# QCD effects in top pair production in Randall-Sundrum model

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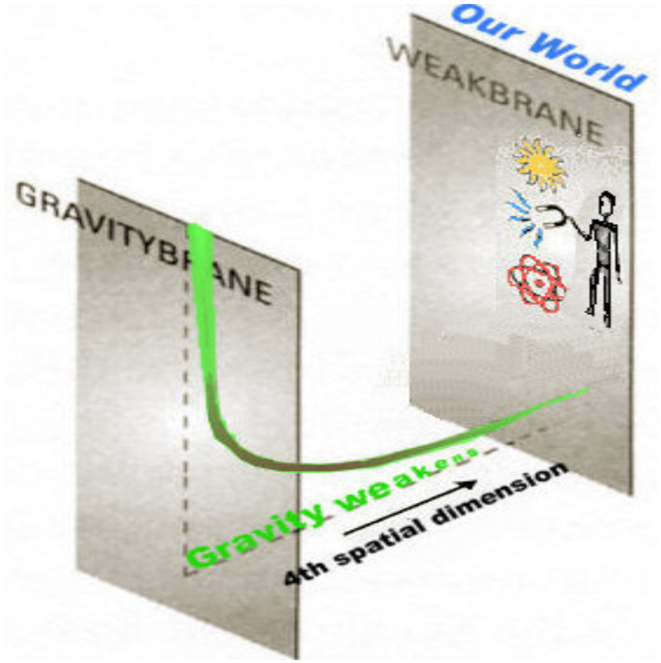
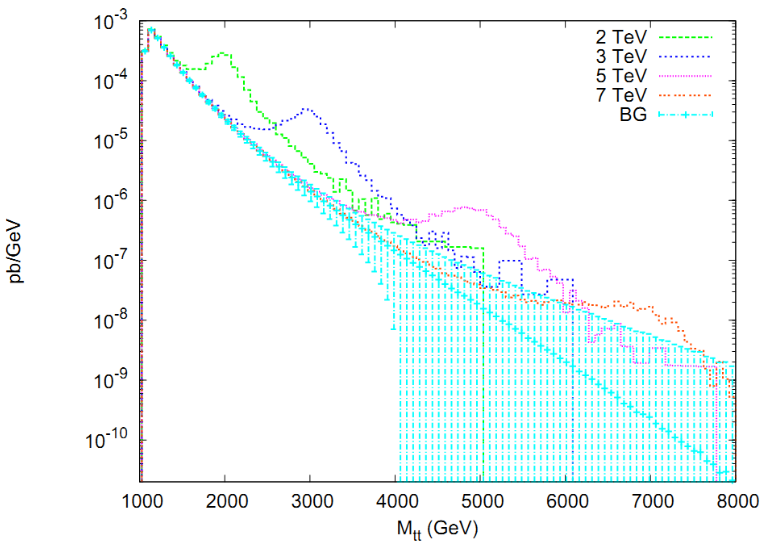
# ➢ Motivation

➢ Warped extra dimension model (Randall-Sundrum) provides interesting solution to the Hierarchy problem. It would be very exciting if extra dimension is discovered at the LHC.




➢ KK gluon in RS model induces large top pair cross section at the resonant region.

➢Observation of heavy resonance in top pair invariant mass distribution at the LHC may be the first hint of RS model (Agashe et.al, 2006)




Lillie, Randall, Wang, 2007

➢ KK Gluon in Randall-Sundrum model might also provide a promising explanation to top pair Forward-Backward asymmetry ( Djouadi et.al, 1105.3358)

# •Experimental status

- ➢ No resonance in ttbar final state has been discovered yet.

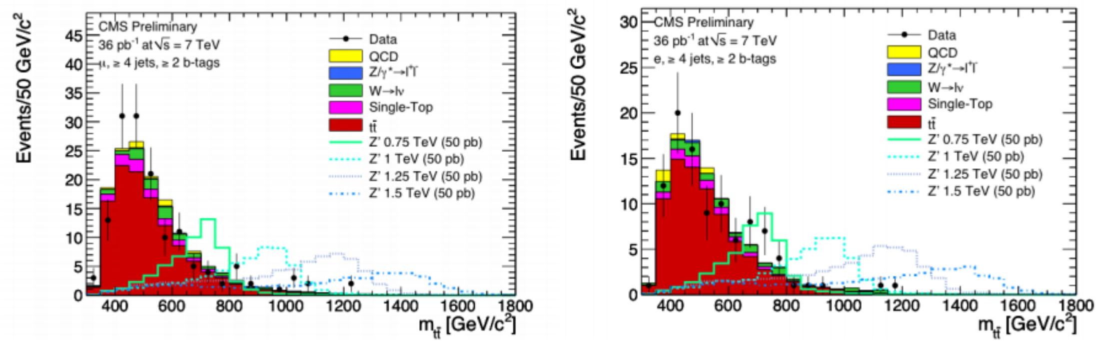
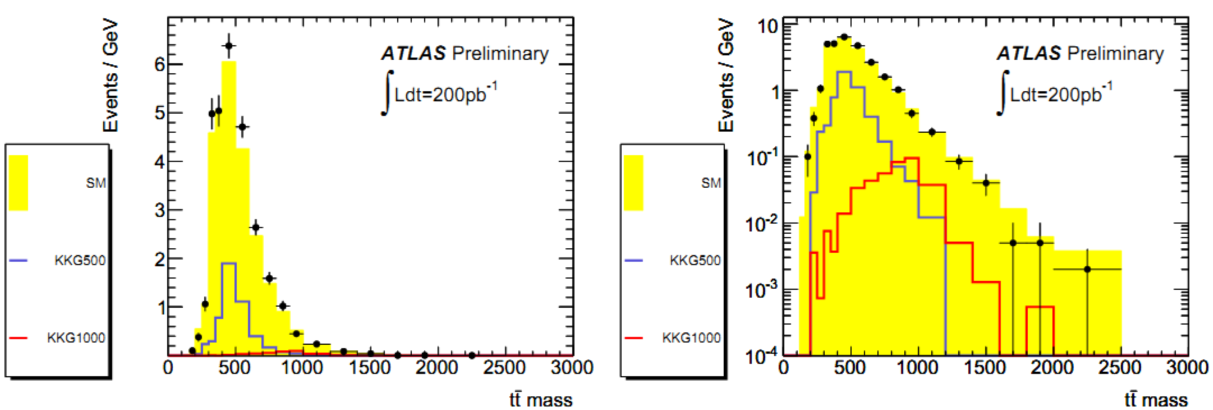



Figure 6: Reconstructed $m_{t\bar{t}}$ in data for 36 pb$^{-1}$ of luminosity, for the muon (left) and electron (right) channels. The data are compared with the expectations of the SM, divided into the various components.

