Beyond the Standard Model Searches at the LHC

Ulrich Heintz

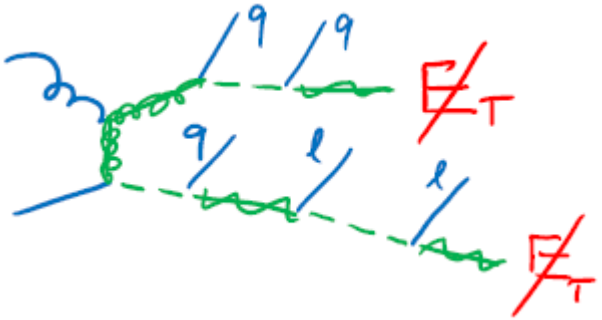
Brown University

outline

- The standard model is not the complete story
  - light Higgs - hierarchy problem
  - matter antimatter asymmetry
  - dark matter
  - ...
- where is physics beyond the standard model?
  - new symmetries
    - SUSY, LR symmetry
  - new dimensions
    - gravitons participate in particle interactions
  - new bosons
    - gauge bosons, KK states
  - new fermions
    - 4th generation, vector-like
  - something completely different

Supersymmetry

- inspired by string theory
- fundamental structure of space time
- predicts a superpartner for every known particle
  - enables unification of coupling constants
  - stabilizes a light Higgs boson mass
    - need at least the 3rd generation squarks to be light
  - mass spectrum is model dependent
    - interpret in simplified model scenarios
- R-parity conservation
  - superpartners produced in pairs
  - LSP is stable
  - provides a dark matter candidate
  - cascade decay to LSP
  - signature includes missing p_T

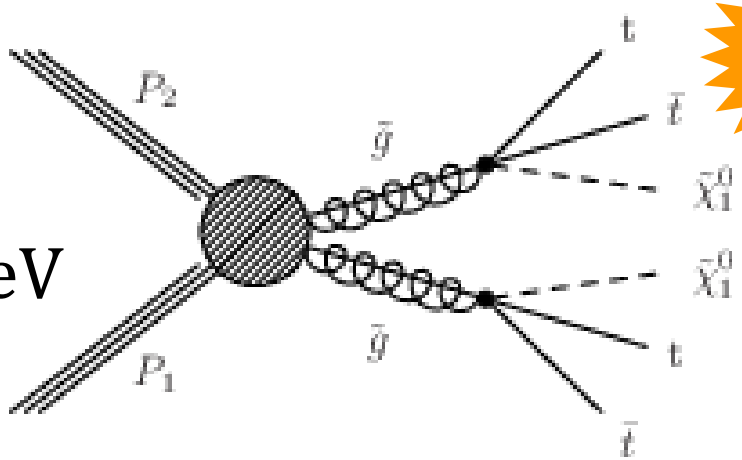


missing pT and b-jets

CMS PAS SUS-12-016

8 TeV
3.9/fb

- event selection
  - no isolated e or μ or γ
  - 2 jets with $p_T > 100$ GeV
  - no jets with $|\eta| > 3$
  - $H_T = \sum_{jets>50\ GeV} p_T > 275$ GeV

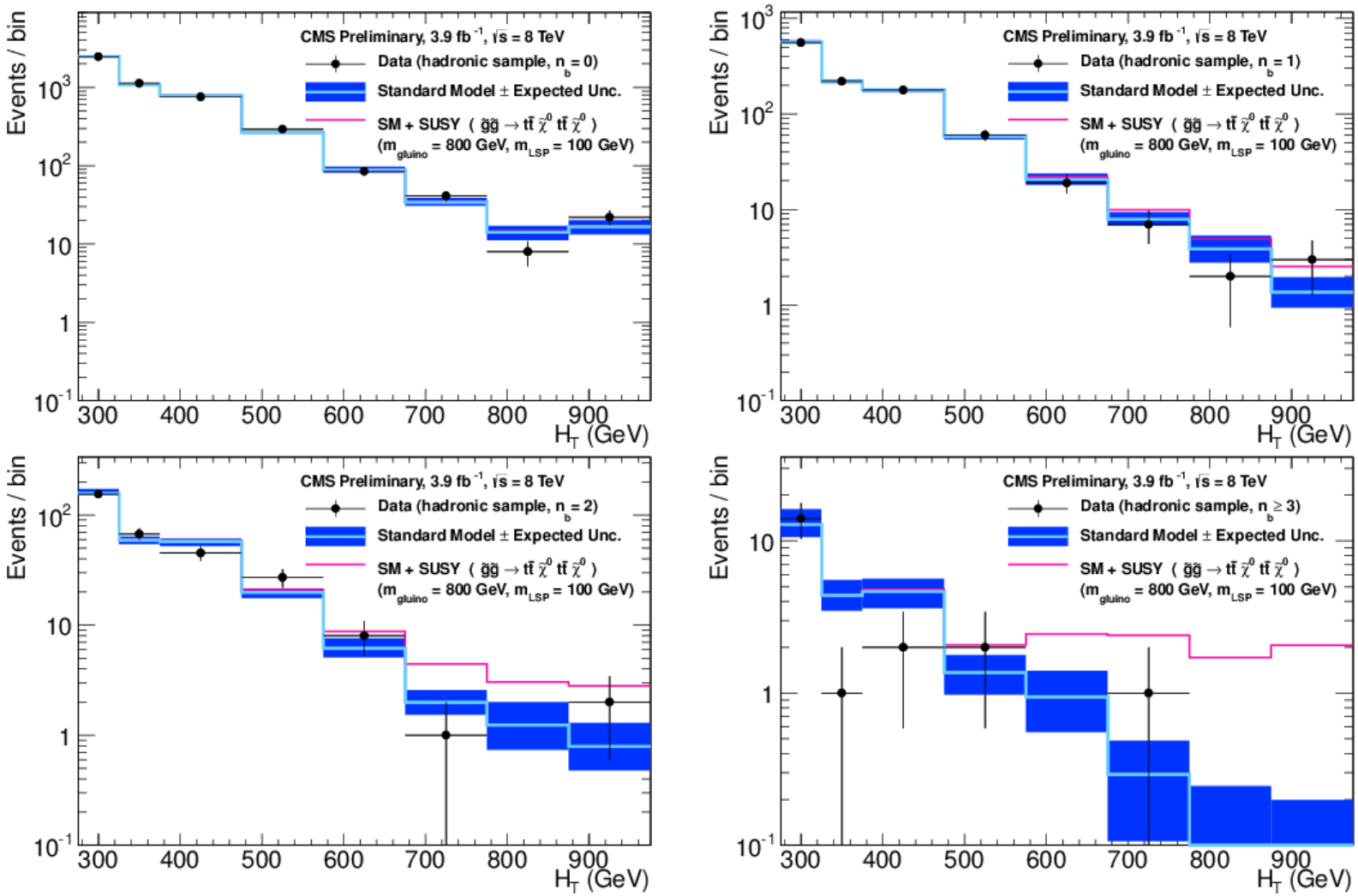


missing pT and b-jets

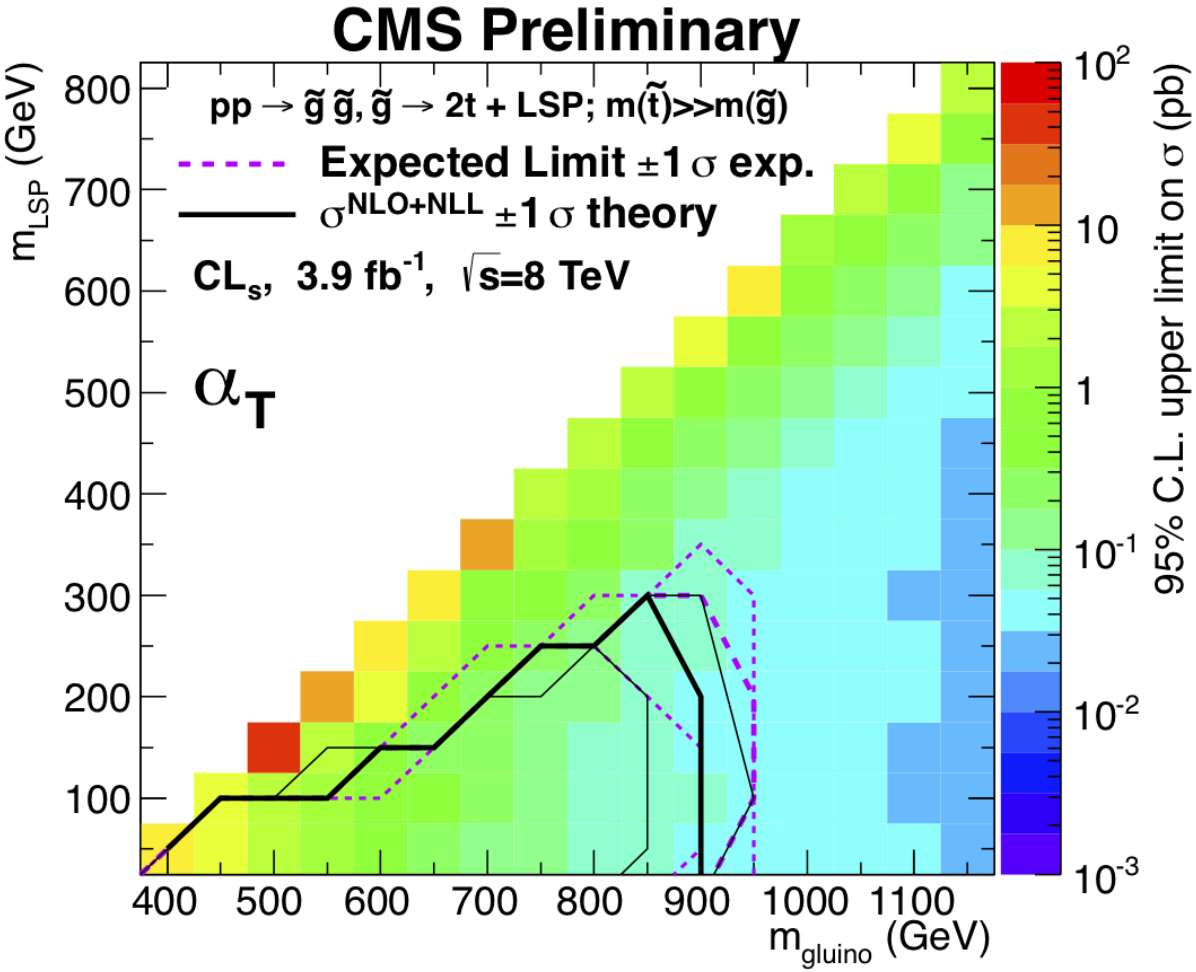
- combine all jets with $p_T > 50\ \mathrm{GeV}$ into two pseudojets
- analysis variable
  - $\alpha_T = \frac{{E_T}^{j2}}{M_T}$ with $M_T = \sqrt{\left(\sum_i {E_T}^{ji}\right)^2 - \left(\sum_i {p_x}^{ji}\right)^2 - \left(\sum_i {p_y}^{ji}\right)^2}$
  – for a perfectly balanced dijet event $\alpha_T = 0.5$
  – if the two jets don't balance $\alpha_T < 0.5$
  – if the two jets are not back-to-back $\alpha_T > 0.5$
- select $\alpha_T > 0.55$
- dominant backgrounds
  – for events w/o b-jets: $\mathrm{Z} \to \nu\nu$ and $\mathrm{W} \to \ell\nu$
  – for events with b-jets: $\mathrm{t\bar{t}}$ and $\mathrm{b} \to \ell\nu$
  – constrain with $\mu + jets$, $\mu\mu + jets$, and $\gamma + jets$ control samples

missing pT and b-jets

- simultaneous fit to H_T spectrum for 0,1,2, and ≥3 b-jets



missing pT and b-jets



systematic uncertainties	
background	20-70%
$\int \mathcal{L} dt$	4.4%
acc × eff	13%

- m(gluino) > 850 GeV for m(neutralino) = 50 GeV

like-sign dileptons and b-jets

8 TeV
3.9/fb

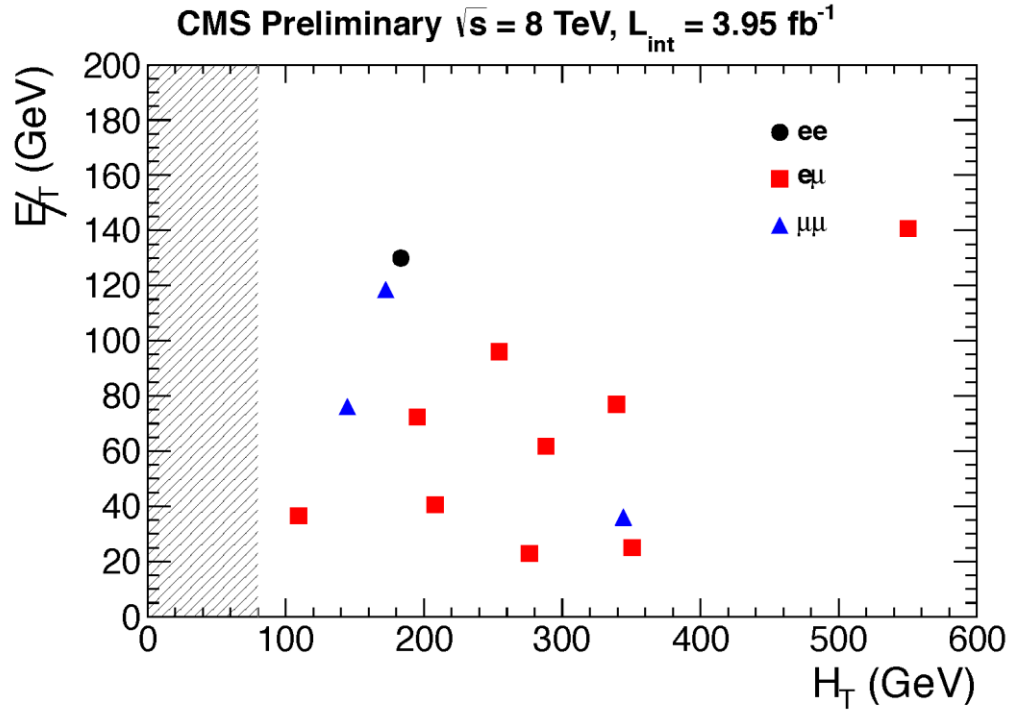
CMS PAS SUS-12-017

- event selection
  - two like sign leptons (e, μ) with $p_T > 20\ \mathrm{GeV}$
  - two b-tagged jets with $p_T > 40\ \mathrm{GeV}$
- backgrounds
  - non-prompt leptons
  - leptons (mostly e) with mismeasured charge
  - rare sm processes (mostly $\mathrm{pp} \rightarrow \mathrm{t\bar{t}W}$ and $\mathrm{t\bar{t}Z}$)

like-sign dileptons and b-jets

- event yields

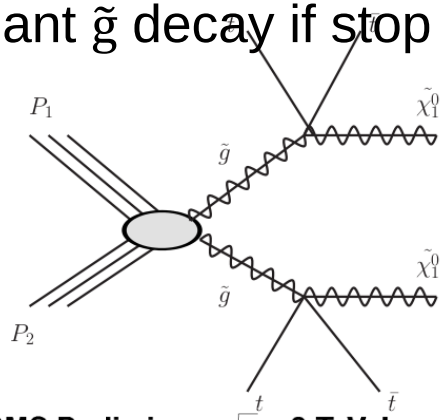
systematic uncertainties	
$\int \mathcal{L} dt$	4.4%
trigger efficiency	3%
lepton efficiency	5%
b-tag efficiency	2.7-10%
jet energy scale	2-5%

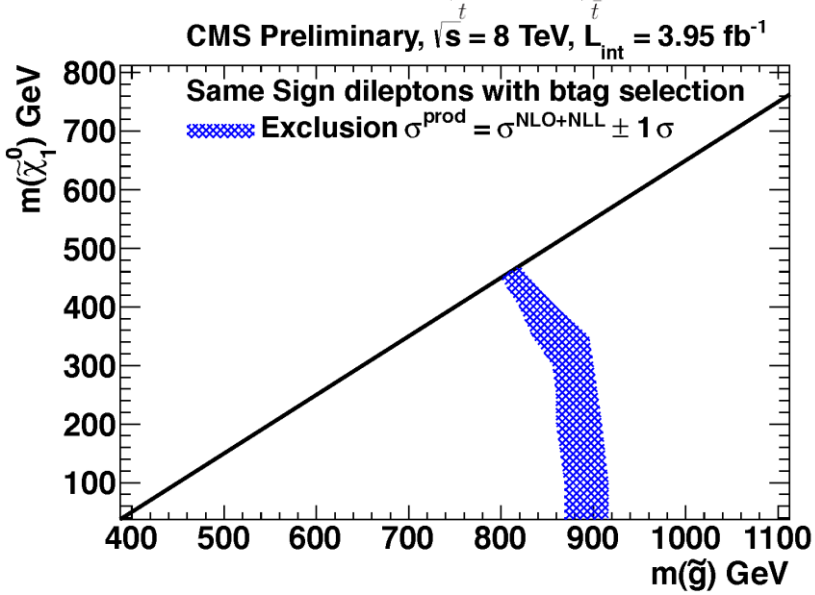


signal region	I	II							IX
b-jets	≥2	≥2	≥2	≥2	≥2	≥2	≥2	≥3	≥2
lepton charge	± ±	± ±	+ +	± ±	± ±	± ±	± ±	± ±	± ±
$\not{p}_T$ (GeV)	n/a	>30	>30	>120	>50	>50	>120	>50	n/a
H_T (GeV)	>80	>80	>80	>200	>200	>320	>320	>200	>320
background	12.1±4.6	9.9±3.6	5.3±2.0	1.4±0.7	5.8±2.7	2.6±1.3	0.9±0.6	0.3±0.7	3.8±1.7
observed	13	11	0	1	4	2	1	1	4

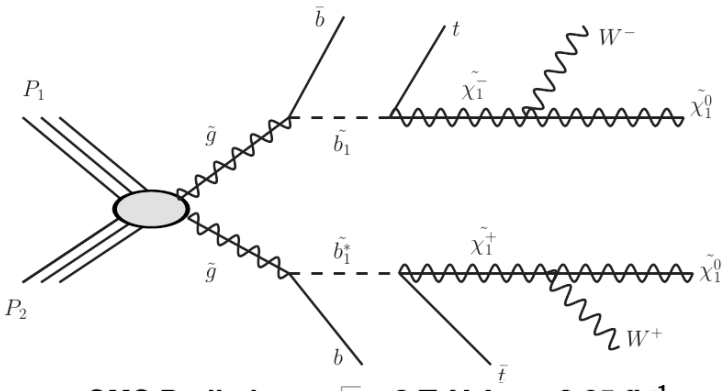
like-sign dileptons and b-jets

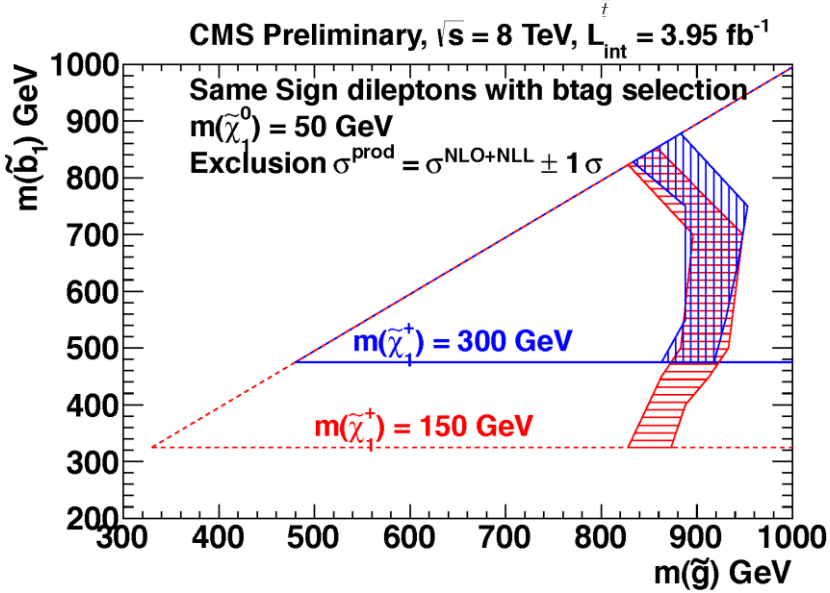
- $\tilde{g} \to t\bar{t}\tilde{\chi}_1{}^0$
- dominant $\tilde{g}$ decay if stop lightest squark





