A DARK FORCE FOR BARYONS

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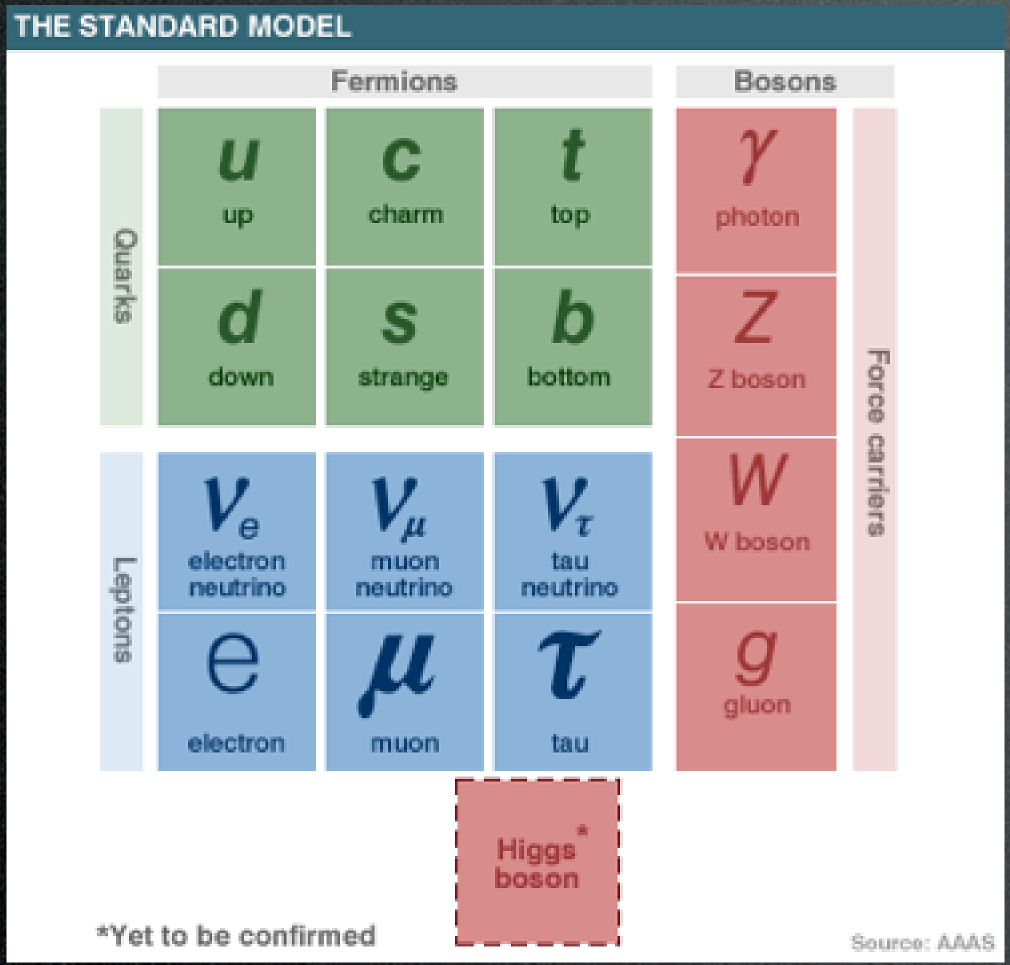
with Michael Graesser and Luca Vecchi

Dark matter à la Occam

lex parsimoniae

Visible sector $\sim 17\%$



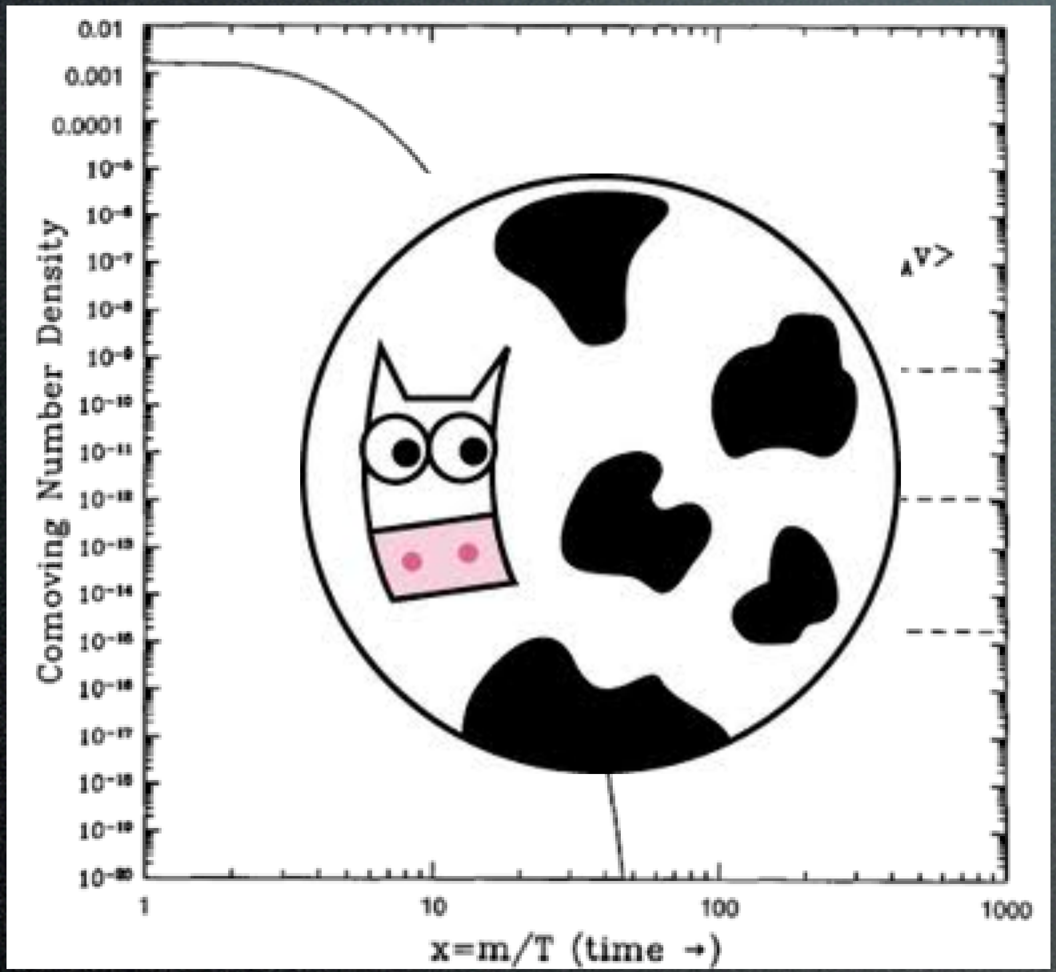
Dark sector $\sim 83\%$

$$\chi$$

WIMP

The WIMP "miracle"

$$\chi\chi \leftrightarrow \bar{f}f$$



$= \; ?$

$$\Omega_{DM}h^2 = 0.1\left(\frac{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle}\right)$$

What do we really know about DM?

1. Cosmological abundance.
2. It's stable (or at least very long-lived).

[Larson, et al. (2010)]

Clue #1: WMAP

- The amounts of dark and visible matter are comparable. WMAP 7 tells us:

$$\Omega_{DM} h^2 = 0.1109 \pm 0.0056$$

$$\Omega_B h^2 = 0.02258^{+0.00057}_{-0.00056}$$

DMB ratio:

$$\frac{\Omega_{DM}}{\Omega_B} \approx 5$$

- This could be

1. A remarkable coincidence.
2. An anthropic selection effect? [Freivogel (2008)]
3. An indication of an underlying origin.

