Triggering DM to LL

Phil Harris (MIT)

input from
D. Curtin/J. Shelton/
M. Maccoullough/P. Meade

Smattering of EXO searches

- ttbar+MET
- Z(ll)+MET
- monoH(γγ)
- monoH(bb)
- monoH(ττ)
- monoH(WW)
- monojet
- mono-γ
- monotop
- Mono-Leptoquark
- displaced e-mu
- Stopped long lived particle
- Displaced jet
- Disappearing track

- dijets
- low-mass dijets
- Boosted dijet
- B-tagged dijets
- Z'→ee/μμ/W'→e/μ/τν
- Black Holes
- LQ(ee/ττ)
- l*→lγ
- q*→qγ
- N→lqj
- Multilepton
- Z(ll)γ
- Z(qq)γ
- γγ

Color coded roughly by types of models

Smattering of EXO searches

- ttbar+MET
- Z(ll)+MET
- monoH(γγ)
- monoH(bb)
- monoH(ττ)
- monoH(WW)
- monojet
- mono-γ
- monotop
- Mono-Leptoquark

- displaced e-mu
- Stopped long lived particle
- Displaced jet
- Disappearing track

- dijets
- low-mass dijets
- Boosted dijet
- B-tagged dijets
- Z'→ee/μμ/W'→e/μ/τν

- Black Holes
- LQ(ee/ττ)
- l*→lγ
- q*→qγ
- N→lqj
- Multilepton

- Z(ll)γ
- Z(qq)γ
- γγ

Smattering of EXO searches

Dark Matter

- ttbar+MET
- Z(ll)+MET
- monoH(γγ)
- monoH(bb)
- monoH(ττ)
- monoH(WW)
- monojet
- mono-γ
- monotop
- Mono-Leptoquark

Long lived

- displaced e-mu
- Stopped long lived particle
- Displaced jet
- Disappearing track

Resonance

- dijets
- low-mass dijets
- Boosted dijet
- B-tagged dijets
- Z'→ee/μμ/W'→e/μ/τν

Exotic sig.

- Black Holes
- LQ(ee/ττ)
- l*→lγ
- q*→qγ
- N→lqj
- Multilepton

γs

- Z(ll)γ
- Z(qq)γ
- γγ

What are the triggers we use?

- Broadly speaking can assign triggers to few cats

- MET triggers : *MET* > 150-200 GeV (L1 limited)
- Jet triggers : p_T > 400-450 GeV (L1 to 205 GeV)
- Photon : p_T > 170 GeV (L1 to 100 GeV)
- Lepton triggers : p_T > 24/27 GeV (L1 20/20)
- Exotic triggers : No L1 (comes from above)
  - Displaced object @HLT
  - Out of bunch object

Trigger Assignment

- ttbar+MET
- Z(ll)+MET
- monoH(γγ)
- monoH(bb)
- monoH(ττ)
- monoH(WW)
- monojet
- mono-γ
- monotop
- Mono-Leptoquark

Dark Matter

MET Trigger
Jet Trigger
Photon Trigger
Lepton Trigger
Exotic Trigger

MET and lepton triggers drive dark matter searches
Likely will be for future

Smattering of EXO searches

MET Trigger
Jet Trigger
Photon Trigger
Lepton Trigger
Exotic Trigger

The most exotic signatures are not trigger sensitive
...to be honest these will quickly become lower priority

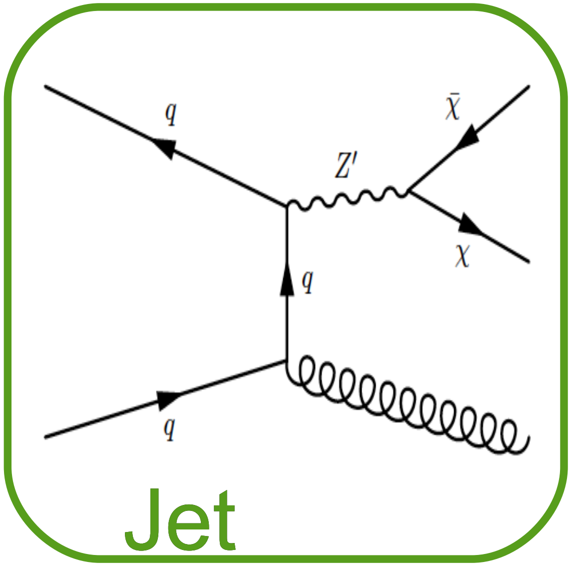
- Black Holes
- LQ(ee/ττ)
- $l^* \to l\gamma$
- $q^* \to q\gamma$
- $N \to lqj$
- Multilepton

Exotic sig.

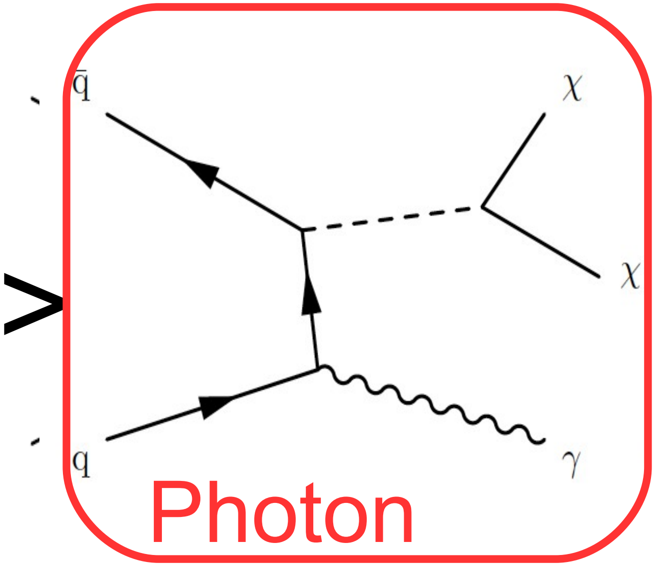
Lack of $s^{1/2}$ is a powerful thing

Smattering of EXO searches

MET Trigger
Jet Trigger
Photon Trigger
Lepton Trigger
Exotic Trigger



>



γ related searches have been an exciting time.... but to be honest with exception of γγ for Higgs/Resonance they tend to be the 2nd string when jets/MET fail

- Z(ll)γ
- Z(qq)γ
- γγ

vs

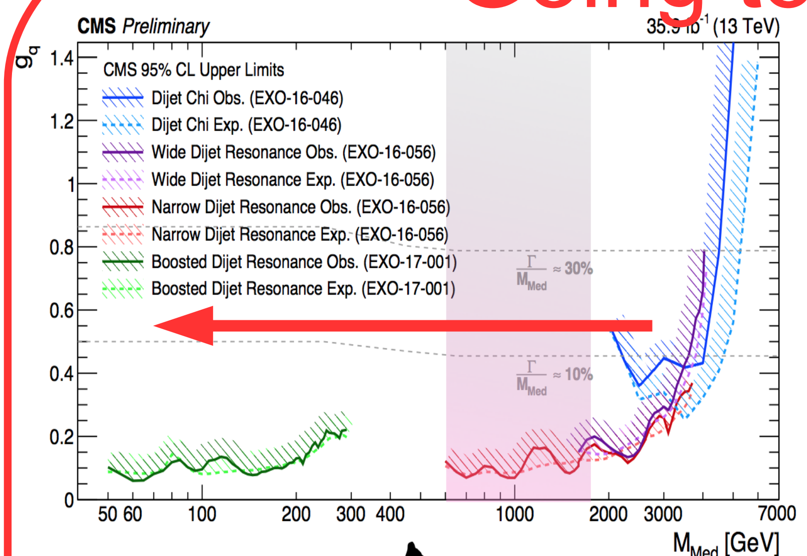
Smattering of EXO searches

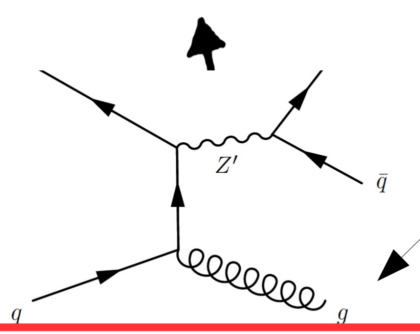
MET Trigger
Jet Trigger
Photon Trigger
Lepton Trigger
Exotic Trigger

Resonance

- dijets
- low-mass dijets
- Boosted dijet
- B-tagged dijets
- Z'→ee/μμ/W'→e/μ/τν

Going to low mass





Data Scouting

Resonances are simple objects basically 2 4-vectors

Store reduced dataset down to L1

(Use HLT objects with L1 rate)

ISR Tagging

Can use an additional ISR Jet/γ to push events over the trigger threshold

Smattering of EXO searches

MET Trigger

Jet Trigger

Photon Trigger

Lepton Trigger

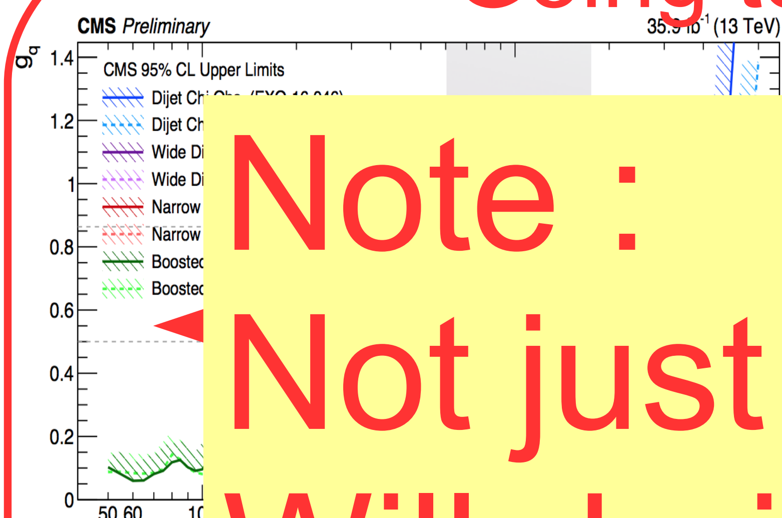
Exotic Trigger

Resonance

- dijets
- low-mass dijets
- Boosted dijet
- B-tagged dijets
- Z'→ee/μμ/W'→e/μ/τν

Going to low mass

Data Scouting



jects

wn to L1

rate)

Jet/γ to

er

Note :
Not just about jets
Will do it for leptons and photons? ….

Smattering of EXO searches

MET triggers can drive a lot in upgrade

Hold this thought....

MET Trigger
Jet Trigger
Photon Trigger
Lepton Trigger
Exotic Trigger

Maximizing displacd signatures is something we are just starting to think about

Long lived

- displaced e-mu
- Stopped long lived particle
- Displaced jet
- Disappearing track

Summarizing

Dark Matter
- ttbar+MET
- Z(ll)+MET
- monoH(γγ)
- monoH(bb)
- monoH(ττ)
- monoH(WW)
- monojet
- mono-γ
- monotop
- Mono-Leptoquark

Long lived
- displaced e-mu
- Stopped long lived particle
- Displaced jet
- Disappearing track

Resonance
- dijets
- low-mass dijets
- Boosted dijet
- B-tagged dijets
- Z'→ee/μμ/W'→e/μ/τν

Exotic sig.
- Black Holes
- LQ(ee/ττ)
- l*→lγ
- q*→qγ
- N→lqj
- Multilepton

γs
- Z(ll)γ
- Z(qq)γ
- γγ

Tally
5 MET
6 Jet
5 Photon
11 Lepton
1 Exotic

Summarizing

- ttbar+MET
- Z(ll)+MET
- monoH
- mon
- mon
- mon
- mon
- mon
- mon
- Mon

- displ
- Stopp
- Displaced j
- Disappearing track

Lo

- dijets
- low-mass dijets
- jiet
- ets
- '→e/μ/τν

Resonance

Exotic sig.

- γγ

γs

Excluding exotic sig and

Worst acept.
5 Jet
5 MET
4 Photon
7 Lepton
Best accept.

Close to even split

Tally
5 MET
6 Jet
5 Photon
11 Lepton
1 Exotic

Back to displaced searches

MET triggers can drive a lot in upgrade

Hold this thought....

MET Trigger
Jet Trigger
Photon Trigger
Lepton Trigger
Exotic Trigger

Maximizing displacd signatures is something we are just starting to think about

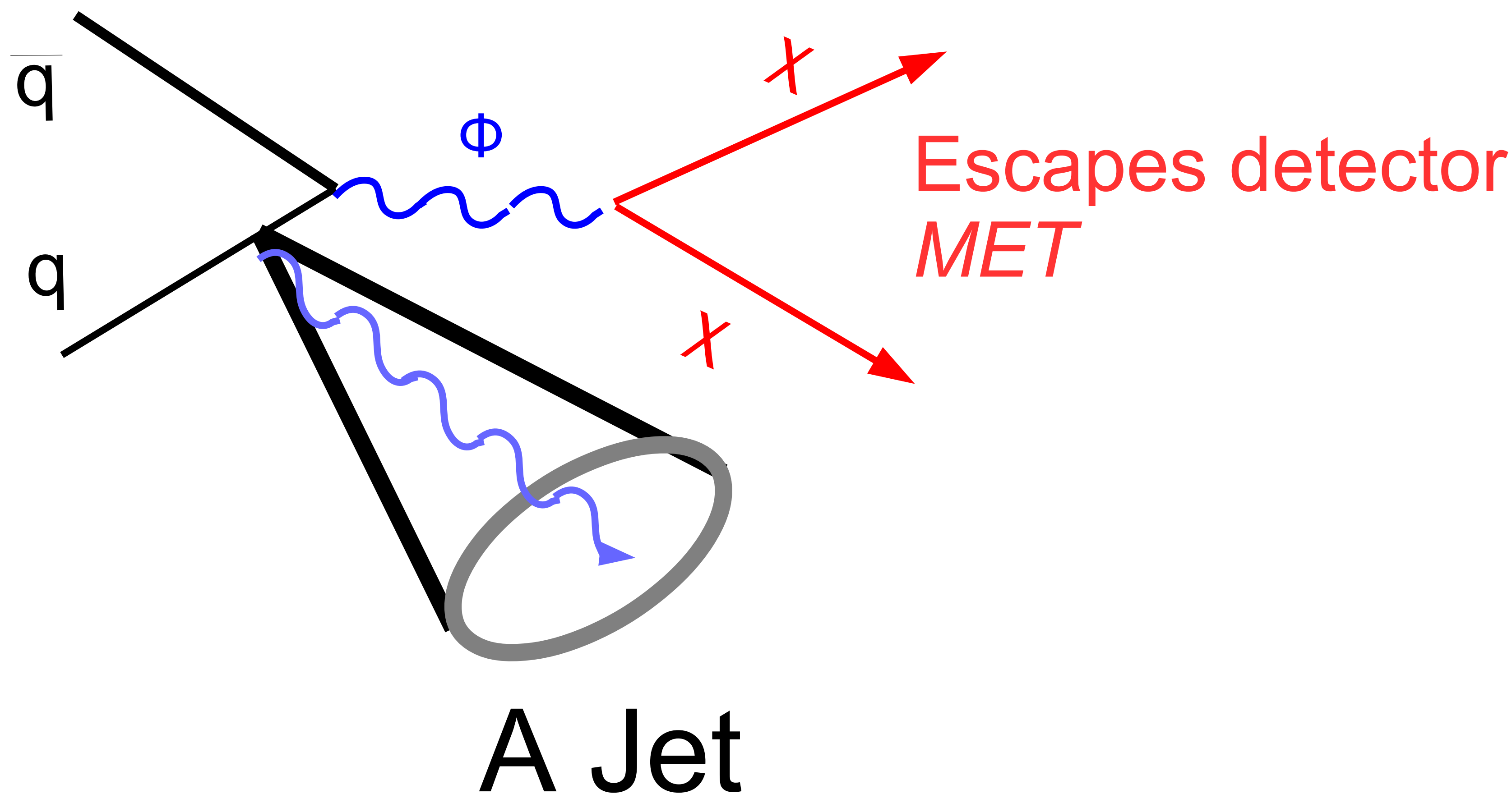
- displaced e-mu
- Stopped long lived particle
- Displaced jet
- Disappearing track

Long lived

Dark Matter Search

Mono-jet

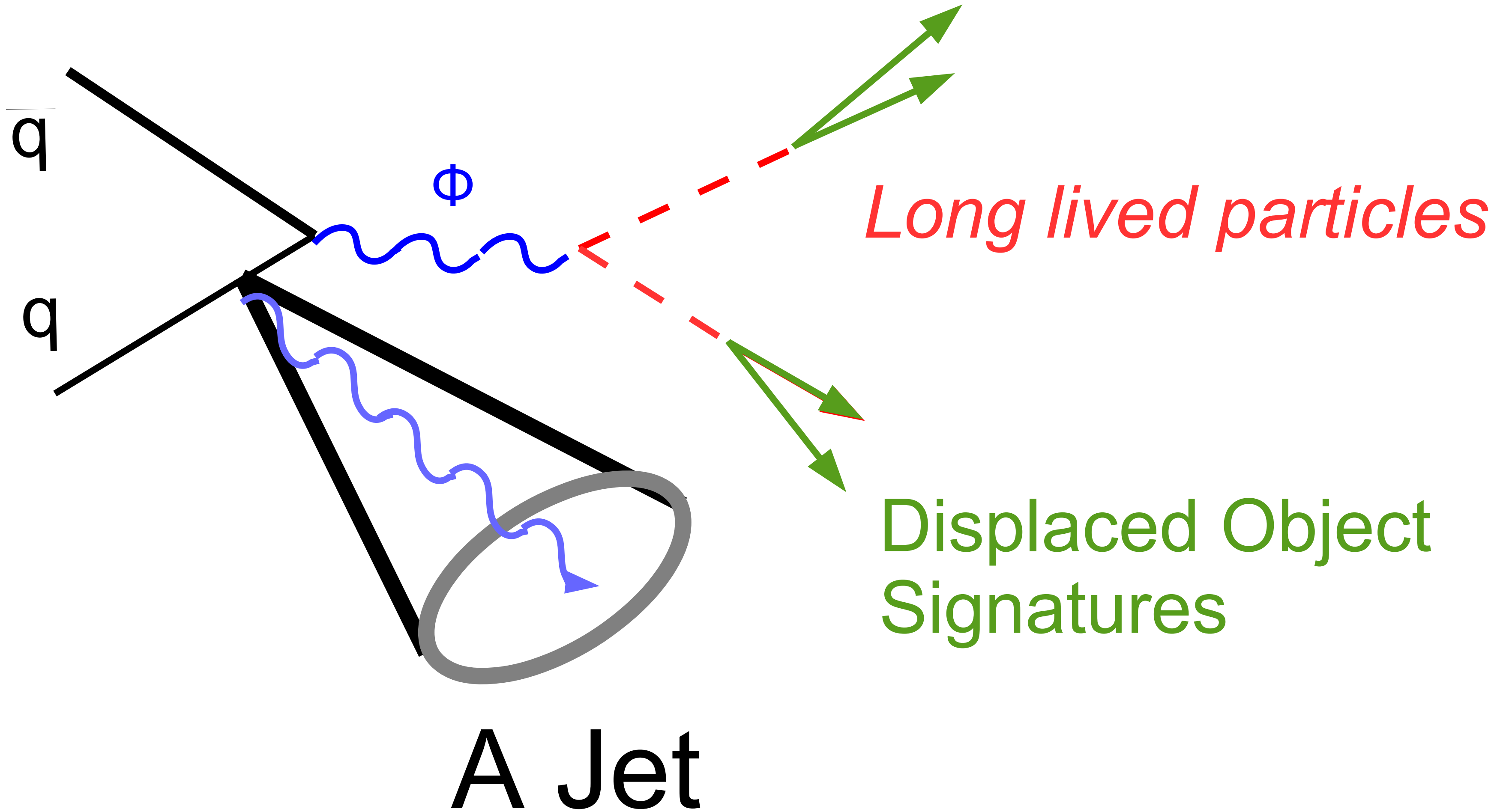
Models : Vector,Axial,Scalar,Pseudoscalar



Dark Matter Search extended

Mono-jet

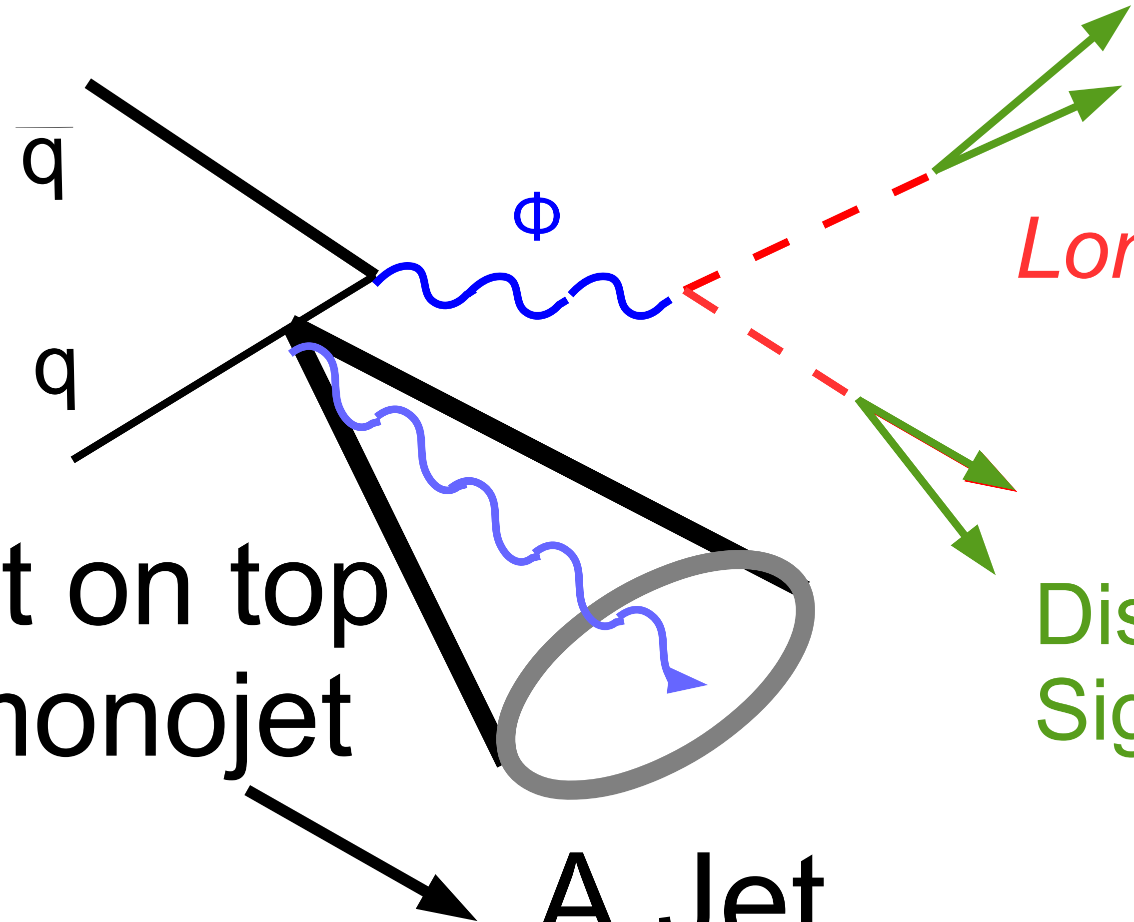
Models : Vector,Axial,Scalar,Pseudoscalar



How Do We Discriminate Models?

Mono-jet

Models : Vector,Axial,Scalar,Pseudoscalar



Long lived particles

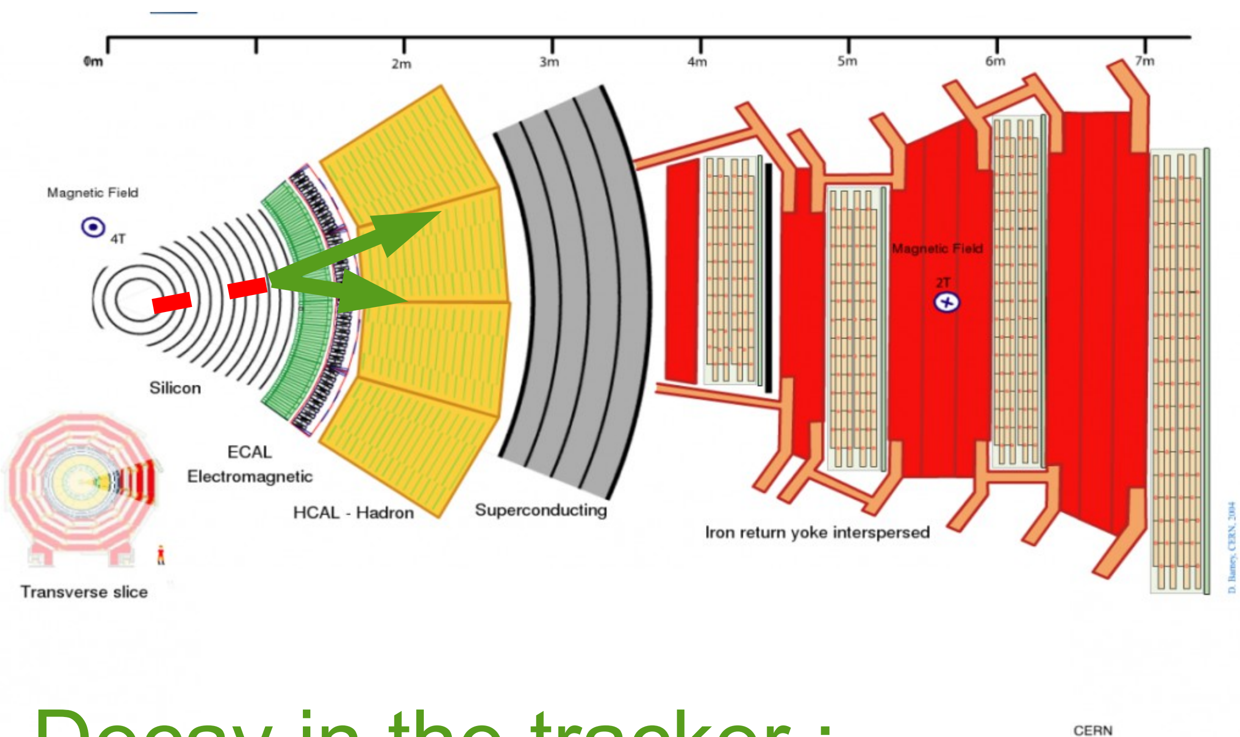
Displaced Object Signatures

Built on top of monojet

A Jet

How can we go beyond?

- Tagging a long lived particle



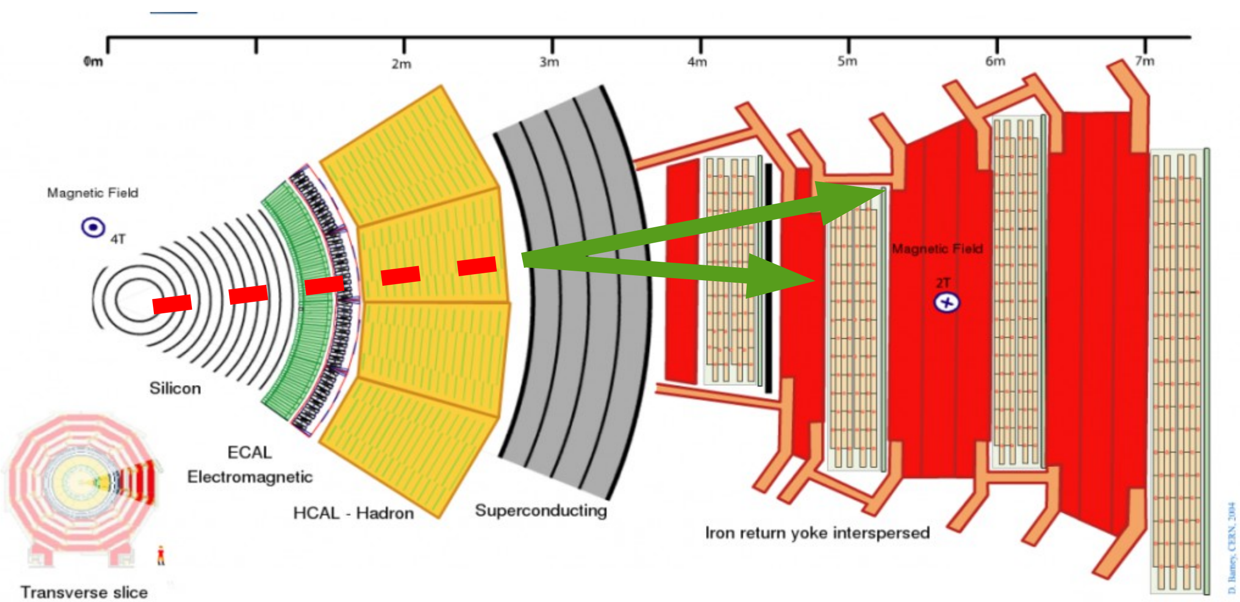
Decay in the tracker :

Displaced track signature

No missing transverse energy

How can we go beyond?

