Spin-identification of the Randall-Sundrum resonance at LHC

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Outline

- Observables at LHC to study RS G in $p + p \to l^+ l^- + X$
- Signature spaces of RS G, sneutrino in $\not{R}_p$ and Z′. Discovery reaches.
- Angular distributions in the dilepton channel.
- Identification of the spin-2 RS graviton:
  - With center-edge asymmetry,
  - Exclusion **both spin-1 and spin-0** hypothesis.
- Discovery of the **second excitation** of graviton as a **smoking gun** signal for the non-factorizable geometry of RS.
- Conclusion.

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Introduction

- Heavy resonances with mass $\geq$ 1 TeV are predicted by several models beyond the SM:
  - Models with extra spatial dimensions RS (spin-2)
  - E_6 GUT and LR models (spin-1)
  - SUSY with $\not{R}_p$ (spin-0)
  - etc.

- Once a heavy resonance is discovered, its observables can be used in the attempt to identify the theoretical framework to which it belongs. The measurement of the total number of events, the angular distribution $d\sigma/d\cos\theta$, and the center-edge asymmetry A_{CE} of leptonic decay products at the resonance peak is a powerful tool to disentangle the graviton (spin-2) from the Z' and sneutrino, and hence to identify the spin of G.

$$p + p \to l^+ l^- + X, \qquad (l = e, \mu)$$

- The angular study is not considered here as it requires more integrated luminosity as the one available in the first phase of data taking at the LHC.

Previous studies on search for heavy graviton resonances:

- ATLAS:
  - *Allanach* (2000, 2002)

- CMS:
  - *Cousins* et al. (2005)
  - *Belotelov* et al. (2006)
  - *Clerbaux* et al. (2006)
  - *Collard* et al. (2003)

Here:

- In this talk we discuss the **identification** reach at LHC on the spin-2 RS resonance against spin-1 and spin-0 non-standard exchanges in the process: $p+p \to l^+ l^- + X$
- Basic observables:

  $\sigma \cdot B_\ell$ - resonant cross section and

  A_{CE} – center-edge asymmetry.
- **Identification** reach on spin-2 G ≡ exclusion reach on both the **spin-1** and **spin-0** hypotheses.
- Discuss a potential of LHC to discover the second graviton excitation => distinction of the RS model.

RS model parameters

The properties of the model are determined by two parameters:

– $c = k/M_{Pl}$ - the coupling parameter

– $M_G = m_1$ - mass of the first graviton resonance

- Masses of higher excitations $G^{(n)}$:

where x_n are roots of the Bessel function $J_1(x_n)=0$

(x_1=3.83, x_2=7.01, x_3=10.17, …) => unevenly spaced.

Mass pattern is distinctive of the model, if higher excitations in addition to the ground state would be discovered.

RS model constraints

- "Theoretical":
  - $0.01 \leq c \leq 0.1$
  - $\Lambda_\pi < 10$ TeV

- Experimental:
  - TEVATRON: $M_G > 300$ GeV @ $c = 0.01$
    $M_G > 900$ GeV @ $c = 0.1$

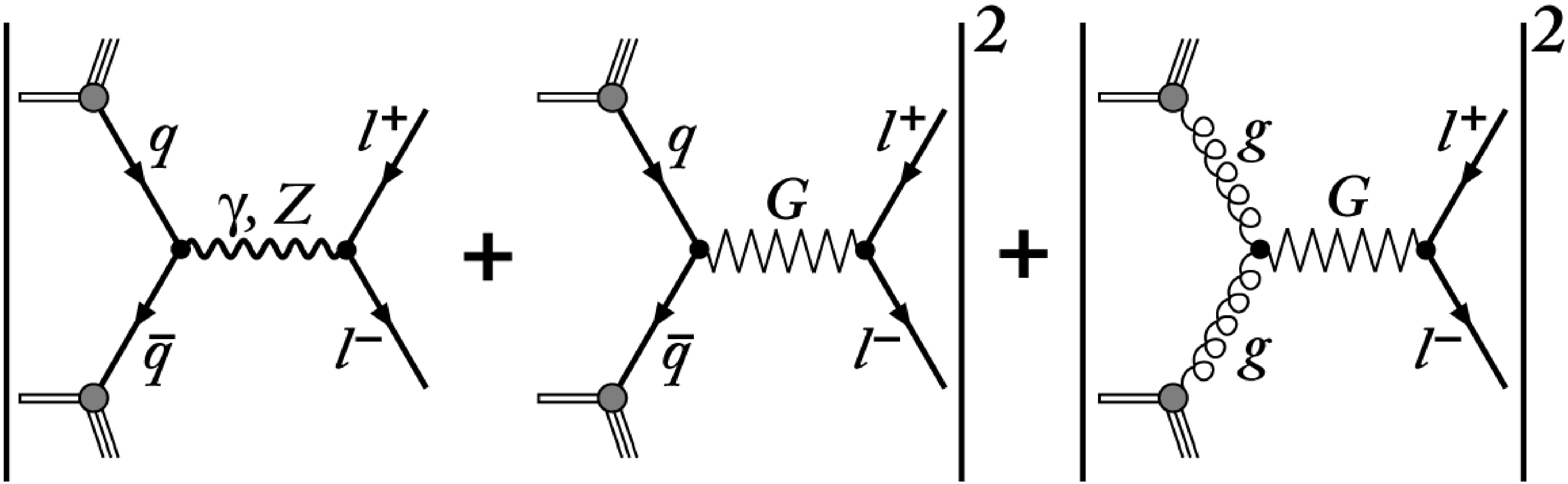
- Total width: $\Gamma_n = \rho\, m_n\, x_n^2\, c^2$

  where ρ is a constant depending on the number of open decay channels.

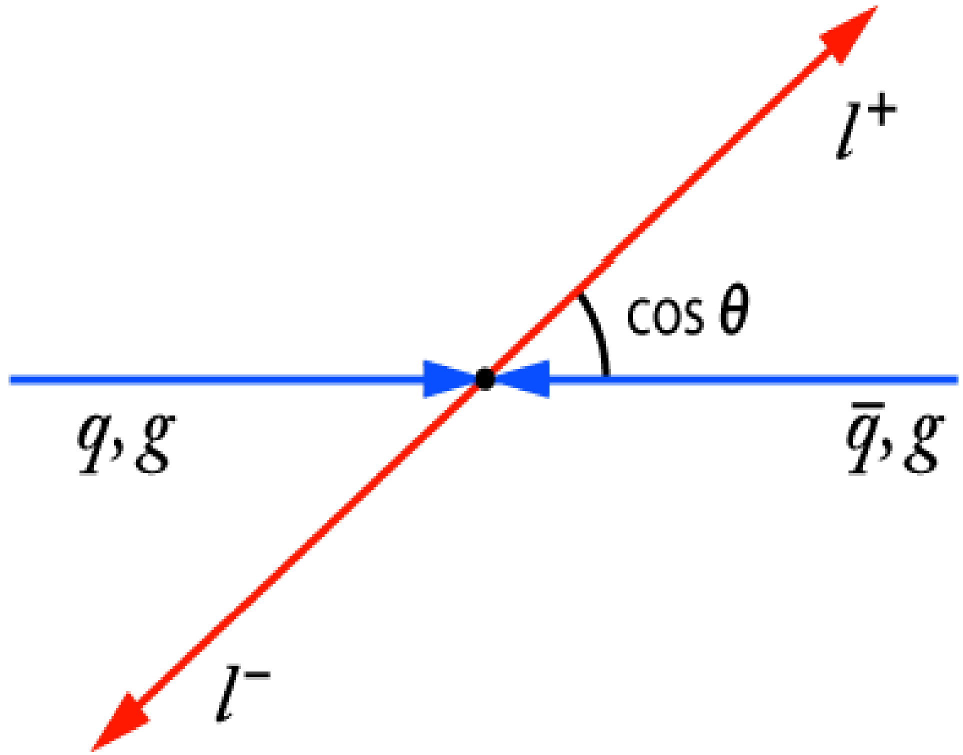
Hadron level $\boxed{pp \to l^+ l^- + X}$

