ELECTROWEAK BREAKING IN EXTRA DIMENSIONS

MINI REVIEW

Gero von Gersdorff (École Polytechnique)

Moriond Electroweak Session, La Thuile, March 2011

OUTLINE

- How can Extra Dimensions explain the electroweak scale?
- What are the key signatures of such models?
- How well do they comply with Electroweak Precision data?

RS MODELS

Randall & Sundrum ’99

RS MODELS

Randall & Sundrum '99

$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} + dy^2$$

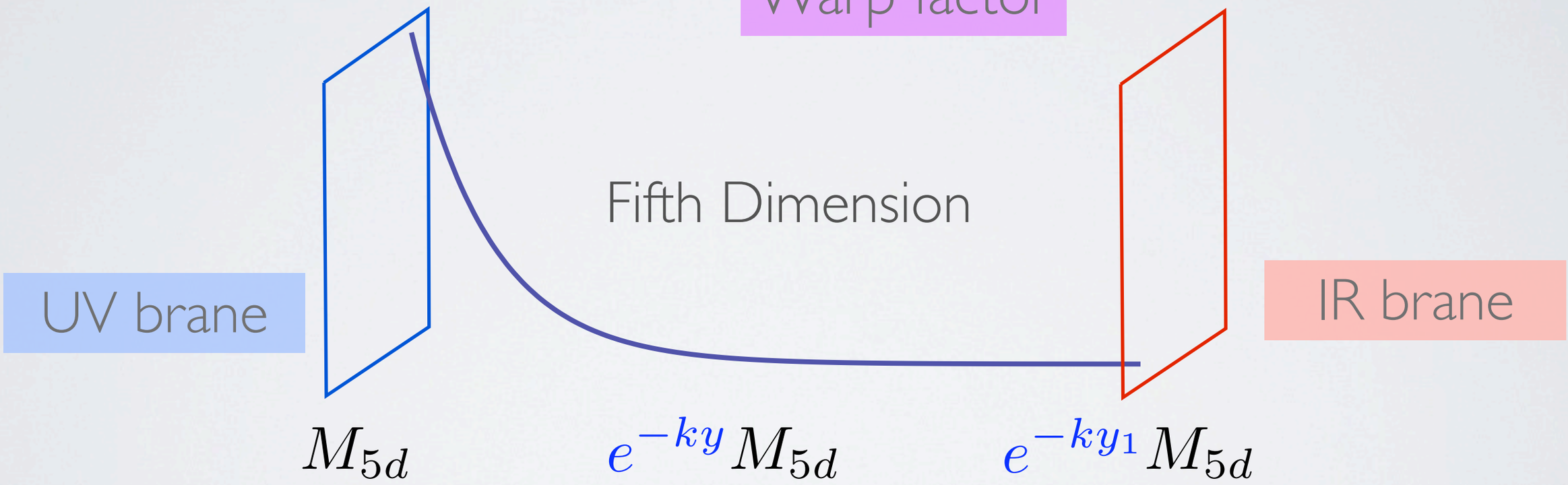
Warp factor

RS MODELS

Randall & Sundrum '99

$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} + dy^2$$

Warp factor

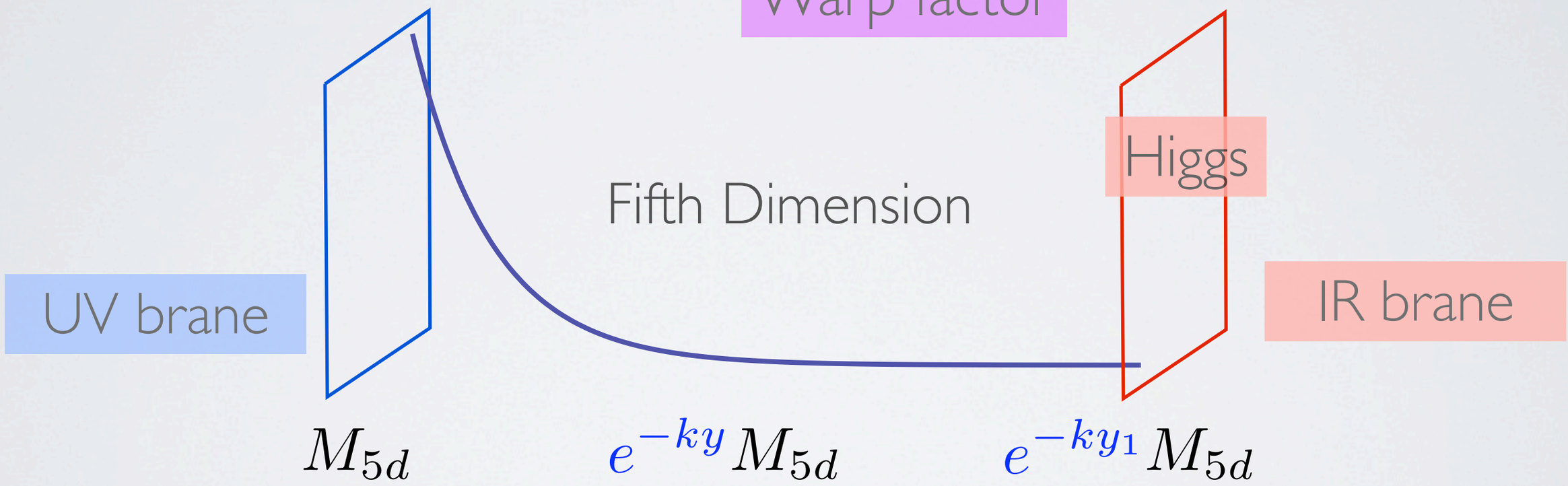


RS MODELS

Randall & Sundrum '99

$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} + dy^2$$

Warp factor

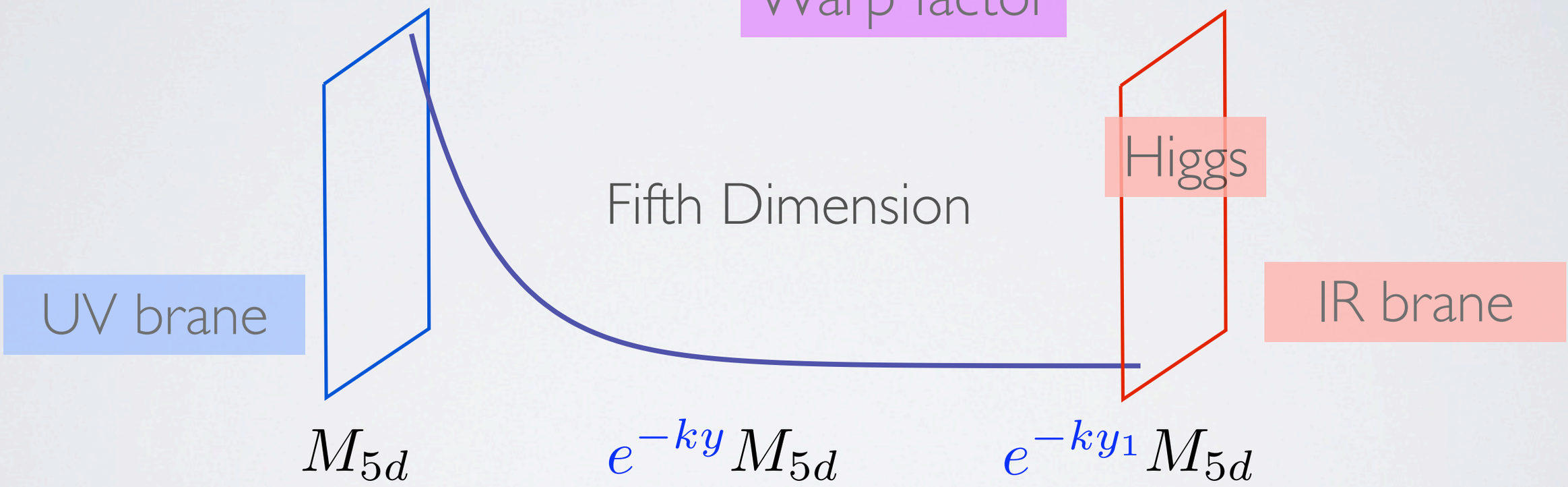


RS MODELS

Randall & Sundrum '99

$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} + dy^2$$

Warp factor



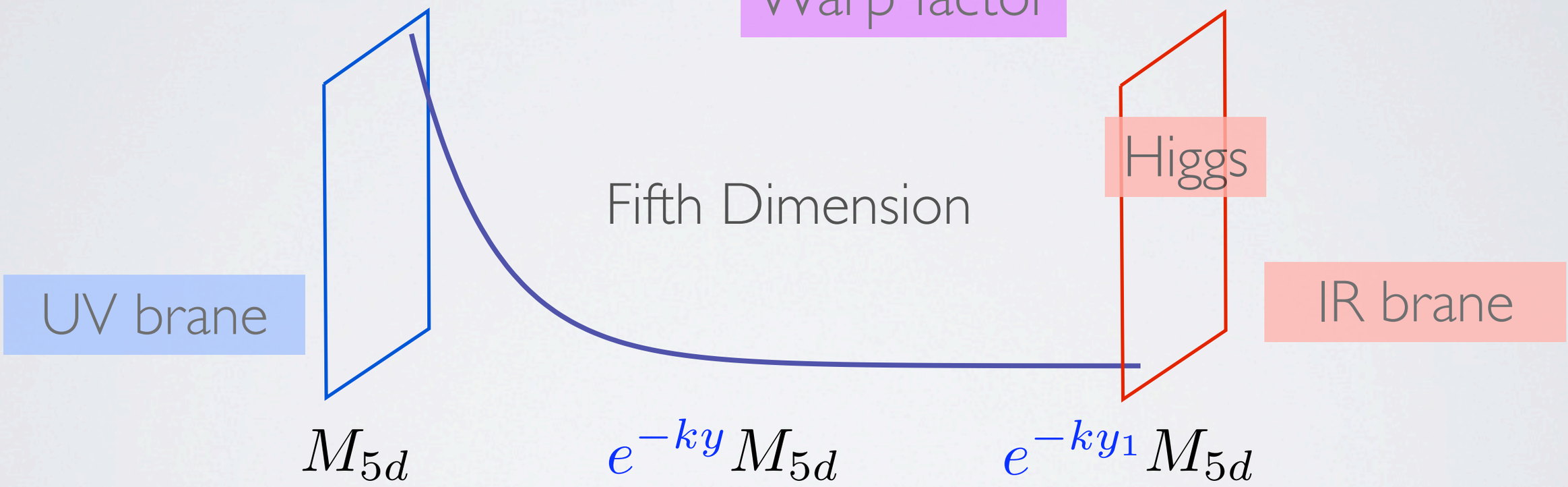
$$\mathcal{L} = \sqrt{g} \left(g^{\mu\nu} D_\mu H^\dagger D_\nu H - M_{5d}^2 |H^2| \right)$$

