Search for BSM physics in monophoton final states with CMS data at $\sqrt{s} = 8$ TeV

CMS PAS EXO-12-047, arXiv:1410:8812

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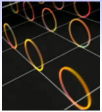
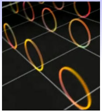
Outline



Motivations

1 - Motivations



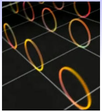
Motivations

ADD model

Large extra dimensions ($\approx$ mm) can address the hierarchy problem and be searched in particle physics experiments.

ADD model description : [Arkani-Hamed , Dimopoulos and Dvali (1998)]

- Introduction of n extra compact (typically on torus of size R) extra dimensions in which only gravity can propagate
- If two test masses are separated by $r \gg R$, gravitational potential is $V(r) = \frac{m_1 m_2}{M_D^{n+2} R^n} \frac{1}{r}$ with Planck mass $M_P^2 = M_D^{n+2} R^n$
- Signature in particle physics colliders : possible production of a graviton G escaping detection
- Monophoton signature possible : $pp \to \gamma G$



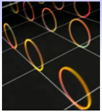
Motivations

Branon model

The Branon is a scalar field introduced to account for the fluctuations of our 4D brane into a D-dimensional space.

Properties : [Dobado & Maroto (2000), Cembranos et al. (2001)]

- Effective low-energy theory
- Massive scalar field... dark matter candidate ?
- Couplings with Standard Model ⇒ possible search at LHC !
- Complementary to the ADD model



Motivations

Branon model

Geometric setup :

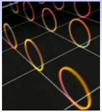
- gravity propagating in the $\mathcal{M}_D$ bulk space with fondamental energy scale M_D (Planck mass with D dimensions)
- SM fields living only in the 4D brane $\mathcal{M}_4$

ADD approach : [Arkani-Hamed, Dimopulos & Dvali (1998)]

- brane position is **fixed** in the $\mathcal{M}_D$ bulk : $Y^M(x) = (x^\mu, 0)$
- produces KK gravitons

Branon approach : [Dobado & Maroto (2000), Cembranos et al. (2001)]

- brane can **fluctuate** : $Y^M(x) = (x^\mu, Y^m(x))$
- size of fluctuations f^{-1} (f=brane tension energy scale), with $f \ll M_D$



Motivations

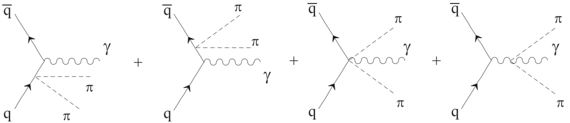
Branon signature in hadronic collider

- Branon action (Minkowski metric, weak fluctuations) :

$$\mathcal{S}_B^{(2)} \approx \int_{\mathcal{M}_4} d^4x \left[\frac{1}{2}(\delta_{\alpha\beta}\partial_\mu\pi_B^\alpha\partial^\mu\pi_B^\beta - M_{\alpha\beta}^2\pi_B^\alpha\pi_B^\beta) + \frac{1}{8f^4}(4\delta_{\alpha\beta}\partial_\mu\pi_B^\alpha\partial_\nu\pi_B^\beta - M_{\alpha\beta}^2\pi_B^\alpha\pi_B^\beta\eta_{\mu\nu})T_{SM}^{\mu\nu} \right]$$

[Alcaraz et al. (2003)]

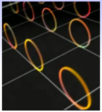
- $\gamma + \not{E}_T$ monophoton signature is possible (π_B is stable and escapes detection) :



$$\frac{d\sigma(q\bar{q} \to \gamma\pi_B\pi_B)}{dk^2 dt} = \frac{Q_q^2 \alpha N (k^2 - 4M_B{}^2)^2}{184320 f^8 \pi^2 \hat{s}^3 tu} \sqrt{1 - \frac{4M_B{}^2}{k^2}} (\hat{s}k^2 + 4tu)(2\hat{s}k^2 + t^2 + u^2)$$

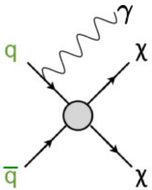
[Cembranos et al. (2004)] $\hat{s}, t, u$: Mandelstam variables, k : Branons 4-momentum sum

