IDENTIFICATION OF WARPED EXTRA DIMENSIONS SIGNATURES AT LHC

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Outline

- Motivations
- Introduction to RS1 spin-2 KK graviton excitations
- Angular distributions for $p + p \to l^+ l^- + X$
- Spin-2 identification potential of $\boldsymbol{A_{CE}}$
- Extension to $p + p \to \gamma\gamma + X$
- Results for identification reach on spin-2
- Phenomenology of the radion

Motivations: hierarchies

- Gauge hierarchy: $M_{EW} \sim 1$ TeV $\ll$ $M_{Pl} \sim 10^{16}$ TeV
- Fermion mass hierarchy: $m_\nu \ll m_{top}$
- Scale of supersymmetry (soft breaking)
- "Duality" to strongly coupled field theories

Simplest model [RS1] (Randall-Sundrum)

- 1 compactified "warped" extra dimension

5D spacetime, 2 branes set up

- Only gravity can propagate in full 5D space

RS1 model of gravity in extra dimensions

- $\mathrm{d}s^2 = \left(a(y)\right)^2 \eta_{\mu\nu}\, \mathrm{d}x^\mu\, \mathrm{d}x^\nu + \mathrm{d}y^2$

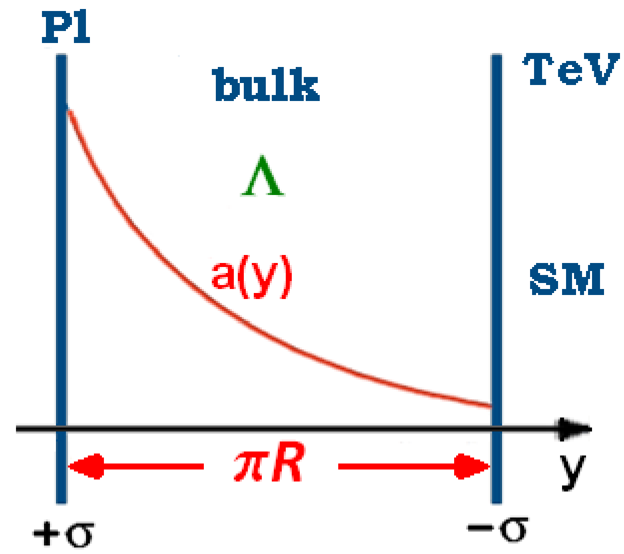
  → warp factor

- RS solution: $a(y) = e^{-k|y|}$; $k > 0$ (5D curvature)
- Fundamental mass scales (G = Newton constant)

  $G^{(4)} \propto M_{Pl}^{-2}$; $G^{(5)} \propto M_*^{-3}$; k.

- 4D effective theory gives $M_{Pl}^2 = \dfrac{M_*^3}{k}\left(1 - e^{-2k\pi R}\right)$
- “Natural”: $M_{Pl} \sim M_* \sim k$
- Mass spectrum on Planck brane $\propto M_* \sim 10^{16}\ \mathrm{TeV}$
- Mass spectrum on TeV brane exponentially warped

down: $M_\mathrm{H} \propto M_* e^{-k\pi R} \sim \mathrm{TeV}$ for $kR \sim 10!$ (automatic)



TeV (SM)

$x^\mathrm{M} \equiv (x^\mu, y)$

$\mathrm{d}s^2 = G_{\mathrm{MN}}\, \mathrm{d}x^\mathrm{M}\, \mathrm{d}x^\mathrm{N}$

$$\eta_{\mu\nu} = \begin{pmatrix} -1 & . & . & . \\ . & 1 & . & . \\ . & . & 1 & . \\ . & . & . & 1 \end{pmatrix}$$

- Exponential twist of hierarchy problem
- Junction conditions at ***y=0***, ***y=πR*** =>

  tower of KK, spin-2, graviton excitations h_n
- Masses and couplings to SM matter (TeV brane):
  - Zero mode: $M_0 = 0$ (ordinary gravitation) Coupling $\propto \dfrac{1}{M_{Pl}}$
  - Higher modes: $M_n = x_n\, k\, e^{-k\pi R}, \quad J_1(x_n) = 0$

    $(x_1 \approx 3.8;\ x_2 \approx 7.0;\ x_3 \approx 10.2;\ \ldots)$ Coupling $\propto \dfrac{1}{\mathrm{TeV}}$
- Interaction: $$\int d^4x \left[\frac{1}{M_{Pl}} h^{(0)}_{\mu\nu}(x)\, T^{\mu\nu} + \frac{1}{\Lambda_\pi} \sum_{n=1}^{\infty} h^{(n)}_{\mu\nu}(x) T^{\mu\nu} + \ldots \right]$$
- $\Lambda_\pi = M_{Pl}\, e^{-k\pi R} \quad [kR \approx 10]$ => gravity effects at TeV scale
- Of interest for colliders: narrow peaks in dilepton/diphoton production

- RS-model parameters and notations:
  - $M_1 \equiv M_G$ mass of first KK graviton (expected $M_G \approx$ TeV)
  - $c = k/M_*$ coupling to matter [universal]

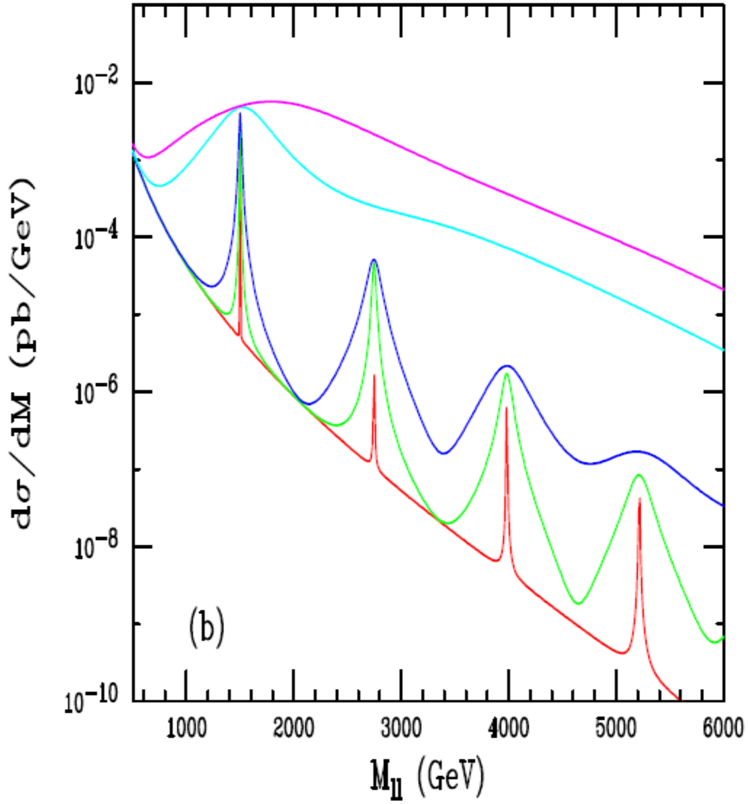
- Unevenly spaced spectrum:

  $M_n = (x_n/x_1)\, M_G$ distinctive of the model by itself

- Constraints:
  - $c < 0.1$ [$k \sim$ 5D curvature]
  - $c \geq 0.01$ [string arguments]
  - $\Lambda_\pi < 10$ TeV [no extra hierarchy]

Width $\Gamma_n = \rho\, M_n\, x_n^2\, c^2$:

narrow resonances for small c



DY production, M_1=1.5 TeV and subsequent tower states at LHC (c = 1, 0.5, 0.1, 0.05, 0.2, and 0.01, from top to bottom). **[*Davoudiasl et al.*]**

Experimental (TEVATRON):

$M_G > 560$ GeV ($c = 0.01$)

$M_G > 1050$ GeV ($c = 0.1$)

[arXiv:1004.1826v1 [hep-ex], 2010]

Extensions of RS1:

- SM fermions and gauge bosons in the bulk (but not Higgs) → fermion mass hierarchy.
- Stability of R: massless scalar "graviton" → spin-0 "radion".
- Complicated phenomenology predicted.

