LLP's @ LHC: Taking Stock

M.J. Ramsey-Musolf

U Mass Amherst

AMHERST CENTER FOR FUNDAMENTAL INTERACTIONS
Physics at the interface: Energy, Intensity, and Cosmic frontiers
University of Massachusetts Amherst

http://www.physics.umass.edu/acfi/

LLP Workshop,
CERN April 2017
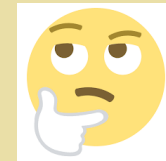
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LLP's For Newcomers

LLP's For Newcomers
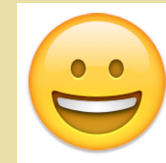

LLP Dog Race

LLP's: Roadmap for Theory & Expt

Experimental LLP Search: Motivation

- *Theorists think it's interesting*

- *It's something we can do*

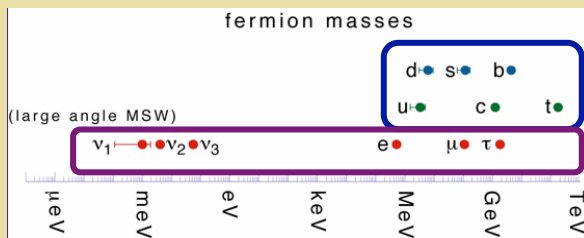- *It addresses fundamental Q's*
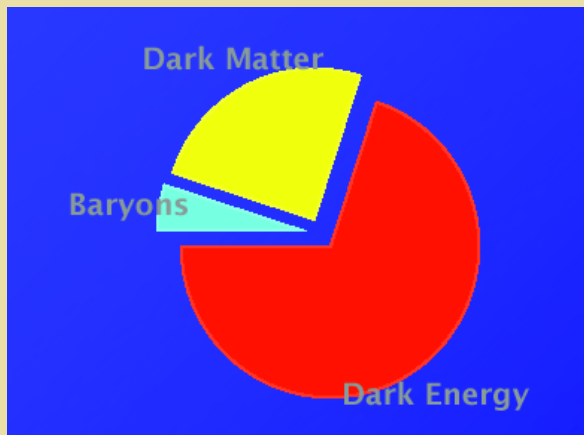
LLP's @ LHC: Motivation

- *Discovery of LLP's may provide clues to key open questions in fundamental physics*

- *Consideration of physical scales $\rightarrow$ LLP decay lengths ~ ATLAS, CMS & LHCb detectors*

- *Energy frontier capabilities are unique and complementary to those at Intensity & Cosmic frontiers*

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LLP's @ LHC: Motivation

- *Discovery of LLP's may provide clues to key open questions in fundamental physics*

- *Consideration of physical scales $\rightarrow$ LLP decay lengths ~ ATLAS, CMS & LHCb detectors*

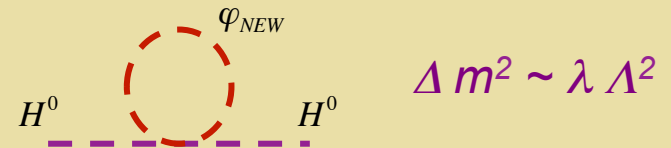- *Energy frontier capabilities are unique and complementary to those at Intensity & Cosmic frontiers*
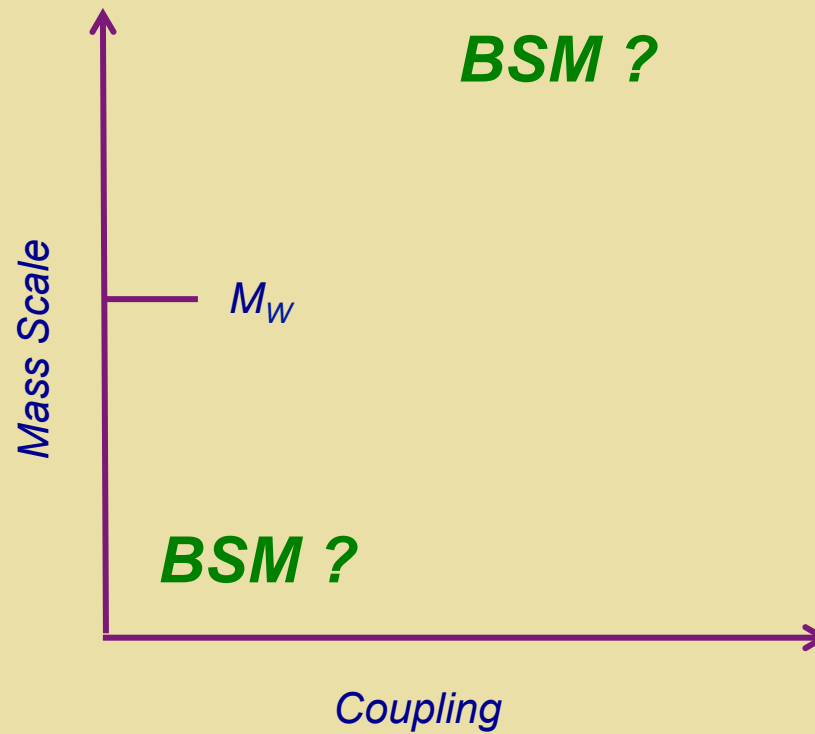
Fundamental Questions

$$\varphi_{NEW}$$

$$H^0 \qquad\qquad H^0 \qquad \Delta m^2 \sim \lambda \, \Lambda^2$$

Origin of m_ν

$$\Lambda$$ *Cosmological*

BSM Physics: Where Does it Live ?

BSM ?

M_W

Mass Scale

BSM ?

Coupling

BSM Physics: Where Does it Live ?

Mass Scale (vertical axis)

M_W

BSM ?   SUSY, see-saw, BSM Higgs sector…

BSM ?   Sterile ν's, axions, dark U(1)…

Coupling (horizontal axis)

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BSM Physics: Where Does it Live ?

Mass Scale (vertical axis), Coupling (horizontal axis)

M_W

BSM ?   SUSY, see-saw, BSM Higgs sector…

LLP's

BSM ?   Sterile ν's, axions, dark U(1)…
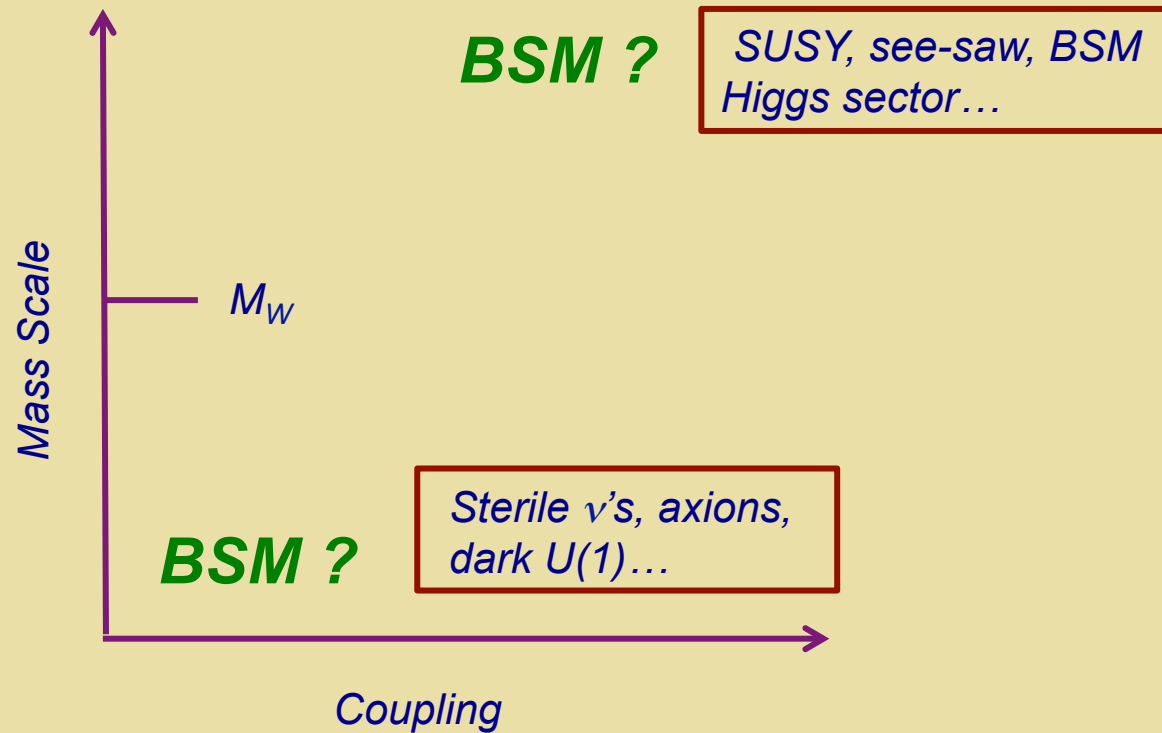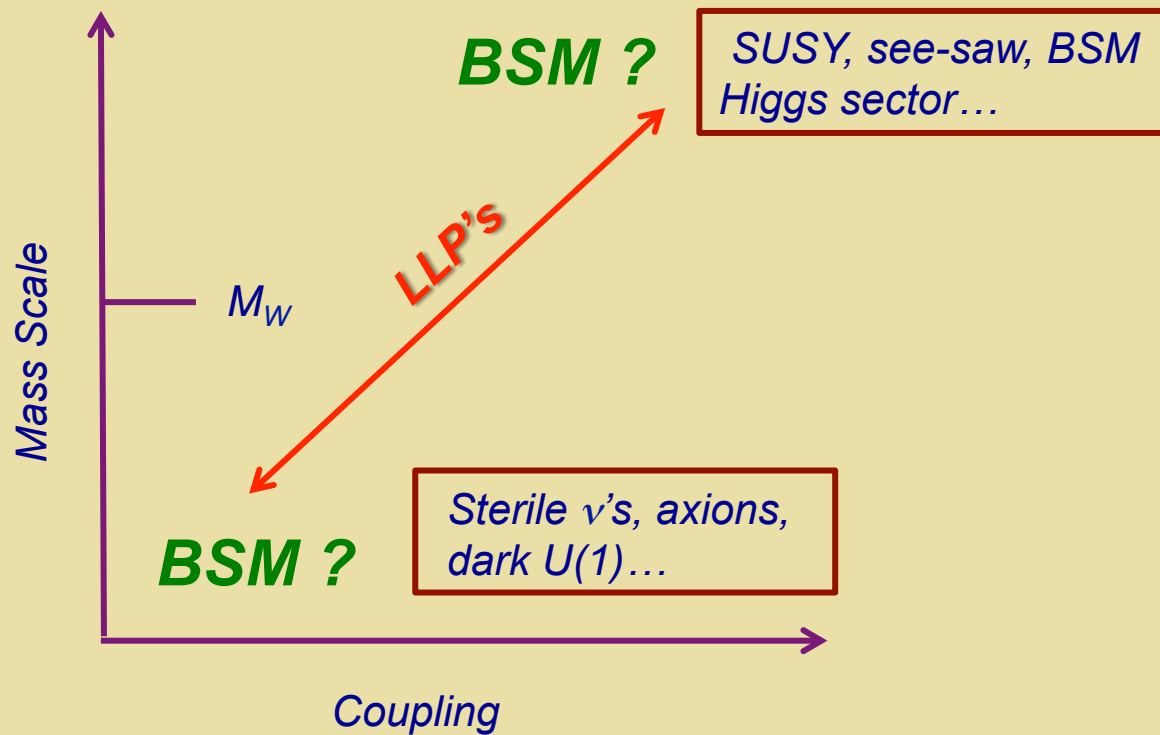
Solutions w/ LLP's: A Sampler

