VECTOR DYNAMICS IN LOCALLY INVARIANT BRANE WORLD MODELS

S.T. LOVE

EPS-HEP07
MANCHESTER, July 19-25, 2007

Outline

- **Appearance of massive vector field(s) generic feature of locally invariant brane world models**

- **Couple vector to the Standard Model via induced metric and/or extrinsic curvature**

- **Isotopic or anisotropic co-dimensions**

- **Examine various accelerator (LEP I, II) and dark matter constraints.**

Collaborators: T.E. Clark, T. ter Veldhuis, C. Xiong

Insert 4-d Minkowski space probe brane at position $(x^\mu, y^i(x))$ in D-dimensional space

Presence of probe brane breaks D-dimensional space-time symmetries

Associated with broken translations are Nambu-Goldstone boson field $\phi_i(x)$

Nambu-Goldstone field dynamics describes motion of probe brane into the extra dimensions

Brane oscillations gives rise to induced metric on the brane

Invariant 4-dimensional space-time interval:

$$ds^2 = \eta_{\mu\nu} dx^\mu dx^\nu + \frac{1}{F_X^4} \partial_\mu \phi_i(x) h^{ij}(\phi) \partial_\nu \phi_j(x) dx^\mu dx^\nu$$

Nambu-Goto action (brane tension: $\sigma = F_X^4$)

$$S_{NG} = -F_X^4 \int d^4x \sqrt{1 + \frac{1}{F_X^4} \partial_\mu \phi_i h^{ij}(\phi) \partial^\mu \phi_j}$$

Will focus on 2 cases:

1) $h^{ij}(\phi) = \delta^{ij}$**,** N **isotropic flat codimensions**

2) $h^{ij}(\phi) = \delta^{i5}\delta^{j5}$**,** 5^{th} **codimension anisotropic**

Make extra dimensional translations locally invariant; part of D-dimensional general covariance

Introduce gauge field $X^{\mu}(x)$ and covariant derivative:

$$\partial^{\mu}\phi_i \to \partial^{\mu}\phi_i - gF_X X_i^{\mu}$$

S_{NG} **in unitary gauge,** $\phi_i = 0$**, gives vector mass term**

$$S_{mass} \ = \ -\frac{1}{2}M_X^2 \int d^4x X_i^{\mu} X_{\mu i} + ...$$

$M_X \equiv gF_X$ **independent mass scale:**

Higgs mechanism

Presence of massive vector generic consequence of locally invariant brane world models

Include locally invariant X_i^{μ} **kinetic term**

Massive vector field Proca action:

$$S_{Proca} \ = \ -\frac{1}{4}\int d^4x X_i^{\mu\nu} X_{\mu\nu i} - \frac{1}{2}M_X^2 \int d^4x X_i^{\mu} X_{\mu i} + ...$$

with $X_i^{\mu\nu} = \partial^{\mu} X_i^{\nu} - \partial^{\nu} X_i^{\mu}$

Isotropic co-dimensions:

Coupling to Standard Model

X_i **transforms as** $SU(3) \times SU(2) \times U(1)$ **singlet, but carries global** $SO(N)$ **label** i

$SO(N)$ **invariant couplings require even powers of** X_i

Massive vector is stable particle

• **Induced metric couples to Standard Model symmetric energy momentum tensor** $T^{\mu\nu}_{SM}$

$$S_{ind} = \frac{M_X^2}{2F_X^4} \int d^4x X_{\mu i} X_{\nu i} T^{\mu\nu}_{SM} + \ldots$$

•Coupling to Standard Model using extrinsic curvature

Measures curvature of embedded D3 brane relative to enveloping D-dimensional geometry

Extrinsic curvature tensor in unitary gauge:

$$K_i^{\mu\nu} = -\frac{M_X}{F_X^2}\partial^\mu X_i^\nu + \frac{M_X^3}{2F_X^6} X_{\lambda j} X_j^\lambda \partial^\mu X_i^\nu + \frac{M_X^3}{2F_X^6} X_i^\mu X_{\lambda j} \partial^\nu X_j^\lambda + ... \quad (1)$$

Invariant couplings constructed by contracting $K_i^{\mu\nu}$ with other tensors

Couples to Standard Model weak hypercharge field strength, $B_{\mu\nu}$:

$$S_{extr} = \frac{M_X^2}{F_X^4}(K_1 B_{\mu\nu} + K_2 \tilde{B}_{\mu\nu})\partial^\mu X_i^\rho \partial_\rho X_i^\nu + ...$$

