Dark Matter searches at LHC with displaced leptons

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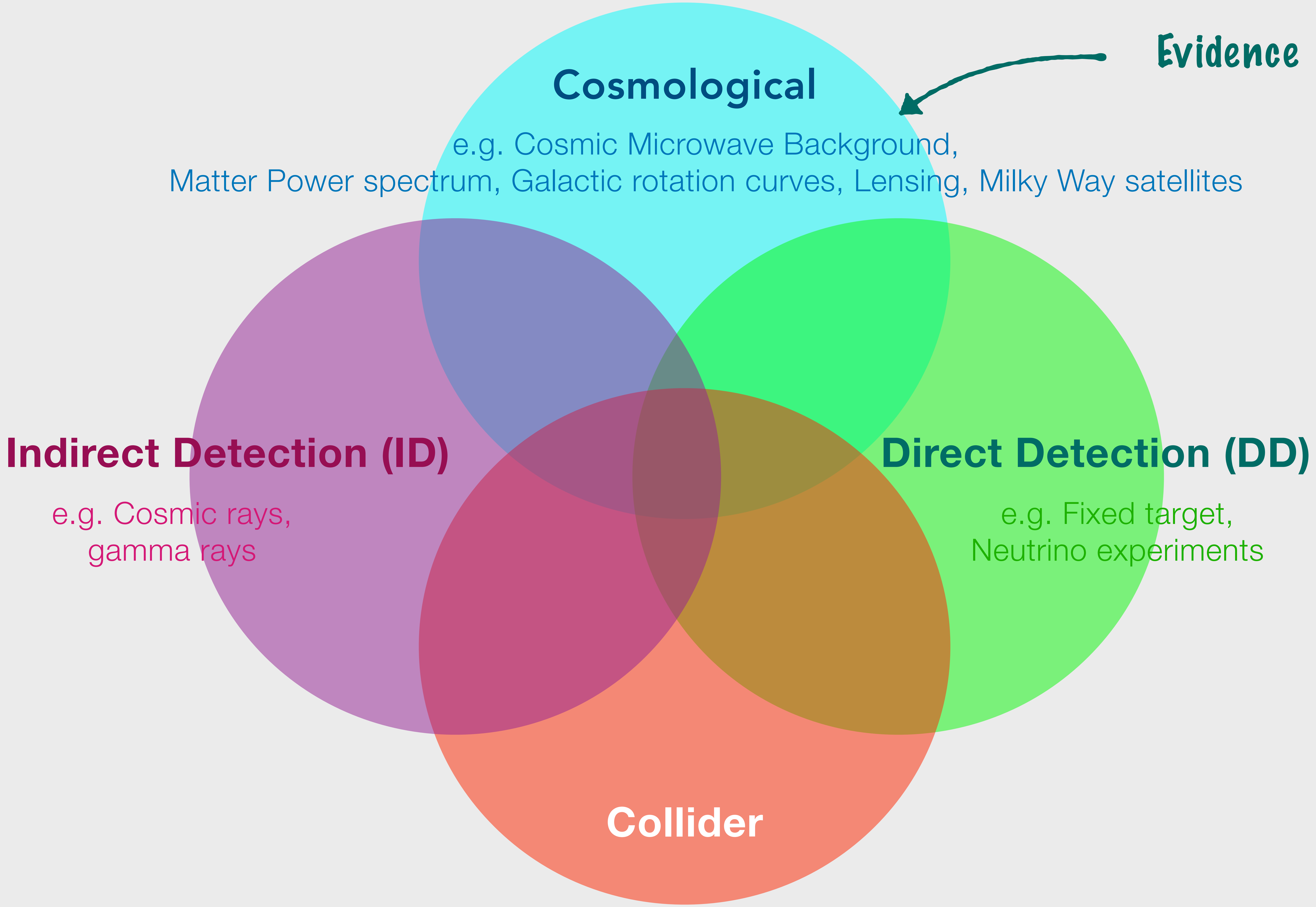
Based on work done with Blekman, Filimonova, Sahasransu and Westhoff (arXiv:2007.03708)

Anomalies 2020 • IIT Hyderabad • 11 Sep 2020


Evidence
Cosmological
e.g. Cosmic Microwave Background,
Matter Power spectrum, Galactic rotation curves, Lensing, Milky Way satellites
Indirect Detection (ID)
e.g. Cosmic rays,
gamma rays
Direct Detection (DD)
e.g. Fixed target,
Neutrino experiments
Collider

The DM story

- We know there is **five times more matter** in the Universe than visible baryonic matter.
- This invisible matter **does not interact appreciably with SM** and does not carry strong (QCD) or electric (QED) charge.
- It **may or may not** have self-interactions.
- It **may or may not** be a single fundamental particle.
- A lot of early DM study was motivated by the "**WIMP miracle**"
(Right thermal relic density with minimal assumptions: assuming early Universe in equilibrium, solve Boltzmann equations in expanding Universe, mass and interaction strength should be EW-scale.)
- **After ~35 years of experiments**, we have **strong DD constraints***, reasonable WIMP region (> 1 GeV) will soon hit irreducible neutrino BG making it difficult to observe.

The models that we believe are the most likely will inform our experimental search design.

How do we choose a model?

1. Model agnostic (i.e. using EFT)

   Great for DD, bad for LHC (large momentum transfer)

2. Simplest completions of EFTs

   Good first step, but lead to generic signatures that can be from non-DM; also miss a lot of possibilities

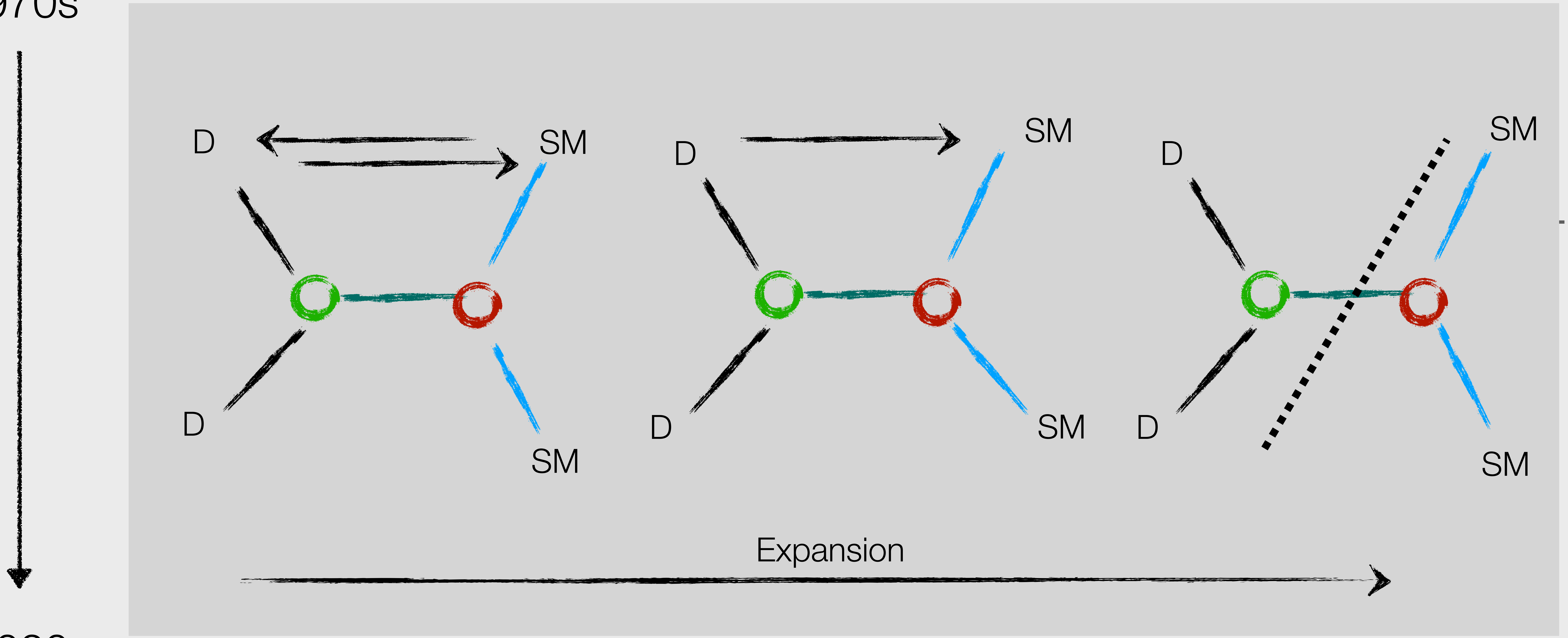
3. Based on all possibilites that give the right DM density

   Gets complicated very fast.

Design "not-so-simple" simplified models informed by DM density calculations.

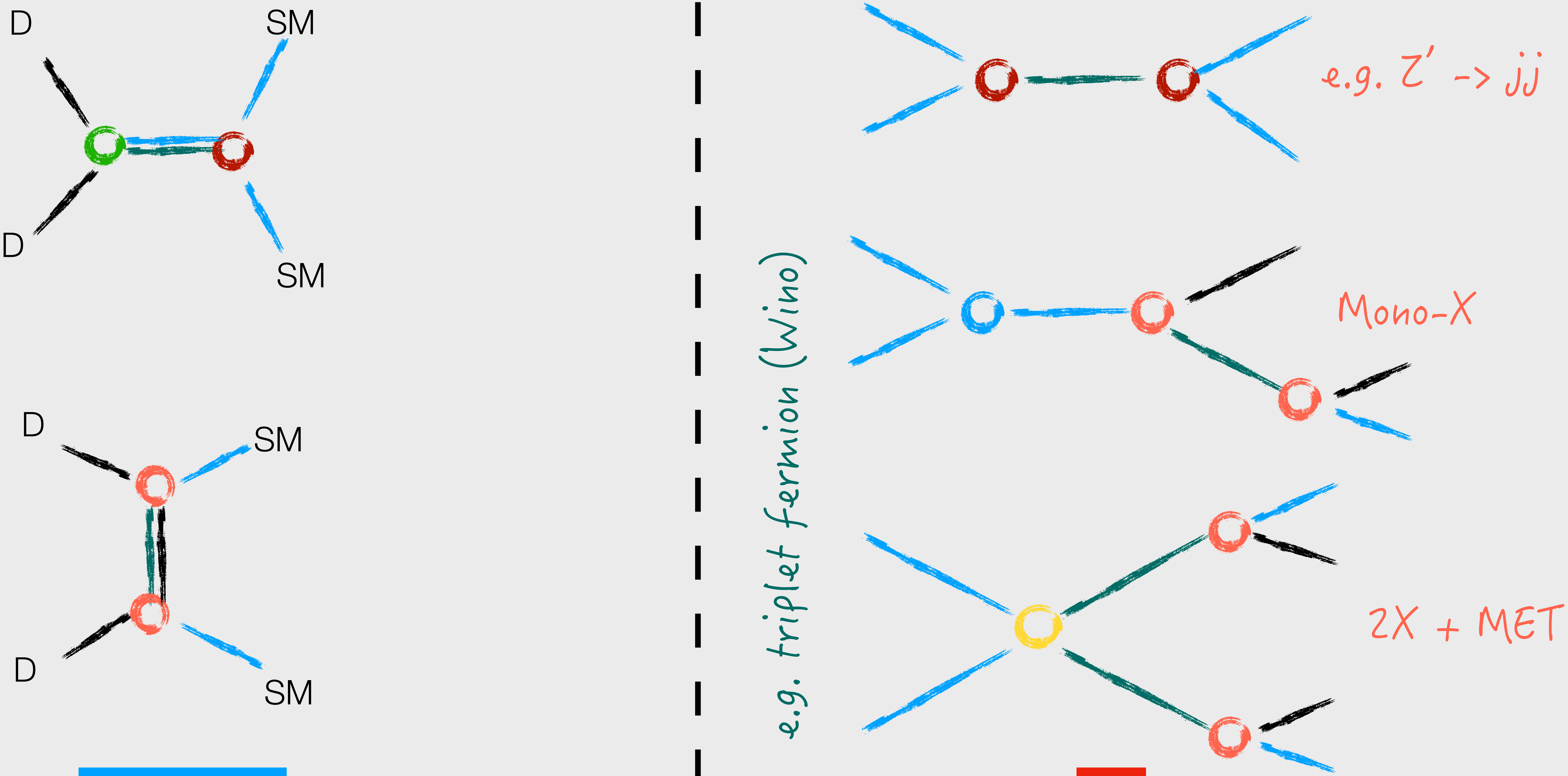
What we know about calculating DM density is changing

1970s



2020s

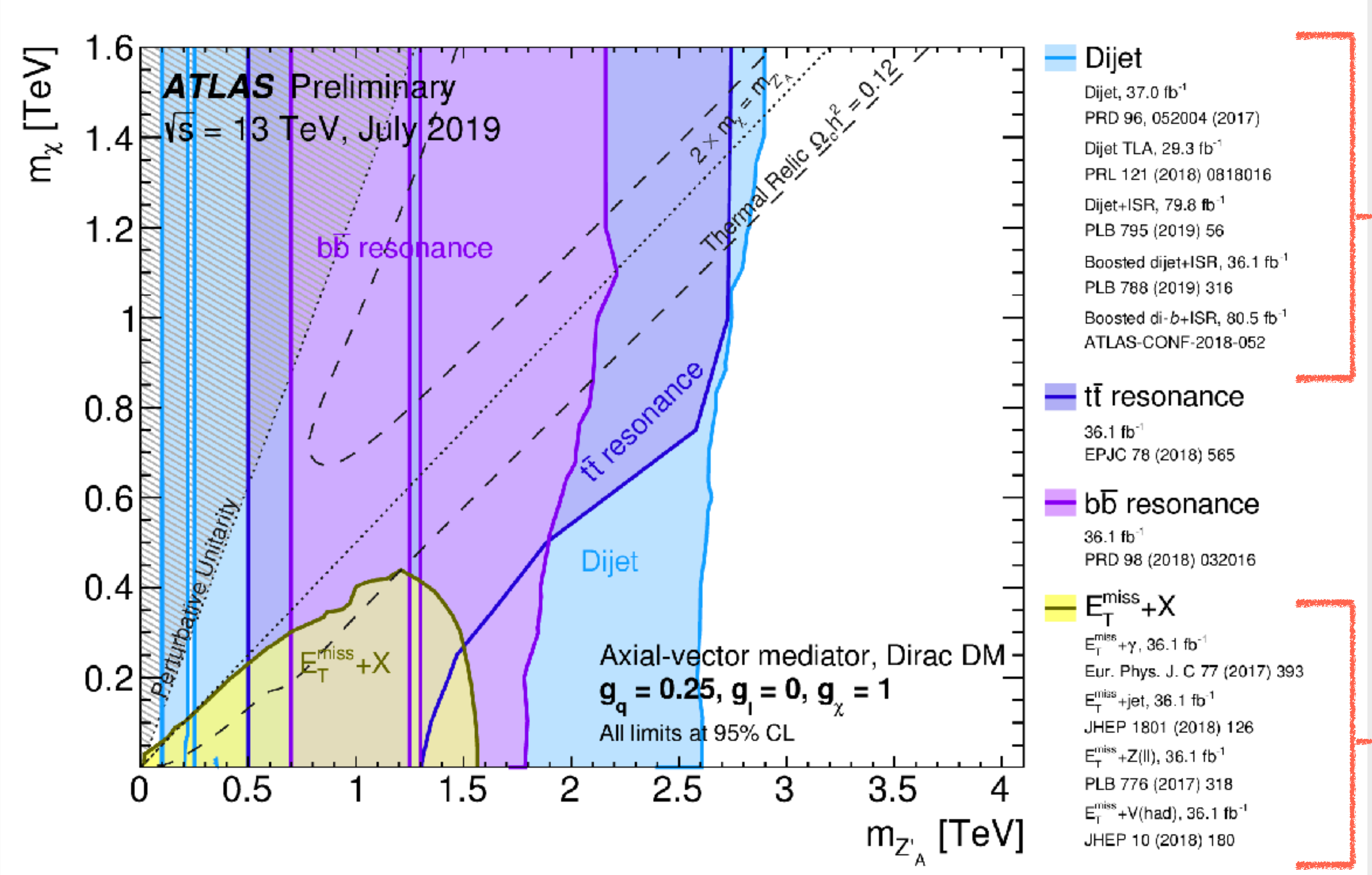
Translating Early Universe annihilation into LHC prediction

