QCD corrections in the Extra Dimension searches at the LHC

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In collaboration with
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Outline

1. Large extra dimension model (ADD model)
2. Warped extra dimension model (RS model)
3. Next-to-Leading order QCD corrections
4. Phase space slicing method
5. Diphoton production at the LHC
6. Vector boson plus Graviton production at the LHC
7. Numerical Results
8. Conclusions

Kaluza-Klein theories

A scalar field in $4+1$ dimensions

$$\mathcal{L} = -\frac{1}{2}\partial_A\Phi\partial^A\Phi, \qquad A = 0,1,2,3,5$$

$\Phi(x,y) \equiv \Phi(x_\mu, y)$ with periodic boundary condition $y = y + 2\pi L$

We expand the field in terms of the spherical harmonics. The coefficients are the conventional 4 - dimensional fields.

$$\Phi(x,y) = \sum_{k=-\infty}^{+\infty}\phi_k(x)e^{iky/L}, \qquad \phi_{-k}(x) = \phi_k^*(x)$$

After compactification, the $effective$ action in 4- dimensions can be given as

$$S = \int d^4x\left[-\frac{1}{2}\partial_\mu\varphi_0\partial^\mu\varphi_0\right] - \int d^4x\sum_{k=1}^{+\infty}\left[\partial_\mu\varphi_k\partial^\mu\varphi_k^* + \frac{k^2}{L^2}\varphi_k\varphi_k^*\right]$$

where $\varphi_k \equiv \sqrt{2}\phi_k$.

There are one massless mode and an infinite tower of massive modes φ_k with mass $m_k^2 = k^2/L^2$, together called $Kaluza\text{-}Klein$ modes.

Kaluza-Klein theories

The U(1) gauge field A_B in 5-dimensions after compactification has the following mass spectrum:

- A massless gauge field $A_\mu^{(0)}$ with $g_4^2 = g_5^2/2\pi L$
- An infinite tower of massive gauge bosons with mass $m_k^2 = k^2/L^2$
- A massless scalar field $A_5^{(0)}$

After compactification the n-dimensional gauge transformation will be reduced to an infinite number of 4-dimensional $gauge\ transformations$ - one for each KK level.

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  Kingman Cheung and Greg Landsberg; **PRD 65, 076003**

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- Gravity has been tested upto sub milli-meter range, so far.
- Only $gravity$ can be allowed to propagate the bulk while the statndard model fields are confined to the brane.

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 3-brane.
2. The size of the extra dimensions can be as large as sub millimeter.
3. The scale M_s of the gravity is of the order of few TeV and so the Higg's $hierarchy$ problem can be addressed.
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

ADD model

The action of gravity in $4+n$-dimensions is

$$ds^2 = (\eta_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu - r^2 d\Omega^2_{(n)}$$

$$S^{4+n} = -\frac{M_s^{n+2}}{2}\int d^4x \int_0^{2\pi L} d^n y \sqrt{g^{4+n}}\; R^{4+n}$$

$$S^4_{effec.} = -\frac{M_s^{2+n}(2\pi L)^n}{2}\int d^4x \sqrt{g^4}\; R^4$$

Action in $4-dim.$ is

$$S^4 = -\frac{M_{Pl}^2}{2}\int d^4x \sqrt{g}\; R$$

$$M_{Pl}^2 = M_s^{n+2}(2\pi L)^n$$

For $M_s \sim$ TeV,

$$L \sim 10^{-17+30/n}$$

For $2 \leq n \leq 6$, $\qquad 10^{-2}\; cm. \leq L \leq 10^{-6}\; \mu m.$

Kaluza-Klein reduction

The KK reduction of this linearized gravity to 4-dimensions can be given as :

$$h_{AB} = V_n^{-1/2} \begin{pmatrix} h_{\mu\nu} + \eta_{\mu\nu}\phi & A_{\mu i} \\ A_{\nu j} & 2\phi_{ij} \end{pmatrix},$$

The KK decomposition follows as :

$$h_{\mu\nu}(x, y) = \sum_{\vec{k}} h_{\mu\nu}^{\vec{k}}(x) \, \text{exp} \left(i \frac{\vec{k}.\vec{y}}{L} \right)$$

Compactification leads to a tower of KK modes with mass $m_k^2 = k^2/L^2$. The mass spectrum consists of spin-2, spin-1 and spin-0 states.
The KK-modes couple to the energy-momentum tensor $T_{\mu\nu}$ of the SM fields.

$$\mathcal{L}_G^{int} = -\frac{\kappa}{2} \int d^4x \, h_{\mu\nu}^{\vec{n}} T^{\mu\nu}$$

Spin-2 and the spin-0 (dilaton) states couple to the SM fields while the spin-1 states decouple.

RS MODEL

This model is proposed by Randall and Sundrum.

1. There is only one very small extra dimension with orbifold symmetry.
2. The gravity only can propagate the $extra\ dimension$ while the SM fields are confined to the $brane$.
3. The metric in the RS model is given by

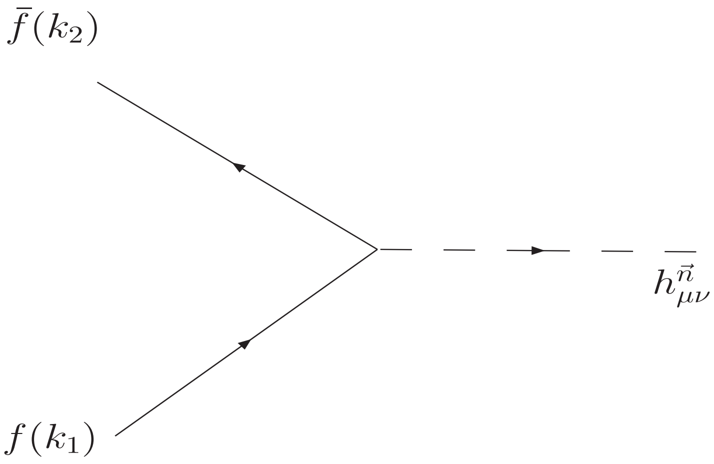
$$ds^2 = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$$

4. There are two branes on the extra dimension, namely $SM\ brane$ and the $Planck\ brane$ at $\phi = \pi$ and $\phi = 0$ respectively.
5. Any fundamental mass parameter M_0 in higher dimensions will correspond to a physical mass $m_p \simeq e^{-kr_c\pi}M_0$ on the brane.
6. For $kr_c \sim 12$, one can generate $\Lambda = e^{-kr_c\pi}M_{Pl}$, where $\Lambda \sim \mathcal{O}$(TeV).

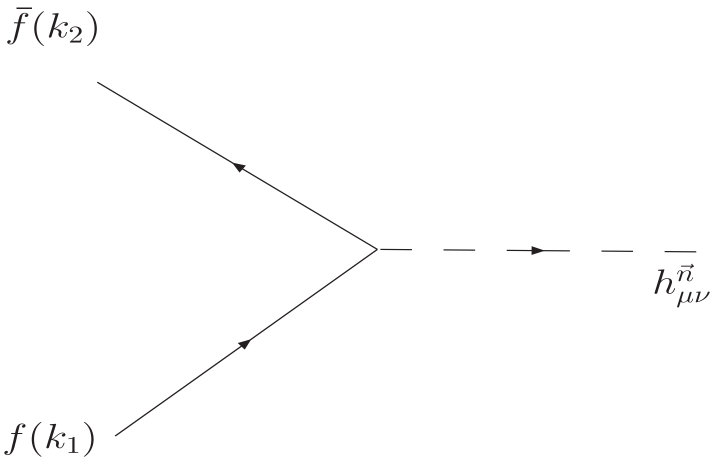
Phy. Rev. Lett.83 (1999) 3370

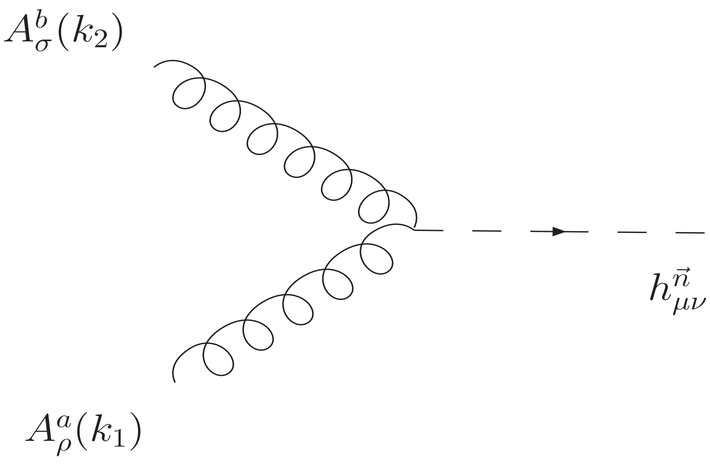
L.Randall and R.Sundrum

BSM vertices



BSM vertices





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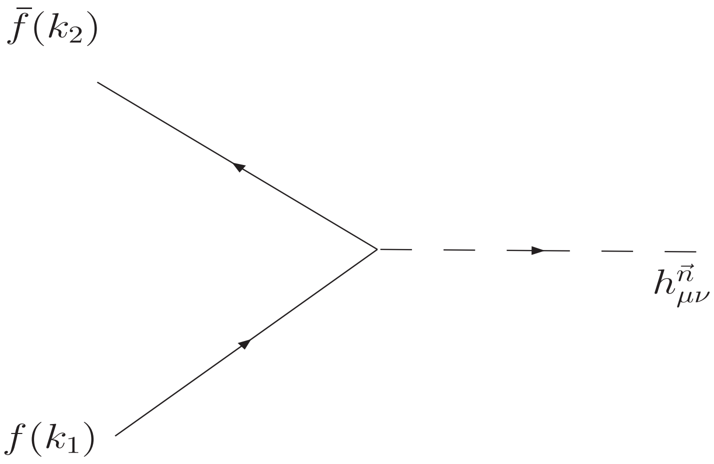