Coefficients K_1, K_2 dimensionless constants of effective action

- **LEPII limits for isotropic codimensions**

$e^+e^- \to \gamma XX$ **appears as** γ **plus missing energy**

Expt limit: $\sigma(e^+e^- \to \gamma \not{E}) < .45\ pb$
leads to restriction of allowed M_X, F_X **values**

- **Induced metric coupling (to** $T^{\mu\nu}_{SM}$**) only**

Scalar branon (longitudinal vector) contribution considered by
Creminelli and Strumia, Nucl. Phys. **B596**, 125 (2001);
Alcaraz, Cembranos, Dobabo and Maroto, Phys. Rev. D **67**, 075010 (2003);
L3 Collaboration, P. Achard et al., Phys. Lett. **B597**, 145 (2004);
S. Mele, EPS-HEP05, 153.

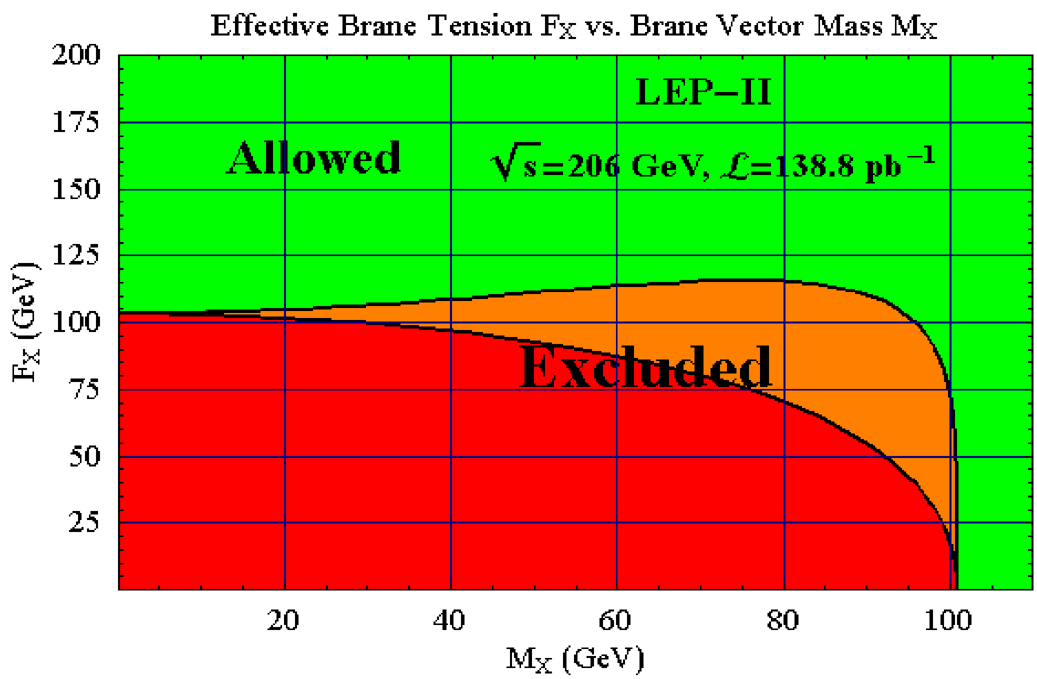


Figure 1: Excluded red shaded region from longitudinal component of vector (branon); Orange shaded region from transverse components of vector.

• **Extrinsic curvature coupling (to $B^{\mu\nu}$) only**

Transverse vector modes required

Limits from $e^+e^- \rightarrow \gamma + \not{E}$ and from allowed invisible Z decay width: $\Gamma_{Z\rightarrow XX} \leq 2\ MeV$

