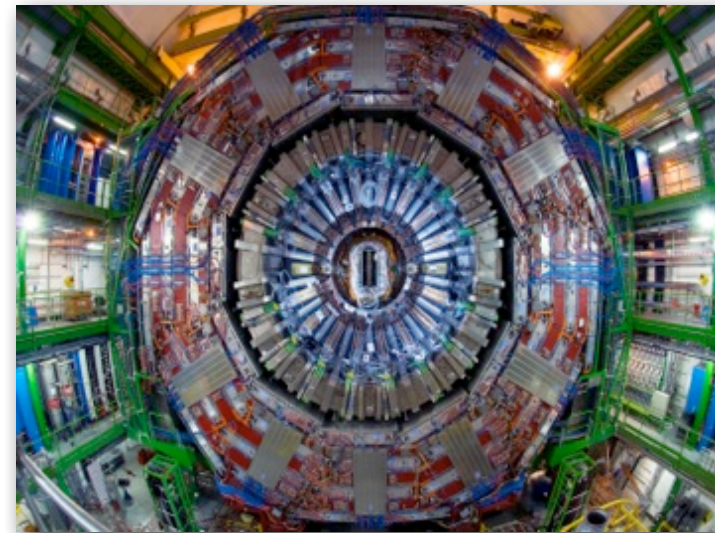


SEARCHES FOR EXOTIC PHYSICS AT CMS AND ATLAS



Steve Worm

ECFA LC2013

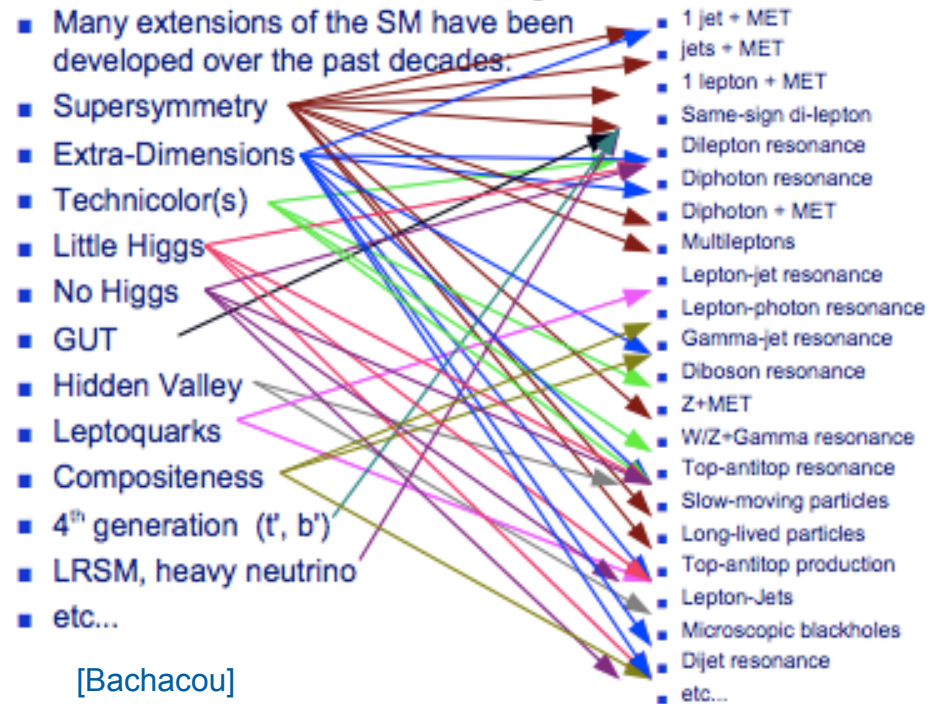
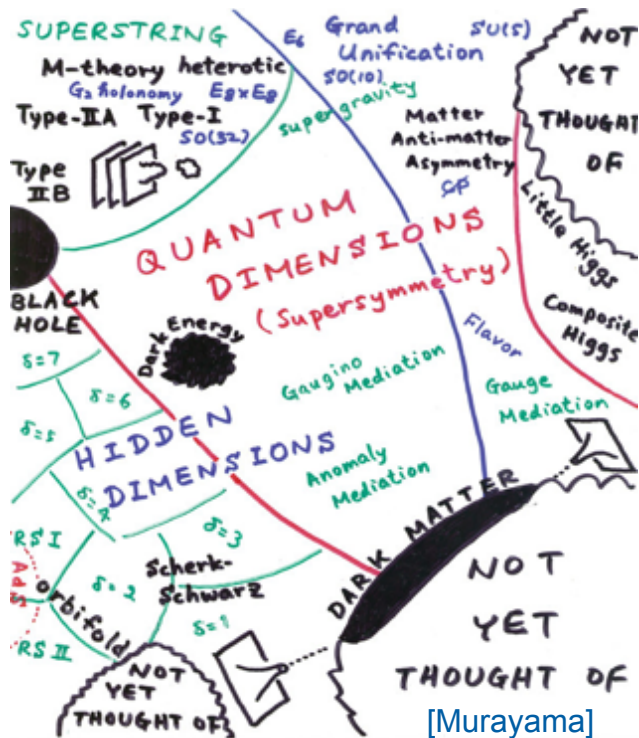
European Linear Collider Workshop

DESY, 30 May 2013



BSM AND EXOTICA: WHAT IS “EXOTIC”?

- Comprehensive search of the landscape of $\sqrt{s} = 8$ TeV proton collisions
 - Unlike Higgs, no “EXO-Hunters Guide” to show us the way
 - no SUSY-like plot of parameter space to map out progress
- Wide variety of search strategies used
 - look for interesting features in the data – new resonant states e.g. Z' , W'
 - look at all possible channels for disagreements with expectation – leptons, photons, jets
 - follow-up interesting new BSM models

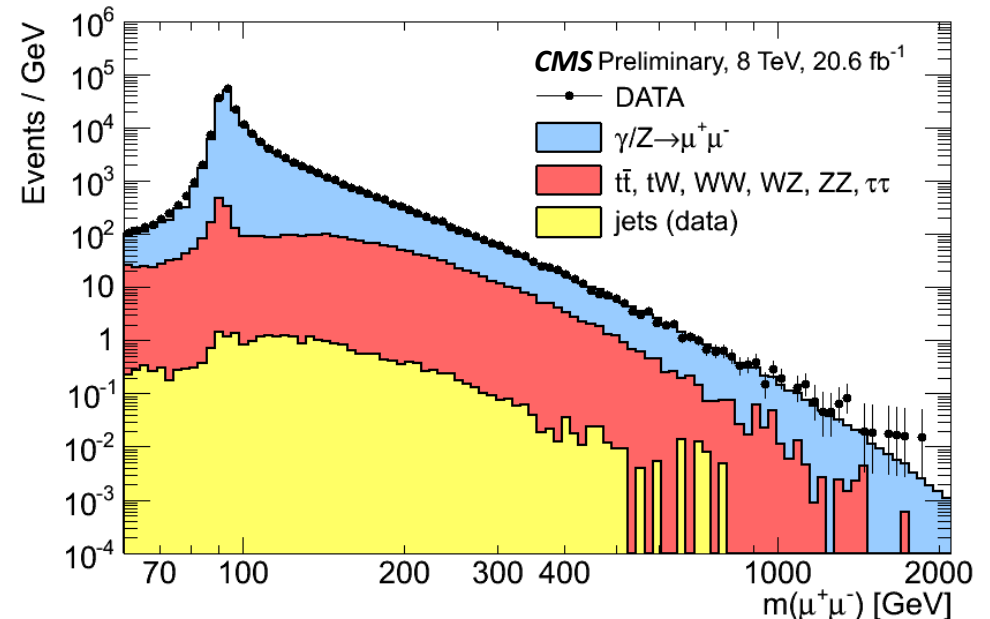
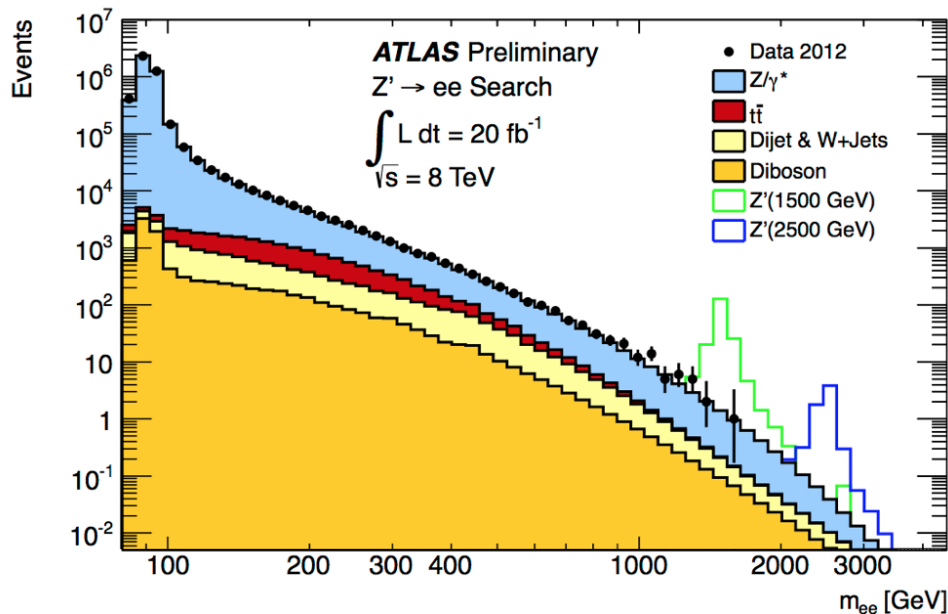


SEARCH FOR Z' (DILEPTON RESONANCE)

[ATLAS-CONF-2013-017, CMS EXO-12-061]

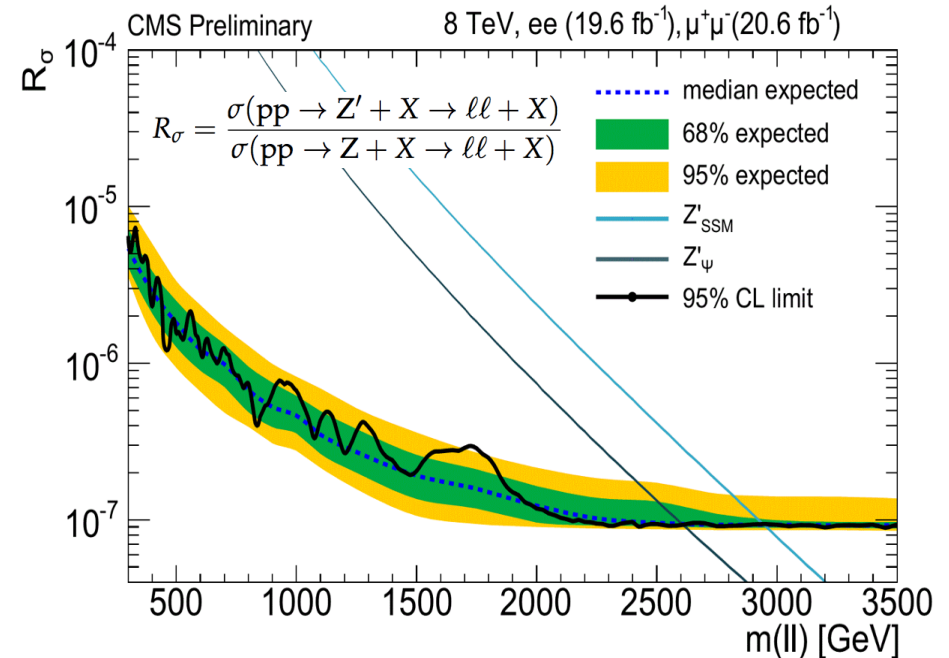
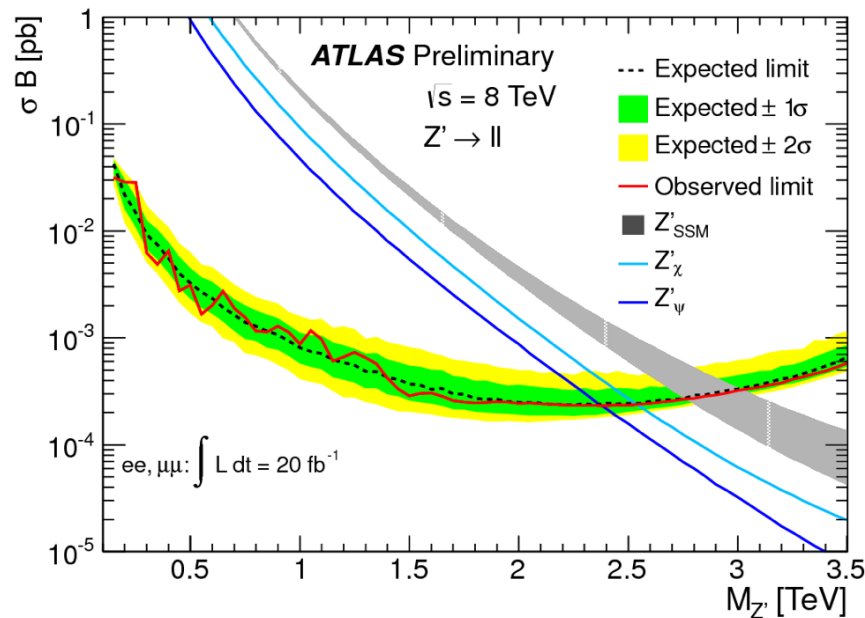
- Event selection
 - CMS: $E_T(e1,e2) > 35$ GeV, $p_T(\mu1,\mu2) > 45$ GeV, plus isolation criteria
 - ATLAS: $E_T(e1,e2) > (40,30)$ GeV, $p_T(\mu1,\mu2) > 25$ GeV, plus isolation criteria
- Backgrounds
 - Z/γ^* , $t\bar{t}$, tW , VV , $Z \rightarrow \tau\tau$, multijets with ≥ 1 jet reconstructed as lepton
 - estimated by functional fit

No obvious excess observed in 2012 data



SEARCH FOR Z' (DILEPTON RESONANCE)

- Both experiments analysed full 8 TeV datasets, combined ee and $\mu\mu$ channels
- No excess; limits set for a variety of narrow resonances (Z'_{SSM} , Z'_ψ , etc.)