CMS note, TOP-10-007, 2010



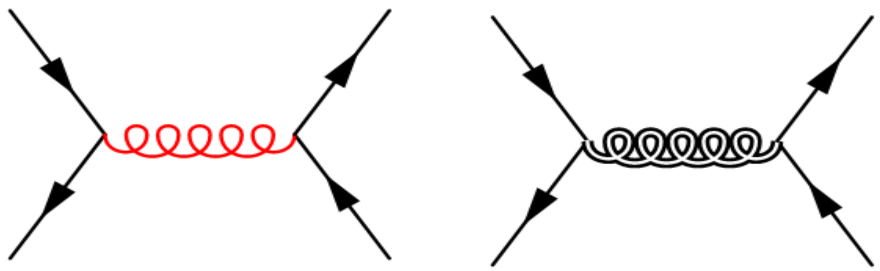

(a) (b)

Figure 4: Reconstructed $t\bar{t}$ mass on linear (a) and logarithmic (b) scales using the *dRmin* algorithm after all cuts. The electron and muon channels have been added together and all events beyond the range of the histogram have been added to the last bin. Only statistical uncertainties are shown.

ATLAS-CONF-2011-087

# •Theoretical status and our aim

- We mainly concern S-channel for LO partonic process in top pair production



- LO result suffers from large scale uncertainty. Also as we know that NLO SM ttbar production has large K factor. It's reasonable to expect that KK gluon channel will also has large K factor, which has not been reported in the previous literature.

- Partial NLO result

    - Interference between one-loop SM amplitudes and tree-level KK gluon amplitude (Bauer, Goertz, Haisch, Pfoh, Westhoff, 2010)

    - Effects of KK gluon on ttbar production through one loop diagrams via gluon-gluon fusion (Allanach, Mahmoudi, Skittrall, Sridhar, 2009)

- For a massive vector boson, propagator is usually chosen in unitary gauge

$$\left(g^{\mu\nu} - \frac{k^\mu k^\nu}{m_{KK}^2}\right) \frac{-i}{k^2 - m_{KK}^2}$$

- For LO calculation, unitary gauge is as good as any other gauge. But for a NLO calculation, unitary gauge is not convenient, because of its bad UV behavior.

- Two options:

  - Direct calculation in unitary gauge is feasible using pinch technique (Binosi, Papavassiliou, 2009)

  - Alternatively, we can carry out the calculation in ‘t Hooft-Feynman gauge, if all the ghost and Goldstone degrees of freedom are properly taken into account

- We adopt the latter choice in our work:

1. First derive the relevant Feynman rules for the KK gluon, the ghost of KK gluon and 5th component of 5D KK gluon field in $R_\xi$ gauge.

2. Show how to renormalize the resulting one –loop amplitudes.

3. Finally present the full one-loop helicity amplitudes of ttbar production induced by KK gluon, and give the preliminary numerical results.

# • Quantization of KK gluon field in covariant gauge

➢ To illustrate our approach, we consider the 5D pure SU(3) QCD lagrangian in warped AdS space:

$$ds^2 = \frac{1}{k^2 z^2}\left(\eta_{\mu\nu} dx^\mu dx^\nu - dz^2\right) \qquad dz = e^{-ky} dy$$

➢ The 5 dimensional action for SU(3) gauge field in this space is

$$S_{5D} = \int d^4x dz \sqrt{G} \left(-\frac{1}{2} \mathrm{Tr} F_{MN} F^{MN}\right)$$

➢Expanding the gauge field strength into 4D component and 5th component, leads to the following Lagrangian:

$$F^a_{MN} = \partial_M A^a_N - \partial_N A^a_M + g_5 f^{abc} A^b_M A^c_N, \qquad F_{MN} = F^a_{MN} T^a,$$

$$S_{5D} = \int d^4x \int \frac{dz}{kz}\left[-\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu,a} - \frac{1}{2} F^a_{\mu 5} F^{\mu 5,a}\right].$$

➢ As in 4D QCD, the propagator of the vector boson in the above lagrangian is not well-defined. Boundary and bulk gauge fixing terms, as well as ghost lagrangian need to be added to the complete lagrangian in order to have a well-defined gauge boson propagator (to cancel the mixing between 4D and $5^{th}$ component in the quadratic term):

$$S_{GF,bulk} = \int d^4x \int \frac{dz}{kz}\left(-\frac{1}{2\xi}\right)\left[\partial^\mu A^a_\mu - \xi(kz)\partial_z\left(\frac{1}{kz}A^a_5\right)\right]^2,$$

$$S_{GF,boundary} = -\frac{1}{2\xi_b}\int d^4x \left[\left(\partial^\mu A^a_\mu + \xi_b\frac{1}{kz}A^a_5\right)^2\Big|_{z=z_2} + \left(\partial^\mu A^a_\mu - \xi_b\frac{1}{kz}A^a_5\right)^2\Big|_{z=z_1}\right]$$

$$S_{5D,ghost} = \int d^4x \int \frac{dz}{kz}\bar{u}^a\left[-\partial^\mu \mathcal{D}_\mu + \xi\,(kz)\,\partial_z\frac{1}{kz}\partial_z\right]^{ab} u^b,$$

where the boundary condition for the boundary gauge field is chosen to be

$$\partial_z A^{\mu,a}|_{z=z_1,z_2} = 0, \qquad A^a_5|_{z=z_1,z_2} = 0.$$

And the covariant derivative in the ghost Lagrangian is

$$(\mathcal{D}_M)^{ab} = \delta^{ab}\partial_M + g_5 f^{acb} A^c_M.$$

The complete Lagrangian is just the sum of these separate terms:

$$S = S_{5D} + S_{GF,bulk} + S_{GF,boundary} + S_{5D,ghost}.$$

➢ We perform a usual KK decomposition on the 5D gauge field, and the ghost field:

$$A_\mu(x,z) = \sqrt{k}\sum_{j=0}^{\infty} A_\mu^{(j)}(x)\chi_j(z), \qquad u(x,z) = \sqrt{k}\sum_{j=0}^{\infty} u^{(j)}(x)\,\chi_j(z)\,,$$

$$A_5(x,z) = \sqrt{k}\sum_{j=1}^{\infty} A_5^{(j)}(x)\frac{1}{m_j}\partial_z\chi_j(z), \qquad \bar{u}(x,z) = \sqrt{k}\sum_{j=0}^{\infty} \bar{u}^{(j)}(x)\,\chi_j(z)\,.$$

where $\chi_j$ is a set of orthonomal basis.

