Next-to-leading order corrections to the di-photon production in ADD and RS models at the LHC

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Outline

- Extra dimensional models
- Phase space slicing method
- cuts
- Numerical results
- conclusions

Diphoton production

1. Improtant process for the higgs search at the LHC
2. Precision study of the Standard model
   Eur.Phys.J.C16:311-330,2000
   Phys.Rev.D76:013009,2007
3. To probe the BSM phyiscs **(ADD, RS, SUSY)**
   $D\emptyset$ **Collaboration**
   Phys.Rev.D61:094007,2000
4. Includes non perturbative PDFs and fragmentation functions.

ADD MODEL

This model proposed by Arkani-Hamed, Dimopoulos and Dvali (ADD) is based on the Kaluza-Klein scenario.

1. Gravity only can propagate into the $bulk$ while the SM fields are confined to the $3brane$.
2. The size of the extra dimensions can be as large as sub millimeter.
3. The scale M_s of the gravity, the UV cut off are of the order of few TeV and so the $hierarchy$ problem can be lifted up.
4. For simplicity, the extra dimensions are considered to be of the same size.
5. The extra n dimensions are compactified on n dim. torus leading to KK modes.
6. The effective interactions are due to either the exchange or the emission of these KK modes.
7. The coupling of each KK mode with the SM fields is $\kappa = \frac{1}{M_{Pl}}$
8. The large multiplicity of KK modes can give an observable effect.

Phys. Lett. B249 (1998) 263

N.Arkani Hamed, S.Dimopoulos and G.Dvali

RS MODEL

This model is proposed by Randall and Sundrum.

1. There is only one extra dimension with orbifold symmetry.
2. The gravity only can propagate the $extra\ dimension$ 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 $hierarchy$.
5. The size of the extra dimension need not be very large.
6. Compactification of the extra dimension leads to the RS modes.
7. The RS modes are $very\ massive$ and are not evenly spaced.
8. The effective coupling of the RS modes with the SM fields is $c_0 = \frac{k}{M_{Pl}}$

Phy. Rev. Lett.83 (1999) 3370

L.Randall and R.Sundrum

Summation of the virtual KK modes

- Virtual KK states have to be summer over at the amplitude level.
- Real KK states have to be summed over at the cross section level.

The sum of the virtual KK states in the propagator is

$$D(s) = -\sum_{\vec{n}} \frac{i}{s - m_{\vec{n}}^2 + i\epsilon} = \frac{s^{n/2-1} R^n}{\Gamma(n/2)(4\pi)^{n/2}} [2iI(\Lambda/\sqrt{s})] \quad \text{(ADD)}$$

and

$$I(\Lambda/\sqrt{s})]\mathcal{D}(s) = \sum_{n=1}^{\infty} \frac{1}{s - m_n^2 + i m_n \Gamma_n} \equiv \frac{\lambda}{m_0^2}$$

$$= \frac{1}{m_0^2} \sum_{n=1}^{\infty} \frac{X^2 - X_n^2 - i\frac{\Gamma_n}{m_0} X_n}{(X^2 - X_n^2)^2 + \frac{\Gamma_n^2}{m_0^2} X_n^2} \quad \text{(RS)}$$

where Λ is the explicit cut off for the summation of the KK modes

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

$$X = \frac{\sqrt{s}}{m_0}, \qquad X_n = \frac{m_n}{m_0}$$

Hadronic cross section

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

$$\sigma^{\mathrm{P_1P_2}} = \sum_{ab=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2 f_a^{P_1}(x_1,\mu_F) f_b^{P_2}(x_2,\mu_F) \quad d\hat{\sigma}^{ab}(x_1,x_2,\mu_F)$$

- Parton Distribution Functions are universal and non-perturbative in nature.
- Factorization of the mass singularities from partonic cross sections introduces a scale μ_F ($\overline{MS}$ scheme) into both the partonic cross sections (perturbative) and PDFs (non-perturbative).
- The truncation of the perturbative series gives rise to the explicit scale dependence of the cross sections.
- Need for the higher order QCD corrections for the reliable estimation of the cross sections.

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.