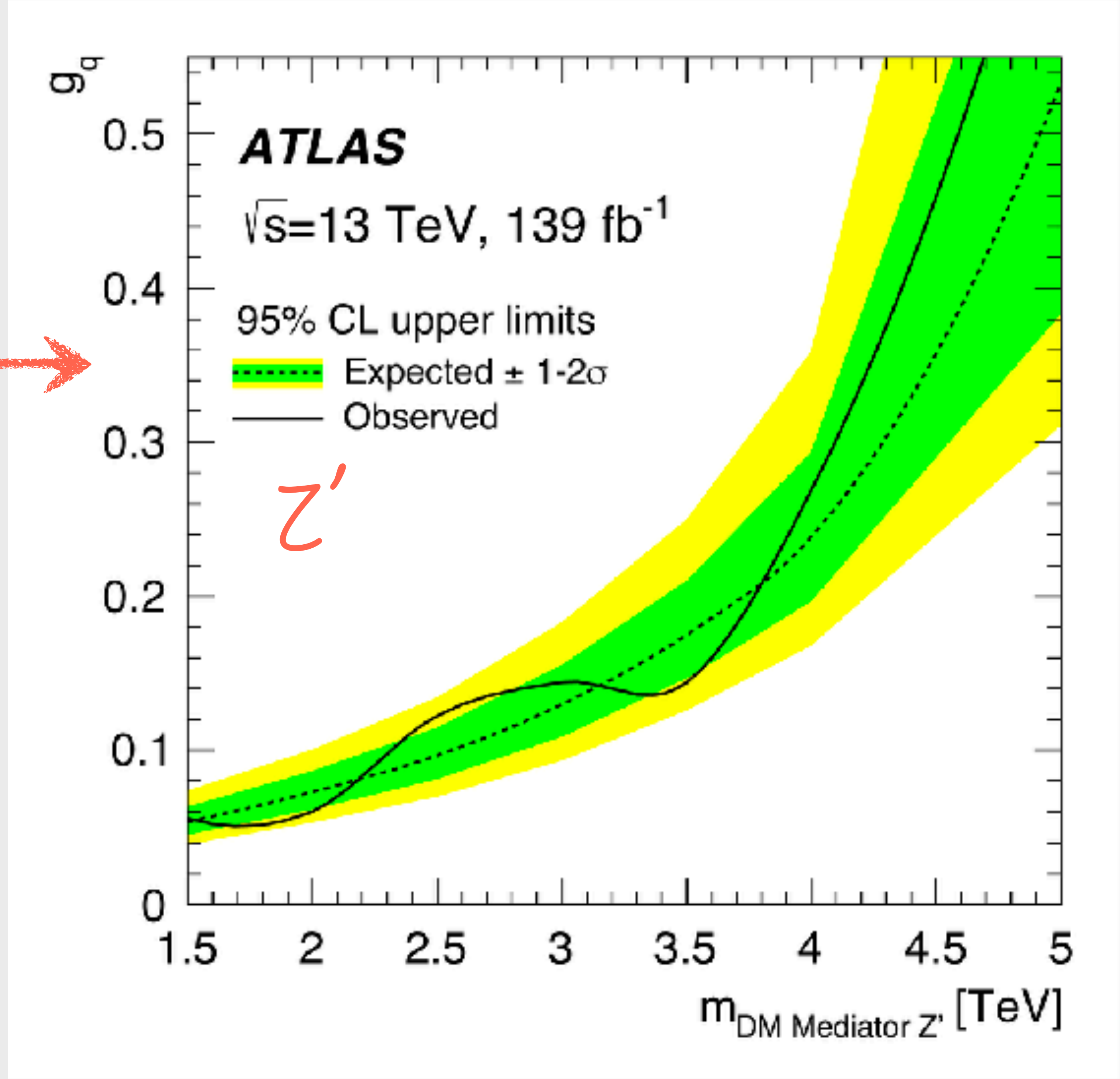


Early Universe

LHC

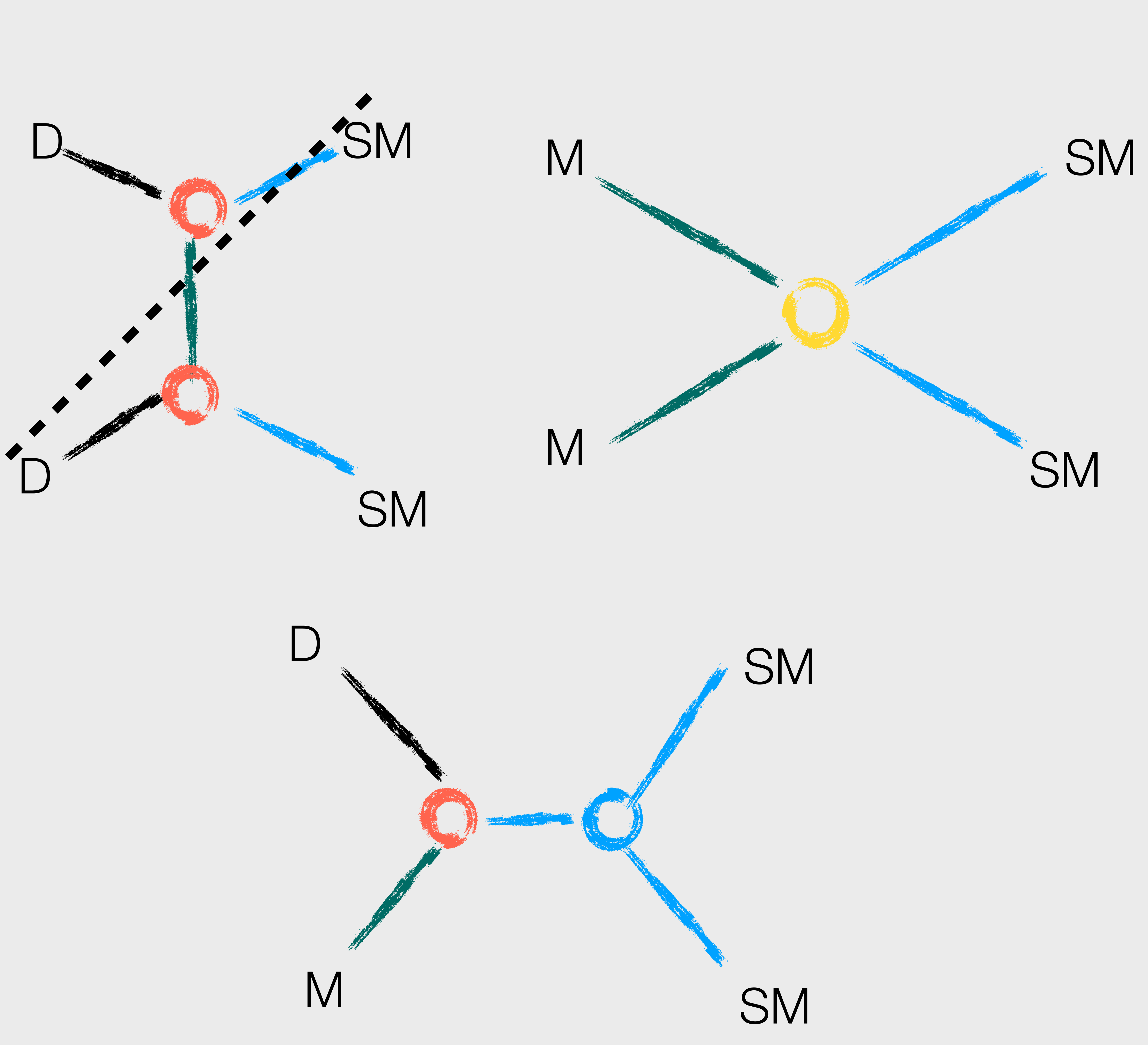
Collider “DM” searches sometimes rely on non-DM parts



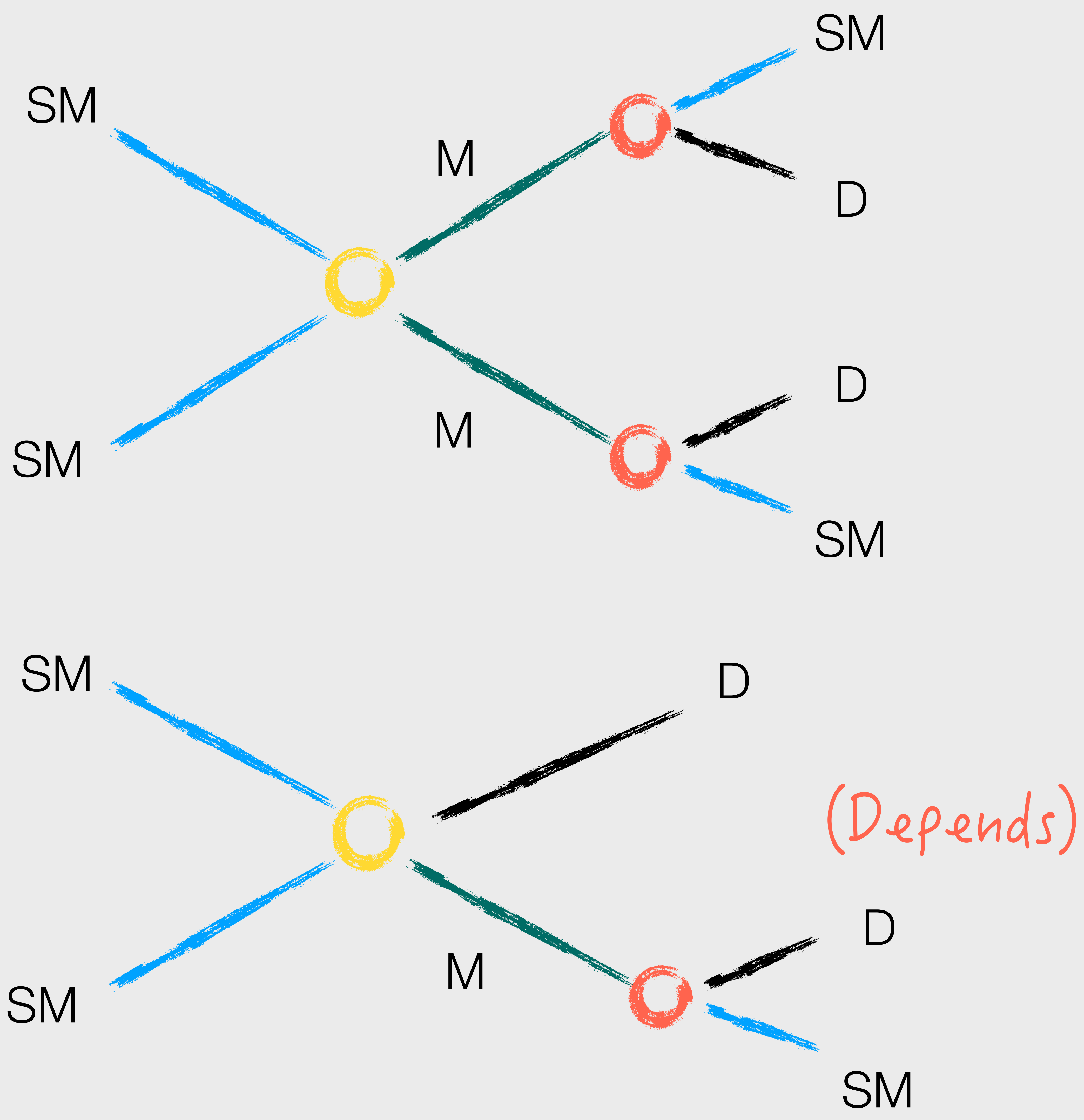


“model independent”

Phenomenology of co-annihilation models



Early Universe



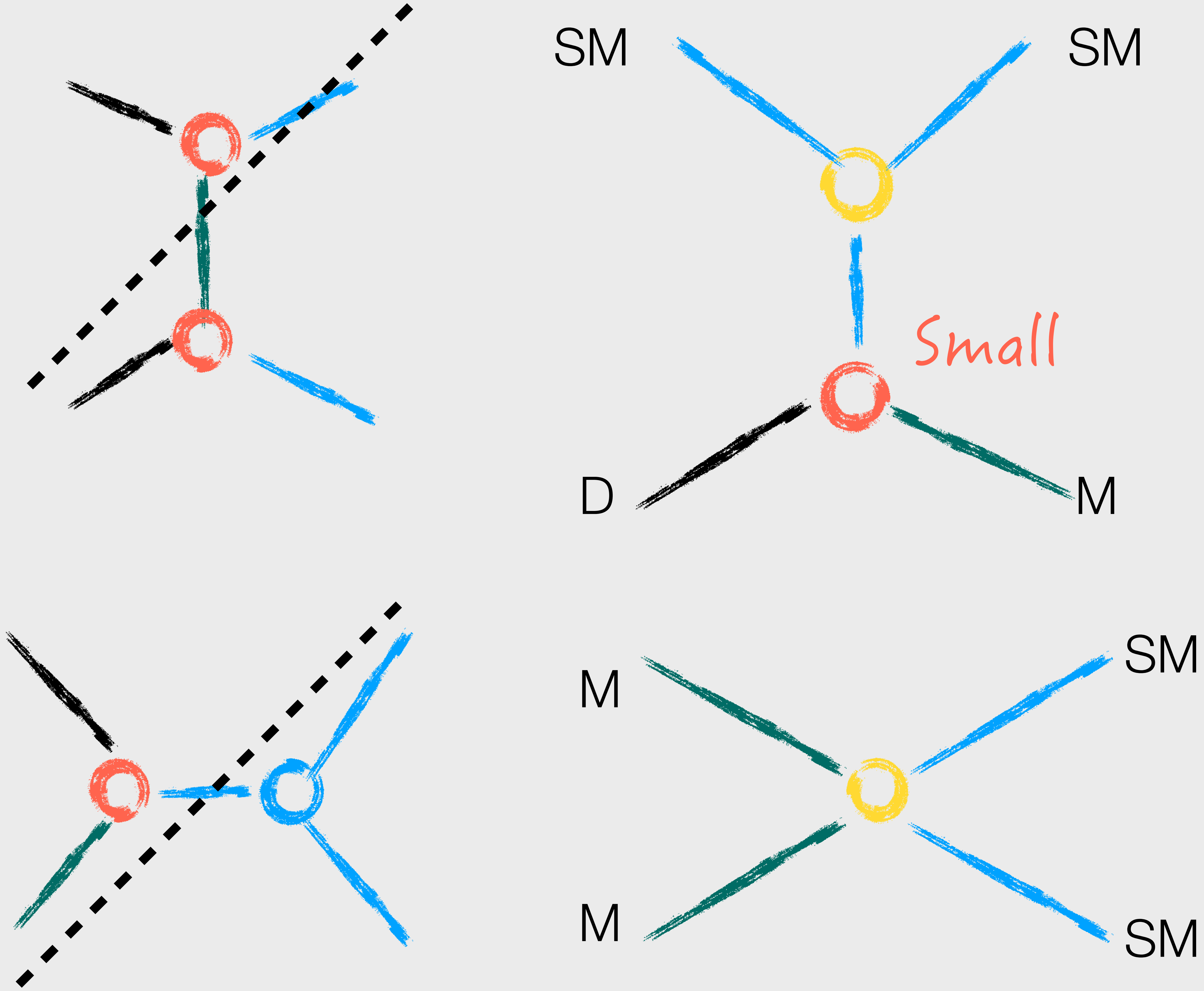
LHC

Popular DM models (maybe with co-annihilation)

