# Scalar Production in Association with a Z Boson at LHC and ILC: the Mixed Higgs-Radion Case of Warped Models

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# Warped Extra-Dimensional (Randall-Sundrum) Models

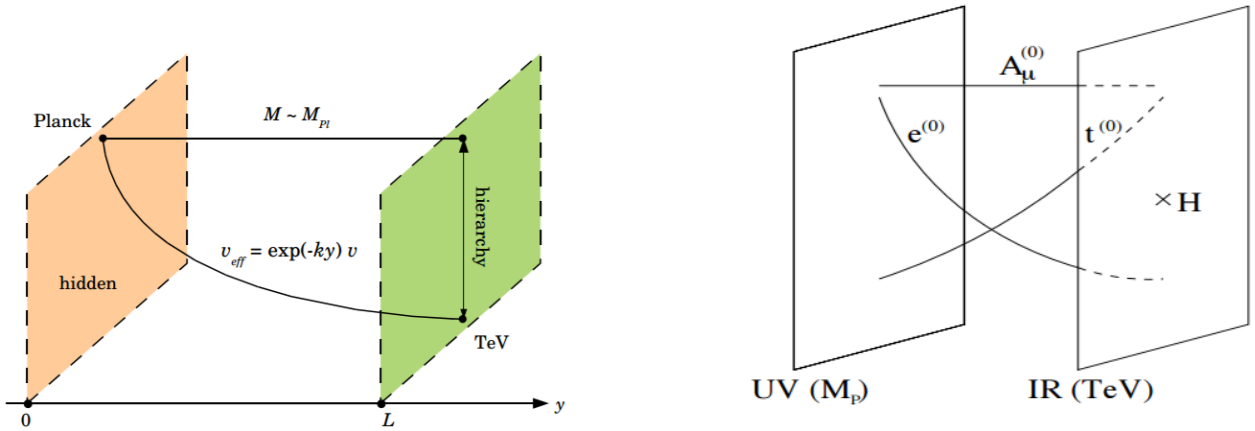



Figure: Randall-Sundrum setup with a brane-localized Higgs scalar (i.e. propagating only in 4D).

- Setup $\rightarrow$ 5D anti-de Sitter space: $\mathrm{d}s^2 = \mathrm{e}^{-2ky}\eta_{\mu\nu}\mathrm{d}x^\mu \mathrm{d}x^\nu + \mathrm{d}y^2, \quad y \in [0, L]$.
- Higgs boson propagates only in 4D, the other SM fields (+graviton) in 5D;
- Main motivation: gauge hierarchy problem (also, fermion hierarchy);
- Main prediction: Kaluza-Klein (KK) partners. Typical mass: $m_{KK} = \mathcal{O}$ (few TeV).

# What is the Radion?

- Extra dimension is microscopic ($L = \mathcal{O}(10/M_{\rm Pl})$)
  $\Rightarrow$ its fluctuations are parametrized by a scalar called the radion ($\phi_0$), with mass $m_\phi$;

- Unmixed radion couplings similar to SM Higgs scalar couplings ($\Lambda$ = radion VEV):

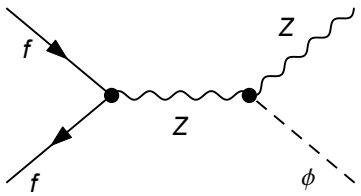
$$S_{\rm rad} \sim \frac{\phi_0}{\Lambda} T^\mu_\mu \;\Rightarrow\; c_{\phi_0 ff} \sim \frac{m_f}{\Lambda},\; c_{\phi_0 VV} \sim \frac{m_V^2}{\Lambda}\,(V = W, Z); \tag{1}$$

- Higgs - gravity coupling $\Rightarrow$ kinetic mixing between radion and Higgs:

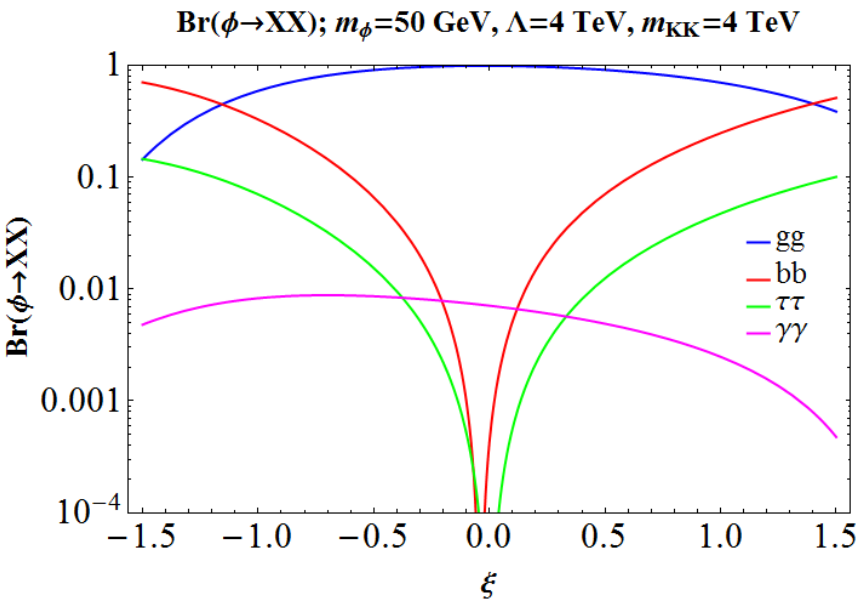
$$S_{\rm mix} = \xi \int {\rm d}^4x \sqrt{g_{\rm 4D}}\, R(g_{\rm 4D})\, H^\dagger H. \tag{2}$$