Phys.Rev.D65:094032,2002

B.W.Harris and J.F.Owens

NLO2 & NLO3

- Soft region : $0 \leq E_5 \leq \delta_s \sqrt{s_{12}}/2$.
- Hard region : $\delta_s \sqrt{s_{12}}/2 \leq E_5 \leq E_5(max)$.
- Collinear region : $0 \leq t_{15} \leq \delta_c s12$ where $\delta_c << \delta_s$.
- NLO2 $\longrightarrow$ Soft + Virtual + Collinear terms.
- NLO3 $\longrightarrow$ Hard non-collinear part.
- NLO2 + NLO3 is expected to be independent of δ_s and δ_c.

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

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

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

BSM NLO2 remnants

$\underline{q\overline{q}}$

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

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

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

$\underline{gg}$

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

$$\sigma(\text{ virtual }) = [-N(203/9)+n_fT_f(70/9)+8N\zeta(2)]$$

$$\times\quad\left[G_{g/P}(xa,\mu_F)G_{g/P}(xb,\mu_F)\sigma_0^{gg}\right]$$

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

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

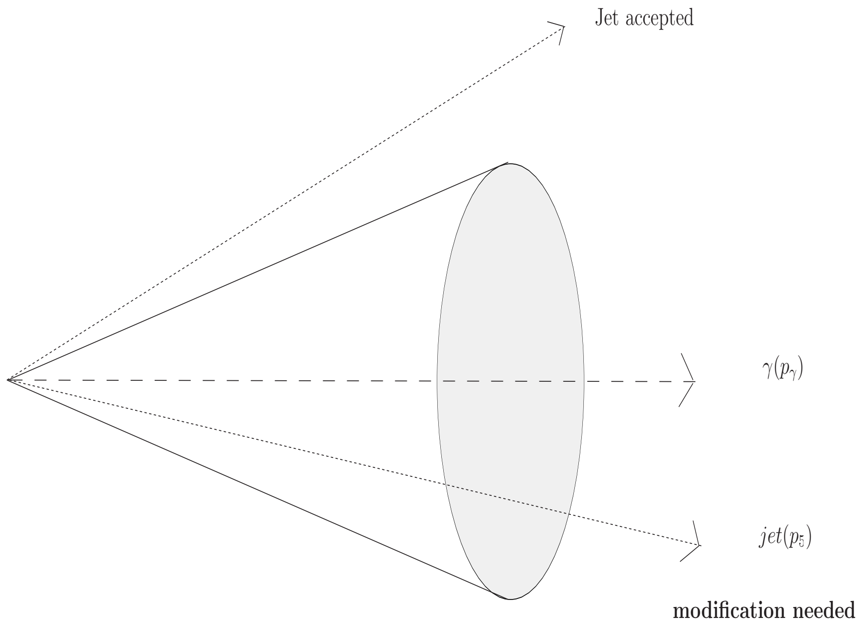
$$\Delta r(p_\gamma, p_j) = \sqrt{(y_\gamma - y_j)^2 + (\phi_\gamma - \phi_j)^2}$$

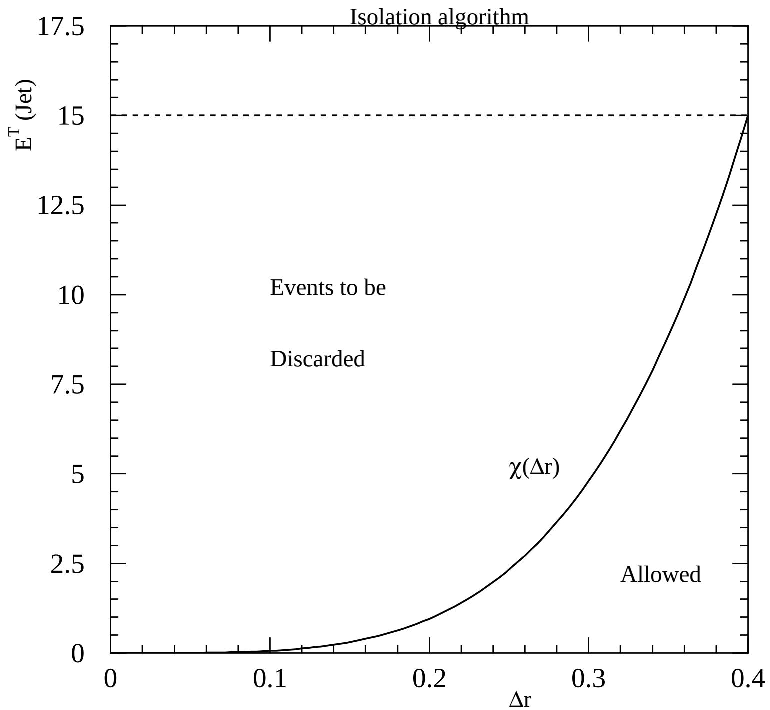
- $\Delta R = 0.4, E^{iso} = 15$ GeV
- Discard the event with $\Delta r(p_{\gamma_1} p_{\gamma_2}) \leq 0.4$
- Discard the event if $\Delta r(p_\gamma, p_{jet}) \leq 0.4$ and $E_T^5 \geq 15$ GeV .

