Non-SUSY Searches

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Outline

- Broad (and rapid) overview of the BSM (non-SUSY, non-Top, non-Higgs) from ATLAS & CMS
  - When relevant, Tevatron results are mentioned.
- Priority put on the latest results using the 2010 dataset
  - 35-43 pb^{-1} of integrated luminosity @ 7TeV
- Results are grouped largely by experimental signature.
  - Hadronic resonances
  - Leptonic and photonic resonances
  - Lepton+jets resonances
  - Non-resonance production
  - Long-lived particles

Links to Results Webpages

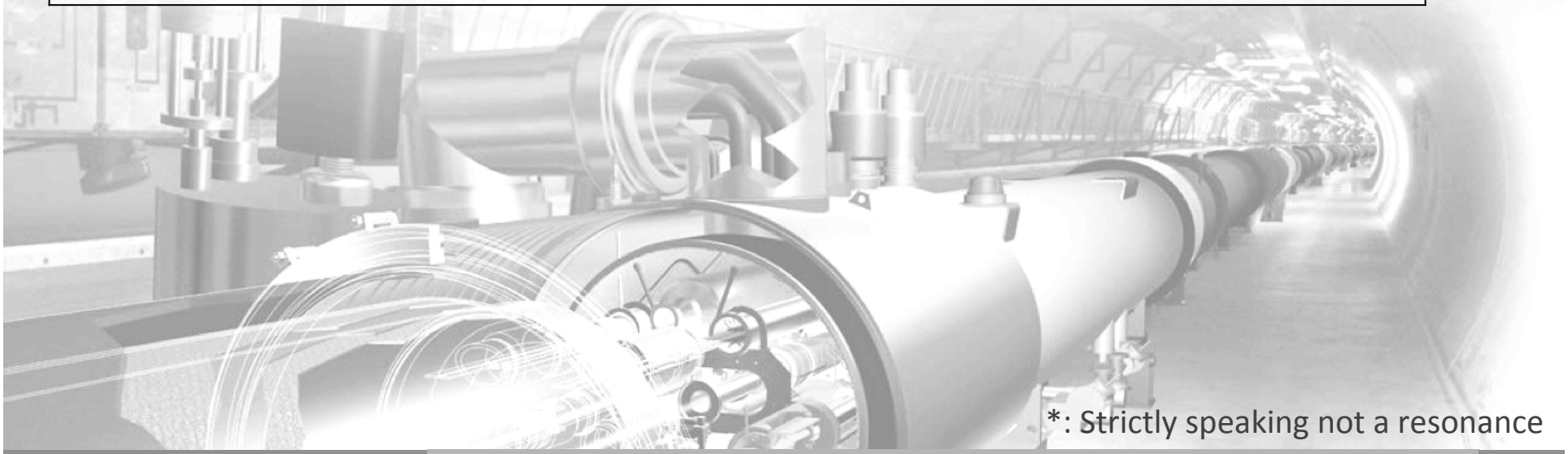
LHC	**ATLAS**	**CMS**
Tevatron	**CDF**	**D0**

Apologies for not covering all the results

- Almost all search analyses require data-driven estimates of backgrounds from data control region and extrapolation to signal region.
  - This is the primary analysis challenge
  - These estimate rely on pioneering SM measurements and accurate understanding of the physics objects

Hadronic Resonances

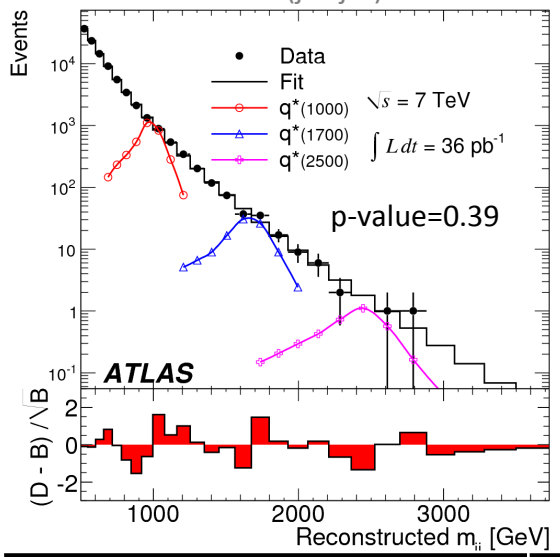
Signature	ATLAS	CMS	Example
Dijet mass	arXiv:1103.3864	arXiv:1010.0203	q*
Dijet angular variables*	arXiv:1103.3864	arXiv:1102.2020	Q*, contact interaction
Dijet centrality ratio*		arXiv:1010.4439	contact interaction
Three jets		EXO11001	RPV SUSY gluino
ttbar resonance (l+jets)	ATLAS-CONF-2011-070	EXO10023	Z'→ttbar



*: Strictly speaking not a resonance

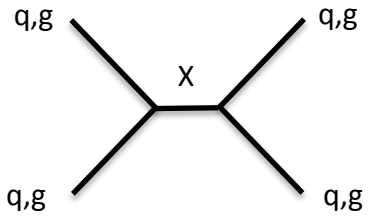
Dijet Mass Resonance

Observed & fitted m(jet-jet) distributions



Bump hunt in dijet invariant mass spectrum.

- Sensitive to the coupling of any new massive object to quarks and gluons.



No deviations from SM → set limits

Model	ATLAS Observed (expected) limit at 95% CL (36pb^{-1})	CMS Observed (expected) limit at 95% CL (2.6pb^{-1})
Excited quarks	m_{q^*} > 2.15 (2.07) TeV	m_{q^*} > 1.58 (1.32) TeV
Axigluons	m > 2.10 (2.01) TeV	m >1.17 (1.23) TeV
E6 diquark (M_D)		[0.50,0.58] [0.97,1.08] [1.45,1.60]
Quantum Black holes (d=6)	M_D > 3.67 (3.64) TeV	

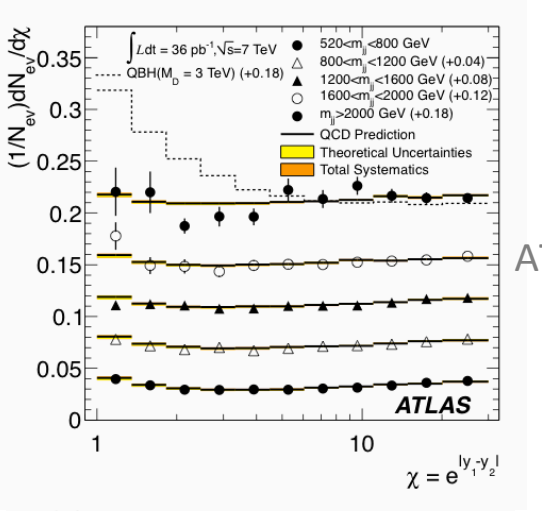
ATLAS also provide upper-limits on Nobs for Gaussian reconstructed m_{jj}
CMS also provides upper limits on σ×BR×A for qq, gg, qg decay modes.
Also exclude string resonance 0.5-2.5 TeV

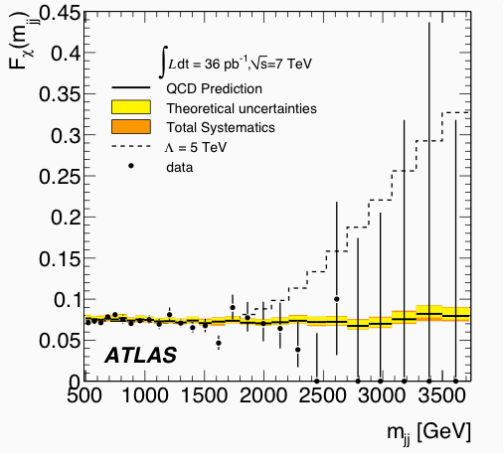
Dijet Angular Distribution

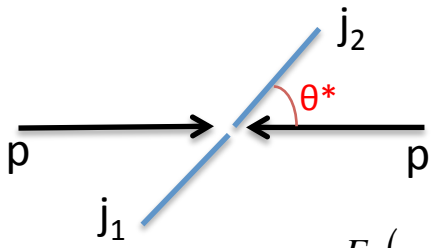
Look at dijet COM scattering angle θ* via χ variable.

$$\chi \equiv \exp\left(|y_1 - y_2|\right) = \exp\left(2|y^*|\right)$$

Isotropic new physics peaks at low χ, while QCD is flat in χ:







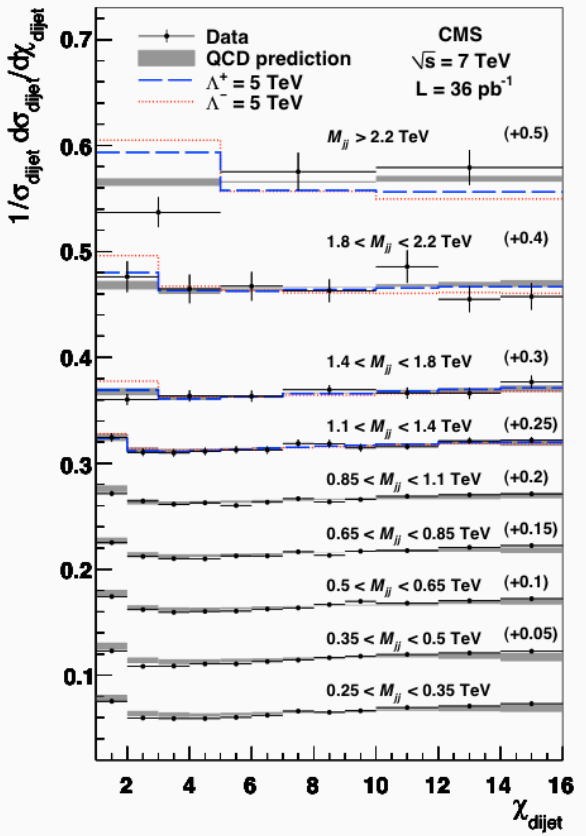
$$y^* = \frac{1}{2}\ln\frac{1+|\cos\theta^*|}{1-|\cos\theta^*|}$$

ATLAS also measured $F_\chi(m_{jj}) = \dfrac{N_{events}\left(|y^*|<0.6\right)}{N_{events}\left(|y^*|<1.7\right)}$

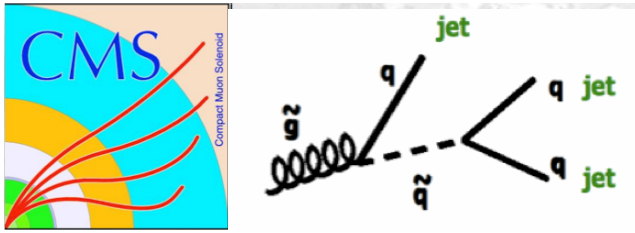
ATLAS limits

Model and Analysis Strategy	95% C.L. Limits (TeV) Expected	Observed
Excited Quark q^*		
Resonance in m_{jj}	2.07	2.15
$F_\chi(m_{jj})$	**2.12**	**2.64**
Randall-Meade Quantum Black Hole for $n = 6$		
Resonance in m_{jj}	**3.64**	**3.67**
$F_\chi(m_{jj})$	3.49	3.78
θ_{np} Parameter for $m_{jj} > 2$ TeV	3.37	3.69
11-bin χ Distribution for $m_{jj} > 2$ TeV	3.36	3.49
Axigluon		
Resonance in m_{jj}	**2.01**	**2.10**
Contact Interaction Λ		
$F_\chi(m_{jj})$	**5.7**	**9.5**
F_χ for $m_{jj} > 2$ TeV	5.2	6.8
11-bin χ Distribution for $m_{jj} > 2$ TeV	5.4	6.6

