Graviton production with 2 jets
in Large Extra Dimensions at LHC

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ADD Collider signature

- $(4+\delta)$ dimensional theory with extra δ 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
  $\Rightarrow$ Infinite tower of Kaluza-Klein states with masses
  $m_n^2 \sim \frac{\vec{n}^2}{R^2}$ $\quad \vec{n} = (n_1, n_2, \ldots n_\delta)$
  $n_i = 0, \pm 1, \pm 2, \ldots$
- 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

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

$\longrightarrow$ 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

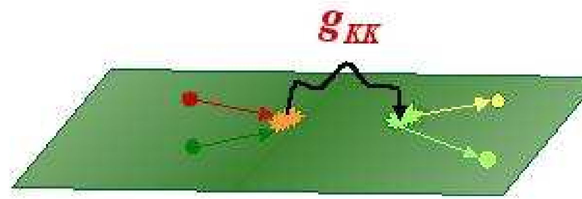
- In ADD scenario hierarchy problem is not solved; it is rather transfered from one sector $[M_p : M_{EW}]$ to another $[M_s : R^{-1}]$!
- Still it is a popular model. (Hoping that a mechanism for R - stabilization will ultimately be found.)
- Two types of large extra dimension signals :

  .

- Virtual graviton exchange :

  $\Rightarrow$ Coherent sum

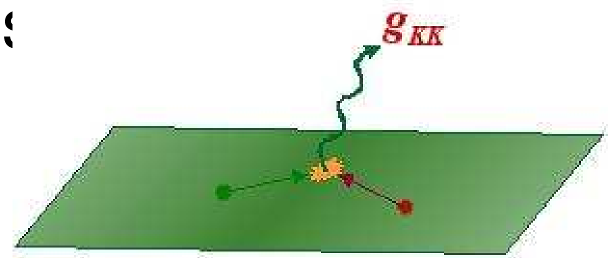
  $\Rightarrow$ affecting the S.M. signals



- Real graviton emission :

  $\Rightarrow$ Incoherent sum

  $\Rightarrow$ missing energy-momentum.



We consider the second scenario

ADD Collider signature

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

$$e^+e^- \to \gamma(Z)\, G_n \to \gamma(Z)\, E^{\rm miss}$$
$$p\bar{p} \to \gamma(j)\, G_n \to \gamma(j)\, P_T^{\rm miss}$$

Note: γ is not monochromatic.

One can probe M_s upto 95% CL

LEP	Tevatron	no of ex-dim(δ)
1.60 TeV	1.18 TeV	for $\delta = 2$
1.20 TeV	0.99 TeV	for $\delta = 3$
0.94 TeV	0.91 TeV	for $\delta = 4$
0.77 TeV	0.86 TeV	for $\delta = 5$
0.66 TeV	0.83 TeV	for $\delta = 6$

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

ADD Collider signature

- LHC : Graviton production with a monojet.

$$pp \rightarrow j\, G_n \rightarrow j\, P_T^{\rm miss}$$

- 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.

Vacavant, Hinchliffe

jjG_n at LHC – Calculation

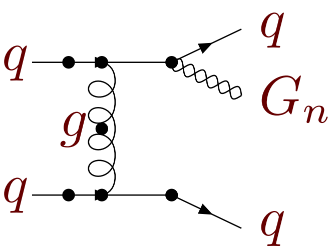
⊙ We studied whether the 2-jet rate and correlations can give us more information about the mass scale of the missing object, in addition to the missing P_T distribution.

$$pp \longrightarrow jj\,G_n \longrightarrow jj\,P_T^{\rm miss}$$

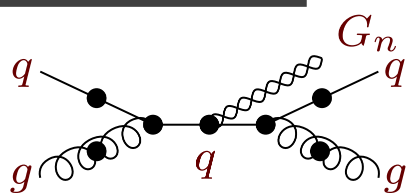
- QCD order α_s^2 production of $pp \longrightarrow jjG_n$ includes
  - $qq^{(\prime)} \longrightarrow qq^{(\prime)}G_n$
  - $gq \longrightarrow gqG_n$
  - $gg \longrightarrow ggG_n$
- As gravity couples to the energy-momentum tensor, each component of the tower of ADD gravitons couples to all SM fields, as well as to each SM interaction vertex.

