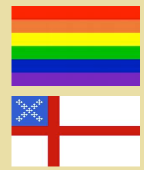
Beyond the Standard Model: The Low & High Energy Interface

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/

Collaborators: Carlos Arguelles, Chien-Yi Chen, Xiao-Gang He, Haolin Li, Grigory Ovanesyan, Tao Peng, Peter Winslow

LEPONP Workshop, Mainz
May 2017

Outline

I. The BSM Context

II. The Dark Portal

III. The Higgs Portal

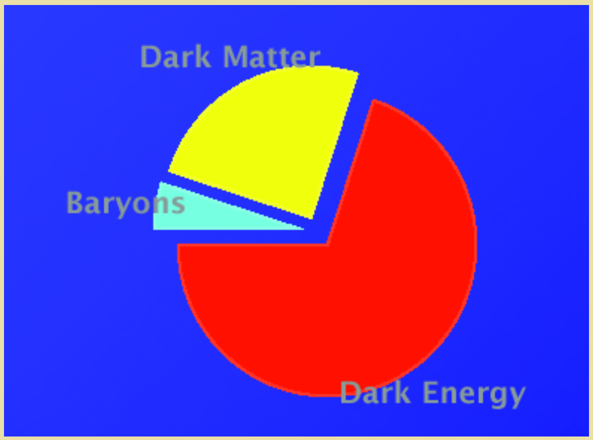
IV. Outlook

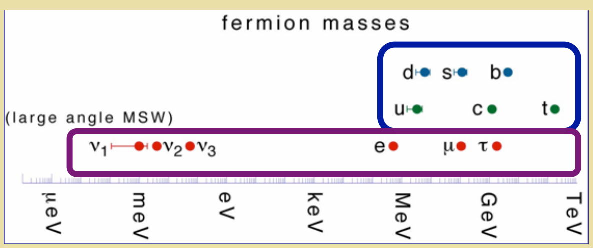
V. Backup: The Neutrino Portal

I. The BSM Context

Fundamental Questions

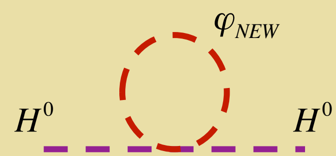
MUST *answer*





Origin of m_ν

SHOULD *answer*



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

$\Lambda_{Cosmological}$

BSM Physics: Where Does it Live ?

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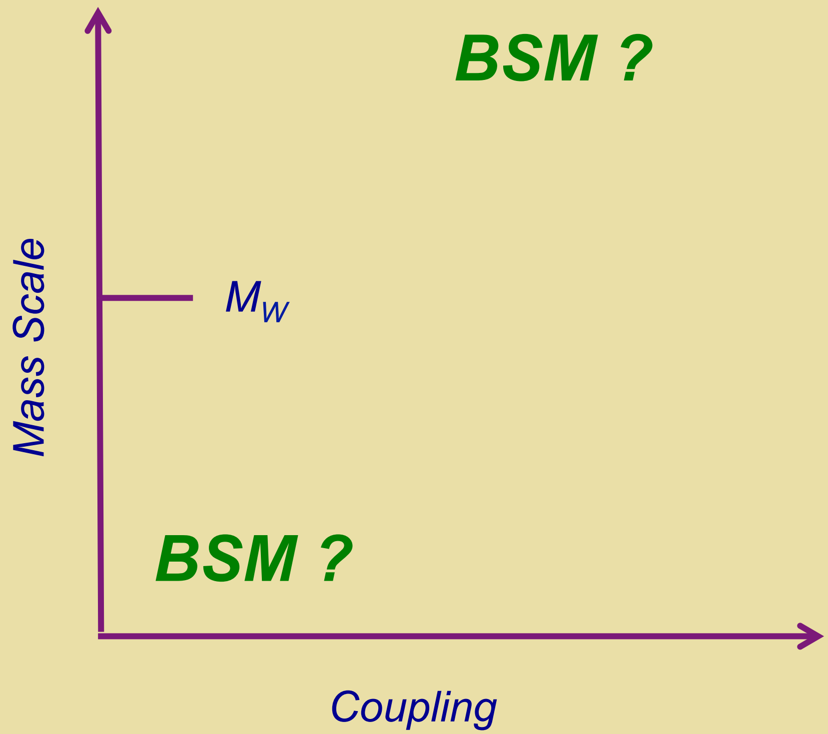
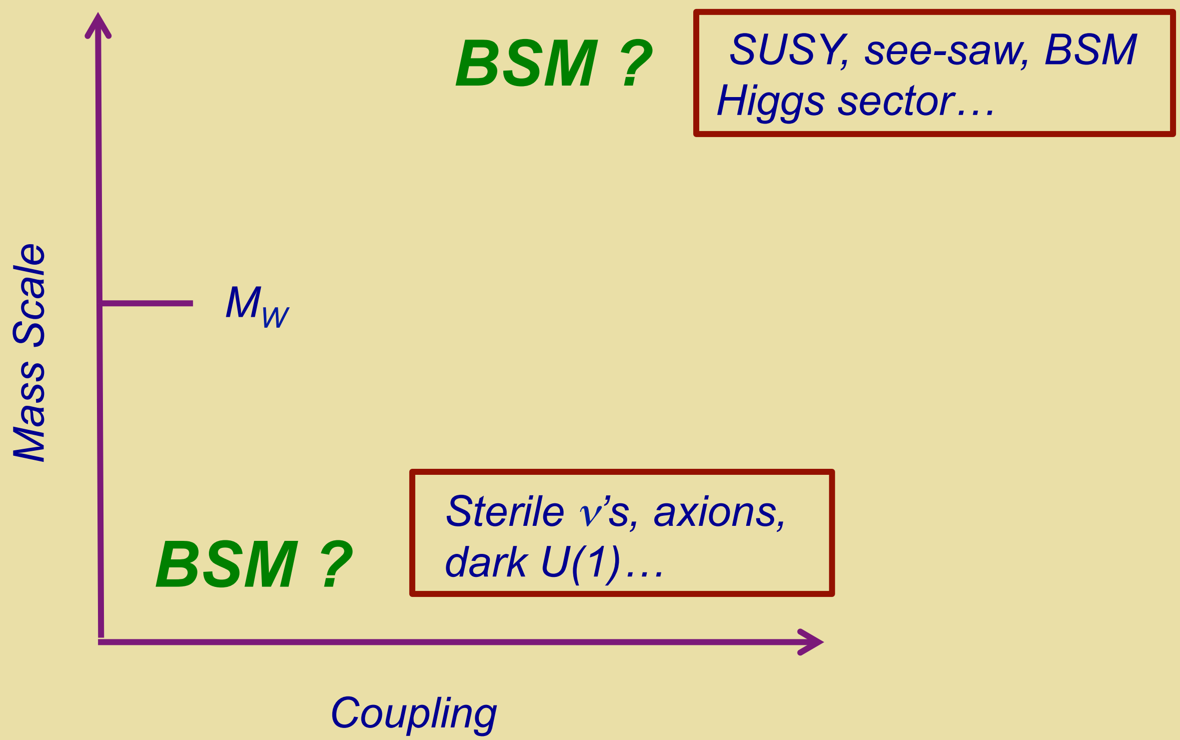
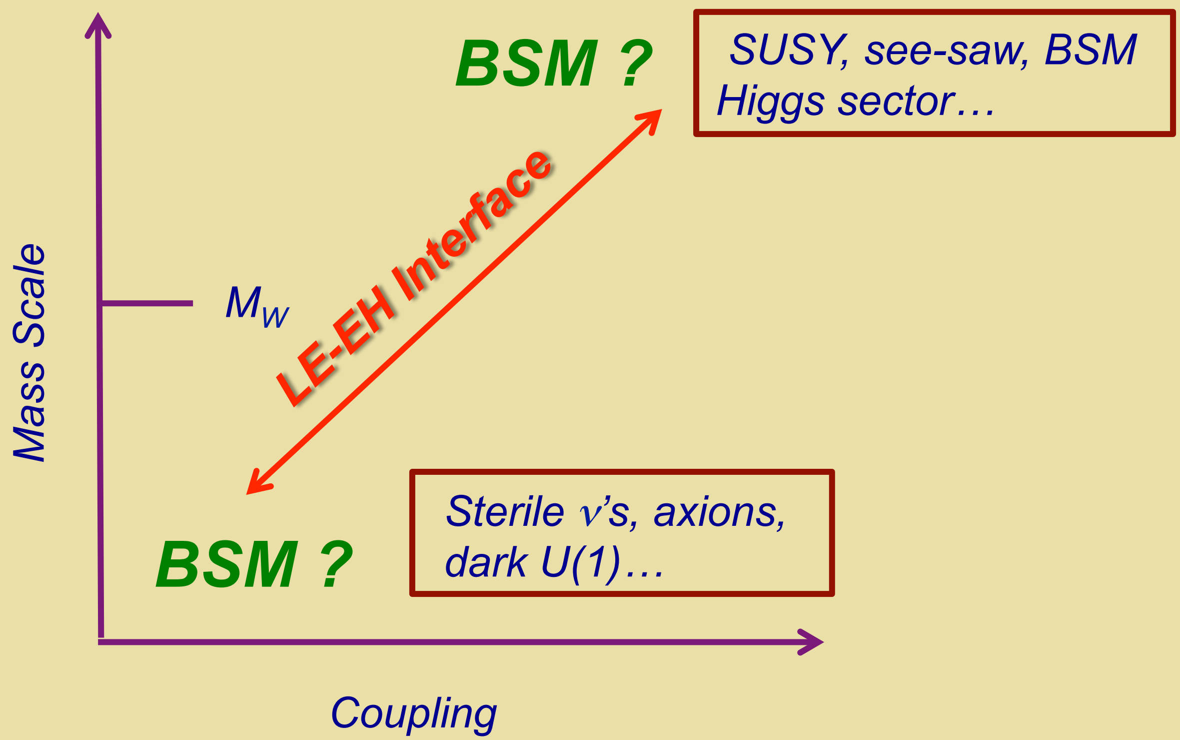


BSM Physics: Where Does it Live ?



BSM Physics: Where Does it Live ?



Low-Energy / High-Energy Interplay

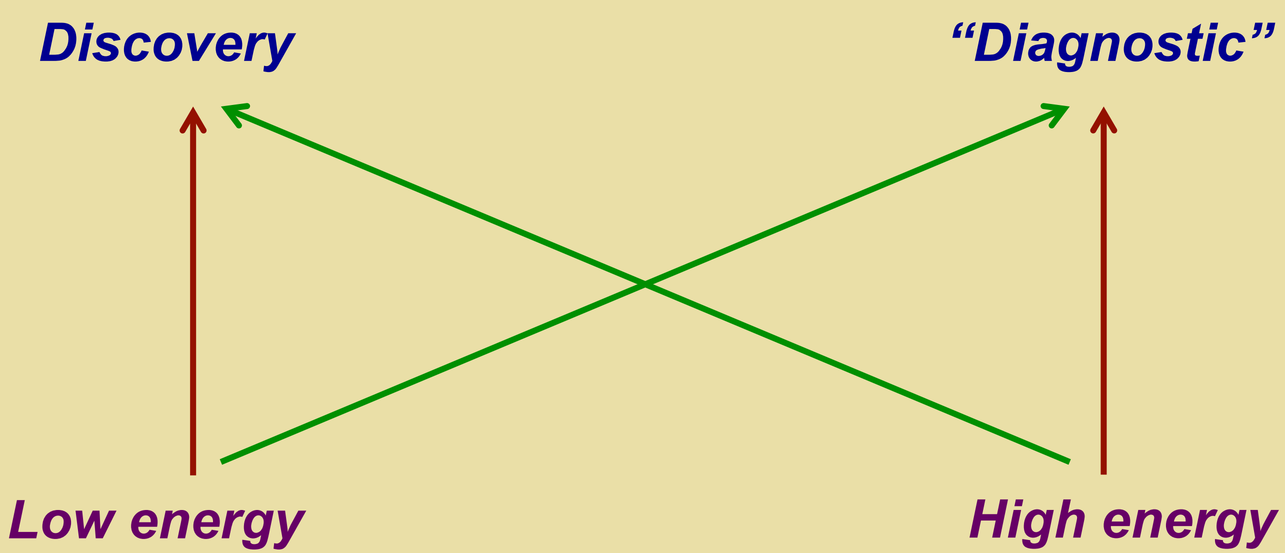
Discovery

Low energy

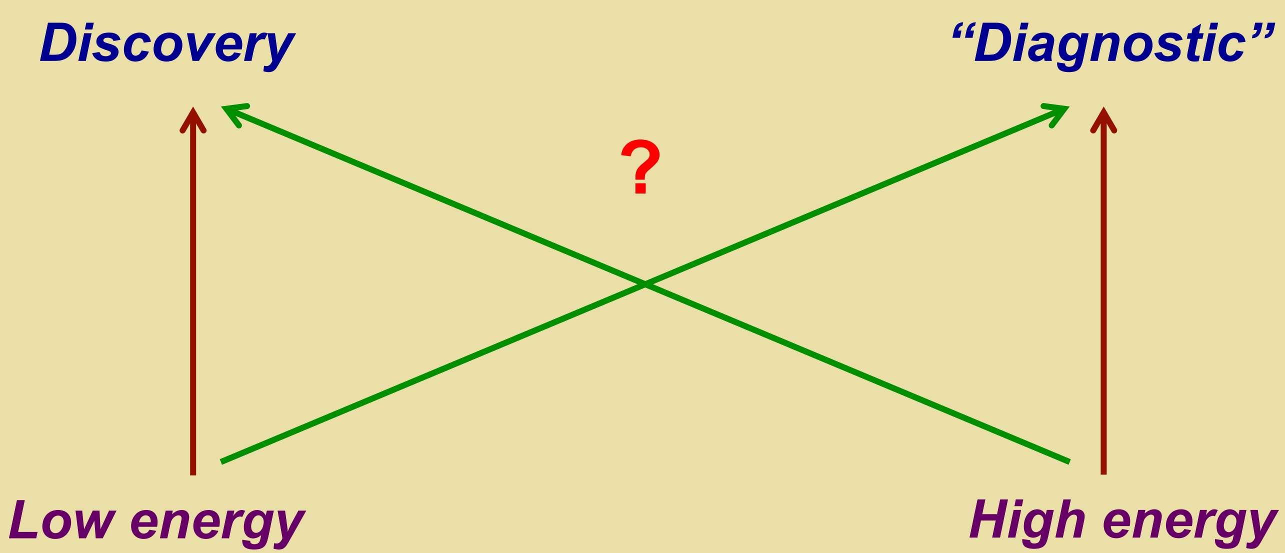
“Diagnostic”