	Z'	"t-channel"	SUSY
DD	✓	(✓)	(✓) Depends
ID	✓	(✓)	(✓) Depends
Collider	(✓) Usually in dijet	✓	(✓) Depends

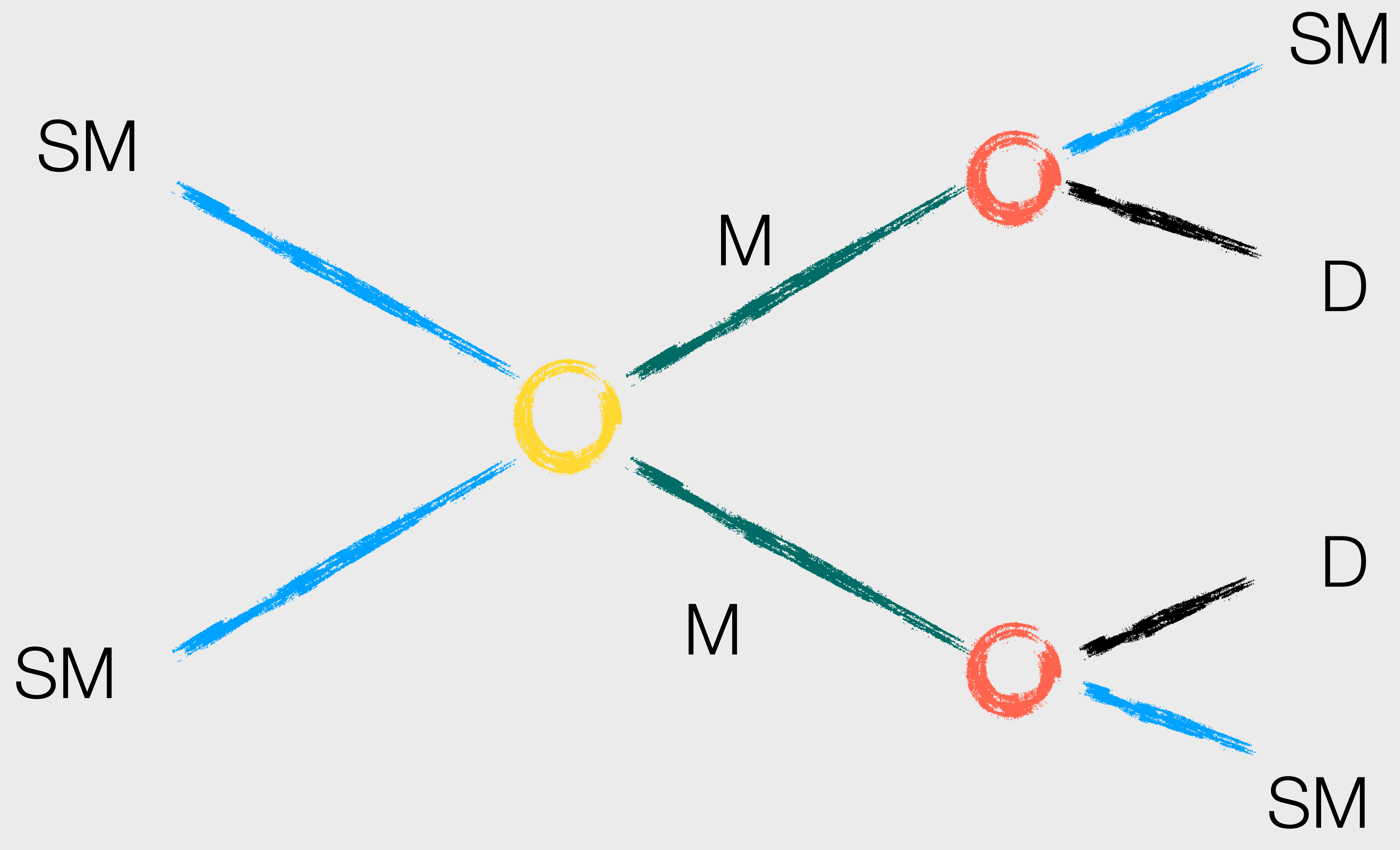
Are usually visible in DD + Indirect + Collider! Good for a cross check.

Phenomenology of the co-scattering model



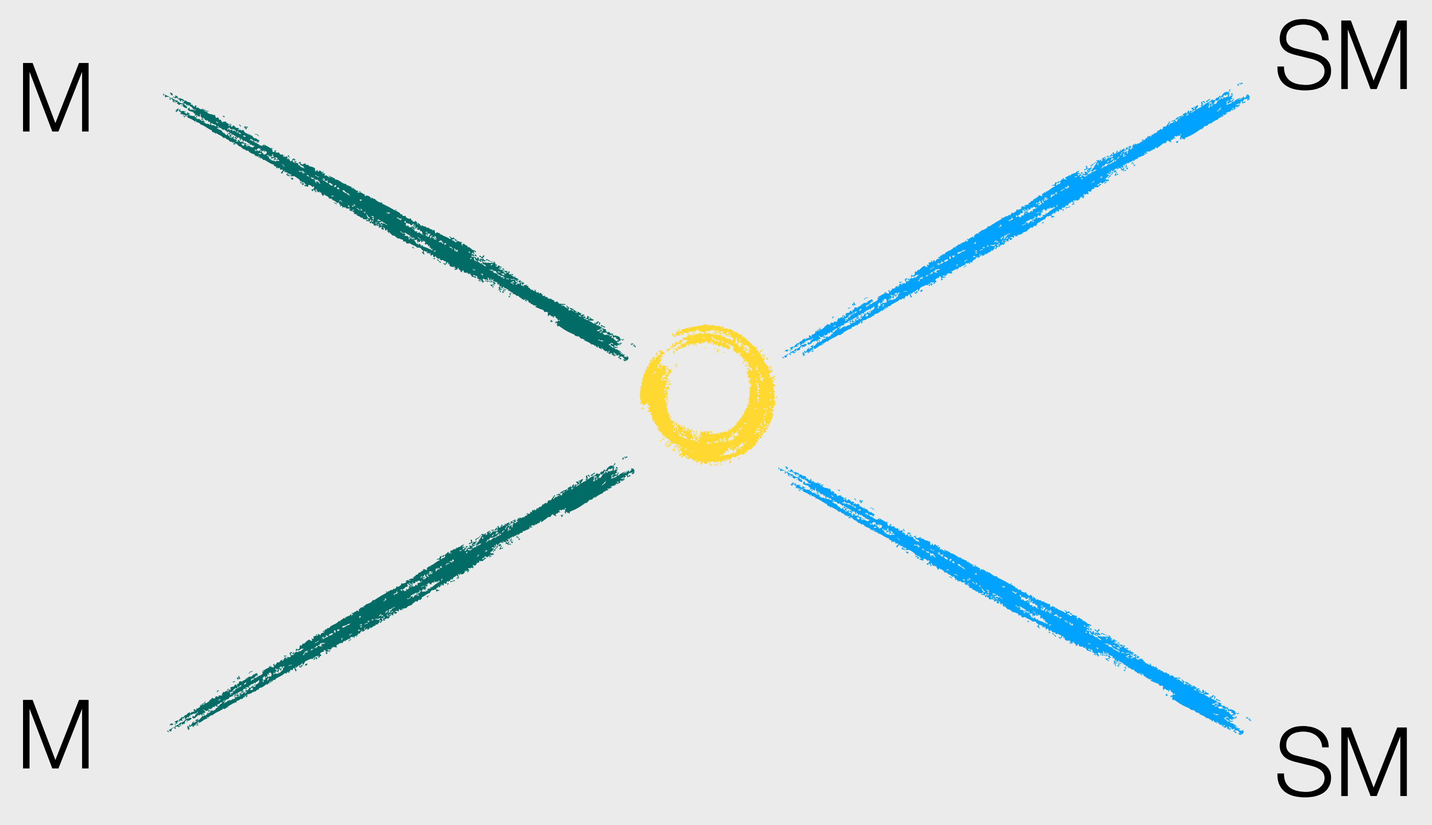
Early Universe

(e.g. 1705.08450,1705.09292)

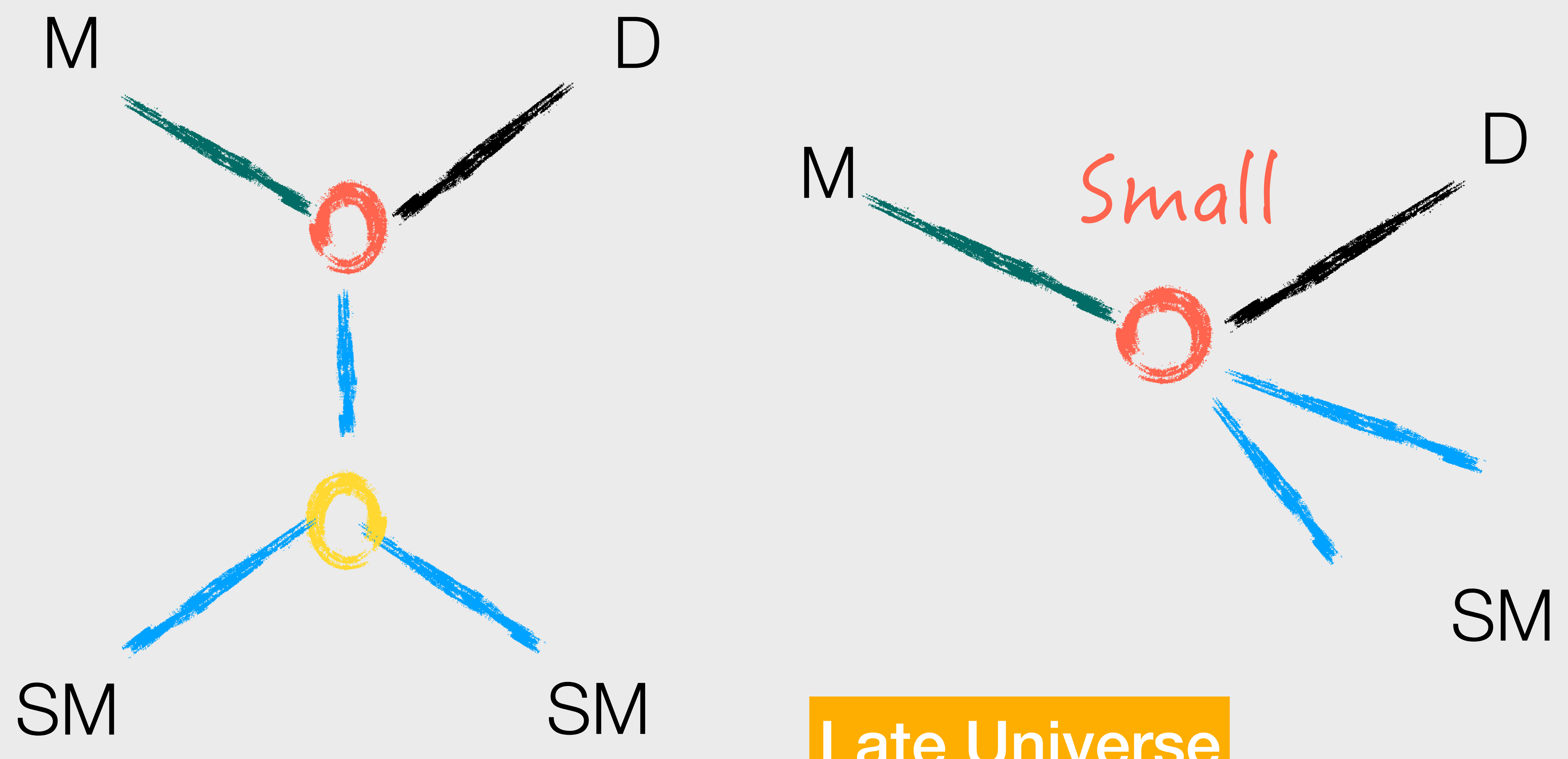


LHC

Phenomenology of a freeze-in (non-thermal production) model

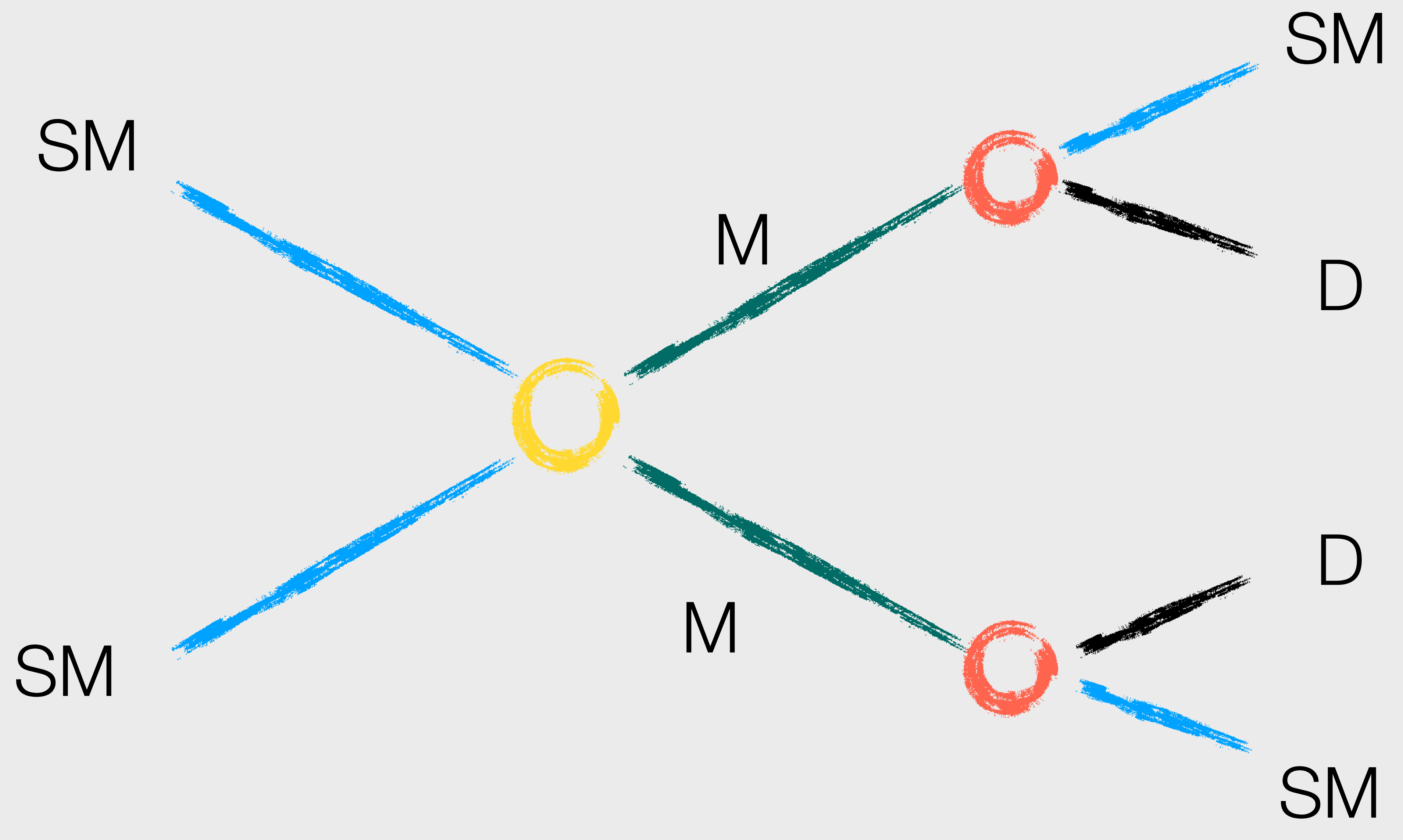


Early Universe



Late Universe

(e.g. 0911.1120,1811.05478)



LHC

Co-scattering and Freeze-in

	Co-scattering	Freeze-in
DD	✗	✗
ID	✗	✗
Collider	✓	(✓)

DM has feeble couplings with SM

Needs mediator with SM

Mediator likely has very small decay width and is long-lived

Look for long-lived mediators

Moral of the story

- Simplified models constructed based on DD are limited
- It is best not to pre-dispose yourself to certain mass/coupling regimes, you may miss the real thing.
- New signatures possible with new parameter space. Cast a wide net.
- Don't forget the lifetime frontier.

