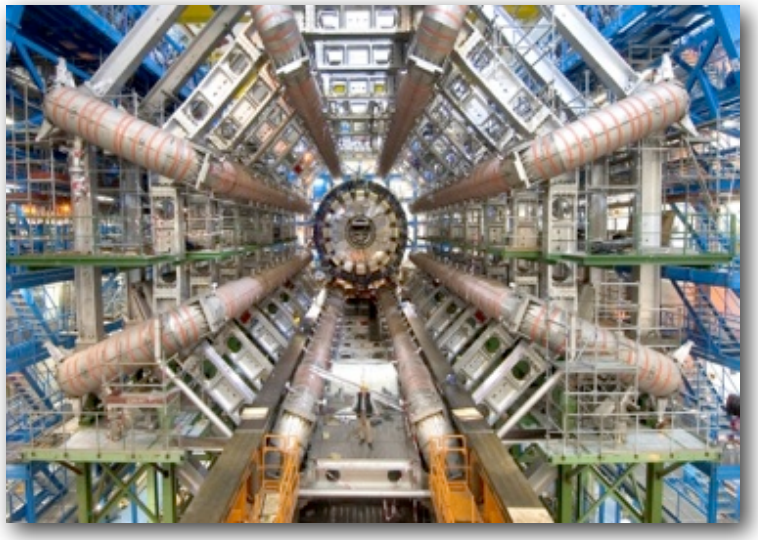
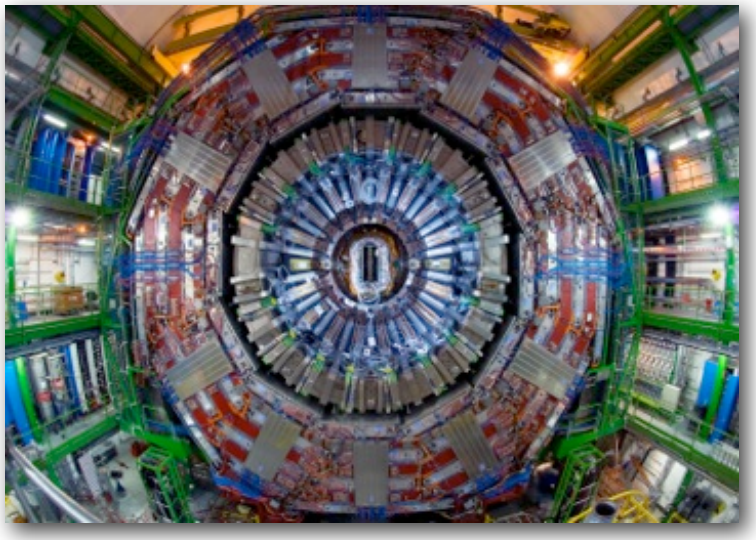
Searches for Physics Beyond the Standard Model





Steven Worm

UK HEP Forum

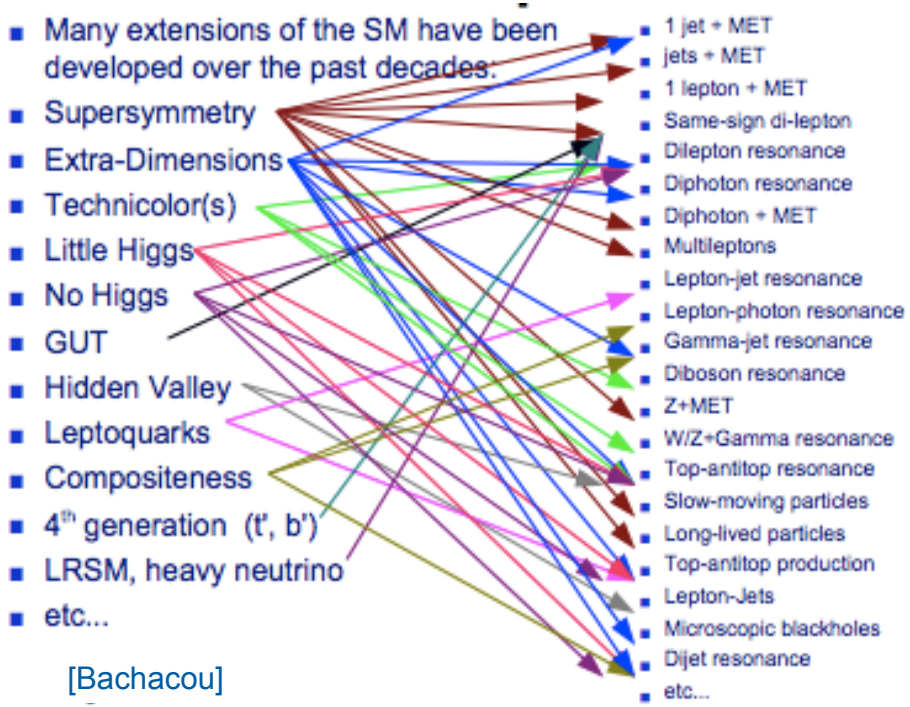
23 November 2012

CERN

Science & Technology Facilities Council
Rutherford Appleton Laboratory

BSM AND EXOTICA: WHAT IS "EXOTIC"?

- Comprehensive search of the landscape of √s = 8 TeV proton collisions
  - Unlike Higgs, no "EXO-Hunters Guide" to show you 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



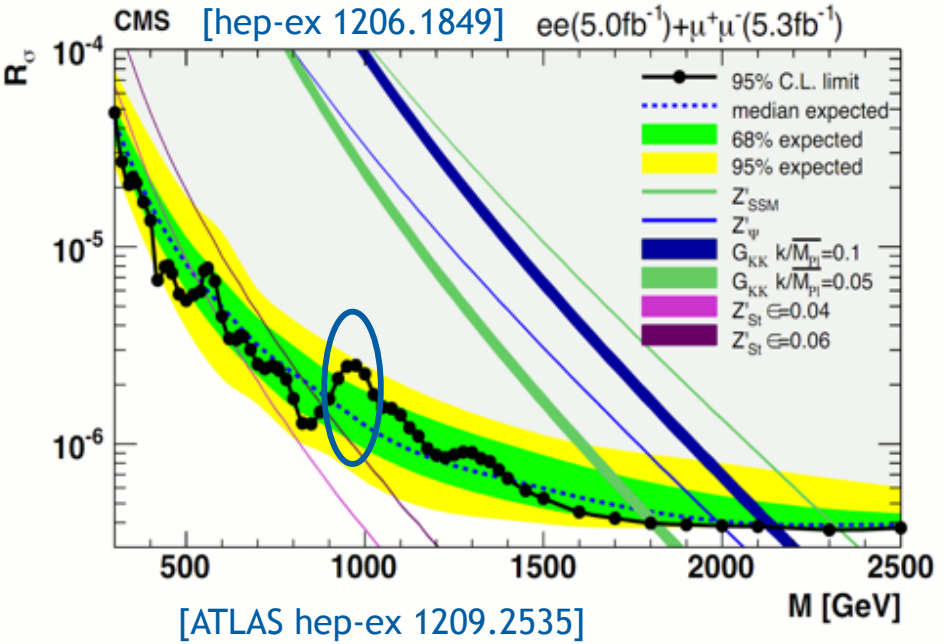
[Bachacou]

[Murayama]

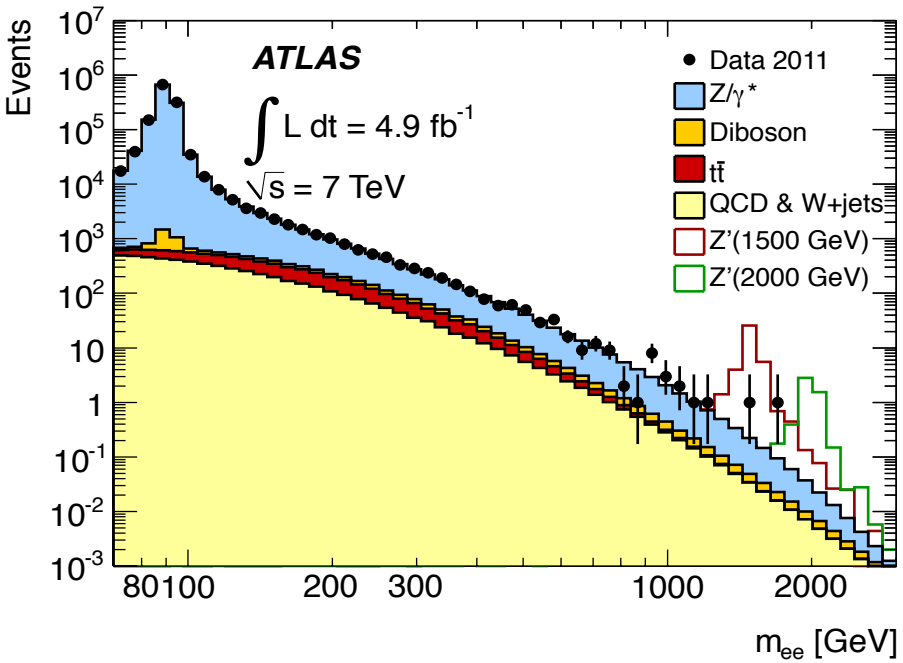
Z' IN 2011 DATA?

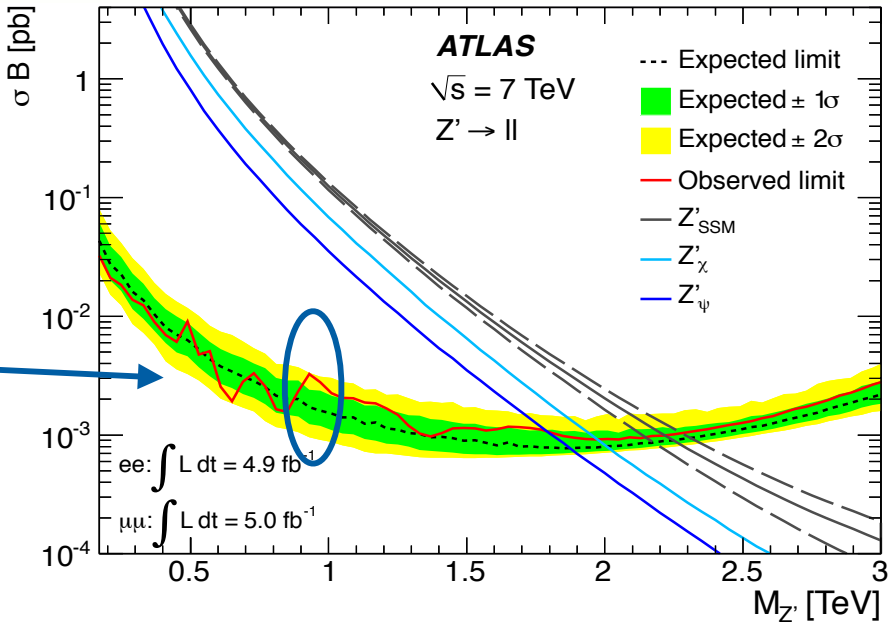
- Many new models have Z-like narrow resonances decaying to dileptons
- Interesting features in dilepton spectra
  - around 2σ each for CMS & ATLAS in e+μ
  - similar in scale to 2011 Higgs excess

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



[ATLAS hep-ex 1209.2535]



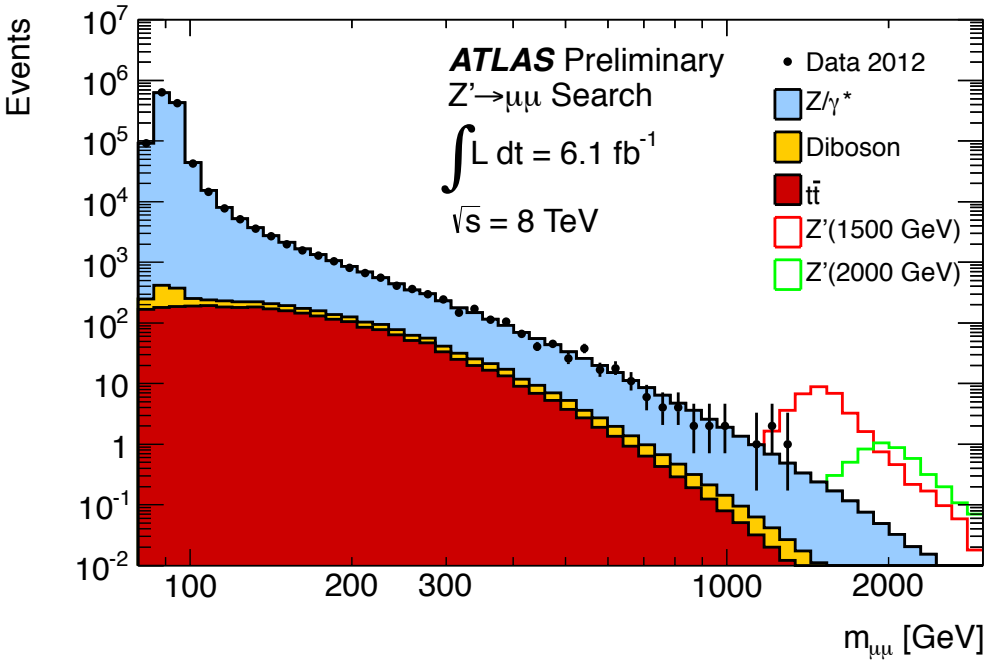


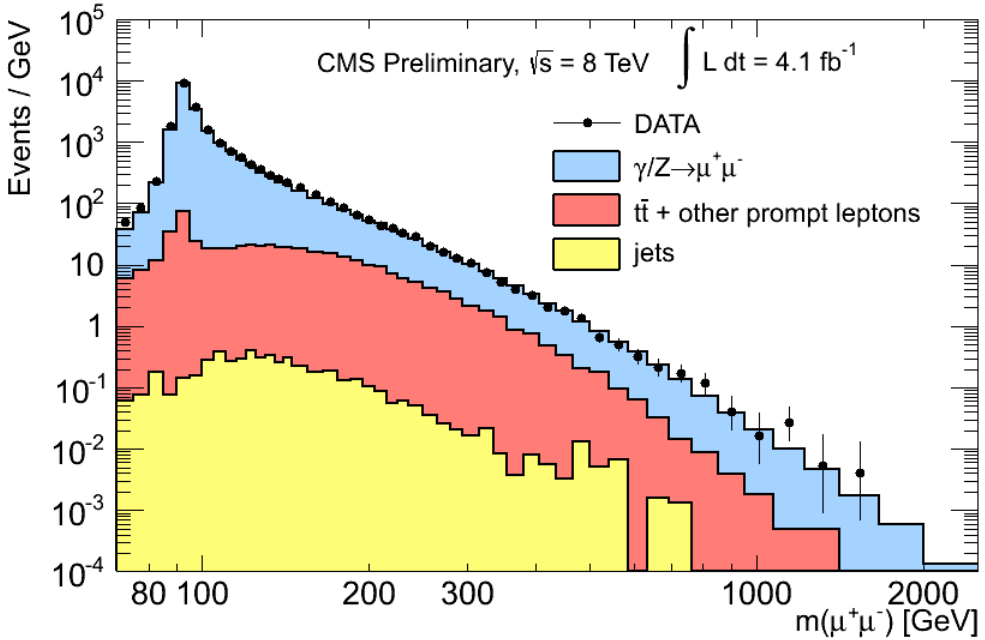
STATUS TODAY: Z' IN 8 TEV DATA

[ATLAS-CONF-2012-129, CMS EXO-12-015]

- Event selection
  - CMS: E_T (e1,e2) > 35 GeV, p_T (μ1,μ2) > 45 GeV, plus isolation criteria
  - ATLAS: E_T (e1,e2) > 35, 25 GeV, p_T (μ1,μ2) > 25 GeV, plus isolation criteria
- Backgrounds
  - Z/γ*, tt, tW, VV, Z → ττ, multijets with ≥1 jet reconstructed as lepton
  - estimated by functional fit to data

