Exotics from a Hidden Sector
(Through Examples)

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Why Exotics?

Significant tension for the “standard” scenarios

Because it could be there
Theoretical prejudice is dangerous!

Exotic signatures are highly motivated by many theories beyond the SM

It’s refreshing and fun to think about…

What is Exotics?

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Anything not predicted by the SM?

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Too obsolete. Exotics is becoming mainstream…

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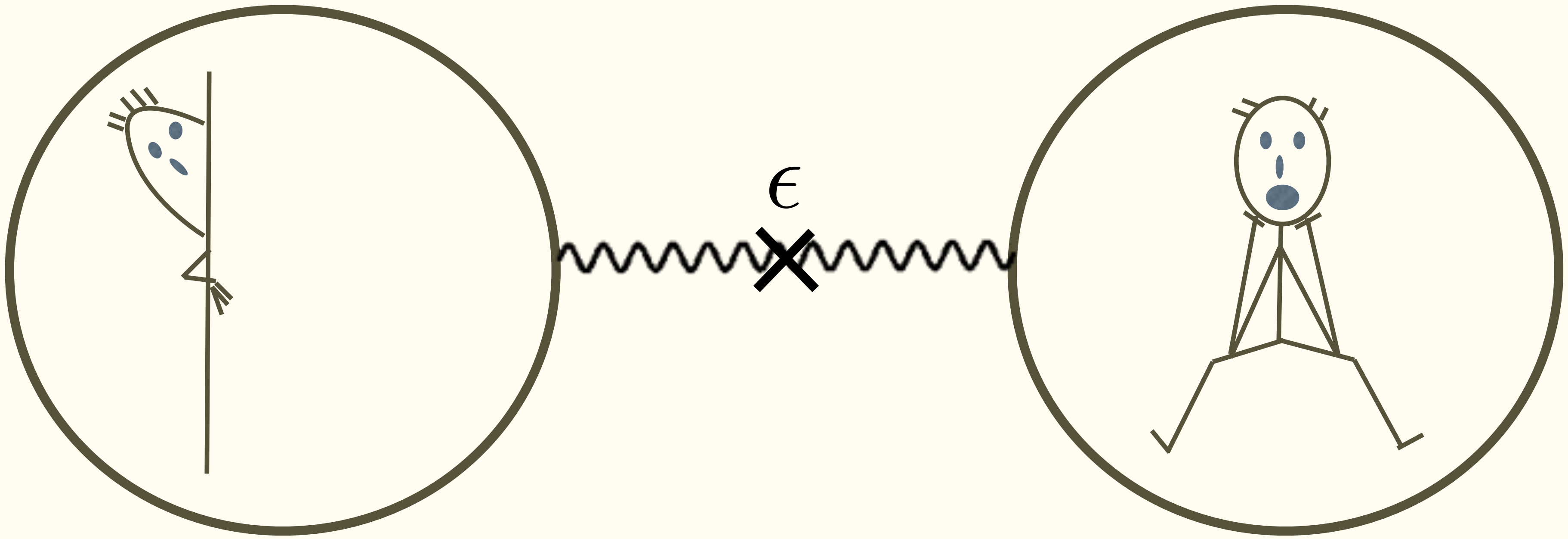
Maybe it's not crucial to define?

Outline

- Hidden Sectors
- Examples
    - Lepton Jets
    - Signals from a Dark Sector
    - The 750 GeV Resonance
    - dRPV

Hidden Sectors

Exotics from a Hidden Sector



- Could be a weakly or strongly coupled version of "Hidden Valleys".
  [Strassler, Zurek, 2006]
- Simple and plausible extensions of the SM.
- Mixing can be naturally generated at high scale, $\varepsilon \lesssim 10^{-3}$.
- Phenomenology vary with hidden sector structure, *which we know nothing about*!

Portals to Hidden Sectors

- We can couple to a hidden sector through several portals
  - Higgs portal: $H^\dagger H(aS + bS^2)$
  - Vector portal: $\epsilon b'_{\mu\nu} F_Y^{\mu\nu}$
  - Neutrino portal: XLH
  - Axion portal: $f_a^{-1} \bar{\psi}\gamma_\mu\gamma_5\psi\partial_\mu a$
  - Heavy Mediator: $\frac{1}{M}\mathcal{O}_{\text{vis}}\mathcal{O}_{\text{hid}}$
- Often, (but not always) hidden particles couple either to mass or charge.

We know nothing about the hidden sector

How do we capture as many models/features as possible?

How to deal with unknown unknowns?

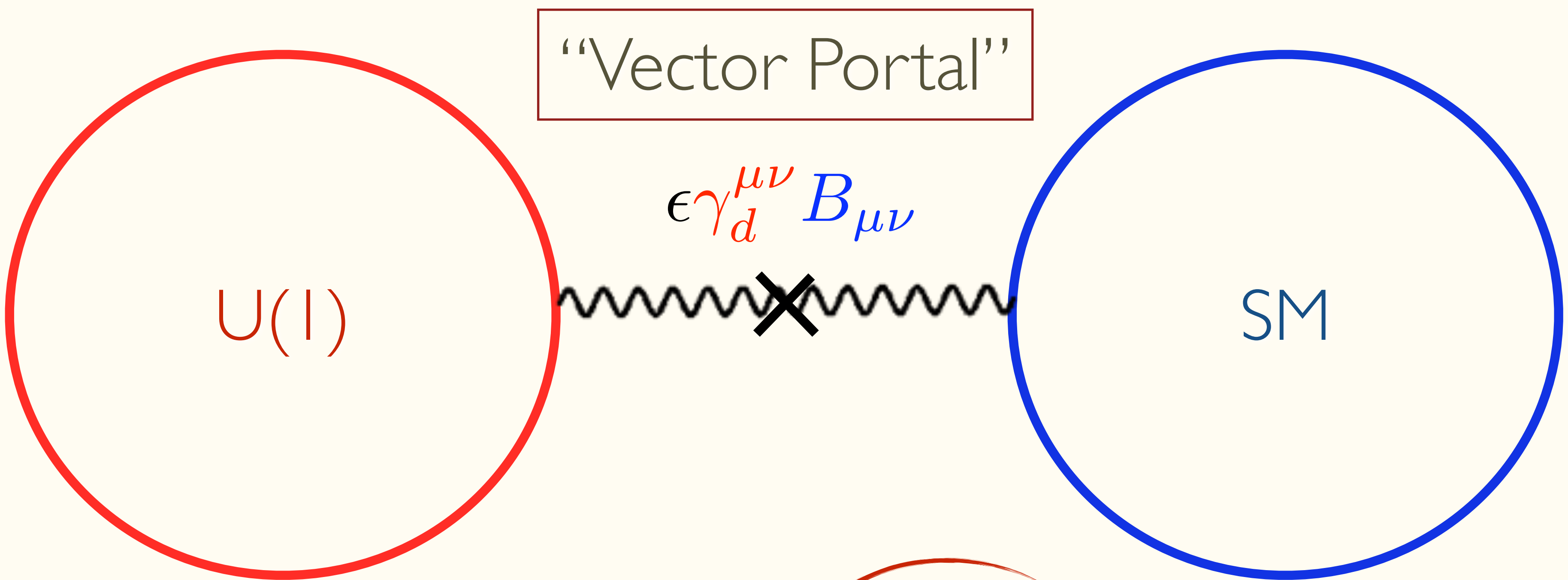
- We think through examples - so come up with as many as we can. (Often motivated by unsubstantiated rumors and weak anomalies...)
- Figure out triggering. Very crucial to understand in advance!!
- Experimental searches - keep general. Better do a signature-based search. Can be done more systematically.

Work with simplified/pseudo models. When the unknowns are unknown, constraining one specific model is almost meaningless...

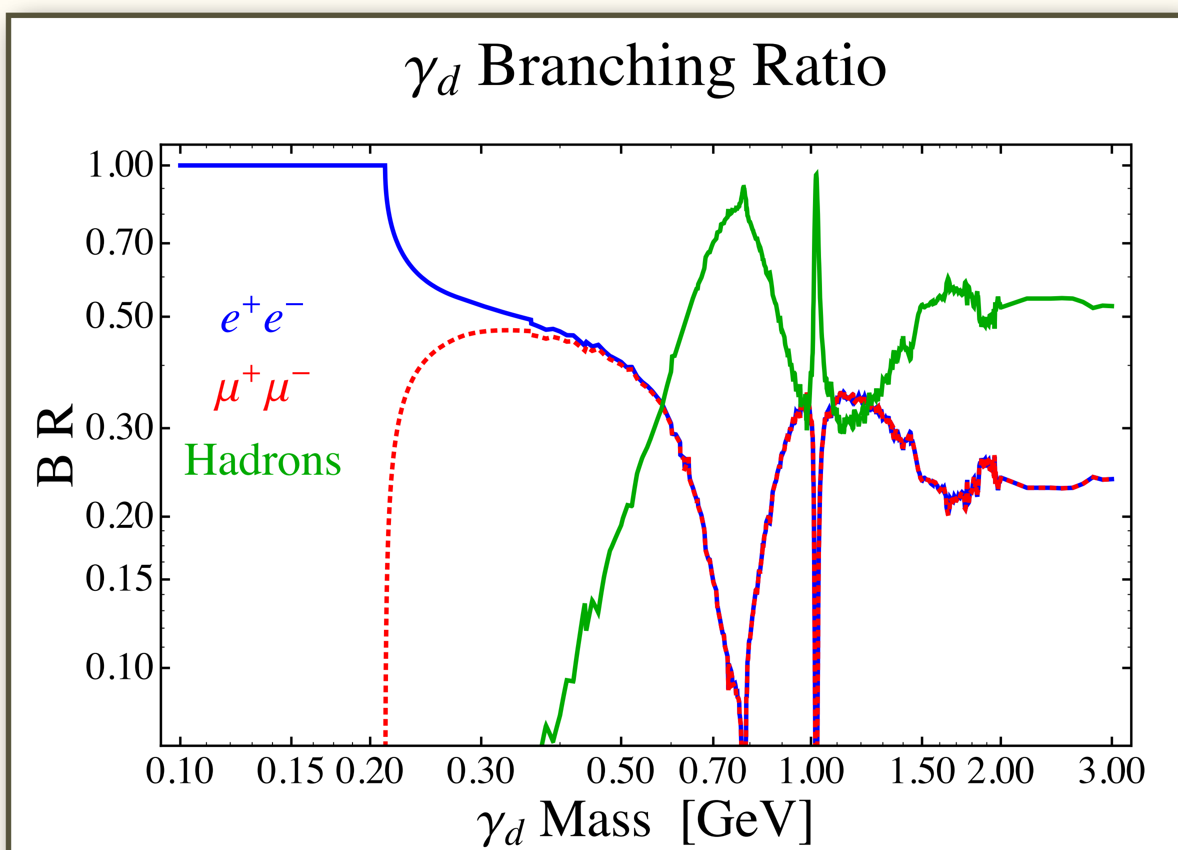
- Provide as much information as possible when presenting results so that the implication for other scenarios can be evaluated.

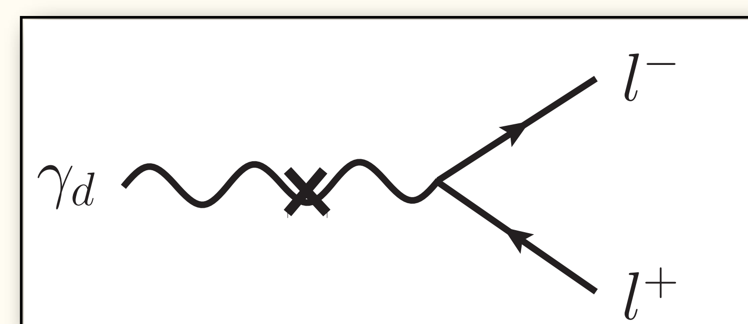
Exotics from a Vector Portal

The Vector Portal



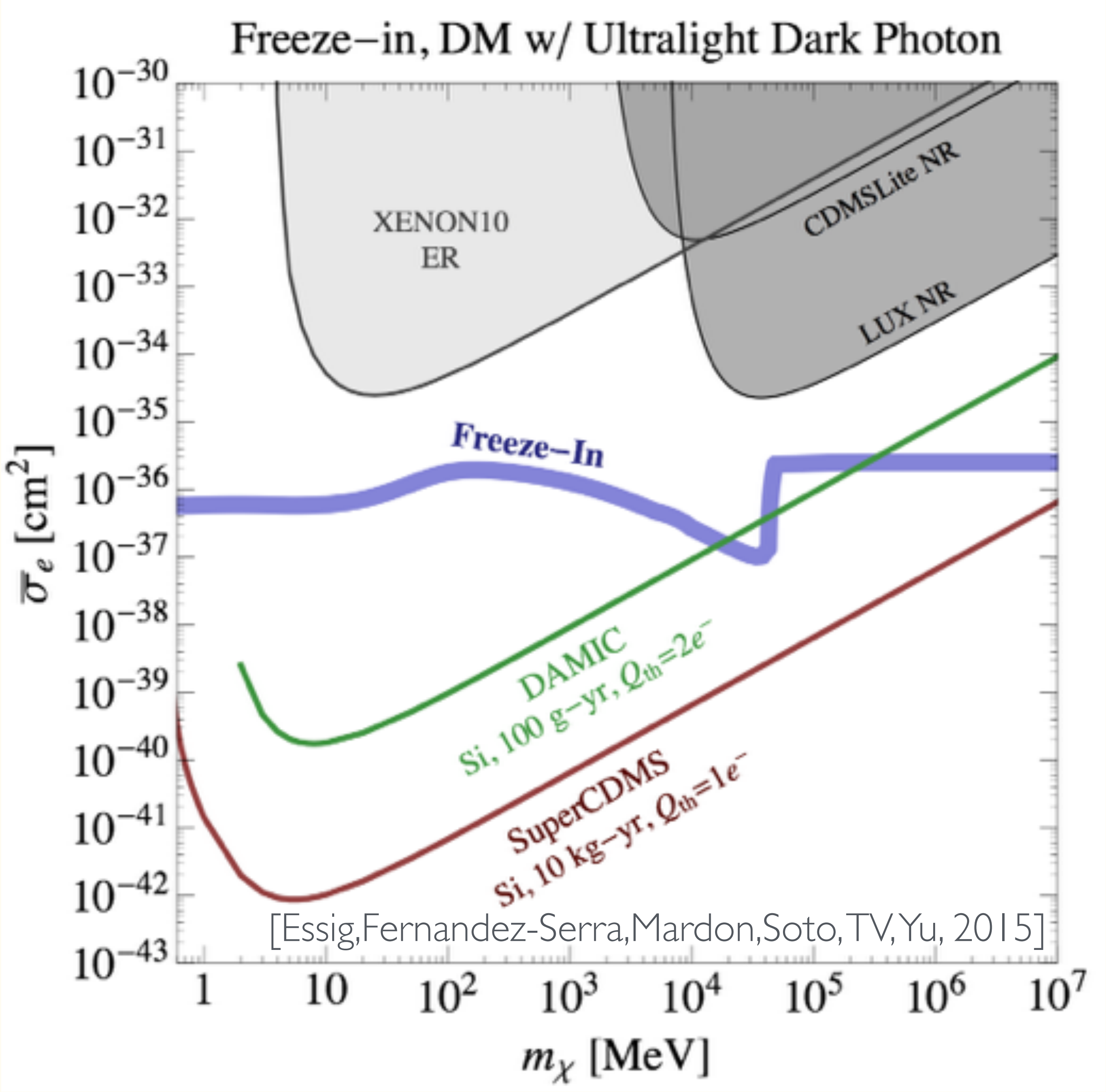
$$\mathcal{L} = -\frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} \tilde{\gamma}_d^{\mu\nu} \tilde{\gamma}_{d\mu\nu} + \frac{1}{2} \epsilon \gamma_d^{\mu\nu} B^{\mu\nu} + g' B^{\mu} J_{\mu} + g_d \gamma_d^{\mu} J_{\mu}$$





The Vector Portal

- The portal is motivated from several directions:
  - Dark Matter. It allows for a portal that may explain the relic abundance.



[Essig,Fernandez-Serra,Mardon,Soto,TV,Yu, 2015]

The Vector Portal

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  - UV Sensitive. It is a marginal operator and therefore does not suffer from a decoupling theorem. Can be generated at very high scale.

$$\epsilon \sim \frac{gg'}{16\pi^2}\log\left(\frac{M_+}{M_-}\right) \sim 10^{-2} - 10^{-4}$$

ε can be much smaller, if arises from non-renormalizable operators.

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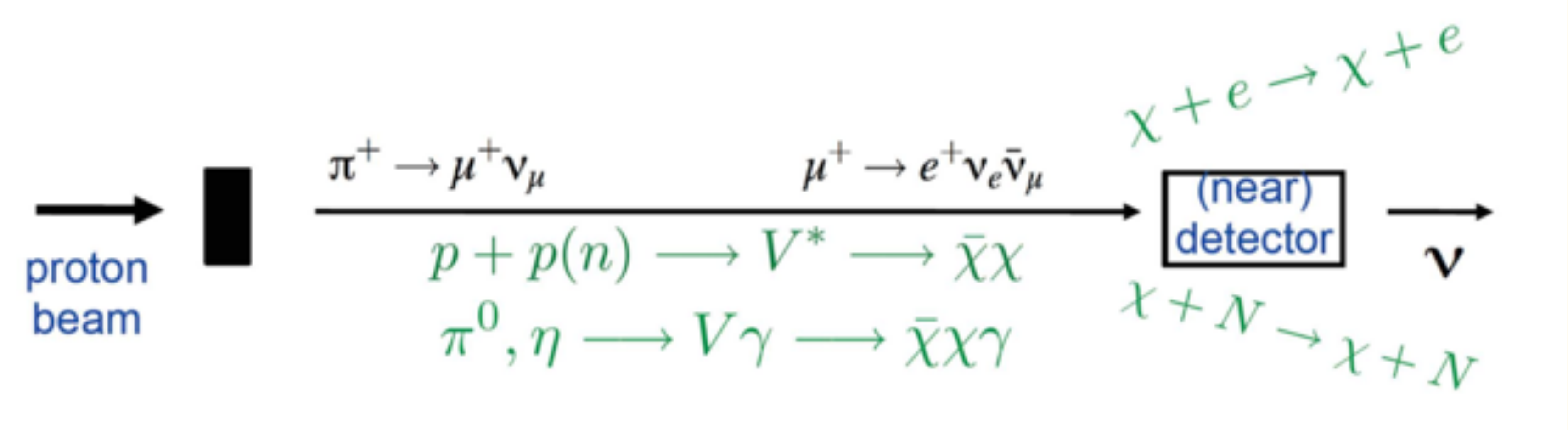
Significant effort to search for a hidden photon is ongoing

Search strategy depends on hidden sector structure

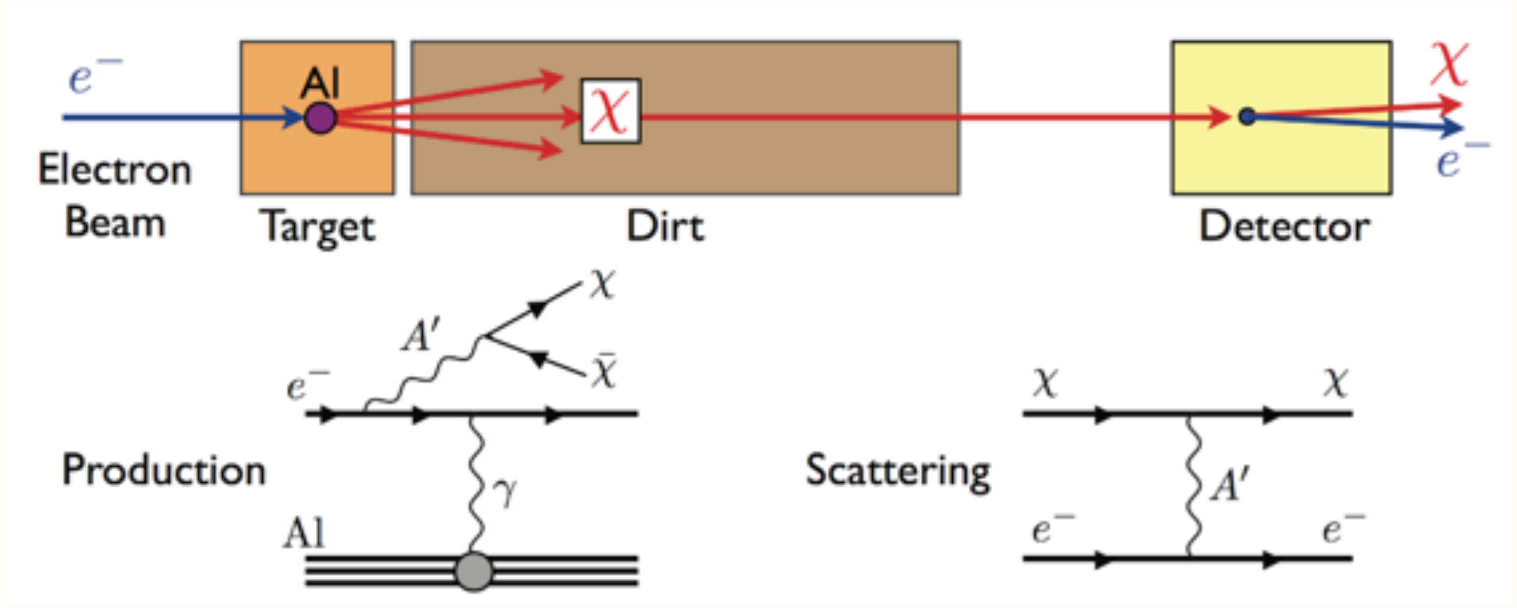
Beam-dump Experiments: A Dark Matter Beam

Neutrino Experiments



[MiniBooNE + Batell, deNiverville, McKeen, Pospelov, Ritz 2012]

Electron Beam-dumps

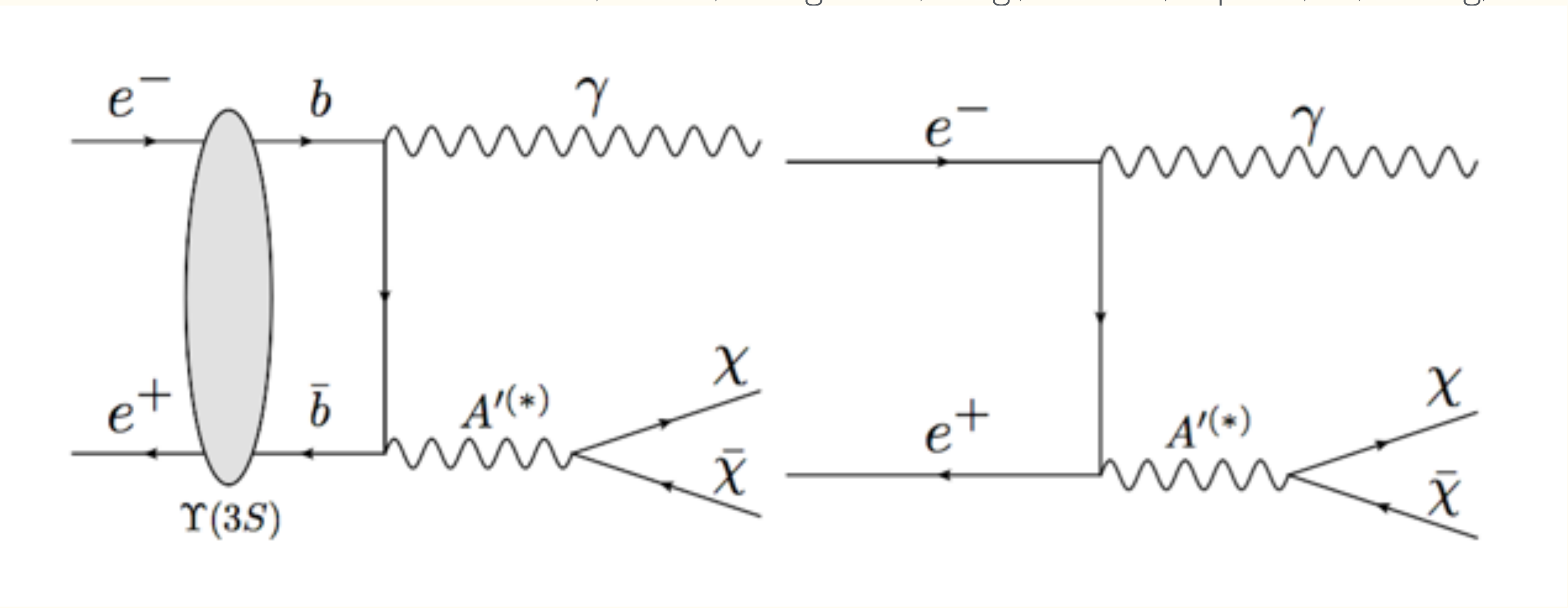


[Batell, Essig, Surujon 2014]

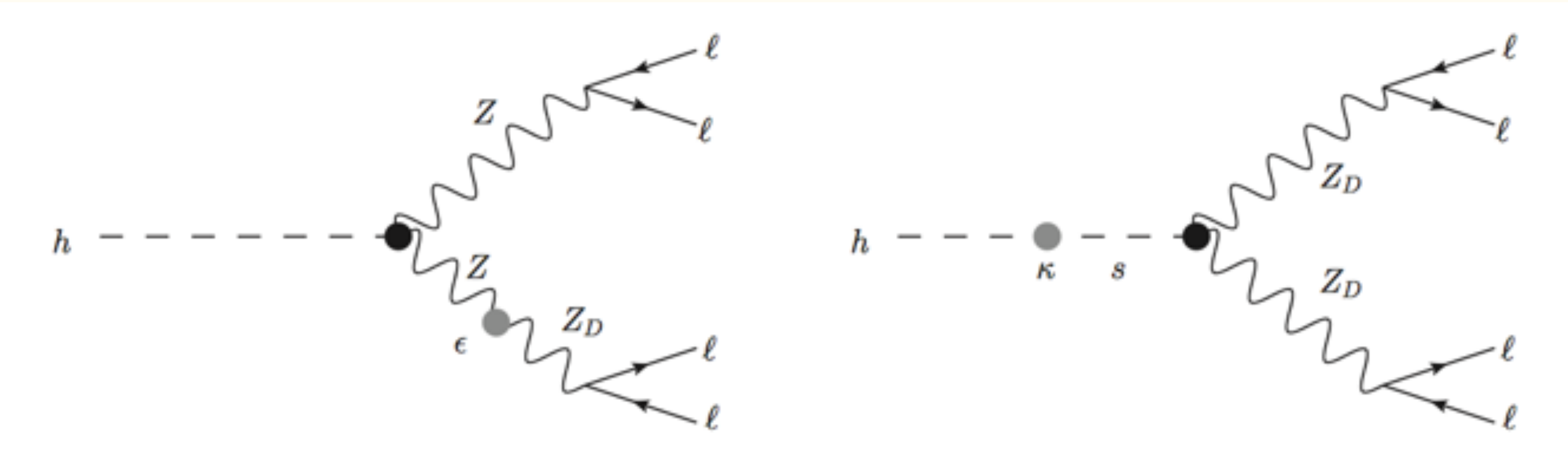
Colliders: Searching for the Mediator

[Bird et al. 2004; McElrath 2005; Fayel 20105; Dreiner et al. 2009; Borodatchenkova et al. 2006; Reece, Wang 2009; Essig., Mardon, Papucci, TV, Zhong, 2013]

Low-E Colliders



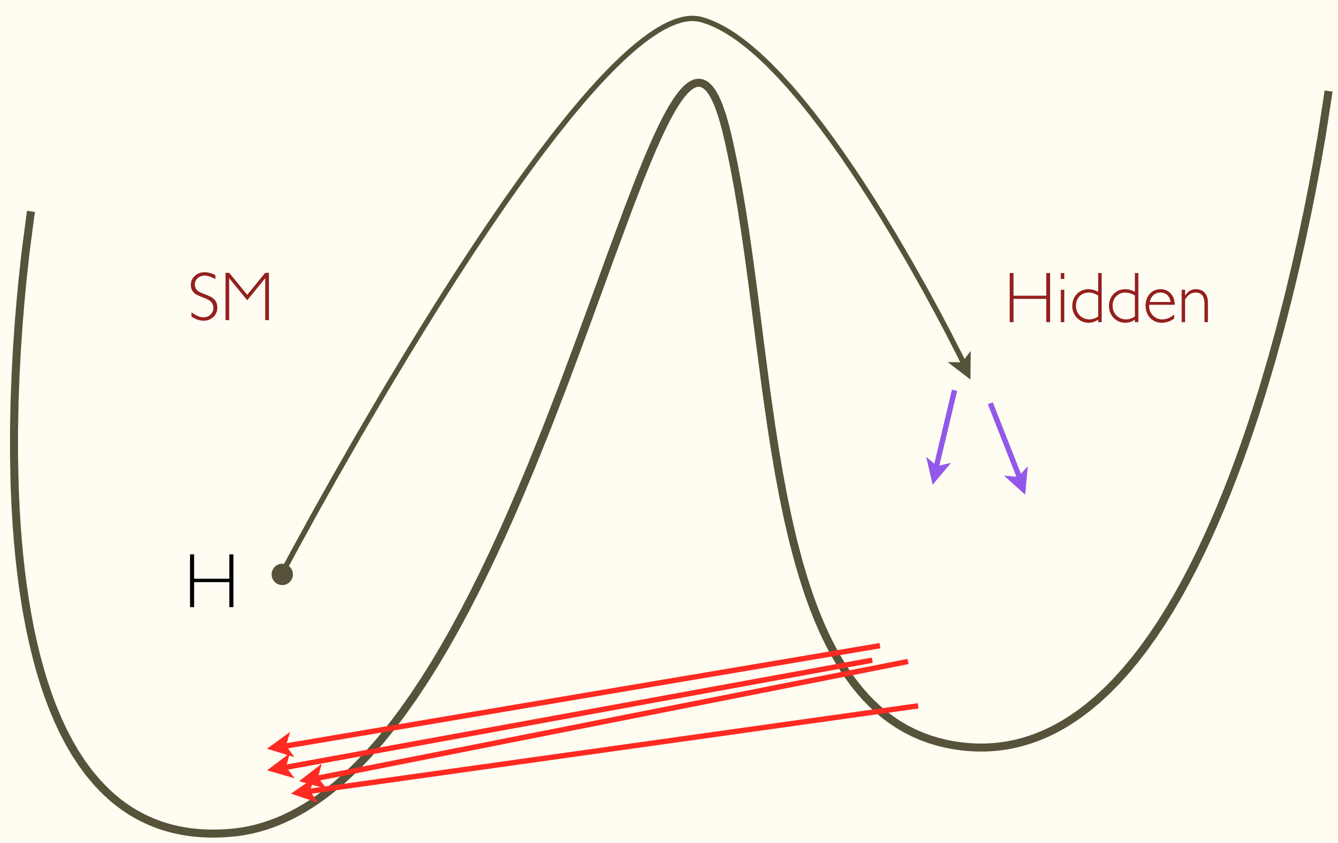
High-E Colliders



[Curtin, Essig, Gori, Shelton, 2014]

Colliders: Searching for the Mediator

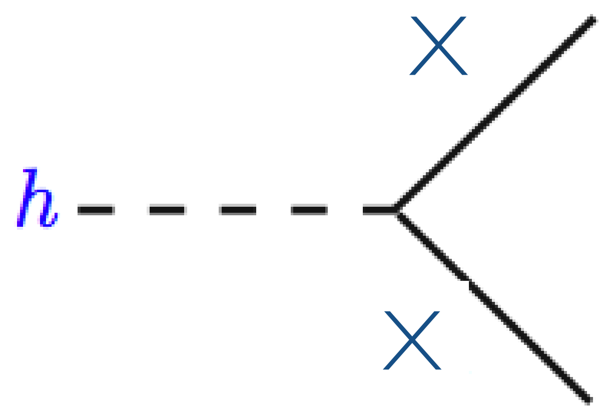
- The hidden photon can also allow to "return" to visible sector from a hidden valley.



- If it is very light, it would result in collimated jets of leptons and (possibly) hadrons. Lepton Jets (LJ).

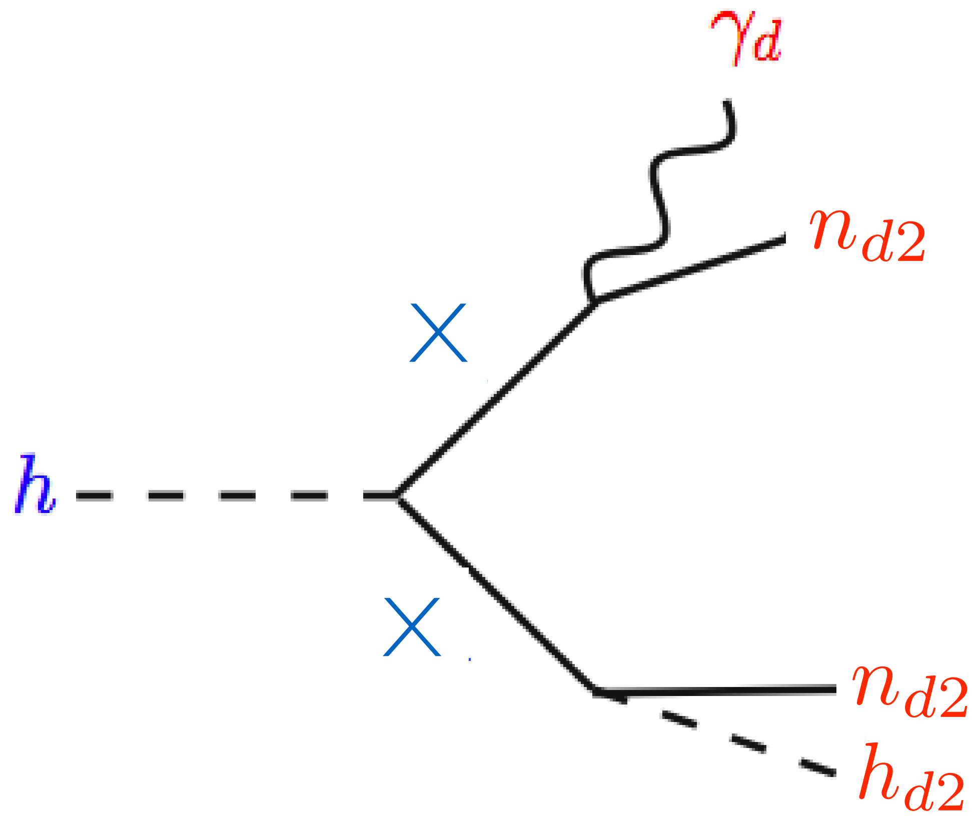
Example: Lepton Jet Topology

Higgs decays...



Example: Lepton Jet Topology

Into the Hidden Sector...



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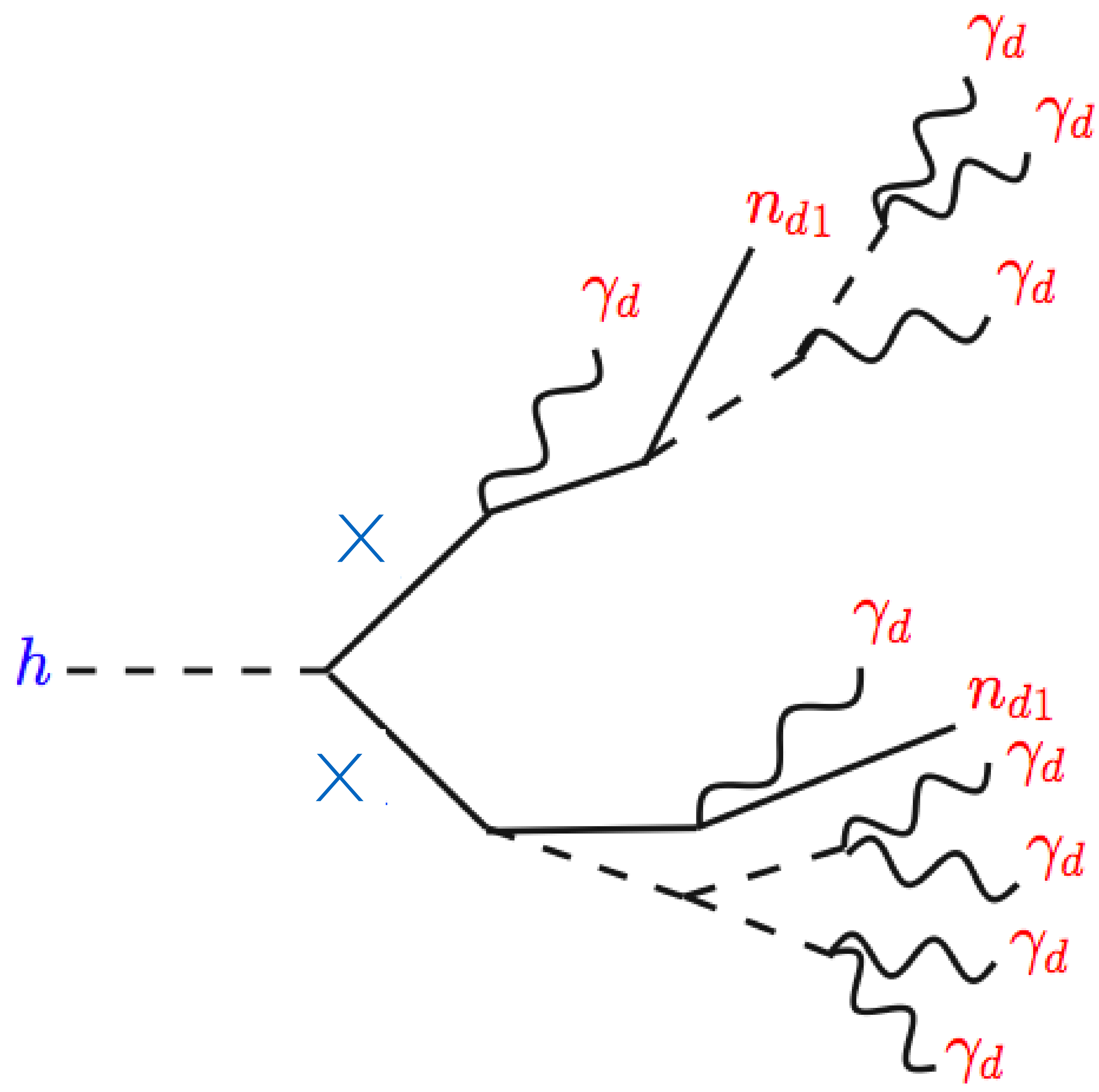
Hidden cascade...



