The small mixing gives rise to very weak interactions

This model can potentially explain dark matter

Right Handed Neutrinos

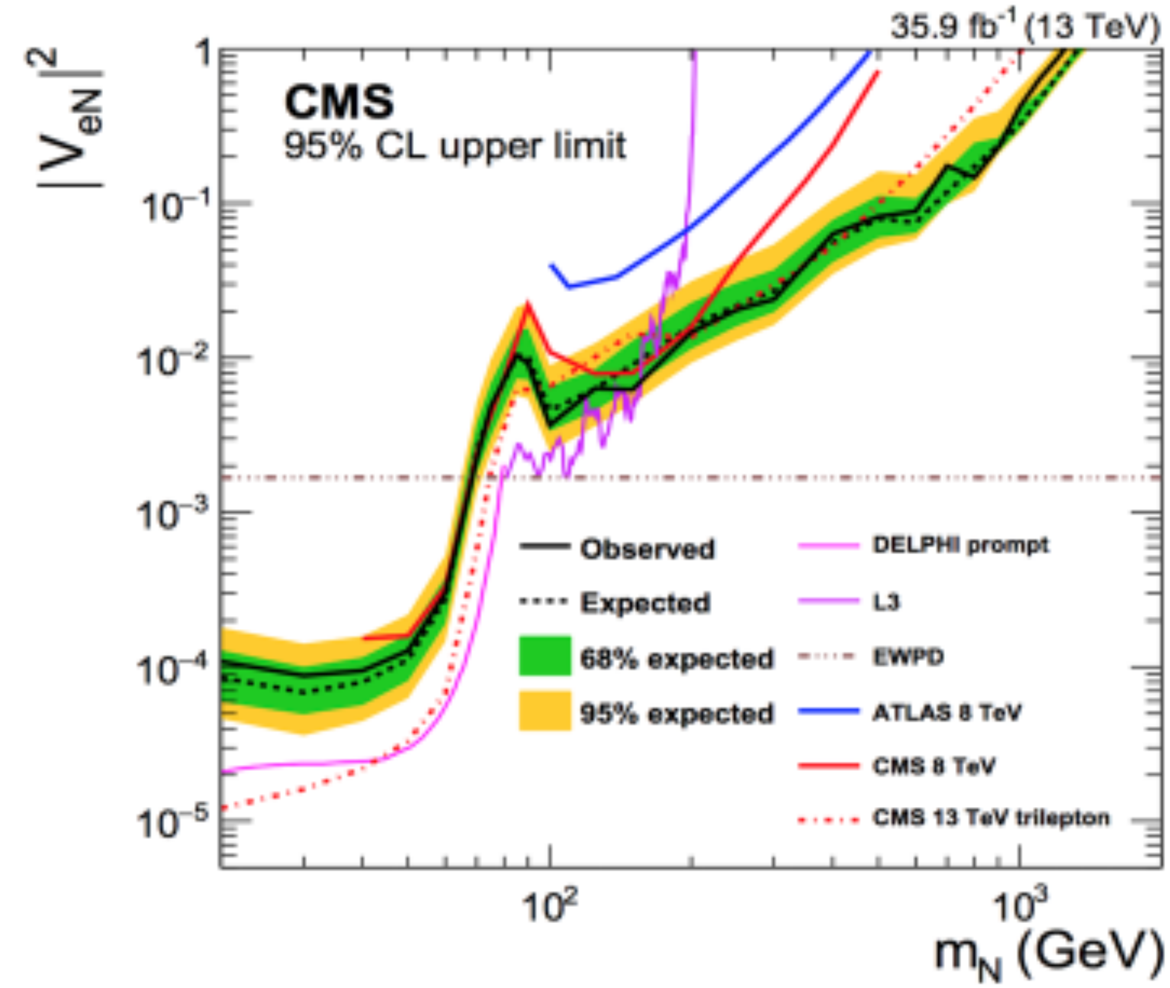


ArXiv:1802.02965

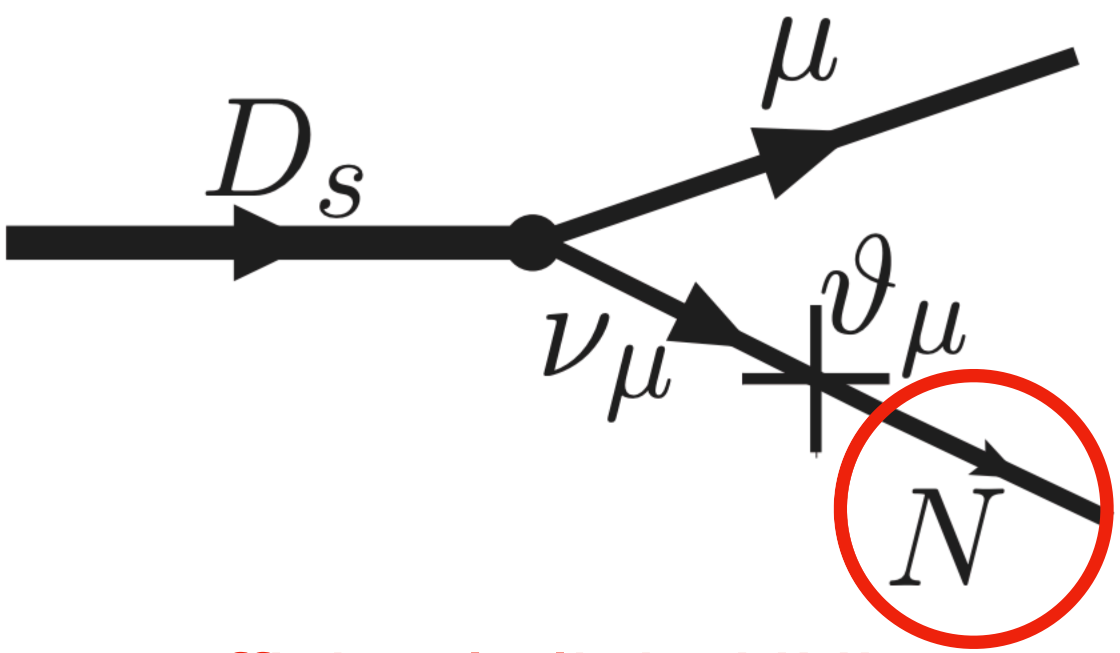
CMS-EXO-17-028

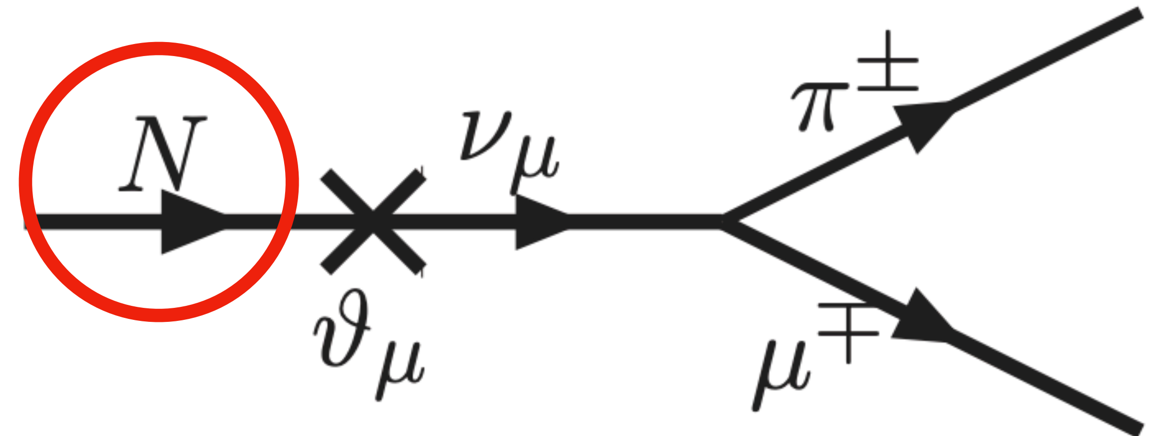
Expect Bounds at low mass to improve

Once long lived analysis is performed



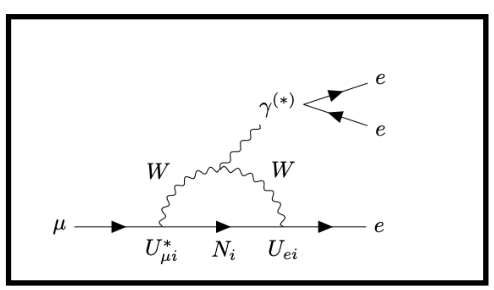
Probing HNLs that are LL





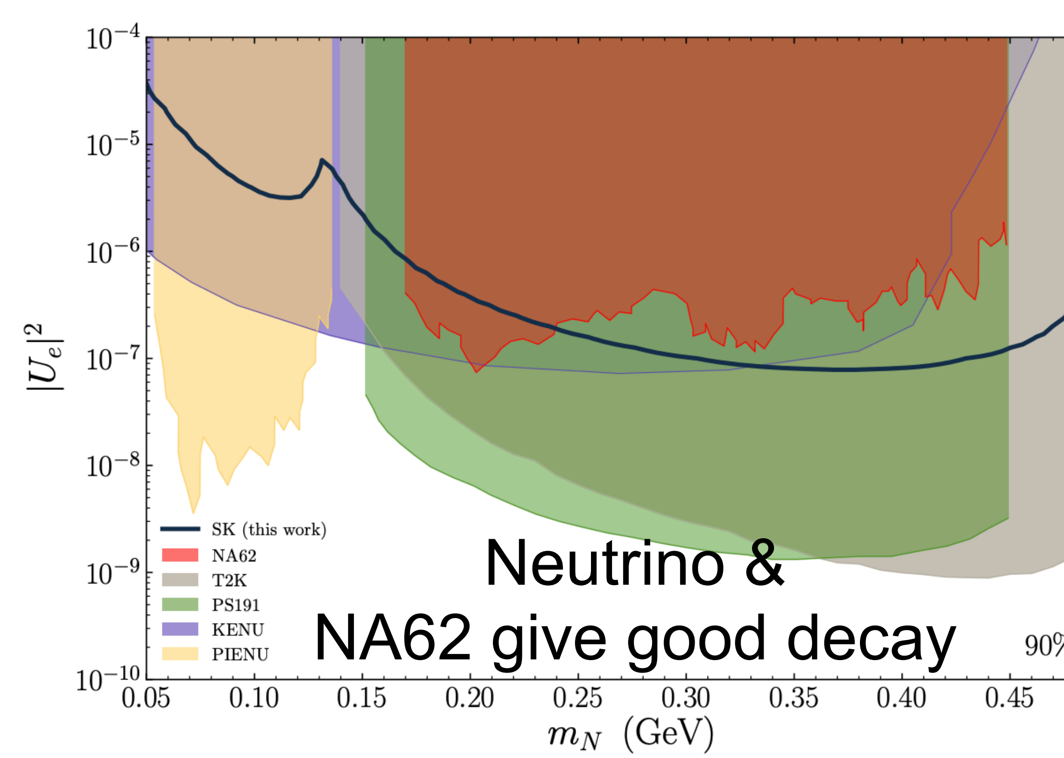
Weak Coupling can make this a Long Lived Decay

For a sufficiently light HNL



$\mu \rightarrow 3e$ puts bounds

- Since HNLs are long-lived objects
  - Search for them at long lived experiments
  - Signature will be similar to a ν_μ decay



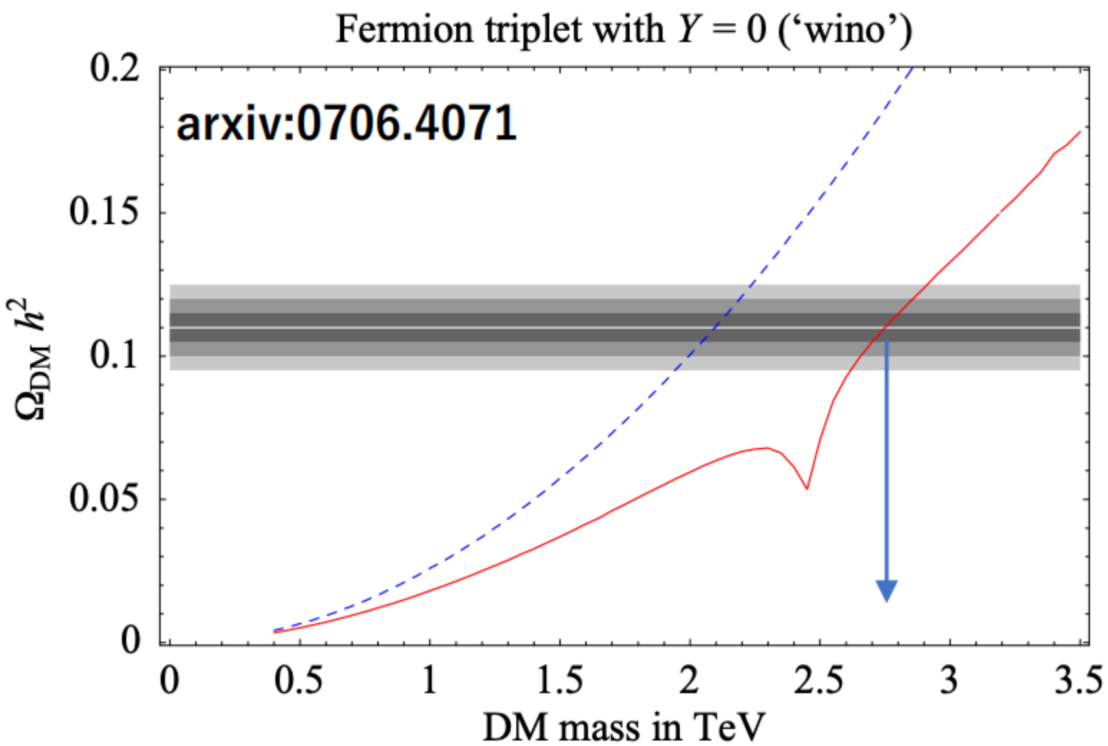
Neutrino & NA62 give good decay

Other Long-Lived Models

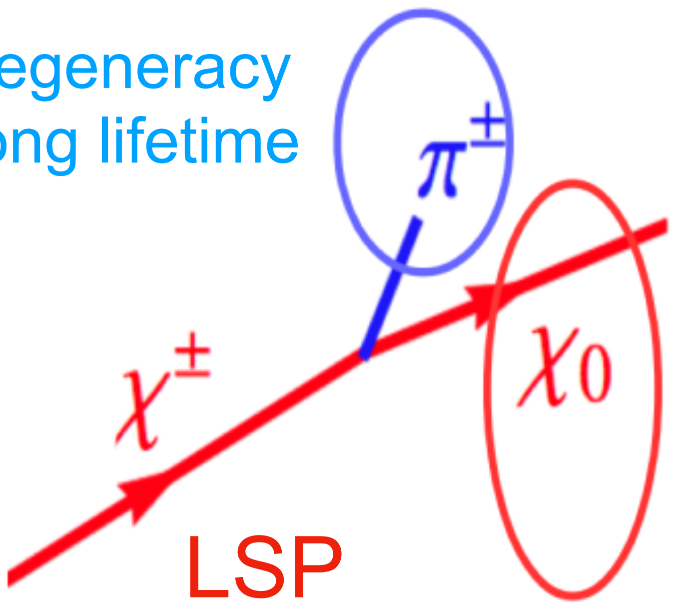
Wino/Higgsino

Classic DM: Wino/Higgsino

$$m_{\chi^\pm} - m_{\chi^0} \sim 165 \text{ MeV}$$



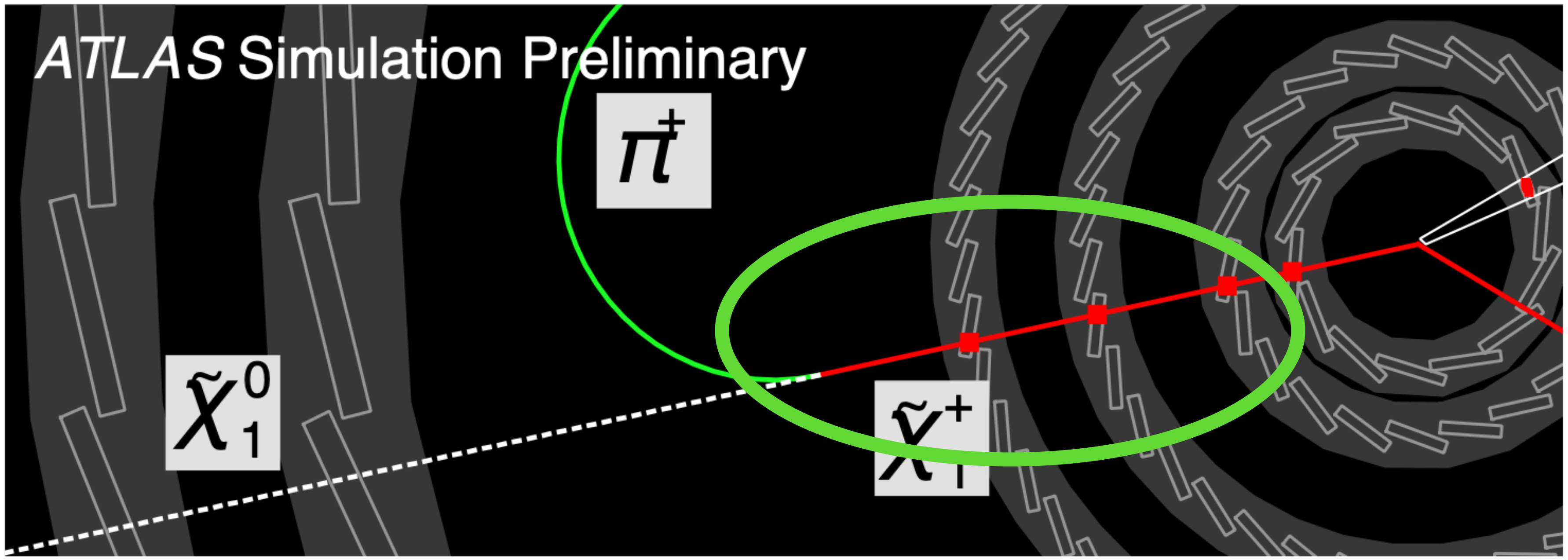
Mass degeneracy
Gives long lifetime

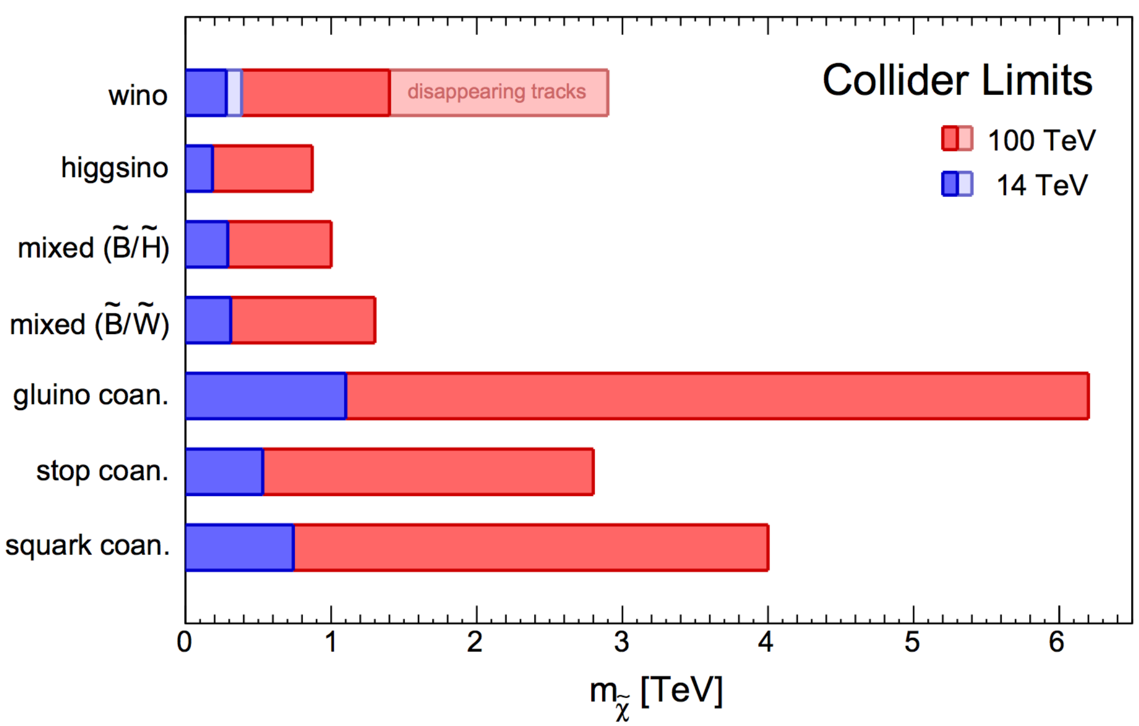


LSP
Mass needs to be < 3TeV

- While it was not the focus of these lectures
  - One potential SUSY possibility can be a long-lived chargino
  - Particle can have a lifetime and decay to dark matter (LSP)
- Wino gives a heavy DM candidate (2-3 TeV)
- Higgsino is lighter (< 1 TeV)

Classic DM: Wino/ Higgsino





Striking signature of a track from a heavy particle disappearing

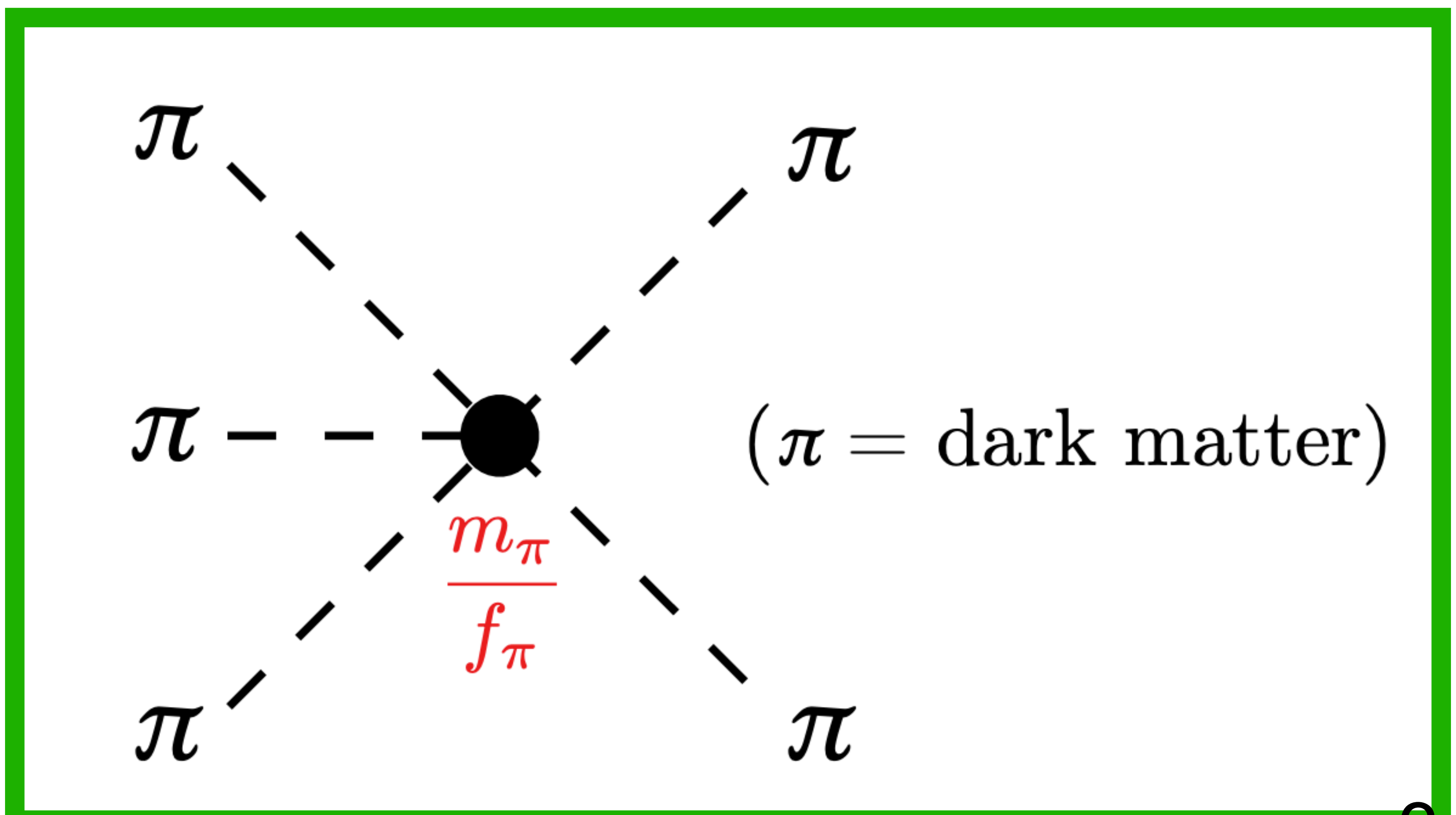
Will have large dE/dx
Will also have a soft pion
Lifetime likely a few m

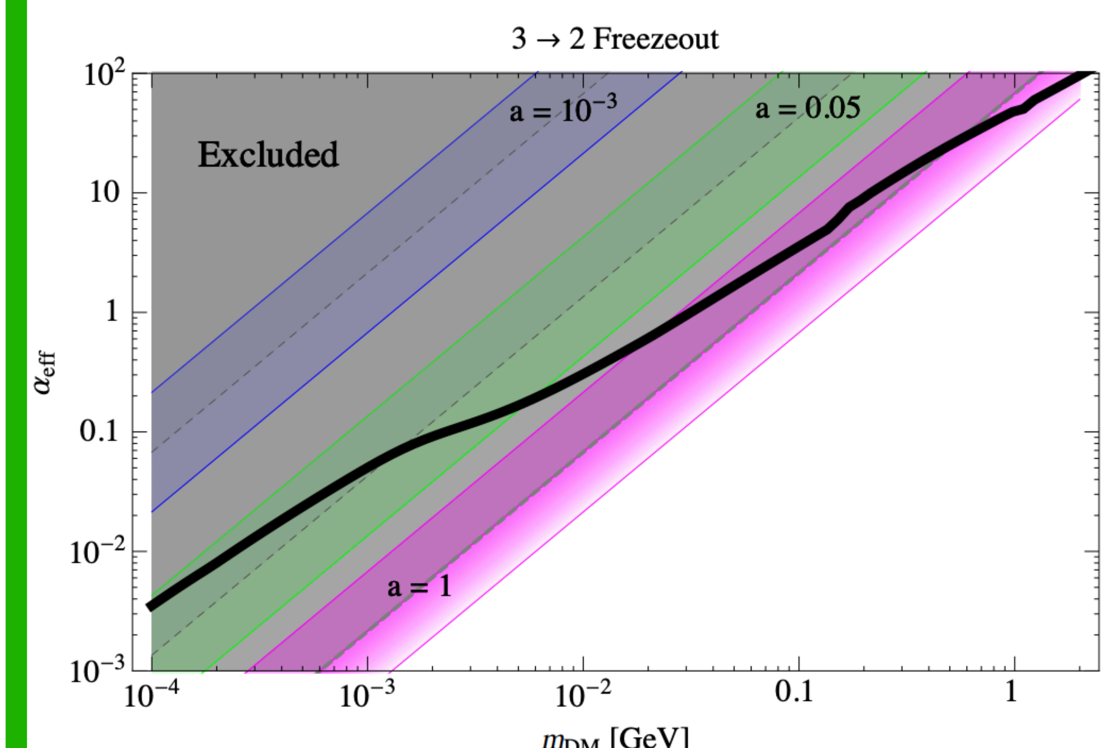
Even Crazier Models

SIMPs

- Going beyond the simplified models
  - There are even other ways to make dark matter at collider
  - A popular way is to modify the strong coupling sector