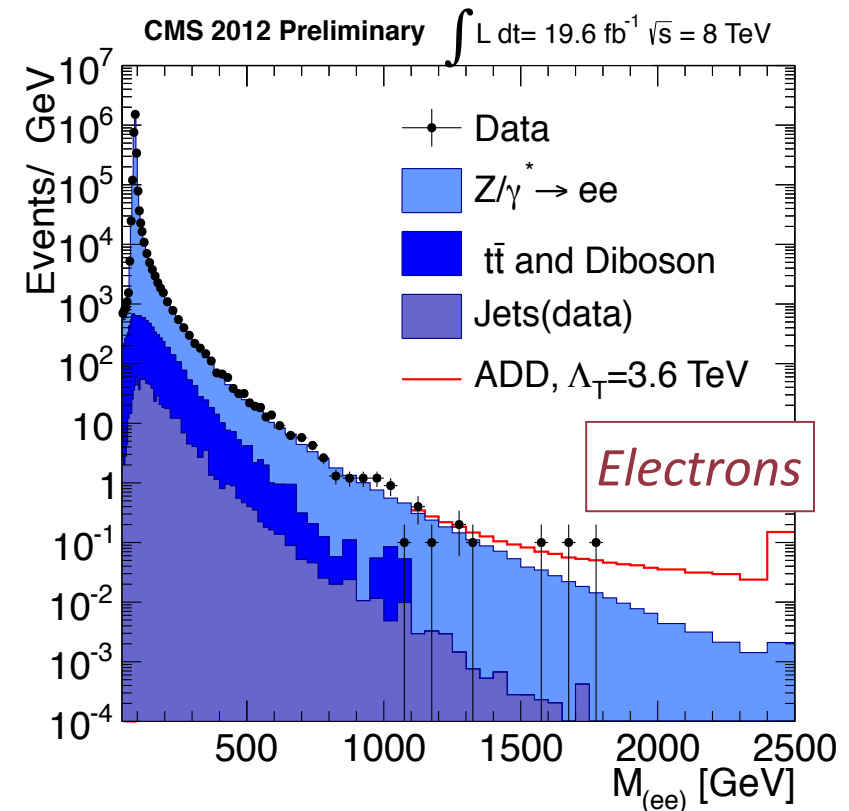
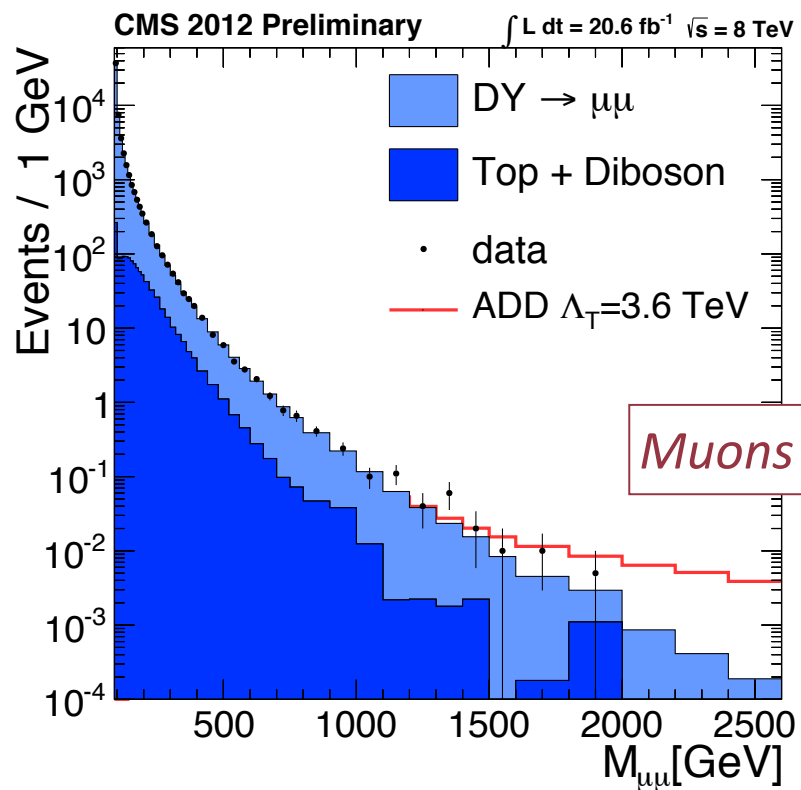
$M(Z'_{SSM})$	expected	observed
CMS	> 2.96 TeV	> 2.96 TeV
ATLAS	> 2.85 TeV	> 2.86 TeV

Excess in 2011 data just below 1 TeV all but gone in 2012

SEARCH FOR EXTRA DIMENSIONS IN DILEPTONS

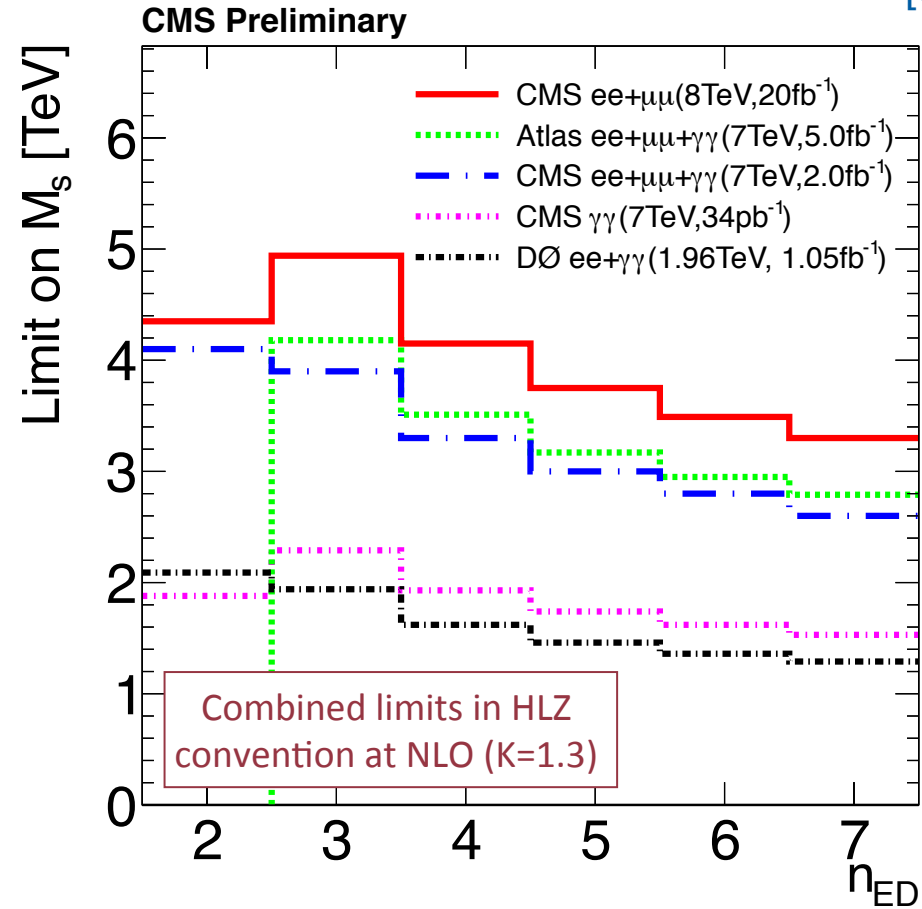
[CMS EXO-12-027, CMS EXO-12-031]

- Extra Dimension search in dilepton invariant mass spectra (same as Z')
- Simple counting experiment on integral above a mass threshold (Bayesian)
- Leading systematics from momentum scale (muons) and PDF (electrons)



EXTRA DIMENSIONS IN DILEPTONS

[CMS EXO-12-027, CMS EXO-12-031]

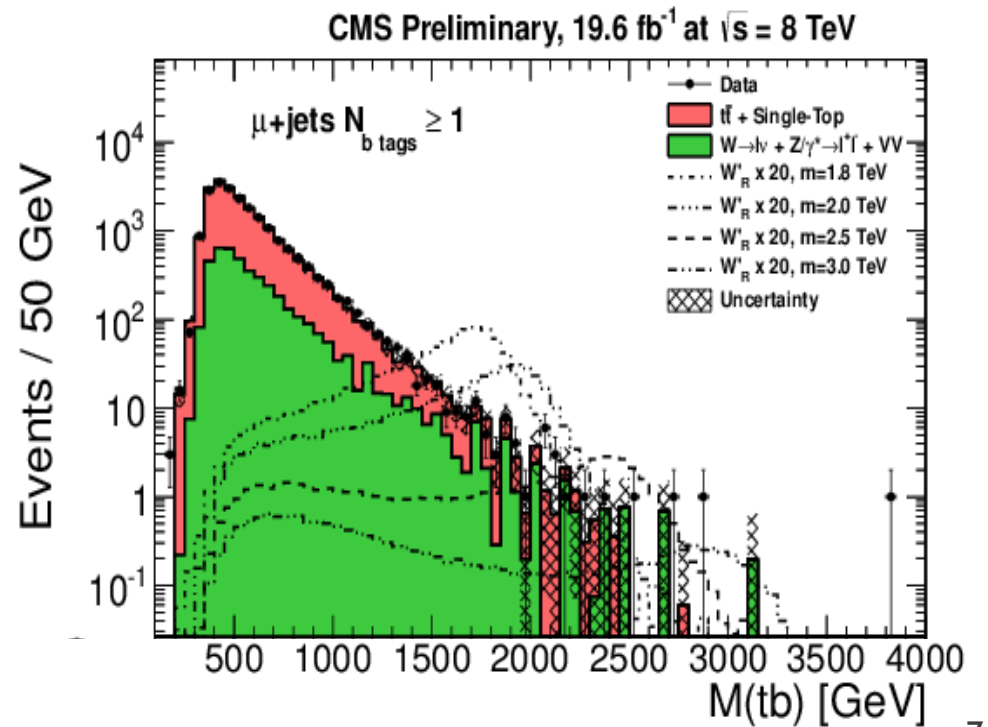
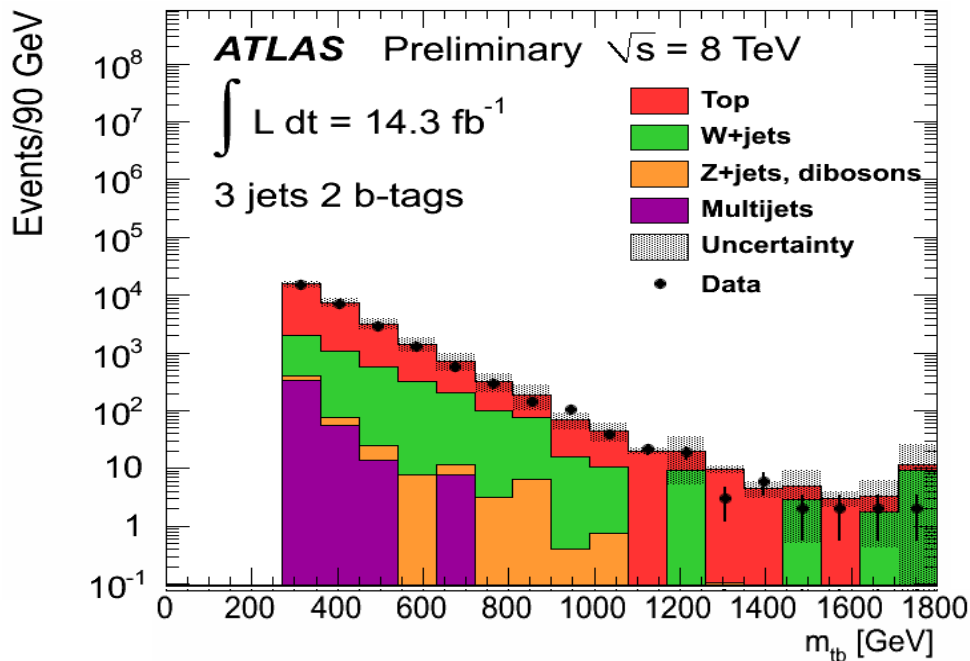
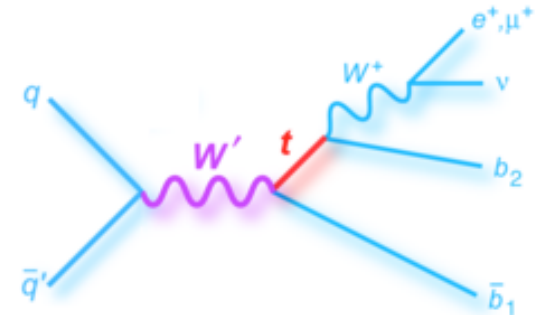


M_s (ADD) at LO 95% CL limits	Lumi. [fb ⁻¹]	$\delta=3$ Exp.	$\delta=3$ Obs.	$\delta=6$ Exp.	$\delta=6$ Obs.	Λ_T (GRW) [TeV]
CMS dimuon	20.6	4.34	4.33	3.07	3.06	3.64
CMS dielectron	19.6	4.62	4.64	3.27	3.28	3.90
Combined:	20.6+19.6	4.76	4.77	3.37	3.37	4.01

W' TO TOP + BOTTOM

[ATLAS-CONF-2013-050, CMS B2G-12-010]

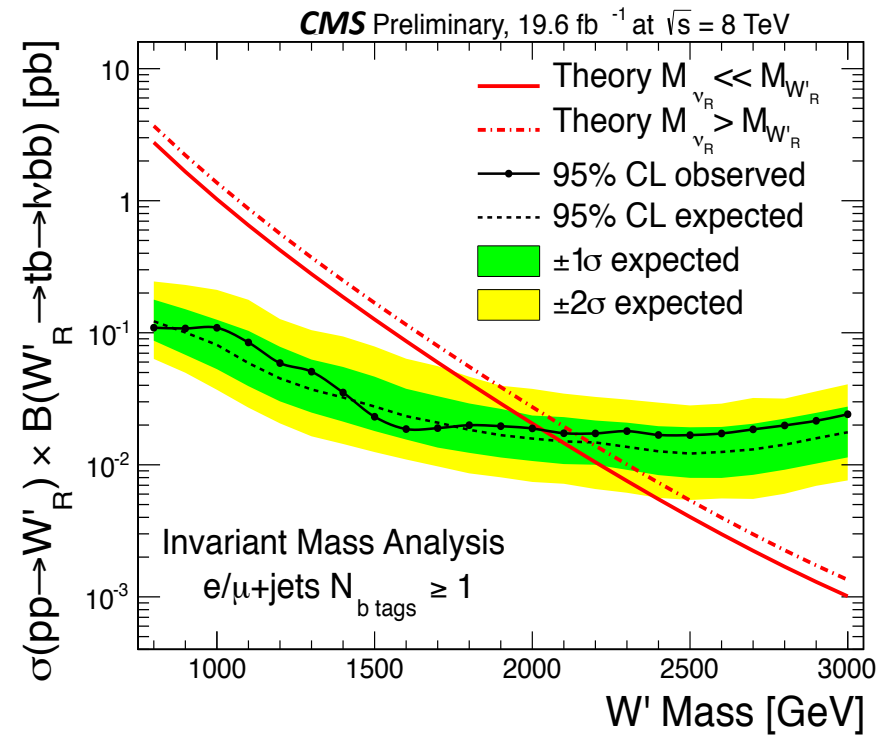
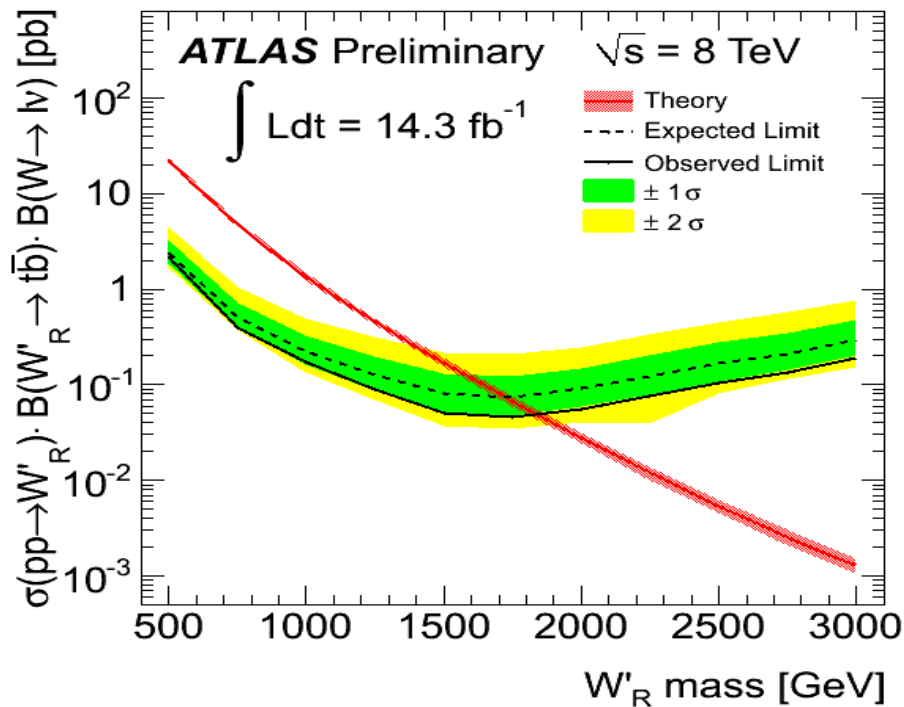
- Search lepton (e, μ) plus jets and E_T^{miss} for decays $W' \rightarrow tb, t \rightarrow bW \rightarrow bl\nu$,
- Event selection:
 - Several jets, with ≥ 2 b-tag(s)
 - Require small E_T^{miss} (20–35 GeV) to reduce QCD
 - Kinematic cuts to enhance signal (e.g. p_T^{top} or $E_T^{\text{miss}} + m_T(W)$)



