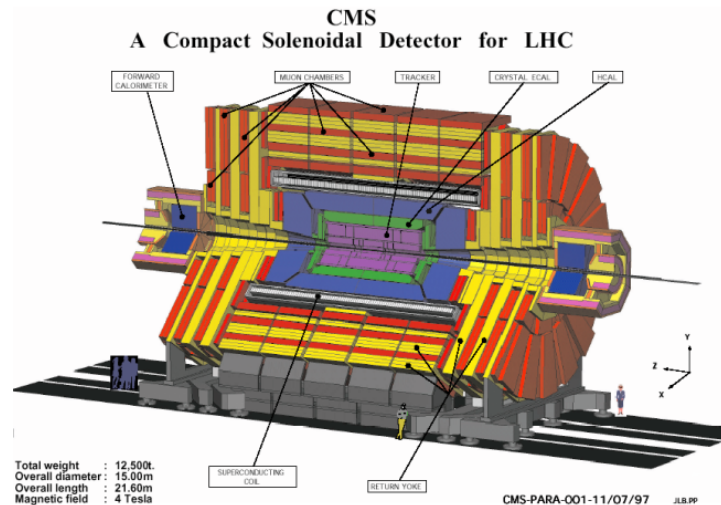




# Highlights of non-SUSY searches for physics beyond the SM from the CMS Detector at the LHC

Ilya Gorbunov and Sergei Shmatov  
Joint Institute for Nuclear Research, Dubna  
on behalf of CMS Collaboration



XXIth International Workshop High Energy Physics and  
Quantum Field Theory  
23-30 June 2013, Saint Petersburg, Russia



# OUTLINE

## Exotica at LHC is Physics beyond SM/SUSY/Higgs

- ❑ Heavy Resonances (extended gauge models, extra dimensions, technicolor)  $\Rightarrow$  dileptons, dijets, diphotons,  $t\bar{t}$ , WZ
- ❑ Non-Resonant Signals
- ❑ Mono-particle + Missing ET (extended gauge models, extra dimensions, technicolor)  $\Rightarrow$  mono-jet + MET, mono-photon + MET, mono-lepton + MET
- ❑ Black Holes (extra dimensions)  $\Rightarrow$  high-multiplicity events
- ❑ Leptoquarks
- ❑ 4<sup>th</sup> Generation  $\Rightarrow$  lepton + jet, dilepton

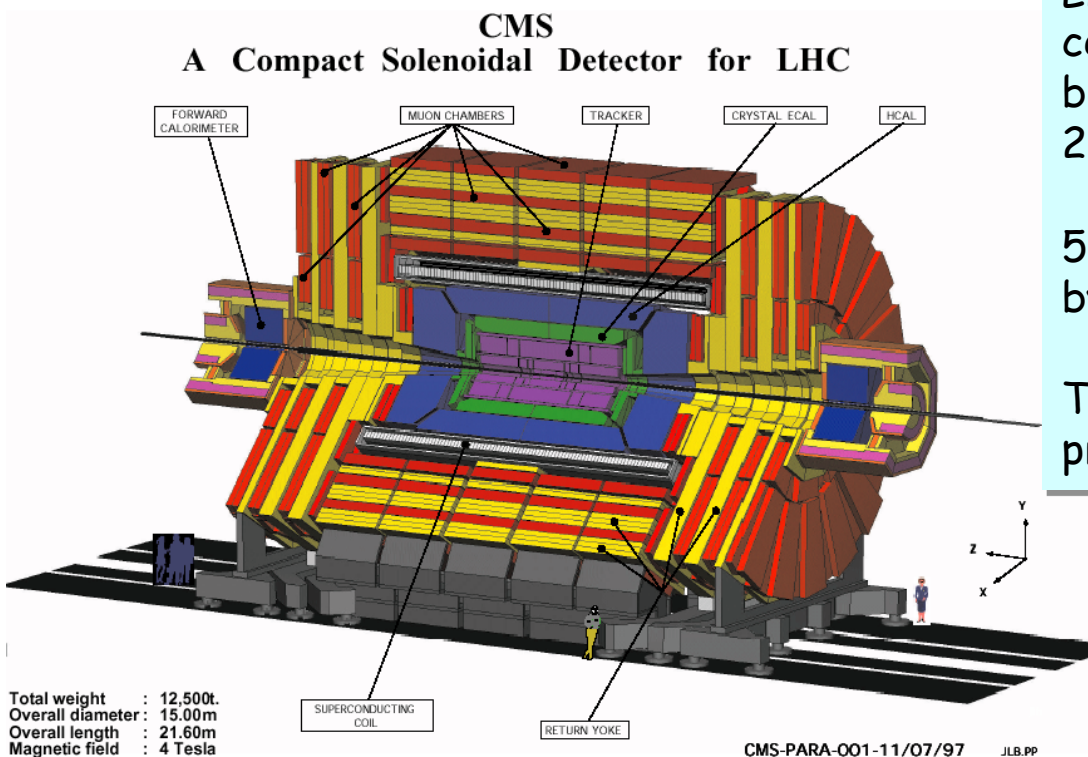
### CMS Exotica Public Physics Results

<https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>



# Compact Muon Solenoid

## Large general-purpose particle physics detector



LHC provided  $6.13 \text{ fb}^{-1}$  at a 7 TeV center-of-mass energy of proton beams for 2011 and  $23.3 \text{ fb}^{-1}$  at a 8 TeV for 2012

$5.55 \text{ fb}^{-1}$  and  $21.79 \text{ fb}^{-1}$  were recorded by CMS in 2011 and 2012

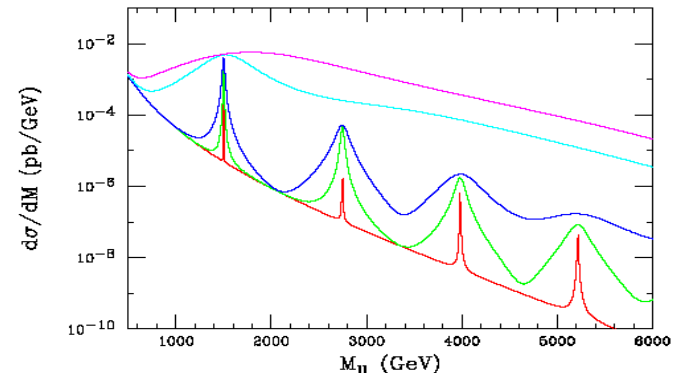
The results covered by this talk were produced with up to  $20 \text{ fb}^{-1}$

<i>Total weight</i>	<b>12 500 t</b>
<i>Overall diameter</i>	<b>15.00 m</b>
<i>Overall length</i>	<b>21.6 m</b>
<i>Magnetic field</i>	<b>3.8 Tesla</b>

**Detector subsystems are designed to measure:**  
 the energy and momentum of photons, electrons, muons, jets, missing  $E_T$  up to a few TeV

# Heavy Resonances

- ❑ Extra gauge bosons predicted by extended gauge models (left-right symmetric models and GUT-inspired models)
- ❑ Kaluza-Klein graviton excitations arising in extra dimensions models with curved bulk space (Randall-Sundrum model)
  - Small extra spatial dimensions, Curved bulk space (AdS<sub>5</sub> - slice)
  - Well separated graviton mass spectrum



- ❑ Kaluza-Klein excitations of SM gauge bosons in large flat extra-dimensions (TeV-1 Models)
  - Bosons could also propagate in the bulk
  - Fermions are localized at the same (opposite) orbifold point: destructive (constructive) interference between SM gauge bosons and KK excitations

## ❑ Technicolor

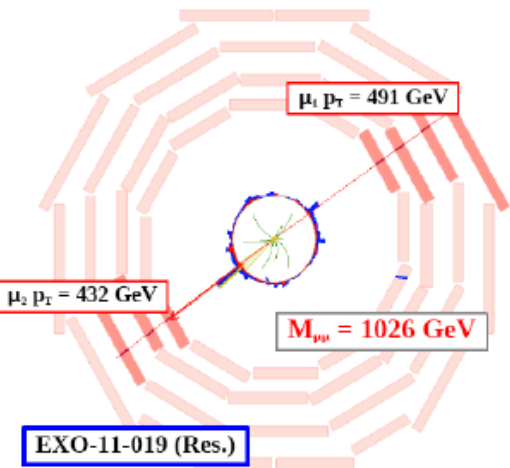
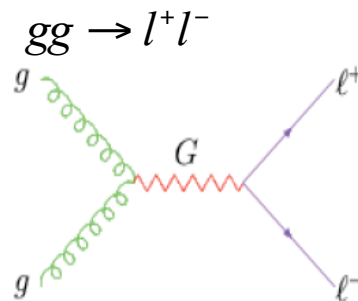
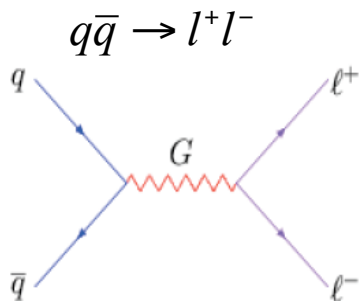
Signals: di-leptons/di-jets/di-photons resonance states in high (~TeV) invariant mass range ⇒ new particles would be observed as a bump, excess in the mass spectrum

Excellent momentum and energy resolutions are required !!

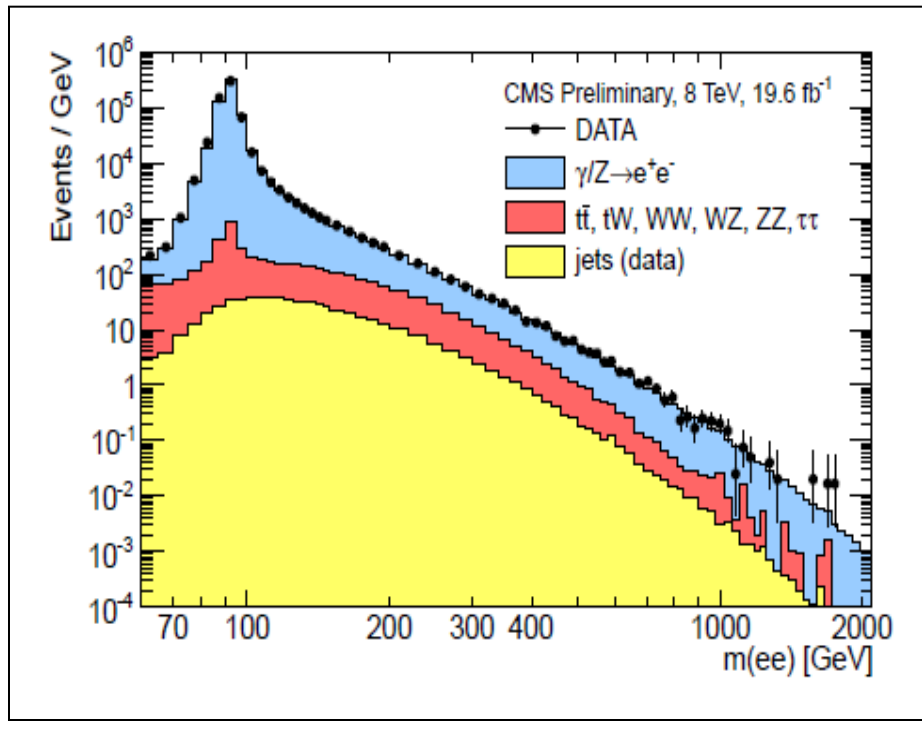
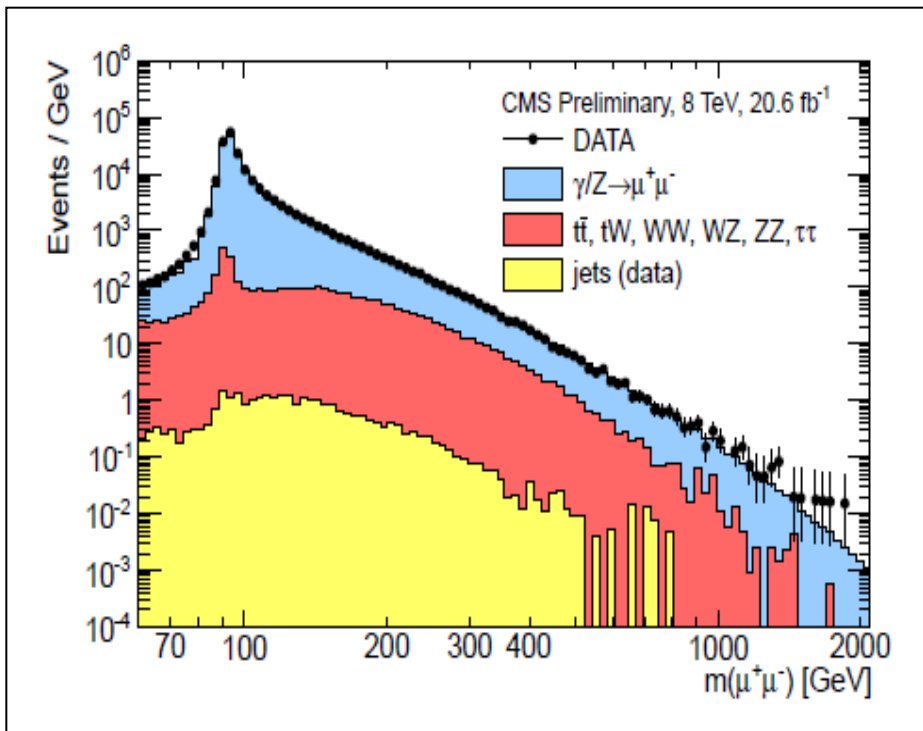


# Dileptons: Spectra

New Physics ( $Z'/Z_{KK}/G_{KK}$ ) contributions to SM processes:



CMS PAS EXO-12-061

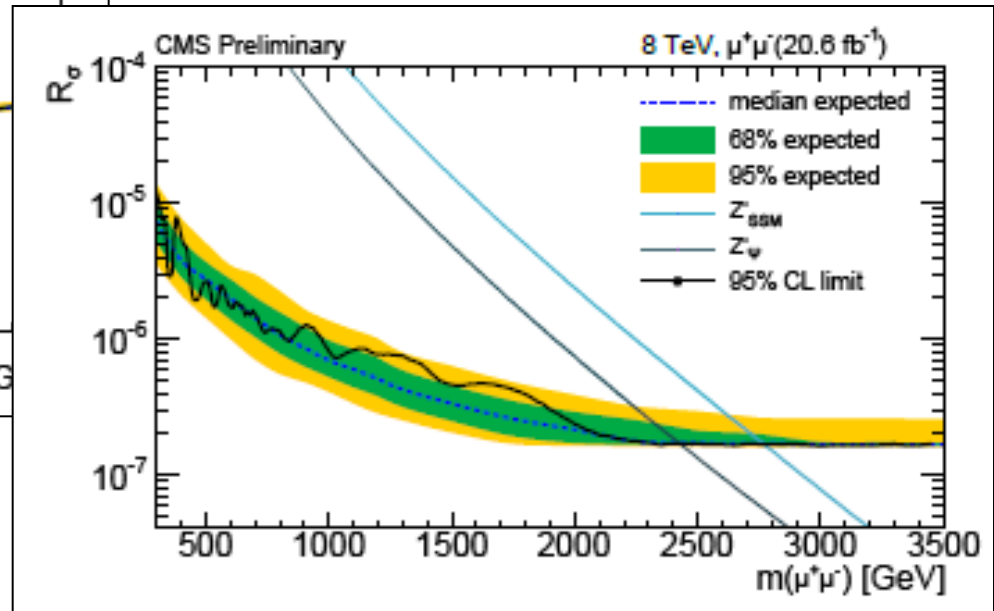
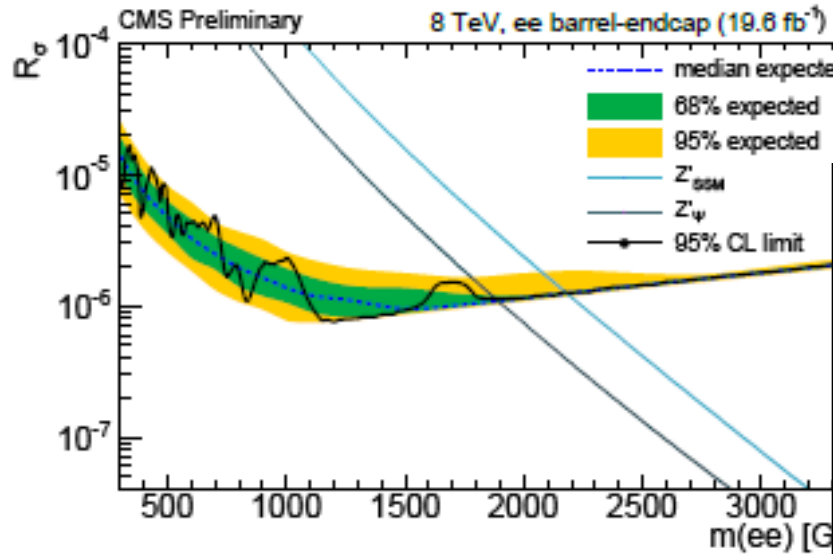


# Dileptons: Limits

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

95% C.L. mass limits have been set on neutral gauge bosons using the combined muon and electron channels

**CMS PAS EXO-12-061**



A Sequential Standard Model Z'<sub>SSM</sub> with standard-model-like couplings is excluded with 8 TeV data **below 2960 GeV**, and the superstring-inspired Z'<sub>ψ</sub> **below 2600 GeV**

Combined 7 TeV + 8 TeV data (5.3 fb<sup>-1</sup> + 4.1 fb<sup>-1</sup>) excludes RS Kaluza–Klein gravitons **below 2390 (2030) GeV** for couplings of 0.1 (0.05) (Phys. Lett. B 720 (2013) 63)

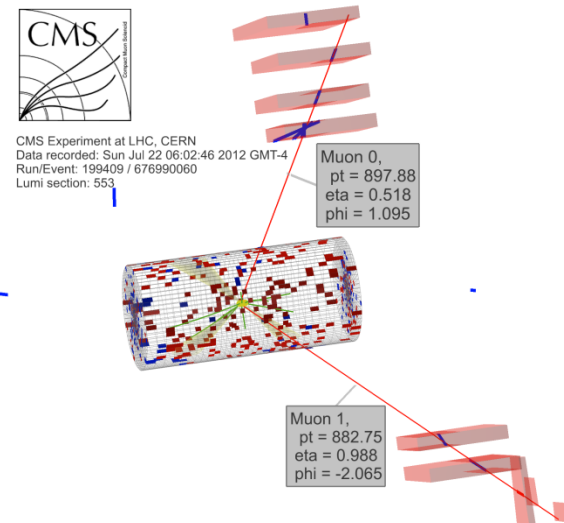
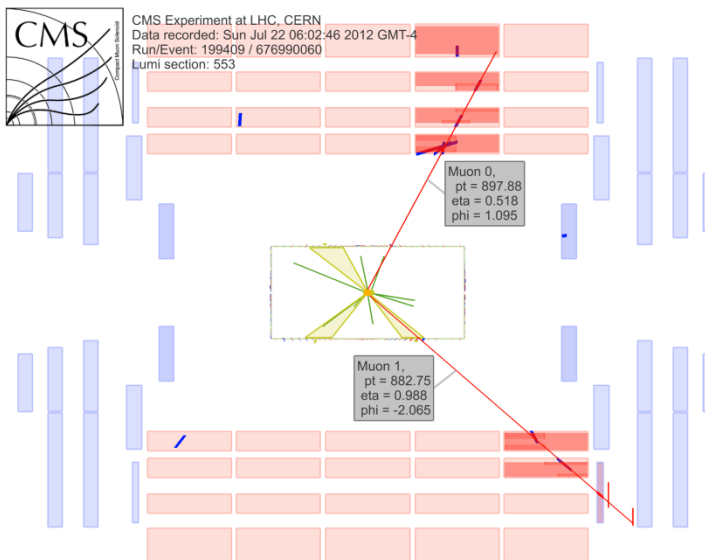
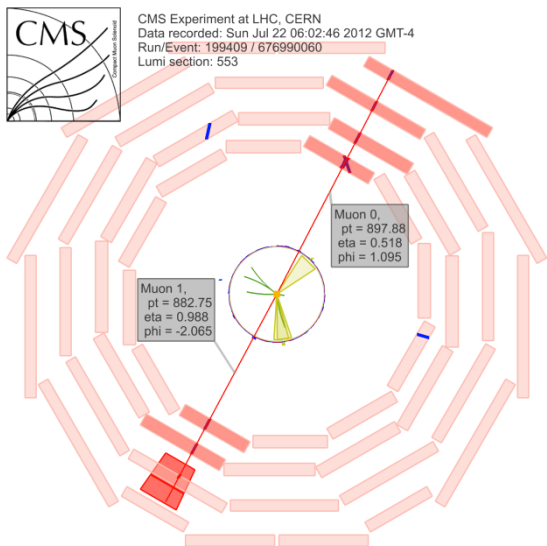




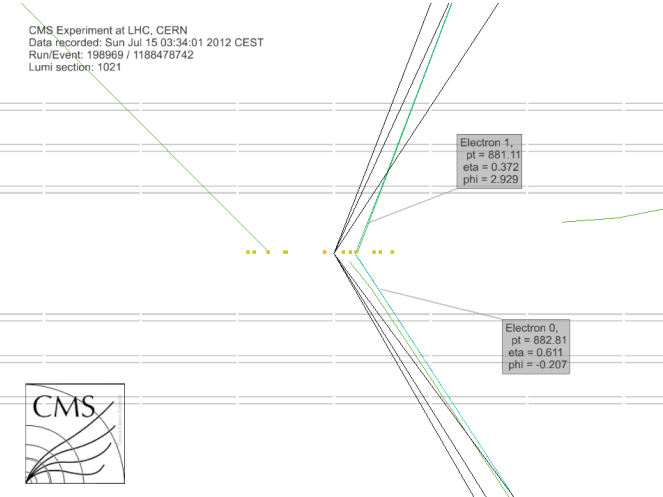
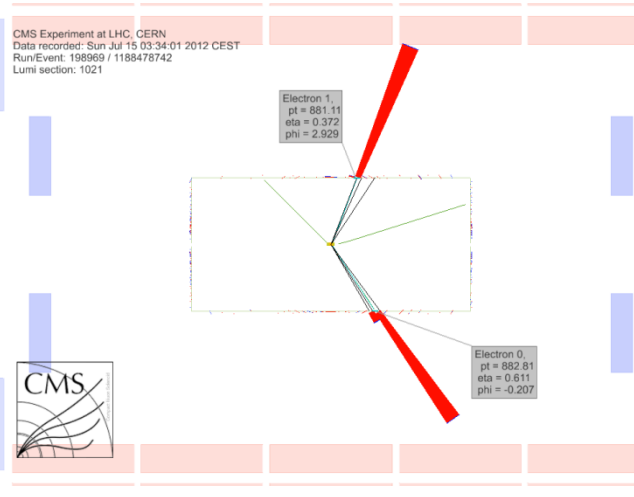
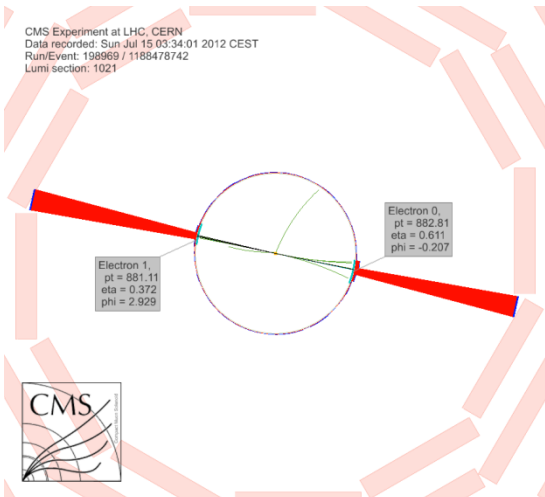
# Dilepton Events at CMS

CMS PAS EXO-12-061

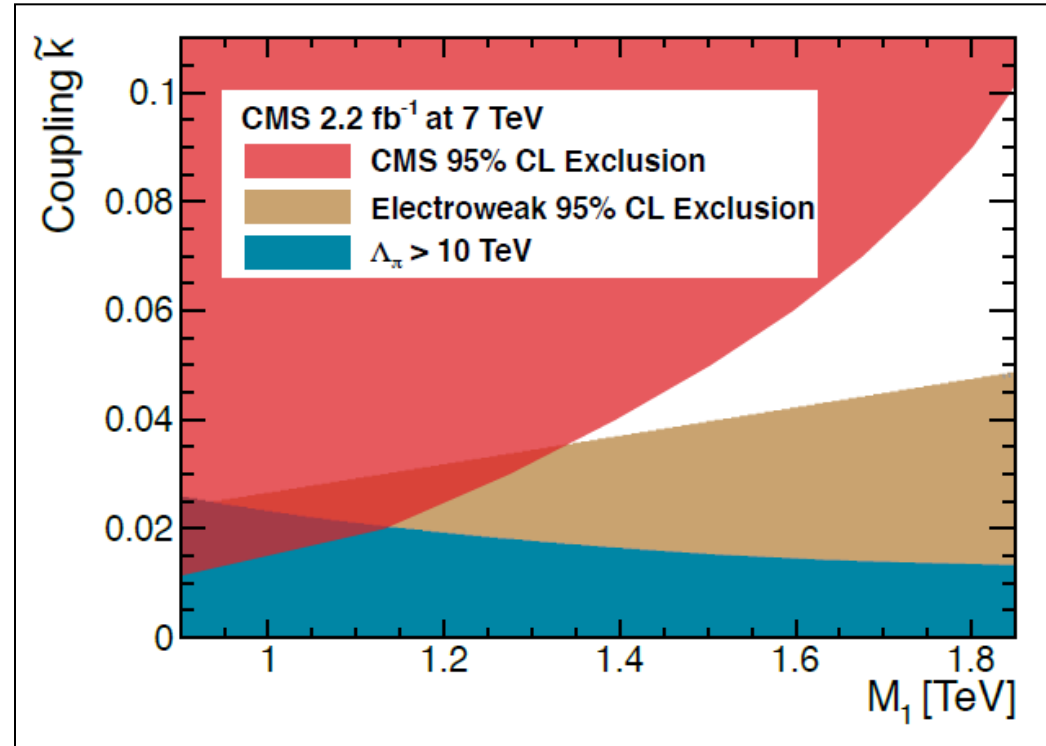
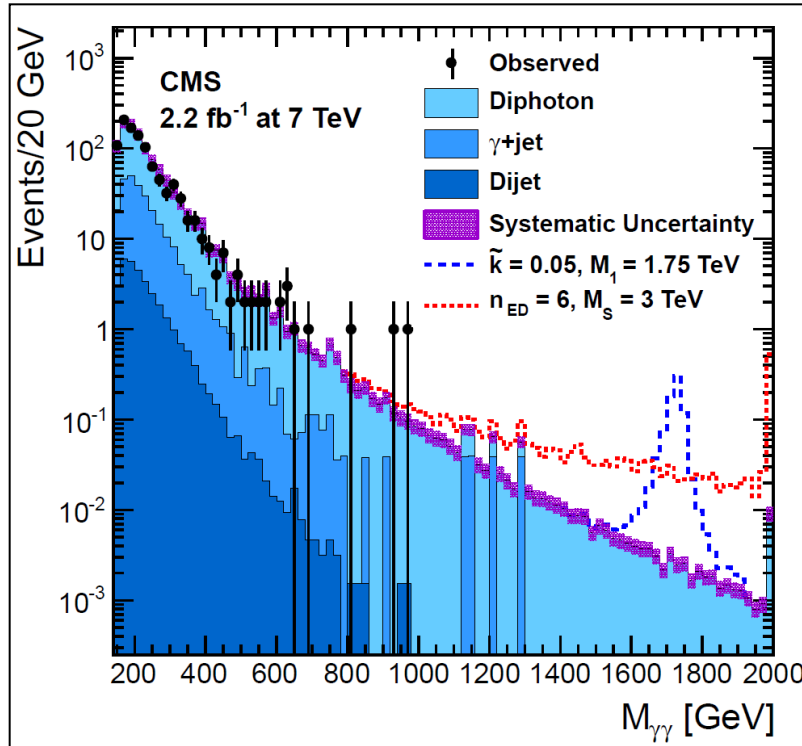
## Dimuon, M = 1824 GeV