Dark Matter eats itself

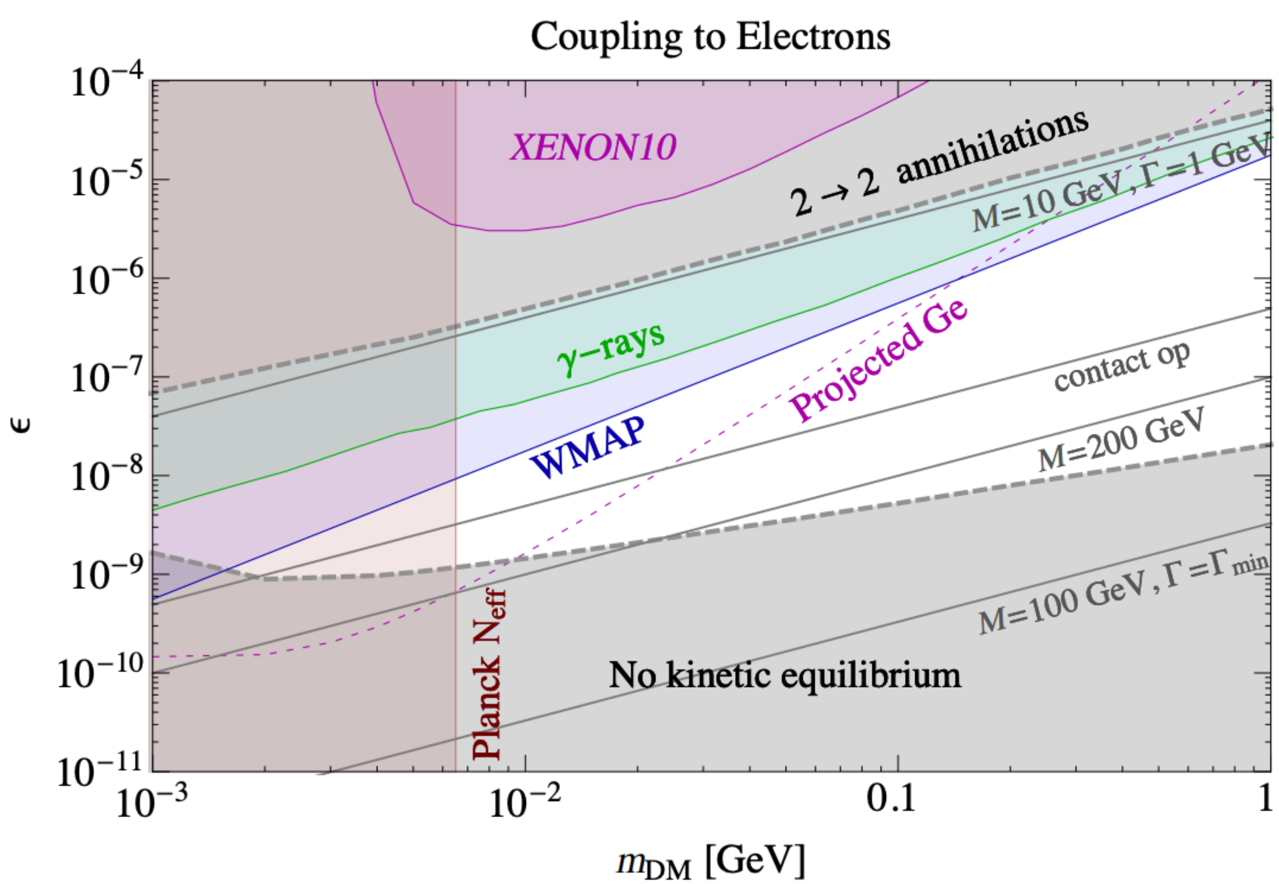


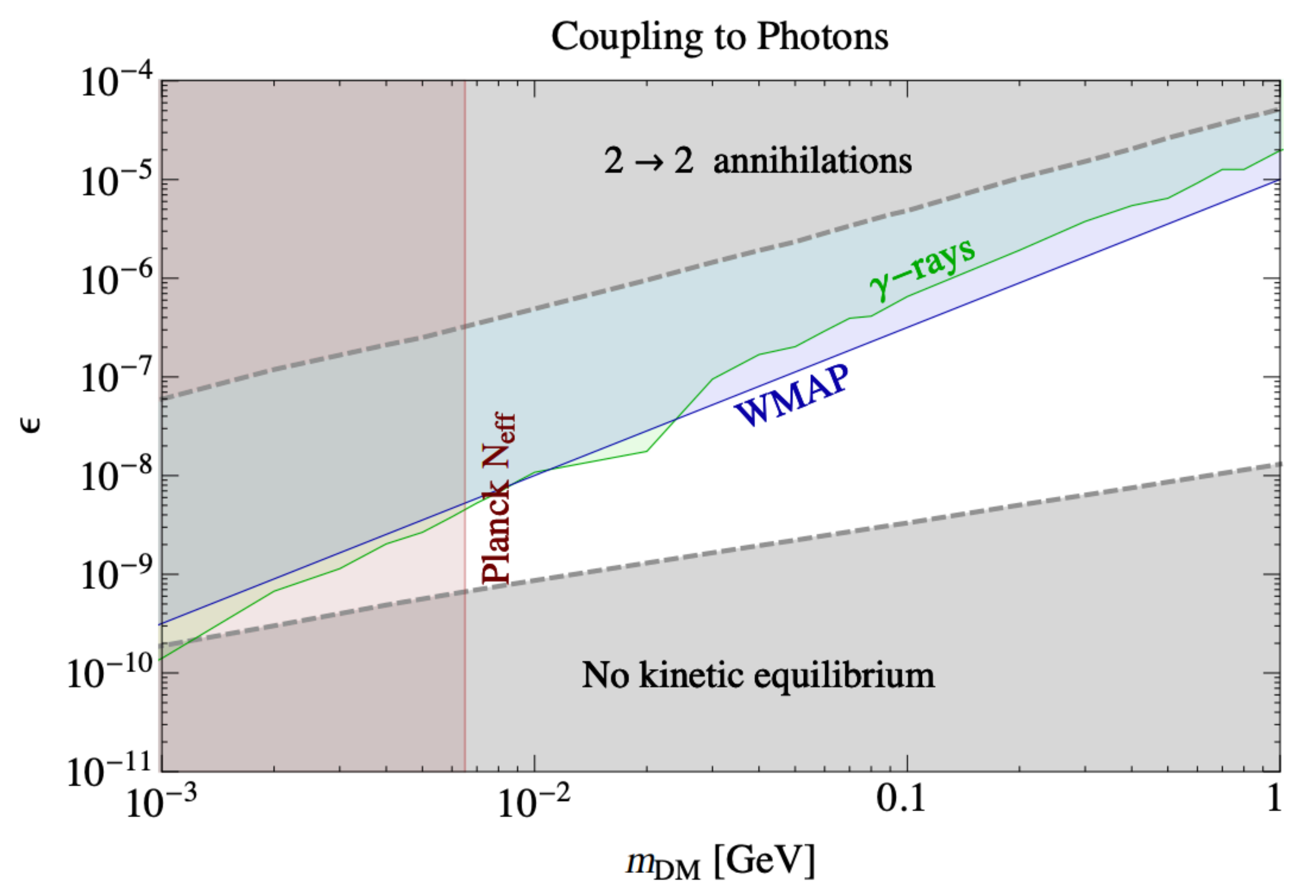


3→2 Mechanism explains several astrophysical phenomenon

How it manifests

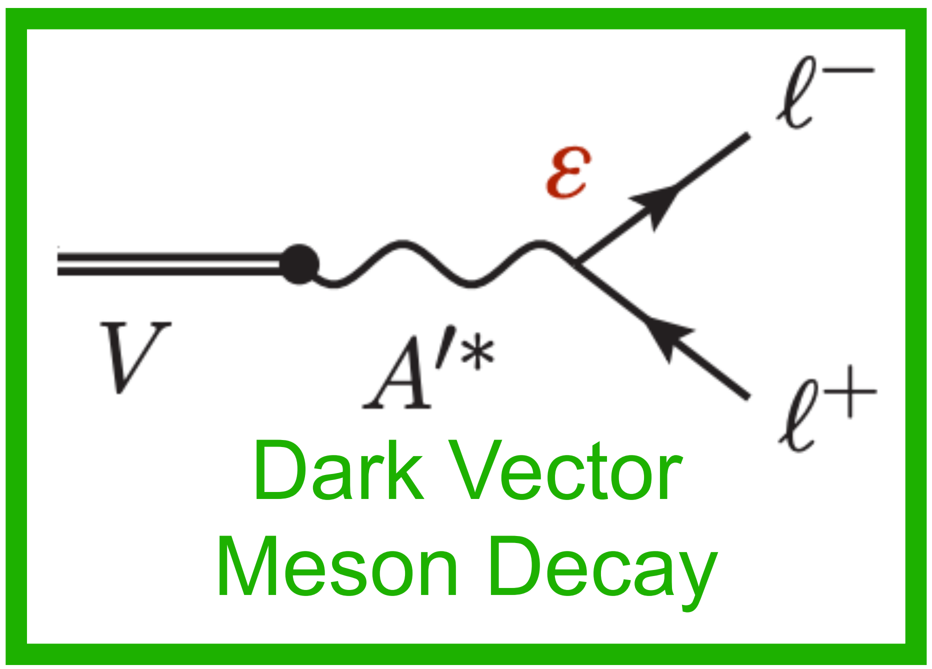
- Get the right relic density Dark Sector SM interaction is needed
  - Coupling needed to SM through a dark photon or other portal
  - Coupling needs to be small, gives long lived signatures
- This model allows for a rich complex dark sectors
  - Dark Pions, and other Dark QCD options

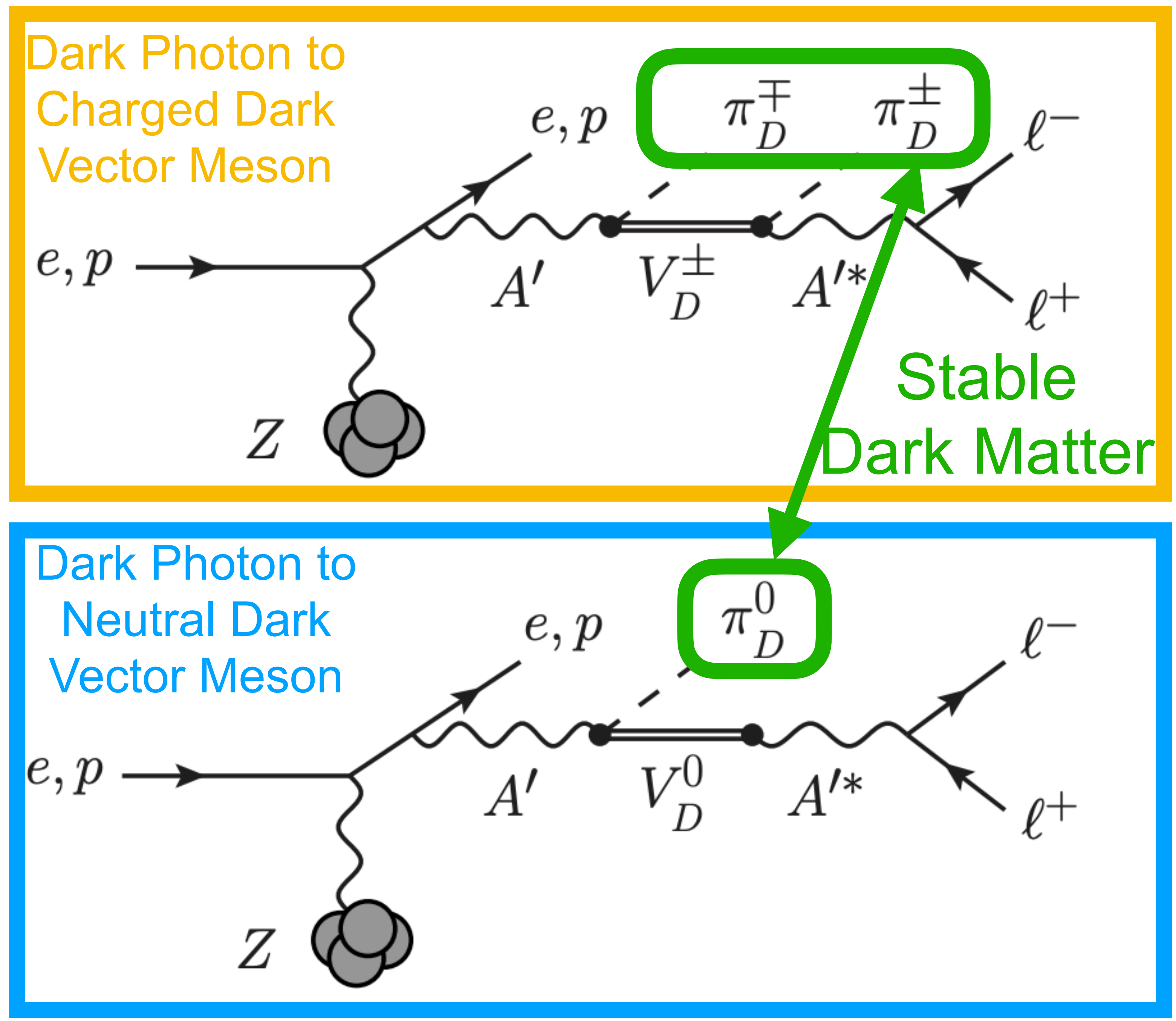




Phenomenology

- From the rich dark sector we have a few decays



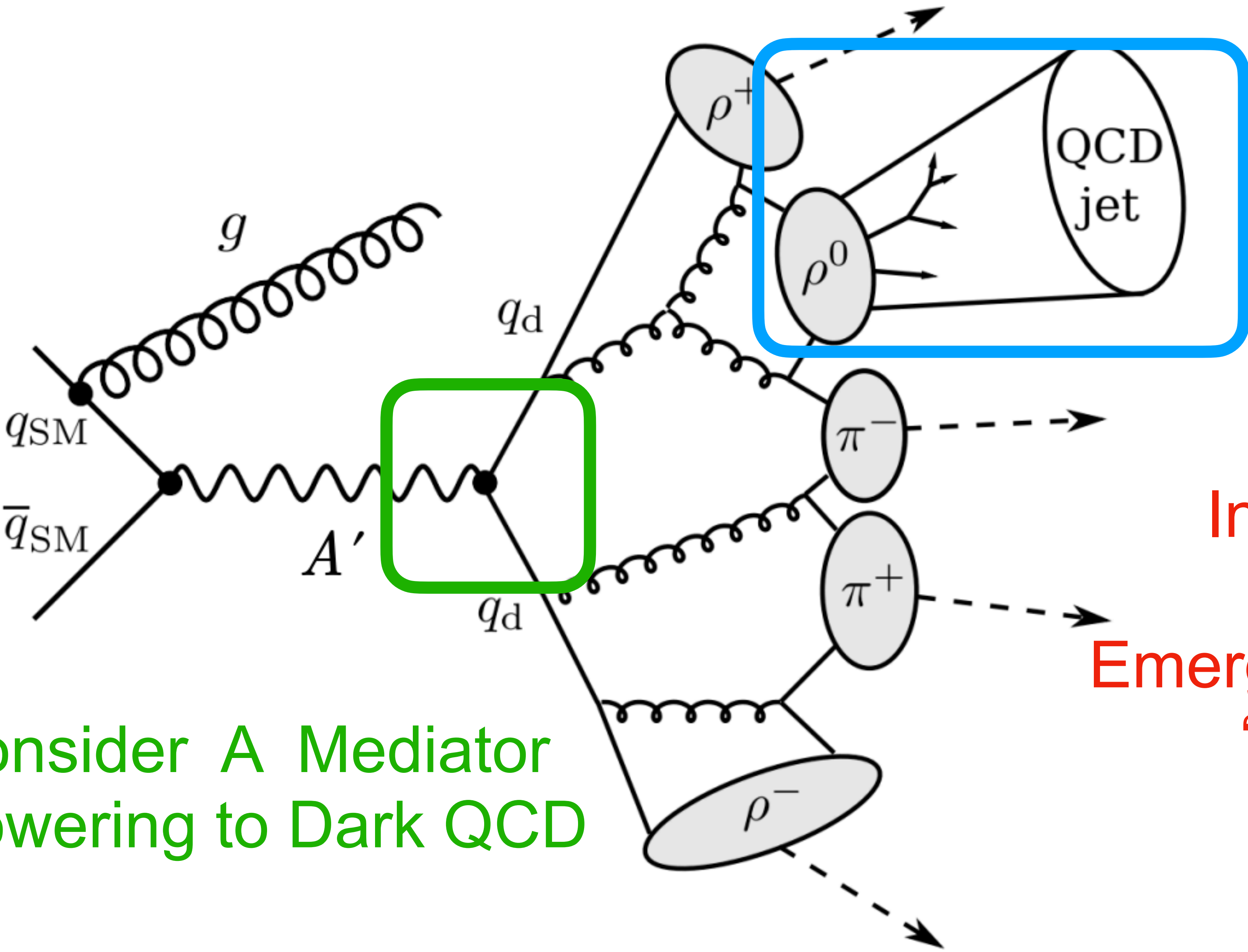


Like other DM models Long lived signatures present

Presence of complex Dark Sector makes interesting signals

And at LHC

- We can have even more complex scenarios



These dark sector Quarks can decay into SM

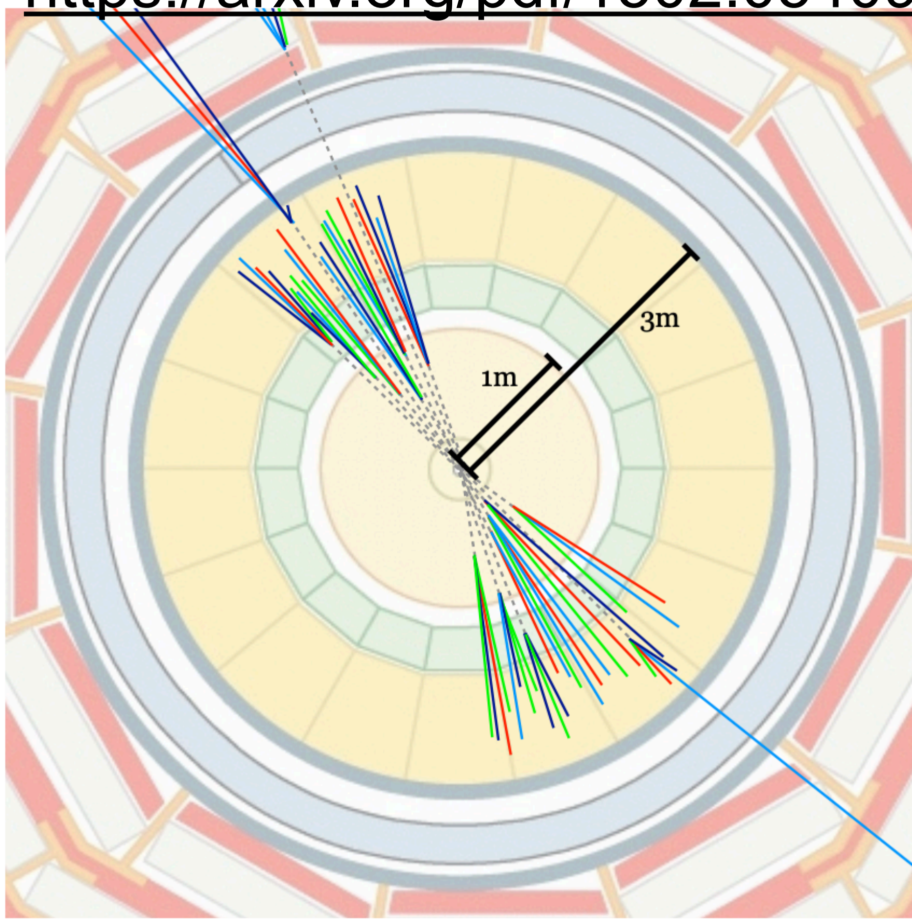
In some scenarios these jets will Emerge with some lifetime "Emerging Jets"

Consider A Mediator Showering to Dark QCD

How do we search for these?

- Again there are many ways to search for these:

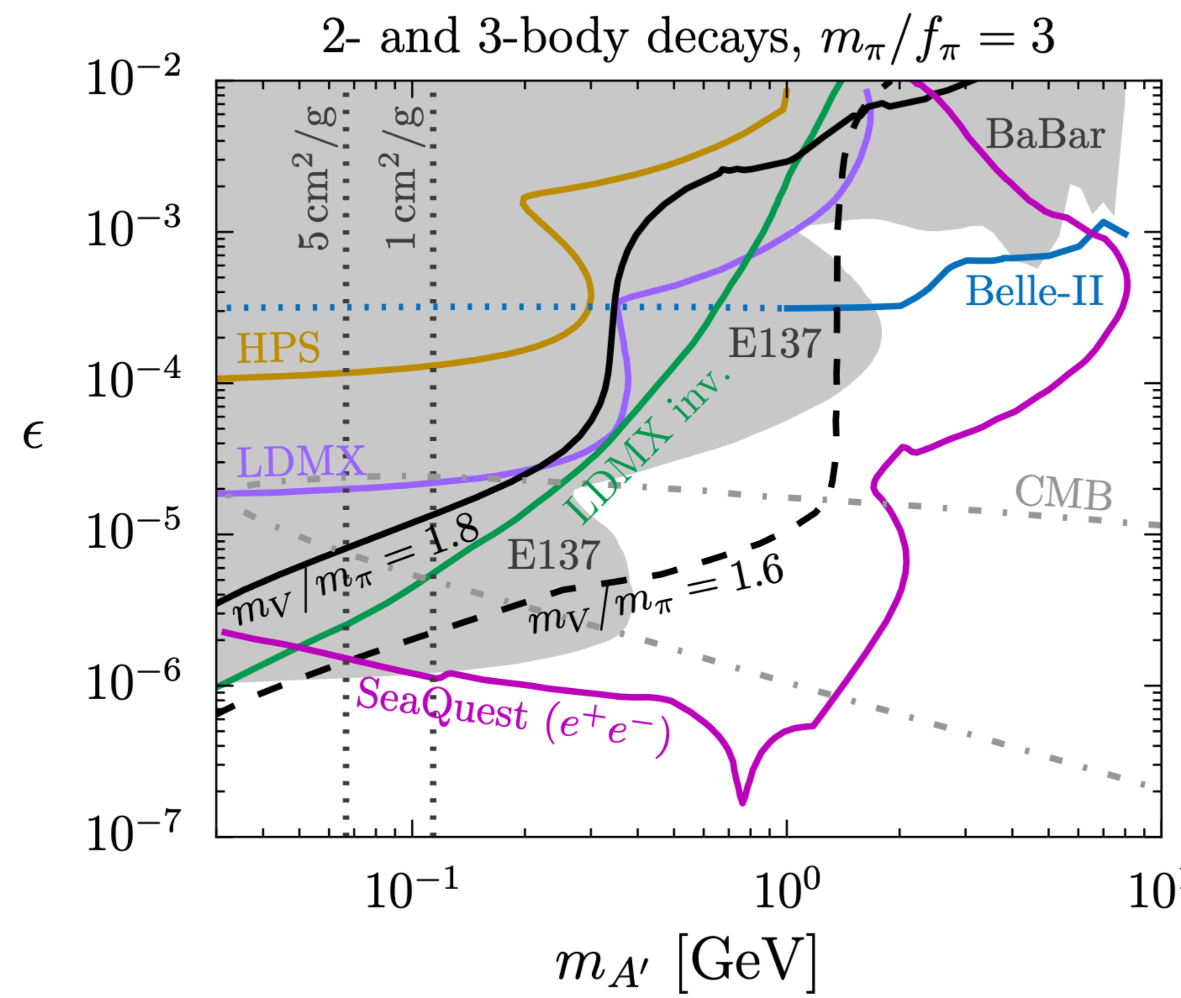
https://arxiv.org/pdf/1502.05409.pdf



Can get displaced jets

@LHC

Emerging Jets

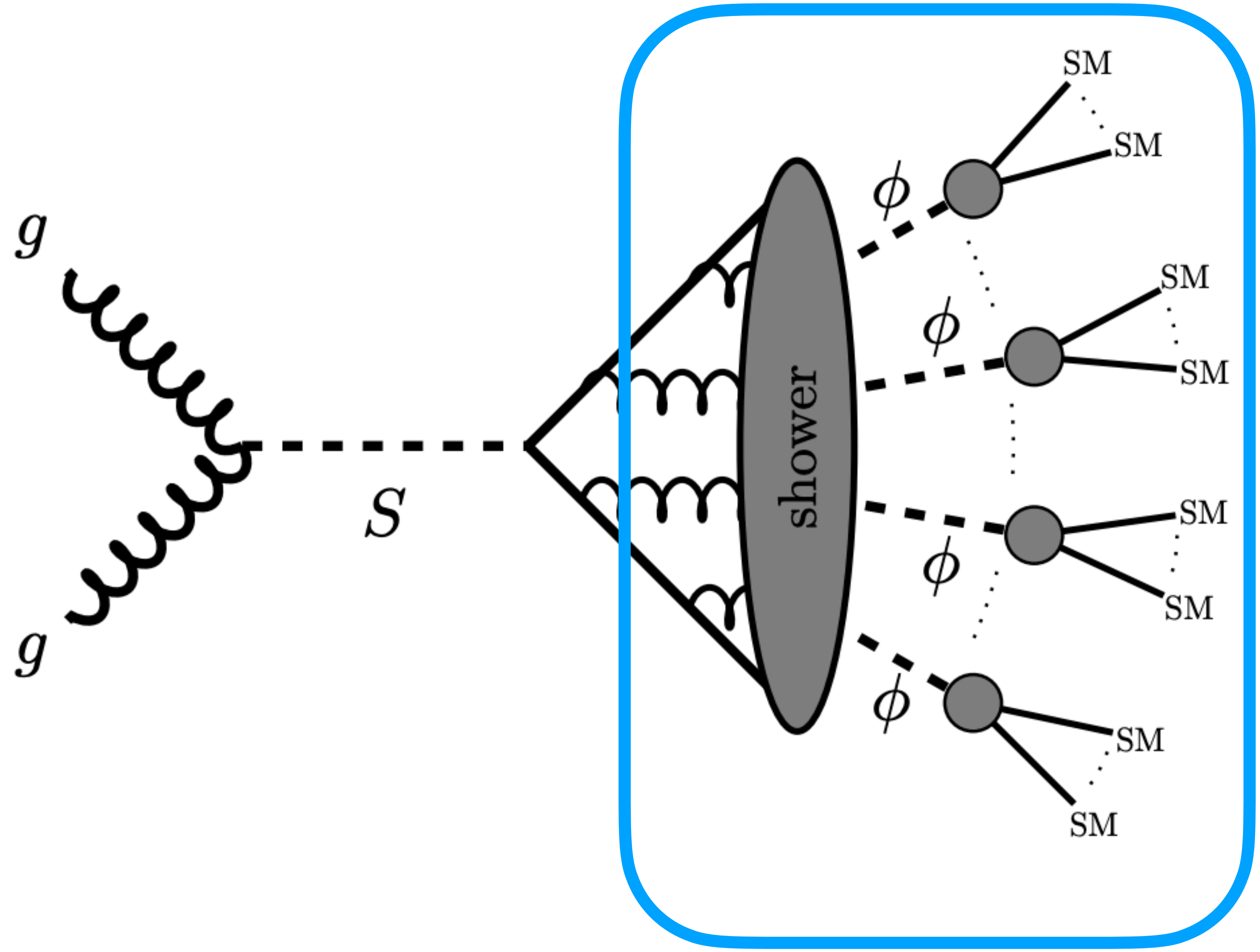


@Lower Energy (Beam Dump)