High energy

Low-Energy / High-Energy Interplay



Low-Energy / High-Energy Interplay



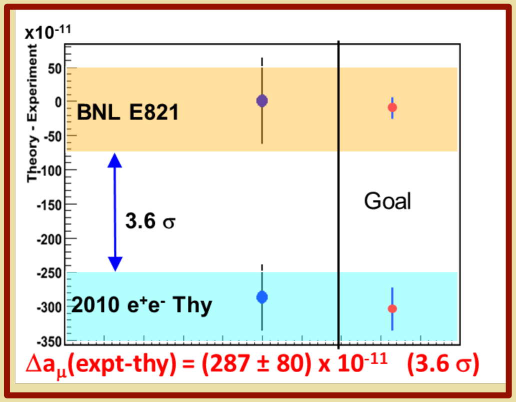
II. The Dark Portal

Standard Model ⟷ Hidden Sector

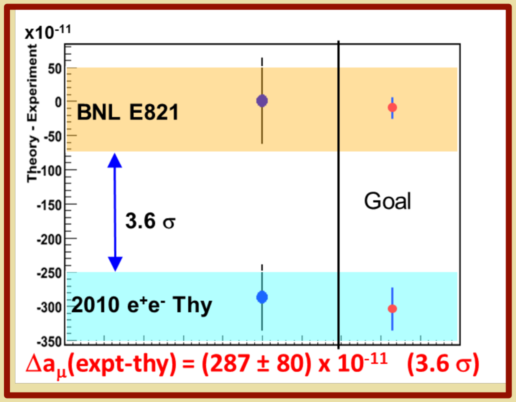
The Dark Portal

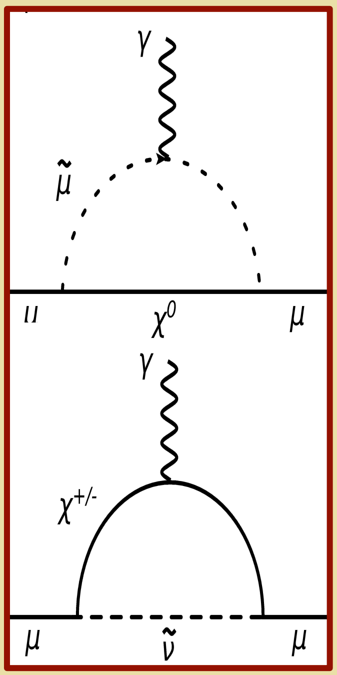
$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_D$$

Muon Anomalous Magnetic Moment



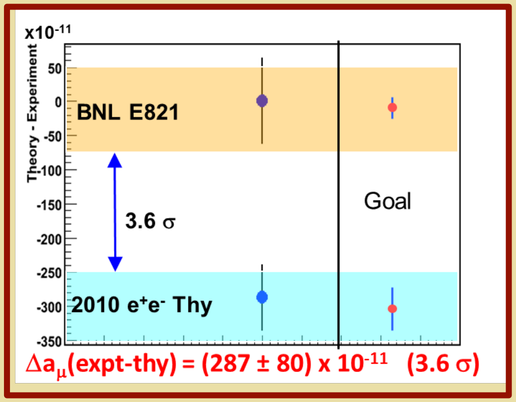
Muon Anomalous Magnetic Moment

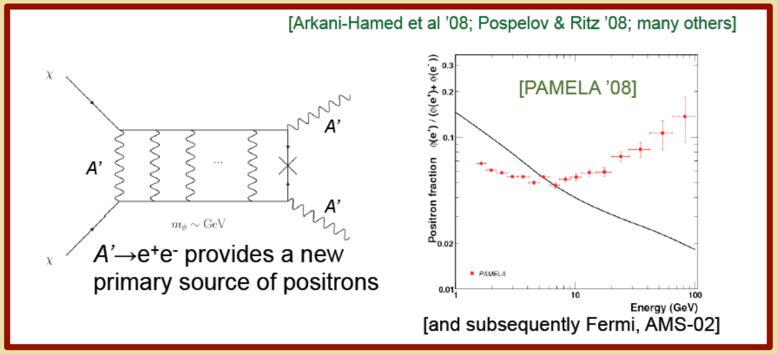


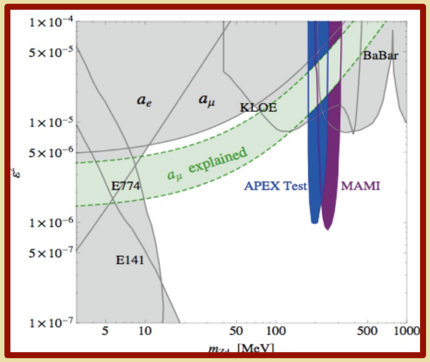


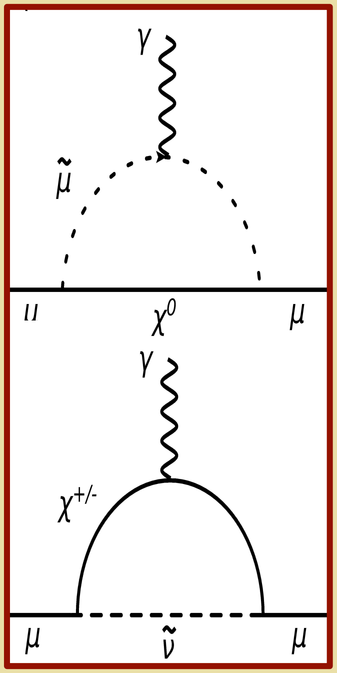
New TeV Physics (SUSY)

Muon Anomalous Magnetic Moment







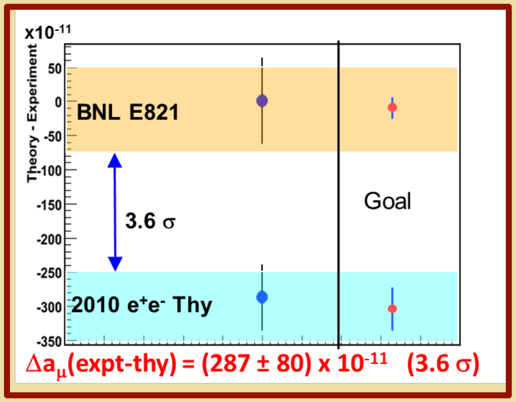


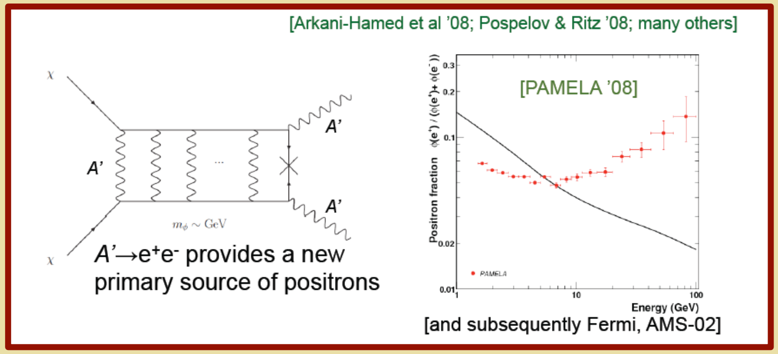
New TeV Physics (SUSY)

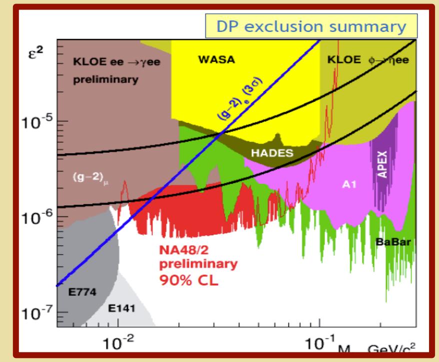
New Ultralight Physics (Dark Z)

New excitement since 2008

Muon Anomalous Magnetic Moment



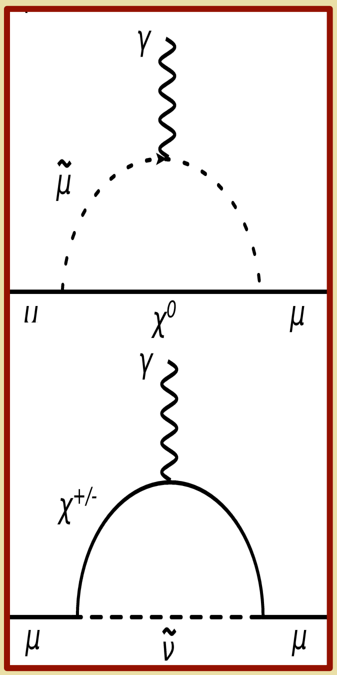




Muon g-2 region essentially ruled out (assumptions)

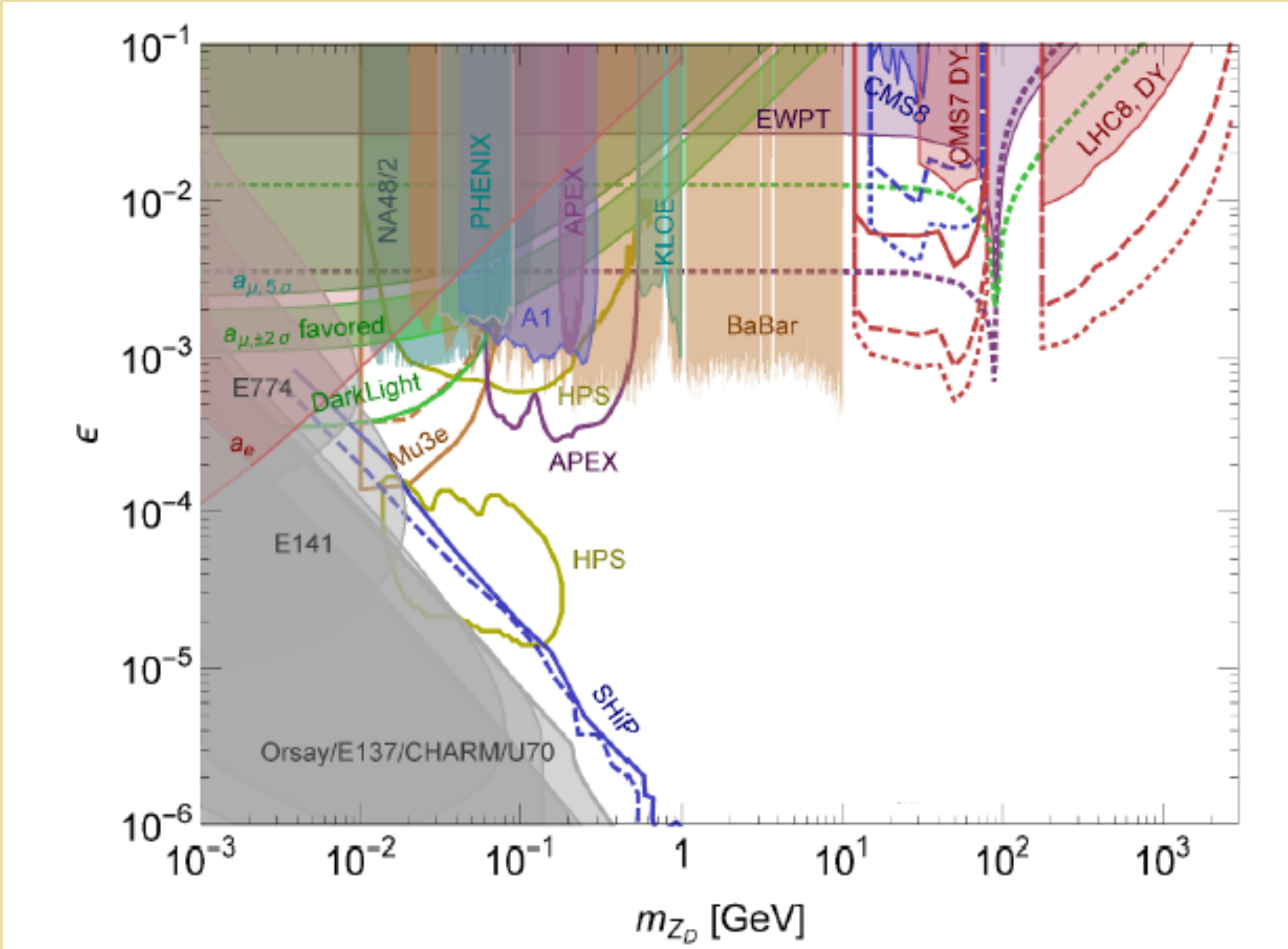
New Ultralight Physics (Dark Z)