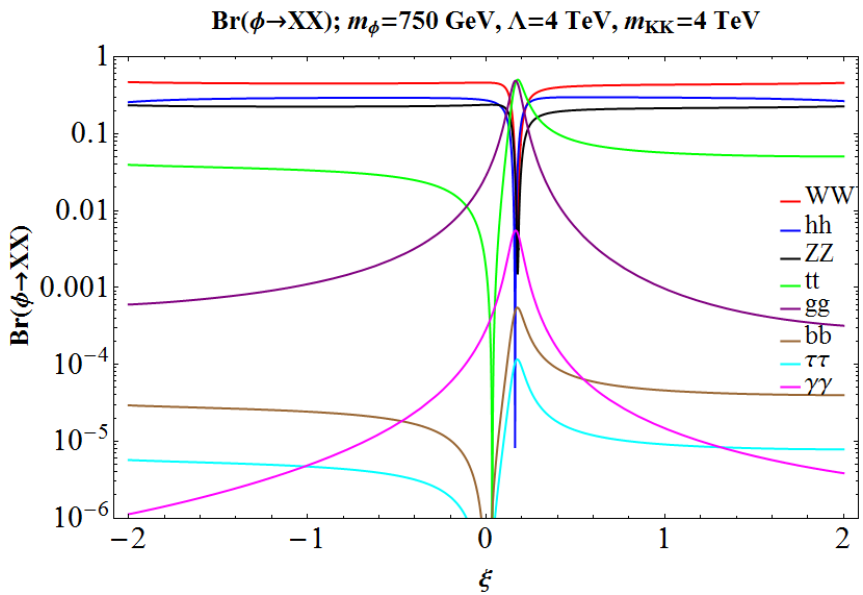
## At colliders:

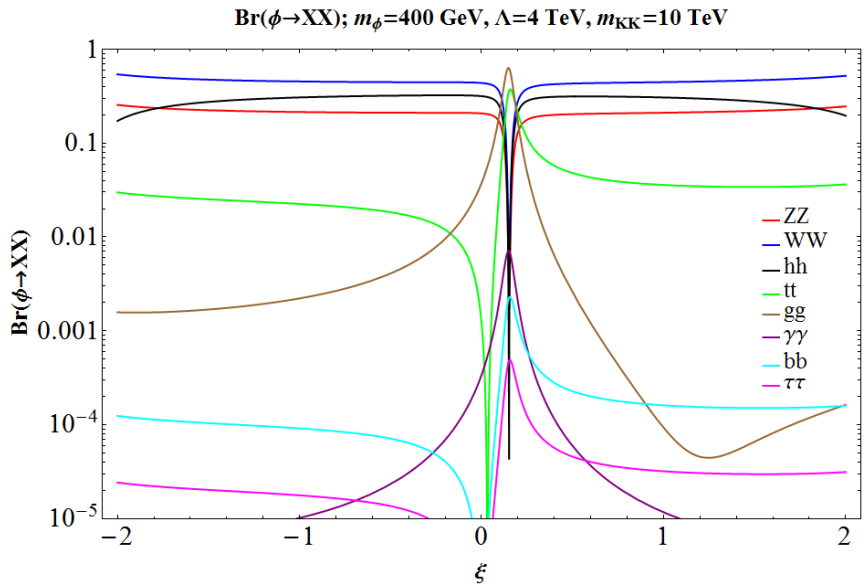
Radion = lightest new particle $\Rightarrow$ first sign of new physics?
Relevant production channels: ggF, Z$\phi$,... at (HL-)LHC; Z$\phi$, VBF at ILC.



# Radion Branching Ratios



# Radion + Z at the LHC

Theoretical calculation of the $\phi ZZ$ coupling, including $Z - Z_{KK} - Z'$ mixing (custodial RS)
$\Rightarrow$ cross section for $\boxed{pp \to Z, Z_{KK}, Z' \to Z\phi}$.

