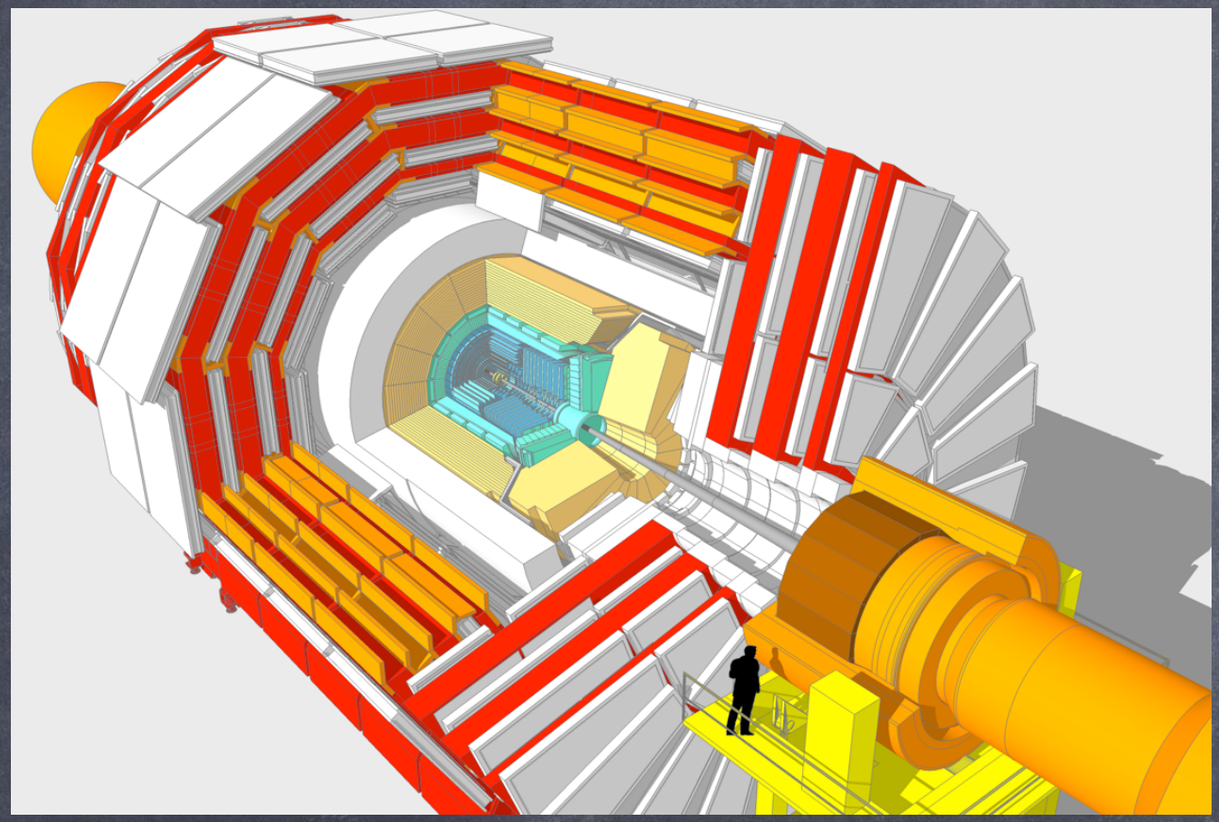
Searches for Leptoquarks, Extra Dimensions, and Dark Matter



Lovedeep Kaur Saini
Kansas State University
for the CMS Collaboration
@ LHCP 2014, NY

In this talk

- **Leptoquark searches**
  - ✓ First generation leptoquarks, LQ1
  - ✓ Second generation leptoquarks, LQ2
  - ✓ Third generation leptoquarks, LQ3

  *EXO-11-028 (10.1103/PhysRevD.86.052013)
  *EXO-12-042 (New)
  *EXO-12-030 (New)
  *EXO-12-032 (New)

- **Dark matter**
  - ✓ Mono-X
  - ✓ Top quark pair
  - ✓ Higgs-portal and so on

  *EXO-12-048
  *EXO-12-047 (New)
  B2G-12-022
  B2G-13-004
  EXO-13-004 (New)
  HIG-13-030

- **Extra dimensions**
  - ✓ **ADD: Mono-X, di-leptons**, di-jets and so on
  - ✓ RSmodel

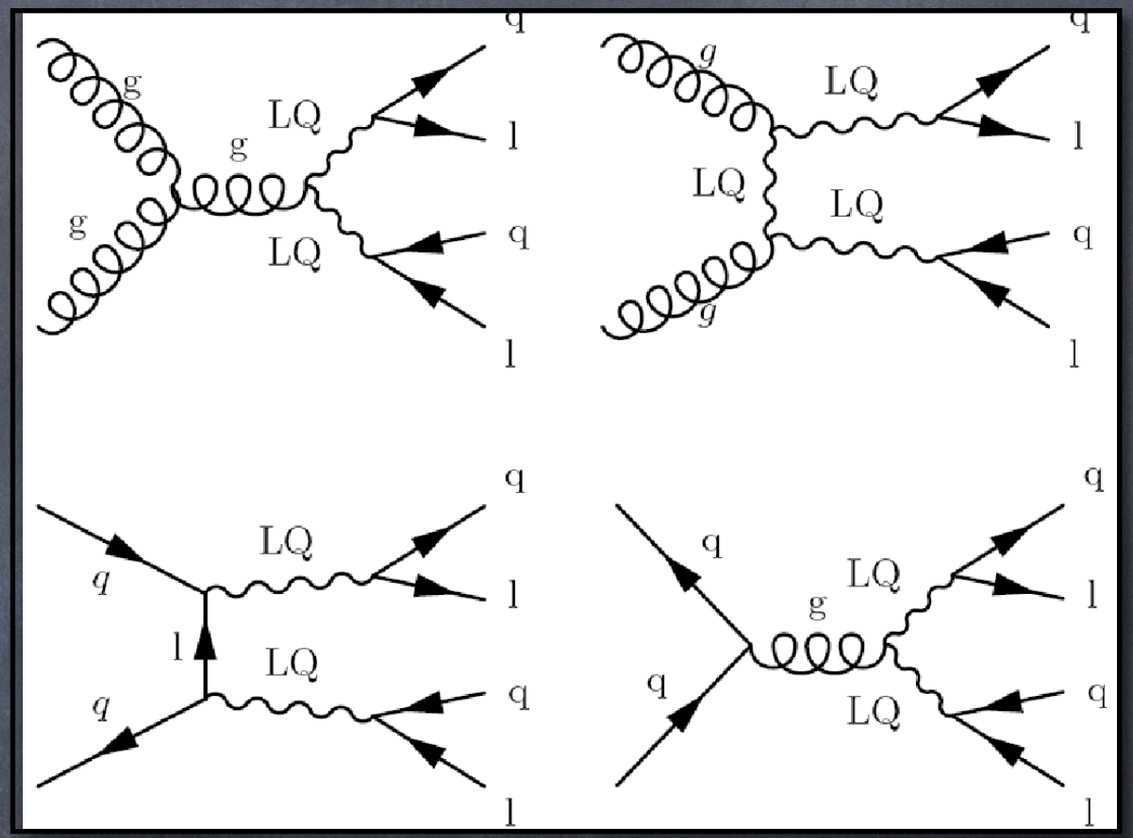
  ***EXO-12-048**
  ***EXO-12-047**
  EXO-12-009 (10.1007/JHEP07(2013)178)
  ***EXO-12-031** (New)
  ***EXO-12-027** (New)
  EXO-12-022
  EXO-12-059

- Conclusions

*only underlined analyses are covered in this talk

Leptoquarks - Introduction

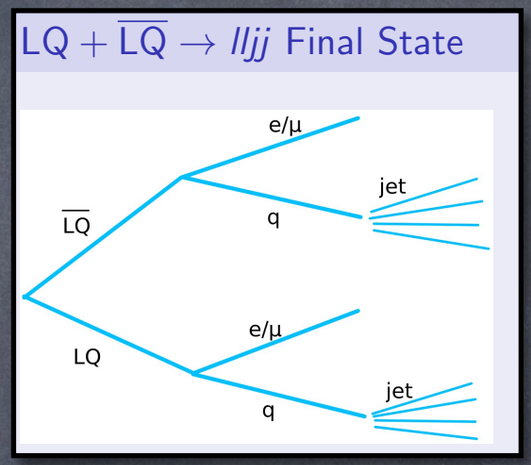
- Leptoquarks (LQ's) are hypothetical particles carrying both baryon and lepton numbers
- Predicted by many theories beyond the SM - GUTs, compositeness models...
- Couple to leptons and quarks of a single generation
- Dominant processes for LQ pair production at LHC - gluon-gluon fusion & quark-antiquark annihilation

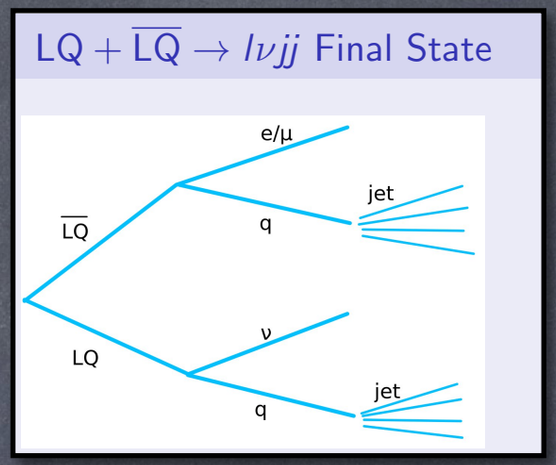


Model parameters	
M_{LQ}	LQ mass
β	BR(LQ→$l^{+/-}$ + q)
$\lambda_{l\text{-}q\text{-}LQ}$	l-q-LQ coupling
LQs can be scalar* or vector	

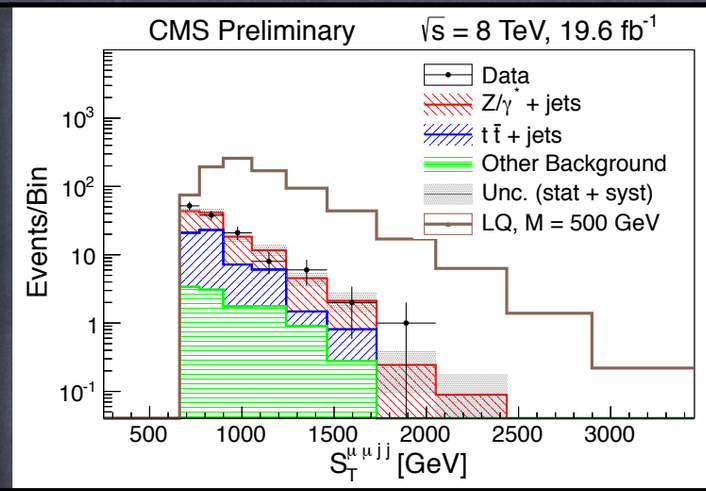
Search for LQ1, LQ2

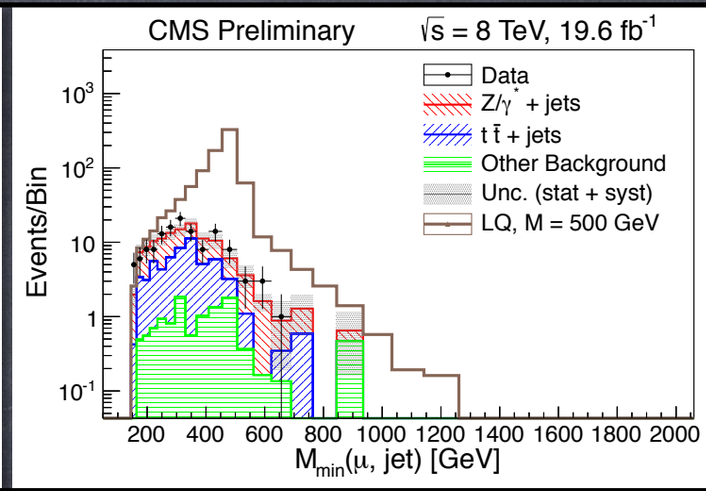
- Search for pair production of first & second generation LQ's in "di-lepton+di-jet" and "lepton+di-jet+missing Et (MET)" final states
- β = 1 for lljj final states
- β = 0.5 for l ν jj final states