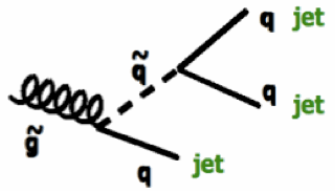
ATLAS sets limits on contact interactions: Λ*>9.5 (5.7) TeV



CMS sets limits on contact interactions: Λ*>5.6 (5.0) TeV



Multijets



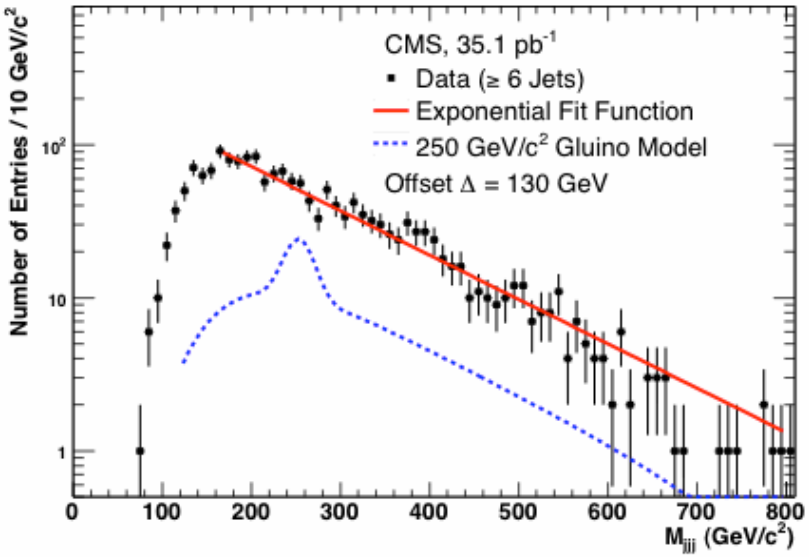
Search for strongly coupled resonance decaying to 3-jets

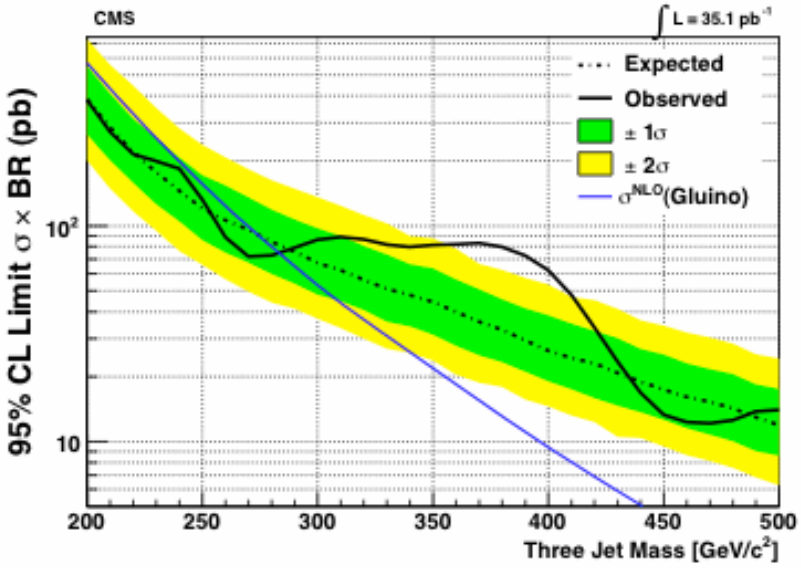
Look for 3 jets resonances in 6 jet final states

Modeled with RPV $\tilde{g}$ decays

Signature Selection

- ✓ ≥6jets & large Σp_T (>425GeV)
- ✓ Use an ensemble of jet combinations (Mjjj)





Limit set on RPV decaying gluinos, excluding mass form 200-280 GeV

Highest limits to data, first pp limits (CDF excludes below 144GeV – CDF10256)

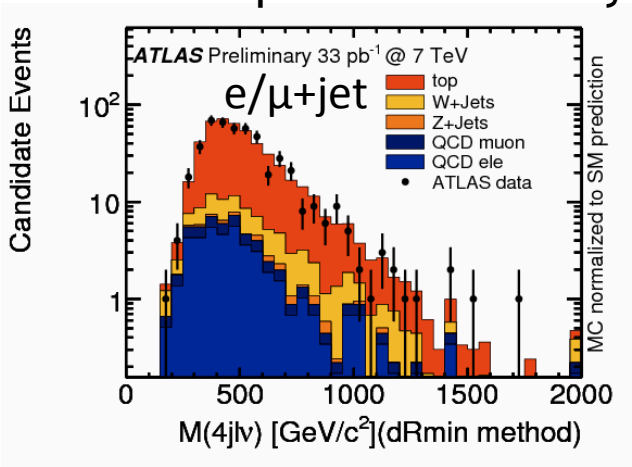
Largest excess seen @390GeV → significance of 1.9σ

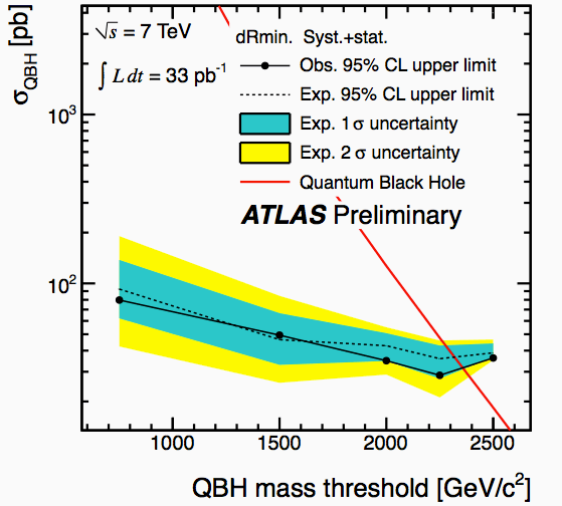
ttbar resonance (l+jets)

Z' resonance Non-resonance: stop, QBH (t+X, tt)

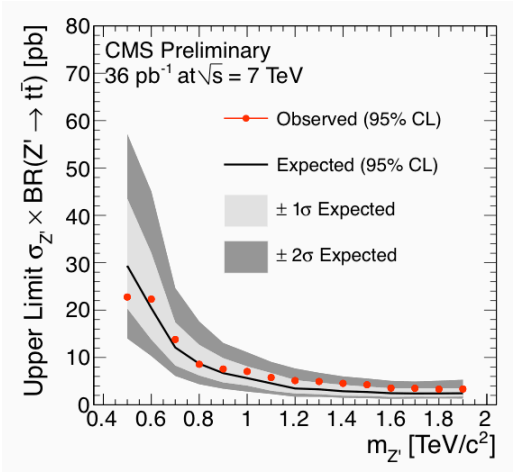
Search for resonance in ttbar decay (l+jets)

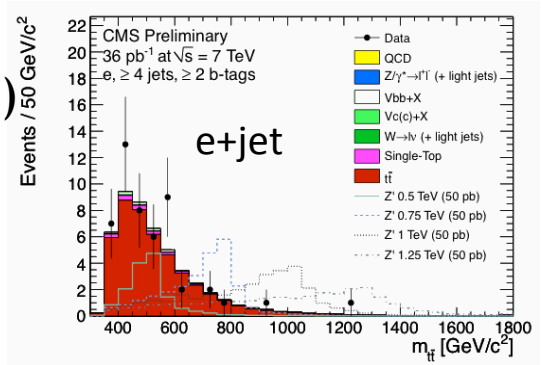
CMS improves sensitivity by categorizing events (l, #j, btag)

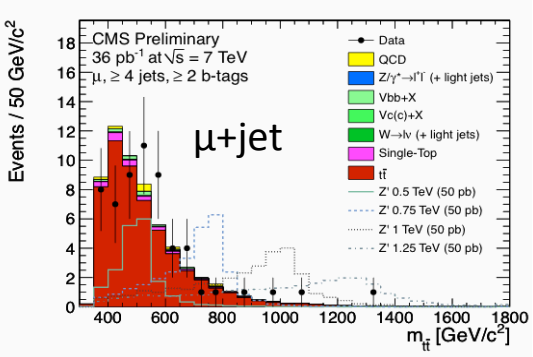




Exclude QBH with mass below 2.35TeV







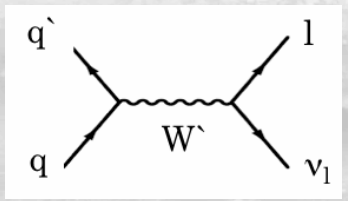
95% CL Upper limit on σ×BR (Z'→ttbar) [pb]

	ATLAS	CMS
$m_{Z'}$=500GeV	55 (40)	25
$m_{Z'}$=1000GeV	2.2 (5.0)	7
$m_{Z'}$=1500GeV		4

Leptonic and Photonic Resonances

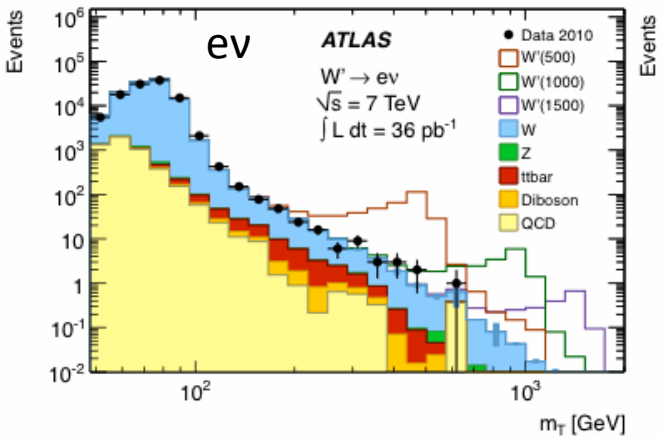
Signature	ATLAS	CMS	Example
lν (l=e,μ)	arXiv:1103.1391	arXiv:1103.0030 arXiv:1012.4945	W’
l^+l^- (l=e,μ)	arXiv:1103.6218	arXiv:1103.0981 EXO10025	Z’ q*
l^+l^- ϒ(l=e,μ)		EXO10016	e*, μ*
ϒϒ	ATLAS-CONF-2011-044	EXO10019	RS graviton
Muon jets		EXO11013	“dark photon”

