BEYOND THE STANDARD MODEL

Lecture III

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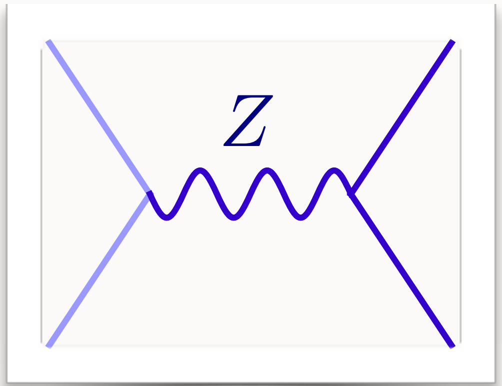
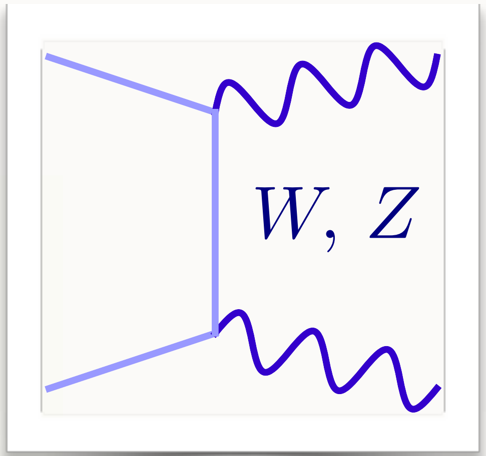
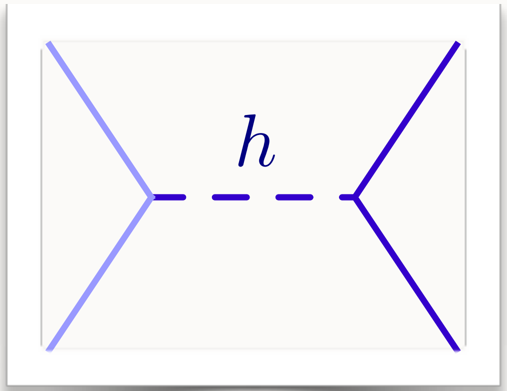
WIMP(Y) DM AT THE LHC

- Thermal DM is one of the main motivations for new physics to lie near weak scale
  - WIMP DM: freezeout governed by SM interactions
    - highly predictive, highly constrained

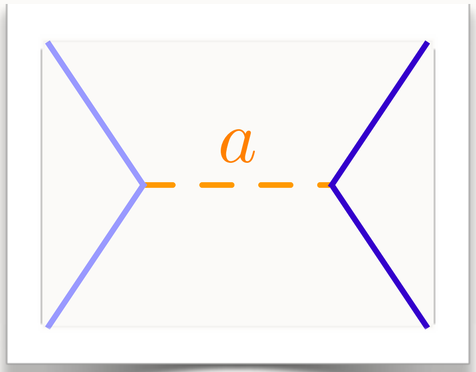


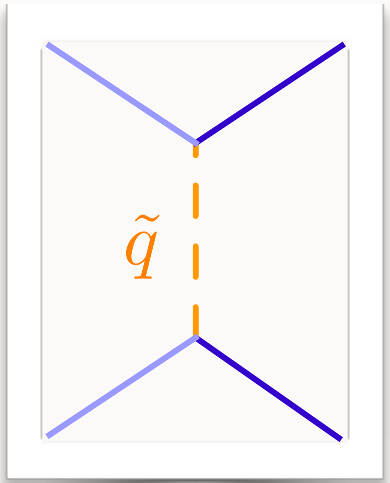


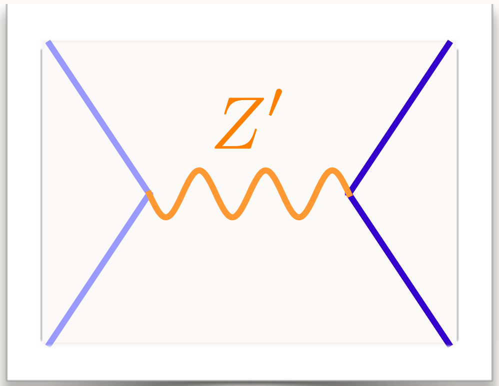


WIMP(Y) DM AT THE LHC

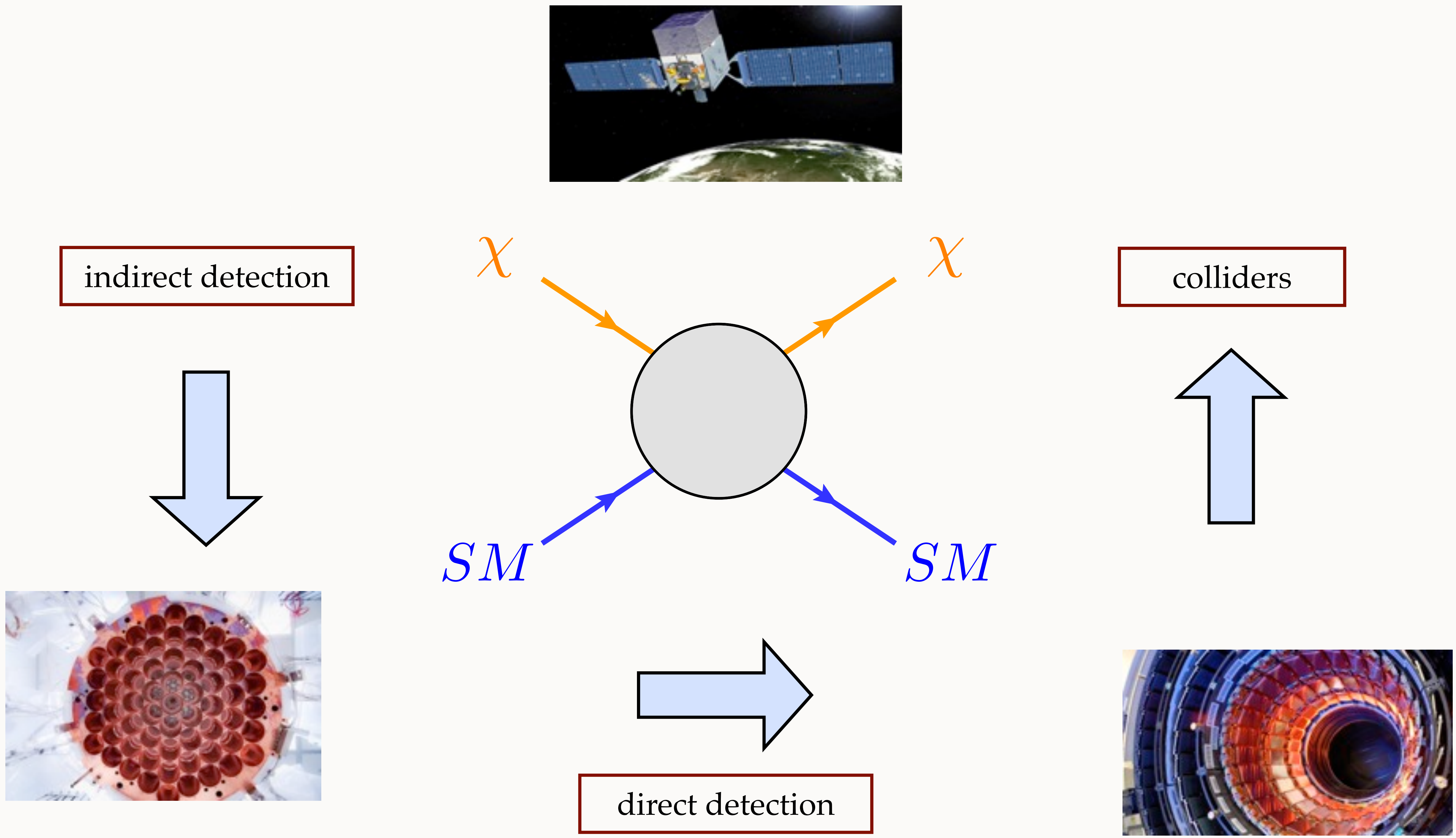
- Thermal DM is one of the main motivations for new physics to lie near weak scale
  - WIMP DM: freezeout governed by SM interactions
    - highly predictive, highly constrained
  - "WIMPy DM": freezeout to SM through new interactions
    - interaction strength of DM, mediator with SM fixed by requiring specific relic abundance for DM
    - broader range of possible signatures, depending on quantum numbers





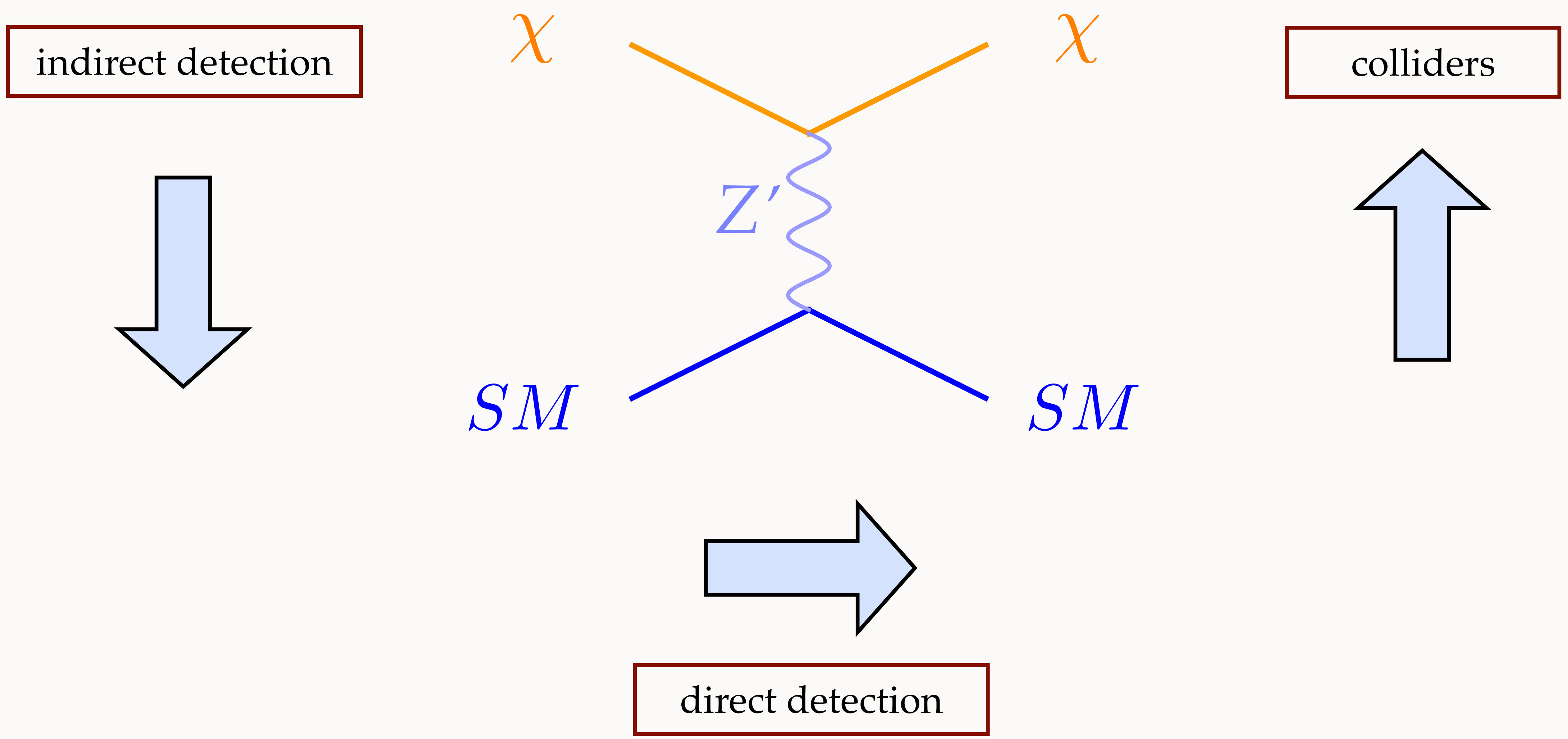


DM COMPLEMENTARITY



DM COMPLEMENTARITY

relationship between signals in different experimental probes of thermal DM is highly model-dependent: rich source of information