Frixione algorithm

Discard the event if

$$\Delta R \leq 0.4 \text{ and } \chi\left(\Delta r\right) \leq E_T^5 \leq 15\text{GeV} \;\; \text{where } \chi(x) = E^{iso}\left[\frac{1-\cos(x)}{1-\cos\Delta R}\right]^n$$





Parameters

ADD model

- The no. of extra spatial dimensions, 'd = 3'.
- The higher dimensional scale, $M_s = 2$TeV
- The cut-off of KK mode summation, $\Lambda = \alpha M_s$

RS model

- $M_1 = 1.5$TeV
- Effective coupling between RS modes and the SM fields, $c_0 = 0.01$

Stability Analysis

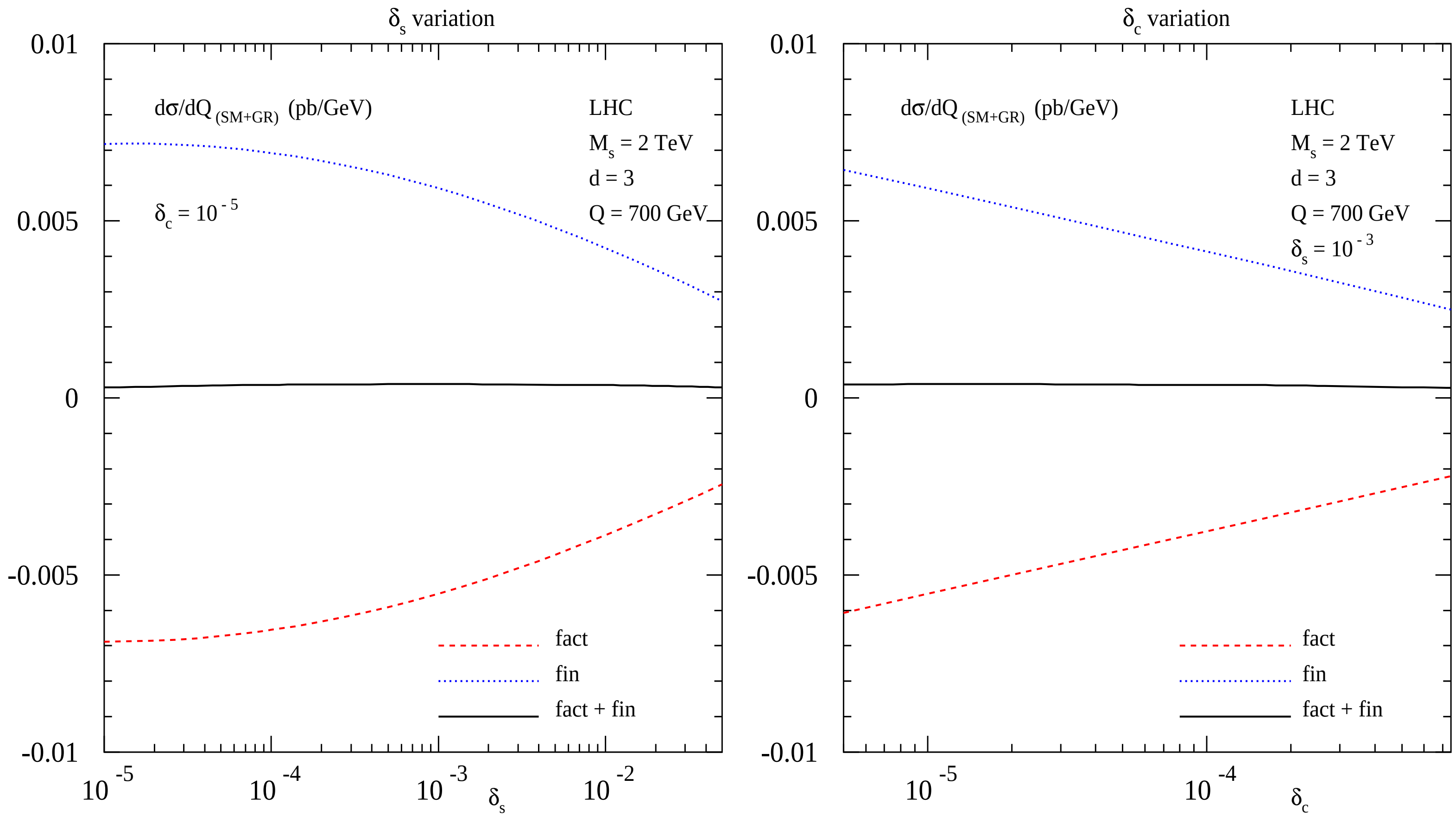


Figure 1: Invariant mass distribution: $M_s = 2$ TeV and $d = 3$. Variation with δ_s (left) and δ_c (right).

