KK Gluons at NLO

K. Sridhar

Tata Institute of Fundamental Research, Mumbai

Small Extra Dimensions

- A model with a large compactification radius is not stable – the hierarchy problem returns in a different garb.
- An attempt to solve the hierarchy problem without introducing a large compactification radius – the model of Randall and Sundrum.
- In this 5-d model, the fifth dimension y of a small radius R_c is compactified on a $\mathbf{S}^1/\mathbf{Z}^2$ orbifold in an AdS spacetime.

Warped Model

- Two branes are at the orbifold fixed points: a Planck brane at $y = 0$ and a TeV brane at $y = \pi$.
- The model uses a warped metric

$$ds^2 = e^{-KR_c y}\eta_{\mu\nu}dx^\mu dx^\nu + R_c^2 dy^2. \qquad (1)$$

where K is a mass scale related to the curvature.

Warped suppressions

- The warp factor acts as a conformal factor for fields on the brane.
- The term $\exp(-KR_c y)$ for the TeV brane at $y = \pi$ generates a factor of 10^{15} by an exponent of order 30 and solves the hierarchy problem.
- Problem: Mass scales that suppress higher dimensional operators inducing proton decay or neutrino masses also get rescaled.

Gauge-Gravity Correspondence

- Dual nature of branes has profound consequences.
- On the one hand, branes localise open strings and yield a SUSY gauge theory.
- On the other, branes are solitonic solutions of supergravity theories.
- Suggestive of a deep connection between the gravity and gauge aspects.

AdS/CFT

- AdS/CFT posits a duality between:
  Type IIB String Theory on $\mathrm{AdS}_5 \times S^5$ with string coupling g_s, radius R and N units of five-form flux $\tilde{F}_5$ through S_5
  Superconformal $\mathcal{N} = 4$ SU(N) 4D gauge theory with coupling g_{YM}.
  with

$$g_{YM}^2 = 4\pi g_s \tag{2}$$

$$\frac{R_{AdS}^4}{l_s^4} = 4\pi g_s N \tag{3}$$

Weaker forms of AdS/CFT

- Quantisation of strings on a curved space like $\mathrm{AdS}_5 \times S^5$ is intractable.
- Take the 't Hooft limit: $N \to \infty$, $\lambda \equiv g_{YM}^2 N$ fixed. This is the classical string limit $g_s \to 0$.
- Strong coupling limit: $\lambda \to \infty$ which corresponds to $l_s \to 0$ which gives low-energy supergravity on $\mathrm{AdS}_5 \times S^5$.

More on AdS/CFT

- Upshot: The RS model is dual to a 4-d theory which is strongly coupled.
- The dual theory is conformally invariant down to the TeV scale and the invariance is broken by the TeV brane.
- Distance from the TeV brane determines the compositeness or elementarity of the 5D fields.
- Since all the SM fields are localised on the TeV brane, the RS theory is dual to a theory of TeV-scale compositeness.

Exploring the Bulk

- The way out is to localise only the Higgs on the brane – composite Higgs.
- Localise zero modes paying attention to flavour hierarchy, EW precision tests and avoidance of FCNCs.
- S parameter is handled by having the fermions in the bulk but a custodial $SU(2)_L \times SU(2)_R \times U(1)_{(B-L)}$ symmetry is required for the T parameter.

Locating the fermions

- To get a large Yukawa coupling i.e. overlap with the Higgs one needs to localise the fermion close to the TeV brane and far away from the brane to get a small Yukawa.
- The top sector: the doublet needs to be as far away from the TeV brane as allowed by R_b whereas the t_R needs to be close to the TeV brane to get the large Yukawa of the top.
- FCNCs and precision electroweak tests $\Longrightarrow$ KK gauge bosons masses $\sim$ 2-3 TeV.

KK gluons

- Interesting signal – KK gluon production.
- The KK gluon coupling to t_R is enhanced by a factor ξ compared to α_s where $\xi \equiv \sqrt{\log(M_{pl}/\mathrm{TeV})} \sim 5$.
- Consequently, it decays predominantly to tops if produced.
- To the $(t, b)_L$ doublet its coupling is α_s.
- To the light quarks its couplings are suppressed by a factor $1/\xi$.

KK Gluon Production

- However, the ggg_{KK} vanishes because of the the orthogonality of the profiles of these particles.
- So gg initial state does not contribute, only $q\bar{q}$ does. The has been studied in the context of the LHC and Tevatron.

KK gluon at NLO

- It is interesting to look at the NLO production coming from gg initial states.
- We have completed a full calculation including sub-leading terms coming from KK gluon loops.

