Diphoton production in the RS model at the LHC.

M.C.Kumar
Saha Institute of Nuclear Physics

In collaboration with
Prakash Mathews, V.Ravindran and Anurag Tripathi

Plan of the talk

1. RS Model
2. Diphoton production
3. Phase space slicing method
4. cuts
5. stability
6. SM NLO results
7. RS model NLO results
8. conclusions

RS MODEL

1. There is only one extra dimension.
2. The gravity only can propagate in the $bulk$ while the SM fields are confined to the $brane$.
3. There are two branes on the extra dimension, namely $SM\ brane$ and the $Planck\ brane$ at $\phi = \pi$ and $\phi = 0$ respectively.
4. The space time is highly warped. The $warp\ factor$ is responsible for the large $hierarchy$ between the electroweak scale and the Planck scale.
5. The size of the extra dimension need not be very large.
6. The RS modes are $very\ massive$ and are not evenly spaced.
7. The metric in the RS model is given by

$$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2\, d\phi^2$$

8. The effective coupling of the RS modes with the SM fields is $c_0 = \frac{k}{M_{Pl}}$

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L.Randall and R.Sundrum

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$$m_n = x_n k \text{exp}(-\pi k r_c) \equiv x_n m_0$$
$$\text{and } c_0 = \frac{k}{M_{Pl}}, k \sim M_{Pl}$$

The sum over the KK(RS) modes is given by

$$\mathcal{D}(Q^2) \quad = \quad \sum_{n=1}^{\infty} \frac{1}{s - m_n^2 + i\, m_n \Gamma_n}$$

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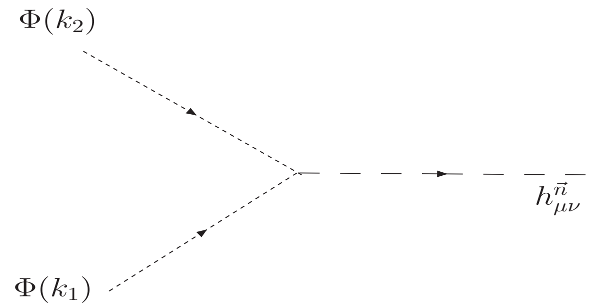
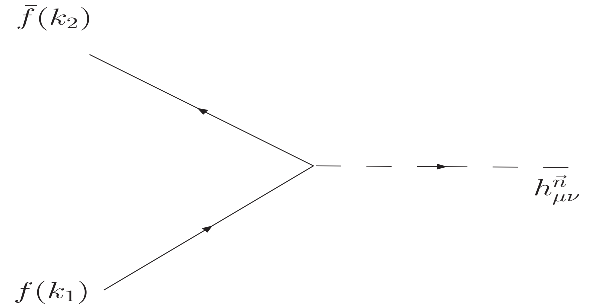
Parameters

- $M_1 = 1.5$ TeV for LHC
- Effective coupling between RS modes and the SM fields, $c_o = 0.01$

Additional interactions

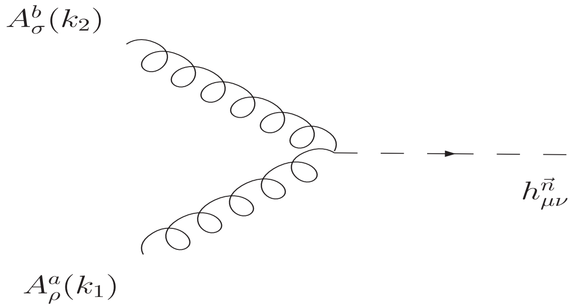


$$h^{\vec{n}}_{\mu\nu}\Phi\Phi : \quad -i\frac{\kappa}{2}\delta_{mn}[m_\Phi^2\eta_{\mu\nu} + C_{\mu\nu,\rho\sigma}k_1^\rho k_2^\sigma]$$

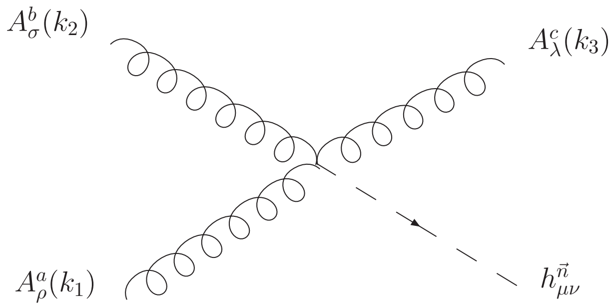


$$h^{\vec{n}}_{\mu\nu}\bar{\psi}\psi : \quad -i\frac{\kappa}{8}\delta_{mn}[\gamma_\mu(k_{1\nu} + k_{2\nu}) + \gamma_\nu(k_{1\mu} + k_{2\mu}) - 2\eta_{\mu\nu}(\not{k}_1 + \not{k}_2 - 2m_\psi)]$$

