Searches for Large Extra Dimensions at CMS

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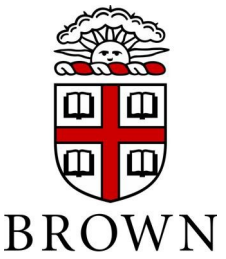
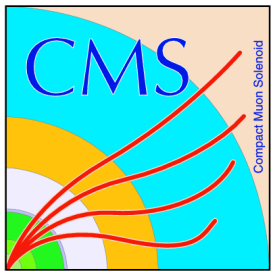
Brown University

On behalf of the CMS Collaboration





Meeting of the Division of Particles and Fields of the APS

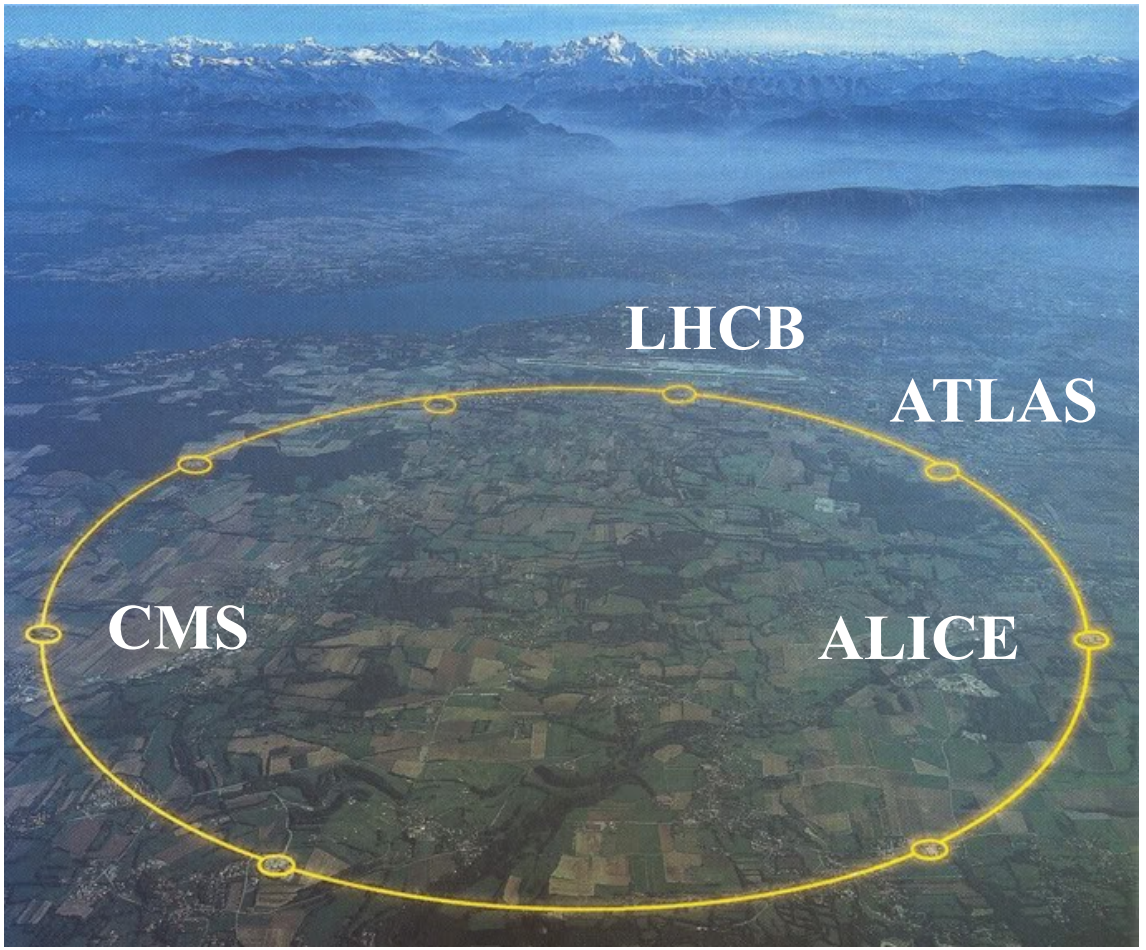
Brown University, Providence, RI,

August 9 - 13th, 2011

Outline

- **Large Hadron Collider (LHC) and Compact Muon Solenoid (CMS)**
- **Theoretical introduction**
- **Searches for Large Extra Dimensions (LED) at CMS:**
  - LED and Randall-Sundrum gravitons in diphoton final state
  - LED in dimuon final state
  - Microscopic black holes
- **Conclusions**

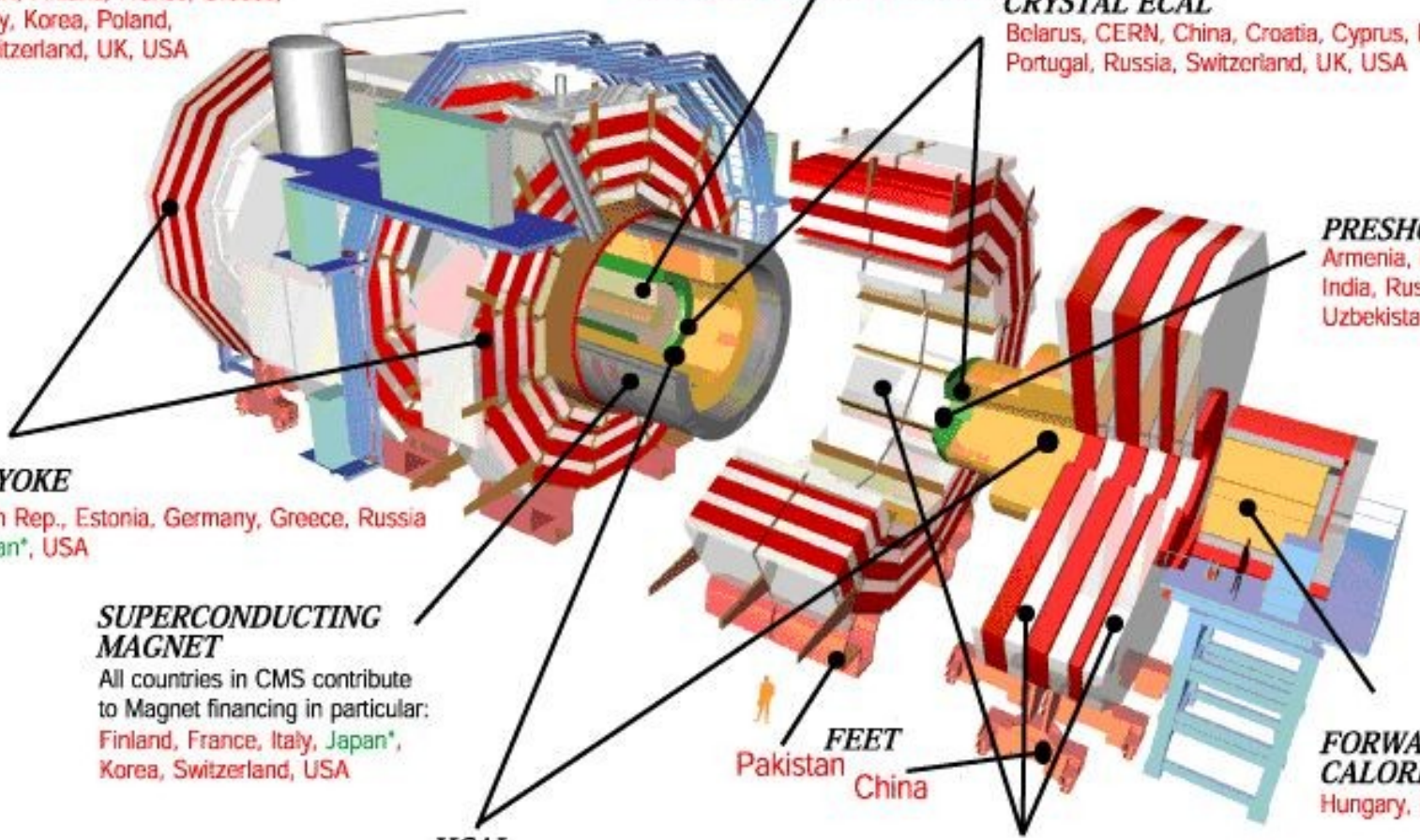
Large Hadron Collider



- **proton-proton collider with $\sqrt{s} = 7$ TeV**
- **2e33 $cm^{-2}s^{-1}$ achieved instantaneous luminosity**
- **More than 2 fb^{-1} delivered to experiments (Thanks LHC!!)**