There is a lot of room for exploration here

Or Even More Complicated

- We can have even more complex scenarios



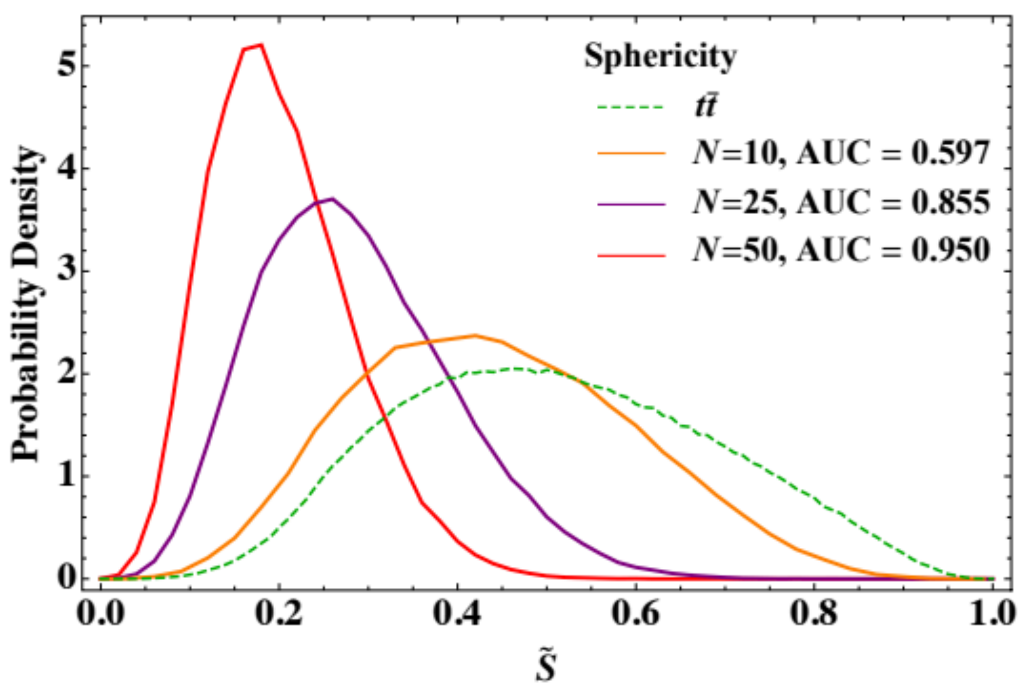
In the dark sector we can have heavily modified physics

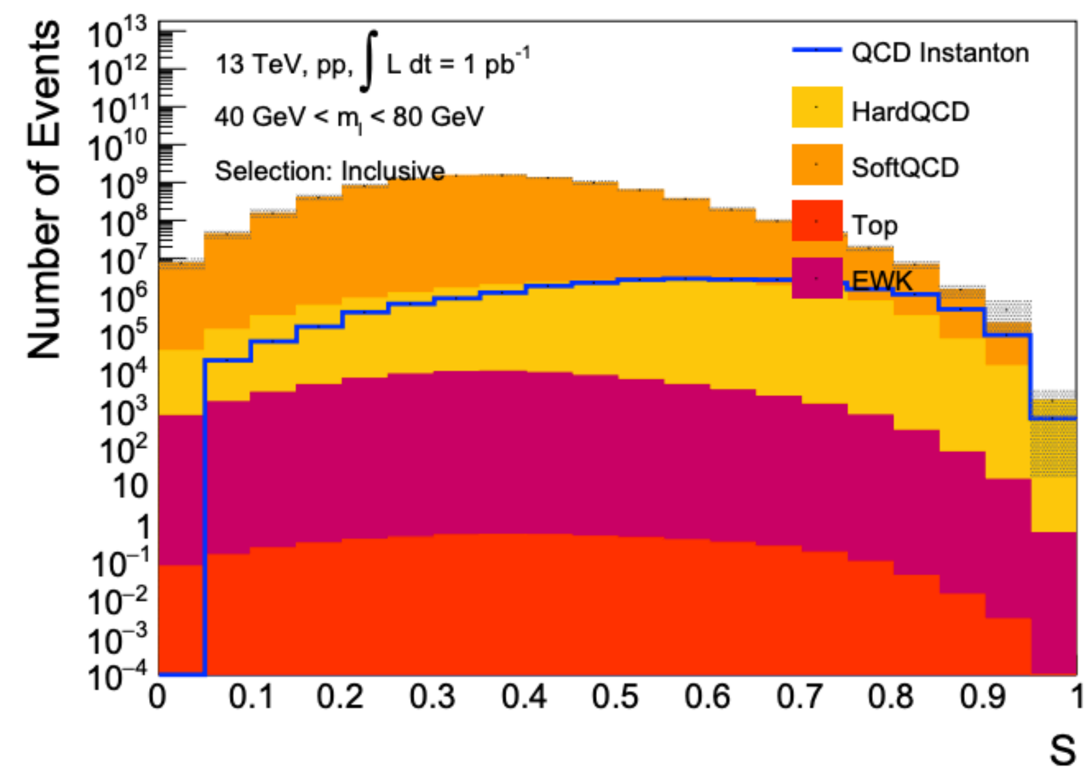
One type of interaction is an Instanton

Soft Unclustered Energy Pattern (SUEP aka “soup”) or Soft Bomb

SUEP dynamics

- We can have even more complex scenarios





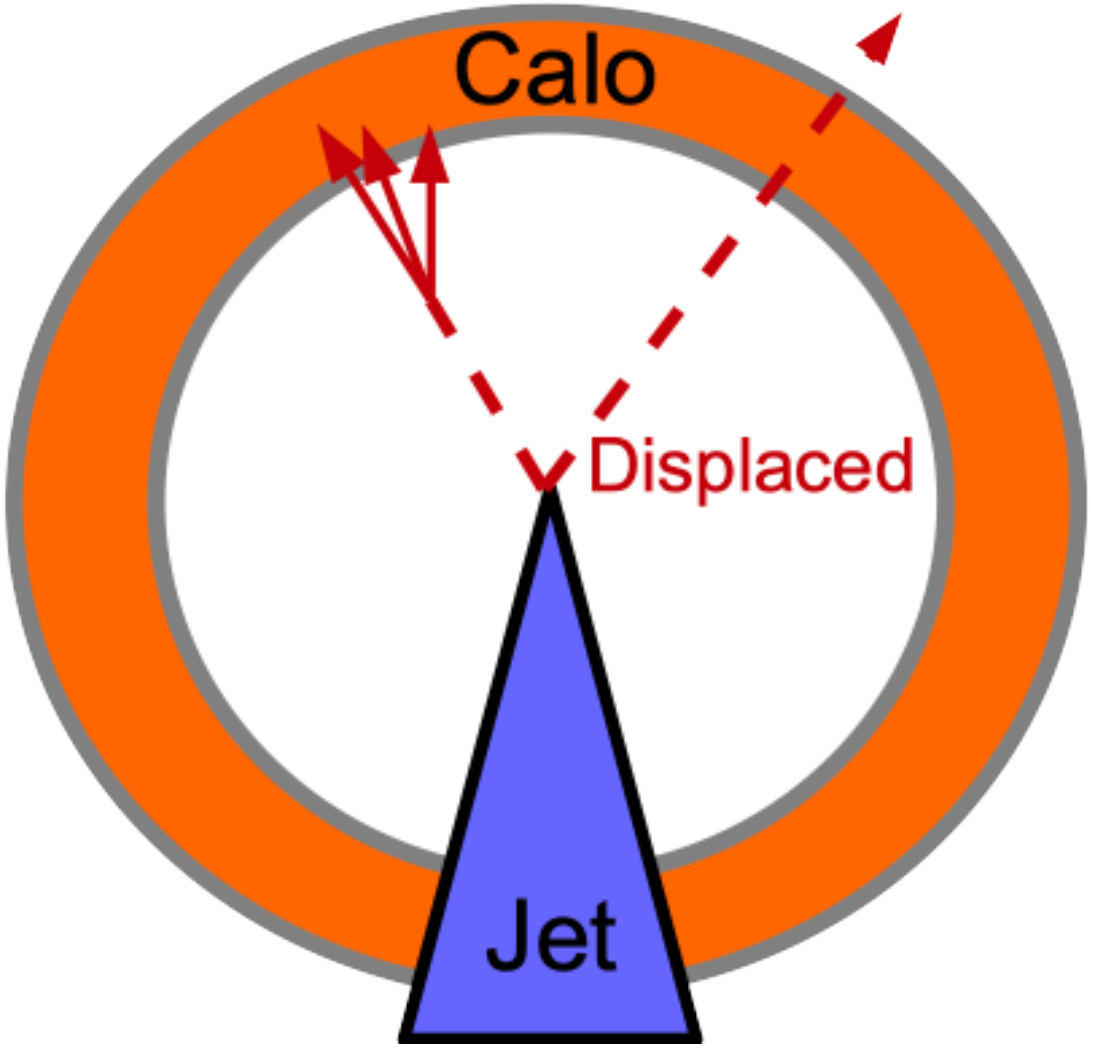
$$S^{\alpha\beta} = \frac{\sum_i p_i^\alpha p_i^\beta}{\sum_i |\vec{p}_i|^2}$$

Same for both

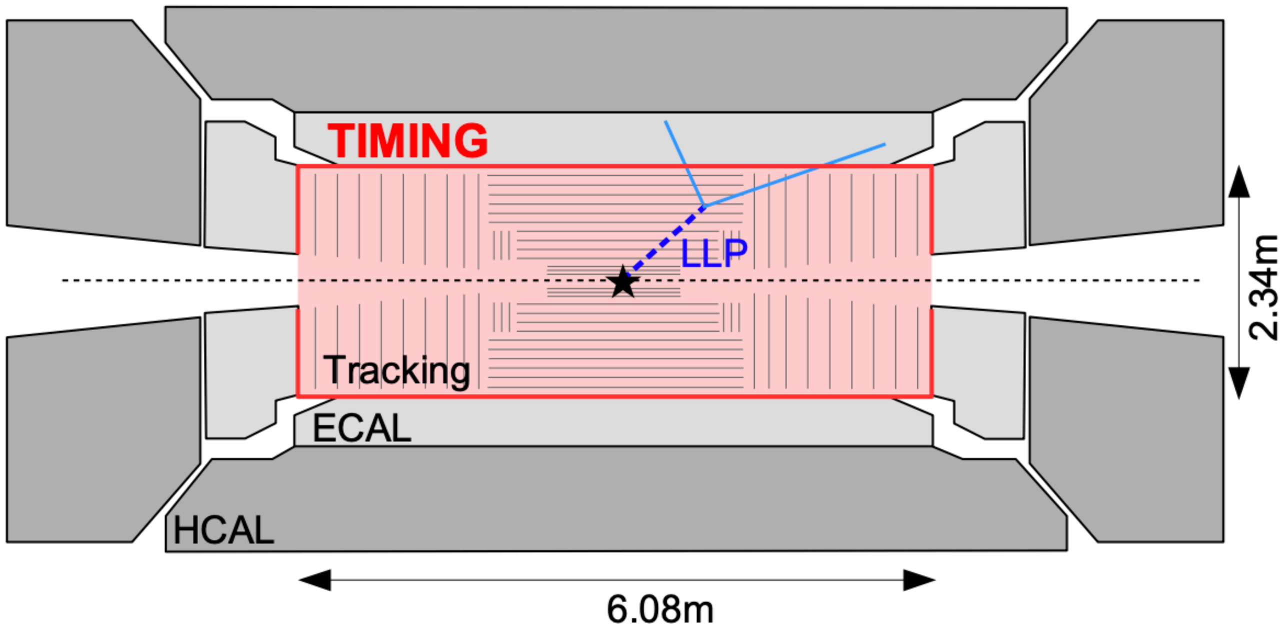
Selecting The Long Lived Events

How do we Trigger these?

- Displaced tag can reduce the background by 10^{-3}
- Displaced objects
  - Depend on whether we can reconstruct them



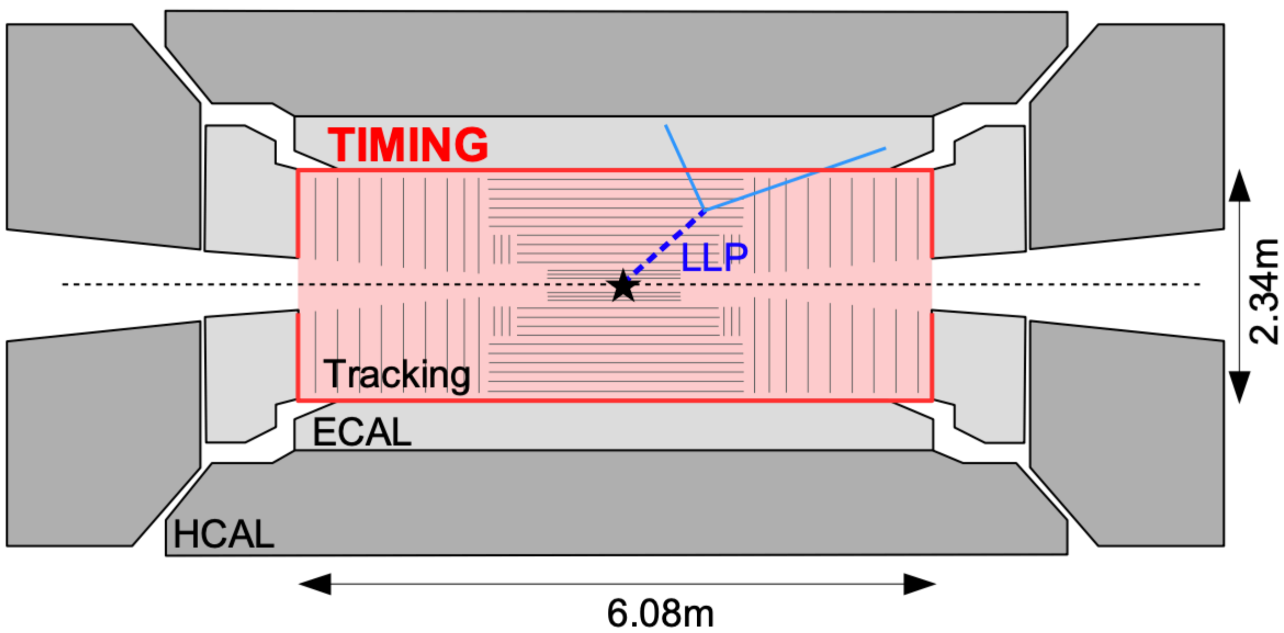
Tools for Displacement

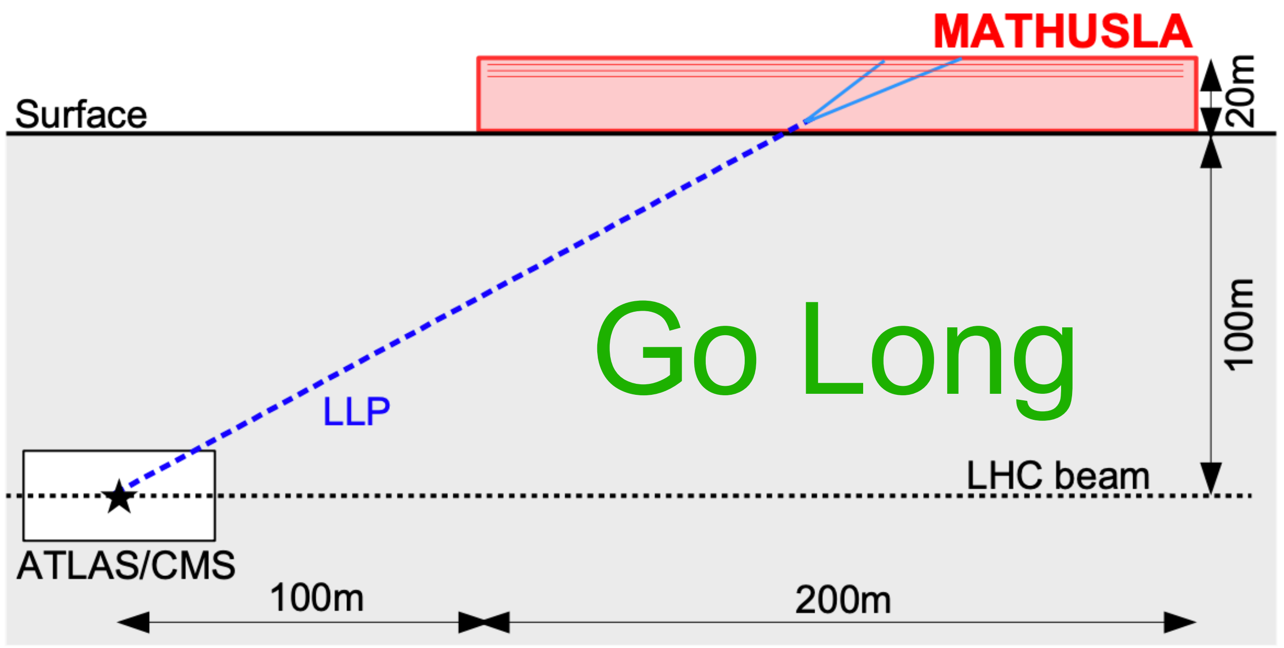


Go Fast

Go Fast: Heavy Long Lived Particles will not move at the speed of light

Tools for Displacement



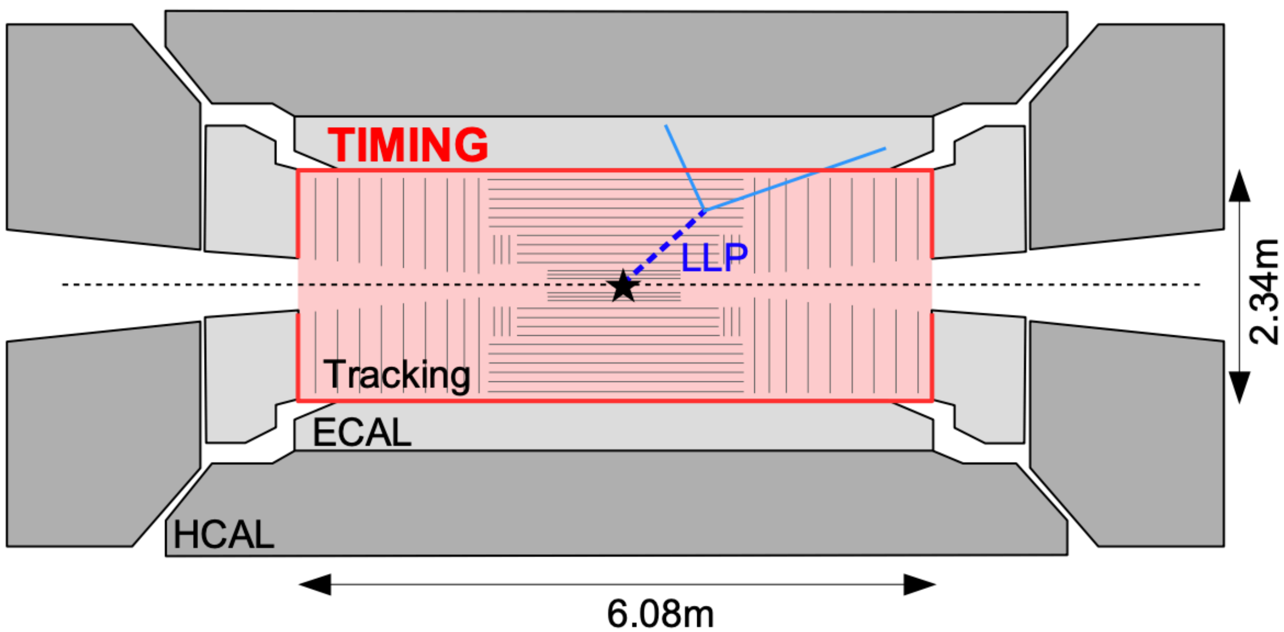


Go Fast

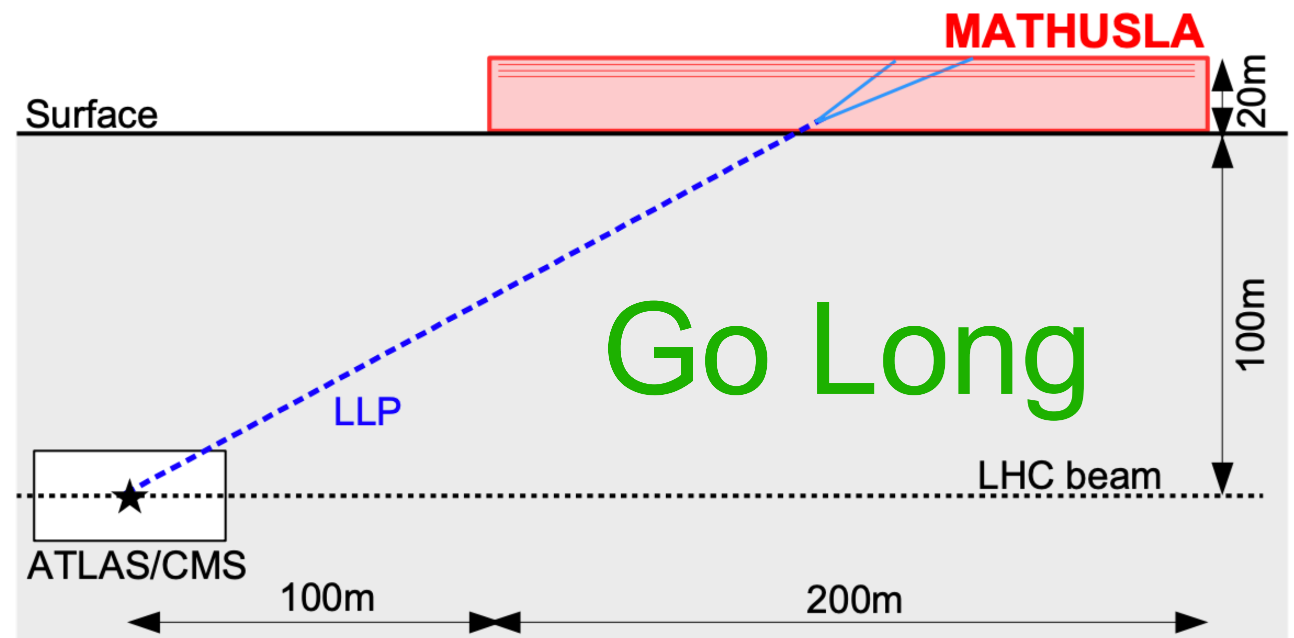
Go Fast: Heavy Long Lived Particles will not move at the speed of light

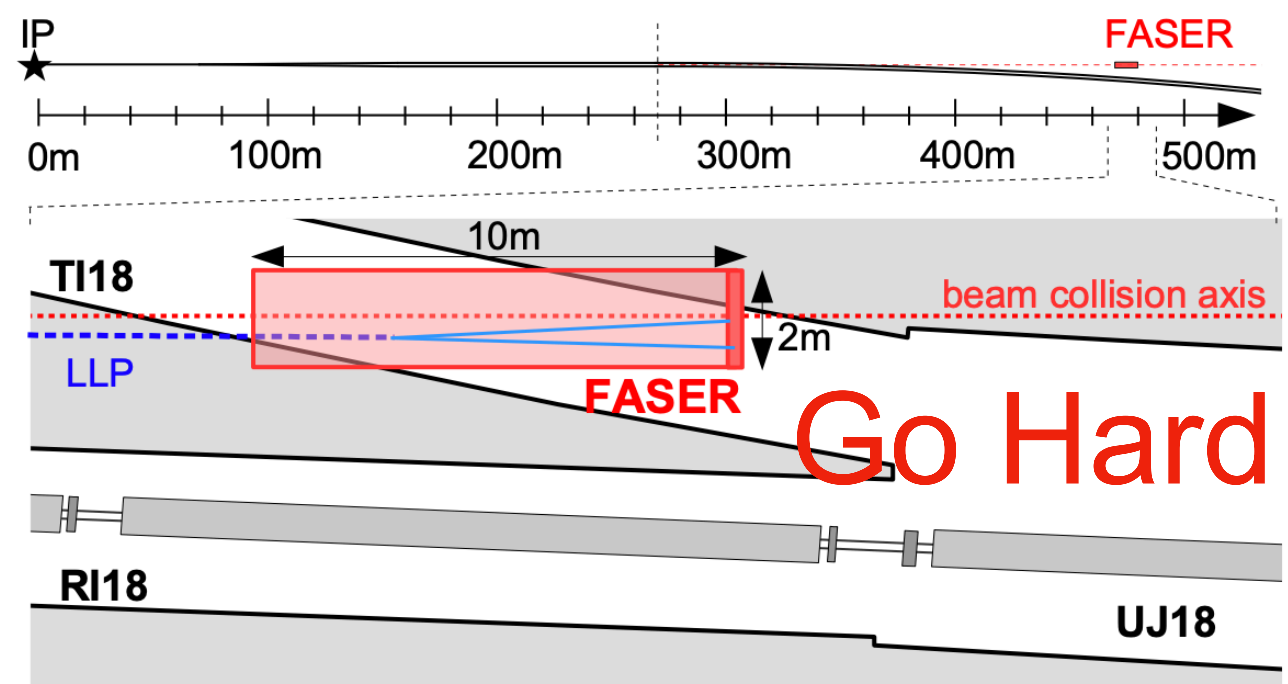
Go Long: Long Lived particles will escape the detector by a long range