RS MODELS

Randall & Sundrum '99

$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} + dy^2$$

Warp factor



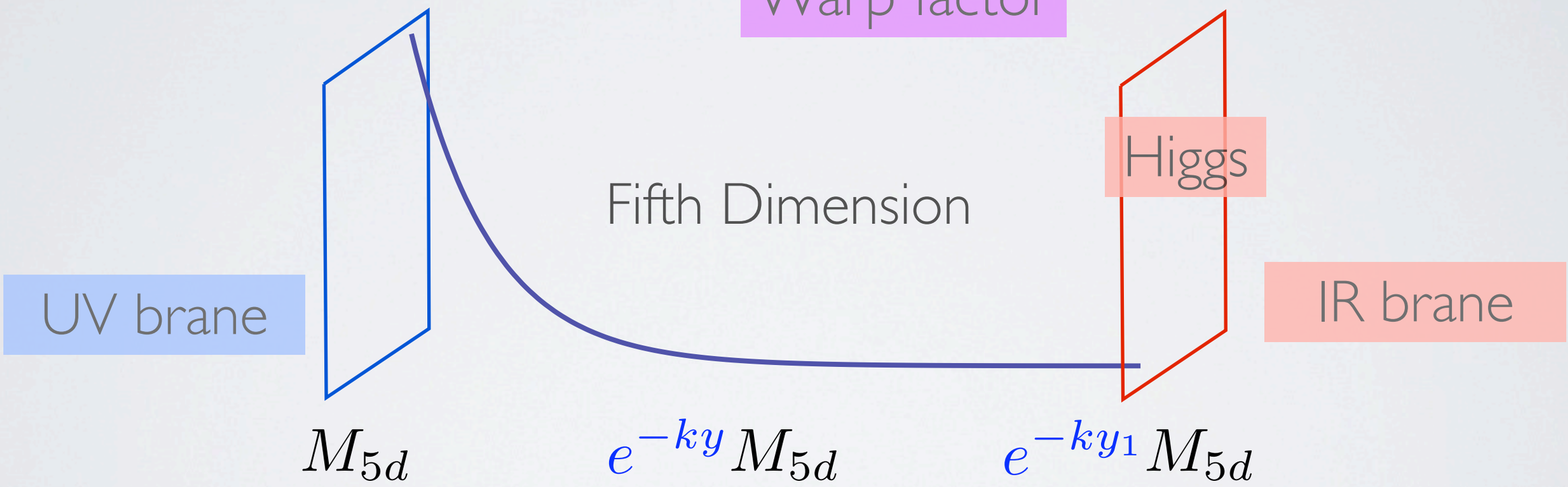
$$\mathcal{L} = e^{-4ky_1} \left(e^{2ky_1} \eta^{\mu\nu} D_\mu H^\dagger D_\nu H - M_{5d}^2 |H^2| \right)$$

RS MODELS

Randall & Sundrum '99

$$ds^2 = e^{-2ky} dx^\mu dx^\nu \eta_{\mu\nu} + dy^2$$

Warp factor



$$\mathcal{L} = \eta^{\mu\nu} D_\mu H^\dagger D_\nu H - e^{-2ky_1} M_{5d}^2 |H^2|$$

RS - MODELS

The proper distance between branes (volume)
= # "e-folds" to generate Planck/Weak hierarchy
Need $ky_1 \sim 35$

RS - MODELS

The proper distance between branes (volume)
= # "e-folds" to generate Planck/Weak hierarchy
Need $ky_1 \sim 35$

IR ~ $k \exp(-ky_1)$ ~ TeV

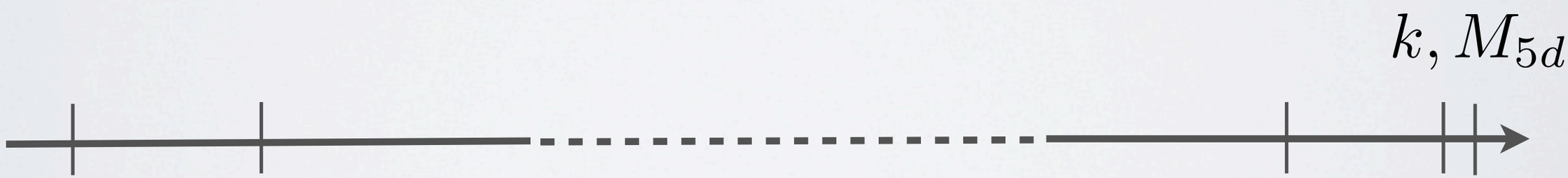
UV ~ 10^{18} GeV

RS - MODELS

The proper distance between branes (volume)
= # "e-folds" to generate Planck/Weak hierarchy
Need $ky_1 \sim 35$

IR ~ $k \exp(-ky_1)$ ~ TeV

UV ~ 10^{18} GeV

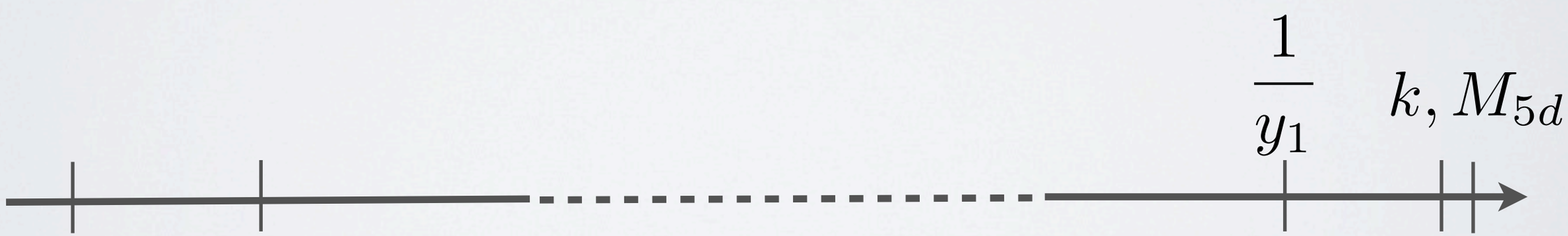


RS - MODELS

The proper distance between branes (volume)
= # "e-folds" to generate Planck/Weak hierarchy
Need $ky_1 \sim 35$

IR ~ $k \exp(-ky_1)$ ~ TeV

UV ~ 10^{18} GeV

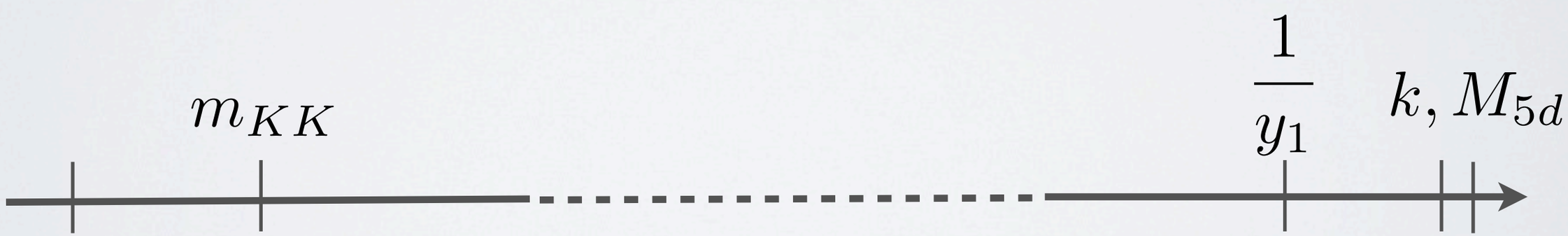


RS - MODELS

The proper distance between branes (volume)
= # "e-folds" to generate Planck/Weak hierarchy
Need $ky_1 \sim 35$

IR ~ $k \exp(-ky_1)$ ~ TeV

UV ~ 10^{18} GeV

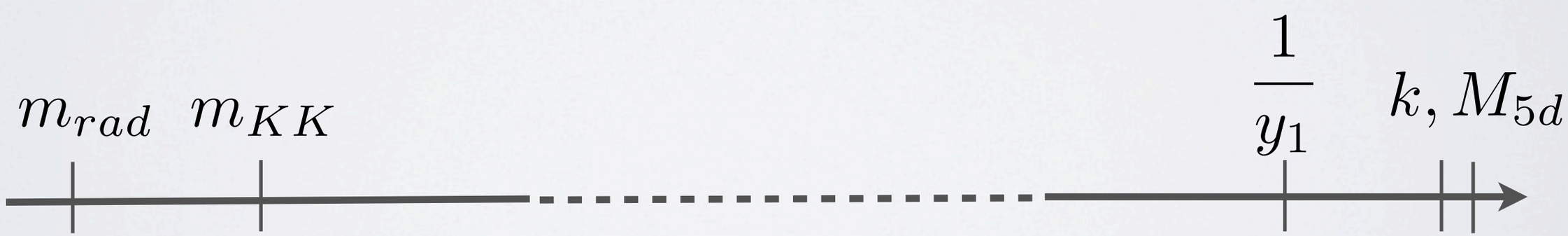


RS - MODELS

The proper distance between branes (volume)
= # "e-folds" to generate Planck/Weak hierarchy
Need $ky_1 \sim 35$