W' TO TOP + BOTTOM

[ATLAS-CONF-2013-050, CMS B2G-12-010]

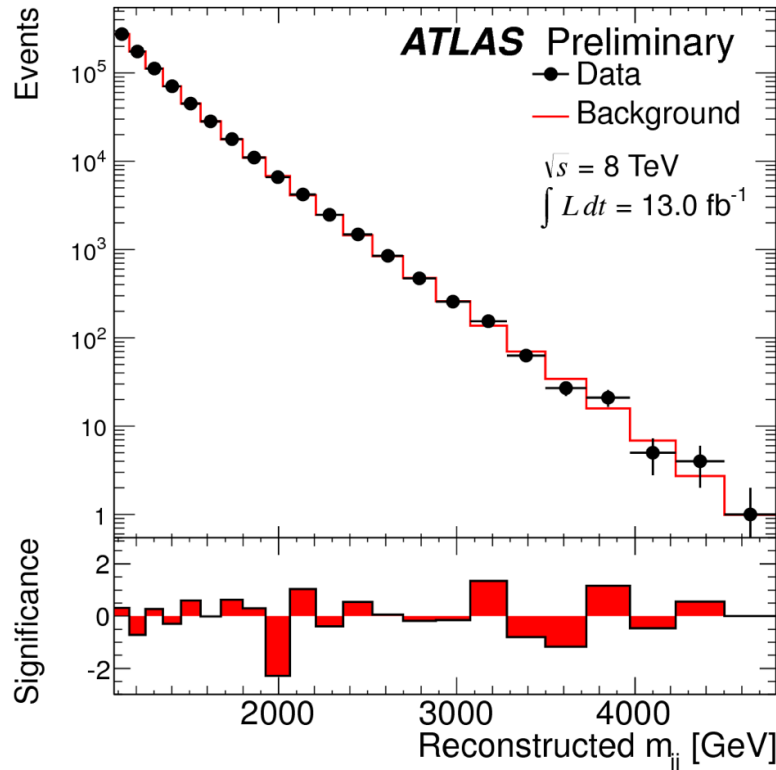
- No evidence for W' in data; proceed to set limits at 95% C.L.
- Limits shown below for right-handed W' (no interference with SM)



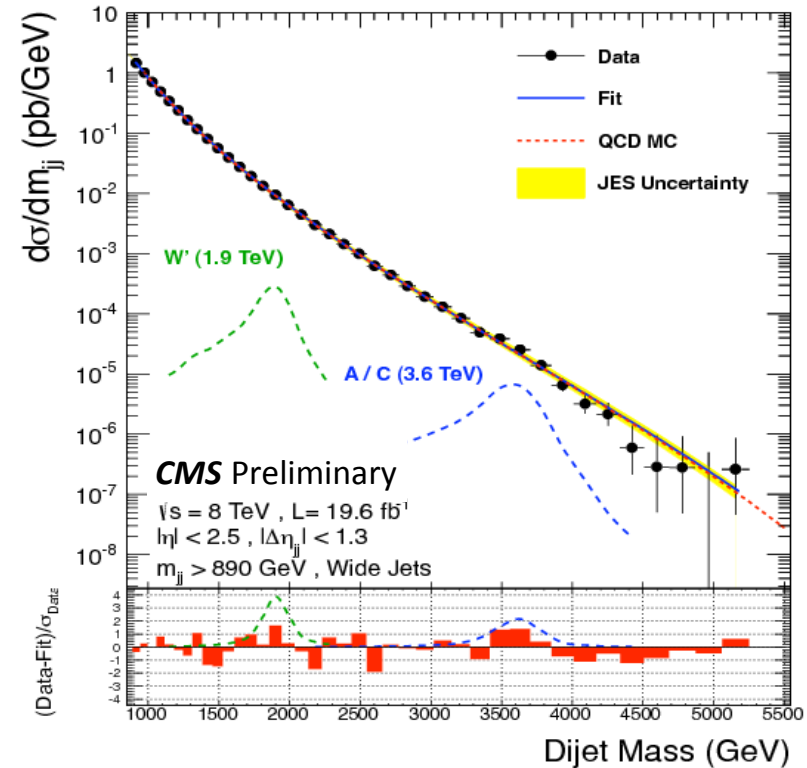
$M_{W'_R(tb)}$ 95% CL	Luminosity	Expected	Observed
ATLAS W'_R	14.3	> 1.72 TeV	> 1.84 TeV
CMS W'_R	19.6	> 2.09 TeV	> 2.03 TeV

DIJETS IN 8 TeV DATA

[ATLAS-CONF-2012-148]



[CMS PAS EXO-12-059]

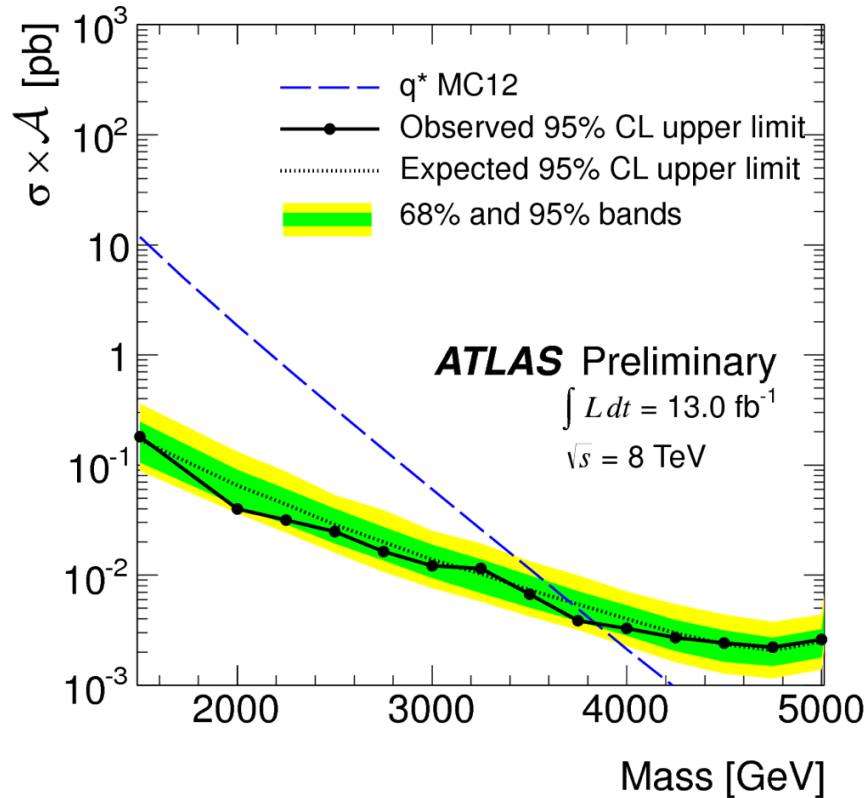


- Search for dijet resonance in smoothly falling mass spectrum
 - leading jet mass $m_{jj} > 0.9\text{-}1 \text{ TeV}$ from trigger and other constraints
 - Background estimated from smooth functional fit

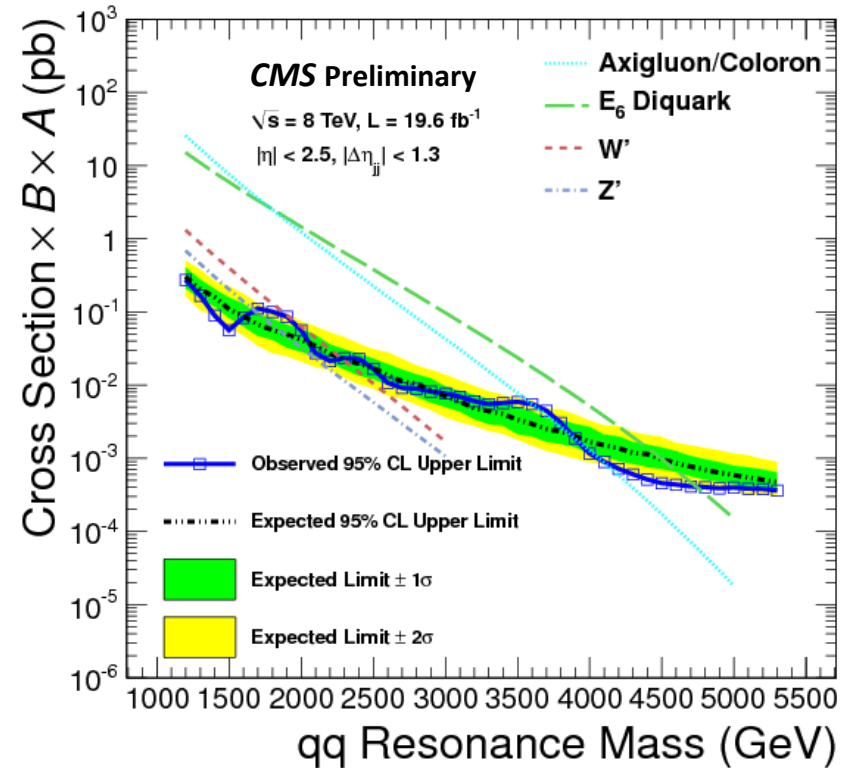
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3 \ln(x)}}$$

DIJETS IN 8 TeV DATA

[ATLAS-CONF-2012-110]



[CMS PAS EXO-12-016]



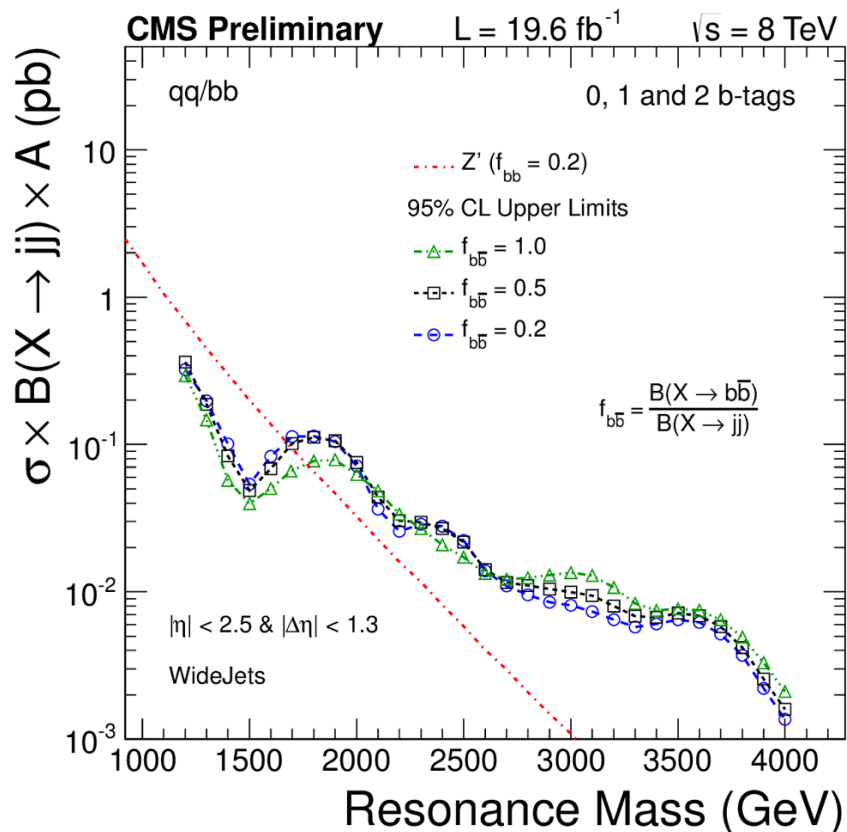
$M(q^*)$ 95% CL	Luminosity	Expected	Observed
ATLAS 2011	4.8	> 3.09 TeV	> 3.55 TeV
CMS 2011	5.0	> 3.27 TeV	> 3.05 TeV
ATLAS 2012	13.0	> 3.70 TeV	> 3.84 TeV
CMS 2012	19.6	> 3.75 TeV	> 3.50 TeV

DIJET WITH b-TAG

[CMS EXO-12-023]

- Dijet with 0, 1, 2 b-tags
 - model-independent limits vs. BR
 - Simultaneous search in 0, 1 and 2 b-tags

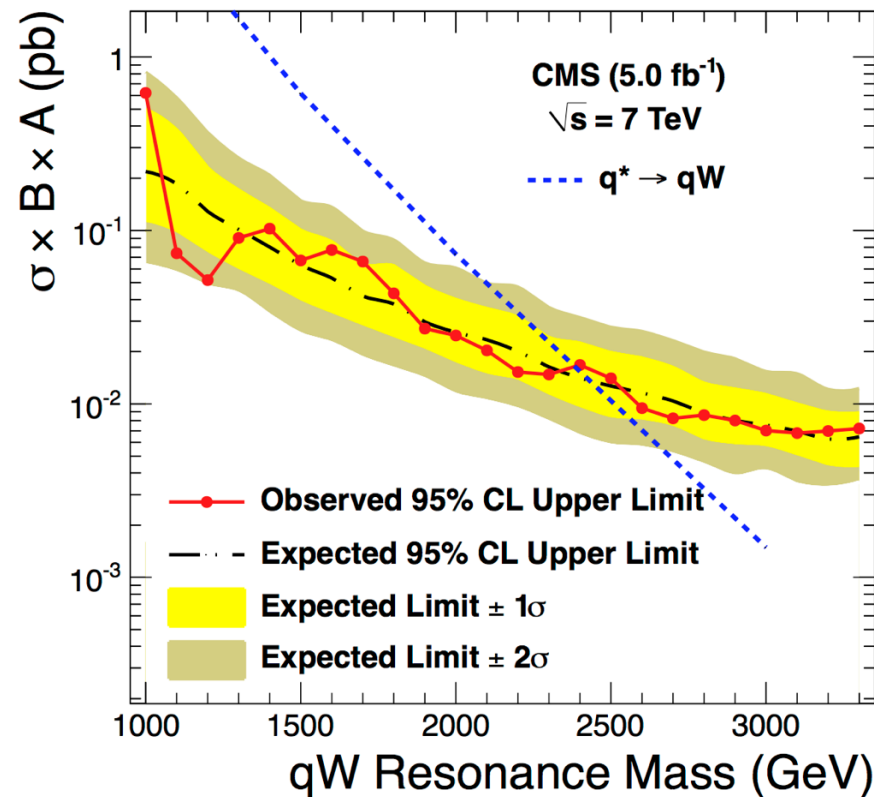
$$f_{b\bar{b}} = \frac{\text{BR}(X \rightarrow b\bar{b})}{\text{BR}(X \rightarrow jj)}$$



