DARK MEDIATORS

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Probing Dark Matter with a Next Generation pp Collider
Fermilab
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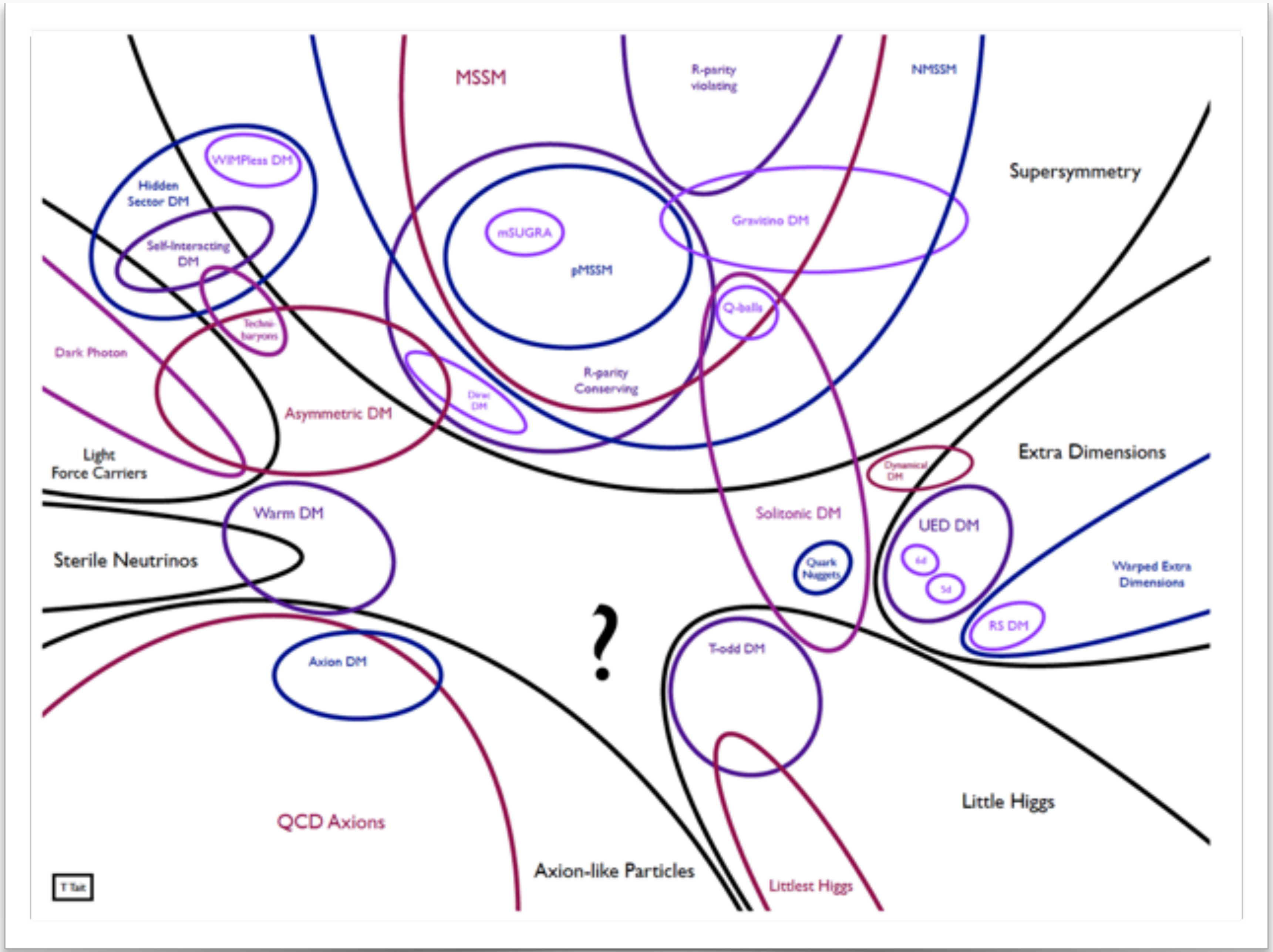
The dark universe

- The space of dark matter theories is enormous



[Tait]

The dark universe

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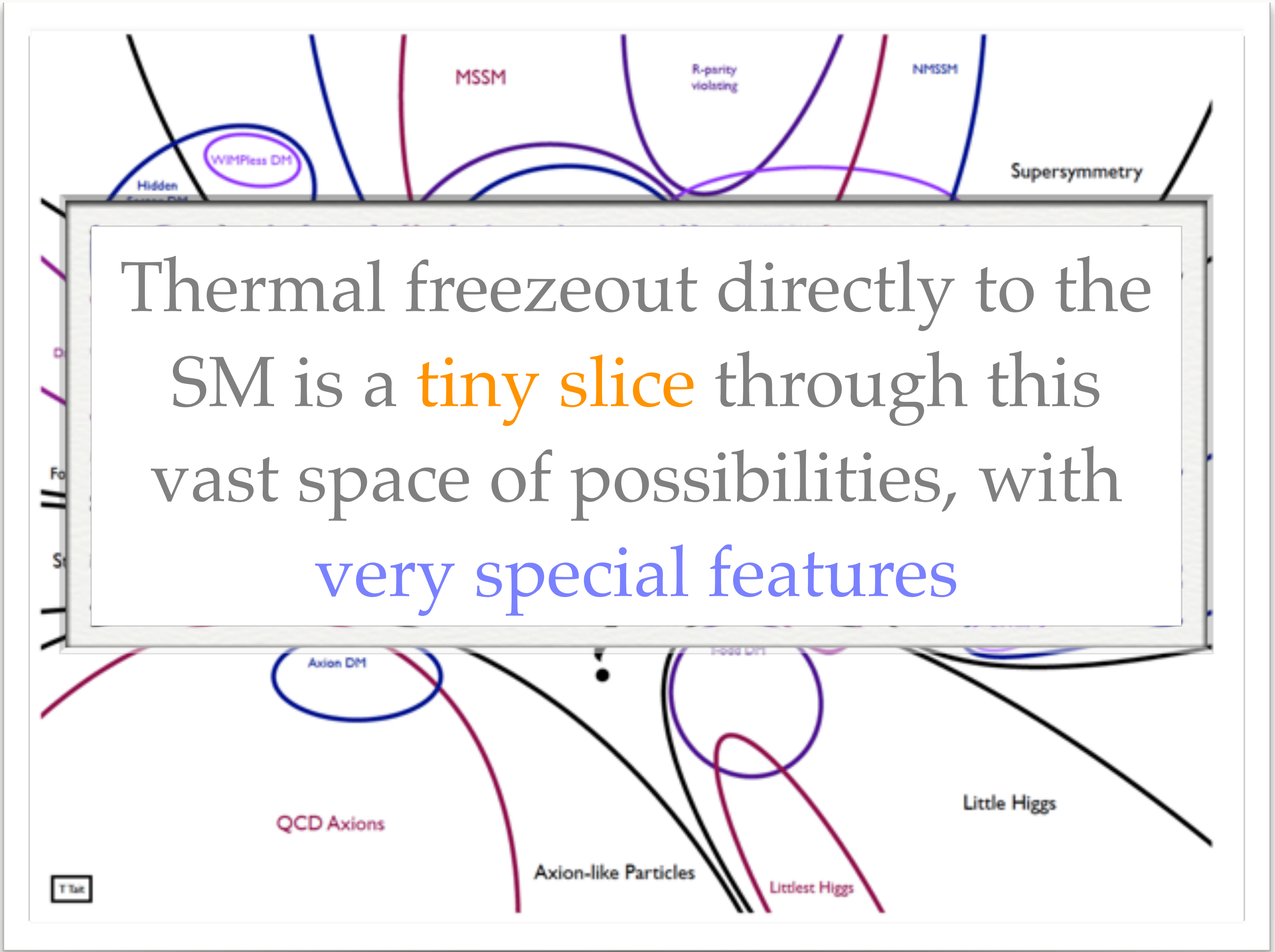
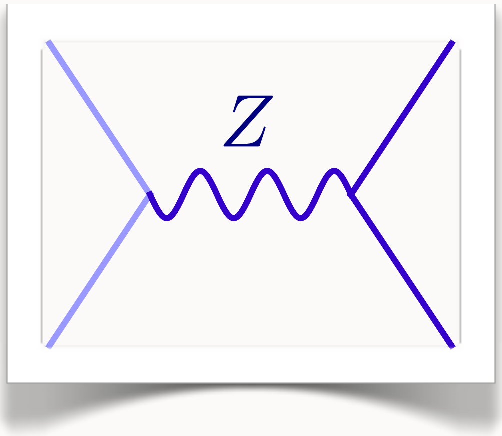


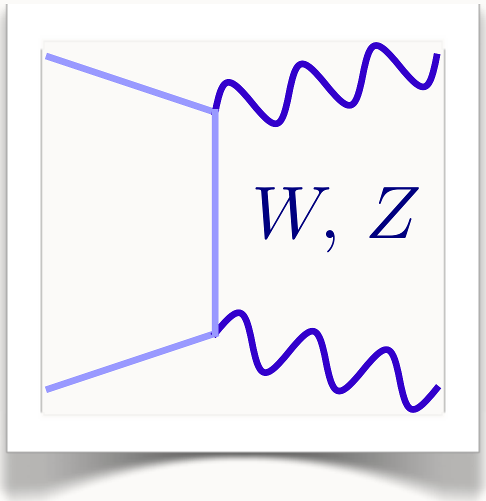
Thermal freezeout directly to the SM is a tiny slice through this vast space of possibilities, with very special features

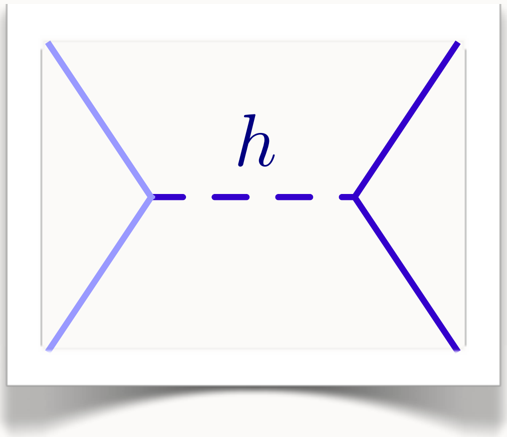
[Tait]

Thermal freezeout

- Three possibilities:
  - DM annihilates to SM via SM mediators
    - sharply predictive

