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Brane Oscillations In Collider Physics

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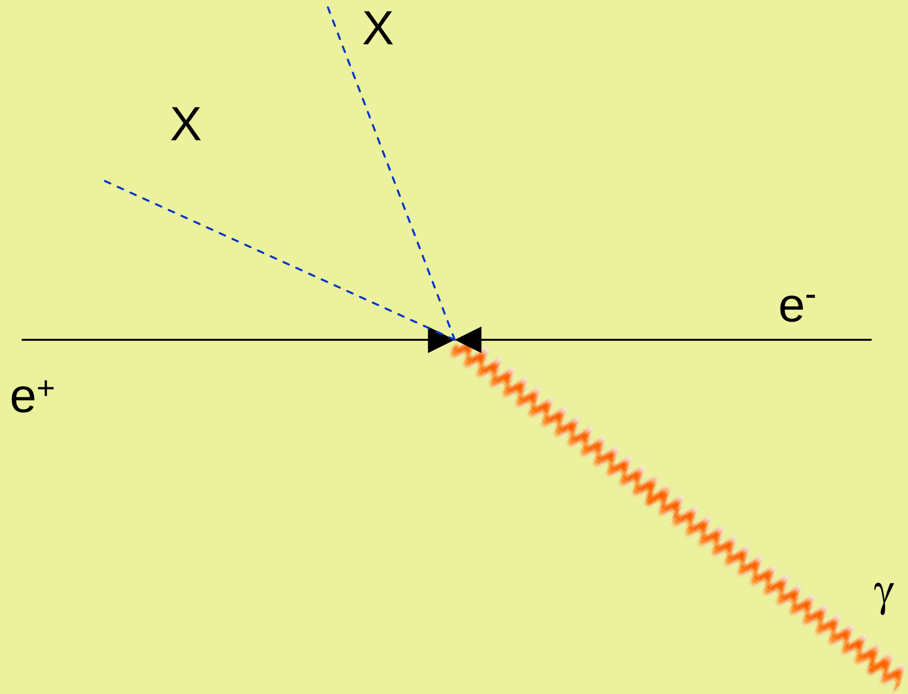


Outline:

1. Brane-Standard Model Effective Action
2. Collider Physics: $e^+ e^- \to \gamma + \not{E}$
3. Brane Oscillations =World Volume Massive Vector (Proca) Fields—Re-visit $e^+ e^- \to \gamma + XX \to \gamma + \not{E}$
4. LEP-II Bounds on Parameter Space
5. ILC Reach In Parameter Space

*Speaker

1. Brane Dynamics Effective Lagrangian

Brane World Nambu-Goto Effective Action:

$$\Gamma_{Brane} = -f^4 \int d^4x \det e$$

Where the 3-brane embedded in D=5,6,… bulk space-time induces a vierbein $e_\mu{}^m$ (and metric $g_{\mu\nu} = e_\mu{}^m \eta_{mn} e_\nu{}^n$) on the brane

$$e_\mu{}^m = \delta_\mu{}^m + \frac{1}{f^4} \partial_\mu \phi^i G_{ij} \partial^m \phi^j = \delta_\mu{}^m - \frac{1}{2f^4} \partial_\mu \phi^i \partial^m \phi^i + \cdots$$

with $G_{ij} = H_{ik}^{-1/2} \left[\sqrt{(1-H)} - 1 \right]_{kl} H_{lj}^{-1/2}$, where $H_{ij} = \frac{1}{f^4} \partial_\mu \phi_i \partial^\mu \phi_j$ The brane oscillation coordinates into the *N*-dimensional covolume are given by the Nambu-Goldstone boson world volume fields $\phi^i(x)$, with $i = 1, 2, \cdots, N$.

D-dimensional Poincare' invariant coupling to the Standard Model given by induced gravitational interaction

$$\Gamma = \int d^4x \det e \left[-f^4 + L_{\rm SM}(e) \right]$$

For small oscillations $\partial\phi \ll f$, expand action in powers of the branon field ϕ^i. Standard Model fields couple to the branon fields via the SM energy-momentum tensor $T_{\mu\nu}^{SM}(x)$

$$\Gamma = \int d^4x \det e\left[-f^4 + L_{\text{SM}}(\eta) + \tfrac{1}{2}\partial_\mu\phi^i\partial^\mu\phi^i + \tfrac{1}{2}\frac{1}{f^4}\partial^\mu\phi^i T_{\mu\nu}^{SM}\partial^\nu\phi^i + \cdots\right]$$

A curved bulk requires energy to deform the brane which appears as mass for the branons

$$\Gamma = \int d^4x \det e\left[-f^4 + L_{\text{SM}}(\eta) + \tfrac{1}{2}\partial_\mu\phi^i\partial^\mu\phi^i - \tfrac{1}{2}m^2\phi^i\phi^i + \frac{1}{2f^4}\partial^\mu\phi^i T_{\mu\nu}^{SM}\partial^\nu\phi^i - \frac{m^2}{8f^4}\phi^i\phi^i\eta^{\mu\nu}T_{\mu\nu}^{SM} + \cdots\right]$$

- Since the bulk is curved, the Nambu-Goldstone branon fields will be eaten by the bulk gravi-photon fields which now appear as massive vector (Proca) brane oscillation fields in the world volume.