DIJET WITH W/Z TAGS

[CMS PAS EXO-11-095]

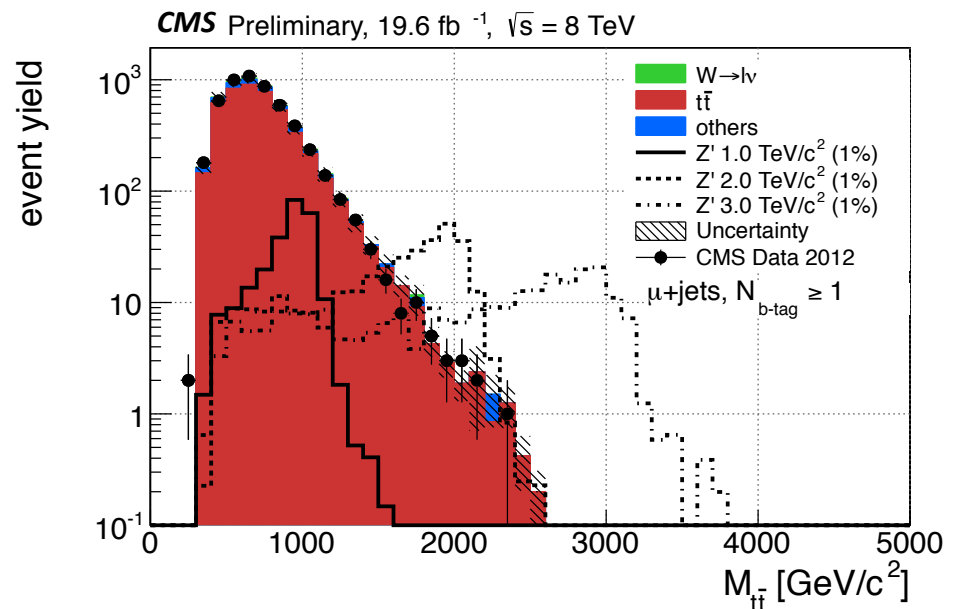
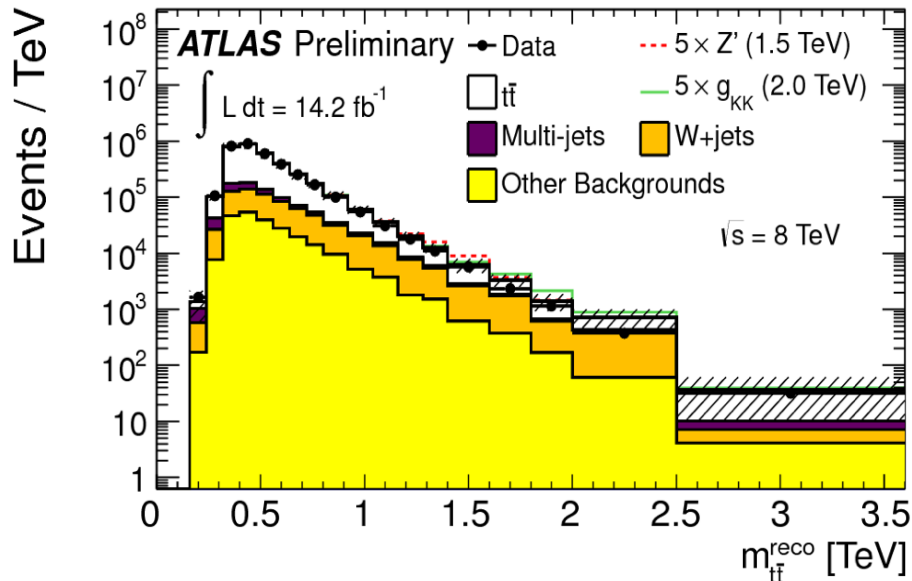
- Dijet with 1, 2 W/Z-tags
 - jet substructure used for tagging
 - single tags: qW/qZ resonances
 - double tags: WW/WZ/ZZ resonances



TOP – ANTITOP RESONANCE

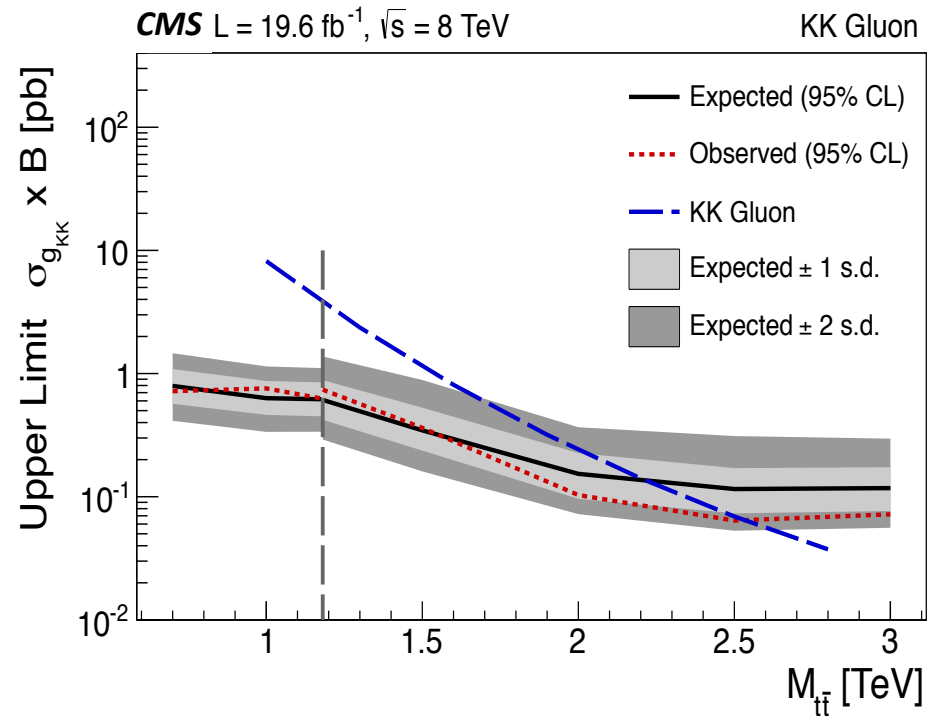
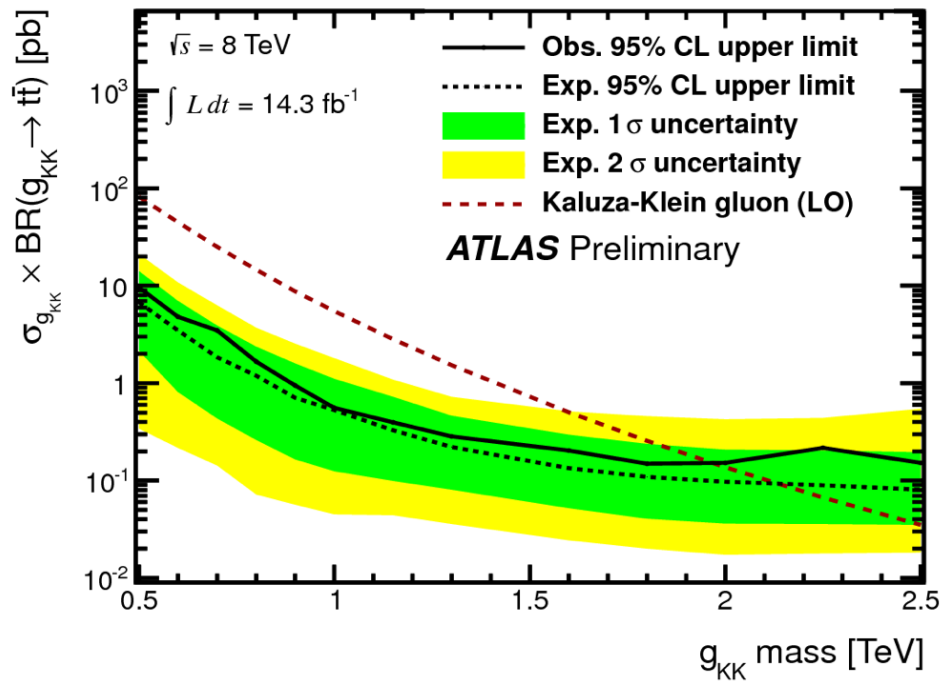
[ATLAS-CONF-2013-052, CMS B2G-12-006]

- Search for heavy resonance decaying to $t\bar{t}$ in e or μ plus ≥ 2 jets
- Two search regions; resolved jets and high Lorentz boost (above ~ 1 TeV)
- Backgrounds:
 - $t\bar{t}$ and single top main backgrounds (especially after b-tagging), some W +jets
 - Data-driven techniques used for some backgrounds



TOP – ANTITOP RESONANCE

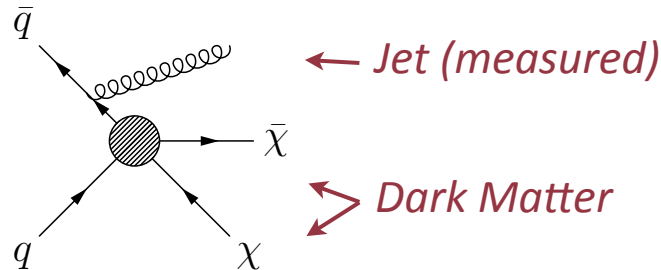
- Leading systematics: jet energy scale (17% ATLAS), background xsections (9%)
- No significant excesses; set limits at 95% C.L.



M(Z' or g _{KK}) 95%	Luminosity	Expected	Observed
ATLAS Z'	14.3	> 1.9 TeV	> 1.8 TeV
CMS Z'	19.6	> 2.0 TeV	> 2.1 TeV
ATLAS g _{KK}	14.3	> 2.1 TeV	> 2.0 TeV
CMS g _{KK}	19.6	> 2.2 TeV	> 2.5 TeV

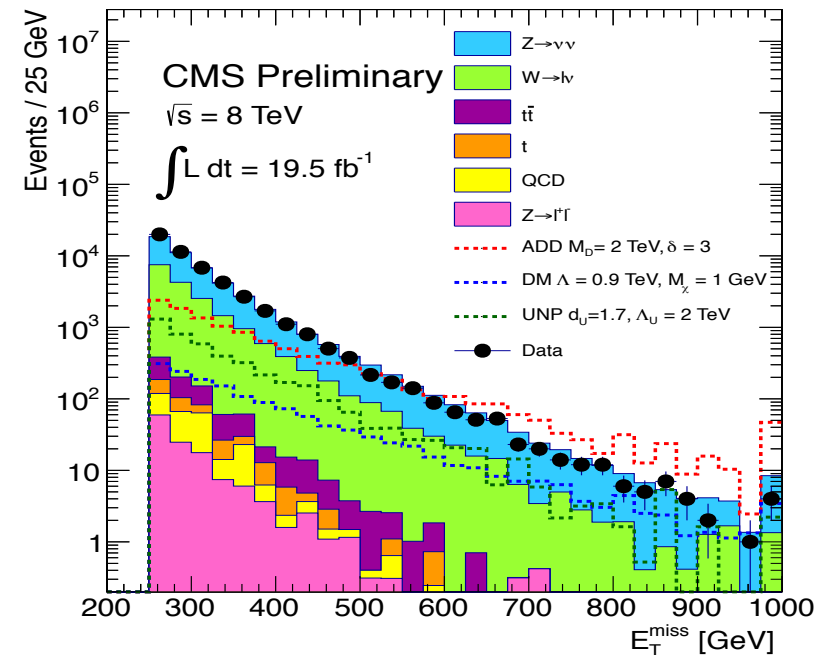
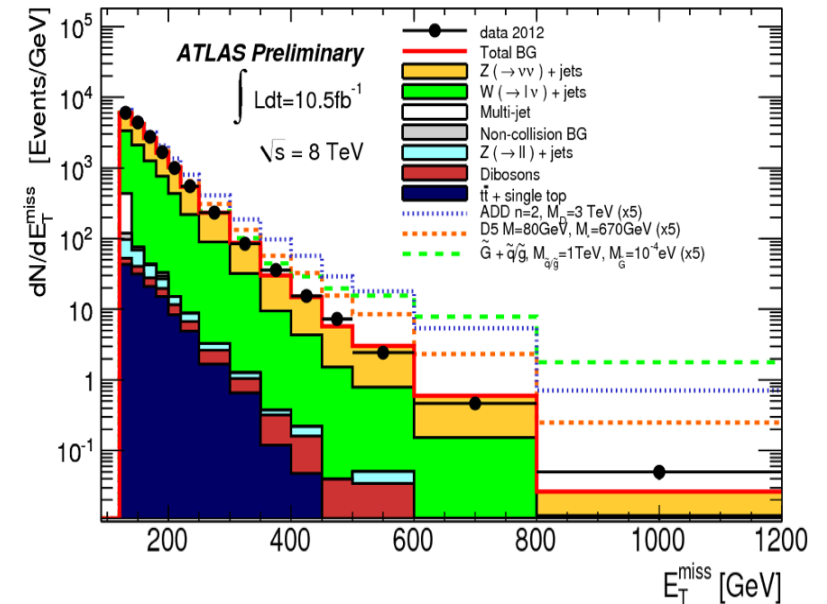
DARK MATTER AND ADD FROM MONOJETS

