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# Brane Oscillations At The TeVatron and LHC


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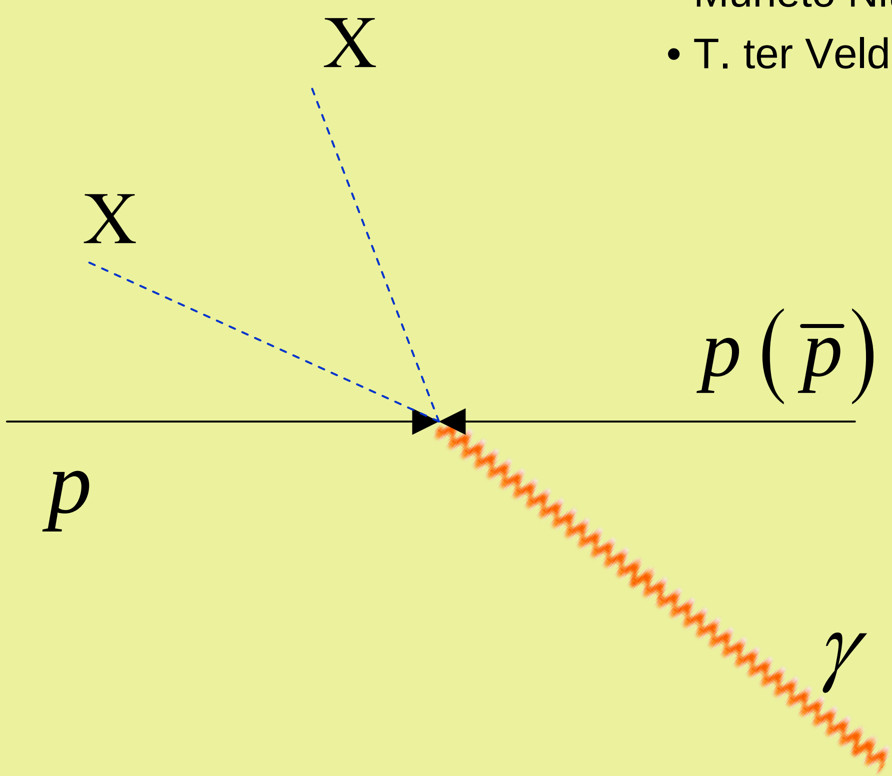



Outline:

1. Brane-Standard Model Effective Action: Massive Brane Vector (Proca) Fields
2. Brane Vector Production
   $$q\,\bar{q} \to \gamma + XX \to \gamma + \not{E}$$
3. TeVatron Bounds on Brane Vector Parameter Space
4. TeVatron Reach In Parameter Space
5. LHC Reach In Parameter Space


*Speaker

# 1. Flexible Brane Effective Action

Bulk ISO(1,D-1) → (Poincaré Symmetries) → Brane ⊗ Co-Volume: ISO(1,3) ⊗ SO(N)

**Nonlinear Realization:**

Bulk Coordinates: $x^M = (x^\mu, \phi(x))$ ($N=1$ Domain Wall Case)

Symmetry Generators: $P^M = (P^\mu, Z)$, $M^{MN} = (M^{\mu\nu}, K^\mu)$

Coset Element: $$U(x) = e^{ix^\mu P_\mu} e^{i\phi(x) Z} e^{iv^\mu(x) K_\mu}$$

Coset Coordinates: $\{x^\mu, \phi(x), v^\mu(x)\}$

**Maurer-Cartan Form= Covariant Building Blocks: Global Symmetries**

$$U^{-1}(x)\partial_\mu U(x)$$

- $P_m$ → Induced Vierbein $e_\mu{}^m(\phi, v)$
- $Z$ → Covariant Derivative $\nabla_\mu \phi$
- $K_m$ → Extrinsic Curvature $K_{\mu\nu} = e_\nu{}^n K_{n\mu} = \partial_\mu v_\nu + \cdots$
- $M_{mn}$ → Spin Connection $\omega_\mu^{mn} = v^m \partial_\mu v^n - v^n \partial_\mu v^m + \cdots$

Covariant Constraint = Eliminate Redundant

Coordinate $v^{\mu}$ Field Equation:

$$\nabla_{\mu}\phi = 0 \Rightarrow \partial_{\mu}\phi = v_{\mu} + \cdots$$

Invariant Nambu-Goto Action = Induced Gravity:

$$g_{\mu\nu} = \eta_{\mu\nu} - \partial_{\mu}\phi(x)\partial_{\nu}\phi(x)$$

$$\Gamma = \int d^4x \sqrt{-\det g}\left[-f^4 + \mathcal{L}_{\text{SM}}(g)\right]$$

Expand in powers of a rescaled Branon field $\phi$ and add a mass for the branons as a curved bulk requires energy to deform the brane

$$\Gamma_{\text{Effective}} = \int d^4x \left[\mathcal{L}_{\text{SM}}(\eta) + \tfrac{1}{2}\partial_{\mu}\phi\,\partial^{\mu}\phi - \tfrac{1}{2}m^2\phi^2 + \frac{1}{2f^4}\partial^{\mu}\phi\, T^{\text{SM}}_{\mu\nu}\,\partial^{\nu}\phi - \frac{m^2}{8f^4}\phi^2\eta^{\mu\nu}T^{\text{SM}}_{\mu\nu} + \cdots\right]$$

Standard Model fields couple to the branon fields via the SM energy-momentum tensor $T^{\text{SM}}_{\mu\nu}(x)$

Alcaraz, Cembranos, Dobado and Maroto: Phys. Rev. D **67**, 075010 (2003), etc.

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

General Coordinate and Local Lorentz Transformations
Dynamic Gravitational Fields require locally covariant Maurer-Cartan Form:

Gravitational Fields: $E_\mu(x) = E_\mu{}^m(x)P_m + X_\mu(x)Z + V_\mu{}^m(x)K_m + \gamma_\mu^{mn}(x)M_{mn}$

Locally Covariant Maurer-Cartan Form= Covariant Building Blocks:

$$U^{-1}(x)[\partial_\mu + ie^{ix\cdot P}E_\mu e^{-ix\cdot P}]U(x)$$

Use Broken Local Lorentz Transformation to go to
Partial Unitary Gauge: $v^\mu = 0$

$$e_\mu^m = \delta_\mu^m + E_\mu^m + 2\phi V_\mu^m$$

$$\nabla_\mu \phi = \partial_\mu \phi + X_\mu$$

$$K_\mu^m = V_\mu^m$$

$$\omega_\mu^{mn} = \gamma_\mu^{mn}$$

## Covariant Building Blocks:

Field Strength Tensor: $F_{\mu\nu} = \left[\nabla_\mu, \nabla_\nu\right]\phi = \partial_\mu X_\nu - \partial_\nu X_\mu$