Additional interactions

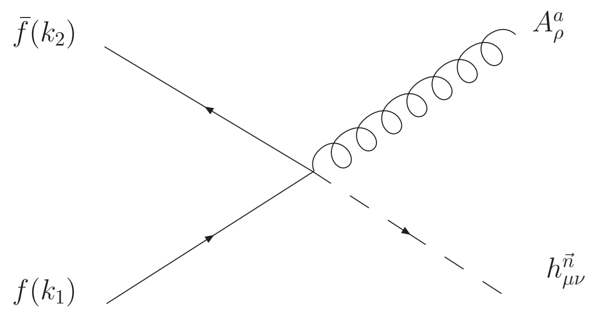


$$h^{\vec{n}}_{\mu\nu}AA: \quad -i\frac{\kappa}{2}\delta^{ab}[(m_A^2 + k_1\dot{k}_2)C_{\mu\nu,\rho\sigma} + D_{\mu\nu,\rho\sigma}(k_1,k_2) + \xi^{-1}E_{\mu\nu,\rho\sigma}(k_1,k_2)]$$



$$h^{\vec{n}}_{\mu\nu}AAA: \quad -g\frac{\kappa}{2}f^{abc}[C_{\mu\nu,\rho\sigma}(k_{1\lambda} - k_{2\lambda}) + C_{\mu\nu,\rho\lambda}(k_{3\sigma} - k_{1\sigma}) + C_{\mu\nu,\sigma\lambda}(k_{2\rho} - k_{3\rho}) + F_{\mu\nu,\rho\sigma\lambda}(K_1,k_2,k_3)]$$

Additional interactions



$$h^{\vec{n}}_{\mu\nu}\bar{\psi}\psi A: \quad -ig\frac{\kappa}{4}T^a_{nm}(C_{\mu\nu,\rho\sigma}-\eta_{\mu\nu}\eta_{\rho\sigma})\gamma^\sigma$$

where

$$\begin{aligned}
C_{\mu\nu,\rho\sigma} &= \eta_{\mu\rho}\eta_{\nu\sigma}+\eta_{\mu\sigma}\eta_{\nu\rho}-\eta_{\mu\nu}\eta_{\rho\sigma}\\
D_{\mu\nu,\rho\sigma}(k_1,k_2) &= \eta_{\mu\nu}k_{1\sigma}k_{2\rho}-[\eta_{\mu\sigma}k_{1\nu}k_{2\rho}+\eta_{\mu\rho}k_{1\sigma}k_{2\nu}-\eta_{\rho\sigma}k_{1\mu}k_{2\nu}+(\mu\leftrightarrow\nu)]\\
E_{\mu\nu,\rho\sigma}(k_1,k_2) &= \eta_{\mu\nu}(k_{1\rho}k_{1\sigma}+k_{2\rho}k_{2\sigma}+k_{1\rho}k_{2\sigma})-[\eta_{\nu\sigma}k_{1\mu}k_{1\rho}+\eta_{\nu\rho}k_{2\mu}k_{2\sigma}+(\mu\leftrightarrow\nu)]\\
F_{\mu\nu,\rho\sigma\lambda}(k_1,k_2,k_3) &= \eta_{\mu\rho}\eta_{\sigma\lambda}(k_2-k_3)_\nu+\eta_{\mu\sigma}\eta_{\rho\lambda}(k_3-k_1)_\nu+\eta_{\mu\lambda}\eta_{\rho\sigma}(k_1-k_2)_\rho+(\mu\leftrightarrow\nu)
\end{aligned}$$

and $\kappa=\dfrac{1}{M_{Pl}}$

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T.Han, J.D.Lykken, R-J. Zhang

Diphoton production

It is the process in which two Hadrons collide to give photon pair.

$$P_1(p_1) + P_2(p_2) \rightarrow \gamma(p_3) + \gamma_{(}p_4) + X(p_x)$$

- The interaction takes place at the parton level and the $sea\ quarks$ play an important role.
- SM LO : quark anti-quark annilations (EM)
- BSM: quark anti-quark annihilations as well as gluon gluon fusions
- The ED signal can be looked for due to the large gluon flux at LHC.

Hadronic cross section

The hadronic cross section can be expressed in terms of the partonic cross sections convoluted with the appropriate partonic distribution functions as

$$d\sigma^{P_1 P_2} = \sum_{ab=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2 f_a^{P_1}(x_1, \mu_F) f_b^{P_2}(x_2, \mu_F) d\hat{\sigma}^{ab}(x_1, x_2)$$

where $$d\hat{\sigma}^{ab}\,(x_1, x_2) \;=\; d\hat{\sigma}^{ab}_{SM}\,(x_1, x_2) \;+\; d\hat{\sigma}^{ab}_{BSM}\,(x_1, x_2)$$

LO matrix elements

$$\begin{aligned}
|\overline{M}_{q\bar{q}}|^2 &= \frac{1}{8N}\Bigg[e^4 Q_f^4 8\left(\frac{u}{t}+\frac{t}{u}\right) \\
&\quad -8e^2 Q_f^2 c_0^2 \mathcal{D}(Q^2)\frac{1}{s^2}(u^2+t^2) \\
&\quad +2c_0^4\left(\mathcal{D}(Q^2)\right)^2 \frac{1}{s^4} tu(u^2+t^2)\Bigg] \\
|\overline{M}_{gg}|^2 &= \frac{1}{8(N^2-1)} 2c_0^4\left(\mathcal{D}(Q^2)\right)^2 \frac{1}{s^4}(u^4+t^4)
\end{aligned}$$

Two cut off phase space slicing method

1. Separation of the singular regions from the three body phase space
2. Introduce two parameters namely δ_s and δ_c for separating soft and collinear regions.
3. Regularize this singular region in n-dimensions
4. Cancellation of infra red divergences between real and virtual diagrams.
5. Initial state collinear singularities are absorbed into Parton Distribution Functions.
6. Integration over the remaining hard and non-collinear part in 4-dim.
7. Physical observables should not depend on the parameters δ_s and δ_c. Finding the stable region of these two parameters.

