The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

**2263-7**

# Beyond the Standard Model: Results with the 7 TeV LHC Collision Data

*19 - 23 September 2011*

## The CMS Experiment Results for the Extra Dimensions

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# The CMS Experiment Results for the Extra Dimensions

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On behalf of CMS Collaboration

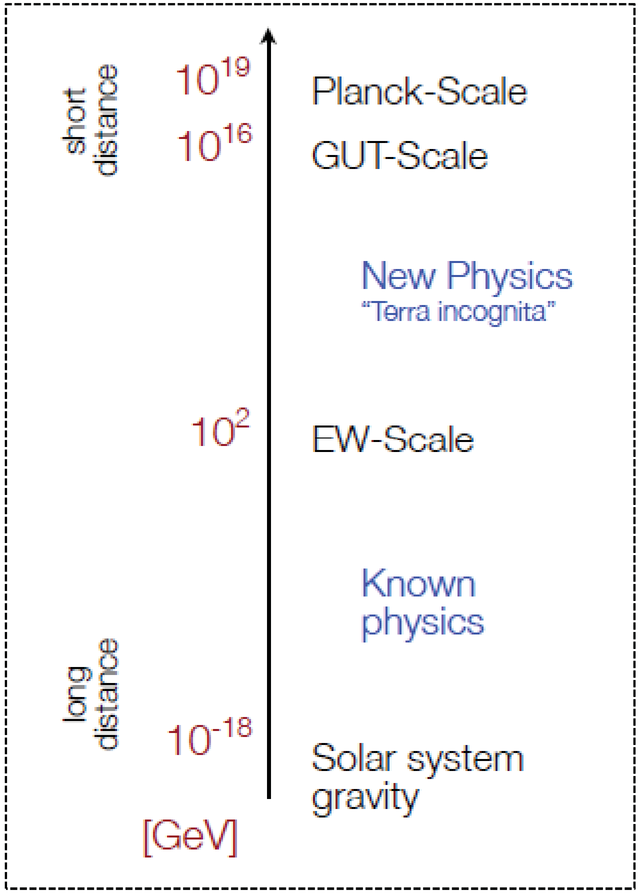
**Beyond the Standard Model: results with the 7 TeV LHC Collision Data, 19-23 Sep 2011, ICTP, Trieste (Italy)**

# Outlines

- Extra Dimensions
  - ADD
  - RS
- Consequences of Extra Dimensions

- Extra Dimensions at the LHC with the CMS Detector
  - Mono Photon + Missing Energy Analysis
  - Mono Jet + Missing Energy Analysis
  - Diphoton Analysis
  - Dilepton Analysis

# Why Extra Dimensions: Hierarchy Problem




**Planck Scale: $10^{19}$ GeV**

**Scale at which the gravitational force becomes as strong as the other forces; effects of quantum gravitation become relevant ...**

**GUT Scale: $10^{16}$ GeV**

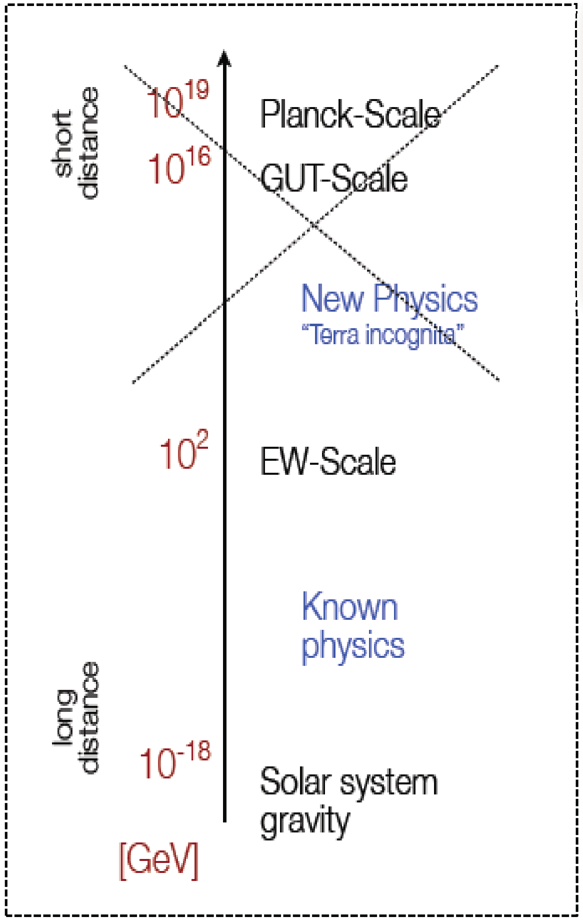
**Unification scale where strong, weak and electromagnetic forces become equal ...**

**Electroweak Scale: $10^{2}$ GeV**

**Scale of electroweak symmetry breaking ...**

# Extra Dimensions: ADD Scenario

**The existence of New Spatial Dimensions is proposed.**




-If Large Extra Dimensions exist the 4D Planck Scale ($M_P$) **is not a fundamental scale** and the 4+n Planck Scale ($M_S$) is the Fundamental Scale.

- **To solve the Hierarchy Problem: $M_S \sim M_{EW}$**

**The Planck scale $M_P \sim G^{-1/2}$ is not a fundamental scale; its enormity is simply a consequence of the large size of the new dimensions. While gravitons can freely propagate in the new dimensions, at sub-weak energies the Standard Model SM. Fields must be localized to a 4-dimensional manifold of weak scale "thickness" in the extra dimensions.**

ADD- Physics Letters B 429 1998. 263–272

# Extra Dimensions: ADD Scenario

**4-Dimensions** → $$M_{Pl} = \sqrt{\frac{hc}{G}} \sim 10^{19}\, GeV$$

**(4+n)-Dimensions** → $$M_{Pl}^{\dim=(4+n)} \equiv M_S$$

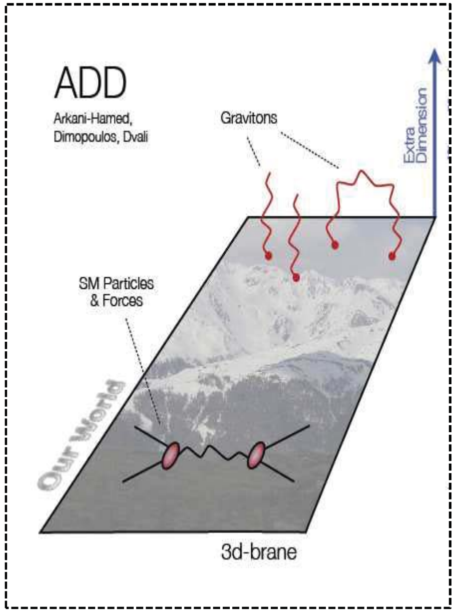
**With n-extra dimensions** $$M_{Pl}^2 \approx M_S^{2+n} \times R^n$$

# Extra Dimensions: ADD Scenario

$$M_{Pl}^2 \approx M_S^{2+n} \times R^n$$ **To solve the Hierarchy Problem: $M_S \sim M_{EW}$**

By setting $M_s = 1$ TeV

| n | $R \approx \left(M_{Pl}^2 / M_S^{2+n}\right)^{1/n}$ |
|---|---|
| 1 | 70 AU |
| 2 | 1 mm |
| 3 | 1 nm |
| 4 | 10 pm |
| 7 | 3.7 fm |




**The SM (4-dimension) has been tested up to few hundred GeV→ Consistent with Experimental Data.**

**Therefore, SM fields can not propagate into the Extra Dimensions and have to be localized on the 3-brane.**

# Extra Dimensions: ADD Scenario

The effect of Extra Dimensions can be parameterized in terms of a single parameter:

$$\eta = F/M_s^4$$

$\eta$ describes the strength of gravity in the presence of extra dimensions.
F is a dimensionless parameter and in different in ADD conventions:

-HLZ (Han, Lykken and Zhang) Conventions→

$$F = \begin{cases} \log\left(\frac{M_S^2}{\hat{s}}\right), \ for \quad n=2 \\ \frac{2}{2-n} \quad for \ \ n>2 \end{cases}$$