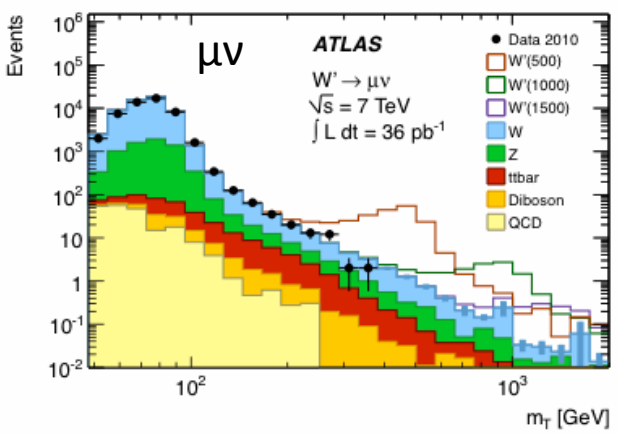
lν Resonance Searches

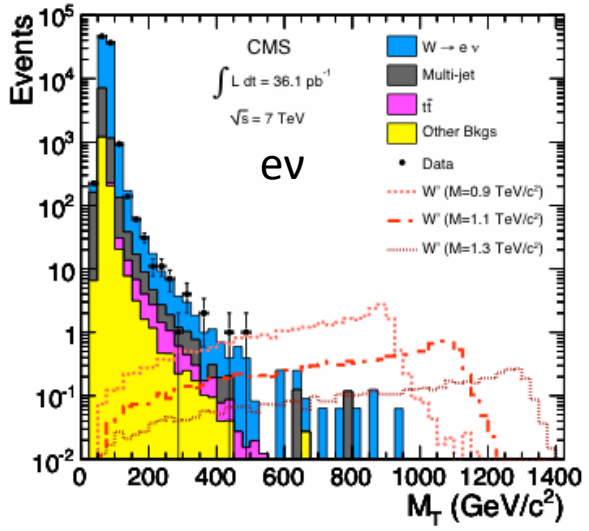


Look for Jacobian peak in M_T(eν) and M_T(μν)

No devisation from SM

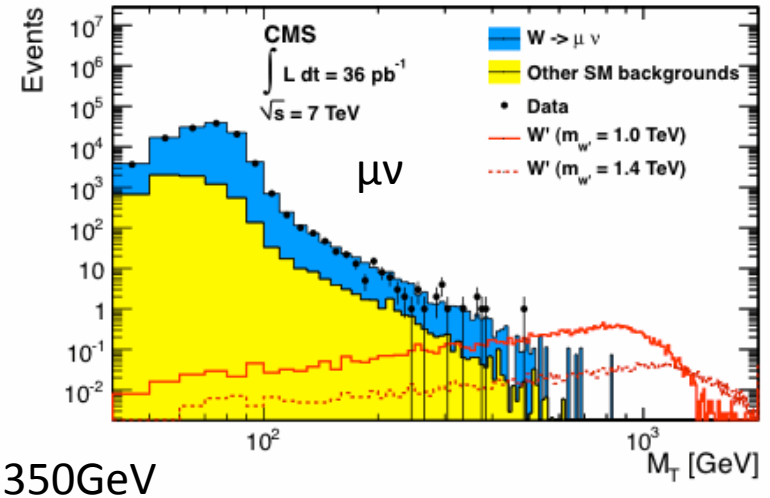






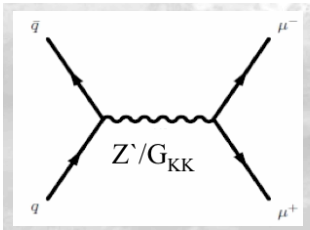
95% CL lower limit on W'_{SSM} [in TeV]

Channel	ATLAS Obs (Exp)	CMS Obs
Electron	1.37(1.37)	1.36
Muon	1.29(1.21)	1.40(1.35)
Combined	1.49(1.45)	1.58



Tevatron limit: 1.1 TeV

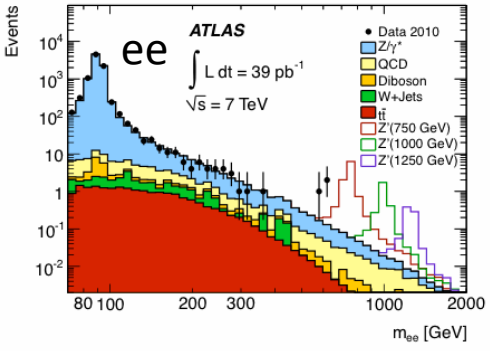
ATLAS sets also limit on W* up to 1350GeV

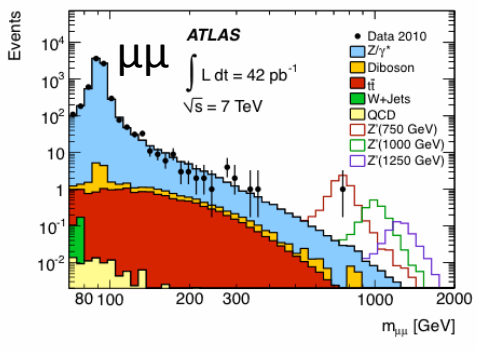


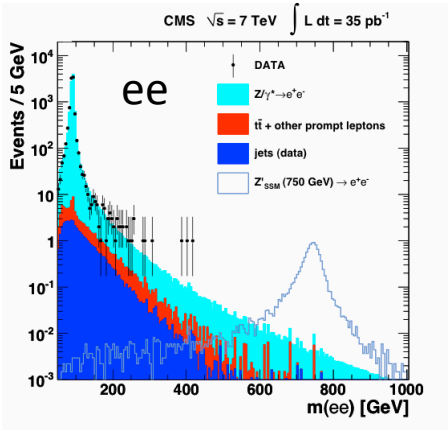
l^+l^- Resonance Searches

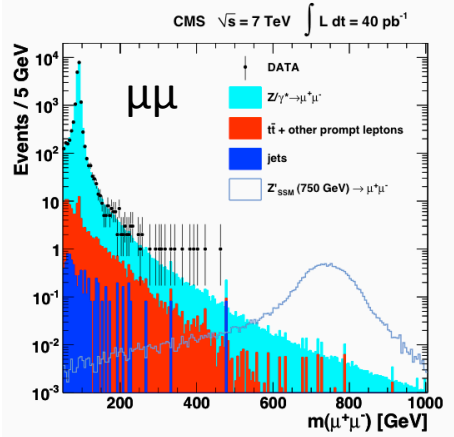
Look for bump in dilepton mass spectrum (isolated high p_T leptons OSSF)

No deviation from SM (dominantly Drell-Yan)







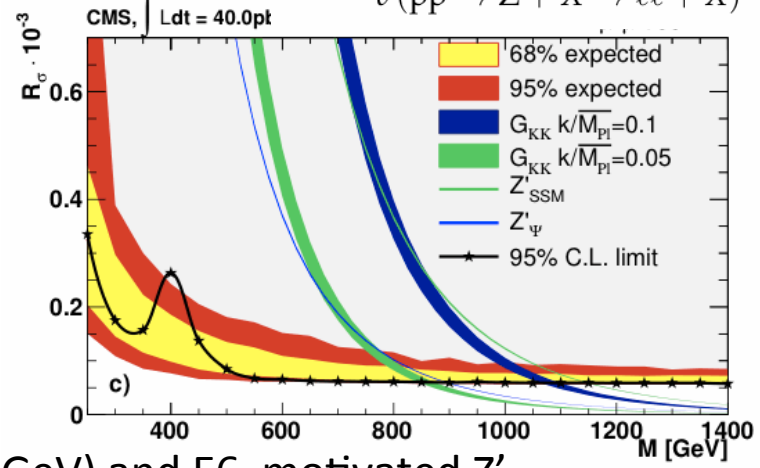


Express limit as a ratio b/w σ(Z') to the SM Z

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

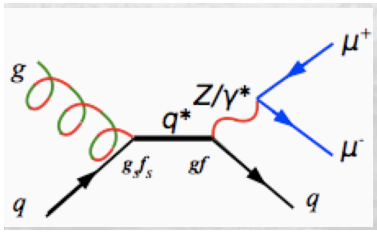
95% CL lower limit on Z'_{SSM} [in GeV]

Channel	ATLAS Obs (Exp)	CMS Obs
Electron	957 (967)	958
Muon	834 (900)	1027
Combined	1048 (1088)	1140



Tevatron limit: 1071 GeV

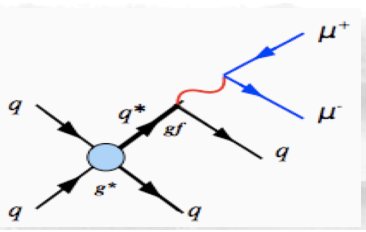
ATLAS sets also limit on Z* (1152GeV) and E6 motivated Z'



