Long Lived Particles at the LHC

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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/

Thanks: UMass Experimental HEP Group

LLP Workshop, ICTP Trieste
October 2017

Goals For This Talk

- *Energize: remind ourselves why searching for LLP's is exciting*
- *Evangelize: convince our colleagues that this scientific quest is important*
- *Engage: help set the foundation for the workshop and white paper completion*

Outline

I. BSM LLP Searches: Motivation

II. LLP Scenarios: A Sampler

III. Building a Roadmap

I. BSM LLP Searches: Motivation

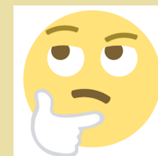
LLP's For Newcomers

LLP's For Newcomers

LLP Dog Race

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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Fundamental Questions

***MUST** answer*

***SHOULD** answer*

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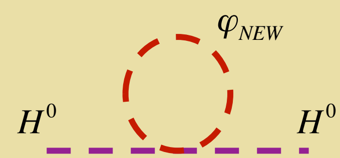


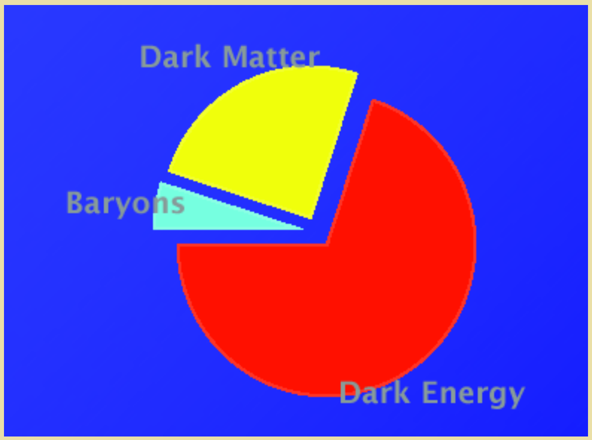
$\Delta m^2 \sim \lambda \Lambda^2$

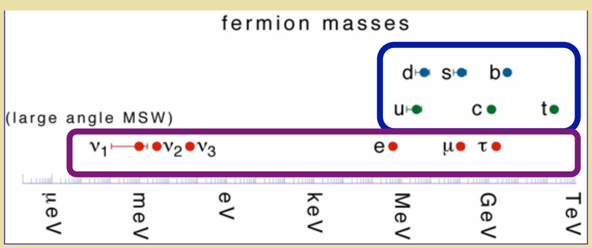
$\Lambda_{Cosmological}$

θ_{QCD} , *parity, unification...*

Fundamental Questions

***MUST** answer*

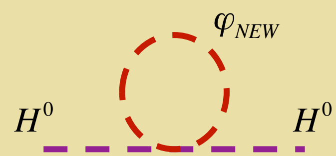




Origin of m_ν

flavor…

***SHOULD** answer*



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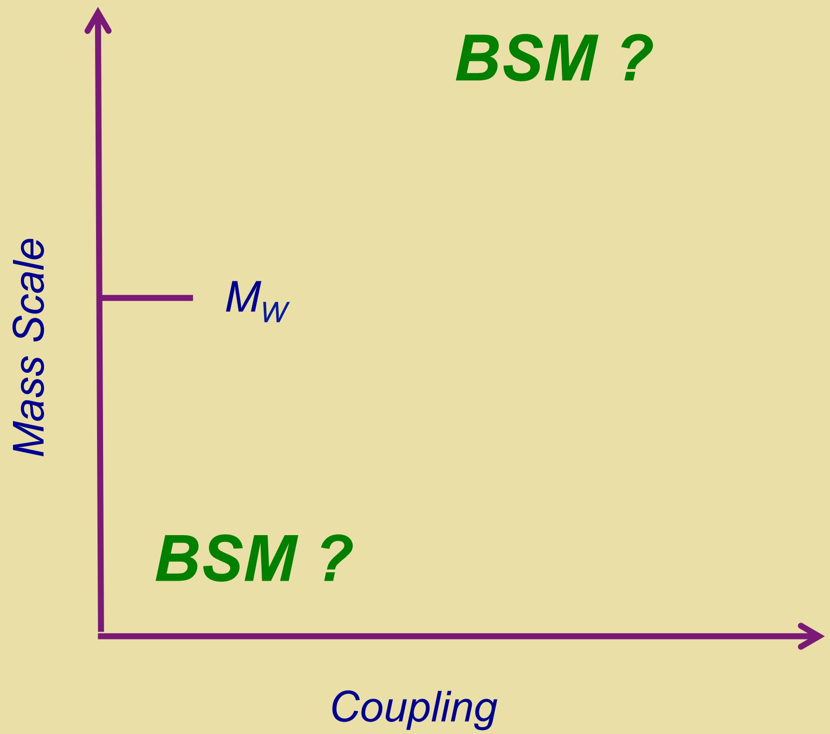
BSM Physics: Where Does it Live ?



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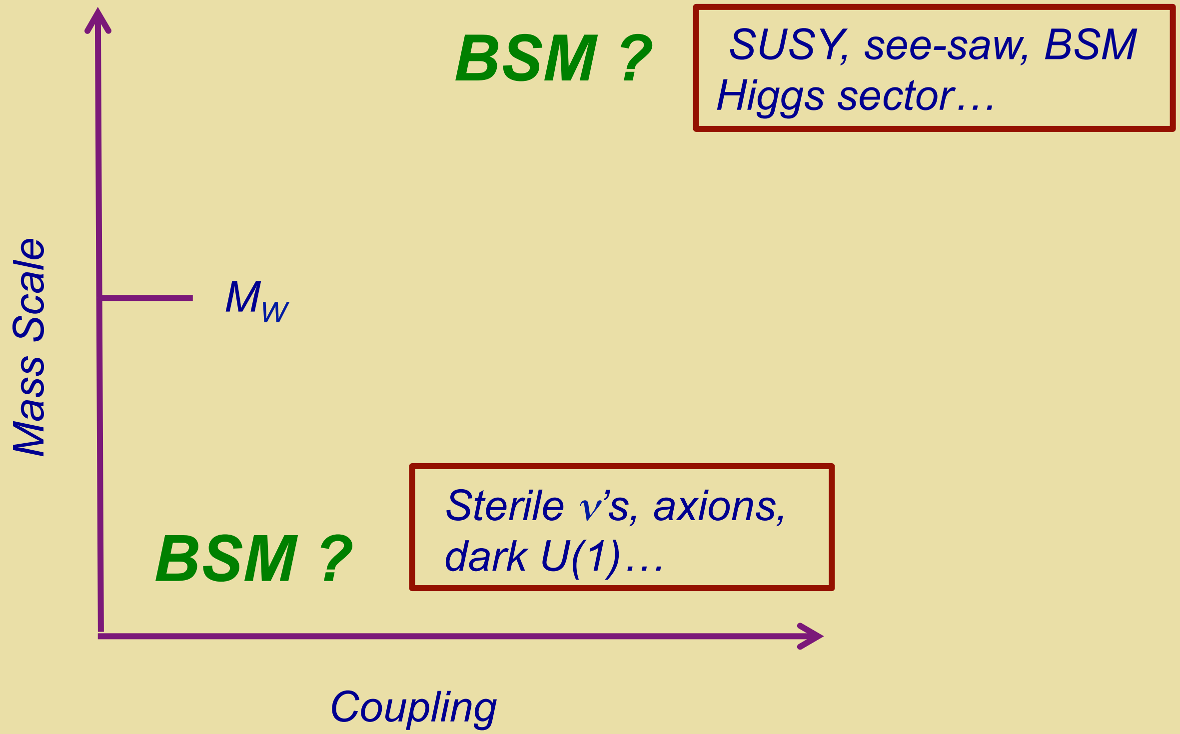

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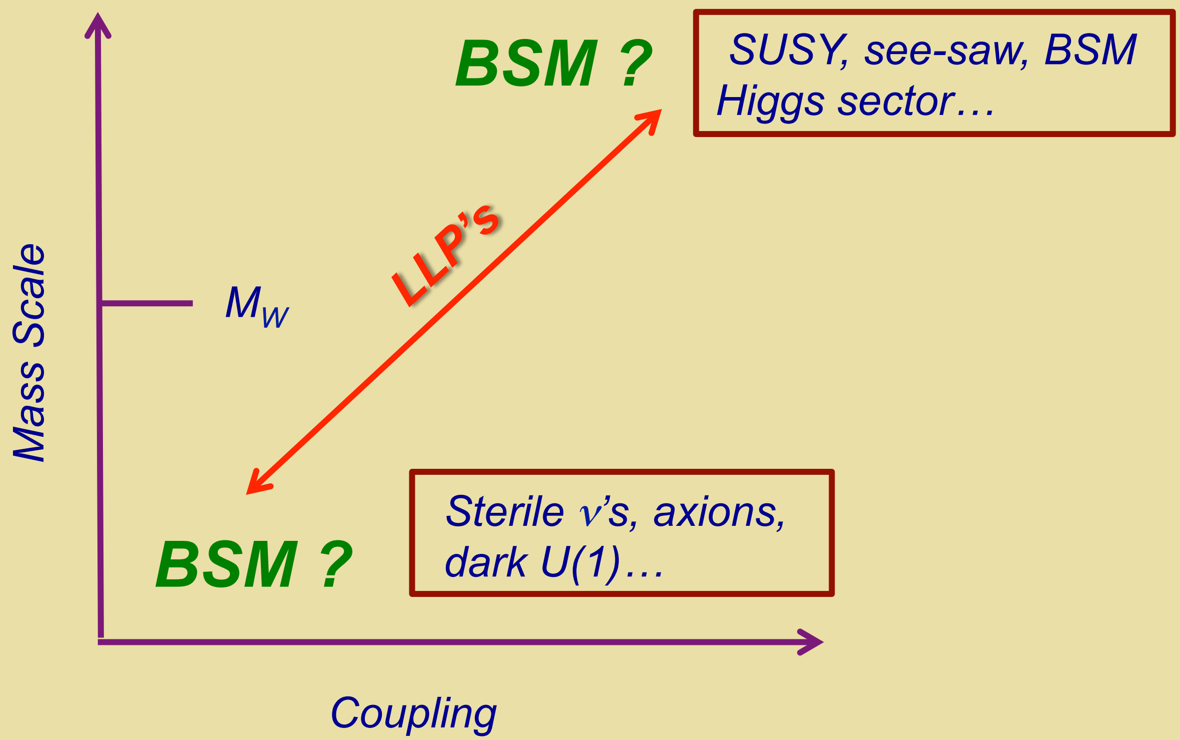
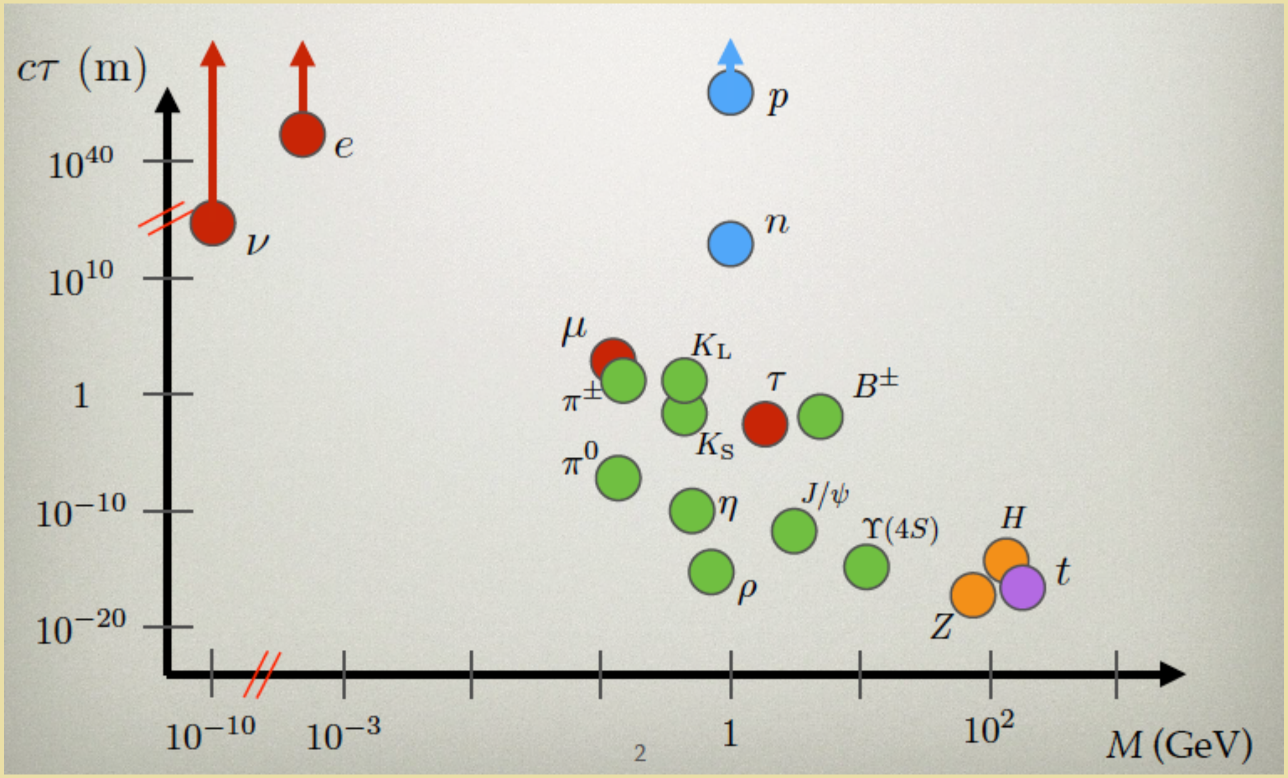


Why Should BSM LLP's Exist ?