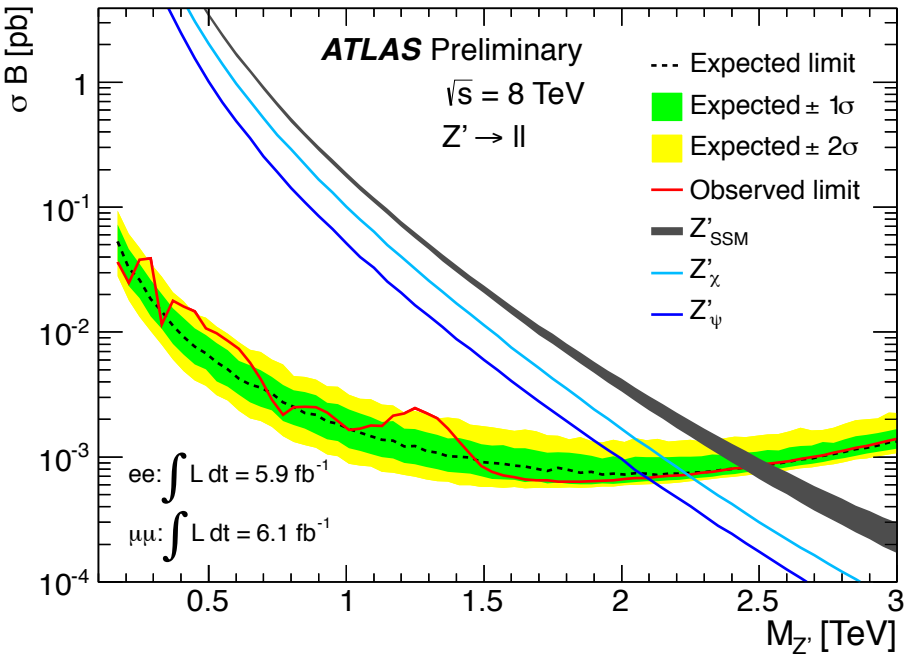
No obvious excess observed in 2012 data

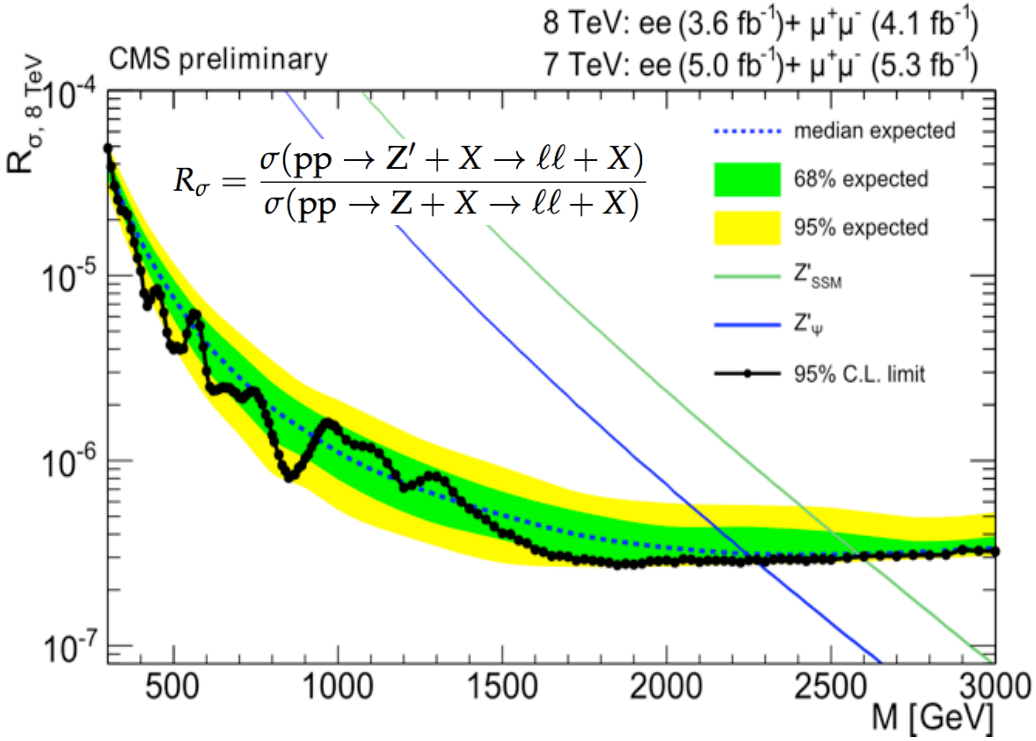




Z' IN 8 TEV DATA

[ATLAS-CONF-2012-129, CMS EXO-12-015]





- Short time between data-taking and result
- CMS limits on the combined 7 + 8 TeV data
  - $M(Z'_{SSM}) > 2590$ GeV at 95% C.L.
  - $M(Z'_{\psi}) > 2260$ GeV at 95% C.L.

$M(Z'_{SSM})$	expected	observed
CMS	> 2.6 TeV	> 2.6 TeV
ATLAS	> 2.5 TeV	> 2.5 TeV

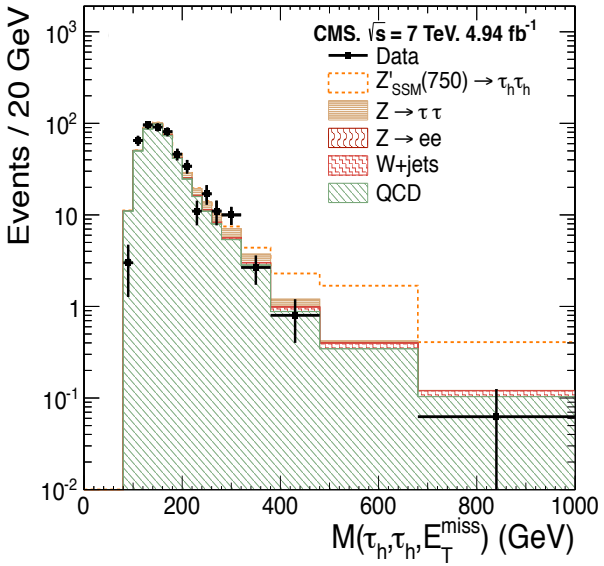
Excess just below 1 TeV all but gone...

Z' → τ τ

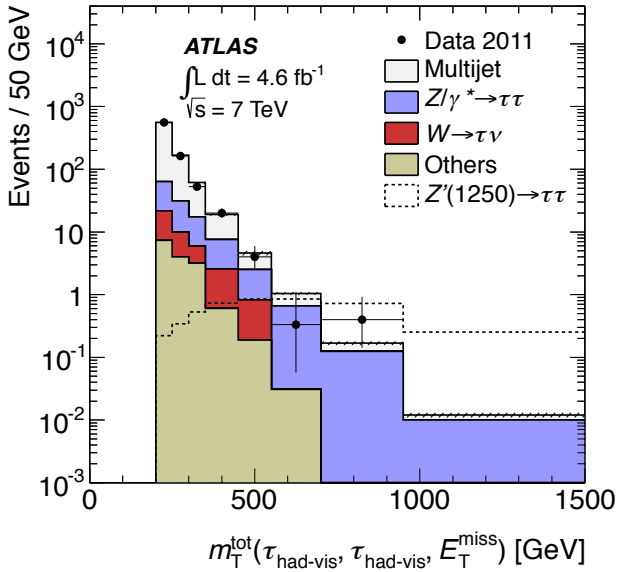
- Z' might couple preferentially to third-generation fermions
  - 5 fb^{-1} at √s = 7 TeV
  - Study: $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$
  - plot effective (visible) mass
- Backgrounds:
  - DY Z → ττ, W+jets, tt, VV, QCD
  - estimated from data where possible

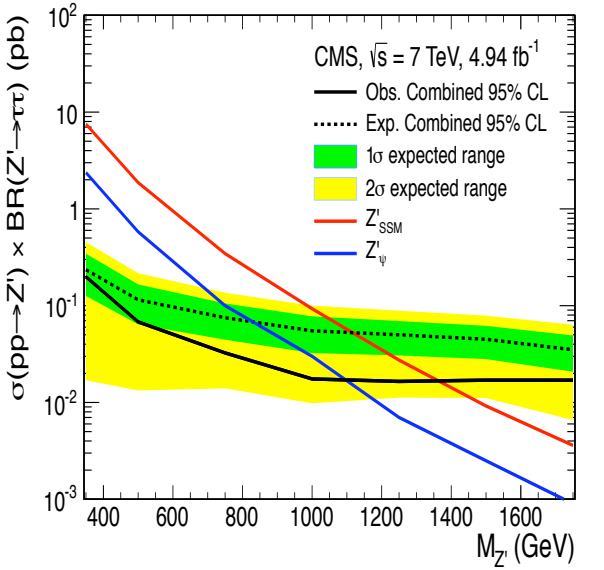
M(Z'$_{SSM}$)	expected	observed
CMS	> 1.1 TeV	> 1.4 TeV
ATLAS	> 1.4 TeV	> 1.4 TeV

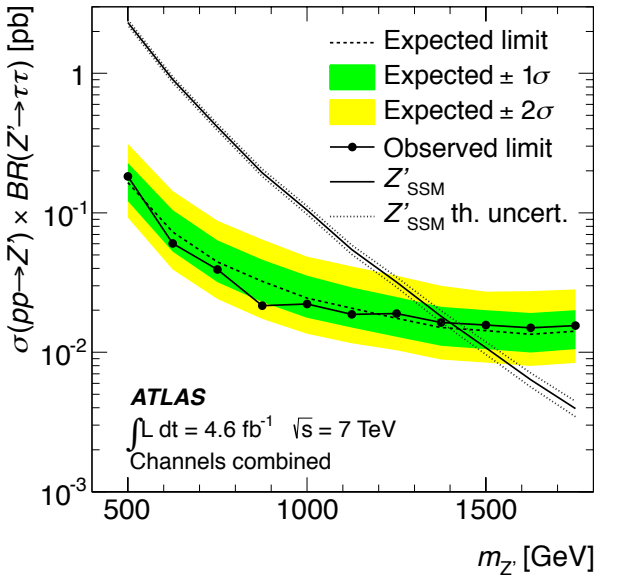
[CMS EXO-11-031, hep-ex 1206.1725]



[ATLAS hep-ex 1210.6604]







W' → lν IN 8 TEV DATA

- Search for a new heavy gauge boson W' decaying to a charged lepton (μ or e) and ν

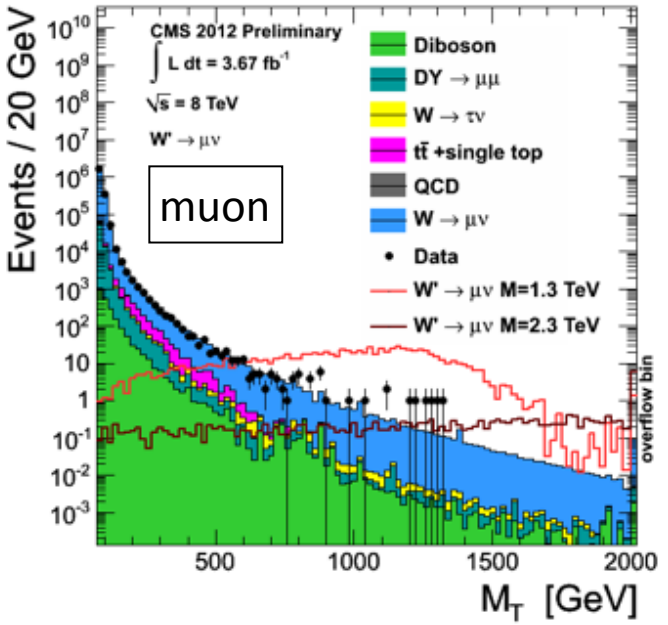
$$M_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

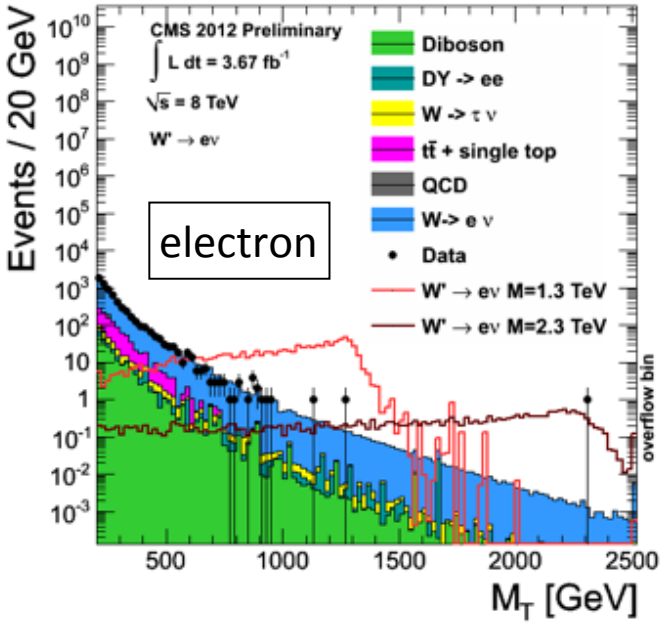
- Many models possible
  - right-handed W' bosons with standard-model couplings
  - left-handed W' bosons including interference
  - Kaluza-Klein W'_{KK}-states in split-UED
  - Excited chiral boson (W*)

- Event Selection and Backgrounds
  - back-to-back isolated lepton and E_T^{miss}
  - Plot transverse mass of lν system
  - backgrounds from W, QCD, tt+single t, DY, VV from data

No significant excess observed

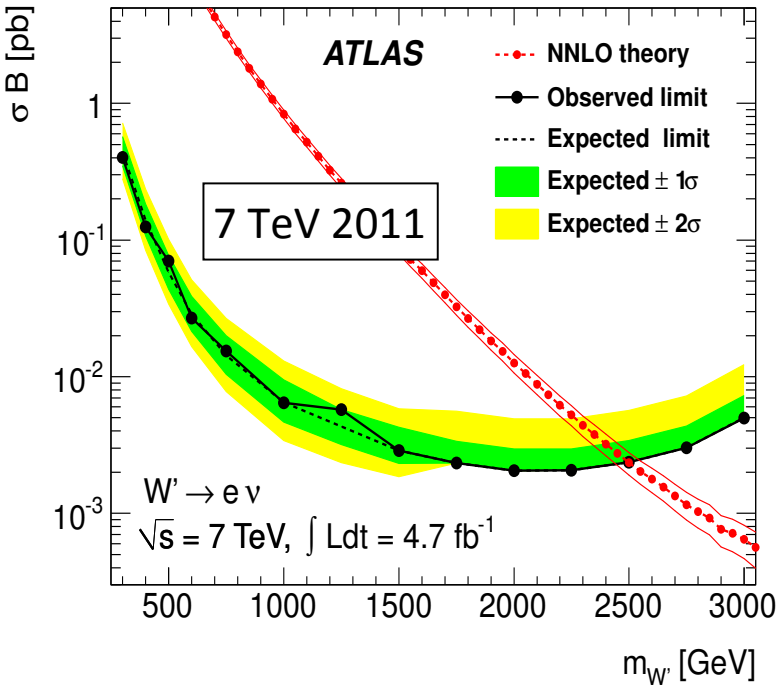
[CMS PAS EXO-12-010]



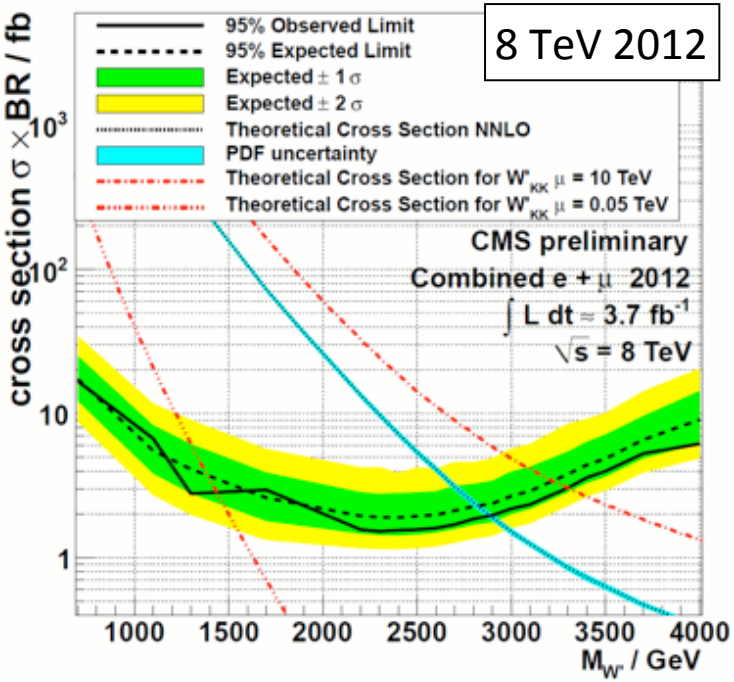


W' → lν IN 7 AND 8 TEV

[ATLAS hep-ex 1209.4446]



