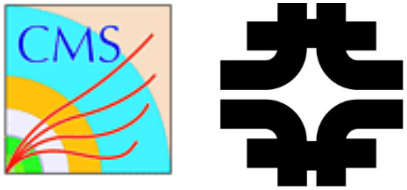
Searches for BSM Physics with the CMS Experiment



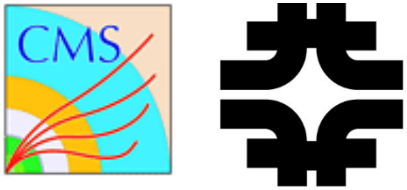
Christos Leonidopoulos

LPC, Fermilab

Implications of LHC results for TeV-scale physics

26-30 March 2012, CERN, Geneva

Searches for BSM(*) Physics with the CMS Experiment



Christos Leonidopoulos

LPC, Fermilab

(*) Review of Exotica results presented at Moriond
No Higgs or SUSY discussed here

Implications of LHC results for TeV-scale physics
26-30 March 2012, CERN, Geneva

Outline

- Summary of searches carried out with 2011 data
  - Including a list of signatures on which CMS is working on
- First priority
  - Examine as many final states and topologies as possible
  - Discover "something" new (it doesn't really matter what it is)
- Obvious questions to ask
  - What else is there? What are we forgetting?
- Goal: give an idea of analyses under consideration
  - Details discussed in parallel sessions (when time allows)
  - Links given to public analysis notes

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

“Tell me that you have found no sign of
New Physics again, I dare you.
I double dare you. Tell me
one more goddamn time!”

Well, allow me to retort

- Huge amount of data, very large number of analyses
- No smoking gun yet, but
  - Small excesses here & there. Keep an eye on them!
- Planning for this year
  - Expand our discovery potential

CMS: 25 New Results

- Resonances (Z'-like and extra dimensions)
  - dijet, $ee, \mu\mu, \gamma\gamma, t\bar{t}, t\bar{t}$ (boosted)
- W'
  - $e + \nu, \mu + \nu, qq', \ell N_\ell$ (aka: right-handed W), WZ
- More extra dimensions:
  - mono-jet, mono-photon, black holes
- Fourth generation
  - Heavy bottom-like and top-like quarks
- "Weird" stuff: leptoquarks & long-lived particles

Resonances (aka: Z'-like) and Extra Dimensions

CMS: 25 New Results

- Resonances (Z'-like and extra dimensions)
  - dijet, $ee, \mu\mu, \gamma\gamma, t\bar{t}, t\bar{t}$ (boosted)
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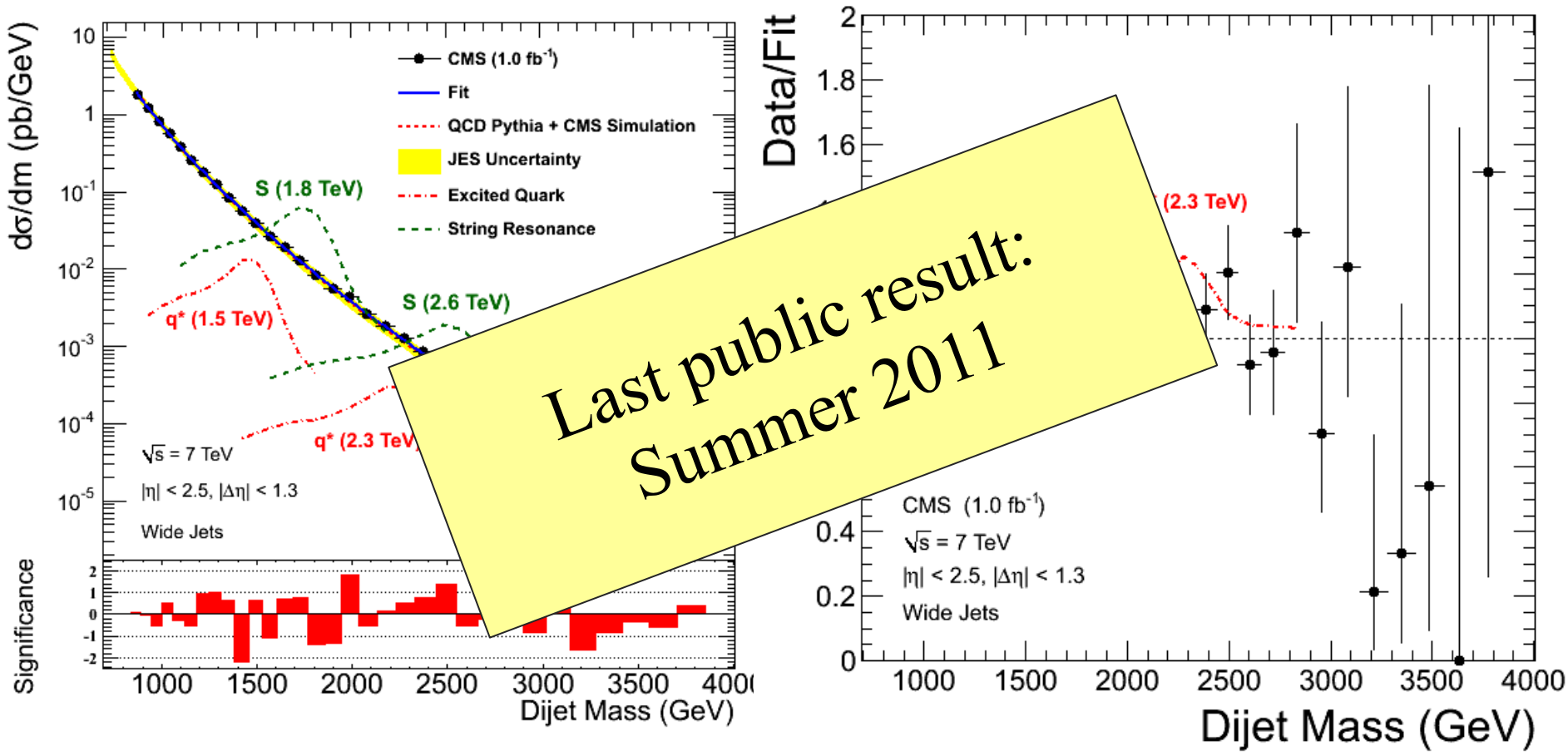
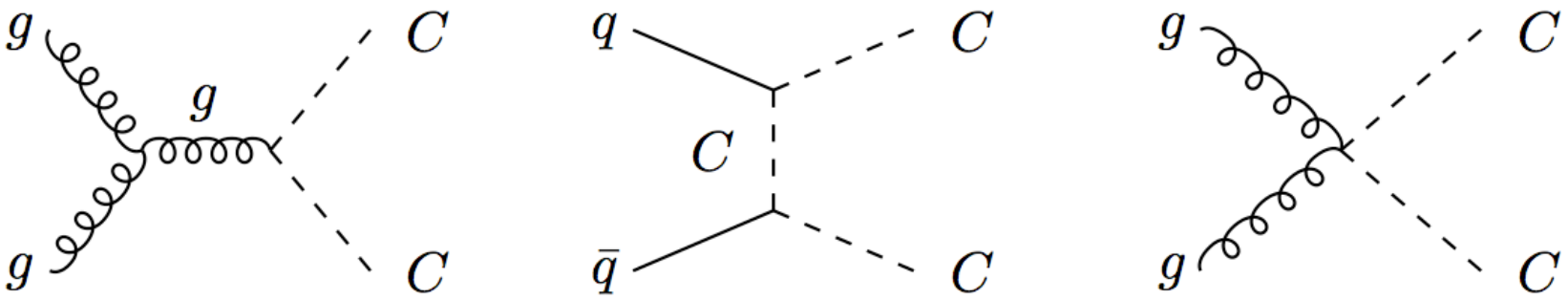
Resonances: dijets



Last public result:
Summer 2011

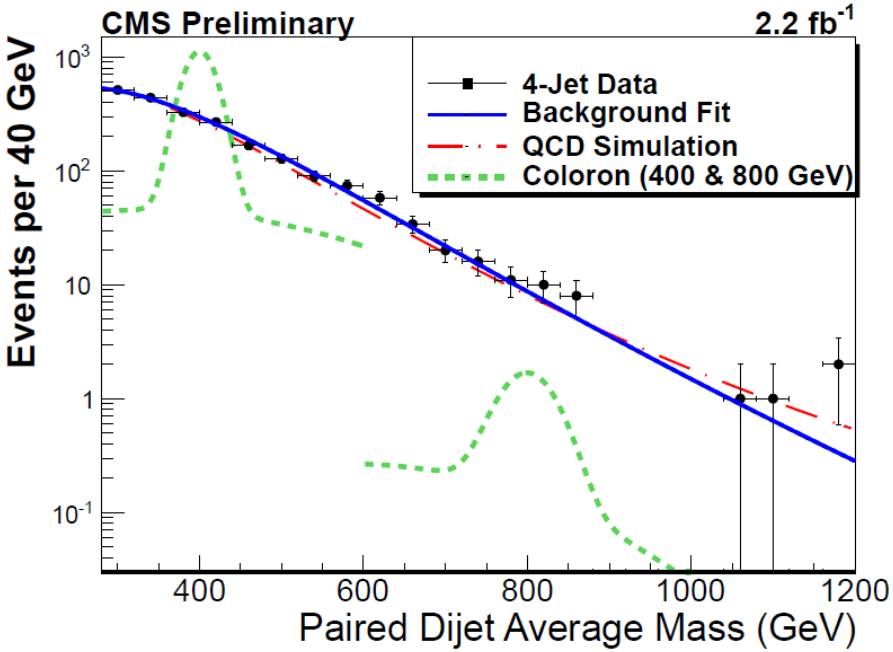
10.1016/j.PhysLetB.2011.09.015
(EXO-11-015)

Pairs of dijet resonances

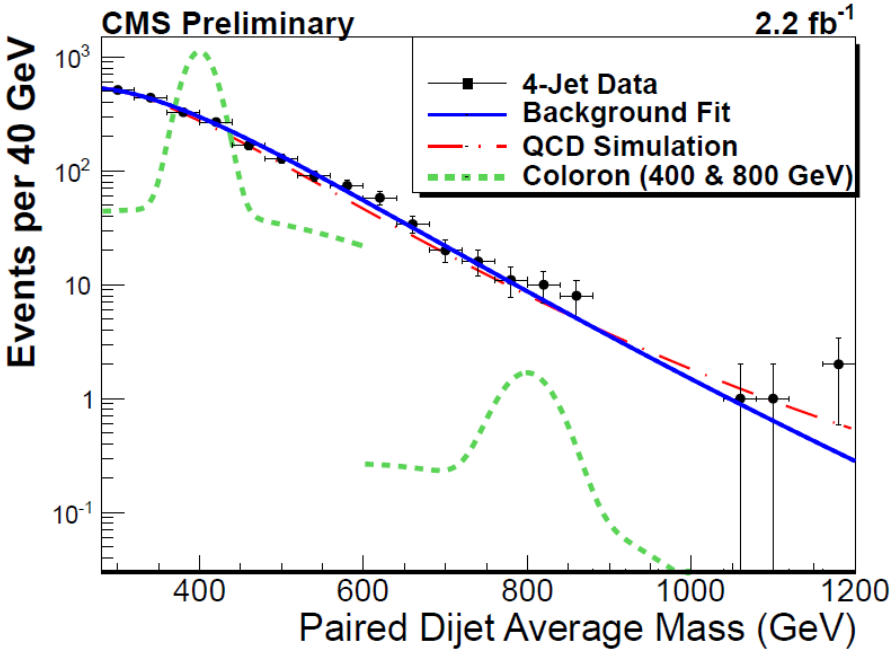


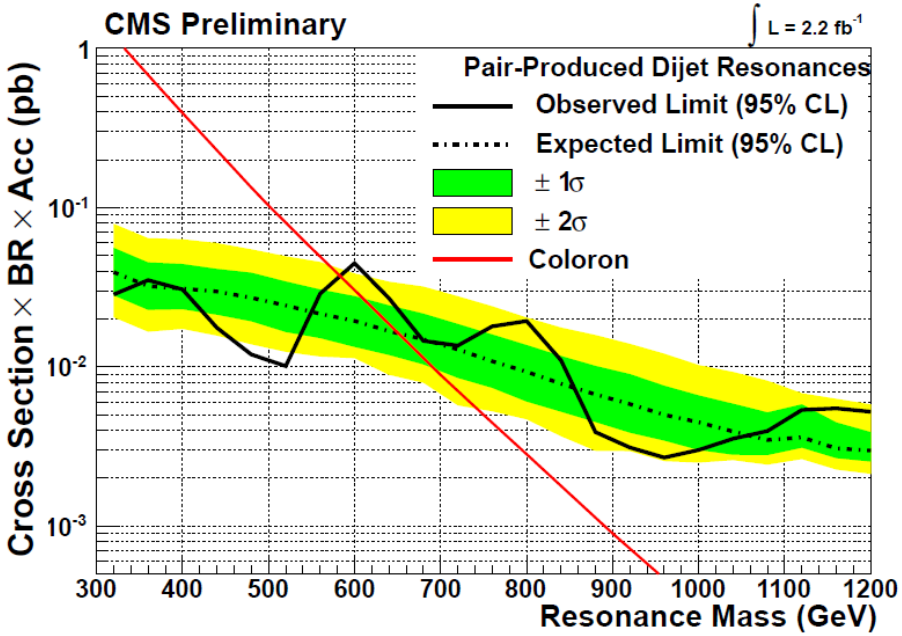
- Looking for narrow colored resonances
- Produced strongly in pairs
- Each one decaying into dijets (with same mass)

Pairs of dijet resonances #2



Pairs of dijet resonances #2

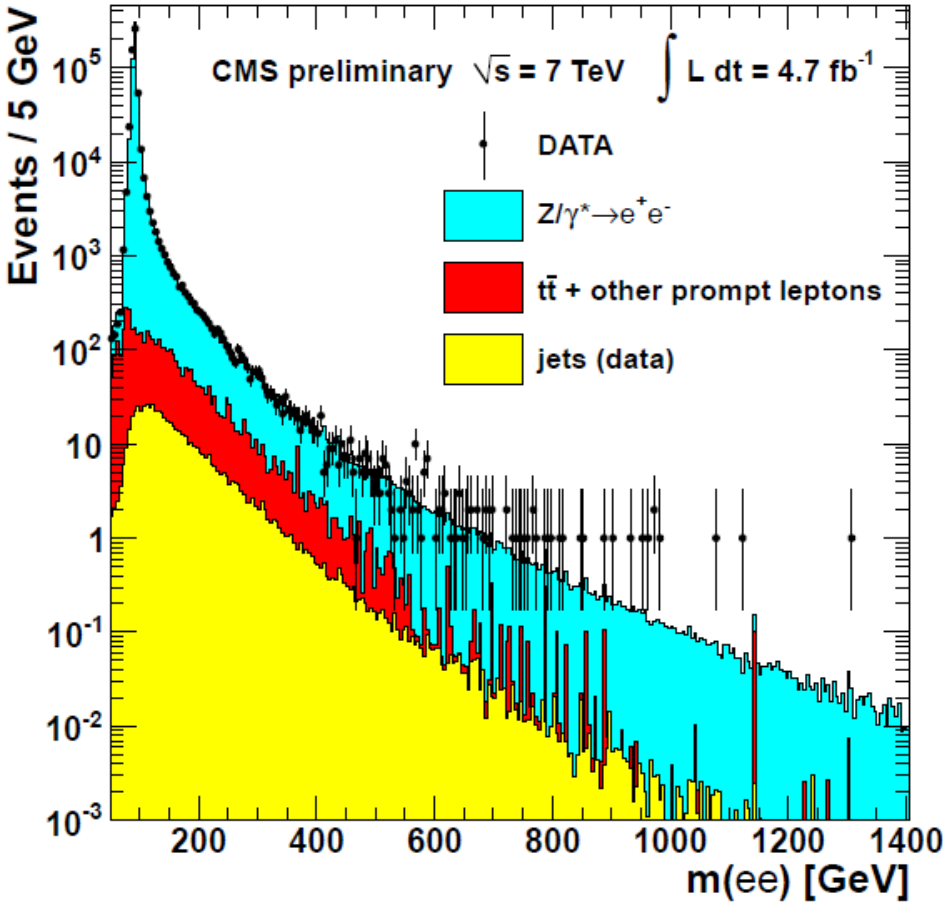


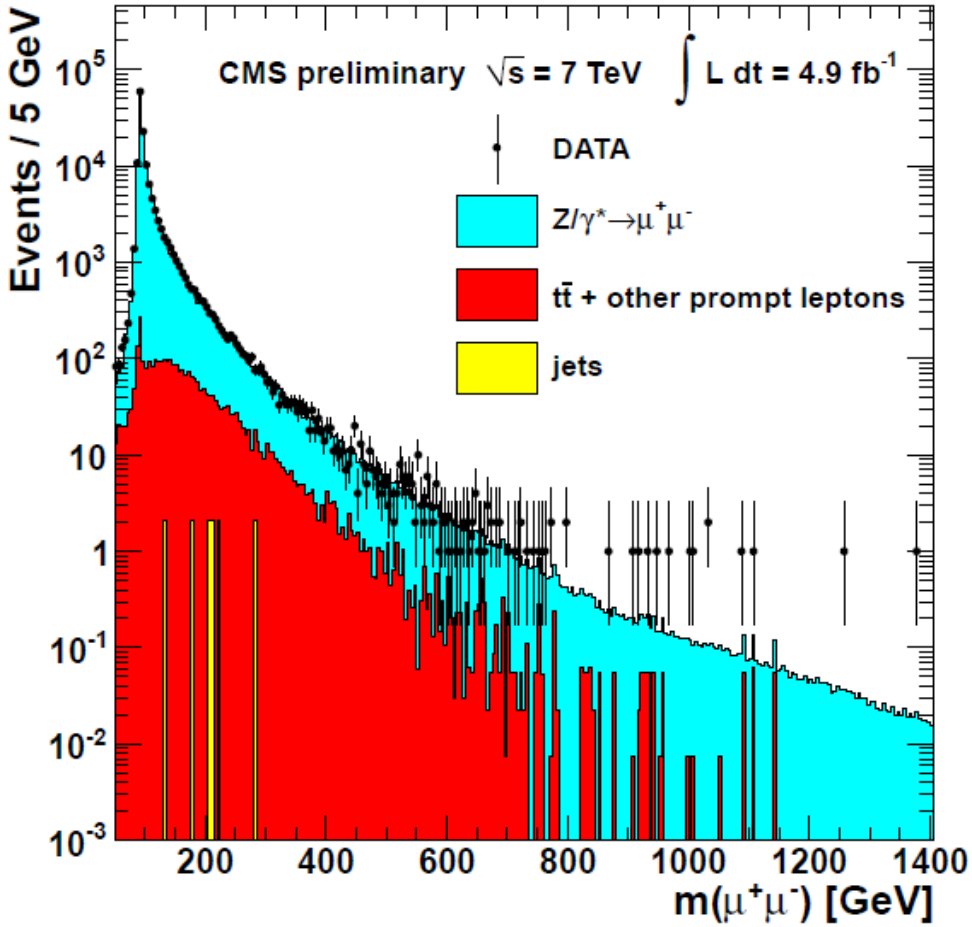


- Maximum local significance values ~ 2σ (w/o LEE)
- Something to keep an eye on in 2012
- Color masses excluded: 320-580 GeV