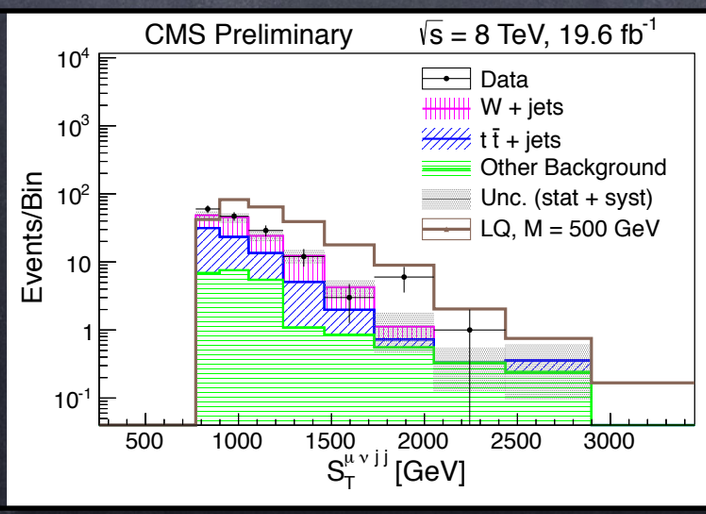


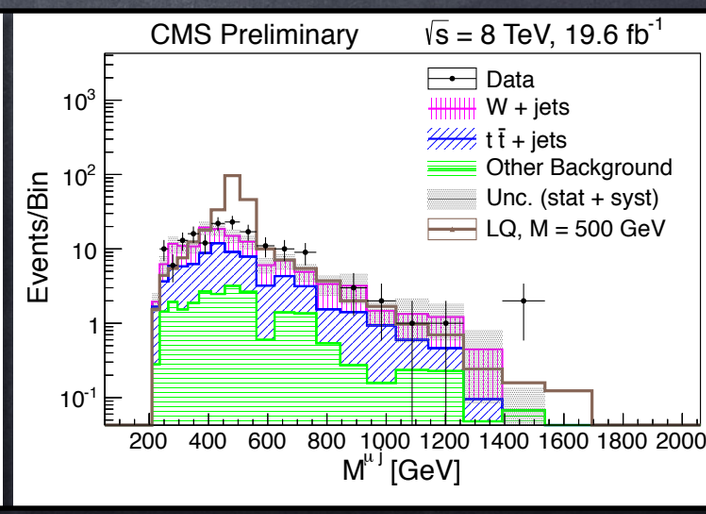


- For lljj analyses:
  - ✓ M_{ll}, M_{lj}
  - ✓ $S_T^{ll} = p_T(l_1) + p_T(l_2) + p_T(j_1) + p_T(j_2)$
- For l ν jj analyses:
  - ✓ MET, M_{lj}
  - ✓ $S_T^{l\nu} = p_T(l) + MET + p_T(j_1) + p_T(j_2)$







