A 750 GeV spin-2 resonance?

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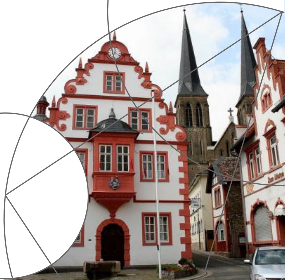
Composite Dynamics: from Lattice to the LHC Run II

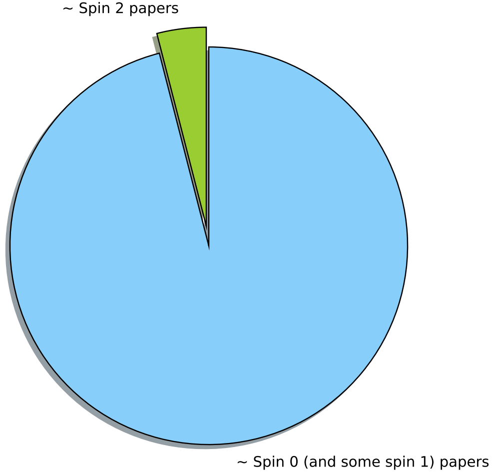


A (preliminary) bunch of questions

- What do the data say? Does it prefer spin-0 or 2?
- Is it possible to expect such a light spin-2 resonance?
- What would be the typical spectrum? What is the interplay with other resonances?
- Can the spin-2 guy be the lightest?
- What is the validity of the EFT?

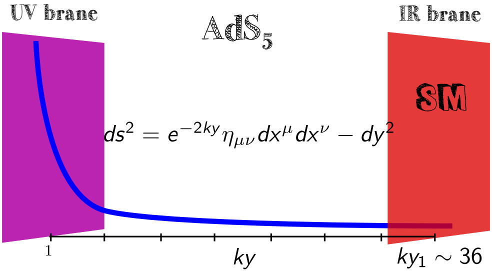
A sloppy sociological overview

Assuming a total of 250 papers on the di-photon excess



What do the data say?

ATLAS and CMS looked for what they call a 'RS graviton'. It is based on the original RS1, where the whole SM was localized at the IR brane



In practice, they look for a spin-2 resonance with universal dim-5 couplings to the SM

$$\mathcal{L} \supset \frac{1}{\Lambda_\pi} T^{\mu\nu} h_{\mu\nu}, \quad \Lambda_\pi = e^{-ky_1}\bar{M}_{\rm Pl}, \quad T_{\mu\nu} = -\frac{2}{\sqrt{g}}\frac{\delta(\sqrt{g}\mathcal{L})}{\delta g^{\mu\nu}} = -2\frac{\delta\mathcal{L}}{\delta g^{\mu\nu}} + g_{\mu\nu}\mathcal{L}$$

What do the data say?

In ATLAS analysis, we find

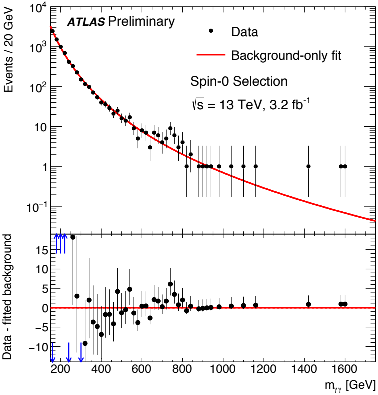
- A search for a narrow resonance $\Gamma_h \sim 1.5(k/\bar{M}_{\rm Pl})^2 m_h \sim 10\,\text{GeV}$
- Looser selection cuts (RS graviton decays to more forward photons) $E_T > 55\,\text{GeV}$ (vs $E_T > 0.4(0.3)\,m_{\gamma\gamma}$ for the spin-0)
- Same photon identification and event pre-selection criteria
- Different mass range searches $500\,\text{GeV} \leq m_h \leq 3500\,\text{GeV}$ (vs $200\,\text{GeV} \leq m_S \leq 2000\,\text{GeV}$), leading to $5\% - 35\%$ uncertaintity in the modelling of the background $m_{\gamma\gamma}$ distribution

What do the data say?