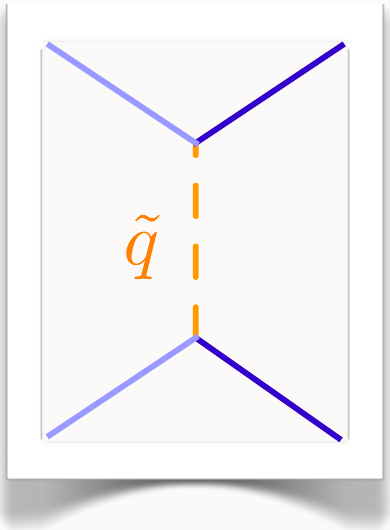


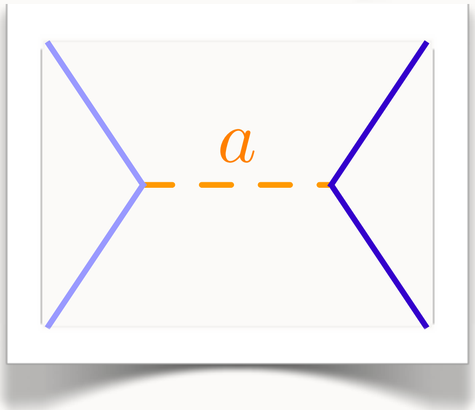


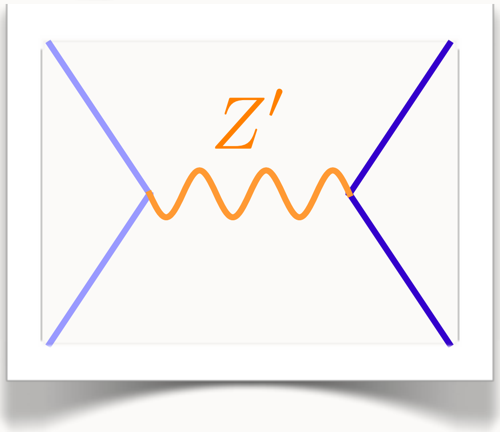


Thermal freezeout

- Three possibilities:
  - DM annihilates to SM via SM mediators
    - sharply predictive
  - DM annihilates to SM via BSM mediators
    - lower bound on couplings from freezeout

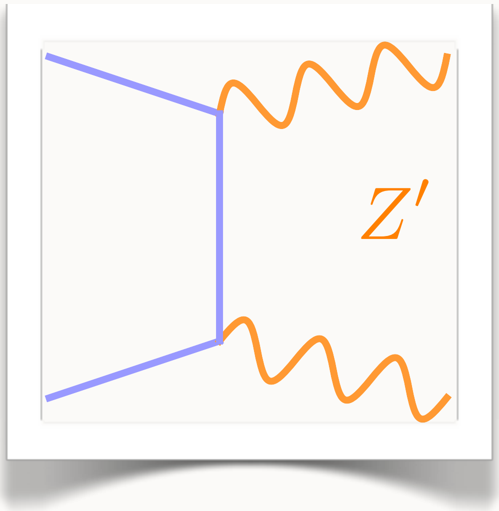


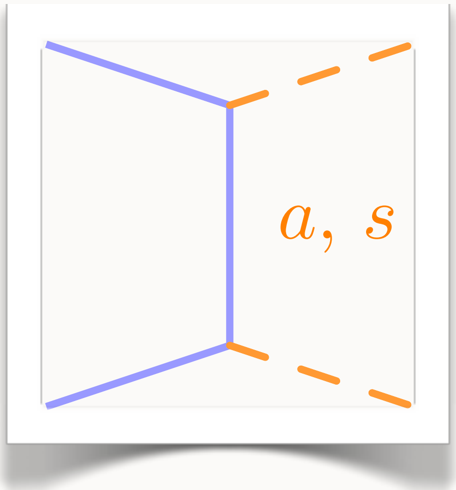




Thermal freezeout

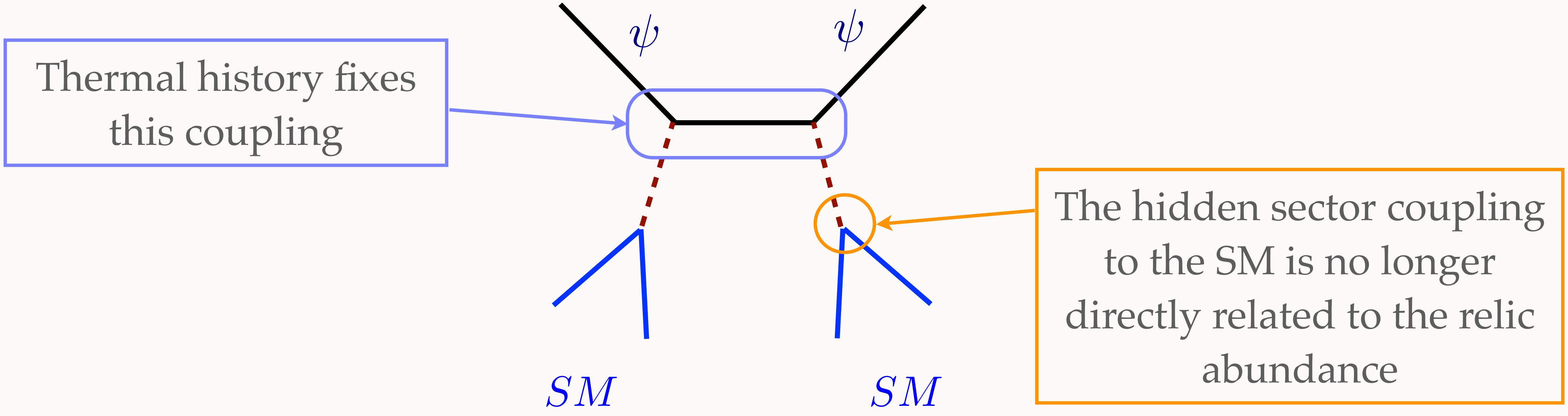
- Three possibilities:
  - DM annihilates to SM via SM mediators
    - sharply predictive
  - DM annihilates to SM via BSM mediators
    - lower bound on couplings from freezeout
  - DM annihilates to BSM mediators directly





Dark freezeout

- Dark matter freezeout proceeds more or less independently of SM until mediator ultimately decays



Thermal history fixes this coupling

The hidden sector coupling to the SM is no longer directly related to the relic abundance

- Dark sector couplings to SM can be parametrically small

[Pospelov, Ritz, Voloshin; ...]

Dark freezeout

- Simple class of minimal models
- Perturbative thermal relics: expect signals in ~SM mass range

- upper bound on m: perturbativity

  $\Rightarrow\ m \lesssim 40\,\mathrm{TeV}$

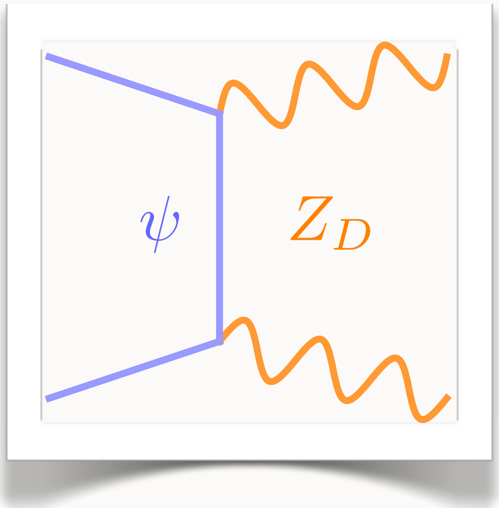
- lower bound on m: generalized Tremaine-Gunn bound,

  $\Rightarrow\ m \gtrsim \mathrm{keV}$

[Pospelov, Ritz, Voloshin; Das, Sigurdson; ...]

A simplified model (I)

- A simple model of dark freezeout:
- two state hidden sector: ψ , Z_D
- (HS Higgs mechanism)
- thermal freezeout sets α_D : s-wave
- small coupling to SM allows Z_D to decay promptly on cosmological times



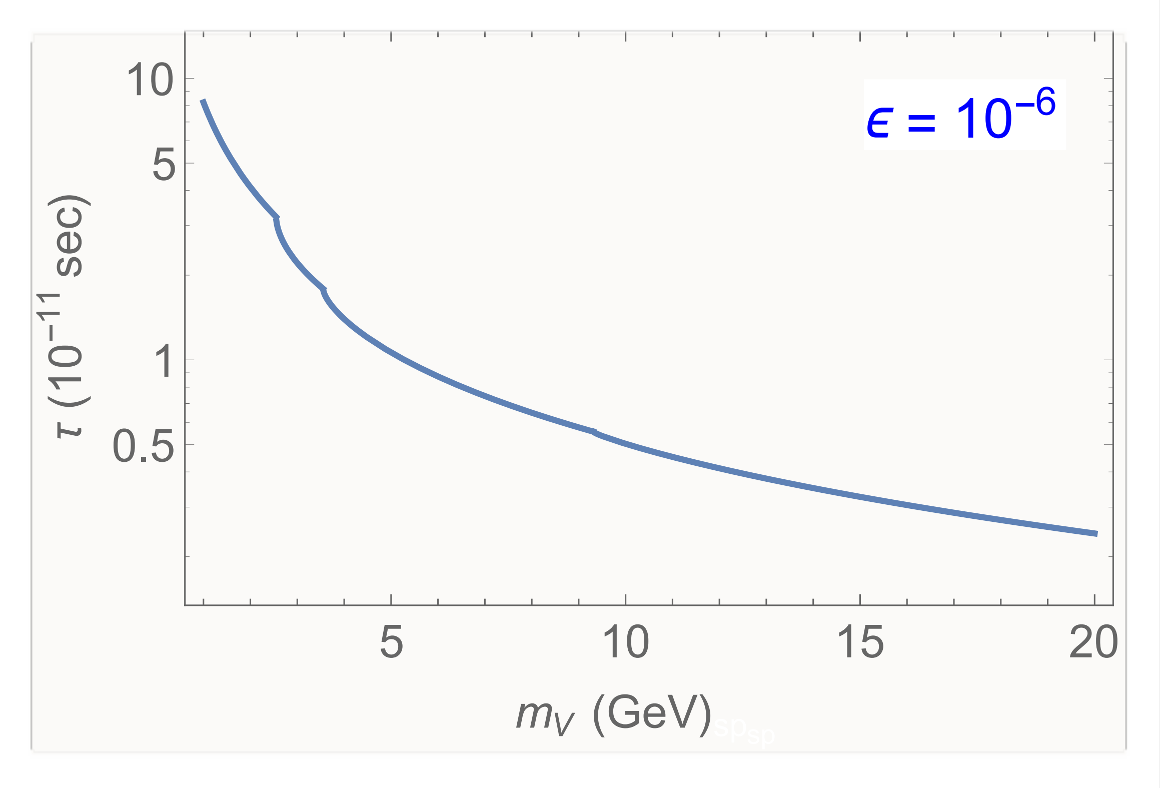
A simplified model (I)

