# Cogeneration of Baryons and Twin Quark Dark Matter

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SUSY
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With Can Kilic and Taewook Youn
arXiv:2109:03248

# Puzzles Within the SM and Beyond

Why is the mass of the Higgs so much lighter than our most basic estimates?

$$\frac{M^2_{\text{Higgs}}}{M^2_{\text{Planck}}} \sim 10^{-34}$$

What is dark matter?

85% of the matter in the universe

cannot be SM particles

Baryogenesis

Why is there more matter than anti-matter?

SM cannot generate the asymmetry

Cold Dark Matter - Cornelia Parker

# Dark Sectors

Each puzzle may have a distinct solution, but…

Structures that address several questions at once are intriguing

Experimental searches have yet to discover the new particles or interactions that resolve these mysteries

Perhaps they only interact weakly with the SM

$$\mathcal{L}_{\rm SM} + \mathcal{L}_{\rm Dark\ Sector} + \lambda \mathcal{O}_{\rm SM}\mathcal{O}_{\rm DS}$$

Suggests a "dark sector"

$$\lambda \ll 1$$

# Rich Dark Sectors

Early ideas were of a simple dark sector


Perhaps the dark sector is as varied and interesting as the SM

Huge space of alternatives, what are motivated possibilities

One interesting possibility is the Twin Higgs scenario

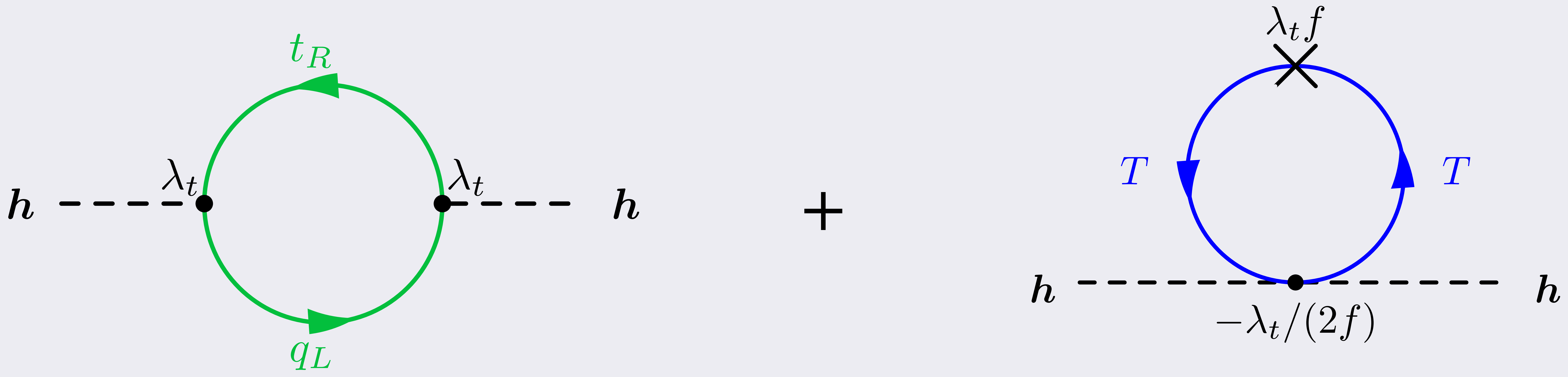
# Twin Higgs

Chacko, Goh, Harnik,
*Phys.Rev.Lett.* 96 (2006) 231802

Symmetry based solutions to the Higgs mass Hierarchy Problem

Copy SM and assume discrete $Z_2$ exchange symmetry

Quark Symmetry Partners do not carry any SM charge, including color




Protects Higgs mass at 1-loop

# Twin Higgs

Chacko, Goh, Harnik, *Phys.Rev.Lett.* 96 (2006) 231802

Scalar sector has approximate $SU(4)$ global symmetry

$$\mathcal{H} = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$$

$$V = -\mu^2|\mathcal{H}|^2 + \lambda|\mathcal{H}|^4$$

Breaks $SU(4)$ $\longrightarrow$ $\boxed{+\, m_\Delta^2 \left(|H_A|^2 - |H_B|^2\right) + \delta\left(|H_A|^4 + |H_B|^4\right)}$

Breaks $Z_2$

Need $Z_2$ breaking term to match experimental Higgs couplings

Rich twin sector with many DM possibilities (twin baryons, twin leptons,…)

# Symmetry Breaking

Batell, Hu, CV
*JHEP* 08 (2020) 009

Twin sector can differ from the SM and keep Higgs natural
(e.g. fraternal twin Higgs: Craig, Katz, Strassler, Sundrum *JHEP* 07 (2015) 105)

Spontaneous breaking of twin color and discrete $Z_2$

Consider SM and twin color triplets $\Phi = \begin{pmatrix} \phi_A \\ \phi_B \end{pmatrix}$

$$\begin{aligned} V = &- \mu_{\mathcal{H}}^2 |\mathcal{H}|^2 + \lambda_{\mathcal{H}} |\mathcal{H}|^4 - \mu_{\Phi}^2 |\Phi|^2 + \lambda_{\Phi} |\Phi|^4 + \lambda_{\mathcal{H}\Phi} |\mathcal{H}|^2 |\Phi|^2 \\ &+ \delta_{\mathcal{H}} \left( |H_A|^4 + |H_B|^4 \right) + \delta_{\Phi} \left( |\phi_A|^4 + |\phi_B|^4 \right) \\ &\boxed{+ \delta_{\mathcal{H}\Phi} \left( |H_A|^2 - |H_B|^2 \right) \left( |\phi_A|^2 - |\phi_B|^2 \right)} \longleftarrow Z_2 \text{ Symmetric} \end{aligned}$$

For $\delta_{\Phi} < 0 \, , \langle \phi_B \rangle \neq 0$ and $\langle \phi_A \rangle = 0$

