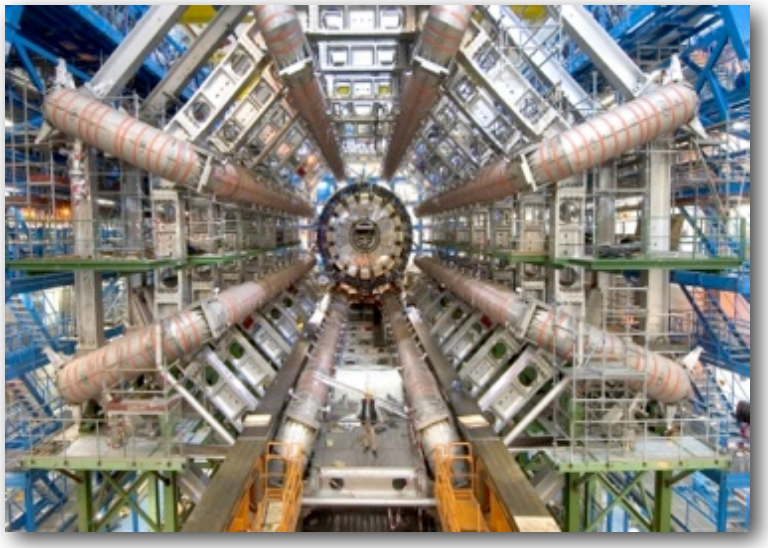
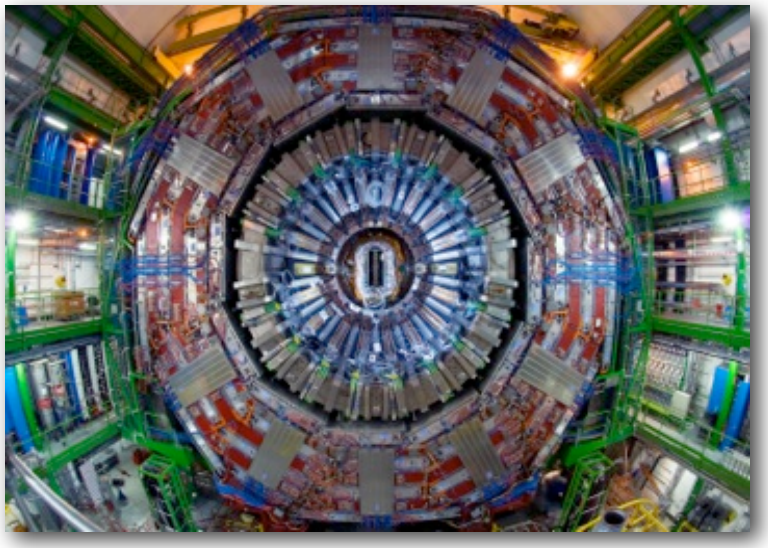
Searches for Physics Beyond the Standard Model





Steven Worm

For the CMS and ATLAS Collaborations

ICHEP Melbourne, 10 July 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

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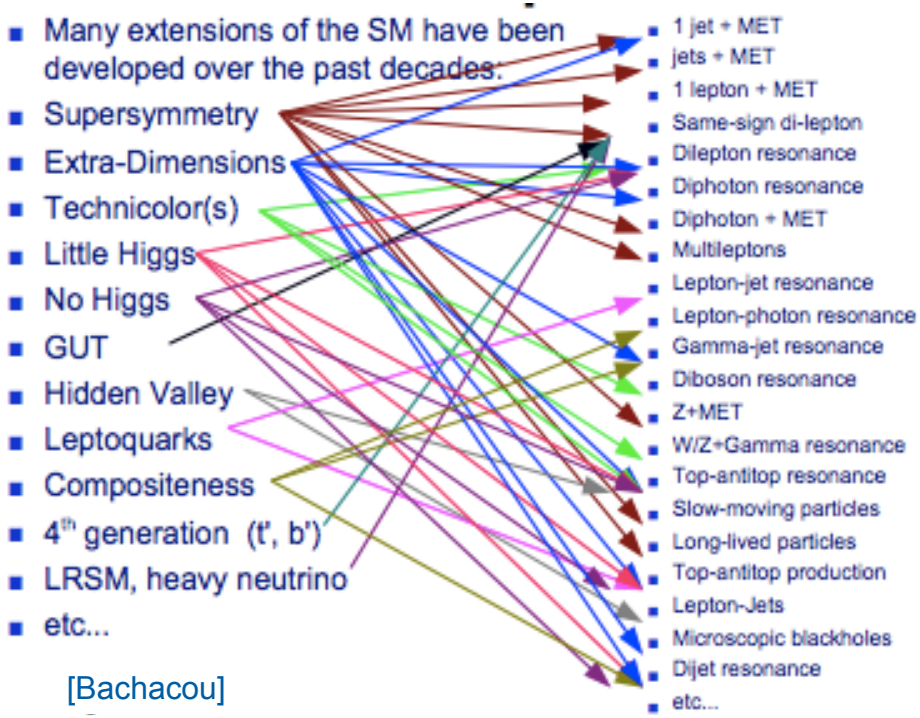

[Bachacou]

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[Murayama]

BSM Searches @ LHC – New Results

Heavy Resonance, Leptons

TeV-scale gravity l+j arXiv:1204.4646

Resonant WZ → lvll arXiv:1204.1648

b' to Zb ATLAS arXiv:1204.1265

Like-sign leptons ATLAS-CONF-2012-069

Z' to ττ ATLAS-CONF-2012-067

WW to lvlv ATLAS-CONF-2012-068

Monophoton ATLAS-CONF-2012-085

W' ATLAS-CONF-2012-086

Diphoton ATLAS-CONF-2012-087

μμ contact interact. CMS EXO-11-009

Boosted Z to μμ CMS EXO-11-025

e* CMS EXO-11-033

μ* CMS EXO-11-034

ADD in ee CMS EXO-12-013

Jet-based Searches

Monojet ATLAS-CONF-2012-084

b-jet resonances CMS EXO-11-008

Three-jet resonance CMS EXO-11-060

Dijet resonances CMS EXO-11-094

Boosted VV, Vjet CMS EXO-11-095

Lepton + Jets

LQ1 (eejj + evjj) CMS EXO-11-027

LQ2 (μμjj + μνjj) CMS EXO-11-028

Heavy Majorana N to ll EXO-11-076

VZ to l+jets CMS EXO-11-081

Heavy neutrino to μμjj EXO-11-091

RS Graviton in ZZ(2l2q) EXO-11-102

LQ3 -> τ+b CMS EXO-12-002

Long-Lived

Monopole ATLAS-CONF-2012-062

SUSY R-Hadron ATLAS-CONF-2012-075

Displaced μ jets ATLAS-CONF-2012-089

Non prompt lepton jets in HV decays ATLAS-CONF-2012-110

Stopped HSCP CMS EXO-11-020

Displaced photons CMS EXO-11-035

Fractionally charged CMS EXO-11-074

Multiply charged CMS EXO-11-090

Long-lived to displaced lep EXO-11-101

Top, 4th Gen and Boosted

Z' to ttbar l+j ATLAS arXiv:1205.5371

Z' to ttbar l+j boosted ATLAS-TOPQ-2011-23

t+b resonance ATLAS arXiv:1205.1016

t+j resonance ATLAS-CONF-2012-096

W' to top pair + jet CMS EXO-11-056

B to bZ CMS EXO-11-066

Z' to ttbar in l+jets CMS EXO-11-093

b'/t' inclusive CMS EXO-11-098

W' to tb CMS EXO-12-001

8 TeV Searches

Dijet 8 TeV ATLAS-CONF-2012-088

Black holes in 8 TeV CMS EXO-12-009

W' in 8 TeV CMS EXO-12-010

Z' in 8 TeV CMS EXO-12-015

Dijet in 8 TeV CMS EXO-12-016

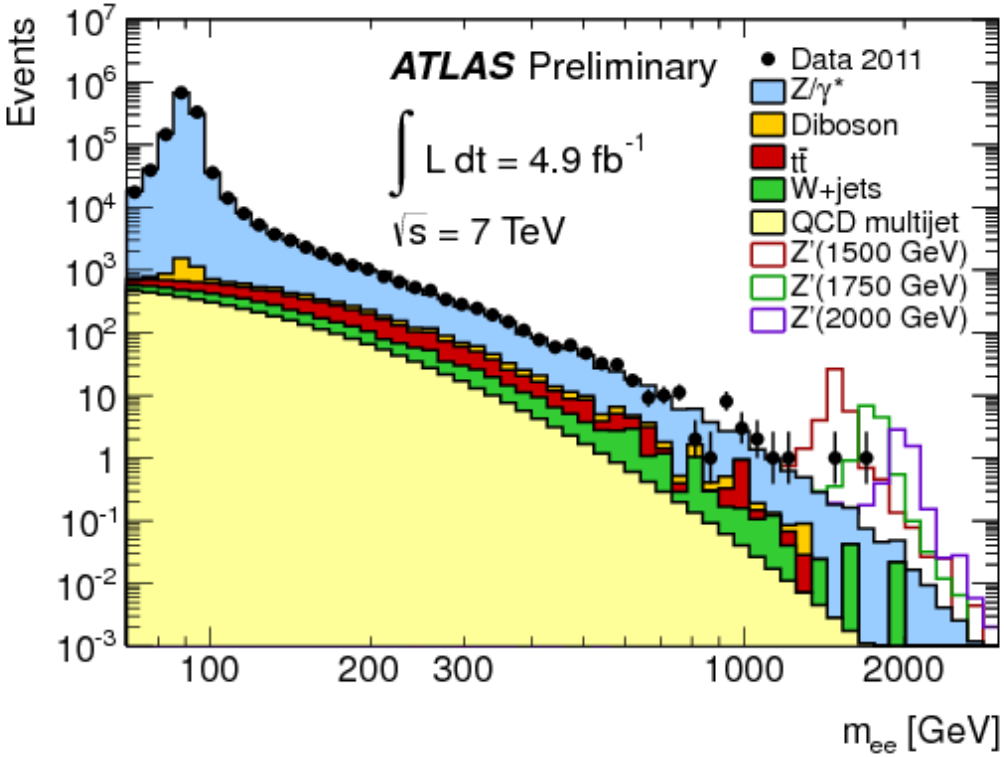
Heavy neutrino 8 TeV EXO-12-017

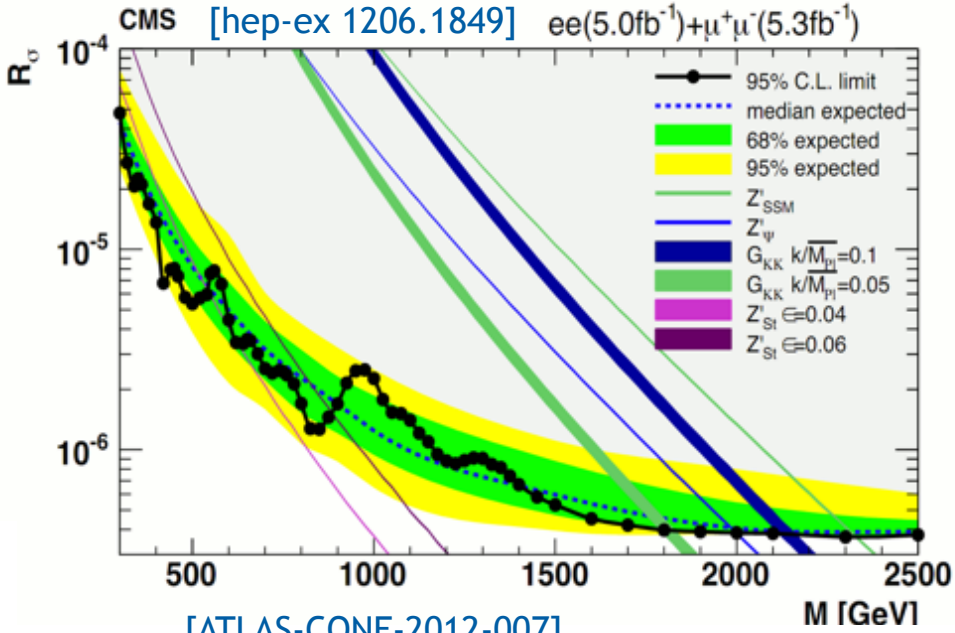
50 brand-new results since Moriond!

Z' IN 2011 DATA?