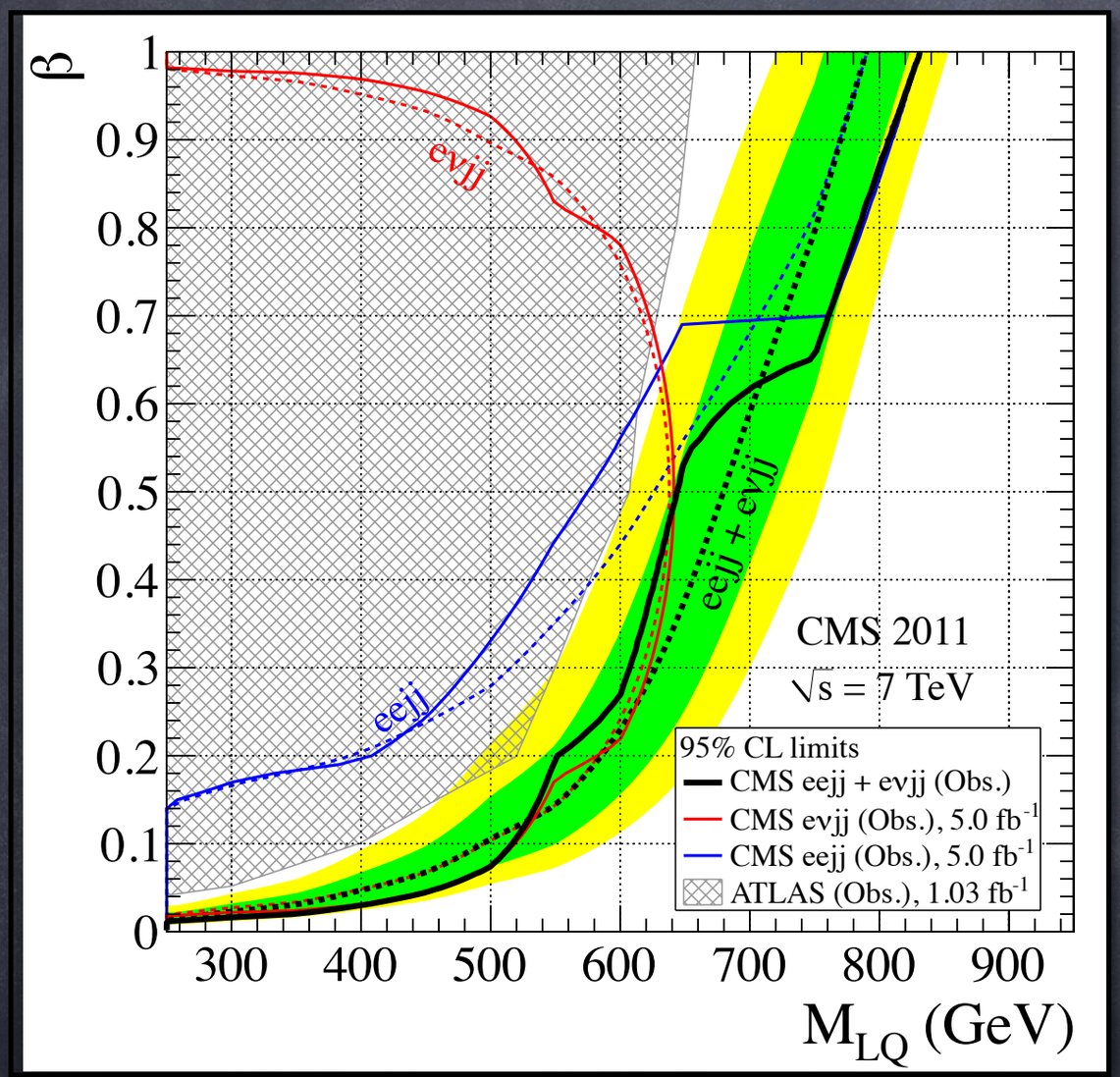


LQ1 - EXO-11-028 - 7TeV CMS data, 8TeV results about to come

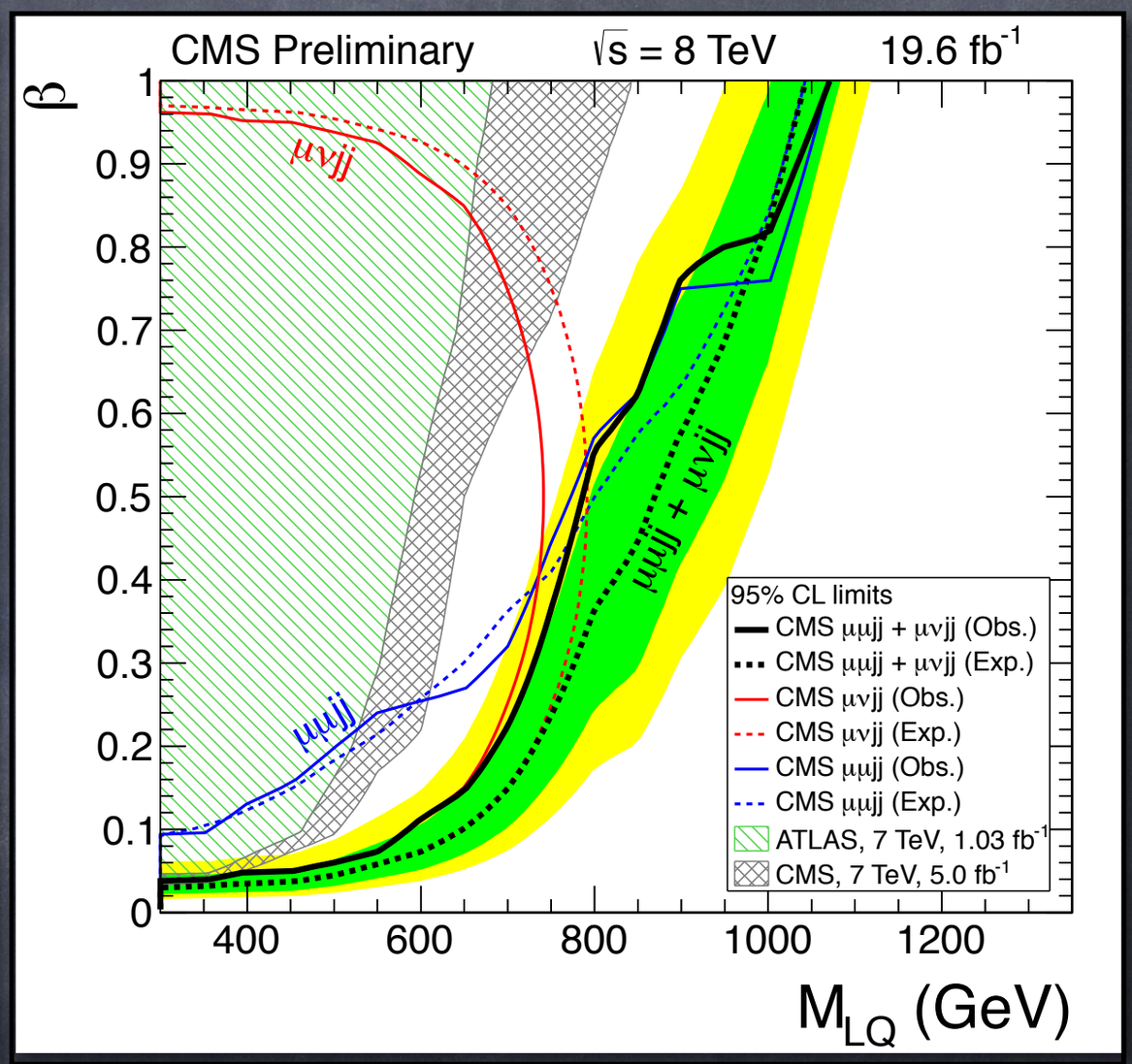
LQ2, EXO-12-042 with full 8TeV CMS data

LQ1 & LQ2 Limits

EXO-11-028 with full 7TeV CMS data



EXO-12-042 with full 8TeV CMS data

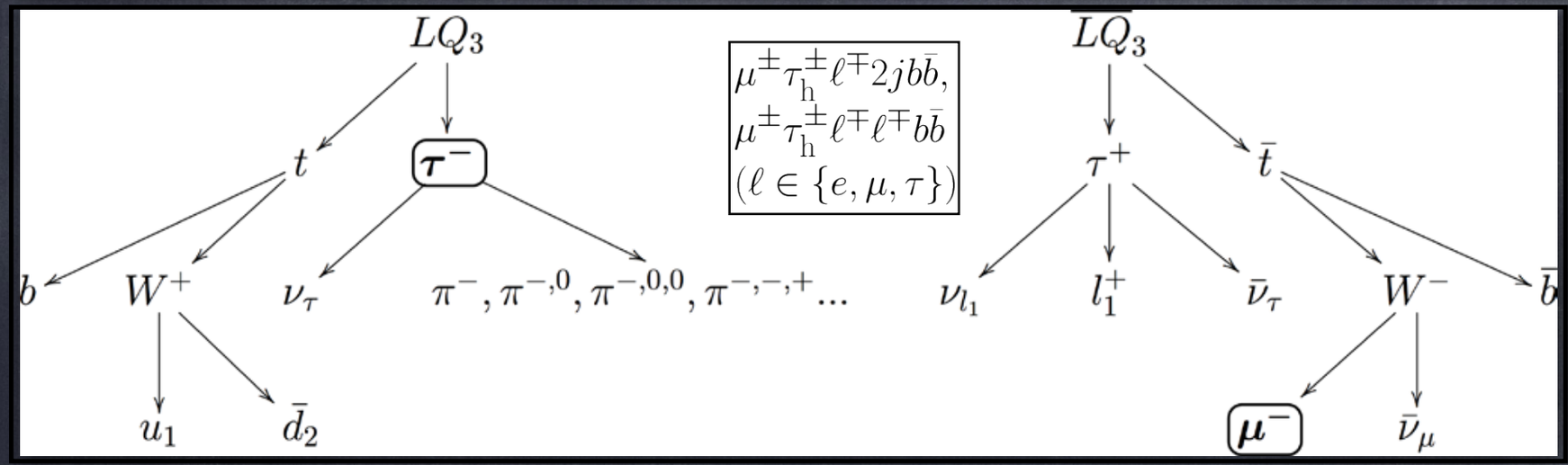


Scalar LQ1 with mass below 830 (640) GeV are excluded for β = 1 (0.5) at 95% CL

Scalar LQ2 with mass below 1070 (785) GeV are excluded for β = 1 (0.5) at 95% CL

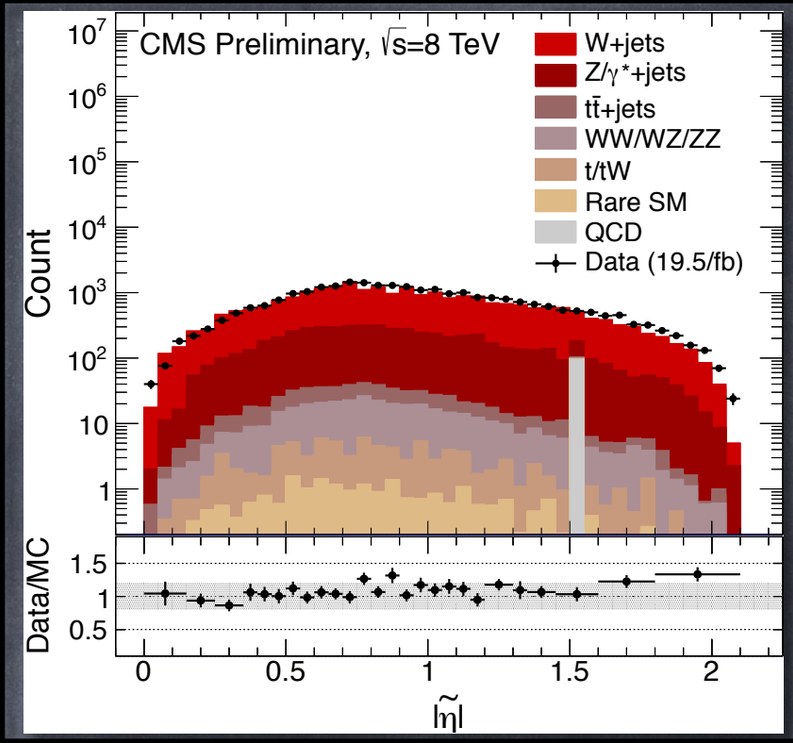
Search for LQ3 ($\rightarrow t\,\tau$)

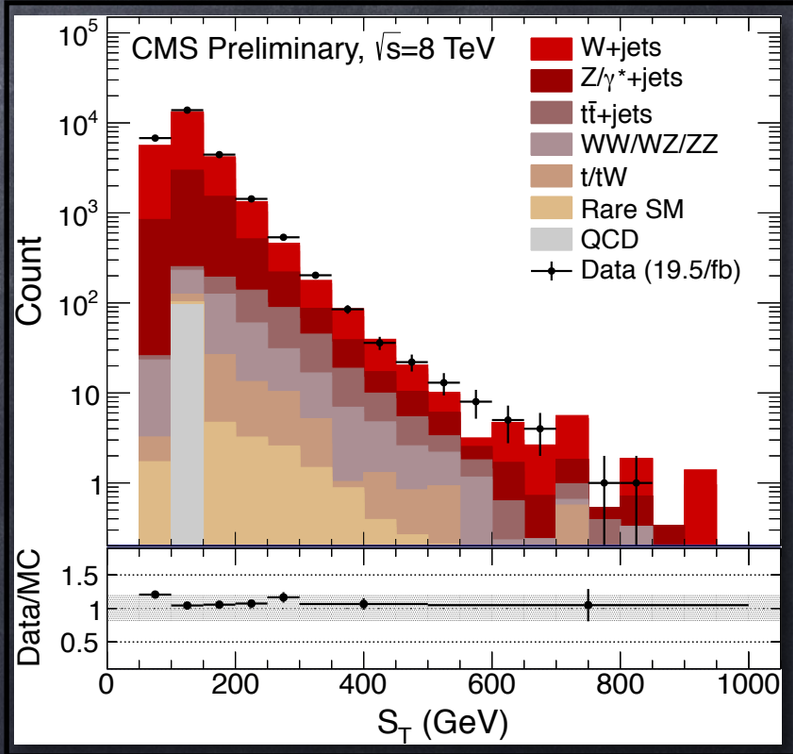
- Search for scalar LQ3 pair each decaying to top + τ
- Q = -1/3, β = 1



- Require same-sign (SS) $\mu\,\tau_h$ + X final state
- $S_T = p_T(l) + p_T(\tau) + p_T(j) + MET$, S_T > 400 GeV
- N_{jets} >1, Z-veto, $M_T(\mu, MET)$ > 40 GeV
- event centrality: average absolute η of all e's, μ's, τ's in the event.
  - ✓ LQ3 dominant in central region
  - ✓ search split in two channels (<0.9, >0.9)
- Final cuts on S_T and $p_T(\tau_h)$ are optimized for each LQ3 mass hypothesis.

EXO-12-030 with full 8TeV CMS data

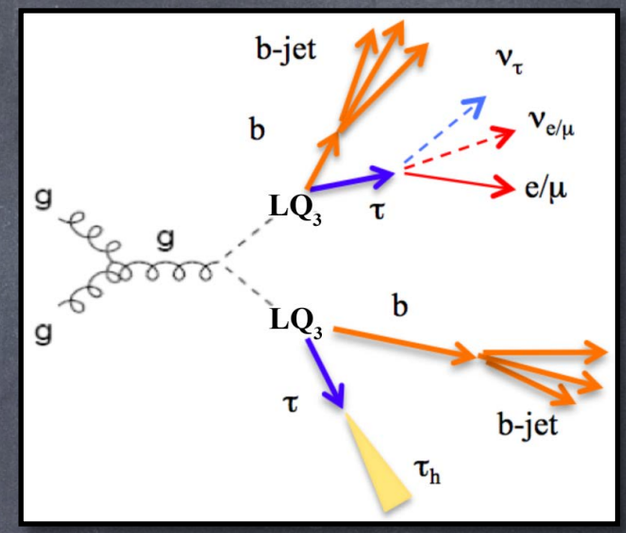




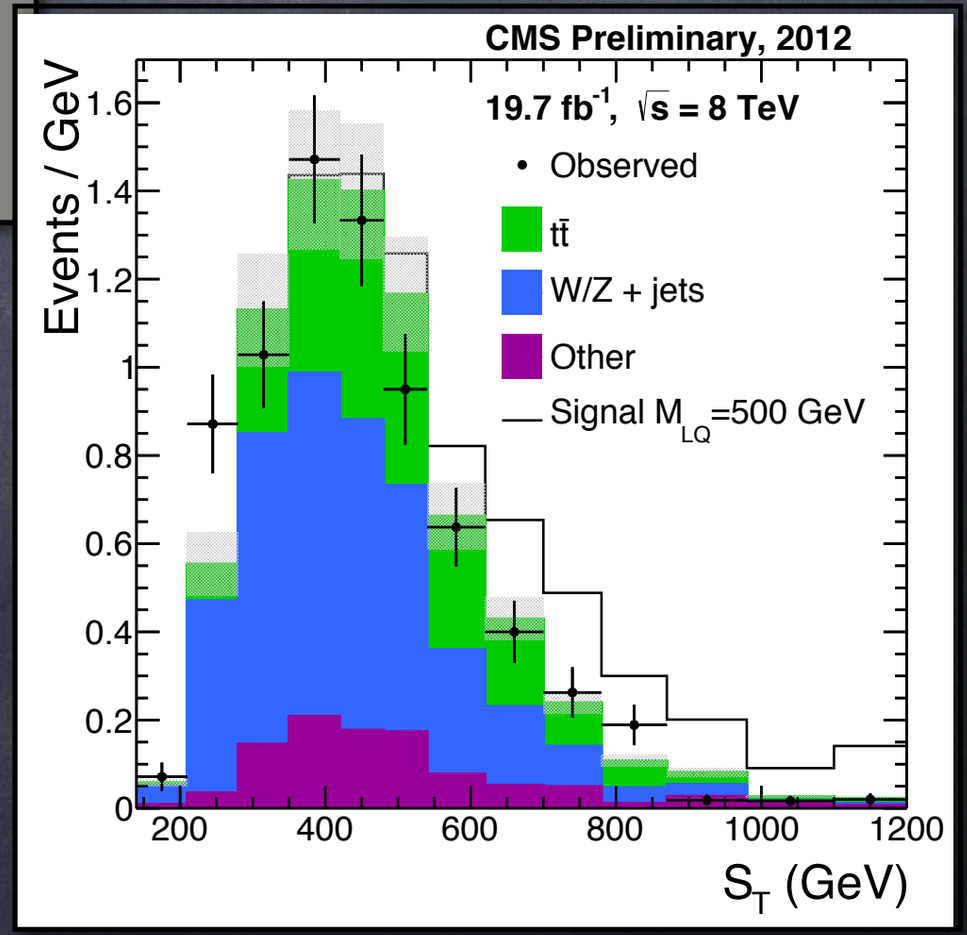
Search for LQ3 ($\rightarrow b\tau$)

- Search for scalar LQ pair each decaying to b and τ
- Q = 2/3 or 4/3, $\beta = 1$
- One τ decay leptonically (τ_l) & other hadronically (τ_h)
- Require two jets, at least one tagged as b-jet
- M (τ_h, j) > 250 GeV
  - ✓ minimize difference b/w mass of τ and one jet and the mass of the light lepton and the other jet
- $S_T = p_T(l) + p_T(\tau_h) + p_T(j) + p_T(\text{b-jet})$
- S_T distribution used to extract limits