Compact Muon Solenoid

31 Nations, 150 Institutions, 1870 Scientists



TRIGGER & DATA ACQUISITION
Austria, CERN, Finland, France, Greece, Hungary, Italy, Korea, Poland, Portugal, Switzerland, UK, USA

TRACKER
Austria, Belgium, CERN, Finland, France, Germany, Italy, Japan*, Switzerland, UK, USA

CRYSTAL ECAL
Belarus, CERN, China, Croatia, Cyprus, France, Italy, Japan*, Portugal, Russia, Switzerland, UK, USA

PRESHOWER
Armenia, Belarus, CERN, Greece, India, Russia, Taiwan (PC), Uzbekistan

RETURN YOKE
Barrel: Czech Rep., Estonia, Germany, Greece, Russia
Endcap: Japan*, USA

SUPERCONDUCTING MAGNET
All countries in CMS contribute to Magnet financing in particular:
Finland, France, Italy, Japan*, Korea, Switzerland, USA

FEET
Pakistan
China

FORWARD CALORIMETER
Hungary, Iran, Russia, Turkey, USA

HCAL
Barrel: Bulgaria, India, Spain*, USA
Endcap: Belarus, Bulgaria, Russia, Ukraine
HO: India

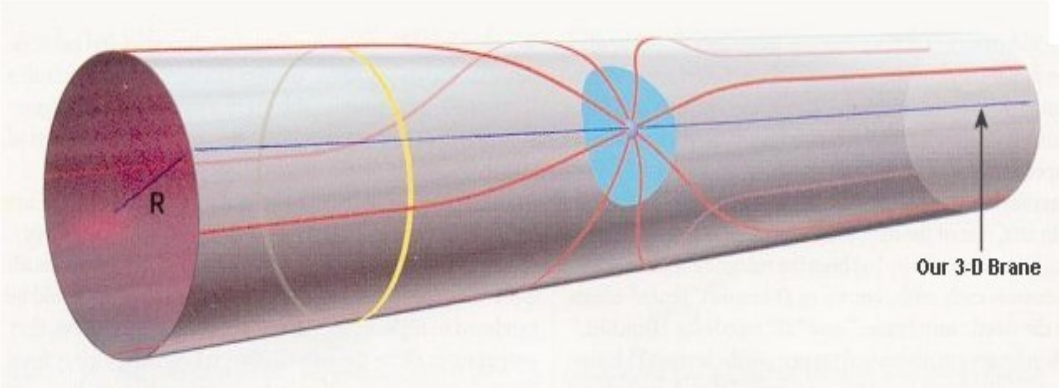
MUON CHAMBERS
Barrel: Austria, Bulgaria, CERN, China, Germany, Hungary, Italy, Spain,
Endcap: Belarus, Bulgaria, China, Korea, Pakistan, Russia, USA

* Only through industrial contracts

Total weight	**:**	**12500 T**
Overall diameter	**:**	**15.0 m**
Overall length	**:**	**21.5 m**
Magnetic field	**:**	**4 Tesla**

Extra Dimensions – ADD

- **Universe is (3+1)-dim:**
  - Planck scale O(10^{16} TeV)
  - EWK scale O(0.1 - 1 TeV)



- **Hierarchy problem:**
  - Gravity is much weaker than EWK interactions
- **Possible solution – ADD extra dimensions (Arkani-Hamed, Dimopoulos, Dvali –** ***PLB 429 (1998) 263*****):**
  - Gauge interactions are localized on (3+1)-dim brane
  - Gravity (strong!) propagates in ***n*** flat extra-dimensions compactified on torus or sphere with radius ***r***

n	R
1	8×10^{12} m
2	0.7 mm
3	3 nm
4	6×10^{-12} m

- **True Planck scale (M_D):** M_D = O(TeV)

$$M_{Pl}^2 = 8\pi M_D^{n+2} r^n$$

Extra Dimension – Kaluza-Klein Gravitons

- **Production of Kaluza-Klein (KK) graviton modes:**
  - Gives raise to diphoton/dilepton cross section
  - Non-resonant production – continuum spectrum of diphotons, dimuons, and dielectrons
  - Sum of all KK diverges – need an UV cutoff M_S
  - Virtual graviton effects are parameterized by $\eta_G = \mathcal{F}/M_S^4$, where

$$\mathcal{F} = 1 \quad \text{(Guidice, Rattazzi, and Wells, GRW [5]),}$$

$$\mathcal{F} = \begin{cases} \log\left(\frac{M_S^2}{\hat{s}}\right) & \text{if } n_{ED} = 2 \\ \frac{2}{(n_{ED}-2)} & \text{if } n_{ED} > 2 \end{cases} \quad \text{(Han, Lykken, and Zhang, HLZ [6]),}$$