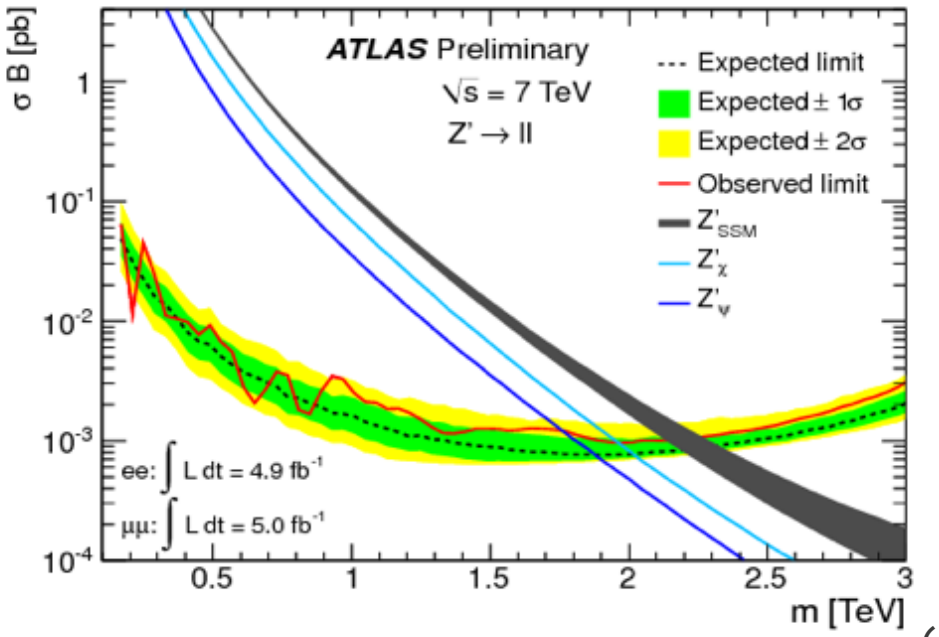
- Many new models have Z-like narrow resonances decaying to dileptons
- Interesting features in dilepton spectra
  - around 2σ each for CMS & ATLAS in e+μ
  - similar in scale to 2011 Higgs excess

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





[ATLAS-CONF-2012-007]

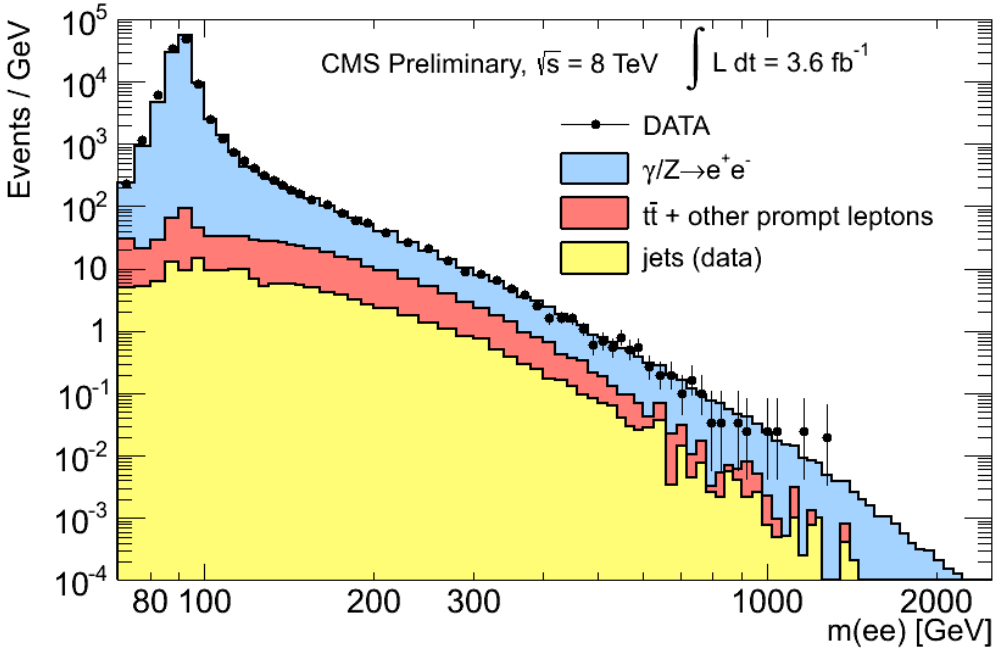


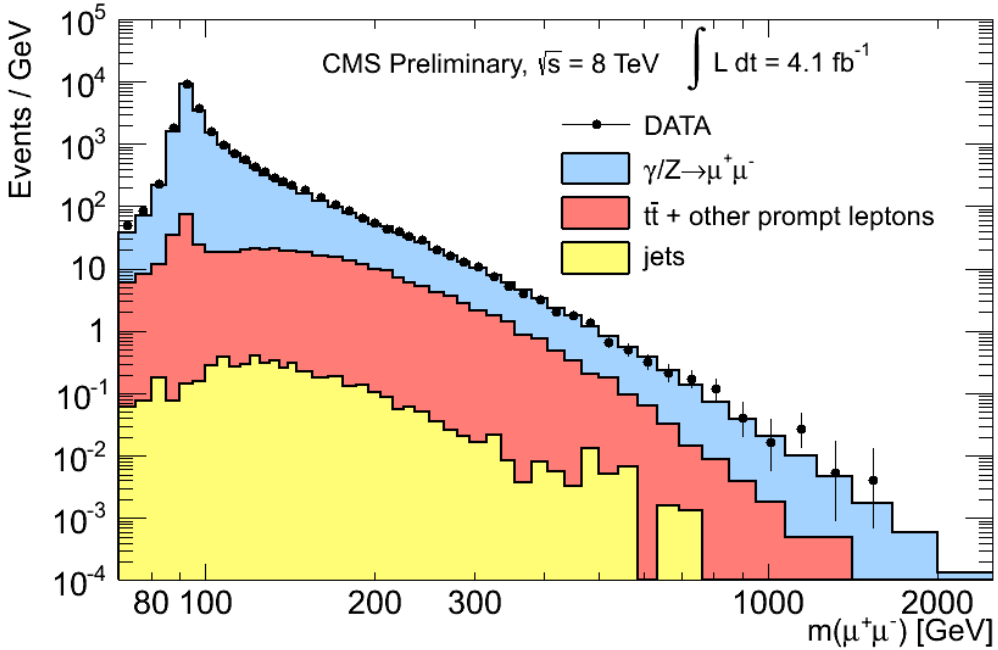
STATUS TODAY: Z' IN 8 TEV DATA

[CMS EXO-12-015]

- Event selection
  - E_T (e1,e2) > 35 GeV, p_T (μ1,μ2) > 45 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

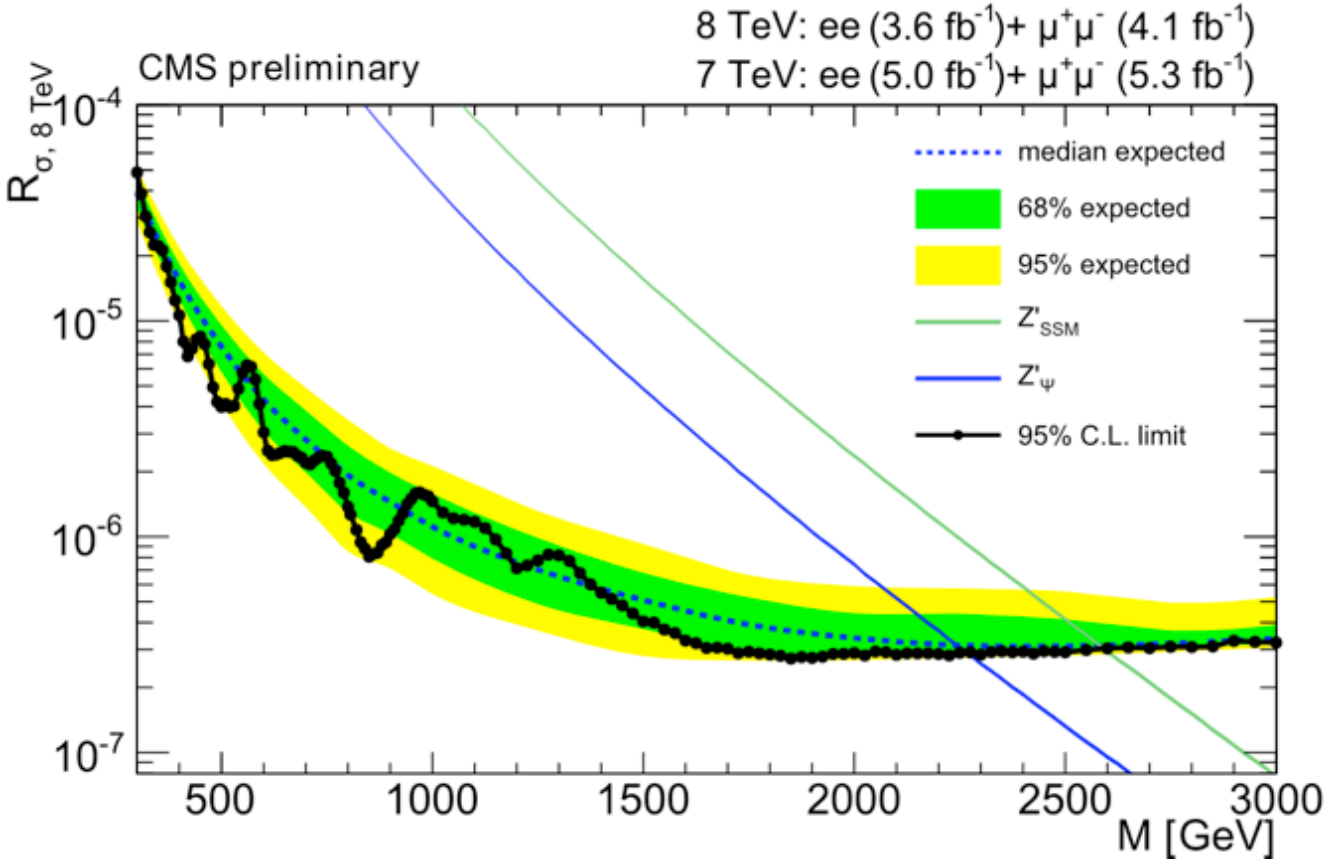
No obvious excess observed in 2012 data





Z' IN 8 TEV DATA

[CMS EXO-12-015]



- Short time between data-taking and result

$$R_\sigma = \frac{\sigma(pp \to Z' + X \to \ell\ell + X)}{\sigma(pp \to Z + X \to \ell\ell + X)}$$

- Limits on the combined 7 TeV and 8 TeV data from 2011+2012
  - M(Z'$_{SSM}$) > 2590 GeV at 95% C.L.
  - M(Z'$_{\psi}$) > 2260 GeV at 95% C.L.

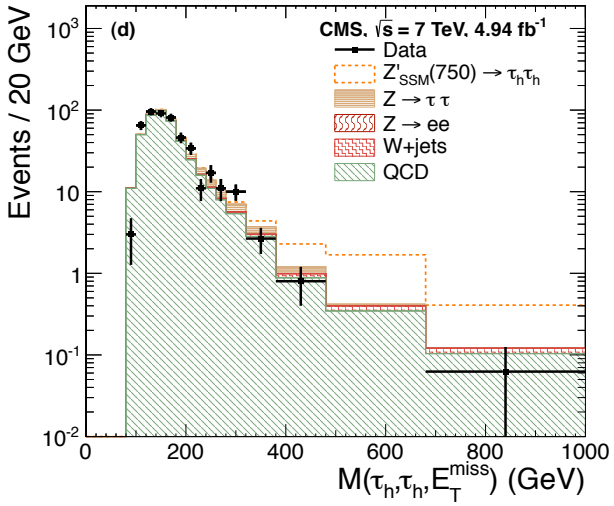
Excess just below 1 TeV all but gone in CMS data

Z' → τ τ

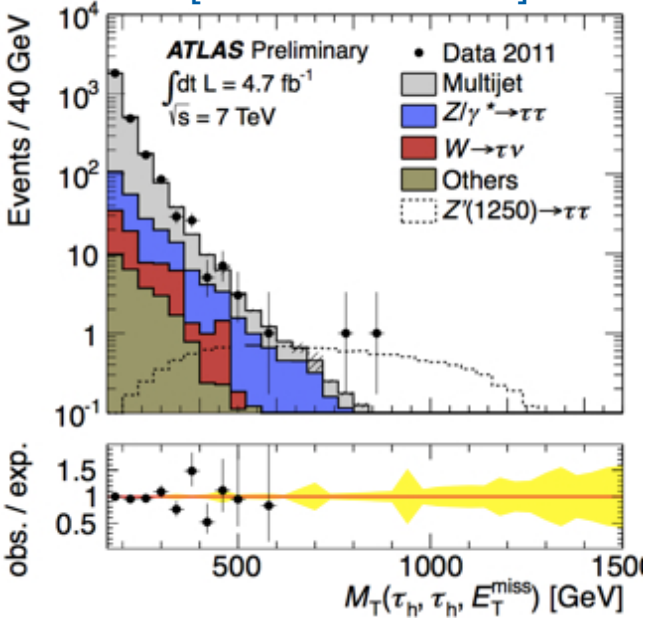
- Z' might couple preferentially to third-generation fermions
  - 5 fb-1 at √s = 7 TeV
  - Study: $\tau_e\tau_\mu$, $\tau_e\tau_h$, $\tau_\mu\tau_h$, $\tau_h\tau_h$
  - plot effective (visible) mass
- Backgrounds:
  - DY Z → ττ, W+jets, tt, VV, QCD
  - estimated from data where possible