## Dielectron, M = 1776 GeV



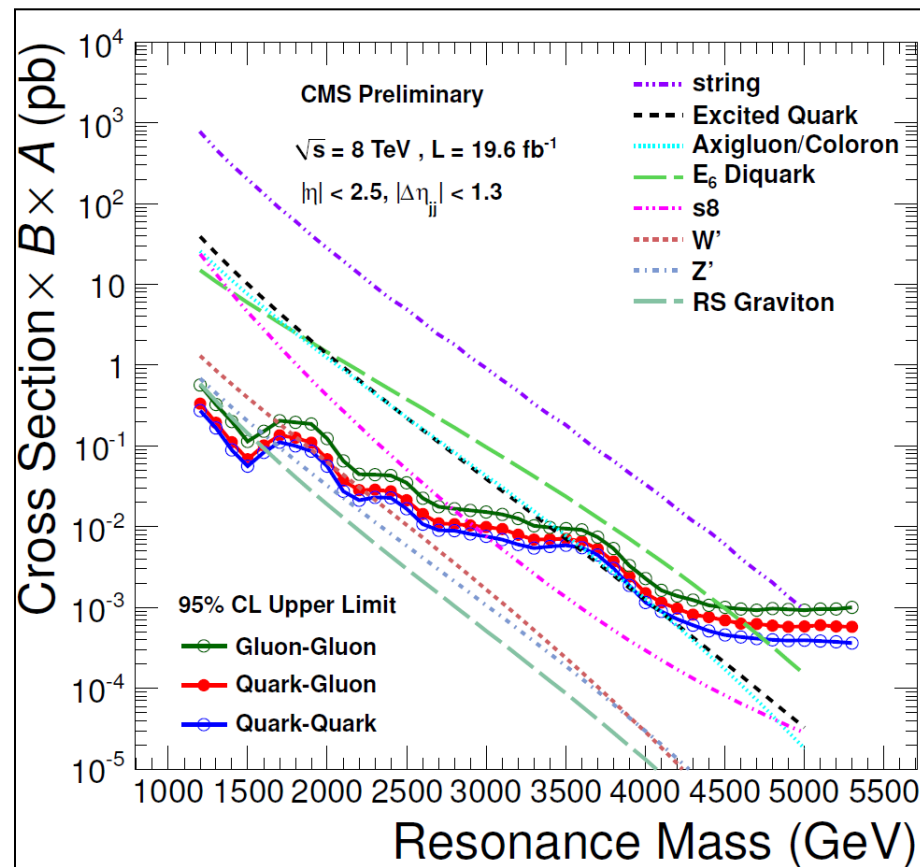
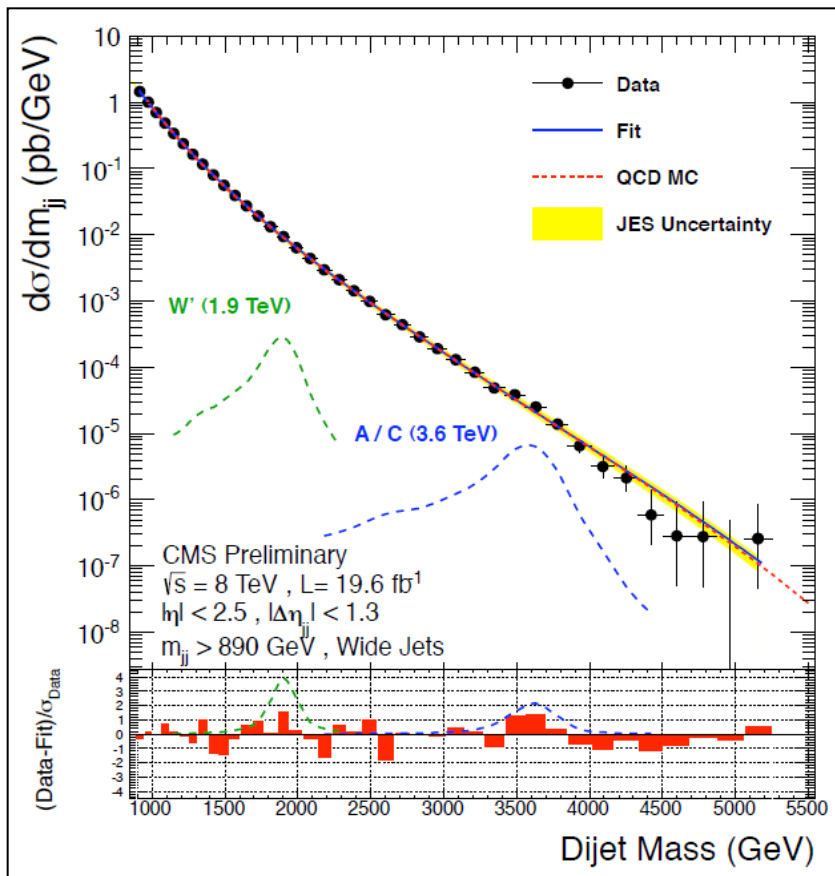
PRL 108 (2012) 111801, arXiv:1112.0688



95% CL lower limits on a mass of RS Kaluza–Klein gravitons for given values of the coupling parameter  $k$

$\tilde{k}$	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]	0.86	1.13	1.27	1.39	1.50	1.59	1.67	1.74	1.80	1.84	1.88





**The observed 95% C.L. upper limits on  $\sigma \times Br \times A$**

Model	Final State	Obs. Mass Excl. [TeV]	Exp. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]	[1.20,5.00]
Excited Quark (q*)	qg	[1.20,3.50]	[1.20,3.75]
$E_6$ Diquark (D)	qq	[1.20,4.75]	[1.20,4.50]
Axigluon (A)/Coloron (C)	q $\bar{q}$	[1.20,3.60] + [3.90,4.08]	[1.20,3.87]
Color Octet Scalar (s8)	gg	[1.20,2.79]	[1.20,2.74]
W' Boson (W')	q $\bar{q}$	[1.20,2.29]	[1.20,2.28]
Z' Boson (Z')	q $\bar{q}$	[1.20,1.68]	[1.20,1.87]
RS Graviton (G)	q $\bar{q}$ +gg	[1.20,1.58]	[1.20,1.43]



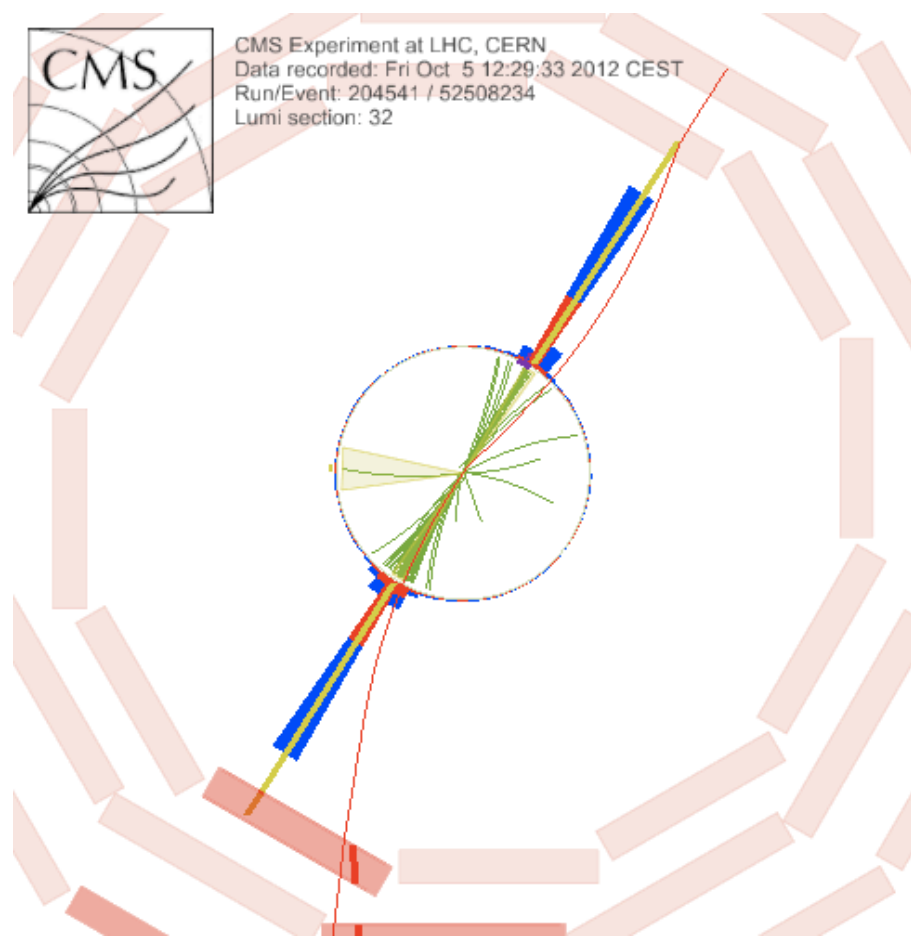
# Highest Dijets Mass at CMS

CMS PAS EXO-12-059

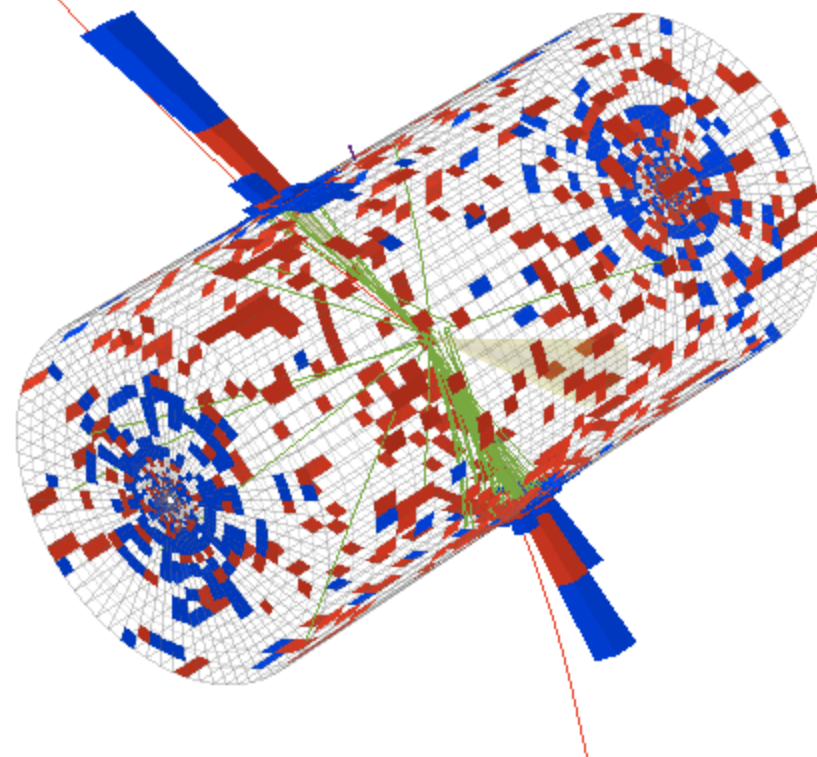
Display for the event with the highest di-wide-jet mass  
(5.15 TeV)



CMS Experiment at LHC, CERN  
Data recorded: Fri Oct 5 12:29:33 2012 CEST  
Run/Event: 204541 / 52508234  
Lumi section: 32



CMS Experiment at LHC, CERN  
Data recorded: Fri Oct 5 12:29:33 2012 CEST  
Run/Event: 204541 / 52508234  
Lumi section: 32



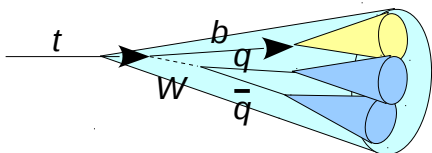


# *ttbar in the Boosted All-Hadronic Final State*

Massive new particles from color singlet  $Z'$ , colorons or axigluons, KK-excitations of gluons or gravitons etc could manifest as resonances in the production of  $t\bar{t}$  pairs

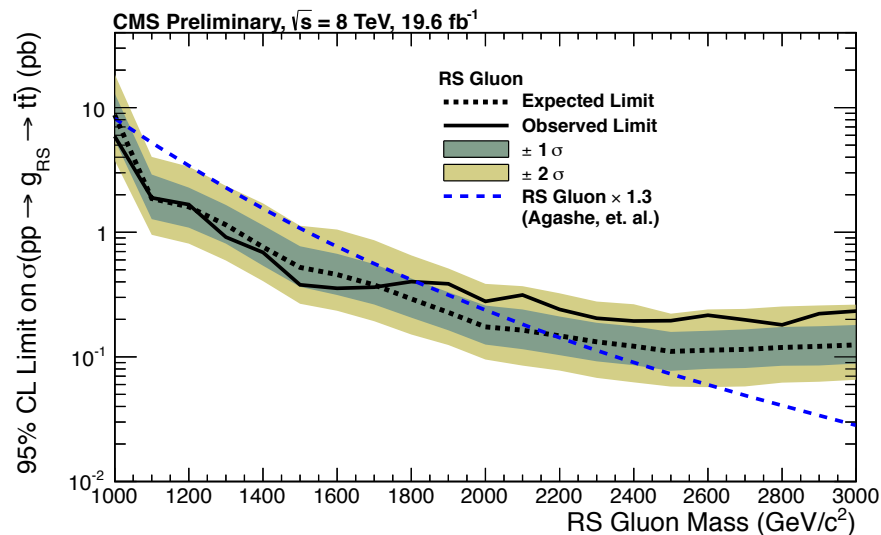
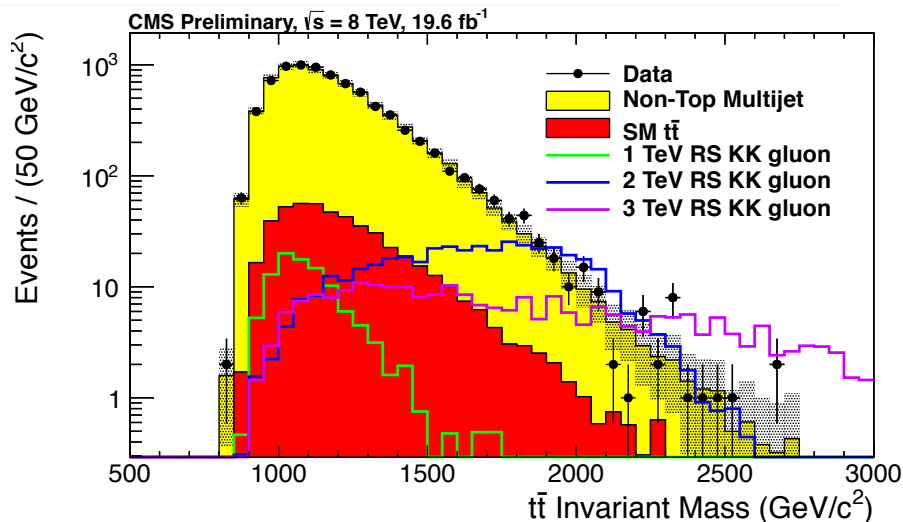
**CMS-PAS-B2G-12-005**

a search for  $t\bar{t}$  resonances in events with  $\geq 2$  top-tagged jets:



**top-tagged jet ( $p_T > 400$  GeV/c):**

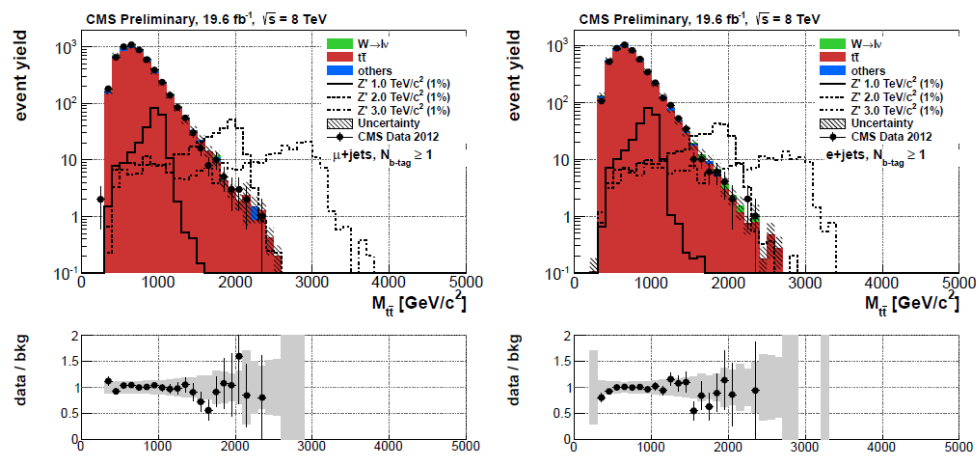
- find  $\geq 3$  subjets (reverse CA)
- $140 < m_{jet} (\text{GeV}/c^2) < 250$
- $m_{2 \text{ subjets}}^{\text{min}} > 50 \text{ GeV}/c^2$