- **SM:** $q\bar{q} \to \gamma, Z \to l^+ l^-$
- **Graviton exchange** signatures in RS scenario:

$$q\bar{q} \to G \to l^+ l^-, \quad gg \to G \to l^+ l^-$$



$\bar{q}q, gg \rightarrow \gamma, Z, G \rightarrow l^+l^-$ **C.M. l^+l^- system:**



$$z \equiv \cos(\theta)$$

Cross section of RS G

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}z} = \frac{\mathrm{d}\sigma_{q\bar{q}}}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}z} + \frac{\mathrm{d}\sigma_{gg}}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}z},$$

The lepton differential angular distribution, for dilepton invariant mass M in an interval of size ΔM around the (narrow) resonance peak M_R, is defined by

$$\frac{\mathrm{d}\sigma}{\mathrm{d}z} = \int_{M_R-\Delta M/2}^{M_R+\Delta M/2} \mathrm{d}M \int_{-Y}^{Y} \frac{\mathrm{d}\sigma}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}z}\,\mathrm{d}y,$$

with $Y = \log(\sqrt{s}/M)$.

The cross section for the narrow state production and subsequent decay into a DY pair, $pp \to R \to l^+l^-$, is given by:

$$\sigma(R_{ll}) \equiv \sigma(pp \to R)\cdot \mathrm{BR}(R \to l^+l^-) = \int_{-z_{\mathrm{cut}}}^{z_{\mathrm{cut}}} \mathrm{d}z \int_{M_R-\Delta M/2}^{M_R+\Delta M/2} \mathrm{d}M \int_{-Y}^{Y} \mathrm{d}y \frac{\mathrm{d}\sigma}{\mathrm{d}M\,\mathrm{d}y\,\mathrm{d}z}.$$

The number of signal events, N_S, in the RS model with $c = 0.01$ including ATLAS detector cuts as a function of resonance mass M_G in a run of 100 fb^{-1} for the process $pp \to e^+e^- + X$; the number of the SM background events, N_B, integrated over the bin and the minimum number of signal events $N_S^{\rm min}$ required to detect the resonance (at 5σ).

M_G (GeV)	Bin ΔM (GeV)	N_S	N_B	$N_S^{\rm min}$
1000	30.6	878.6	81.5	45.1
1500	42.9	108.9	14.6	19.1
1700	47.8	54.7	8.2	14.3
1800	50.2	39.6	6.2	12.5
1900	52.6	29.0	4.8	10.9
2000	55.0	21.4	3.7	10.0
2100	57.4	16.0	2.9	10.0
2200	59.8	12.1	2.2	10.0
2300	62.3	9.2	1.8	10.0
2400	64.7	7.0	1.4	10.0
2500	67.1	5.4	1.1	10.0

Experimental and theoretical inputs

At the LHC, with integrated luminosity $\mathcal{L}_{\rm int} = 100\ \mathrm{fb}^{-1}$, the number of signal (resonant) events can be computed by using $N_S = \sigma(R_{ll})\,\epsilon_l\,\mathcal{L}_{\rm int}$ and the background events are defined as $N_B = N_{SM}$ (background integrated over the bin). Here, ϵ_l is the experimental reconstruction efficiency, taken to be 0.9 both for electrons and muons. To compute cross sections we use the CTEQ6 parton distributions. We impose angular cuts relevant to the LHC detectors. The lepton pseudorapidity cut is $|\eta| < \eta_{\rm cut} = 2.5$ for both leptons (this leads to a boost-dependent cut on z), and in addition to the angular cuts, we impose on each lepton a transverse momentum cut $p_\perp > p_\perp^{\rm cut} = 20$ GeV.

The criterion used for the discovery limit in the analysis given here is the assumption that $5\sqrt{N_B}$ events or 10 events, whichever is larger, constitutes a signal.