The brane effective action is obtained by gauging the previous Nambu-Goto-SM action, replacing $\partial_\mu\phi^i \rightarrow \partial_\mu\phi^i + gf X_\mu^i$, and adding the gauge field X_μ^i kinetic energy term (as well as the world volume gravitational fields—which we ignore here) to the action.

Using the broken extra dimensional general coordinate transformations to transform to the unitary gauge in which ϕ^i is eliminated the resultant effective action containing the X_μ^i is obtained

Brane Gauge Field Effective Action

$$\Gamma_{\text{eff}} = \int d^4x \left[L_{SM}(\eta) - \tfrac{1}{4} F^i_{\mu\nu} F_i^{\mu\nu} + \tfrac{1}{2} M_X^2 X^i_\mu X_i^\mu + \tfrac{1}{2} \frac{1}{F_X^2} X_i^\mu T^{SM}_{\mu\nu} X_i^\nu \right]$$

with phenomenologically determined mass M_X and effective brane tension F_X and where $F^i_{\mu\nu} = \partial_\mu X^i_\nu - \partial_\nu X^i_\mu$ are the *N* extra dimension-Abelian field strength tensors for the brane (Proca) gauge fields.

2. Collider Physics:

$e^+ e^- \rightarrow \gamma + XX$ where the 2 *X* particles appear as missing energy. Similar missing energy processes occur for *Z + XX* and in hadron colliders like the TeVatron: $p\bar{p} \rightarrow \gamma + XX$ as well as $p\bar{p} \rightarrow jet + XX$ and the LHC: $pp \rightarrow \gamma + XX$ and $pp \rightarrow jet + XX$

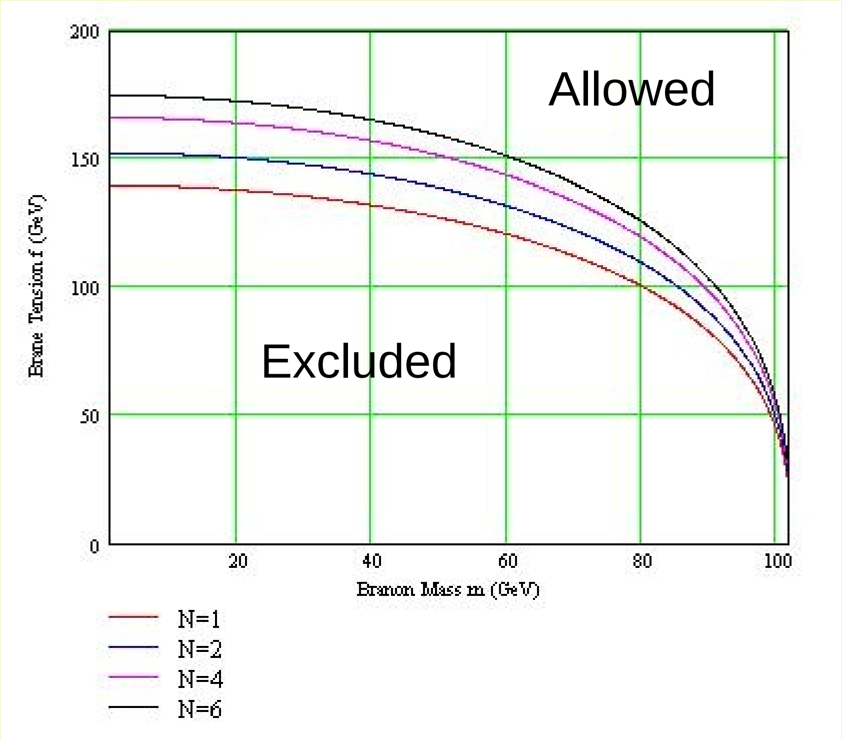
LEP-II has searched for $e^+ e^- \rightarrow \gamma + XX \rightarrow \gamma + \not{E}$ and determined an excluded/allowed region of *f* vs. *m* parameter space for the massive scalar branon cross-section based on the lack of branon production.