- Very small couplings to SM can allow the mediator to decay cosmologically promptly

$$\mathcal{L}_{int} = \frac{\epsilon}{2\cos\theta_W} V_{\mu\nu} B^{\mu\nu}$$

  - BBN: $\tau \lesssim 1$ sec
  - so for $m \gtrsim$ GeV,

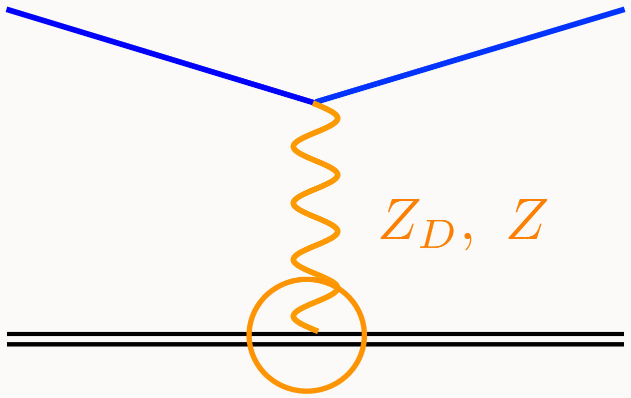
$$\epsilon \gtrsim 10^{-12}$$

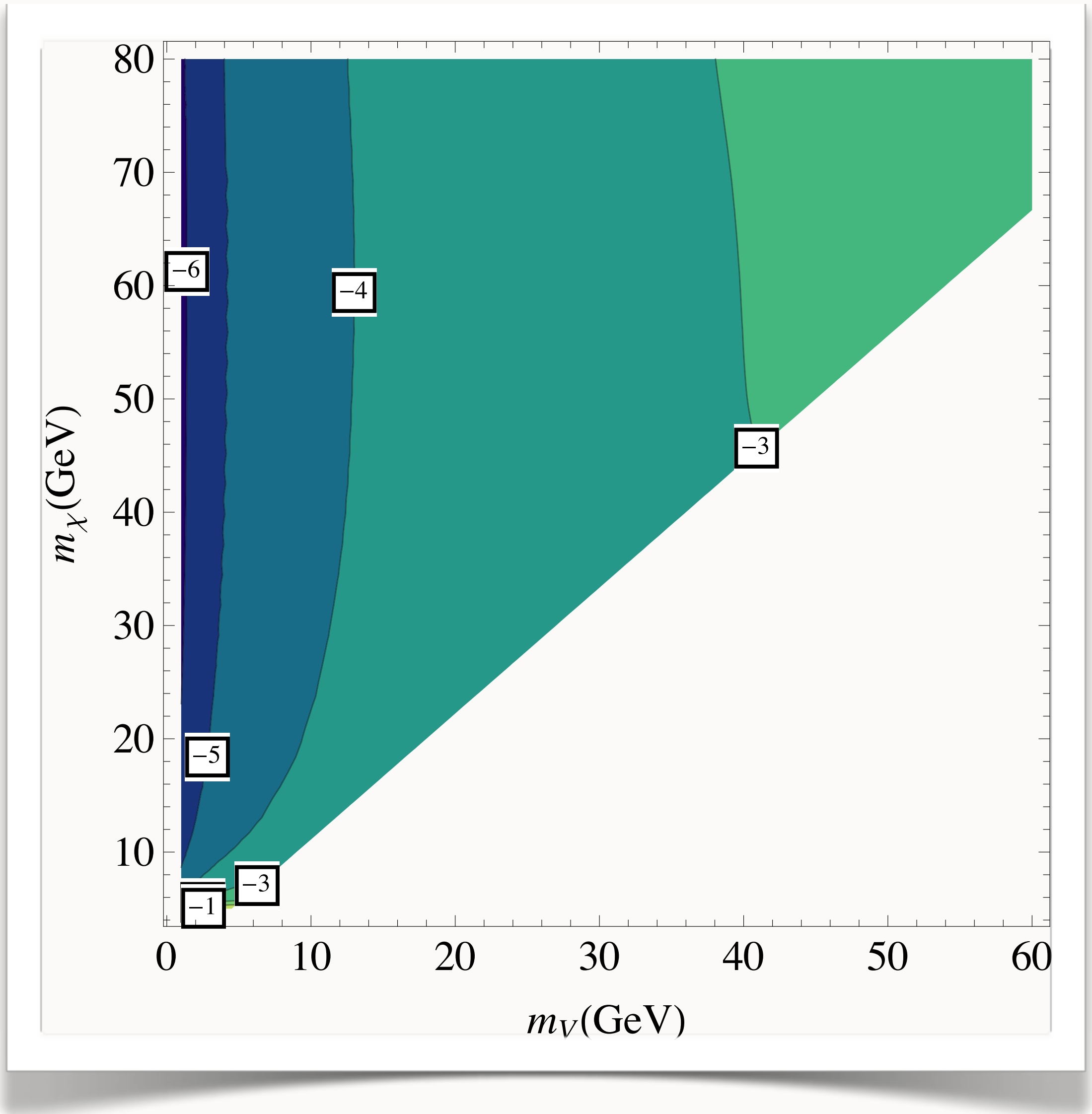


- Generically: lower end of allowed range still well out of reach for terrestrial experiments

A simplified model (I)

- Direct detection
  - given α_D , LUX constrains kinetic mixing



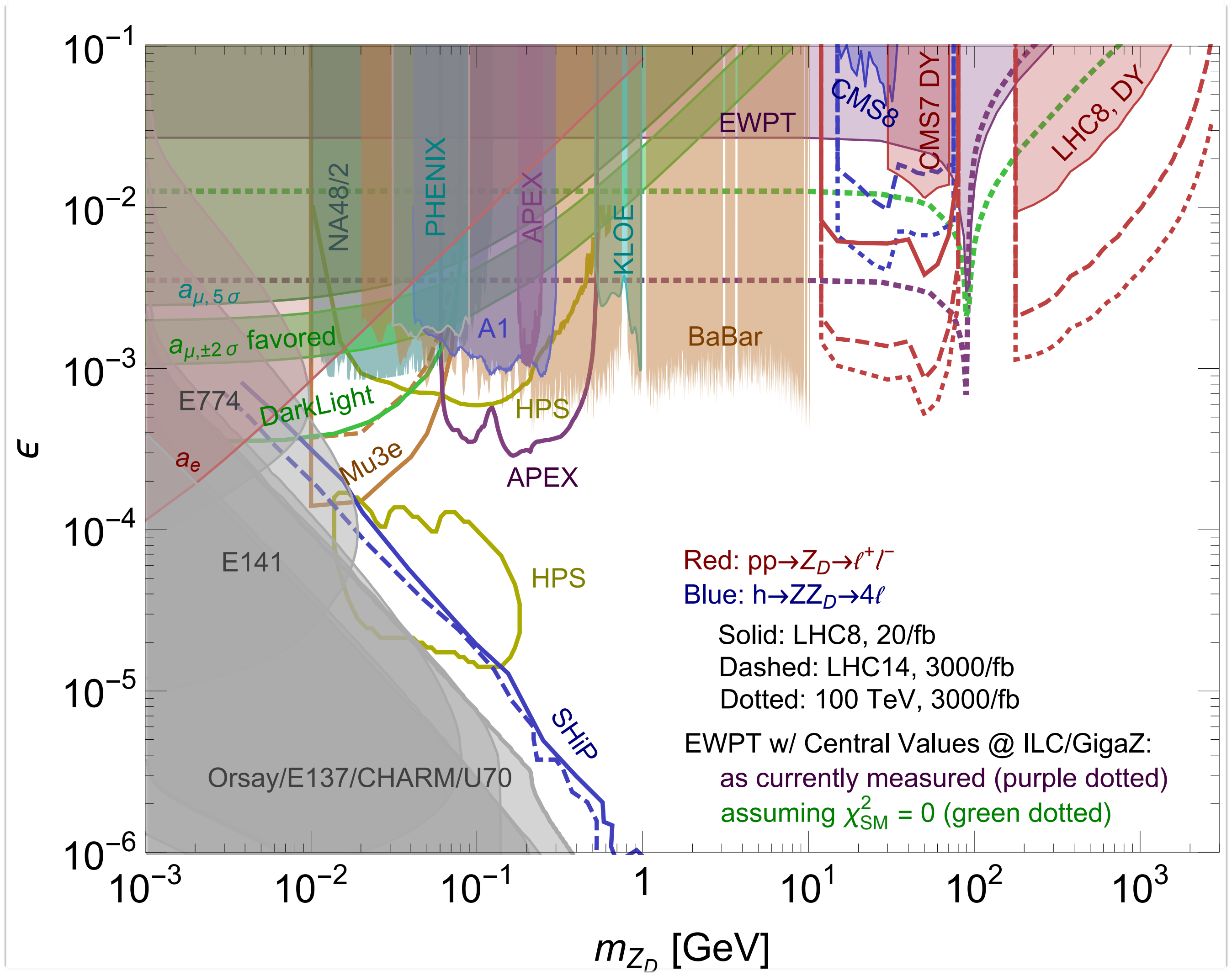


$\log_{10} \epsilon$

[Martin, JS, Unwin; see also Cline, Dupuis, Liu, Xue; ...]

A simplified model (I)

- Leading collider signal: direct mediator production
  - minimal model: mediator is lightest dark state --> only SM decays

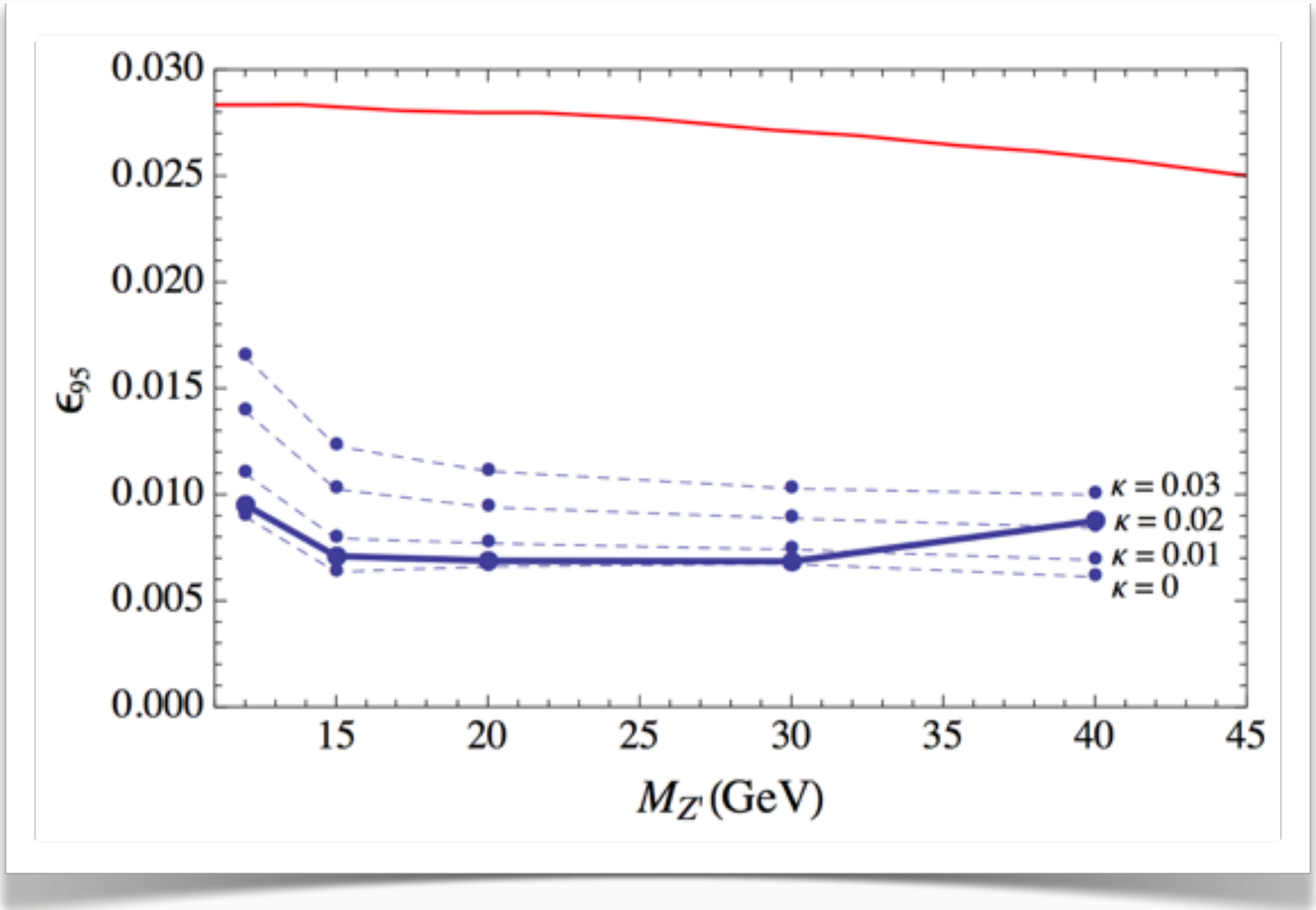


[Curtin, Essig, Gori, JS; ...]