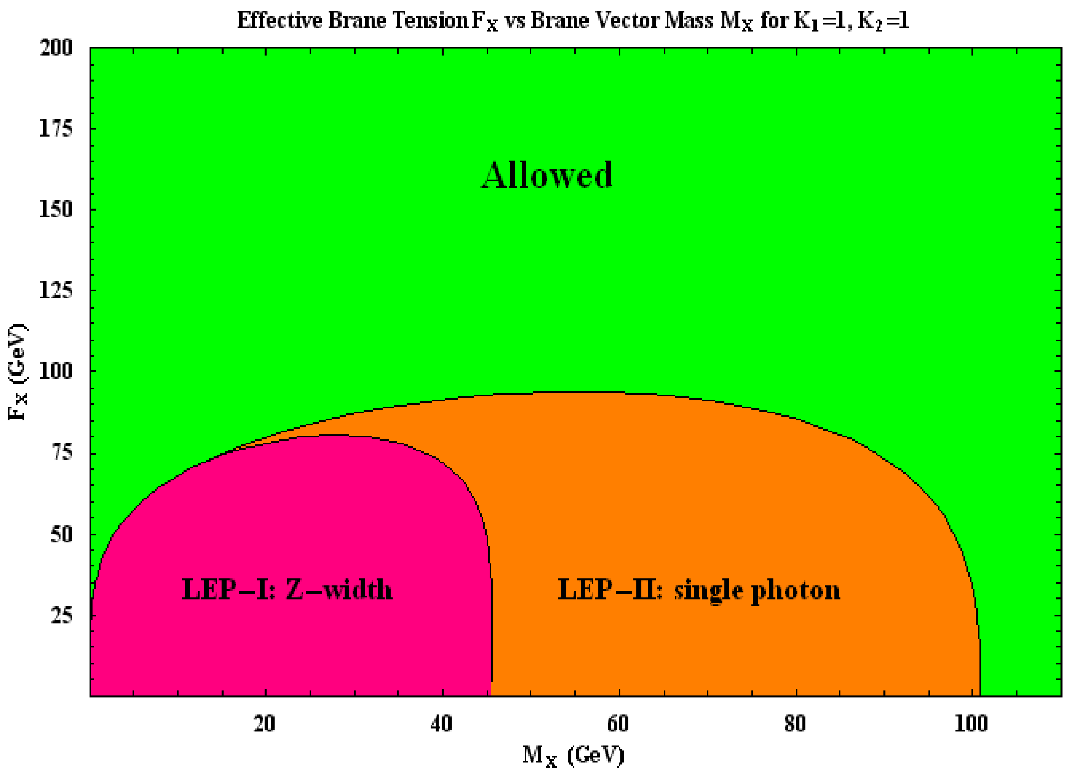
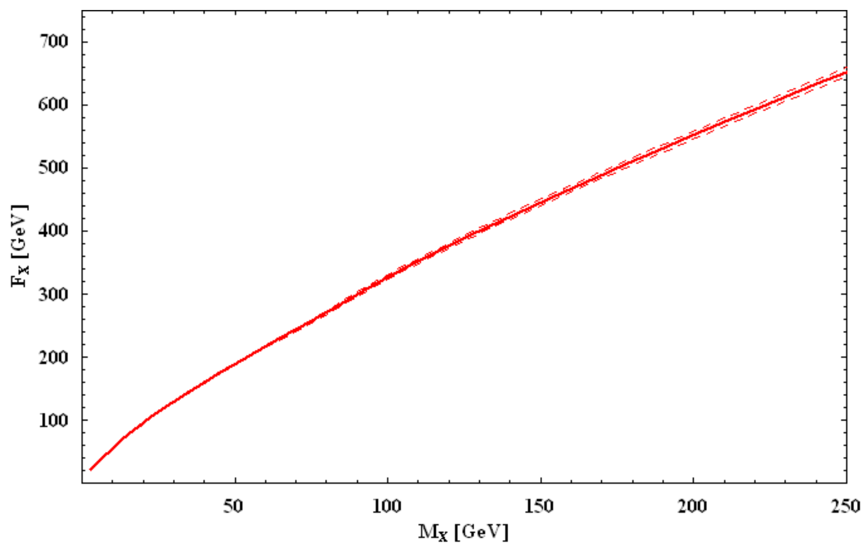


Figure 2: Excluded red region from allowed width of invisible Z decay; excluded purple plus orange from $e^+e^- \rightarrow \gamma + XX$

•X **vector as dark matter candidate:**

Relic abundance constraint (red curve) with induced metric (no extrinsic curvature) coupling using WMAP result: $\Omega_c h^2 = 0.105 \pm 0.009$



Region above red curve excluded: X **density exceeds limit set by WMAP**
Region below red curve allowed provided X **gives only partial contribution to dark matter**

