RS in LHC Era
KK modes and Radion

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CERN, Aug, 2011

Outline

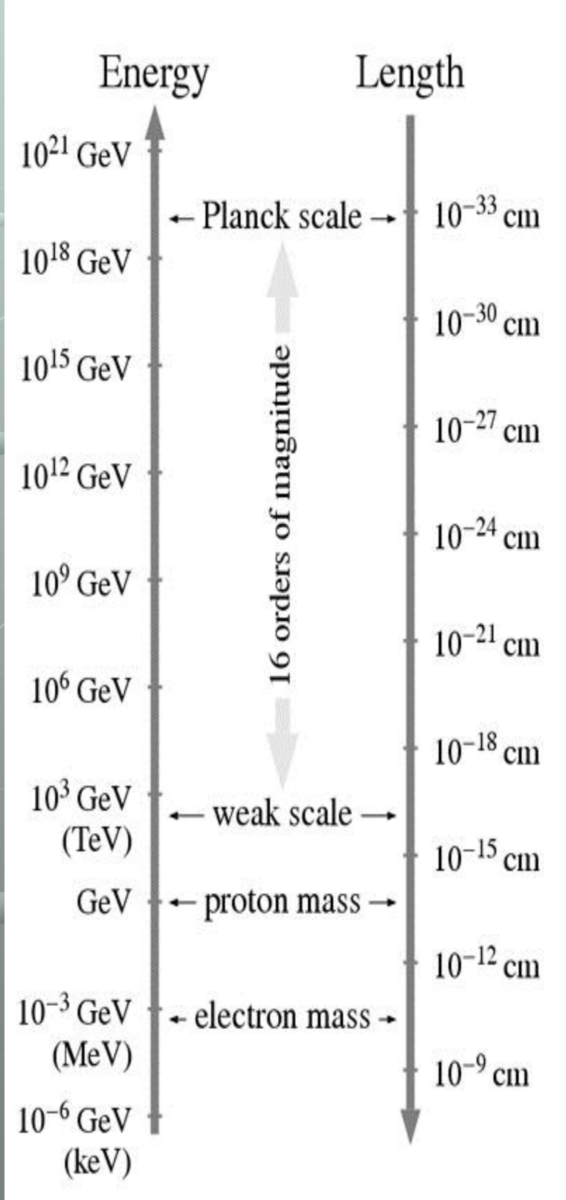
- "Review"
- KK modes in brane RS
  - Wide resonances
- KK modes in bulk RS
- Comment on compositess
- Radions
- Comment on RS Higgs

Hierarchy Problem

Need "fine-tuning" to get very different masses

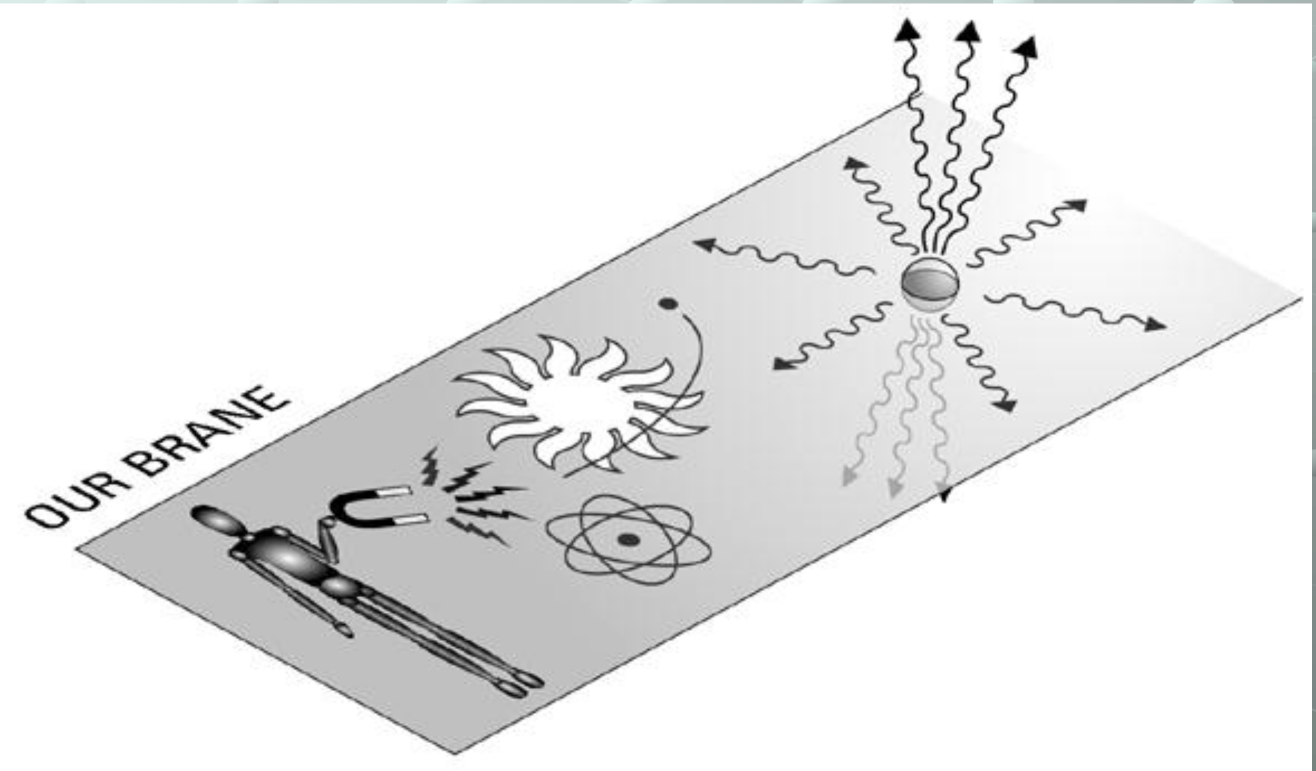
Key issue in particle physics today

One that will be resolved at LHC



Braneworld

Higher-dimensional world in which particles and matter are stuck on a brane



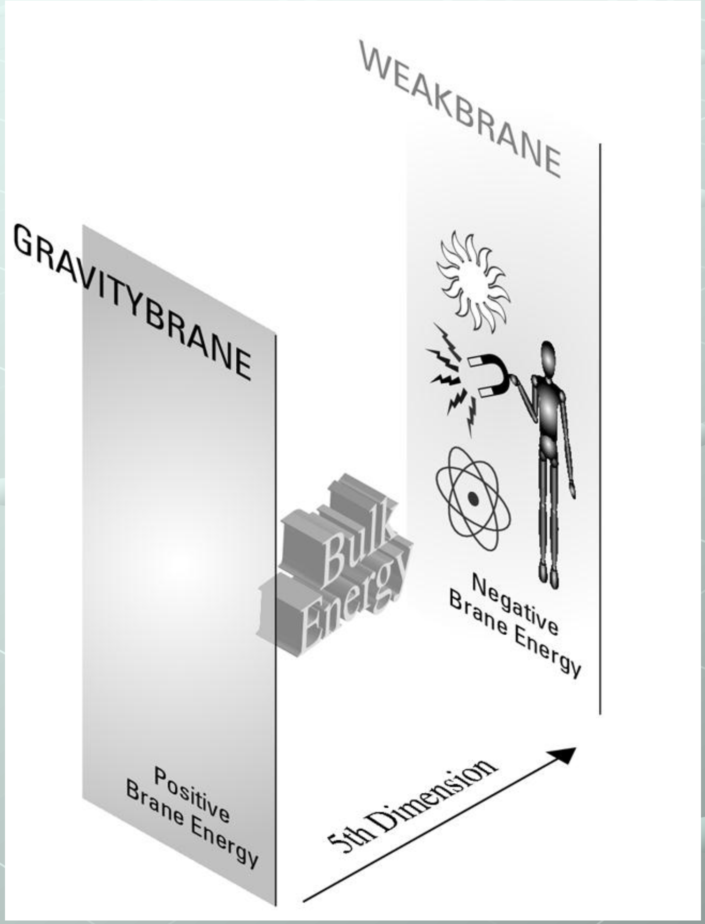
Drawn as 2D

Really 3D

And really

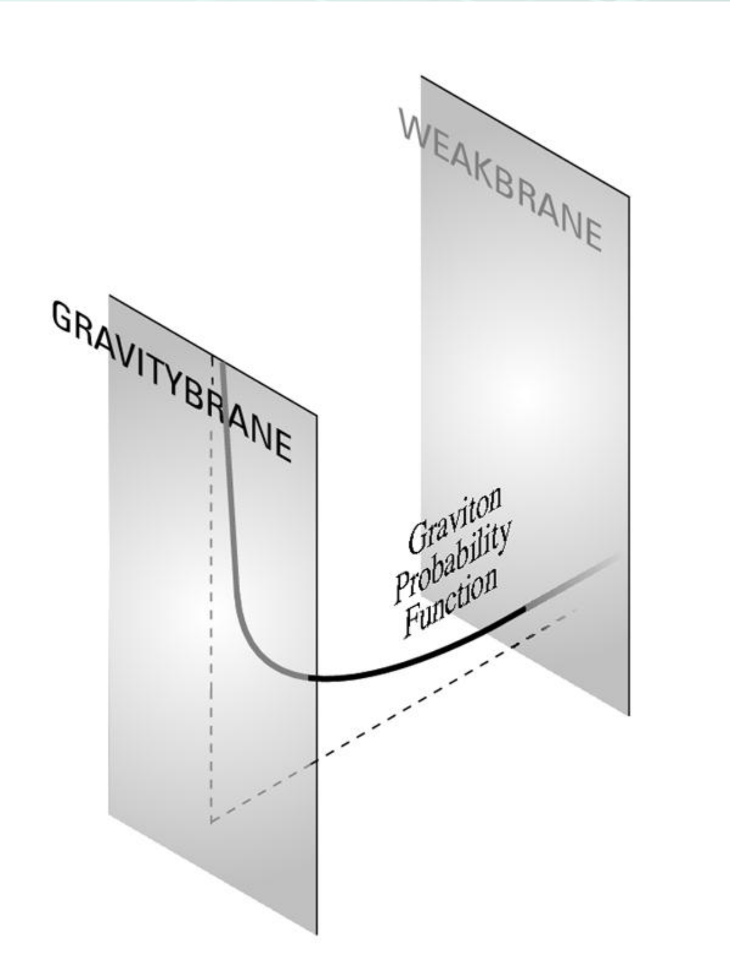
infinite

RS1 “Multiverse:”
Warped Spacetime Geometry



- Two branes
- Gravity will be concentrated on Gravitybrane
- But we live on a second brane:
  - Keep in mind brane versus bulk localized
- The Weakbrane/TeV Brane

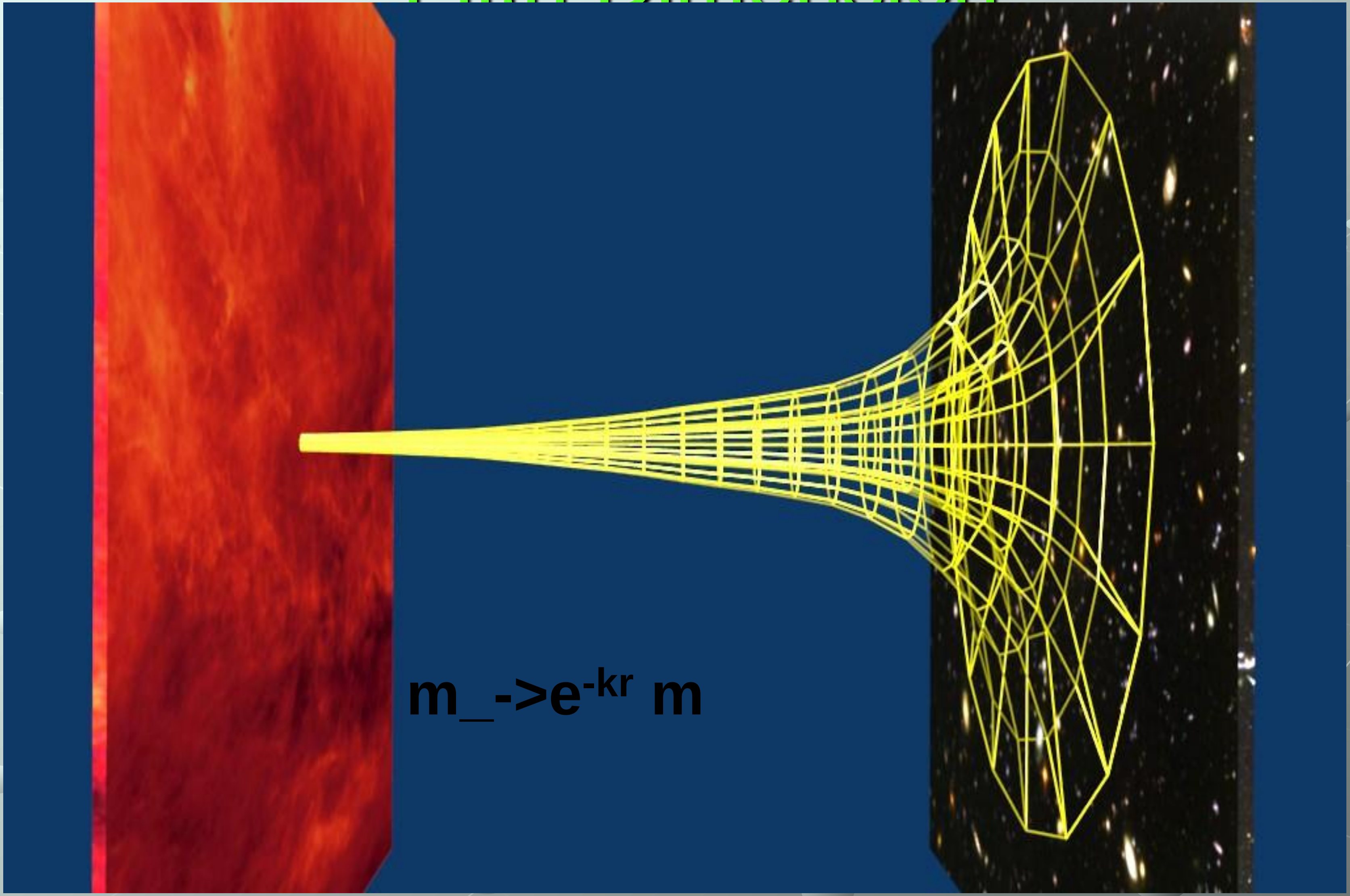
Natural for gravity to be weak!



- Small probability for graviton to be near the Weakbrane
- If we live anywhere but the Gravitybrane, gravity will seem weak
- Natural consequence of warped geometry

$$ds^2 = g_{MN} dx^M dx^N = e^{-2\sigma} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2 ,$$

Keep in mind rescaling across Fifth Dimension



KK Particles: Weak Scale Fingerprints [Experimental Signatures] of Extra Dimensions

- With extra dimensions, there are new Kaluza-Klein (KK) particles
- We find TeV modes localized on weak brane
- Have "warped" gravitational interaction
- 1/TeV scale graviton interaction with Standard Model particles

KK modes

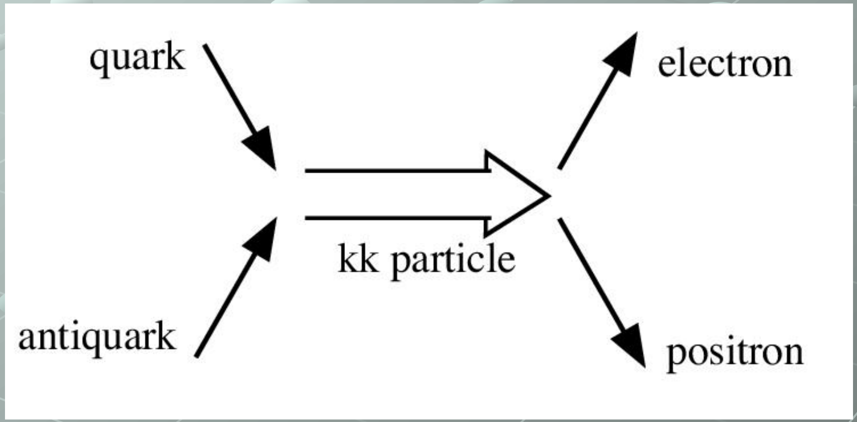
- Find modes at every mass scale
- However essentially linearly quantized in multiples of k within mass range of order m
- That is (m/k) modes in our vicinity
- To us theory looks strongly interacting at TeV
- (not true for full 5d theory)

KK modes of graviton

- In RS1, KK spectrum very distinctive
- TeV, 2 TeV, 3 TEV (rough) spectrum
- With much stronger than gravitational interaction strength!
- Interaction strength is warped too!
- Not $1/M_P$
- Instead, 1/TeV

Experimental Signal: resonances

- Kaluza-Klein particles
- Definite mass spectrum and "spin"-2
  - Truly different than other strongly interacting theories
  - Light spin-2 but gap
  - No other strongly interacting states as light



- If you produce a KK mode of the gravition
- Not just missing energy
- Mode decays inside detector—just like most other heavy particles we hope to discover
- Means we can reconstruct mass, spin (we hope!)
  - Would be first genuine signature of quantum gravity
  - Graviton itself too weakly interacting to detect directly
  - Not true for its KK modes!