There are some viable models which can ONLY be seen at colliders.

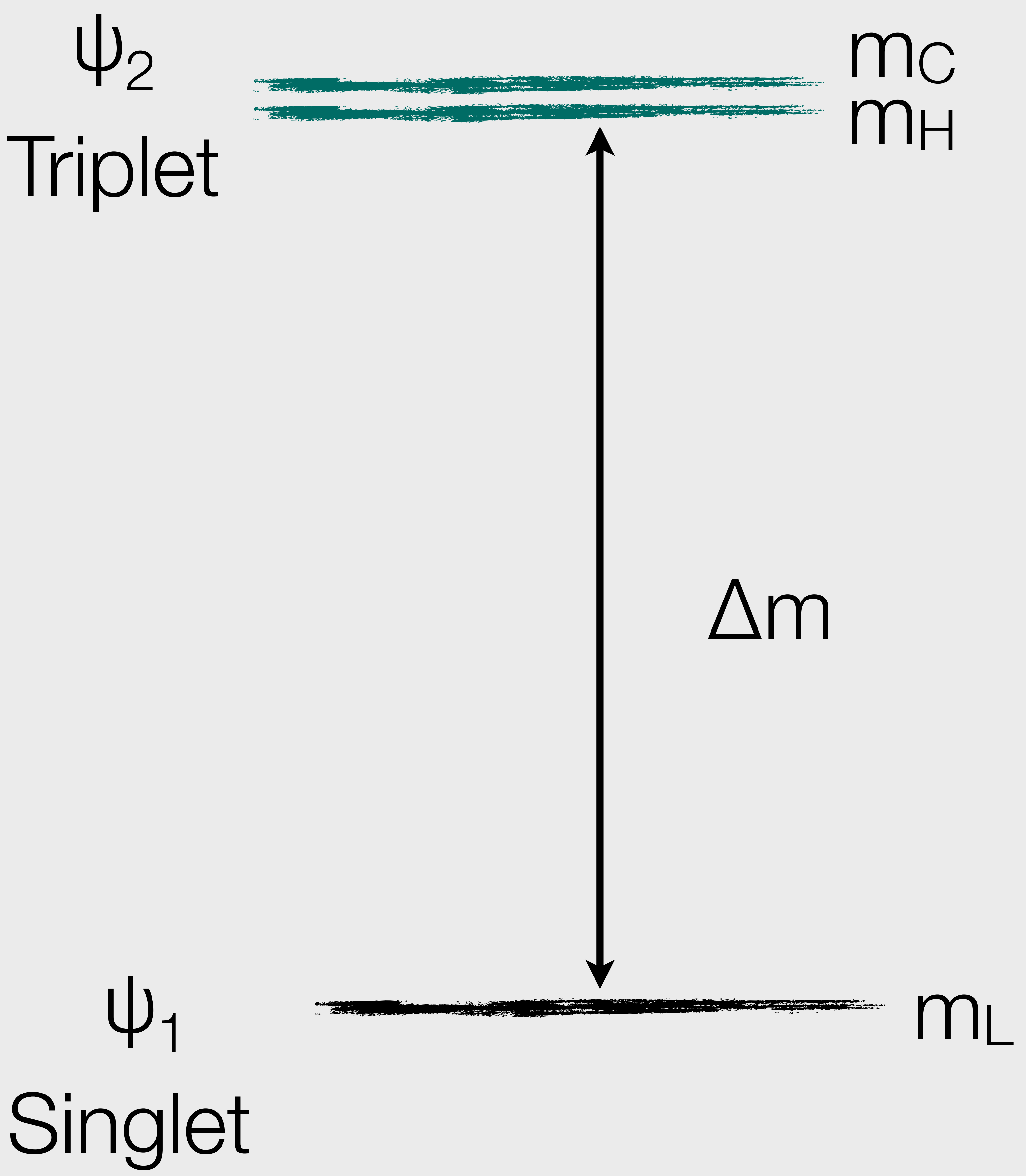
What is a “good” DM model to focus on for colliders?

- Has a small number of parameters
- Whose LHC signature is not “tangential” (i.e. not Z’ via dijet/dilepton) but probes the actual coupling relevant for DM.

Side benefits

- Shows the smooth transition from co-scattering to co-annihilation so we can explore the full mass/coupling parameter space

Spectrum for Singlet-Triplet model



$$\psi_L = \cos\theta\ \psi_1 + \sin\theta\ \psi_2$$
$$\psi_H = -\sin\theta\ \psi_1 + \cos\theta\ \psi_2$$

Decay modes

$\psi_C \to \psi_L + W^*$	depends on θ
$\psi_C \to \psi_H + \pi^+$	fixed by mass splitting

$W^* \to \ell\nu$	Soft lepton + MET
$\to j\,j$	Soft jets

Particle lifetime and what it tells you

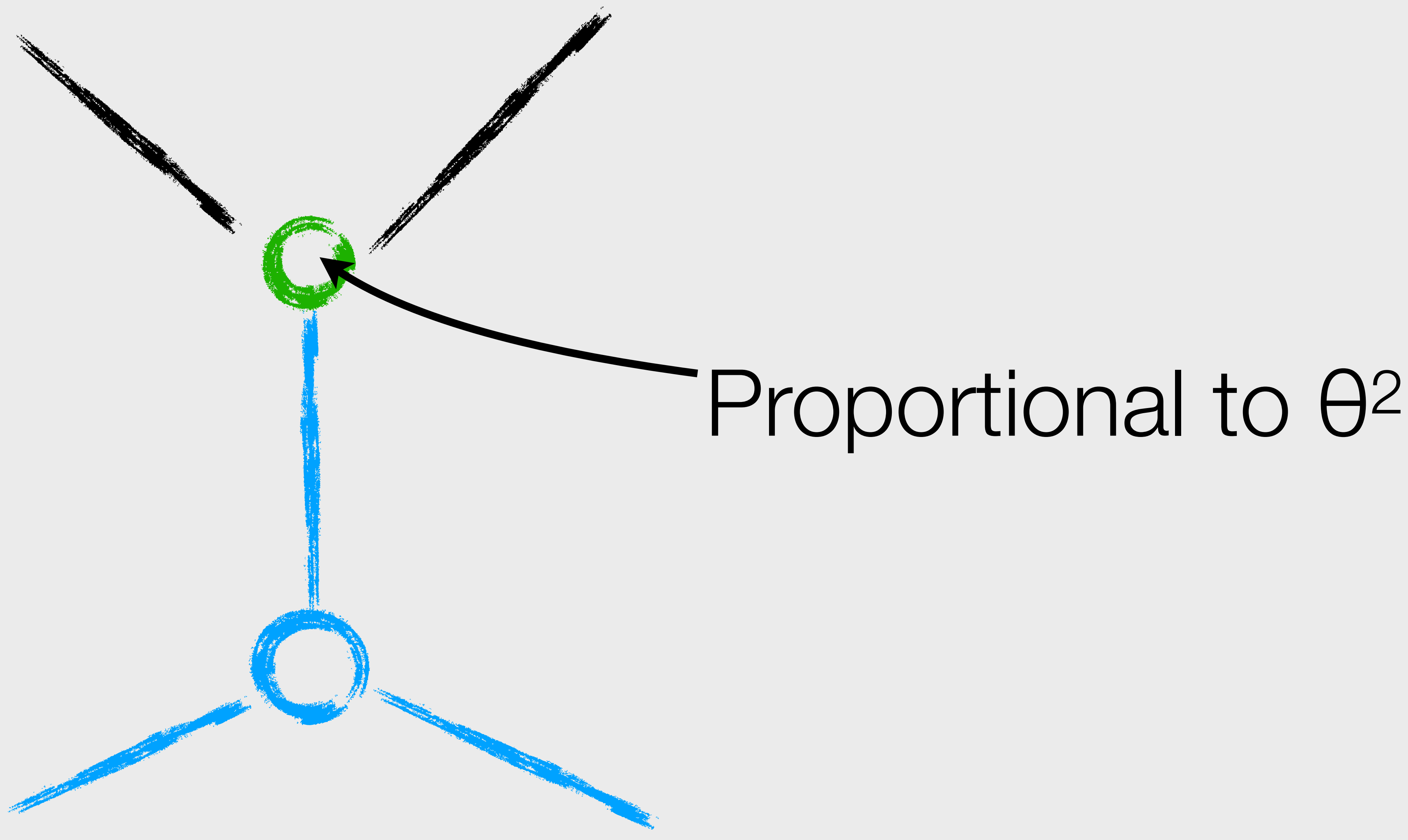
Three ways to get a long-lived particle:

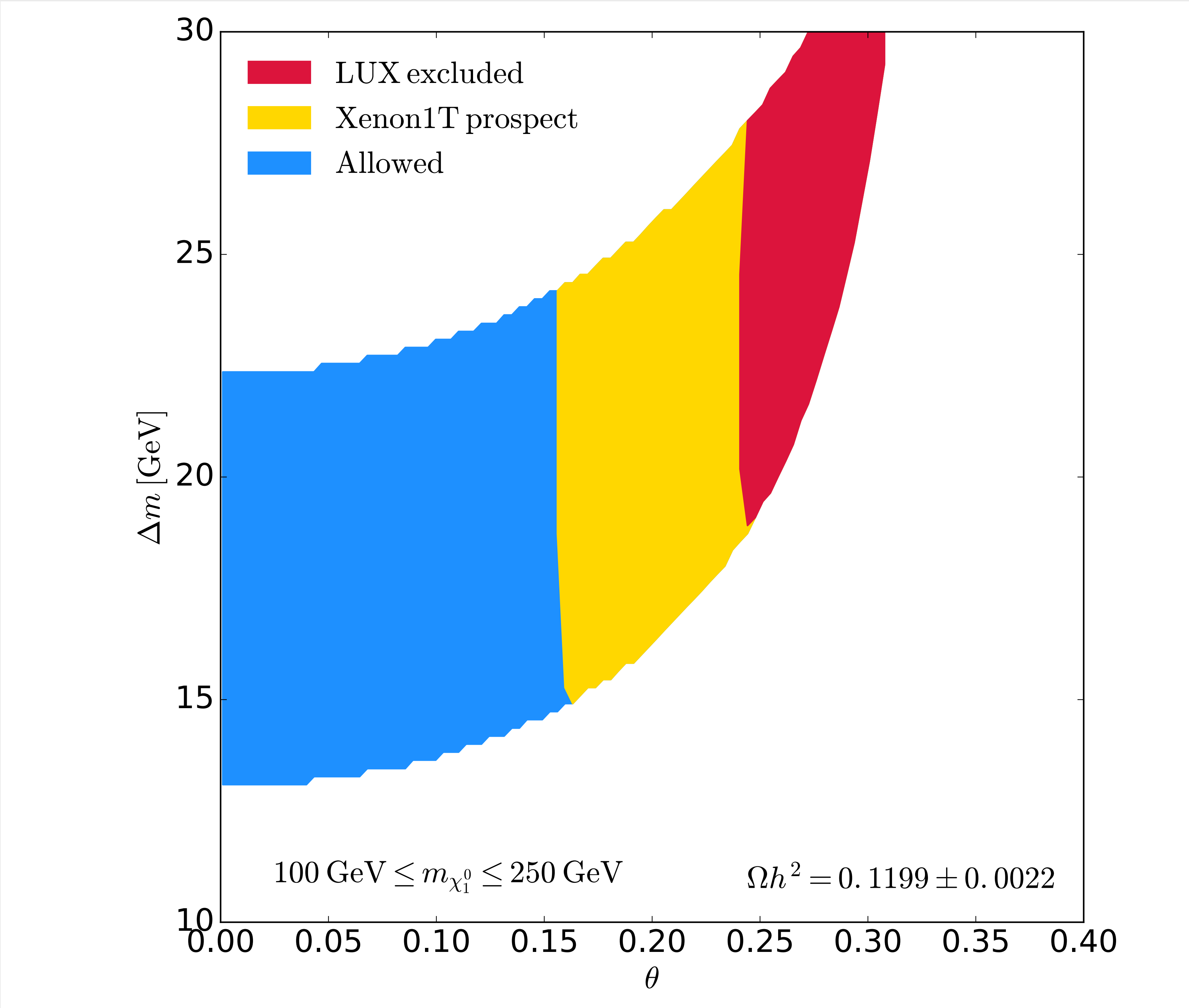
1. Small couplings
2. Heavy intermediate particle (e.g. most meson decays in SM)
3. Compressed spectrum (e.g. SU(2) Triplet fermion)

Coupling to W $\propto \theta$ (small coupling); $\psi_C \rightarrow \psi_H + \pi^+$ is highly compressed.

ψ_C likely to be long-lived.

What would be the possible Direct Detection signals?