Only induced metric coupling (no extrinsic curvature) included

Direct dark matter detection expts
CDMSII, Xenon10

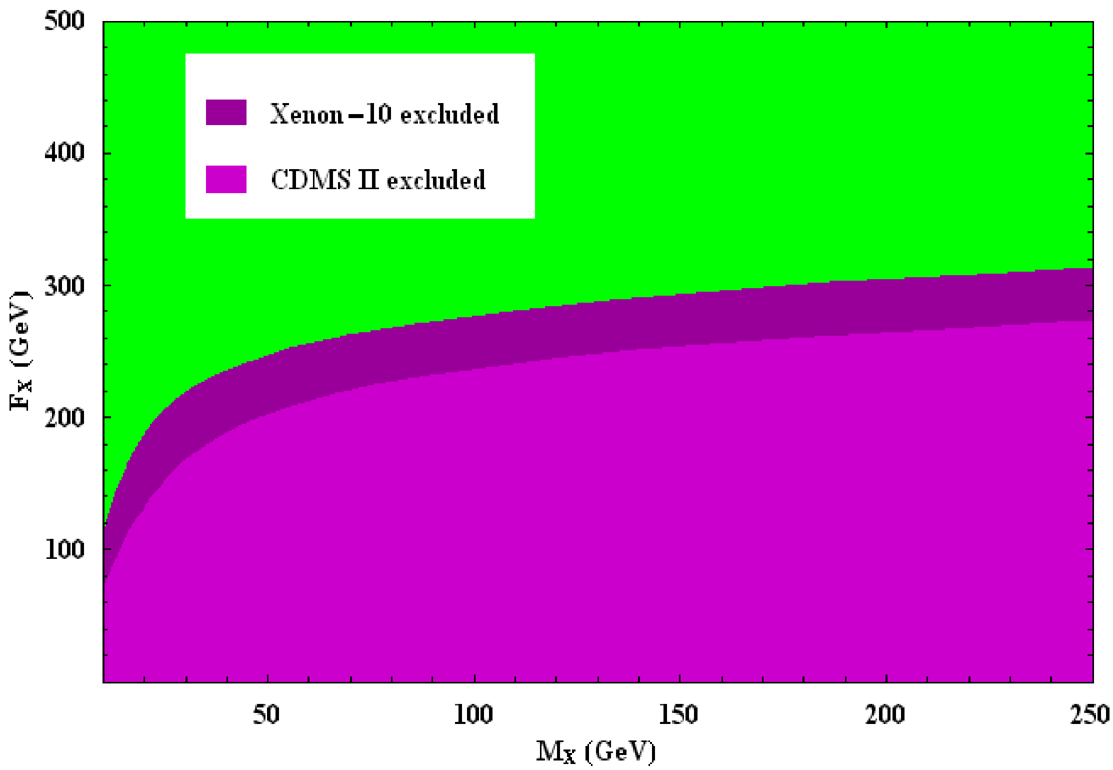


Figure 3: Green region allowed

Plot assumes X vector comprises all dark matter in Milky Way dark matter halo

Combined dark matter constraints

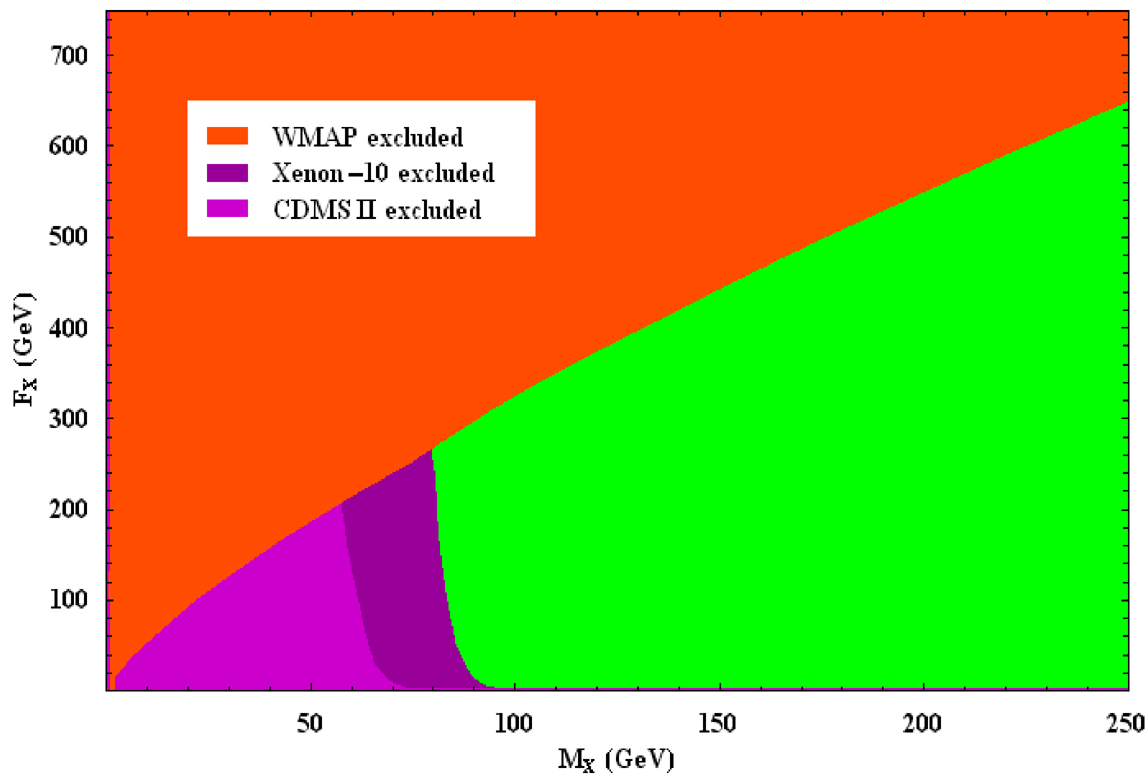


Figure 4: Green region allowed

Plot allows for dark matter other than X vectors in Milky Way dark matter halo

Anisotropic co-dimension

X^μ linear couplings from extrinsic curvature

- **LEPII limits for anisotropic codimension**

No X s-channel resonance for $\sqrt{s} < 206\ GeV$

Off resonance cross section restricted using

$$\sigma(e^+e^- \to X \to \text{ hadrons})|_{\sqrt{s}=206\ GeV} < 5\sqrt{\frac{\sigma_{had}}{\mathcal{L}}} \simeq 0.1\ pb$$

Leading $\frac{1}{F_X}$ contribution from operator:
$\mathcal{O}_{f1} = \frac{M_X}{F_X^2} \int d^4x (\partial^\nu X_\nu) \bar{f}_i (c_{1V_{ij}} + c_{1A_{ij}} \gamma_5) f_j$

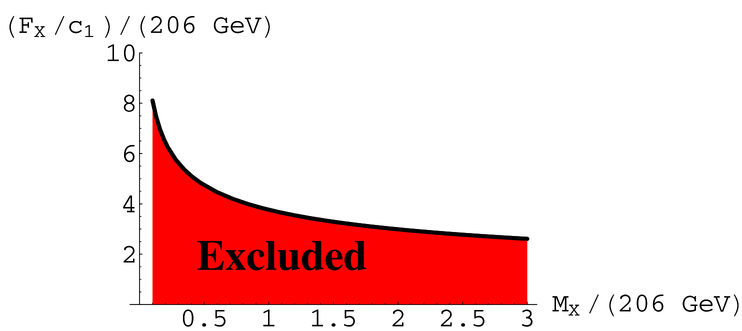


Figure 5: Allowed F_X/c_1 values lie above the curve: $c_1 \equiv (c^2_{1V_{ff}} + c^2_{1A_{ff}})^{1/3}$

- **X decays:** $X \to \bar{f}_i f_j$

Leading in $1/F_X$ contribution obtained from effective couplings