Search for Resonances

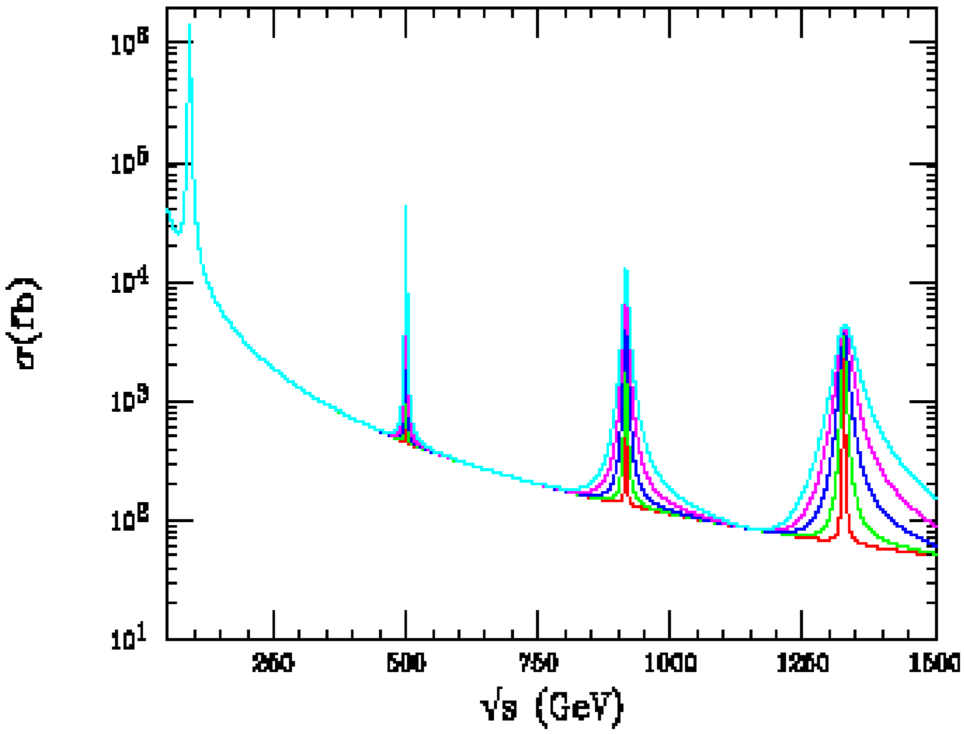
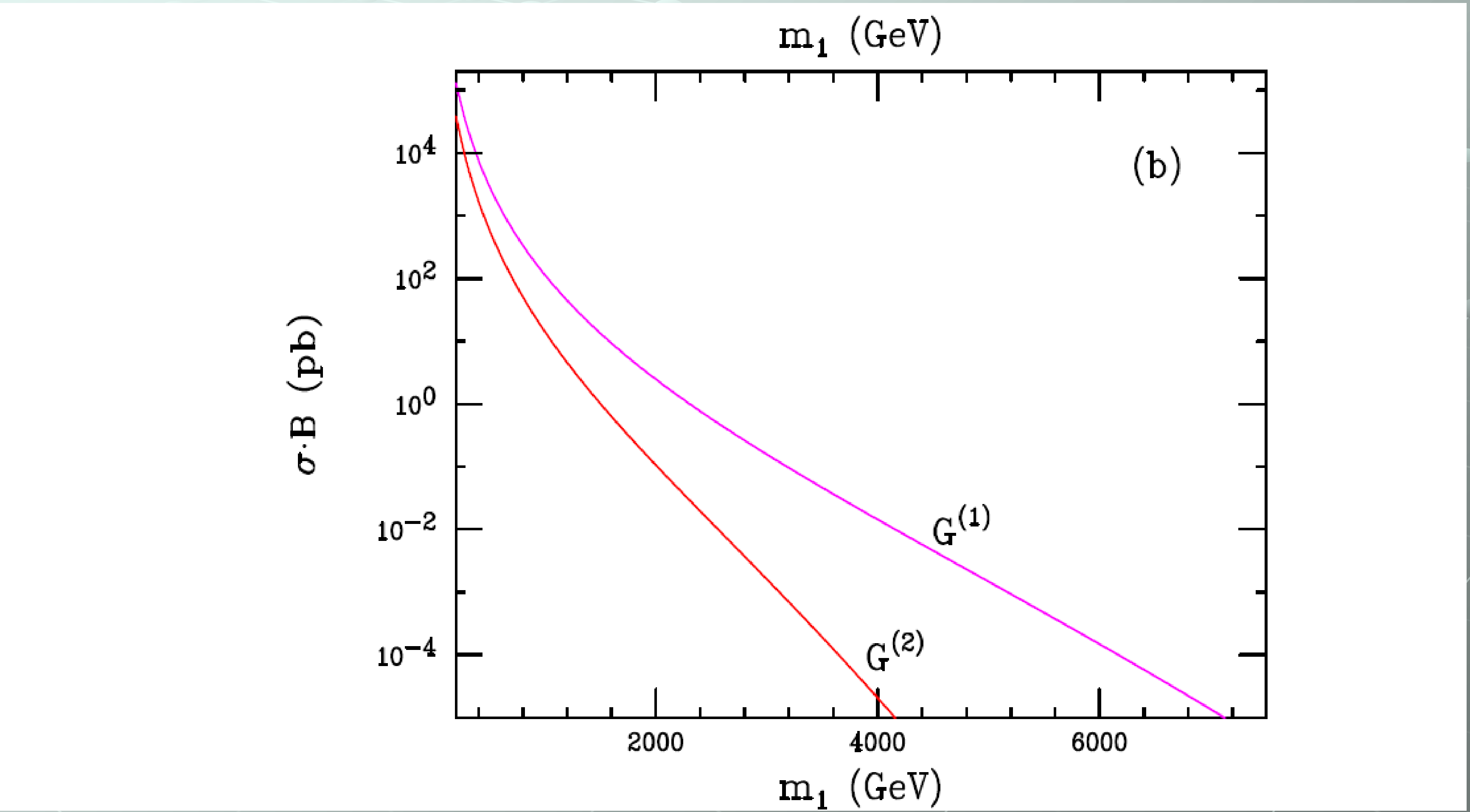


Figure 4: The cross section for $e^+e^- \to \mu^+\mu^-$ including the exchange of a KK tower of gravitons in the Randall-Sundrum model with $m_1 = 500$ GeV. The curves correspond to $k/\overline{M}_{Pl} =$ in the range 0.01 – 0.05.

H. Davoudiasl, J. Hewett, T. Rizzo

Reach for Graviton KK Modes

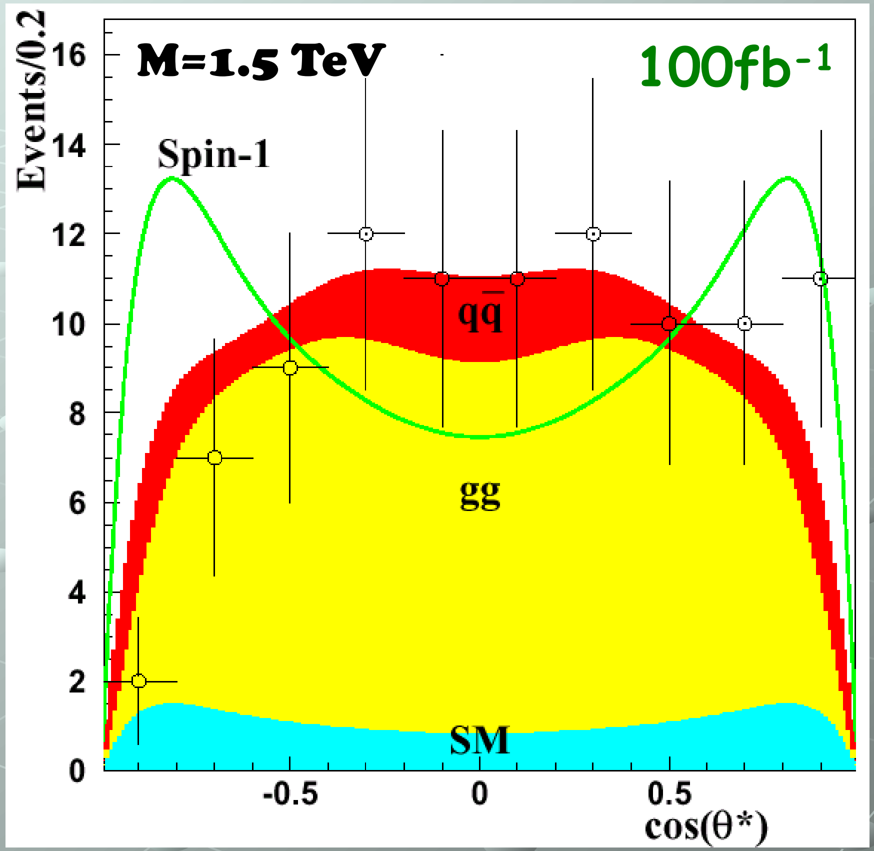


Davoudiasl, Hewett, Rizzo

graviton has spin 2

Angular distributions

- $qq \to G \to ff$: $1 - 3\cos^2\theta + 4\cos^4\theta$
- $gg \to G \to ff$: $1 - \cos^4\theta$
- $qq \to G \to VV$: $1 - \cos^4\theta$
- $gg \to G \to VV$: $1 + 6\cos^2\theta + \cos^4\theta$
- DY background: $1 + \cos^2\theta$



Easier than spin measurement

LR, M Wise

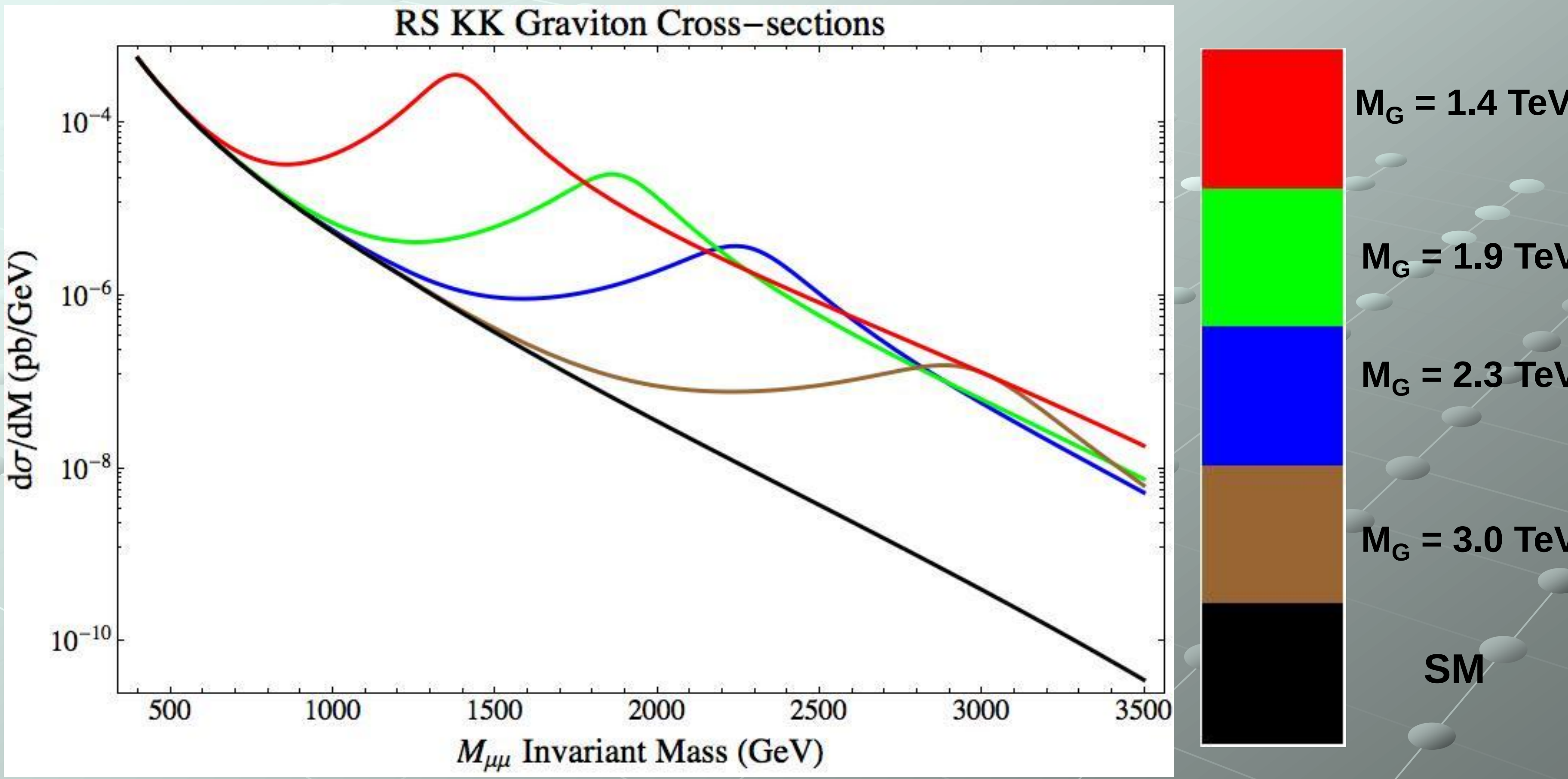
- Measure BR ($\gamma\gamma$)
- And BR (e+ e-) or (μ+ μ-)
- Ratio factor of 2
- Difficult to explain unless coupled to energy-momentum tensor
- On general principles, don't even expect sizable BR to both
  - Unless leptons composite