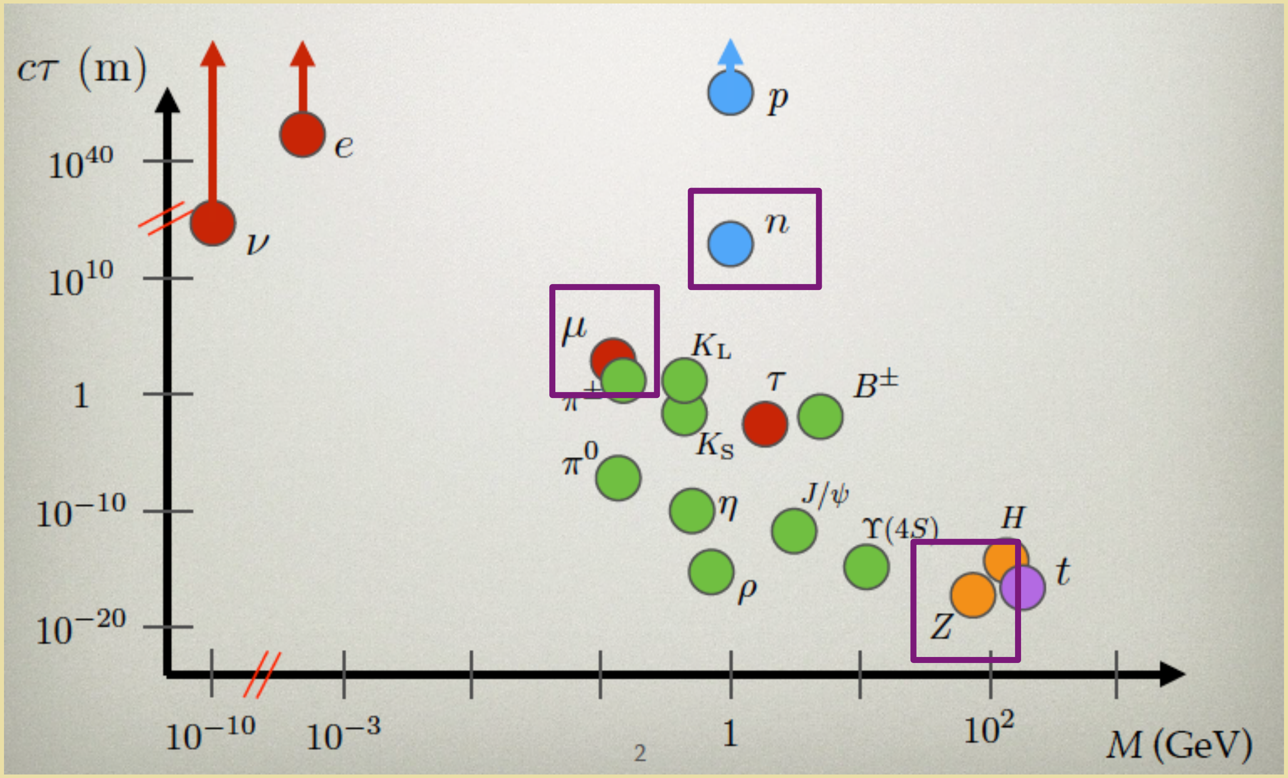
LLP's Exist in the SM



Thanks: B. Shuve, 2017 CERN LLP Workshop

Why Should BSM LLP's Exist ?

Lessons from τ_μ , τ_n and τ_Z :



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Why Should BSM LLP's Exist ?

Lessons from τ_μ *,* τ_n *and* τ_Z *:* $Y \to X^* \to SM$

Phase space ($192\,\pi^3 \sim 6000$)

$$c\tau \approx \frac{1.2\,\mathrm{fm}}{g_X^4} \left(\frac{M_X}{M_Y}\right)^4 \left(\frac{1\,\mathrm{TeV}}{M_Y}\right)$$

Muon decay:

- $M_X \sim 80$ GeV, $M_Y \sim 0.1$ GeV & $g_X^4 \sim 0.004 \to c\tau \sim 660$ m *

* *Additional ½ for half-life*

Why Should BSM LLP's Exist ?

Lessons from τ_μ , τ_n *and* τ_Z *:* $Y \to X^* \to SM$

Phase space ($192\,\pi^3 \sim 6000$)

$$c\tau \approx \frac{1.2\,\mathrm{fm}}{g_X^4}\left(\frac{M_X}{M_Y}\right)^4\left(\frac{1\,\mathrm{TeV}}{M_Y}\right)$$

BSM Examples:

- $M_X \sim 100$ GeV, $M_Y \sim 10$ GeV , $g_X^4 \sim 10^{-7} \to c\tau \sim 1$ cm — N_R *decay*
- $M_X \sim 1$ TeV , $M_Y \sim 10$ GeV , $g_X^4 \sim 10^{-3} \to c\tau \sim 1$ cm — *Hidden Valley*

Why Should BSM LLP's Exist ?

Lessons from τ_μ , τ_n and τ_Z :

$Y \rightarrow X^* \rightarrow Z + SM$

Phase space ($192\ \pi^3 \sim 6000$)

$\Delta M = M_Y - M_Z$

$$c\tau \approx \frac{1.2\,\mathrm{fm}}{g_X^4} \left(\frac{M_X}{\Delta M}\right)^4 \left(\frac{1\,\mathrm{TeV}}{\Delta M}\right)$$

BSM Examples:

- $M_X \sim 100$ GeV, $\Delta M \sim 1$ GeV $g_X^4 \sim 10^{-2} \rightarrow c\tau \sim 1$ cm *SUSY*

Why Should BSM LLP's Exist ?

Lessons from τ_μ , τ_n and τ_Z: *$Y \rightarrow SM$*

Phase space (24 x $2^{1/2}$ x π ~ 100)

$$c\tau \approx \frac{0.02\,\mathrm{fm}}{g_Y^2}\left(\frac{1\,\mathrm{TeV}}{M_Y}\right)$$

BSM Examples:

- *M_Y ~ 1 GeV & g_Y^2 ~ $10^{-12} \rightarrow$ $c\tau$ ~ 1 cm*   *Z_D*

Why Should BSM LLP's Exist ?

Large scale hierarchies & broken symmetries

$$\left(\frac{M_X}{M_Y}\right) >> 1$$

- *Heavy (off shell) mediator: Hidden valley*

$$\left(\frac{M_X}{\Delta M}\right) >> 1$$

- *Compressed spectrum : Stealth SUSY*

$$g_X << 1$$

- *Broken symmetry: RPV SUSY*
- *Scale ratio: N_R , Z_D*

Why Should BSM LLP's Exist ?

Large scale hierarchies & broken symmetries

- *Theories that address key open questions may involve scale hierarchies and/or symmetry breaking implying LLP's*
- *Are we looking in the right places in order to discovery the answers ?*
- *What is the roadmap to potential discoveries ?*

II. LLP Scenarios: A Sampler

Apologies for omissions !

Solutions w/ LLP's: A Sampler

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

Solutions w/ LLP's: A Sampler

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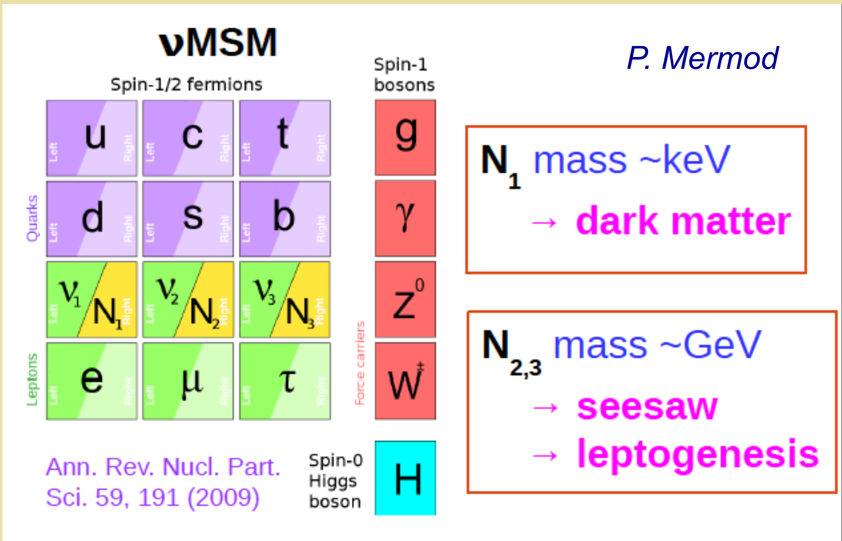
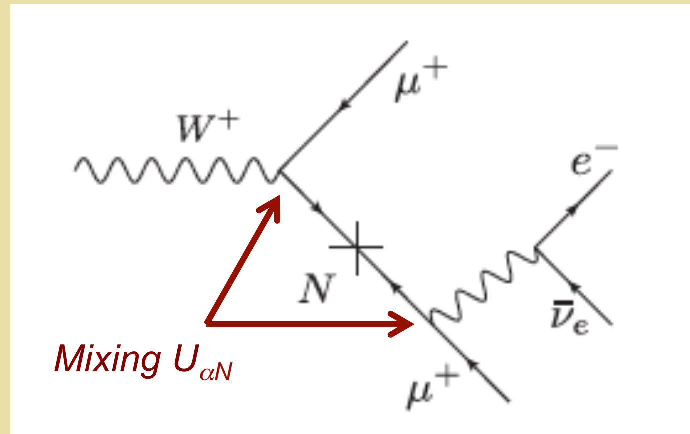
Stealth SUSY	✔	✔	✔	✖
Neutral Naturalness	✔	✖	✖	✖
Dark U(1)	✖	✖	✔	✖