- $\tilde{g} \to b\bar{t}W\tilde{\chi}_1{}^0$





m(gluino) > 880 GeV (if they decay to $\tilde{t}$ or $\tilde{b}$) and m($\tilde{b}$) > 408 GeV

photons and missing p_T

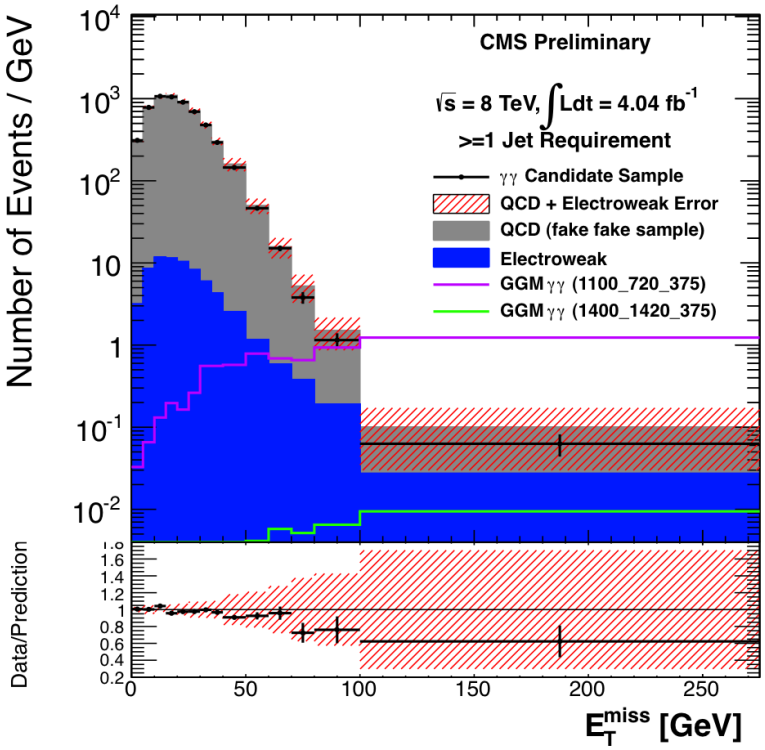
8 TeV
4/fb

CMS PAS SUS-12-018

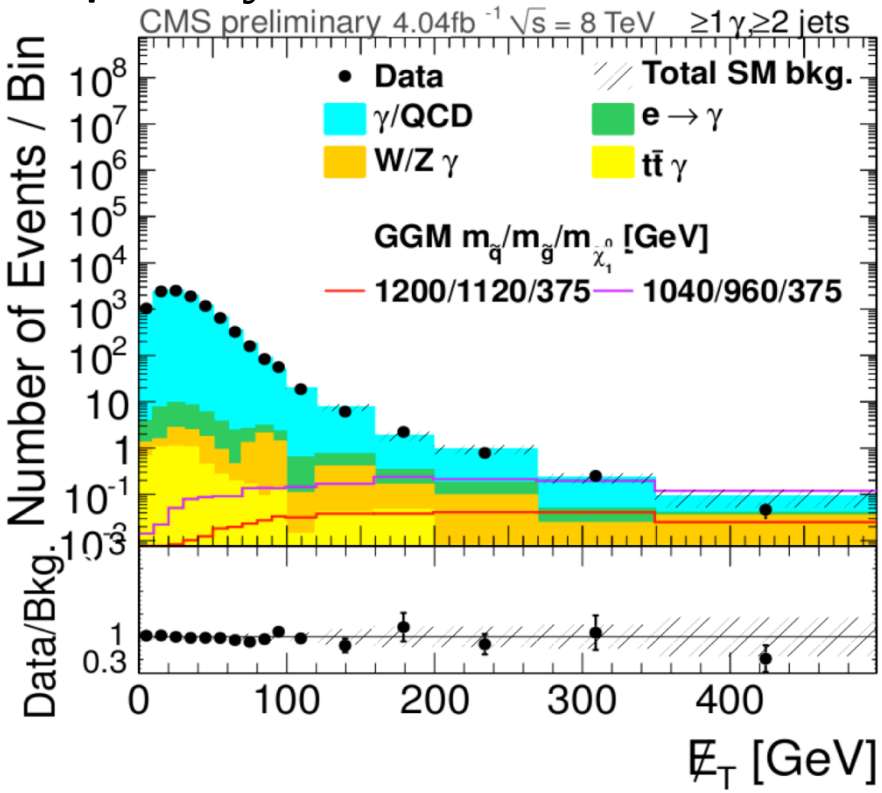
- gauge mediated SUSY
  - gravitino is LSP
  - neutralino is NLSP
    - decays to γ +LSP (bino-like) or to Z +LSP (wino-like)
- event topologies
  - $\geq 2\gamma$ ($p_T > 40/25$ GeV) + ≥ 1 jet ($p_T > 30$ GeV) + $\not{p}_T > 50$ GeV
  - $\geq 1\gamma$ ($p_T > 80$ GeV) + ≥ 2 jets ($p_T > 30$ GeV) + $\not{p}_T > 100$ GeV
  - no lepton veto
- backgrounds
  - γ + jets, multijets (no true missing p_T)
    - from control samples with low missing p_T
  - Wγ + jets, W + jets (true missing p_T)
    - from eγ control data samples

photons and missing p_T

$\gamma\gamma$ analysis



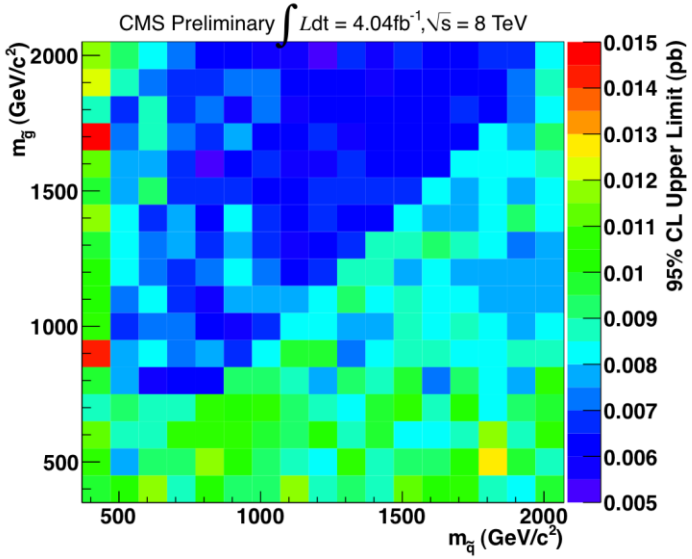
γ analysis

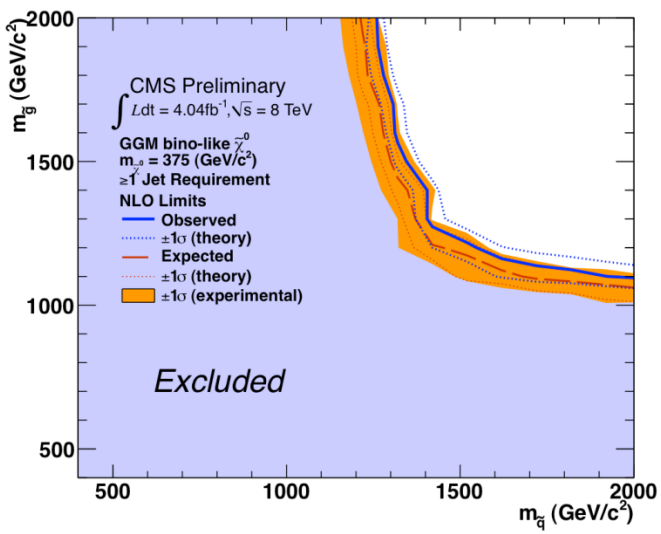


- assume m(neutralino) = 375 GeV
- compare to GGM-SUSY predictions for m(squark) and m(gluino)
- determine upper limit for cross section in bins of missing pT

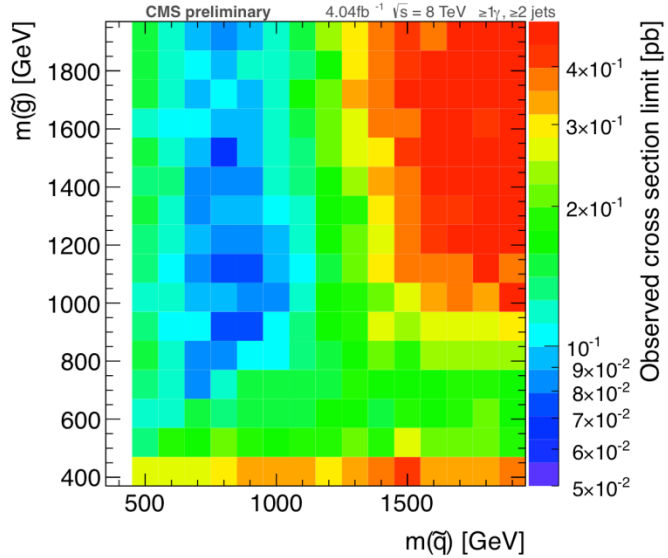
photons and missing p_T

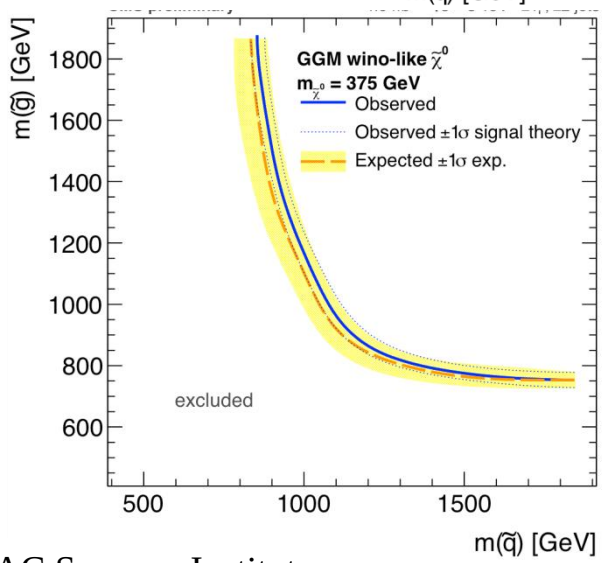
$\gamma\gamma$ analysis – bino like neutralino





γ analysis – wino like neutralino





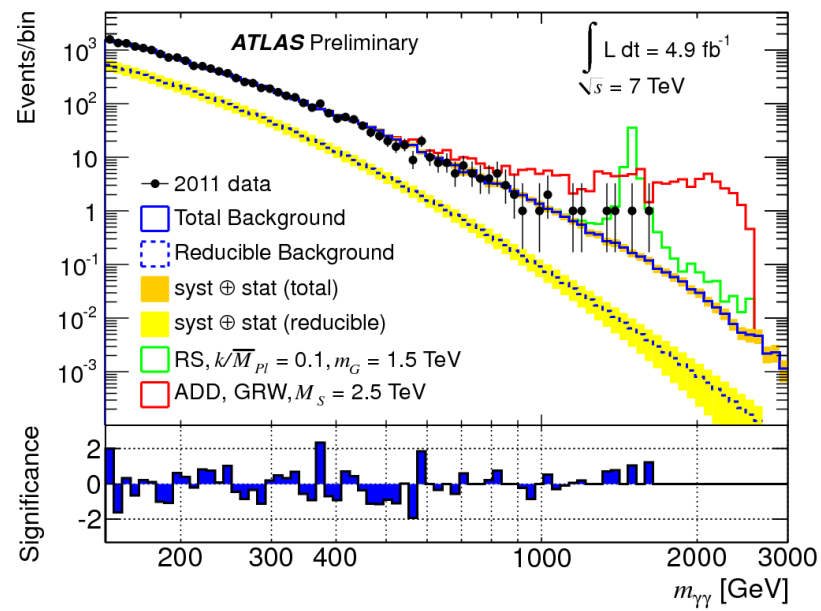
new dimensions

- removes the hierarchy problem
- consider 4+n dimensional space time
  - gravity propagates in all dimensions
  - appears weak in 4 dim space time
  - gravity becomes strong at short distances
- expect
  - effects of virtual graviton interactions
  - KK excitations of graviton
- ADD Arkani-Hamed, Dimopoulos, Dvali, PL **B429** (1998)
  - n dimensions, compactified over multidim torus of radius R
  - $M_{Pl} \approx {M_D}^{n+2} R^n$
- RS Randall and Sundrum, PRL 83, 3370 (1999)
  - one warped dimension

new dimensions

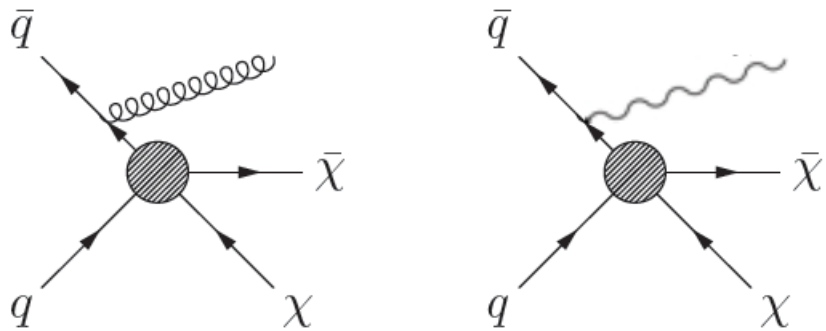
- virtual gravitons modify production of sm particles
  - enhanced production at high mass
- graviton production
  - KK excitations → resonances
  - graviton unobserved → missing momentum
- example: $\gamma\gamma$ mass spectrum
  - ADD $M_D > 2.6 \ldots 3.9$ TeV
    - for $n = 7 \ldots 3$
  - RS $m(g_{RS}) > 1.0 \ \ldots 2.1\ TeV$
    - for $k/\bar{M}_{Pl} = 0.01 \ \ldots 0.1$

7 TeV
4.9/fb



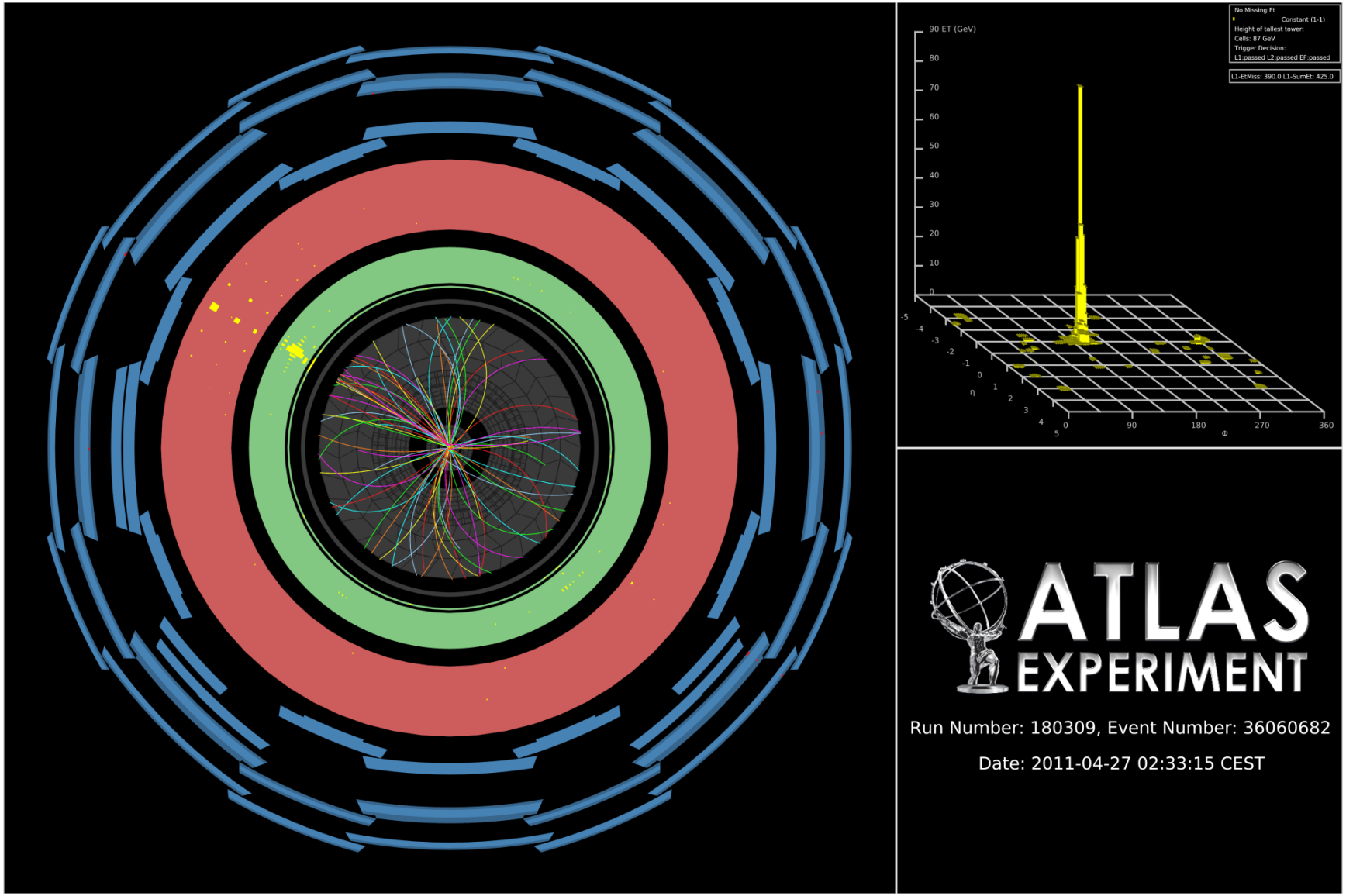
ATLAS-CONF-2012-087

monojets



- gravitons in extra dimension models
- dark matter particles WIMPs (χ)
  - kinematically accessible
  - produced via exchange of particle with mass M
  - contact interaction with scale $\Lambda = M/\sqrt{g_\chi g_q}$
  - assume Dirac fermions
  - relate production at LHC to χ nucleon interactions