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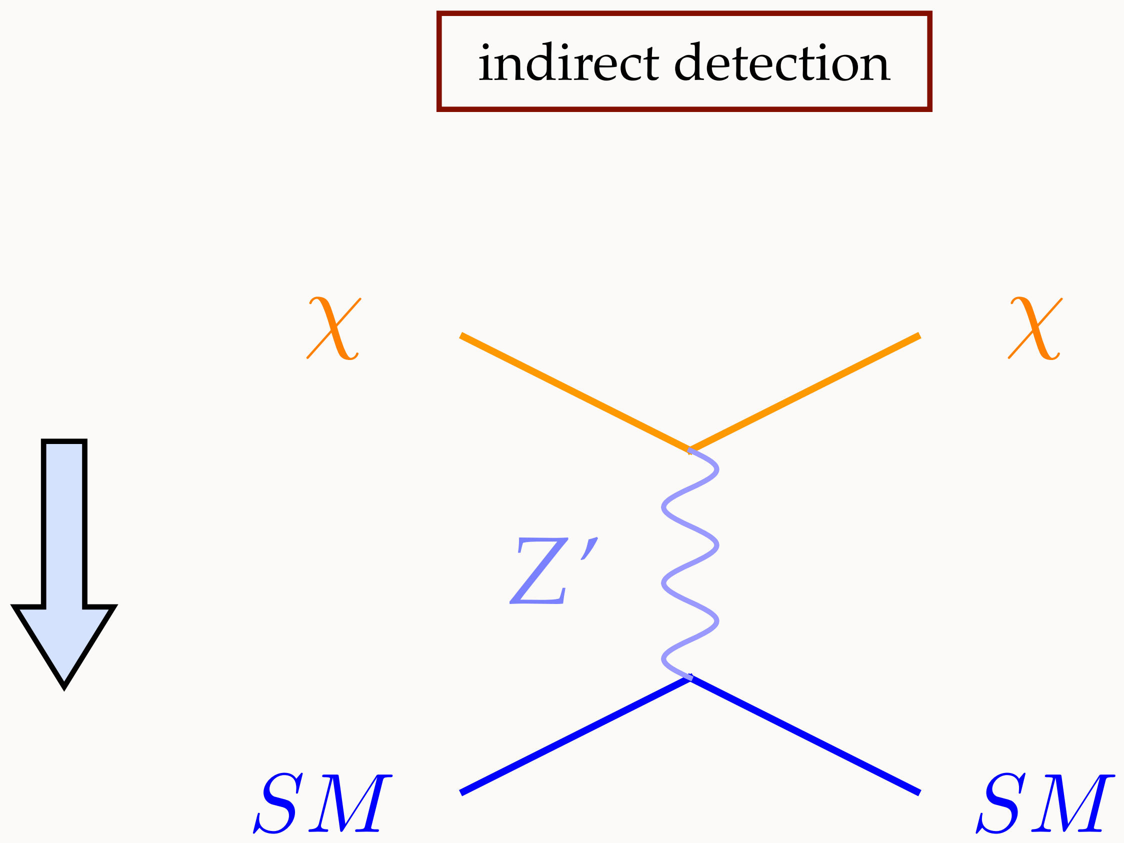
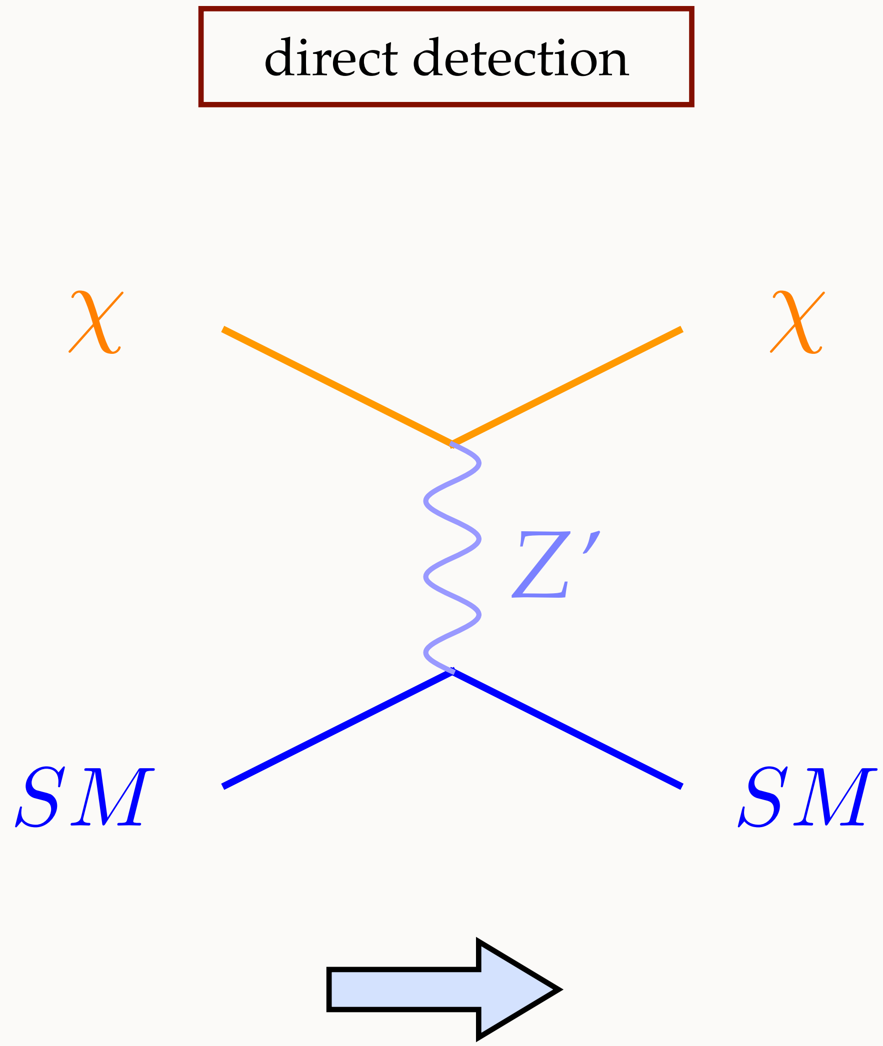


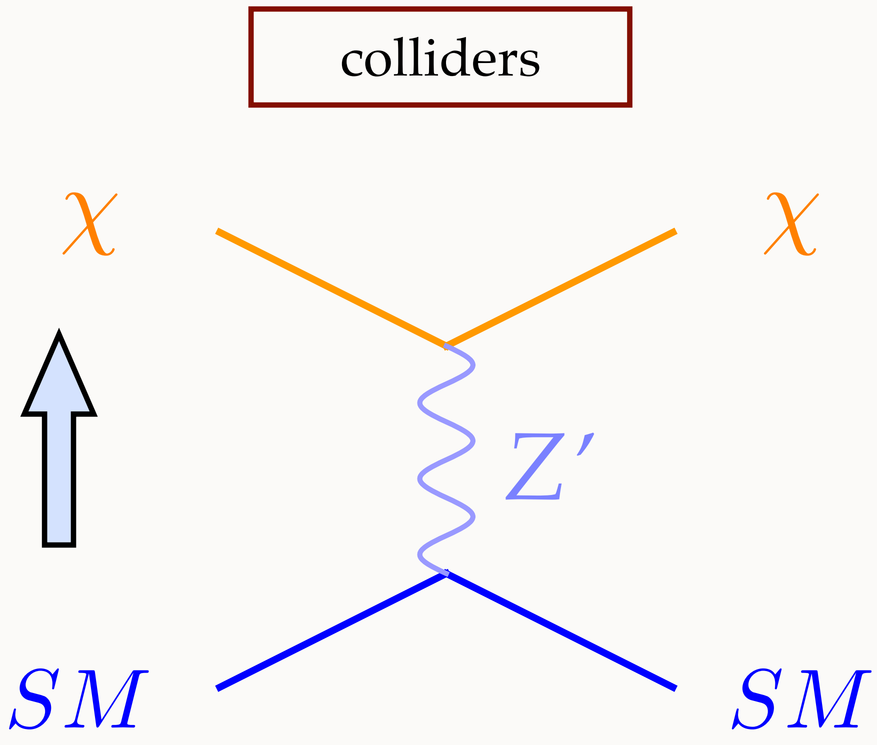
- Annihilation cross-section is $\langle \sigma v \rangle = a + bv^2 + \ldots$, with values of a, b largely fixed by quantum numbers of DM, mediator
- since $v_{\rm today} \ll v_{fo}$, annihilation cross-section today can be substantially suppressed if a is small
- Ex: scalar DM with Z′ mediator

DM COMPLEMENTARITY



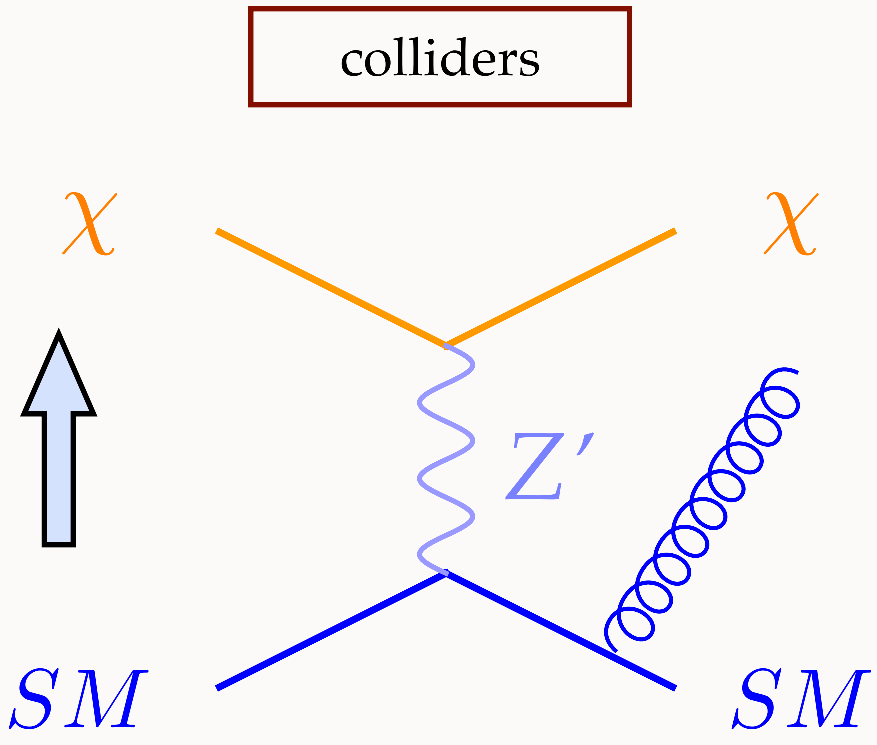
- Direct detection prospects typically good for Z' mediators: DM-nucleon cross-section has a leading spin-independent cross-section, thus large coherent enhancement
  - (for a pseudo-scalar, spin-independent cross-section only shows up at loop level)
- But if DM is light, the nuclear recoil energy can be too small to detect

DM COMPLEMENTARITY



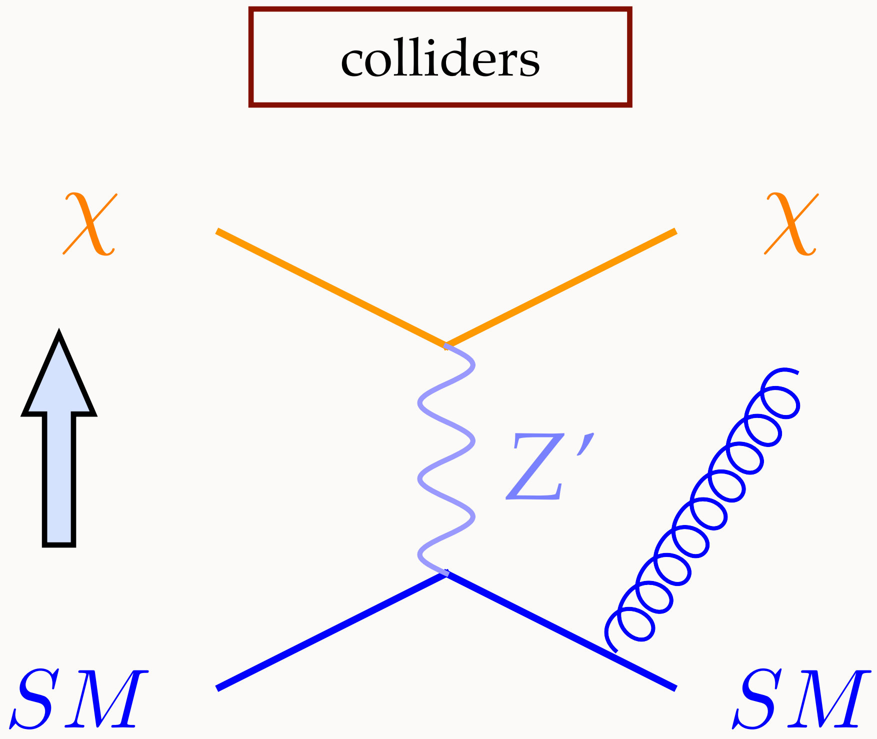
- Directly produce DM, i.e., MET at the LHC