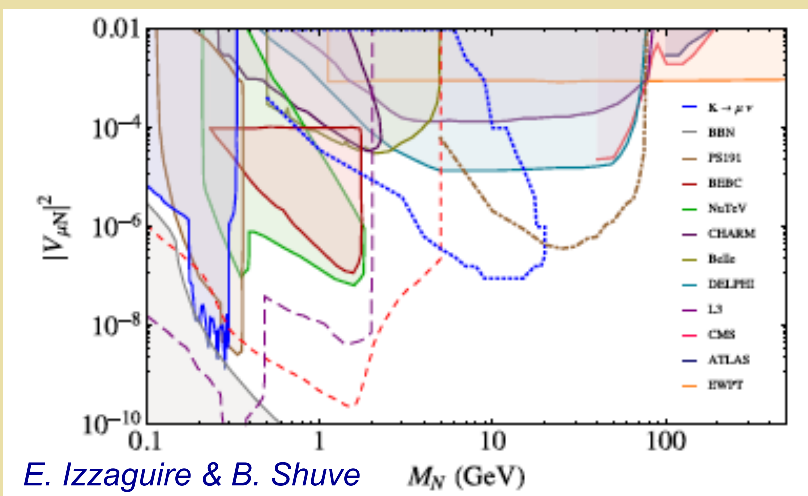
→ *Hidden Valleys*

Strassler, Zurek '06…

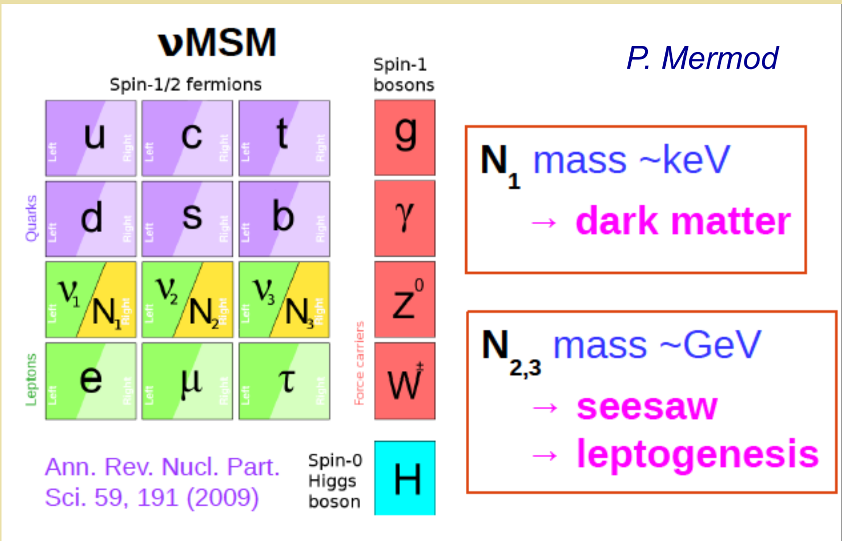
Solutions w/ LLP's: RH Neutrinos

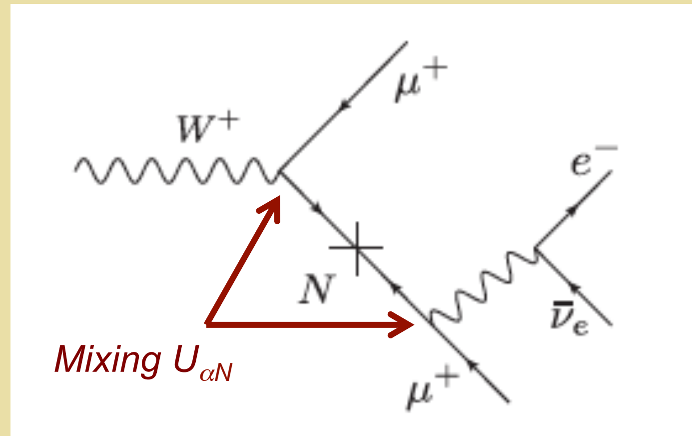


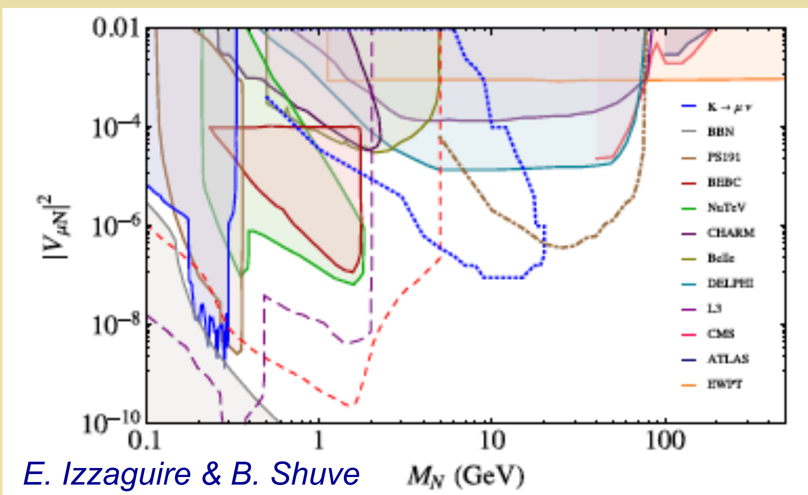




Solutions w/ LLP's: RH Neutrinos







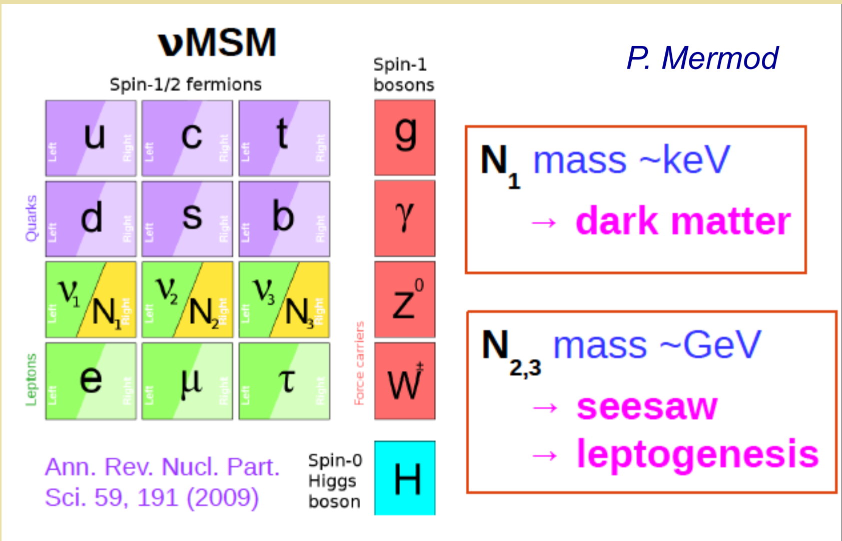
Type I see-saw: νSM

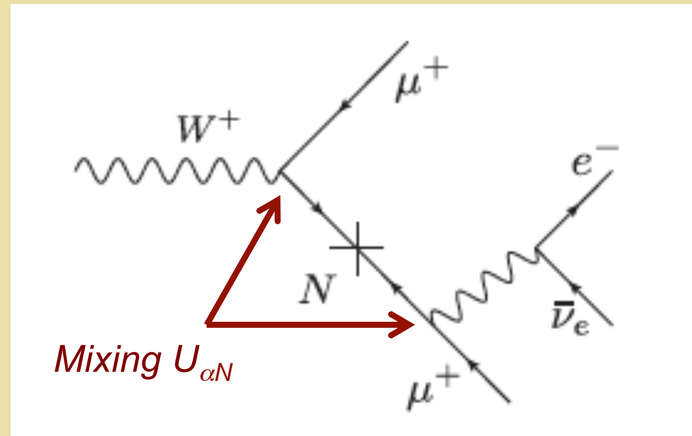
$$U_{\alpha N} \sim \frac{m_D}{M_N}$$

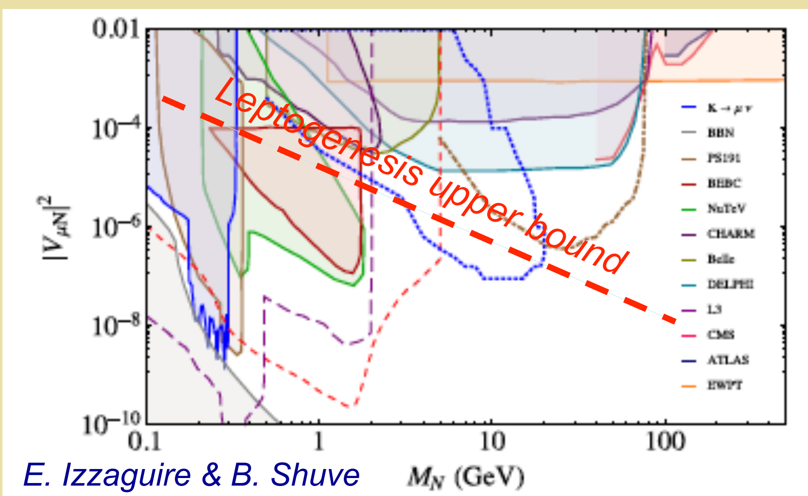
Type I & II see-saw: LRSM

$$U_{\alpha N} \sim \sqrt{\frac{v_L}{v_R} - \frac{m_\nu}{M_N}}$$

Solutions w/ LLP's: RH Neutrinos





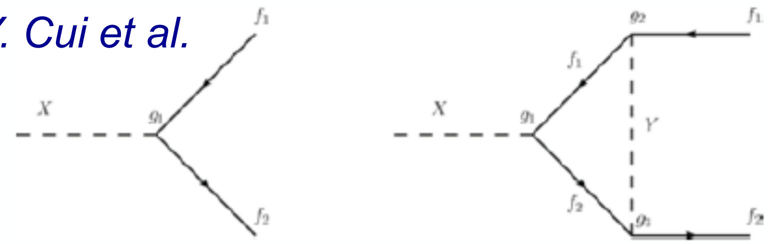


BAU from Leptogenesis

- *Drewes et al '16*
- *Lower bound < 10^{-10}*

Solutions w/ LLP's: Wimpy Baryogenesis

Y. Cui et al.



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

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

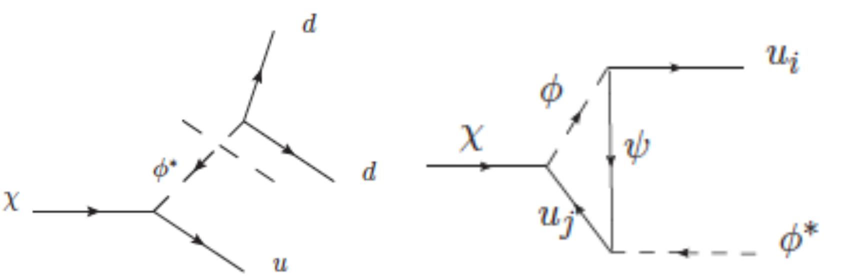
Baryon number violating:

$$\chi \to u_i d_j d_k$$

Lepton number violating:

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

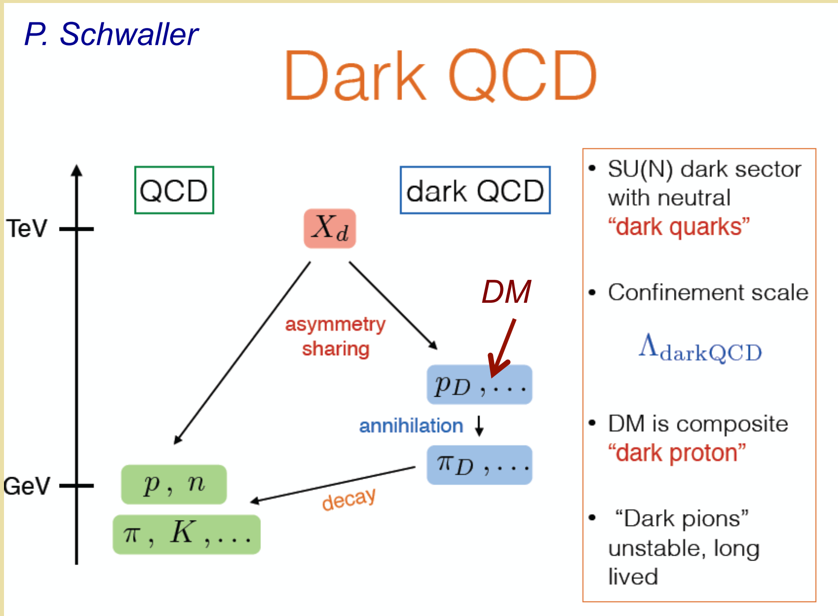
$$\chi \to L_i L_j \bar{E}_k$$



Like leptogenesis

Solutions w/ LLP's: Hidden Valleys

Solutions w/ LLP's: Dark QCD

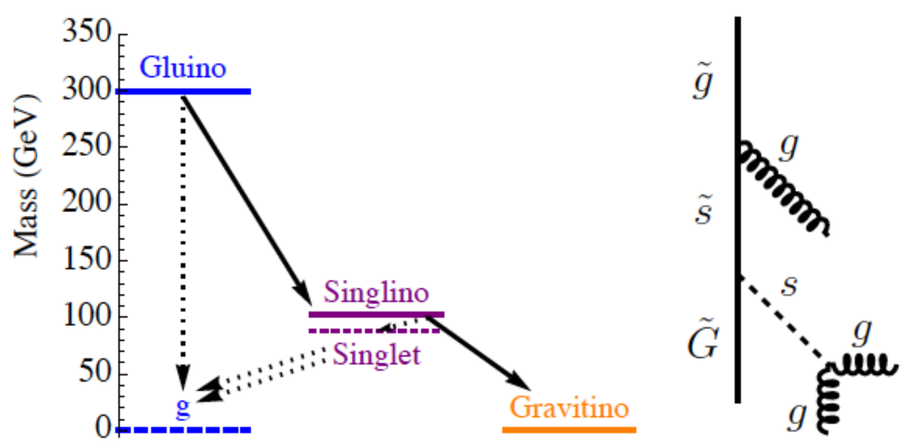


Asymmetric DM: $m_{DM}\, n_{DM} \sim 5\, m_N\, n_B \rightarrow$

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

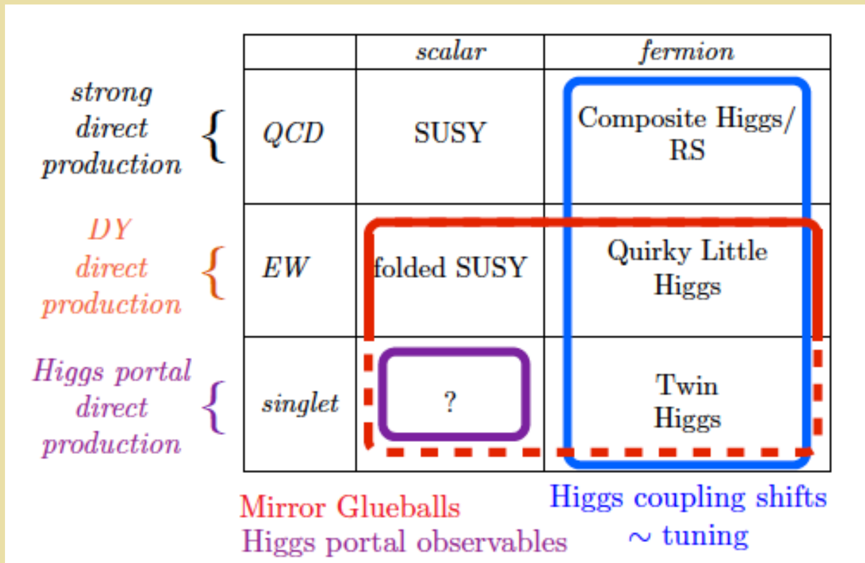
Solutions w/ LLP's: Stealth SUSY

Fan, Reece, Ruderman



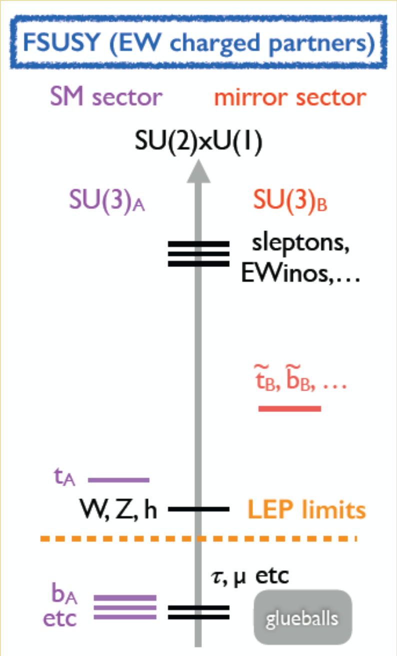
Solutions w/ LLP's: Neutral Naturalness

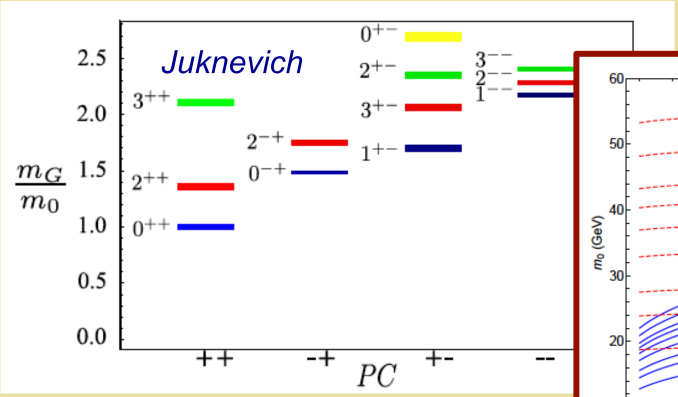
D. Curtin, C. Verhaaren

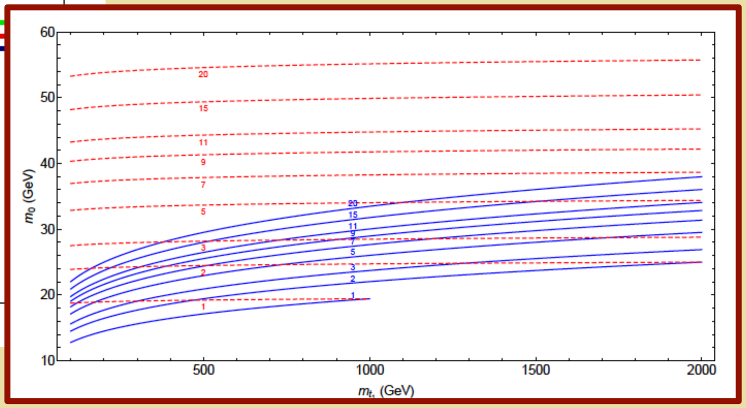


Top partners

Solutions w/ LLP's: Neutral Naturalness

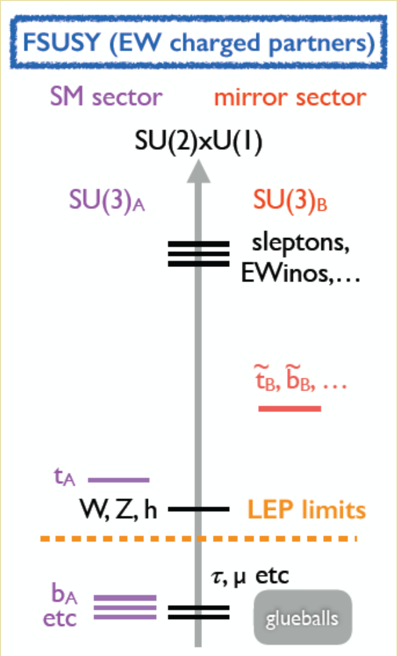


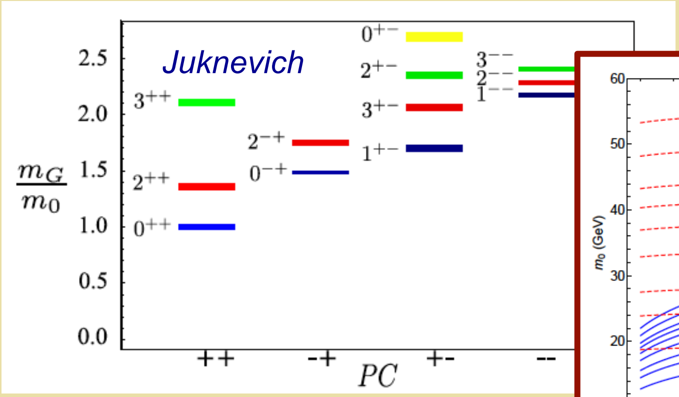


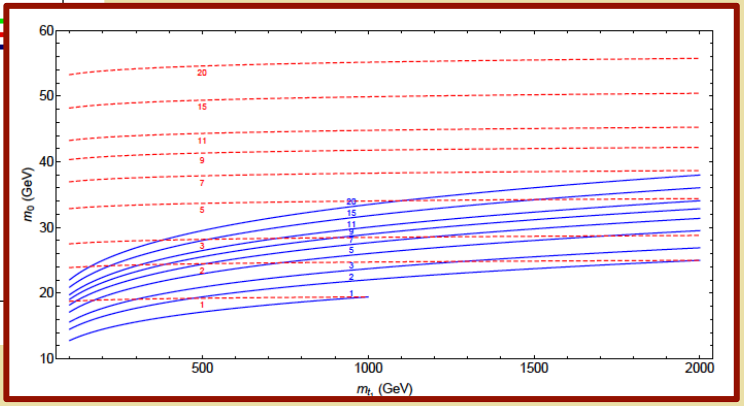


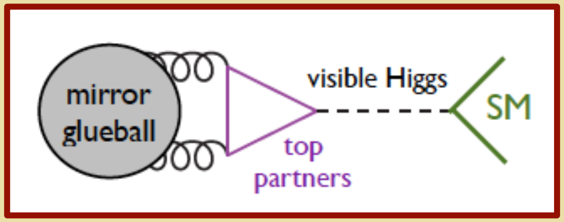
D. Curtin, C. Verhaaren

Solutions w/ LLP's: Neutral Naturalness









D. Curtin, C. Verhaaren

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

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

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

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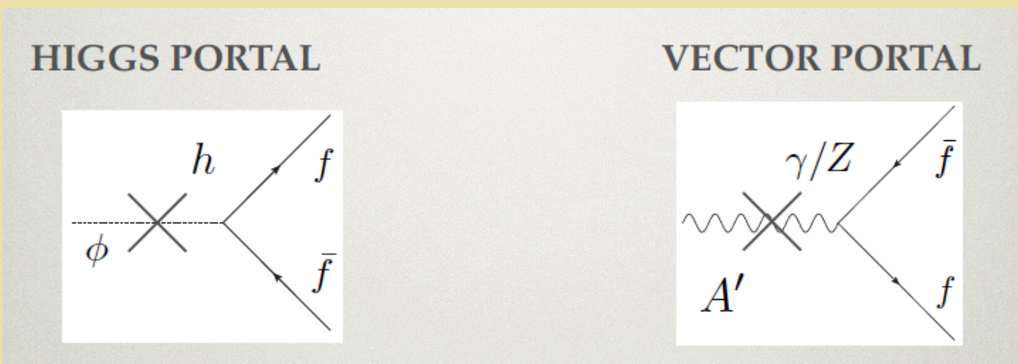
Abelian Kinetic Mixing — *Mass Mixing*

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

Higgs Mixing



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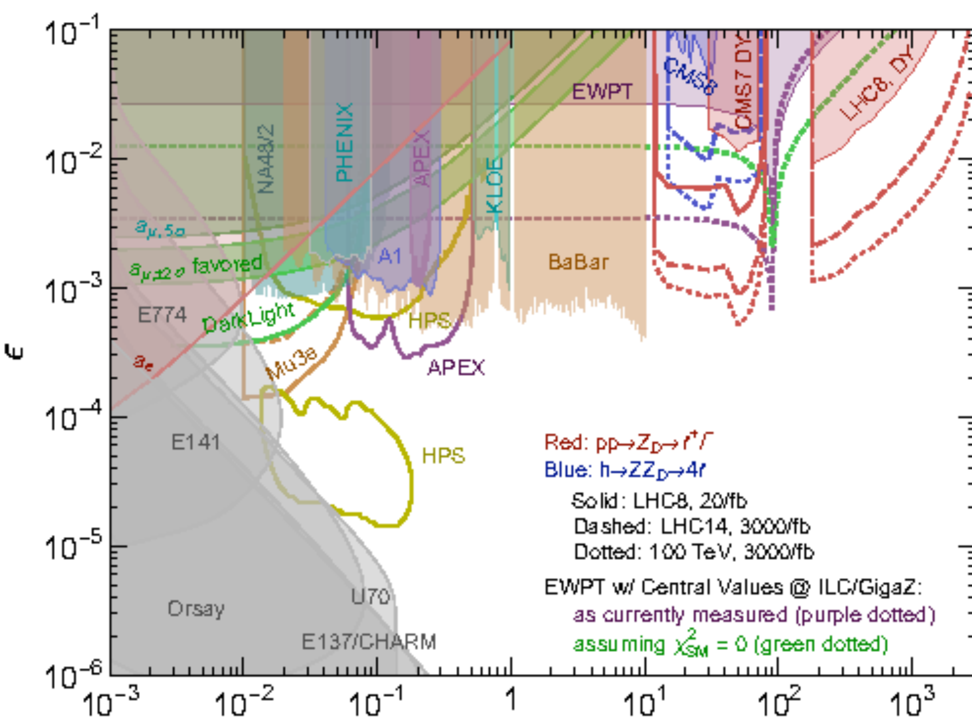
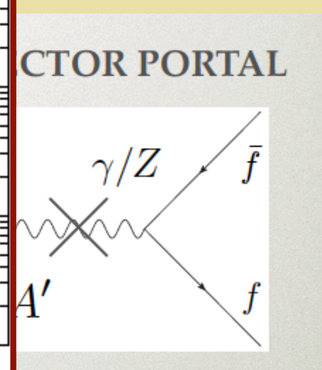
Abelian Kinetic Mixing *Mass Mixing*

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

Higgs Mixing



Curtin et al '15



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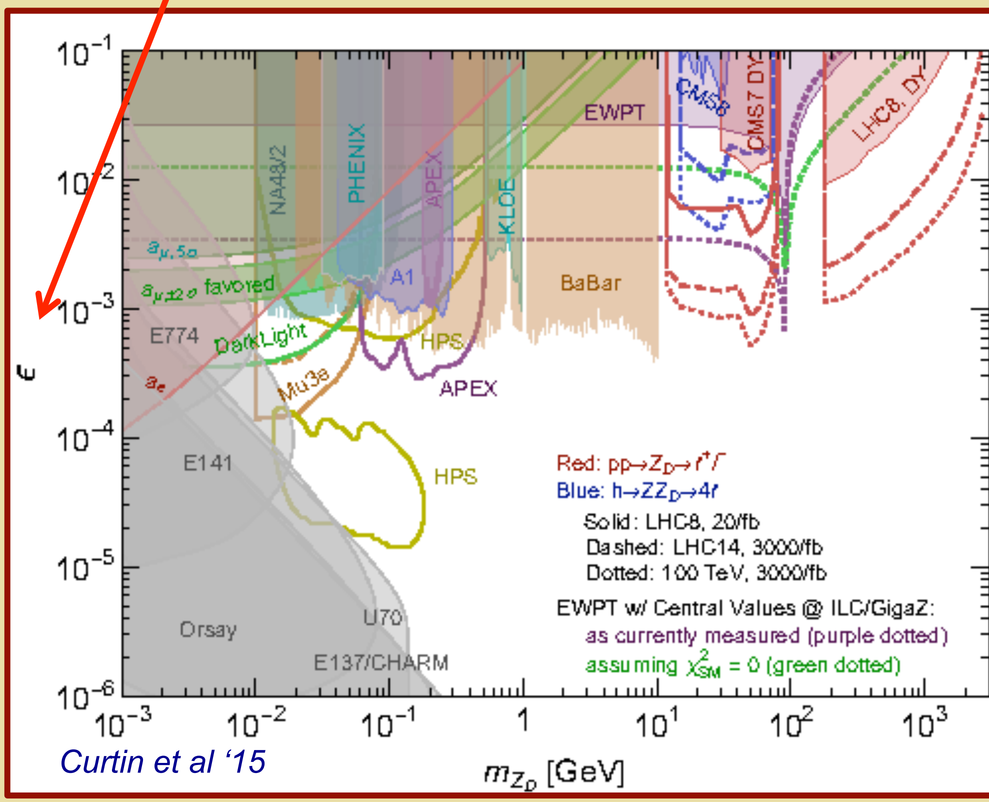
Abelian Kinetic Mixing — *Mass Mixing*

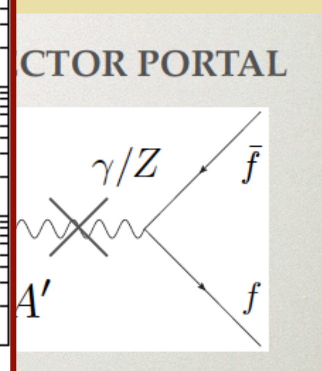
$$+\,\lambda_S|S|^4 + \kappa|S|^2|H|^2$$

Higgs Mixing

Why so tiny?



