



MINISTERIO  
DE CIENCIA  
E INNOVACIÓN

**Ciemat**  
Centro de Investigaciones  
Energéticas, Medioambientales  
y Tecnológicas

# Searches for physics beyond the Standard Model at CMS

Carmen Diez Pardos  
for the CMS collaboration

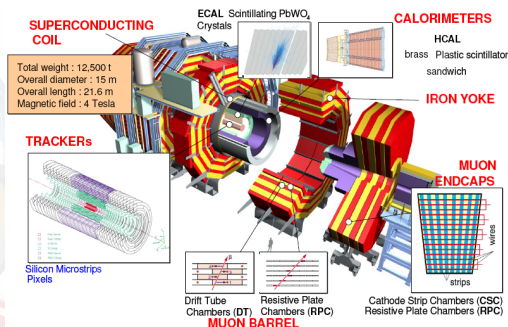
CIEMAT (Madrid)

III CPAN days, Barcelona  
2-4 November 2011



# Outline

- 1 Introduction
- 2 Heavy Resonances
- 3 Heavy long-lived Particles
- 4 4th Generation Quarks
- 5 Outlook



# Introduction

- 2010/2011 have been very exciting and productive for exotica searches
- We present most recent results: New analysis with 2011 data and updates ( $\sim 1 \text{ fb}^{-1}$ ) of 2010 analysis
- Complete information about all results:  
<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>
- This talk will not cover SUSY searches  
(<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults/SUS>),  
see G. Gómez's CMS Plenary talk, Thursday.

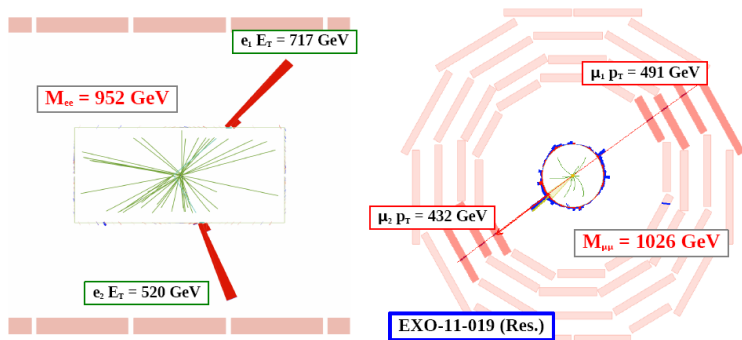
# Search for Heavy Resonances

- Predicted by numerous extensions of the Standard Model:
  - GUT-inspired theories, Little Higgs
  - Technicolor
  - Randall-Sundrum Extra Dimensions model. It has two free parameters
    - mass of the first graviton excitation
    - coupling  $k/\overline{M}_{Pl}$ ,  $k$  is the curvature of the extra dimension,  $\overline{M}_{Pl}$  reduce effective Planck scale
- Experimental challenge: understand detector performance (resolution, efficiency) at very high momentum
- New particles would be observed as a bump, excess in the mass spectrum

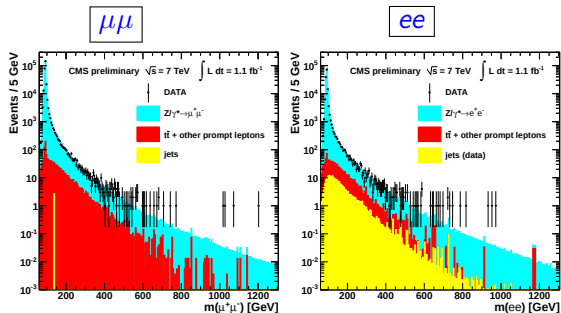
# Dilepton Resonances

## CMS-EXO-11-019

- Models used as benchmark: Randall-Sundrum graviton excitation, SSM  $Z'$ ,  $Z'_\psi$  predicted by grand unified theories
- Signature: two isolated electrons or muons, explicit requirement of opposite sign for the muon channel
- Search for a resonance in dilepton invariant mass spectrum

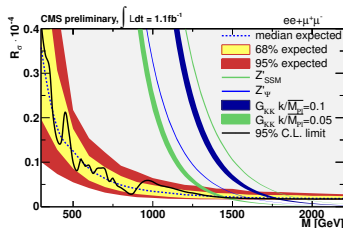


# Dilepton Resonances



Obtain limit in the ratio between the new gauge boson cross-section and the Z SM cross-section

$$R_\sigma = \frac{\sigma(pp \rightarrow Z' + X \rightarrow \ell\ell + X)}{\sigma(pp \rightarrow Z + X \rightarrow \ell\ell + X)}$$



