Constraints on RS model from the events of dijet production at the LHC

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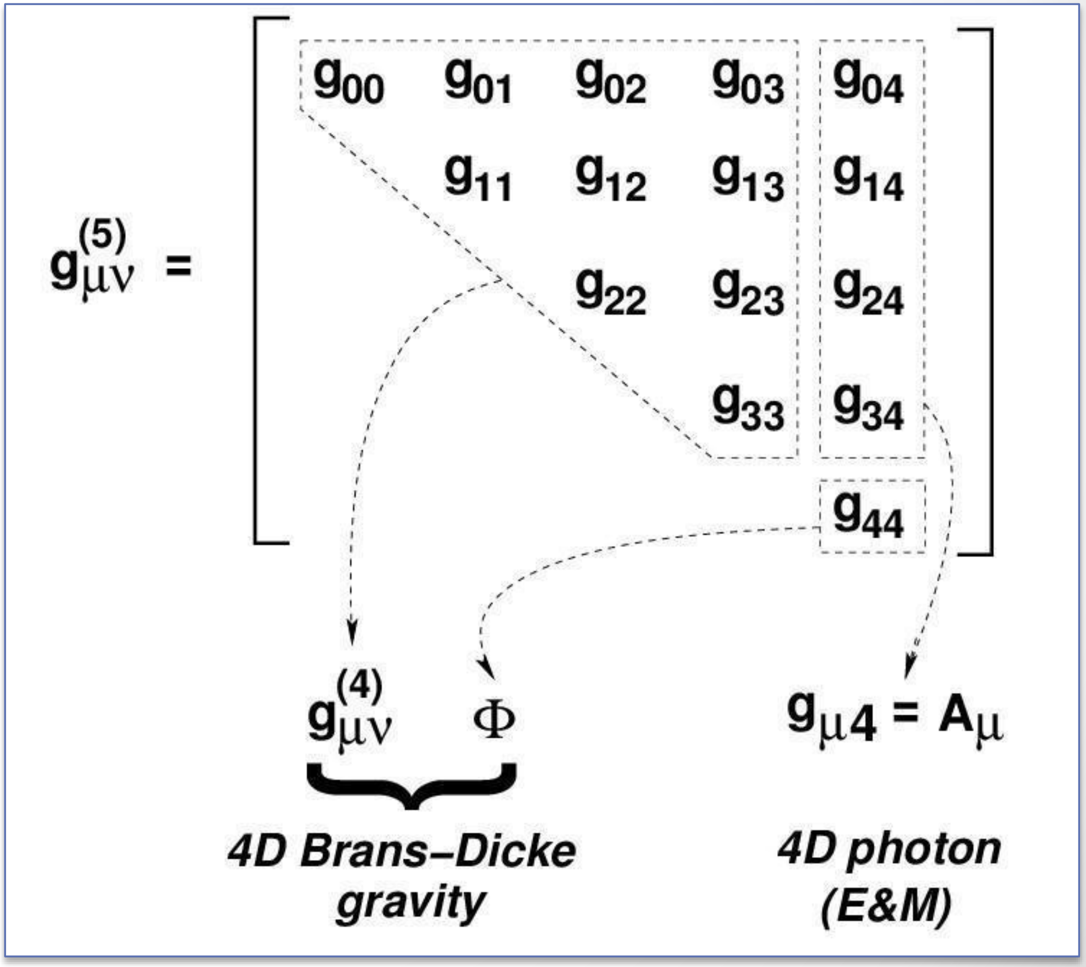
Outline

- Motivation
  - RS extra dimension
  - Dijet process
- NLO QCD
  - Renormalization
  - Two cut-off
  - NLO decay width
- Numerical discussion
  - Total cross section and Kinematics distribution
  - Signal analysis
- Conclusion

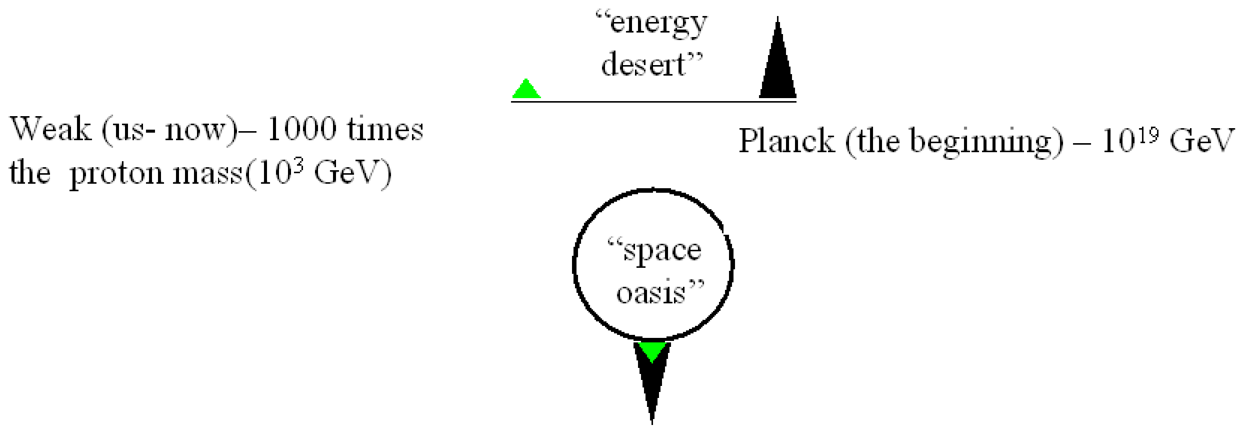
Kaluza-Klein idea

- The fundamental field is the five-dimensional metric $g_{\mu\nu}^{(5)}$
- Decomposed into representations of the four-dimensional Lorentz group
- Yields three different representations, spin-2, spin-1, spin-0
- $g_{gauge}^2 = \frac{2\kappa_5}{R^2}$

