Graviton production with 2 jets

in Large Extra Dimensions at LHC

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ADD Collider signature

- $(4 + \delta)$ dimensional theory with extra $\delta$ dimension(s) which are compactified (with radius $R$).

- Standard Model fields are confined on $(1+3)$- dimensional brane though gravity can propagate anywhere in the $(4 + \delta)$ dimensional bulk.

- Our 4 dimensional Planck scale ($M_p$) is related to the $(4 + \delta)$ dimensional Planck scale ($\bar{M}_s$) which is actually fundamental scale in this scenario.

\[
M_p^2 = 8\pi V_\delta R^\delta \times \bar{M}_s^{\delta+2}
\]

Volume element $V_\delta = (2\pi)^\delta$ assuming toroidal compactification of extra dimensions.

- By choosing large $R$ (exp. limit $\approx \# mm$), fundamental scale ($\bar{M}_s \sim 1 TeV$) can produce the Planck scale ($M_p \sim 10^{19} GeV$) in 4 dimension.

Adelberger [EOT-WASH Group]
ADD Collider signature

- δ compact extra spatial dimensions
  - ⇒ Infinite tower of Kaluza-Klein states with masses
    \[ m_n^2 \sim \frac{\tilde{n}^2}{R^2} \]
    \[ \tilde{n} = (n_1, n_2, \ldots n_\delta) \]
    \[ n_i = 0, \pm 1, \pm 2, \ldots \]

- The coupling of each graviton KK states to the SM fields remain small, being proportional to \( 1/M_p \).

- But cumulative effect from full tower of KK states, considering KK state density

\[
\rho(m)dm = \left[ \frac{2\pi^{\frac{\delta}{2}}}{\Gamma(\frac{\delta}{2})} \right] \frac{\bar{M}_p^2}{M_s^{2+\delta}} m^{\delta-1} dm
\]

→ cross-section sizable to have collider signature.

\( e.g. \) final cross section \( \sim \frac{1}{M_s^2} \) for graviton emission (say).
ADD Collider signature

In ADD scenario hierarchy problem is not solved; it is rather transferred from one sector \([M_p : M_{EW}]\) to another \([M_s : R^{-1}]\)!

Still it is a popular model. (Hoping that a mechanism for R-stabilization will ultimately be found.)

Two types of large extra dimension signals:

- Virtual graviton exchange:
  - Coherent sum
  - affecting the S.M. signal

- Real graviton emission:
  - Incoherent sum
  - missing energy-momentum.

We consider the second scenario
ADD Collider signature

A widely studied channel for discovering ADD in LEP and Tevatron:

\[ e^+e^- \rightarrow \gamma(Z) G_n \rightarrow \gamma(Z) E_{\text{miss}}^{\text{miss}} \]
\[ p\bar{p} \rightarrow \gamma(j) G_n \rightarrow \gamma(j) P_T^{\text{miss}} \]

Note: \( \gamma \) is not monochromatic.

One can probe \( M_s \) upto 95% CL

<table>
<thead>
<tr>
<th>LEP</th>
<th>Tevatron</th>
<th>no of ex-dim(( \delta ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.60 TeV</td>
<td>1.18 TeV</td>
<td>for ( \delta = 2 )</td>
</tr>
<tr>
<td>1.20 TeV</td>
<td>0.99 TeV</td>
<td>for ( \delta = 3 )</td>
</tr>
<tr>
<td>0.94 TeV</td>
<td>0.91 TeV</td>
<td>for ( \delta = 4 )</td>
</tr>
<tr>
<td>0.77 TeV</td>
<td>0.86 TeV</td>
<td>for ( \delta = 5 )</td>
</tr>
<tr>
<td>0.66 TeV</td>
<td>0.83 TeV</td>
<td>for ( \delta = 6 )</td>
</tr>
</tbody>
</table>

Mirabelli, Perelstein, Peskin [PRL82:2236,99]
Giudice, Rattazzi, Wells [NPB544:3,99]
ADD Collider signature

- LHC: Graviton production with a monojet.

  \[ pp \rightarrow j G_n \rightarrow j P_T^{\text{miss}} \]

- Strong ability to probe up to much higher extra dimension scale

BUT, this single jet carry:

- very little information on the underlying physics
- transverse momentum and the rapidity of the single jet
- additional jets in graviton production can be used as a more sophisticated probe.