EXO-11-016

Resonances: dielectrons, dimuons

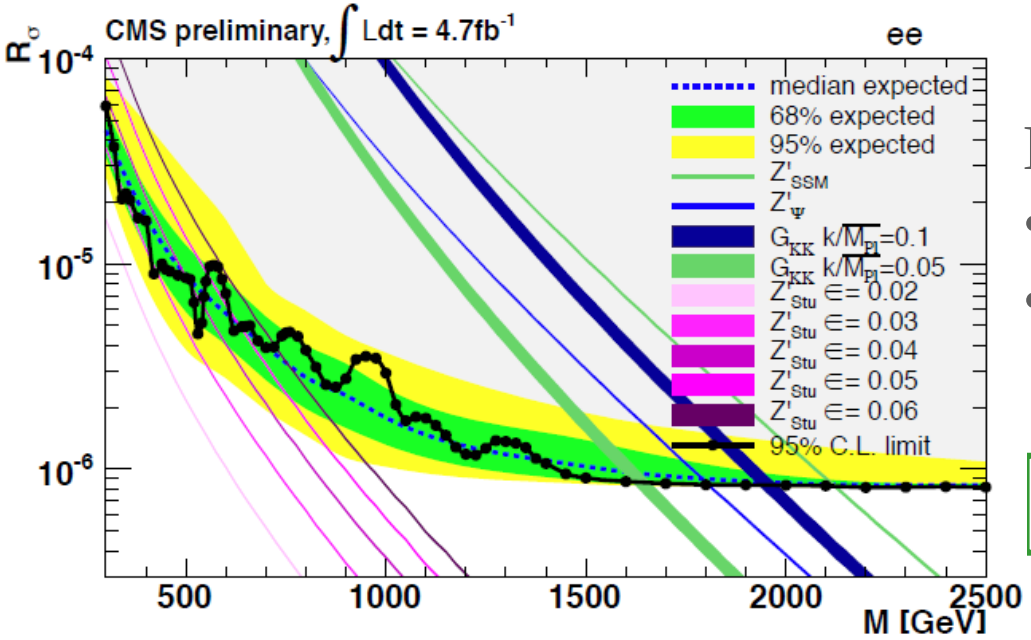


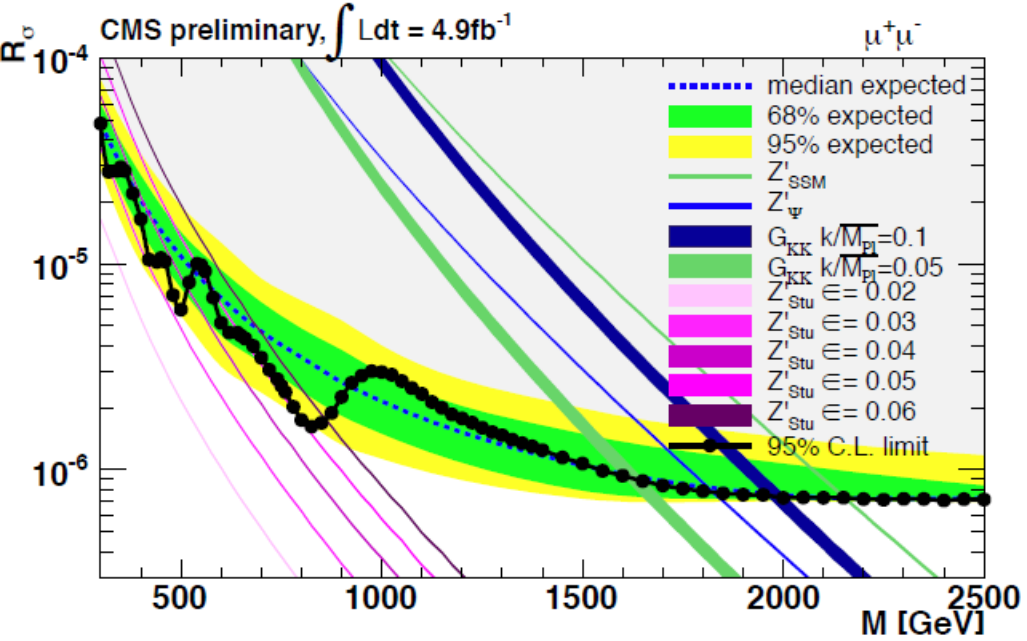


ee

$\mu\mu$

Limits with dimuons, dielectrons





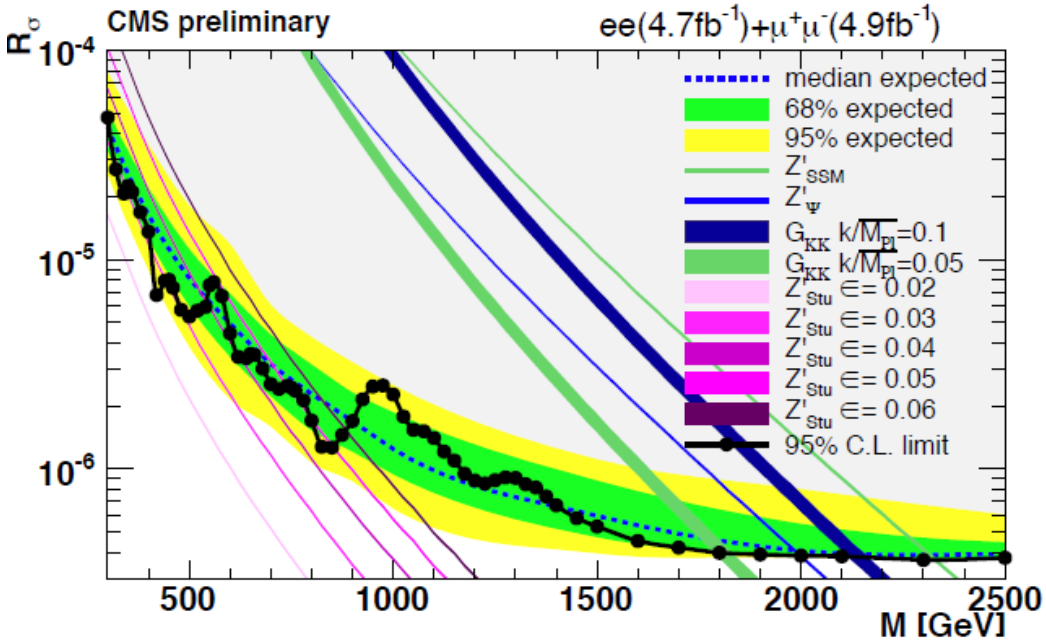
Maximum local significance value

- 2.4σ (before LEE)
- 0.3σ (after LEE)

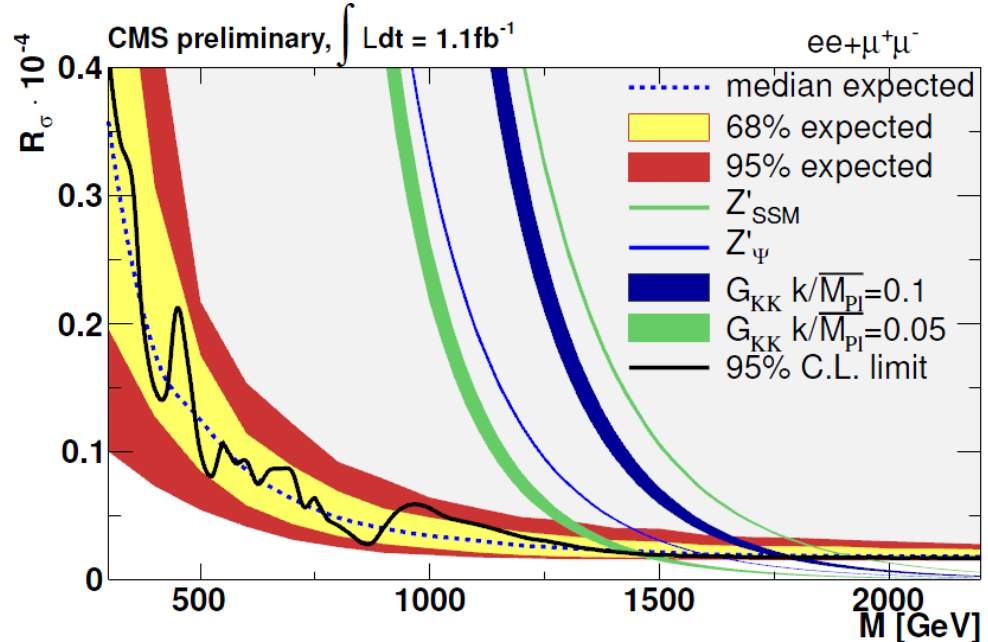
ee

μμ

Limits with dimuons, dielectrons

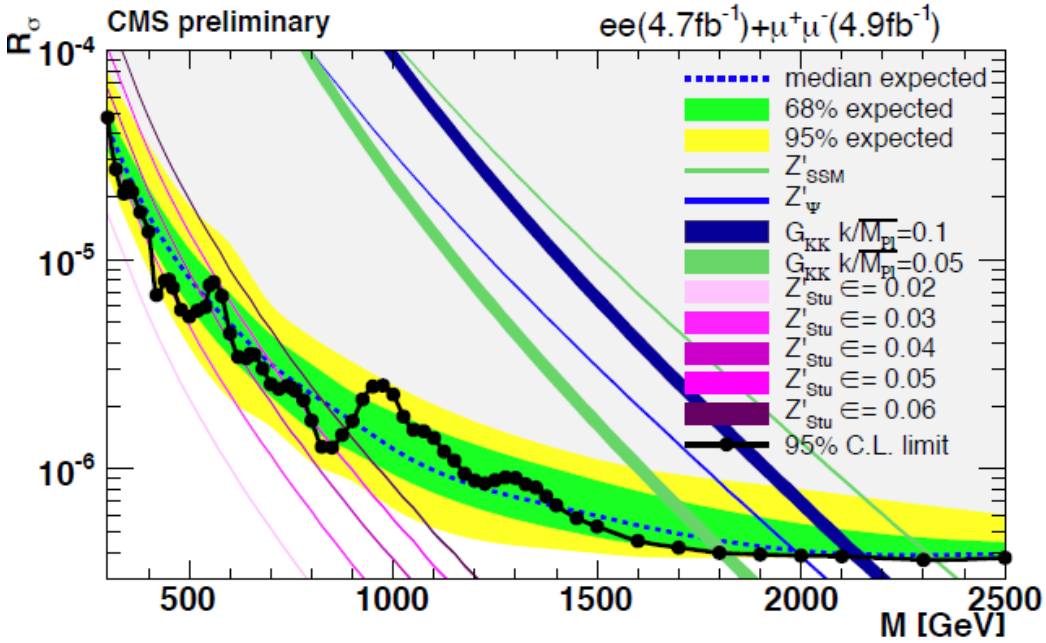


$ee + \mu\mu$: 5 fb^{-1}
Winter 2012



$ee + \mu\mu$: 1 fb^{-1}
Summer 2011

Limits with dimuons, dielectrons



Z'_{SSM}: 2320 GeV

Z'_{ψ}: 2000 GeV

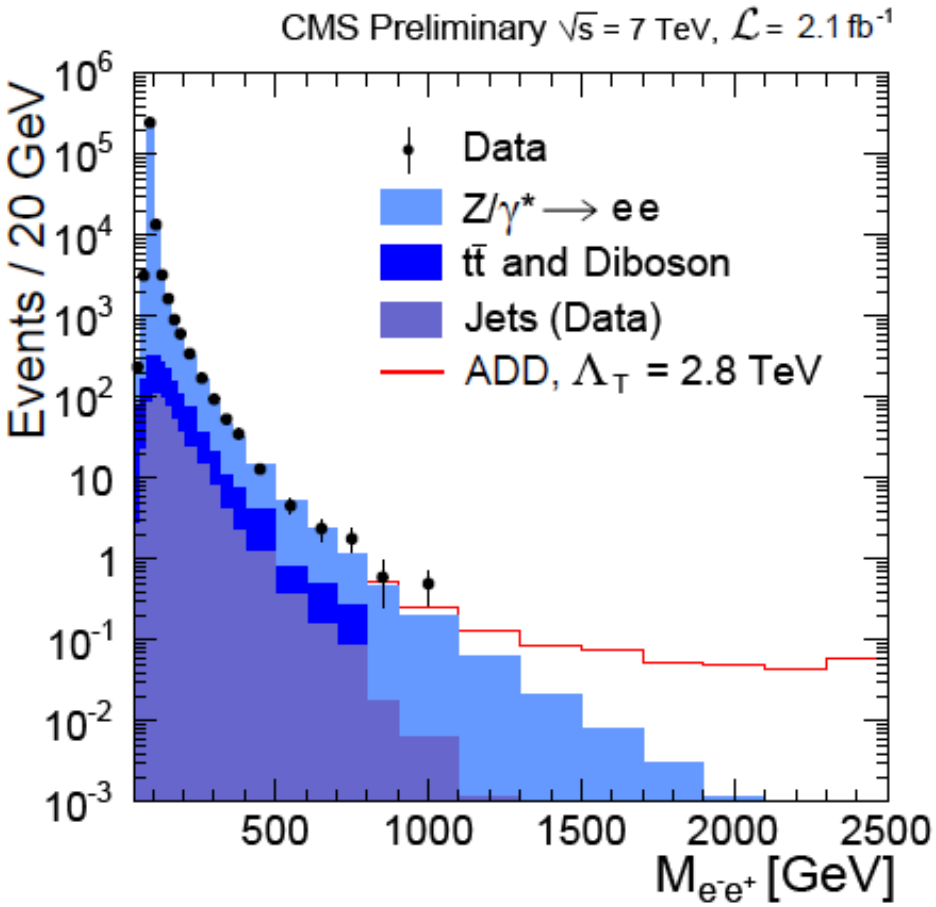
KK: 1810 GeV ($\frac{k}{M}$ =0.05)

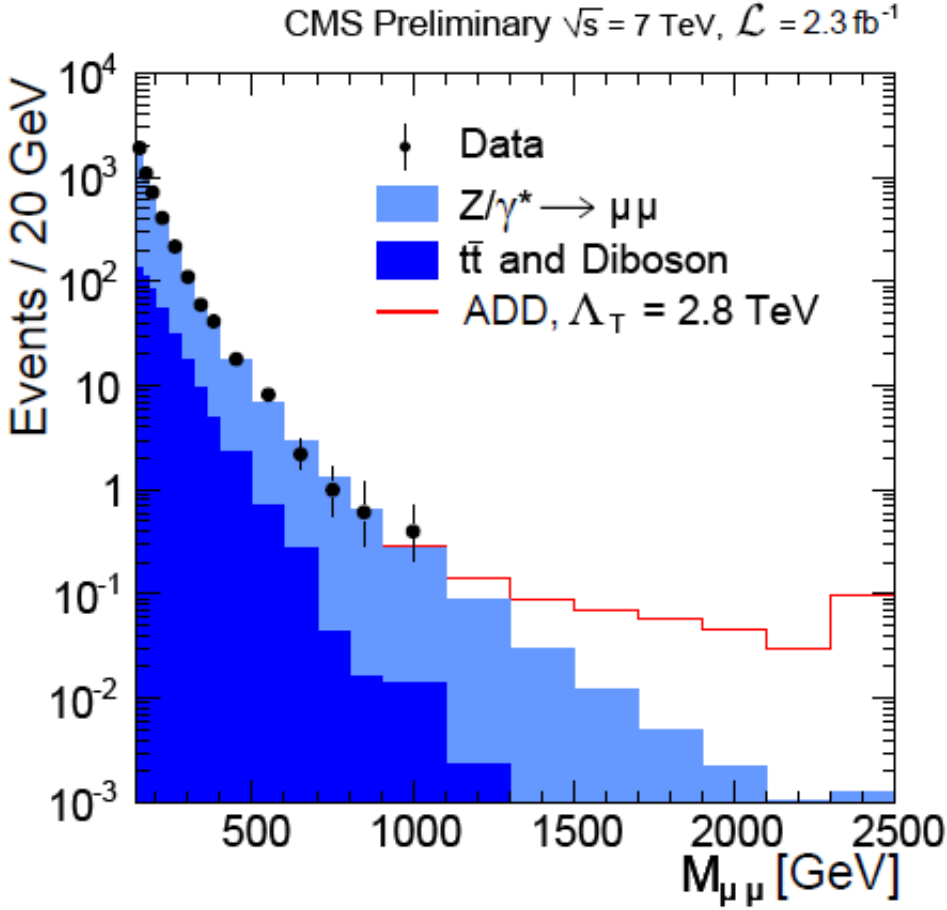
KK: 2135 GeV ($\frac{k}{M}$ =0.1)