-GRW (Guidice-Rattazzi-Wells)→

$$F = 1$$

-Hewett→

$$F = \frac{\pm 2}{\pi}$$

# Extra Dimensions: RS Scenario

Critics on ADD: Hierarchy of gauge fields replaced by new hierarchy of length scales

**Alternative: Randall-Sundrum Model(s)**

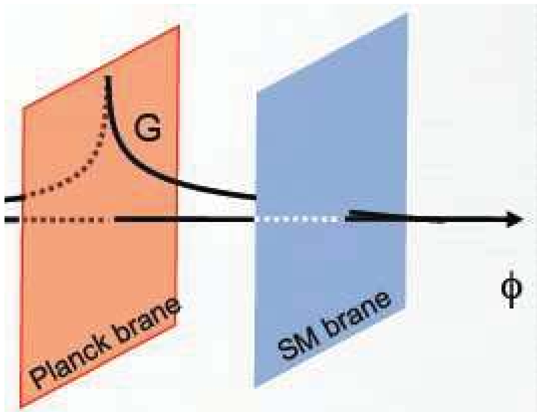
The Warped Extra Dimensions scenario was created by Randall and Sundrum (RS) and is quite different and more flexible than the ADD model. The basic RS model assumes the existence of only one highly curved ED. In this setup there are two branes, one at y = 0 (called the Planck brane) while the other is at $y = \pi r_c$ (called the TeV or SM brane).

What makes this model special is the metric:

$$ds^2 = e^{-2kr_c\phi}\eta_{\mu\nu}dx^\mu dx^\nu + r_c^2 d\phi^2$$

Warp Factor:

$$\Lambda_\pi \sim M_{\text{Pl}} e^{-\pi k r_c}$$




**Phys. Rev. Lett. 83 (99)**

# Extra Dimensions: RS Scenario

-In spite of ADD, light KK modes might be accessible and are well separated.

-Low energy effects on the SM brane are given by $\Lambda_\pi$; for $kr_c \sim 11\text{-}12$: $\Lambda_\pi \sim 1$ TeV and the hierarchy problem is solved naturally.

-Need only two parameters to define the model: $k$ (curvature of the space) and $r_c$ (compactification radius of the extra dim.)

Equivalent set of parameters:

- The mass of the first KK mode, $M_1$
- Dimensionless coupling $k/M_{Pl}$, which determines the graviton width.

# Experimental Consequences of EDs

The ADD model predicts a number of observable signatures at the Large Hadron Collider (LHC).

- One of the direct signatures is the production of a graviton in the final state of pp collisions. Graviton is emitted into the hidden space dimensions and appears as missing energy.

- Exchange of virtual gravitons: Change of cross sections

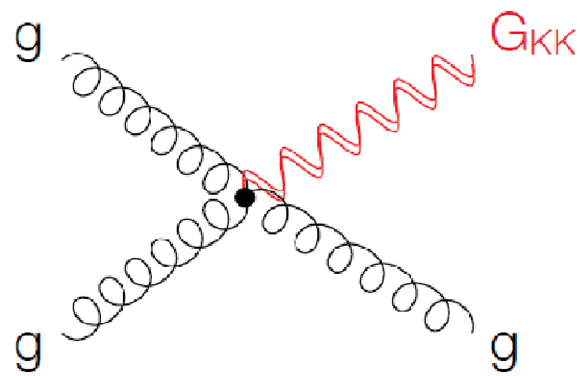
- New Particles: Kaluza-Klein excitations

- Production of Mini Black Holes

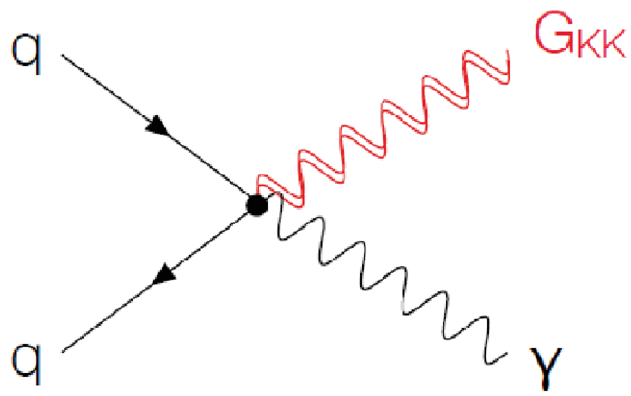
# Graviton Radiation

**Graviton can be produced along with a jet (or a photon).**
**Gravitons interact weakly with the detector and radiate into the bulk appearing as missing energy.**

Two clean signatures of the ED are:




- **High-energy monojet & missing energy**



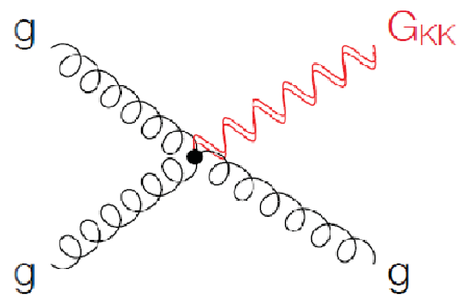

- **High-energy single photon & missing energy**

# Mono-jet + Missing Energy

**Signal: An Energetic Jet + Large Missing Energy**

**Backgrounds:**

**Z(invisible)+Jet→Missing Energy+Jet.**
**Z+Jets, W+Jets, Top pair, Single top, multijet**




**The signal events are selected by requiring:**

-$E^{miss}_T$ > 200 GeV.

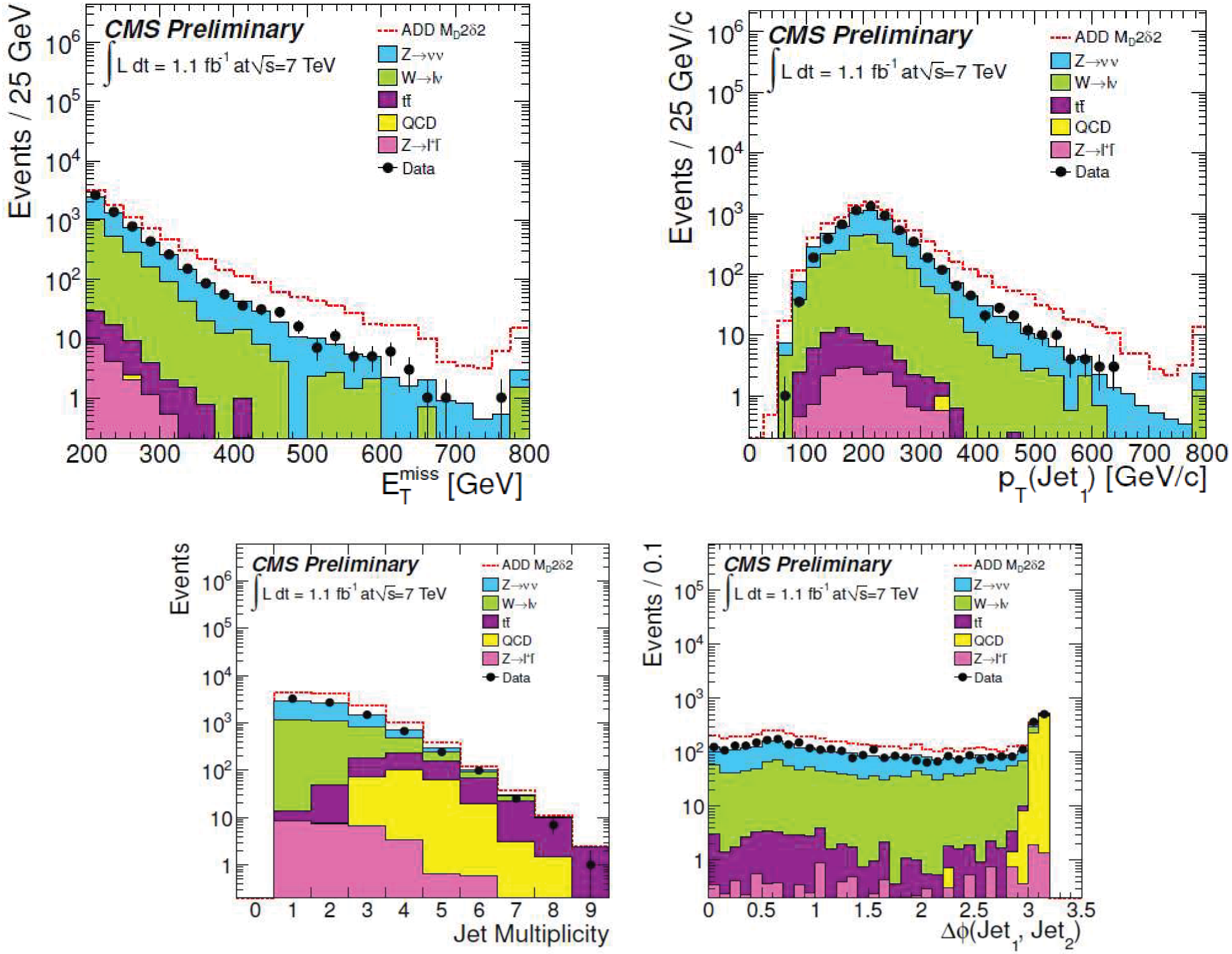
-$P_{T,j1}$ > 110 GeV with |eta|<2.4.