C. Csaki et al.: From fields to strings [hep-ph/0404096]



Extra dimension



$$S_4 = -M_{Pl}^2 \int d^4x \sqrt{g^{(4)}} R^{(4)}$$

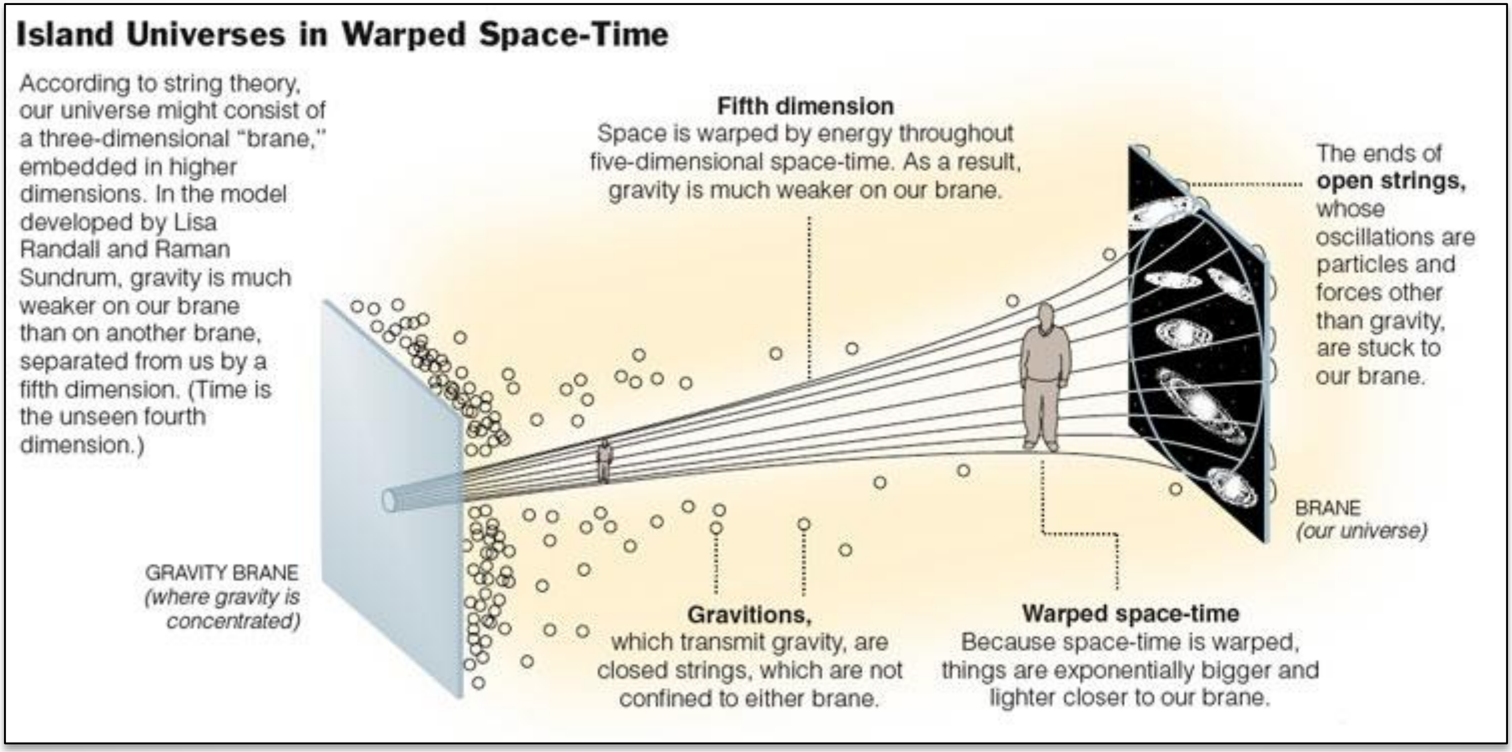
$$S_{4+n} = -M_*^{n+2} \int d^{4+n}x \sqrt{g^{(4+n)}} R^{(4+n)}$$

$$= -M_*^{n+2} \int d\Omega_{(n)} r^n \int d^4x \sqrt{g^{(4)}} R^{(4)}$$

$$M_{Pl}^2 = M_*^{n+2} V_{(n)} = M_*^{n+2} (2\pi r)^n$$

- Have not observed the extra dimension, so they must be compactified to a small length scale
- Compactify δ extra spacetime dimensions $M_4 \times K$

Randall-Sundrum model

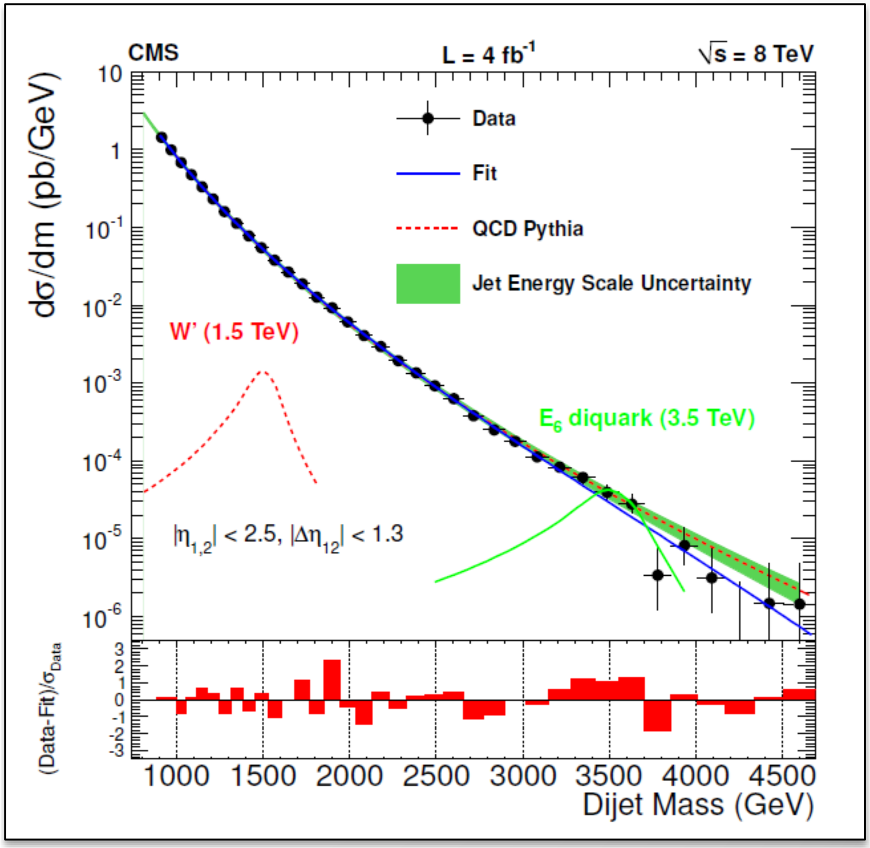


$$\mathcal{L} = -\frac{1}{\bar{M}_P} T^{\alpha\beta}(x) h^{(0)}_{\alpha\beta}(x) - \frac{1}{\Lambda_\pi} T^{\alpha\beta}(x) \sum_{n=1}^{\infty} h^{(n)}_{\alpha\beta}(x)$$