Quark Loops

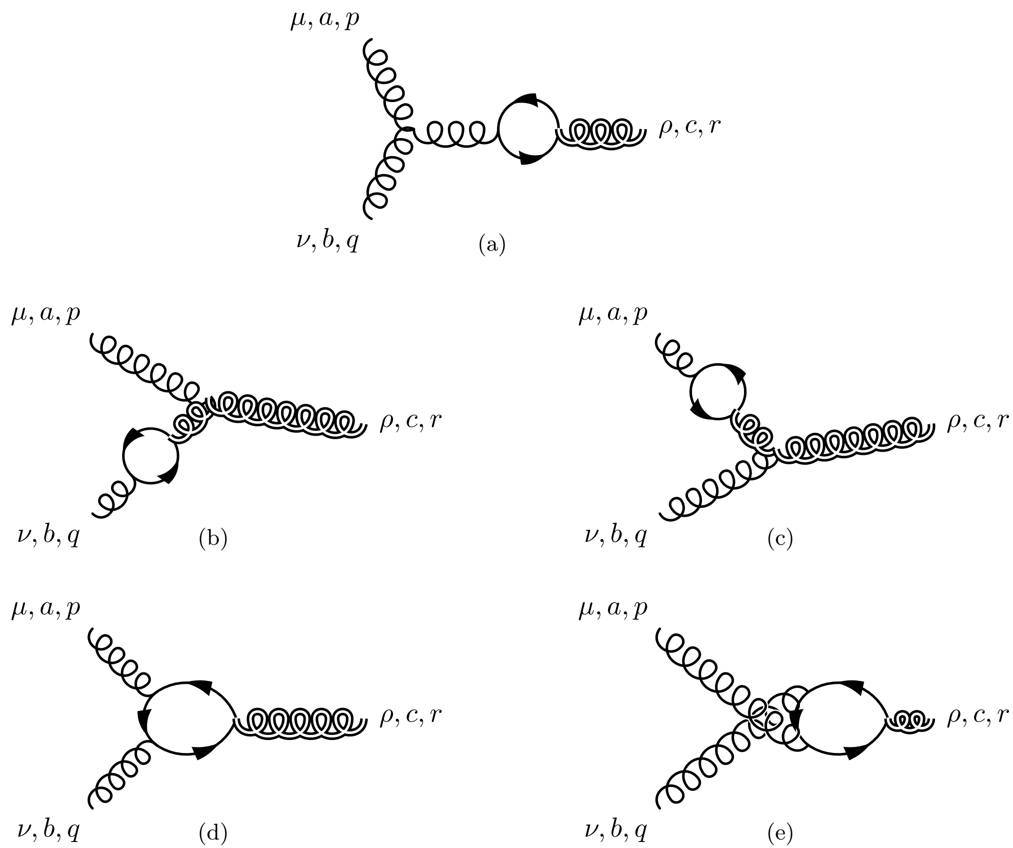
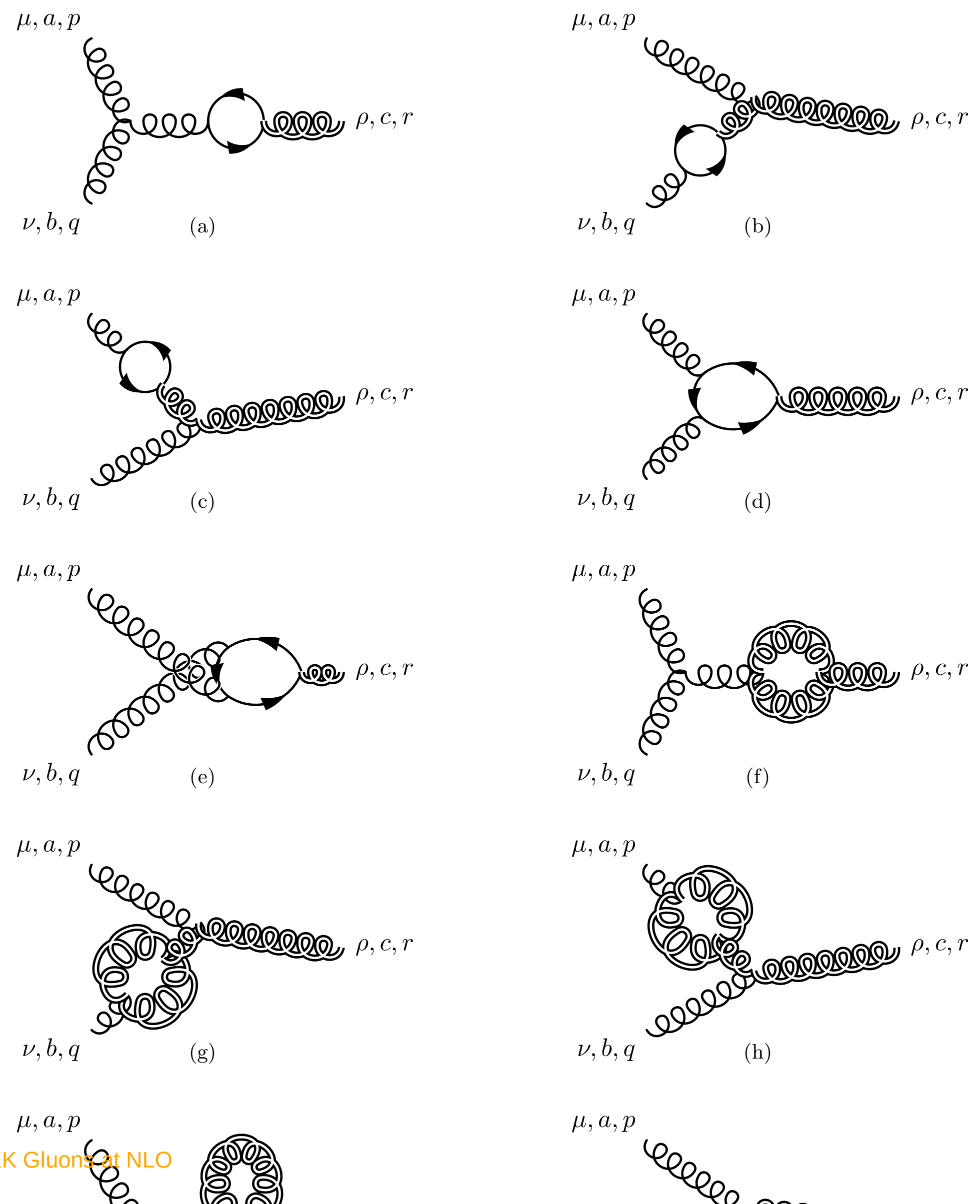