$Z'_{SSM}$ : 1940 GeV

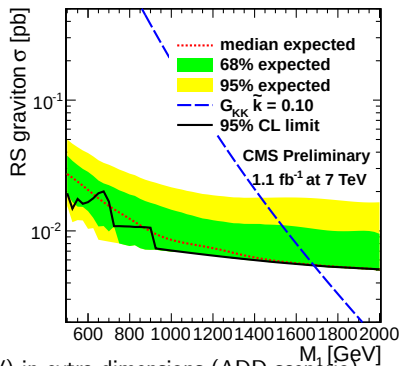
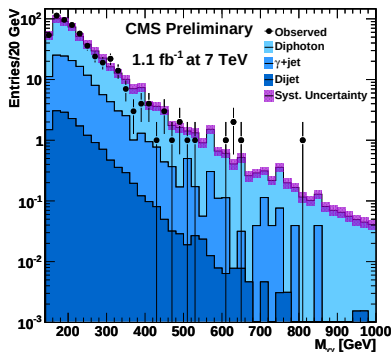
$G_{KK} (k/M_{Pl}=0.05)$ : 1450 GeV

$G_{KK} (k/M_{Pl}=0.10)$ : 1780 GeV

$Z'_\psi$ : 1620 GeV

# Heavy Resonance: Diphoton channel EXO-11-038

Looked for RS gravitons via resonances in the diphoton channel  $G_{KK} \rightarrow \gamma\gamma$ : lower limit on the mass set at 1.7 TeV ( $k/M_{Pl} = 0.1$ )



- Also limits on the effective Planck scale (in TeV) in extra dimensions (ADD scenario)

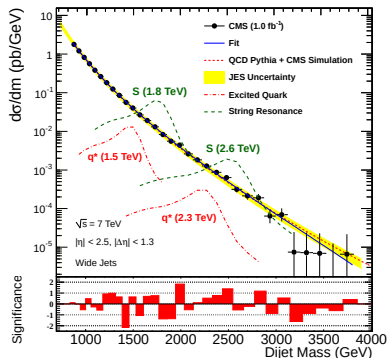
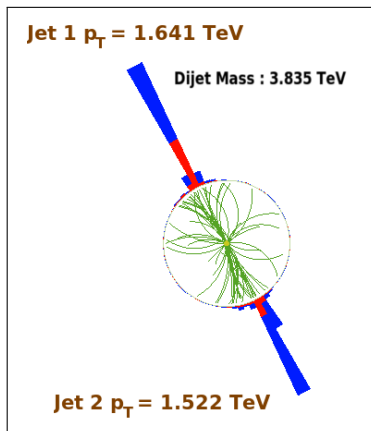
| K factor | $n_{ED} = 2$ | $n_{ED} = 3$ | $n_{ED} = 4$ | $n_{ED} = 5$ | $n_{ED} = 6$ | $n_{ED} = 7$ |
|----------|--------------|--------------|--------------|--------------|--------------|--------------|
| 1.0      | 3.2          | 3.4          | 2.8          | 2.6          | 2.4          | 2.2   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

# Dijet resonances

10.1016/j.PhysLetB.2011.09.015

High sensitivity to strongly produced new resonances predicted in numerous models: string phenomena, excited quarks, colorons, diquarks

- Looking for resonances above expectation from phenomenological fit to the data



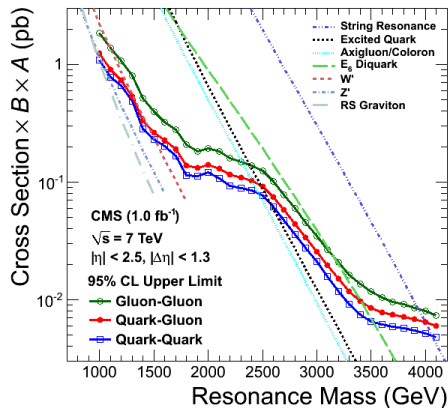


# Model independent cross-section limits

- 95% CL upper limits on  $\sigma \times \text{BR} \times A$  for dijet resonances of type **gluon-gluon**, **quark-gluon** and **quark-quark**.
- These upper limits are compared to the theoretical predictions for seven resonance models.

