Graviton production with 2 jets at the LHC in Large Extra Dimensions

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Outline

- Introduction

Outline

- Introduction
- Calculations

Outline

- Introduction
- Calculations
- MadGraph/MadEvent for Graviton

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- Numerical Results

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- Calculations
- MadGraph/MadEvent for Graviton
- Numerical Results
- Summary

Introduction

Extra Dimensions (ED)

- Now search for extra dimensions has been one of the major objects at the LHC, since its physical effects can appear at the TeV energy scale.
- Two major classes of Extra Dimensions models:
    - **"Flat" (factorizable) ED**
        - Large ED (ADD) (Arkani-Hamed, Dvali & Dimopoulos)
        - TeV^{-1} ED (variation of ADD)
        - Universal ED(UED) (Appelquist, Cheng & Dobrescu)
        - ...
    - **"Warped" (non-factorizable) ED**
        - Randall-Sundrum(RS) model
        - ...

ADD Model

- Assuming the n-extra dimensions are compacted into n torus with the same radius r,the metrics in ADD Model are given by:

$$ds^2 = (\eta_{\mu\nu} + h_{\mu\nu})dx^\mu dx^\nu - r^2 d\Omega_n^2 + ...,$$

- From dimensional analysis, the scalar curvature $[R^{(4+n)}] = 2$, thus the D-dimensional(D=4+n) Einstein-Hilbert (EH) action is

$$S_D = -\overline{M}_D^{n+2} \int d^{4+n}x \sqrt{|g^{(4+n)}|}[R^{(4+n)}],$$

compared with 4-dimensional EH action

$$S_D = -\overline{M}_P^2 \int d^4x \sqrt{|g^{(4)}|}[R^{(4)}],$$

we have

$$\overline{M}_P^2 = \overline{M}_D^{n+2}(2\pi r)^n = r^n M_D^{n+2},$$

$$\frac{1}{r} = M_D \left(\frac{M_D}{\overline{M}_P}\right)^{2/n}.$$

ADD Model: Large extra dimensions

- The Seattle Experiment probed directly gravity and tested Newton's law only at Submillimeter level (0.2mm). Thus the length of extra dimensions can be much larger than the Planck length.
- Possibility of TeV scale extra dimensions:
  - If $n = 1$ and $M_D \sim 1$TeV, $\rightarrow r \sim 10^{15}$cm, excluded,
  - If $n = 2$ and $r < 0.2$mm, $\rightarrow M_D > 3$TeV,
  - If $n > 2$ and $M_D \sim$TeV, $\rightarrow r < 10^{-6}$cm, thus it will be difficult to probe extra dimensions by direct gravity test: High Energy Colliders.

ADD Model: Kaluza-Klein (KK) towers

- In ADD model, there is an infinite tower of 4D KK modes.

$$\mathcal{L}_{int} = -\frac{1}{\bar{M}_p} \sum_{\vec{m}} (G^{(\vec{m})})^{\mu\nu} T_{\mu\nu},$$

- The mass of the KK mode $G_{\mu\nu}^{(\vec{m})}$ is $|\vec{m}|/r$.