Generates $Z_2$ breaking mass term required for the Higgs potential

# Twin Sector Quarks

Begin with

$$\mathcal{L}_{\text{vis}} \supset \mathcal{L}_{\text{SM}} - \lambda \phi_A^\dagger \overline{D}_A \overline{D}_A$$

Antisymmetric in flavor

$$\mathcal{L}_{\text{twin}} \supset -y_\tau H_B^\dagger L_B \overline{E}_B - y_t Q_B H_B \overline{U}_B - y_b H_B^\dagger Q_B \overline{D}_B$$

When $\phi_B$ gets a VEV $\langle \phi_B \rangle = f_\phi/\sqrt{2}$ twin color breaks,

Twin quarks separate

Asymmetric DM candidate

$$Q_B \to \widehat{Q}_{Bi} + Q_{B3}$$

Charged under residual $SU(2)$ color group

# Baryogenesis & DM-genesis

$$\mathcal{L}_{\text{portal}} \supset -M_N \overline{N}_A N_B - \kappa_A \phi_A \overline{U}_A \overline{N}_A - \kappa_B \phi_B \overline{U}_B N_B$$

See also Farina, Monteux, Shin *Phys.Rev.D* 94 (2016) 3, 035017

Baryon number $B_N = 1$

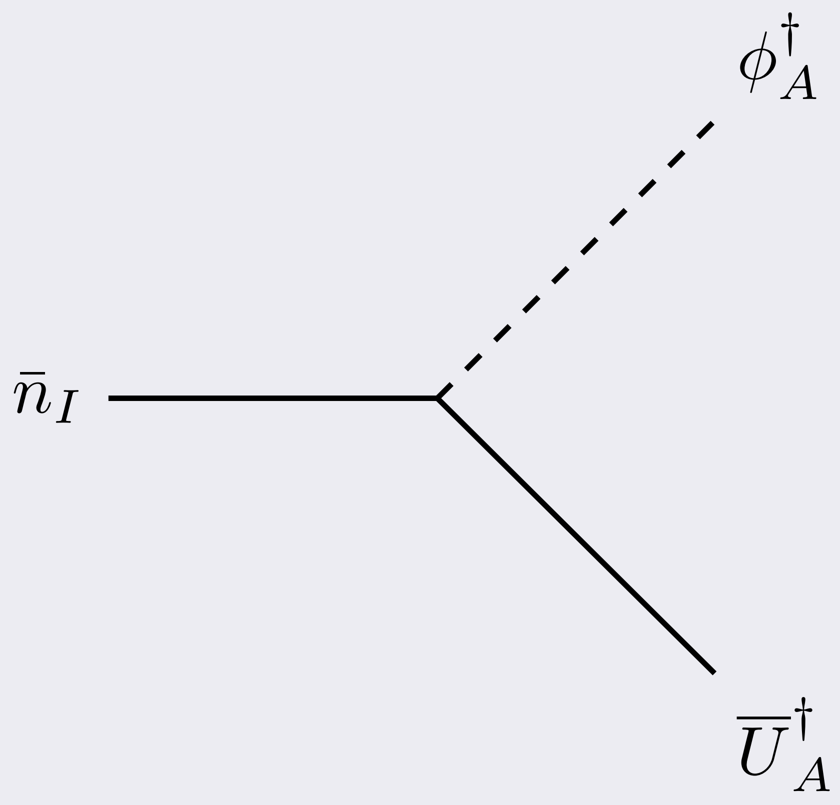
$B_{\overline{U}} = -\dfrac{1}{3}$ $\qquad B_\phi = -\dfrac{2}{3}$

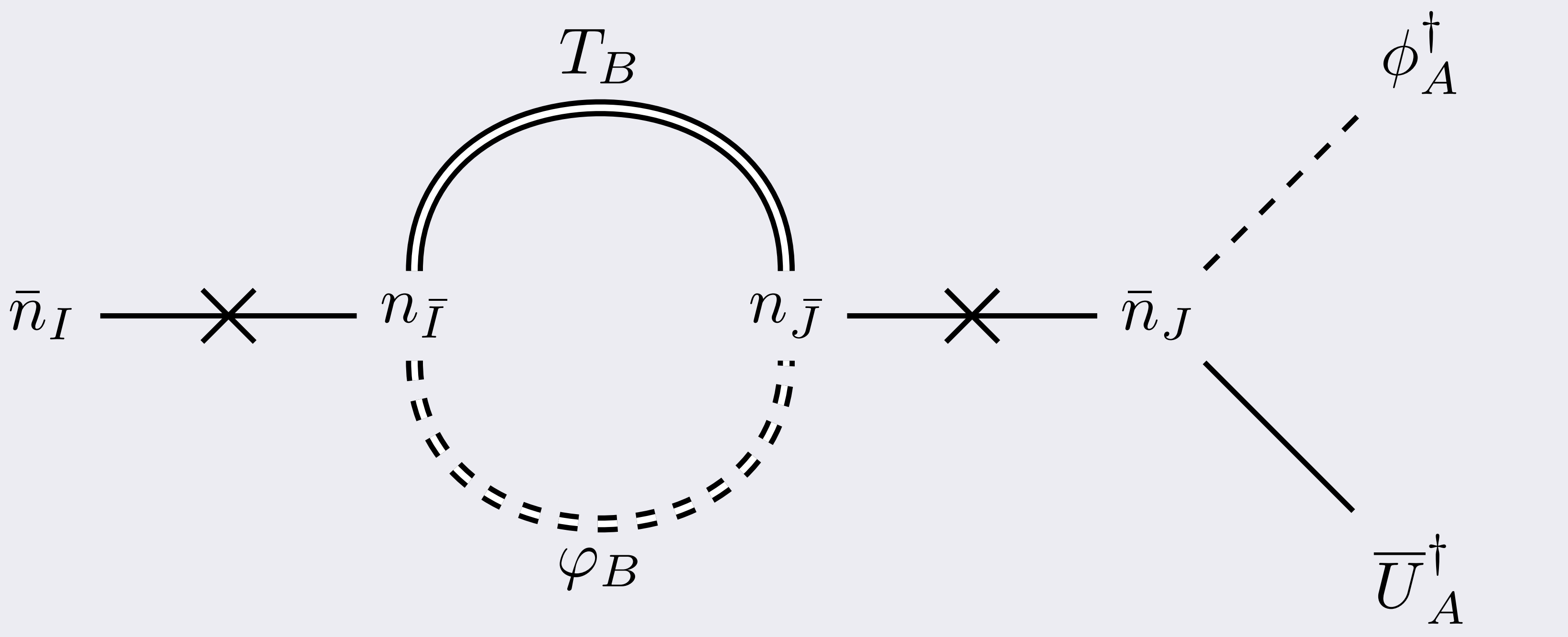
Portal interaction only preserve $U(1)_{B_A - B_B}$