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B.W.Harris and J.F.Owens

Soft

Suppose a process where p_5 is soft

$$p_1 + p_2 = p_3 + p_4 + p_5$$

soft region is : $0 \leq E_5 \leq \delta_s \sqrt{s_{12}}/2.$

The three body phase space in $n - dim$ in the soft region is

$$\begin{aligned} d\Gamma_3|_{\text{soft}} &= \left[\frac{d^{n-1}p_3}{2p_3^0(2\pi)^{n-1}} \frac{d^{n-1}p_4}{2p_4^0(2\pi)^{n-1}} (2\pi)^n \delta^n(p_1 + p_2 - p_3 - p_4) \right] \frac{d^{n-1}p_5}{2p_5^0(2\pi)^{n-1}} \\ &= d\Gamma_2 \left[\left(\frac{4\pi}{s_{12}} \right)^{\epsilon} \frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)} \frac{1}{2(2\pi)^2} \right] dS \\ \text{with } dS &= \frac{1}{\pi} \left(\frac{4}{s_{12}} \right)^{-\epsilon} \int_0^{\delta_s \sqrt{s_{12}}/2} dE_5 E_5^{1-2\epsilon} \sin^{1-2\epsilon}\theta_1 \, d\theta_1 \sin^{-2\epsilon}\theta_2 \, d\theta_2 \end{aligned}$$

Soft

Matrix element ($2 \to 3$) in this region can be approximated to

$$M_3^a|_{\mathrm{soft}} \simeq g\mu_r^{\epsilon}\varepsilon^{\mu}(p_5)\mathbf{J}_{\mu}^a(p_5)\mathbf{M}_2$$

with Eikonal current $\mathbf{J}_{\mu}^a(p_5) = \sum_{f=1}^{4} \mathbf{T}_f^a \frac{p_f^{\mu}}{p_f \cdot p_5}$

The cross section in the soft region will be

$$d\sigma_{\mathrm{S}} = \left[\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu_r^2}{s_{12}}\right)^{\epsilon}\right]\sum_{f,f'=1}^{4} d\sigma_{ff'}^0 \int \frac{-p_f \cdot p_{f'}}{p_f \cdot p_5 \; p_{f'} \cdot p_5} dS$$

where $d\sigma_{ff'}^0 = \frac{1}{2\Phi}\overline{\sum} M_{ff'}^0 d\Gamma_2$.

Collinear

The hard collinear region is : $0 \leq t_{15} \leq \delta_c s12$ where $\delta_c << \delta_s$.

Phase space in this collinear region :

$$\begin{aligned} d\Gamma_3|_{coll} &= \left[\frac{d^{n-1}p_3}{2p_3^0(2\pi)^{n-1}}\frac{d^{n-1}p_4}{2p_4^0(2\pi)^{n-1}}(2\pi)^n\delta^n(zp_1+p_2-p_3-p_4)\right] \\ &\times \frac{(4\pi)^\epsilon}{16\pi^2\Gamma(1-\epsilon)}dz dt_{15}[-(1-z)t_{15}]^{-\epsilon} \end{aligned}$$

Corresponding matrix element squared :

$$\overline{\sum}|M_3(1+2\rightarrow 3+4+5)|^2 \simeq \overline{\sum}|M_2(1'+2\rightarrow 3+4)|^2 P_{1'1}(z,\epsilon)g^2\mu_r^{2\epsilon}\frac{-2}{zt_{15}}$$

Collinear

The cross section in the collinear region can be given as

$$
\begin{aligned}
d\sigma_{HC}^{P+P\to 3+4+5} &= G_{1/P}(x/z)G_{2/P}(y)d\hat{\sigma}_0^{1'+2\to 3+4}(s_{12},t_{13},t_{14})\left[\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu_r^2}{s_{12}}\right)^{\epsilon}\right] \\
&\times \left(-\frac{1}{\epsilon}\right)\delta_c^{-\epsilon}P_{1'1}(z,\epsilon)\frac{dz}{z}\left[\frac{(1-z)}{z}\right]^{-\epsilon} dx dy
\end{aligned}
$$

$\overline{MS}$ scheme :

$$
G_{b/B}(x,\mu_f) = G_{b/B}(x) + \left(-\frac{1}{\epsilon}\right)\left[\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu_r^2}{\mu_f^2}\right)^{\epsilon}\right]\int_z^1 \frac{dz}{z}P_{bb'}(z)G_{b'/B}(x/z)
$$

- There is a mismatch between the range of the limits.
- Soft collinear terms will be present.

SM NLO2 remnants

- Soft singularities appearing as $1/\epsilon^2$ and $1/\epsilon$ will cancel between real and virtual diagrams
- Initial state collinear singularities are absorbed into PDFs

$$
\begin{aligned}
\sigma^{soft} &= G_{a/P}(xa,\mu_F)G_{b/P}(xb,\mu_F)\sigma_0^{ab}\left[8C_F\left[log\delta_s\right]^2\right] \\
\sigma^{collinear} &= G_{a/P}(xa,\mu_F)G_{b/P}(xb,\mu_F)\sigma_0^{ab}\left[C_F(\,\ln\delta_s+6)\,\ln\,\left(\frac{s_{12}}{\mu_F^2}\right)\right] \\
\sigma^{virtual} &\sim G_{a/P}(xa,\mu_F)G_{b/P}(xb,\mu_F) \\
&\times C_F\{\ln(-u/s)(4+6t/u)+[\ln(-u/s)]^2(4+4u/t+2t/u) \\
&+ \ln(-t/s)(4+6u/t)+[\ln(-t/s)]^2(4+4t/u+2u/t)\;+\;\frac{\pi^2}{6}(8u/t+8t/u)\}
\end{aligned}
$$

$$
\begin{aligned}
\sigma^{NLO2} &= \sigma^{soft}+\sigma^{virutal}+\sigma^{collinear} \\
&+ \tilde{G}_{a/P}(xa,\mu_F)G_{b/P}(xb,\mu_F)\sigma_0^{ab}\;+\;(xa\leftrightarrow xb\text{ terms })
\end{aligned}
$$

cuts

Primary cuts

- Rapidity cut on the individual photons : $|y^{\gamma_{1,2}}| \leq 2.5$
- Transverse momentum cuts on the photons : $|p_T^\gamma| \geq 40$ GeV (hard) , 25 GeV (soft)