Apologies for omissions !

Solutions w/ LLP's: A Sampler

LLP Scenario	m_H	BAU	DM	m_ν
νSM				
WIMPY baryogenesis				
Dark QCD				
Stealth SUSY				
Neutral Naturalness				
Dark U(1)				

Solutions w/ LLP's: A Sampler

LLP Scenario	m_H	BAU	DM	m_ν
νSM	✖	✔	✔	✔
WIMPY baryogenesis	✖	✔	?	✖
Dark QCD	✖	✔	✔	✖
Stealth SUSY	✔	✔	✔	✖
Neutral Naturalness	✔	✖	✖	✖
Dark U(1)	✖	✖	✔	✖

Solutions w/ LLP's: A Sampler

LLP Scenario	m_H	BAU	DM	m_ν
νSM	✖	✔	✔	✔
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Stealth SUSY	✔	✔	✔	✖
Neutral Naturalness	✔	✖	✖	✖
Dark U(1)	✖	✖	✔	✖

Hidden Valleys

Strassler, Zurek '06…

Solutions w/ LLP's: νSM

νMSM

Spin-1/2 fermions

Quarks: u c t / d s b
Leptons: ν₁/N₁ ν₂/N₂ ν₃/N₃ / e μ τ

Spin-1 bosons: g γ Z⁰ W±
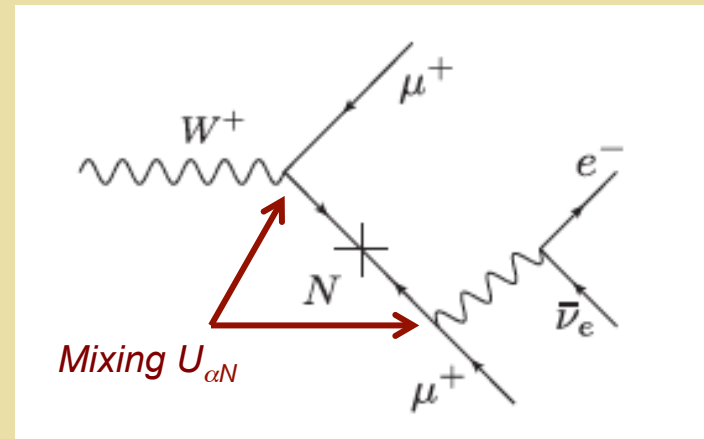
Spin-0 Higgs boson: H

P. Mermod

N_1 mass ~keV
→ **dark matter**

$N_{2,3}$ mass ~GeV
→ **seesaw**
→ **leptogenesis**

Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)

Mixing $U_{\alpha N}$

E. Izaguire & B. Shuve

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Solutions w/ LLP's: νSM

νMSM

Spin-1/2 fermions

Quarks: u, c, t / d, s, b
Leptons: ν_1/N$_1$, ν_2/N$_2$, ν_3/N$_3$ / e, μ, τ

Spin-1 bosons: g, γ, Z^0, W$^\pm$

Force carriers

Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)

Spin-0 Higgs boson: H

P. Mermod

N$_1$ mass ~keV
→ **dark matter**

N$_{2,3}$ mass ~GeV
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Mixing U$_{\alpha N}$

Leptogenesis upper bound

E. Izzaguire & B. Shuve

Legend: K → μν, BBN, PS191, BEBC, NuTeV, CHARM, Belle, DELPHI, L3, CMS, ATLAS, EWPT
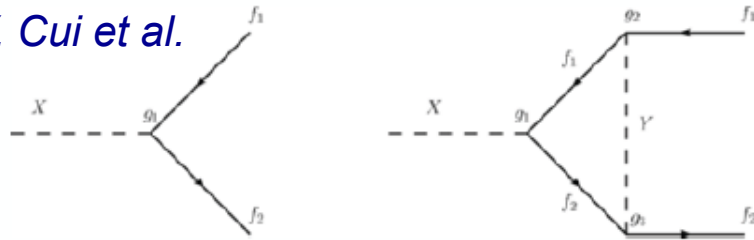
BAU from Leptogenesis

- *Drewes et al '16*

- *Lower bound < 10^{-10}*

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Solutions w/ LLP's: Wimpy Baryogenesis

Y. Cui et al.

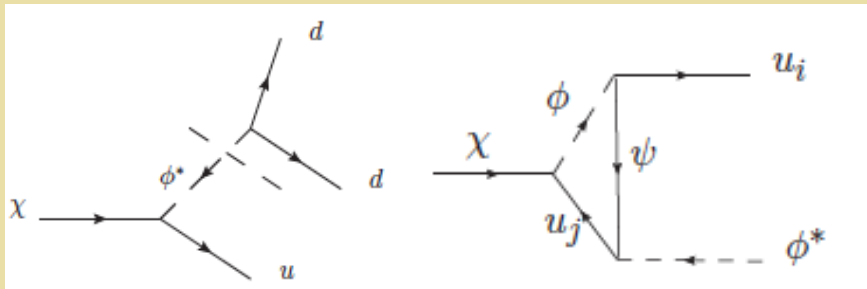$$\Gamma(\chi \to f) \neq \Gamma(\chi \to \bar{f})$$

$$n_f - n_{\bar{f}} \neq 0$$

Baryon number violating:

$$\chi \to u_i d_j d_k$$

Lepton number violating:

$$\chi \to L_i Q_j \bar{d}_k$$
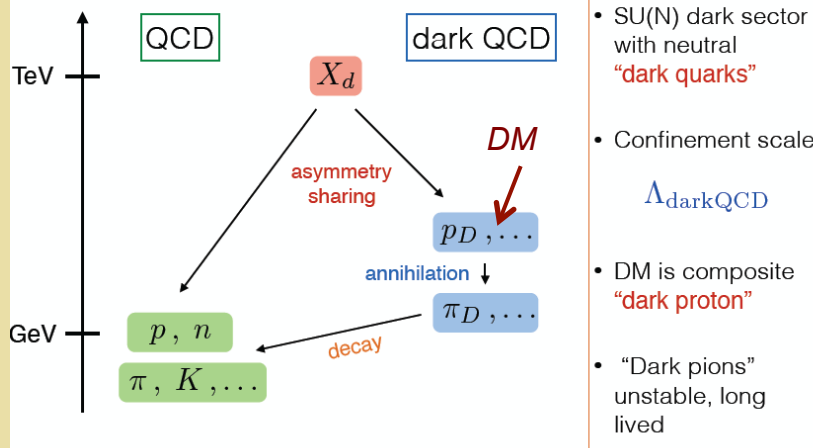$$\chi \to L_i L_j \bar{E}_k$$