Extrinsic Curvature Constraint: $K_{\mu\nu} = e^{-1}_{m\nu} V_\mu^{\ m} \equiv \tfrac{1}{2}\left\{\nabla_\mu, \nabla_\nu\right\}\phi$

Invariant Action is obtained (normal field dimensions):

$$\Gamma = \int d^4x[\Lambda + \tfrac{1}{2\kappa^2}R - \tfrac{1}{4}F^{\mu\nu}F_{\mu\nu} + \mathcal{L}_{\mathrm{SM}}(e) + \tfrac{1}{2}\nabla^\mu\phi\nabla_\mu\phi + \frac{\tau}{F_X^4}\nabla^\mu\phi\nabla^\nu\phi T^{\mathrm{SM}}_{\mu\nu}$$
$$+ \frac{M_X^2}{2F_X^4}\left(K_1 B_{\mu\nu} + K_2\tilde{B}_{\mu\nu}\right)F^{\mu\rho}K_\rho^{\ \nu} + \cdots]$$

Use broken bulk general coordinate transformations
to go to Full Unitary Gauge: $\phi=0$ (gravi-photon $X^\mu$ eats $\phi$ to get Mass $M_X$)

$$e_\mu^m = \delta_\mu^m + E_\mu^m \quad ; \quad \nabla_\mu\phi = M_X X_\mu$$

$$K_{\mu\nu} = V_{\mu\nu} = \tfrac{1}{2}\left(\partial_\mu X_\nu + \partial_\nu X_\mu\right) \quad ; \quad \omega_\mu^{mn} = \gamma_\mu^{mn}$$

Ignore gravity and expand in powers of $X_\mu^i$ , where the index *i=1,2,…,N*, the number of additional space dimensions, to obtain the

## Brane Vector Effective Action

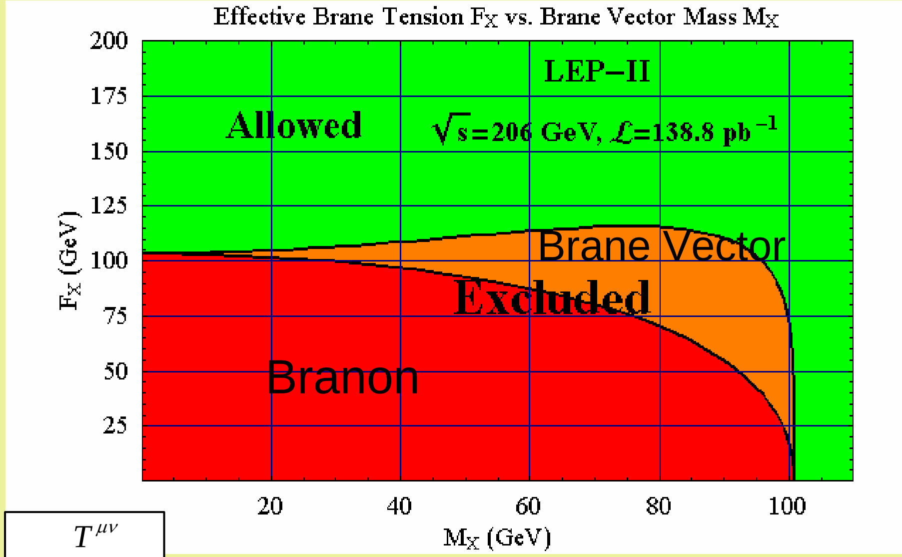
$$\Gamma = \int d^4x [\mathcal{L}_{\mathrm{SM}}(\eta) - \tfrac{1}{4} F^{i\mu\nu} F^i_{\mu\nu} + \tfrac{1}{2} M_X^2 X^{i\mu} X^i_\mu + \frac{\tau}{2} \frac{M_X^2}{F_X^4} X^{i\mu} T^{\mathrm{SM}}_{\mu\nu} X^{i\nu} + \frac{M_X^2}{2F_X^4}\left(K_1 B_{\mu\nu} + K_2 \tilde{B}_{\mu\nu}\right) F^{i\mu\rho} K^{i\nu}_\rho ]$$

with phenomenologically determined mass $M_X$ and effective brane tension $F_X$ as well as couplings $\tau$, $K_1$ , $K_2$ 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 vector (Proca) gauge fields.

The covolume SO(N) symmetry is envisioned to be spontaneously broken, hence their gauge fields are massive and not considered here. Although the SO(N) symmetry amongst the brane vectors is now broken, for simplicity the covolume is taken to be isotropic, thus the brane vectors have a common mass $M_X$ and effective brane tension $F_X$. Similarly, the bilinear $X$ coupling can be to any SU(3), SU(2), U(1) invariant. These have been chosen to be equal for simplicity, hence the Standard Model energy-momentum tensor appears.

# 2. Brane Vector Missing Energy:

LEP-II has searched for $e^+ e^- \to \gamma + XX \to \gamma + \not{E}$ and we determined an excluded/allowed region of $F_X, M_X, K_1, K_2$ parameter space based on the agreement with the Standard Model.