EXO-12-032 with full 8TeV CMS data

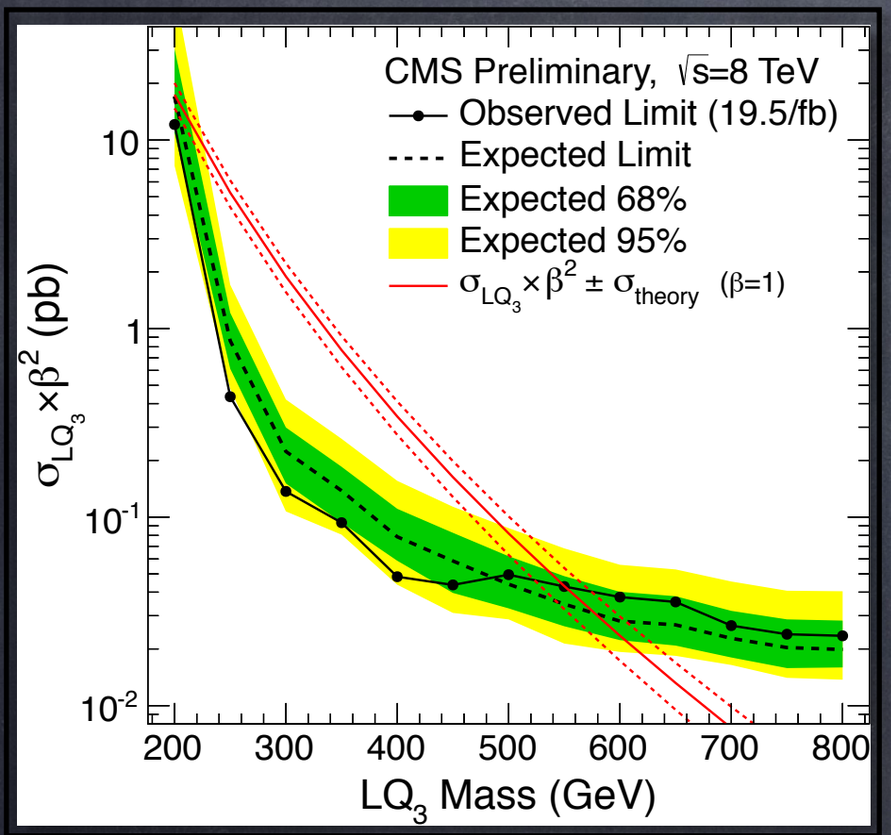


	$\mu\tau_h$ Channel	$e\tau_h$ Channel
$t\bar{t}$ (irreducible)	66.7 ± 12.6	105.6 ± 18.1
Reducible	117.3 ± 18.9	147.8 ± 33.0
$Z(\ell\ell/\tau\tau)$+jets	$7.5 \pm 4.6 \pm 0.2$	$21.4 \pm 7.4 \pm 4.9$
Single-t	$17.3 \pm 2.8 \pm 4.7$	$16.0 \pm 2.8 \pm 4.4$
VV	$2.6 \pm 0.5 \pm 0.8$	$4.1 \pm 0.6 \pm 1.3$
Total Bkg.	$211.4 \pm 5.4 \pm 23.4$	$294.9 \pm 7.9 \pm 39.1$
Observed	216	289
Signal (500 GeV)	$51.6 \pm 1.3 \pm 5.3$	$57.7 \pm 1.4 \pm 5.9$
Signal (600 GeV)	$17.7 \pm 0.4 \pm 1.6$	$20.1 \pm 0.5 \pm 1.9$
Signal (700 GeV)	$6.2 \pm 0.1 \pm 5.5$	$7.1 \pm 0.2 \pm 6.3$
Signal (800 GeV)	$2.3 \pm 0.1 \pm 0.2$	$2.7 \pm 0.1 \pm 0.2$

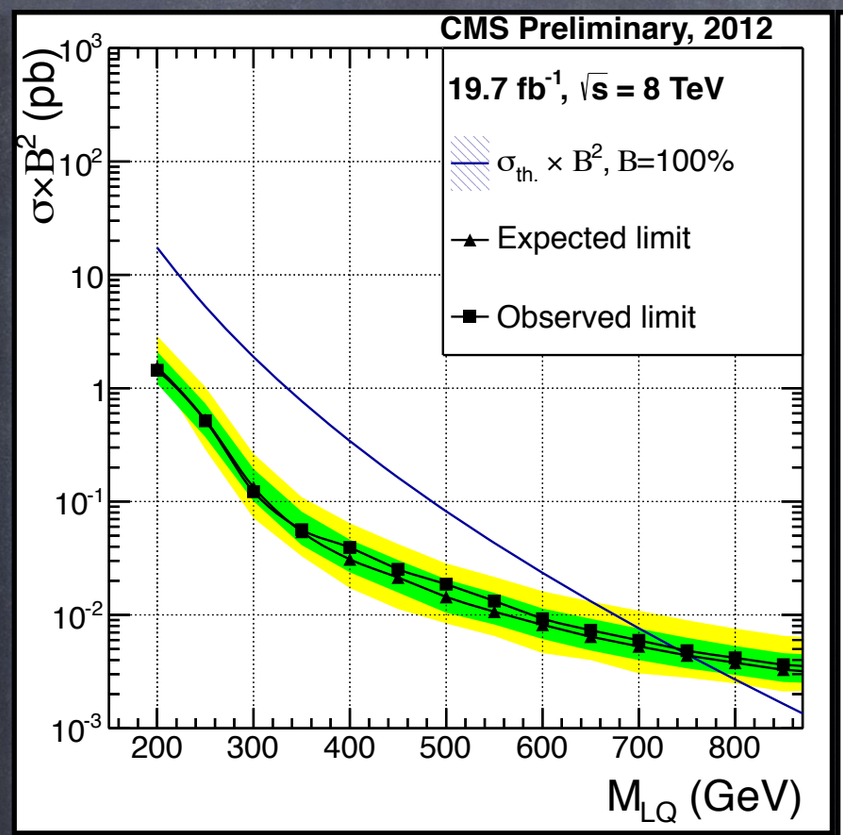


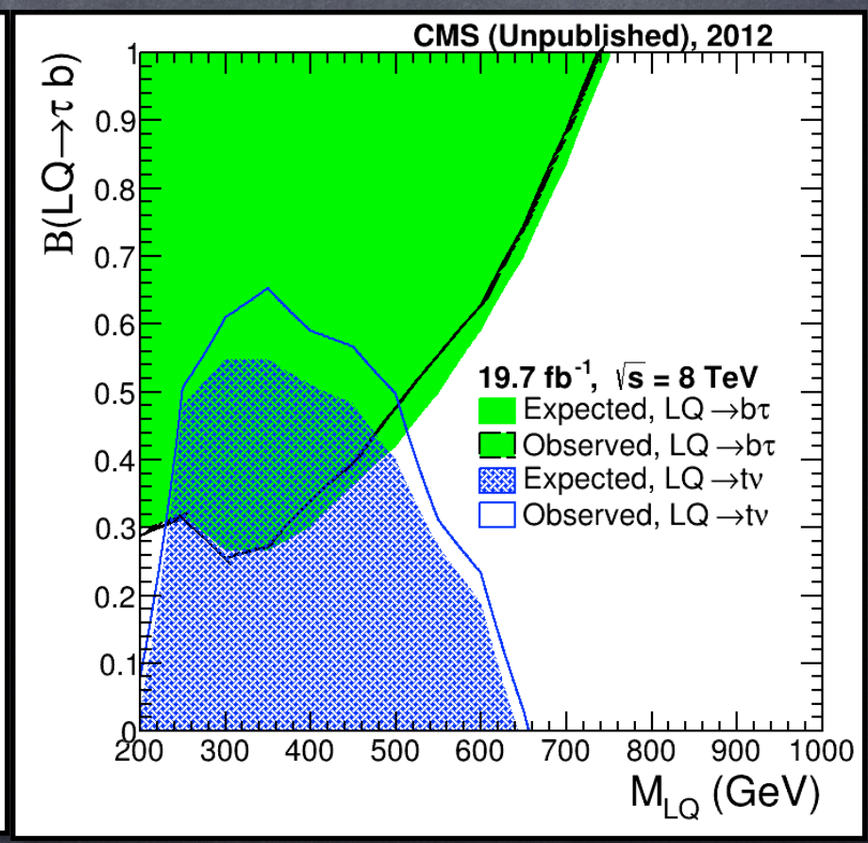
LQ3 Limits

EXO-12-030 with full 8TeV CMS data



EXO-12-032 with full 8TeV CMS data





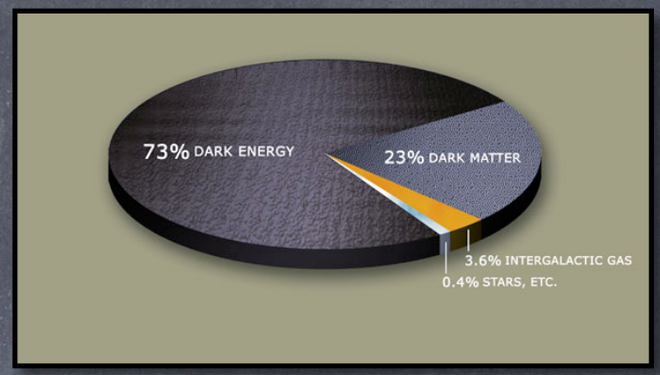
-1/3 LQ3 decaying to top +tau with mass below 550 GeV excluded at 95% CL (582 GeV expected)

LQ3 decaying to b+tau with mass below 740 GeV excluded at 95% CL (754 GeV expected)

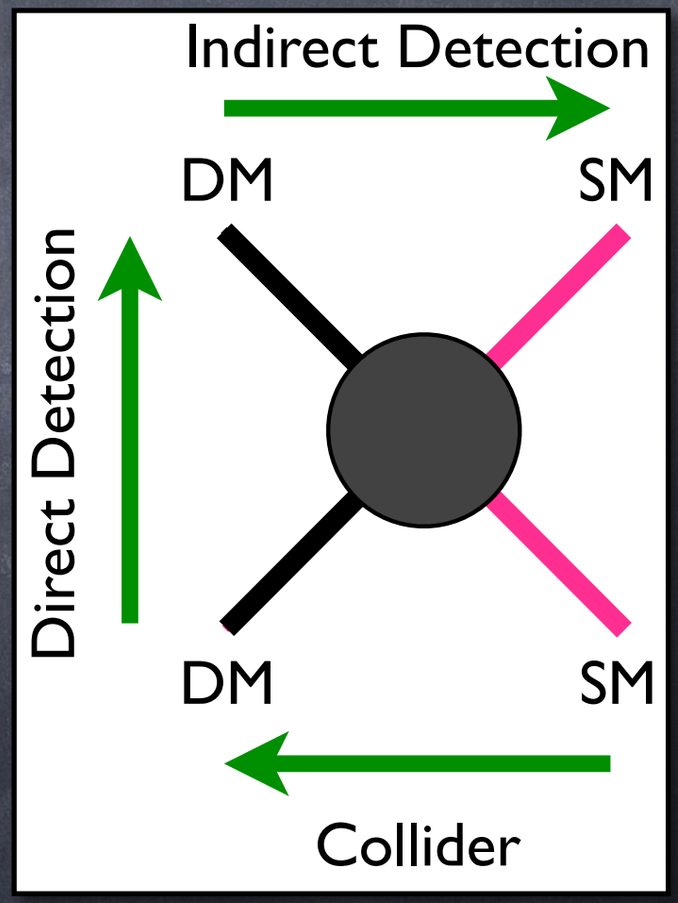
Limits for LQ3 search as a function of BR and mass are calculated too

DarK Matter - Introduction

- Strong astrophysical evidences for the existence of DM
- No unambiguous direct detection so far
- Needs independent verifications from various astrophysical and non-astrophysical experiments.