Like leptogenesis

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Solutions w/ LLP's: Hidden Valleys

Solutions w/ LLP's: Dark QCD

P. Schwaller

Dark QCD
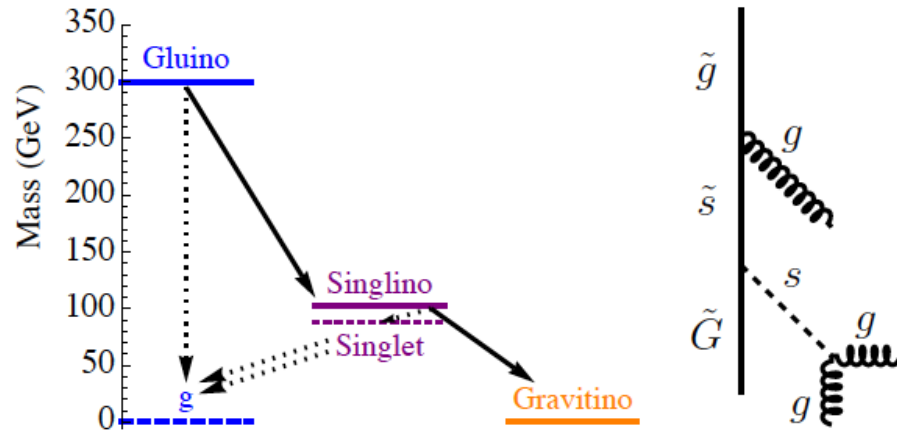
QCD | dark QCD

TeV — X_d

asymmetry sharing

DM

p_D , . . .

annihilation ↓

GeV — p, n ← decay — π_D , . . .

π, K , . . .

- SU(N) dark sector with neutral "dark quarks"
- Confinement scale Λ_{darkQCD}
- DM is composite "dark proton"
- "Dark pions" unstable, long lived

X

SM QCD   Dark QCD

Asymmetric DM: $m_{DM}\, n_{DM} \sim 5\, m_N\, n_B \;\rightarrow$

- For $n_{DM} \sim n_B \rightarrow m_{DM} \sim$ few x m_B

- $\Lambda_{dark\ QCD} \sim$ few x Λ_{QCD}

Solutions w/ LLP's: Stealth SUSY

Fan, Reece, Ruderman

Singlets

SM   Gravitino

Solutions w/ LLP's: Neutral Naturalness

D. Curtin, C. Verhaaren

Top partners

Solutions w/ LLP's: Neutral Naturalness

D. Curtin, C. Verhaaren

Solutions w/ LLP's: Neutral Naturalness

FSUSY (EW charged partners)

SM sector   mirror sector

SU(2)xU(1)

SU(3)$_A$ SU(3)$_B$

sleptons, EWinos,…

$\tilde{t}_B, \tilde{b}_B, …$

t_A

W, Z, h   LEP limits

τ, μ etc

b_A etc   glueballs

Juknevich

mirror glueball   visible Higgs   SM

top partners

O_{EFF}

SM   Mirror Glueballs

D. Curtin, C. Verhaaren

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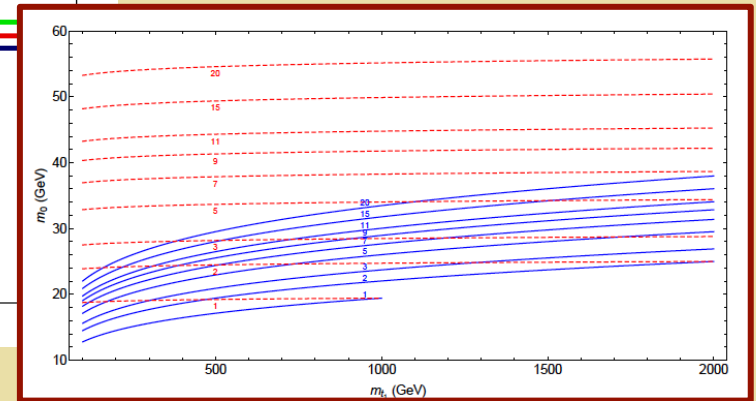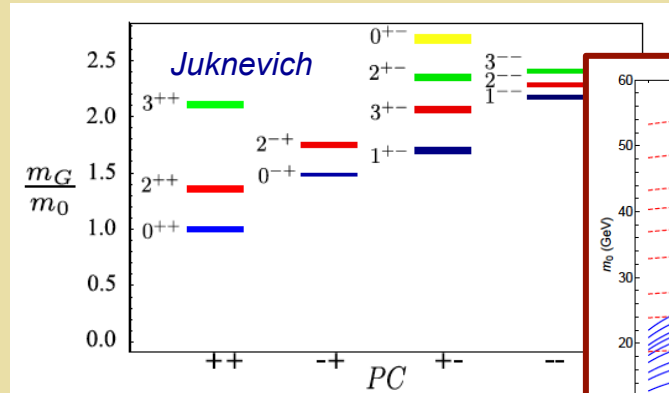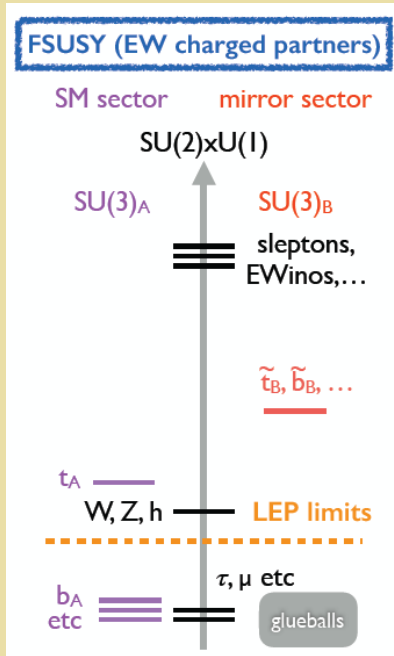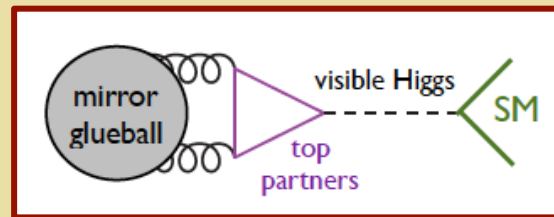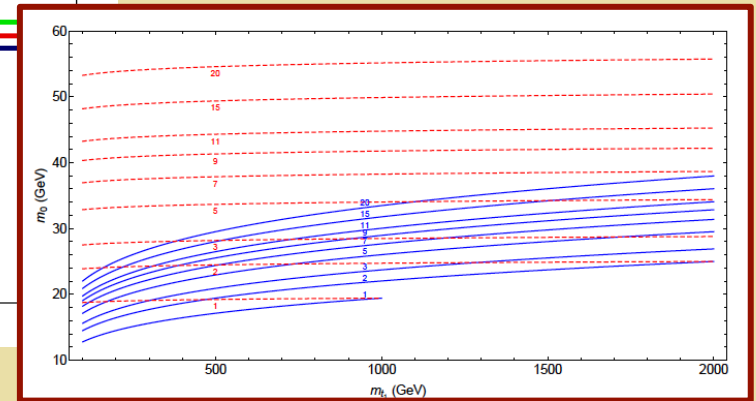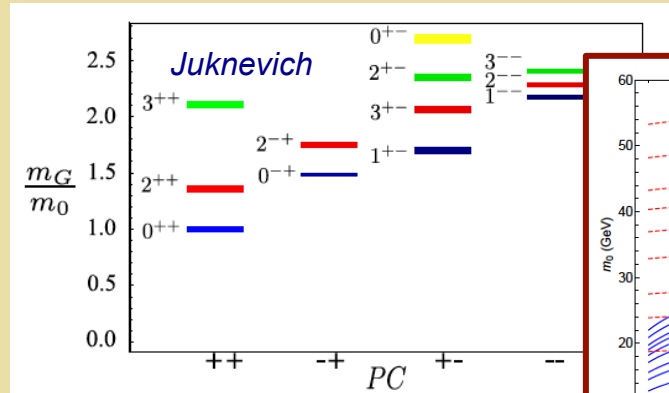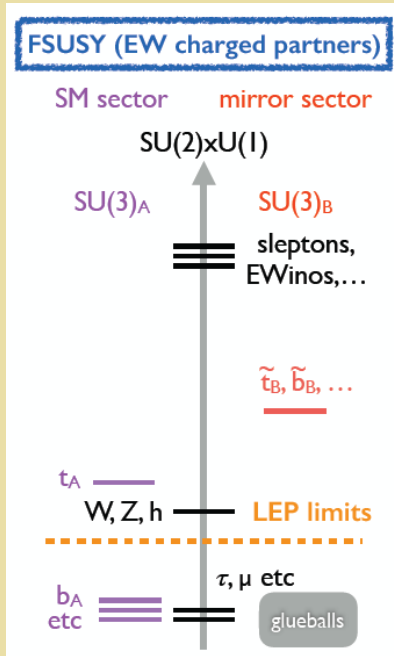
Solutions w/ LLP's: Dark U(1)