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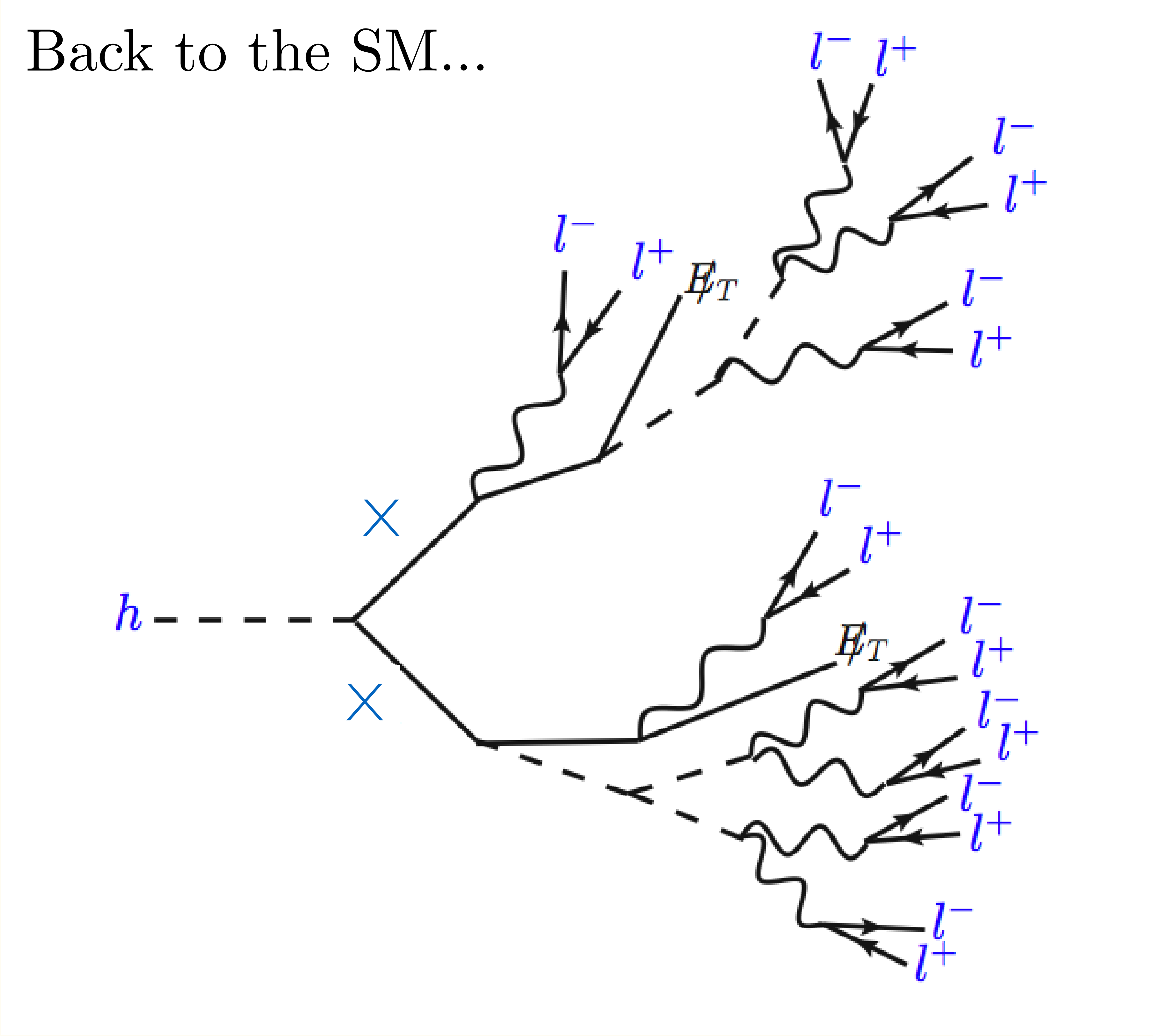
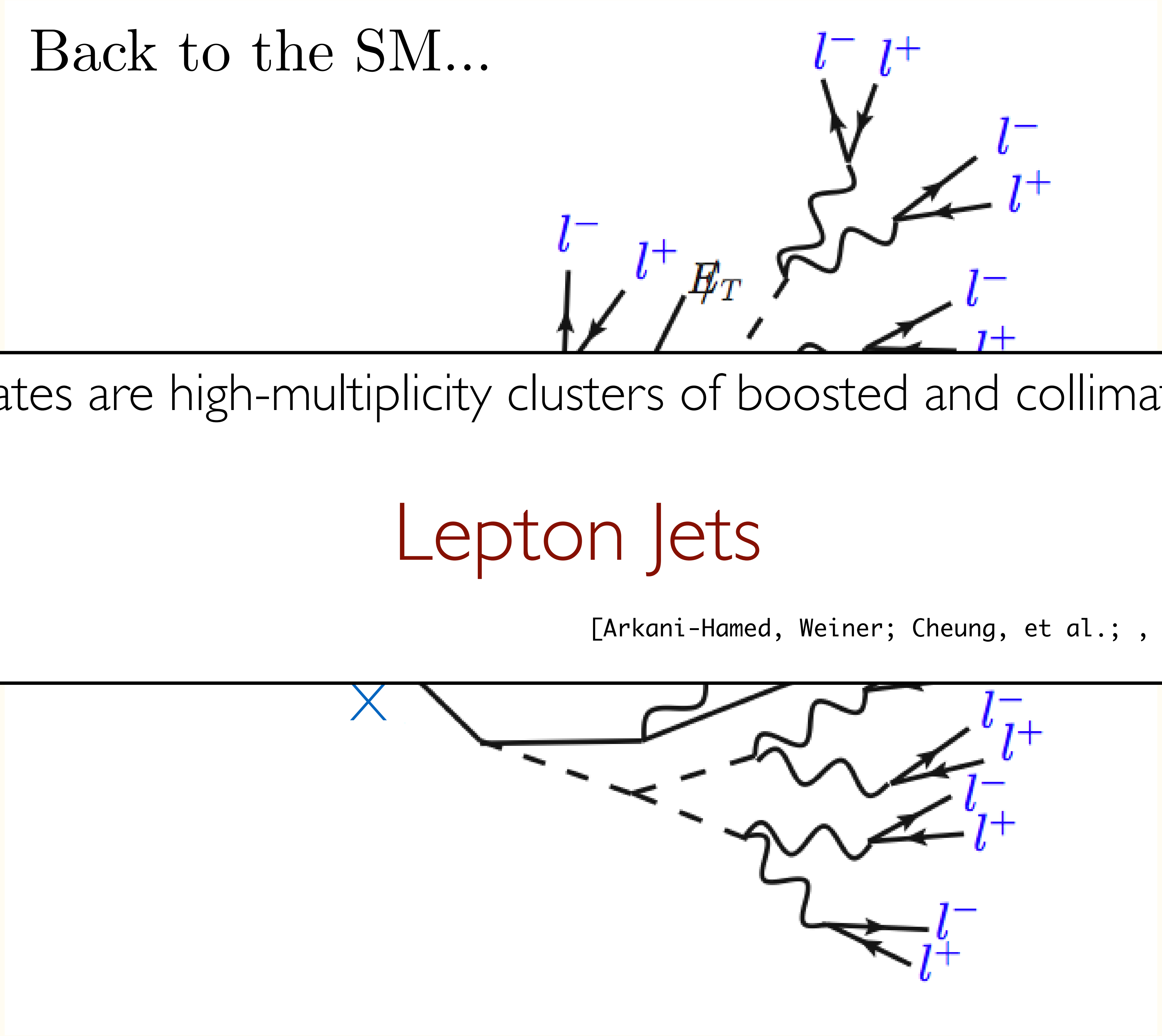


Example: Lepton Jet Topology

Back to the SM...



The final states are high-multiplicity clusters of boosted and collimated leptons

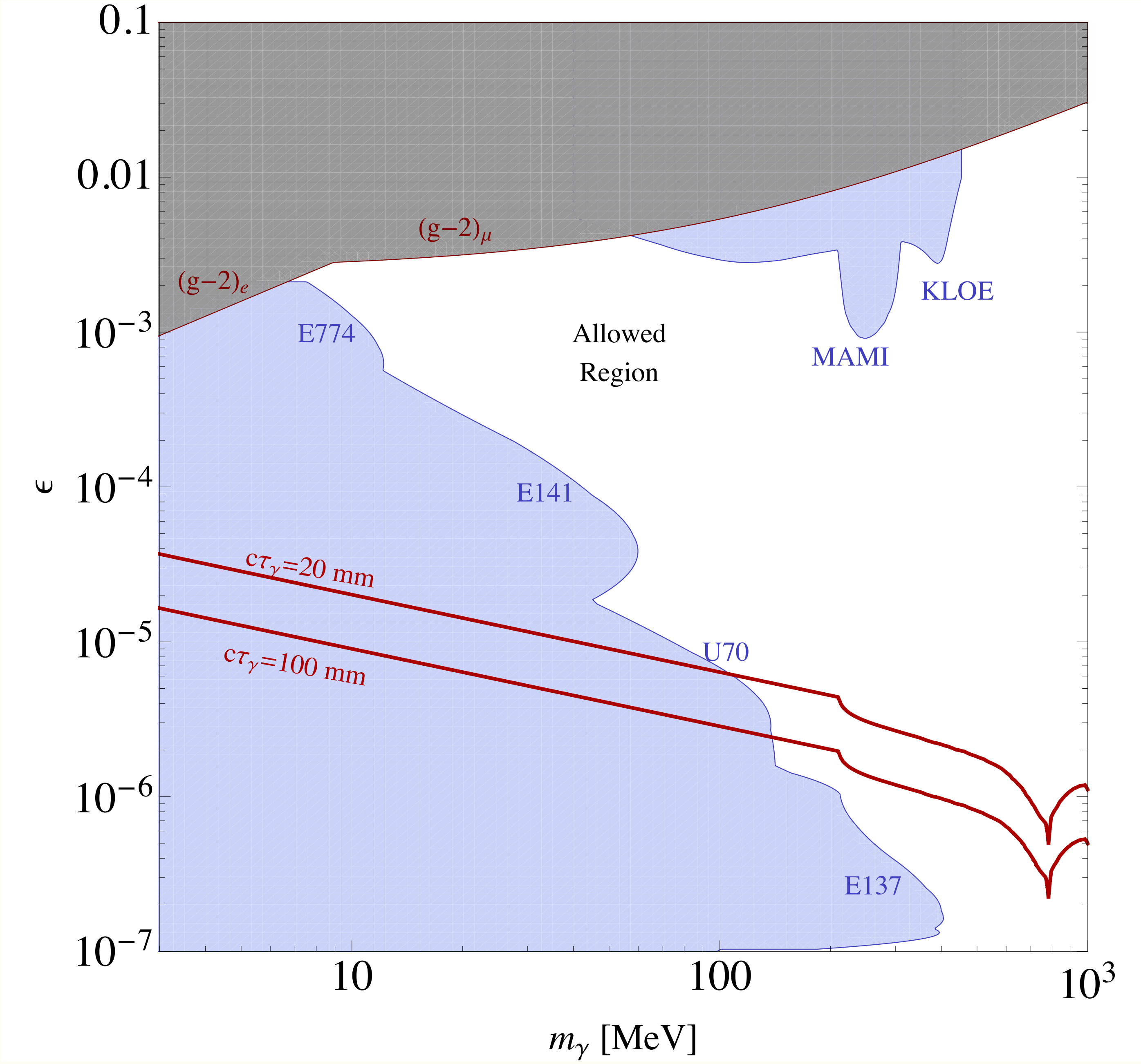
Lepton Jets

[Arkani-Hamed, Weiner; Cheung, et al.; , Baumgart, et al.]

Long Lived Higgs

- Lifetime is controlled by ε,

$$\tau_{\gamma_d} \sim (\epsilon^2 \alpha_{\rm EM} m_{\gamma_d})^{-1} \simeq 10^{-12}\ \mathrm{sec} \left(\frac{10^{-3}}{\epsilon}\right)^2 \left(\frac{\mathrm{MeV}}{m_{\gamma_d}}\right)$$



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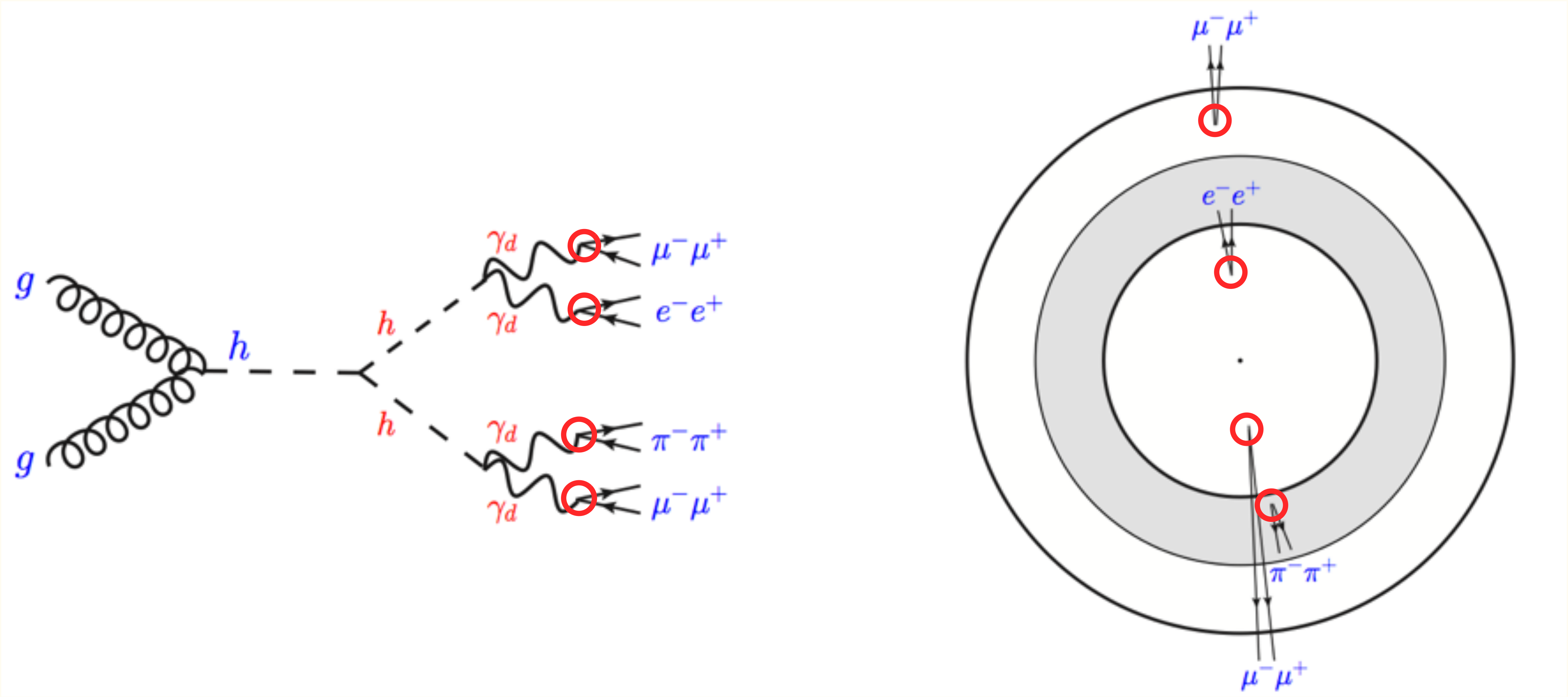
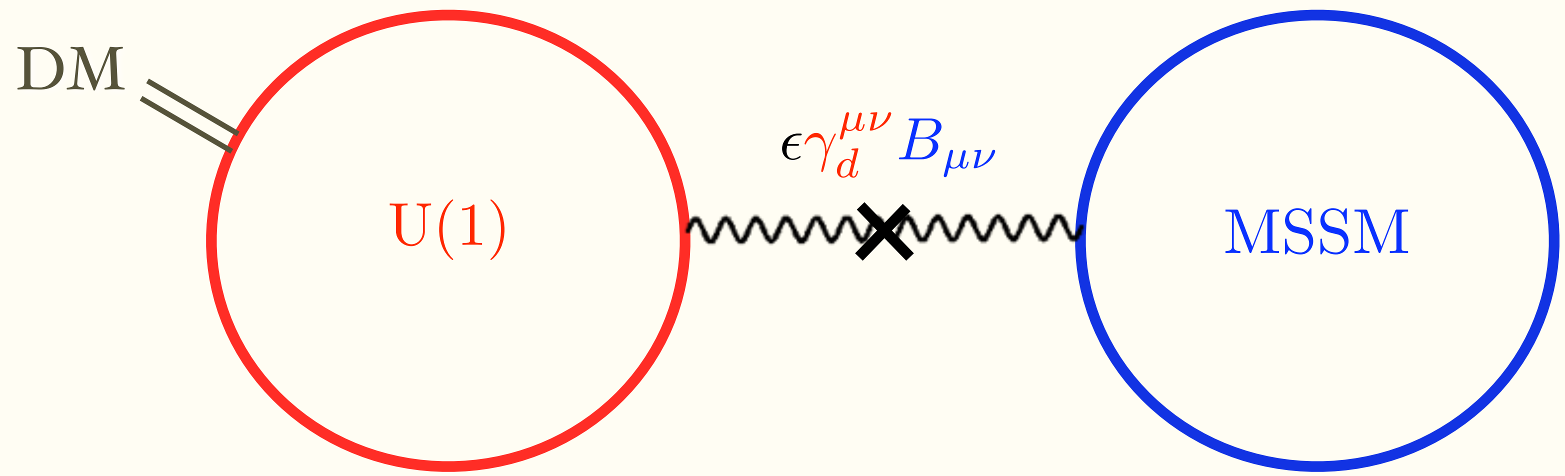
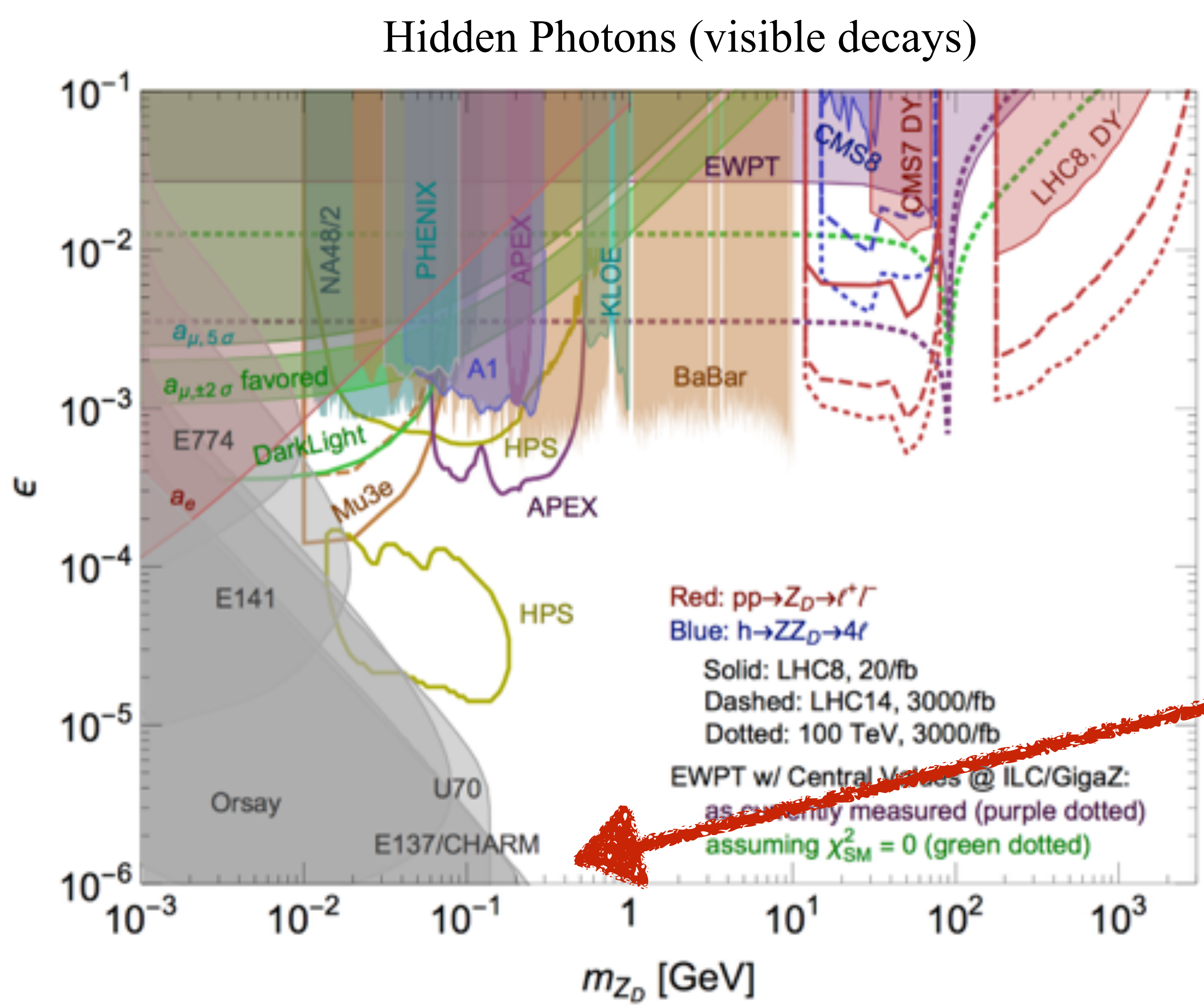
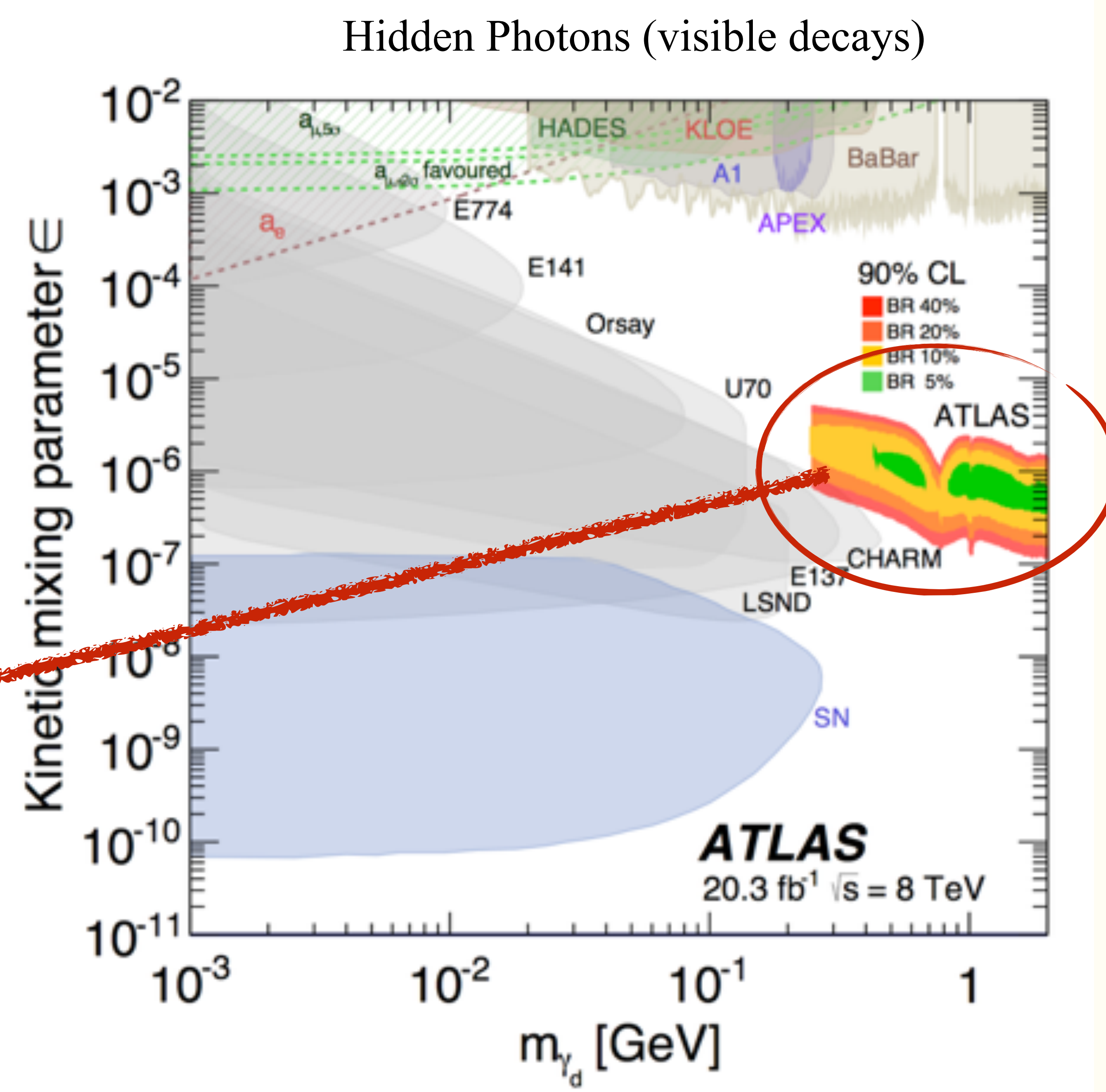


Collider and Beam-dumps: Selected Results







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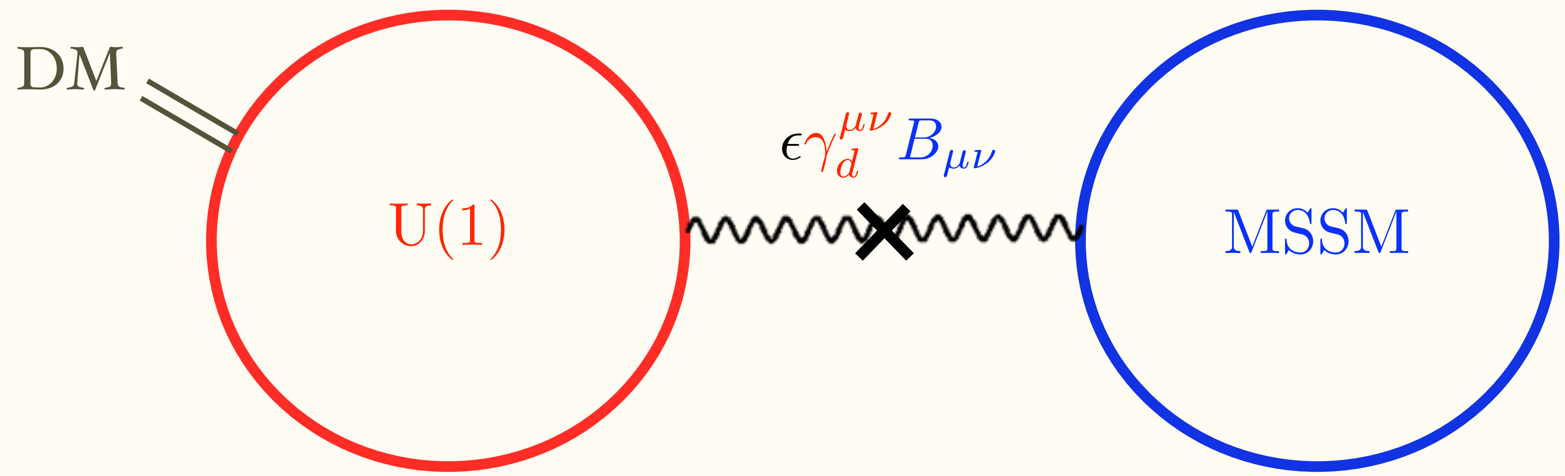

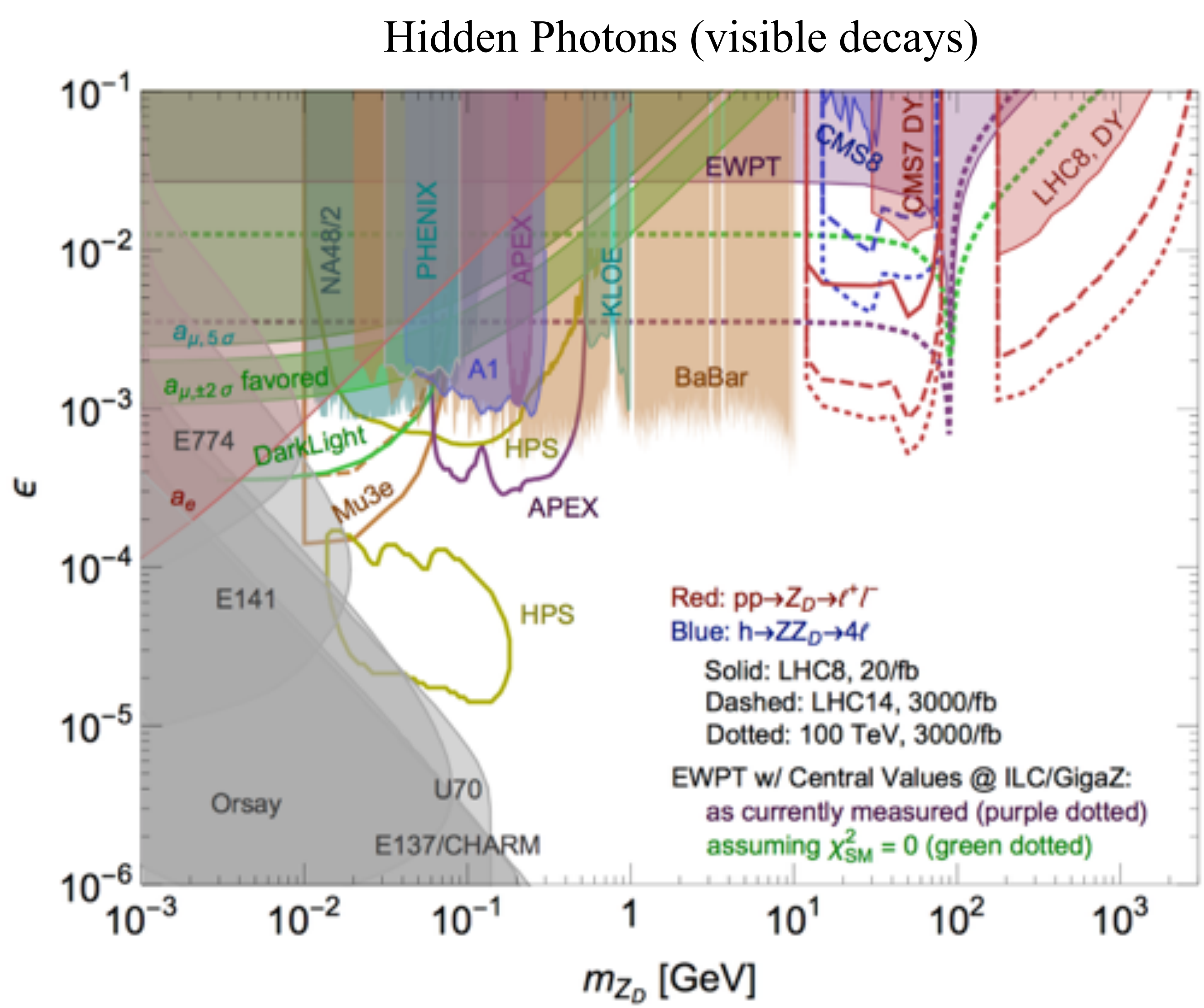

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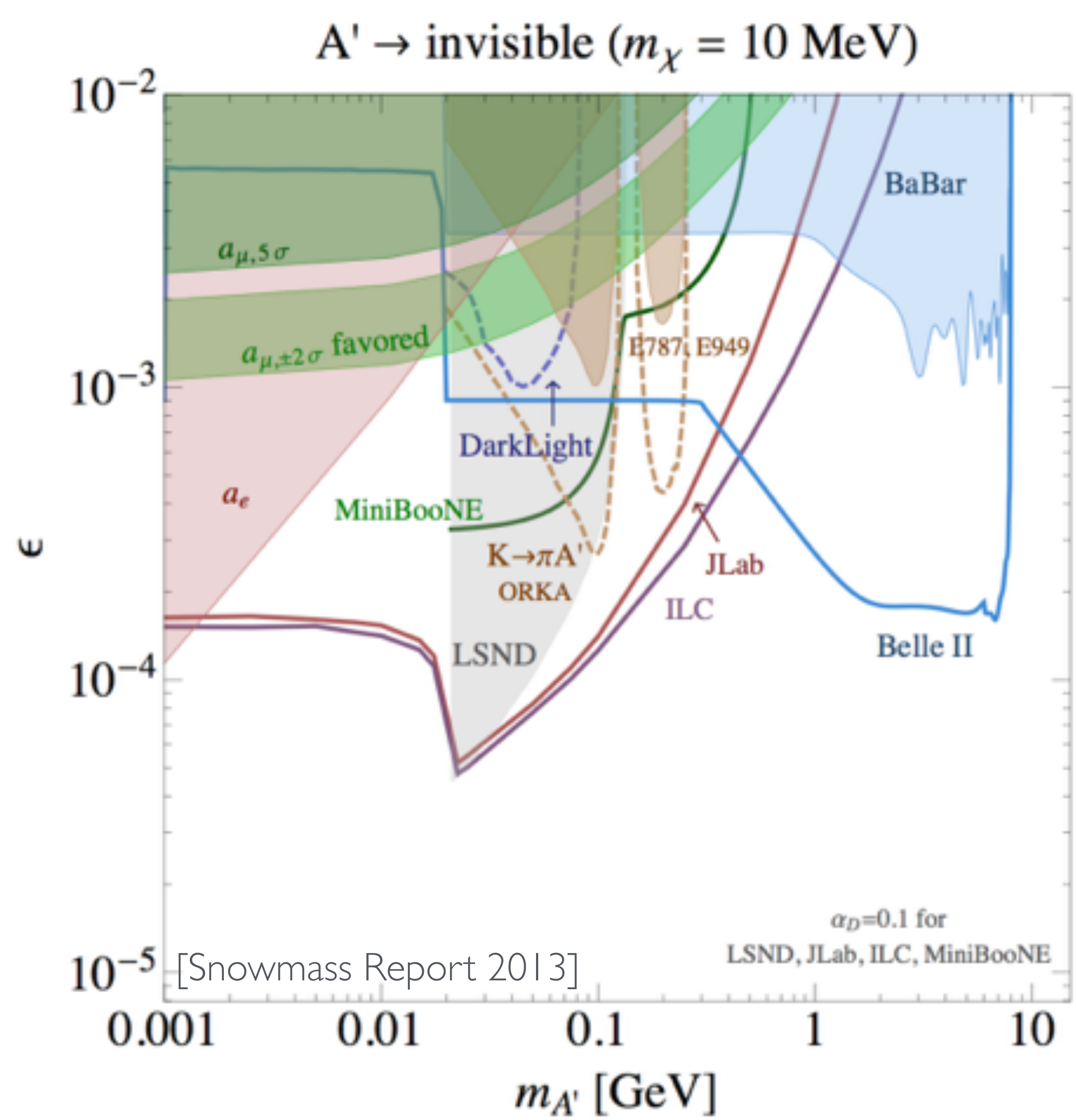


Pseudo Models

- When studying LJs at colliders, we should not make the mSUGRA mistake - do not focus on one specific (and unmotivated) model.

- Better use an effective description!

- The simplified model framework can be divided into two types:

    - **Effective models -** Models that capture the relevant low lying states of motivated theories - in the spirit of EFT.

    - **Pseudo models -** Effective models that reproduce a set of signatures. The only way to go with low-scale theories.

- **NOTE**: Simplified and pseudo-models are very useful, but still require work to extract (rough) bounds on a specific model. So how the results are presented is crucial!

Pseudo Models

- A wide range of parameters can be captured with a small set of pseudo-models.

- Assume N-step cascade.

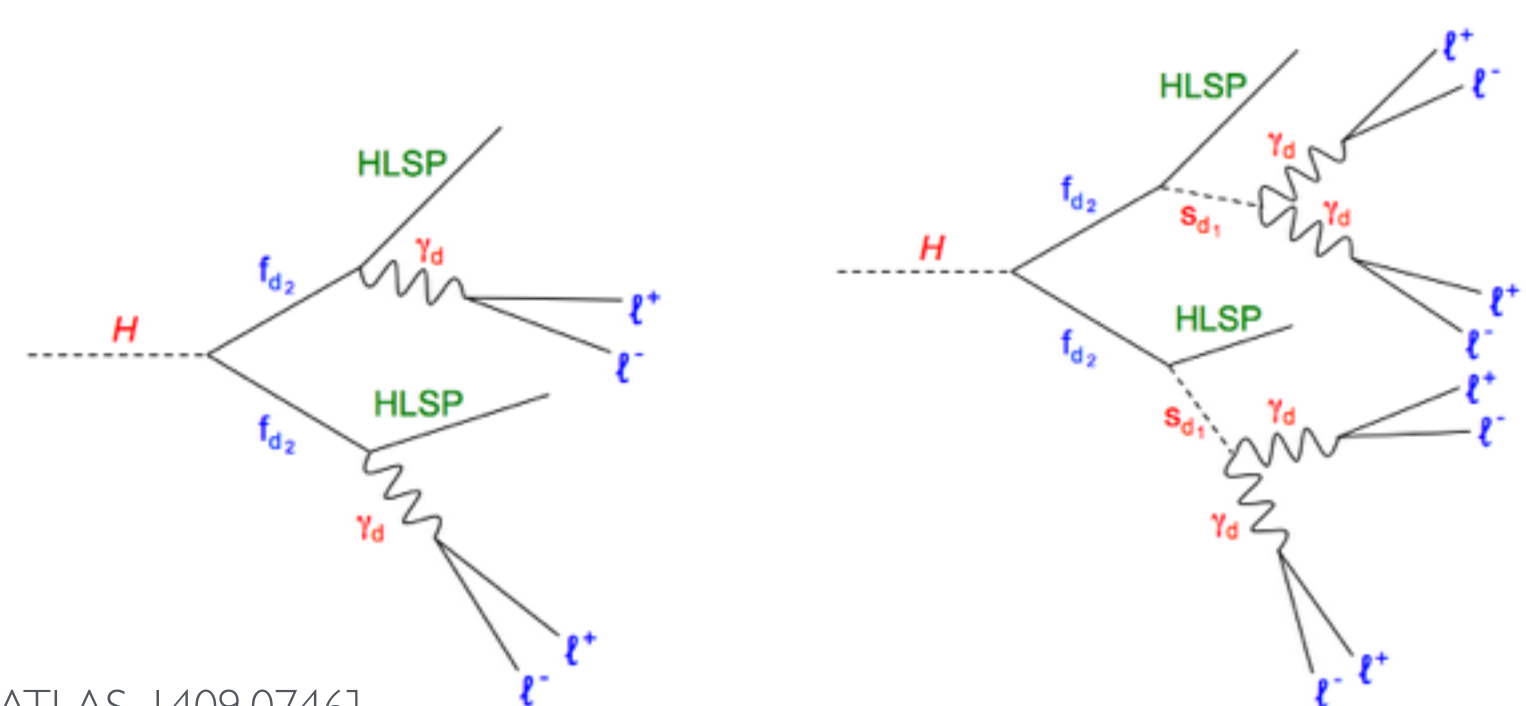
- Tunable parameters:

  - **Topology**: number of cascade steps (multiplicity and pT).

  - **Composition**: BR's of last step to SM (composition and MET distribution).

  - **Masses**: hidden spectrum (number and width of LJ).

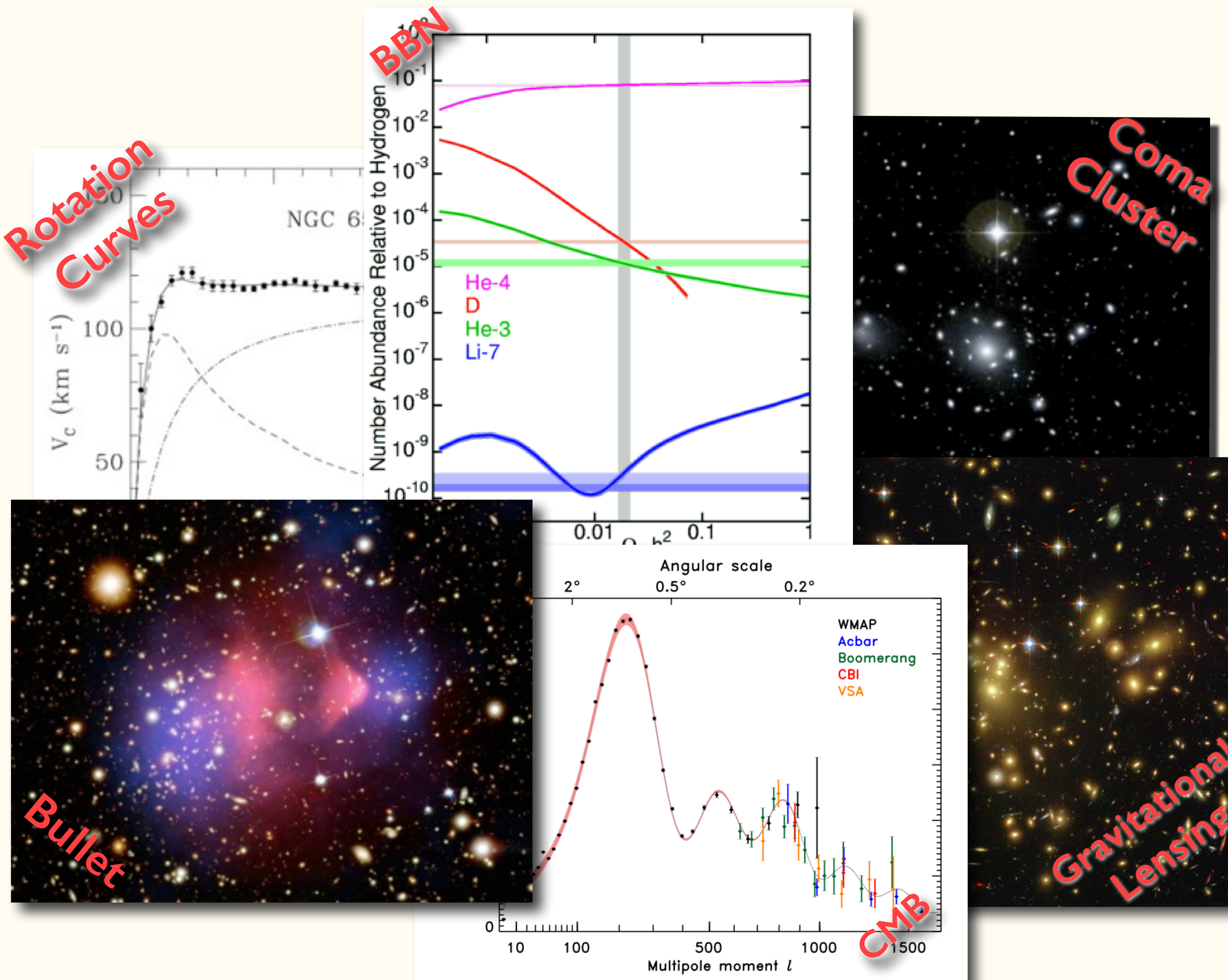
  - **Lifetime**.