Asymmetric dark matter

- Perhaps DM carries a particle anti-particle asymmetry like baryons.
- Earliest attempts made use of EW sphalerons (Nussinov 1985; Barr, Chivukula, Farhi 1990; Kaplan 1992).
- Modern version makes use of higher dimensional operators to transfer the asymmetry (Kaplan, Luty, Zurek 2009).
- ADM models prefer GeV scale masses, but can accommodate weak scale masses (Buckley, Randall 2010), or sub-GeV masses (Falkowski, Ruderman, Volansky 2011).

What to call it?

- Darkogenesis? [J. Shelton, K. Zurek (2010)]
- Xogensis? [M. Buckley, L. Randall (2010)]
- Aidnogenesis? [Blennow, et al. (2010)]
- Hylogenesis? [H. Davoudiasal et al. (2010)]
- Cladogenesis? [R. Allahverdi, B. Dutta, K. Sinha (2011)]
- Pangenesis. [N. Bell, K. Petraki, I.M.S., R. Volkas (2011)]

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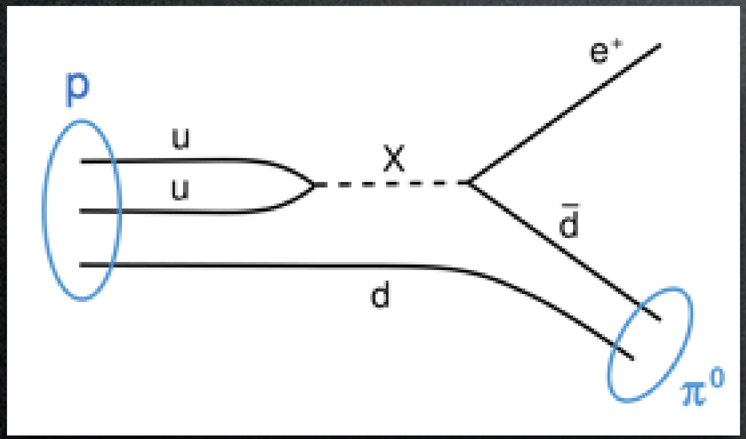
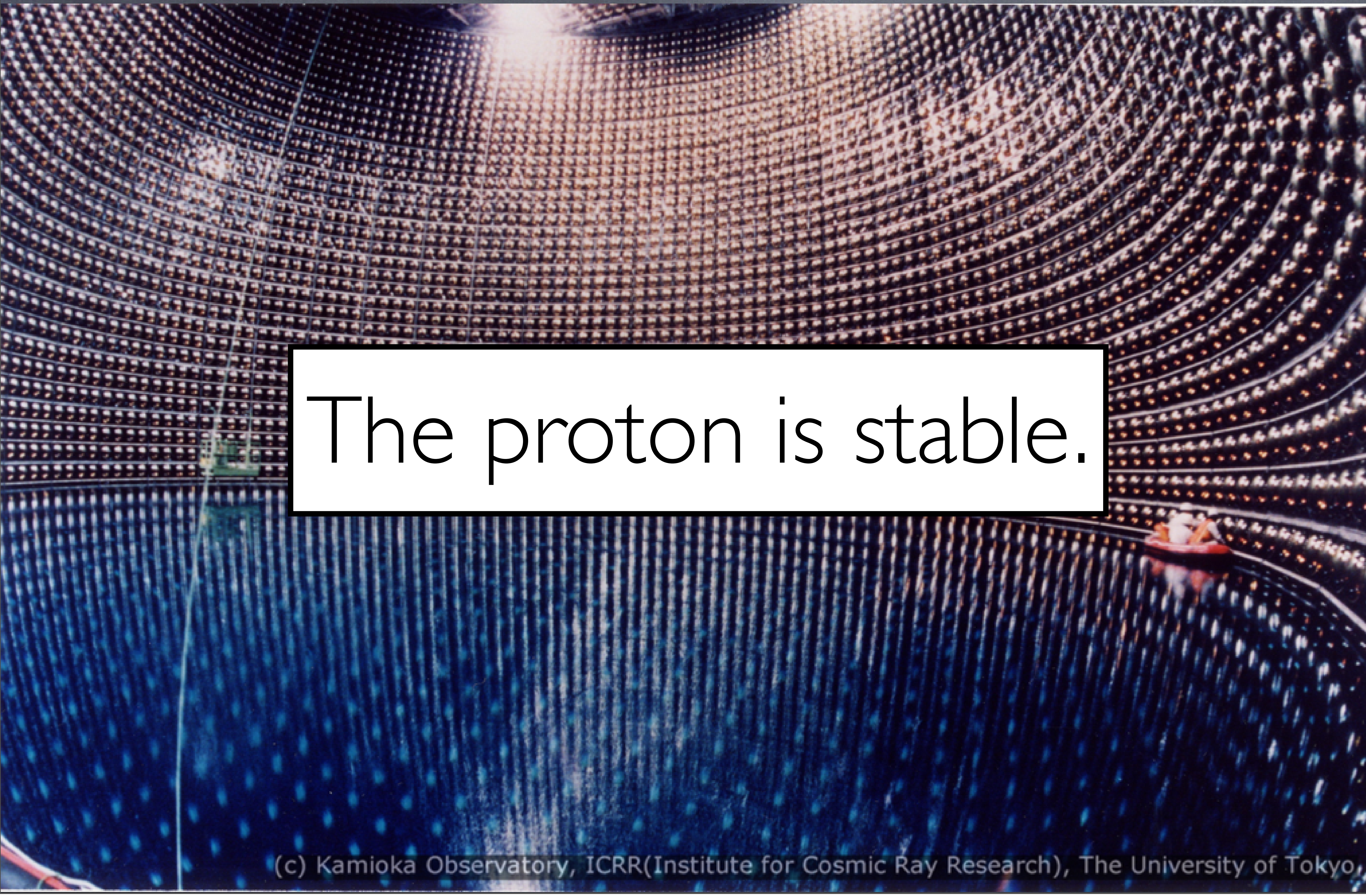
Clue #2: BSM physics has a love/hate relationship with the proton

- New physics models often predict an intriguing signal...



The only problem is...

Super Kamiokande says:



The proton is stable.

The proton is stable

- What does this imply?

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{eff}$$

$$\mathcal{L}_{eff} \subset \frac{QQQL}{\Lambda^2}$$

Baryon number is an **unreasonably** good symmetry

$$p \longrightarrow e^+\pi^0$$

$$\tau_p > 10^{33} yr$$

$$\Lambda > 10^{15}\mathrm{GeV!}$$

Think globally? **Act locally**.

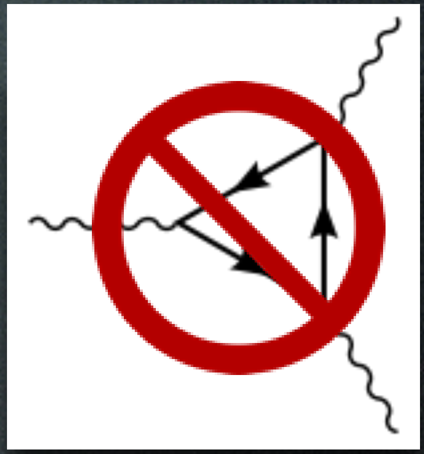
Promote $U(1)_B$ to a local gauge symmetry.

- New quarks to cancel anomalies.
- To avoid stable colored particles, introduce new particle X to facilitate their decay.
- X is **automatically** stable.
- Baryogenesis *requires* a DM asymmetry.
- Shared gauge interactions with baryons predict novel signatures: monojets and low mass DD.

Gauging baryon number

- Older examples:
  - Bailey and Davidson 1995; Carone and Murayama 1998; Aranda and Carone 1998.
- More recently:
  - Dulaney, Fileviez-Perez and Wise (2010); Buckley, Fileviez-Perez, Hooper, and Neil (2011).