$$\mathcal{F} = \pm\frac{2}{\pi} \quad \text{(Hewett [7]),}$$

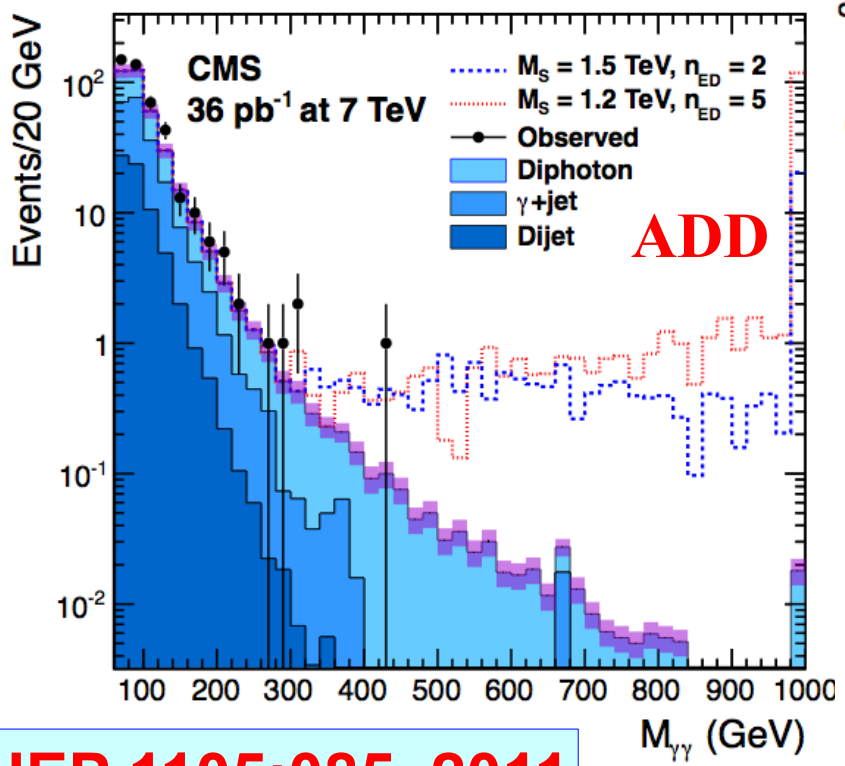
ADD and Randall-Sundrum in Diphotons

ADD → JHEP 1105:085, 2011
RS → CMS PAS EXO-10-019

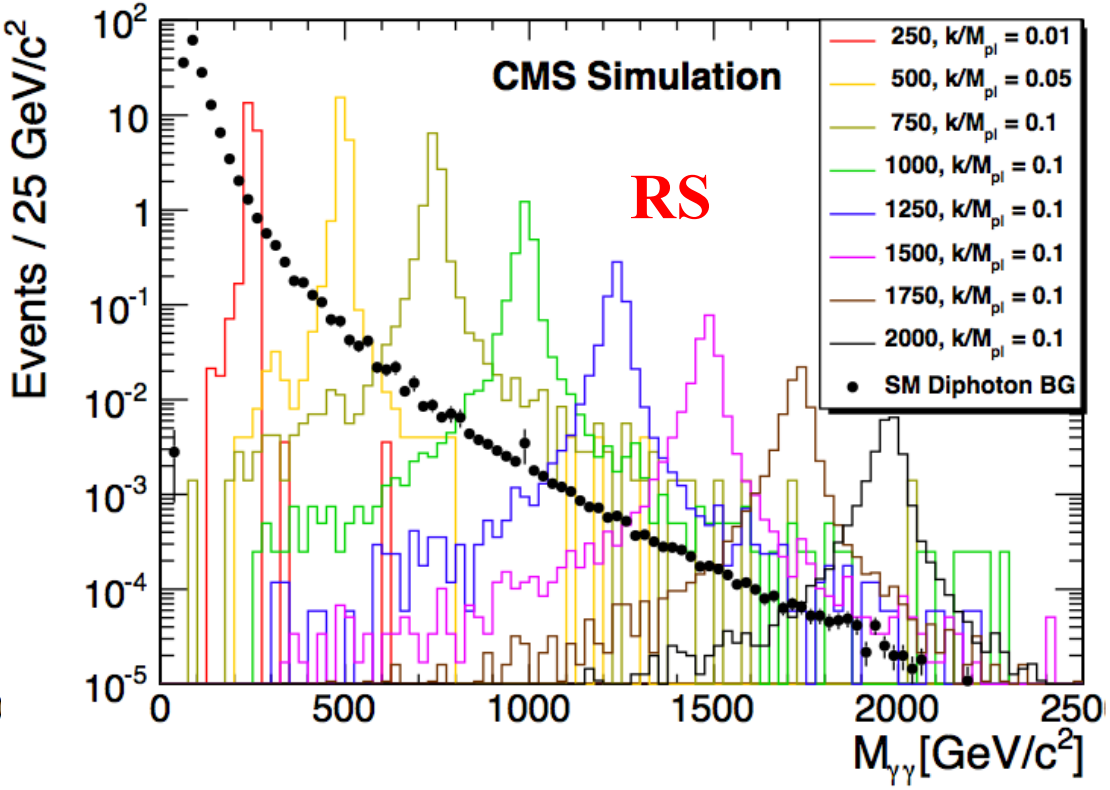
- **Event selection:**
  - Two central isolated photons $E_T > 30$ GeV, $M(\gamma\gamma) > 60$ GeV
  - $60 < M(\gamma\gamma) < 500$ GeV – control regions; $M(\gamma\gamma) > 500$ GeV – signal
- **Backgrounds highlights:**
  - $\gamma\gamma$ background is estimated with Sherpa; NLO *K*-factor = 1.3
  - Data-driven method to estimate jet-γ fake rate (for dijet and γ+jet backgrounds): 28 – 2% at 30 –120 GeV
- **Signal:**
  - ADD $\gamma\gamma$ is simulated with Sherpa; NLO *K*-factor = 1.3
  - Same $\gamma\gamma$ spectrum can also be searched for resonant RS gravitons; one warped dimension with $k/M_{Pl} = 0.01, 0.05, 0.10$, where k is curvature
    - Pythia simulated, corrected for NLO *K*-factor = 1.3

Data Yields

JHEP 1105:085, 2011



CMS PAS EXO-10-019

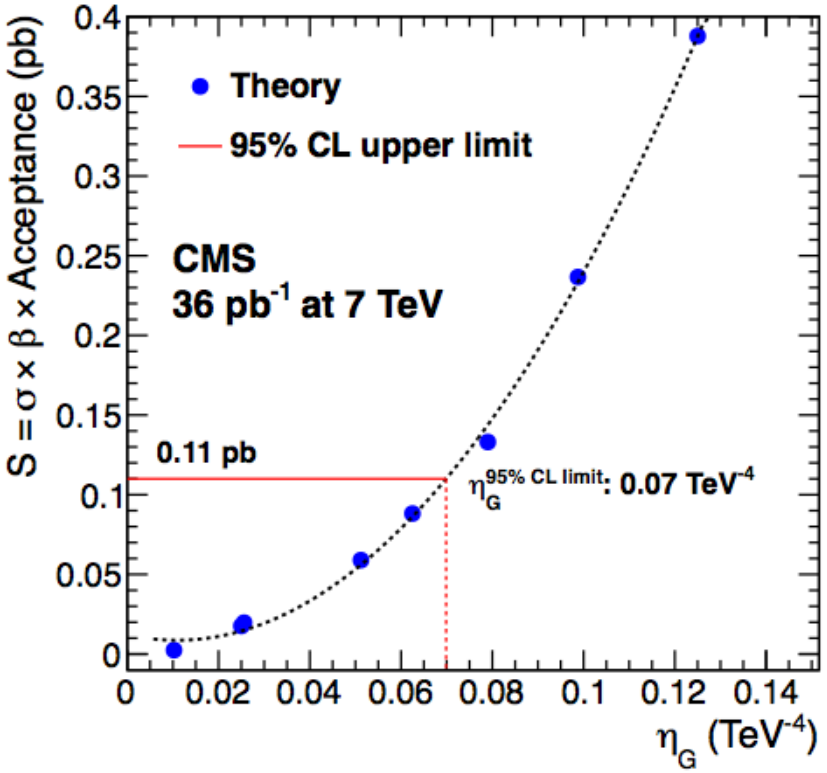


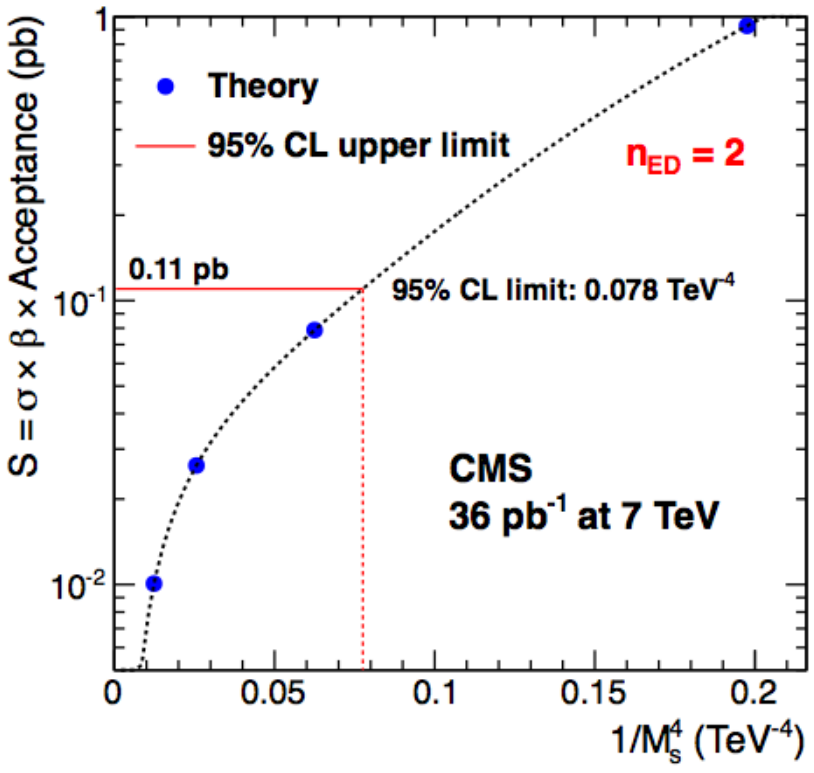
JHEP 1105:085, 2011

Process	$60 < M_{\gamma\gamma} < 200$ GeV	$200 < M_{\gamma\gamma} < 500$ GeV	$500\text{ GeV} < M_{\gamma\gamma}$
Dijets	70 ± 28	0.5 ± 0.2	0.0009 ± 0.0004
$\gamma +$ Jets	145 ± 7	2.3 ± 0.3	0.016 ± 0.003
Diphotons	150 ± 35	6.2 ± 1.4	0.29 ± 0.07
Total Backgrounds	365 ± 49	9.0 ± 1.5	0.30 ± 0.07
Observed	428	12	0