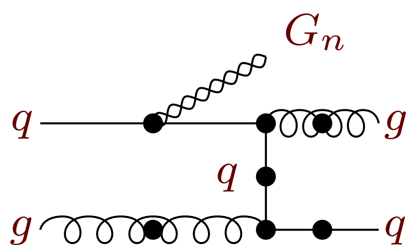
jjG_n at LHC – Calculation

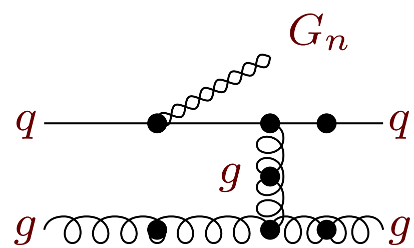
q q -> q q G_n



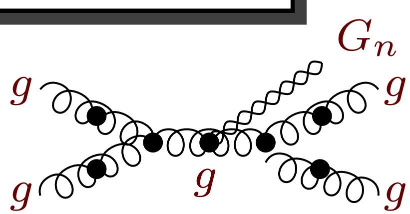
q g -> q g G_n

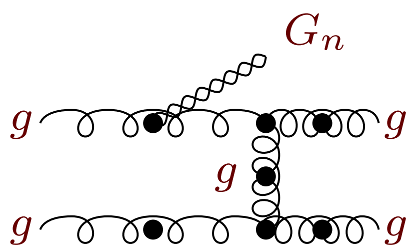


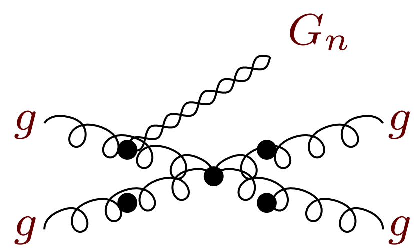




g g -> g g G_n

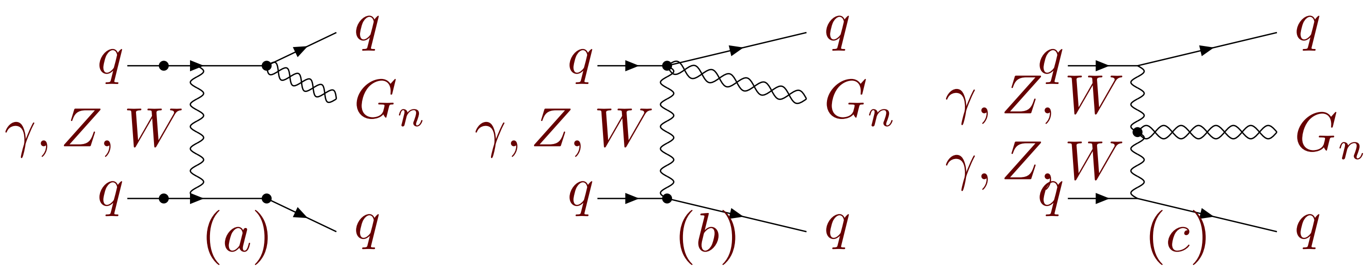






jjG_n at LHC – Calculation

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

jjG_n at LHC – Calculation

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.*

$$uu \to uuG_n : 7 \times 3(A, Z, g) \times 2(crossing) = 42$$

$$ug \to ugG_n : 7 \times 3(q, q, g) \times 1(crossing) = 21$$

$$gg \to ggG_n : 7 \times 1(g - tch) \times 2(cr) + 7 \times 1(g - sch) + 5 \times 1(g) \times 3(color) = 36$$

$$gg \to u\bar{u}G_n : 7 \times 3(q, q, g) \times 1(crossing) = 21[ug \to ugG_n]$$

$$u\bar{u} \to ggG_n : 7 \times 3(q, q, g) \times 1(crossing) = 21[ug \to ugG_n]$$

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

jjG_n at LHC – Calculation

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-F-F, G-V-V, G-F-F-V, G-V-V-V, G-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

jjG_n at LHC – Checks

- Ward identities arising from general coordinate invariance — an essential feature of any theory involving gravity.

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

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

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

must now satisfy the Ward identities

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

$\Rightarrow$ Highly sensitive to errors in signs and factors.

jjG_n at LHC – Checks

- 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 $e^+e^- \to f\bar{f}G_n$, $pp \to l^+l^-G_n$.
- 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).

 - Truncation schemes

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

$$Q_{truncation} = \sqrt{\hat{s}} > M_S$$

jjG_n at LHC – Background

- Significant background can come from any processes leading to two jets and missing transverse momentum.
- Dominant background Zjj production with subsequent decay $Z \to \nu\bar{\nu}$.
- QCD production of Wjj with subsequent decay $W^{\pm} \to l^{\pm}\nu$ when the charged leptons $l = e, \mu, \tau$ are not identified. — significant at least when missing P_T is not too large. [a]

[a] We follow the procedure of Eboli, Zappenfeld [PLB495:147,00]