Two parameters to constrain : M_B and f (and N)
Search for new physics in the $\gamma + \not{E}_T$ channel



Motivations

Dark matter model



Dark matter model description :

- A Dark Matter pair production could lead to $\gamma + \not{E}_T$ final state at the LHC where γ is radiated from the initial quark.
- DM interaction can be described as higher DM operators :
  $\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$ (spin independent)
  $\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma^5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$ (spin dependent)
- Production cross section is assumed to scale with $1/\Lambda^4$

2 - Backgrounds and event selection

Event selection - I

Strategy : search for events with one high transverse momentum isolated photon and high missing transverse energy $\not{E}_T$

- Preliminary cuts (triggers, track quality, vertex quality)

Photon selection

- Kinematic cuts : $p_T^\gamma > 145\,\text{GeV}$ and $|\eta^\gamma| < 1.4$
- Isolation cuts
- EM-shower quality cuts
- No associated detection in the central pixel detector

Backgrounds and event selection

Event selection - II

$\not{E}_T$ selection

- High missing transverse energy $\not{E}_T > 140$ GeV
- Photon and $\not{E}_T$ back to back : $\Delta\phi(\gamma, \not{E}_T) > 2$
- Rejection of events with low $\not{E}_T$ resolution (MHT minimisation) to reduce contribution from fake $\not{E}_T$

Vetoes

- Lepton veto : no isolated muon or electron with $p_T^l > 10$ GeV
- Jet veto : at most one isolated non-pileup jet with $p_T^j > 30$ GeV

$\gamma + \not{E}_T$ event and backgrounds

Several SM and instrumental backgrounds can mimic a $\gamma + \not{E}_T$ final state :

- Collision backgrounds :

Process	Causes	Estimation	NLO Corr.
$Z\gamma \to \nu\bar{\nu}\gamma$	irreducible	MC	$\surd$
$W\gamma \to \nu l\gamma$	lepton out/misidentified	MC	$\surd$
$W \to e\nu$	electron faking photon	Data	
multi-jets	jets faking $\gamma + \not{E}_T$	Data	
γ+jets	jets reconstructed as $\not{E}_T$	MC	$\surd$
$\gamma\gamma$, $W \to \mu\nu$, $Z\gamma \to ll\gamma$	diverse	MC	

- Other backgrounds (estimated on data) :
  - beam halo particles
  - anomalous signals ("spikes")
  - cosmic rays

Backgrounds and event selection

Systematics

- **Photon energy scale :** 1.5% on photon energy scale translated into acceptance systematics
- **MET :** jet energy scale, jet resolutions and unclustered energy are accounted in the uncertainty on $\not{E}_T$
- **Pile-up :** 5% variation of total inelastic cross-section of 69.4 mb is propagated
- **Luminosity :** 2.6% uncertainty on luminosity

Source	Signal Branon	$Z(\nu\bar{\nu})\gamma$	$W\gamma$	$e\to\gamma$	jet$\to\gamma$	Halo	Other MC
Scale factor ρ	6.4%	6.4%	6.4%	–	–	–	6.4%
Luminosity	2.6%	2.6%	2.6%	–	–	–	2.6%
$\not{E}_T$ resolution	0.7%	0.7%	0.7%	–	–	–	0.7%
Pileup	0.3%	0.3%	0.3%	–	–	–	0.3%
Photon energy scale	2.0%(*)	3.3%(*)	4.2%(*)	–	–	–	2.0%(*)
Specific uncertainties	–	–	–	13%	30%	25%	–
K-factors (correlated)	–	11%(*)	20%(*)	–	–	–	–

Other MC = γ+jets, $W\to\mu\nu$, $Z(ll)\gamma$ and $\gamma\gamma$
(*) stands for p_T^γ-dependent systematics

