



Search for new resonances from BSM at Tevatron and LHC



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on behalf of ATLAS, CDF,
CMS and D0 collaborations



Why looking for Beyond Standard Model (BSM)?

Sensational success of Standard Model, however still numerous *unanswered questions...*

What are the details of the EW symmetry breaking mechanism?

Why is the Higgs light?

Why left-handed weak interactions?

Where are the right-handed neutrinos?

Why not coupling unification?

Why quantized electric charges?

Why three generations?

Why fermion mass hierarchy?

What is dark matter?

How about gravity?

...

BSM theories

GRAND UNIFICATION

COMPOSITENESS

SUPERSYMMETRY

EXTRA DIMENSIONS

TECHNICOLOR

...

BSM theories

GRAND UNIFICATION

-new vector bosons (Z' , W' ,...),
heavy fermions (t' , b' , T , B ,...),
 ν_R , leptoquarks, **diquarks**,
Higgses,...

EXTRA DIMENSIONS

-Kaluza-Klein excitations of
particles ($G^{(*)}$, Z_{KK} , W_{KK} , g_{KK} ,
 q_{KK} ,...), **Black Holes**, string
resonances,...

All these theories can be revealed by new boson or
new fermion **resonances!**

COMPOSITENESS

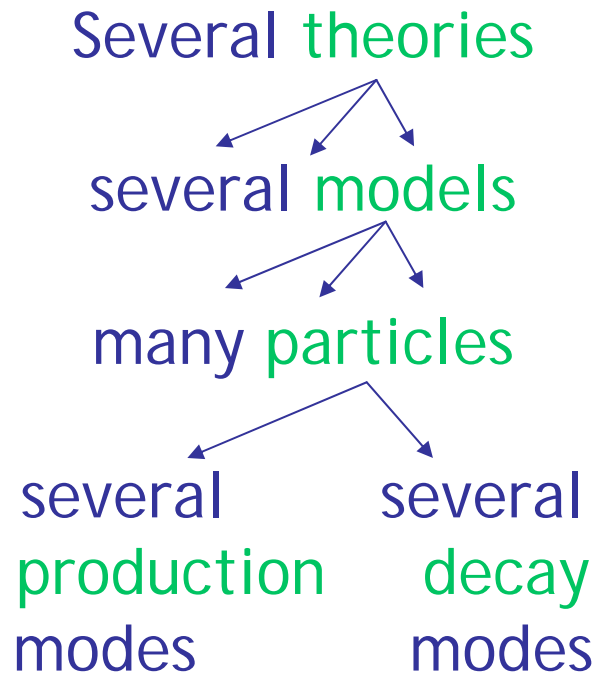
-excited states of known
particles (l^* , q^* , Z^* , W^* ,...),
leptoquarks,...

TECHNICOLOR

-new composite particles:
techni-hadrons (ρ_T ,...),
leptoquarks, $T_{5/3}$,...

Search strategy

Theories not enough: need models to derive phenomenology (mass spectrum, production and decay modes, etc)



Look for signatures!

- as model independent as possible
- as many as possible
- interpret results with benchmarks

Outline

Signatures with one
or two leptons

Signatures with
two jets or photons

Other signatures

LHC results at 8 TeV

All limits at 95% C.L.

Warning: even though labeled the same, limits are not always strictly comparable across experiments