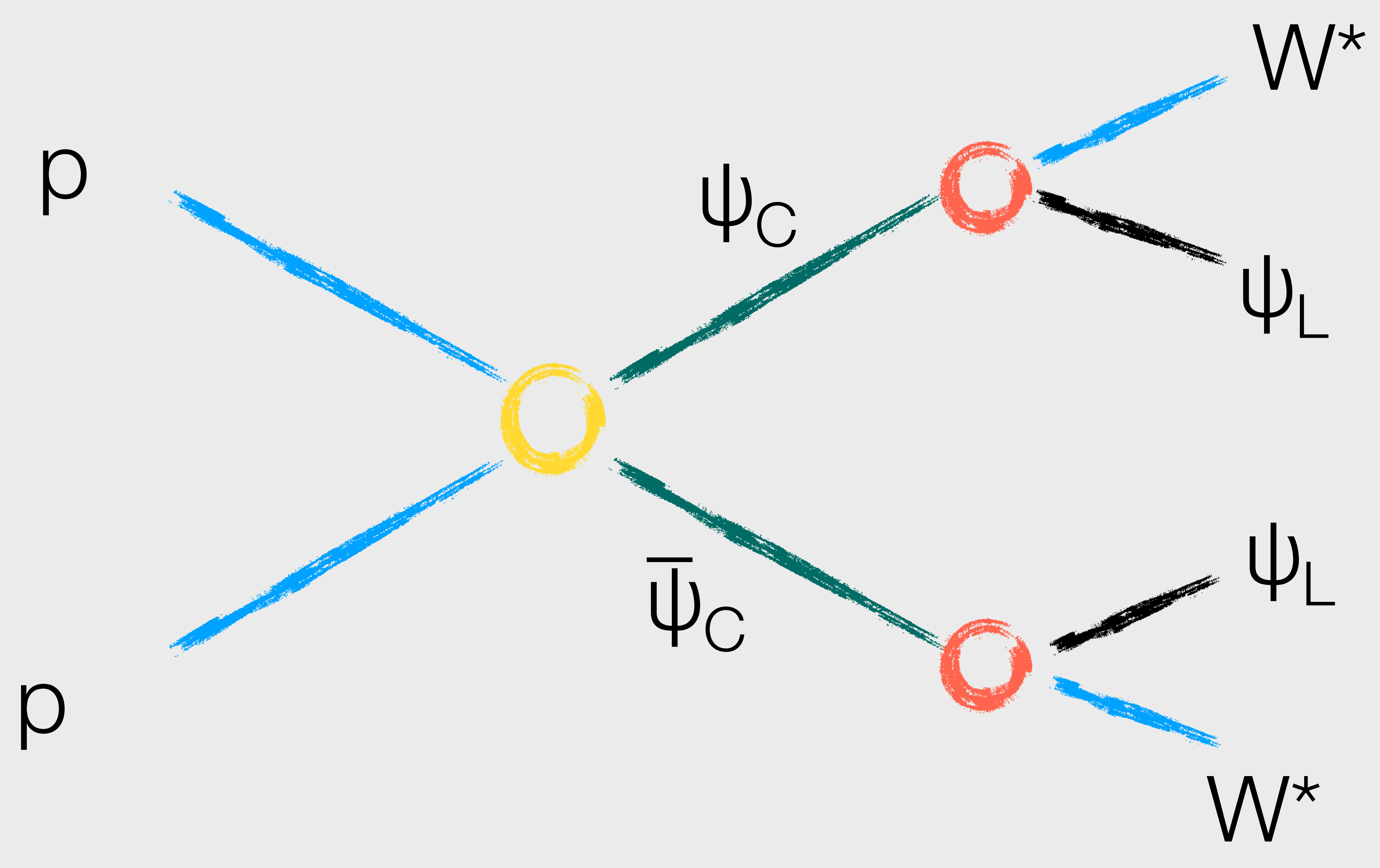




Direct detection can only probe up to $\theta \sim 0.15$

Bharucha et al.1703.00370

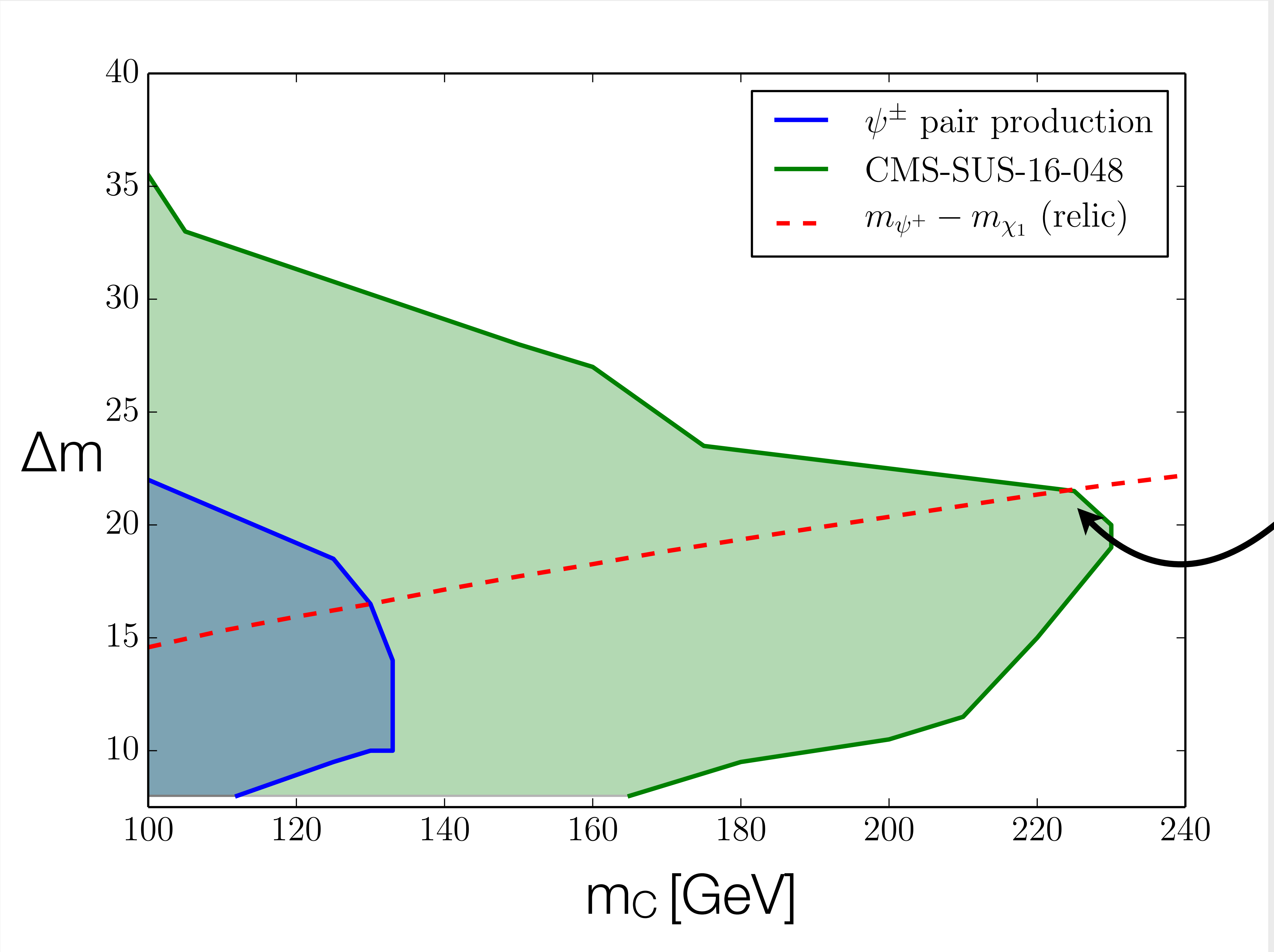
What would be the possible LHC signals?



W* W* + MET

1. (Soft) dijet + MET
2. (Soft) dilepton + MET
3. (Soft) lepton + 2 (soft) jets + MET
4. Tracks from long-lived ψ_C
5. Displaced (soft) jets + MET
6. Displaced (soft) leptons + MET

The singlet-triplet model: limits from prompt LHC searches



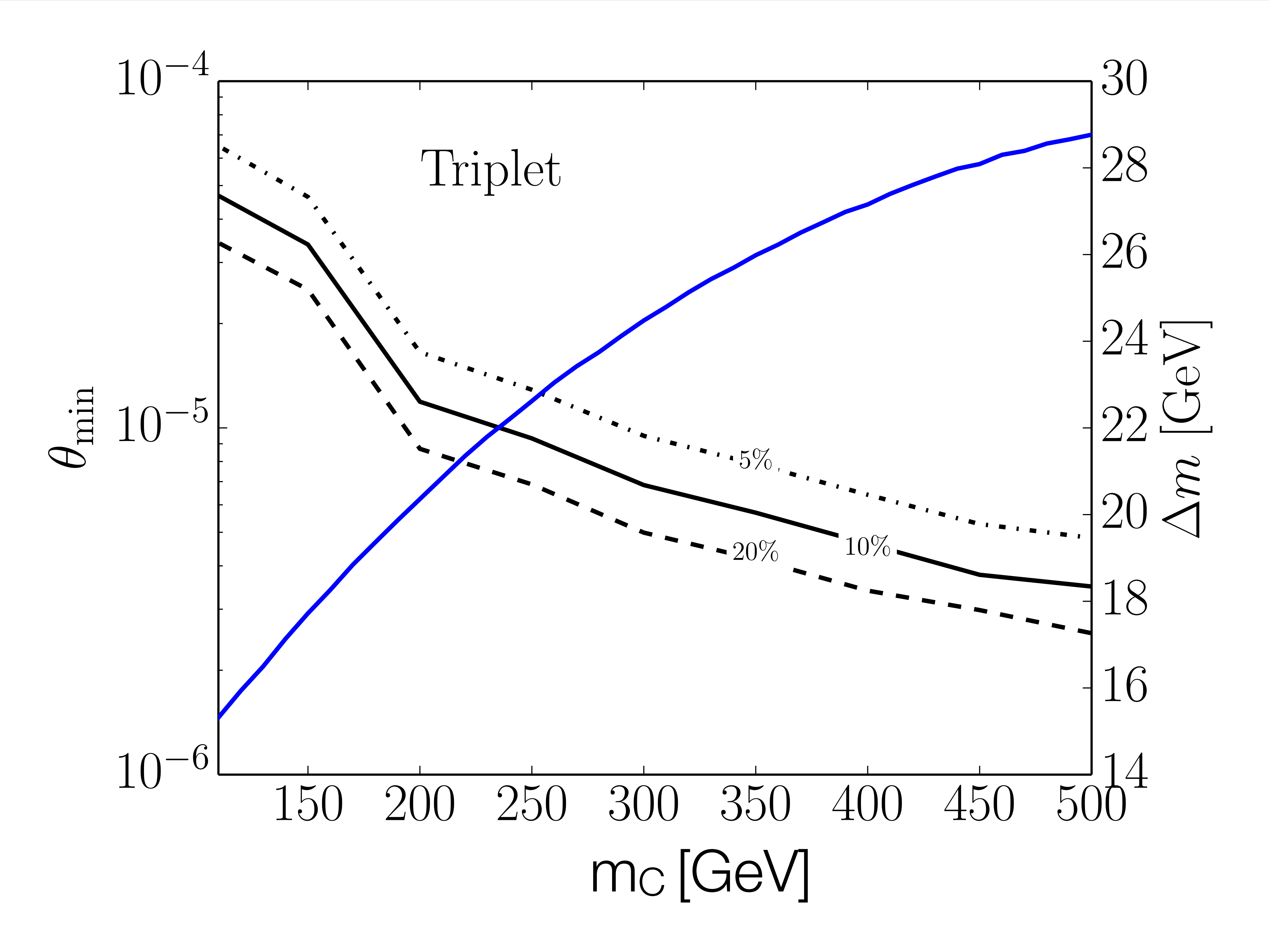
~ (220 GeV, 20 GeV)

Bharucha, Brümmer, Desai
1804.02357

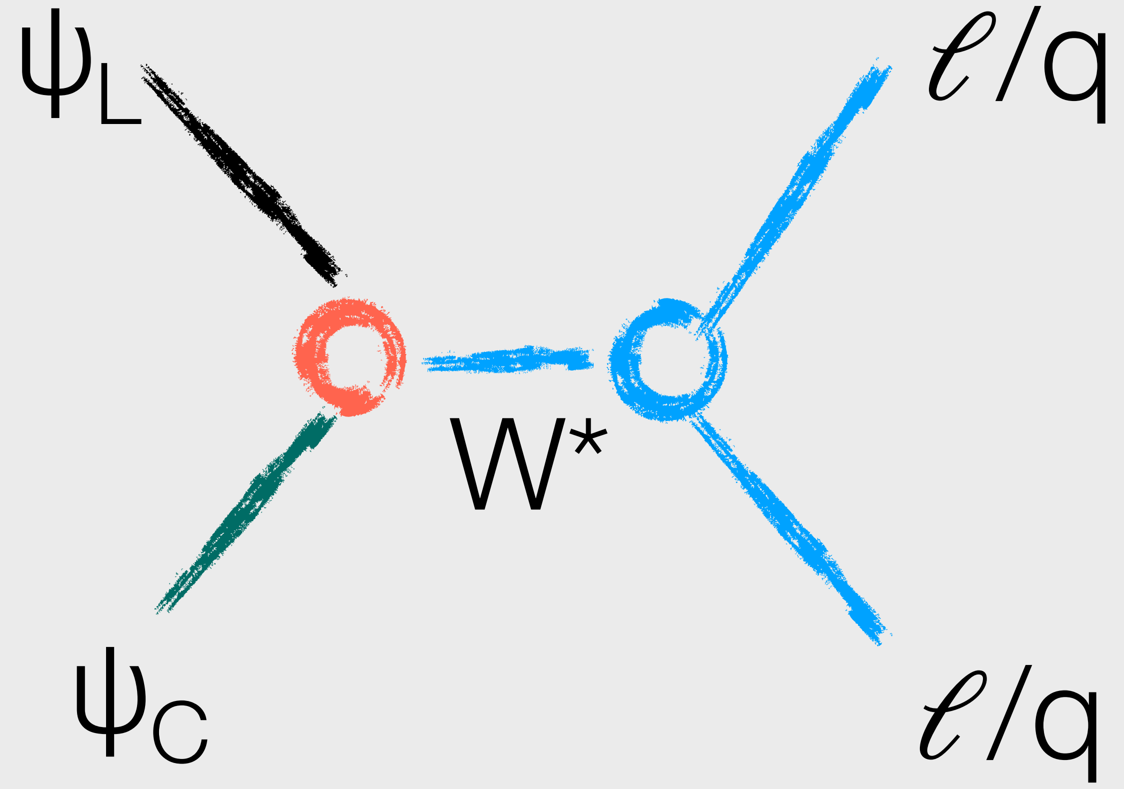
As long as ψ_C lifetime is smaller than ~O(1 ns), the scenario is visible in standard searches.

Current limit ~ 220 GeV.