Dijet Process

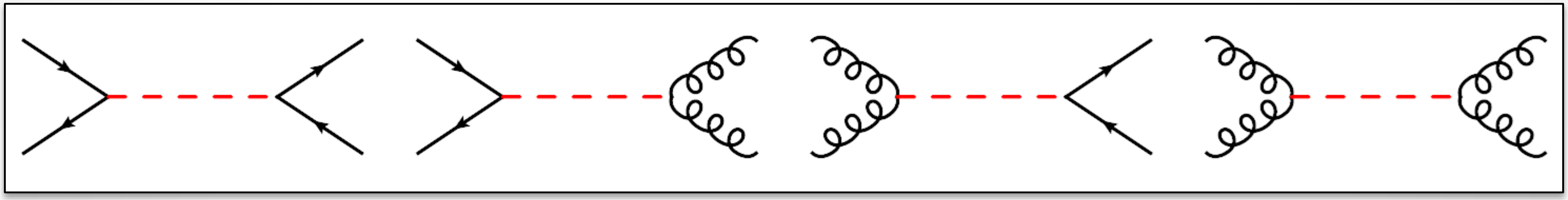
$$p + p \to G \to jet + jet$$

- In the SM, the dijet events are mostly produced through quantum chromodynamics(QCD) interactions in hadron colliders, which predicts a smooth and steeply falling dijet mass spectrum.
- Used the dijet invariant mass to constrain the mass of these new resonances



CMS Collaboration .CMS-PAS-EXO-12-016

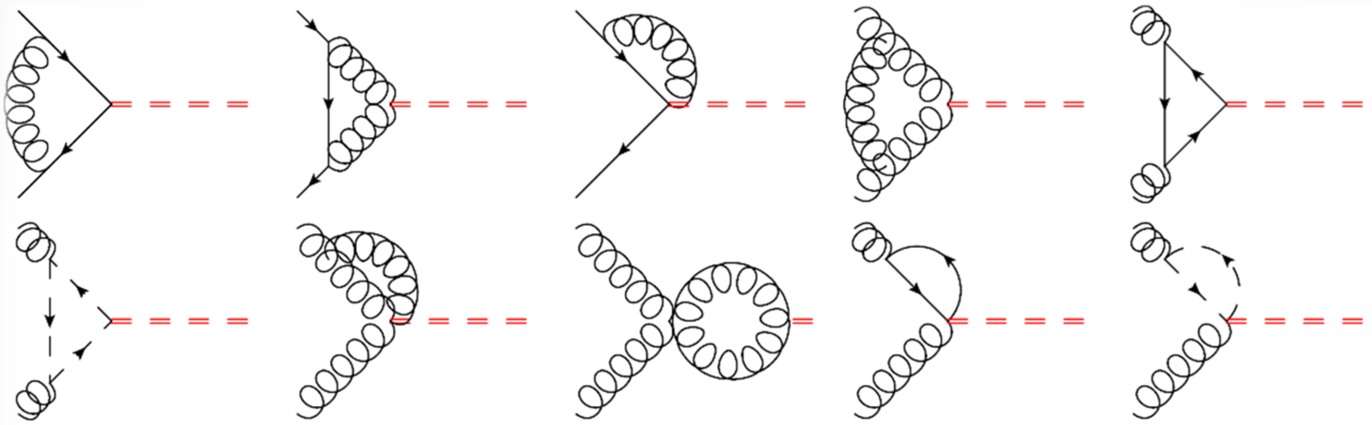
Breit-Wigner resonance

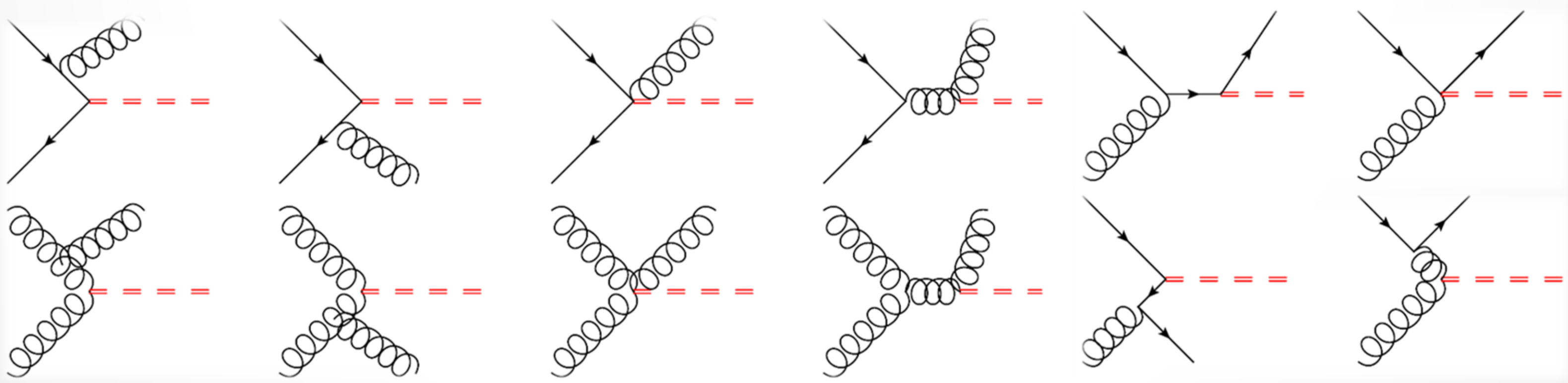


The QCD NLO corrections can be factorized into two independent gauge invariant parts, production at the NLO with decay at the LO, and production at the LO with decay at the NLO. We neglect interference between radiation in the two stages, which are expected to be small, of order O(αs Γ/M)