Results

SPIN-0 ANALYSIS

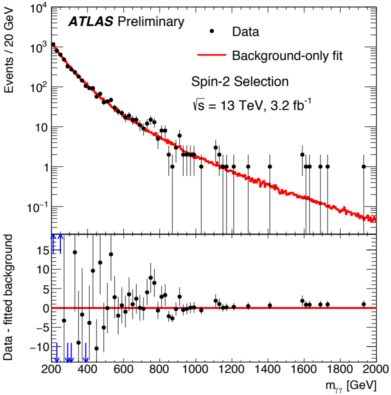
background-only fit



2878 events ($m_{\gamma\gamma}$ > 200 GeV)

SPIN-2 ANALYSIS

background-only fit

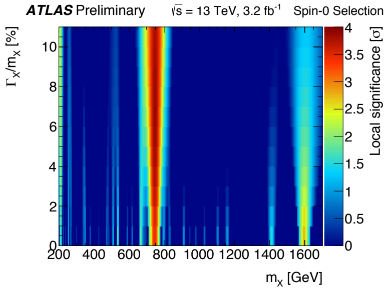


5066 events ($m_{\gamma\gamma}$ > 200 GeV)

What do the data say?

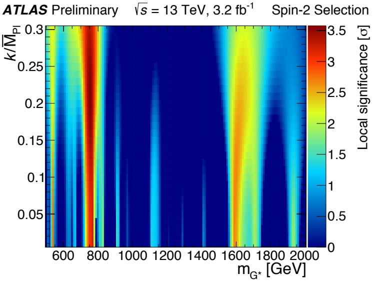
Results

SPIN-0 ANALYSIS



- Largest deviation from B-only hypothesis
  - ✓ m_X ~ 750 GeV, Γ_X ~ 45 GeV (6%)
  - ✓ Local Z = **3.9 σ**
  - ✓ Global Z = **2.0 σ**
    - m_X = [200 GeV - 2 TeV]
    - Γ_X/m_X = [1% - 10%]

SPIN-2 ANALYSIS

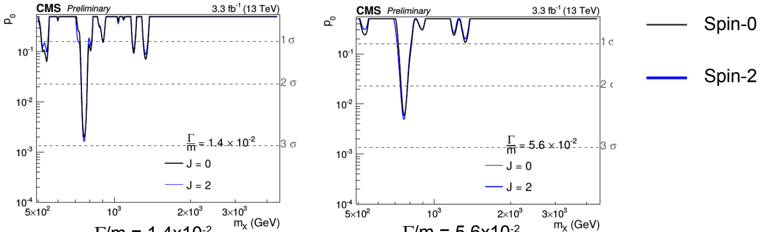


- Largest deviation from B-only hypothesis
  - ✓ m_G ~ 750 GeV, κ/M_{Pl} ~ 0.2 (Γ_G ~ 6% m_G)
  - ✓ Local Z = **3.6 σ**
  - ✓ Global Z = **1.8 σ**
    - m_X = [500 GeV – 3.5 TeV]
    - κ/M_{Pl} = [0.01 – 0.3]

What do the data say?

p-values

- Largest excess observed for **m_X = 760GeV** and **Γ/m = 1.4x10^{-2}**.
  - **Local** significance: **2.8-2.9σ** depending on the spin hypothesis.
  - Similar significance for narrow-width hypothesis.
  - **Trial factors** estimated from **sampling distribution** of max(p_0), taking into account all the 6 signal hypotheses (spin and width).
  - **"Global"** significance **< 1σ**.



Γ/m = 1.4x10^{-2} Γ/m = 5.6x10^{-2}

What do the data say?