DM COMPLEMENTARITY



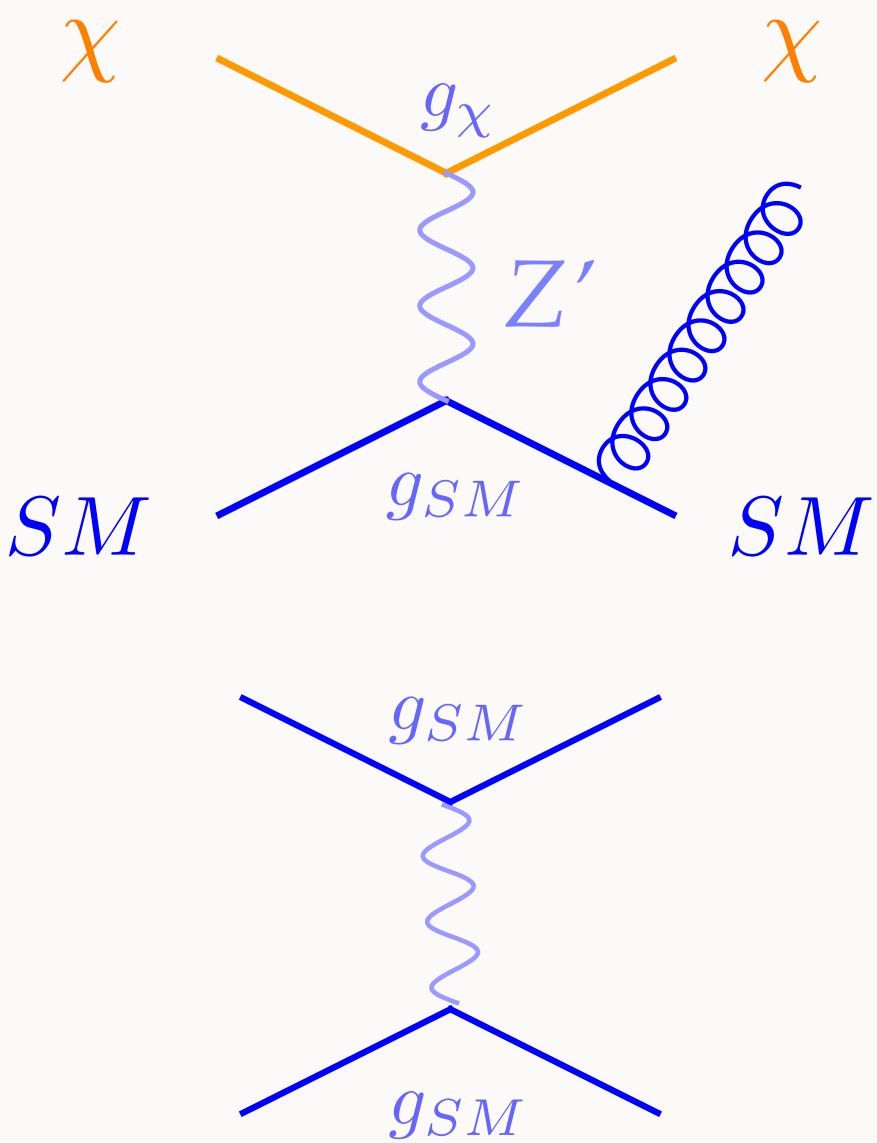
- Directly produce DM, i.e., MET at the LHC
- Need ISR to make system visible

DM COMPLEMENTARITY



- Directly produce DM, i.e., MET at the LHC
- Need ISR to make system visible
- Differences in production rates between axial, vector interactions are less dramatic (can be O(1) at high mass)
- unique sensitivity to very light DM

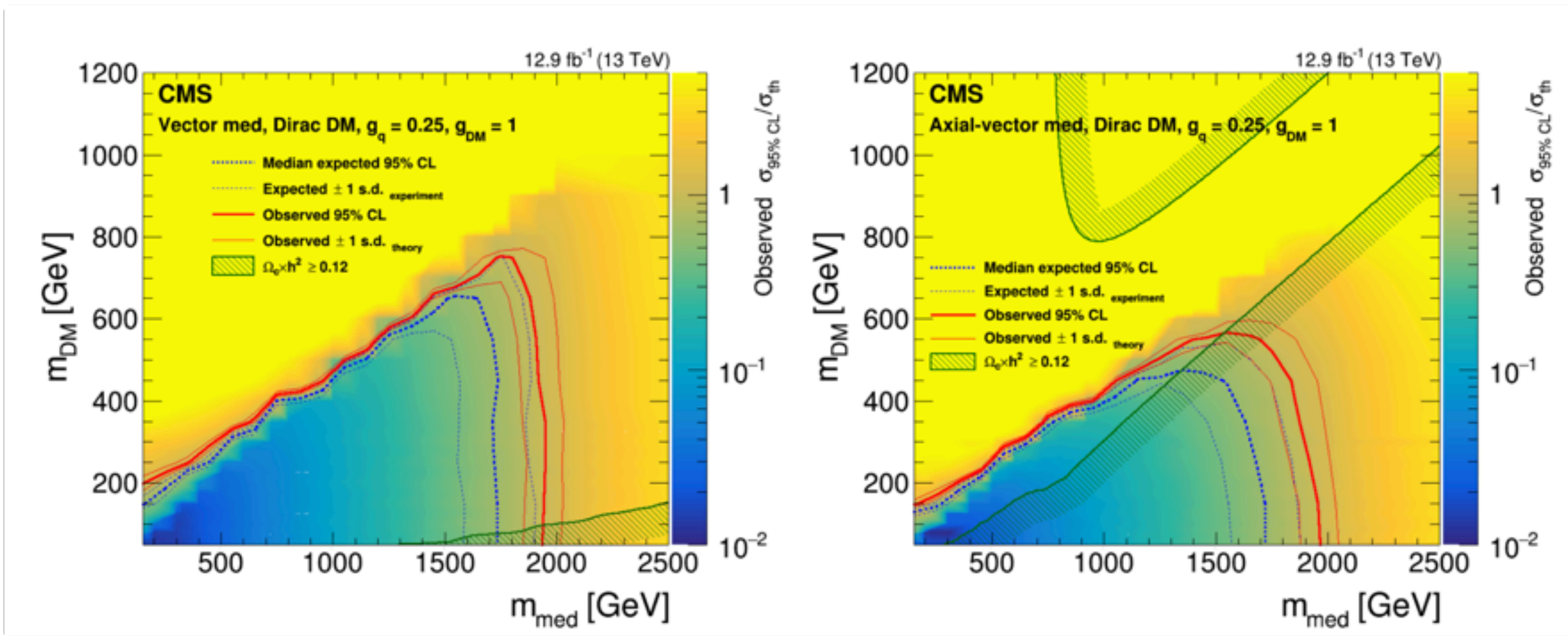
DM AT THE LHC



- Kinematics of DM production depends on $m_{Z'}$, m_χ : need for simplified models beyond EFT description
- Related processes: mediator production (i.e., no direct involvement of DM)
- Since thermal freezeout only constrains product $g_{SM}\, g_\chi$, relationship between MET signal and resonance signal is not uniquely fixed

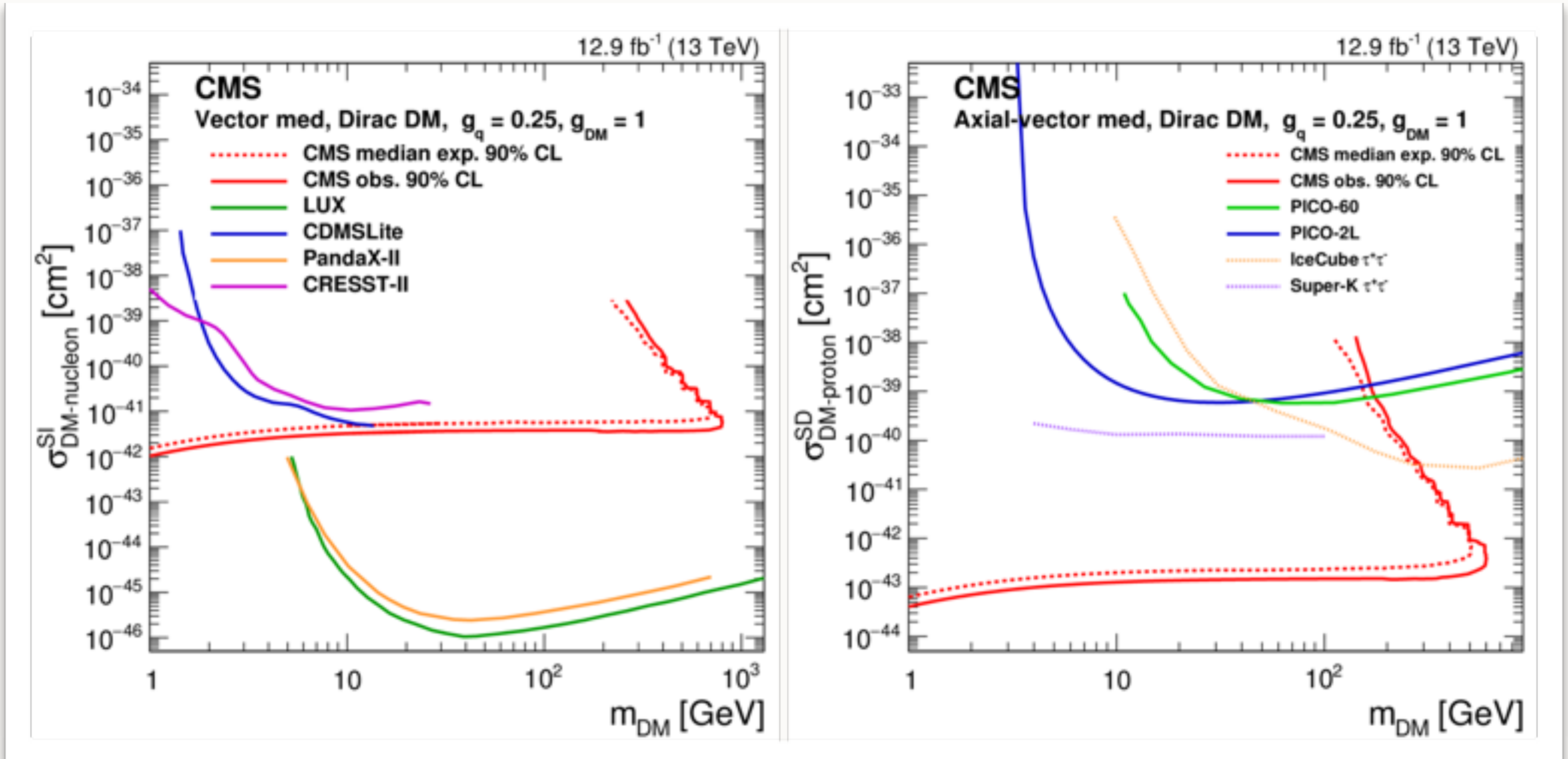
DM AT THE LHC

- The shape of exclusions should look familiar



DM AT THE LHC

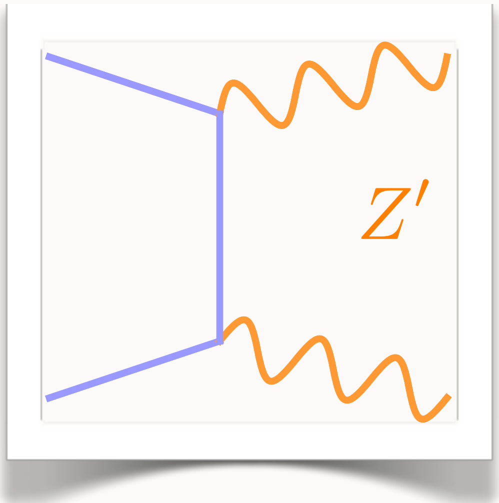
- Unique sensitivity at low mass; spin-dependent σ_N

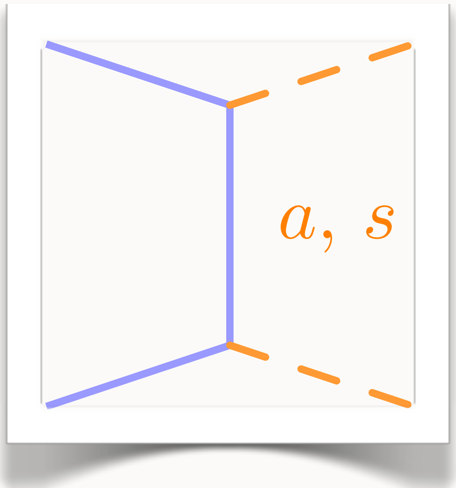


  - though bear in mind that these kinds of plots are apples-to-oranges comparisons

DARK FREEZEOUT

- But since we're talking about adding two new particles to describe DM freezeout, we should also consider the equally simple and minimal case $m_\chi > m_{med}$:

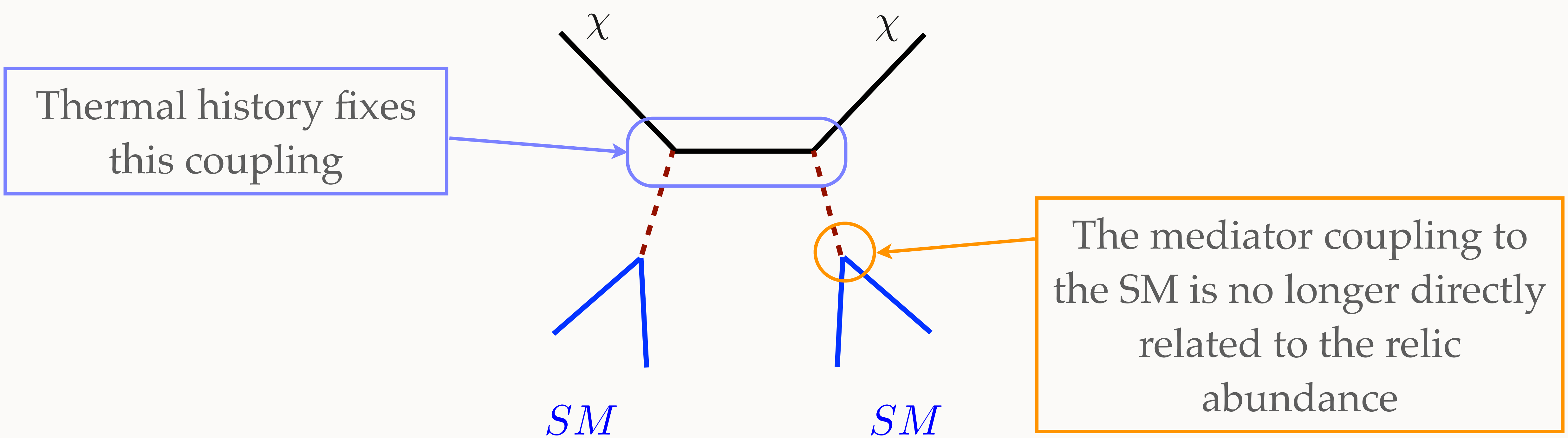




- then DM can annihilate directly to pairs of mediators

DARK FREEZEOUT

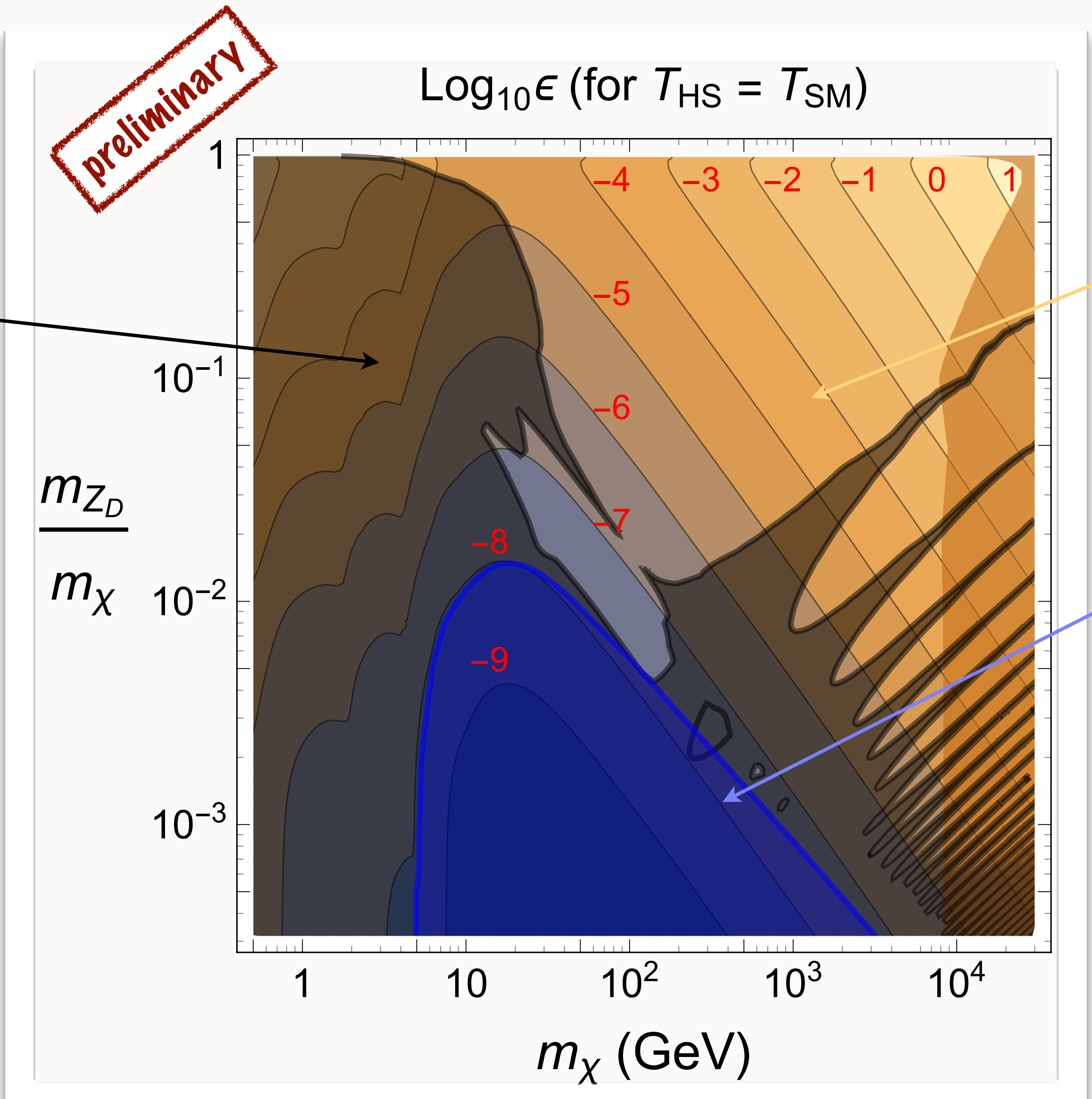
- If $g_{SM} \sim g_\chi$, these diagrams just give an additional contribution to DM annihilation
- But if $g_{SM} \ll g_\chi$, dark matter freezeout proceeds more or less independently of SM until the mediator ultimately decays



DARK FREEZEOUT

- Dark freezeout with Dirac DM and kinetically-mixed Z':

indirect detection is independent of Z' coupling to SM



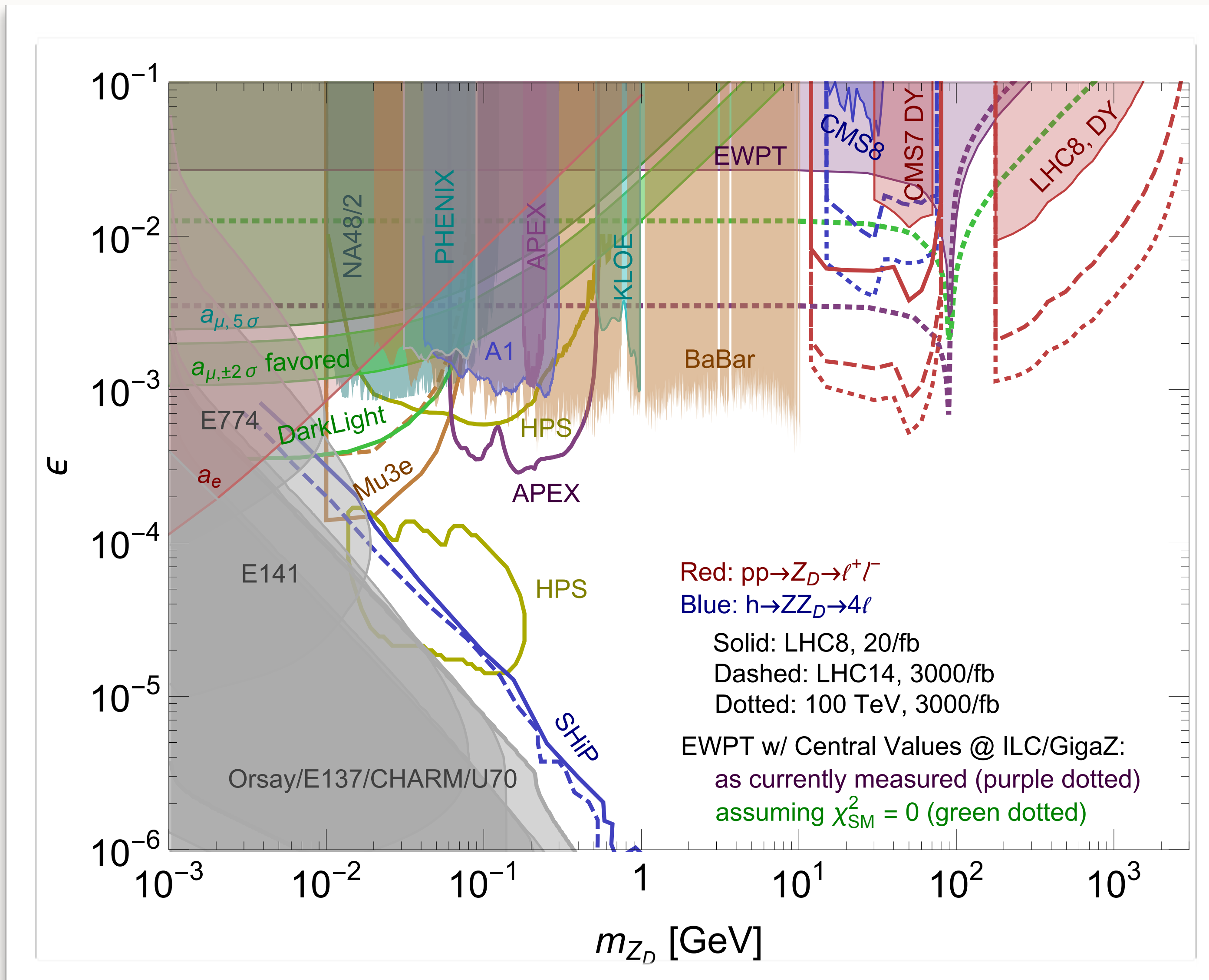
given thermal abundance, direct detection limits Z' coupling to SM

dark sector is no longer in thermal equilibrium with SM in early universe

[Evans, Gori, JS]

DARK FREEZEOUT

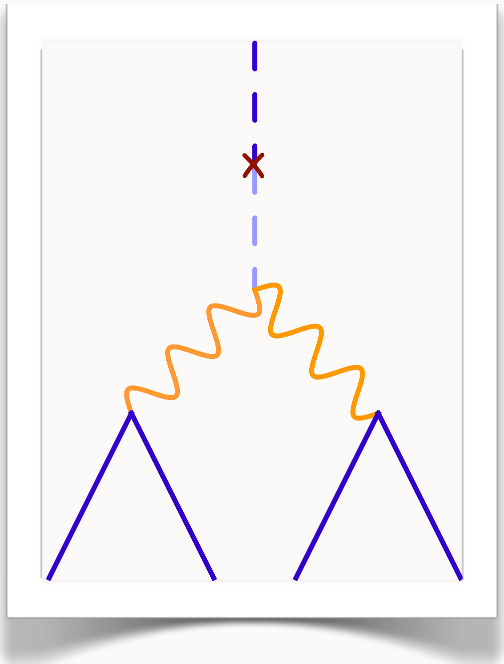
- Leading LHC signal: dark photon production
  - simple model: dark photon is lightest dark state, only SM decays

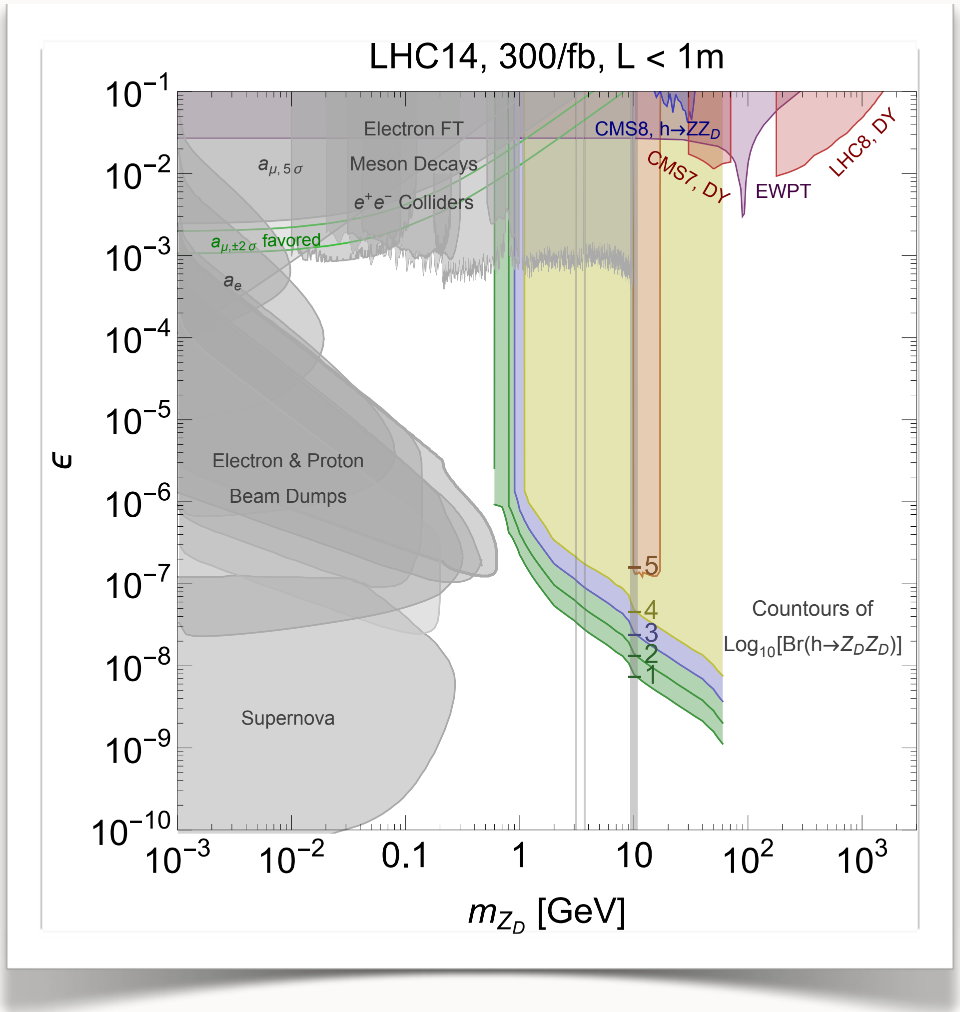


[Curtin, Essig, Gori, JS]

DARK FREEZEOUT

- Dark and visible Higgses will in general also mix, giving an entirely separate probe of the dark sector





- Higgs mixing opens a deep window into otherwise inaccessible territory: displaced dark photon decays

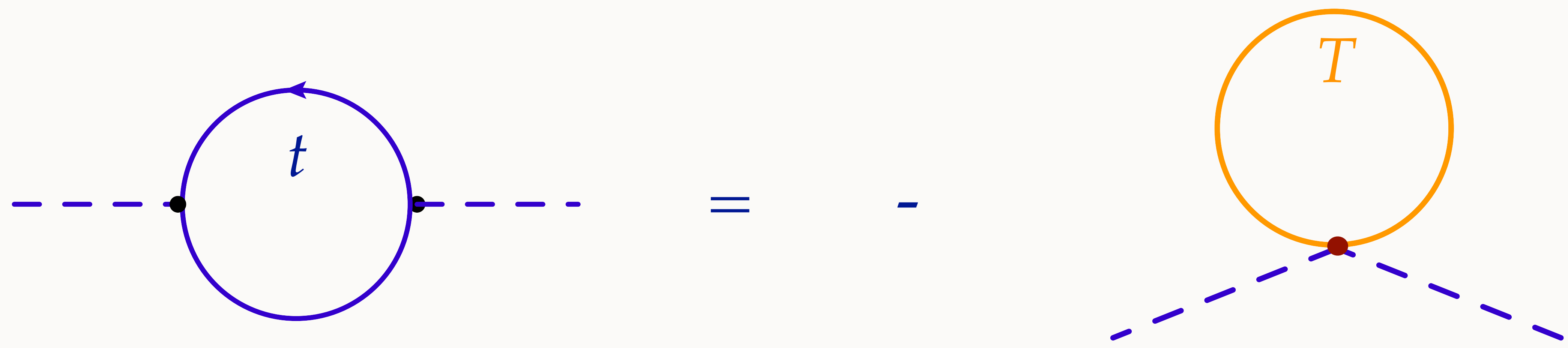
[Curtin, Essig, Gori, JS]

HIDDEN SECTORS

- These kinds of DM models are examples of hidden sectors: a set of fields uncharged under SM interactions, interact among themselves
- One way to approach lack of evidence for SM-charged new physics to date is to use hidden sectors to solve puzzles of the SM
- Not surprising this works for dark matter. But it can be applied to the hierarchy problem too!