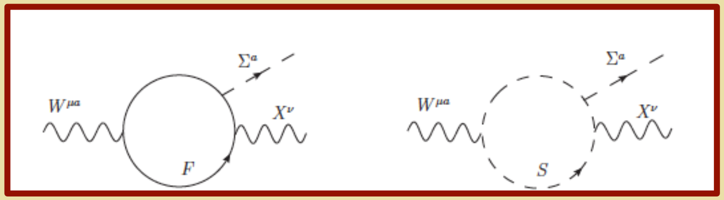
Curtin et al '15



Dark Z: Scale Hierarchy

Non-Abelian Kinetic Mixing

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



$SU(2)_L$ x $U(1)_D$ mediators

$$\epsilon = \beta \sin\theta_W \left(\frac{v_\Sigma}{\Lambda}\right)$$

Small ε from scale ratio;

β ~ O(1)

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

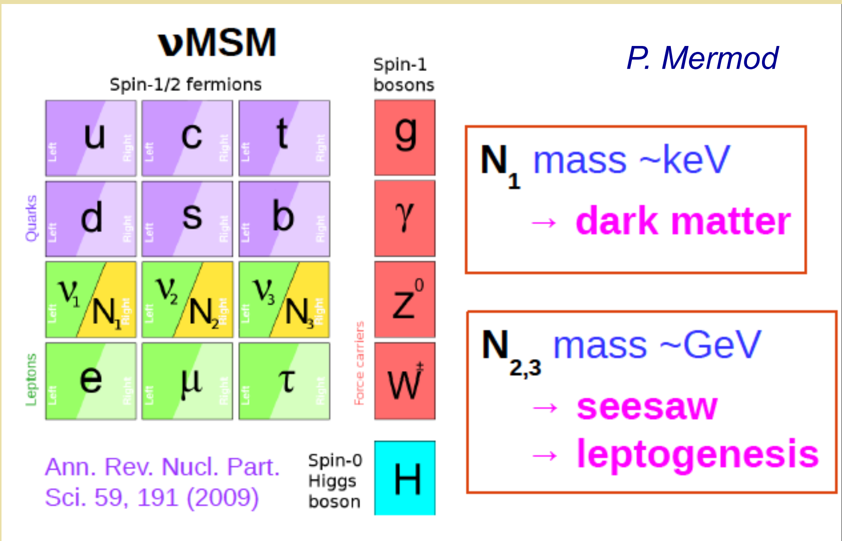
LLP's @ LHC: Motivation

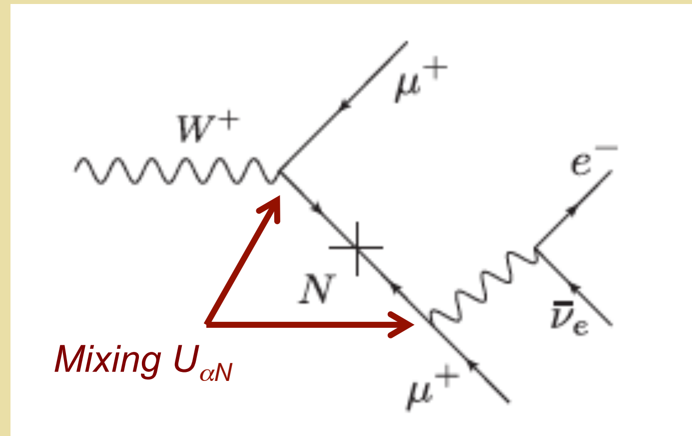
- *Discovery of LLP's may provide clues to key open questions in fundamental physics*

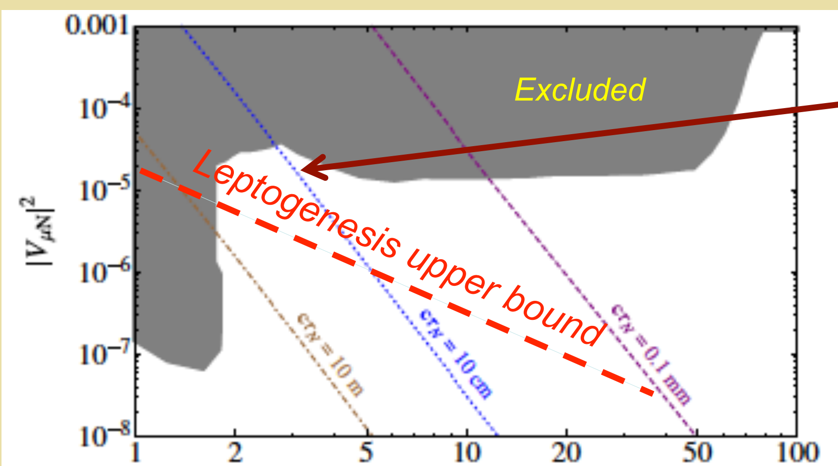
- *Consideration of physical scales $\rightarrow$ LLP decay lengths ~ ATLAS, CMS & LHCb detectors*

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

Solutions w/ LLP's: RH Neutrinos







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

Solutions w/ LLP's: Wimpy Baryogenesis

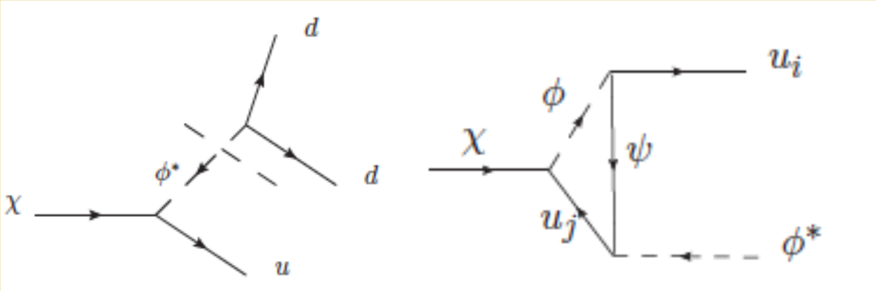
Baryon number violating:

$$\chi \to u_i d_j d_k$$

Lepton number violating:

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

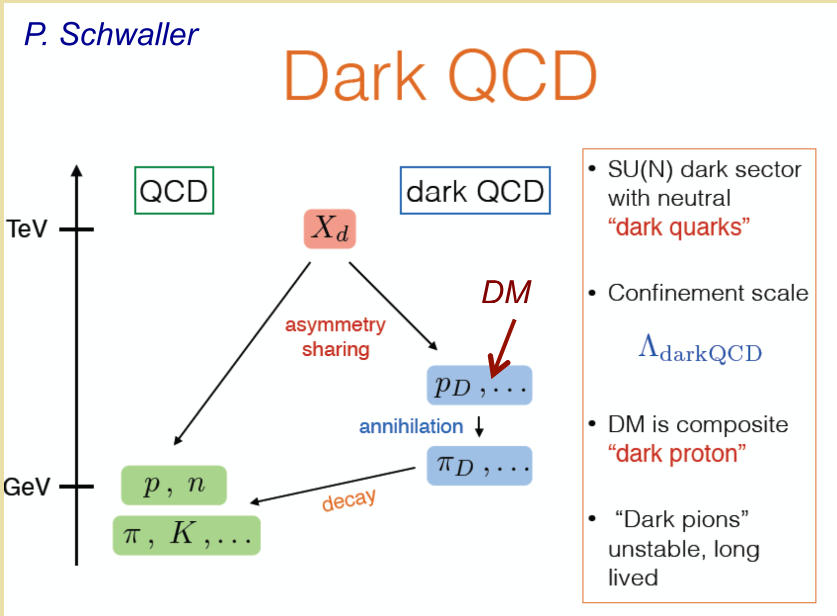
3-body phase space



Sakharov: out-of-eq condition

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

Solutions w/ LLP's: Dark QCD



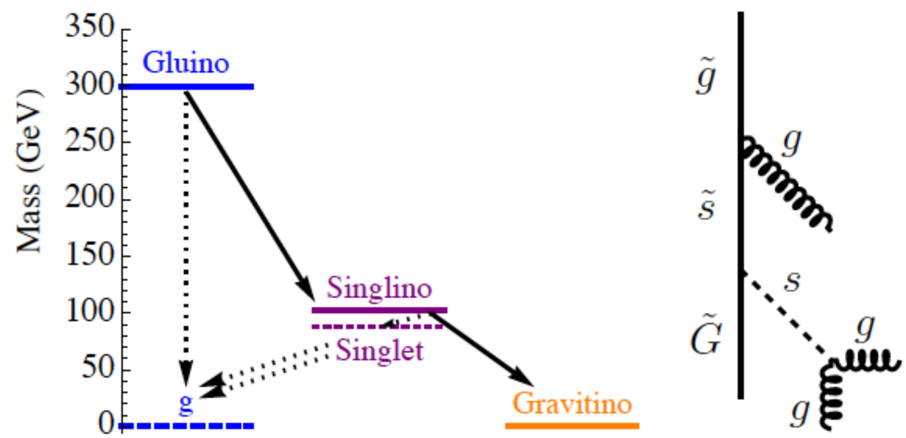
Asymmetric DM: $m_{DM}\, n_{DM} \sim 5\, m_N\, n_B \rightarrow$

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

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

Solutions w/ LLP's: Stealth SUSY

Fan, Reece, Ruderman

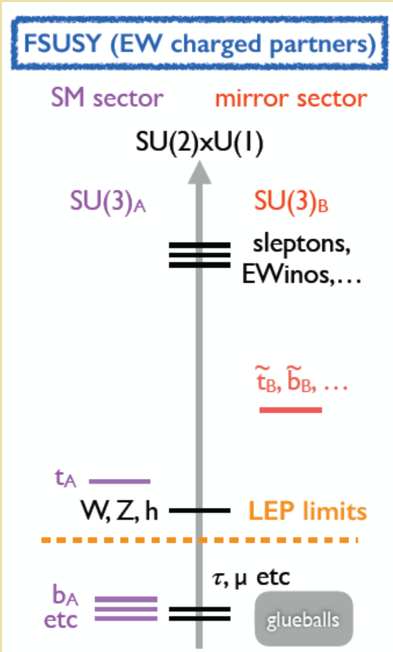


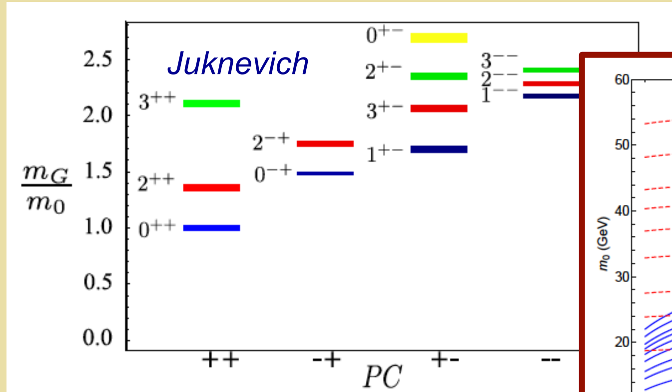
$$\Gamma_{\tilde{X}} = \frac{m_{\tilde{X}}^5}{16\pi F^2}\left(1 - \frac{m_X^2}{m_{\tilde{X}}^2}\right)^4 \approx \frac{m_{\tilde{X}}\,(\delta m)^4}{\pi F^2}$$

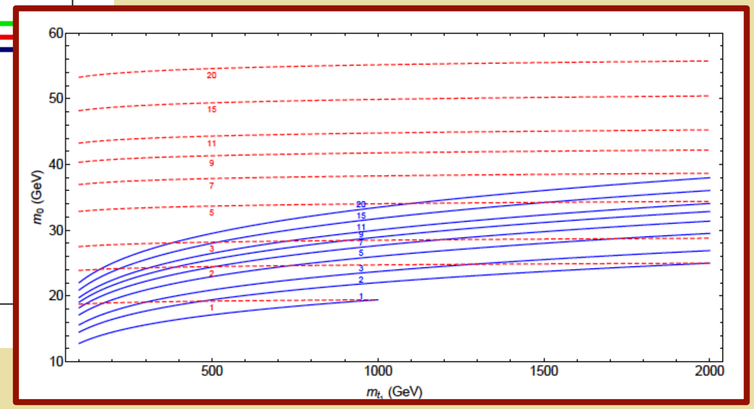
m_X = 100 GeV
δm ~ 10 GeV
F ~ $(100\ \mathrm{TeV})^2$

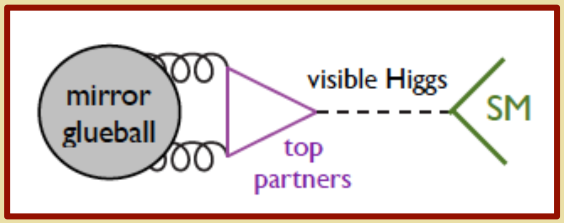
$c\,\tau$ ~ 10 cm

Solutions w/ LLP's: Neutral Naturalness

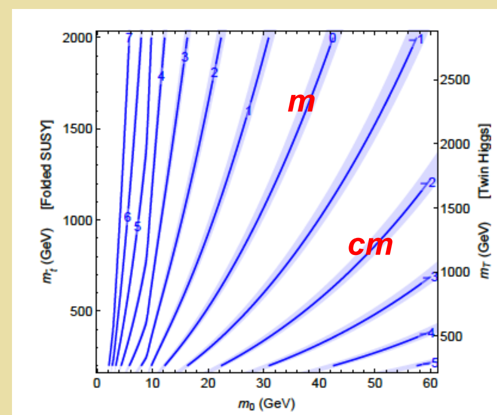








$$\Gamma_{0^{++}} \sim m_0^7/(M^4 m_h^2)$$



D. Curtin, C. Verhaaren

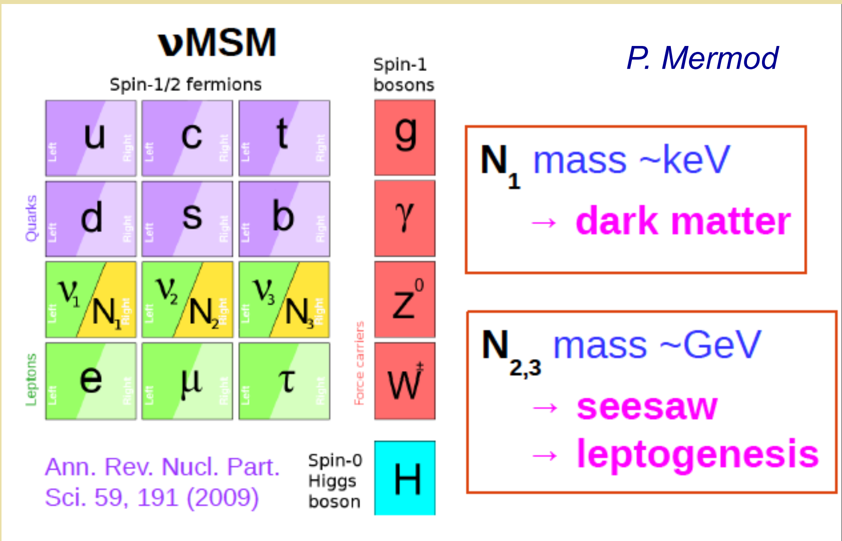
LLP's @ LHC: Motivation

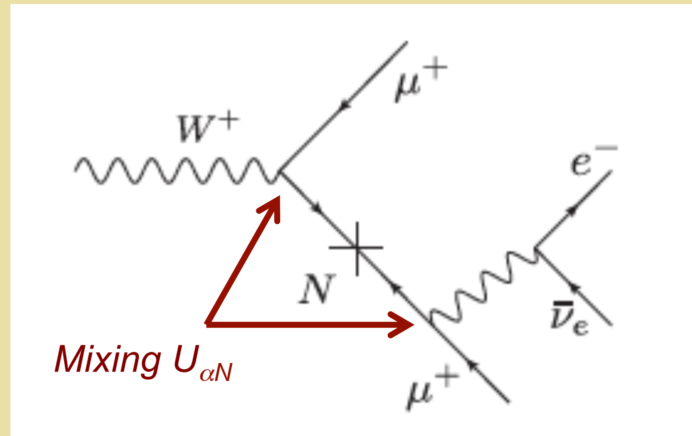
- *Discovery of LLP's may provide clues to key open questions in fundamental physics*