- Tagging a long lived particle



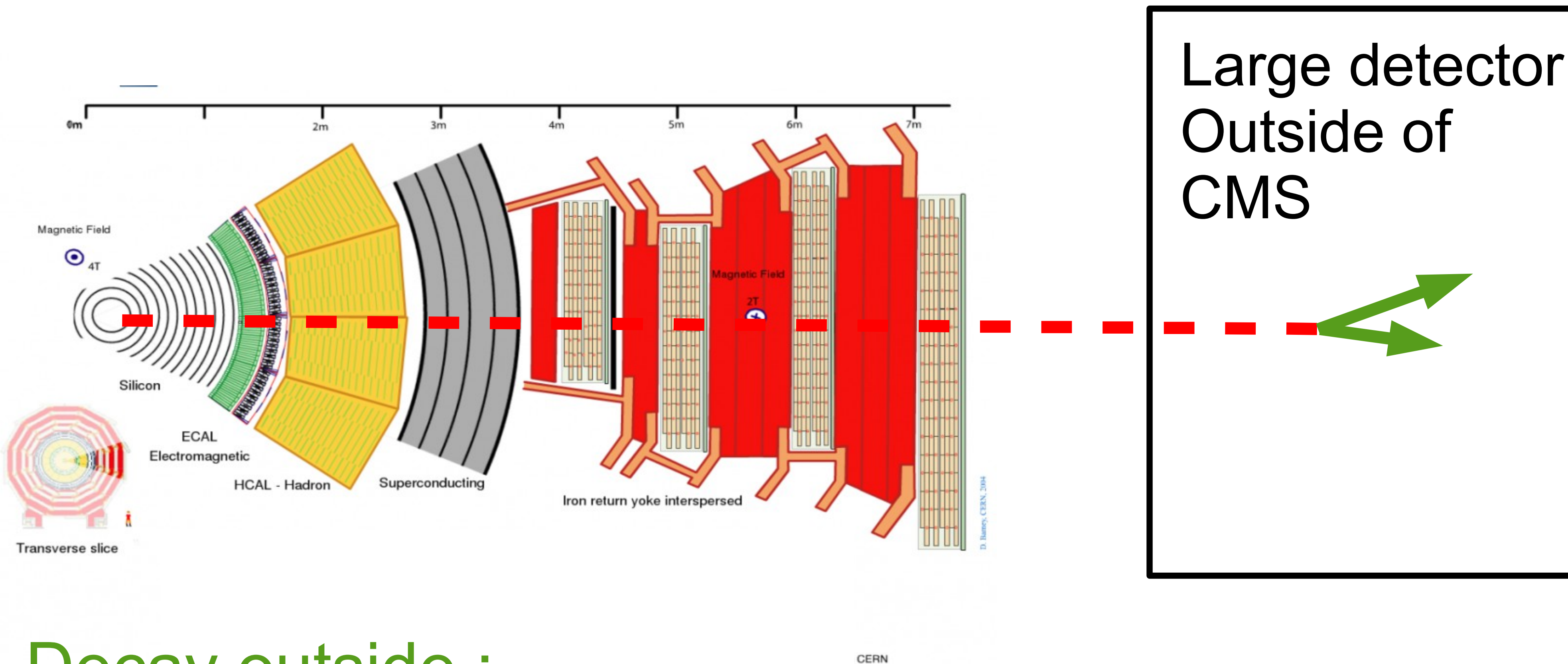
Decay in the Calorimeters : CERN

Calorimeter/Muon signature

Missing transverse energy

How can we go beyond?

- Tagging a long lived particle



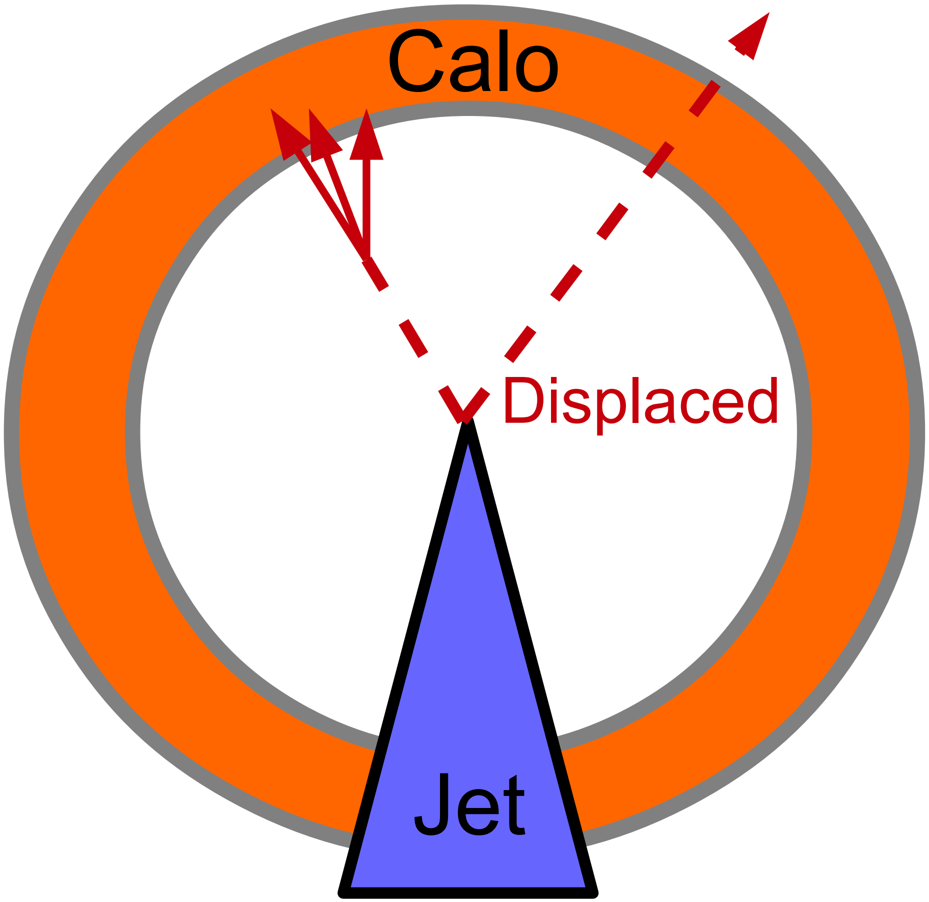
Decay outside :

Missing transverse energy → monojet signature

Few proposals are out like MATHUSLA

What about the trigger?

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



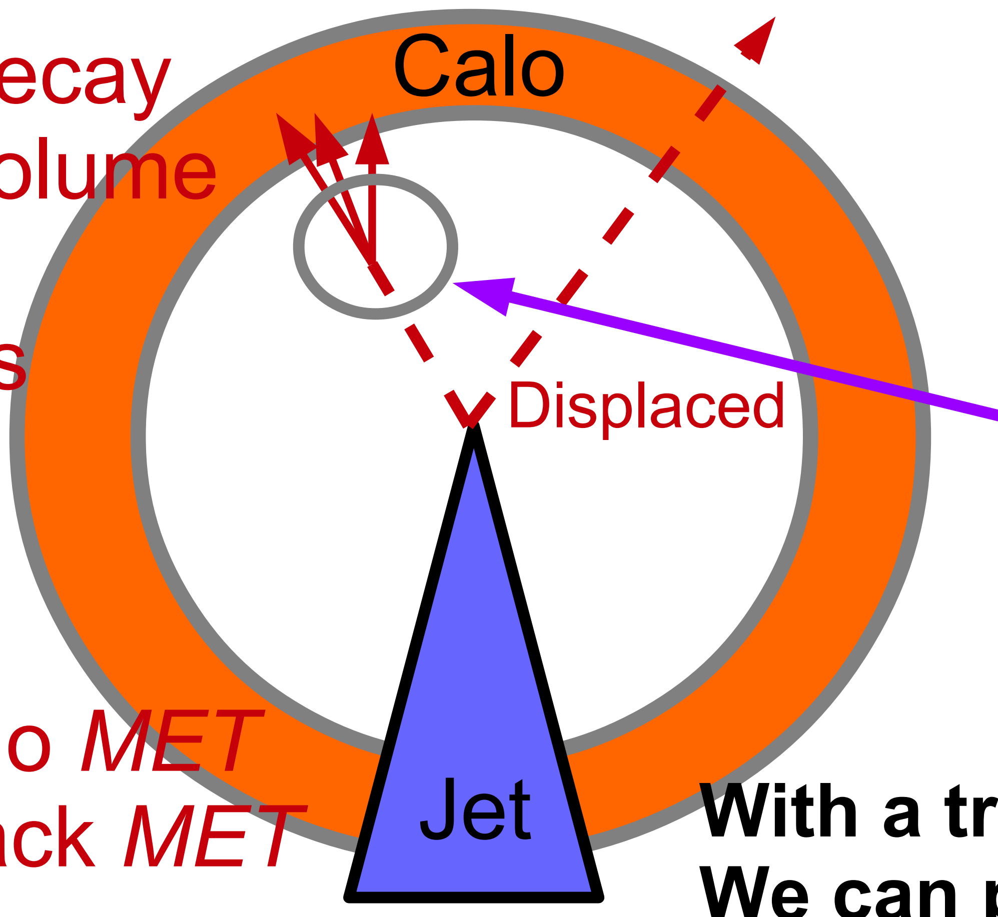
What about the trigger?

- 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

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



Special Trigger

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

With a track trigger at L1
We can probably get this

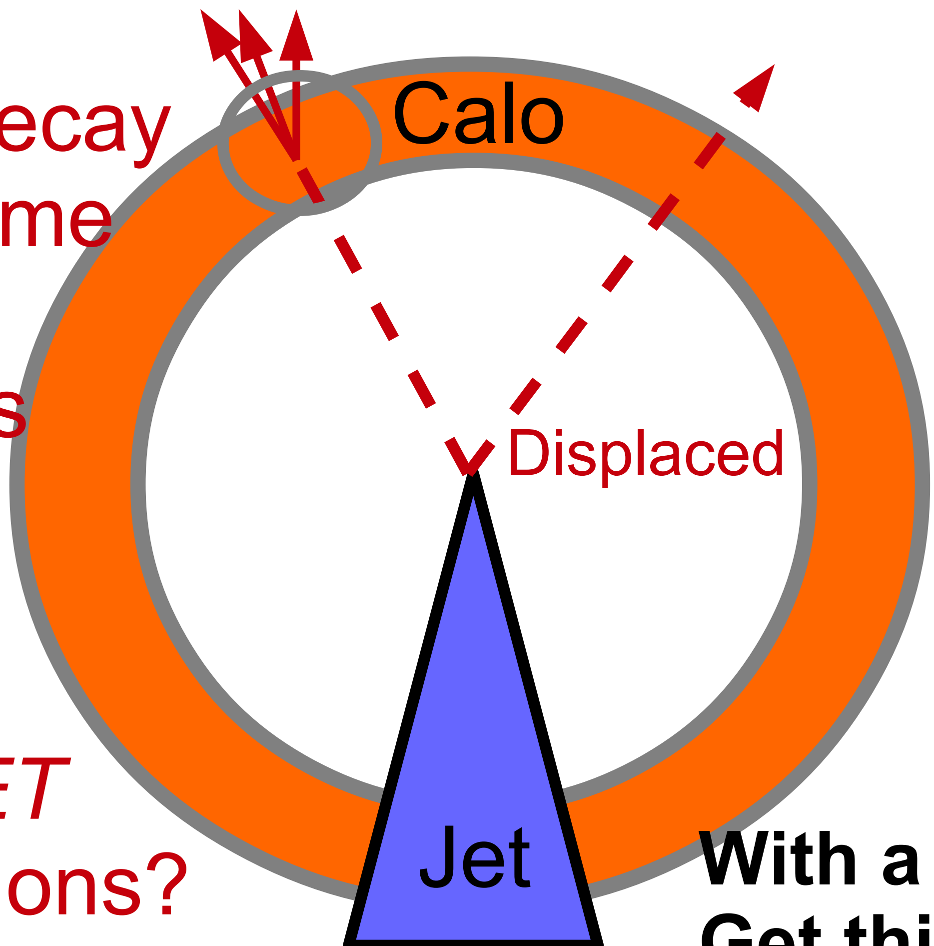
What about the trigger?

- 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

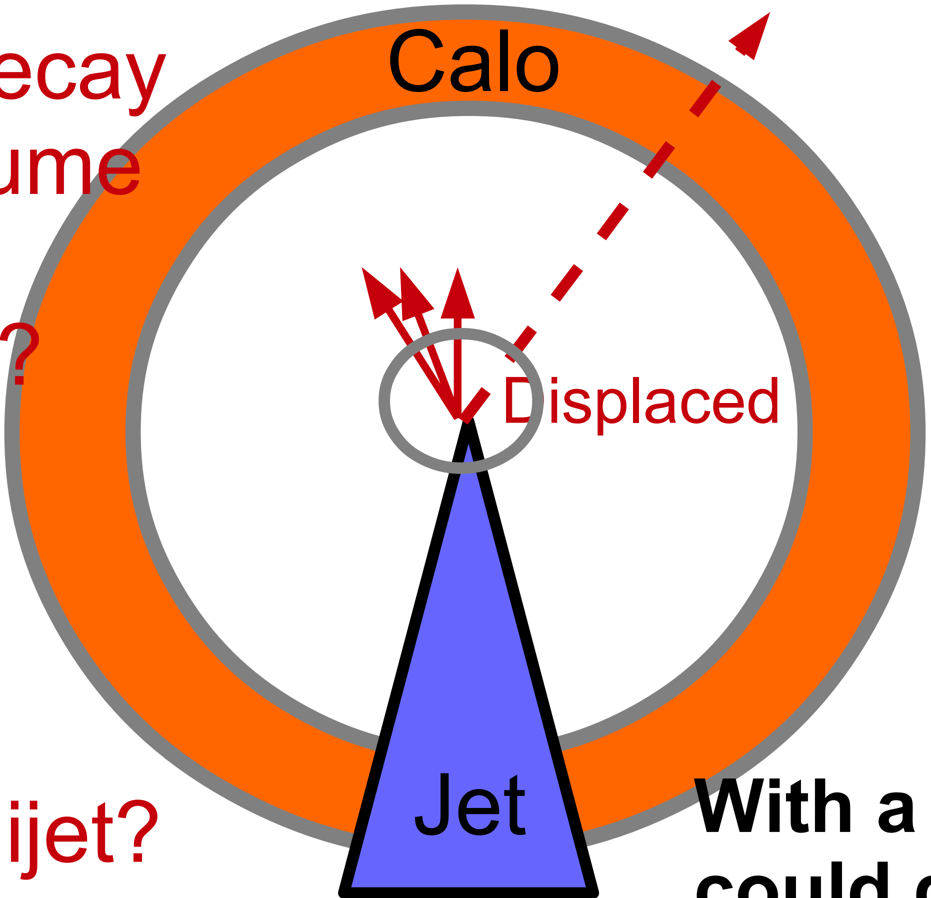
With a MET trigger at L1
Get this <u>but not great</u>

What about the trigger?

- 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

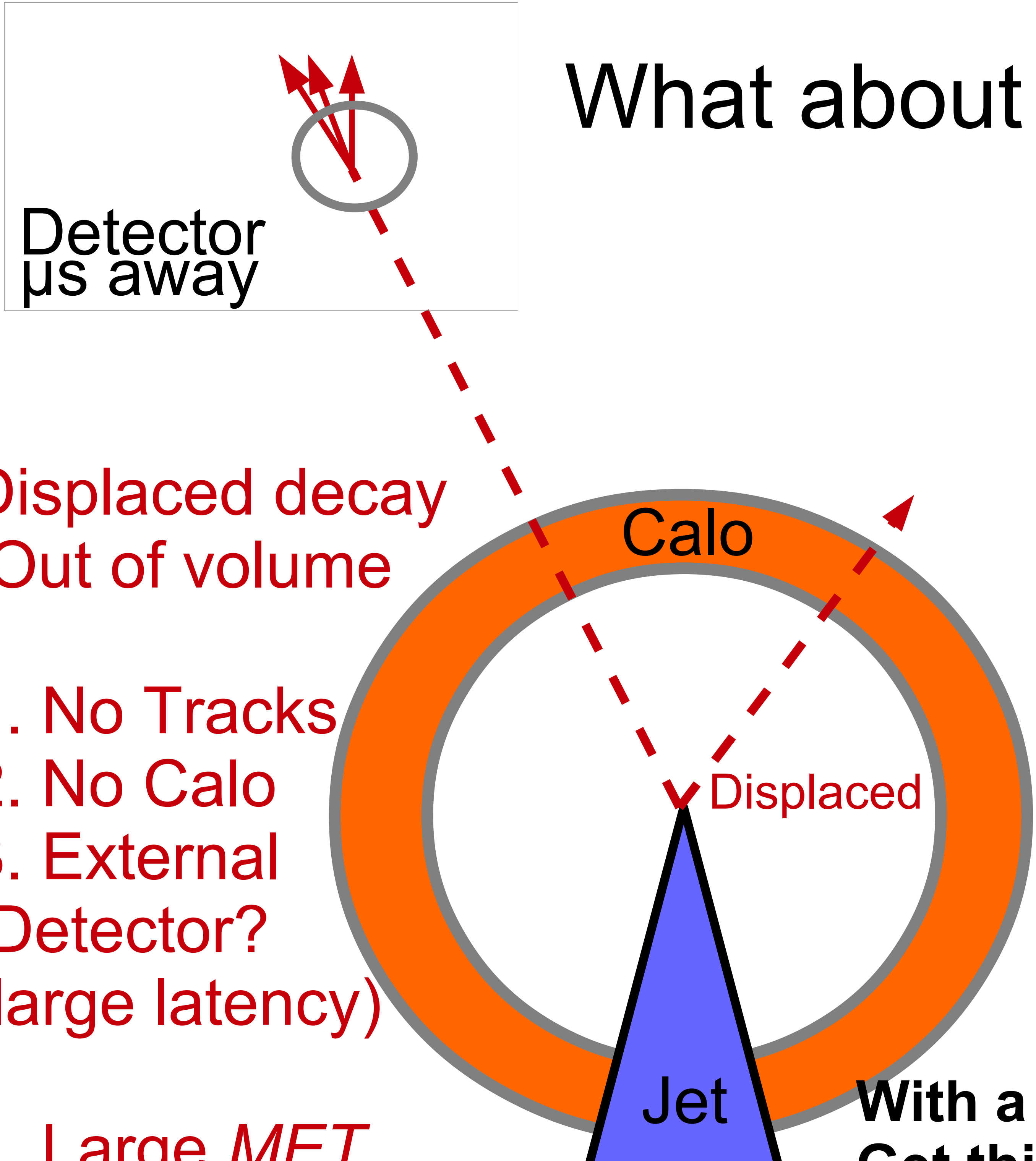


Displaced at L1 does not exist now

1. Strange dijet?

With a displaced L1 we could do thi

What about the trigger?



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

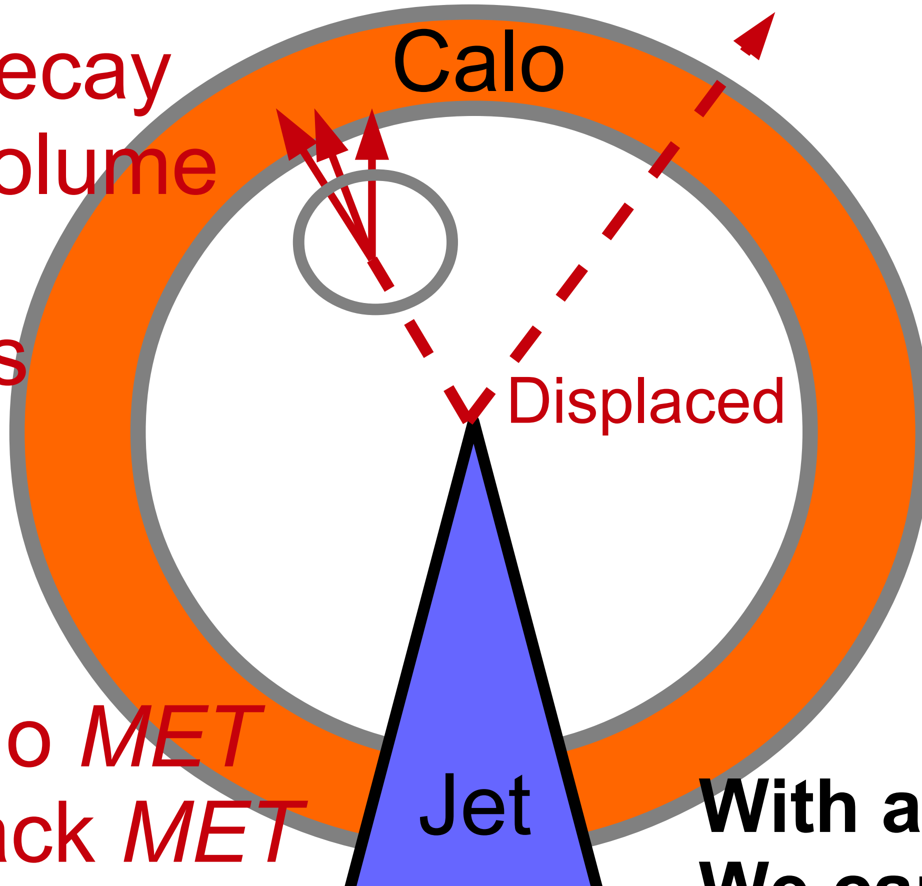
With a MET trigger at L1
Get this <u>but not great</u>

Current default: *MET* trigger

- 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



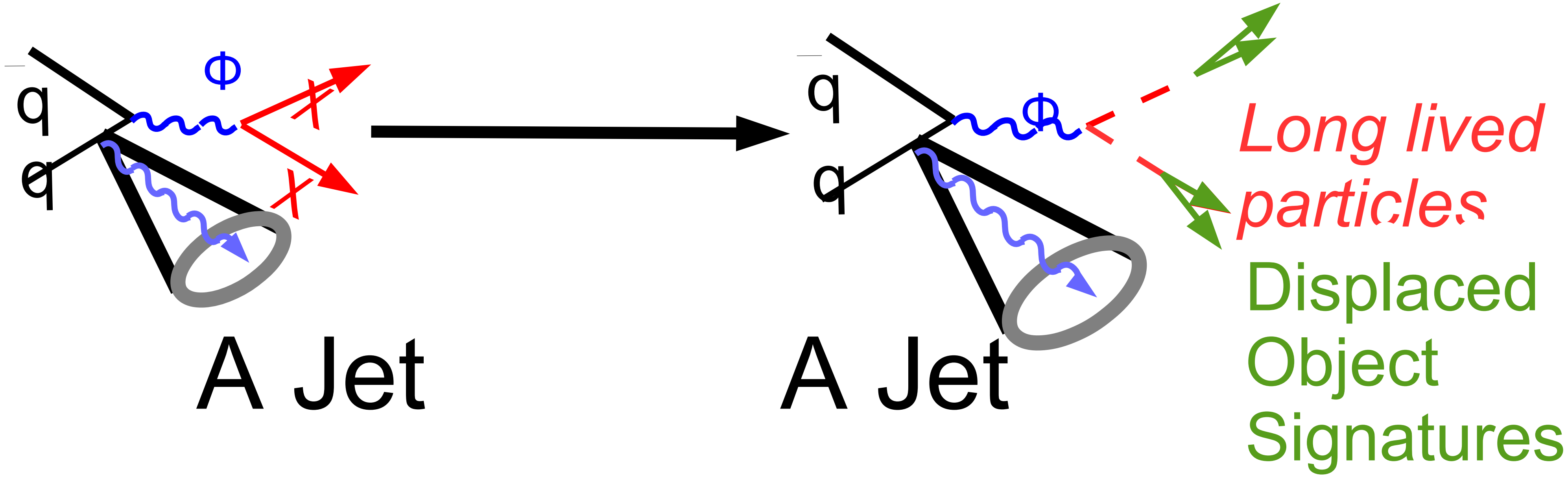
Special Trigger

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

With a track trigger at L1 We can probably get this

Part 2 : Implications of Long Lived Signatures

Dark Matter Search



From a dark matter perspective:

Transition from a dark matter to an LLP is natural

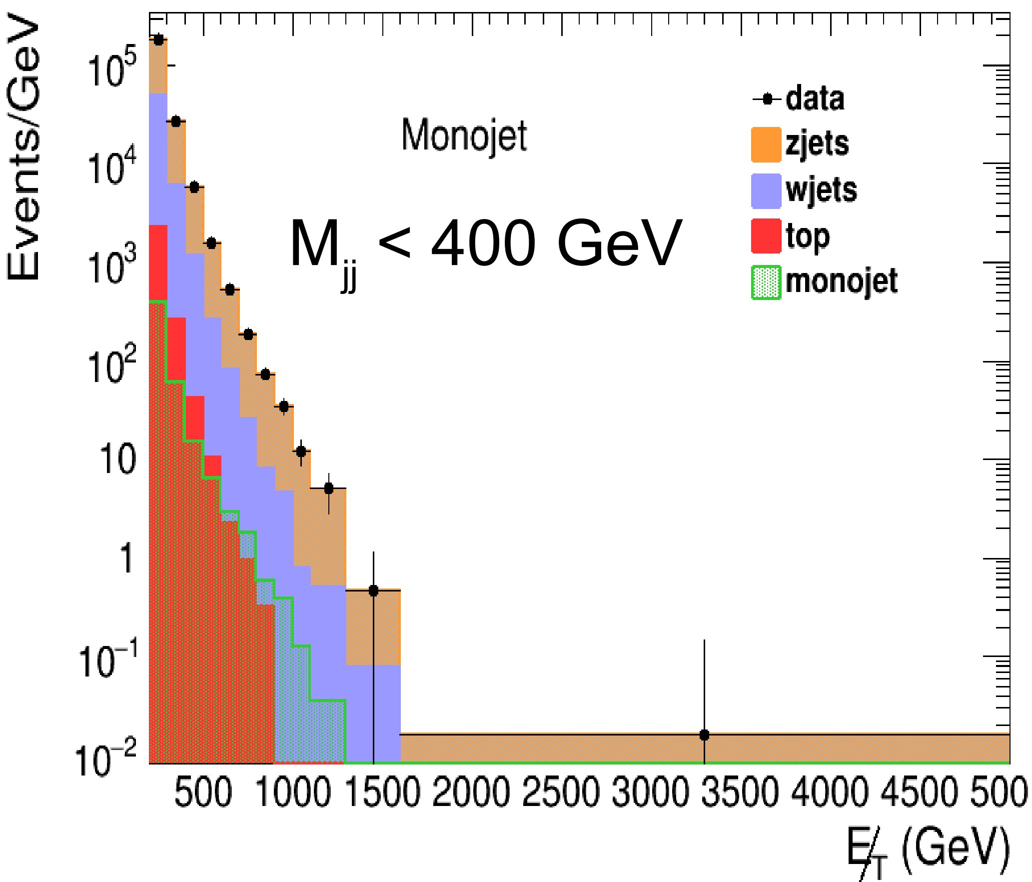
Great way to maintain relic density & bounds