Isolation cuts

- The radius of the cone around each of the photons in the rapidity-azimuthal angular plane is given by

$$\Delta r(p_\gamma, p_j) = \sqrt{(y_\gamma - y_j)^2 + (\phi_\gamma - \phi_j)^2}$$

- $\Delta R = 0.4, E^{iso} = 15$ GeV
- Discard the event with $\Delta r(p_{\gamma_1} p_{\gamma_2}) \leq 0.4$
- Discard the event if $\Delta r(p_\gamma, p_{jet}) \leq 0.4$ and $E_T^5 \geq 15$ GeV .
- Discard the event if $\Delta R(p_\gamma, p_{jet}) \leq 0.4$ and $\chi\left(\Delta r(p_\gamma, p_{jet})\right) \leq E_T^5 \leq 15$GeV (Frixione's algorithm)

SM stability analysis

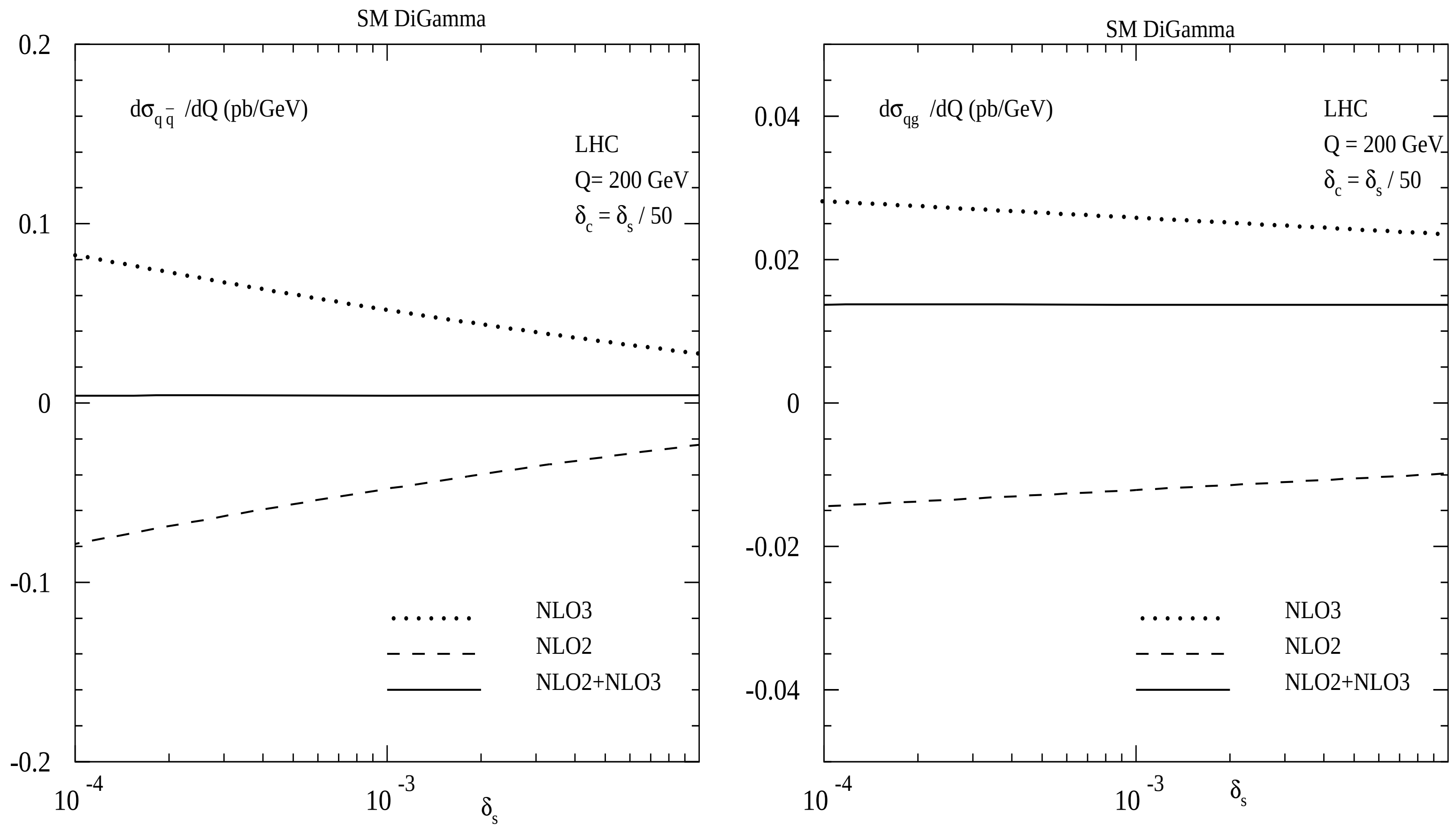

Figure 1: Variation of differential cross section $d\sigma/dQ$ with δ_s for Q=200 GeV in $q\overline{q}$ and qg channels.