"Principal" signatures

- Spin-2 KK graviton excitations – cleanest events:

$$p + p \to l^+ l^- + X \qquad \qquad \left[p + p \to R + X \right.$$
$$\gamma\gamma + X \qquad \qquad \left. \hookrightarrow l^+ l^-, \; \gamma\gamma \right]$$

- Discovery *vs.* identification

$$p + p \to R \to l^+ l^-$$

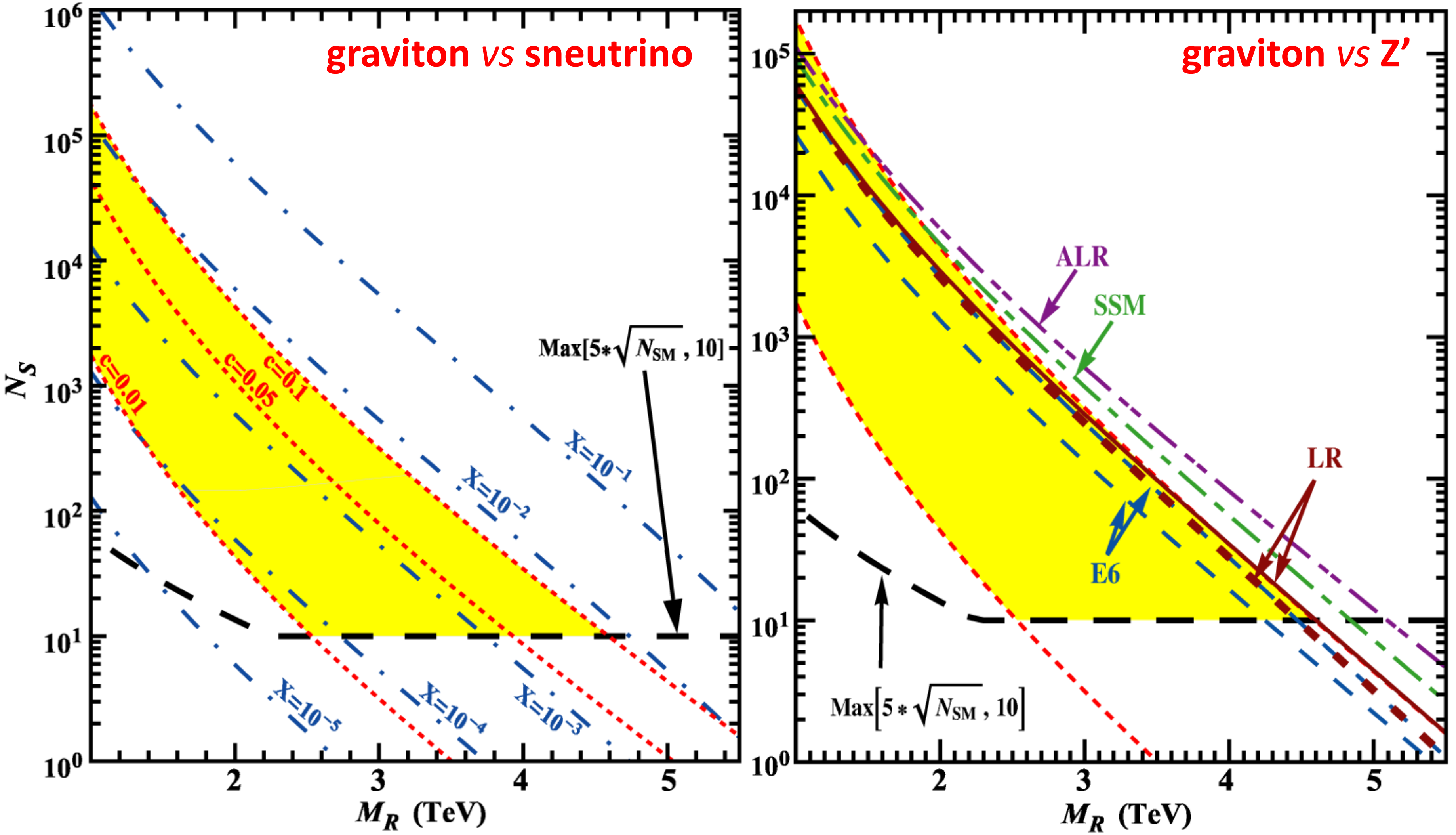
- Discovery reach: peak observation at some M_R over SM background → allowed region on model parameters $(R \to l^+ l^-, R \to \gamma\gamma, \ldots)$
- Identification reach: identify source of observed peak (different models can give same M_R and same number of events under the peak) ↔ test the peak quantum numbers → more stringent conditions on parameters.

Model examples: production of narrow peaks with same n. of events

- Spin:
  - Model of gravity with extra warped dimension (**spin-2**)
  - Z' models (**spin-1**)
  - SUSY with $\not{R}_p$ sneutrinos (**spin-0**)

} **" CONFUSION REGIONS"**

- Identify spin of peak → discriminate among models



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

$$0.01 < c < 0.1, \ \mathcal{L}_{\text{int}} = 100 \text{ fb}^{-1}.$$

Cross section for $p + p \to R \to l^+ l^-$

I) Production cross section: $\sigma(R_{ll}) = \int_{-z_{\rm cut}}^{z_{\rm cut}} dz \int_{M_R-\Delta M/2}^{M_R+\Delta M/2} dM \int_{-Y}^{Y} dy \frac{d\sigma}{dM\,dy\,dz}.$

→ number of events under the peak

Experimental inputs & cuts

- Minimal number of signal events over SM background (discovery):

$$[\ signal \equiv \max(5\cdot\sqrt{N_B},\ 10)\ ]$$

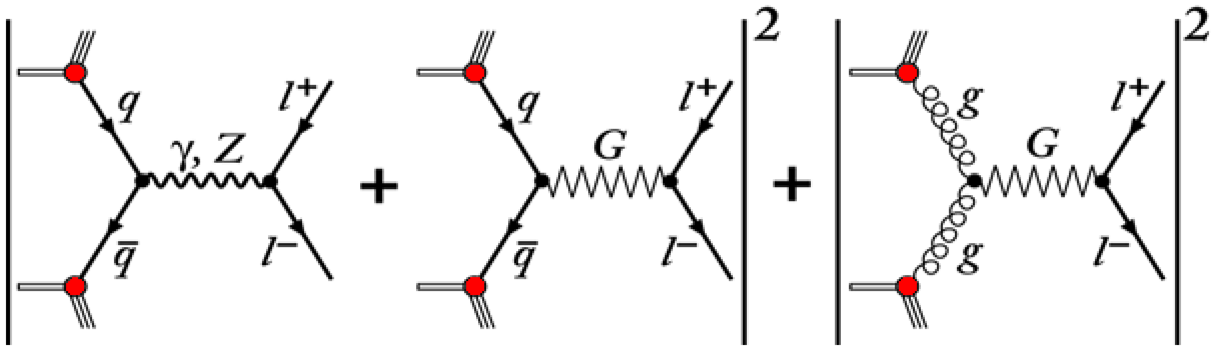
- Inputs: reconstruction efficiency $\varepsilon_l = 90\%$; $L_{\rm int} = 10;\ 100\ {\rm fb}^{-1}$;
- cuts $|y| \le 2.5$; $P_T^l > 20\,{\rm GeV}$; $|\eta_{l,\bar{l}}| < 2.5$; $z_{\rm cut} = 0.987$
- ATLAS detector resolution: $\mathbf{\Delta M = 24\ (0.625\ M + M^2 + 0.0056)^{1/2}}$ GeV, dilepton mass ***M*** measured in TeV units.