Of interest now:
Wide Resonances

LR, Brian Shuve, Randall Kelly

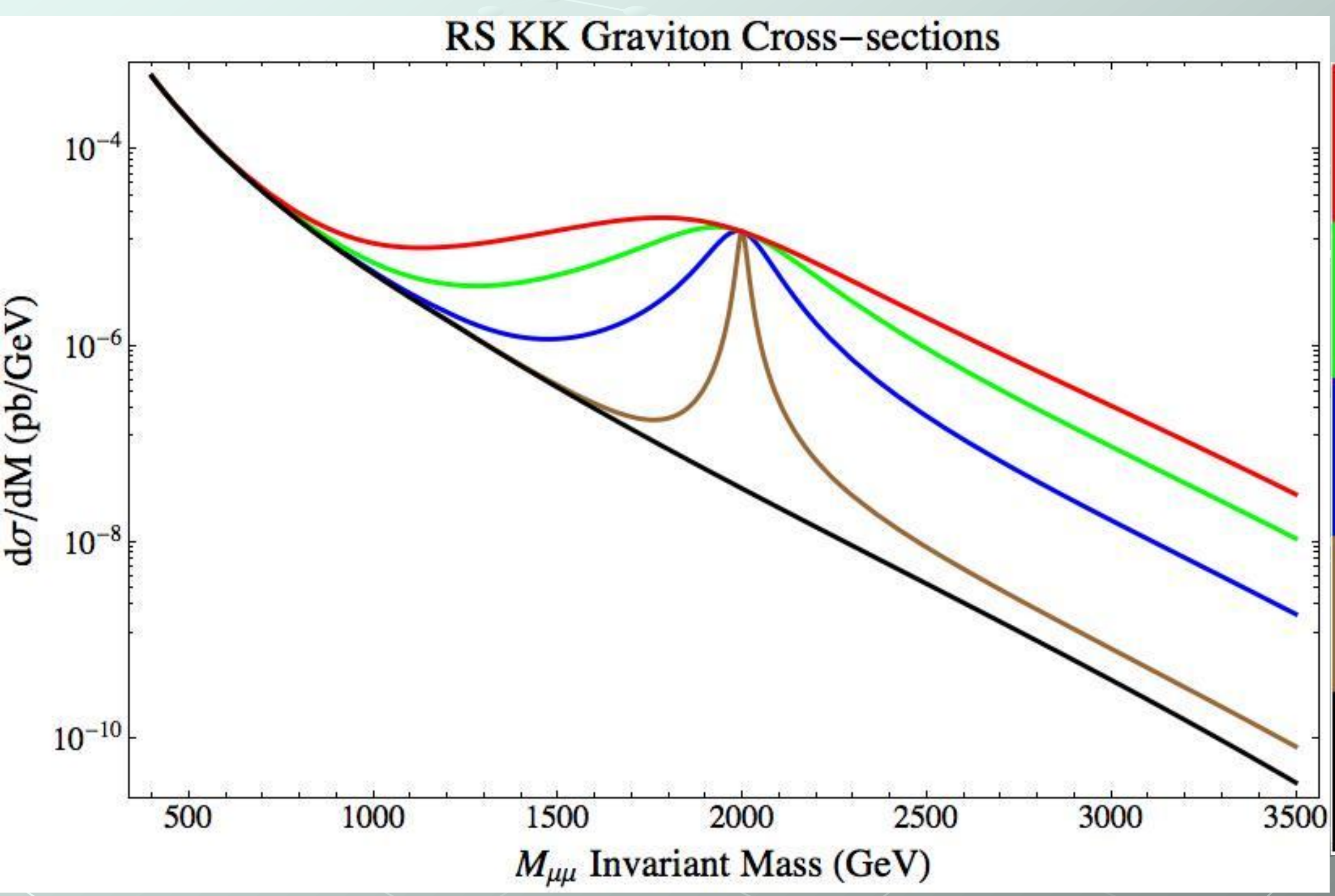
- Resonances will be first and simplest place to look
- Particularly Drell-Yan processes with decays to muons
  - Background well understood
  - Low background at high invariant mass
- Useful for models
  - Z'
  - RS
  - Understanding detector and experiment reach

RS X-sections (varying mass)



$k/M_{Pl} = 0.35$

RS X-sections (varying k/M_{Pl})



$k/M_{Pl} = 0.55$

$k/M_{Pl} = 0.4$

$k/M_{Pl} = 0.25$

$k/M_{Pl} = 0.1$

SM

$M_G = 2$ TeV

On vs Off Resonance

On peak:

$$\hat{\sigma}(M_g^2) \sim \frac{1}{M_g^2}.$$

Off peak-need to integrate against parton distribution
Estimate using narrow width.

$$\frac{1}{(\hat{s} - M_g^2)^2 + M_g^2\Gamma^2} \approx \frac{\pi}{M_g\Gamma}\delta(\hat{s} - M_g^2)$$

$$\sigma \sim \frac{(k/M_{Pl})^2}{s}\frac{d\mathcal{L}}{d\tau}(M_g^2, s).$$

Favors wide states, large k/M, Resonance mass through luminosity

Wide Resonances

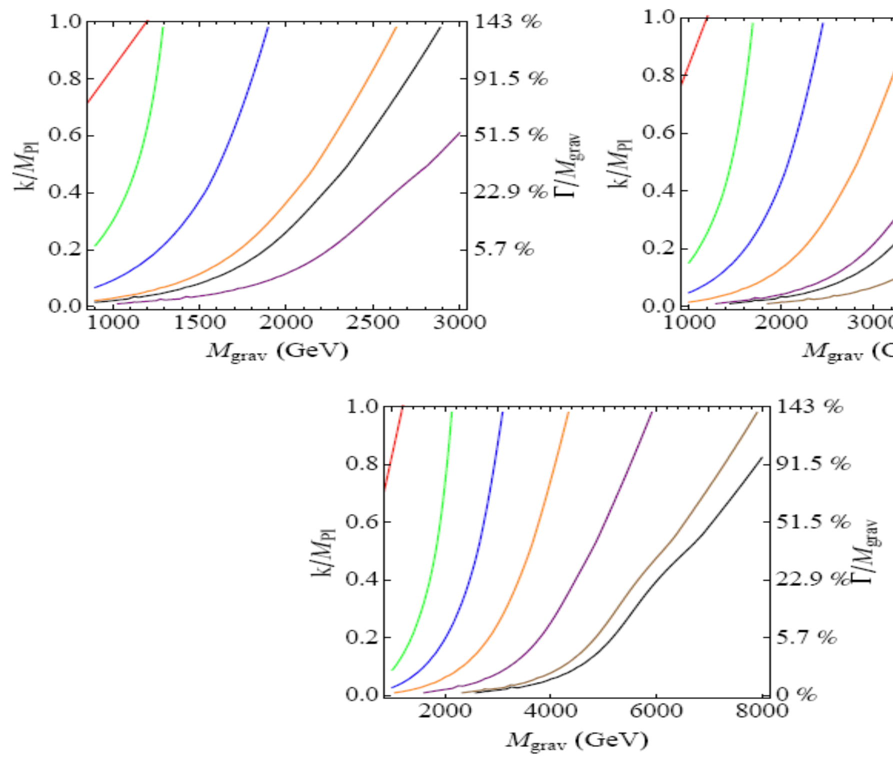


Figure 2: Plots showing contours of constant cross section for the first KK mode of the graviton in RS models as a function of the curvature $k/M_{\rm Pl}$. The width of the corresponding resonance is also shown. The cross sections are shown for $\sqrt{s} = 7$ TeV (left), 10 TeV (center), and 14 TeV (right). Legend: green is 1 pb, blue is 100 fb, orange is 10 fb, purple is 1 fb, brown is 100 ab. The black curve indicates the cross section for 5 events at certain benchmark luminosities: 1 fb^{-1} at 7 TeV, 10 fb^{-1} at 10 TeV, and 100 fb^{-1} at 14 TeV. The red lines are bounds from

- Understand reach of various LHC parameters
- Better than Tevatron when
  - Higher masses
  - Resonances from glue-glue initial state
  - Wide resonances
    - Especially important since large coupling gives bigger rate
- When can we see resonances?
- When can we distinguish them from contact interactions?
- Can we learn about nature of interaction that produced resonance?

Focus

- *Shape* of distribution
- For much of parameter space can distinguish broad resonance from featureless falling distribution (SM or SM +contact)
- Simple: look for "upturn" or absolute rise in rate
- More sophisticated statistical analysis
  - Use both excess events in some bins and absence in others

– Binned maximum likelihood analysis

Sample Results

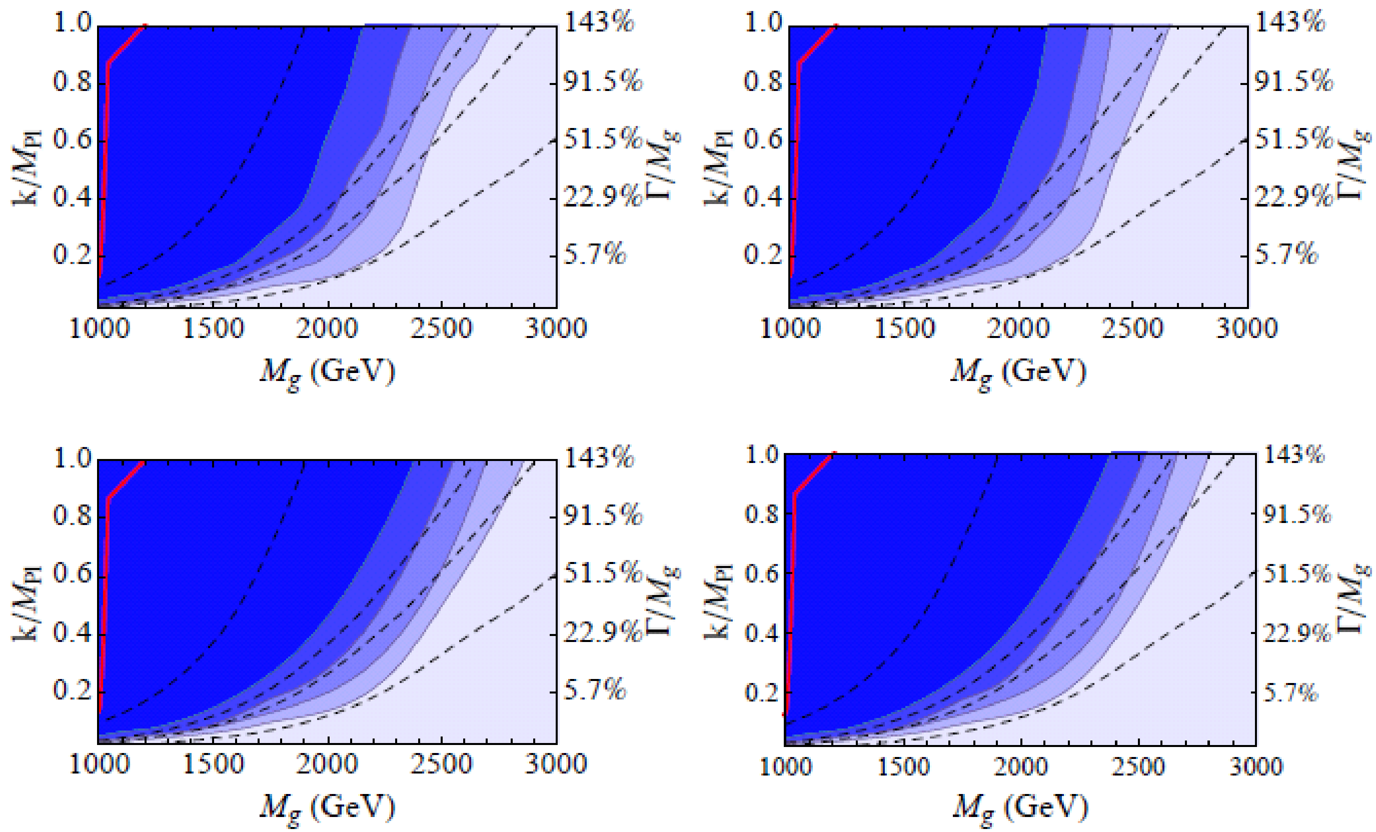


Figure 10: Reliability of distinguishing RS resonance at 95% confidence level from VV destructive (top left), LL destructive (top right), VV constructive (bottom left), and LL constructive contact interactions. The shaded regions, from darkest to lightest, show regions with reliability: > 99%, 90-99%, 70-90%, 50-70%, < 50%. Excluded regions are to the left of the solid red line, while the dashed lines show cross sections: 100 fb (top), 10 fb, 5 fb, 1 fb (bottom).

Electron Photon too of course

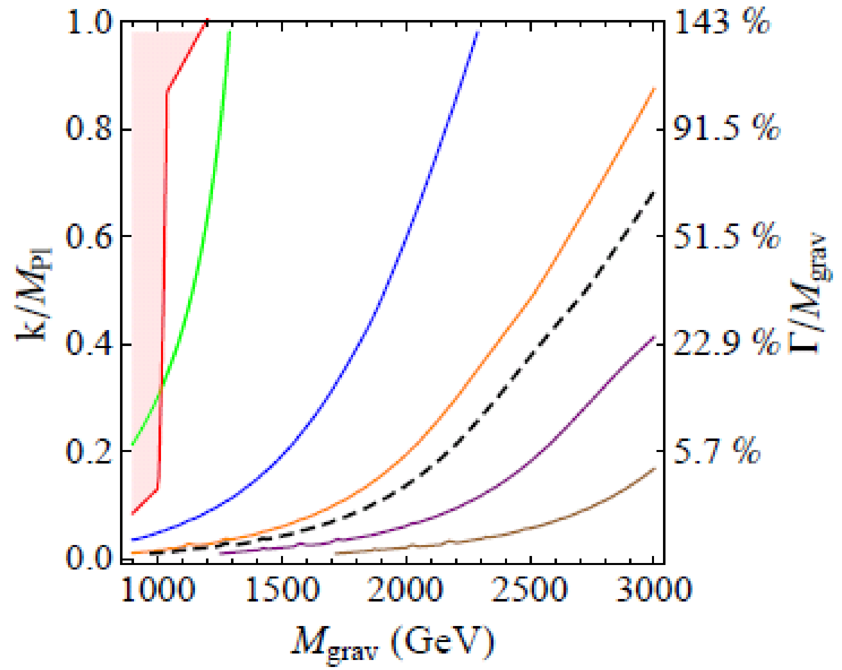


Figure 12: Plots showing dimuon cross section for the first KK mode of the graviton in RS models (to muons, electrons, and photons) at $\sqrt{s} = 7$ TeV. Legend: green is 1 pb, blue is 100 fb, orange is 10 fb, purple is 1 fb. The black curve indicates the cross section for 5 events.

Can we learn more?

- Seems reasonable event rate
- And distinguishable
- We’ve considered total cross section and distribution with energy so far
- With enough statistics, angular information can also prove valuable

- In particular, can distinguish parity-violating interactions
- SM interactions violate parity whereas new physics does not necessarily