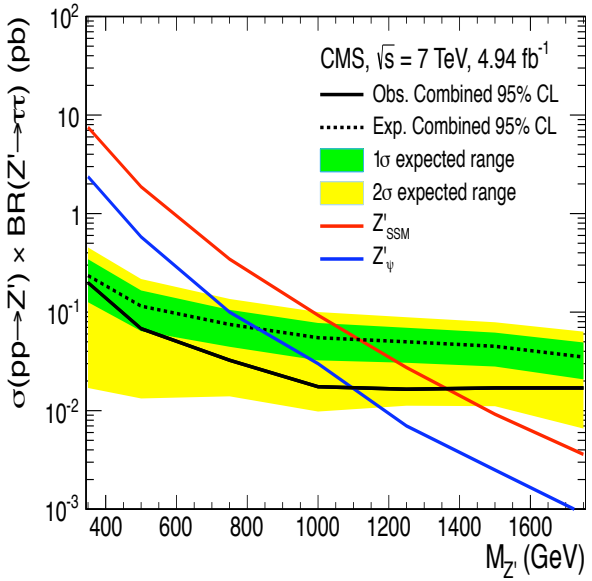
$M(Z'_{SSM})$	expected	observed
CMS	> 1.1 TeV	> 1.4 TeV
ATLAS	> 1.4 TeV	> 1.3 TeV

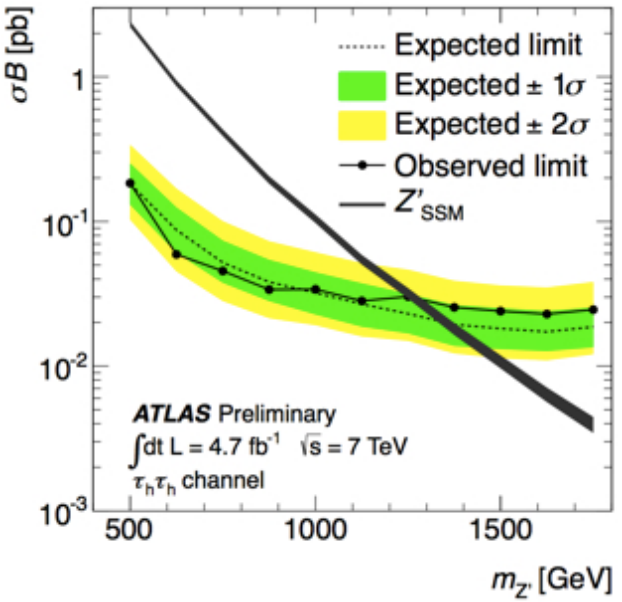
[CMS EXO-11-031, hep-ex 1206.1725]



[ATLAS-CONF-12-067]







W' → lν IN 8 TEV DATA

[CMS PAS EXO-12-010]

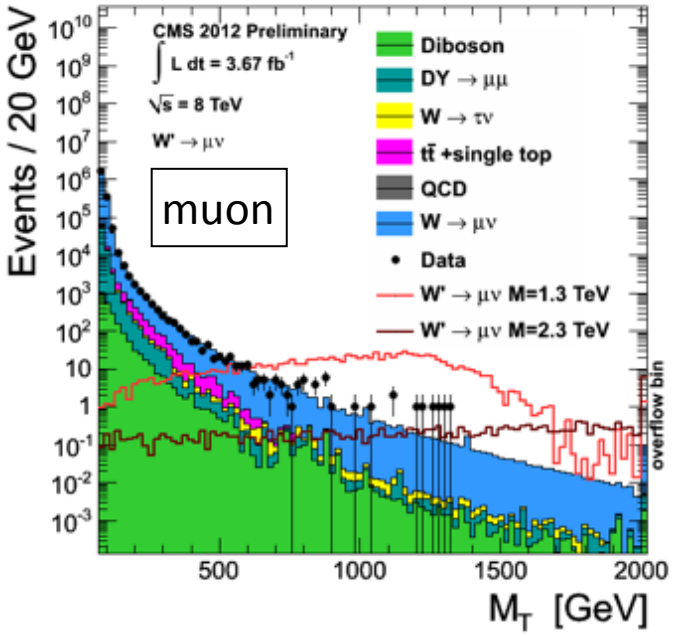
- Search for a new heavy gauge boson W' decaying to a charged lepton (μ or e) and ν

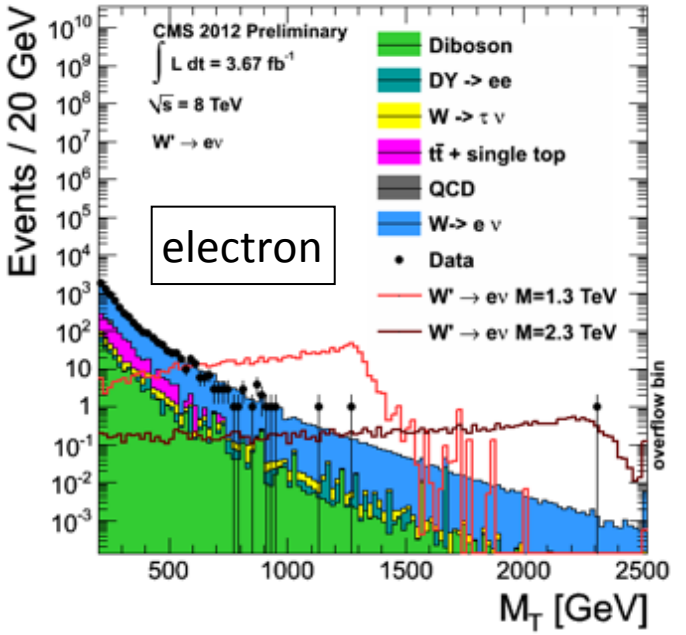
$$M_{\mathrm{T}} = \sqrt{2 \cdot p_{\mathrm{T}}^{\ell} \cdot E_{\mathrm{T}}^{\mathrm{miss}} \cdot (1 - \cos \Delta\phi_{\ell,\nu})}$$

- 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

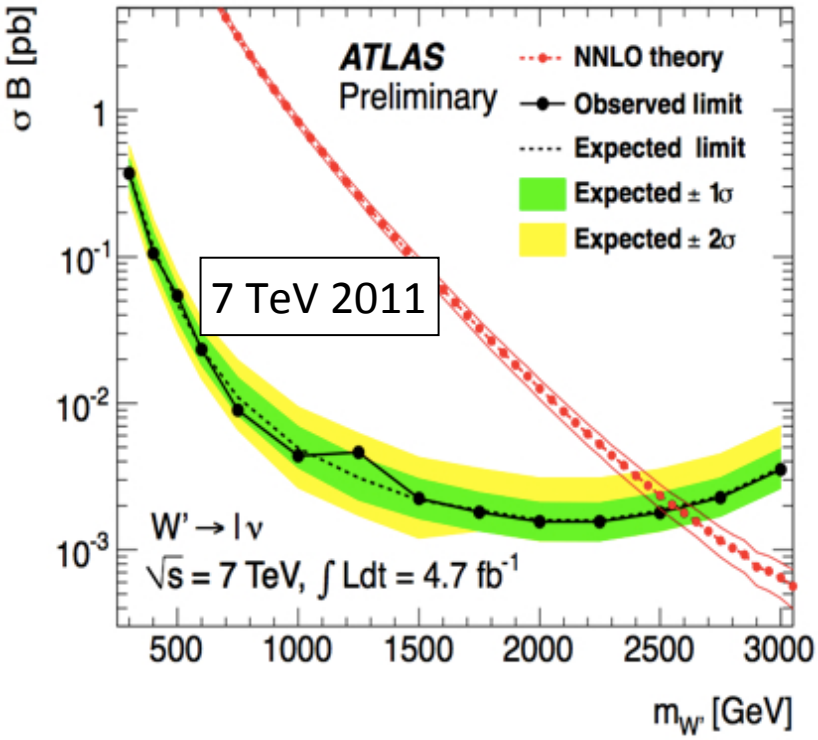
No significant excess observed



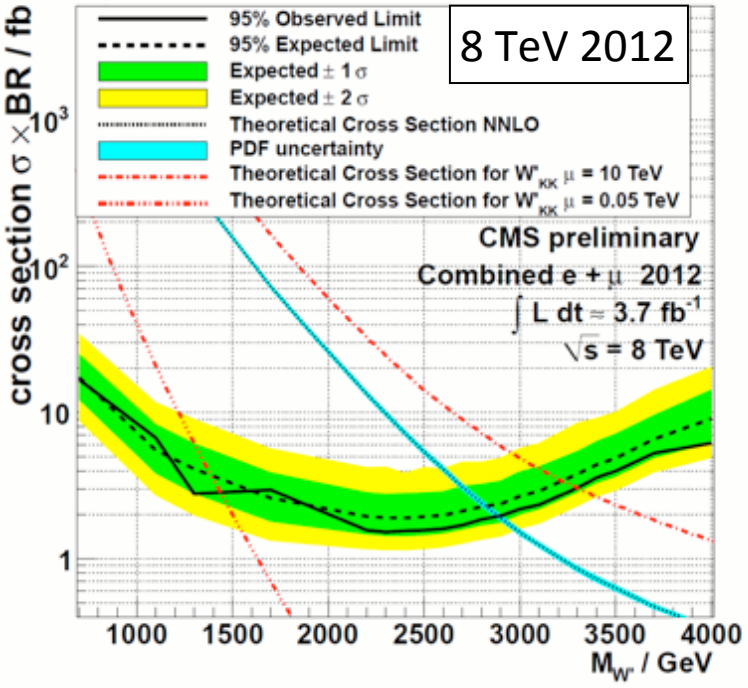


W' → lν IN 7 AND 8 TEV

[ATLAS-CONF-2012-086]



[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

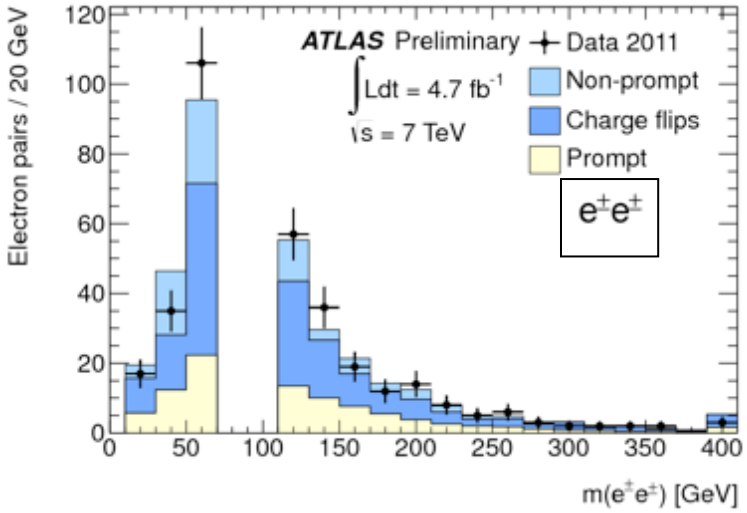
LIKE-SIGN DILEPTONS

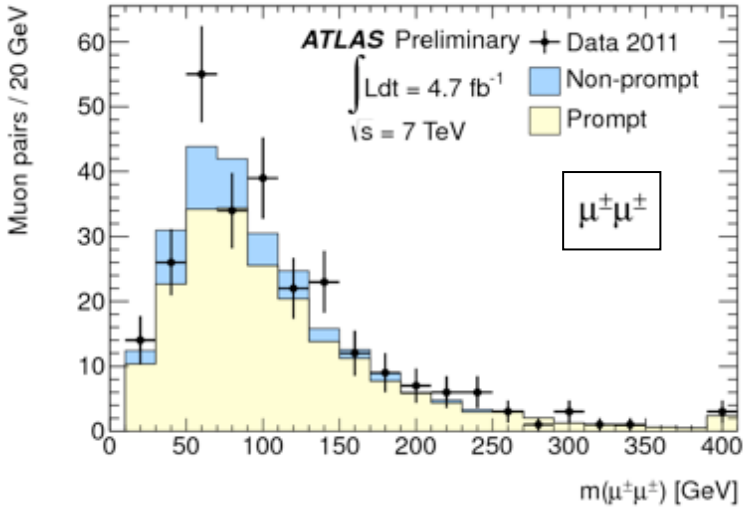
- Simple topology, yet sensitive to a wide range of new physics models
- Selection: high p_T $e^{\pm}e^{\pm}$, $\mu^{\pm}\mu^{\pm}$ pairs with m(ll) > 15 GeV (exclude Z peak from ee)
- Backgrounds:
  - WZ, ZZ: Sherpa/MCFM MC
  - Charge misid: MC + data-driven
  - Non-prompt leptons, fakes: Data-driven