One could consider more general couplings

[Panico, Vecchi, Vulzer, arXiv:1603.04248]

$$\begin{aligned}\mathcal{L}^{(J=2)} &= \mathcal{R}_{\mu\nu}\left[\frac{a_2^{g/\gamma}}{M}F^{\mu\alpha}F^{\nu}_{\alpha} - \sqrt{6}\frac{a_0^{g/\gamma}}{M^3}\partial^\mu F_{\alpha\beta}\partial^\nu F^{\alpha\beta} + \sqrt{6}\frac{\widetilde{a}_0^{g/\gamma}}{M^3}\partial^\mu F_{\alpha\beta}\partial^\nu \widetilde{F}^{\alpha\beta}\right] \\ &+ \mathcal{R}_{\mu\nu}\left[\frac{a_1^q}{M}i\overline{q}\left(\frac{1+\gamma^5}{2}\right)\gamma^\mu\partial^\nu q + \frac{a_{-1}^q}{M}i\overline{q}\left(\frac{1-\gamma^5}{2}\right)\gamma^\mu\partial^\nu q + \text{h.c.}\right] \\ &+ \mathcal{R}_{\mu\nu}\left[-4\sqrt{\frac{3}{2}}\frac{a_0^q}{M}\partial^\mu\overline{q}\partial^\nu q + 4\sqrt{\frac{3}{2}}\frac{\widetilde{a}_0^q}{M}i\partial^\mu\overline{q}\gamma^5\partial^\nu q\right],\end{aligned}$$

For a gg initiated process,

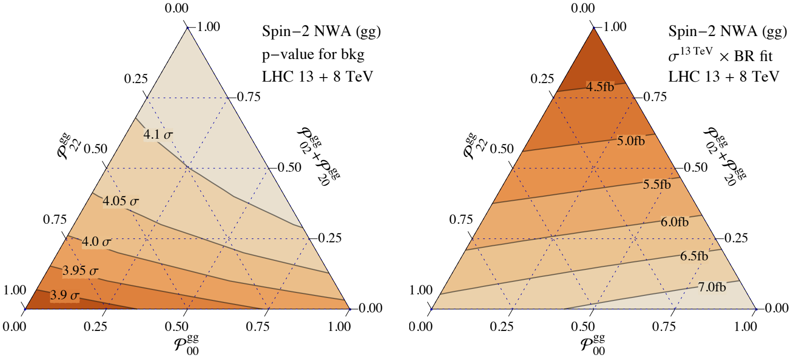
$$\frac{d\bar{\sigma}}{d\cos\theta} \propto \mathcal{D}^{(2)}_{0,0}\mathcal{P}_{00} + \mathcal{D}^{(2)}_{0,2}(\mathcal{P}_{02}+\mathcal{P}_{20}) + \mathcal{D}^{(2)}_{2,2}\mathcal{P}_{22}$$

In the RS1 case, $1/M^3 \ll 1/M$, $a_2^{g/\gamma} = a_1^q = a_{-1}^q$ and $a_0^q = \tilde{a}_0^q = 0$, leading to

$$\mathcal{P}_{22} = 1 \quad \text{and} \quad \mathcal{P}_{02}+\mathcal{P}_{20} = 0 = \mathcal{P}_{00}$$

What do the data say?

[Panico, Vecchi, Vulzer, arXiv:1603.04248]

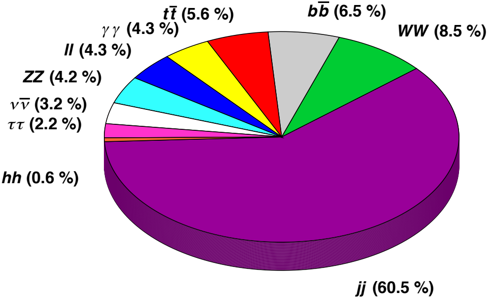


A case study

A spin-2 resonance from WED

The RS1 graviton faces a strong tension with di-lepton searches since $\mathcal{B}(h \to \gamma\gamma) = \mathcal{B}(h \to \ell\ell) \sim 4.3\%$ and thus

$$\sigma(pp \to h \to \ell^+\ell^-) \sim 5(1)\,\text{fb} \quad \text{@LHC13(8)}$$