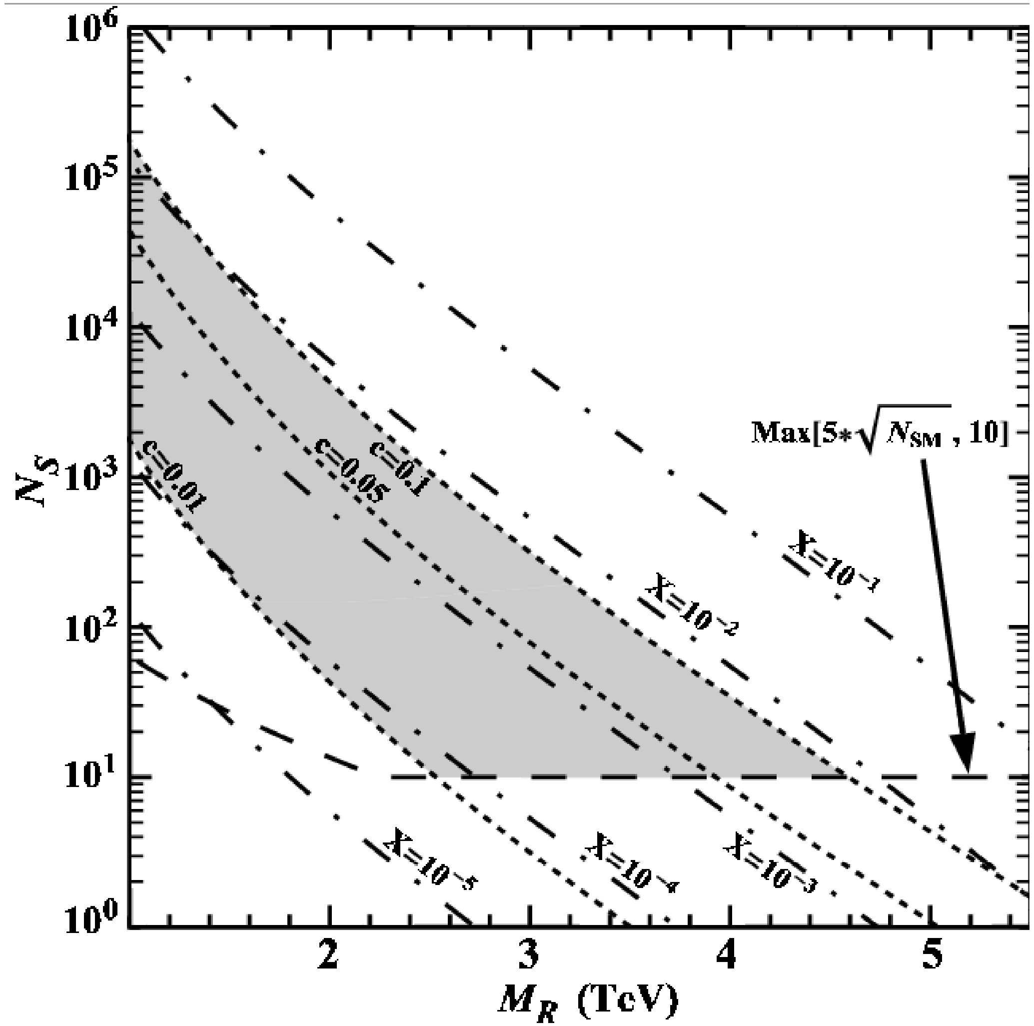
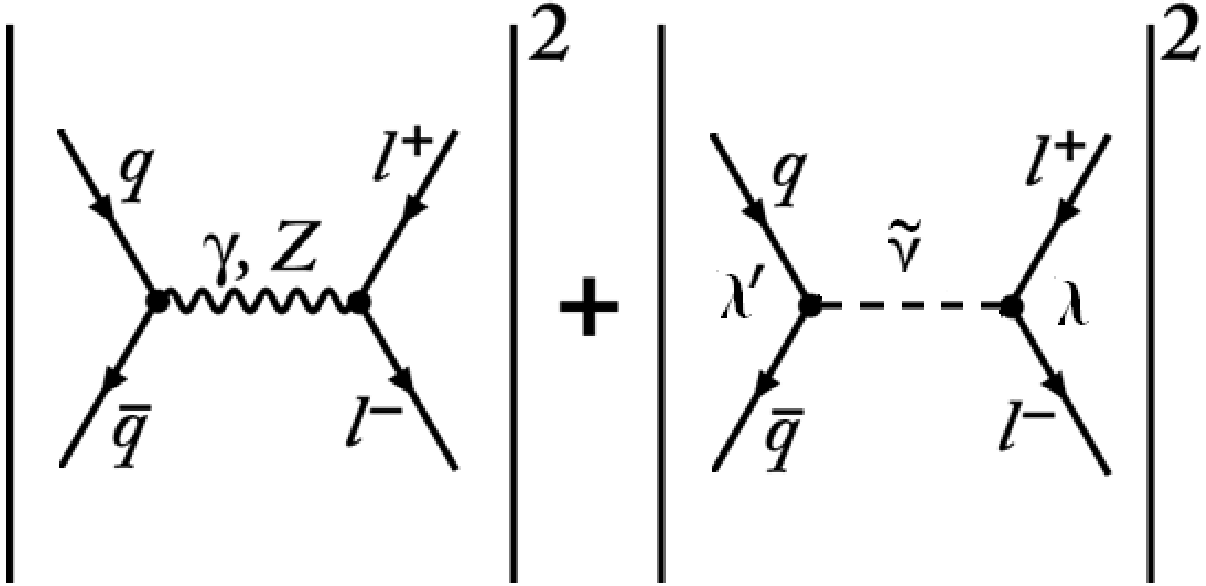


Figure 1. Expected number of resonance (signal) events N_S vs. M_R ($R = G, \tilde{\nu}_\tau$) at $\mathcal{L}_{\rm int} = 100$ fb^{-1} for graviton and sneutrino resonant production with values of c= 0.01, 0.05, 0.1 (short dashed curves) and X values ranging from 10^{-5} to 10^{-1} in steps of 10 (dash-dotted curves) and the minimum number of signal events (dashed curve) needed to detect the resonance above the background in the process $pp \to l^+l^- + X$ ($l = e, \mu$). Shaded area corresponds to potential overlap of graviton signature space with that for sneutrino resonant production.