An anomaly-free example



- New chiral states

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_B$
Q'_i	3	2	$+\frac{1}{6}$	$-\frac{1}{N}$
u'_{ci}	$\bar{3}$	1	$-\frac{2}{3}$	$+\frac{1}{N}$
d'_{ci}	$\bar{3}$	1	$+\frac{1}{3}$	$+\frac{1}{N}$
L'_i	1	2	$-\frac{1}{2}$	0
ν'_{ci}	1	1	0	0
e'_{ci}	1	1	$+1$	0

N dark generations

- Spontaneously break $U(1)_B$

S^+	1	1	0	$+B(S)$
S^-	1	1	0	$-B(S)$

Not your typical 4th generation

- Gauge symmetry forbids mass mixing.
  - ✶ No tree-level flavor changing processes, decay modes not like conventional 4th gen.
- New quarks carry their own global $U(1)_{B_{q'}}$
  - ✶ The lightest particle in Q'-sector will be stable.

Absence of stable colored particles

- Exotic quarks must decay...

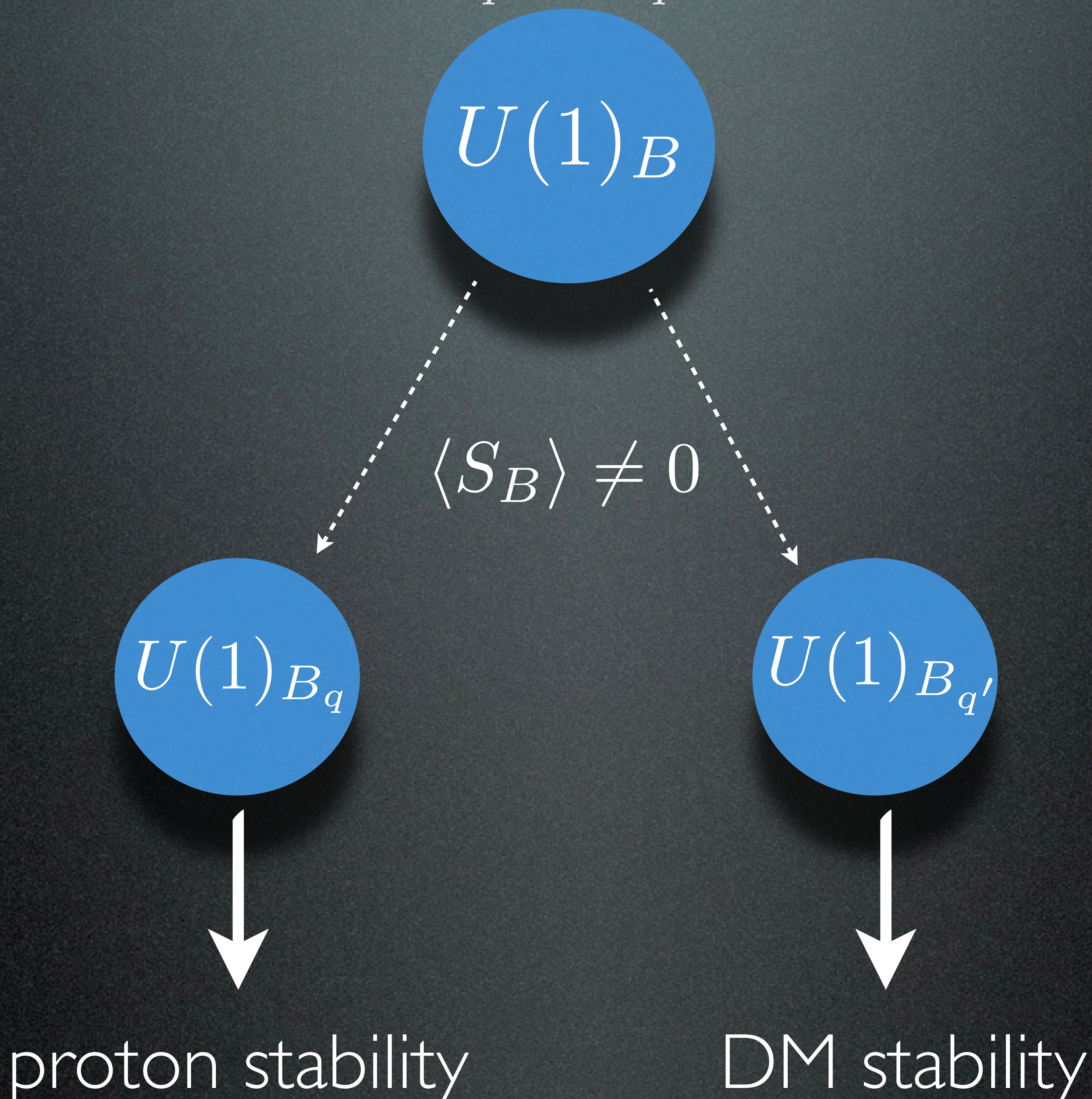
Introduce: $$X^{\pm} \sim \left(1, 1, 0, \pm\left(\frac{2}{3} - \frac{1}{N}\right)\right)$$

$$\mathcal{L} \supset \frac{u_c d_c d'_c X}{\Lambda} \qquad \overline{q'} \to qqX$$

Decay operator ↔ asymmetry transfer operator

Spontaneous breaking

$$B = B_q + B_{q'} + B_S$$



Baryogenesis implies a DM asymmetry

- The only global symmetry is a non-anomalous $U(1)_D$:

$$D = B_q + B_{q'}$$

$$n_B \neq n_{\overline{B}} \quad \Rightarrow \quad n_X \neq n_{\overline{X}}$$

- Unlike conventional ADM, the asymmetries are generated simultaneously.

- Recent work by: Bell, Petraki, IMS, Volkas [1105.3730]. **See Kallia's talk**.