Signatures with one or two leptons

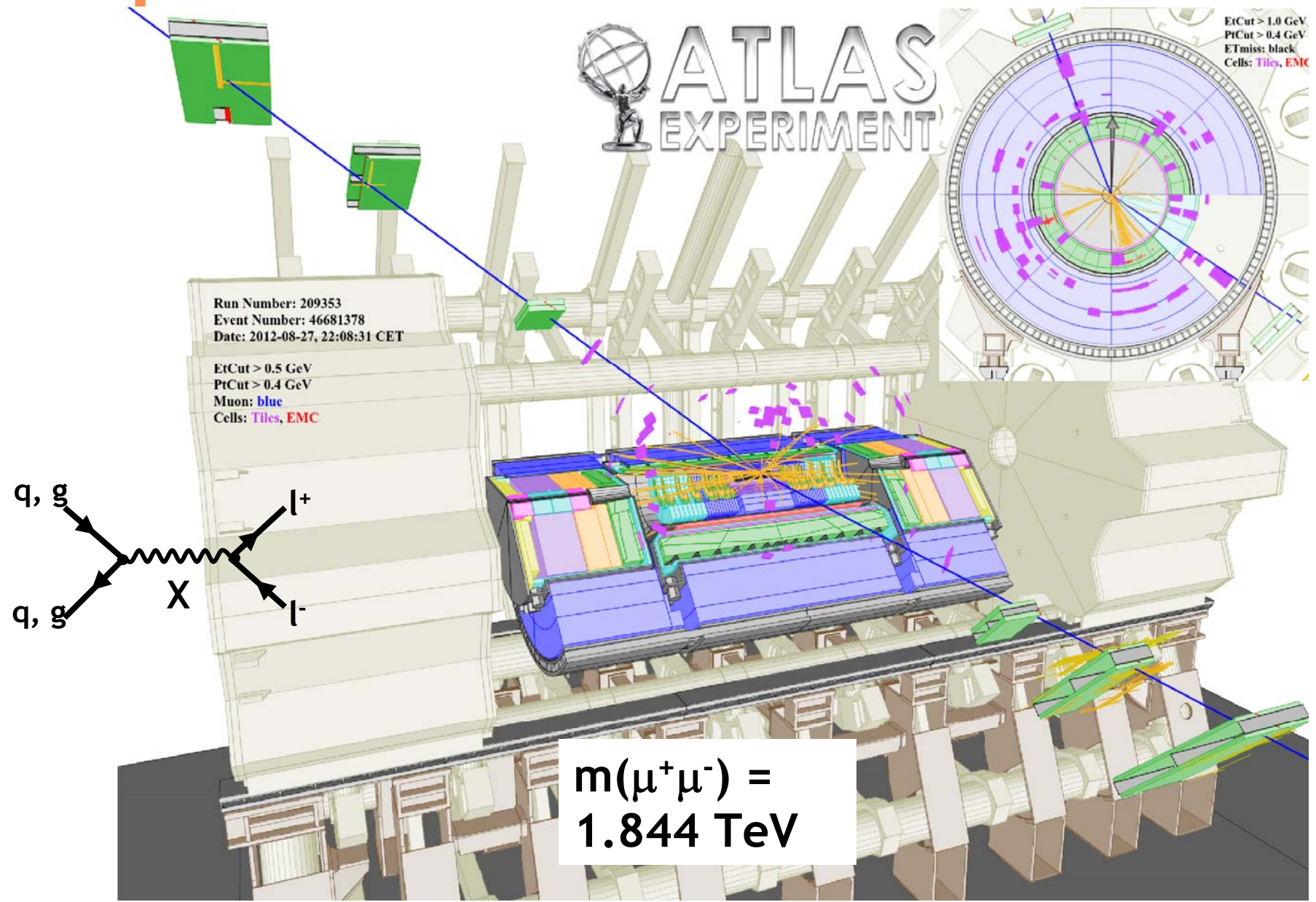
-dileptons

-ditaus



-lepton + missing E_T

Dileptons

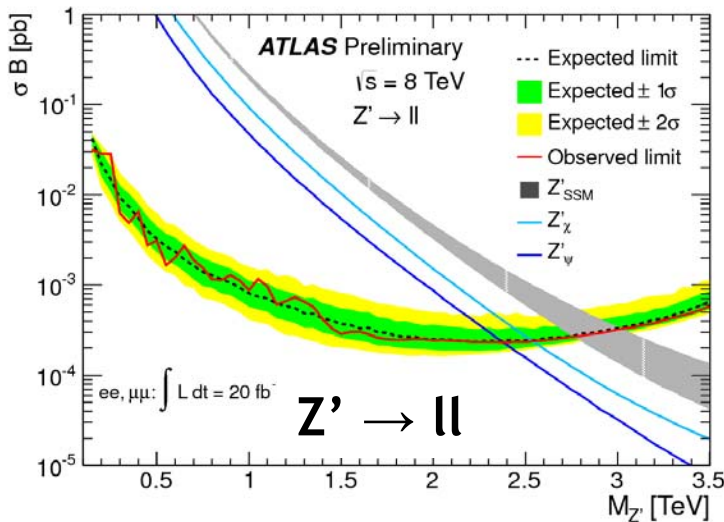
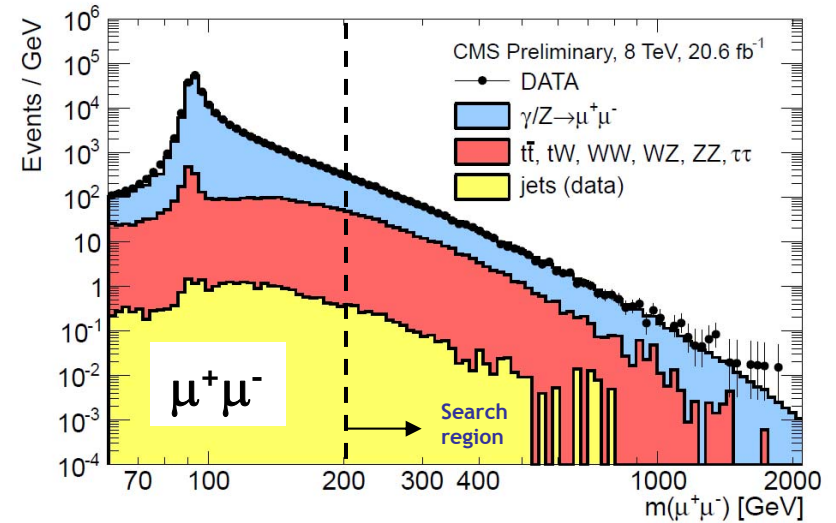
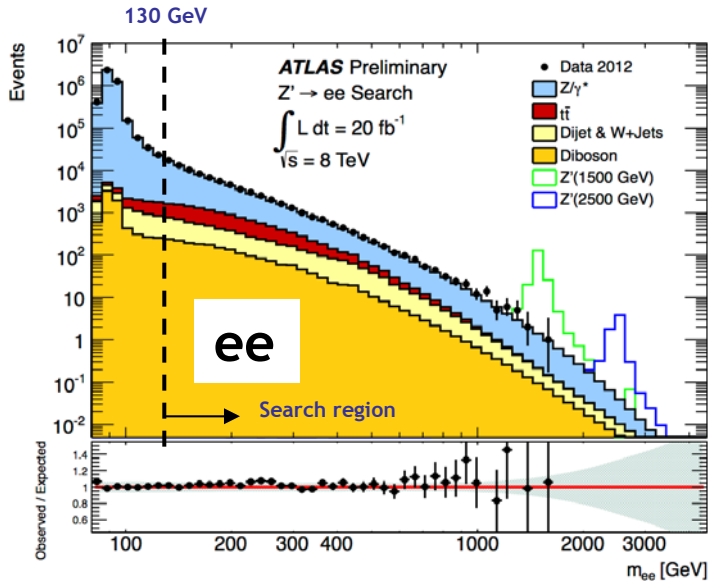


Dileptons

[ATLAS-CONF-2013-017]

[CMS-EXO-12-061]

- Experimental challenge: lepton p_T resolution and efficiency up to 1 TeV!