$$SU(3)_C \; x \; SU(2)_L \; x \; U(1)_Y \; x \; U(1)_D$$

Dark Z: Mechanism

$$\mathcal{L} \subset -\frac{1}{4}\,\hat{B}_{\mu\nu}\,\hat{B}^{\mu\nu} - \frac{1}{4}\,\hat{Z}_{D\mu\nu}\,\hat{Z}_D^{\mu\nu} + \frac{1}{2}\,\frac{\epsilon}{\cos\theta}\,\hat{Z}_{D\mu\nu}\,\hat{B}^{\mu\nu} + \frac{1}{2}\,m_{D,0}^2\,\hat{Z}_D^{\mu}\,\hat{Z}_{D\mu}$$

$$V_0(H,S) = -\mu^2|H|^2 + \lambda|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \kappa|S|^2|H|^2$$

Dark Z: Mechanism

$$\mathcal{L} \subset -\frac{1}{4}\,\hat{B}_{\mu\nu}\,\hat{B}^{\mu\nu} - \frac{1}{4}\,\hat{Z}_{D\mu\nu}\,\hat{Z}_D^{\mu\nu} + \boxed{\frac{1}{2}\,\frac{\epsilon}{\cos\theta}\,\hat{Z}_{D\mu\nu}\,\hat{B}^{\mu\nu}} + \boxed{\frac{1}{2}\,m_{D,0}^2\,\hat{Z}_D^{\mu}\,\hat{Z}_{D\mu}}$$

Abelian Kinetic Mixing   *Mass Mixing*

$$V_0(H,S) = -\mu^2|H|^2 + \lambda|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \boxed{\kappa|S|^2|H|^2}$$
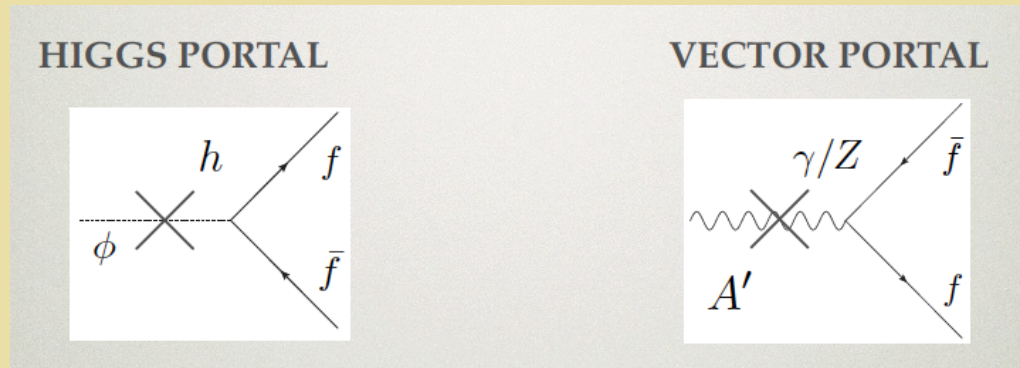
Higgs Mixing

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Dark Z: Mechanism

$$\mathcal{L} \subset -\frac{1}{4}\,\hat{B}_{\mu\nu}\,\hat{B}^{\mu\nu} - \frac{1}{4}\,\hat{Z}_{D\mu\nu}\,\hat{Z}_D^{\mu\nu} + \boxed{\frac{1}{2}\,\frac{\epsilon}{\cos\theta}\,\hat{Z}_{D\mu\nu}\,\hat{B}^{\mu\nu}} + \boxed{\frac{1}{2}\,m_{D,0}^2\,\hat{Z}_D^{\mu}\,\hat{Z}_{D\mu}}$$

Abelian Kinetic Mixing   *Mass Mixing*

$$+\,\lambda_S|S|^4 + \boxed{\kappa|S|^2|H|^2}$$
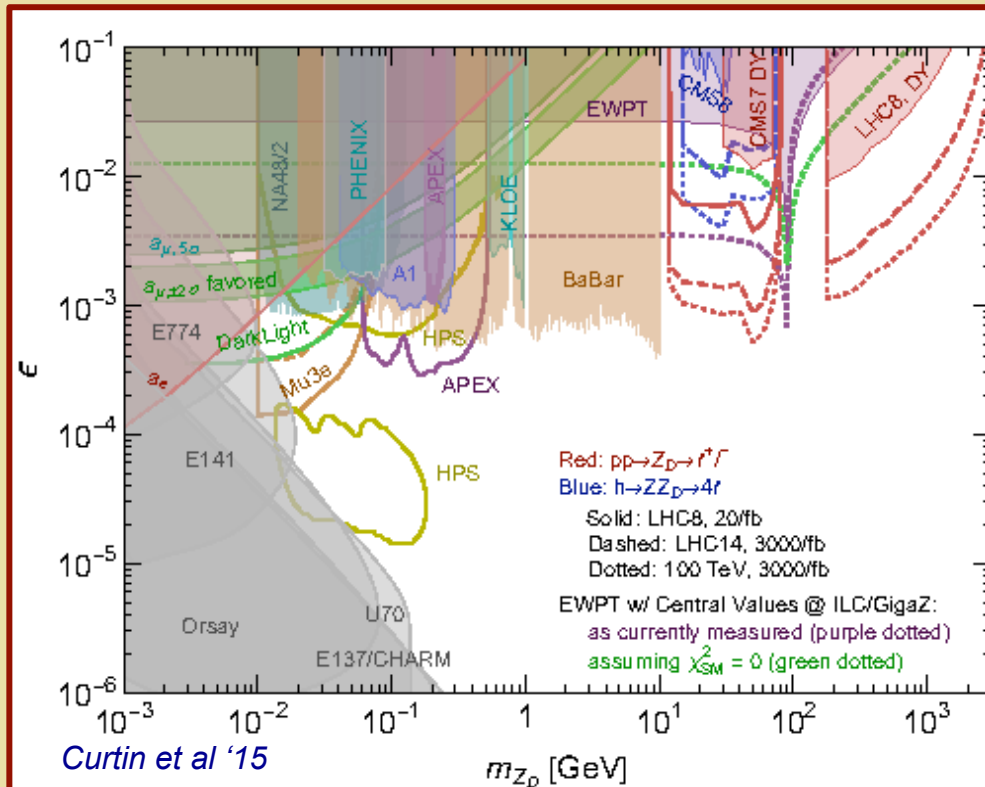
Higgs Mixing

Curtin et al '15

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Dark Z: Mechanism

$$\mathcal{L} \subset -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{Z}_{D\mu\nu}\hat{Z}_D^{\mu\nu} + \frac{1}{2}\frac{\epsilon}{\cos\theta}\hat{Z}_{D\mu\nu}\hat{B}^{\mu\nu} + \frac{1}{2}m_{D,0}^2\hat{Z}_D^{\mu}\hat{Z}_{D\mu}$$

Why so tiny?

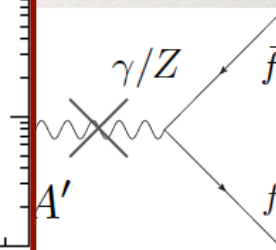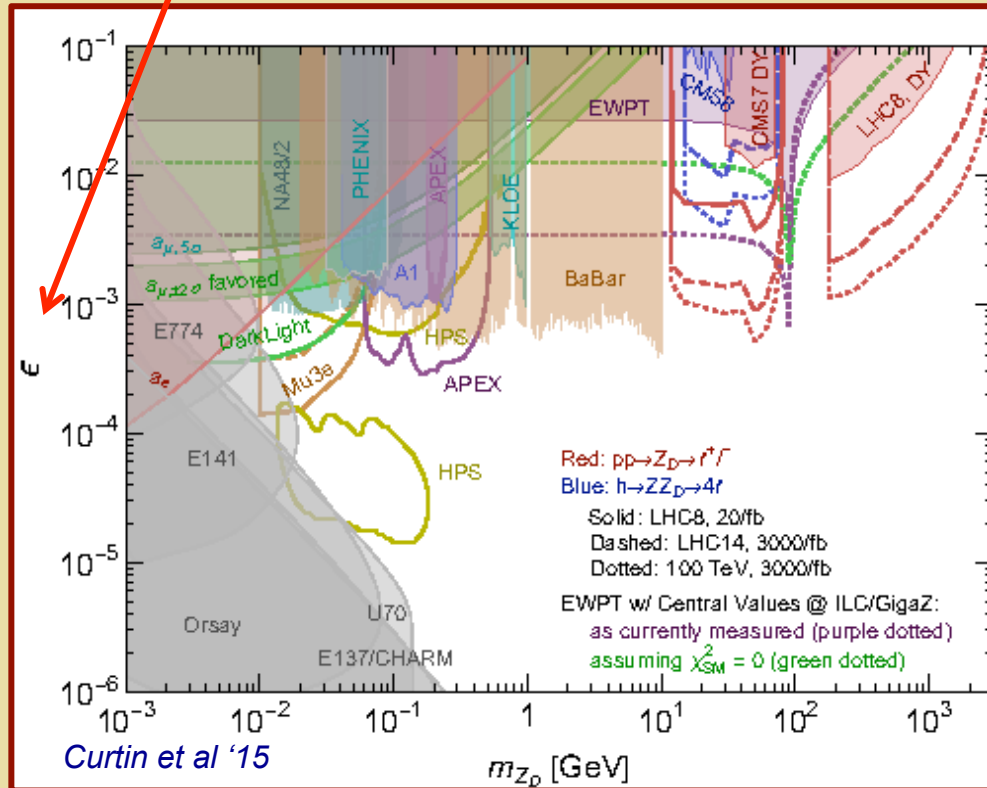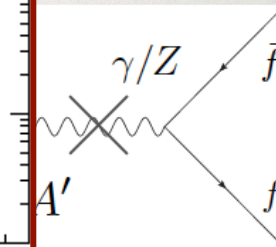**Abelian Kinetic Mixing**   **Mass Mixing**