[ATLAS, 1409.0746]

Exotics from Dark Matter

(Gravitational) Evidence for Dark Matter



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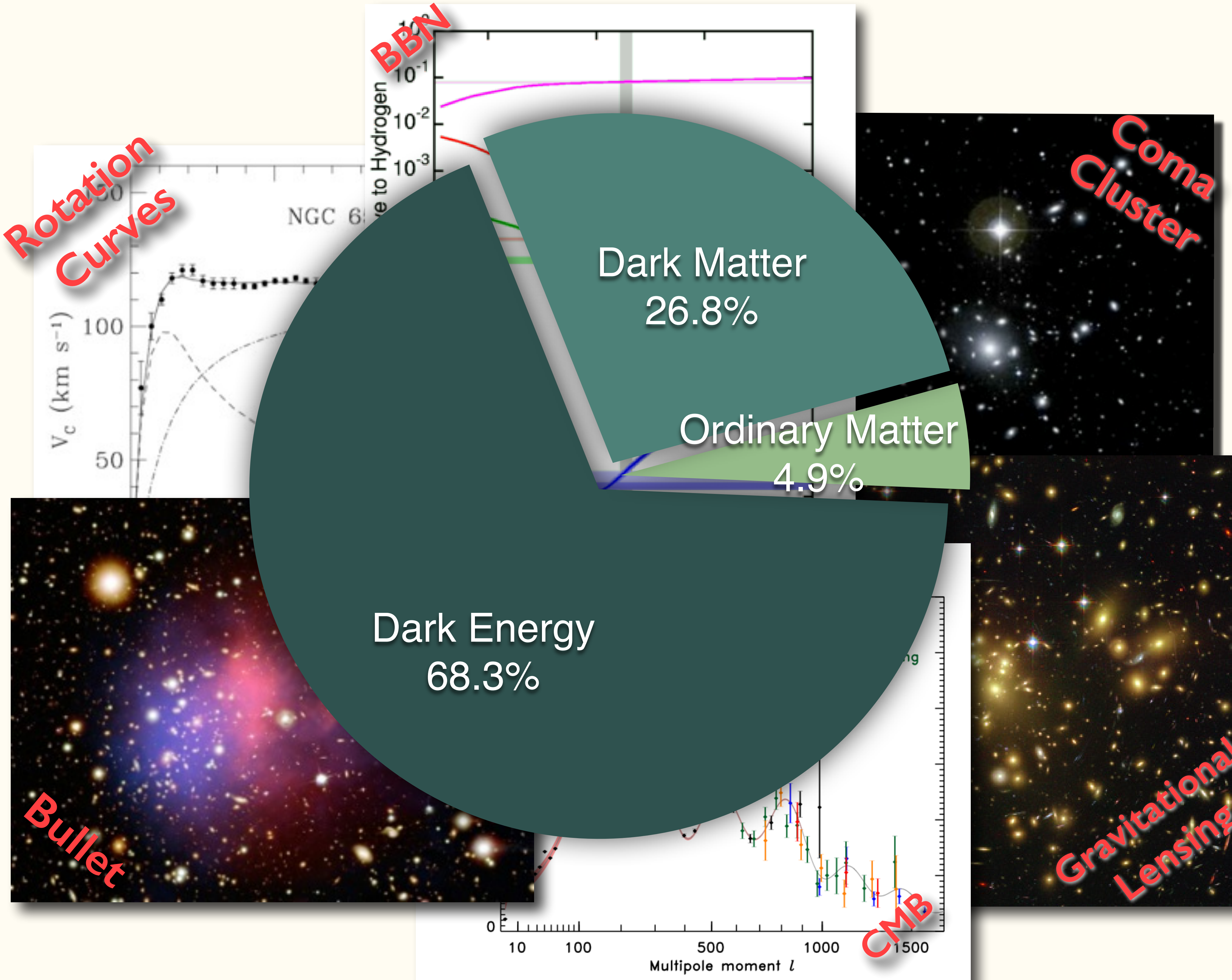

Will We Find Dark Matter?

All experimental signatures of dark matter are *gravitational*.

Q: Why should we see dark matter anywhere else?

A: Because it was produced in the early universe!

How do we explain the 85% DM abundance?

Thermal WIMP
(Weakly Interacting Massive Particle).

Going Beyond WIMPs?

Obsessed with the WIMP...

For the last ~30 years we have been (mostly) focusing on the WIMP scenario

Problem made up by theorists..

Obsessed with the WIMP...

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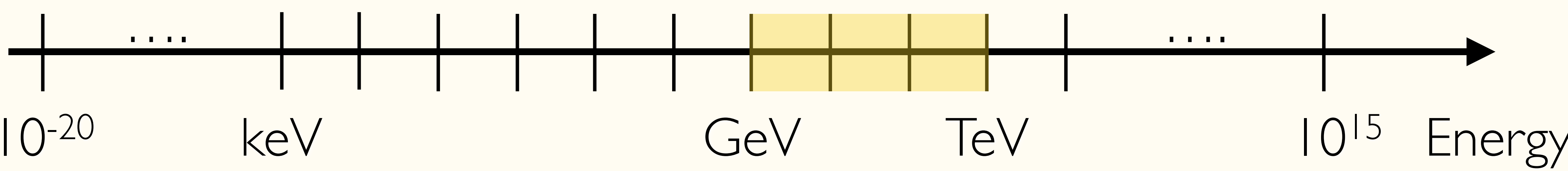
WIMP ⟷ Naturalness Problem

Our experimental effort is strongly focused on the WIMP!



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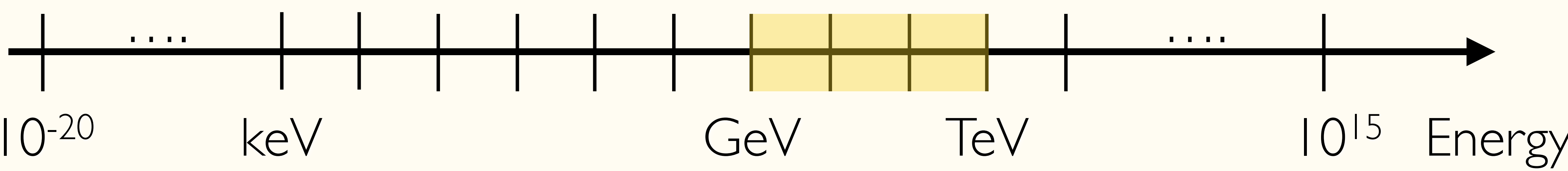

Lots more to do!

(repeat everything we did for the WIMP…)

Classifying Theories of DM

Dark Sector

- Spin
- Mass
- Self-Interactions
- Light States
- Gauge symmetries
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- Non-thermal
- Asymmetric
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Classifying Theories of DM

Dark Sector	Production Mech.	Mediation Scheme
• Spin	• Freeze-out	• Gravity
• Mass	• Freeze-in	• Weak-scale Mediator
• Self-Interactions	• Freeze-out and decay	• Light Hidden photon
• Light States	• Non-thermal	• Axion portal
• Gauge symmetries	• Asymmetric	• Higgs portal
• …	• Misalignment	• …
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Classifying Theories of DM

Dark Sector	Production Mech.	Mediation Scheme	Couplings
• Spin	• Freeze-out	• Gravity	• Quarks
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Couplings

- Quarks
- Gluons
- Charged Leptons
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- …

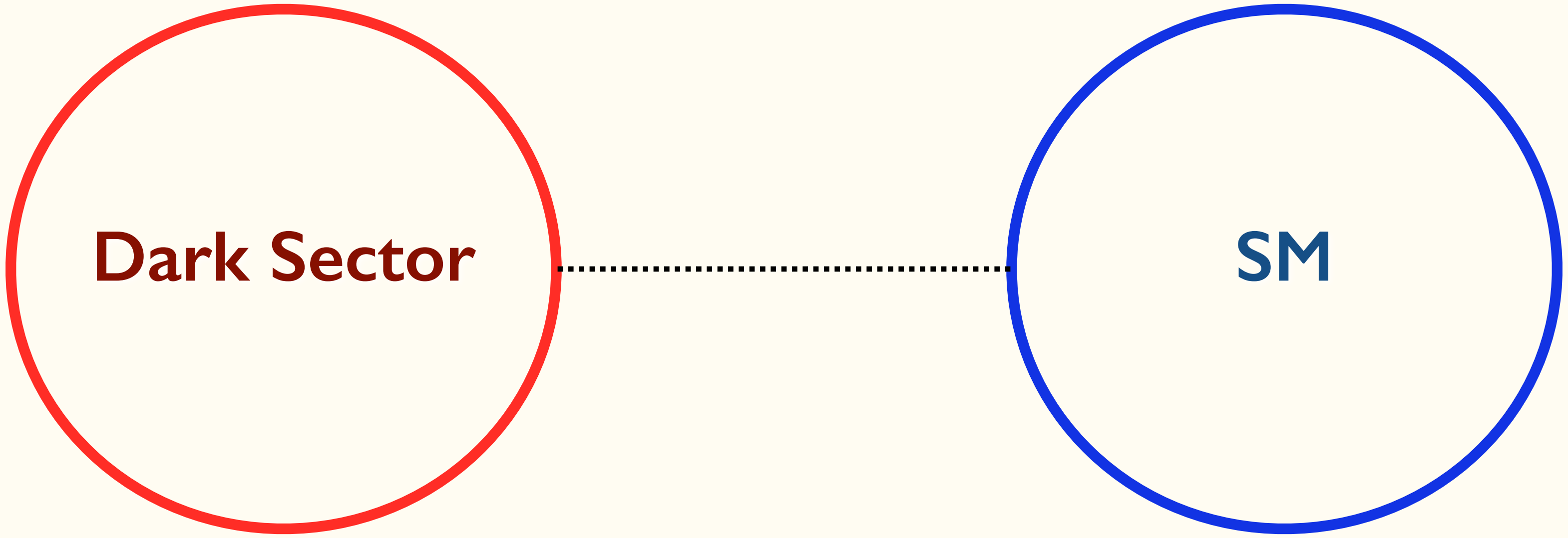
Direct

Colliders

Indirect

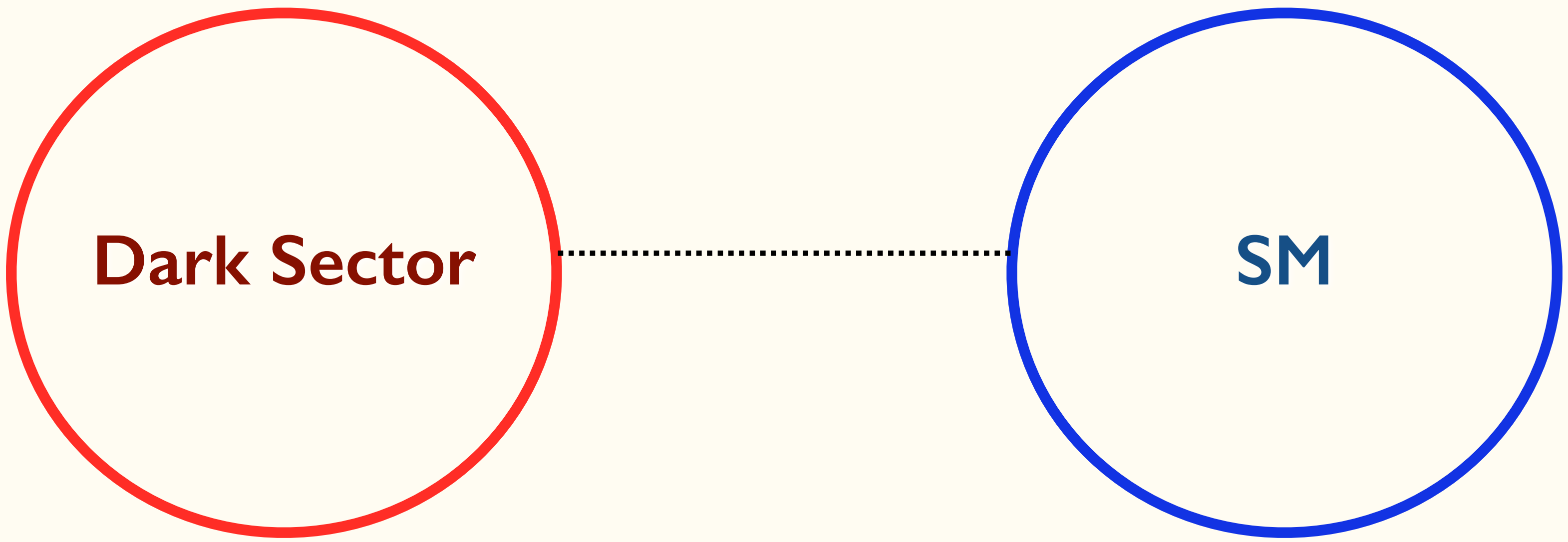
Only a small fraction is probed for the WIMP

New production mechanisms and mediation schemes often imply a hidden dark sector. Possibly with complex dynamics.



Such hidden sectors often include low scale particles, below the GeV scale.

Very different from the WIMP paradigm!!



Signatures from the dark sector strongly depend on the production mechanism and mediation scheme!

Three examples:

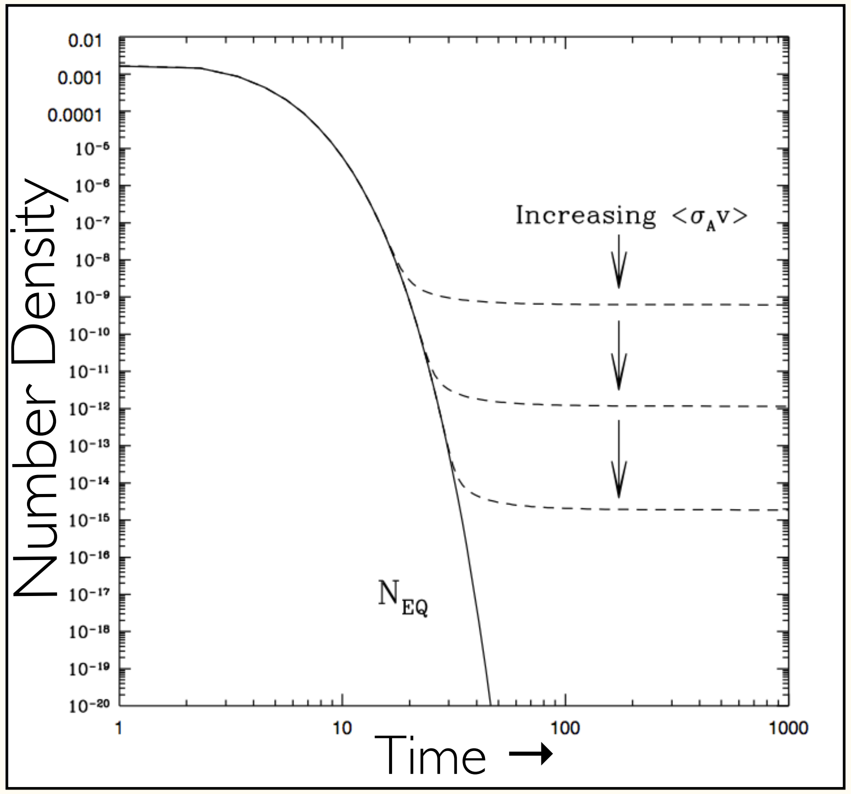
- WIMP Coannihilation: Soft final states
- SIMP with vector mediator: Semi-visible Jets
- Freeze-in: Displaced vertices

Example I
Coannihilations

The Thermal WIMP

- Single parameter: $\langle \sigma v \rangle$

- A simple analysis shows,



$$\langle \sigma v \rangle \sim 2 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{sec}$$

- For standard annihilation cross-section:

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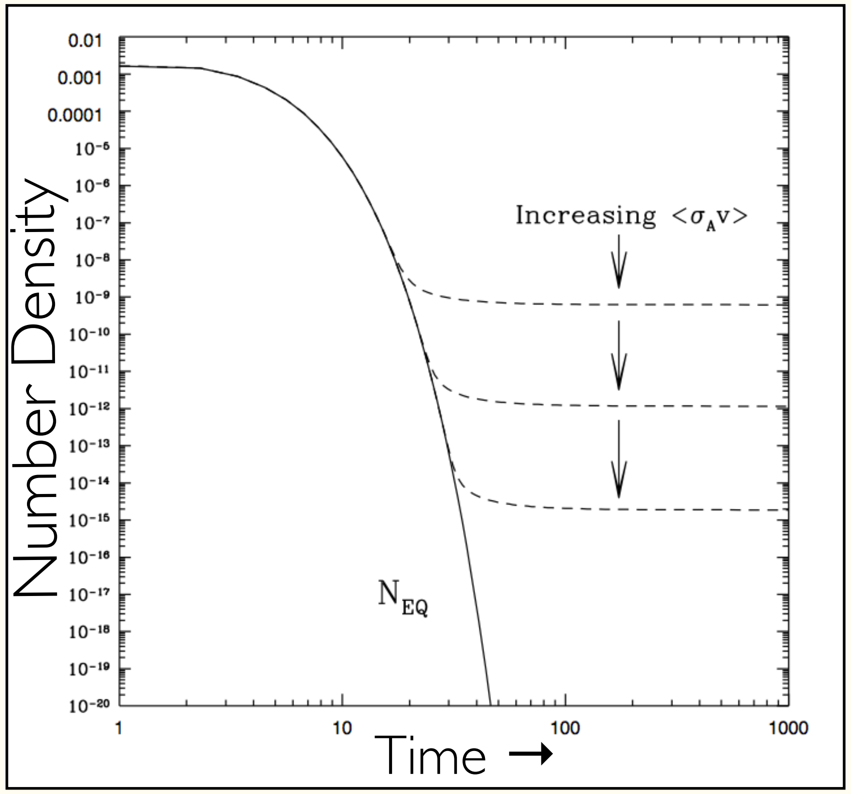

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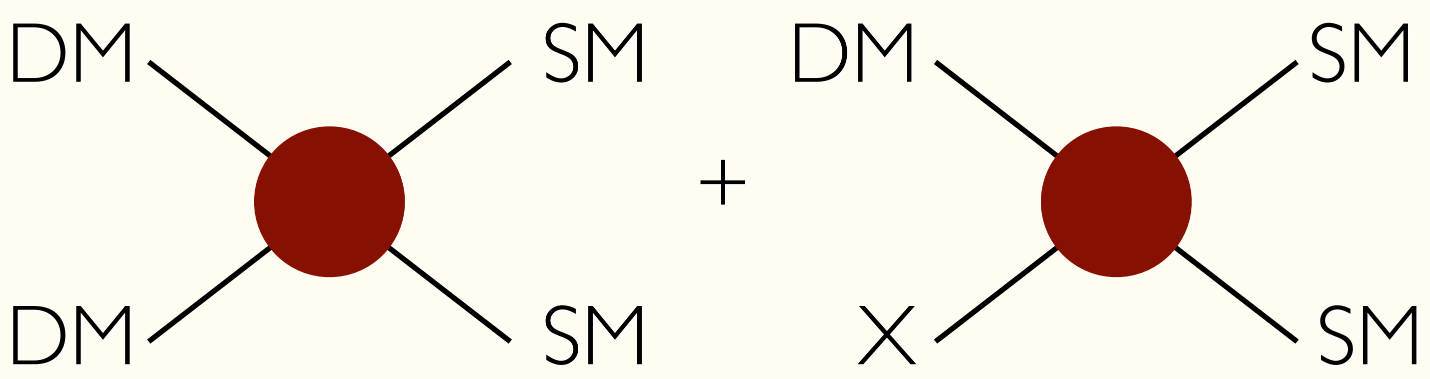
Same mass-scale we are now probing at the LHC

Coannihilations

- If there are additional states which are semi-degenerate with DM, the DM annihilations is supplemented with coannihilations.

- Coannihilations may then be crucial for the freeze out mechanism



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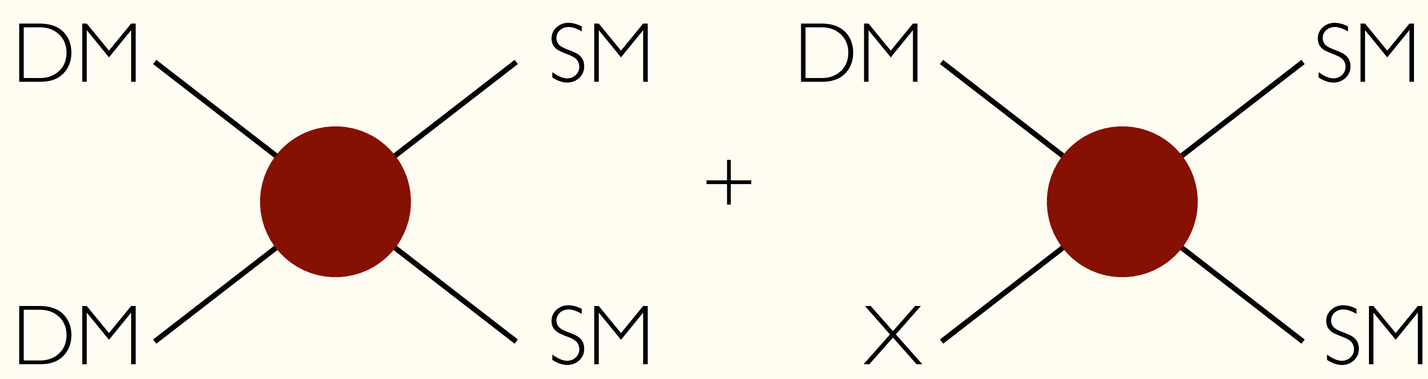

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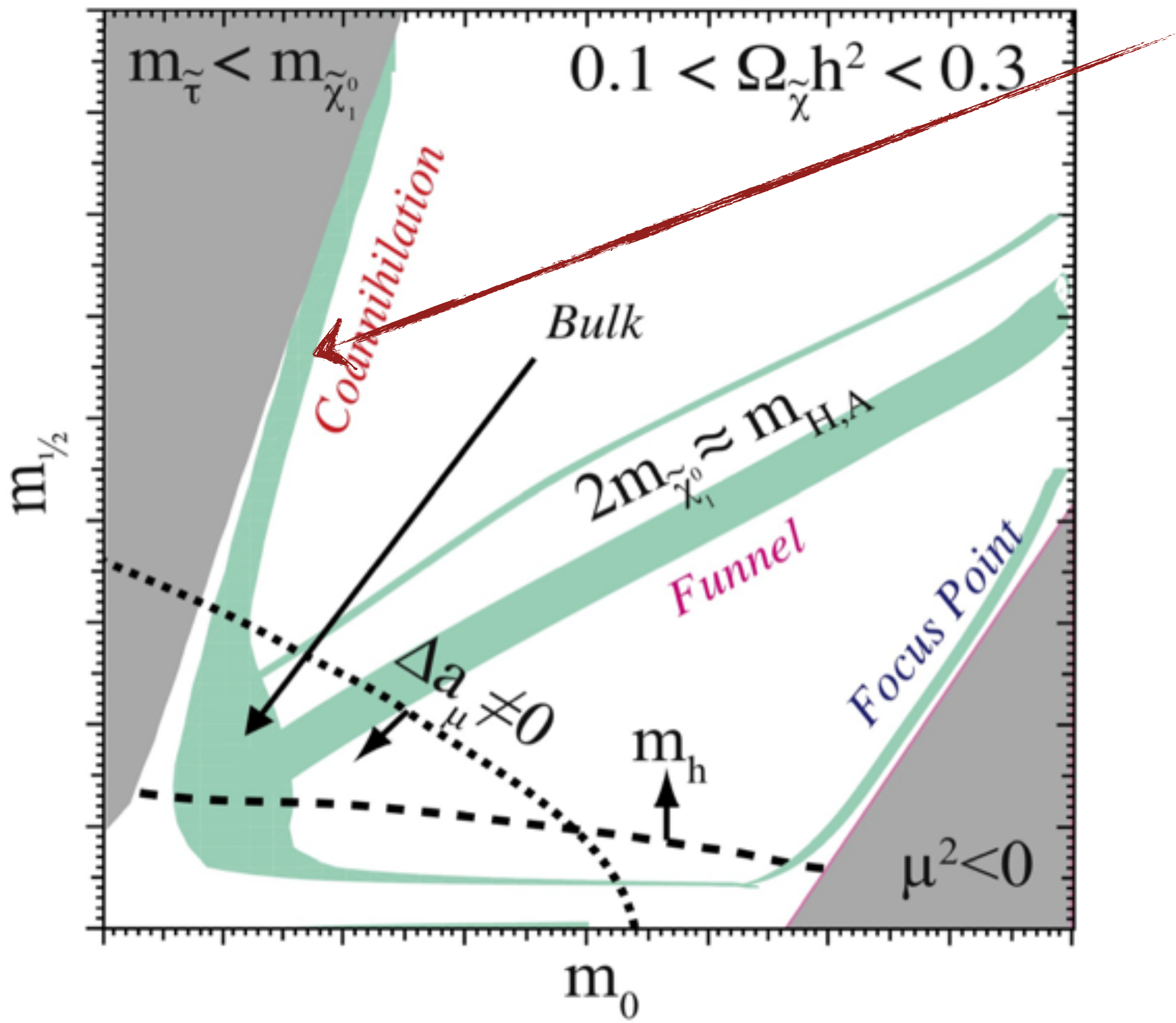
Coannihilations

Known example: mSUGRA



Degenerate neutralino and stau. Annihilation rate enhanced.

Asymmetric DM

[Nussinov, 1985; , Kaplan, 1992]

Experimental fact:

$$\Omega_{\rm DM} \simeq 5\Omega_b$$

Main idea:

Relate the DM abundance to the baryon abundance.

But:

Baryon density is asymmetric (no anti-baryons), so DM may also be asymmetric.

Asymmetric DM

- If we take this as a hint, both densities are related through some joint dynamics.

[Nussinov, `85; Gelmini, Hall, Lin, `87';
Barr, Chivukula, Farhi, `90'; Kaplan, Luty, Zurek, `09;…

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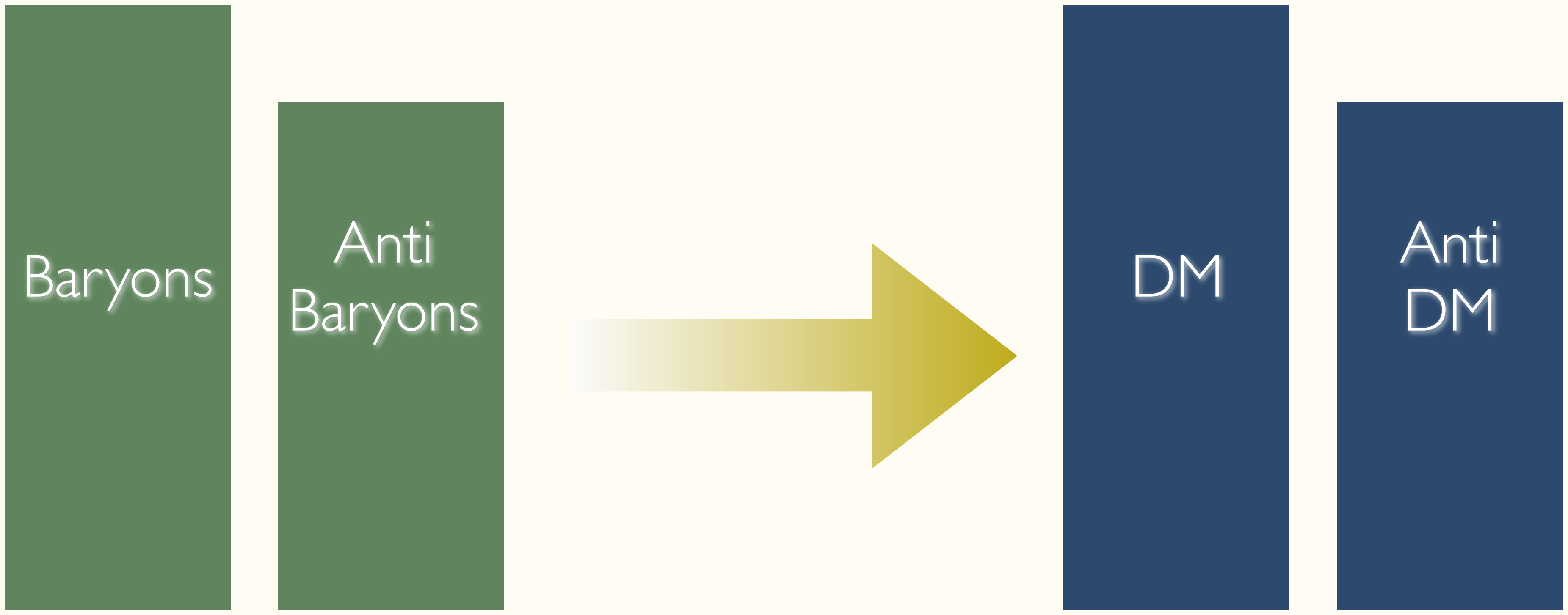

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1. Asymmetry is **created** in one or both sectors. Couplings between the two sectors ensure an asymmetry in both.

2. The two sectors **decouple**.

Asymmetric DM

- If we take this as a hint, both densities are related through some joint dynamics.

[Nussinov, `85; Gelmini, Hall, Lin, `87’;
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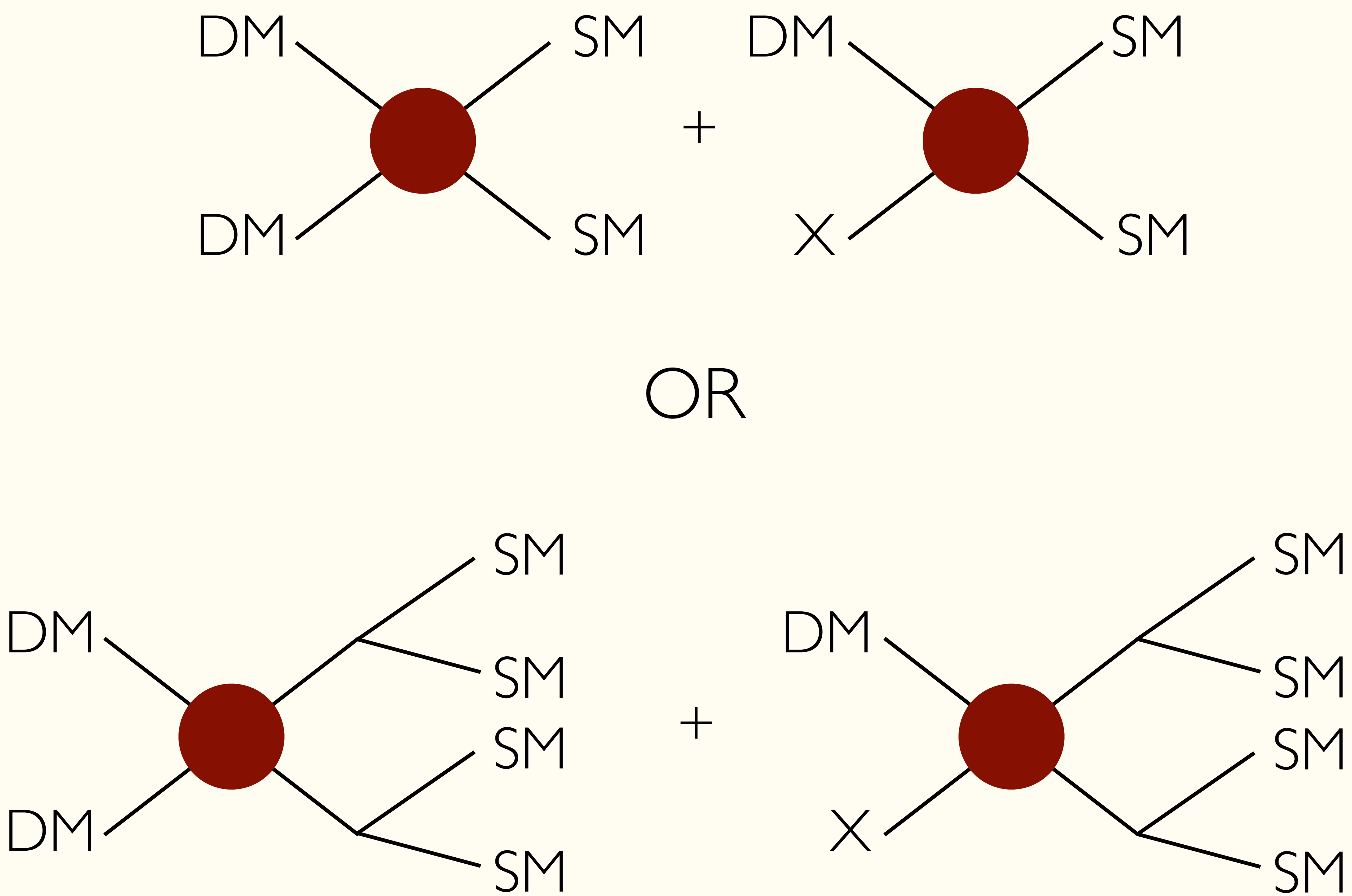
Coannihilations in Asymmetric Dark Matter

- Coannihilations is also motivated in ADM.
- ADM requires very large annihilation rate.
- Heavy mediators is more or less excluded by monojets and direct detection if dark sector is mediated by heavy fields. [March-Russell, Unwin, West, 2012]
- These could be evaded if annihilations are either via light mediators or coannihilations with soft final states.

Coannihilations in a Hidden Sector

If DM resides in a hidden sector, it may easily be part of a semi-degenerate multiplet of some hidden symmetry (just like our pions).

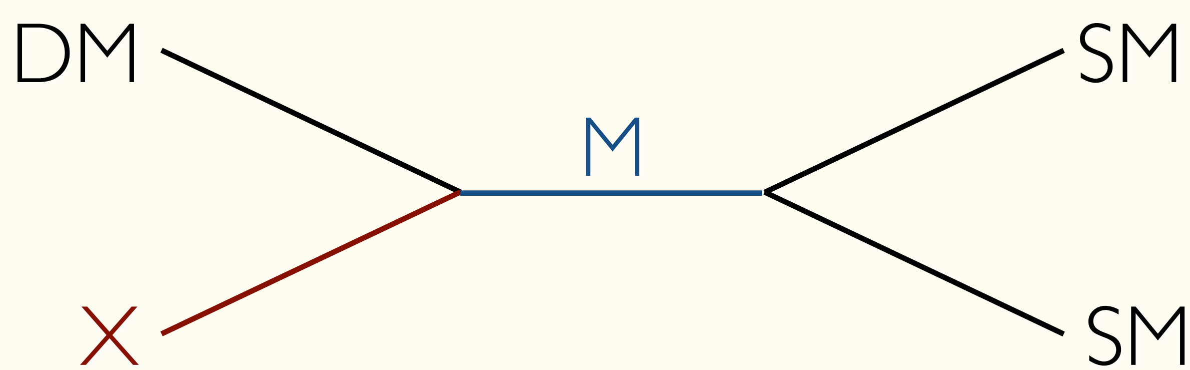


Coannihilations in a Hidden Sector

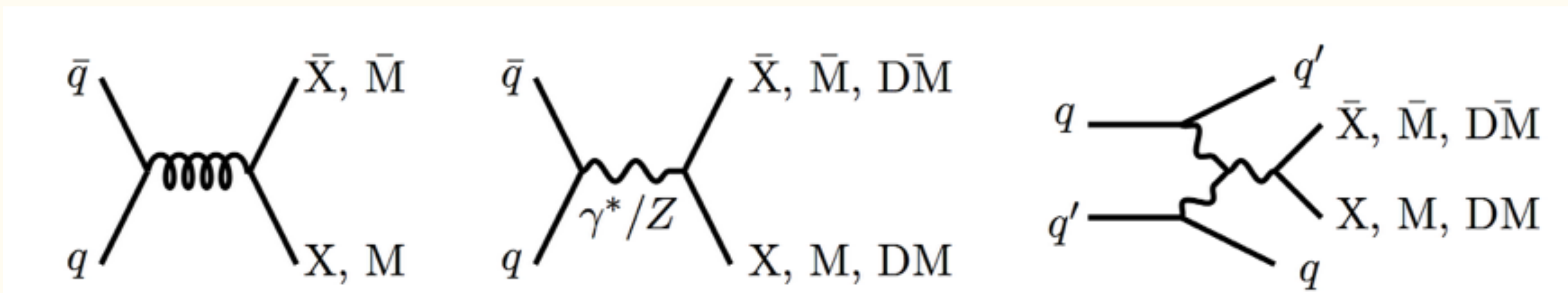
What are the LHC consequences of coannihilations?

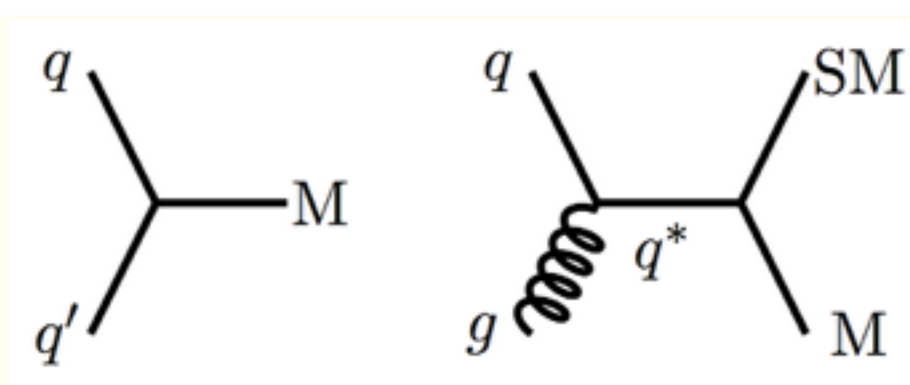
[Baker et al. 2015]

- Assume for simplicity the s-channel case:



- Production mechanism depends on charges of X and M.



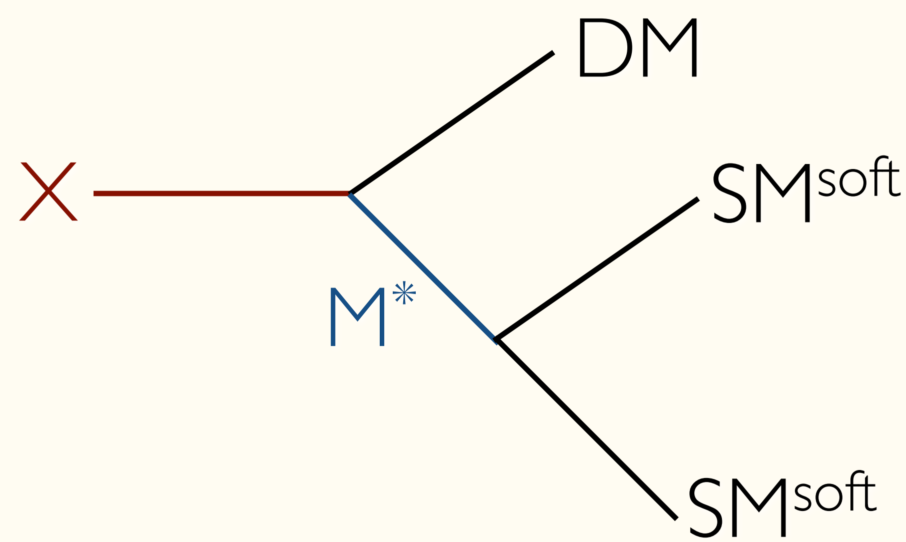


Coannihilations in a Hidden Sector

What are the LHC consequences of coannihilations?