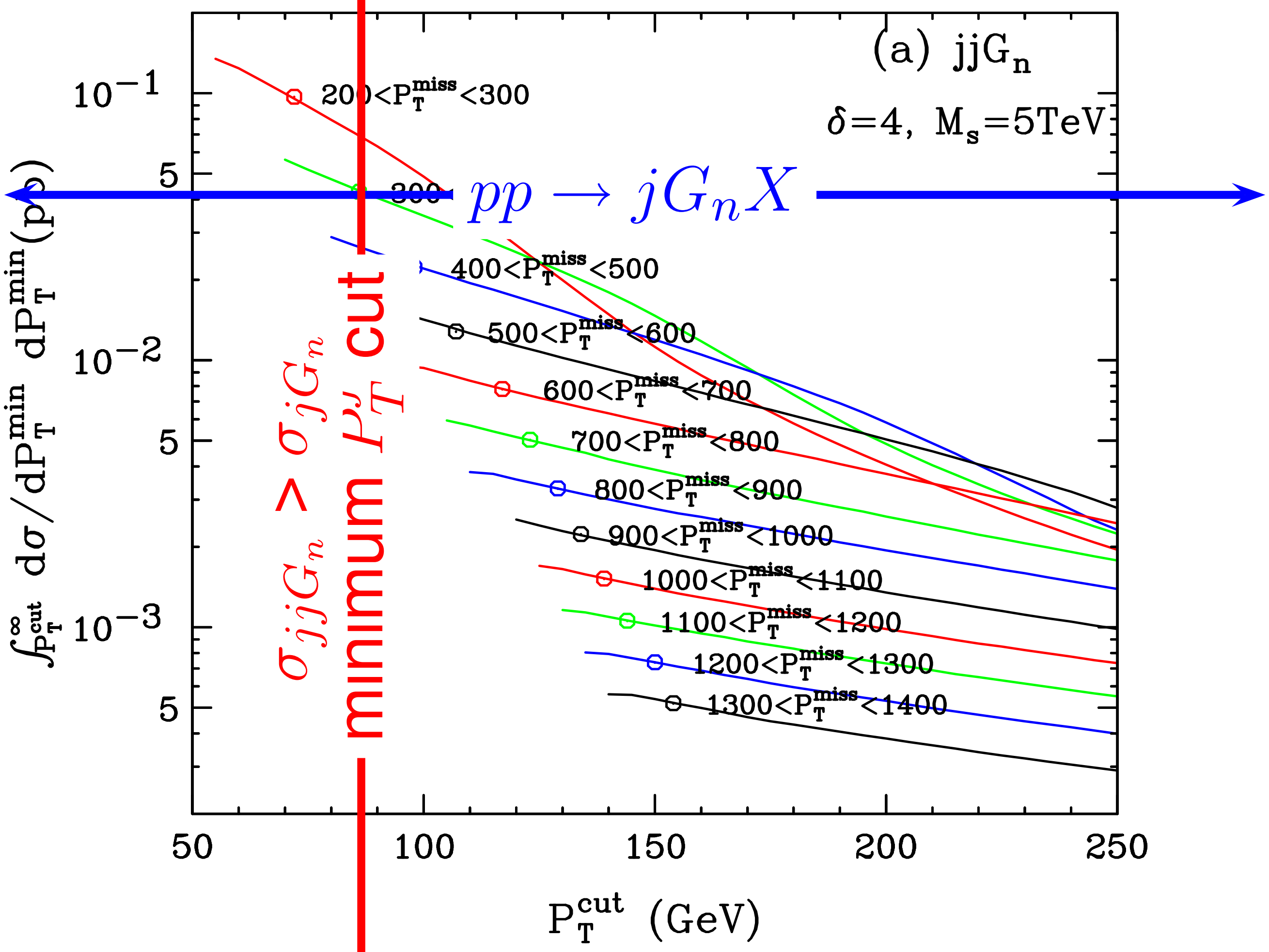
jjG_n at LHC – Conventions and Cuts

- 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+δ)-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 δ -dependent factor.