- Also something to keep an eye on in 2012
- Strictest limits in the world

EXO-11-019

Extra dimensions in dileptons





ee

$\mu\mu$

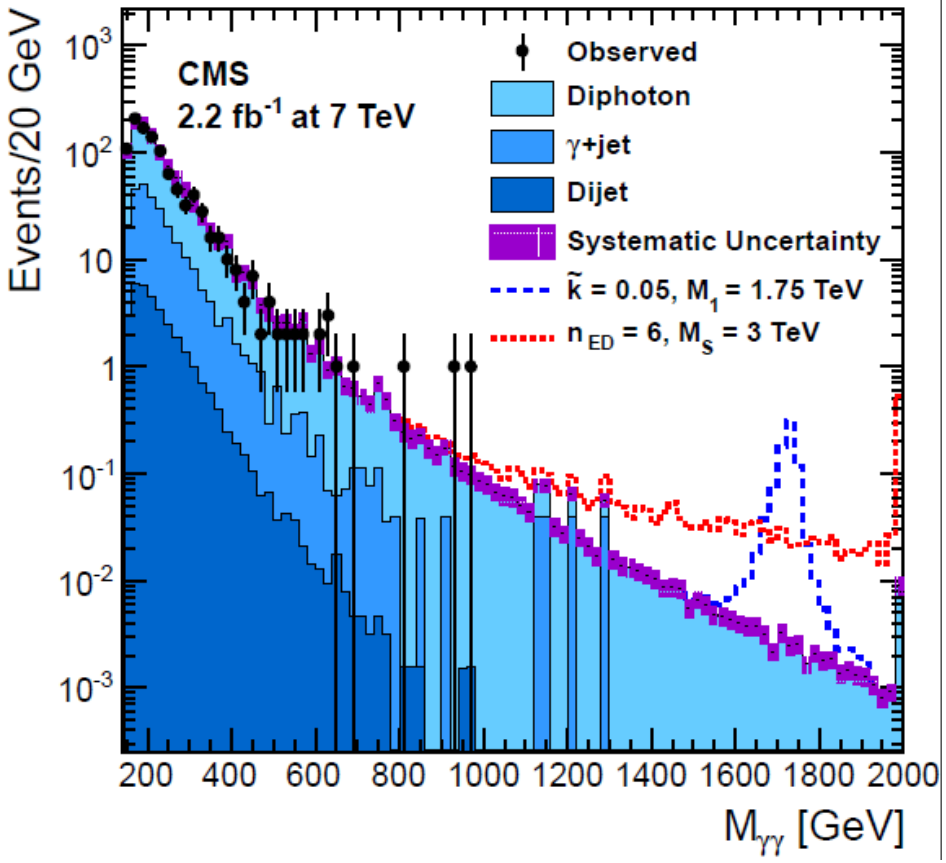
Limits with dimuons, dielectrons

ADD K-factor	Λ_T [TeV] (GRW)	M_s [TeV] (HLZ) $n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
$\mu\mu$, $\sigma_{s,\mu\mu}<$ 1.2 fb (1.8 fb expected) at 95% CL							
1.0	2.8	3.0	3.4	2.8	2.5	2.3	2.2
1.3	3.0	3.2	3.5	3.0	2.7	2.4	2.3
ee, $\sigma_{s,ee}<$ 1.6 fb (2.3 fb expected) at 95% CL							
1.0	2.8	2.9	3.3	2.8	2.5	2.3	2.2
1.3	2.9	3.1	3.4	2.9	2.5	2.4	2.2
$\mu\mu$ and ee, $\sigma_{s,\mu\mu+ee}<$ 1.4 fb (2.2 fb expected) at 95% CL							
1.0	3.1	3.7	3.7	3.1	2.8	2.5	2.4
1.3	3.2	3.8	3.8	3.2	2.9	2.7	2.5

Exclusion limits for GRW and HLZ models for several parameters (2.2-3.8 TeV)

arXiv:1202.3827
Accepted by Phys.Lett.B
(EXO-11-087)

Resonances: diphotons



10.1103
PhysRevLett.108.111801
(EXO-11-038)

Exclusion limits on RS gravitons (860-1880 GeV) and several ADD models (2.3-3.8 TeV)

Effective Planck scale (TeV) in ADD

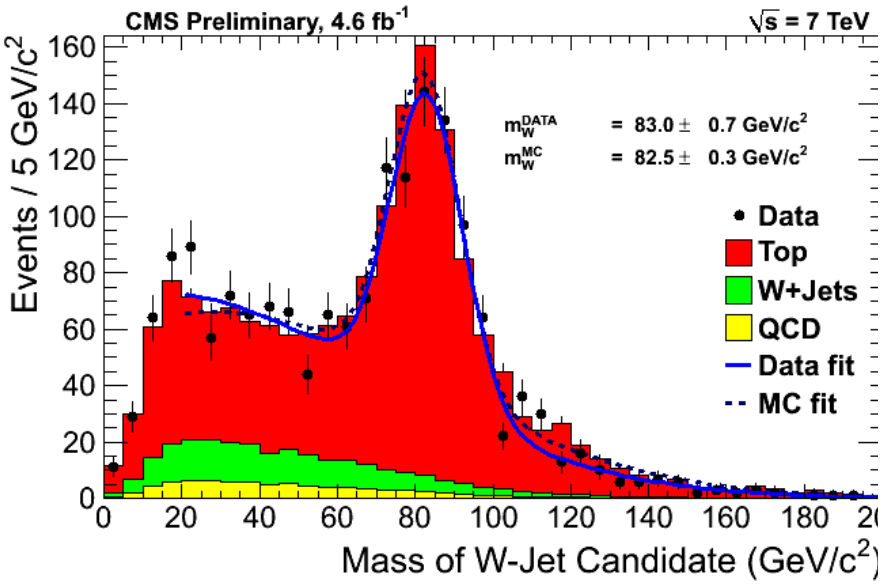
K factor	GRW	Hewett		HLZ					
		pos.	neg.	$n_{ED}=2$	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
1.0	2.94	2.63	2.28	3.29	3.50	2.94	2.66	2.47	2.34
1.6	3.18	2.84	2.41	3.68	3.79	3.18	2.88	2.68	2.53

RS gravitons: Mass (TeV)

$\tilde{k}$	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

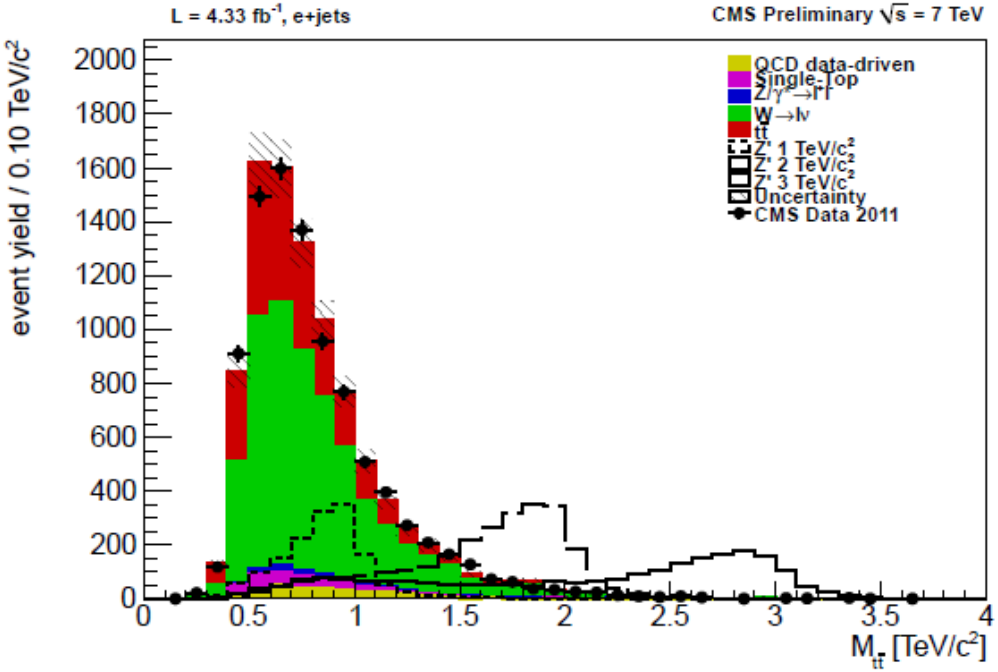
Resonances: $t\bar{t}$

Boosted all-hadronic final state



EXO-11-006

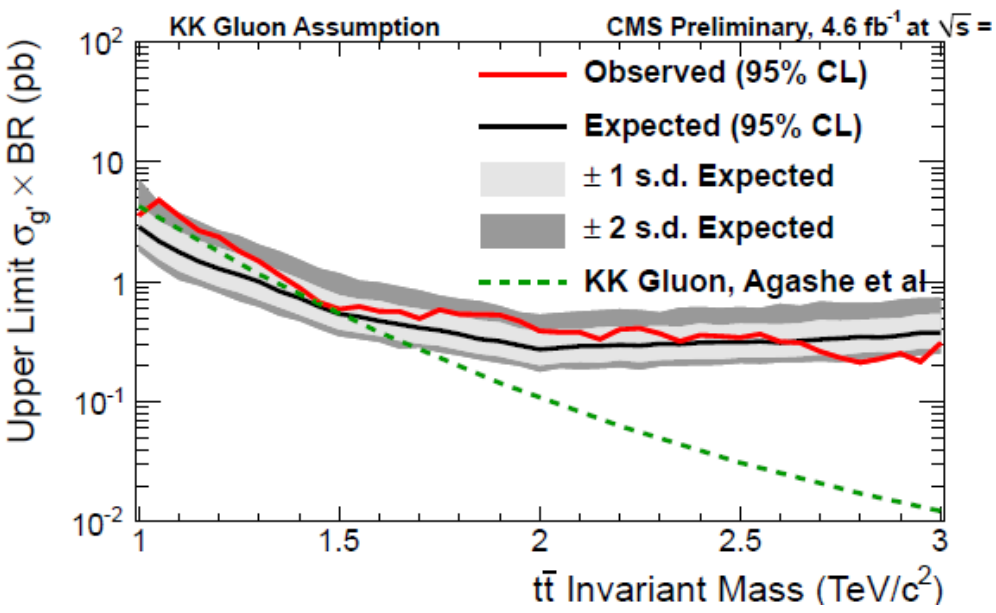
Electron + jets



EXO-11-092

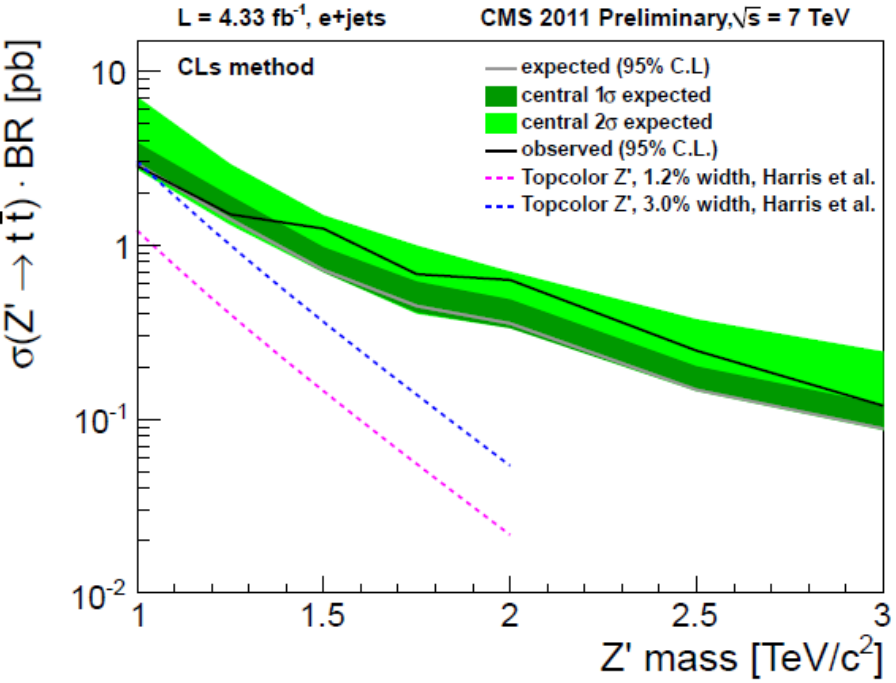
Limits with $t\bar{t}$

Boosted all-hadronic final state



EXO-11-006

Electron + jets



EXO-11-092

Z'_{SSM}: 1.3 – 1.5 TeV (width=1.2%)
Z'_{SSM}: 1.0 – 2.0 TeV (width=10%)
KK: 1.4-1.5 TeV

Exclusion limits on SSM, KK and topcolor models

“Non-Resonances” (aka: W'-like)

CMS: 25 New Results

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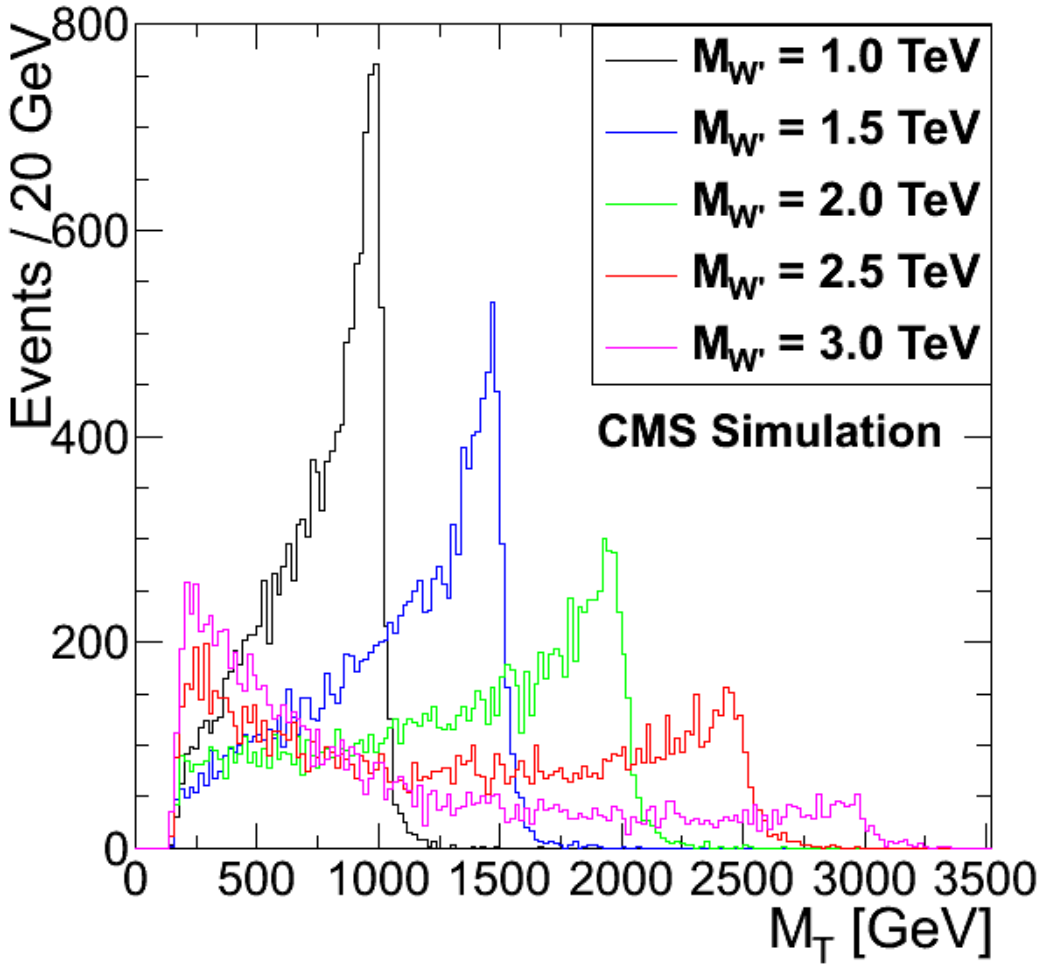
- Fourth generation
  - Heavy bottom-like and top-like quarks

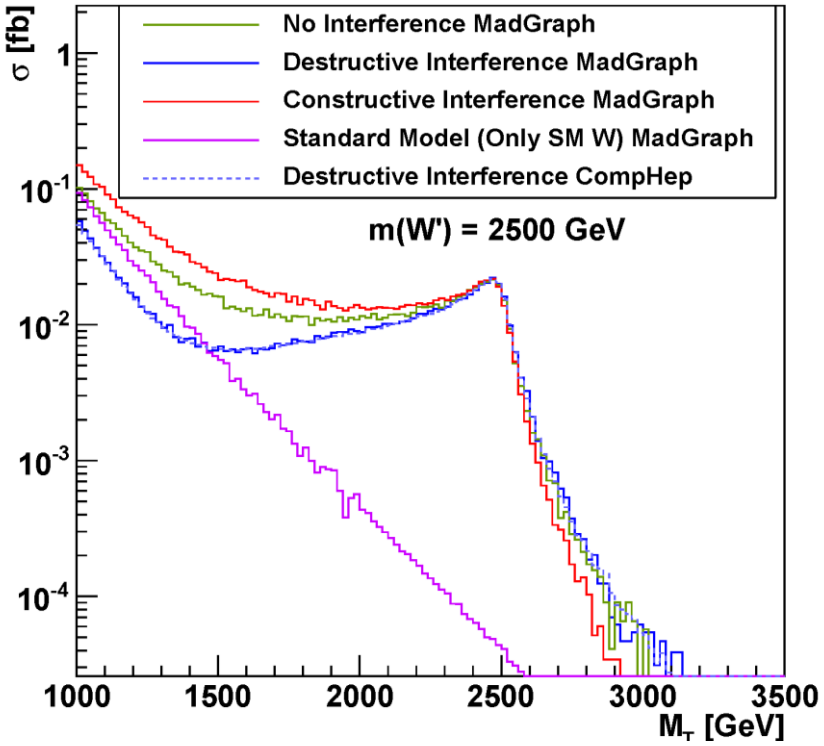
- "Weird" stuff: leptoquarks & long-lived particles