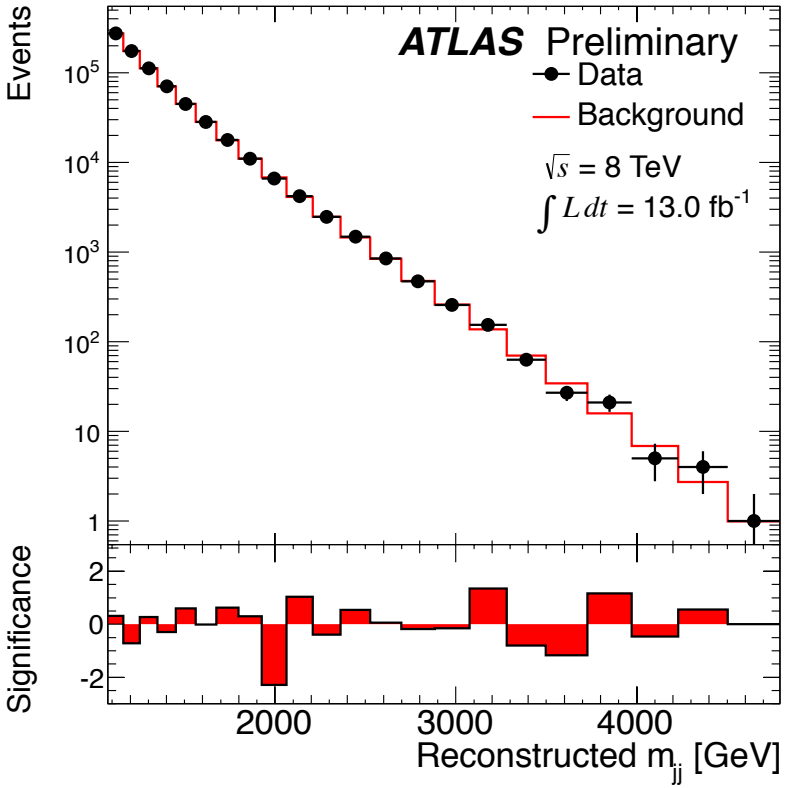
[CMS PAS EXO-12-010]



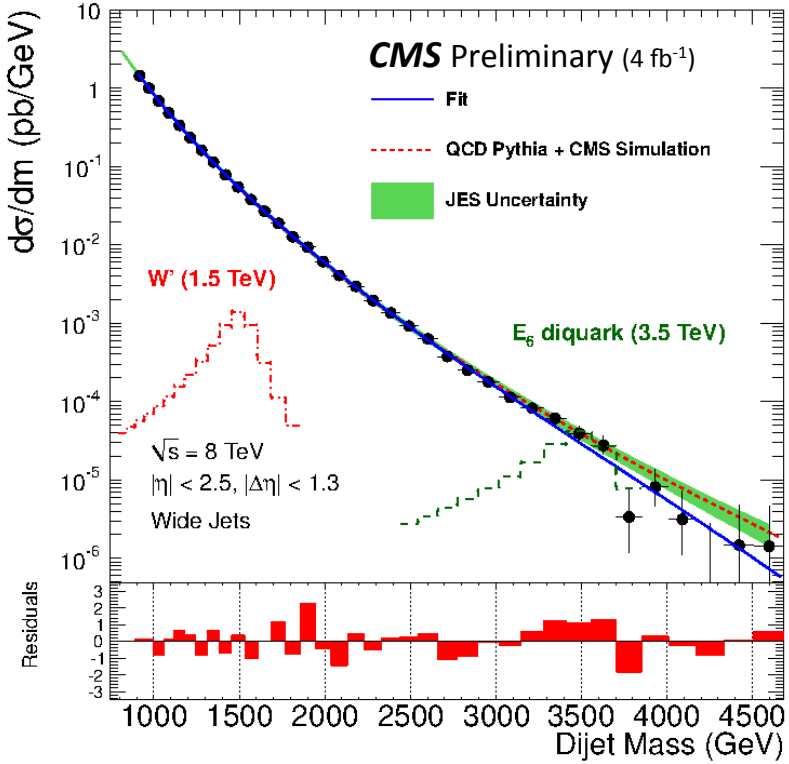
M(W'$_{SSM}$) 95% CL	Luminosity	Expected	Observed
ATLAS e+μ, 2011	4.7	> 2.55 TeV	> 2.55 TeV
CMS e+μ, 2012	3.7	> 2.80 TeV	> 2.85 TeV
CMS e+μ, 2011+2012	5.0 + 3.7	> 2.85 TeV	> 2.85 TeV

DIJETS IN 8 TEV DATA

[ATLAS-CONF-2012-148]



[CMS PAS EXO-12-016]

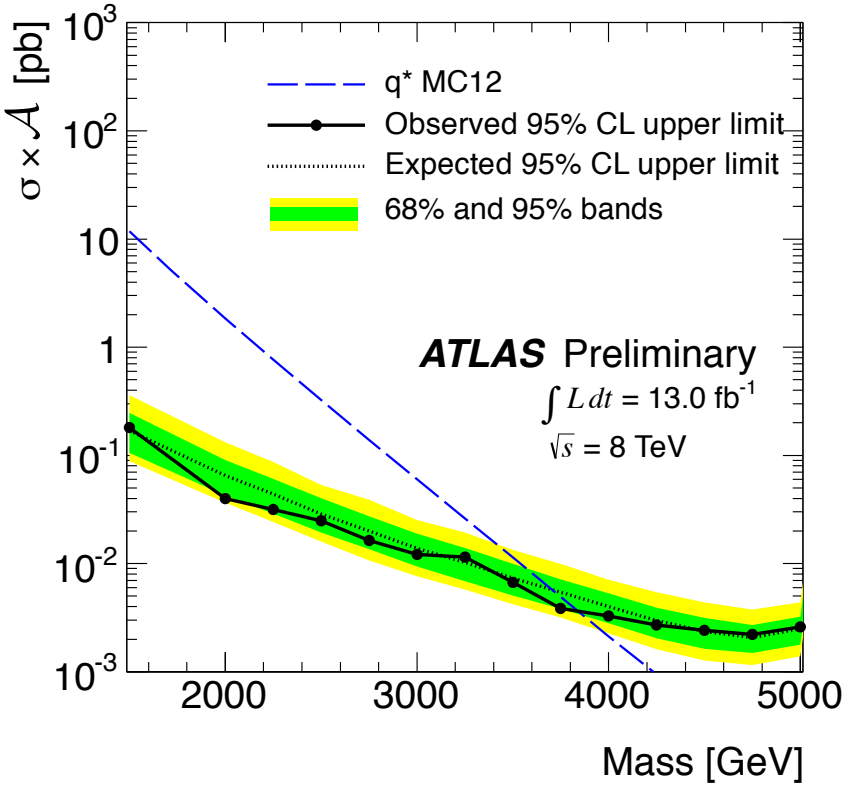


- Search for dijet resonance in smoothly falling mass spectrum
  - leading jet mass m_{jj} > 0.9-1 TeV from trigger and other constraints
  - Background estimated from smooth functional fit

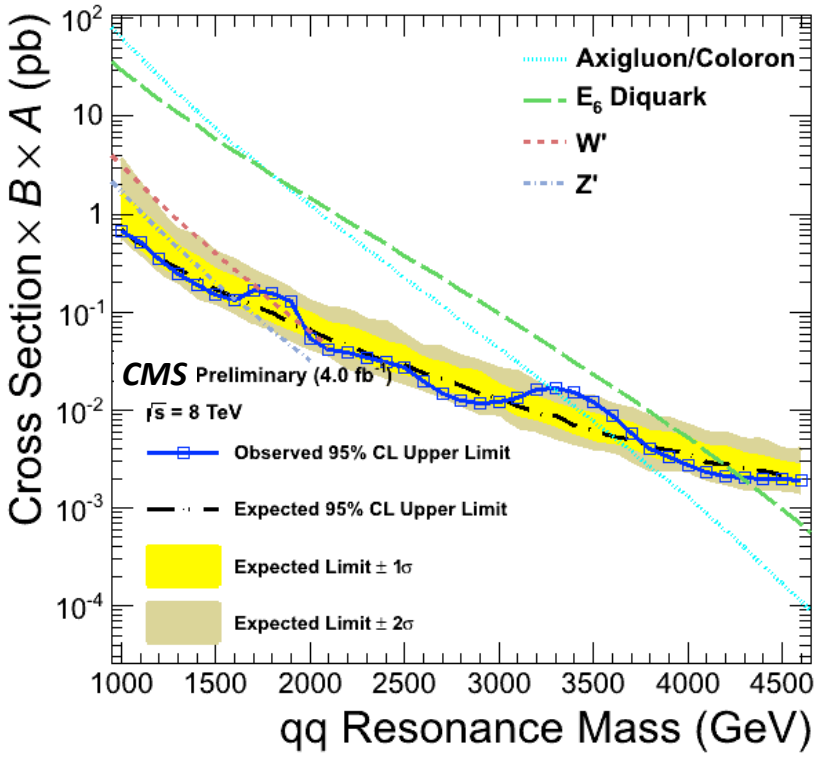
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

DIJETS IN 8 TEV DATA

[ATLAS-CONF-2012-148]



[CMS PAS EXO-12-016]

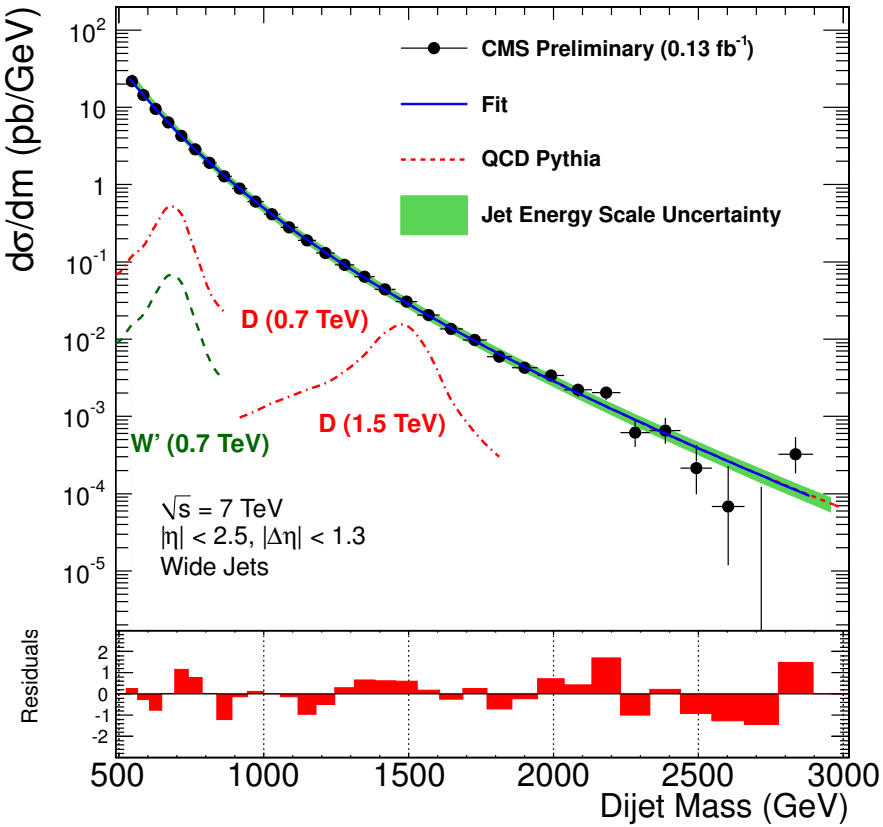


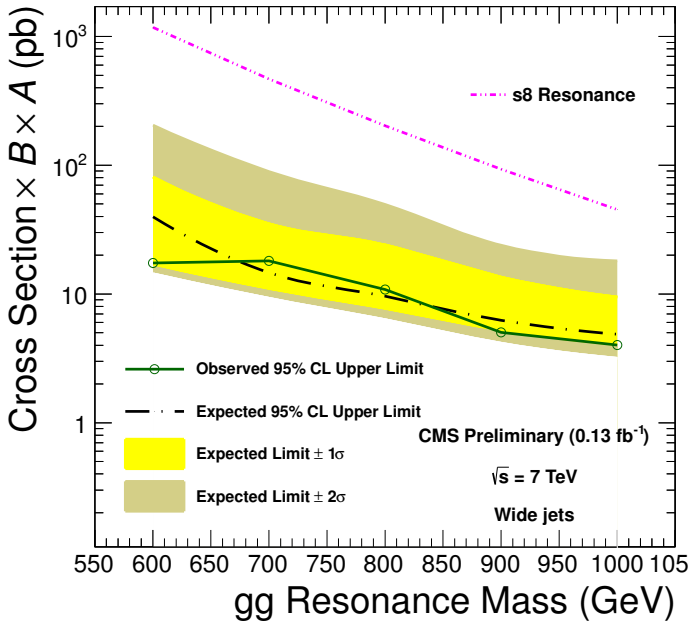
M(q*) 95% CL	Luminosity	Expected	Observed
ATLAS 2011	4.8	> 3.09 TeV	> 3.55 TeV
CMS 2011	5.0	> 3.27 TeV	> 3.05 TeV
CMS 2012	4.0	> 3.43 TeV	> 3.19 TeV
ATLAS 2012	13.0	> 3.70 TeV	> 3.84 TeV

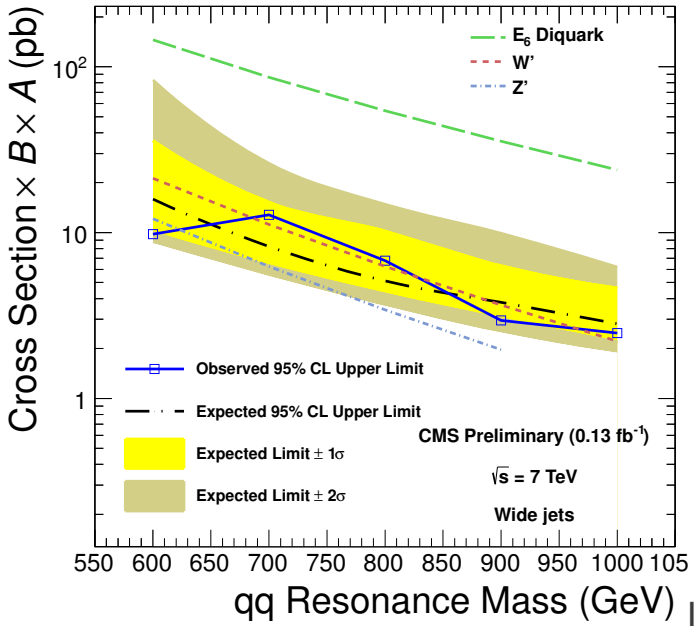
Low-Mass Dijets

- Lower dijet mass from trigger sample
- $H_T > 350$ GeV or m(dijet) > 400 GeV and $|\Delta\eta_j| < 2$