ADD model distributions

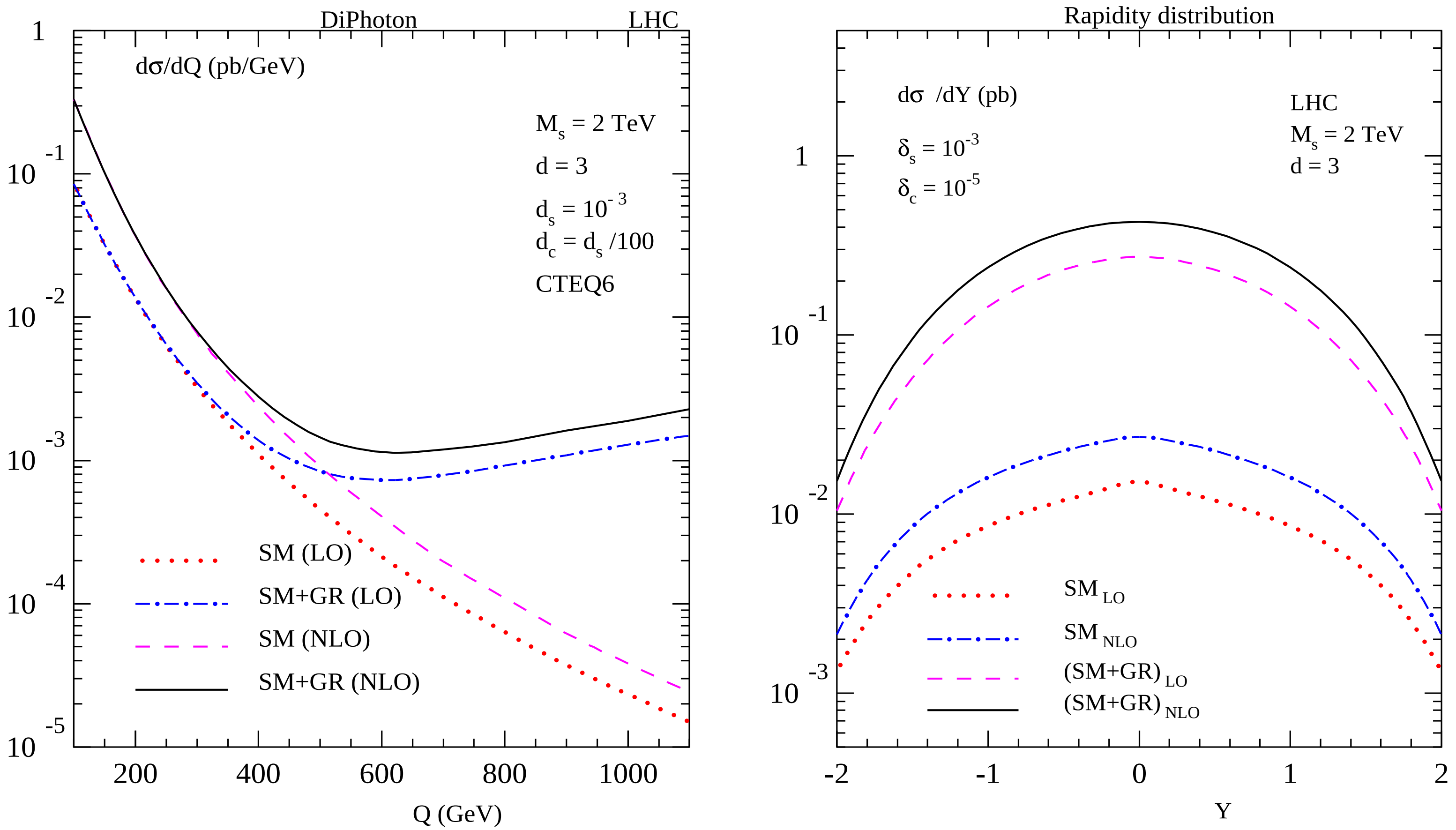


Figure 2: $d\sigma/dQ$ (left) and $d\sigma/dY$ (right). $M_s = 2$TeV , $d = 3$. For Y, $600 \leq Q \leq 1100$ GeV.

arXiv:0811.1670[hep-ph]; M.C.Kumar, Prakash Mathews, V. Ravindran, Anurag.Tripathi.