Pseudorapidity distribution

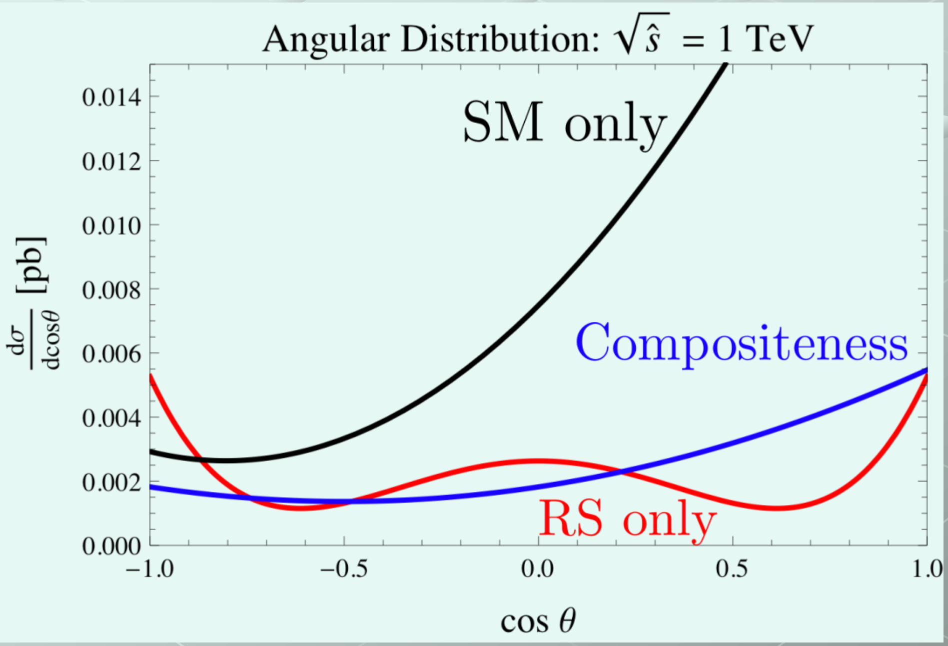
partonic: $u\bar{u} \to \mu^- \mu^+$

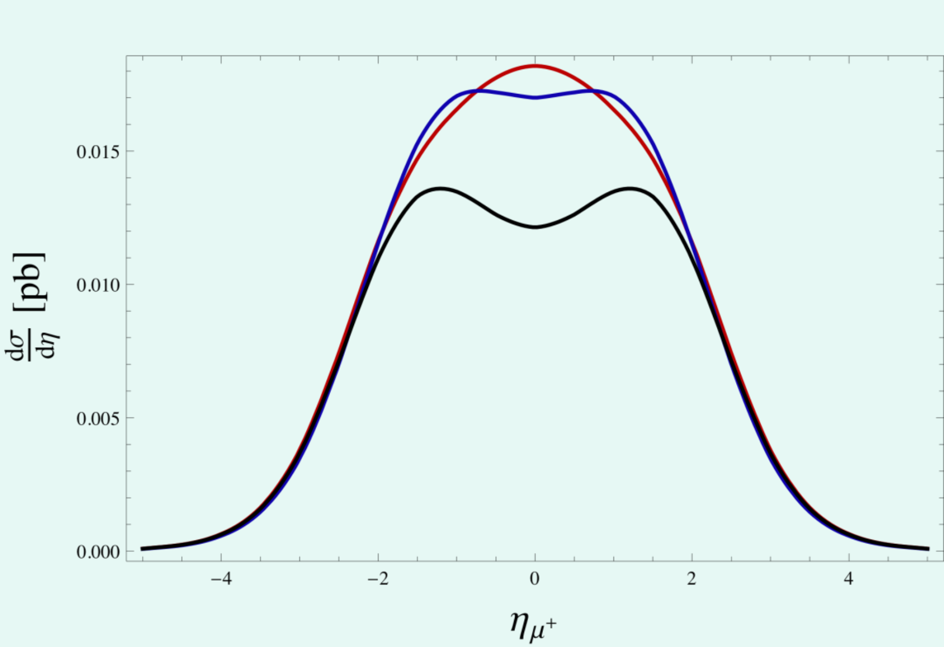
differential in $\cos\theta$

hadronic: $pp \to \mu^- \mu^+$

differential in η

$$\eta = -\ln\left(\tan\frac{\theta}{2}\right)$$

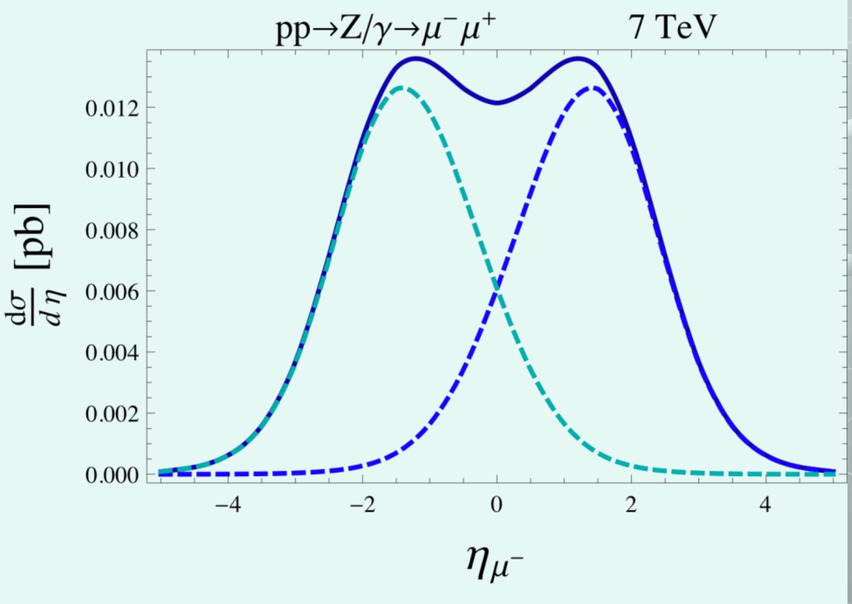




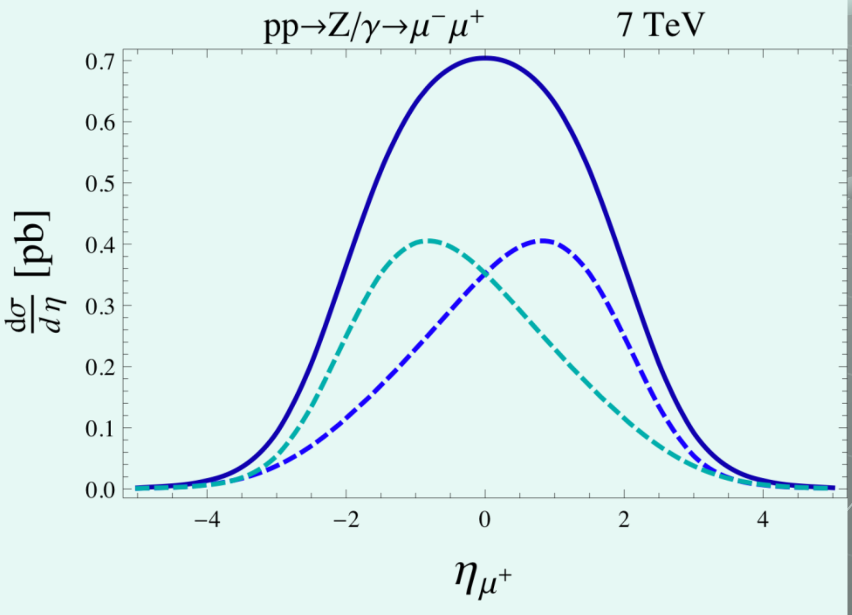
Interpretation

- Muon preferentially forward (wrt quark) due to parity violating SM interactions
- Quark has on average more momentum (larger x) therefore boosted more forward
- Large η, small θ, large cos θ
- Sum curves and get the McD curve
- Wider with less hard invariant mass cut

RS model



pp→Z/γ→μ⁻μ⁺ 7 TeV
$\frac{d\sigma}{d\eta}$ [pb]
0.012
0.010
0.008
0.006
0.004
0.002
0.000
−4
−2
0
2
4
η_{μ^-}



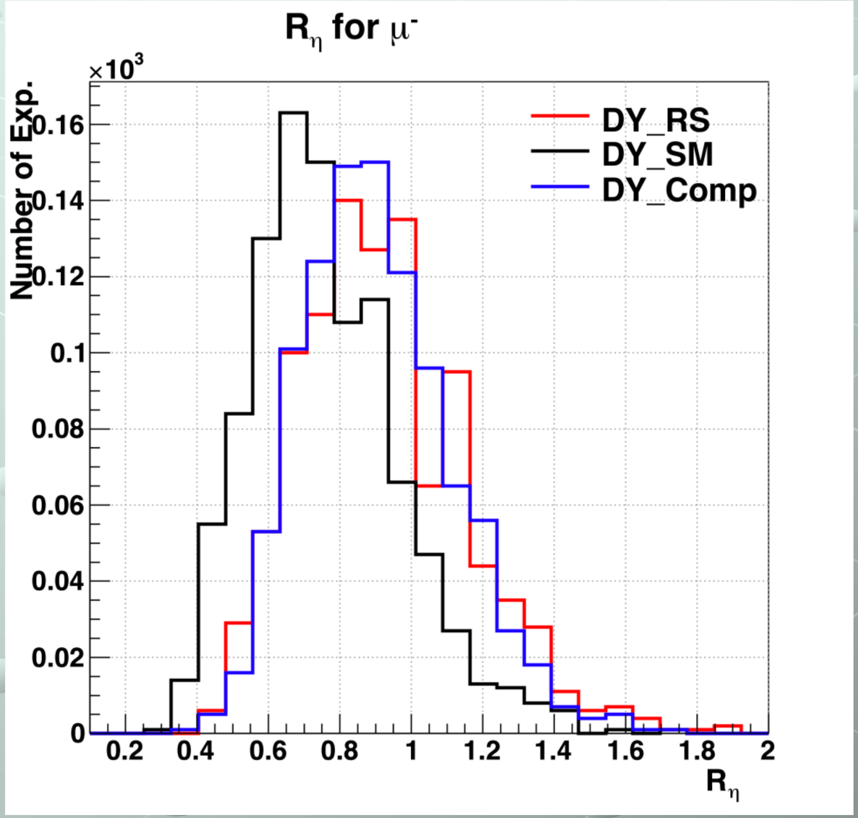
pp→Z/γ→μ⁻μ⁺ 7 TeV
$\frac{d\sigma}{d\eta}$ [pb]
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
−4
−2
0
2
4
η_{μ^+}

Ellipticity

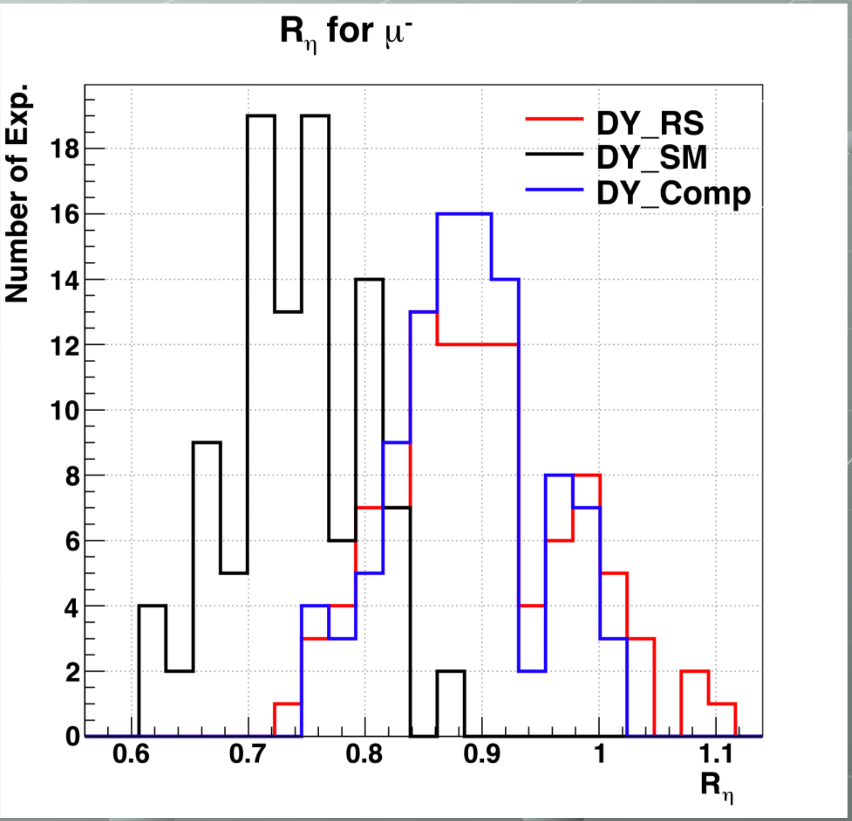
$$E_\eta = \frac{\left[\int_{-x}^{x} - \left(\int_{-\eta_{\max}}^{-x} + \int_{x}^{\eta_{\max}}\right)\right] d\eta^- \frac{d\sigma}{d\eta^-}}{\int_{-\eta_{\max}}^{\eta_{\max}} d\eta^- \frac{d\sigma}{d\eta^-}},$$

Separation of Distributions in Ellipticity

$1\ \text{fb}^{-1}$



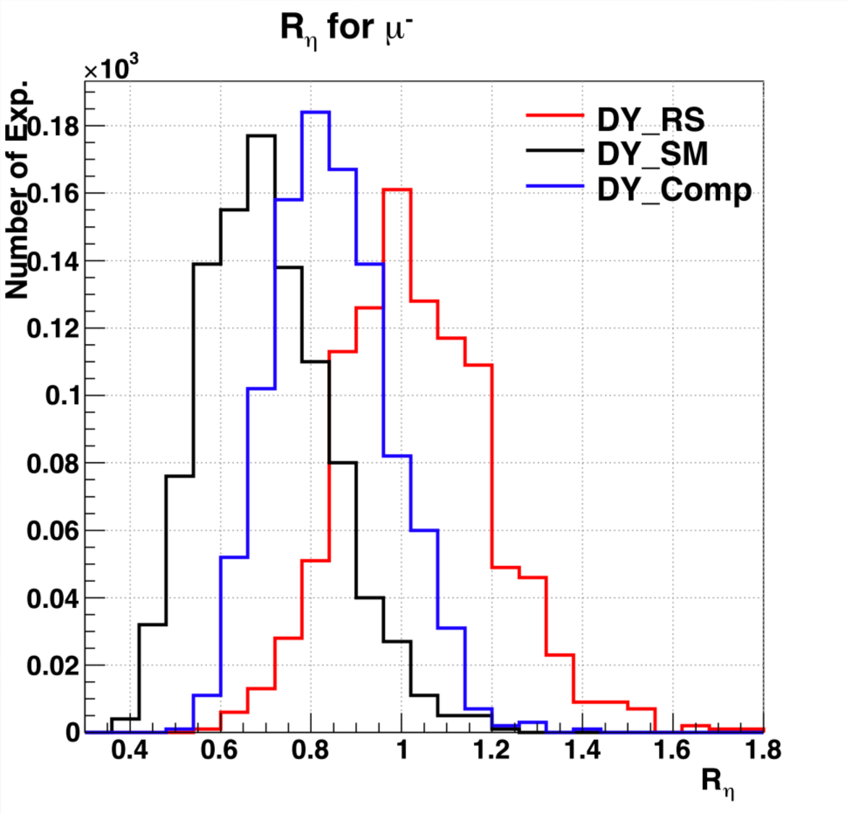
$10\ \text{fb}^{-1}$



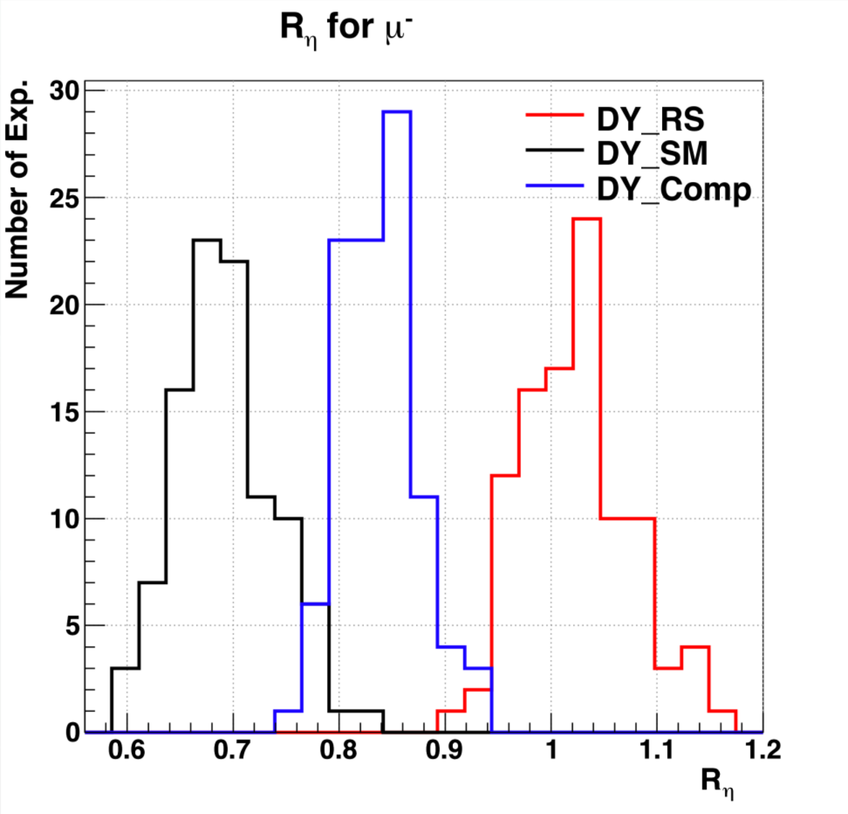
Better at Higher Energy

$$E_{cm} = 10\ \mathrm{TeV}$$
$$k/M_{\mathrm{pl}} = 0.1$$
$$M_{\mathrm{g}} = 1300\ \mathrm{GeV}$$
$$\Lambda = 6250\ \mathrm{GeV}$$

$1\ \mathrm{fb}^{-1}$



$10\ \mathrm{fb}^{-1}$



Wide Resonances

- ✓Large cross section
- ✓Distinctive shape wrt energy
- ✓Distinctive wrt pseudorapidity

- ✓Very promising

- RS1 gives clean TeV-KK-graviton signal
- Spin-2 or BR ratio and gap in spectrum definite indication of warped extra-dimensional geometry

Only question is how light modes should be

Unfortunately answer not very precise

Want to search for as heavy modes as we can

Also: Strongly interacting physics

- Lots of strongly interacting TeV-scale physics to complement this measurement

- if we are very lucky, other signs of strong gravity

Quantum Gravity/Compositeness

- Black holes not as "spectacular" as advertised

BUT

- Lots of information about quantum gravity buried in 2->2!
- Initial increase in rate for more central processes always occurs
- Could be related to fundamental partons in black holes?
- R behavior: bh, string resonances, different forms for string, Z' all distinctive
- Threshold behavior where interference matters
- Hadron vs. Lepton cross section

Other warped scenarios addressing the hierarchy?