$W' \to \ell\nu\ (\ell = e, \mu)$



W' : mainly off-peak production for higher masses at 7 TeV

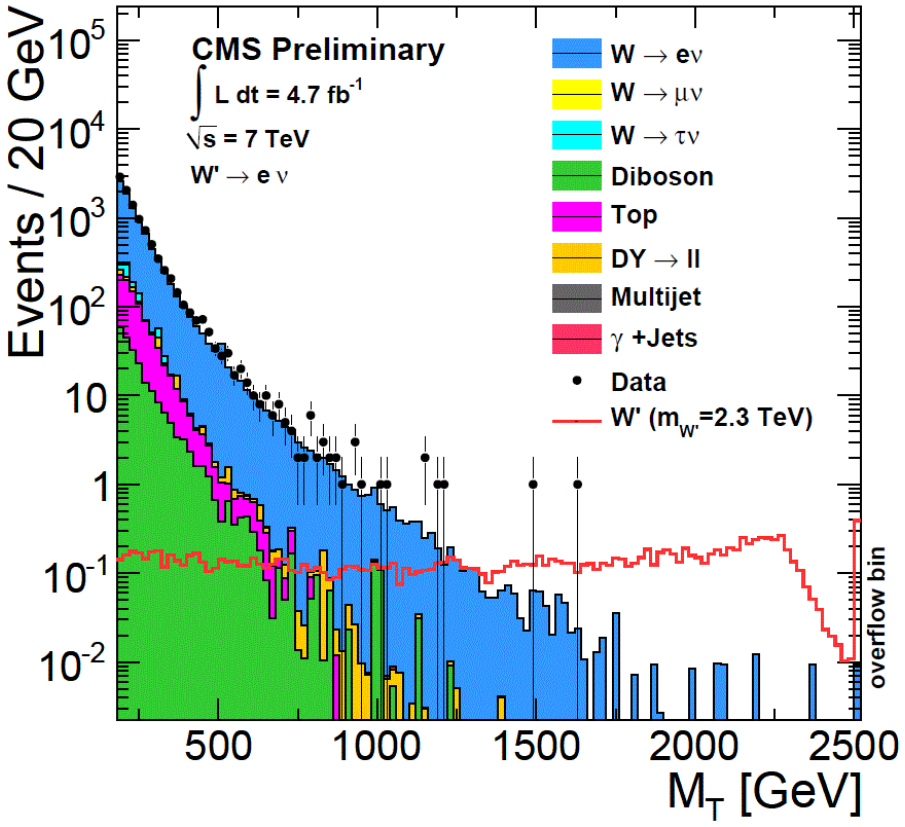
$W' \to \ell\nu\ (\ell = e, \mu)$



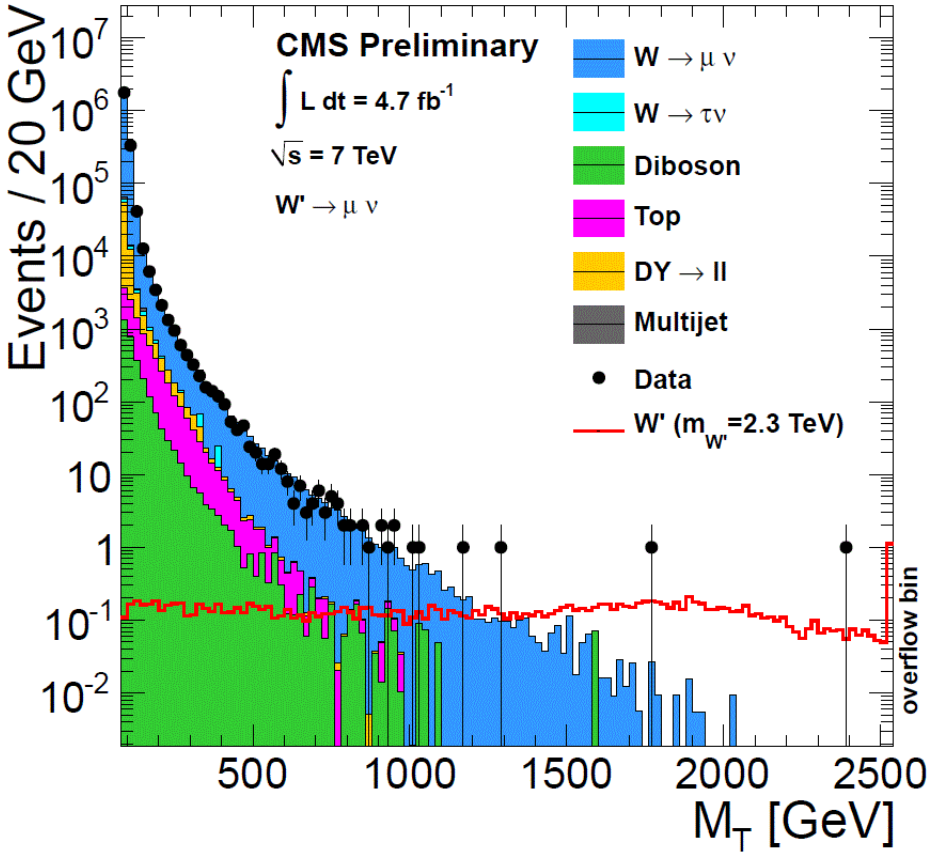
$$M_T = \sqrt{2 \cdot (p_T^{\mu} \cdot c) \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\mu,\nu})}$$

- $W - W'$ interference considered for first time in leptonic decays
- Can potentially detect interference term even for very high masses

$W' \to \ell\nu\ (\ell = e, \mu)$



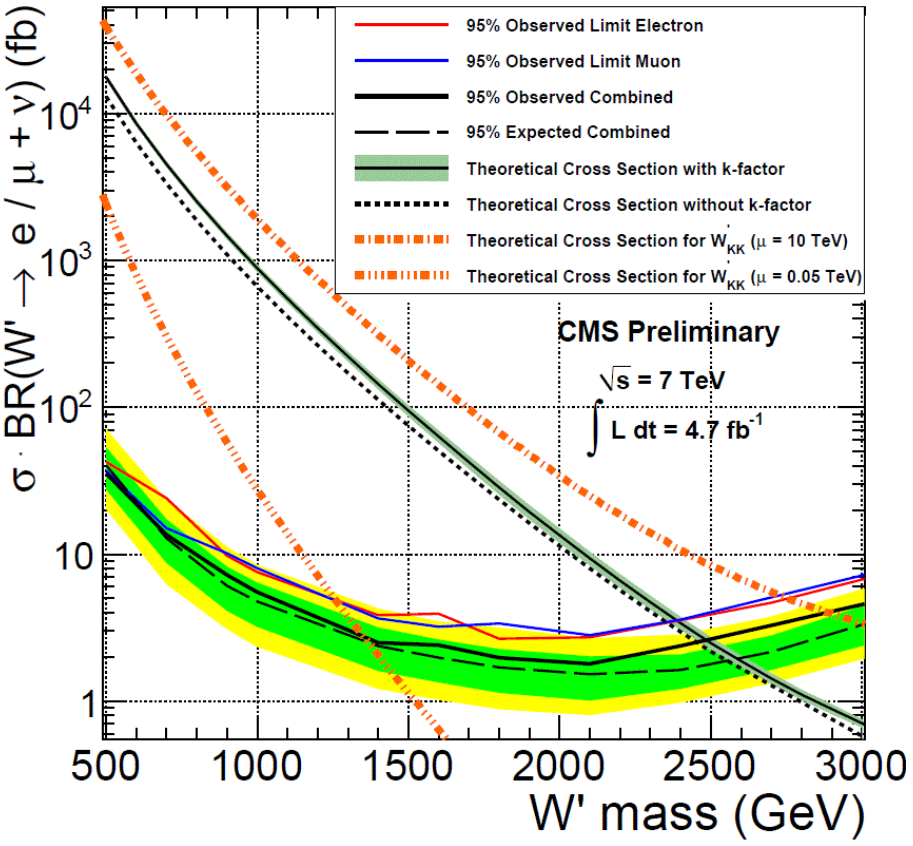
$e + MET$

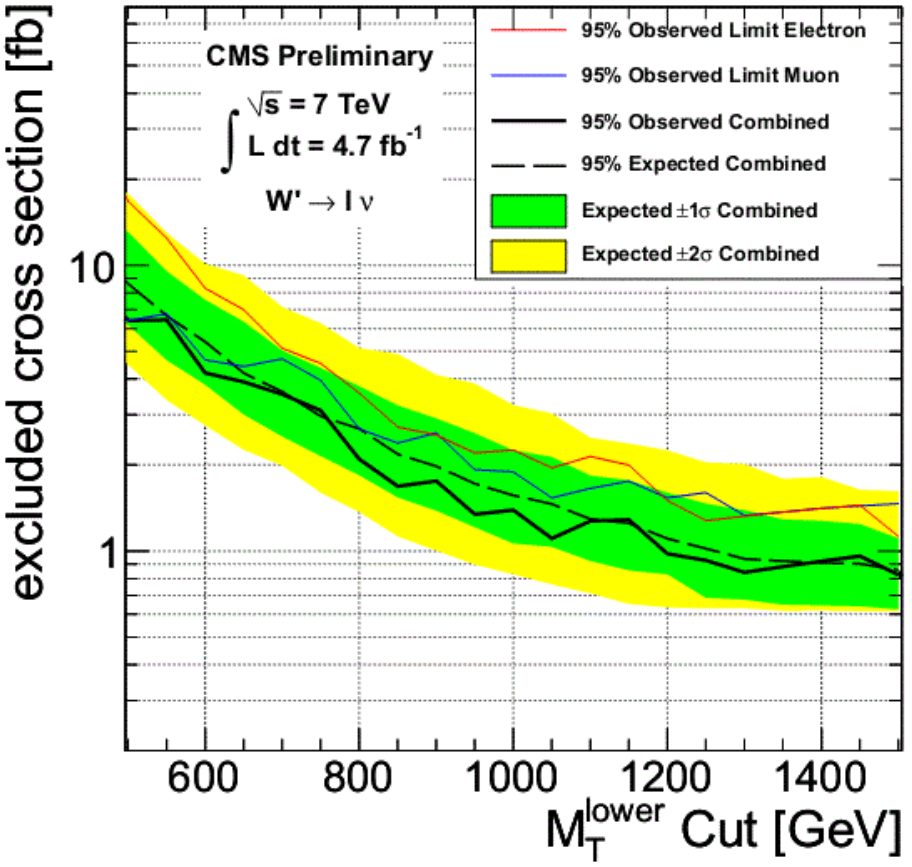


$\mu + MET$

$$M_T = \sqrt{2 \cdot (p_T^{\mu} \cdot c) \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\mu,\nu})}$$

$W' \to \ell\nu\ (\ell = e, \mu)$

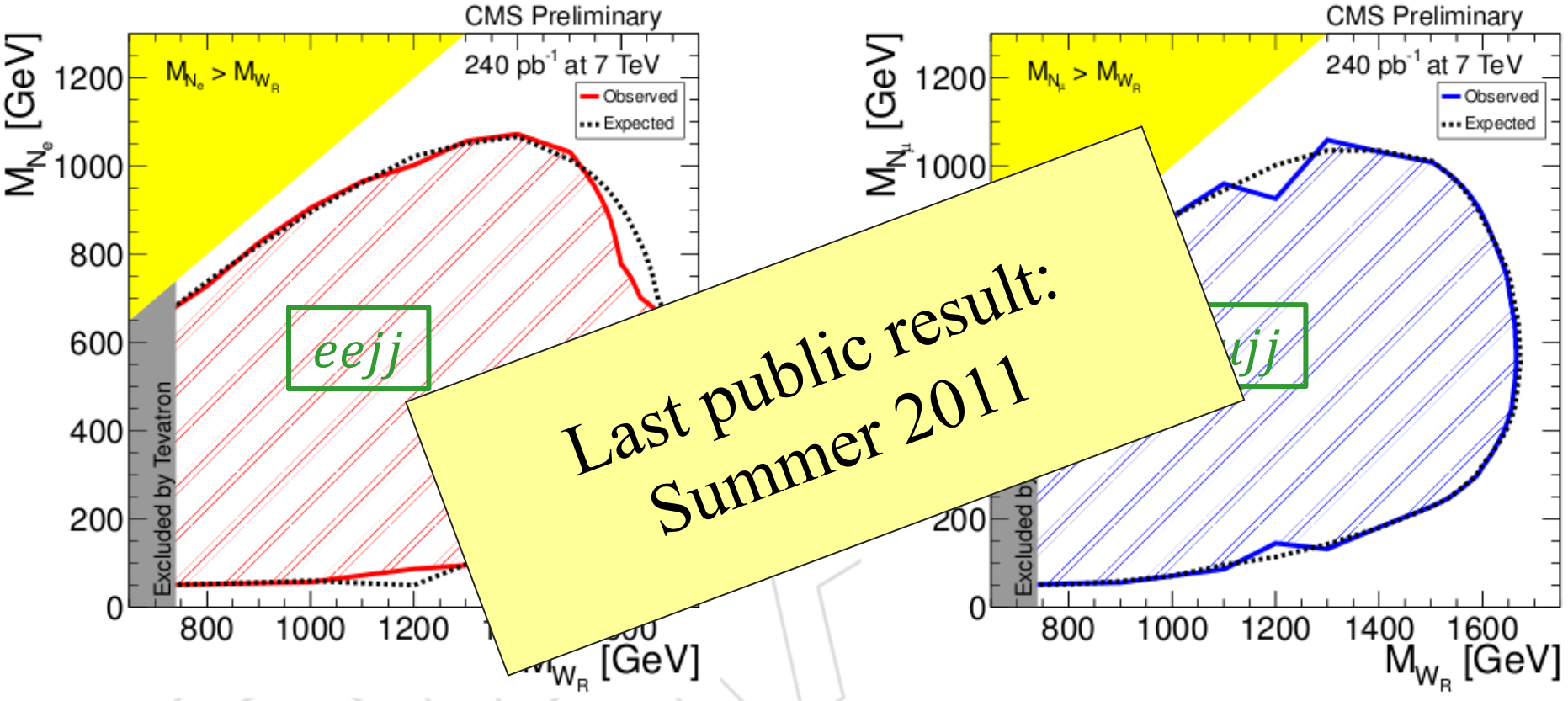




Strictest limits in SSM model:
No interference: 2.5 TeV
Destructive: 2.43 TeV
Constructive: 2.63 TeV

EXO-11-024

$W' \to \ell\, N_\ell\,, N_\ell \to qq'\ell'$

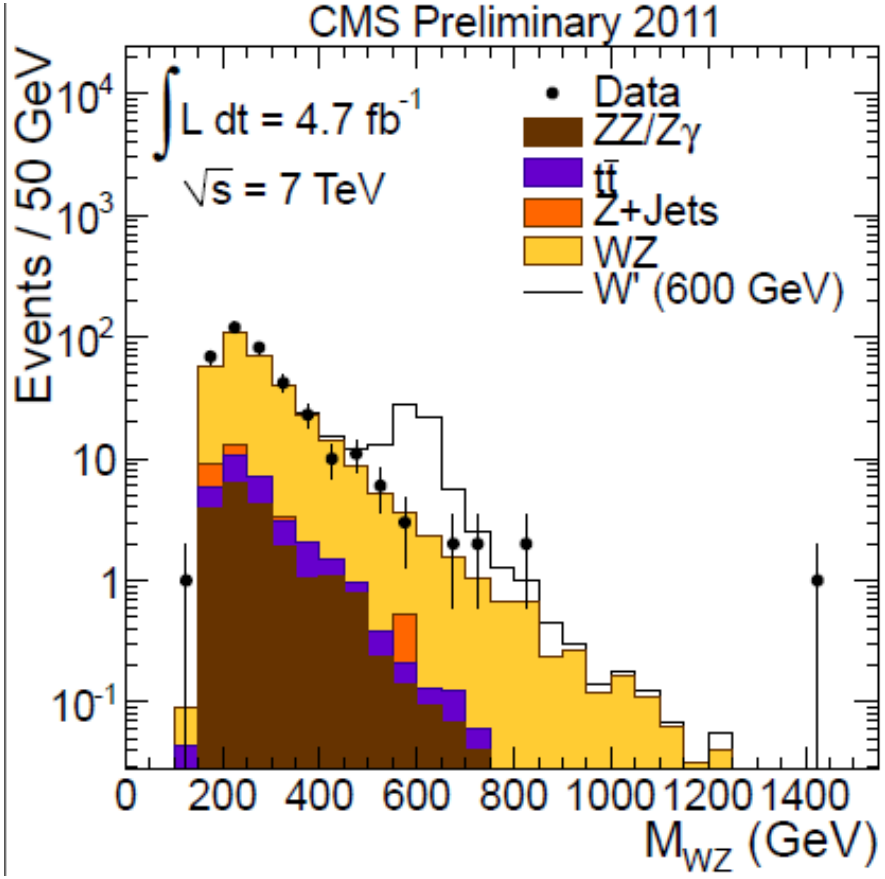


Last public result:
Summer 2011

W'_{SSM}: extends to 1.7 TeV

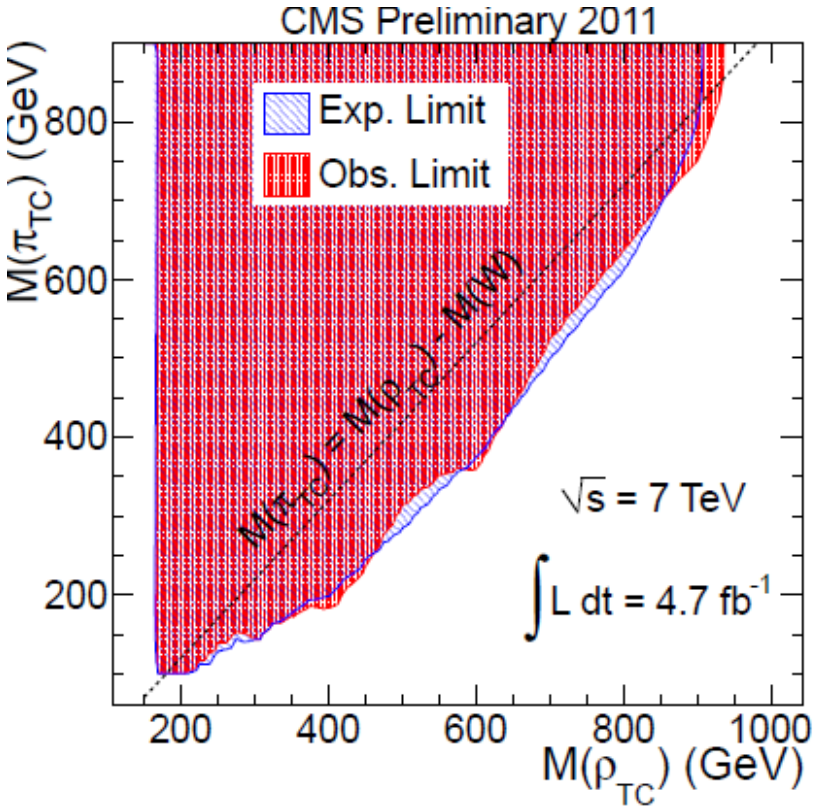
EXO-11-002

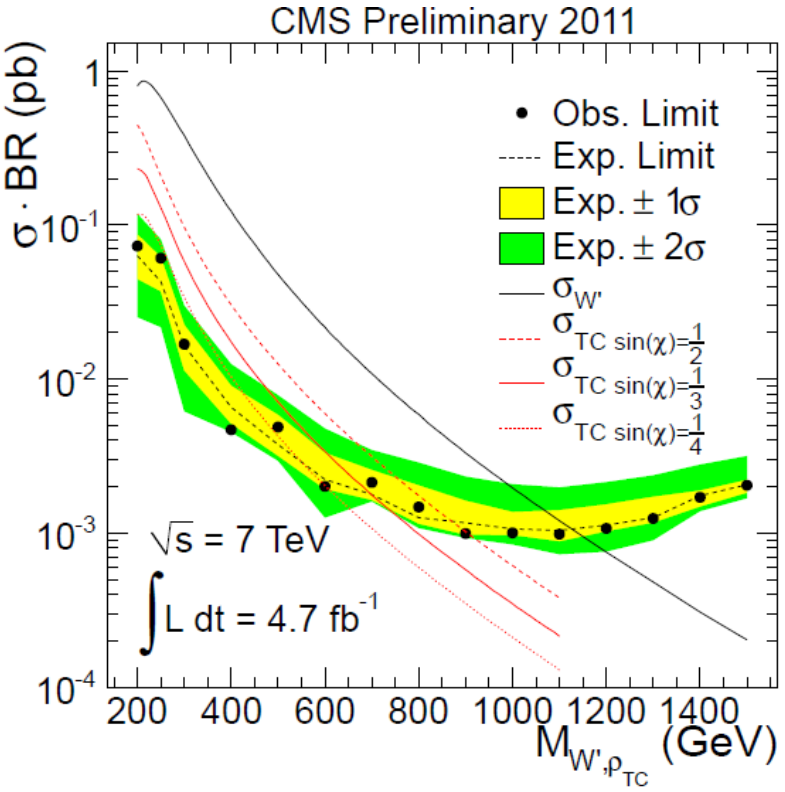
$W'(\rho_{TC}) \rightarrow WZ \rightarrow 3\ell\nu\ (\ell = e, \mu)$