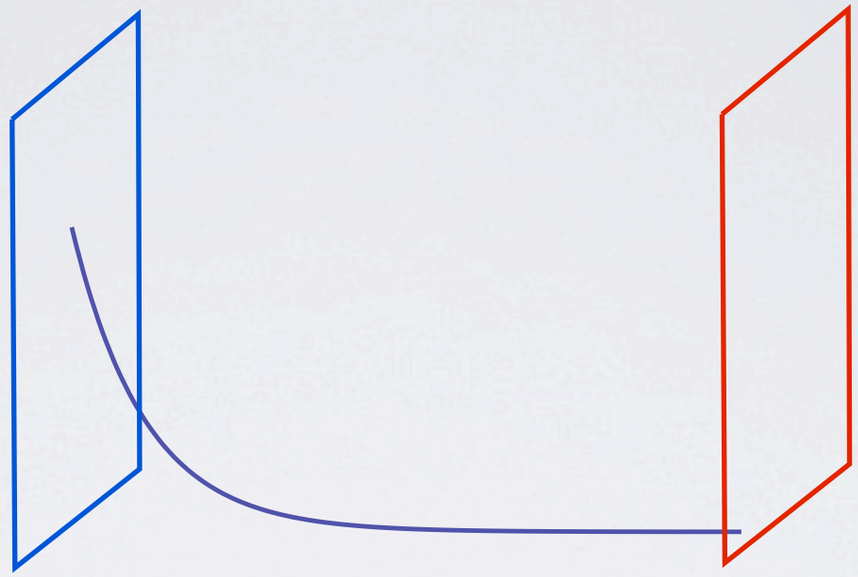
IR ~ $k \exp(-ky_1)$ ~ TeV

UV ~ 10^{18} GeV



RS - SIGNATURES

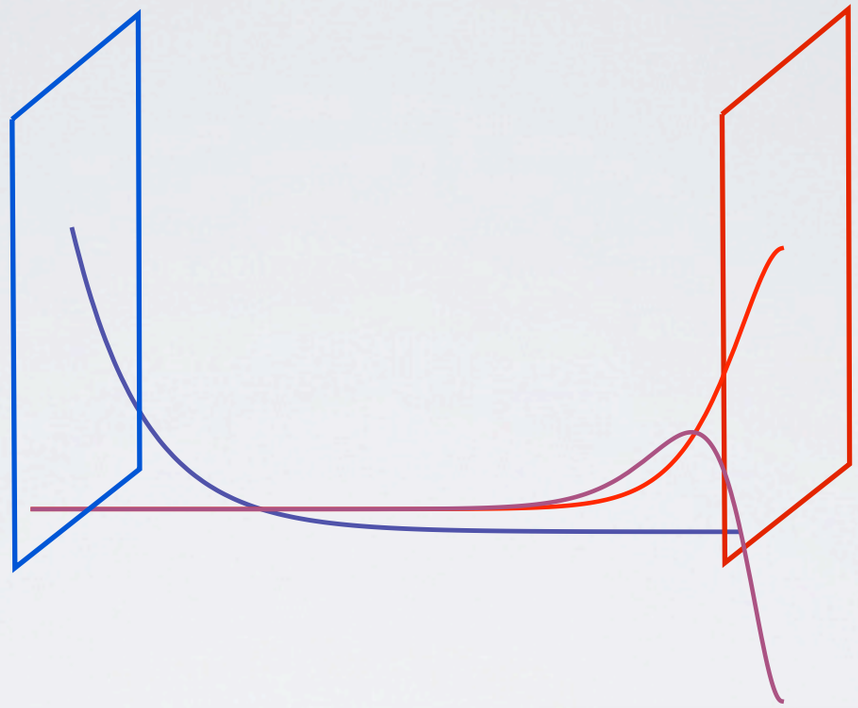
Graviton zero mode:
UV-Localized



Graviton zero mode is
weakly coupled
$(1 / M_{Planck})$

RS - SIGNATURES

Graviton zero mode:
UV-Localized



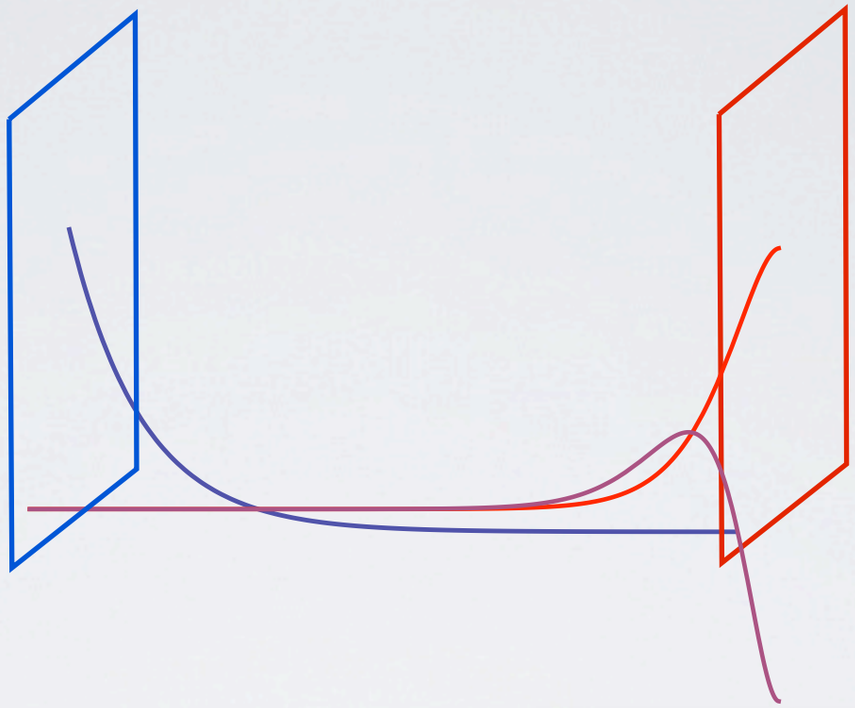
Graviton KK mode:
IR-Localized

Graviton zero mode is
weakly coupled
($1 / M_{Planck}$)

Graviton KK modes
have TeV masses
and are strongly coupled
($1/TeV$)

RS - SIGNATURES

Graviton zero mode:
UV-Localized



Graviton KK mode:
IR-Localized

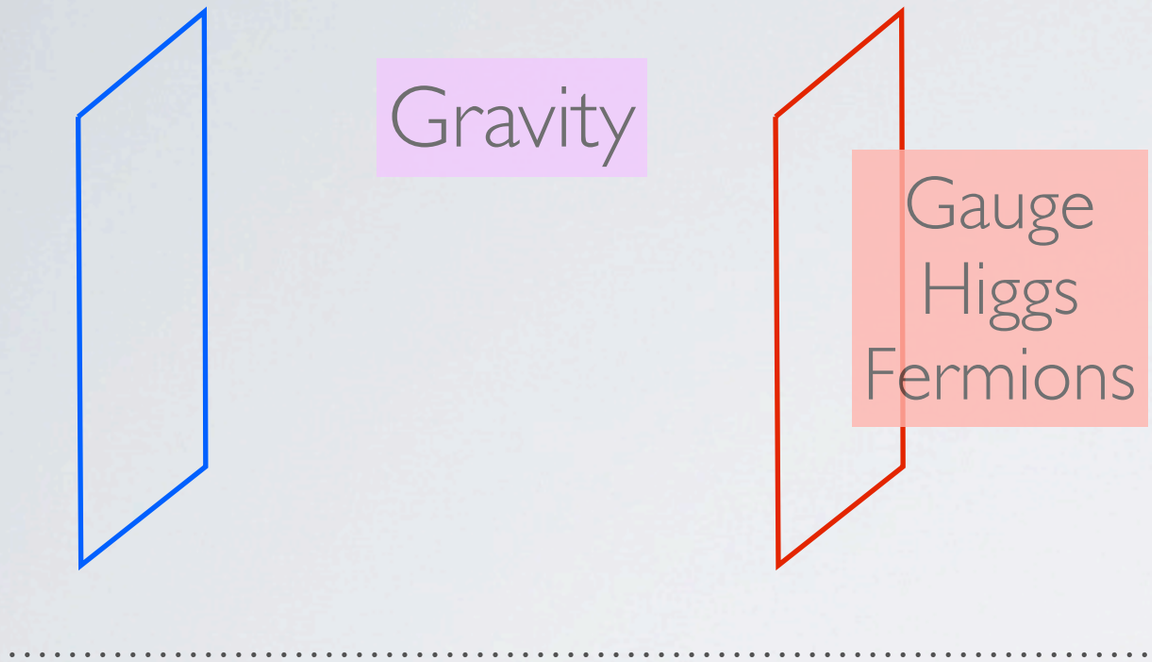
Graviton zero mode is
weakly coupled
($1 / M_{Planck}$)

Graviton KK modes
have TeV masses
and are strongly coupled
(1/TeV)