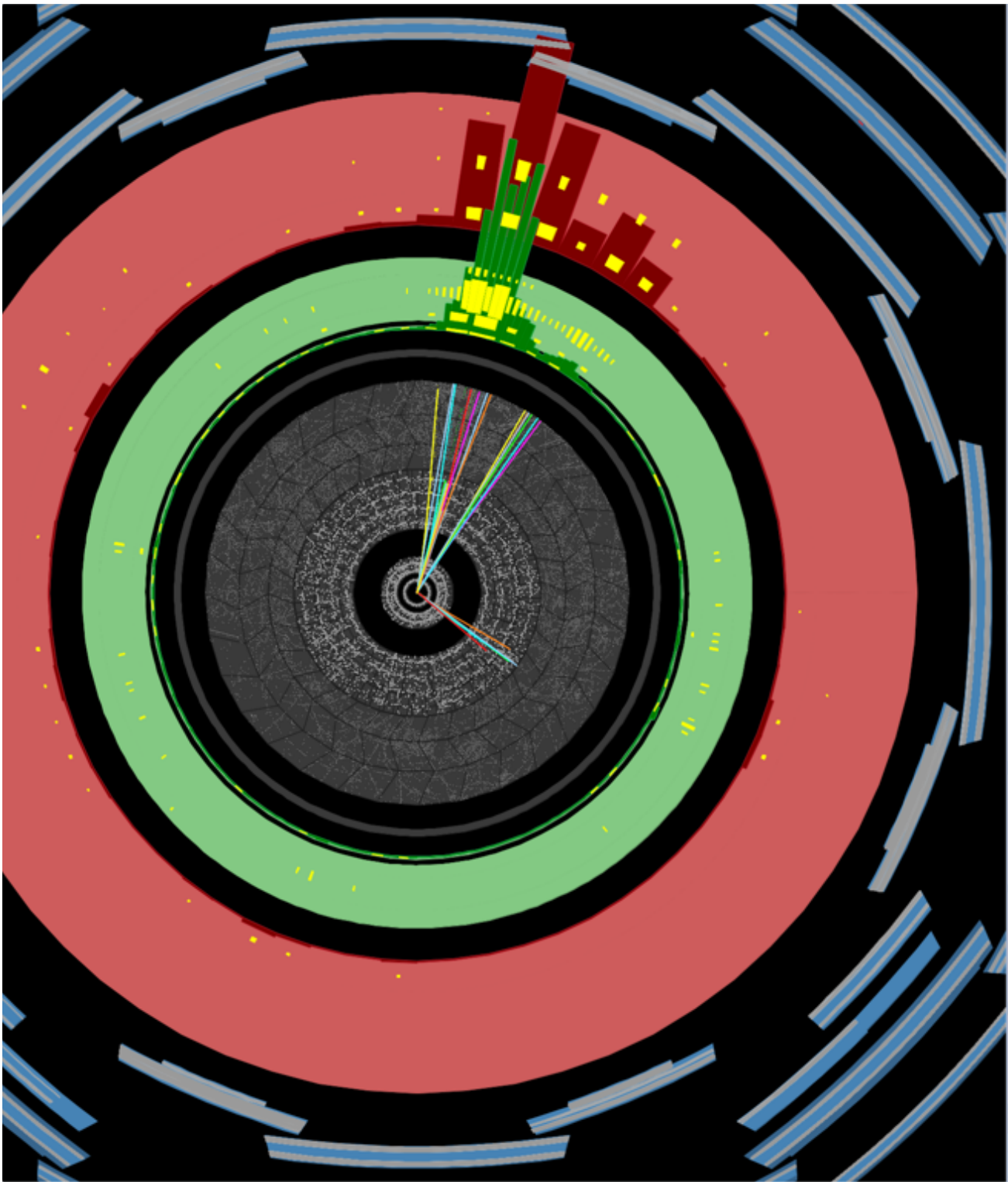
- Pair-produced Dark Matter or Extra Dimensions
 - Search for missing energy and radiated jet
 - Similar searches in monophoton and other channels



- Monojet Selection for CMS (similar for ATLAS):
 - Leading jet $p_T > \sim 120$ GeV
 - topological cuts to reduce QCD, e.g. $\Delta\phi(j_1, j_2) < 2.5$
 - veto events with isolated leptons
- Backgrounds from Data-Driven and MC
 - Measure Z + jets \rightarrow predict Z($\nu\nu$) + jets
 - Measure W + jets \rightarrow predict W(lv) + jets
 - smaller backgrounds from top, QCD, non-collision
- Best limits with $E_T^{\text{miss}} > 350\text{--}400$ GeV

[ATLAS-CONF-12-147, CMS EXO-12-048]

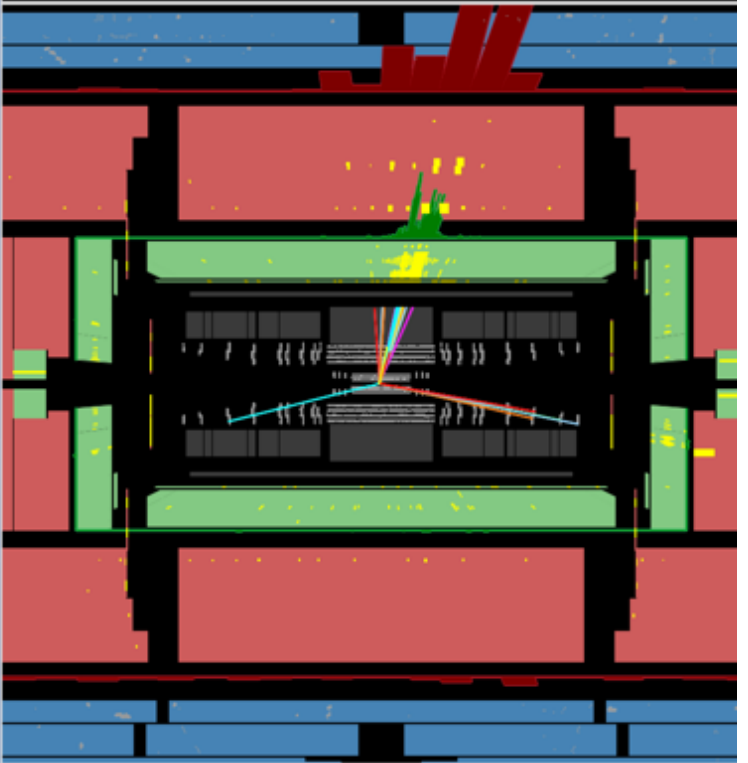




ATLAS EXPERIMENT

Run Number: 206962, Event Number: 55091300

Date: 2012-07-14 10:42:26 CEST



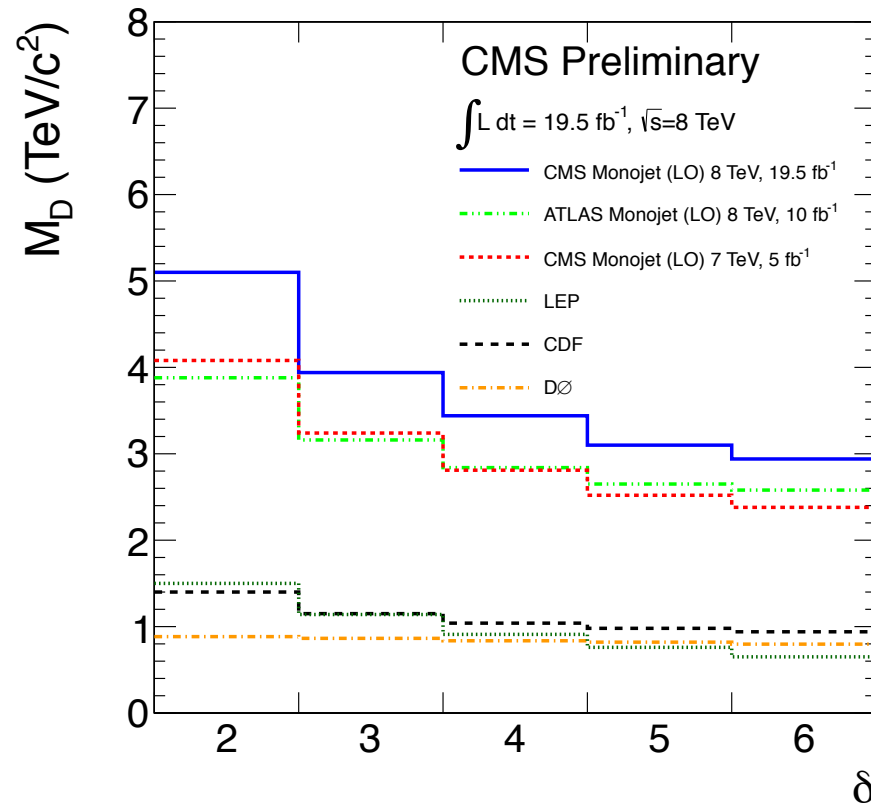
LARGE EXTRA DIMENSIONS FROM MONOJET

[ATLAS-CONF-12-147, CMS EXO-12-048]

Large Extra Dimensions: Arkani-Hamed, Dimopoulos, Dvali (ADD)

$$M_{Pl}^2 \sim M_D^{2+n} R^n$$

M_{Pl} = 4-dimensional Planck scale
 M_D = fundamental (4+n)-dimensional Planck scale
 n = number of the extra dimensions
 R = size of the extra dimensions

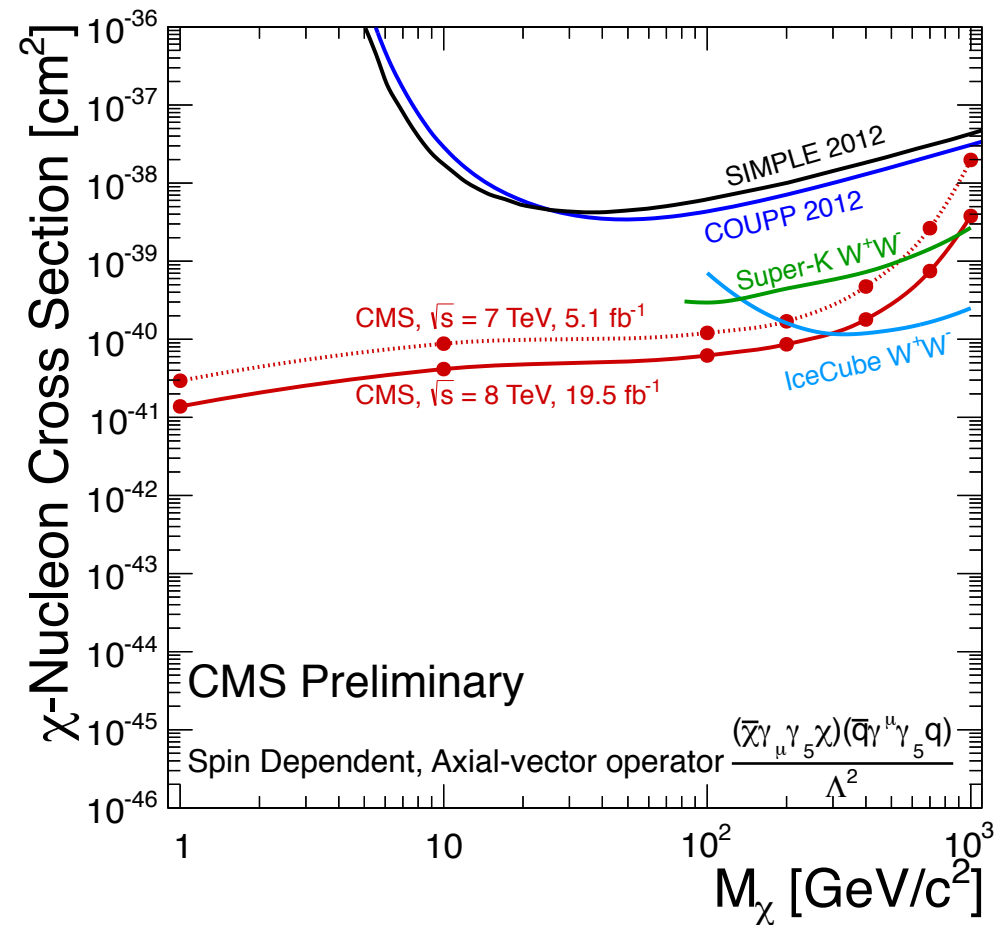
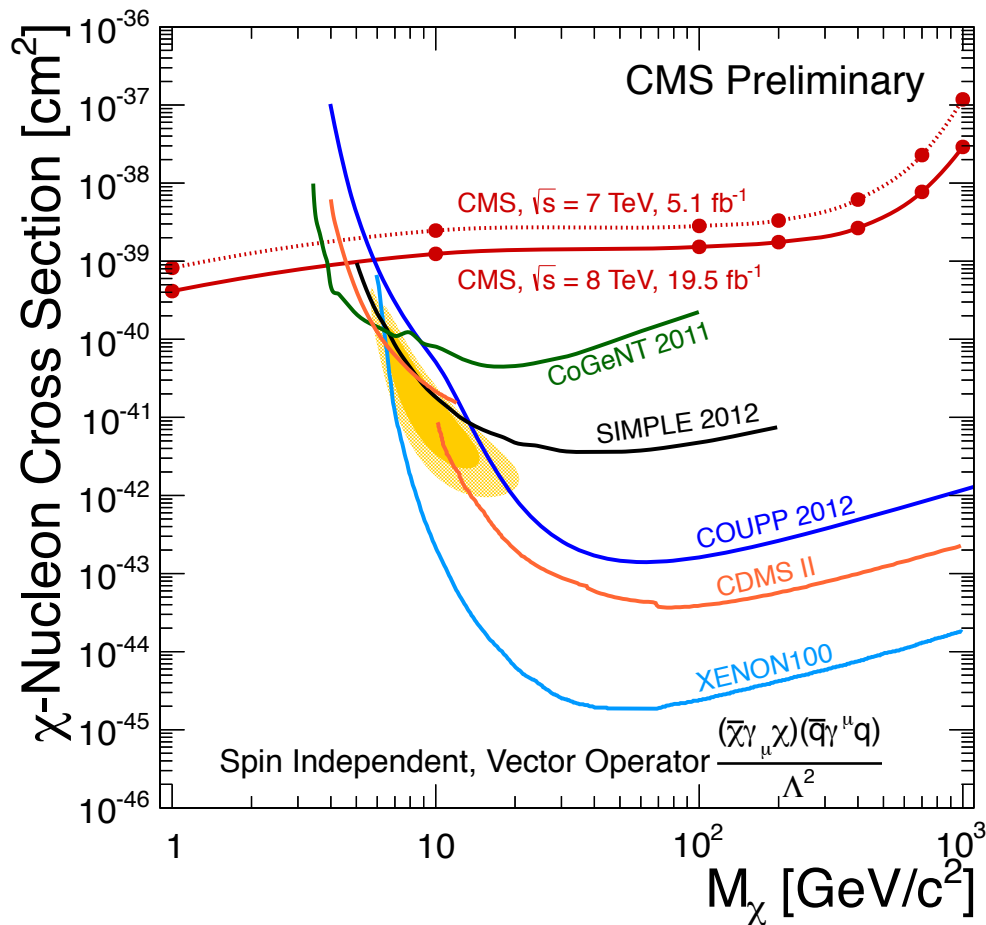


M_D (ADD) at LO 95% CL limits	\sqrt{s} [TeV]	Lumi [fb ⁻¹]	$\delta=3$ Exp.	$\delta=3$ Obs.	$\delta=6$ Exp.	$\delta=6$ Obs.
ATLAS Monojet	8	10.5	3.39	3.16	2.69	2.58
CMS Monojet	8	19.5	3.94	3.96	2.95	2.94

DARK MATTER AND MONOJETS

[CMS EXO-12-048]