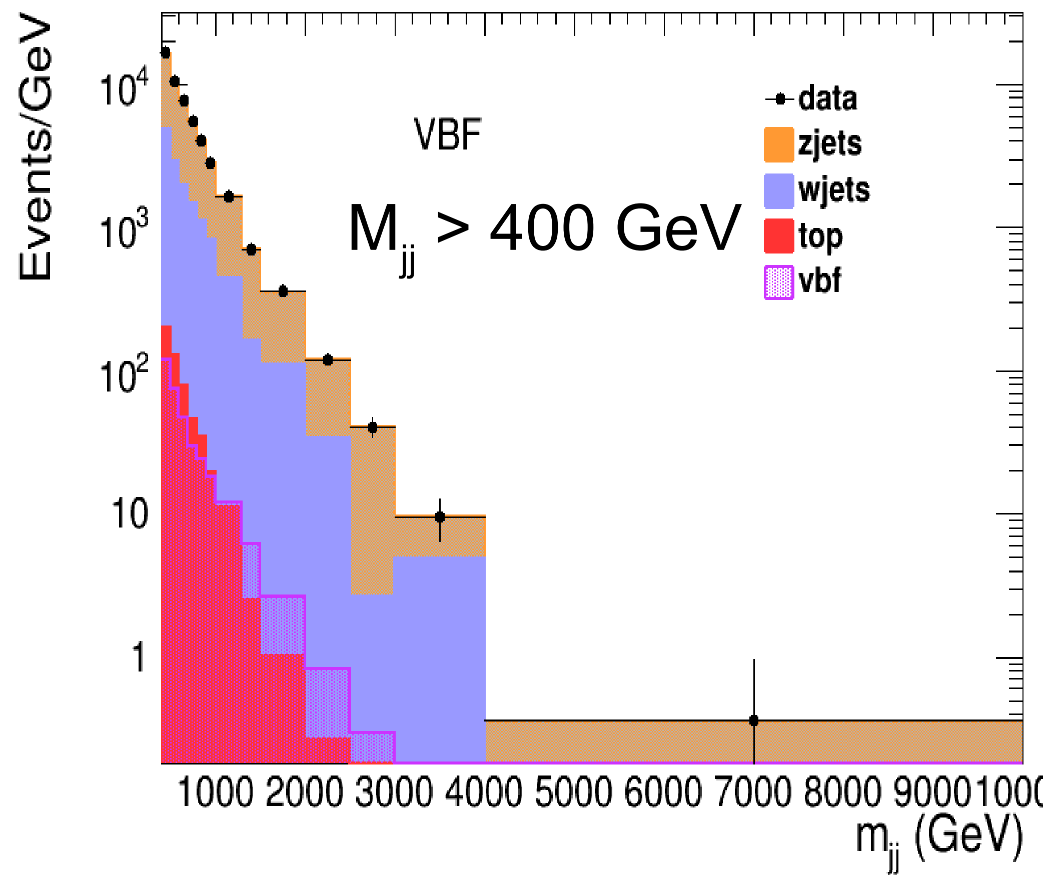
Many ways to extend the dark sector with LLPs

Take current DM searches and understand impact

The Classic Higgs to invisible

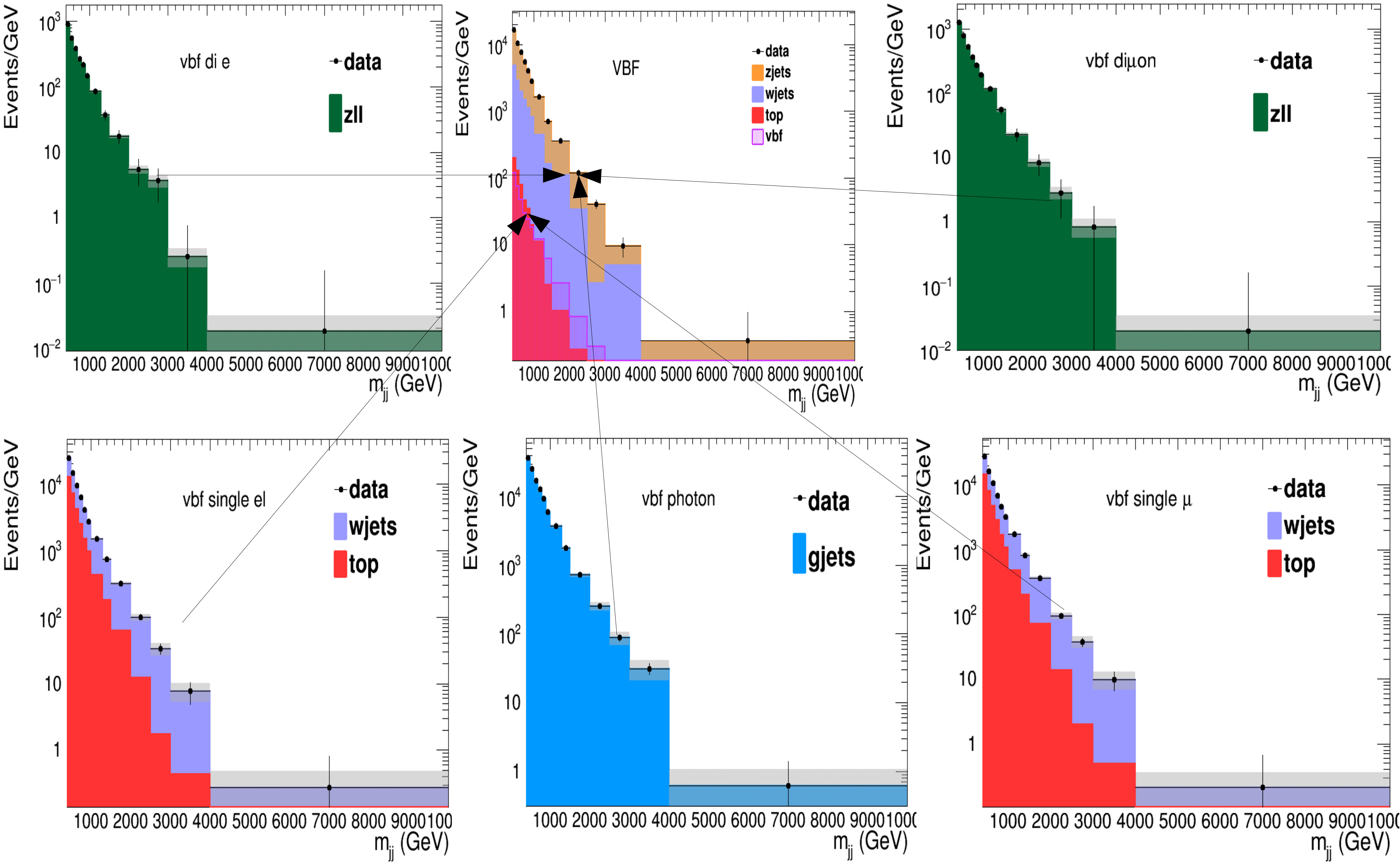
- Construct a modern version of Higgs to invisible
  - Dominant signal is VBF
  - Two category fit
  - Pre-selection: No leptons & *MET* > 200 GeV





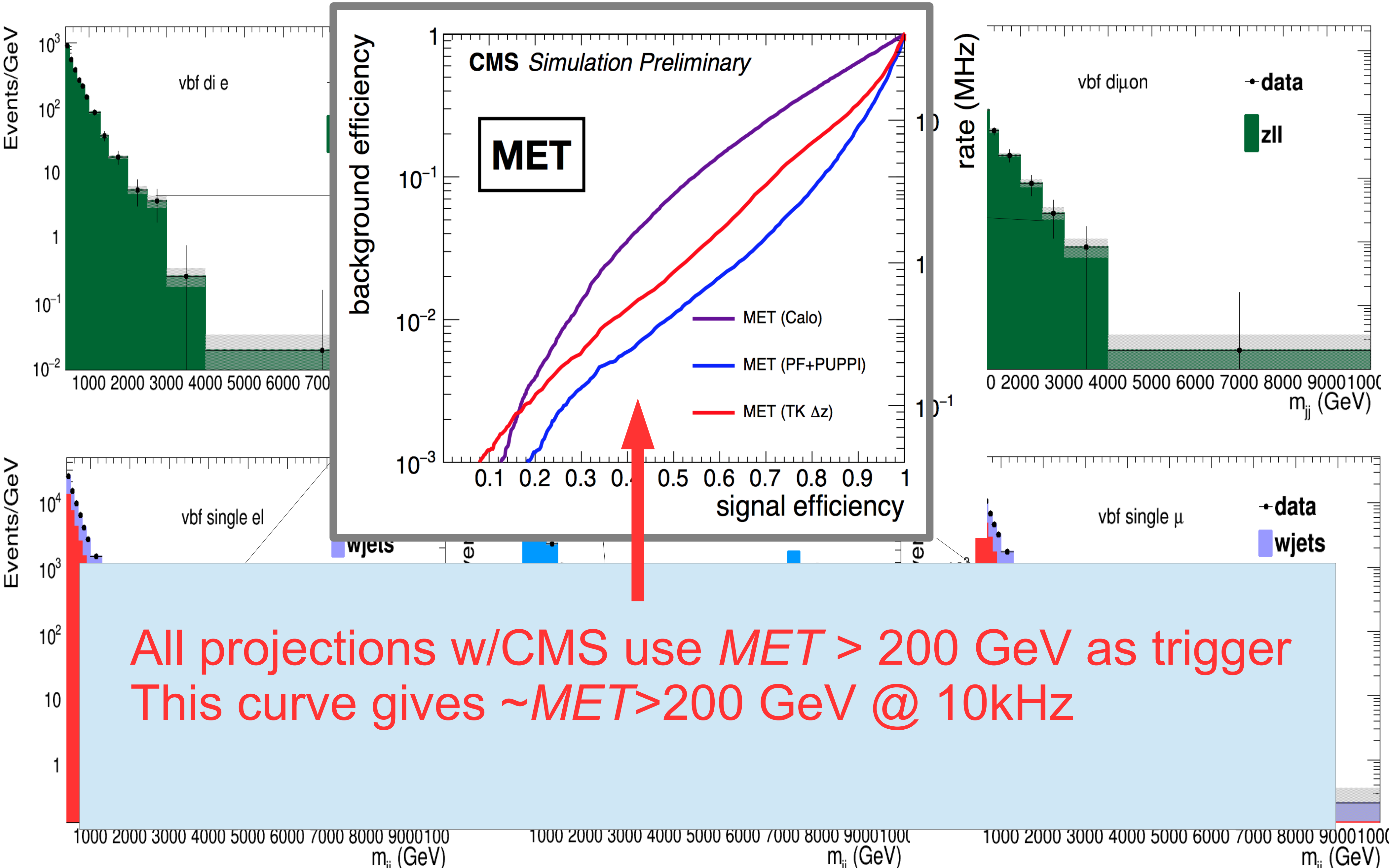
Fit each bin with a control region

Full Fit



Fit each bin with a control region

Full Fit

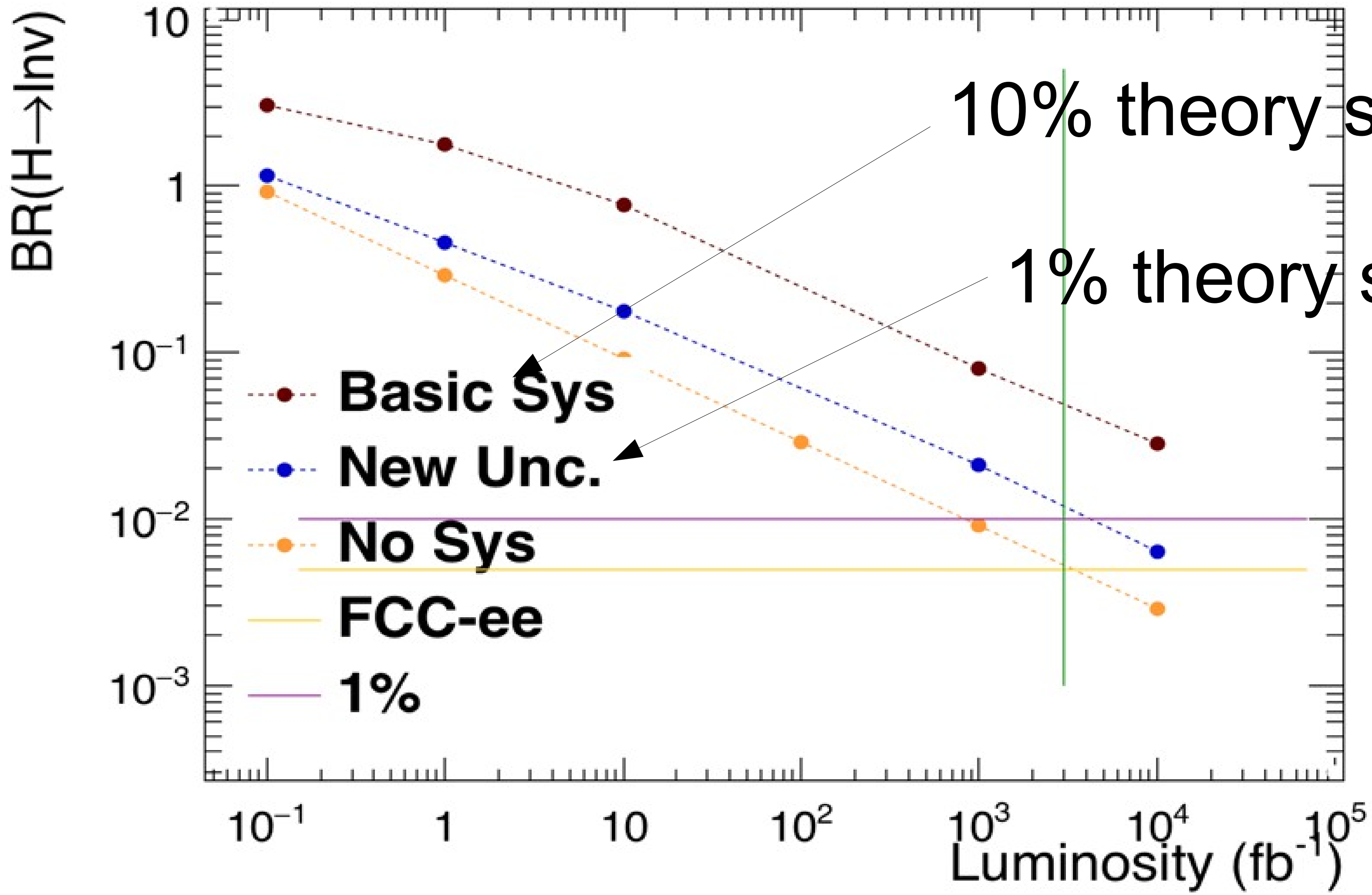


All projections w/CMS use *MET* > 200 GeV as trigger

This curve gives ~*MET*>200 GeV @ 10kHz

How does it look?

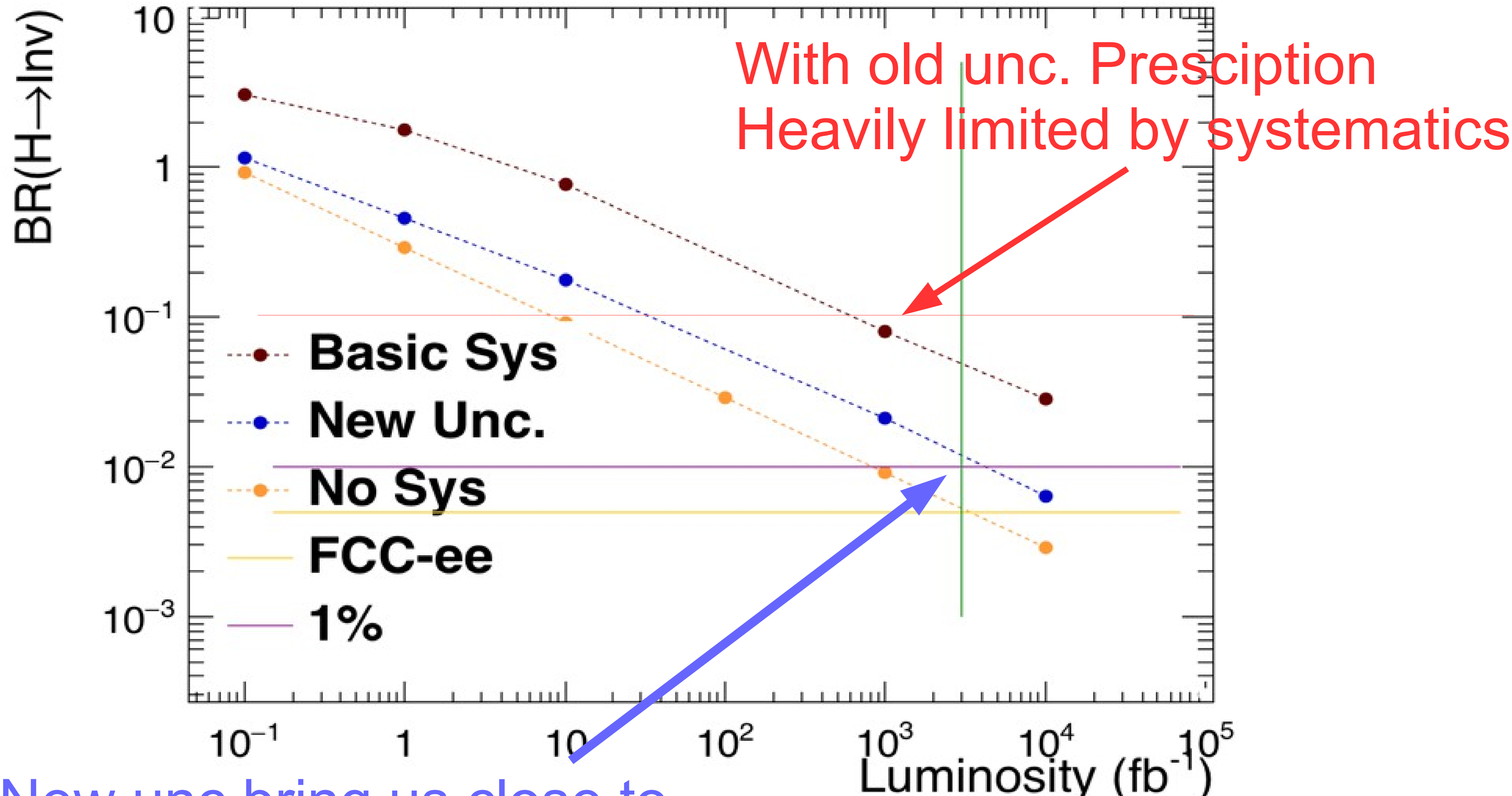
- Higgs Invisible propagated through



Hit 1% with the full unc. Scheme and 3 ab^{-1}

How does it look?

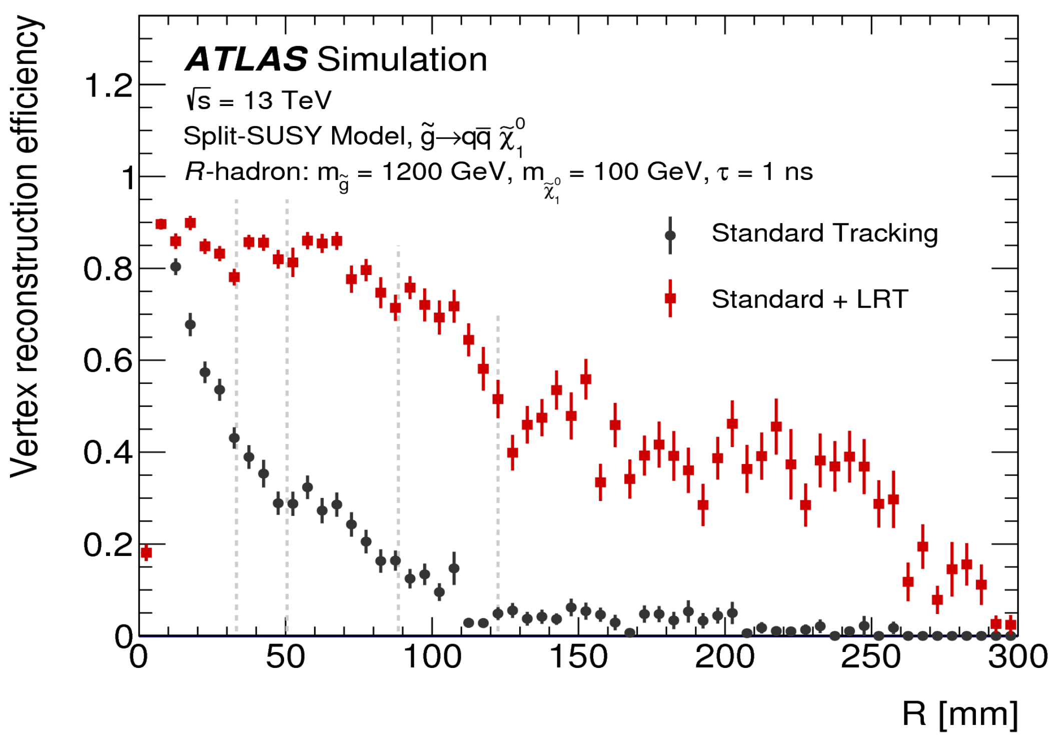
- Higgs Invisible propagated through

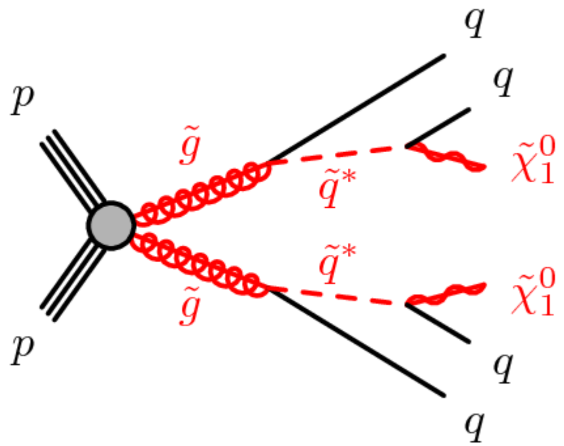


New unc bring us close to
Ulitimate sensitivity

Case #1: a long lived signature

- Follow ATLAS approach **_MET > 250 GeV_**
  - SUSY-2016-08 :
    - Search for LLP with displaced vertices + *MET*
  - *MET* triggered events + displaced vertex tag
    - Cut tight on vertices to have almost 0 bkg events

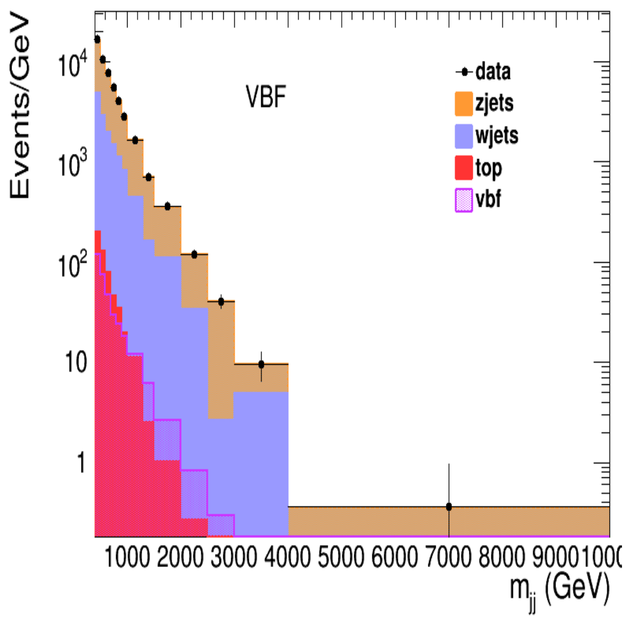




Requiring a secondary vertex alone with 3 tracks and mass > 10 GeV reduces background by 3 orders of magnitude

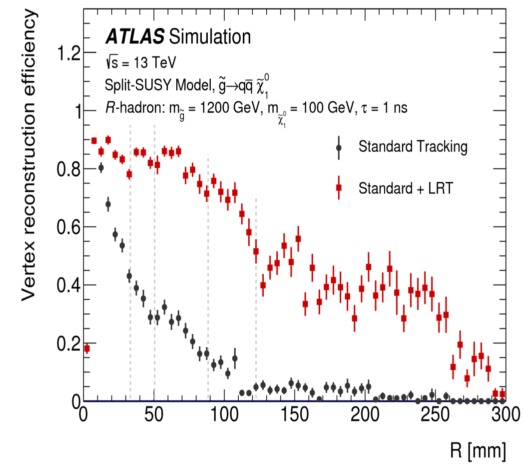
Constructing an LL analysis

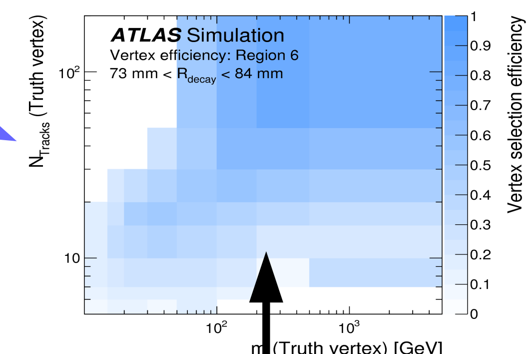
- Can recast the dark matter searches



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

Preselection





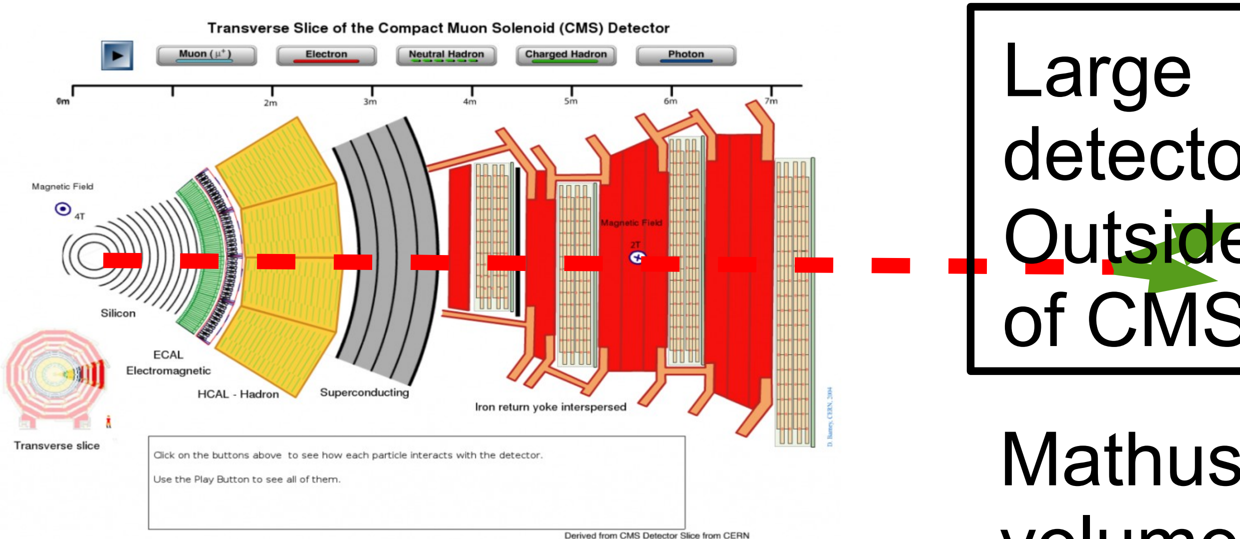
Efficiency map given lifetime

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

Case #2: Mathusla signature

- Follow conventional Mathusla approach
  - Take the same signal model
  - Assume zero background
  - Count number of Mathusla interactions
  - If interactions greater than ≥ 4 then exclude