[Baker et al. 2015]

- Small mass splitting imply soft SM final states.
- Decay modes include:



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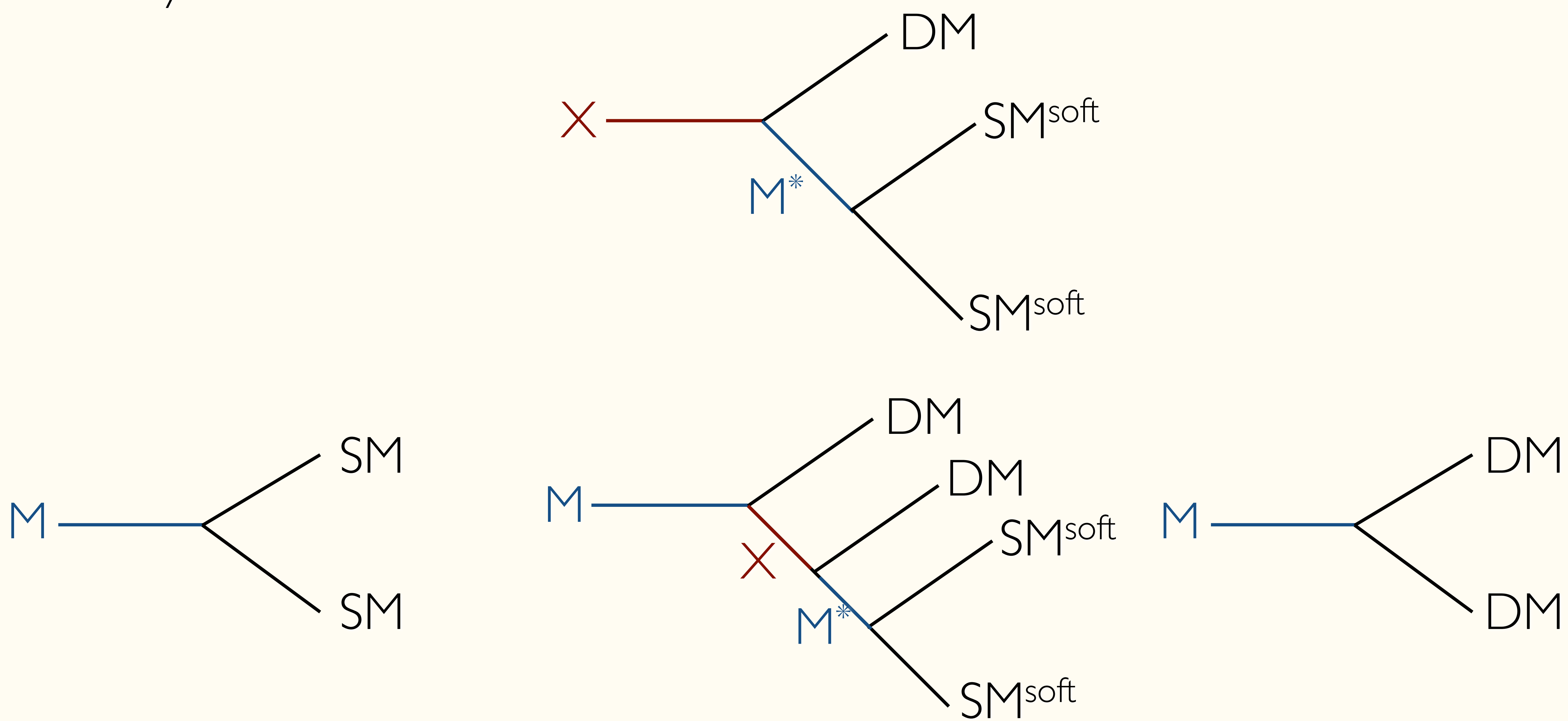


Coannihilations in a Hidden Sector

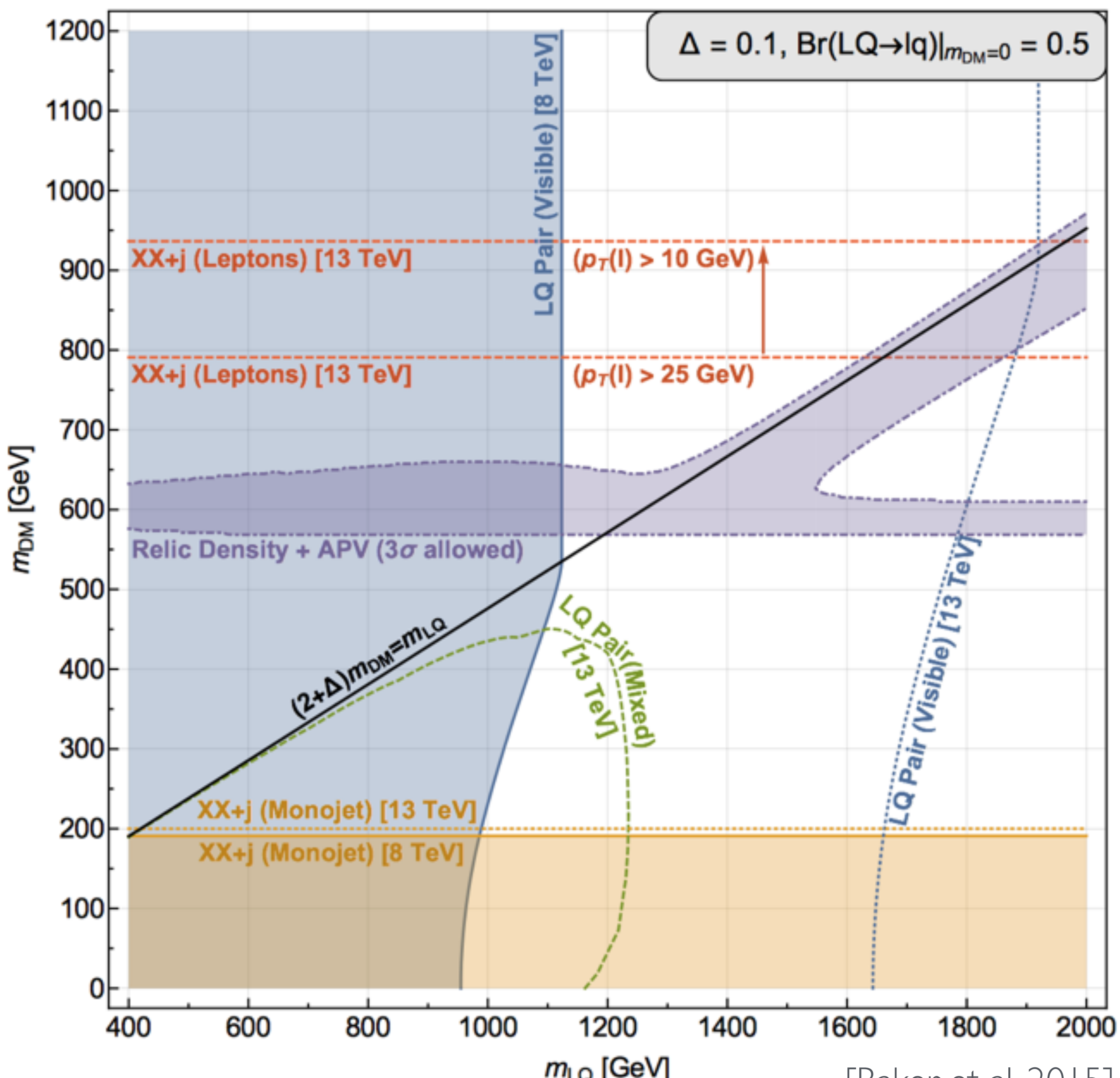
What are the LHC consequences of coannihilations?

[Baker et al. 2015]

- Several interesting channels:
  - If M couples to the Higgs, could induce invisible Higgs, exotic decays or have imprints in Higgs precision measurements.
  - Monojets, mono-photons, mono-Z/W.
  - (hard) ISR + MET + 1 (pp->X DM) or 2 (pp->XX) soft SM pairs.
  - Paired resonances
  - 1 resonance + 1 soft pair.

If there's a light mediator, all SM final states can show up in the form of LJs or other collimated objects.

Coannihilations Case Study: Leptoquarks



[Baker et al. 2015]

Example 2
Strongly Interacting Massive Particles

The hidden sector may be strongly coupled!

Several motivations:

- Naturalness Problem
- Experimental Hints (as in the 750 GeV case)
- Dark matter self-interactions
- Dark matter production mechanism
- …

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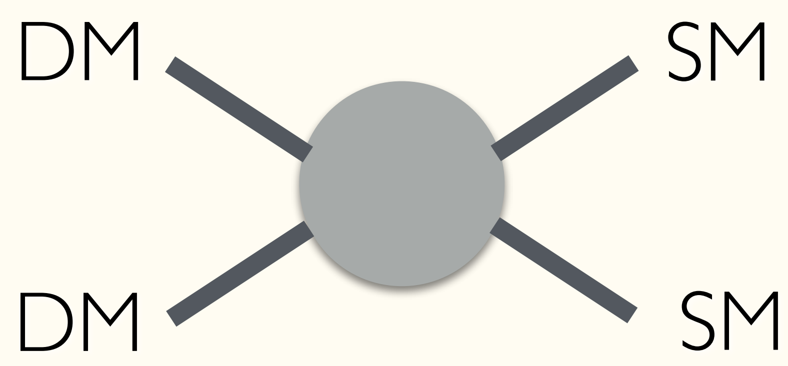
[Kuflik, Hochberg, TV, Wacker, 2014]
[Kuflik, Hochberg, Murayama, TV, Wacker, 2014]

No 2-2 Annihilations..

- The WIMP paradigm assumes significant 2-2 annihilations (typically to SM) that suppresses the number density.



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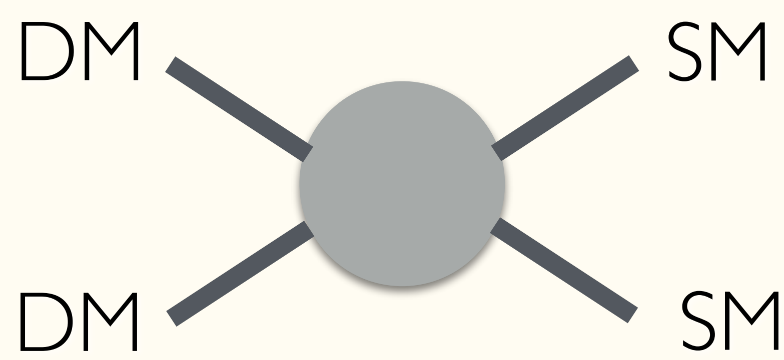
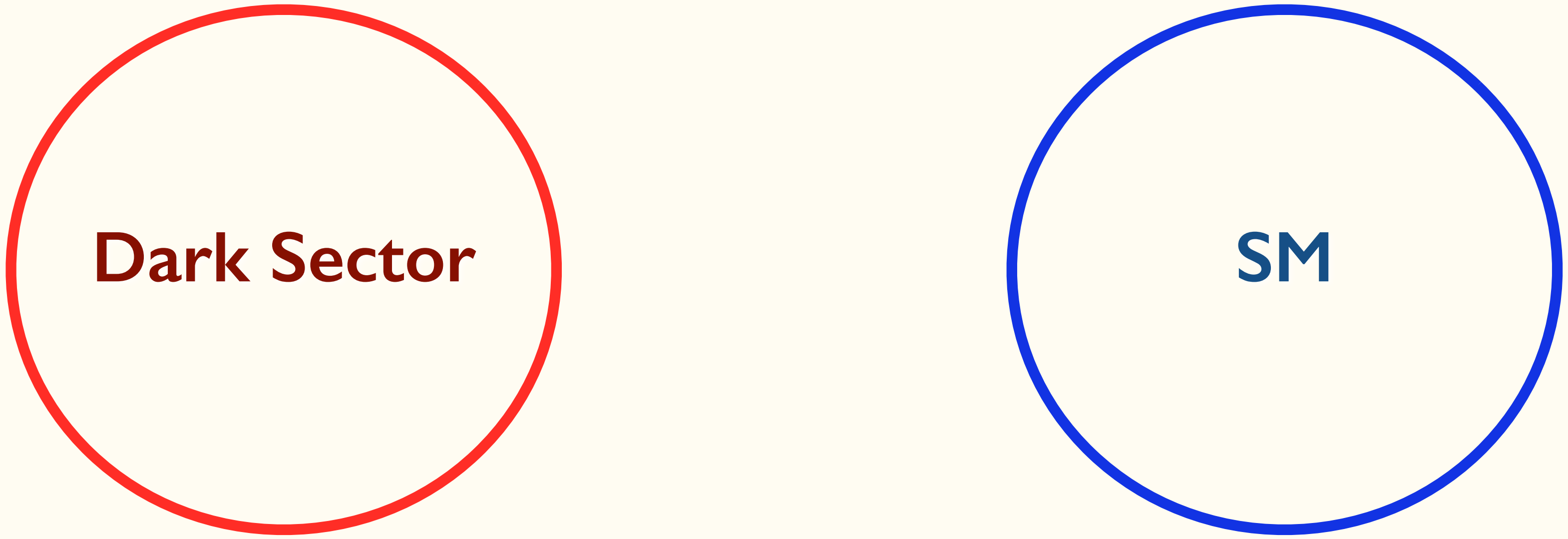


- But what if DM is the lightest state in a hidden (sequestered) sector?



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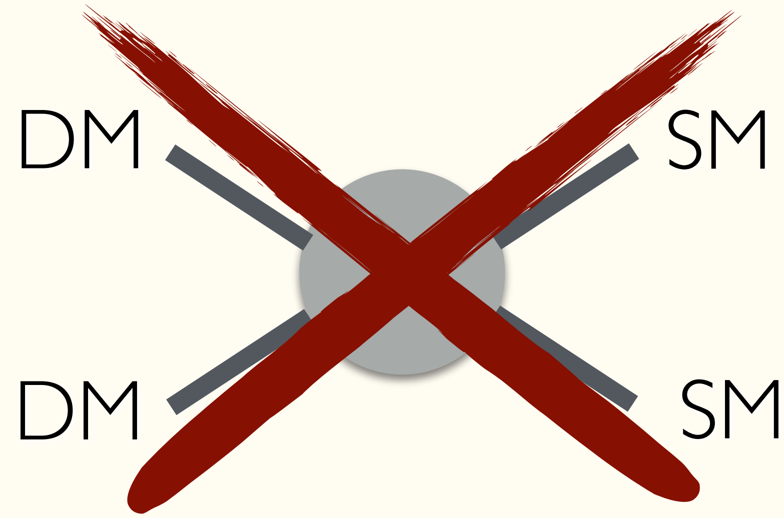

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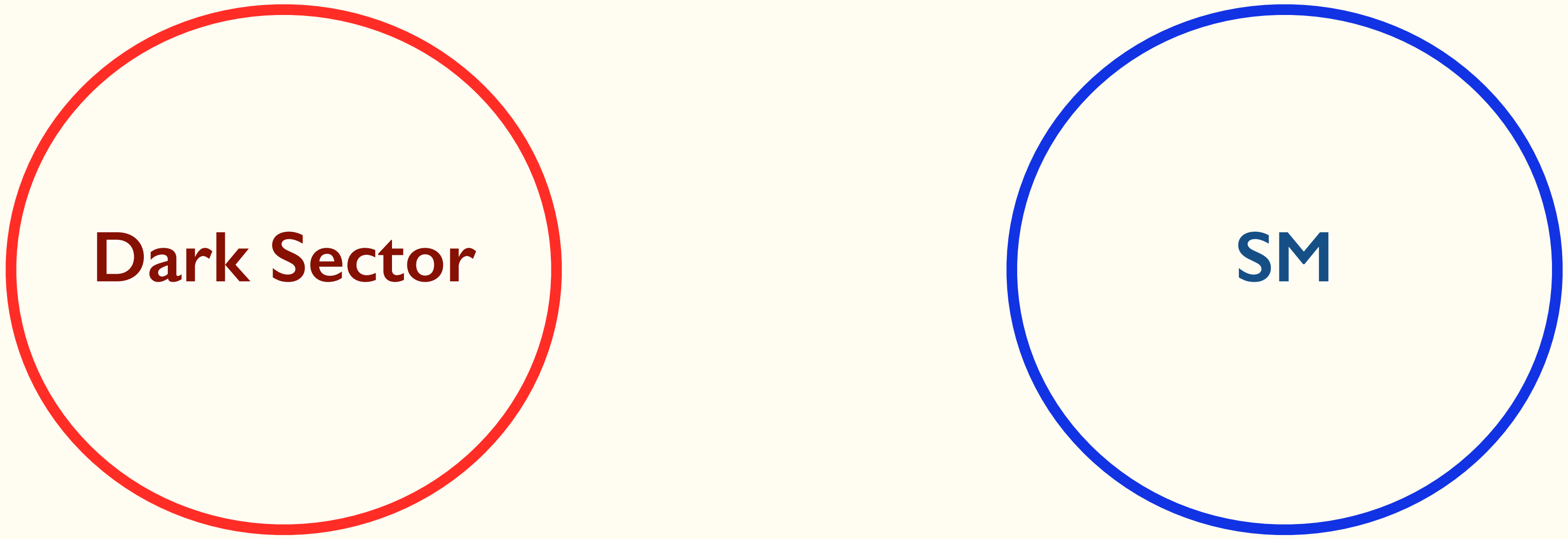
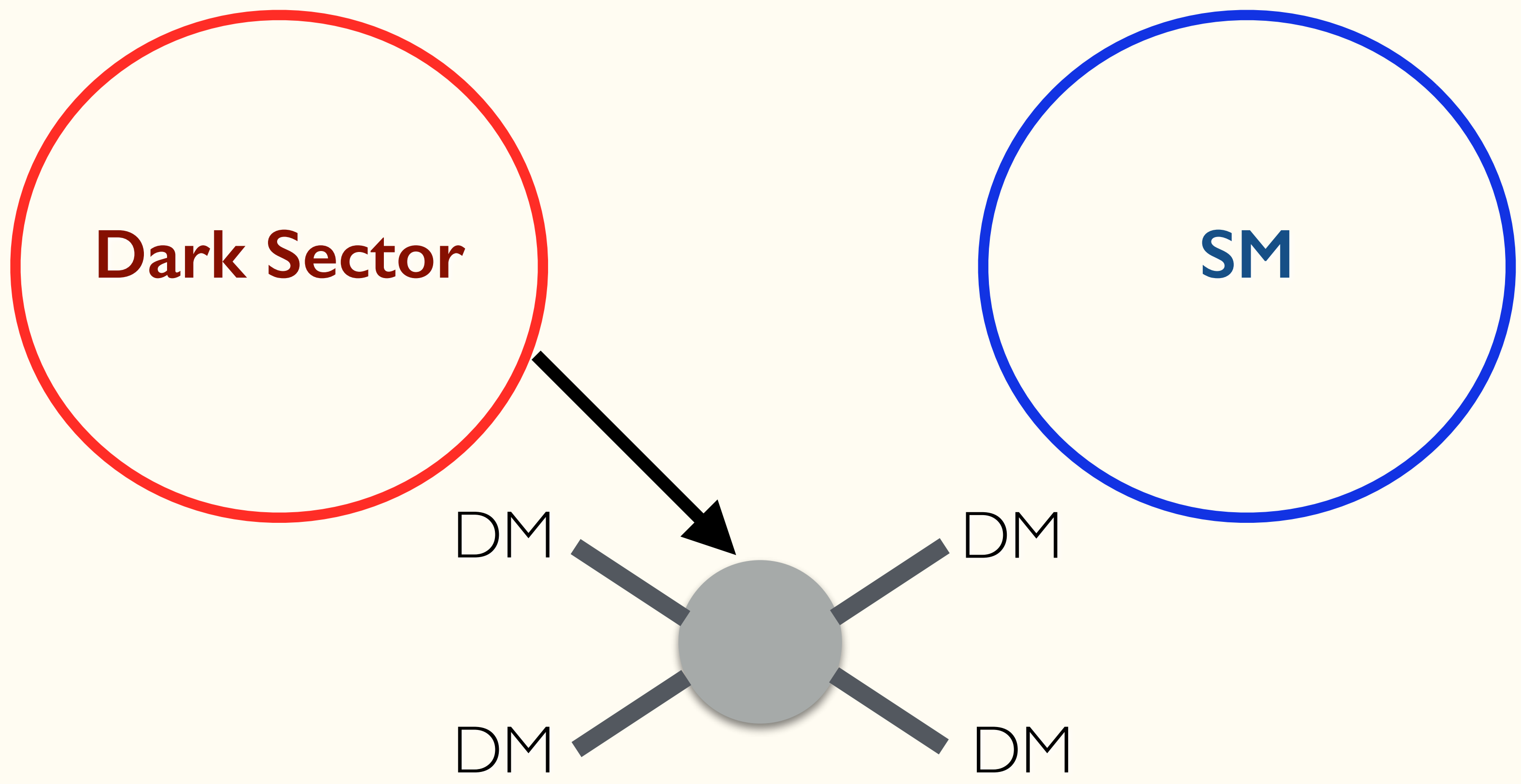
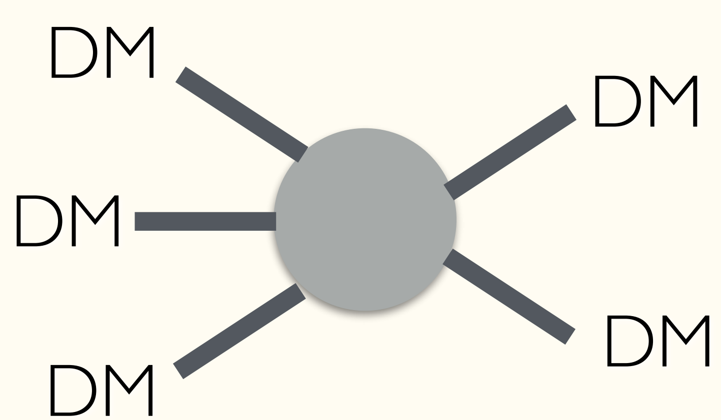


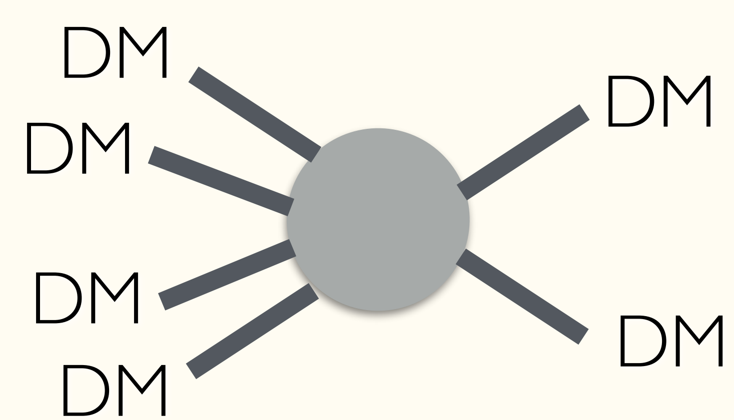
- Then 2-2 annihilations may be highly suppressed

No 2-2 Annihilations..



- More generally, the hidden sector will have additional interactions (especially in a strongly coupled case).





3-2 Freeze Out

WIMP
DM

Weak scale emerges for a weak-strength interactions

$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq} M_{\rm Pl}\right)^{1/2} \sim {\rm TeV}$$

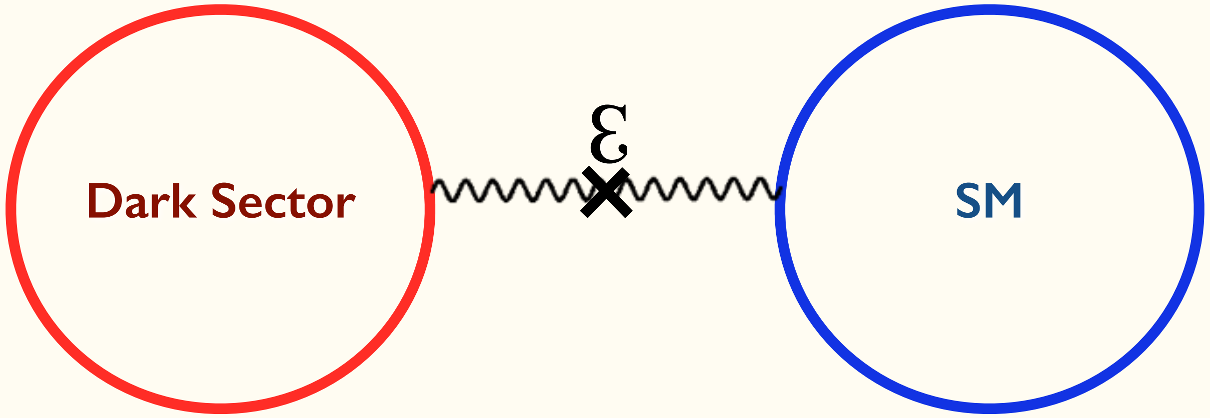
SIMP
DM

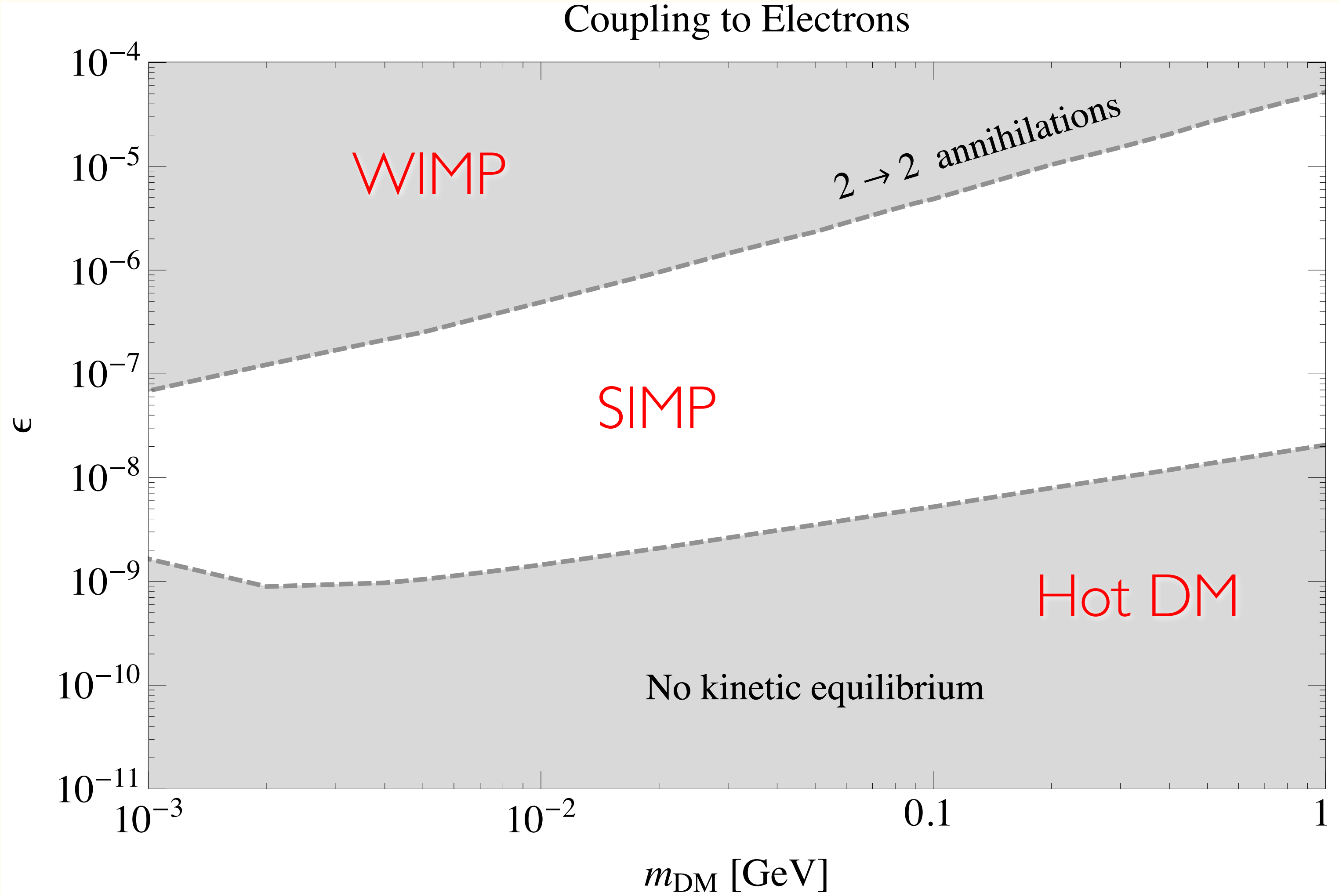
QCD scale emerges for a strongly-interacting sector.

$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100 \ {\rm MeV}$$

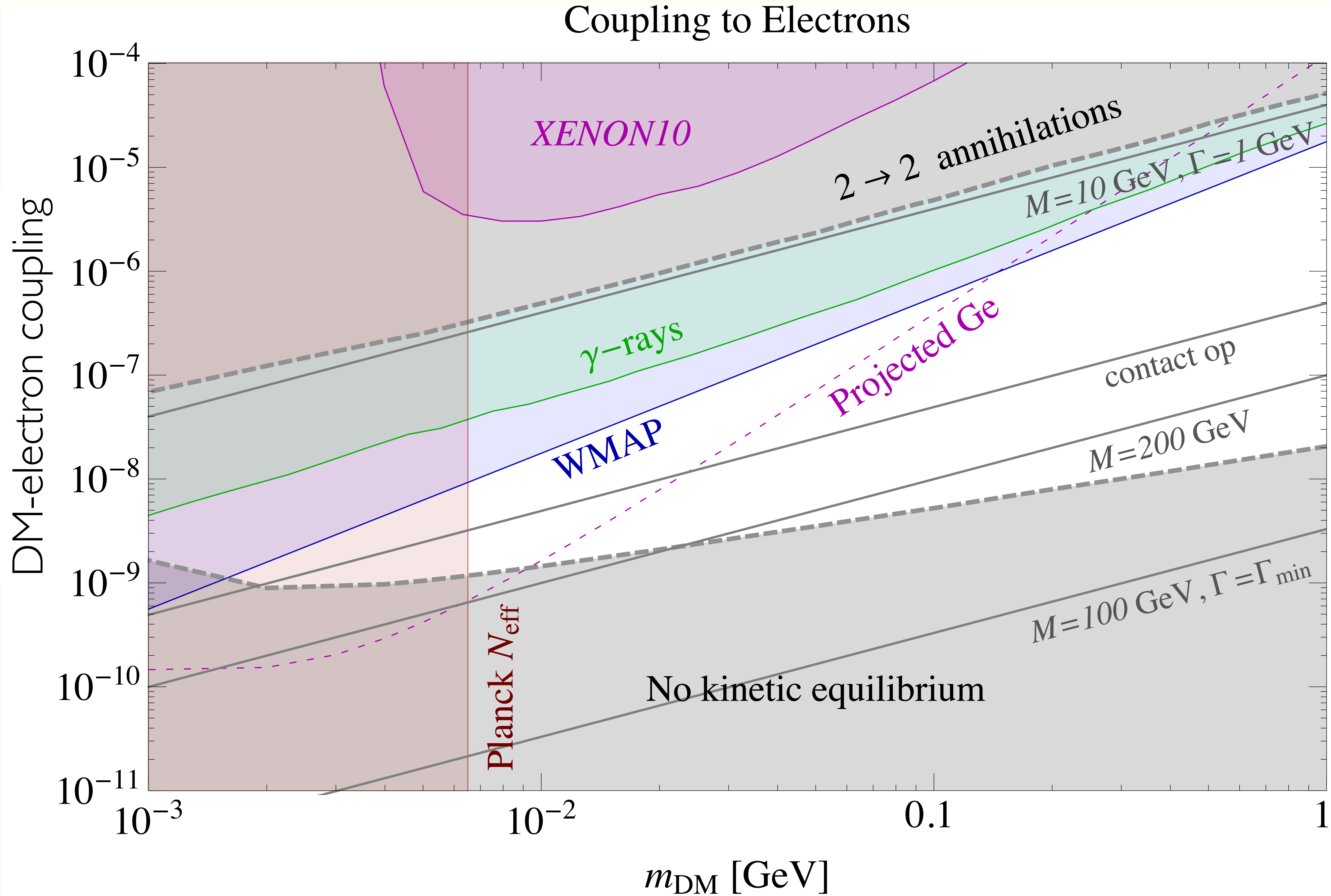
3-2 Freeze Out

- Problem: We implicitly assumed that $\mathbf{T_{dark} = T_{SM}}$. Otherwise DM is hot and excluded.
- To evade limits on hot DM, the dark sector needs to be in thermal equilibrium with SM.





SIMP DM: Experimental Status



SIMP: Collider Implications?

- The standard search for "DM at colliders" is mono-jets/W/Z/γ etc.
- If the dark sector is strongly coupled, other interesting signatures may be important. For example:
    - Quirks (see Matt's talk).
    - Emerging jets (see Andi's talk).
    - Trackless and photon jets (see Jakub's talk).
    - Semi-visible jets.
    - …

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  - Semi-visible jets. [Cohen, Lisanti, Lou, 2015]
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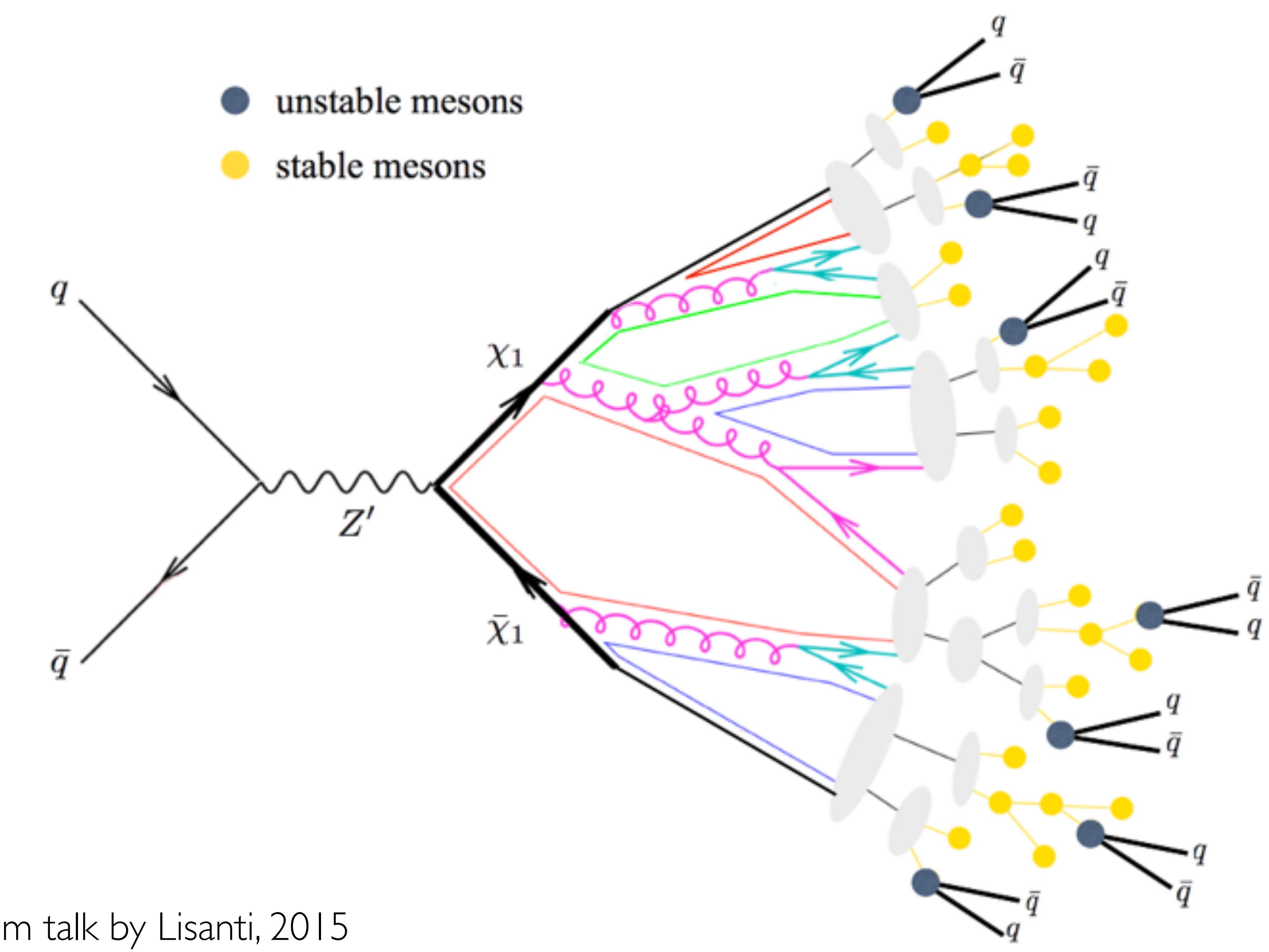
Semi-visible Jets

- Showering in the dark sector may result in numerous visible and invisible particles



From talk by Lisanti, 2015

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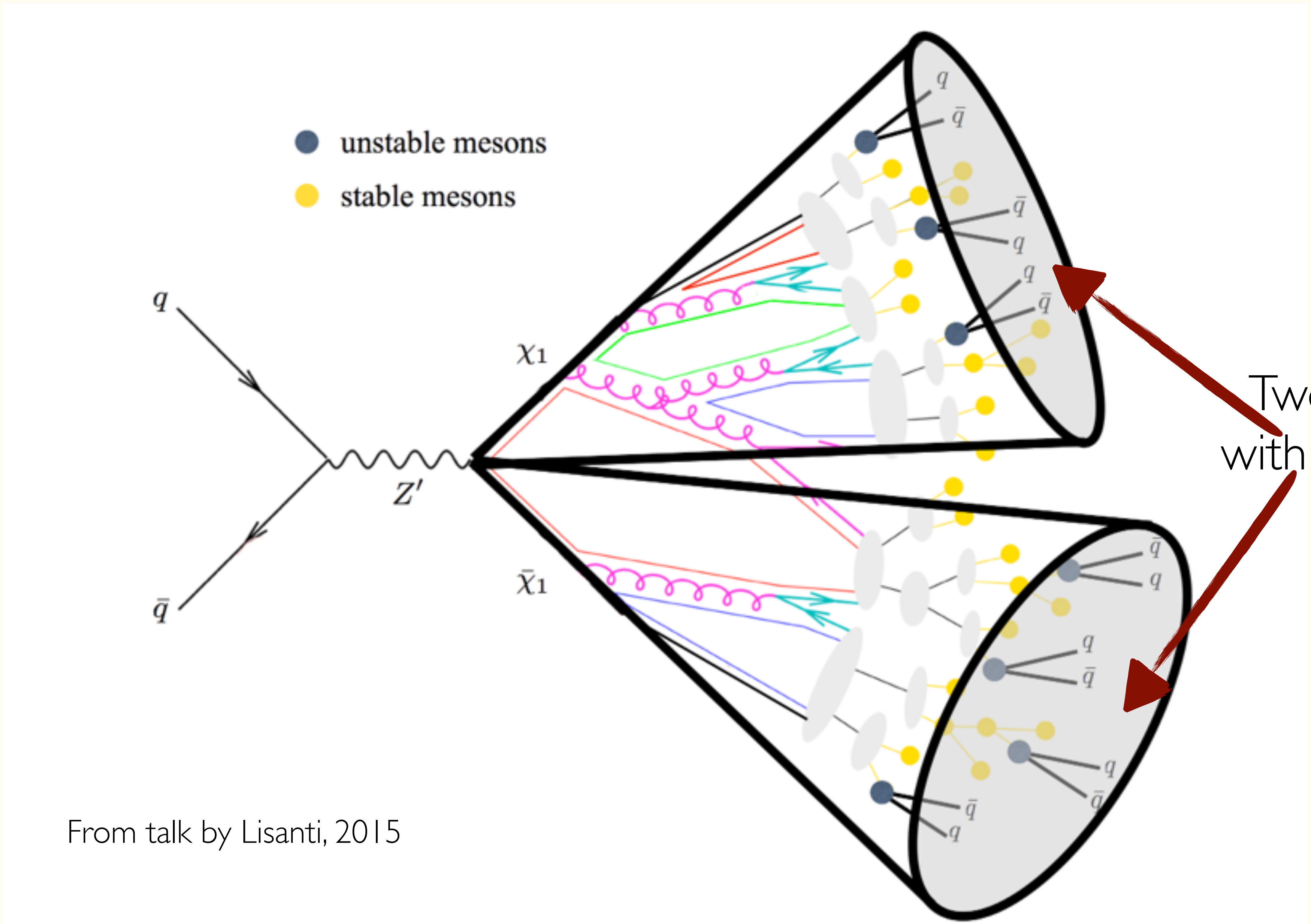
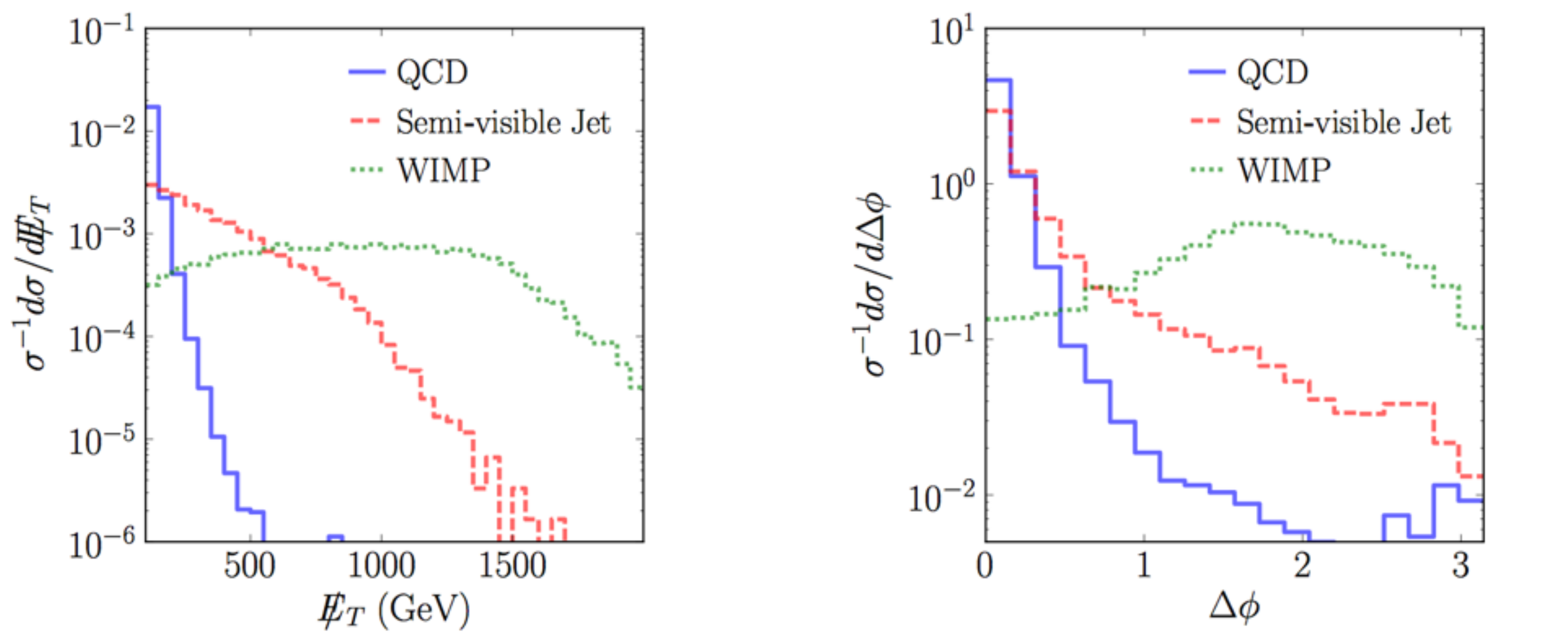


From talk by Lisanti, 2015

Two jets with holes..