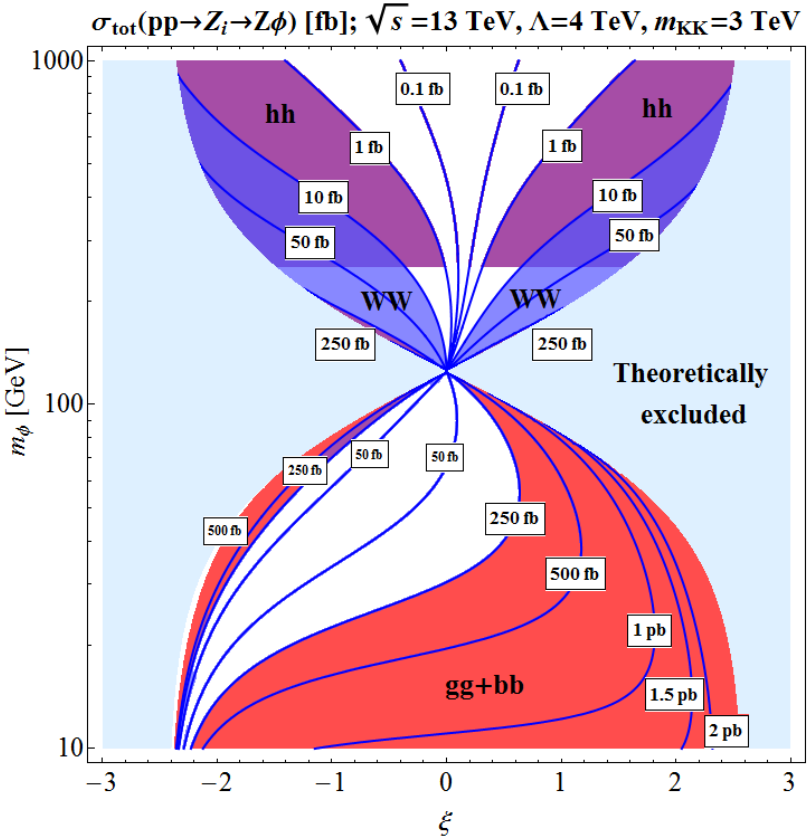
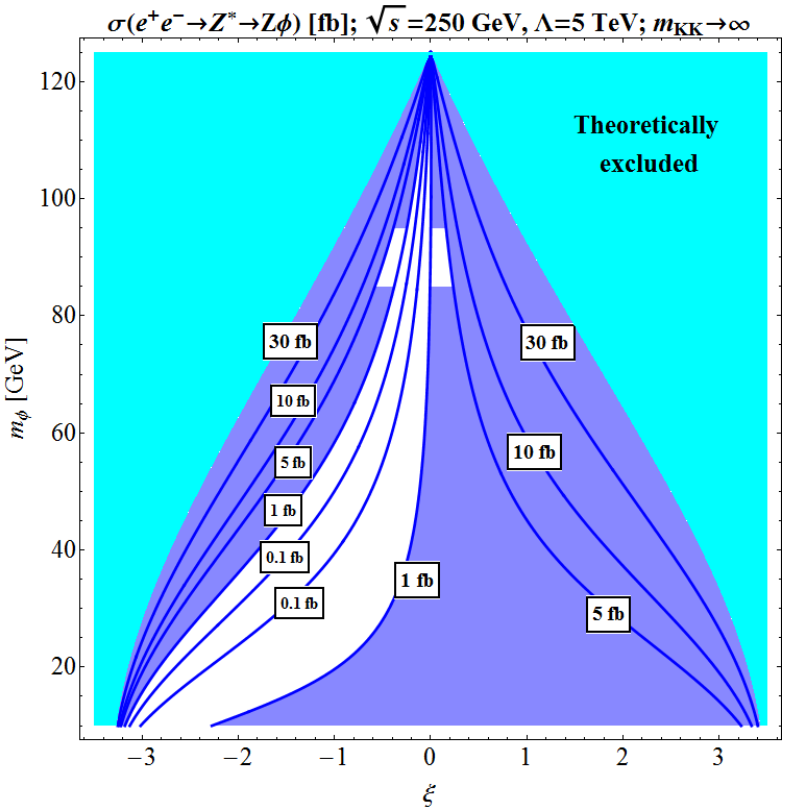
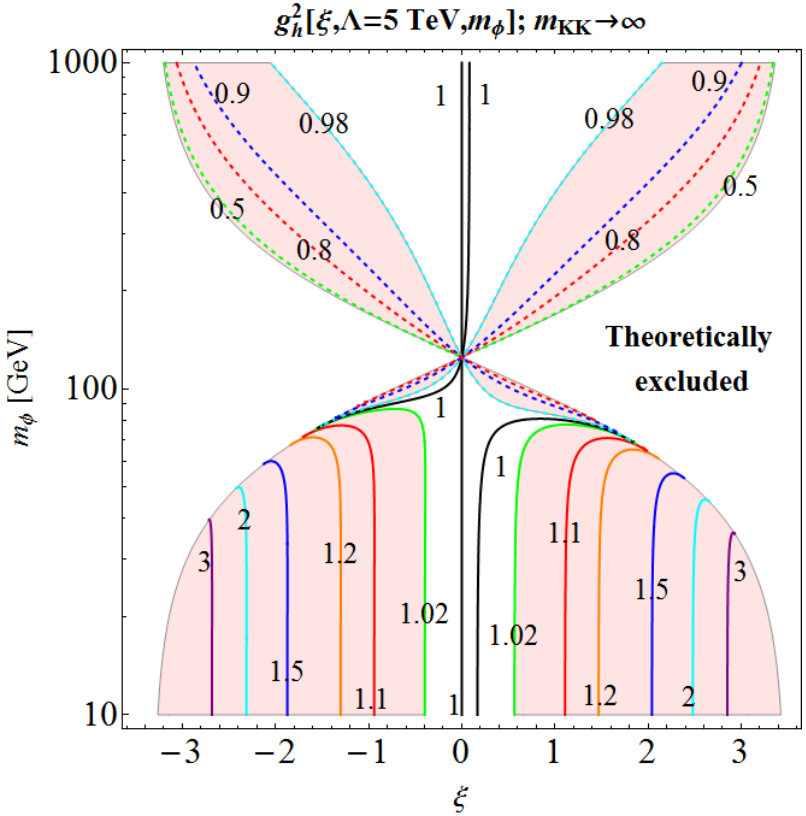