-Jet veto: Events with more than two jets (Njets > 2) with $p_T$ above 30 GeV/c are discarded.

-The angular separation of the two jets should be less than 2.5.

CMS PAS EXO-11-058

# Mono-jet + Missing Energy



# Mono-jet + Missing Energy

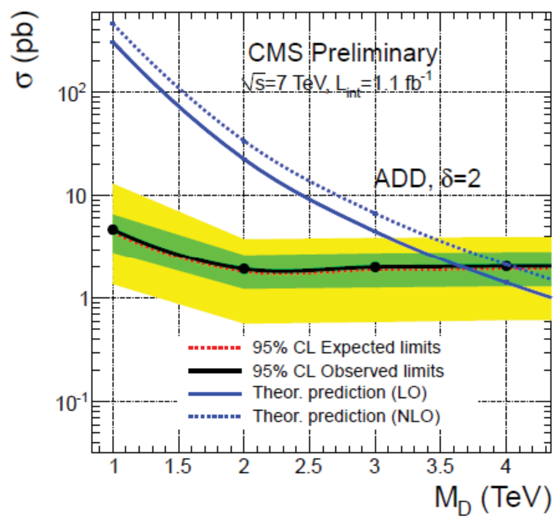
| Requirement | $W$+jets | $Z(\nu\nu)$+j | $Z$+j | $t\bar{t}$ | t | QCD | Total BG | Data |
|---|---|---|---|---|---|---|---|---|
| $E_T^{miss} > 200$ GeV, jet cleaning | 13689 | 5182 | 1103 | 2837 | 213 | 2588 | 25613 | 24428 |
| $p_T(j_1) > 110$ GeV/$c$, $\|\eta(j_1)\| < 2.4$ | 13080 | 4936 | 1056 | 2601 | 195 | 2558 | 24425 | 23623 |
| $N_{Jets} \leq 2$ | 8553 | 3686 | 725 | 299 | 46.4 | 768 | 14078 | 14544 |
| $\Delta\phi(j_1, j_2) < 2.5$ | 7448 | 3446 | 659 | 253 | 40.0 | 19.2 | 11865 | 12345 |
| Lepton Removal | 2174 | 3328 | 16.1 | 47.9 | 6.7 | 0.5 | 5573 | 5965 |
| $E_T^{miss} > 250$ GeV | 639 | 1192 | 4.0 | 14.1 | 1.9 | 0.5 | 1851 | 1930 |
| $E_T^{miss} > 300$ GeV | 200 | 483 | 0.9 | 4.6 | 0.6 | 0.1 | 689 | 708 |
| $E_T^{miss} > 350$ GeV | 67.8 | 217 | 0.3 | 1.7 | 0.2 | 0.1 | 288 | 293 |
| $E_T^{miss} > 400$ GeV | 36.2 | 105 | 0.1 | 0.9 | 0.1 | 0.1 | 142 | 151 |

**The total number of background events for $E^{miss}_T > 200$ GeV is measured to be 5573 +/-305. The uncertainty includes both statistical and systematic sources**

# Mono-jet + Missing Energy: Results

The limits on the ADD model for two values of $E^{miss}_T$ , one at $E^{miss}_T$ > 200 GeV where we have the largest acceptance, and another at $E^{miss}_T$ > 350 GeV where we have the greatest sensitivity.

| $\delta$ | $K$ factor | CMS 36 $pb^{-1}$ | $E_T^{miss} > 200$ GeV | | $E_T^{miss} > 350$ GeV | |
|---|---|---|---|---|---|---|
| | | Obs. Limit | Exp. Limit | Obs. Limit | Exp. Limit | Obs. Limit |
| 2 | | 2.29 | 2.96 | 2.72 | 3.72 | 3.67 |
| 3 | | 1.92 | 2.41 | 2.21 | 3.00 | 2.96 |
| 4 | | 1.74 | 2.17 | 2.00 | 2.68 | 2.66 |
| 5 | | 1.65 | 2.02 | 1.87 | 2.44 | 2.41 |
| 6 | | 1.59 | 1.94 | 1.81 | 2.27 | 2.25 |
| 2 | 1.5 | 2.56 | 3.26 | 3.00 | 4.10 | 4.03 |
| 3 | 1.5 | 2.07 | 2.63 | 2.39 | 3.25 | 3.21 |
| 4 | 1.4 | 1.86 | 2.30 | 2.13 | 2.83 | 2.80 |
| 5 | 1.4 | 1.74 | 2.13 | 1.98 | 2.57 | 2.55 |
| 6 | 1.4 | 1.68 | 2.04 | 1.91 | 2.39 | 2.36 |




Limits at 95% CL on ADD model parameters are $M_S$ > 3.7 TeV for $n_{ED}$ = 2 at Leading Order and 4.03 TeV at NLO.

# Mono-photon + Missing Energy

**Signal: Single Photon + Missing Energy**

**Backgrounds:**

**The main irreducible background: Z+Photon→Missing Energy+Photon.**

**Other relevant backgrounds:**

W+Photon, Photon+jet, and diphoton (estimated from MC).

**Event Selection:**

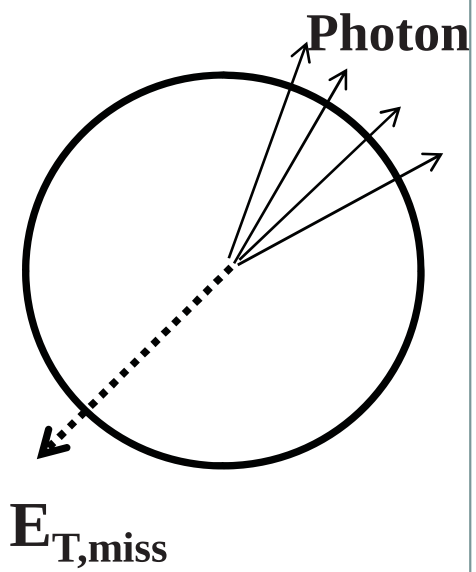
-Photon candidate with $P_T$ > 90 GeV and |eta|<1.44 is selected.

-MET (PF) > 80 GeV.