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Vacavant, Hinchliffe
We studied whether the 2-jet rate and correlations can give us more information about the mass scale of the missing object, in addition to the missing $P_T$ distribution.

$$pp \rightarrow jjG_n \rightarrow jjP_T^{\text{miss}}$$

QCD order $\alpha_s^2$ production of $pp \rightarrow jjG_n$ includes:
- $qq' \rightarrow qq'G_n$
- $gq \rightarrow gqG_n$
- $gg \rightarrow ggG_n$

As gravity couples to the energy-momentum tensor, each component of the tower of ADD gravitons couples to all SM fields, as well as to each SM interaction vertex.
$jjG_n$ at LHC – Calculation

$q q \rightarrow q q G_n$

$q g \rightarrow q g G_n$

$g g \rightarrow g g G_n$
What about electroweak (EW) contributions to $jjG_n$?

WBF cross sections for $jjG_n$ production represents a small correction below 1%, even when imposing typical cuts to enhance WBF over QCD sources.

WBF processes do not appear as a promising avenue for studying graviton production at the LHC.

we do not include them in the results.
Calculation technique:

- Simulated at the parton level with full tree level matrix elements.

- As Graviton couples to all particles with energy-momentum, there are significant number of Feynman diagrams contributing to the processes in each channels. e.g.
  
  \[
  uu \rightarrow uuG_n : 7 \times 3(A, Z, g) \times 2(\text{crossing}) = 42 \\
  ug \rightarrow ugG_n : 7 \times 3(q, q, g) \times 1(\text{crossing}) = 21 \\
  gg \rightarrow ggG_n : 7 \times 1(g - tch) \times 2(\text{cr}) + 7 \times 1(g - sch) + 5 \times 1(g) \times 3(\text{color}) = 36 \\
  gg \rightarrow uuG_n : 7 \times 3(q, q, g) \times 1(\text{crossing}) = 21[ug \rightarrow ugG_n] \\
  uu \rightarrow uuG_n : 7 \times 3(q, q, g) \times 1(\text{crossing}) = 21[ug \rightarrow ugG_n]
  \]

- Full calculation has been done numerically by using the helicity amplitude method.
Calculation technique:

- We have added all the relevant HELAS subroutines for the massive graviton and its interactions.

- We developed some new HELAS routines, which includes $G\rightarrow F-F$, $G\rightarrow V-V$, $G\rightarrow F-F-V$, $G\rightarrow V-V-V$, $G\rightarrow V-V-V-V$ vertices.

- Amplitudes are calculated in the factorization scheme which implements the Breit-Wigner propagators of the resonant $W$ and $Z$-boson in a gauge invariant way.

Dutta, P.K., Mukhopadhyaya, Raychaudhuri; 2003
P.K., Roy; 2006
Ward identities arising from general coordinate invariance — an essential feature of any theory involving gravity.

Most useful check: with $\epsilon^{(n)}_{\mu\nu}(k)$ as the polarisation tensor,

$$Amplitude = A_n(k, p_i) = T^{\mu\nu}(k, p_i) \epsilon^{(n)*}_{\mu\nu}(k)$$

Where, $T^{\mu\nu}(k, p_i) = \sum_{i=1}^{N} T_{i}^{\mu\nu}(k, p_i)$

must now satisfy the Ward identities

$$k^\mu T_{\mu\nu}(k, p_i) = k^\nu T_{\mu\nu}(k, p_i) = 0$$

⇒ Highly sensitive to errors in signs and factors.
We have performed two independent calculations to check each other.

Implemented ADD spin-2 gravitons into MadGraph /MadEvent.

$s$ and $t$-channel calculations matches with other earlier calculations like $e^+e^- \rightarrow f\bar{f}G_n$, $pp \rightarrow l^+l^-G_n$.

$t$-channel contributions checked using crossing symmetry.

Results for $jG_n$ production agree with Giudice et. al. within about 5 percent (which may be due to different PDF and scale choices).
Graviton at collider - Truncation schemes

- Effective low-energy theory: some truncation scheme is necessary in order to predict in this framework.

- Behavior above the string scale ($M_S$).

- Different kind of truncation schemes: no-truncations, hard-truncation

- A less drastic approach may be a soft-truncation.