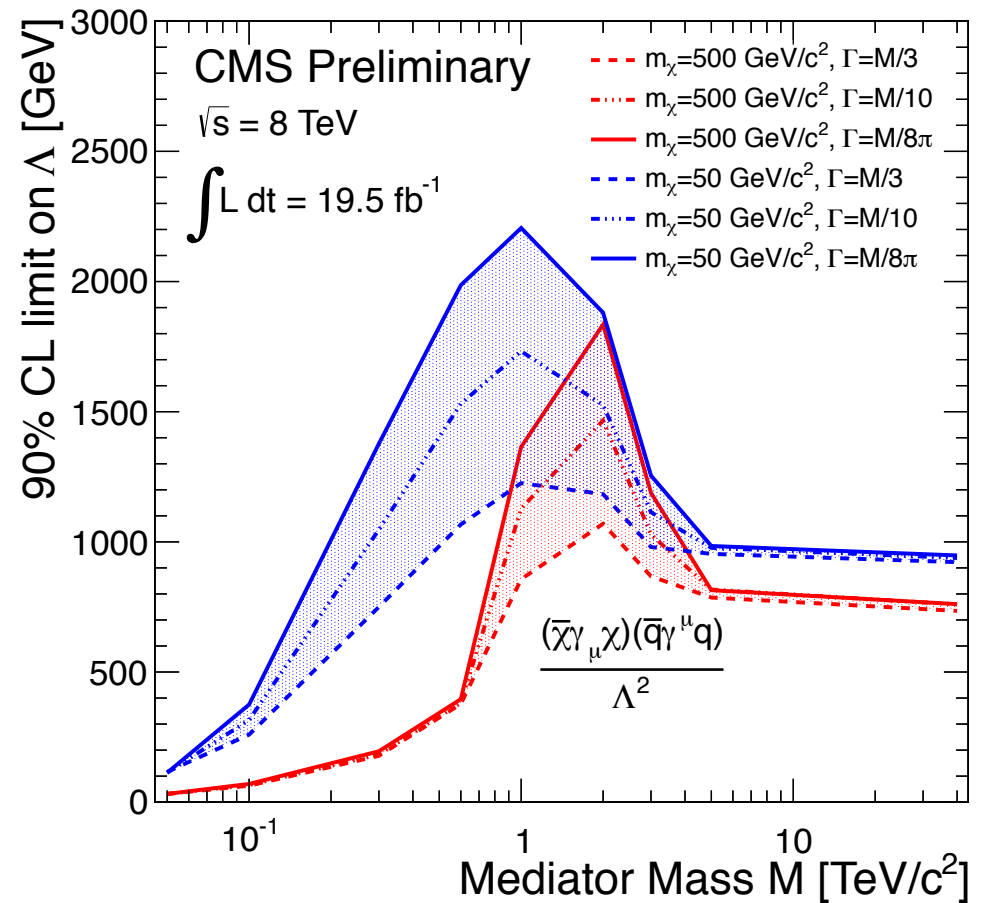
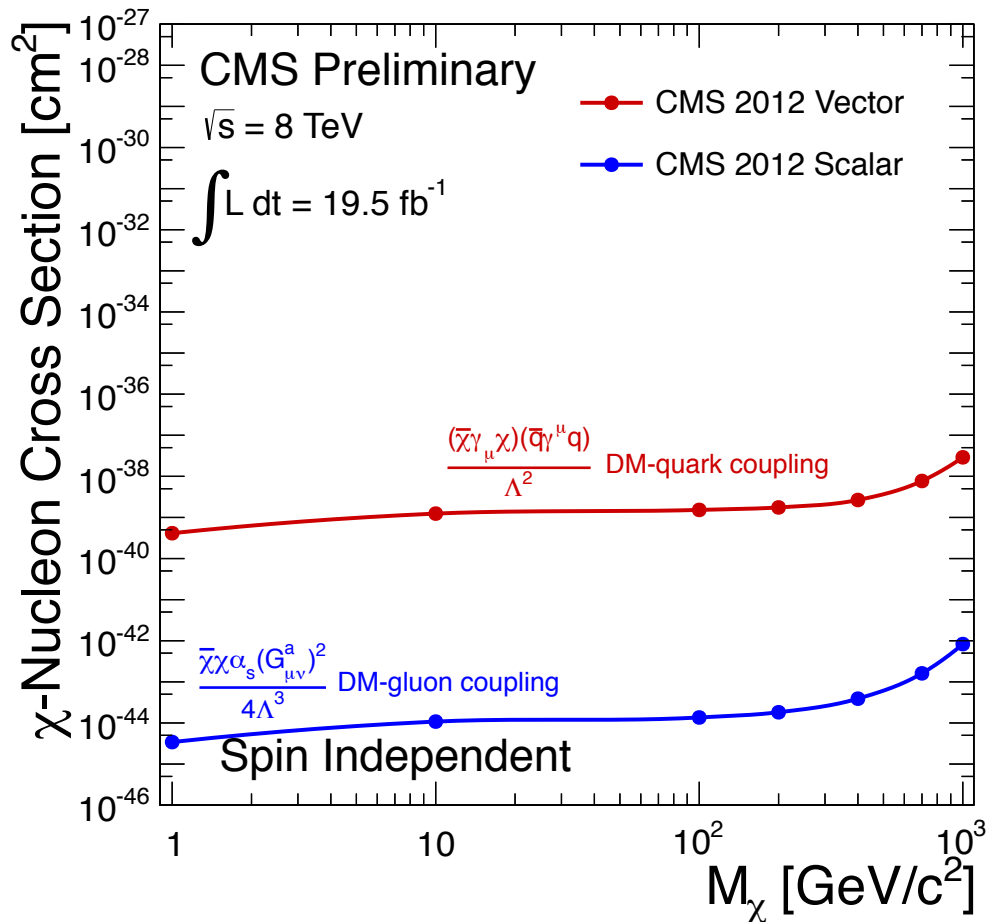
- Pair-production of DM (χ) characterized by a contact interaction effective theory
- Derived limits then compared to direct-detection experiments
- ATLAS & CMS results similar for 7 TeV data, improved with 8 TeV



DARK MATTER AND MONOJETS

[CMS EXO-12-048]

- Starting to extend simple contact interaction scenario with new operators and a scan over mediator mass



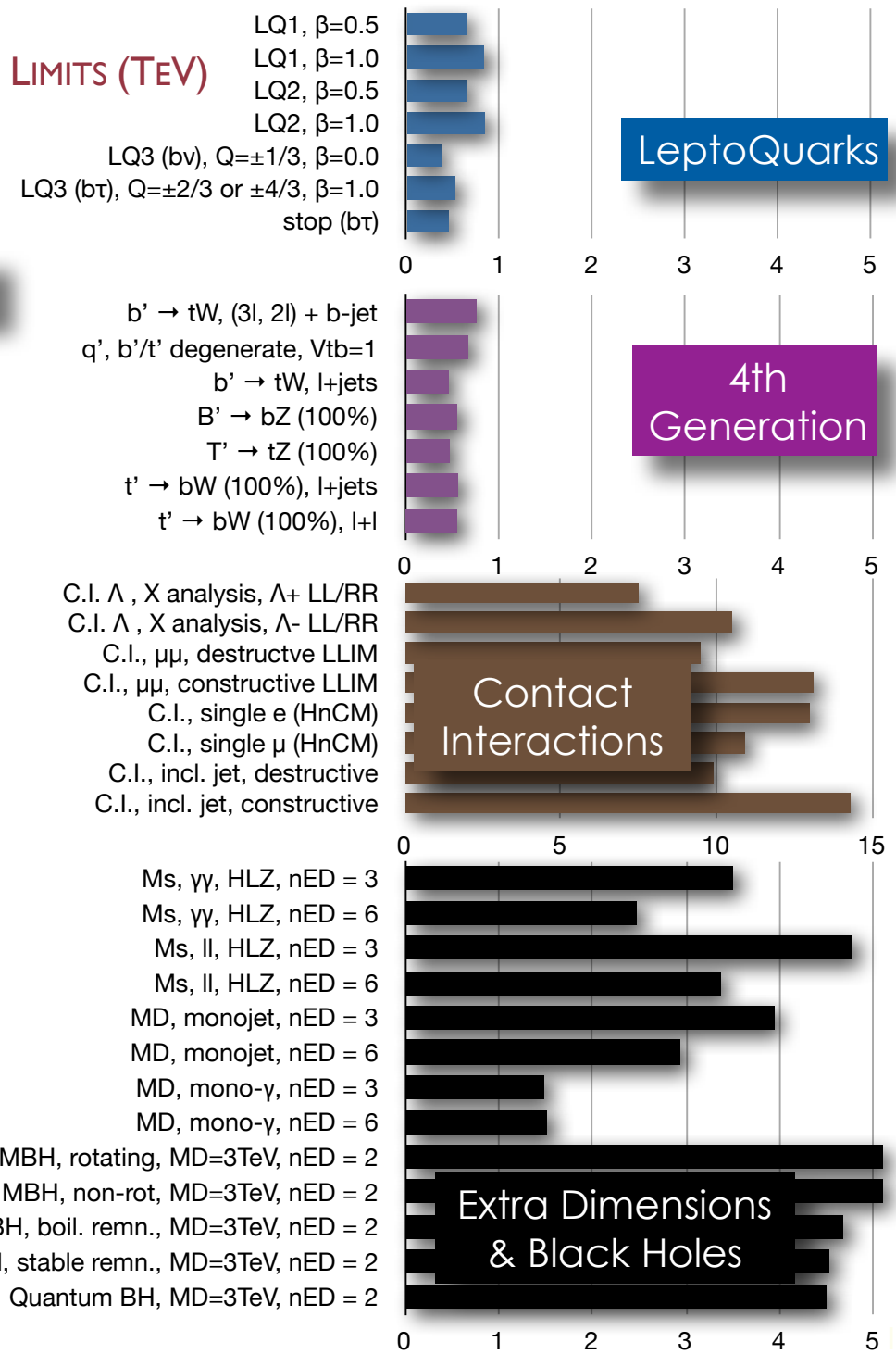
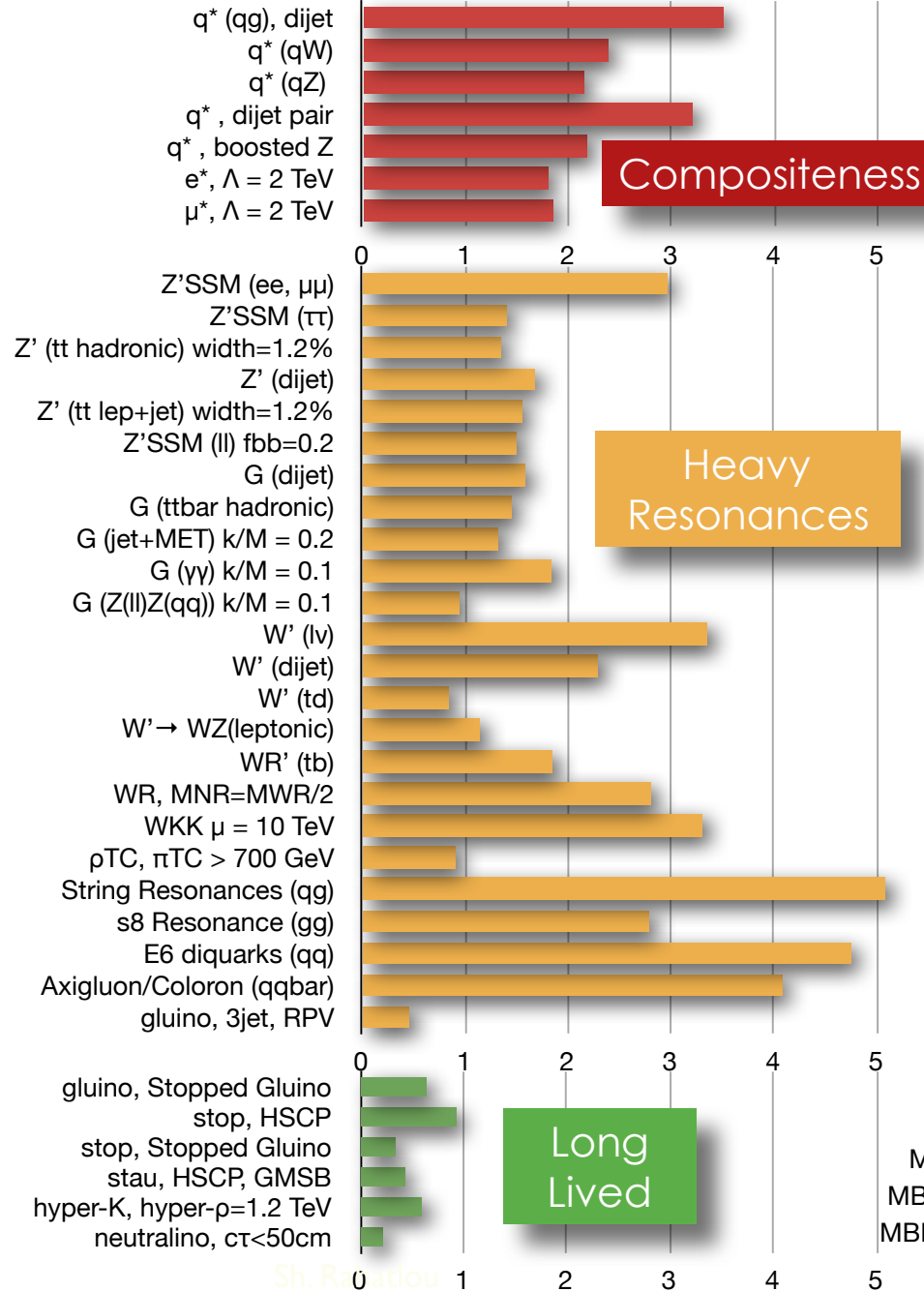
CONCLUSIONS

- CMS and ATLAS have very active programmes searching for hints of new physics
- New results presented today:
 - High-mass dilepton resonance (Z') [ATLAS-CONF-2013-017, CMS EXO-12-061]
 - Large Extra Dimensions in $\mu\mu$ and ee [CMS EXO-12-027, CMS EXO-12-031]
 - $W' \rightarrow tb$ [ATLAS-CONF-2013-050,]
 - Dijet resonances [ATLAS-CONF-2012-148, CMS EXO-12-059]
 - Dijet with b-tag or W/Z tag [CMS EXO-12-023, CMS EXO-11-095]
 - $t\bar{t}$ resonance [ATLAS-CONF-2013-052, CMS B2G-12-006]
 - Monojet Dark Matter, Extra Dimensions [ATLAS-CONF-2012-147, CMS EXO-12-048]
- More than 100 more results available on the web:
 - <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>
 - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO> & B2G