-Jet and track veto.

| Source | Estimate |
|---|---|
| $Z(\nu\bar{\nu})\gamma$ (MC) | $36.4 \pm 6.6$ |
| Jet Fakes Photon (data) | $14.1 \pm 3.3$ |
| Electron Fakes Photon (data) | $8.4 \pm 2.6$ |
| Beam Halo (data) | $4.6 \pm 3.2$ |
| $W\gamma$ (MC) | $2.7 \pm 0.5$ |
| $\gamma\gamma$ (MC) | $0.8 \pm 0.2$ |
| $\gamma$+jet (MC) | $0.2 \pm 0.1$ |
| Total Background | $67.3 \pm 8.4$ |
| Total Observed Candidates | 80 |

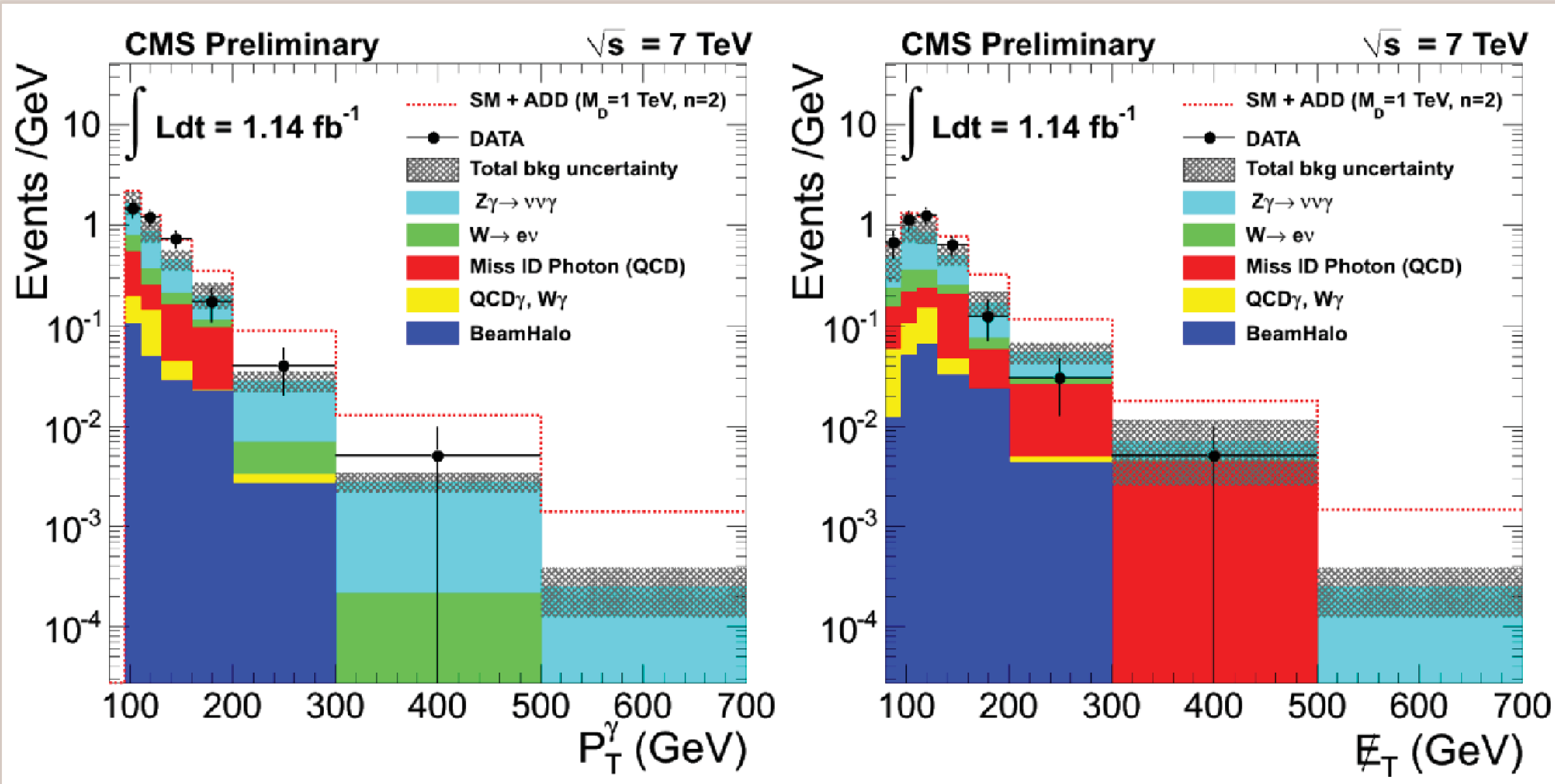
**Clear Signature**




CMS PAS EXO-11-058

# Mono-photon + Missing Energy

The distribution of photon $p_T$ and Missing Transverse Energy for the candidate sample, estimated background processes, and an ADD prediction with $M_S$ = 1 TeV and $n_{ED}$ = 2.

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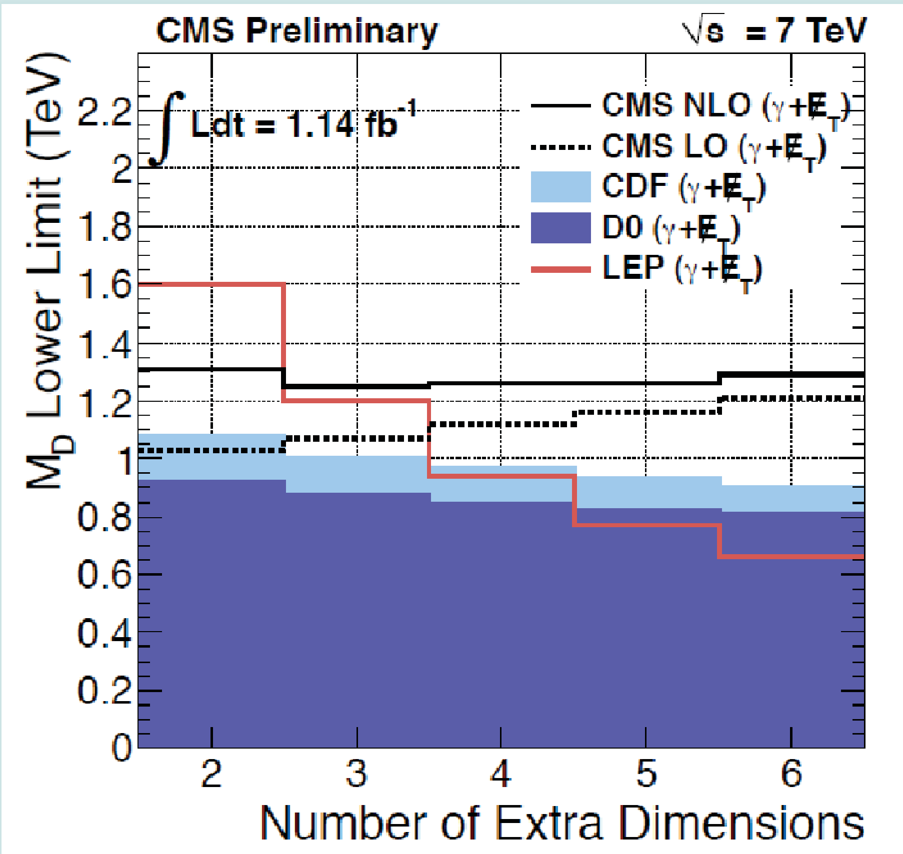
# Mono-photon + Missing Energy