Tools for Displacement



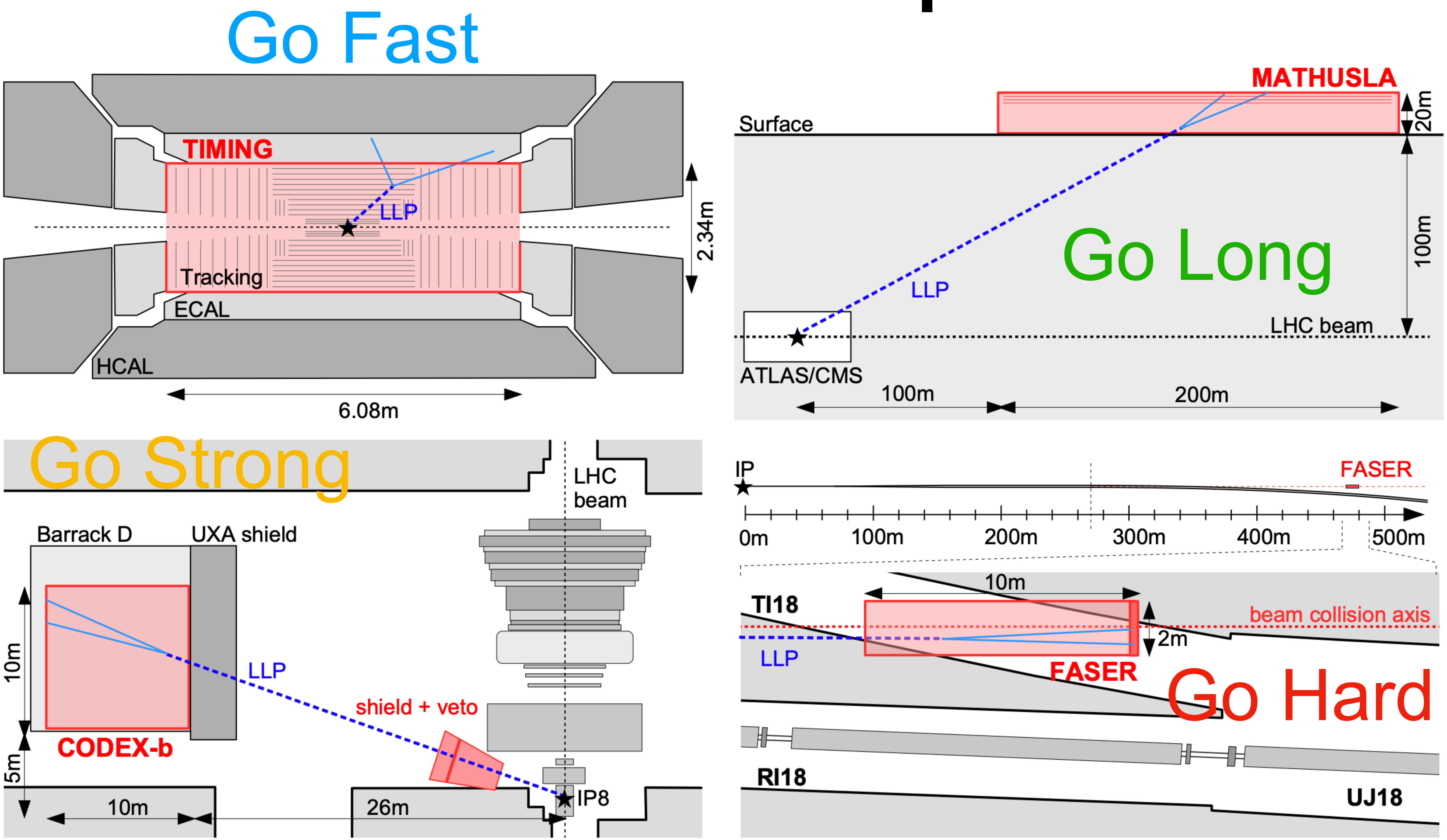
Go Fast





Go Hard: Forward region contains high boost and high particle flux

Tools for Displacement



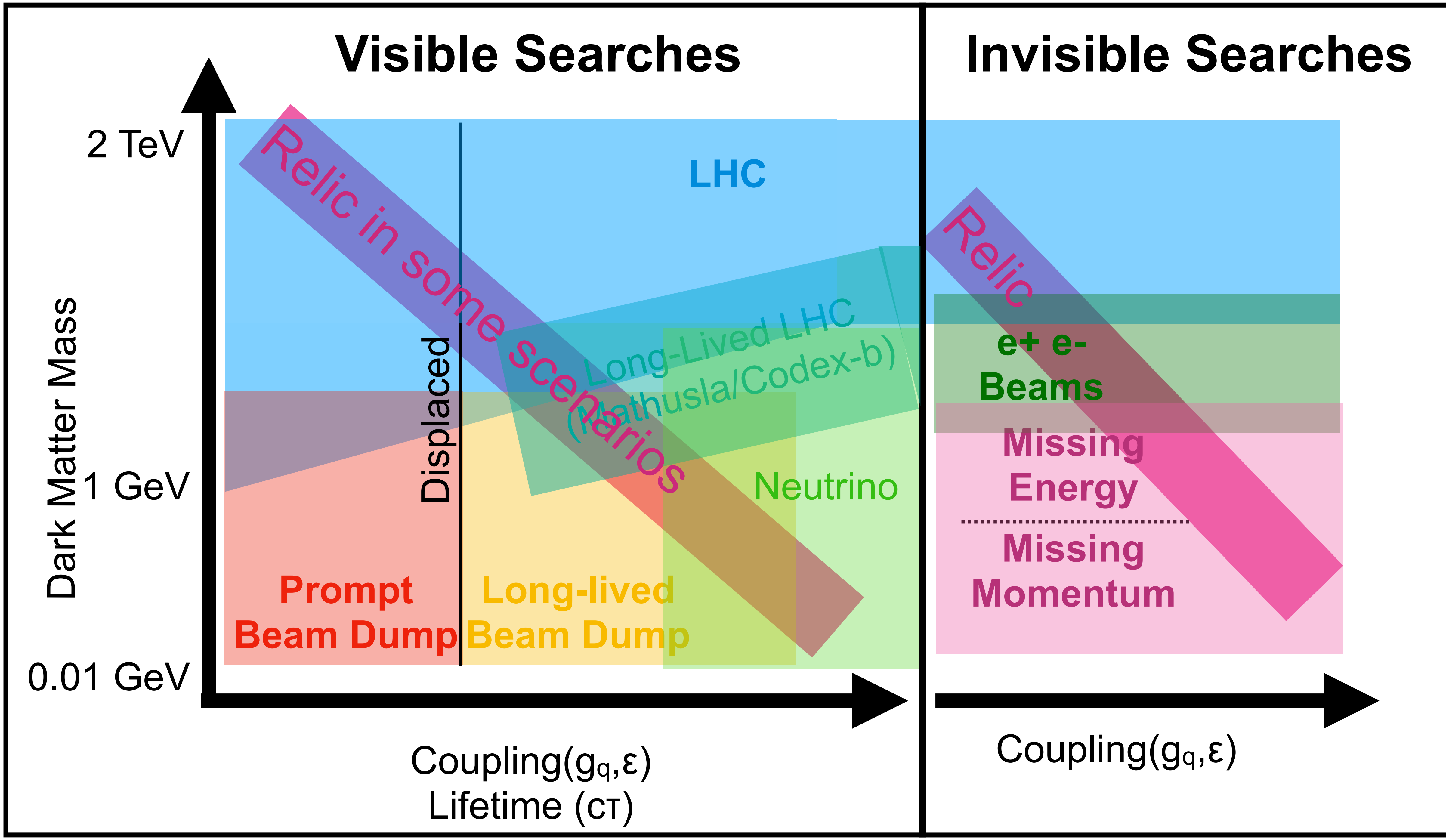
Go Strong: Small detectors (LHCb) give us space to get closer to beam


Fast Long Hard & Strong
TOKYO 2020
TM
Long Lived Dark Matter

Recapping

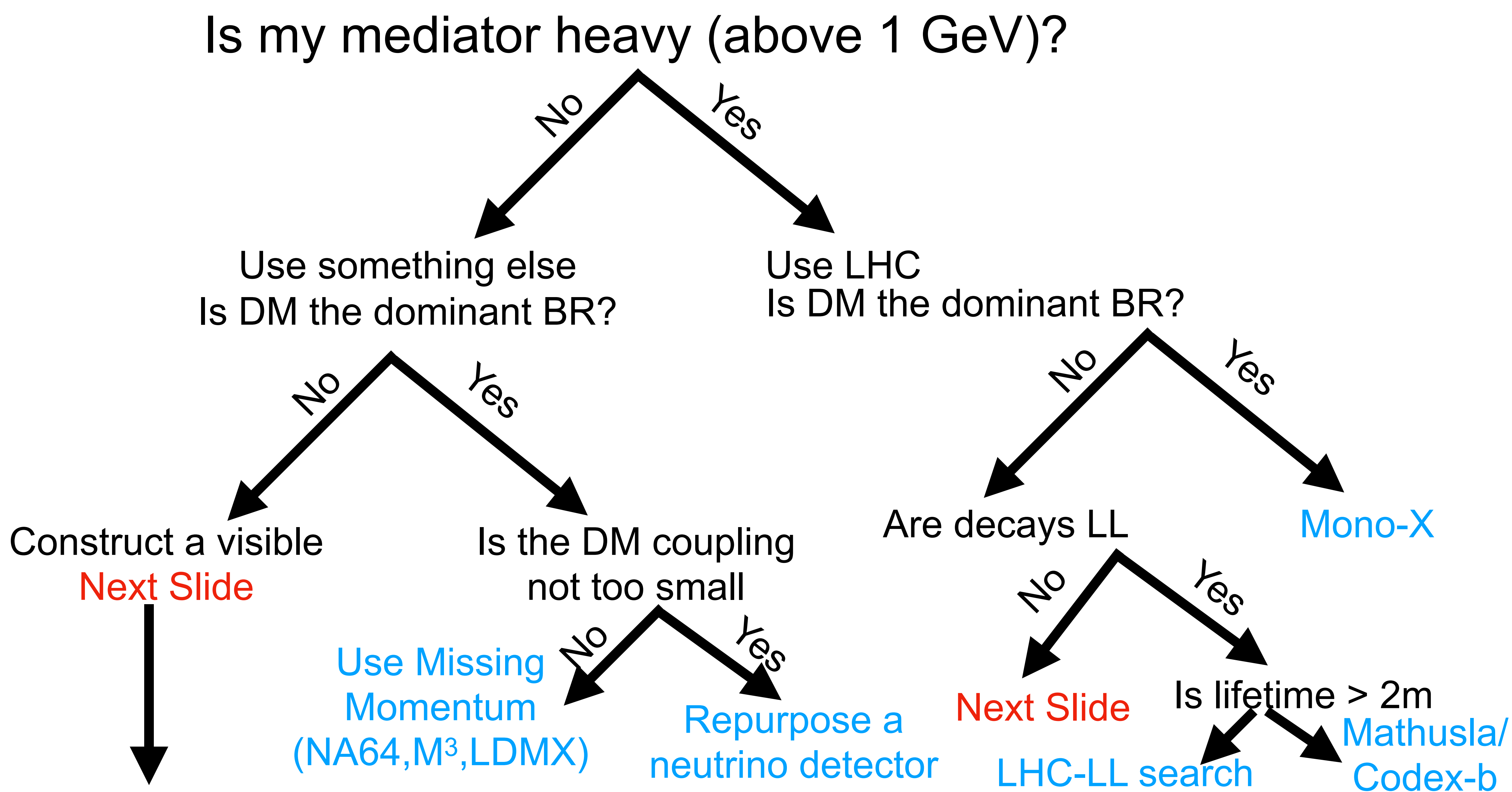
It All

What to take away?



What to take away?

I want to search for dark matter at an accelerator, what do I do?
Is there a portal mediator that couples to the SM?
(if no proceed to jail do not collect $200 and find another DM model)

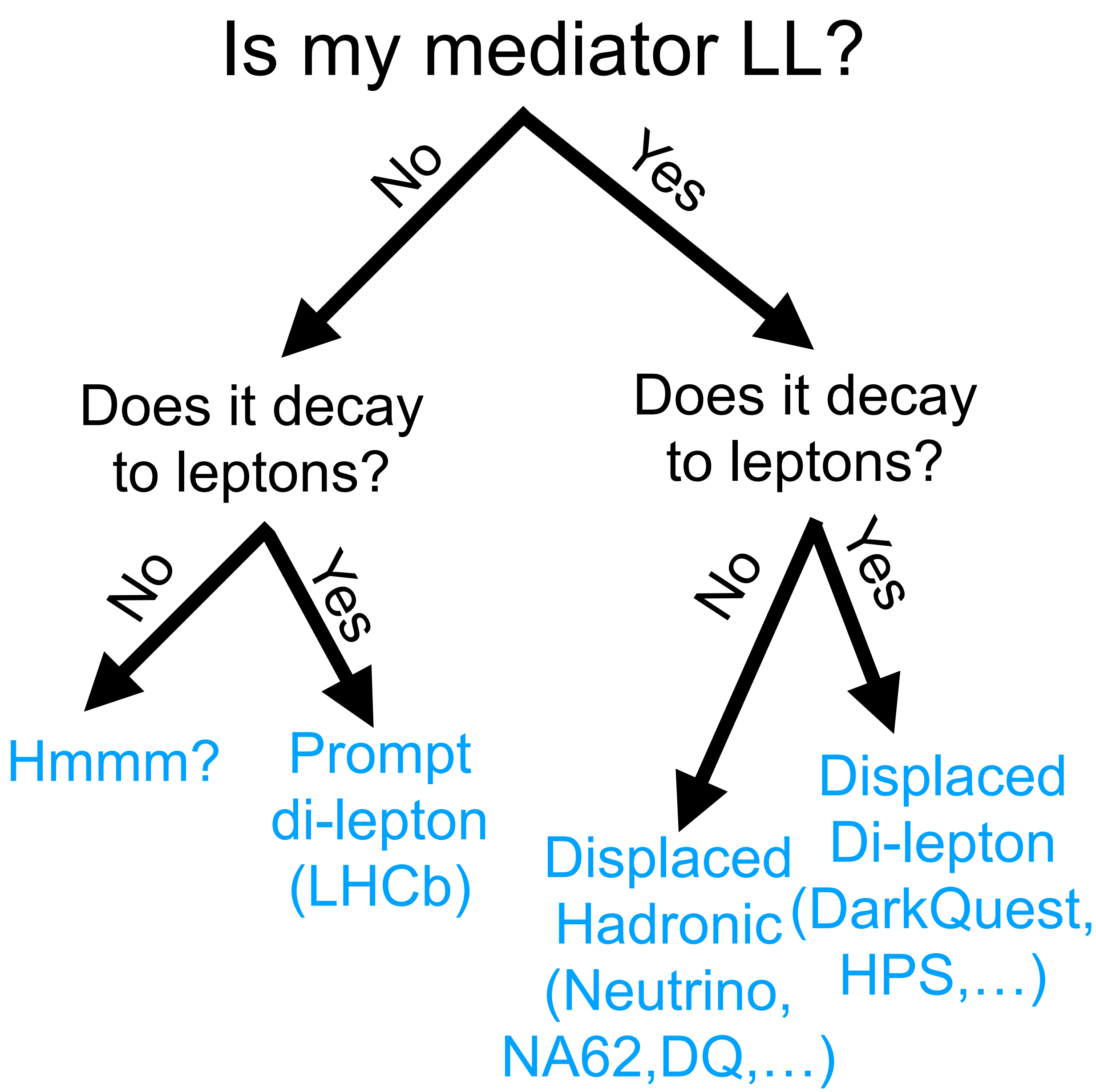


What to take away (cont'd)?

Light DM

Constructing a visible search

LHC



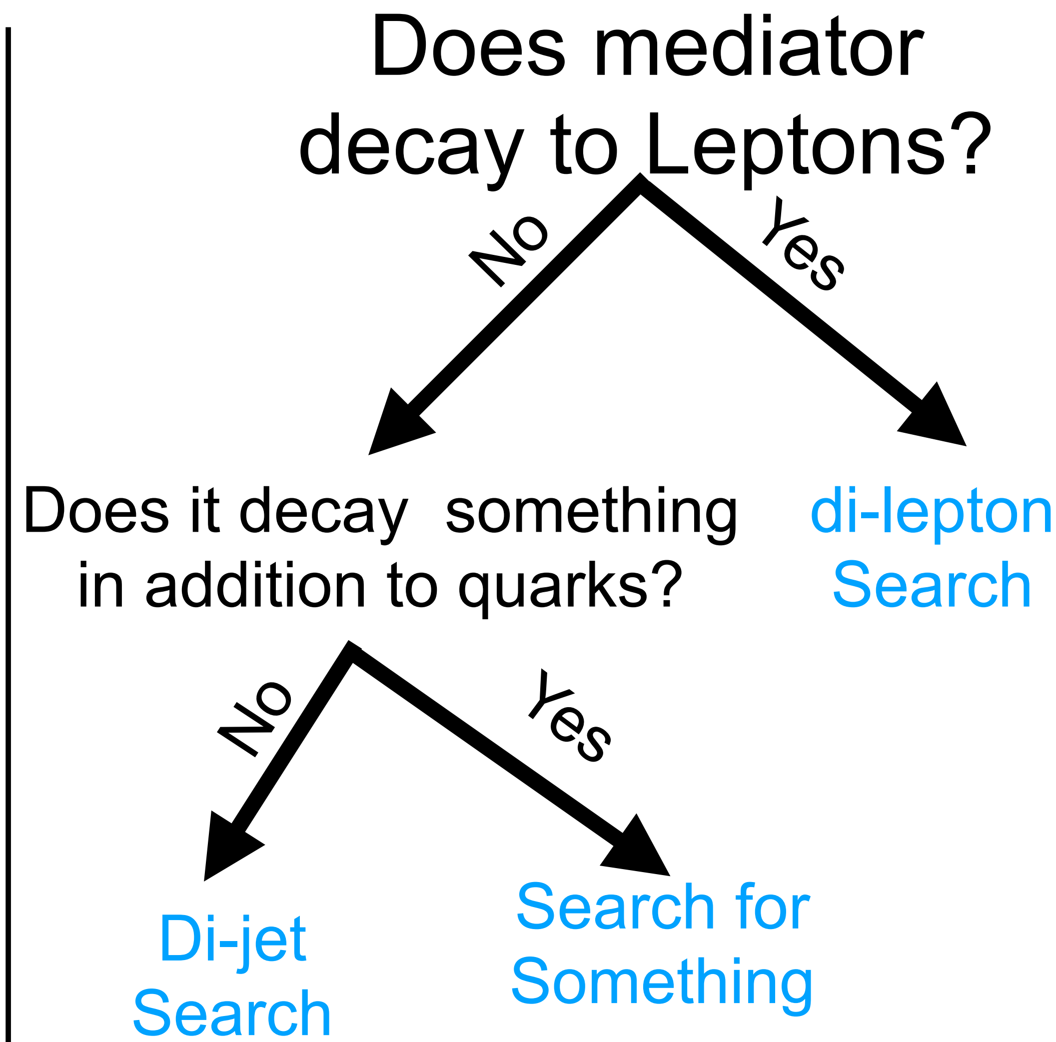


Table of Useful Info

	Scalar	ALP/ PseudoScalar	(Axial) Vector/ Dark Photon	Heavy Neutral Lepton
Other ways to observe it	Spin Independent DD	Indirect Detection	Vector: Spin Independent DD Axial-Vector: Spin Dependent DD	Indirect Detection
Missing Energy Final state	Missing mass Monojet/Higgs Invisible	Missing mass Monojet/Mono-Higgs	Missing mass Monojet	N/A
Visible final state	di-muons/ di-photons di b-quarks/ di-tops	di-muons/ di-photons di b-quarks/ di-tops	di-leptons di-leptons/ di-jets	π+μ same-sign leptons +W boson
Benchmark	Relic Benchmark At High mass	Relic Benchmark At High mass	Relic Benchmark	Relic? Neutrinoless 2β decay

Dark Sector from Snowmass

Benchmarks in Final State x Portal Organization

	DM Production	Mediator Decay Via Portal	Structure of Dark Sector
Vector	*m_χ vs. y [$m_{A'}/m_\chi$=3,α_D=.5]* **$m_{A'}$ vs. y** [α_D=0.5, 3 m_χ values] m_χ vs. α_D [$m_{A'}/m_\chi$=3, y=y_{fo}] m_χ vs. m_A [α_D=0.5, y=y_{fo}] ***Millicharge m vs. q***	$m_{A'}$ vs. ϵ [decay-mode agnostic] ***$m_{A'}$ vs. ϵ [decays]***	**iDM m_χ vs. y [$m_{A'}/m_\chi$=3,α_D=.5] (anom connection)** **SIMP-motivated cascades [slices TBD]** $U(1)_{B-L\ /\ \mu-\tau\ /\ B-3\tau}$ (DM or SM decays)
Scalar	m_χ vs. sinθ [λ=0, fix m_S/m_χ, g_D] (thermal target excluded 1512.04119, should still include) Note secluded DM relevance of S→SM of mediator searches	*m_S vs. sinθ* [λ=0] *m_S vs. sinθ* [λ=s.t. Br(H→ϕϕ ~10^{-2})]?	Dark Higgsstrahlung (w/vector) scalar SIMP models? Leptophilic/leptophobic dark Higgs?
Neutrino	e/μ/τ a la1709.07001?	*m_N vs. U_e* *m_N vs. U_μ* *m_N vs. U_τ* Think more about reasoanble flavor structures	Sterile neutrinos with new forces?
ALP	m_χ vs. fq/l [λ=0, fix m_a/m_χ, g_D] (thermal target excluded) What about f_γ, f_G?	*m_a vs. f_γ* *m_a vs. f_G* *m_a vs. f_q=f_l* (separate?) Think more about reasoanble coupling relations including $f_{W/Z}$	FV axion couplings

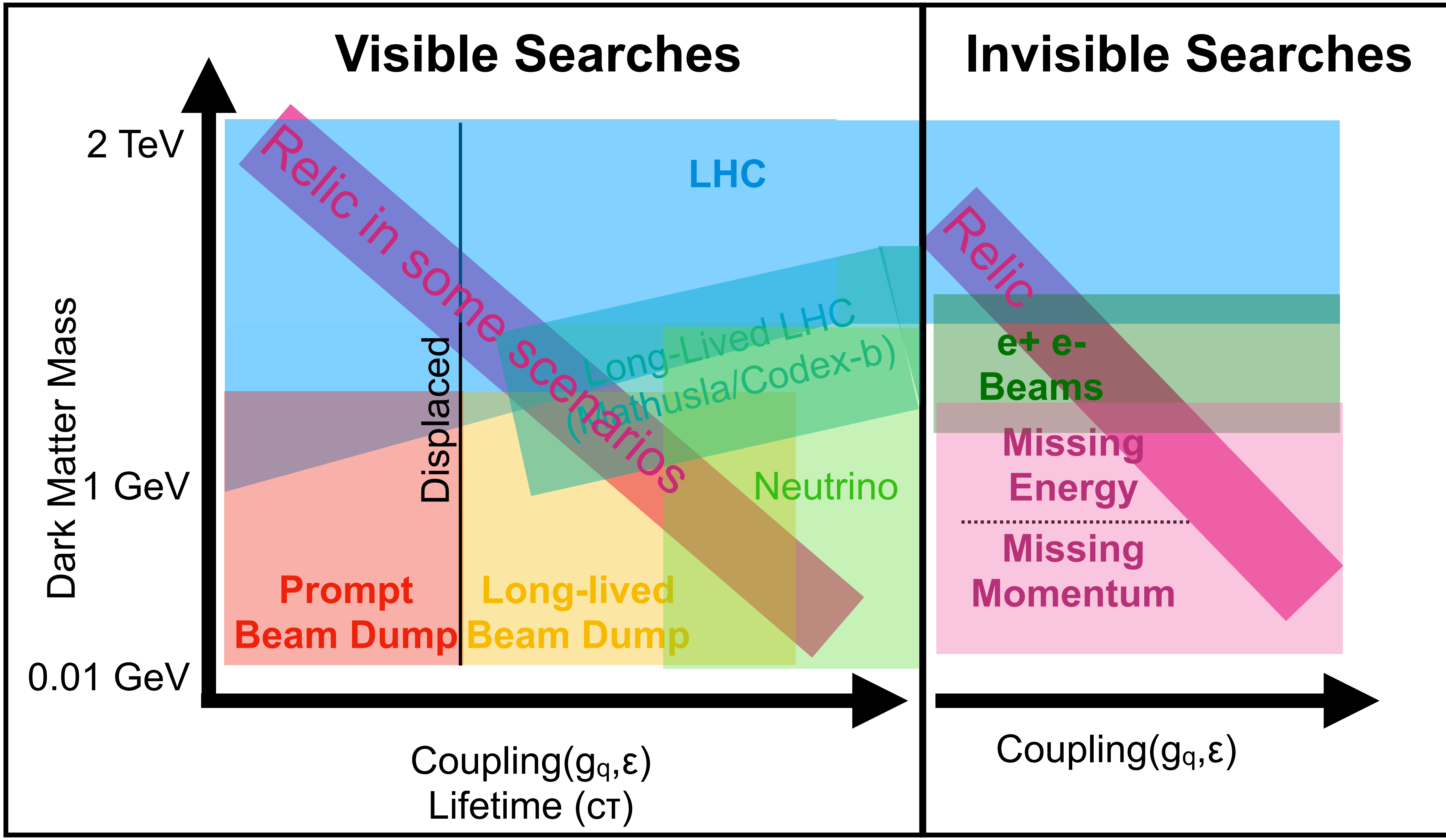
+ Neutron portal? Hidden valleys (or are these out-of-scope?)? See e.g. 2003.02270

Bold = BRN benchmark, ***italic=PBC benchmark.*** others are new suggestions. Underline=CV benchmarks that were not used in BRN

Conclusions

- Particle dark matter always comes in at least pairs:
  - A DM candidate and a (portal) mediator
  - It can quickly become much more complicated
- The type of mediator interaction drives the interpretation
  - Vector/Dark Photons yield diff benchmarks to ALPs/Scalars
  - However Relic bounds underpin much of our exploration
- Both the Visible and invisible searches play a role
  - Its all about the mediator in the end
- Rich dark sector leads to a large variety of new final states
  - Motivating new low energy experiments & searches

What to take away?