$$\mathcal{O}_{f2} = \frac{M_X}{F_X^2} \int d^4x (\partial^\nu X_\mu) \bar{f}_i \sigma^{\mu\nu} (c_{2V_{ij}} + c_{2A_{ij}} \gamma_5) f_j$$

as $(m_f = 0)$

$$\Gamma(X \to f_i \bar{f}_j) = \frac{c_{2_{ij}}^2}{24\pi} \frac{M_X^5}{F_X^4}$$

where $c_{2_{ij}}^2 = |c_{2V_{ij}} + c_{2A_{ij}}|^2$

Assume only flavor diagonal decays

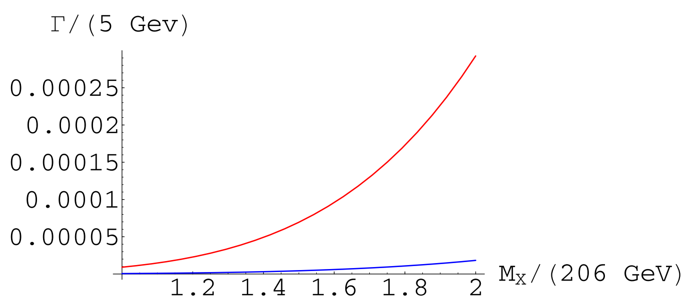


Figure 6: Decay rate $X \to$ hadrons ; red (blue) curve corresponds to $\frac{F_X}{c_2} = 500\ GeV (1000\ GeV)$: $c_2^2 = \sum_q c_{2_{qq}}^2$

Summary

• Embedded 4-d probe brane into D dimensional space-time which breaks extra dimensions translation invariance. Dynamics of associated Nambu-Goldstone mode describes oscillations of brane into extra dimension.

• Gauging broken translations leads to massive Proca vector fields X_i which are Standard Model singlets

• Coupled X_i to the Standard Model using both intrinsic and extrinsic curvatures

• Distinguished isotropic and anisotropic codimensions cases

• Isotropic codimensions: Massive vector is stable

• Anisotropic codimensions: Massive vector is narrow resonance

• Examined constraints on the brane tension and vector mass arising from $LEP I, II$ and dark matter.