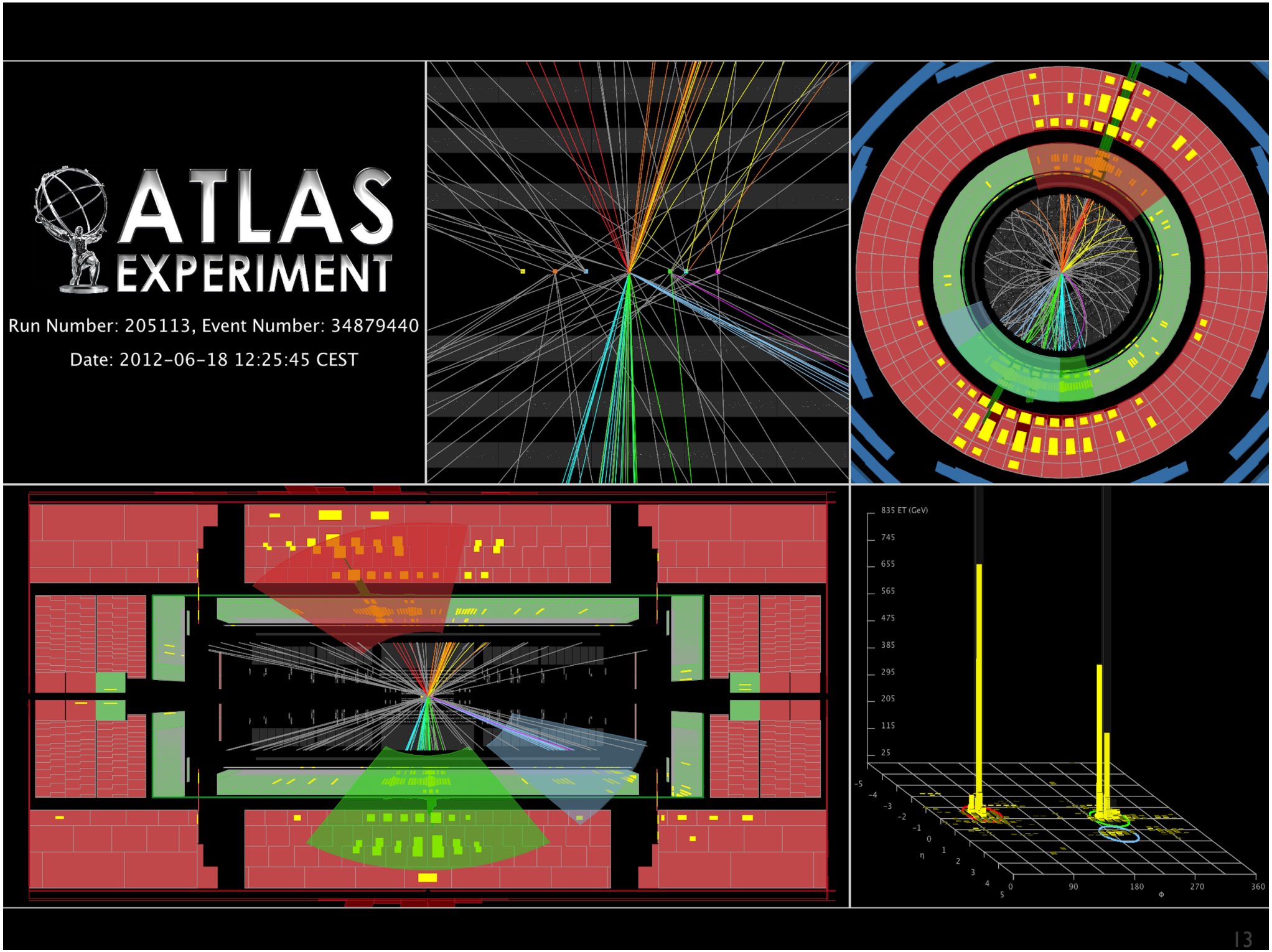
95% CL limits on σ between 1.7 fb and 45.7 fb

[ATLAS-CONF-2012-069]

Mass range	95% C.L. upper limit [fb] expected	observed	expected	observed
	$e^{\pm}e^{\pm}$		$\mu^{\pm}\mu^{\pm}$	
M > 15 GeV	$45.0^{+17.3}_{-12.0}$	45.7	$23.4^{+8.6}_{-5.8}$	29.1
M > 200 GeV	$8.8^{+3.2}_{-2.9}$	8.1	$4.2^{+1.8}_{-1.1}$	6.6
M > 400 GeV	$2.9^{+1.1}_{-0.9}$	2.3	$1.6^{+0.6}_{-0.5}$	1.7
	$e^{+}e^{+}$		$\mu^{+}\mu^{+}$	
M > 15 GeV	$27.3^{+10.0}_{-7.9}$	23.8	$14.7^{+6.0}_{-3.2}$	14.9
M > 200 GeV	$6.6^{+2.8}_{-1.5}$	6.5	$3.4^{+1.5}_{-0.7}$	4.2
M > 400 GeV	$2.4^{+1.1}_{-0.6}$	1.7	$1.5^{+0.6}_{-0.3}$	1.7
	$e^{-}e^{-}$		$\mu^{-}\mu^{-}$	
M > 15 GeV	$24.6^{+8.5}_{-6.8}$	29.1	$11.9^{+4.4}_{-3.4}$	18.0
M > 200 GeV	$4.7^{+1.9}_{-1.3}$	4.4	$2.7^{+1.1}_{-0.7}$	4.3
M > 400 GeV	$1.8^{+1.0}_{-0.4}$	2.2	$1.2^{+0.4}_{-0.0}$	1.1

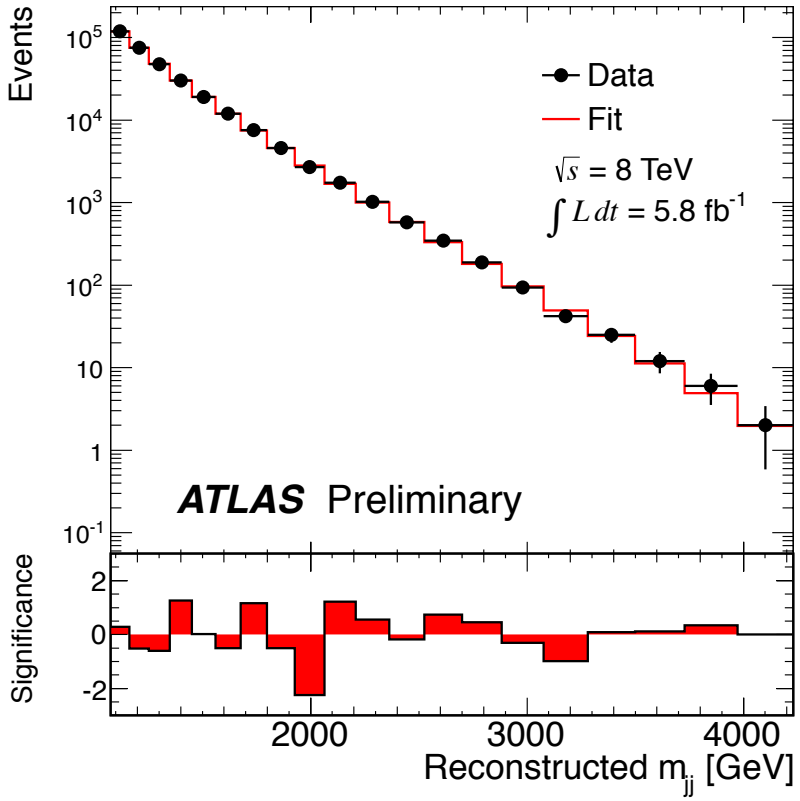




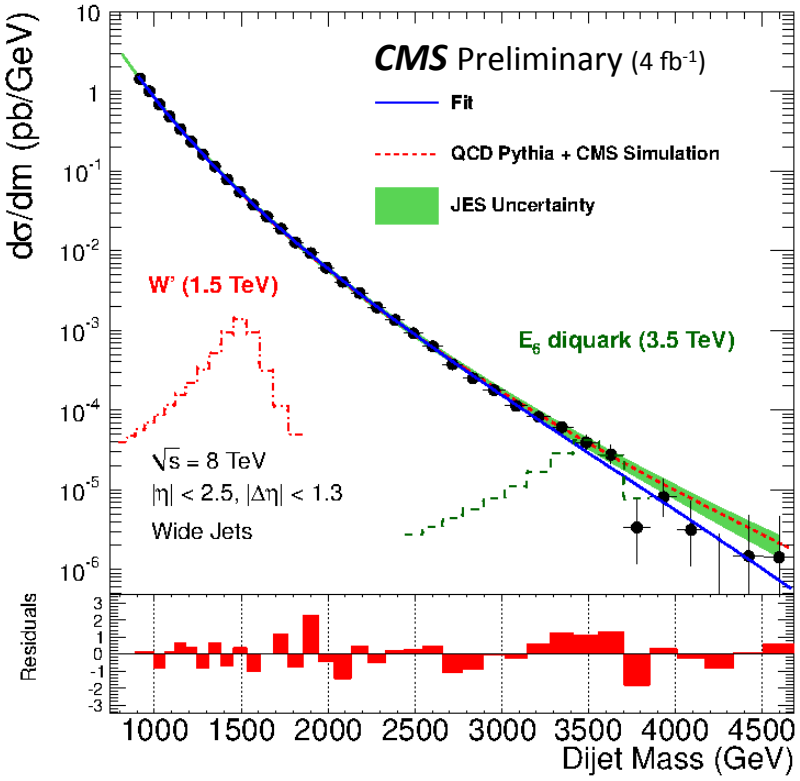

ATLAS
EXPERIMENT
Run Number: 205113, Event Number: 34879440
Date: 2012-06-18 12:25:45 CEST
835 ET (GeV)
745
655
565
475
385
295
205
115
25
η
Φ
0
90
180
270
360

DIJETS IN 8 TEV DATA

[ATLAS-CONF-2012-110]



[CMS PAS EXO-12-016]

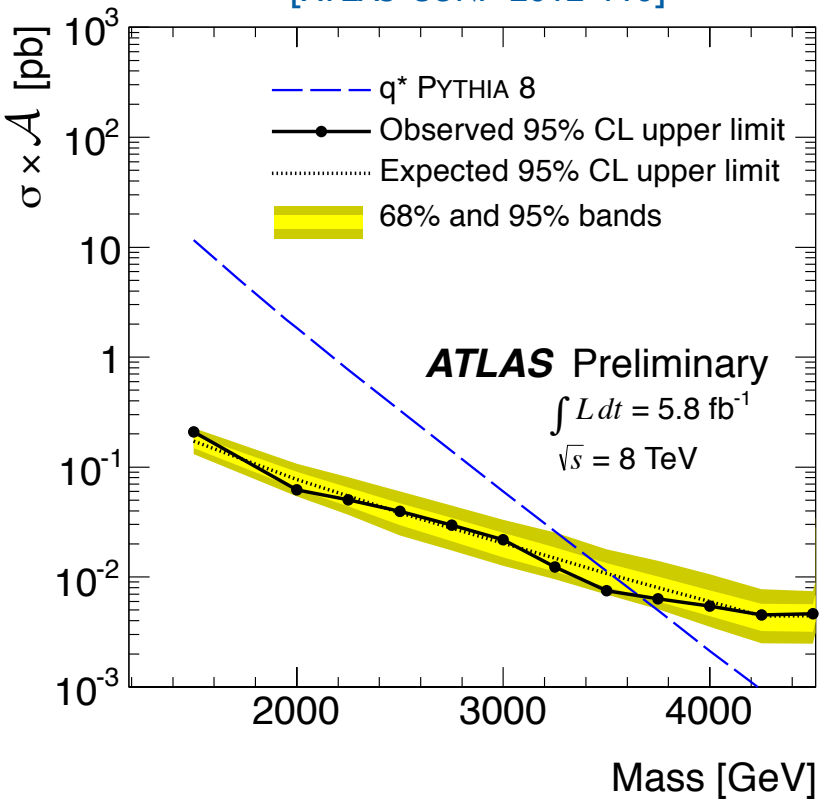


- Search for dijet resonance in smoothly falling mass spectrum
  - leading jet mass m_{jj} > 0.9-1 TeV from trigger and other constraints
  - Background estimated from smooth functional fit

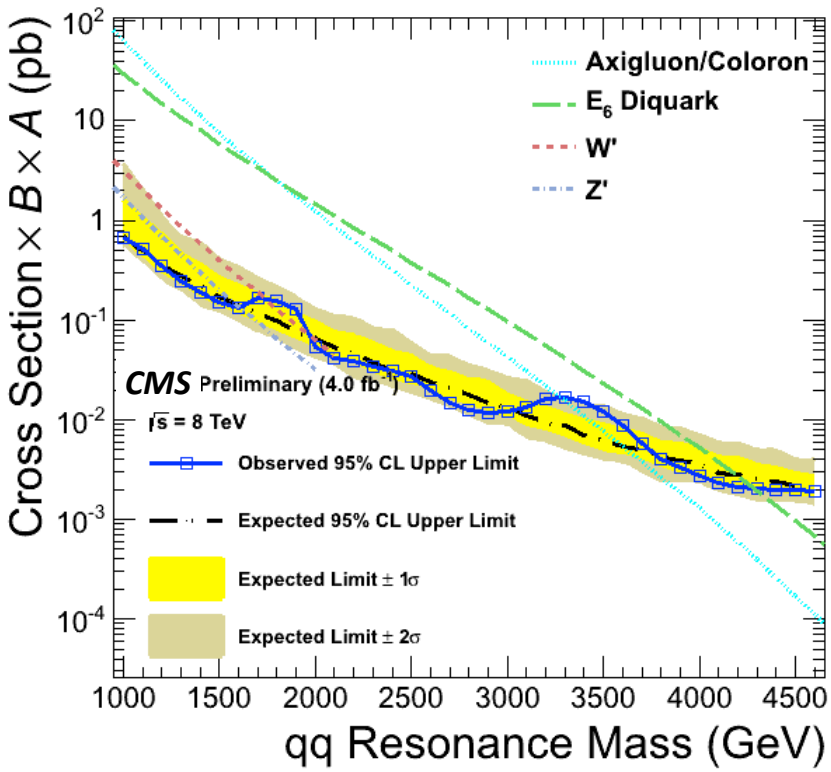
$$\frac{d\sigma}{dm_{jj}} = \frac{P_0(1-x)^{P_1}}{x^{P_2+P_3\ln(x)}}$$