Observed lower mass limits (TeV)

Model	ATLAS	CMS
SSM Z'	2.86	2.96
$E_6 Z'_\psi$	2.38	2.60
RS G^* ($k/\bar{M}_{Pl}=0.1$)	2.47	

SSM =
Sequential SM

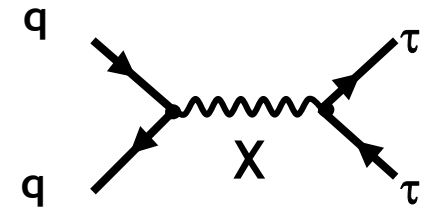
RS= Randall
Sundrum model

Many more interpretations with 7 TeV data:
 Z^* , LSTC ρ_T , MWT M_A , Z_{KK}/γ_{KK} , TS

[ATLAS, EPJC 72 (2012) 2244]

Ditaus

[ATLAS-CONF-2013-066]

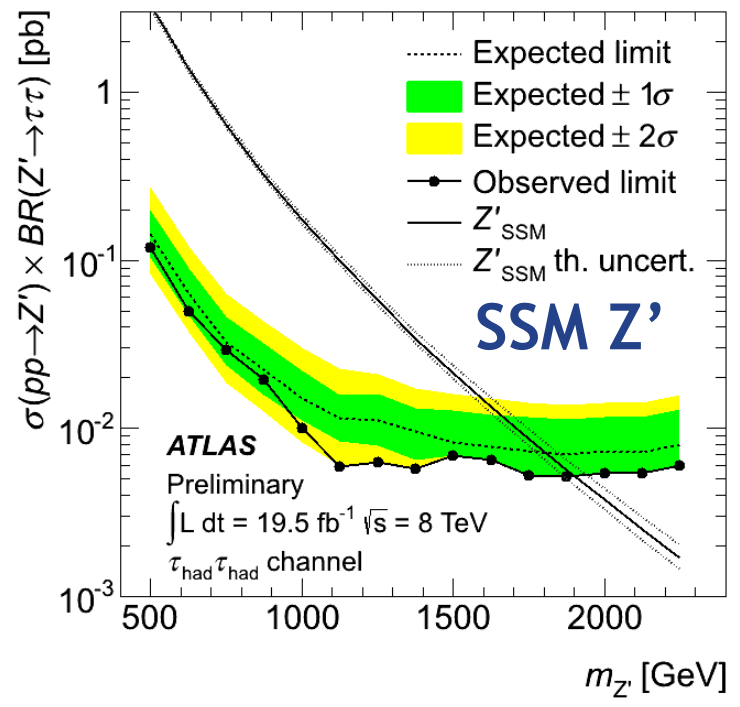
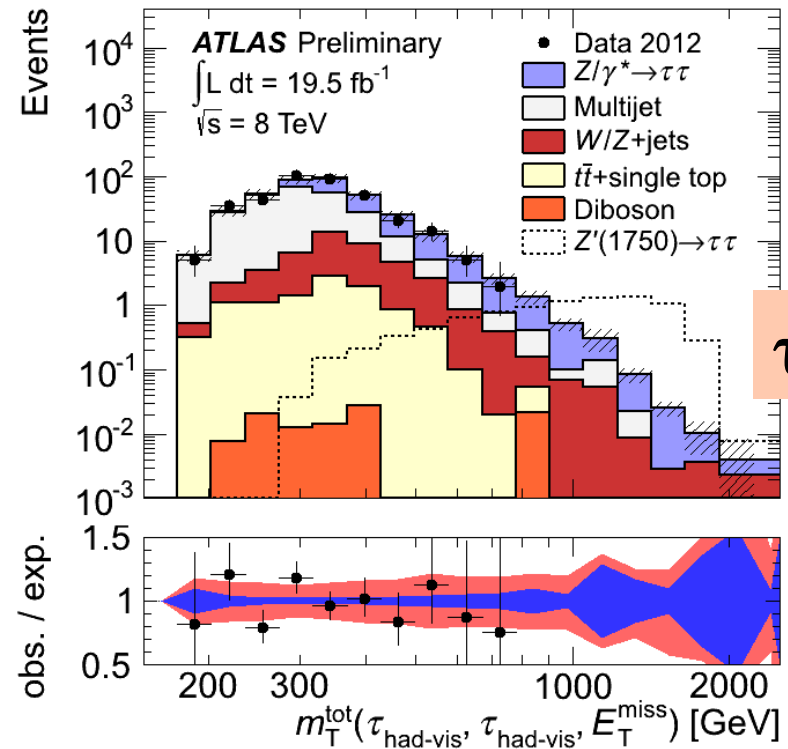


- Lepton universality not always required
- tau candidates = jets (1 or 3 tracks) with BDT identification

$$m_T^{\text{tot}} = \sqrt{2p_{T1}p_{T2}C + 2|E_T^{\text{miss}}|p_{T1}C_1 + 2|E_T^{\text{miss}}|p_{T2}C_2}$$