Semi-visible Jets

- Showering in the dark sector may result in numerous visible and invisible particles
- Signals of this kind have MET aligned with one of the visible jets.
- This evades standard mono-jet searches.



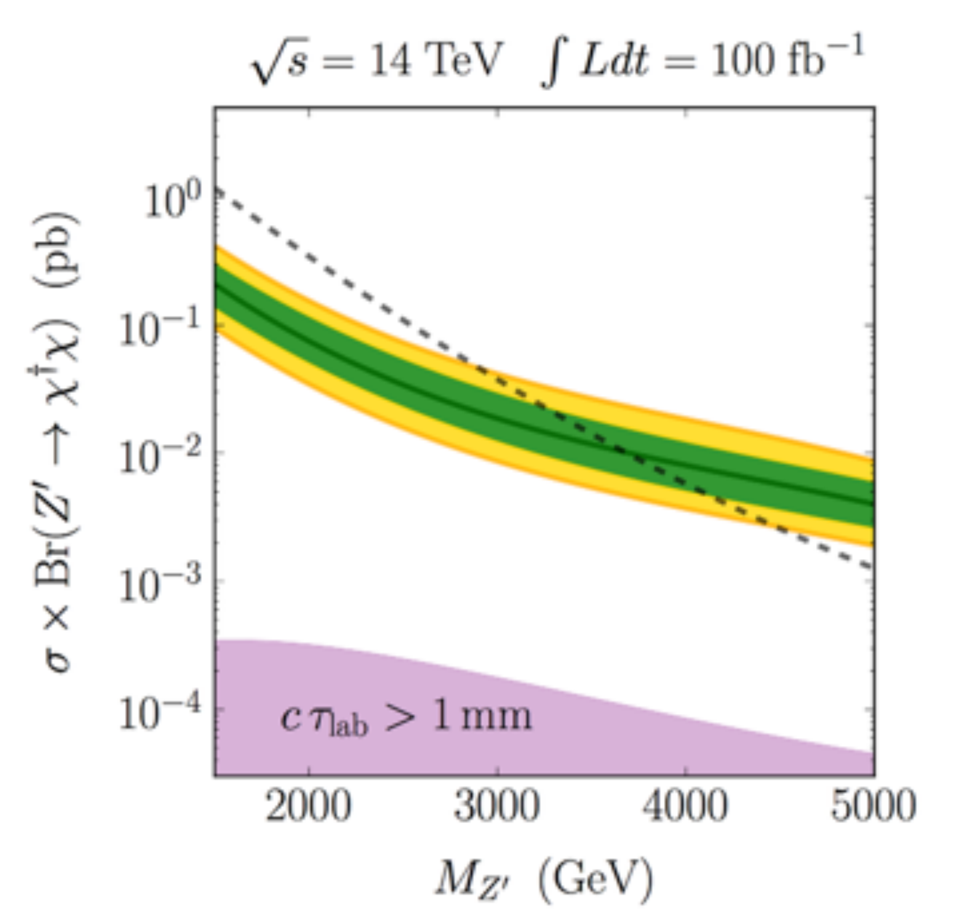
Semi-visible Jets

- Cohen et al. study a hidden valley model with an SU(2) gauge group and scalar quarks.
- Hidden sector couples to visible one via a Z':

$$\mathcal{L} \supset -\frac{1}{4} Z'^{\mu\nu} Z'_{\mu\nu} - \frac{1}{2} M^2_{Z'} Z'_\mu Z'^\mu - g^{\rm SM}_{Z'} Z'_\mu J^\mu_{\rm SM}$$

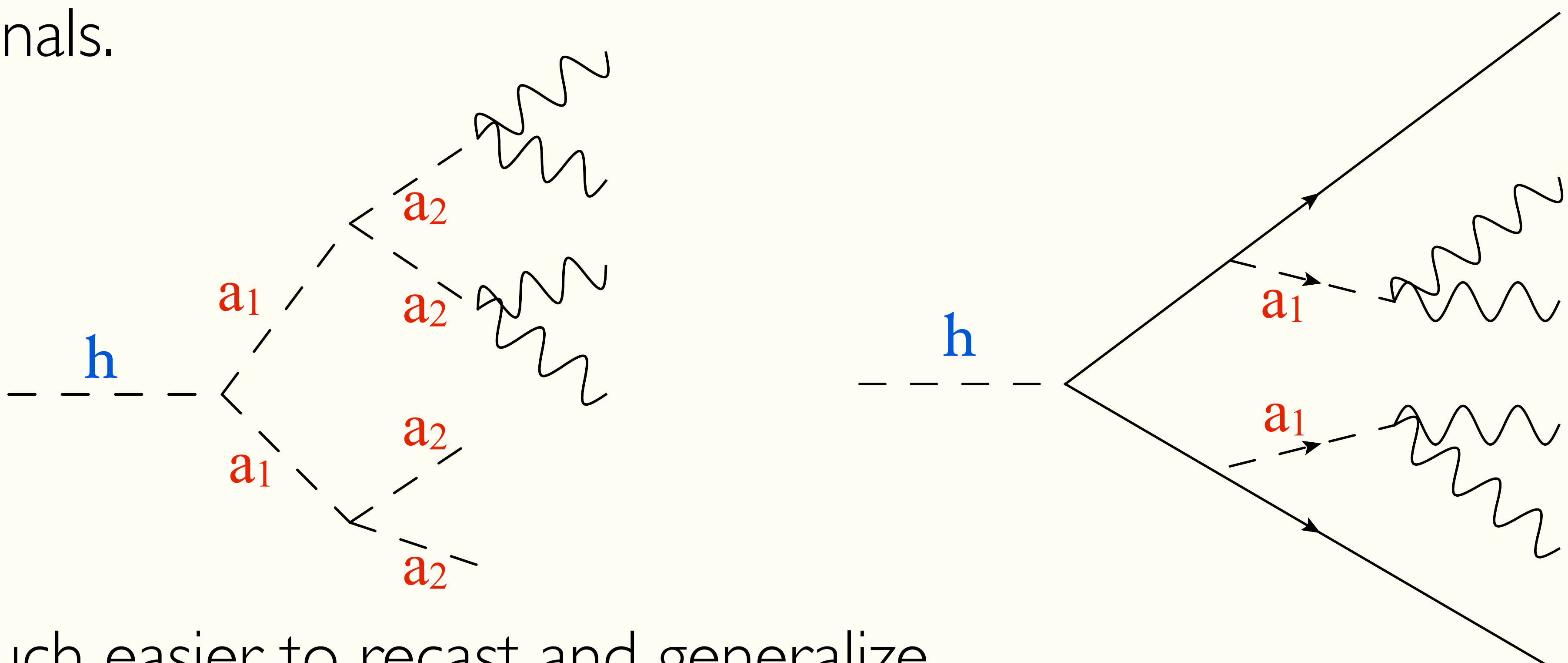
- Global hidden symmetry ensures stability of some of the states.
- Search strategy:
    - 2 fat jets (R=1.1)
    - $|\eta_{j1}-\eta_{j2}| < 1.1$
    - $\Delta\Phi(\mathrm{MET}, j_i) < 1$
    - $\mathrm{MET}/M_T > 0.15$
    - Perform bump hunt on M_T:

$$M_T^2 = M_{jj}^2 + 2\left(\sqrt{M_{jj}^2 + p_{Tjj}^2}\, \not{E}_T - \vec{p}_{Tjj} \cdot \vec{\not{E}}_T\right)$$



Semi-visible Jets

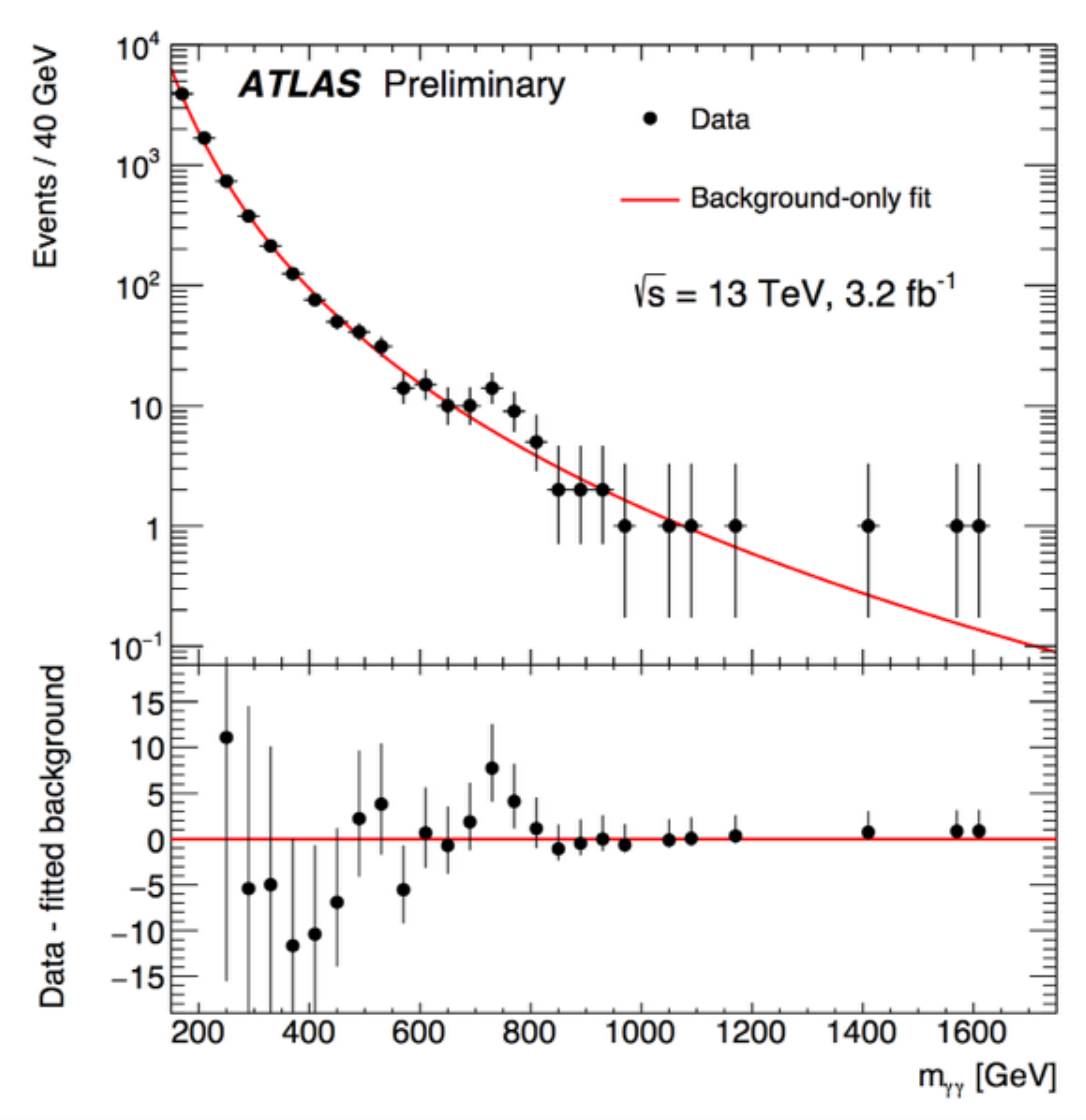
- The above study was performed with a specific simplified model, which includes a gauge coupling parameter, α_s.
- Working with such simplified models make it very hard to recast on other scenarios.
- It is much simpler to use a weakly-coupled simplified model.
- In fact, the exact same scenario can occur in a cascading model used with LJ signals.



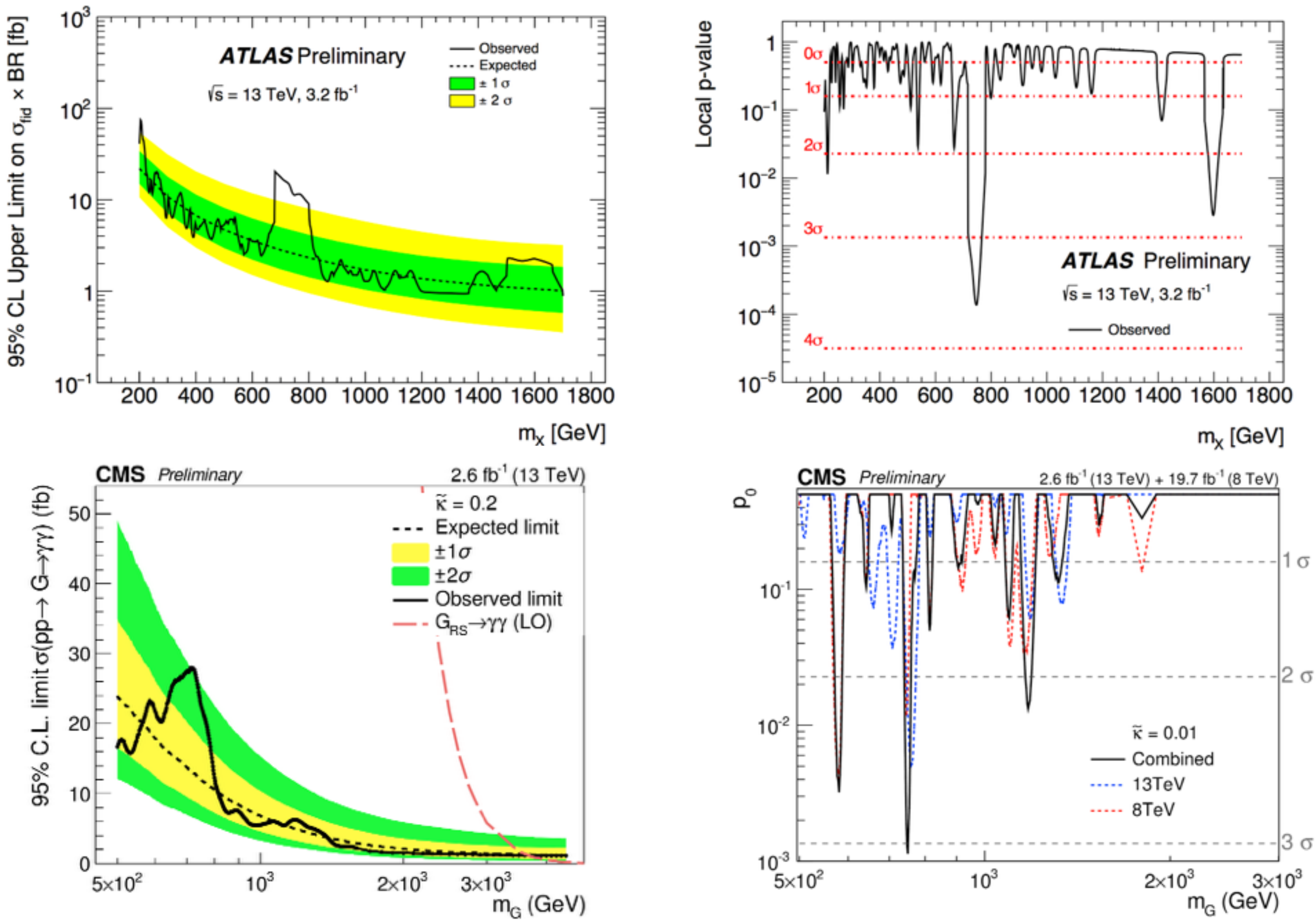
- Much easier to recast and generalize.

Exotics from a 750 GeV Resonance

So what is this??

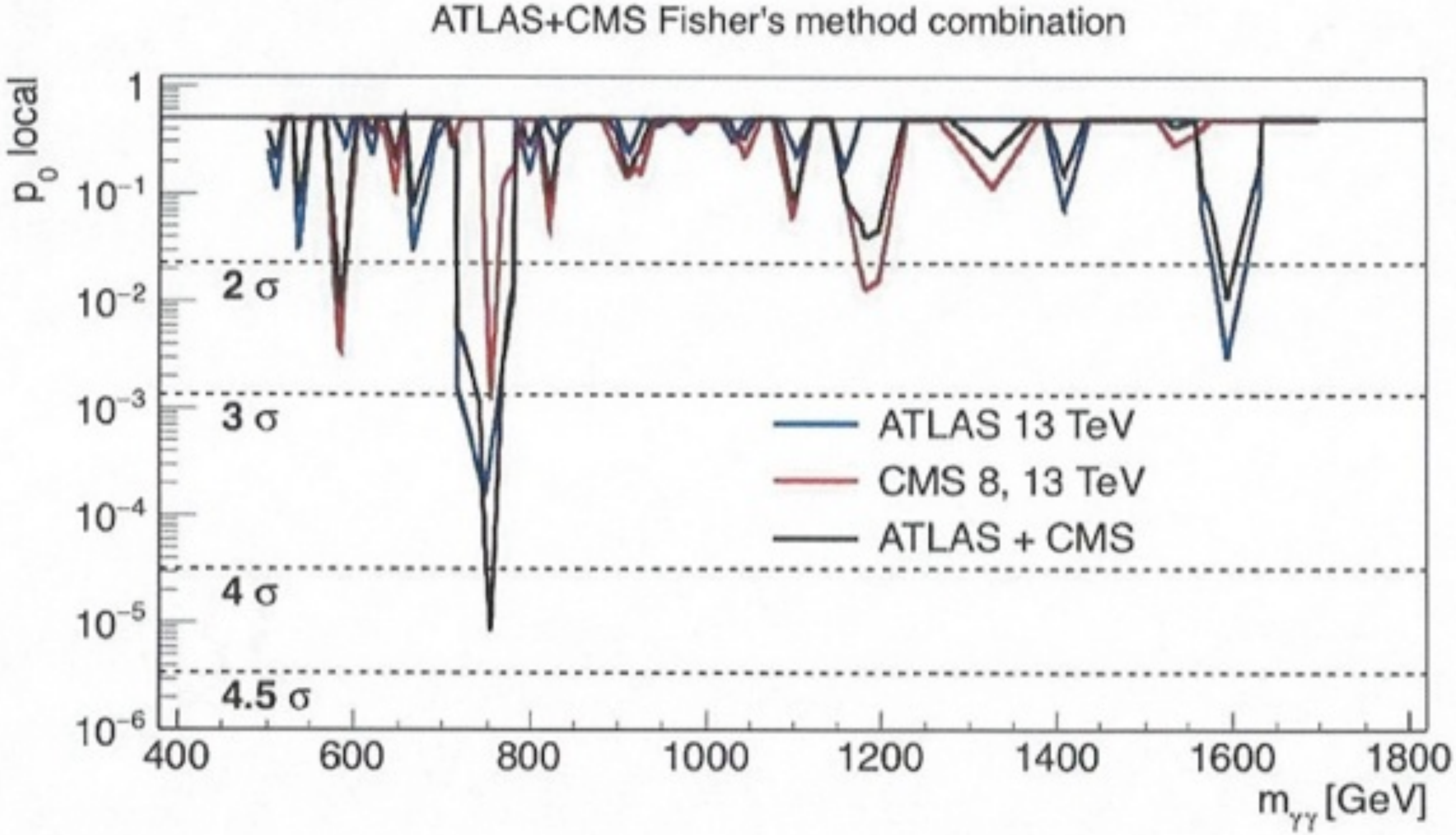


What do we know?



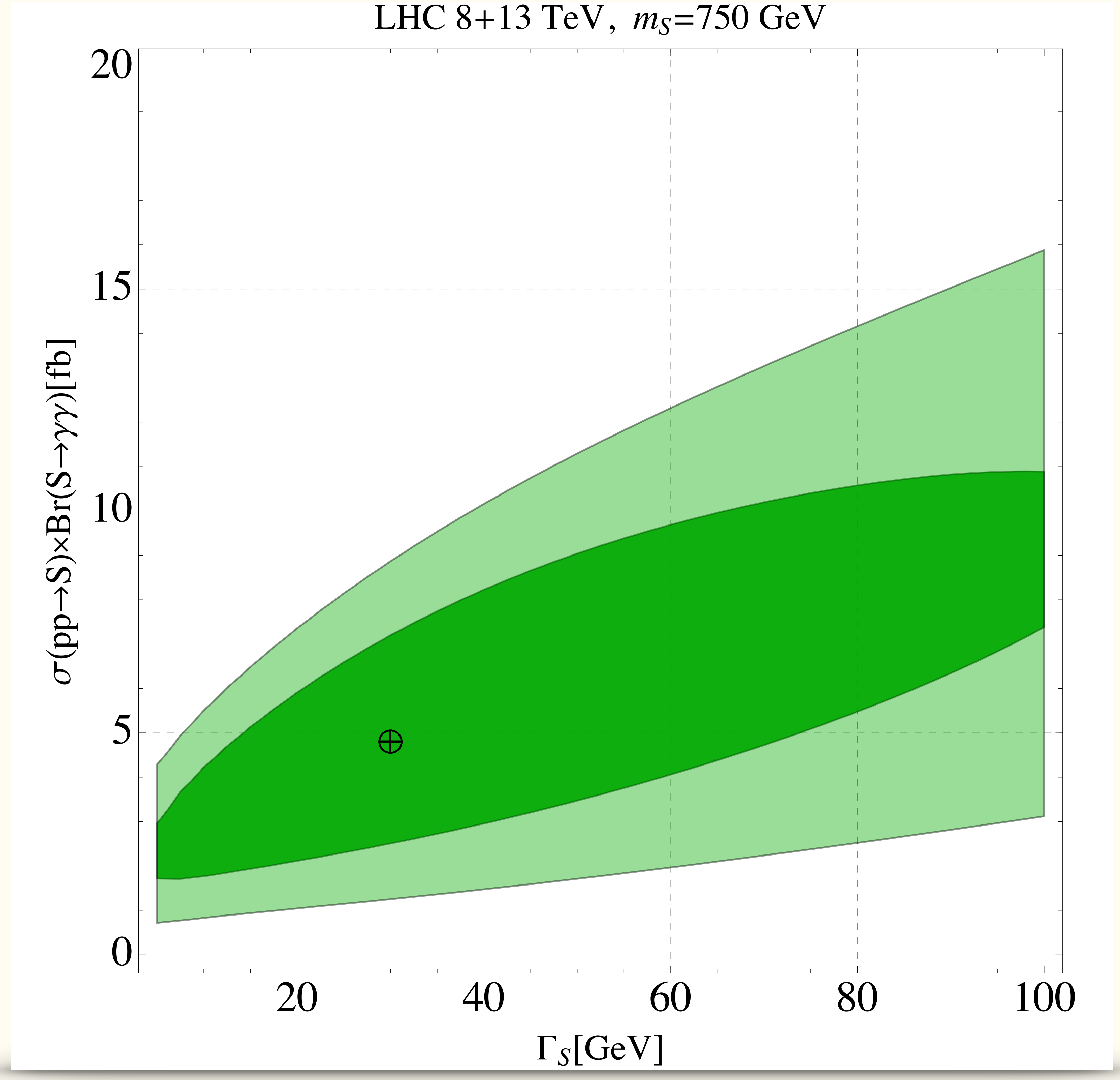
What do we know?

Very Informal…



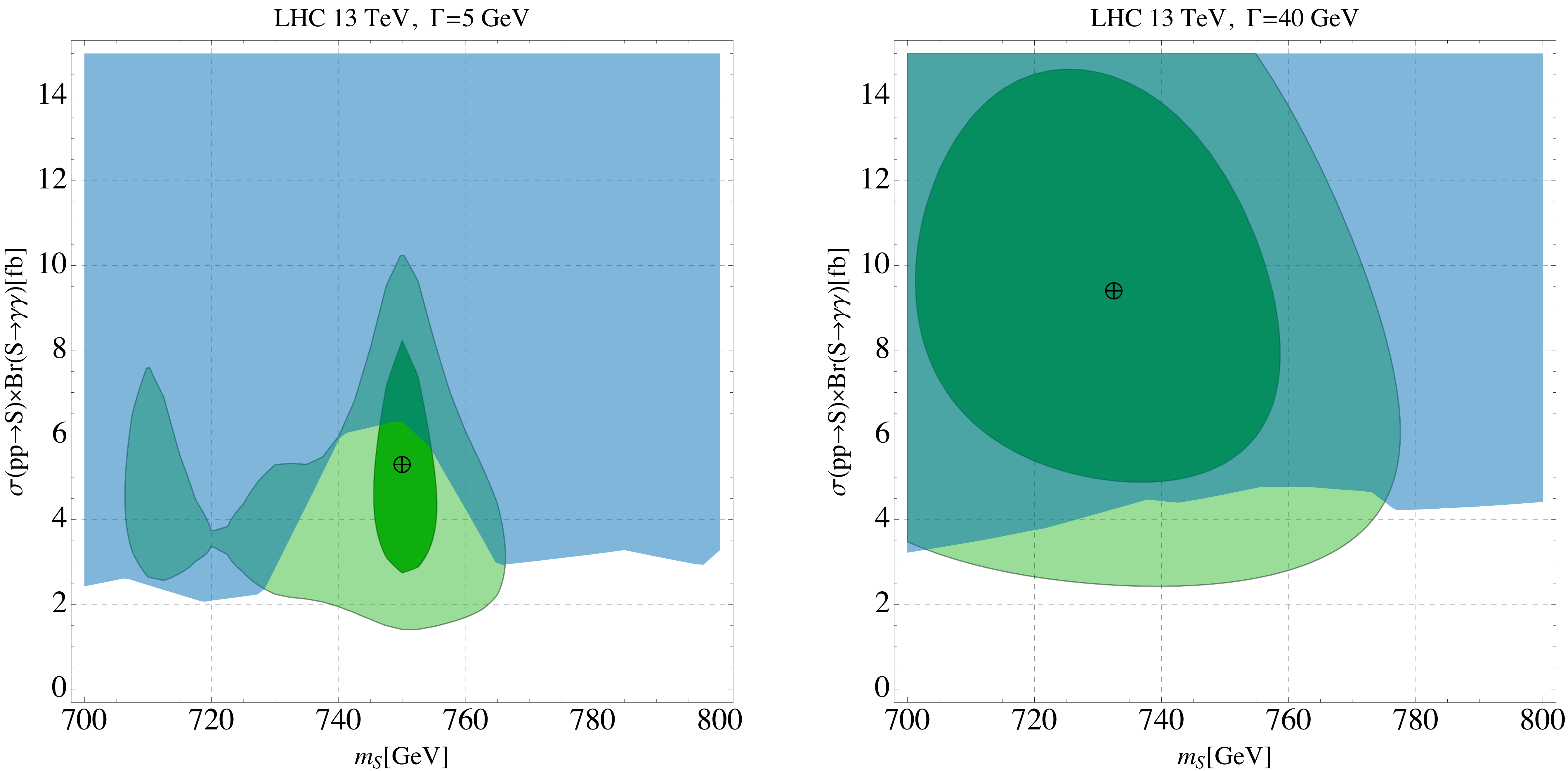
4.4**σ** local @750 GeV, 3.2**σ** global.

Is it a broad resonance?



Maybe, but not statistically significant!

Is it a broad resonance?



Narrow scalar resonance fits well and is consistent with 8 TeV data.

Broad resonance also fits well but (very) mildly inconsistent with 8 TeV data.

The Case of a Singlet

- Let's assume the resonance is real.
- Perhaps the simplest explanation is a singlet.
- To be produced, the singlet must couple to quarks or gluons.
- Production through quarks is in more tension with 8 TeV data (except bb production).
- Straightforward to describe using an effective theory:

$$\mathcal{L}_{S,\text{eff}} = \frac{e^2}{4v} c_{s\gamma\gamma} S A_{\mu\nu} A^{\mu\nu} + \frac{g_s^2}{4v} c_{sgg} S G^a_{\mu\nu} G^{a\mu\nu} + \frac{1}{v} c_{sqq} S \left(H \bar{Q} d + \text{h.c.} \right)$$

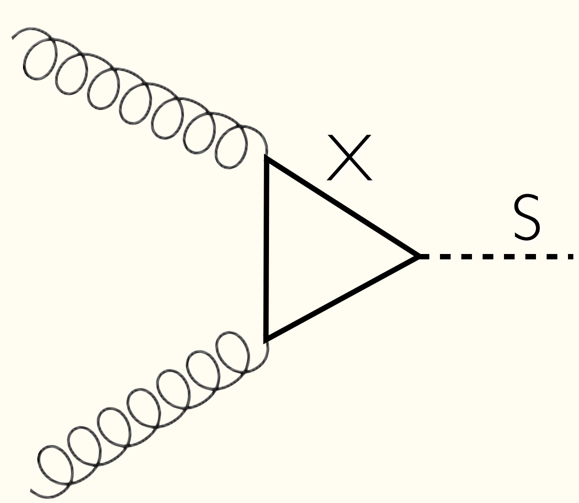
- Consider the simplest case of gluon production.

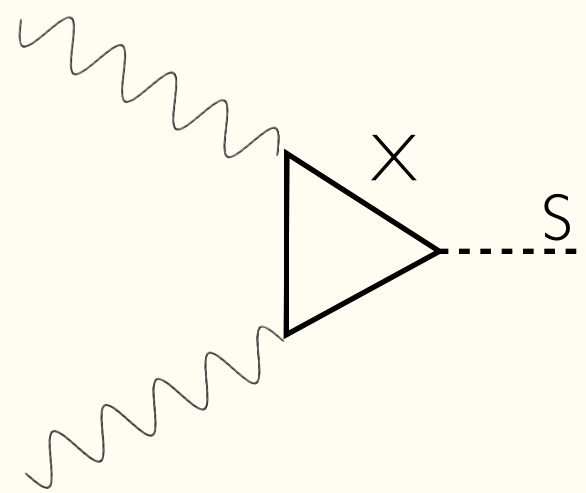
The Case of a Singlet

How do we generate such an effective theory?

- Couplings of S to tt or WW is excluded.
- Instead, introduce new fermions:

$$\mathcal{L} = -y_x S \bar{X} X$$





$$c_{sgg} = \frac{y_X v}{12\pi^2 m_X}$$

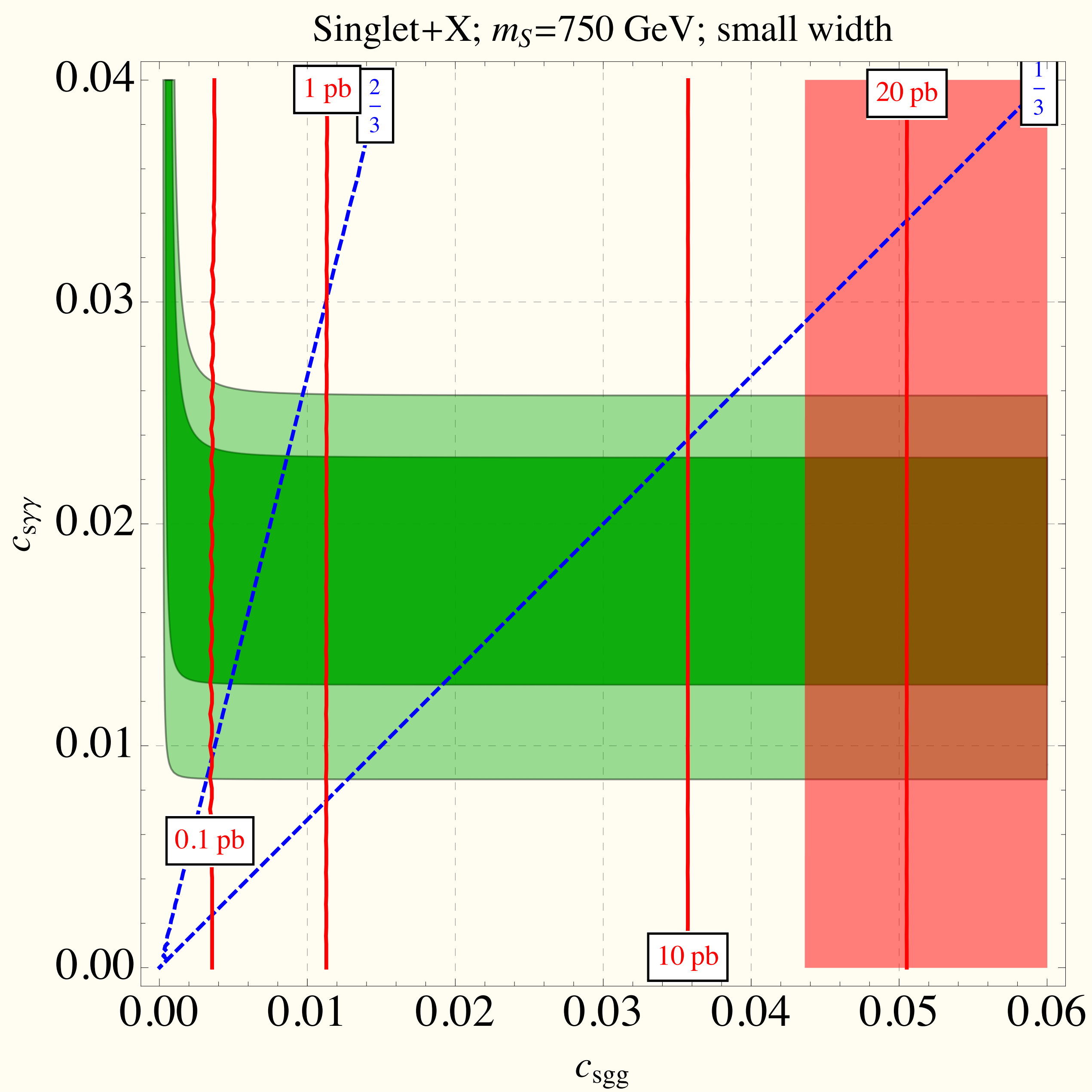
$$c_{s\gamma\gamma} = \frac{y_X Q_X^2 v}{2\pi^2 m_X}$$

The Case of a Singlet

- If that's all there is (S, X), then everything is set.

$$\sigma(pp \to S) = k \frac{\pi c_{sgg}^2 g_s^4 m_S^2}{64 v^2 E_{\text{LHC}}^2} L_{gg}\left(\frac{m_S^2}{E_{\text{LHC}}^2}\right) \qquad \text{Br}(S \to \gamma\gamma) = \frac{e^4 c_{s\gamma\gamma}^2}{8 g_s^4 c_{sgg}^2 + e^4 c_{s\gamma\gamma}^2}$$

- Total decay width is small.
- Significant opened parameter space.



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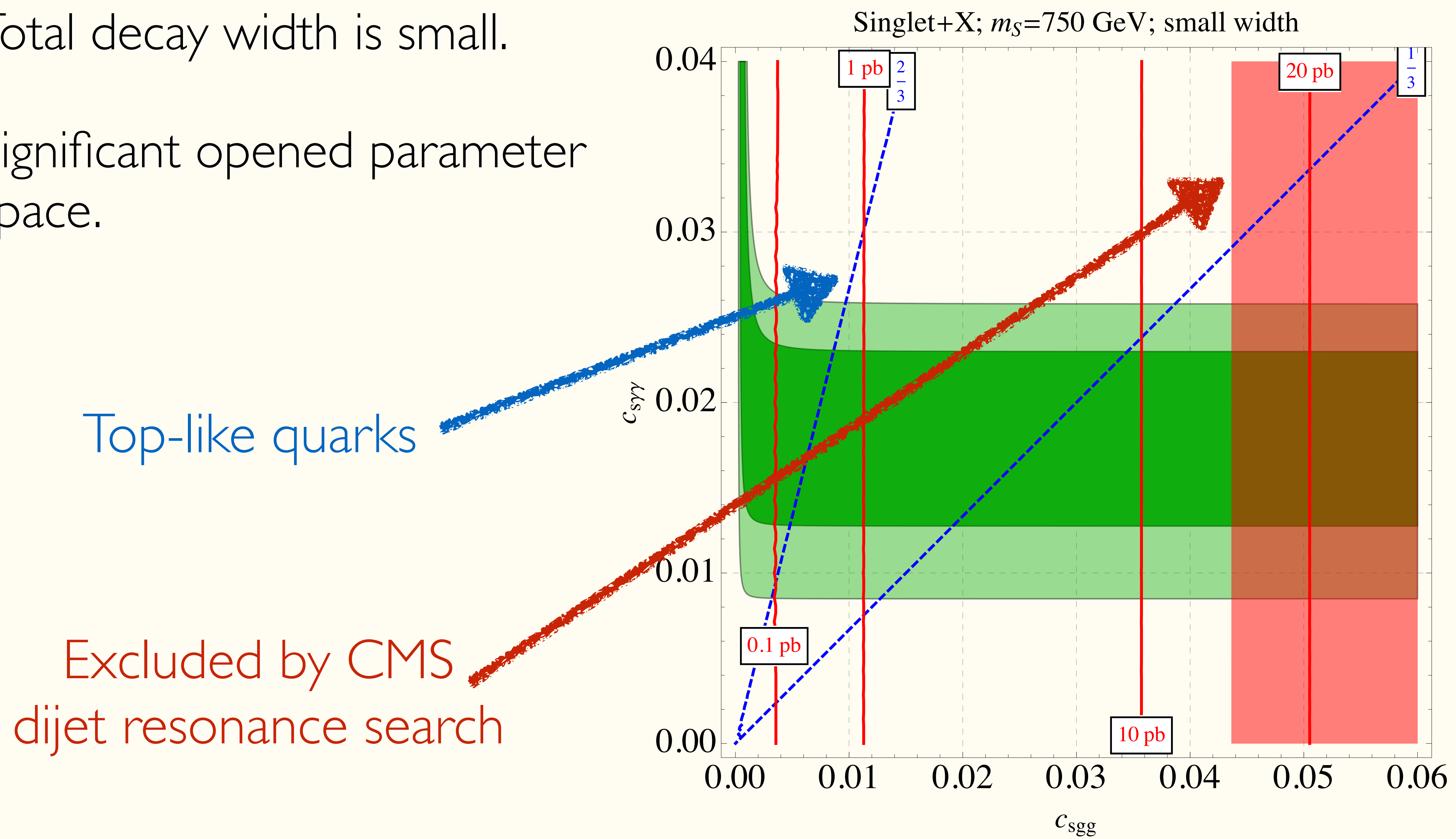
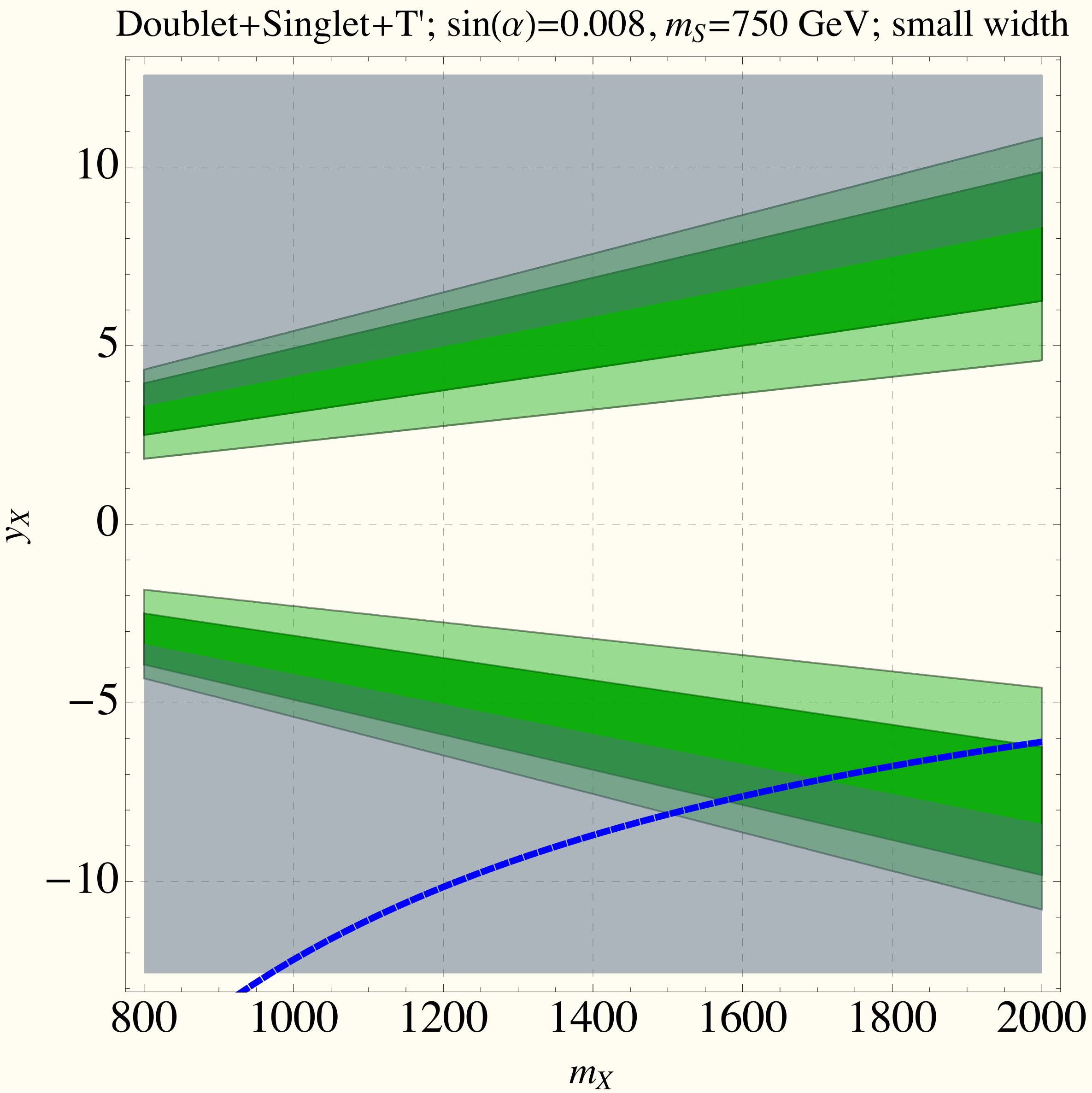


What do we learn?