II) Angular distribution $\frac{d\sigma}{dz} = \int_{M_R-\Delta M/2}^{M_R+\Delta M/2} dM \int_{-Y}^{Y} \frac{d\sigma}{dM\,dy\,dz} dy,$

$Y = \log(\sqrt{s}/M).$ (y ≡ rapidity of lepton pair, ***M*** ≡ dilepton mass, ***z*** ≡ **cosθ***)

Hadron level $pp \to l^+ l^- + X$

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

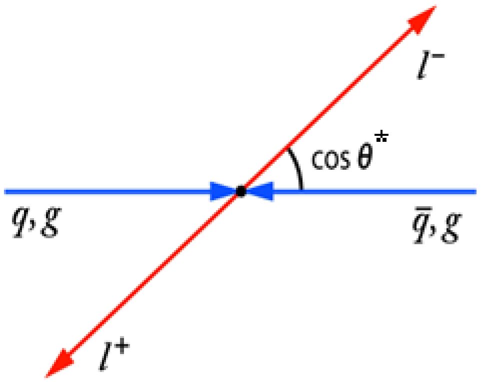


- Parton distribution functions $f_q(\xi, M)$ – CTEQ6
- Partonic cross sections $\hat{\sigma}$ [*Giudice et al., 1999; Han et al., 1999*]

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

C.M. $l^+ l^-$ **system:**

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



Summary of angular distributions

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

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

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

($l = e, m$)

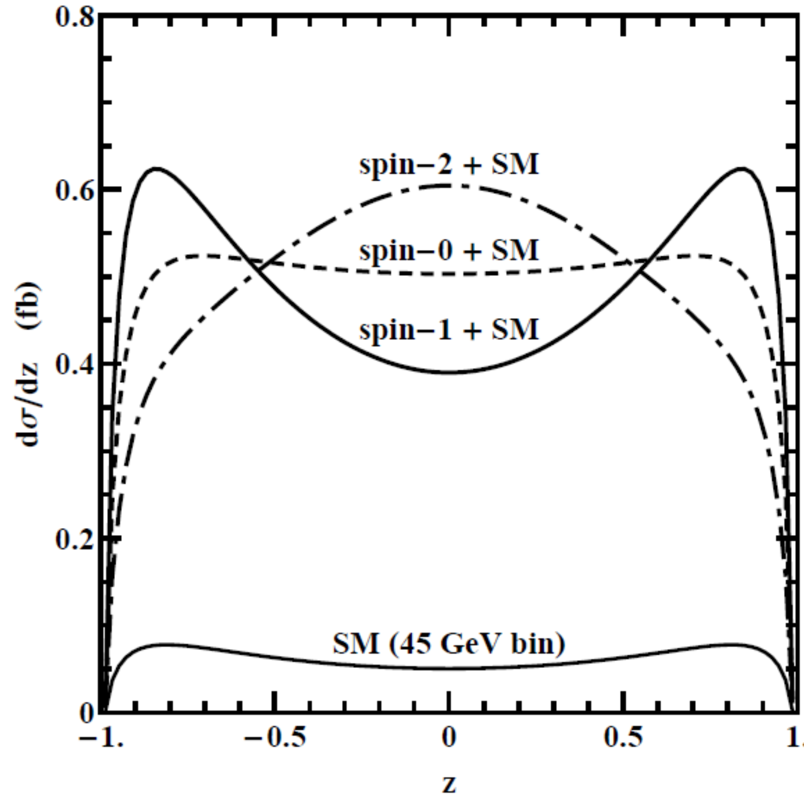
$$\sigma(G_{ll}) = \sigma_{q\bar q}^{SM} + \sigma_{q\bar q}^{G} + \sigma_{gg}^{G},$$

$$\sigma(V_{ll}) = \sigma_{q\bar q}^{SM} + \sigma_{q\bar q}^{V},$$

$$\sigma(S_{ll}) = \sigma_{q\bar q}^{SM} + \sigma_{q\bar q}^{S}.$$

z-even

Process	Normalized density
$q\bar q \to (\gamma, Z) \to l^+l^-$, $q\bar q \to Z' \to l^+l^-$	$\frac{3}{8}(1+z^2)$
$gg \to G \to l^+l^-$	$\frac{5}{8}(1-z^4)$
$q\bar q \to G \to l^+l^-$	$\frac{5}{8}(1-3z^2+4z^4)$
$q\bar q \to \tilde\nu \to l^+l^-$	$\frac{1}{2}$ (flat)

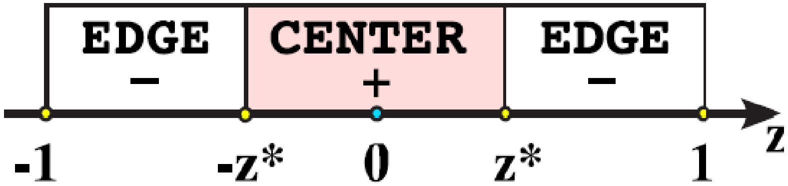


c = 0.01, M_R = 1.6 TeV, equal numbers of DY resonant events

Identification reach on spin-2

- Difficulty of angular analysis: boost to CM frame and sign of z
- Centre-Edge Asymmetry $A_{CE} = \dfrac{\sigma_{CE}(R_{ll})}{\sigma(R_{ll})}$: **z-symmetric integration!**

$$\sigma_{CE}(R_{ll}) = \left[\int_{-z^*}^{z^*} - \left(\int_{-1}^{-z^*} + \int_{z^*}^{1}\right)\right]\frac{d\sigma(R_{ll})}{dz}dz,$$



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

$$A_{\rm CE}^{V} \equiv A_{\rm CE}^{\rm SM} = \frac{1}{2} z^*(z^{*2} + 3) - 1, \quad A_{\rm CE}^{S} = \epsilon_q^{\rm SM}\, A_{\rm CE}^{V} + \epsilon_q^{S}\,(2 z^* - 1).$$

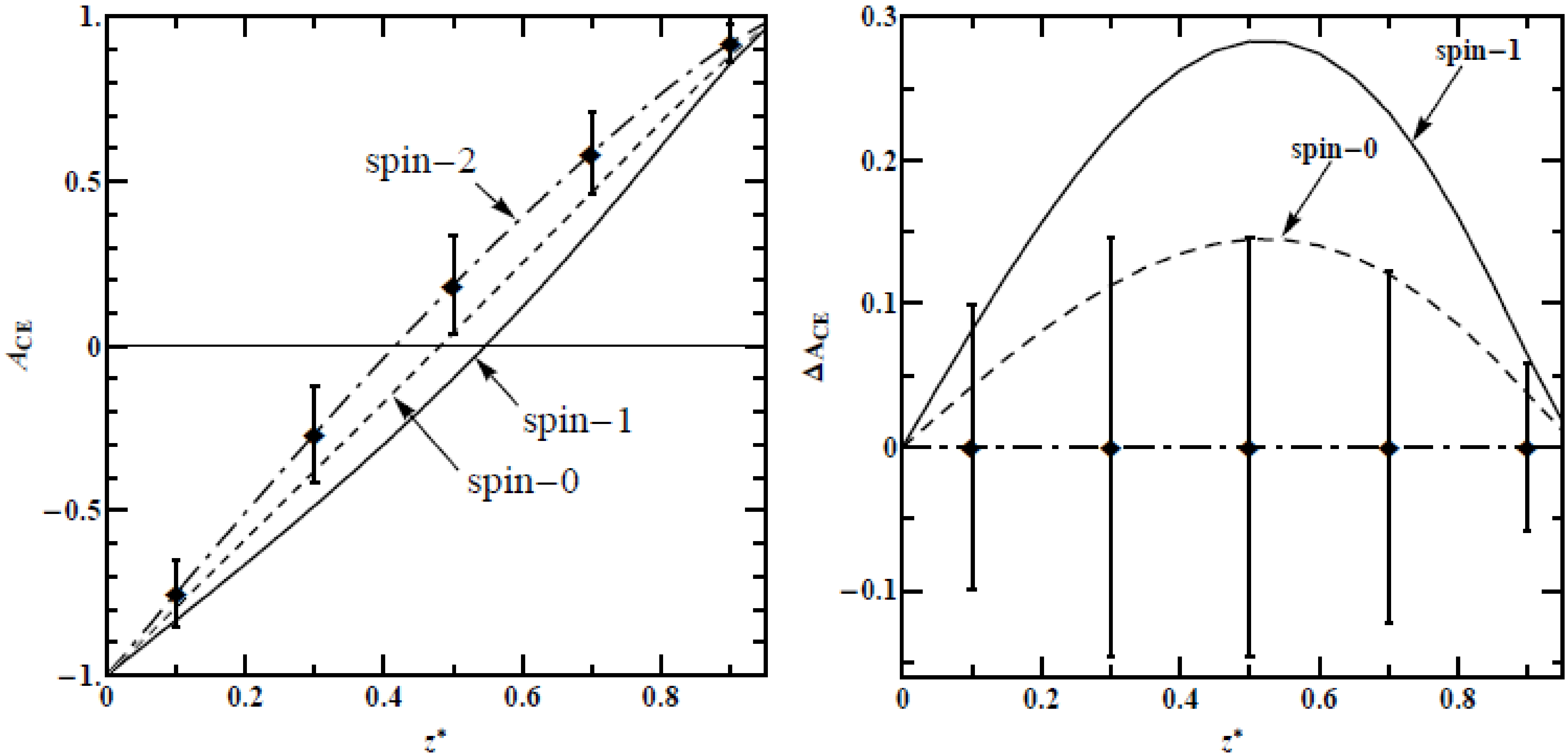
ϵ_q^G, ϵ_g^Gs and $\epsilon_q^{\rm SM}$: fractions of peak events from $q\bar{q}, gg \to G \to l^+l^-$ and SM background, respectively. $\epsilon_q^G + \epsilon_g^G + \epsilon_q^{\rm SM} = 1$.