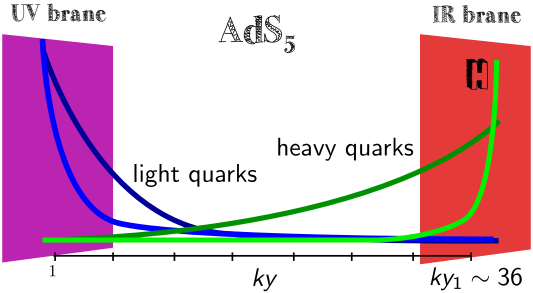


[Giddings, Zhang, arXiv:1602.02793]

A case study

A spin-2 resonance from WED

If one considers more 'realistic' scenarios, trying to address the flavor puzzle



we will not longer have universal couplings to the stress-energy tensor.

A case study

A spin-2 resonance from WED

In this case, the interactions of the first KK graviton with the SM are given by

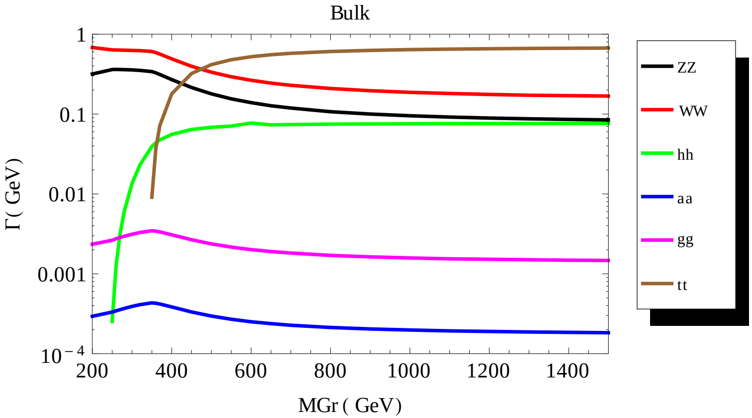
XX	$T^{\mu\nu}_{XX}$	c_{XXG}
ss	$\frac{1}{2}\partial^\mu\phi\partial^\nu\phi$	$\frac{2}{(\bar{M}_{\rm Pl}/k)ke^{-ky_1}}$
$f\bar{f}$	$i\psi^\dagger\bar{\sigma}^\mu D^\nu\psi$	$\frac{1}{(\bar{M}_{\rm Pl}/k)ke^{-ky_1}}\left(\frac{1+2\nu}{1-e^{-ky_1(1+2\nu)}}\right)\frac{\int_0^1 dy\ \ y^{2+2\nu}J_2(3.83y)}{J_2(3.83)}$
$t\bar{t}_1$	$i\psi^\dagger\bar{\sigma}^\mu D^\nu\psi$	$\frac{1}{(\bar{M}_{\rm Pl}/k)ke^{-ky_1}}\sqrt{\frac{2(1+2\nu)}{1-\epsilon^{1+2\nu}}}\int_0^1 dyy^{\nu+5/2}\frac{J_{\nu-1/2}(x_1^R y)}{J_{\nu-1/2}(x_1^R)}\frac{J_2(3.83y)}{\lvert J_2(3.83)\rvert}$
gg	$F^{\mu\rho}F^\nu_{\ \rho}$	$\frac{1}{ky_1(\bar{M}_{\rm Pl}/k)ke^{-ky_1}}\frac{\int_0^1 dy\ \ yJ_2(3.83y)}{J_2(3.83)}\approx\frac{0.47}{ky_1(\bar{M}_{\rm Pl}/k)ke^{-ky_1}}$

[Fitzpatrick, Kaplan, Randall, Wang '08]

A case study

A spin-2 resonance from WED

However, the BRs to gg and $\gamma\gamma$ become really small!