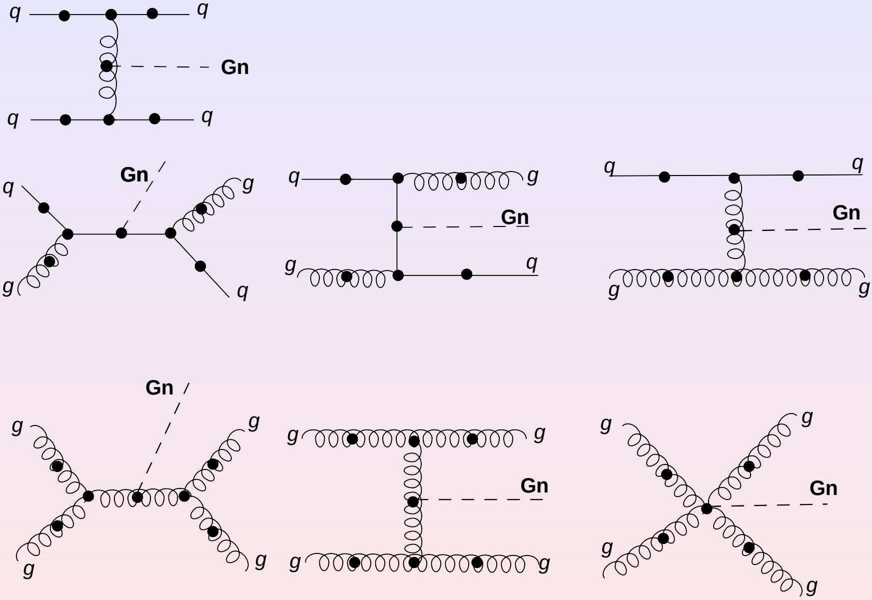
$$\Delta m \sim \frac{1}{R} = M_D \left(\frac{M_D}{\overline{M}_P}\right)^{2/n} \sim \left(\frac{M_D}{\mathrm{TeV}}\right)^{\frac{n+2}{2}} 10^{\frac{12n-31}{n}} \mathrm{eV}.$$

  - For $M_D = 1$TeV and n =4, 6 and 8, Δm=20KeV, 7MeV and 0.1GeV, respectively. Thus for $n \leq 6$, the KK tower can be looked as continuous.
  - Mass density function:

$$dN = S_{\delta-1}|n|^{\delta-1}dn = S_{\delta-1}\frac{\bar{M}_p^2}{M_D^{2+\delta}} m^{\delta-1} dm, \mathrm{with}\ \mathrm{S}_{\delta-1} = \frac{2\pi^{\delta/2}}{\Gamma(\delta/2)}.$$

Constraints and Collider Phenomenology

- Virtual KK-graviton exchange and direct KK-graviton production: LEP and Tevatron datas lead to $M_D > 1.4$TeV(n=3) and 1.0TeV(n=6).
- Supernova (SN1987A) cooling constraints:
  $M_D > 30$TeV (n=2) and 4TeV (n=3).
  However, the constraints can be relaxed easily without large change on collider phenomenology.
- At the LHC, Graviton production with monojet has been studied and found can have strong ability to probe higher extra dimension scale.
- We studied Graviton QCD production with 2 jets at the LHC in large extra dimensions, where the 2 jets correlation can give us more information.
  qg→qgGn: 21 diagrams; gg→ggGn: 34 diagrams; qq→qqGn:14 diagrams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Calculations

Two independent calculations

- We performed two independent calculations, and get results with differences below 1 percent. Both calculations used the helicity amplitude technique, and passed the gague checking.
  - 1. Genetating the MC codes for calculations of radiated gravitons ($e^+e^- \rightarrow l^+l^-G_n$) at linear colliders (hep-ph/0307117 and hep-ph/0509161). Since the calculation order can be chosen, so only several new Helas subroutines for Graviton added: $TXXXXX$, $VVTXXX$, $VVVTXX$, $VVVVTX$, $IOTXXX$ and $IOVTXX$.
  - 2. Implementing Spin-2 Graviton into MadGraph/MadEvent: more new Helas Subroutines including those for off-shell wavefunctions, Modifing MadGraph and let it know Spin-2 particle and its interaction, Modifing MadEvent to add one more integration on Graviton mass.

MadGraph/MadEvent for Graviton

New HELAS Subroutines

- Tensor's wavefunctions $\epsilon_{\mu\nu}^{(*)}(P, M)$:
  TXXXXX(P, M, λ(=0,$\pm$1, $\pm$2), IF = $\pm$, TWF)
  $\epsilon_\mu^+\epsilon_\nu^+$, $\frac{1}{\sqrt{2}}(\epsilon_\mu^+\epsilon_\nu^0 + \epsilon_\mu^0\epsilon_\nu^+)$,$\frac{1}{\sqrt{6}}(\epsilon_\mu^+\epsilon_\nu^- + \epsilon_\mu^-\epsilon_\nu^+ + \epsilon_\mu^0\epsilon_\nu^0)$, $\frac{1}{\sqrt{2}}(\epsilon_\mu^-\epsilon_\nu^0 + \epsilon_\mu^0\epsilon_\nu^-)$, $\epsilon_\mu^-\epsilon_\nu^-$.