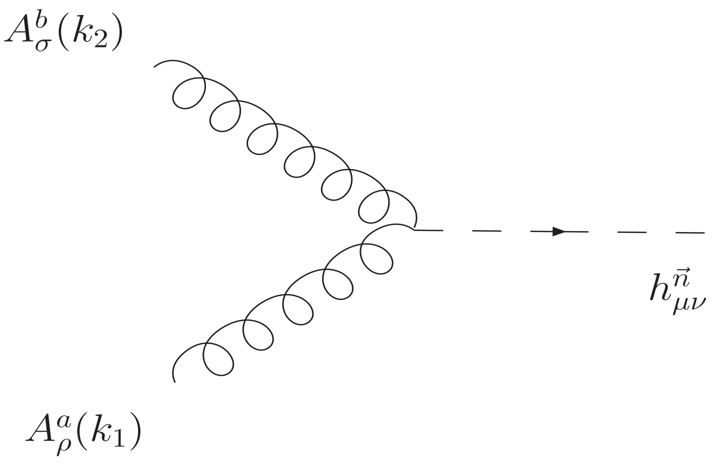

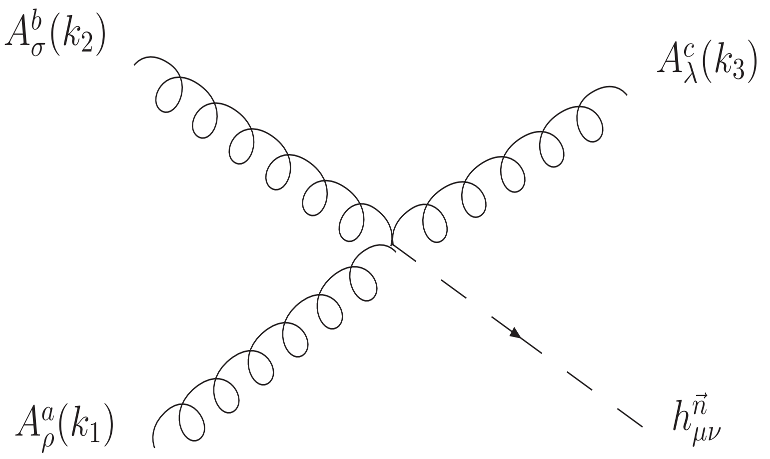

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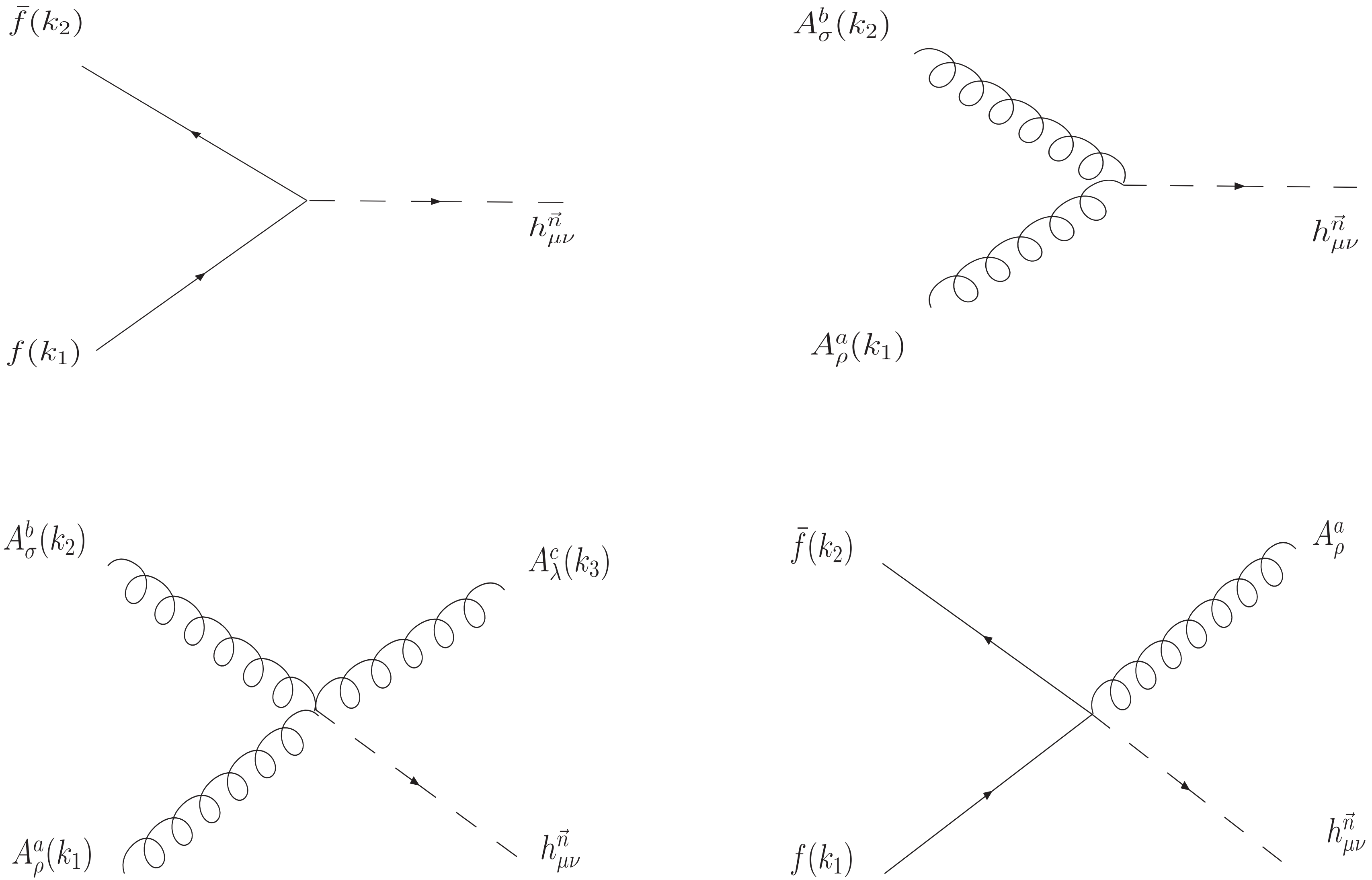

T. Han, J. D. Lykken and R. J. Zhang **Phys. Rev. D59 (1999) 105006**

Summation of the virtual modes in ADD model

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

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

The sum of the virtual KK states in the propagator is

$$D(s) = -\sum_{\vec{n}} \frac{1}{s - m_{\vec{n}}^2 + i\epsilon}$$

$$= \frac{s^{n/2-1} R^n}{\Gamma(n/2)(4\pi)^{n/2}} [-i\,\pi + 2I(\Lambda/\sqrt{s})]$$

where

$$I(\Lambda/\sqrt{s}) = -\sum_{k=1}^{n/2-1} \frac{1}{2k} \left(\frac{\Lambda}{\sqrt{s}}\right)^{2k} - \frac{1}{2} \log \left(\frac{\Lambda^2}{s} - 1\right) \qquad \text{n=even,}$$

$$= -\sum_{k=1}^{(n-1)/2} \frac{1}{(2k-1)} \left(\frac{\Lambda}{\sqrt{s}}\right)^{2k-1} + \frac{1}{2} \log \left(\frac{\Lambda + \sqrt{s}}{\Lambda - \sqrt{s}}\right) \qquad \text{n=odd.}$$

and Λ is the explicit cut off for the summation of the KK modes.

Summation of the virtual modes in the RS model

The RS modes are given by

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

where $x_1 = 3.8317$ and $x_n = 7.0156 + (n-2)\pi$ for $n > 2$.

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

$$\begin{aligned} \mathcal{D}(Q^2) &= \sum_{n=1}^{\infty} \frac{1}{s - m_n^2 + i m_n \Gamma_n} \equiv \frac{\lambda}{m_0^2} \\ &= \frac{1}{m_0^2} \sum_{n=1}^{\infty} \frac{X^2 - X_n^2 - i \frac{\Gamma_n}{m_0} X_n}{(X^2 - X_n^2)^2 + \frac{\Gamma_n^2}{m_0^2} X_n^2} \end{aligned}$$

where

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

Summation over the real graviton modes in the ADD model

- Different graviton modes give rise to the same missing energy signals.
- Cross sections correspodning to different graviton modes have to be summed over
- In the continuum limit, this sum can be approximated to an integral

$$d\sigma = \int \rho(m)\,\frac{d\sigma}{dm}, \quad \text{where} \quad \rho(m) = \frac{R^d\, m_n^{d-1}}{(4\pi)^{d/2}\,\Gamma(d/2)} \text{ (mode density)}$$

- The limits depend both on the kinematics and on the cut-off M_s.
- The upper limit, hence, is min. of $\{\sqrt{s} - m_Z,\ M_s\}$.