NEUTRAL NATURALNESS

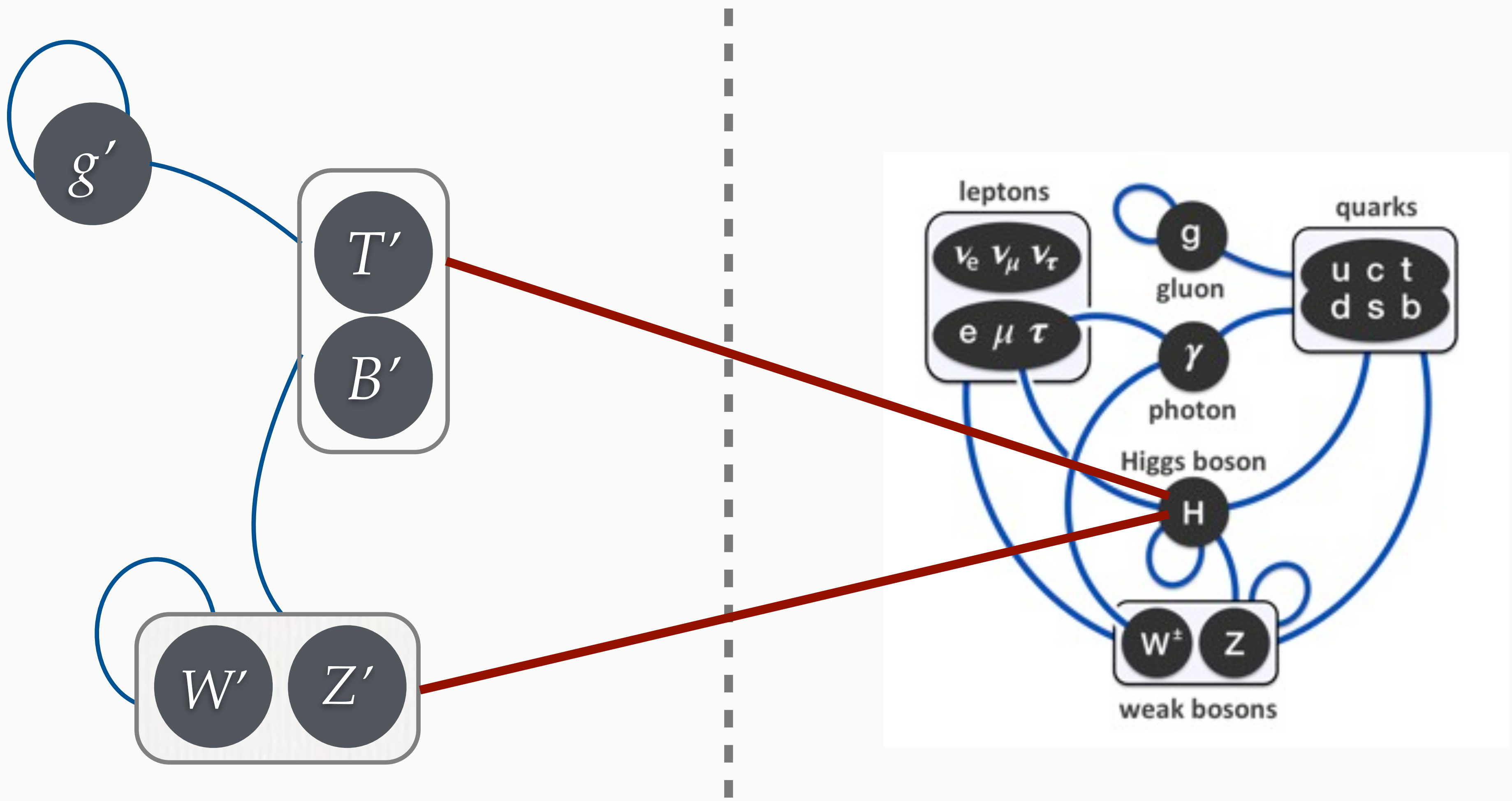
- Solving the hierarchy problem in the dark:



  - top partner neutral under SM forces: dark top
  - this structure only works if T has same kind of interactions as t
  - can charge T under mirror copy of SM forces. Dark gluons, dark W, Z bosons

NEUTRAL NATURALNESS

- Only the Higgs talks directly to dark sector:



- strength of interaction: depends on amount of fine-tuning in m_h

NEUTRAL NATURALNESS

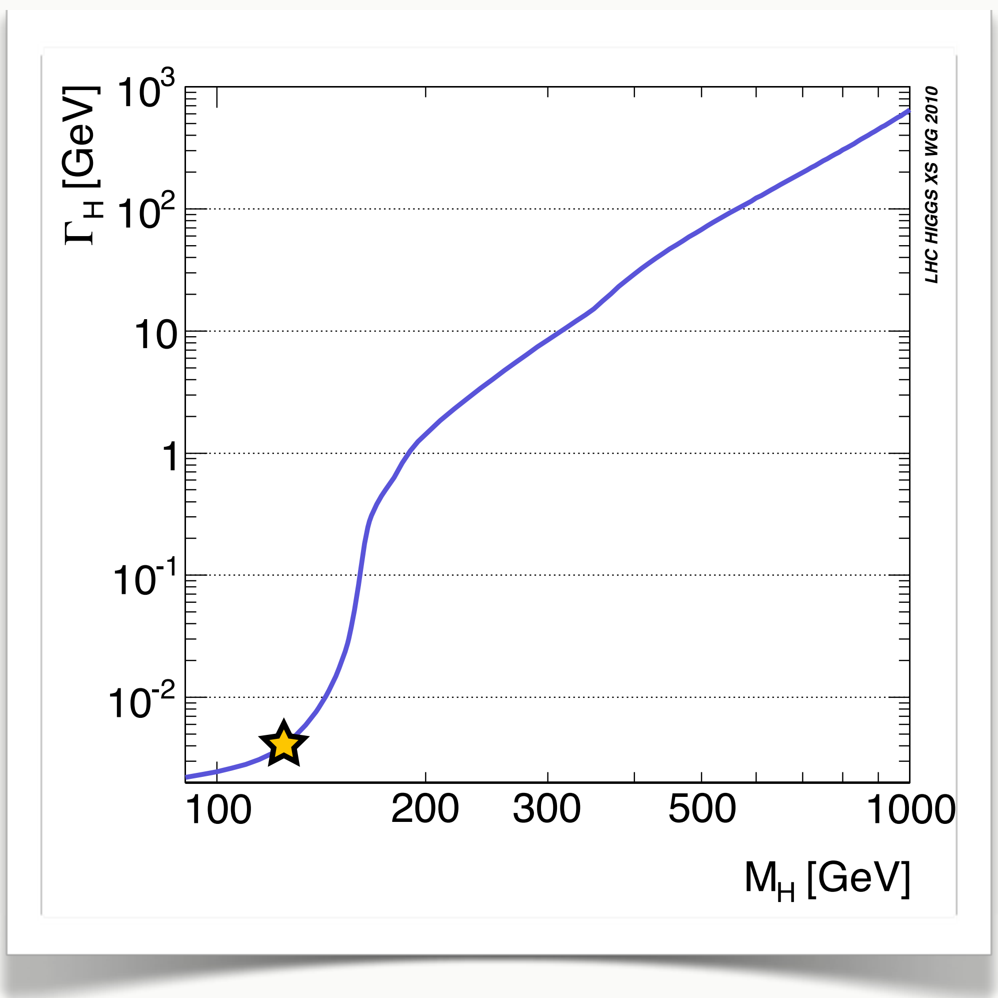
- Since there are no new colored states in this solution to the hierarchy problem, experimental results do not force these models to be fine-tuned
- Best signatures:
  - Higgs properties
  - exotic Higgs decays to light mirror hadrons
  - pair production of mirror T: rare but distinctive

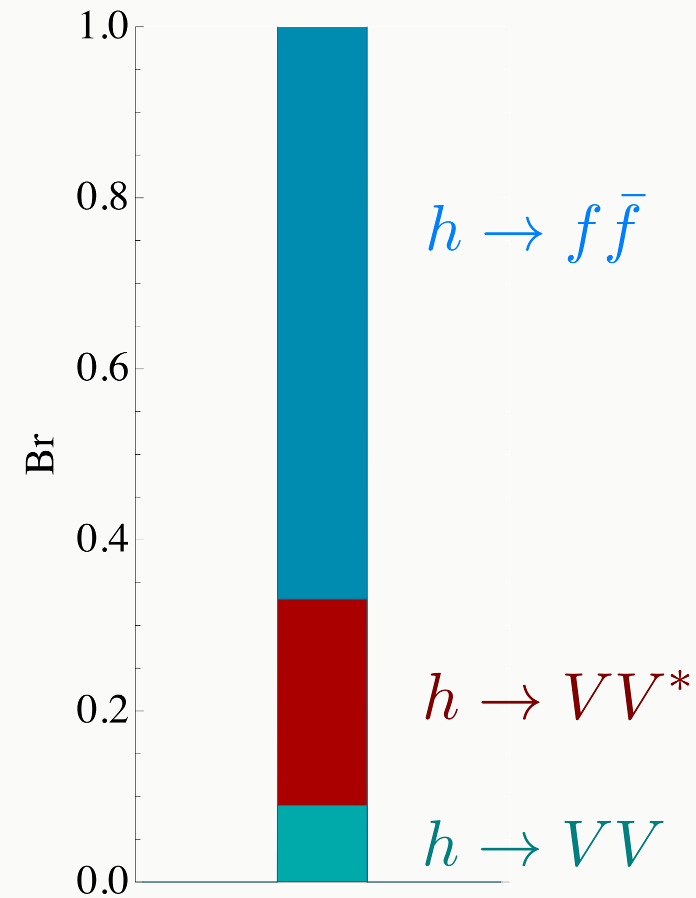
EXOTIC HIGGS DECAYS

- Exotic Higgs decays are one of the most important probes of dark sectors at the LHC
  - The Higgs is one of the easiest places in the SM for SM-singlet new physics to couple: $|H|^2$ carries no SM charge
  - Higgs branching ratios are unusually sensitive to existence of BSM decay modes
- LHC is the only place where Higgs bosons are made on-shell: unique discovery possibilities for dark sectors

EXOTIC HIGGS DECAYS

- A light SM-like Higgs is narrow:

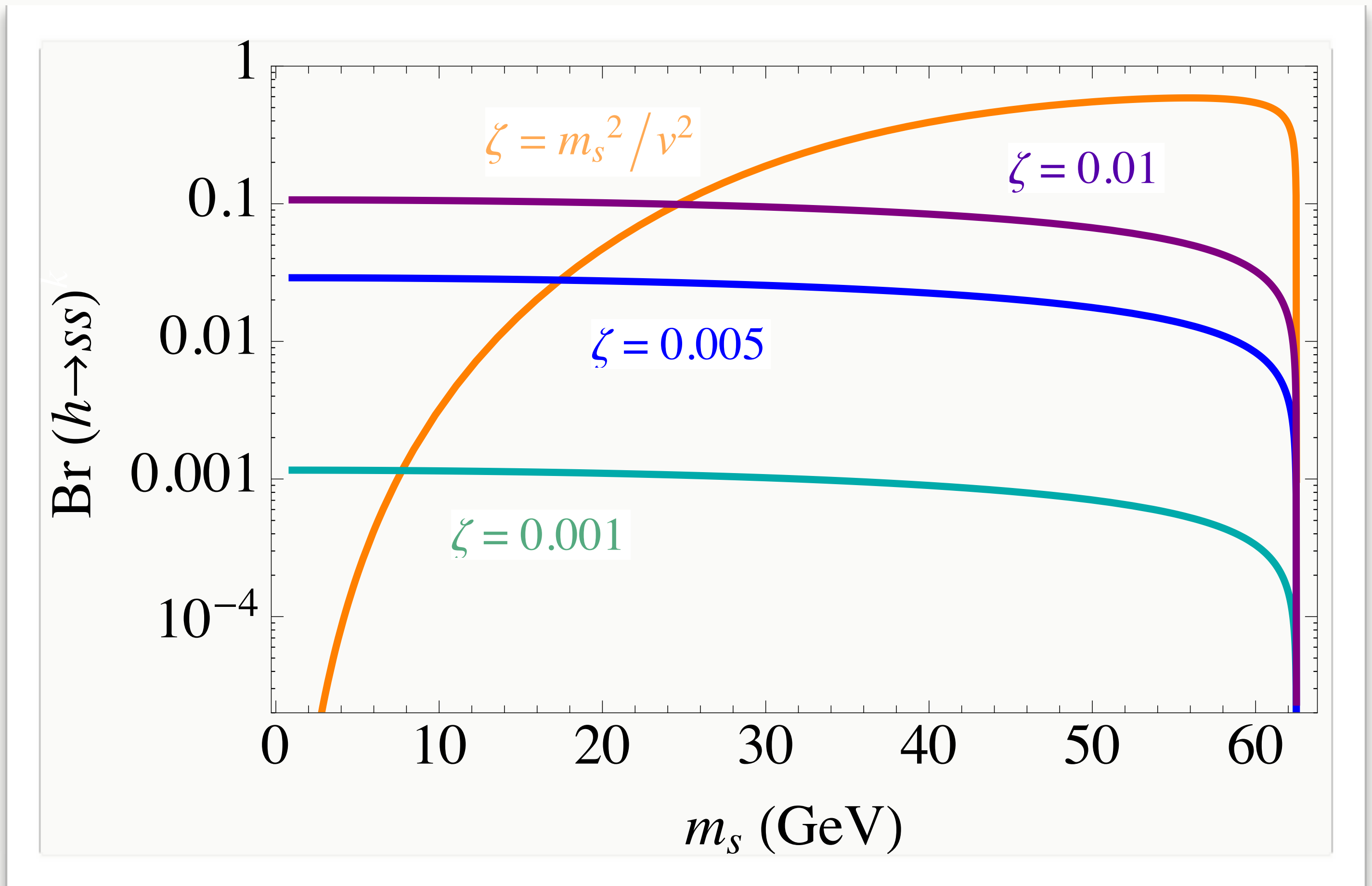




$$\Gamma_h(125 \text{ GeV}) = 4.1 \text{ MeV}$$

EXOTIC HIGGS DECAYS

- Presence of new light degrees of freedom can distort Higgs *Brs* by *O(1)* even for small couplings

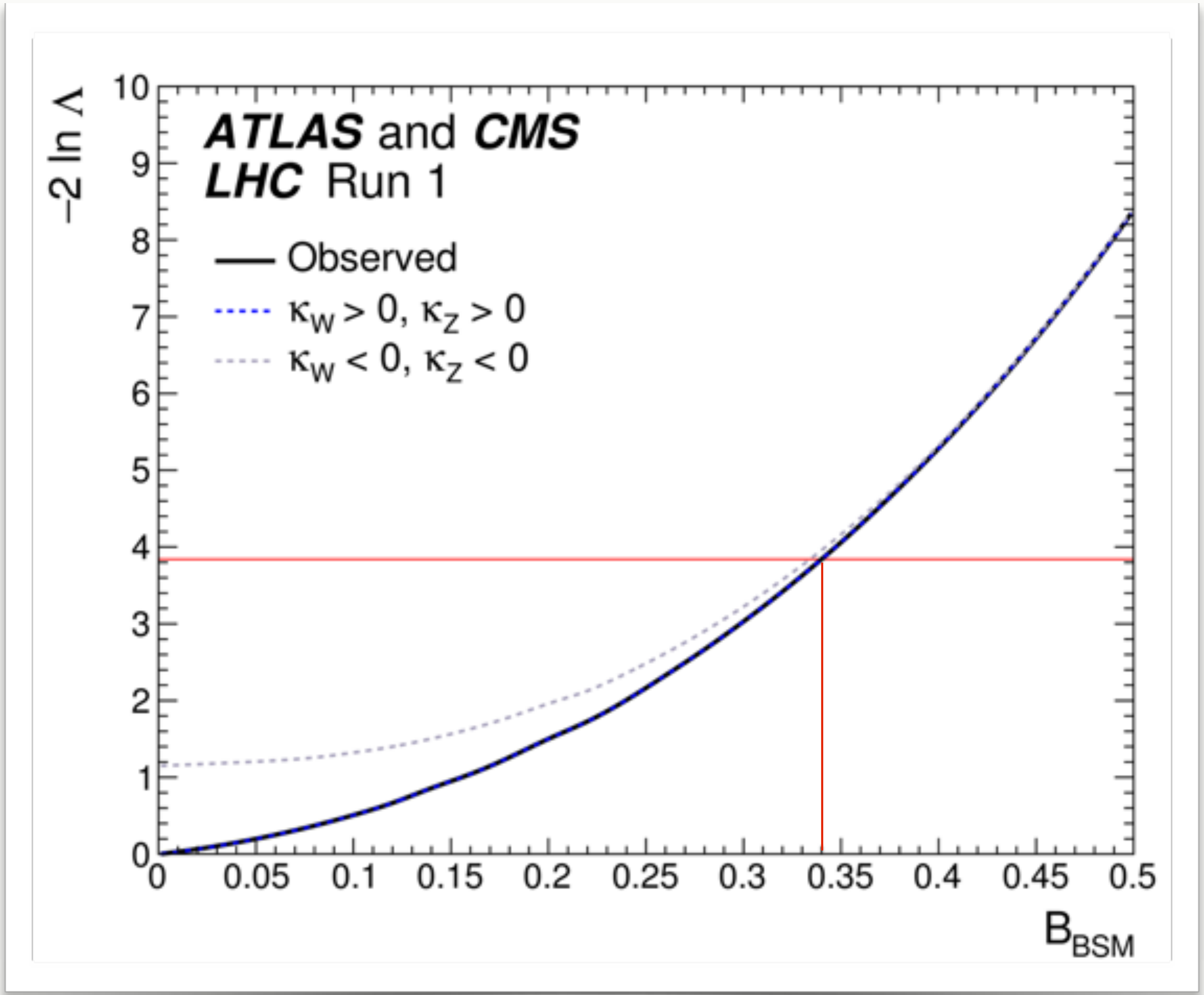


Simple example: one new scalar

$$\Delta\mathcal{L} = \frac{\zeta}{2} s^2 |H|^2$$

EXOTIC HIGGS DECAYS

- Indirect limits: observation of SM modes



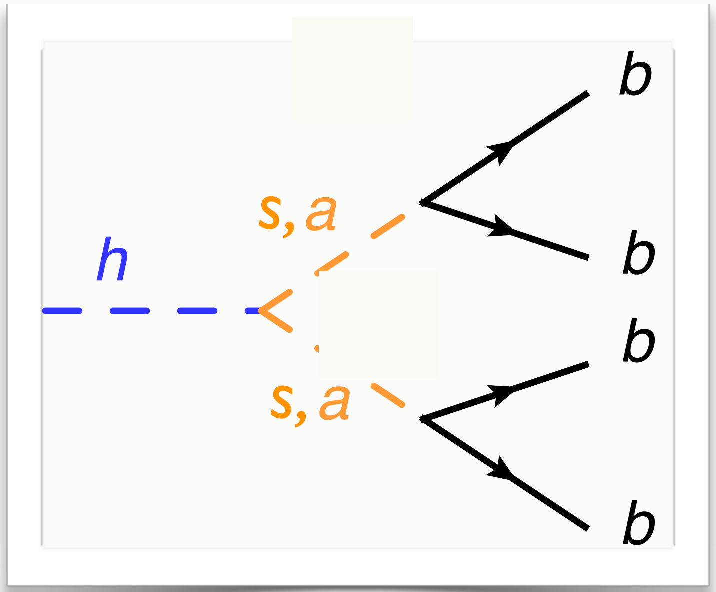
EXOTIC HIGGS DECAYS

- The LHC as an intensity frontier machine
  - Higgs production cross-section at 13 TeV: ~50 pb
  - Integrated luminosity, ~35/fb
    - → 10^6 Higgs bosons served
    - If: reasonable reconstruction efficiency, good S/B: statistics for branching fractions ~10^{-5}
  - this is like the kinematic limit: best possible reach
    - But getting to this limit is often challenging: Higgs is light

EXOTIC HIGGS DECAYS

- Example: one especially well-motivated mode:

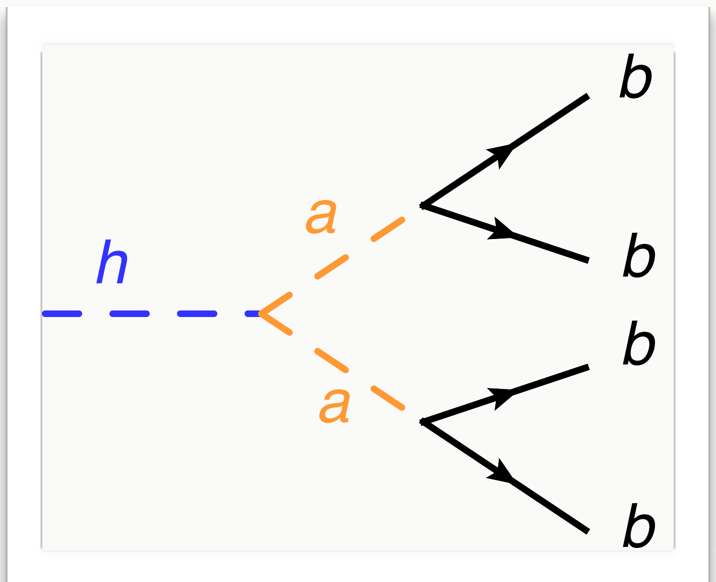
$$h \to ss(aa) \to 4b$$



- Dark matter:
  - Thermal WIMP: $XX \longrightarrow a \longrightarrow$ SM, $XX \longrightarrow ss\ (aa)$
- Neutral naturalness:
  - s is composite: dark glueballs
  - in this case the decays can rapidly become displaced

EXOTIC HIGGS DECAYS

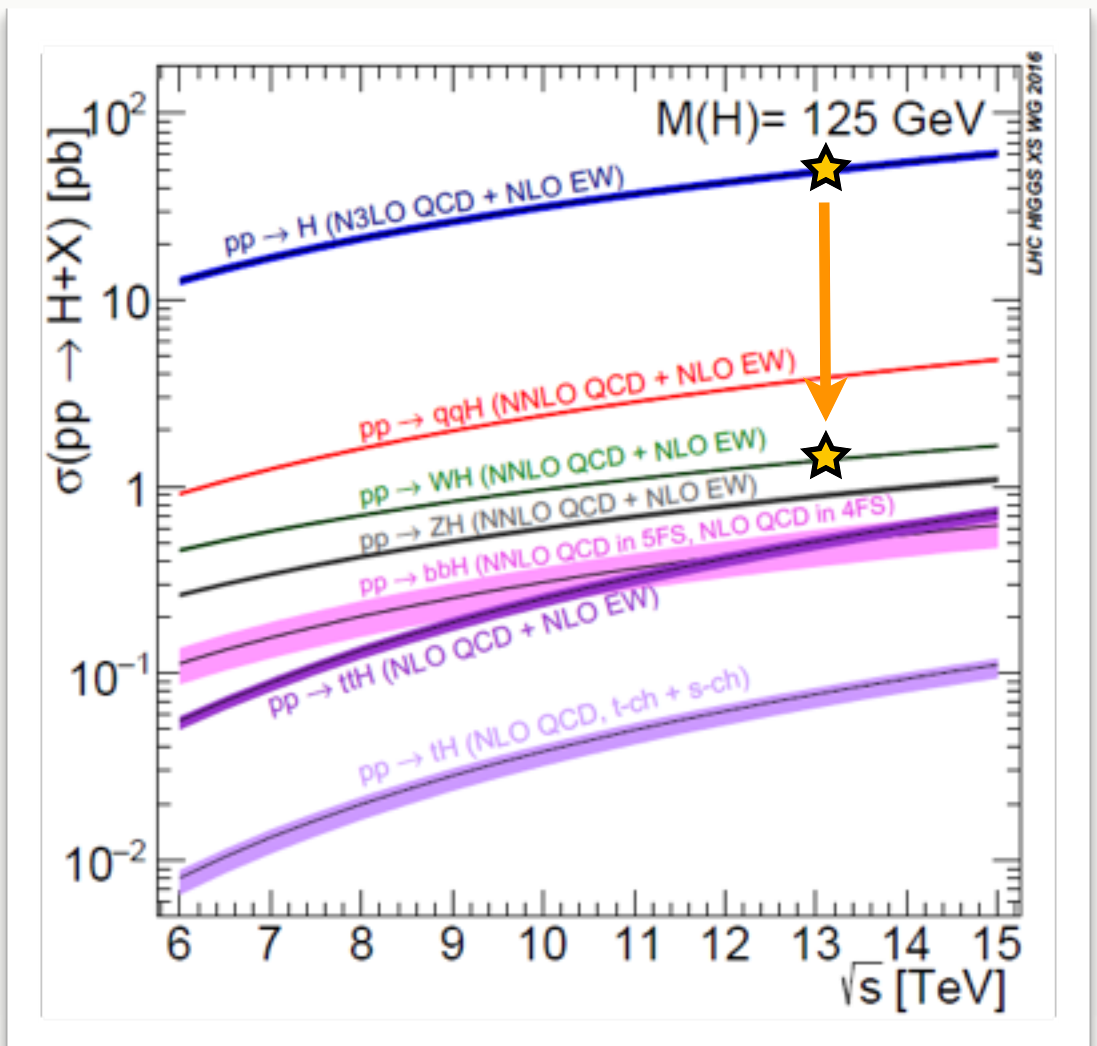
- Currently ATLAS has a search that is not yet constraining
  - high backgrounds, starting with trigger