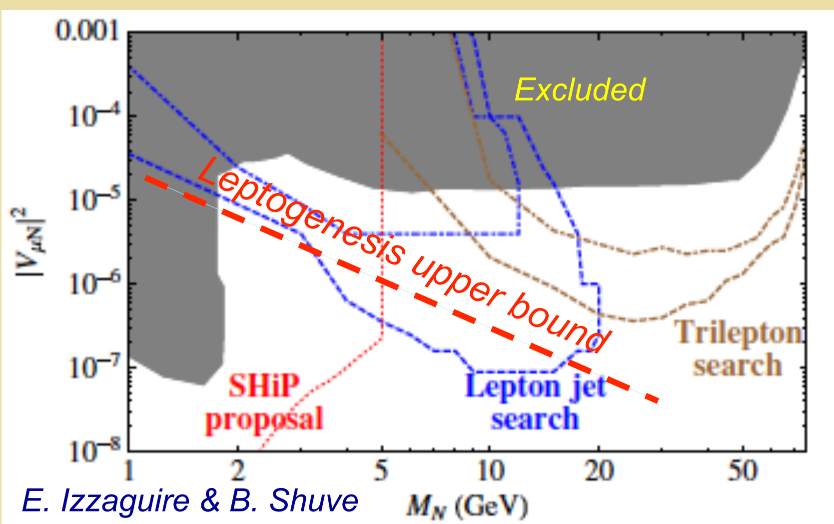
- *Consideration of physical scales $\rightarrow$ LLP decay lengths ~ ATLAS, CMS & LHCb detectors*

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

Solutions w/ LLP's: RH Neutrinos







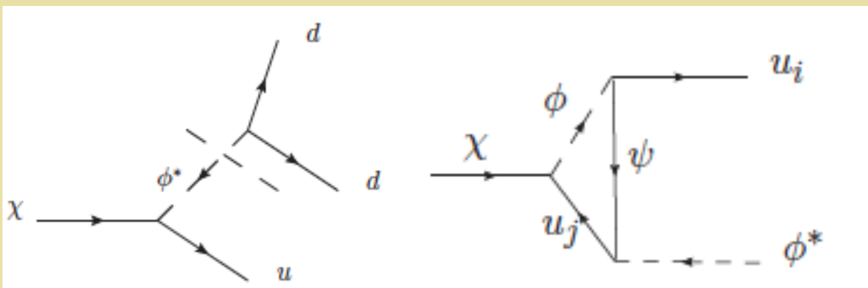
$$\Gamma(N \to \ell_\alpha^- \ell_\beta^+ \nu_\beta) = \frac{G_F^2 M_N^5 |V_{\alpha N}|^2}{192\pi^3}$$

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

Solutions w/ LLP's: Wimpy Baryogenesis

Baryon number violating:	Lepton number violating:
$\chi \to u_i d_j d_k$	$\chi \to L_i Q_j \bar{d}_k$ $\chi \to L_i L_j \bar{E}_k$

3-body phase space

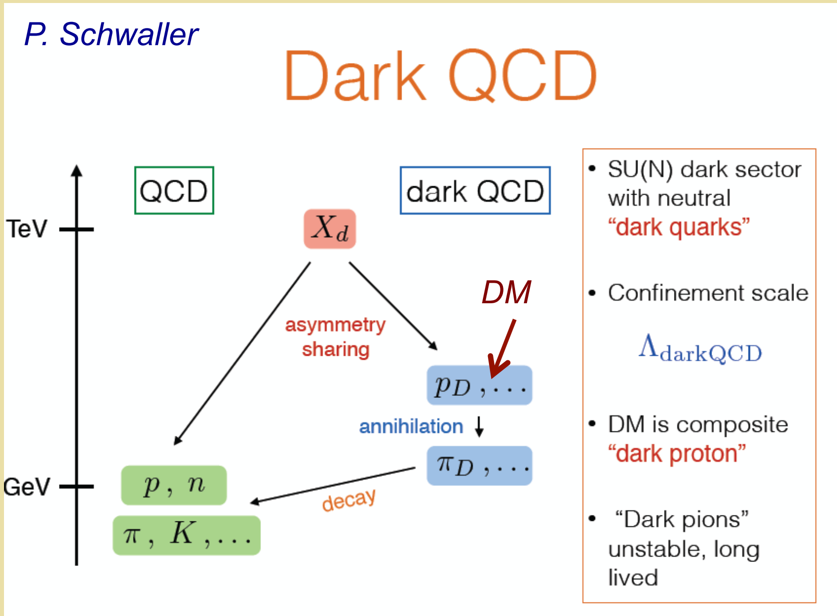


- *BNV: displaced jets*
- *LNV: displaced μ + tracks*

Sakharov: out-of-eq condition

$$\Gamma_\chi < H(T = M_\chi) \quad \longleftrightarrow \quad c\tau_\chi \gtrsim \text{mm}$$

Solutions w/ LLP's: Dark QCD



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

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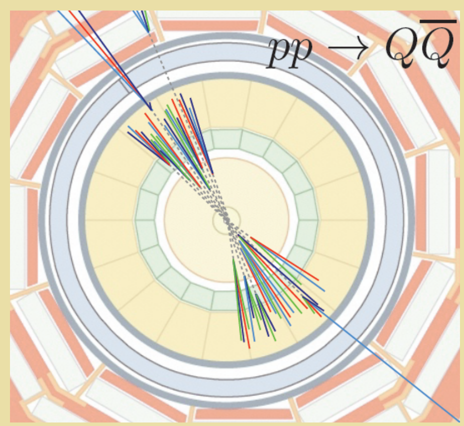
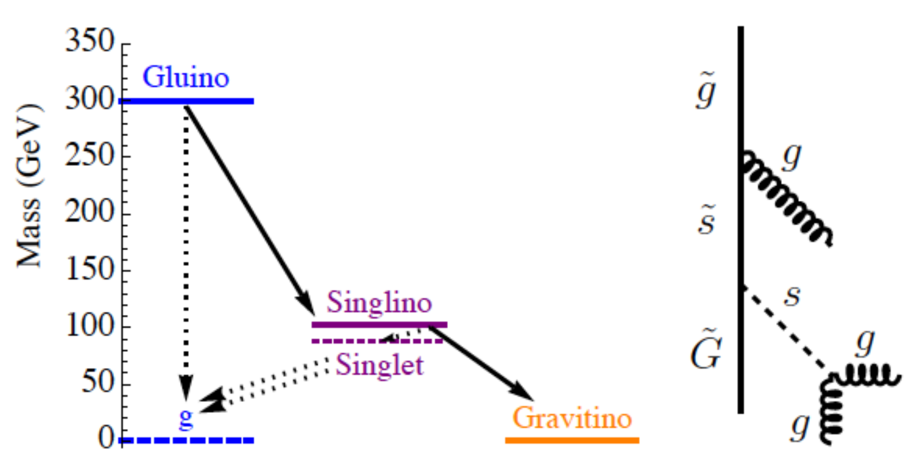
$$c\tau(\pi_D \rightarrow \mathrm{SM}) \sim \frac{M_X^4}{m_{\pi_D}^5} \sim \mathrm{cm} \times \left(\frac{\mathrm{M_X}}{\mathrm{TeV}}\right)^4 \left(\frac{\mathrm{GeV}}{\mathrm{m_{\pi_D}}}\right)^5$$

Emerging Jets



Solutions w/ LLP's: Stealth SUSY

Fan, Reece, Ruderman

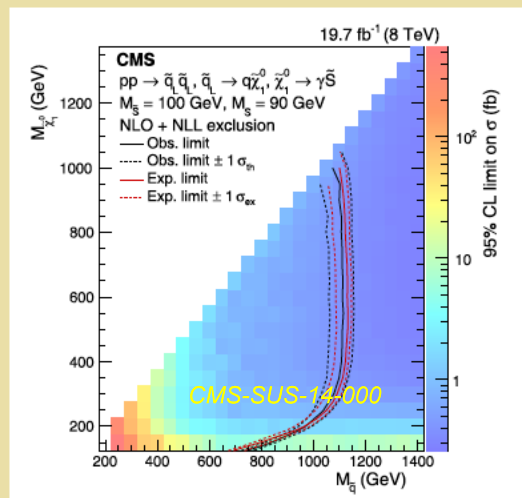


$$\Gamma_{\tilde{X}} = \frac{m_{\tilde{X}}^5}{16\pi F^2}\left(1-\frac{m_X^2}{m_{\tilde{X}}^2}\right)^4 \approx \frac{m_{\tilde{X}}\,(\delta m)^4}{\pi F^2}$$

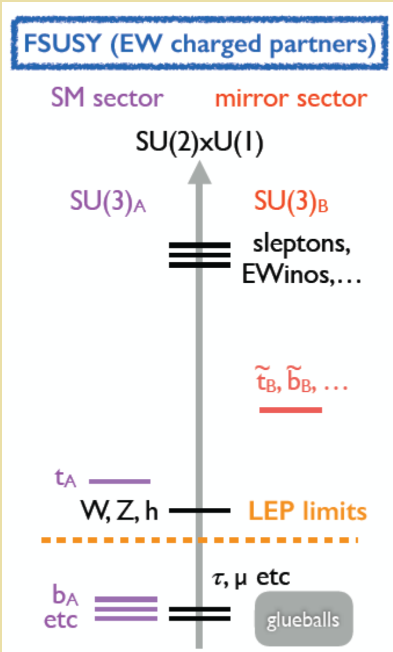
m_X = 100 GeV
δm ~ 10 GeV
F ~ (100 TeV)^2

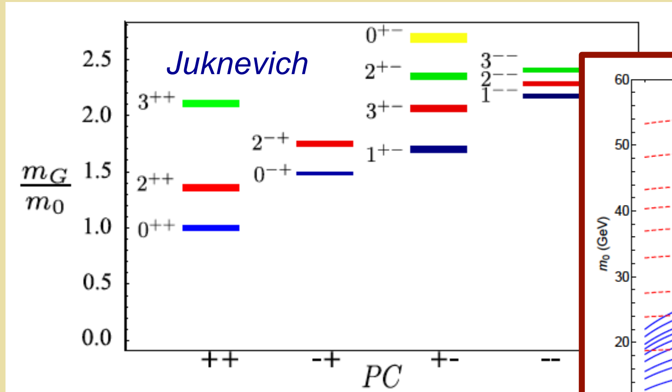
$c\,\tau$ ~ 10 cm

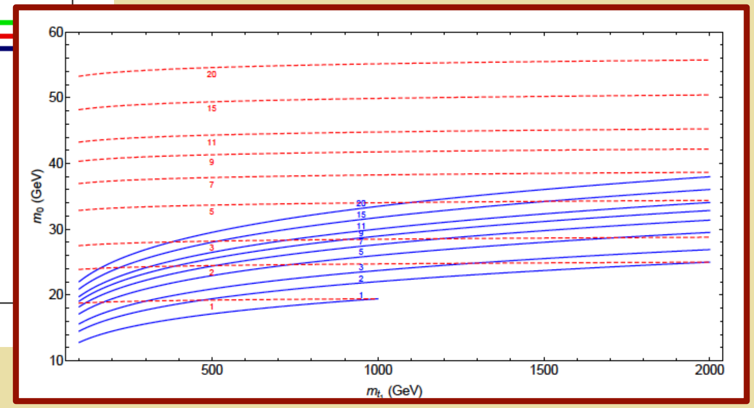
- *Prompt V + displaced jj ("false resonances")*
- *DV's + high multiplicity b-jets*
- *…*