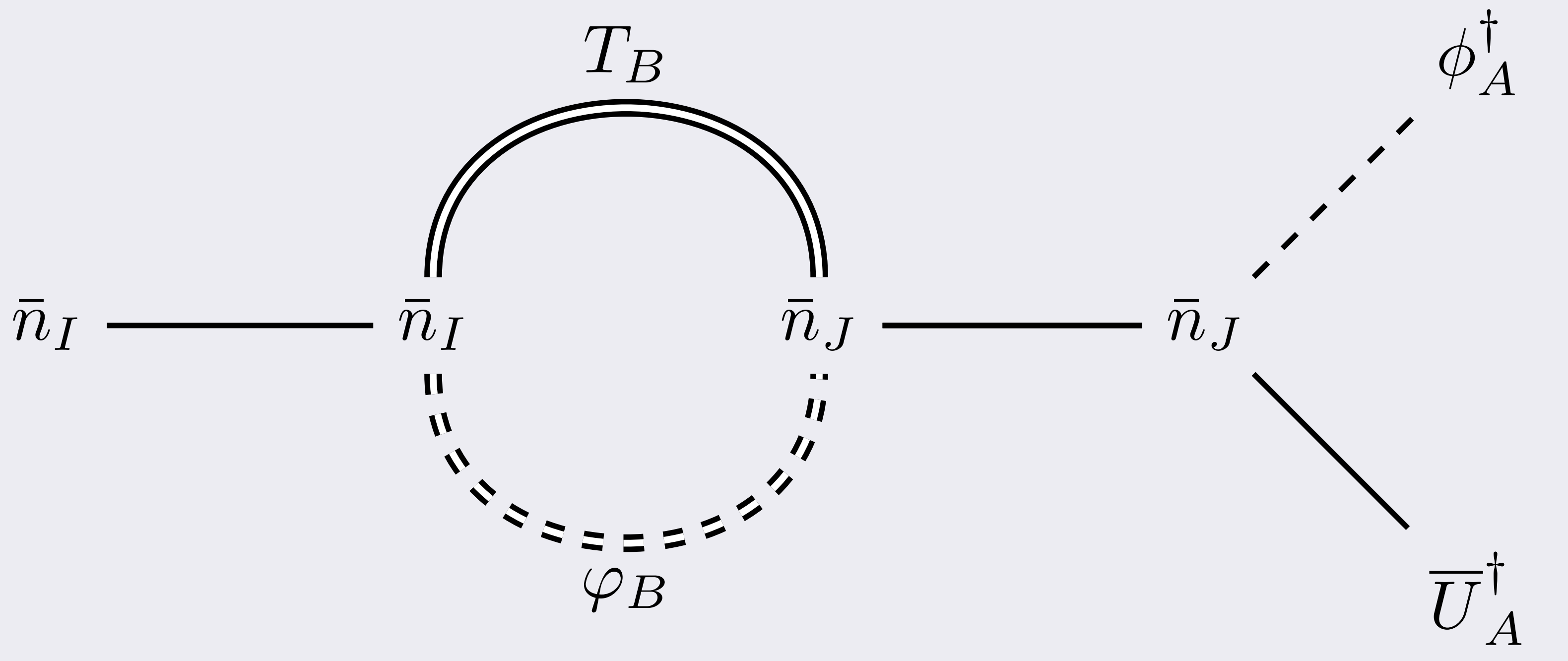
Ensures equal baryon asymmetry in each sector

Produce baryon asymmetry

$$\overline{n}_\pm \to \phi_A^\dagger + \overline{U}_A^\dagger$$




Scalar decays to quarks $\longrightarrow$ $\lambda \phi_A^\dagger \overline{D}_A \overline{D}_A$

# Baryogenesis & DM-genesis

$$\mathcal{L}_{\text{portal}} \supset -M_N \overline{N}_A N_B - \kappa_A \phi_A \overline{U}_A \overline{N}_A - \kappa_B \phi_B \overline{U}_B N_B$$

Produce DM asymmetry through

$$\overline{n}_\pm \to \varphi_B + T_{3B}$$

Asymmetry only generated in residual twin color singlets!