[Oliveira arXiv:1404.0102]

A case study

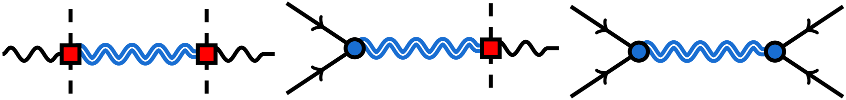
A spin-2 resonance from WED

In addition, a priori, we have $m_h/m_\rho \approx 1.5$ and therefore $m_\rho \approx 500\,\text{GeV}$.

However

$$\hat{T} \sim [\hat{\alpha} - 2\hat{\beta} + \hat{\gamma}], \qquad \hat{S} \sim [-\hat{\beta} + \hat{\gamma}], \qquad W = Y \sim \hat{\gamma}$$

where



$\hat{\alpha}$ $\qquad$ $\hat{\beta}$ $\qquad$ $\hat{\gamma}$

and ■ $\sim \sqrt{ky_1}$, ● $\sim 1/\sqrt{ky_1}$, $\quad \hat{T} \sim ky_1$, $\quad \hat{S} \sim 1$, $\quad W = Y \sim 1/ky_1$

We need therefore at least $m_\rho > 2 - 3\,\text{TeV}$

A case study

A spin-2 resonance from WED

Concilliating a 750 GeV graviton with $m_\rho \sim 3\,\text{TeV} \gg m_h$ requires large kinetic terms for the graviton and large values of k/M_5, but ...

- In principle, k/M_5 should be $\lesssim 1$ in order to keep perturbativity in the 5D gravity theory
- Moderately large kinetics term for the graviton can lead to a radion ghost!

A case study

A spin-2 resonance from WED

Another possibility is that the WED is parametrizing a strongly interacting dark sector, with elementary Higgs and elementary fermions
e.g. [AC, Chala, arXiv:1504.00332]

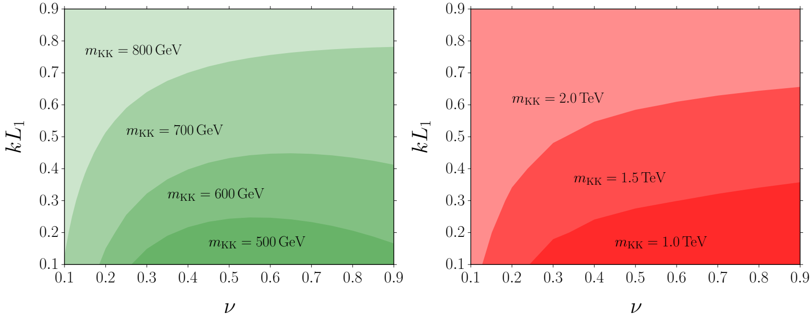
In this case, only gauge bosons propagate into the Xdim and

- We obtain much larger BRs for gg and $\gamma\gamma$
- Since $\hat{T} = 0 = \hat{S}$, EWPT allow much lighter vector resonances
- Since DM and the vector resonances arise for the strong sector, EW vector resonances decay most of the time to invisible
- Heavy color octets are mostly probed by dijet searches

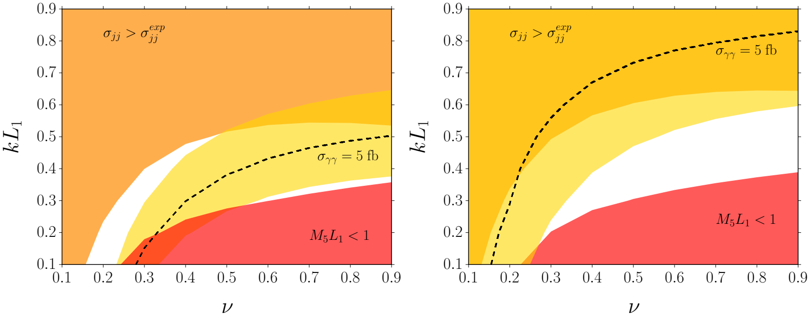
[AC, arXiv:1603.08913]