SM Diphoton production

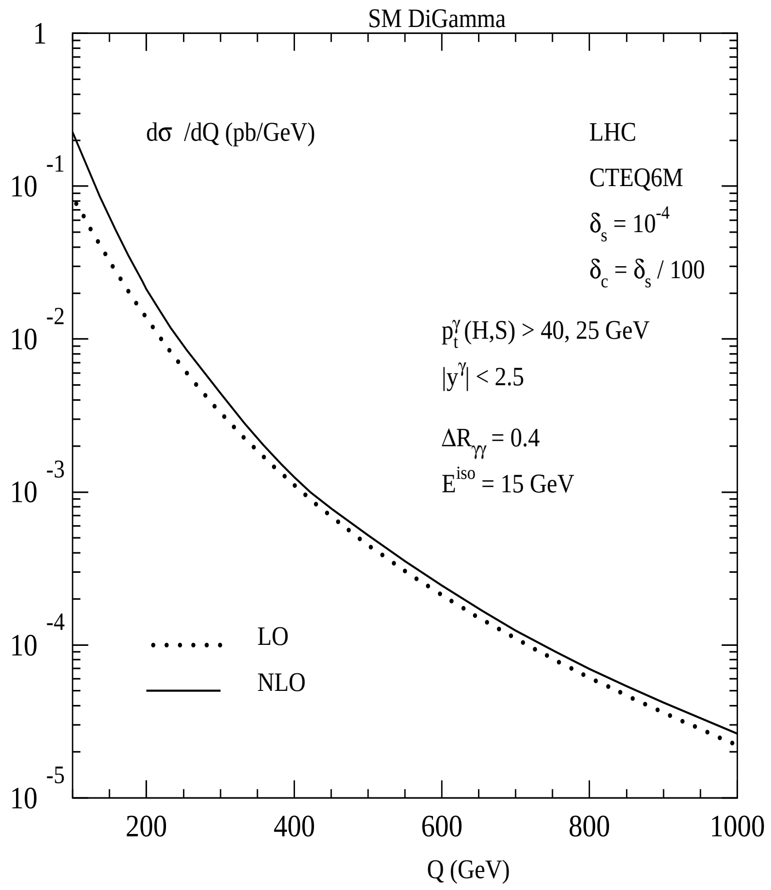

Figure 2: Diphoton invariant mass distribution at NLO using phase space slicing method.

RS NLO2 remnants

$q\overline{q}$

$$\sigma(soft) = 8C_F[\ln(\delta_s)]^2\{G_{q/P}(xa,\mu_F)G_{\overline{q}/P}(xb,\mu_F)\sigma_0^{q\overline{q}}\}$$

$$\sigma(virtual) = C_F(-20+8\zeta(2))\{G_{q/P}(xa,\mu_F)G_{\overline{q}/P}(xb,\mu_F)\sigma_0^{q\overline{q}}\}$$

$$\sigma(collinear) = C_F\left(4\ln\delta_s+3\right)\ln\frac{s_{12}}{\mu_F^2}\{G_{q/P}(xa,\mu_F)G_{\overline{q}/P}(xb,\mu_F)\sigma_0^{q\overline{q}}\}$$

gg

$$\sigma(soft) = 8N(\ln\delta_s)^2\{G_{g/P}(xa,\mu_F)G_{g/P}(xb,\mu_F)\sigma_0^{gg}\}$$

$$\sigma(virtual) = \left(-N(203/9)+n_fT_f(70/9)+8N\zeta(2)\right)\{G_{g/P}(xa,\mu_F)G_{g/P}(xb,\mu_F)\sigma_0^{gg}$$

$$\sigma(collinear) = N\left(4\ln\delta_s+11/3-2/3n_f\right)\ln\frac{s_{12}}{\mu_F^2}$$