Twin top undergoes weak decay $T_{3B} \to b_{3B} + \tau_B^\dagger + \nu_{\tau_B}$

$$\frac{\Omega_{\text{DM}}}{\Omega_B} = \frac{n_{\text{DM}}}{n_B}\frac{m_{\text{DM}}}{m_B} \qquad \Rightarrow \qquad m_{b_{3B}} + m_{\tau_B} \approx m_p \frac{\Omega_{\text{DM}}}{\Omega_B} \approx 5\ \text{GeV}$$

Symmetric populations decay to twin glueballs and (massive) twin photons, these decay into SM through kinetic mixing

# Thermal History

Inflation

$N$ fields produced non-thermally from "reheaton" decays

Decays are late, after expansion the bath temperature well below $N$ mass

Reheating - below the scale of color breaking

Baryogenesis and asymmetric-DM-genesis

Symmetric decays through twin photon to SM

$\Lambda_{\mathrm{Inf}}$

4 TeV~ $m_N$

TeV~ $f_\phi$

10 GeV > $\Lambda_{\mathrm{ReHeat}}$

SM

# Decaying Dark Matter?

For correct relic $m_{b_{3B}} + m_{\tau_B} \sim 5\ \mathrm{GeV}$

To ensure timely symmetric decays $m_{\tau_B} > m_{\gamma_B} \sim 1\ \mathrm{GeV}$

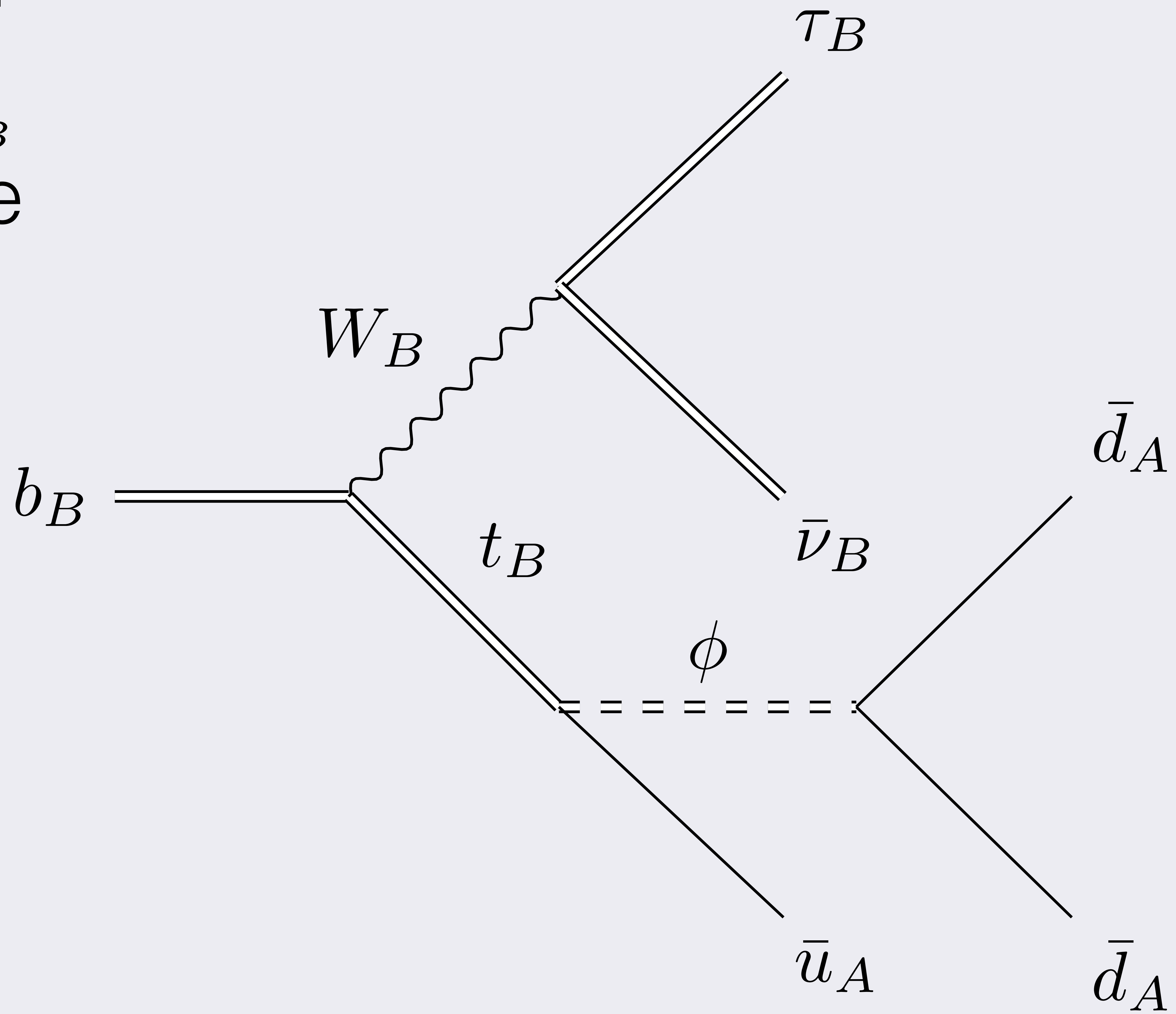
Twin tau's are stable due to unbroken lepton number

Twin bottom may decay, but $U(1)_{B_A - B_B}$
implies a SM baryon in the final state

Only allowed if $m_{b_{3B}} > m_{\tau_B} + m_p$

If $2.5\ \mathrm{GeV} < m_{b_{3B}} < 3\ \mathrm{GeV}$
the twin bottom quark is stable