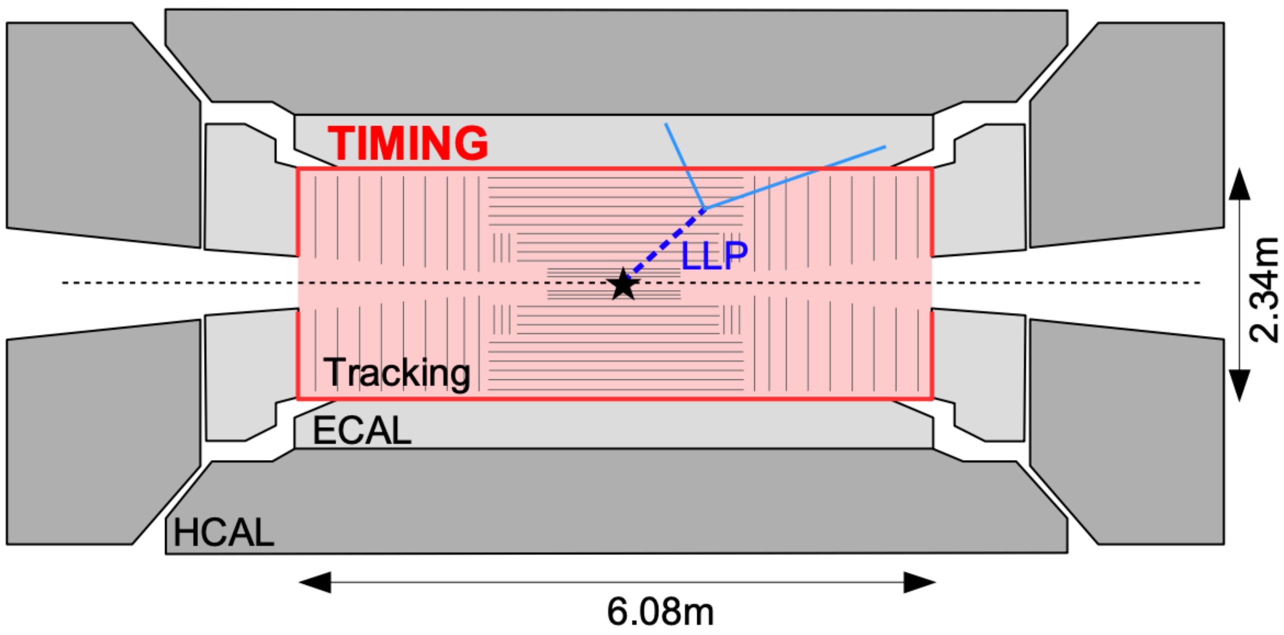


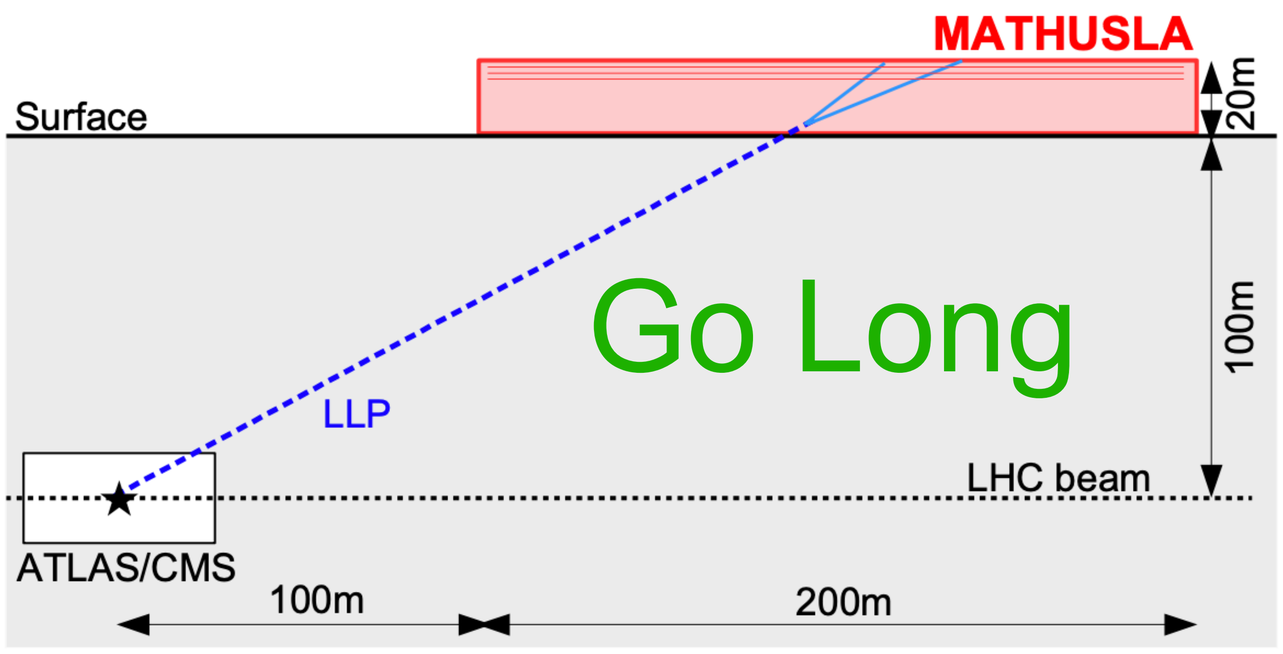
Thanks!

How do we search for these?

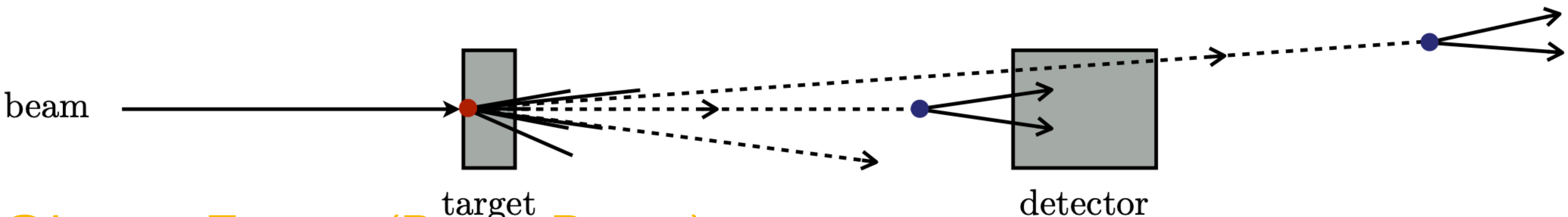
- Again there are many ways to search for these:

Go Fast





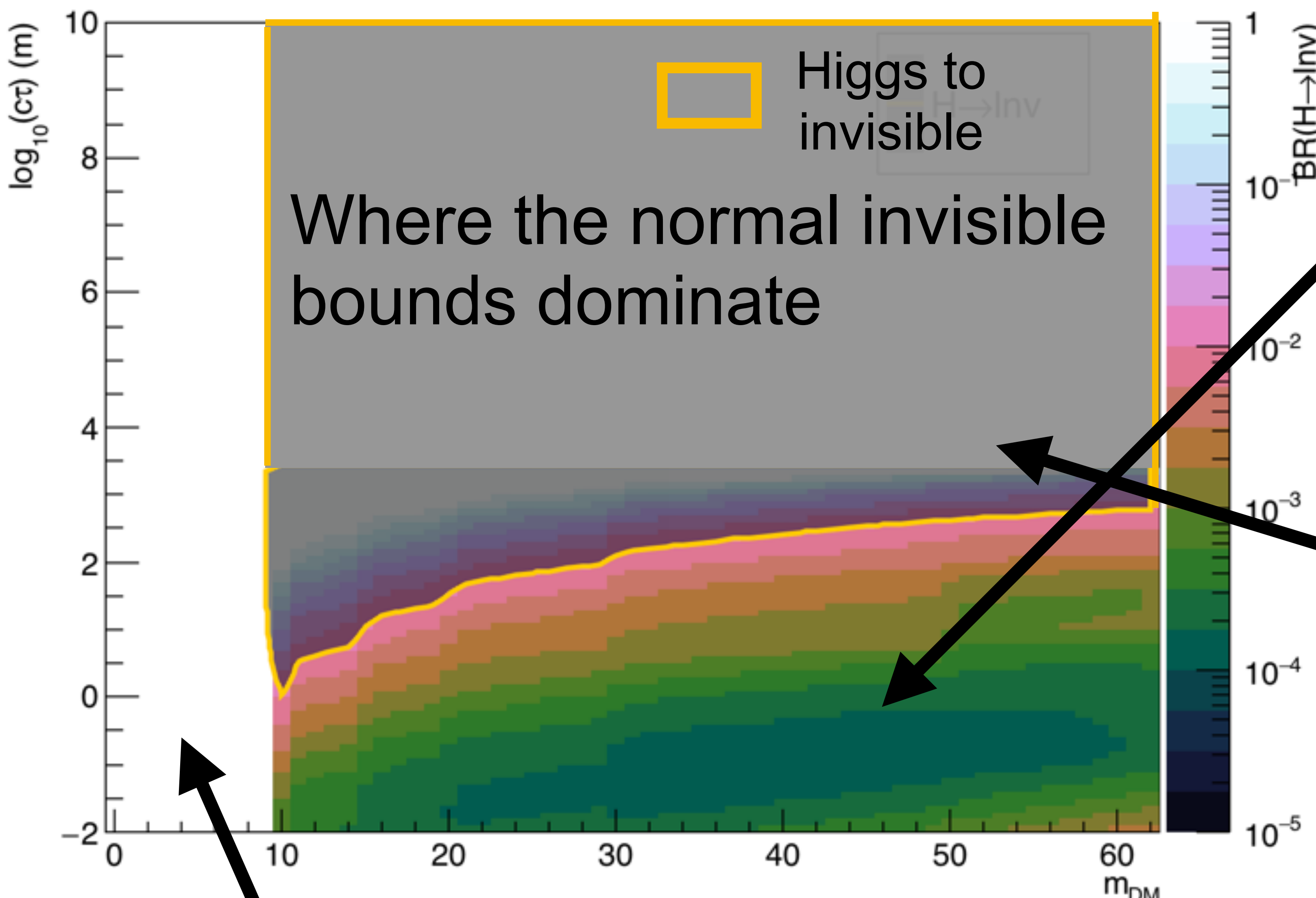
@LHC



@Lower Energy (Beam Dump)

Now run the fit and extrapolate

- Here is Higgs to Invisible:

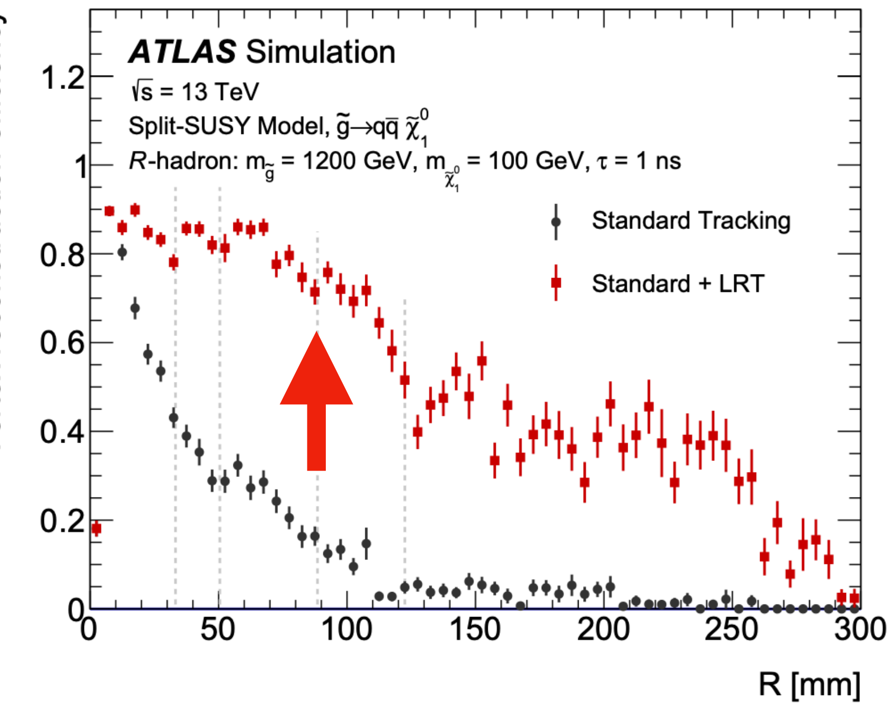


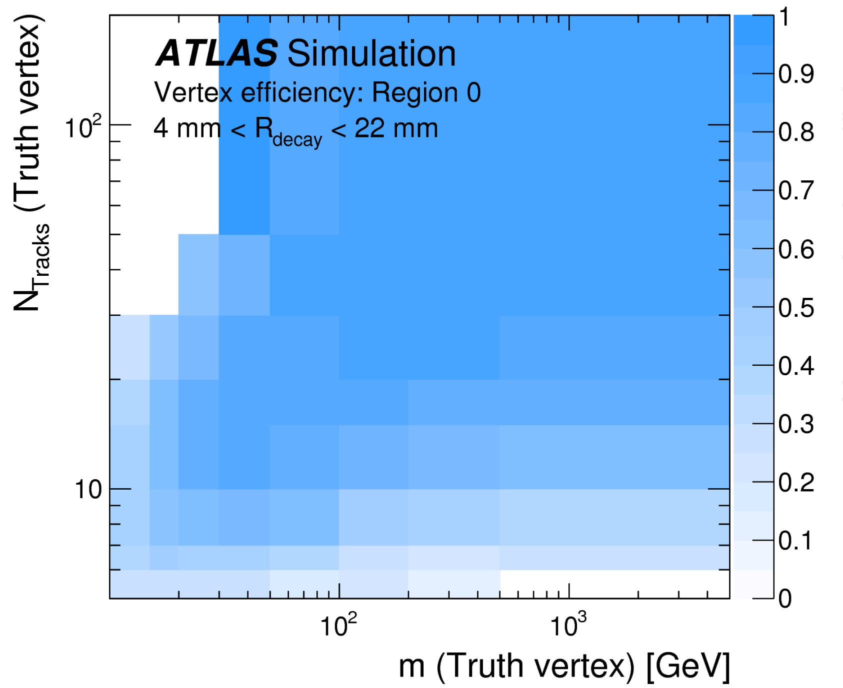
This is where displaced tagging dominates

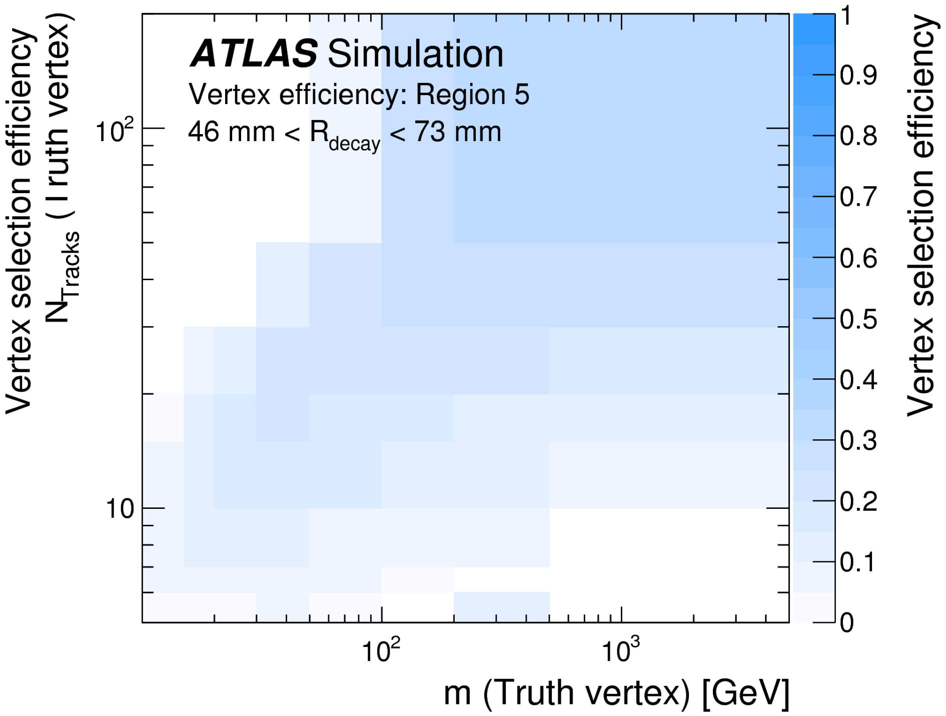
For long lifetimes Higgs to invisible still dominates

Efficiency map was only released for mass > 10 GeV

How Do 2ndary vtxs behave?





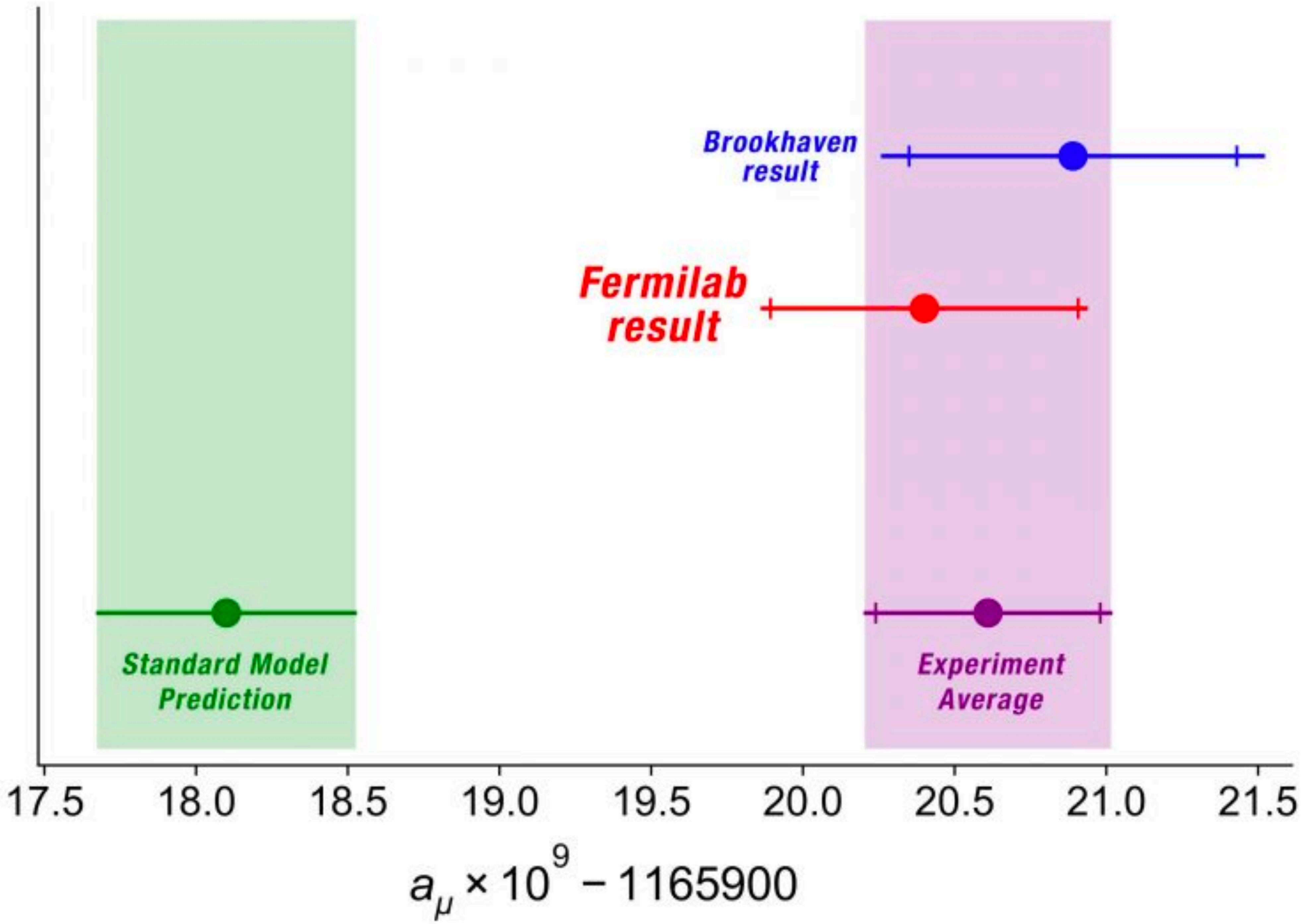


Modifying the tracking is critical

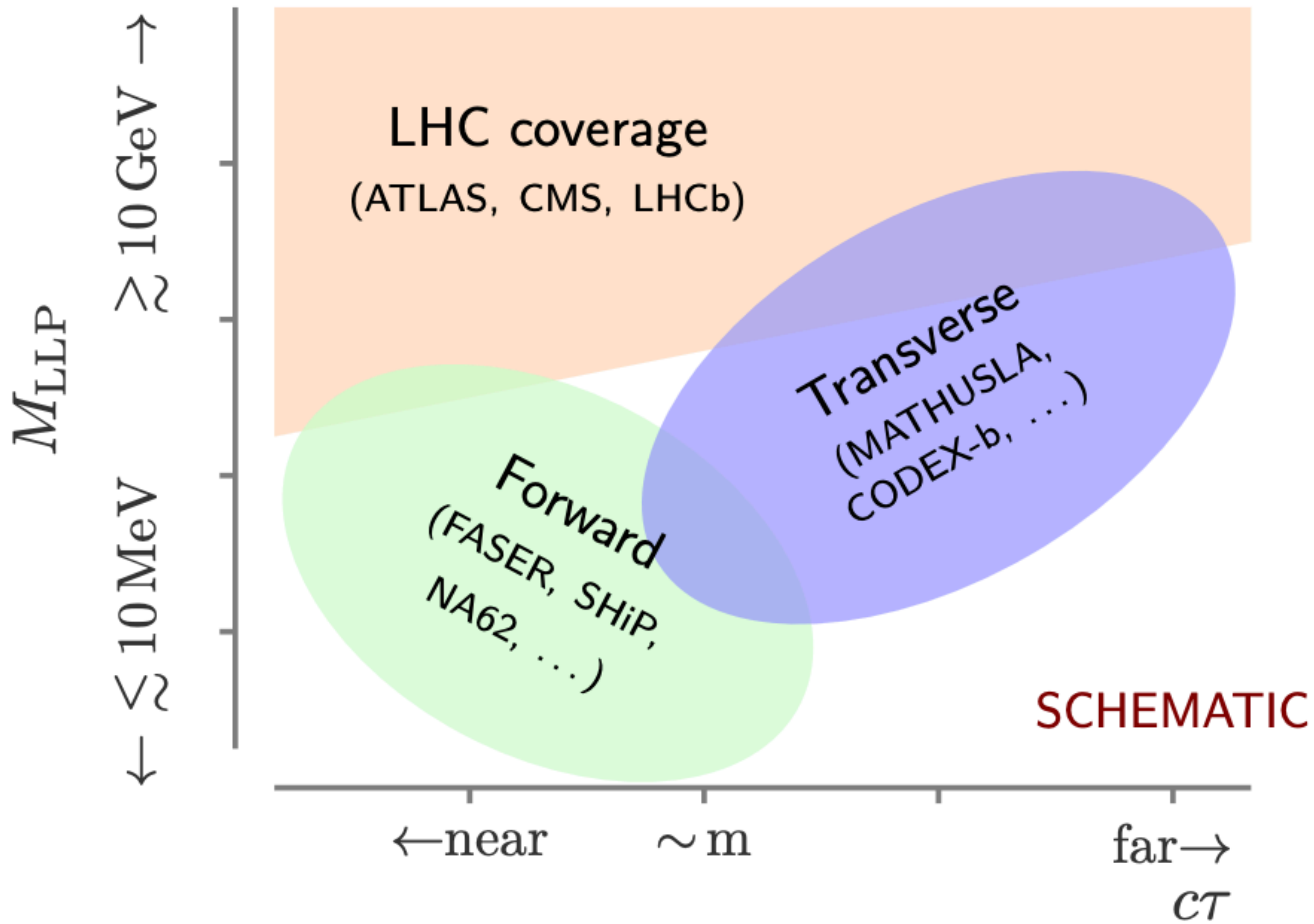
High Eff
For short-ish
Vertices

10-30%
For displaced
Vertices

- Tracking modified
  - Use unassigned hits and allow for large displaced vertices
  - Hit sharing in the track fit is also modified


Brookhaven result
Fermilab result
Standard Model Prediction
Experiment Average
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
21.5
$a_\mu \times 10^9 - 1165900$

@LHC



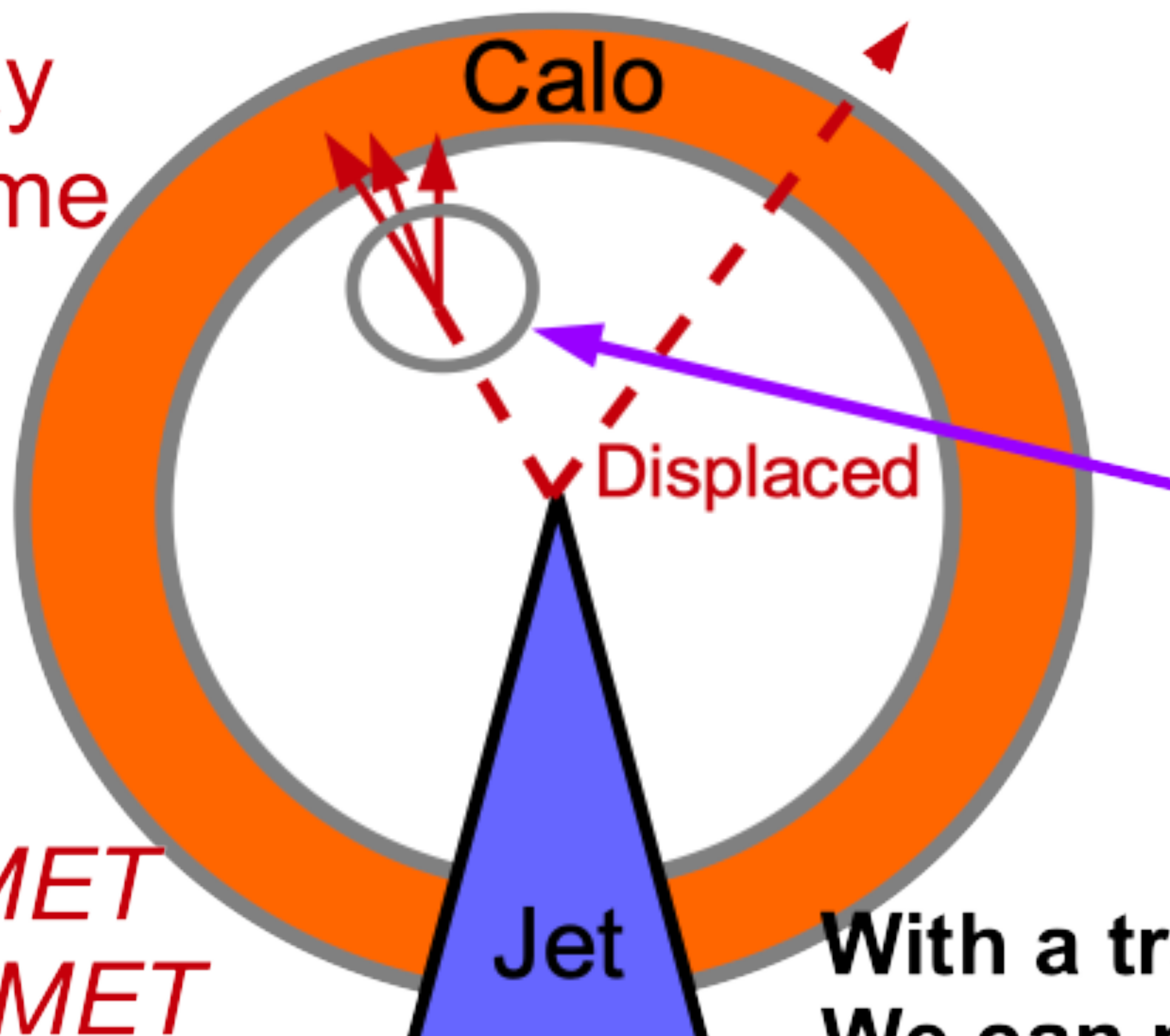
- LHC long lived experiments probe very high COM collisions
  - There are many other things we can explore (see later)

How do we Trigger these?