Scale variation - Rapidity distribution

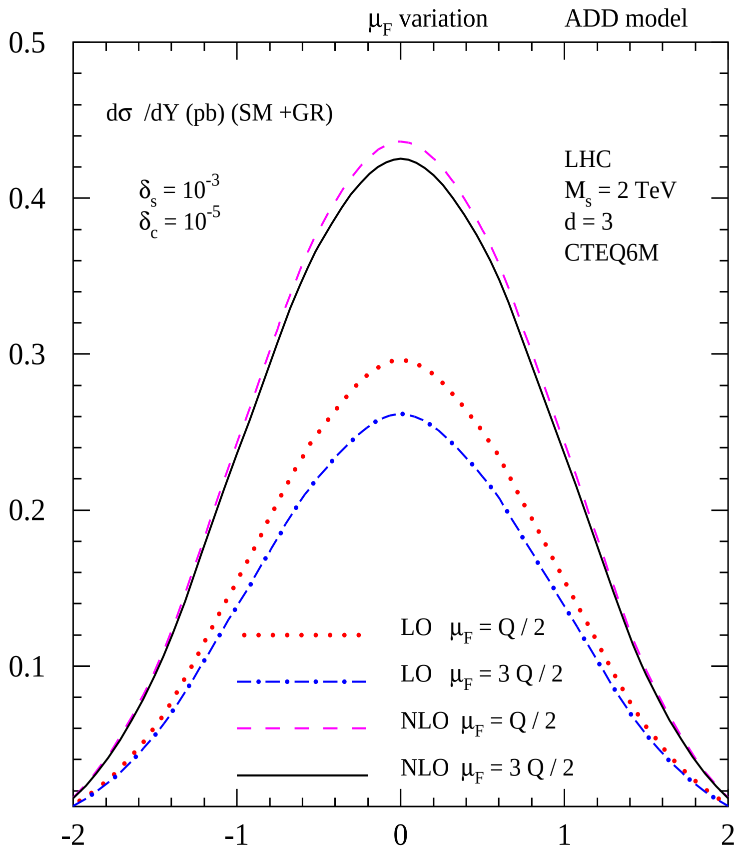


Figure 3: μ_F variation from Q/2 to 3Q/2 in the rapidity distribution of the diphoton (ADD model). $M_s = 2$ TeV and $d = 3$