Limits on ADD

Published in JHEP 1105:085, 2011





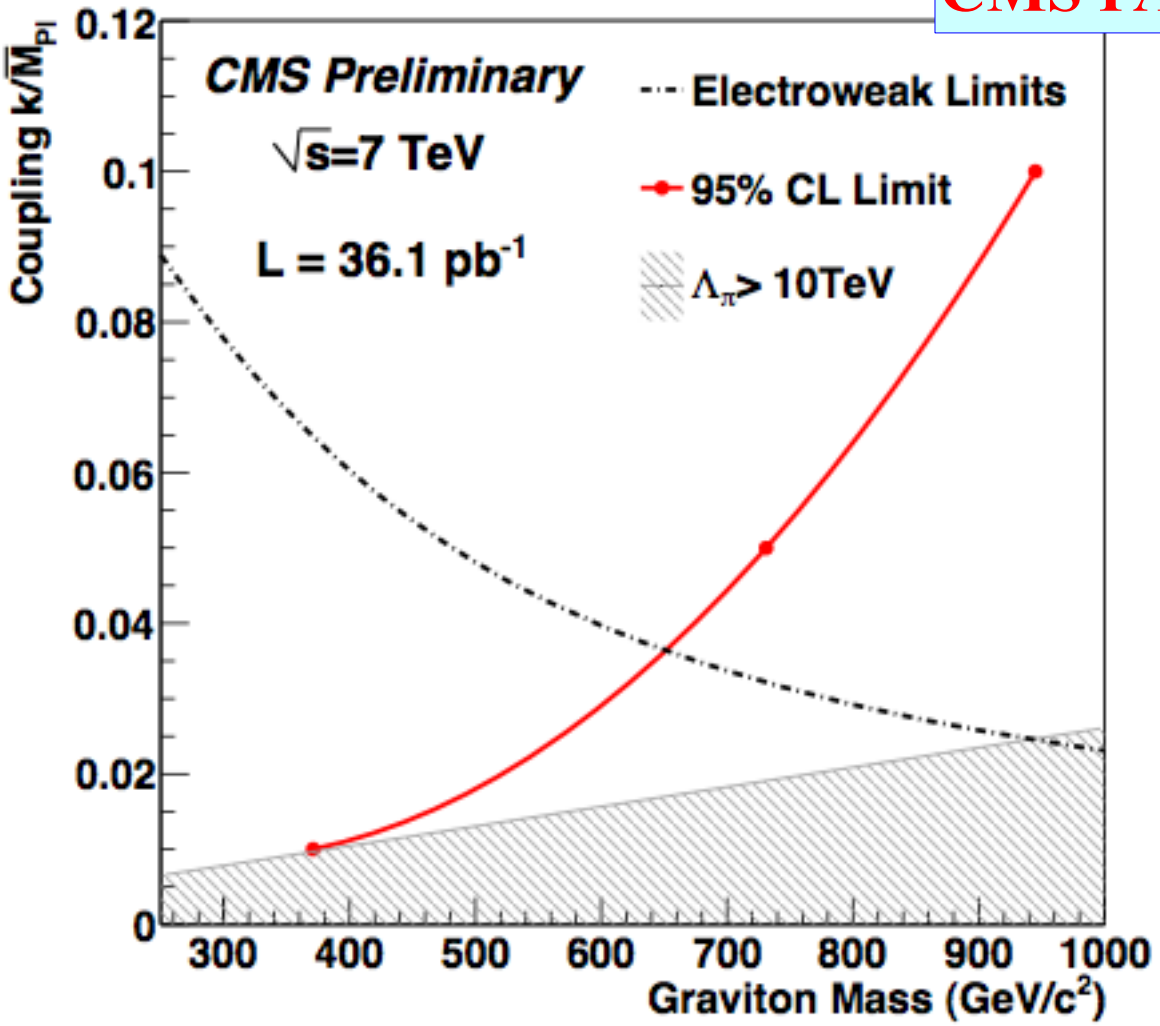
- **Limits on M_D**

	GRW	Hewett		HLZ					
		Pos.	Neg.	$n_{ED}=2$	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
Full	1.94	1.74	1.71	1.89	2.31	1.94	1.76	1.63	1.55
Trunc.	1.84	1.60	1.50	1.80	2.23	1.84	1.63	1.46	1.31

$M_{\gamma\gamma} < M_S$

Limits on RS

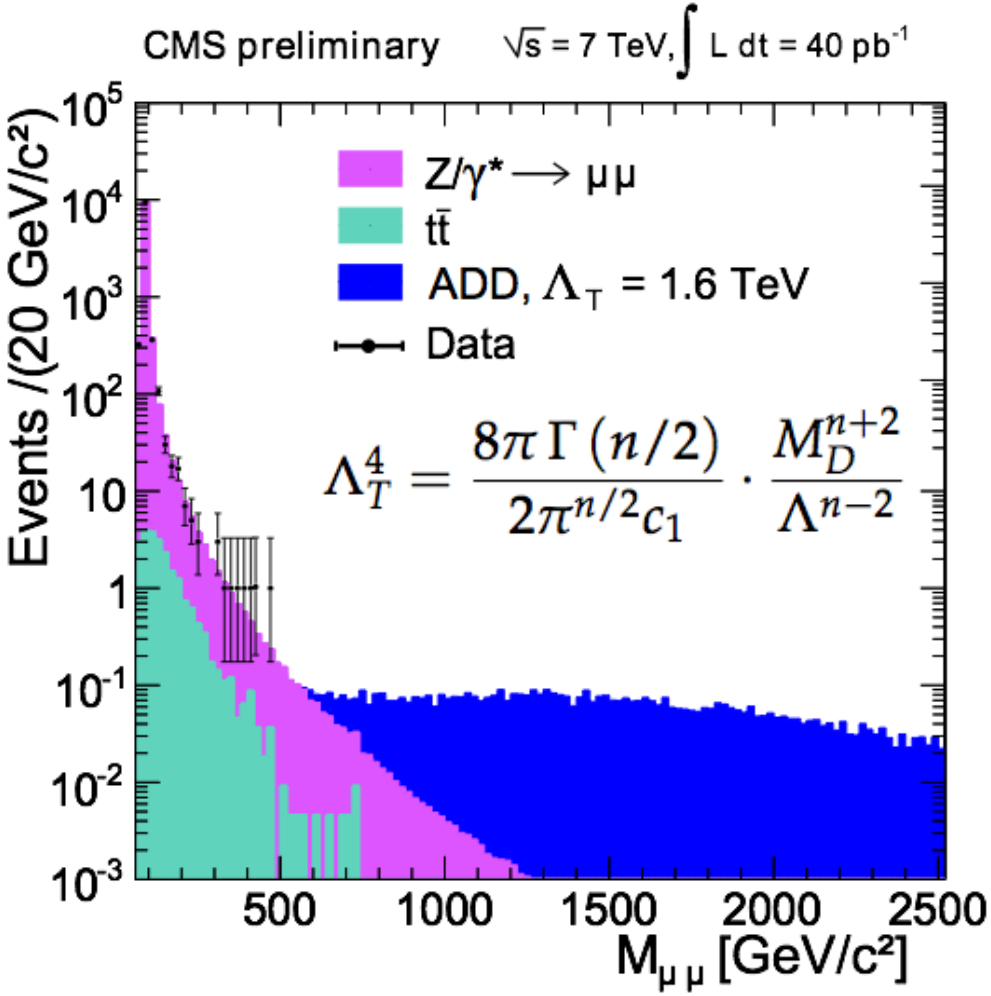
CMS PAS EXO-10-019



- **Exclude M_1 (first excited mode mass) below 371 – 945 GeV for $k/M_{Pl} = 0.01 – 0.1$**