Dark photons at high-energy colliders

- Direct on-shell production at hadron machines:

$$q\bar{q} \to Z_D \to \ell\ell$$



[Hoenig, Samach, Tucker-Smith; Cline, Dupuis, Liu, Xue]

Dark photons at high-energy colliders

- Estimate reach at HL-LHC, 100 TeV by rescaling these analyses
  - assuming Gaussian statistics dominate limit:

$$\epsilon_2^{95\%CL} = \epsilon_1^{95\%CL} \left(\frac{B_2}{B_1}\right)^{1/4} \left(\frac{S_1}{S_2}\right)^{1/2}$$

  - additional assumption: 100 TeV lepton ID, acceptance will not differ significantly from LHC, even at low end of p_T spectrum

Dark photons at high-energy colliders

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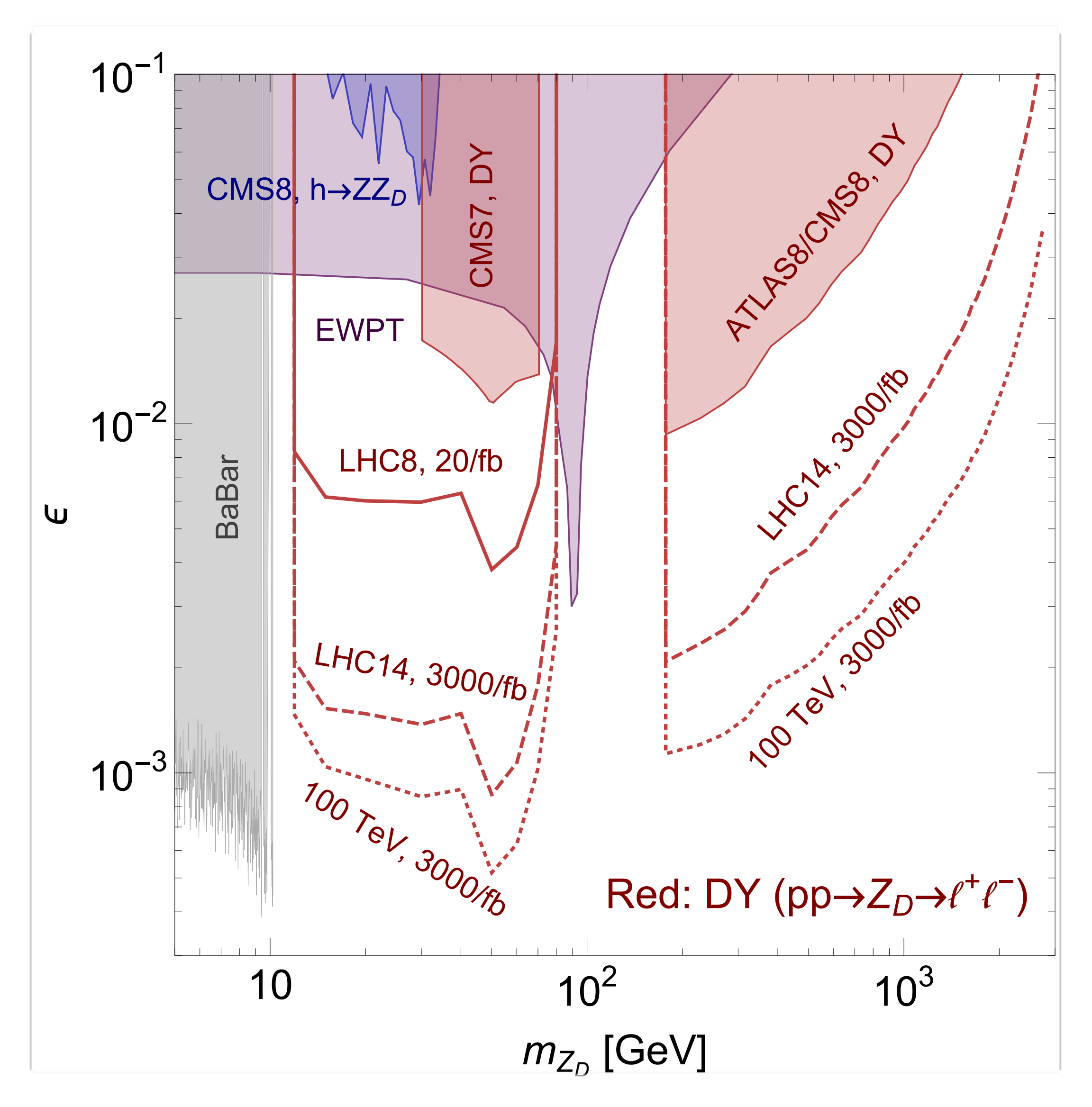
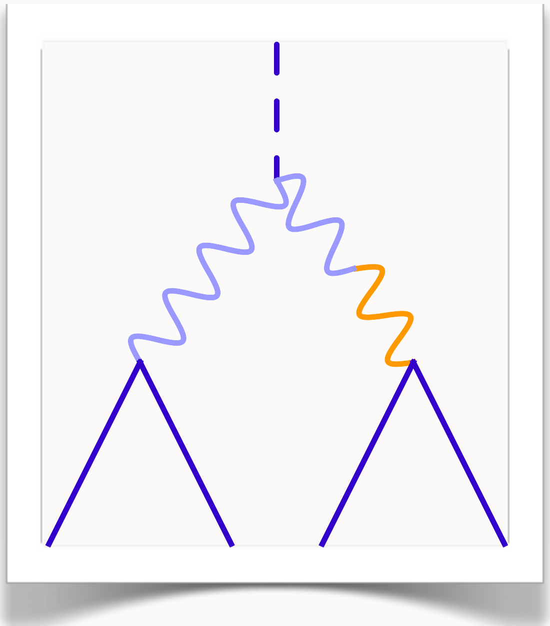
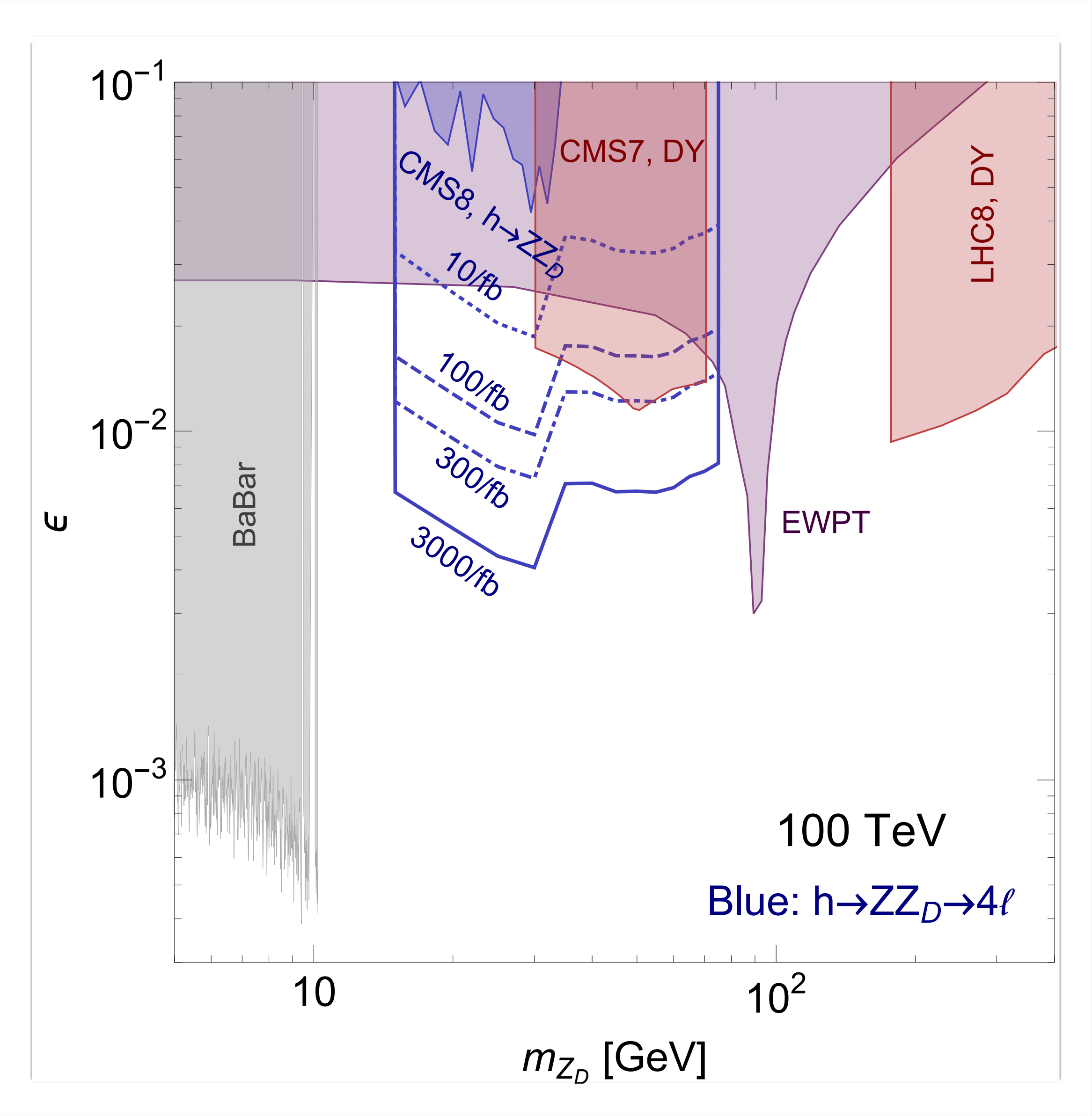


[Curtin, Essig, Gori, JS; Hoenig, Samach, Tucker-Smith; Cline, Dupuis, Liu, Xue]