- HELAS Subroutines for graviton's interaction:

  1. SST: SSTKXX, HSTKXX, YSSKXX;
  2. FFT: IOTKXX, FTIKXX, FTOKXX, YIOXXX;
  3. FFVT: IOVTKX, FVTIKX, FVTOKX, JIOTKX, YIOVKX;
  4. VVT: VVTKXX, JVTKXX, YVVKXX;
  5. GGGT: GGGTKX, JGGTKX, YGGGKX;
  6. GGGGT: GGGGTX.

- Example: FVTIKX(fi, vc, tc, g, fmass, fwidth, fvti)

$$\frac{(\not{k}) + m_f}{k^2 - m_f^2 + i m_f \Gamma_f}[2\eta_{\mu\nu}\eta_{\rho\sigma} - \eta_{\mu\rho}\eta_{\nu\sigma} - \eta_{\mu\sigma}\eta_{\nu\rho}]\gamma^\sigma(g_1 P_L + g_2 P_R)\psi(k_1)$$
$$\times\epsilon^\rho(k_2)\epsilon^{\mu\nu}(k_3),$$

- Gauge invariance checking:
  $q\bar{q} \to ST$: SSTKXX, HSTKXX;
  $q\bar{q} \to gT$: IOTKXX, FTIKXX, FTOKXX, IOVTKX, VVTKXX;
  $gg \to gT$: GGGTKX, JVTKXX;
  $q\bar{q} \to ggT$: FVTIKX, FVTOKX, JIOTKX, YIOKXX, YVVKXX, YIOTKX;
  $gg \to ggT$: JGGGKX, YGGGKX, GGGGTX;

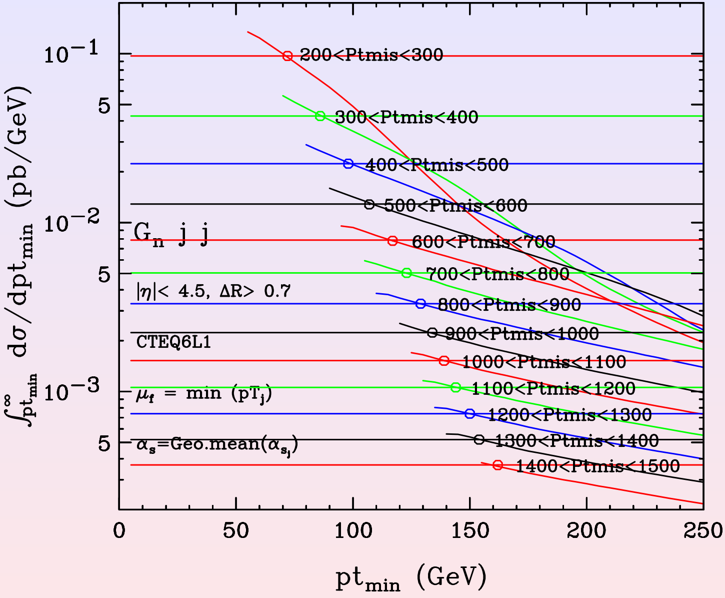
Modifying MadGraph/MadEvent for our purpose

- Using "User model" framework in MadGraph to write our new Model, including the massive KK Graviton;
  Parameters: M_D and n (And you may also fix Graviton mass, thus can study Randall-Sundrum model).
- Inserting the new HELAS Subroutines of Graviton, radion and Higgs into MadGraph. Adding codes for telling MadGraph how to call the FFT and FFVT type of new HELAS subroutines.
- Adding codes for Graviton's helicity.
- Adding 5-point diagrams by hand.
- Modifying the phase space generating codes in MadEvent to add the Graviton mass integration.