Constraints on BSM models

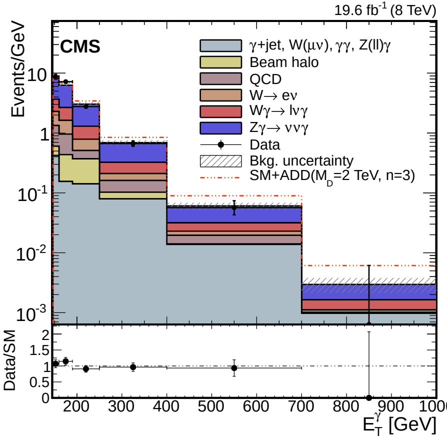
3 - Constraints on BSM models

Constraints on BSM models

Data and predictions

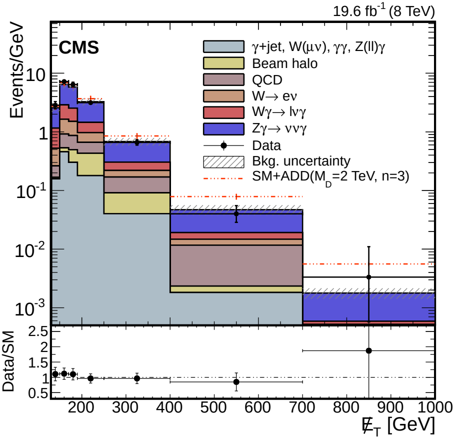
Process	Event numbers
$Z\gamma$	345 ± 43
$W\gamma$	103 ± 21
$e \to \gamma$	60 ± 6
jet$\to \gamma$	45 ± 14
Beam halo	25 ± 6
Other MC	36 ± 3
Total	**614 ± 63**
Data	**630**

Other MC = γ+jets, $W \to \mu\nu$, $Z(ll)\gamma$ and $\gamma\gamma$



Constraints on BSM models

Data and predictions

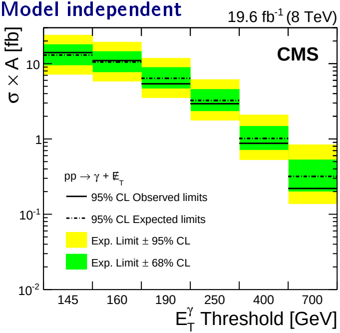


Constraints on BSM models

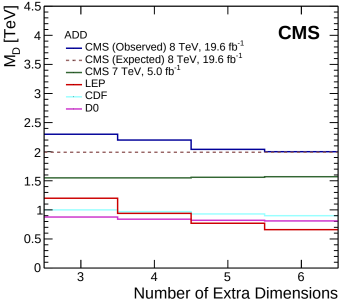
Experimental limits at 95% C.L. Model independent and ADD limits

- No indication for new physics in data
- Statistical method using the p_T^γ spectrum shapes to derive limits on BSM models

Model independent

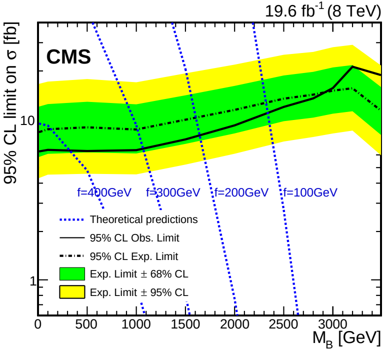


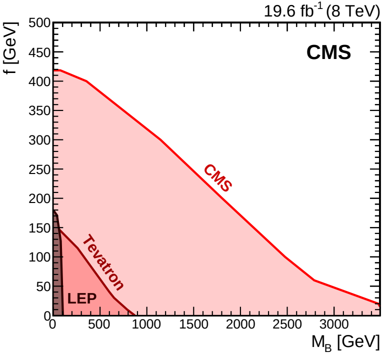
ADD



Constraints on BSM models

Experimental limits at 95% C.L. Branon



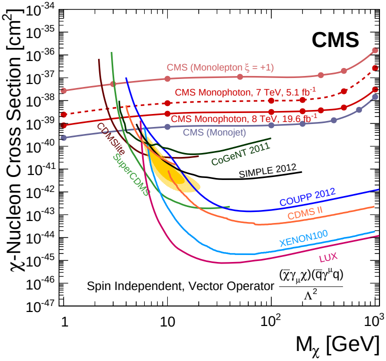


[CMS PAS EXO-12-047, arXiv :1410 :8812]