New excitement since 2008



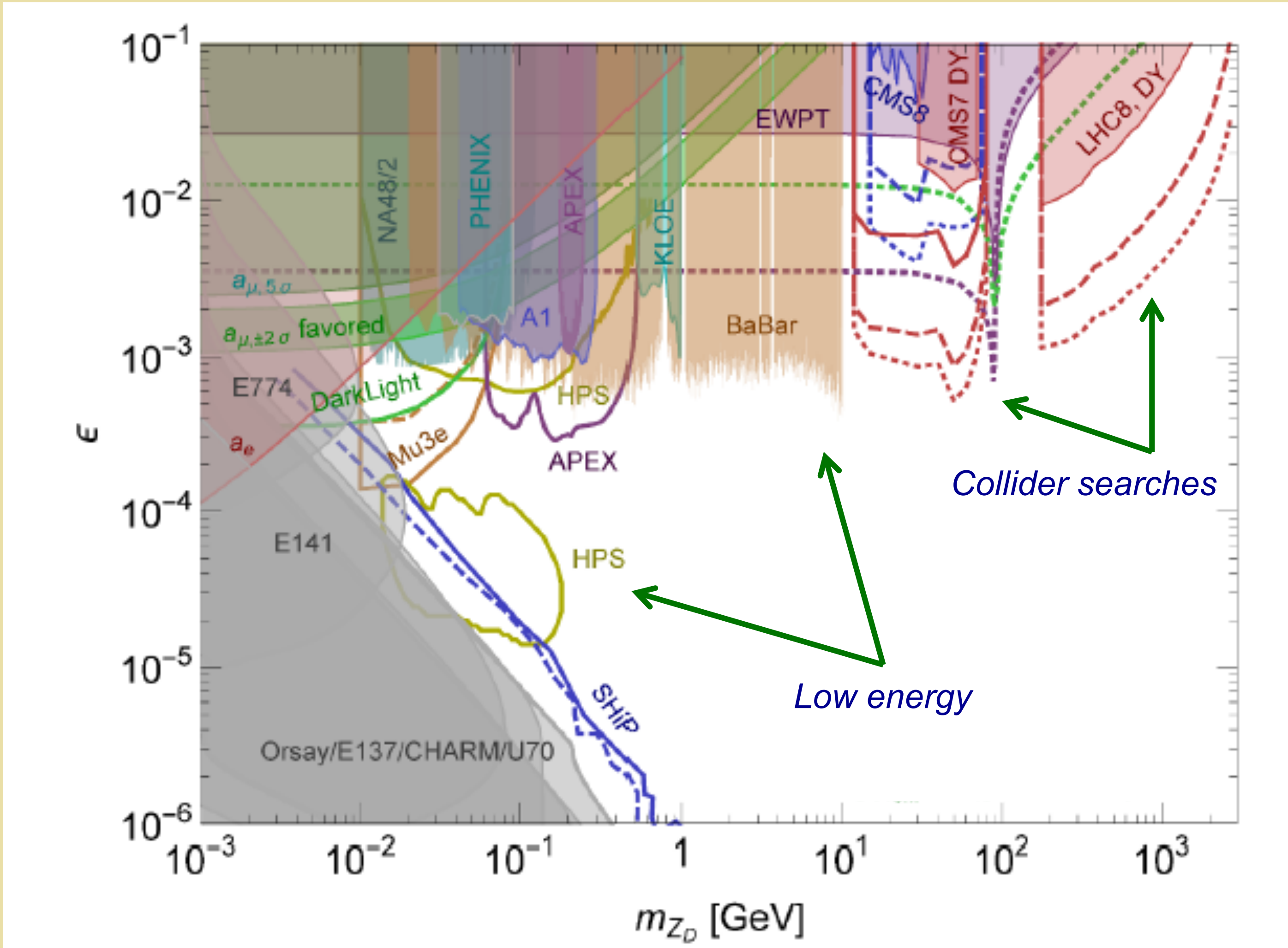
New TeV Physics (SUSY)

The Hunt for a Dark Z



Curtin et al, '14

The Hunt for a Dark Z



Curtin et al, '14

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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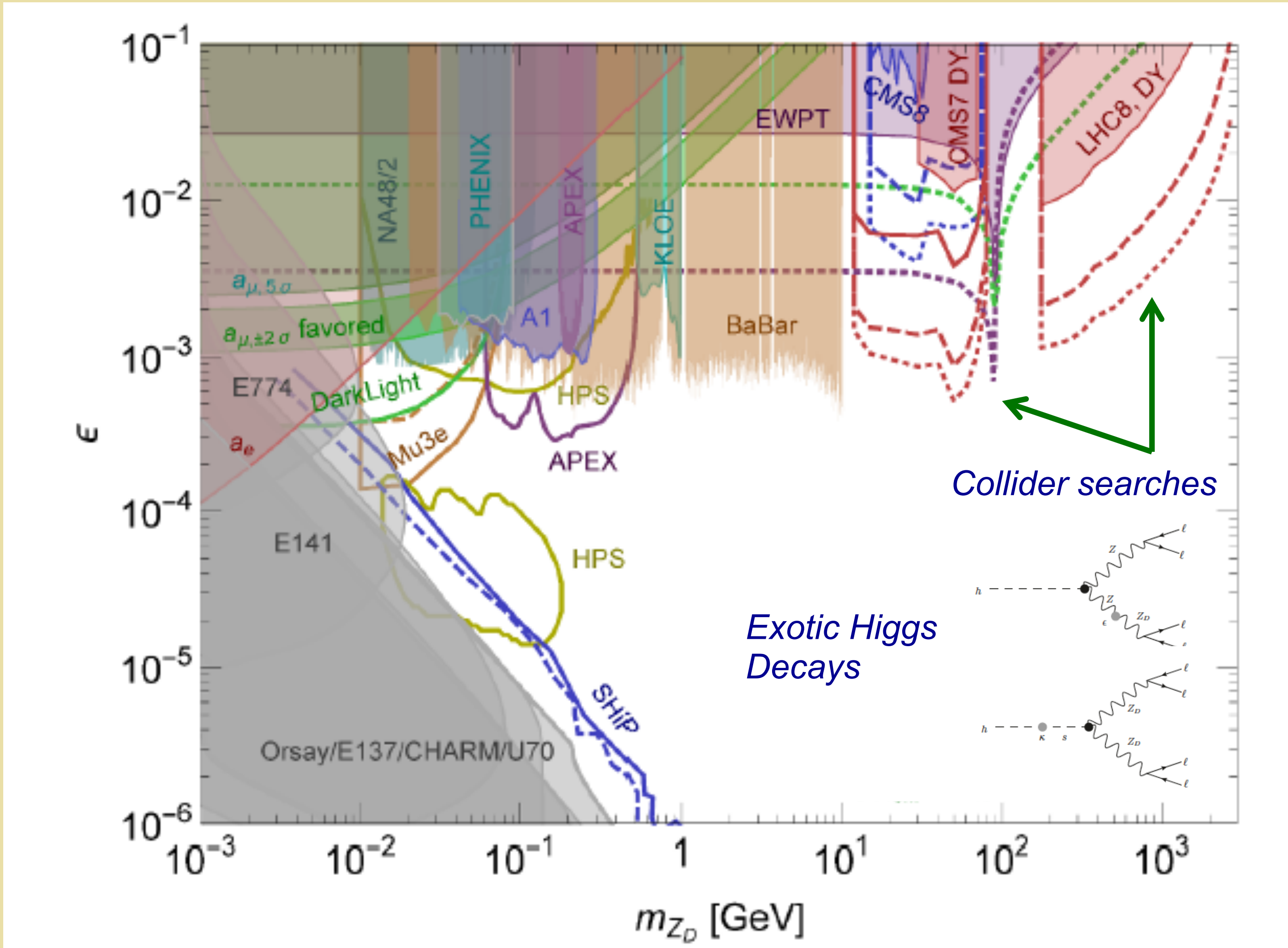
Kinetic Mixing *Mass Mixing*