Branon Scattering Summary: LEP-II average center of mass energy= 206 GeV

$$e^+ e^- \to \gamma + \phi\phi \to \gamma + \not{E}$$

Massive Scalar Branon

LEPII Excluded/Allowed
Parameter Regions

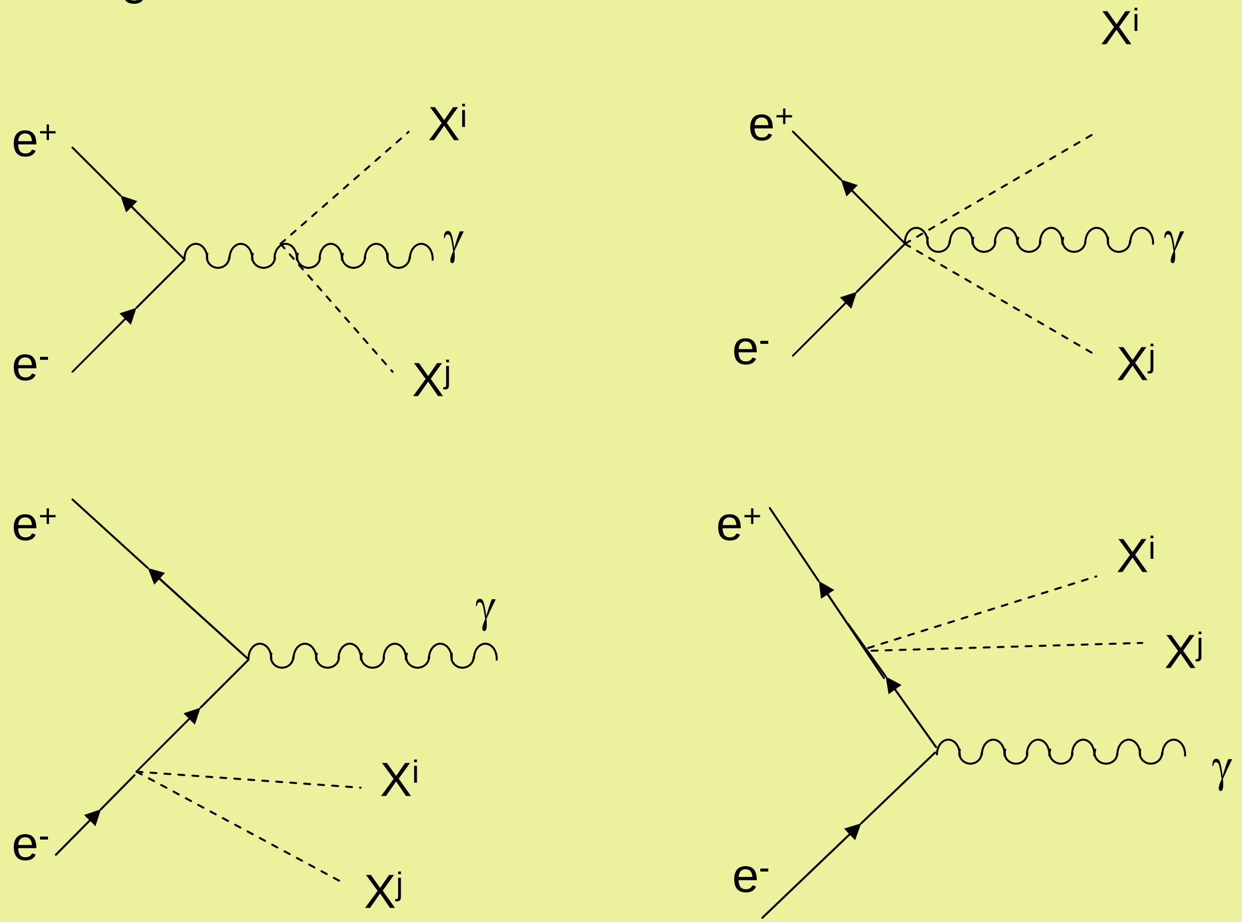


Creminelli and Strumia: Nucl. Phys. **B596**, 125 (2001);
Alcaraz, Cembranos, Dobado and Maroto: Phys. Rev. D **67**, 075010 (2003);
L3 Collaboration, P. Achard et al.: Phys. Lett. B 597 (2004) 145;
S. Mele, Search for Branons at LEP, Int. Europhys. Conf. on High Energy Phys., PoS(HEP2005)153.

3. Re-visit $e^+ e^- \rightarrow \gamma + XX \rightarrow \gamma + \not{E}$

Massive Vector Brane Oscillation Fields

The Feynman Diagrams for Brane Particle Production:



The differential cross-section for spin averaged e+- e- collisions producing a photon and 2 *X* particles with summed over polarizations and the *X* species, *i=1,2,…,N* = # of extra dimensions

$$\frac{d^2\sigma_\gamma}{dx\,d(\cos\theta)} = \frac{\alpha}{4\pi}\frac{1}{15,360\pi}\left[\frac{N}{F_X^4 M_X^4}\right]\frac{\sqrt{s}\sqrt{s(1-x)-4M_X^2}}{\sqrt{(1-x)}}\times$$

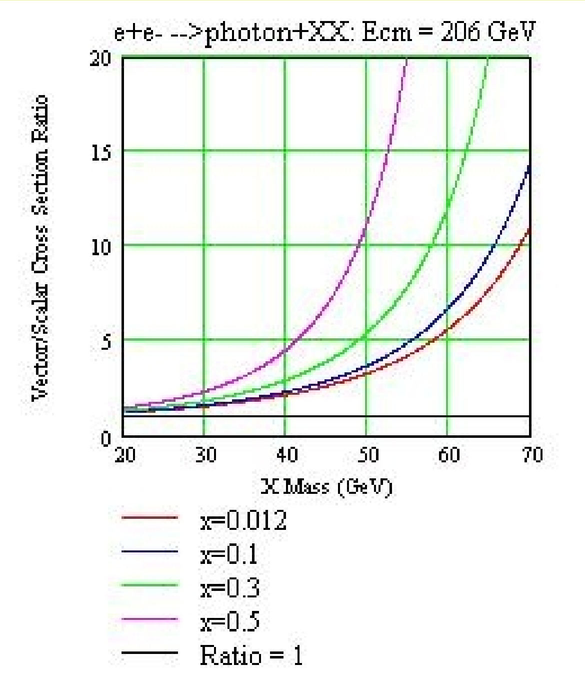
$$\times\left[\left[s(1-x)-4M_X^2\right]^2+20M_X^2\left(s(1-x)+2M_X^2\right)\right]\times$$

$$\times\left[x(3-3x+2x^2)-x^3\sin^2\theta+\frac{2(1-x)\left[1+(1-x^2)\right]}{x\sin^2\theta}\right]$$