1. To achieve these sizeable c_{sgg}, $c_{s\gamma\gamma}$, the couplings of the fermions must be large.

   Such large couplings could imply a strongly coupled sector around the corner.



What do we learn?

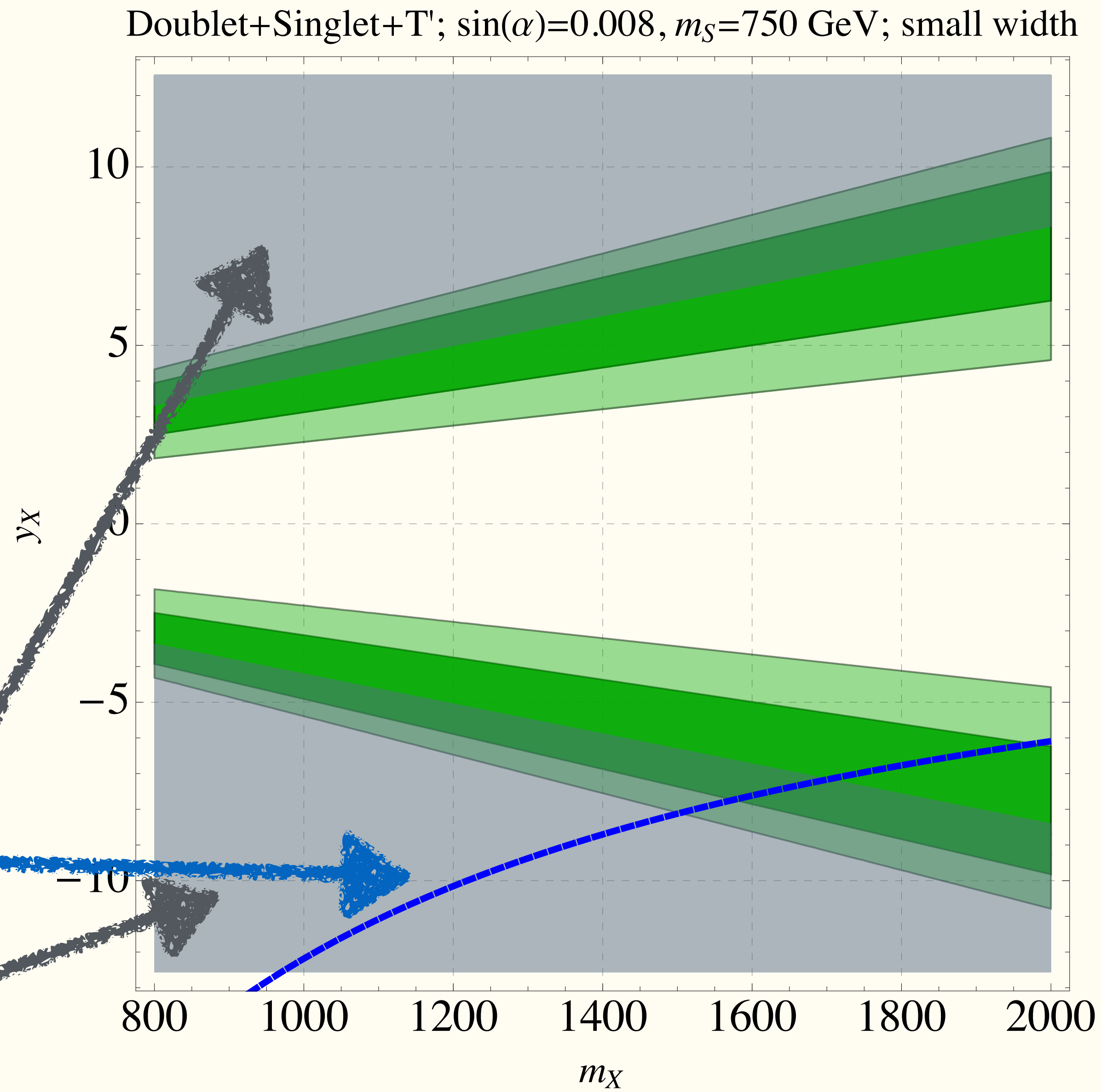
1. To achieve these sizeable c_{sgg}, $c_{s\gamma\gamma}$, the couplings of the fermions must be large.

2. In order to relate to the Naturalness problem, the Higgs should couple to the heavy fermions.

This could occur via Higgs-S mixing

$$S|H|^2$$

$$h \to h\cos\alpha + S\sin\alpha$$
$$S \to -h\sin\alpha + S\cos\alpha$$



T' cancels top loop

Constraints from S→WW/ZZ

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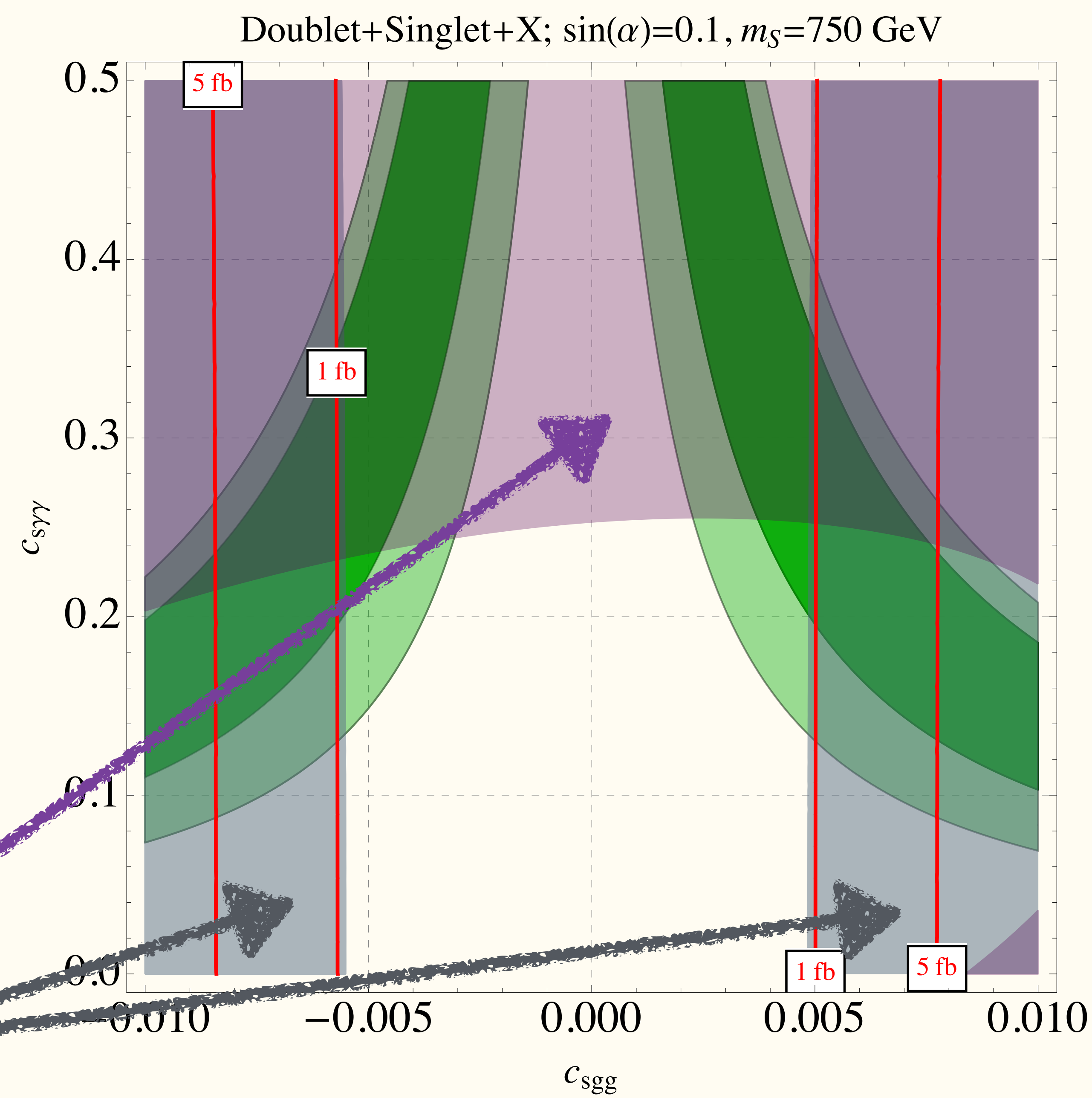
Mixing cannot be too large!



Constraints from precision Higgs

Constraints from S→WW/ZZ

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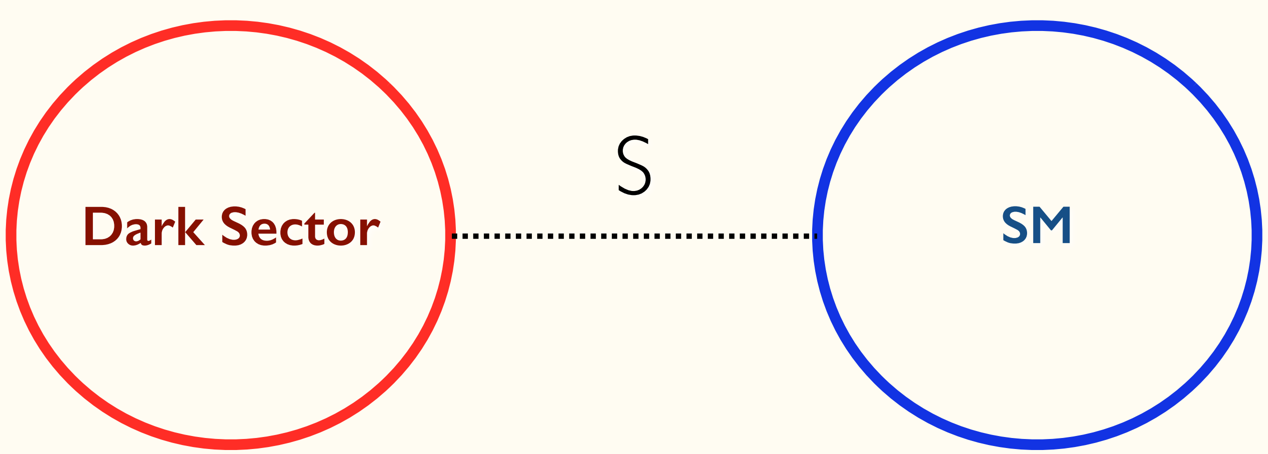
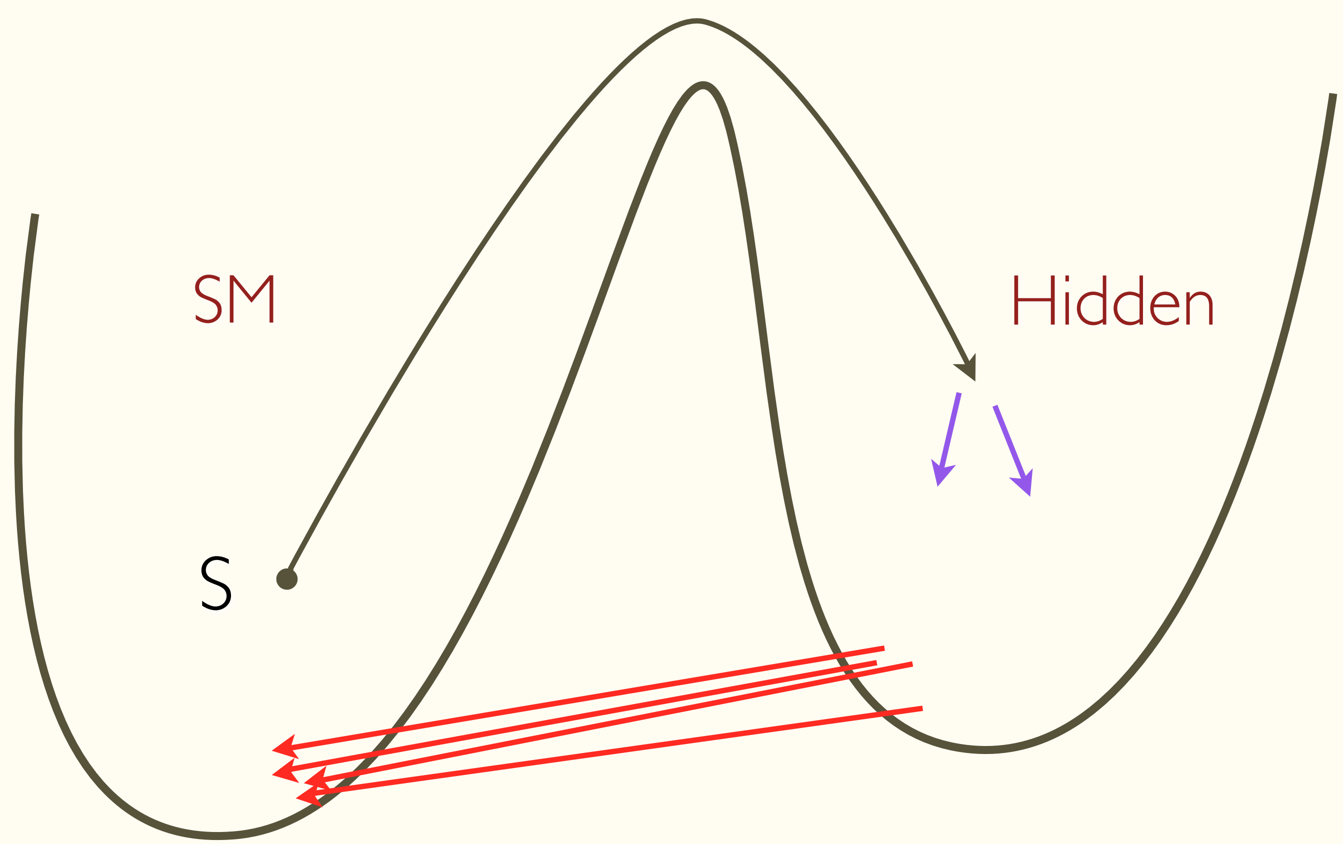
2. In order to relate to the Naturalness problem, the Higgs should couple to the heavy fermions.

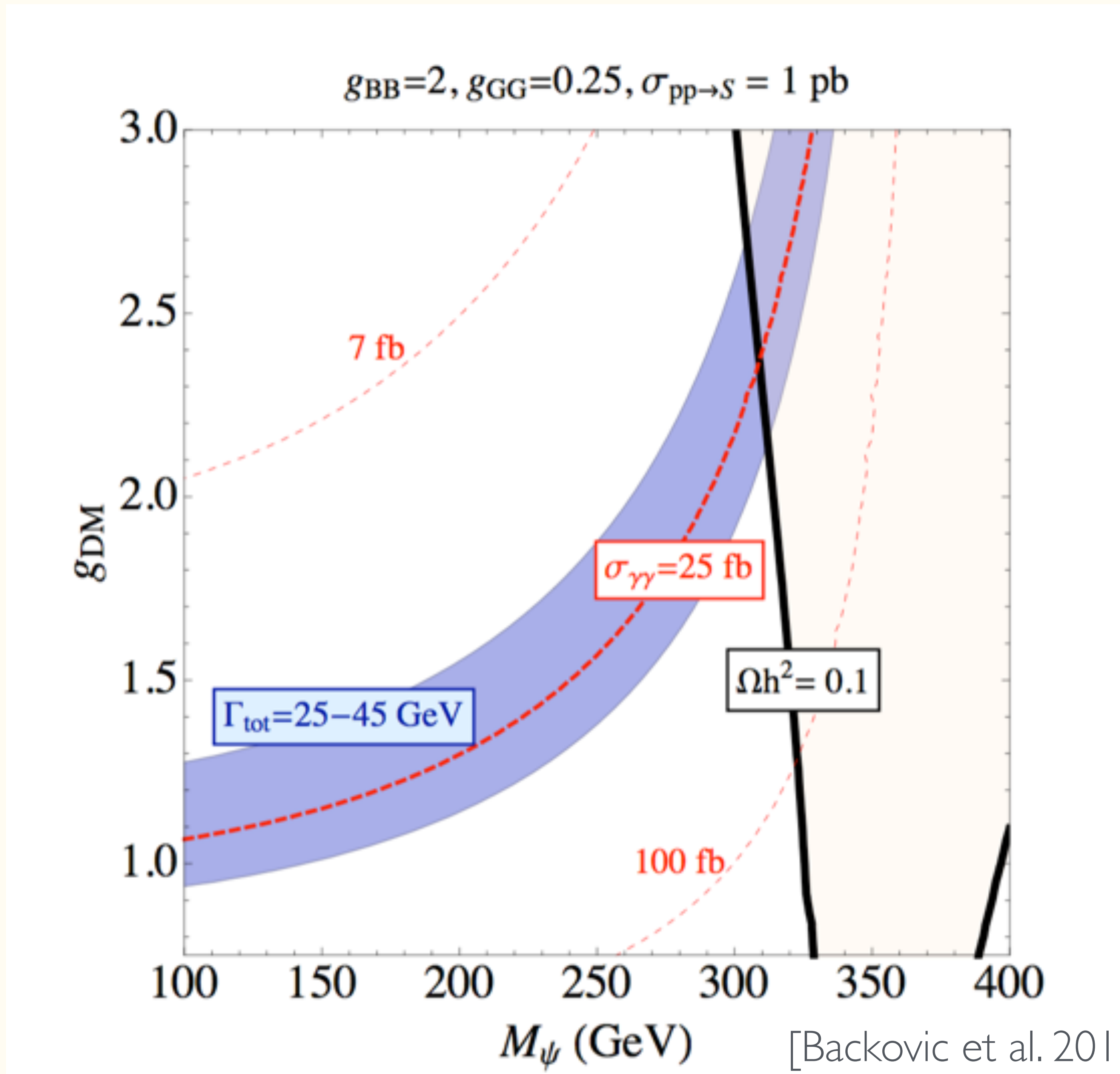
3. H-S mixing suggest that S could be a mediator to a hidden sector.
Possibly dark and possibly strong.
Could this be a gateway to a hidden valley?





S as a Mediator

1. S could mediate the production of a WIMP (although given the strong dynamics this could be a SIMP).



[Backovic et al. 2015]

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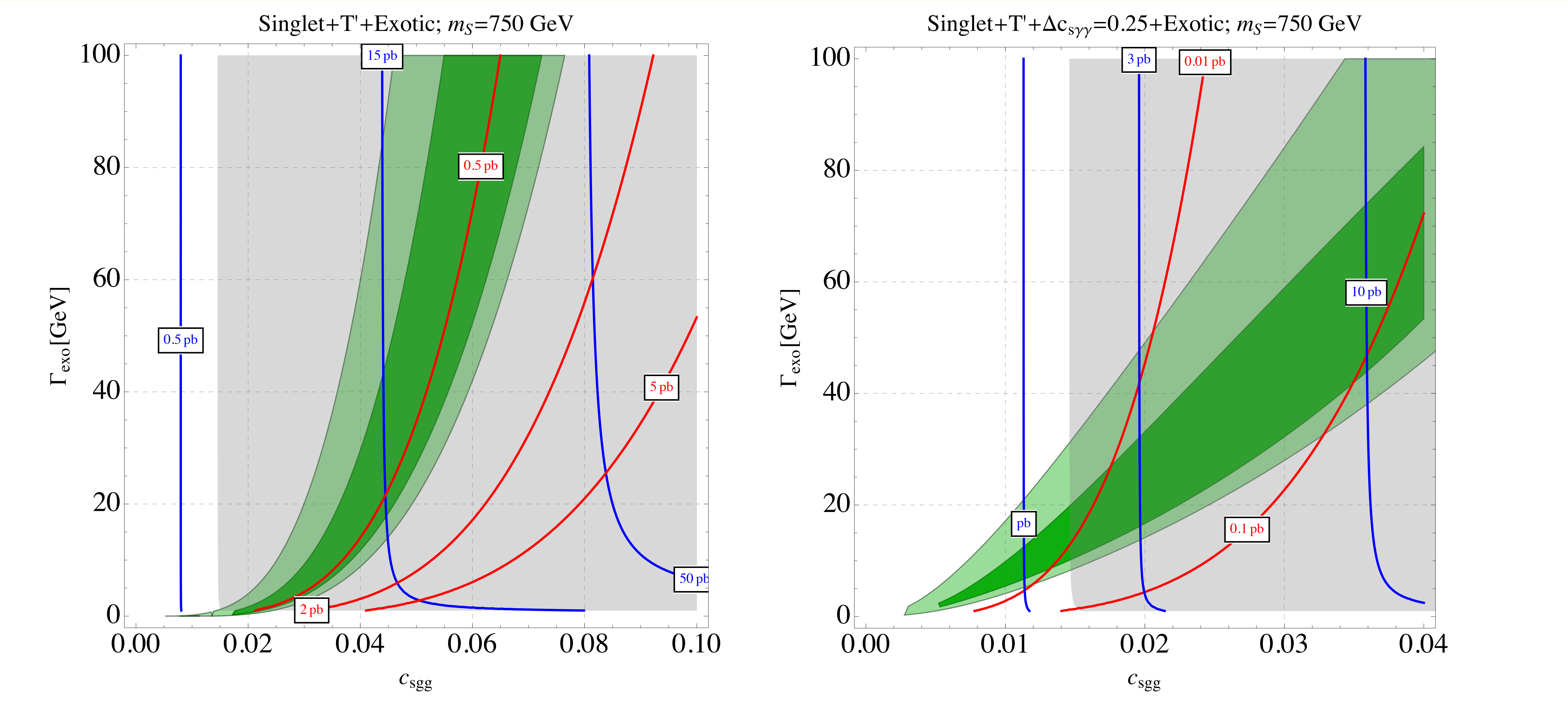
2. The width can be naturally large if S decays to a hidden sector. However, strong constraints from invisible decays.



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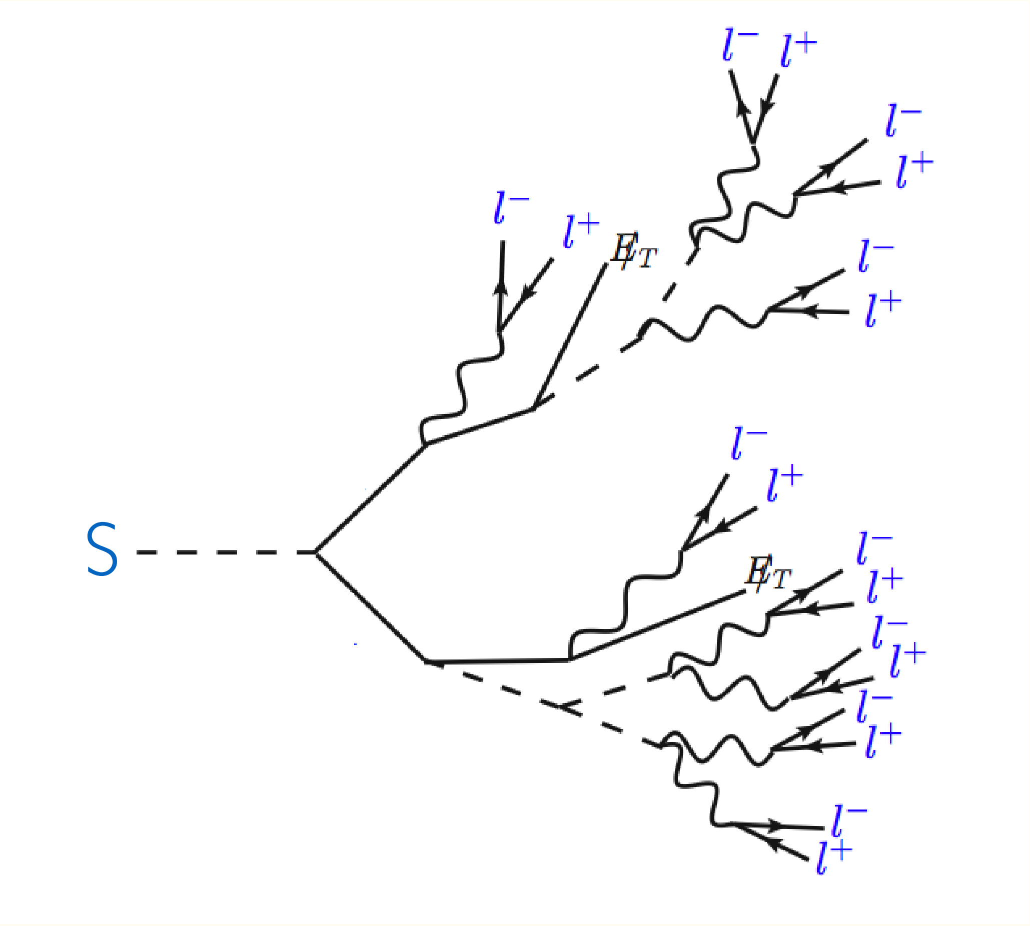
If the large width is real,
S is likely to decay visibly, introducing exotic signatures!

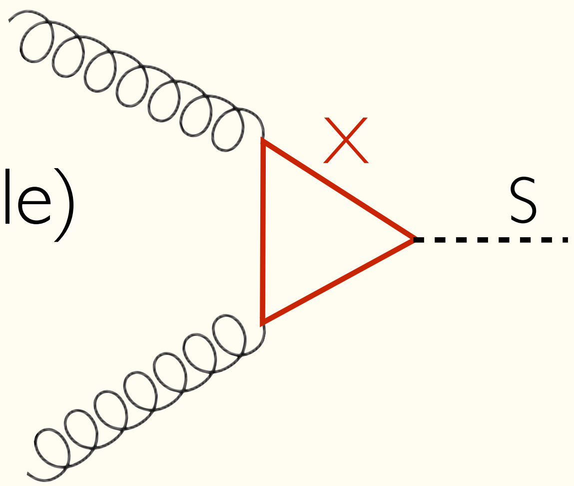
Exotic Signatures: Lepton Jets

- Just like with the Higgs scenario, S could cascade down a hidden sector and decay to collimated jets, possibly lepton jets (photon jets also relevant).
- Just as with the Higgs, decays could be displaced.
- LJs (especially displaced) may be a good way to hide S.
- We should search for such lepton jets at this mass scale!

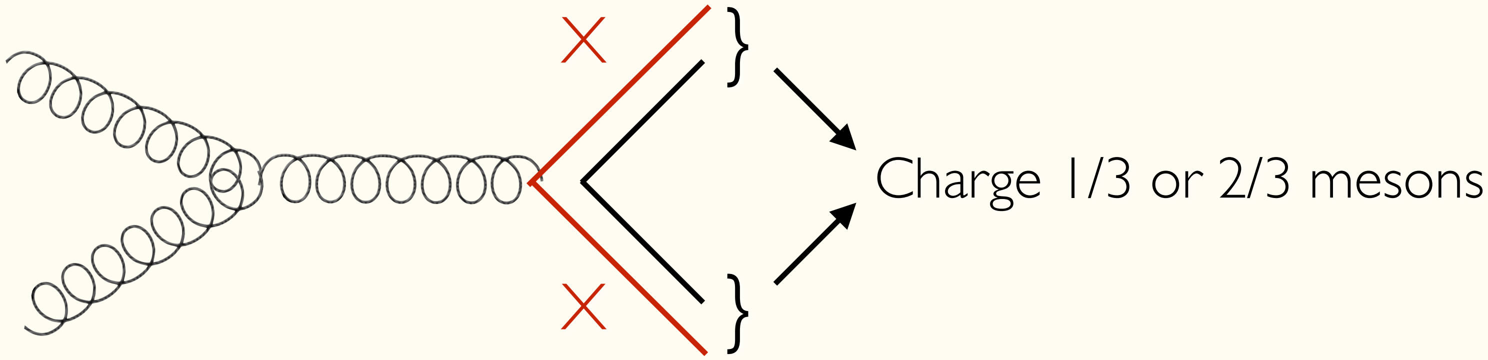


Exotic Signatures: Fractionally Charged Particles

- The glue-glue couplings to S may be generated by vector-like fermions, charged under QCD (but with no hypercharge).



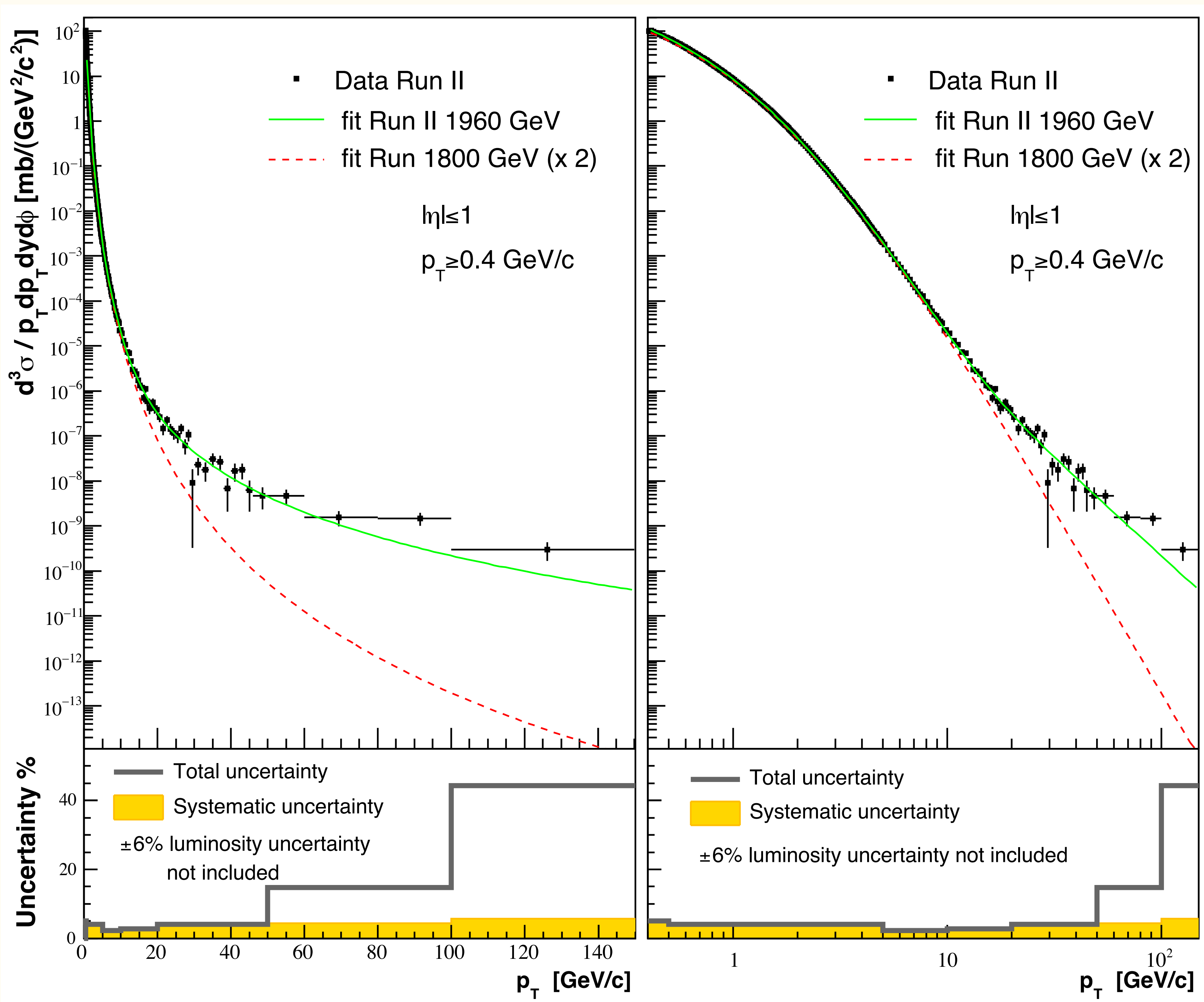
- Direct production of X would form (possibly unstable) fractionally charged mesons.

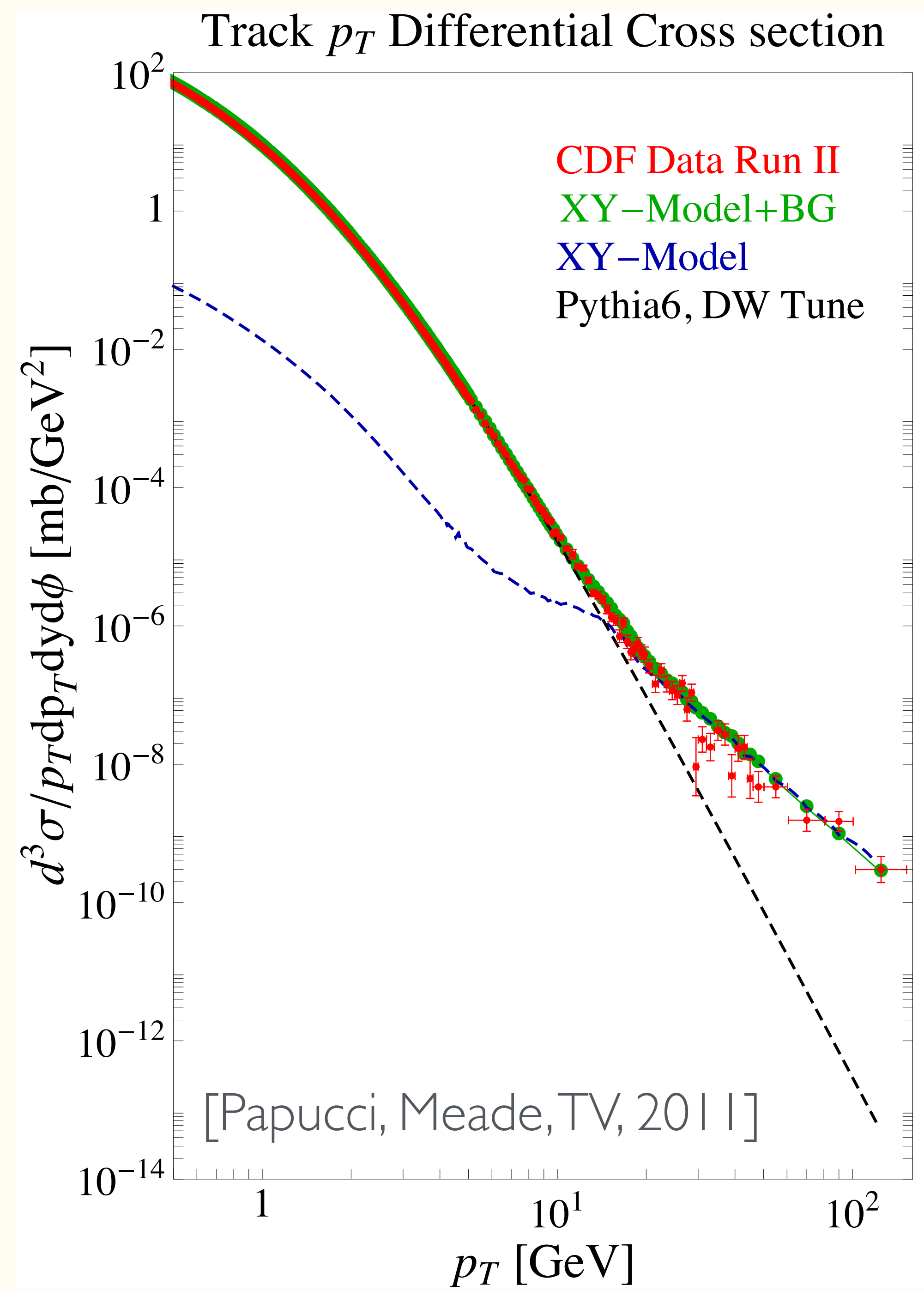


- The p_T that will be measured is enhanced: $$p_{T,\text{measured}} = \frac{p_T}{q}$$

Exotic Signatures: Fractionally Charged Particles

- Strange signatures like these showed up in the past… [CDF, 0904.1098]





Open Questions

- What is this related to?
  - Naturalness?
  - Extended Higgs Sector?
  - Mediator to a Hidden Sector?
  - Breakdown of Antropics?

Exotic searches may play a key role!

Exotics from SUSY

[Csaki,Kuflik,TV, 2013]
[Csaki,Kuflik,Slone,TV, 2015]
[Csaki,Kuflik,Lombardo,Slone,TV, 2015]

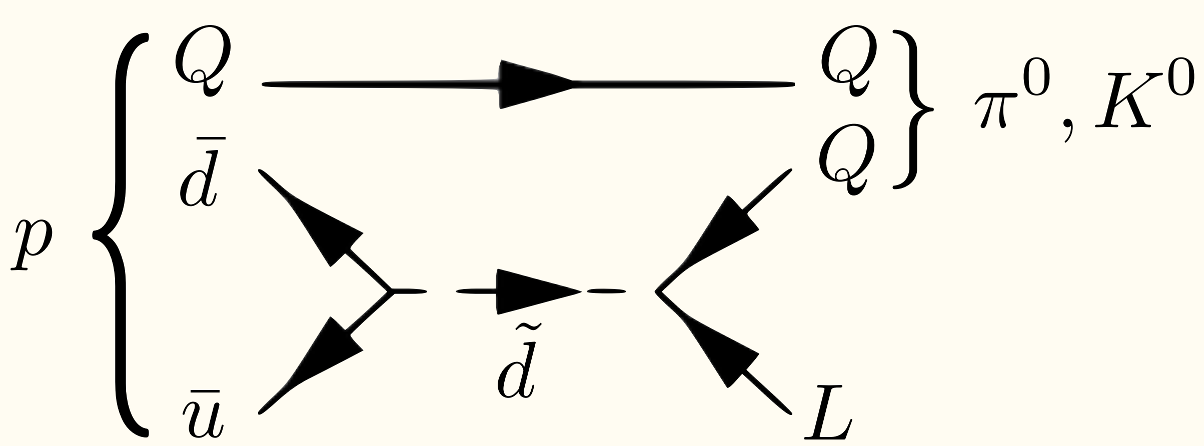
R-Parity Violation (RPV)

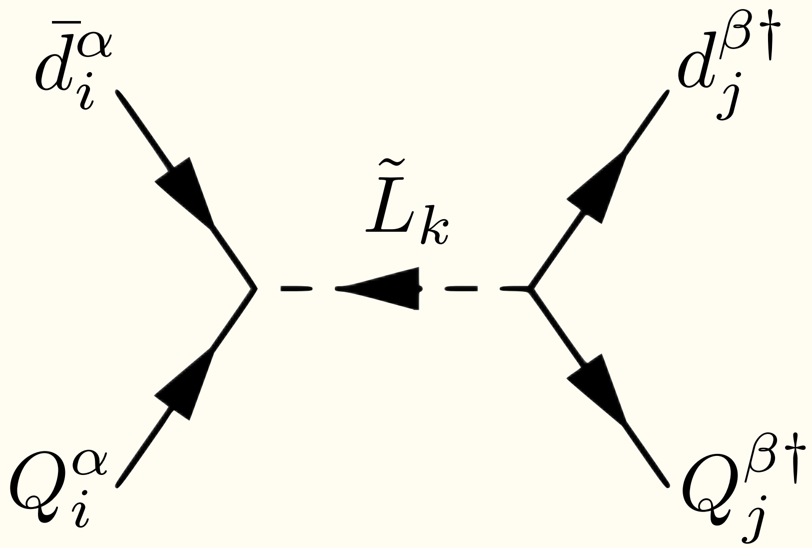
Problem

- Without additional symmetries, one may write in the superpotential the following terms:

$$W = \lambda L L \bar{e} + \lambda' L Q \bar{d} + \lambda'' \bar{u}\bar{d}\bar{d}$$

- The above leads to many problems, such as proton decay or FCNCs:

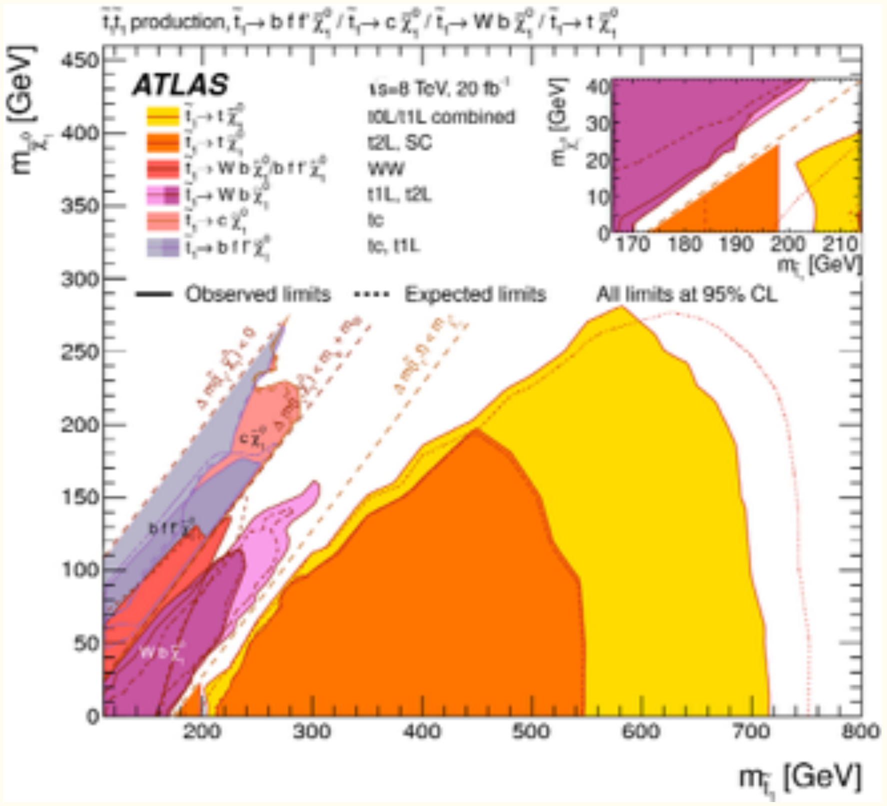




R-Parity Violation (RPV)

Solution

- Impose a discrete symmetry: $P_R = (-1)^{3(B-L)+2s}$
- Symmetry forbids the above terms.
    - No problem with proton decay.
    - LSP stable.
    - Implies MET in all events related to supersymmetry.
- Standard searches place strong constraint on this scenario.