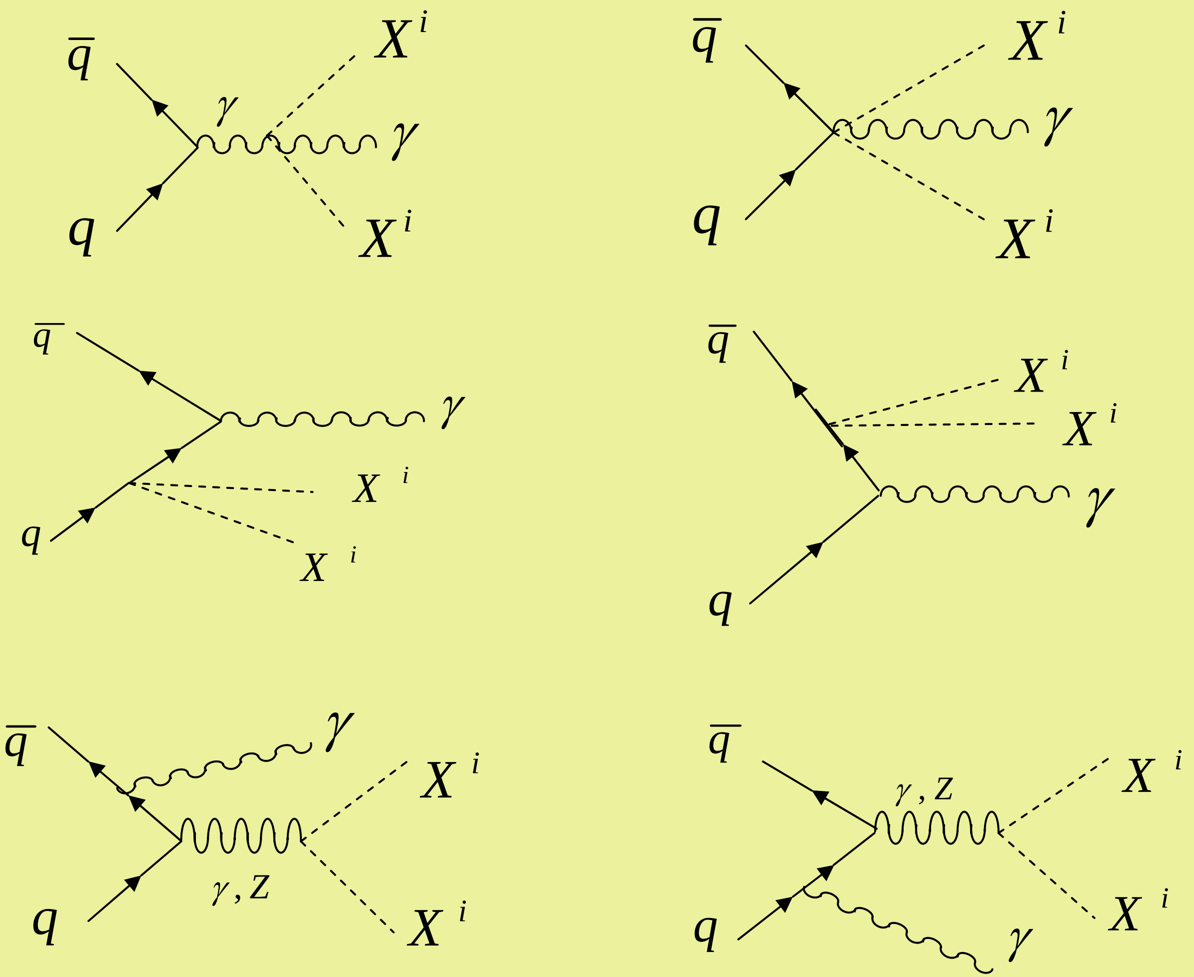

$T^{\mu\nu}$

$K_1 = 0 = K_2$

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.

$p\bar{p} \to \gamma + XX$ at the TeVatron and $pp \to \gamma + XX$ at the LHC where the 2 $X$ particles escape the detector as missing energy have also been used to bound parameter space. Likewise, the TeVatron Ib and II data exclude regions of brane parameter space. The TeVatronII reach based on an integrated luminosity of 6000 pb$^{-1}$ and the LHC reach can be used to delineate accessible/inaccessible regions of parameter space.

## The Feynman Diagrams for Brane Vector Production: $q\,\bar{q} \to \gamma + XX \to \gamma + \not{E}$



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

$$\frac{d^2\sigma_{\gamma XX}}{dk^2\,dt} = \frac{\alpha}{4\pi}\frac{1}{15{,}360\pi}\left[\frac{N}{F_X^8}\right]\frac{1}{\hat{s}^3 ut}\frac{\sqrt{k^2-4M_X^2}}{\sqrt{k^2}}\left[2\hat{s}k^2+u^2+t^2\right]\times$$
$$\times\left\{\tau^2\left(\hat{s}k^2+4ut\right)\left(\left[k^2-4M_X^2\right]^2+20M_X^2\left(k^2+2M_X^2\right)\right)\right.$$
$$\left.+\left[K_1^2k^2+K_2^2\left(k^2-4M_X^2\right)\right](SM)\left[80M_X^2\hat{s}\left(k^2\right)^2\right]\right\}$$

with $p_1, p_2$ the antiquark and quark momenta, $q$ the photon momenta and $k_1, k_2$ the brane vector momenta. The Mandelstam variables $\hat{s}=(p_1+p_2)^2, t=(p_1-q)^2, u=(p_2-q)^2$ and $k^2=(k_1+k_2)^2$. Neglecting the quark masses implies $\hat{s}+t+u=k^2$. The Standard Model coupling and propagator factor

$$SM \equiv \pi\alpha\left[\frac{\cos^2\theta_W}{(k^2)^2}+\frac{1}{(k^2-M_Z^2)^2+M_Z^2\Gamma_Z^2}\left(\left(\frac{1}{\cos^2\theta_W}\right)\left(\frac{1}{16}+(\sin^2\theta_W-\frac{1}{4})^2\right)+2\cos^2\theta_W\left(\sin^2\theta_W-\frac{1}{4}\right)\frac{\left(k^2-M_Z^2\right)}{k^2}\right)\right].$$

No Interference—Energy-Momentum Tensor and Extrinsic Curvature Terms Add

## 3. TeVatron Bounds on Parameter Space: Total Cross Section for $p\bar{p} \rightarrow \gamma + XX \rightarrow \gamma + \not{E}$

The single photon cross section with missing energy of the brane vectors is found by integrating over the parton distribution functions using CTEQ-6.5M distributions:

$$\sigma_{\gamma XX} = \int_{x_{\min}}^{1} dx \int_{y_{\min}}^{1} dy\; f(x,y;\hat{s}) \int_{k^2_{\min}}^{k^2_{\max}} dk^2 \int_{t_{\min}}^{t_{\max}} dt\, \frac{d\sigma_{\gamma XX}}{dk^2 dt}$$

where the quark distribution function is

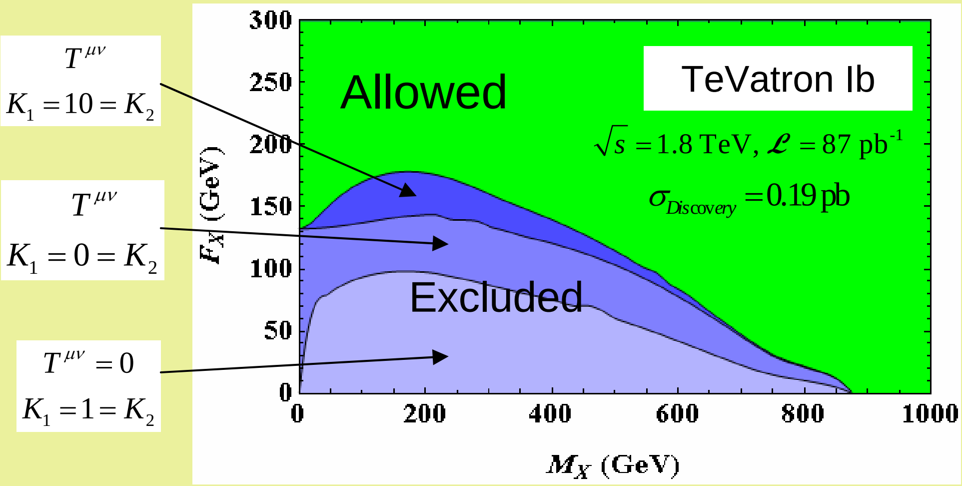
$$f(x,y;\hat{s}) = \tfrac{1}{3}(\tfrac{2}{3})^2[u_p(x,\hat{s})\bar{u}_{\bar{p}}(y,\hat{s}) + \bar{u}_p(x,\hat{s})u_{\bar{p}}(y,\hat{s})]$$
$$+\tfrac{1}{3}(-\tfrac{1}{3})^2[d_p(x,\hat{s})\bar{d}_{\bar{p}}(y,\hat{s}) + \bar{d}_p(x,\hat{s})d_{\bar{p}}(y,\hat{s})].$$