Otherwise, decay suppressed by
5-body phase space



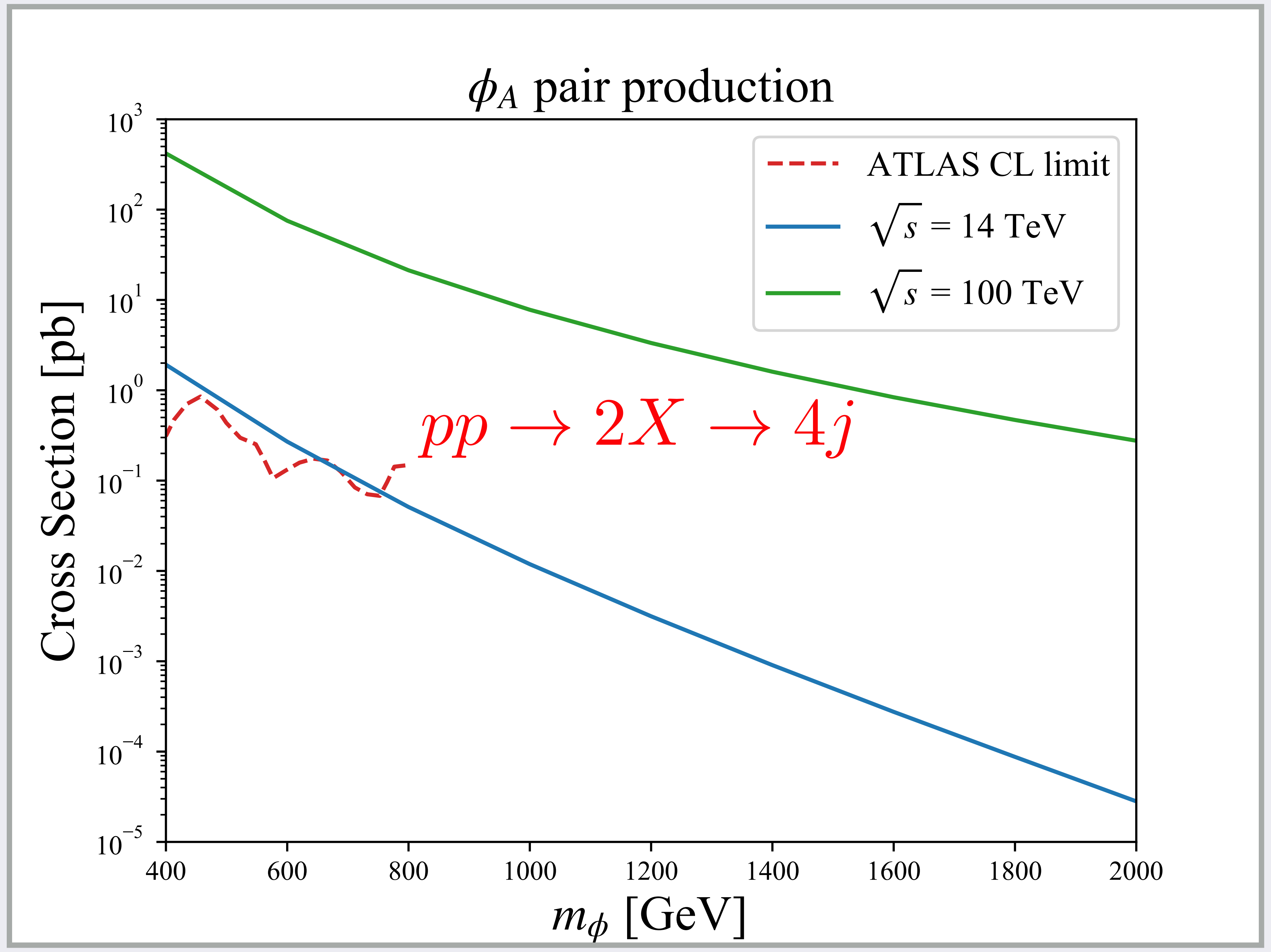
# Collider Bounds

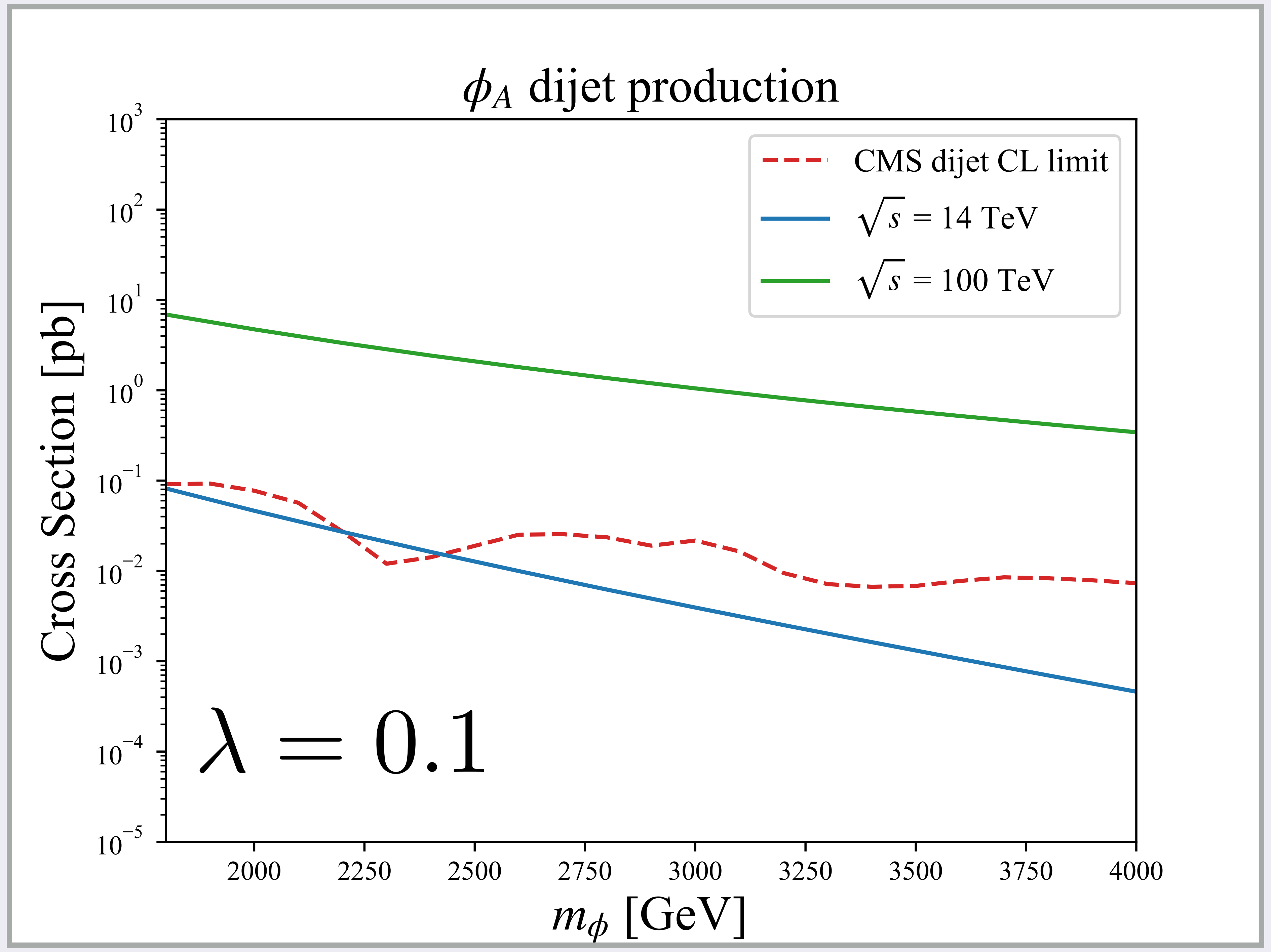
Colored scalar $\phi_A$ can be pair produced through gluon fusion