95% CL Mass Limit (TeV) using CTEQ6L

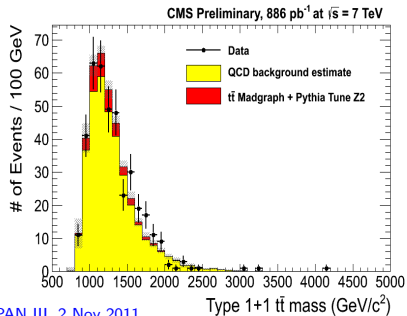
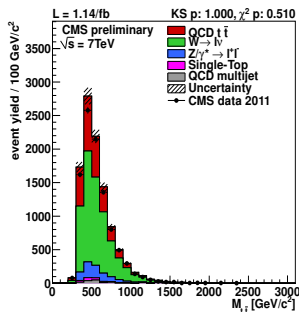
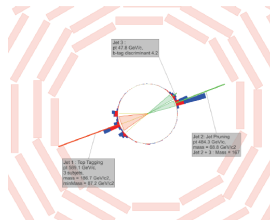
| Model         | Observed | Expected |
|---------------|----------|----------|
| String        | 4.0      | 3.9      |
| $q^*$         | 2.49     | 2.68     |
| Axigluon      | 2.47     | 2.66     |
| $E_6$ diquark | 3.52     | 3.28     |
| $W'$          | 1.51     | 1.40     |



Probing the quark structure up to 4 TeV

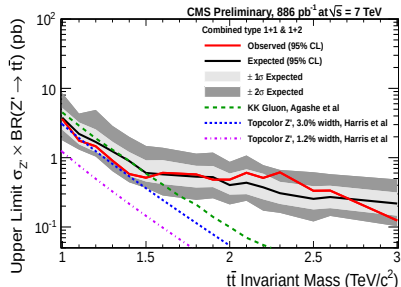
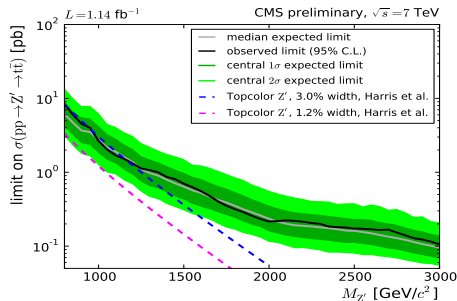
# $Z' \rightarrow t\bar{t}$

- Search in the semileptonic ( $t\bar{t} \rightarrow WbWb \rightarrow qq b \mu \nu b$ ) and all hadronic decay channel ( $t\bar{t} \rightarrow WbWb \rightarrow qq b q q b$ ).
- Tops are boosted for high mass  $Z'$ , their products either partially or fully merged into one jet. Developed dedicated algorithms for jet-reconstruction for  $M_{t\bar{t}} \geq 1$  TeV.



# Semileptonic EXO-11-055 and All-Hadronic EXO-11-006

- Exclusion limits on SSM  $Z'$ , KK and topcolor models
  - Semileptonic:  $Z'$  topcolor excluded in mass regions 850-935 GeV, 960-1060 GeV, sub-pb limits set on  $\sigma(pp \rightarrow Z' \rightarrow t\bar{t})$  for masses above 1.35 TeV
  - All hadronic: KK gluon excluded 1.0-1.5 TeV, subpicobarn limits to  $Z'$  masses above 1.1 TeV



# W' Searches

- **Left-Right symmetry** of electroweak interactions: Extend the SM gauge group to include RH interactions.
- **Technicolor**.
- General extensions of the SM gauge group, as **Little Higgs models**

$$W' \rightarrow l\nu$$

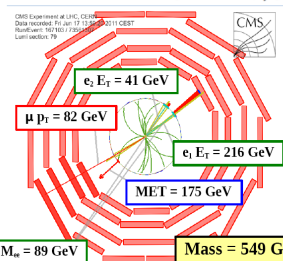
$$W'/\rho_{TC} \rightarrow WZ \rightarrow l\nu ll$$

$$W_R \rightarrow lW^* \rightarrow l(jj'l)$$

**M<sub>T</sub> = 778 GeV**

**MET = 374 GeV**

**μ p<sub>T</sub> = 404 GeV**



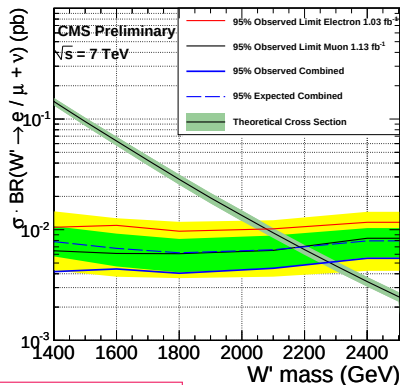
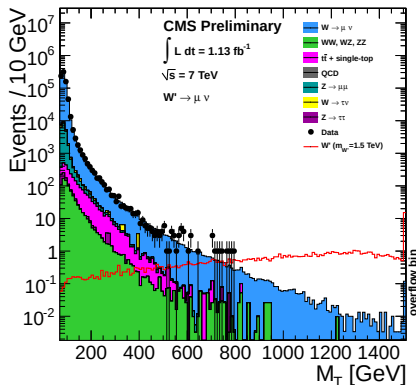
**Mass = 1009 GeV**