DIJETS IN 8 TEV DATA

[ATLAS-CONF-2012-110]



[CMS PAS EXO-12-016]



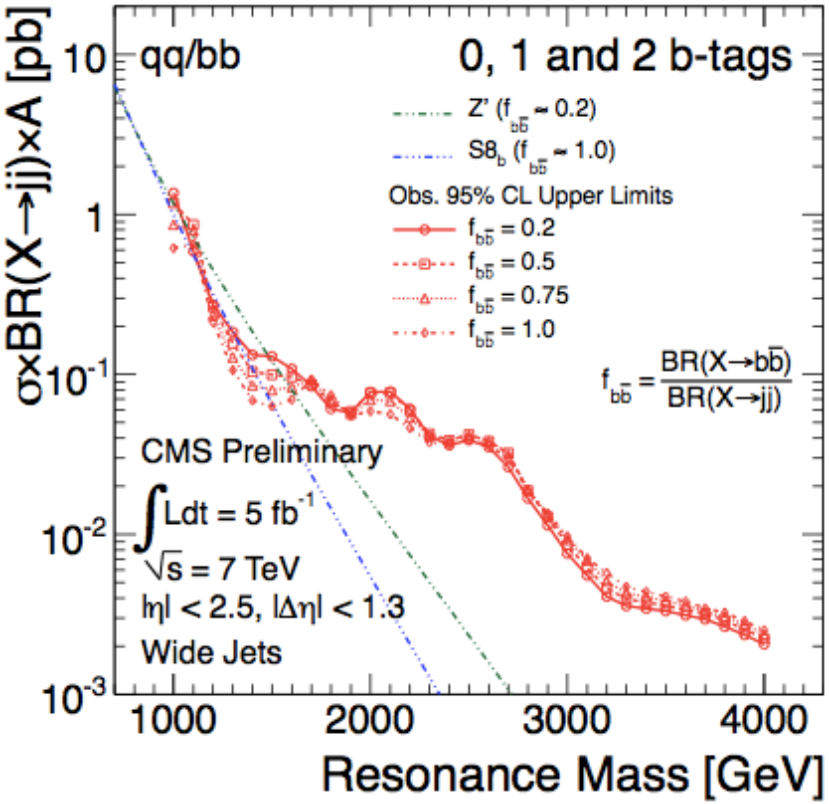
M(q*) 95% CL	Luminosity	Expected	Observed
ATLAS 2011	4.8	> 3.09 TeV	> 3.55 TeV
CMS 2011	5.0	> 3.27 TeV	> 3.05 TeV
CMS 2012	4.0	> 3.43 TeV	> 3.19 TeV
ATLAS 2012	5.8	> 3.53 TeV	> 3.66 TeV

DIJET WITH b-TAG

[CMS PAS EXO-11-008]

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

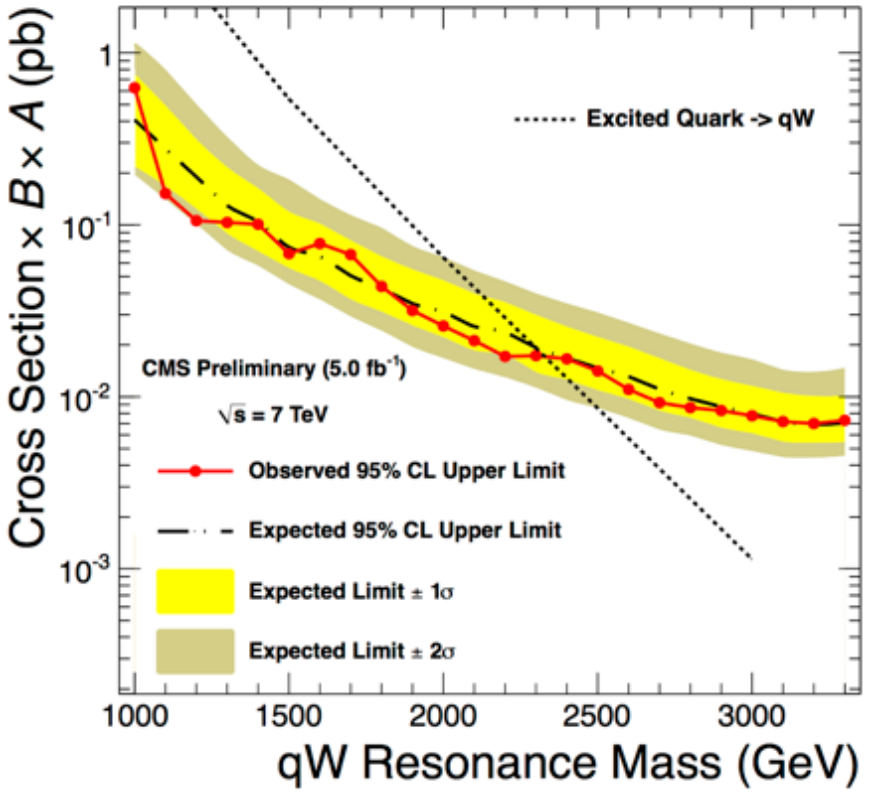
$$f_{b\bar{b}} = \frac{BR(X \to b\bar{b})}{BR(X \to jj)}$$



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



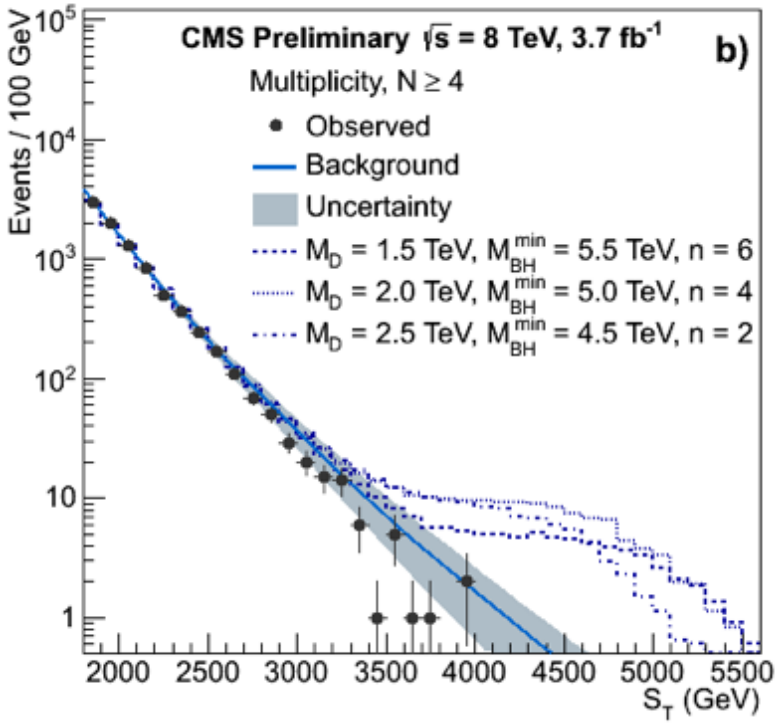
BLACK HOLES IN 8 TEV DATA

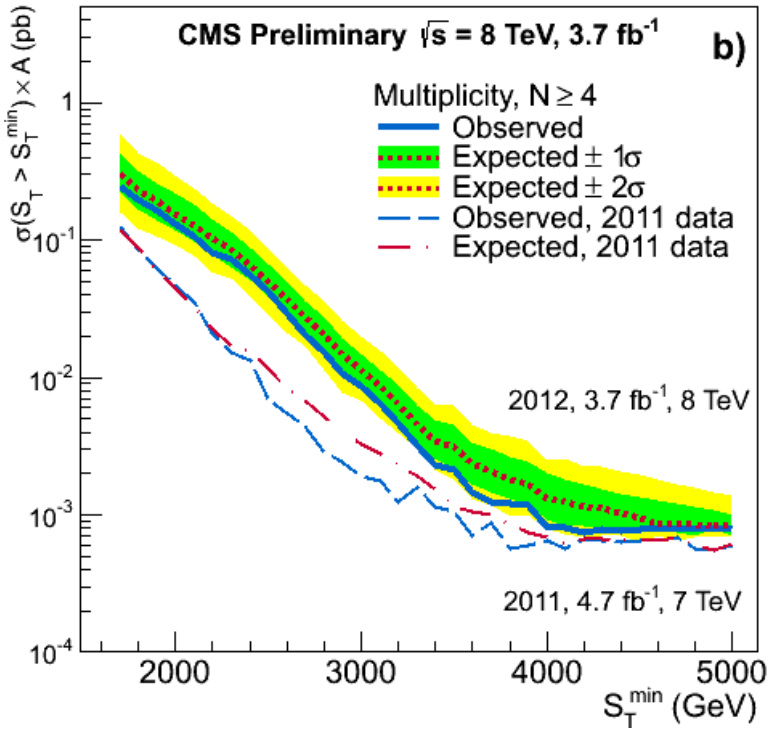
[CMS PAS EXO-12-009]

- 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

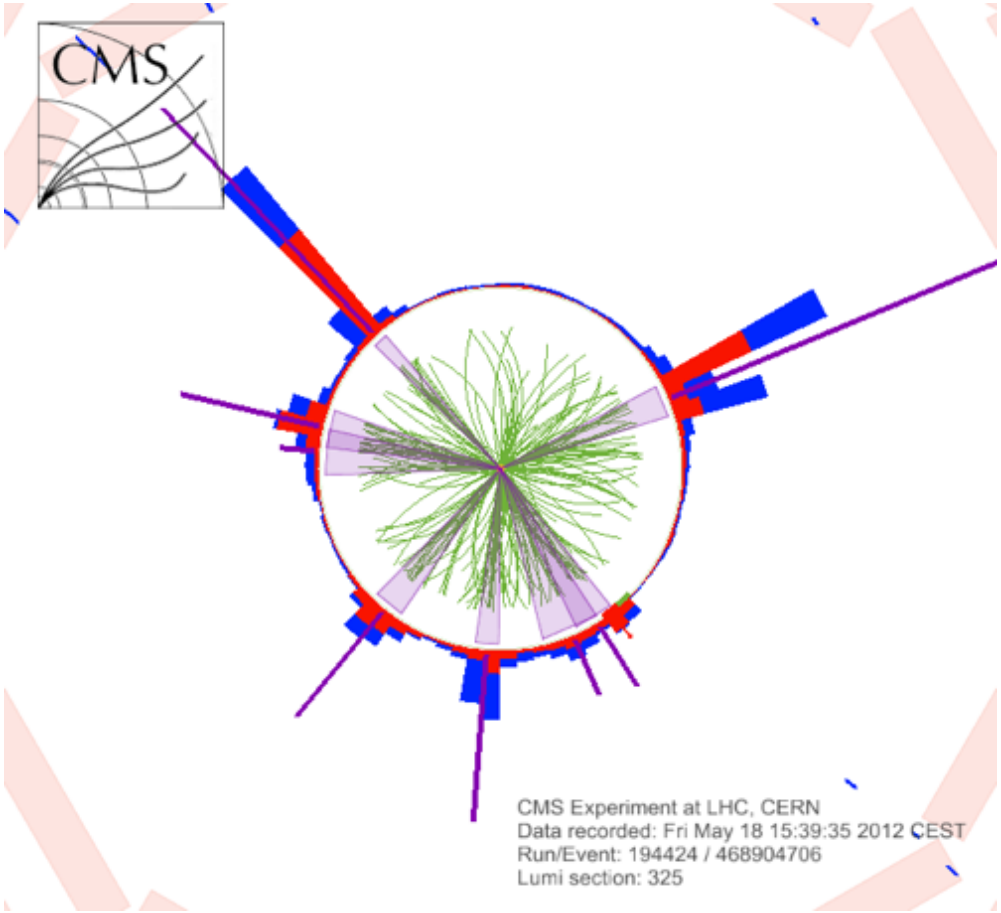
$$S_T = \sum_{j,e,\mu,\gamma,MET}^{N} p_T$$