Figure: $Z\phi$ production cross section at the LHC + estimated sensitivity for 300 fb$^{-1}$.

# Radion + Z and Higgs Couplings at the ILC

Estimated ILC sensitivity for 2 ab$^{-1}$ at 250 GeV via $\boxed{e^+e^- \to Z \to Z\phi}$ (left) and for a precise measurement of the $hZZ$ coupling (1% at $2\sigma$) at the ILC (right):



# Summary of ILC Sensitivity to the Radion

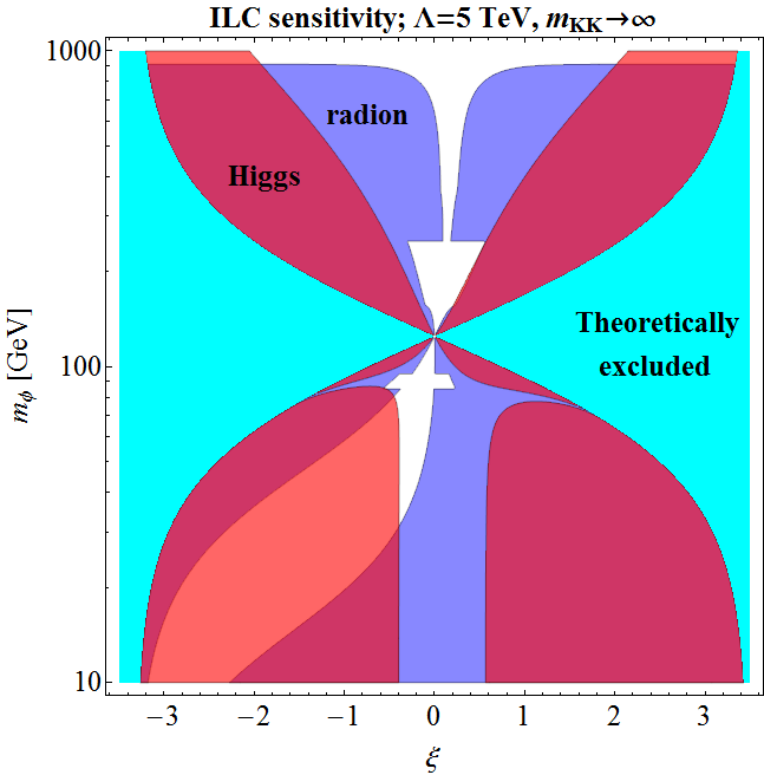



Figure: Estimated sensitivity (at $2\sigma$) of direct (radion search) and indirect ($hZZ$ coupling measurement) radion searches at the ILC for 2 $ab^{-1}$ at 250 GeV, 4 $ab^{-1}$ at 500 GeV, and 8 $ab^{-1}$ at 1 TeV.

# Conclusions

- ggF dominant $\phi$ production mode at the LHC, but $Z\phi$ can be complementary (for light radion/suppressed $gg\phi$ coupling).
- Much better sensitivity at the ILC (via the Z recoil mass technique).
- The radion can also be indirectly probed at the ILC through $hZZ$ precision measurements $\Rightarrow$ complementarity with direct searches.