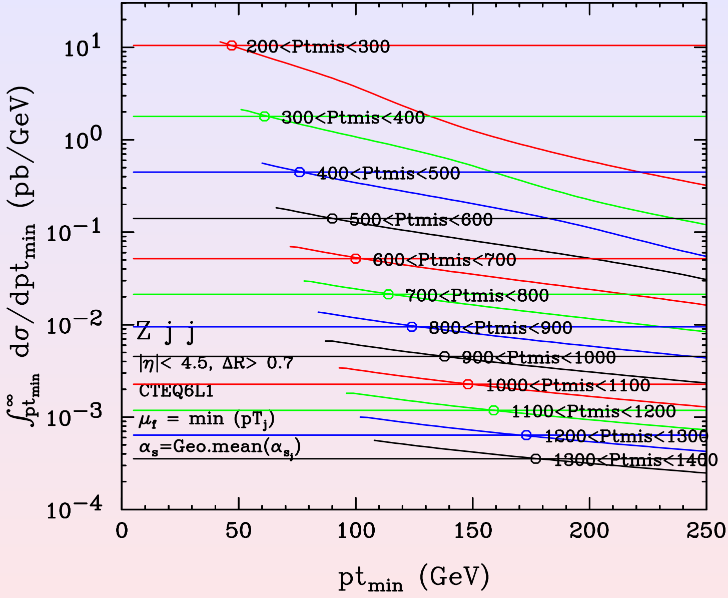
Numerical Results

Inputs

- n=3, 4, 5, and 6, 2 TeV$<M_D<$10 TeV,
- PDF: Cteq6L1, $\mu_f = min(\mathrm{Pt}_{j1}, \mathrm{Pt}_{j2})$,
- Using $\sqrt{\alpha_s(\mathrm{Pt}_{j1})\alpha_s(\mathrm{Pt}_{j2})}$,
- $\Delta R_{jj} > 0.7$, $|\eta_j| < 4.5$
- $Ptmis > 1$TeV unless specified,
- *Ptmin* cut will be studied in detail to make results reliable.
- Focus on $\delta = 4$ and $M_s = 5$ TeV first, then discuss the scale sensitivity and present the differential distributions for various δ.