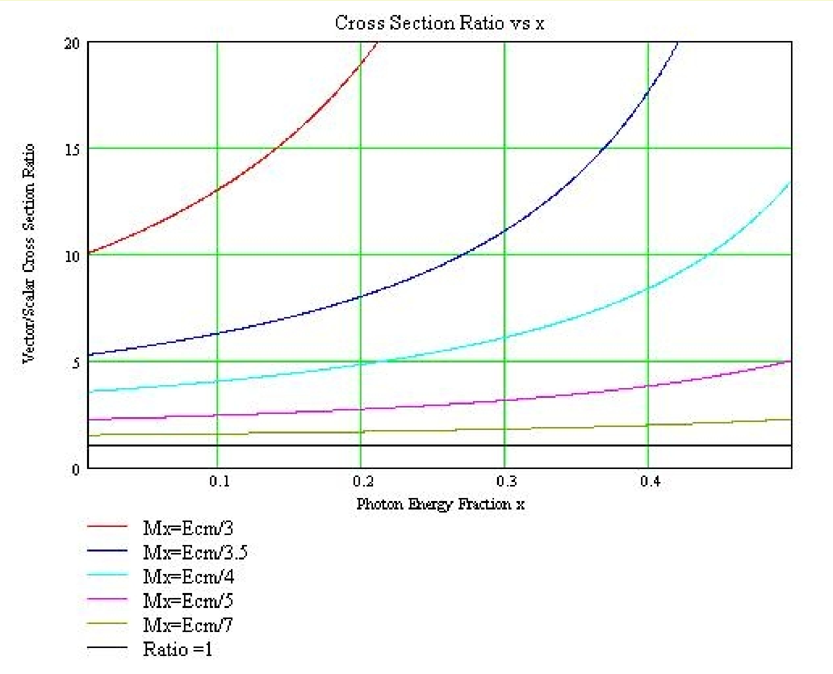
$E_{CM}=\sqrt{s}$ and the outgoing γ carries the fraction x of the beam energy $E_\gamma = x\sqrt{s}/2$ and θ is the photon's polar angle from the beam axis. α is the electromagnetic fine structure constant $\alpha = 1/128$.

Importance of vector field degrees of freedom:

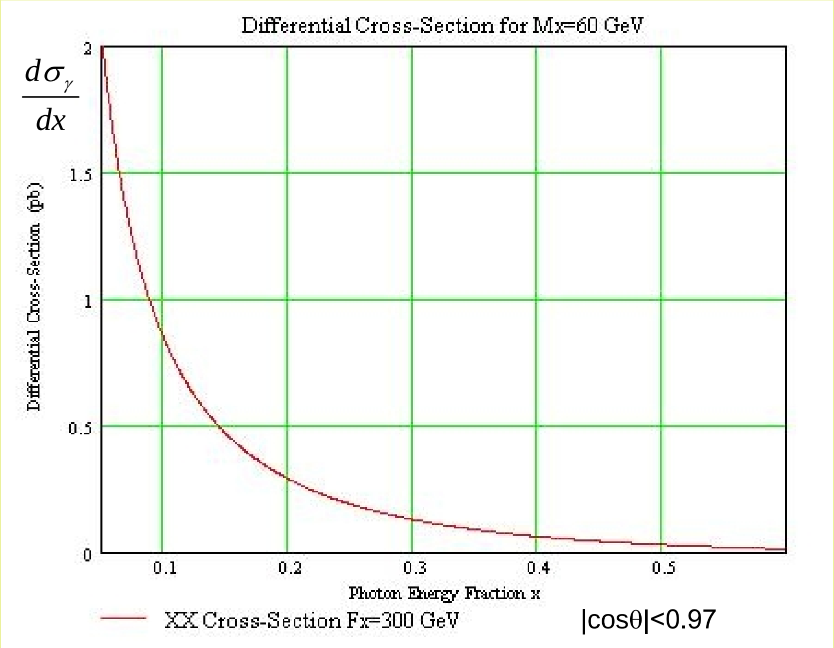
The ratio, *R*, of the brane vector *X* cross-section, scaled by $F_X^4 M_X^4$, to the scalar branon ϕ cross-section, scaled by f^8, can become appreciable for $M_X \approx (\frac{1}{3}, \frac{1}{4})\sqrt{s}$, (with $m=M_X$),