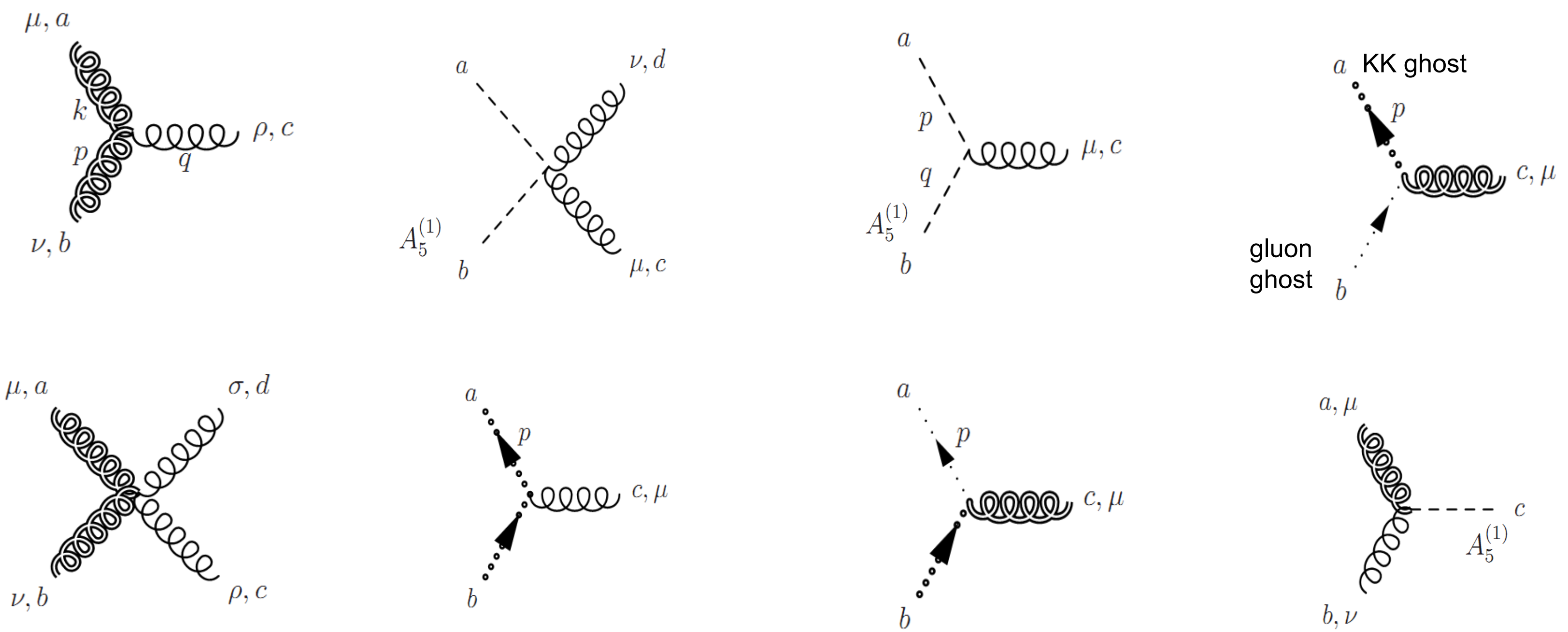
➢ First few KK modes enter into our calculation:

$a,\mu$  $b,\nu$ ($p$) $= -\frac{i\delta^{ab}}{p^2 - m_{KK}^2}\left(g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2 - \xi m_{KK}^2}(1-\xi)\right)$, $A_\mu^{(1)}$ ⟵ **KK gluon**

$a$  $b$ ($p$) $= \frac{i\delta^{ab}}{p^2 - \xi m_{KK}^2}$, $A_5^{(1)}$ ⟵ **The would-be Goldstone boson**

$a$  $b$ ($p$) $= \frac{i\delta^{ab}}{p^2 - \xi m_{KK}^2}$, $u^{(1)}$ ⟵ **Ghost field for KK gluon**

- We  following the procedure below to derive the relevant Feynman rule:
  - Keep the zero mode and the first KK mode of the 5D gluon field
  - Keep the interactions whose form are fixed by gauge invariance
- We give for the first time a complete set of interaction Feynman rule fixed by gauge symmetry, thus are the same for a variety of model of new physics with a massive color octet gauge boson, for example, KK gluon, axial gluon, coloron, et.al.




- Using these Feynman rule we perform a complete NLO QCD calculation for ttbar production in the Randall-Sundrum model.

- Now we also need to know the interaction between fermion zero mode and first KK mode of gauge field. Their Feynman rules can be derived from the 5D interaction term:

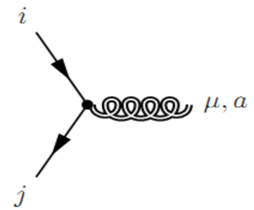
$$\begin{aligned} S_{5D,fermion} &= \int d^5x\sqrt{-g}\left\{i\bar{\Psi}\Gamma^M D_M\Psi\right\}|_{\bar{\Psi}A\Psi\,\text{piece}} \\ &= \int d^4x\int dz\left(\frac{1}{kz}\right)^4\bar{\Psi}\left[g_5\gamma^\mu A_\mu + ig_5\gamma^5 A_5\right]\Psi \\ &= \int d^4x\int dz\left(\frac{1}{kz}\right)^4 g_5\left\{\psi\sigma^\mu A_\mu\bar{\psi}+\bar{\chi}\bar{\sigma}^\mu A_\mu\chi + i\left(-\psi\chi+\bar{\chi}\bar{\psi}\right)A_5\right\} \end{aligned}$$

- Expand the fermion KK mode as above:

$$\begin{aligned} \chi(x,z) &= \sum_{j=0} g_j(z)\,\chi^{(j)}(x) \\ \bar{\psi}(x,z) &= \sum_{j=1} f_j(z)\,\bar{\psi}^{(j)}(x) \end{aligned}$$

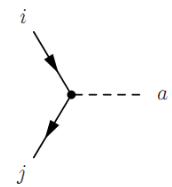
  - Usual vertex between fermion zero mode and KK gluon:

$$\int d^4x\left\{C_R\psi^{(0)}\sigma^\mu A^{(1)}_\mu\bar{\psi}^{(0)} + C_L\bar{\chi}^{(0)}\bar{\sigma}^\mu A^{(1)}_\mu\chi^{(0)}\right\}$$




  - Extra vertex between fermion zero mode and Goldstone boson, required by gauge invariance