- Technicolor interpretation
- Complementary to previous channels (e.g. fermiophobic models)
- First search after TeVatron

$W'(\rho_{TC}) \rightarrow WZ \rightarrow 3\ell\nu\ (\ell = e, \mu)$





EXO-11-041

W'_{SSM}: 1141 GeV

$169 < M(\rho_{TC}) < 680$ GeV ($M_{\pi_{TC}} = \frac{3}{4} M_{\rho_{TC}}$-25 GeV)

$180 < M(\rho_{TC}) < 935$ GeV ($M_{\rho_{TC}} < M_{\pi_{TC}} + M_W$)

Excluding Technicolor interpretation [$M(\rho_{TC})$=290 GeV, $M_{\pi_{TC}}$=160 GeV] of "CDF bump"

(More) Large Extra Dimensions

CMS: 25 New Results

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  - dijet, $ee, \mu\mu, \gamma\gamma, t\bar{t}, t\bar{t}$ (boosted)
- W'
  - $e + \nu, \mu + \nu, qq', \ell N_\ell$ (aka: right-handed W), WZ
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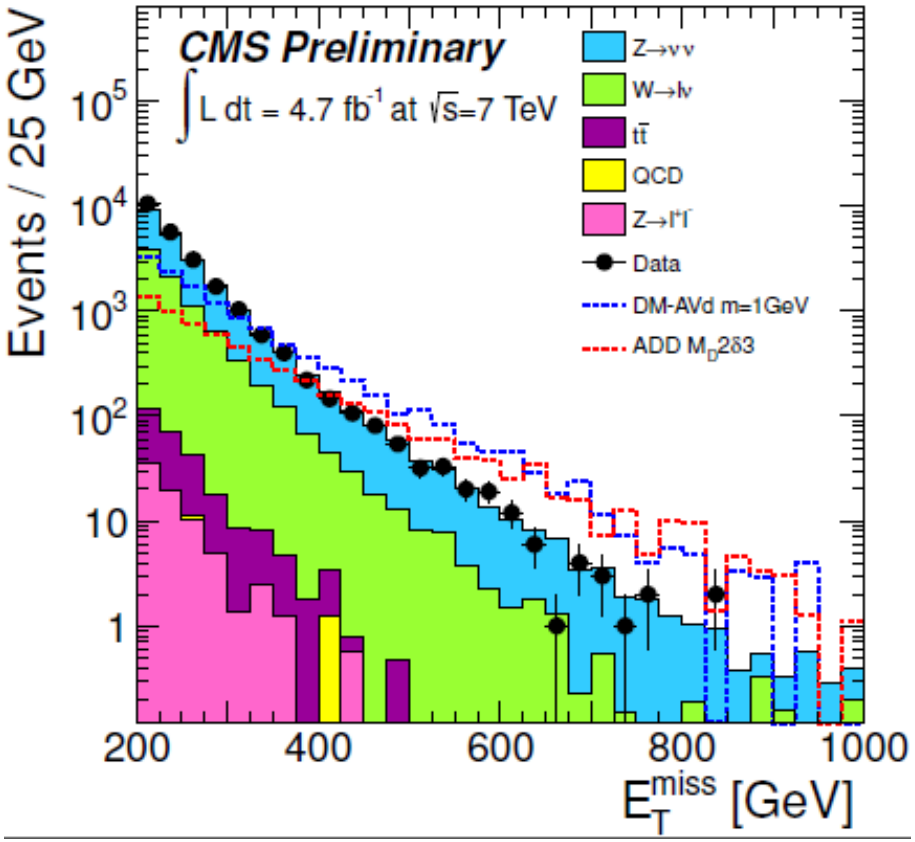
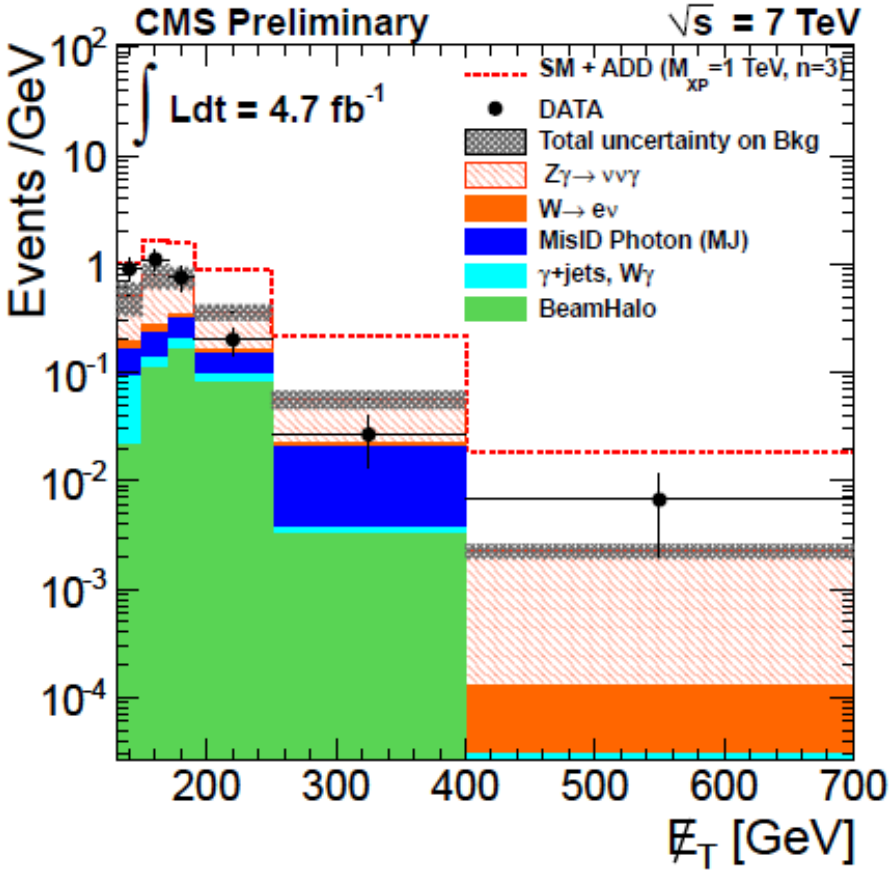
- Fourth generation
  - Heavy bottom-like and top-like quarks
- "Weird" stuff: leptoquarks & long-lived particles

(Mono)Jet + ME_T, $\gamma + ME_T$

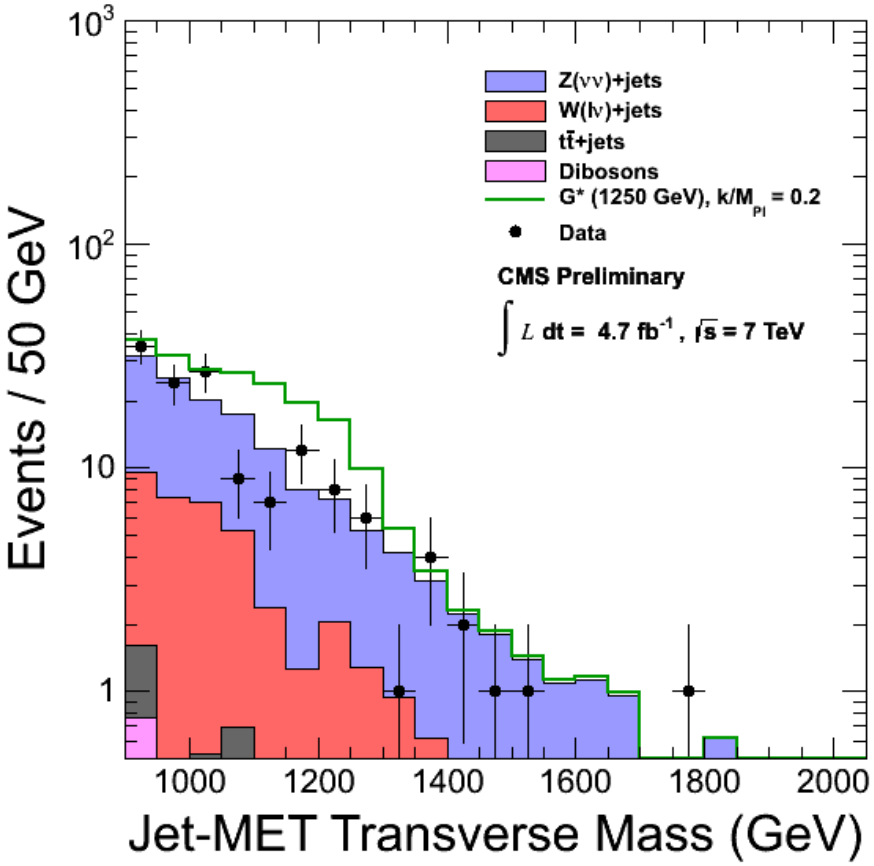




Jet +MET

γ + MET

(Mono)Jet + ME_T #2

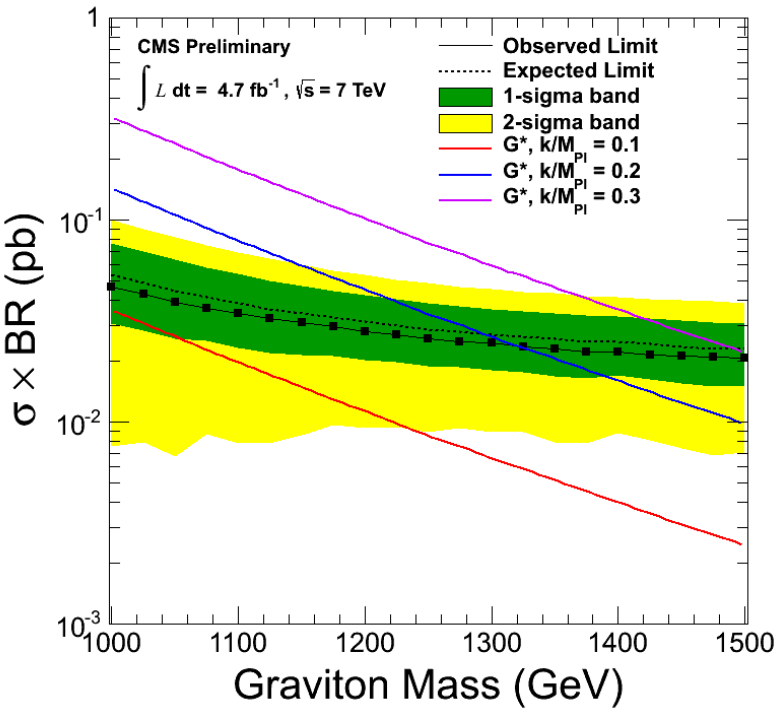


Jet +MET

Limits with (mono)jet/$\gamma + ME_T$

	LO		NLO	
δ	Exp. Limit	Obs. Limit	Exp. Limit	Obs. Limit
2	3.76	4.00	4.16	4.44
3	3.04	3.18	3.29	3.46
4	2.68	2.78	2.83	2.94
5	2.42	2.52	2.56	2.66
6	2.27	2.37	2.39	2.49

M_{DM} [GeV]	90% CL Limits		95% CL Limits	
	σ[fb]	Λ[GeV]	σ[fb]	Λ[GeV]
1	16.8 (16.4)	549 (553)	21.3 (19.5)	518 (529)
10	16.8 (16.4)	549 (552)	21.3 (19.5)	517 (529)
100	16.8 (16.3)	546 (550)	21.2 (19.4)	515 (526)
200	16.8 (16.4)	527 (530)	21.3 (19.5)	497 (508)
500	16.1 (15.6)	425 (428)	20.3 (18.6)	401 (410)
1000	16.6 (16.1)	235 (237)	20.9 (19.2)	222 (227)



Exclusions limits:

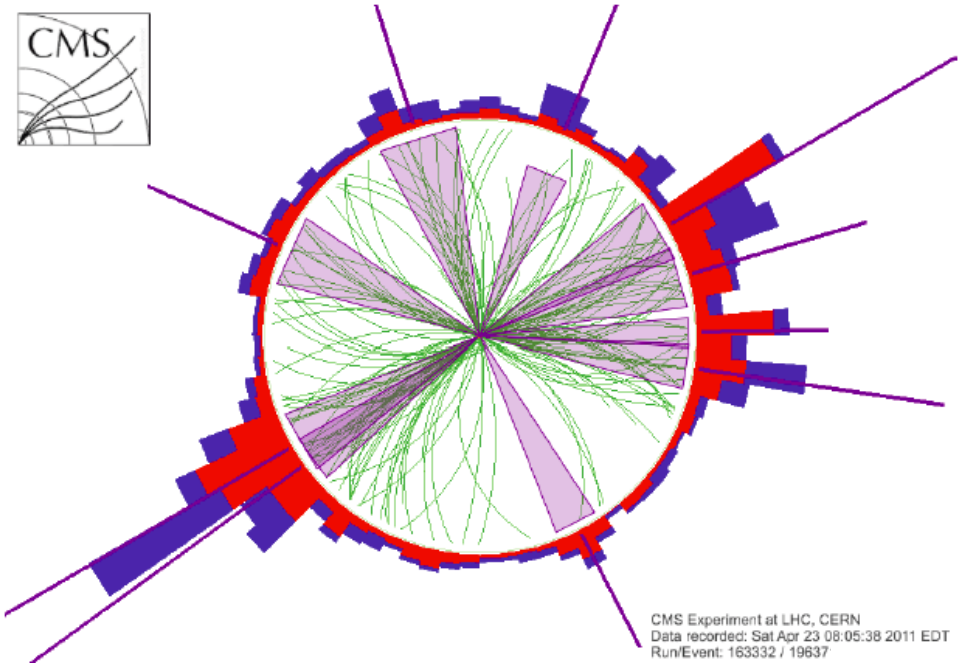
- Graviton mass ($\frac{k}{M} = 0.3$): 1000-1500 GeV
- Extra dimension models: 2.3-4.4 TeV
- Dark matter models (several parameters)