Interesting scenario: a light radion could be invisible at LHC but discovered at the ILC!

Thank you for your attention!

# Higgs-Radion Mixing

- Higgs-Gravity coupling $\rightarrow$ Higgs-radion kinetic mixing:

$$\mathcal{L} = -\begin{pmatrix}\phi_0 & h_0\end{pmatrix} \underbrace{\begin{pmatrix}1+6\xi\ell^2 & -3\xi\ell \\ -3\xi\ell & 1\end{pmatrix}}_{\det \equiv Z^2} \begin{pmatrix}\Box\phi_0 \\ \Box h_0\end{pmatrix} - \frac{1}{2}m_{\phi_0}^2\phi_0^2 - \frac{1}{2}m_{h_0}^2 h_0^2, \quad \ell \equiv \frac{v}{\Lambda_\phi}. \tag{3}$$

- "Rotating" to mass basis:

$$\begin{pmatrix}\phi_0 \\ h_0\end{pmatrix} = \begin{pmatrix}a & -b \\ c & d\end{pmatrix}\begin{pmatrix}\phi \\ h\end{pmatrix}, \tag{4}$$

$$a = \frac{c_\theta}{Z},\ b = \frac{s_\theta}{Z},\ c = s_\theta + \frac{6\xi\ell}{Z}c_\theta,\ d = c_\theta - \frac{6\xi\ell}{Z}s_\theta. \tag{5}$$

- Dominant couplings to $h$ and $\phi$:

$$g_\phi = c - \ell a,\ g_h = d + \ell b; \tag{6}$$

$$g_h^2 + g_\phi^2 \geq 1. \tag{7}$$

# Couplings to Massive Gauge Bosons

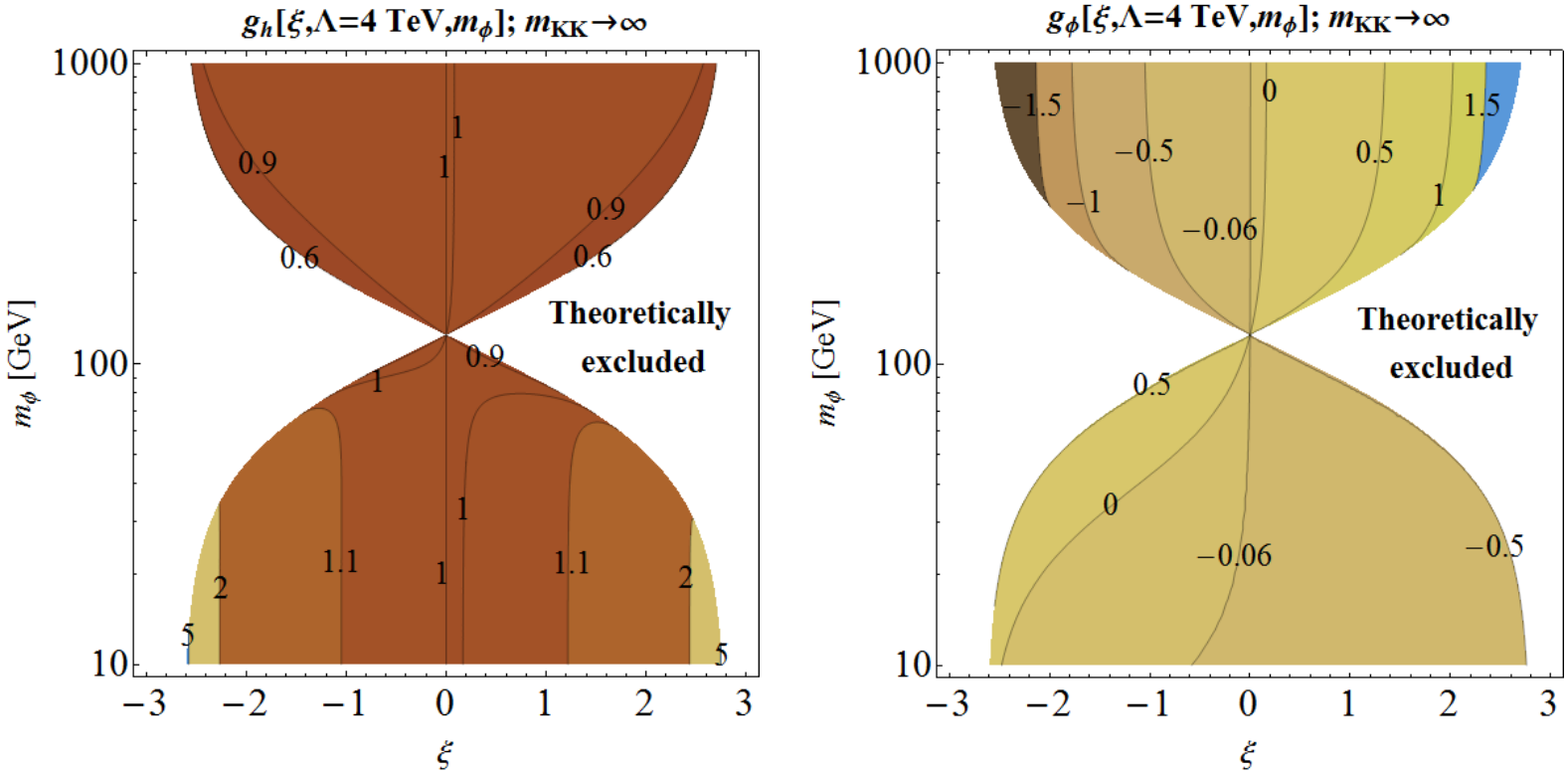



Figure: $g_h \equiv g_{hZZ}/g_{hZZ}^{\rm SM}$ and $g_\phi = g_{\phi ZZ}/g_{hZZ}^{\rm SM}$.

# BR($h \to \phi\phi$)

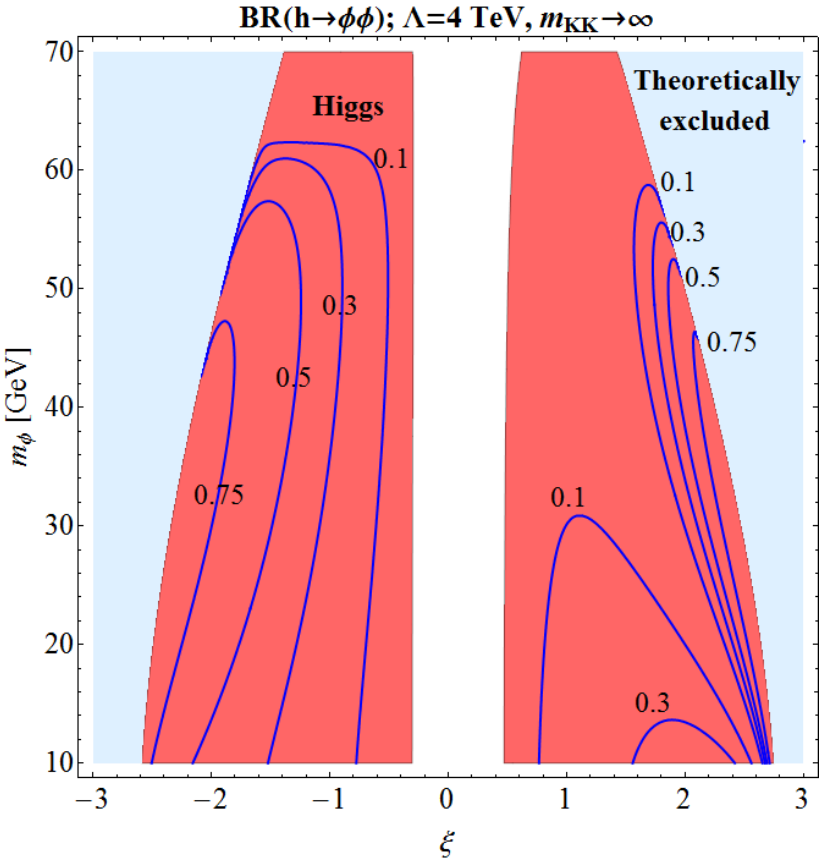



Figure: Branching ratio of $h$ to $\phi\phi$.