Co-scattering in the singlet-triplet model



Bharucha, Brümmer, Desai 1804.02357



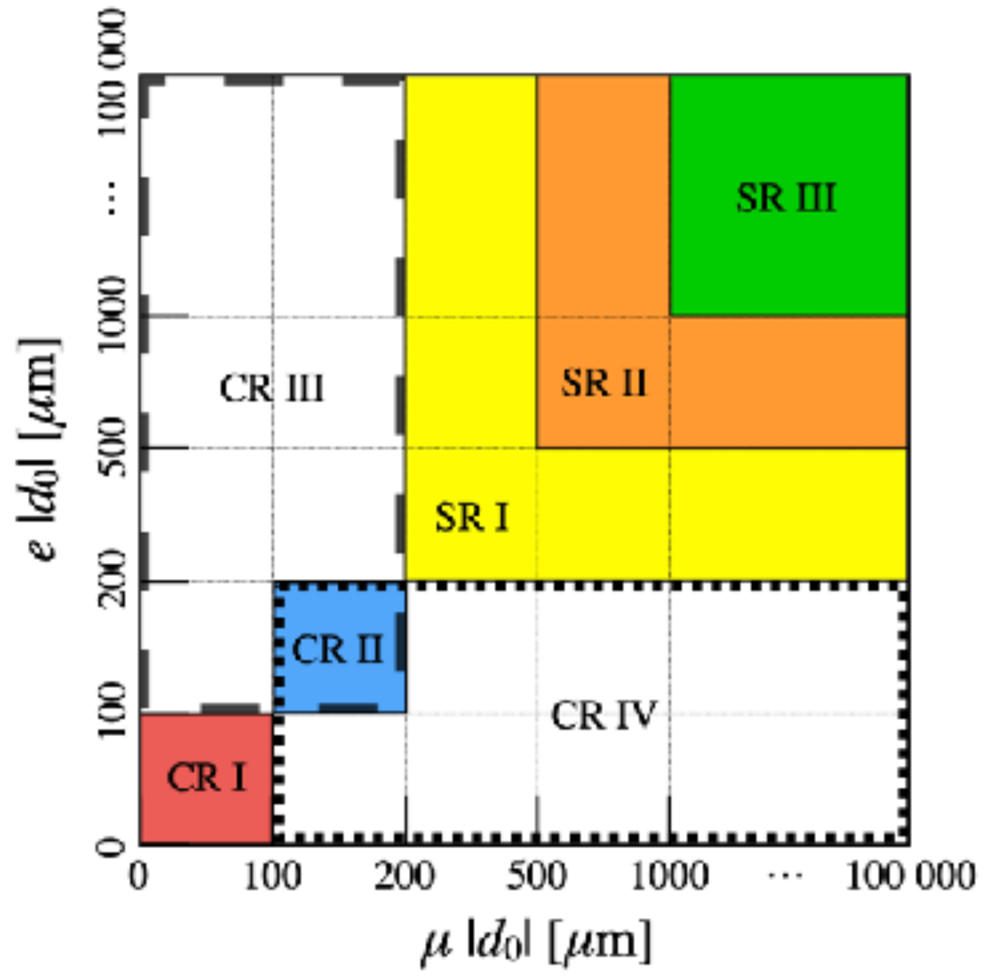
Mass difference expected is about $\Delta m \sim 0.1\ m_C$.

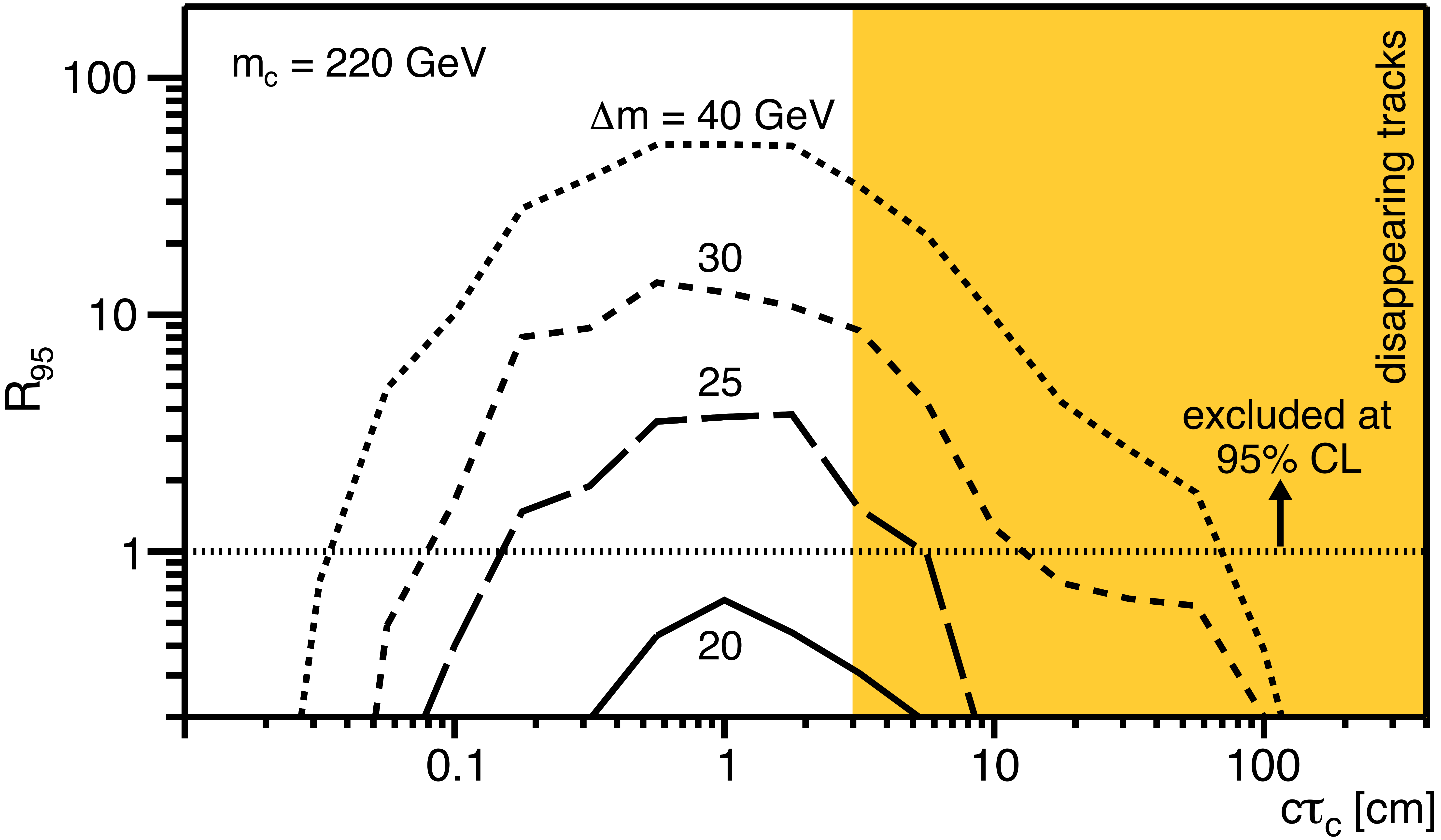
Co-annilihiation becomes ineffective at about $\theta \sim 10^{-5}$

Point to take away: for current prompt limit of 220 GeV, Δm ~ 20 GeV, θ ~ 10^{-5}
This gives long-lived ψ_C

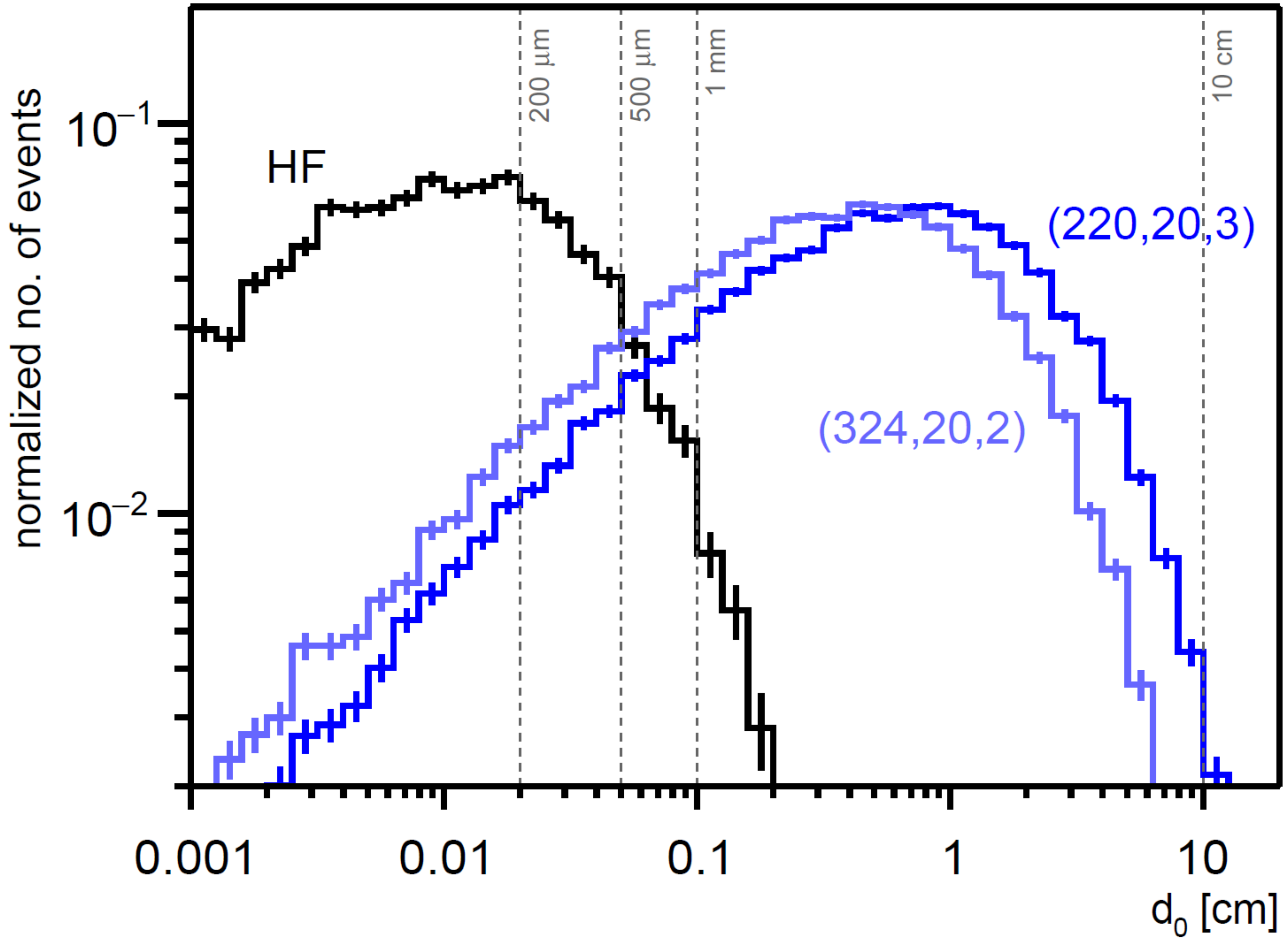
Understanding the displaced lepton search

CMS-PAS-EXO-16-022

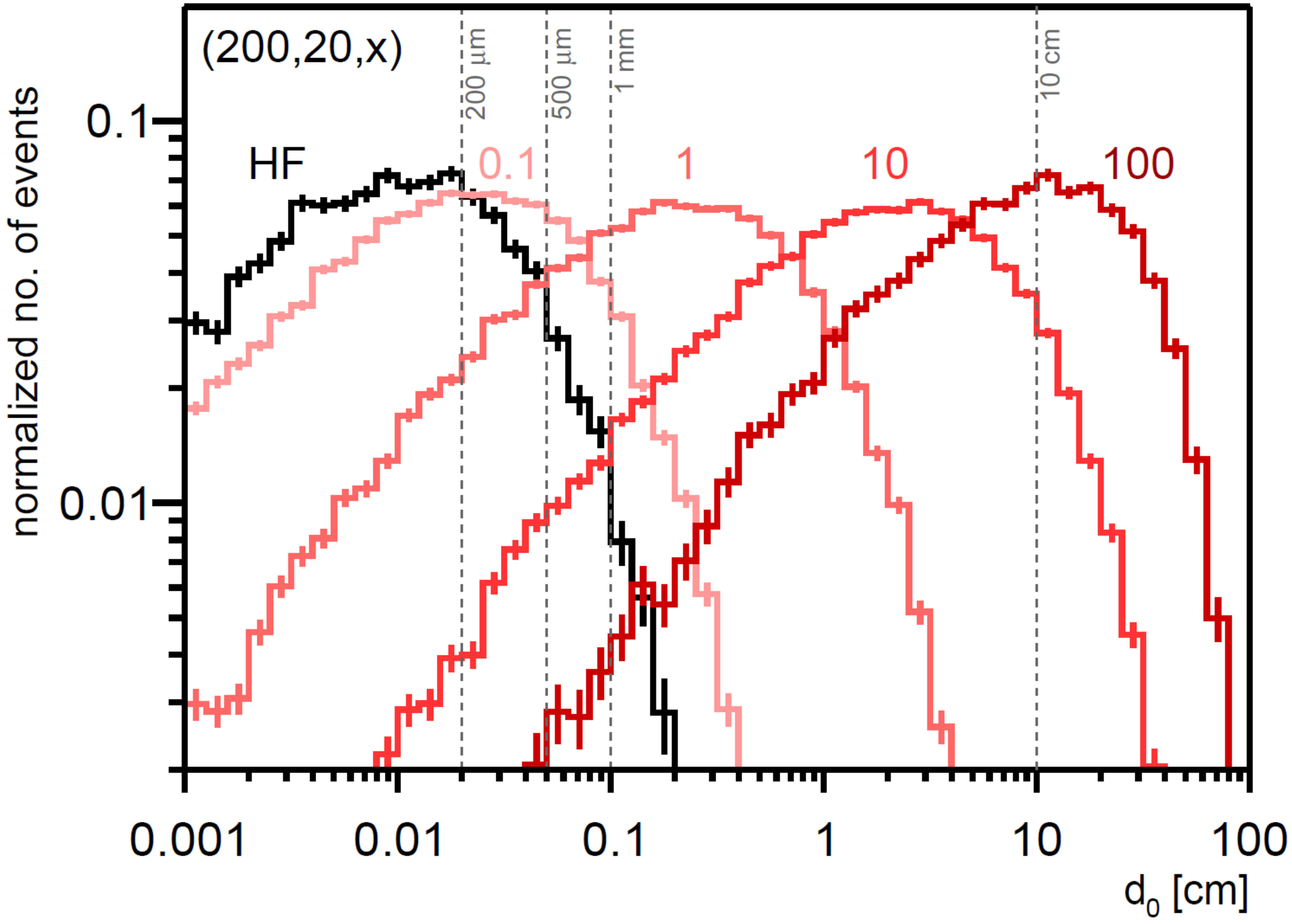




Behaviour predicted by DM requirements



Benchmarks



(200,20,x)
200 µm
500 µm
1 mm
10 cm
HF
0.1
1
10
100
normalized no. of events
0.1
0.01
0.001
0.01
0.1
1
10
100
d_0 [cm]