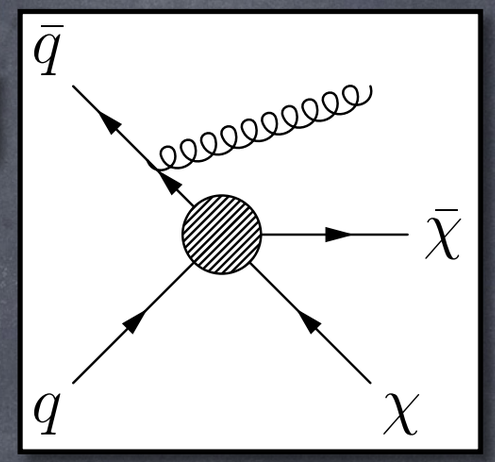
- Colliders provide an alternative way of searching through DM production
- Signal characterstics:
  - ✓ large missing transverse energy (MET) from production of DM particles recoiling against X (=g,W/Z, γ)
- Effective theory approach (EFT) used
  - ✓ assuming interaction mediated by a heavy particle with mass M, scale of the process M* or Λ, and coupling g_χ and g_q $\Lambda = M_* = \frac{M}{\sqrt{g_\chi g_q}}$
  - ✓ express limits in terms of DM-nucleon cross-section, then compared with constraints from direct and indirect experiments.



More on DM will be covered in plenary talk by N. Neumeister

Mono-jet

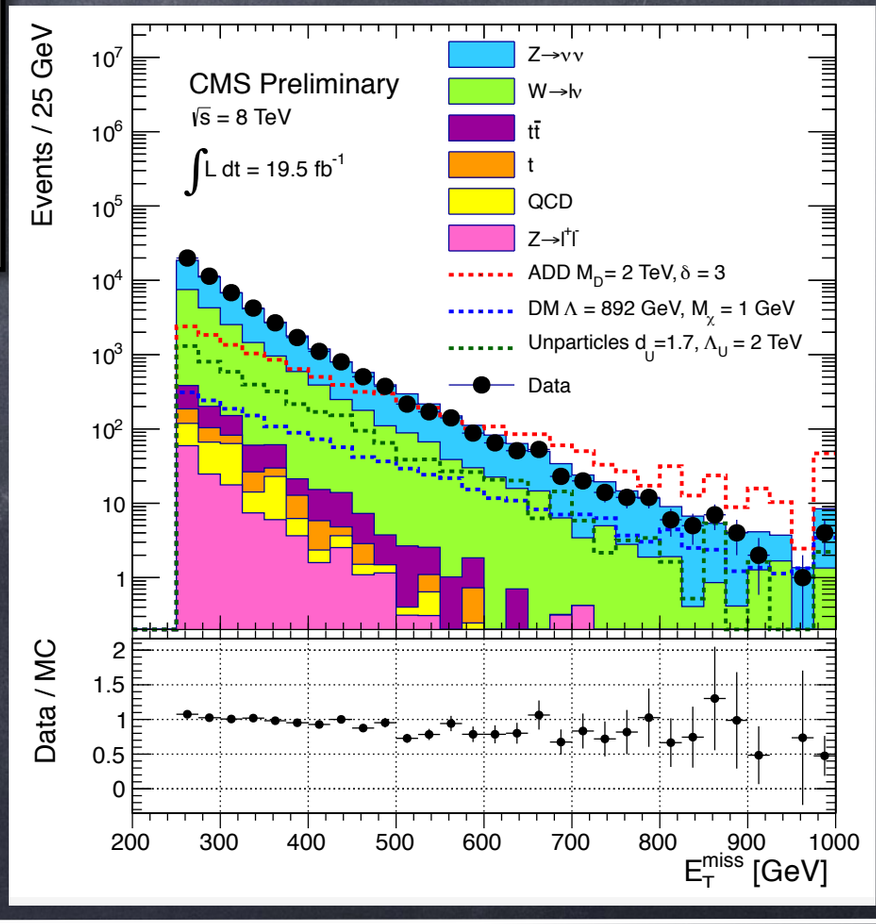
EXO-12-048 with full 8TeV CMS data



Large missing transverse energy recoiling against a high pT jet

- One jet with pT > 110 GeV and allow an additional jet (pT > 30 GeV) provided $\Delta\phi$(j1, j2) < 2.5
- Veto event if has third jet with pT>30GeV
- Veto event if has isolated leptons with pT>10GeV (20GeV for taus)
- Several signal regions with increasing MET thresholds
  - ✓ MET > 250, 300, 350, 400, 450, 500, 550 GeV
- MET > 400 GeV used for limit

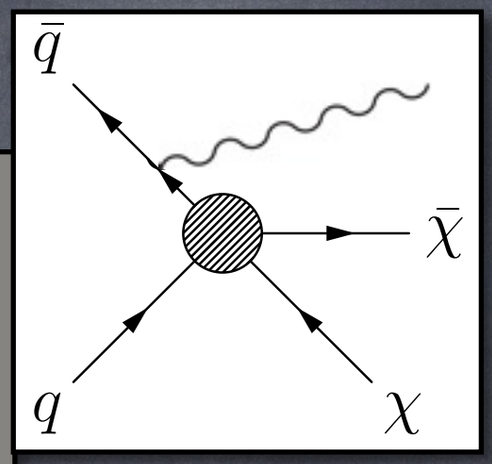
E_T^{miss} (GeV) →	> 250	> 300	> 350	> 400	> 450	> 500	> 550
Z($\nu\nu$)+jets	30600 ± 1493	12119 ± 640	5286 ± 323	2569 ± 188	1394 ± 127	671 ± 81	370 ± 58
W+jets	17625 ± 681	6042 ± 236	2457 ± 102	1044 ± 51	516 ± 31	269 ± 20	128 ± 13
$t\bar{t}$	470 ± 235	175 ± 87.5	72 ± 36	32 ± 16	13 ± 6.5	6 ± 3.0	3 ± 1.5
Z($\ell\ell$)+jets	127 ± 63.5	43 ± 21.5	18 ± 9.0	8 ± 4.0	4 ± 2.0	2 ± 1.0	1 ± 0.5
Single t	156 ± 78.0	52 ± 26.0	20 ± 10.0	7 ± 3.5	2 ± 1.0	1 ± 0.5	0 ± 0
QCD Multijets	177 ±88.5	76 ±38.0	23 ±11.5	3 ±1.5	2 ±1.0	1 ± 0.5	0 ± 0
Total SM	49154 ± 1663	18506 ± 690	7875 ± 341	3663 ± 196	1931 ± 131	949 ± 83	501 ± 59
Data	50419	19108	8056	3677	1772	894	508
Exp. upper limit	3580	1500	773	424	229	165	125
Obs. upper limit	4695	2035	882	434	157	135	131



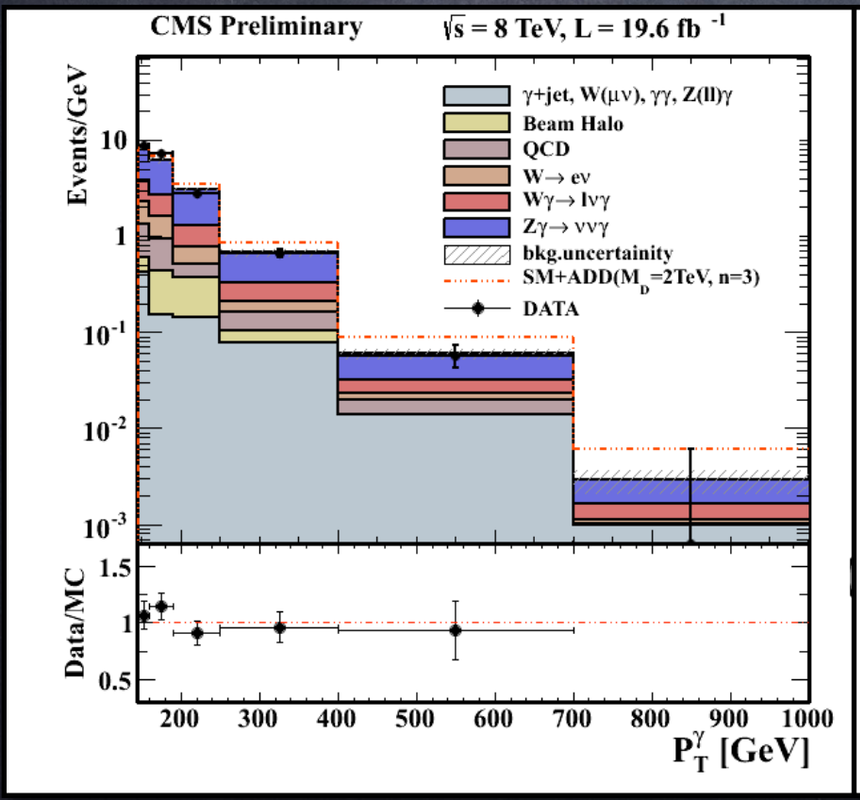
Mono-photon

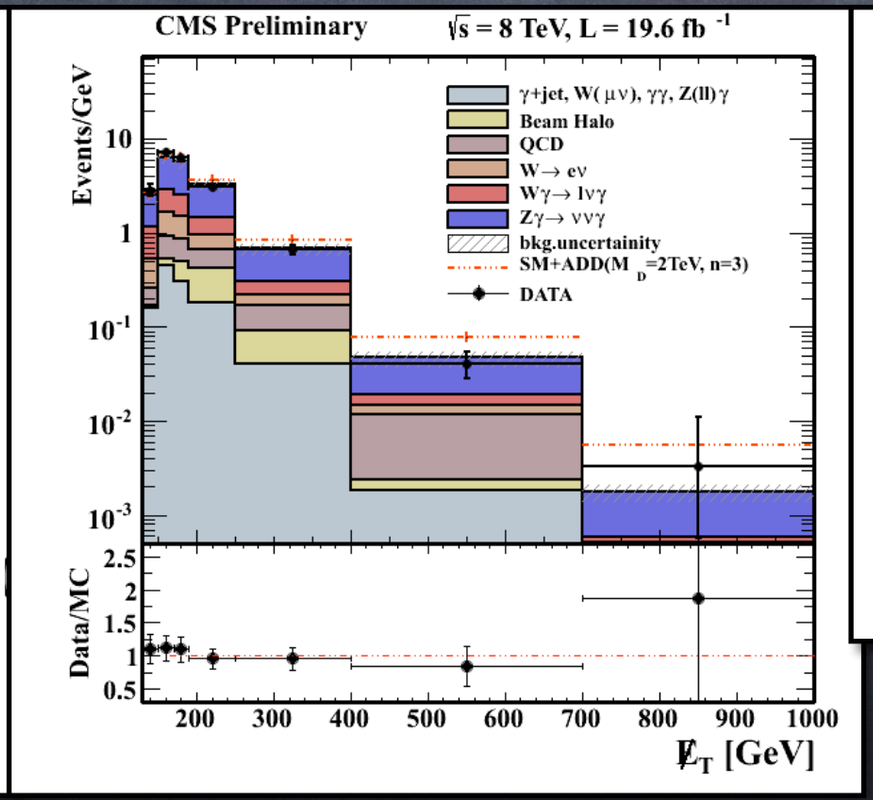
EXO-12-047 with full 8TeV CMS data

Large missing transverse energy recoiling against a high pT γ



- One energetic photon with pT > 145 GeV within $|\eta|$ < 1.4442
- Veto events with leptons and significant hadronic activity
- MET > 140 GeV
- $\Delta\phi$(photon,MET) > 2