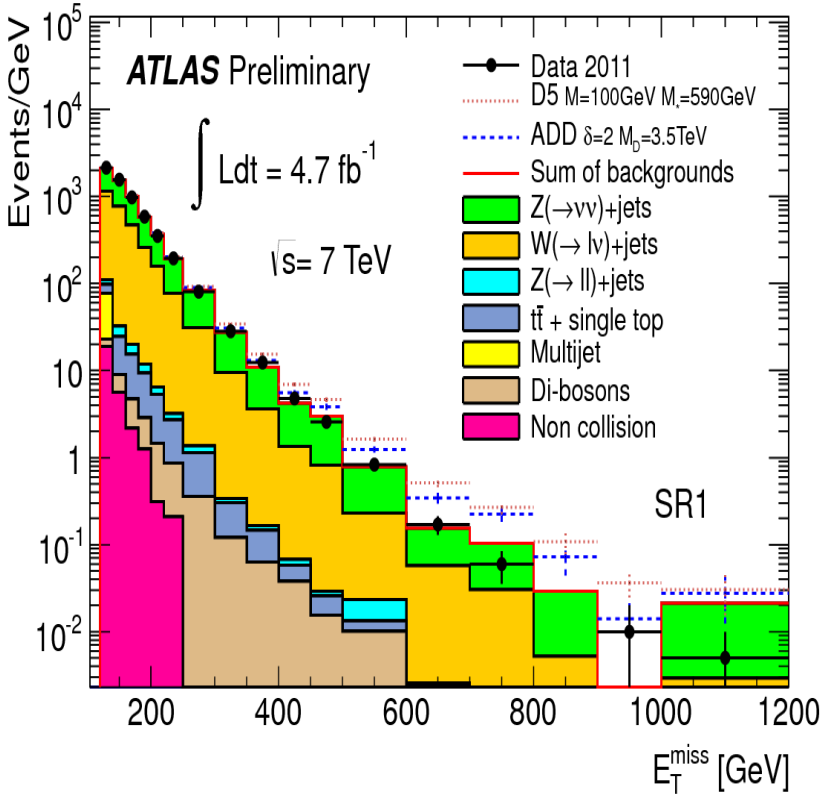
monojets


No Missing Et
Constant (1-1)
Height of tallest tower:
Cells: 87 GeV
Trigger Decision:
L1:passed L2:passed EF:passed
L1-EtMiss: 390.0 L1-SumEt: 425.0
90 ET (GeV)
80
70
60
50
40
30
20
10
0
-5
-4
-3
-2
-1
0
η
1
2
3
4
5
0
90
180
270
360
Φ
ATLAS
EXPERIMENT
Run Number: 180309, Event Number: 36060682
Date: 2011-04-27 02:33:15 CEST

monojets

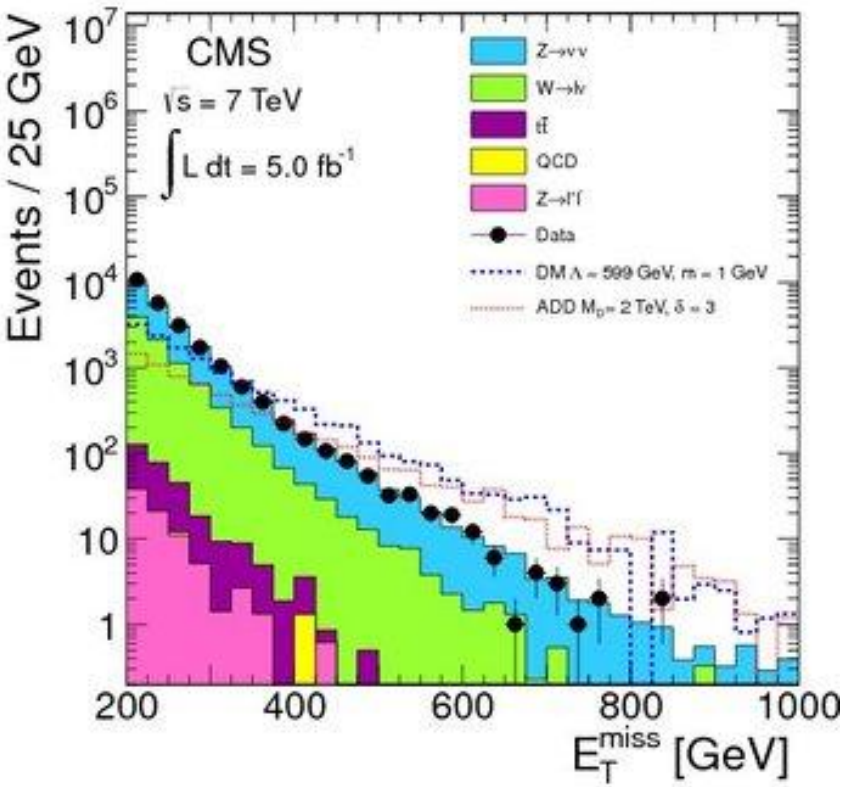
7 TeV
5/fb

ATLAS-CONF-2012-084



≤ 2 jets $p_T > 120/30$ GeV, $|\eta| < 2$
lepton veto

CMS arXiv:1206.5663

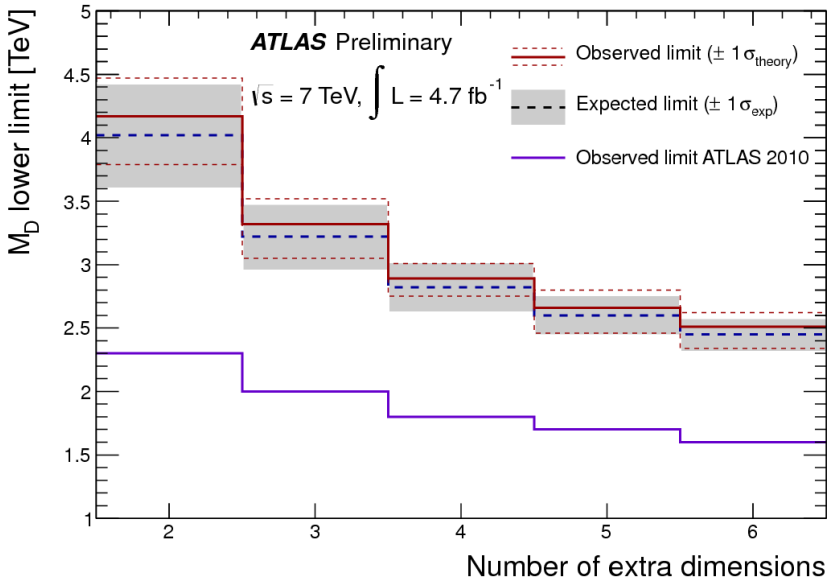


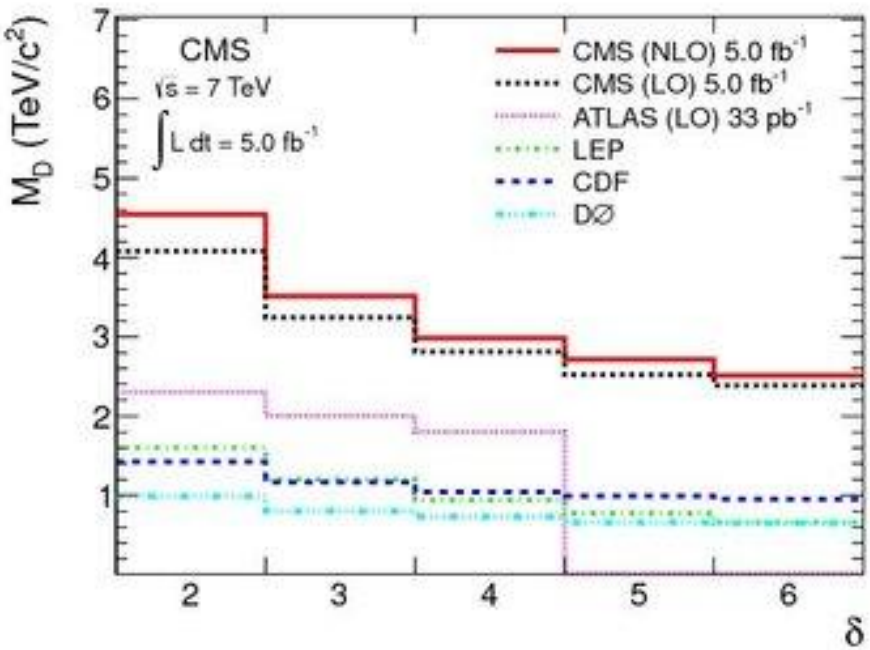
≤ 2 jets $p_T > 110/30$ GeV, $|\eta| < 2.4$
lepton veto

dominant background: $Z \to \nu\nu$ and $W \to \ell\nu$ - estimated from data

monojets

limits on extra dimensions in the ADD model



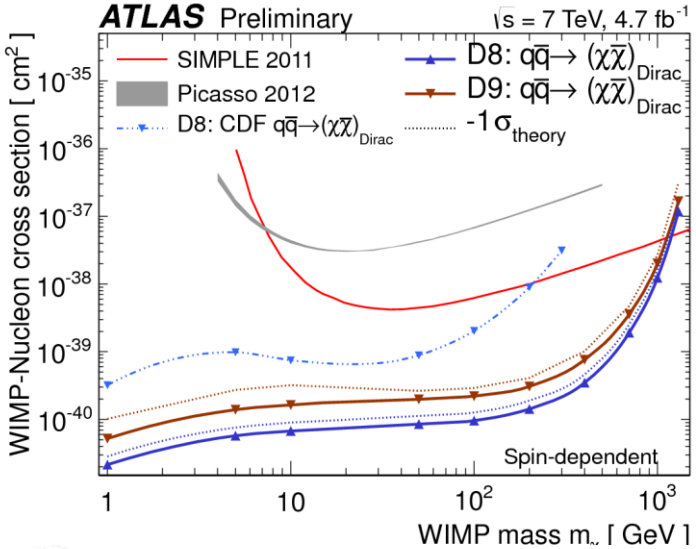


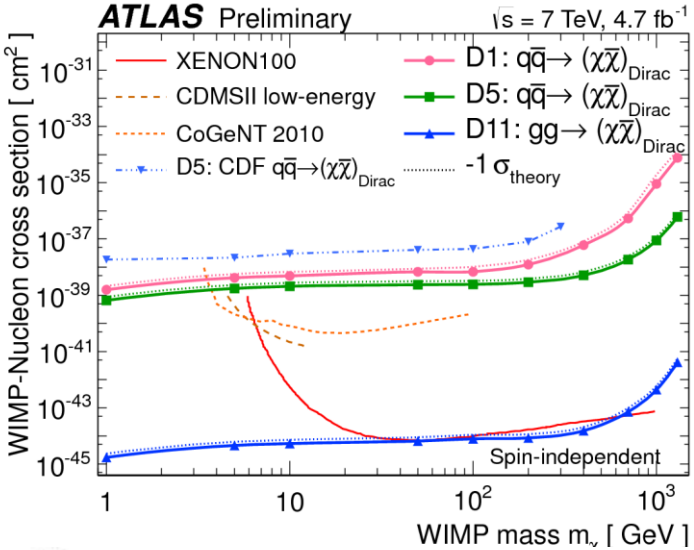
$M_D > 2.3 \ \ldots 3.8$ TeV
for $n = 6 \ \ldots 2$

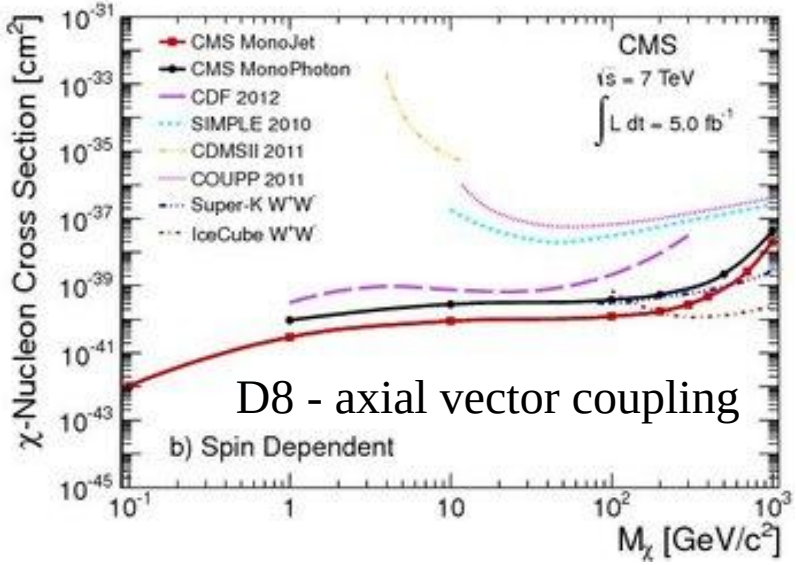
$M_D > 2.5 \ \ldots 4.5$ TeV
for $n = 6 \ \ldots 2$

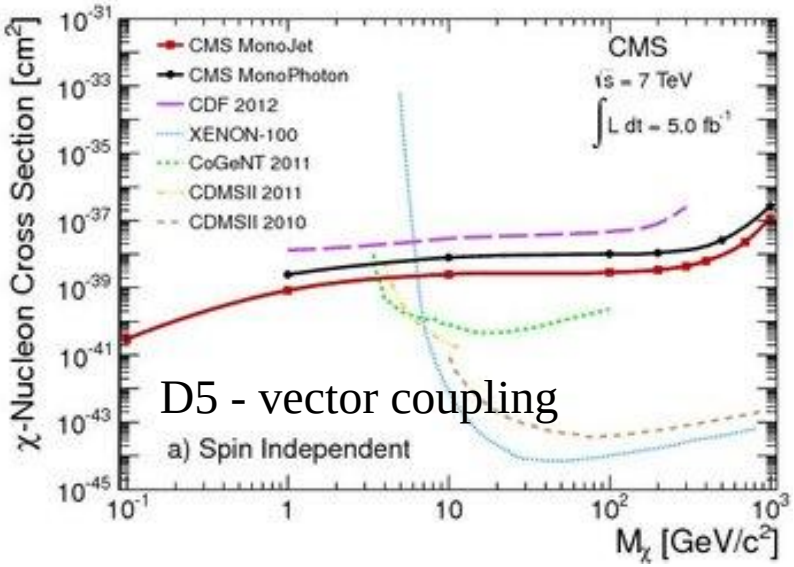
monojets

limits on Λ → limits on χ-nucleon xsec









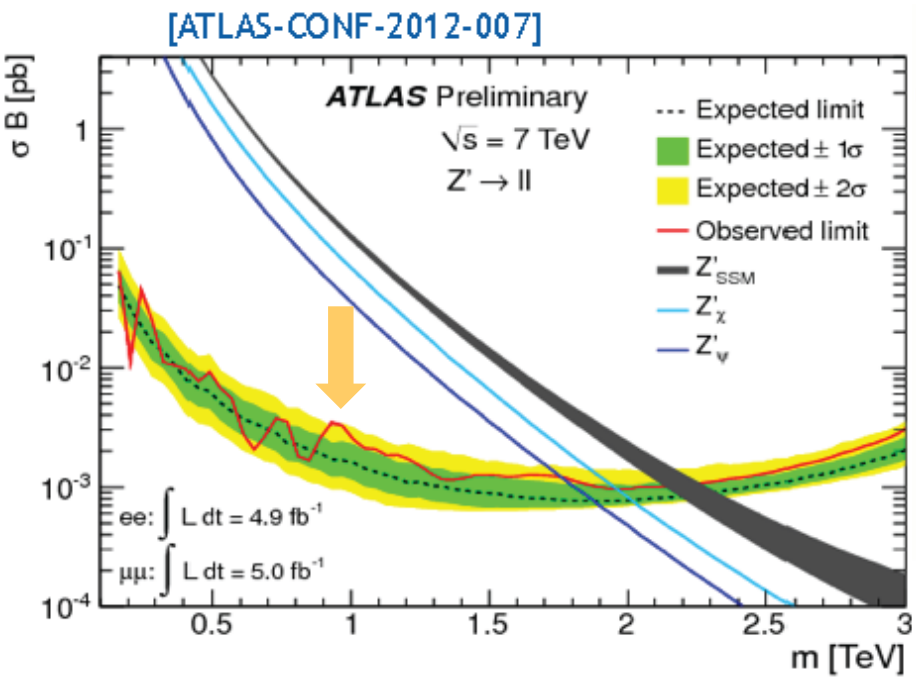
new bosons

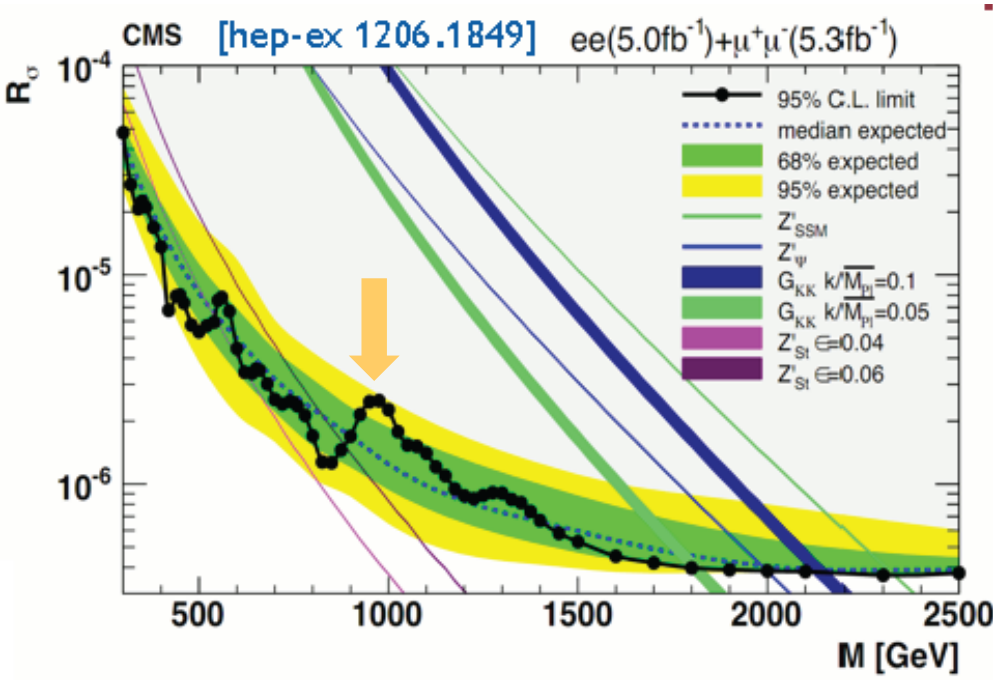
- predicted in many models
  - new symmetries → new gauge bosons
  - KK excitations
- appear as resonances
  - dijets (boosted),
  - dilepton

dilepton resonances

7 TeV
5/fb

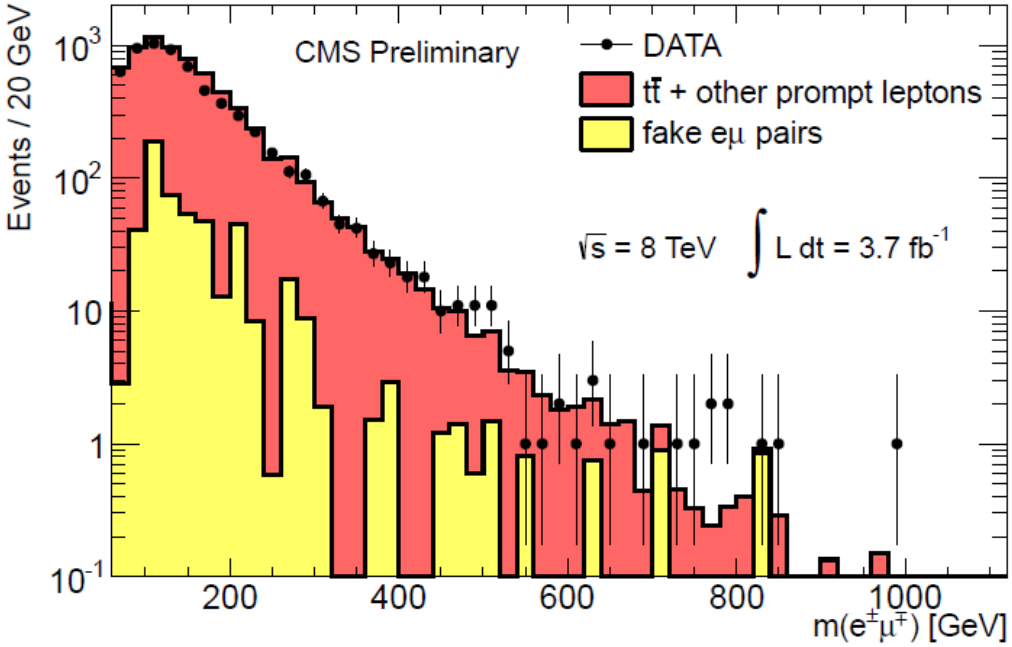
- many BSM models predict narrow $\ell\ell$ resonances
  - Z' with sm like couplings ($\Gamma = 30\ \mathrm{GeV}\ @\ M = 1\ \mathrm{TeV}$)
  - Z' of grand unified theories ($\Gamma = 6\ \mathrm{GeV}\ @\ M = 1\ \mathrm{TeV}$)
- some excitement in 2011 data