Dark photons at high-energy colliders

- A diagnostic test of Z_D couplings from Higgs decays





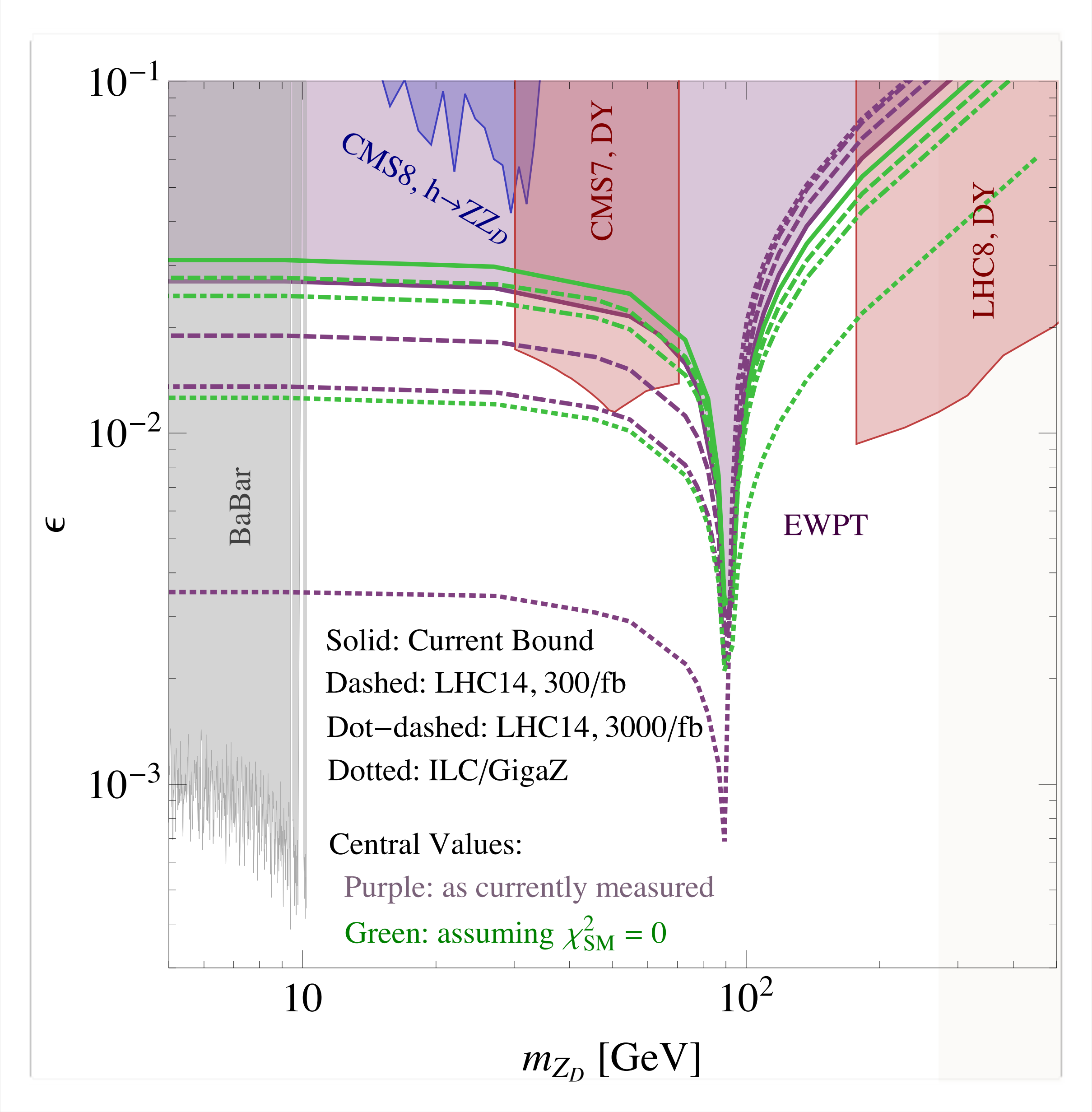
[Exotic Higgs working group 1312.4992; ATLAS 1505.07645; Curtin, Essig, Gori, JS]

Dark photons at high-energy colliders

- Model-independent constraints on kinetic mixing from precision electroweak measurements
  - full fit following Gfitter procedures, including (e.g.) m_W
  - Z_D introduces tree level shifts to Z mass, Z couplings at $\mathcal{O}(\epsilon^2)$
  - constrain Z_D model by requiring $\chi^2_{Z_D} - \chi^2_{SM} < 3.8$
  - most important pulls: m_W, A_l

Dark photons at high-energy colliders

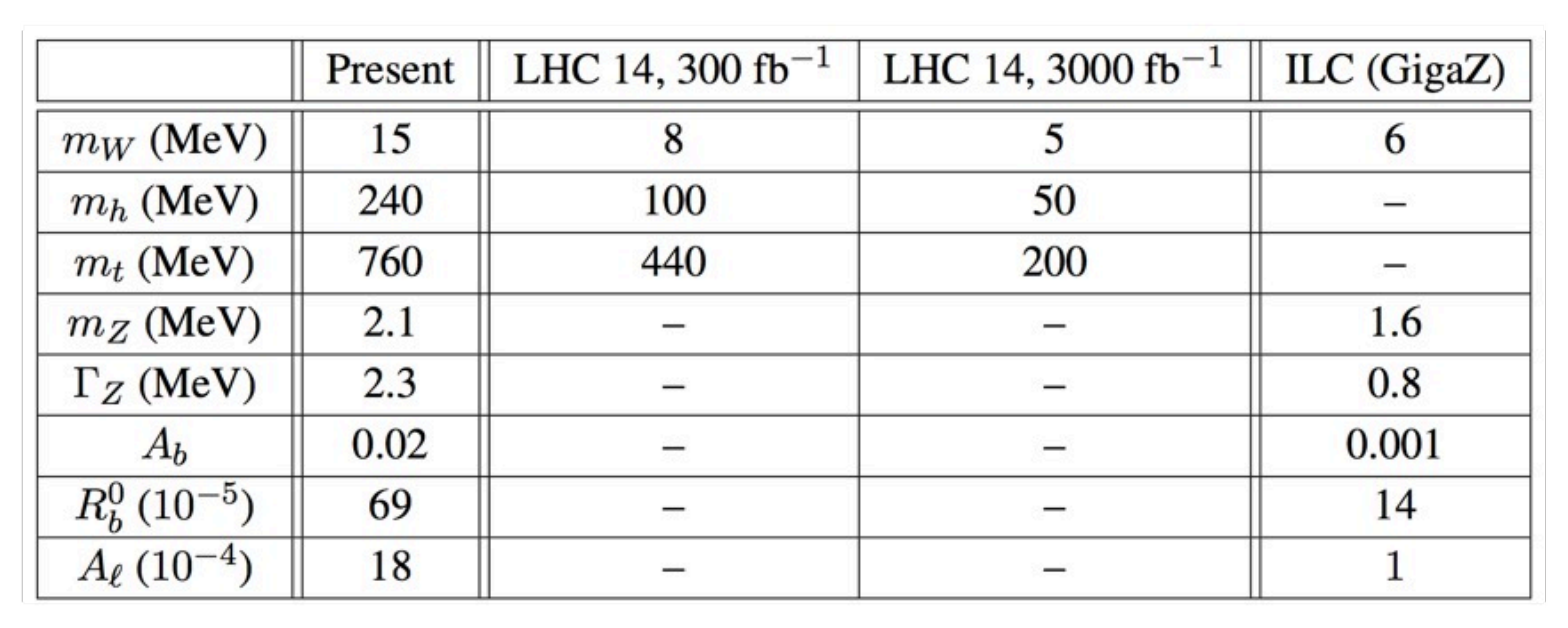
- Current and forecast EWPM constraints:



[Curtin, Essig, Gori, JS]

Dark photons at high-energy colliders

- The fine print:



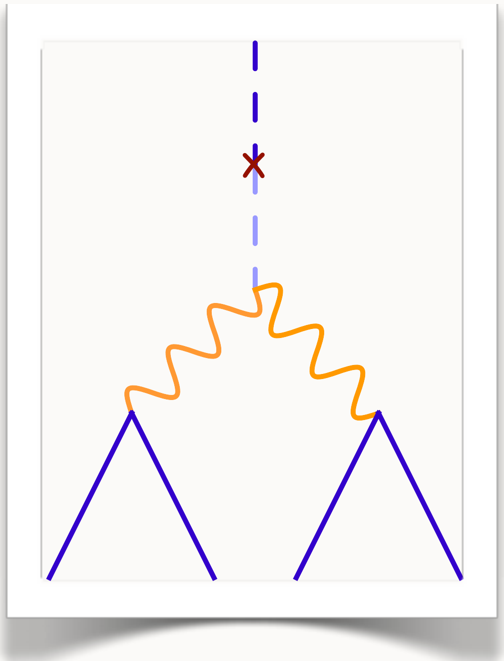
	Present	LHC 14, 300 fb^{-1}	LHC 14, 3000 fb^{-1}	ILC (GigaZ)
m_W (MeV)	15	8	5	6
m_h (MeV)	240	100	50	–
m_t (MeV)	760	440	200	–
m_Z (MeV)	2.1	–	–	1.6
Γ_Z (MeV)	2.3	–	–	0.8
A_b	0.02	–	–	0.001
R_b^0 (10^{-5})	69	–	–	14
A_ℓ (10^{-4})	18	–	–	1

Also factor of ~2 improvement in $\Delta\alpha^{(5)}_{\rm had}$

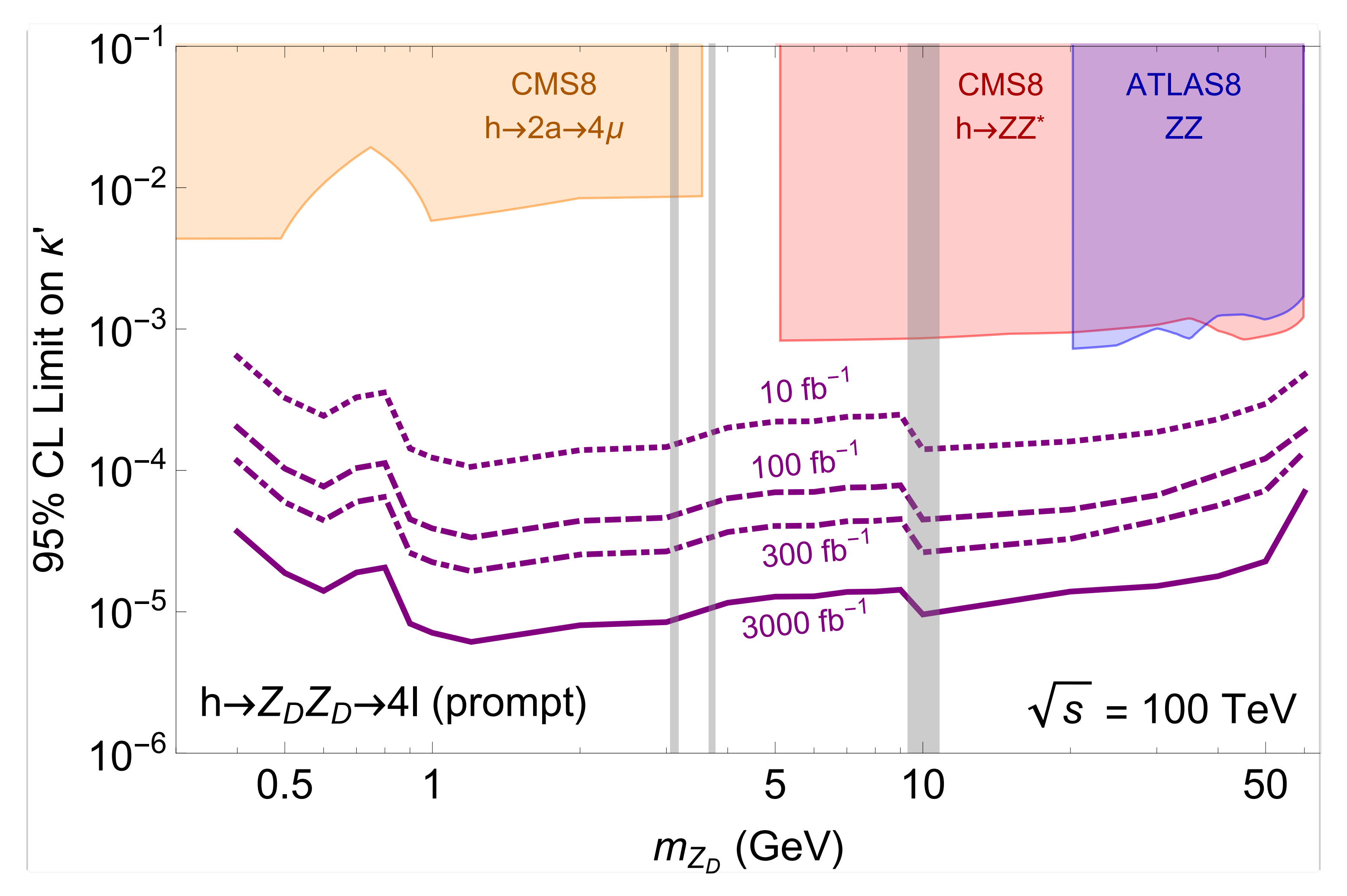
[Curtin, Essig, Gori, JS]