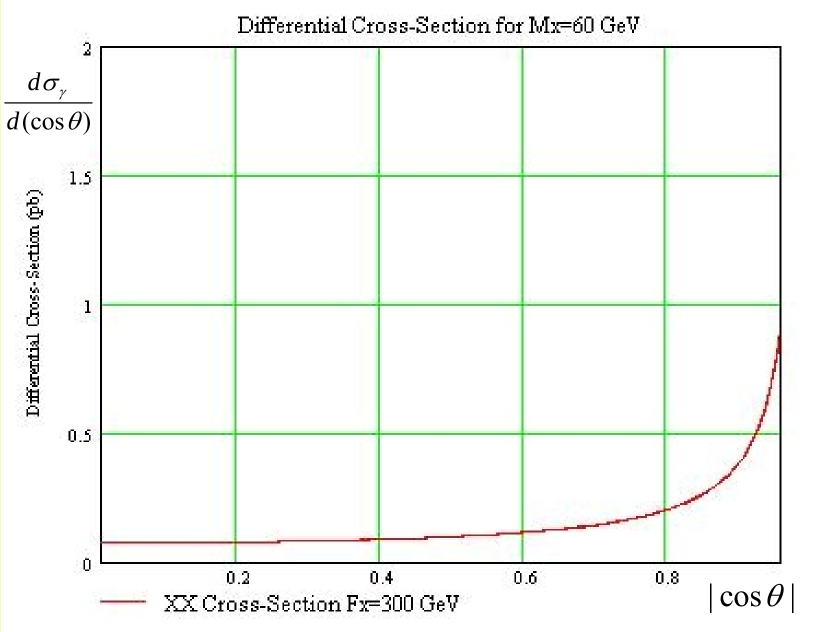
$$R = 1 + \frac{20M_X^2[s(1-x)+2M_X^2]}{[s(1-x)-4M_X^2]^2}$$



- The differential cross-section vs. photon energy fraction and polar angle



$$\sqrt{s} = 206 \text{ GeV}$$



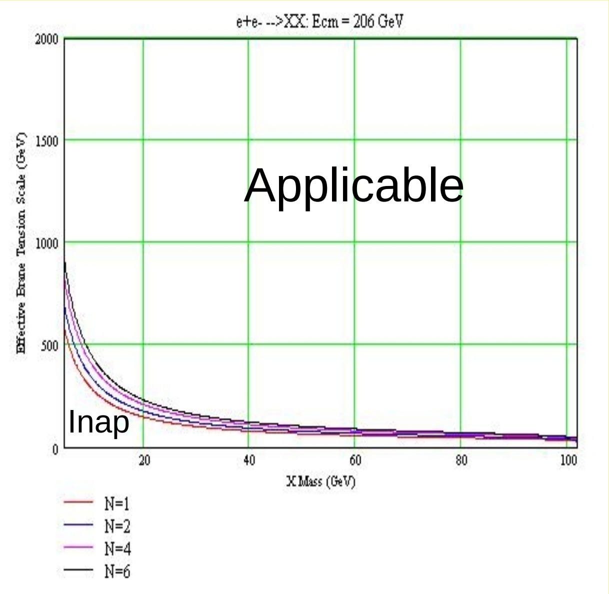
$$x \in [0.012, 1 - \frac{4M_X^2}{s} = 0.661]$$

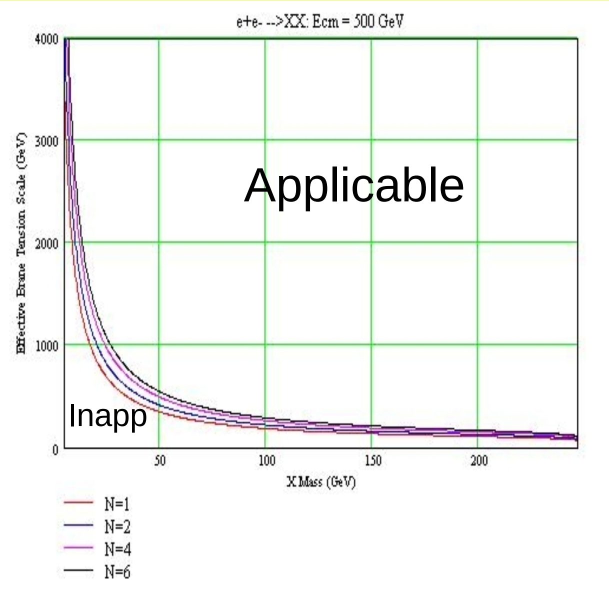
Effectiveness of the Effective Action—Model Applicability

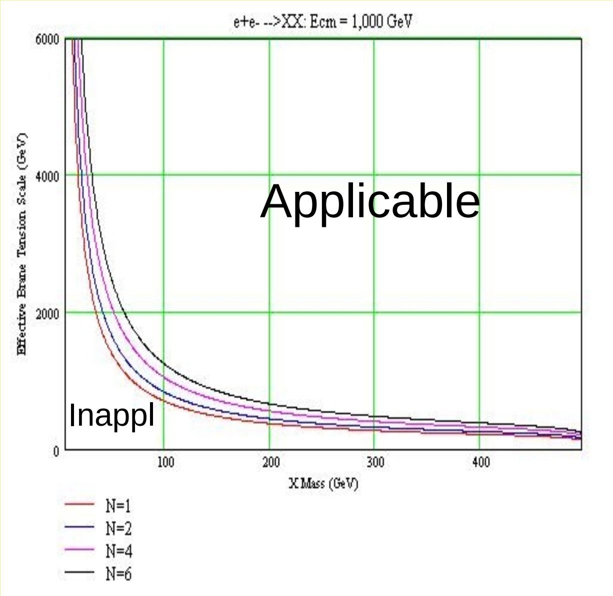
- A theoretical estimate on the total cross-section for $e^+e^- \to XX$ from the unitarity bound requires $\sigma_{XX} \sim 1/s$.
- This yields a region of applicability in parameter space.
- The total XX production cross-section is

$$\sigma_{XX} = \frac{N}{15{,}360\,\pi F_X^4 M_X^4} \sqrt{s}\sqrt{s-4M_X^2}\left[s^2 + 12M_X^2\,s + 56M_X^4\right]$$