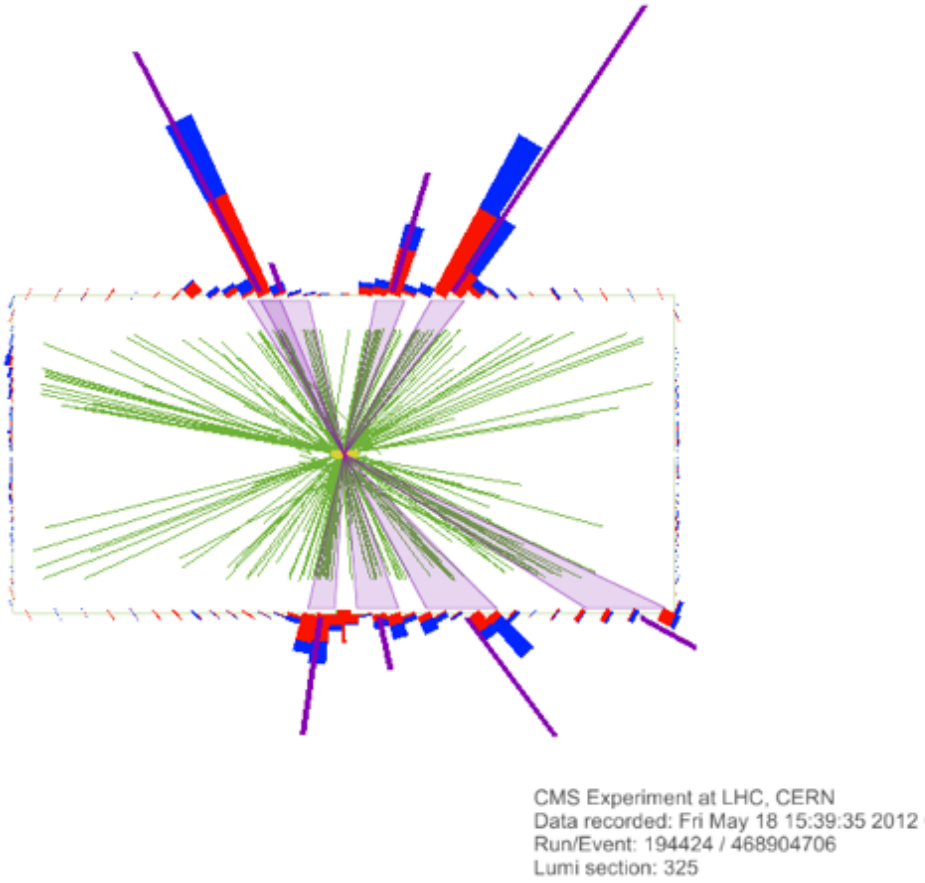
Large improvement in sensitivity (~10-20%) with respect to 2011 analysis





8-Jet Event, S_T = 3 TeV

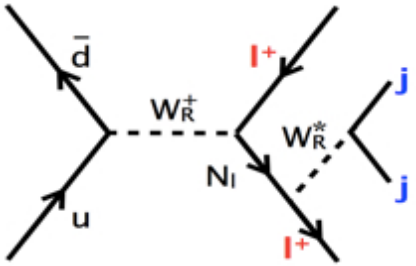




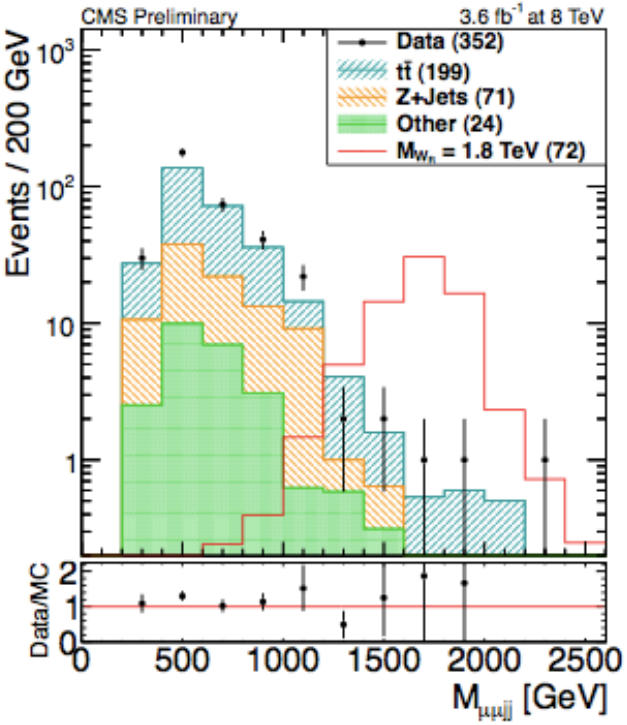
HEAVY NEUTRINO IN 8 TEV

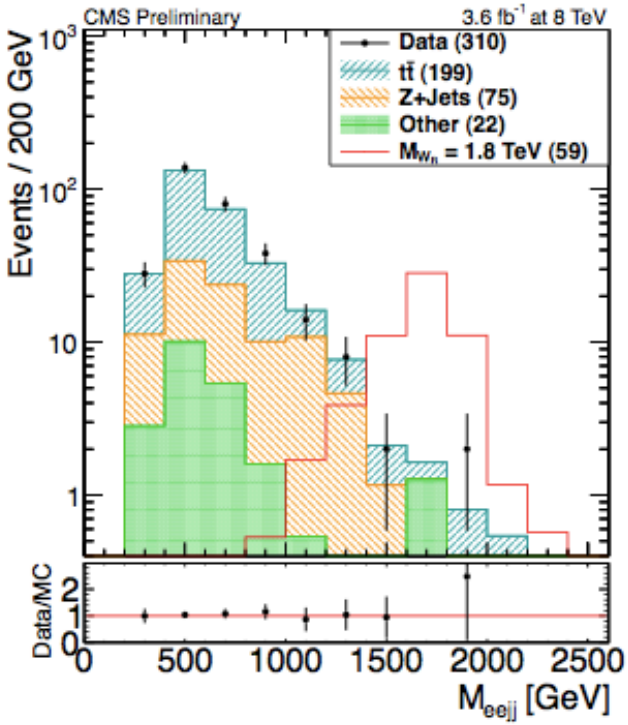
[CMS PAS EXO-12-017]

- 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



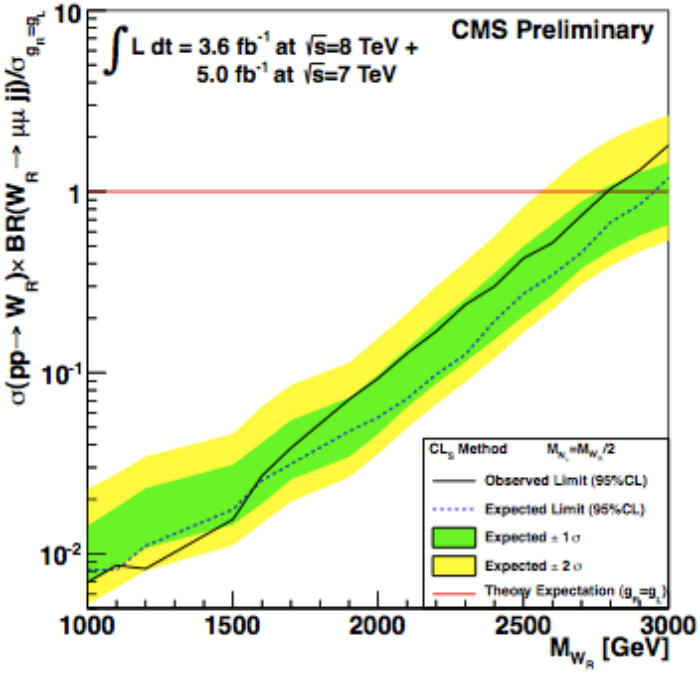


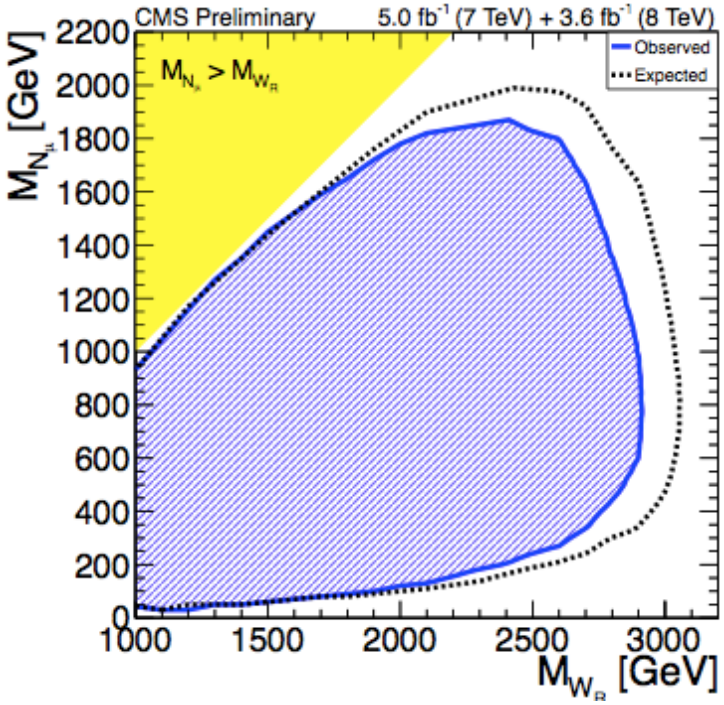
HEAVY NEUTRINO IN 8 TEV DATA

[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





MAGNETIC MONOPOLES

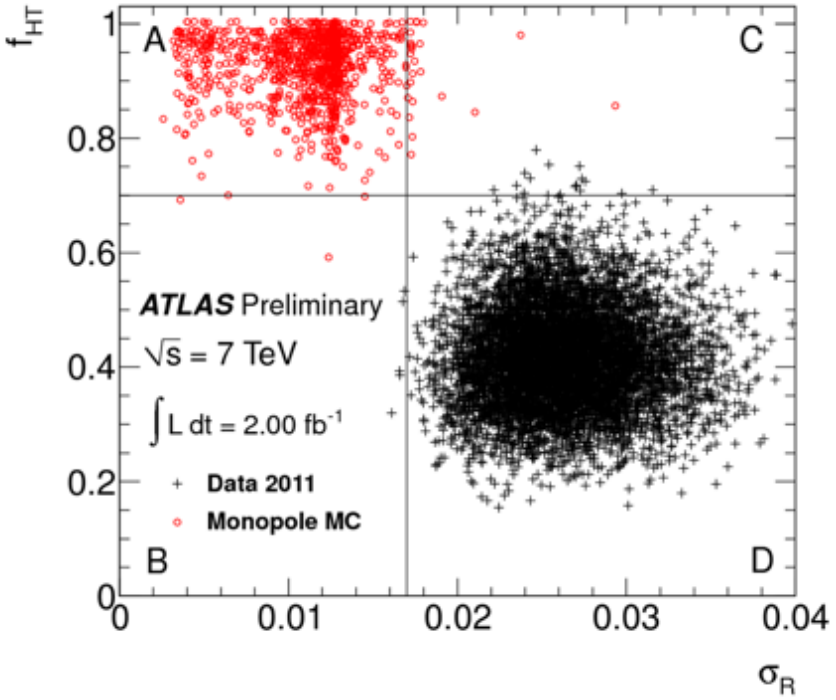
[ATLAS-CONF-2012-062]

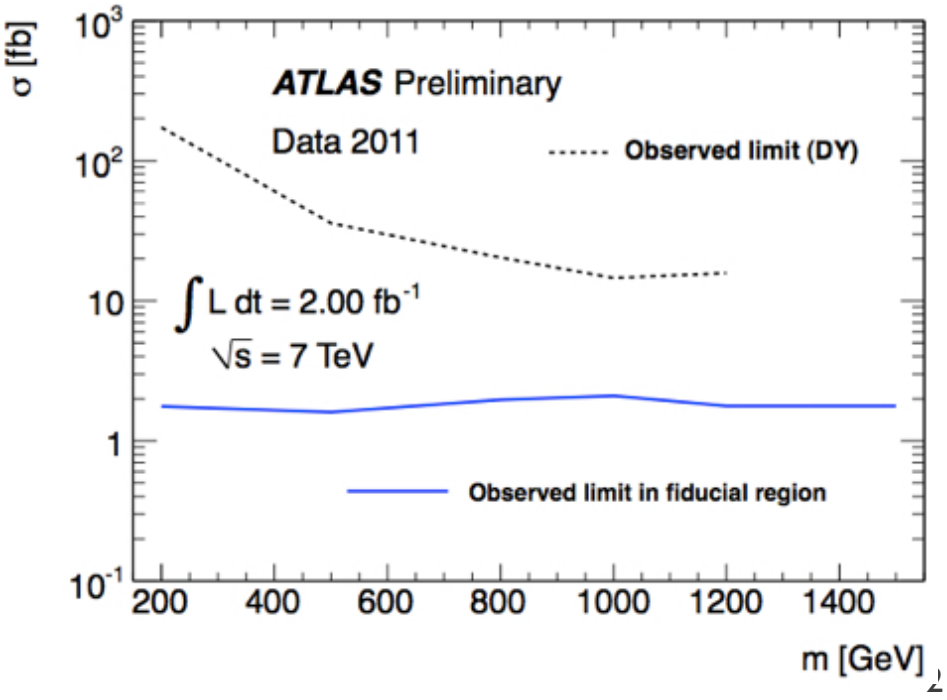
- Magnetic charge *g* yields strong coupling α_m and very high ionisation