Cone variations - Invariant mass distribution

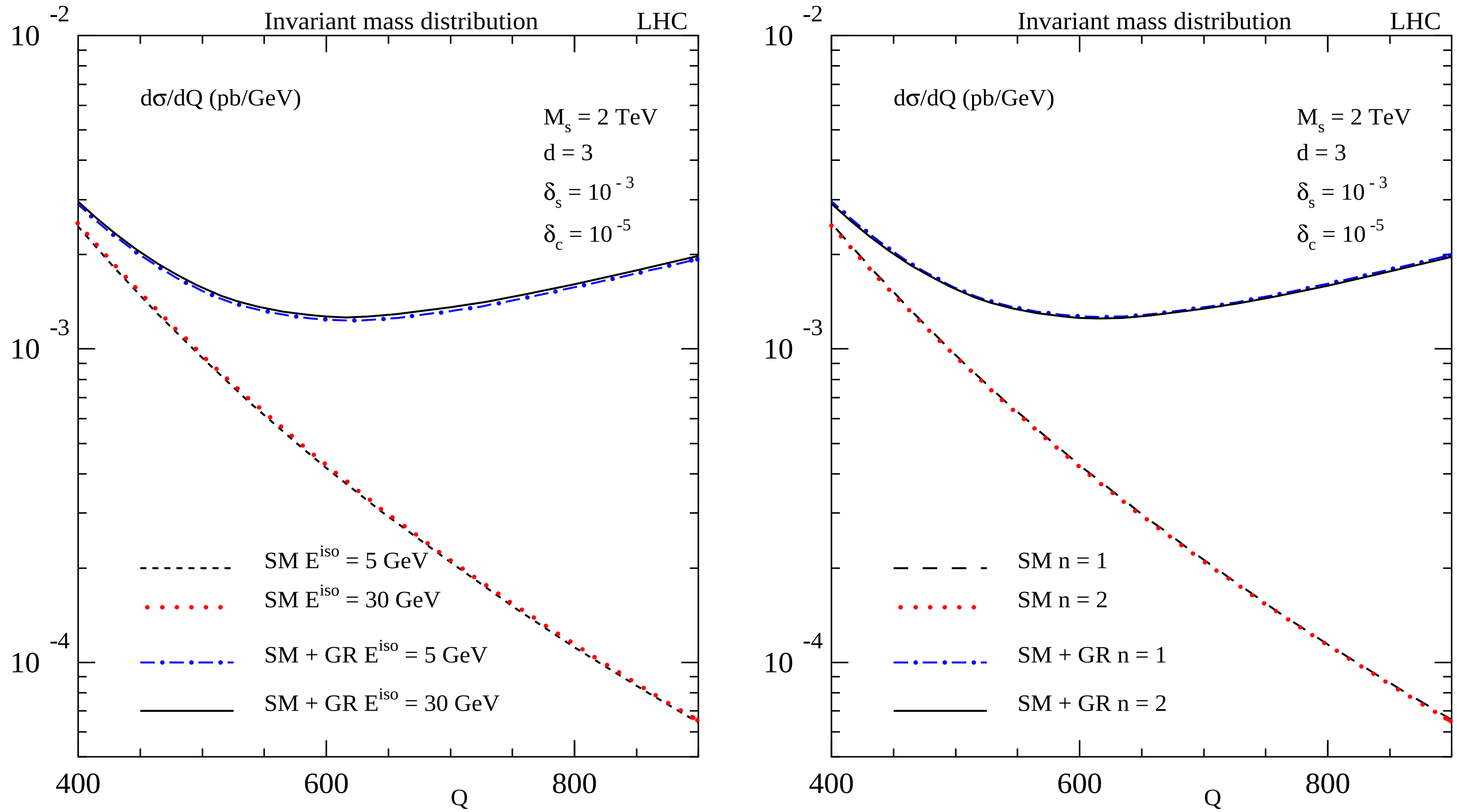


Figure 4: ADD model: Variation of E^{iso} (left) and n (right) in the invariant mass distribution.