Low masses of great interest, are being probed





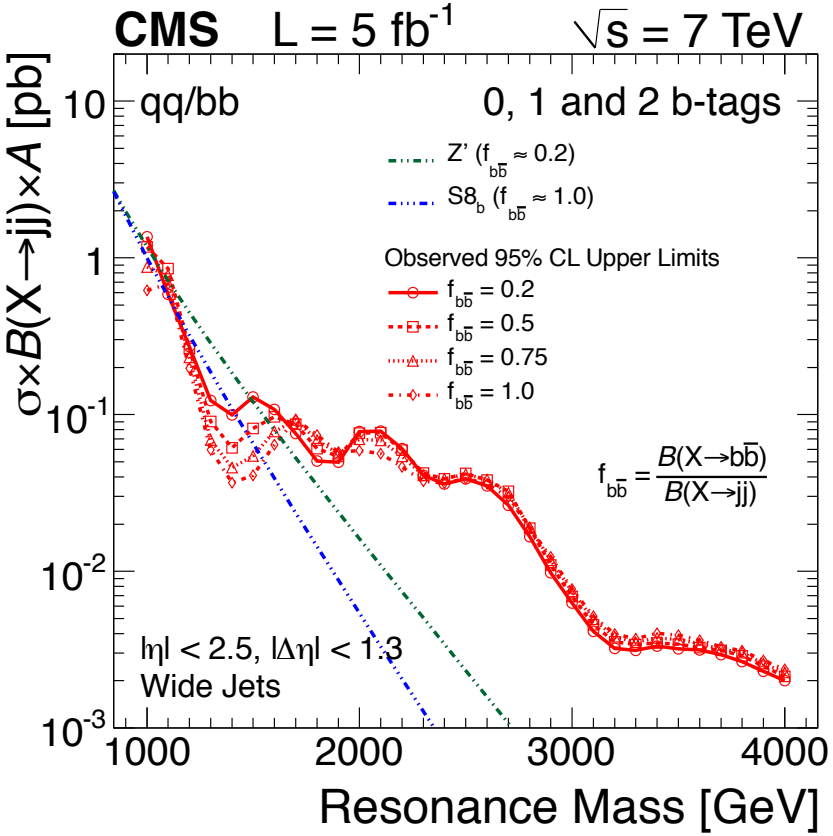


DIJET WITH b-TAG

[CMS hep-ex 1210.2387]

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

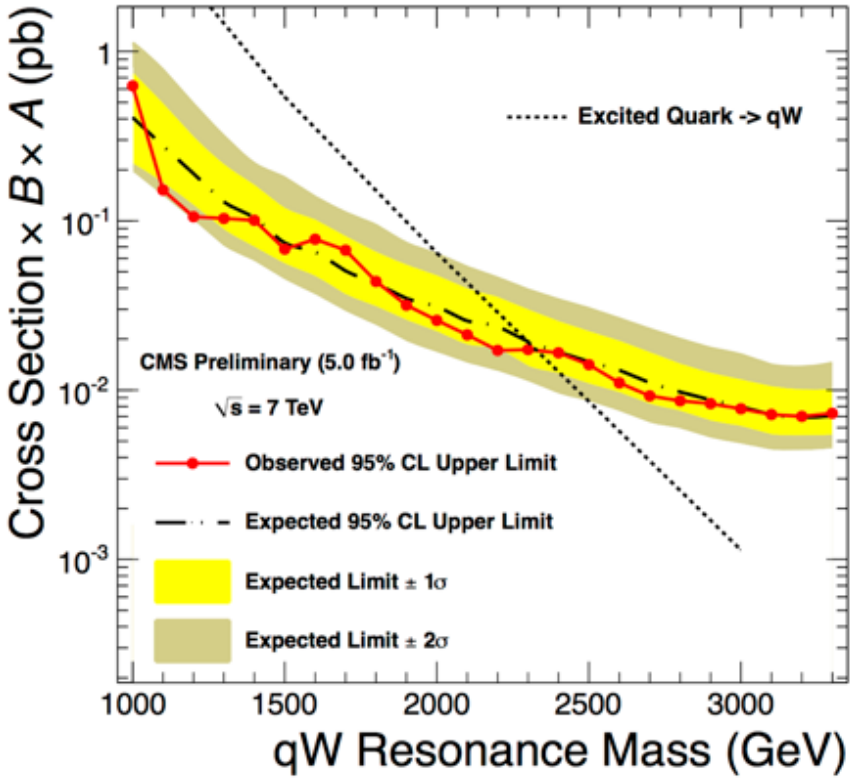
$$f_{b\bar{b}} = \frac{\mathrm{BR}(X \to b\bar{b})}{\mathrm{BR}(X \to jj)}$$



DIJET WITH W/Z TAGS

[CMS PAS EXO-11-095]

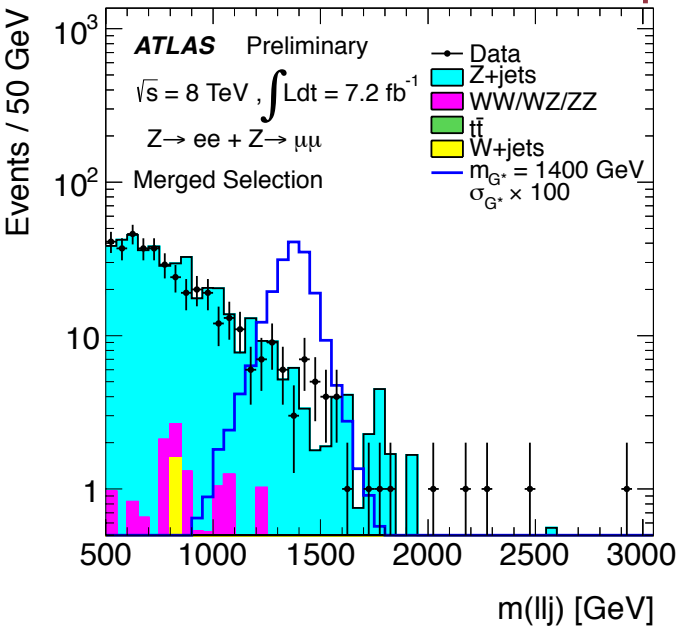
- Dijet with 1, 2 W/Z-tags
  - jet substructure used for tagging
  - single tags: qW/qZ resonances
  - double tags: WW/WZ/ZZ resonances

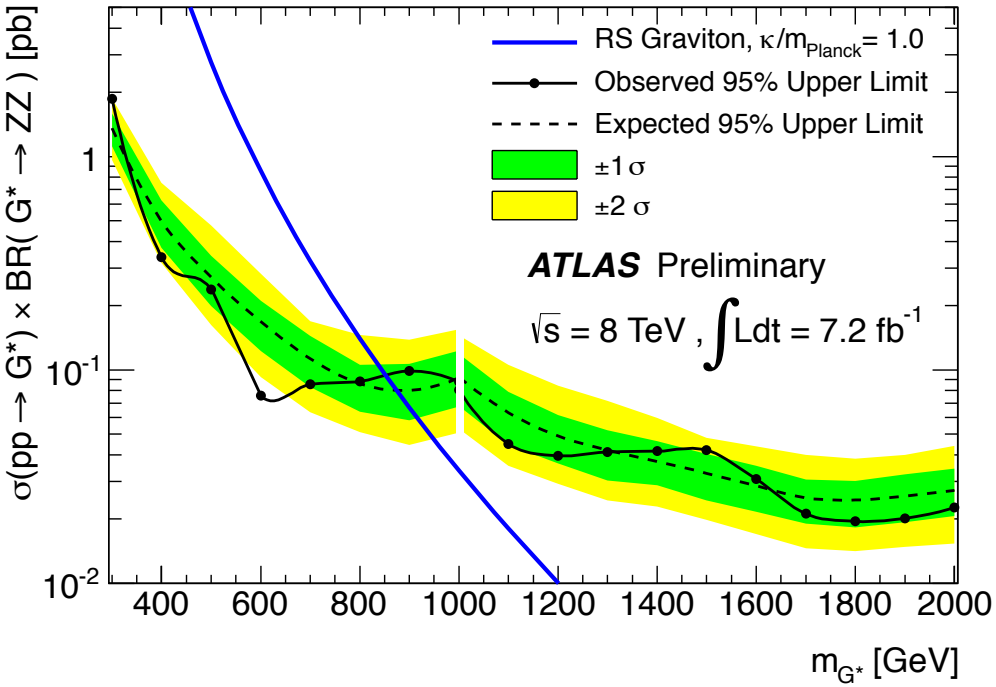


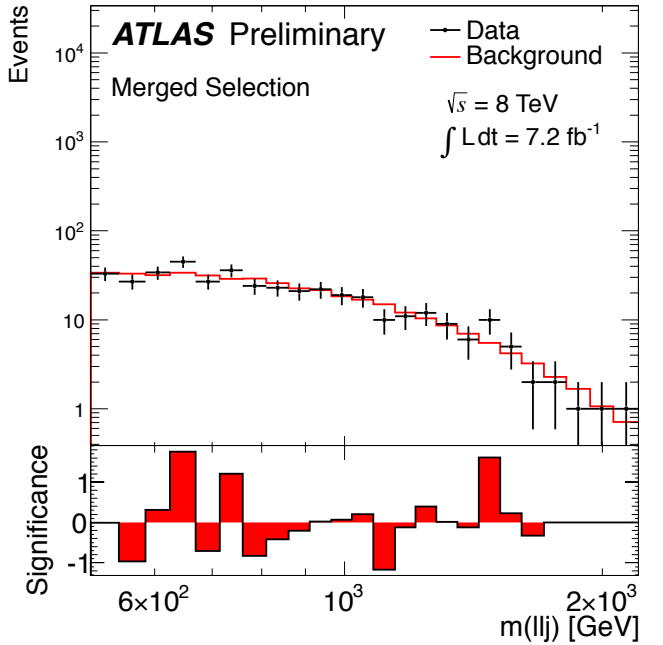
RESONANT ZZ PRODUCTION

[ATLAS-CONF-2012-150]

- Search for resonant ZZ production ZZ → llqq (l=e,μ)
- No significant deviation of diboson mass on a smoothly falling background
- For k/Mpl = 1.0, 95% observed (expected) lower limit on the graviton mass of 850 (870) GeV







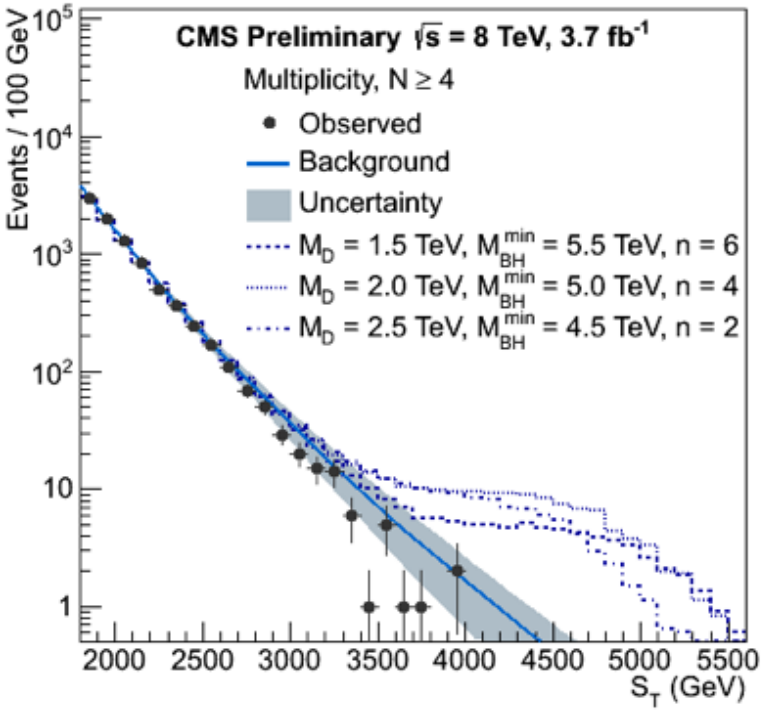
BLACK HOLES IN 8 TEV DATA

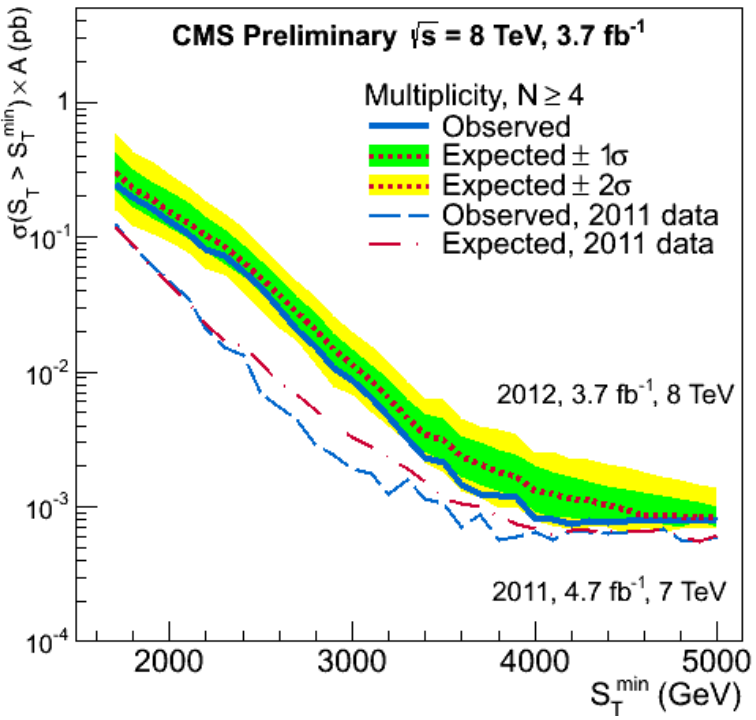
[CMS PAS EXO-12-009]

- Hypothetical BH would evaporate into many high-p_T objects
  - Estimate by S_T, the p_T sum of physics objects with $p_T > 50$ GeV
- Main background of QCD estimated by fit to n=2 distribution
  - Normalised for each multiplicity bin separately at S_T = 1.8–2.2 TeV
  - Model-independent limits vs S_T and multiplicity

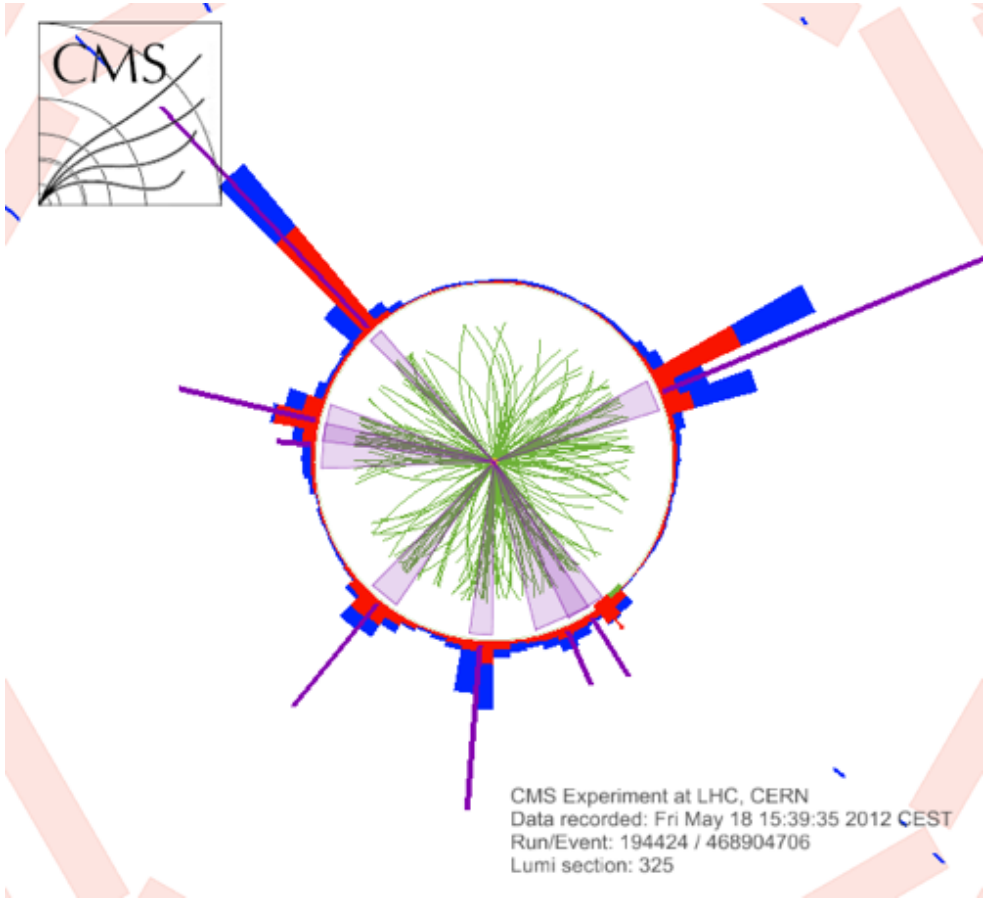
$$S_T = \sum_{j,e,\mu,\gamma,MET}^{N} p_T$$