RS stability Analysis

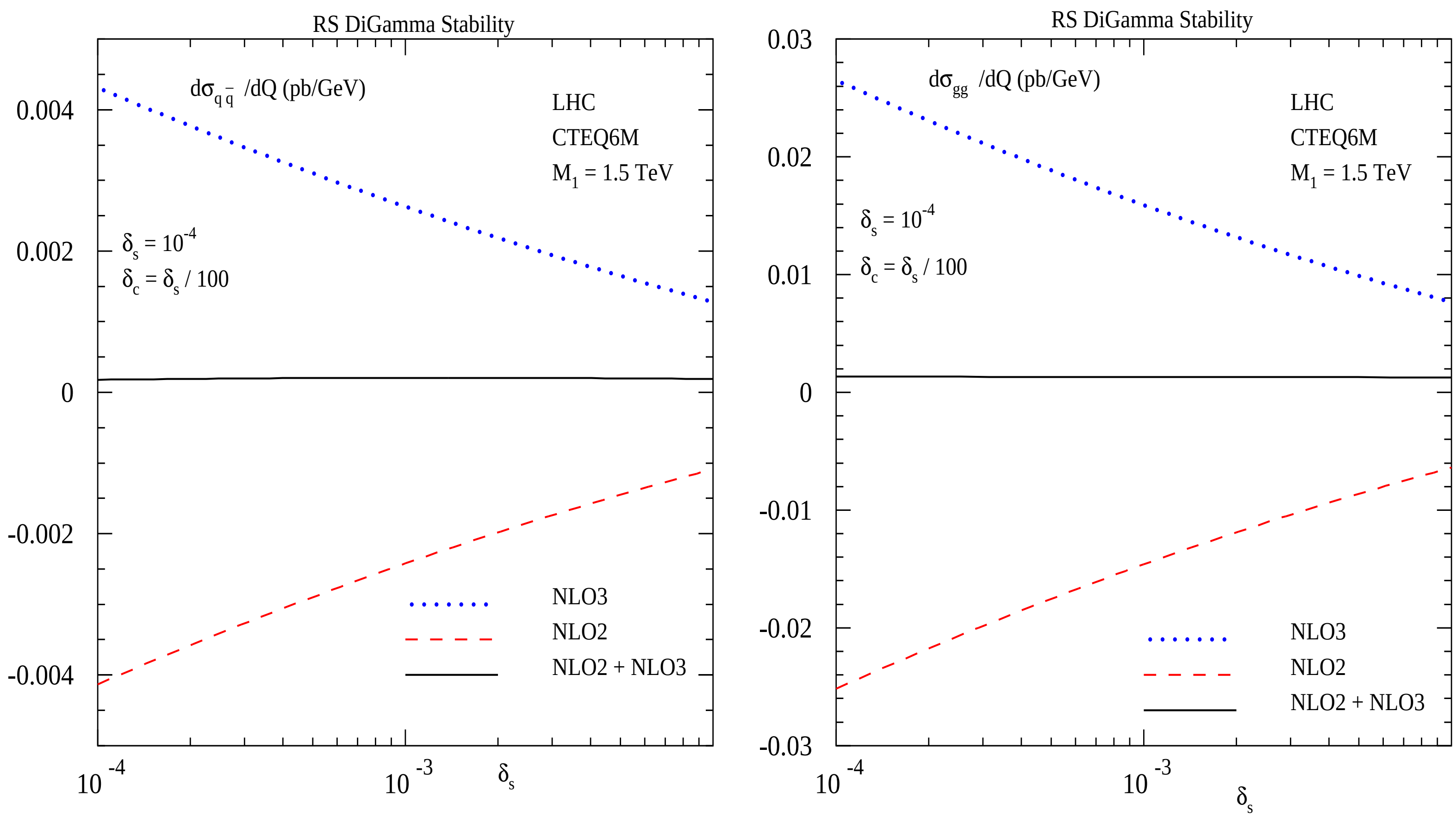

Figure 3: Invariant mass distribution: $M_1 = 1.5$ TeV. $c_0 = 0.01$. $q\bar{q}$ (left) and gg (right).

RS stability Analysis

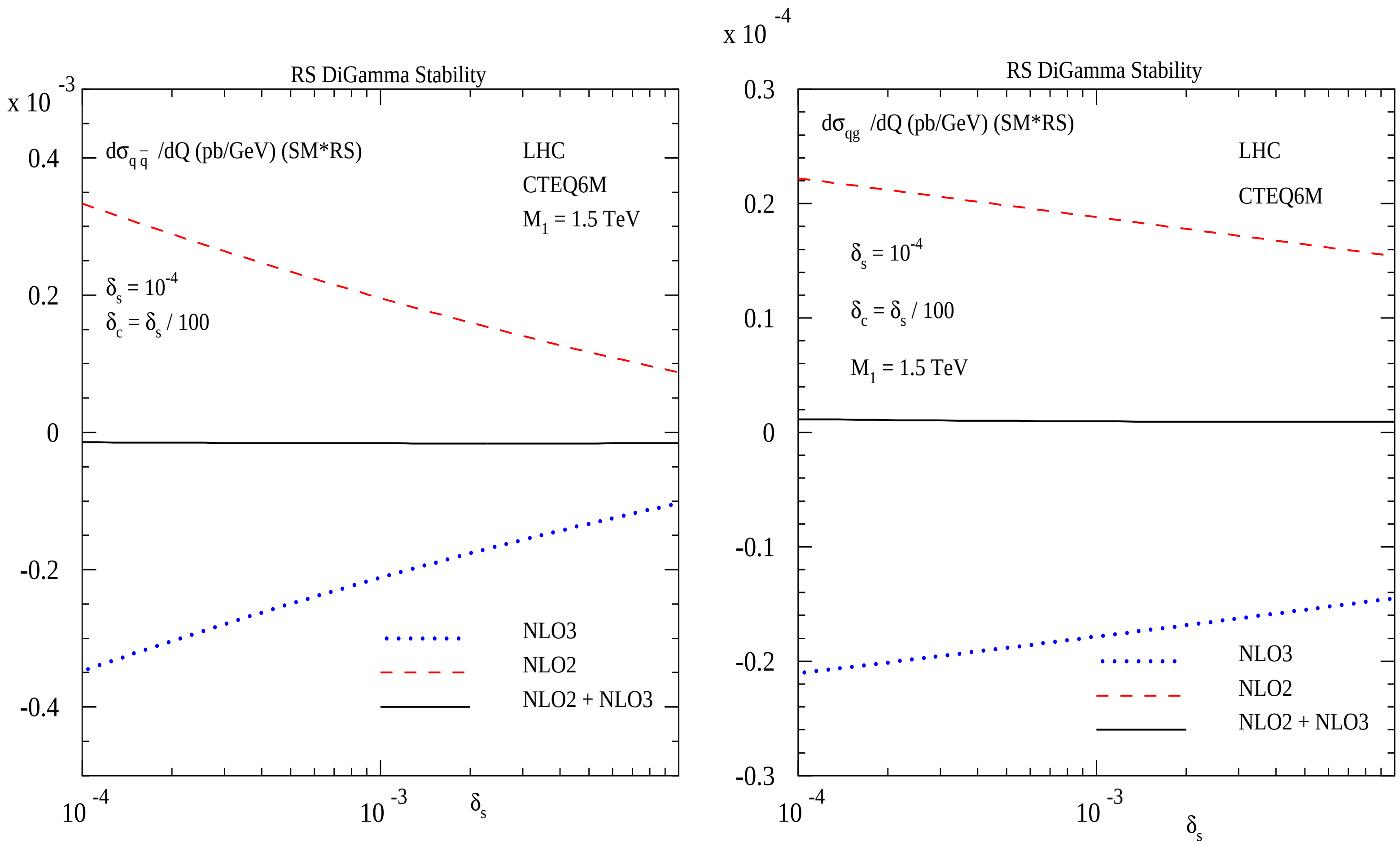

Figure 4: Invariant mass distribution: $M_1 = 1.5$ TeV. $c_0 = 0.01$. $q\bar{q}$ SM*RS (left) and gg SM*RS (right).