The kinematic constraints are given by $k^2 = (4M_X^2, \hat{s}(1-\frac{2E_T}{\sqrt{\hat{s}}}))$,

$$t^{\max}_{\min} = (k^2 - \hat{s})x\frac{1-\tanh\eta^{\max}_{\min}}{(y+x)+(y-x)\tanh\eta^{\max}_{\min}}.$$ The pseudo-rapidity is denoted $\eta$ and $E_T$ is the minimum transverse energy of the photon while $x$ and $y$ denote the fraction of proton CM energy $\frac{1}{2}\sqrt{s}$ that the quark and antiquark have, respectively.

$\eta^{\max}_{\min} = \pm 1.0$ is taken for the TeVatron and LHC plots while the transverse energy is 45-50 GeV for the TeVatron and scaled to 350 GeV for the LHC.

TeVatron agreement with the Standard Model has put a limit on the new physics contribution to the single $\gamma$ plus missing energy cross-section of $\sigma_{\text{Discovery}}(TeVIb) \leq 0.19 \text{ pb}$ and $\sigma_{\text{Discovery}}(TeVII) \leq 0.25 \text{ pb}$ . This limit on $\sigma_{\gamma XX} \leq \sigma_{\text{Discovery}}$ results in TeVatron excluded and allowed regions in the $F_X$ , $M_X$ , $K_1$ , $K_2$ parameter space.

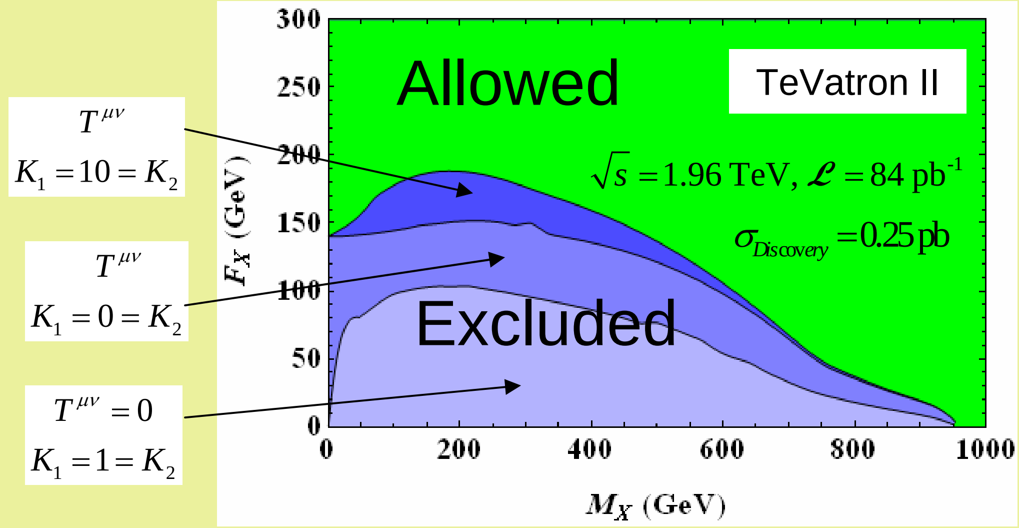



Plot $F_X$ vs. $M_X$ for fixed $K_1$ , $K_2$ slices of parameter space.

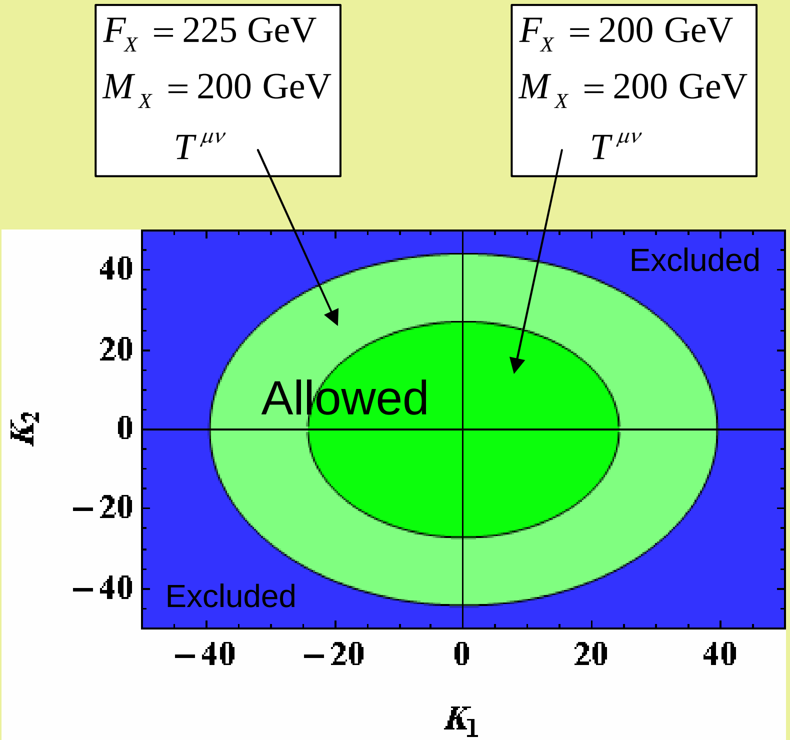
The line of exclusion varies as $N^{1/8}$ , only $N=1$ is plotted.

$$\sigma_{\text{Discovery}}(\text{TeVII})\, \mathcal{L}_{\text{TeVII}} = 5\sqrt{\sigma_{\text{SMBackgnd}}\, \mathcal{L}_{\text{TeVII}}}$$