*More results on the way
– leaving no stone unturned!*

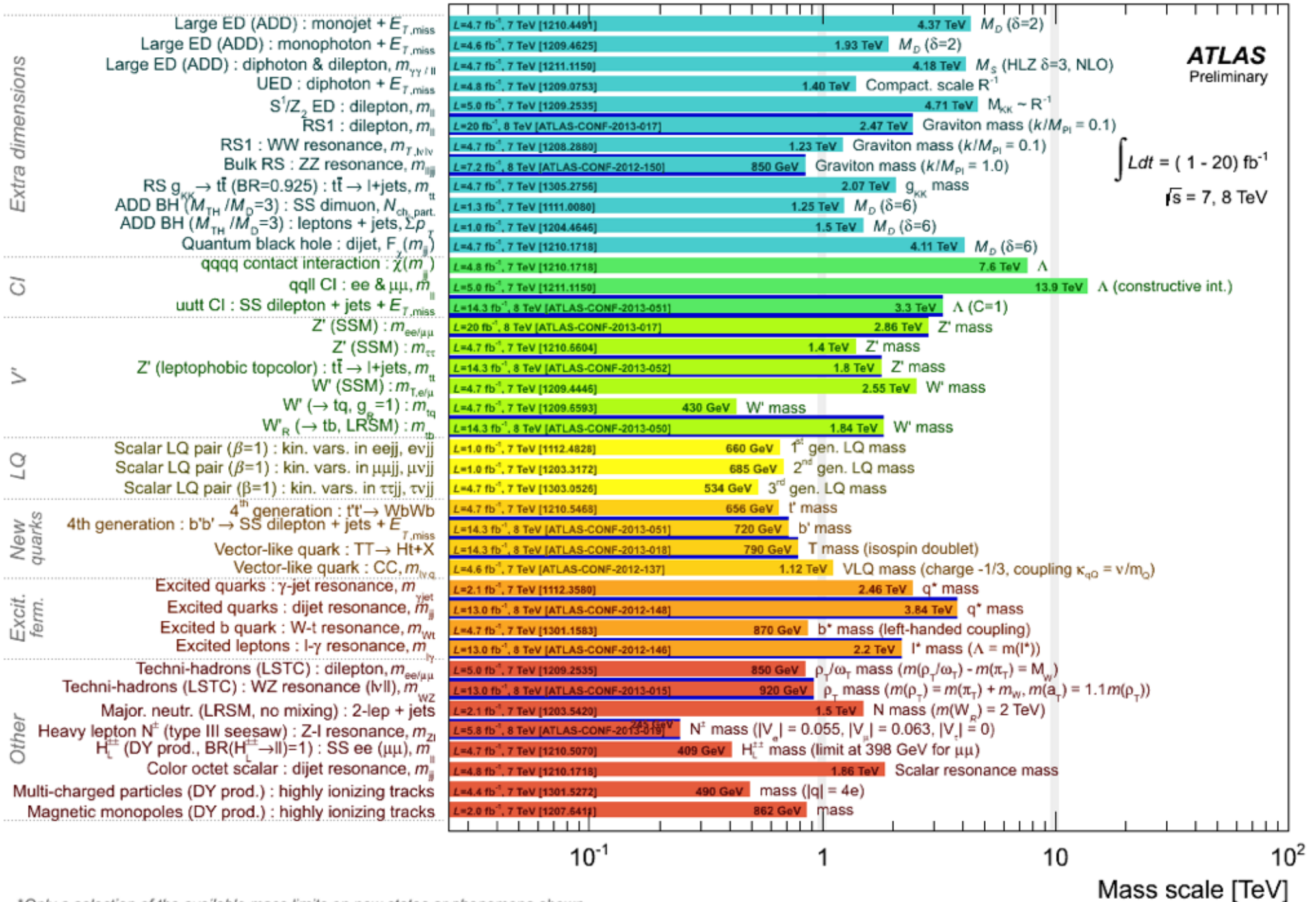


CMS EXOTICA 95% CL EXCLUSION LIMITS (TeV)



ATLAS Exotics Searches* - 95% CL Lower Limits (Status: May 2013)

ATLAS
Preliminary



$\int Ldt = (1 - 20) \text{ fb}^{-1}$
 $\sqrt{s} = 7, 8 \text{ TeV}$

*Only a selection of the available mass limits on new states or phenomena shown

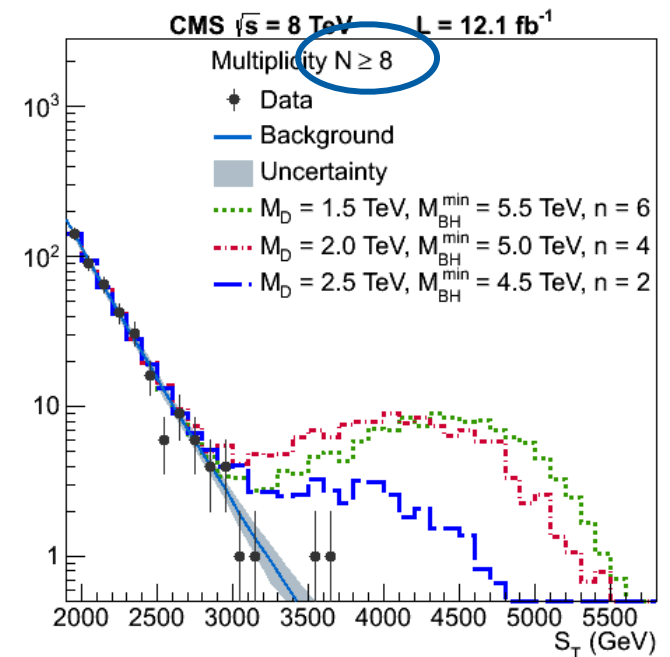
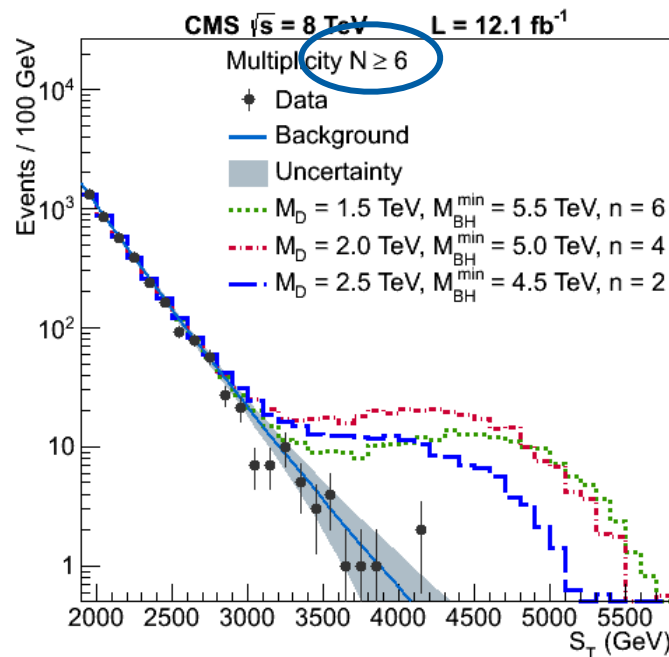
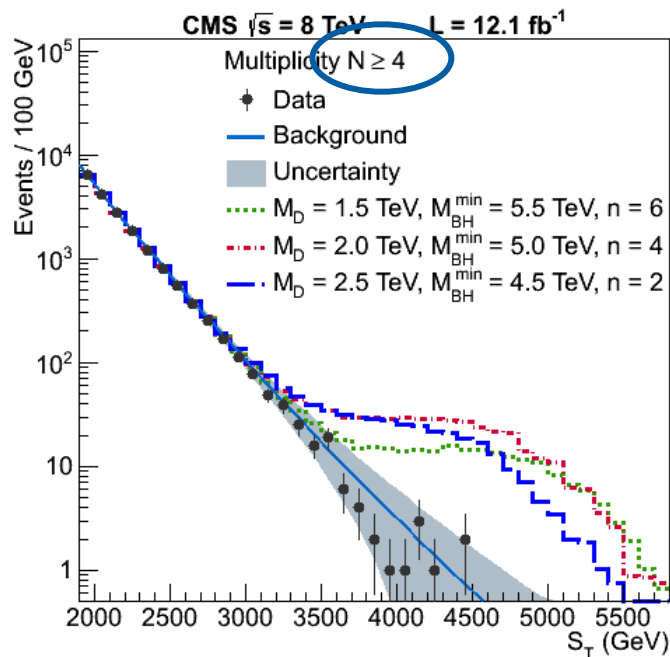
SEARCH FOR BLACK HOLES

[arXiv:1303:5338, EXO-12-009]

- Search for microscopic Black Holes in 12 fb^{-1} of 8 TeV data
 - Hypothetical BH would evaporate into many high- p_T objects
 - Estimate by S_T , the p_T sum of physics objects with $p_T > 50 \text{ GeV}$
- Main background of QCD estimated by fit to $n=2$ distribution
 - Normalised for each multiplicity bin separately at $S_T = 1.8\text{--}2.2 \text{ TeV}$
 - Model-independent limits vs S_T and multiplicity

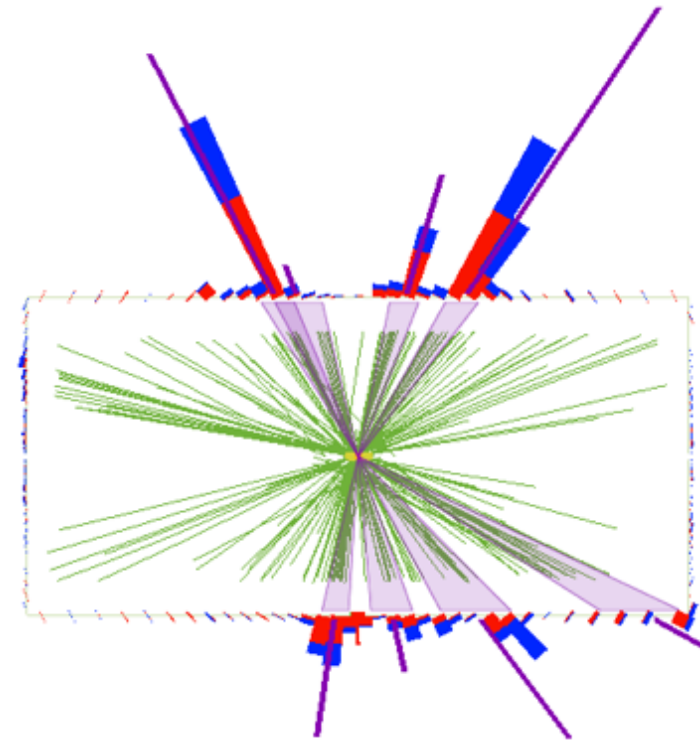
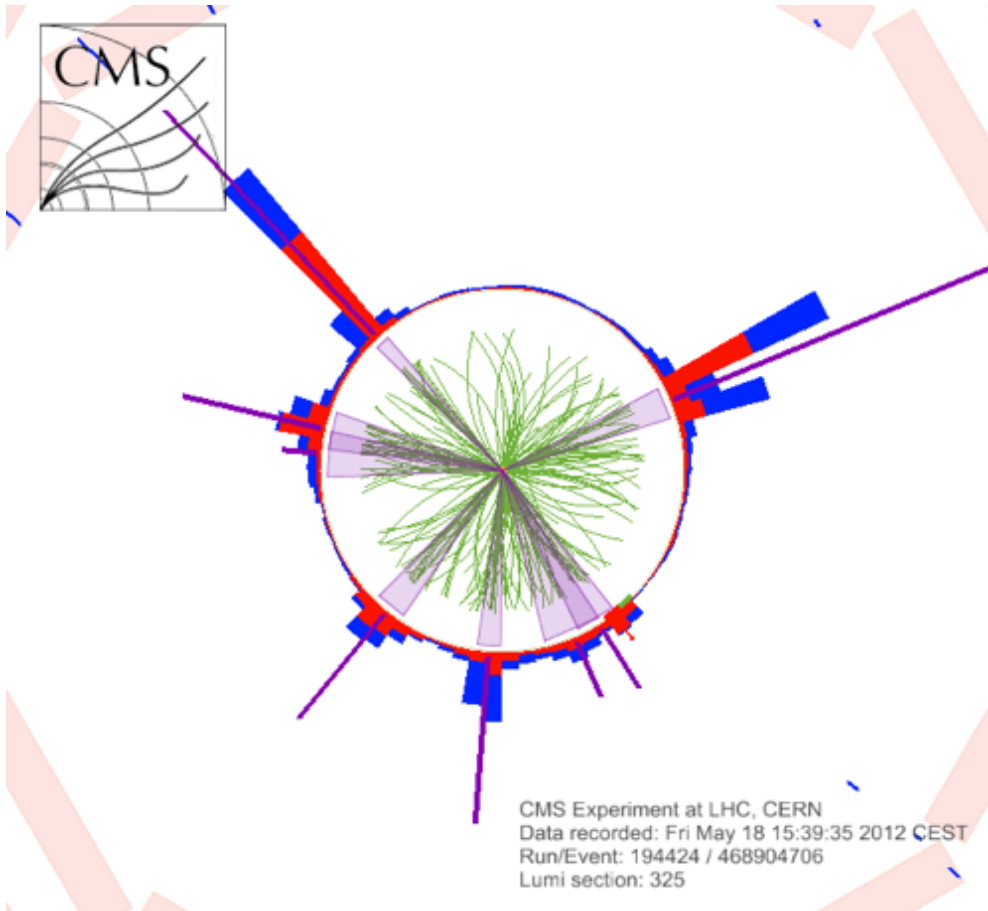
$$S_T = \sum_{j,e,\mu,\gamma,MET}^N p_T$$

Significant improvement in sensitivity ($\sim 15\text{--}20\%$) with respect to 7 TeV data



8-JET EVENT, $S_T = 3$ TEV

[arXiv:1303:5338, EXO-12-009]



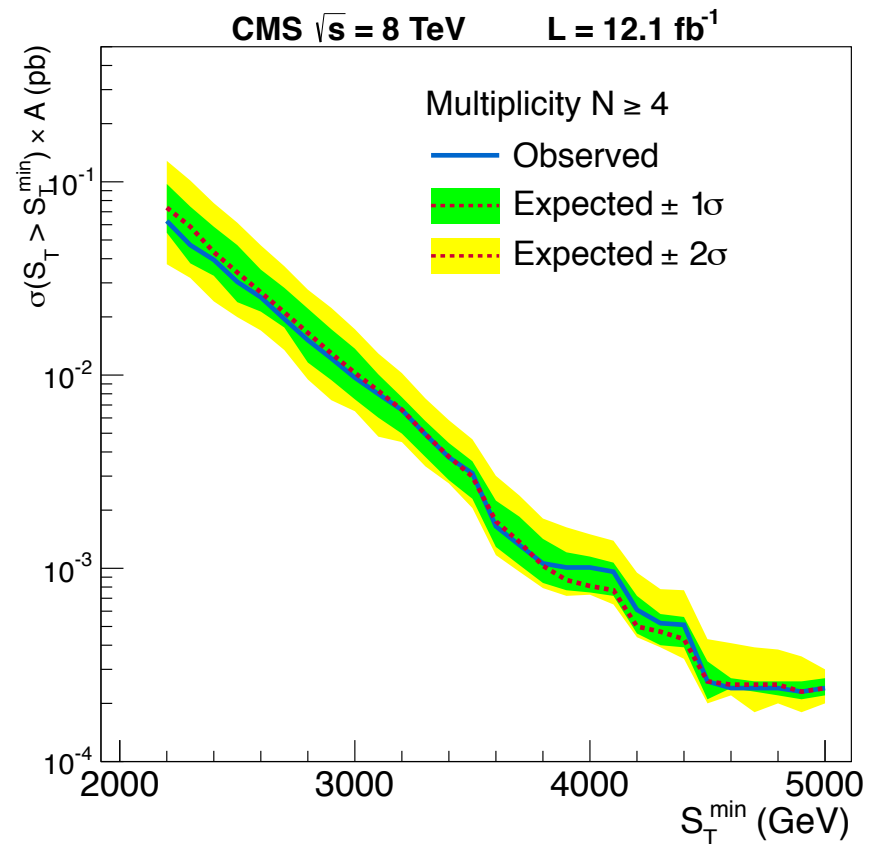
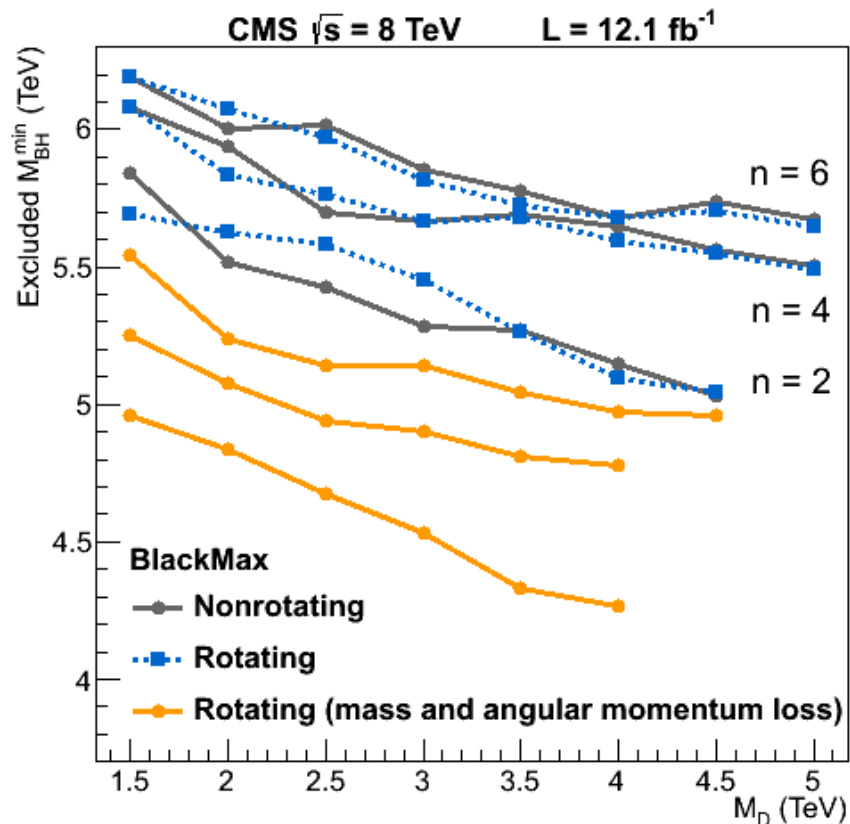
Many interesting events found!