Virtual graviton contribution

- Pair production process

$$q + \bar{q} \to G^* \to f + \bar{f}(VV) \quad (1)$$

Examples

- Drell-Yan production : $q + \bar{q} \to G^* \to l + \bar{l}$
- Di-photon production : $q + \bar{q} \to G^* \to \gamma\gamma$
- Di-jet production : $q + \bar{q} \to G^* \to j_1 \; j_2$
- Pair of Z bosons : $q + \bar{q} \to G^* \to ZZ$
- W Pair production : $q + \bar{q} \to G^* \to W^+W^-$
- Top quark pair production : $q + \bar{q} \to G^* \to t\bar{t}$

Real graviton production (ADD model)

$$q + \bar{q} \rightarrow G + X$$

Examples

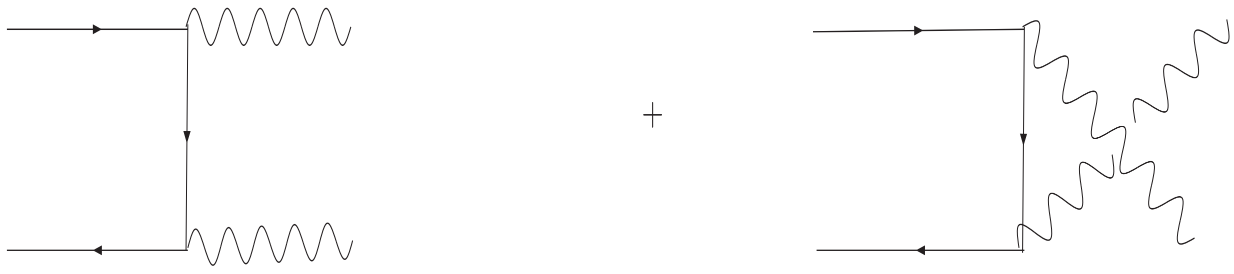
- Graviton plus jet production
- Graviton plus di-jet production
- Graviton plus photon production
- Graviton plus Z production
- Graviton plus lepton pair production
- Graviton plus top quark pair production
- ADD gravitons couple to SM fields with coupling $\kappa \sim \frac{1}{\bar{M}_p}$
- Negligible decays into SM particles even for heavy modes
- Can not be detected $\Longrightarrow$ missing energy signals

Diphoton production-SM background

$$P_A(p_1) + P_B(p_2) \longrightarrow \gamma(p_3) + \gamma(p_4) + X(p_x)$$

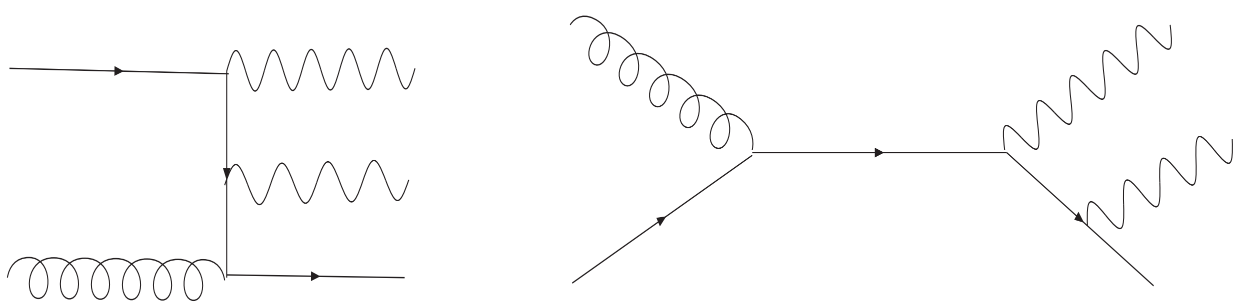
1. Improtant process for the Higgs search at the LHC. Golden channel.
2. Precision study of the Standard model
   Eur.Phys.J.C16:311-330,2000
   Phys.Rev.D76:013009,2007
3. To probe the BSM phyiscs **(ADD, RS, SUSY)**
4. ATLAS/CMS collaborations interested in the di-photon final states with the mass spectrum upto 2 TeV.
5. Includes non perturbative PDFs and fragmentation functions.

Diphoton production - SM background



$$\sim 2\, e^4 \left[\frac{t}{u} + \frac{u}{t} \right]$$

$$t \to 0; \quad u \to 0.$$



Final state collinearity
Fragmentation contribution (non-perturbative)

$\Rightarrow$ By proper definition of the observable.

Need for NLO QCD corrections

- For quantitative estimation of the higher order corrections.
-

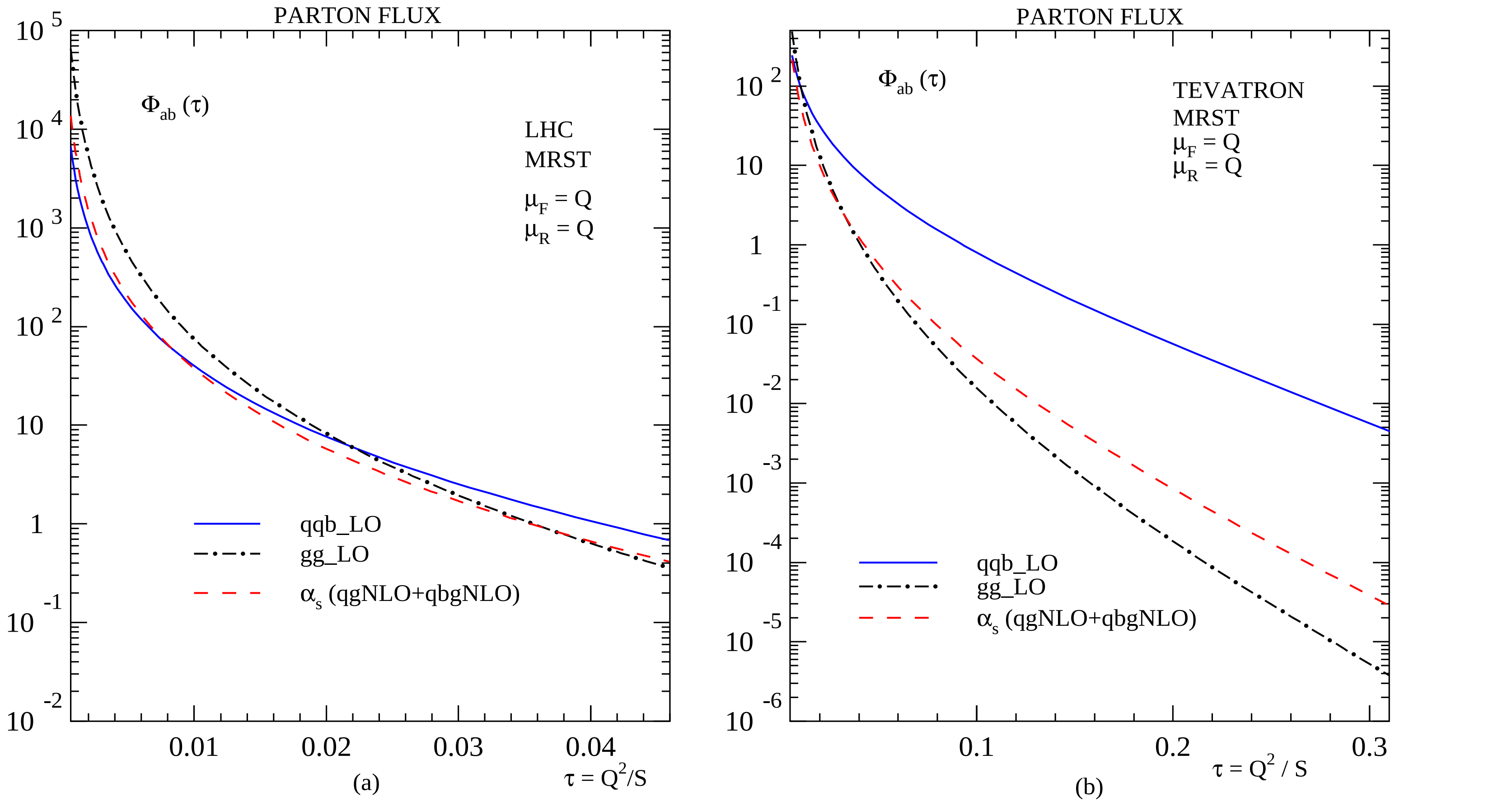
$$\sigma^{\mathrm{P_1P_2}} = \sum_{ab=q,\bar{q},g} \int_0^1 dx_1 \int_0^1 dx_2 f_a^{P_1}(x_1,\mu_F) f_b^{P_2}(x_2,\mu_F) \quad d\hat{\sigma}^{ab}(x_1,x_2,\mu_F)$$

  To reduce the scale uncertainties.
- Q_T distributions possible at NLO.
- Quantum corrections can be more pronounced in the BSM case than in the SM, because of the additional interactions in ED models.

The parton flux at LHC and TEVATRON

The parton flux is given by

$$\Phi_{ab}(\tau) = \int_\tau^1 \frac{dx}{x} f_a\left(x, \mu_F\right) f_b\left(\frac{\tau}{x}, \mu_F\right)$$



Two cut off phase space slicing method

1. Parton level NLO process is : $p_1 + p_2 \to p_3 + p_4 + p_5$
2. Separate the three body phase space into $soft$ and $hard$ regions :

$$\sigma = \int_S d\sigma_s \ + \ \int_H d\sigma_H$$

3. Separate of hard region into $collinear$ and $non\text{-}collinear$ regions:

$$\sigma_H = \int_{HC} d\sigma_{HC} \ + \ \int_{\overline{HC}} d\sigma_{\overline{HC}}$$

4. Two small cut-off parameters, namely, δ_s and δ_c are required to define $soft$ and $collinear$ regions.
5. Regularize the singular regions in $n = 4 + \epsilon$ dimensions.

Phys.Rev.D65:094032,2002

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

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

Soft

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

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

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

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

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

Collinear

The hard collinear region is : $0 \leq t_{15} \leq \delta_c \, s_{12}$ where $\delta_c << \delta_s$.

Phase space in this collinear region :

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

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

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

$\overline{MS}$ 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.