Quark Compositeness

Gauge interaction

Contact interaction



Search for anomalous production of highly boosted Z^0

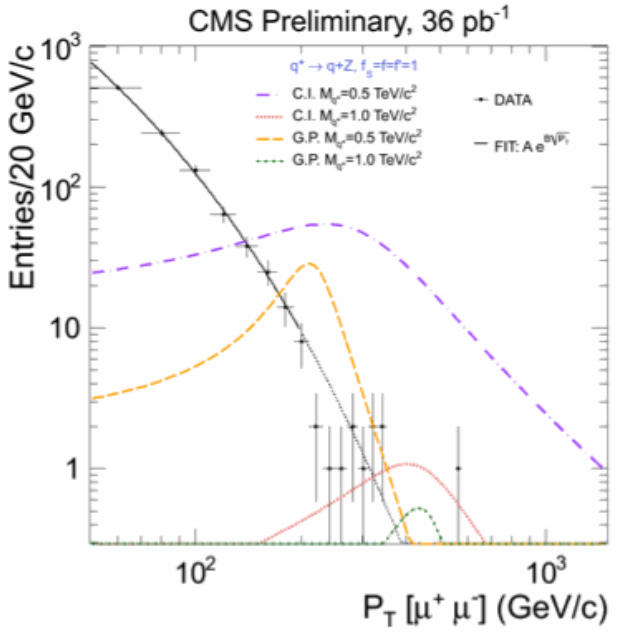
Search for bump in Zp_T spectrum

Weakly decaying excited quark $q^* \to qZ \to q\mu^+\mu^-$

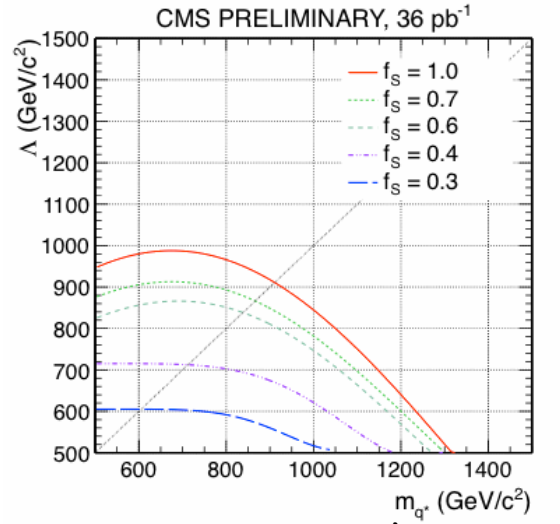
$\Lambda = M_{q^*}$ and $f = f' = 1$

Complementary to $q^* \to jj$ decay channel

No deviation from SM predictions



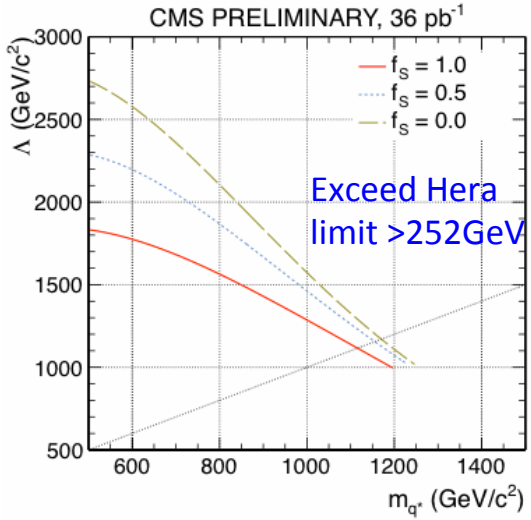
Gauge interaction



$M_{q^*} = \Lambda, f = f' = f_s = 1$

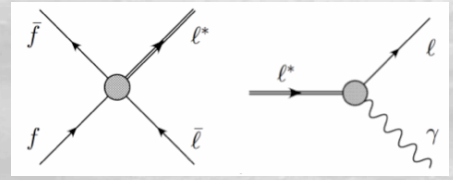
$M_{q^*} > 0.91 TeV$

Contact interaction



$M_{q^*} = \Lambda, f = f' = 1, f_s = 0$

$M_{q^*} > 1.17 TeV$



l(lγ) resonance searches

Search for excess in at high M(eγ) or M(μγ)

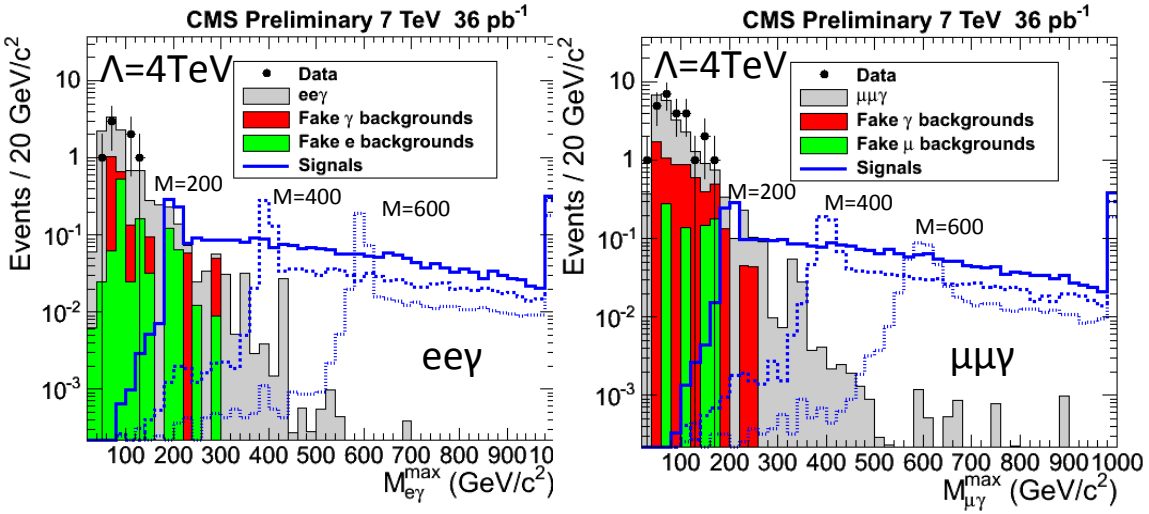
Production via new contact interaction

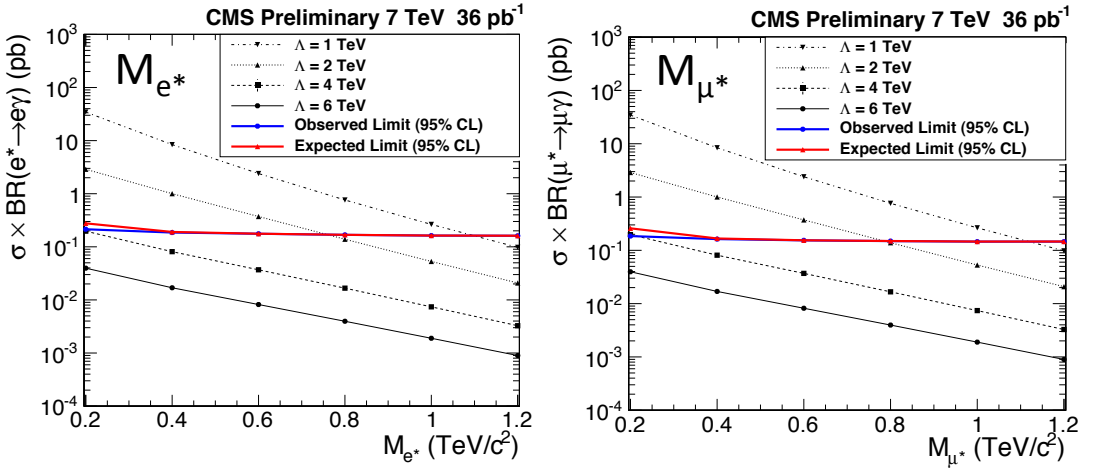
$$qq \to ee^* \to ee\gamma$$

$$qq \to \mu\mu^* \to \mu\mu\gamma$$

Experimental signature:

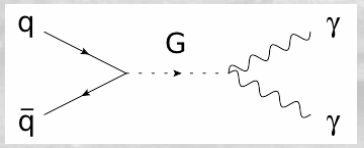
- ✓ 2 isolated e/μ of opposite charge
- ✓ Isolated γ ΔR(γ,l)>0.5

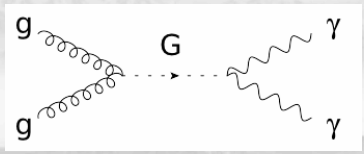




Channel	95% CL lower limit M(l*) for Λ=2TeV [GeV]
Electron	760
Muon	785

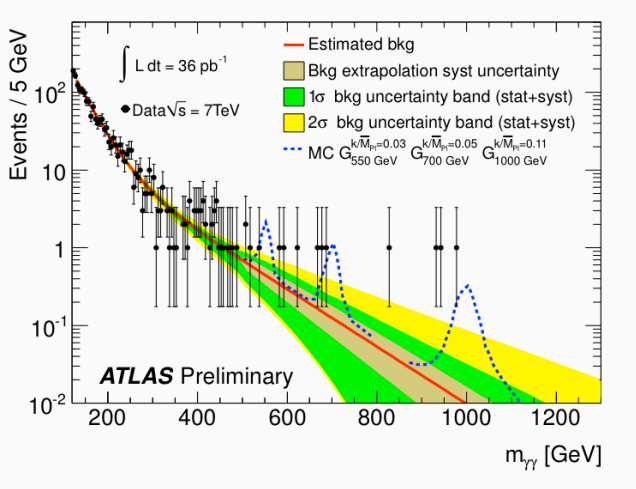
γγ resonances

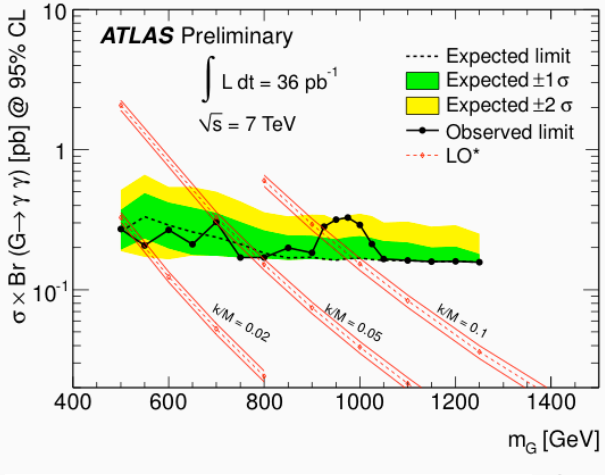


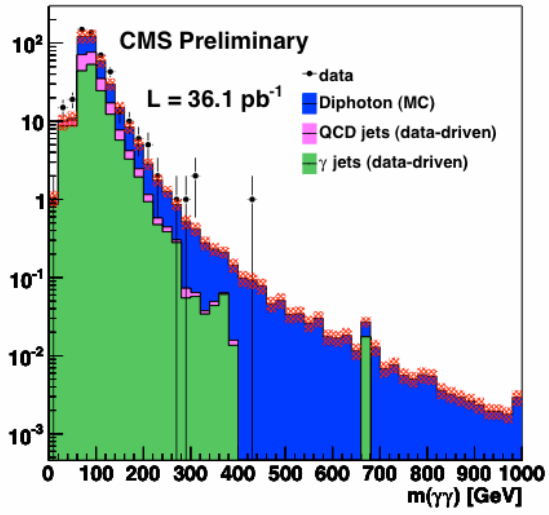


Bump hunt in γγ mass (at high mass !)

Randall-Sundrum Graviton



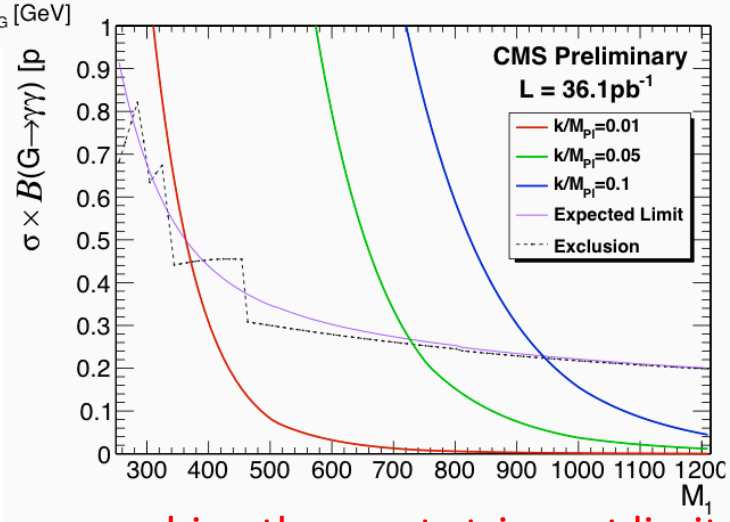




95% CL Upper limit on RS Graviton [GeV]