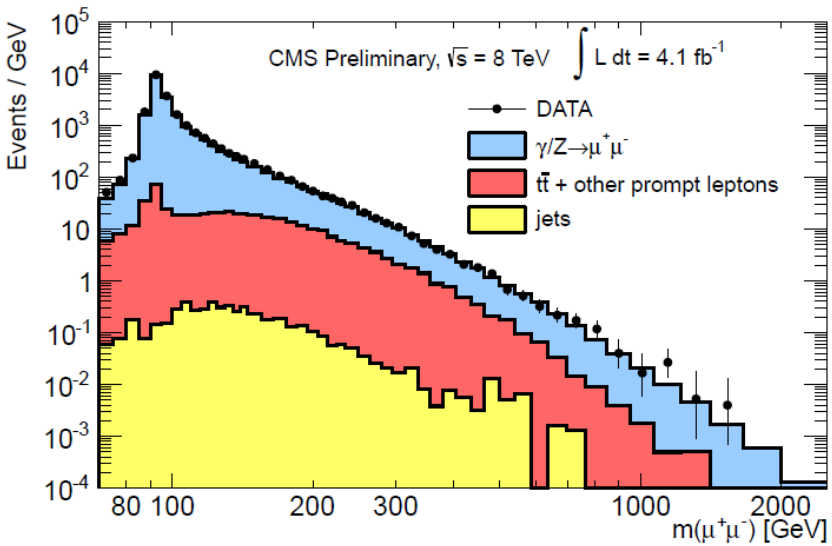
dilepton resonances

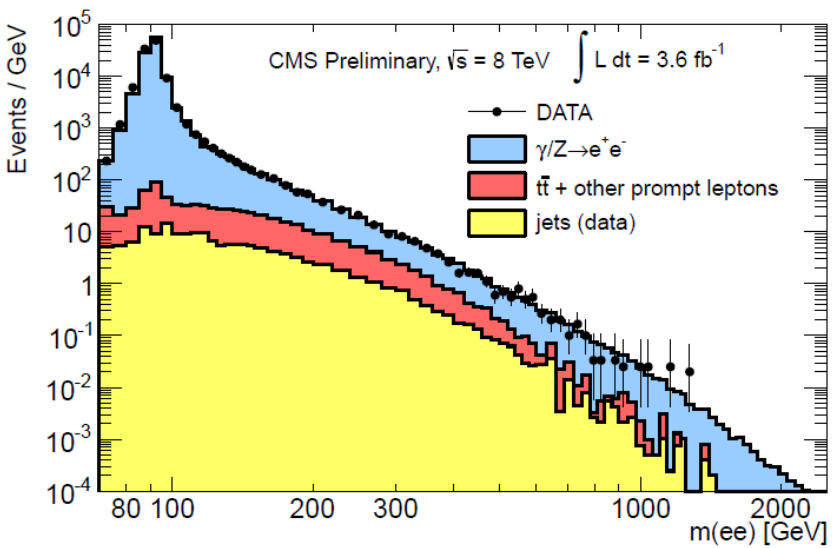
- event selection
  - isolated e: $p_T > 35\ \mathrm{GeV}$
  - isolated μ: $p_T > 45\ \mathrm{GeV}$
- background
  - prompt leptons
    - based on MC
    - verify data-MC agreement in eμ
  - jets
    - based on data



dilepton resonances

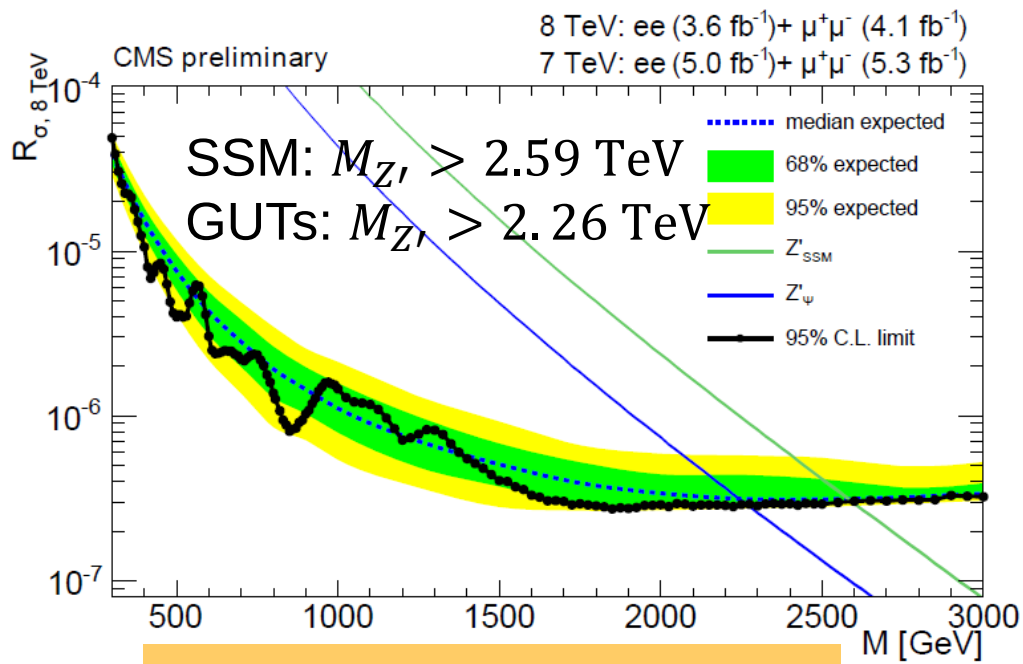
CMS PAS EXO-12-015





- fit $m(\ell\ell)$ spectra
  - background: analytic fit to MC
  - signal: BW $*$ Gaussian
- limits on $R_\sigma = \dfrac{\sigma(Z' \to \ell\ell)}{\sigma(Z \to \ell\ell)}$

8 TeV
5/fb



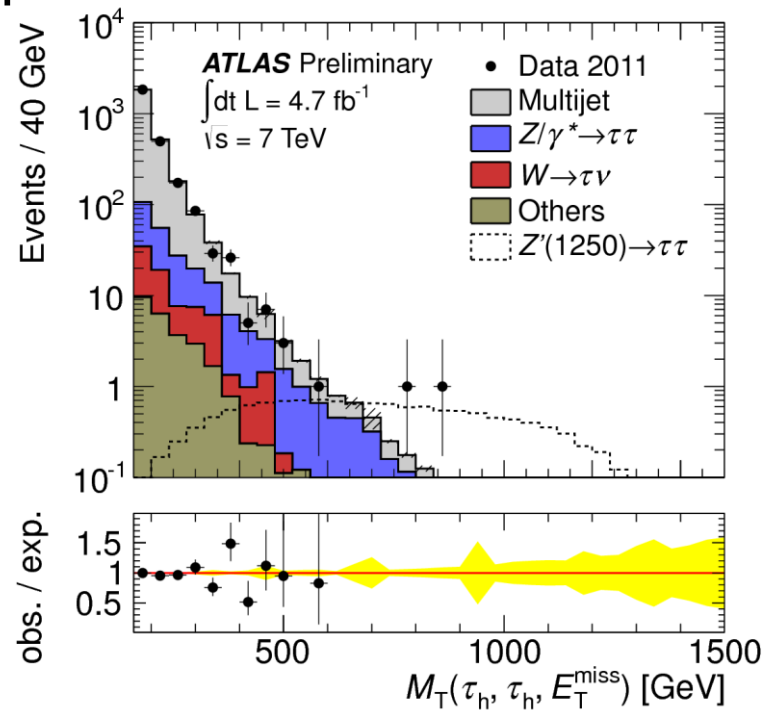
ATLAS-CONF-2012-007
SSM: $M_{Z'} > 2.21$ TeV
$e\nu$ and $\mu\nu$ data - 5.0/fb @ 7 TeV

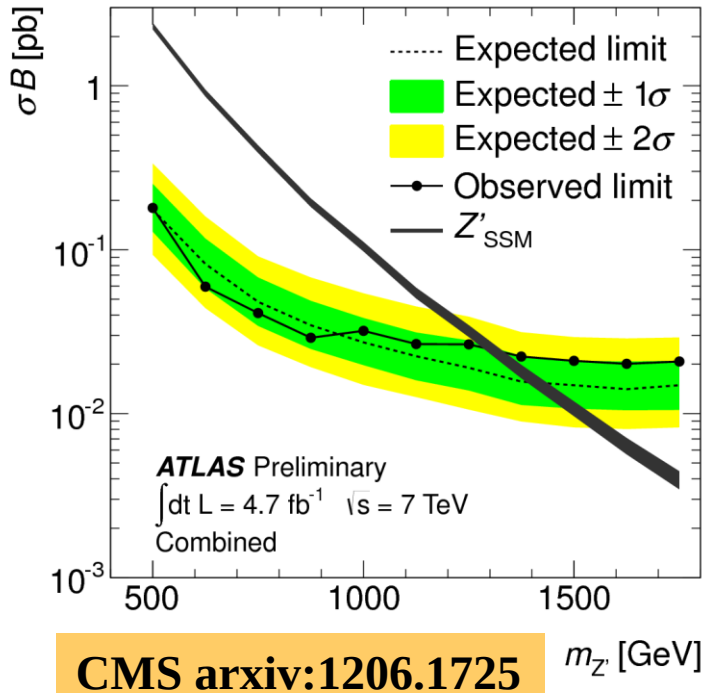
$\tau\tau$ resonances

ATLAS-CONF-2012-067

- in some models Z' couples preferentially to 3rd generation
- consider $\tau_h\tau_h$ (42%), $\mu\tau_h$ (23%), $e\mu$ (6%) decays
- plot effective transverse mass

7 TeV
4.7/fb





CMS arxiv:1206.1725
SSM: $M_{Z'} > 1.4$ TeV
E6: $M_{Z'} > 1.1$ TeV
4.9/fb @ 7 TeV

- SSM: $m(\mathrm{Z}') > 1.3$ TeV

heavy W bosons

8 TeV
3.7/fb

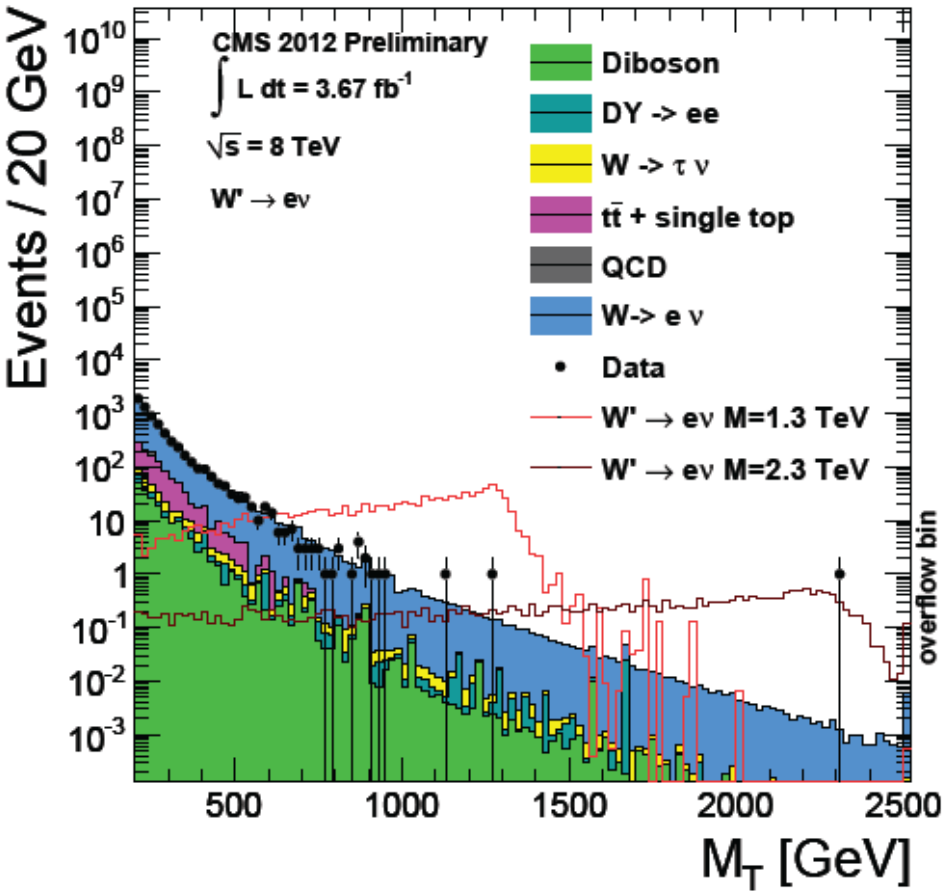
- many models predict new gauge bosons
  - W' with sm like couplings
  - decays to $e\nu$ or $\mu\nu$

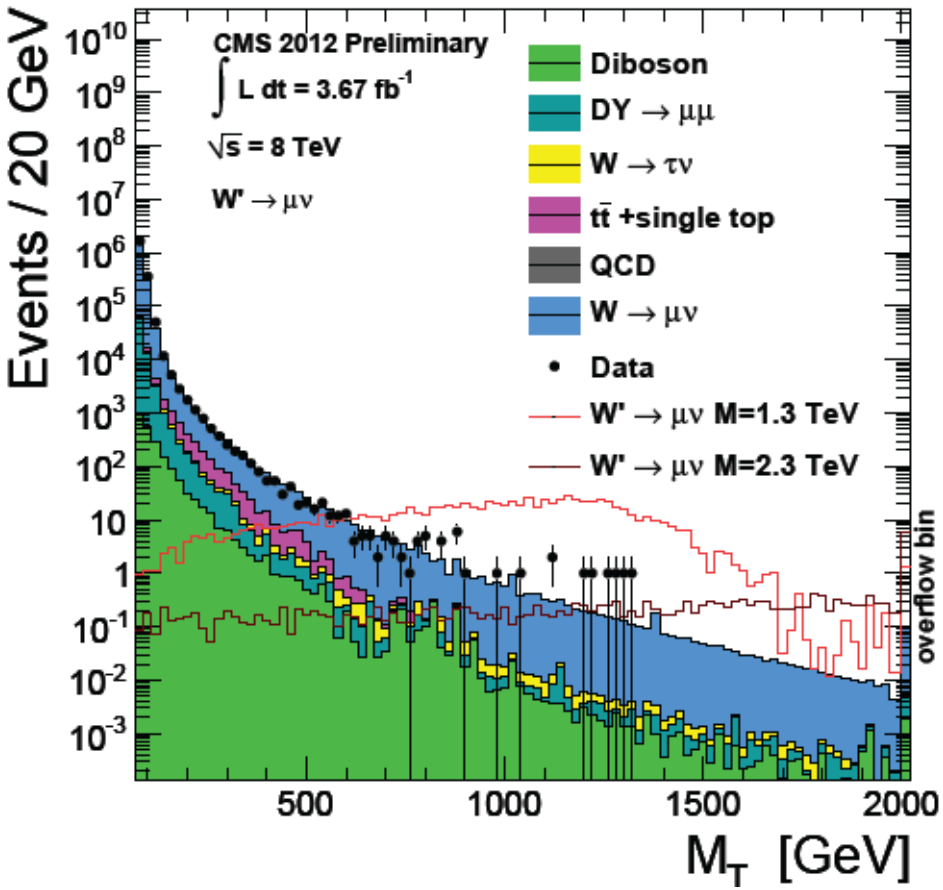
CMS PAS EXO-12-010

- event selection
  - isolated e: $p_T > 45\ \mathrm{GeV}$
  - isolated μ: $p_T > 90\ \mathrm{GeV}$
    - driven by trigger thresholds
  - 0.4 < missing p_T/p_T < 1.5
  - lepton back-to-back in ϕ with missing p_T
- backgrounds
  - analytical fit to MC, normalization from fit to data