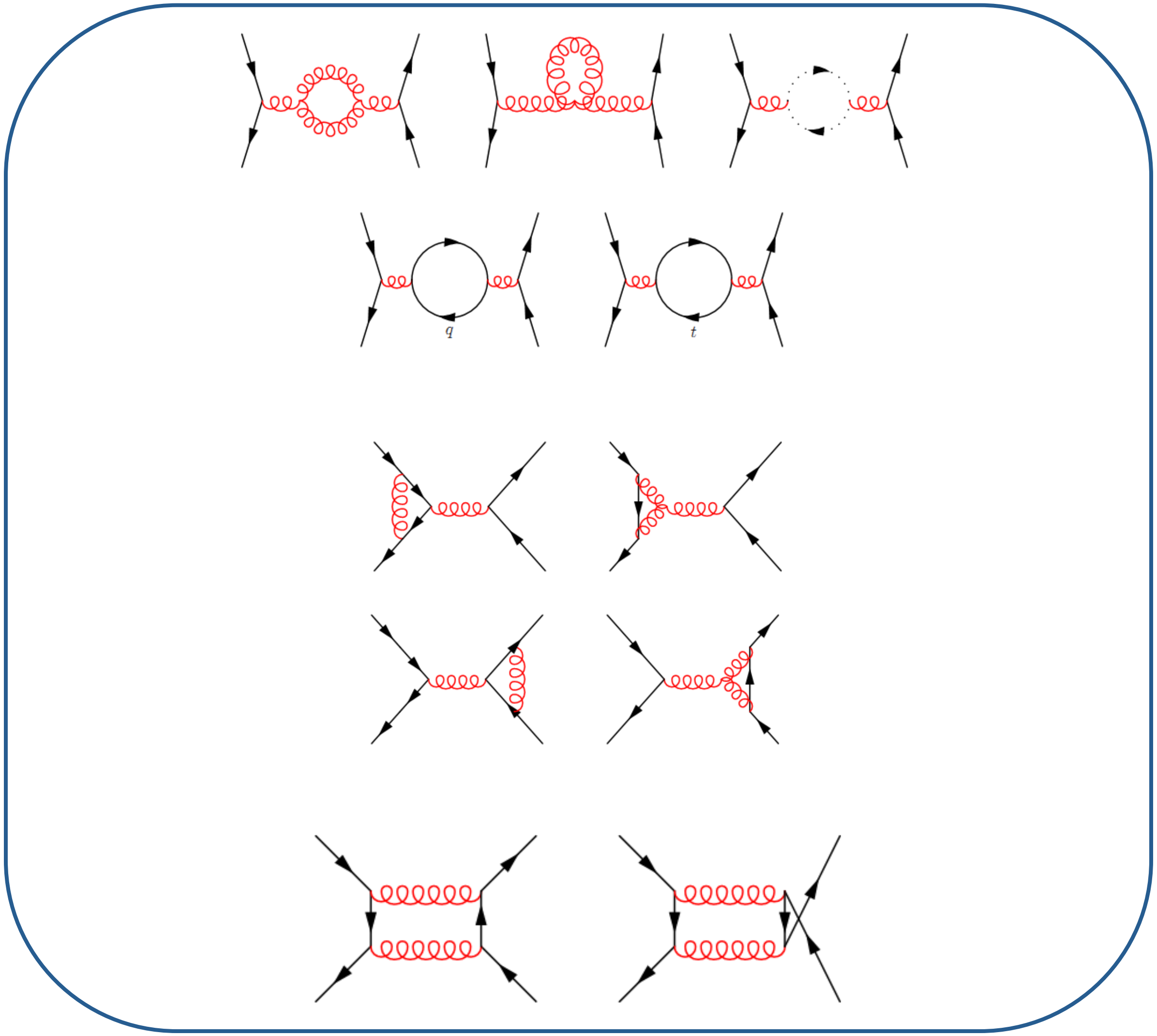
$$\int d^4x\left(-i\frac{M_0}{m_{KK}}\right)(C_R - C_L)\left(-\psi^{(0)}\chi^{(0)}+\bar{\chi}^{(0)}\bar{\psi}^{(0)}\right)A^{(1)}_5$$




- Using these Feynman rules, we perform a complete NLO QCD calculation for ttbar production in the Randall-Sundrum model.

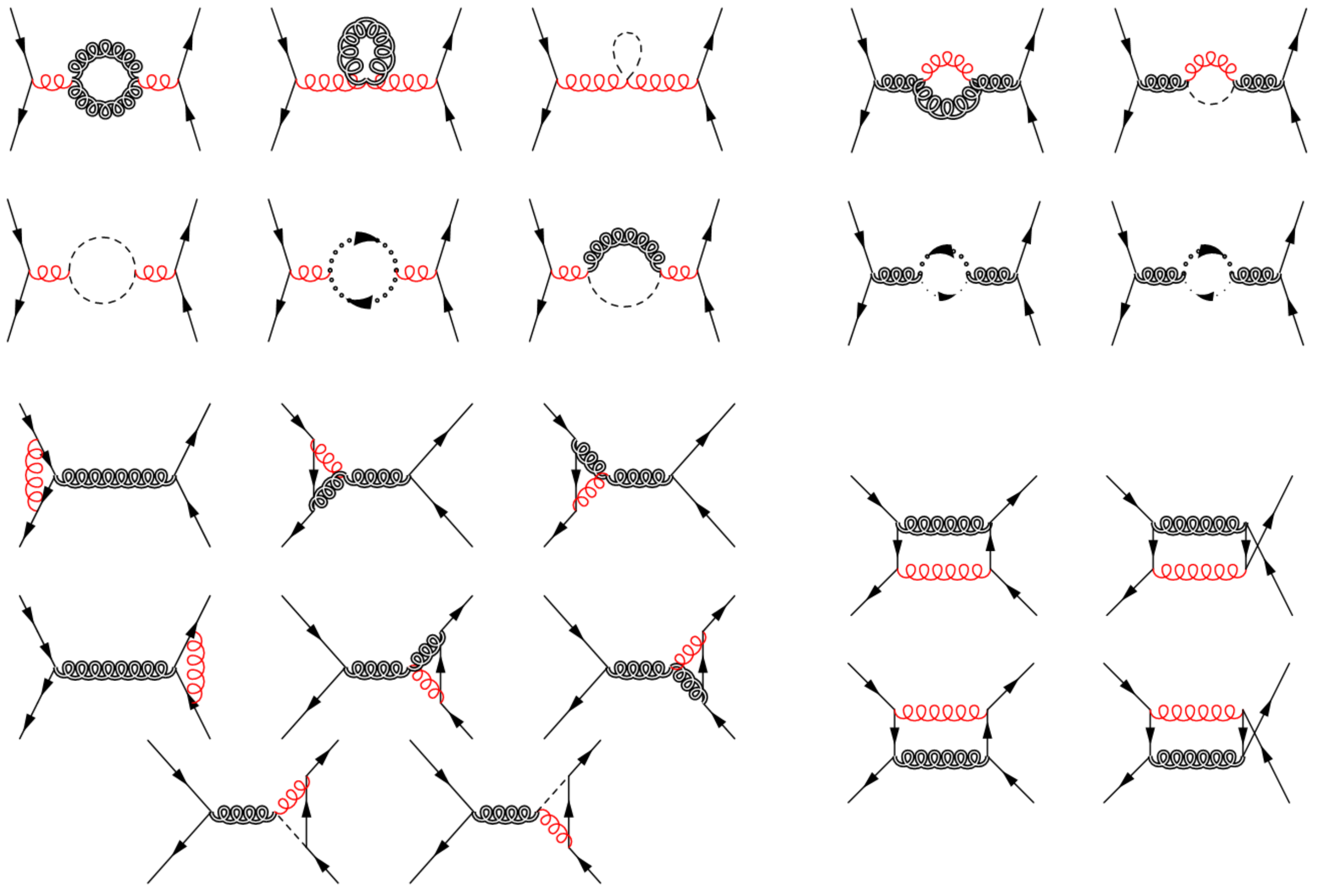
# • pp(pbar) -> ttbar: virtual corrections

- SM one-loop Feynman diagrams:



# • pp(pbar) -> ttbar: virtual corrections

➢ KK gluon induced one-loop Feynman diagrams:



# • pp(pbar) -> ttbar: virtual corrections

- Amplitudes analytically calculated in modified spinor-helicity formalism (Kleiss and Stirling, 1985), full spin information.