- RS1 isn't the only scenario: variations interesting
- Depends on whether particles on brane or in bulk
- Two key features that make bulk matter possible
  - Size of fifth dimension extremely small (only about 30 times fundamental scale—exponential hierarchy)
    - Means coupling won't be too diluted/weak
  - You only need Higgs on the Weakbrane to address the hierarchy
    - Problem only for the Higgs scalar: gauge boson and fermion masses are protected

Suggests new scenarios

- Fermions and gauge bosons can be in the bulk
- Because **5D** cut-off is Planck scale
- ✓ Allows for unification!
- Allows for interesting model-building:
- ✓ Fermion masses from wavefunction overlap with Higgs field (on Weakbrane)
- Important because bulk scenarios have distinctive signatures
- Raise interesting challenges

Phenomenology?

- Bulk gauge bosons
- Means KK modes of
  - Weak bosons
  - Gluons
  - Fermions
  - As well as gravitons

Precise signatures depend on fermion wavefunction profiles

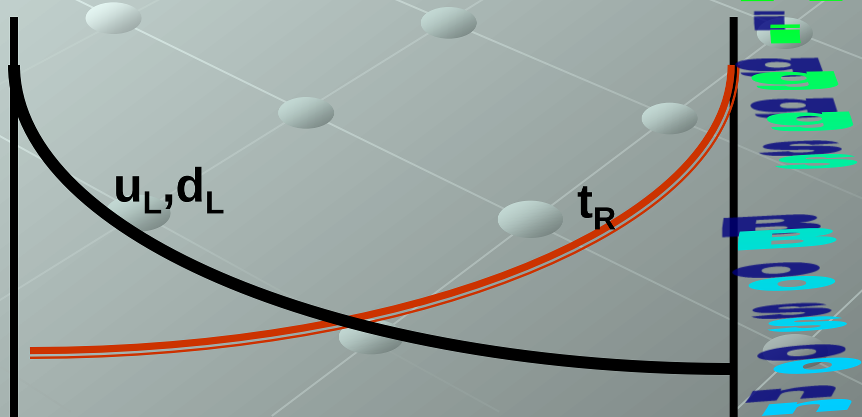
- Nontrivial profiles help solve flavor problem
- Masses depend on overlap with Higgs
- Expect light fermions localized near Planck/Gravity brane
- Top near Weakbrane since it's heavy

KK

d

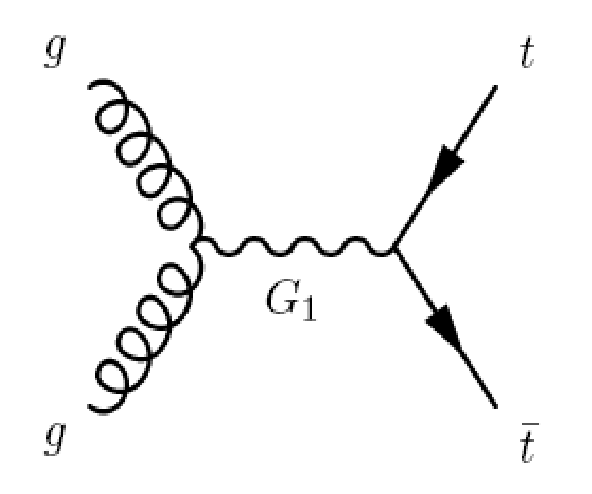
s

IR



Richer Spectrum… But Lower Production Cross Section for the Graviton

- Light quarks are localized away from Higgs
  - Hence away from TeV brane
  - No Drell-Yan production from quarks
- Gluons are spread throughout the bulk
  - Hence coupling to graviton down



w/LiamFitzpatrick,Jared Kaplan, Liantao Wang

KK Graviton Production

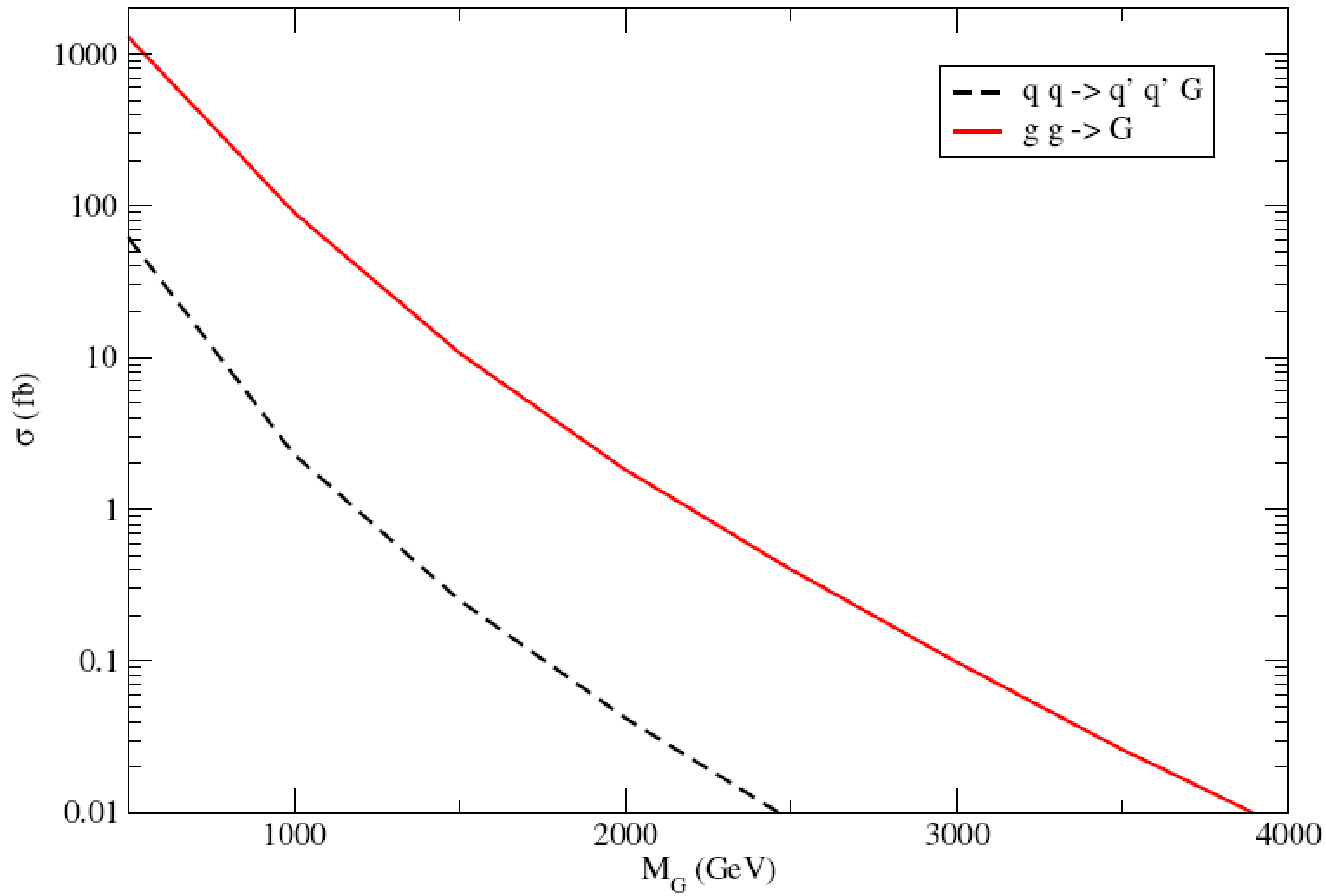


Figure 1: Cross section of KK-graviton production.

Final State? Dominant Decay to right-handed tops

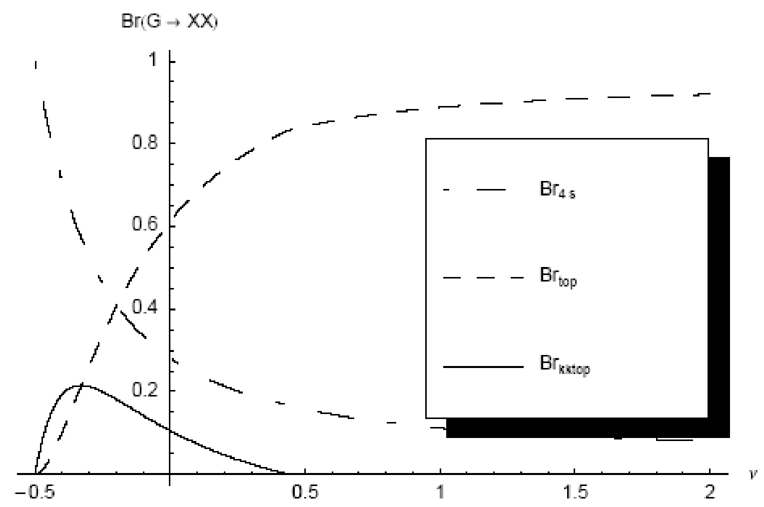
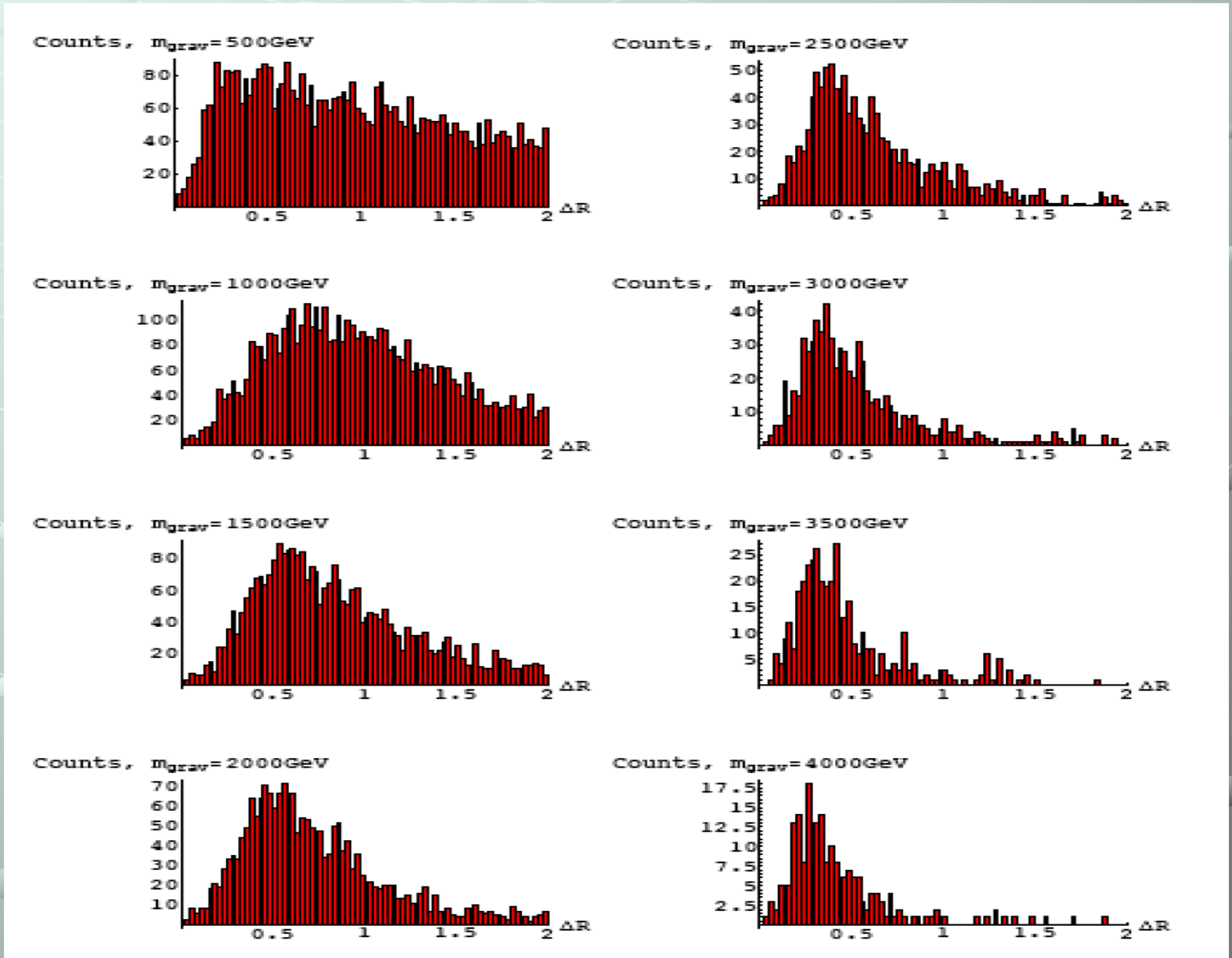
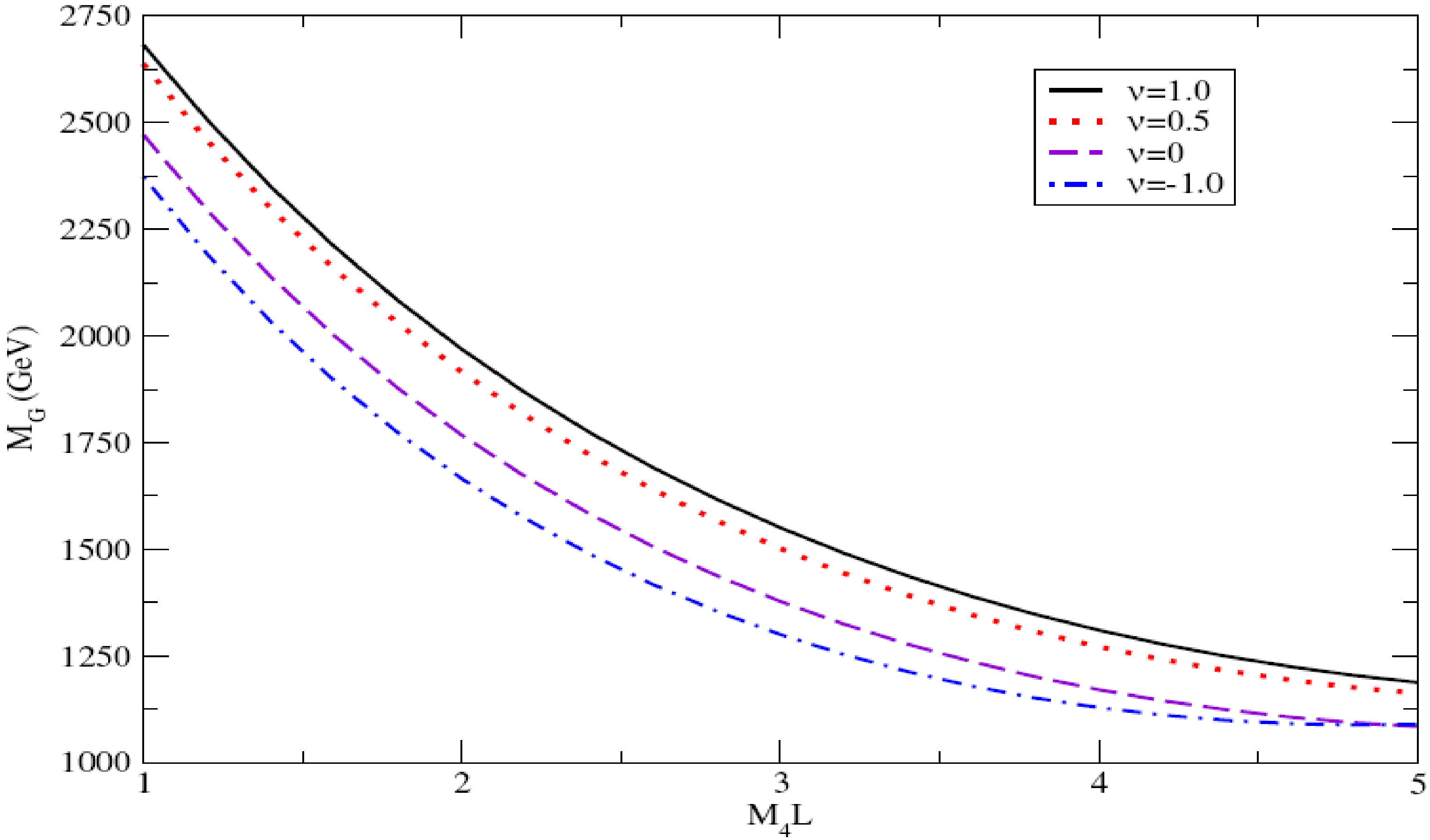


Figure 1: Branching Ratios for graviton decay to scalars and quarks.

$$\Gamma_{top} = \frac{1}{(M_4 L)^2 \mu_{TeV}^2} \left(\frac{1+2\nu}{1-e^{-\pi k r_c (1+2\nu)}} \frac{\int_0^1 dy\, y^{2+2\nu} J_2(3.83y)}{J_2(3.83)} \right)^2 \frac{3m_{grav}^3}{160\pi}$$

Determining top jets: delta R: Angle between decay products





3: The $s/\sqrt{b} = 5$ reach as a function of graviton mass and the parameter (M_4L). From
ach is shown for $\nu = 1.0, 0.5, 0.0, -0.1$.