heavy W bosons

- plot transverse mass: $m_T = \sqrt{2 p_T \not{p}_T (1 - \Delta\phi)}$



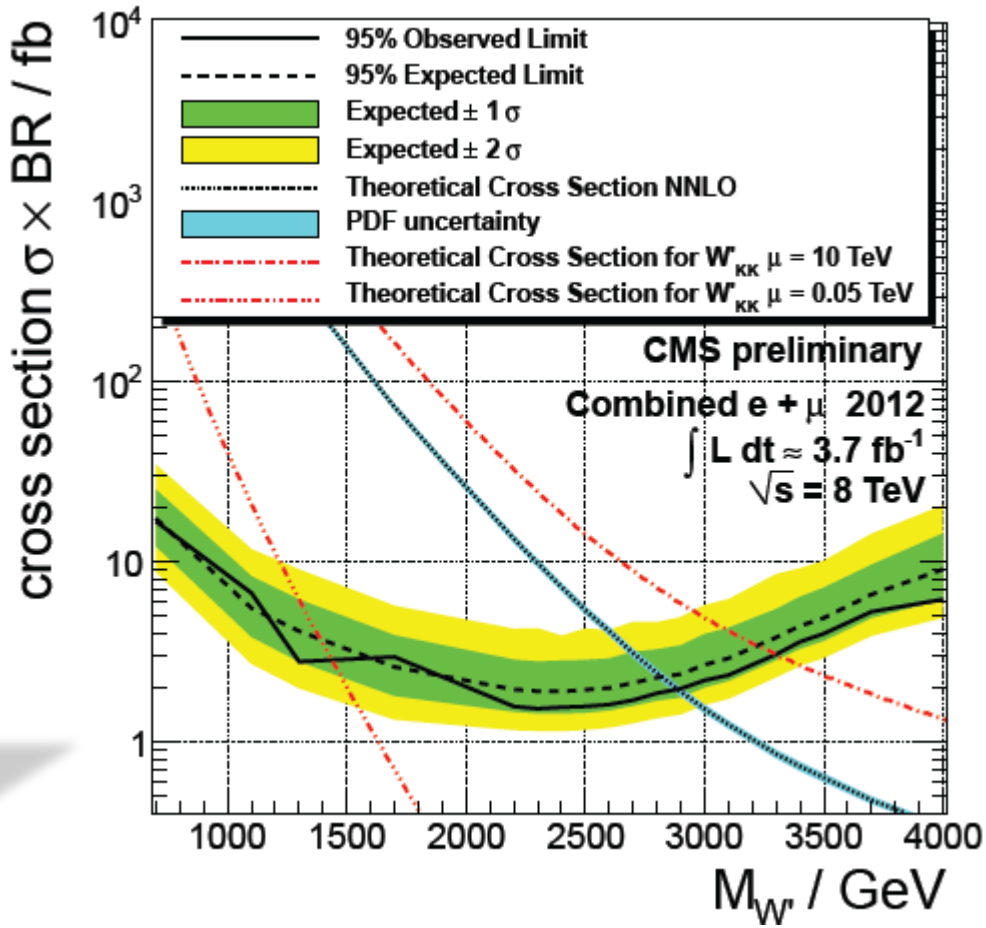


heavy W bosons

- Bayesian limit calculation
  - based on counting events with $m_T >$ threshold

- $M_{W'} > 2.85$ TeV
  - 2011 + 2012 data
  - $e\nu$ and $\mu\nu$ data

ATLAS-CONF-2012-086
$M_{W'} > 2.55$ TeV
$e\nu$ and $\mu\nu$ data
4.7/fb @ 7 TeV



dijet resonances

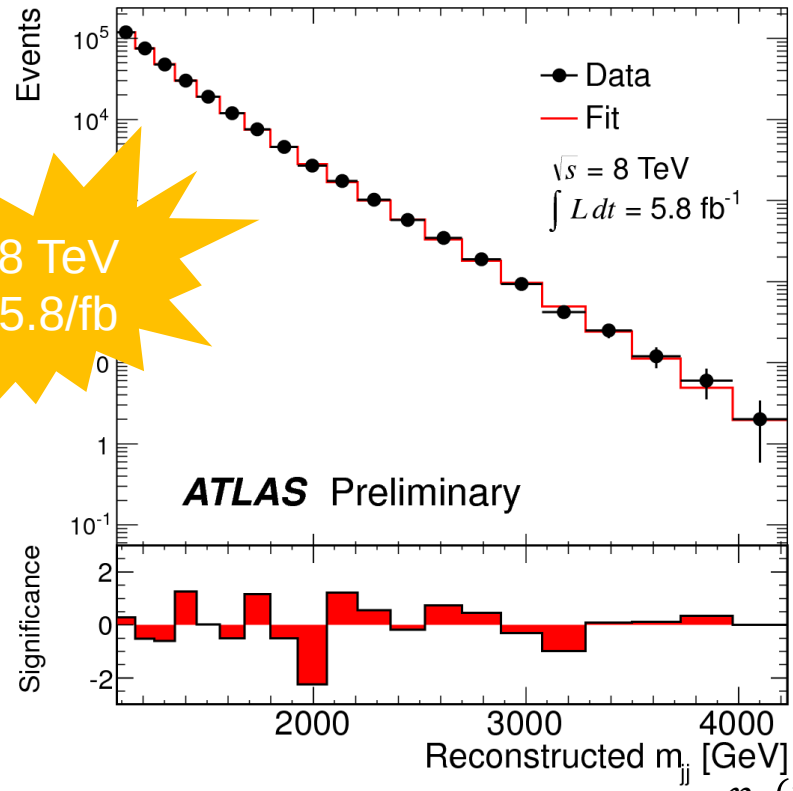
ATLAS-CONF-2012-088

anti kT jets with $R = 0.6$

$p_T > 150$ GeV, $|\eta_j| < 2.8$

$|\Delta\eta_{jj}| < 0.6$ $m_{jj} > 1$ TeV

8 TeV 5.8/fb



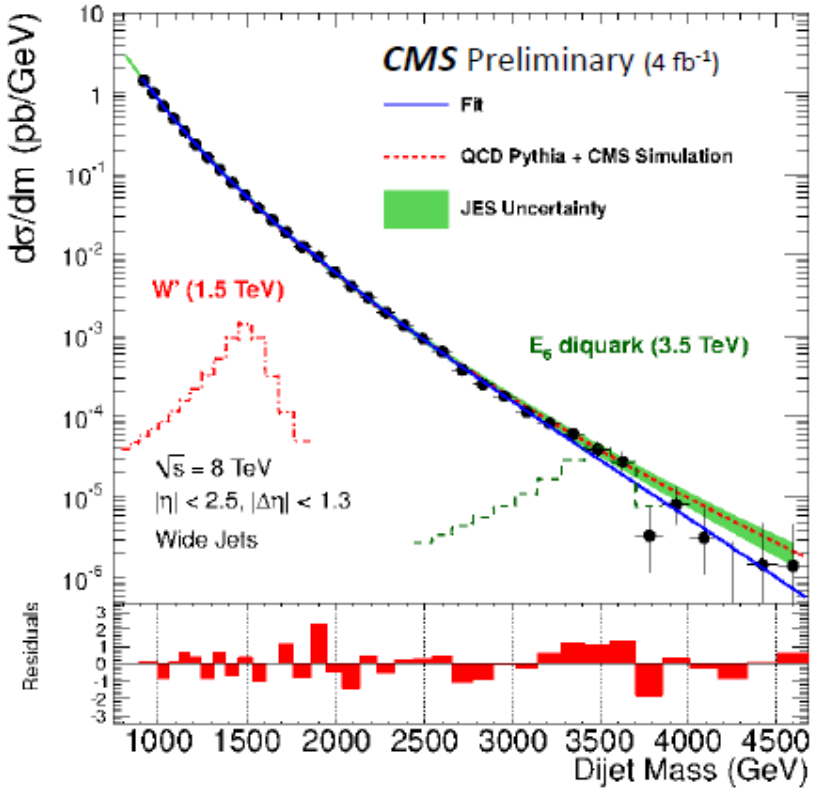
CMS PAS EXO-12-016

8 TeV 4/fb

absorb jets with $\Delta R < 1.1$ into leading two jets

$p_T > 30$ GeV, $|\eta_j| < 2.5$

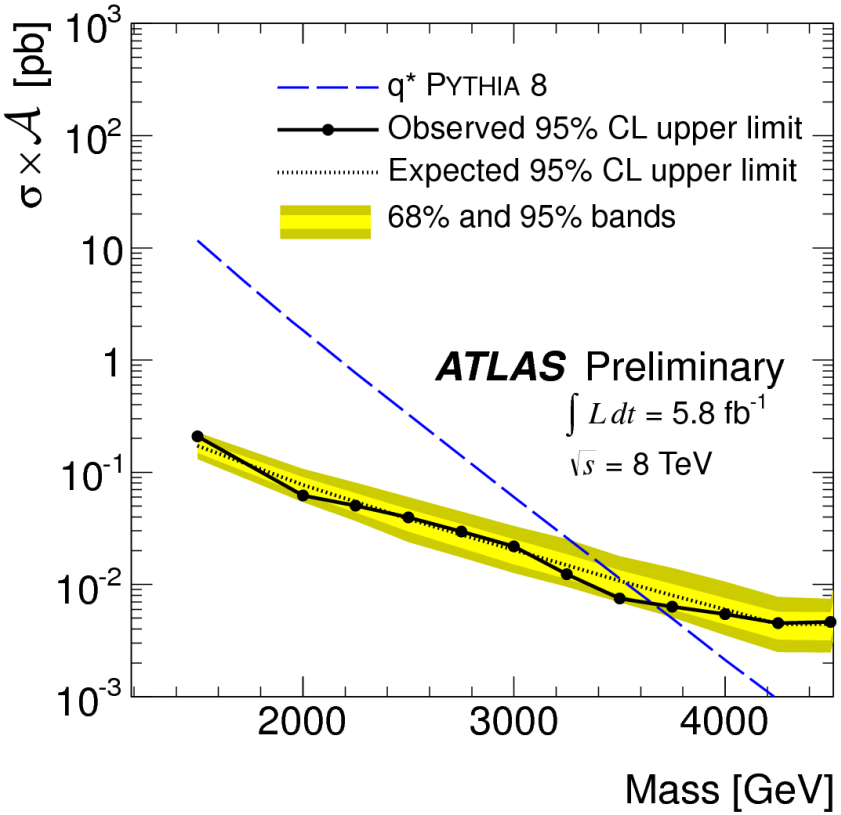
$|\Delta\eta_{jj}| < 1.3, m_{jj} > 890$ GeV



fit background to $\frac{p_0(1-x)^{p_1}}{x^{p_2+p_3\ln(x)}}$ where $x = m_{jj}/\sqrt{s}$

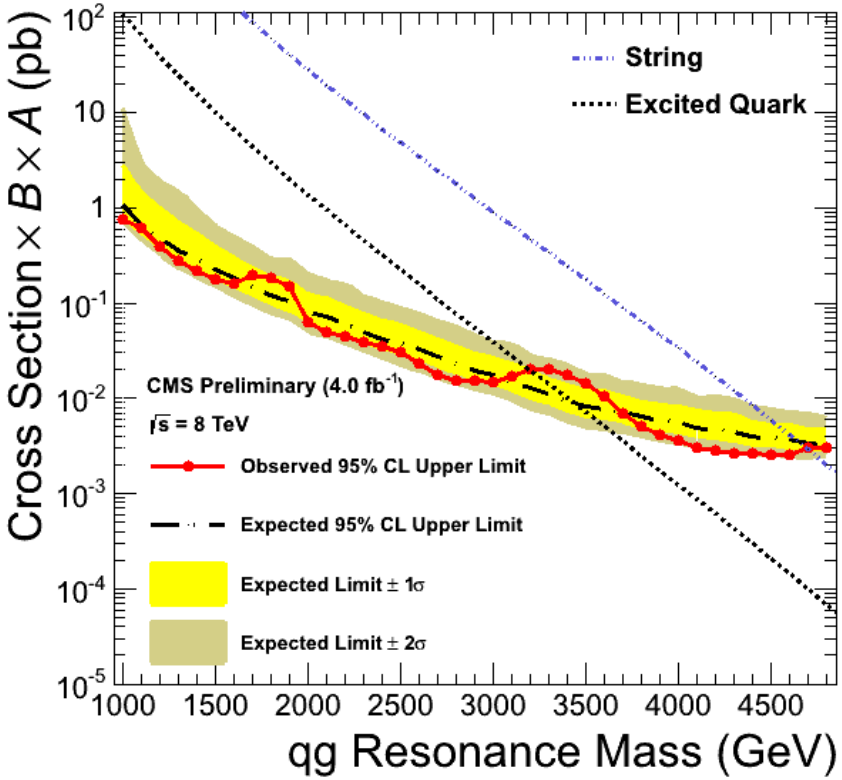
dijet resonances

ATLAS



$m(q^*) > 3.66$ TeV @ 95% CL

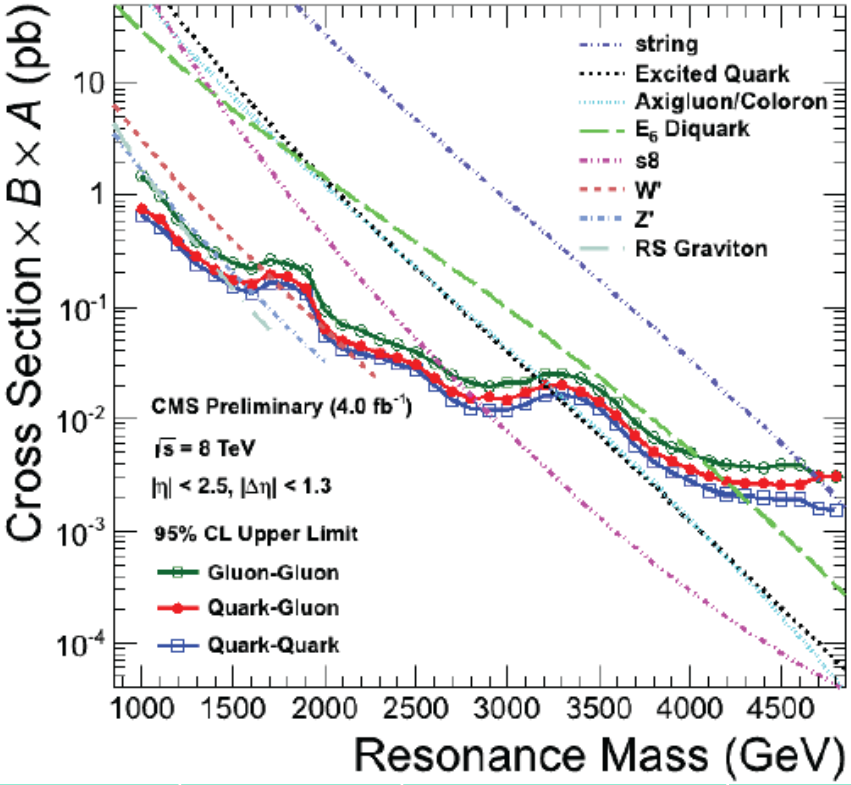
CMS

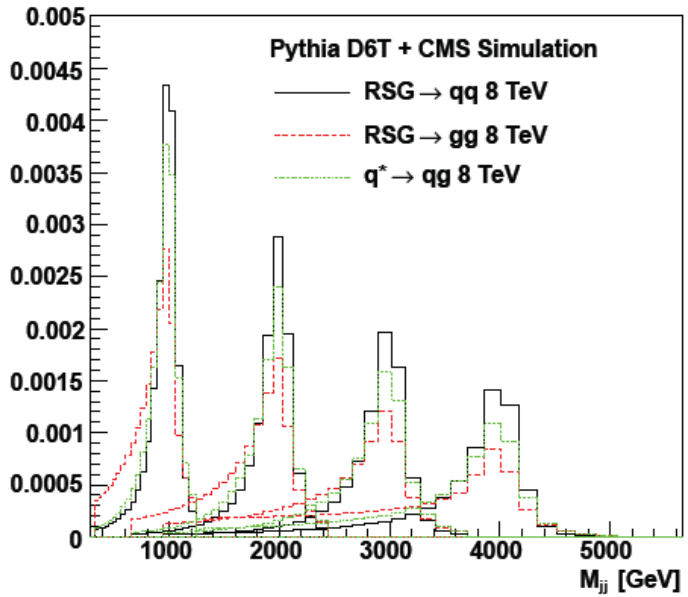


$m(q^*) > 3.19$ TeV @ 95% CL

dijet resonances

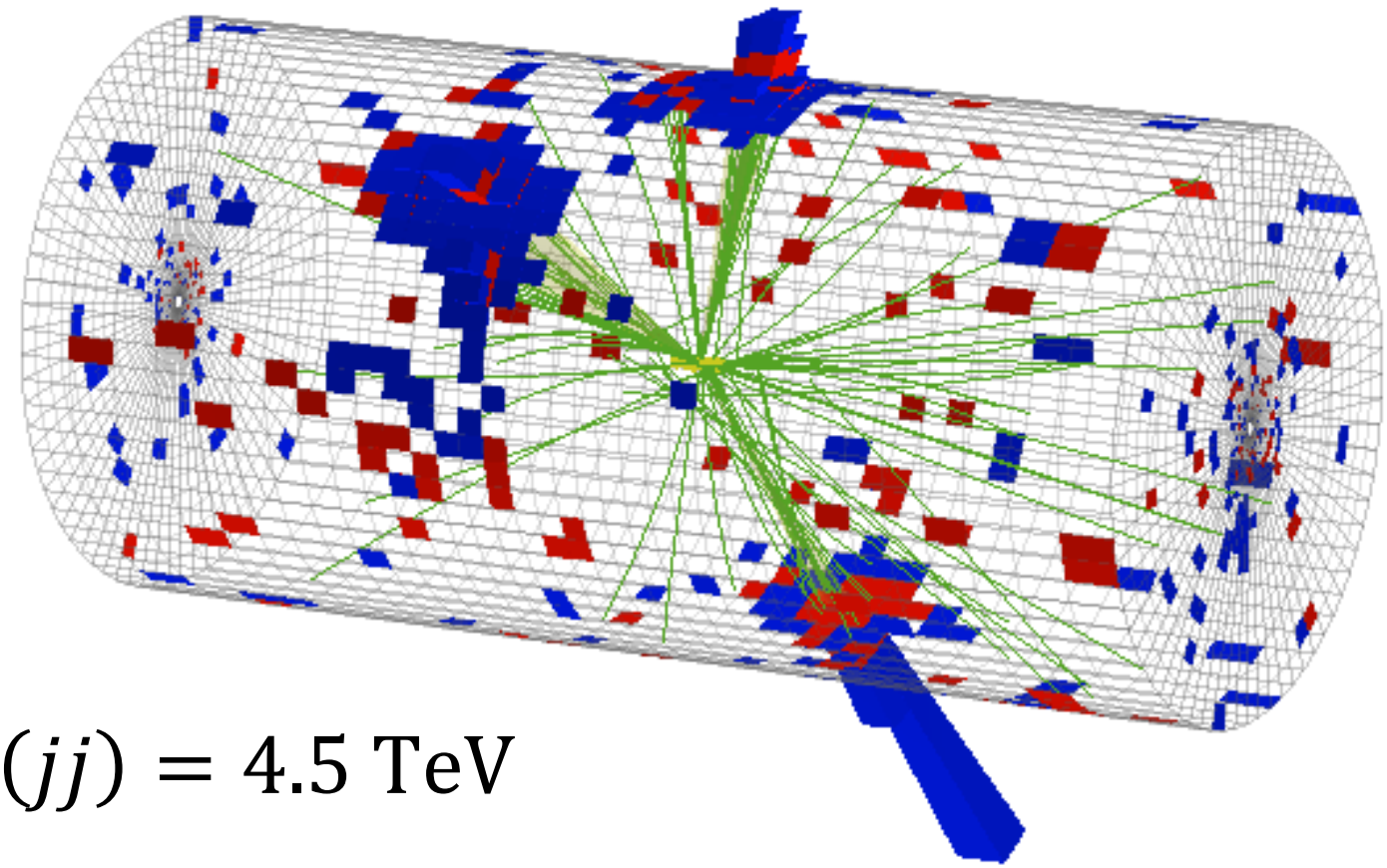
- upper limits on $\sigma \times B \times A$
  - Bayesian statistics
  - signal shapes for
    - qq resonances
    - qg resonances
    - gg resonances





	final state	observed	expected
string resonances	qg	4.69 TeV	4.64 TeV
excited quarks	qg	3.19 TeV	3.43 TeV
E6 diquarks	qq	4.28 TeV	4.12 TeV
axigluon/coloron	$q\bar{q}$	3.28 TeV	3.55 TeV
s8 resonances	gg	2.66 TeV	2.53 TeV
W' boson	$q\bar{q}$	2.12 TeV	1.92 TeV
Z' boson	$q\bar{q}$	1.60 TeV	1.50 TeV
RS graviton	$q\bar{q} + gg$	1.36 TeV	1.20 TeV