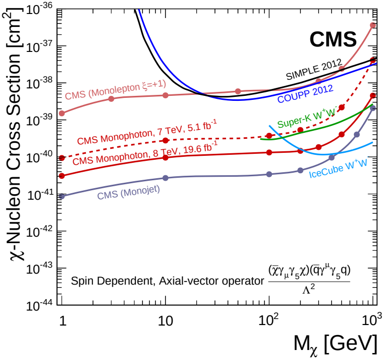
Constraints on BSM models

Experimental limits at 90% C.L. - DM

Spin independent



Spin dependent



[CMS PAS EXO-12-047, arXiv :1410 :8812]

Constraints on BSM models

Summary and conclusion

- Search for BSM physics at LHC with CMS Run-I data ($\sqrt{s} = 8\,\text{TeV}, L = 19.6\,\text{fb}^{-1}$) in the $\gamma + \not{E}_T$ channel
- No excess in p_T^γ data spectrum $\Rightarrow$ experimental limits
  - ADD : $M_D \gtrsim 2\,\text{TeV}$ for $n = 3 - 6$
  - Branon : $f \gtrsim 420\,\text{GeV}$ at low Branon mass M_B and $M_B \gtrsim 3.5\,\text{TeV}$ at low brane tension f
  - DM : limits complementary to direct searches, especially at low M_χ mass and for spin dependent interactions
  - Limits on $A \times \sigma$ published

[CMS PAS EXO-12-047 (2014), arXiv :1410 :8812]

Backup slides

Branon model

Simple case study :

1. Bulk $\mathcal{M}_5$ ($D = 5$ dimensions)
2. $\mathcal{M}_4$ brane position in $\mathcal{M}_5$ parametrized by : $Y^M = (x^\mu, Y(x))$

⇒ Break $U(1)$ translation invariance along 5^{th} dimension !

⇒ Apparition of a Goldstone boson $\pi_B = Y/f^2$ parametrizing the brane fluctuations

3. With N broken symmetries ⇒ N Branons
4. With N symmetries partially broken ⇒ N massive Branons

[Dobado & Maroto (2000), Cembranos et al. (2001)]

Branon model

Start with a simple case :

1. Space-time $\mathcal{M}_5 = \mathcal{M}_4 \times \mathcal{S}_1$ ($D = 5$ dimensions)
2. Parametrize the position of the brane $\mathcal{M}_4$: $Y^M = (x^\mu, Y(x))$

$\Rightarrow$ **spontaneously breaks $U(1)$ translation invariance along 5^{th} dimension !**

3. Simple metric on the bulk $\mathcal{M}_5$: $G_{MN} = \begin{pmatrix} \tilde{g}_{\mu\nu}(x) & 0 \\ 0 & -1 \end{pmatrix}$
4. Metric induced on the brane :

$$g_{\mu\nu} = \partial_\mu Y^M \partial_\nu Y^N G_{MN} = \tilde{g}_{\mu\nu} - \partial_\mu Y \partial_\nu Y$$

5. Low-energy effective action of Nambu-Goto :

$$S_B = -f^4 \int_{\mathcal{M}_4} d^4x \sqrt{g} \approx f^4 \int_{\mathcal{M}_4} d^4x \sqrt{\tilde{g}} + \frac{f^4}{2} \int_{\mathcal{M}_4} d^4x \sqrt{\tilde{g}} \tilde{g}^{\mu\nu} \partial_\mu Y \partial_\nu Y$$

$\Rightarrow$ **Goldstone Boson parametrizing the brane position Y(x) fluctuations**

$\Rightarrow$ **branon π !**

Branon model

More generally :

1. $n = D - 4$ extra-dimensions : $\mathcal{M}_D = \mathcal{M}_4 \times \mathcal{B}$ with isometry symmetry group $G(\mathcal{M}_D) = G(M_4) \times G(\mathcal{B})$
2. Brane position breaks spontaneously $G(\mathcal{B})$ in $H \subset G(\mathcal{B})$ subgroup : $k = dim(G) - dim(H)$ **broken generators**

$\Rightarrow$ k Goldstone Bosons fields
(excitations of the brane along the broken Killing fields)
$\Rightarrow$ k branons π^α

3. Effective action from same development of $\sqrt{g}$:

$$S_B^{(2)} \approx \frac{1}{2} \int_{\mathcal{M}_4} d^4x \sqrt{\tilde{g}} \tilde{g}^{\mu\nu} h_{\alpha\beta} \partial_\mu \pi^\alpha \partial_\nu \pi^\beta$$

[Sundrum R. 2001, Cembranos et al. 2006]

"In the brane-world scenario, with $f \ll M_D$, the relevant low-energy excitations on the brane correspond to the branons rather than to the Kaluza-Klein graviton excitations."