Graviton: some reach Other Bulk Modes?

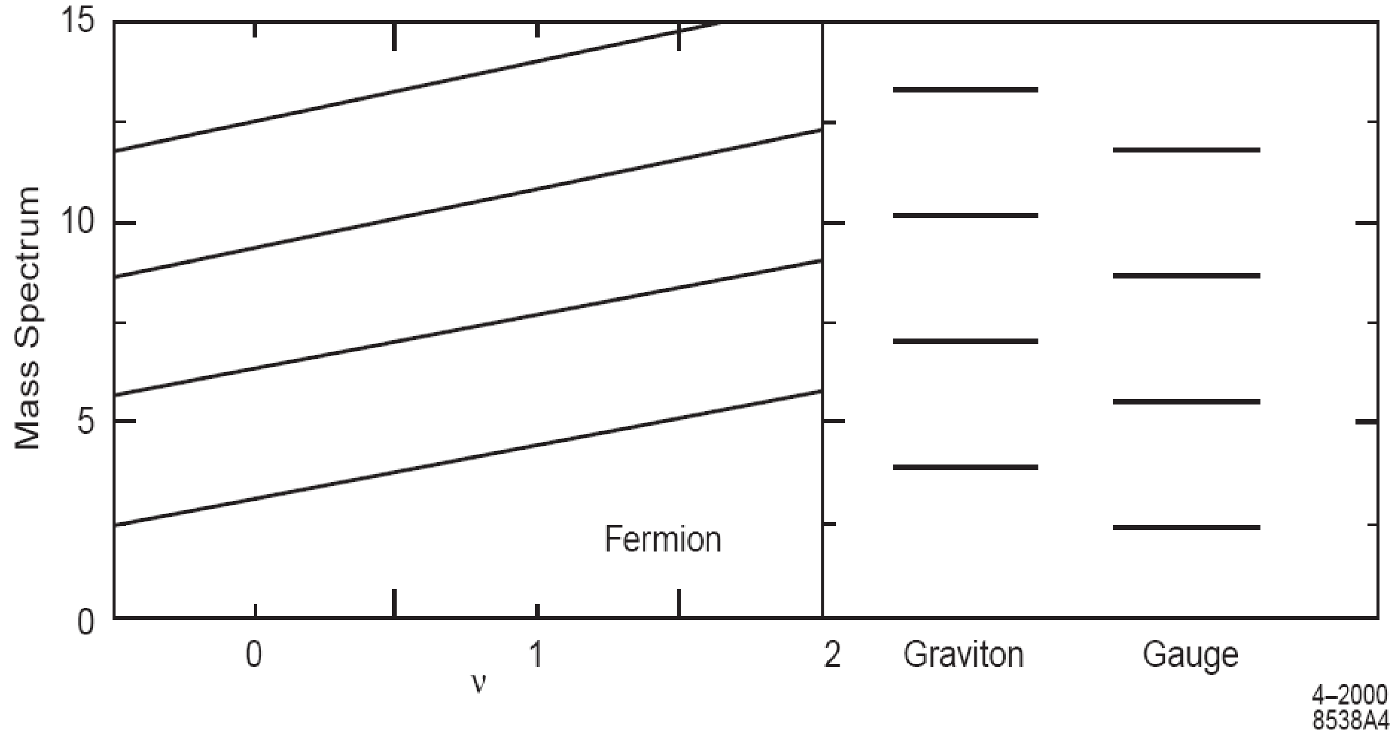


Figure 1: Relative mass spectra in units of $ke^{-kr_c\pi}$ of the KK excitations of the fermion fields as a function of their bulk mass parameter ν, as well as for the graviton and the gauge boson fields as described in the text.

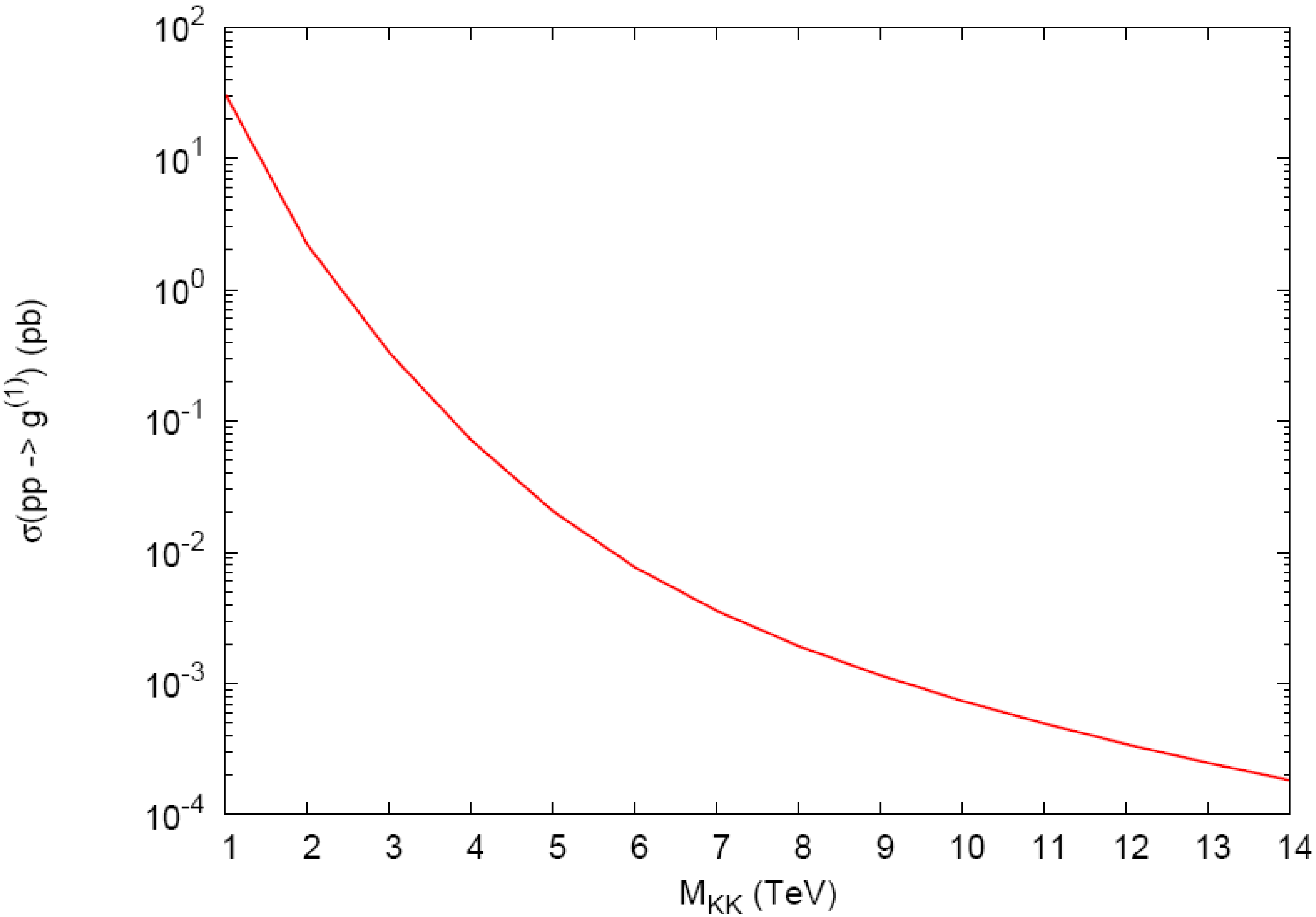
Gluon KK Mode

- Gluon KK mode coupling to light quarks is less suppressed than graviton
  - Gluon KK mode wave function relatively flat in bulk
- Benefit from light quark coupling:
- not as for gluon
- No 1/ML,
- Gluon KK mode lighter by factor 1.5
- Larger reach for gluon KK mode

$$C^{f\bar{f}A}_{00n} = \frac{g^{(n)}}{g^{SM}} = \sqrt{2\pi k r_c}\left[\frac{1+2\nu}{1-\epsilon^{2\nu+1}}\right]\int_\epsilon^1 dz\ z^{2\nu+1}\frac{J_1(x_n^A z)+\alpha_n^A Y_1(x_n^A z)}{|J_1(x_n^A)+\alpha_n^A Y_1(x_n^A)|}$$

w/Ben Lillie, Liantao Wang

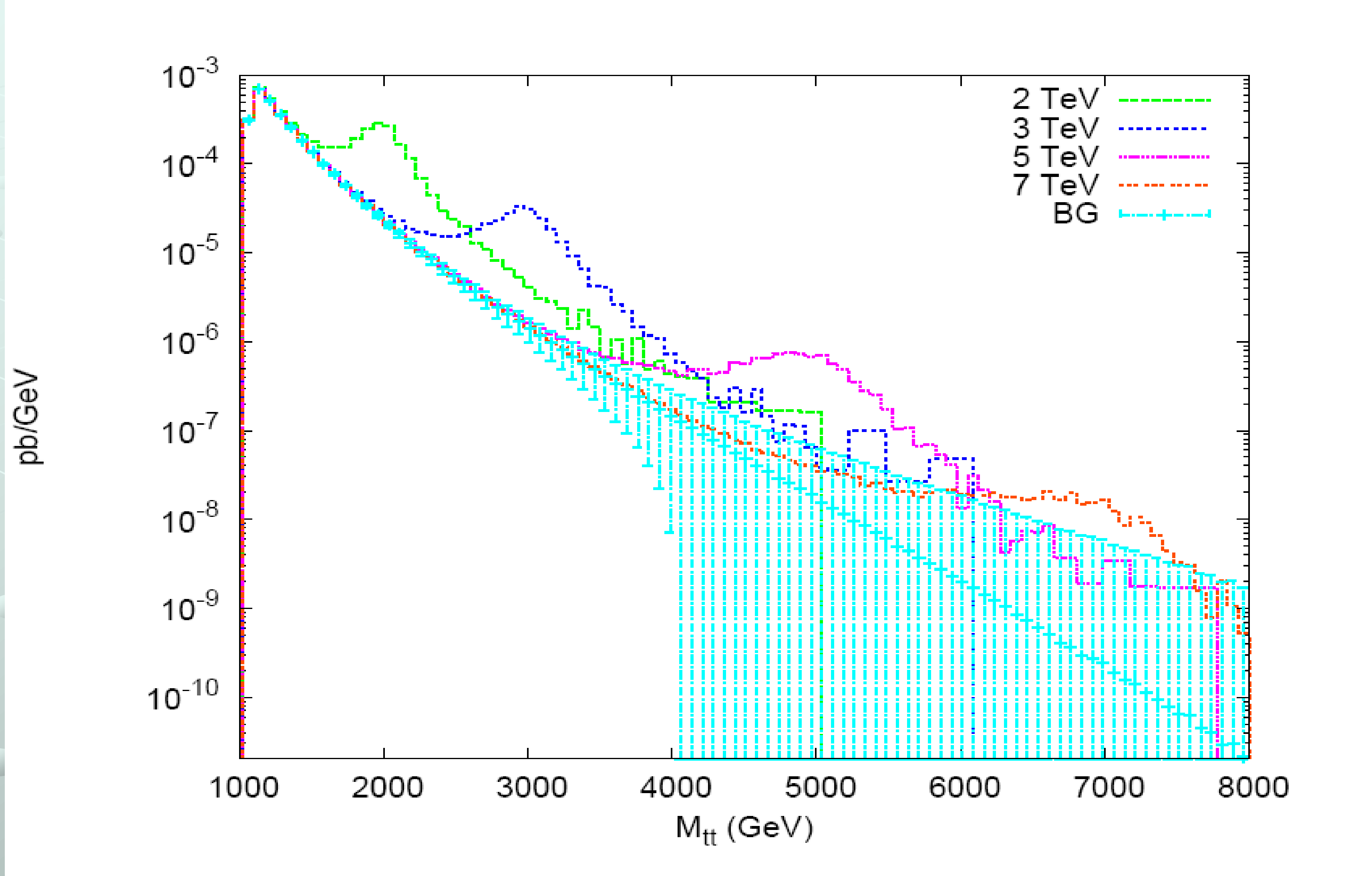
b



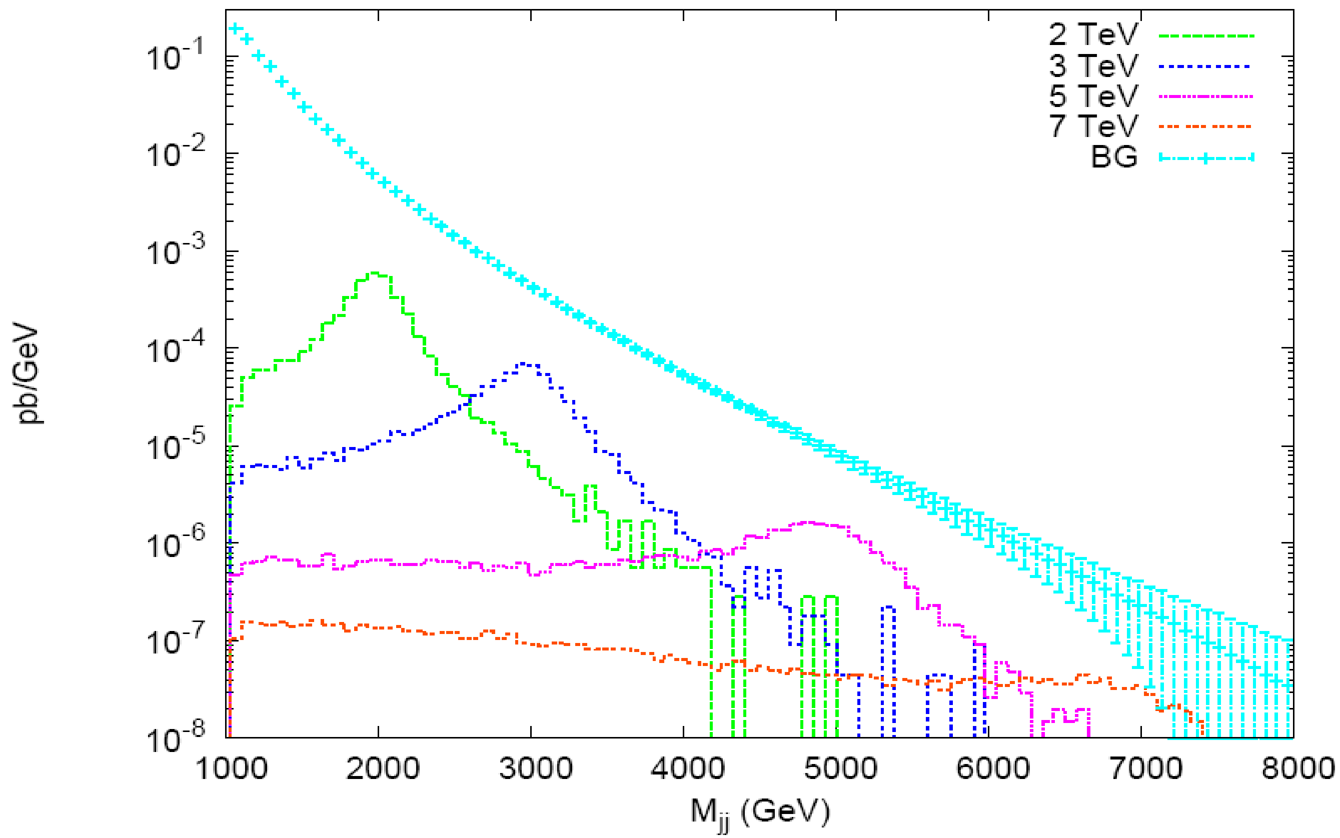
Total cross-section for production of the first KK gluon, as a function of KK mass.