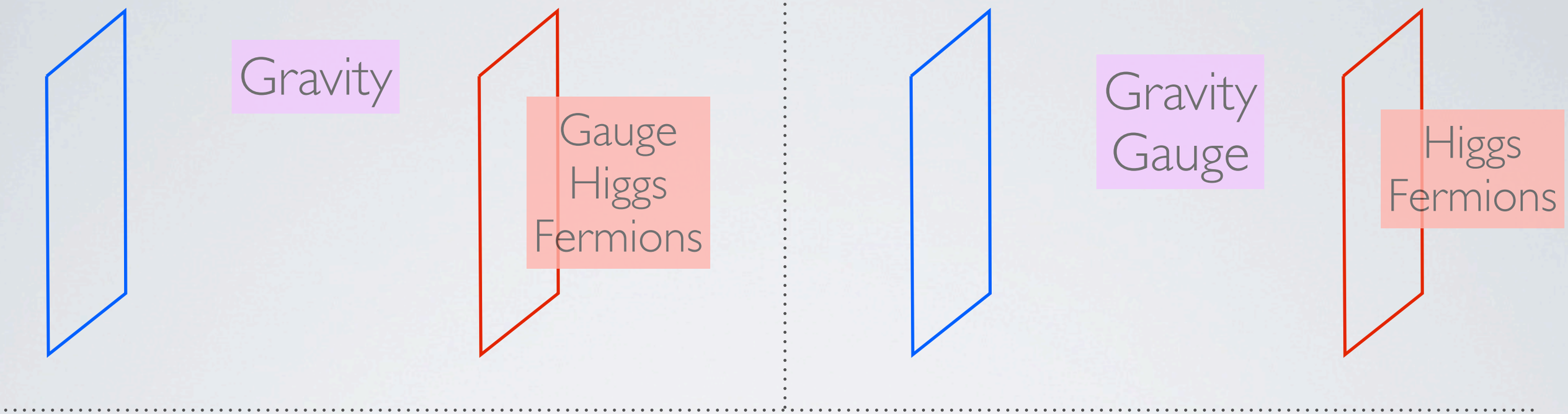
RS predicts spin-2 resonances at LHC

MODEL VARIANTS

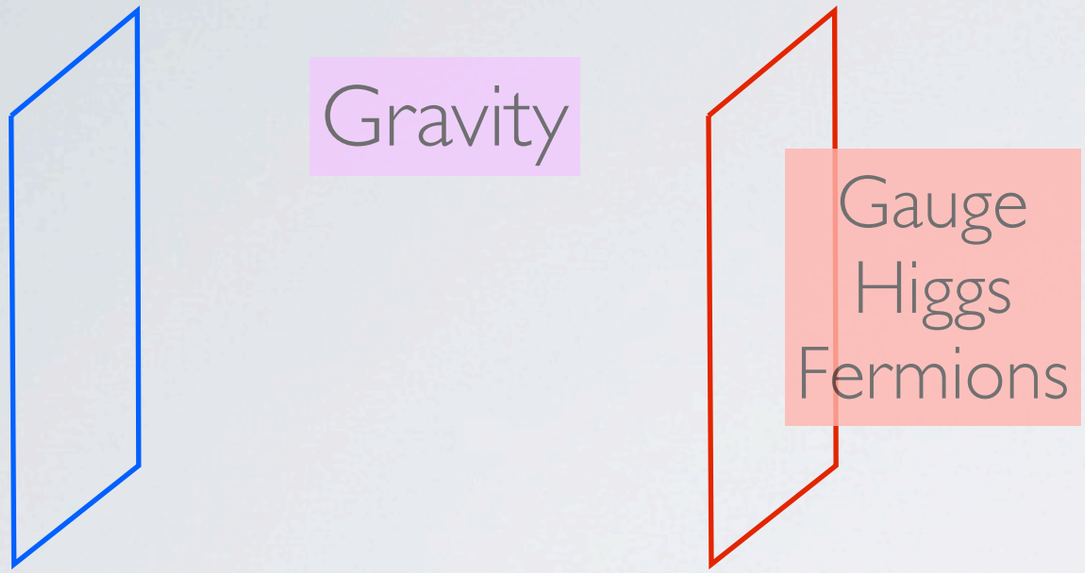
MODEL VARIANTS

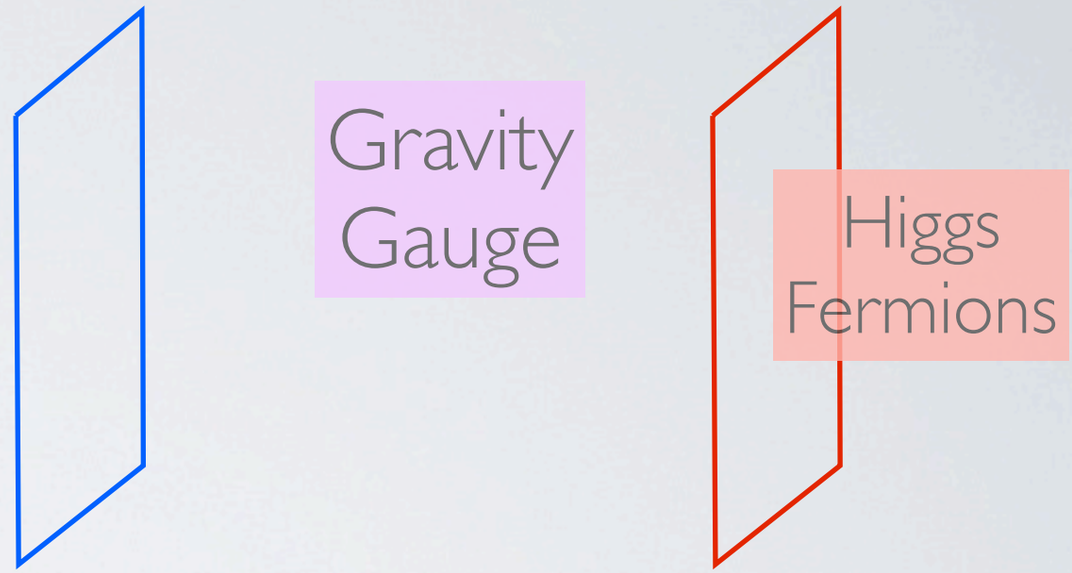


MODEL VARIANTS

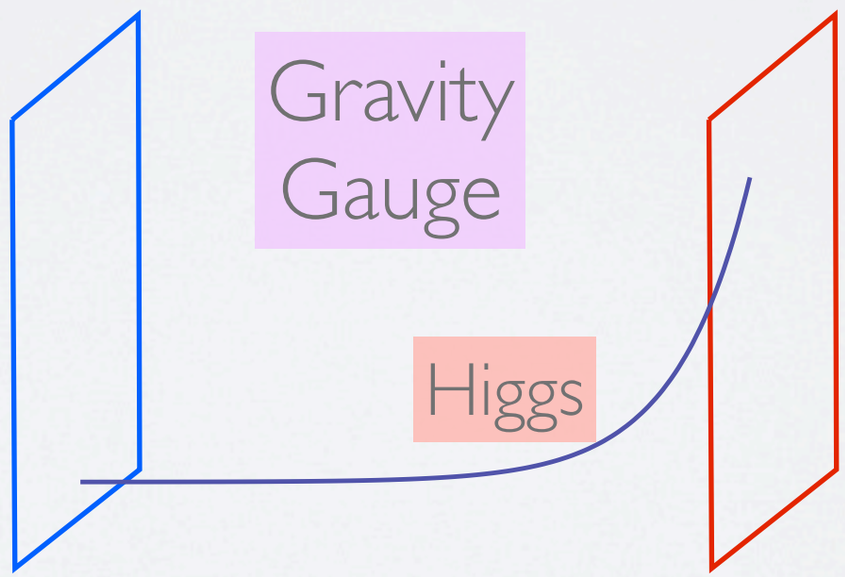


MODEL VARIANTS

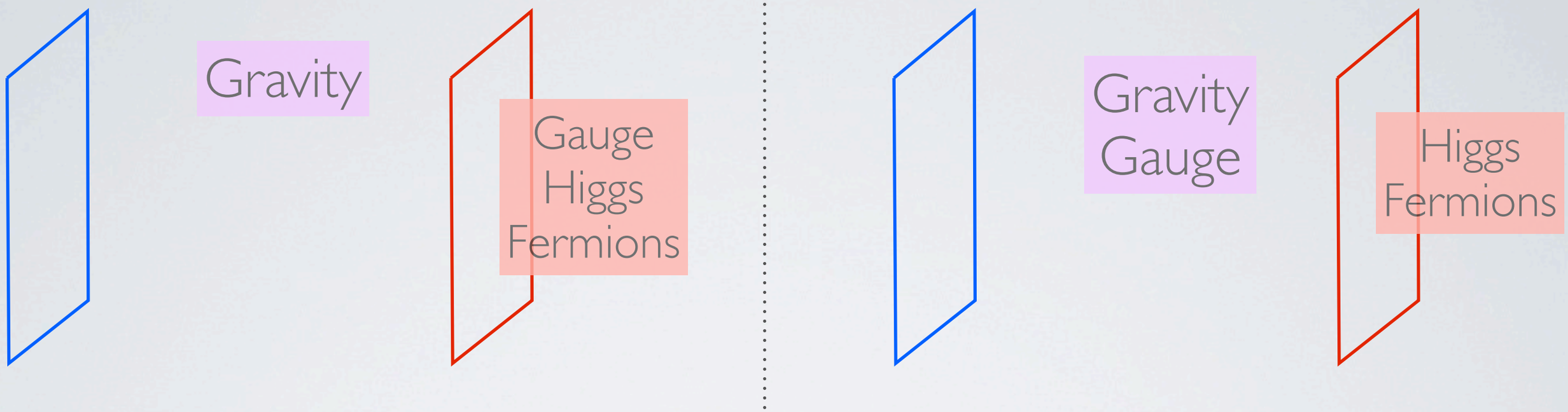




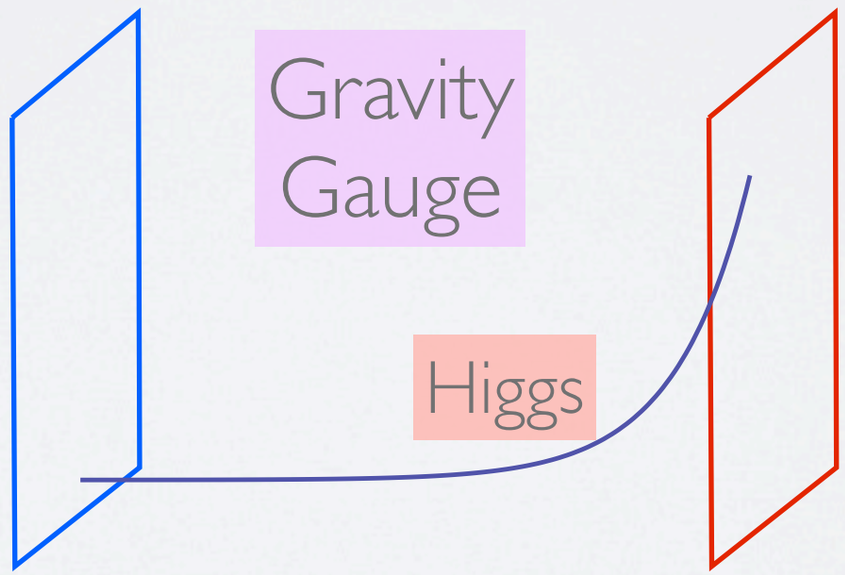
Higgs can be moved to the bulk (but not arbitrarily much)



MODEL VARIANTS

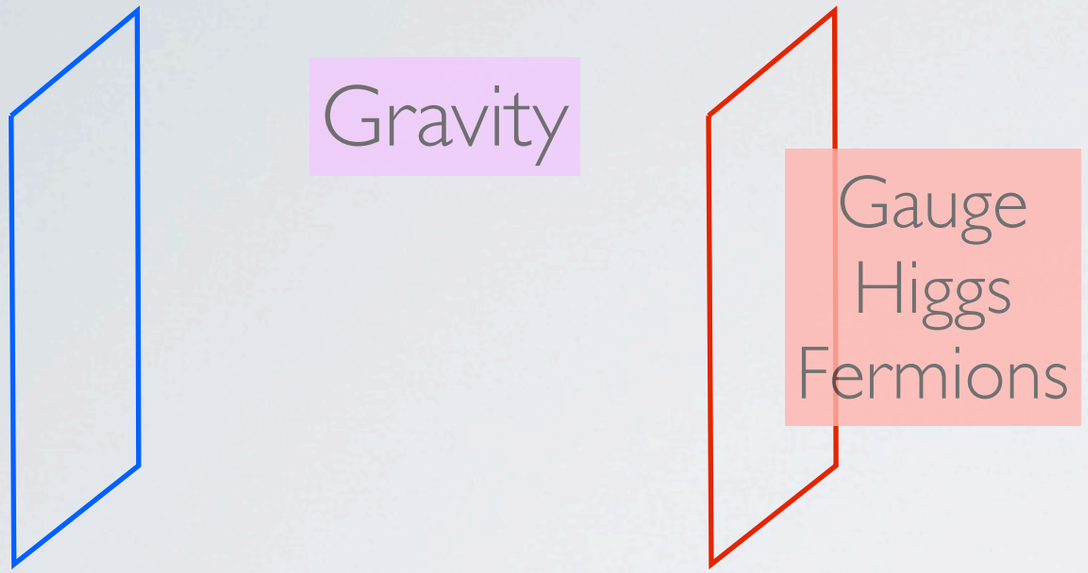


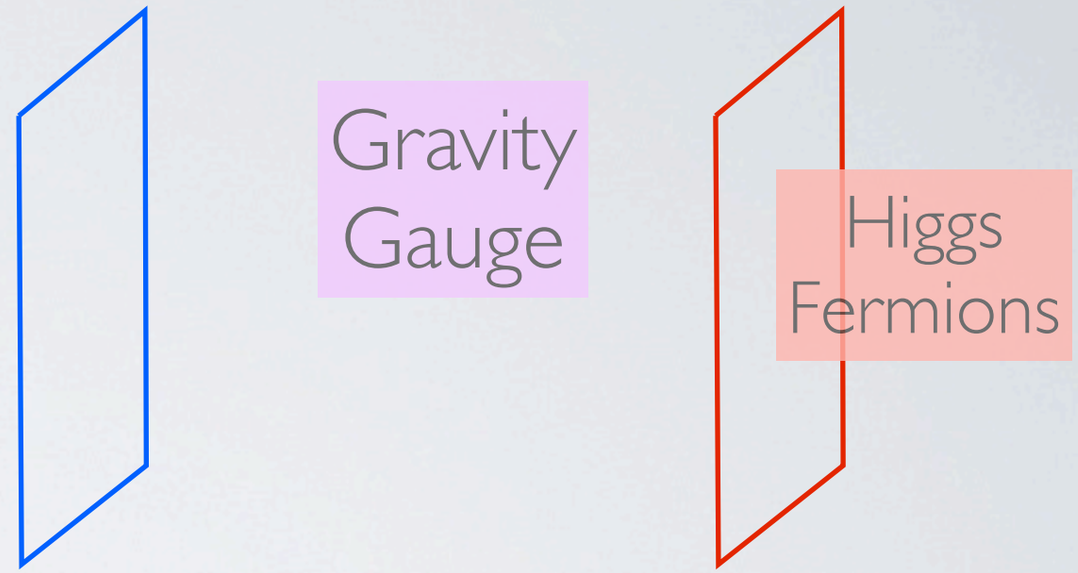
Higgs can be moved to the bulk (but not arbitrarily much)



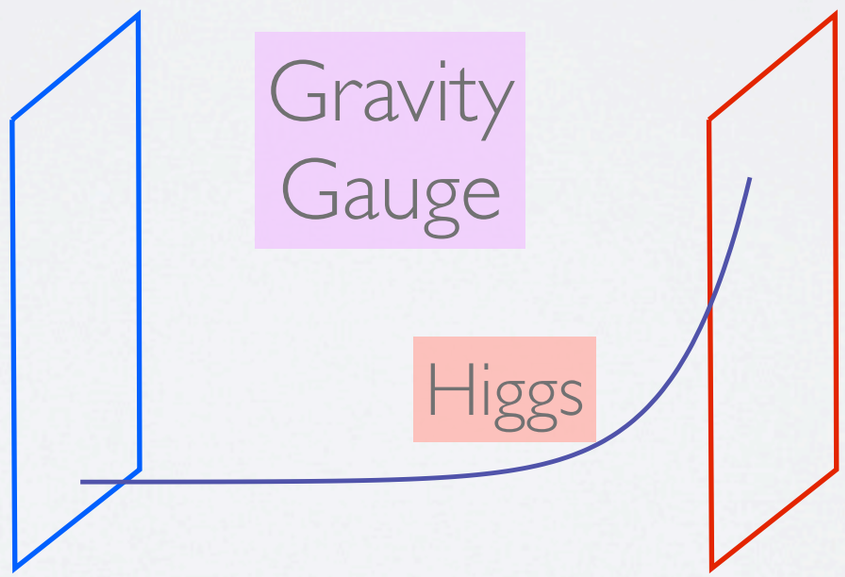
$$\int_0^{y_1} e^{-2ky} h^2(y)$$ needs to be IR dominated

MODEL VARIANTS





Higgs can be moved to the bulk (but not arbitrarily much)



Fermions can be anywhere (even UV brane)

$$\int_0^{y_1} e^{-2ky} h^2(y)$$ needs to be IR dominated

NEW PHYSICS STATES

RS models predict:

- KK gravitons at LHC
- Light scalar mode (Radion), fluctuations of volume
- KK modes of other fields, notably spin-1 (KK gluons)

CONSTRAINING NEW PHYSICS

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{C_i}{\Lambda^2}\mathcal{O}_i^{d=6}$$

CONSTRAINING NEW PHYSICS

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{C_i}{\Lambda^2}\mathcal{O}_i^{d=6}$$

LEP measurements

FIT

Coefficients of dim 6 operators

CONSTRAINING NEW PHYSICS

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{C_i}{\Lambda^2}\mathcal{O}_i^{d=6}$$

LEP measurements → FIT → Coefficients of dim 6 operators

In particular oblique corrections

$$\mathcal{O}_S = H^\dagger W_{\mu\nu} H B^{\mu\nu}$$

$$\mathcal{O}_T = |H^\dagger D_\mu H|^2$$

CONSTRAINING NEW PHYSICS

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{C_i}{\Lambda^2}\mathcal{O}_i^{d=6}$$