Back-up Slides

A 750 GeV graviton from an holographic dark sector



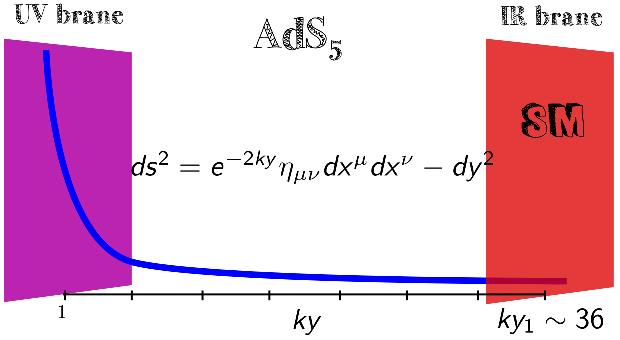
A 750 GeV graviton from an holographic dark sector



Models with Warped Extra Dimensions

Models with WED provide a solution to the gauge hierarchy problem by red-shifting the fundamental scale of the theory $\mathcal{O}(M_{\text{Planck}})$ to $\mathcal{O}(\text{TeV})$

[Randall, Sundrum '99]

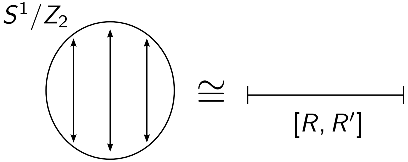


Models with Warped Extra Dimensions

They can also provide a "solution" to the flavor puzzle if fermions and gauge bosons are allowed to propagate through the extra dimension [Grossman, Neubert '99] [Gherghetta, Pomarol '00]

1. 5D fermions $\psi(x,z)$ are vector-like and a bulk mass is allowed

2. We can still get a 4D chiral spectrum



$$\psi_L(x,-\phi) = Z\psi_L(x,\phi) \qquad Z^2 = 1$$

$$\psi_L(x,R^{(\prime)}) = 0 \quad \partial_z\psi_L(x,R^{(\prime)}) = 0$$

After KK decomposition, we can have a chiral massless state

$$\psi_L(x,z) = f_L^{(0)}(z)\psi_L^{(0)}(x) + \sum_{n=1}^{\infty} f_L^{(n)}(z)\psi_L^{(n)}(x)$$

Models with Warped Extra Dimensions

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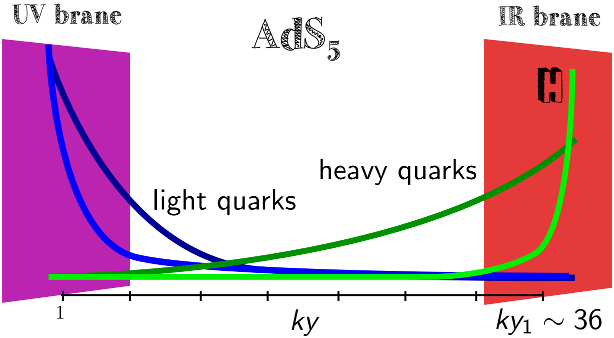
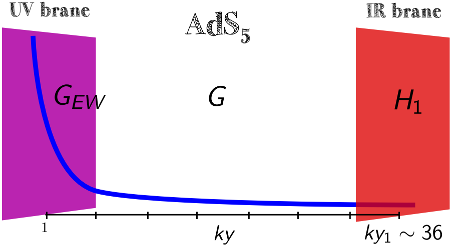
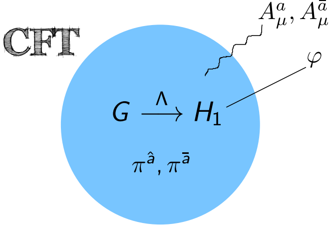


Models with Warped Extra Dimensions

They can provide a calculable framework for models of strong dynamics like Composite Higgs Models via the AdS/CFT correspondance

[Agashe, Contino, Pomarol '04]





- Bulk gauge group G
- H_1 at the IR brane
- G_{EW} at the UV

- Global symmetry group G
- $G \to H_1$ breaking at $\mathcal{O}(\text{TeV})$
- Weakly gauge of G_{EW}