$$\rightarrow \sigma_{\text{Discovery}} = 0.25 \text{ pb}$$



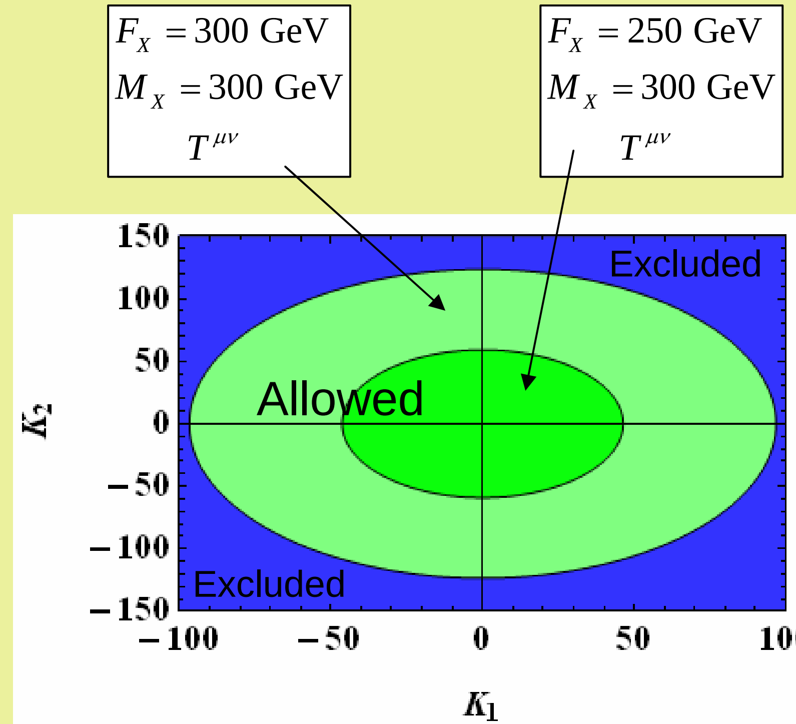
## Extrinsic Curvature Dependence: Plot $K_1$ vs. $K_2$ for fixed $F_X$ and $M_X$ slices of parameter space ($N=1$)




TeVatron Ib

$\sqrt{s} = 1.8$ TeV, $\mathcal{L} = 87$ pb$^{-1}$

$\sigma_{Discovery} = 0.19$ pb



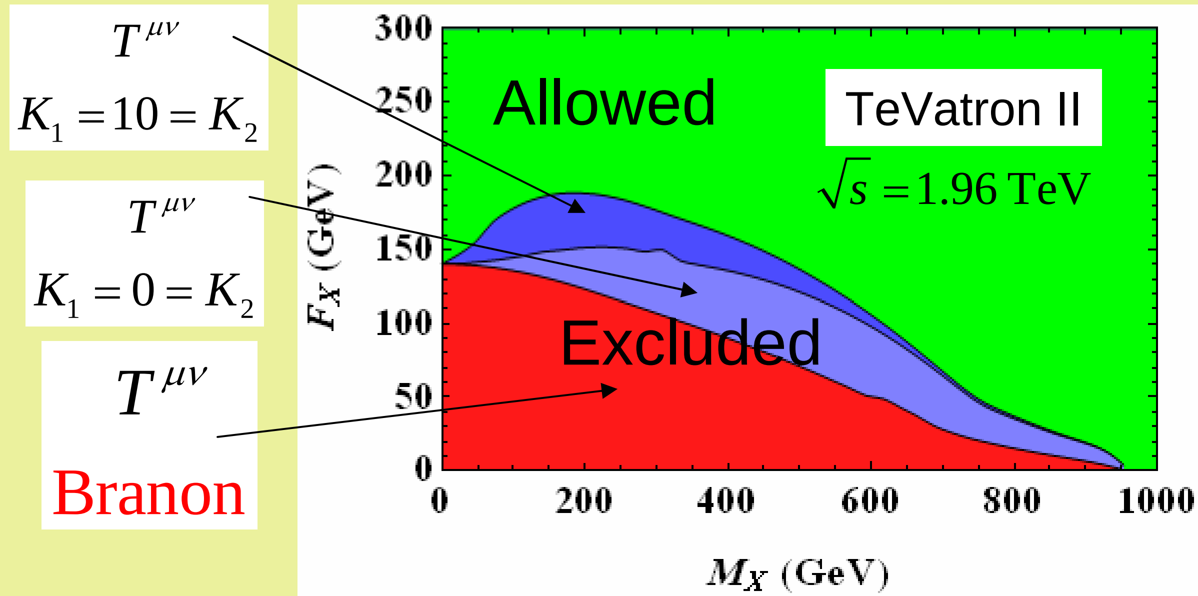

TeVatron II

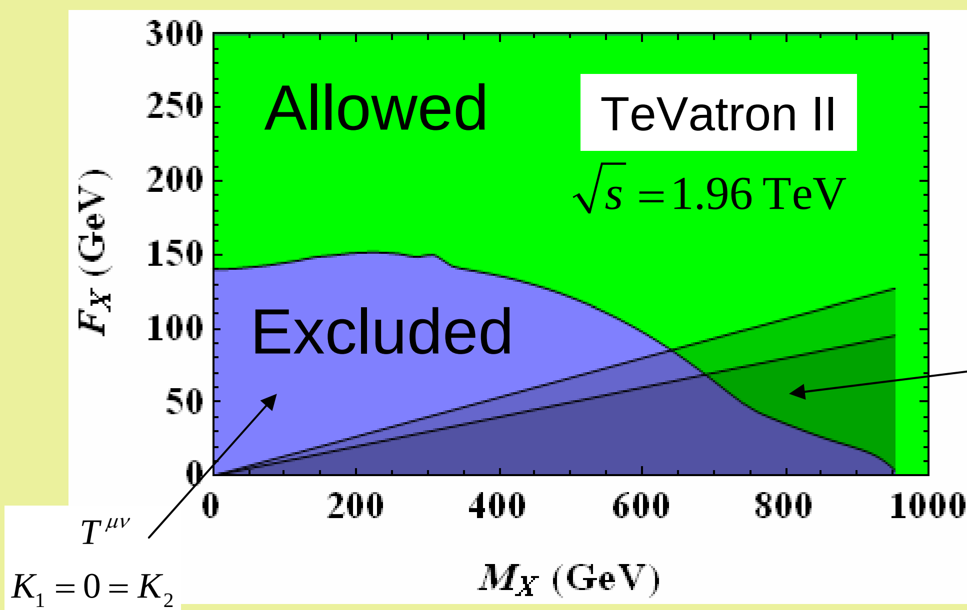
$\sqrt{s} = 1.96$ TeV, $\mathcal{L} = 84$ pb$^{-1}$

$\sigma_{Discovery} = 0.25$ pb

# Branon Comparison and Applicability

Brane Vector modes important. At low $X$ mass (~high energy) the equivalence theorem applies, as seen.