$$C = 1 - \cos\Delta\phi$$

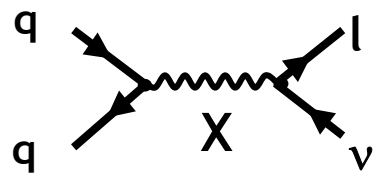
- resolution 30-50%



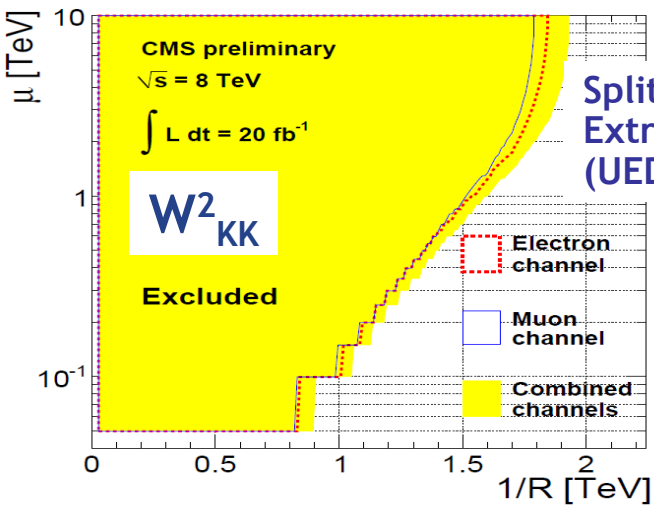
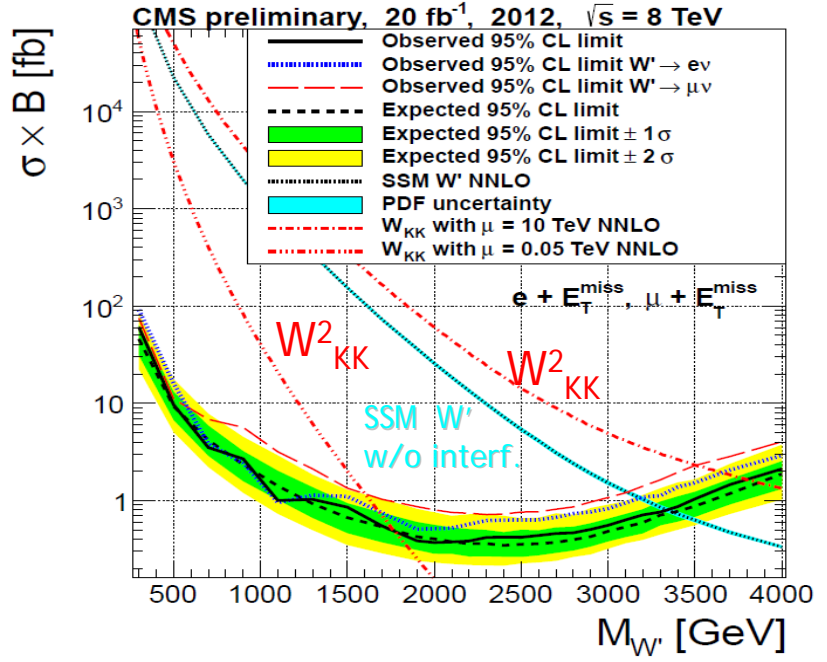
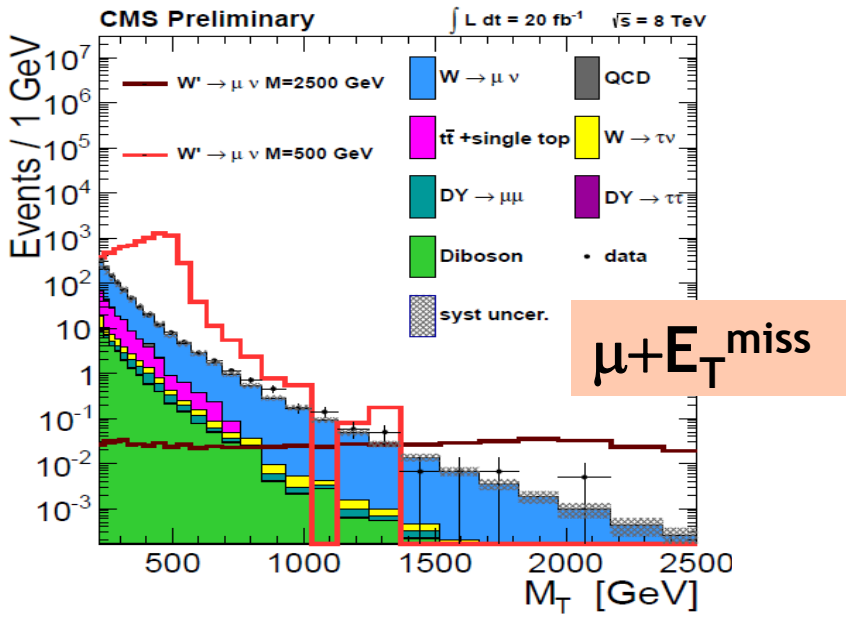
Model	Observed mass exclusion [TeV]
SSM Z'	[0.5, 1.90]

Lepton + missing E_T

[CMS-EXO-12-060]



- $$m_T = \sqrt{2p_T E_T^{\text{miss}} (1 - \cos \phi_{\ell\nu})}$$



Model	Mass [TeV]
SSM W' no interference	3.35
SSM W' dest./const. int.	3.10 / 3.60
W_{KK}^2 , $\mu=0.05$ TeV	1.7
W_{KK}^2 , $\mu=10$ TeV	3.7