NLO2 contributions

$$\sigma_S = a_s\, C_F\, F(\epsilon, \mu_R, s) \left(\frac{16}{\epsilon^2} + \frac{16}{\epsilon} \ln\delta_s + 8\ln^2(\delta_s) \right) \sigma_0$$

$$\sigma_V = a_s\, C_F\, F(\epsilon, \mu_R, s) \left(-\frac{16}{\epsilon^2} + \frac{12}{\epsilon} + V_{\text{finite}} \right) \sigma_0$$

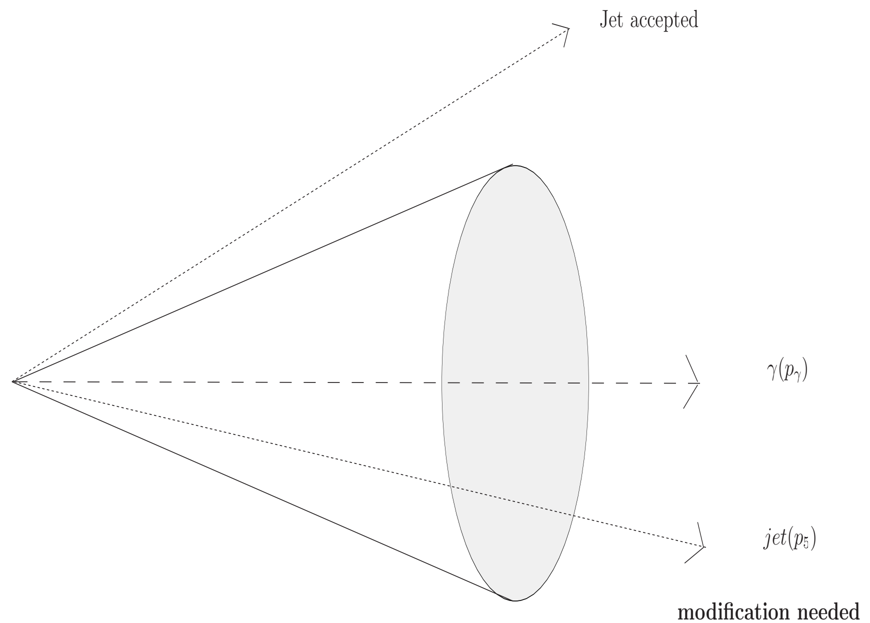
$$\sigma_{SC} = a_s\, C_F\, F(\epsilon, \mu_R, s) \left(-\frac{16}{\epsilon} \ln\delta_s - \frac{12}{\epsilon} + 2\ln\frac{s}{\mu_F^2} \left(4 \ln\delta_s + 3/2\right) \right) \sigma_0$$

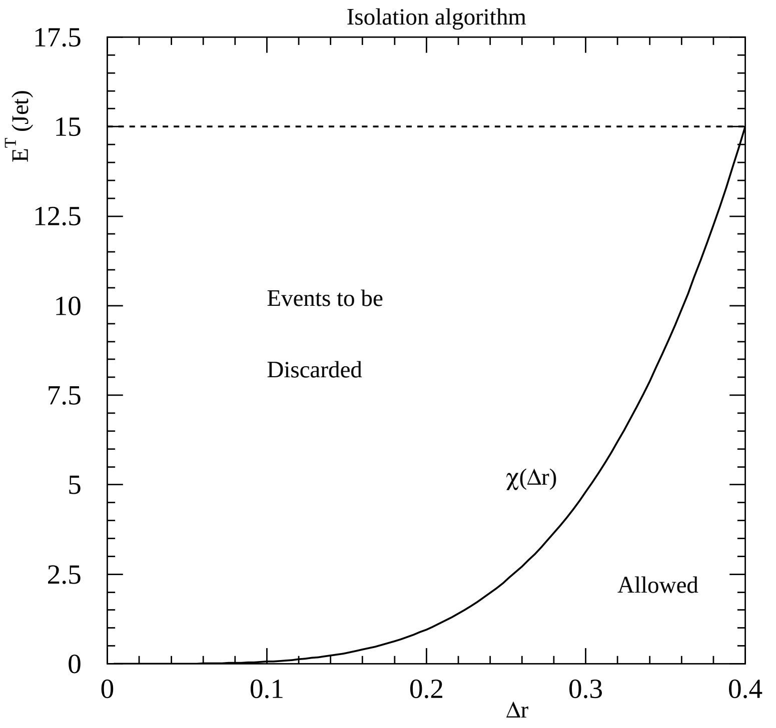
- $\sigma^{2-body} = \sigma_S + \sigma_V + \sigma_{SC}$ = finite
- $\sigma^{3-body} = \sigma_{\overline{HC}}$
- Cancellation of soft singularities between real and virtual diagrams.
- Integration over the remaining hard and non-collinear part in 4-dim. using monte-carlo techniques.
- Physical observables are expected to be independent of the choice of the cut-off parameters δ_s and δ_c.

Frixione algorithm

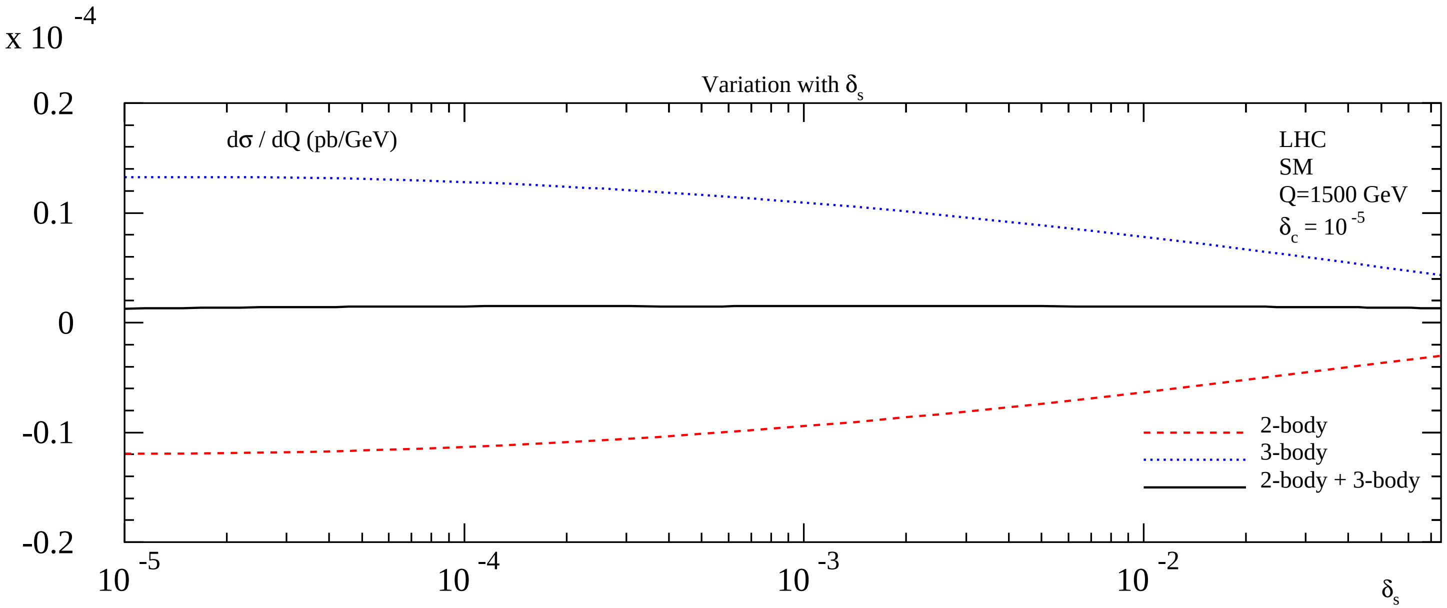
Discard the events if

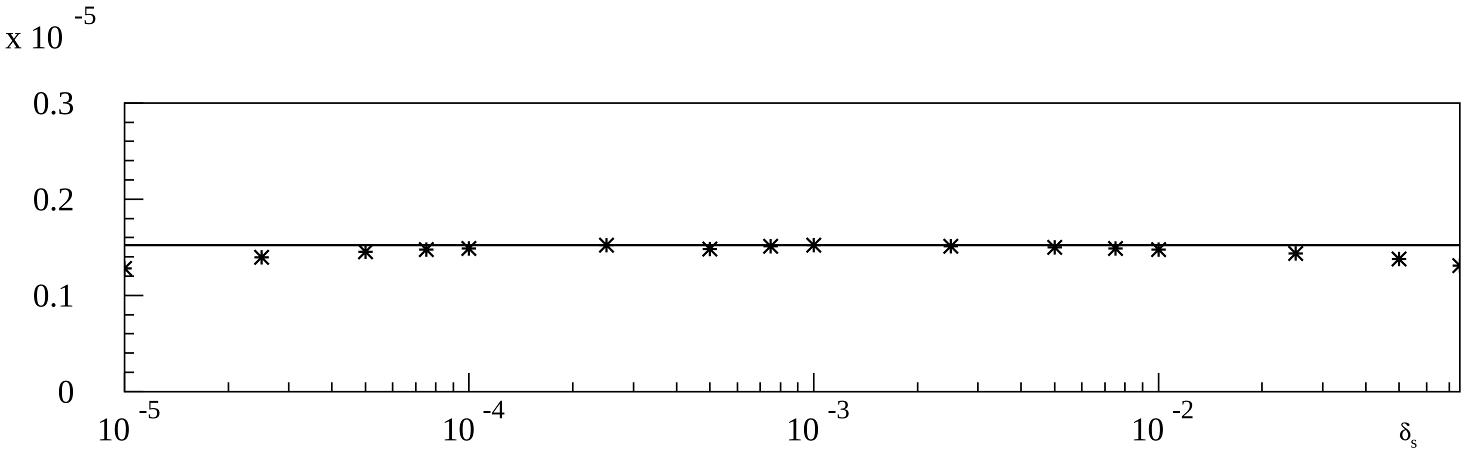
$$\Delta R \leq 0.4 \qquad \text{and} \quad \chi\left(\Delta r\right) \leq E_T^5 \leq 15\text{GeV} \qquad \text{where } \chi(x) = E^{iso}\left[\frac{1-\cos(x)}{1-\cos\Delta R}\right]^n$$