Figure 2: Feynman diagrams for the process that involve a quark in the loop.

KK gluon loops



Ghost loops

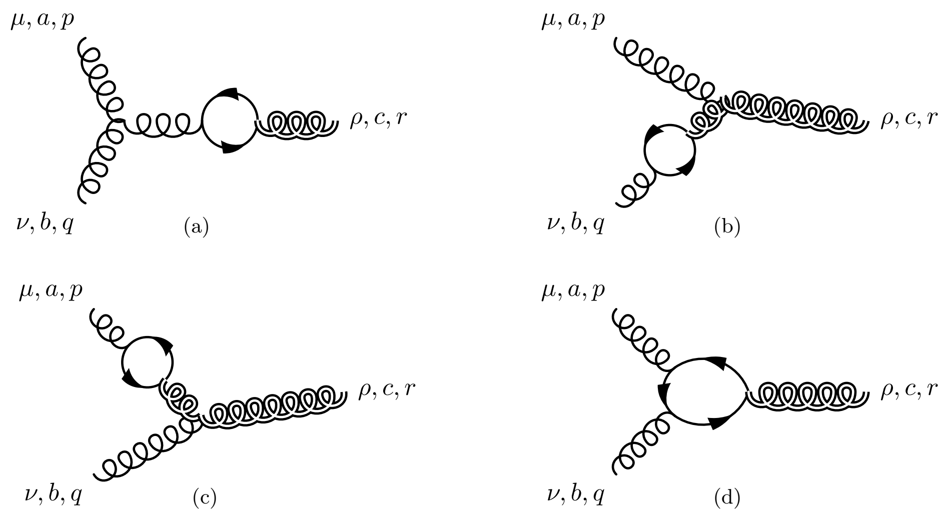


Figure 2: Feynman diagrams for the process that involve a Kaluza-Klein ghost in the loop.

Calculation

- The general form of the amplitude $F^{\mu\nu\rho}$, consistent with current conservation (related to the incoming massless gluons) is:

$$F_{\mu\nu\rho} = A\left(\eta_{\mu\nu} p\cdot q - q_\mu p_\nu\right) p_\rho + B\epsilon_{\mu\nu\gamma\delta} p^\gamma q^\delta p_\rho + \\ + C\left(\epsilon_{\mu\nu\rho\gamma} p^\gamma p\cdot q - \epsilon_{\mu\rho\gamma\delta} p^\gamma q^\delta p_\nu\right) + \\ D\left(\epsilon_{\mu\nu\rho\gamma} q^\gamma p\cdot q - \epsilon_{\nu\rho\gamma\delta} p^\gamma q^\delta q_\mu\right), \quad (4)$$

where A, B, C and D are constants.