EXO-11-059

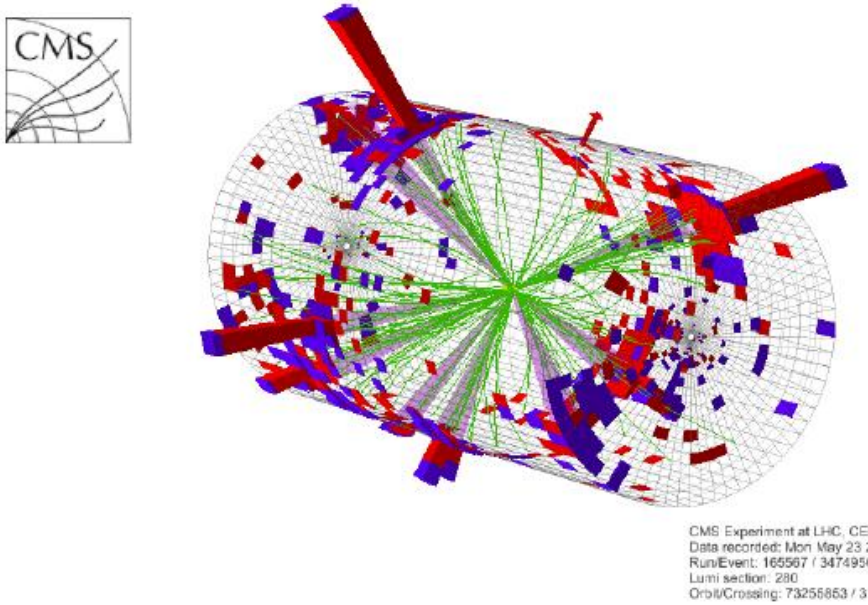
EXO-11-061

EXO-11-096

Black Holes

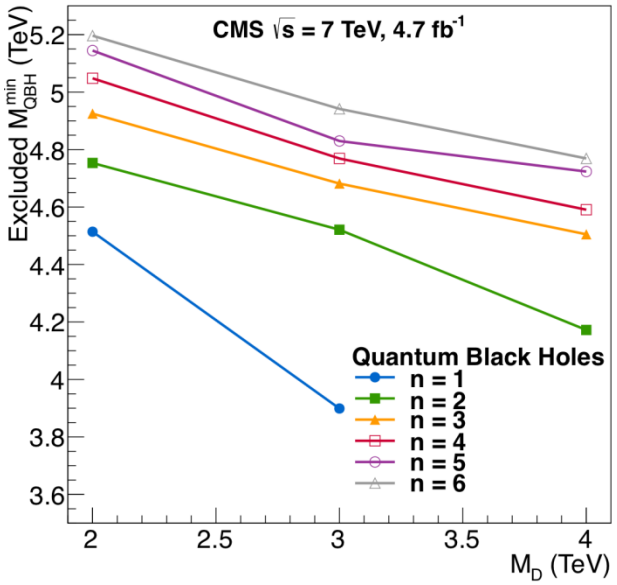


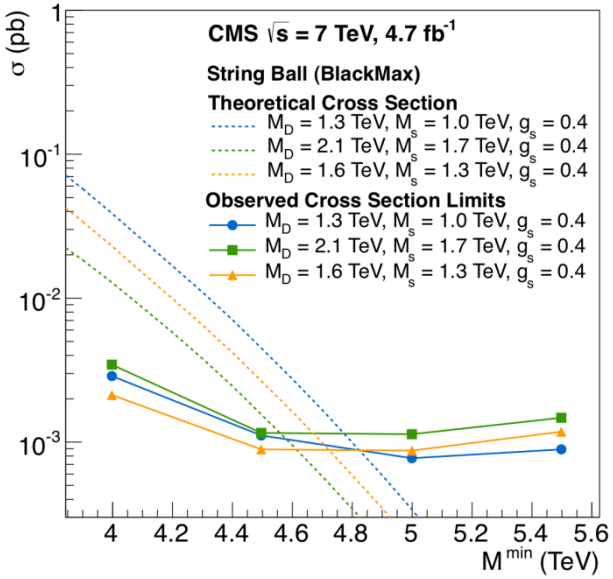
$$N = 10, S_T = 1.1 \text{ TeV}$$

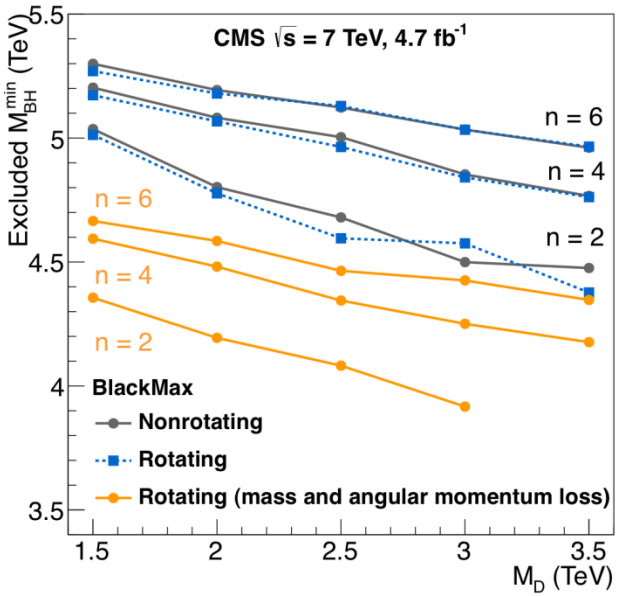


$$N = 9, S_T = 2.5 \text{ TeV}$$

Limits on Black Holes







Quantum Black Holes: 3.8 – 5.2 TeV

String Balls: 4.6 – 4.8 TeV

arXiv:1202.6396
Submitted to JHEP
(EXO-11-071)

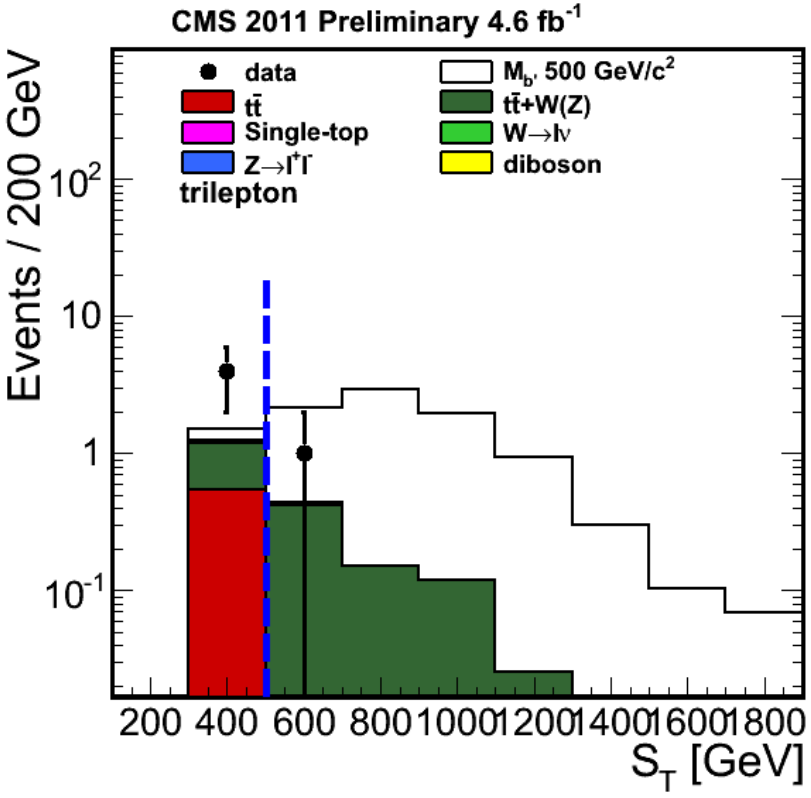
Exclusions limits on (quantum) black holes, string balls and several other models

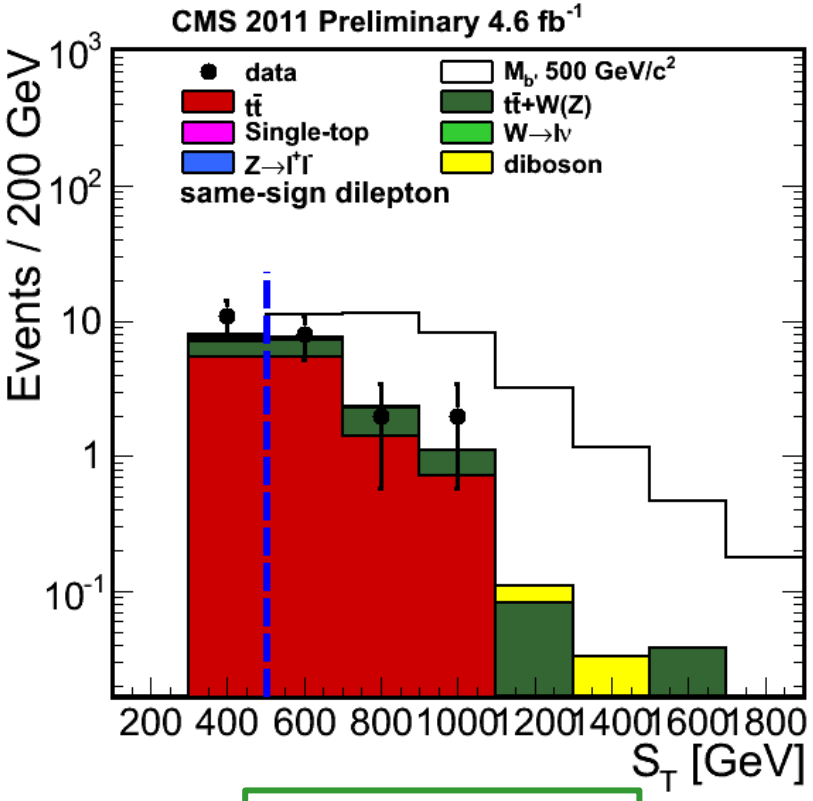
Fourth Generation

CMS: 25 New Results

- Resonances (Z'-like and extra dimensions)
  - dijet, $ee, \mu\mu, \gamma\gamma, t\bar{t}, t\bar{t}$ (boosted)
- W'
  - $e + \nu, \mu + \nu, qq', \ell N_\ell$ (aka: right-handed W), WZ
- More extra dimensions:
  - mono-jet, mono-photon, black holes
- Fourth generation
  - Heavy bottom-like and top-like quarks
- "Weird" stuff: leptoquarks & long-lived particles

Heavy new bottom-like quark





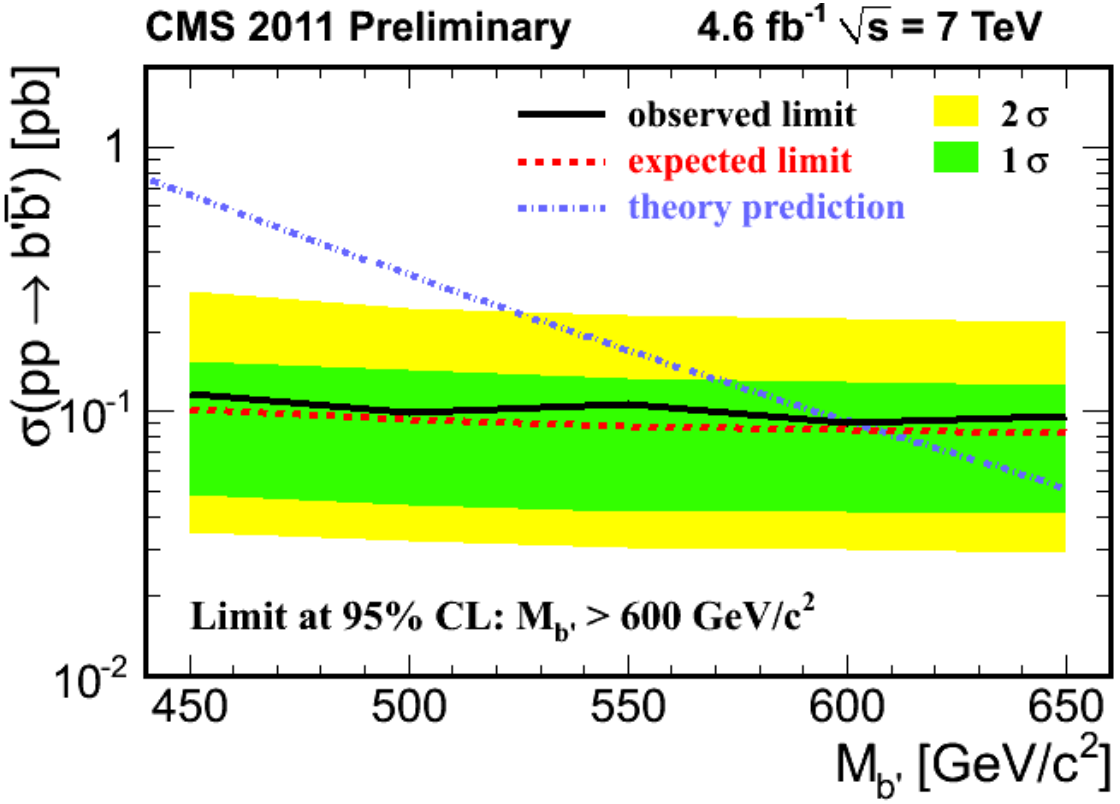
3ℓ

Same-sign $\ell\ell$

$$\sum p_{\mathrm{T}}(\text{jets}) + \sum p_{\mathrm{T}}(\text{leptons}) + \not{E}_{\mathrm{T}}$$

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

Heavy new bottom-like quark



$M_{b\prime}$: 600 GeV **EXO-11-036**

Significant improvement over
Summer 2011 result (495 → 600 GeV)

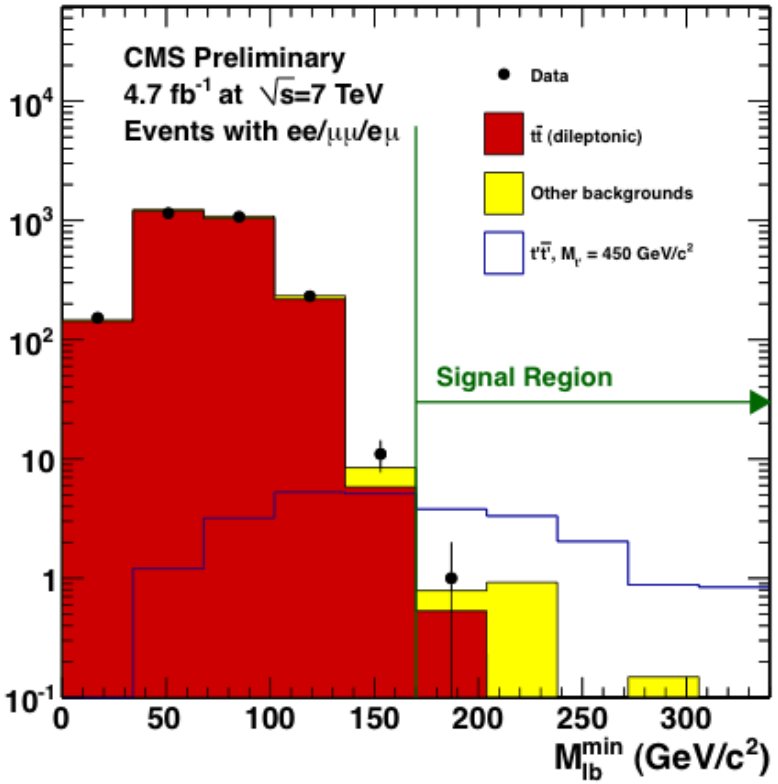
Heavy new top-like quark

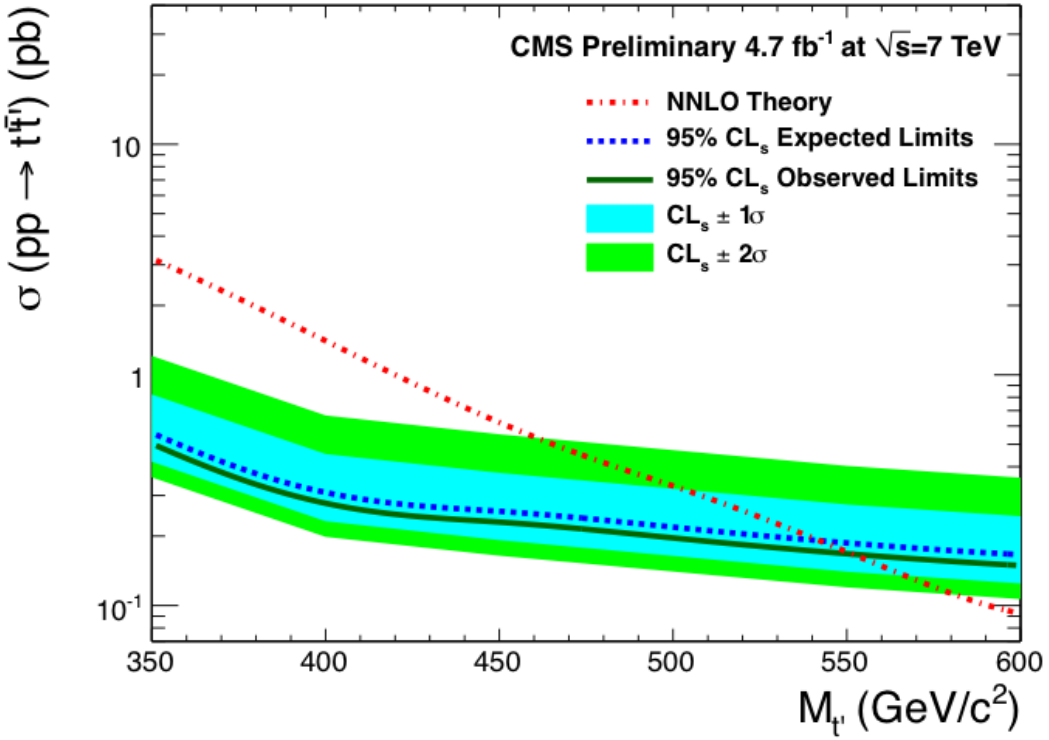
- Two analyses assuming heavy top decays exclusively to *b*-quark and a *W*
  - Fully leptonic
  - Lepton + jets