w/Ben Lillie,
Liantao Wang

Dominates over top jet background



However, signal doesn't dominate over jet background



7: Invariant mass distribution of the decay products for several masses of the KK gluon. sumes all $t\bar{t}$ events are fully collimated. "BG" is QCD dijet production. All jets are

Now well known

- Important to identify top quarks
- Entirely determines LHC reach for this mode

Decay to W_L W_L

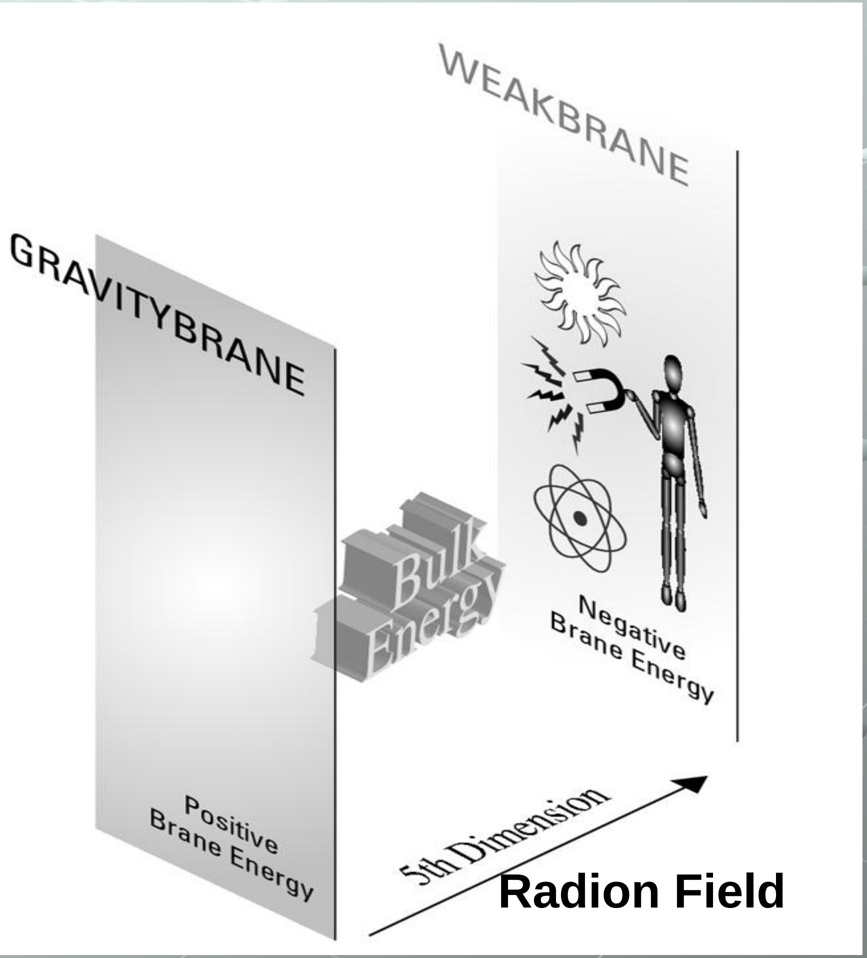
- Antipin, Atwood, Soni
- Z', Graviton decay to this mode (not gluon kk)
- Use semileptonic channels
- First see lighter Z'
- (If very good statistics, also look at purely leptonic)
- Use mass relationship and other modes to extend mass reach as much as possible

that with 300 fb^{-1} integrated luminosity of data the semileptonic $G \to W(\to l\nu_l)W(\to 2jets)$ mode offers a good opportunity to search for the RS KK graviton mode with mass lighter than $\sim$ 3-3.5 TeV at the CERN LHC. Efficient WW mass reconstruction in the

Summary So Far

- If RS1 solves the hierarchy problem, we should be able to tell
- Clean KK graviton signal if SM on brane
- Best signature: spin-2 resonance and mass gap
- In bulk, gluon KK mode will be important
- Decays into tops critical
- Challenge is to maximize energy reach
- Critical for many possibilities for electroweak sector
- Models give insights into what to look for
- End of Part II

Next Target: Radion



Radion VEV determines distance between branes
Of order 10 so natural

Radion Phenomenology

- Lightest state
  - Likely to be of order $\Lambda/10$
  - Could be lighter than KK resonance
- Couples to energy-momentum tensor
- Higgs-like couplings
  - But different wrt fermions versus gauge bosons
- Can set bounds now
- And can accommodate Higgslike…

Two parts here too

- Also two types
  - Brane RS1
  - Bulk RS1

Brane RS1

- Giudice, Rattazzi, Wells
- Radion couples to energy momentum tensor
  - They consider mixing with Higgs as well through curvature terms
  - General conclusion in this case more Higgs-like
  - We focus on pure radion here
- Gluon fusion dominant production
- As with Higgs, loop effect but can be big

Bigger gluon BR low mass

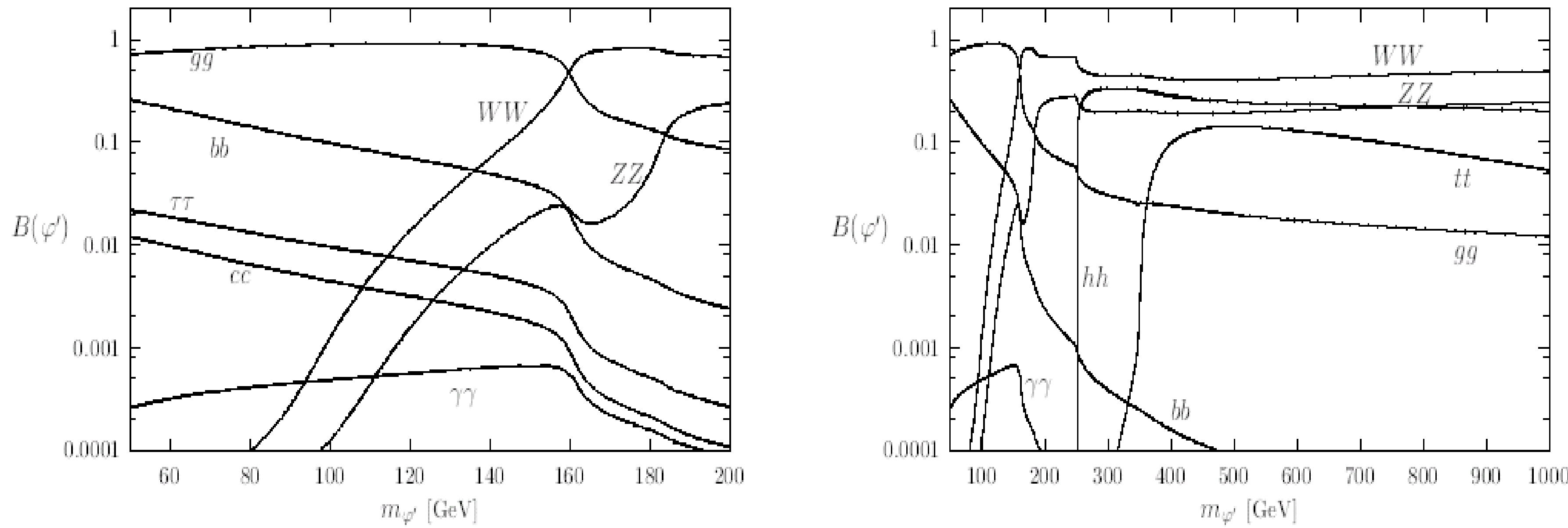


Figure 5: Branching fractions of φ' as a function of its mass given $m_h = 125\,\mathrm{GeV}$, $\Lambda_\varphi = 10\,\mathrm{TeV}$ and $\xi = 0$. The left and right panels are the same except a different range in radion mass is covered.

Radion Can be More Narrow than Higgs

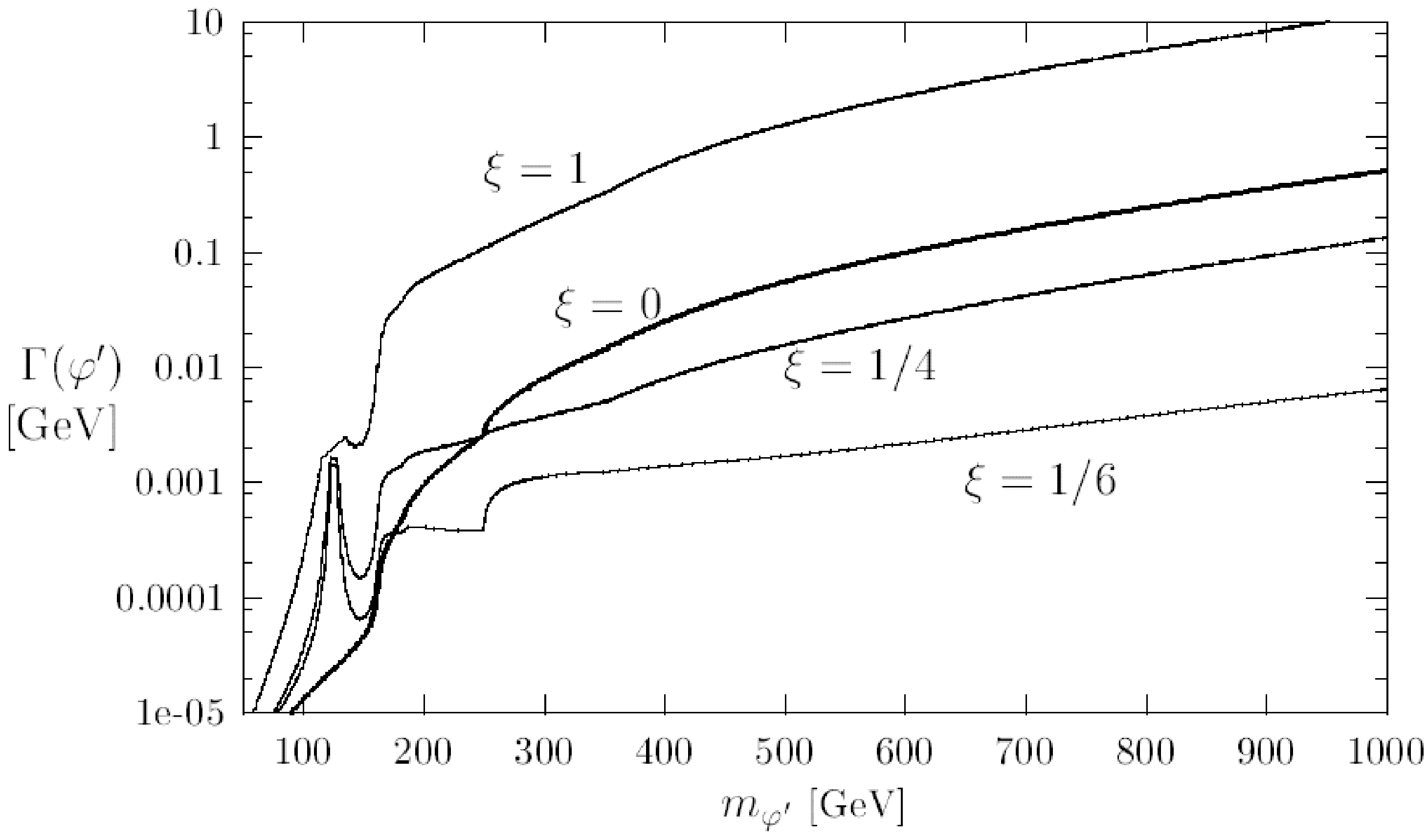


Figure 7: The total width of the radion mass eigenstate given $m_h = 125\,\mathrm{GeV}$ and $\Lambda_\varphi = 10\,\mathrm{TeV}$. The various curves plotted correspond to different values of the Higgs-curvature mixing parameter ξ.

Showed can put significant bounds

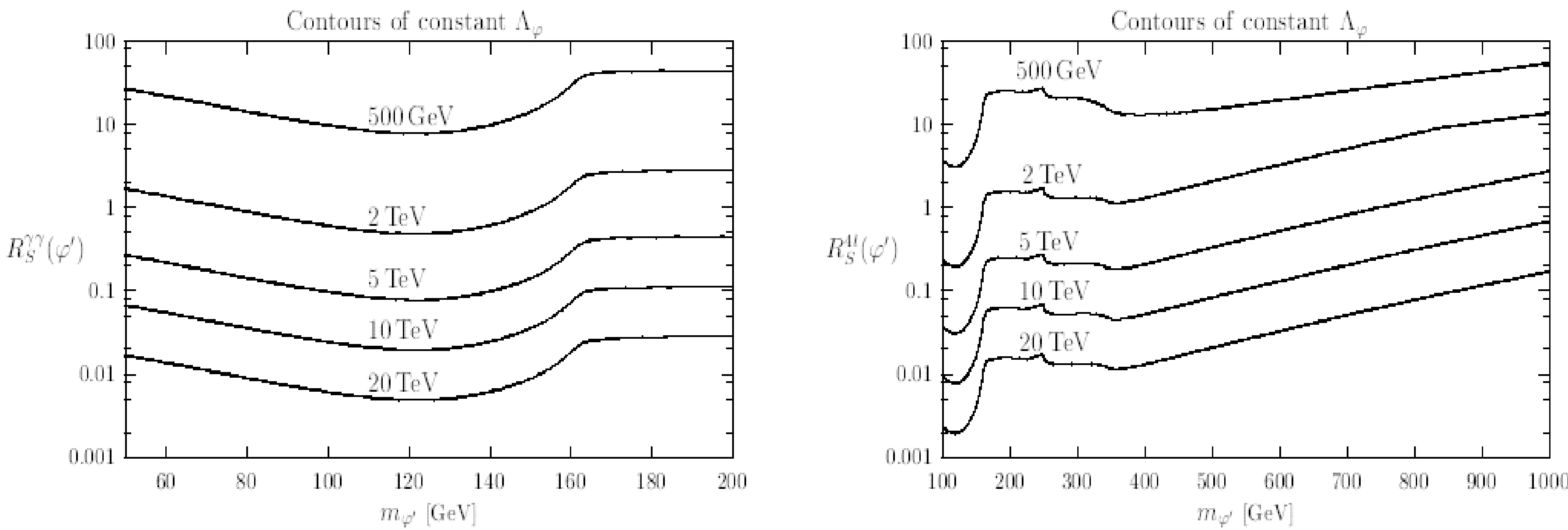


Figure 9: Plots of the ratio of radion signal significance to the signal significance of a SM Higgs boson of the same mass in the $\gamma\gamma$ and $4l$ channels. These plots are made for $\xi = 0$ and $m_{h'} = 125\,\text{GeV}$. The different lines on the graph represent various choices of constant Λ_φ.