  - Massive momentum is decomposed as:

$$p = p^\flat + \frac{M^2}{2p\cdot\eta}\eta, \quad p^2 = M^2, \quad \left(p^\flat\right)^2 = \eta^2 = 0.$$

  - Massive spinor can then be written as:

$$u_\pm\left(p, M; \eta, p^\flat\right) = \frac{\left(\not{p} + M\right)|\eta^\mp\rangle}{\langle p^{\flat\pm}|\eta^\mp\rangle}, \quad \overline{u_\pm}\left(p, M; \eta, p^\flat\right) = \frac{\langle\eta^\mp|\left(\not{p} + M\right)}{\langle\eta^\mp|p^{\flat\pm}\rangle}$$

$$v_\pm\left(p, M; \eta, p^\flat\right) = \frac{\left(\not{p} - M\right)|\eta^\pm\rangle}{\langle p^{\flat\mp}|\eta^\pm\rangle}, \quad \overline{v_\pm}\left(p, M; \eta, p^\flat\right) = \frac{\langle\eta^\pm|\left(\not{p} - M\right)}{\langle\eta^\pm|p^{\flat\mp}\rangle}$$

  We only need to calulcate the helicity (++++) and (+-++). The other configuration can be obtained using the above formula.

- We do the one-loop reduction in conventional Passarino-Veltman formalism, and simplify the resulting expressions to a compact form.

- Unstable particle treated in complex mass scheme, therefore full on shell and finite width effects (Denner, Dittmaier, Roth, Wieders, 2005)

- All the amplitudes are reduced to a combination of 4 independent spinor-helicity product:

$$\langle \eta_4\, 1\rangle\, \langle \eta_3|\mathbf{3}|2] \qquad \langle \eta_3\, 1\rangle\, \langle \eta_4|\mathbf{4}|2]$$

$$\langle \eta_4\, 2\rangle\, \langle \eta_3|\mathbf{3}|1] \qquad \langle \eta_3\, 2\rangle\, \langle \eta_4|\mathbf{4}|1]$$

where the symbol | j > and | j ] are abbreviation of chiral spinor:

$$|i\rangle \;= |i+\rangle = u_+(k_i),\ \ |i] \;= |i-\rangle = u_-(k_i)\ ,$$
$$\langle i| \;= \langle i-| = \bar{u}_-(k_i),\ \ [i| \;= \langle i+| = \bar{u}_+(k_i)\ .$$

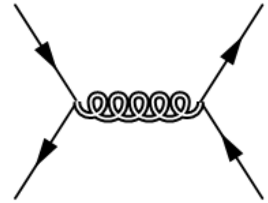
For example, the first spinor string is:

$$\langle \eta_4 1\rangle\langle \eta_3|\mathbf{3}|2] = \bar{u}_-(\eta_4)u_+(p_1)\bar{u}_-(\eta_3)\not{p}_3 u_-(p_2)$$

# • pp(pbar) -> ttbar: virtual corrections

Only two helicity configuration need to be calculated; the others can be obtained by simple replacement.

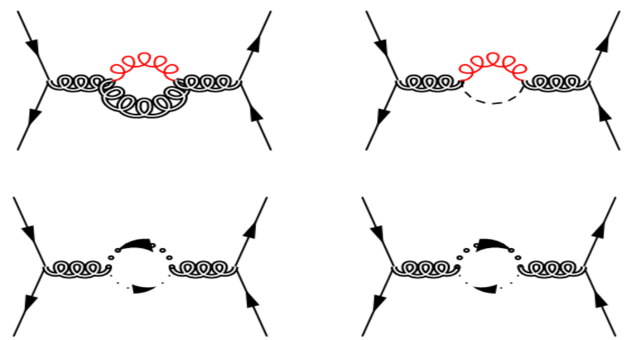
- Relatively compact helicity amplitude:
  - Tree diagram:



$$\mathcal{A}_{tree,KK}(+,-,+,+) = \frac{2iC_R^q m_t}{s-m_{KK}^2}\,\frac{C_R^t\,\langle\eta_4\,1\rangle\,\langle\eta_3|\mathbf{3}|2] + C_L^t\,\langle\eta_3\,1\rangle\,\langle\eta_4|\mathbf{4}|2]}{\langle 3^\flat\,\eta_3\rangle\,\langle\eta_4\,4^\flat\rangle},$$

$$\mathcal{A}_{tree,KK}(-,+,+,+) = \frac{2iC_L^q m_t}{s-m_{KK}^2}\,\frac{C_R^t\,\langle\eta_4\,2\rangle\,\langle\eta_3|\mathbf{3}|1] + C_L^t\,\langle\eta_3\,2\rangle\,\langle\eta_4|\mathbf{4}|1]}{\langle 3^\flat\,\eta_3\rangle\,\langle\eta_4\,4^\flat\rangle}.$$

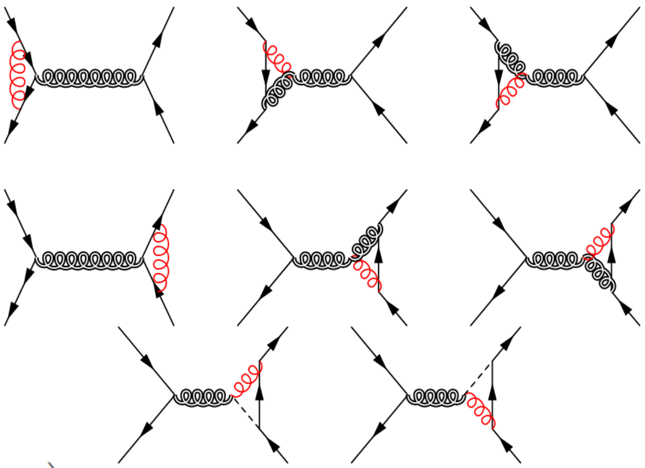
  - Self energy diagram:



$$\mathcal{A}_{sf,KK}(\lambda_1,\lambda_2,\lambda_3,\lambda_4) = \mathcal{A}_{tree,KK}(\lambda_1,\lambda_2,\lambda_3,\lambda_4)\,\frac{\alpha_s}{\pi}\,\frac{s}{s-m_{KK}^2}\left\{\frac{1}{\epsilon_{\rm UV}}\left(\frac{9m_{KK}^2}{4s}+\frac{5}{2}\right)\right.$$
$$+\frac{1}{12s^3}\left[3\ln\left(\frac{m_{KK}^2}{\mu^2}\right)\left(2m_{KK}^4-6sm_{KK}^2-15s^2\right)m_{KK}^2\right.$$
$$\left.\left.-6\ln\left(\frac{m_{KK}^2-s}{\mu^2}\right)\left(m_{KK}^6-3sm_{KK}^4-3s^2m_{KK}^2+5s^3\right)+s\left(-6m_{KK}^4+51sm_{KK}^2+56s^2\right)\right]\right\}$$