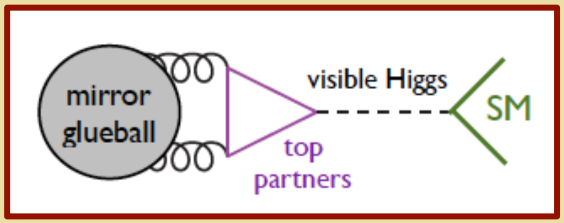


Solutions w/ LLP's: Neutral Naturalness

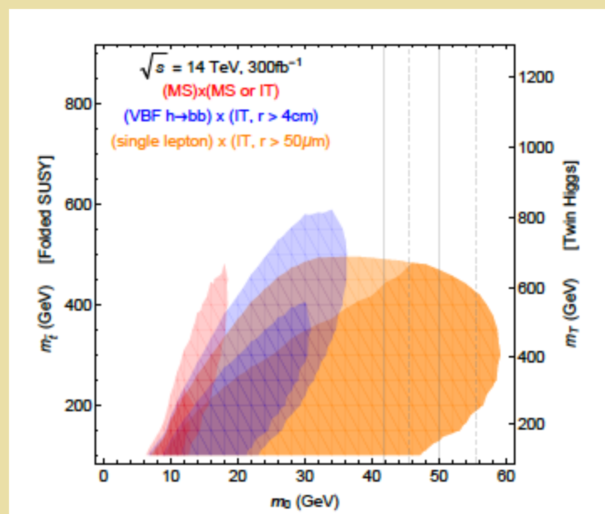








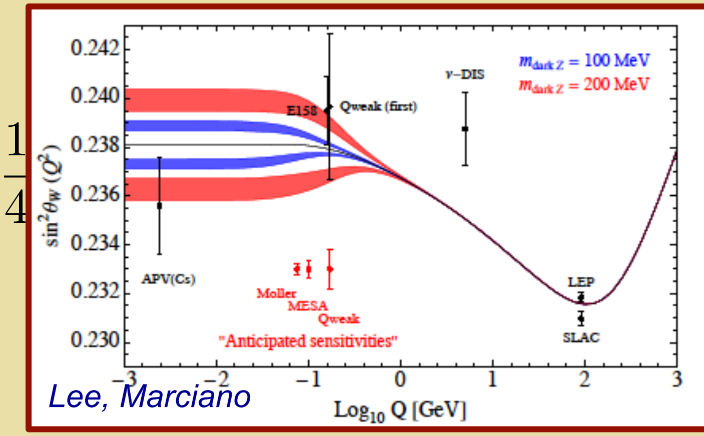
Exotic Higgs decays: h → 0^{++} 0^{++}
w/ 2 DV's or 1 DV +…



D. Curtin,
C. Verhaaren

Dark Z: Mechanism

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

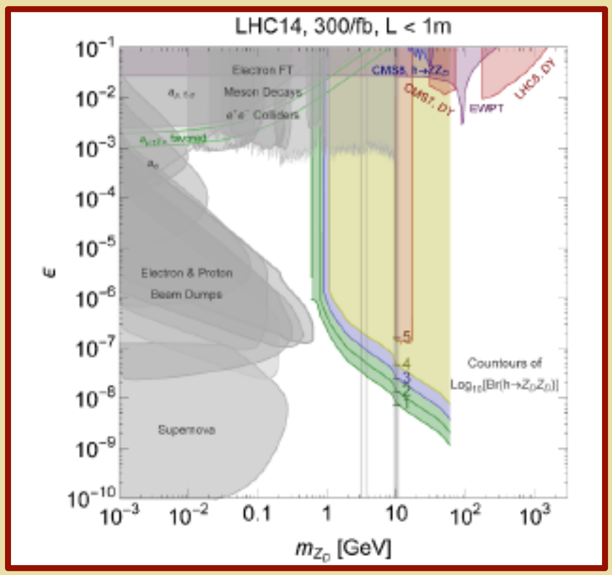


Lee, Marciano

PVES

Mass Mixing

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



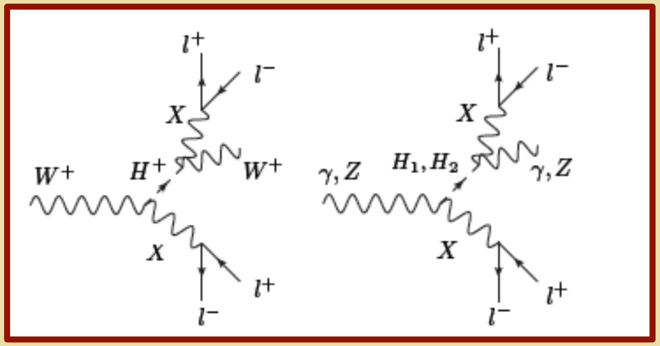
Higgs Mixing

$h \to Z_D\, Z_D$

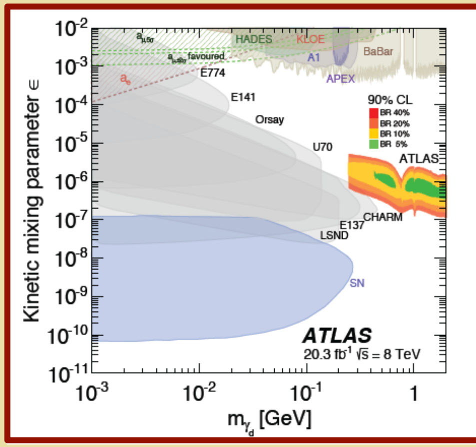
Dark Z: Mechanism

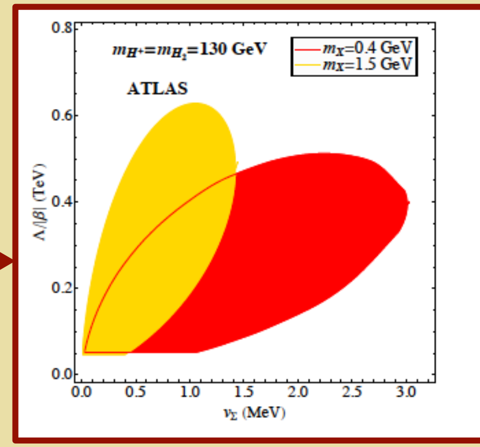
Non-Abelian Kinetic Mixing

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



Prompt V + 2 displaced LJ's





Recast ATLAS '14
(no prompt V)

Arguelles, He, Ovaneysan, Peng, MRM '16

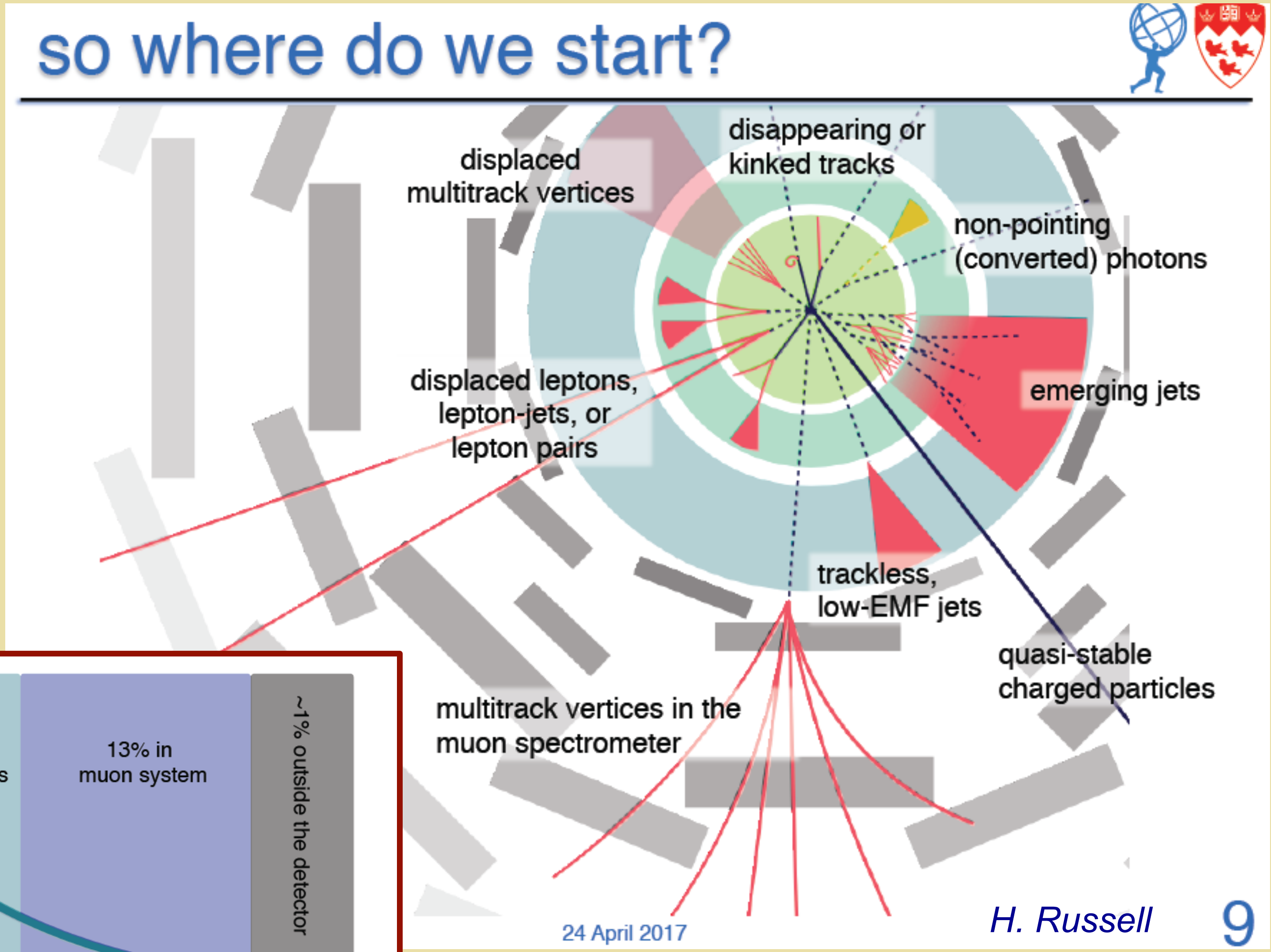
III. Building a Roadmap

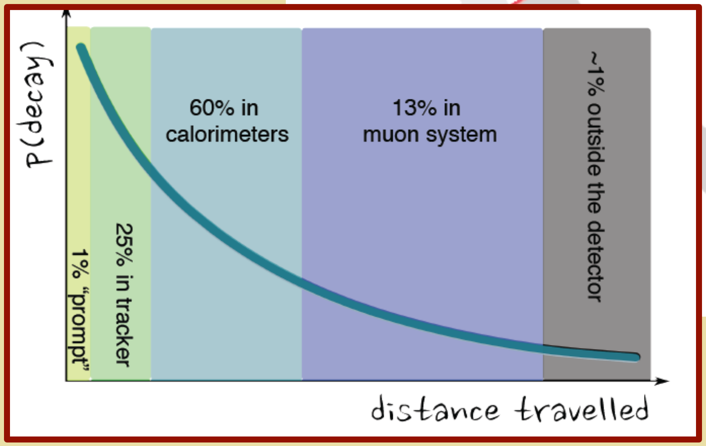
Time to extend the coverage & reach !

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…)*
- *…*

LLP's: Challenges





LLP’s: Challenges

April CERN WS & Progress

LLP's: Challenges (April)

WG 1

Simp models & recast

WG 2

Backgrounds

Triggering

WG 3

Dark Shower

WG 4

LLP's: Challenges (Now)

WG 1 & 4

Simp models & recast

WG 2

Expt Coverage

Triggering

WG 3

Dark Shower

WG 5

LLP's: Challenges

WG 1 & 4

Simp models & recast

(Common production) x
(Variety of decay objects)