LEP measurements → FIT → Coefficients of dim 6 operators

In particular oblique corrections

$$\mathcal{O}_S = H^\dagger W_{\mu\nu} H B^{\mu\nu}$$

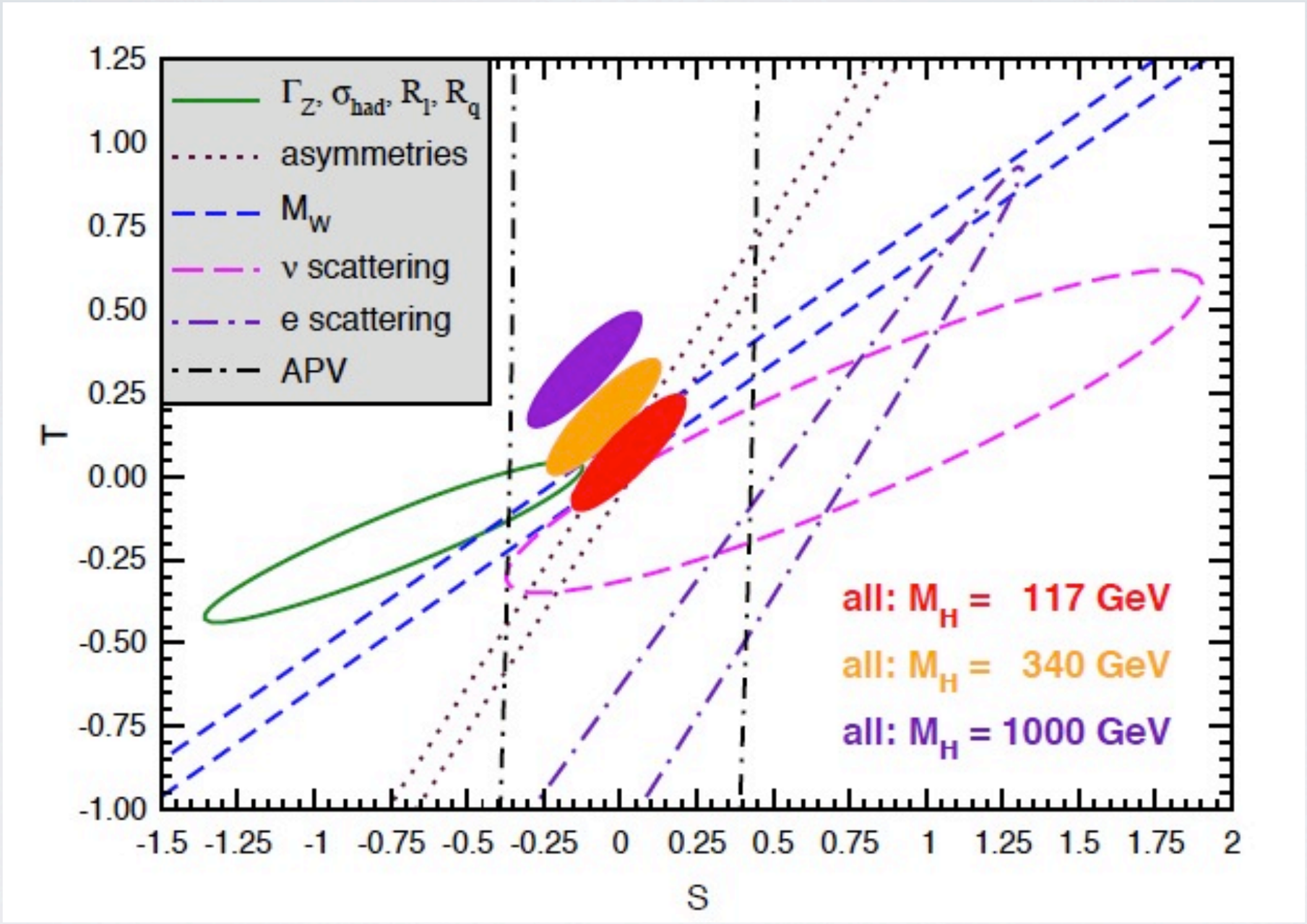
$$\mathcal{O}_T = |H^\dagger D_\mu H|^2$$

$$\mathcal{O}_Y = (\partial_\mu B_{\nu\sigma})^2$$

$$\mathcal{O}_W = (D_\mu W_{\nu\sigma})^2$$

See, e.g., Barbieri et al '04

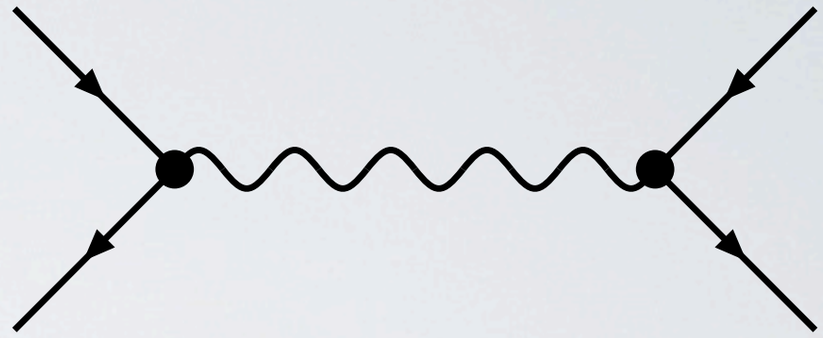
THE S - T ELLIPSE



PDG 2010

RS - EFFECTIVE THEORY

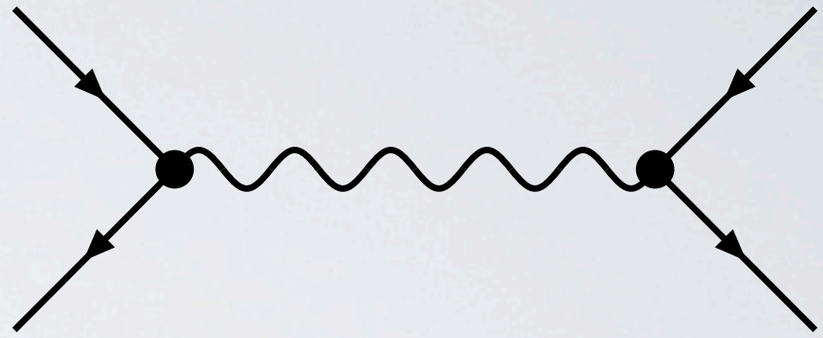
Integrating out KK modes
creates these operators



$$\alpha S \sim \frac{m_W^2}{m_{KK}^2} \qquad \alpha T \sim \frac{m_W^2}{m_{KK}^2} y_1 \qquad (\alpha T = \rho - 1)$$

RS - EFFECTIVE THEORY

Integrating out KK modes
creates these operators



$$\alpha S \sim \frac{m_W^2}{m_{KK}^2} \qquad \alpha T \sim \frac{m_W^2}{m_{KK}^2} y_1 \qquad (\alpha T = \rho - 1)$$

◇ T is parametrically enhanced and provides dominant bounds on KK scale

◇ Best available bounds within RS

$m_{KK} > 7$ TeV

Chang et al '99
Davoudiasl et al '99
Huber + Shafi '00

Cabrer, GG, Quiros '10

CUSTODIAL SYMMETRY

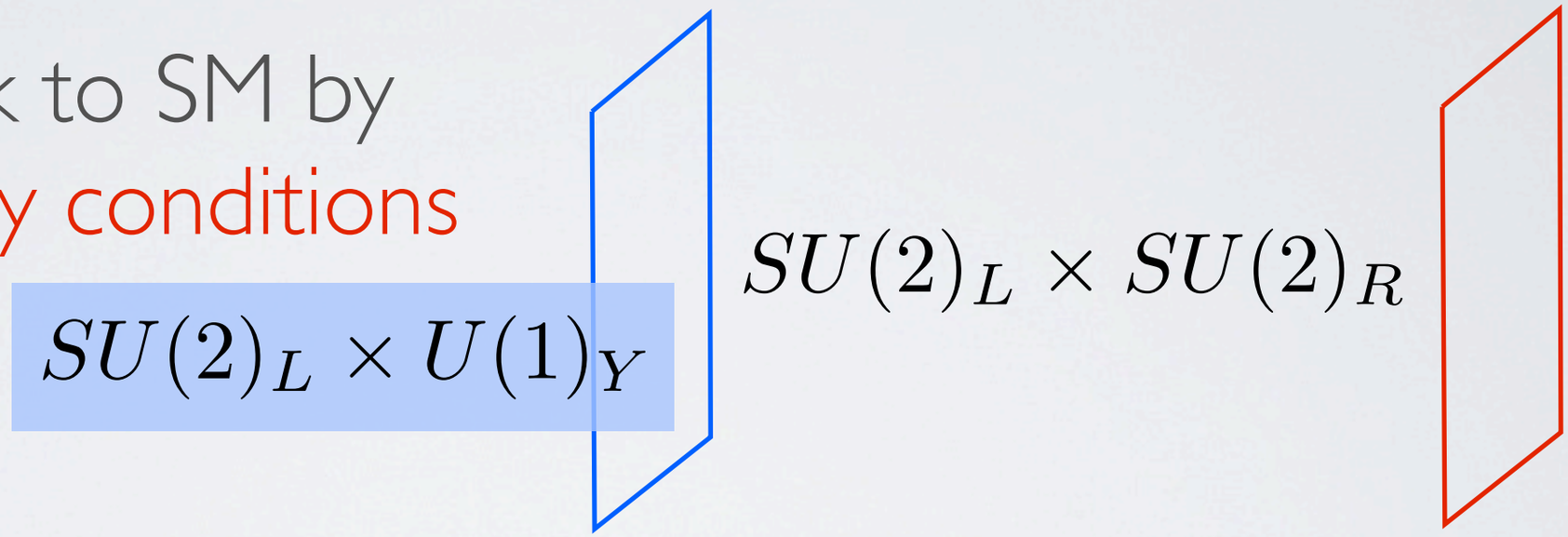
CUSTODIAL SYMMETRY

Extend gauge sector: $U(1)_Y \subset SU(2)_R \; [\times U(1)_X]$ Agashe et al 2003

CUSTODIAL SYMMETRY

Extend gauge sector: $U(1)_Y \subset SU(2)_R \; [\times U(1)_X]$ Agashe et al 2003