$$+ \lambda_S|S|^4 + \kappa|S|^2|H|^2$$

Higgs Mixing

Curtin et al '15

Red: $pp \to Z_D \to l^+l^-$
Blue: $h \to ZZ_D \to 4l$
Solid: LHC8, 20/fb
Dashed: LHC14, 3000/fb
Dotted: 100 TeV, 3000/fb
EWPT w/ Central Values @ ILC/GigaZ:
as currently measured (purple dotted)
assuming $\chi^2_{SM} = 0$ (green dotted)

...CTOR PORTAL

γ/Z $\bar{f}$

A' f

Dark Z: Mechanism

Non-Abelian Kinetic Mixing

$$\mathcal{O}^{(5)}_{WX} = -\frac{\beta}{\Lambda}\,\mathrm{Tr}\left(W_{\mu\nu}\Sigma\right)X^{\mu\nu}$$

$$\epsilon = \beta\sin\theta_W\left(\frac{\upsilon_\Sigma}{\Lambda}\right)$$
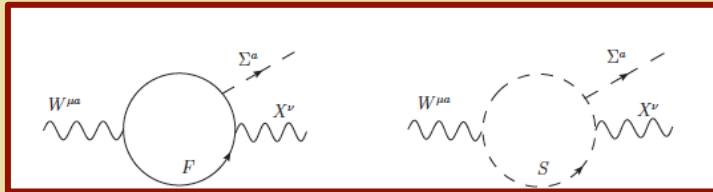
SU(2)$_L$ x U(1)$_D$ mediators

Small ε from scale ratio;

$\beta \sim O(1)$

Arguelles, He, Ovaneysan, Peng, MRM '16
See also Barello, Chang, Newby '15

LLP's @ LHC: Motivation

- *Discovery of LLP's may provide clues to key open questions in fundamental physics*

- *Consideration of physical scales $\rightarrow$ LLP decay lengths ~ ATLAS, CMS & LHCb detectors*

- *Energy frontier capabilities are unique and complementary to those at Intensity & Cosmic frontiers*

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Solutions w/ LLP's: νSM

νMSM

Spin-1/2 fermions

Quarks: u, c, t / d, s, b

Leptons: ν_1/N_1, ν_2/N_2, ν_3/N_3 / e, μ, τ

Spin-1 bosons: g, γ, Z^0, $W^\pm$

Spin-0 Higgs boson: H

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P. Mermod

N_1 mass ~keV
→ **dark matter**

$N_{2,3}$ mass ~GeV
→ **seesaw**
→ **leptogenesis**

Mixing $U_{\alpha N}$

Excluded

Leptogenesis upper bound

$c\tau_N = 10$ m

$c\tau_N = 10$ cm

$c\tau_N = 0.1$ mm

E. Izzaguire & B. Shuve

$$\Gamma(N \to \ell_\alpha^- \ell_\beta^+ \nu_\beta) = \frac{G_F^2 M_N^5 |V_{\alpha N}|^2}{192\pi^3}$$

See also: Helo, Kovalenko & Hirsch
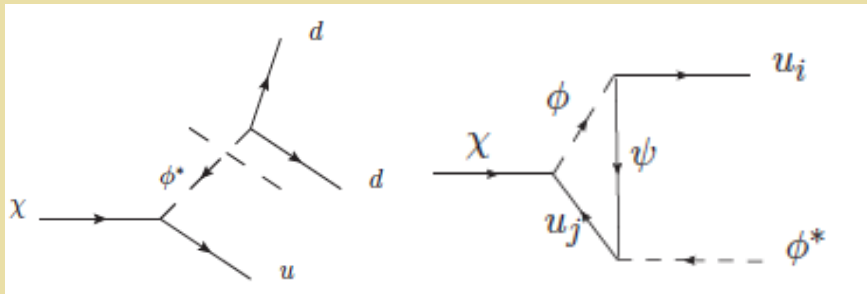
32

Solutions w/ LLP's: Wimpy Baryogenesis

Baryon number violating:

$$\chi \to u_i d_j d_k$$

Lepton number violating:

$$\chi \to L_i Q_j \bar{d}_k$$
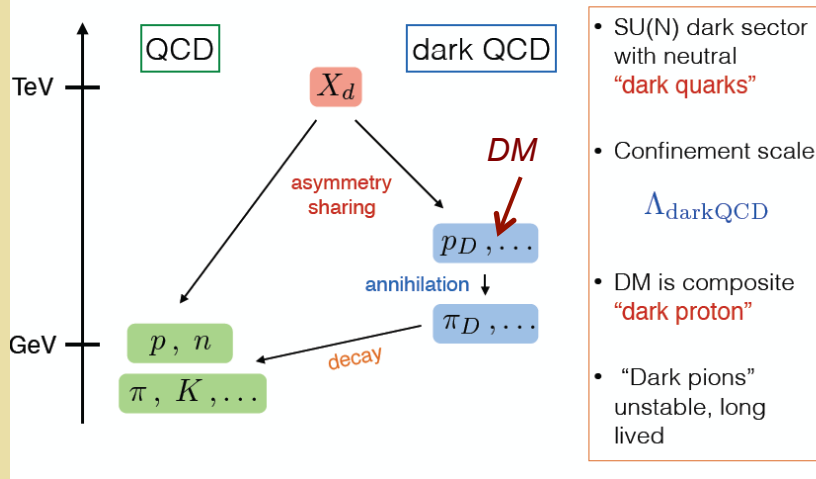$$\chi \to L_i L_j \bar{E}_k$$

3-body phase space

Sakharov: out-of-eq condition

$$\Gamma_\chi < H(T = M_\chi) \qquad \Longleftrightarrow \qquad c\tau_\chi \gtrsim \mathrm{mm}$$

Solutions w/ LLP's: Dark QCD

P. Schwaller

Dark QCD

- SU(N) dark sector with neutral "dark quarks"
- Confinement scale $\Lambda_{\mathrm{darkQCD}}$
- DM is composite "dark proton"
- "Dark pions" unstable, long lived

Asymmetric DM: $m_{DM}\, n_{DM} \sim 5\, m_N\, n_B \;\rightarrow$

- *For* $n_{DM} \sim n_B \rightarrow m_{DM} \sim$ *few x* m_B

- $\Lambda_{dark\, QCD} \sim$ *few x* Λ_{QCD}

$$c\tau(\pi_D \to \mathrm{SM}) \sim \frac{M_X^4}{m_{\pi_D}^5} \sim \mathrm{cm} \times \left(\frac{M_X}{\mathrm{TeV}}\right)^4 \left(\frac{\mathrm{GeV}}{m_{\pi_D}}\right)^5$$