# • pp(pbar) -> ttbar: virtual corrections

- Relatively compact helicity amplitude:
  - Triangle diagram:



$$\mathcal{A}^q_{vt,KK}(\lambda_1,\lambda_2,\lambda_3,\lambda_4) = \mathcal{A}_{tree,KK}(\lambda_1,\lambda_2,\lambda_3,\lambda_4)\,\frac{\alpha_s}{\pi}\left\{\frac{53}{24\epsilon_{\text{UV}}}+\frac{1}{12\epsilon^2_{\text{IR}}}\right.$$
$$+\frac{1}{\epsilon_{\text{IR}}}\left[-\frac{3m^2_{KK}}{2s}\ln\left(\frac{m^2_{KK}-s}{m^2_{KK}}\right)-\frac{1}{12}\ln\left(-\frac{s}{\mu^2}\right)-\frac{4}{3}\right]+\frac{1}{24}\ln^2\left(-\frac{s}{\mu^2}\right)-\frac{1}{8}\ln\left(-\frac{s}{\mu^2}\right)$$
$$+\frac{3}{2}C_0\left(0,0,s,m^2_{KK},0,0\right)m^2_{KK}-\frac{3m^2_{KK}}{4s}+\ln\left(\frac{m^2_{KK}-s}{\mu^2}\right)\left(\frac{3}{4}-\frac{3m^4_{KK}}{4s^2}\right)$$
$$\left.+\frac{3}{4}\ln\left(\frac{m^2_{KK}}{\mu^2}\right)\left(\frac{m^4_{KK}}{s^2}-2\right)+\frac{25}{24}\right\}, \qquad (75)$$

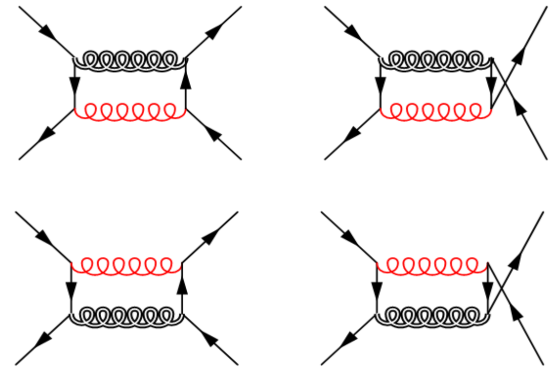
$$\mathcal{A}^t_{vt,KK}(+,-,+,+) = \frac{2iC^q_R m_t}{s-m^2_{KK}}\frac{\alpha_s}{\pi}\frac{1}{\langle 3^\flat\,\eta_3\rangle\langle\eta_4\,4^\flat\rangle}\left\{B^{KK}_1\left(C^t_R\langle\eta_4\,1\rangle\langle\eta_3|\mathbf{3}|2] + C^t_L\langle\eta_3\,1\rangle\langle\eta_4|\mathbf{4}|2]\right)\right.$$
$$+B^{KK}_2\left(C^t_R+C^t_L\right)\left(\langle\eta_4\,1\rangle\langle\eta_3|\mathbf{3}|2]+\langle\eta_3\,1\rangle\langle\eta_4|\mathbf{4}|2]\right)$$
$$\left.+B^{KK}_3\left(C^t_R+C^t_L\right)\left(m^2_t\,[2\,1]\langle\eta_3\,1\rangle\langle\eta_4\,1\rangle+\langle 1\,2\rangle\langle\eta_3|\mathbf{3}|2]\langle\eta_4|\mathbf{4}|2]\right)\right\},$$

$$\mathcal{A}^t_{vt,KK}(-,+,+,+) = \frac{2iC^q_L m_t}{s-m^2_{KK}}\frac{\alpha_s}{\pi}\frac{1}{\langle 3^\flat\,\eta_3\rangle\langle\eta_4\,4^\flat\rangle}\left\{B^{KK}_1\left(C^t_R\langle\eta_4\,2\rangle\langle\eta_3|\mathbf{3}|1] + C^t_L\langle\eta_3\,2\rangle\langle\eta_4|\mathbf{4}|1]\right)\right.$$
$$+B^{KK}_2\left(C^t_R+C^t_L\right)\left(\langle\eta_4\,2\rangle\langle\eta_3|\mathbf{3}|1]+\langle\eta_3\,2\rangle\langle\eta_4|\mathbf{4}|1]\right)$$
$$\left.-B^{KK}_3\left(C^t_R+C^t_L\right)\left(m^2_t\,[2\,1]\langle\eta_3\,2\rangle\langle\eta_4\,2\rangle+\langle 1\,2\rangle\langle\eta_3|\mathbf{3}|1]\langle\eta_4|\mathbf{4}|1]\right)\right\}, \qquad (76)$$

The massive vertex amplitude doesn't proportional to tree amplitude. The form factor BKK contain all the corrections.

# • pp(pbar) -> ttbar: virtual corrections

- Relatively compact helicity amplitude:



- Box diagram:

$$\mathcal{A}_{b1,KK}(+,-,+,+) = \frac{2iC_R^q m_t}{\langle 3^\flat\,\eta_3\rangle\langle\eta_4\,4^\flat\rangle}\frac{\alpha_s}{\pi}\Big\{\Big(B_{4,1}^{KK}C_R^t\langle\eta_4\,1\rangle\langle\eta_3|\mathbf{3}|2] + B_{4,2}^{KK}C_L^t\langle\eta_3\,1\rangle\langle\eta_4|\mathbf{4}|2]\Big)$$
$$+\Big(B_{5,1}^{KK}C_L^t\langle\eta_4\,1\rangle\langle\eta_3|\mathbf{3}|2] + B_{5,2}^{KK}C_R^t\langle\eta_3\,1\rangle\langle\eta_4|\mathbf{4}|2]\Big)$$
$$+\Big(B_{6,1}^{KK}C_R^t + B_{6,2}^{KK}C_L^t\Big)\Big(m_t^2\,[2\,1]\langle\eta_3\,1\rangle\langle\eta_4\,1\rangle + \langle 1\,2\rangle\langle\eta_3|\mathbf{3}|2]\langle\eta_4|\mathbf{4}|2]\Big)\Big\}$$

$$\mathcal{A}_{b1,KK}(-,+,+,+) = \frac{2iC_L^q m_t}{\langle 3^\flat\,\eta_3\rangle\langle\eta_4\,4^\flat\rangle}\frac{\alpha_s}{\pi}\Big\{\Big(B_{4,2}^{KK}C_R^t\langle\eta_4\,2\rangle\langle\eta_3|\mathbf{3}|1] + B_{4,1}^{KK}C_L^t\langle\eta_3\,2\rangle\langle\eta_4|\mathbf{4}|1]\Big)$$
$$+\Big(B_{5,2}^{KK}C_L^t\langle\eta_4\,2\rangle\langle\eta_3|\mathbf{3}|1] + B_{5,1}^{KK}C_R^t\langle\eta_3\,2\rangle\langle\eta_4|\mathbf{4}|1]\Big)$$
$$-\Big(B_{6,2}^{KK}C_R^t + B_{6,1}^{KK}C_L^t\Big)\Big(m_t^2\,[2\,1]\langle\eta_3\,2\rangle\langle\eta_4\,2\rangle + \langle 1\,2\rangle\langle\eta_3|\mathbf{3}|1]\langle\eta_4|\mathbf{4}|1]\Big)\Big\}$$

The massive box amplitude doesn’t proportional to tree amplitude. The coefficient $B^{KK}_{ij}$ are the form factors of box corrections, which are consist of IR terms, function of logarithm, dilogarithm, etc,  which appear in one-loop corrections.