Compute the probability for this



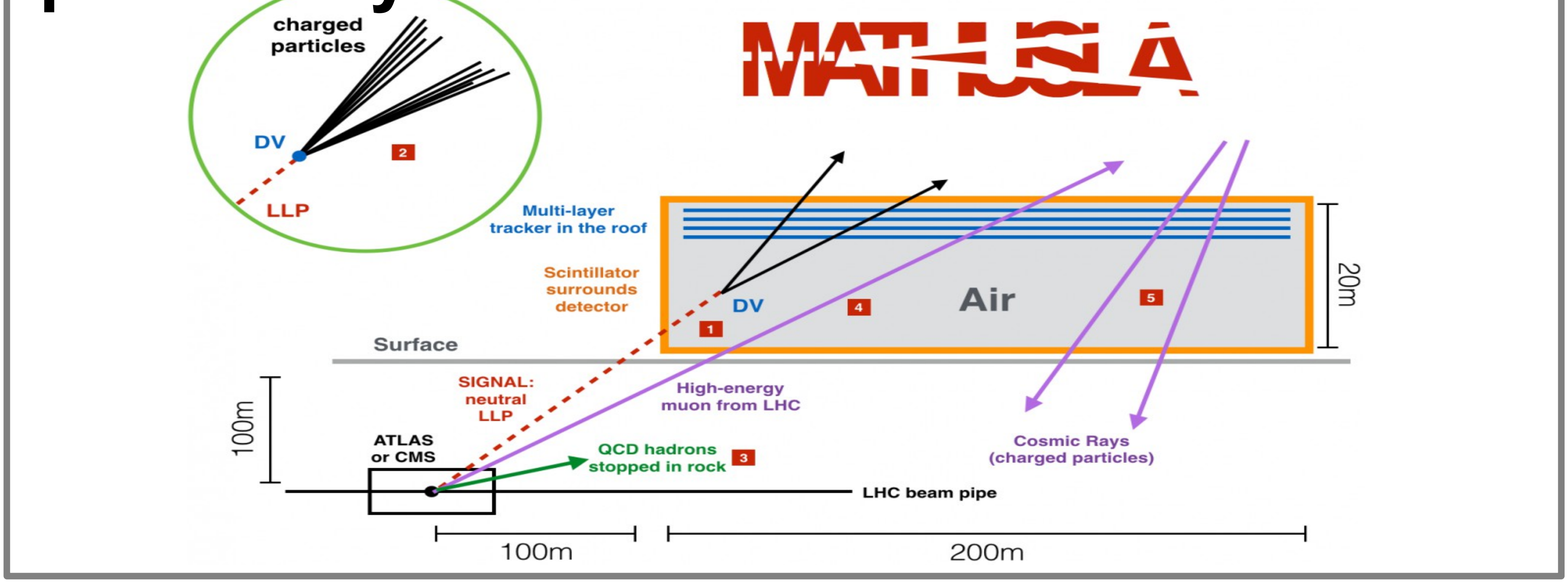
Large detector Outside of CMS

Mathusla Large volume

Case #2: Mathusla signature

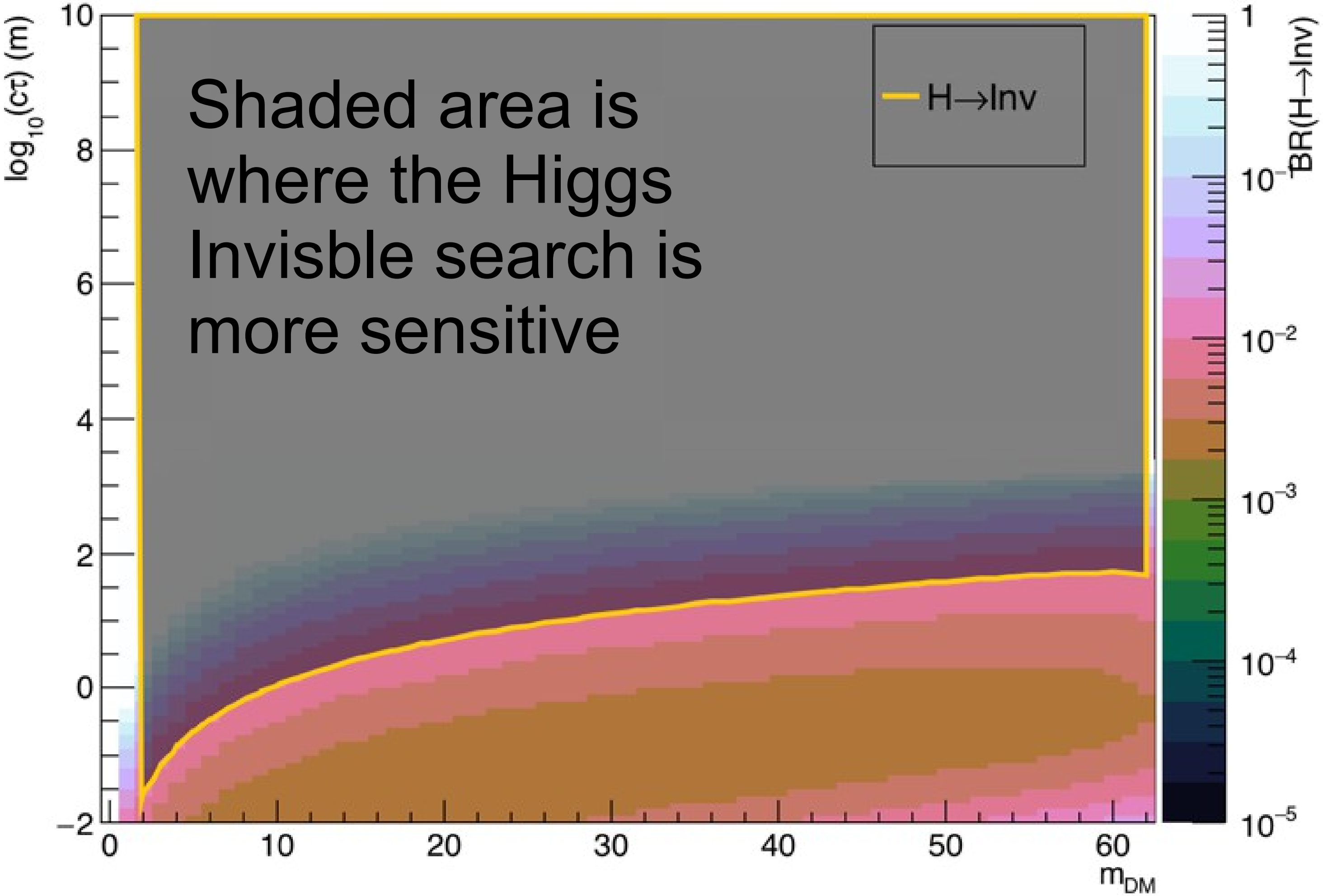
- Follow conventional Mathusla approach
  - Take the same signal model
  - Assume zero background
  - Count number of Mathusla interactions
  - If interactions greater than ≥ 4 then exclude

probability



Lifetime Bounds w/Tracker

- Higgs Invisible in with a decay in tracker



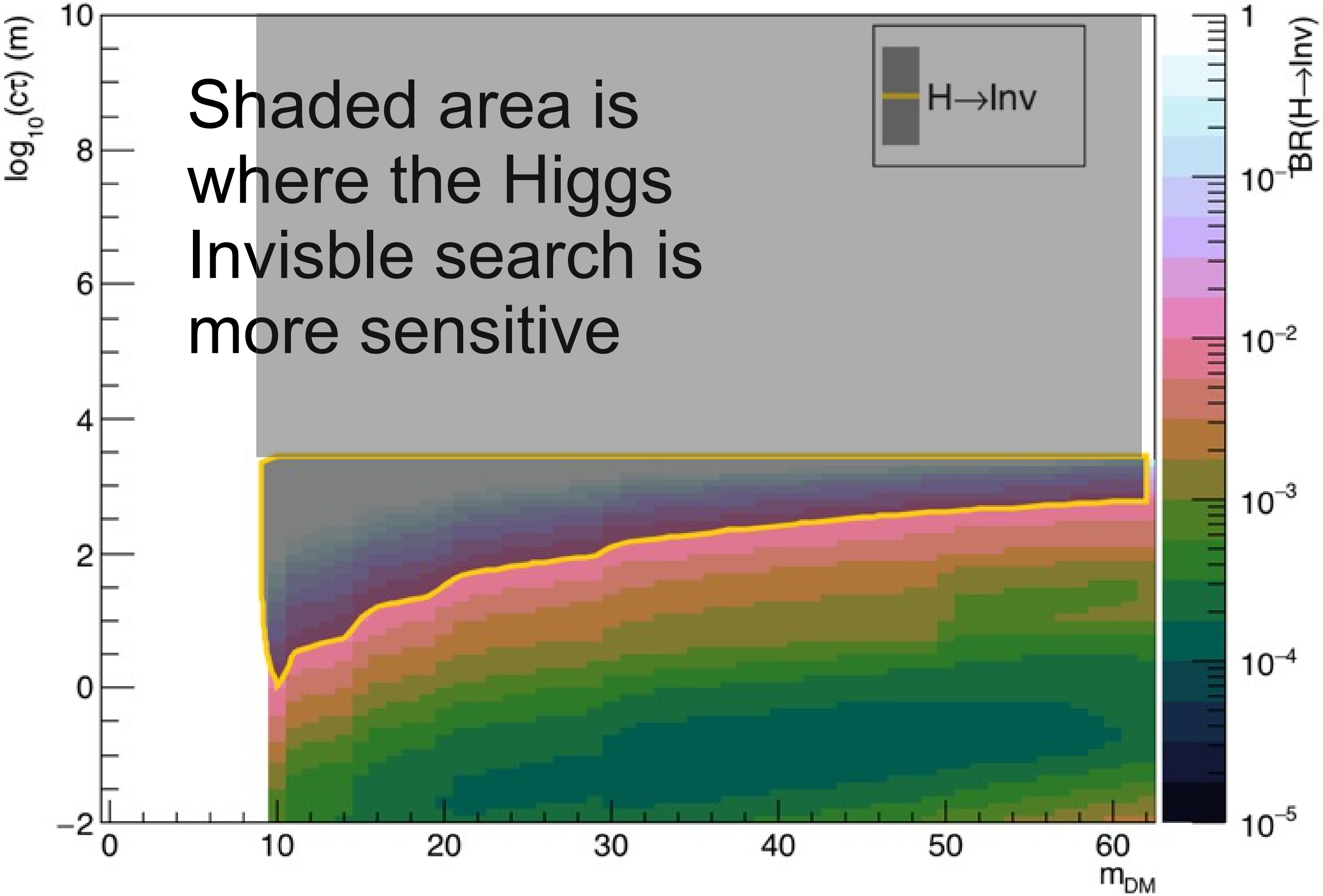
This result is
With the
preselection only

10-3

Covers the lower range beyond H→Inv (10^{-3})

Lifetime Bounds w/Tracker

- Higgs Invisible in with a decay in tracker



Shaded area is where the Higgs Invisble search is more sensitive

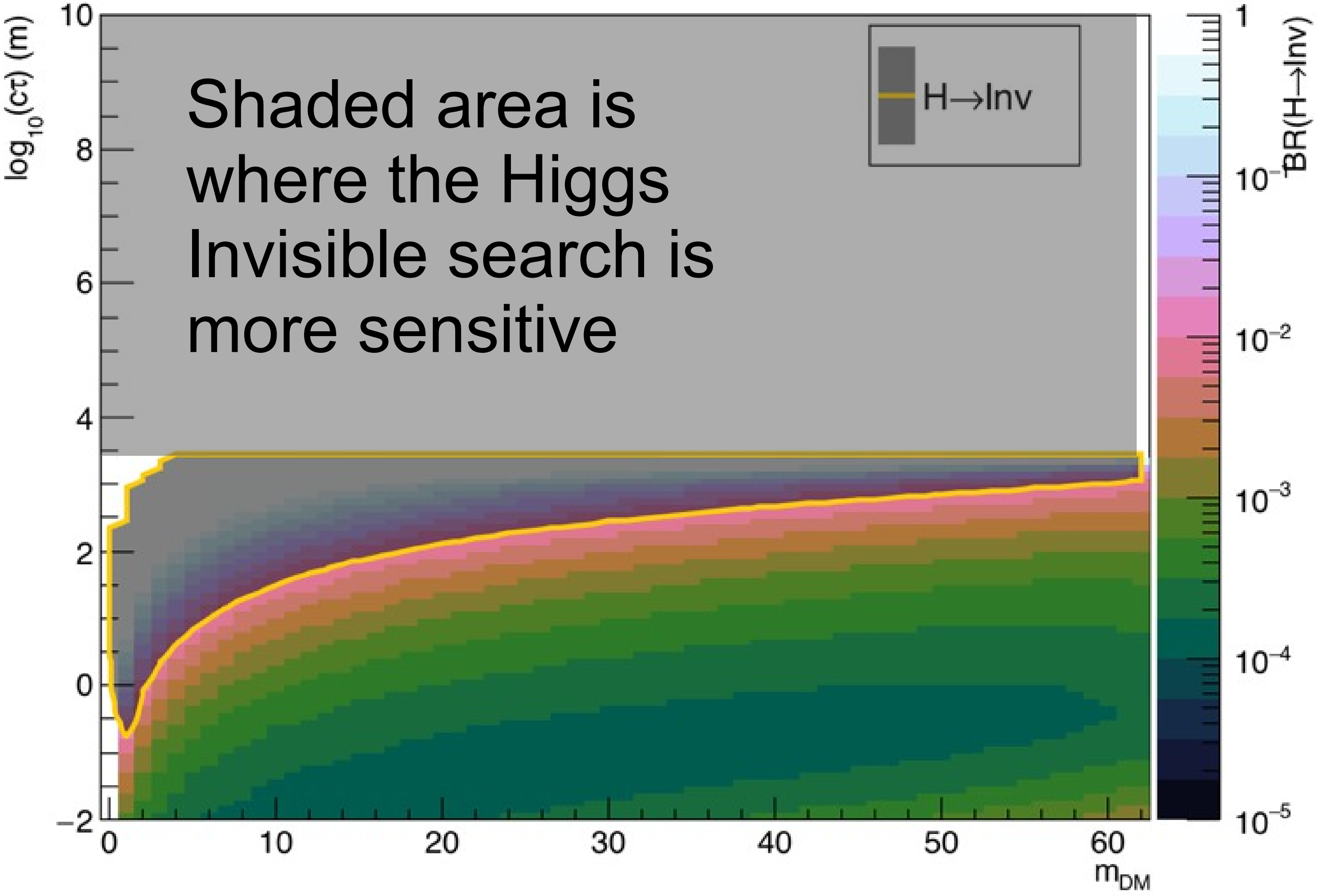
This result is With the full selection &parametrization

10-4

Covers the lower range beyond H→Inv (10^{-3})

Lifetime Bounds w/Tracker

- Higgs Invisible in with a decay in tracker

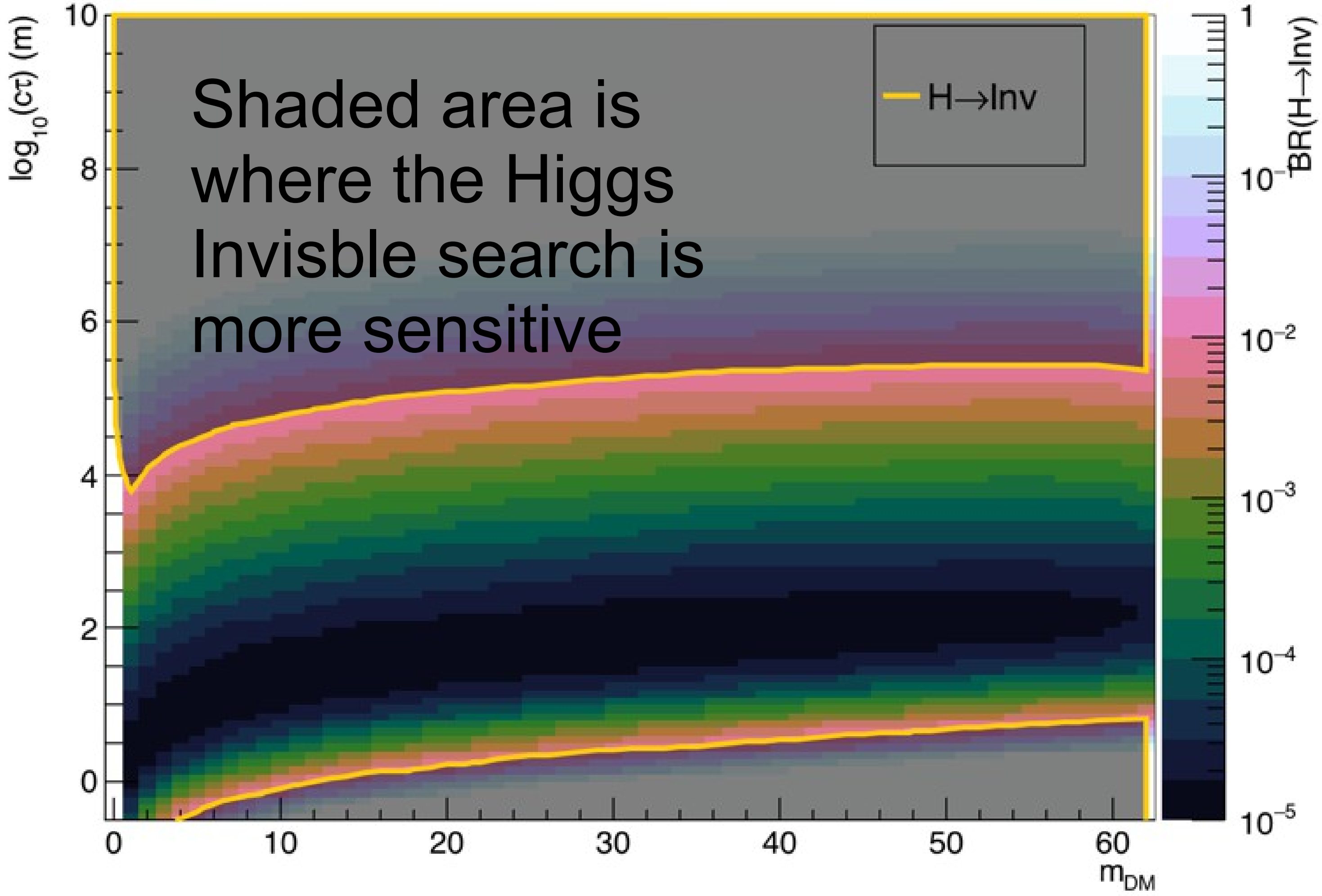


This result is With the full selection & modifed Parametrization That goes to 0 10-4

Covers the lower range beyond H→Inv (10^{-3})

Lifetime Bounds w/Tracker

- Higgs Invisible in with a decay in tracker



This result is With the preselection only

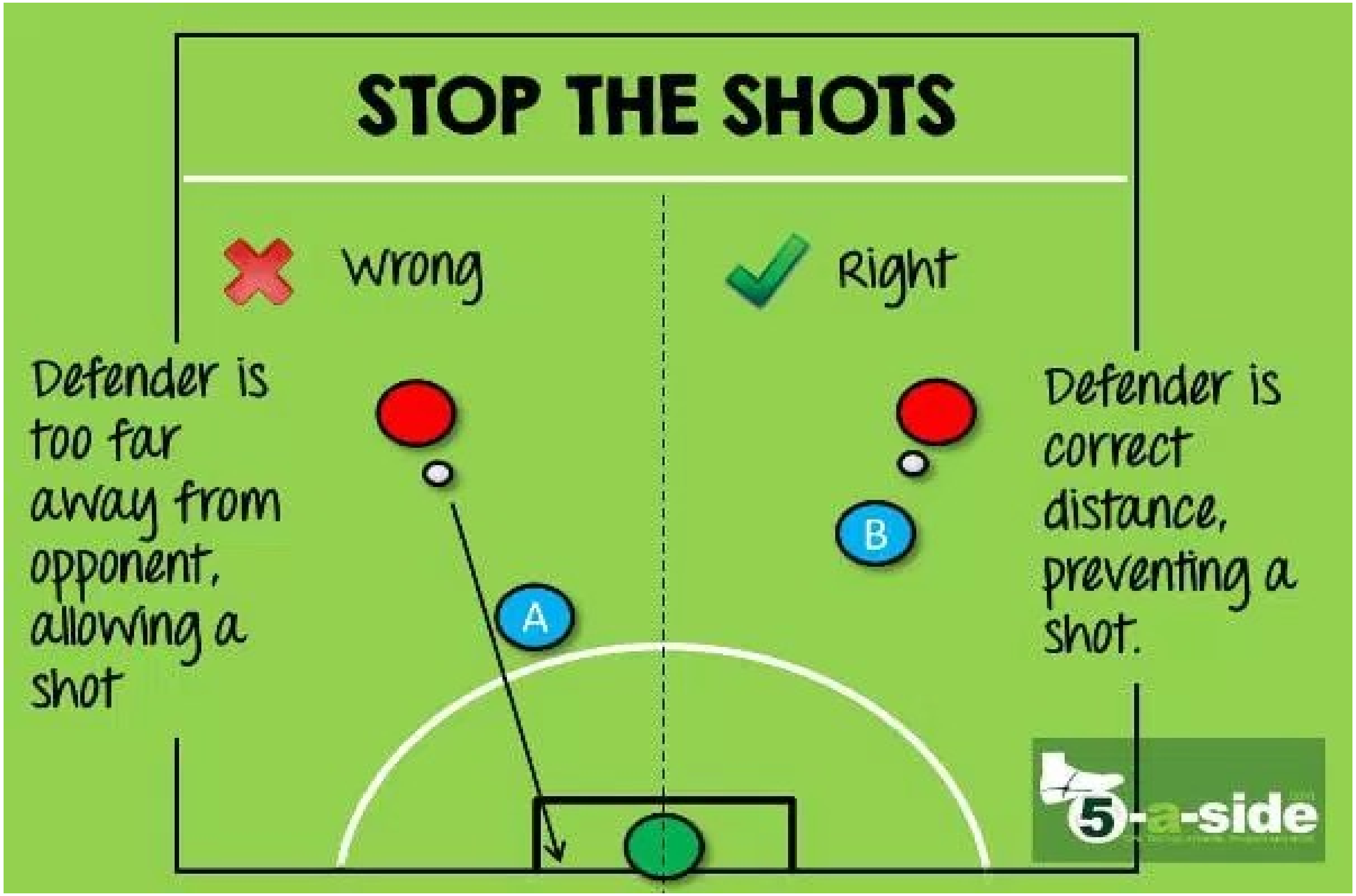
10-5

Covers the lower range beyond H→Inv (10^{-3})

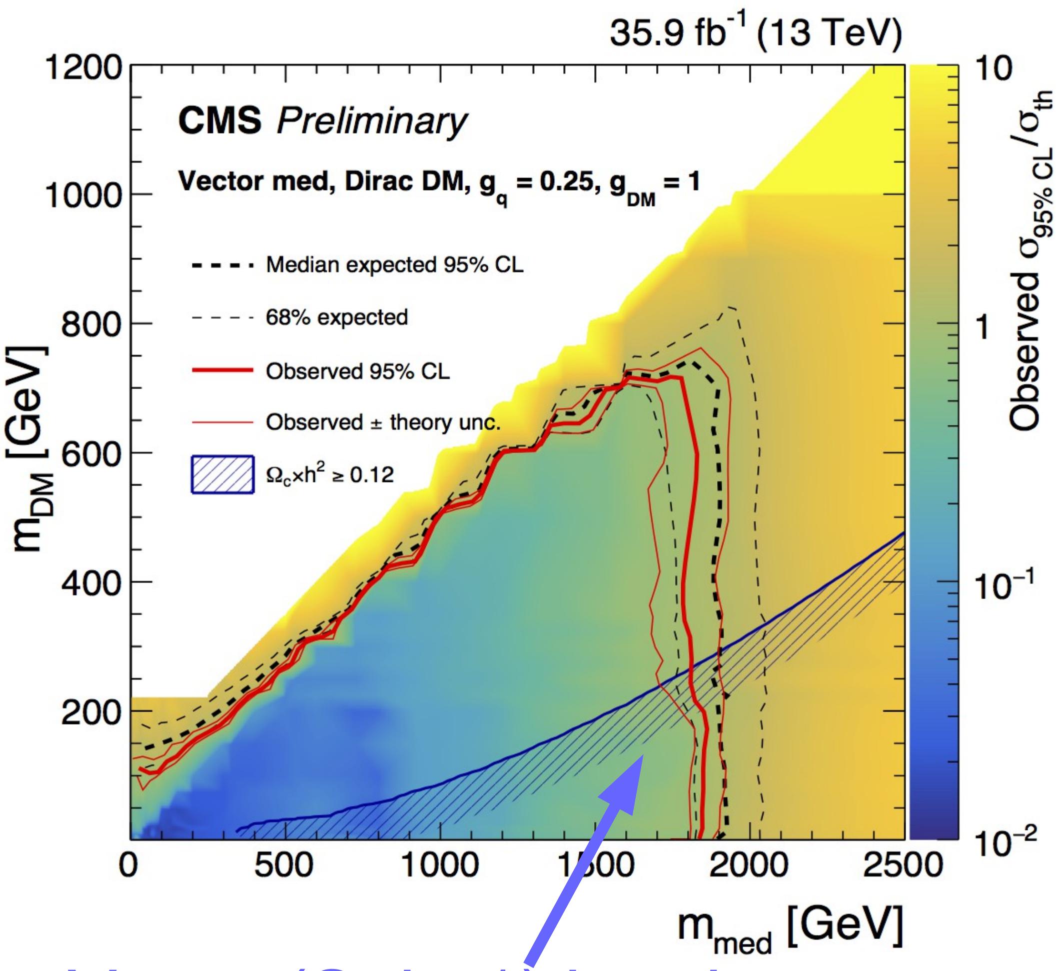
Fate of the LIfetime

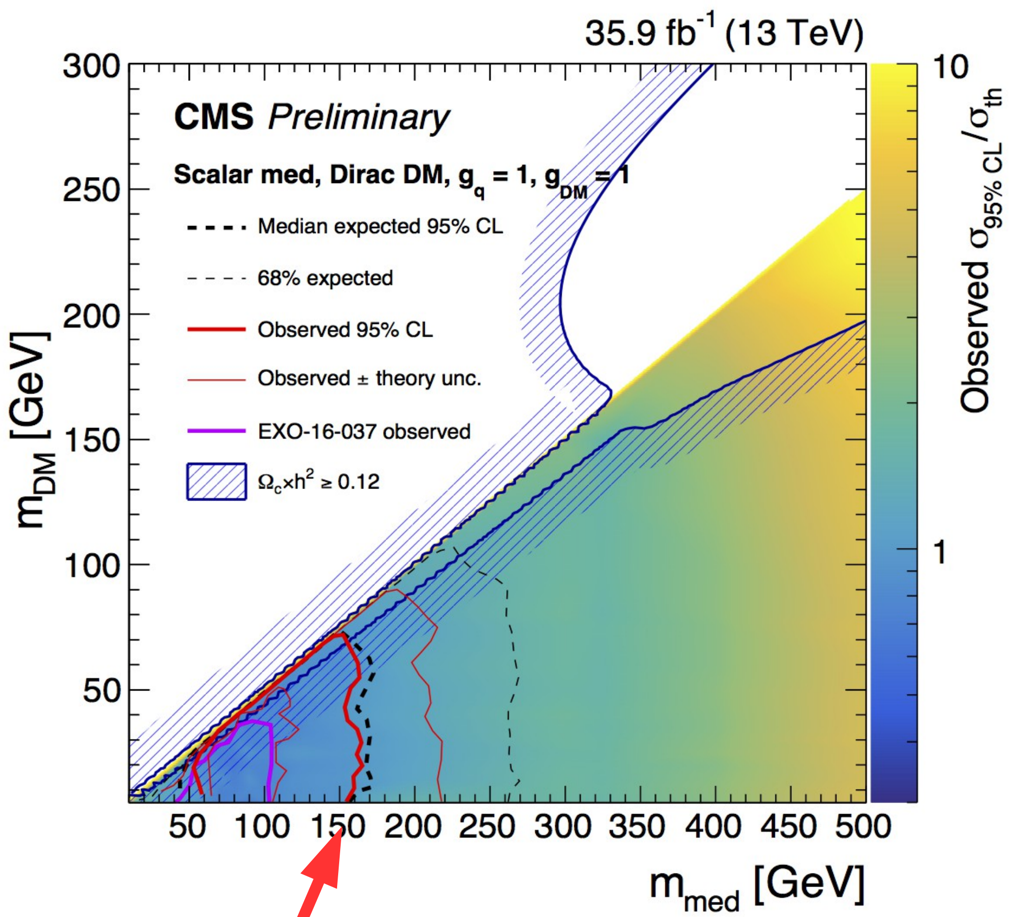
- With higgs to invisible as a benchmark
  - Can probe coefficients down to very small values
  - Detector like Mathusla reaches order of mag more
    - What if we have full trigger acceptance for others?
    - In principle acceptance can increase significantly
    - How important are out of volume detectors?
- Triggers for long lived searches possible?
  - Projects listed have been motivated by *MET* trigger
  - Can we build a more sophisticated trigger?
- Is Mathusla the appropriate volume?