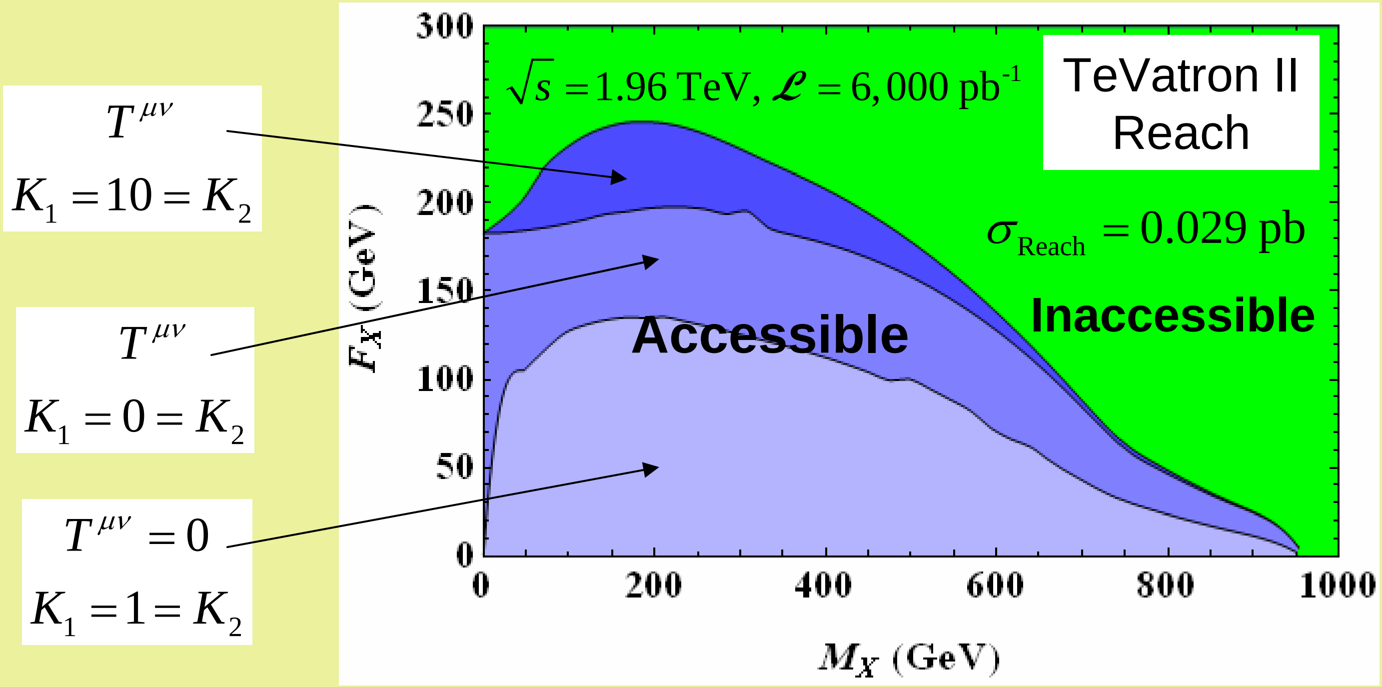

Effectiveness of the Effective Action—Region of Applicability in parameter space.

Estimate Production of $4\ X < 2X$ to get bounds on $7.5\text{-}10\ F_X > M_X$ and $K$

4. TeVatron Reach: The reach of the TeVatron can be expressed in terms of the accessible and inaccessible regions of parameter space for an integrated luminosity of 6,000 pb$^{-1}$. Assume Discovery cross-section is estimated by the gain in statistics from the ratio of integrated luminosities

$$\sigma_{\text{Discovery}}(TeV6)\,\mathcal{L}_{\text{TeV6}} = 5\sqrt{\sigma_{\text{SMBackgnd}}\mathcal{L}_{\text{TeV6}}} = 5\sqrt{\sigma_{\text{SMBackgnd}}/\mathcal{L}_{\text{TeVII}}}\sqrt{\mathcal{L}_{\text{TeVII}}\mathcal{L}_{\text{TeV6}}}$$

$$\rightarrow \sigma_{\text{Discovery}}(TeV6) = \sqrt{\frac{\mathcal{L}_{\text{TeVII}}}{\mathcal{L}_{\text{TeV6}}}}\,\sigma_{\text{Discovery}}(TeVII) = 0.029 \text{ pb}$$

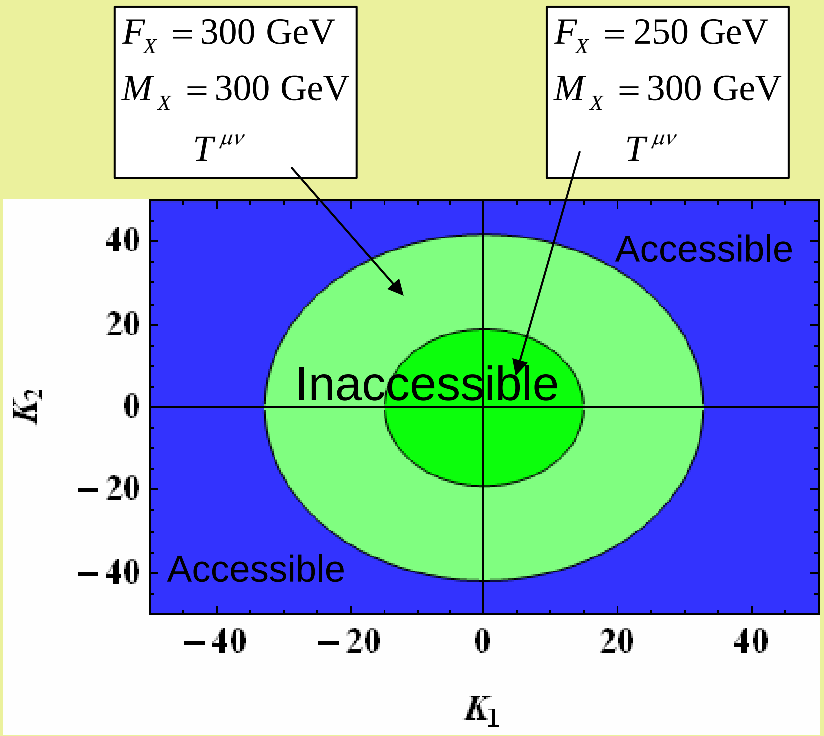


## Extrinsic Curvature Dependence:

Plot $K_1$ vs. $K_2$ for fixed $F_X$ and $M_X$ slices of parameter space ($N=1$)