Dark photons at high-energy colliders

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



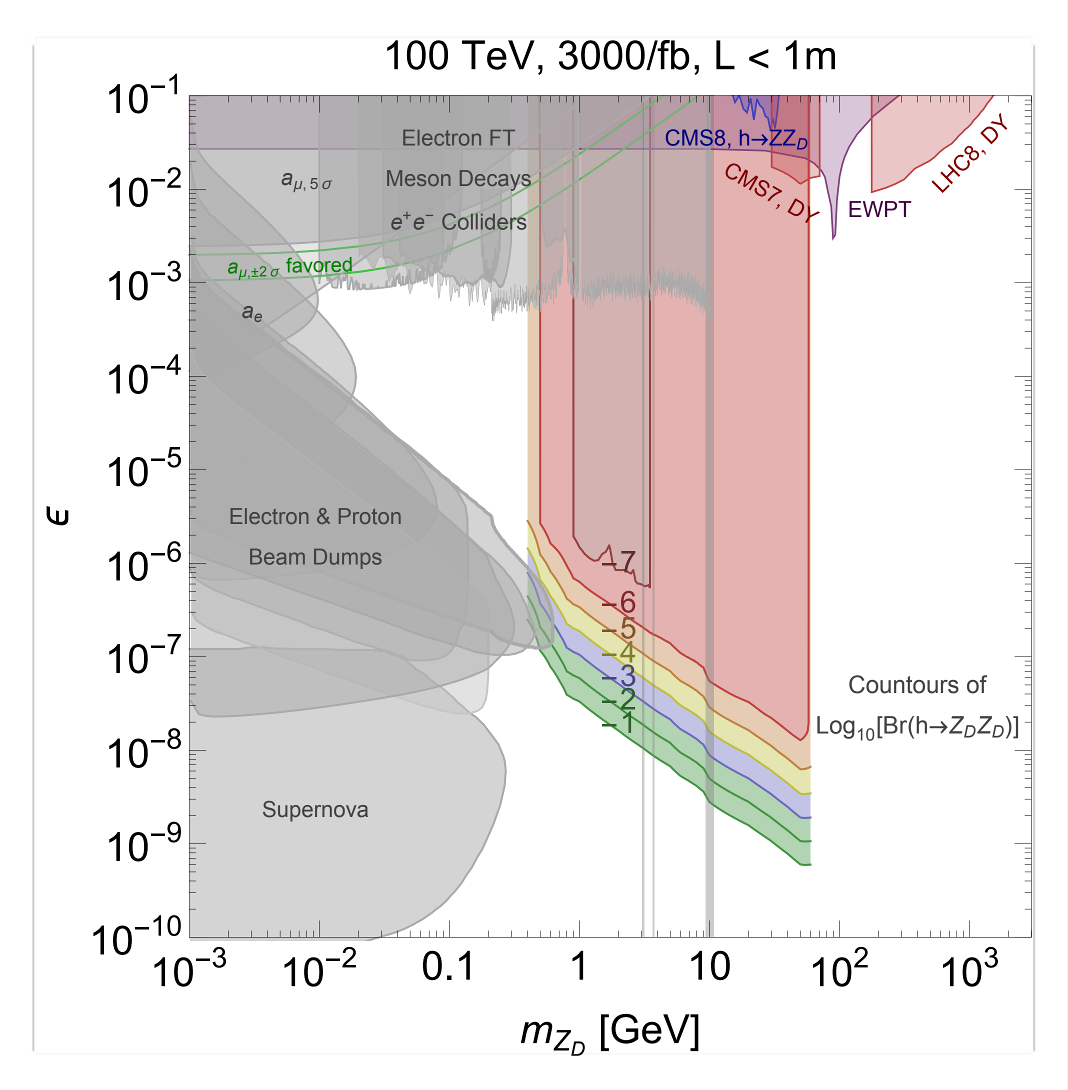
$$\kappa' = \kappa \frac{m_h^2}{|m_h^2 - m_s^2|}$$

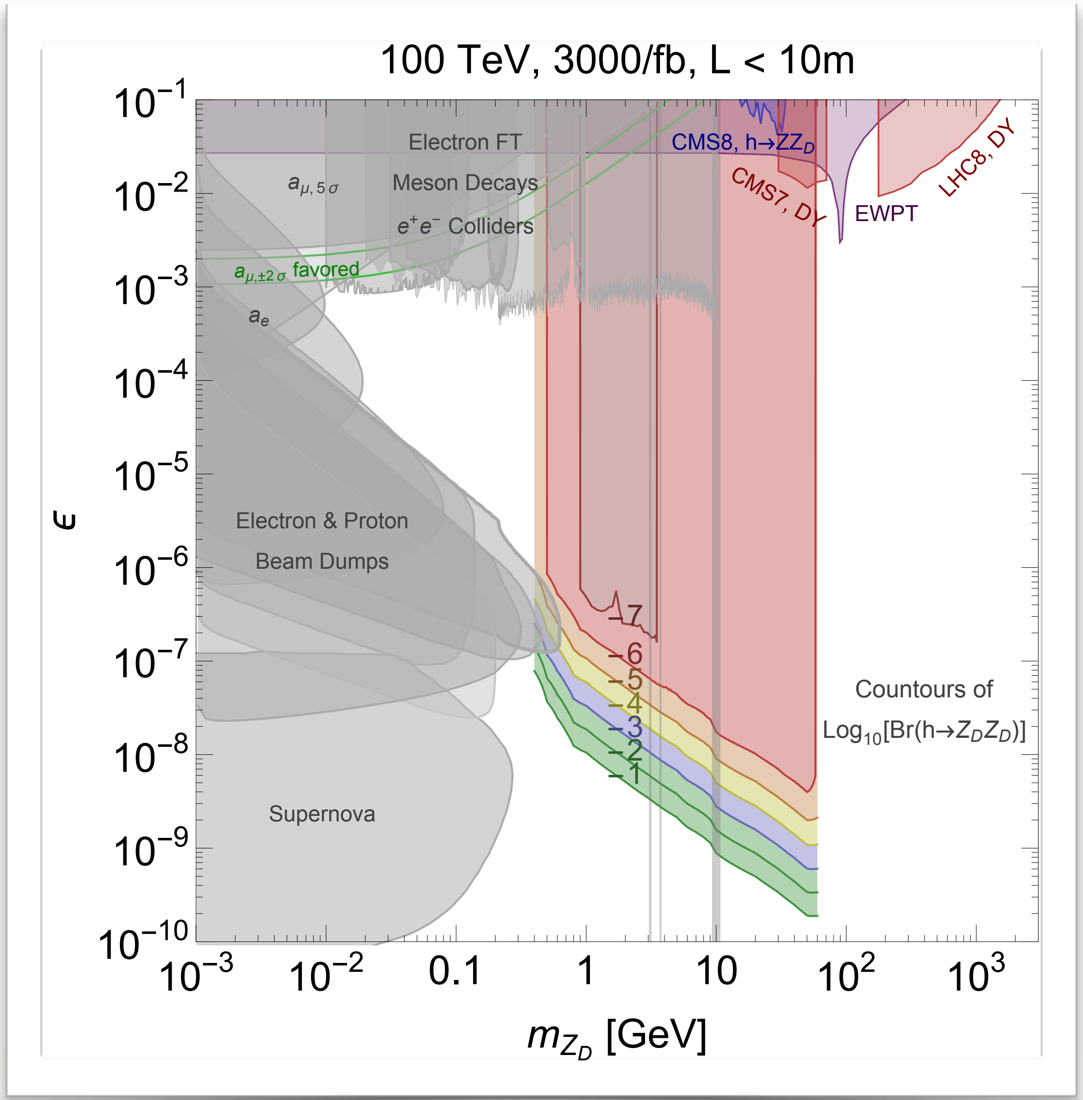


[Curtin, Essig, Gori, JS]

Dark photons at high-energy colliders

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

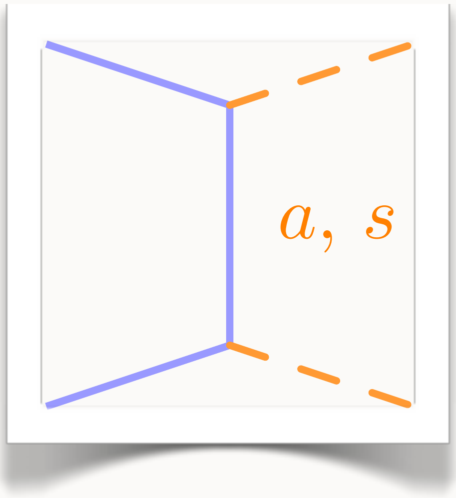




[Curtin, Essig, Gori, JS]

A simplified model (II)

- Collider, direct detection, and indirect detection interplay is quite different for spin-0 mediators



  - scalars: couple to SM via Higgs portal
  - pseudo-scalars: A^0 mixing in 2HDM, fermiophobic couplings $\frac{1}{\Lambda}F\tilde{F}$
  - Again consider a simple model with one fermionic DM species freezing out to one mediator species

A simplified model (II)

- Biggest nightmare: indirect detection signals are now also suppressed
  - annihilation cross-section is p-wave: simple consequence of CP
  - $\Longrightarrow$ need to consider novel indirect detection strategies: for instance, exploit DM focusing, acceleration provided by supermassive black holes
    - necessary price: further astrophysical uncertainties

[JS, Shapiro, Fields]