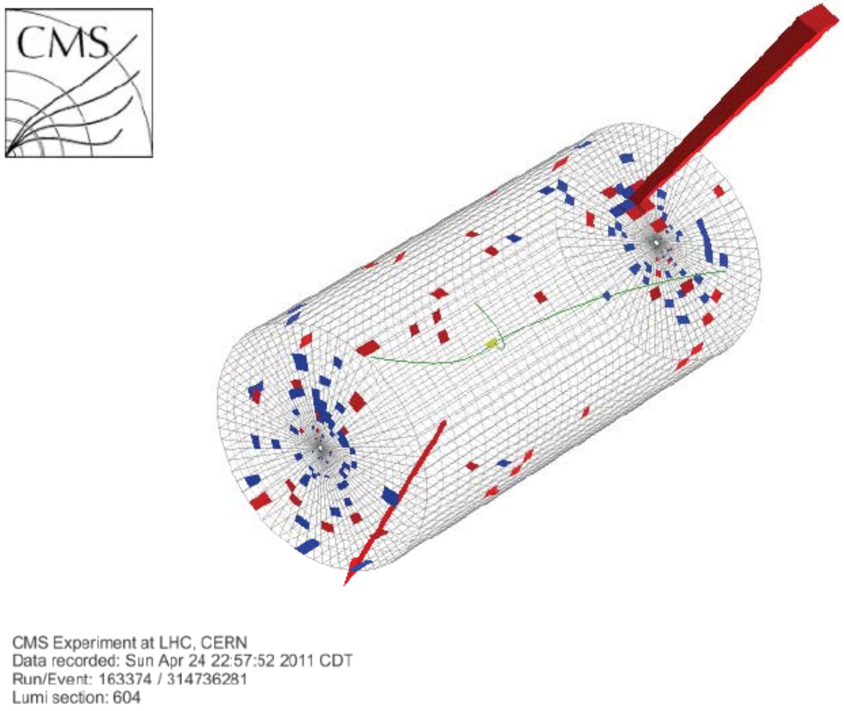
Limits on $M_D$ as a function of $n_{ED}$ compared to the LEP and Tevatron results for Photon+Missing Energy searches

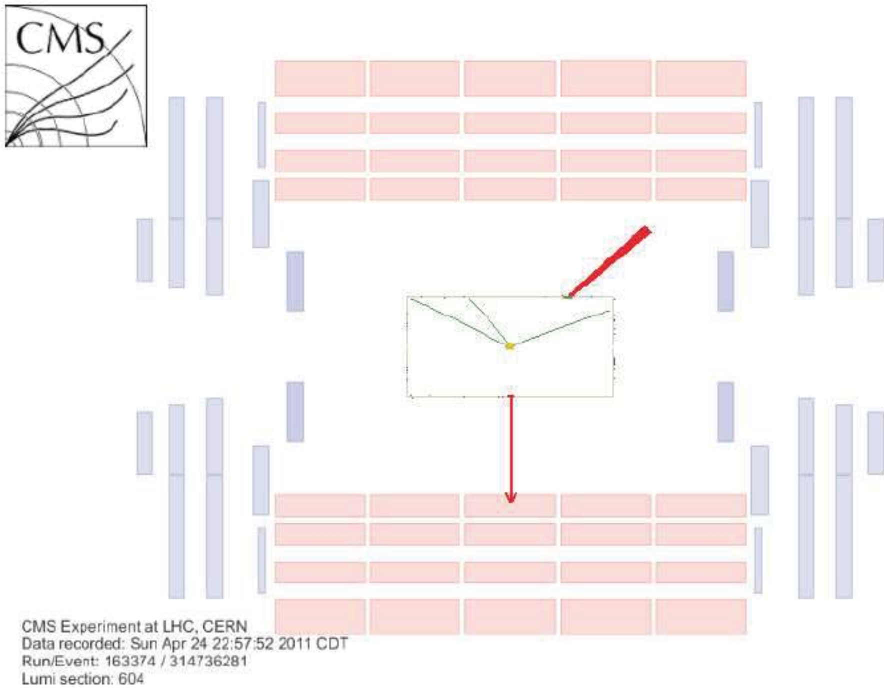



**The 95% CL observed and expected limits on $M_D$ as a function of $n_{ED}$, with and without the k-factor applied.**

| n | k-factor | Exp. Limit [TeV] | Obs. Limit, [TeV] |
|---|---|---|---|
| 2 | - | 1.17 | 1.03 |
| 3 | - | 1.20 | 1.07 |
| 4 | - | 1.24 | 1.12 |
| 5 | - | 1.27 | 1.16 |
| 6 | - | 1.31 | 1.21 |
| 2 | 2.0 | 1.45 | 1.31 |
| 3 | 1.7 | 1.38 | 1.25 |
| 4 | 1.5 | 1.36 | 1.26 |
| 5 | 1.4 | 1.37 | 1.26 |
| 6 | 1.3 | 1.38 | 1.29 |

# Interesting CMS Single Photon Candidate:



# Exchange of Virtual Gravitons: Di-photon Production

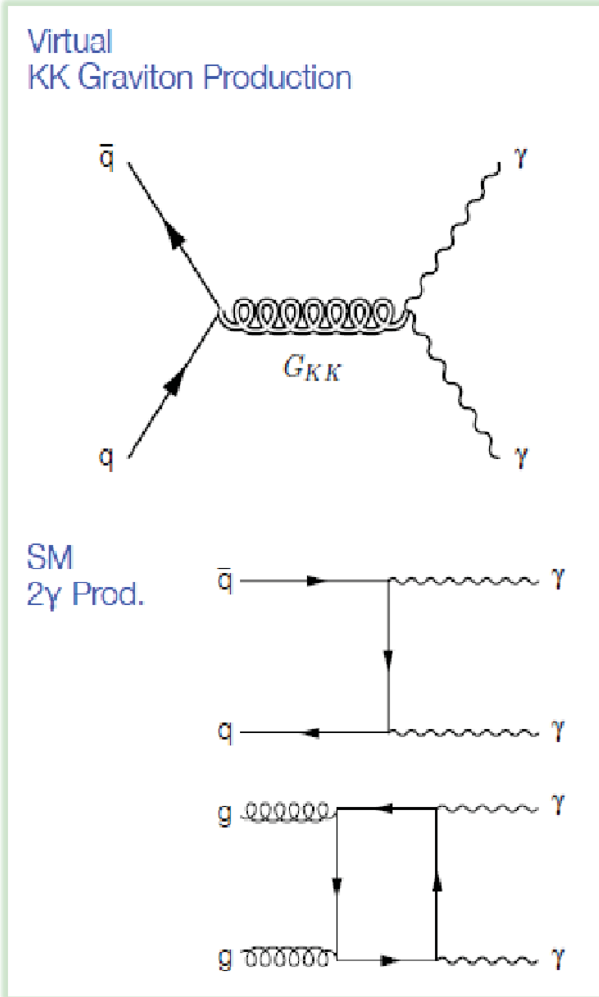
Signal: Two Prompt Photons

Backgrounds:

- Irreducible: SM diphoton production
- Photon+jet (jet is misidentified as a photon)
- Multijet

-γγ background is estimated from MC (Sherpa); NLO K-factor = 1.3.

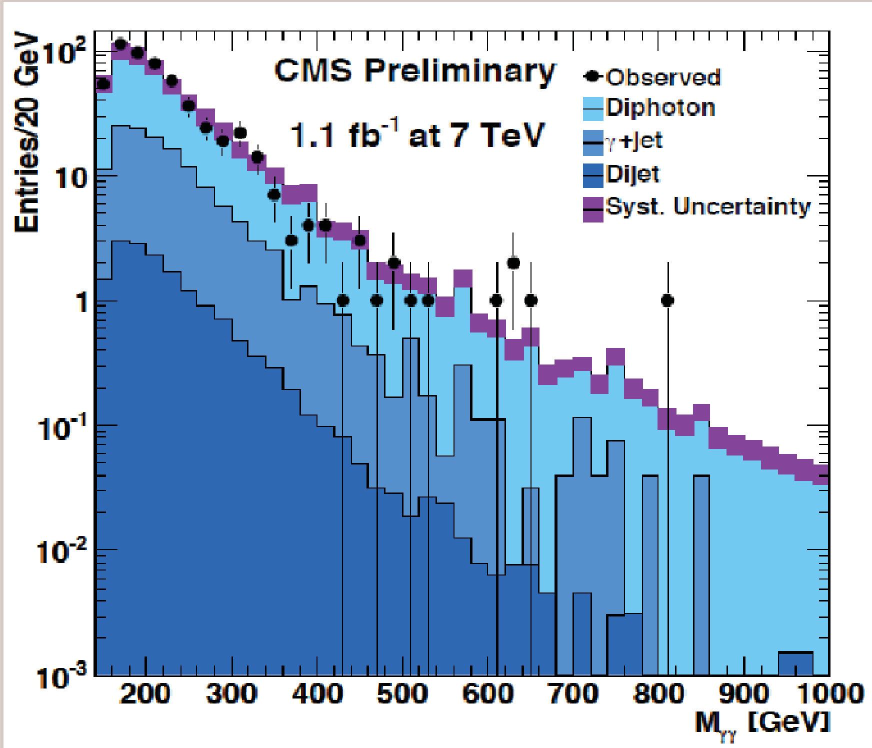
-Data-driven method to estimate jet-γ fake rate (for dijet and γ+jet backgrounds)



# Exchange of Virtual Gravitons: Di-Photon Production

-Two well reconstructed photons with $E_T > 70$ GeV and $|eta| < 1.44$ are required.