jjG_n at LHC – Conventions and Cuts

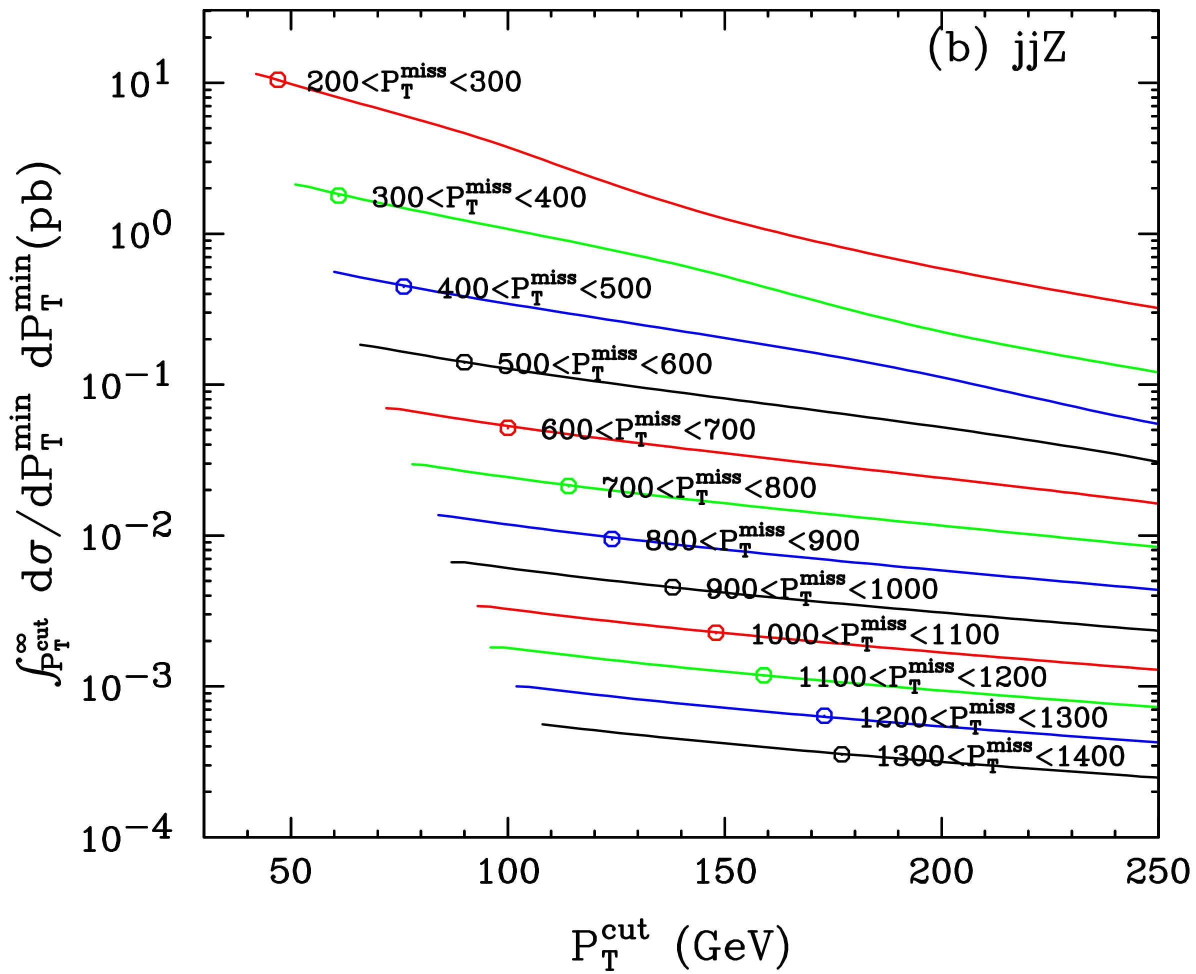
- CTEQ6L1 parton distribution functions.
- Factorization scale chosen as $\mu_f = \min(P_T)$ of the jets
- QCD coupling is set to the geometric mean value, $\alpha_s = \sqrt{\alpha_s(P_T^{j_1})\, \alpha_s(P_T^{j_2})}$.
- Focus on the $\delta = 4$ and $M_s = 5$ TeV.
- In the tree level numerical calculations, we identify massless partons with jets.
- $\Delta R_{jj} = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.7\,, \qquad |\eta_j| < 4.5$
- $P_T^j > 6\ \mathrm{GeV} \times \sqrt{P_T^{\mathrm{miss}}/1\ \mathrm{GeV}}$
- $P_T^{\mathrm{miss}} > 1\ \mathrm{TeV}$