$$
\begin{aligned}
|\mathcal{M}^{tree}_{2\to 2}|^2 &= |\mathcal{M}^{tree}_{pro}|^2 \otimes |\mathcal{M}^{tree}_{dec}|^2 \otimes |P_G|^2 , \\
|\mathcal{M}^{real}_{2\to 3}|^2 &= \{|\mathcal{M}^{tree}_{pro}|^2 \otimes |\mathcal{M}^{real}_{dec}|^2 + |\mathcal{M}^{real}_{pro}|^2 \otimes |\mathcal{M}^{tree}_{dec}|^2\} \otimes |P_G|^2 , \\
\mathcal{M}^{tree*}_{2\to 2}\mathcal{M}^{loop}_{2\to 2} &= \{|\mathcal{M}^{tree}_{pro}|^2 \otimes (\mathcal{M}^{tree*}_{dec}\mathcal{M}^{loop}_{dec}) + |\mathcal{M}^{tree}_{dec}|^2 \otimes (\mathcal{M}^{tree*}_{pro}\mathcal{M}^{loop}_{pro})\} \otimes |P_G|^2
\end{aligned}
$$

Feynman diagrams





NLO QCD Calculation

- Using the on-shell subtraction scheme to renormalize the UV divergences by introducing counterterms.

$$M_{ij}^{V} = M_{ij}^{unren} + M_{ij}^{con}$$

- UV renormalized partonic cross section

$$\hat{\sigma}_{q\bar{q}}^{V} = \hat{\sigma}_{q\bar{q}}^{B} \frac{\alpha_s}{2\pi} D_\epsilon \left\{ \frac{A_2^{v,q}}{\epsilon_{IR}^2} + \frac{A_1^{v,q}}{\epsilon_{IR}} + A_0^{v,q} \right\}$$

$$\hat{\sigma}_{gg}^{V} = \hat{\sigma}_{gg}^{B} \frac{\alpha_s}{2\pi} D_\epsilon \left\{ \frac{A_2^{v,g}}{\epsilon_{IR}^2} + \frac{A_1^{v,g}}{\epsilon_{IR}} + A_0^{v,g} \right\}$$

NLO QCD Calculation

- We adopt two cut off phase space slicing method to cancel and absorb the IR divergences.

$$E_i \leq \delta_s s \qquad -\delta_c s < (p_i - p_5)^2 < 0$$

$$\hat{\sigma}_{ij}^{R} = \hat{\sigma}_{ij}^{S} + \hat{\sigma}_{ij}^{H} \qquad \hat{\sigma}_{ij}^{H} = \hat{\sigma}_{ij}^{HC} + \hat{\sigma}_{ij}^{\overline{HC}}$$

$$\boxed{\begin{aligned}\sigma^{NLO} &= \int dx_1 dx_2 [G_{q/p}(x_1,\mu_f)G_{\bar{q}/p}(x_2,\mu_f) + (x_1 \leftrightarrow x_2)](\hat{\sigma}_{q\bar{q}}^{B} + \hat{\sigma}_{q\bar{q}}^{V} + \hat{\sigma}_{q\bar{q}}^{S} + \hat{\sigma}_{q\bar{q}}^{HC,F} \qquad (44)\\ &+ \hat{\sigma}_{q\bar{q}}^{\overline{HC}}) + \int dx_1 dx_2 G_{g/p}(x_1,\mu_f)G_{g/p}(x_2,\mu_f)(\hat{\sigma}_{gg}^{B} + \hat{\sigma}_{gg}^{V} + \hat{\sigma}_{gg}^{S} + \hat{\sigma}_{gg}^{HC,F} + \hat{\sigma}_{gg}^{\overline{HC}}) + \hat{\sigma}^{coll,I}\\ &+ \int dx_1 dx_2 \sum_{\alpha=q,\bar{q}} [G_{g/p}(x_1,\mu_f)G_{\alpha/p}(x_2,\mu_f) + (x_1 \leftrightarrow x_2)]\hat{\sigma}_{\alpha g}^{\overline{HC}})\end{aligned}}$$

Consistent treatment

Narrow-Width Approximation

$$\sigma^{NLO} = \sigma_0 + \alpha_s \sigma_1$$

$$\Gamma^{NLO} = \Gamma_0 + \alpha_s \Gamma_1$$

$$\sigma^{NLO} = \sigma_0 \times \frac{\Gamma_0^i}{\Gamma_0} + \sigma_0 \times \frac{\alpha_s \Gamma_1^i}{\Gamma_0} + \alpha_s \sigma_1 \times \frac{\Gamma_0^i}{\Gamma_0} - \alpha_s \sigma_0 \times \frac{\Gamma_0^i}{\Gamma_0}\frac{\Gamma_1}{\Gamma_0}$$