KK Gravitons in Dimuons

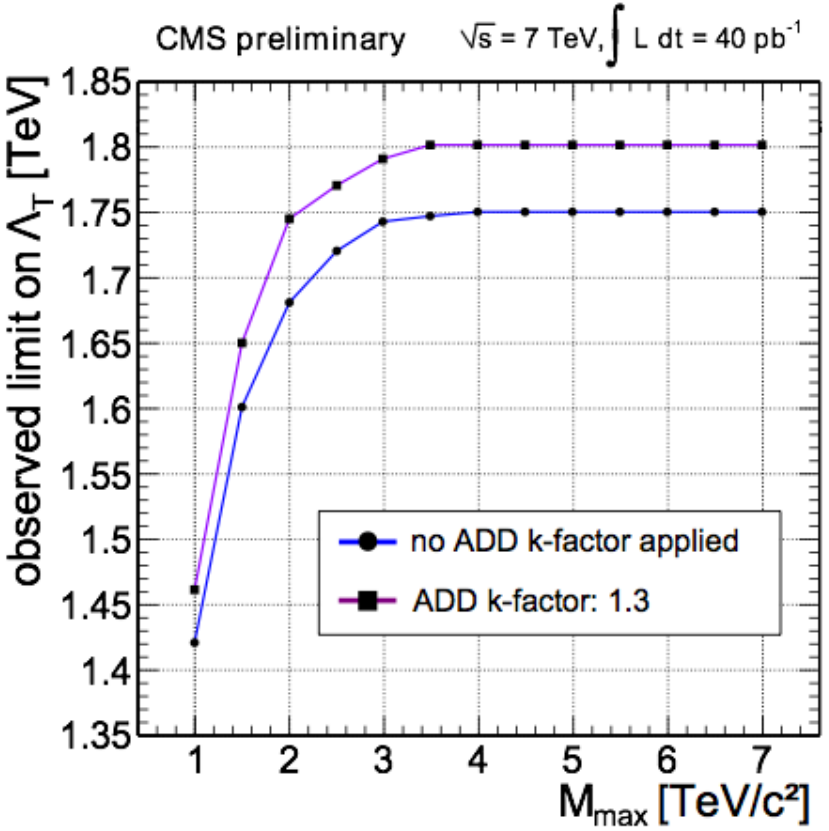
- **Select 2 isolated muons: $p_T > 30$ GeV**
- **Main backgrounds:**
  - DY (from Pythia) is corrected to NNLO (1.4 – 1.45); main source of systematics
- **Signal samples:**
  - Pythia corrected for NLO (1.3)
- **No excess in signal region (M(μμ) > 0.6 TeV)**

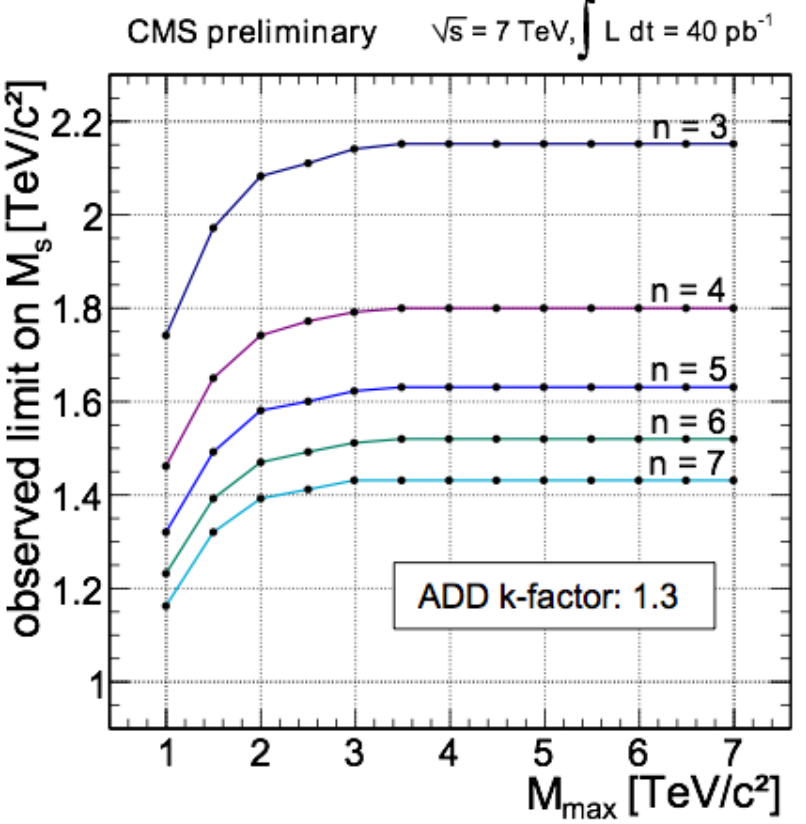


CMS PAS EXO-10-020

KK Gravitons in Dimuons – Limits

- **95% CL upper limit on σ_S = 0.088 – 0.098 pb**
- **Limits on model parameters: Λ_T (GRW), M_S (HLZ)**





CMS PAS EXO-10-020

	Λ_T [TeV] (GRW)	M_s [TeV/c^2] (HLZ)					
		$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
Full	1.80	1.75	2.15	1.80	1.63	1.52	1.43
Truncated	1.68	1.67	2.09	1.68	1.49	1.34	1.24

$M_{\mu\mu} < M_S$

A Microscopic Black Hole?

- **Strong gravity in extra dimensions allows for formation of micro black holes with size r_S:**

$$r_S = \frac{1}{\sqrt{\pi} M_D} \left[\frac{M_{BH}}{M_D} \frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \right]^{\frac{1}{n+1}}$$

  - Thermal decay via Hawking radiation into all kinds of particles (75% quarks/gluons; 25% the rest, e.g. photons, leptons, gauge bosons, H)
  - Cross section (PDG definition) ~ πr_S^2, up to few hundred pb with extra dimensions
  - Semi-classical approximation: $M_{BH} > M_{min} > M_D$

Or a String Ball?

- **What if $M_S < M < M_{min} \sim M_S/g_S^2$?**
  - Proposed by Dimopoulos and Emparan (*PLB* ***526*** *(2002) 393*)
  - GR breaks – this is string theory now!
  - A string ball forms with cross section:

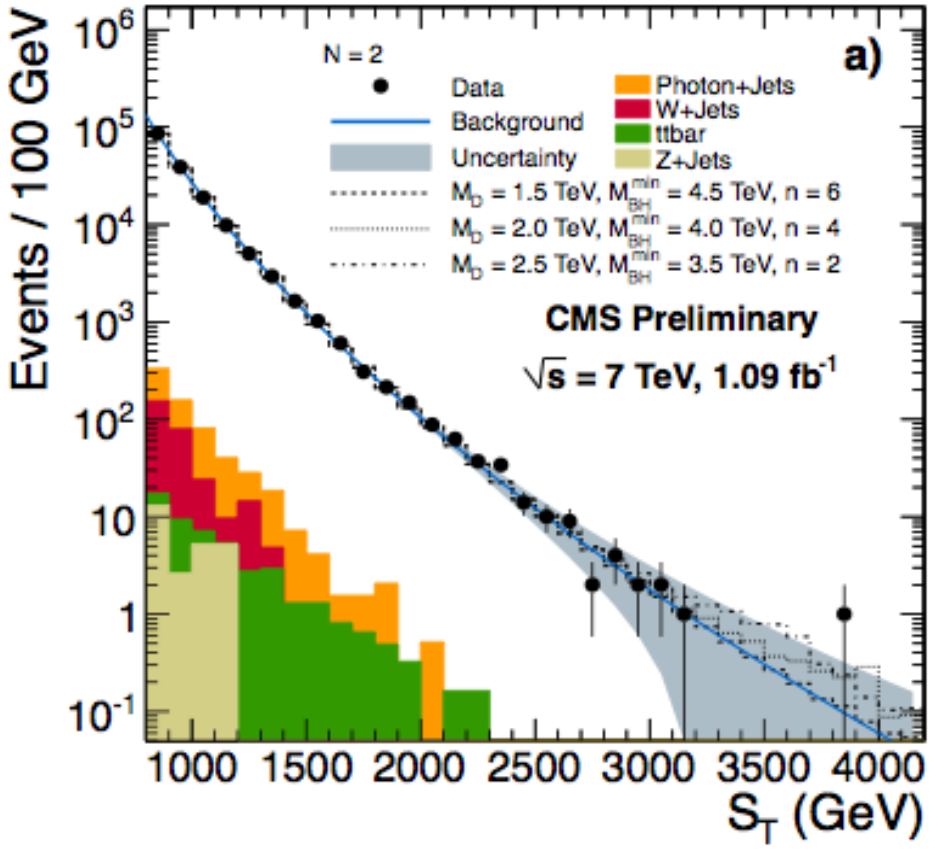
$$\sigma \sim \begin{cases} \dfrac{g_s^2 M_{SB}^2}{M_s^4} & M_s \ll M_{SB} \leq M_s/g_s\,, \\ \dfrac{1}{M_s^2} & M_s/g_s < M_{SB} \leq M_s/g_s^2 \\ \dfrac{1}{M_P^2}\left(\dfrac{M_{BH}}{M_P}\right)^{\frac{2}{n+1}} & M_s/g_s^2 < M_{BH}\,. \end{cases}$$