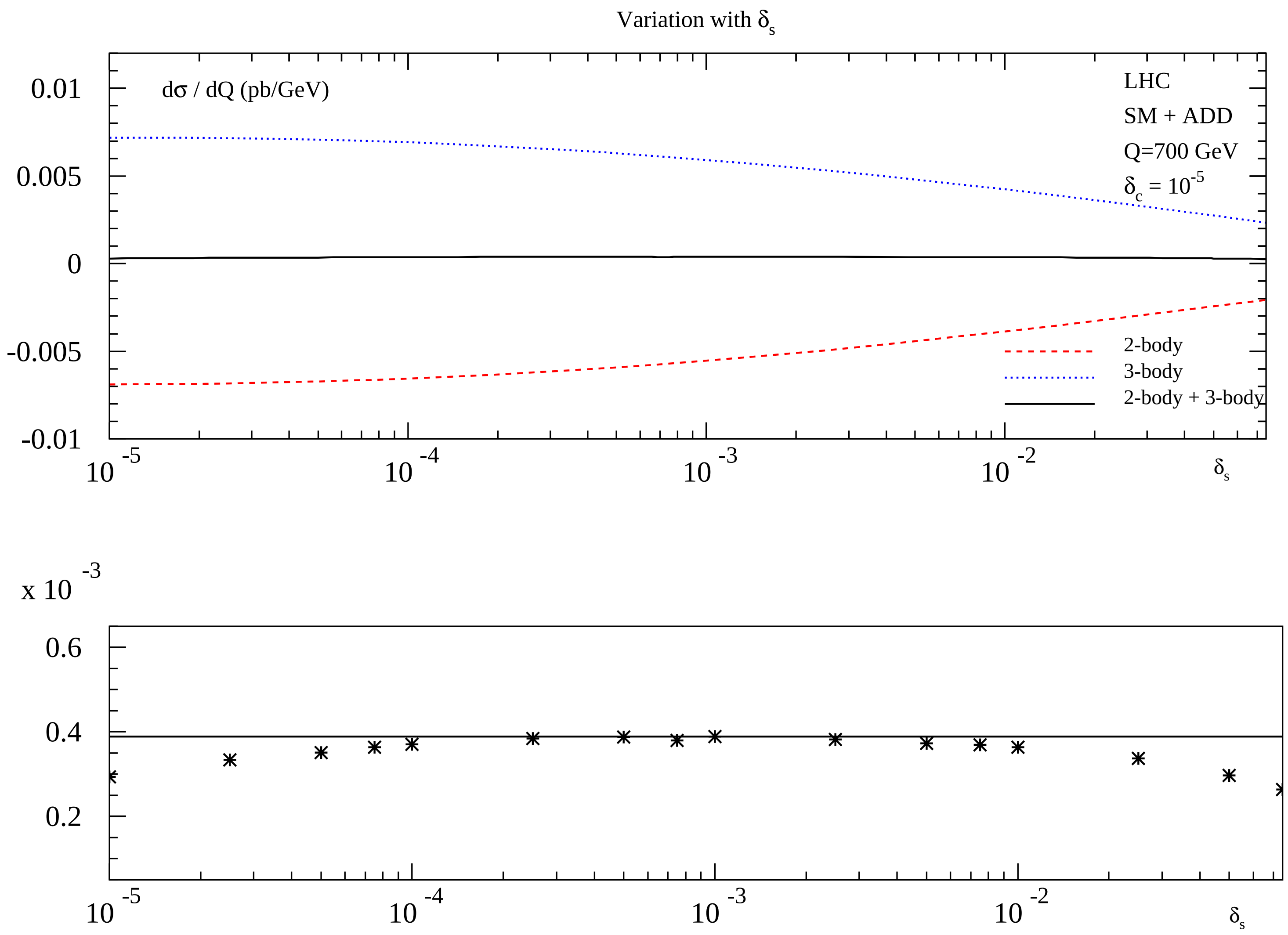


Stability of $d\sigma/dQ$ with δ_s (SM)

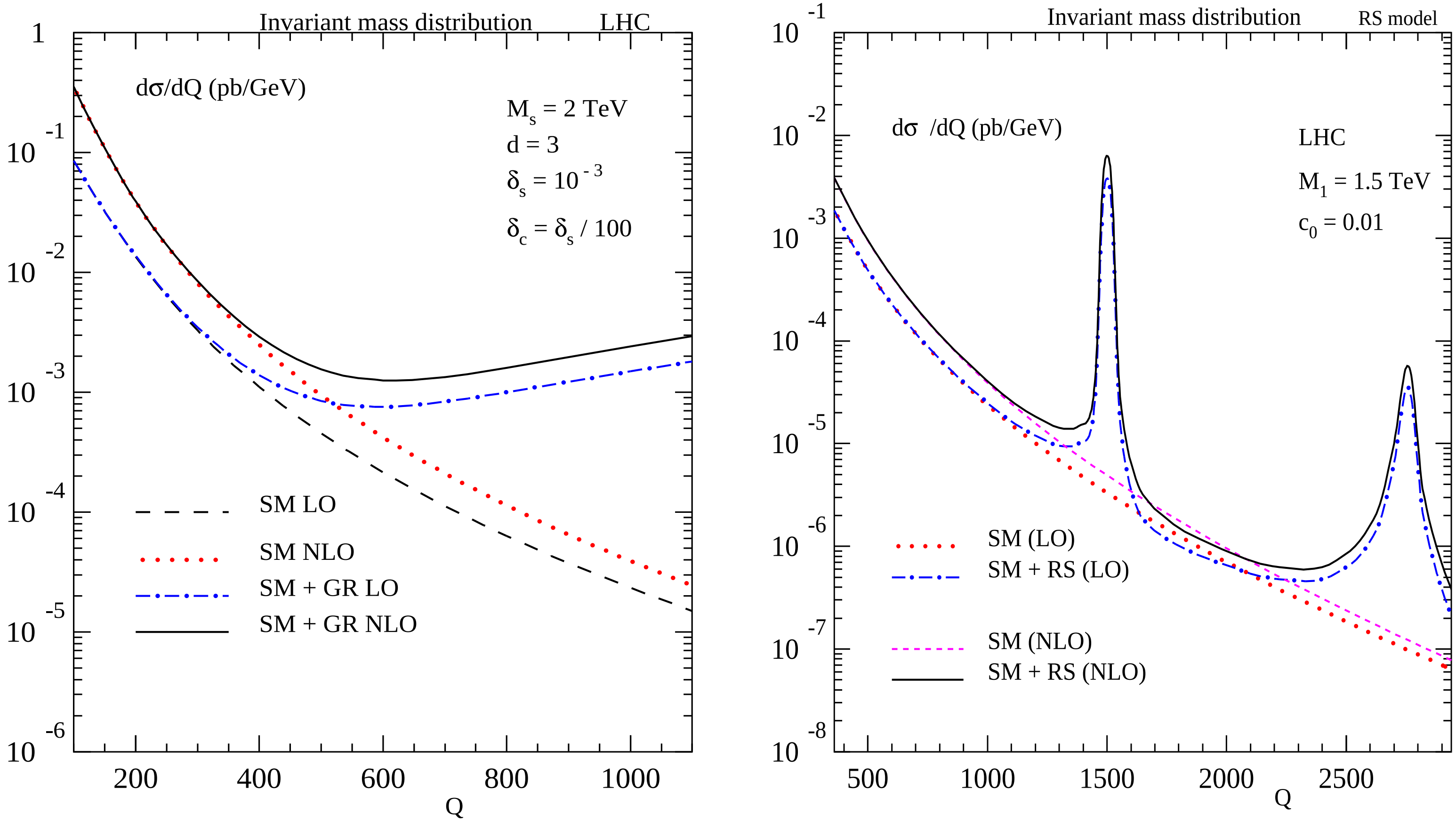




Stability of $d\sigma/dQ$ with δ_s (SM + ADD)