k/M_{Pl}	ATLAS	CMS	CDF	D0
0.01	-	371	459	560
0.02	545	-	-	-
0.1	920	945	963	1050

CDF combined limit G→γγ+G→ee+G→μμ: 1119



LHC experiments approaching the most stringent limits

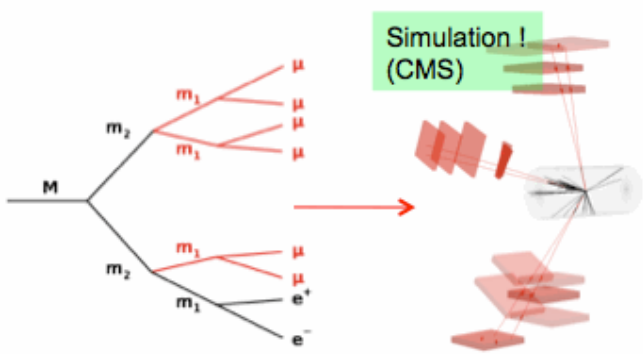
μ-Jets

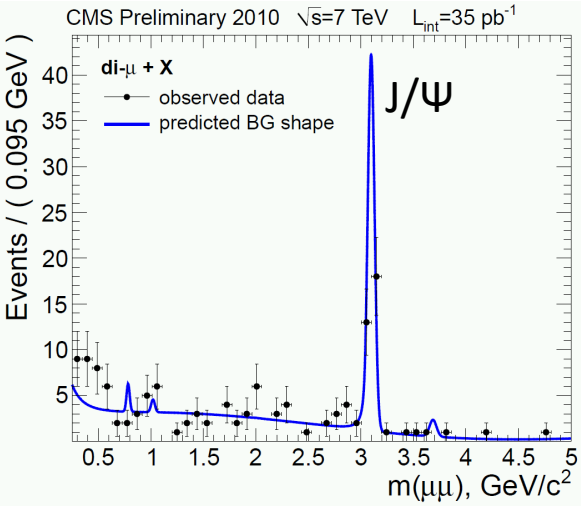
Search collimated groups of di-muons from new low mass resonances (m_l~GeV)

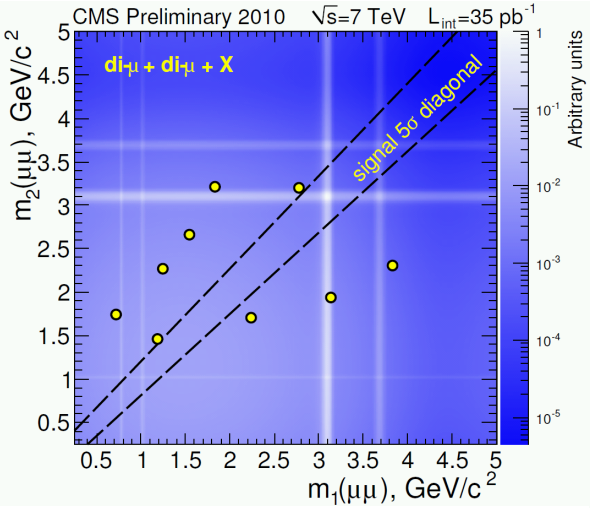
- Studied 3 SUSY with "hidden valley" scenarios
  - Model motivated by PAMELA's positron excess

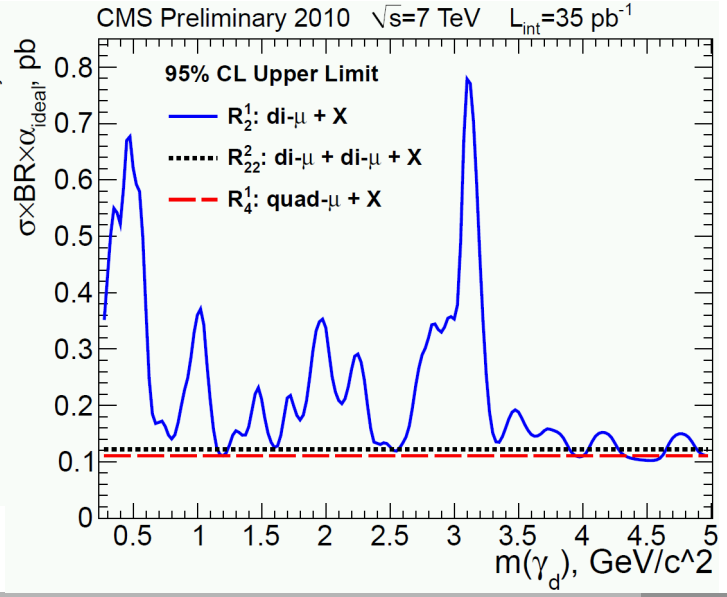
μ's clustered into nearby, pairs of opposite charge

- Channels: [μμ], [μμ] [μμ](same mass), [μμμμ], [≥5μ]



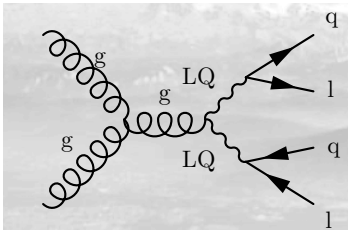






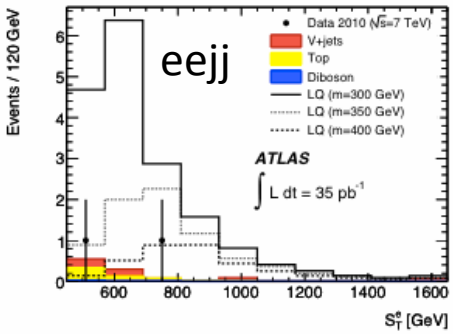
Leptons+jet Resonances

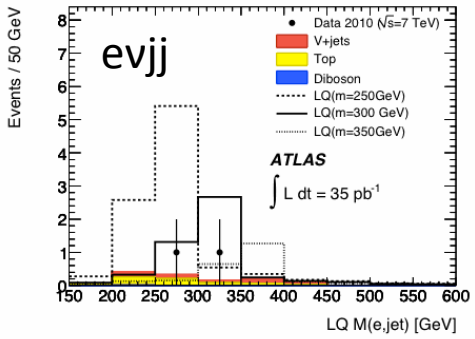
Signature	ATLAS	CMS	Example
ejej	arXiv:1104.4481	arXiv:1012:4031	LQ(1)
ejvj	arXiv:1104.4481	arXiv:1005:5237	LQ(1)
μjμj	arXiv:1104.4481	arXiv:1012:4033	LQ(2)
μjvj	arXiv:1104.4481		LQ(2)
WqWq→lvqlvq	ATL-CONF-2011-022		Heavy quark



LQ(1) searches

Look for excess in high S_T for eejj or evjj final states



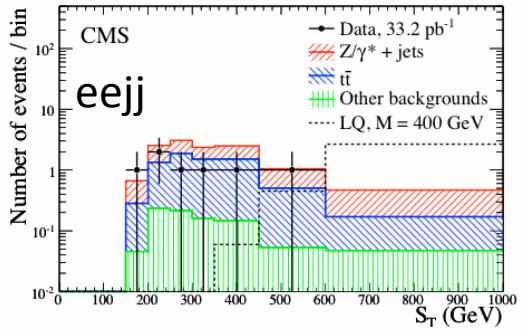


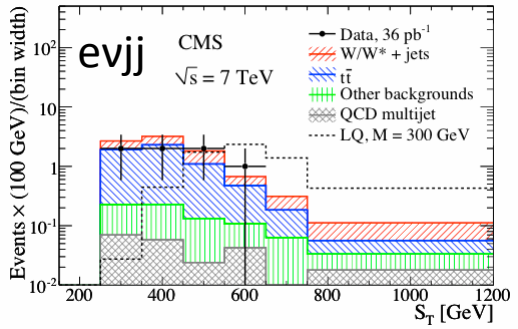
$$S_T = p_T^{l_1} + p_T^{l2} + p_T^{j_1} + p_T^{j2}$$

ATLAS signal region definition

$eejj$ and $\mu\mu jj$	$e\nu jj$
$M_{ll} > 120$ GeV	$M_T > 200$ GeV
$M_{LQ} > 150$ GeV	$M_{LQ} > 180$ GeV
$p_T^{all} > 30$ GeV	$M_{LQ}^T > 180$ GeV
$S_T^{\ell} > 450$ GeV	$S_T^{\nu} > 410$ GeV

Cuts optimized for each LQ mass hypo.
(CMS doesn't use M_{LQ} as discriminant)





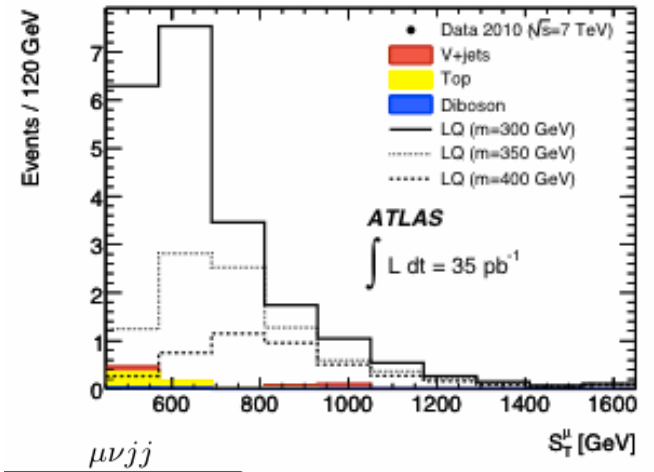
95% CL upper limits [GeV] on LQ1 (eejj, evjj combined)

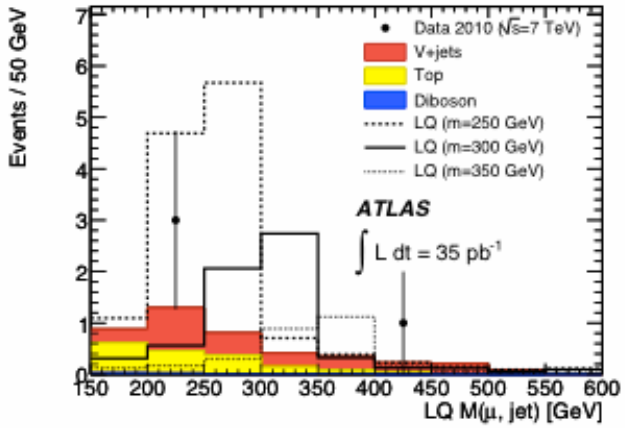
β	ATLAS	CMS	CDF	D0
0.1	-	255	145	-
0.5	319	340	205	284
1.0	376	384	235	299

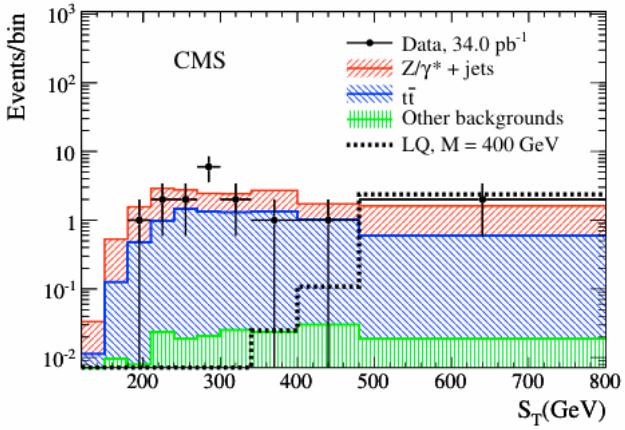
$$\beta = \mathrm{BR}(LQ \to lq)$$
$$1-\beta = \mathrm{BR}(LQ \to \nu q)$$