Can be singly produced from $d$-$s$ initial state through $\lambda \phi_A^\dagger \overline{D}_A \overline{D}_A$

Dominant production and decay modes depend on relative sizes of $\lambda$ and $\kappa$

Either dijet or monotop



# Washout and Kinetic Mixing

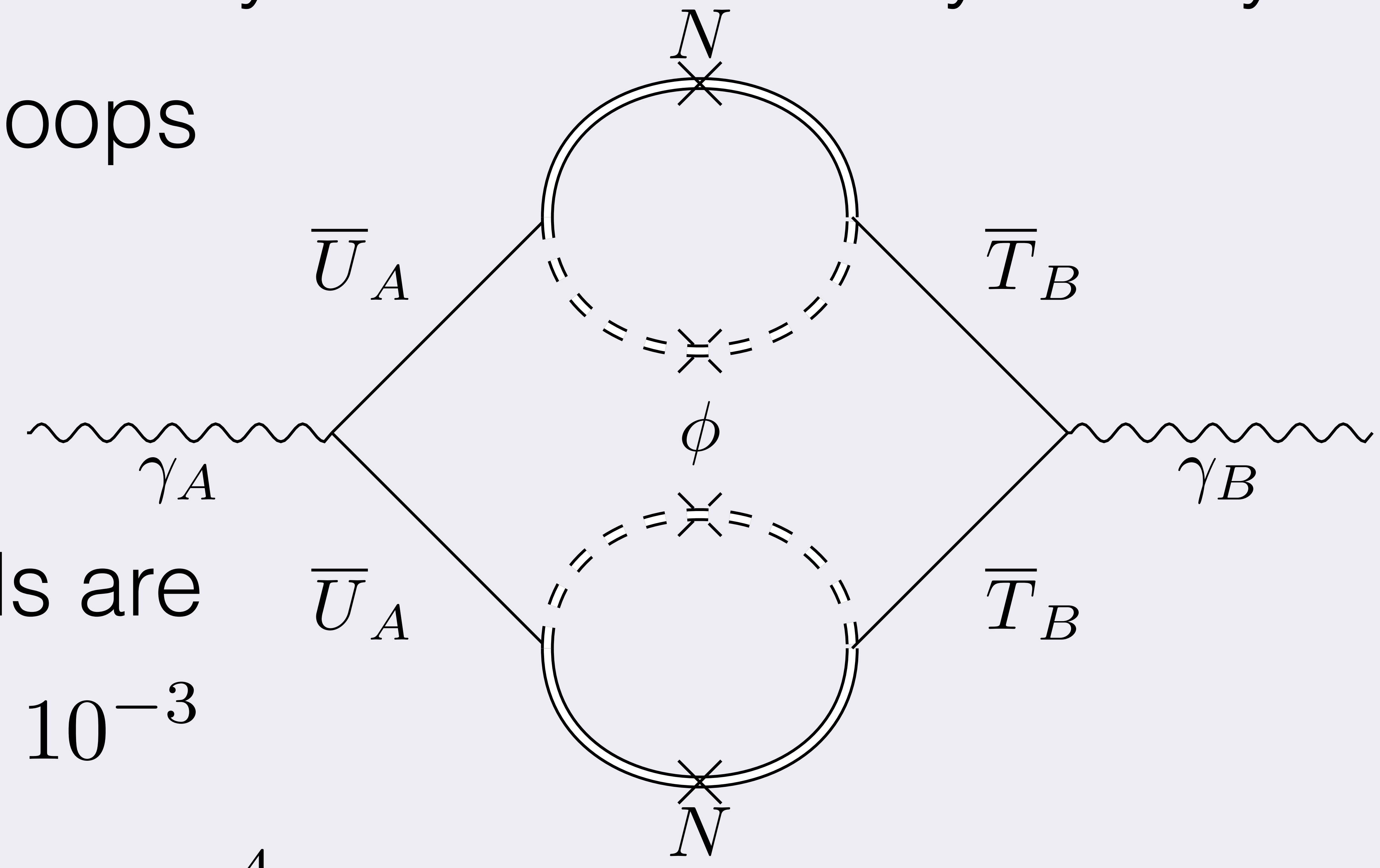
$$\mathcal{L}_{\rm portal} \supset -M_N \overline{N}_A N_B - \kappa_A \phi_A \overline{U}_A \overline{N}_A - \kappa_B \phi_B \overline{U}_B N_B$$

$$\mathcal{L}_{\rm vis} \supset \mathcal{L}_{\rm SM} - \lambda \phi_A^\dagger \overline{D}_A \overline{D}_A$$