Where to put a detector?



What about other DM models?





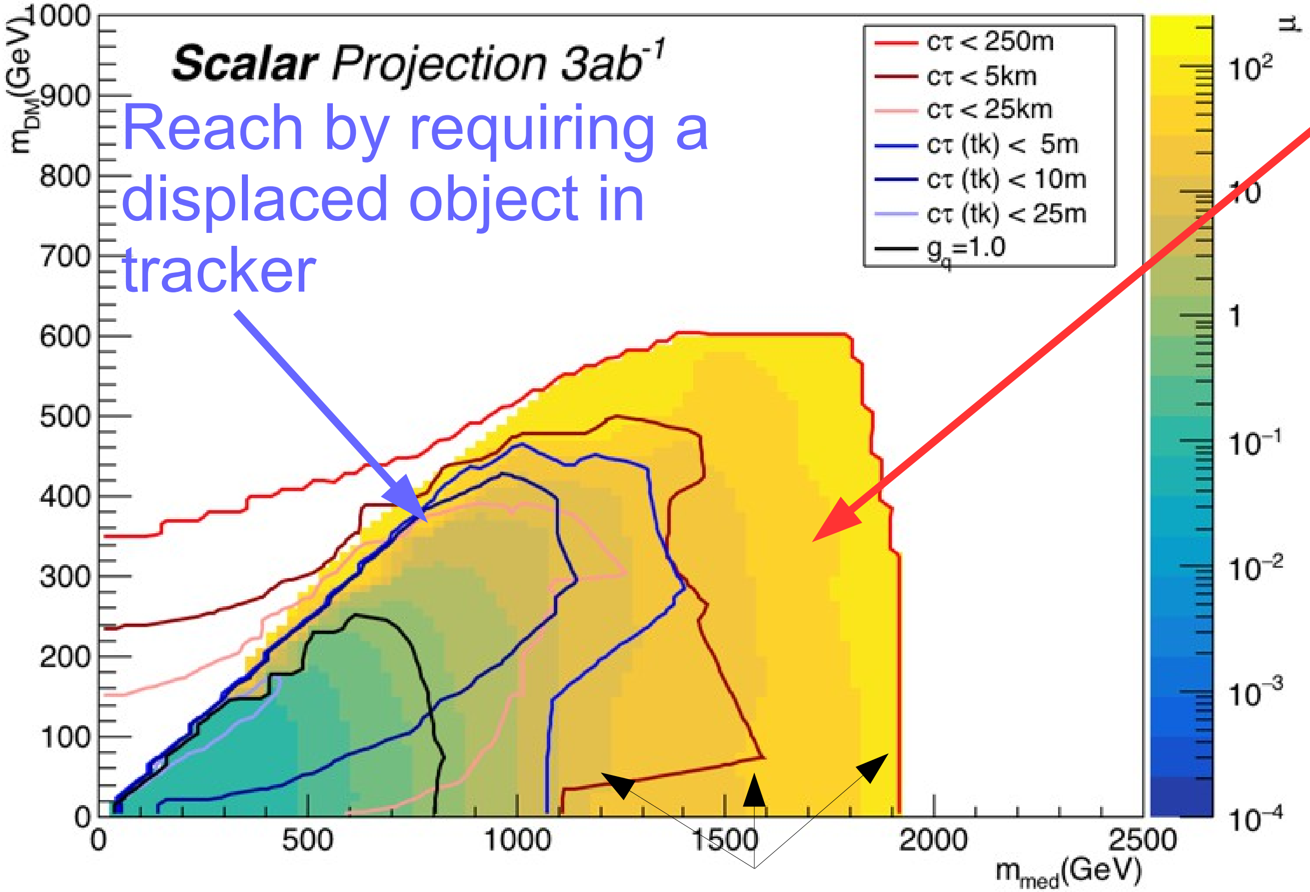
Vector(Spin 1) has been pushed out far and is well covered by monojet and dijet

Scalar and pseudoscalar models are just starting to be excluded

Scalar Simplified models: $3ab^{-1}$

- Scalar Bounds
  - Similar gains for Higgs invisible

Reach by requiring a displaced object in the MATHUSLA detector



In the low mass region

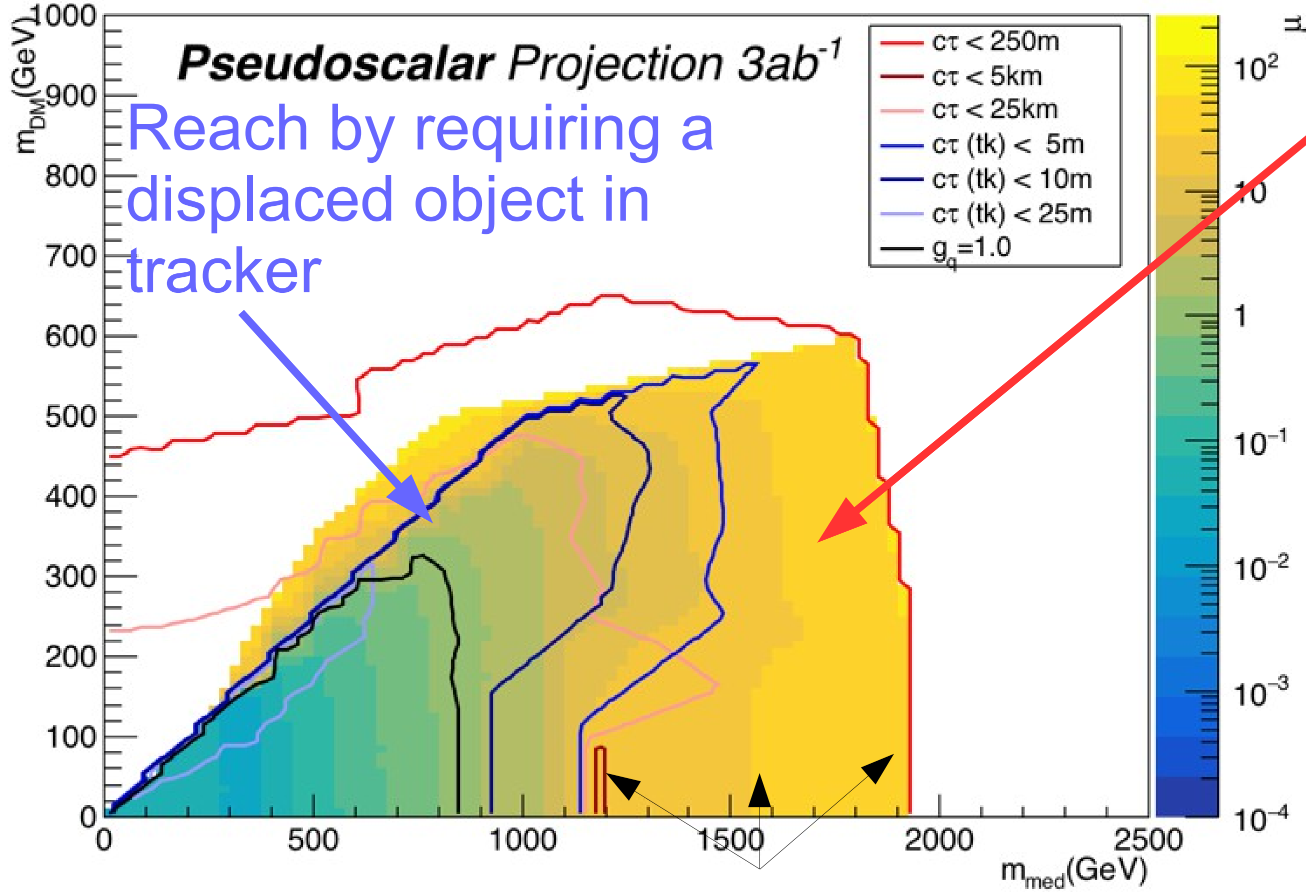
Note: interpolation error these should curve down

gains from LL searches more important (@high mass its less)

Pseudoscalar models: $3ab^{-1}$

- Pseudoscalar Bounds
  - Stronger bounds than scalar

Reach by requiring a displaced object in the MATHUSLA detector



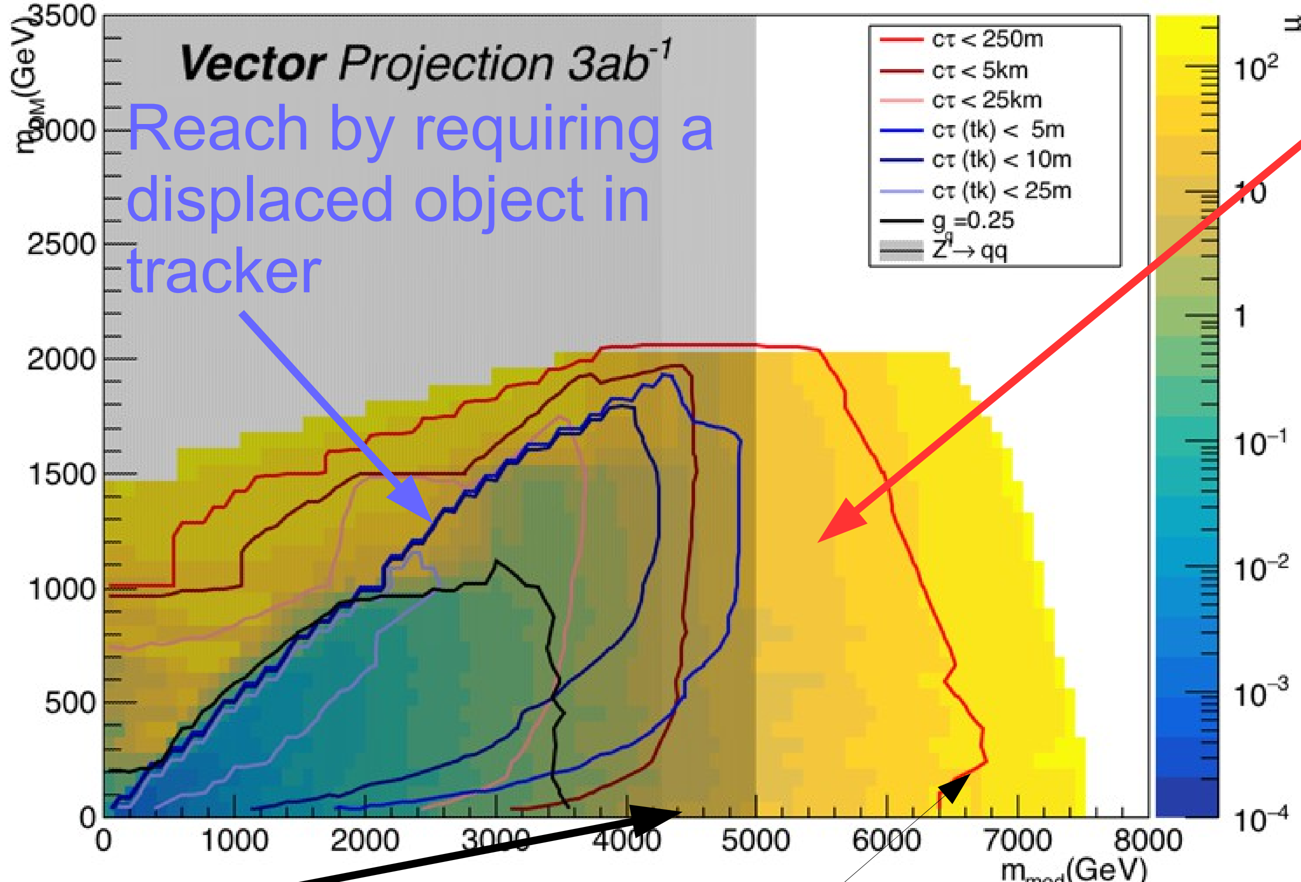
Note: interpolation error these should curve down

Tracker based displaced vertices can pus out beyond a TeV

Vector Simplified models: $3ab^{-1}$

- Vector Bounds
  - Now contend with dijet bounds

Reach by requiring a displaced object in the MATHUSLA detector



Dijet bounds

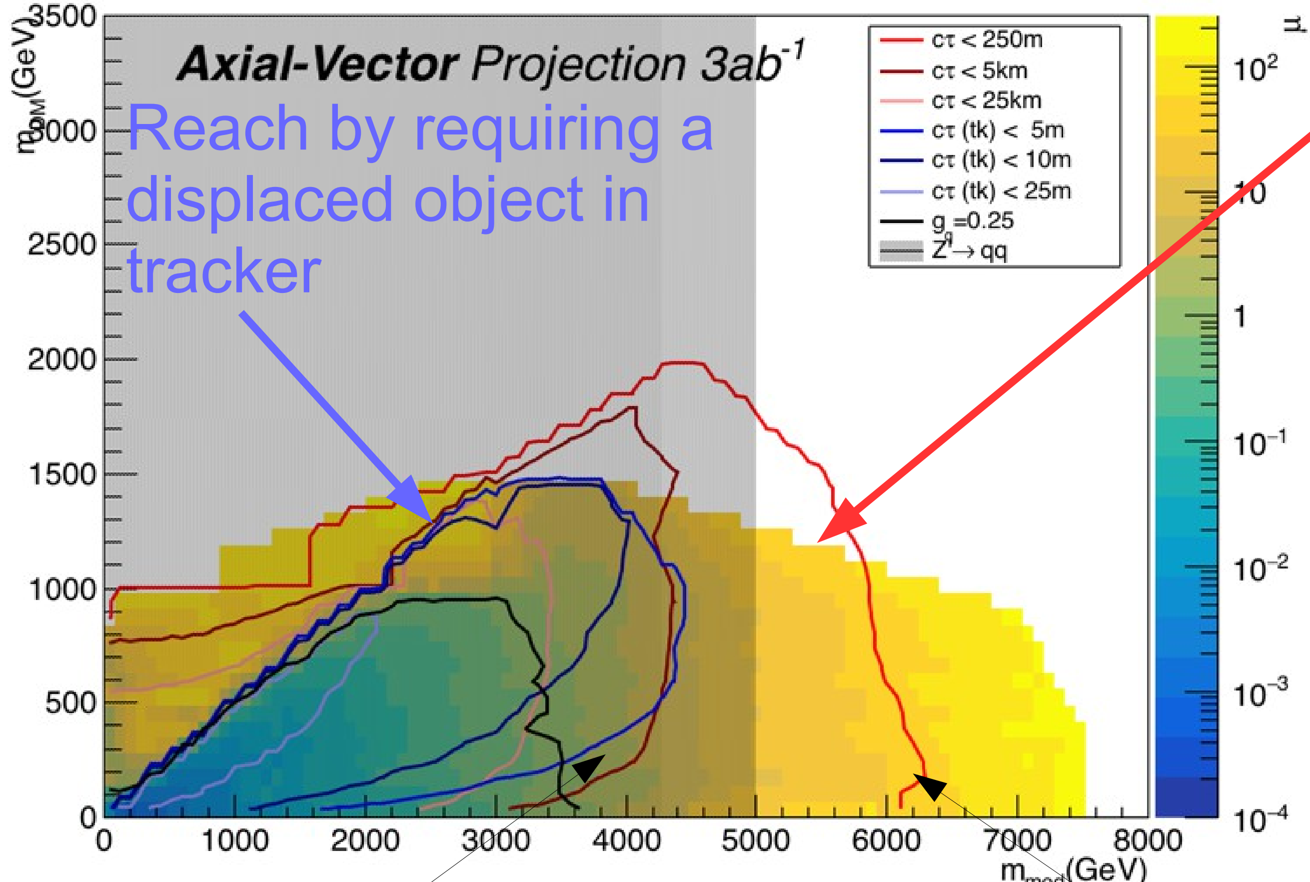
Note: interpolation error these should curve down

MATHUSLA can exceed bounds from dijet

Axial-Vector Simplified models: $3ab^{-1}$

- Axial-vector Bounds
  - Have to contend with dilepton

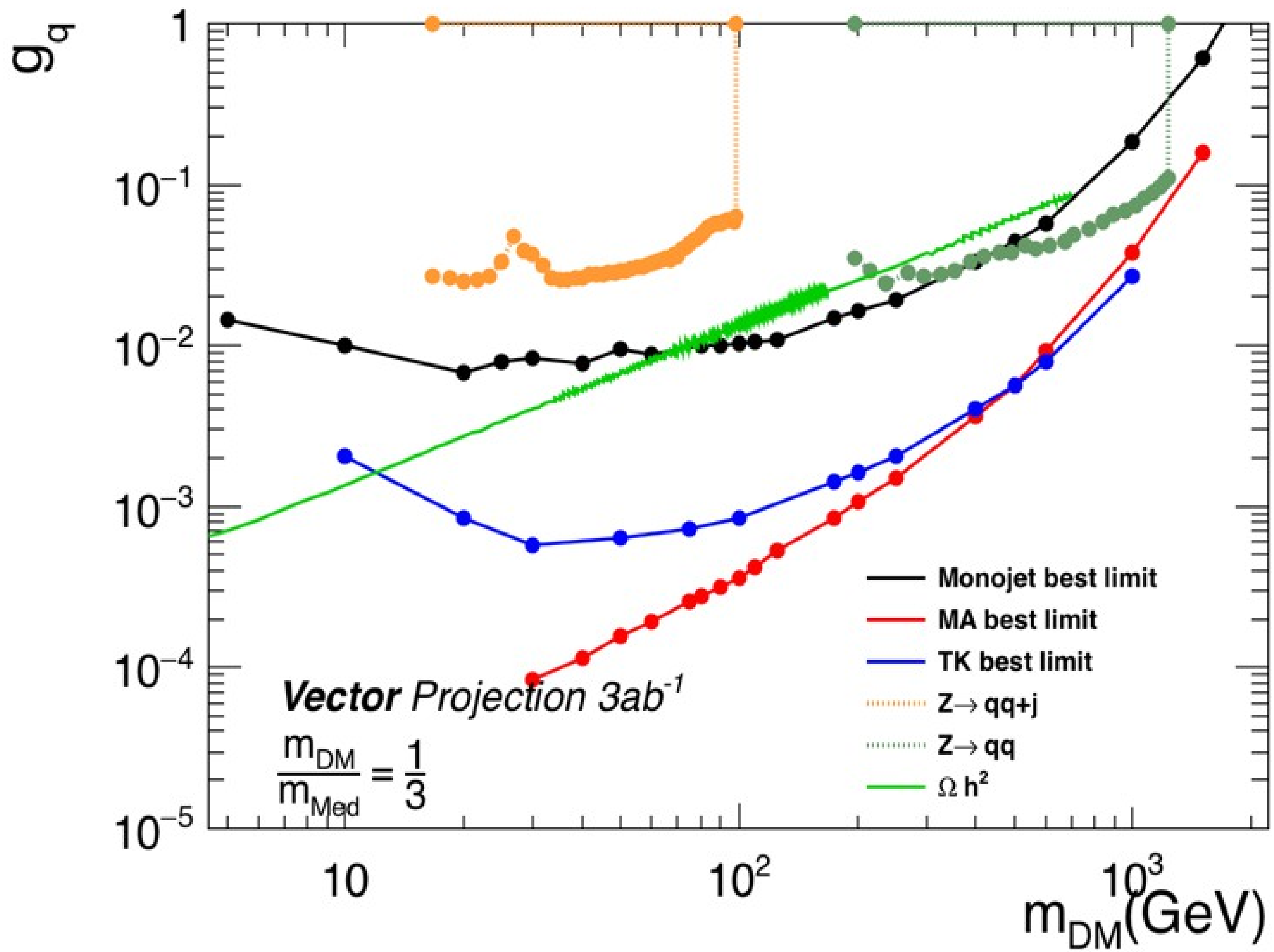
Reach by requiring a displaced object in the MATHUSLA detector



Dijet bounds

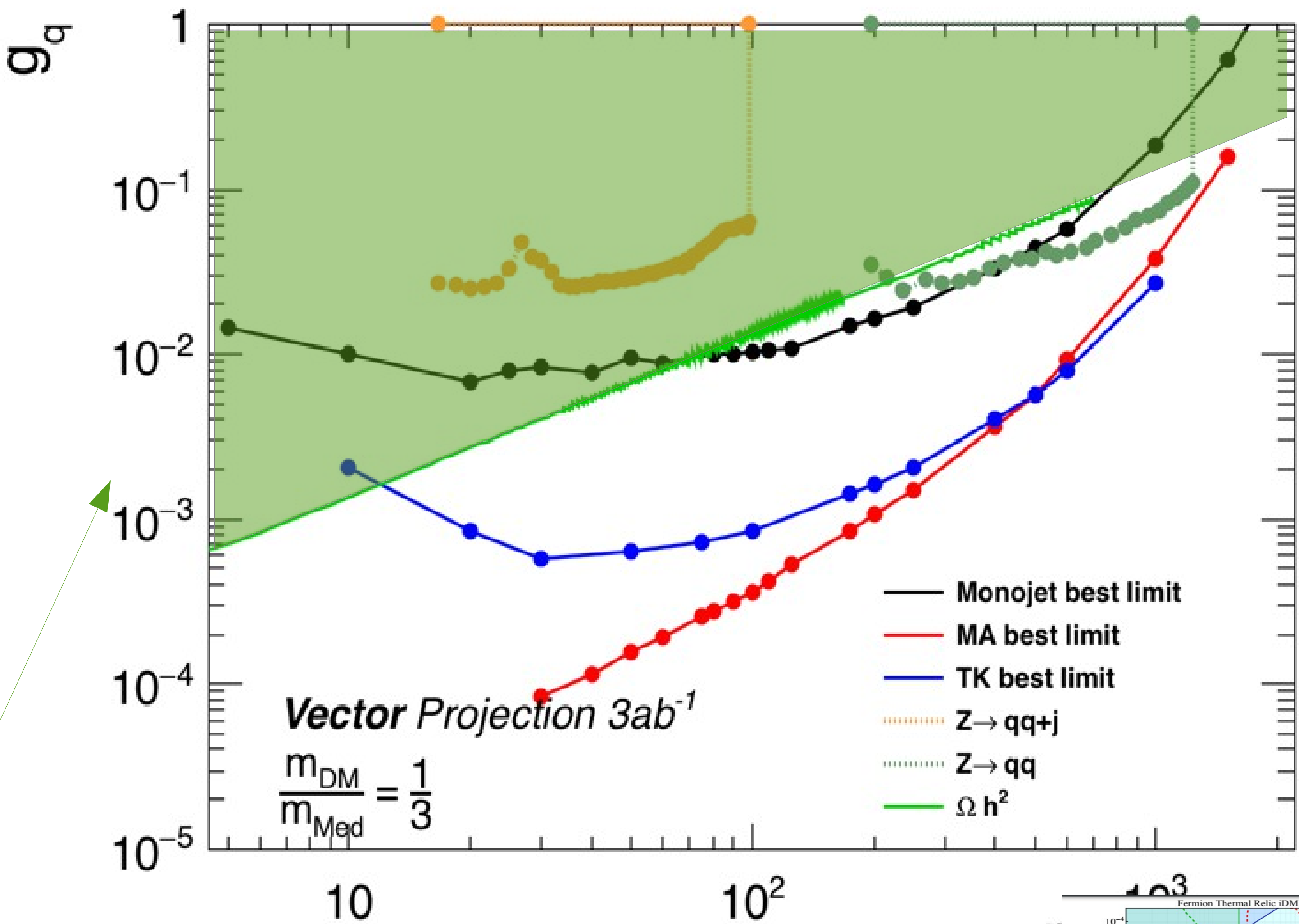
Dilepton bounds will go to roughly 6-7TeV