RS model distributions

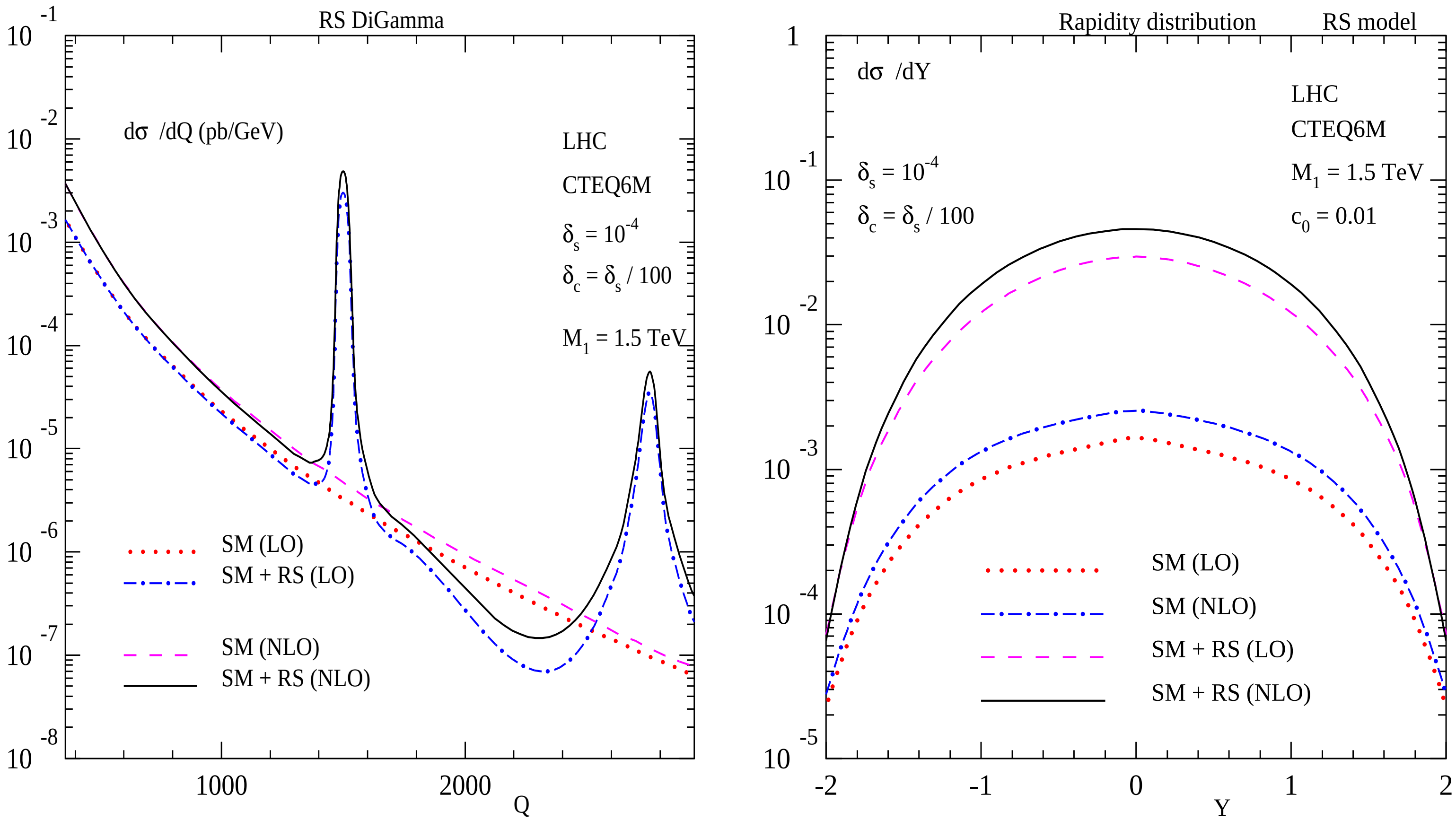


Figure 5: $d\sigma/dQ$ (left) and $d\sigma/dY$ (right). For Y, $1100 \leq Q \leq 1600$ GeV. $M_1 = 1.5TeV$ and $c_0 = 0.01$.