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

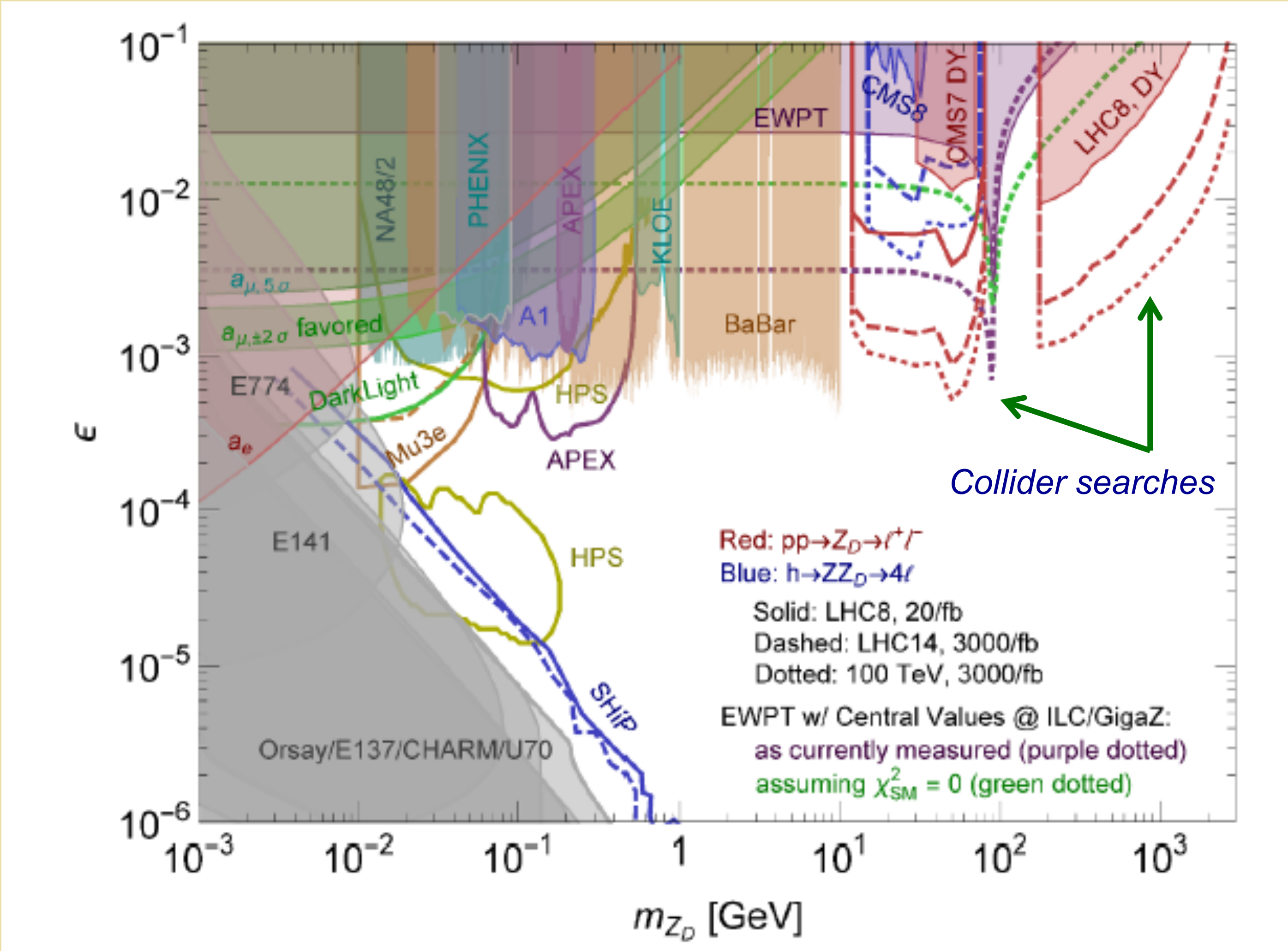
Higgs Mixing

The Hunt for a Dark Z



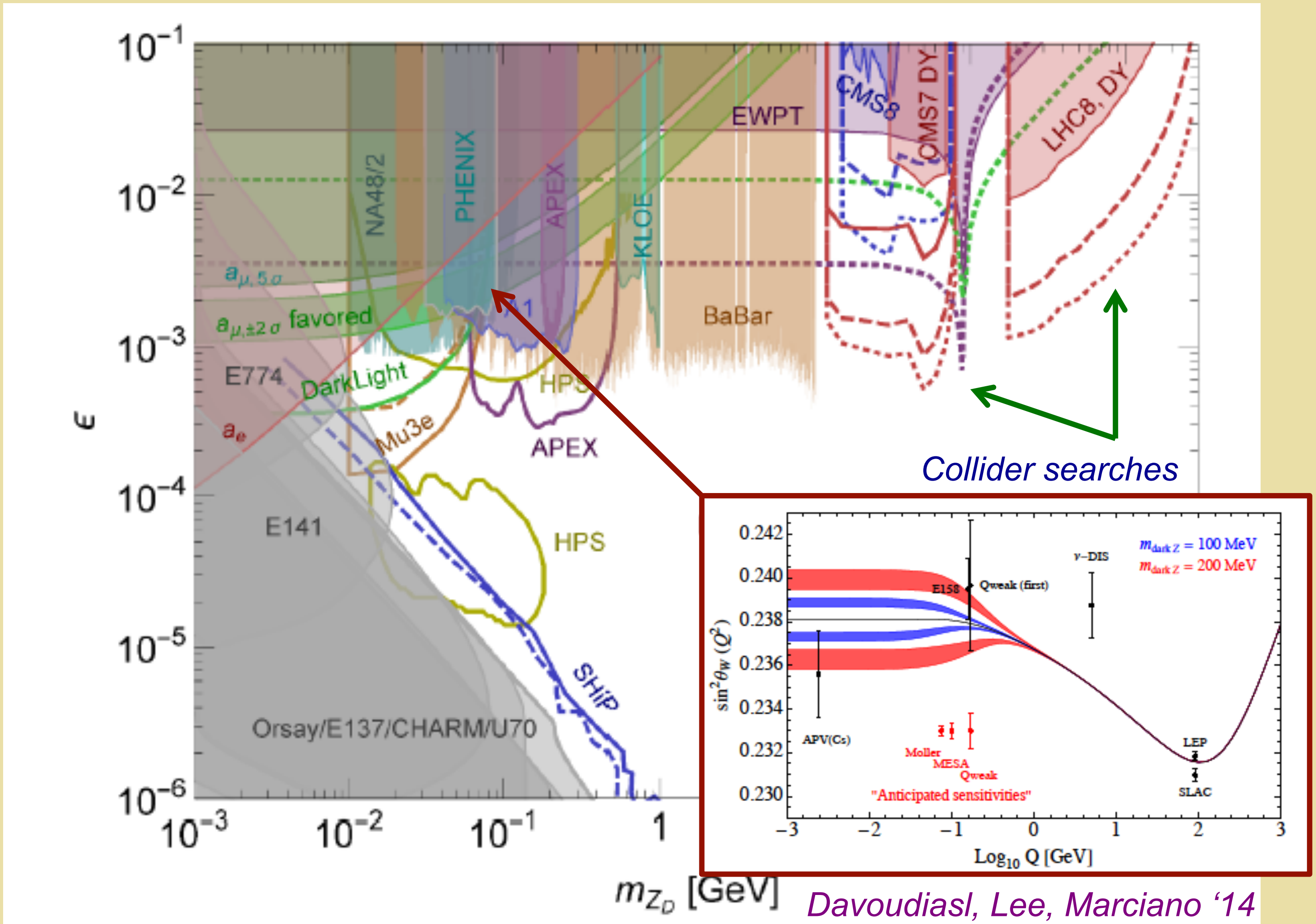
Curtin et al, '14

The Hunt for a Dark Z



Curtin et al, '14

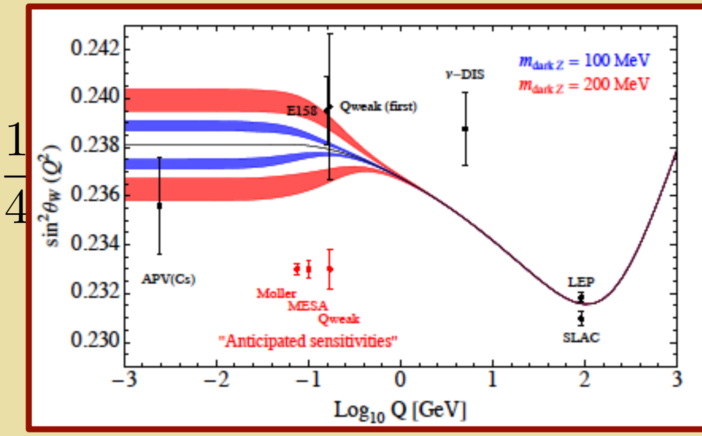
The Hunt for a Dark Z: PVES



Dark Z: Mechanism

PVES

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

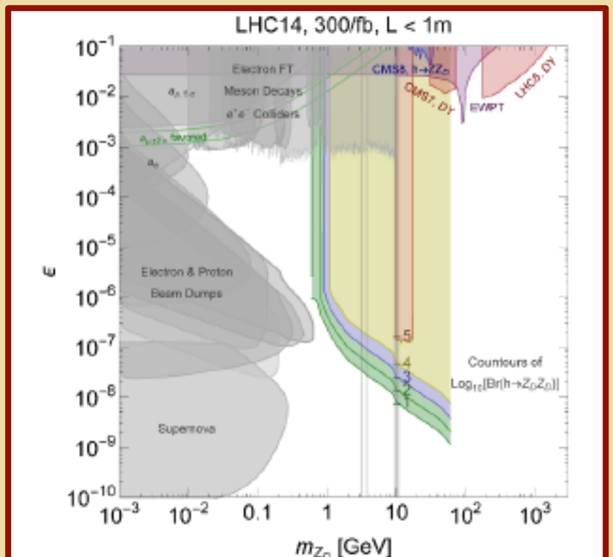


Mass Mixing

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

Higgs Mixing

$h \to Z_D\, Z_D$



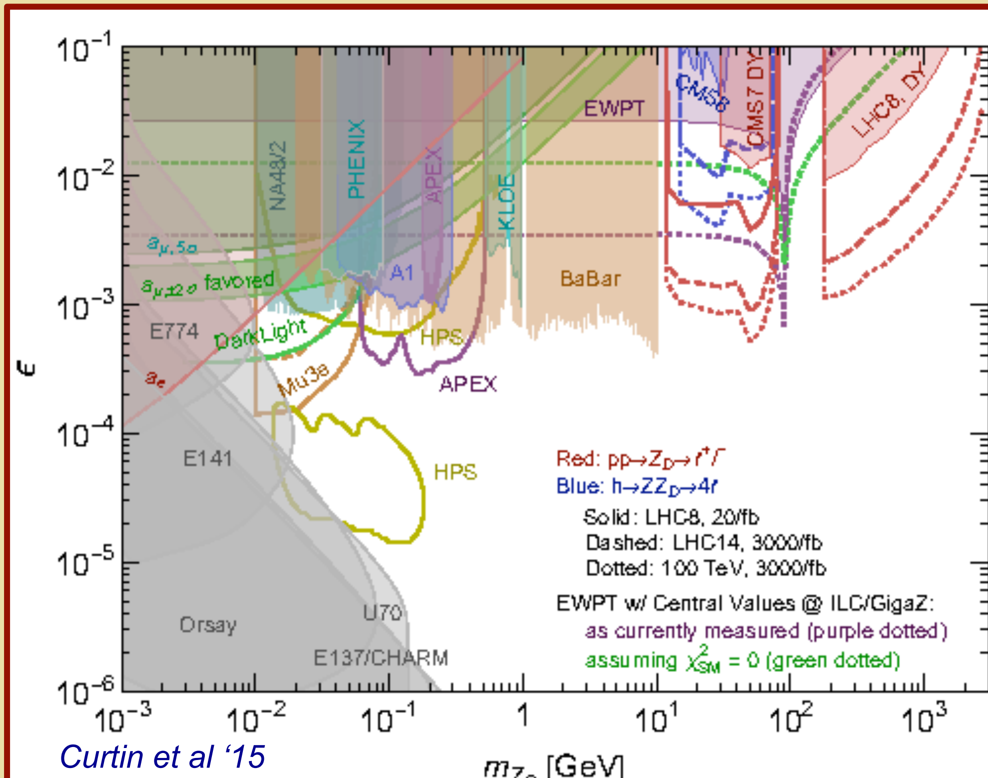
Dark Z: Mechanism

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

Abelian Kinetic Mixing *Mass Mixing*

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

Higgs Mixing



Curtin et al '15

Dark Z: Mechanism

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

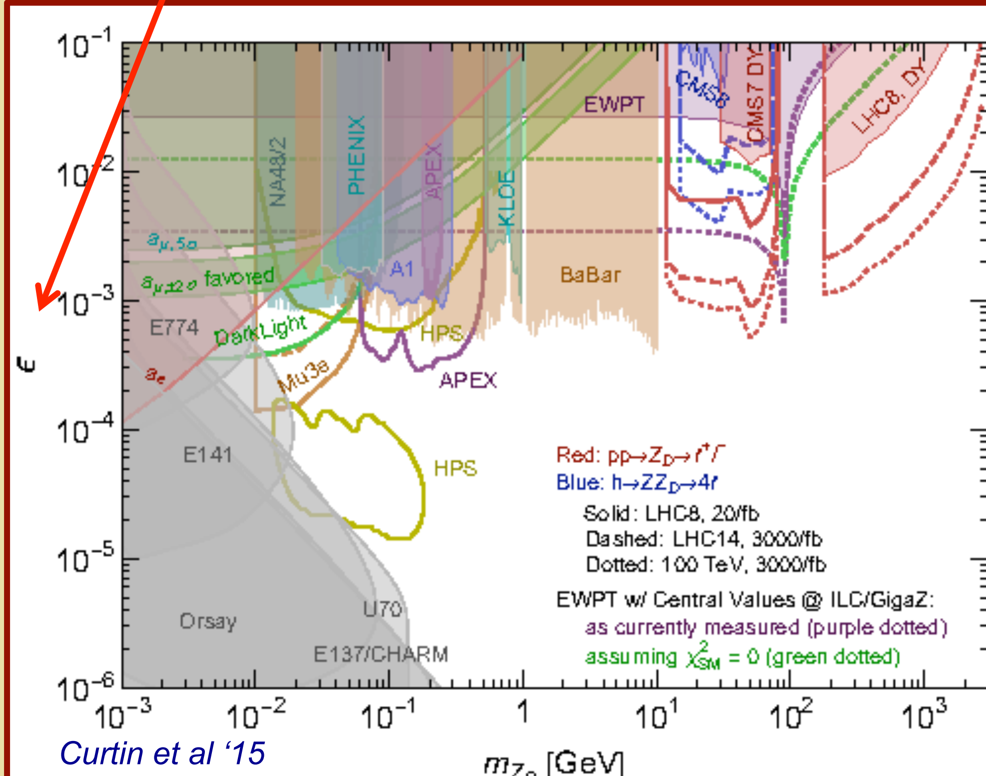
Abelian Kinetic Mixing

Mass Mixing

Why so tiny?

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

Higgs Mixing



Curtin et al '15

Dark Z: Non-Abelian Mechanism

Non-Abelian Kinetic Mixing

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

$\Sigma \sim (1,3,0)$

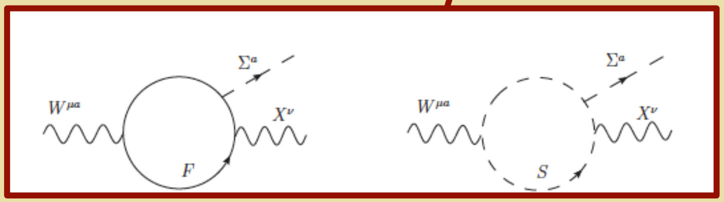
Arguelles, He, Ovaneysan, Peng, MRM '16
See also Barello, Chang, Newby '15

Dark Z: Non-Abelian Mechanism

Non-Abelian Kinetic Mixing

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

Σ ~ (1,3,0)



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

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

Dark Z: Non-Abelian Mechanism

Non-Abelian Kinetic Mixing

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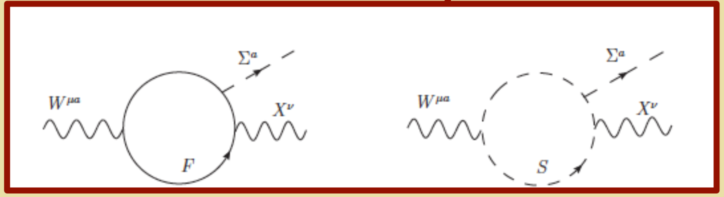


$SU(2)_L$ x $U(1)_D$ mediators

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

Small ε from scale ratio;

β ~ O(1)

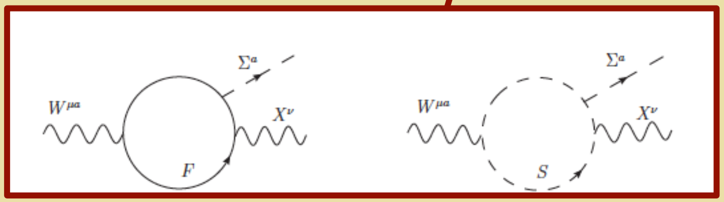
Arguelles, He, Ovaneysan, Peng, MRM '16
See also Barello, Chang, Newby '15

Dark Z: Non-Abelian Mechanism

Non-Abelian Kinetic Mixing

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

$\Sigma \sim (1,3,0)$



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

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

Small ε from scale ratio;

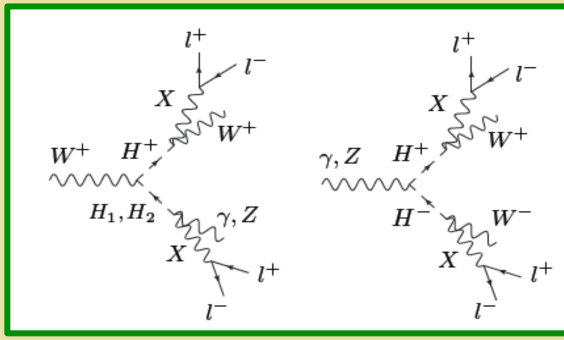
$\beta \sim O(1)$

All pheno except W-X mixing not ε suppressed

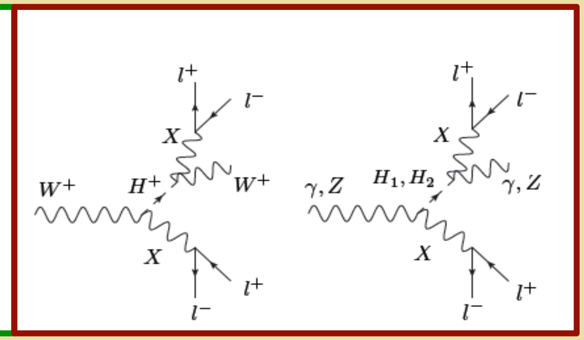
Arguelles, He, Ovaneysan, Peng, MRM '16
See also Barello, Chang, Newby '15