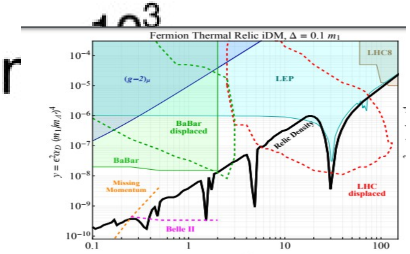
Coupling Bound



Note with lifetime added
Relic bound is roughly the same

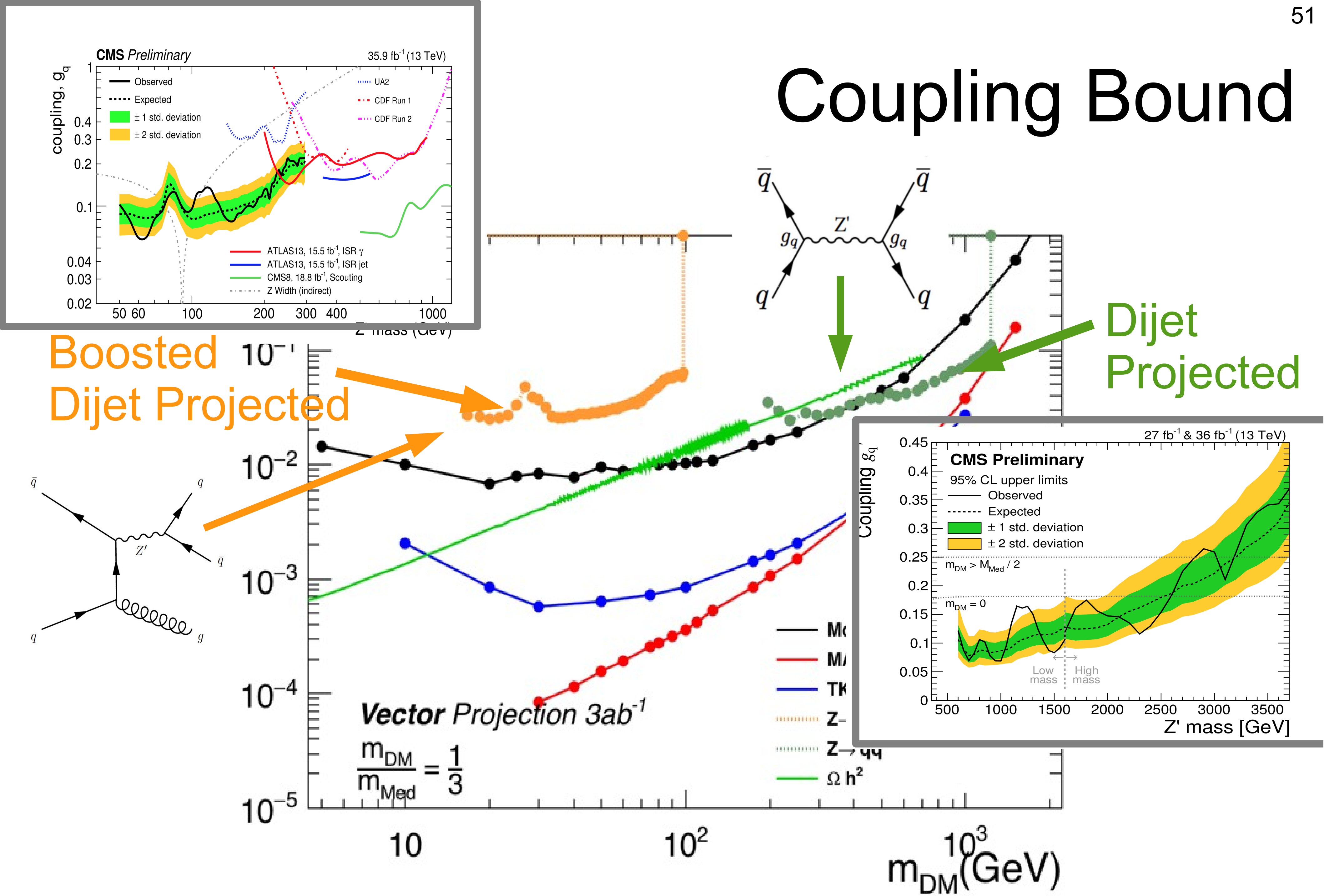
Coupling Bound





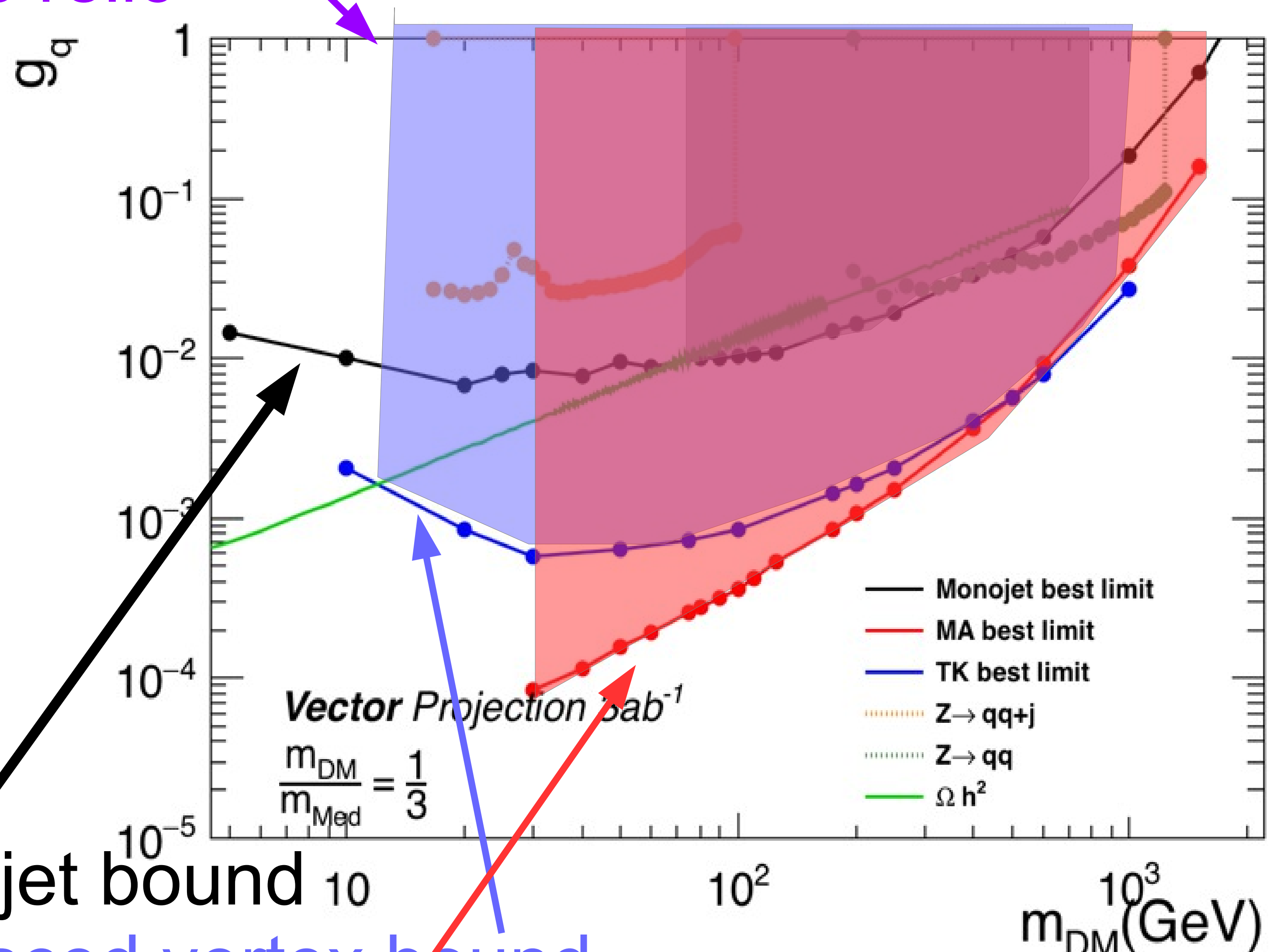
Relic bound below we overclose
(see https://arxiv.org/abs/1508.03050)

Coupling Bound



Coupling Bound

For masses down to 10 exclude all couplings that give relic

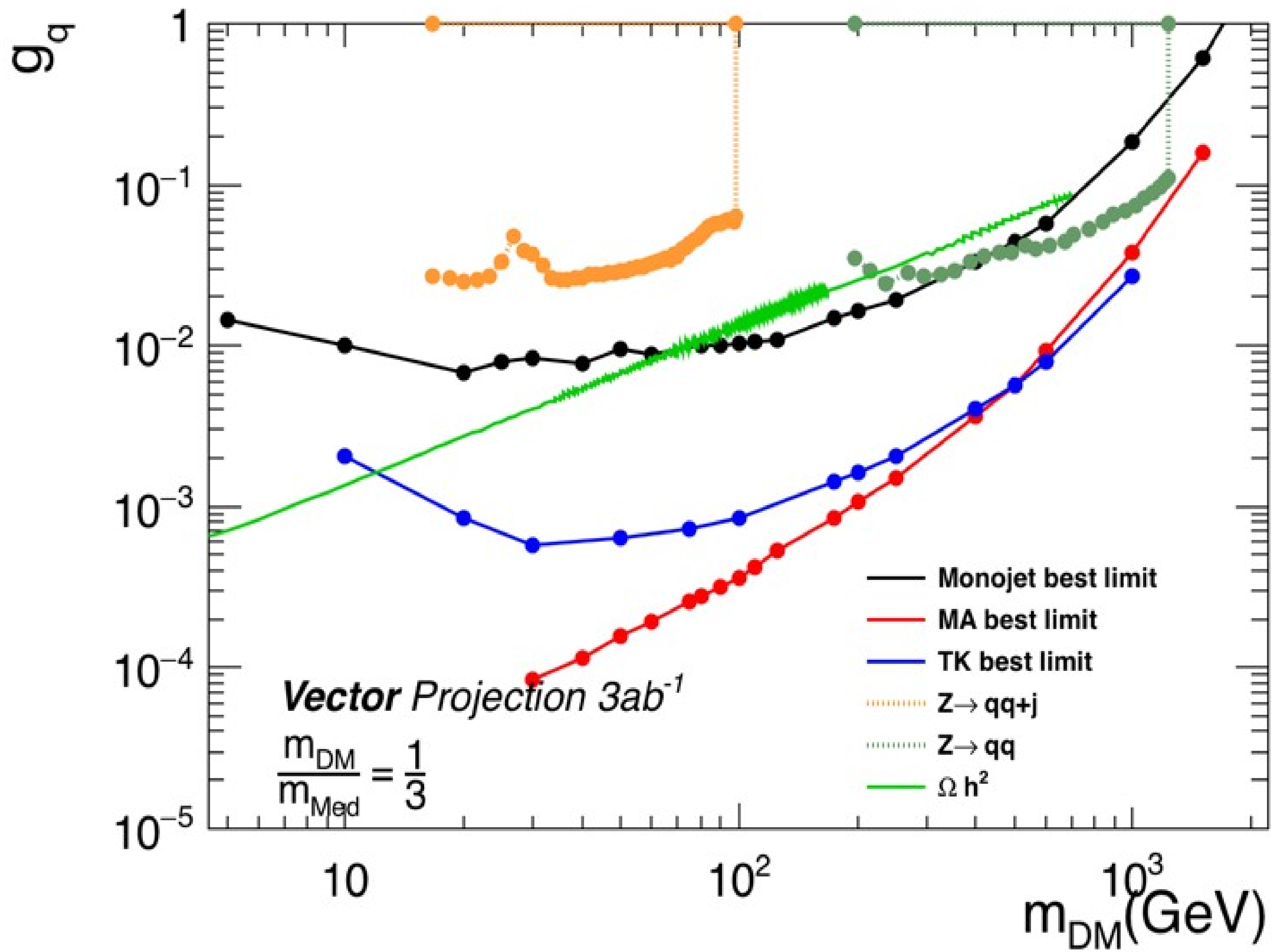


Monojet bound

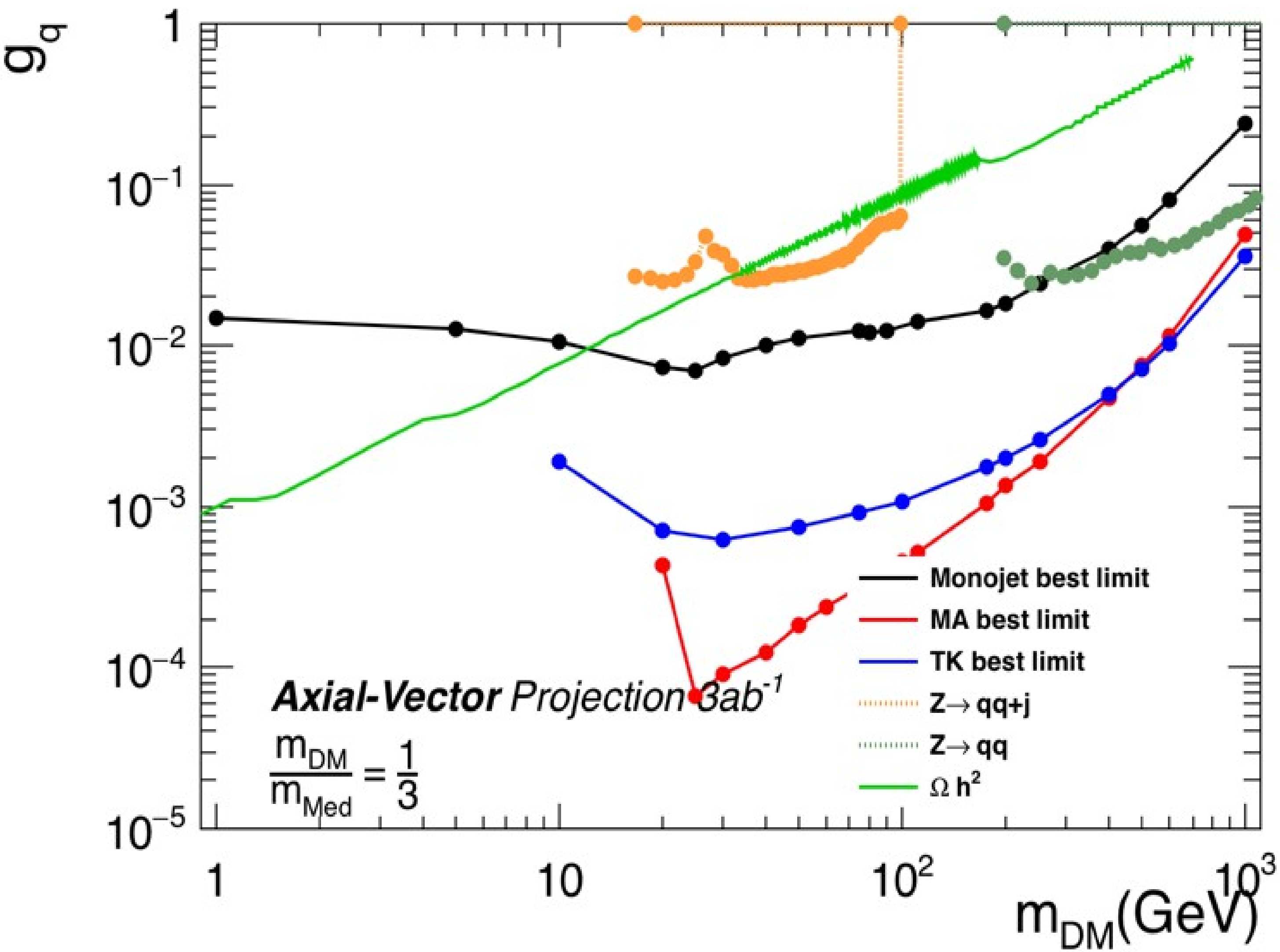
Displaced vertex bound

Mathusla bound

Vector Coupling Bound

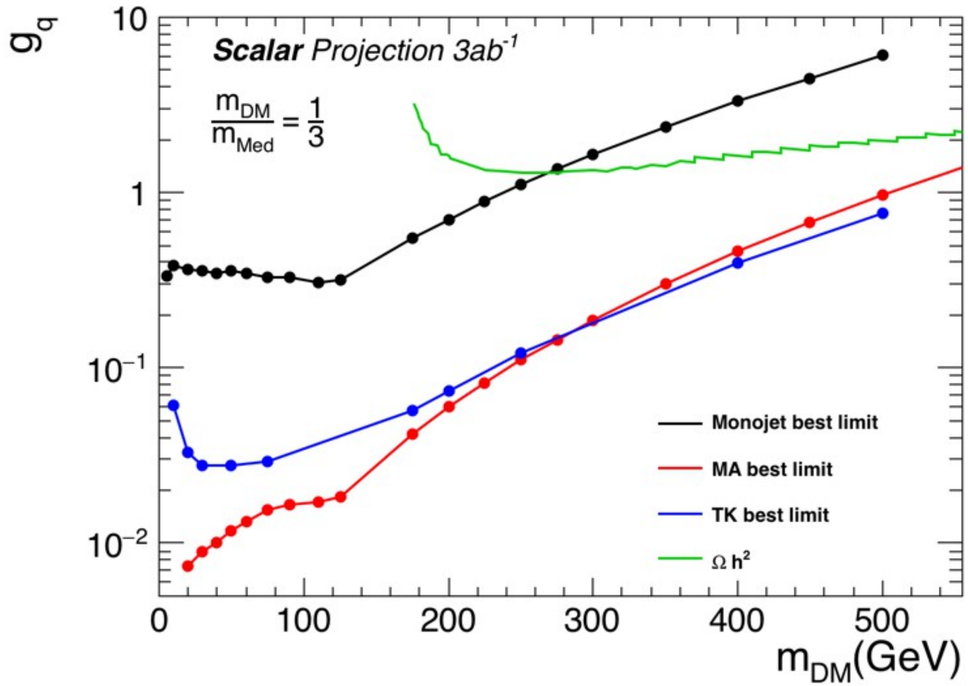


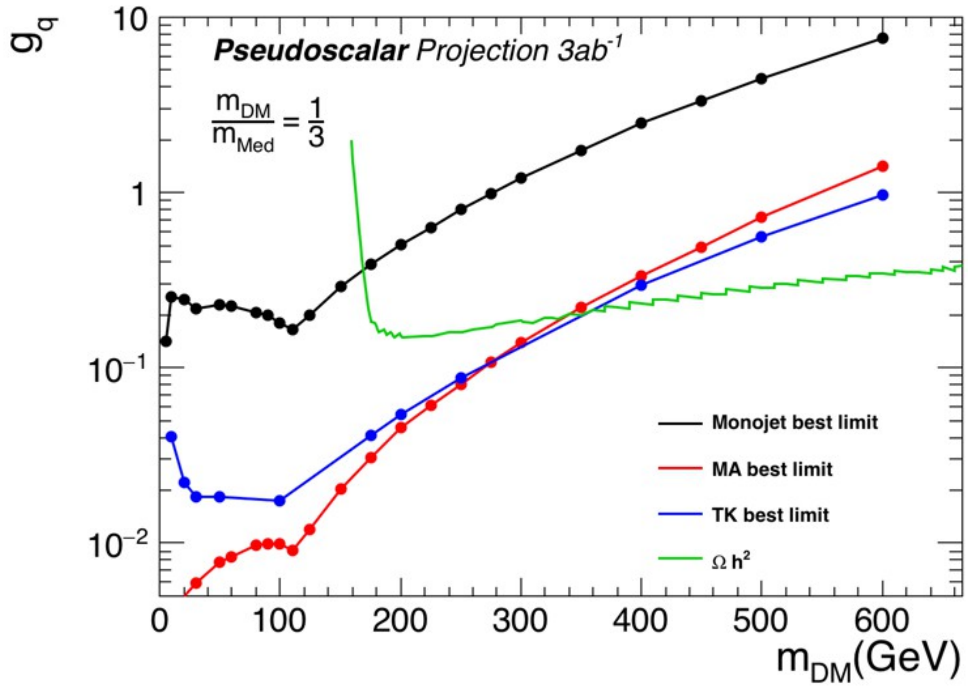
Axial-Vector Coupling Bound



Bounds are strong for Axial vector coupling

(Pseudo) Scalar Coupling Bounds





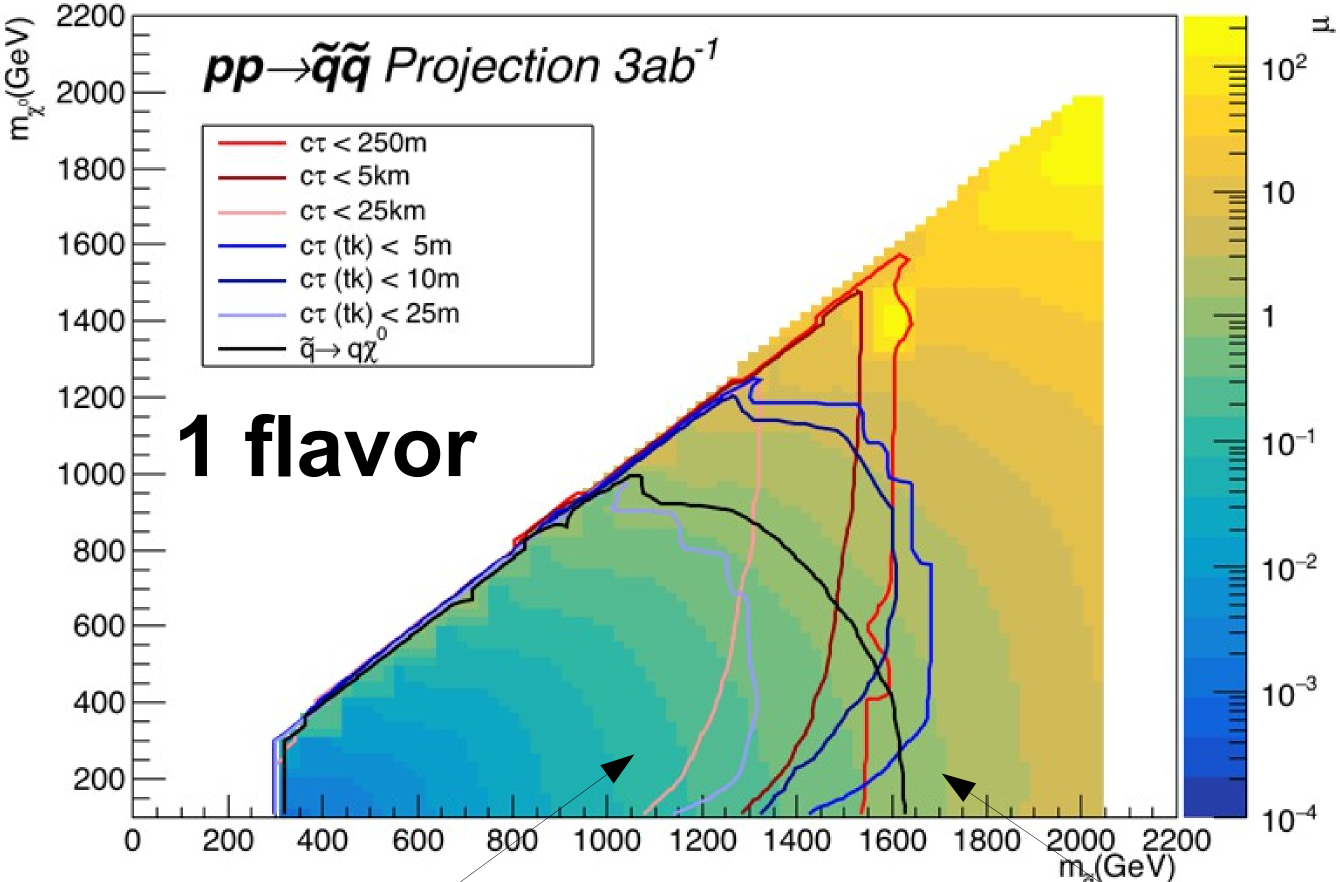
Long lived searches down to small couplings

Full implications need to be investigated

A SUSY example

- SUSY bounds
  - Lots of heavy objects

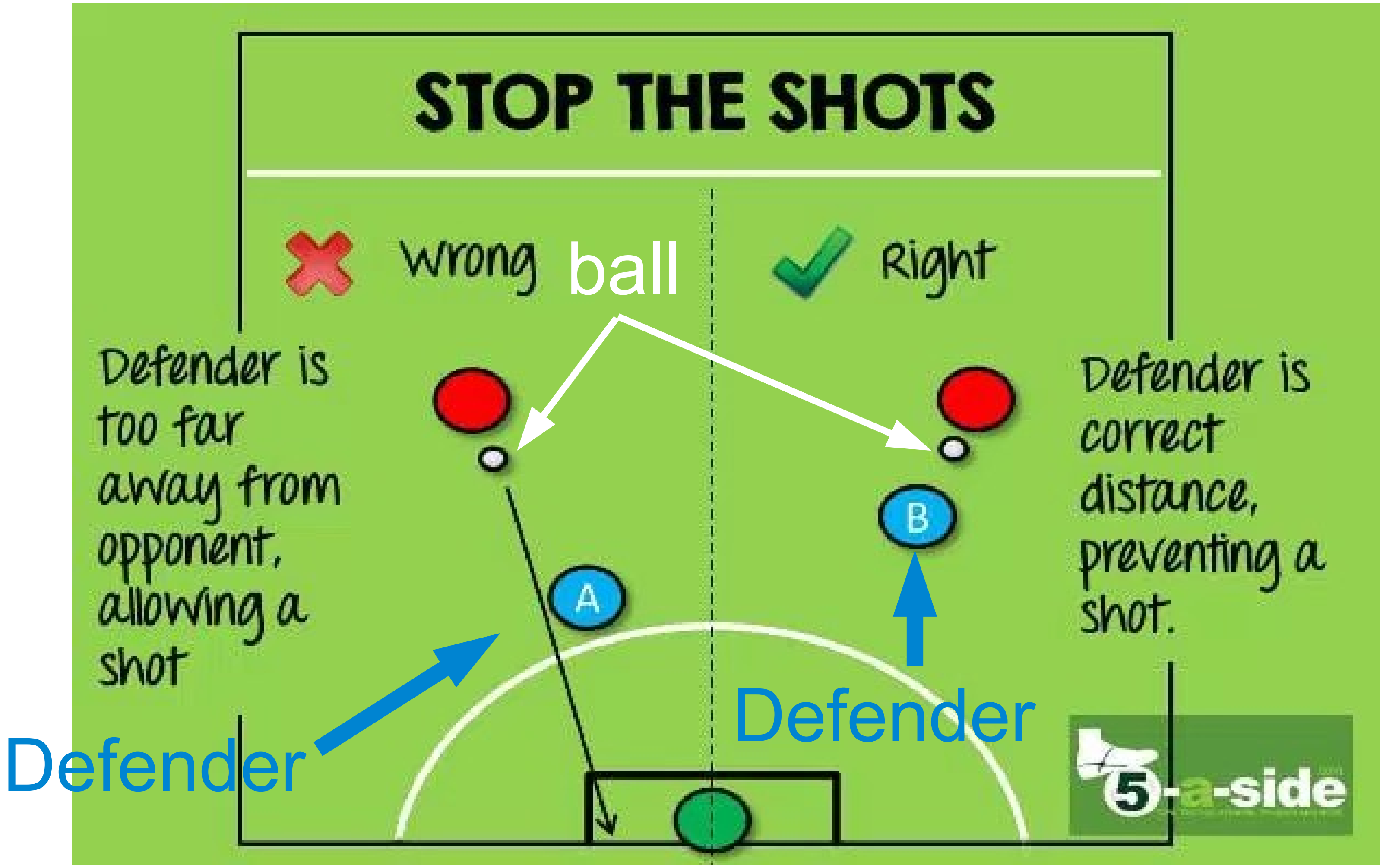
With heavy objects its harder to win



Project CMS bound

LL and MATHUSLA bring less

Put a long lived detect close?



Conclusions

- In terms of trigger coverage for EXO:
  - Rely heavy on Jets/*MET*/Leptons
  - No supremely dominant trigger (leptons a bit of help)
- Long-lived decays
  - Powerful tool to push down invisible branching ratio
  - Mainstay inside CMS is from the *MET* trigger
    - Can benefit from external detectors to trigger
    - Can potentially benefit from smarter triggers in CMS?
- Are there other possibilities?