jjG_n at LHC – Conventions and Cuts



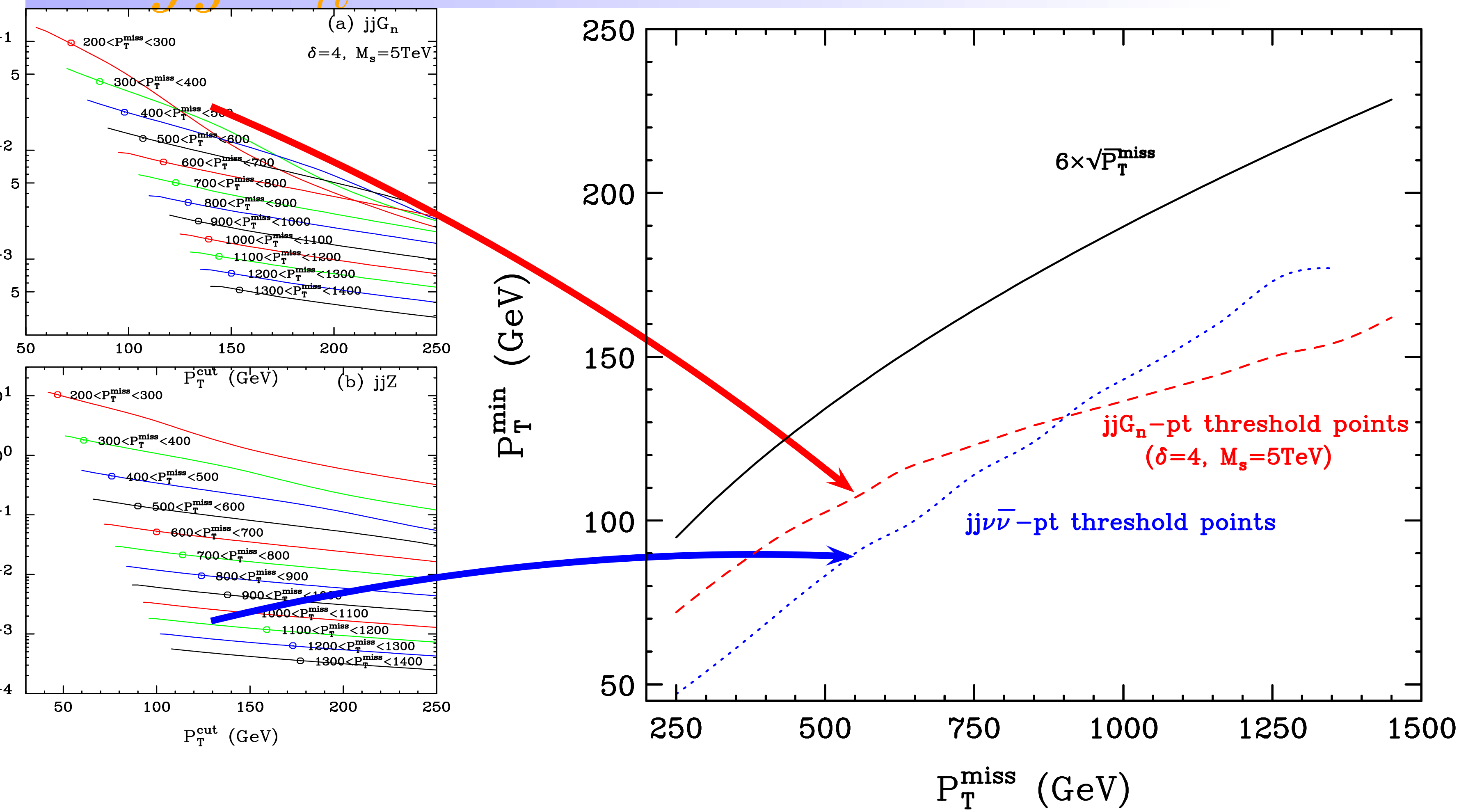
⊙ P_T^j cut dependence of dijet cross sections for $pp \to jjG_nX$ at the LHC in various $P_T^{\rm miss}$ bins. The open circles show the monojet cross section in the same missing P_T bin.

jjG_n at LHC – Conventions and Cuts



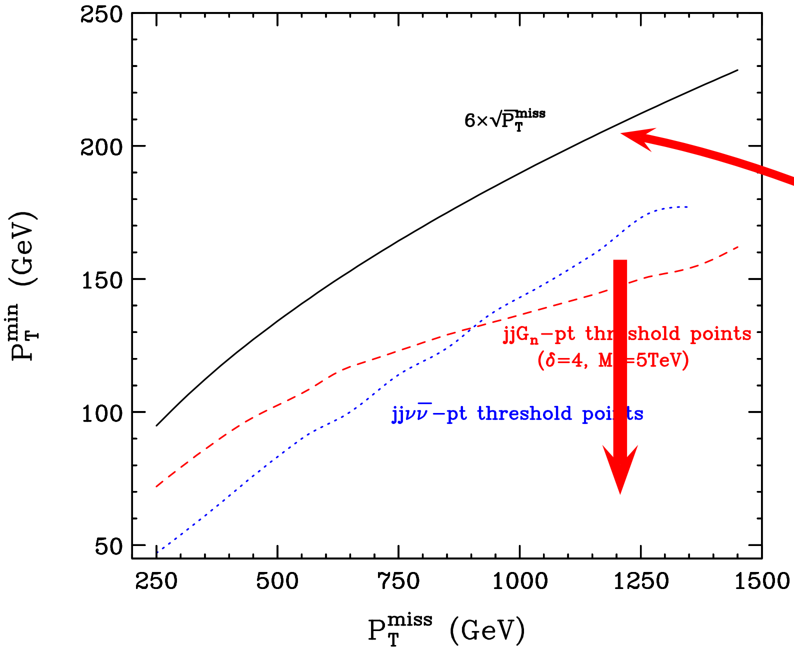
⊙ P_T^j cut dependence of dijet cross sections for $pp \to jj(Z \to \nu\bar{\nu})X$ at the LHC in various $P_T^{\rm miss}$ bins. The open circles show the monojet cross section in the same missing P_T bin.

jjG_n at LHC – Conventions and Cuts



⊙ Missing transverse momentum dependence of the $P_T^{\rm cut}$ value of equal 2-jet and 1-jet cross sections. Our jet selection cut is also presented.