# $W'$ leptonic ( $\mu, e$ ) channels

EXO-11-024

- Signature: 1 isolated high  $p_T$  lepton + missing transverse energy,  $E_T^{miss}$ , look for a jacobian peak in the transverse mass spectrum

$$M_T = \sqrt{2(p_T^l \cdot c)E_T^{miss}(1 - \cos \Delta\phi_{l,\nu})}$$

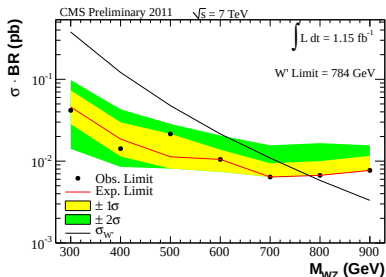
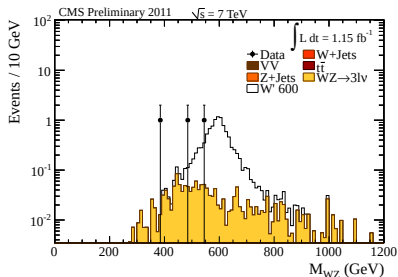
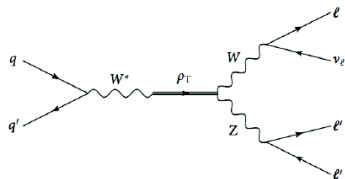


$W'$  with SM-like couplings is excluded below

$M_{W'} = 2.27 \text{ TeV}$

# WZ Resonances EXO-11-041

- $W'$  or  $\rho_{TC}$  to WZ
- All leptonic channel ( $W \rightarrow l\nu$ ,  $Z \rightarrow ll$ )
- Reconstruct  $M_{WZ}$  by constraining  $m_W$



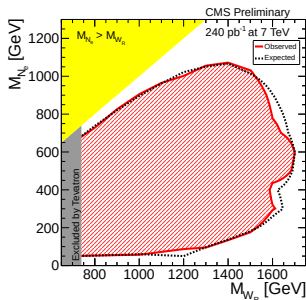
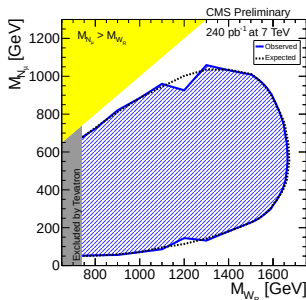
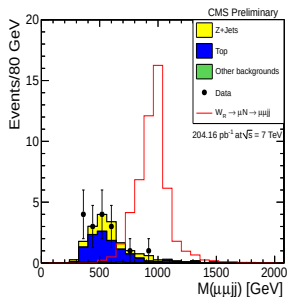
Sequential SM:  $M_{W'} > 784 \text{ GeV}$

Technicolor:  $M_\rho > 384 \text{ GeV}$

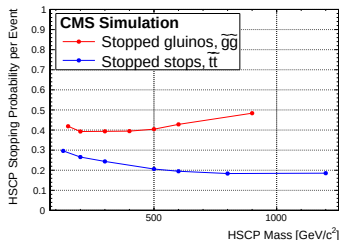
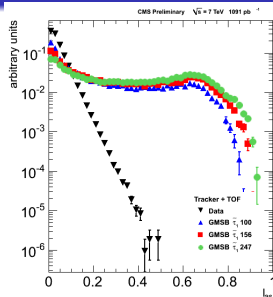
# $W' \rightarrow lN$ EXO-11-002

- Search for  $W'$  decaying to a lepton plus a right-handed (heavy) neutrino
- Benchmark: LR symmetric models
- Final state: two (same-flavour) **muons** or **electrons** plus two jets

$$W'_R \rightarrow lN \rightarrow l(IW_R^*) \rightarrow l(ljj)$$



# Heavy long-lived Particles

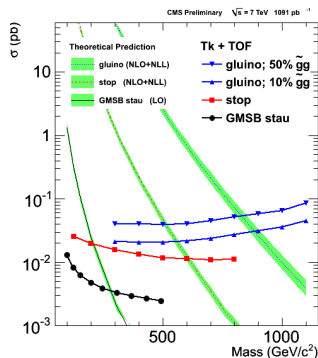
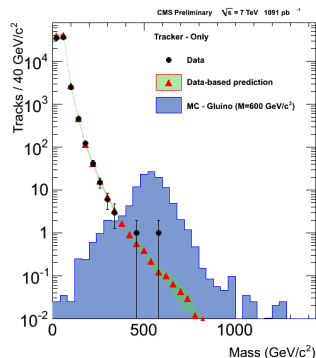


- Predicted by many new physics scenarios
  - Some flavours of SUSY
  - Hidden valley models
  - GUT's
  - Split SUSY
- Charged heavy particles: Slow moving particles will lose E at a higher rate than MIP. If hadron-like, can stop in the detector.
- Two complementary methods:
  - High momentum tracks with high  $dE/dX$ .
  - Stopped particles, decay product signals out-of-synch. w.r.t. bunch crossing ( $\beta < 0.4$ ).