SM QCD   X   Dark QCD

Solutions w/ LLP's: Stealth SUSY

Fan, Reece, Ruderman

$$\Gamma_{\tilde{X}} = \frac{m_{\tilde{X}}^5}{16\pi F^2} \left(1 - \frac{m_X^2}{m_{\tilde{X}}^2}\right)^4 \approx \frac{m_{\tilde{X}} (\delta m)^4}{\pi F^2}$$

m_X = 100 GeV
δm ~ 10 GeV $c\,\tau$ ~ 10 cm
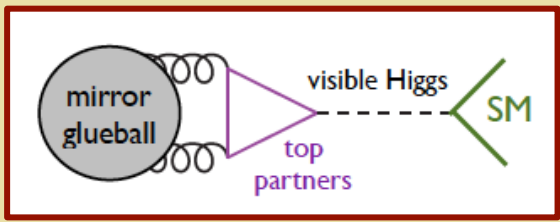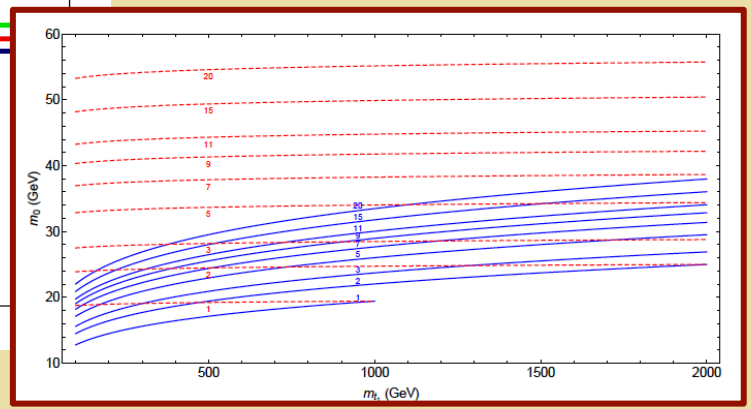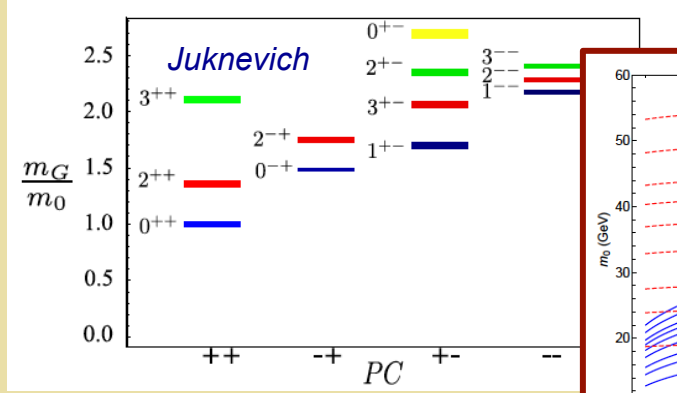F ~ (100 TeV)^2

Solutions w/ LLP's: Neutral Naturalness

FSUSY (EW charged partners)

SM sector   mirror sector

SU(2)xU(1)

SU(3)$_A$ SU(3)$_B$

sleptons, EWinos,…

$\tilde{t}_B, \tilde{b}_B, \ldots$

t_A

W, Z, h   LEP limits

b_A etc τ, μ etc

glueballs

Juknevich

$\frac{m_G}{m_0}$

PC

mirror glueball   visible Higgs

top partners   SM

$$\Gamma_{0^{++}} \sim m_0^7/(M^4 m_h^2)$$

O_{EFF}

SM   Mirror Glueballs

m

cm

D. Curtin, C. Verhaaren

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Spin-1 bosons: g, γ, Z⁰, W±

Force carriers

Ann. Rev. Nucl. Part. Sci. 59, 191 (2009)

Spin-0 Higgs boson: H

N_1 mass ~keV
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$N_{2,3}$ mass ~GeV
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→ **leptogenesis**

P. Mermod

W^+, μ^+, e^-, N, $\bar{\nu}_e$, μ^+

Mixing $U_{\alpha N}$

Excluded

Leptogenesis upper bound

SHiP proposal

Lepton jet search

Trilepton search

$|V_{\alpha N}|^2$ vs M_N (GeV)

E. Izzaguire & B. Shuve

$$\Gamma(N \to \ell_\alpha^- \ell_\beta^+ \nu_\beta) = \frac{G_F^2 M_N^5 |V_{\alpha N}|^2}{192\pi^3}$$

- *Displaced LJ + μ*
- *3 resolved prompt leptons*

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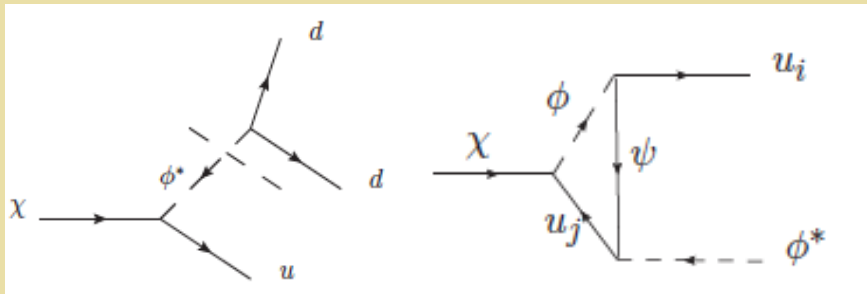# Solutions w/ LLP's: Wimpy Baryogenesis

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Lepton number violating:

$$\chi \to L_i Q_j \bar{d}_k$$
$$\chi \to L_i L_j \bar{E}_k$$

3-body phase space

- BNV: displaced jets
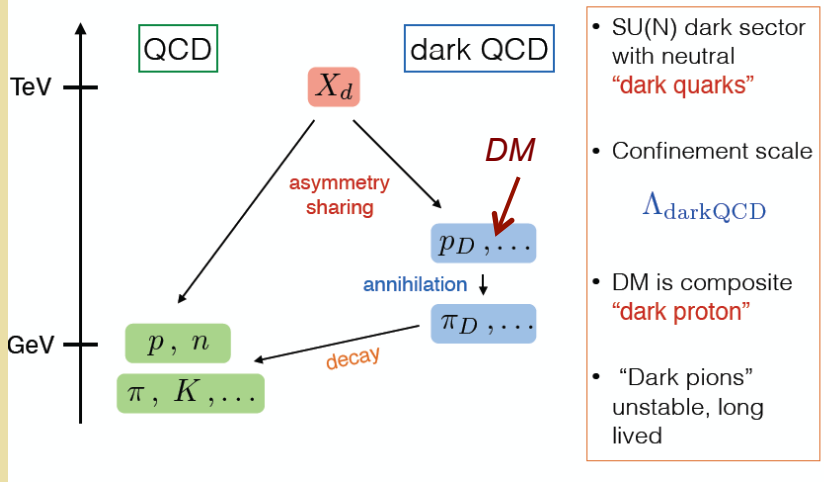- LNV: displaced μ + tracks

Sakharov: out-of-eq condition

$$\Gamma_\chi < H(T = M_\chi) \quad \longleftrightarrow \quad c\tau_\chi \gtrsim \text{mm}$$
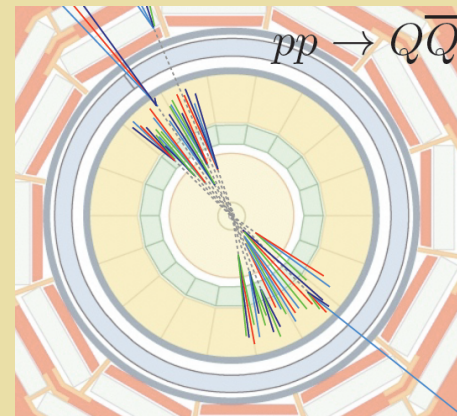
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P. Schwaller
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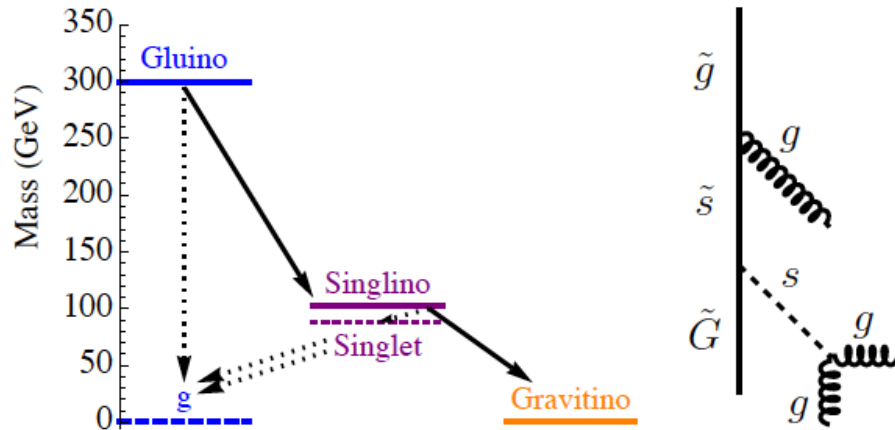
Emerging Jets
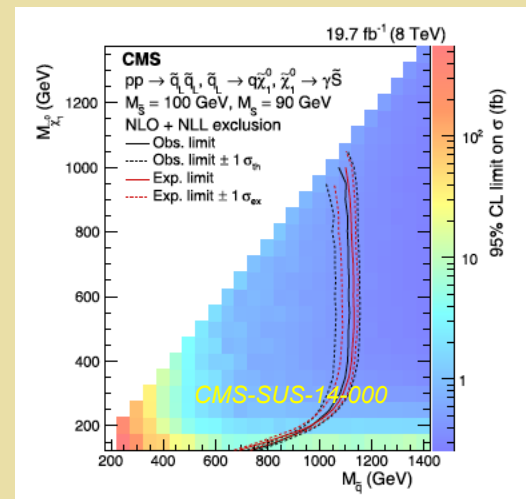
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Fan, Reece, Ruderman