dijet resonances



$m(jj) = 4.5\ \mathrm{TeV}$

massive $t\bar{t}$ resonances

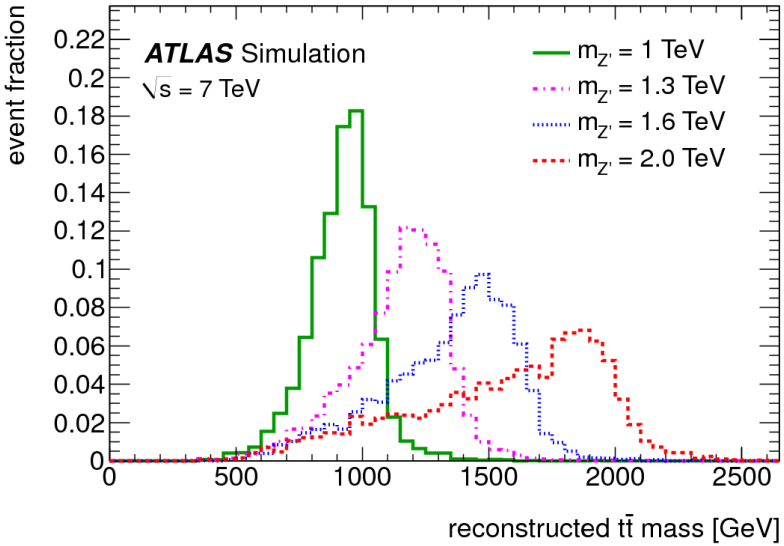
7 TeV
2/fb

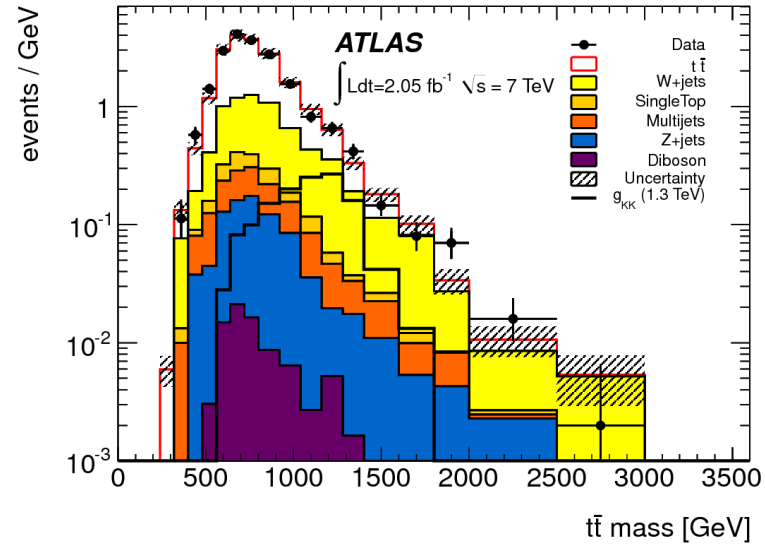
ATLAS arXiv:1207.2409

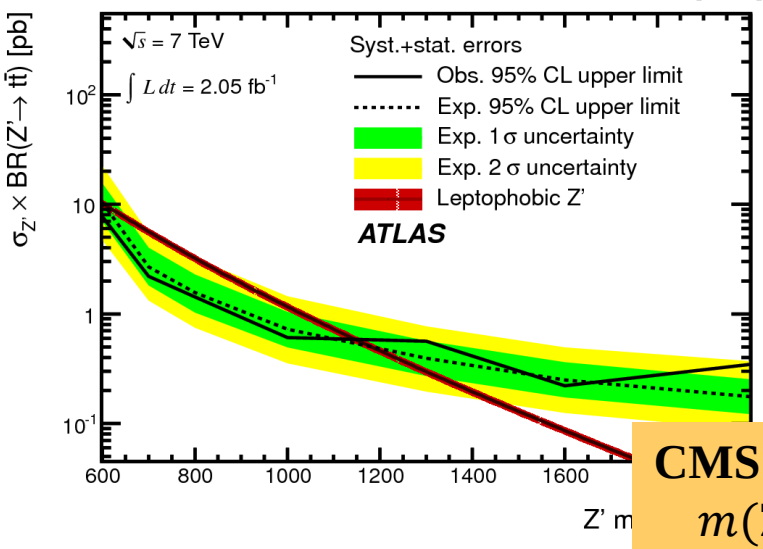
- benchmark models
  - leptophobic topcolor Z' (Harris et al., hep-ph/9911288)
  - KK gluon (Lillie et al., PRD 76 (2007) 115016)
- signature
  - l+jets
  - for $m(t\bar{t}) > 1\ \mathrm{TeV}$ the decay products of hadronic t quark decay are not resolved
- event selection
  - one muon $p_T > 20\ \mathrm{GeV}$ or electron $p_T > 25\ \mathrm{GeV}$
  - missing p_T
  - ≥ 1 jet with $p_T > 30\ \mathrm{GeV}$ close to lepton
  - ≥ 1 fat jet ($R = 1$) with $p_T > 250\ \mathrm{GeV}$, $m_j > 100\ \mathrm{GeV}$
- dominant background: $t\bar{t}$, W+jets, multijets

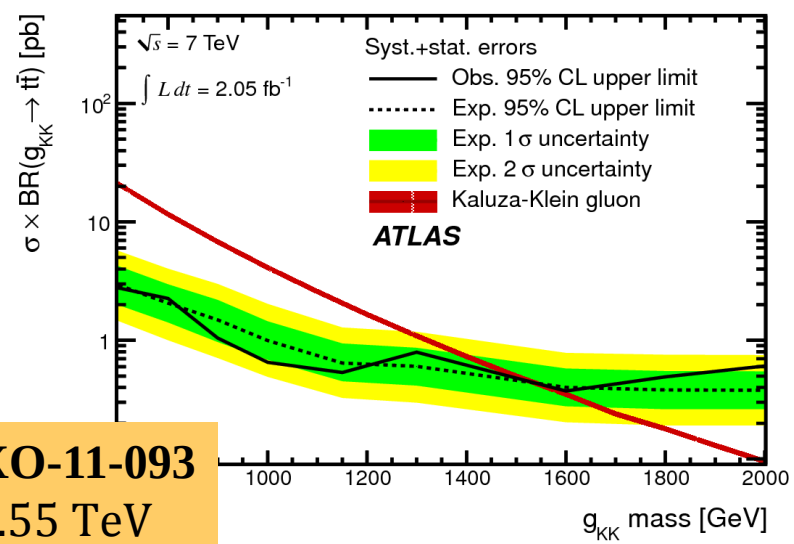
channel	e+jets	μ+jets
expected	830±60	1010±70
observed	803	1034

massive $t\bar{t}$ resonances









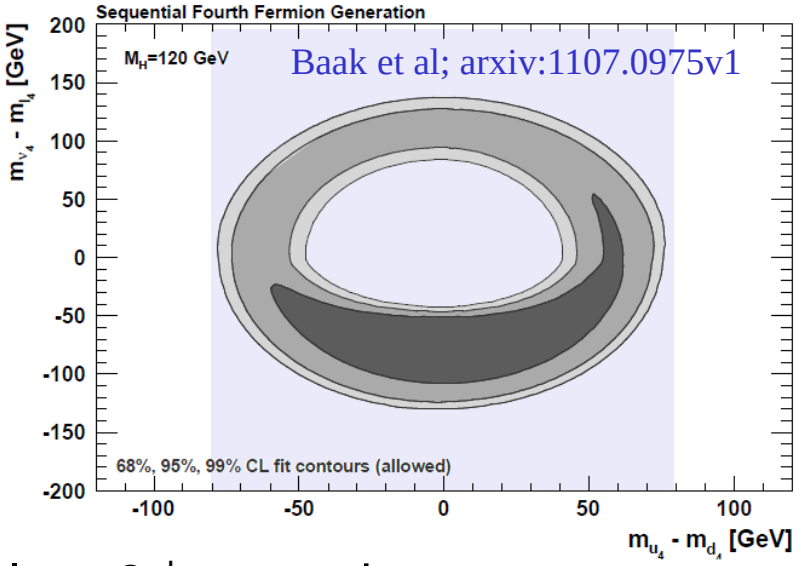
CMS PAS EXO-11-093
$m(Z') > 1.55$ TeV
5/fb @ 7 TeV

$m(g_{KK}) > 1.5$ TeV

$m(Z') > 1.15$ TeV

new fermions

- 4th generation is straightforward extension of sm
  - constraints from experiment
    - $m_{\nu'} > ½ M_Z$
    - $m_{t'} > 358$ GeV
    - $m_{b'} > 385$ GeV
    - $|m_{t'} - m_{b'}| < M_W$
  - decay modes
    - $t' \rightarrow bW$
    - $b' \rightarrow tW \rightarrow bWW$
    - 4th generation decays predominantly to 3rd generation
  - 4th generation would
    - enhance production cross section of a Higgs boson
    - make ewk measurements consistent with larger m_H

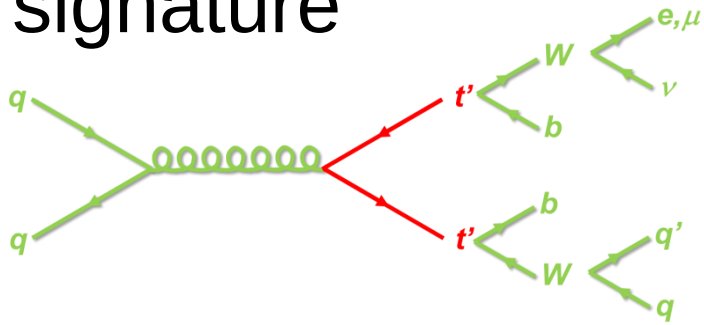


- vector-like fermions
  - avoid sm constraints

t'→bW – lepton+jets final state

7 TeV
4.7/fb

- signature



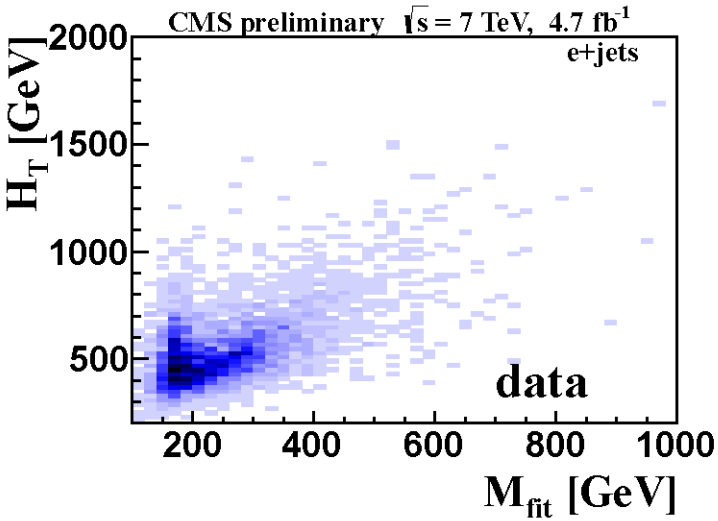
CMS PAS EXO-11-099

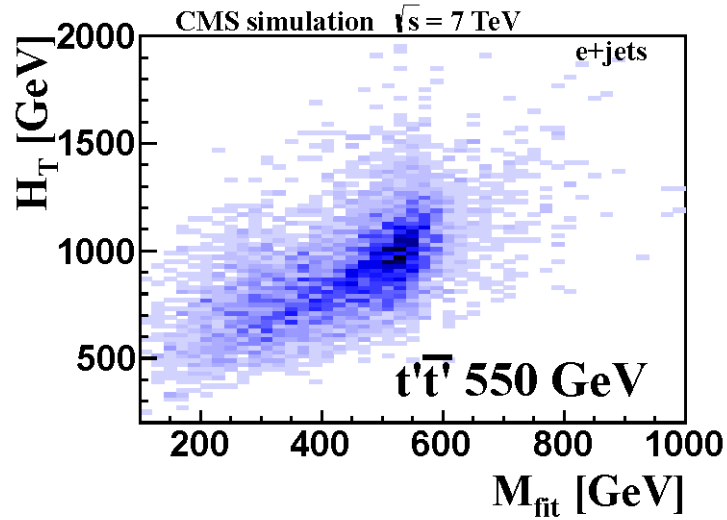
- large branching fraction – significant background
- event selection
  - 1 lepton
    - electron $p_T > 35$ GeV
    - muon $p_T > 35 \ldots 42$ GeV
  - ≥4 jets
    - $p_T > 120, 90, 50 \ldots 30$ GeV
    - ≥ 1 b-tagged jet
  - missing $p_T > 25$ GeV

discriminating variables

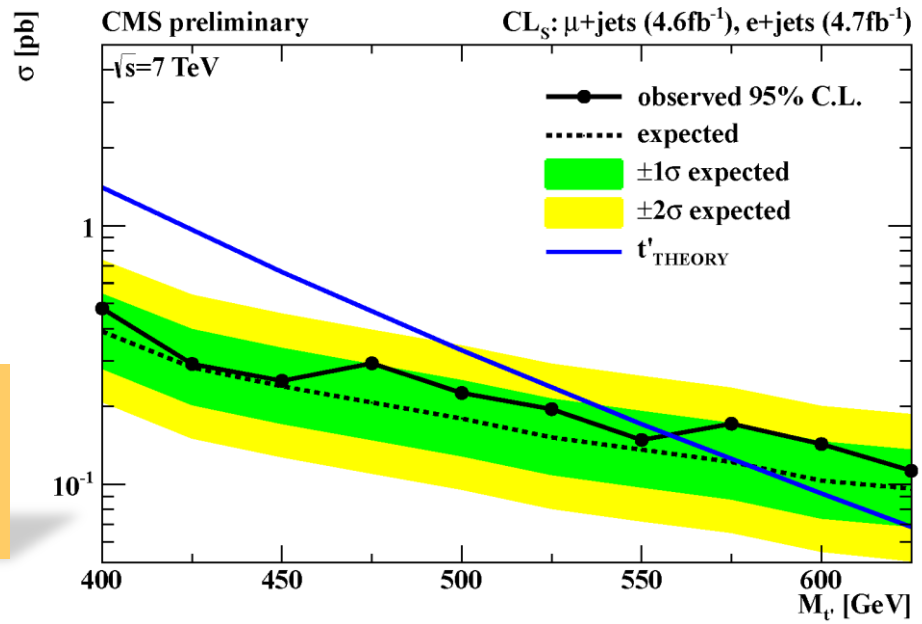
M_{fit}	t′ mass from kinematic fit
H_T	scalar sum of p_T of all $t'\overline{t'}$ decay products

t'→bW – lepton+jets final state





$m(\mathrm{t}') > 560$ GeV

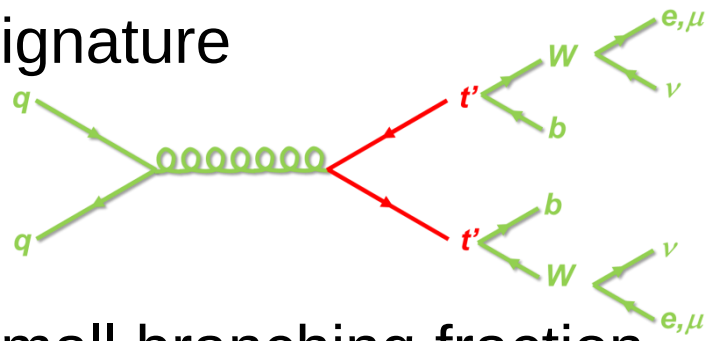


ATLAS *PRL 108 (2012) 261802*
$M_{t'} > 404$ GeV
1/fb @ 7 TeV

t'→bW – dilepton final state

7 TeV
5/fb

- signature

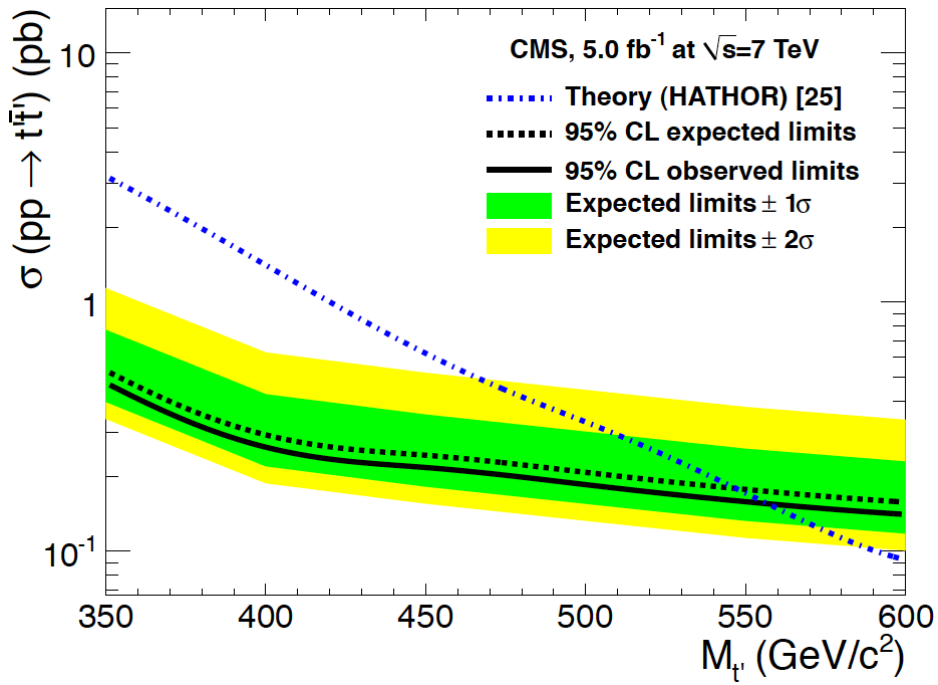


$$M_{\ell b} < \sqrt{{m_t}^2 - {M_W}^2}$$

CMS arXiv:1203.5410

- small branching fraction – little background
- event selection
  - 2 opposite-sign leptons
    - $p_T > 20$ GeV
    - $Z, \Upsilon, J/\chi$ veto
  - ≥2 jets $p_T > 30$ GeV, ≥ 2 b-tags
  - missing $p_T > 50$ GeV
  - $min(M_{\ell b}) > 170$ GeV