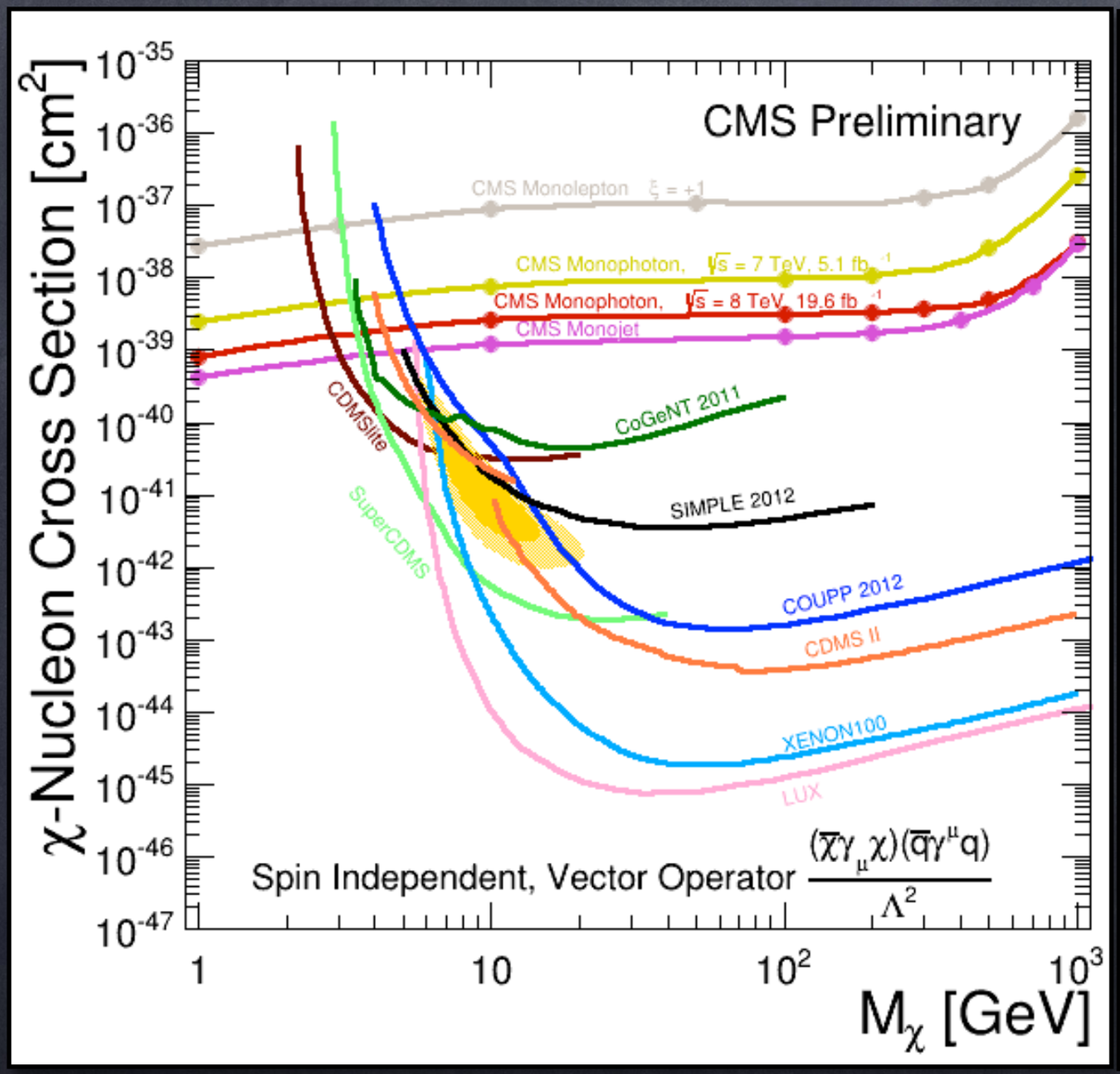


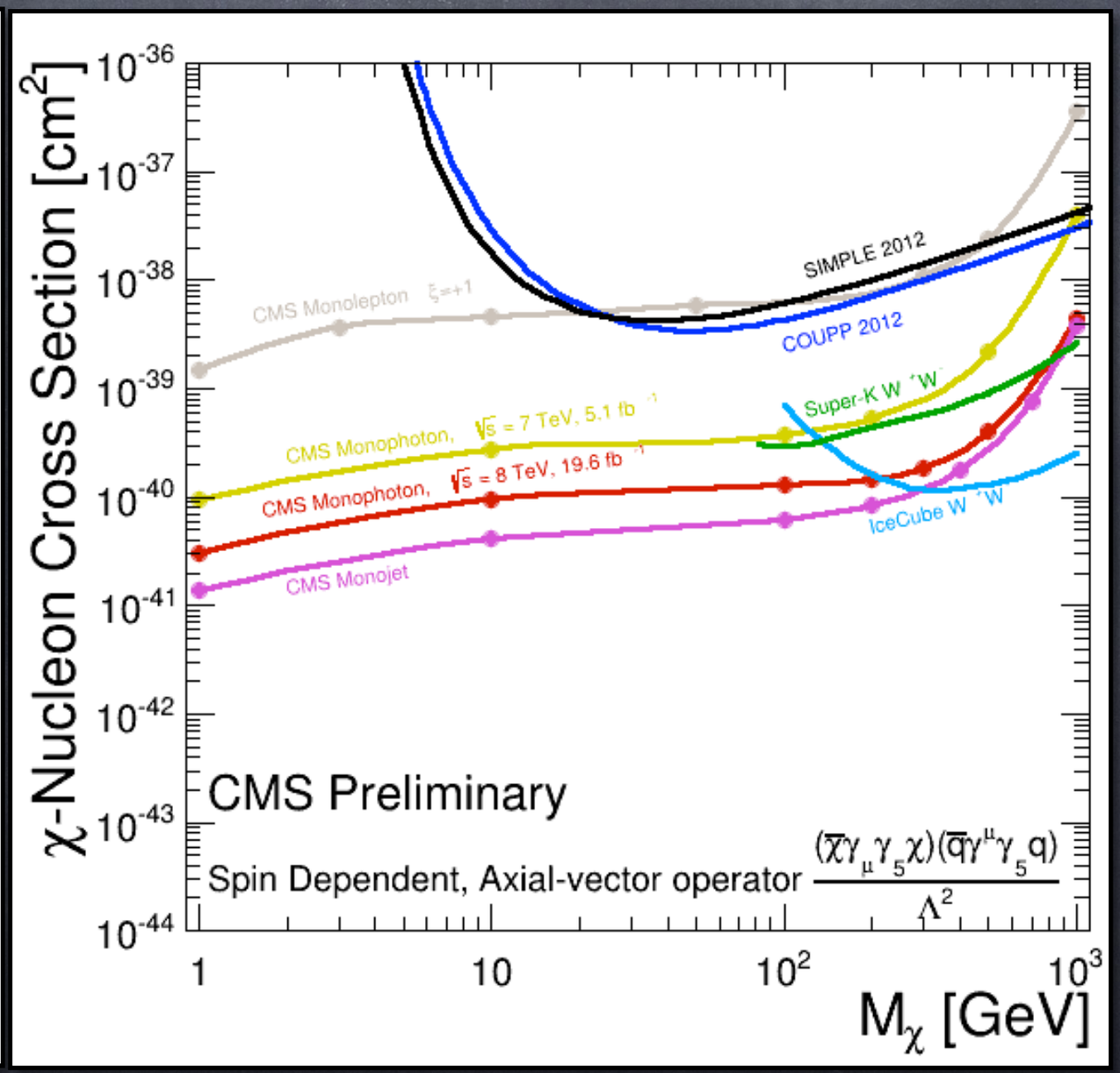
Process	Estimate
$Z(\to \nu\bar{\nu}) + \gamma$	344.8 ± 42.5
$W(\to \ell\nu) + \gamma$	102.5 ± 20.6
$W \to e\nu$	59.5 ± 5.5
jet $\to \gamma$ fakes	45.4 ± 13.9
Beam halo	24.7 ± 6.2
Others	35.7 ± 3.1
Total background	612.6 ± 63.0
Data	630.0

more details - poster by Z. Demiragli

Mono-X (results)

EXO-12-047 with full 8TeV CMS data



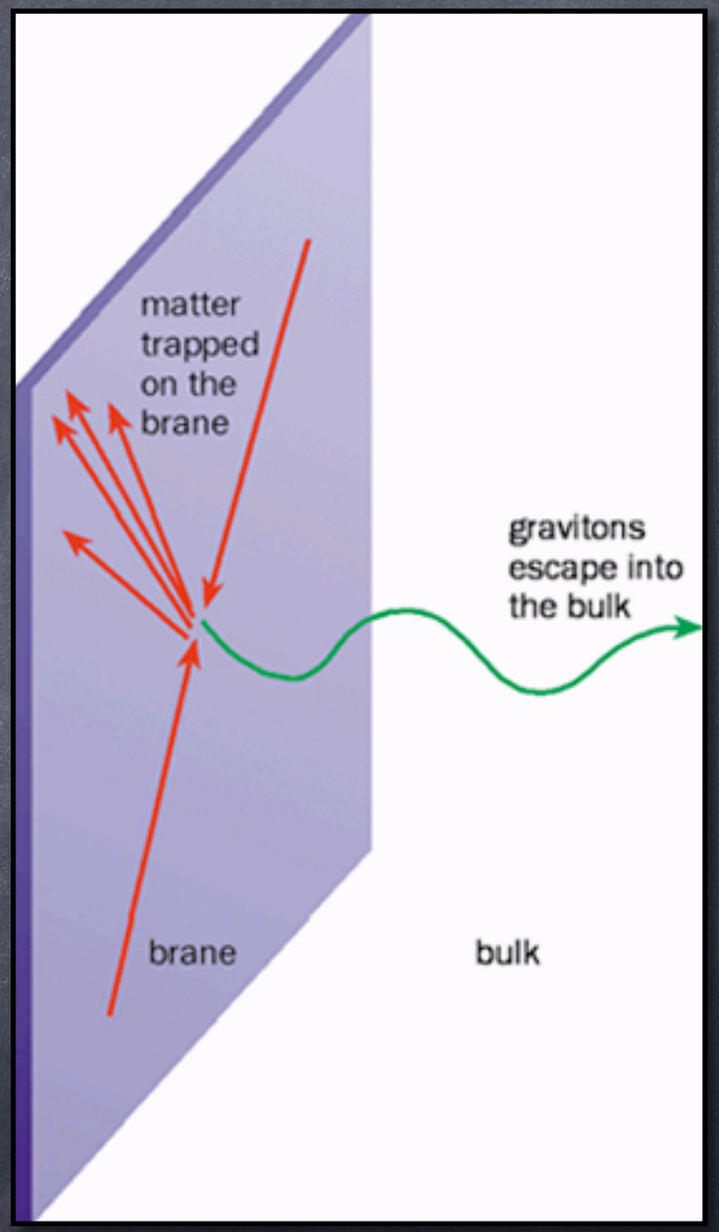


Extends the limits for M_χ < 3 GeV - which remained unexplored by direct detection experiments