SEARCH FOR BLACK HOLES

[arXiv:1303:5338, EXO-12-009]

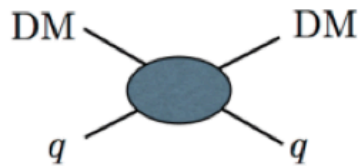
- No excess of events above expected backgrounds observed
 - Limits on ADD parameter M_D assuming specific BH models (Charybdis, BlackMax, ...)
 - Model-specific limits on semiclassical BH masses in the 4.3 – 6.2 TeV range

Also interesting as a model-independent search vs S_T and multiplicity

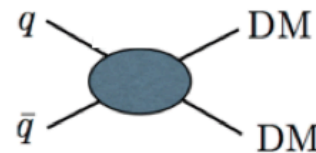


PRODUCTION OF DARK MATTER AT CMS

- Search for evidence of pair-production of Dark Matter particles (χ)

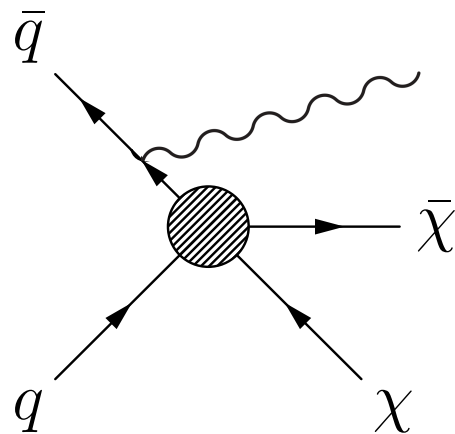


Direct Detection (t-channel)

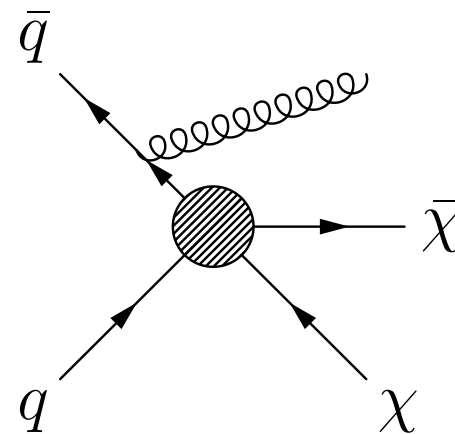


Collider Searches (s-channel)

- Dark Matter production gives missing transverse energy (MET)
- Photons (or jets from a gluon) can be radiated from quarks, giving monophoton (or monojet) plus MET



Monophoton + MET



Monojet + MET

PHENOMENOLOGY

- Pair-production of χ can be characterised by a contact interaction with operators

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2} \quad \text{vector} \rightarrow \text{spin independent (SI)}$$

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5q)}{\Lambda^2} \quad \text{axial-vector} \rightarrow \text{spin-dependent (SD)}$$

- Cross section depends on the mass (m_χ) and the scale Λ (for couplings g_χ, g_q)

$$\sigma_{SI} = 9 \frac{\mu^2}{\pi\Lambda^4}$$
$$\sigma_{SD} = 0.33 \frac{\mu^2}{\pi\Lambda^4}$$

*spin-independent
and spin-dependent
cross sections*

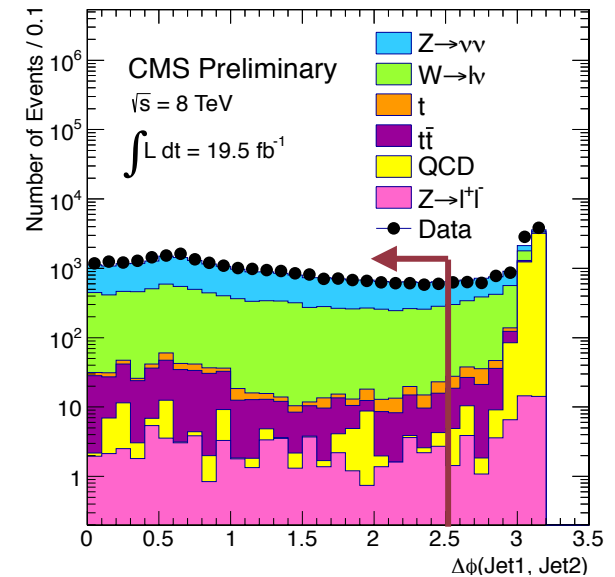
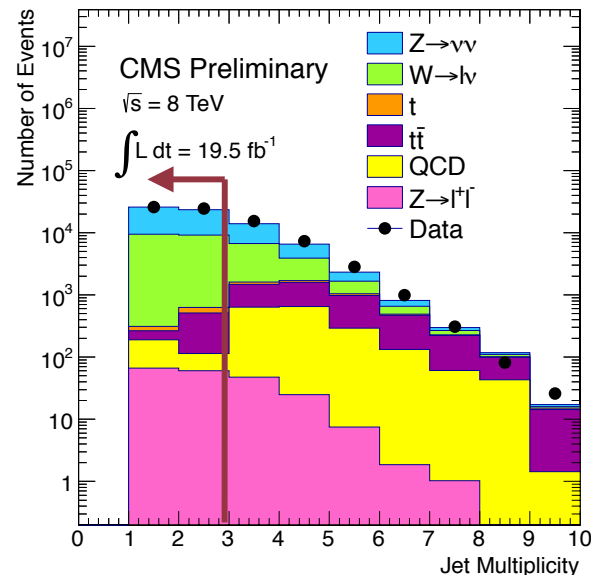
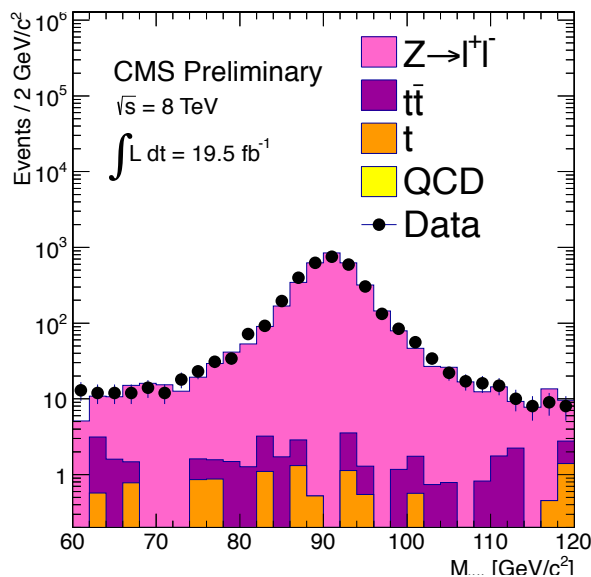
$$\Lambda = M/\sqrt{g_\chi g_q} \quad \mu = \frac{m_\chi m_p}{m_\chi + m_p}$$

[Bai, Fox and Harnik, JHEP 1012:048 (2010)]

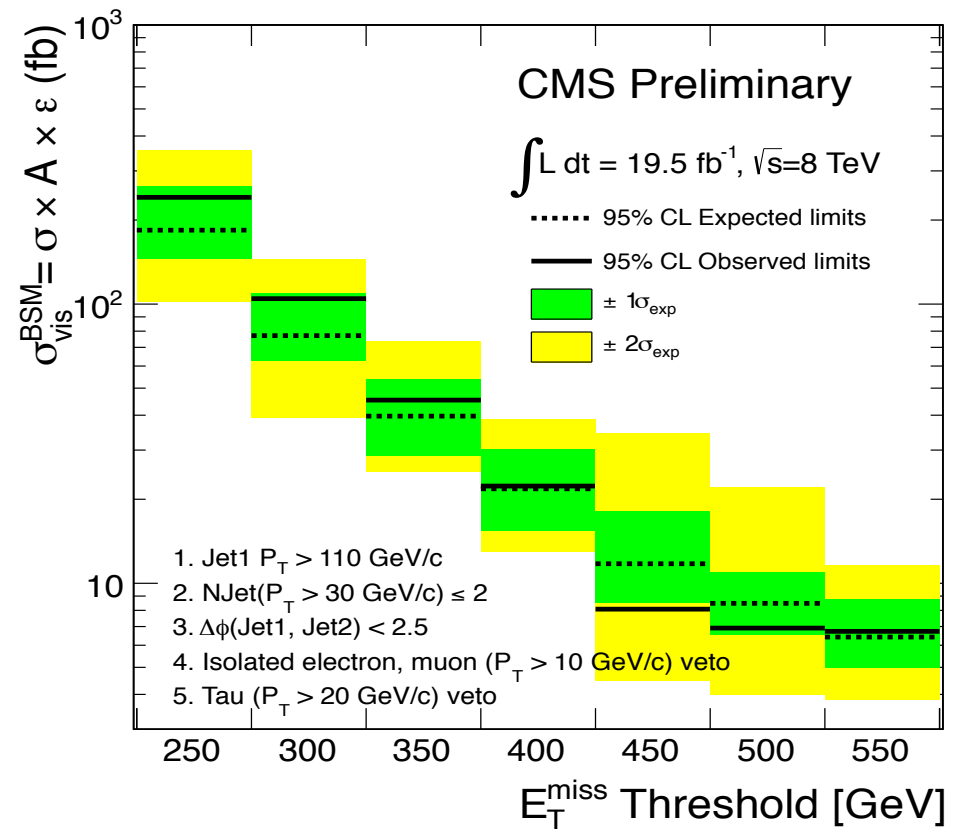
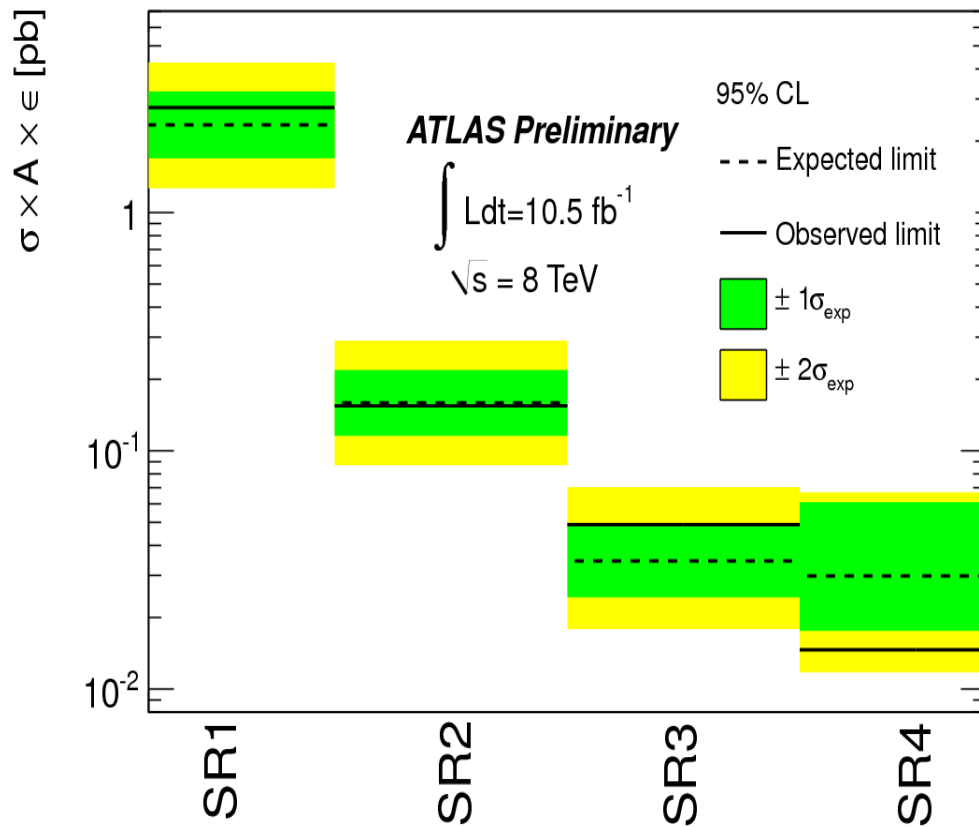
[Goodman, Ibe, Rajaraman, Shepherd, Tait, Yu, Phys.Rev.D82:116010 (2010)]

MONOJET SELECTION AND BACKGROUNDS

- Data-driven Background Estimation (Lepton Identification)
 - Require isolated muon > 20 GeV/c; select 1 and 2 muon events
 - Obtain Z+jet sample from $M(\mu\mu)$, W+jet sample from $p_T(\mu)+MET$
- Basic topological selection
 - Reject events with isolated leptons
 - MET > 250 GeV, # of Jets = 1 or 2
 - Leading Jet: $p_T > 110$ GeV, $|\eta| < 2.4$
 - Second Jet: $p_T > 30$ GeV
 - $\Delta\phi(\text{jet1}, \text{jet2}) < 2.5$



MONOJET MODEL-INDEPENDENT LIMITS



Z' IN 2011 DATA?

- Many new models have Z-like narrow resonances decaying to dileptons
- Interesting features in dilepton spectra
 - around 2σ each for CMS & ATLAS in $e\mu$
 - similar in scale to 2011 Higgs excess

Worth watching in 2012's 8 TeV data...