Result

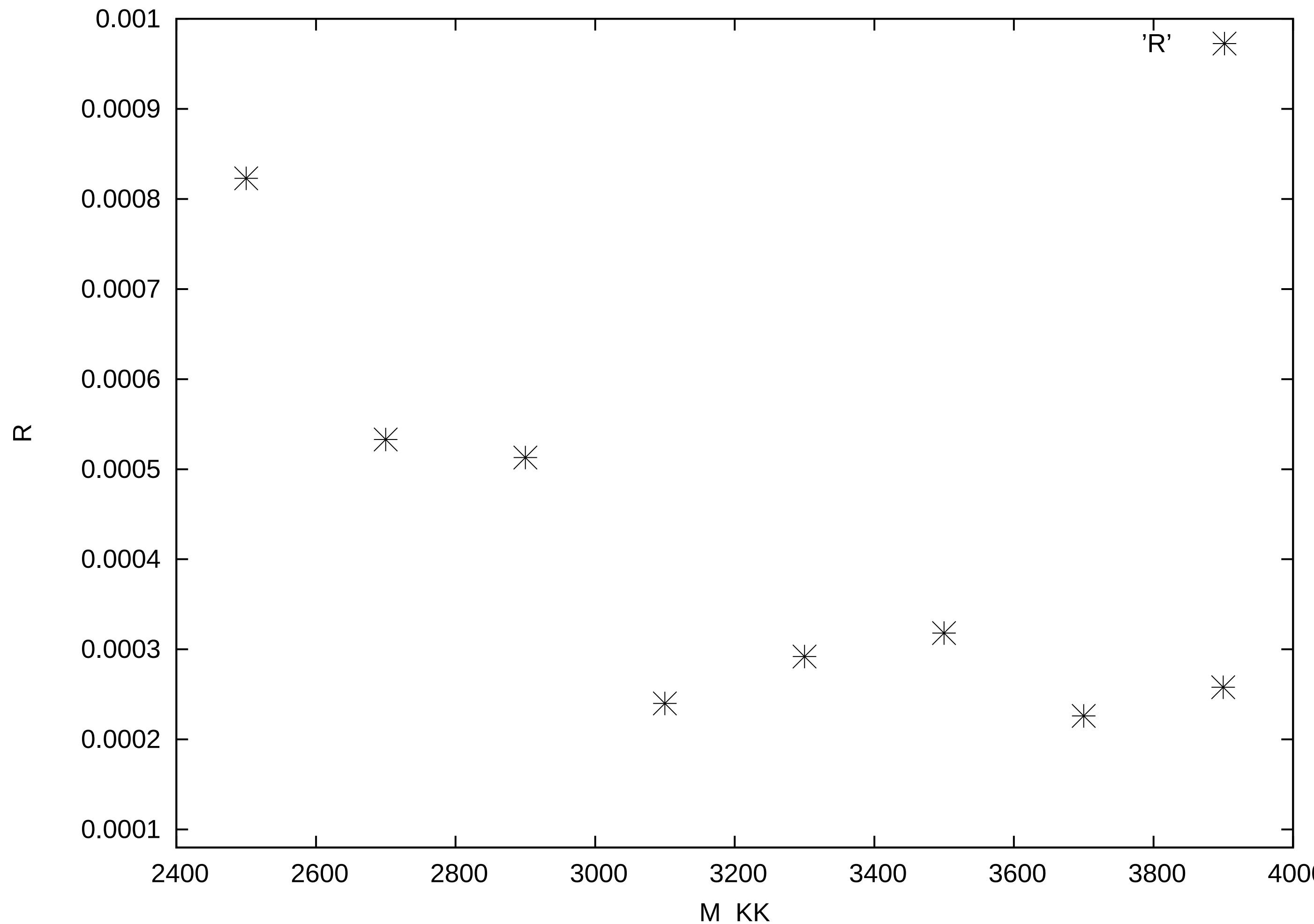
$$|\mathcal{M}|^2 = \frac{M_{KK}^6 g^4}{(4\pi)^4} \Bigg| \frac{4046}{16384} g^{(111)^2} \left[I(M_{KK}, M_{KK}) \right]^2$$

$$- \frac{51}{256} g^{(111)} \sum_{q_L, q_R} g^{(1q)} [I(M_{KK}, M_{KK}) I(m_q, M_{KK})]$$

$$+ \frac{3}{64} \left[\sum_{q_L, q_R} g^{(1q)} I(m_q, M_{KK}) \right]^2 \Bigg|, \qquad (5)$$

$$I(a,b) = \int_0^1 dx \int_0^{1-x} dy \frac{xy(1-x-y)}{a^2 - xyb^2} \qquad (6)$$

Result



'R'
R
0.001
0.0009
0.0008
0.0007
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
2400
2600
2800
3000
3200
3400
3600
3800
4000
M_KK

Conclusions

- The RS model with all SM fields localised on the TeV brane is inconsistent.
- The Bulk RS model, with gauge bosons and fermions localised in the bulk replaces the original model.
- KK gluon production is the most important signal of the Bulk RS model.
- The gluon-initiated contribution to KK gluon production at NLO in QCD is computed and is found to be small.