- The unitarity limit implies a region of applicability:





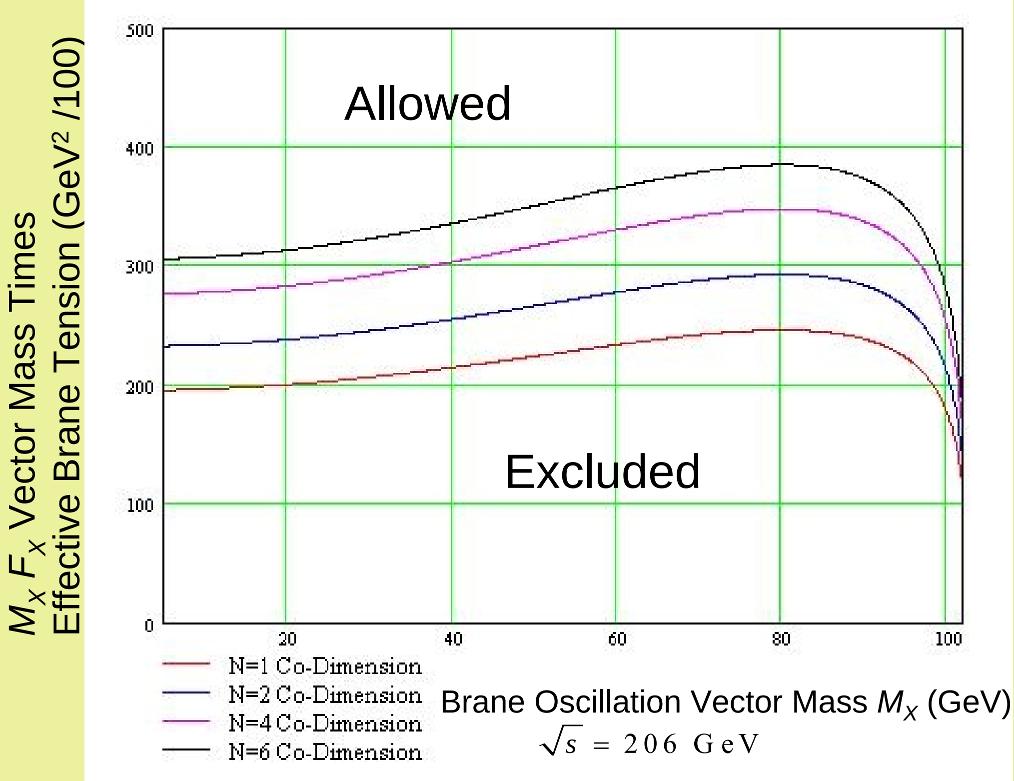


4. LEP-II Determined Allowed/Excluded Regions of Parameter Space

- LEP-II agreement with Standard Model has put a limit on the new physics contribution to the single γ plus missing energy cross-section of $\sigma_{new} \tilde{<} 0.1\text{pb}$. This limit on $\sigma_{\gamma} \leq \sigma_{new}$ results in
- LEP-II excluded and allowed regions in the F_X, M_X and N parameter space.

Brane Oscillation Massive Vector

LEPII Excluded/Allowed Parameter Regions



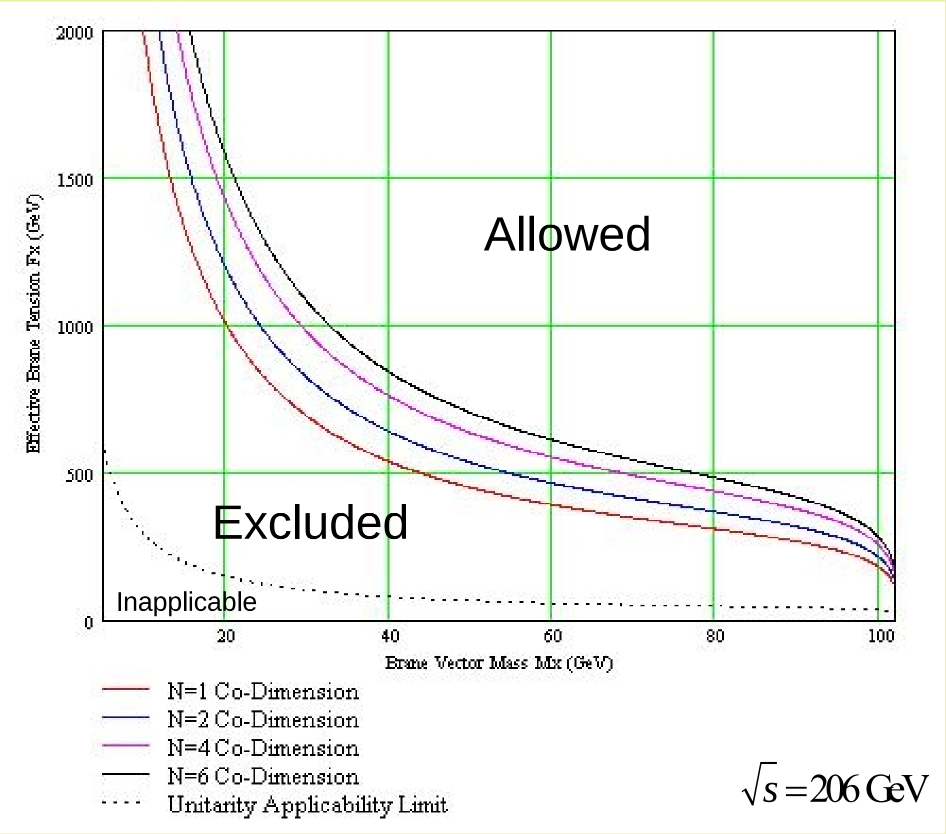
$$\left[0.012 \leq x \leq \left(1 - \frac{4M_X^2}{s}\right), \quad |\cos\theta| \leq 0.96\right]$$