-ADD Signal events are in the high invariant mass region → A cut is applied on $M\gamma\gamma$ . The optimized cut is 800 GeV.

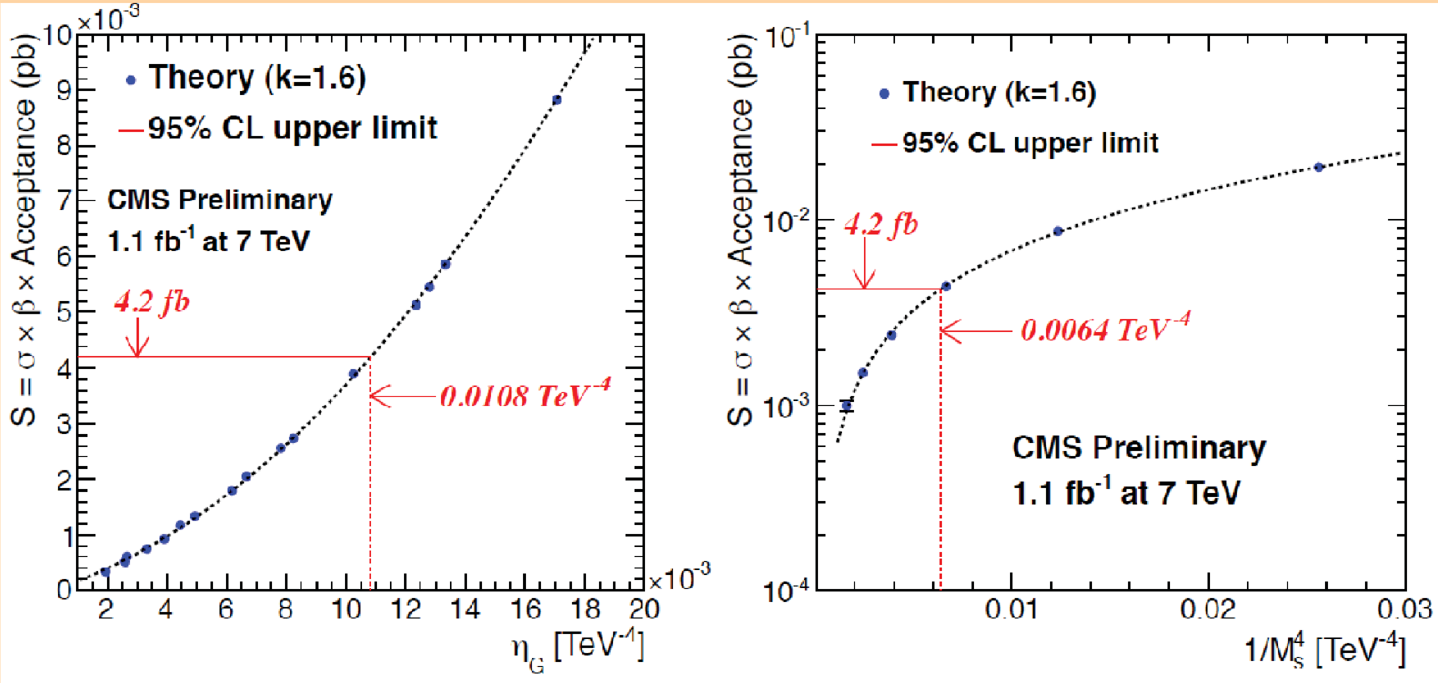



Data is in agreement with the SM background prediction

| Process | Diphoton Invariant Mass Range [TeV] | | | |
|---|---|---|---|---|
| | [0.14,0.2] | [0.2,0.5] | [0.5,0.8] | [0.8, ∞) |
| Multijet | $7 \pm 3$ | $9 \pm 3$ | $0.1 \pm 0.1$ | $0.003 \pm 0.001$ |
| $\gamma +$ jet | $53 \pm 8$ | $67 \pm 10$ | $1.5 \pm 0.2$ | $0.19 \pm 0.04$ |
| Diphoton | $185 \pm 33$ | $205 \pm 37$ | $7.6 \pm 1.4$ | $1.1 \pm 0.2$ |
| Total Backgrounds | $245 \pm 35$ | $283 \pm 39$ | $9.2 \pm 1.4$ | $1.3 \pm 0.2$ |
| Observed | 263 | 276 | 6 | 1 |

# Exchange of Virtual Gravitons: Di-Photon Production

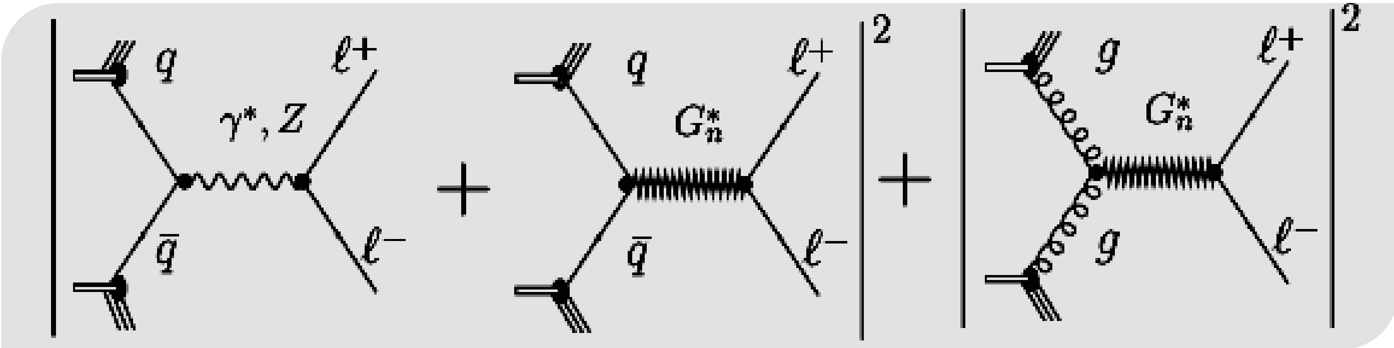
**Signal cross section parameterization as a function of the strength of the ED effects, $\eta_G$ (left) and as a function of $1/M^4_s$ for the $n_{ED}$ = 2 case (right)**




| K factor | $n_{ED} = 2$ | $n_{ED} = 3$ | $n_{ED} = 4$ | $n_{ED} = 5$ | $n_{ED} = 6$ | $n_{ED} = 7$ |
|---|---|---|---|---|---|---|
| 1.0 | 3.2 | 3.4 | 2.8 | 2.6 | 2.4 | 2.2 |
| 1.6 | 3.5 | 3.7 | 3.1 | 2.8 | 2.6 | 2.4 |

CMS PAS EXO-11-038

## Exchange of Virtual Gravitons: Di-lepton Production: P+P→l+l+X




$$\sigma = \sigma_{SM} + \eta_G \sigma_{int} + \eta_G^2 \sigma_{KK} \qquad \eta_G = F / M_s^4$$