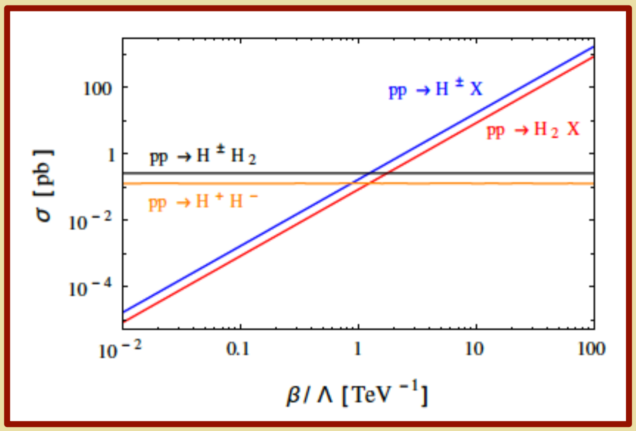
Non-Abelian Mechanism: Production

Pair production



O_{WX} production

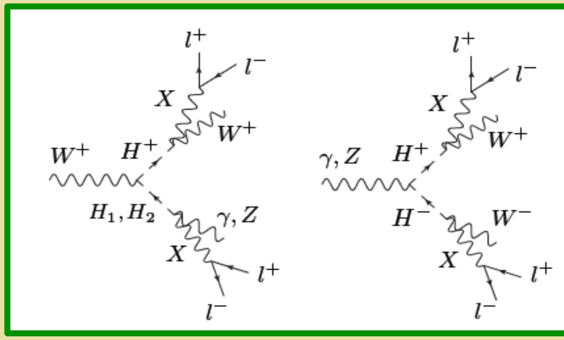


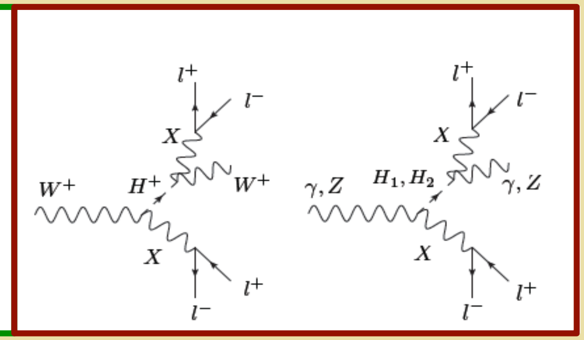


Arguelles, He, Ovaneysan, Peng, MRM '16
See also Barello, Chang, Newby '15

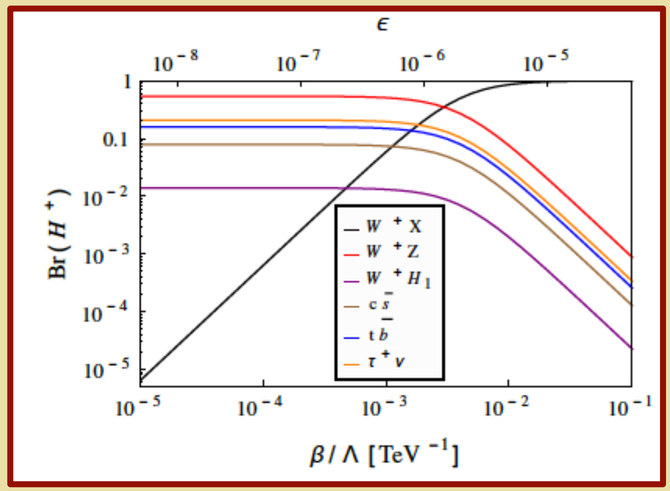
Non-Abelian Mechanism: Decay

Pair production *O_{WX} production*





$\Gamma\,(H^+ \rightarrow SM)$: ε dependent due to mixing w/ Higgs doublet

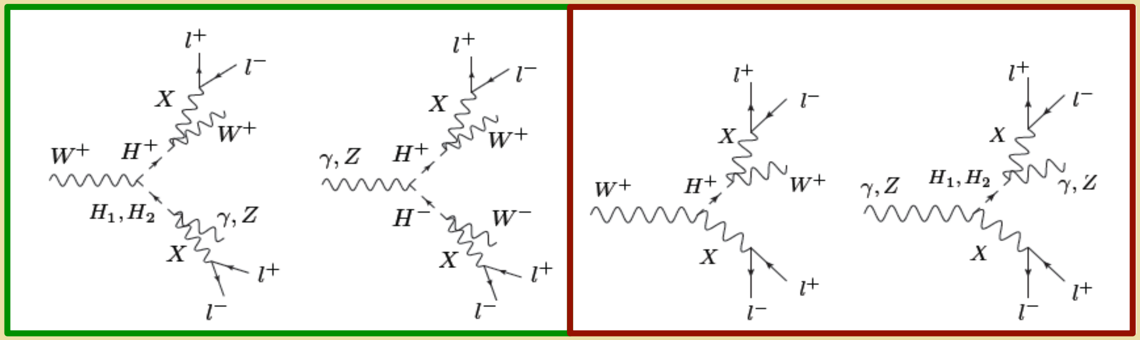


$$V(H,\Sigma) \sim a_1\, H^+ \Sigma\, H + a_2\, H^+ H\, \Sigma^2$$

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

Non-Abelian Mechanism: Signatures

Pair production *O_{WX} production*

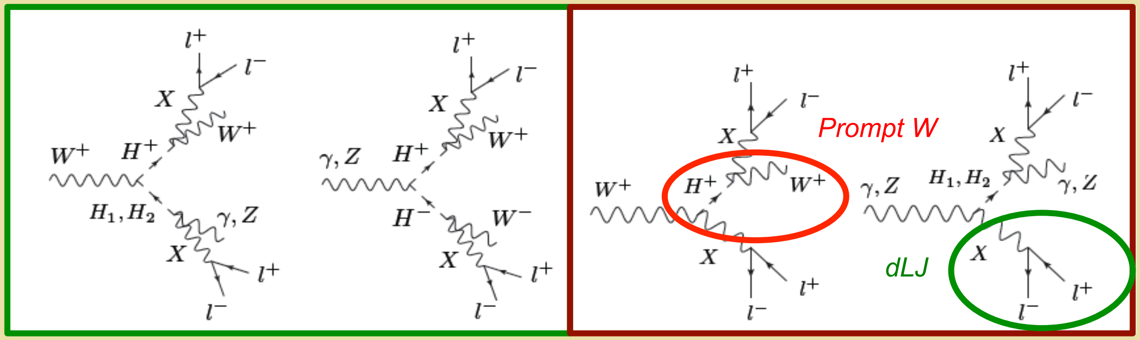


- *Two displaced vertex lepton jets (dLJ)*
- *1 or 2 Prompt V's*

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

Non-Abelian Mechanism: Signatures

Pair production *O_{WX} production*



- *Two displaced vertex lepton jets (dLJ)*
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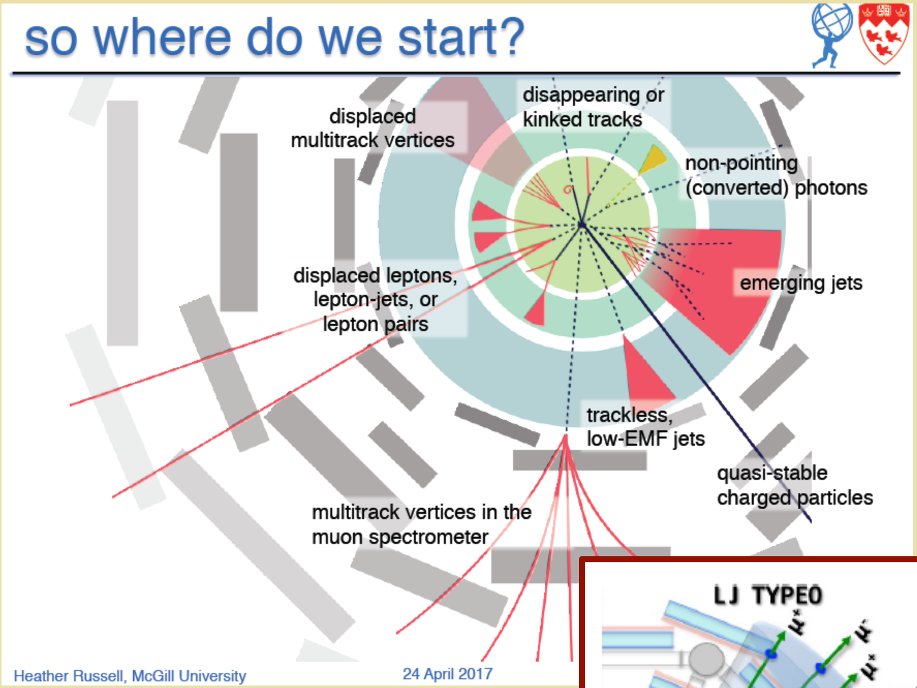
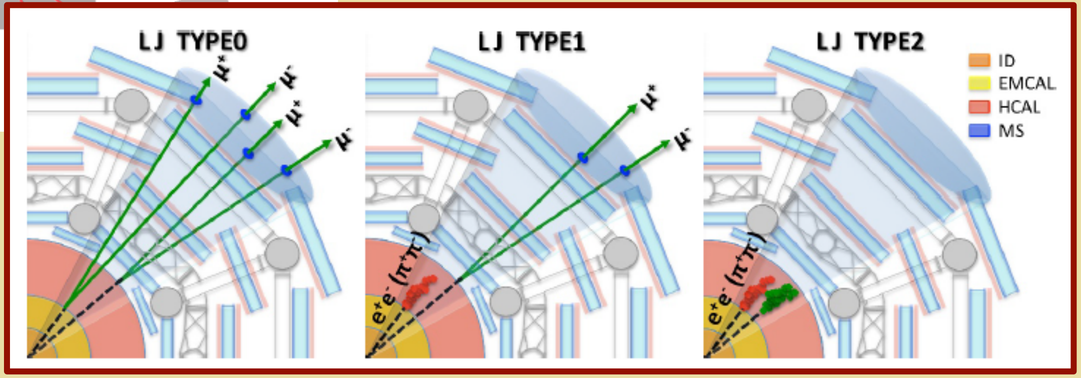
Arguelles, He, Ovaneysan, Peng, MRM '16
See also Barello, Chang, Newby '15

Displaced Lepton Jets



H. Russell, CERN LLP workshop, April 17



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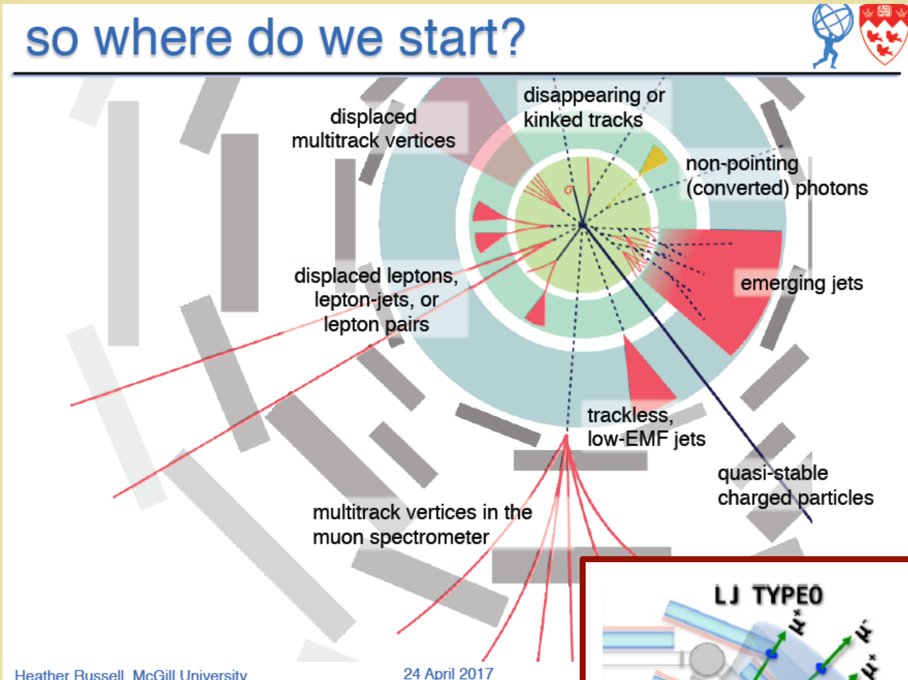
Displaced Lepton Jets



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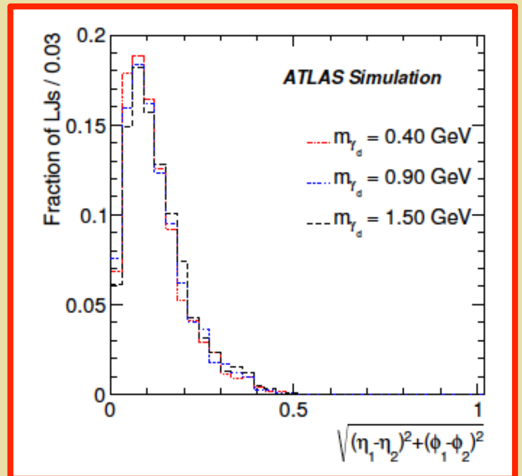

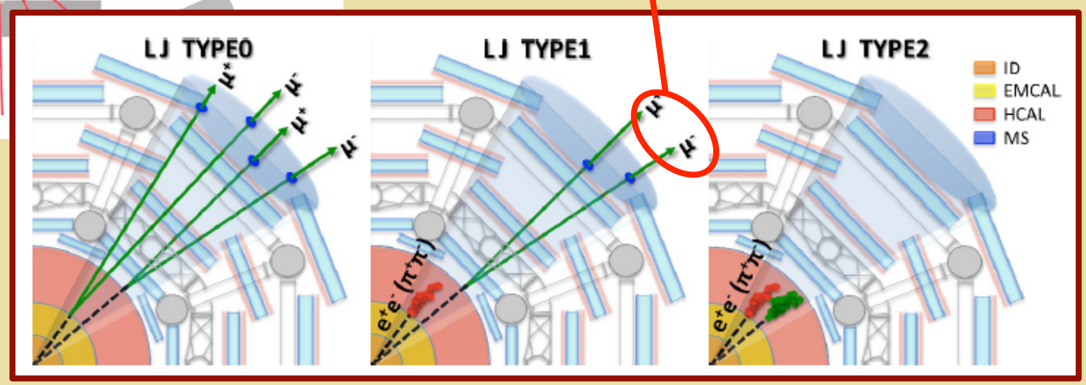

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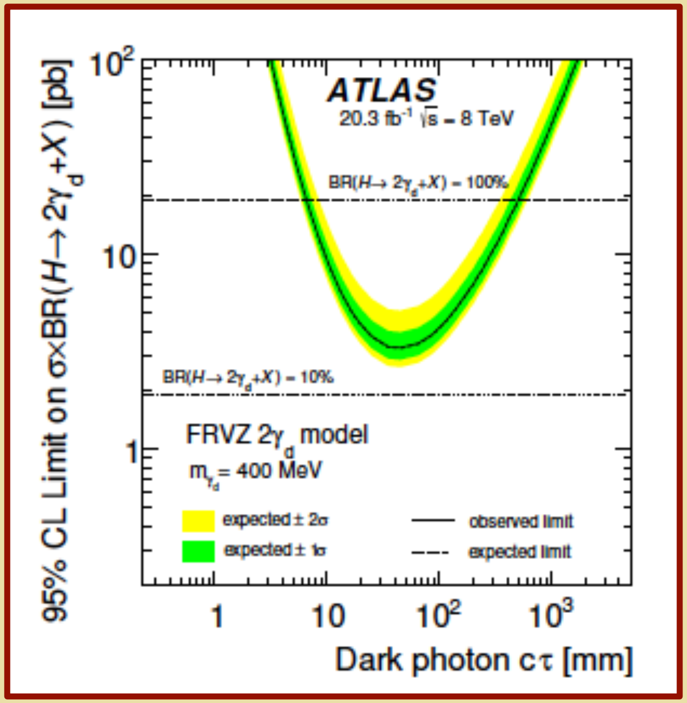
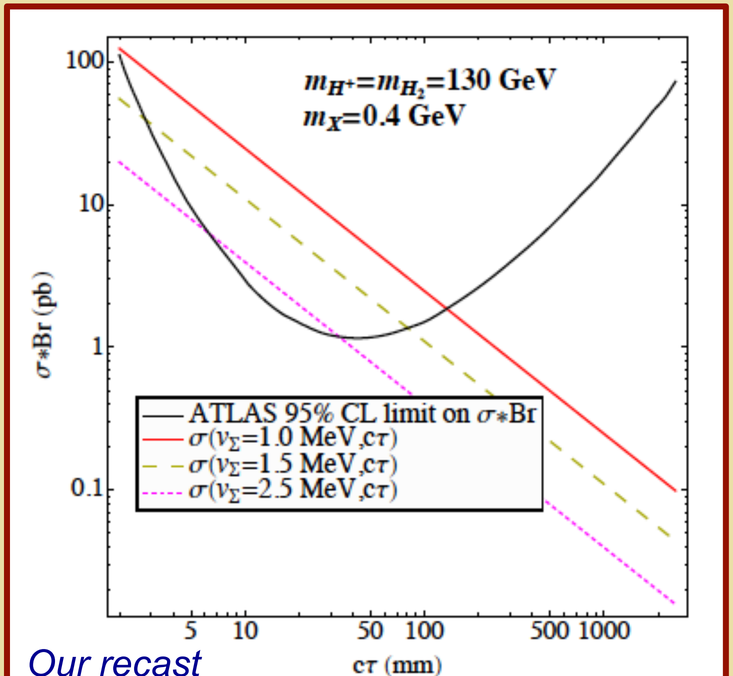
ATLAS Recast