Sneutrino at parton level



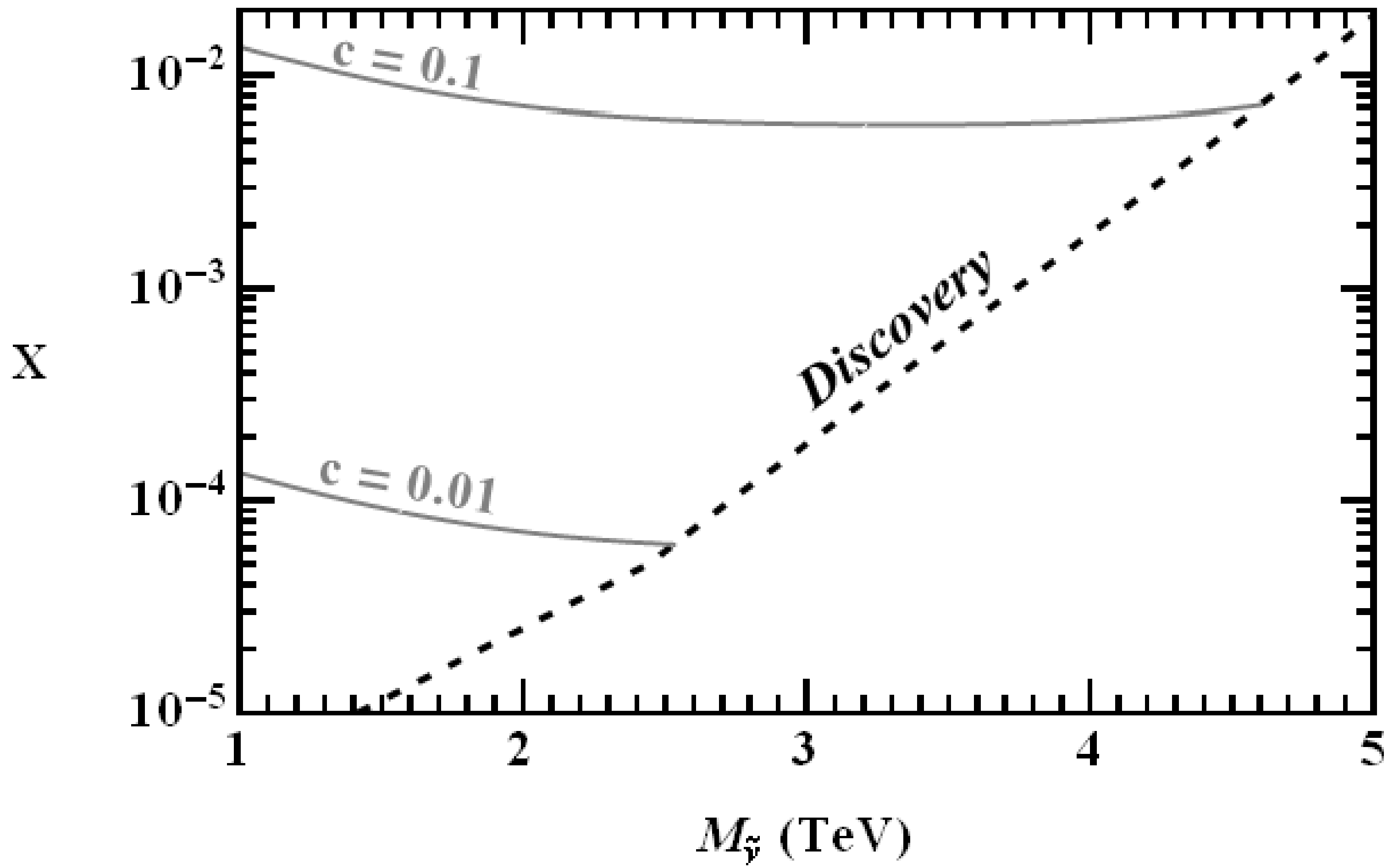
Cross section of sneutrino

$$\frac{\mathrm{d}\hat{\sigma}_{q\bar{q}}}{\mathrm{d}z} = \frac{\mathrm{d}\hat{\sigma}^{\mathrm{SM}}_{q\bar{q}}}{\mathrm{d}z} + \frac{\mathrm{d}\hat{\sigma}^{\tilde{\nu}}_{q\bar{q}}}{\mathrm{d}z},$$

$$\frac{\mathrm{d}\hat{\sigma}^{\tilde{\nu}}_{q\bar{q}}}{\mathrm{d}z} = \frac{1}{3}\,\frac{\pi\alpha^2_{\mathrm{em}}}{4\,M^2}\left(\frac{\lambda\lambda'}{e^2}\right)^2 |\chi_{\tilde{\nu}}|^2\,\delta_{qd} \approx \frac{\pi}{24}\,\frac{X}{M_{\tilde{\nu}}}\,\delta(M - M_{\tilde{\nu}})\,\delta_{qd},$$

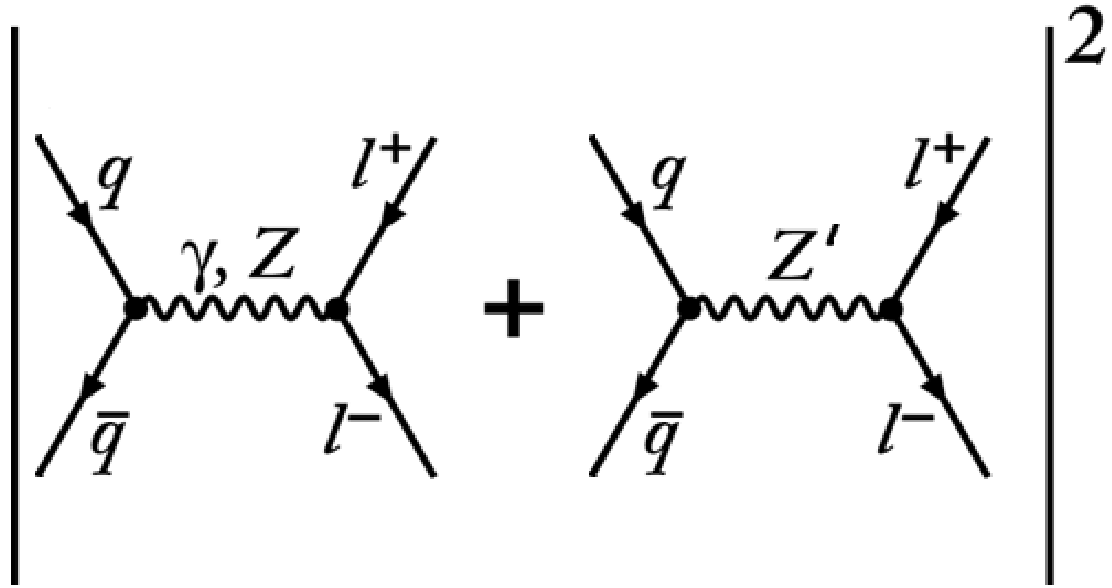
$$X = (\lambda')^2 B_l$$

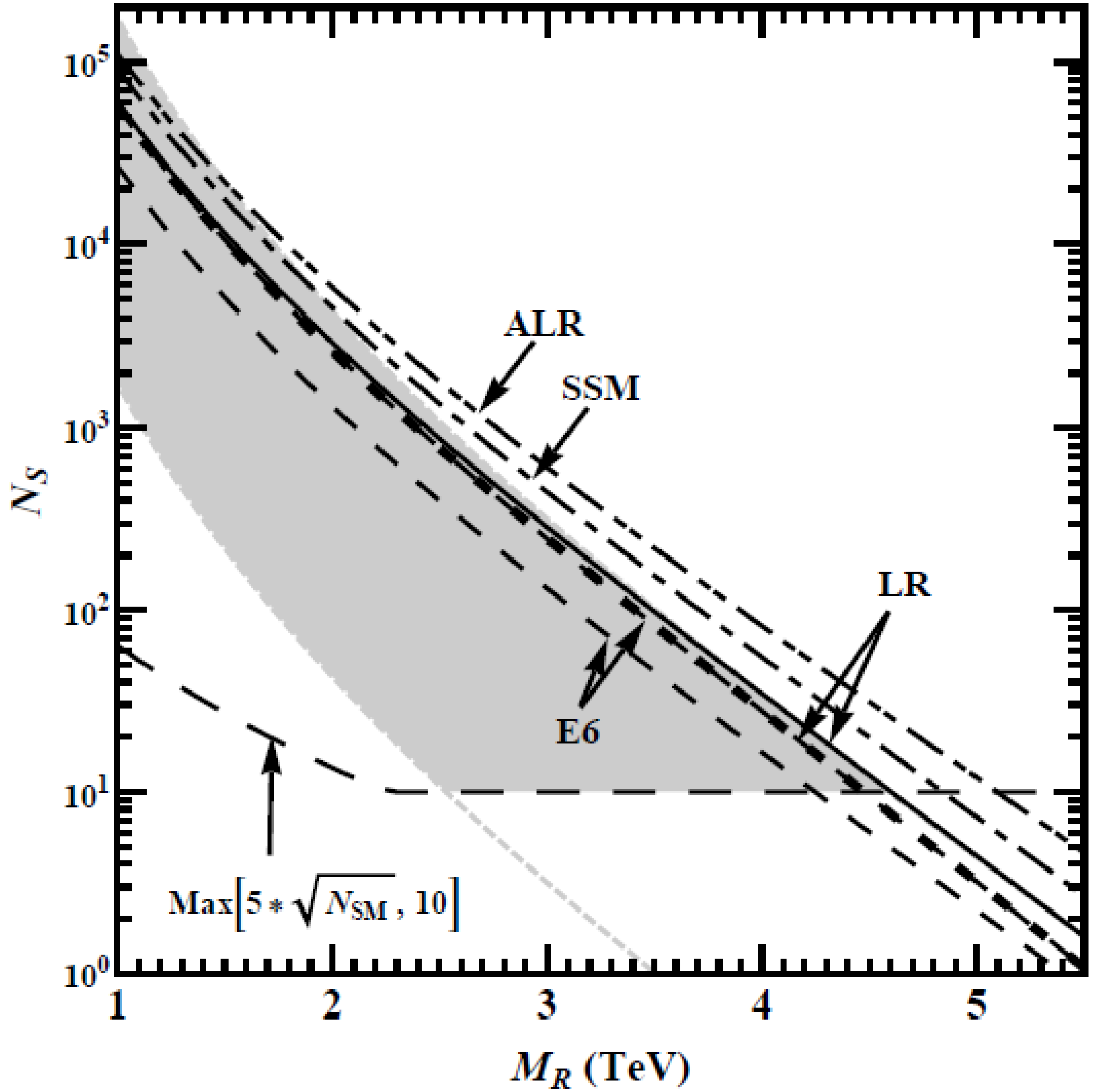
λ' and λ are the relevant R-parity-violating couplings of $d\bar{d}$ and l^+l^- to the sneutrino, respectively.