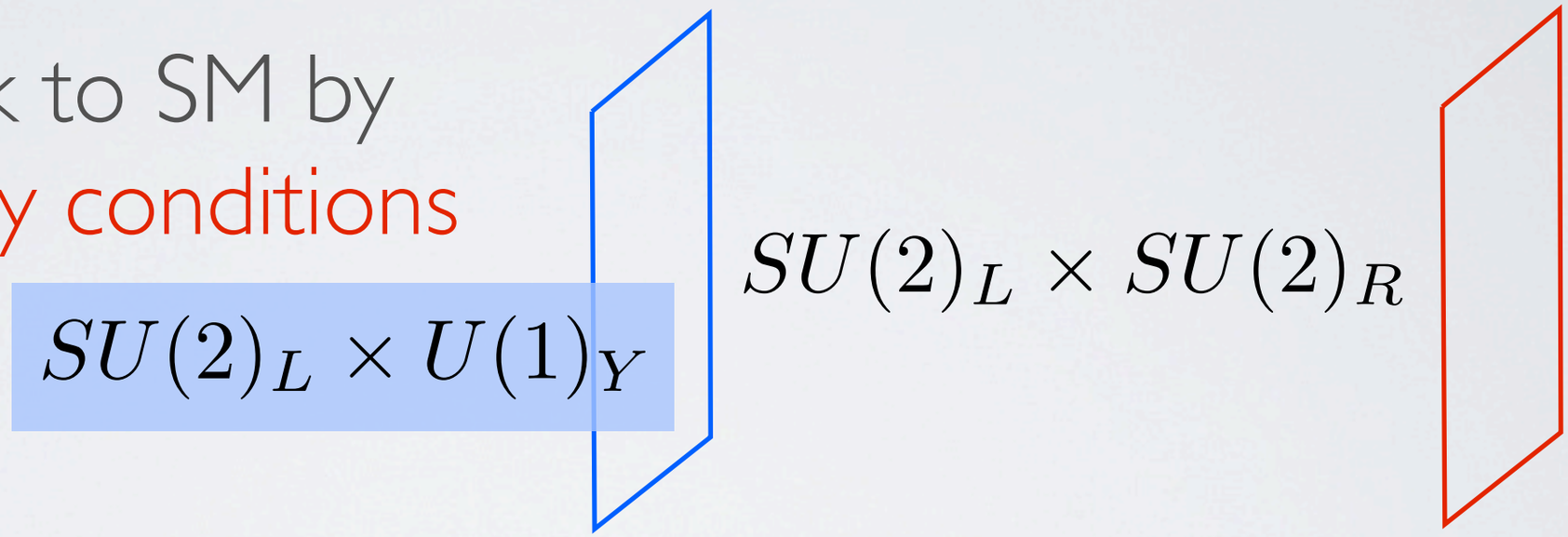
Then break to SM by
UV boundary conditions



CUSTODIAL SYMMETRY

Extend gauge sector: $U(1)_Y \subset SU(2)_R \; [\times U(1)_X]$ Agashe et al 2003

Then break to SM by
UV boundary conditions



- Zero modes: only SM gauge fields
- KK modes: complete $SU(2)_L \times SU(2)_R$ multiplets
- Custodial Symmetry kills T at tree level
- Dominant bounds from S: $m_{KK} > 2\text{-}3$ TeV

MODELS BASED ON CS

MODELS BASED ON CS

Models with brane or bulk Higgs
(based on SO(4))
(composite Higgs model)

Agashe et al 2003
Carena et al 2006

MODELS BASED ON CS

Models with brane or bulk Higgs
(based on SO(4))
(composite Higgs model)

Agashe et al 2003
Carena et al 2006

Gauge-Higgs unification models
(based on SO(5)/SO(4) etc)
(Higgs as a composite Pseudo-Nambu-Goldstone boson)

Agashe, Contino, Pomarol 2004
Carena et al 2006
Contino, Pomarol, da Rold 2006

MODELS BASED ON CS

Models with brane or bulk Higgs
(based on SO(4))
(composite Higgs model)

Agashe et al 2003
Carena et al 2006

Gauge-Higgs unification models
(based on SO(5)/SO(4) etc)
(Higgs as a composite Pseudo-Nambu-Goldstone boson)

Agashe, Contino, Pomarol 2004
Carena et al 2006
Contino, Pomarol, da Rold 2006

Brout-Englert-Higgsless models (breaking by boundary conditions)
(based on SO(4)/SO(3))
(large N_C Technicolor-like)

Csaki et al 2003

MODELS WITHOUT CS

Large IR Brane Kinetic Terms
- Calculability an issue

Davoudiasl, Hewett, Rizzo 2002
Carena et al 2002

Little RS models
- Reduce volume such that T is reduced
- Only generates Hierarchy ~ 10^3 - 10^4

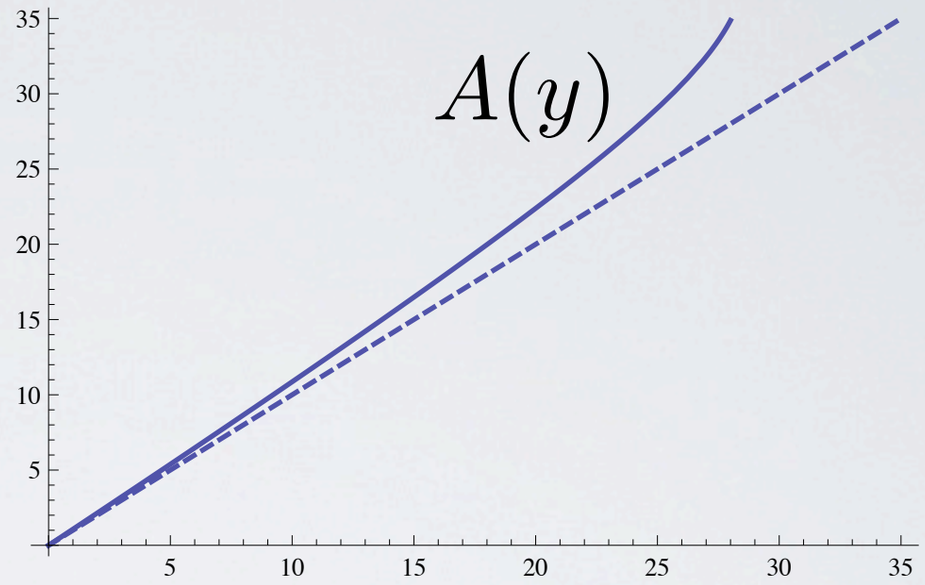
Davoudiasl, Perez, Soni 2008

Metric Deformations...

Cabrer, GG, Quiros 2010

METRIC DEFORMATIONS

Modified Warping creates large WFR for bulk Higgs



$$\mathcal{L}_{eff} = Z|D_\mu H|^2 - V(H) + S\, H^\dagger W_{\mu\nu} H B^{\mu\nu} + T|H^\dagger D_\mu H|^2$$