$$\Gamma_{\tilde{X}} = \frac{m_{\tilde{X}}^5}{16\pi F^2} \left(1 - \frac{m_X^2}{m_{\tilde{X}}^2}\right)^4 \approx \frac{m_{\tilde{X}} \, (\delta m)^4}{\pi F^2}$$
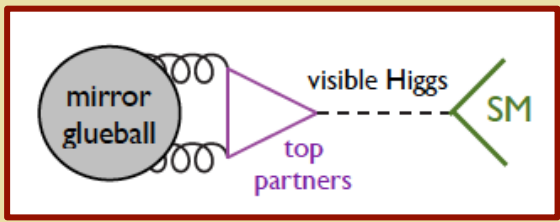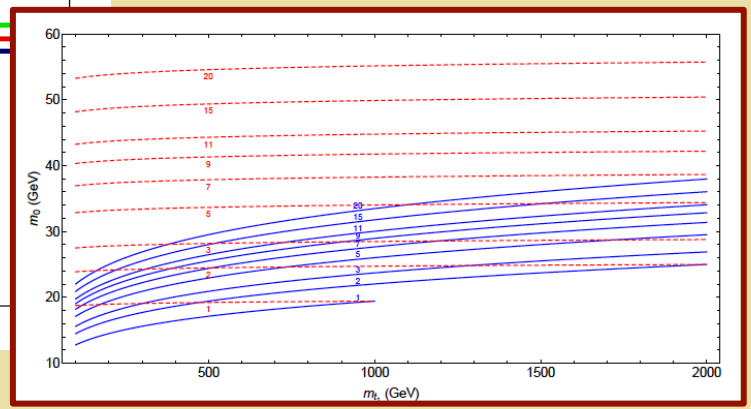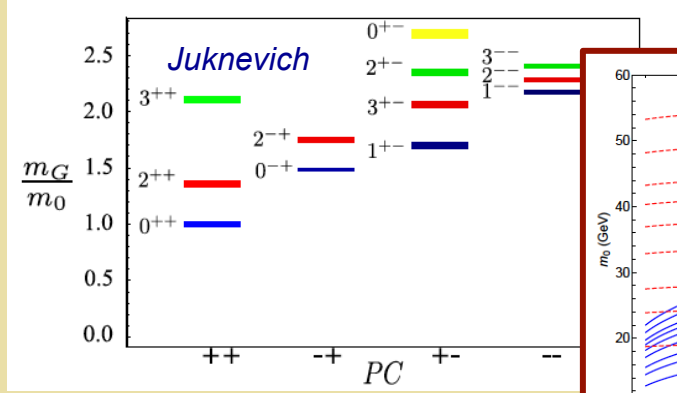
m_X = 100 GeV
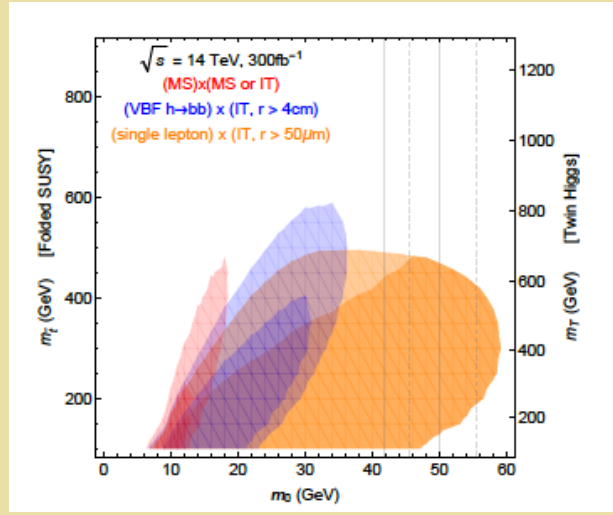δm ~ 10 GeV $c \, \tau$ ~ 10 cm
F ~ (100 TeV)^2

- Prompt V + displaced jj ("false resonances")
- DV's + high multiplicity b-jets
- …

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Solutions w/ LLP's: Neutral Naturalness

FSUSY (EW charged partners)

SM sector   mirror sector

$SU(2) \times U(1)$

$SU(3)_A$ $SU(3)_B$

sleptons, EWinos,…

$\tilde{t}_B, \tilde{b}_B, …$

t_A

W, Z, h   LEP limits

τ, μ etc

b_A etc   glueballs

Juknevich

$\frac{m_G}{m_0}$

0^{+-} 2^{+-} 3^{++} 2^{++} 0^{-+} 2^{-+} 1^{+-} 3^{+-} 3^{--} 2^{--} 1^{--}

PC

m_0 (GeV) m_{t_1} (GeV)

mirror glueball → visible Higgs → SM

top partners
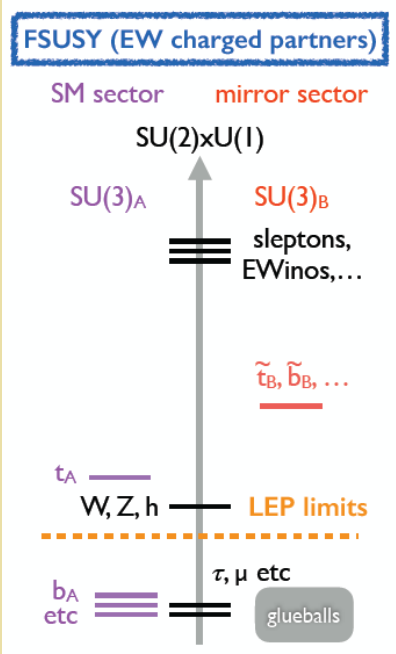
Exotic Higgs decays: $h \to 0^{++} 0^{++}$
w/ 2 DV's or 1 DV +…

O_{EFF}

SM   Mirror Glueballs

$\sqrt{s}$ = 14 TeV, 300fb⁻¹
(MS)x(MS or IT)
(VBF h→bb) x (IT, r > 4cm)
(single lepton) x (IT, r > 50μm)

$m_{\tilde{t}}$ (GeV) [Folded SUSY] m_T (GeV) [Twin Higgs]

m_0 (GeV)

D. Curtin,
C. Verhaaren

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Dark Z: Mechanism

$$\mathcal{L} \subset -\frac{1}{4}\,\hat{B}_{\mu\nu}\,\hat{B}^{\mu\nu} - \frac{1}{4}\ \dots \quad + \boxed{\frac{1}{2}\,m_{D,0}^2\,\hat{Z}_D^\mu\,\hat{Z}_{D\mu}}$$

PVES

Mass Mixing

Lee, Marciano
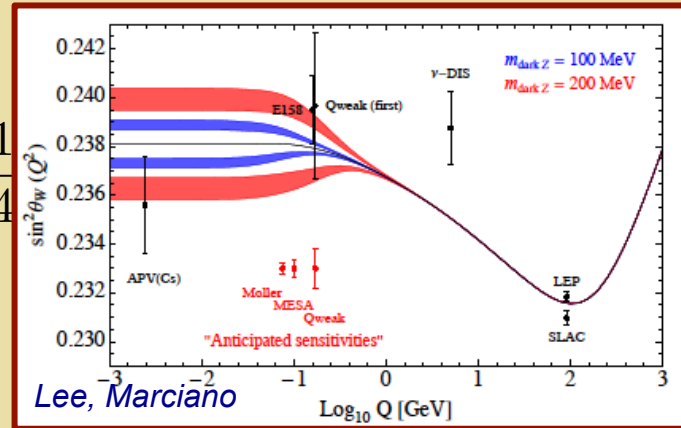
$$V_0(H,S) = -\mu^2|H|^2 + \lambda|H|^4 - \mu_S^2|S|^2 + \lambda_S|S|^4 + \boxed{\kappa|S|^2|H|^2}$$
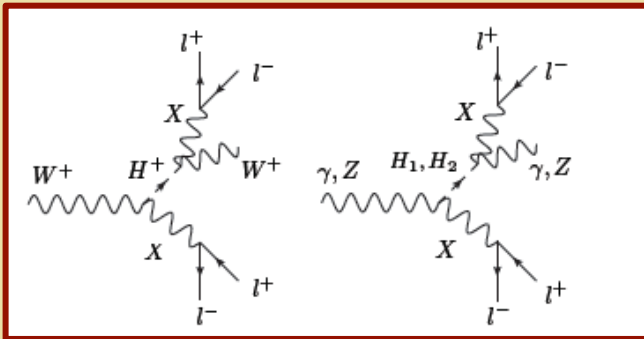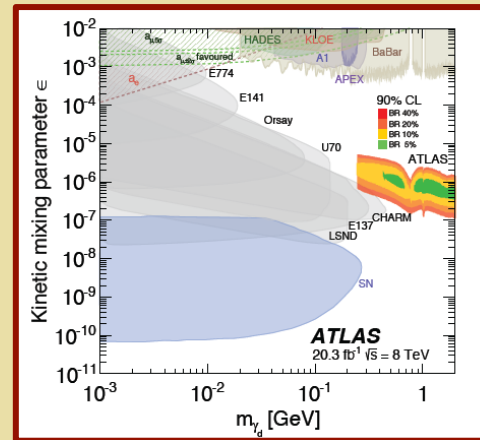
Higgs Mixing