***A_{CE}* is the same for *Z'* models and SM.**

χ^2 analysis using A_{CE}

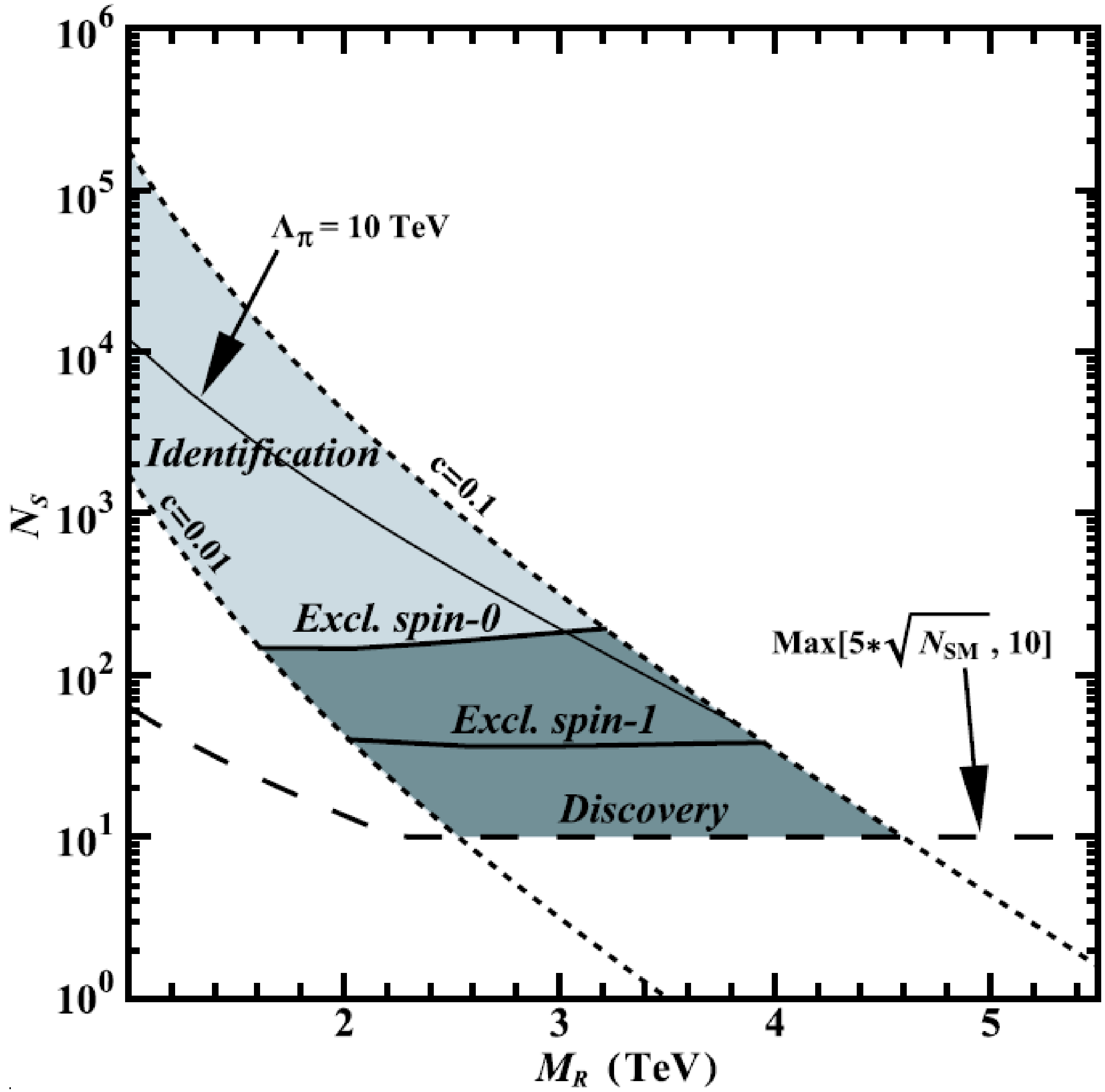
- Constraints for identification reach on spin-2:
  - Exclusion spin-0: $\Delta A_{\rm CE} = A^G_{\rm CE} - A^S_{\rm CE}$

  &
  - Exclusion spin-1: $\Delta A_{\rm CE} = A^G_{\rm CE} - A^V_{\rm CE}$
- $$\chi^2 = \left[\frac{\Delta A_{\rm CE}}{\delta A_{\rm CE}}\right]^2, \quad \delta A_{\rm CE} = \sqrt{\frac{1-(A^G_{\rm CE})^2}{\epsilon_l \mathcal{L}_{\rm int}\sigma(G_{ll})}}.$$
- Condition: $\chi^2 \geq \chi^2_{C.L.}$ => determine range in (*c*, M_G)



c = 0.01; $\boldsymbol{M_R}$ = 1.6 TeV; $\boldsymbol{L_{int}}$ = 100 fb^{-1}; same number of events;
error bars correspond to 2σ; with experimental cuts

- z*≈ 0.55 is "optimal" – and χ^2 smooth
- $\Delta A_{CE}^{spin-1} > \Delta A_{CE}^{spin-0}$ => Excl. spin-0 => Excl. spin-1