Estimating backgrounds

Goal: to estimate background for p_T > 20 GeV from p_T > 40 GeV data

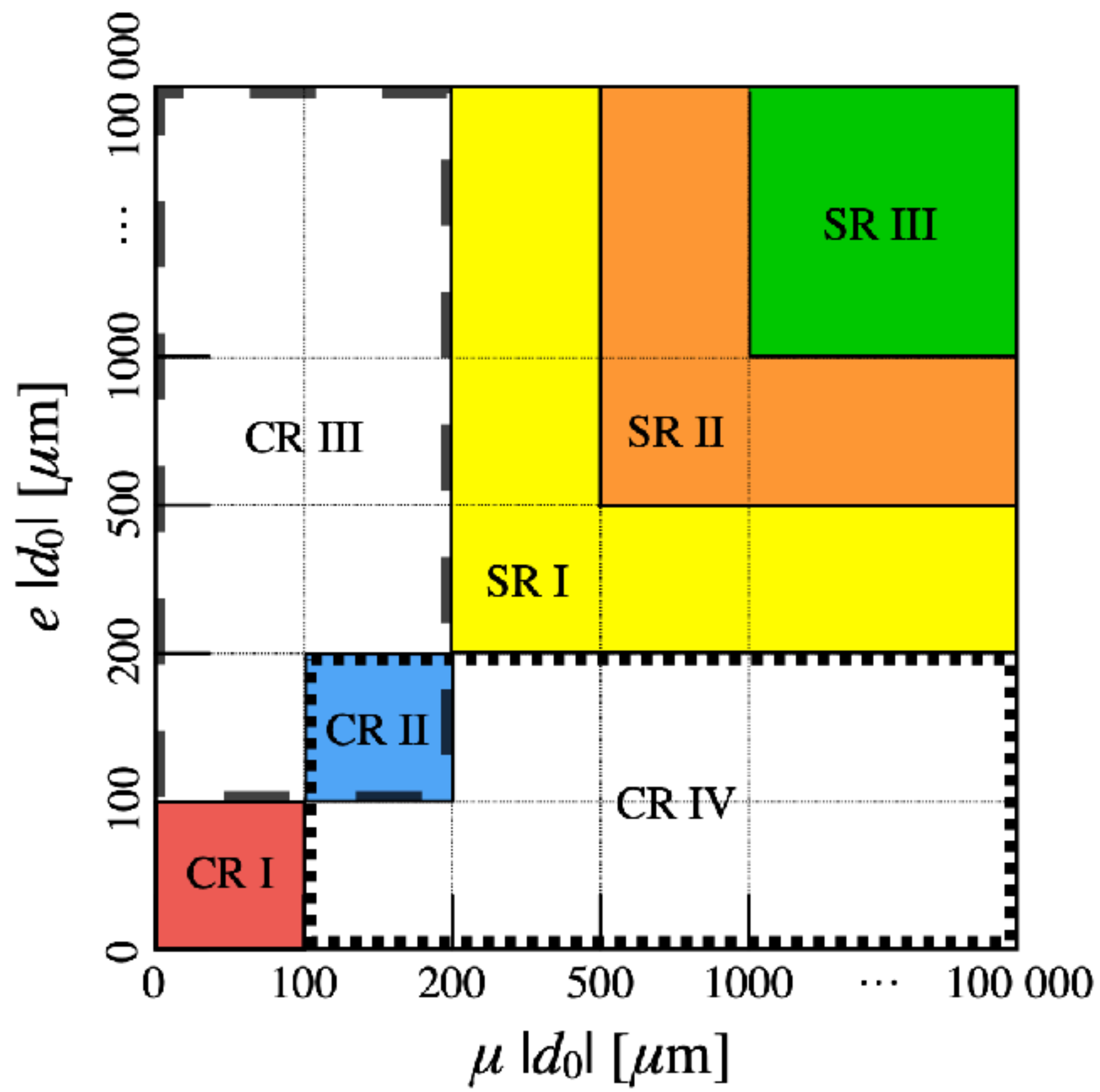
We know that exact HF cannot be estimated by MC to enough accuracy

Model shape of BG using MC

Main source of BG is heavy flavour, i.e. B-meson decays

Check that d0 and pT are independent

CMS-PAS-EXO-16-022



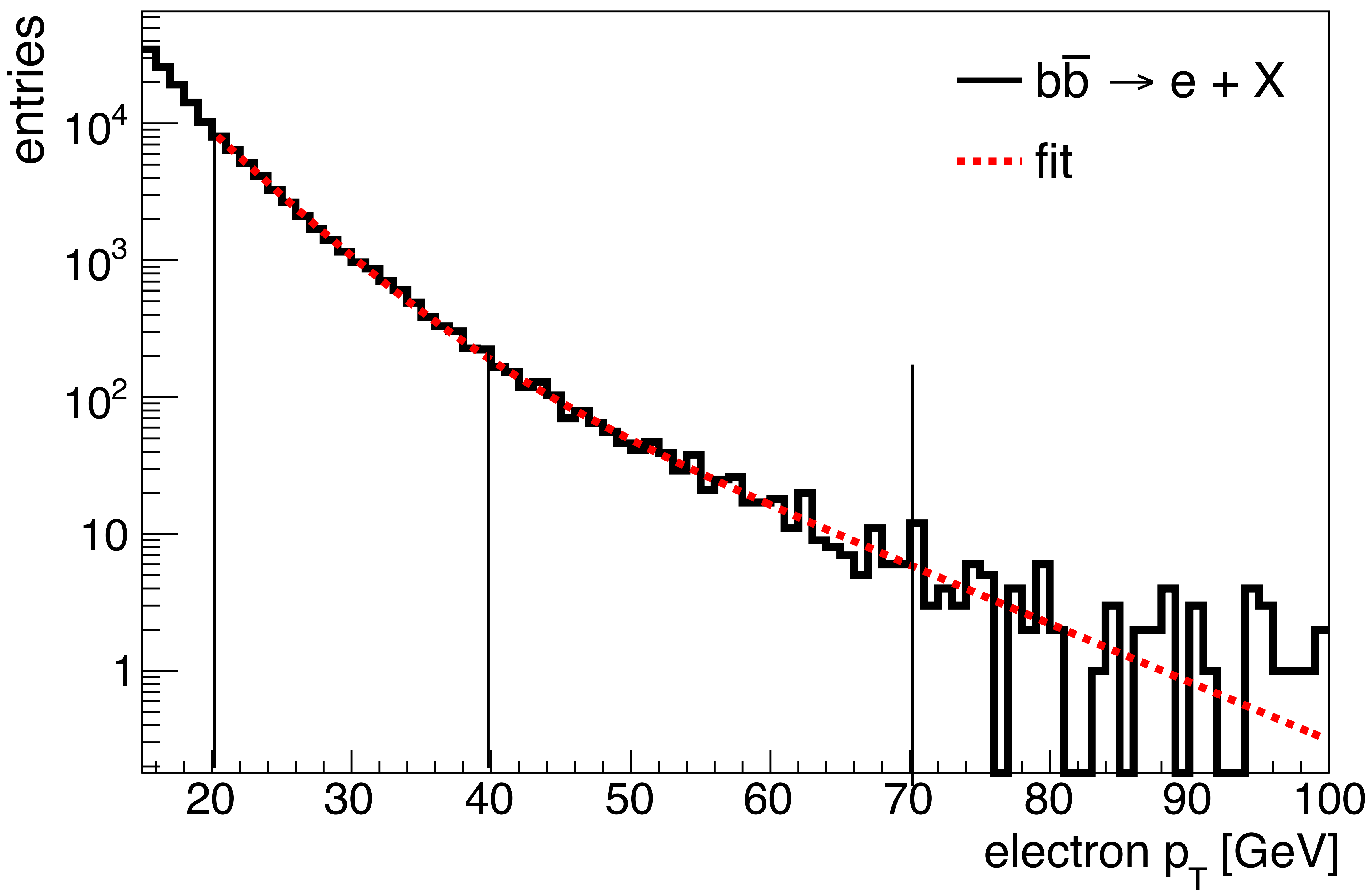
Estimating backgrounds

1. Model background shape using a lepton-enriched pp →bb sample

2. Calculate transfer factors

$$\kappa_e(p_T) = \frac{\int_{p_T}^{70} d\tilde{p}_T f_e(\tilde{p}_T)}{\int_{42}^{70} d\tilde{p}_T f_e(\tilde{p}_T)},$$

$$\kappa_\mu(p_T) = \frac{\int_{p_T}^{70} d\tilde{p}_T f_\mu(\tilde{p}_T)}{\int_{40}^{70} d\tilde{p}_T f_\mu(\tilde{p}_T)},$$



3. CMS provides 95% UL on background in the signal regions. Scale this with the transfer factors.

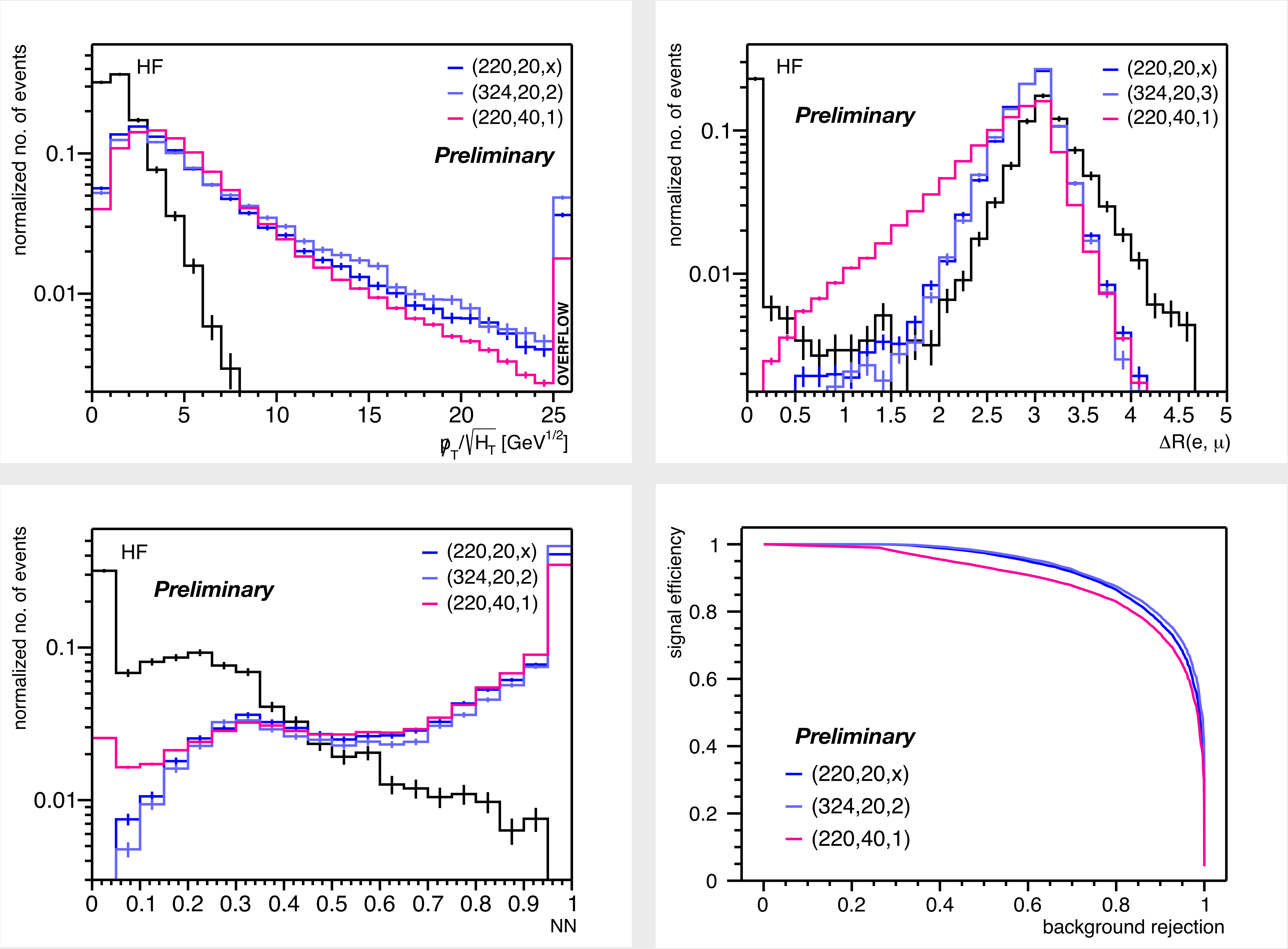
Cut-and-count is not good enough!

#	(m_c [GeV], Δm [GeV], $c\tau_c$ [cm])	N_{I}	N_{II}	N_{III}
	HF background	<221997	<34688	<1318
1	(324, 20, 2)	0.38	0.43	1.18
2	(220, 20, 3)	1.18	1.40	5.55
3	(220, 20, 0.1)	139	37	5.98
4	(220, 20, 1)	174	157	283
5	(220, 20, 10)	32	93	318
6	(220, 20, 100)	1.35	2.15	31
7	(220, 40, 1)	1067	980	1826

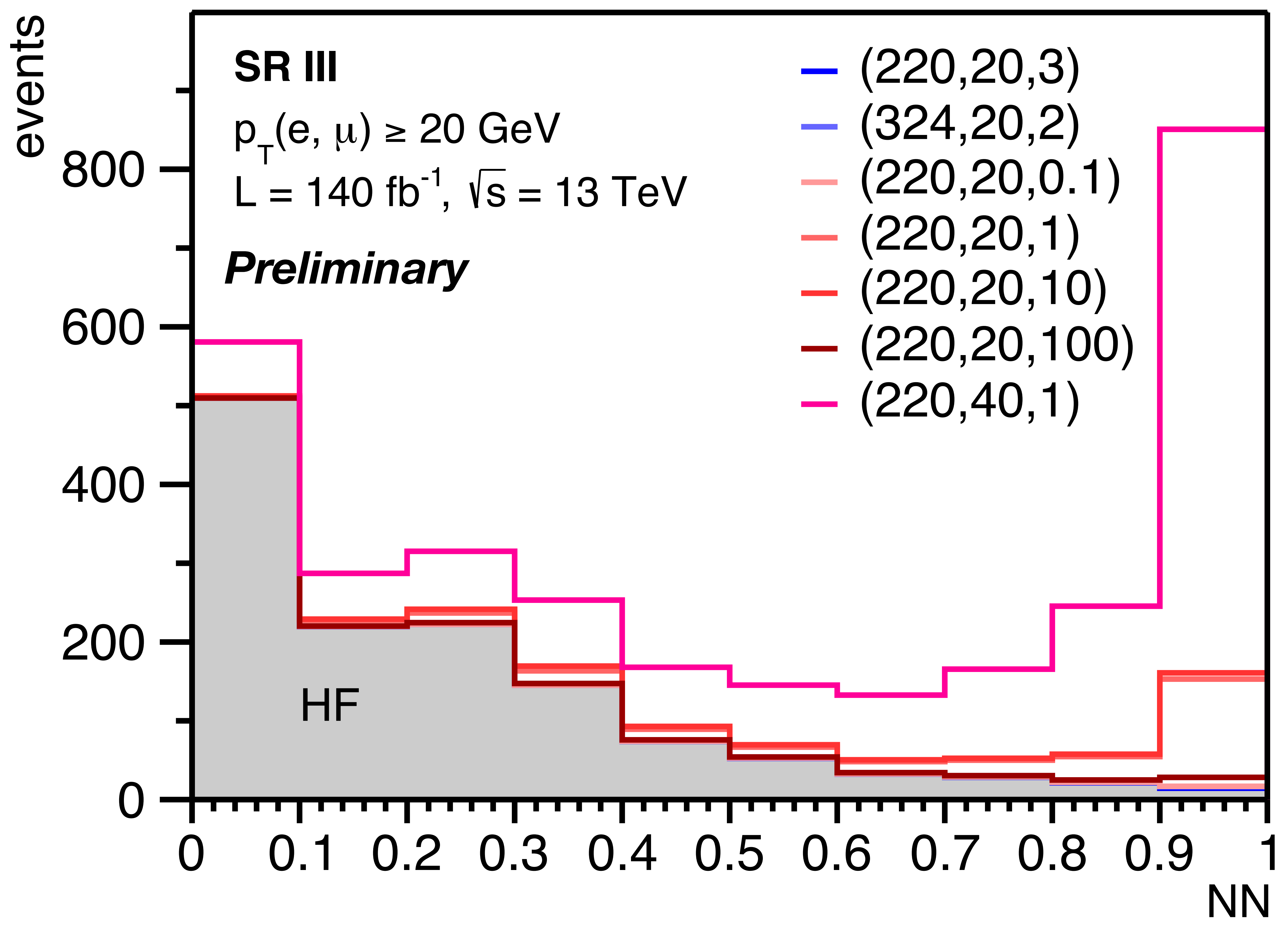
Training a neural network

Neural Network trained with 9 variables

Good separation of signal and background for all benchmarks.