## Branon Comparison and Region of Applicability

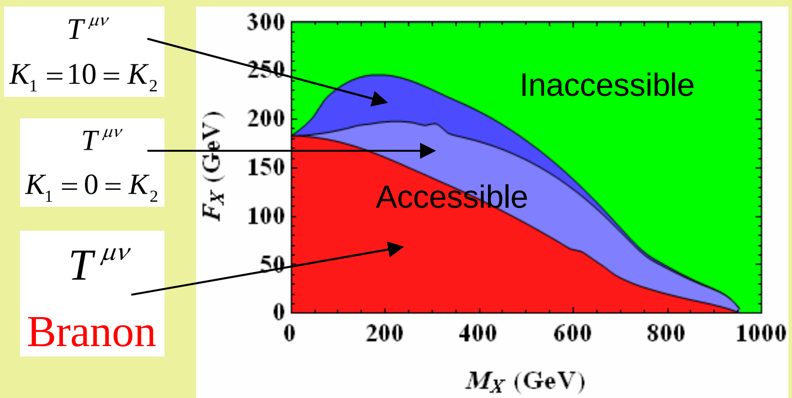
### TeVatron II Reach




$\sqrt{s} = 1.96$ TeV, $\mathcal{L} = 6{,}000$ pb$^{-1}$

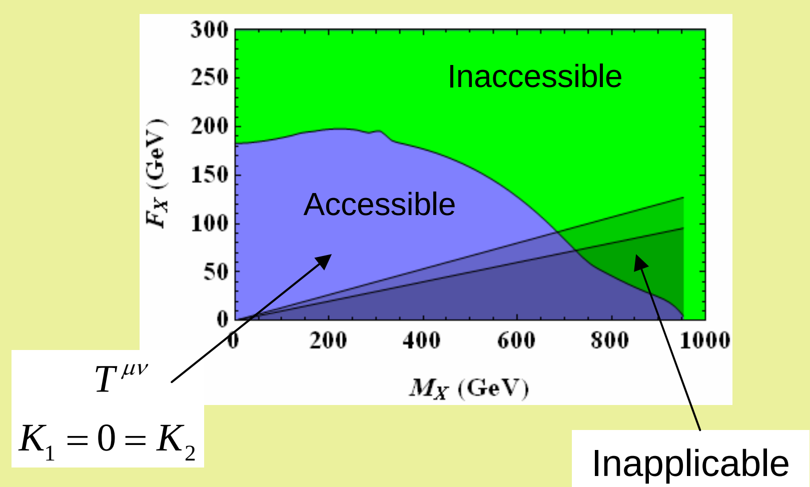
$\sigma_{Discovery} = 0.029$ pb

### TeVatron II Reach




$\sqrt{s} = 1.96$ TeV, $\mathcal{L} = 6{,}000$ pb$^{-1}$

$\sigma_{Discovery} = 0.029$ pb

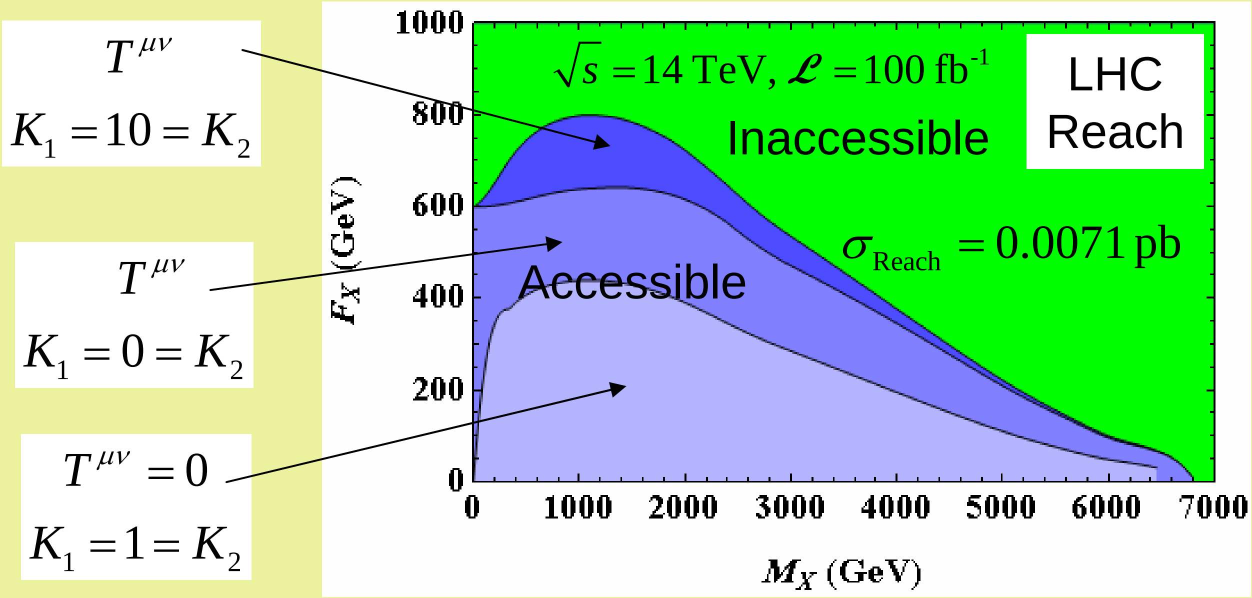


5. LHC Reach: The reach of the LHC can be expressed in terms of the accessible and inaccessible regions of parameter space for an integrated luminosity of 100 $\text{fb}^{-1}$. Assume Discovery cross-section is estimated by the gain in statistics from the ratio of integrated luminosities

Where now the quark distribution function is

$$f(x,y;\hat{s}) =$$
$$\tfrac{1}{3}(\tfrac{2}{3})^2[u_p(x,\hat{s})\bar{u}_p(y,\hat{s}) + \bar{u}_p(x,\hat{s})u_p(y,\hat{s})]$$
$$+\tfrac{1}{3}(-\tfrac{1}{3})^2[d_p(x,\hat{s})\bar{d}_p(y,\hat{s}) + \bar{d}_p(x,\hat{s})d_p(y,\hat{s})].$$

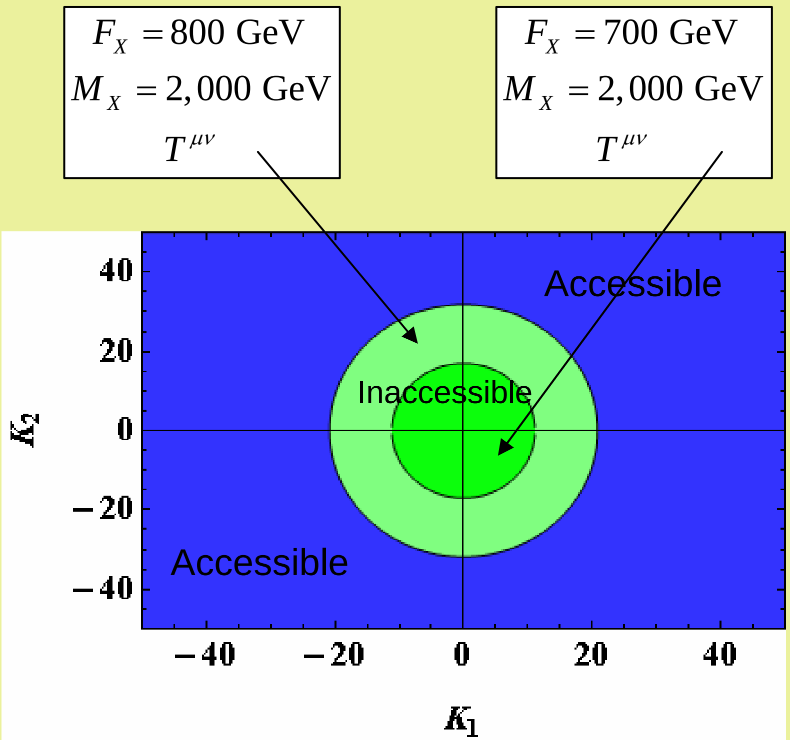
$$\sigma_{\text{Discovery}}(LHC)\,\mathcal{L}_{\text{LHC}} = 5\sqrt{\sigma_{\text{SMBackgnd}}\mathcal{L}_{\text{LHC}}}$$
$$= 5\sqrt{\sigma_{\text{SMBackgnd}}/\mathcal{L}_{\text{TeVII}}}\sqrt{\mathcal{L}_{\text{TeVII}}\mathcal{L}_{\text{LHC}}}$$
$$\rightarrow \sigma_{\text{Discovery}}(LHC) = \sqrt{\frac{\mathcal{L}_{\text{TeVII}}}{\mathcal{L}_{\text{LHC}}}}\,\sigma_{\text{Discovery}}(TeVII)$$
$$= 0.0071\ \text{pb}$$