jjG_n at LHC – Conventions and Cuts

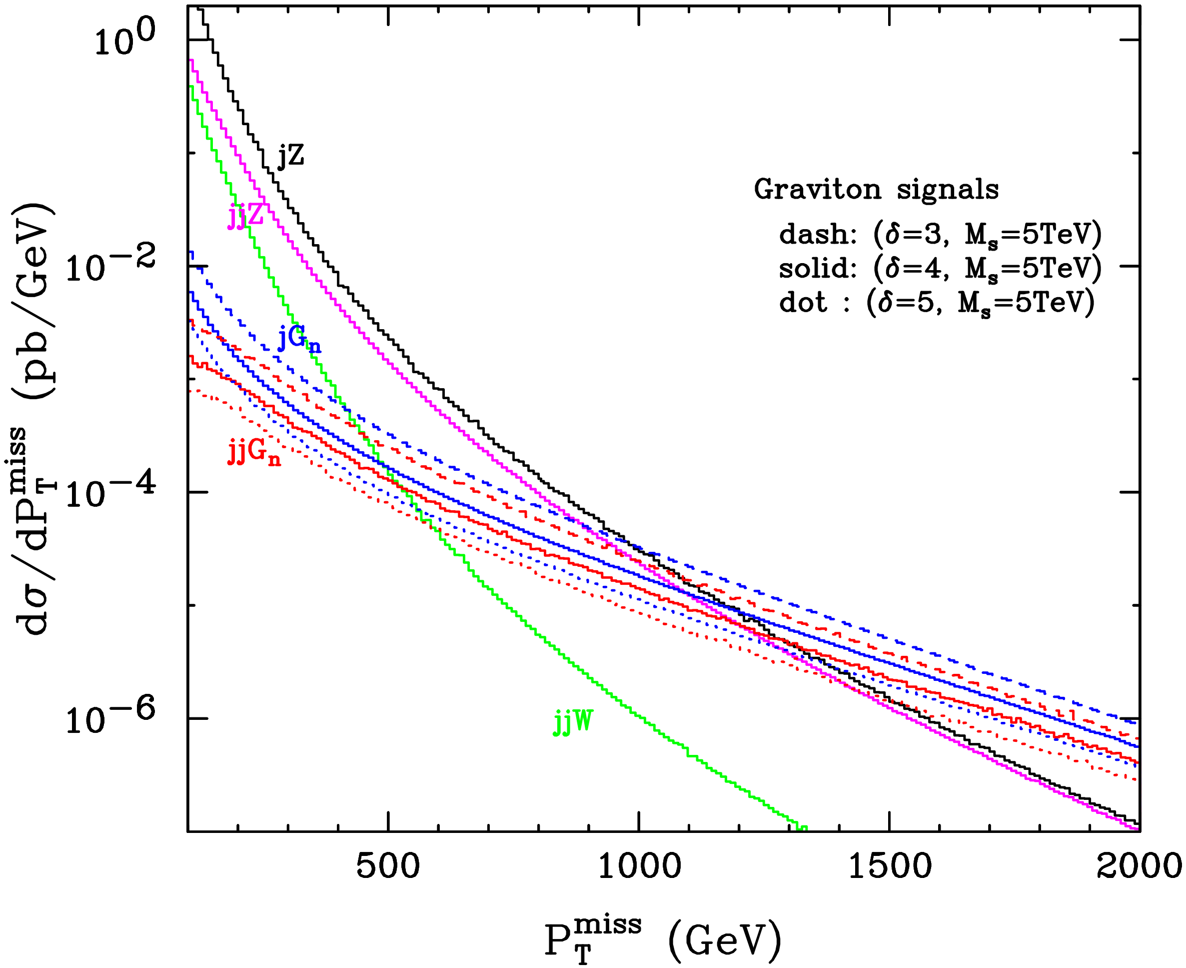


perturbatively reliable $\longrightarrow P_T^j > 6\ \text{GeV} \times \sqrt{P_T^{miss}/1\ \text{GeV}}$

- $\sigma_{jj} > \sigma_j$
- perturbative results cannot be trusted
- multiple soft jet emission to appear

- 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



⊙ P_T^{miss} dependence of the total cross sections for the signal and background