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

- 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



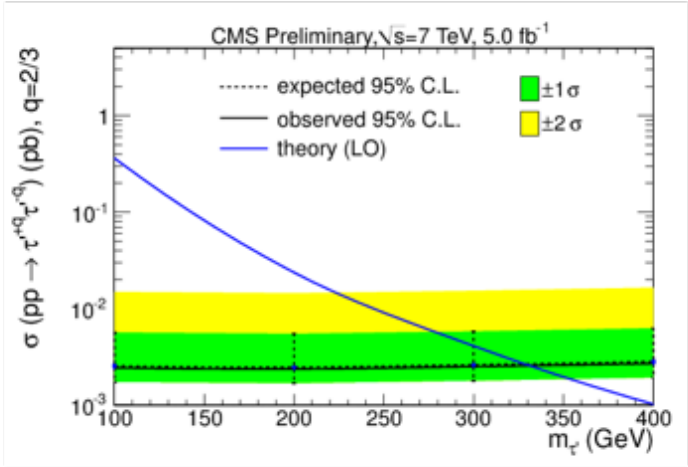


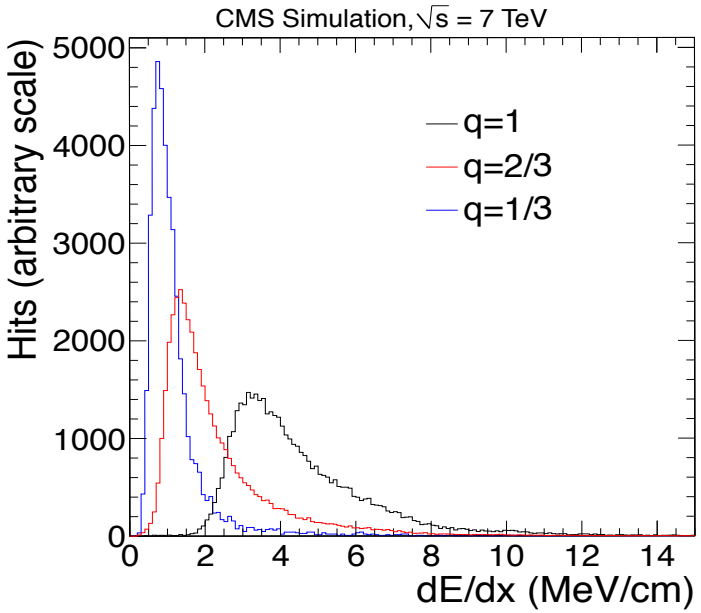
FRACTIONALLY CHARGED PARTICLES

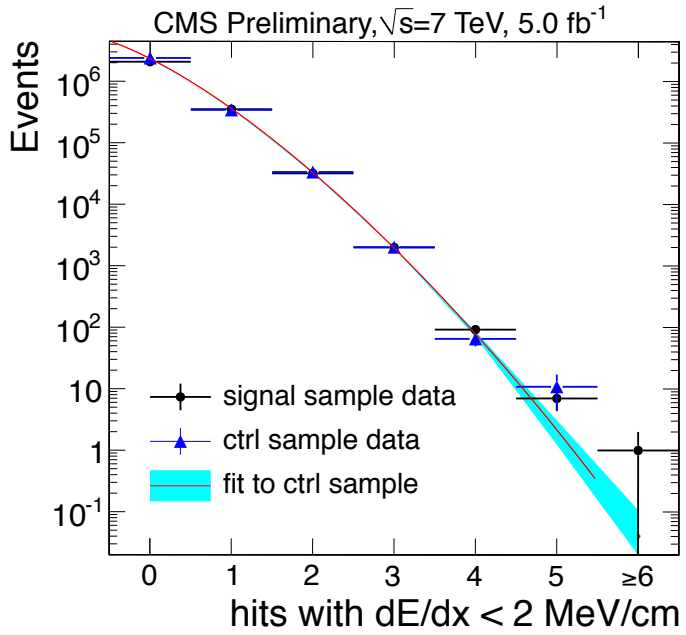
[CMS PAS EXO-11-074]

- 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



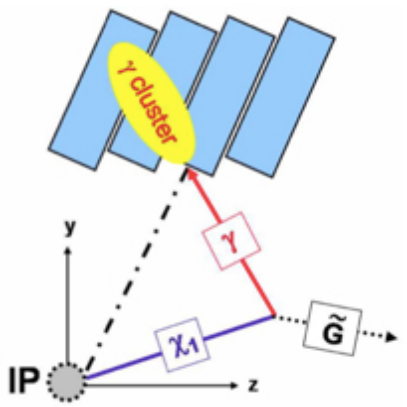




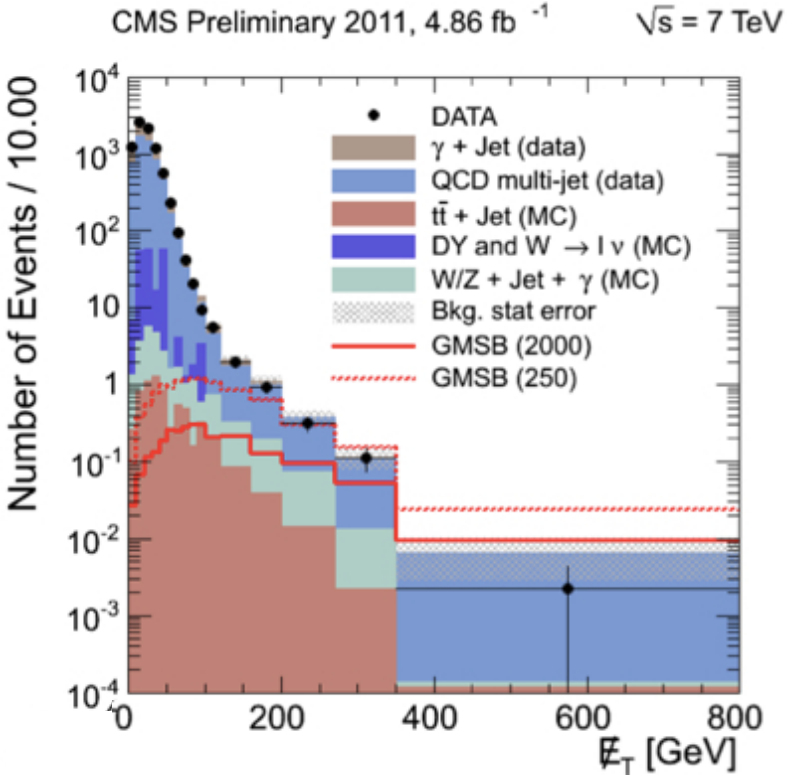
GMSB WITH DISPLACED PHOTON

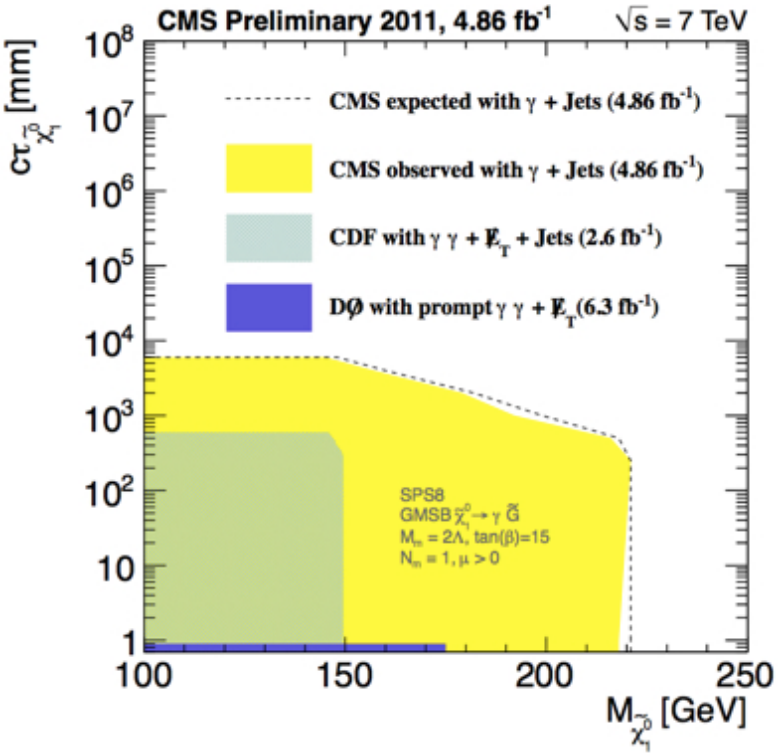
- GMSB (SUSY) decays typically include many jets and $\tilde{\chi}_1^0 \rightarrow \tilde{G}\gamma$
- Selection: photon with $E_T > 100$, three jets with $p_T > 35$
  - relaxed ECAL timing and shower-shape cuts
  - E_T^{miss} and ECAL timing main discriminants

[CMS PAS EXO-11-035]



Much-improved sensitivity to long-lived neutralino

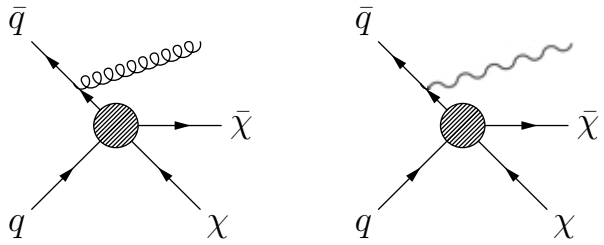




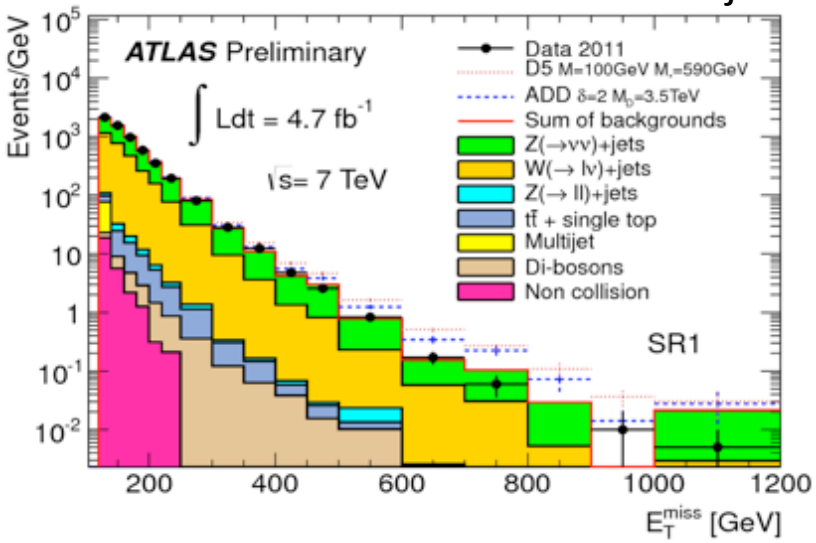
MONOJET AND MONOPHOTON

[ATLAS-CONF-2012-084, ATLAS-CONF-2012-085]

- Look for missing energy and radiated jet (photon)



monojet

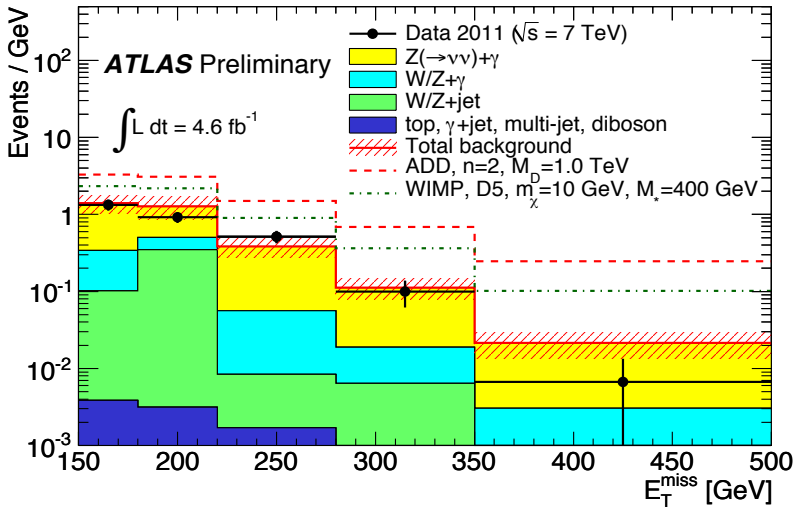


- Monojet Selection:
  - Leading jet p_T > 120 GeV, |η| < 2
  - allow a second jet if not back-to-back
  - veto isolated leptons