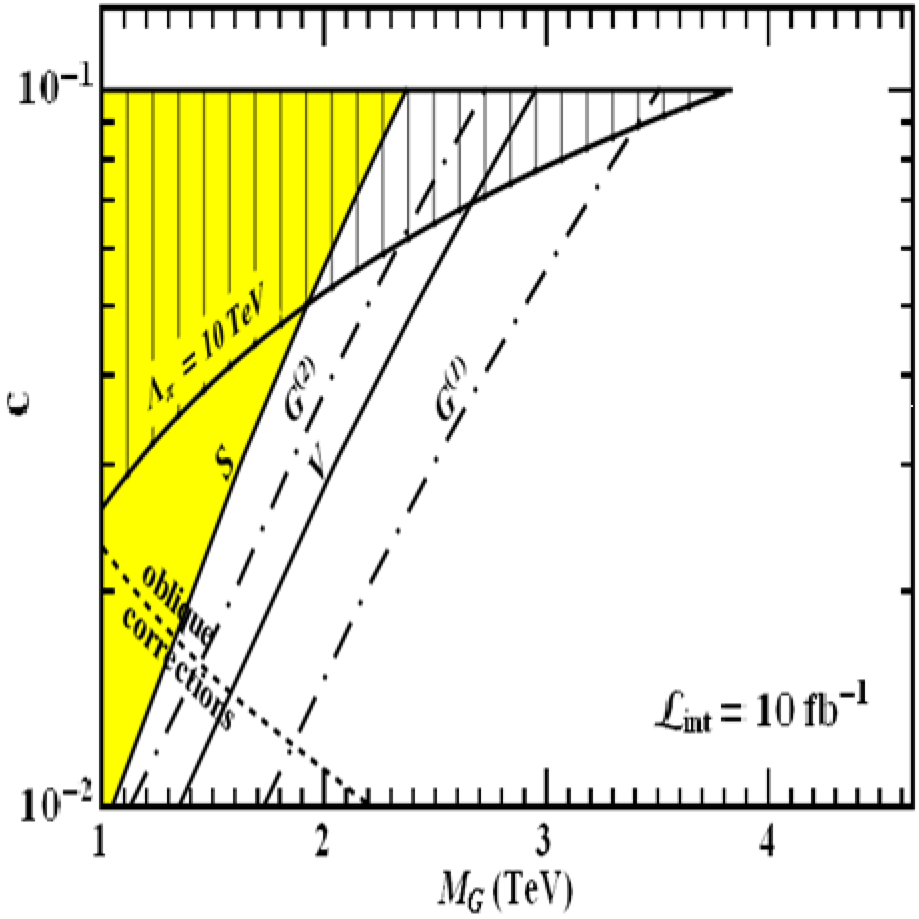


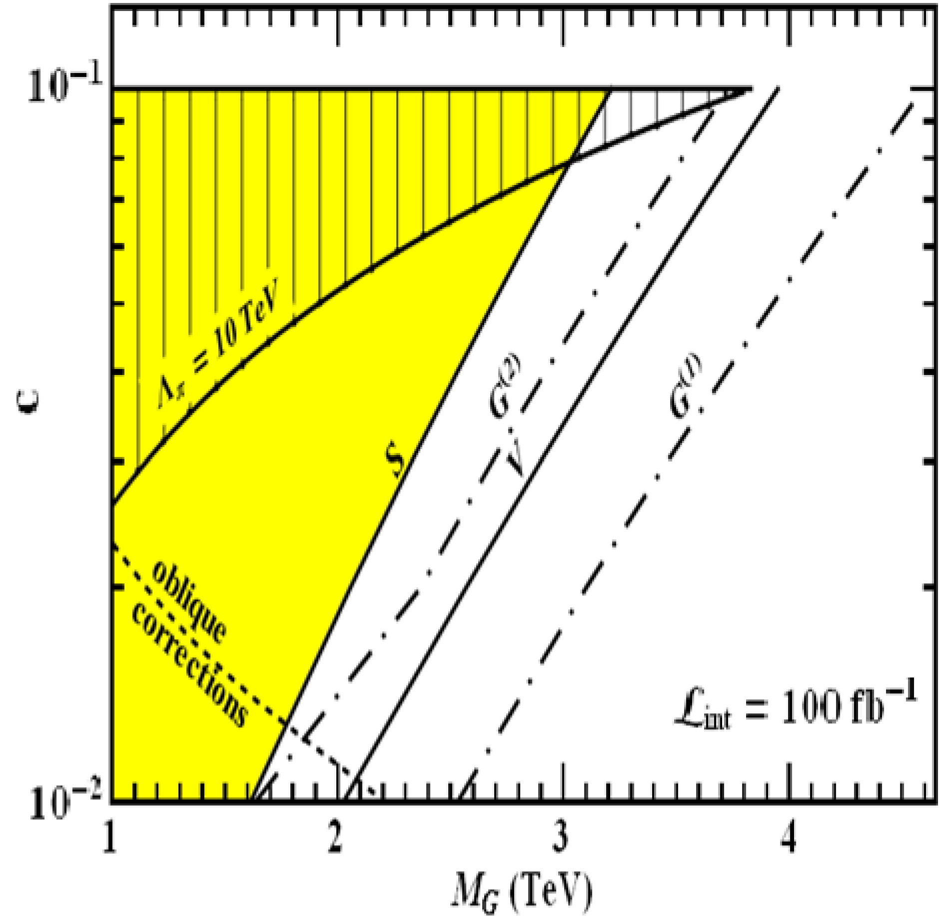
Exclusion limits and identification reach at 95% C.L. and $\mathcal{L}_{\rm int} = 100$ fb^{-1}. The channels $l = e, \mu$ are combined. The theoretically favored region, limited by the $\Lambda_\pi = 10$ TeV and $c = 0.1$ lines, is also indicated.

RS parameter plane

– domain allowing for spin-2 identification

vs. domain allowed for discovery (95% C.L.)





- Potential advantage of A_{CE}
  - "transparency" to spin-1 ***Z'*** (model independence)
  - ratio of cross sections --> minimized systematic uncertainties
  - "free" from sign ambiguity in **cosθ*** (cfr FB asymmetry)
  - Boost to CM must still be performed …
- Attempt with pseudorapidity [Diener *et al.*, 2009]

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \rightarrow \eta = -\ln\tan\left(\frac{\theta}{2}\right)$$

Then: $$\Delta\eta_{lab} = \Delta\eta^* = \ln\left(\frac{1+\cos\theta^*}{1-\cos\theta^*}\right)$$

$$\tilde{A}_{CE} = \frac{\left(\int_{-\Pi}^{\Pi} - \int_{-\infty}^{-\Pi} - \int_{\Pi}^{\infty}\right)\frac{d\sigma}{d\Delta\eta}d\Delta\eta}{\int_{-\infty}^{\infty}\frac{d\sigma}{d\Delta\eta}d\Delta\eta}$$

TABLE I: $\tilde{A}_{CE}$ values with corresponding statistical uncertainties for 100 fb^{-1} integrated luminosity, $p_{T_l} > 20$ GeV, $|\eta_l| < 2.5$, within one bin $\Delta M_{l^+l^-} = 42.9$ GeV and $M_R = 1.5$ TeV. Also shown are the expected number of total events for each model assuming 100 fb^{-1} integrated luminosity.

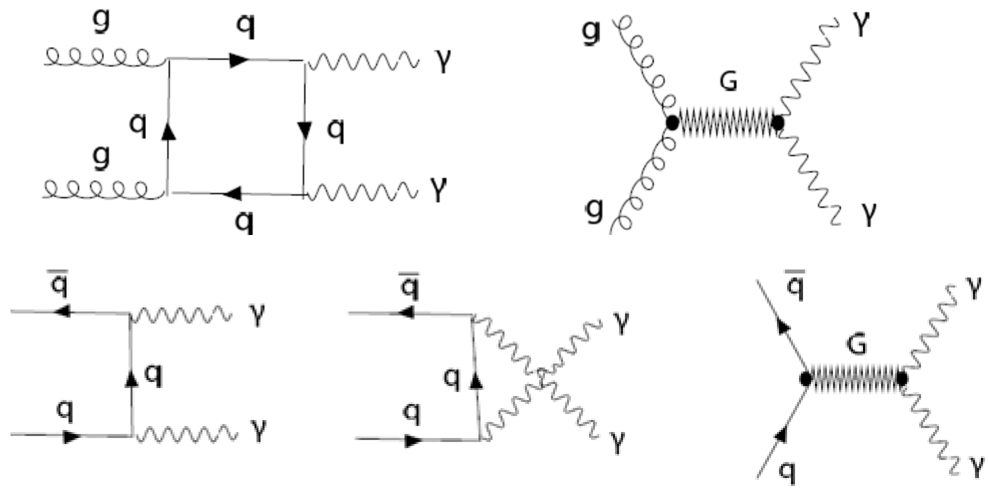
Model	$\tilde{A}_{CE} \pm \delta\tilde{A}_{CE}$	N Events
$E_6\ \chi$	-0.106 ± 0.017	3875
$E_6\ \psi$	-0.095 ± 0.022	2223
$E_6\ \eta$	-0.092 ± 0.021	2480
LR Symmetric	-0.099 ± 0.018	3350
Sequential SM	-0.097 ± 0.016	4162
Littlest Higgs	-0.095 ± 0.001	6217
Simplest Little Higgs	-0.094 ± 0.017	3542
RS Graviton	$+0.228 \pm 0.011$	8208
R-parity violating $\tilde{\nu}$	$+0.055 \pm 0.066$	251

$p+p \to G \to \gamma\gamma$ (work in progress)