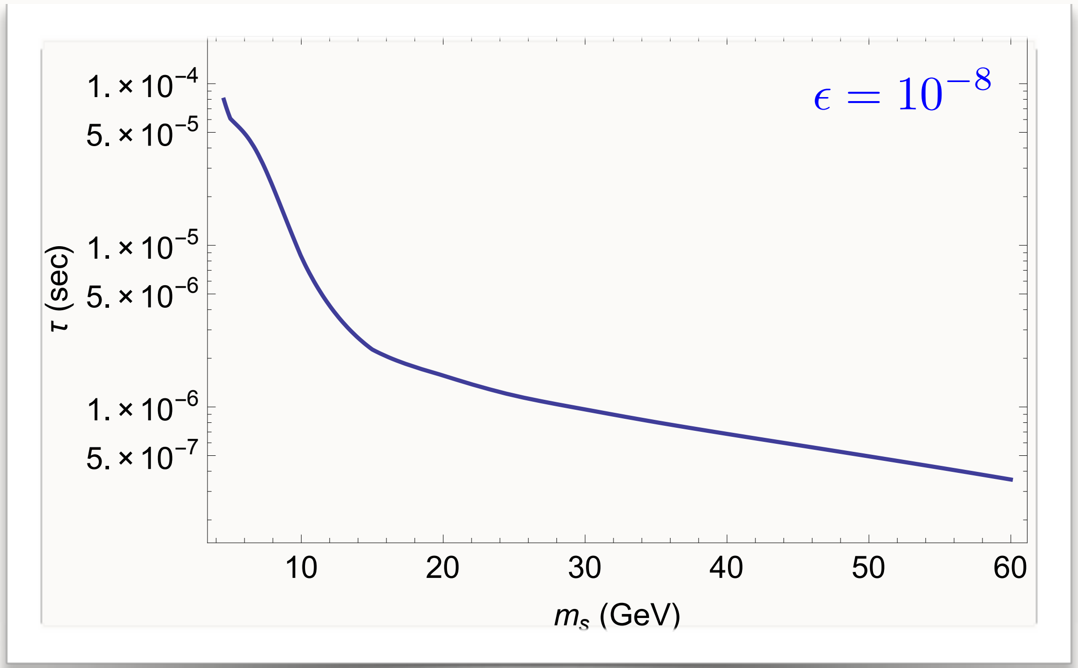
A simplified model (II)

- A stripped-down model for scalar mediators:

$$\mathcal{L}_{int} = -yS\bar{\chi}\chi + \frac{\mu_s^2}{2}S^2 - \frac{\lambda_s}{4!}S^4 + \frac{\epsilon}{2}S^2|H|^2$$

- S gets a vev: Higgs portal mixing

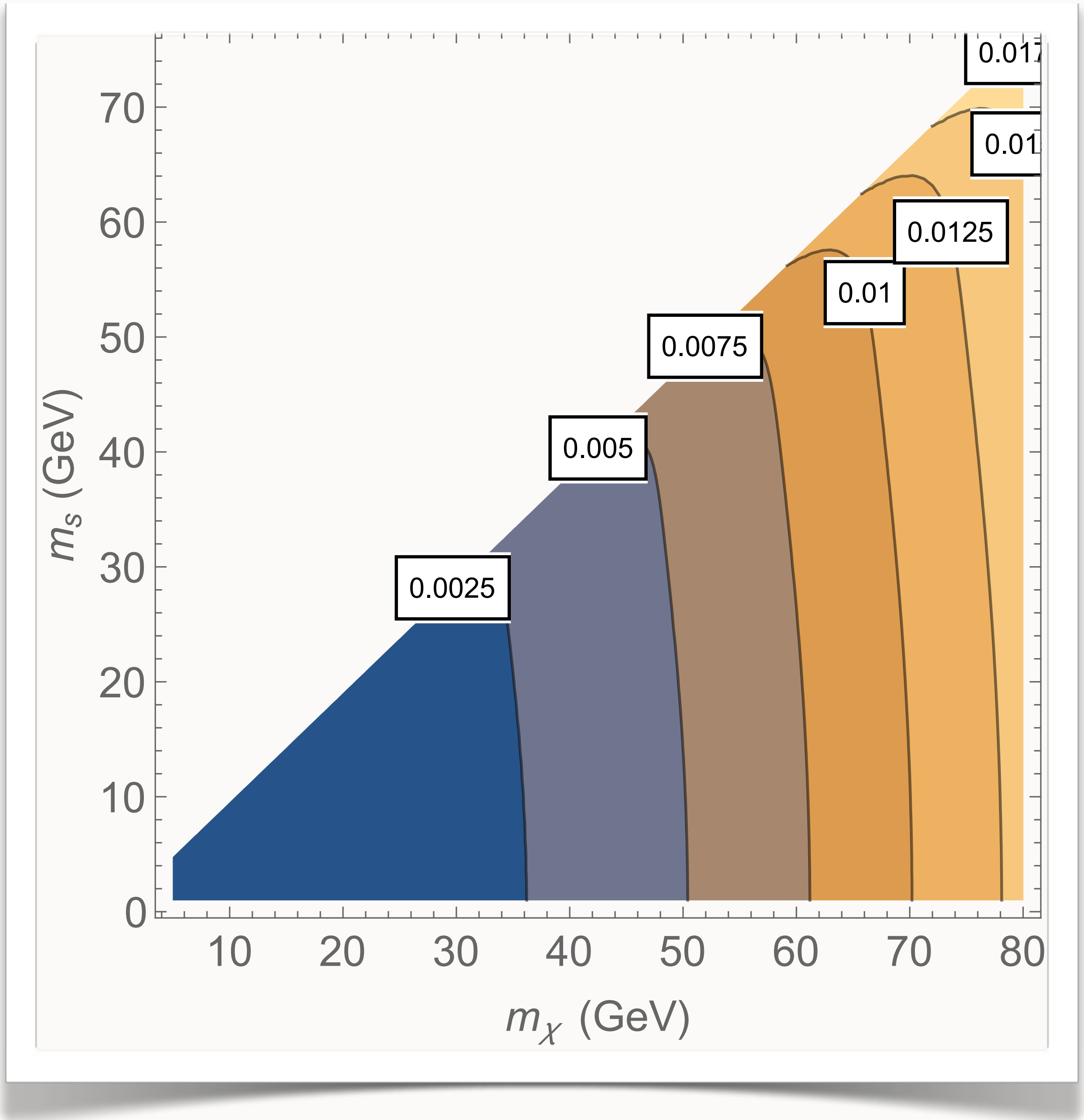
- Cosmologically prompt decay (provided s not too light):



$$\theta_h = \frac{\epsilon\langle S\rangle v_h}{m_h^2 - m_s^2}$$

[JS, Shapiro, Fields]

A simplified model (II)

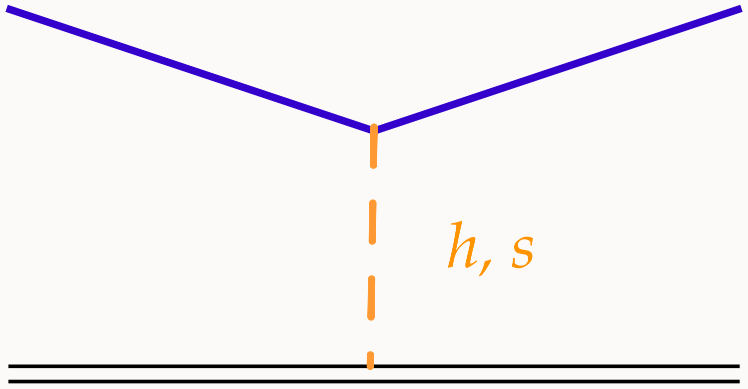


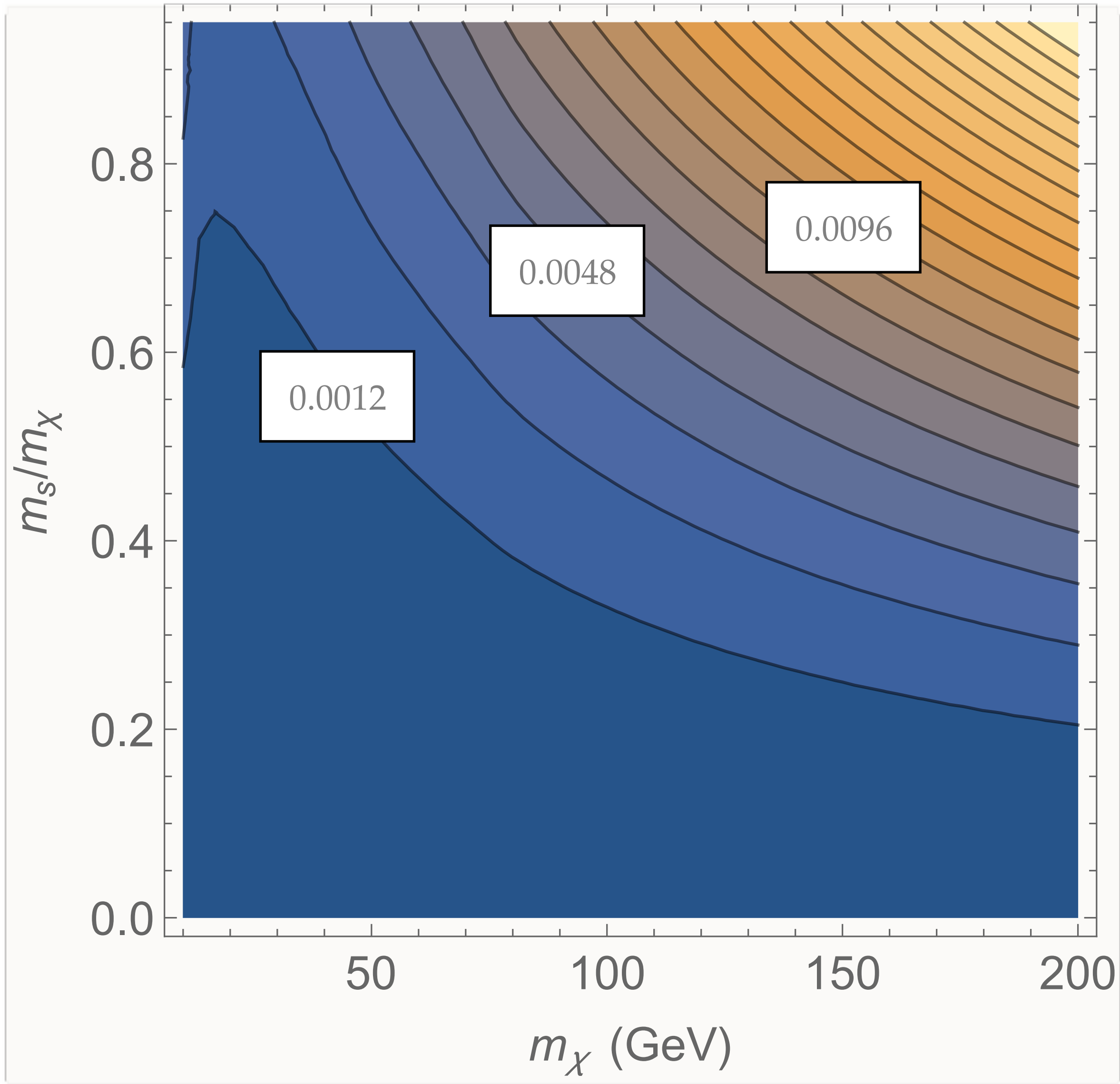
Approximate value of y^4 needed to obtain $\Omega_{DM} h^2 = 0.112$.