Stringent constraints by colliders over the whole mass range

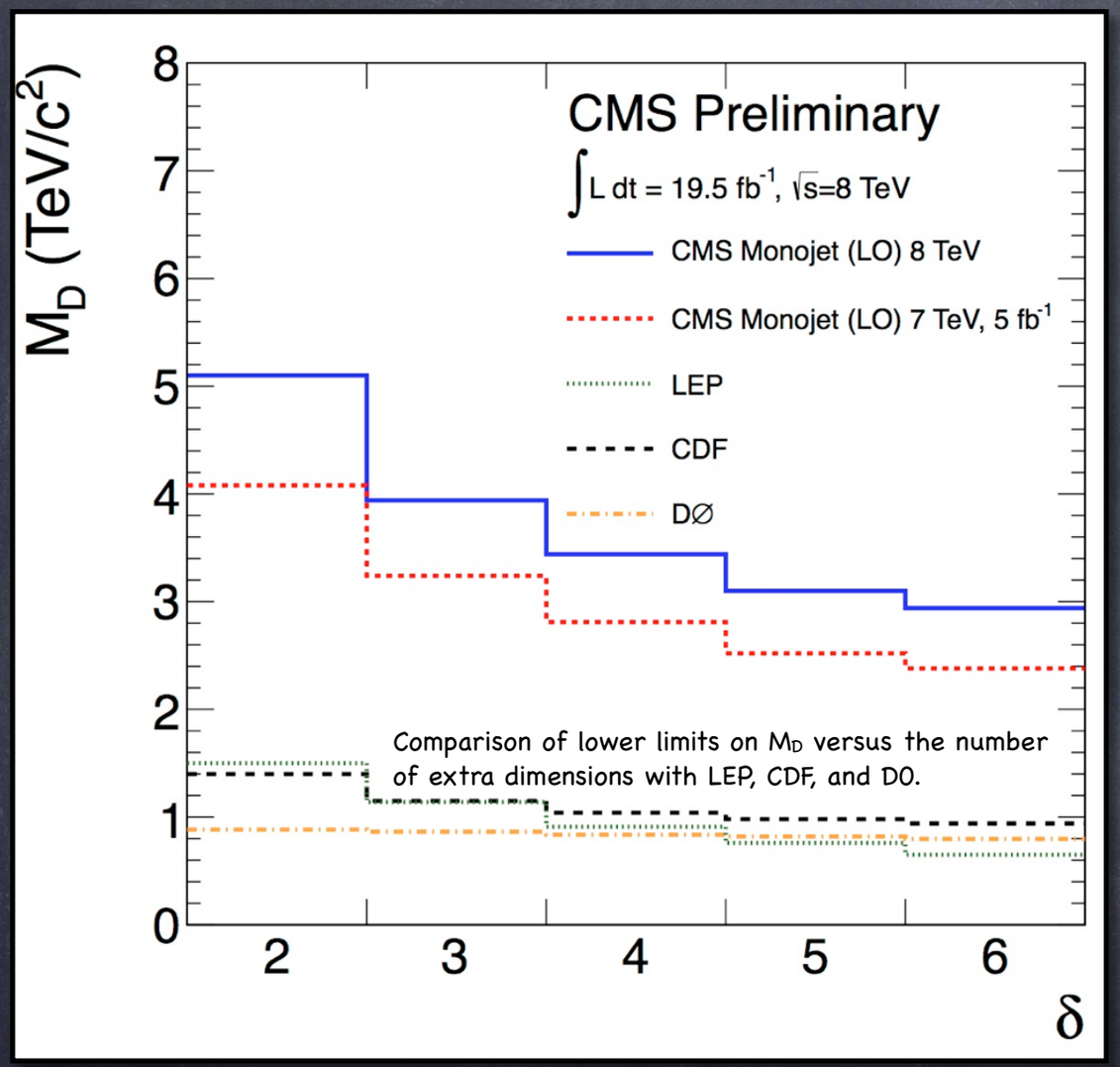
Extra Dimensions - Introduction

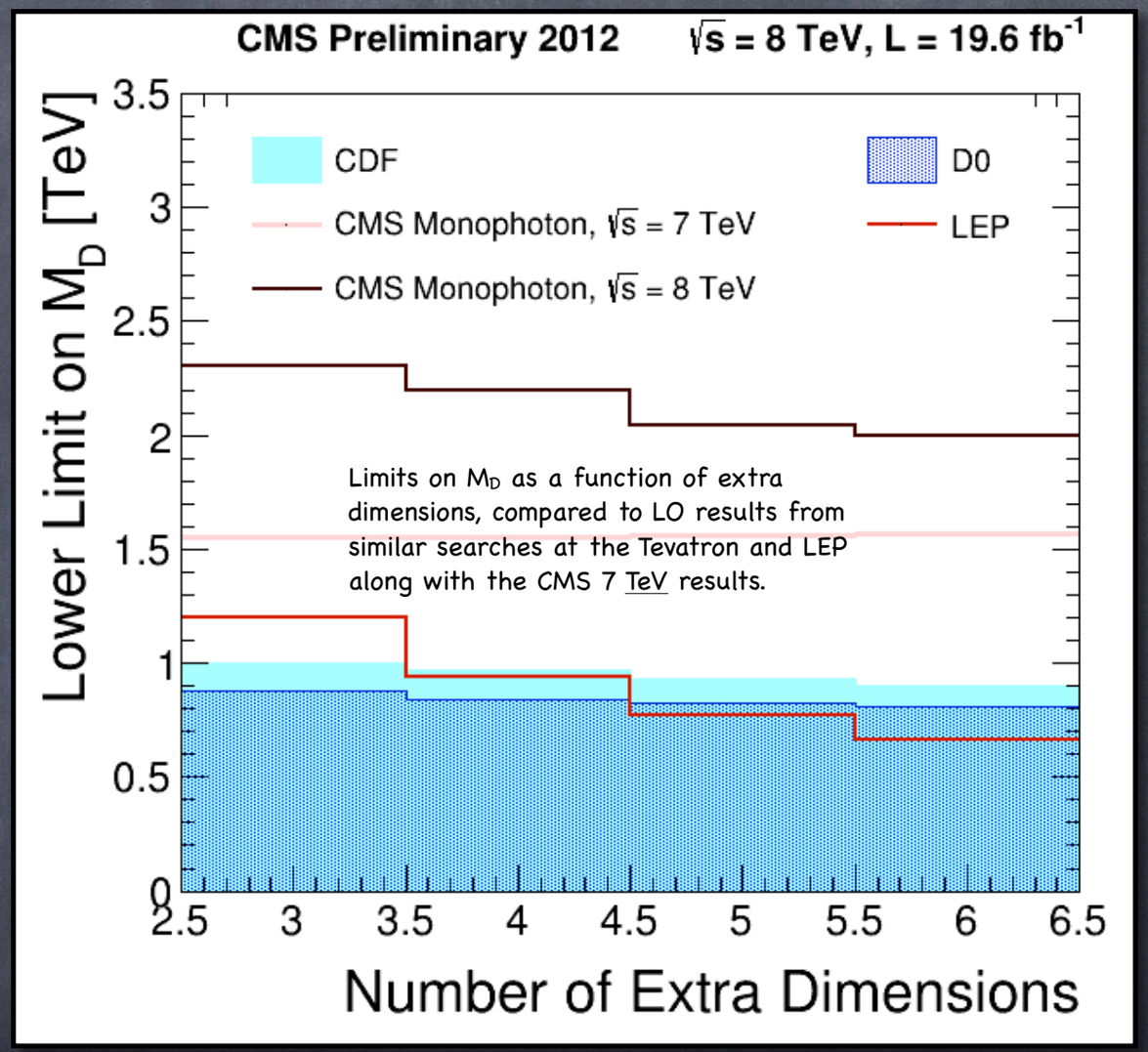
- Non-SUSY solutions to the hierarchy problem: extra dimensions (ED)
  - ✓ ADD: SM particles are confined to 4D subspace (brane) gravity propagates in additional dimensions (bulk). Its 4D projection is weak.
  - ✓ Signature:
    - mono-X from direct graviton production
    - enhanced high mass di-object events (virtual graviton exchange)



ADD with Mono-jet/photon

EXO-12-047/48 with full 8TeV CMS data



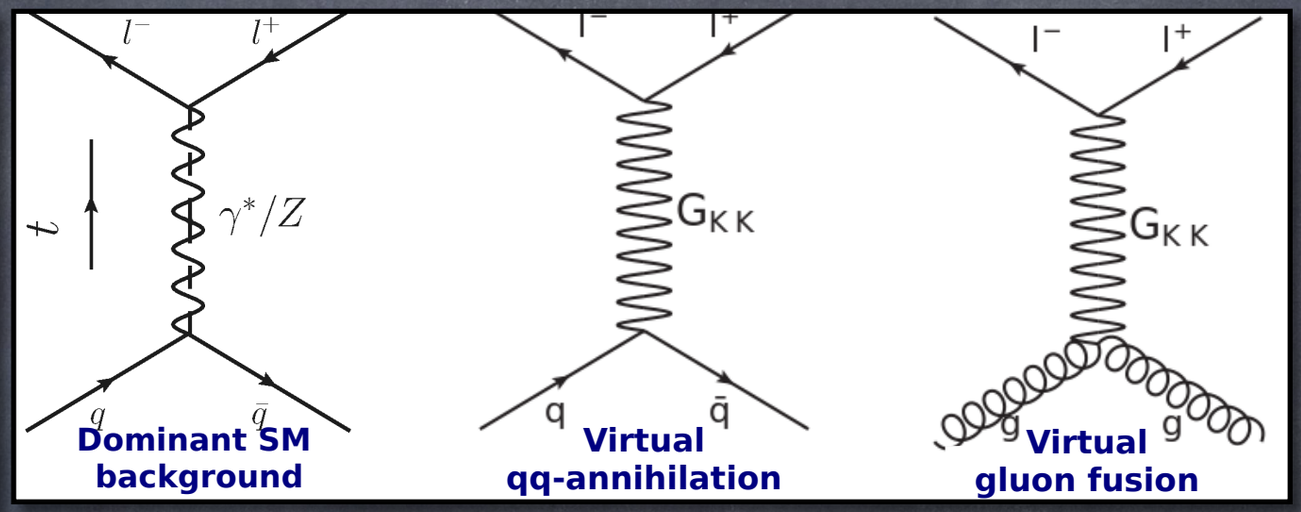


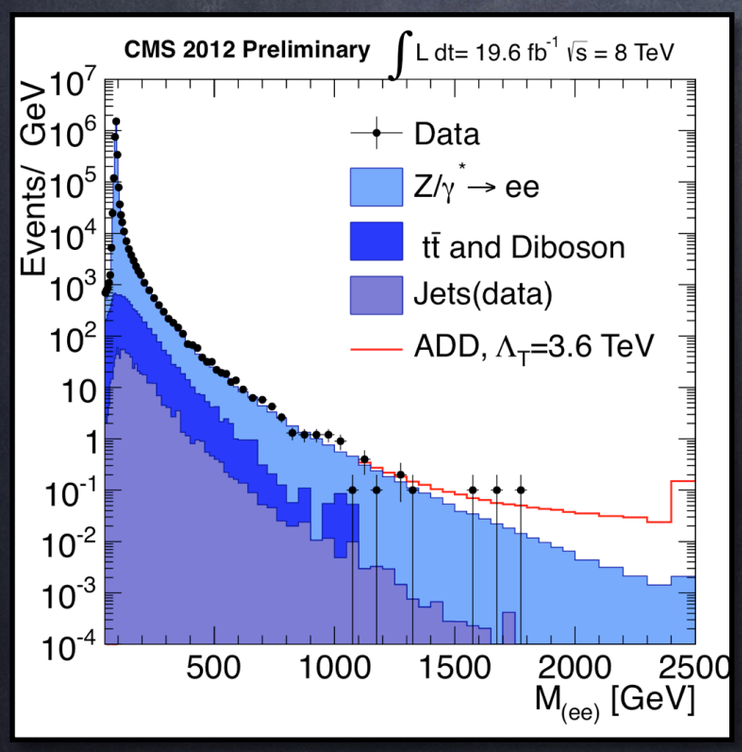
Limits on the order of 3-5 TeV, lower for larger number of EDs