200<Ptmis<300
300<Ptmis<400
400<Ptmis<500
500<Ptmis<600
600<Ptmis<700
700<Ptmis<800
800<Ptmis<900
900<Ptmis<1000
1000<Ptmis<1100
1100<Ptmis<1200
1200<Ptmis<1300
1300<Ptmis<1400
1400<Ptmis<1500
G_n j j
$|\eta|< 4.5, \Delta R> 0.7$
CTEQ6L1
μ_f = min (pT_j)
α_s=Geo.mean(α_{s_j})
$\int_{pt_{min}}^{\infty} d\sigma/dpt_{min}$ (pb/GeV)
pt_{min} (GeV)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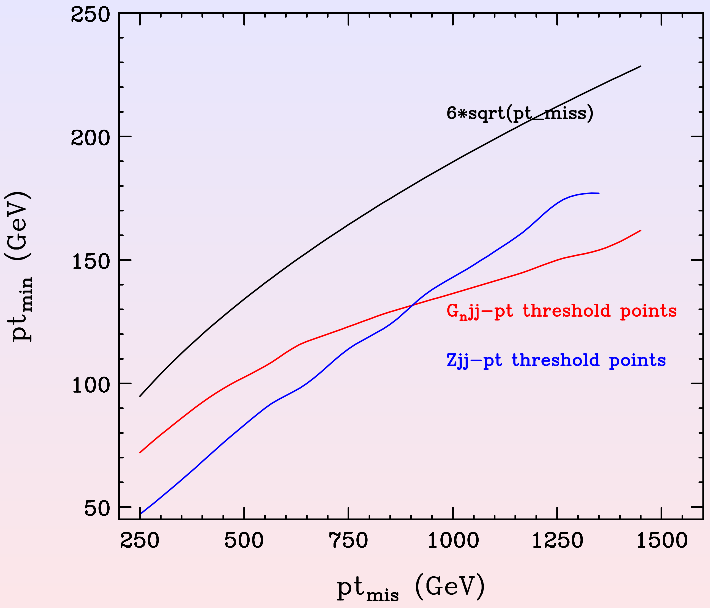
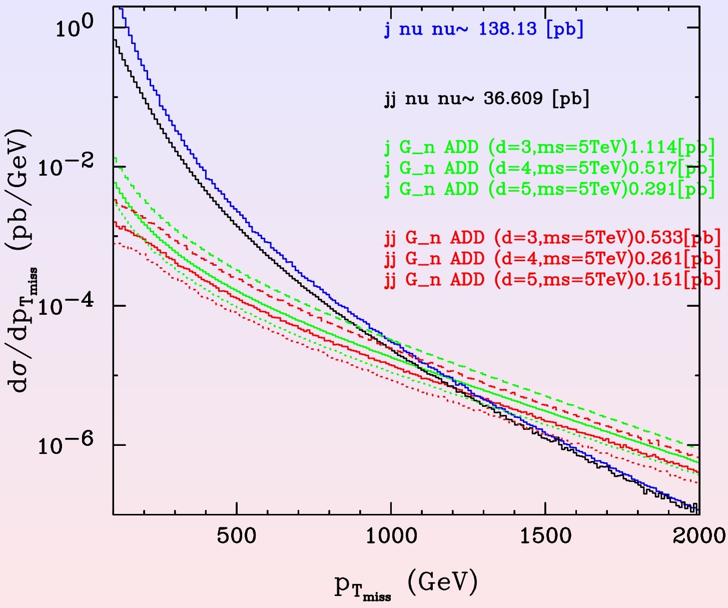
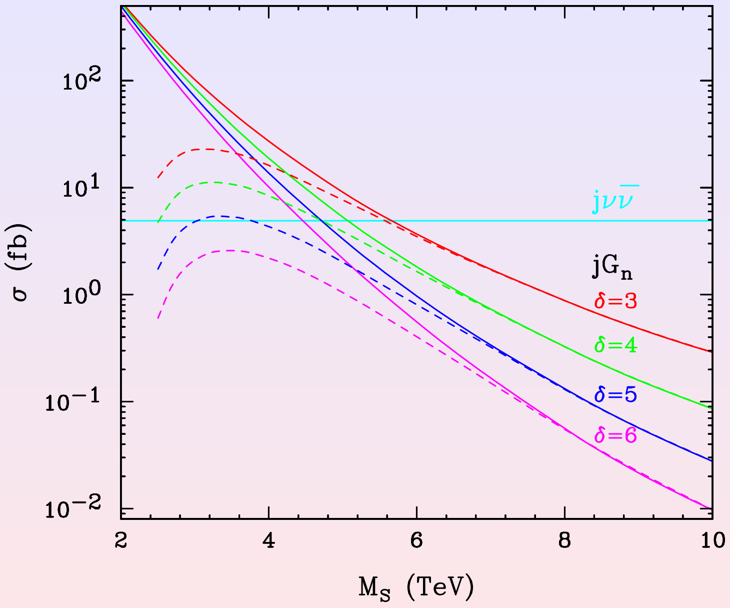
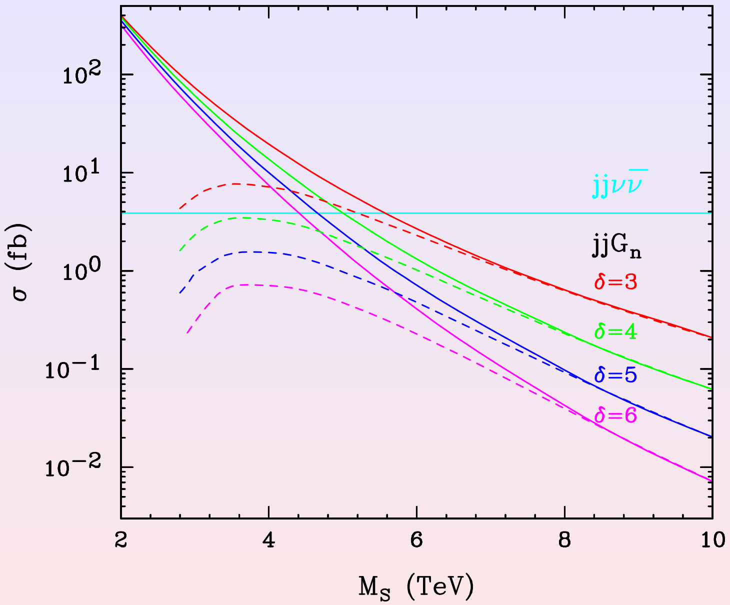
300<Ptmis<400
400<Ptmis<500
500<Ptmis<600
600<Ptmis<700
700<Ptmis<800
800<Ptmis<900
900<Ptmis<1000
1000<Ptmis<1100
1100<Ptmis<1200
1200<Ptmis<1300
1300<Ptmis<1400
Z j j
|η|< 4.5, ΔR> 0.7
CTEQ6L1
μ_f = min (pT$_j$)
α_s=Geo.mean(α_{s_j})
$\int_{pt_{min}}^{\infty} d\sigma/dpt_{min}$ (pb/GeV)
pt_{min} (GeV)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
50
100
150
200
250