- Third analysis assuming heavy top decays to (SM) top and a *Z*

Heavy new top-like quark #1

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



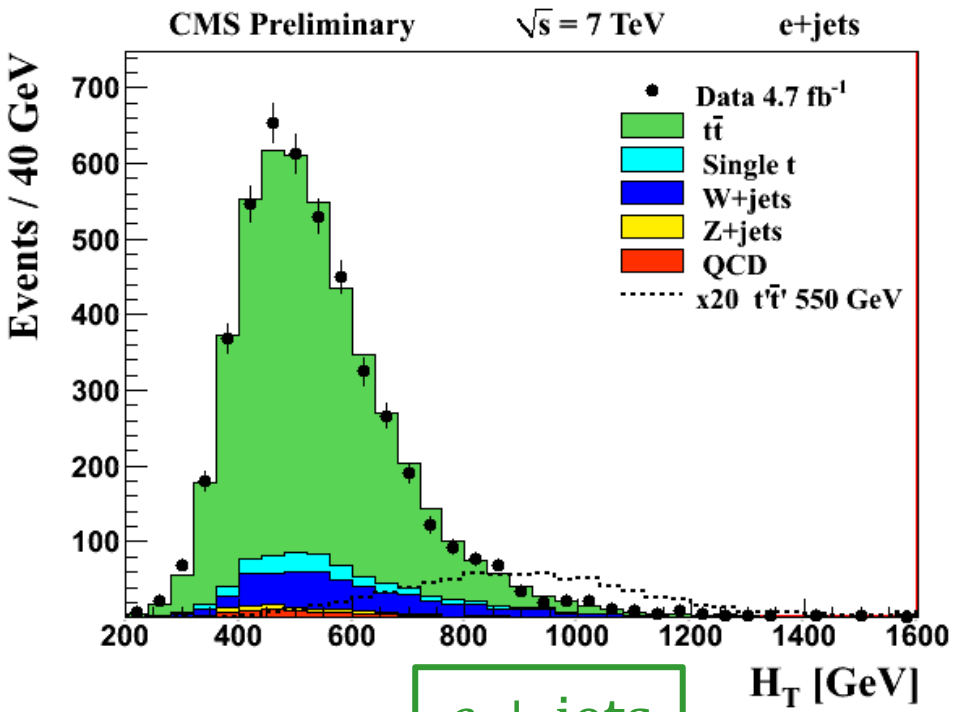


EXO-11-050

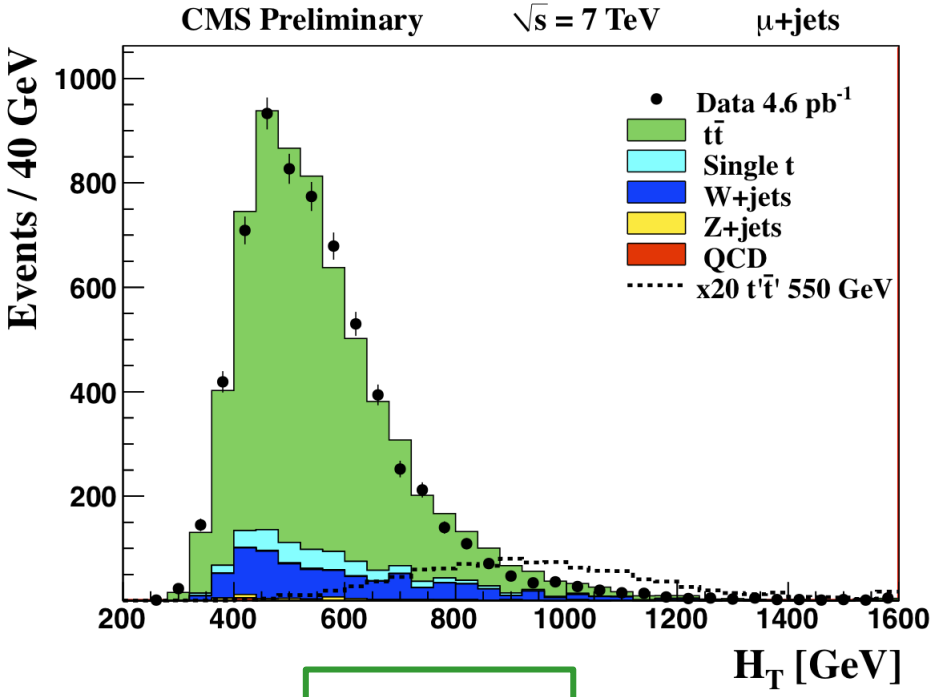
$M_{t\prime}$: 552 GeV

Heavy new top-like quark #2

$$t'\bar{t}' \rightarrow WbW\bar{b} \rightarrow \ell\nu bq\bar{q}\bar{b}$$



e + jets



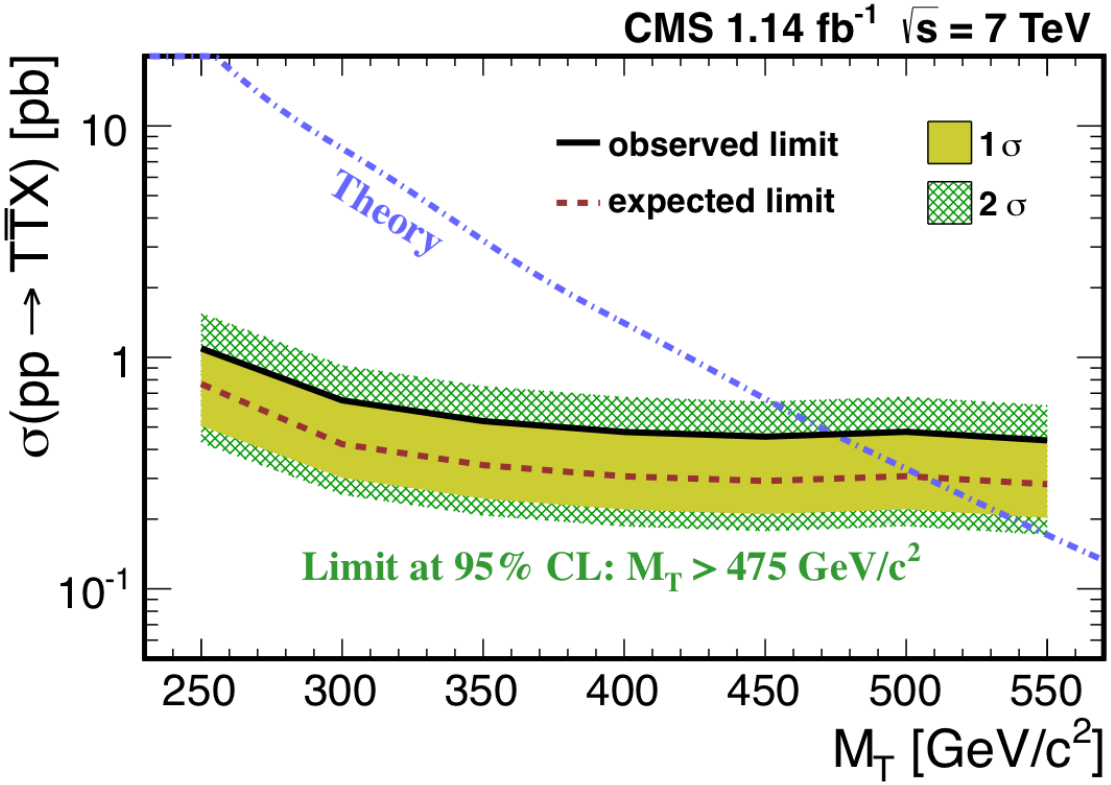
μ + jets

EXO-11-099

$M_{t\prime}$: 560 GeV

Heavy new top-like quark #3

$T \rightarrow tZ$



$M_{t\prime}$: 475 GeV

10.1103
PhysRevLett.107.271802
(EXO-11-005)

Weird Things

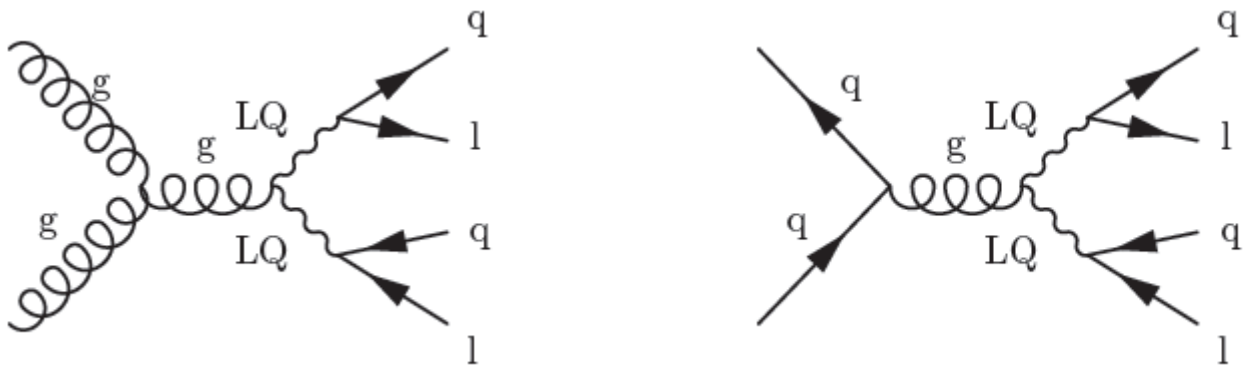
CMS: 25 New Results

- Resonances (Z'-like and extra dimensions)
  - dijet, $ee, \mu\mu, \gamma\gamma, t\bar{t}, t\bar{t}$ (boosted)
- W'
  - $e + \nu, \mu + \nu, qq', \ell N_\ell$ (aka: right-handed W), WZ
- More extra dimensions:
  - mono-jet, mono-photon, black holes
- Fourth generation
  - Heavy bottom-like and top-like quarks
- "Weird" stuff: leptoquarks & long-lived particles

Leptoquarks

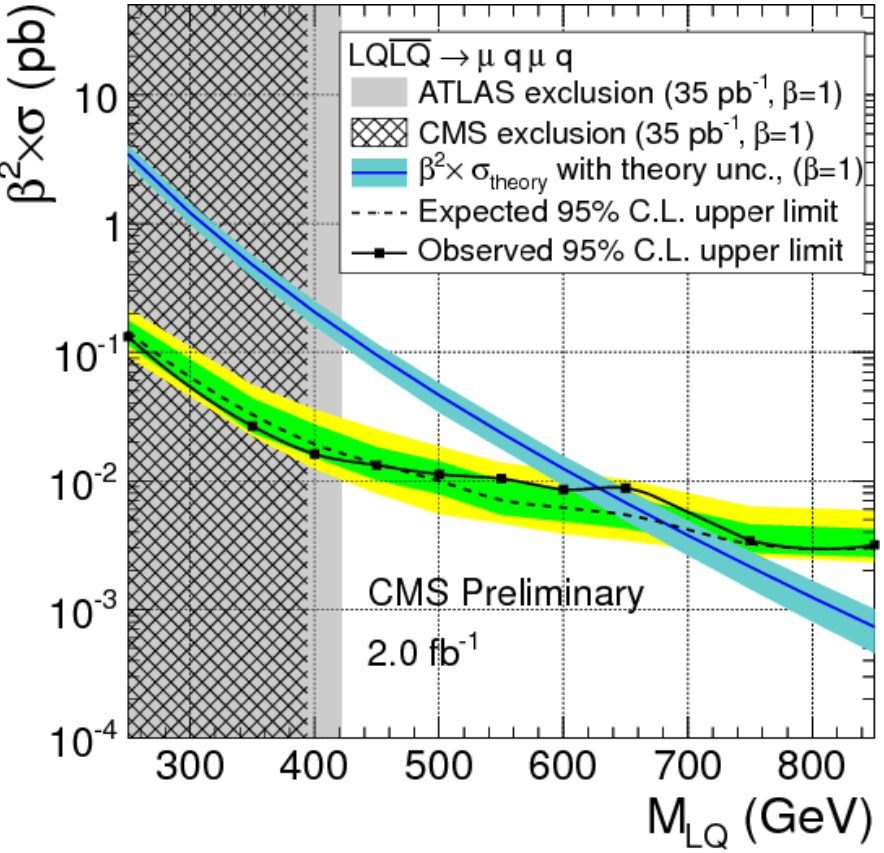
Supporting theory

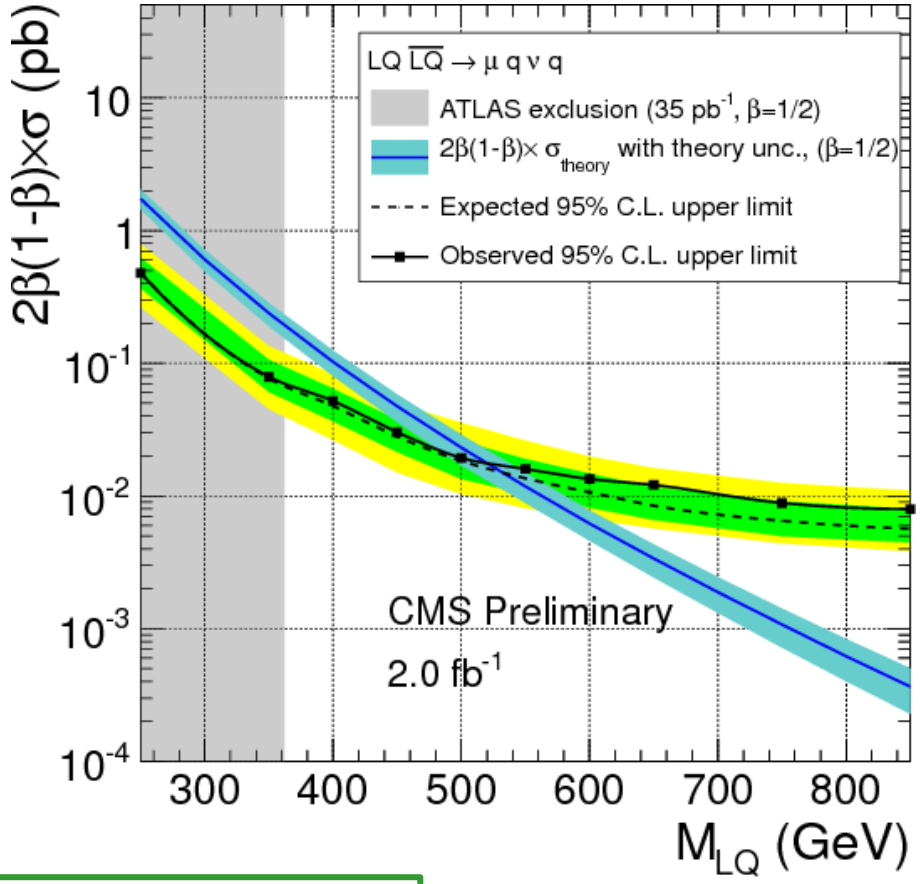
- Hypothetical particles that carry both lepton & baryon #
- Have both color and electric charge
- Couple to quarks & leptons: unlike anything else!
- Predicted in GUT models, would explain why (# of leptons) = (# of quarks)



Second Generation Leptoquarks

Considering both $\mu\mu jj$ and $\mu\nu jj$





$\beta \equiv \mathrm{BR}(LQ \to \ell q)$, $1 - \beta \equiv \mathrm{BR}(LQ \to \nu q)$

EXO-11-028

LQ2: 632 GeV (if β=1)

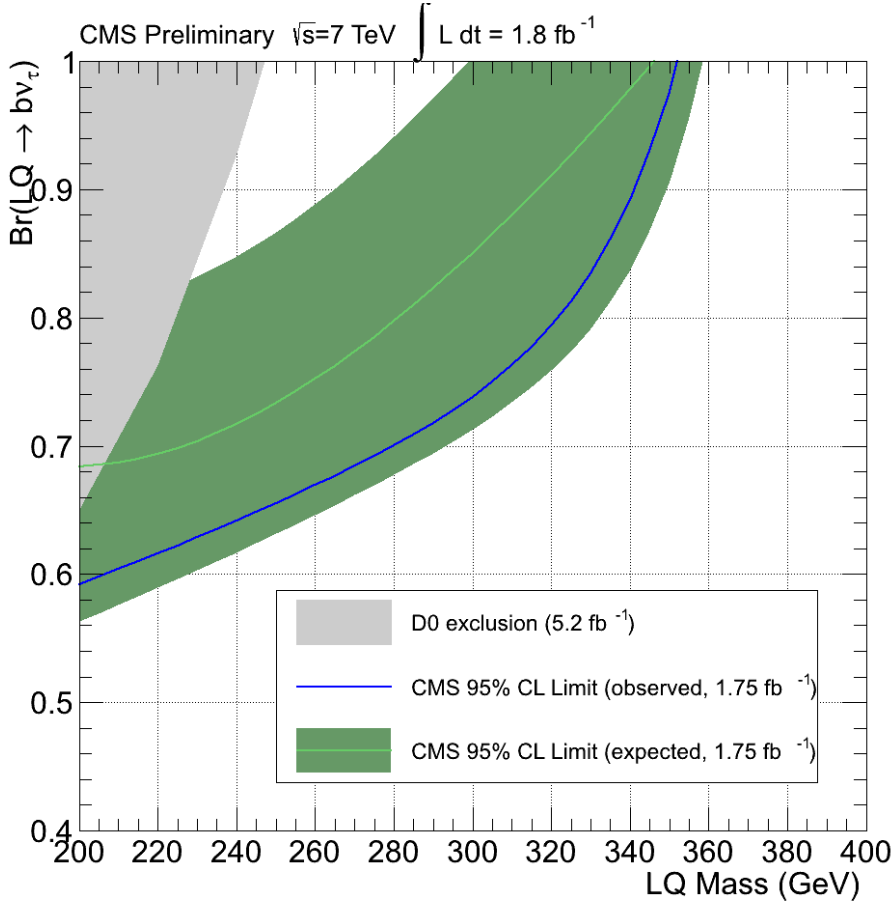
Third Generation Leptoquarks

Considering $\nu_\tau \nu_\tau bb$

$$R \equiv \frac{M_T^R}{M_R}$$

$$M_R \equiv \sqrt{(E_{j_1} + E_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}\,.$$

$$M_T^R \equiv \sqrt{\frac{\not{E}_T (p_T^{j1} + p_T^{j2}) - \vec{\not{E}}_T \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$



EXO-11-030

LQ3: 350 GeV (if β=1)

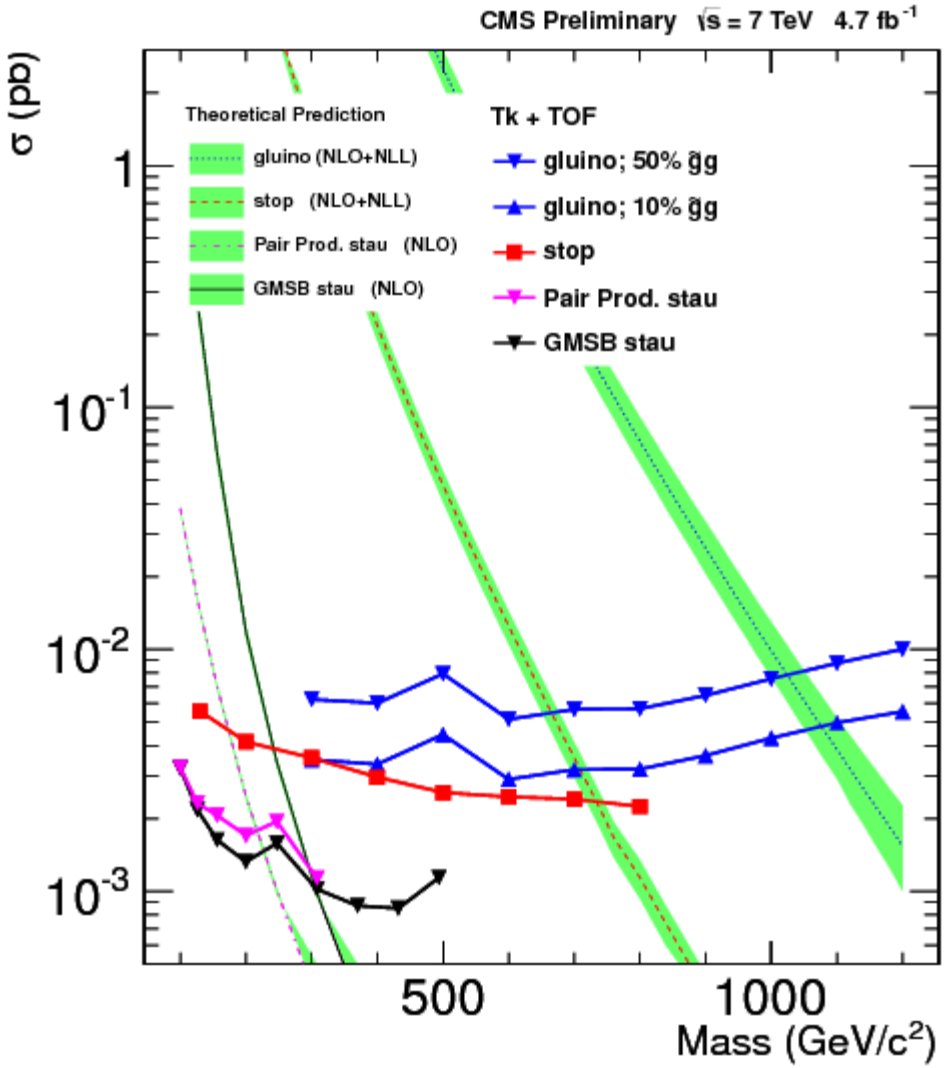
Long-lived particles

Experimental considerations

- Massive charged long-lived particles leaving highly ionizing tracks in the tracker (and muon): identified by dE/dx (TOF)
- Massive neutral long-lived particles: non-prompt decay to displaced leptons, photons, jets, etc..
- Long-lived, strongly interacting, slow ($\beta<0.4$) particles stopping in the detector and decaying out-of-time
  - Complicated LHC beam structure with gaps sequence allows for a large coverage of particles lifetimes
  - Identified as jets