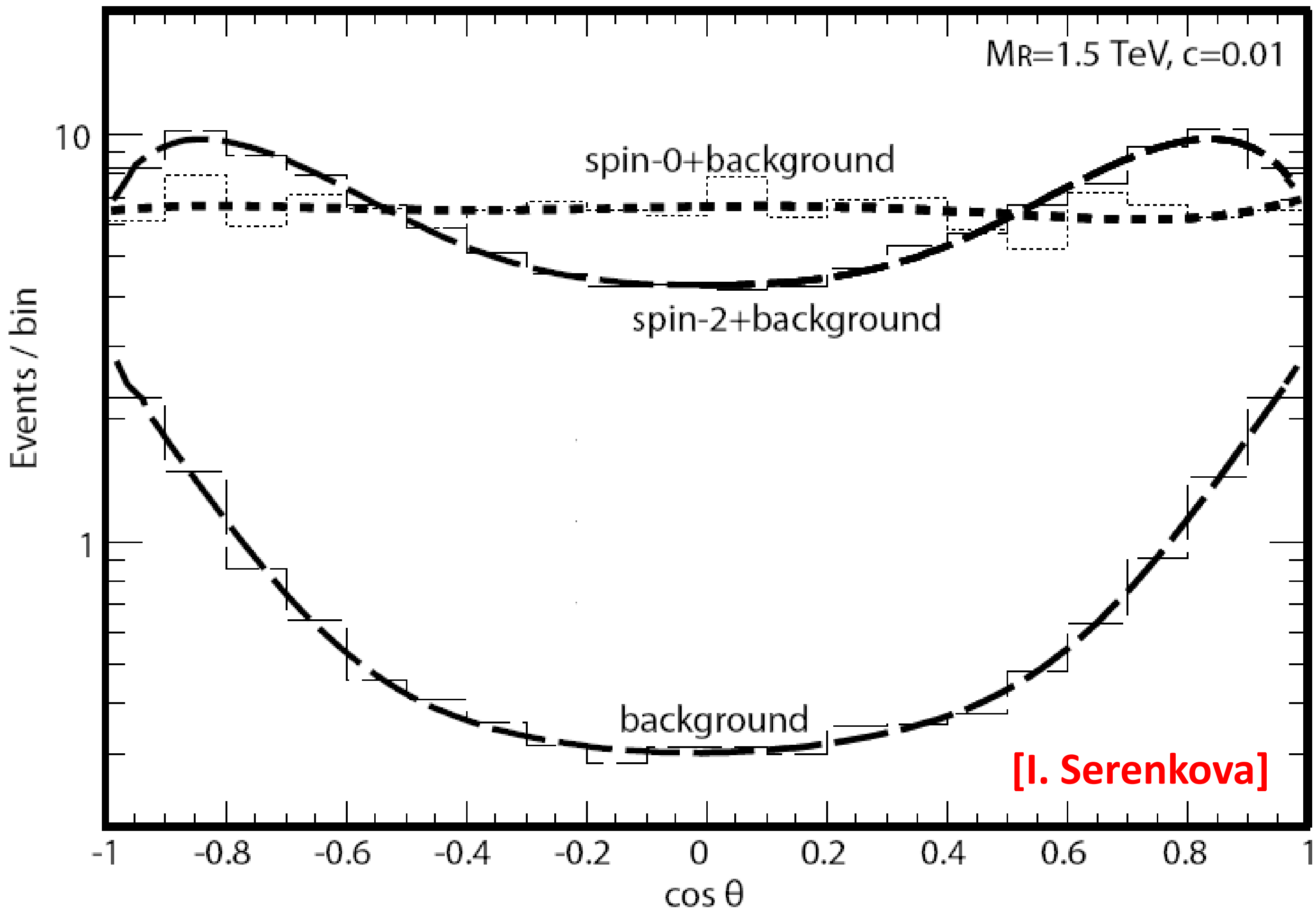
- $V \not\to \gamma\gamma$ excludes spin-1: $\dfrac{G \to \gamma\gamma}{G \to l^+l^-} \sim 2$ – <u>predicted</u> => strong test
  (Randall – Wise)

- Can exclude spin-0? ***A**$_{CE}$*–based analysis applicable.

z = cosθ*



- $g\,g \to G \to \gamma\gamma \;\propto\; 1+6z^2+4z^4$: dominant, peaked at **z = ±1**
- $q\,\bar{q} \to G \to \gamma\gamma \;\propto\; 1-z^4$
- Potential background from initial brehmsstrahlung – not for M_G ~ TeV



Angular distribution of photons in the diphoton c.m. system for spin-2 graviton resonant production in the RS model with c=0.01; spin-0 resonant production, and prompt photon background. We take M_R = 1.5 TeV. The spin-0 distribution is normalized so that the total number of events is the same for the graviton and the scalar.

Results for spin-2 identification

- Discovery reach [5σ] and spin-2 identification reach on lowest RS graviton from ACE analysis (95% CL)

	Discovery		Identification	
L_{int}	c=0.01	c=0.1	c=0.01	c=0.1
10 fb^{-1}	1.7 TeV	3.5 TeV	1.1 TeV	2.4 TeV
100 fb^{-1}	2.5 TeV	4.6 TeV	1.6 TeV	3.2 TeV

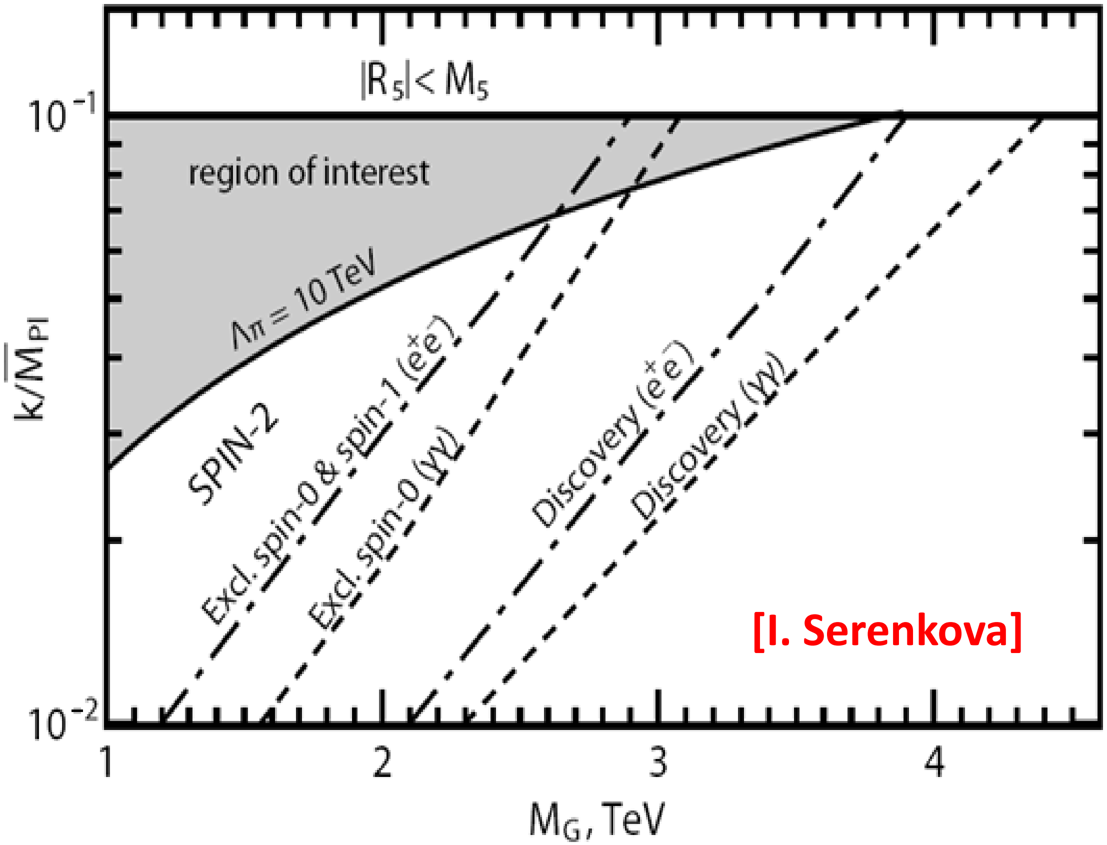
- Allowed region for discovery substantially reduced by spin-0 and spin-1 rejection
- Dramatic restriction from Λ_π < 10 TeV (order of magnitude)

- Discovery of $G^{(n=2)}$ in addition to lowest $G^{(n=1)}$:

Feasible (5σ) for M_G=

L_{int}	c=0.01	c=0.1
10 fb^{-1}	1.1 TeV	2.7 TeV
100 fb^{-1}	1.6 TeV	3.7 TeV

- Recall $\frac{M_2}{M_1} = \frac{x_2}{x_1}$ predicted.
- Relevant (c, M_G) pairs always stay within the spin-0 (=> spin-1) rejection domain.
- RS resonance doubly clinched: spin-2 from angular analysis & mass spectrum.



Experimental cuts:

Detector response has been taken into account: the photons considered are the two isolated highest transverse momentum photons with $|\eta| \leq 2.4$ and $p_T \geq 40$ GeV.