Need $\kappa_A \gtrsim \lambda$ or else $\phi_A \to \overline{U}_A^\dagger + \overline{T}_{B3}^\dagger$ decays washout the asymmetry

Kinetic mixing generated in IR at three loops

$$\varepsilon \sim 2.5 \times 10^{-8} \kappa^4$$

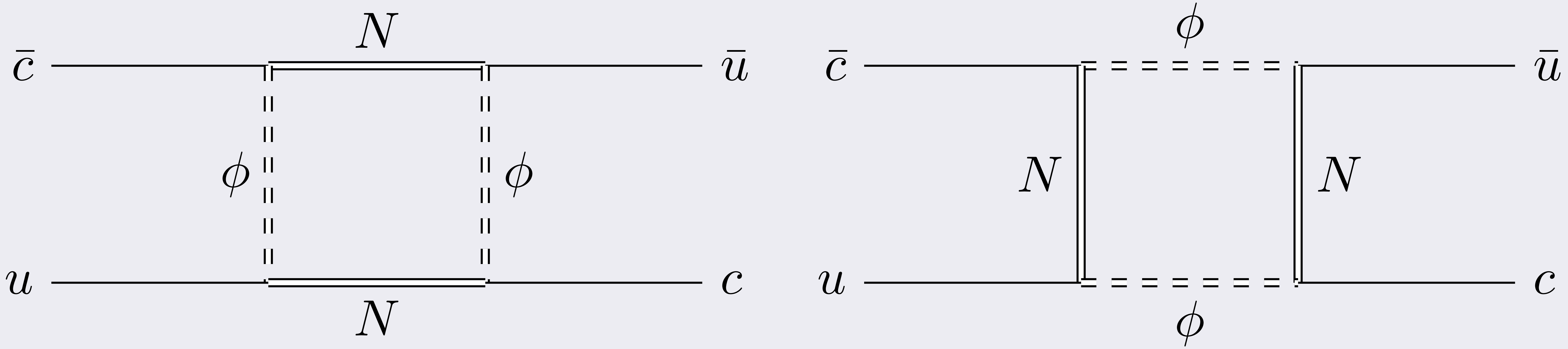



For twin photon with mass ~GeV bounds are

$$\varepsilon \lesssim 10^{-3}$$

Future direct detection will probe $\varepsilon \sim 5 \times 10^{-4}$

# Flavor Changing Neutral Currents




Strongest constraint is from $D^0$—$\overline{D}^0$ mixing

Constrains $\kappa < \mathcal{O}(0.1)$

# Electric Dipole Moment

CP violating phases in $\kappa$ generate EDMs

Coupling is to quarks, leading effect is neutron EDM

Best limit is

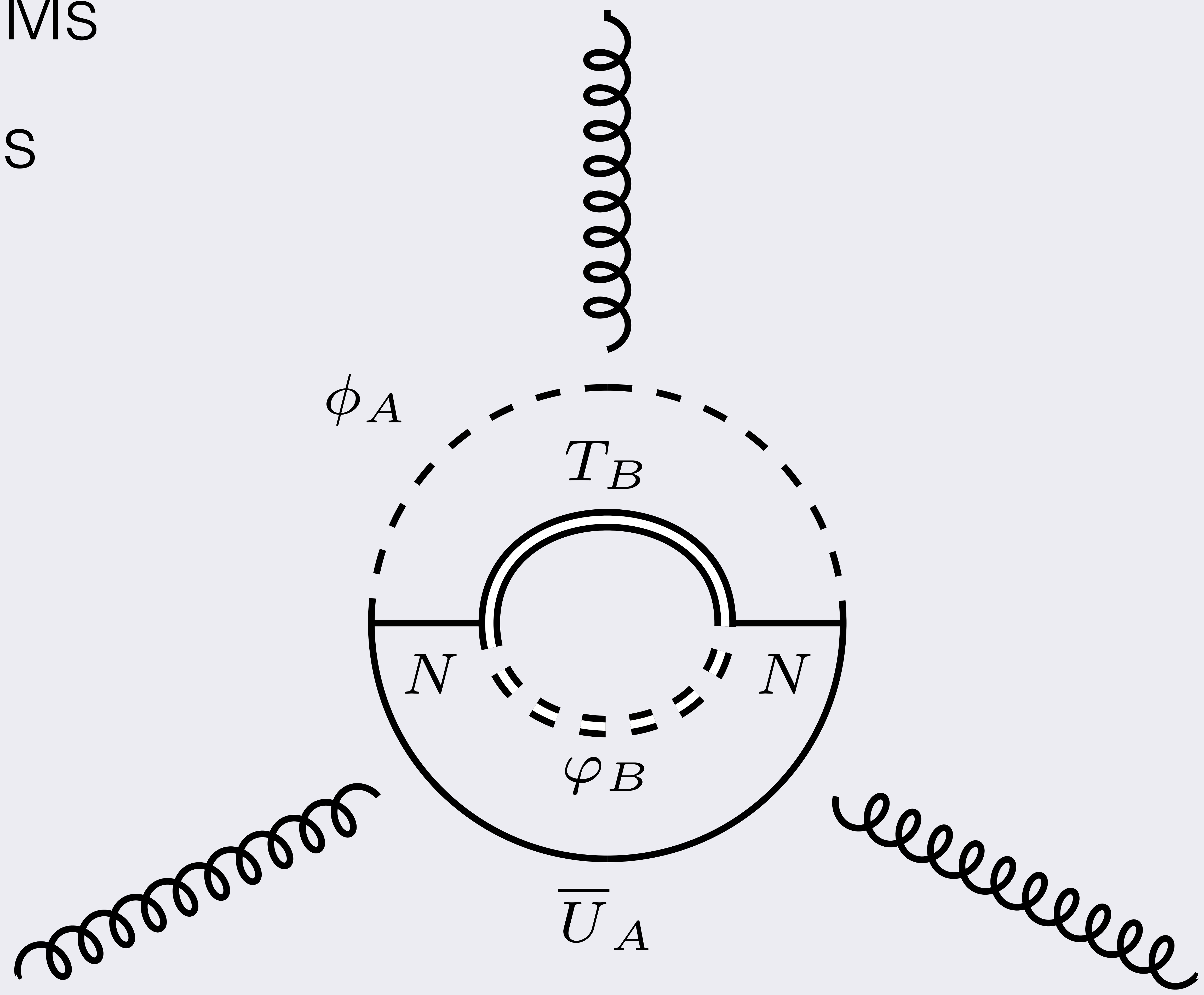
$$d_n = (0.0 \pm 1.1) \times 10^{-26} e \cdot \mathrm{cm}$$