- Hadronic channel:
  - Top tagging algorithm
  - Signal region: fully merged (1+1) top jets
  - Control region: fully (1+1) and partially (1+2) merged with muon +jets sample.
- CMS @ 20/fb:**
  - $g_{KK}$ :  $M > 1.8 \text{ TeV}$
  - Topcolor  $Z'$ :  $M > 2.5 \text{ TeV}$

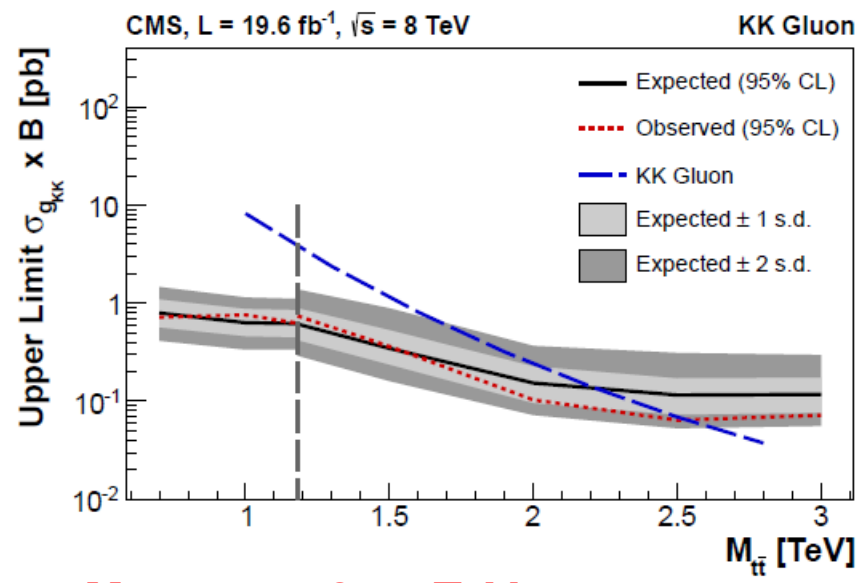


# *ttbar in the Semileptonic Final States*

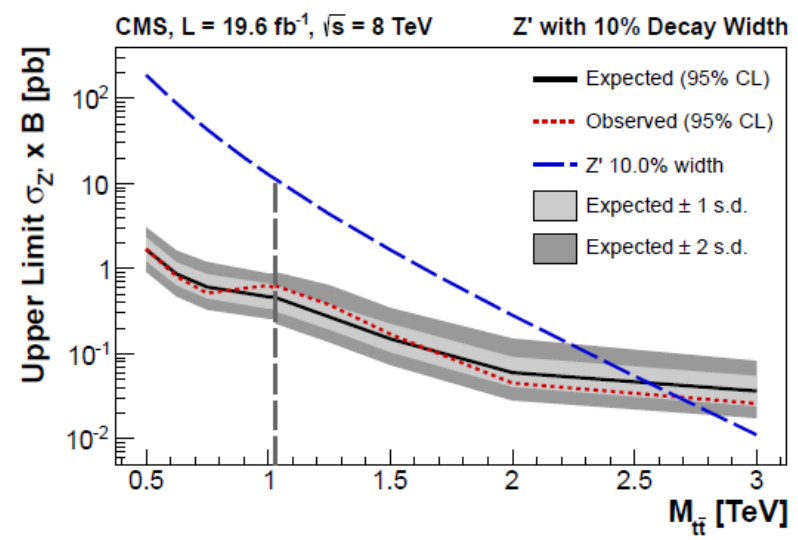


**CMS-PAS-B2G-12-006**

A upper limit of 1.94 (1.71) pb and 0.029 (0.045) pb is set on the production cross section times branching fraction for a narrow (wide) resonance mass of 0.5 TeV and 2 TeV respectively.



**$M_{\text{KK Gluon}} > 2.54 \text{ TeV}$**

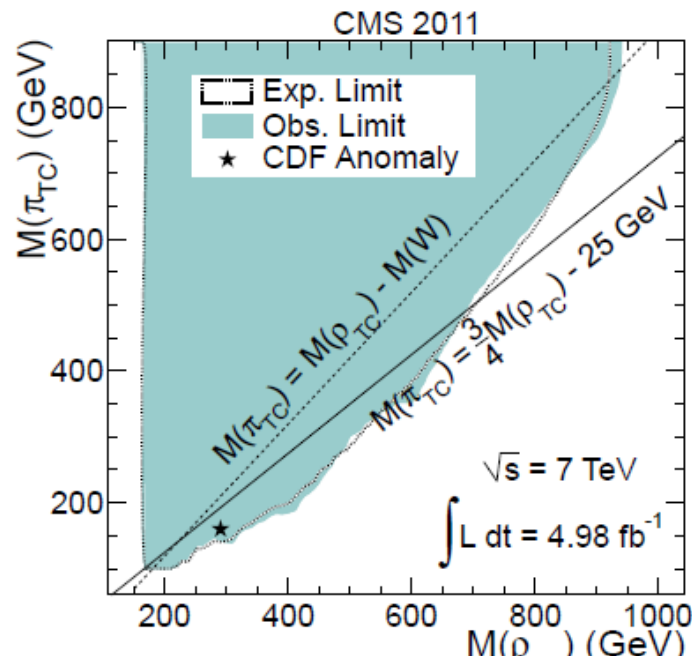
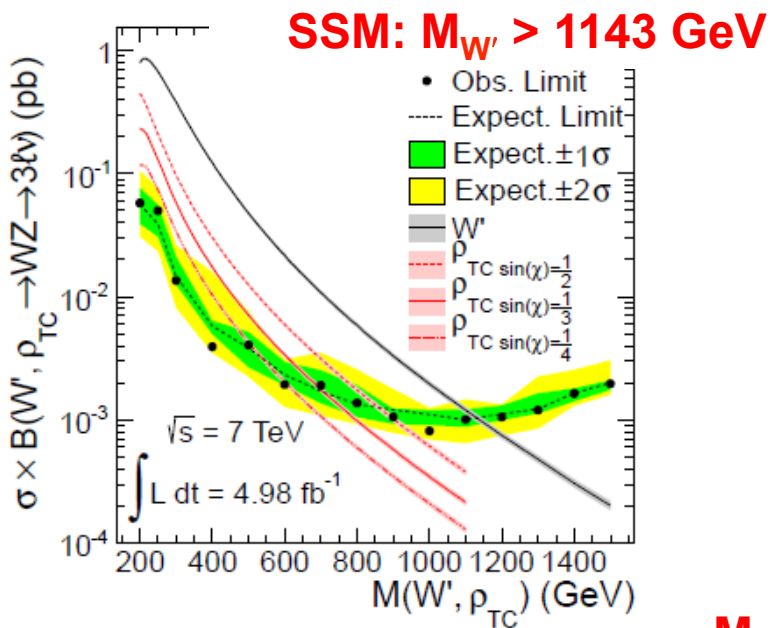
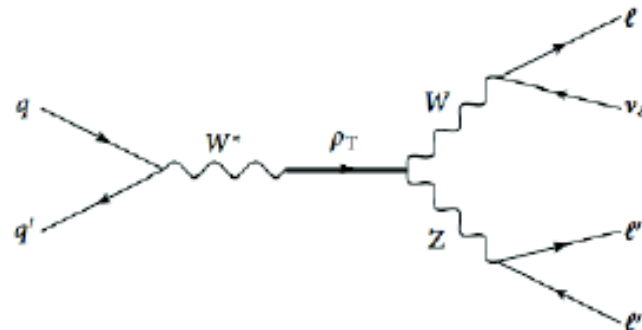
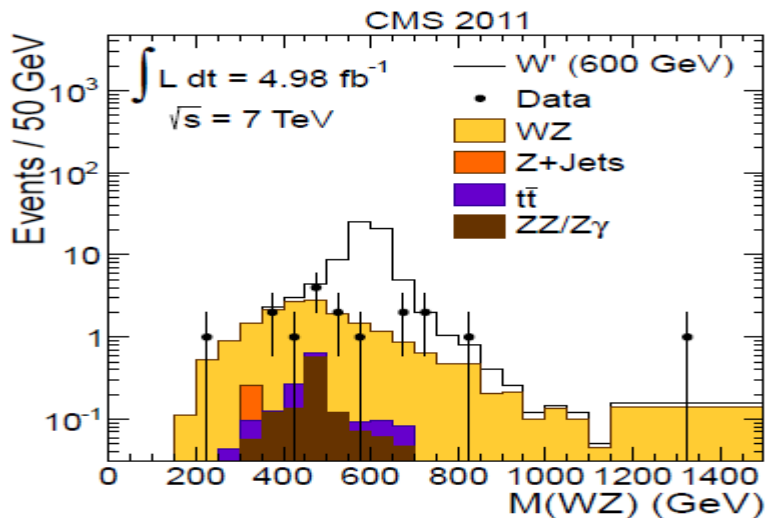


**$M_{\text{topcilorZ'}} > 2.68 \text{ TeV}$**



# WZ Resonances

arXiv:1206.0433, PRL 109 (2012) 141801

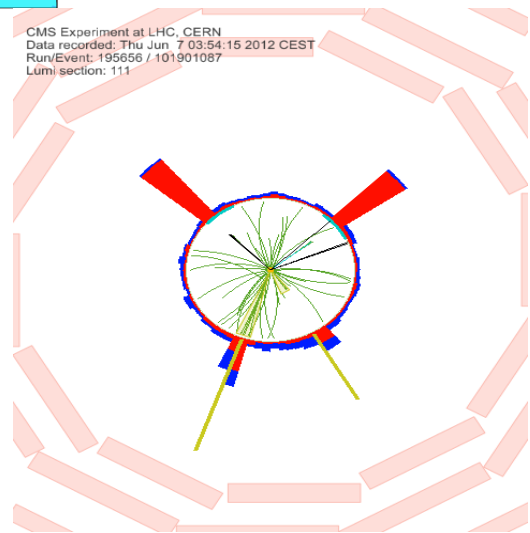


$M_{\rho_{TC}}$  is excluded between 167 and 687 GeV

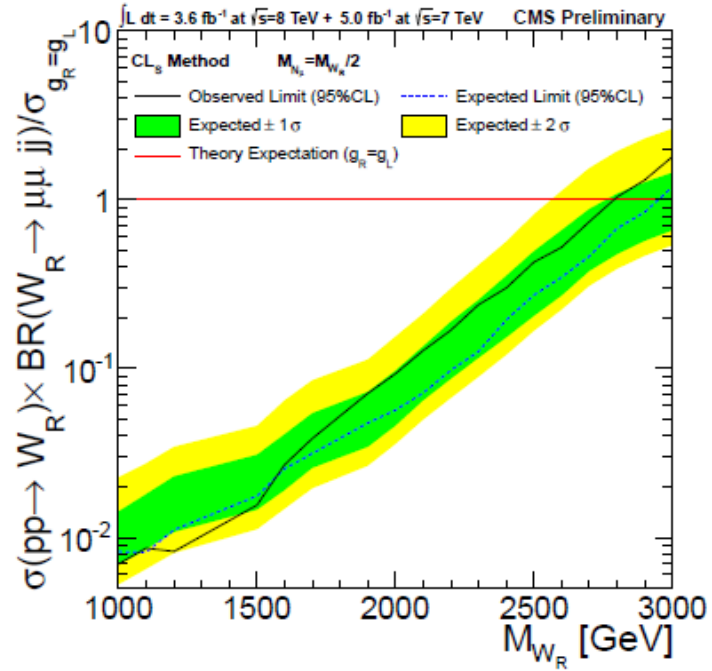
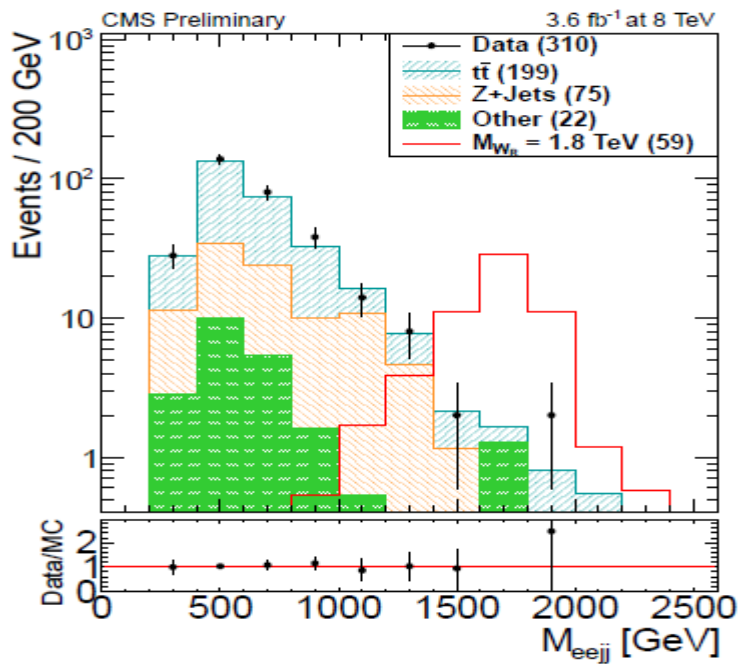
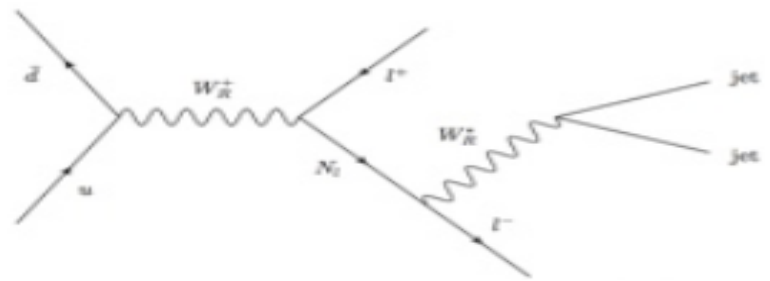
# (Lepton-Lepton) + (Jet-Jet) Resonance

**CMS PAS EXO-12-017**

$W_R$  and heavy neutrino from LR models



CMS Experiment at LHC, CERN  
Data recorded: Thu Jun 7 03:54:15 2012 CEST  
Run/Event: 195656 / 101901087  
Lumi section: 111