$$\sigma_{\text{Discovery}}\, IL_{\text{LEP-II}} = 5\sqrt{\sigma_{\text{SMBackgnd}}\, IL_{\text{LEP-II}}} \to \sigma_{\text{Discovery}} \simeq 0.1\ \text{pb}$$

- In terms of the parameters directly

Brane Oscillation Massive Vector

LEPII Excluded/Allowed Parameter Regions



$$\left[0.012 \le x \le \left(1 - \frac{4M_X^2}{s} \right),\ \ |\cos\theta| \le 0.96 \right]$$

5. ILC: Single Photon Missing Energy Reach For The Brane Oscillation Vector Parameters

Assume SM uncertainties at femtobarn level and the cross-section for new physics is estimated by the gain in statistics from the ratio of integrated luminosities

$$\sigma_{new}^{ILC} = \sqrt{\frac{IL_{LEP-II}}{IL_{ILC}}} \times \sigma_{new}^{LEP-II} \simeq 3-6 \text{ fb}$$

Alcaraz, et al., Phys. Rev. D 67, 075010 (2003)

Creminelli and Strumia: Nucl. Phys. **B596**, 125 (2001)

The reach of the ILC can be expressed in terms of the accessible $(\sigma_\gamma \geq \sigma_{new}^{ILC})$ and inaccessible $(\sigma_\gamma \leq \sigma_{new}^{ILC})$ regions of the F_X-M_X parameter space

Conservative Discovery Criteria:

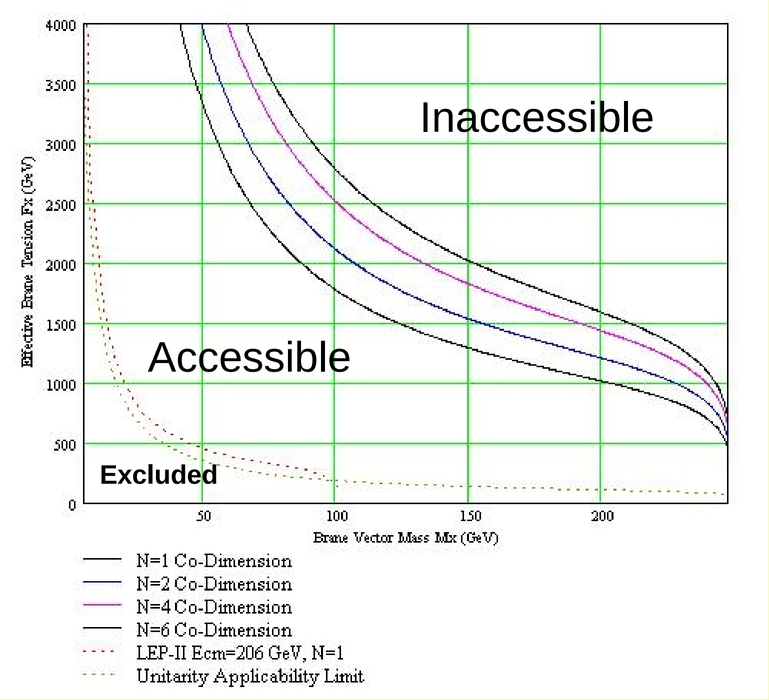
$$\sigma_{\text{Discovery}}^{\text{ILC}}\, IL_{\text{ILC}} = 5\sqrt{\sigma_{\text{SMBackgnd}}\, IL_{\text{ILC}}} = 5\sqrt{\sigma_{\text{SMBackgnd}} / IL_{\text{LEP-II}}}\sqrt{IL_{\text{LEP-II}} IL_{\text{ILC}}} \rightarrow \sigma_{\text{Discovery}}^{\text{ILC}} = \sqrt{\frac{IL_{\text{LEP-II}}}{IL_{\text{ILC}}}}\sigma_{\text{Discovery}}^{\text{LEP-II}} \simeq 3-6 \text{ fb}$$