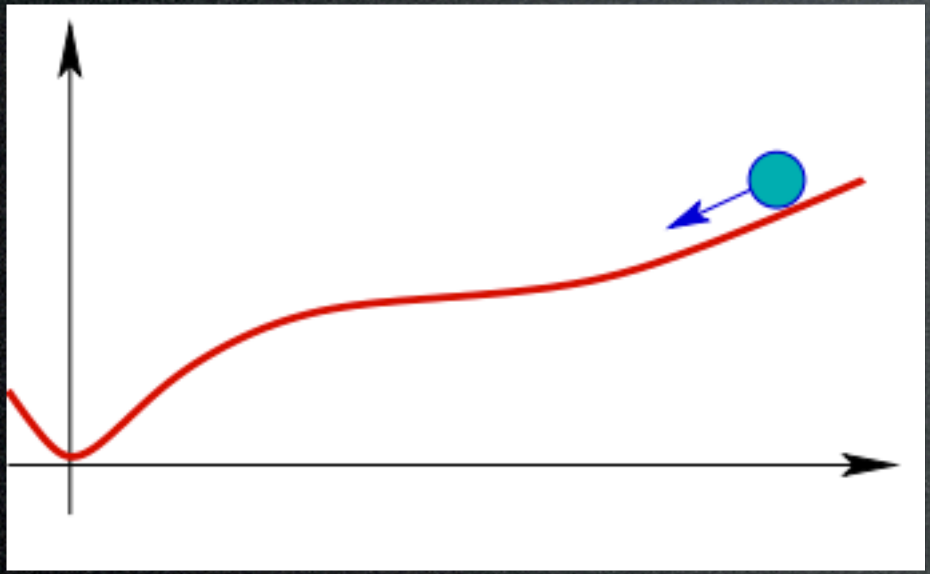
Super example: Affleck-Dine

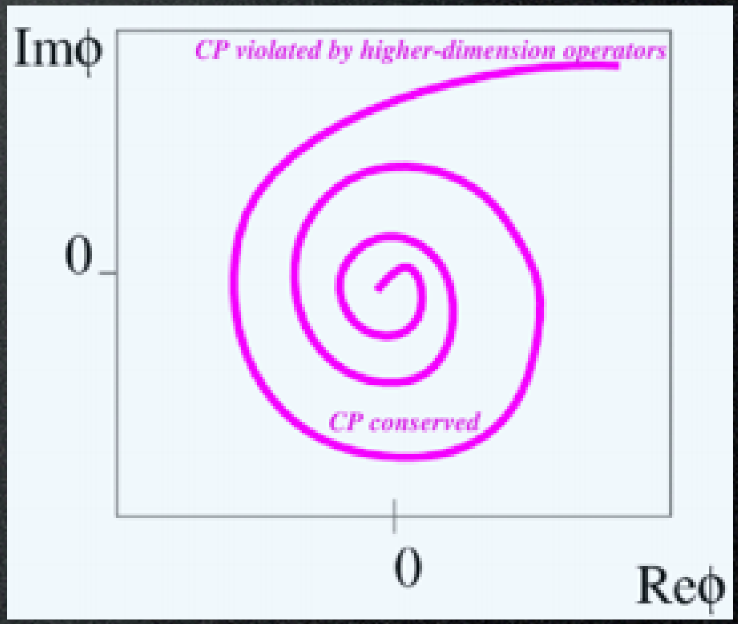
- Affleck-Dine simplified:

$$n_B = \dot{\theta}|\phi|^2$$

  - Acquire a large VEV.
  - Kick the field in the phase direction.

Affleck, Dine (1985); Dine, Randall, Thomas (1995).





Similar asymmetries yield similar masses

Generically: $\dfrac{\eta_B}{\eta_X} = \mathcal{O}(1)$

For the model introduced above: $\dfrac{\eta_B}{\eta_X} \lesssim 6$

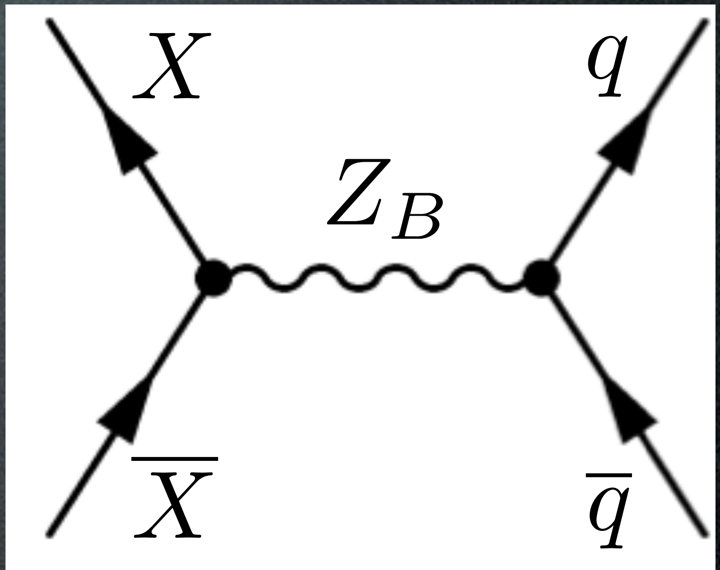
$$\frac{m_X}{m_p}\left(\frac{n_+ - n_-}{n_+ + n_-}\right) = \frac{\eta_B}{\eta_X}\frac{\Omega_{DM}}{\Omega_B}$$

$\Rightarrow$ $m_X \lesssim 30\ \text{GeV}$

Light DM is generic in ADM models.

Abundance via annihilation

Minimal assumption: annihilation dominantly from s-channel ZB



$$\langle \sigma_{ann} v \rangle = \sum_f \frac{N_c}{2\pi} m_X^2 \left(\frac{g_B^2}{m_B^2} \frac{q_X}{3} \right)^2 \frac{\left(2 + \frac{m_f^2}{m_X^2}\right)}{\left(1 - \frac{4m_X^2}{m_B^2}\right)^2 + \frac{\Gamma_B^2}{m_B^2}} \sqrt{1 - \frac{m_f^2}{m_X^2}}$$

$$\simeq \frac{N_f}{3\pi} m_X^2 \left(q_X \frac{g_B^2}{m_B^2} \right)^2 \left[\left(1 - \frac{4m_X^2}{m_B^2}\right)^2 + \frac{\Gamma_B^2}{m_B^2} \right]^{-1}$$

On the origin of asymmetric species

(M. Graesser, I.MS., L. Vecchi. [arXiv:1103:2771])

$$X\overline{X} \leftrightarrow f\overline{f}$$

If an asymmetry exists prior to thermal freeze-out, must solve coupled Boltzmann eqs. for abundances.

Large $\langle\sigma v\rangle$	Small $\langle\sigma v\rangle$
$\Omega_{DM} \propto \eta$	$\Omega_{DM} \propto \langle\sigma v\rangle^{-1}$

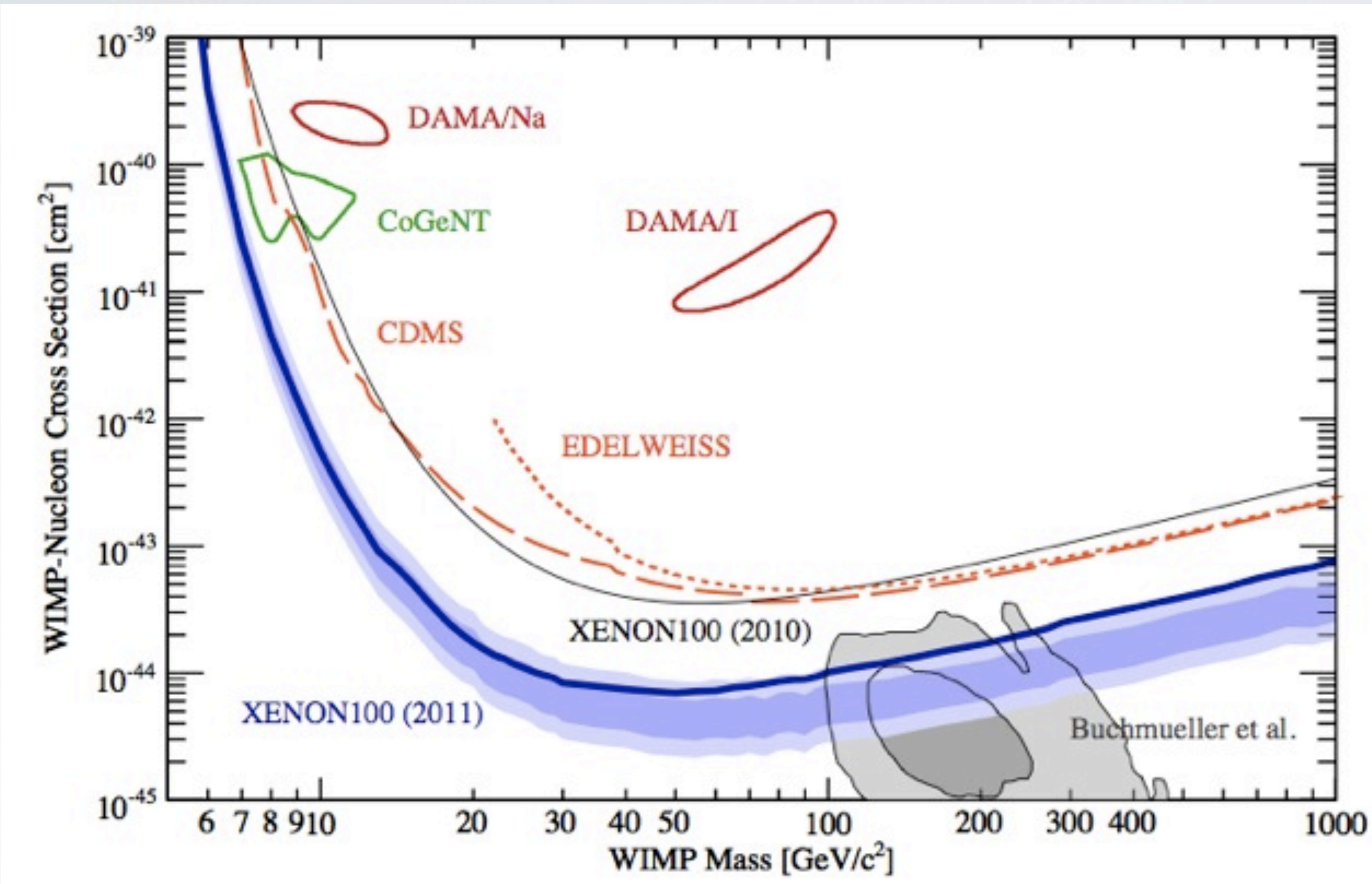
More generally:

$$\Omega_{DM} = f(\eta, \langle\sigma v\rangle, m)$$

$$\langle\sigma v\rangle \geq 3 \times 10^{-26}\text{cm}^3\text{s}^{-1}$$

ADM can have WIMP sized cross sections!

DIRECT DETECTION BOUNDS



annihilation physics

↕

DM-quark scattering

RECOIL SPECTRUM

astrophysics/N-body

$$\frac{dR}{dE_R} = \frac{N_T \rho_\odot}{m_X} \int_{|\vec{v}|>v_{min}} d^3v \; v f(\vec{v}, \vec{v}_\oplus) \frac{d\sigma}{dE_R}$$

particle physics

- Velocity distribution must be consistent with NFW:

$$f(v) \propto \left[\exp\left(\frac{v_{esc}^2 - v^2}{k v_0^2}\right) - 1\right]^k$$

[Lisanti, Strigari, Wacker, Wechsler (2010)]

High-velocity tail is important for light DM.

RECOIL SPECTRUM

VECTOR CASE:

$$\frac{d\sigma}{dE_R} = \frac{m_N A^2}{2\pi v^2}\left(\frac{q_V g_B^2}{m_B^2}\right)^2 F^2(E_R)$$

DD imposes:

$m_X \lesssim \text{few GeV}$

AXIAL CASE:

$$\frac{d\sigma}{dE_R} = \frac{m_N A^2}{8\pi v^2}\left(\frac{q_A g_B^2}{m_B^2}\right)^2 \left[Av^2 + Bq^2\right] F^2(E_R)$$

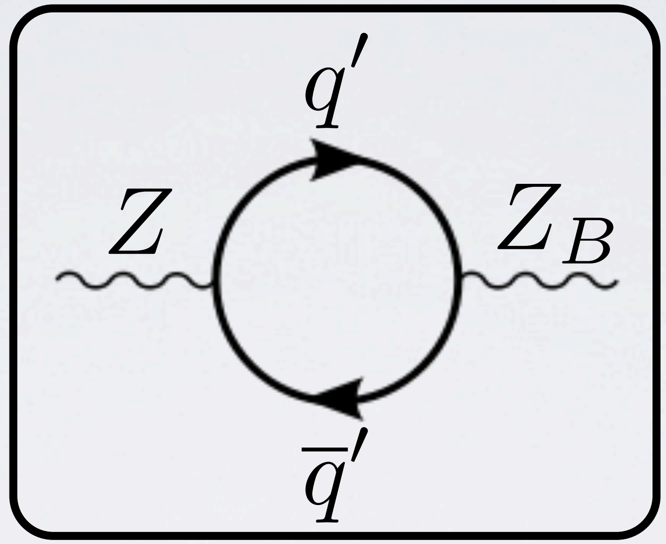
DD imposes:

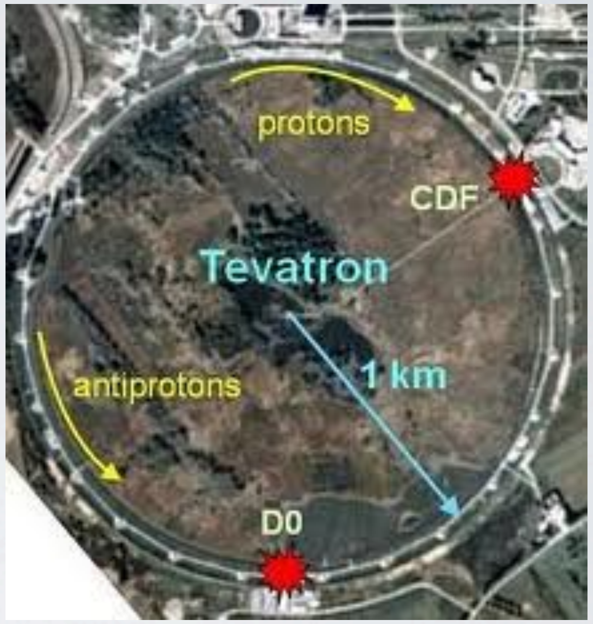
no bound

BARYONIC DARK FORCES AND COLLIDERS

A TRIFECTA OF EXPERIMENTS

LEP





- BaBar: invisible/hadronic upsilon decays.
- LEP: hadronic width of the Z boson.
- Tevatron: monojets + missing energy.

B-FACTORY CONSTRAINTS

If $m_X \lesssim m_\Upsilon/2$, the upsilon can decay to DM.

$$\Upsilon(1S) \to Z_B \to \overline{X}X$$

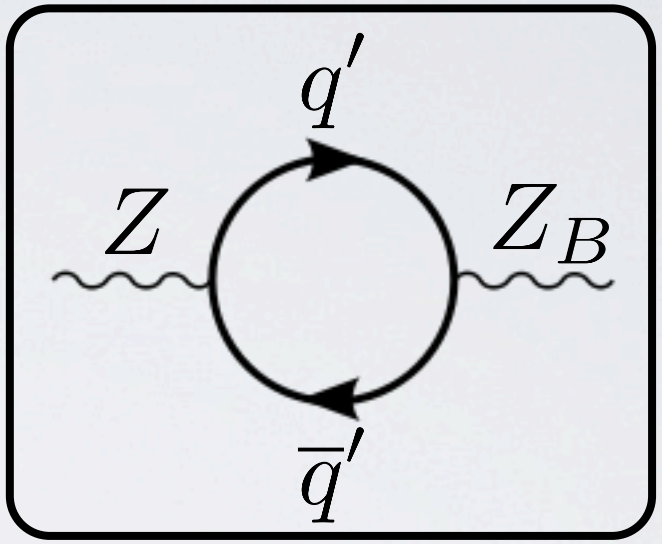
BaBar constrains:

$$\mathcal{BR}(\Upsilon(1S) \to \text{“invisible”}) < 3 \times 10^{-4}$$

$$\frac{\mathcal{BR}(\Upsilon(1S) \to \text{“invisible”})}{\mathcal{BR}(\Upsilon(1S) \to \mu^+\mu^-)} = \left(q_V^2 + q_A^2\right)\left[\frac{g_B^2}{e^2}\frac{m_\Upsilon^2}{m_B^2 - m_\Upsilon^2}\right]^2 < 1.2 \times 10^{-2}$$

BOUNDING A BARYONIC GAUGE BOSON WITH LEPTONS

Kinetic mixing:



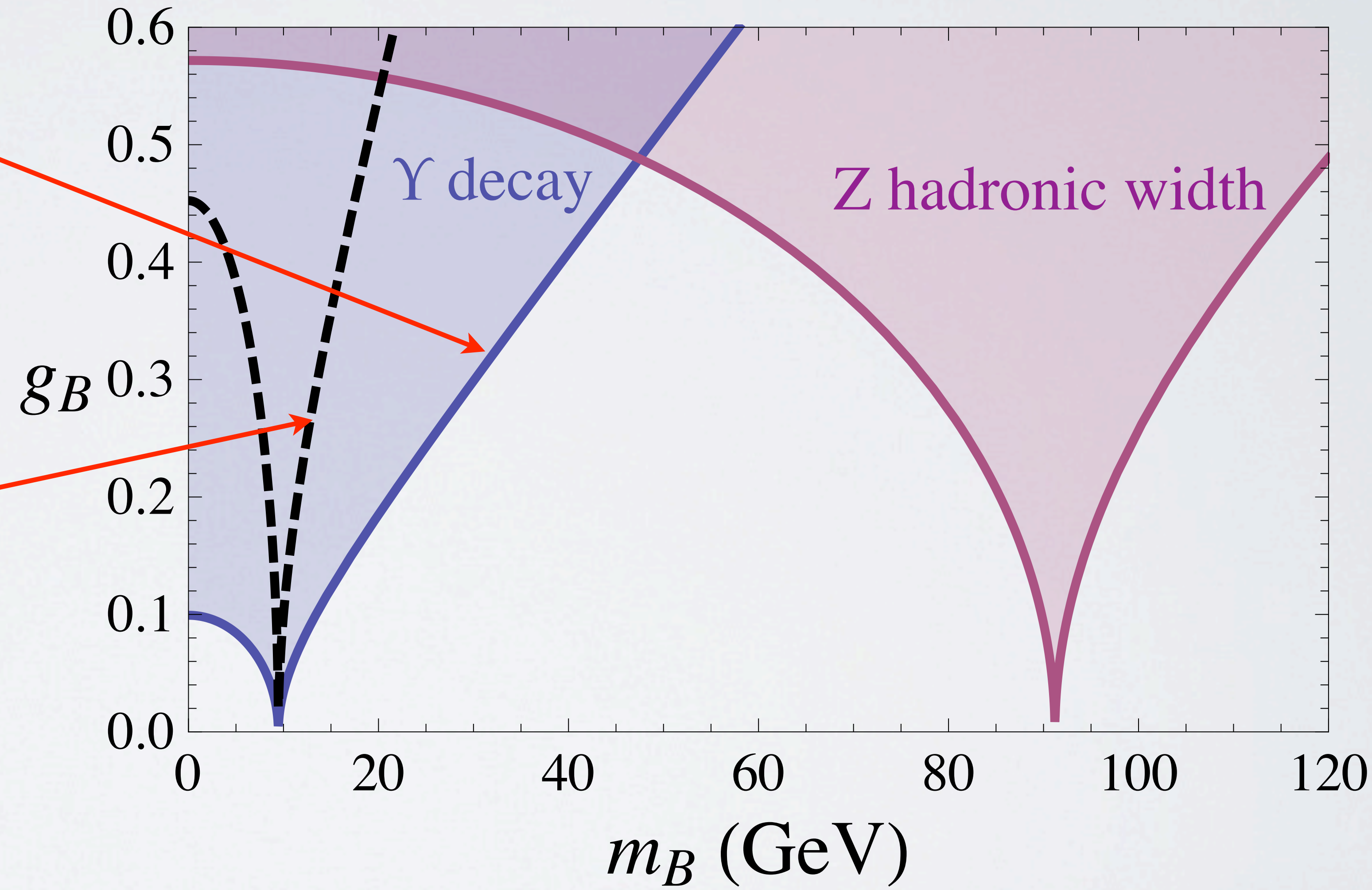
$$\mathcal{L}_{kin} = -\frac{1}{4}\left(Z_B^{\mu\nu} Z_B^{\mu\nu} - 2c_Z s_W Z_B^{\mu\nu} Z^{\mu\nu} + 2c_\gamma c_W Z_B^{\mu\nu} A^{\mu\nu}\right)$$

$$\frac{\Delta\Gamma_{had}}{\Gamma_{had}} \approx 1.193 \frac{g_B}{\sqrt{4\pi}} c_Z(m_Z) \frac{m_Z^2}{m_Z^2 - m_B^2} \lesssim \pm 1.1 \times 10^{-3}$$

Experimental constraints: LEP + B-factories

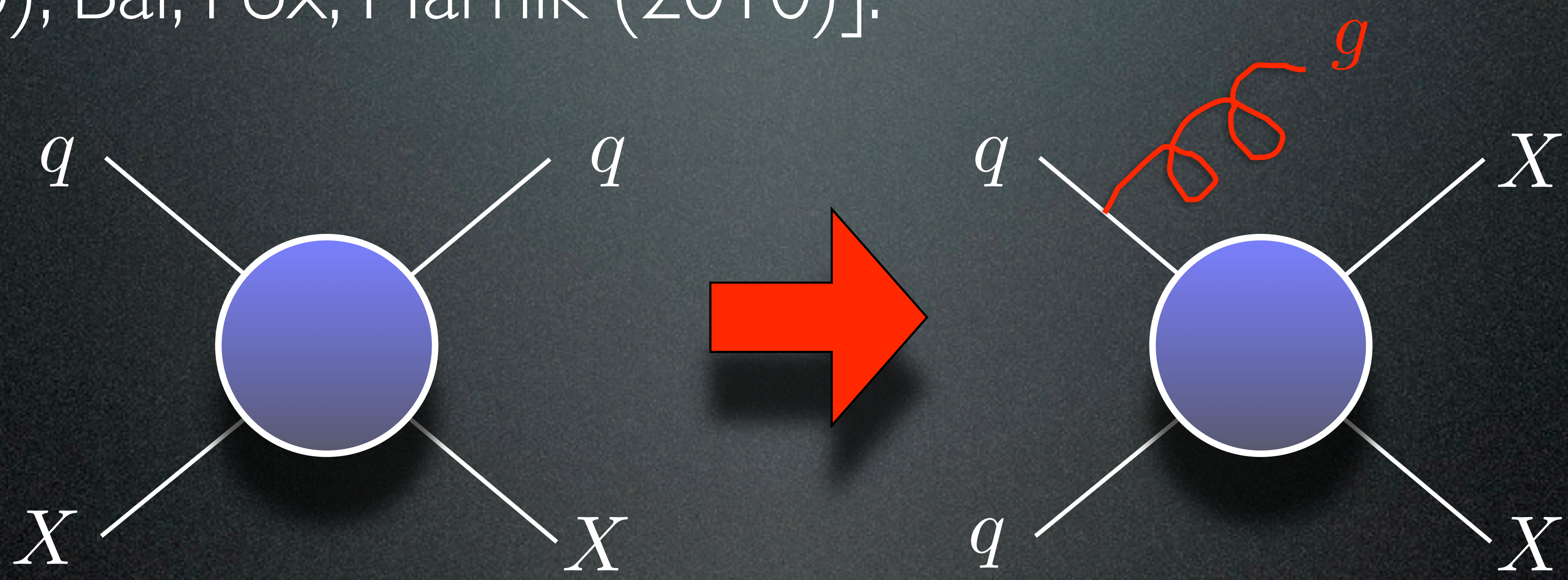
$m_X \lesssim m_\Upsilon/2$
invisible upsilon width