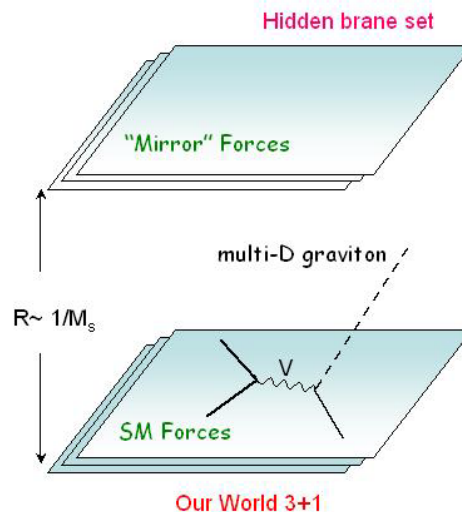
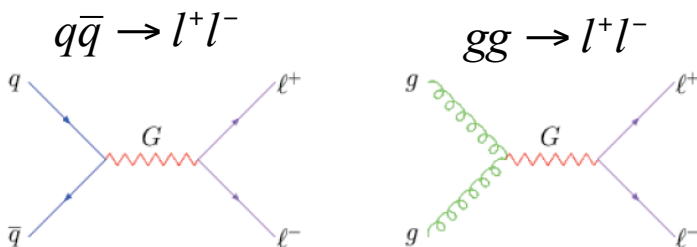


**Combined limit for M<sub>WR</sub> > 2.9 TeV**



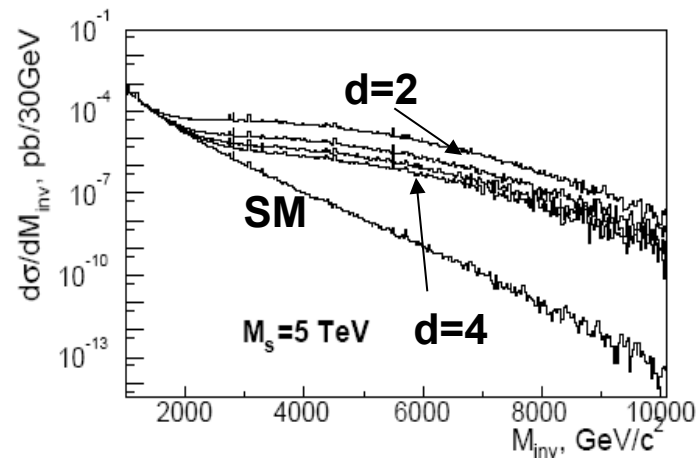
# Non-Resonant Signals

- ADD-graviton contribution in the SM processes (Drell-Yan, diphotons productions)



- Compositeness

Signals: excess in di-particle spectrum







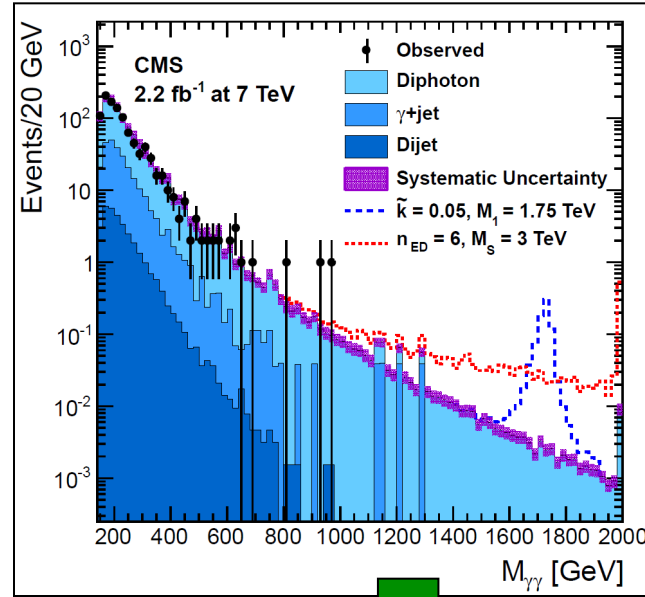
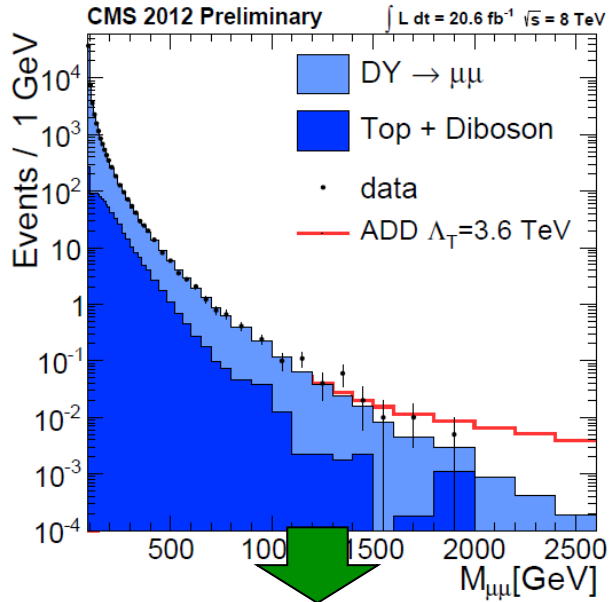
# Exclusion Limits for ADD

Dimuons

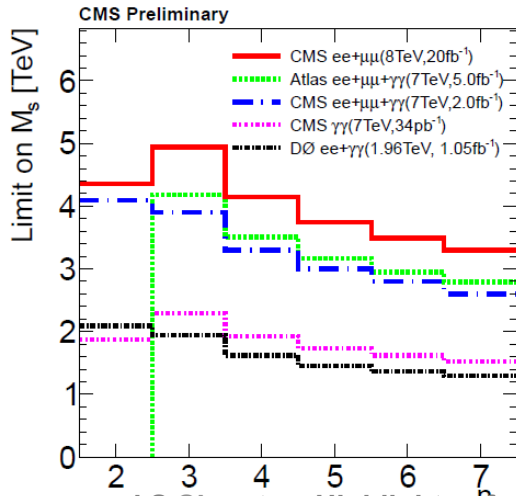
CMS PAS EXO-12-027

Diphotons

PRL 108 (2012) 111801,  
arXiv:1112.0688



The 95% CL limits on fundamental Planck scale,  $M_s$

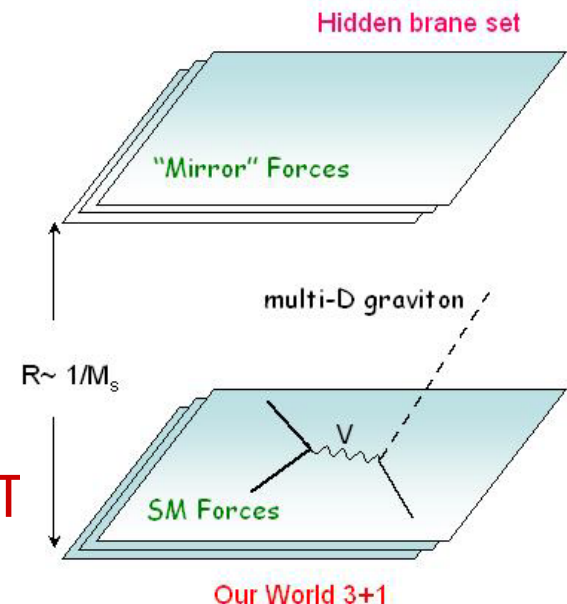


K	GRW	Hewett		HLZ					
		pos.	neg.	$n_{\text{ED}} = 2$	$n_{\text{ED}} = 3$	$n_{\text{ED}} = 4$	$n_{\text{ED}} = 5$	$n_{\text{ED}} = 6$	$n_{\text{ED}} = 7$
1.0	2.94	2.63	2.28	3.29	3.50	2.94	2.66	2.47	2.34
	(2.99)	(2.67)	(2.31)	(3.37)	(3.56)	(2.99)	(2.71)	(2.52)	(2.38)
$1.6 \pm 0.1$	3.18	2.84	2.41	3.68	3.79	3.18	2.88	2.68	2.53
	(3.24)	(2.90)	(2.44)	(3.77)	(3.85)	(3.24)	(2.93)	(2.73)	(2.58)

# Mono-Particle + MET

- ❑ Extra gauge bosons ( $W'$ ) predicted by extended gauge models (left-right symmetric models and GUT-inspired models)
- ❑ Kaluza-Klein graviton emission in large flat extra-dimensions (ADD model)
- ❑ Technicolor

Signals: lepton + MET, photon +MET, jet +MET





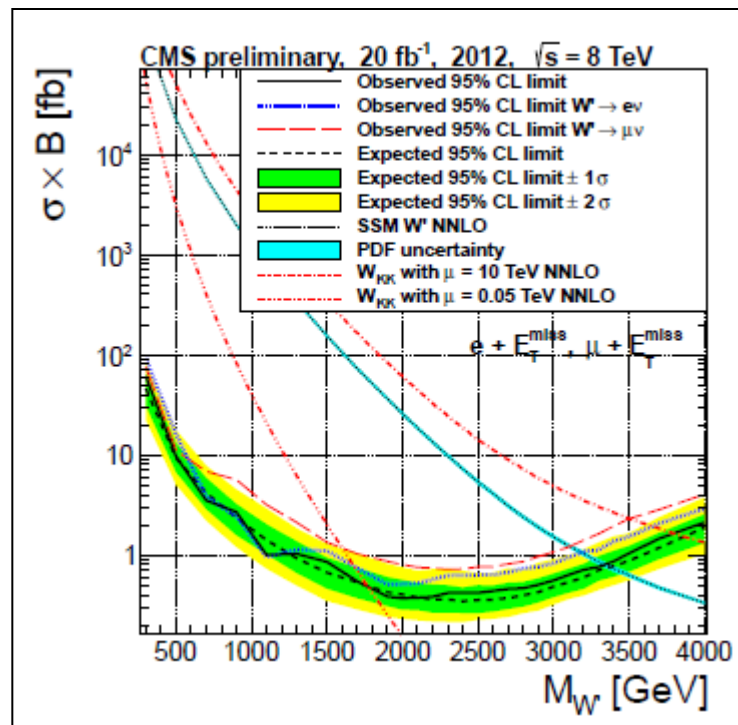
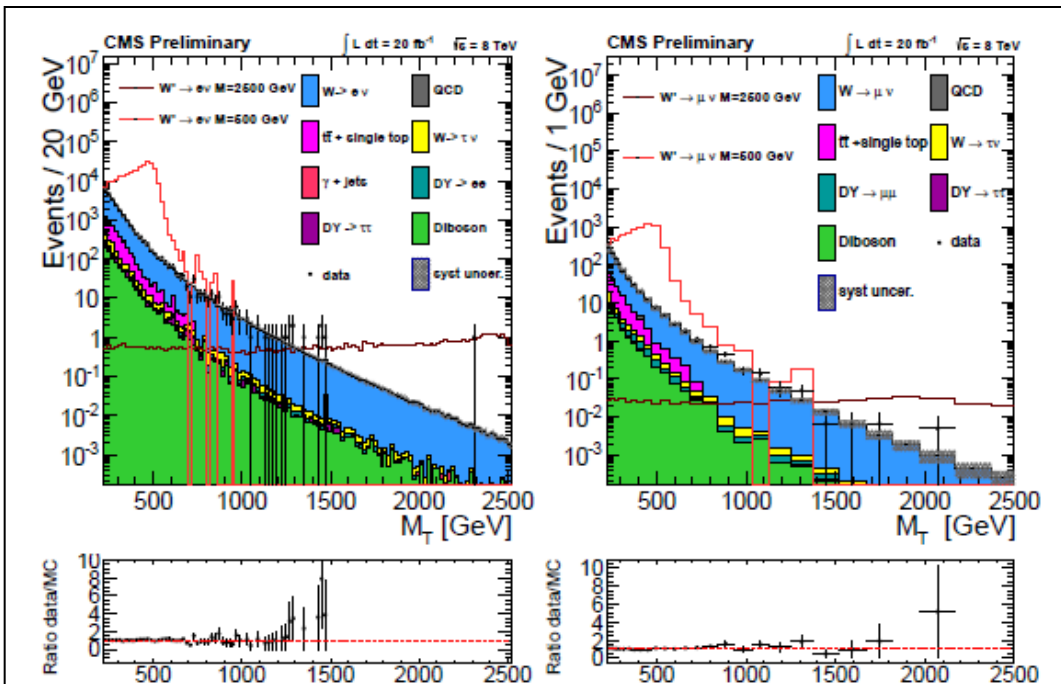
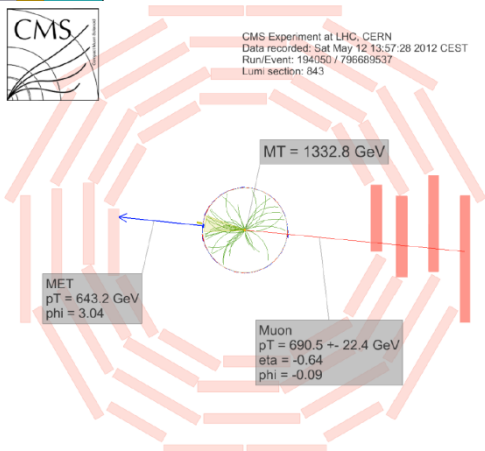
# Lepton + MET

CMS PAS EXO-12-060

Signature is W-like at high mas  
Background is SM W production!

W' with SM-like coupling is excluded with  $M_{W'} < 3.35$  TeV

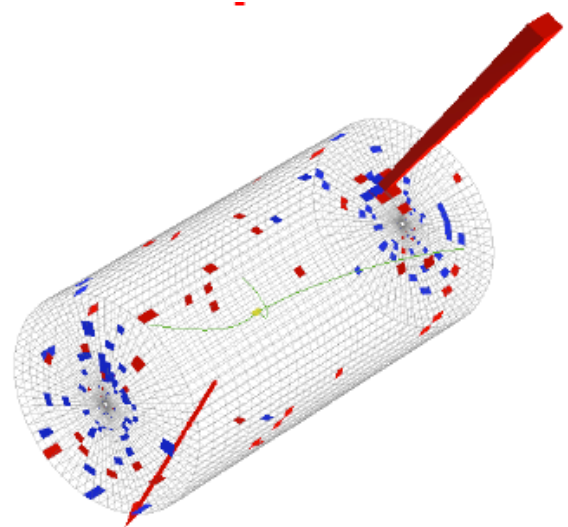
$$M_T = \sqrt{2 \cdot p_T^\ell \cdot E_T^{\text{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$