## Extrinsic Curvature Dependence:

Plot $K_1$ vs. $K_2$ for fixed $F_X$ and $M_X$ slices of parameter space ($N=1$)

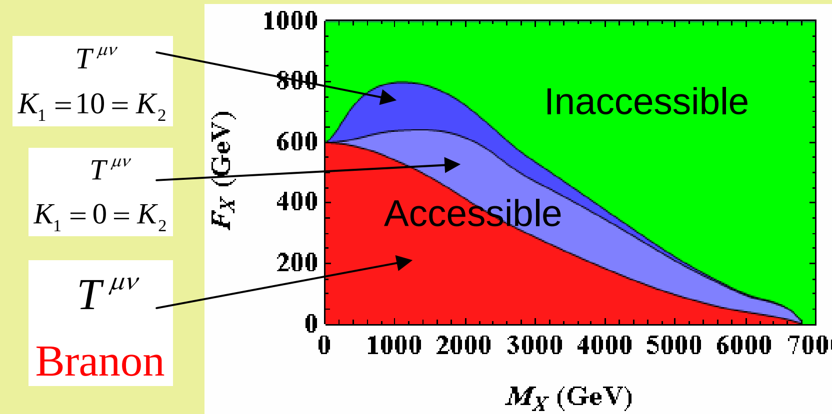
### LHC Reach



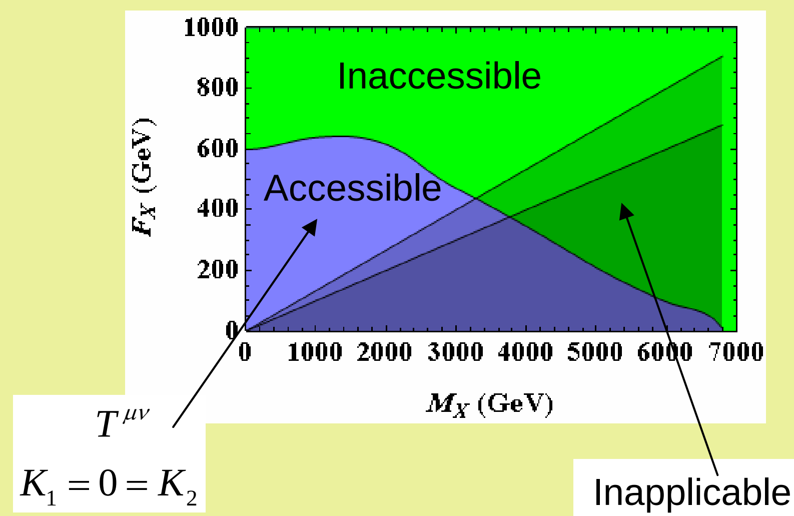

$\sqrt{s} = 14$ TeV, $\mathcal{L} = 100$ fb$^{-1}$ $\sigma_{Discovery} = 0.0071$pb

## Branon Comparison and Region of Applicability

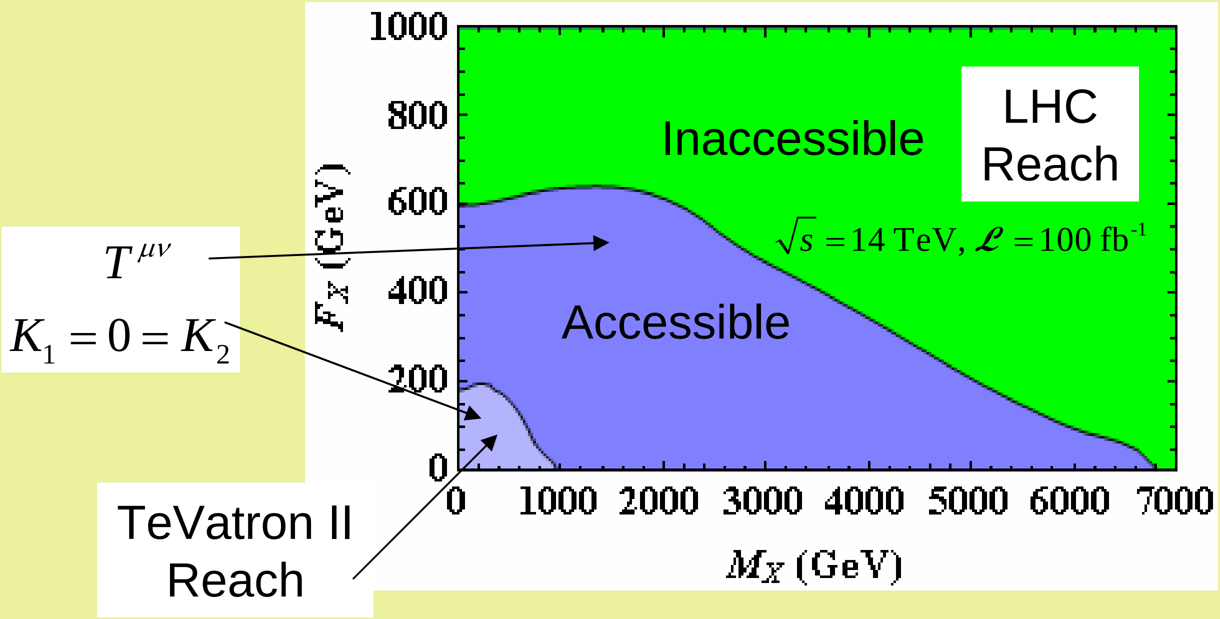
### LHC Reach




$\sqrt{s} = 14$ TeV, $\mathcal{L} = 100$ fb$^{-1}$ $\sigma_{Discovery} = 0.0071$pb



# LHC Era




$\sqrt{s} = 1.96$ TeV, $\mathscr{L} = 6{,}000$ pb$^{-1}$