[Evans, Gori, JS (to appear)]

A simplified model (II)

- Constraints on Higgs portal coupling from LUX:





for pseudo-scalars, direct detection much more suppressed!

[Evans, Gori, JS (to appear)]

A simplified model (II)

- Again, leading collider signals are direct mediator production
  - scalar, A^0-mixed pseudo-scalar will typically have similar signatures
  - best prospects: Higgs decays are kinematically allowed (or rare meson decays)

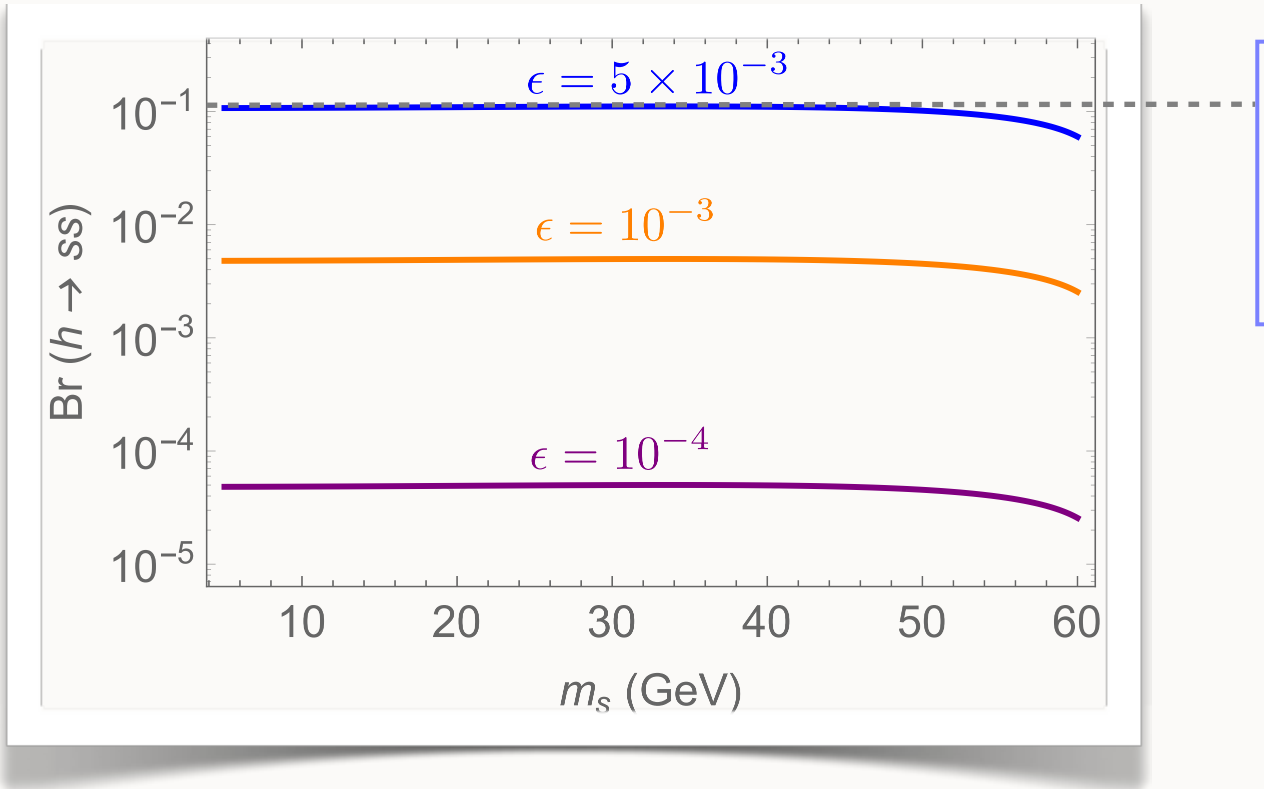
$$\boxed{\mathcal{L}_{hs^2} = \epsilon v \, \frac{m_h^2 + 2m_s^2}{m_h^2 - m_s^2}}$$

$$\mathcal{L}_{h\chi\chi} = \theta y h \bar{\chi}\chi$$

[see e.g. Kozaczuk and Martin for heavier *a*; SHiP physics case for a mesons; Clarke, Foot, Volkas]

A simplified model (II)

- Leading exotic decay mode is $h \to ss \to 4b$: all hadronic signal is a notorious challenge for *pp* machines



approximate ultimate direct *and* indirect sensitivity from LHC

- Have not done careful study of future prospects! Will make a few general remarks

[Kaplan, McEvoy; Cao, Ding, Han, Yang, Zhu]

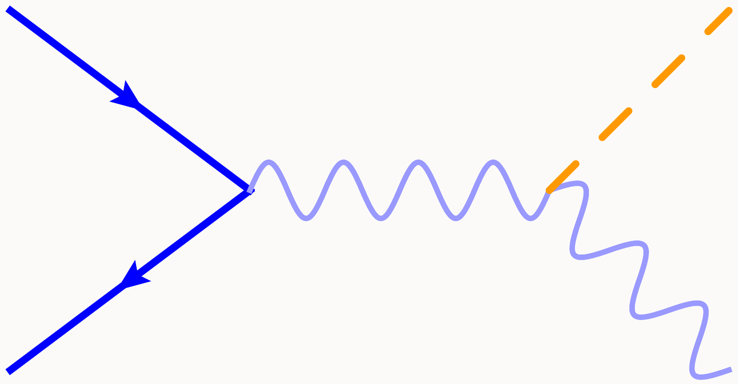
Higgs decays, indirectly

- LHC: fits to exclusive measurements of (production) x (decay)
  - Currently: ATLAS, CMS Run I: $\delta\Gamma_h \lesssim 20\%$
  - anticipated ultimate precision: $\delta\Gamma_h \lesssim 5 - 10\%$
  - important theoretical uncertainties: $m_b,\ m_c,\ \sigma(gg \to h)$
    - improvement from FCC-*pp* dependent on theory progress

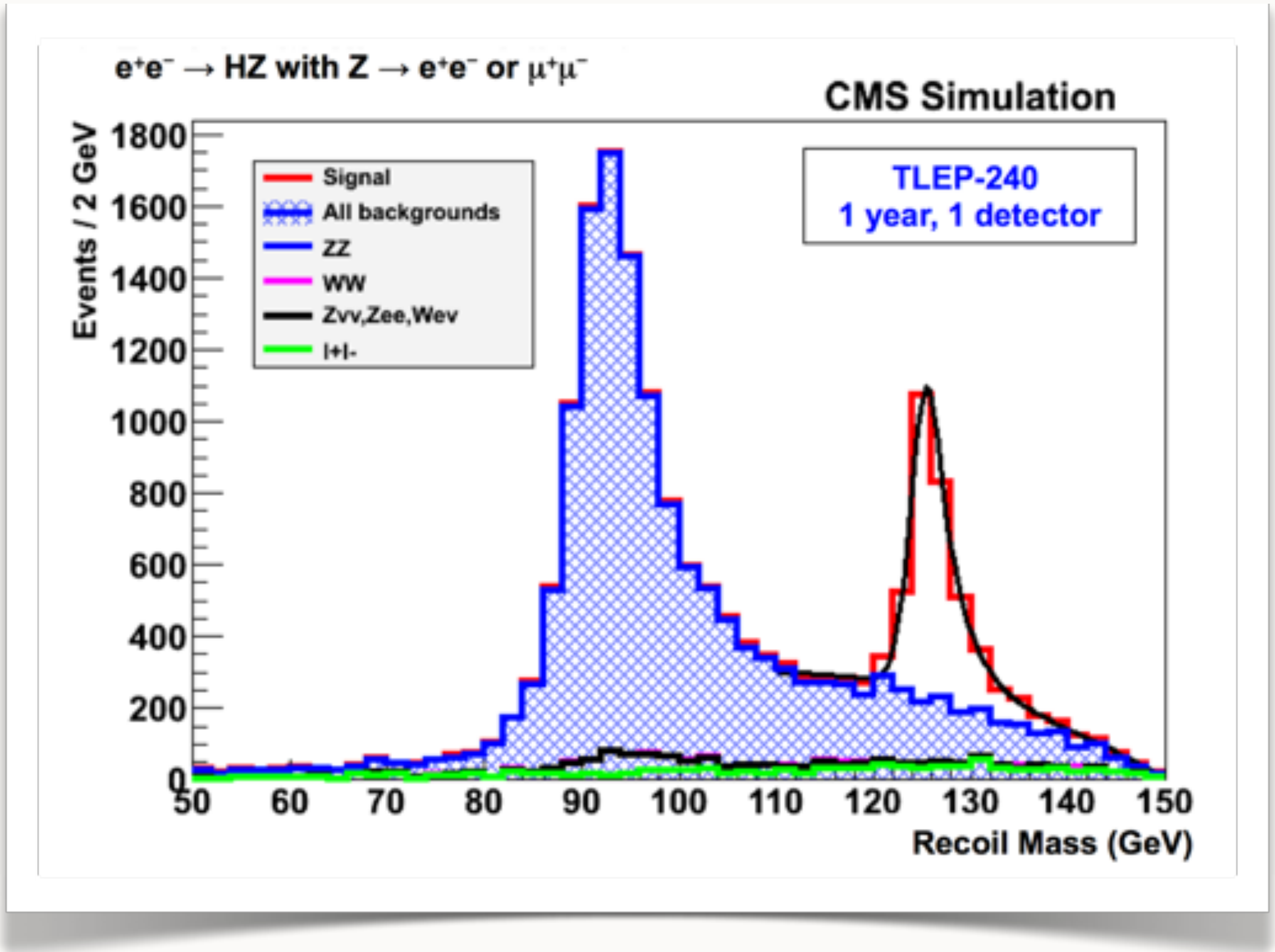
[Peskin; Almeida, Lee, Pokorski, Wells; ...]

Higgs decays, indirectly

- Famously, e^+-e^- collider: inclusive ZH measurement
  - model-independent measurement of $\delta\Gamma_h$



$$\boxed{\delta\Gamma_h \approx 3.1\%}$$



[TLEP physics case, 1308.6176]

Higgs decays, directly

- Planned Higgs factories offer great prospects for directly seeing specific Higgs decay modes
  - total Higgses at 100 TeV *pp* machine with 3 ab^{-1}: $\sim 10^9$
  - total Higgses at FCC-*ee* with 240 GeV CM energy, 10 ab^{-1}: $\sim 10^6$
  - Which facility offers better prospects for any given decay mode will depend on backgrounds, detector capabilities

Conclusions

- Dark freezeout is a simple and minimal framework for dark matter origin
  - expect signals broadly coincident with SM energy range
  - but at parametrically suppressed rates in terrestrial experiments
- Leading collider signals: direct mediator production
  - relative merits of colliders vs direct detection (and even indirect detection) depend on properties of mediator
  - interesting signals can be displaced, low mass, low-pT
  - high-energy colliders as intensity frontier experiments