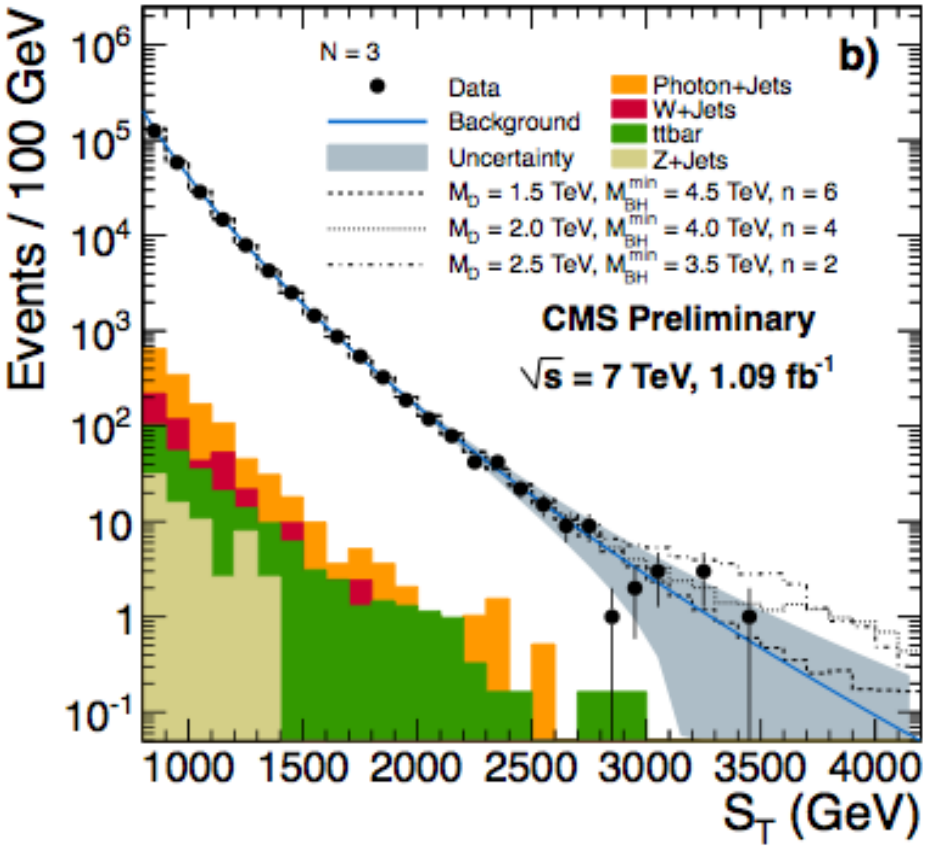
  - Properties are similar to semi-classical black hole
  - Search strategy for both: high-multiplicity (N) and high-S_T ($S_T = \sum p_T$ [jets, leptons, photons] with $p_T > 50$ GeV + missing $E_T > 50$ GeV)
  - Search/control region: $S_T > 800$ GeV

Backgrounds

- **QCD background – data-driven method**
  - Extract S_T shape from N = 2 and 3 data samples
  - Scale to higher multiplicities (exclusive and inclusive)

CMS PAS EXO-11-071

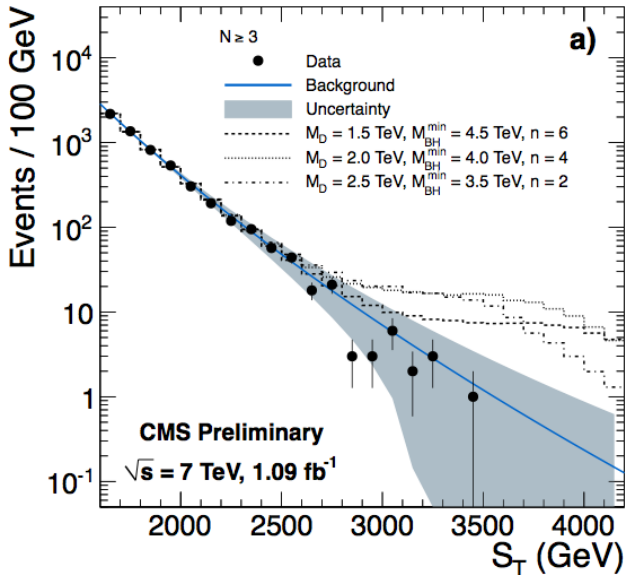


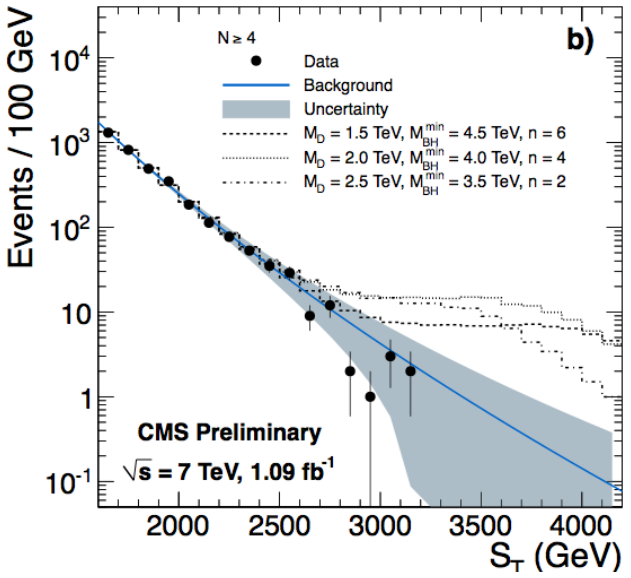


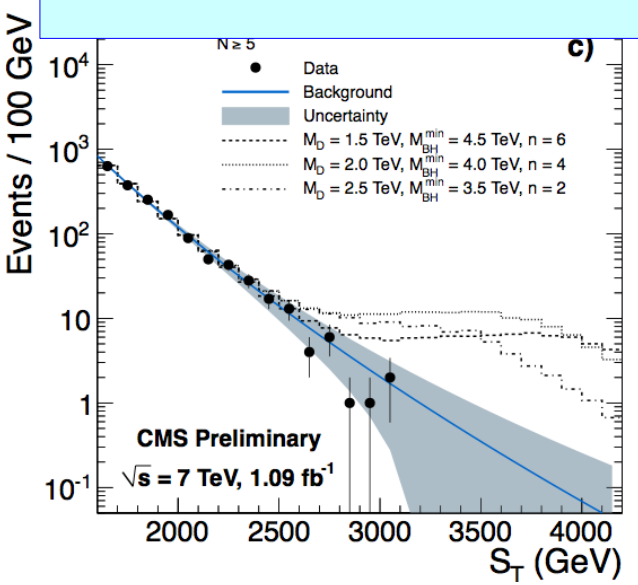
- **Non-multijet backgrounds contribution is < 1%**
- **Very little signal leakage to low multiplicity bins**

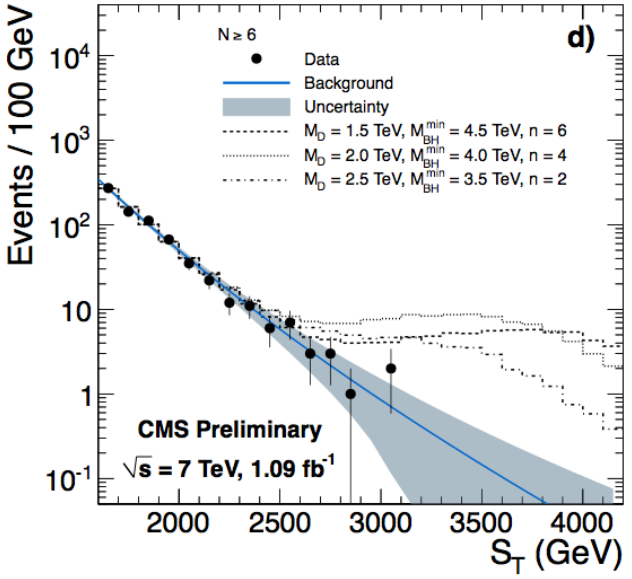
S_T Distributions (Inclusive Multiplicities)