Transverse momentum distributions

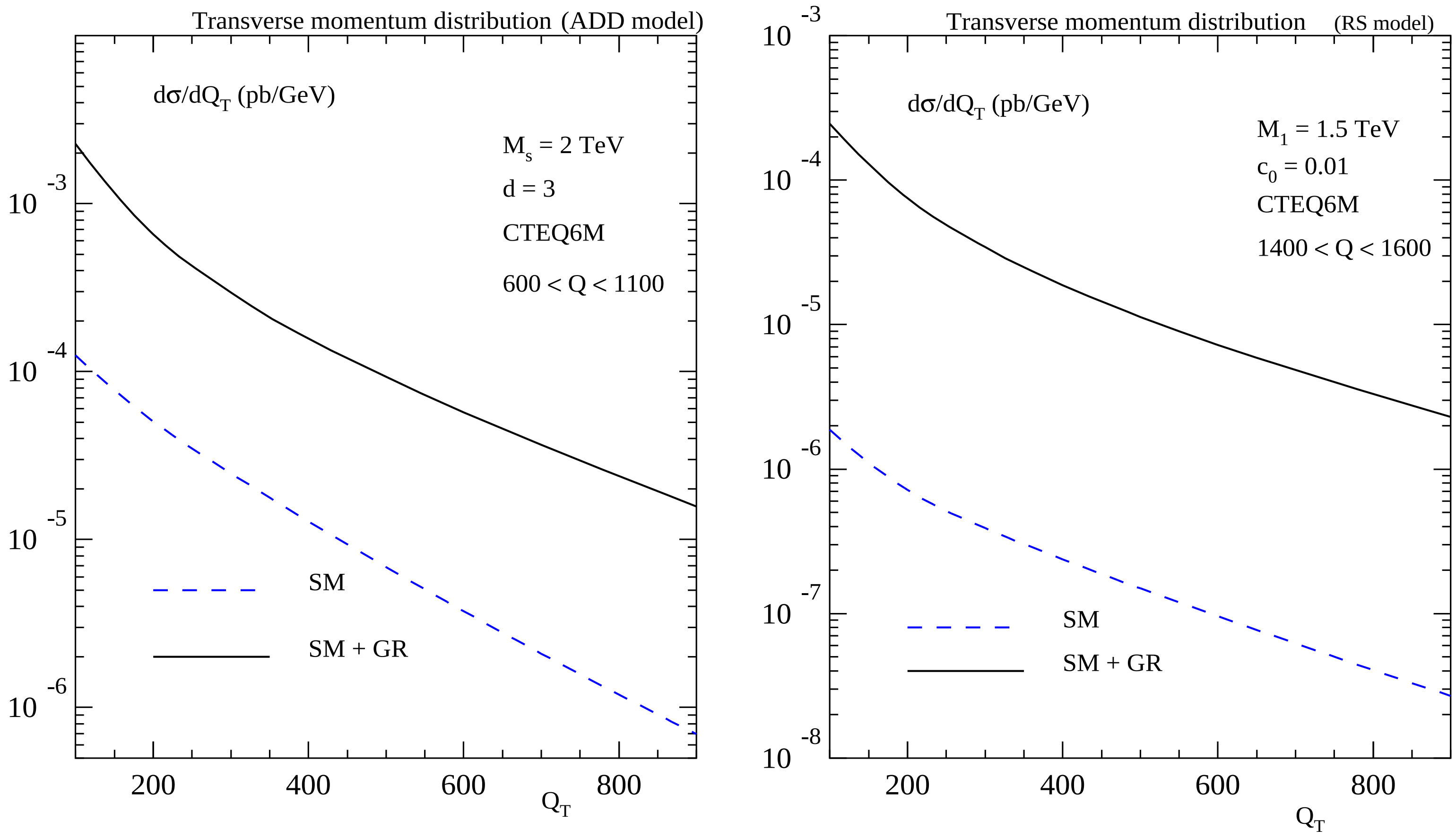


Figure 6: Q_T distributions of the diphoton in ADD model (left) and RS model (right)

Summary

1. Diphoton production process at the LHC is an important probe for the BSM physics search.

2. For reliable estimation one needs to minimize the QCD uncertainties by computing higher order corrections.

3. Phase space slicing method is useful to compute the NLO cross sections with ease numerically.

4. Transverse momentum distributions of the di-photon come only at NLO and are important at the experiments.

5. NLO QCD corrections could decrease one of the theoretical uncertainties.