Four soft b-jets:

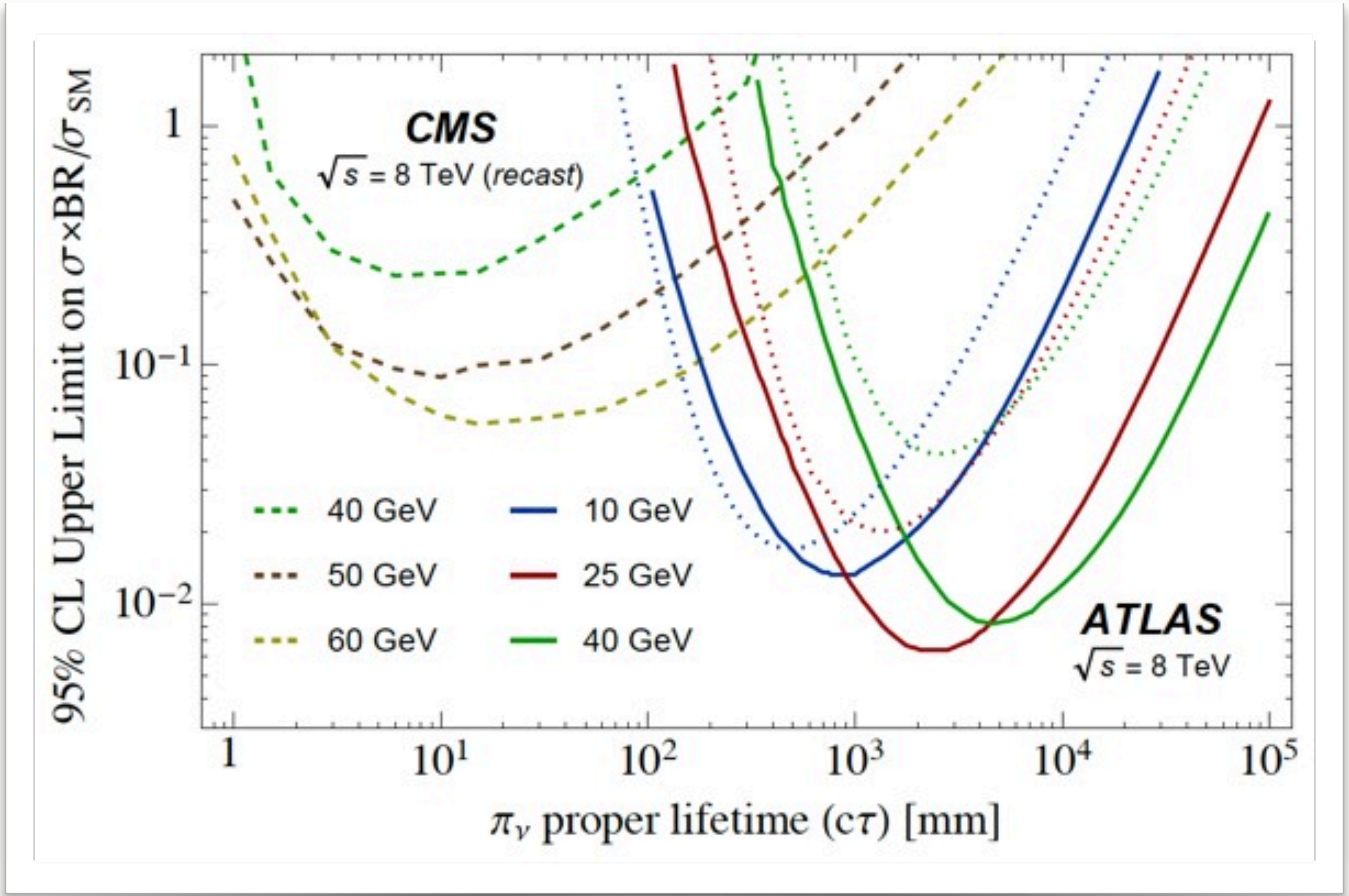
$p_T \lesssim 30$ GeV

use VH associated production



EXOTIC HIGGS DECAYS

- Displaced decays are in some ways easier: S/B

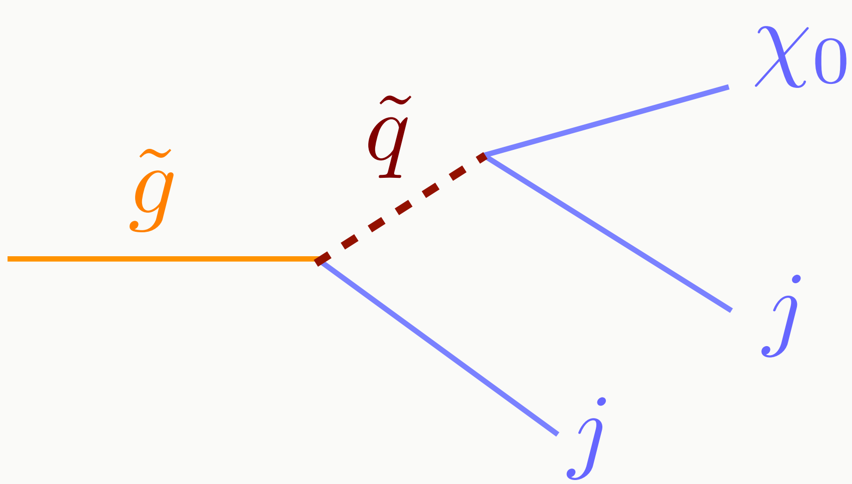


- but in some ways harder: triggering, reconstruction, backgrounds

[Csaki, Kuflik, Lombardo, Slone]

LONG LIVED PARTICLES

- LLPs arise naturally in a wide variety of models
- Perhaps SUSY is a little bit tuned:



- Mini-split: ino lifetime suppressed by high sfermion scale

$$c\tau \approx 100\mu m \times \left(\frac{m_{\tilde{q}}}{1000\,\text{TeV}}\right)^4 \left(\frac{\text{TeV}}{m_{\tilde{g}}}\right)^5$$

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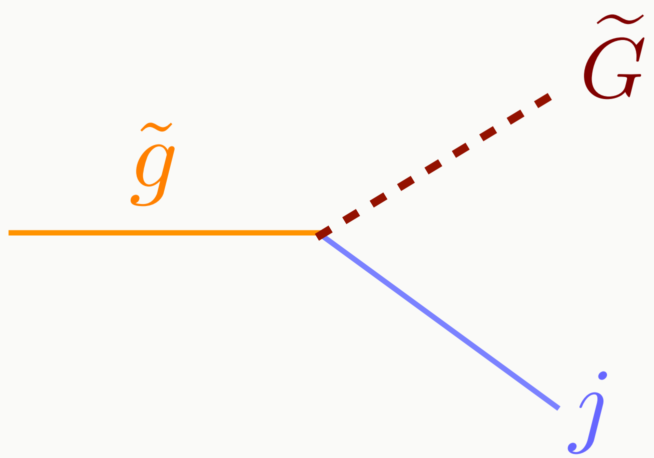
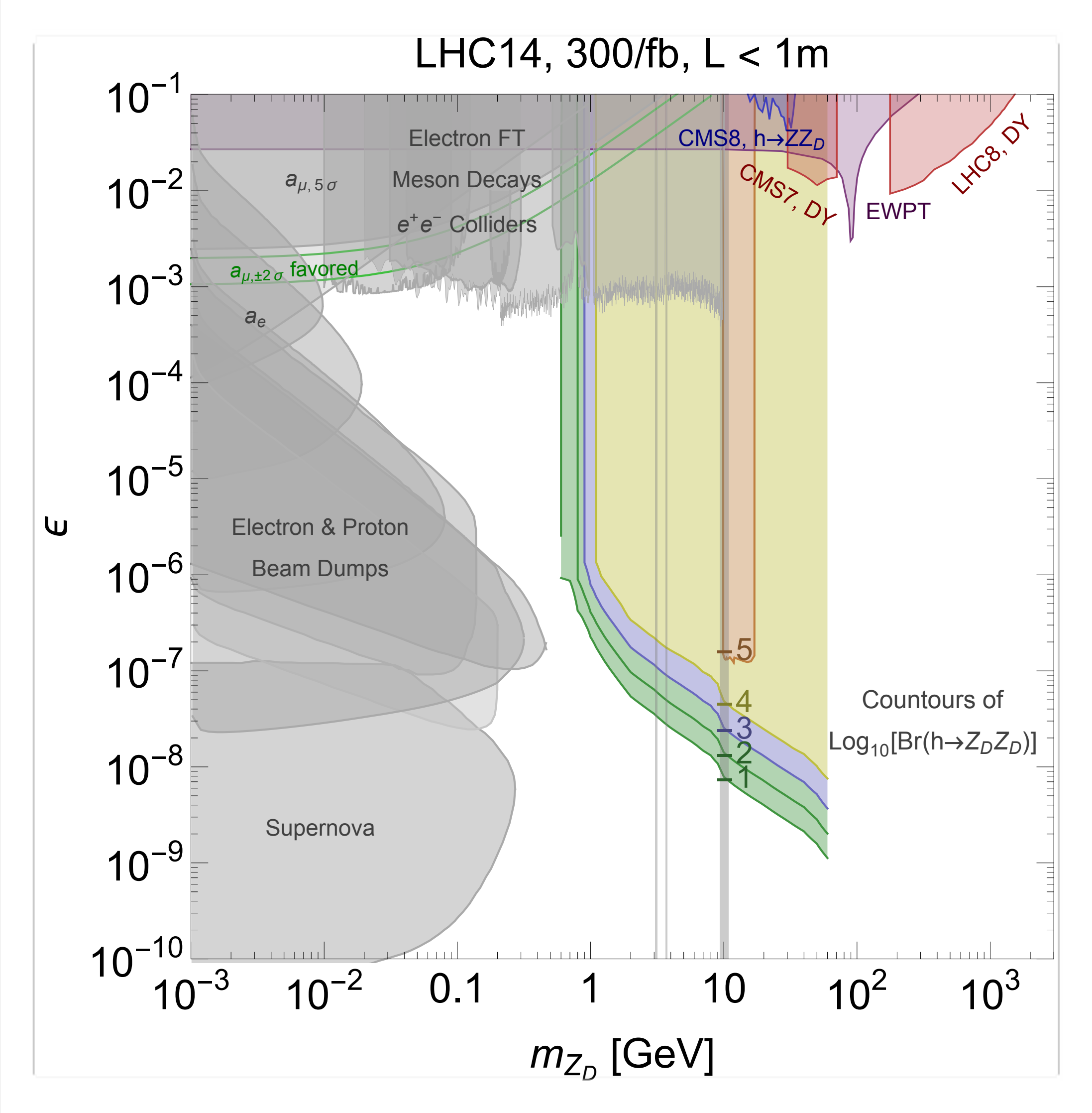


- Gauge-mediated SUSY-breaking: high SUSY-breaking scale suppresses gravitino couplings

$$c\tau \approx 100\mu m \times \left(\frac{\sqrt{F}}{100\,\mathrm{TeV}}\right)^4 \left(\frac{100\,\mathrm{GeV}}{m_{\tilde{g}}}\right)^5$$

LONG LIVED PARTICLES

- And as we've already seen, multi-state hidden sectors can easily give displaced decays:
  - Presence of multiple states allows production to be governed by different couplings than decay: appreciable production cross-sections, suppressed decays
  - Symmetries can also do this: in our SUSY examples, *R*-parity



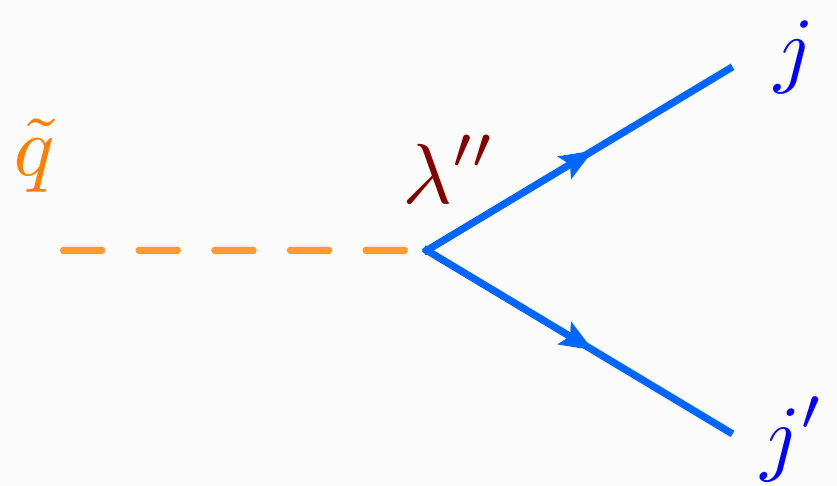
[Curtin, Essig, Gori, JS]