# Other Values for $\Lambda$

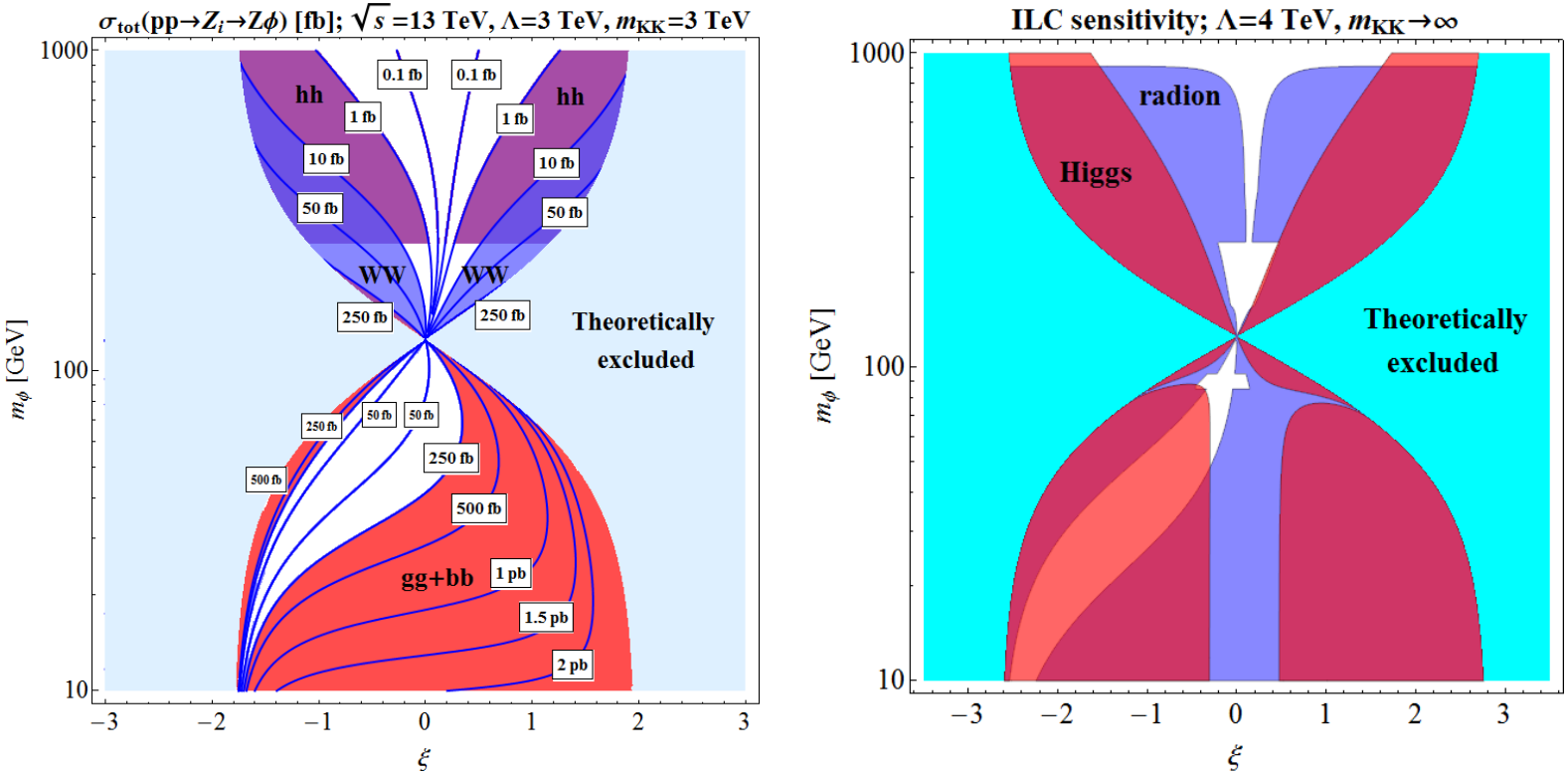
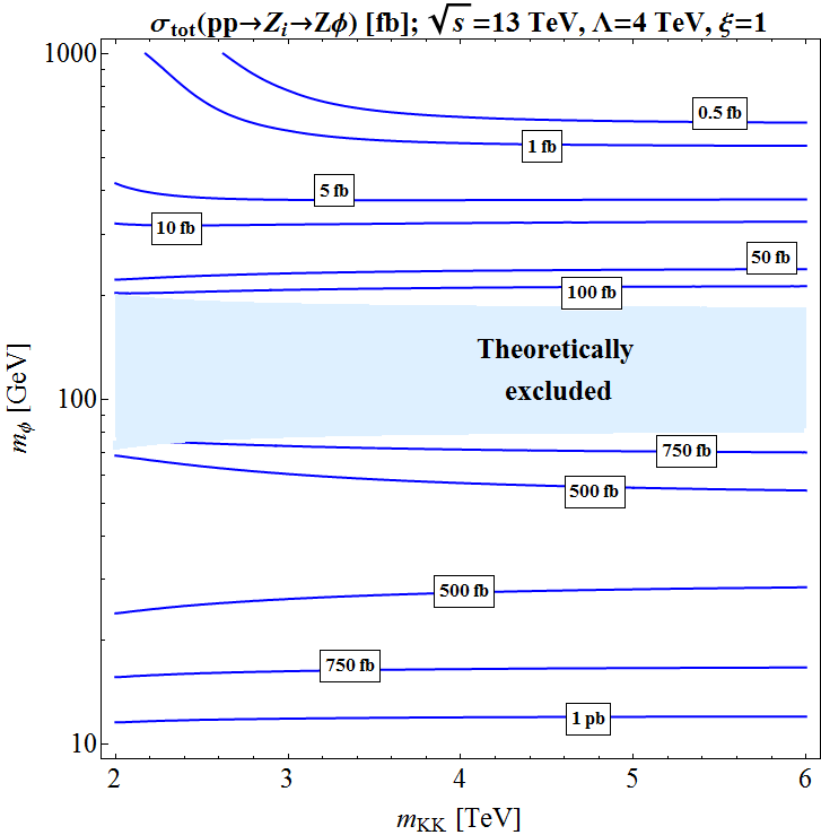



Figure: Estimated sensitivity for radion searches (left) at LHC for $\Lambda = 3$ TeV and (right) at ILC for $\Lambda = 4$ TeV.