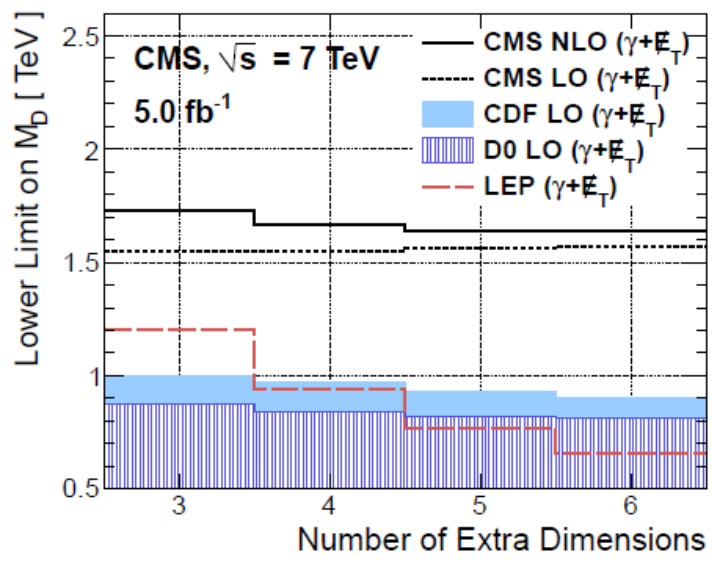
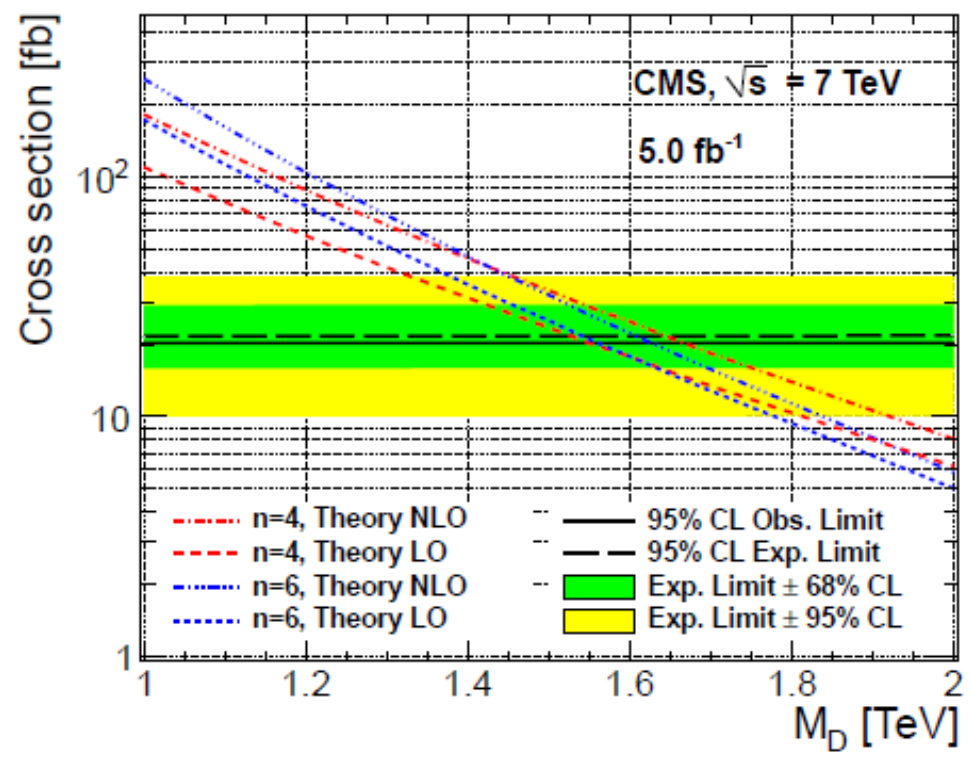


# Photon + MET

arXiv:1204.0821, PRL108 (2012) 261803



CMS Experiment at LHC, CERN  
Data recorded: Sun Apr 24 22:57:52 2011 CDT  
Run/Event: 163374 / 514736281

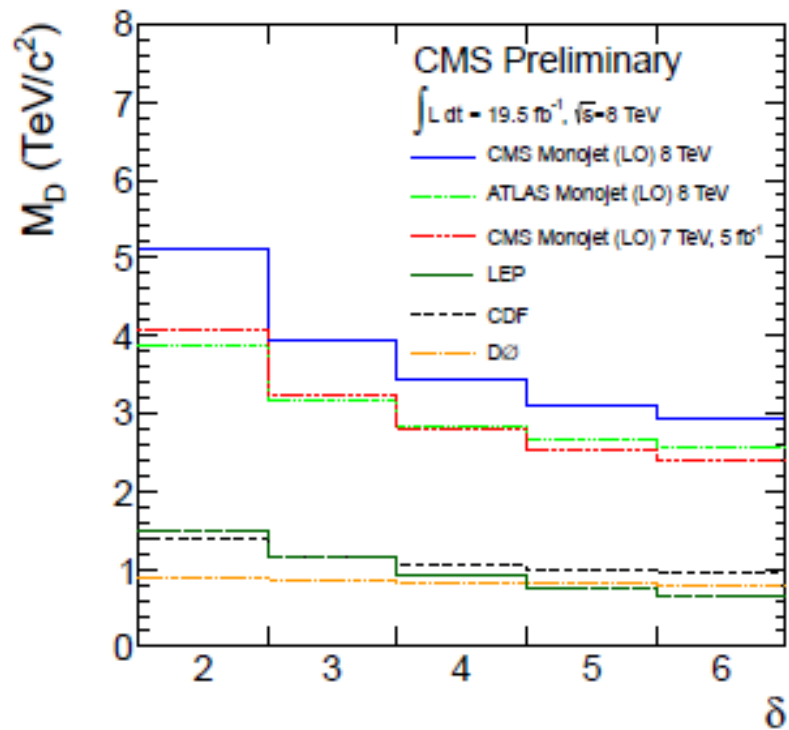
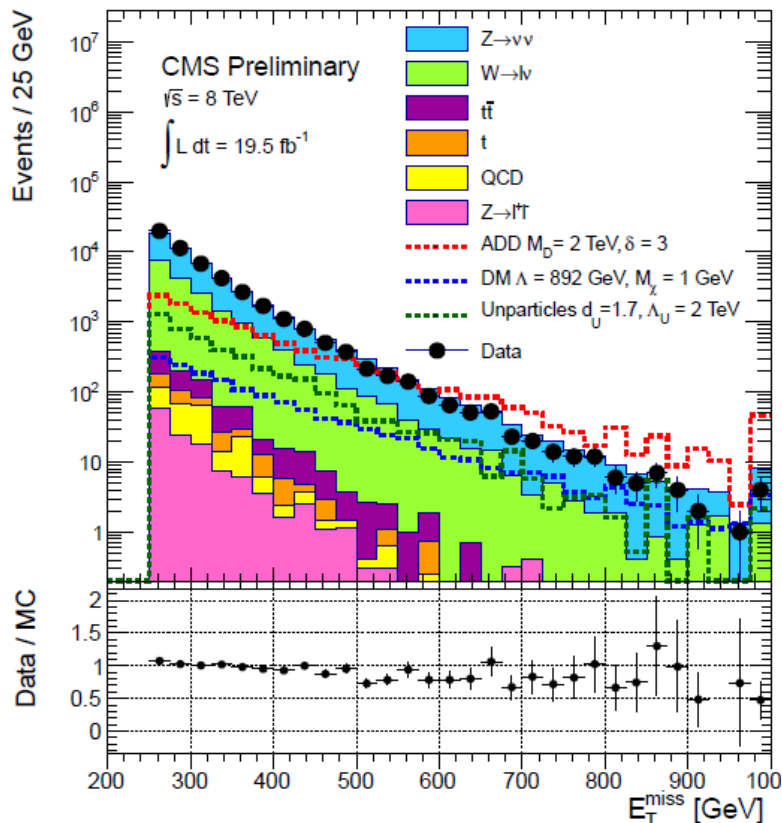
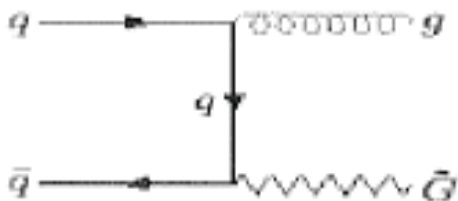


**CMS extends the current limits to be  $M_D > 1.59-1.66$  TeV for  $n = 3 - 6$**

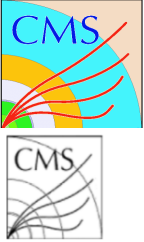


# Jet + MET

CMS PAS EXO-12-048



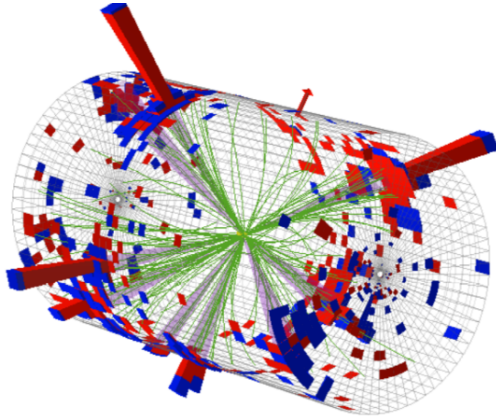
$E_T^{\text{miss}}$ (GeV) $\rightarrow$	> 250	> 300	> 350	> 400	> 450	> 500	> 550
ADD LO $M_D = 3 \text{ TeV}, \delta = 3$	4496	2888	1885	1265	881	603	422
ADD LO $M_D = 4 \text{ TeV}, \delta = 3$	1071	685	454	310	210	150	108
DM $\Lambda = 850 \text{ GeV}, M_\chi = 1 \text{ GeV}$	1774	1103	693	454	297	202	137
DM $\Lambda = 950 \text{ GeV}, M_\chi = 1 \text{ GeV}$	1137	707	444	291	190	129	88
Unparticles $d_U = 1.7, \Lambda_U = 2 \text{ TeV}$	4328	2220	1237	700	378	218	141
Unparticles $d_U = 1.7, \Lambda_U = 3 \text{ TeV}$	1859	905	478	247	158	103	60



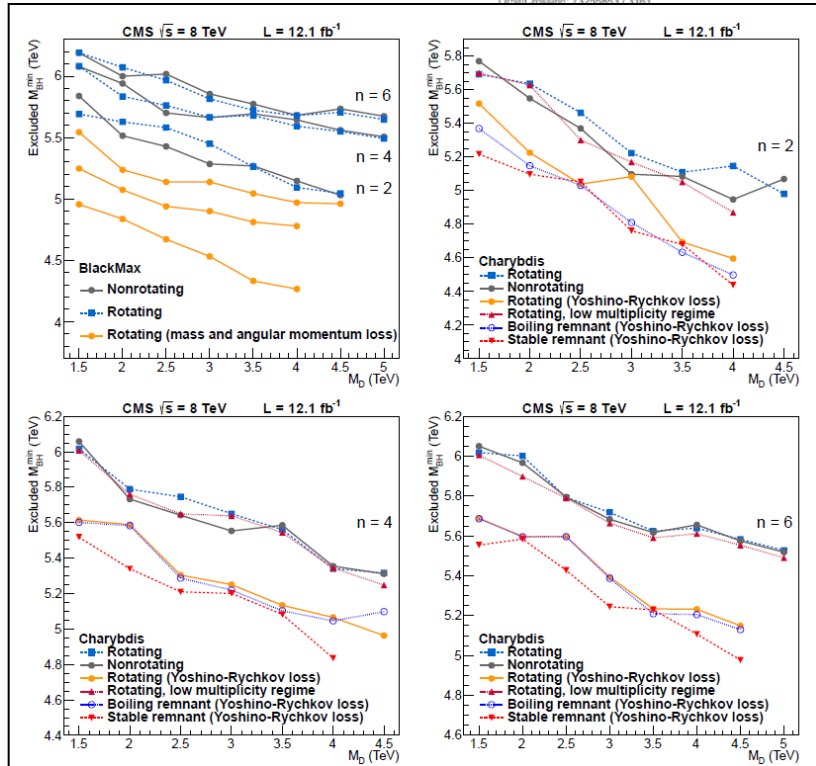
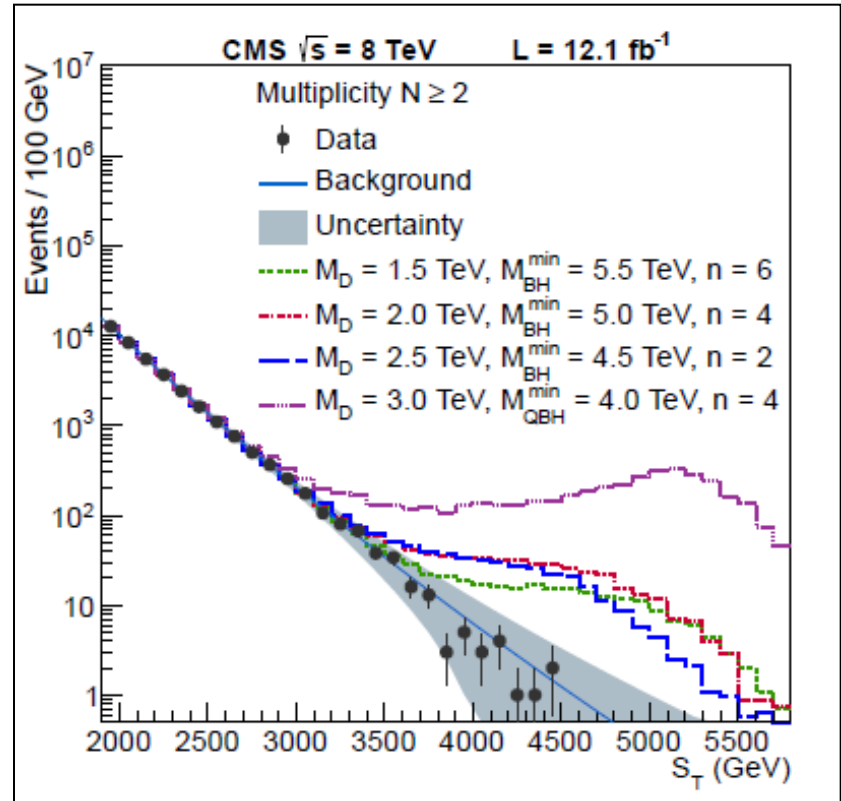
# Black Holes

arXiv:1303.5338

$$S_T \equiv \sum E_T$$



CMS Experiment at LHC, CERN  
Data recorded: Mon May 23 21:46:26 2011 EDT  
Run/Event: 165567 / 347495624  
Lumi section: 280  
Data/Position: T255963 / 3481