# Direct Search for HSCP EXO-11-022

- Look for the distinctive signature of a high momentum particle with an anomalously large rate of energy loss through ionization ( $dE/dx$ ) and an anomalously long time-of-flight (TOF).
- Limits on the production cross-section for **stau**, **stop** and **gluino**, translated into the mass of the particle



$$m_{\text{stau}} > 293 \text{ GeV}$$

$$m_{\text{stop}} > 829 \text{ GeV}$$

$$m_{\text{gluino}} > 885 \text{ GeV}$$

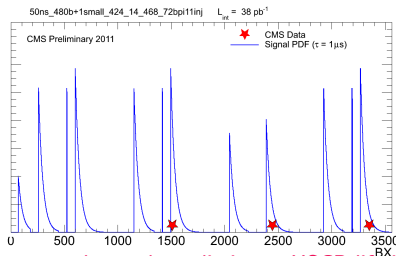
# Search for Stopped HSCP

## EXO-11-020

- If long-lived gluinos (stops) are produced at CMS will hadronise into 'R-hadrons' ( $\tilde{g}g, \tilde{g}q\bar{q}, \tilde{g}qqq$  states).
- These stopped R-hadrons may decay during time intervals when there are no pp collisions.

### Time profile analysis

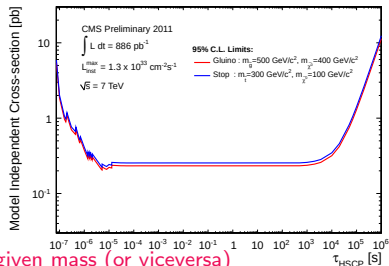
- HSCP stops in the hadronic calorimeter, its decay produces large energy deposit outside collision window
- Look for signal without collisions: No beam in the machine and between bunch trains



No excess observed, set limits on HSCP lifetime for a given mass (or viceversa)

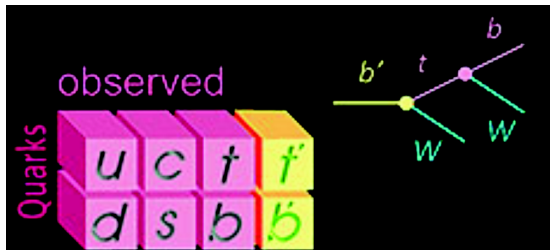
### Counting experiment

- Hypothesis on lifetime from 75ns to  $10^6$ s: set limits on  $\sigma \times$  stopping probability over 13 orders of magnitude in  $\tau_{HSCP}$ .
- Result independent of models of R-hadron formation and nuclear int.



# Search for 4th Generation quarks

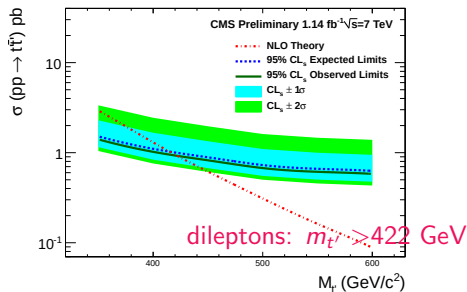
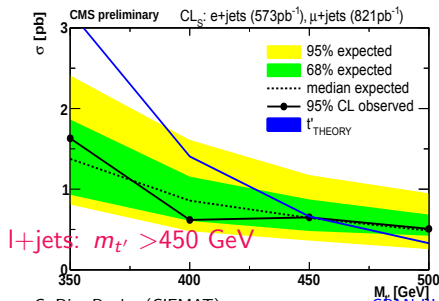
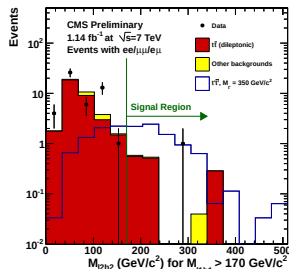
- Flavour physics: It could explain some observed discrepancies
- It is not excluded by EWK precision measurements
- New CP source for Baryogenesis