6*sqrt(pt_miss)
$G_n$jj−pt threshold points
Zjj−pt threshold points
pt_{min} (GeV)
pt_{mis} (GeV)
250
200
150
100
50
250
500
750
1000
1250
1500


j nu nu~ 138.13 [pb]
jj nu nu~ 36.609 [pb]
j G_n ADD (d=3,ms=5TeV)1.114[pb]
j G_n ADD (d=4,ms=5TeV)0.517[pb]
j G_n ADD (d=5,ms=5TeV)0.291[pb]
jj G_n ADD (d=3,ms=5TeV)0.533[pb]
jj G_n ADD (d=4,ms=5TeV)0.261[pb]
jj G_n ADD (d=5,ms=5TeV)0.151[pb]
10^0
10^{-2}
10^{-4}
10^{-6}
500
1000
1500
2000
$d\sigma/dp_{T_{miss}}$ (pb/GeV)
$p_{T_{miss}}$ (GeV)



10^2
10^1
10^0
10^{-1}
10^{-2}
σ (fb)
2
4
6
8
10
M_S (TeV)
$j\nu\bar{\nu}$
jG_n
$\delta=3$
$\delta=4$
$\delta=5$
$\delta=6$


$jj\nu\overline{\nu}$
jjG_n
$\delta=3$
$\delta=4$
$\delta=5$
$\delta=6$
σ (fb)
M_S (TeV)
10^2
10^1
10^0
10^{-1}
10^{-2}
2
4
6
8
10

	Max M_s sensitivity	Max M_s sensitivity
	$\mathcal{L}$ =100 fb^{-1}	$\mathcal{L}$ =100 fb^{-1}
δ	No truncation	Hard truncation ($Q_{trunc} = \sqrt{\hat{s}} < M_s$)
3	6.4 (6.6) TeV	6.3 (6.5)TeV
4	5.6 (5.7)	5.1 (5.5)
5	5.2 (5.3)	- (4.8)
6	4.9 (5.0)	- (3.6)

TABLE I: Maximum ADD scale M_s sensitivity which can be reached by studying the 2 jets (1jet) and missing transverse momentum signal at the LHC, with integrated luminosity $\mathcal{L}$ =100 fb^{-1} or 10 fb^{-1}, assuming the systematic error to be 10%. The sensitivity range is defined by $\sigma_{jjG_n}(\sigma_{jG_n}) > 5(10\%)\sigma_{background} = 1.93(2.45)fb$.

distributions :

G_n jj (red/solid)[d=4,MS=5TeV] : 3.83[fb]