- Displaced tag can reduce the background by 10^{-3}
- Displaced objects
  - Depend on whether we can reconstruct them

Displaced decay in tracker volume

1. No Tracks
2. Calo hits



Special Trigger

Note PUPPI *MET* Would remove these guys (like TK met)

1. Small Calo *MET*
2. Large Track *MET*

With a track trigger at L1 We can probably get this

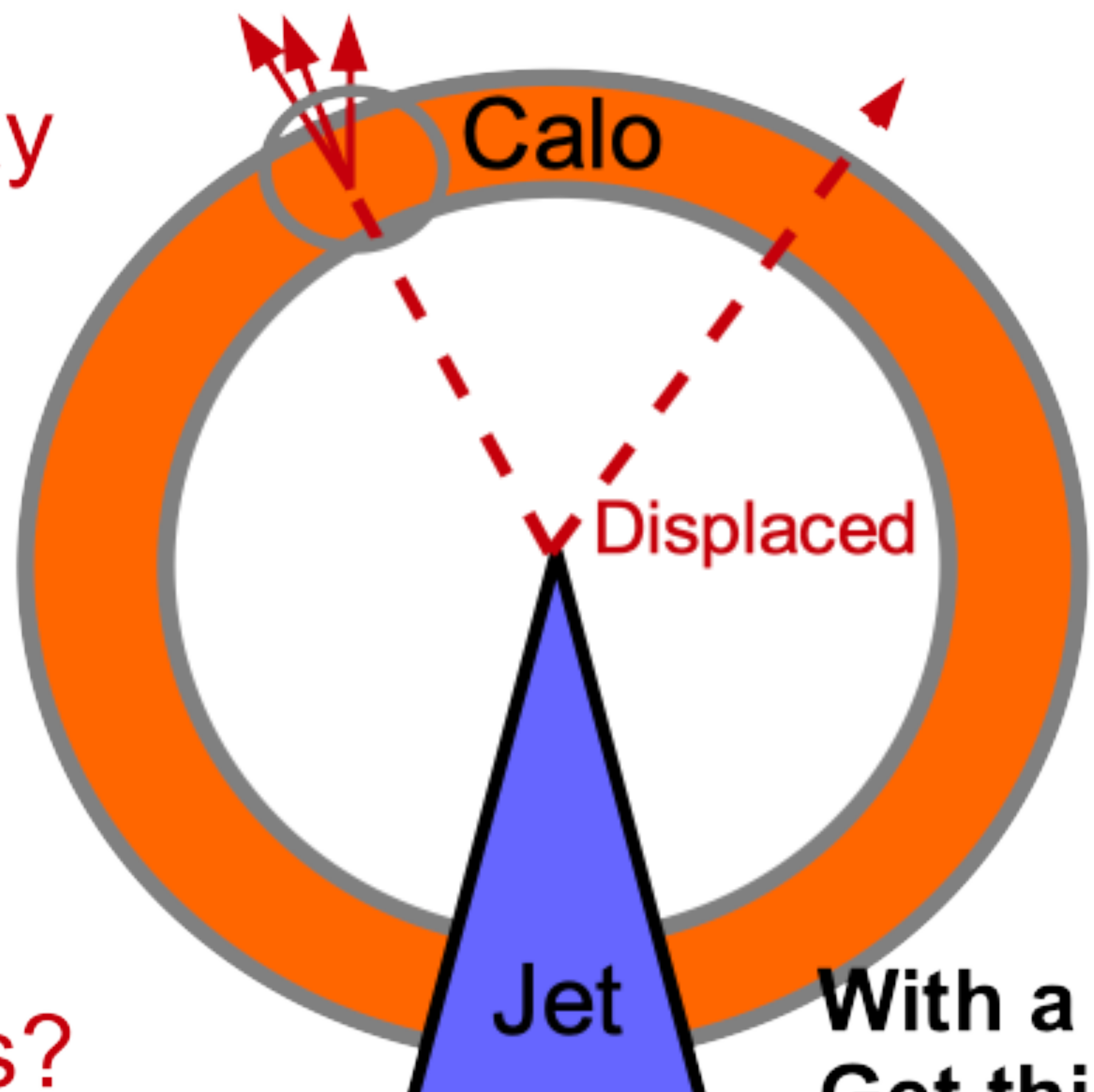
How do we Trigger these?

- Displaced tag can reduce the background by 10^{-3}
- Displaced objects
  - Depend on whether we can reconstruct them

Displaced decay in calo volume

1. No Tracks
2. No Calo
3. Muons?

1. Large *MET*
2. Weird muons?



Normal *MET* trigger

With a MET trigger at L1
Get this <u>but not great</u>

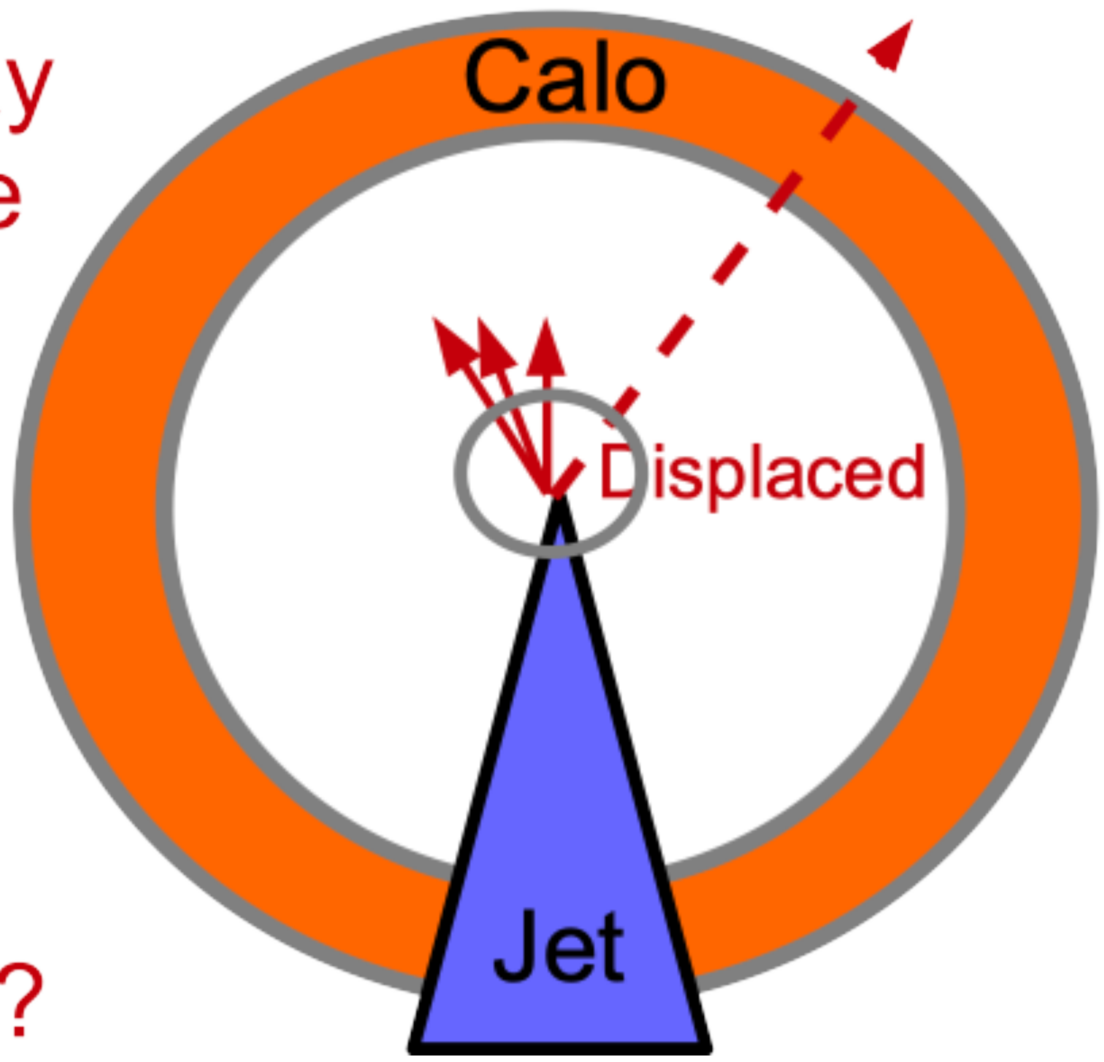
How do we Trigger these?

- Displaced tag can reduce the background by 10^{-3}
- Displaced objects
  - Depend on whether we can reconstruct them

Displaced decay
In Pixel volume

0. displaced?
1. Tracks
2. Calo

1. Strange dijet?



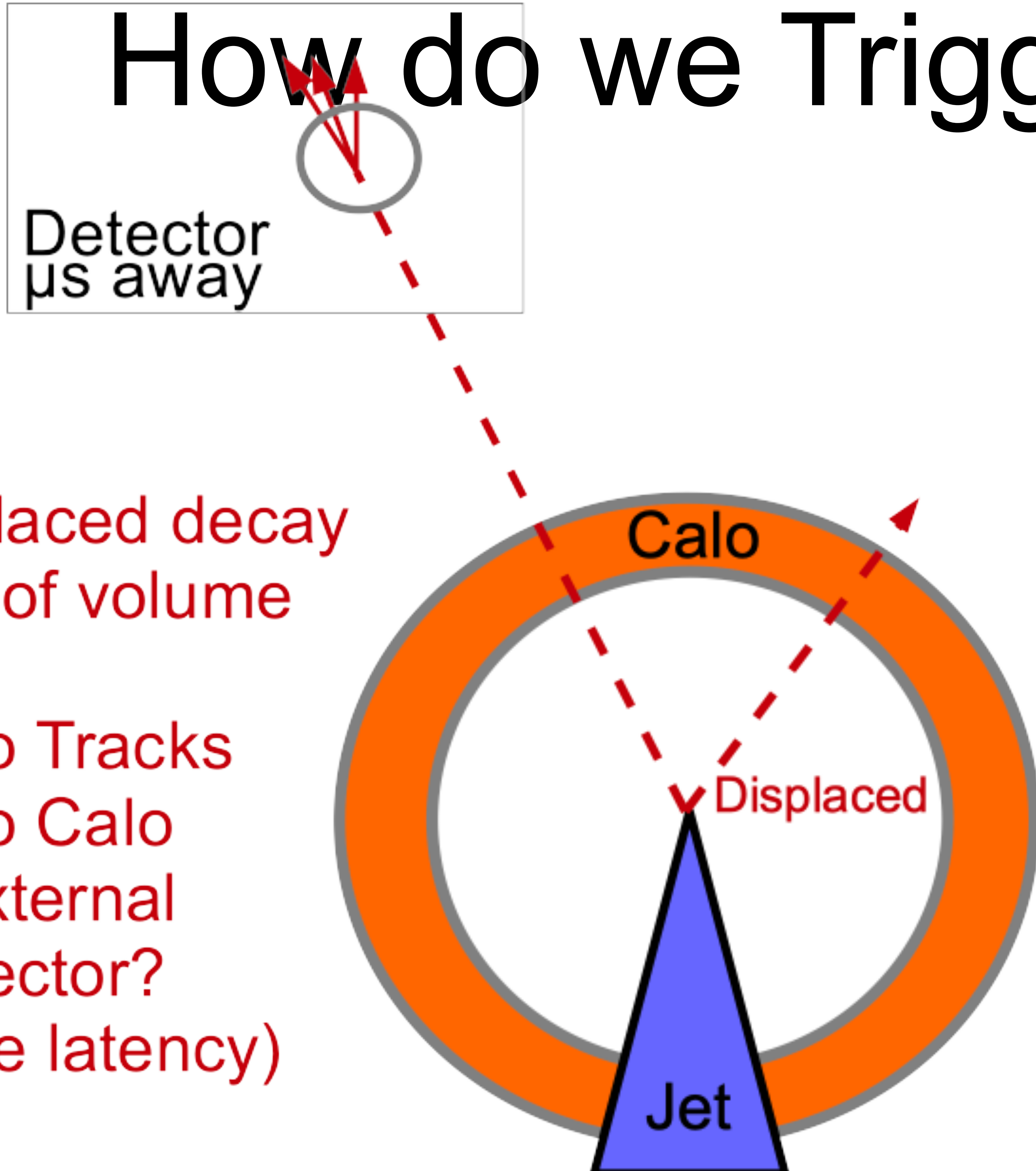
Displaced at L1 does not exist now

How do we Trigger these?

Displaced decay
Out of volume

1. No Tracks
2. No Calo
3. External Detector? (large latency)

1. Large *MET*



Normal *MET* trigger

Contend with normal L1 rates

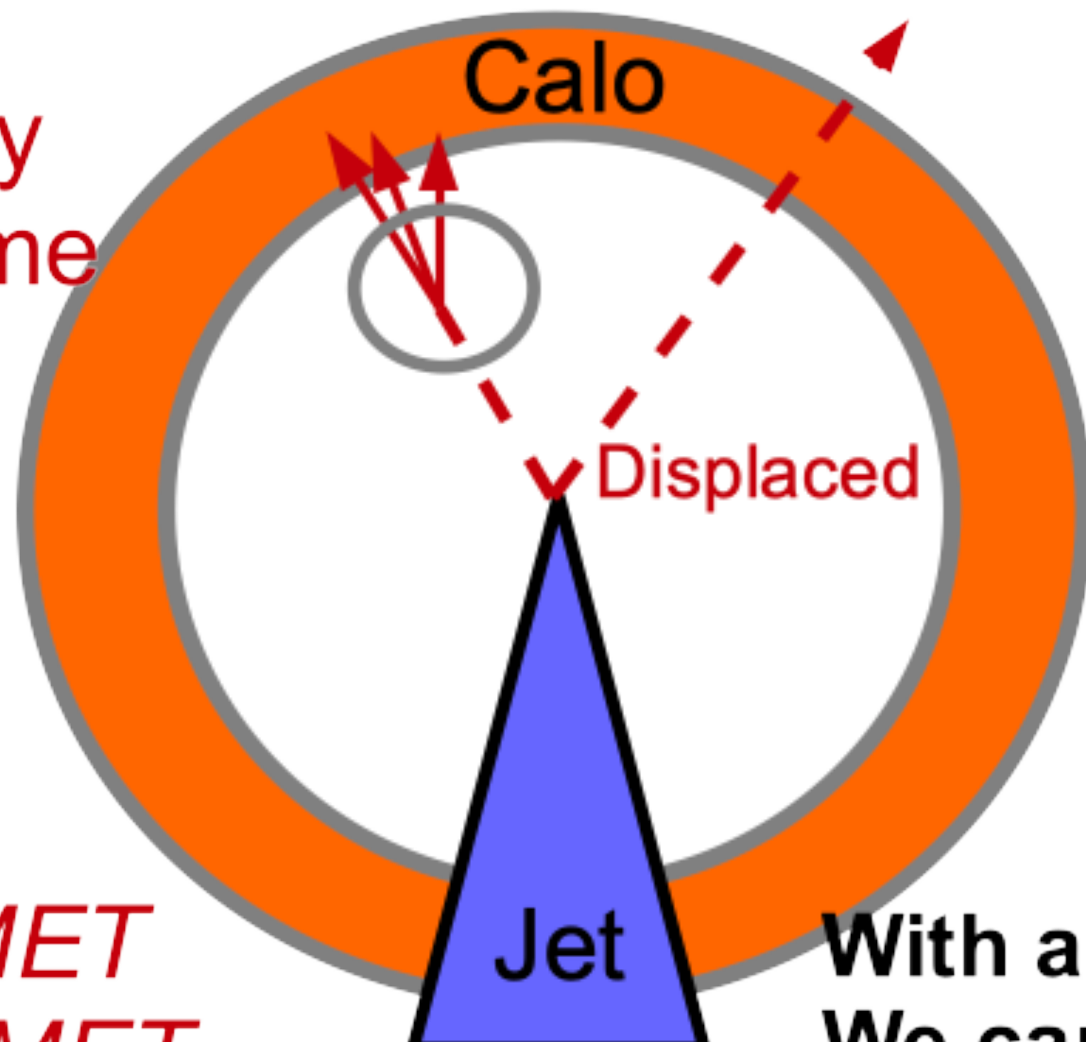
How do we Trigger these?

- Many displaced searches use a *MET* trigger
  - Basically unless there is a displaced lepton
  - **L1 *MET* is high right now** : remains a limiting factor

Displaced decay in tracker volume

1. No Tracks
2. Calo hits

1. Small Calo *MET*
2. Large Track *MET*



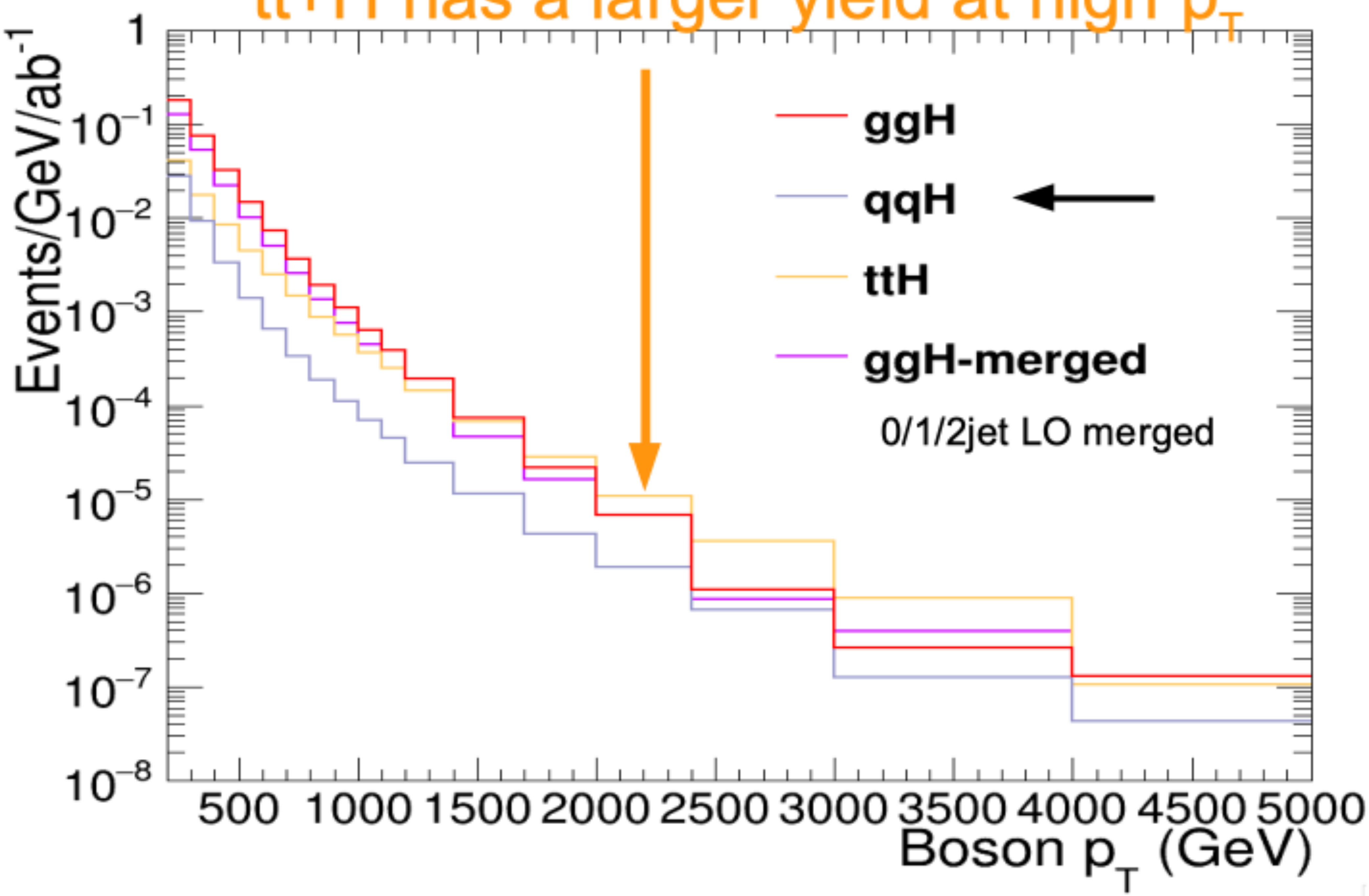
Special Trigger

With a track trigger at L1 We can probably get this

Higgs@100 TeV?

- A key feature at high p_T

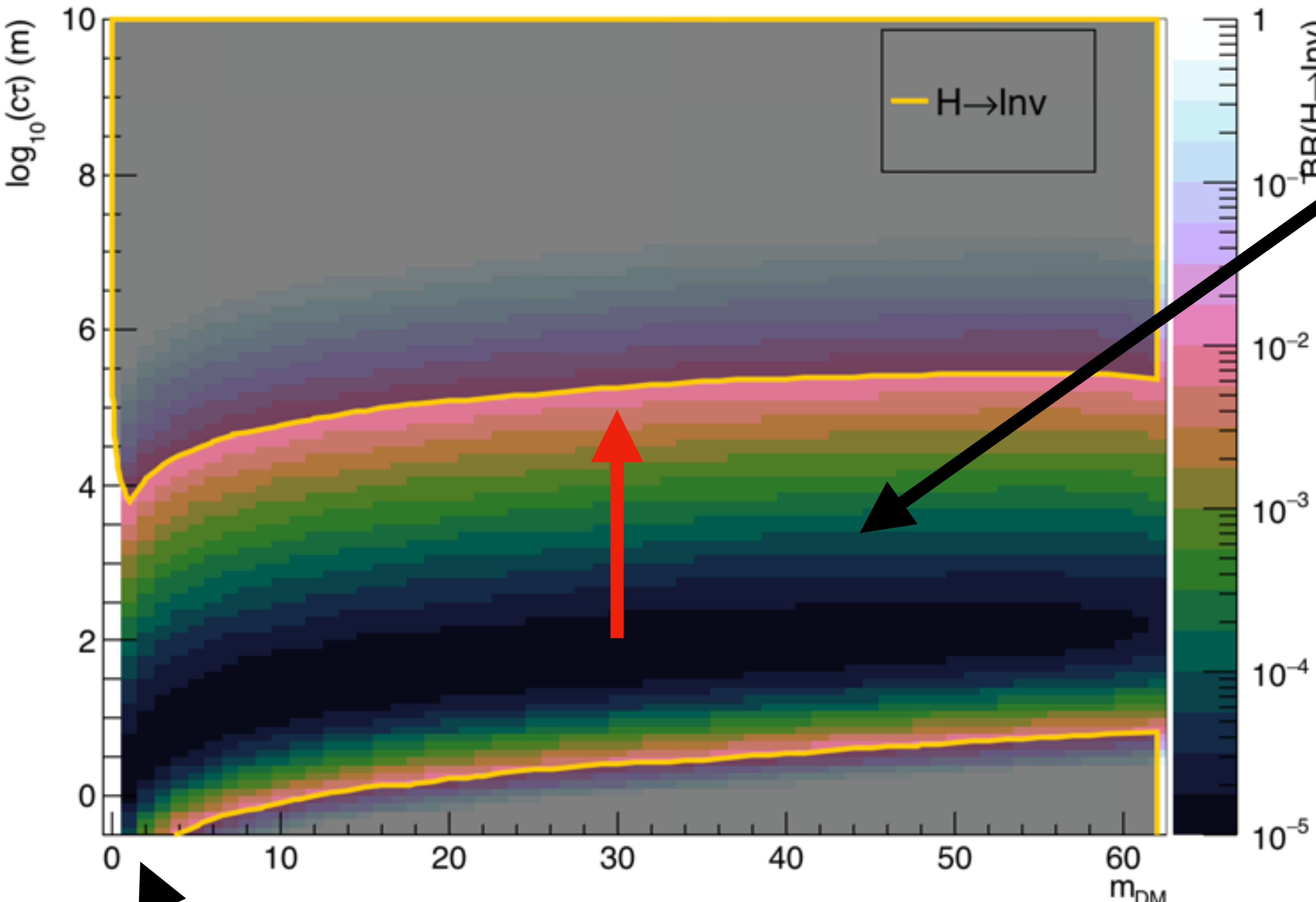
tt+H has a larger yield at high p_T



Inclusive ttH can be made relatively pure

What about a larger detector?