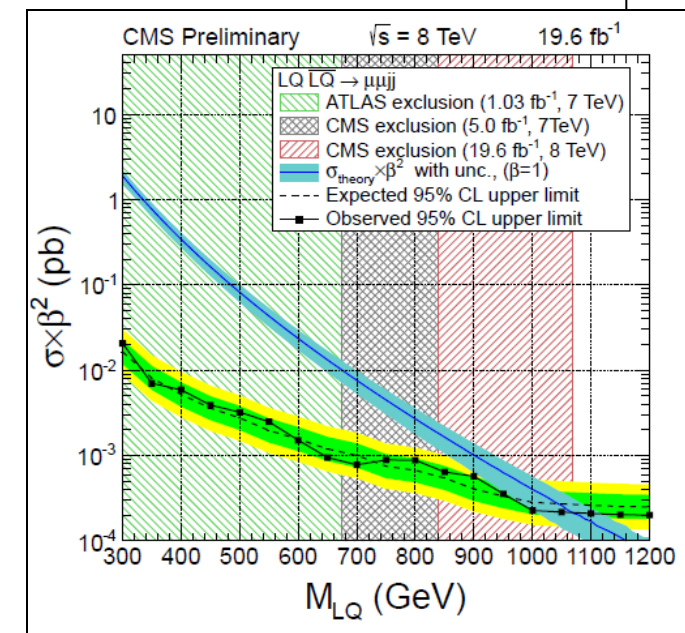
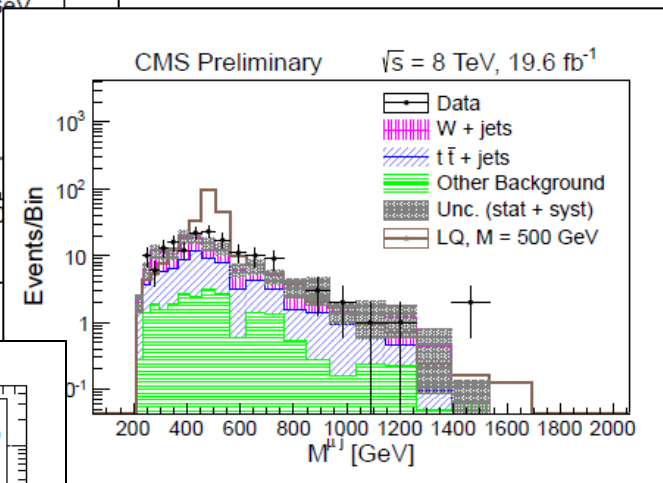
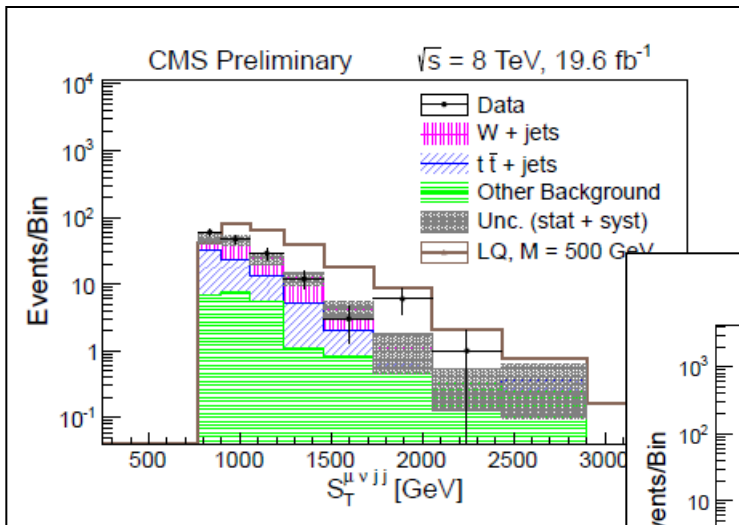
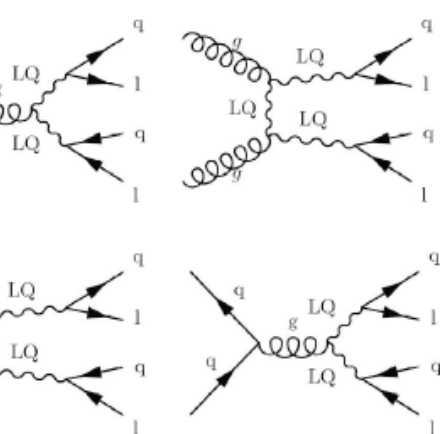
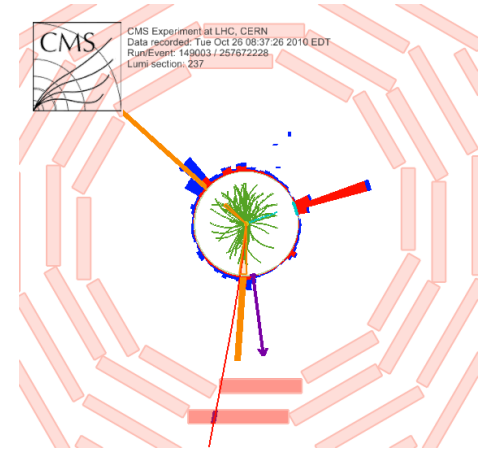
**CMS set limits on the minimum BH mass of 4.3-6.2 TeV**





# Leptoquarks

## CMS PAS-EXO-12-042



$S_T$  is the sum of the magnitudes of the  $p_T$  of the two leading electrons and two leading jets.

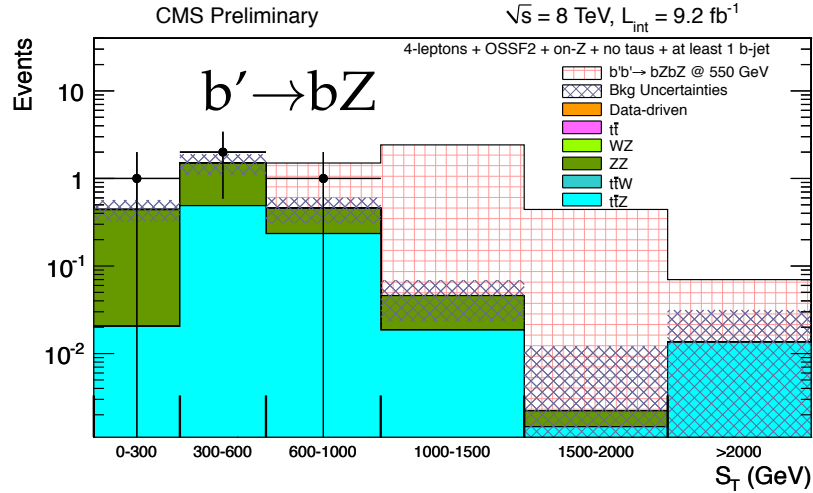
A 95% C.L. lower limit is set on the mass of a second-generation scalar leptoquark at 1070 GeV



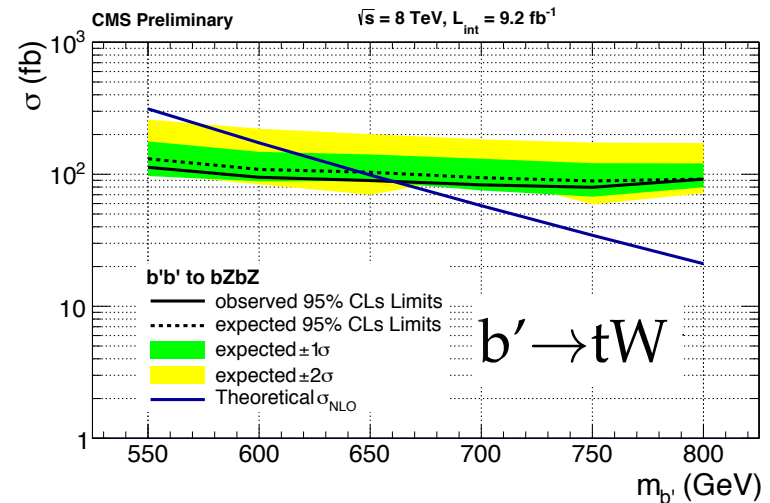
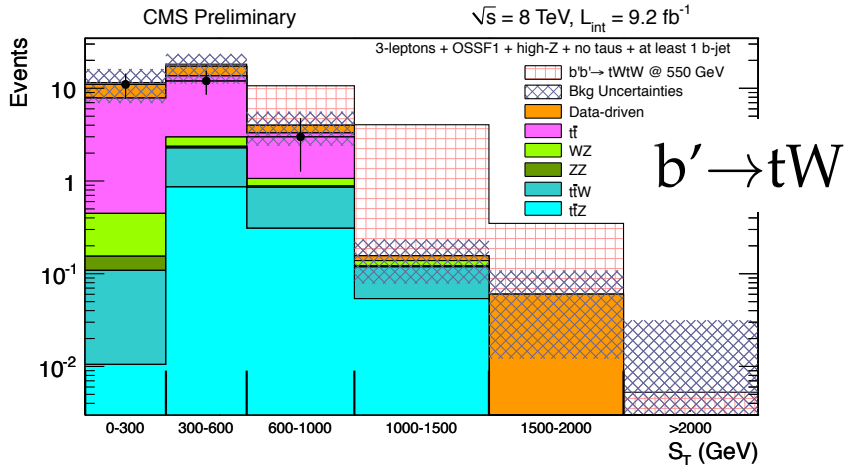
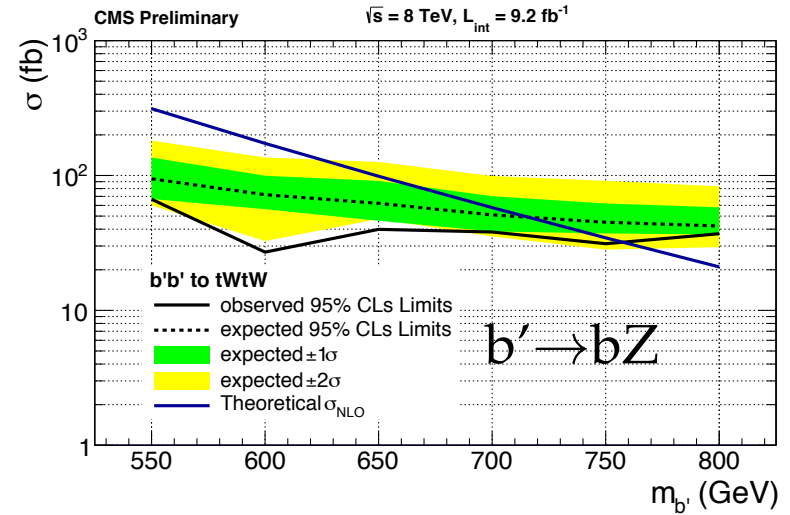


# $b' \rightarrow t + W/Z$

CMS-PAS-SUS-12-027



$$S_T \equiv \sum p_T(\text{jets}) + \sum p_T(\text{leptons}) + E_T$$





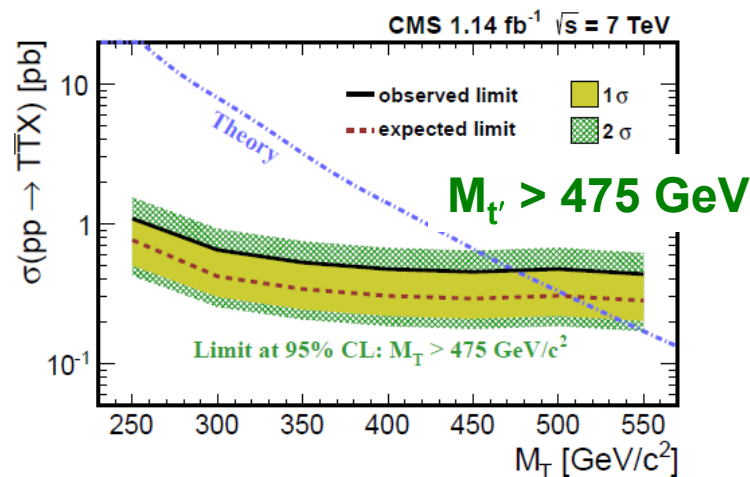
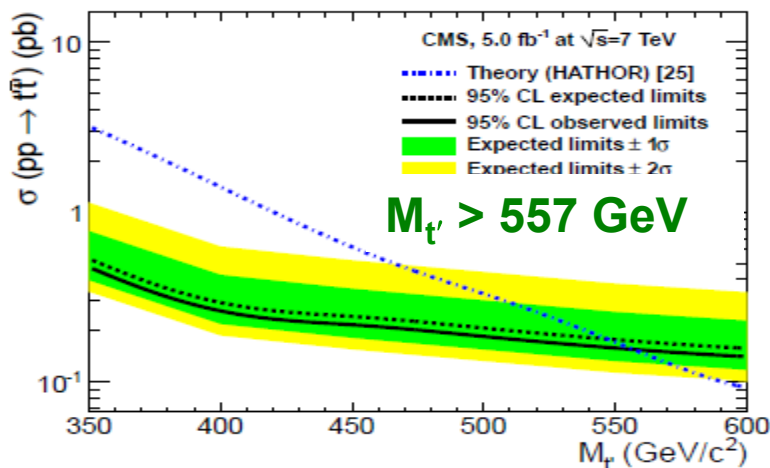
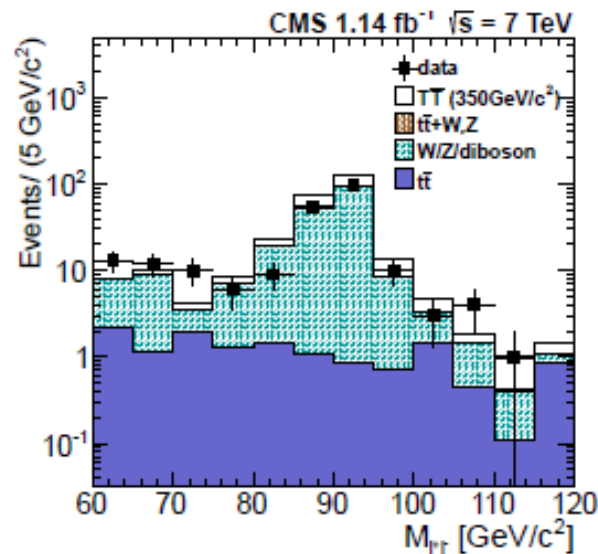
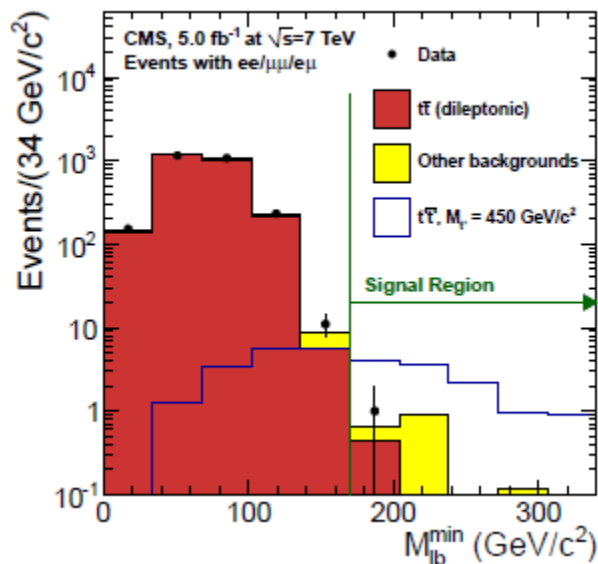
# Searching of $t'$

arXiv:1203.5410, PLB 716 (2012) 103

arXiv:1109.4985, PRL 107 (2011) 271802

$$t\bar{t}' \rightarrow bW^+ \bar{b}W^- \rightarrow b\ell^+ \nu \bar{b}\ell^- \bar{\nu}$$