- Search for production of  
 $t'\bar{t}'$ ,  $b'\bar{b}'$   
 $t'b$ ,  $b't$

# Heavy top-like quark EXO-11-050/051

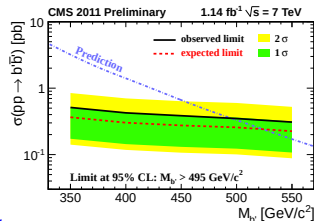
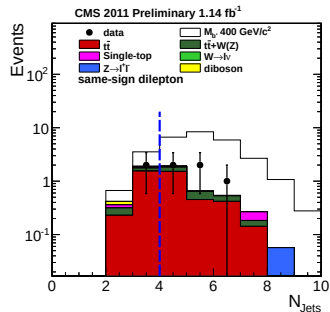
- Search for the production of  $t'\bar{t}' \rightarrow WbWb$
- $t' \rightarrow Wb$ : top-like signal (l+jets, dilepton), but heavier
- Experimental challenge: large  $t\bar{t}$  background



# Heavy Bottom-Like Quarks

EXO-11-036

- Search for production of  $b'\bar{b}' \rightarrow tW^-tW^+ \rightarrow bW^+W^-\bar{b}W^-W^+$
- Signature: 3-lepton or same signed-dileptons +  $\geq 1$  b-jet
- Higher mass than top quark and more jets than top pair decays
- $b'$  excluded below 495 GeV



# Inclusive Search for 4th Generation Quarks EXO-11-054

- Inclusive search for  $t'$  and  $b'$  quarks, produced singly or in pairs
- Muon + jets channel: Signature a high  $p_T$  isolated muon,  $E_T^{miss}$  and at least 1 b-tag jet
- Classify events according to number of hadronically decaying Ws and b-tags
- Assume simplified model where  $m_{t'} = m_{b'}$  and one free parameter in the CKM4

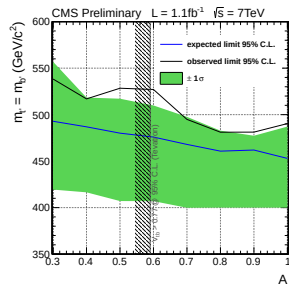
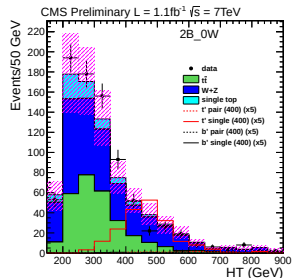
$$\text{CKM4} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{ub'} \\ V_{cd} & V_{cs} & V_{cb} & V_{cb'} \\ V_{td} & V_{ts} & V_{tb} & V_{tb'} \\ V_{t'd} & V_{t's} & V_{t'b} & V_{t'b'} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & \sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