ATLAS *arXiv:1202.3389*
$m(\mathrm{t}') > 350$ GeV
1/fb @ 7 TeV



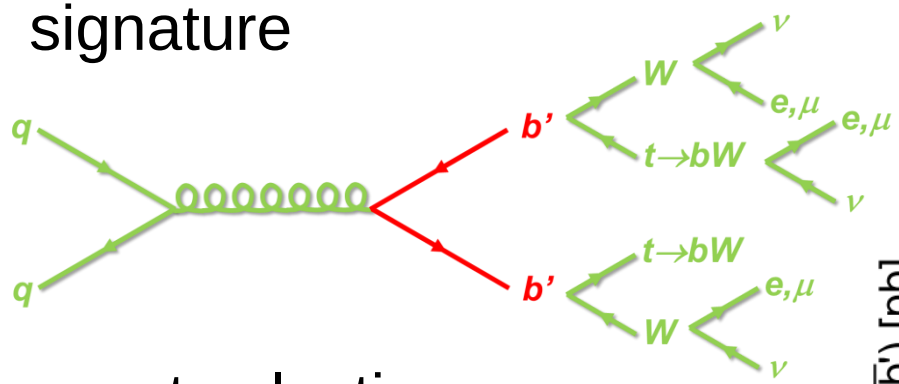
$m(\mathrm{t}') > 557$ GeV

b'→tW

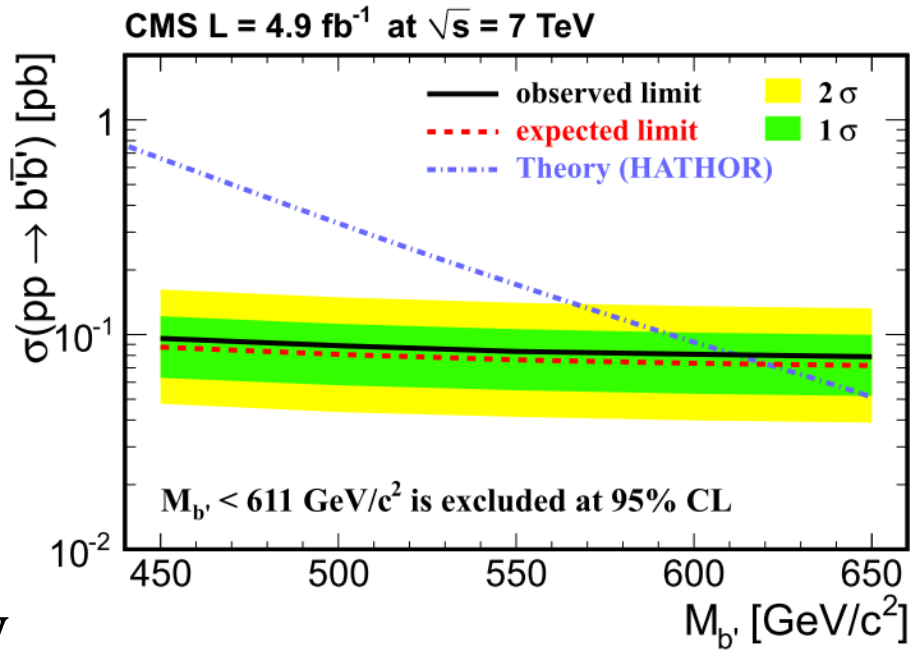
CMS arXiv:1204.1088

7 TeV
4.9/fb

- signature



- event selection
  - 2 same-sign leptons + ≥ 4 jets
  - 3 leptons + ≥ 2 jets
    - muons $p_T > 15$ GeV
    - electrons $p_T > 20$ GeV
    - jets $p_T > 25$ GeV, ≥ 1 b-jet
  - $S_T = \sum p_T(\text{jet}, \text{lepton}) > 500$ GeV



$m(\mathrm{b}') > 611$ GeV

4th generation quarks

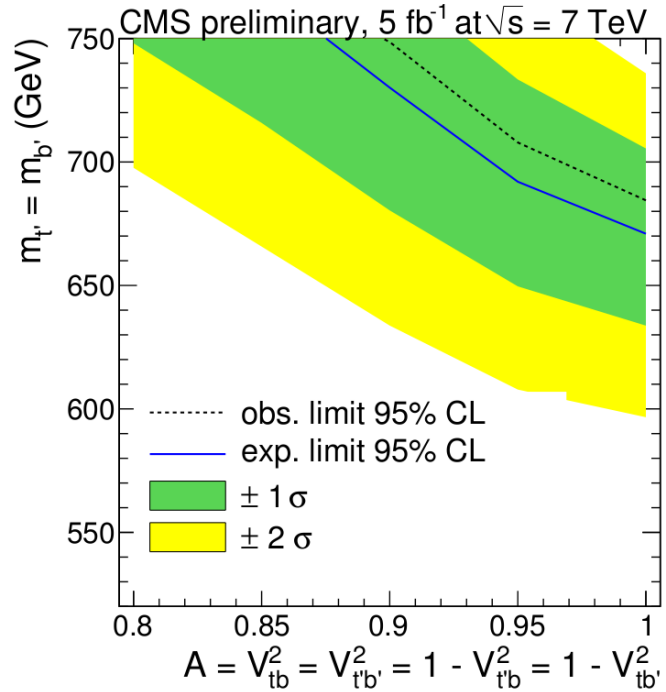
7 TeV
5/fb

- complete 4th gen model

$$V_{CKM}{}^{4\times4} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \sqrt{A} & \sqrt{1-A} \\ 0 & 0 & \sqrt{1-A} & \sqrt{A} \end{pmatrix}$$

- include all t' and b' production processes
  - event selection
    - one electron/muon $p_T > 40\ \mathrm{GeV}$
    - missing $p_T > 40\ \mathrm{GeV}$
    - ≥ 1 jet $p_T > 30\ \mathrm{GeV}$
    - ≥ 1 b-tagged jet
  - classify events according to number of hadronic W decays

$$m(\mathrm{t}') = m(\mathrm{b}') > 685\ \mathrm{GeV}$$
$$\text{for } A \approx 1$$



vector-like quarks

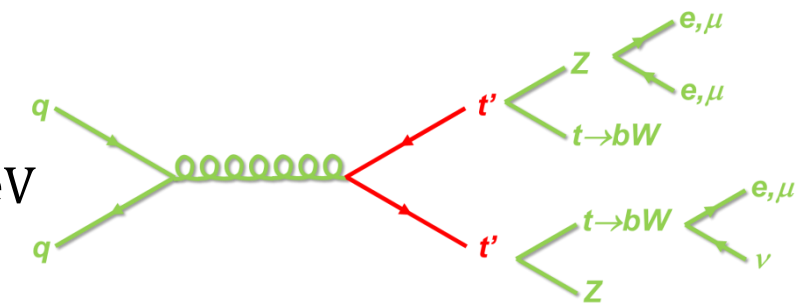
CMS PRL 107, 271802 (2011)

7 TeV
1.1/fb

- not subject to sm constraints, eg on FCNC
- do not have to couple to Higgs boson
- predicted e.g. by little Higgs models
- can decay to bW, tZ, tH
- assume 100% $t'\overline{t'} \rightarrow tZtZ$
  - 3 isolated leptons $p_T > 15 \ldots 20$ GeV
    - $60 < m_{\ell\ell} < 120$ GeV
  - ≥2 jets $p_T > 25$ GeV
  - $R_T = \sum_{i \geq 3} p_T(\text{jet} + lepton) > 80$ GeV

  ➔ $m(t') > 475$ GeV
- assume 100% $b'\overline{b'} \rightarrow bZbZ$
  - 2 isolated leptons $60 < m_{\ell\ell} < 120$ GeV
  - ≥2 jets $p_T > 25$ GeV , ≥1 b-jet
  - reconstruct bZ mass spectrum

  ➔ $m(b') > 550$ GeV



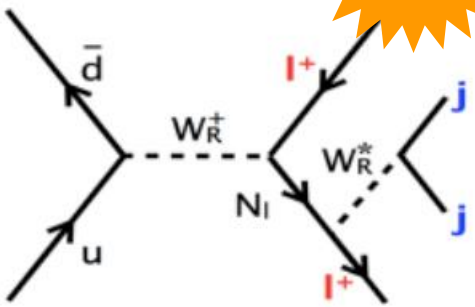
7 TeV
5/fb

CMS PAS EXO-11-066

heavy neutrinos

CMS PAS EXO-12-017

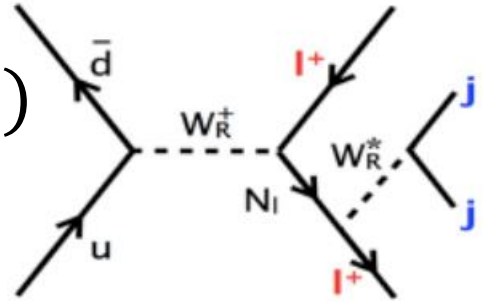
8 TeV
3.6/fb

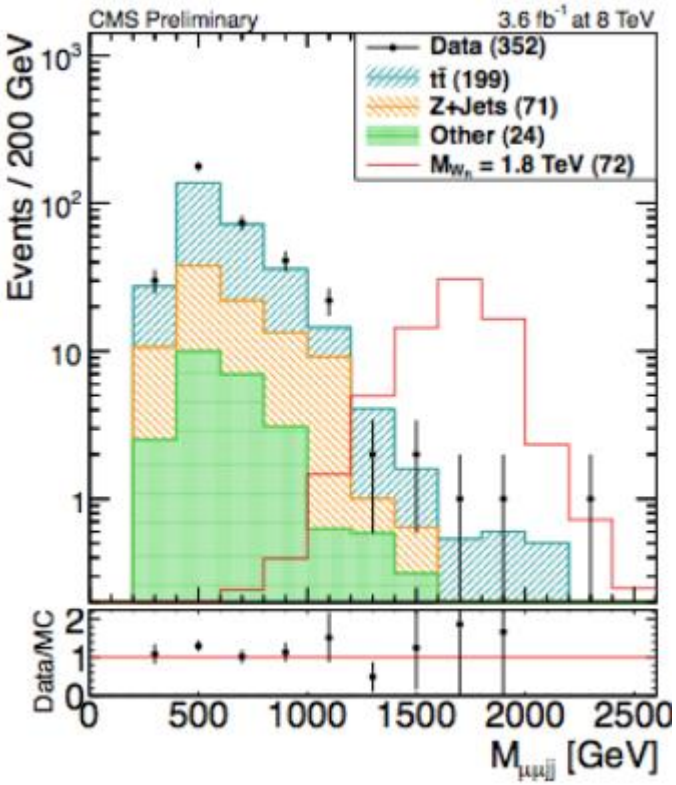


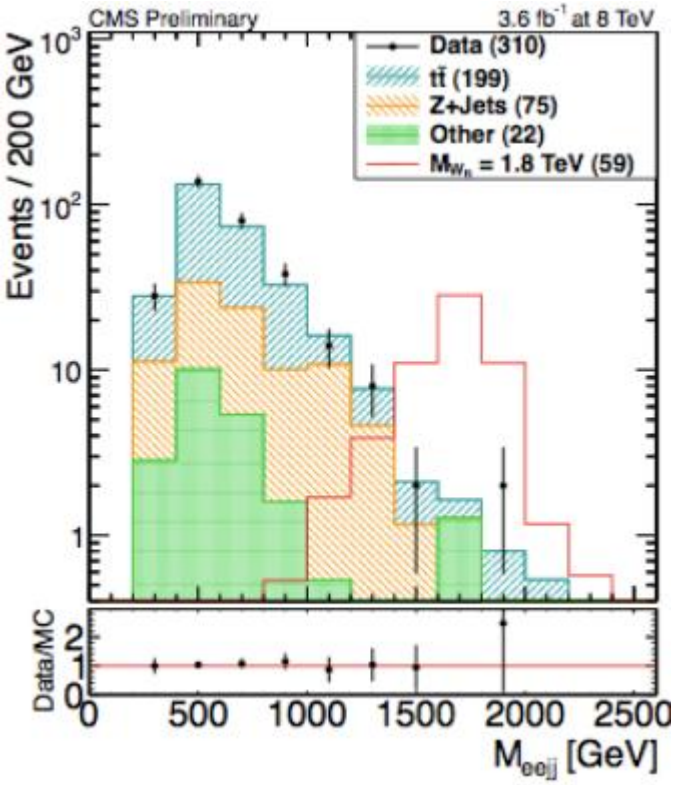
- LR symmetric model
  - introduces W_R, Z', ν_R
- event selection
  - leptons (ee or μμ): $p_T > 60/40$ GeV
  - jets: $p_T > 40$ GeV
  - $m(\ell\ell) > 200$ GeV
- backgrounds
  - top pair production: normalize to eμ data
  - Dell-Yan: normalize to Z peak in data
  - multijets: data-derived fake rates
  - WW,WZ,ZZ, single top production: MC

heavy neutrinos

– expect peaks in $m(\ell\ell jj)$ and $m(\ell jj)$

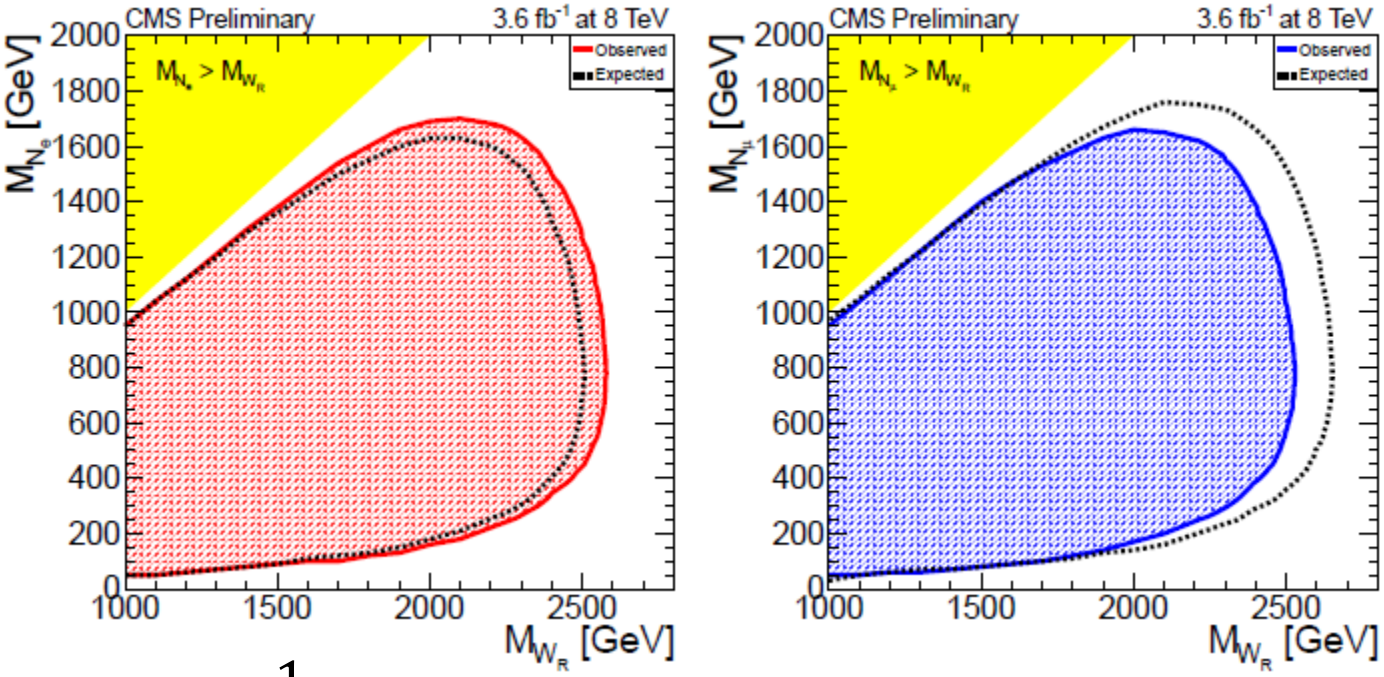






heavy neutrinos

- limits
  - assume $g_R = g_L$ and negligible LR mixing
  - assume only one flavor (e or μ) is accessible



  - for $m_{\nu_R} = \frac{1}{2} M_{W_R}$ exclude W_R up to 2.5 TeV

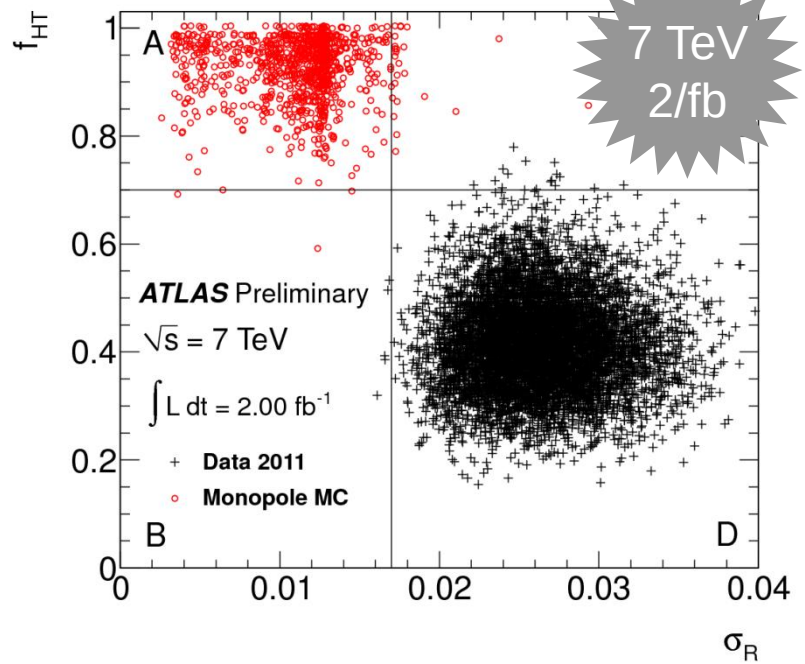
something completely different

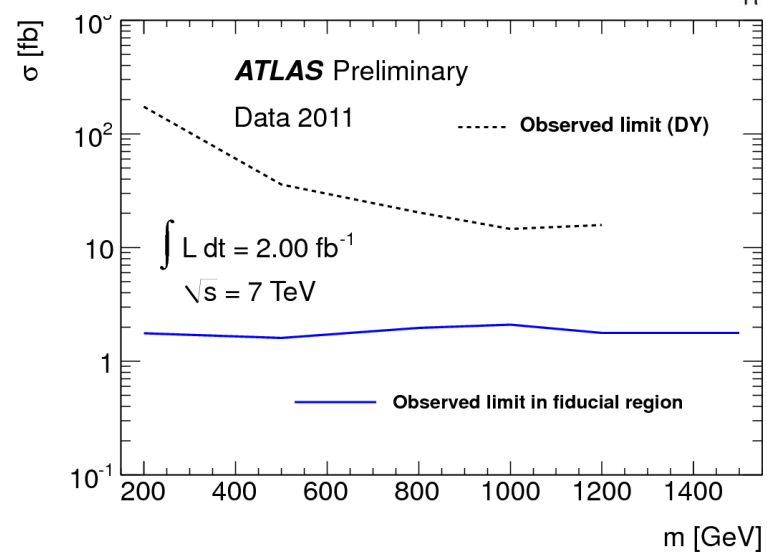
- magnetic monopoles
- black holes
- ????