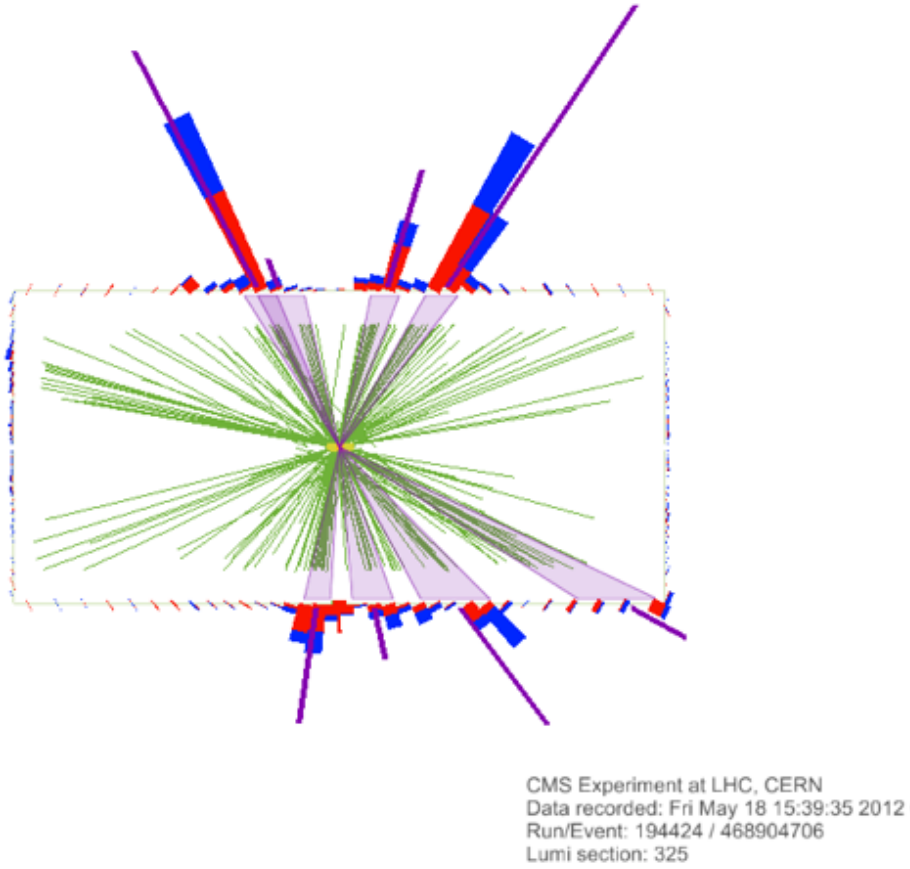
Large improvement in sensitivity (~10-20%) with respect to 2011 analysis





8-Jet Event, S_T = 3 TeV

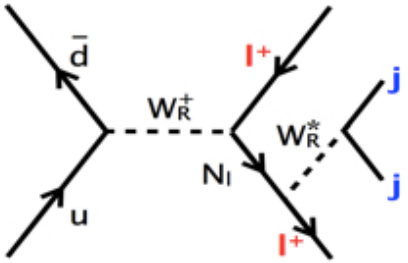




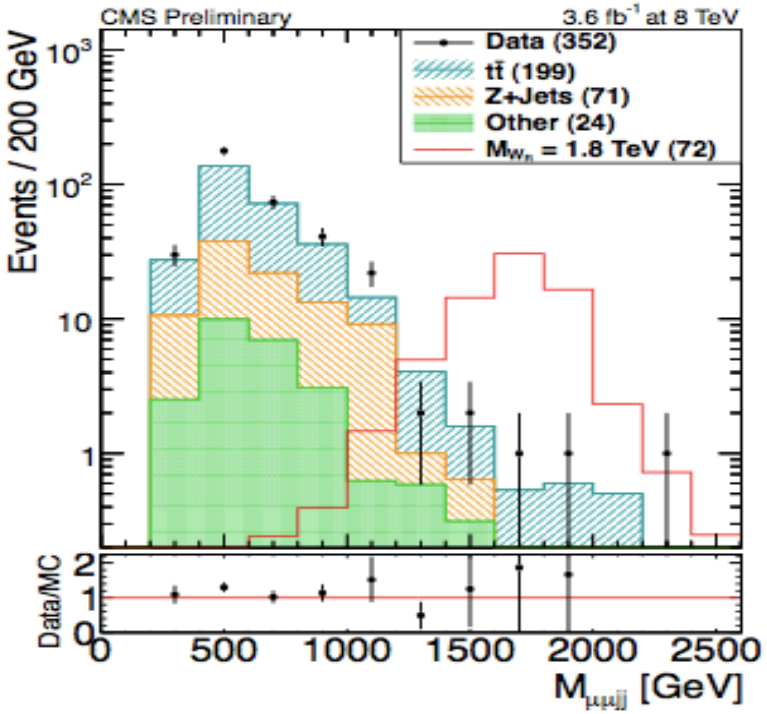
HEAVY NEUTRINO IN 8 TEV

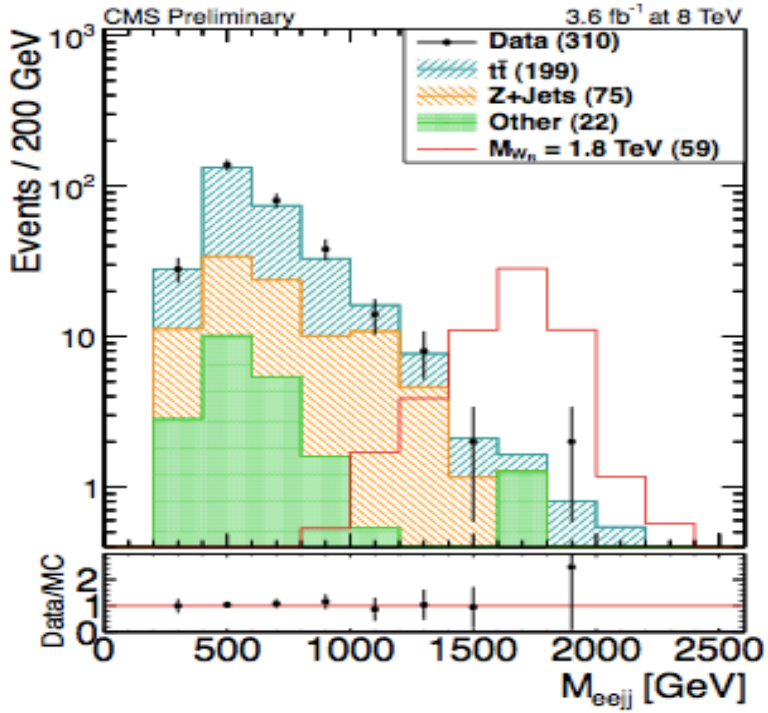
[CMS PAS EXO-12-017]

- We search for the decay of $W_R \rightarrow \mu\mu jj$ and eejj, as in a Left-Right Symmetric Model



- Selection
  - Lepton p_T >60/40 GeV, motivated by W decay
  - Jet p_T > 40 GeV
  - M(ll) > 200 GeV to reduce DY+jets.
- Background
  - Top: data-driven from eμjj
  - DY+jets: normalised to data, MC shape in Z peak
  - QCD: data-driven fake rate
  - VV, Single top: from MC



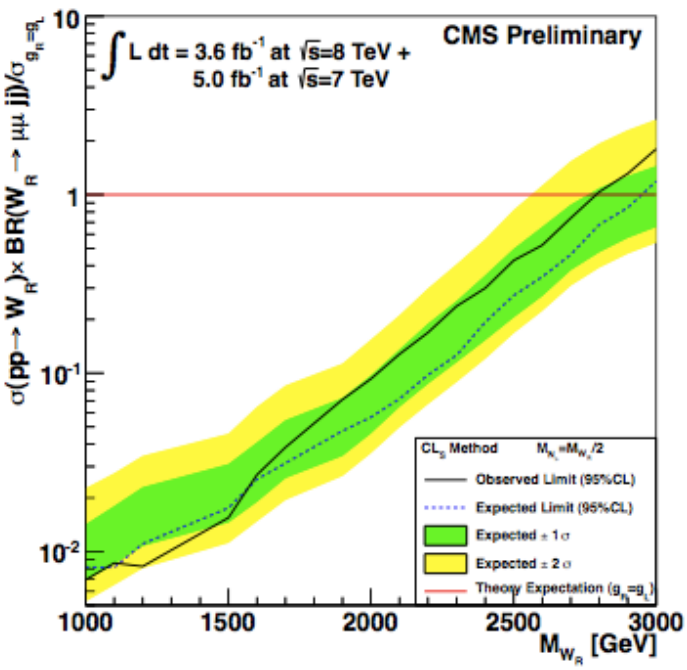


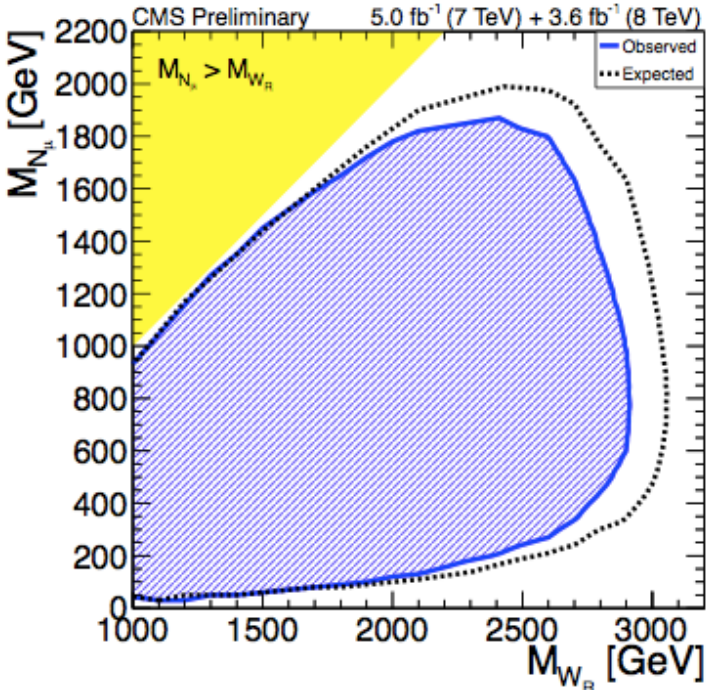
HEAVY NEUTRINO IN 8 TEV DATA

[CMS PAS EXO-12-017]

- Search assumes small W_R–W_L and N_l–$N_{l'}$ mixing angles, only one lepton channel kinematically accessible
- Primary Systematic Uncertainties
  - Signal Eff.: 6-10% from lepton
  - Background: ~50% from DY+jets shape, ~16% from top shape

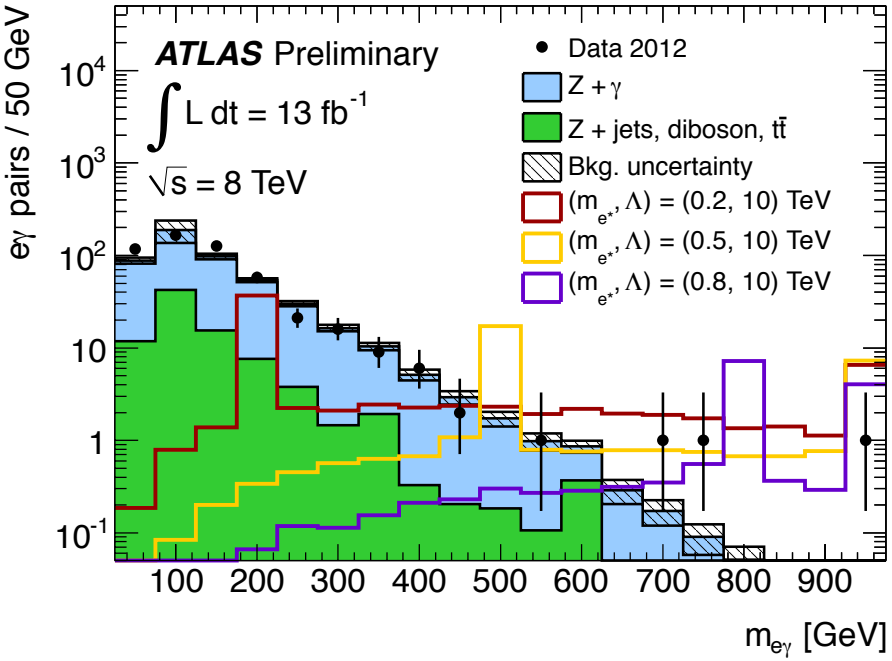
For $M(N)=M(W_R)/2$; $M(W_R) > 2.8$ TeV

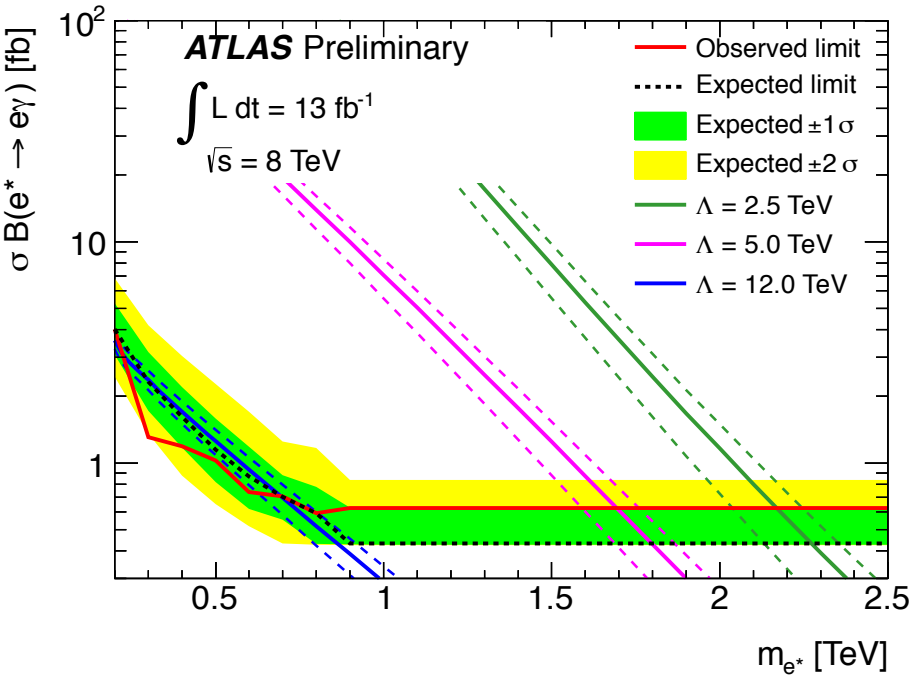




EXCITED LEPTONS

- Search for excited e and μ in the electromagnetic radiative decay channel $l^* \rightarrow l\gamma$
  - Production via $qq \rightarrow l^{\pm *} l^{\mp}$ or in pairs via $qq \rightarrow l^{\pm *} l^{\mp *}$, yielding final state $ll\gamma$.
  - E_T (e1,e2) > 40, 30 GeV, p_T (μ1,μ2) > 25 GeV, plus isolation,
  - m_{ll} > 110 GeV to suppress Drell-Yan
- No evidence for signal, limits on the compositeness scale Λ vs. m_{l^*}.
  - For $\Lambda = m_{l^*}$, both excited e and μ masses below 2.2 TeV are excluded at 95% CL.