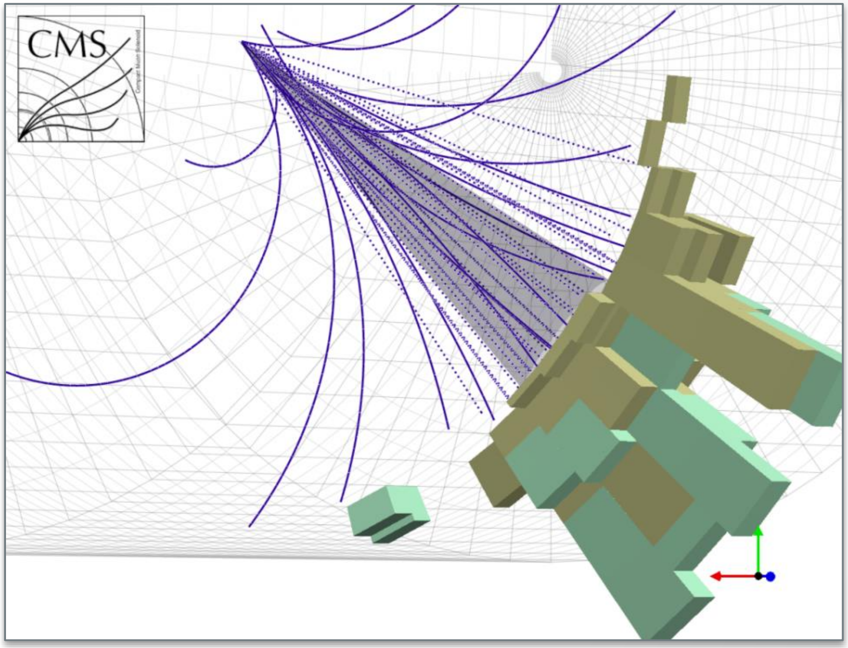
Breit-Wigner Resonance

$$\begin{aligned} & \frac{1}{(s^2 - m_{KK}^2)^2 + [\Gamma_0 + \alpha_s \Gamma_1]^2 m_{KK}^2} \\ = & \frac{1}{(s^2 - m_{KK}^2)^2 + \Gamma_0^2 m_{KK}^2} - \frac{2\alpha_s m_{KK}^2 \Gamma_0 \Gamma_1}{[(s^2 - m_{KK}^2)^2 + \Gamma_0^2 m_{KK}^2]^2} \\ = & R(s)\left[1 - 2\alpha_s R(s) m_{KK}^2 \Gamma_0 \Gamma_1\right] , \end{aligned}$$

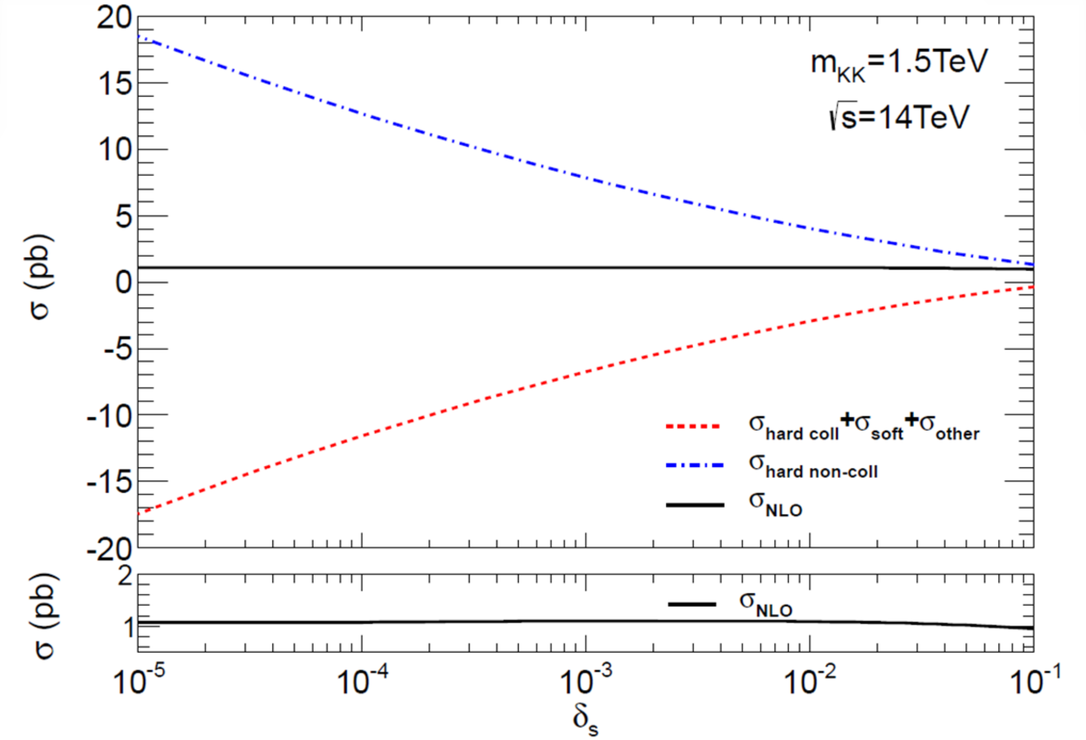
$$\begin{aligned} \sigma_i^{NLO} = & \left[1 - 2\alpha_s R(s) m_{KK}^2 \Gamma_0 \Gamma_1\right] \sigma^0 \otimes \Gamma_0^i \\ & + \alpha_s \sigma^1 \otimes \Gamma_0^i + \alpha_s \sigma^0 \otimes \Gamma_1^i \end{aligned}$$

Cut and Jet algorithm

- We focus on two jets final state process.
- Anti-kt jet algorithm was applied, R=0.5 for jet combination
- We select jets with
  $p_T > 30GeV, \eta < 2.5$
- To improving the result, we formed wide jet around each leading jet.
  $$\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$