$$t\bar{t}' \rightarrow tZ \bar{t}Z \rightarrow bW^+ W^- bZZ$$





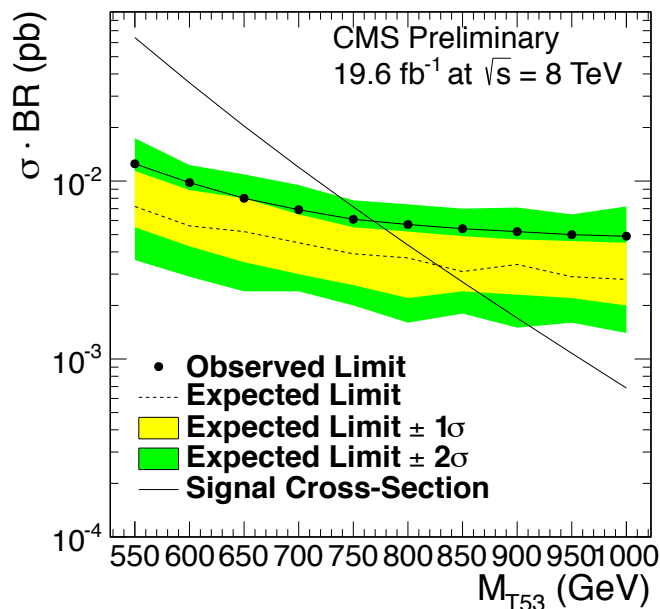
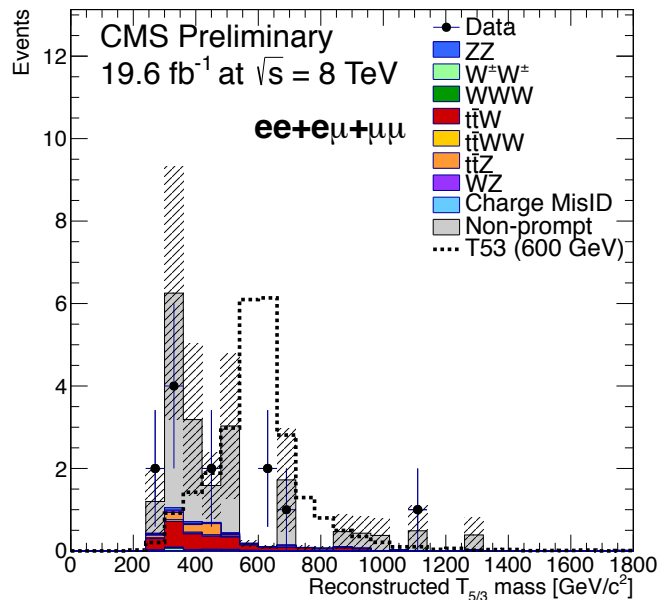
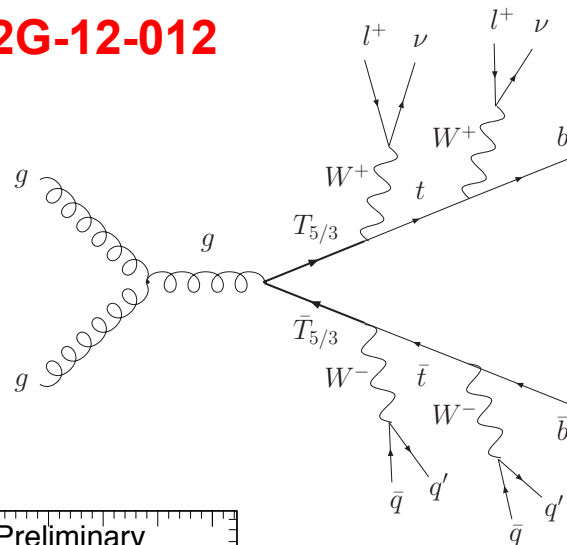
# Searching for top partners with charge 5e/3

Various extensions of the standard model predict the existence of heavy partners for the top quark with charge 5e/3

CMS-PAS-B2G-12-012

$$T_{5/3} \rightarrow W^+ t \rightarrow W^+ W^+ b :$$

- same-sign W's from  $T_{5/3} \rightarrow$  same-sign dilepton signature
- boosted W and t on the other side
- fat jets with 2 and 3 sub-jets (resp.)



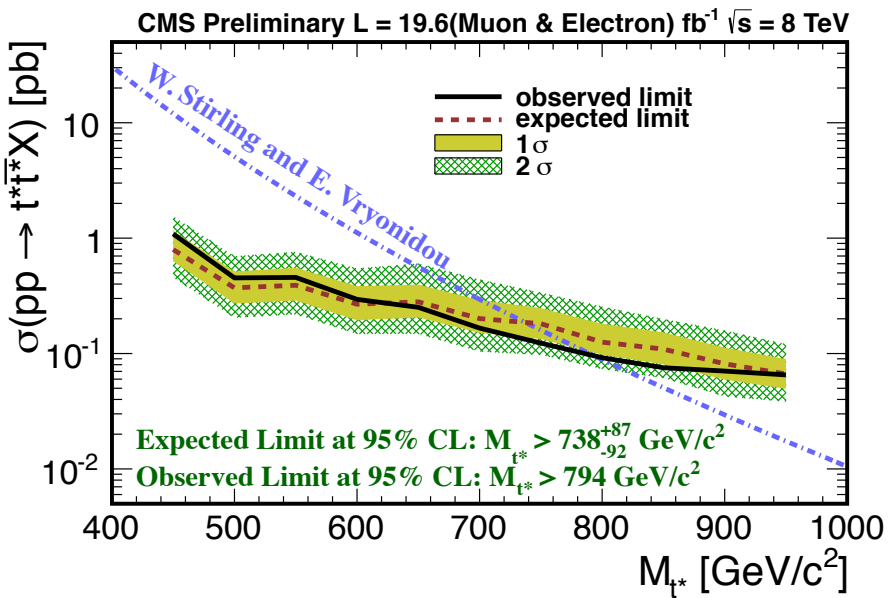
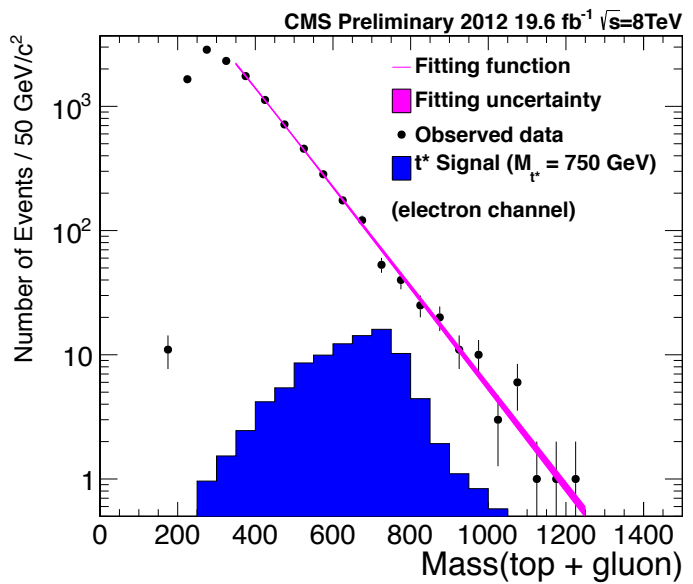
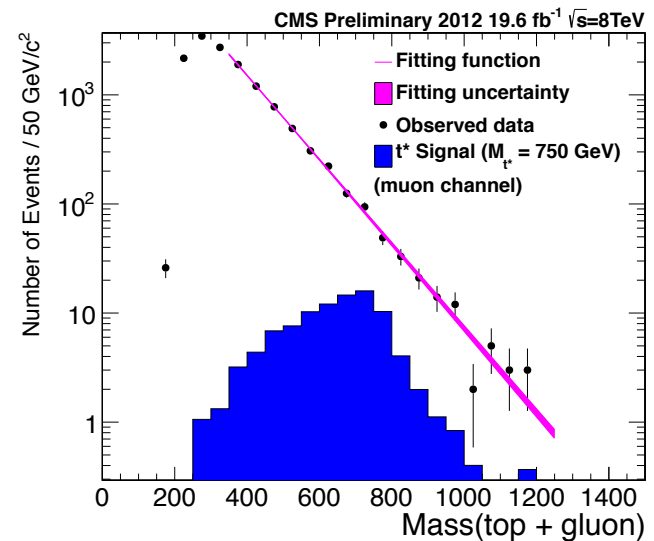
$m(t_{5/3}) > 770 \text{ GeV}$   
(95% CL)



# Searching for excited top quark

- Signature:  $t^* \rightarrow top + gluon$ 
  - One isolated muon or electron
  - At least six hadronic jets
  - At least one b-tagged jet.
- CMS @ 20/fb:
  - $M_{t^*} > 794 \text{ GeV}$

CMS-PAS-B2G-12-014

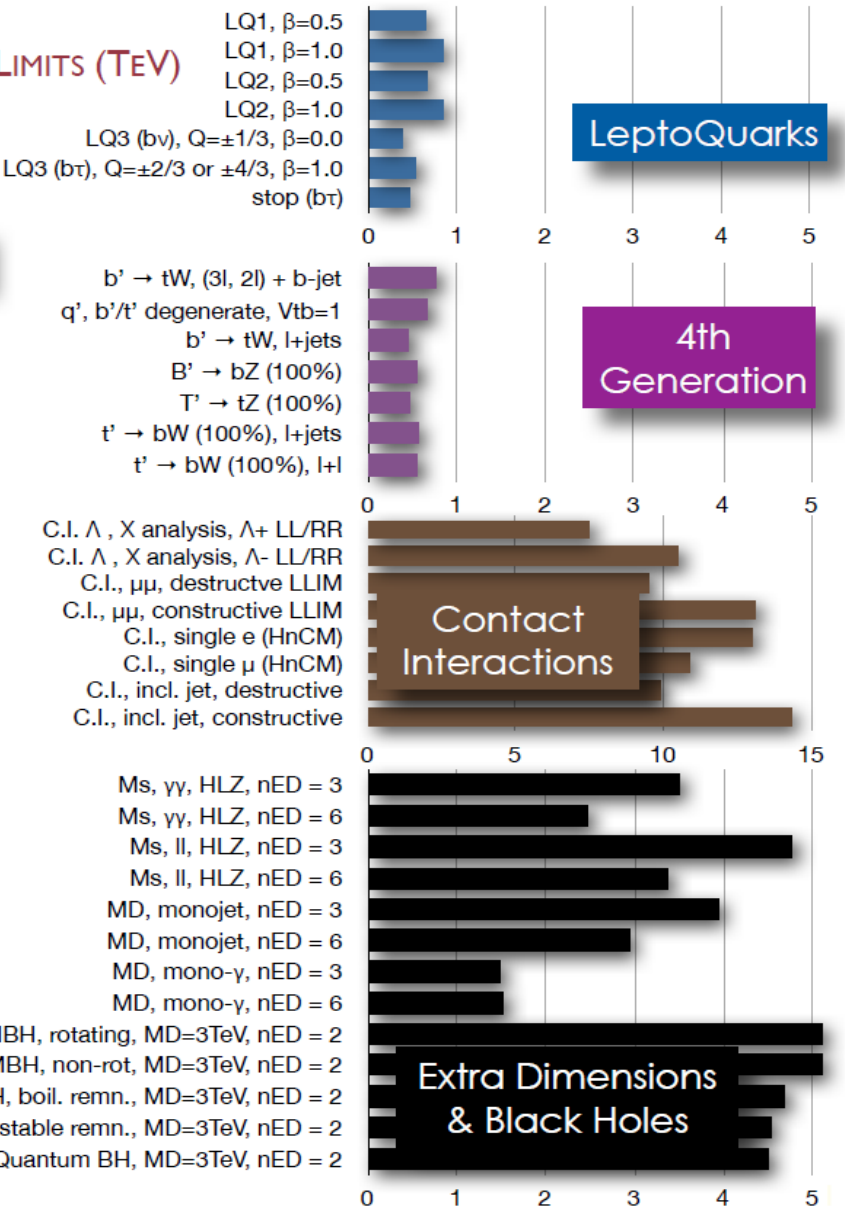
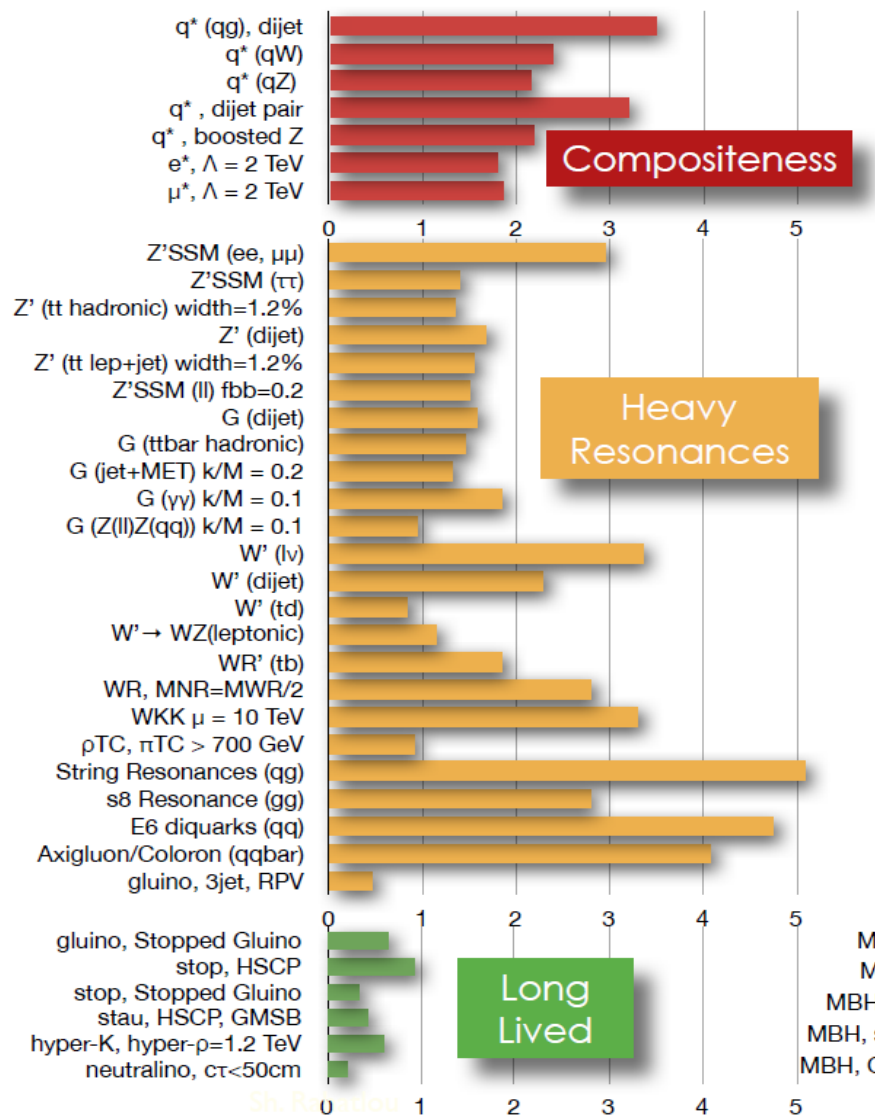


$M_{top^*} > 790 \text{ GeV at 95% CL.}$



# CMS Exotica Summary

## CMS EXOTICA 95% CL EXCLUSION LIMITS (TeV)





# Conclusions and Outlook

☐ CMS demonstrates excellent performance

- ✓ TeV leptons, photons, jets
- ✓ Mono-particle + associated missing energy
- ✓ Complex signatures

☐ Physics analysis with up to  $5 \text{ fb}^{-1}$  at 7 TeV and  $20 \text{ fb}^{-1}$  at 8 TeV set stringent limits to many benchmarks models

☐ Unfortunately, no evident deviations from Standard Model have been seen so far