MAGNETIC MONOPOLES

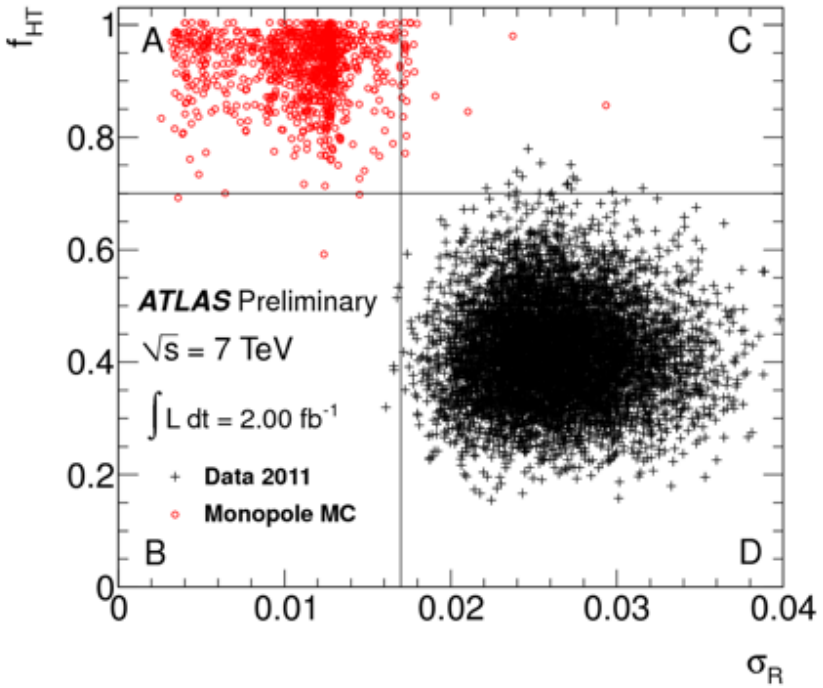
[ATLAS-CONF-2012-062]

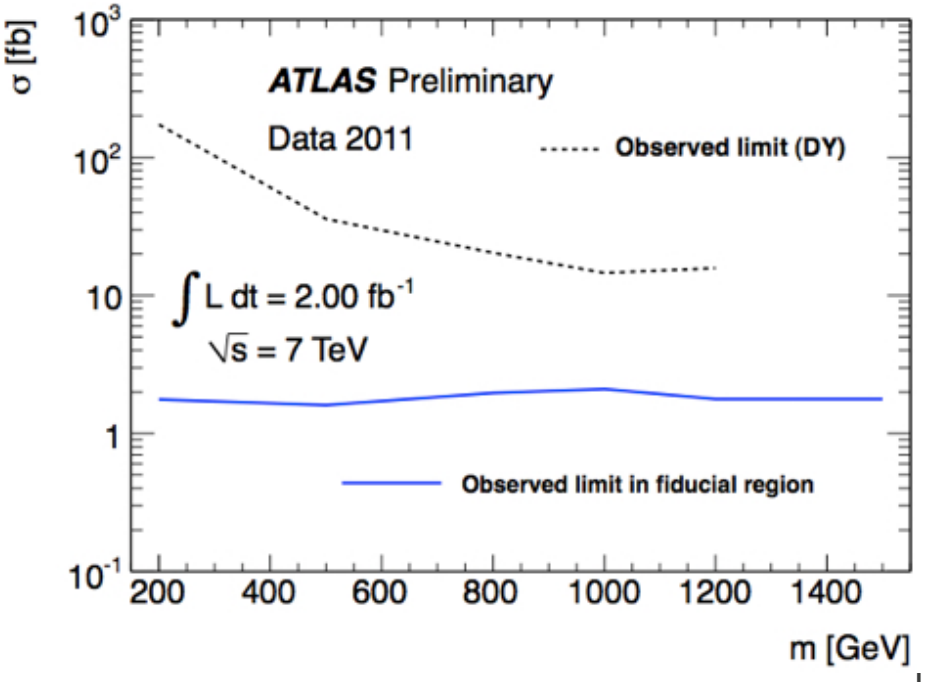
- Magnetic charge *g* yields strong coupling α_m and very high ionisation

$$\frac{ge}{\hbar c} = \frac{1}{2} \Rightarrow \frac{g}{e} = \frac{1}{2\alpha_e} \approx 68.5 \qquad \alpha_m = \frac{(g\beta)^2}{\hbar c} = \frac{1}{4\alpha_e}\beta^2$$

- Look for high ionisation in Transition Radiation Tracker and high hit fraction (f_{HT}) and also deposition in the Liquid Argon Electromagnetic Calorimeter
- Pair-produced (Drell-Yan) production

Cross Section limits set for m(M) = 0.2–1.2 TeV



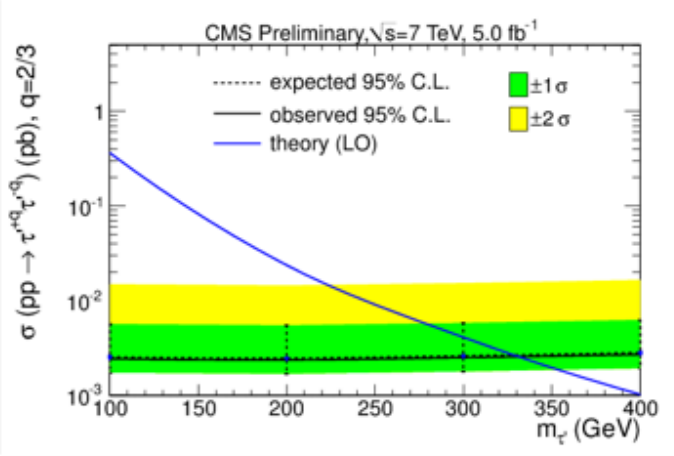


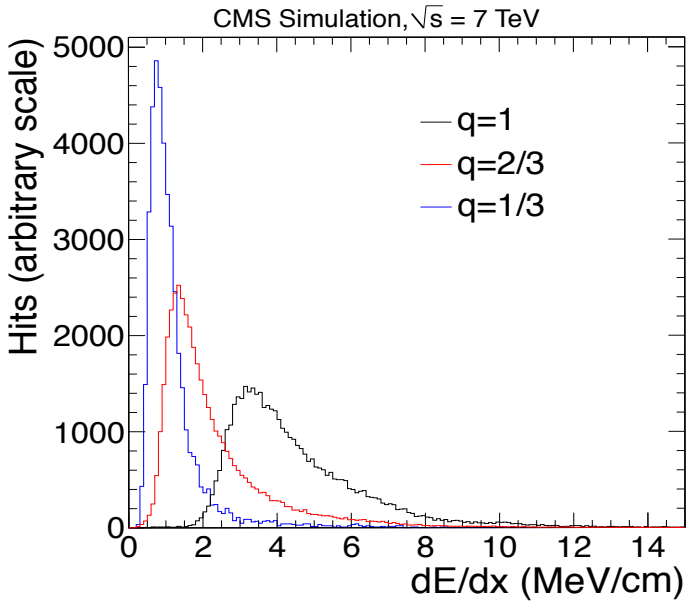
FRACTIONALLY CHARGED PARTICLES

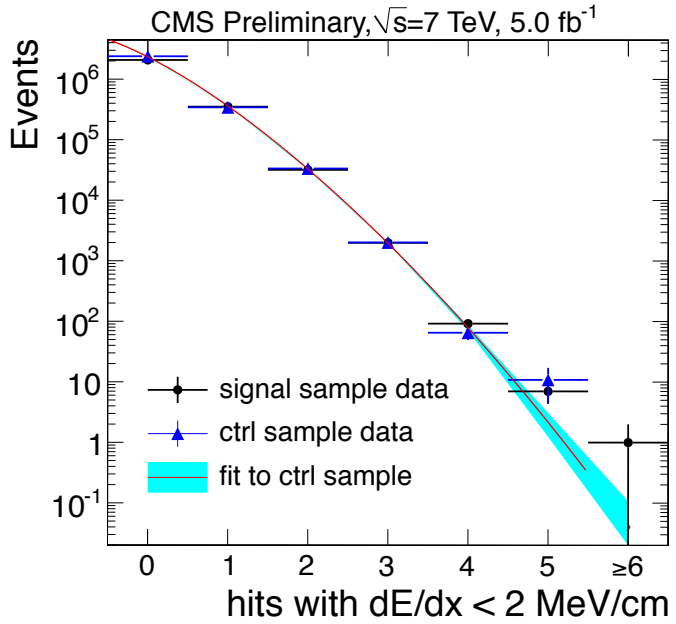
[CMS PAS EXO-11-074]

- Search for long-lived particles with fractional charge
- Backgrounds
  - Cosmics: estimate from d_{xy} sidebands
  - Collisions: using Z→μμ data, fit N_{hits} with low dE/dx
- Assume lepton-like spin=1/2 particle masses

Exclude: Q= e/3: m > 210
Q=2e/3: m > 330

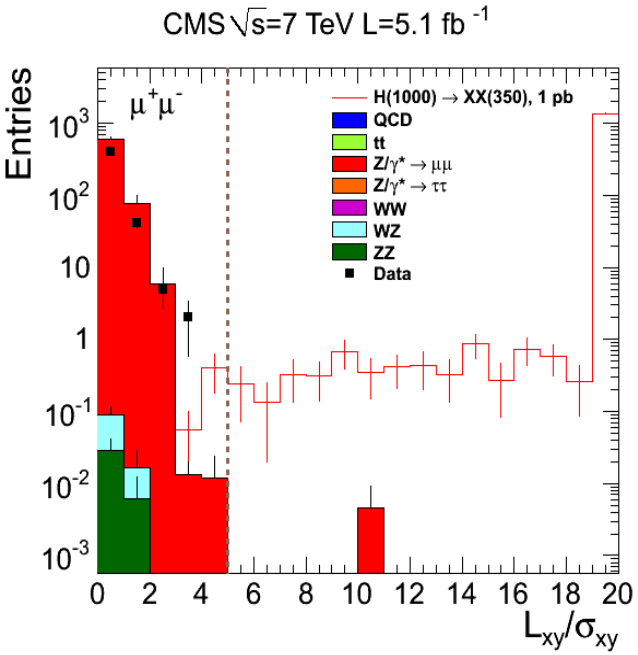


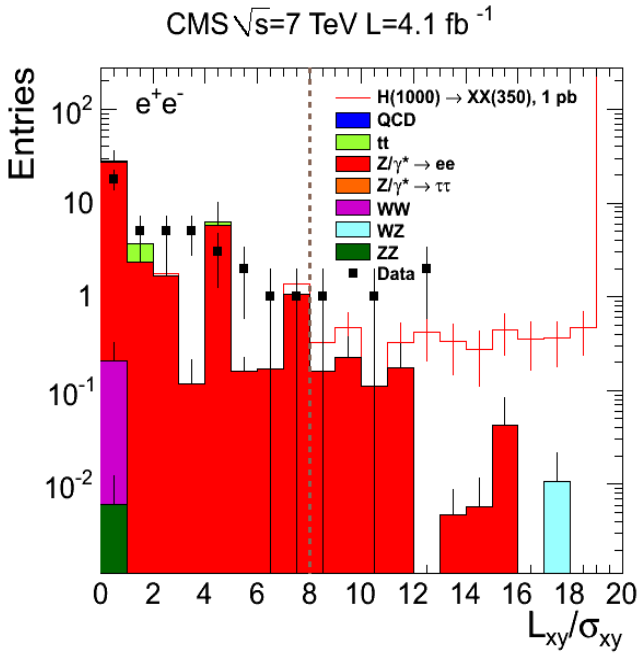


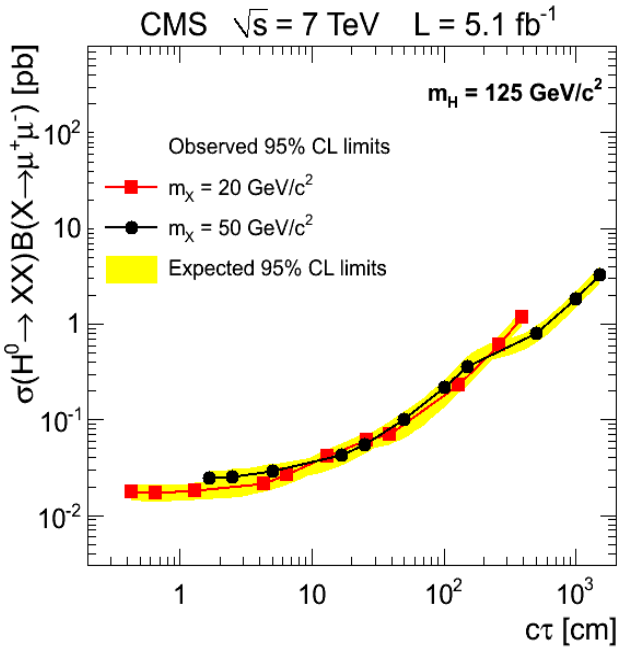


HEAVY RESONANCE TO LONG-LIVED

- Search in leptonic channels for heavy resonances (H^0) decaying to long-lived neutral particles ($H^0 \rightarrow XX$, $X \rightarrow l^{\pm}l^{\mp}$)
  - Good track reconstruction efficiency out to $d_0 \approx 30$ cm.
  - Four candidates in ee (2 in the Z mass region), no candidates in μμ
- No evidence for new physics, limits vs. cτ set for m_H from 200 to 1000 GeV/c^2 and m_X from 20 to 350 GeV/c^2
- Sensitivity also to H^0 at 125 GeV/c^2, in the range of 10-100 fb.



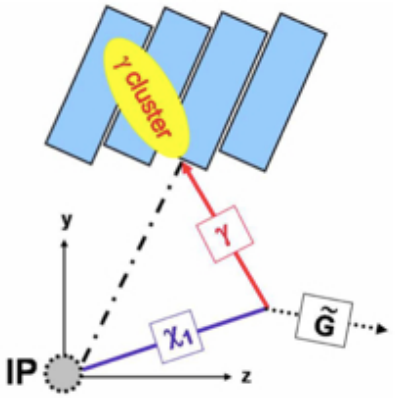




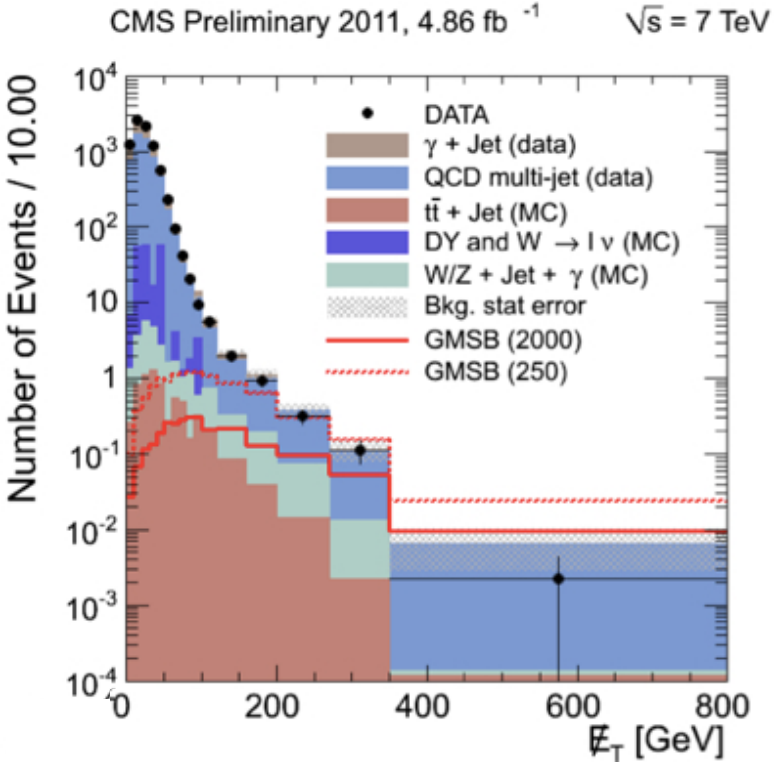
GMSB WITH DISPLACED PHOTON

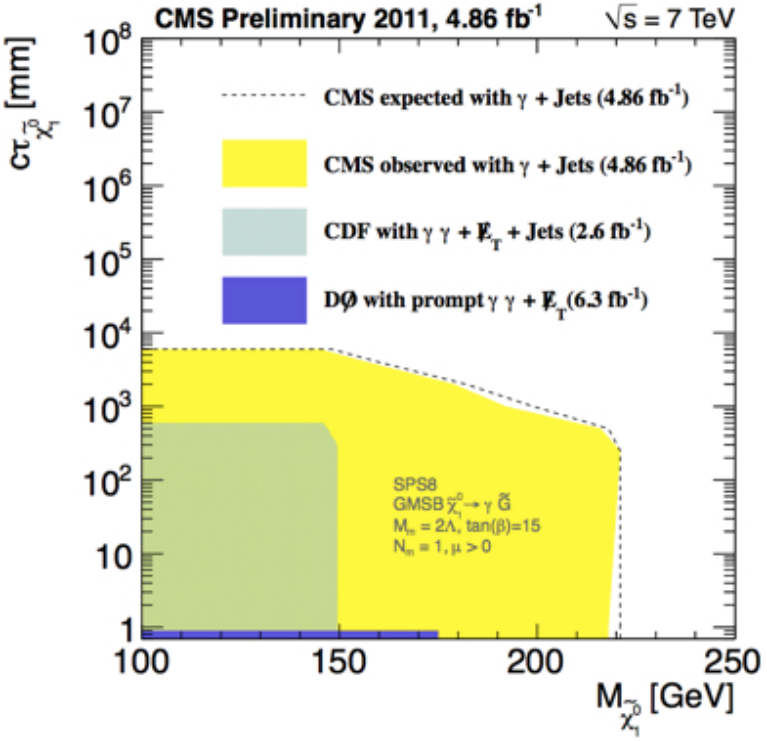
- GMSB (SUSY) decays typically include many jets and $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$
- Selection: photon with $E_T > 100$, three jets with $p_T > 35$
  - relaxed ECAL timing and shower-shape cuts
  - E_T^{miss} and ECAL timing main discriminants