LONG LIVED PARTICLES

- This is especially true if the hidden sector confines, as in neutral naturalness
  - composite states decay through high mass-dimension operators and can thus easily be displaced. Hierarchies of lifetimes are generic
  - importance of (approximate, discrete, ...) symmetries in controlling dark state lifetimes: typically these will vary among states in spectrum
  - dark showers/cascades can yield high multiplicities if there is a separation of scales

LONG LIVED PARTICLES

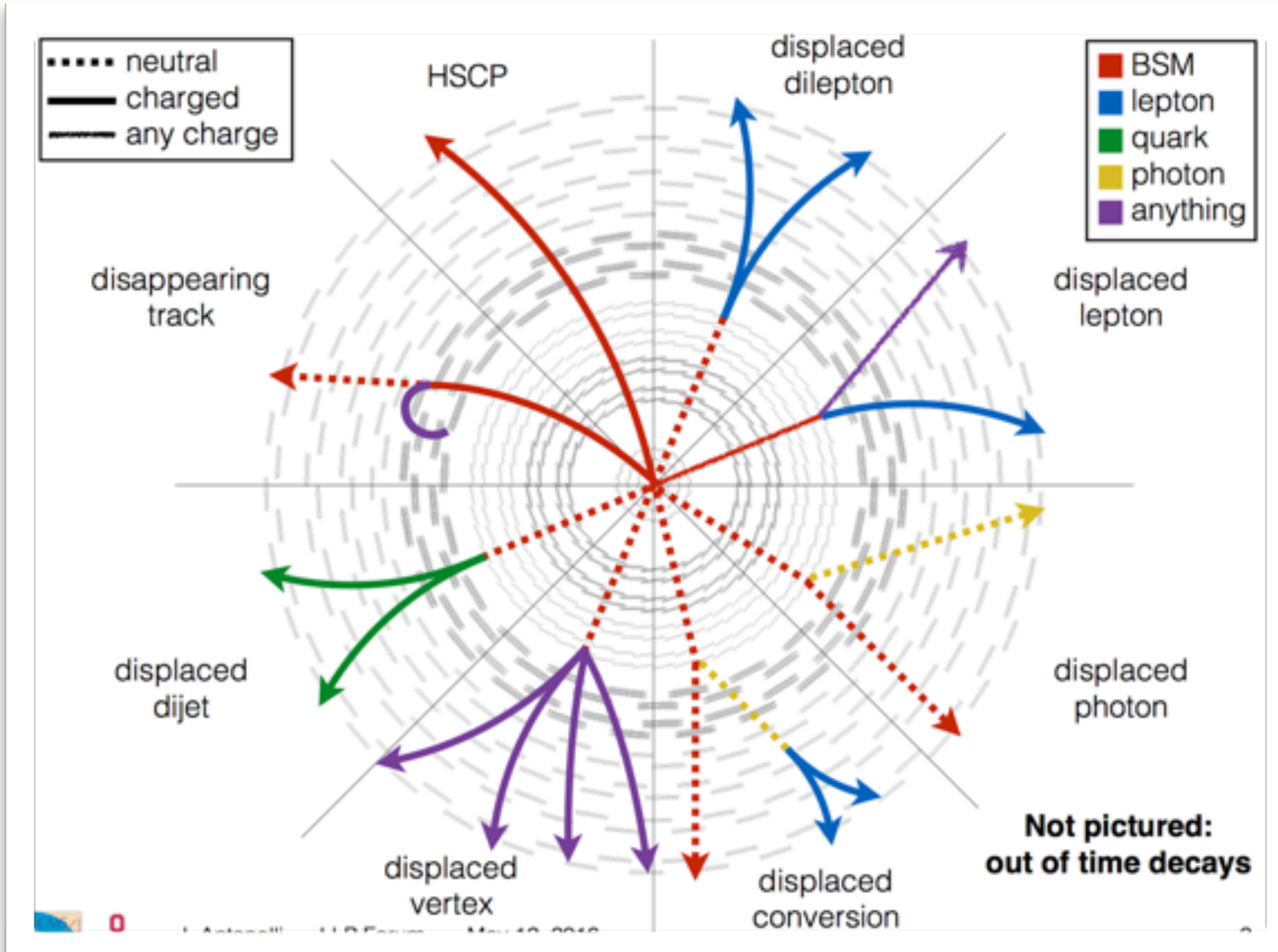
- Independently, there are many cosmological reasons to look for LLPs
- For instance, baryon number:



- avoiding washout of baryon number in early universe requires baryon-violating RPV couplings small

LONG LIVED PARTICLES

- BSM states that have a macroscopic proper lifetime can give spectacular signals



[Antonelli]

LONG LIVED PARTICLES

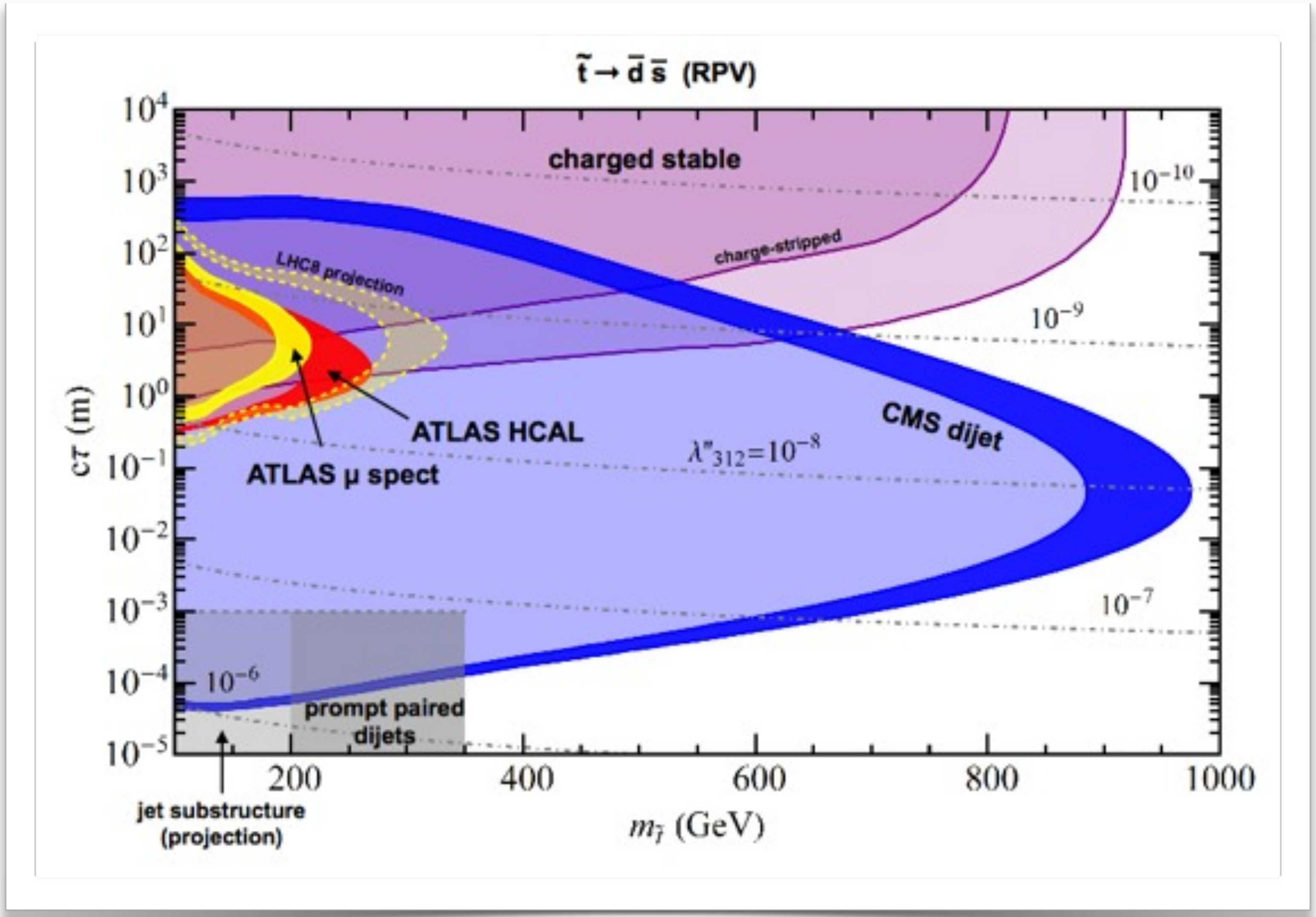
- SM physics backgrounds are very small compared to prompt searches
  - mostly heavy flavor, at relatively short lifetimes
- thus, dominant backgrounds are usually a combination of (weird truth level physics) x (weird detector response)
  - impossible to model reliably from first principles!
  - to date many searches have been background free; this will change as luminosity increases

LONG LIVED PARTICLES

- LLP searches often relatively insensitive to the details of the decay
  - depends on the location of the decay in the detector: there's more information for decays in the tracker than in the HCAL
  - but also because reconstruction criteria for a displaced object can be looser than for prompt objects
- thus LLP searches are often powerful and inclusive

LONG LIVED PARTICLES

- Thus it is actually easier to make sweeping statements about displaced SUSY than prompt SUSY:



[Liu, Tweedie]

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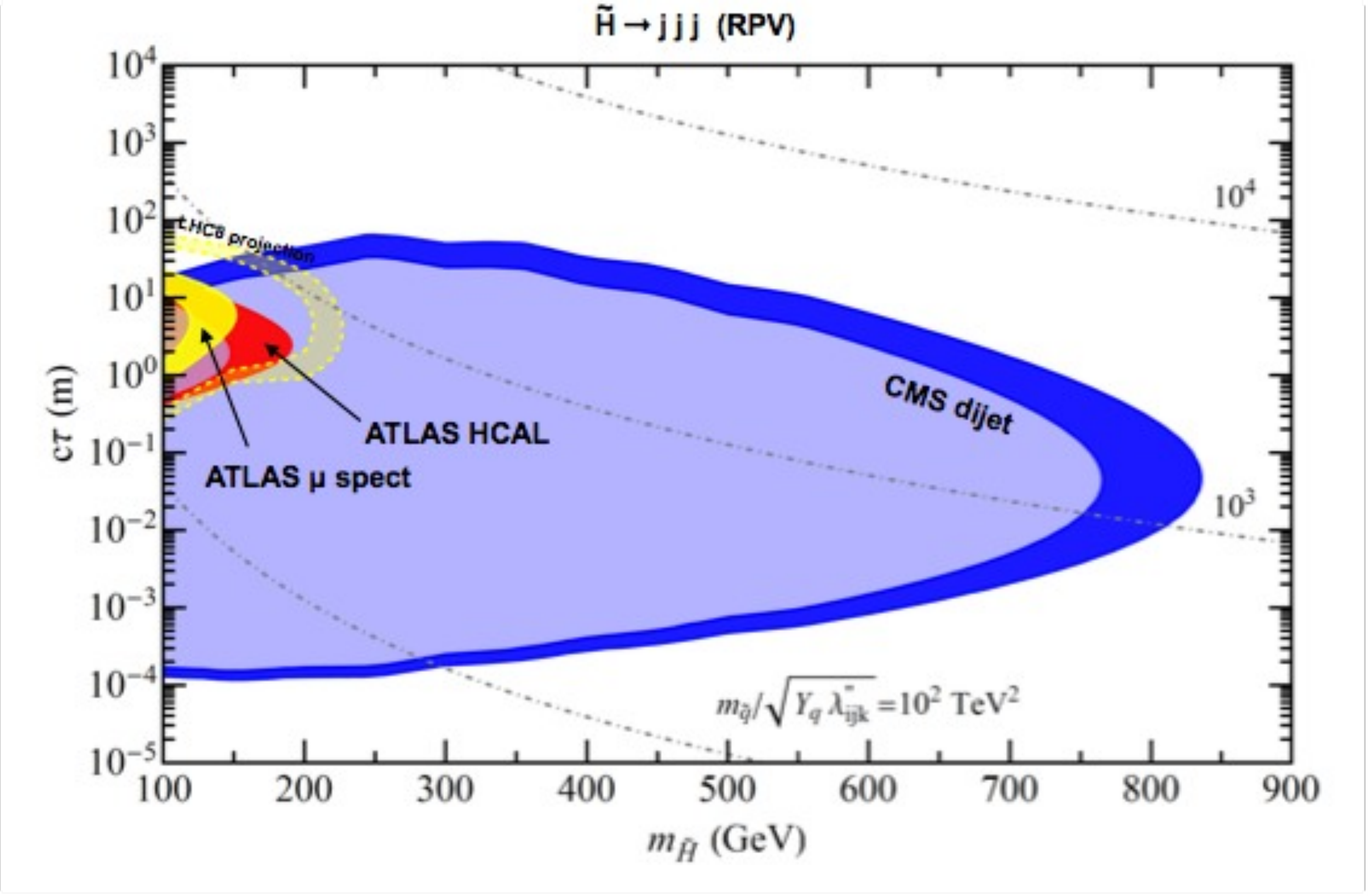

[Liu, Tweedie]

CONCLUSIONS

- Prime motivations for new physics to appear at the LHC:
  - electroweak naturalness
  - thermal dark matter
  - "who ordered that?"
- Many different avenues to discovery:
  - Higgs properties, *B*-meson studies, direct searches for BSM states
- Active interplay with wide range of other experiments
- We are learning a lot about our universe!