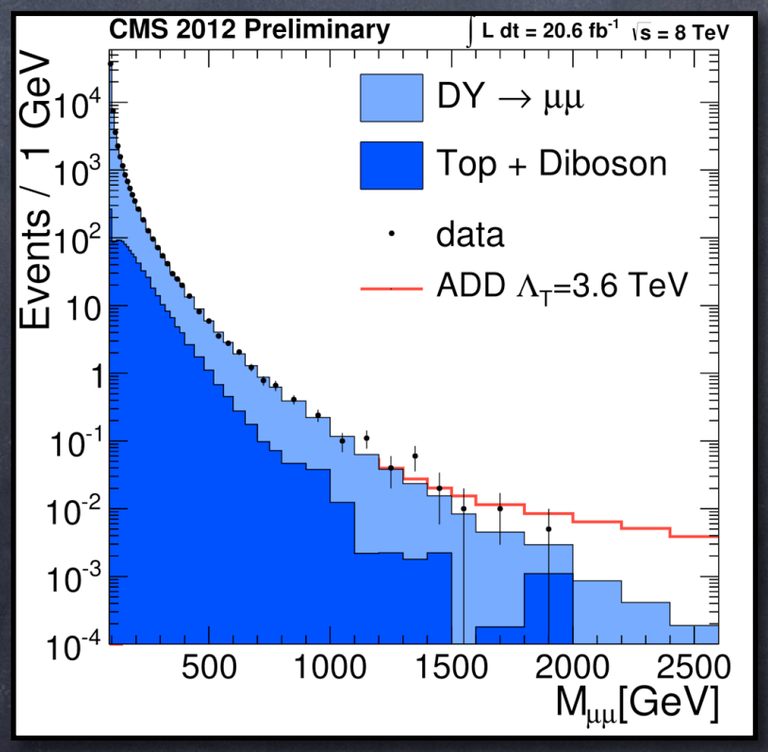
ED with di-leptons

EXO-12-027, EXO-12-031 with full 8TeV CMS data

- Enhanced non-resonant dilepton production
- Best S/B ratio in high mass tail of dilepton spectrum
- Single bin counting experiment with Bayesian approach (Optimized lower mass threshold of Mll > 1.8 TeV)







Model Parameters:

GRW (Giudice, Rattazzi, Wells)

$$\Lambda_T = \frac{8\pi\Gamma\left(n_{ED}/2\right) M_D^{n_{ED}+2}}{2\pi^{n_{ED}/2} c_1 \Lambda^{n_{ED}-2}}$$

Λ_T	Controls phenomenology
Λ	Ultraviolet energy cutoff
n_{ED}	Number of extra dimensions
M_D	Reduced Planck scale

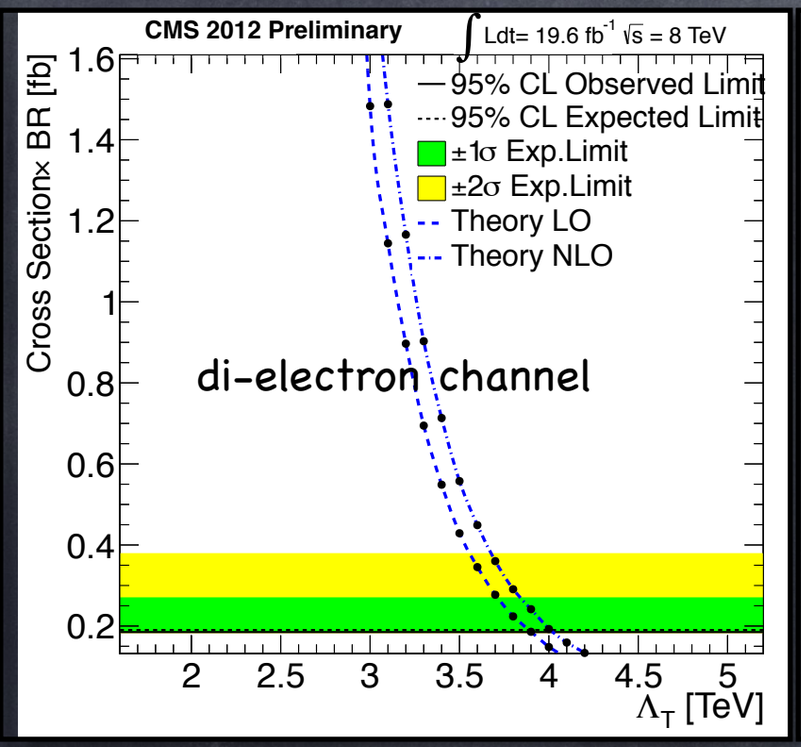
HLZ (Han, Lykken, Zhang)

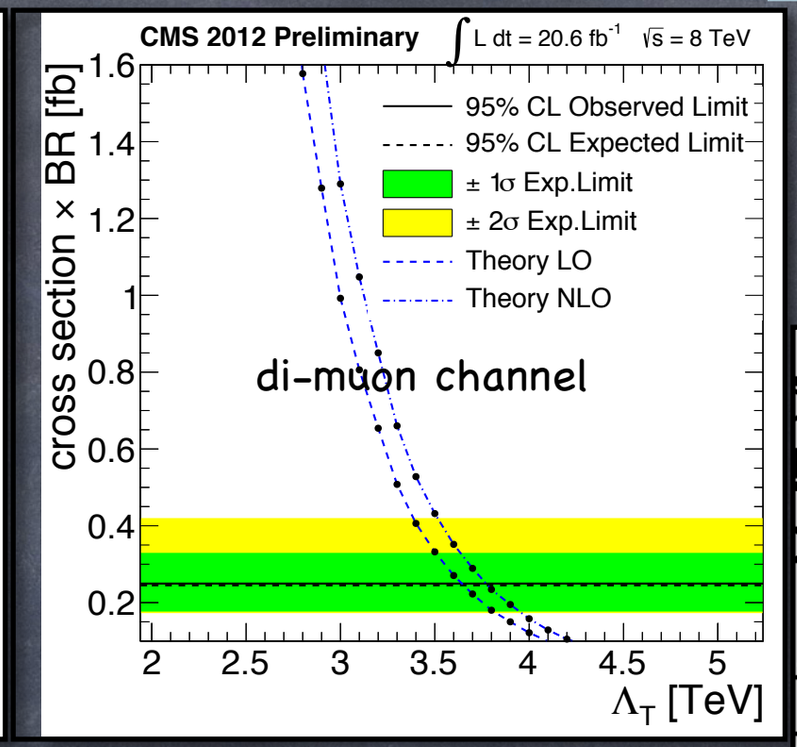
$$\Lambda_T^4 = \frac{n_{ED}-2}{2} M_{s,\mathrm{HLZ}}^4$$

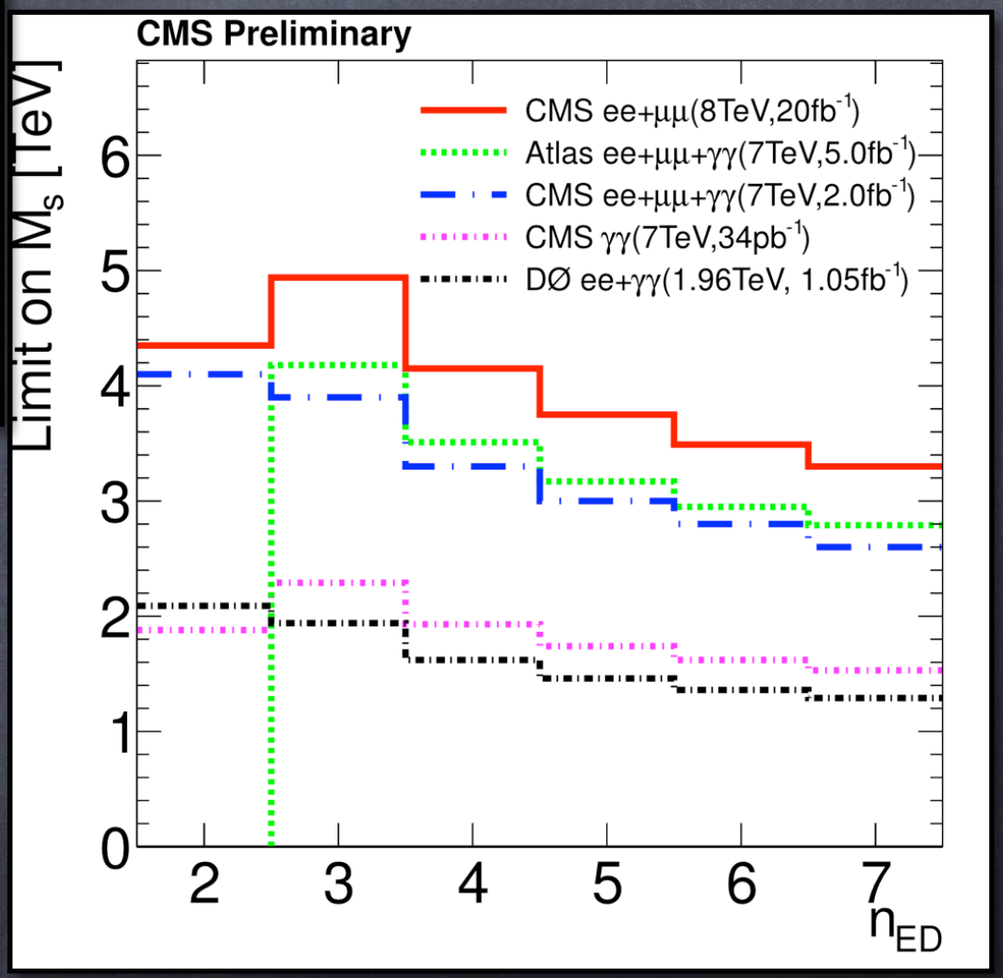
M_S	String Scale
n_{ED}	Number of extra dimensions

ED with di-leptons

EXO-12-027, EXO-12-031 with full 8TeV CMS data







Observed combined limit on σ_s < 0.12 fb at 95% CL

- Observed limits on cross-sections are translated to exclusion limits on ADD model parameters
- Translating in GRW limit (combined ee & $\mu\mu$ limit) Λ_T > 4.15 TeV
- translate into HLZ by

$$\Lambda_T^4 = \frac{n_{ED} - 2}{2} M_{s,\mathrm{HLZ}}^4$$

Conclusions

- Full 8TeV CMS data has been analyzed for most of the searches.
- Huge improvements on the known limits of LQ pair production, dark matter and extra dimensions, have been made. These results are the most stringent to date.
- Searches for all three LQ generations with different channels are shown (LQ1 8TeV results not public yet) .
- Dark matter searches target lots of different ISR objects - sensitivity to different operators in EFT enhanced -competitive with direct searches - especially these collider DM results are relevant at low DM mass and for spin-dependent interactions.
- Search for extra-dimensions in different possible signatures show no sign for its existence.
- But stay tuned - more results are on the way - 13 TeV collisions about to start !

Thanks ...