- Now with the Mathusla detector:



With a larger detector
Farther out

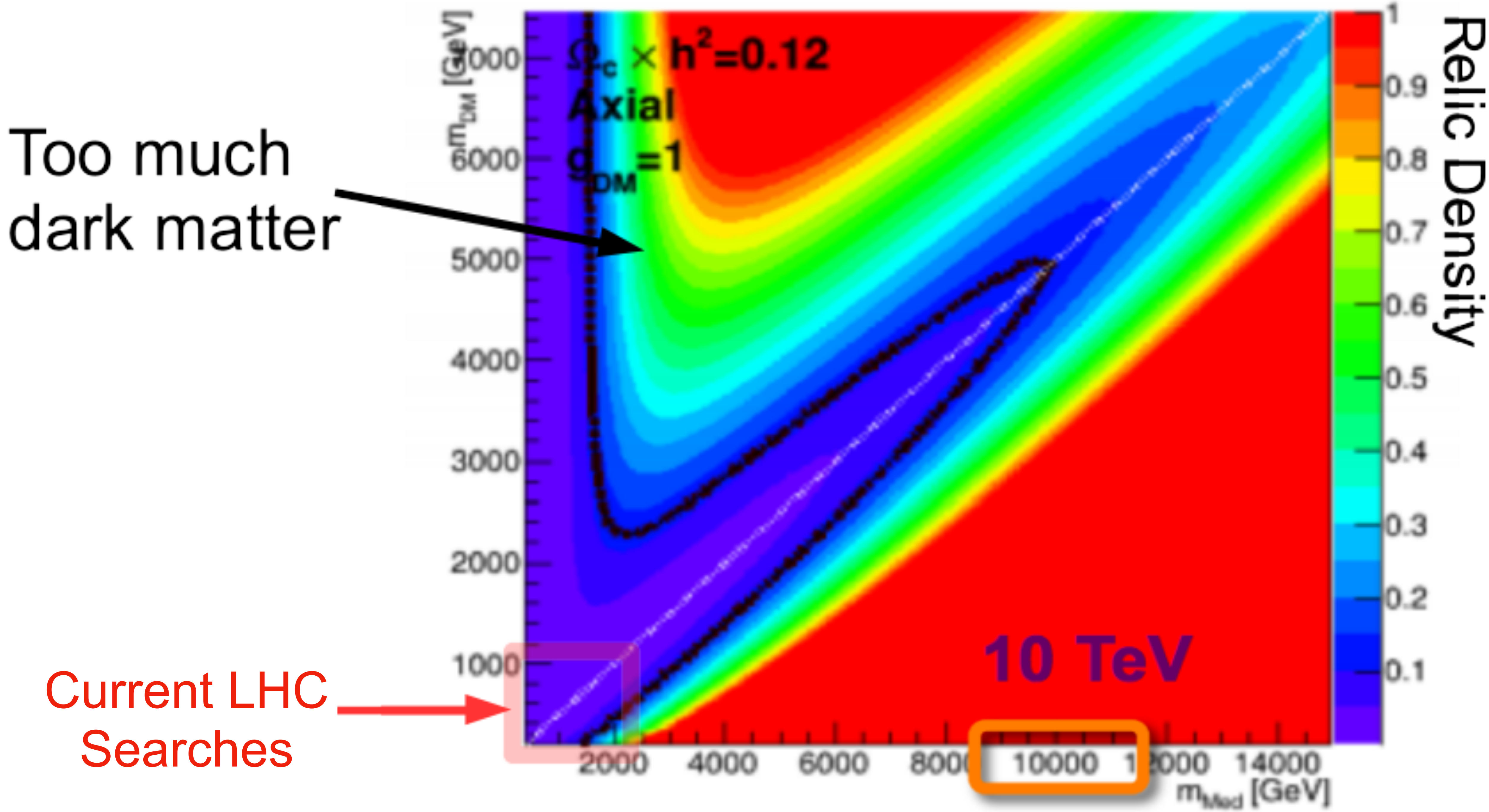
We probe longer lifetimes

We can reach Higgs BR down to 10^{-5}

Since we look for an upward going event low energy is possible

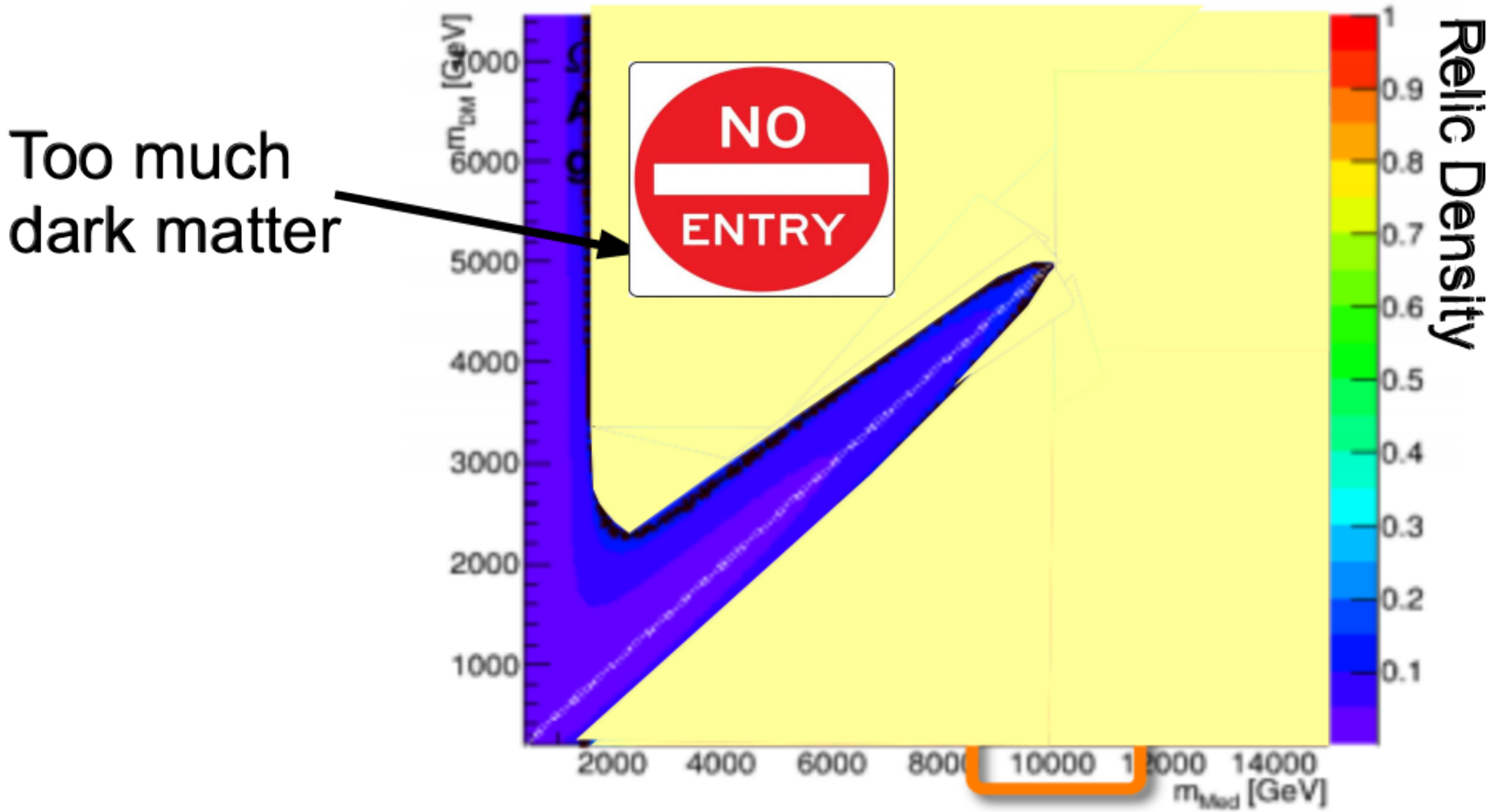
What's the high energy collider goal?

- The universe would collapse outside the line



What's the high energy collider goal?

- The universe would collapse outside the line

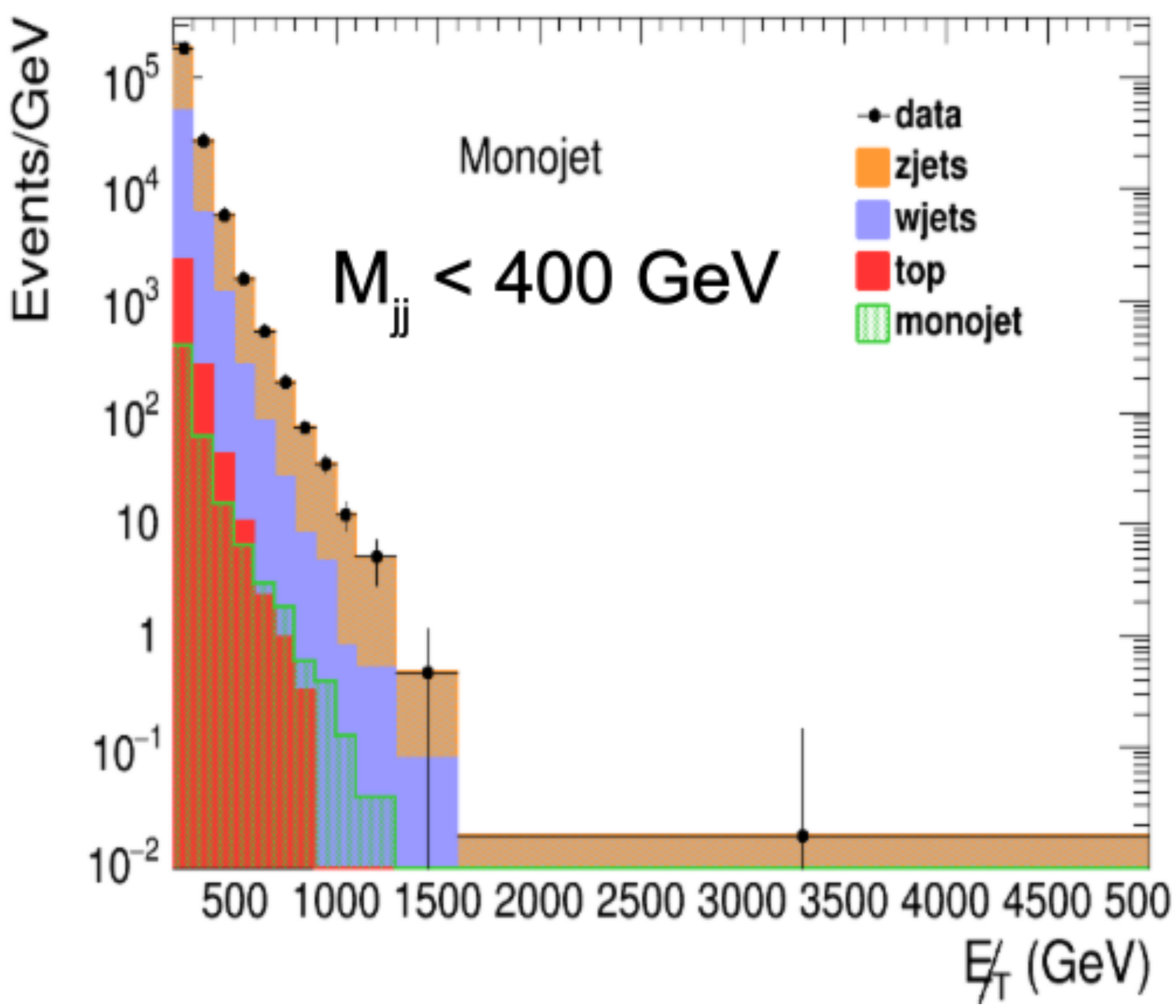


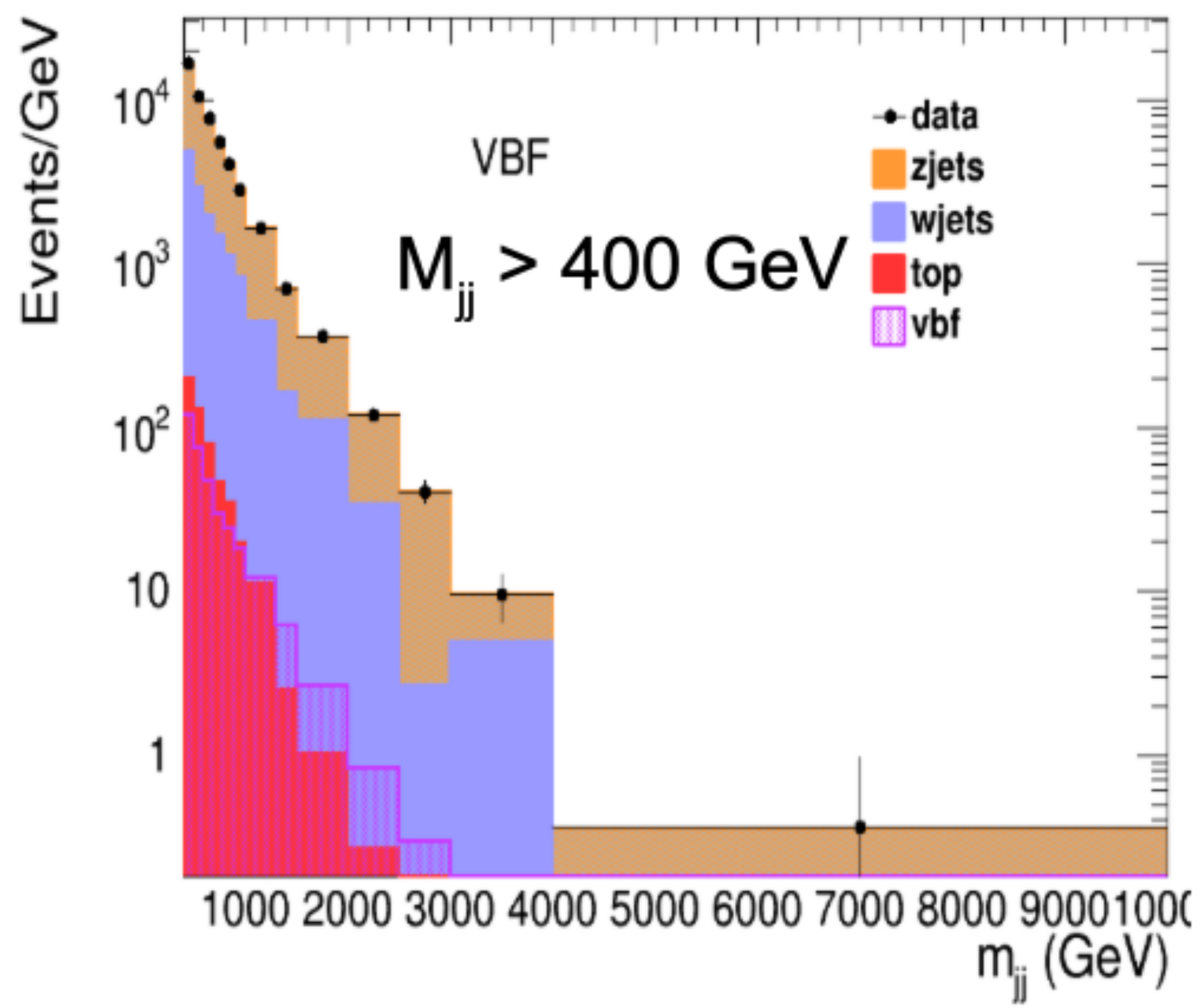
Can we probe to an upper bound in the relic?

Future of the LHC
& High Energy

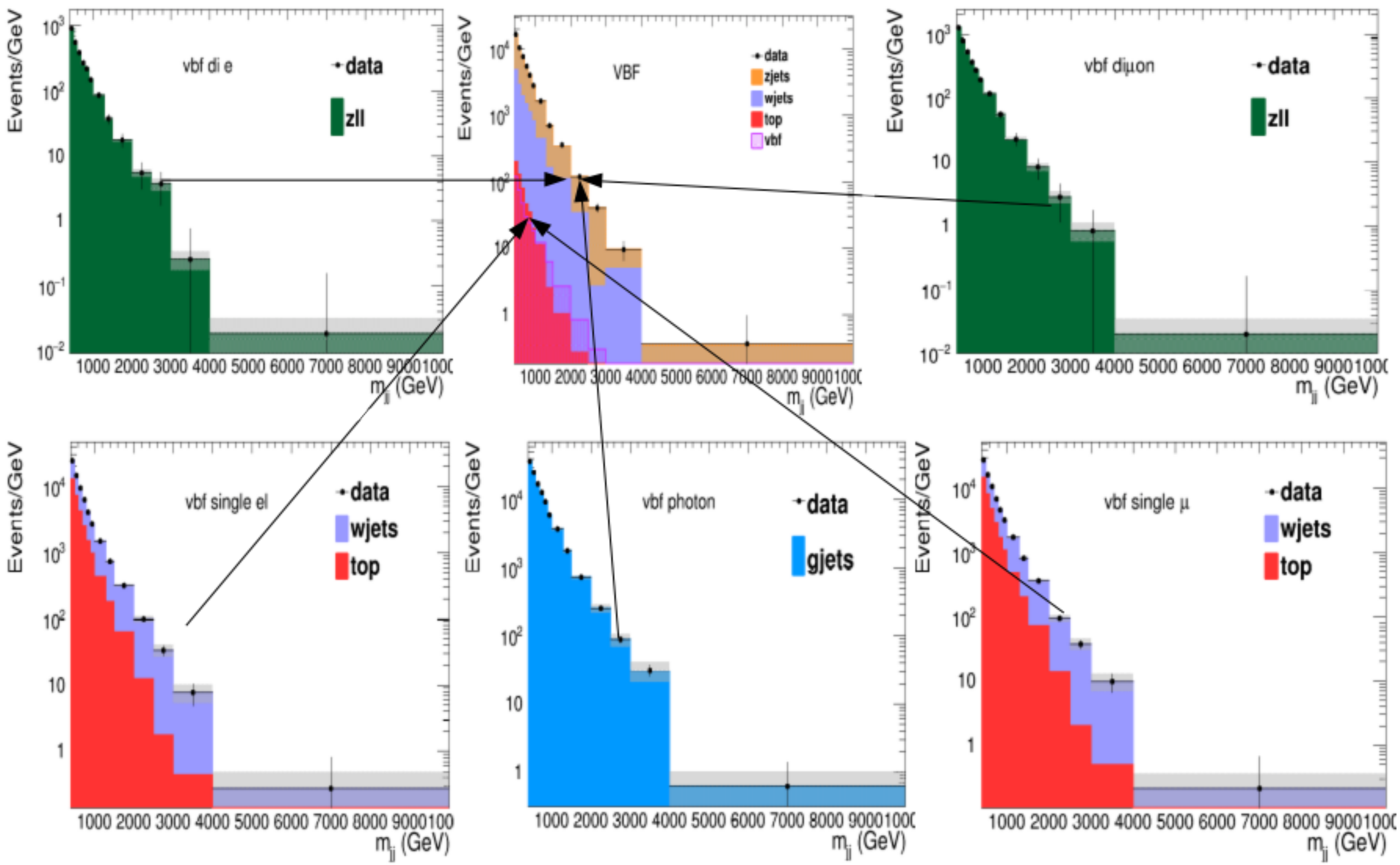
Picking up From Past

- In previous talks we looked at the monojet analyses
  - Lets go back to our toy analyses and look at how it behaves
- For simplicity lets look at the one that did Higgs to invisible



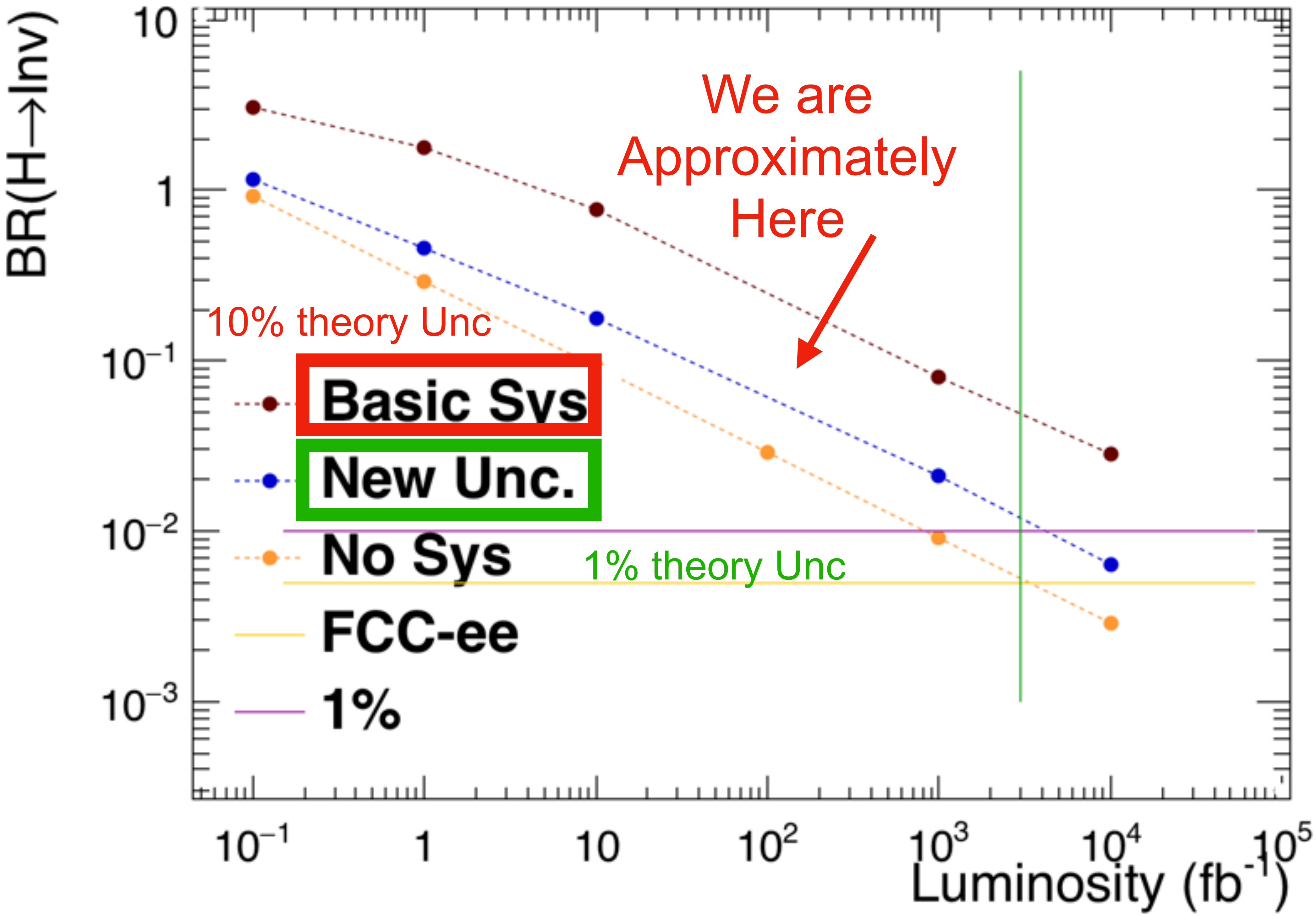


Extrapolating Full analysis



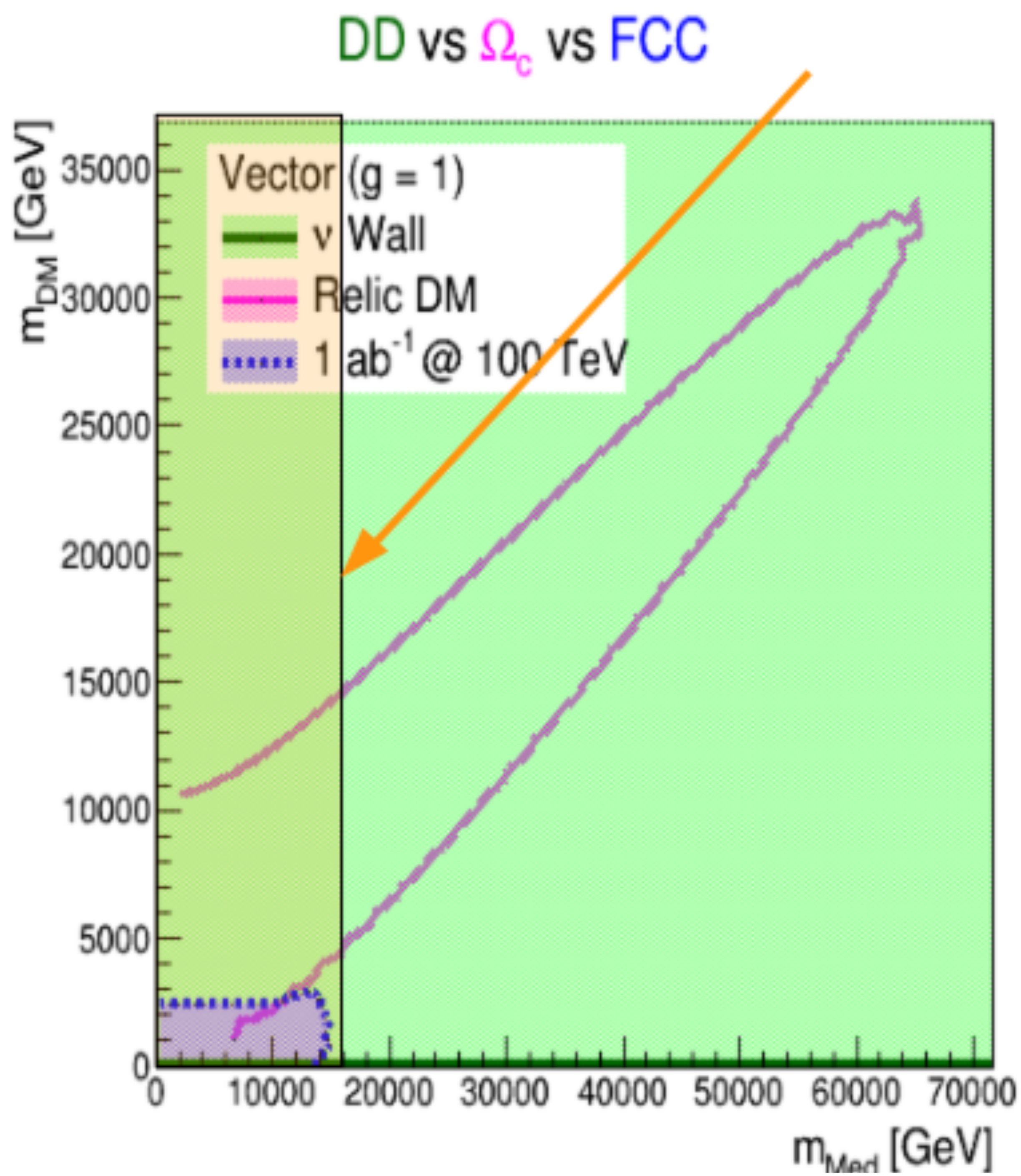
- Can run the full machinery and extrapolate to full LHC luminosity