Signatures with two jets or photons

-dijets

-jet + photon

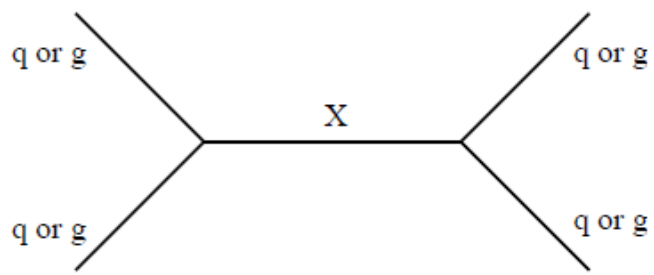
-dijets with b-tagging

-dijets with W/Z tagging

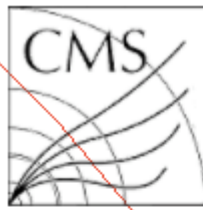
-all hadronic $t \bar{t}$



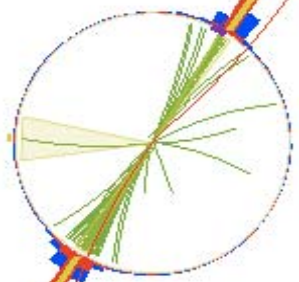
Dijets



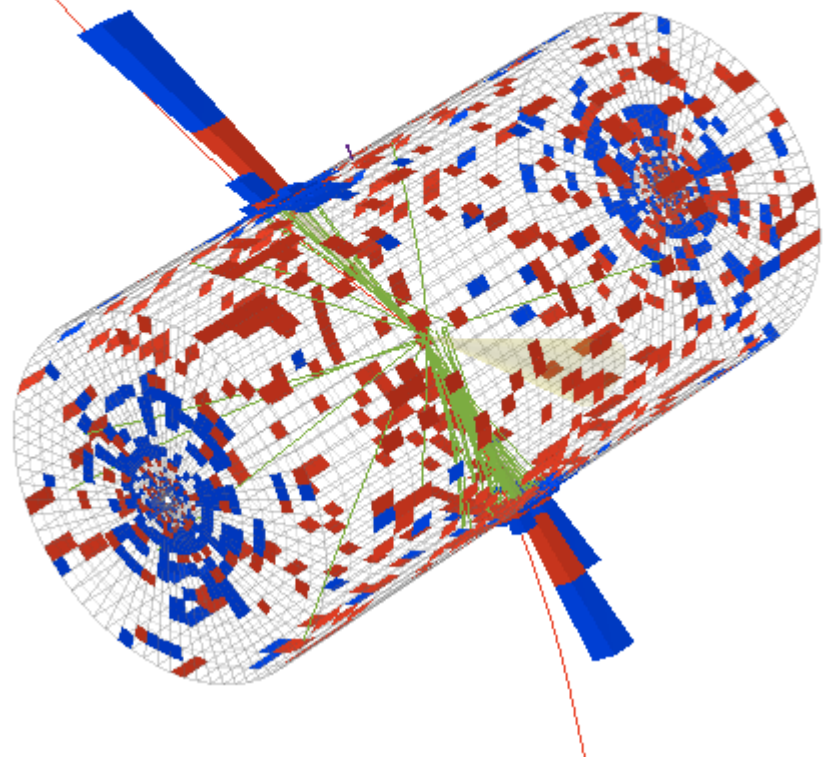
CMS Experiment at LHC, CERN
Data recorded: Fri Oct 5 12:29:33 2012 CEST
Run/Event: 204541 / 52508234
Lumi section: 32



CMS Experiment at LHC, CERN
Data recorded: Fri Oct 5 12:29:33 2012 CEST
Run/Event: 204541 / 52508234
Lumi section: 32



$m(jj) =$
5.15 TeV



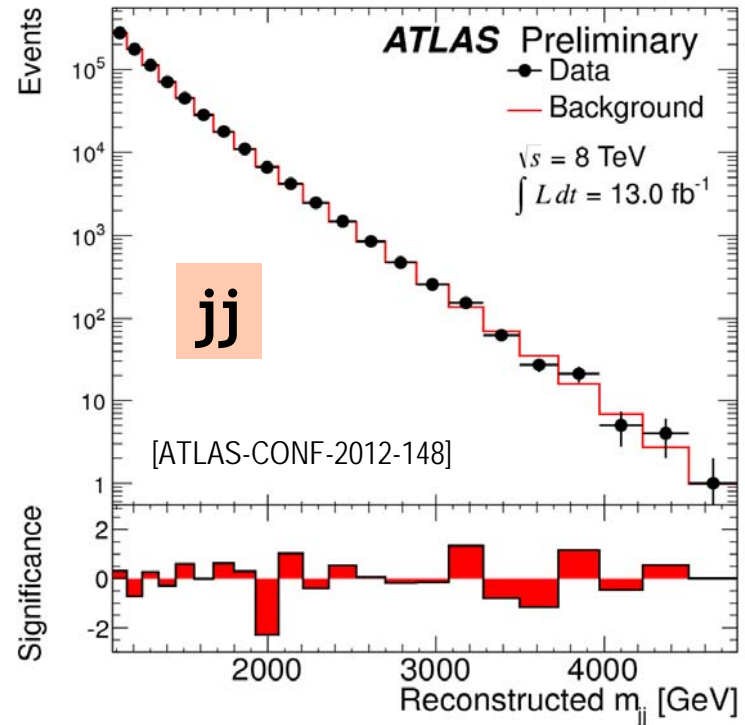
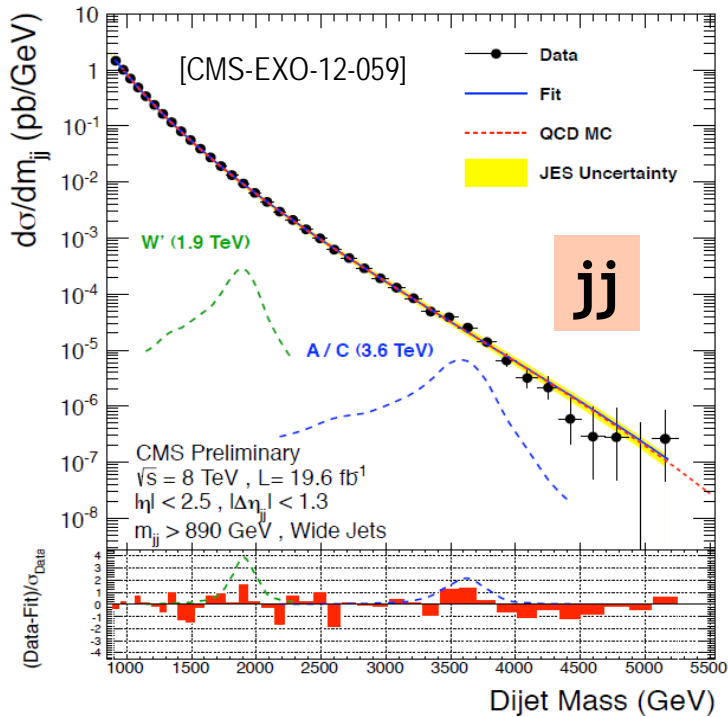
• probing quark structure up to 5 TeV!