Our recast

Recast ATLAS '14 w/o prompt V

Arguelles, He, Ovaneysan, Peng, MRM '16

Dark Z: Non-Abelian Mechanism

Non-Abelian Kinetic Mixing

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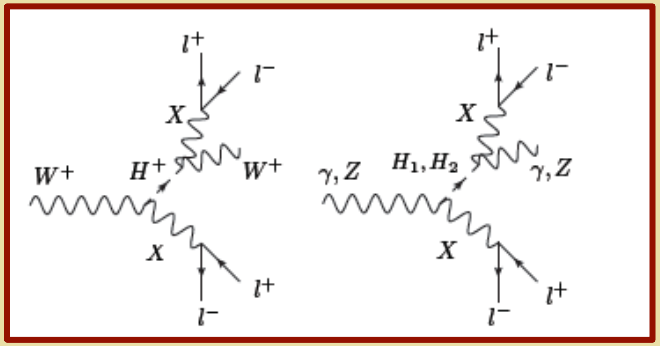
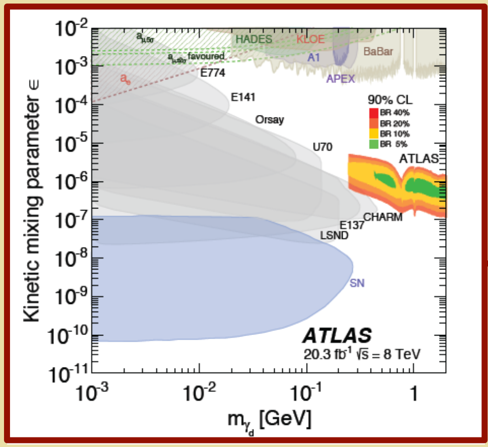
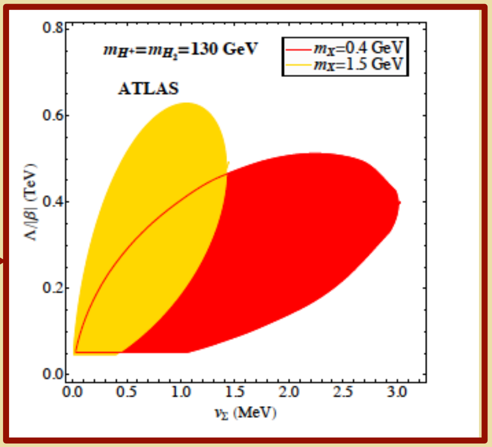


Prompt V + 2 displaced LJ's

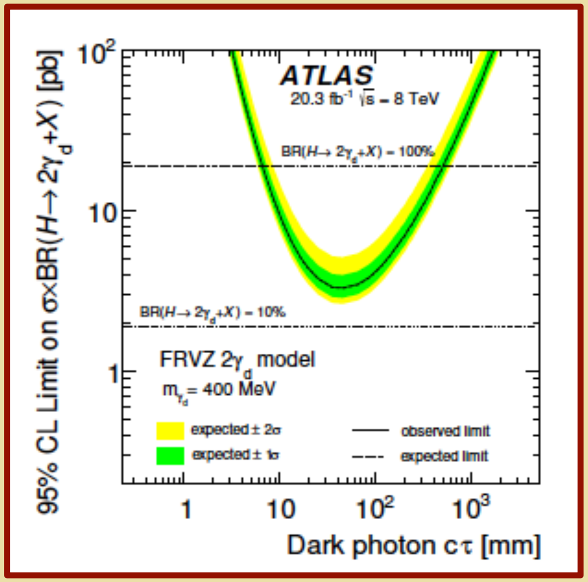


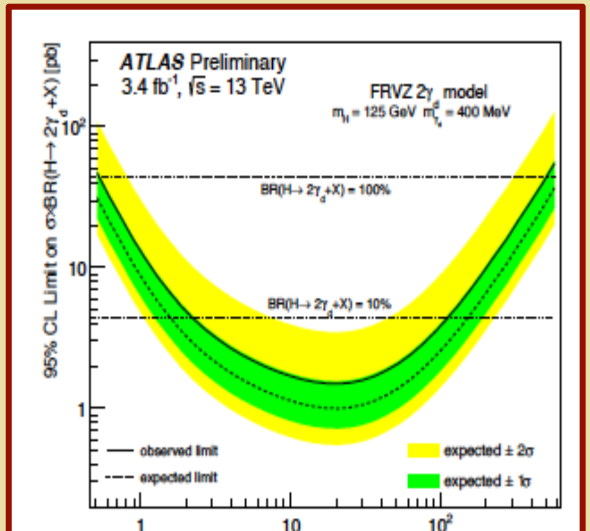


Recast ATLAS '14
(no prompt V)

Arguelles, He, Ovaneysan, Peng, MRM '16

Improving the LHC Reach

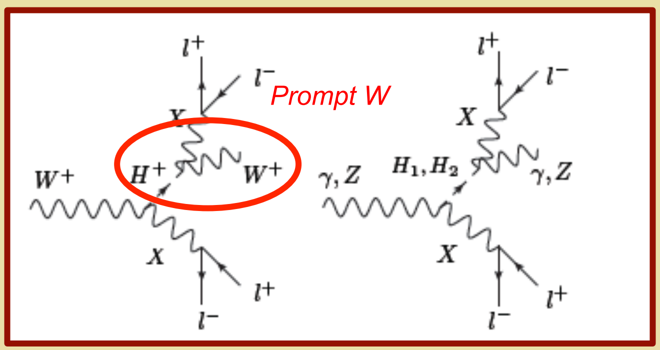




ATLAS-CONF-2016-042

A. Policicchio, CERN LLP workshop, April 17

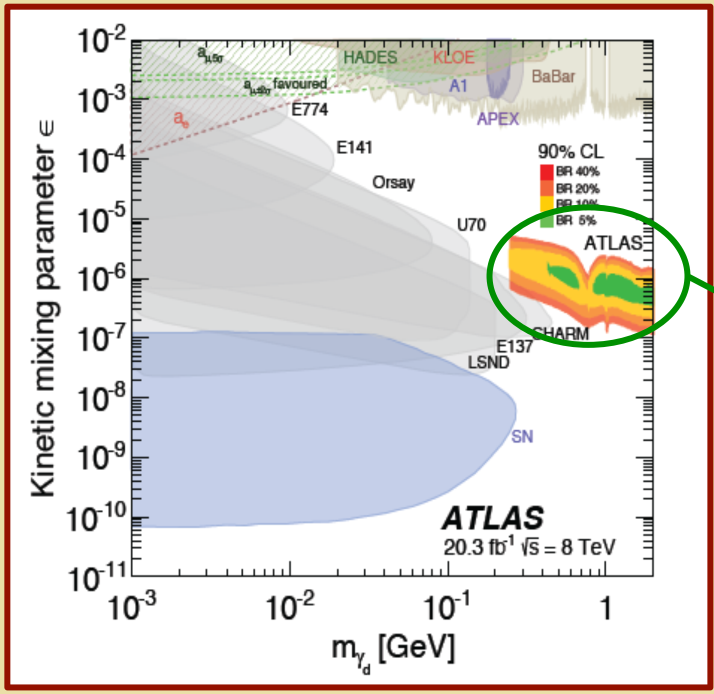
Trigger on prompt W

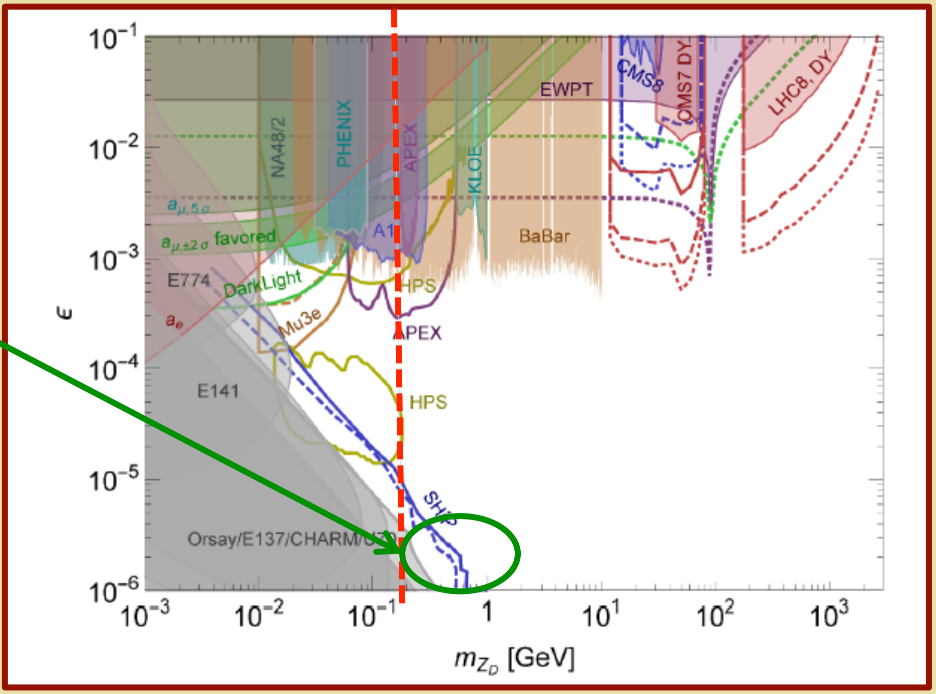


TRIGGERS

- Multi-muon triggers for LeptonJets with muon content
- High p_T isolated, lepton triggers for W/Z associated production
- Single LeptonJet trigger
  - calorimeter ratio for LeptonJets with electrons/pions produced in HCAL
  - muon narrow scan trigger for LeptonJets with muon content
- MET triggers (mono-dLJ with other dark photon(s) escaping form the detector)
- High p_T jet triggers (mono-dLJ with ISR)

Improving the LHC Reach





- *Going to smaller ε ?*
- *Going below 2 m_μ ?*

III. The Higgs Portal

III. The Higgs Portal

BSM CPV ?

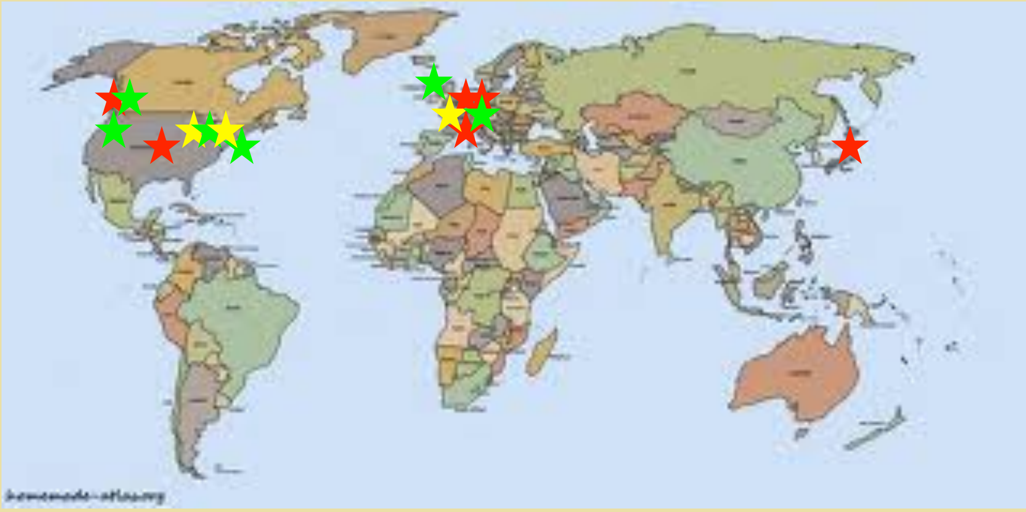
What is the CP Nature of the Higgs Boson ?

- *Interesting possibilities if part of an extended scalar sector*

EDMs: New CPV?

System	Limit (e cm)*	SM CKM CPV	BSM CPV
^{199}Hg	3.1×10^{-29}	10^{-33}	10^{-29}
ThO	8.7×10^{-29} **	10^{-38}	10^{-28}
n	3.3×10^{-26}	10^{-31}	10^{-26}

* 95% CL   ** e^- equivalent



neutron

proton & nuclei

atoms

~ 100 x better sensitivity

Not shown: muon

Higgs Portal CPV

Inoue, R-M, Zhang:
1403.4257

CPV & 2HDM: Type I & II

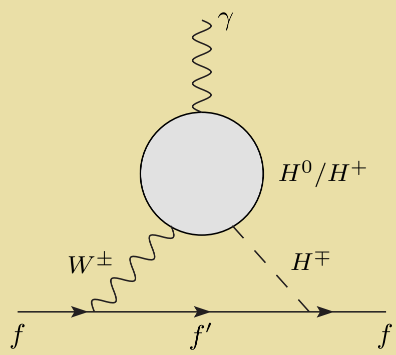
$\lambda_{6,7}$ *= 0 for simplicity*

$$\begin{aligned} V \;=\; & \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \mathrm{h.c.}\right] \\ & -\frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \mathrm{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}. \end{aligned}$$

$$\begin{aligned} \delta_1 &= \mathrm{Arg}\left[\lambda_5^*(m_{12}^2)^2\right] \;, \\ \delta_2 &= \mathrm{Arg}\left[\lambda_5^*(m_{12}^2)v_1 v_2^*\right] \end{aligned}$$

$$\xrightarrow{\text{EWSB}}$$

$$\delta_2 \approx \frac{1 - \left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1 - 2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\,\delta_1$$



Higgs Portal CPV

Inoue, R-M, Zhang: 1403.4257

CPV & 2HDM: Type I & II

$\lambda_{6,7}$ = 0 for simplicity

$$
\begin{aligned}
V &= \frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2 + \frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}\left[\lambda_5(\phi_1^\dagger\phi_2)^2 + \mathrm{h.c.}\right] \\
&\quad - \frac{1}{2}\left\{m_{11}^2(\phi_1^\dagger\phi_1) + \left[m_{12}^2(\phi_1^\dagger\phi_2) + \mathrm{h.c.}\right] + m_{22}^2(\phi_2^\dagger\phi_2)\right\}.
\end{aligned}
$$

$$
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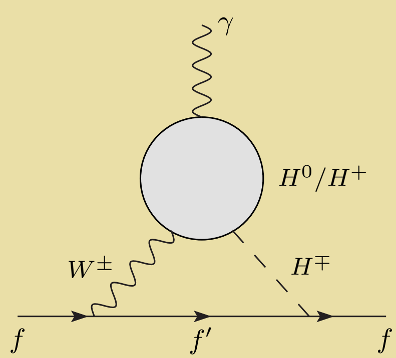
\end{aligned}
$$

EWSB $\longrightarrow$

$$
\delta_2 \approx \frac{1 - \left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1 - 2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\delta_1
$$

h, H^0, $A^0 \rightarrow h_{1,2,3}$

$$
\begin{pmatrix}
-s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\
s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\
s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c}
\end{pmatrix}
$$