jjG_n at LHC – Conventions and Cuts

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- Factorization scale chosen as $\mu_f = \min(P_T)$ of the jets
- QCD coupling is set to the geometric mean value, $\alpha_s = \sqrt{\alpha_s(P_T^{j_1})\,\alpha_s(P_T^{j_2})}$.
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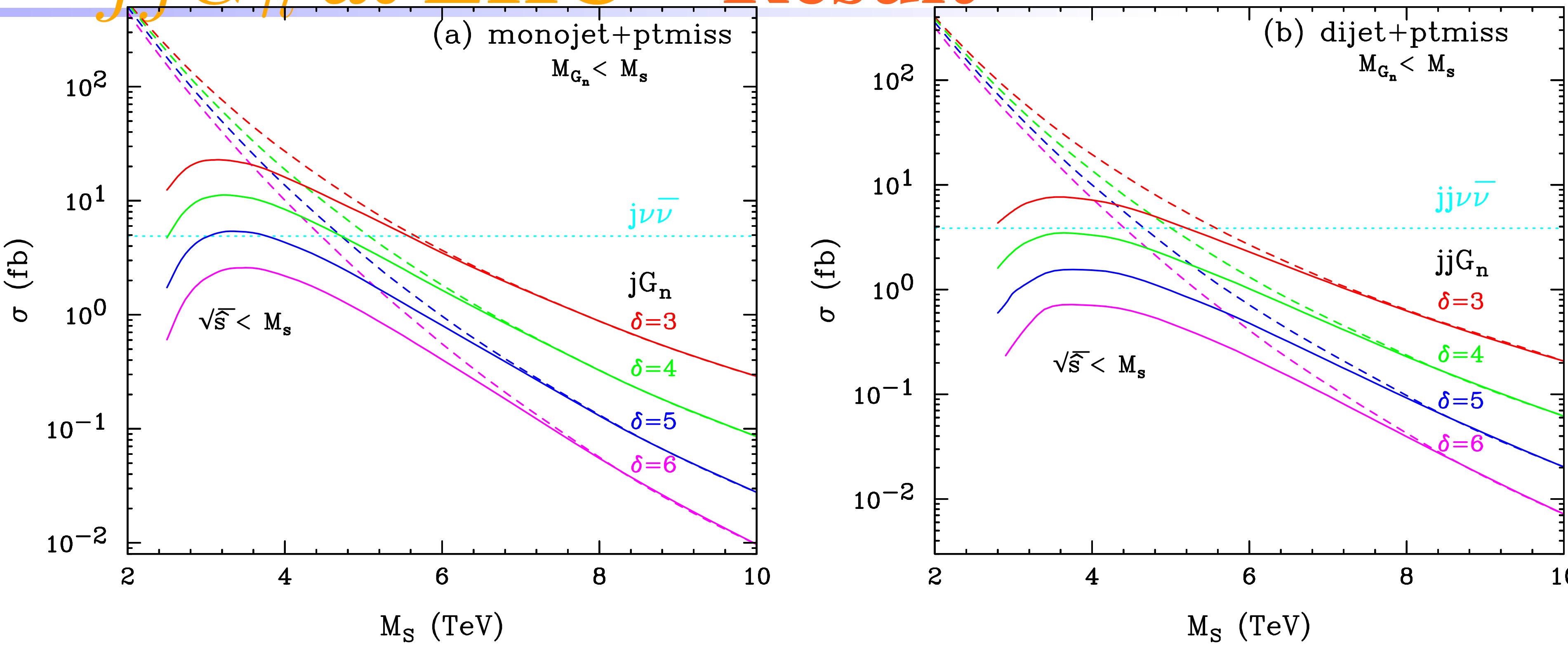
- $P_T^j > 6\ \mathrm{GeV} \times \sqrt{P_T^{\mathrm{miss}}/1\ \mathrm{GeV}}$
- $P_T^{\mathrm{miss}} > 1\ \mathrm{TeV}$

jjG_n at LHC – Result



M_s dependence of the σ_{total} for jG_n and jjG_n at LHC.

- Integrated luminosity $\mathcal{L} = 100$ fb^{-1}, where the systematic error in the background (assumed to be 10%) dominates over the statistical error.
- $\sigma_{jjG_n}(\sigma_{jG_n}) > 5 \times 10\% \times \sigma_{\text{background}} = 1.93\ (2.45)\ \text{fb}$

jjG_n at LHC – Result

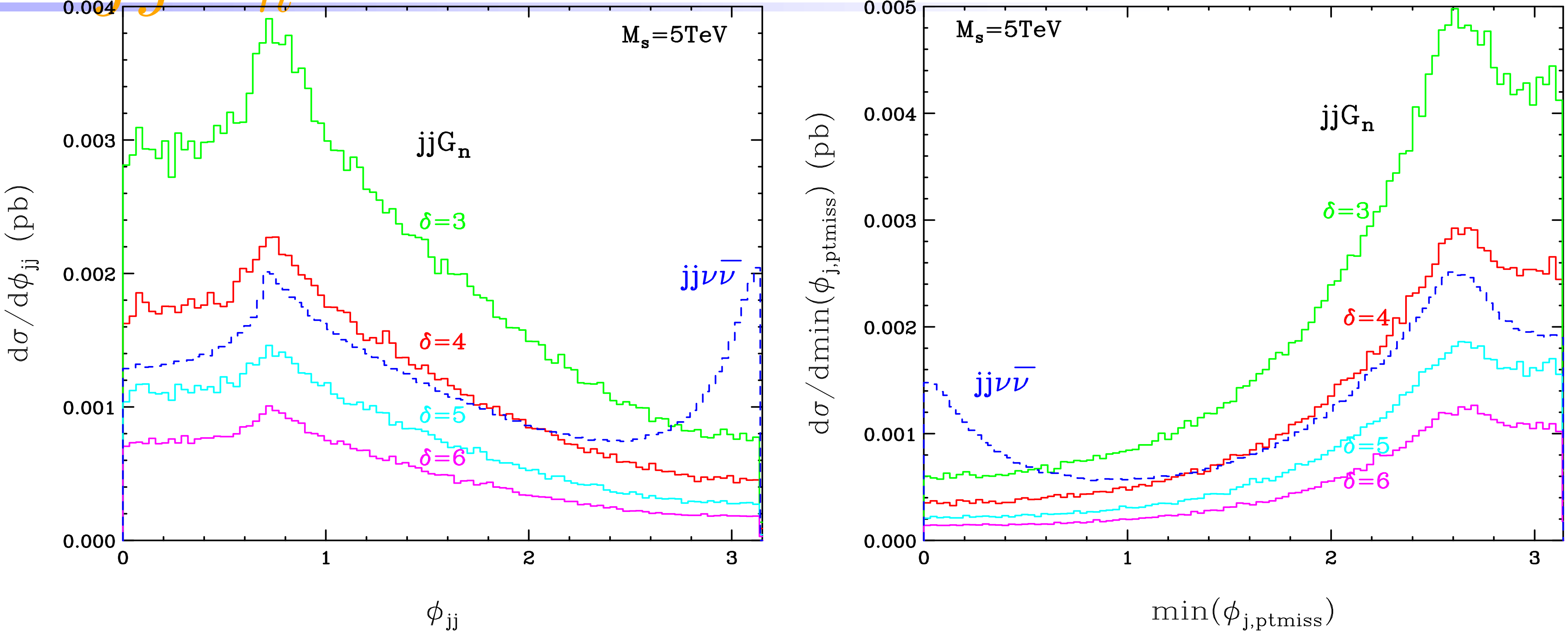
- Maximum ADD scale M_s sensitivity from 2-jet (1-jet) and missing transverse momentum signal at the LHC