Dijets

- anti- k_T jets $R=0.5$ (CMS, with widening algo. $R=1.1$) or $R=0.6$ (ATLAS)
- dijet mass resolution $\sim 5\%$
- 2 leading jets: $|\Delta y| < 1.2$ (ATLAS), $|\Delta \eta| < 1.3$ (CMS)
- smooth background fitted from data

$$f(x) = p_1(1-x)^{p_2} x^{p_3+p_4} \ln x$$

$x \equiv m_{jj} / \sqrt{s}$

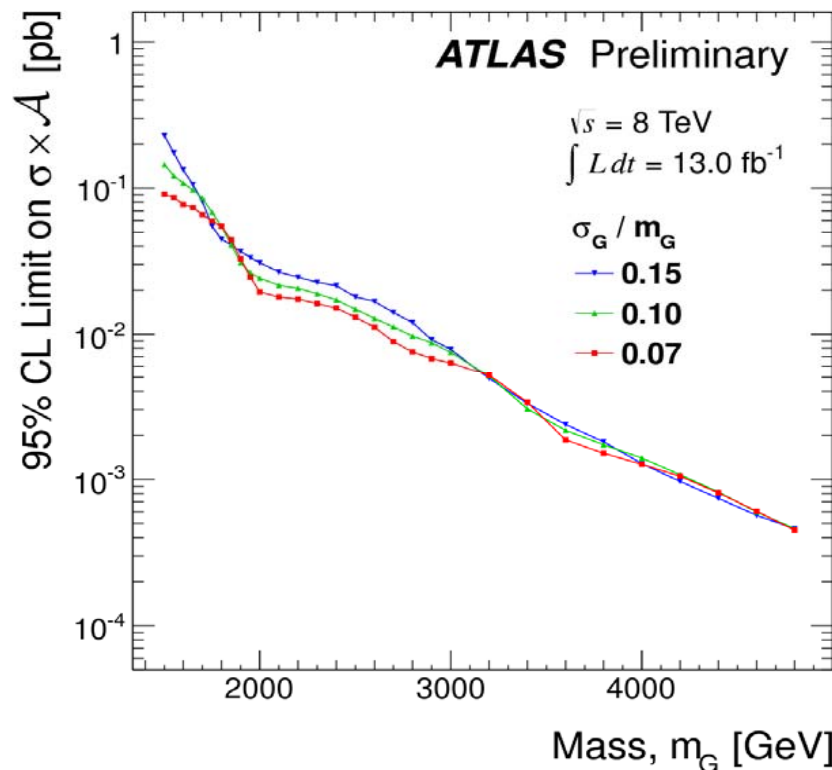
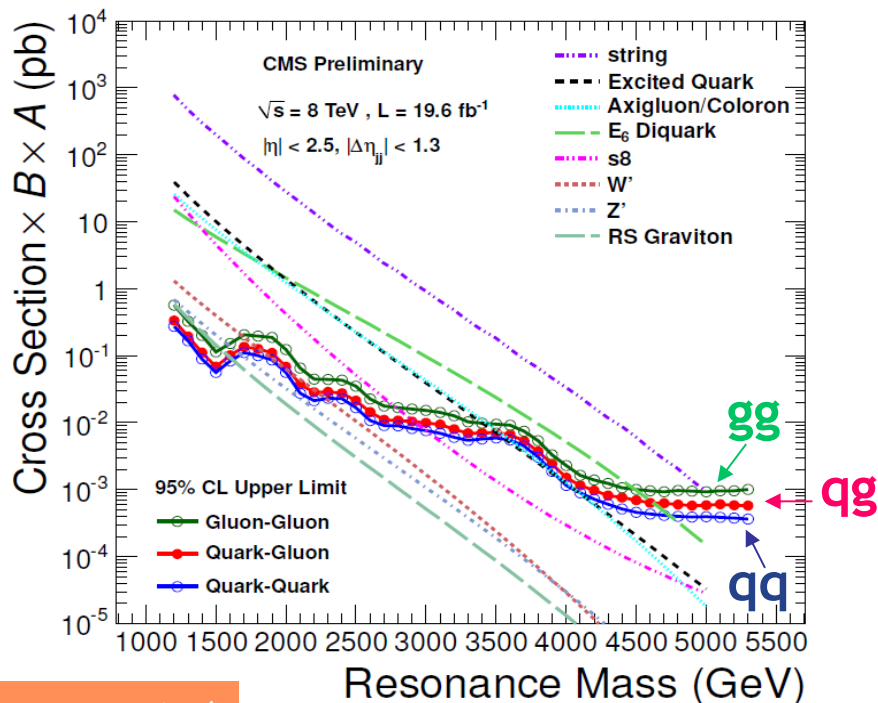


- mass threshold around 1 TeV due to trigger constraints
- specific strategies of ATLAS and CMS to keep sensitivity to masses $< 1 \text{ TeV}$

Dijets

[ATLAS-CONF-2012-148]

[CMS-EXO-12-059]



CMS 20 fb^{-1}

Model	Final State	Obs. Mass Excl. [TeV]
String Resonance (S)	qg	[1.20,5.08]
Excited Quark (q^*)	qg	[1.20,3.50]
E_6 Diquark (D)	qq	[1.20,4.75]
Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.20,3.60] + [3.90,4.08]
Color Octet Scalar (s8)	gg	[1.20,2.79]
W' Boson (W') SSM	$q\bar{q}$	[1.20,2.29]
Z' Boson (Z') SSM	$q\bar{q}$	[1.20,1.68]
RS Graviton (G)	$q\bar{q}+gg$	[1.20,1.58]