Higgs Portal CPV

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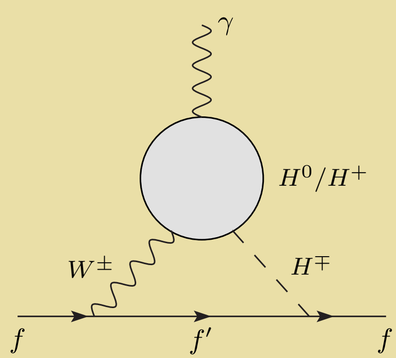
EWSB $\longrightarrow$

$$\delta_2 \approx \frac{1-\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}{1-2\left|\frac{\lambda_5 v_1 v_2}{m_{12}^2}\right|}\delta_1$$

h, H^0, A^0 $\rightarrow$ $h_{1,2,3}$

$$\begin{pmatrix} -s_\alpha c_{\alpha_b} & c_\alpha c_{\alpha_b} & s_{\alpha_b} \\ s_\alpha s_{\alpha_b} s_{\alpha_c} - c_\alpha c_{\alpha_c} & -s_\alpha c_{\alpha_c} - c_\alpha s_{\alpha_b} s_{\alpha_c} & c_{\alpha_b} s_{\alpha_c} \\ s_\alpha s_{\alpha_b} c_{\alpha_c} + c_\alpha s_{\alpha_c} & s_\alpha s_{\alpha_c} - c_\alpha s_{\alpha_b} c_{\alpha_c} & c_{\alpha_b} c_{\alpha_c} \end{pmatrix}$$

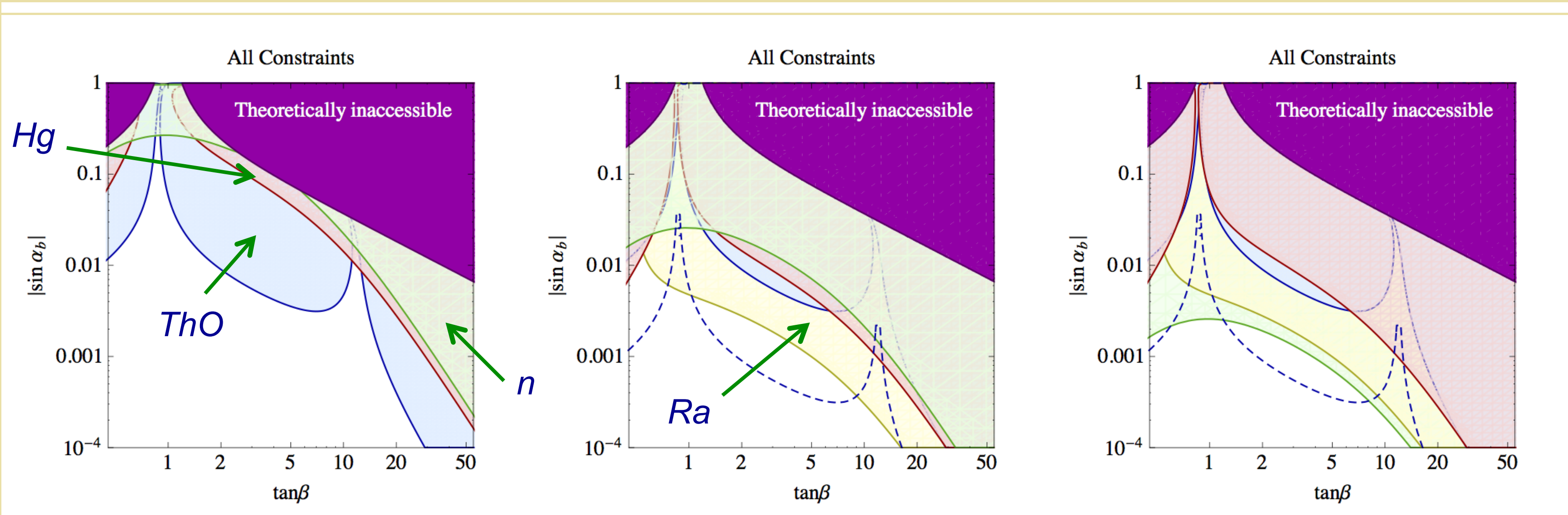


CP mixing: α_b & α_c not independent

Future Reach: Higgs Portal CPV

CPV & 2HDM: Type II illustration

$\lambda_{6,7}$ = 0 for simplicity



Present

sin α_b : CPV scalar mixing

Future:

d_n x 0.1

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

Future:

d_n x 0.01

d_A(Hg) x 0.1

d_{ThO} x 0.1

d_A(Ra)

Inoue, R-M, Zhang: 1403.4257

Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration

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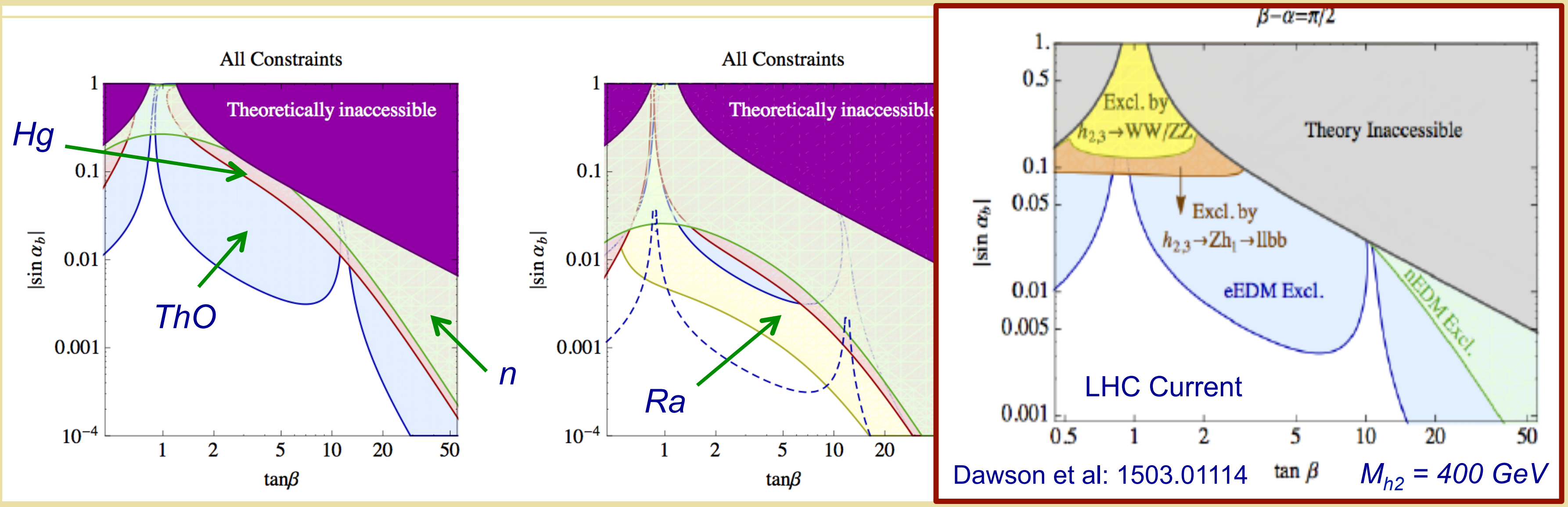

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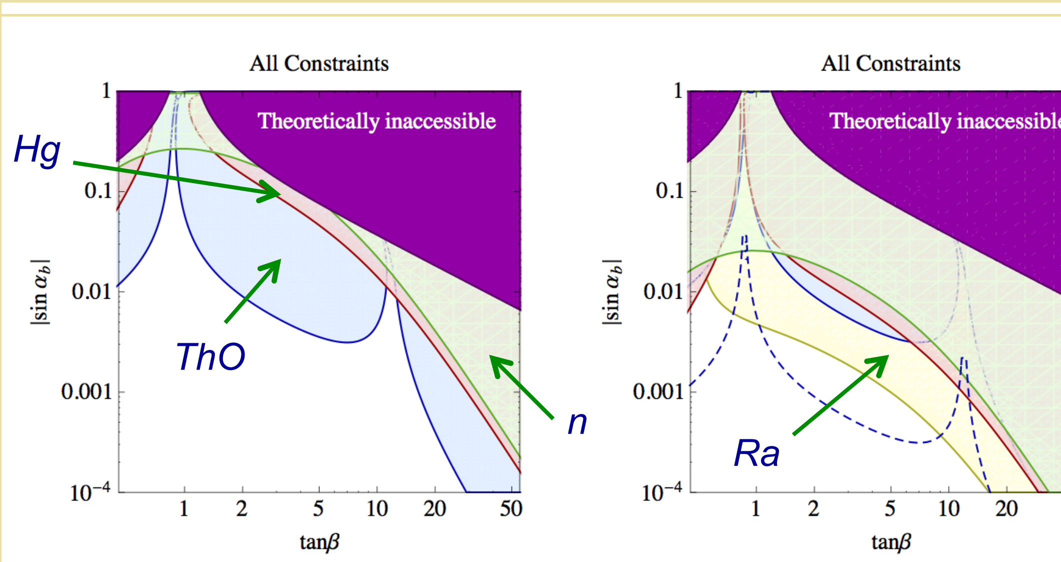

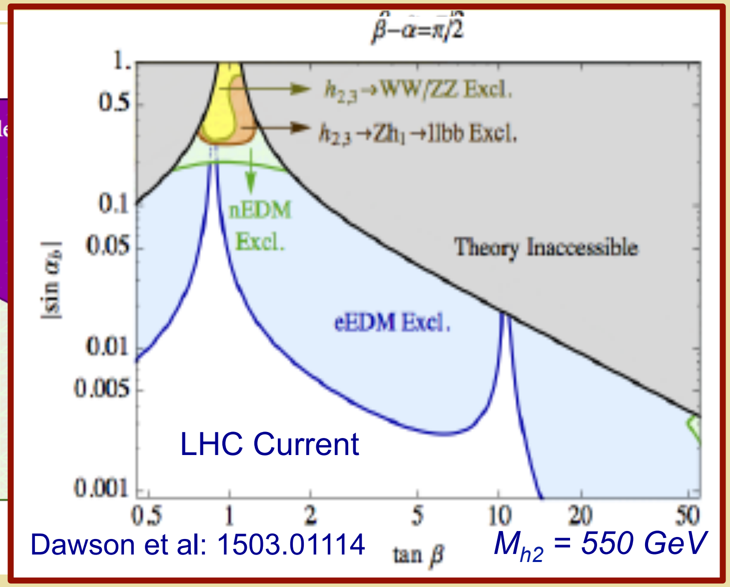

Present	Future:	Future:
	d_n x 0.1	d_n x 0.01
	d_A(Hg) x 0.1	d_A(Hg) x 0.1
	d_{ThO} x 0.1	d_{ThO} x 0.1
	d_A(Ra)	d_A(Ra)

$\sin\alpha_b$: CPV scalar mixing

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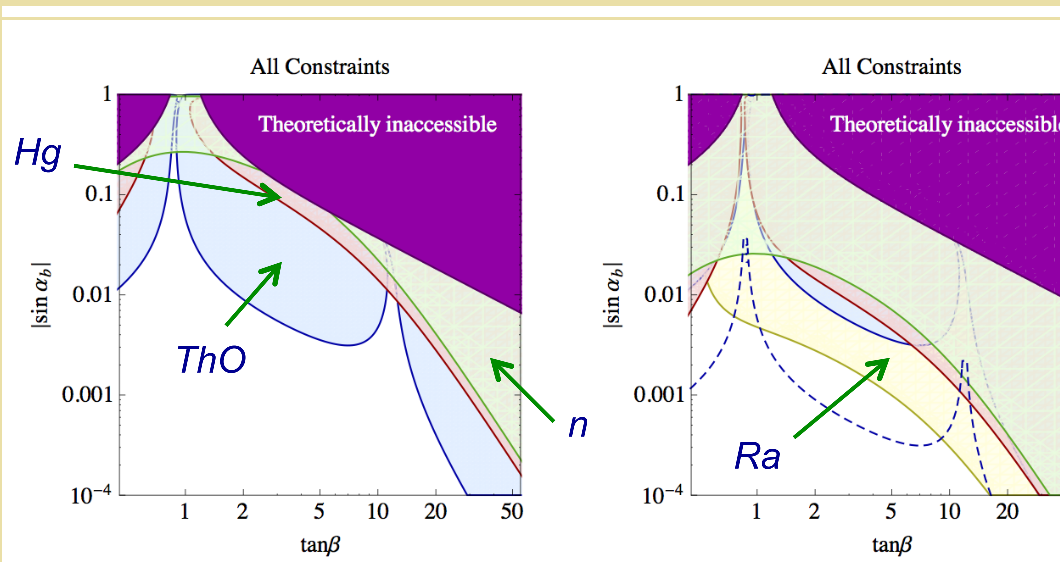
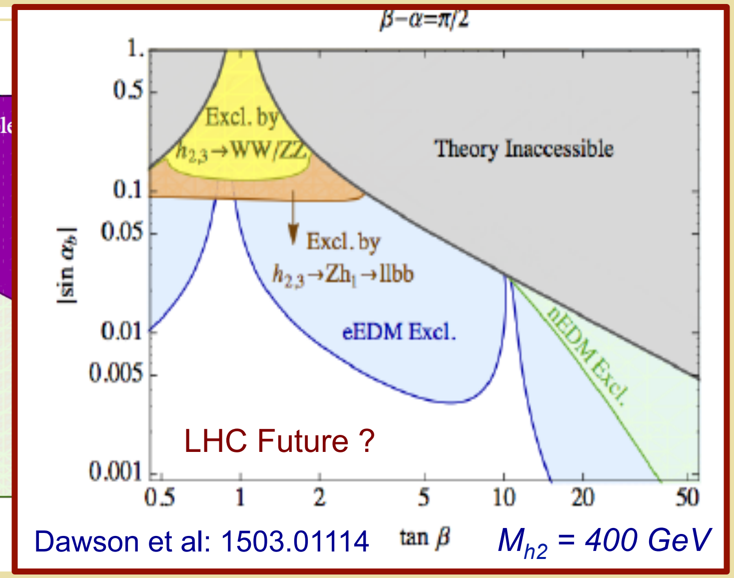
Higgs Portal CPV: EDMs & LHC

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*





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Higgs Portal CPV: EDMs & LHC