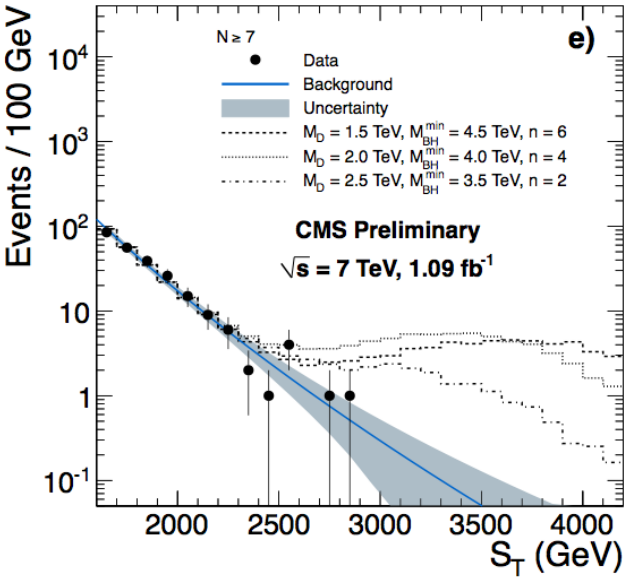
CMS PAS EXO-11-071

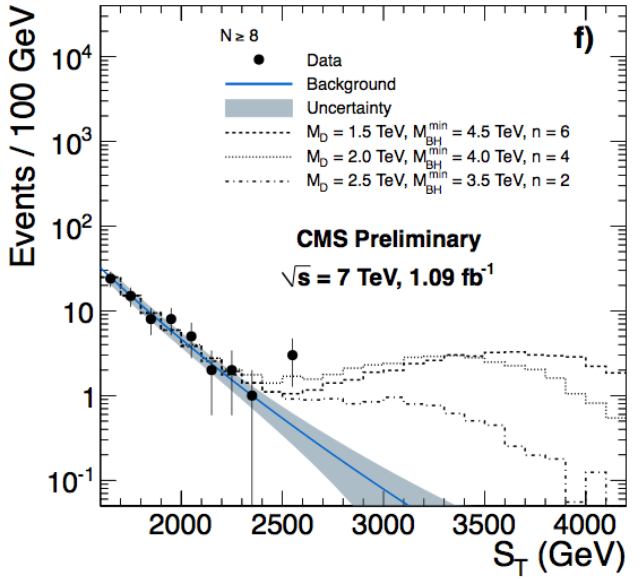




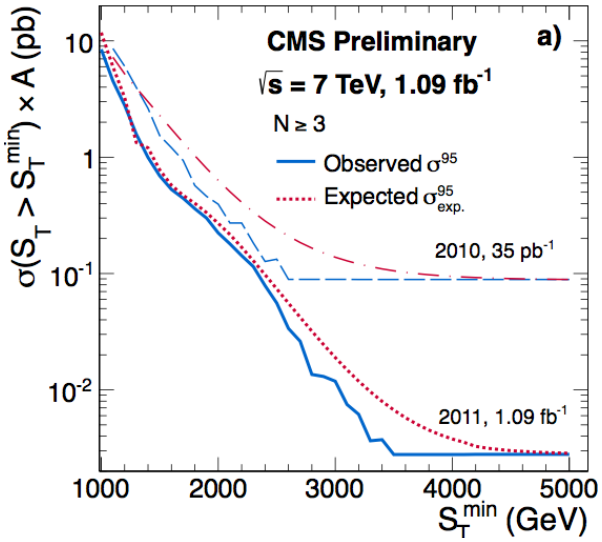


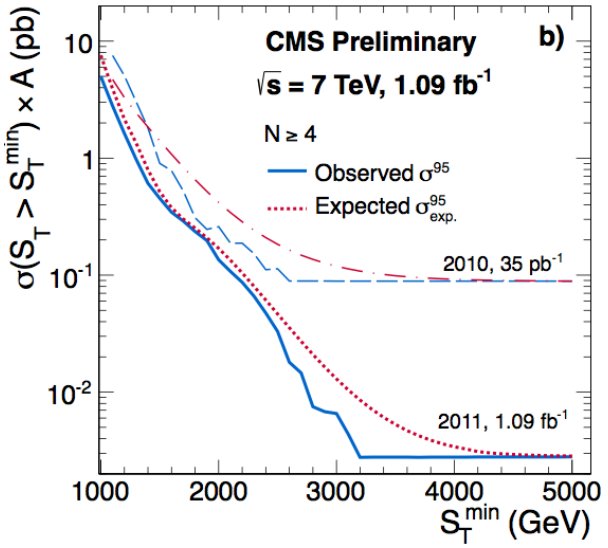


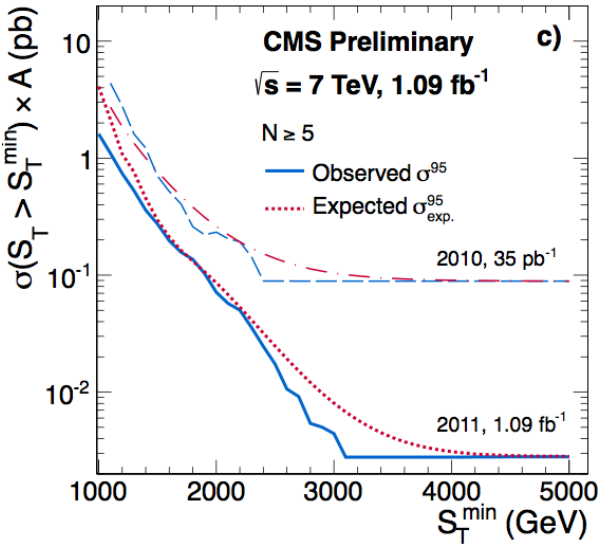


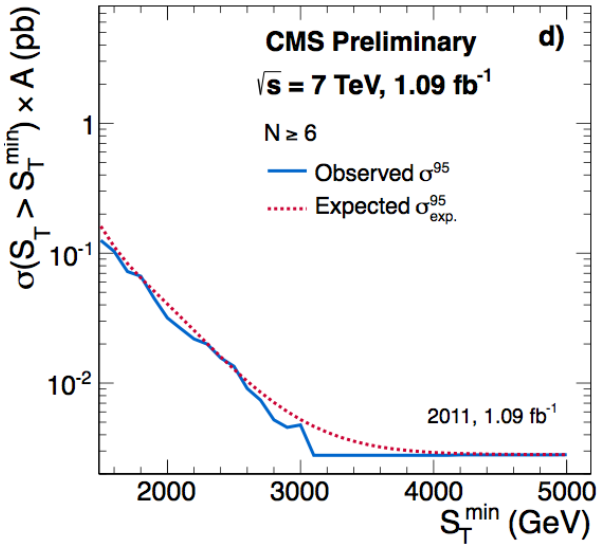


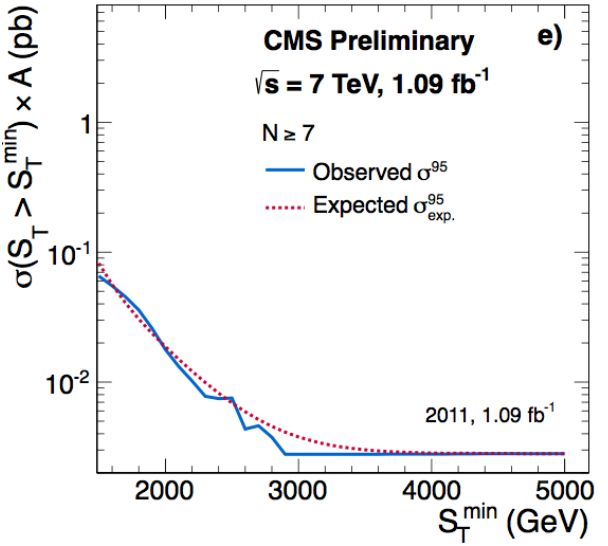
Model-Independent Limits

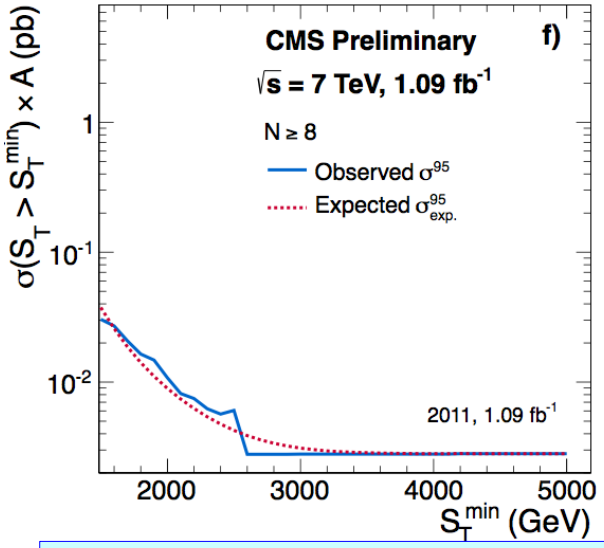










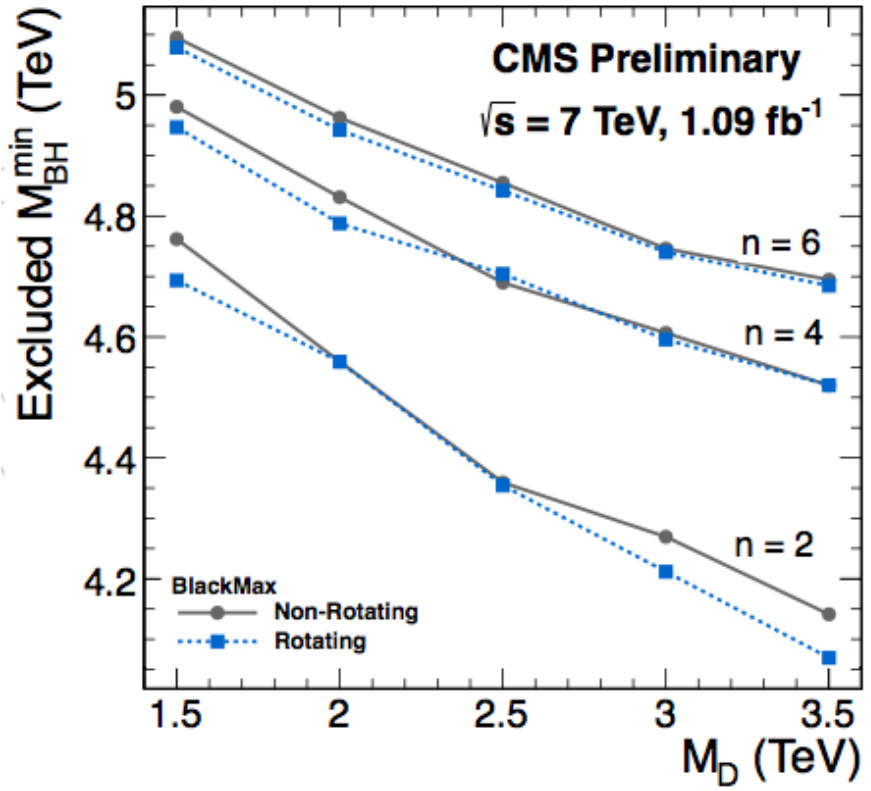


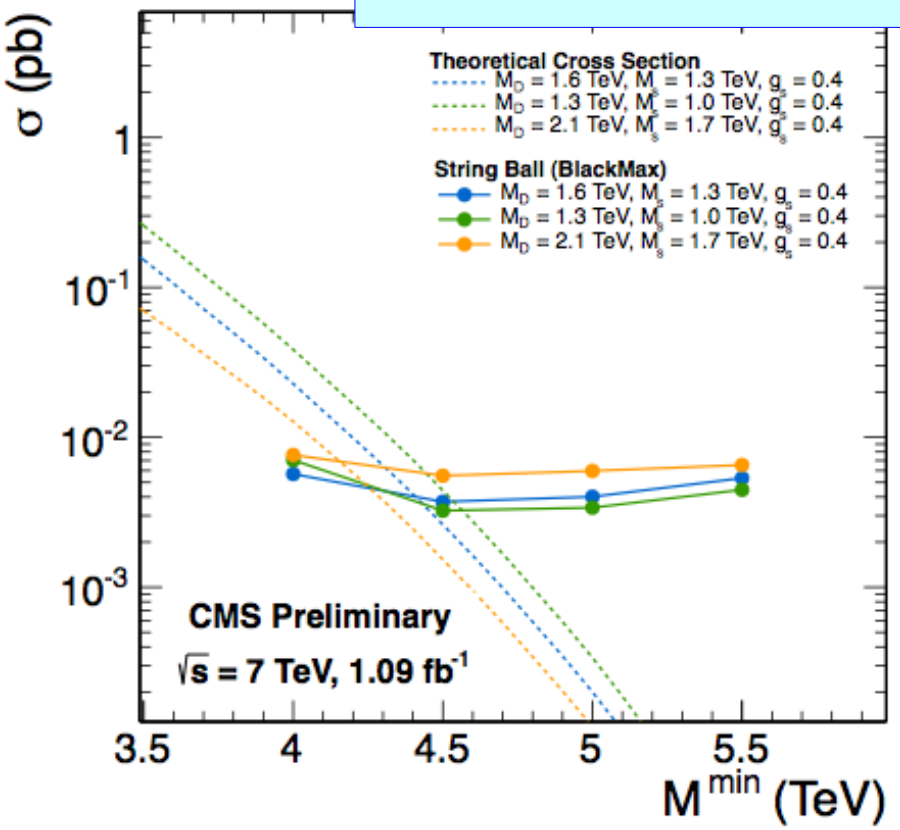
- **High-S_T limits approach 3 fb**
  - 30 times more sensitive than results of *PLB **679** (2011) 434*

CMS PAS EXO-11-071

Limits on Minimum Mass

CMS PAS EXO-11-071





- **In terms of ADD parameters and BlackMax framework:**
  - Exclude BH with M_{min} = 4.1 – 5.1 TeV for M_D = 1.5 – 3.5 TeV and n = 2 – 6
    - ~0.5 TeV improvement w.r.t. *PLB* ***679*** *(2011) 434*
  - Exclude string balls with M_{min} = 4.1 – 4.5 TeV (first direct limit!)

Conclusions

- **All these searches made possible by the LHC – thanks for high-quality data!**
- **Searches for Extra Dimensions are ongoing:**
  - No evidence for new physics yet
  - Many interesting results on LHC data have been obtained