R-Parity Violation (RPV)

Evading the Bounds

- R-parity may be violated. However, couplings must be small and hierarchical.
- Typically, people take the tree-level superpotential terms

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with small and hierarchical parameters, $\lambda, \lambda', \lambda'' \ll 1$

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Why?? Is this motivated?

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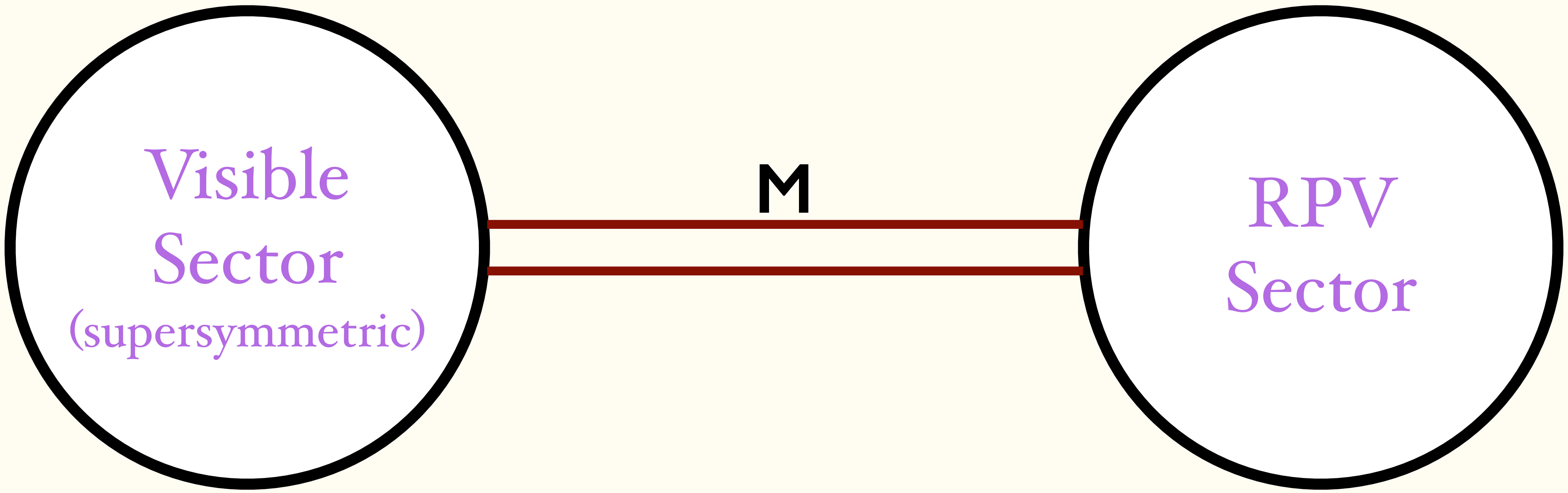
Why?? Is this motivated?

R-parity is an approximate symmetry in the visible sector.
It may be broken in a hidden sector and communicated to us.

Dynamical R-Parity Violation (dRPV)



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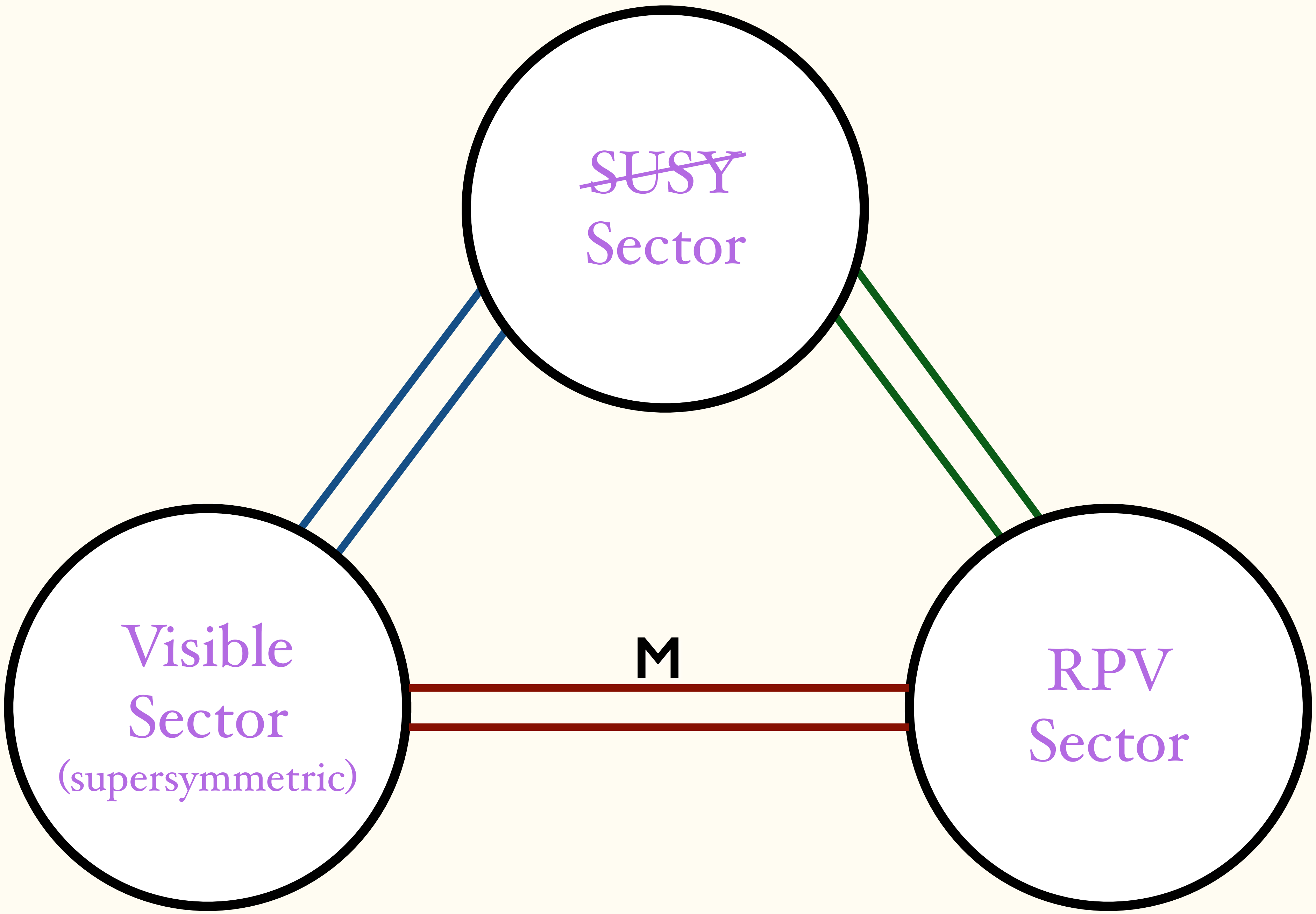

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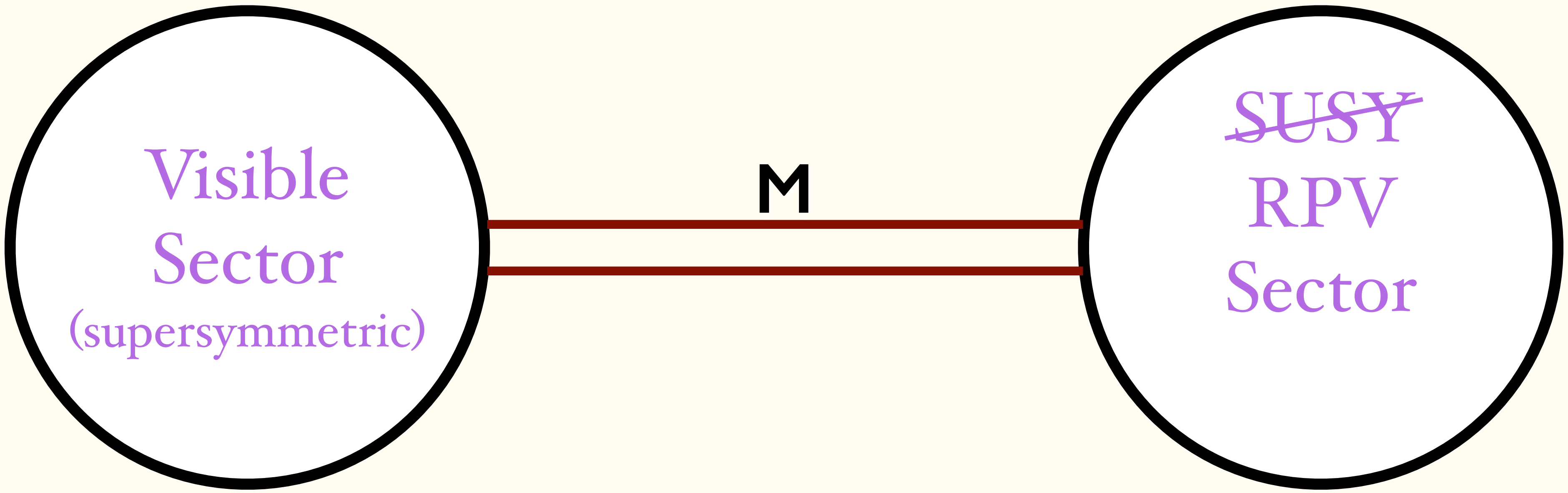

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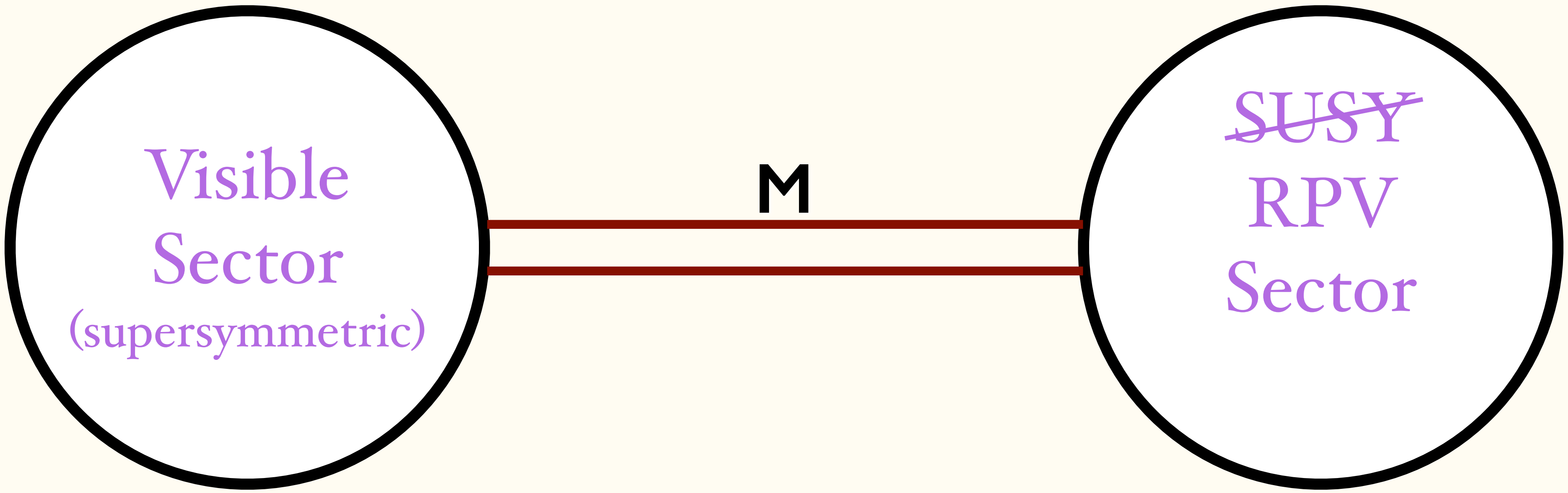


What are the consequences?

dRPV: Basic Consequences

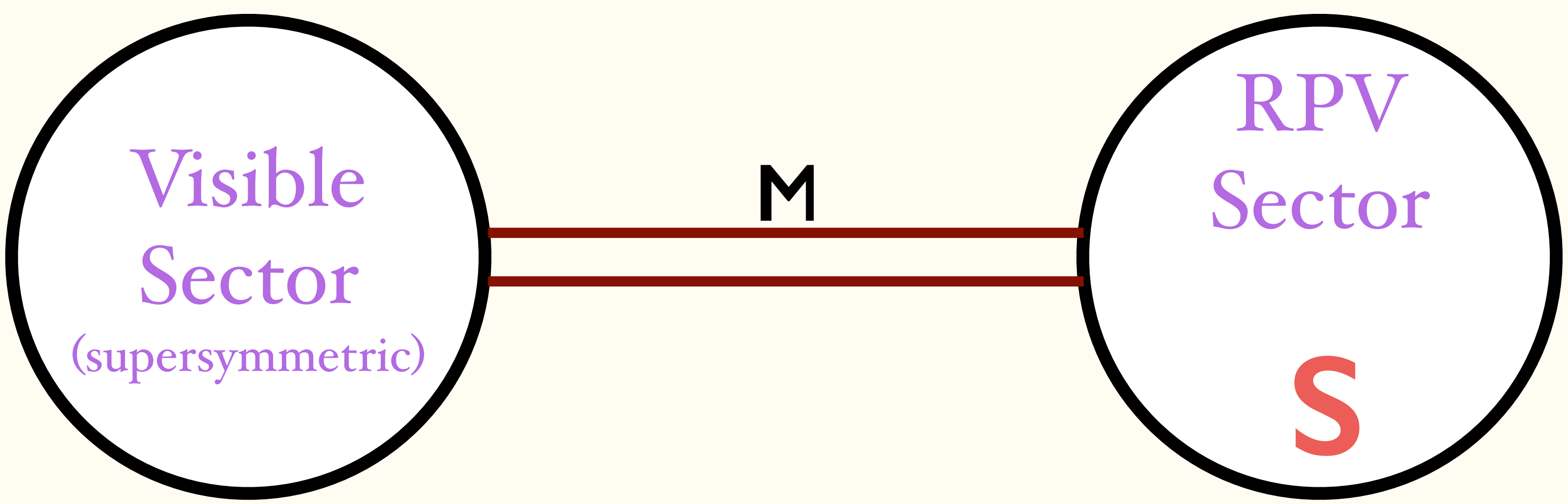
- Because RPV is mediated by some high scale, effects of RPV in the visible sector are automatically suppressed.

- Dynamics imply RPV operators in the Kahler potential (with or without operators in the superpotential).

- In particular, quite generally, dRPV implies new kind of operators:

$$\mathcal{O}_{\rm nhRPV} = \eta \bar{u}\bar{e}\bar{d}^\dagger + \eta' Q\bar{u}L^\dagger + \eta'' QQ\bar{d}^\dagger + \kappa \bar{e} H_d H_u^\dagger$$

- These are non-holomorphic operators that show up in the Kahler potential,



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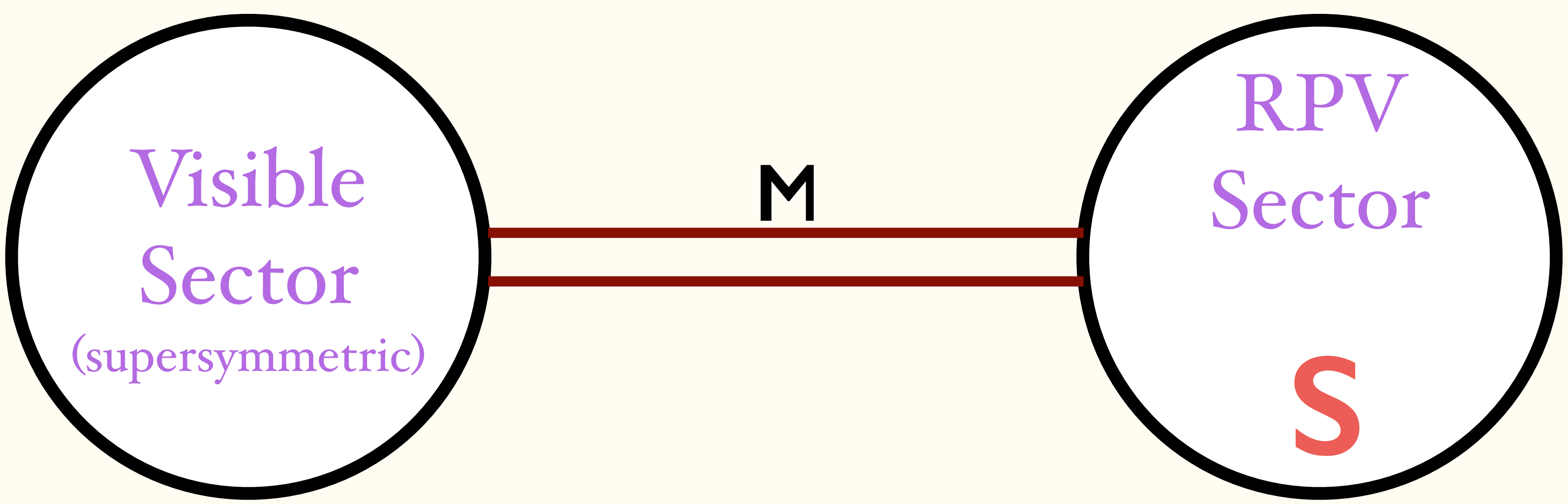

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These could be the leading RPV operators

dRPV: Collider Implications

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- The above have different helicity and flavor structure compared to standard RPV.
- All operators are automatically chirally or SUSY-breaking suppressed!
- Very easy to evade limits from proton decay, di-nucleon decay, FCNCs, etc.
- Interesting decay modes for LSP involving 3rd generation:

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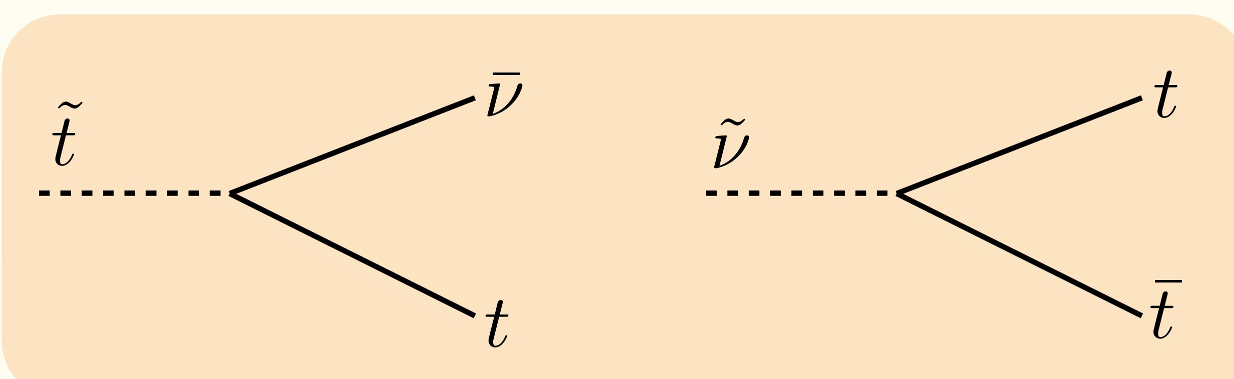

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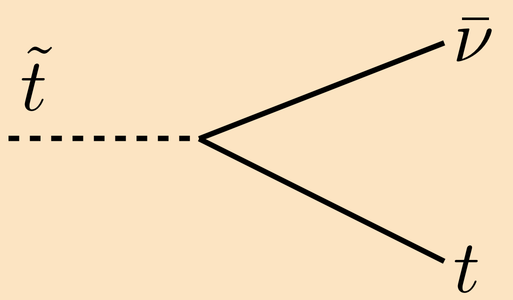

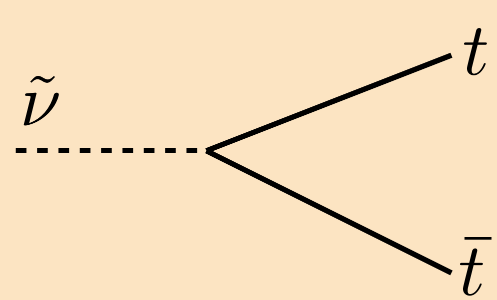

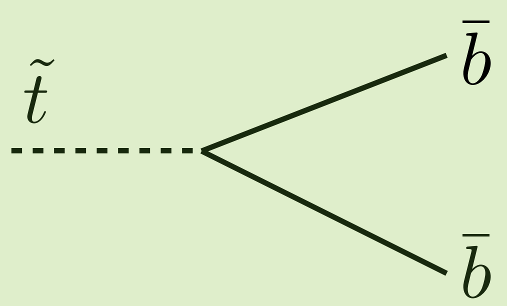

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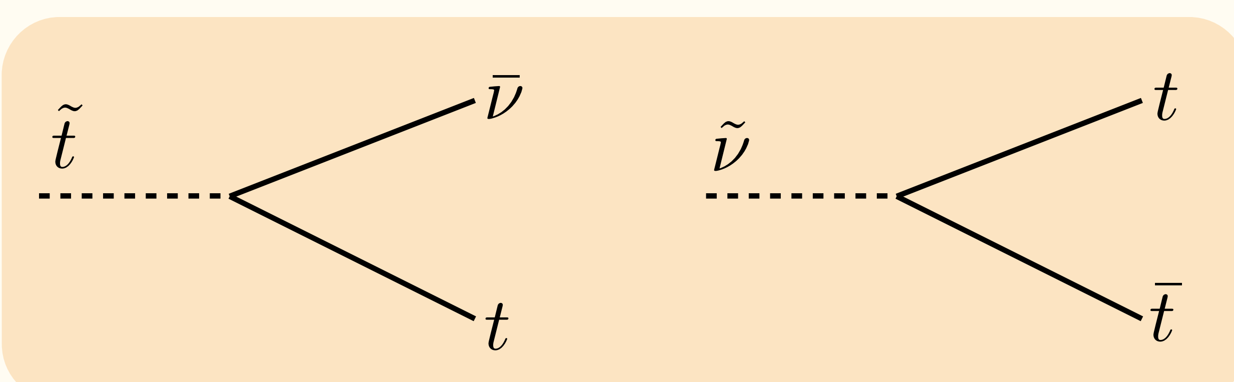

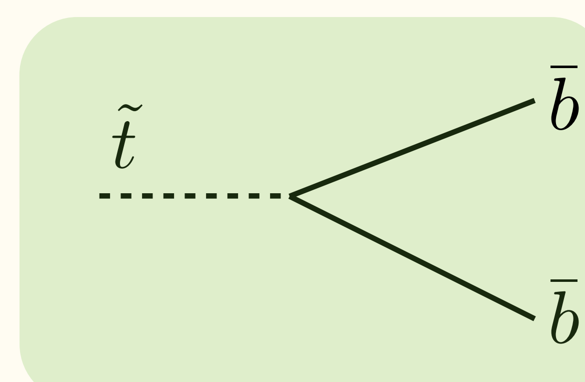

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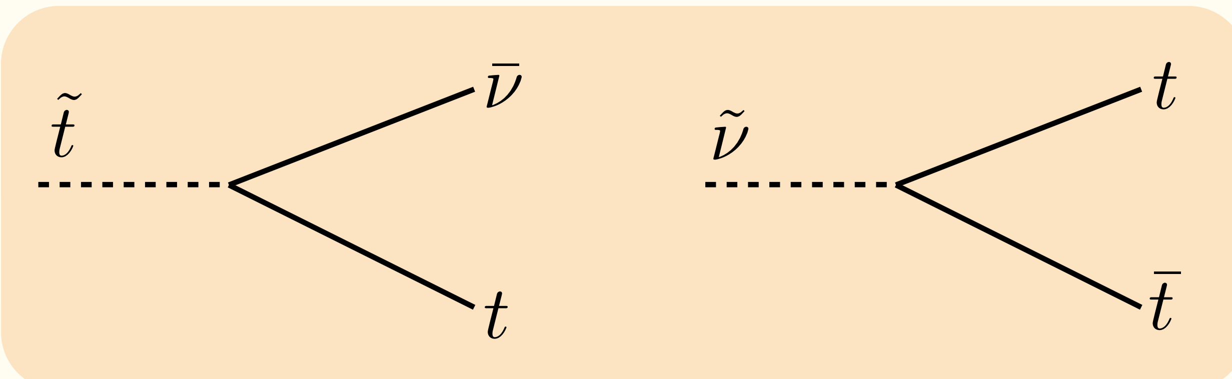
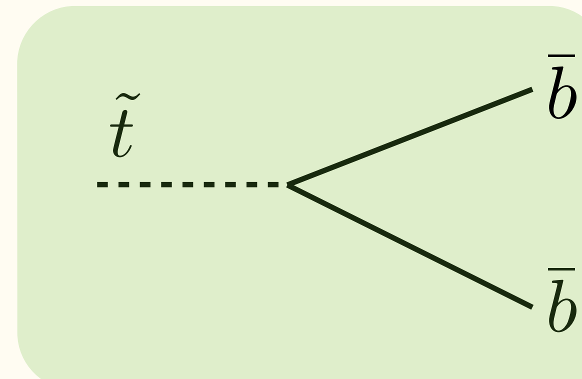


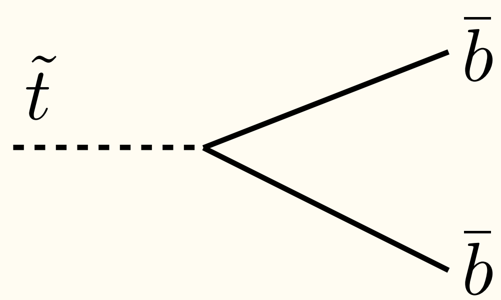


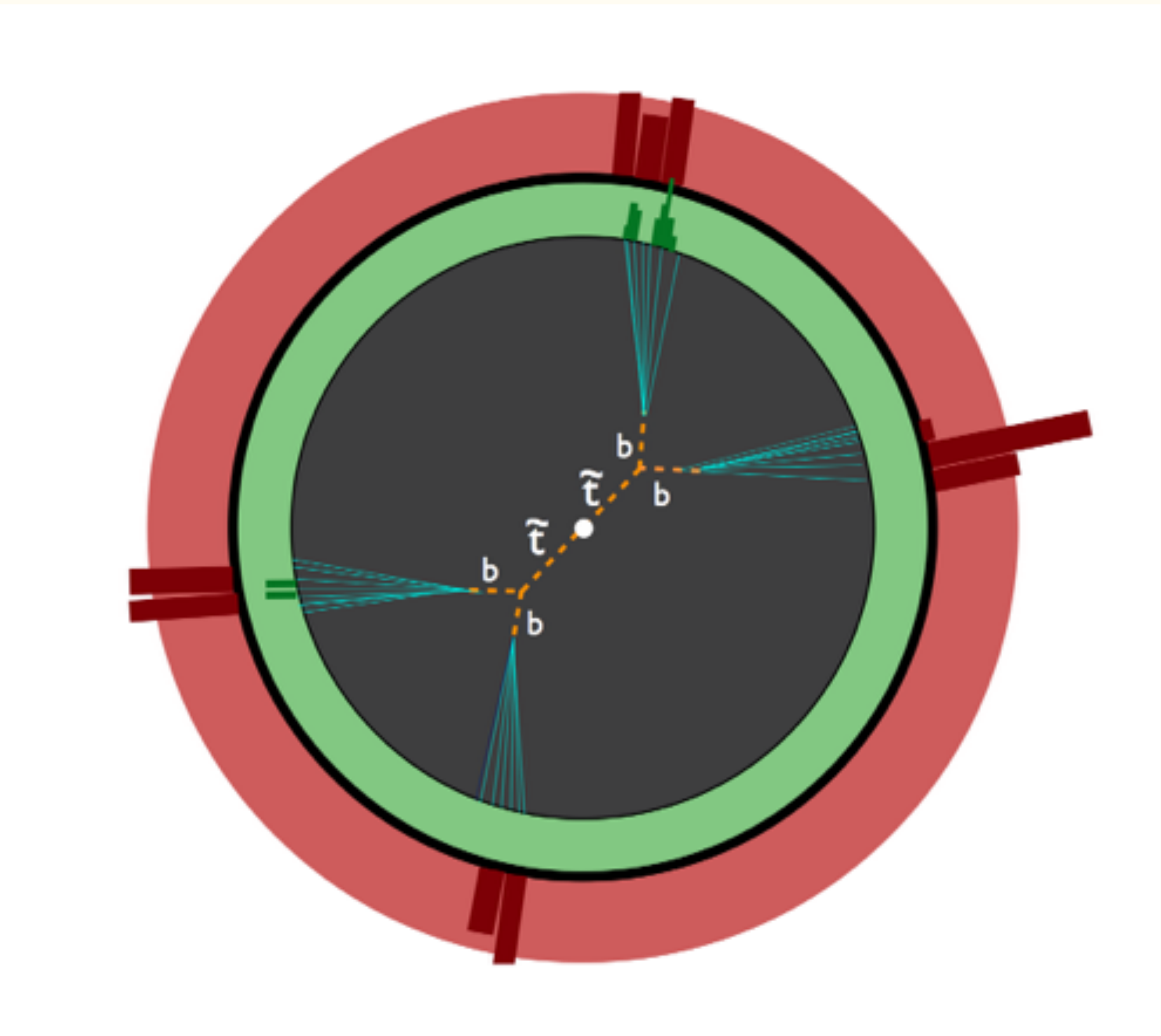
- The suppressions due to the breaking in the hidden sector imply displaced vertices at colliders:

$$c\tau_{\tilde{t}\to\bar{b}\bar{b}} \simeq 10\text{cm}\left(\frac{300\text{ GeV}}{m_{\tilde{t}}}\right)\left(\frac{M^2/\langle S\rangle}{10^9\text{ GeV}}\right)^2\left|\frac{1}{\eta''_{333}}\right|^2$$

dRPV: Collider Implications

- Interesting displaced vertices:





- Stop decay to neutrino could also show up as kinks in the tracker.

dRPV: Constraints

- Sensitivity to such models come from exotic searches with displaced vertices.

- Two main searches:

1. ATLAS DV+μ/e/jets/MET.

   - N_{tracks} > 5
   - m_{DV} > 10 GeV
   - p_T > 55 GeV (muon), 125 GeV (electron), 180 GeV (MET), ~60 GeV (jets)

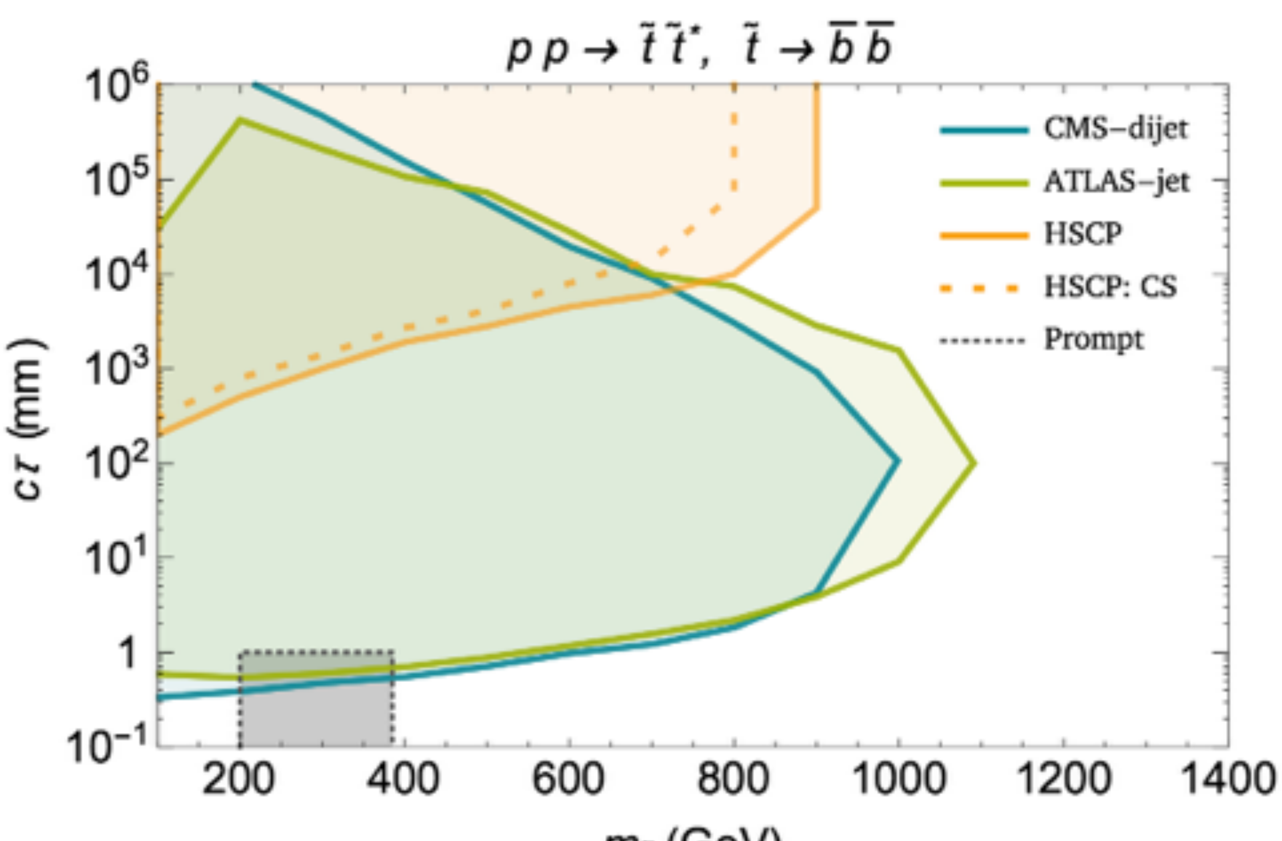
2. CMS Displaced Dijet

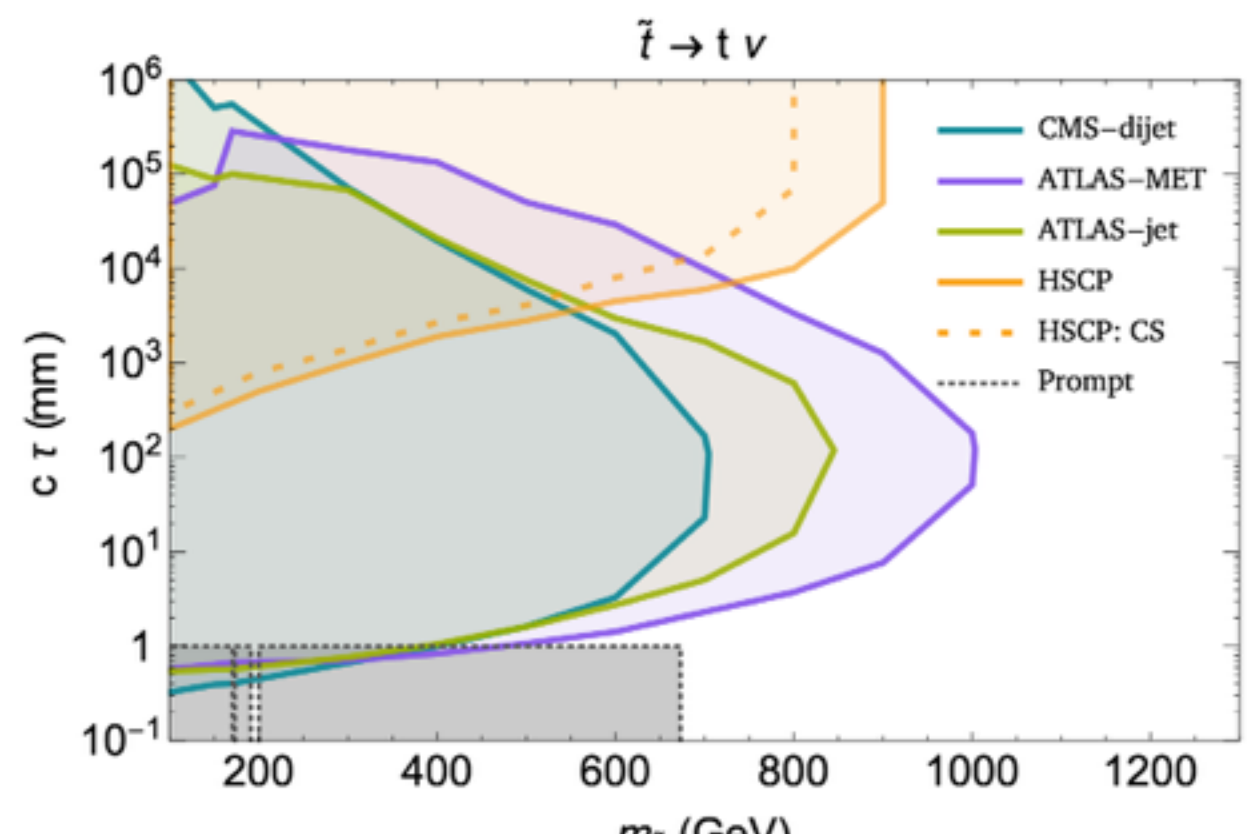
   - pT > 60 GeV for each jet.
   - H_T > 350 GeV (trigger)
   - m_{DV} > 4 GeV (no b's)
   - N_{tracks} > 4, 5
   - At most one prompt (IP <0.5 mm) track per jet
   - Dijet consistent with DV

dRPV: Constraints

Sensitive to various topologies:

Topologies		
LSP	Decay	Operator
$\tilde{t}$	$\bar{d}\,\bar{d}'$	λ'', η''
	$u\,\bar{\nu}$	η'
	$d\,\ell^+$	λ', η
$\tilde{g}$	$t\,d\,d' + c.c$	λ'', η''
	$t\,\bar{u}\,\bar{\nu} + c.c$	η'
	$t\bar{d}\,\ell^- + c.c$	λ', η
$\tilde{H}^0/\tilde{H}^{\mp}$	$(t/b)\,d\,d' + c.c$	λ'', η''
	$(t/b)\,\bar{u}\,\bar{\nu} + c.c$	η'
	$(t/b)\,\bar{d}\,\ell^- + c.c$	λ', η





[Csaki,Kuflik,Lombardo,Slone,TV, 2015]

Conclusions

Exciting times at the LHC!!

Something may be right around the corner

Exotic searches will play a crucial role in upcoming years

Unless vanilla SUSY (or similar) is discovered, exotic searches may be one of the only game in town

Hidden sectors are highly motivated!

Many different signatures are possible

Displaced vertices, lepton jets, soft jets, semi-visible jets, kinks, quirks, etc.

Prepare for the Unexpected!!