magnetic monopoles

ATLAS-CONF-2012-062

- monopoles
  - are highly ionizing
  - interact with matter like particle with large charge
- signature
  - large local energy deposit in LAr EM calorimeter
  - matched to high radiation density in TRT
  - straight in $r\phi$ (if neutral) and curved in rz
  - must have $p_T > 200\ \mathrm{GeV}$ to penetrate to calorimeter





black holes

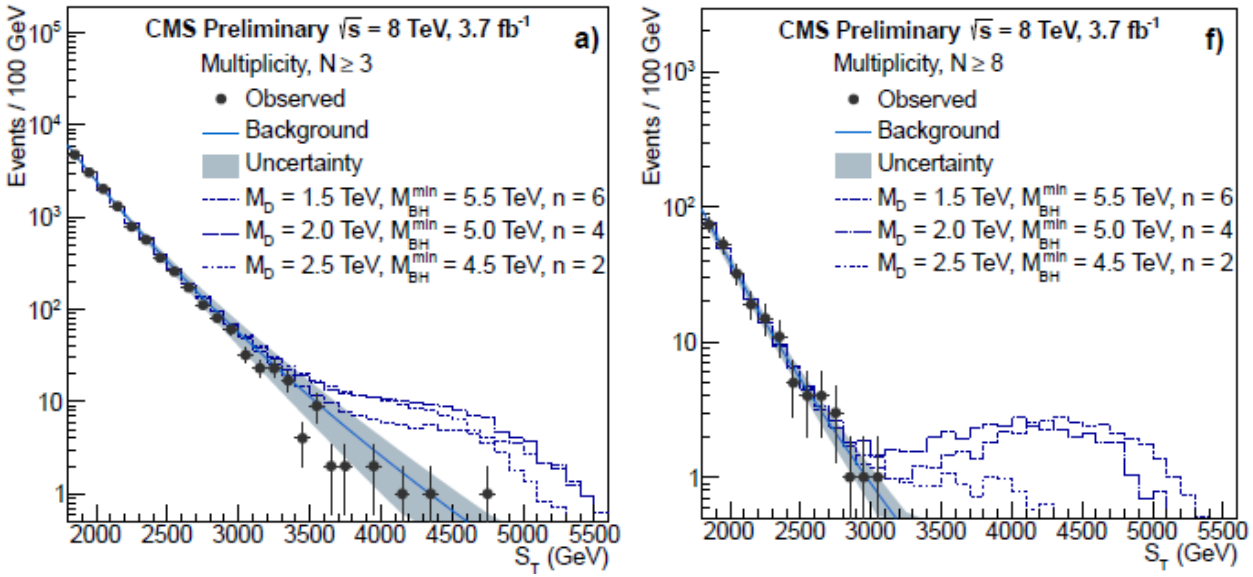
CMS PAS EXO-12-009

8 TeV
3.7/fb

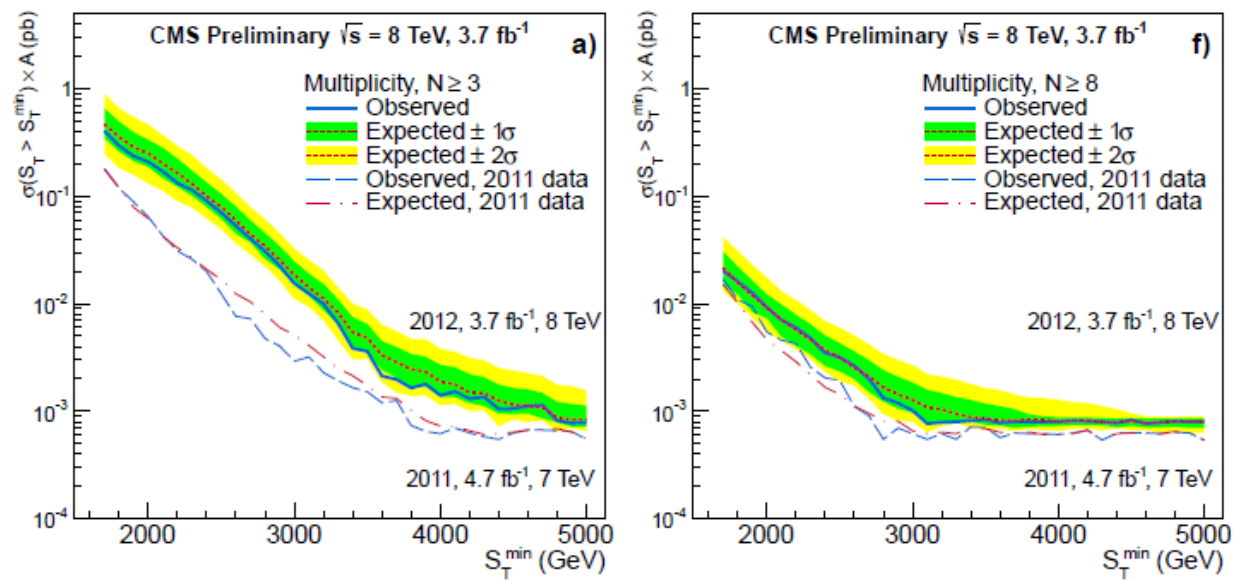
- low scale quantum gravity
  - n extra dimensions
  - multidimensional Planck scale ${M_D}^{n+2} \propto {M_P}^2 R^{-n}$
- black hole production
  - details of final state depend on evaporation model
  - $S_T = \sum_{j,e,\mu,\gamma,\nu} p_T$ provides model independent signature
- main background: multijet production
  - shape independent of jet multiplicity n_j
  - fit distribution for $n_j = 2$ and $S_T < 2.8\ \mathrm{TeV}$
  - normalize to data with $n_j \geq 3$ and $S_T < 2.2\ \mathrm{TeV}$

black holes

- fits to S_T at higher jet multiplicity

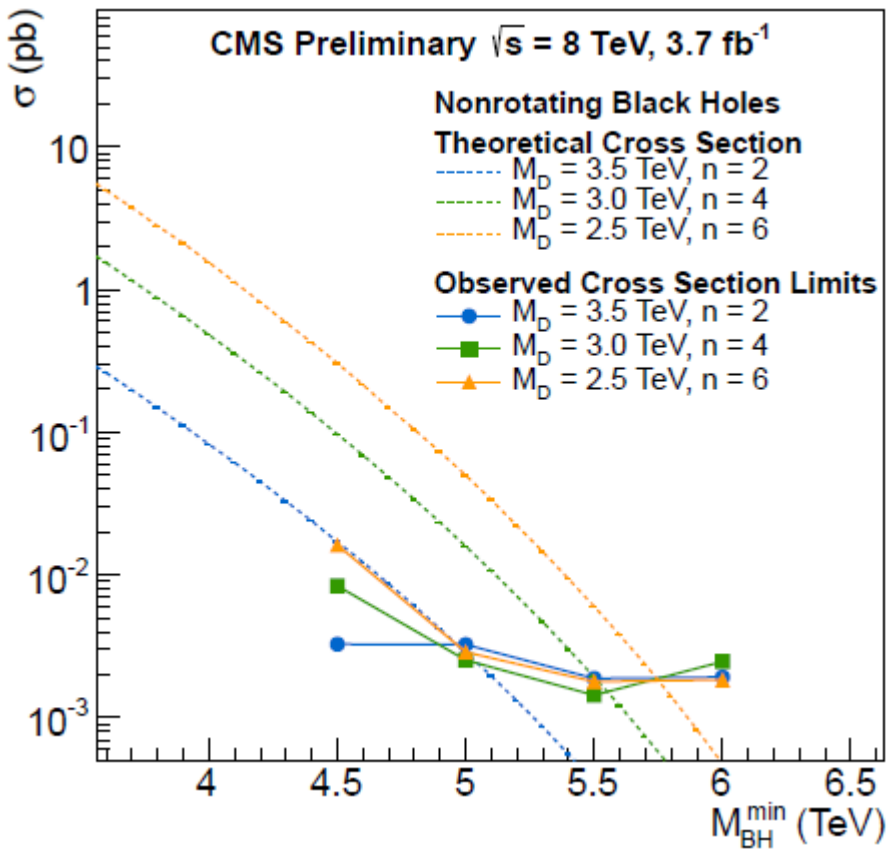


- set limits on xsec for $S_T > S_T^{min}$



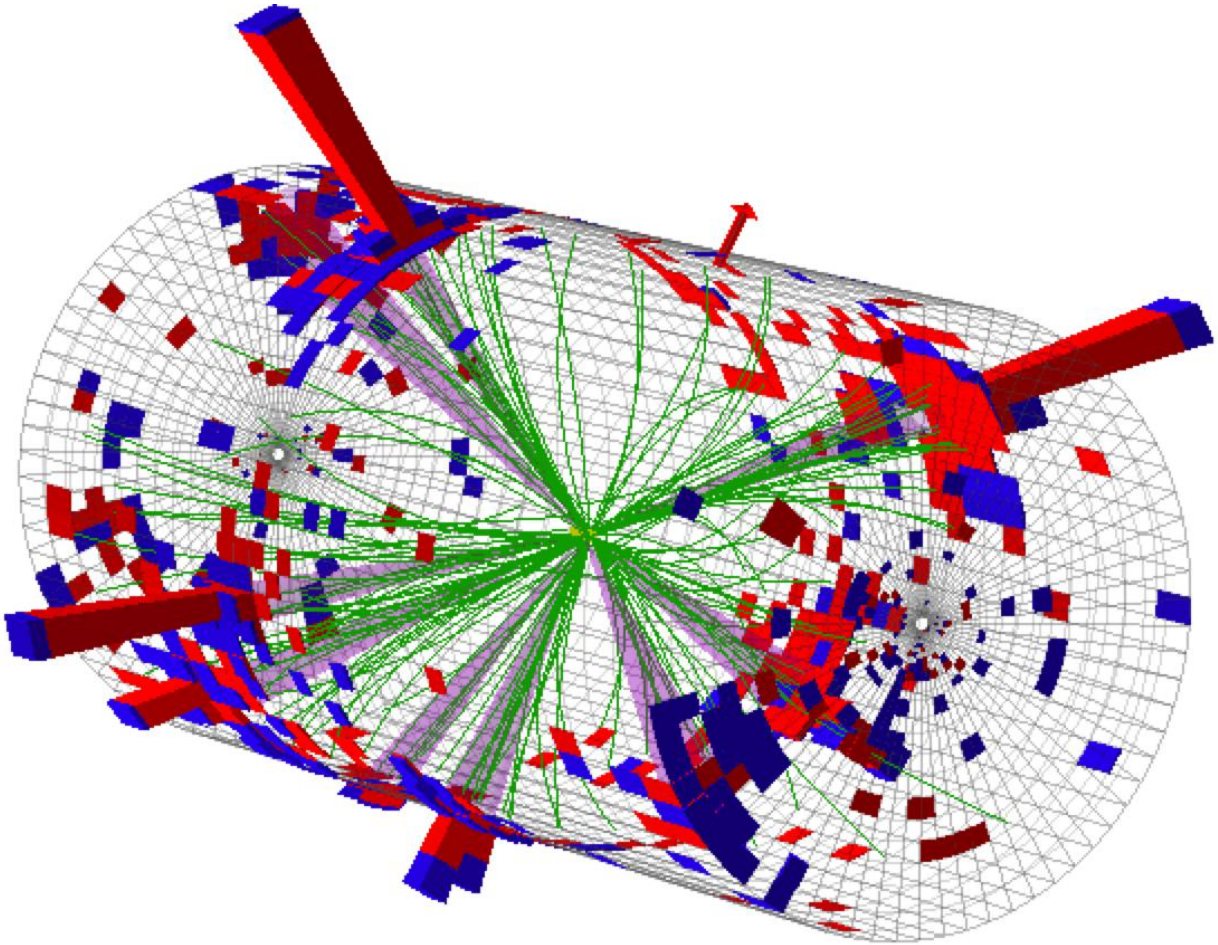
black holes

- limits on semiclassical black hole production



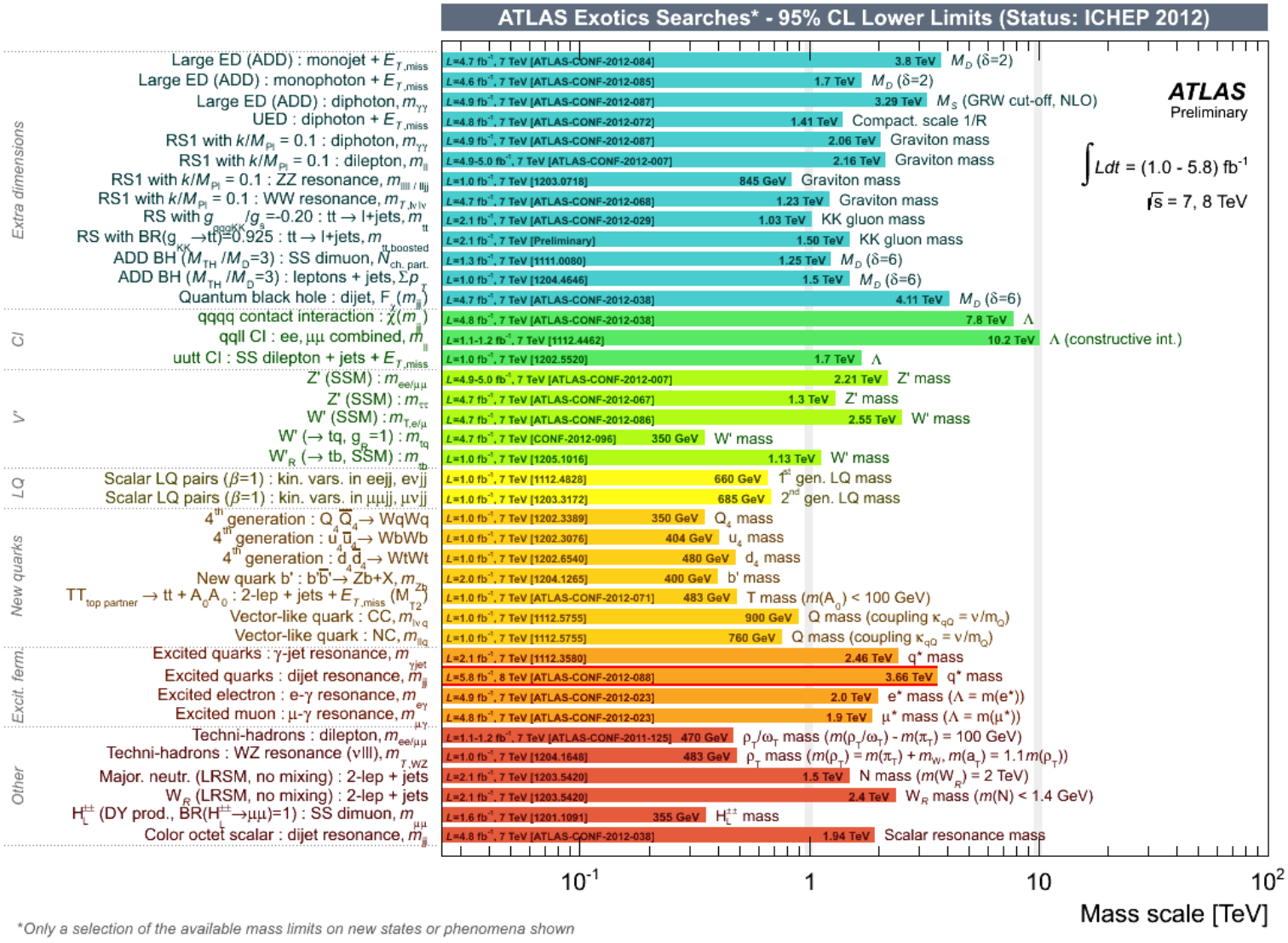
- minimum black hole mass > 4.1-6.1 TeV
  - for $M_D < 4.5\ TeV$ and $n \leq 6$

black holes

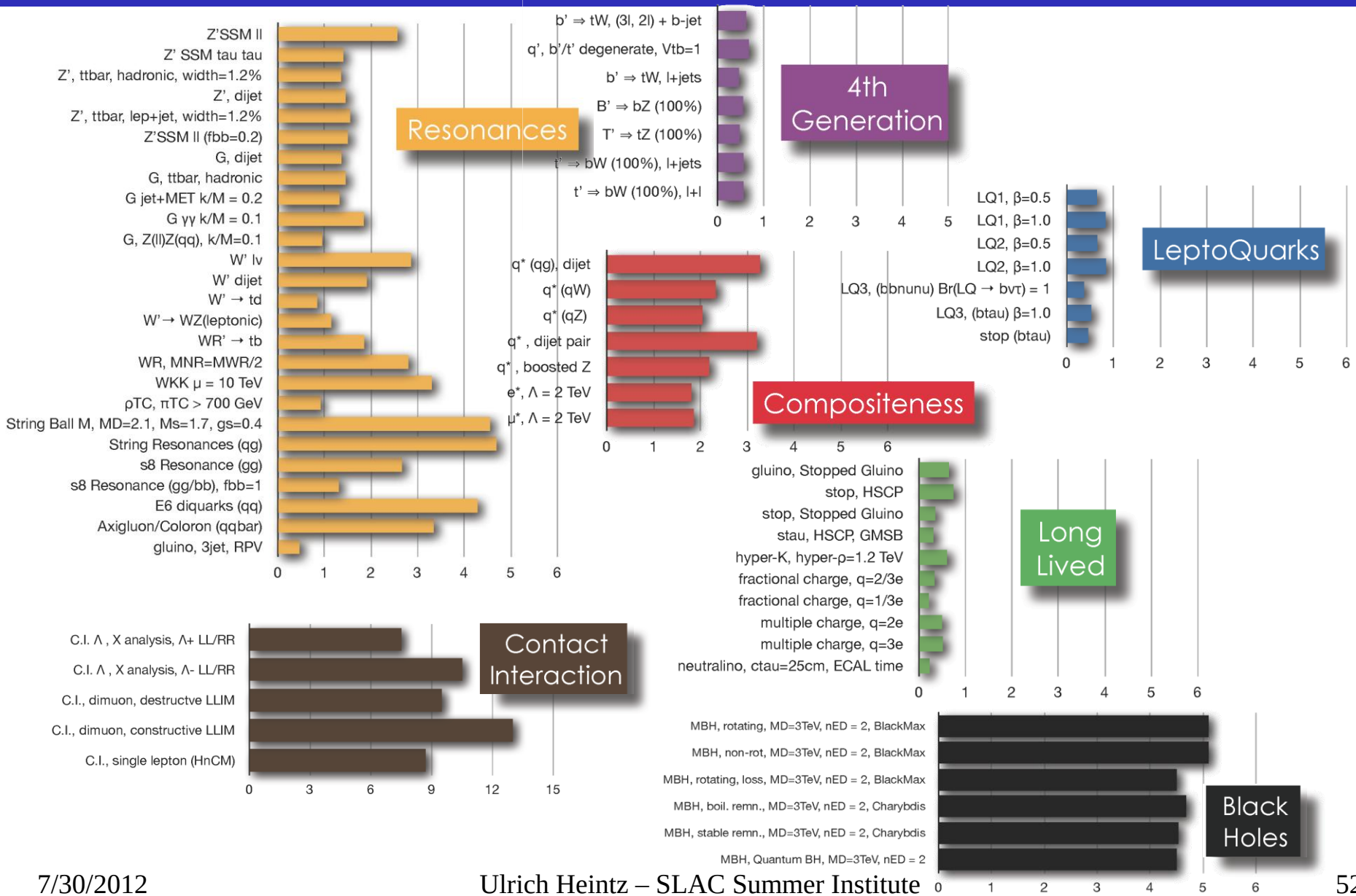


CMS Experiment at LHC, CERN
Data recorded: Mon May 23 21:46:26 2011 EDT
Run/Event: 165567 / 347495624
Lumi section: 280
Orbit/Crossing: 73255853 / 3161

summary of limits from ATLAS



summary of limits from CMS



summary

- LHC delivered
  - in 2011: 5/fb @ 7 TeV
  - in 2012: 8.6/fb @ 8 TeV so far
  - great laboratory to search for new physics at high energies
- ATLAS and CMS
  - have searched for a plethora of signatures
  - already many results from 2012 data @ 8 TeV
    - CMS: 8, ATLAS: 1
  - no sign for BSM physics yet ...
  - I couldn't cover everything ... for more info:

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