Discovery limits and identification reaches on the spin-2 graviton parameters in the plane (***M$_G$***, ***c***), using the **γγ** and ***e$^+$e$^-$*** production cross sections and ***A$_{CE}$*** at the LHC with L_{int}=100 fb^{-1}. *Discovery* – 5σ. *Exclusion* – rejection of the spin-0 hypothesis with **γγ** channel and rejection of both spin-1 and spin-0 hypotheses with ***e$^+$e$^-$*** channel at 95% C.L. Both of them determine the regions lying above the corresponding curves and marked as spin-2 that correspond to the identification of spin-2 RS graviton. The theoretically favored region, Λ_π < 10 TeV (shaded), is also indicated.

[CMS PAS EXO-09-009]

(γγ)

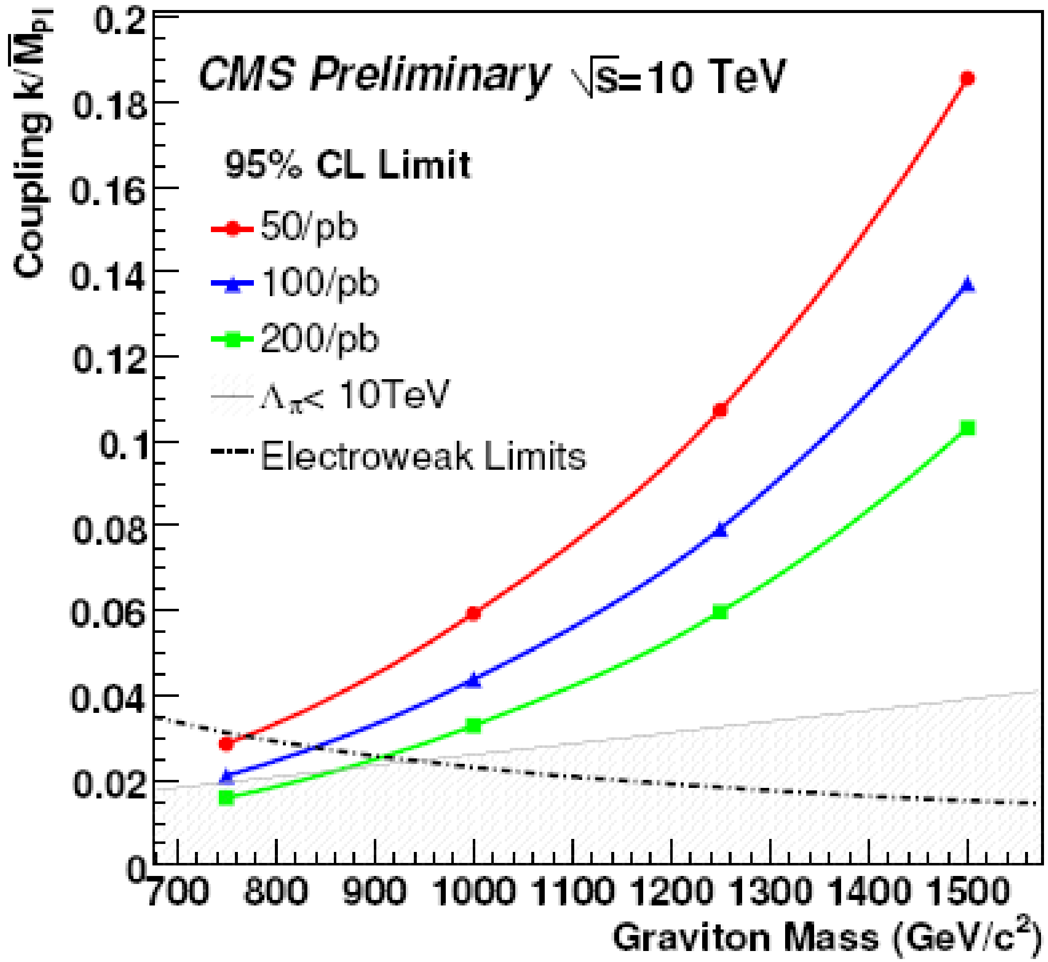


Figure 3: Limit on RS parameters $(M_1, \tilde{k})$, extrapolated from the results of the large ED diphoton search for 100/pb. The area to the left of the curves is excluded. The gray shaded region shows the area excluded for $\Lambda_\pi < 10\,\mathrm{TeV/c^2}$. The area below the dash-dotted line is excluded by precision electroweak data [11].

Radion phenomenology

- 4D massless scalar: $ds^2 = e^{-2k|y|T(x)} g_{\mu\nu}(x)\, dx^\mu\, dx^\nu + (T(x))^2\, dy^2$
- Ruled out (tests of general relativity) & R must be stabilized

- Massive scalar field Φ in the bulk with VEV and "brane" conditions **(Goldberger – Wise)**

$\Rightarrow$ minimum of potential at ***y* = *πR* ≈ 10** (stable 2-brane set-up)

On the TeV brane:

"warped" Planck mass

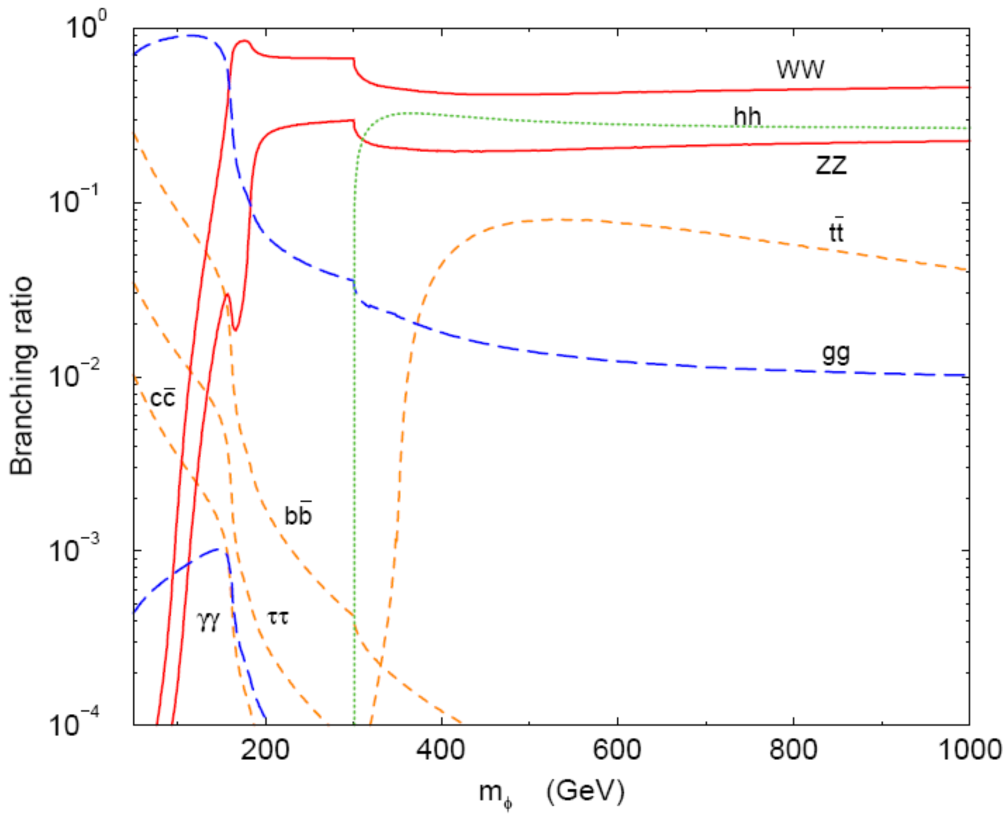
- $m_\Phi \sim \varepsilon \frac{1}{\sqrt{kR}} M_{Pl} e^{-\pi kR} \equiv \varepsilon \frac{\Lambda_\pi}{\sqrt{kR}} \sim \text{TeV}$, but $m_\Phi < G_1(KK)$!