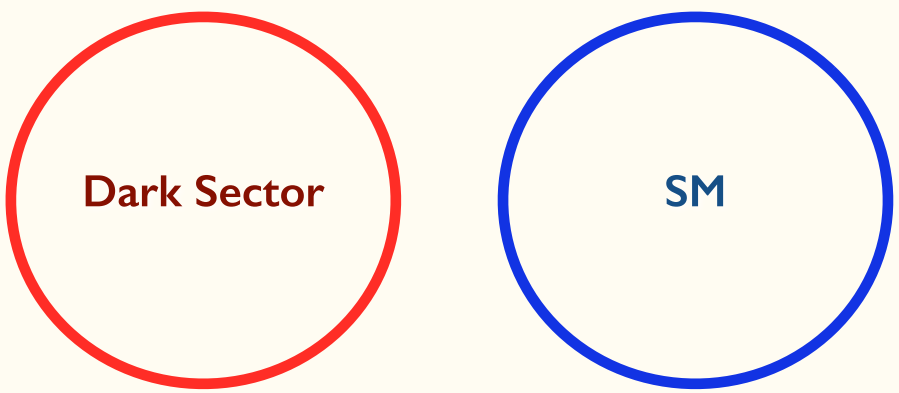
Backup Slides

Self-Interacting Dark Matter?

E.g.: The SIMP

[Carlson, Hall, Machacek, 1992; Kuflik, Hochberg, TV, Wacker, 2014; Kuflik, Hochberg, Murayama, TV, Wacker, 2014; Kuflik, Hochberg, Murayama, TV, Wacker, in progress]

2 sectors weakly coupled



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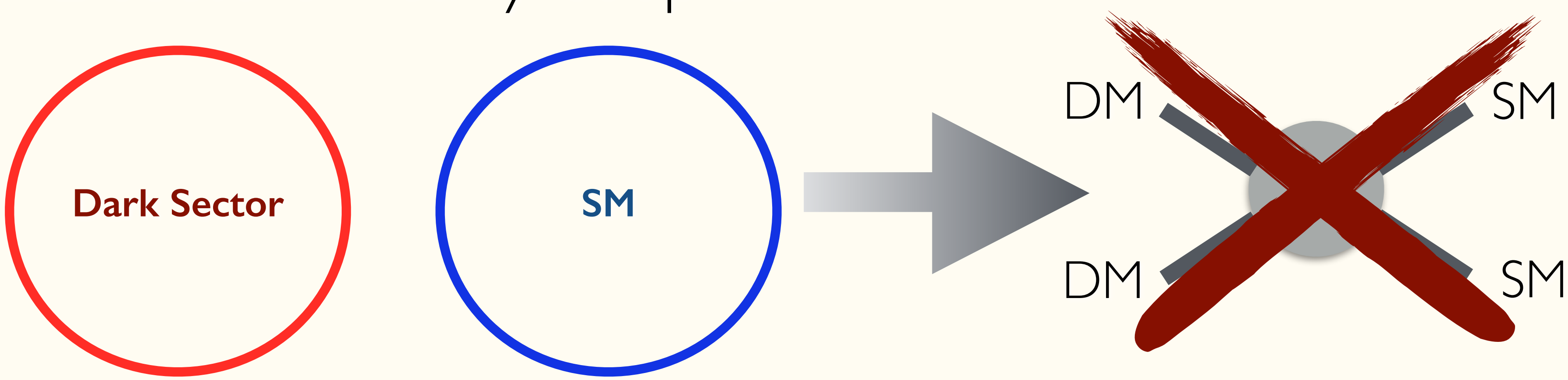

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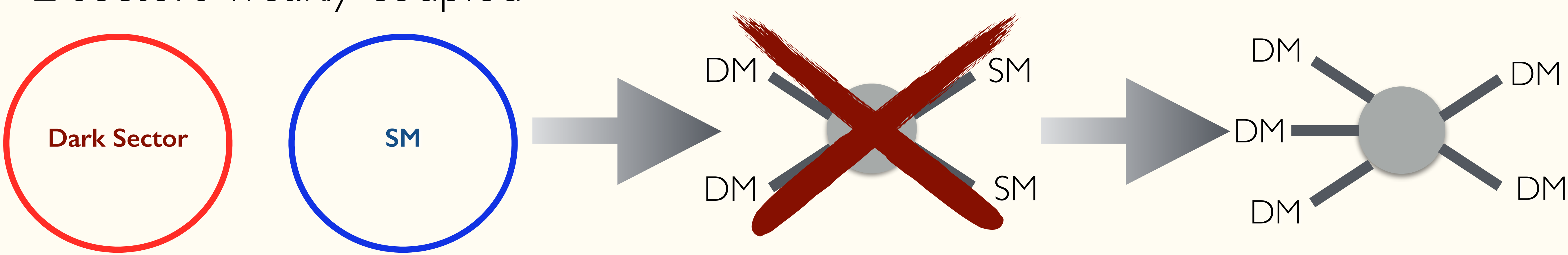

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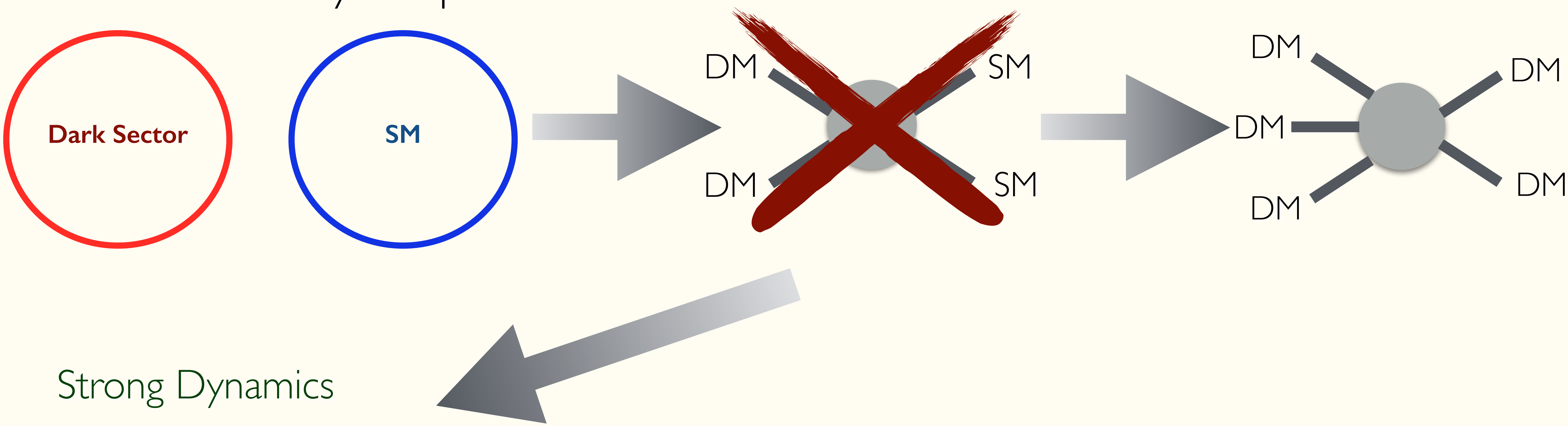

Strong Dynamics

$$\alpha_{\rm eff} \simeq \mathcal{O}(1)$$

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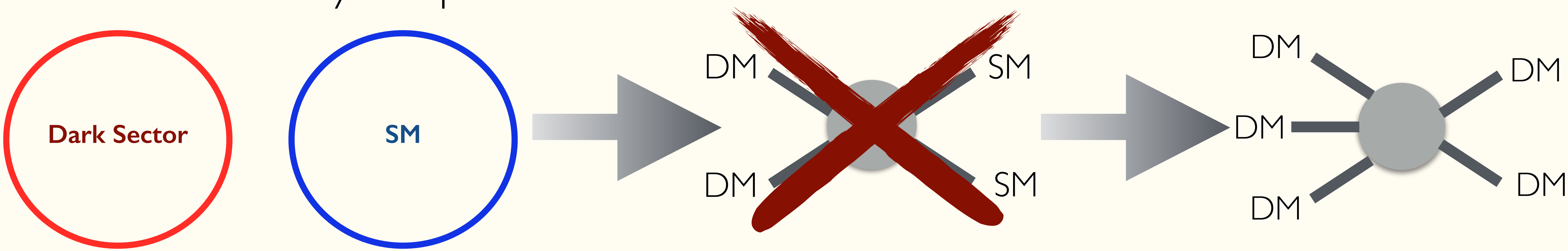

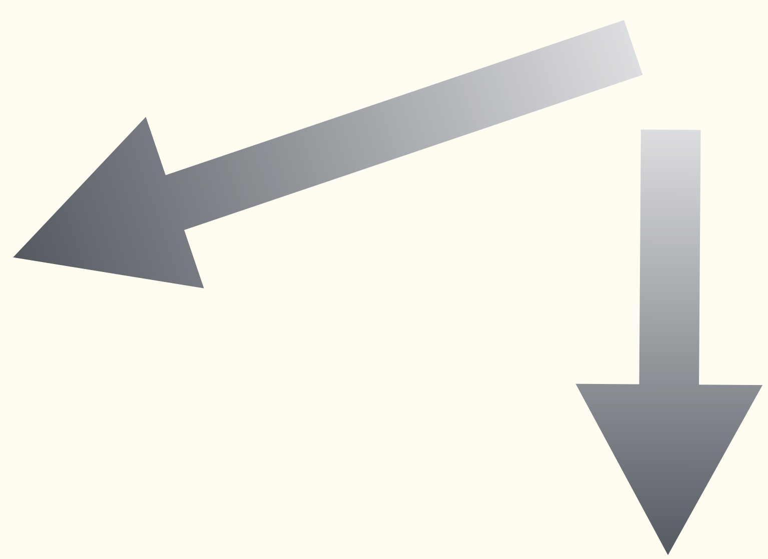

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QCD (low!) scale emerges for a strongly-interacting sector.

$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim 100 \text{ MeV}$$

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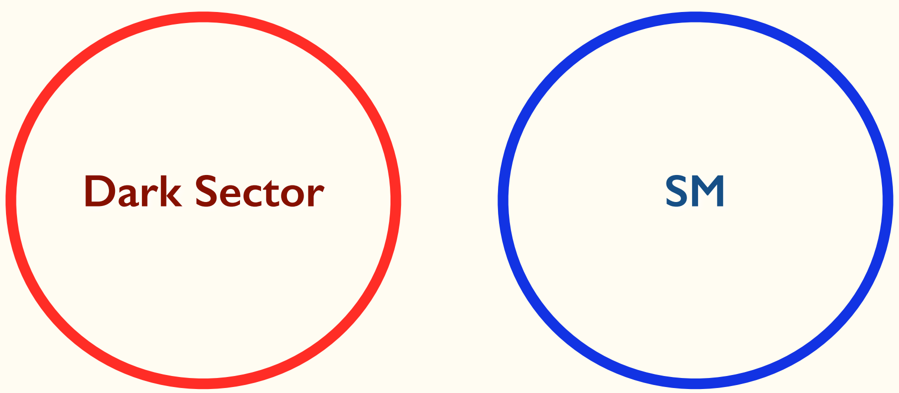

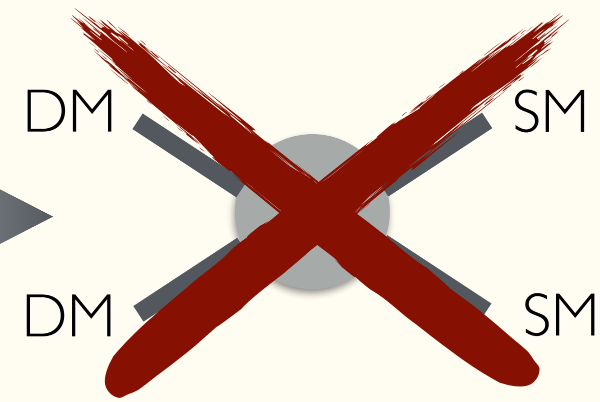

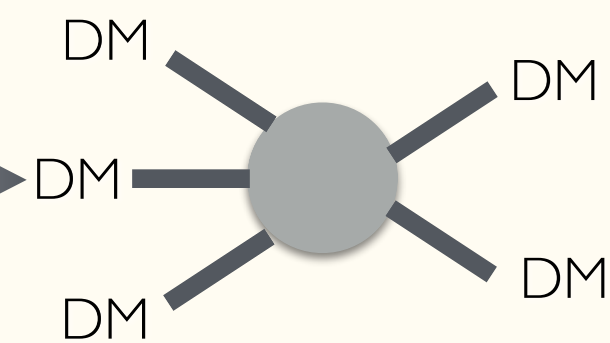

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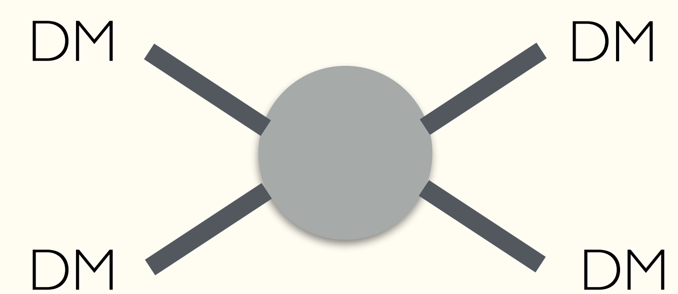
Large self-interactions



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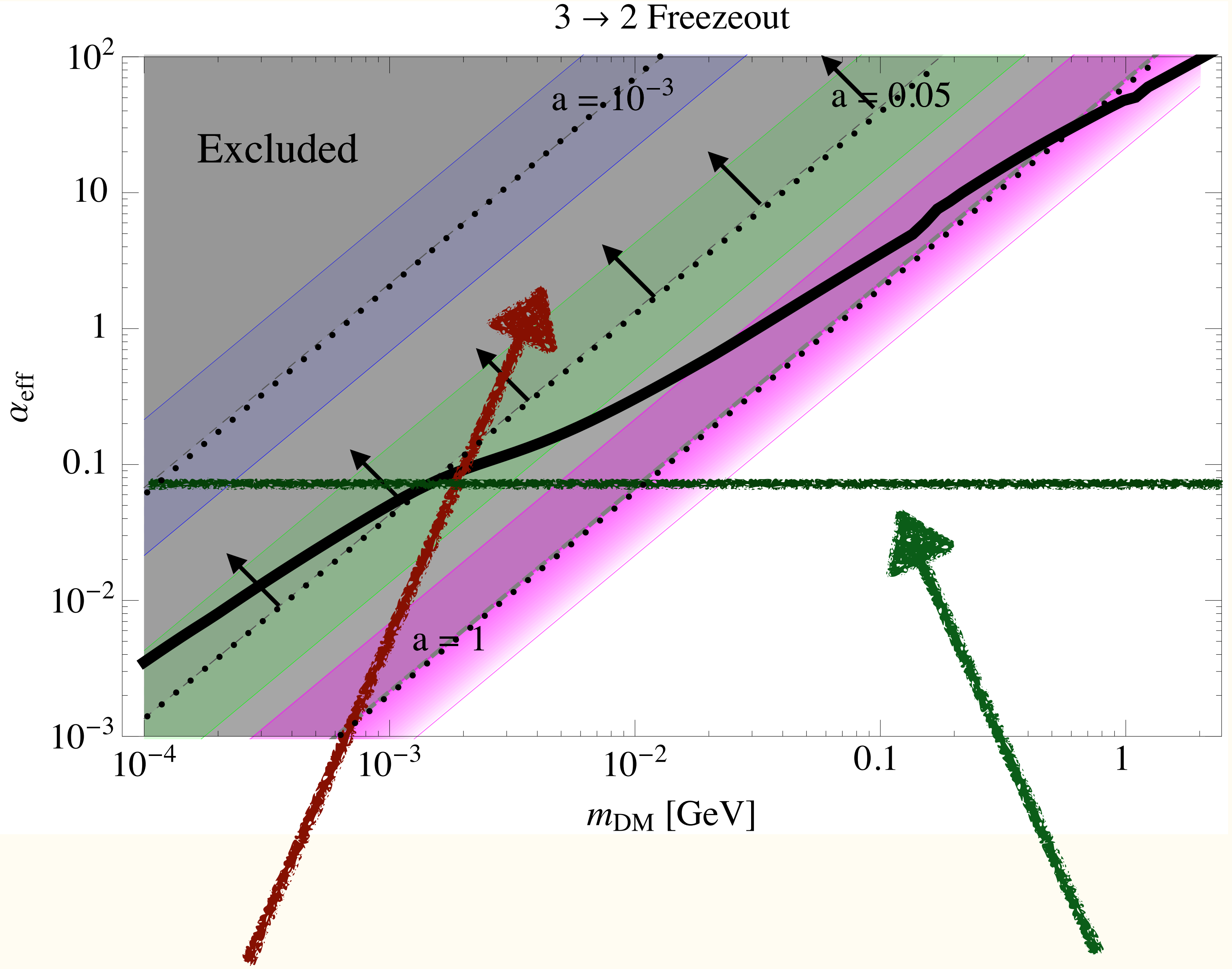
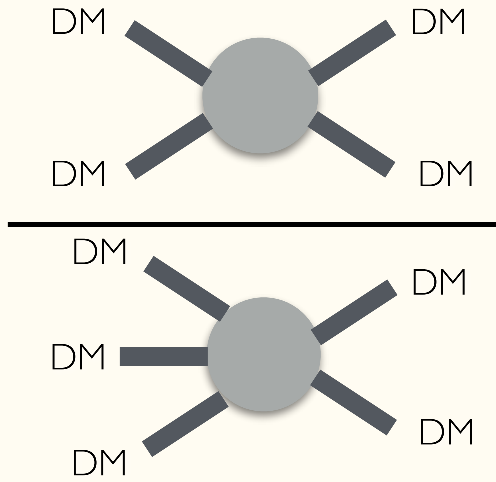
2-2 Good or Bad?

Weak scale emerges for a weak-strength interactions



$$a \equiv \frac{\alpha_{2-2}}{\alpha_{\rm eff}} =$$



Excluded by Bullet-cluster and halo-shape constraints

Constraints push to strong regime ➡ **SIMP**

3-2 Freeze Out

WIMP DM

Weak scale emerges for a weak-strength interactions

$$m_{\rm DM} \simeq \alpha_{\rm eff} \left(T_{\rm eq} M_{\rm Pl}\right)^{1/2} \sim {\rm TeV}$$

SIMP DM

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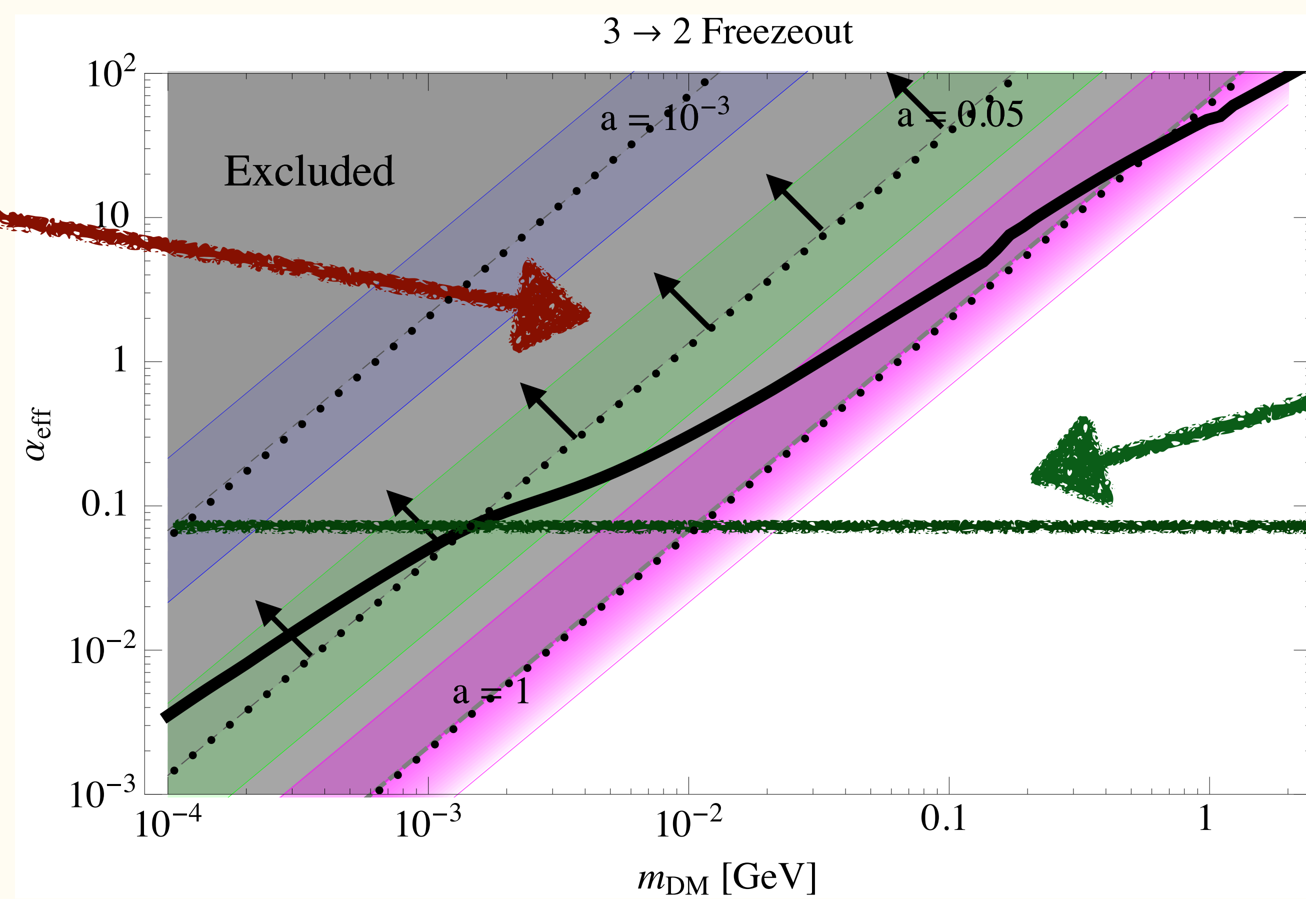

Constraints push to strong regime

⇓

SIMP

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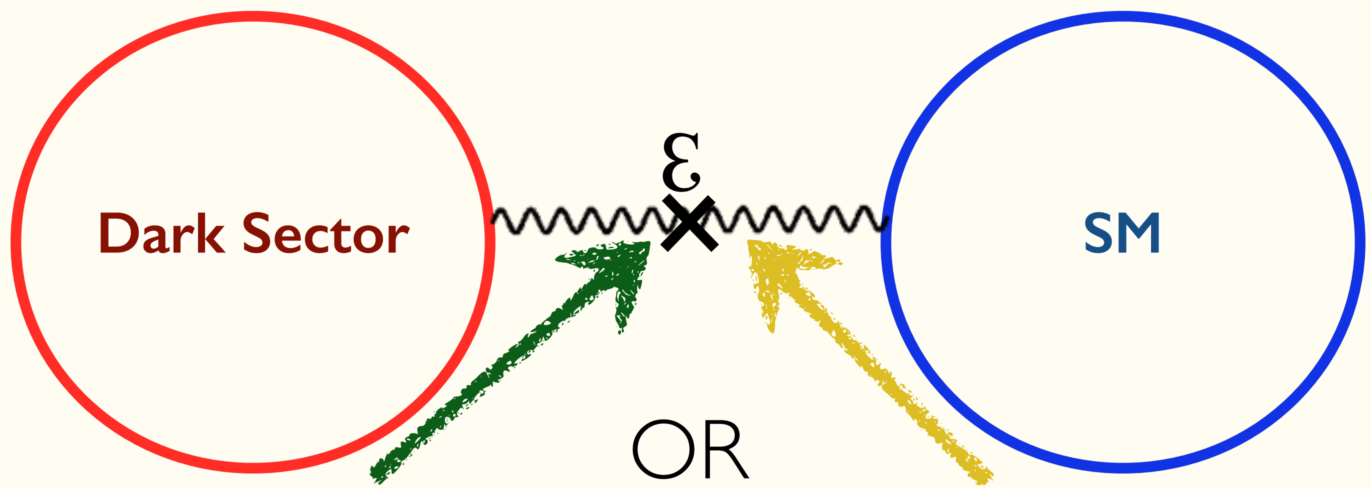
- Problem: We implicitly assumed that $\mathbf{T_{dark} = T_{SM}}$. Otherwise DM is hot and excluded.

- To evade limits on hot DM, the dark sector needs to be in thermal equilibrium with SM.



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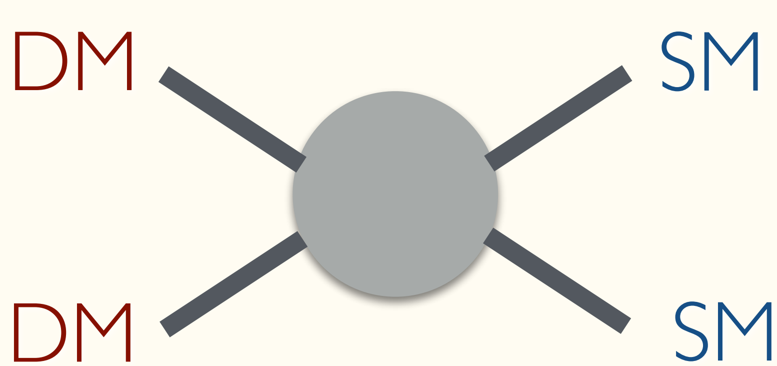
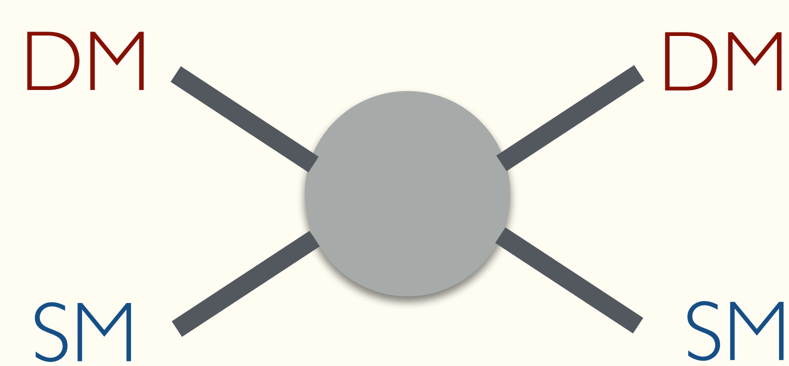
- Consequently, two more diagrams:



2-2 Annihilations



Thermal Equilibrium

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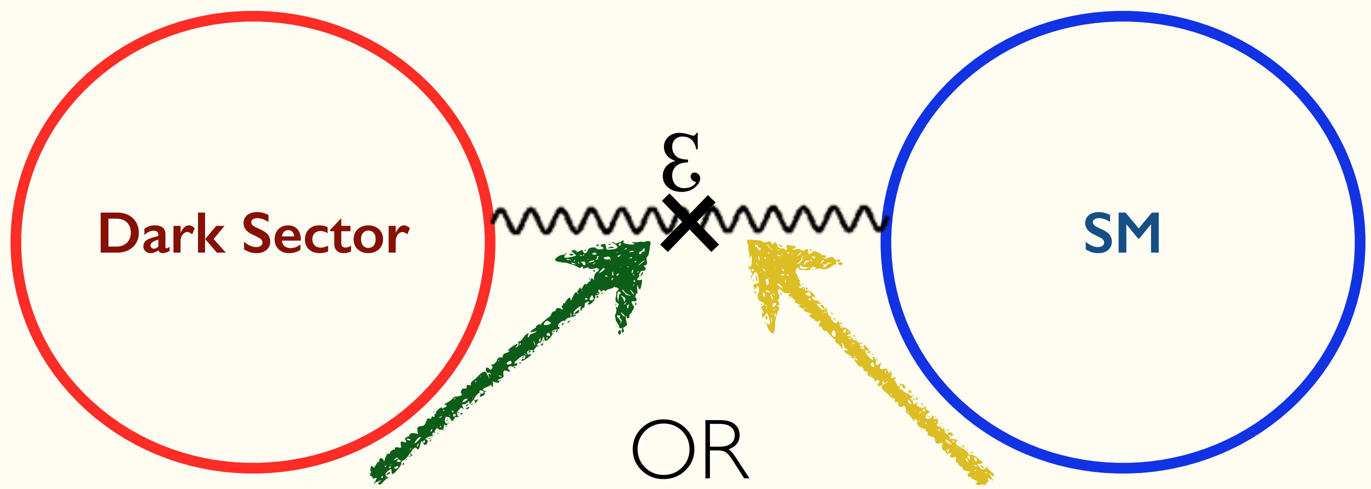

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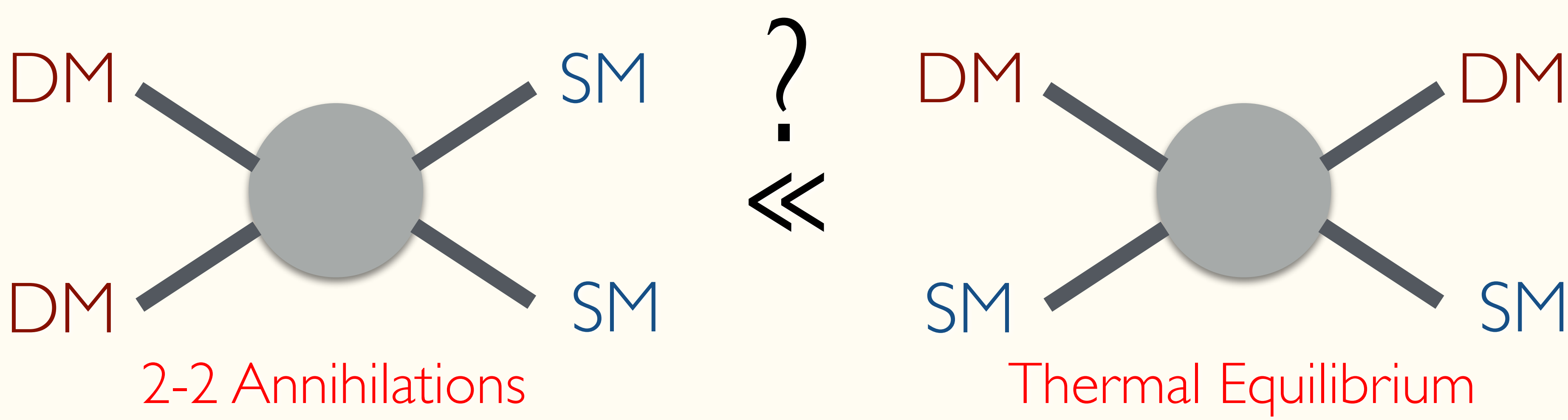

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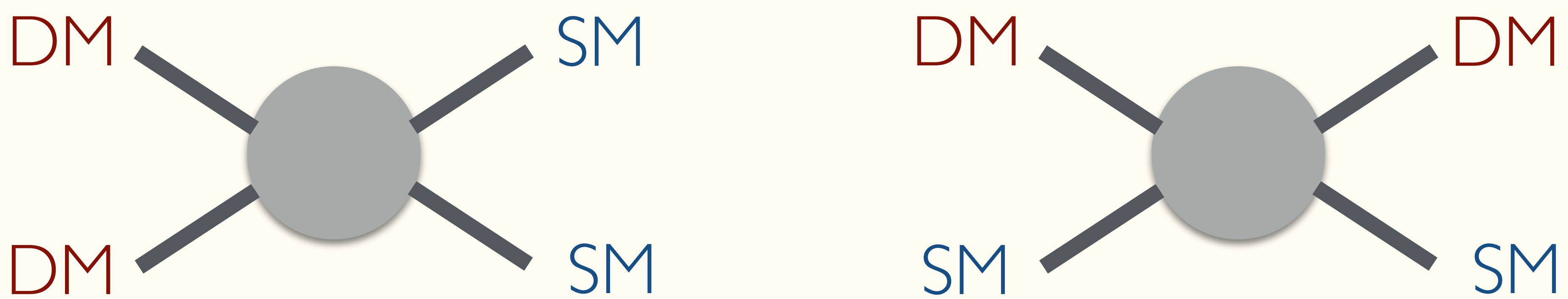
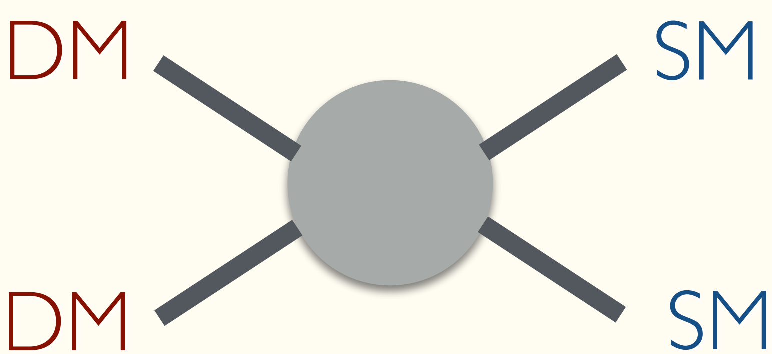


3-2 Freeze Out

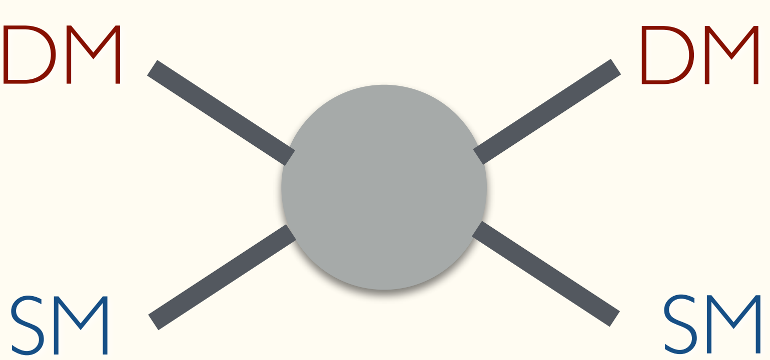
Taking:

$$\langle \sigma v \rangle_{\rm kin} \sim \langle \sigma v \rangle_{\rm ann} \equiv \frac{\epsilon^2}{m_{\rm DM}^2}$$

$$\Longrightarrow \quad \frac{\Gamma_{\rm ann}}{\Gamma_{\rm kin}} \sim \frac{n_{\rm DM}}{n_{\rm SM}} \sim e^{-m_{\rm DM}/T} \sim 2 \times 10^{-7}$$



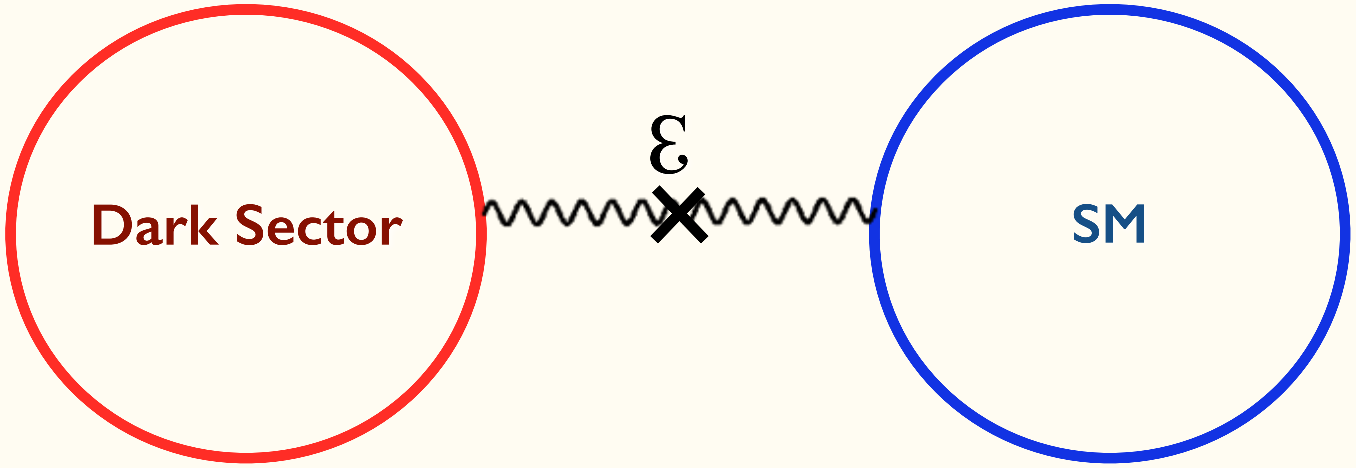
$$\left.\frac{\Gamma_{\rm ann}}{\Gamma_{3\to 2}}\right|_{T=T_F} \lesssim 1 \Longrightarrow \epsilon \lesssim \epsilon_{\rm max} \equiv 0.1\ \alpha_{\rm eff} \left(\frac{T_{\rm eq}}{M_{\rm Pl}}\right)^{1/6} \simeq 3 \times 10^{-6}$$

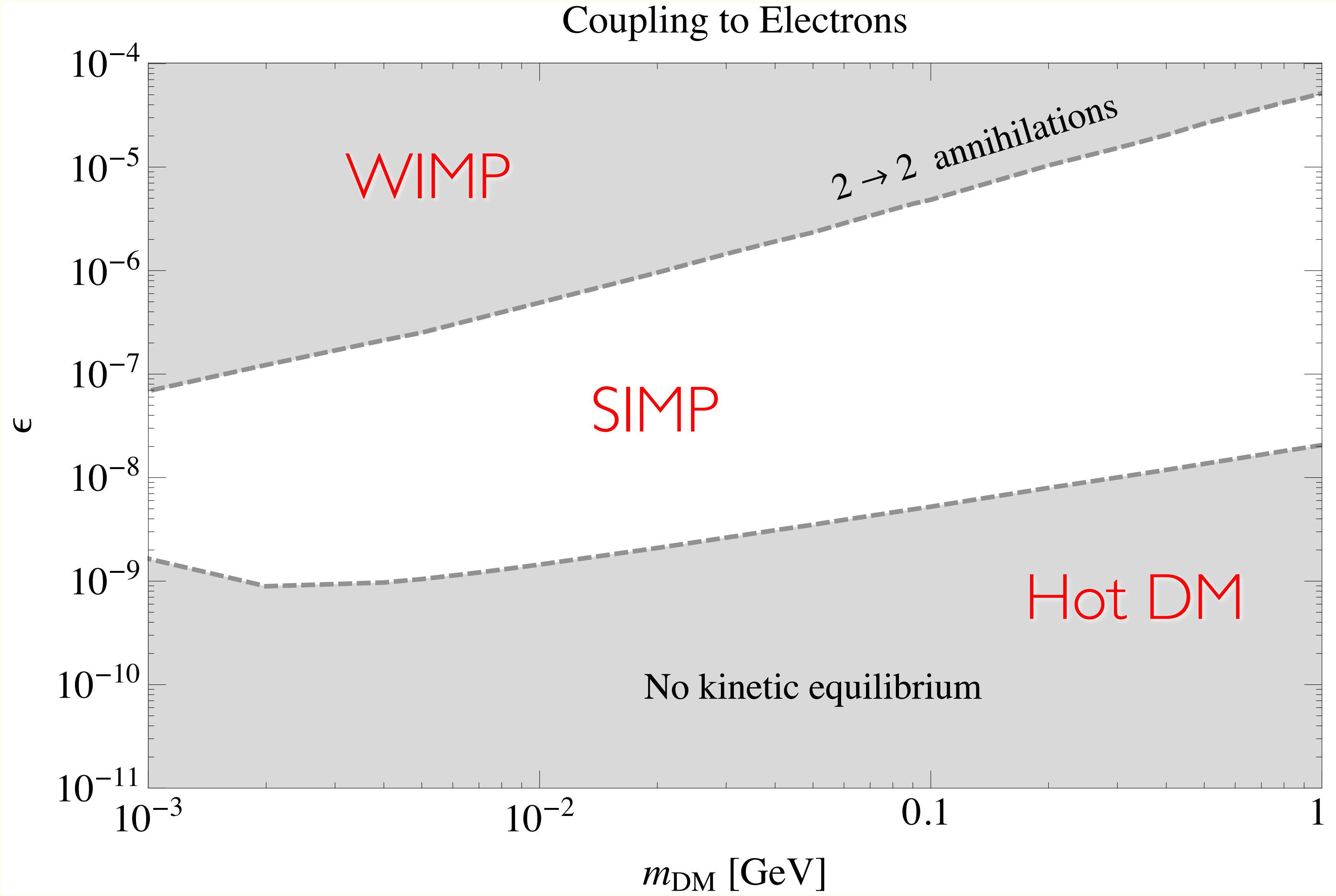


$$\left.\frac{\Gamma_{\rm kin}}{\Gamma_{3\to 2}}\right|_{T=T_F} \gtrsim 1 \Longrightarrow \epsilon \gtrsim \epsilon_{\rm min} \equiv 2\ \alpha_{\rm eff}^{1/2} \left(\frac{T_{\rm eq}}{M_{\rm Pl}}\right)^{1/3} \simeq 1 \times 10^{-9}$$

3-2 Freeze Out

Thus, much like the WIMP, the SIMP scenario predicts couplings to SM.





SIMP DM: Experimental Status