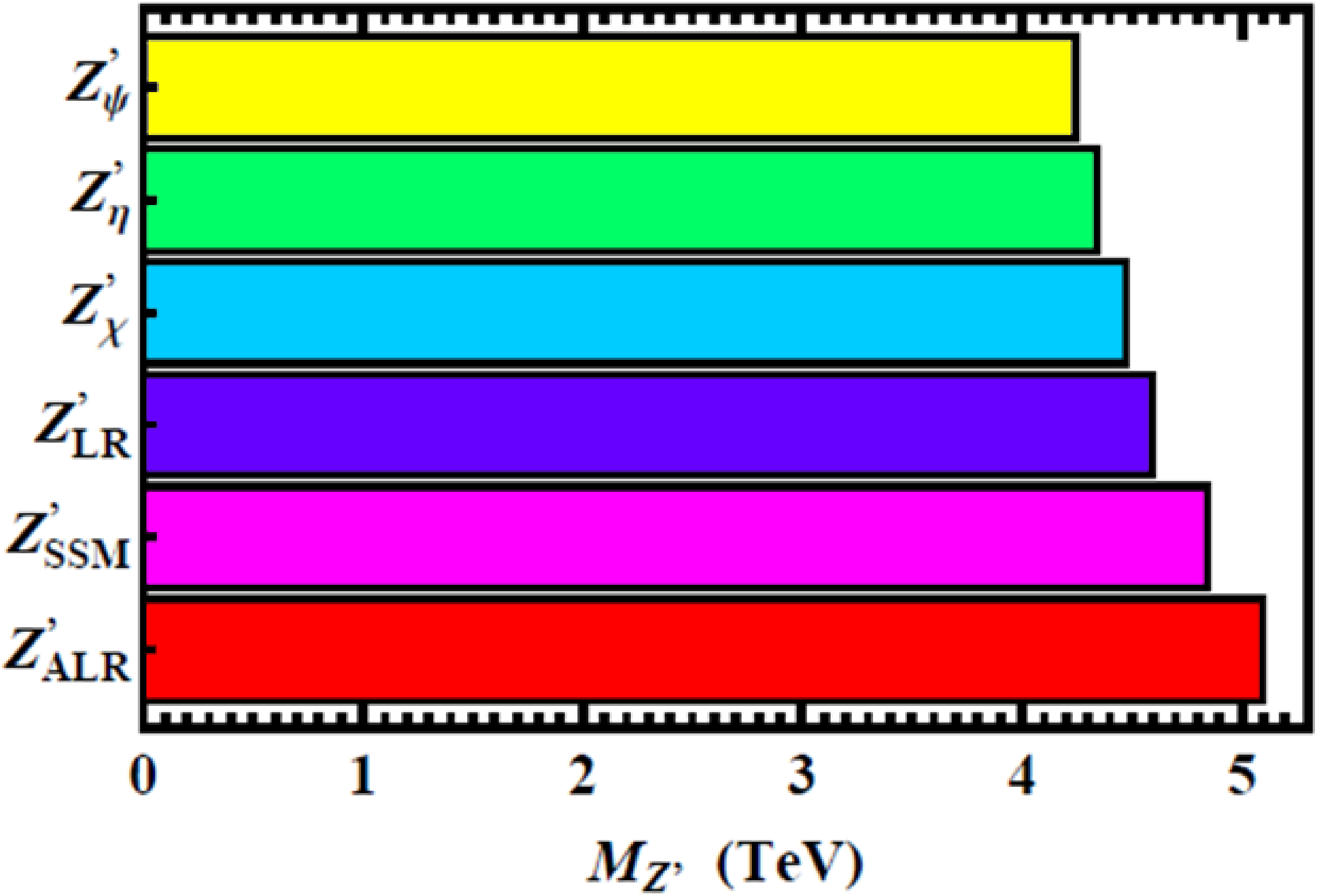
The discovery reach at the 5σ level in the plane $(M_{\tilde{\nu}}, X)$ obtained from lepton pair production $(l = e, \mu)$ at the LHC with $\mathcal{L}_{\rm int} = 100$ fb^{-1}. The discovery limit is defined by $5\sqrt{N_{SM}}$ or by 10 events, whichever is larger. The kink in the plot is the point of transition between the two criteria. Indicated is the domain in sneutrino parameters for discovery in the reach of LHC. The area enclosed between the two solid lines and the dashed line corresponds to the shaded area shown in Fig. 1.

Z' at parton level





Same as in Fig. 1 but for number of resonance events N_S vs. M_R $(R = G, Z')$ for graviton and Z' resonant production and the minimum number of signal events needed to detect the resonances above the background in the process $pp \to l^+l^- + X$ $(l = e, \mu)$. The two "LR" lines refer to the extreme values for α_{LR}. The shaded area is the overlap of graviton and sneutrino signature spaces for $0.01 < c < 0.1$, with $\mathcal{L}_{\rm int} = 100$ fb^{-1}.



Discovery limits at the 5σ level for neutral gauge bosons of representative models, obtained from lepton pair production ($l = e, \mu$) at the LHC with $\mathcal{L}_{\text{int}} = 100\ \text{fb}^{-1}$.