Chien-Yi Chen, Haolin Li, MJRM 1705.XXXX

$\boxed{h_{2,3} \rightarrow Z\, h_1 \rightarrow bb\ \ell\ell}$

$Z\, h_a\, h_b$ couplings

$$g_{2z1} \propto -\alpha_b + O(\alpha_b \theta)$$

Vanishes in CP conserving limit

$$g_{3z1} \propto -\theta + O(\alpha_b^2)$$

Vanishes in alignment limit

$\theta = \beta - \alpha - \pi/2$

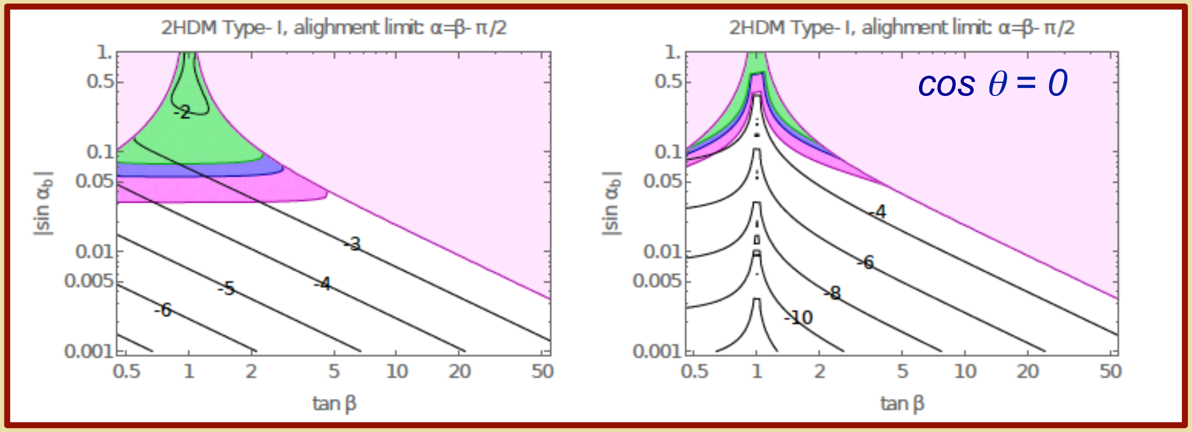
"Alignment": $\theta = 0$

Higgs Portal CPV: EDMs & LHC

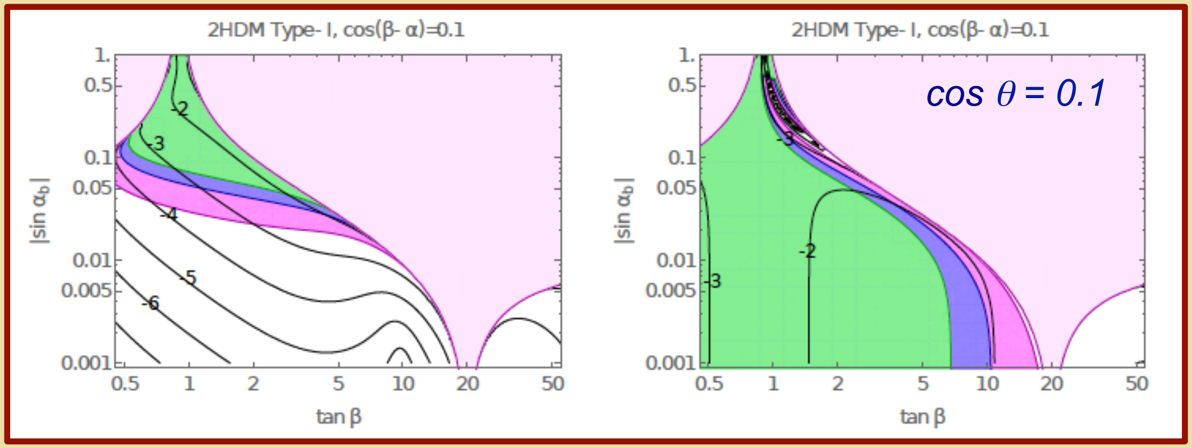
Chien-Yi Chen, Haolin Li, MJRM 1705.XXXX

$h_{2,3} \to Z\, h_1 \to bb\ \ell\ell$

LHC Future



- *Green: 100 fb^{-1}*
- *Blue: 300 fb^{-1}*
- *Magenta: 3 ab^{-1}*



- *Validated vs. ATLAS 8 TeV: 1502.04478*
- *Apply BDT for 14 TeV*

$$g_{2z1} \propto -\alpha_b + O(\alpha_b \theta)$$

$$g_{3z1} \propto -\theta + O(\alpha_b^2)$$

Higgs Portal CPV: EDMs & LHC

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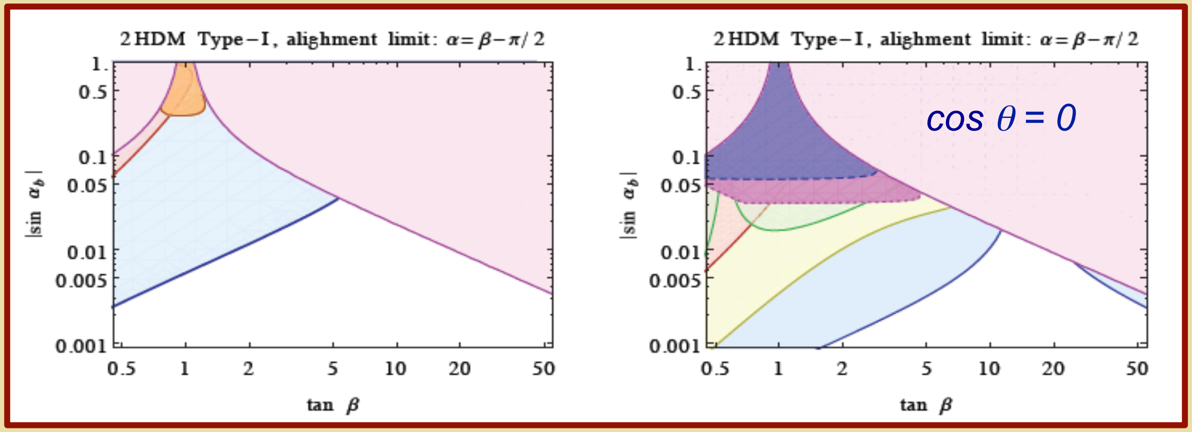
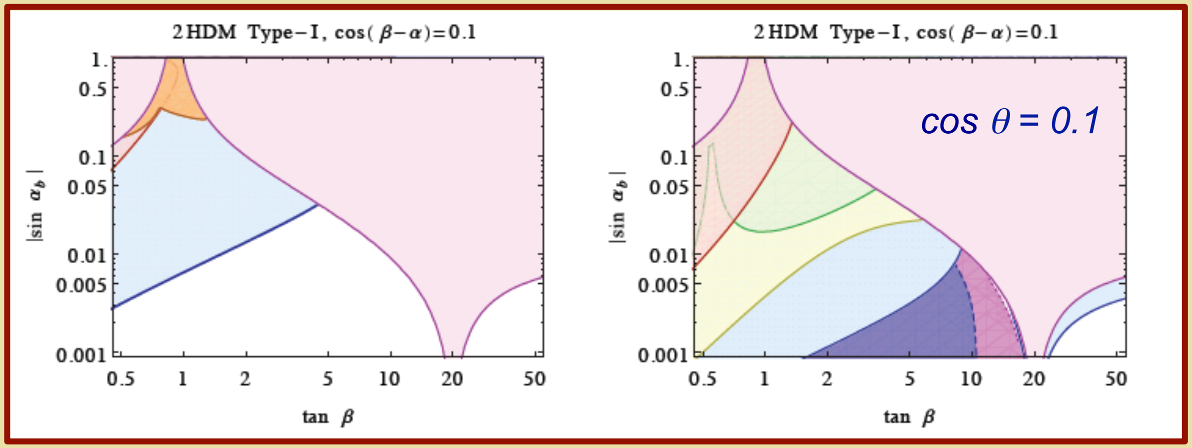
LHC & EDM Future



- Orange: LHC 8 TeV
- Blue: 300 fb^{-1}
- Magenta: 3 ab^{-1}



- Validated vs. ATLAS 8 TeV: 1502.04478
- Apply BDT for 14 TeV

$$g_{2z1} \propto -\alpha_b + O(\alpha_b\theta)$$

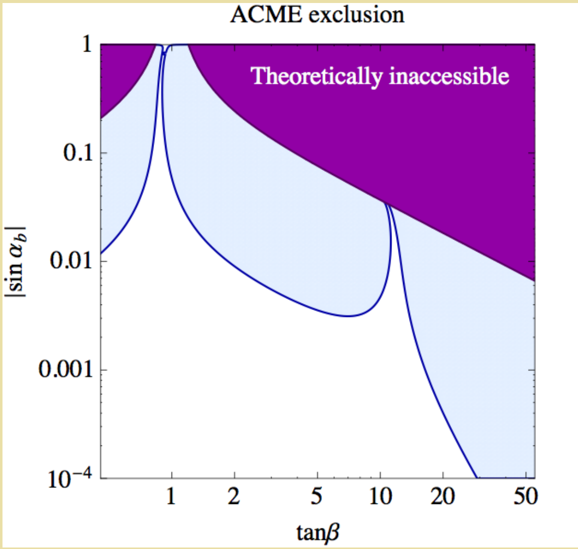
$$g_{3z1} \propto -\theta + O(\alpha_b^2)$$

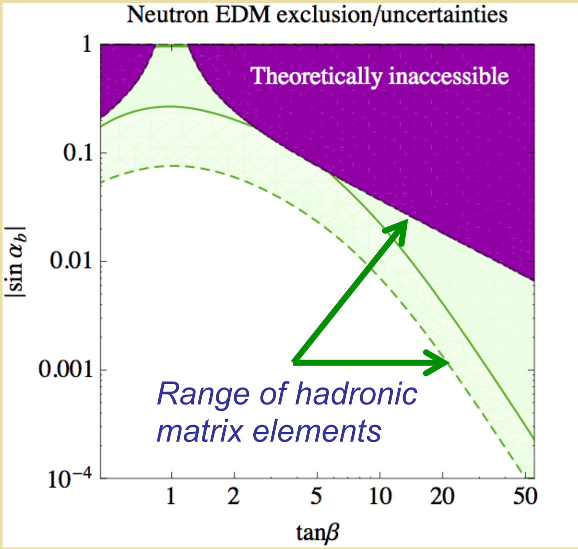
IV. Outlook

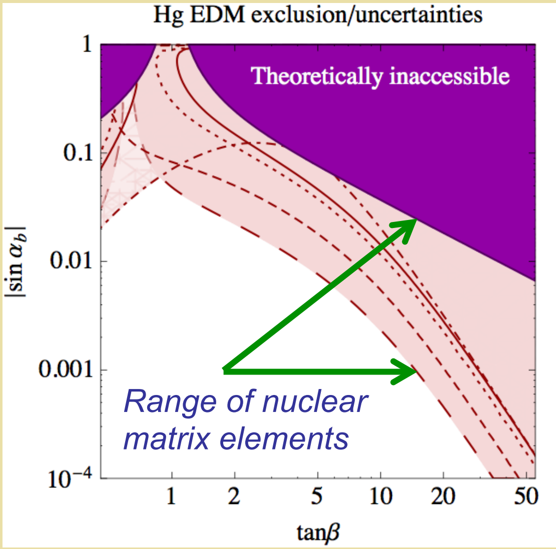
- *Tests of fundamental symmetries & neutrino properties provide powerful windows into key open questions in fundamental physics*
- *There exists a rich interplay with BSM searches at the high energy frontier & both frontiers are essential*
- *Exciting opportunities for discovery and insight lie at the frontier interface*
- *Fully realizing them poses new challenges for hadronic & nuclear structure theory*

Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration *$\lambda_{6,7}$ = 0 for simplicity*







Present

$\sin \alpha_b$: CPV scalar mixing

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Had & Nuc Uncertainties

CPV & 2HDM: Type II illustration

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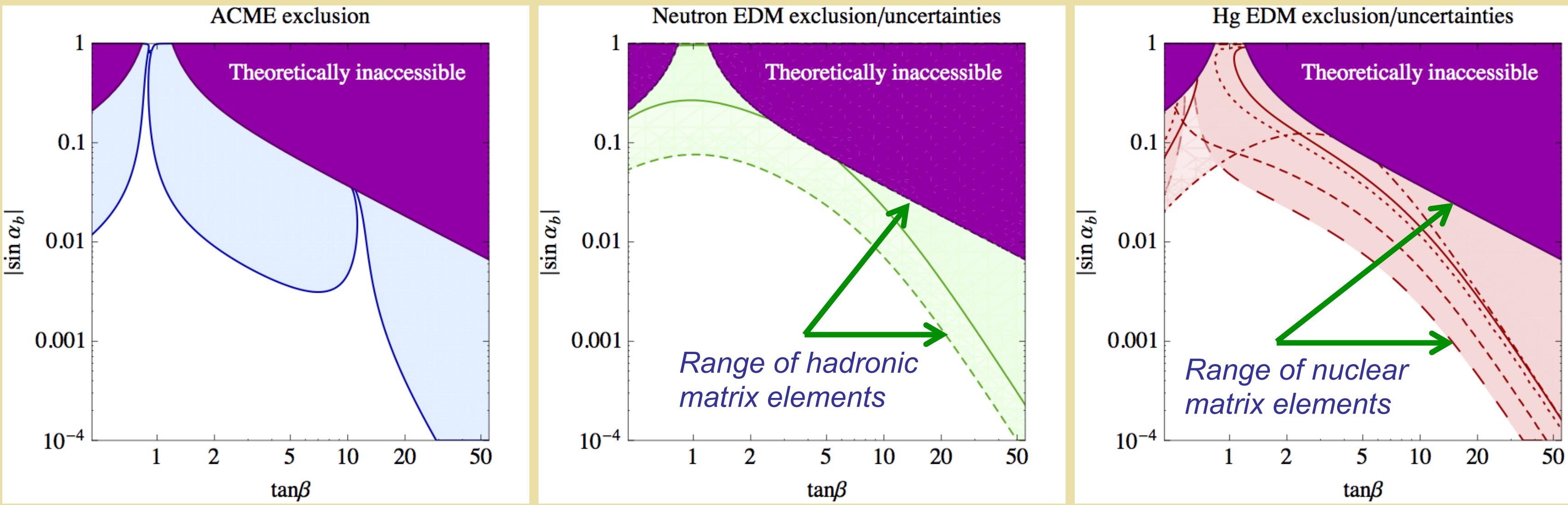

Present

Challenge

sin α_b : CPV scalar mixing

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