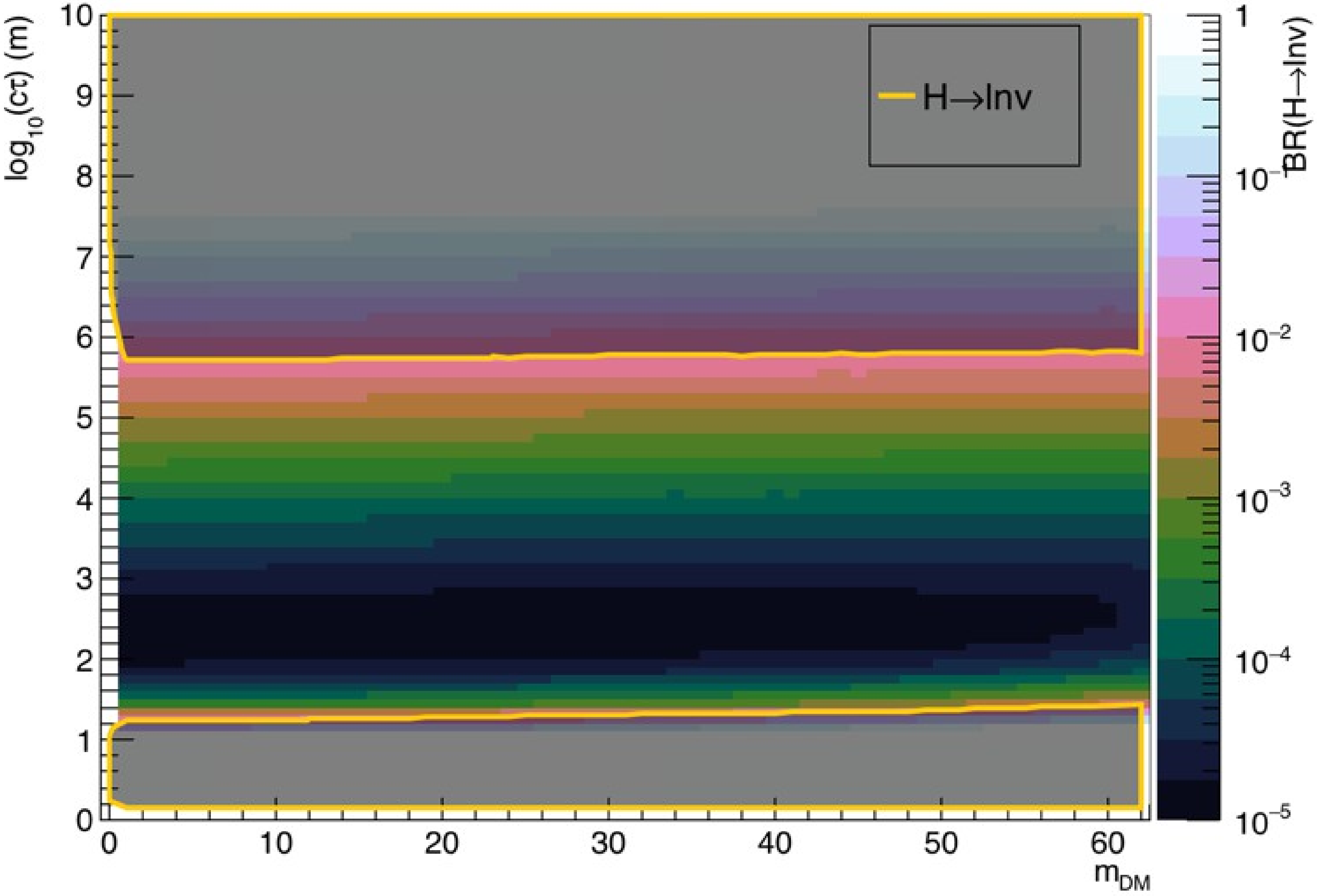
Backup

Make Lifetime Bounds

- We can decay the Higgs signal to DM
  - Sample the sphere in the Higgs rest-frame
    - Insert DM particles and boost back
    - Had to do this: was using an undecayed H sample
  - Compute probability of decay in the MATHUSLA vol.
    - Following verbatim the mathematica notebook
    - For the length sampling a finely binned histogram in θ,φ
- Again use a benchmark for $3ab^{-1}$
  - Require 4 events for the exclusion
  - All of this can be switched, but seems pretty standard

Lifetime Bounds w/MATHUSA

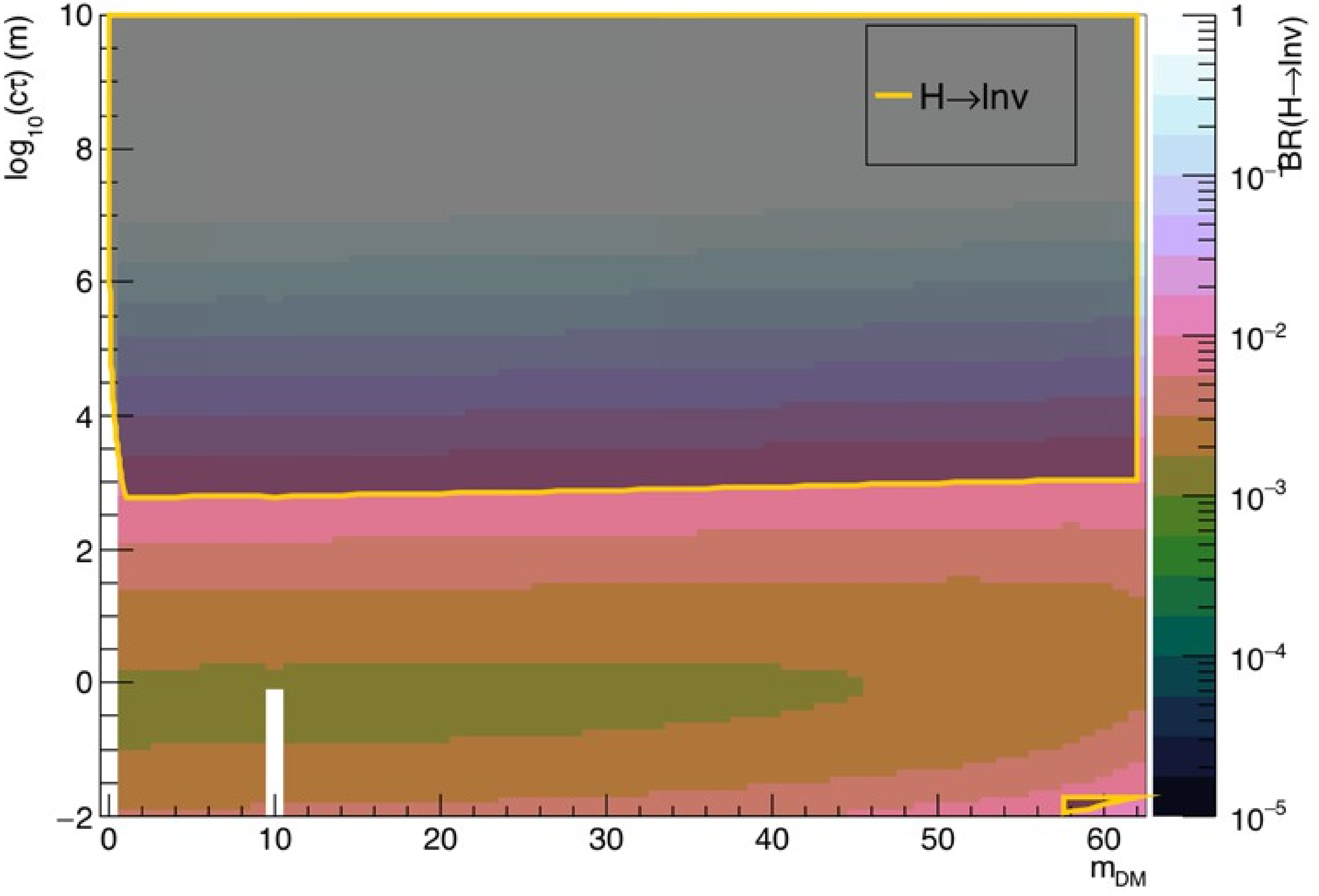
- Higgs Invisible in Mathusla detector



Just as a reminder

Lifetime Bounds w/Tracker

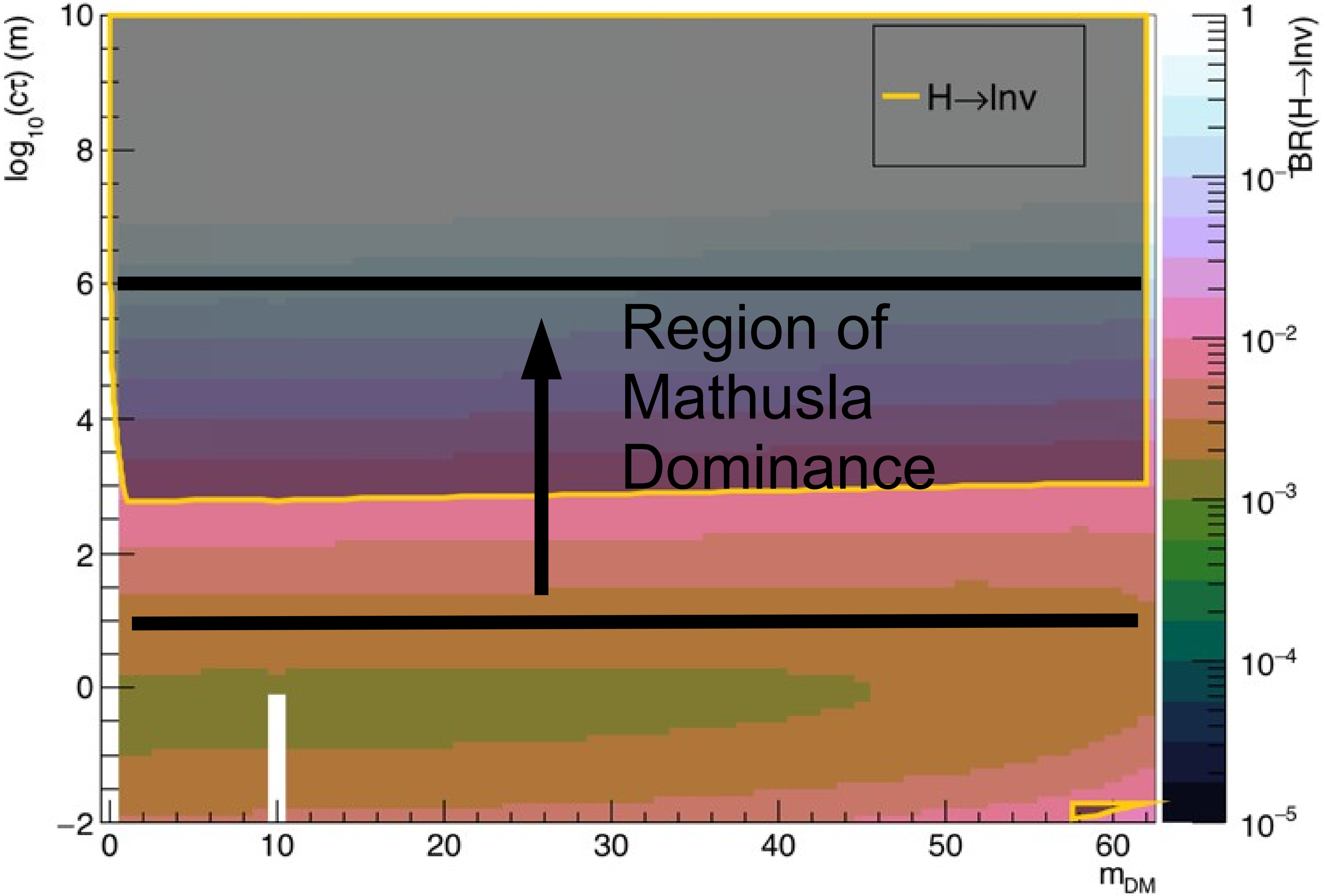
- Higgs Invisible in with a decay in tracker



Covers the lower range beyond H→Inv (10^{-3})

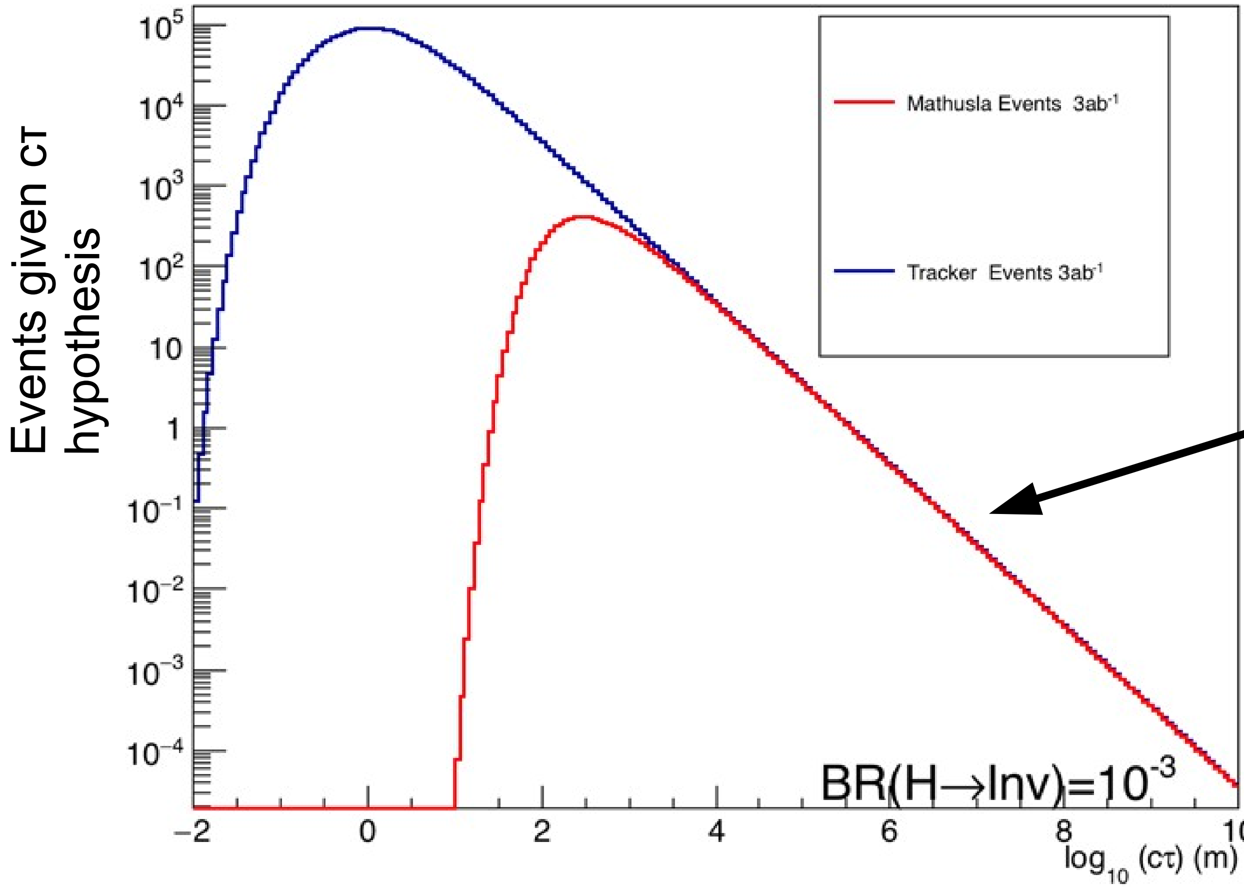
Lifetime Bounds w/MATHUSA

- Higgs Invisible in with a decay in tracker



Is there a way to motivate lifetimes in this range?

Visualizing the Acceptance

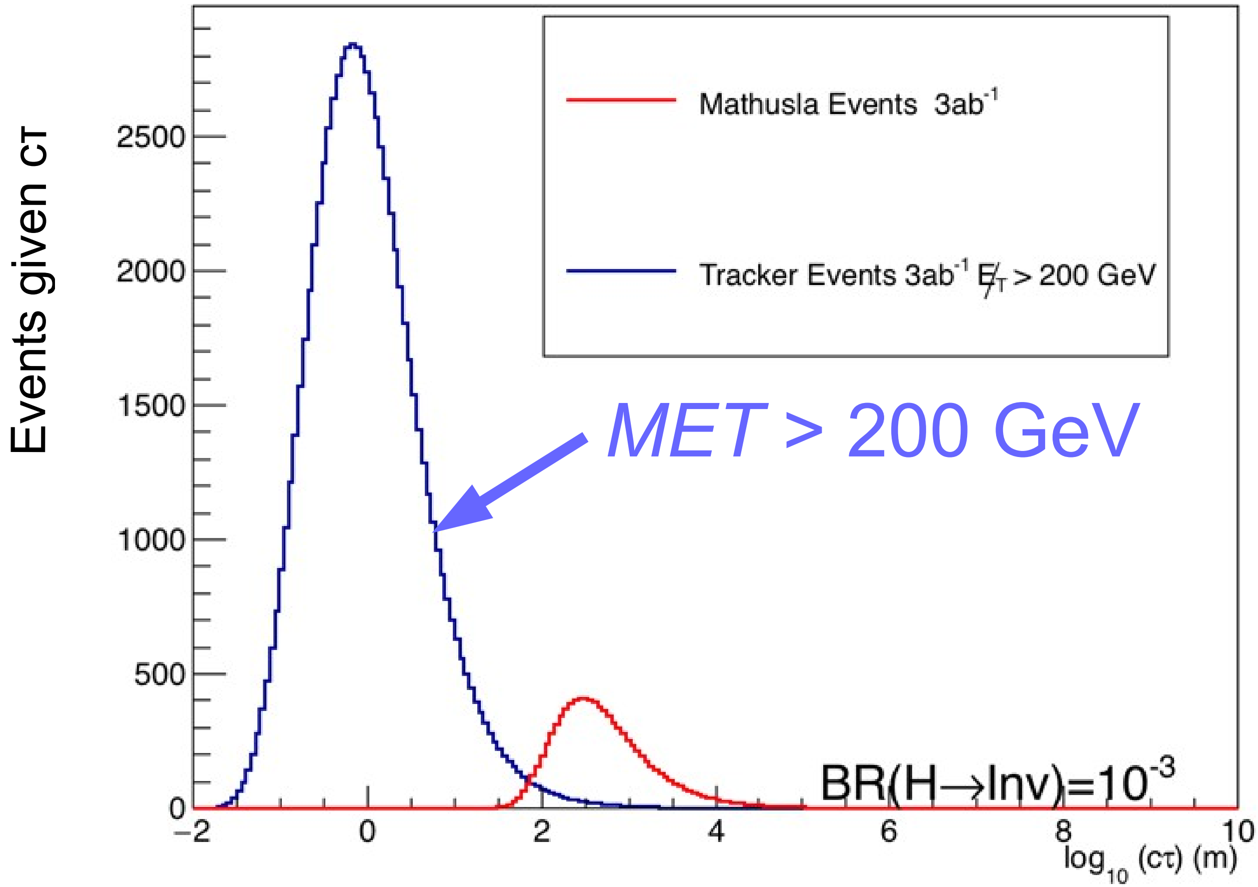


Blue and Red aligned

Were these dimensions purposeful?

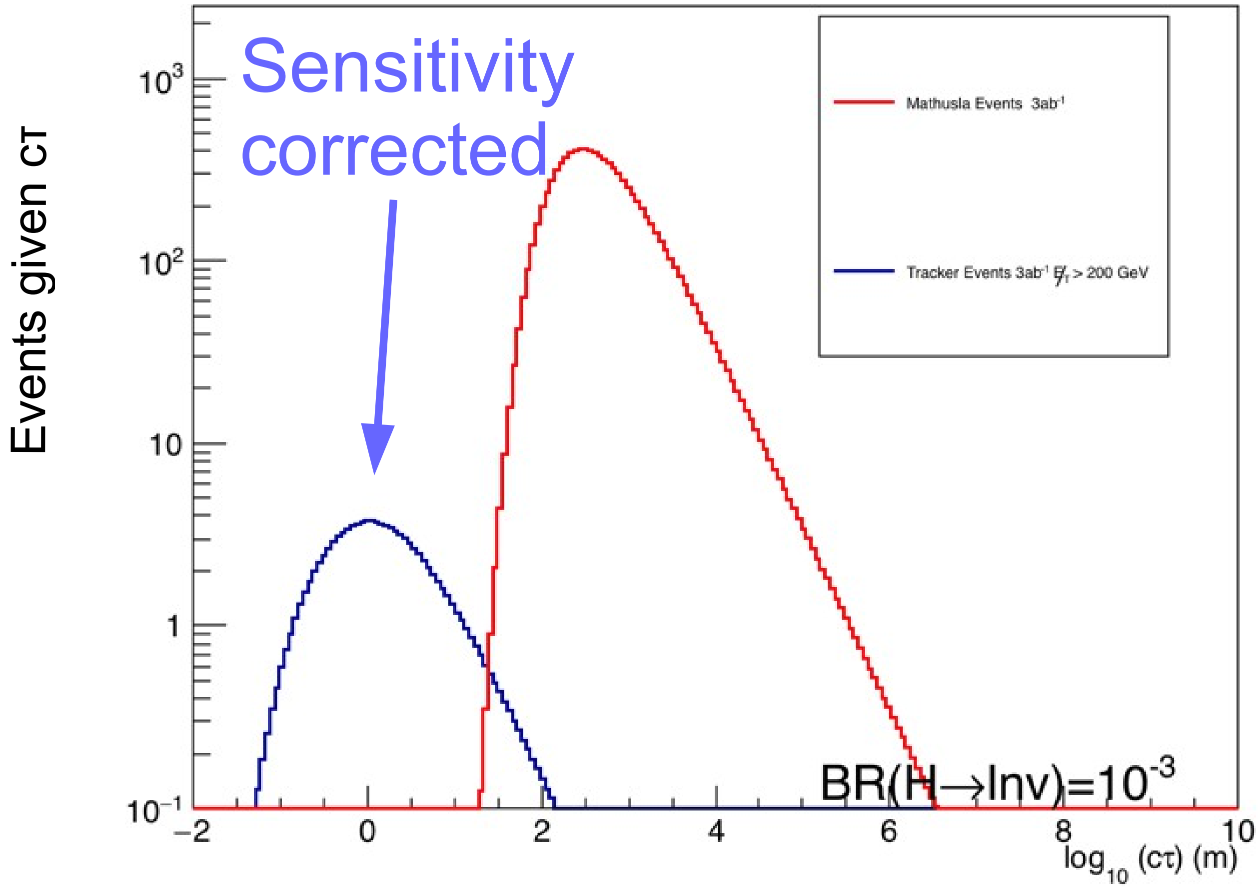
- Large yields with 3/ab and H→Inv
  - No cuts are applied here

Visualizing the Acceptance



- Adding a *MET* cut to the Tracker
  - Now yield are more comparable

Visualizing the Acceptance



- Correcting for the sensitivity from the limit
  - Ie accounting for bkgs
  - Our equivalent yield on no background is 4 events

Recap

- Higgs invisible with best technology
  - 2σ exclusion Limit is 1%
  - Limit approaches FCC-ee (0.5%)
  - Using state of the art technology; not unreasonable

- Long-lived bounds:
  - Tracking will get to 0.1% (conservatively)
  - Mathusla will get to 0.001% (longer lifetimes)

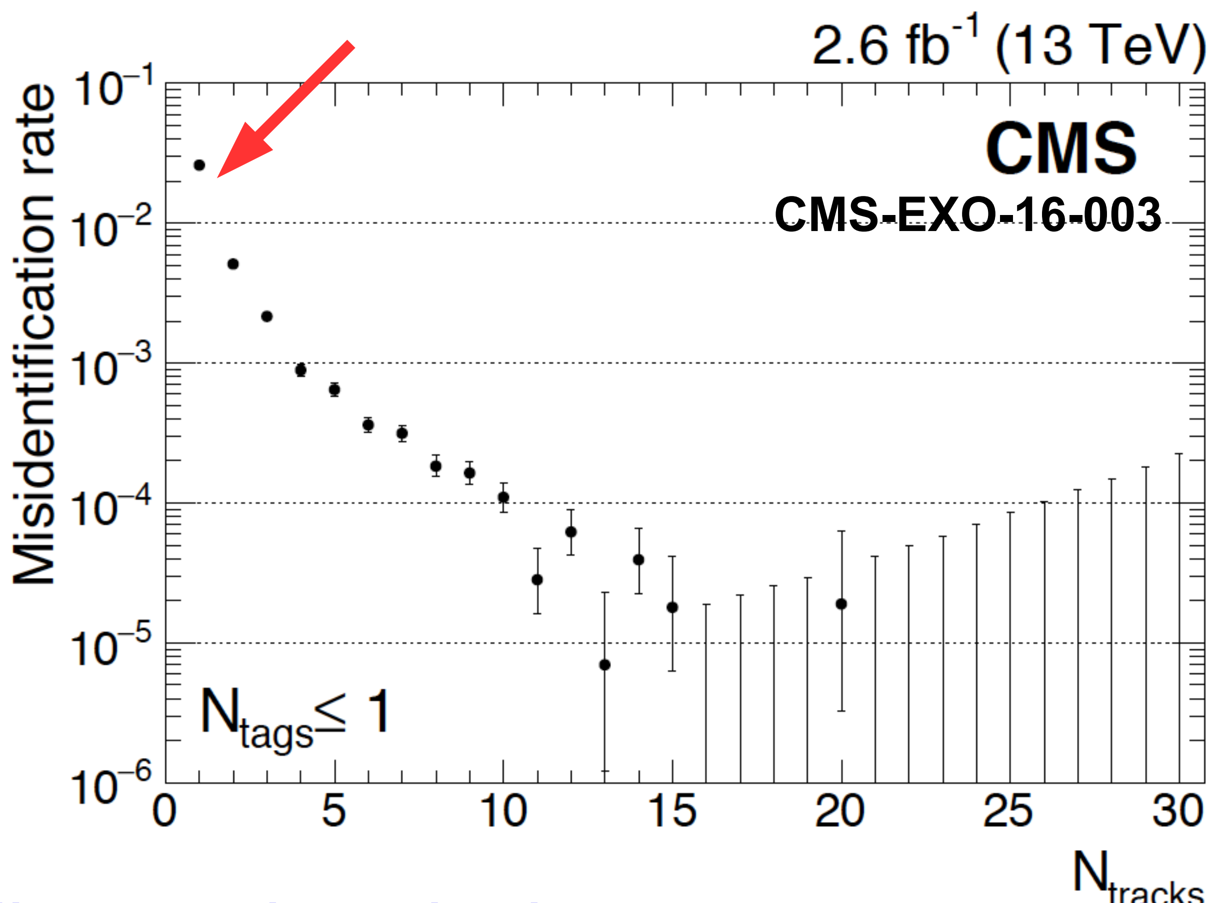
- Can probe 0.1% with lifetimes up to 10km in cτ

Part 2: DM Simplified models

Displaced Object Id

- Given a displaced object :
  - What is the likelihood of a fake id

For a jet w/ a single track jet rate its displaced is 2.5%



Prior is conservative so we take 1% with 100% eff (see later)

For referenced analysis integrated rate was 0.1-0.4% depending on prior

Rate of displaced track given a large calo deposit as prior

Lepton Veto definition & co

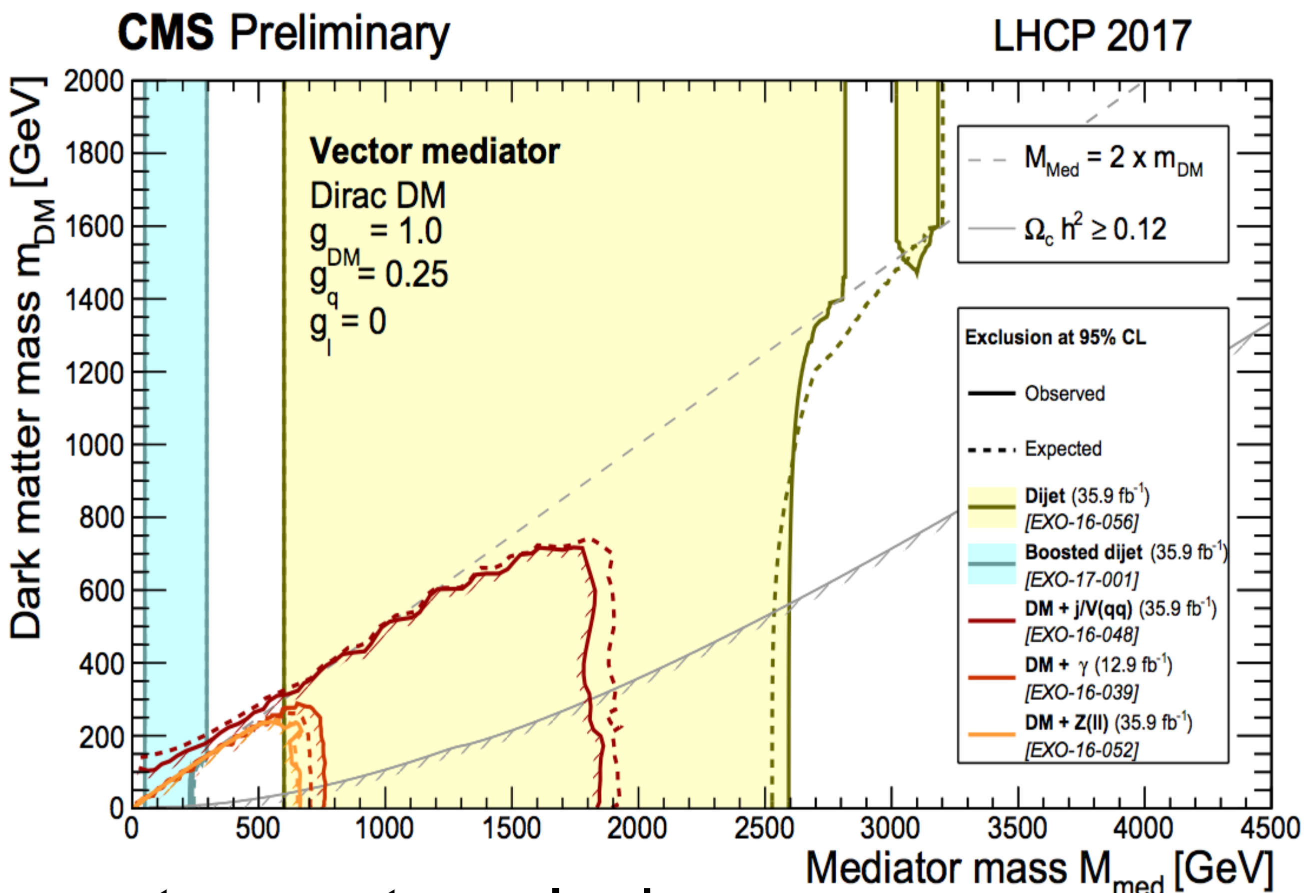
- Select leptons up to $|\eta| < 4.0$
  - Can do this due to pixel upgrade (tracking to $|\eta| < 4.0$)
- Assume a lepton efficiency of :
  - 85% for τ leptons $p_T > 20$ GeV (this is! our current eff)
  - 92% for e leptons $p_T > 15$ GeV (roughly current)
  - 96% for μ leptons $p_T > 10$ GeV (worse than current)
- Events which pass lepton veto are mainly τ
  - Propagate efficiency unc. as a nuisance (5% for τ)
    - Dominant uncertainty is from the τ id efficiency
- Invert lepton selection to make control regions
  - Require single and dilepton control regions