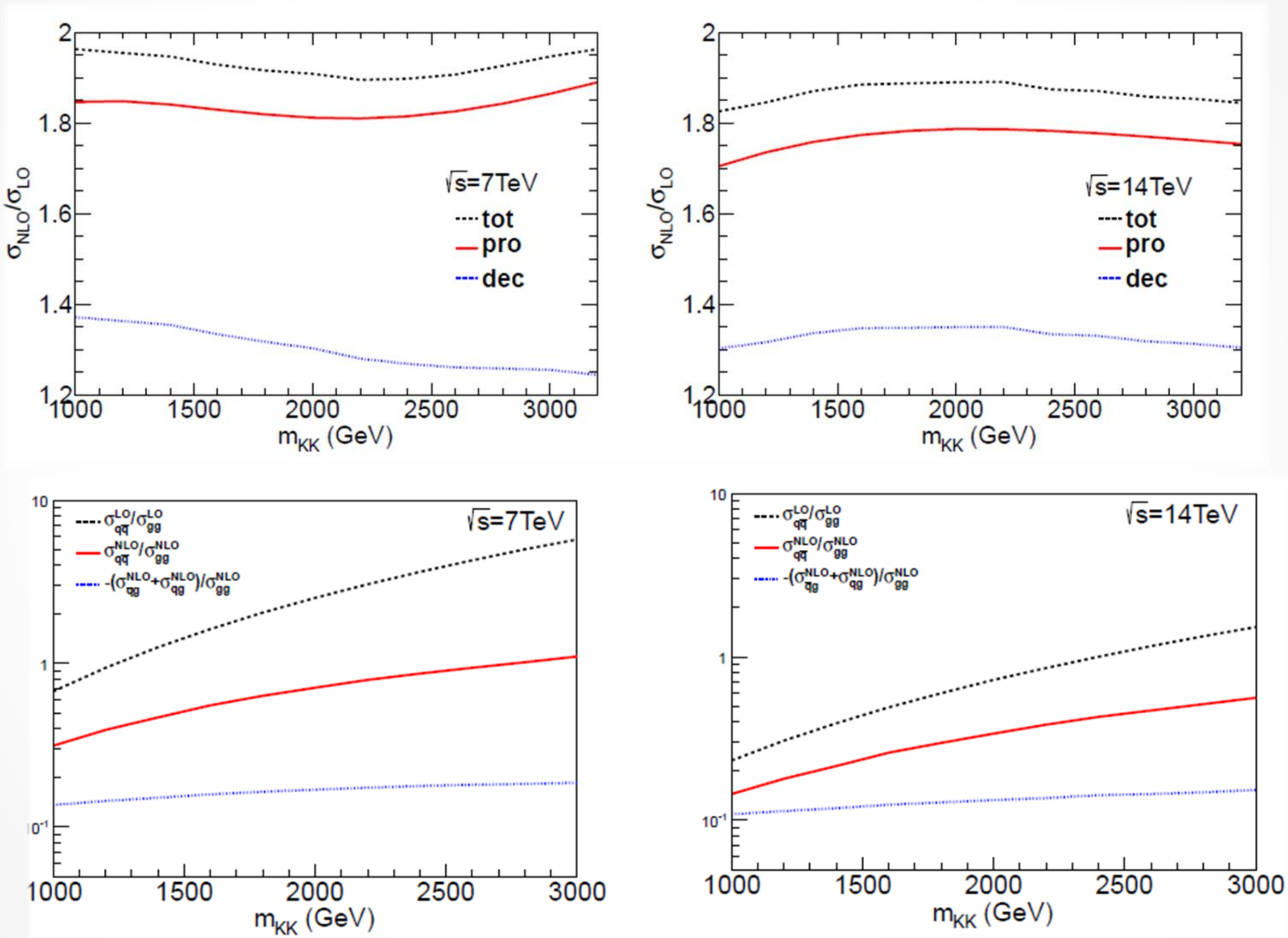
Two cut-off dependence



The dependence of NLO total cross section on the arbitrary cutoff δ_s and δ_c is indeed very weak, our choice in this work is:

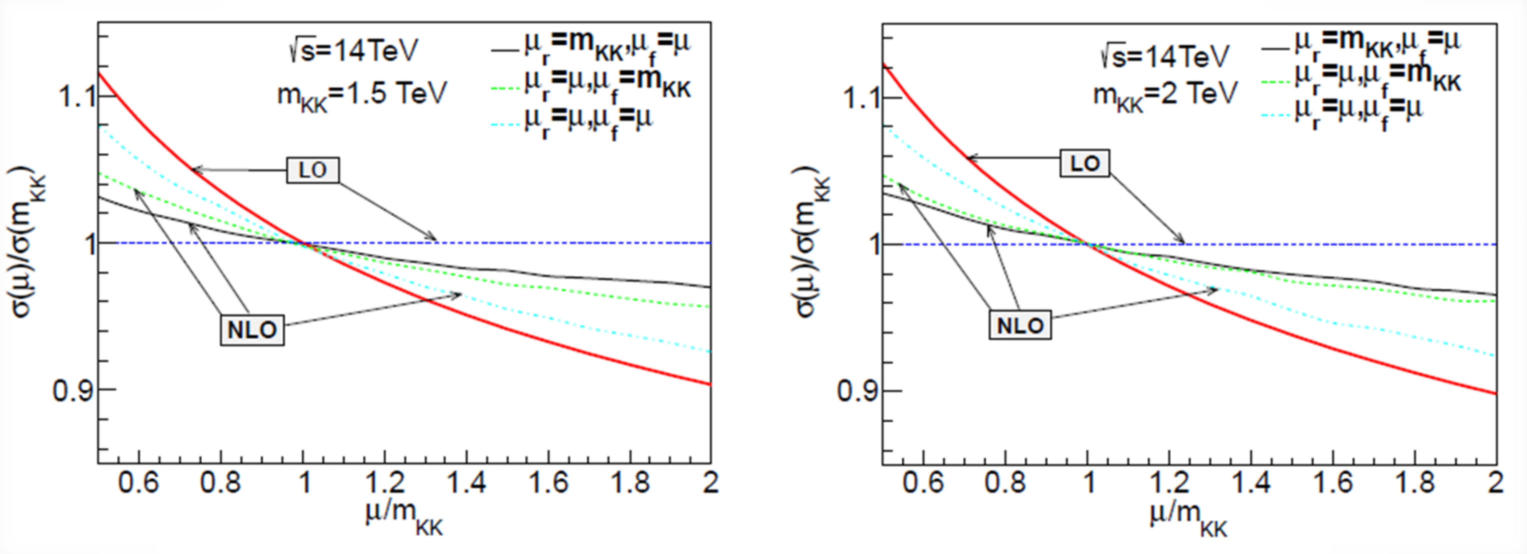
$$\delta_s = 1 \times 10^{-3}, \delta_c = \delta_s/50$$