$h \to Z_D\,Z_D$

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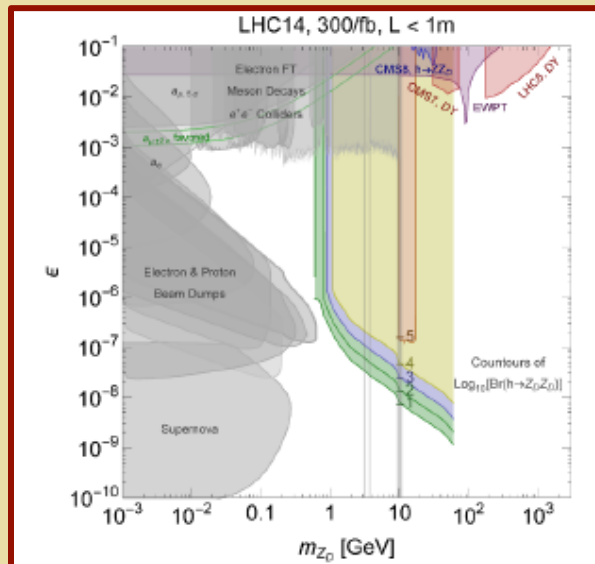
Dark Z: Mechanism
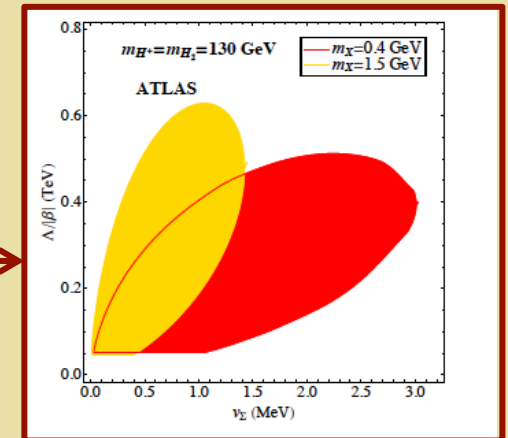
Non-Abelian Kinetic Mixing

$$\mathcal{O}_{WX}^{(5)} = -\frac{\beta}{\Lambda} \, \mathrm{Tr}\left(W_{\mu\nu}\Sigma\right) X^{\mu\nu}$$

Prompt V + 2 displaced LJ's

*Recast ATLAS '14
(no prompt V)*

Arguelles, He, Ovaneysan, Peng, MRM '16

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LLP's: Roadmap for Theory & Expt

Time to extend the coverage & reach !

LLP's: Challenges

- *1 or 2 displaced LJ's + prompt L or V (N_R , non-Abelian Z_D)*

- *Displaced jets (WIMPY baryogenesis, neutral naturalness)*

- *Displaced V + jets (Stealth SUSY)*

- *Displaced μ + tracks (WIMPY baryogenesis)*

- *Emerging jets (Dark QCD)*

- *High multiplicity b-jets + displaced jets (Stealth SUSY, hidden valleys…)*

- *Disappearing or kinked charged tracks (SUSY, quirks, EW multiplet DM…)*

- *…*

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LLP's: Challenges

so where do we start?

displaced multitrack vertices

disappearing or kinked tracks

non-pointing (converted) photons

displaced leptons, lepton-jets, or lepton pairs

emerging jets

trackless, low-EMF jets

quasi-stable charged particles

multitrack vertices in the muon spectrometer

P(decay)

1% "prompt"

25% in tracker

60% in calorimeters

13% in muon system

~1% outside the detector

distance travelled

24 April 2017

H. Russell

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LLP's: Challenges

WG 1

Simp models & recast

WG 2

Backgrounds

Triggering

WG 3

Dark Shower

WG 4

LLP's: Challenges

WG 1

Simp models & recast

(Common production) x
(Variety of decay objects)

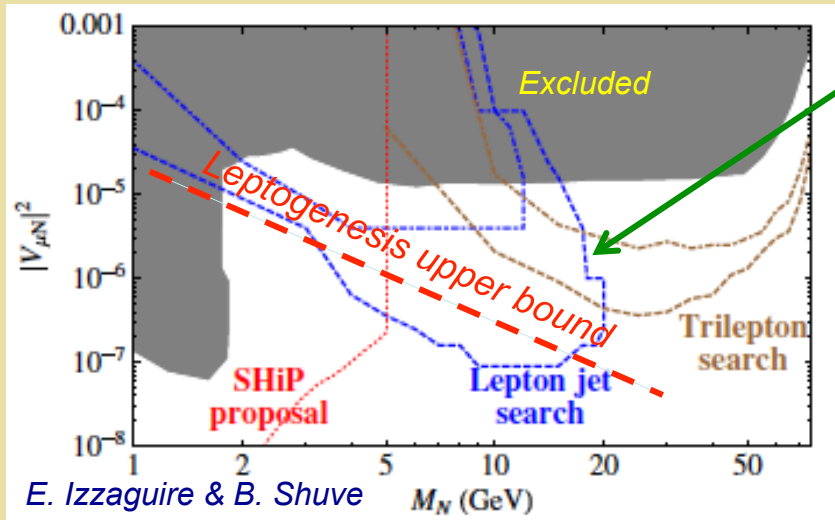L1 in good shape, but
exploit associated objects

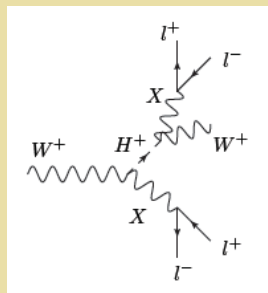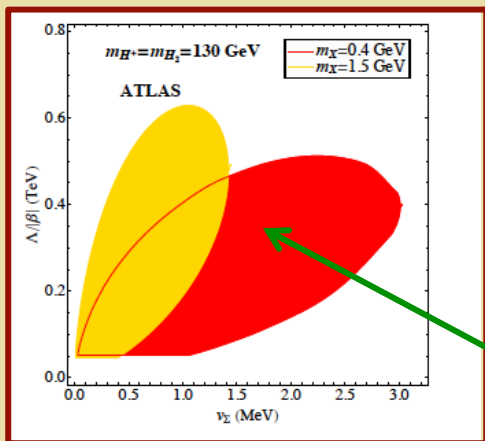Triggering

WG 3

WG 2

Backgrounds

Dark Shower

WG 4

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Push the Reach w/ Prompt Objects

Excluded

Leptogenesis upper bound

SHiP proposal

Lepton jet search

Trilepton search

E. Izzaguire & B. Shuve

Prompt μ + semilept N_R decay

VBF jets or prompt V

$\sqrt{s} = 14$ TeV, 300fb^{-1}
(MS)x(MS or IT)
(VBF h→bb) x (IT, r > 4cm)
(single lepton) x (IT, r > 50μm)

$m_{H^+} = m_{H_1} = 130$ GeV
$m_X = 0.4$ GeV
$m_X = 1.5$ GeV
ATLAS
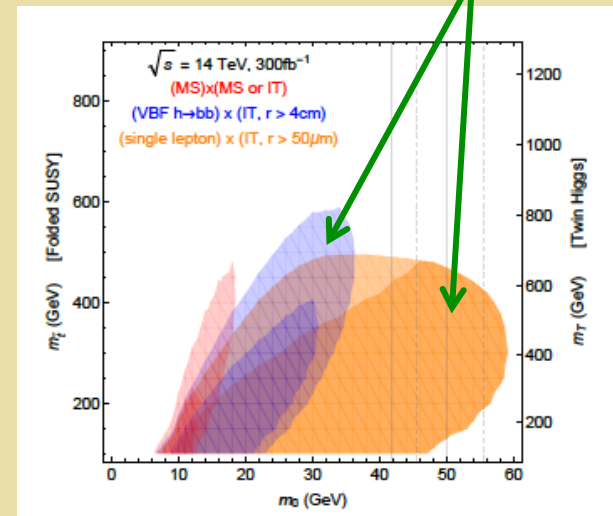
Prompt W + 2 DV lepton jets

Associated prompt objects !

LLP's: Challenges

WG 1

Simp models & recast

(Common production) x (Variety of decay objects)

Initial set

Model library

WG 2

Backgrounds

Vetoing map

L1 in good shape, but exploit associated objects

Triggering

WG 3

New paths ?
Displaced tau's
Mono-X

Upgrade: new layer ?

Many open Q's

Dark Shower

WG 4

LLP's: Outlook