Implies $\kappa < \mathcal{O}(1)$

SM prediction is

$$d_n \sim 10^{-31} e \cdot \mathrm{cm}$$

Improvements in EDM precision can probe interesting parameter space



# Summary Of Experimental Probes

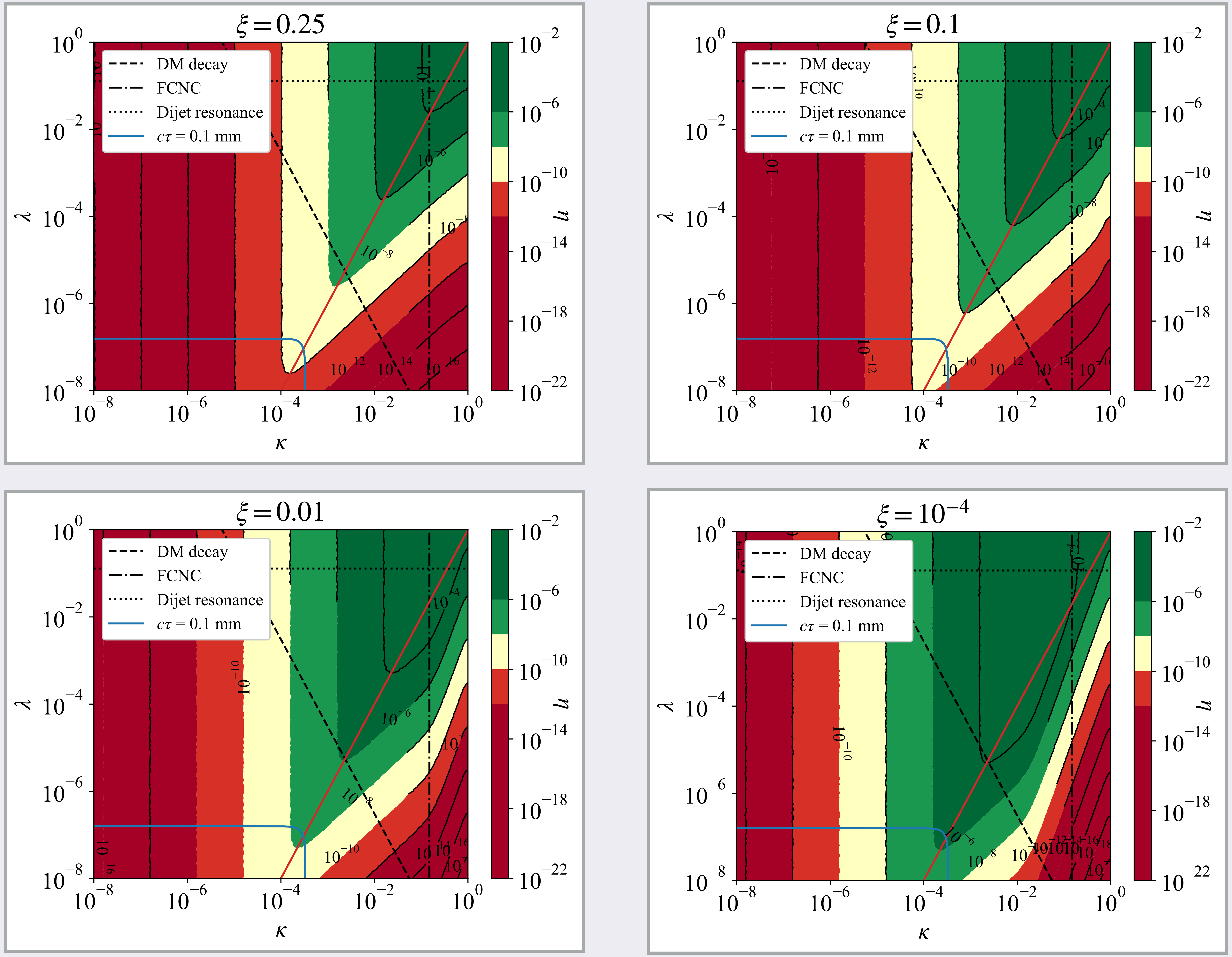
$\xi =$ UV mass splitting

$$Y_B = \eta Y_N \sim \eta T_r/M_r$$

Need $\eta > 10^{-8}$

Must be left of decaying DM constraints when applicable

Above red line dijet
below: top+MET



# Conclusions

Dark sectors may be as rich and varied as the visible sector

Outlined a Twin Higgs inspired model with

- Natural Higgs mass
- Asymmetric dark matter
- Baryogenesis

Many signals to look for at current and upcoming experiments