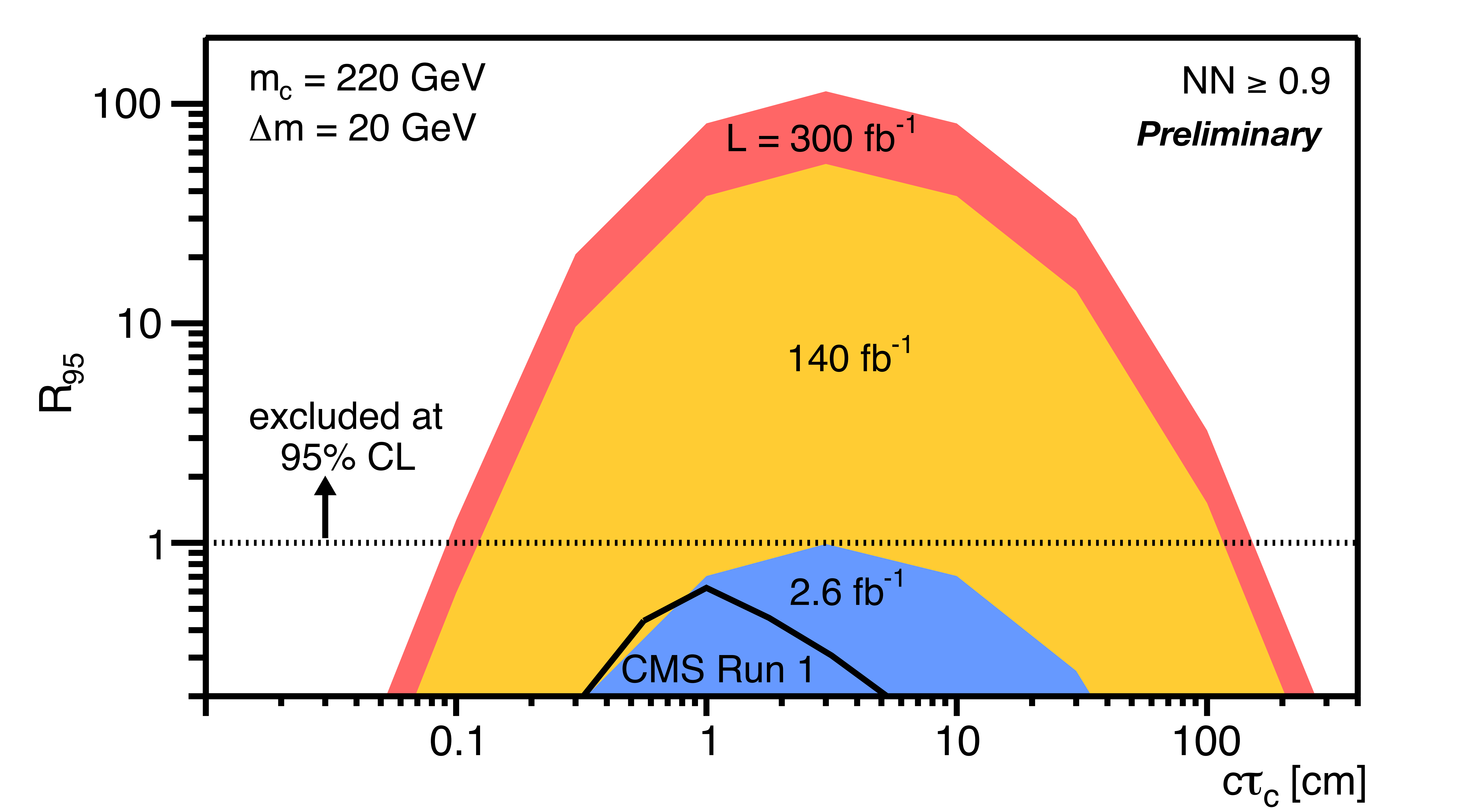


NN improves sensitivity many fold!

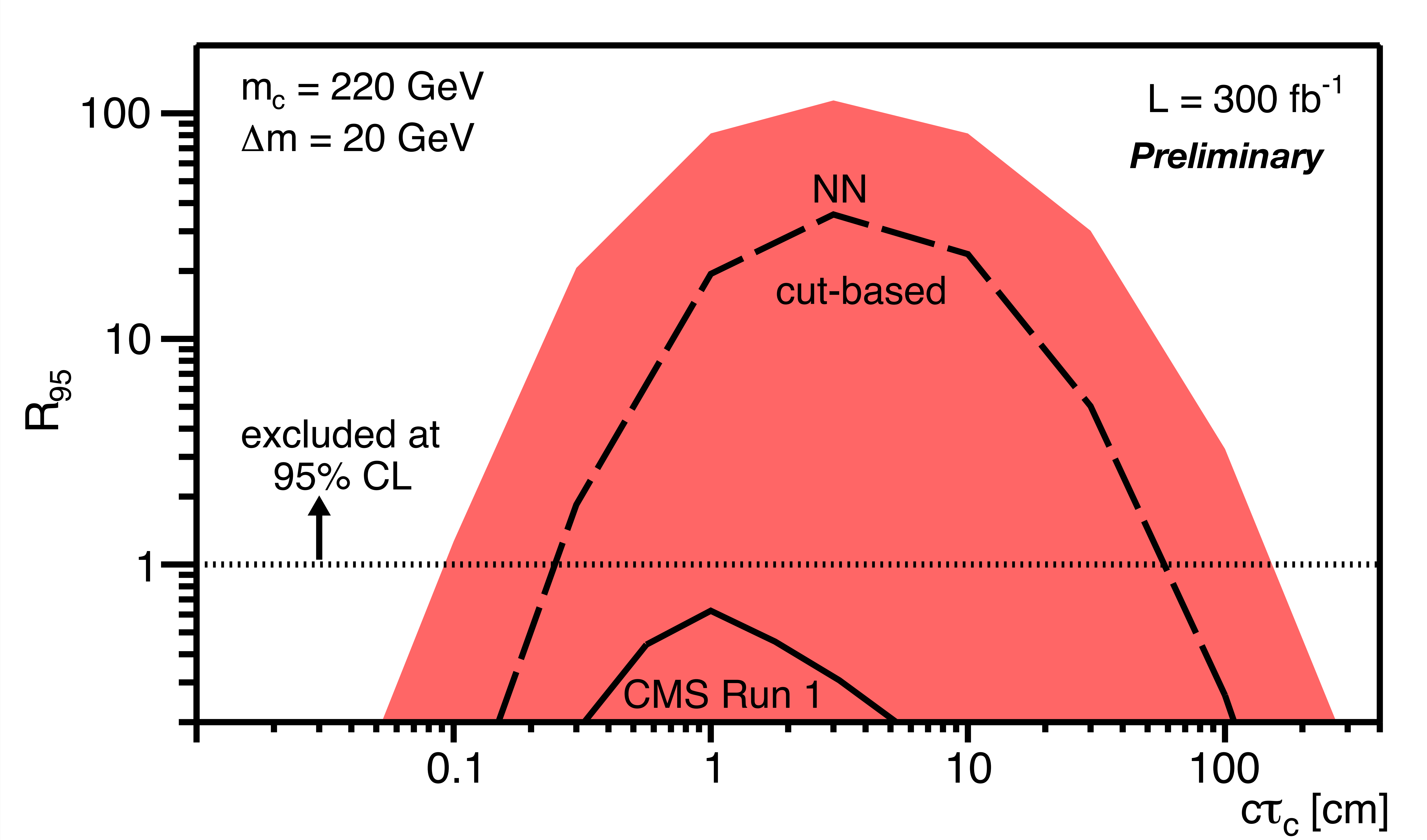


#	(m_c [GeV], Δm [GeV], $c\tau_c$ [cm])	$S_{\rm I}$	$S_{\rm II}$	$S_{\rm III}$
1	(324, 20, 2)	0.21	0.23	0.64
2	(220, 20, 3)	0.57	0.67	2.71
3	(220, 20, 0.1)	68	19	3.06
4	(220, 20, 1)	84	72	139
5	(220, 20, 10)	15	20	147
6	(220, 20, 100)	0.79	0.70	14
7	(220, 40, 1)	449	427	837
	HF background	2323	363	14

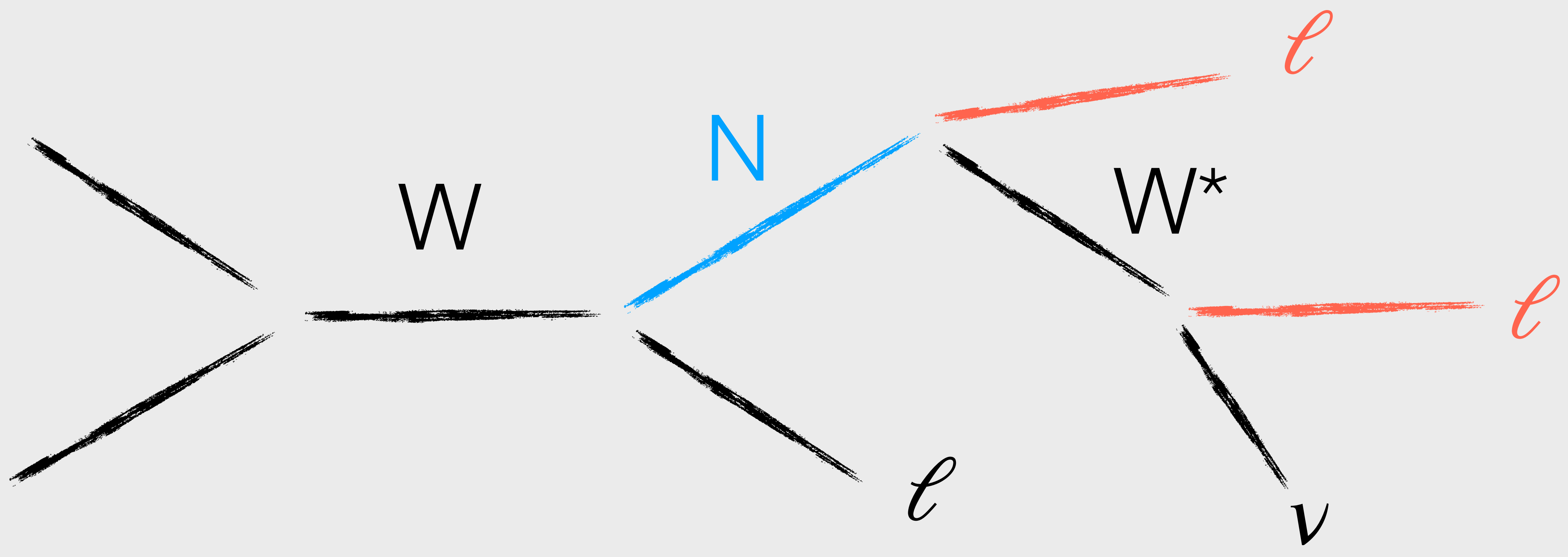
Extrapolation of near-future reach



Performance of the NN

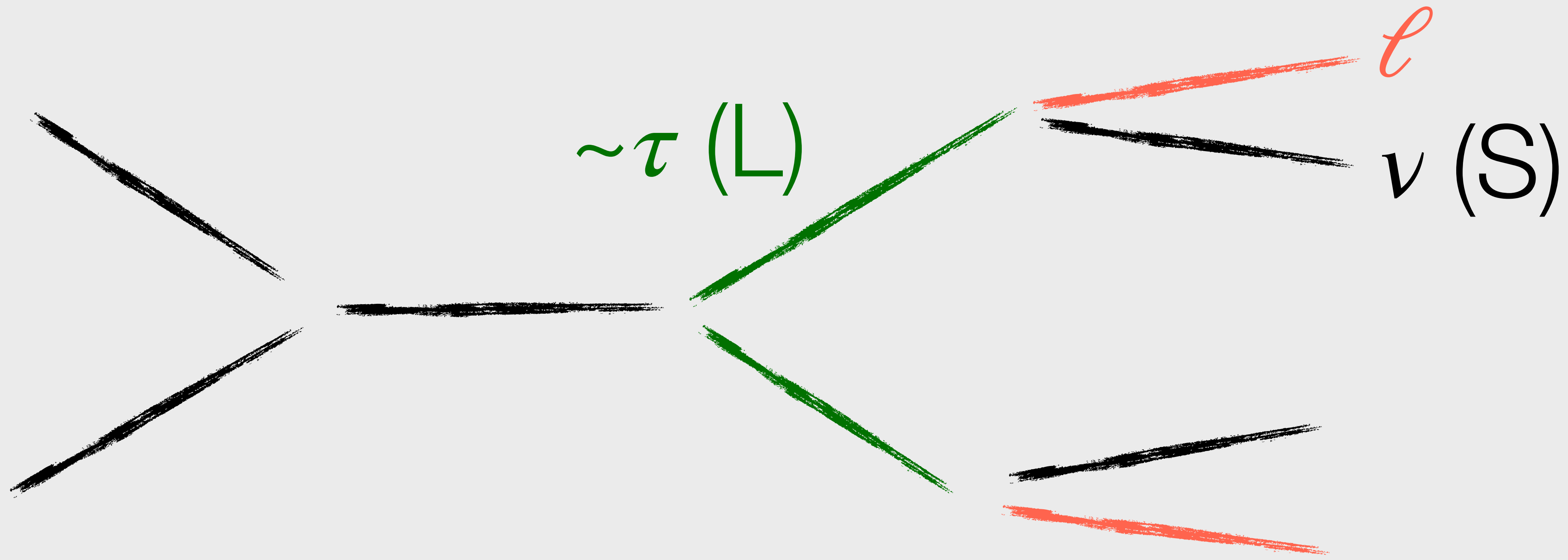


The displaced lepton search is very general



Heavy Neutral leptons

(soft)



RPV SUSY or minimal freeze-in

(hard)

Summary so far…

- The singlet-triplet model is an example of a minimal co-annihilation/co-scattering model
- Co-scattering naturally predicts long-lived particles, which would give a signature of displaced leptons.
- The relic density constraint means a small mass gap between the mediator and DM, therefore implying *soft* displaced leptons
- The current displaced lepton search is not sensitive to this model
- We propose a search that can probe lifetimes in the range 1mm - 1m using the displaced lepton signature.

A note about triggers

- LHC generates far too many collisions to store them all. Also, most of them are “boring”.
- Experiments use “triggers” to select interesting events. The number of events that can be processed fast enough with collision rate is fixed (in Hz).
- For “soft” events, there are too many events from SM that would look similar.
- Most searches use something like hard jets / large MET / hard leptons to select events.
- Possible to have mono jet (ISR) trigger, but this will reduce signal ~ 1/100.
- We need specialised triggers to look for these objects (work ongoing).

LHC running schedule