LQ(2) searches

Look for excess in high S_T for μμjj or μνjj final states





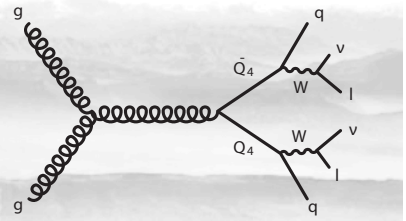


$\mu\nu jj$
$M_{\mathrm{T}} > 160$ GeV
$M_{\mathrm{LQ}} > 150$ GeV
$M_{\mathrm{LQ}}^{\mathrm{T}} > 150$ GeV
$S_{\mathrm{T}}^{\nu} > 400$ GeV

95% CL upper limits [GeV] on LQ1 (μμjj, μνjj combined)

β	ATLAS	CMS	CDF	D0
0.1			~145	185
0.5	362	~290	~210	270
1.0	422	394	~225	316

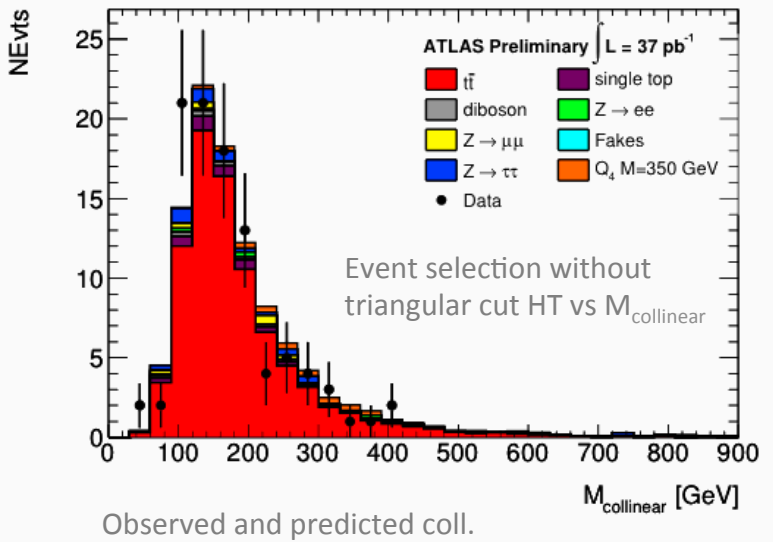
$Q_4Q_4 \rightarrow WqWq \rightarrow lvqlvq$



Events with exactly 2 OS leptons and at least 2 jets, MET>40, Z mass veto (for SF l)

Approximate mass reconstruction possible.

- Neutrinos are about collinear with leptons
  - boosted W's.
- Allocate MET to the two sides to minimize mass difference of the two $M_{collinear}$.

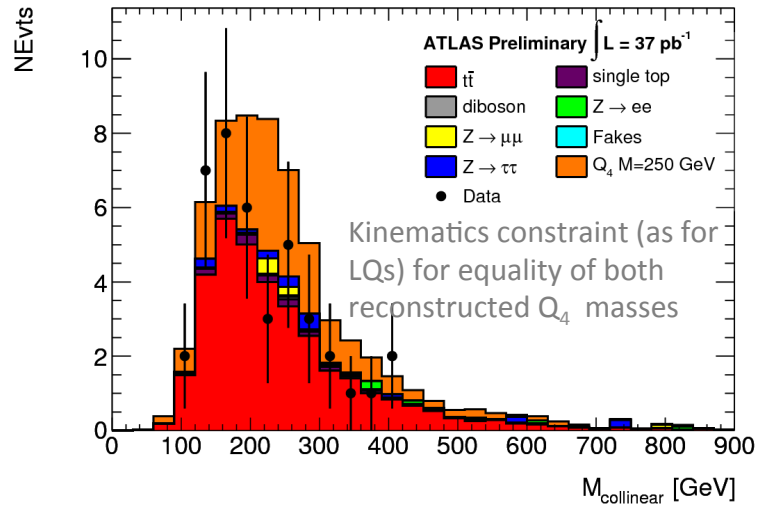


Observed and predicted coll. Mass for $M(Q_4)$=250GeV

Cut in plane of HT vs M(collinear)

Table 4: List of final selection cuts for each Q_4 mass.

Q_4 Mass (GeV)	Final selection
250	$H_T > 500 - 0.7 \times M_{collinear}$
300	$H_T > 600 - 0.5 \times M_{collinear}$
350	$H_T > 600 - 0.2 \times M_{collinear}$
400	$H_T > 700 - 0.3 \times M_{collinear}$



95% CL_{FC} upper limit on $M(Q_4)$>270 GeV,
Applicable to u_4 and other exotic Q_4-like models

CDF limit: m_{u4}>356 GeV (arXiv:1101.5728)

Non-resonance Production

Signature	ATLAS	CMS	Example
μμ (OS)	arXiv:1104.4398	EXO10020	ADD, contact interaction
ϒϒ		arXiv:1003:4279	ADD
Monojet+MET	Preliminary	EXO11003	ADD
ϒϒ+MET	arXiv:1012.4272		UED
μμ (SS)	ATLAS-CONF-2011-065		Black holes
Multijet	ATLAS-CONF-2011-068		Black holes
Multi-object	ATLAS-CONF-2010-088	arXiv:1012.3375	Black holes
Trilepton or SS dilepton +jets		arXiv:1102:4746	b'→tW
ttbar+MET	ATLAS-CONF-2011-036		T→t+A_0

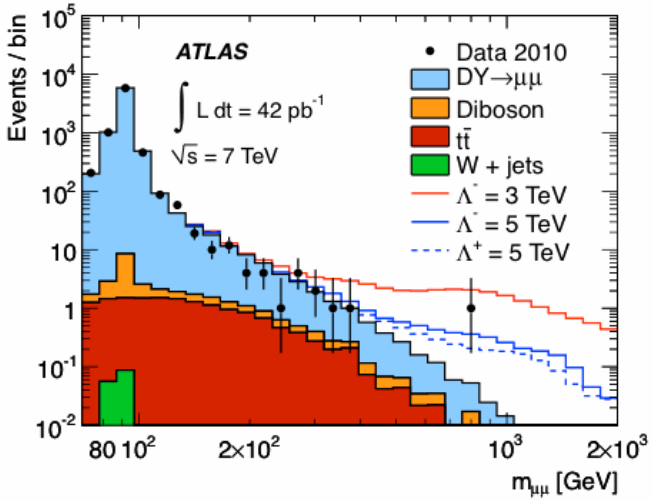
Non-Resonant $\mu^+\mu^-$ production

ADD, quark/lepton compositeness described by four-fermion contact interaction

Similar to the Z' analysis

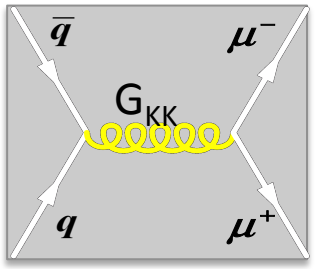
Look for enhancement of dimuon events at high mass

ATLAS: contact interaction



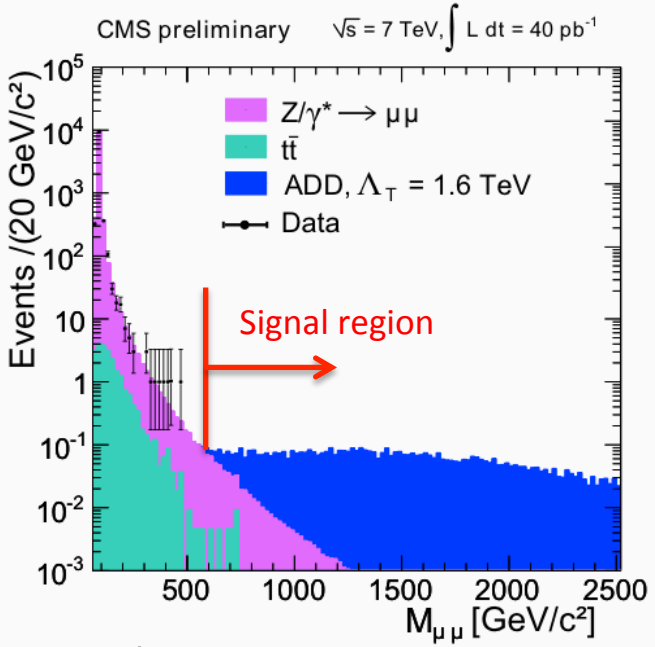
95% CL lower limits of scale of μμqq contact interactions [GeV]

	ATLAS	CDF
Λ^-	4.9	4.2
Λ^+	4.5	2.9



Theory Parameters:
M_S=UV cutoff in σ
N= number of ED

CMS: graviton in ADD



σ_{eff}< 0.088-0.098 pb @ 95% CL

95% CL lower limits on the ADD cutoff scale M_S [TeV]

- NLO k-factor 1.3 applied

	Λ_T [TeV] (GRW)	M_s [TeV/c^2] (HLZ)					
		$n=2$	$n=3$	$n=4$	$n=5$	$n=6$	$n=7$
Full	1.80	1.75	2.15	1.80	1.63	1.52	1.43
Truncated	1.68	1.67	2.09	1.68	1.49	1.34	1.24

Other ADD-inspired searches

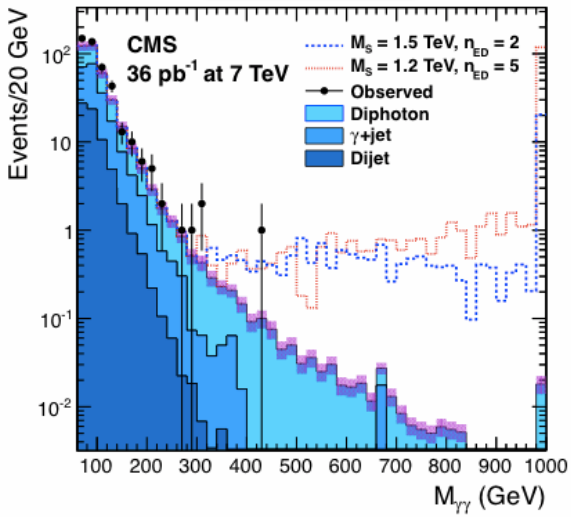
DiPhoton (CMS)

Count number of events with M(γγ)>500GeV

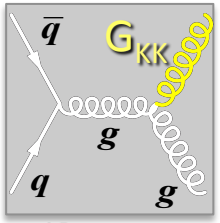
	GRW	Hewett		HLZ					
		Pos.	Neg.	$n_{ED}=2$	$n_{ED}=3$	$n_{ED}=4$	$n_{ED}=5$	$n_{ED}=6$	$n_{ED}=7$
Full	1.94	1.74	1.71	1.89	2.31	1.94	1.76	1.63	1.55
Trunc.	1.84	1.60	1.50	1.80	2.23	1.84	1.63	1.46	1.31