- Amplitudes for crossed box diagrams are in a similar form.
- Other amplitudes of box diagrams can be expressed as their combinations
- There is no UV divergence, and IR divergence is solely proportional to the tree amplitudes:

$$
\begin{aligned}
\mathcal{A}_{b1,KK}(\lambda_1,\lambda_2,\lambda_3,\lambda_4) &= \mathcal{A}_{tree,KK}(\lambda_1,\lambda_2,\lambda_3,\lambda_4)\frac{\alpha_s}{4\pi}\left\{-\frac{2}{\epsilon_{\mathrm{IR}}^2}+\frac{2}{\epsilon_{\mathrm{IR}}}\left(2\ln\left(\frac{t_1}{\mu^2}\right)\right.\right.\\
&\left.\left.-\ln\left(\frac{m_t^2}{\mu^2}\right)+\frac{2m_{KK}^2}{s}\ln\left(\frac{m_{KK}^2-s}{m_{KK}^2}\right)\right)\right\}+\cdots\\
\mathcal{A}_{b2,KK}(\lambda_1,\lambda_2,\lambda_3,\lambda_4) &= \mathcal{A}_{tree,KK}(\lambda_1,\lambda_2,\lambda_3,\lambda_4)\frac{\alpha_s}{4\pi}\left\{\frac{2}{\epsilon_{\mathrm{IR}}^2}-\frac{2}{\epsilon_{\mathrm{IR}}}\left(2\ln\left(\frac{u_1}{\mu^2}\right)\right.\right.\\
&\left.\left.-\ln\left(\frac{m_t^2}{\mu^2}\right)+\frac{2m_{KK}^2}{s}\ln\left(\frac{m_{KK}^2-s}{m_{KK}^2}\right)\right)\right\}+\cdots
\end{aligned}
$$

# • pp(pbar) -> ttbar: renormalization

➢ Wave function of external fields are renormalized as in SM.

$$\delta Z_{g_s} = -\delta Z_{\Gamma}^{\overline{\rm MS}} - \delta Z_{q}^{\overline{\rm MS}} - \frac{1}{2}\delta Z_{g}^{\overline{\rm MS}}$$

$$\delta Z_q^{\rm OS} = -\frac{\alpha_s}{3\pi}\left\{\frac{1}{\epsilon_{\rm UV}} - \frac{1}{\epsilon_{\rm IR}}\right\},$$

$$\delta Z_t^{\rm OS} = \frac{\alpha_s}{3\pi}\left\{-\frac{1}{\epsilon_{\rm UV}} - \frac{2}{\epsilon_{\rm IR}} + 3\ln\left(\frac{m_t^2}{\mu^2}\right) - 5\right\}$$

➢ The remaining UV divergences can be absorbed into the redefinition of chiral coupling between quark zero mode and KK gluon.

$$\delta m_{KK}^2 = m_{KK}^2\frac{\alpha_s}{\pi}\left\{-\frac{19}{4\epsilon_{\rm UV}} + \frac{19}{4}\ln\left(\frac{m_{KK}^2}{\mu^2}\right) - \frac{101}{12}\right\},$$

$$\delta Z_{KK} = \frac{\alpha_s}{\pi}\left\{\frac{5}{2\epsilon_{\rm UV}} - \frac{3}{2\epsilon_{\rm IR}} - \ln\left(\frac{m_{KK}^2}{\mu^2}\right) + \frac{13}{6}\right\}.$$

$$\delta Z_{C_{L,R}^{q/t}} = -\delta Z_{\Gamma_{KK}}^{\overline{\rm MS}} - \delta Z_{q/t}^{\overline{\rm MS}} - \frac{1}{2}\delta Z_{KK}^{\overline{\rm MS}},$$

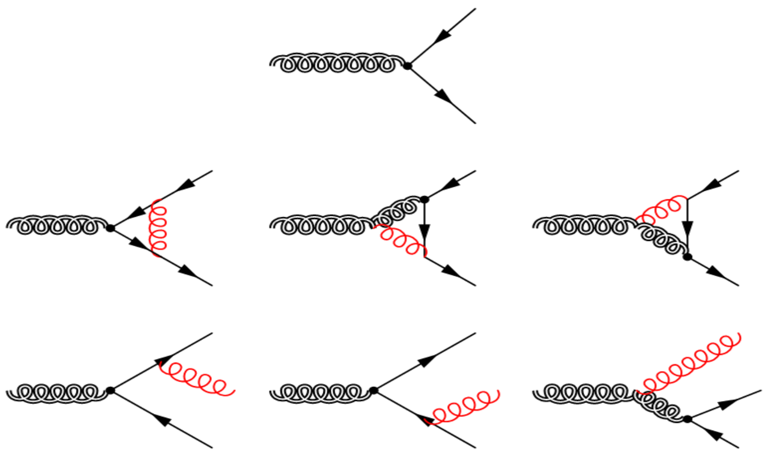
# • pp(pbar) -> ttbar: real corrections

➢ One-loop virtual corrections are IR divergent. The divergences are due to soft and collinear gluon effects, and have the same structure as SM. In general , the divergences are canceled when combined with real corrections and mass factorization as one done in the SM.

➢ Actually we use dipole subtraction method to cancel IR divergences in this work. We implement KK gluon model into the program MADDIPOLE and generating the corresponding dipole terms automatically.

# • KK gluon decay: NLO width

➢ We can also use the Feynman rule to calculate the NLO decay width of KK gluon:



$$\Gamma^I_{KK} = m_{KK}\frac{\left(C^I_L(\mu_R)\right)^2+\left(C^I_R(\mu_R)\right)^2}{48\pi}\left[1+\frac{\alpha_s}{\pi}\left(\frac{167}{12}-\pi^2-\frac{15}{4}\ln\frac{m^2_{KK}}{\mu^2_R}\right)\right]$$

➢ For large couplings, the total decay width is large, ~10%, which invalidates the narrow approximation, which lead that production and decay can not be separated, and is one of motivation of this work. A simple framework for dealing with virtual particles with large width is the so-called complex mass scheme, where mass is complex,

$$m^2_{KK} = \tilde{m}^2_{KK} - i\tilde{m}_{KK}\Gamma_{KK},$$

where $\tilde{m}_{KK}$ is a real mass. All the mass terms in the Feynman rules and in the helicity amplitudes should be understood as complex number.