Angular distributions

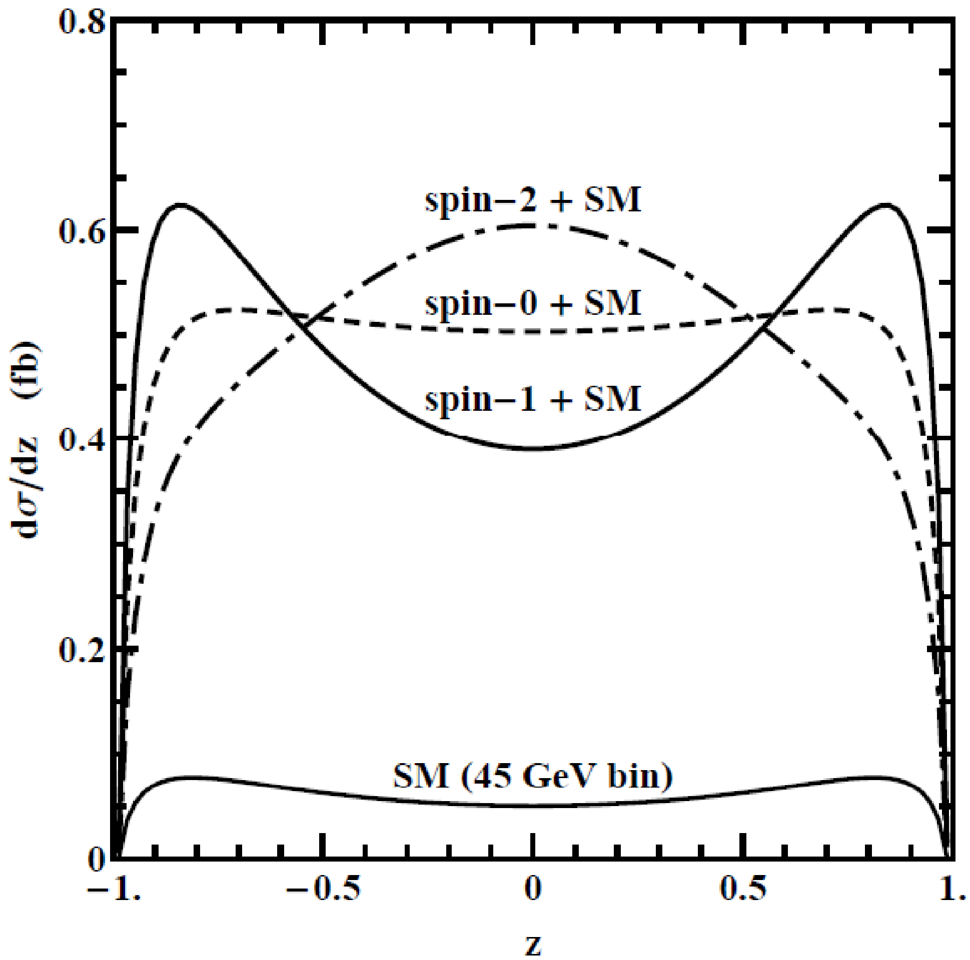
$$\frac{d\sigma(G_{ll})}{dz} = \frac{3}{8}(1+z^2)\,\sigma^{\mathrm{SM}}_{q\bar{q}} + \frac{5}{8}(1-3z^2+4z^4)\,\sigma^{G}_{q\bar{q}} + \frac{5}{8}(1-z^4)\,\sigma^{G}_{gg},$$

$$\frac{d\sigma(V_{ll})}{dz} = \frac{3}{8}(1+z^2)\,(\sigma^{\mathrm{SM}}_{q\bar{q}} + \sigma^{V}_{q\bar{q}}),$$

$$\frac{d\sigma(S_{ll})}{dz} = \frac{3}{8}(1+z^2)\,\sigma^{\mathrm{SM}}_{q\bar{q}} + \frac{1}{2}\,\sigma^{S}_{q\bar{q}}.$$

$$\sigma(G_{ll}) = \sigma^{\mathrm{SM}}_{q\bar{q}} + \sigma^{G}_{q\bar{q}} + \sigma^{G}_{gg},$$

$$\sigma(V_{ll}) = \sigma^{\mathrm{SM}}_{q\bar{q}} + \sigma^{V}_{q\bar{q}}, \qquad \sigma(S_{ll}) = \sigma^{\mathrm{SM}}_{q\bar{q}} + \sigma^{S}_{q\bar{q}}.$$

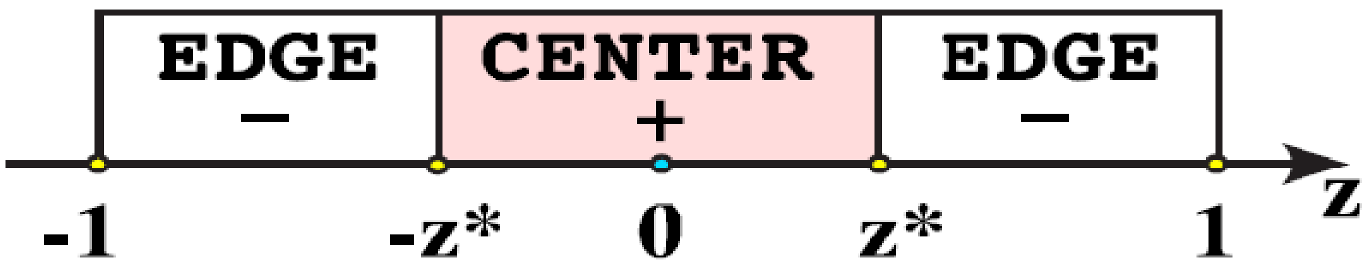


Angular distribution of leptons in the dilepton center of mass system for (i) spin-2 graviton resonant production, $\mathrm{d}\sigma(pp \to G \to l^+l^-)/\mathrm{d}z$, in the RS model with c=0.01; (ii) spin-0 resonant production, $\mathrm{d}\sigma(pp \to S \to l^+l^-)/\mathrm{d}z$; (iii) spin-1 resonant production, $\mathrm{d}\sigma(pp \to V \to l^+l^-)/\mathrm{d}z$. We take $M_R = 1.6$ TeV and assume equal numbers of resonant DY events.

Identification reach

- Centre-Edge Asymmetry A_{CE}

$$A_{CE} = \frac{\hat{\sigma}_{CE}}{\hat{\sigma}}, \qquad \hat{\sigma}_{CE} = \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^{1} \right) \right] \frac{d\hat{\sigma}}{dz} dz,$$