Brane Oscillation Massive Vector

ILC Accessible/Inaccessible Parameter Regions

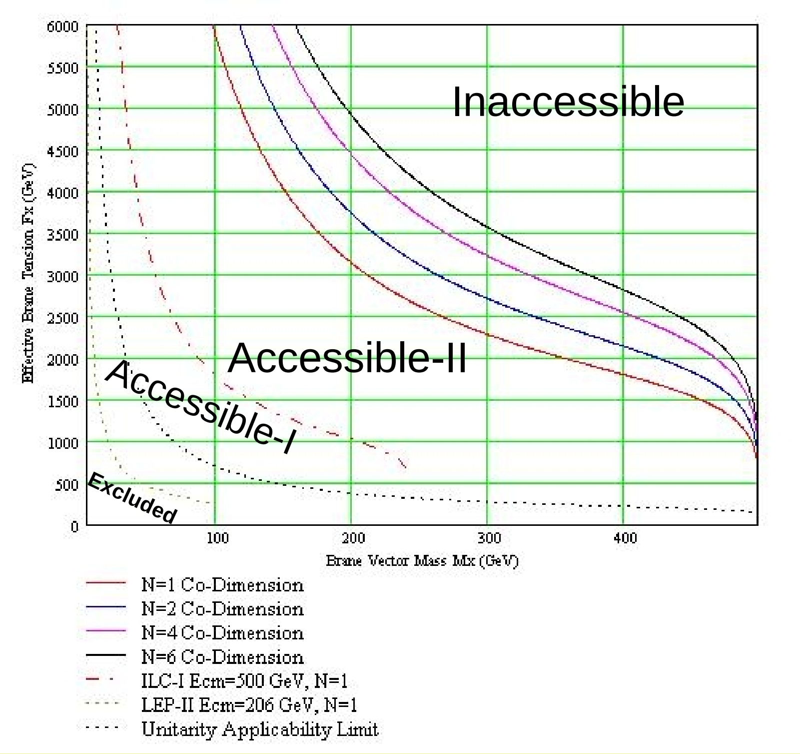
ILC-I: E_{cm} = 500 GeV, IL= 200 fb^{-1}

σ_{newILC} = 6 fb



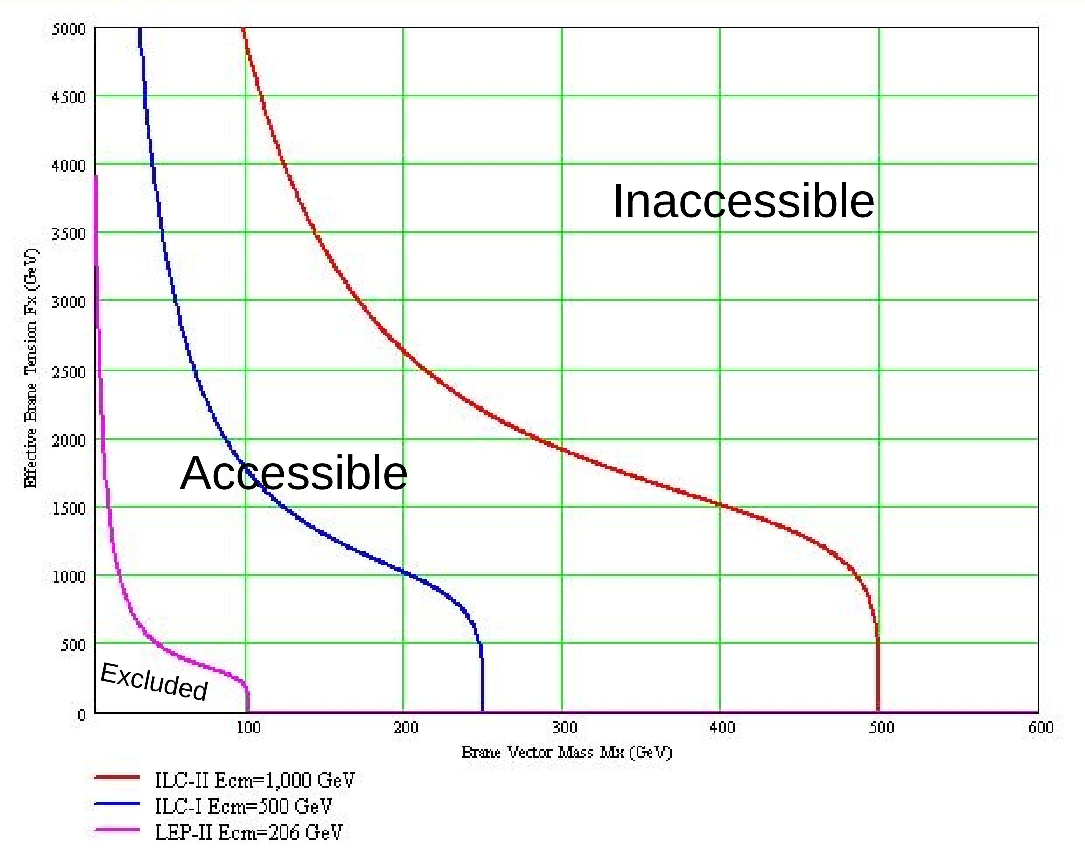
ILC-II: E_{cm} = 1,000 GeV, IL= 1,000 fb^{-1}

σ_{newILC} = 3 fb



$$\left[0.012 \le x \le \left(1 - \frac{4M_X^2}{s}\right),\ \ |\cos\theta| \le 0.96\right]$$

Summary of Effective Brane Tension and Brane Vector Mass Parameter Space For N=1



$$\left[0.012 \le x \le \left(1 - \frac{4M_X^2}{s}\right),\ \ |\cos\theta| \le 0.96\right]$$