Invariant mass distribution

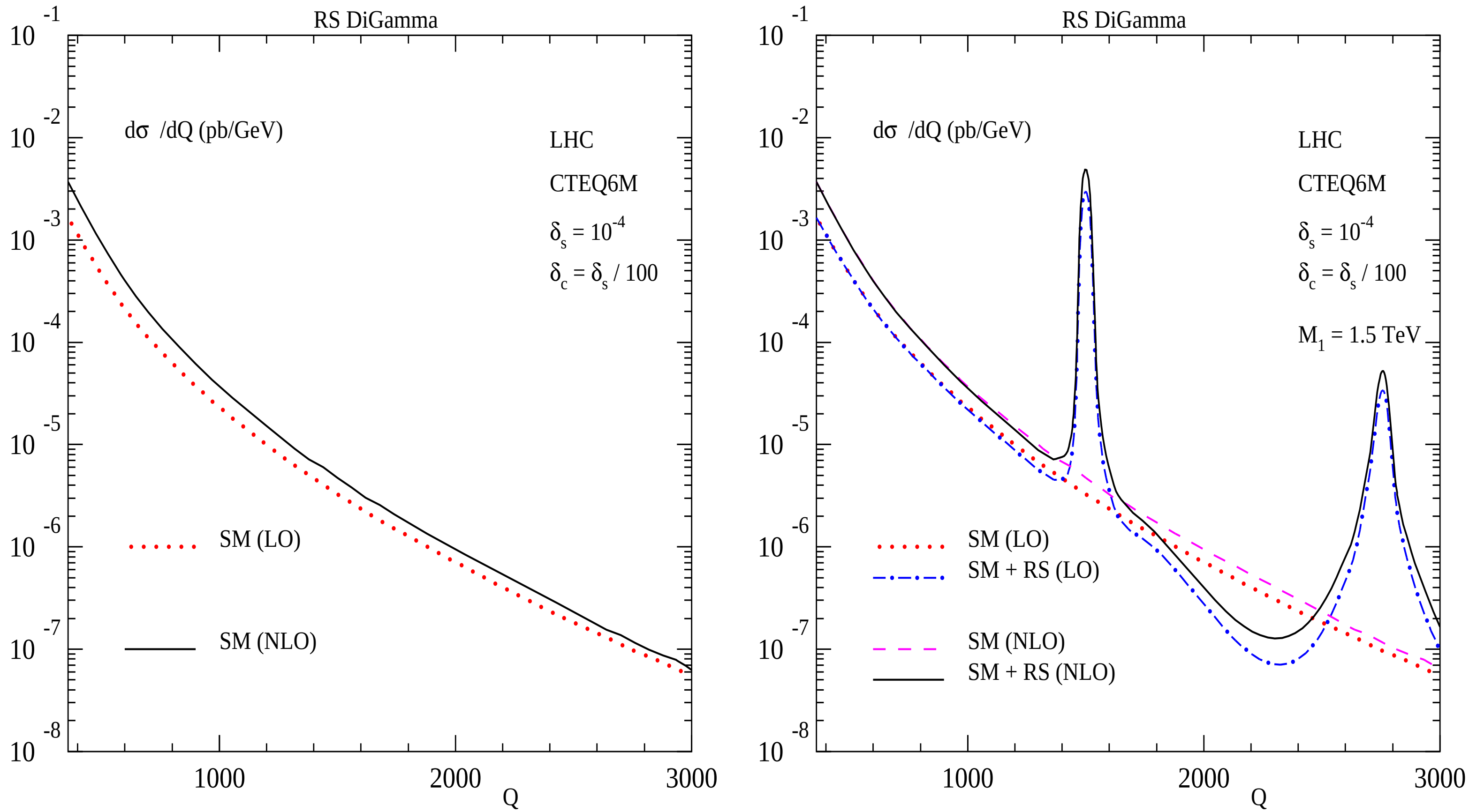

Figure 5: Invariant mass distribution: $M_1 = 1.5$ TeV, $c_0 = 0.01$. SM (left) and SM + RS (right).