## Some preliminary numerical result

We choose a set of coupling parameter similar to the work of Djouadi et.al, which can fit the various precise EW data:

| | u | d | c | s | t | b |
|---|---|---|---|---|---|---|
| L | 0.61 | 0.61 | -0.19 | -0.19 | -0.06 | -0.06 |
| R | -0.19 | -0.19 | -0.19 | 0.07 | 7.19 | -0.14 |

↑

**Parameters for the coupling between quark and KK gluon**

**Top quark mass and KK gluon mass**

↓

$$m_t = 173.1\text{GeV} \qquad m_{KK} = 1.5\text{TeV}$$

# ➢ Some preliminary numerical result

**Total cross section at the Tevatron: theory**

$$\sigma_{\rm SM}^{\rm LO} = 5.45{\rm pb}, \qquad \sigma_{\rm SM+NP}^{\rm LO} = 5.07{\rm pb}$$
$$\sigma_{\rm SM}^{\rm NLO} = 6.77{\rm pb}, \qquad \sigma_{\rm SM+NP}^{\rm NLO} = 6.33{\rm pb}$$

VS

**CDF measured cross section (PRL 102,222003)**

$$\sigma_{t\bar{t}}^{\rm incl.} = 6.9 \pm 1.0 \ {\rm pb}$$

- **CDF measured FB asymmetry (PRD 83,112003)**

$$A_{\rm FB}^{t\bar{t}}(m_{t\bar{t}} > 450 \ {\rm GeV}) = 0.475 \pm 0.114$$

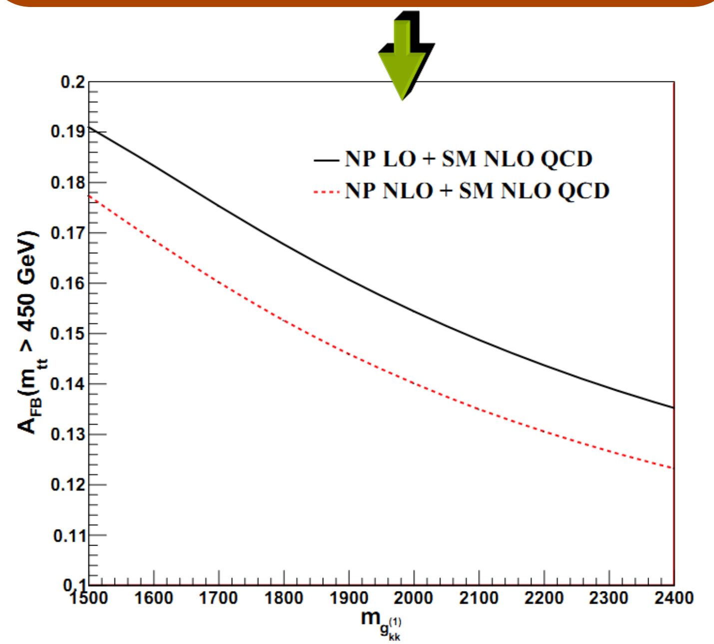
- **SM predictions (Ahrens, et al, 2011)**

$$A_{\rm FB}^{t\bar{t}}(M_{t\bar{t}} \geq 450\,{\rm GeV}) = 10.8^{+1.7}_{-0.9}\,(\%)$$

- **Predictions in RS model at LO (Djouadi et al. 2011)**

$A_{FB}^{t\bar{t}}(M_{t\bar{t}} \geq 450 GeV) \sim 0.27$ **within 2$\sigma$ from data**

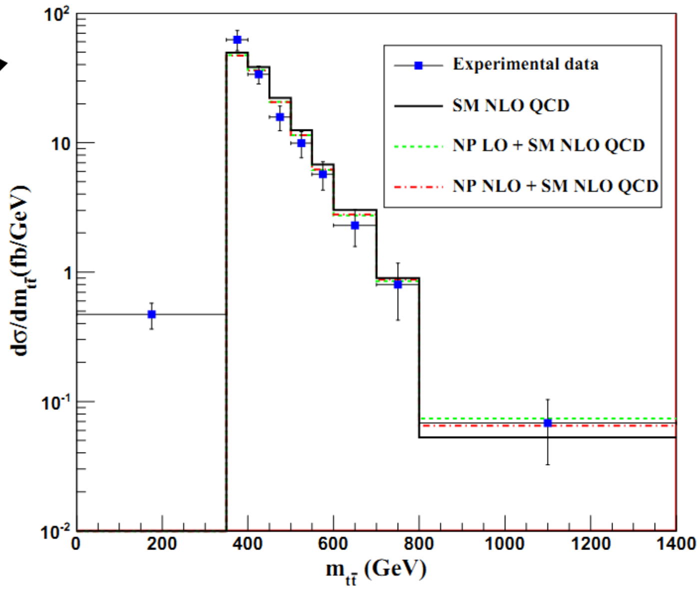
Forward-Backward asymmetry in the large invariant mass region with different KK gluon mass



# ➢ Some preliminary numerical result

➢ Invariant mass distribution at the Tevatron

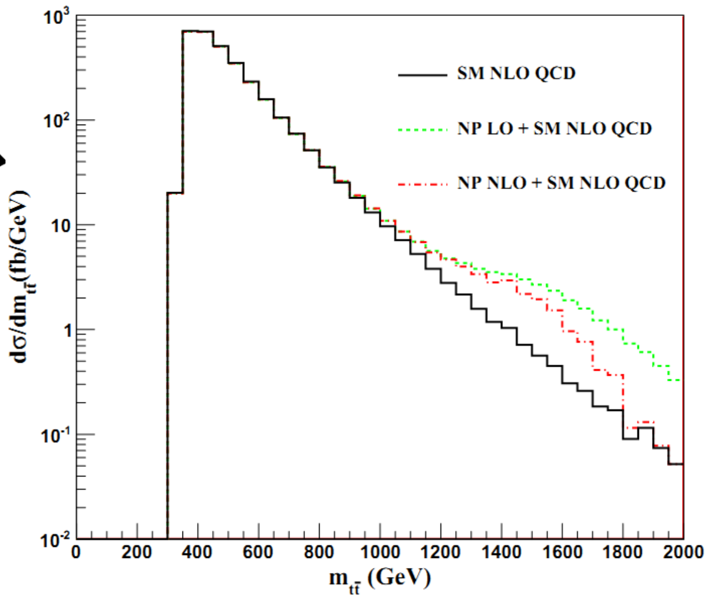
➢ At small invariant mass, NLO effects from KK gluon are negative and small; at large invariant mass, the effects from KK gluon is positive. In general, inclusion of KK gluon leads to better agreement between theory and experiment.




➢ Invariant mass distribution at the LHC (7 TeV).

➢ Obvious deviation from LO distribution is observed at the resonant region.

➢ Numerical accuracy at large invariant mass is low, result stay tuned.



# Summary

- **Top pair production induced by KK gluon is one of the most important signal of warped extra dimension model.**

- **We have carried out a consistent quantization of KK gluon field in warped extra dimension model . A set of interaction vertices uniquely determined by gauge invariance are derived, which enable us to perform a study of QCD effects in the RS model.**

- **We show for the first time how to calculate renormalized one-loop amplitudes for ttbar production induced by KK gluon.**

- **We present an up-to-date most accurate predictions of ttbar total cross section, forward-backward asymmetry and invariant mass distribution in RS model. For the parameters we have chosen, NLO QCD effects reduce the cross section and Forward-Backward asymmetry, comparing with the LO result, but still improve the SM predictions comparing with CDF data.**

- **There is small difference at the LO comparing with the result of Diouadi et al, because of some differences in the choice of parameters.**

# *Thank you!*