$m_X \gtrsim m_\Upsilon/2$
hadronic upsilon width



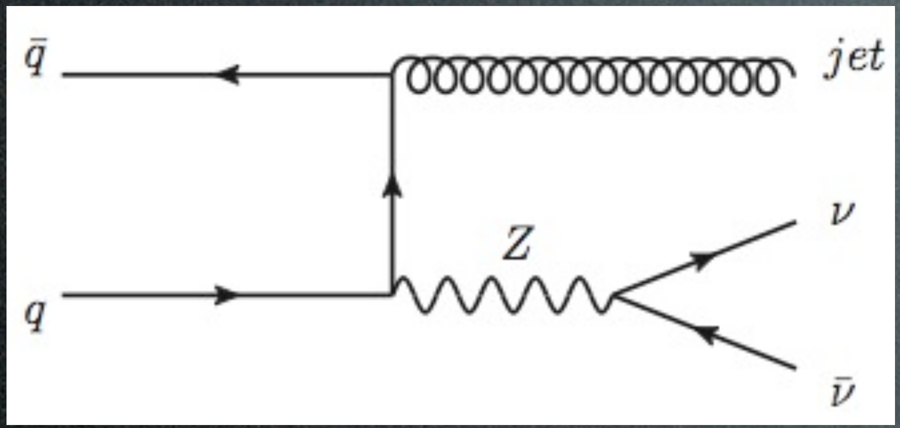
Monojets at the Tevatron

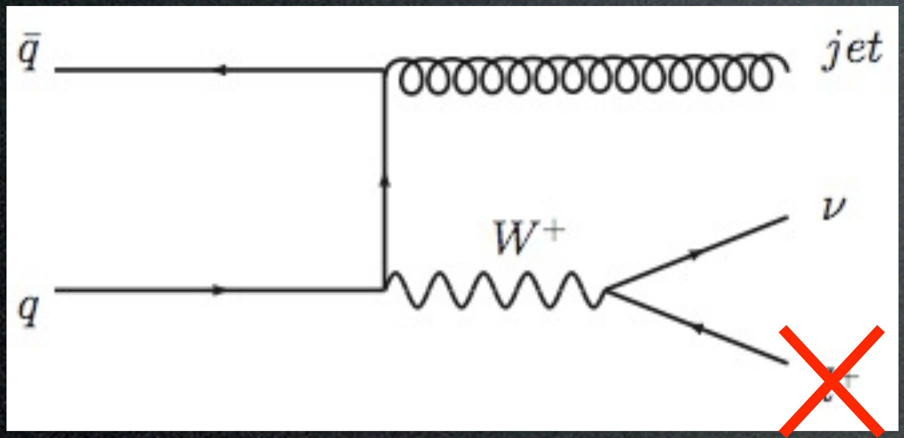
- For light DM, the Tevatron and the LHC are the world's best DD experiments [Goodman, et al. (2010); Bai, Fox, Harnik (2010)].



$$p\bar{p} \to \not{E}_T + j$$

SM monojet backgrounds





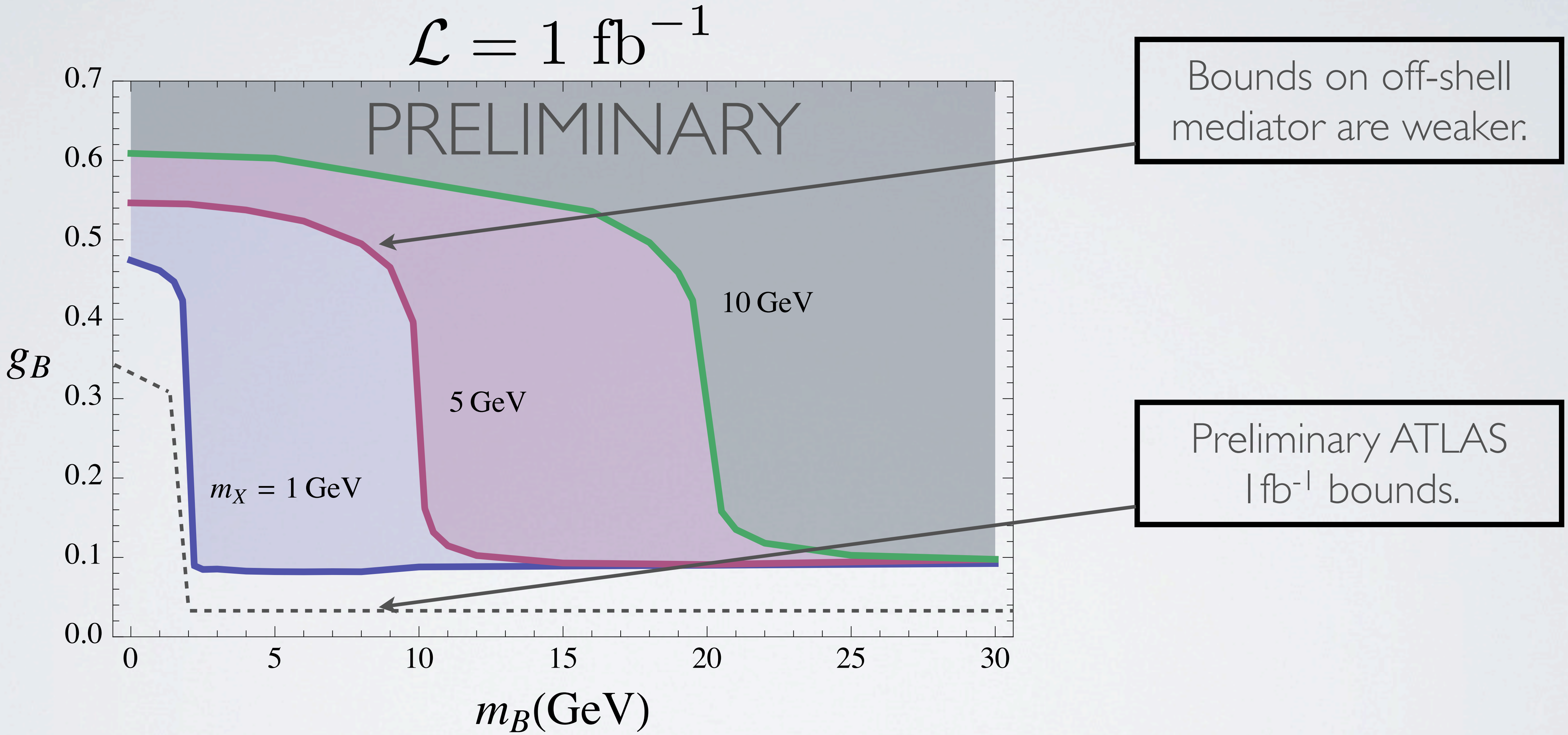
Cut at high Pt to get rid of background.

Simple counting experiment.