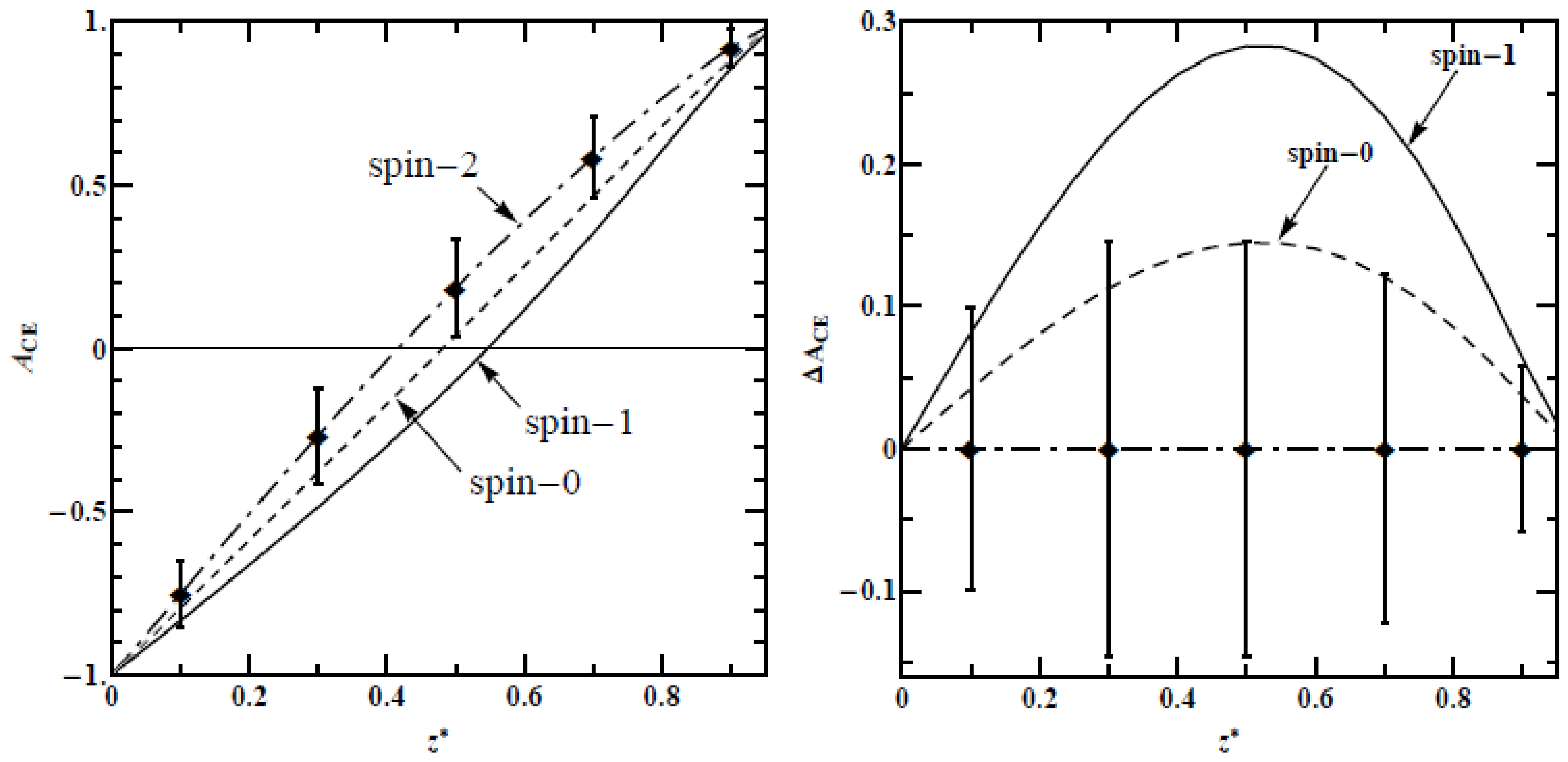
$$A_{\mathrm{CE}}^{G} = \epsilon_q^{\mathrm{SM}}\, A_{\mathrm{CE}}^{V} + \epsilon_q^{G}\left[2\, z^{*5} + \frac{5}{2}\, z^{*}(1 - z^{*2}) - 1\right] + \epsilon_g^{G}\left[\frac{1}{2}\, z^{*}(5 - z^{*4}) - 1\right],$$

$$A_{\mathrm{CE}}^{V} \equiv A_{\mathrm{CE}}^{\mathrm{SM}} = \frac{1}{2}\, z^{*}(z^{*2} + 3) - 1,$$

$$A_{\mathrm{CE}}^{S} = \epsilon_q^{\mathrm{SM}}\, A_{\mathrm{CE}}^{V} + \epsilon_q^{S}\,(2\, z^{*} - 1).$$

Here, ϵ_q^G, ϵ_g^Gs and ϵ_q^{SM} are the fractions of resonant events for $q\bar{q}, gg \to G \to l^+l^-$ and SM background, respectively, with

$$\epsilon_q^G + \epsilon_g^G + \epsilon_q^{\mathrm{SM}} = 1.$$



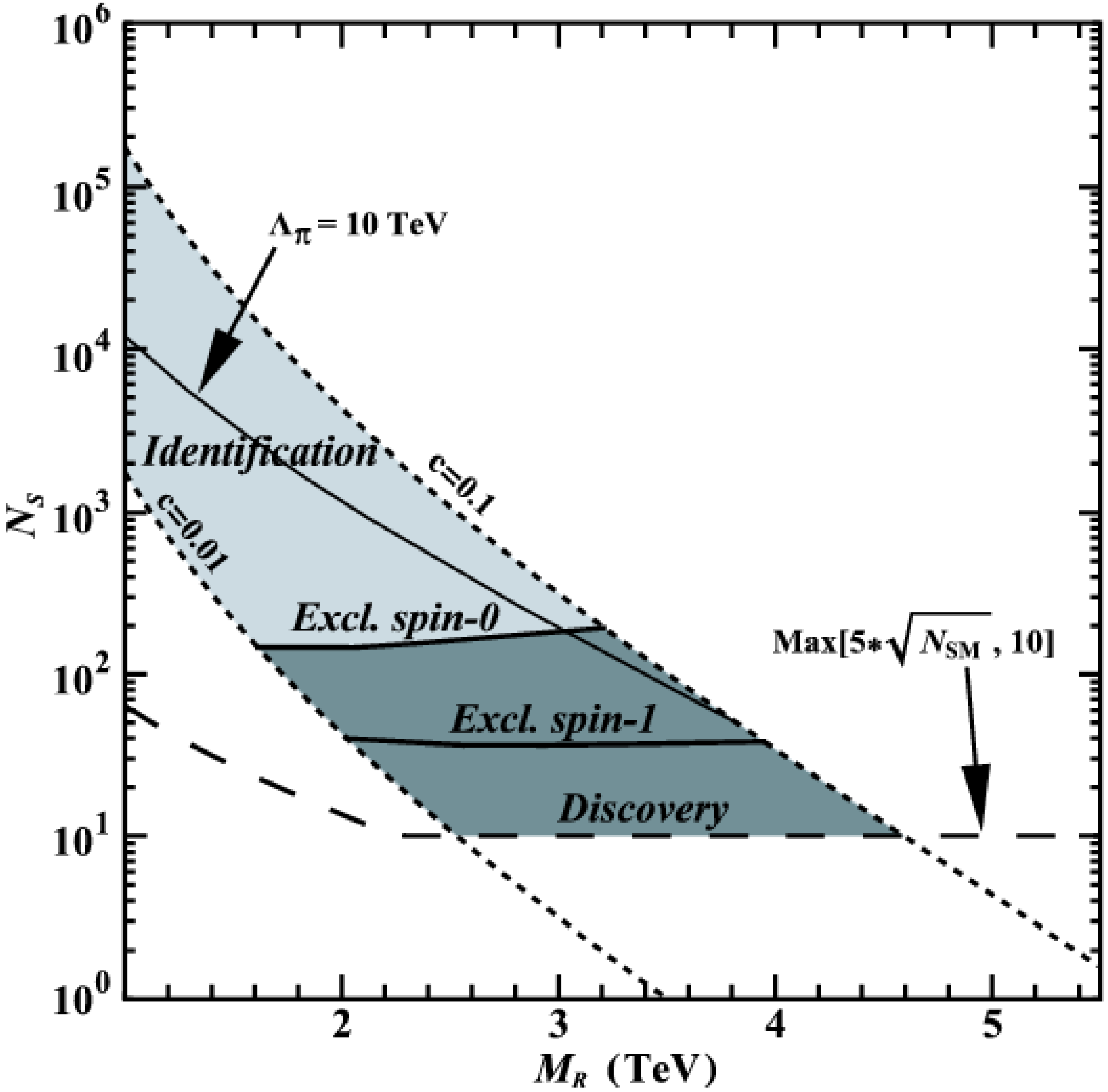
Left panel: $A_{\rm CE}$ *vs.* z^* for the spin-2 resonance G at c =0.01 and M_R=1.6 TeV (dot-dashed curve), and for the spin-0 (dashed curve) and spin-1 (solid curve) hypotheses, all for the same M_R and number of events. The error bar at $z^* = 0.5$ is within the identification reach on G (at the 2σ level) for $\mathcal{L}_{\rm int} = 100$ fb^{-1} as explained in the text. Right panel: Asymmetry deviations, $\Delta A_{\rm CE}$, of the spin-1 and spin-0 hypotheses from the RS one, compared with the uncertainties on $A^G_{\rm CE}$.