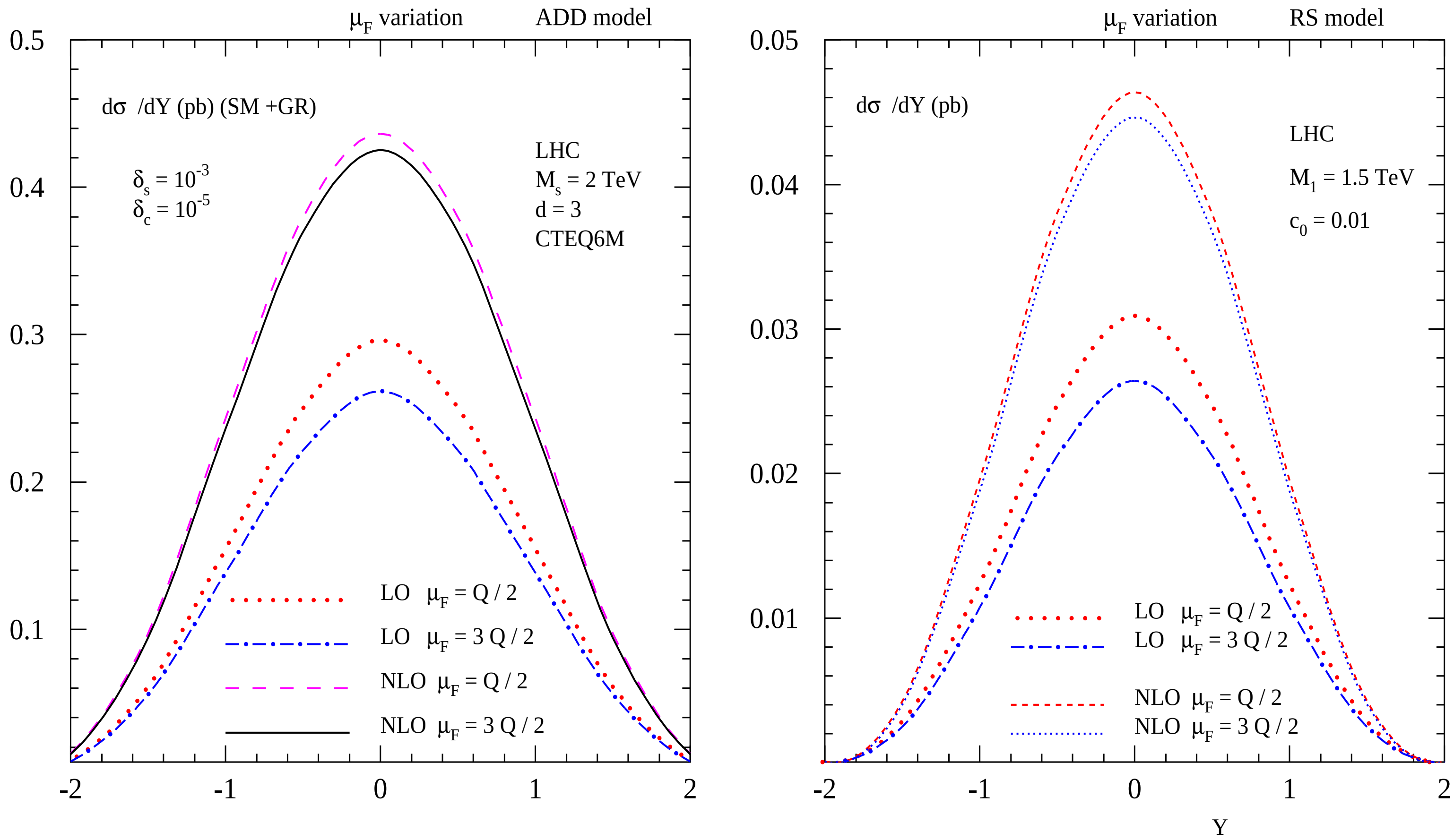
Invariant mass distribution



M.C.Kumar, Prakash Mathews, V. Ravindran, Anurag.Tripathi

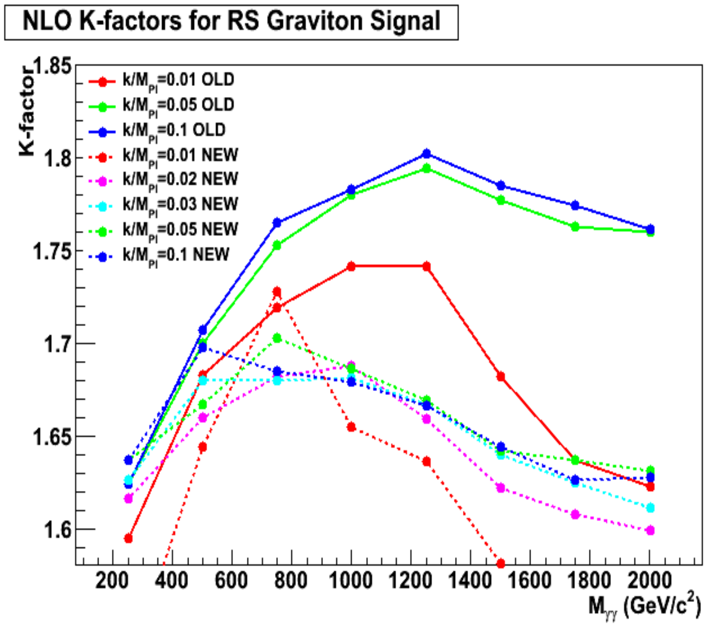
Nucl. Phys. B 818 (2009) 28.

Factorization Scale uncertainties

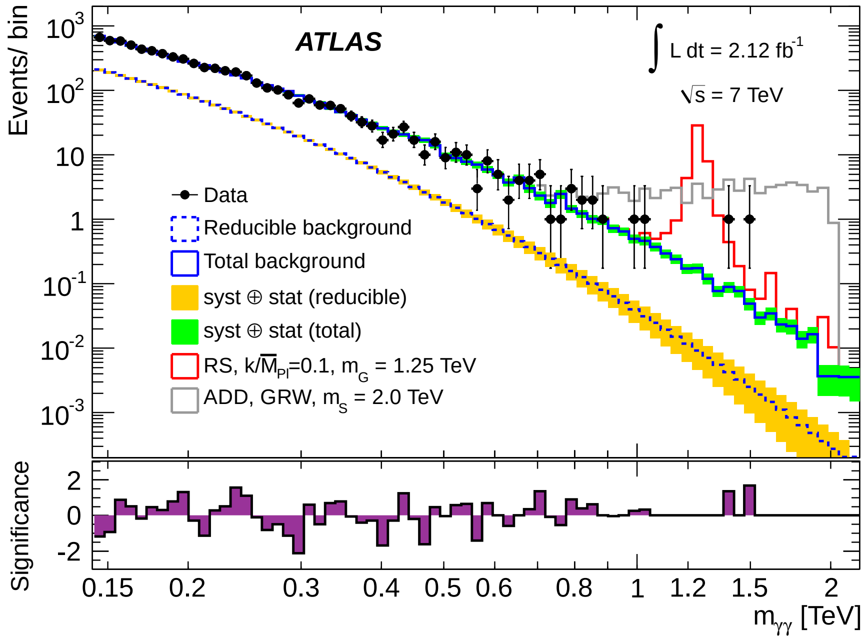


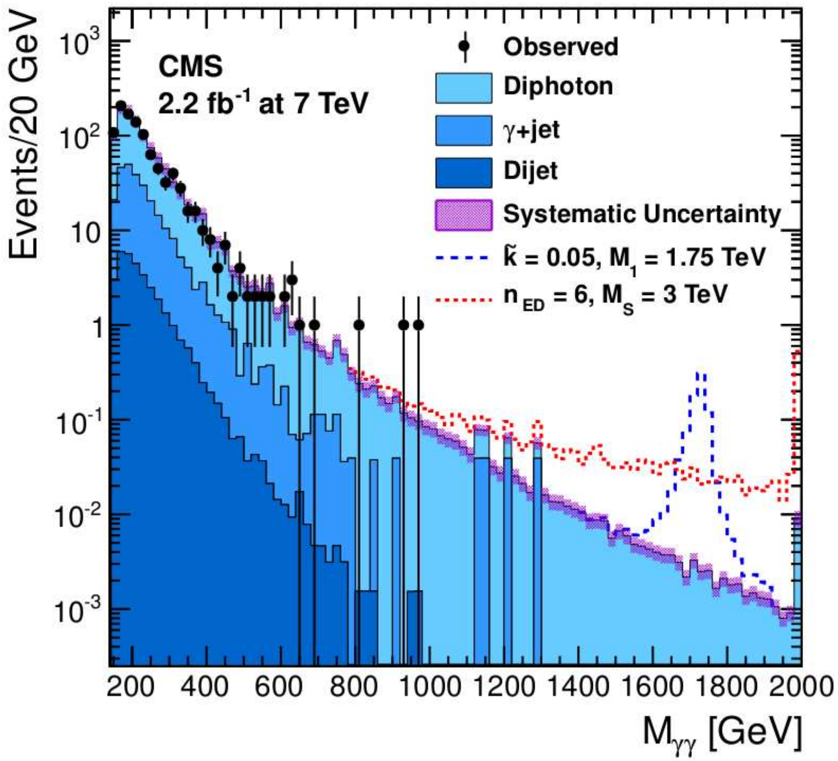
K-factors for the experimental collaborations

- **CDF collaboration: Search for RS gravitons**
  The mass dependent K-factors do range from 1.54 to 0.98 for RS graviton mass from 200 GeV to 1100 GeV.
  T. Aaltonen et al. [CDF collaboration] **Phys.Rev. D83 (2011) 011102**
- **CMS collaboration: Search for Large extra dimensions**
  The mass dependent K-factors do range from 1.69 to 1.62 for diphoton invariant mass from 500 GeV to 2000 GeV.
  Serguei Chatrchyan et al. [CMS collaboration] **JHEP 1105 (2011) 085**
- **CMS collaboration: Search for RS gravitons (for data analysis)**



ATLAS/CMS searches for extra dimensions





ATLAS collaboration **arXiv:1112.2194 [hep-ex]**

CMS collaboration **arXiv:1112.0688 [hep-ex]**

ATLAS search limits

ADD model

k-factor Value	GRW	Hewett Pos	Hewett Neg	HLZ $n=3$	HLZ $n=4$	HLZ $n=5$	HLZ $n=6$	HLZ $n=7$
1	2.73	2.44	2.16	3.25	2.73	2.47	2.30	2.17
1.70	2.97	2.66	2.27	3.53	2.97	2.69	2.50	2.36

RS model

k-Factor Value	Channel(s) Used	95% CL Limit [TeV] $k/\overline{M}_{Pl}$ Value 0.01	0.03	0.05	0.1
1	$G \to \gamma\gamma$	0.74	1.26	1.41	1.79
	$G \to \gamma\gamma/ee/\mu\mu$	0.76	1.32	1.47	1.90
1.75	$G \to \gamma\gamma$	0.79	1.30	1.45	1.85
	$G \to \gamma\gamma/ee/\mu\mu$	0.80	1.37	1.55	1.95