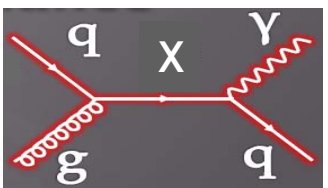
Observed mass exclusions

Model	ATLAS 13 fb^{-1}
q^*	[1.5,3.84] TeV

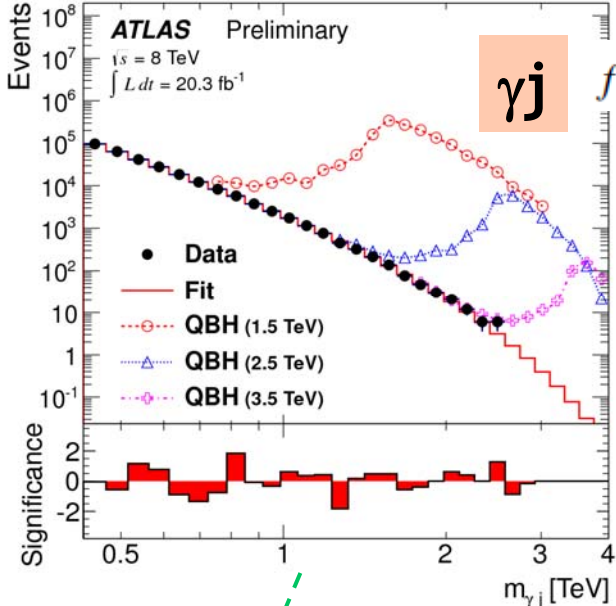
$$f_s = f = f' = 1$$

Jet plus photon

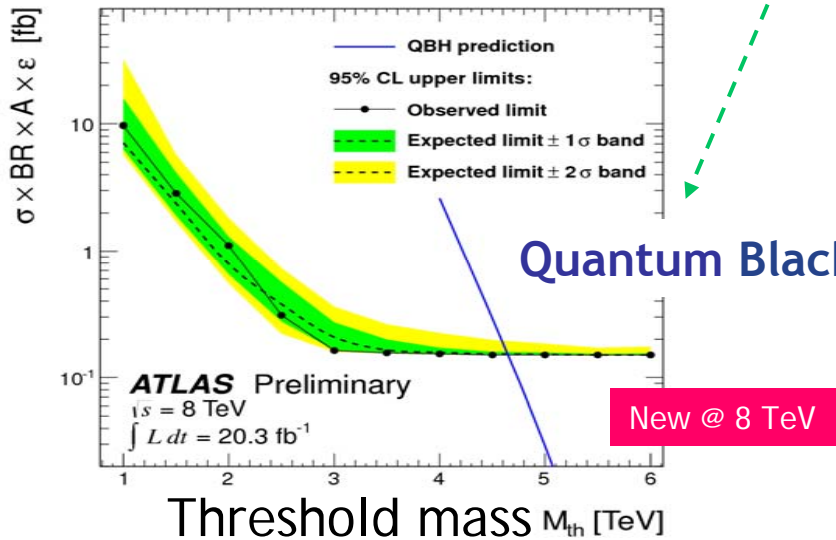
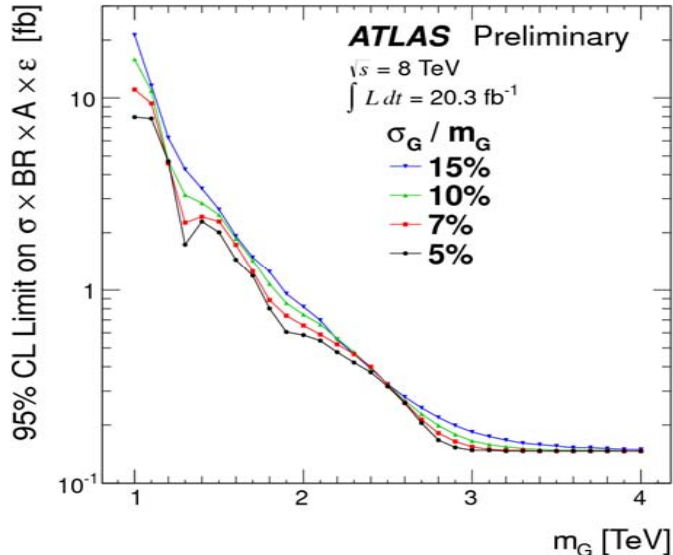
[ATLAS-CONF-2013-059]



- Quantum Black Hole (QBH): production threshold $M_{th} \sim M_D$
- low multiplicities
- mass resolution 3-4%



γj $f(x \equiv m_{\gamma j} / \sqrt{s}) = p_1(1-x)^{p_2} x^{-(p_3+p_4 \ln x)}$



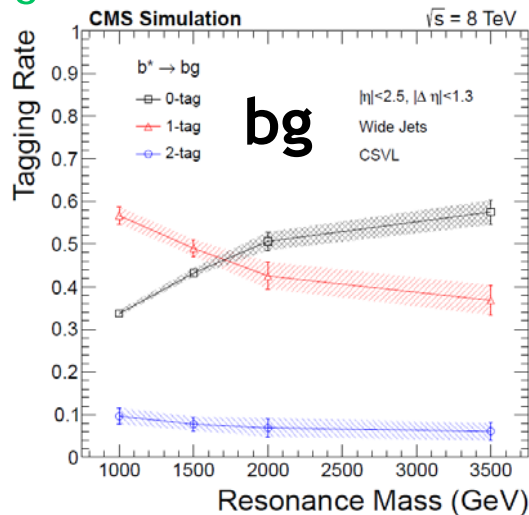
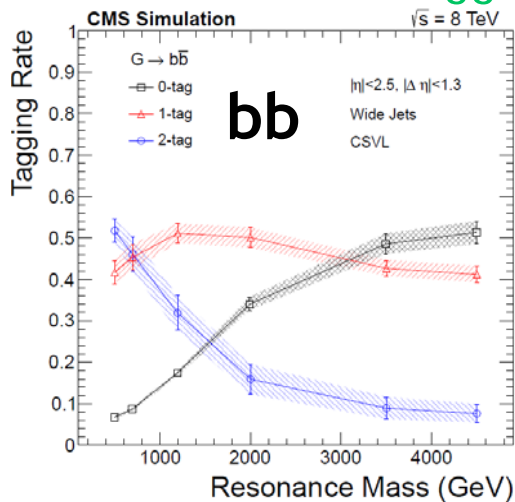
Quantum Black Hole

Model	Observed mass exclusions [TeV]
q^* $\Lambda = m(q^*)$ $f_s = f = f' = 1$	[1.0, 3.48]
QBH $n = 6$ and $M_D = M_{th}$	[1.0, 4.65]