Analysis

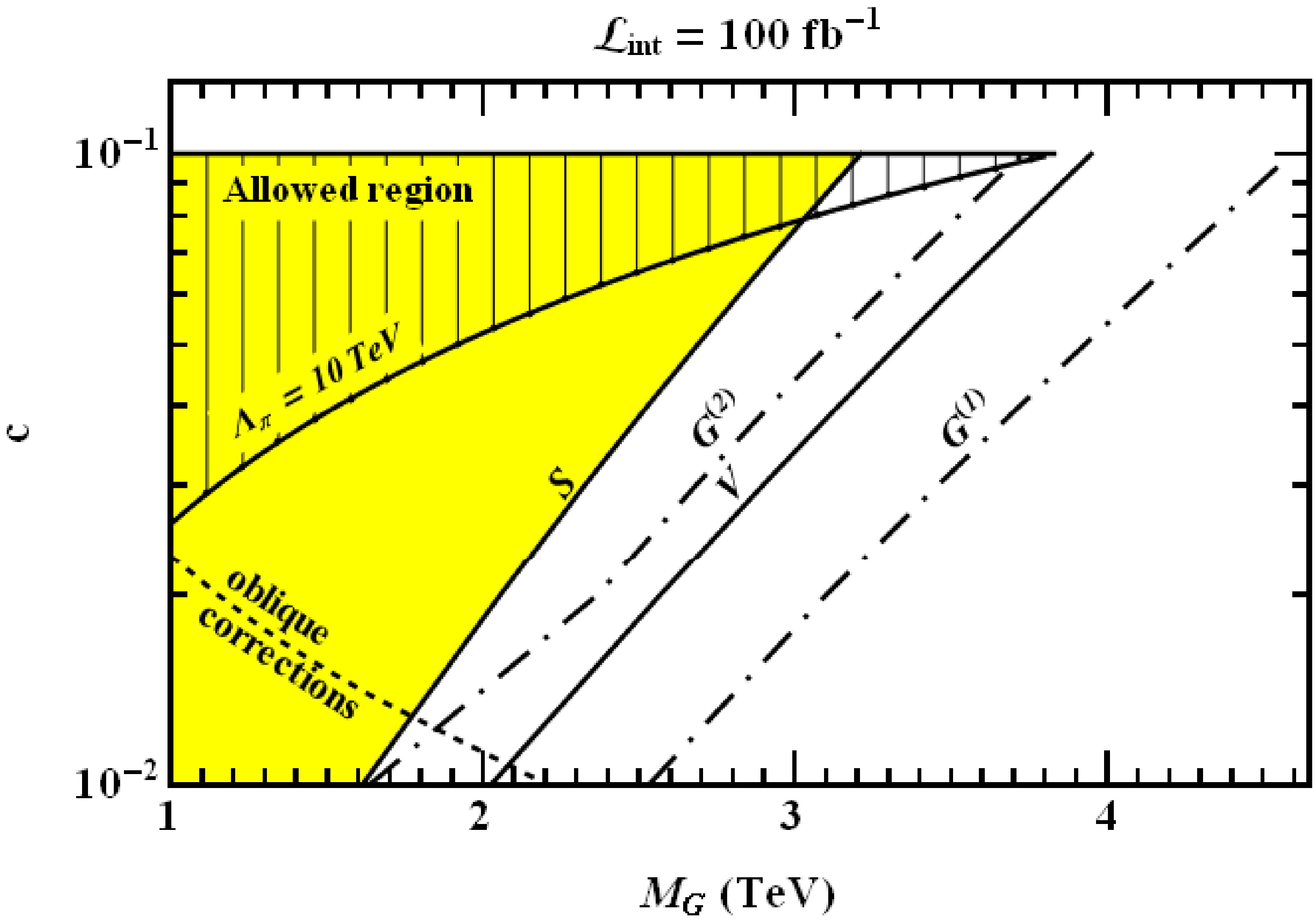
- Exclusion spin-0: $\Delta A_{\mathrm{CE}} = A_{\mathrm{CE}}^{G} - A_{\mathrm{CE}}^{S}$

- Exclusion spin-1: $\Delta A_{\mathrm{CE}} = A_{\mathrm{CE}}^{G} - A_{\mathrm{CE}}^{V}$

- $$\chi^2 = \left[\frac{\Delta A_{\mathrm{CE}}}{\delta A_{\mathrm{CE}}}\right]^2, \quad \delta A_{\mathrm{CE}} = \sqrt{\frac{1-\left(A_{\mathrm{CE}}^{G}\right)^2}{\epsilon_l \mathcal{L}_{\mathrm{int}}\sigma(G_{ll})}}.$$



Same as in Fig. 1 but with exclusion limits and identification reach at 95% C.L. and $\mathcal{L}_{\rm int} = 100$ fb^{-1}. The channels $l = e, \mu$ are combined. The theoretically favored region, limited by the $\Lambda_\pi = 10$ TeV and $c = 0.1$ lines, is also indicated.



Discovery limits ($G^{(1)}$ and $G^{(2)}$, 5σ level) and identification reaches (V, S, 95% C.L.) on the spin-2 graviton parameters in the plane (M_G, c), using the lepton pair production cross section and center–edge asymmetry, at the LHC with integrated luminosity of 100 fb^{-1}. The theoretically favored region, $\Lambda_\pi < 10$ TeV (hatched), and bounds from the global fit to the oblique parameters, are also indicated.

Conclusion

RS spin-2	Discovery		Identification	
L_{int}	c=0.01	c=0.1	c=0.01	c=0.1
100 fb^{-1}	2.5 TeV	4.6 TeV	1.6 TeV	3.2 TeV