- For minimal offdiagonal mixing ( $A \sim 1$ ),

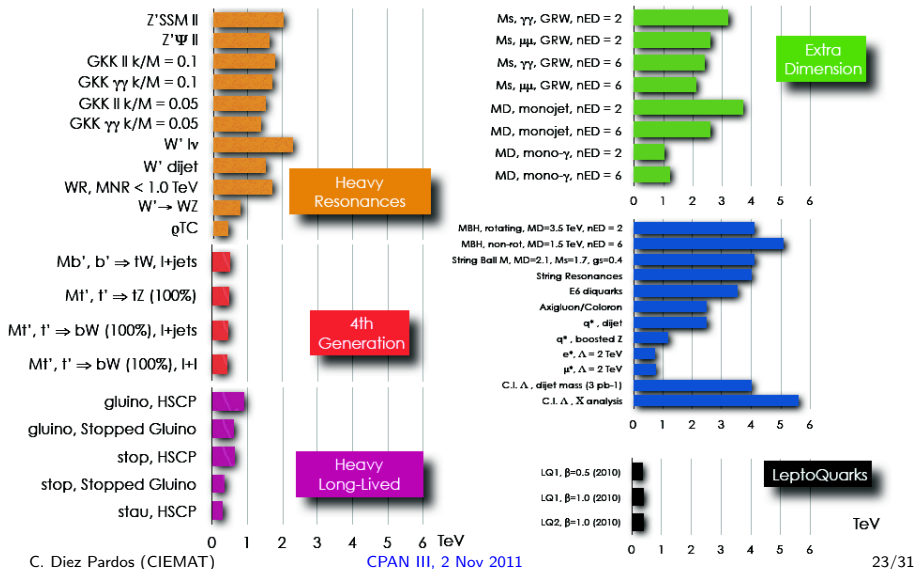
observed lower mass limit 490 GeV

C. Diez Pardos (CIEMAT)

CPAN III, 2 Nov 2011

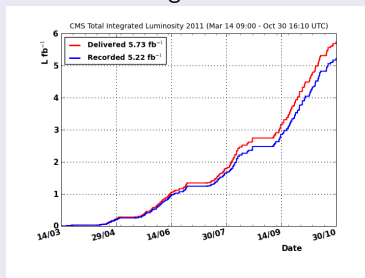


# CMS Grand Summary (as of PIC2011, thanks to S. Rahatlou)



# Summary and outlook

- In this talk we presented results with integrated luminosity of  $\sim 1 \text{ fb}^{-1}$ .
- Rich program of searches for physics beyond the SM, setting stringent limits to many benchmark models.
- Unfortunately, New Physics was not "around the corner".
- Experimental challenges as we enter further the Multi-TeV regime
  - TeV leptons
  - Boosted objects
  - More complex signatures
- Both the LHC and CMS are performing very well, the total luminosity recorded in 2011 amounts to more than  $5 \text{ fb}^{-1}$ , analysis of these data ongoing.

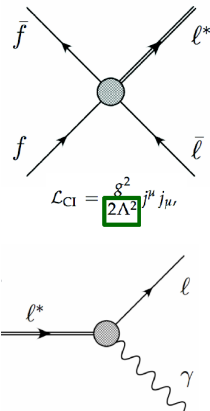




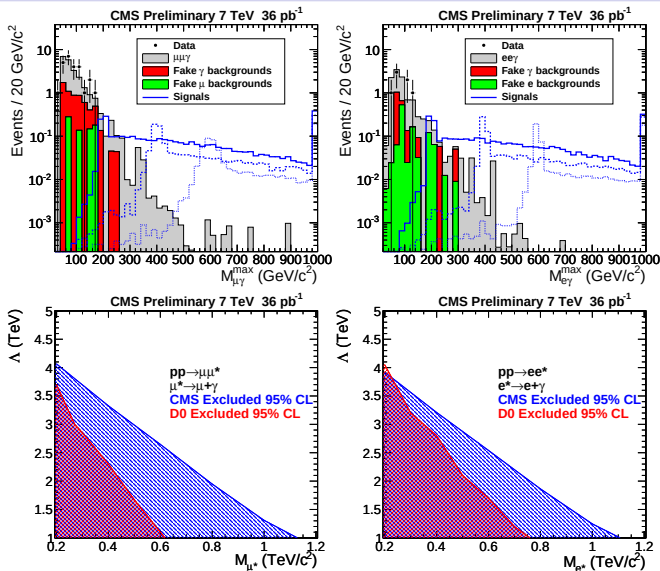
# BACK UP

# Excited leptons: Motivation

- The Standard Model lepton mass hierarchy can be explained by the existence of lepton substructure
  - Leptons made up of bound states of 3 fermions or a fermion and a boson that can be excited and then decay to ordinary leptons
- Search for the production of an excited lepton ( $e^*/\mu^*$ ) in association with a SM Model lepton via novel contact interactions (scale determined by  $\Lambda$ ).
  - $l^*$  decays via the EWK interactions resulting in a final state of two high- $E_T$  leptons and one high- $E_T$   $\gamma$
  - The decay width for other decay modes taken into account:  $\text{BR}(l^* \rightarrow l \gamma) = 25\%$  for low  $M_{l^*}/\Lambda$
  - Two theory parameters:  $\Lambda$  and  $M_{l^*}$

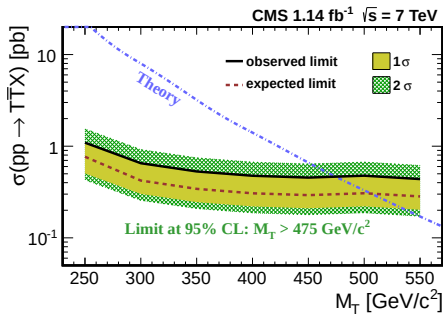
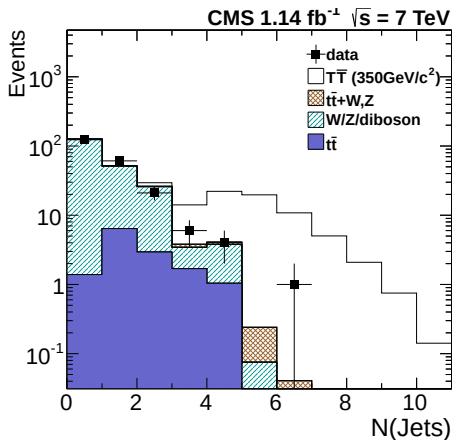