Complementary analyses: jet-analyses sensitive to slow particles, dE/dx & displaced photons: need higher β

Heavy Stable Charged Particles

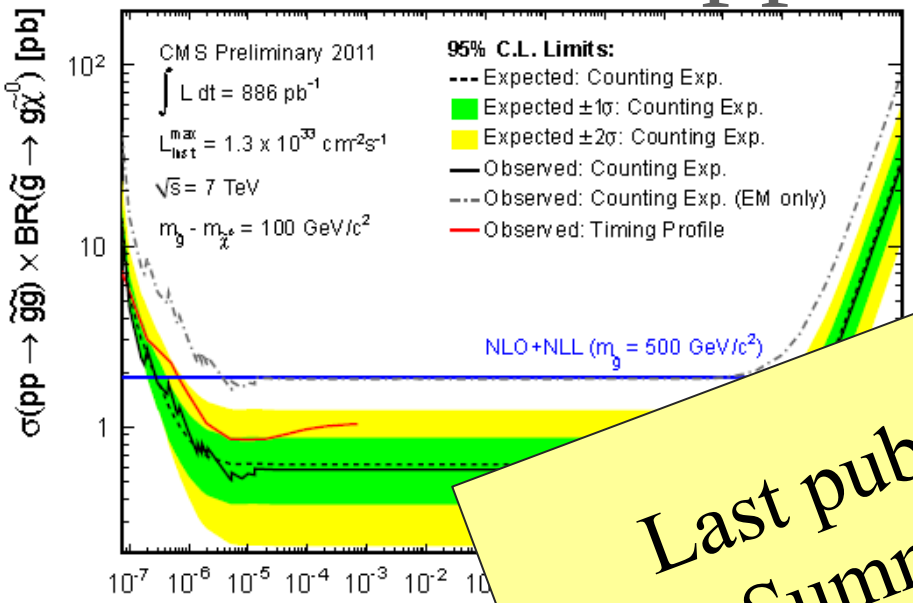


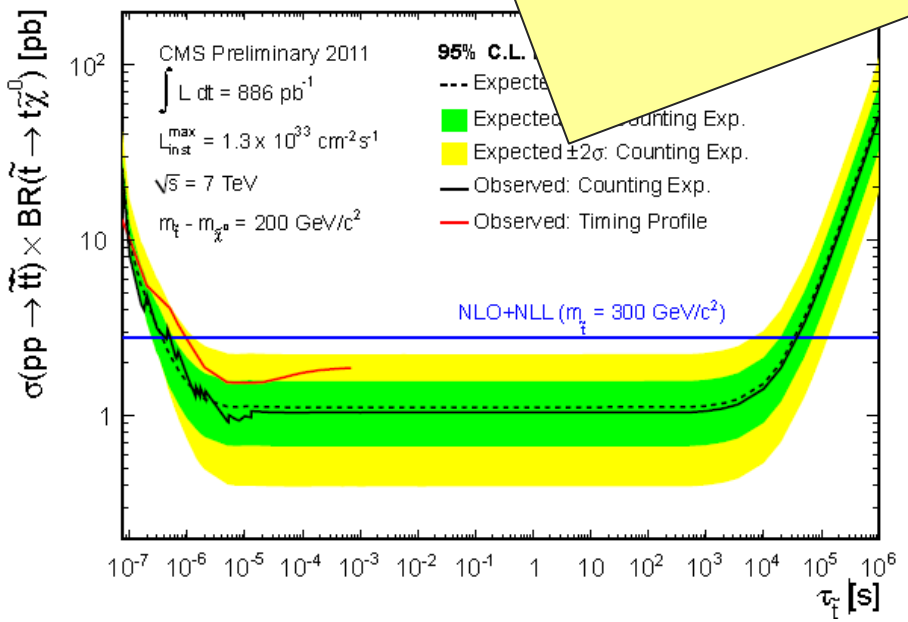
EXO-11-022

gluino: 1091 GeV
stop: 734 GeV
stau: 306 GeV

"dE/dx" analysis: exclusion limits on gluinos, stops and staus

Stopped HSCPs





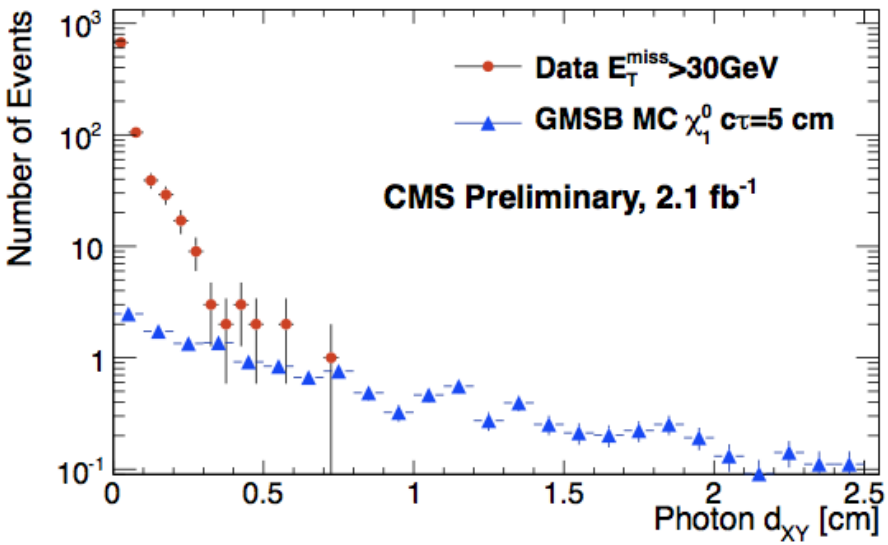
Designed and commissioned
spec requiring a jet in
h empty beam

Last public result:
Summer 2011

gluino: 601 GeV
stop: 337 GeV
Lifetimes: 10 orders of magnitude

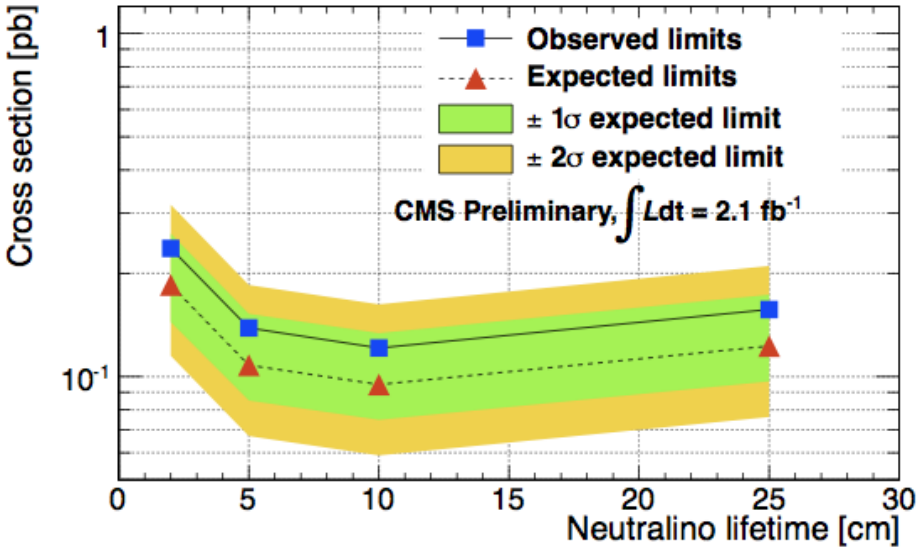
EXO-11-020

Long-lived particles to Photons/MET



Searching for neutralino decaying to gravitino & photon

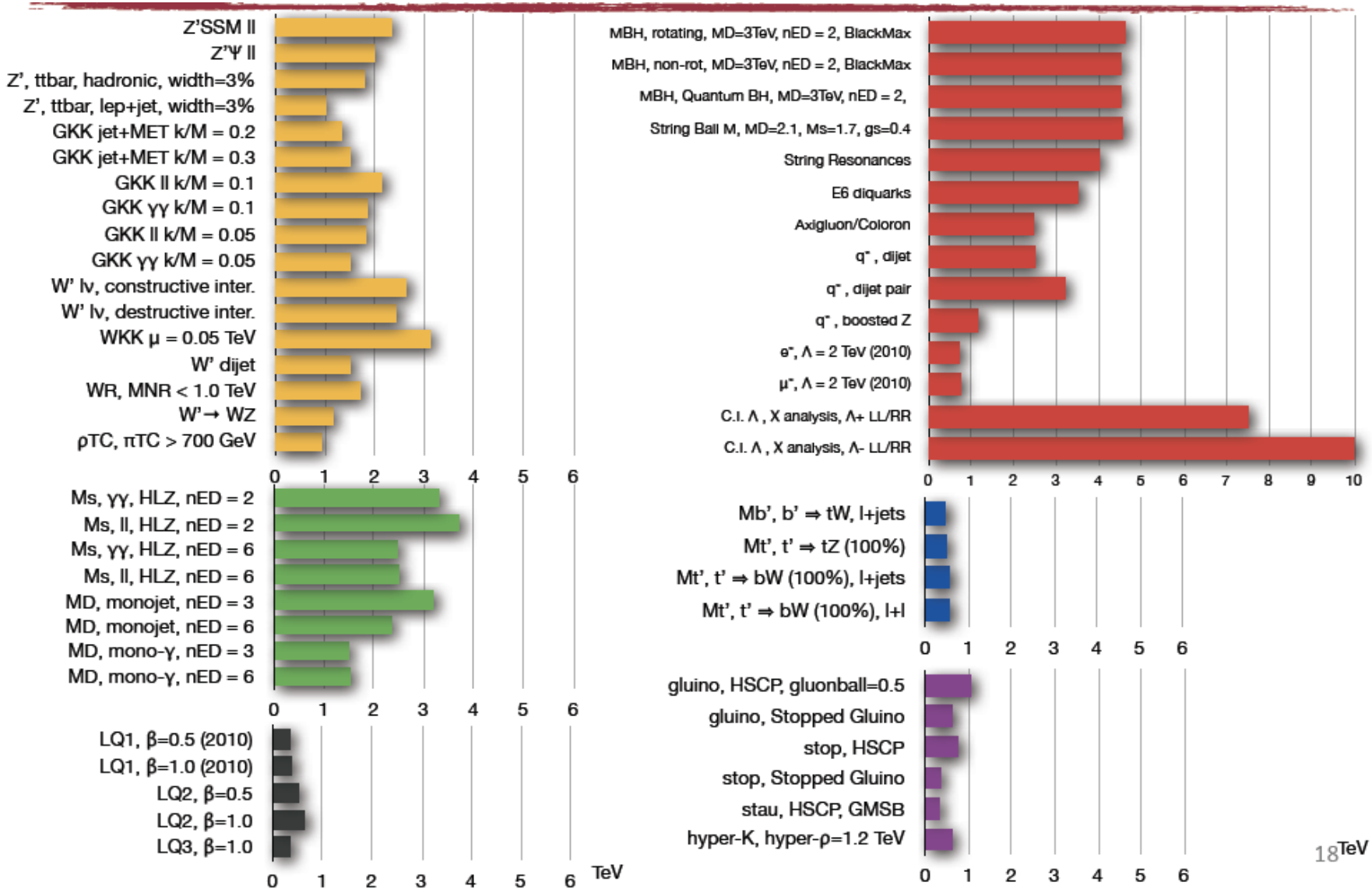
Impact parameter of vertex from photon conversions



Cross-section exclusion limit for neutralino lifetimes: 2-25 cm

EXO-11-067

The Grand Summary



Changes in 2012

- Higher collision energy
  - The higher the mass (of the new particle), the larger the gain

"New Physics is too heavy for $\sqrt{s}$=7 TeV"

8-to-7 TeV: "Parton luminosity ratios"

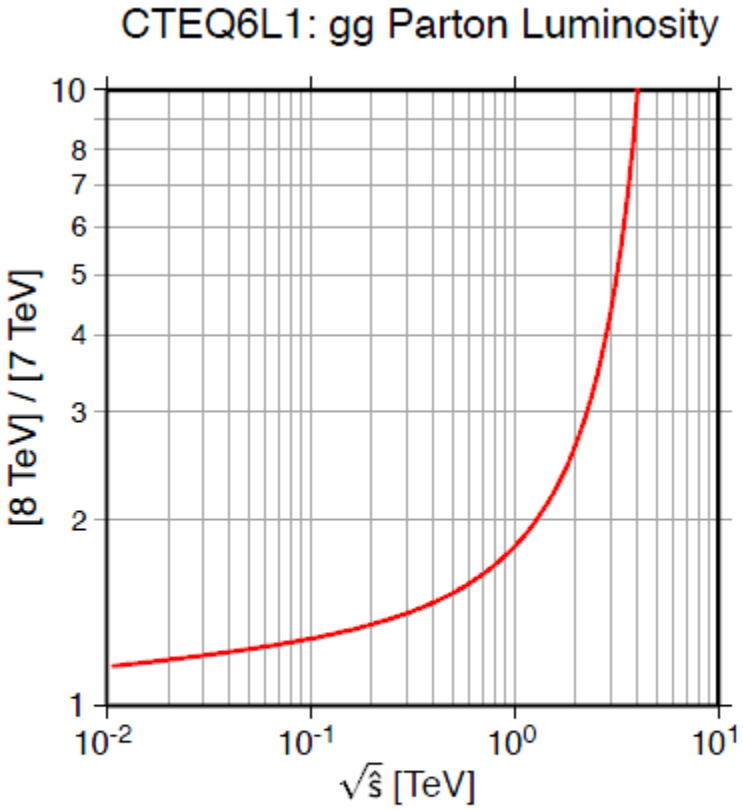


Figure 8: Ratio of parton luminosity for gg interactions in pp collisions at $\sqrt{s} = 8$ TeV to luminosity at 7 TeV (logarithmic scale).

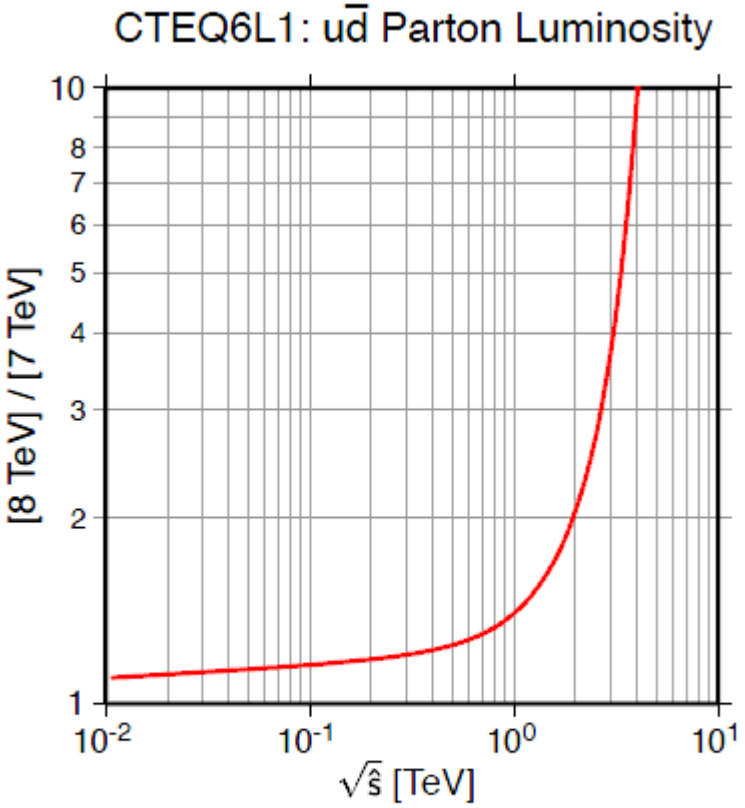


Figure 12: Ratio of parton luminosity for $u\bar{d}$ interactions in pp collisions at $\sqrt{s} = 8$ TeV to luminosity at 7 TeV (logarithmic scale).

Chris Quigg*

arXiv:1101.3201v1 [hep-ph] 17 Jan 2011

Changes in 2012

- Higher collision energy
  - The higher the mass (of the new particle), the larger the gain

- What are we forgetting to analyze?

Changes in 2012

- Higher collision energy
  - The higher the mass (of the new particle), the larger the gain

- What are we forgetting to analyze?

- What are we forgetting to record?

"Are we looking in the right place?"

- Adequate coverage of "unusual topologies"?
  - e.g. "hidden valleys" type of physics
- Long-lived particles: highlight crucial role of trigger
- If New Physics is contained in collected datasets, there is nowhere to hide. But remember:
  - Only 0.001% of all LHC bunch crossings are recorded
  - The trigger has no "undo" button.

Trigger ideas for 2012

- "Data parking"
  - Store twice as many events as the prompt reconstruction capacity allows (~350 Hz × 2)
  - Go back (during shutdown) and reconstruct "bonus" dataset
  - A lot of work (and thought) to decide what goes into doubling of recorded events

- Exploit high-CPU & bandwidth capacity of High Level Trigger
  - Create kinematic distributions of interest in real time: early warning system
  - Offline analysis: sees ~400 Hz
  - Online analysis: sees ~tens of kHz

Summary

Epilogue

• CMS has made public 25 new Exotica results from the analysis of the 2011 data. Very impressive exclusion limits, small deviations in a few channels to keep an eye on

• A lot of work ahead of us in 2012: higher collision energy, three times as much integrated luminosity

• We should not forget: 99.999% of all LHC bunch crossings never get a chance to show up in your favorite analysis. Let's make sure New Physics is in the remaining 0.001%.

Backup

CMS

Total weight 14000 t
Overall diameter 15 m
Overall length 21.6 m