Model independent σ limit: $(\sigma_{total}-\sigma_{SM})\times\beta\times\mathcal{A}>0.11$ pb (95%CL)

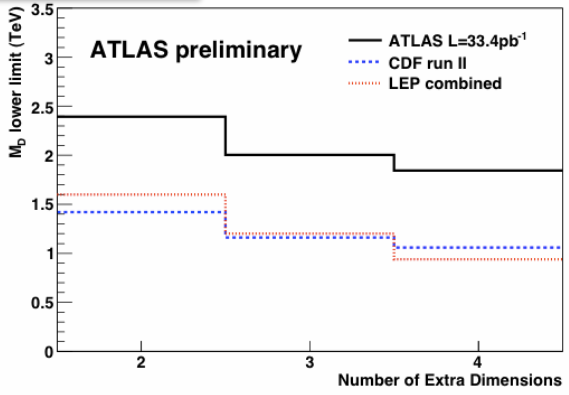
CMS results extend limits on MS from D0 limits for all but n=2

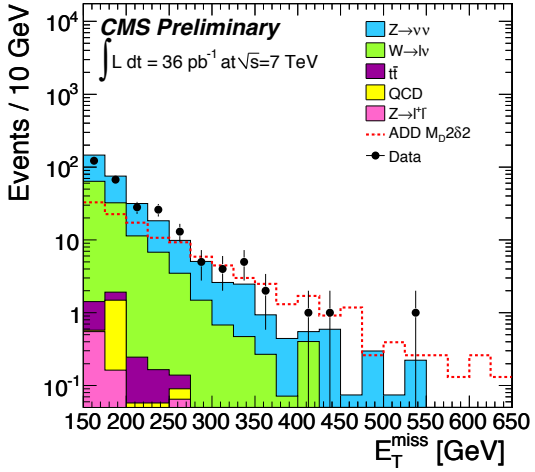


Monojet



Event topology: unbalanced high-pT jet resulting in large MET





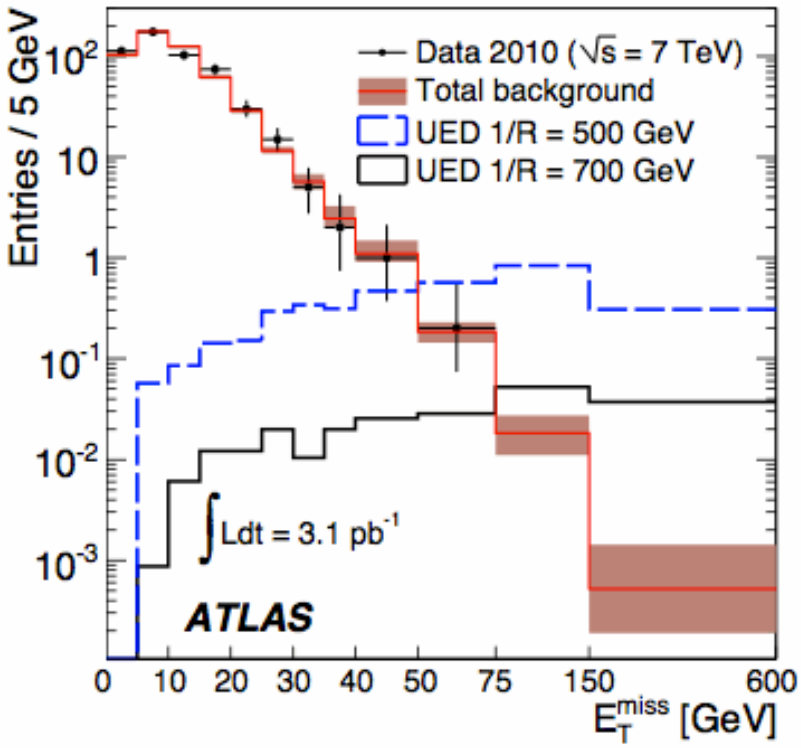
95% CL lower limits on M_D [TeV]

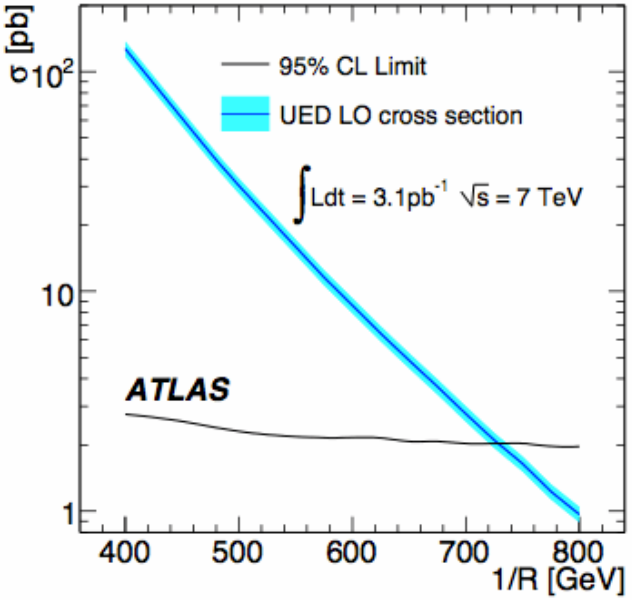
	ATLAS	CMS
δ=2	2.3	2.4
δ=4	1.8	1.8

Di-photon + MET

Look for excess of event in γγ+MET+X

- UED: strong production of pair of KK quarks/gluons which cascade down to LKP (γ*→G+γ)





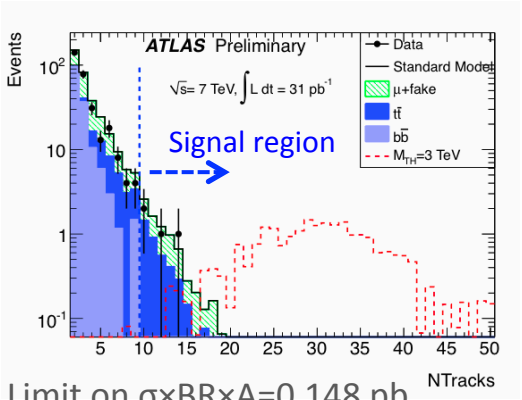
Exclude 1/R values < 728GeV

D0 excludes 1/R<447 GeV @ 95% CL arXiv:1008.2133

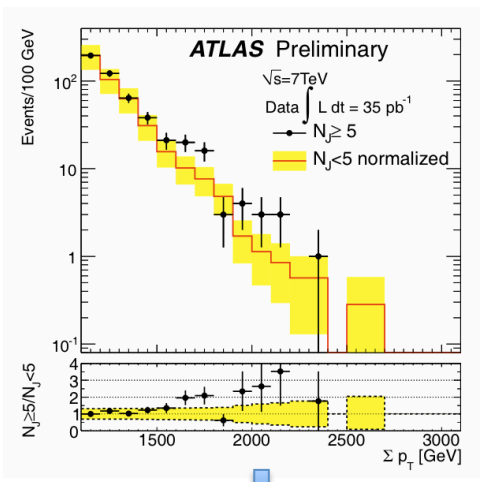
Black hole-inspired searches

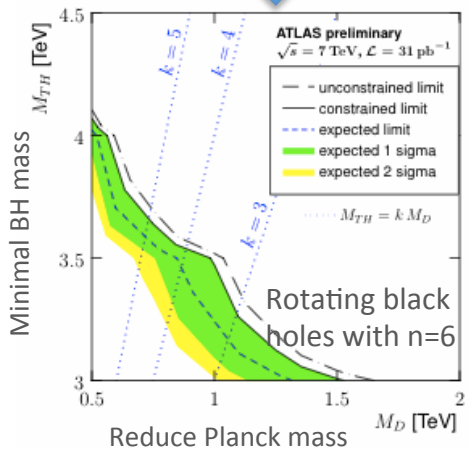
ATLAS:

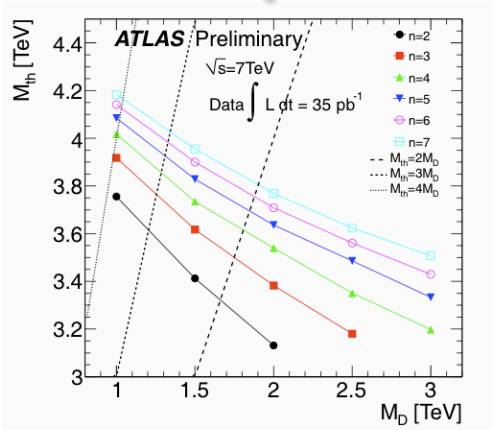
- High Ntrk region in SS dimuon sample
- Search for excess in event with >4jets & high Σp_T



Limit on σ×BR×A=0.148 pb

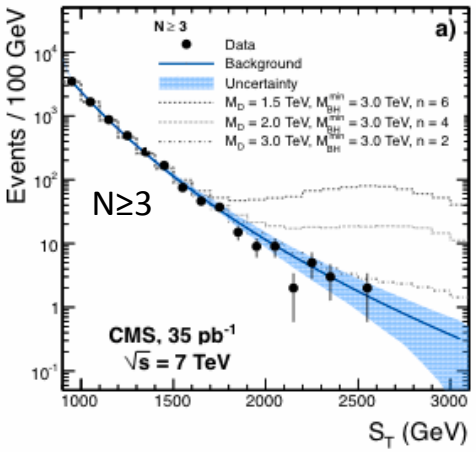


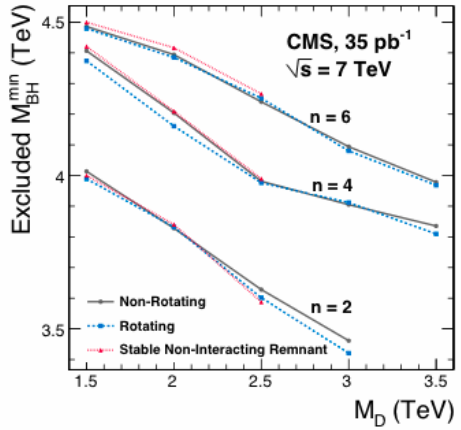




CMS: Search in S_T -vs- N_{obj} (pT>50)

BH decay via Hawking radiation to all SM degree of freedom (mostly quarks and gluons)