CMS search limits

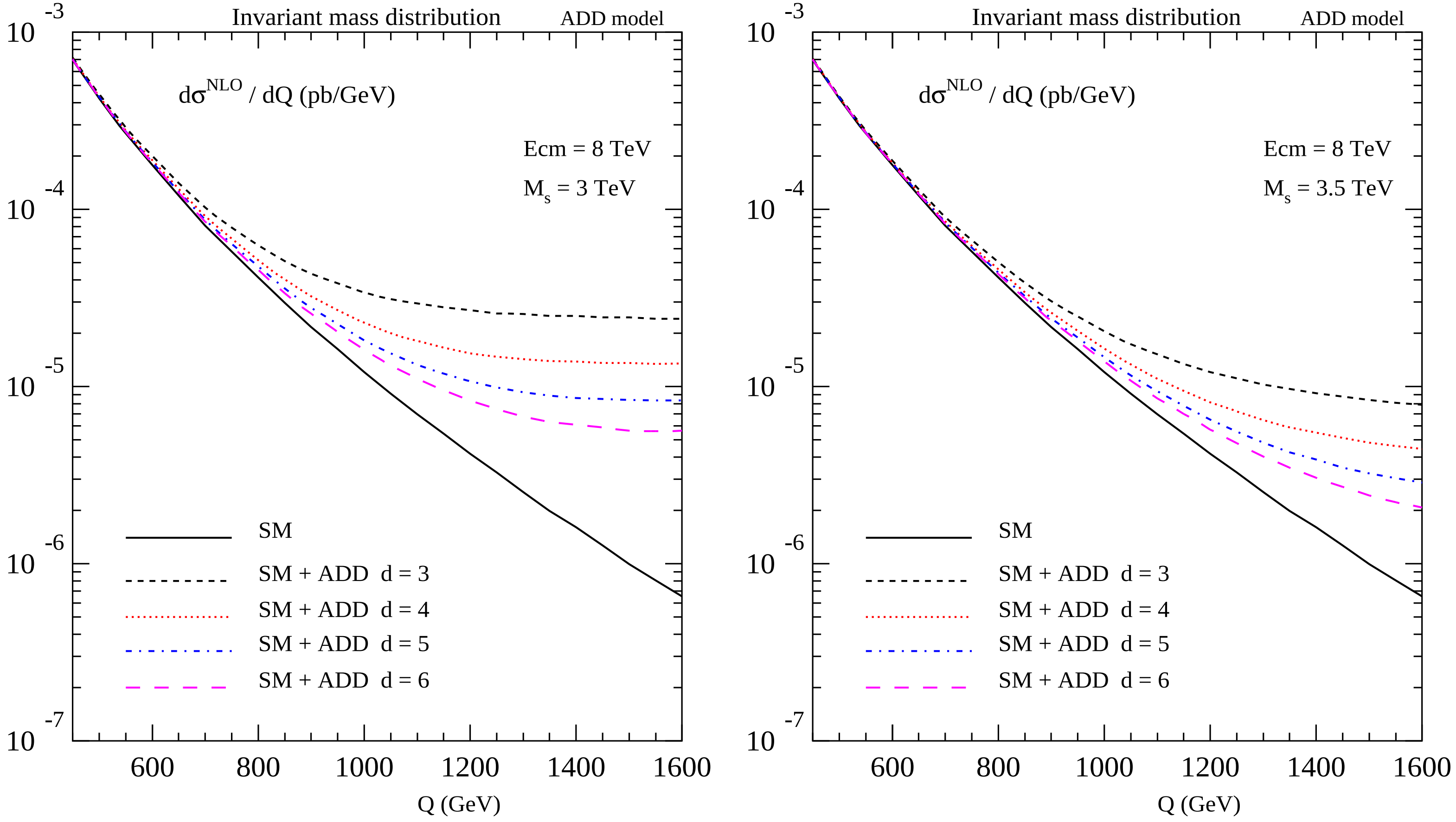
ADD model

K factor	GRW	Hewett		HLZ (n)					
		pos.	neg.	2	3	4	5	6	7
1.0	2.94	2.63	2.28	3.29	3.50	2.94	2.66	2.47	2.34
1.6	3.18	2.84	2.41	3.68	3.79	3.18	2.88	2.68	2.53

RS model

$\tilde{k}$	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11
M_1 [TeV]	0.86	1.13	1.27	1.39	1.50	1.59	1.67	1.74	1.80	1.84	1.88

8 TeV results - Diphoton invariant mass distribution



Diphoton K-factors for ADD model (8TeV LHC)

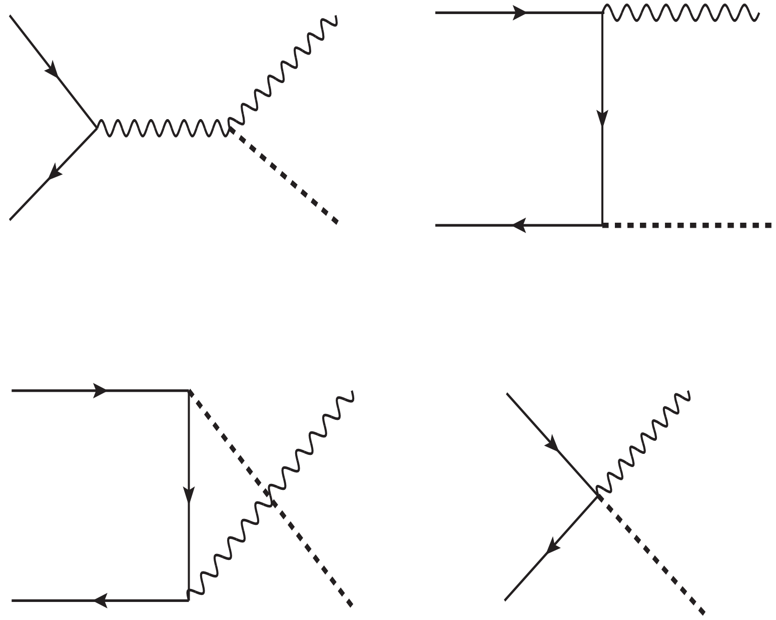
Q (GeV)	SM	GR	SM+ADD
500.00	1.780	1.594	1.753
600.00	1.707	1.672	1.665
700.00	1.603	1.659	1.556
800.00	1.564	1.701	1.519
900.00	1.514	1.699	1.487
1000.00	1.467	1.708	1.482
1100.00	1.430	1.722	1.509
1200.00	1.391	1.729	1.534
1300.00	1.373	1.706	1.554
1400.00	1.357	1.693	1.573
1500.00	1.295	1.678	1.578
1600.00	1.278	1.648	1.575
1700.00	1.259	1.647	1.591
1800.00	1.222	1.634	1.591
1900.00	1.202	1.607	1.575
2000.00	1.208	1.623	1.597

Graviton plus Z production

- The parton level process at LO is :

$$q + \bar{q} \rightarrow Z + G$$

- This process has been studied at LO both at lepton colliders and hadron colliders.



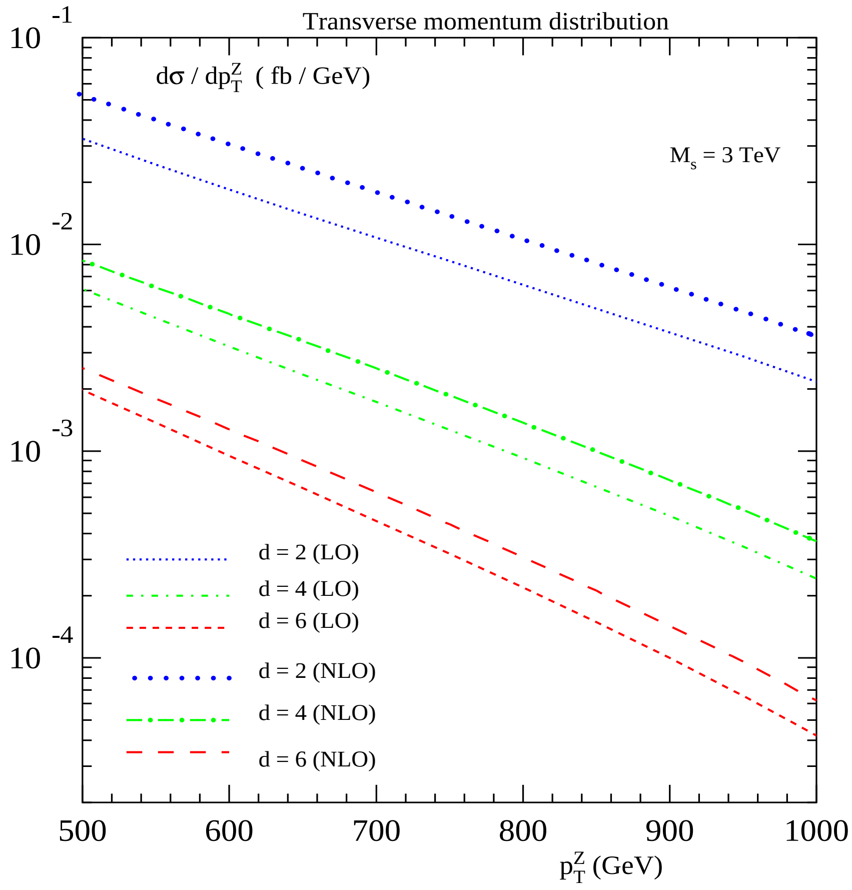
cuts

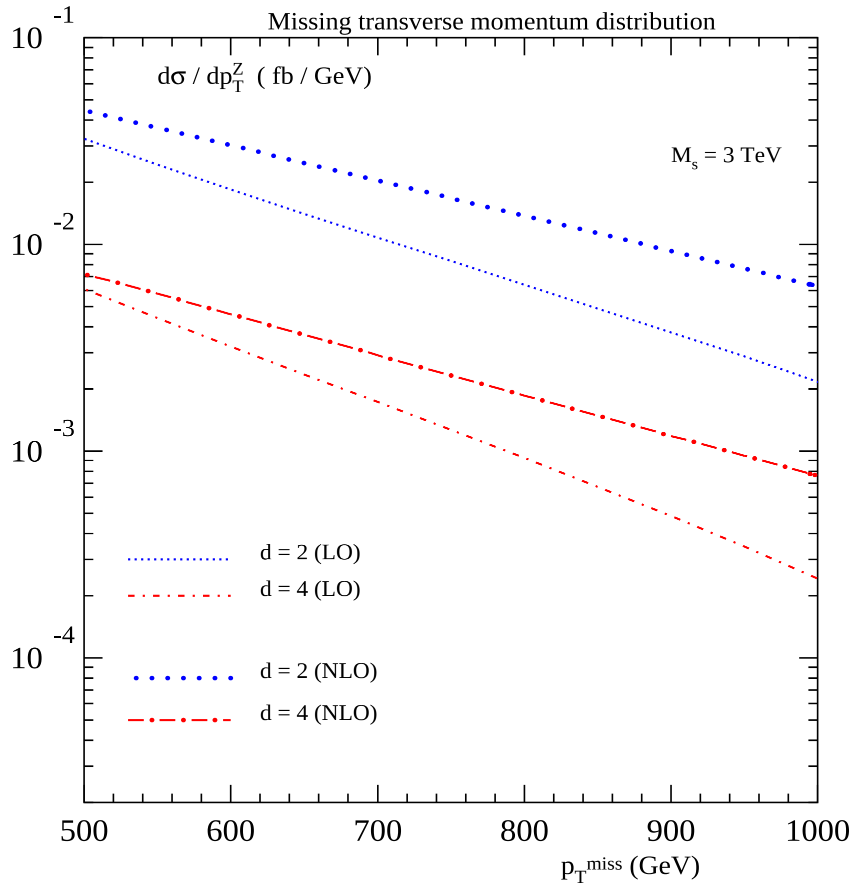
- Rapidity cut on the vector bosons : $|y^Z| < 2.5$
- Transverse momentum cuts on the bosons : $p_T^Z > 400$GeV
- For $2 \to 2$ case, $p_T^{miss} = p_T^Z = p_T^G$