Given SM pred + uncertainty:

$$\sigma < 0.3 \text{ pb}$$

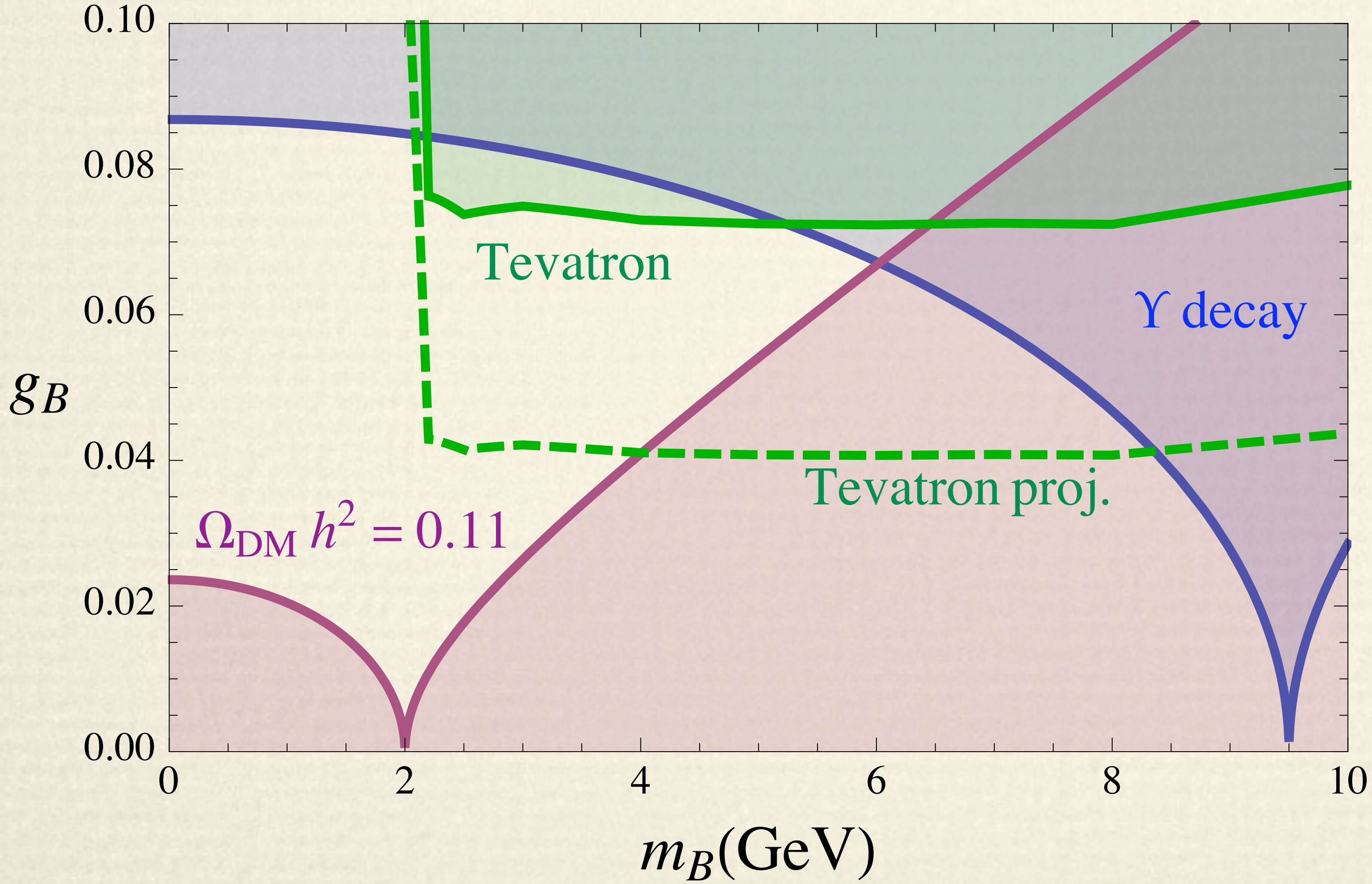
MONOJET BOUNDS



[July 18, 2011: ATLAS-CONF-2011-096]

Combined constraints: vector case

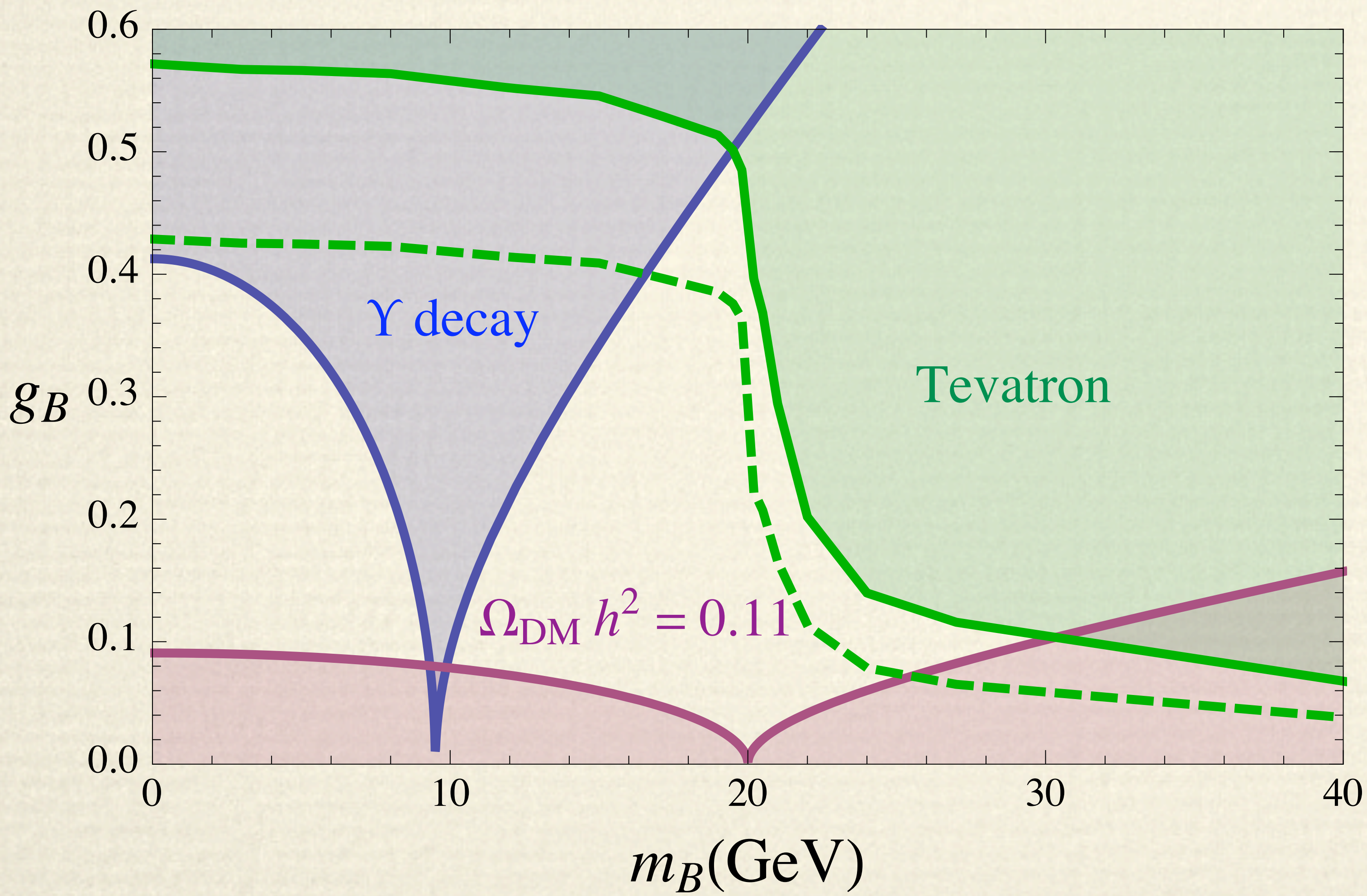
$$D^\mu X = \partial^\mu X + i g_B \left(q_V + \cancelto{0}{q_A}\gamma^5\right) Z_B^\mu X$$



$m_{DM} = 1$ GeV

Combined constraints: axial case

$$D^\mu X = \partial^\mu X + i g_B \left(\cancelto{0}{q_V} + q_A \gamma^5\right) Z_B^\mu X$$



$m_{DM} = 10\ \mathrm{GeV}$

CONCLUSIONS

- Gauging baryon number saves the proton + automatic DM candidate.
- Simultaneous generation of dark and visible asymmetries via Affleck-Dine.
- Consistent with bounds from B-factories, LEP, mono-jet Tevatron searches, and direct detection for:
    - GeV-scale DM with a GeV-scale mediator.
- LHC and direct detection will probe most of the remaining parameter space.