# Effect of KK Z Bosons on $\sigma(pp \to Z\phi)$



# Frank et al., arXiv:1606.07689 [hep-ph]

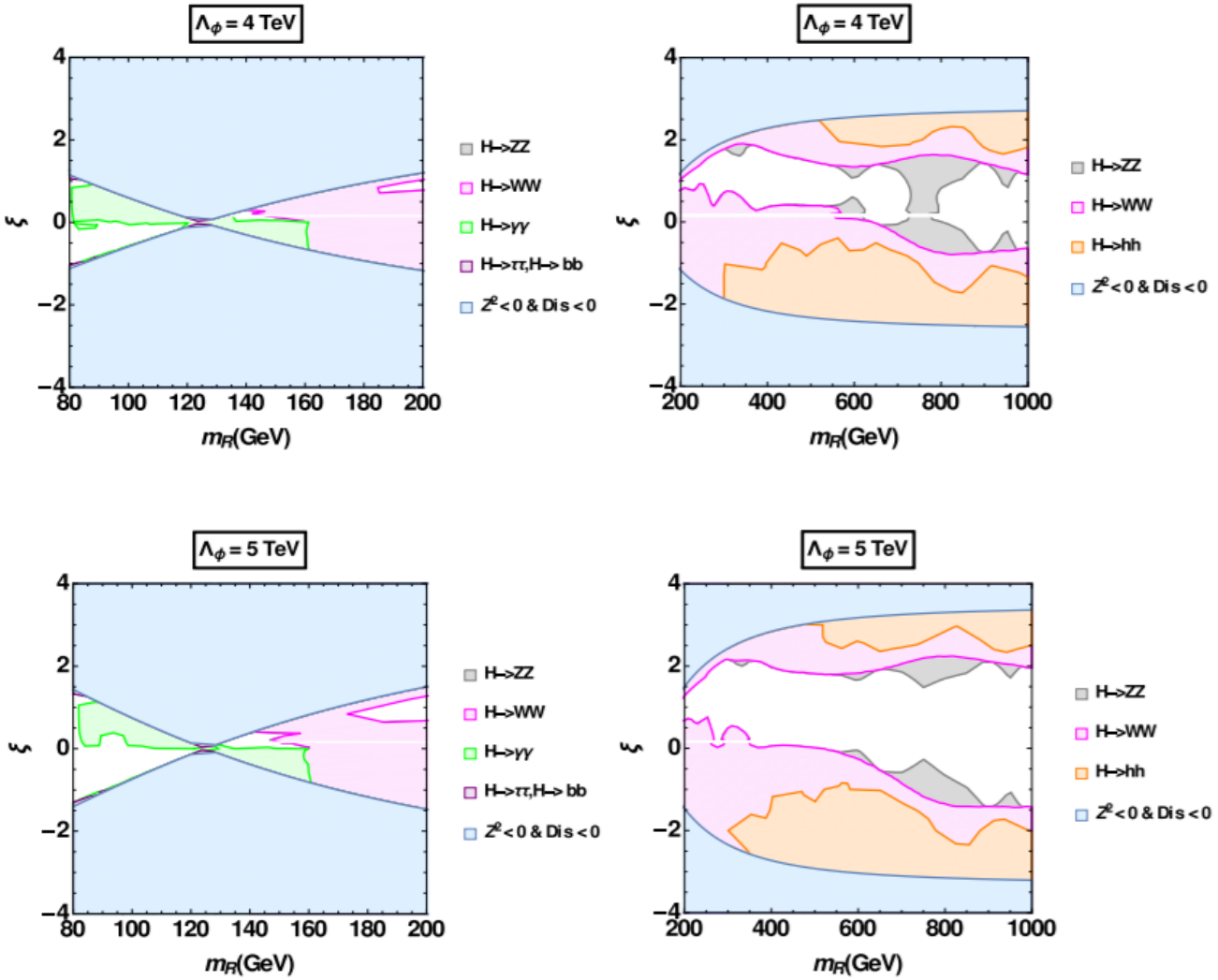



Figure: Current LHC exclusion limits for $\phi$ (from 1606.07689 [hep-ph]; $gg \to \phi$ production mechanism).