$\text{"back reaction"}, \ \varepsilon \leq 1$

- Lightest mode in RS1, most important excitation to study at LHC?
- Interaction with SM fields: $\mathfrak{L} \sim \frac{1}{\sqrt{6}\Lambda_\pi} \Phi T_\mu^{\ \mu} \equiv \frac{1}{\Lambda_\Phi} \Phi T_\mu^{\ \mu}$
- Λ_Φ new scale at ~ TeV, roughly $\frac{\Lambda_\Phi}{4\pi} < m_\Phi < \Lambda_\Phi$

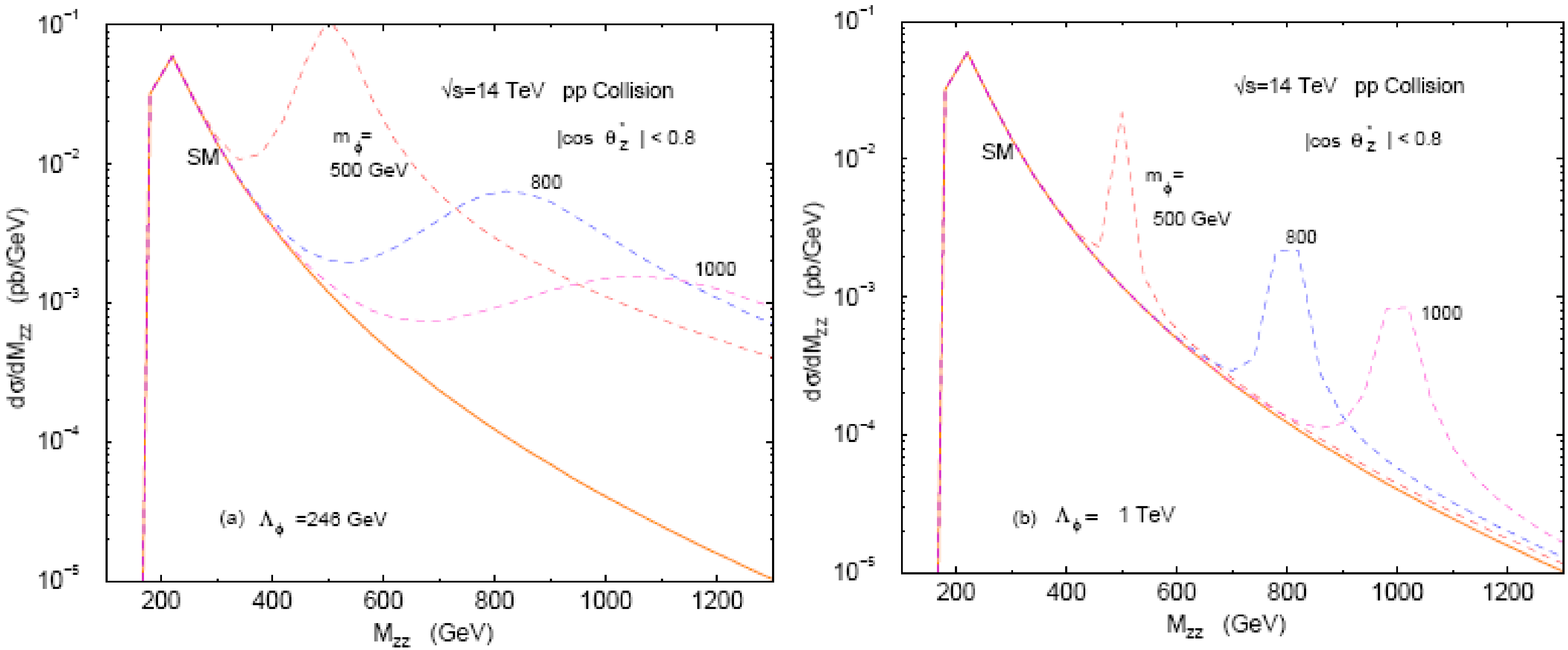
- Similar couplings as SM Higgs (scale factor $\frac{v_{SM}}{\Lambda_\Phi}$)
- Except $g_{\Phi\to gg}$ >> $g_{H\to gg}$ (loop & trace anomaly)

- Φ ←→ H interference for lower m_Φ → accompanies Higgs searches



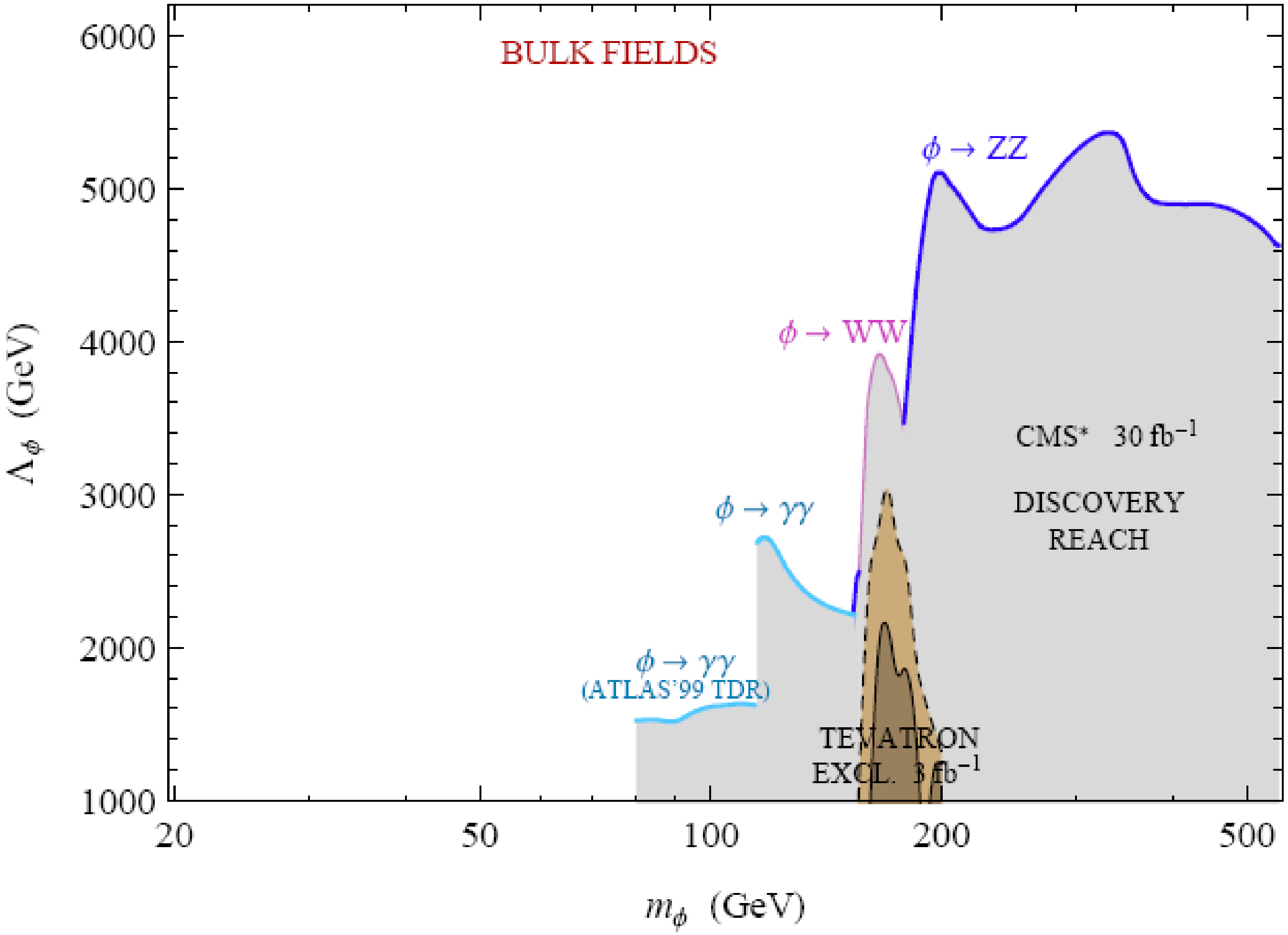
Branching ratios of the radion versus m_Φ. (m_H = 150 GeV.) **[K. Cheung , arXiv:hep-ph/0009232]**

Expected scenario at the LHC



Invariant mass distribution $d\sigma/dM_{ZZ}$ for the radion signal with m_Φ = 500, 800, 1000 GeV and the SM background $q\ qbar \rightarrow Z\ Z$ at the LHC, for (a) Λ_Φ = 246 GeV and (b) Λ_Φ = 1 TeV. A cut of | cos θ^*_Z| < 0.8 is imposed.

[K. Cheung , arXiv:hep-ph/0009232]



LHC discovery reach for the radion using "translated" Higgs projections from CMS (and ATLAS in the lower mass region) for 30 fb^{-1} of luminosity.
[P. Nath et al., arXiv:1001.2693v1 [hep-ph]]