Strategy

- Run same fit on standard DM simplified models
  - Use same categorization (*MET* and m_{jj})
    - Again split by m_{jj} > 400 no reoptimization
  - Category splitting gives slightly better limits to monojet
- Do this for :
  - Spin 1 mediators : Vector and Axial-vector couplings
  - Spin 0 mediators : Scalar and Pseudoscalar
    - I skip the details, since I hope they are known
- Allow the DM cands from mediators to decay
  - Scan lifetime for the TK and M(athulsa) scenarios

Vector Simplified models

- Current Mass Bounds

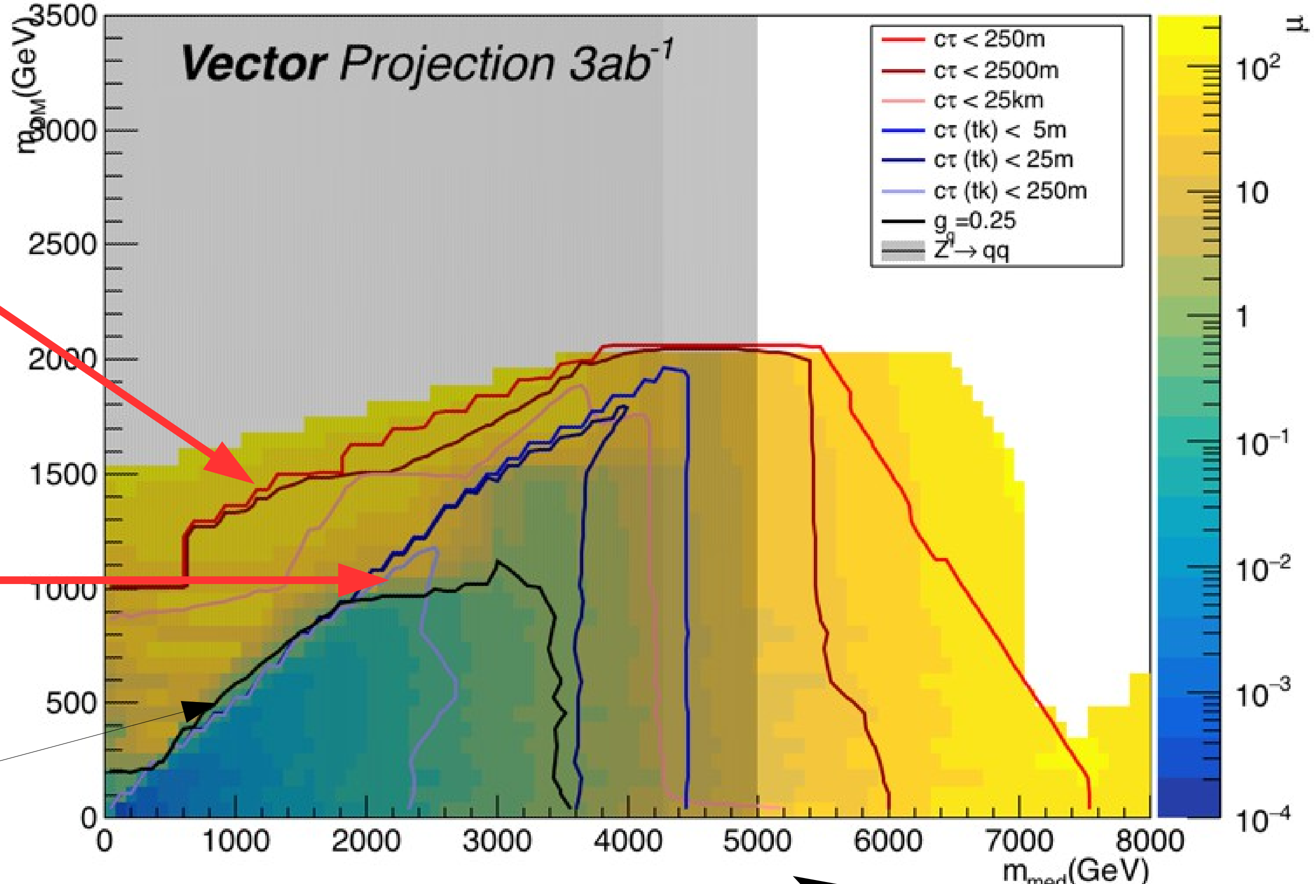


With most recent analysis :
Monojet reach is 2 TeV for spin 1
Dijet reach is 2.6 TeV for spin 1

Vector Simplified models

- Projected bounds to full luminosity

Interpolation is not smooth
Can make it look nicer



Monojet bound

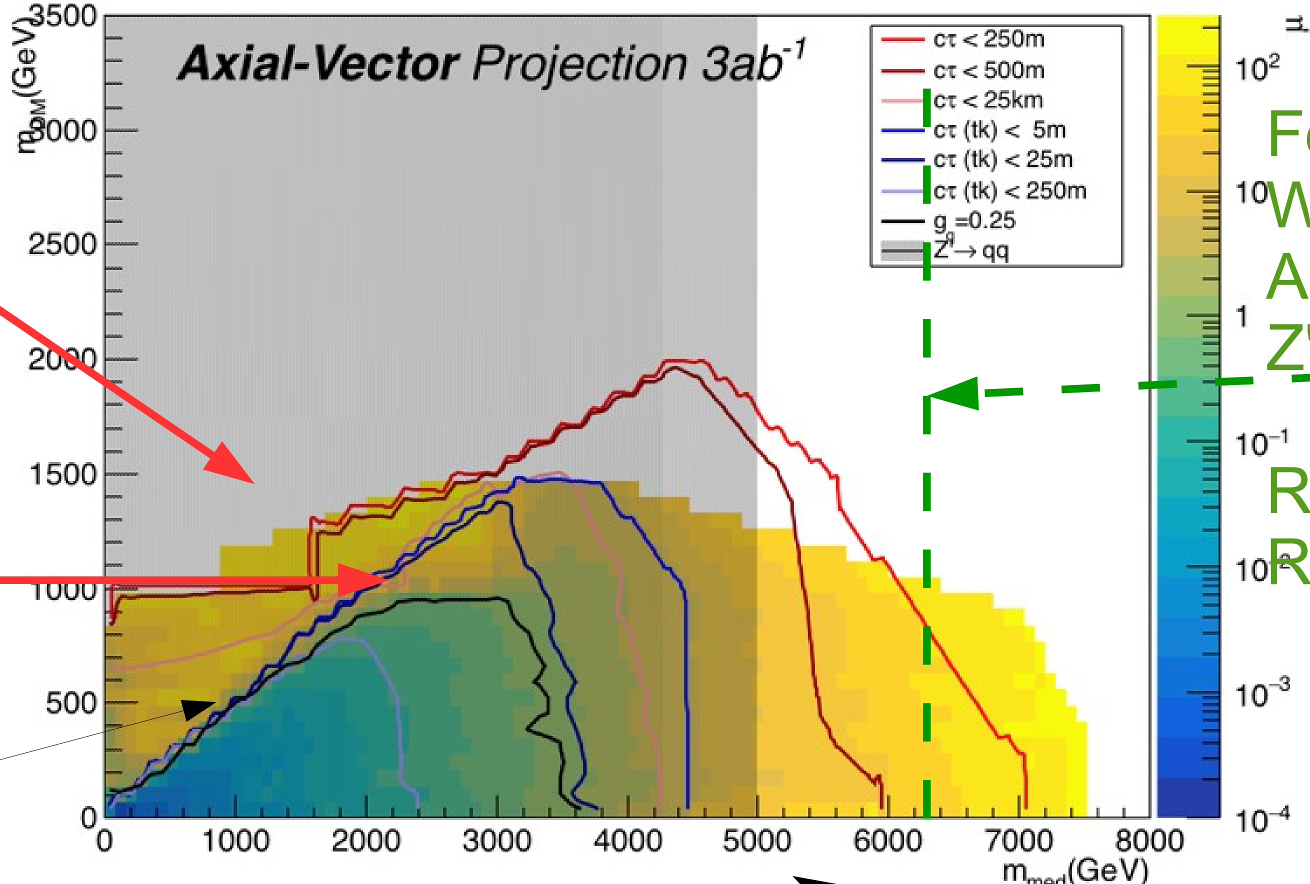
Dijet bounds beat tracker decays
Mathusla wins at very high mass

Expect mass reach for dijet to go to 5 TeV

Axial-Vector Simplified models

- Now with an Axial vector mediator

Interpolation is not smooth
Can make it look nicer



For Axial-vector
Would need to
Add high mass
Z' to leptons

Reach is
Roughly 7 TeV

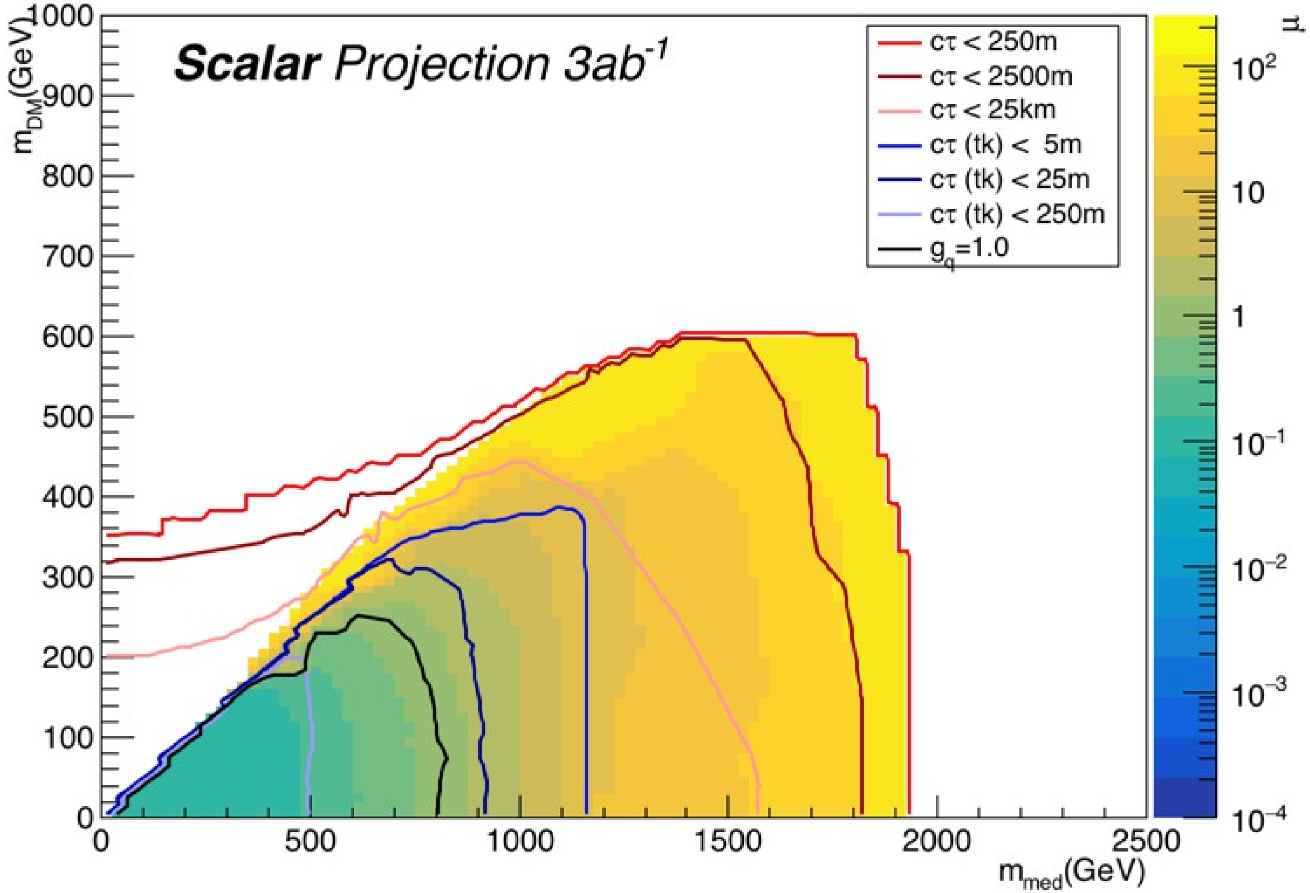
Monojet
bound

Dijet bounds beat tracker decays
Mathusla wins at very high mass

Expect mass reach for
dijet to go to 5 TeV

Scalar Simplified models

- Scalar Bounds
  - This is a very nice plot (note Z axis always μ for monojet)



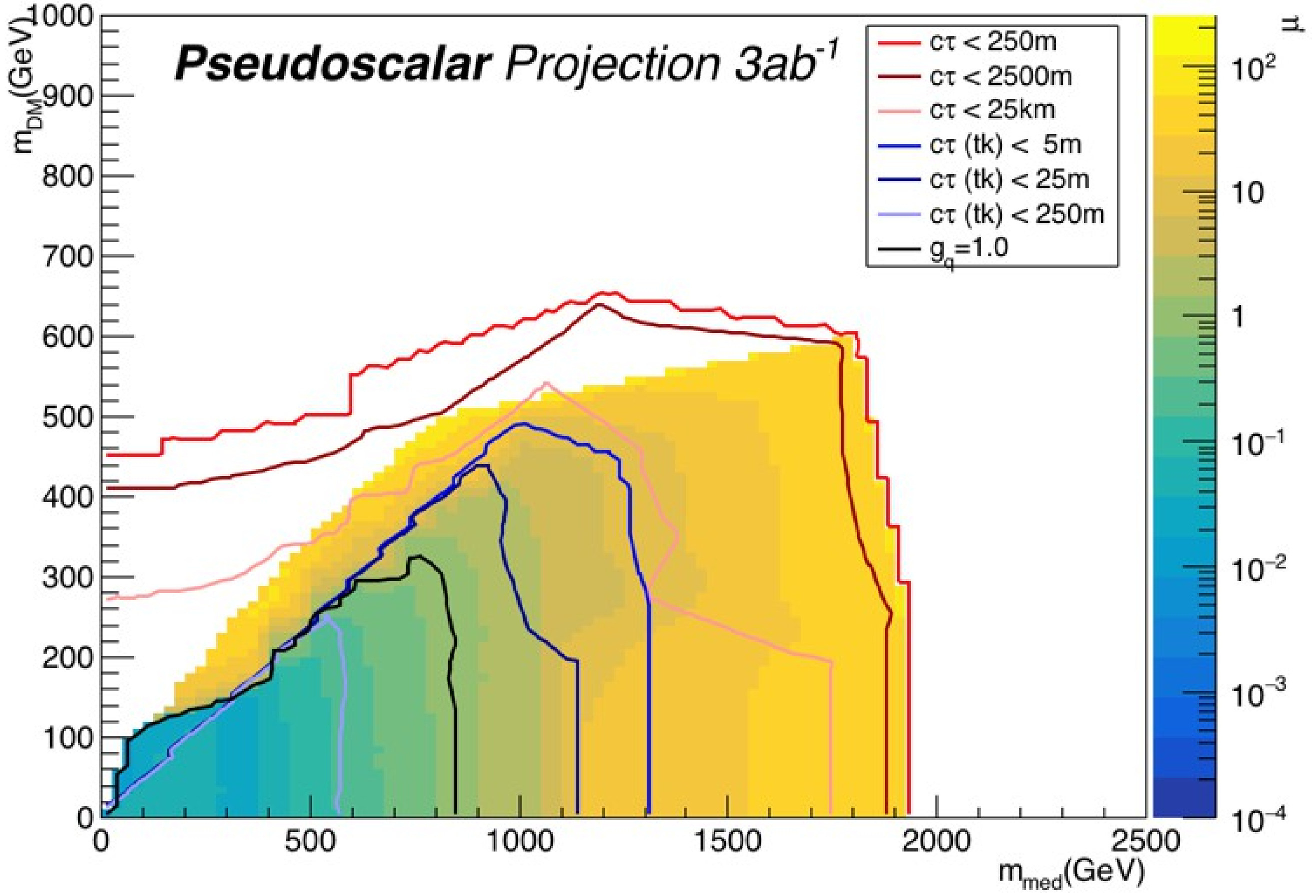
In the low mass region

gains from LL searches are more important

Pseudoscalar Simplified models

- Pseudoscalar bounds
  - Slightly larger than scalar bounds

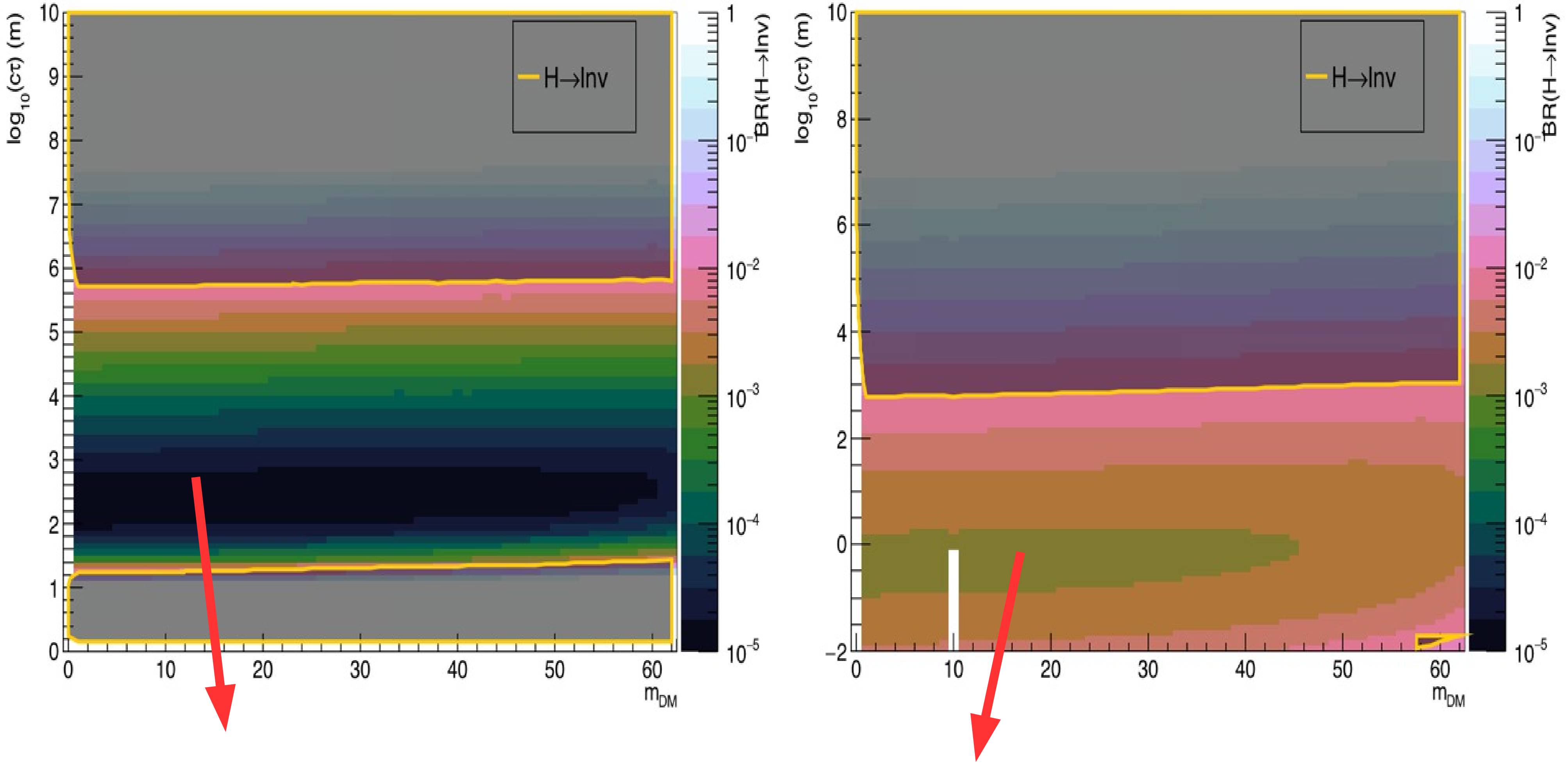
Some more interpolation issues can be smoothed



Both spin 0 mediators give similar bounds to Higgs invisible bounds, now projected in mass

Translating to Coupling

- We can also translate our bounds to coupling



Take the best bound from each displaced experiment
Translate this to a limit on the coupling

Translating to Coupling

- Coupling translation

For $\mu < 1$ limit scales with g_q^2

For $g_q < 0.25$ width is dominated by gq

This means :

$$\mu=(g_q/0.25)^2$$

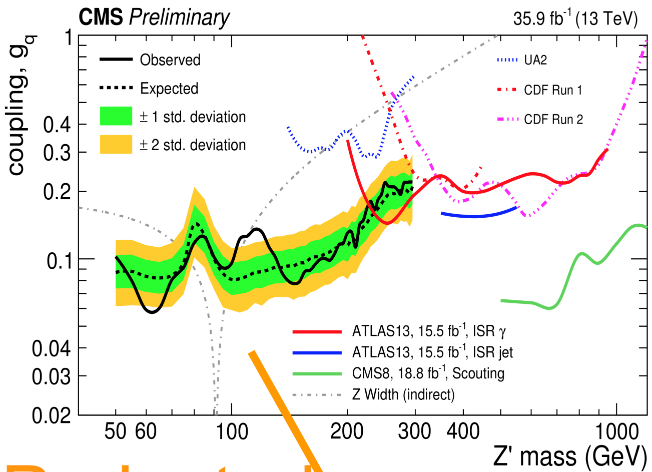
And we solve for g_q

Also applies for g_q=1 in a scalar model

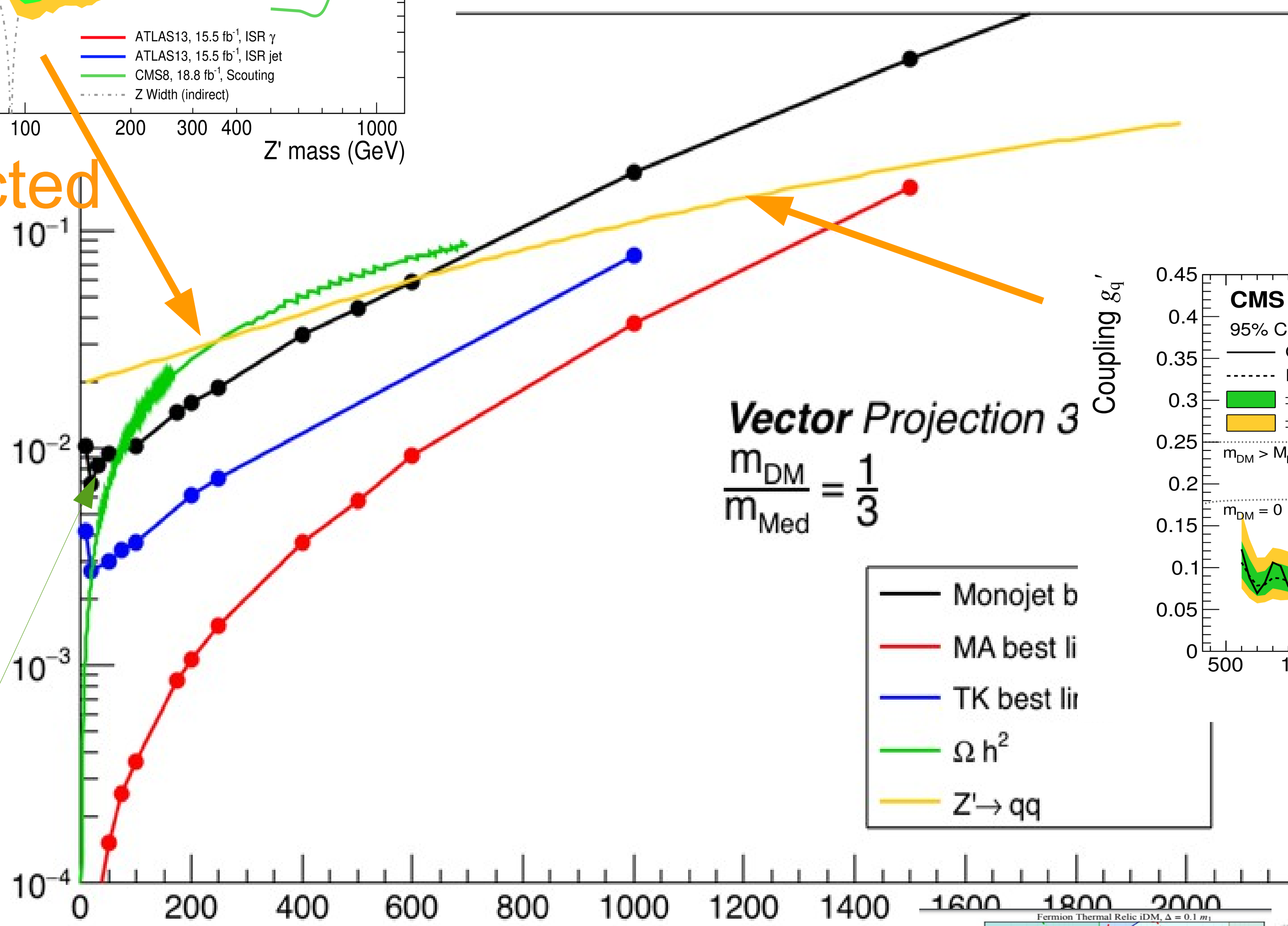
On top add relic bound given just simplified model

Solve for minimum coupling that doesn't over produce

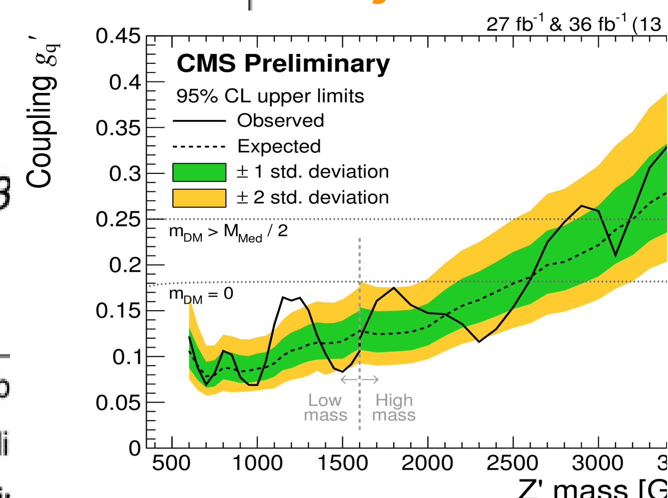
Vector Coupling Bound

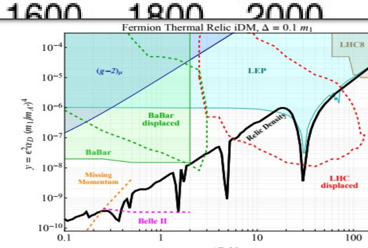


Projected



Projected





Relic bound below we overclose
(see https://arxiv.org/abs/1508.03050

Simplified Model Summary

- For spin 1 mediators:
  - Visible bounds from dijet are competitive with LL
  - For low masses LL can reduce coupling sensitivity
  - Probe relic down to 10 GeV in mediator mass
  - Expect to cover spin 1 almost completely

- For spin 0 mediators:
  - LL adds a very powerful component
  - LL opens interesting region for heavy mediators

- It might be good to tie these to real models?