- 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

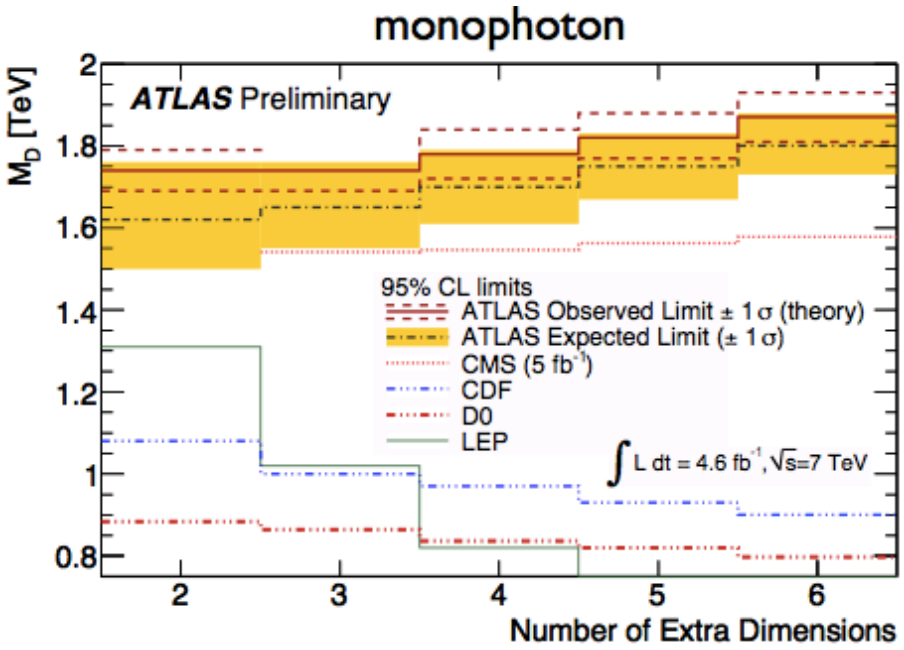


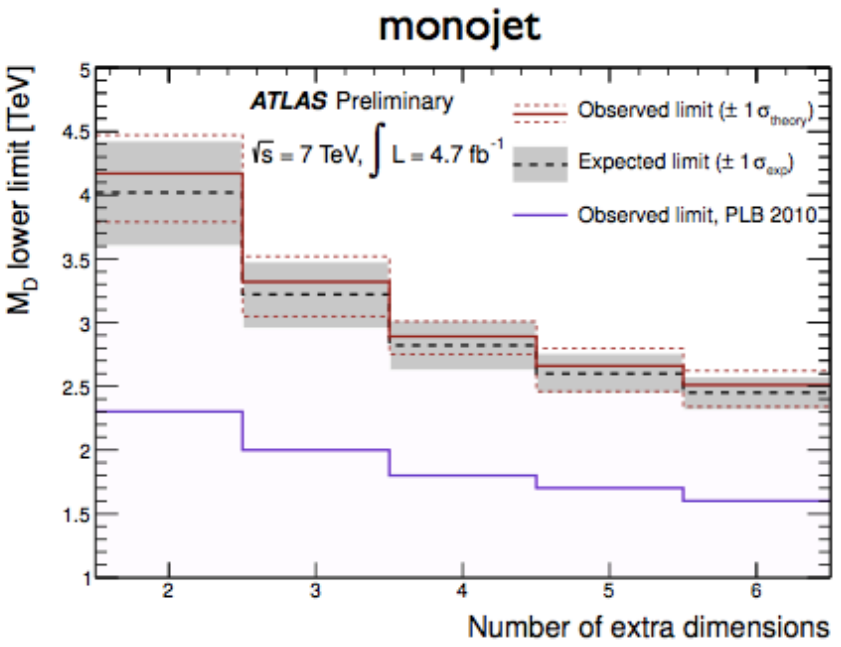
ADD FROM MONOJET AND MONOPHOTON

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

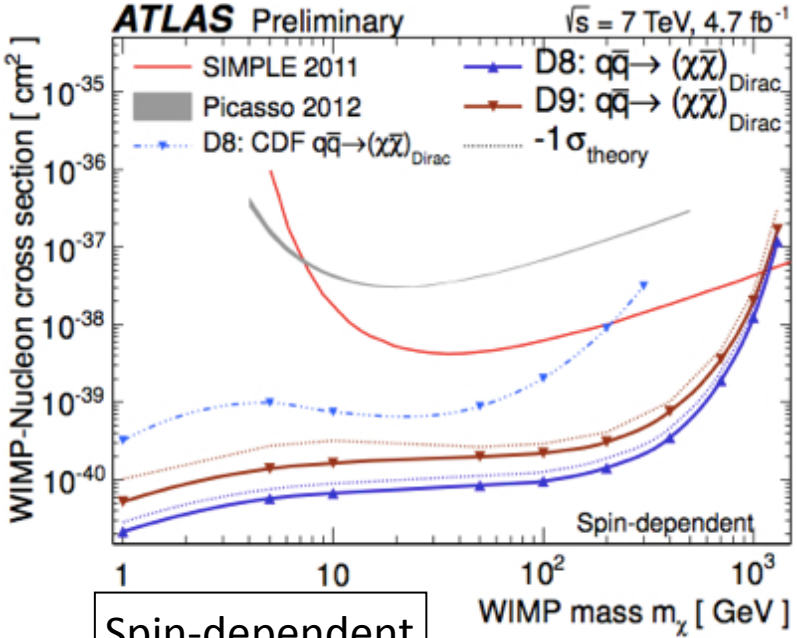




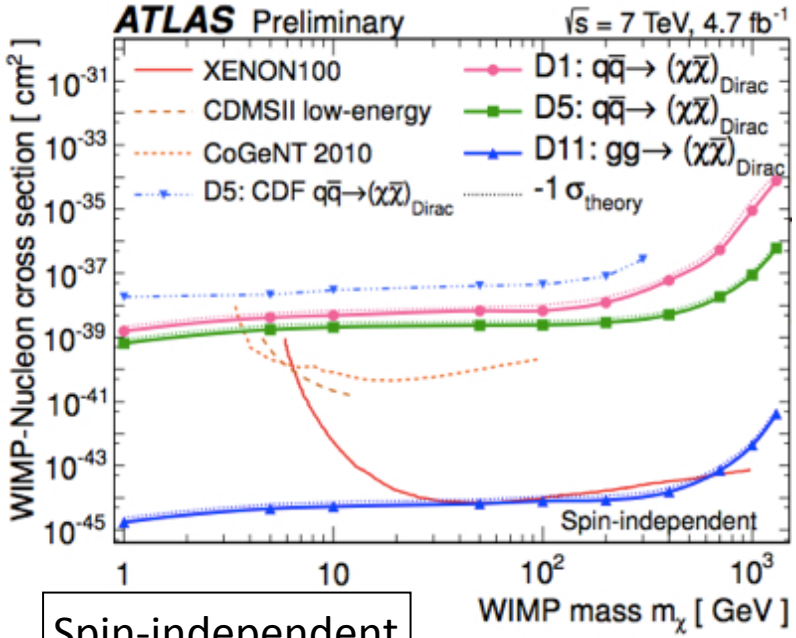
M_D (ADD) at LO 95% CL limits	Lumi [fb^{-1}]	δ=3 Exp.	δ=3 Obs.	δ=6 Exp.	δ=6 Obs.
CMS Monophoton	5.0	1.5	1.6	1.6	1.6
ATLAS Monophoton	4.6	1.7	1.7	1.8	1.9
CMS Monojet	5.0	3.1	3.2	2.3	2.4
ATLAS Monojet	4.7	3.2	3.3	2.4	2.5

DARK MATTER AND MONOJETS

[ATLAS-CONF-2012-084]

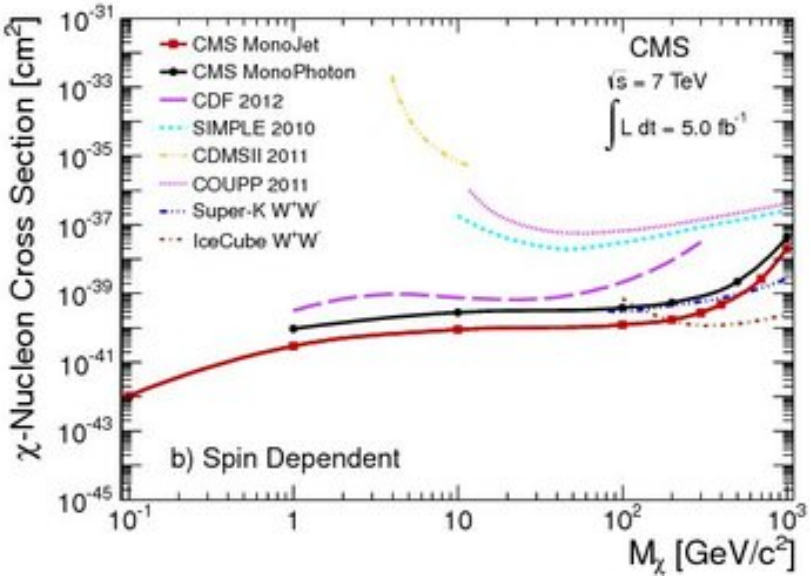


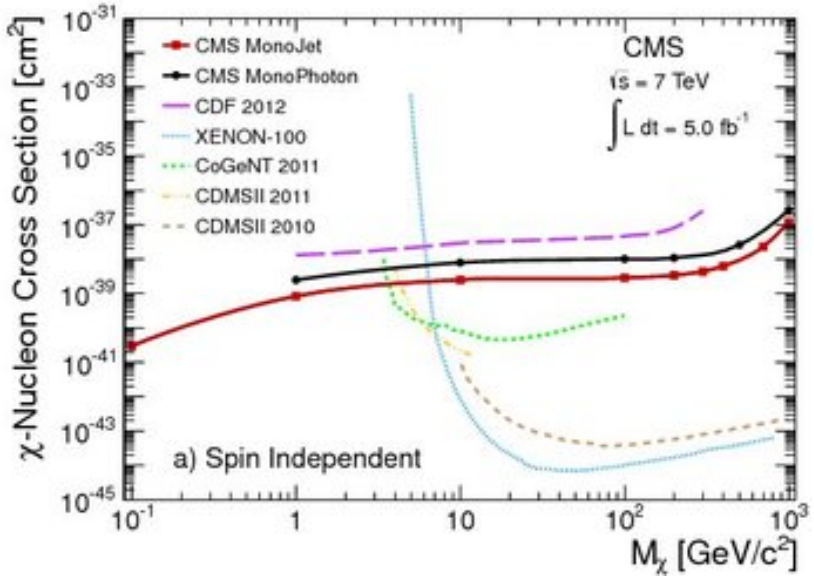
Spin-dependent

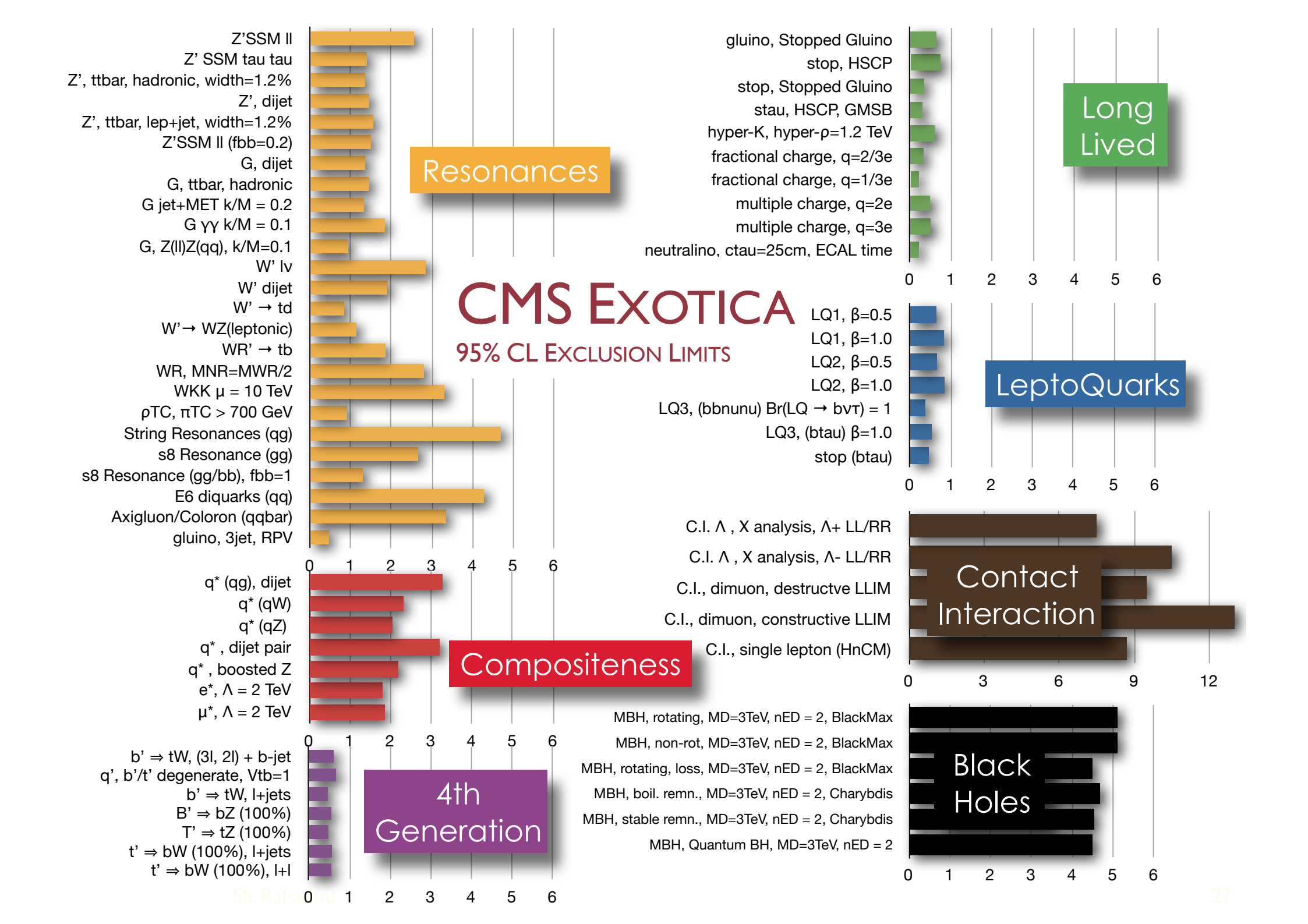


Spin-independent

[CMS EXO-11-059]






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
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

CONCLUSIONS

- Tremendous progress in Beyond the Standard Model searches
  - short time from data to results: already have 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