  - Many give best limits to date
  - Public pages:
    - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
- **More data are streaming in – stay tuned!**

Thanks!

- **Thanks to my colleagues for the results I've shown today**

- **Thanks to DPF2011 Organizers!**

BACKUP

Systematic Uncertainties

- **Diphoton analysis**

	Central Value	Relative Uncertainty
Luminosity	36 pb^{-1}	4.0%
Background diphoton *K* factor	0.30 Events	23%
Signal Efficiency	77.1%	6.0%
Signal diphoton *K* factor	1.3	7.7%

- **Dimuon analysis**

Systematic Uncertainty	Related Parameter	Signal Uncertainty	Background Uncertainty
Trigger and reconstruction efficiency bkg.	$\epsilon_{reco,b}$	—	3%
Trigger and reconstruction efficiency signal	$\epsilon_{reco,s}$	4%	—
Muon momentum resolution	$\epsilon_{res,b}$	—	4%
Drell-Yan higher order corrections	σ_b	—	15%
Drell-Yan PDF uncertainties	σ_b	—	5%
Z normalisation	$\mathcal{L}$	6%	6%
Others		—	1%

Systematic Uncertainties

- **Black Holes**

Uncertainty	Effect on Signal Acceptance	Effect on Background
Integrated Luminosity	±6%	±6%
Jet Energy Scale	±5%	–
PDF	±2%	–
Rescaling	–	±(2.8 – 19.0)% [Table 6]
Shape modeling	–	±(9.9 – 289.5)%, depends on the S_T value.