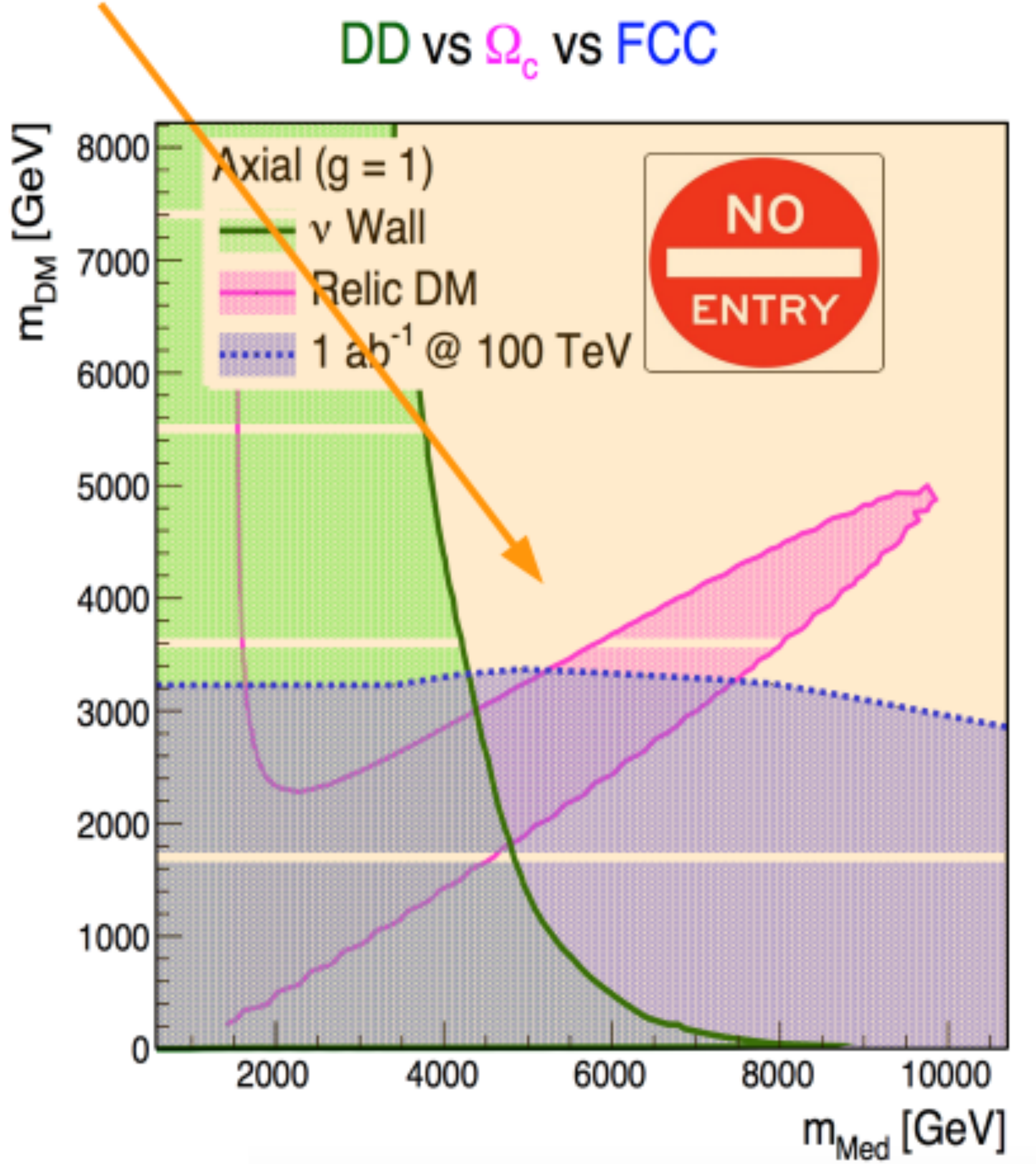
Extrapolating to the full dataset



Combining it all

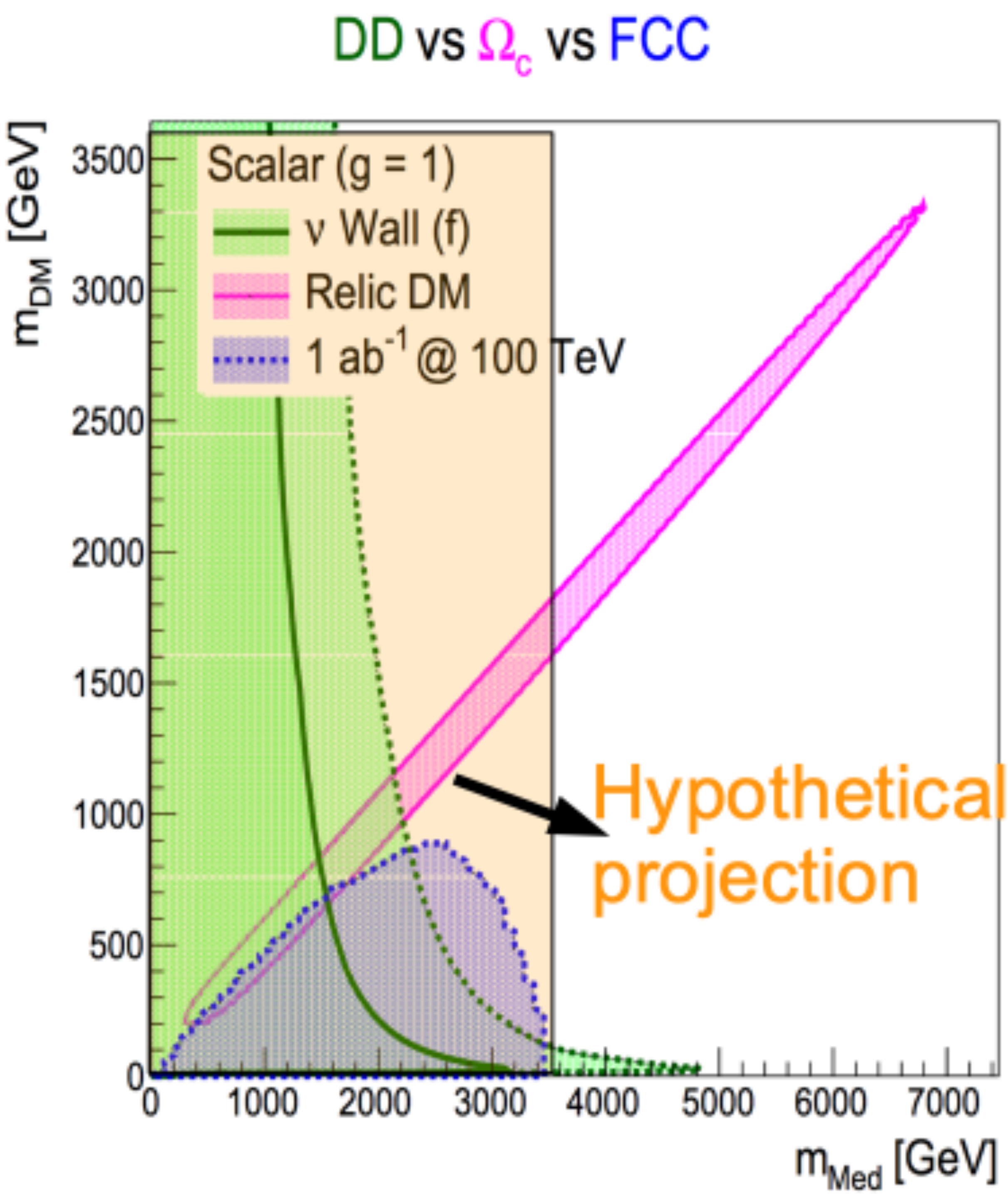
Adding the hypothetical di-jet projection

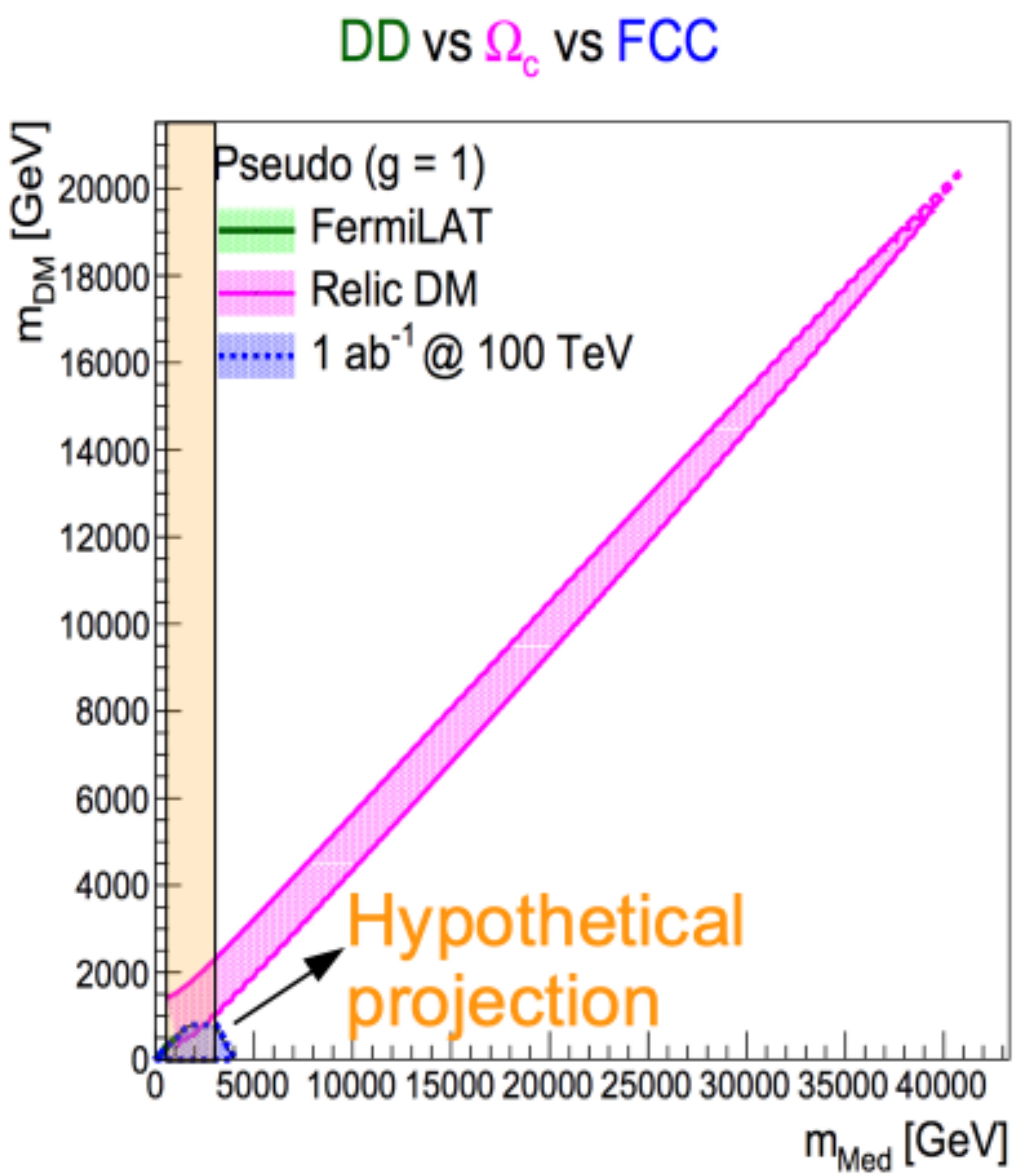




Adding the complementary projection

- Can we bound the scalar and pseudo scalar?





Collider Bounds?

Model	Collider	(In)Direct	Relic	Collider(visible) PRELIMINARY
Vector	15 TeV	>100 TeV	70 TeV	20TeV
Axial	15 TeV	6 TeV	8 TeV	20TeV
Scalar	3.5 TeV	3 TeV	6 TeV	3.5 TeV
Pseudo	4 TeV	1 TeV	40 TeV	3.5 TeV

For Spin 1 mediators 100 TeV Machine can close many scenarios

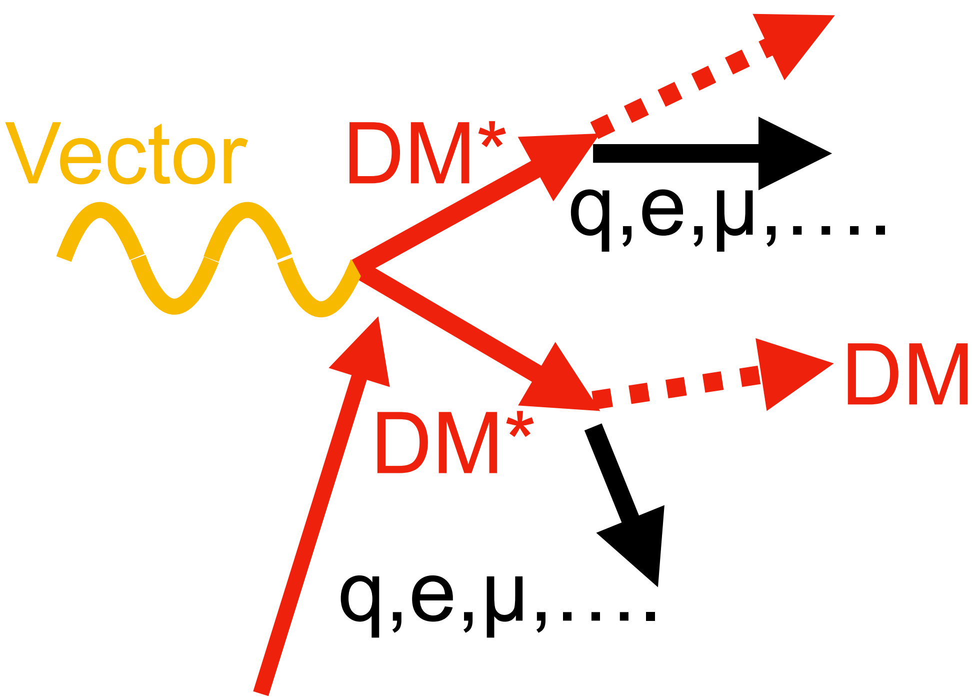
For Spin 0: its mostly closed, but not complete

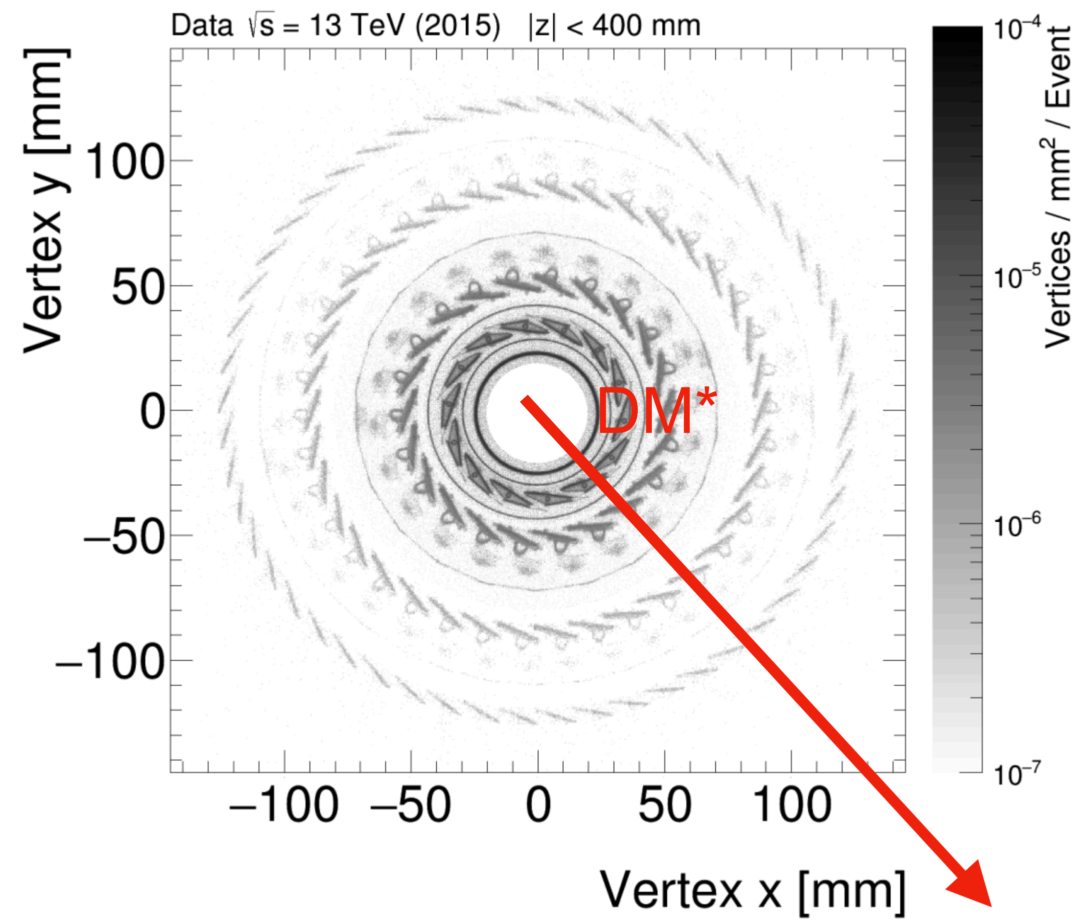
What are our targets now?

- Without a 100 TeV machine we can’t fully bound DM
  - However, we can make very strong statements
  - How strong, really depends on you
    - There is a lot of room to discuss here

- More importantly
  - There is no real ultimate bound for everybody
  - But there are many good targets that we will hit soon
- Can we get better bounds jus with planned future experiments?

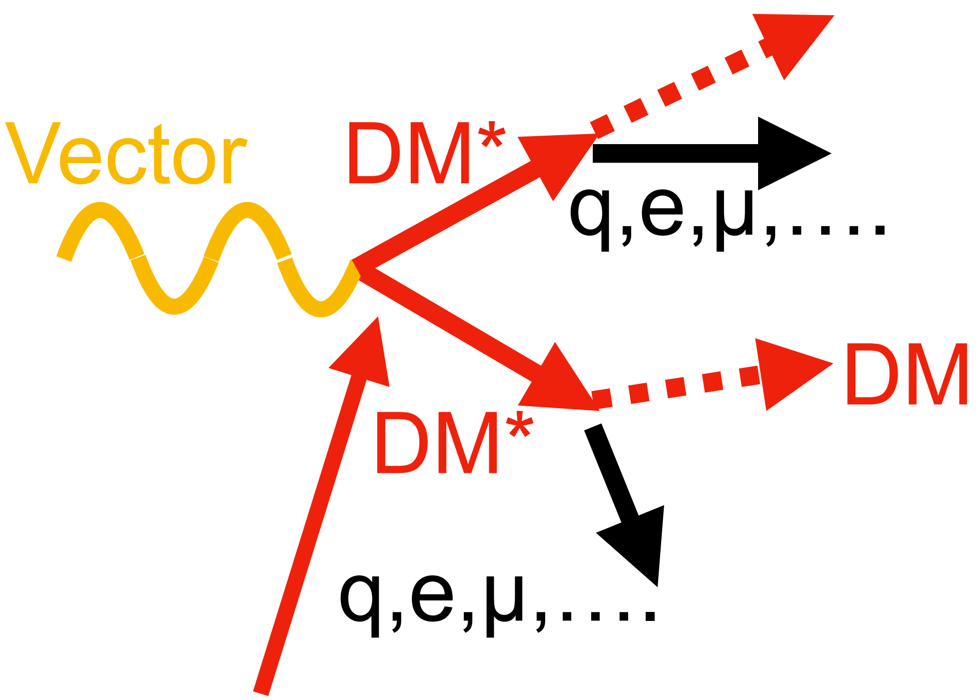
How would you search for it?

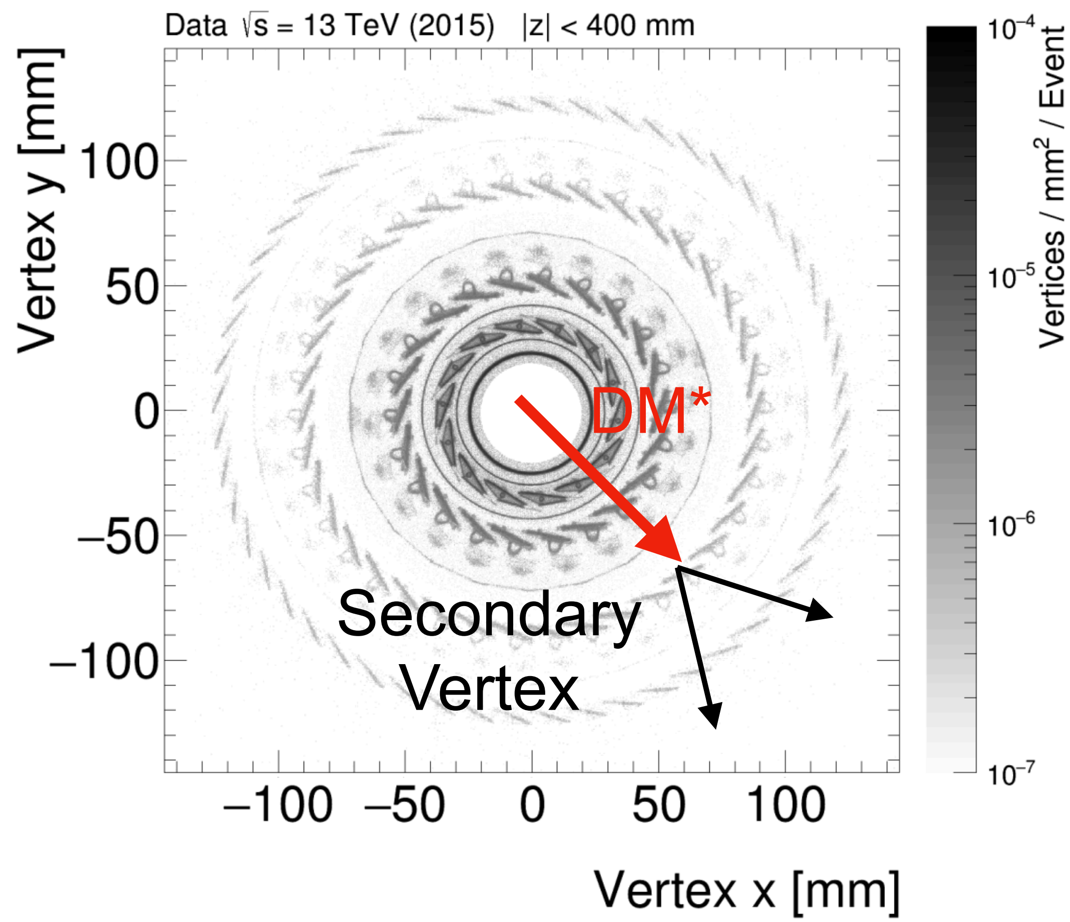




- If the lifetime is very long the unstable DM* escapes
  - This is just our normal monojet search

How would you search for it?

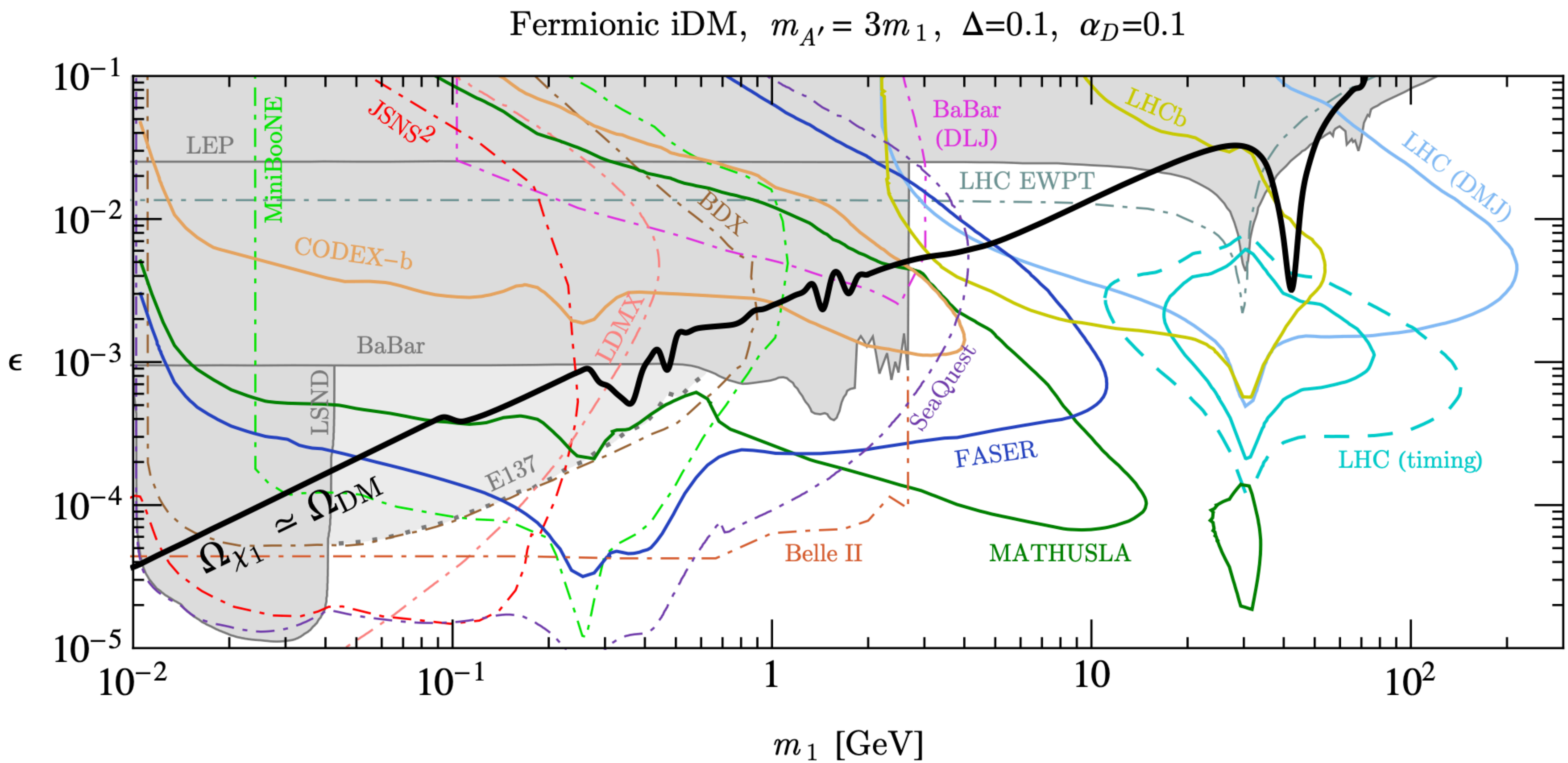




- If the lifetime is very long the unstable DM* escapes
  - This is just our normal monojet search
- If the lifetime is short the unstable DM* leaves a vertex
  - This is unusual and allows us to dramatically reduce bkg

An example search

Inelastic DM



▸ Lifetime can be

Edit me