Significant coverage

We then have estimated the search capability of the radion at the LHC with 100 fb^{-1} of data and find,

$$\begin{aligned} 110\,\text{GeV} < m_{\varphi'} < 150\,\text{GeV} &\;\Rightarrow\; 2\,\text{TeV} \lesssim \Lambda_\varphi \lesssim 3\,\text{TeV} \\ 150\,\text{GeV} < m_{\varphi'} < 550\,\text{GeV} &\;\Rightarrow\; 3\,\text{TeV} \lesssim \Lambda_\varphi \lesssim 7\,\text{TeV} \\ 550\,\text{GeV} < m_{\varphi'} \lesssim 950\,\text{GeV} &\;\Rightarrow\; 7\,\text{TeV} \gtrsim \Lambda_\varphi \gtrsim 4\,\text{TeV}. \end{aligned}$$

Bulk RS Radion

- Csaki, Hubisz, Lee
- Loop effects important for gauge bosons
  - Conformal anomaly
- As are brane-localized kinetic terms
- Results can be different

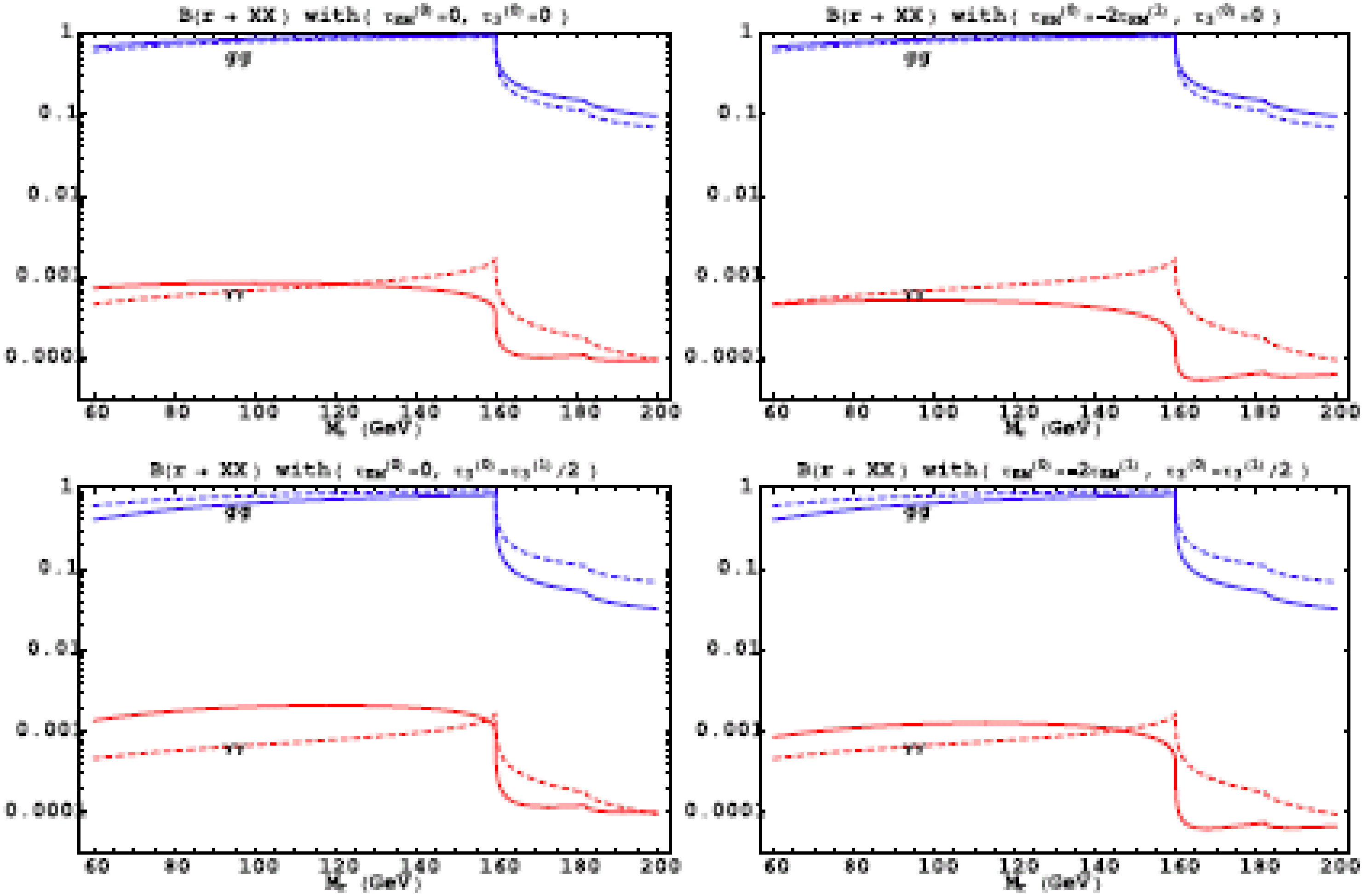


Figure 3: In these plots, we show the branching fractions of the radion into gluons and photons (the solid lines), comparing with RS1 scenario (the dashed curves). For each graph, the solid curves represent the branching fractions in the presence of different combinations of tree level brane localized kinetic terms for the gluon and photon. The magnitudes of the localized terms are given on the top of every plot individually in units of the one-loop corrections to the τ_1^{UV}. We have set $\Lambda_r = 2$ TeV, corresponding to $1/R' = 816$ GeV.

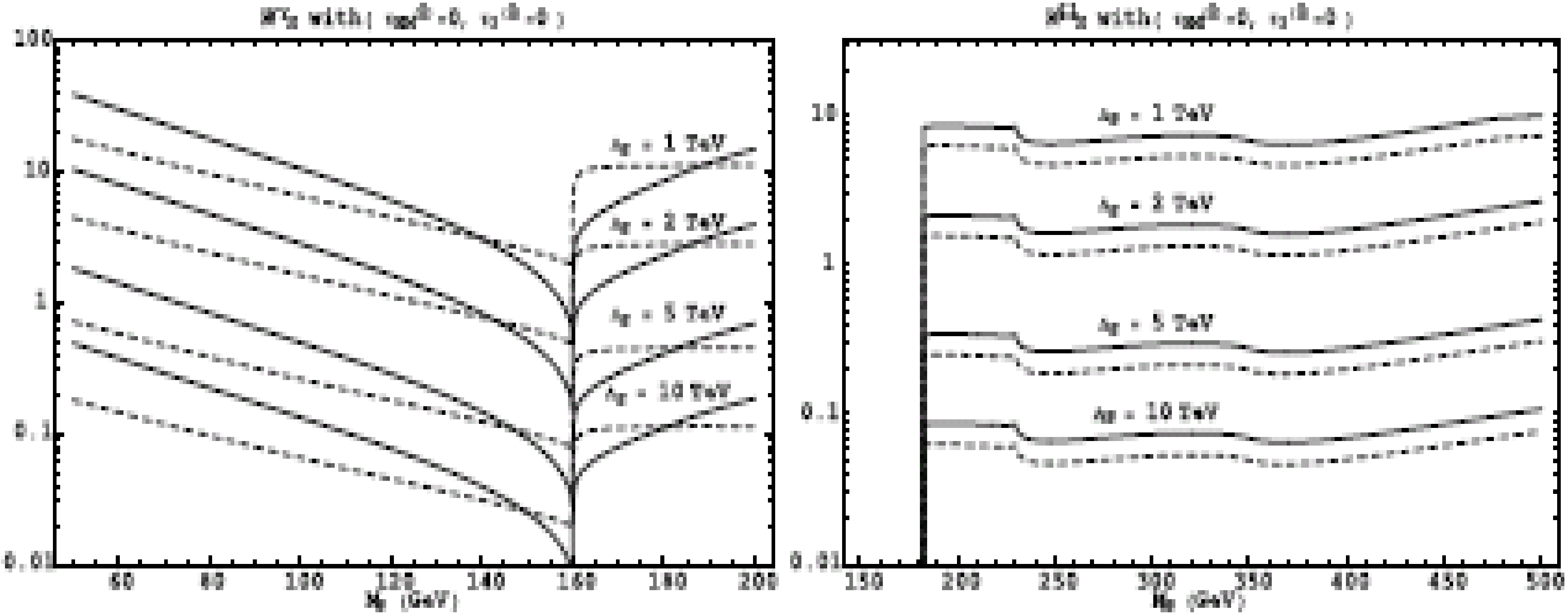


Figure 5: In the plot on the left, we show a comparison of the ratio of discovery significance for a radion vs. a Higgs of the same mass, $R_S^{\gamma\gamma}$, with the scenario where the SM fields are all localized on the IR brane (the dashed curves). In the plot on the right we show the ratio of discovery significance R_S^{4l}. We assume that there are no tree level brane localized kinetic terms for the gluon or photon. For the displayed values of Λ_r, the corresponding values of $1/R'$ are 408, 816, 2041, and 4082 GeV.

With brane localized terms

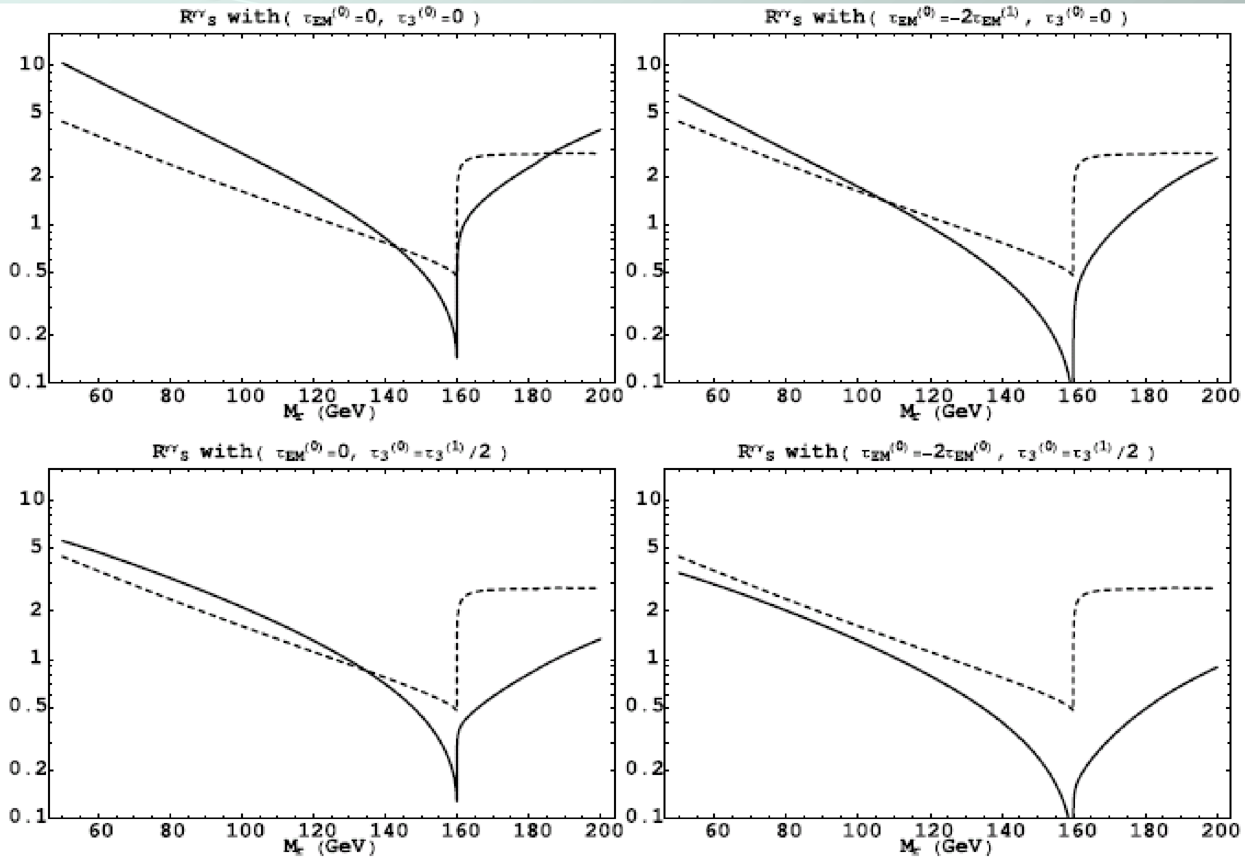


Figure 6: In this figure, we show the ratio of the discovery significance $R_S^{\gamma\gamma}$ with $\Lambda_r = 2$ TeV for various combinations of tree level brane localized kinetic terms for the photon and gluon. We have set $\Lambda_r = 2$ TeV, corresponding to an IR brane with $1/R' = 816$ GeV. Again, the dashed curves represent the signal significance in the original RS1 model.

Still to consider

- Brane IR localized gauge kinetic terms
- In principle can change ratio of WW to other modes
  - Of interest?

Also…Higgs Phenomenology

- Bouchart, Moreau
- Turns out Higgs VEV, couplings can be very different in bulk RS models
- Require custodial SU(2), extra U(1) mixing, extra KK modes
- Can have weakened constraints on MKK
- And reduced Higgs couplings

A] $m_h = 120$ GeV, $g_{Z'} = 1.57$	B] $m_h = 120$ GeV, $g_{Z'} = 0.72$	C] $m_h = 150$ GeV, $g_{Z'} = 1.57$
$M_{KK} = 4025$ GeV	$M_{KK} = 3370$ GeV	$M_{KK} = 4095$ GeV
$\tilde{v} = 322$ GeV	$\tilde{v} = 257$ GeV	$\tilde{v} = 311$ GeV
$g^{RS}_{hZZ}/g^{SM}_{hZZ} = 57.3\%$	$g^{RS}_{hZZ}/g^{SM}_{hZZ} = 87.2\%$	$g^{RS}_{hZZ}/g^{SM}_{hZZ} = 60.1\%$
$g^{RS}_{hWW}/g^{SM}_{hWW} = 57.5\%$	$g^{RS}_{hWW}/g^{SM}_{hWW} = 87.4\%$	$g^{RS}_{hWW}/g^{SM}_{hWW} = 60.3\%$
$\lambda^{RS}_{\tau}/\lambda^{SM}_{\tau} = 76.2\%$	$\lambda^{RS}_{\tau}/\lambda^{SM}_{\tau} = 95.5\%$	$\lambda^{RS}_{\tau}/\lambda^{SM}_{\tau} = 79.1\%$
$\lambda^{RS}_{b}/\lambda^{SM}_{b} = [71, 75]\%$	$\lambda^{RS}_{b}/\lambda^{SM}_{b} = [90, 93]\%$	$\lambda^{RS}_{b}/\lambda^{SM}_{b} = [74, 78]\%$
$g^{RS}_{hgg}/g^{SM}_{hgg} = [77.6, 80.8]\%$	$g^{RS}_{hgg}/g^{SM}_{hgg} = [96.2, 99.1]\%$	$g^{RS}_{hgg}/g^{SM}_{hgg} = [80.1, 83.3]\%$
$g^{RS}_{h\gamma\gamma}/g^{SM}_{h\gamma\gamma} = [74.9, 75.1]\%$	$g^{RS}_{h\gamma\gamma}/g^{SM}_{h\gamma\gamma} = [100.6, 100.8]\%$	$g^{RS}_{h\gamma\gamma}/g^{SM}_{h\gamma\gamma} = [77.1, 77.3]\%$

Conclusion

- Many interesting searches, interpretations
  - Immediately and future
- Immediately
  - KK modes
  - Interpret Higgs bounds on radion
  - And even on Higgs
- Future: Critical to extend reach
  - More challenging modes (tops, WLs)
- Also if we're lucky angular distributions, etc.