No truncation	Hard truncation	no of ex-dim(δ)
6.4 (6.6) TeV	6.3 (6.5) TeV	for $\delta = 3$
5.6 (5.7) TeV	5.1 (5.5) TeV	for $\delta = 4$
5.2 (5.3) TeV	- (4.8) TeV	for $\delta = 5$
4.9 (5.0) TeV	- (3.6) TeV	for $\delta = 6$

⊙ The 2-jet sensitivity is only slightly lower than for the 1-jet case.

⊙ The larger δ 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.

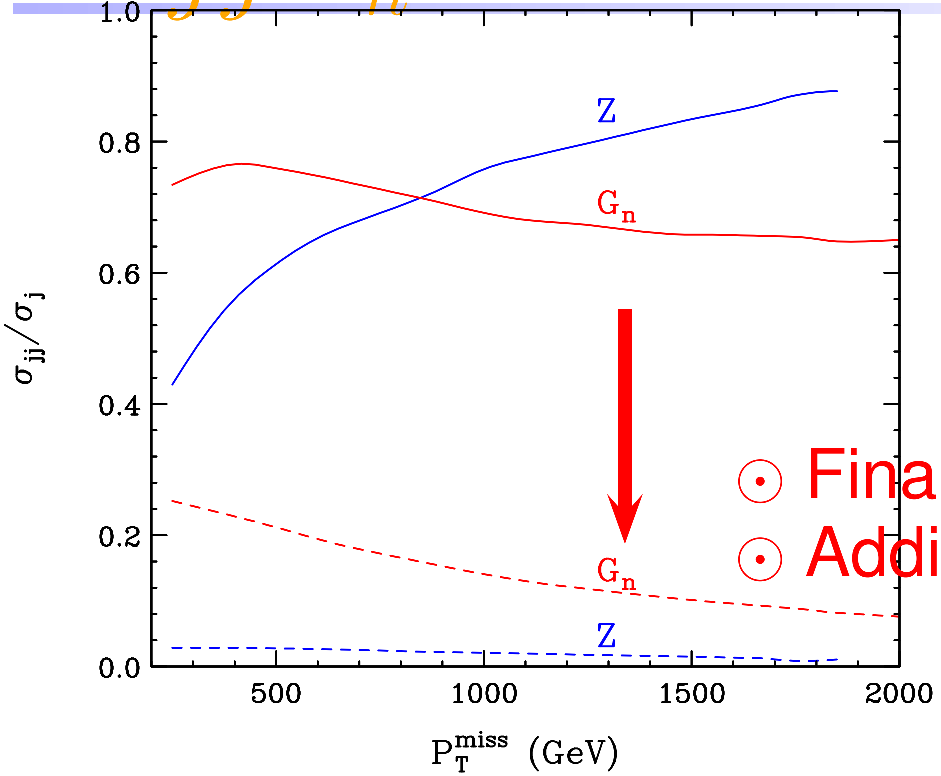
jjG_n at LHC – Result



ϕ_{jj} and $min(\phi_{j,ptmiss})$ 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.

jjG_n at LHC – Result



- 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 $P_T^{\rm miss}$, 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, $pp \to jG_n$ is most sensitive channel, but is not a unique demonstration of ADD.
- Calculated the order α_s^2 graviton plus dijet, jjG_n at the LHC
- For $P_T^{\rm miss}$ 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^{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.

jjG_n at LHC – Summary

- 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 $P_T^{\rm miss}$.
- 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: $\rightarrow$ 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.

jjG_n at LHC – Summary

Thank You