[CMS PAS EXO-11-035]



Much-improved sensitivity to long-lived neutralino

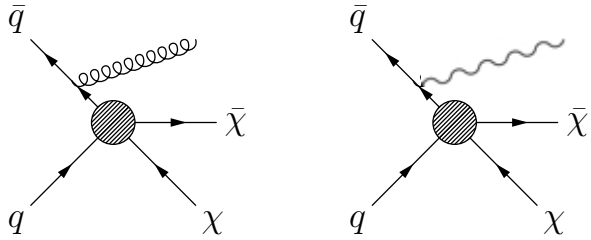




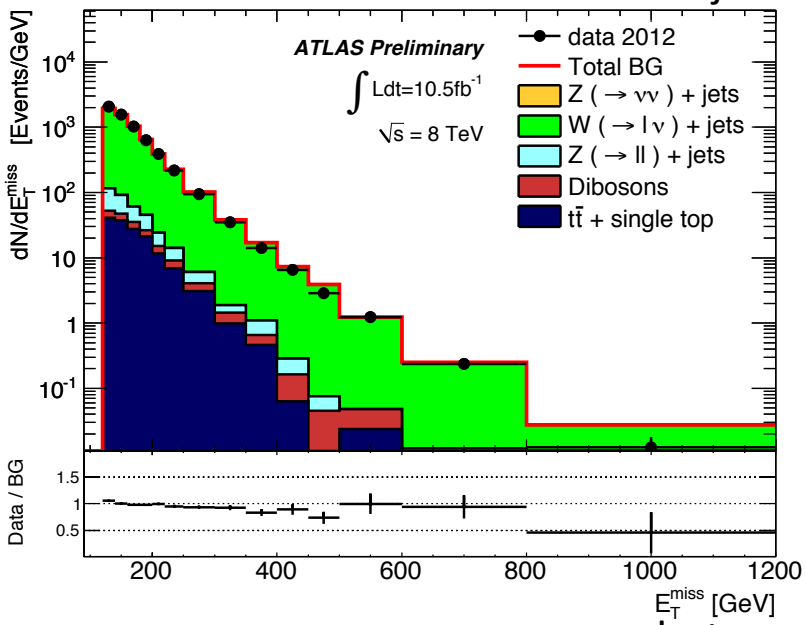
MONOJET AND MONOPHOTON

[ATLAS-CONF-2012-147, ATLAS-CONF-2012-085]

- Look for missing energy and radiated jet (photon)



monojet

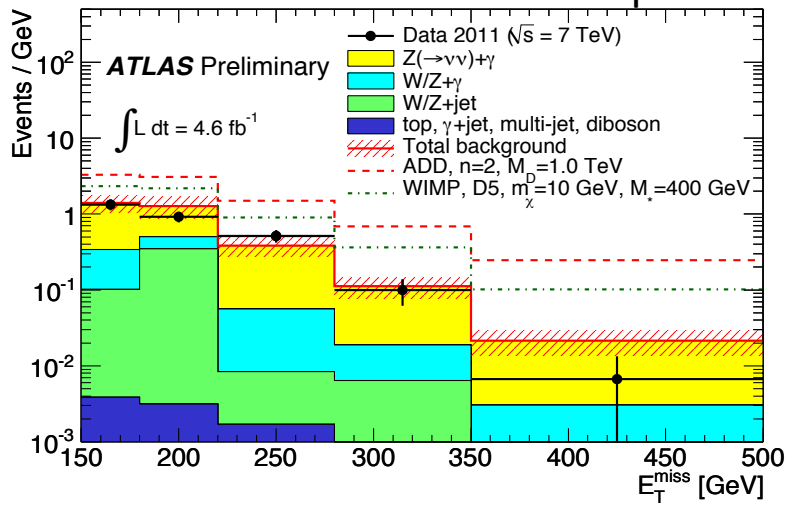


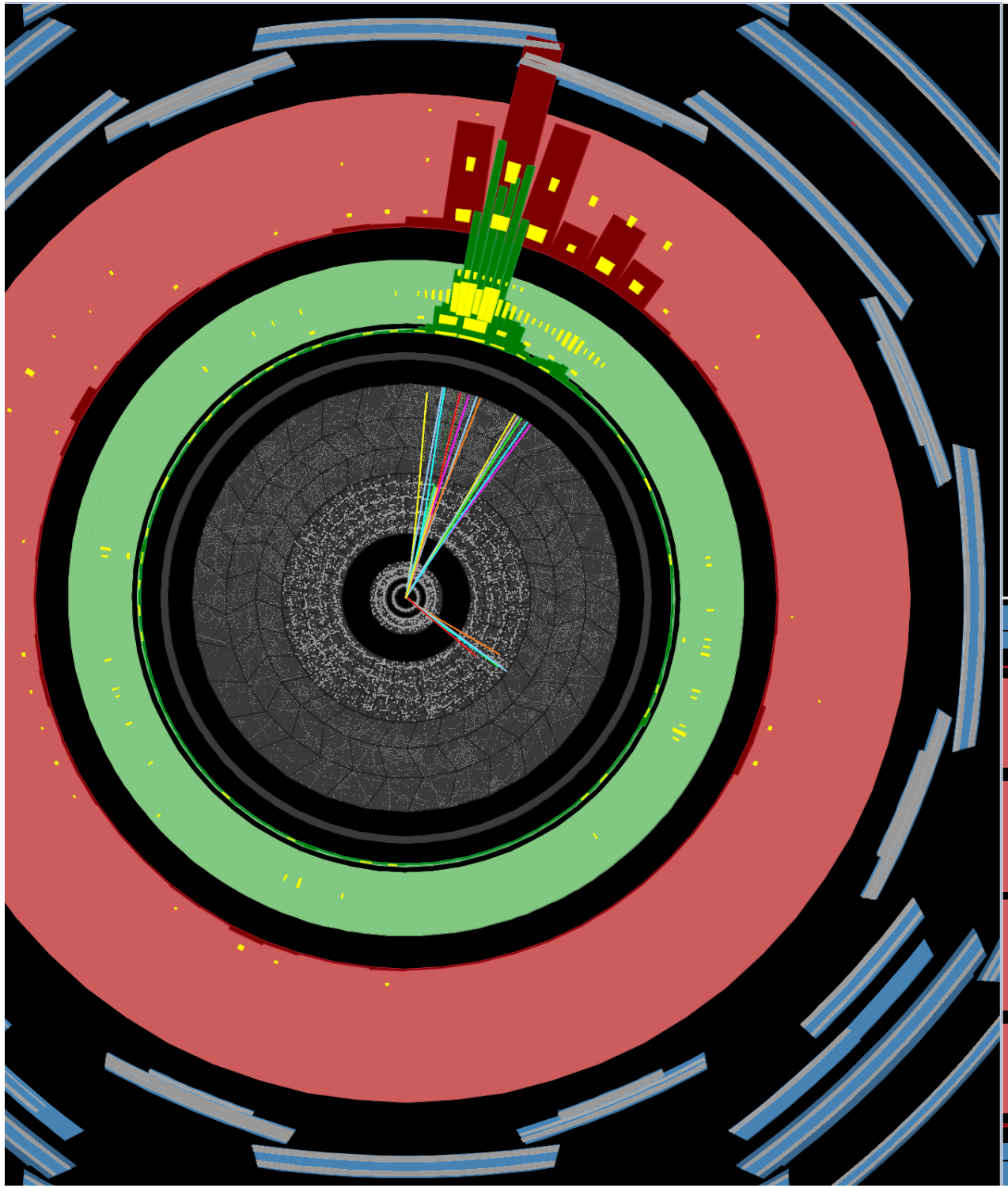
- Monojet Selection:
  - Leading jet p_T > 120 GeV, |η| < 2
  - allow a second jet if not back-to-back
  - veto isolated leptons

- Backgrounds and Uncertainties
  - Z + (jets/γ) --> νν+(jets/γ)
  - W + (jets/γ) --> lν+(jets/γ)
  - smaller backgrounds from top, QCD, non-collision

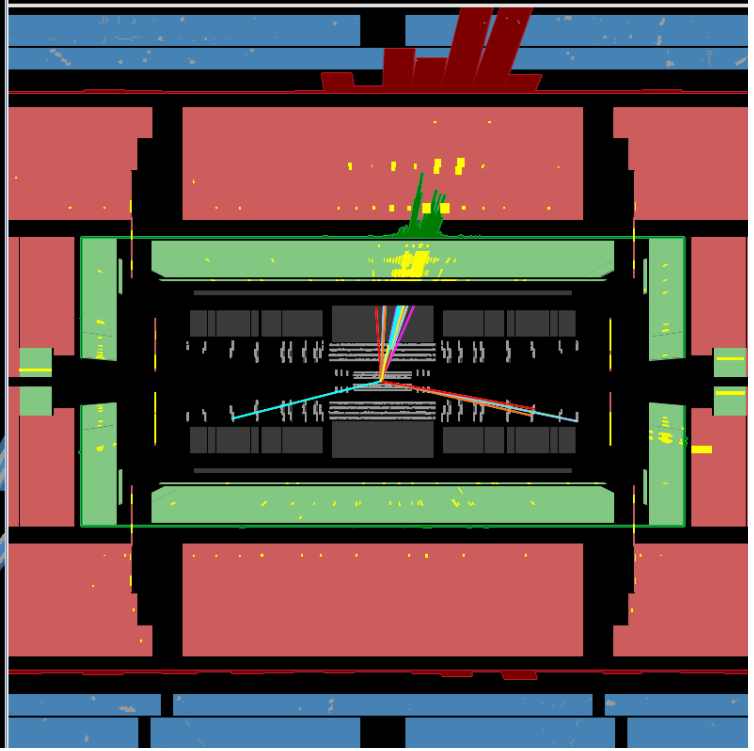
- Missing Energy (E_T^{miss}) to distinguish signal

monophoton






ATLAS
EXPERIMENT
Run Number: 206962, Event Number: 55091306
Date: 2012-07-14 10:42:26 CEST

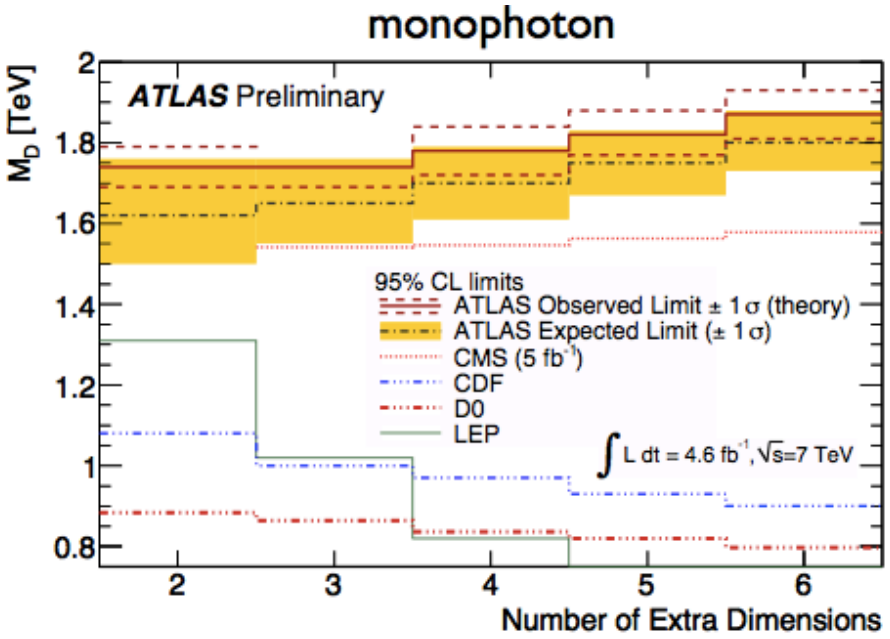


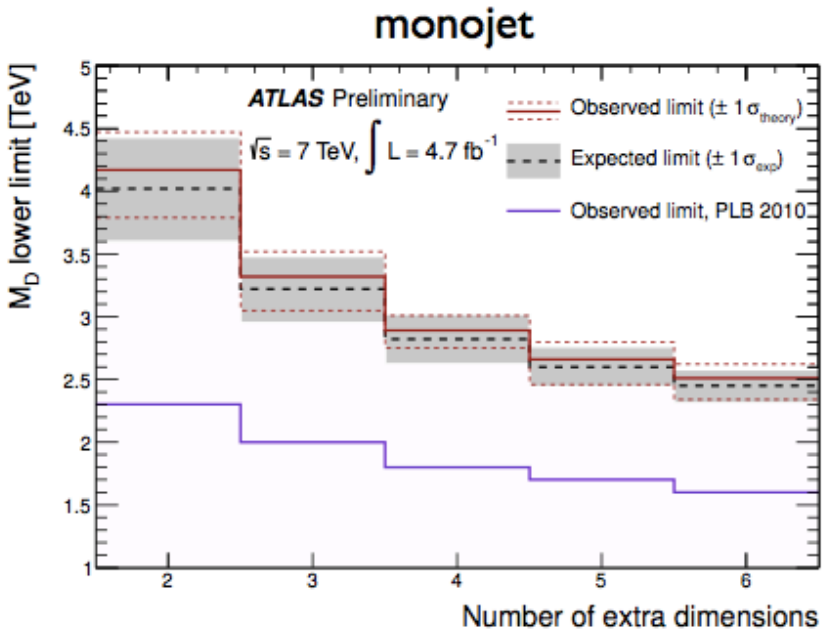
ADD FROM MONOJET AND MONOPHOTON

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

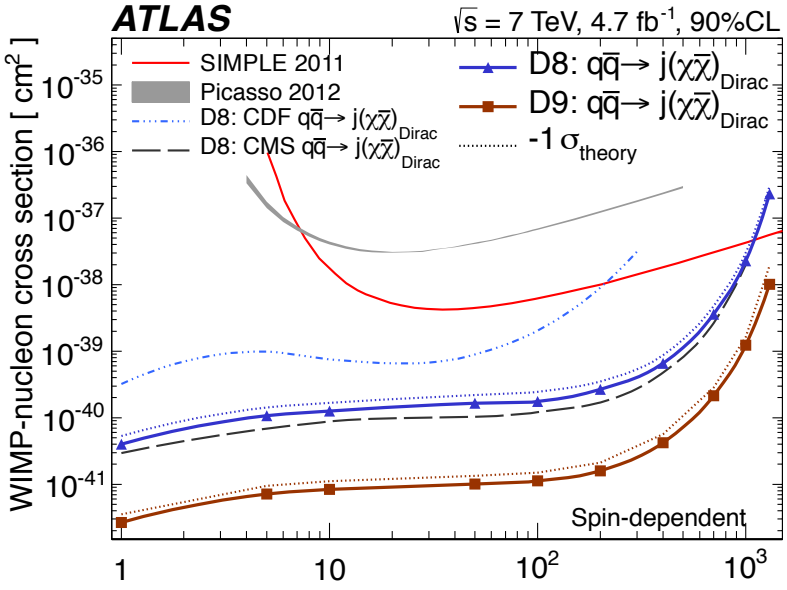




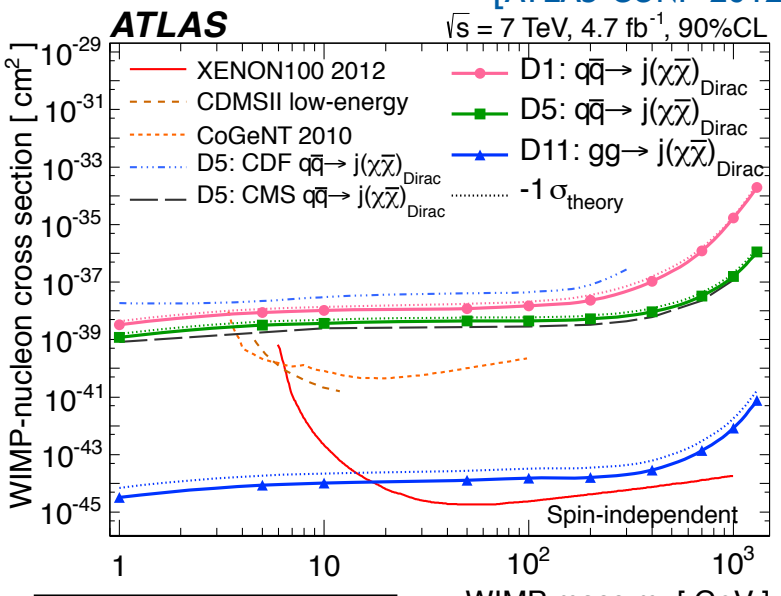
M_D (ADD) at LO 95% CL limits	Lumi [fb^{-1}]	δ=3 Exp.	δ=3 Obs.	δ=6 Exp.	δ=6 Obs.
CMS Monophoton	5.0	1.5	1.6	1.6	1.6
ATLAS Monophoton	4.6	1.7	1.7	1.8	1.9
CMS Monojet	5.0	3.1	3.2	2.3	2.4
ATLAS Monojet 8TeV	10.5	3.4	3.2	2.7	2.6