L1 in good shape, but
exploit associated objects

Triggering

WG 3

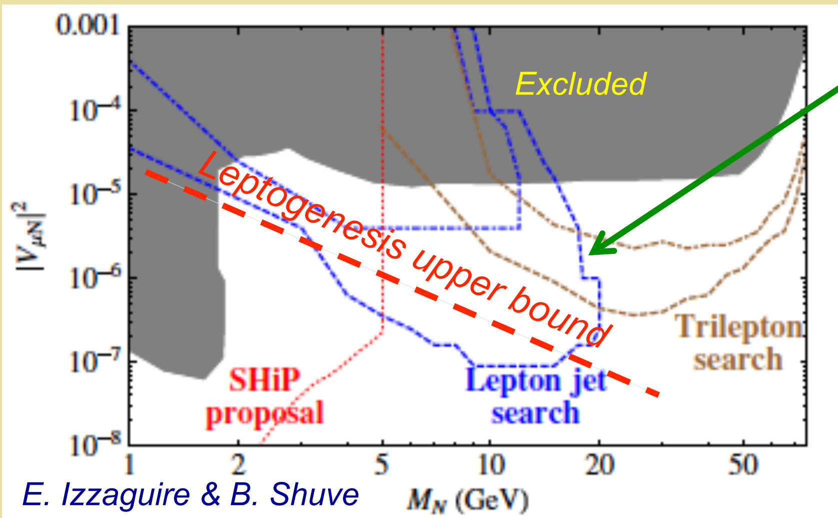
WG 2

Expt Coverage

Dark Shower

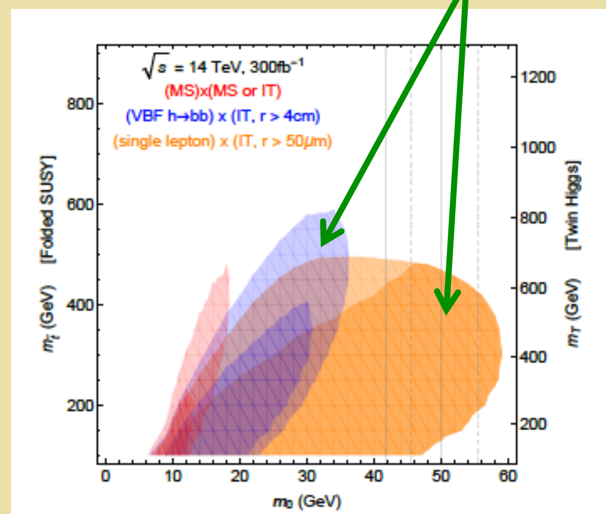
WG 5

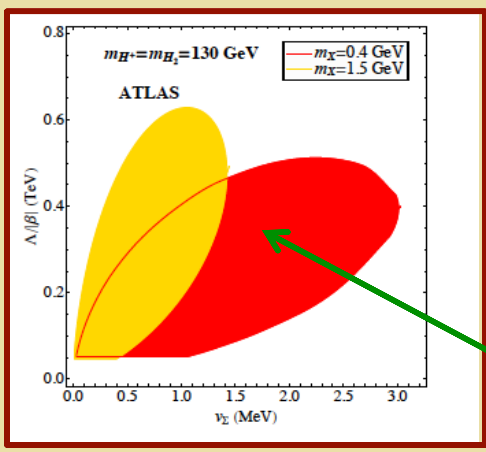
Push the Reach w/ Prompt Objects

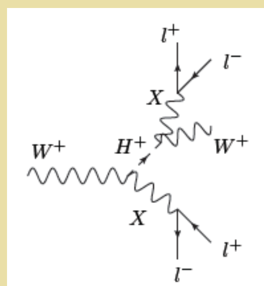


Prompt μ + semilept N_R decay

VBF jets or prompt V



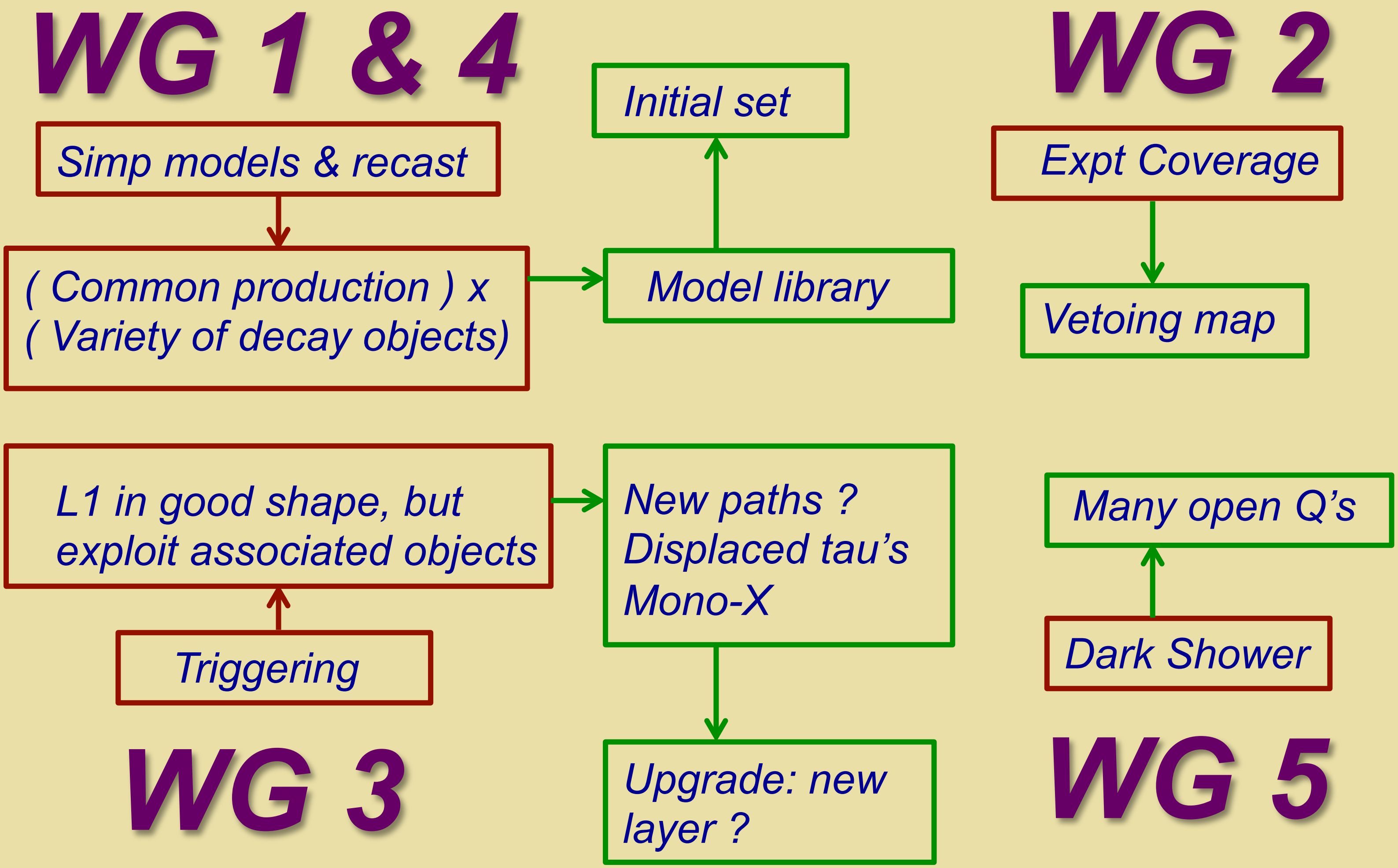




Prompt W + 2 DV lepton jets

Associated prompt objects !

LLP's: Challenges



LLP’s: Challenges

WG 1 & 4

Simp models & recast

(Common production) x
(Variety of decay objects)

Initial set

Model library

WG 2

Expt Coverage

Vetoing map

y open Q’s

Shower

G 5

Production \ Decay	$\gamma\gamma(+\text{inv.})$	$\gamma + \text{inv.}$	$jj(+\text{inv.})$	$jj\ell$	$\ell^+\ell^-(+\text{inv.})$	$\ell^+_\alpha \ell^-_{\beta\neq\alpha}(+\text{inv.})$
DPP: sneutrino pair		SUSY	SUSY	SUSY	SUSY	SUSY
HP: squark pair, $\tilde{q} \to jX$ or gluino pair $\tilde{g} \to jjX$		SUSY	SUSY	SUSY	SUSY	SUSY
HP: slepton pair, $\tilde{\ell} \to \ell X$ or chargino pair, $\tilde{\chi} \to WX$		SUSY	SUSY	SUSY	SUSY	SUSY
HIG: $h \to XX$ or $\to XX + \text{inv.}$	Higgs, DM*		Higgs, DM*		Higgs, DM*	
HIG: $h \to X + \text{inv.}$	DM*		DM*		DM*	
ZP: $Z(Z') \to XX$ or $\to XX + \text{inv.}$	Z', DM*		Z', DM*		Z', DM*	
ZP: $Z(Z') \to X + \text{inv.}$	DM		DM		DM	
CC: $W(W') \to \ell X$			RHν*	RHν	RHν*	RHν*

LLP's: Challenges

WG 1 & 4

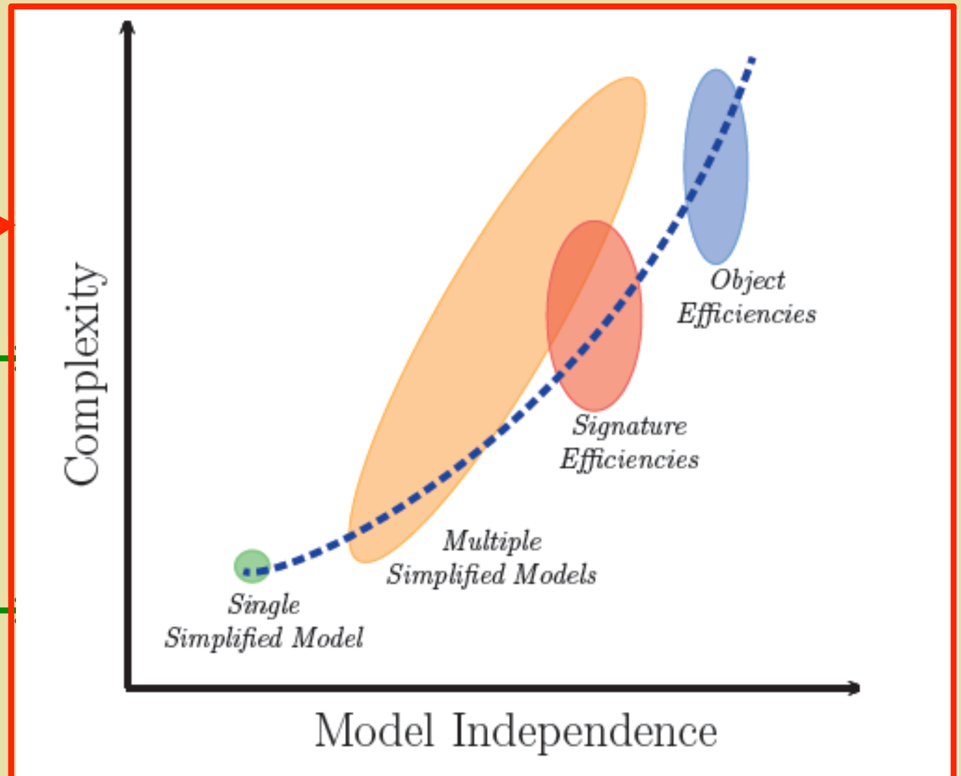
Simp models & recast

(Common production) x
(Variety of decay objects)

L1 in good shape, but
exploit associated objects

Triggering

WG 3

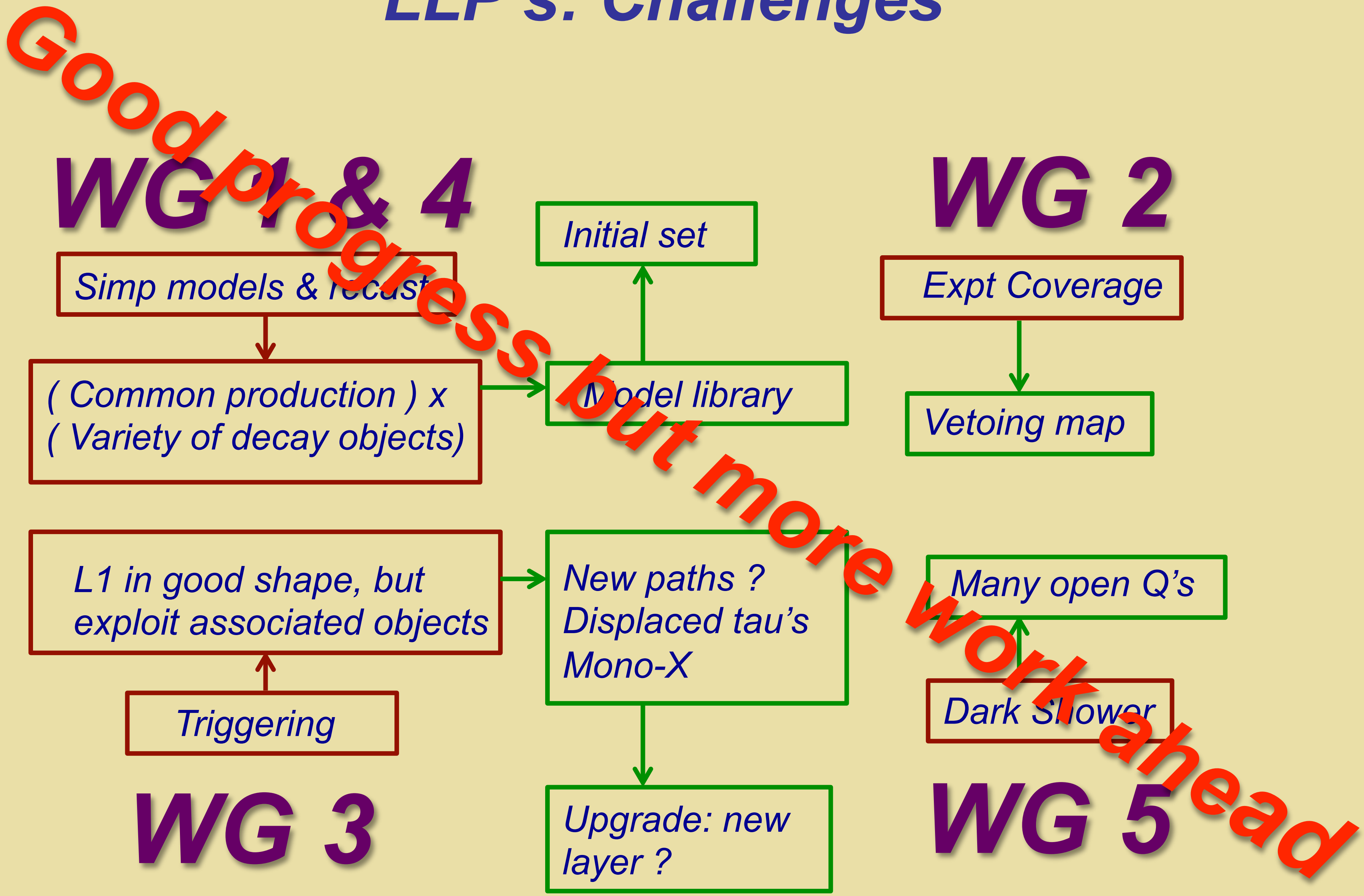


Dark Shower

Upgrade: new
layer ?

WG 5

LLP's: Challenges



LLP's: A Rich Menu of Opportunities