Total cross section



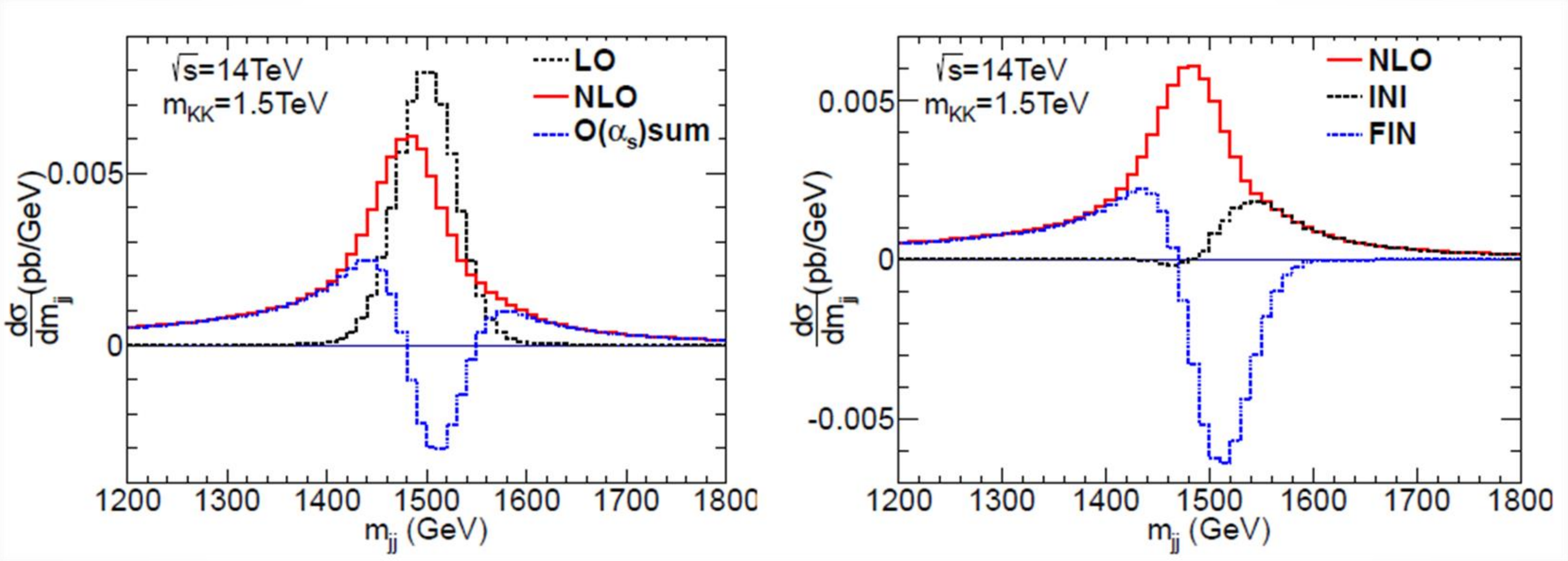
Agree with KK graviton decay to top pair *Phys. Rev. D* ***82****, 014020*

Scale dependence



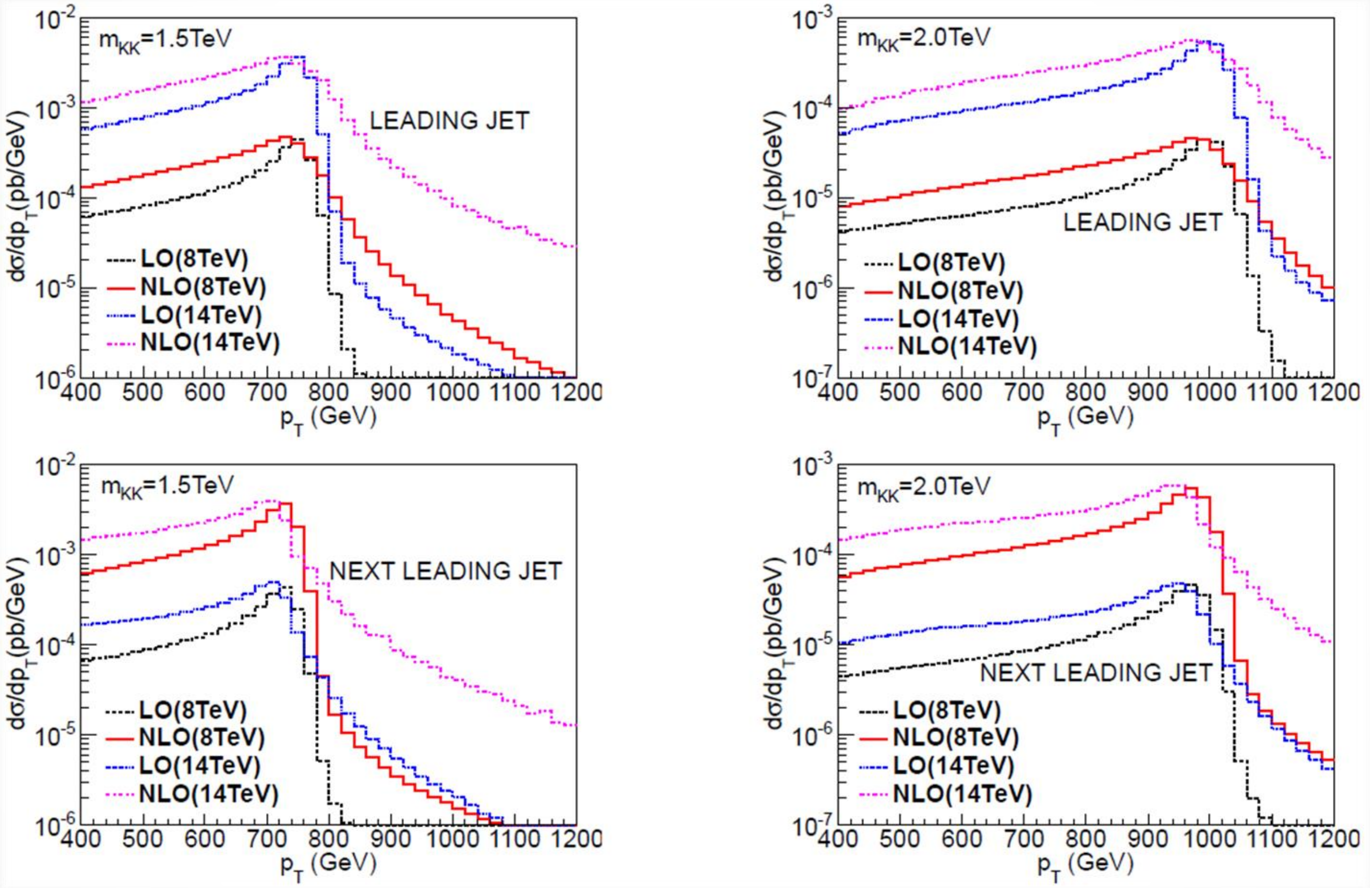
At the LO, the scale dependence is purely from the factorization scale. Figure shows that the factorization scale dependence of the NLO cross section is significantly reduced comparing with the LO result.