- But we choose only conservative choices:
  - Unitarity criterion: tower of gravitons being produced does not extend in mass beyond the ADD scale.
    \[ M_{G_n} < M_S \]

- Hard-truncation when,
  \[ Q_{\text{truncation}} = \sqrt{s} > M_S \]
Significant background can come from any processes leading to two jets and missing transverse momentum.

Dominant background $Zjj$ production with subsequent decay $Z \rightarrow \nu\bar{\nu}$.

QCD production of $Wjj$ with subsequent decay $W^\pm \rightarrow l^\pm \nu$ when the charged leptons $l = e, \mu, \tau$ are not identified. — significant at least when missing $P_T$ is not too large.

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We follow the procedure of Eboli, Zappenfeld [PLB495:147,00]
Throughout we follow the notation: Giudice et al.

Differs from the one in Han et al. mainly by a different factor in the relation between $R$ and $M_s$ in $(4+\delta)$-dimensional space.

Though this factor is crucial in comparing results and quantifying discovery potentials, one can simply convert results from one notation to the other by multiplying a $\delta$-dependent factor.
CTEQ6L1 parton distribution functions.

Factorization scale chosen as $$\mu_f = \min(P_T)$$ of the jets.

QCD coupling is set to the geometric mean value,

$$\alpha_s = \sqrt{\alpha_s(P_T^j_1) \alpha_s(P_T^j_2)}.$$ 

Focus on the $$\delta = 4$$ and $$M_s = 5$$ TeV.

In the tree level numerical calculations, we identify massless partons with jets.

$$\Delta R_{jj} = \sqrt{\Delta \eta^2 + \Delta \phi^2} > 0.7, \quad |\eta_j| < 4.5$$ 

$$P_T^j > 6 \text{ GeV} \times \sqrt{P_T^{\text{miss}}/1 \text{ GeV}}$$ 

$$P_T^{\text{miss}} > 1 \text{ TeV}$$
\( jjG_n \) at LHC – Conventions and Cuts

\[ \int_{P_T^{cut}} \frac{d\sigma}{dP_T^{min}} (pp) \]

\( pp \rightarrow jjG_nX \)

\( \sigma_{jjG_n} > \sigma_{jG_n} \) minimum \( P_T^{cut} \) cut dependence of dijet cross sections for \( pp \rightarrow jjG_nX \) at the LHC in various bins. The open circles show the monojet cross section in the same missing \( P_T^{miss} \) bin.
$P_T^{j}$ cut dependence of dijet cross sections for $pp \rightarrow j.j(Z \rightarrow \nu \bar{\nu})X$ at the LHC in various $P_T^{miss}$ bins. The open circles show the monojet cross section in the same missing $P_T$ bin.
Missing transverse momentum dependence of the $P_T^{cut}$ value of equal 2-jet and 1-jet cross sections. Our jet selection cut is also presented.
For a missing $P_T$ of 1 TeV, for example, gluons with $P_T \lesssim 140$ GeV are in the soft range, and several such “soft” gluon jets are expected.

These gluons are readily observable as distinct jets in the experiment.

An actual monojet event with missing transverse momentum in the TeV range and no additional jets with $p_T \gtrsim 30$ GeV, is a very rare event!
\((jjG_n)\) at LHC – Conventions and Cuts

**Graviton signals**
- dash: \(\delta=3, M_s=5\text{TeV}\)
- solid: \(\delta=4, M_s=5\text{TeV}\)
- dot: \(\delta=5, M_s=5\text{TeV}\)

\[\frac{d\sigma}{dP_T^{\text{miss}}} \text{ (pb/GeV)}\]

\(P_T^{\text{miss}}\) dependence of the total cross sections for the signal and background
CTEQ6L1 parton distribution functions.

Factorization scale chosen as \( \mu_f = \min(P_T) \) of the jets

QCD coupling is set to the geometric mean value,

\[
\alpha_s = \sqrt{\alpha_s(P_{T1}^j) \alpha_s(P_{T2}^j)}.
\]

Focus on the \( \delta = 4 \) and \( M_s = 5 \) TeV.