Z jj (blue/dash) : 3.86[fb]

green:[d=3,MS=5TeV]:6.56fb, cyan:[d=5,MS=5TeV]:2.42fb

magenta:[d=6,MS=5TeV]:1.60fb,

$|\eta|<4.5$, $pt_j>6*sq(pt_{miss})$, $\Delta R>0.7$, $pt_{miss}>1$ TeV

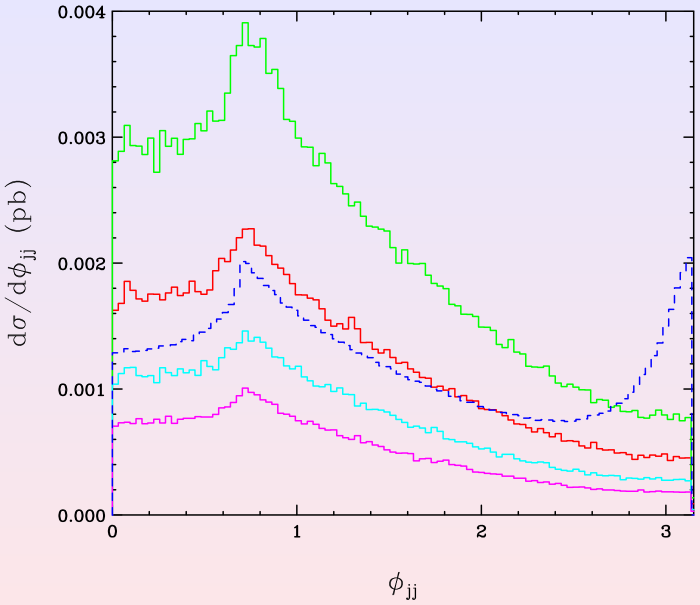
CTEQ6L1

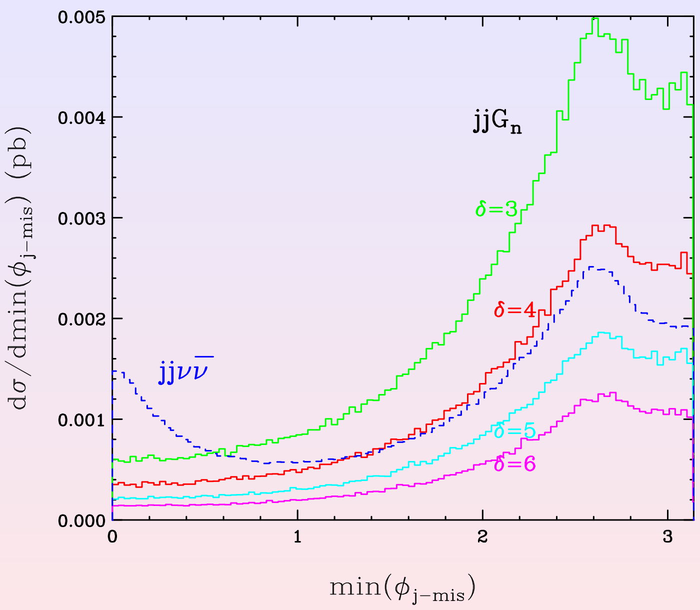
μ_f = min (pT_j)

α_s=Geo.mean(α_{s_j})

+cut:$\phi_{jj}<1.5$ – Black/solid:[d=4,MS=5TeV]:2.65fb

+cut:$\phi_{jj}<1.5$ – Black/dash:[Zjj]: 2.22fb


0.004
0.003
0.002
0.001
0.000
0
1
2
3
$d\sigma/d\phi_{jj}$ (pb)
ϕ_{jj}


0.005
0.004
0.003
0.002
0.001
0.000
0
1
2
3
$d\sigma/d\min(\phi_{j-mis})$ (pb)
$\min(\phi_{j-mis})$
jjG_n
$\delta=3$
$\delta=4$
$\delta=5$
$\delta=6$
$jj\nu\bar{\nu}$

Summary

- We study seaching for Kaluza Klein graviton production in large extra dimension models via 2 jet plus missing transverse momentum signatures at the LHC.
- We present results for both the signal and the dominant Zjj background in a perturbatively reliable way, ensured by a pTmiss dependent cut on the jet transverse momentum.
- The 2 jet results are compared with the 1 jet case. Although the 2 jet results have slightly lower sensitivity to the scale of extra dimensions, the distributions of the two jets and their correlation with the missing transverse momentum provide additional evidence for the production of an invisible massive object.