Jet definition

- $p_T^{jet} > 20$ GeV and $|\eta^{jet}| < 2.5$
- $p_T^{miss} = p_T^Z$: When there is no jet in the final state
- $p_T^{miss} = p_T^G$: When there is a jet in the final state
- Missing transverse momentum: $p_T^{miss} > 400$GeV

Transverse momentum distributions





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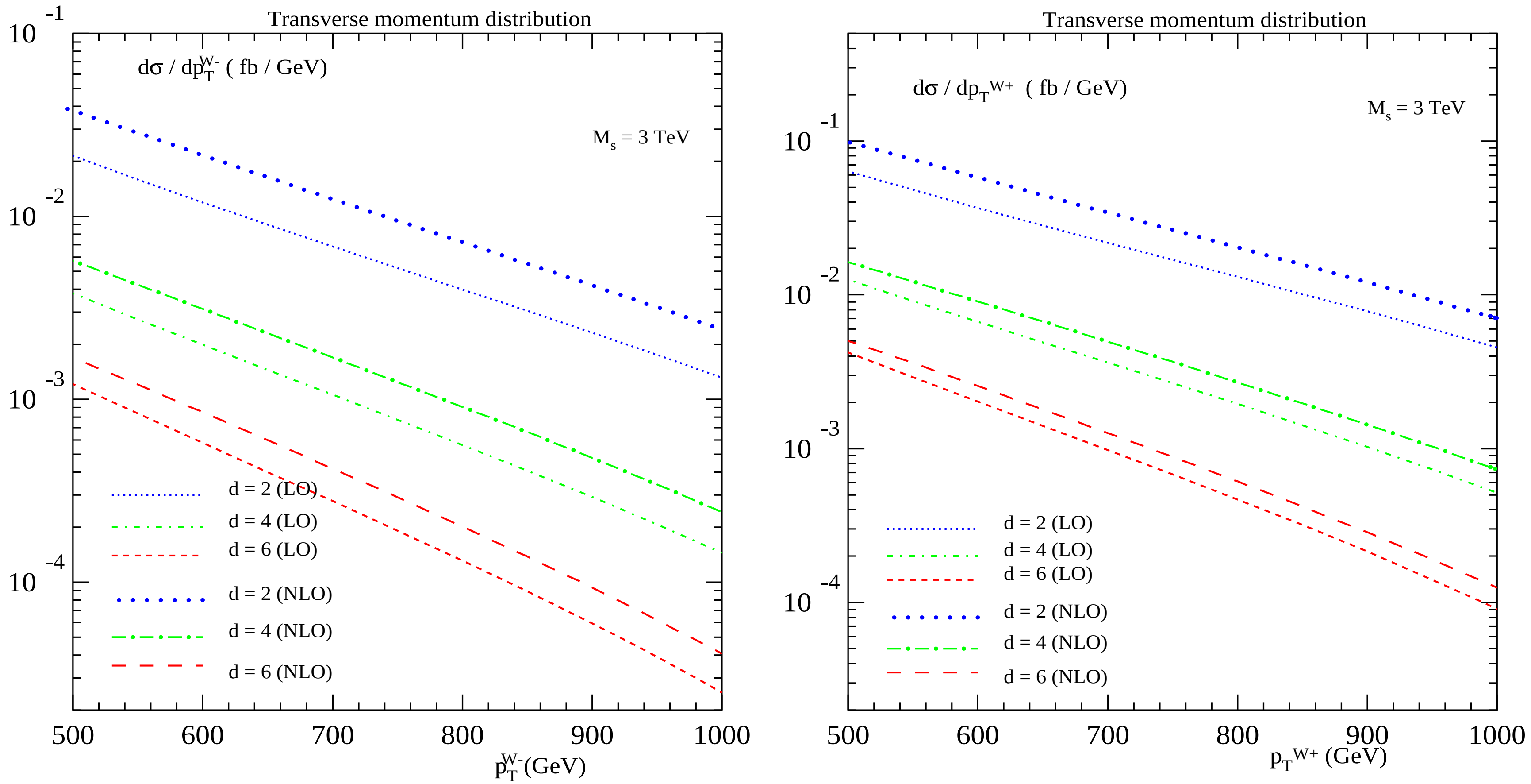
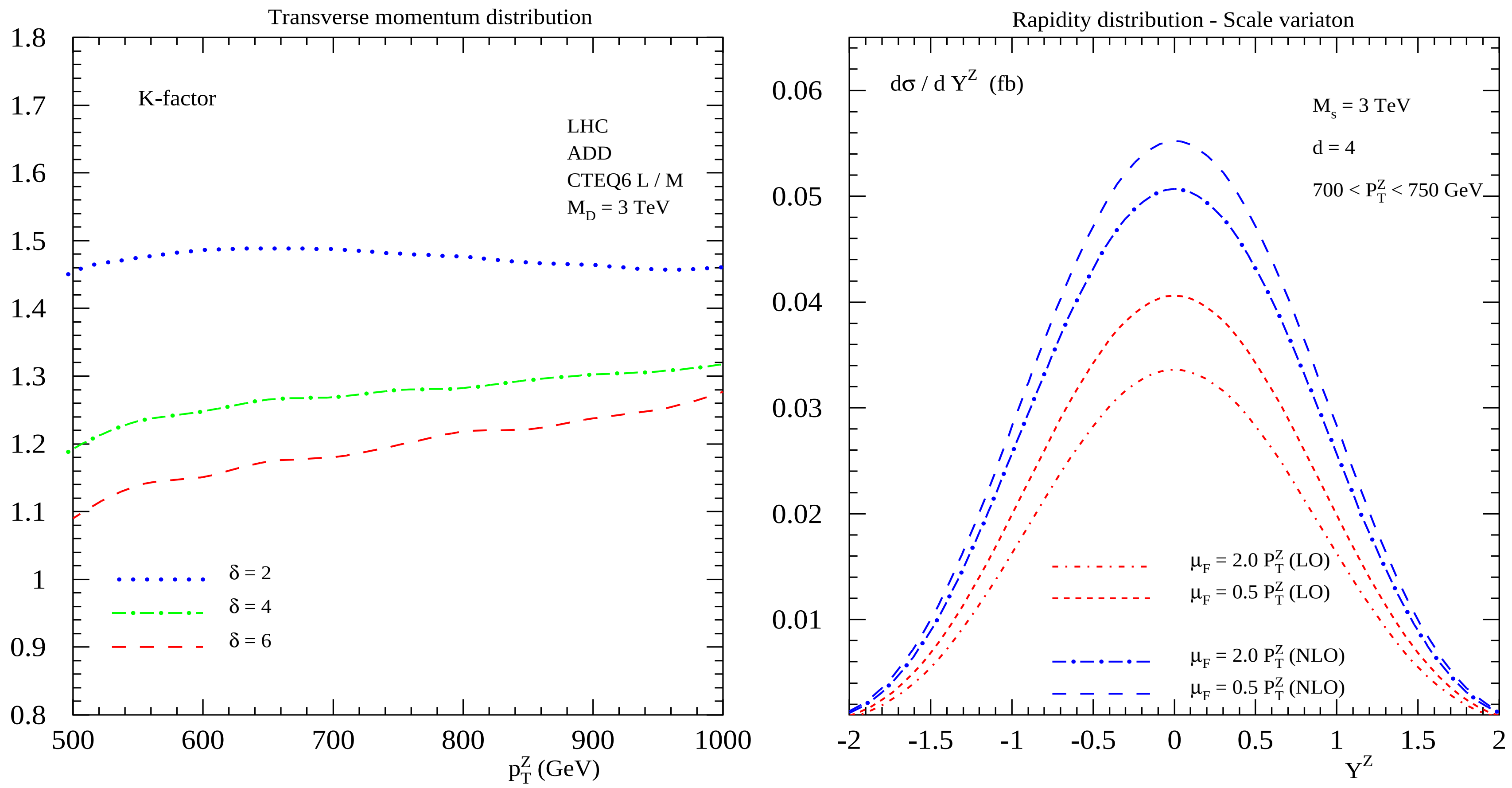
Transverse momentum distributions



K-factors and scale variations



Summary

1. QCD corrections in the extra dimension theories are considerably large.
2. These NLO QCD corrections are very important for they enhance the cross sections and minimize the scale uncertainties.
3. This analysis is, in general, a model independent one, but the K-factors can depend on the choice of the model parameters.
4. NLO QCD cross sections are more reliable than the LO ones in the search of new physics at the LHC.