Invariant mass distribution



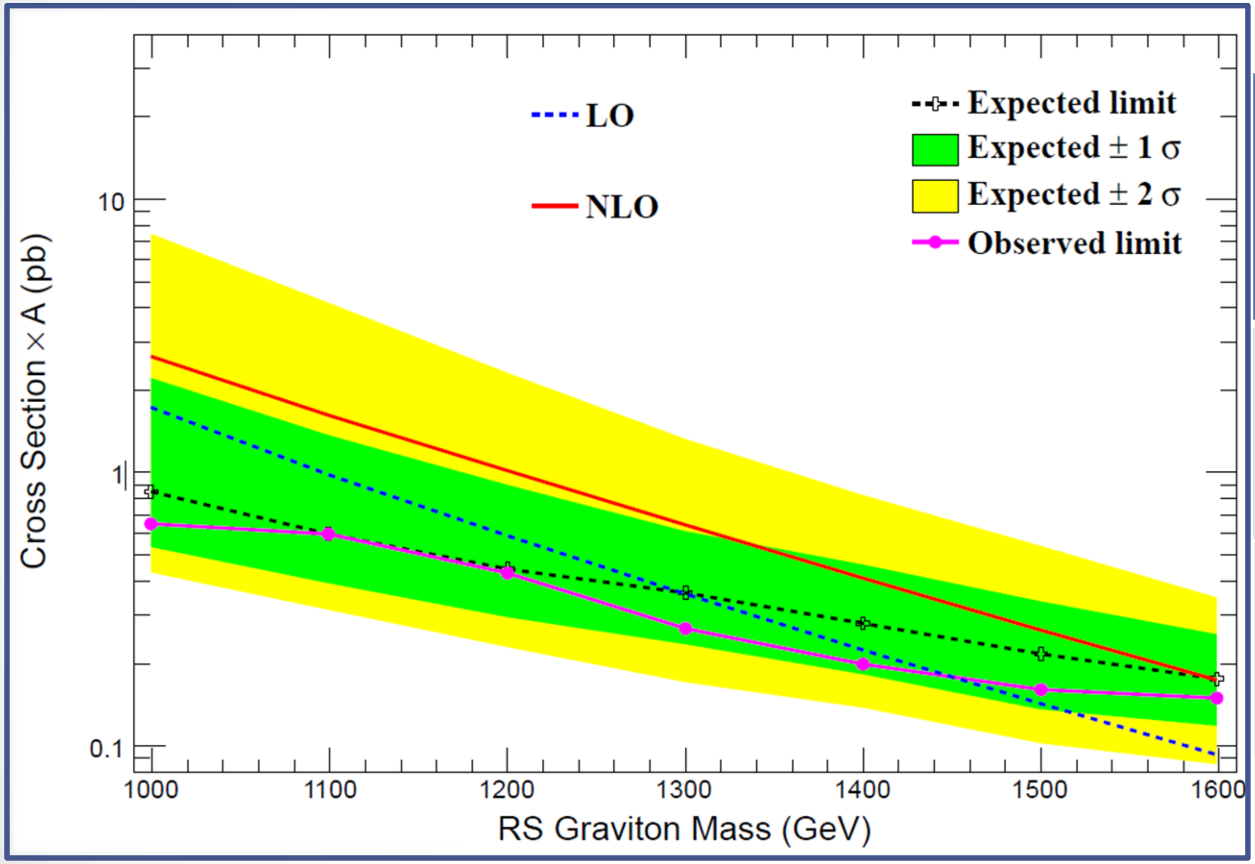
- At the NLO there could exist an additional hard parton besides the two leading jets in the final state. Thus the NLO corrections push the peak of the distributions to the lower invariant mass region.
- The initial state corrections shift the invariant mass distributions to higher region while the final state corrections tend to shift it in opposite way, which is a consequence of different origins of the additional radiated parton.

p_T distribution



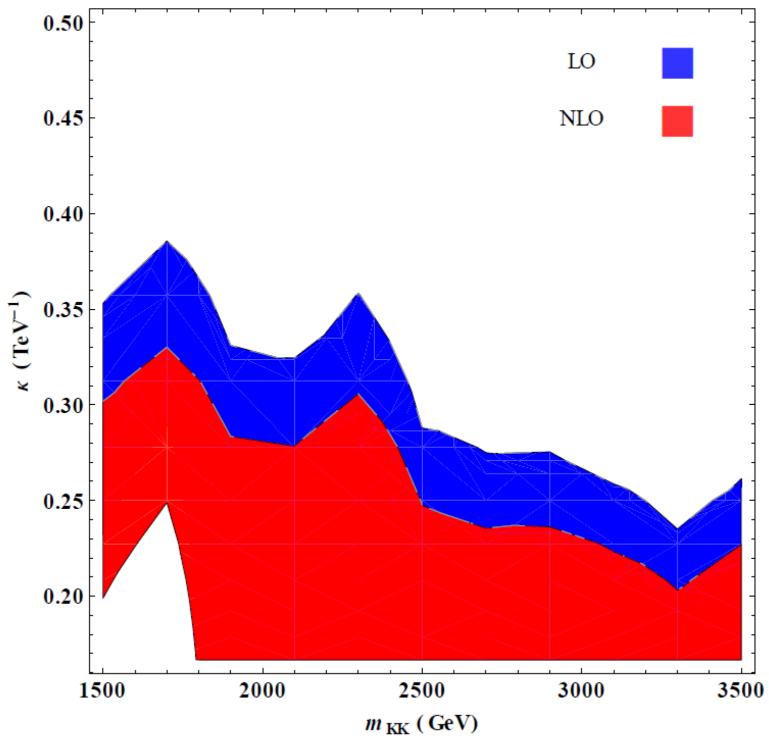
There is a sharply falling in p_T distribution at about half the KK graviton mass, which is called Jacobian Edge.

Signal analysis



RS Graviton	Observed Excluded Mass Range(TeV)
LO	1.45
NLO	>1.60

Parameter space



The red and blue region corresponds to the 95% c.l. It can be seen from Fig. 15 that the NLO corrections significantly tighten the allowed parameter space.

Conclusion

- RS extra dimension model still can play a important role in solving Standard Model problem, such as hierarchy problem.
- Dijet process is a useful way to search for the new physics particles.
- NLO QCD corrections for the dijet production via KK graviton can significantly enhance the LO total cross section and change the shape of the differential distribution of the LO.
- Constraint on the extra dimension model become more and more stringent.
- Future study will give us more information.

Thanks!