In the tree level numerical calculations, we identify massless partons with jets.

\[
\Delta R_{jj} = \sqrt{\Delta \eta^2 + \Delta \phi^2} > 0.7, \quad |\eta_j| < 4.5
\]

\[
P_T^j > 6 \text{ GeV} \times \sqrt{P_{T}^{\text{miss}}/1 \text{ GeV}}
\]

\[
P_{T}^{\text{miss}} > 1 \text{ TeV}
\]
$\sigma_{total}$ dependence of the $jG_n$ and $jjG_n$ at LHC.

- Integrated luminosity $\mathcal{L} = 100 \text{ fb}^{-1}$, where the systematic error in the background (assumed to be 10%) dominates over the statistical error.

- $\sigma_{jjG_n}(\sigma_{jG_n}) > 5 \times 10\% \times \sigma_{\text{background}} = 1.93 \ (2.45) \text{ fb}$
Maximum ADD scale $M_s$ sensitivity from 2-jet (1-jet) and missing transverse momentum signal at the LHC

<table>
<thead>
<tr>
<th>No truncation</th>
<th>Hard truncation</th>
<th>no of ex-dim($\delta$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4 (6.6) TeV</td>
<td>6.3 (6.5) TeV</td>
<td>for $\delta = 3$</td>
</tr>
<tr>
<td>5.6 (5.7) TeV</td>
<td>5.1 (5.5) TeV</td>
<td>for $\delta = 4$</td>
</tr>
<tr>
<td>5.2 (5.3) TeV</td>
<td>- (4.8) TeV</td>
<td>for $\delta = 5$</td>
</tr>
<tr>
<td>4.9 (5.0) TeV</td>
<td>- (3.6) TeV</td>
<td>for $\delta = 6$</td>
</tr>
</tbody>
</table>

- The 2-jet sensitivity is only slightly lower than for the 1-jet case.
- The larger $\delta$ is, the sooner the non-perturbative region is reached, thus the larger is the difference between max $M_s$ sensitivities in no truncation and hard truncation cases.
\[ j j G_n \] at LHC – Result

\[ \phi_{jj} \] and \( \text{min}(\phi_{j,\text{ptmiss}}) \) distributions for background and signal.

- **Zjj** background shows a enhancement for back to back jets.
- Reflects collinear \( Z \) emission along one of the jets.
- Due to the heavier masses of the typical graviton KK modes, such collinear “jet fragmentation” contributions are absent for the signal.
Final state parton emission more in BG

Additional cuts to reduce FSP emission

2-jet over 1-jet ratio for signal and background as a function of $P_T^{\text{miss}}$, with or without the cut $|\Delta \eta_{jj}| > 2$ and $|\phi_{jj} - \pi| > 0.7$.

Typical graviton KK modes are much heavier than the $Z$ boson, thus providing for a much harder event.

Expect naively that the (jj:j) ratio for the signal should always be larger than the one for the background.
$jjG_n$ at LHC – Summary

- LHC can reveal graviton associated with jet(s). ADD graviton gives missing energy signature.
- To explore large extra dimensions at LHC, $pp \rightarrow jG_n$ is most sensitive channel, but is not a unique demonstration of ADD.
- Calculated the order $\alpha_s^2$ graviton plus dijet, $jjG_n$ at the LHC
- For $P_T^{\text{miss}}$ of order 1 TeV or larger, the signature will rarely be a monojet signal.
- Multiple “soft” gluon emission will produce events with several jets balancing the transverse momentum of the graviton.
- The multijet features are simply a reflection of the hardness of the event $P_T^{\text{miss}}$.
- Saturates the leading order monojet cross section for additional “soft” jet $P_T$ in the 100 to 150 GeV range, thus establishing the typical scale for multiple jet emission.
Defining the dijet cross section with a typical constant jet $P_T$ cut, independent of the hardness of the event, will invariably lead to the cross section not being trustworthy at sufficiently high $P_T^{\text{miss}}$.

Also studied $jjG_n$ production via weak boson fusion - strongly suppressed..even with typical weak boson fusion cuts.

Weak Boson Fusion is not a promising process for Kaluza-Klein graviton production at the LHC.

For missing $P_T$ in the TeV range the $Z$ mass becomes negligible and jet fragmentation into a collinear $Z$ becomes an important part of the SM background: → Azimuthal angle correlations of the jets, with a sizable fraction of nearly back-to-back dijet events.

Can provide a powerful tool to test for heavy graviton.
$j j G_n$ at LHC – Summary

Thank You