"In principle, **there would be new physics related to both the KK gravitons and the branons, but the dependence on f in each case is completely different. [...] The cross section for a small value of f is governed by the branon production process, while for a large value, the KK gravitons production rate dominates.** Therefore if the brane tension scale is smaller than the fundamental gravitational one, then the first indications of extra dimensions would be given by the production of branons."

J. Alcaraz, J.A.R. Cembranos, A. Dobado and A.L. Maroto
Phys.Rev.D67 :075010,2003, arXiv :hep-ph/0212269

"In fact, it has been shown that these branons or, equivalently, the brane recoil, give rise to an **exponential suppression of the couplings of the SM particles and the higher KK modes** in such a way that, in the $f \ll M_D$ regime, the most important modes at low energies are the SM particles and the branons. Moreover branons can play a role in the solution of some problems appearing when the flexibility of the brane is not taken into account such as divergent virtual contributions from the KK tower or non-unitary graviton production cross-sections."

J. Alcaraz, J.A.R. Cembranos, A. Dobado and A.L. Maroto
Phys.Rev.D67 :075010,2003, arXiv :hep-ph/0212269

Backgrounds from MC

LO MC simulations : $Z(\nu\bar{\nu})\gamma, W\gamma$, γ+jet, $\gamma\gamma, W\mu\nu, Z(ll)\gamma$

- Scale factor to account for different cut efficiencies in data and MC
$$\rho = \epsilon_{\text{Data}}/\epsilon_{\text{MC}} = 0.94 \pm 0.06$$
- Computation of p_T^γ-dependent K-factors to account for NLO corrections of $Z(\nu\bar{\nu})\gamma$ and $W\gamma$ dominant backgrounds

K-factor estimation with MCFM

- LO cross section from MC sample (generator level cuts)
- NLO cross-section from MCFM (with analysis cuts)
- central values and systematic uncertainties following PDF4LHC recommendations (uncertainties from α_s , PDF and energy scales)

$$k_{MC} = \frac{\sigma^{NLO}_{MCFM}}{\sigma_{MC}} = \begin{cases} k_{MC}(Z\gamma) & = 1.424 \pm 0.001(stat) \pm 0.133(syst) \\ k_{MC}(W\gamma) & = 1.579 \pm 0.001(stat) \pm 0.237(syst) \end{cases} \quad \text{(globally)}$$

Data-driven background estimates $e \to \gamma$, jet$\to \gamma$ and other backgrounds

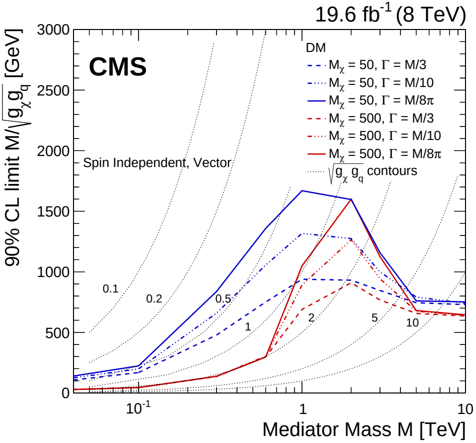
General procedure :

- Get the distribution of a cleverly chosen variable in a signal-free region relaxing a selection cut (pixel veto, EM-shower width $\sigma_{i\eta i\eta}$ or t_{seed})
  - $\Rightarrow$ distribution is enriched in background events
  - $\Rightarrow$ lever arm to estimate the studied background
- Fitting distribution templates to separate contributions from true photons and backgrounds
- Switch back the analysis selection cuts to estimate background distribution in the signal region

Results :

- Electron faking photon $e \to \gamma$: $N_{e \to \gamma} = 60 \pm 6$ events
- Jet faking photon jet$\to \gamma$: $N_{\text{jet} \to \gamma} = 45 \pm 14$ events
- Non-collision background contamination : 25 ± 6 events

Experimental limits - DM



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