**Signal: Two opposite sign same flavor leptons**

**Backgrounds:**

**Irreducible: Standard Model Drell-Yan**

**Other backgrounds:**

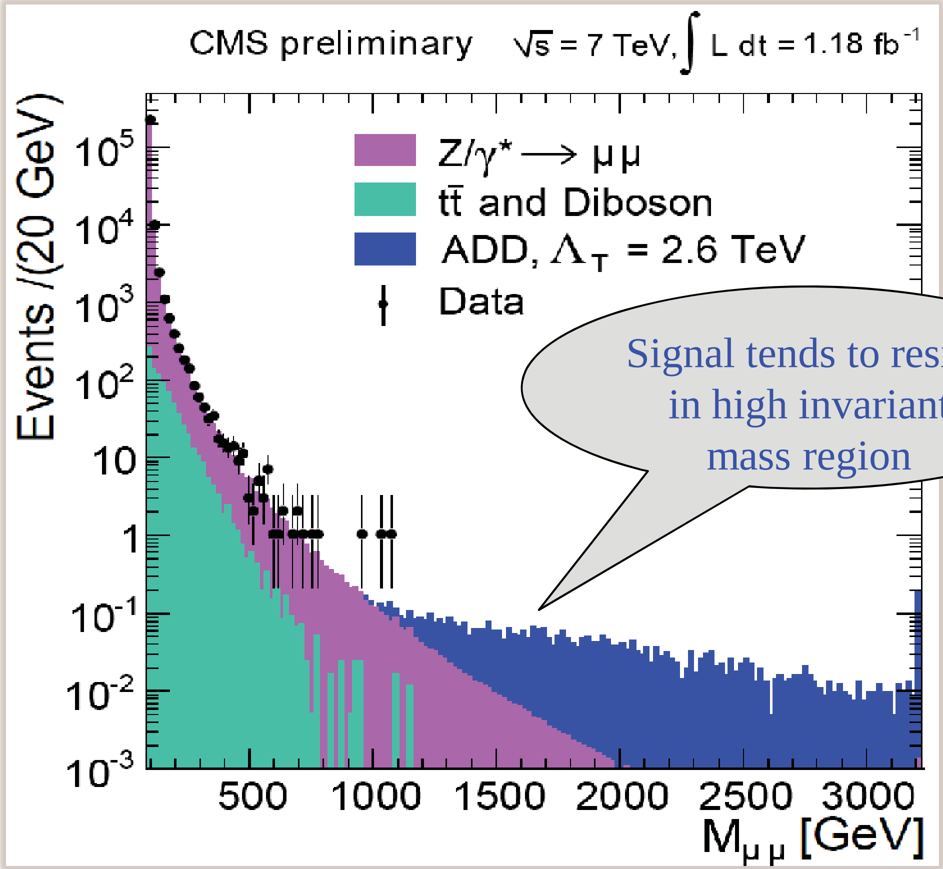
- -Top pair (specially dileptonic), WW,WZ,ZZ
- -Multijet
- -Photon+Jet

# Exchange of Virtual Gravitons: Di-muon Production

-Two isolated muons with:
$P_T$ > 35 GeV and |eta| < 2.1

-Signal events above an invariant mass cut are used for the analysis.
-The optimal invariant mass cut is found to be 1.1 TeV

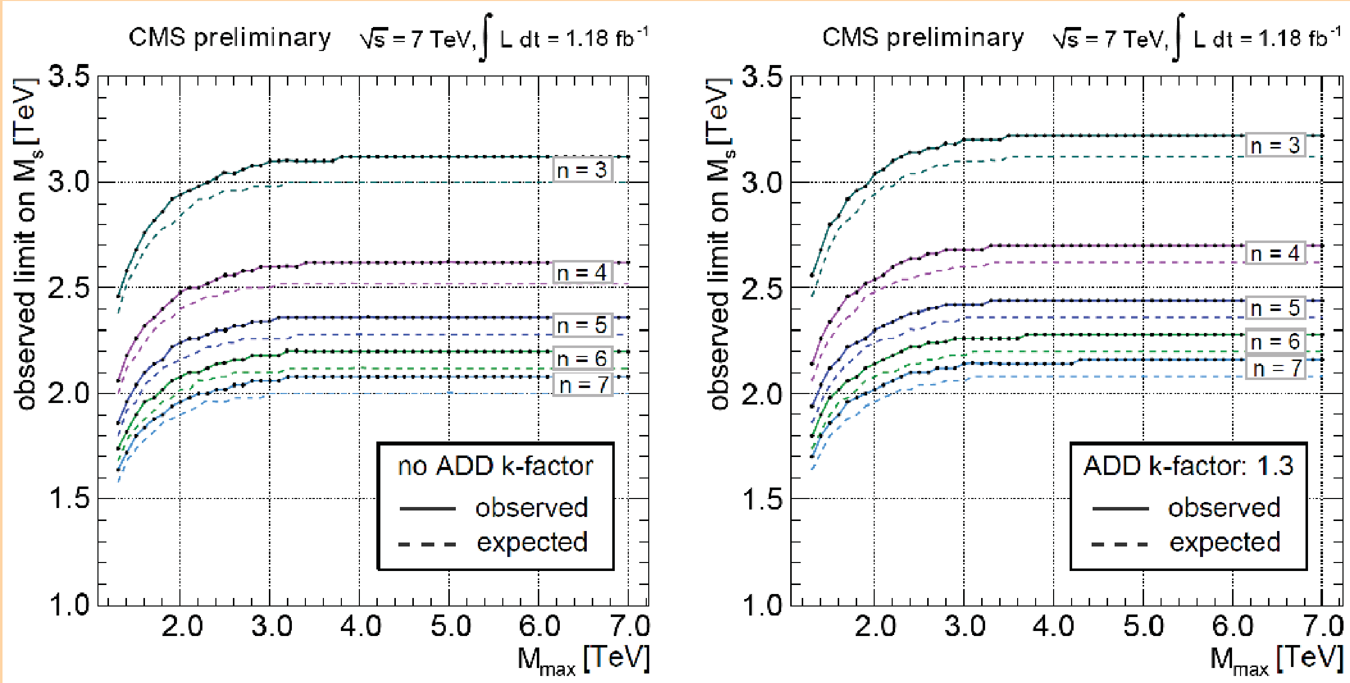
There are only contributions from DY above 1.1 TeV.




| mass region [GeV] | observed events | $\sqrt{N_{obs}}$ | bkg expectation | data/ bkg expectation |
|---|---|---|---|---|
| 80 – 120 | 231706 | 418 | 236321 | 0.98 |
| 120 – 200 | 4515 | 67 | 4583 | 0.99 |
| 200 – 400 | 850 | 29 | 841.3 | 1.01 |
| 400 – 600 | 68 | 8.2 | 62.3 | 1.09 |

# Exchange of Virtual Gravitons: Di-muon Production

Limits on the GRW and HLZ parameters for the two cases of full model validity and truncation at $M_{mu\text{-}mu} = M_s$