DARK MATTER AND MONOJETS

[ATLAS-CONF-2012-084]

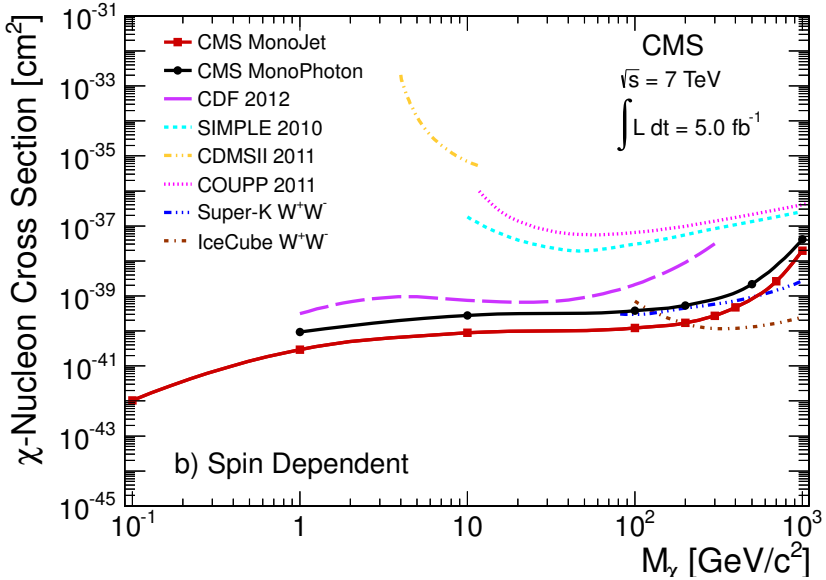


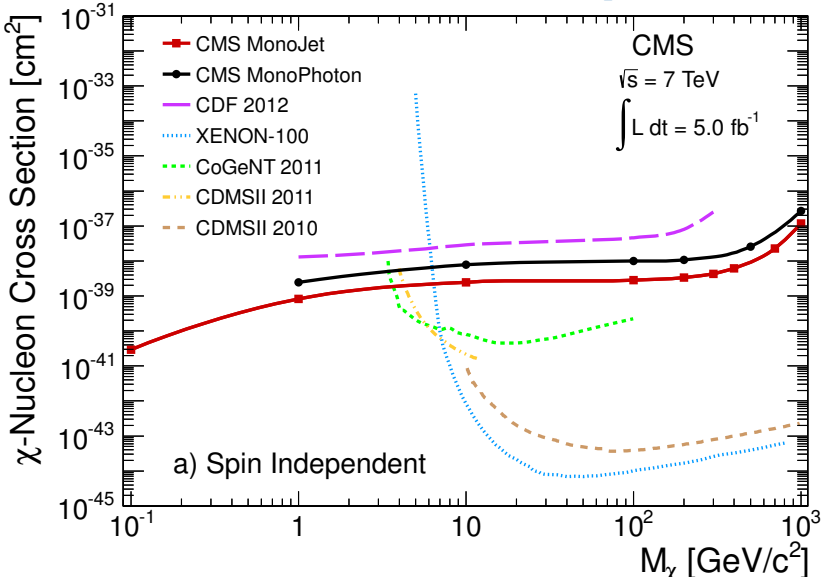
Spin-dependent



Spin-independent

[CMS EXO-11-059]

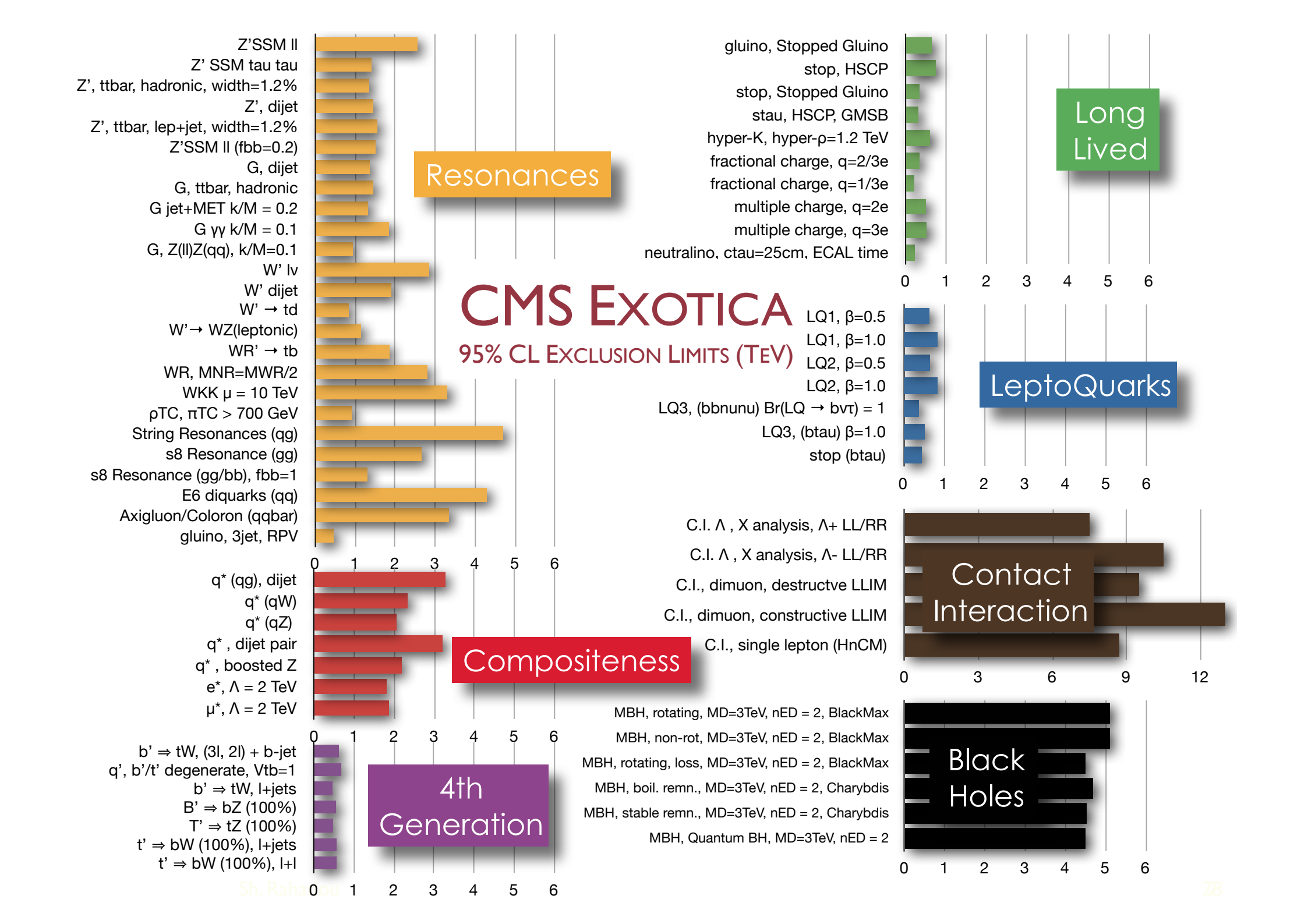


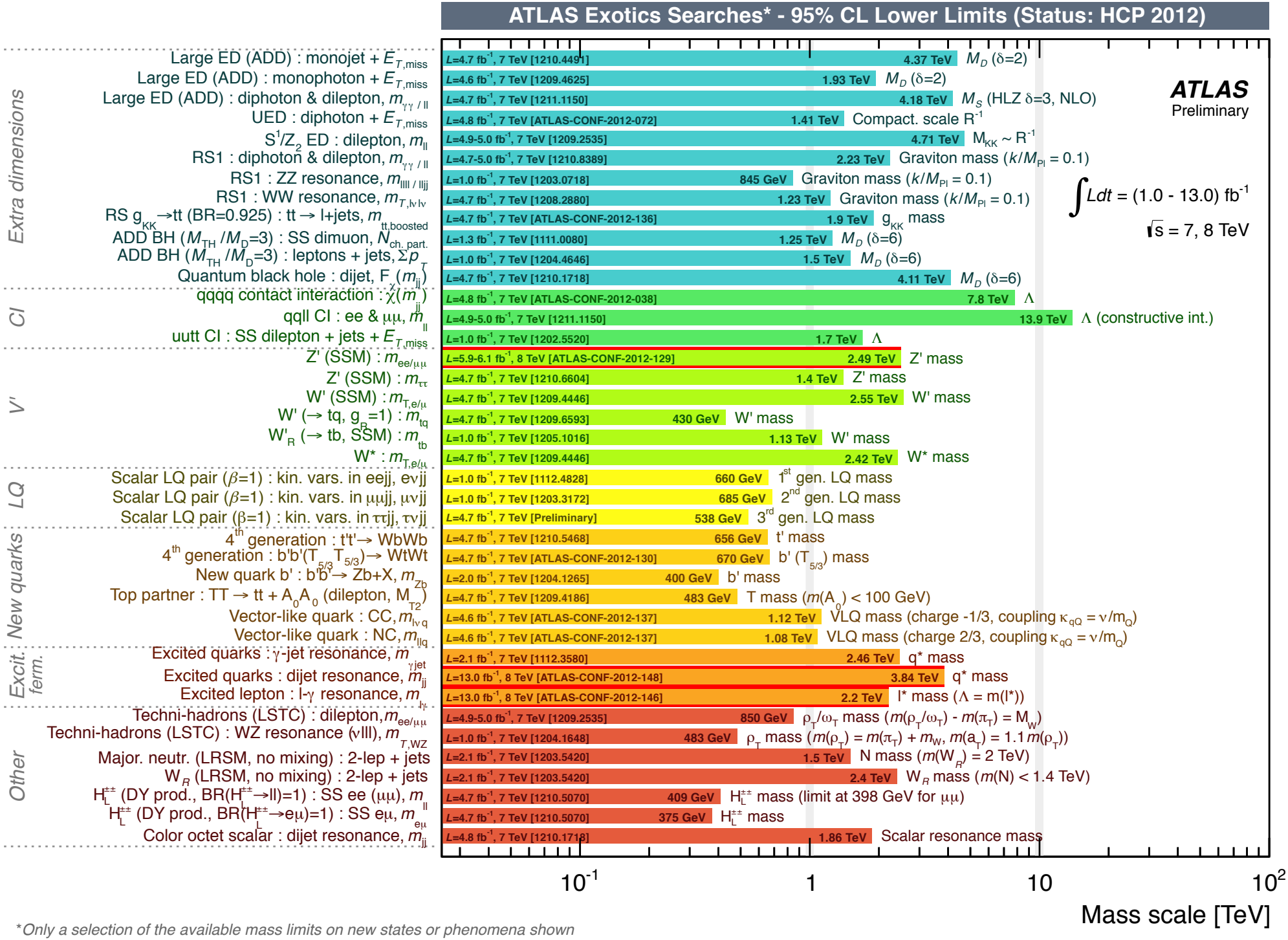


CONCLUSIONS

- Tremendous progress in Beyond the Standard Model searches
  - short time from data to results: already have many 8 TeV results
  - more complete coverage of channels
  - generic searches, less model dependence
  - dedicated searches for more challenging signatures
  - also probing lower in mass, not just pushing for highest exclusion
  - search techniques getting more sophisticated; shape-based or multi-dimensional
  - probing direct connections to other fields (Higgs, SUSY, Top, Dark Matter, etc)

- For complete results:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults


Z'SSM ll
Z' SSM tau tau
Z', ttbar, hadronic, width=1.2%
Z', dijet
Z', ttbar, lep+jet, width=1.2%
Z'SSM ll (fbb=0.2)
G, dijet
G, ttbar, hadronic
G jet+MET k/M = 0.2
G γγ k/M = 0.1
G, Z(ll)Z(qq), k/M=0.1
W' lν
W' dijet
W' → td
W'→ WZ(leptonic)
WR' → tb
WR, MNR=MWR/2
WKK μ = 10 TeV
ρTC, πTC > 700 GeV
String Resonances (qg)
s8 Resonance (gg)
s8 Resonance (gg/bb), fbb=1
E6 diquarks (qq)
Axigluon/Coloron (qqbar)
gluino, 3jet, RPV
Resonances
0 1 2 3 4 5 6
q* (qg), dijet
q* (qW)
q* (qZ)
q* , dijet pair
q* , boosted Z
e*, Λ = 2 TeV
μ*, Λ = 2 TeV
Compositeness
0 1 2 3 4 5 6
b' ⇒ tW, (3l, 2l) + b-jet
q', b'/t' degenerate, Vtb=1
b' ⇒ tW, l+jets
B' ⇒ bZ (100%)
T' ⇒ tZ (100%)
t' ⇒ bW (100%), l+jets
t' ⇒ bW (100%), l+l
4th Generation
0 1 2 3 4 5 6
CMS EXOTICA
95% CL EXCLUSION LIMITS (TEV)
gluino, Stopped Gluino
stop, HSCP
stop, Stopped Gluino
stau, HSCP, GMSB
hyper-K, hyper-ρ=1.2 TeV
fractional charge, q=2/3e
fractional charge, q=1/3e
multiple charge, q=2e
multiple charge, q=3e
neutralino, ctau=25cm, ECAL time
Long Lived
0 1 2 3 4 5 6
LQ1, β=0.5
LQ1, β=1.0
LQ2, β=0.5
LQ2, β=1.0
LQ3, (bbnunu) Br(LQ → bντ) = 1
LQ3, (btau) β=1.0
stop (btau)
LeptoQuarks
0 1 2 3 4 5 6
C.I. Λ , X analysis, Λ+ LL/RR
C.I. Λ , X analysis, Λ- LL/RR
C.I., dimuon, destructve LLIM
C.I., dimuon, constructive LLIM
C.I., single lepton (HnCM)
Contact Interaction
0 3 6 9 12
MBH, rotating, MD=3TeV, nED = 2, BlackMax
MBH, non-rot, MD=3TeV, nED = 2, BlackMax
MBH, rotating, loss, MD=3TeV, nED = 2, BlackMax
MBH, boil. remn., MD=3TeV, nED = 2, Charybdis
MBH, stable remn., MD=3TeV, nED = 2, Charybdis
MBH, Quantum BH, MD=3TeV, nED = 2
Black Holes
0 1 2 3 4 5 6



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