# Excited Leptons: Limit setting



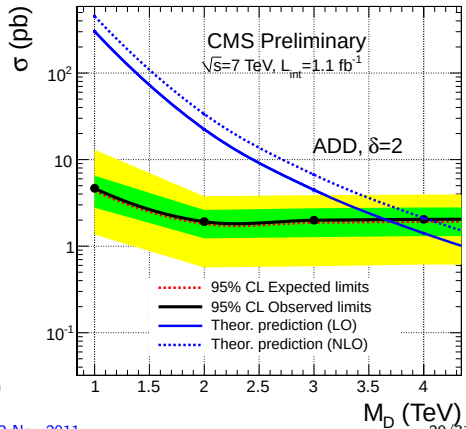
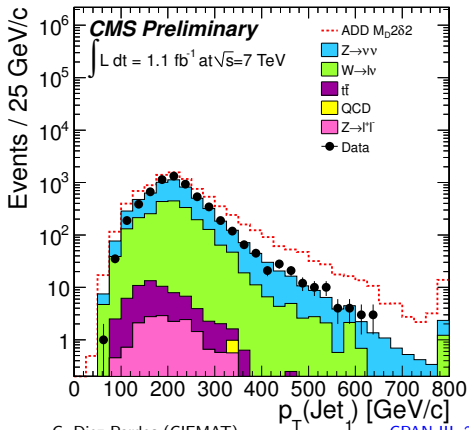
# $T \rightarrow tZ$ ZFCNC processes 1109.4985 (hep-ex)

Flavour-changing neutral current  $t'$  decay, in trilepton channel



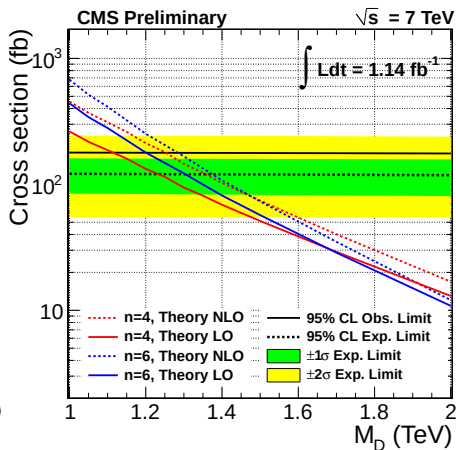
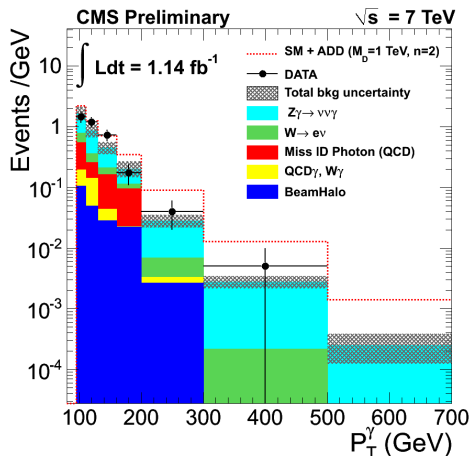
# Search for monojets EXO-11-041

- Large ED (ADD scenario), also split SUSY
- Final states with missing transverse energy plus single-jet



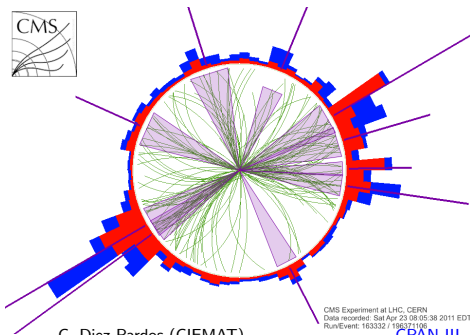
# ED with monophoton Final State EXO-11-058

Large ED (ADD scenario), similarity to monojet: search for a photon and nothing else



# Black holes EXO-11-071

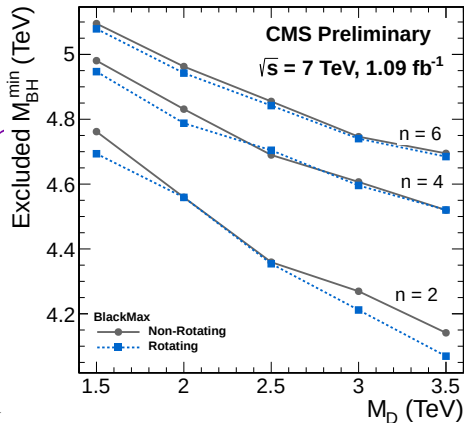
- Microscopic BH decaying through Hawking radiation
- Large uncertainty on models due to our ignorance of quantum gravity



C. Diez Pardos (CIEMAT)

CMS Experiment at LHC, CERN  
Data recorded: Sat Apr 23 08:05:38 2011 EDT  
Run/Event: 163332 / 196371106

CPAN III, 2 Nov 2011



31/31