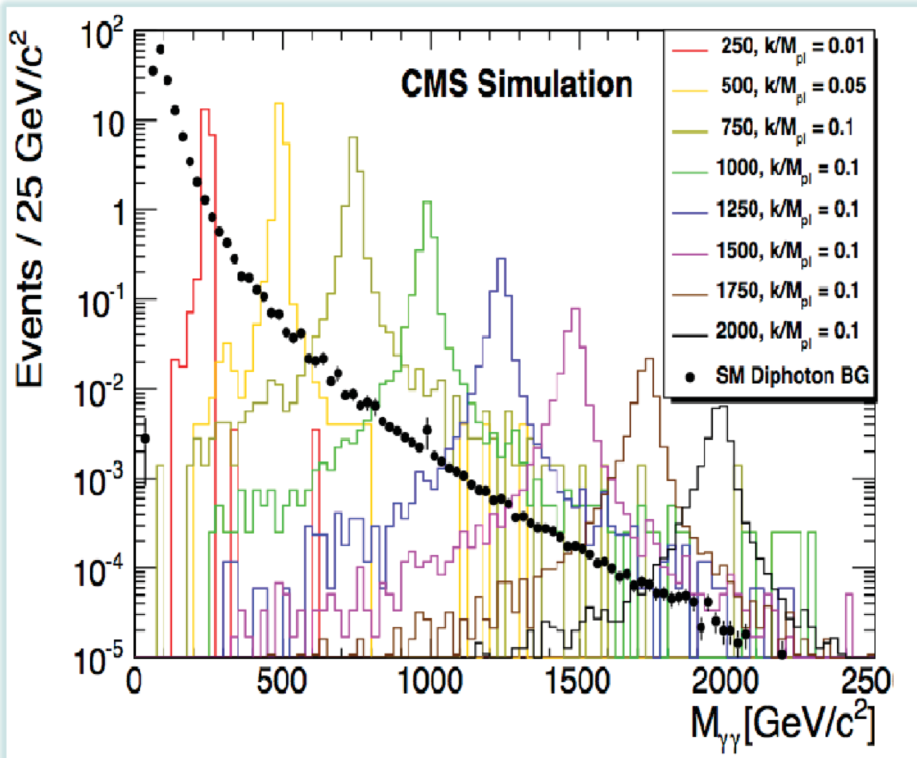

| | $\Lambda_T$ [TeV] (GRW) | $M_s$ [TeV] (HLZ) | | | | | |
|---|---|---|---|---|---|---|---|
| | | $n=2$ | $n=3$ | $n=4$ | $n=5$ | $n=6$ | $n=7$ |
| ADD k-factor: 1.0 | | | | | | | |
| Full | 2.62 | 2.58 | 3.12 | 2.62 | 2.36 | 2.20 | 2.08 |
| Truncated | 2.56 | 2.58 | 3.10 | 2.56 | 2.27 | 2.09 | 1.95 |
| ADD k-factor: 1.3 | | | | | | | |
| Full | 2.70 | 2.72 | 3.22 | 2.70 | 2.44 | 2.28 | 2.16 |
| Truncated | 2.66 | 2.72 | 3.20 | 2.66 | 2.37 | 2.17 | 2.02 |

**CMS PAS EXO-11-039**

# Search for RS Graviton: Di-Photon Production

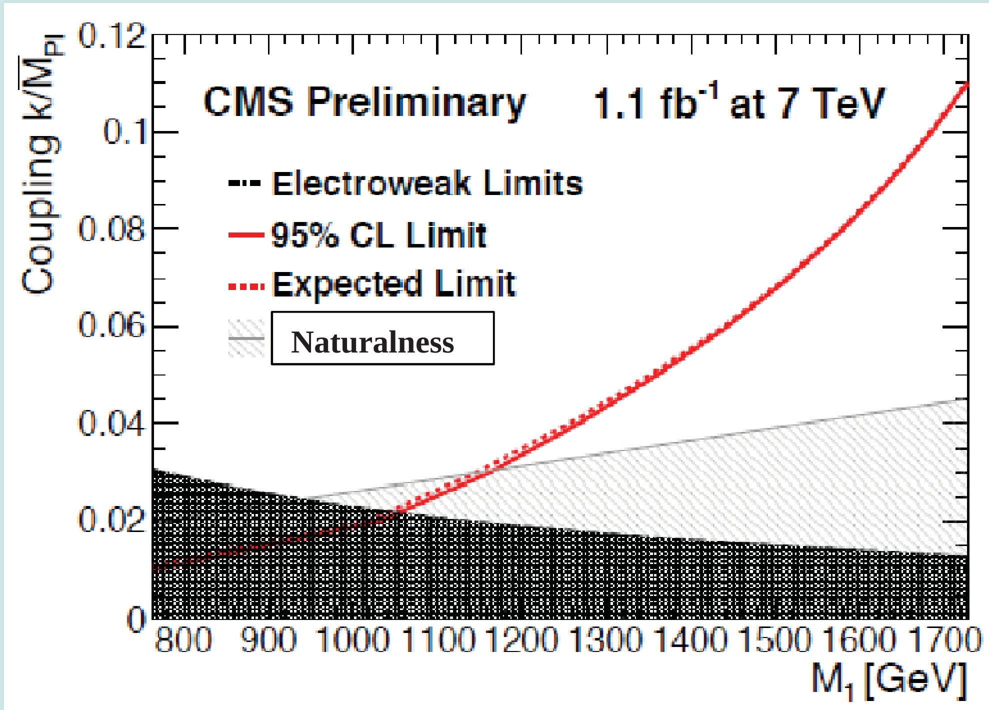
In the RS scenario, gravitons appear as a well-separated tower of Kaluza–Klein (KK) Excitations with masses and widths determined by the parameters of the RS1 model.

The excited gravitons can decay into two photons




The simulated signal shapes for a variety of mass points.

# Search for RS Graviton: Di-Photon Production




$$\tilde{k} \equiv \frac{k}{M_{\mathrm{Pl}}}$$

| $\tilde{k}$ | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 | 0.07 | 0.08 | 0.09 | 0.10 | 0.11 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $M_1$ [TeV] | 0.77 | 1.05 | 1.20 | 1.31 | 1.41 | 1.49 | 1.57 | 1.63 | 1.69 | 1.74 | 1.78 |

# Conclusions



- Several searches for extra dimensions performed in several channels at the CMS detector.
- No evidence of deviations from the Standard Model expectation observed.
- Limits obtained on the effective Planck scale depending on the number of extra dimensions in **ADD** scenario:

  The lower limit on $\mathbf{M_S}$ for n = 2-7 from different channels with almost the same amount of data:

| Channel | Bound on $M_S$ | Integrated Luminosity |
|---|---|---|
| Mono Jet+MET | 2.36-4.03 TeV | 1.1/fb |
| Diphoton | 2.4-3.7 TeV | 0.9/fb |
| Dimuon | 2.16-3.22 TeV | 1.18/fb |
| Mono Photon+MET | 1.29-1.31 TeV | 1.1/fb |

- RS: $M_1$ ~ 770 GeV to 1780 GeV for $k/M_{Pl}$ 0.01 to 0.11

Thanks to

-CMS colleagues for the results I have shown

-Organizing Committee

# Backup Slides

## Summary of the systematic uncertainties in Dimuon analysis

| Systematic Uncertainty | Related Parameter | Signal Uncertainty | Background Uncertainty |
|---|---|---|---|
| Trigger and reconstruction efficiency bkg. | $\epsilon_{\text{reco,b}}$ | — | 3% |
| Trigger and reconstruction efficiency signal | $\epsilon_{\text{reco,s}}$ | 4% | — |
| Muon momentum resolution | $\epsilon_{\text{res,b}}$ | — | 5% |
| Drell-Yan EW corrections | $\sigma_{\text{b}}$ | — | 7% |
| Drell-Yan QCD corrections | $\sigma_{\text{b}}$ | — | 5% |
| Drell-Yan PDF uncertainties | $\sigma_{\text{b}}$ | — | 12% |
| Luminosity | $\mathcal{L}$ | 5% | 5% |

| Source | Sys uncertainty in $A \times \epsilon_{MC}$ [%] |
|---|---|
| Jet energy scale | +3.5, -3.9 |
| PDFs | $\pm$ 2.9 |
| Photon scale $\pm$1.5% | +2.7, -2.3 |
| $\not{E}_T$ scale $\pm$5% | +0.6, -0.8 |
| Jet resolution +10% | -0.6 |
| Photon Vertex | -0.3 |
| $\not{E}_T$ resolution +10% | -0.06 |
| Total | +5.3, -5.5 |

Summary of the systematic Uncertainties in Single Photon analysis

# Summary of the systematic uncertainties in monojet analysis

- jet energy scale, where the uncertainty on signal acceptance varies between 8–11% depending on the jet $p_T$ and $\eta$ when requiring $E_T^{miss} > 200$ GeV, and between 10–20% for $E_T^{miss} > 350$ GeV
- parton density function uncertainties, evaluated using the the reweighting technique and Master Equation on the CTEQ6L model set [17], and measured to be 1–3% when requiring $E_T^{miss} > 200$ GeV, and between 3–8% for $E_T^{miss} > 350$ GeV.
- initial- and final-state radiation, modeled following a prescription for varying Space-like Showers in PYTHIA8 [14], and found to be less than 2%
- uncertainty due to the modeling of pile-up interactions in the background samples, estimated by comparing the distribution of number of primary vertices in the data sample to that of a standard reference sample, and is found to be 3%
- luminosity uncertainty of 4.5% [28].