Rapidity distribution

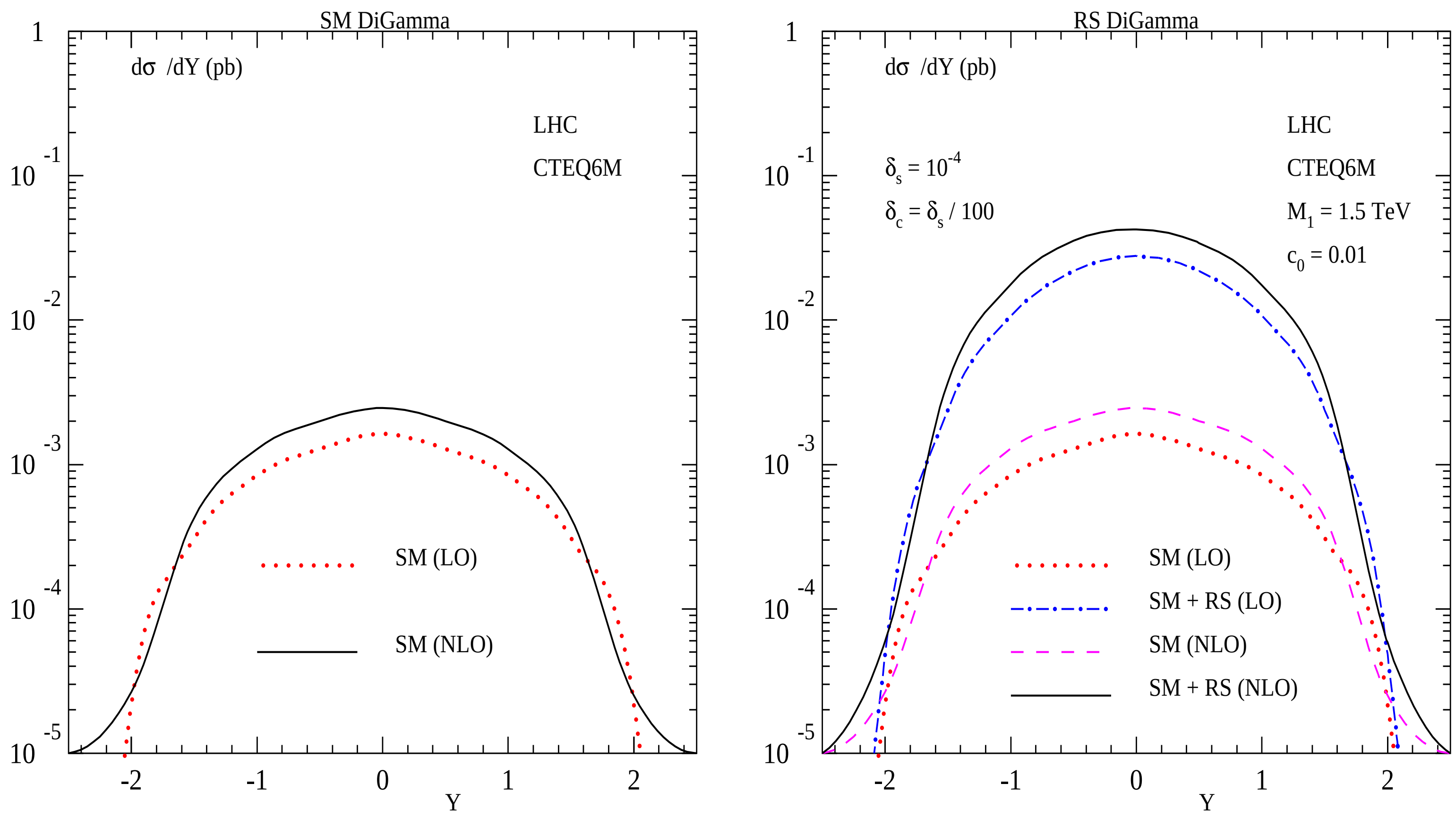

Figure 6: Rapidity distribution: $M_1 = 1.5$ TeV, $c_0 = 0.01$. SM (left) and SM + RS (right). $1100 < Q < 1600$ GeV .

Angular distribution

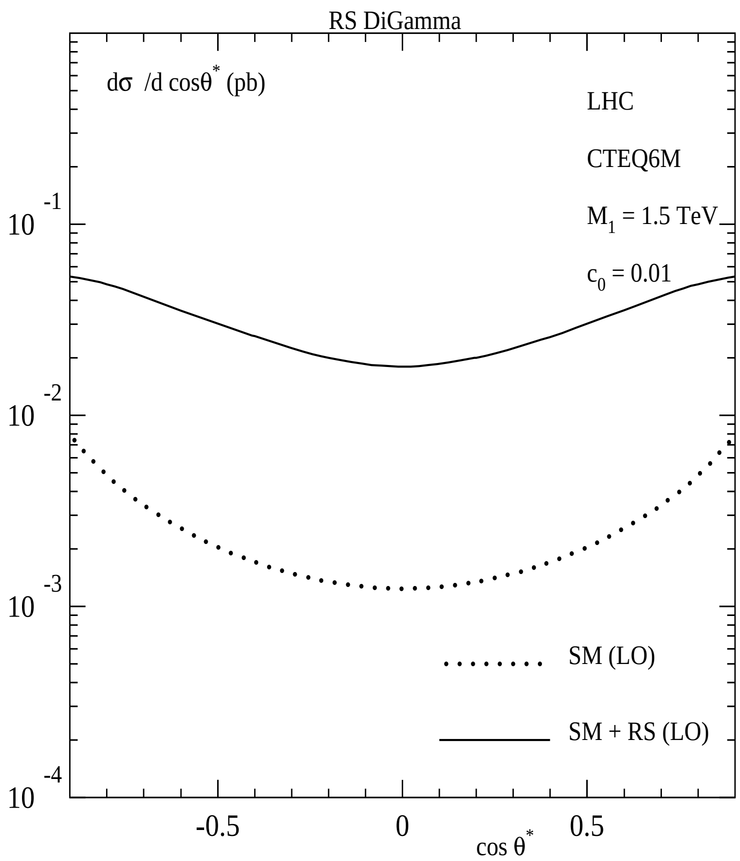

Figure 7: Angular distribution: $M_1 = 1.5$ TeV, $c_0 = 0.01$. SM + RS (right). $1100 < Q < 1600$ GeV .

Summary

1. The gravitational interactions can become stronger at TeV scale.
2. The angular distribution for SM and SM+GR can be distnguished in experiments.
3. The large K factor (~ 1.65) for gravity included process gives the importance of NLO corrections.
4. K factor depends on experimental cuts.
5. NLO QCD corrections to the diphoton production at the LHC in the extra dimensional models could decrease one of the theoretical uncertainties.