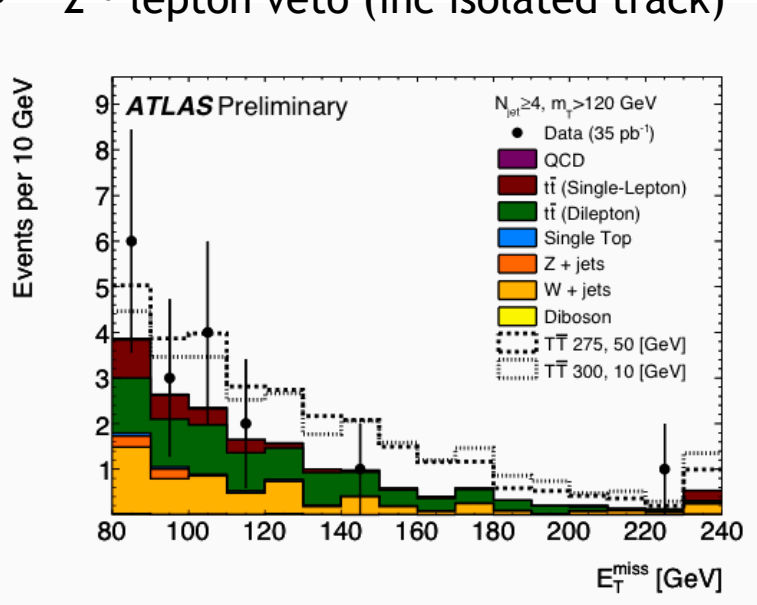


Model-independent limits provided as a function of S_T(cut) for N_{obj}≥3,4,5

Heavy quark-inspired searches

ATLAS: search for anomalous ttbar+MET

- Lepton (p_T>20)+≥4jets (p_T>20)
- MET>80, M_T>120
- 2nd lepton veto (inc isolated track)

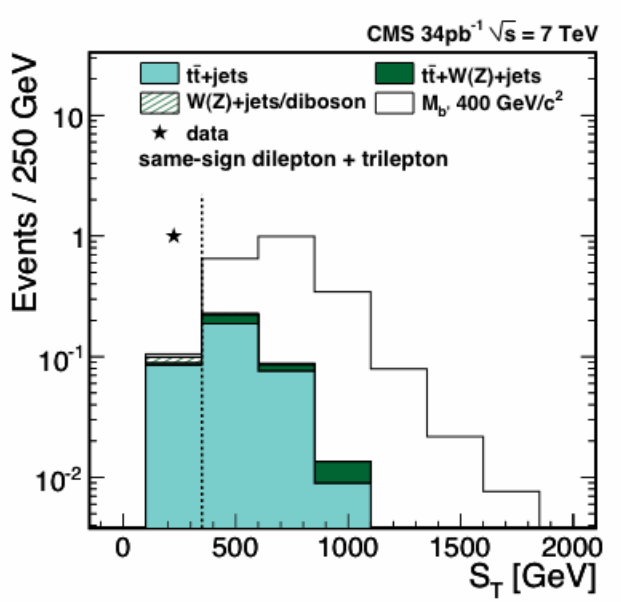


ATLAS excludes m(T)<275 (300) GeV at 95% CL for $m(A_0)$ < 50 (10) GeV

CDF excludes m(T)<360 GeV at 95% CL for $m(A_0)$<100 GeV [CDFnote 10374]

CMS: search for b'→tW via anomalous trilepton or SS dilepton production

- Lepton Pt>2
- ≥4(2) jets pT>25 for SS dilepton (trilepton)
- Z mass veto, S_T>350 $\hat{S_T} = \sum p_T(\text{jets}) + \sum p_T(\text{leptons}) + \not{E}_T$

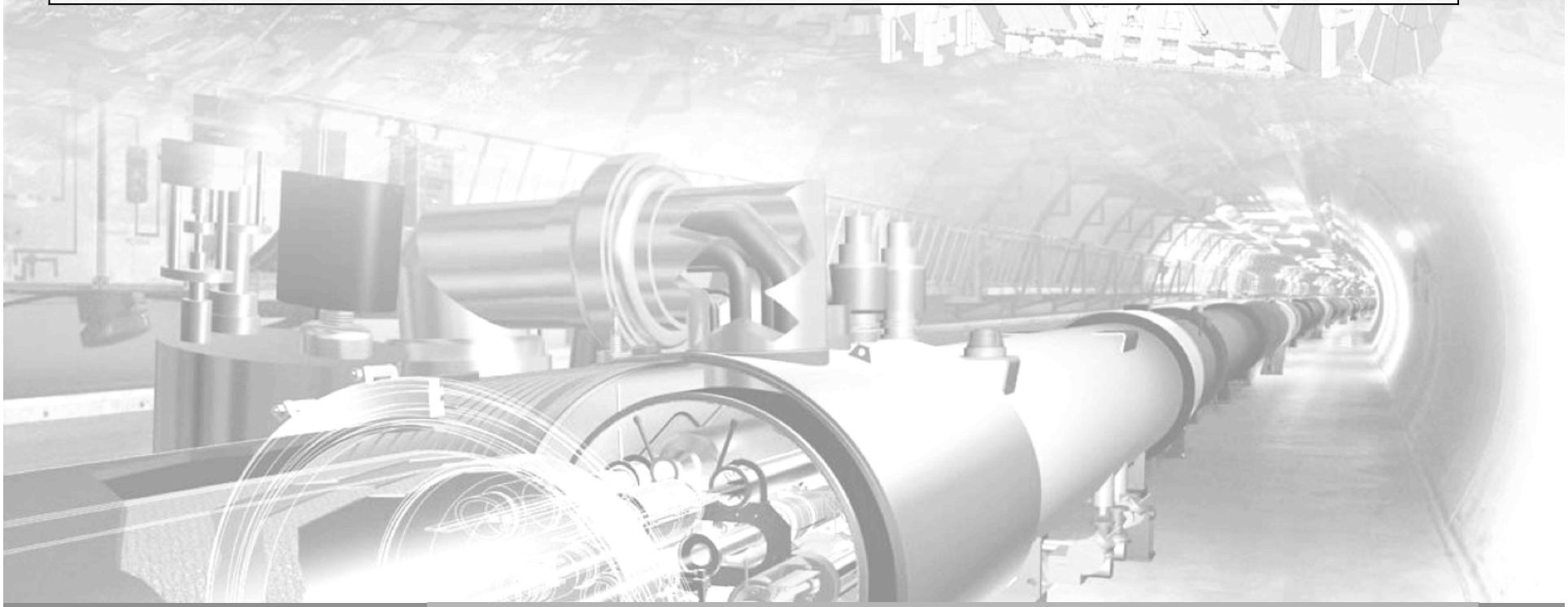


CMS excludes m(b')<361 GeV at 95% CL

CDF excludes m(b')<385 GeV at 95% CL PRL106.141803(2011)

Slow/highly-ionizing/stopped particle

Signature	ATLAS	CMS	Example
Highly-ionizing particle	arXiv:1102.0459		Highly charged object
Slow particle	arXiv:1103.1984	arXiv:1101.1645	R-hadron
Empty bunch crossing		arXiv:1011.5861	Stopped gluino



Slow, massive particle Searches

Long-Lived Heavy particles appear in many BSM (e.g. $\tilde{g}$ in split SUSY)

- Since massive they are slow (β<0.9)
- Gluinos hadronize forming R-hadons

ATLAS

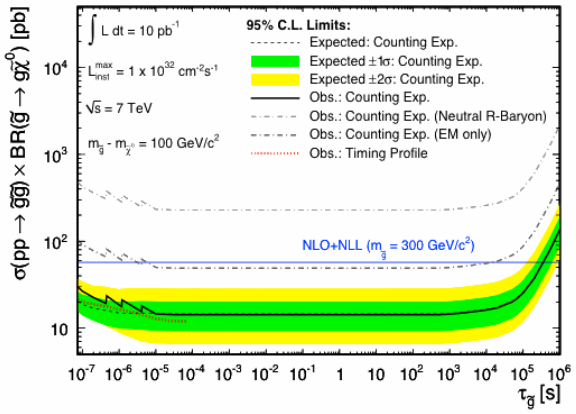
- β from HCAL TOF and PIX dE/dx. Combine w/ p to get mass

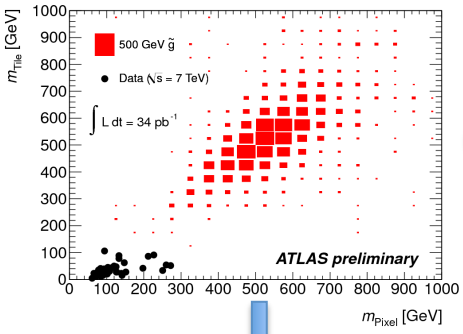
CMS

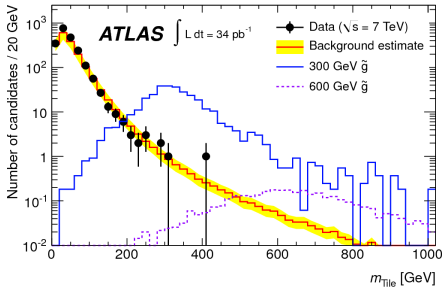
- β from dE/dx in tracker only. Combine w/ p to get mass
- Out-of-Time decays of particles which stopped in the detector

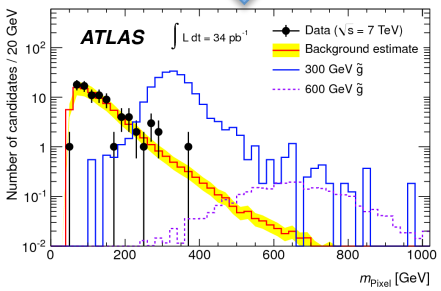
Both

- Fully data-driven bkg estimates



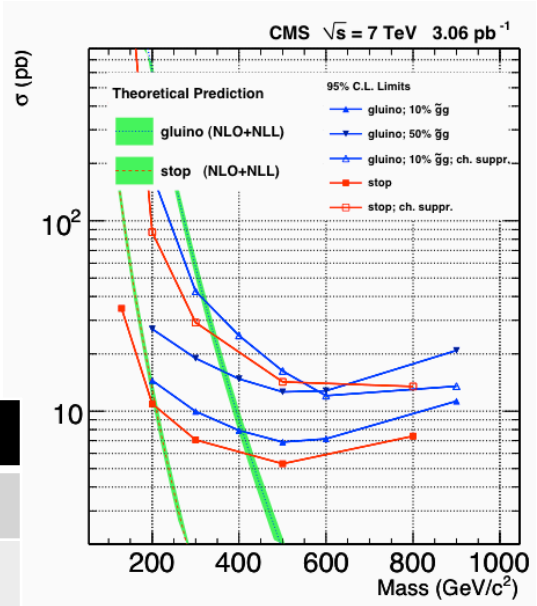






95% CL R-hadron lower limits [GeV]

R-hadron	ATLAS	CMS (3.1pb^{-1})
$\tilde{b}$	294	
$\tilde{t}$	309	202
$\tilde{g}$	586	398



Summary & Prospects

- ATLAS & CMS are mining their data for any sign of new physics
  - 2010 data ~fully analyzed. Strong effort on 2011 data (PLHC, EPS, LP…)

- Searches for beyond-SM phenomena
  - Large amount of searches performed.
  - Limits significantly improved over Tevatron in many cases.
  - No sign of new physics so far (NP not "just around the corner")

- Expect 30-100 times
  more data by the end of 2011.

Collected x12 of 2010 dataset already!