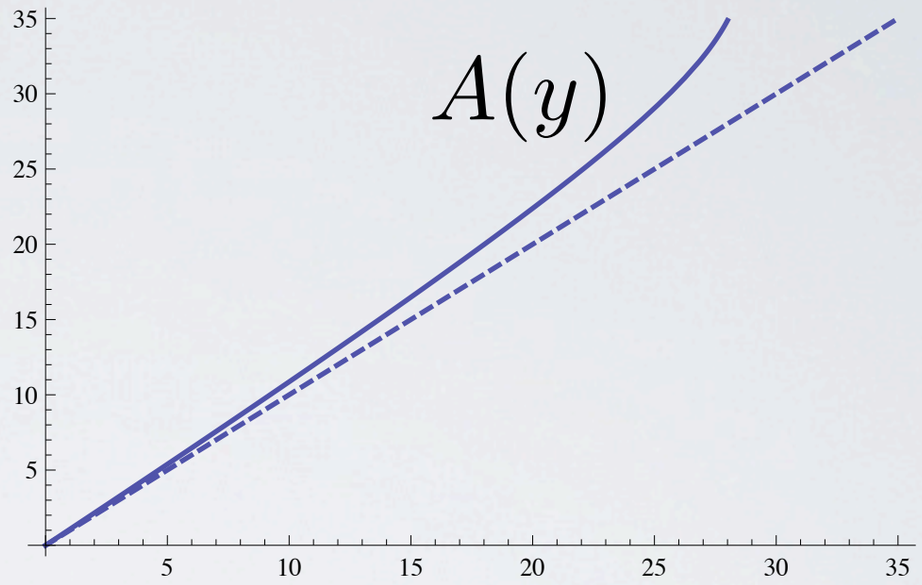
2 powers of H

4 powers of H

Falkowski + Perez Victoria 2008
Cabrer, GG, Quiros 2010

METRIC DEFORMATIONS

Modified Warping creates large WFR for bulk Higgs



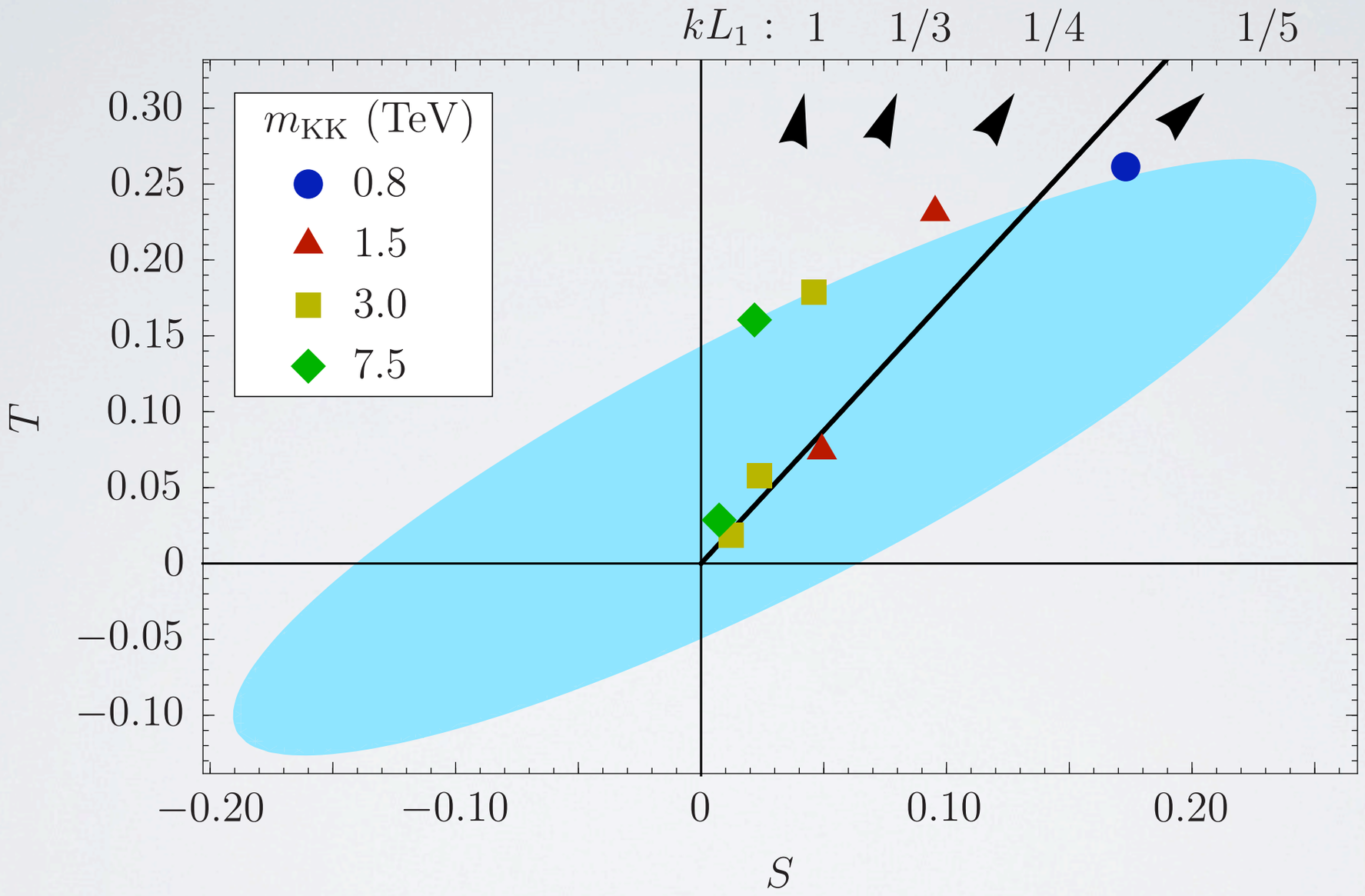
$$\mathcal{L}_{eff} = |D_\mu H|^2 - V(\frac{H}{Z^{\frac{1}{2}}}) + \frac{S}{Z} H^\dagger W_{\mu\nu} H B^{\mu\nu} + \frac{T}{Z^2} |H^\dagger D_\mu H|^2$$

2 powers of H

4 powers of H

Falkowski + Perez Victoria 2008
Cabrer, GG, Quiros 2010

METRIC DEFORMATIONS



Cabrer, GG, Quiros 2011

CONCLUSIONS

- A warped fifth Dimensions can explain electroweak scale.
- Distinctive collider signature (KK-gravitons, KK gluons, Radion)
- Electroweak precision test require some protection mechanism (custodial symmetry, metric deformations, or rather large KK scale)

FLAT SPACE MODELS

FLAT SPACE MODELS

In flat space (no warping), IR scale is given by the volume:

IR ~ TeV

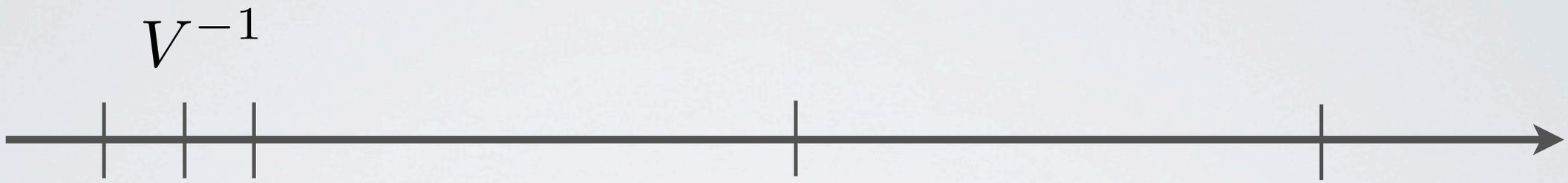
UV ~ 10^{18} GeV

FLAT SPACE MODELS

In flat space (no warping), IR scale is given by the volume:

IR ~ TeV

UV ~ 10^{18} GeV

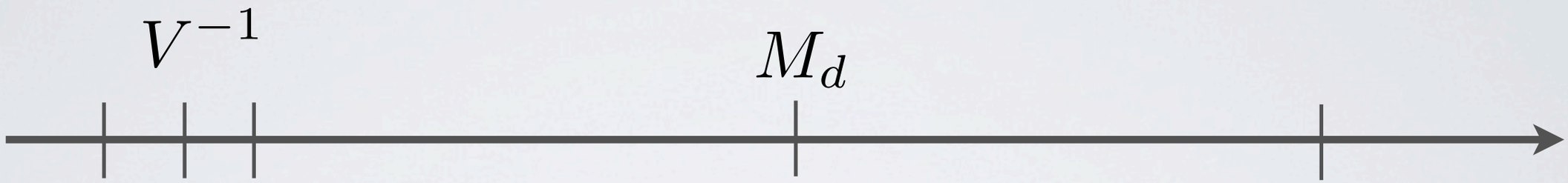


FLAT SPACE MODELS

In flat space (no warping), IR scale is given by the volume:

IR ~ TeV

UV ~ 10^{18} GeV

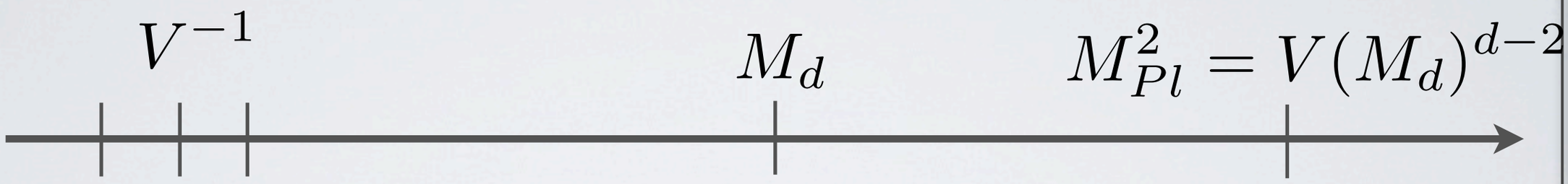


FLAT SPACE MODELS

In flat space (no warping), IR scale is given by the volume:

IR ~ TeV

UV ~ 10^{18} GeV

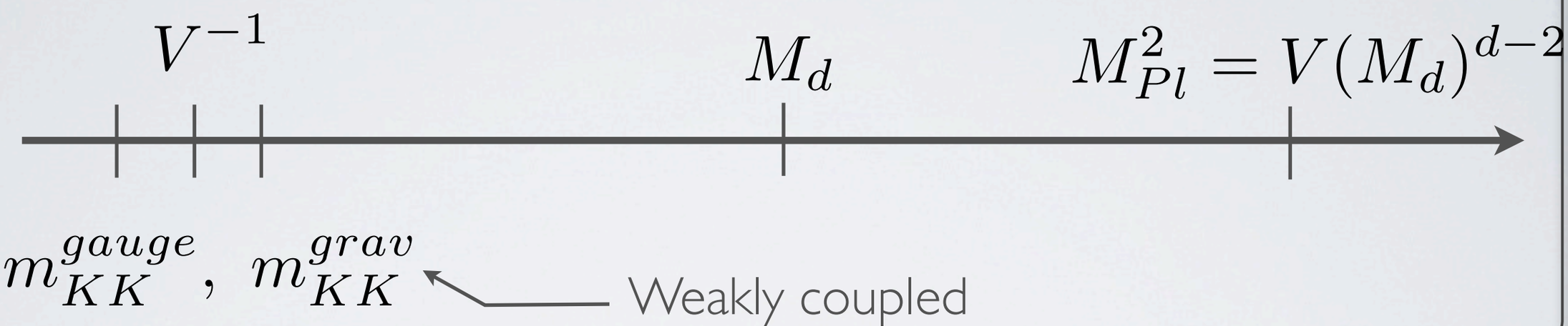


FLAT SPACE MODELS

In flat space (no warping), IR scale is given by the volume:

IR ~ TeV

UV ~ 10^{18} GeV



FLAT SPACE MODELS

In flat space (no warping), IR scale is given by the volume:

IR ~ TeV

UV ~ 10^{18} GeV

V^{-1} M_d $M_{Pl}^2 = V(M_d)^{d-2}$

m_{KK}^{gauge} , m_{KK}^{grav} ← Weakly coupled

IR scale "put by hand" BUT can be made stable in the context of gauge-Higgs unification:

Manton '79, Hosotani '83, Antoniadis et al '01,.....

$A_M \to A_\mu$, A_i

- Embed Higgs in gauge bosons
- Gauge invariance forbids mass terms
- Finite radiative pot. controlled by volume!