Dijets with b-tagging

- wide jets, $|\Delta\eta| < 1.3$
- 3 channels: 0, 1, 2 b-tags

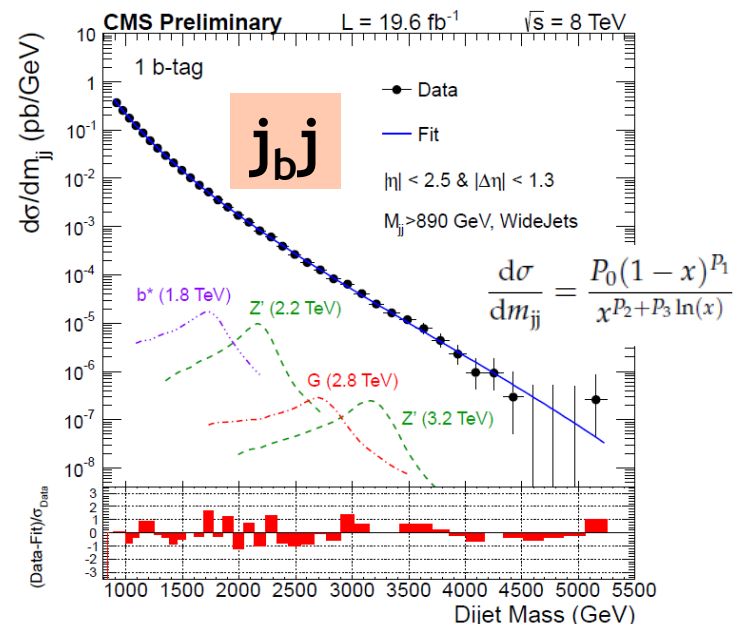
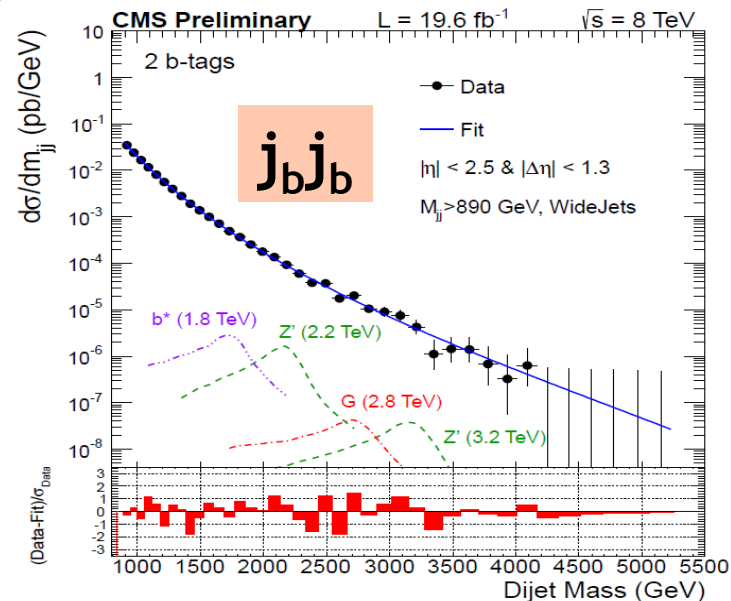
Tagging rates



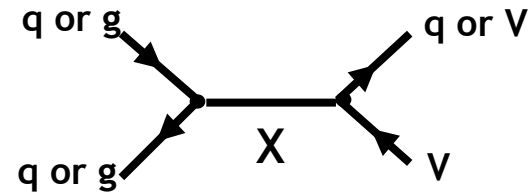
Model	Observed mass exclusions [TeV]
SSM Z' ($f_{bb}=0.2$)	[1.20 , 1.68]
RS G^* ($k/\bar{M}_{Pl}=0.1$) ($f_{bb}=0.1$)	[1.42 , 1.57]
b^*	[1.34 , 1.54]

See also ATLAS' 7 TeV limits on $b^* \rightarrow Wt$, Phys. Lett. B 721 (2013) 171-189

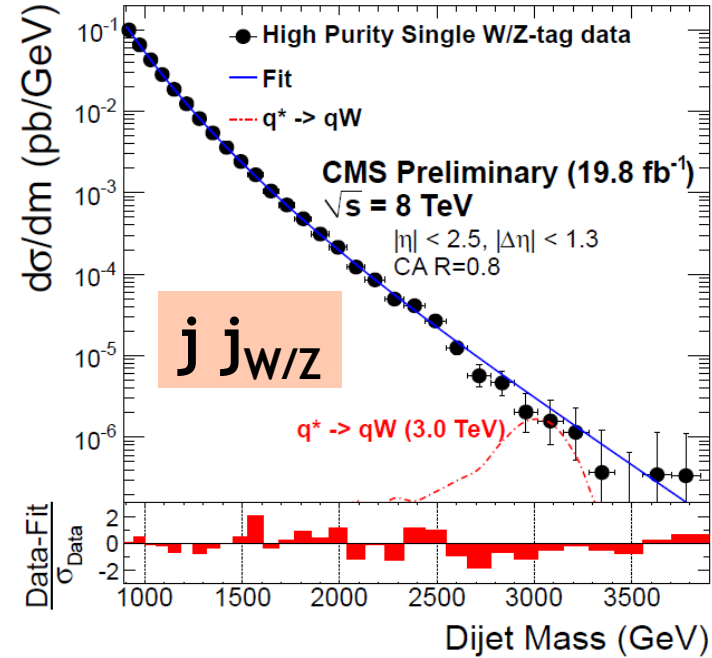
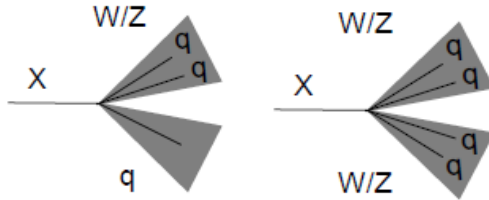
[CMS-EXO-12-023]



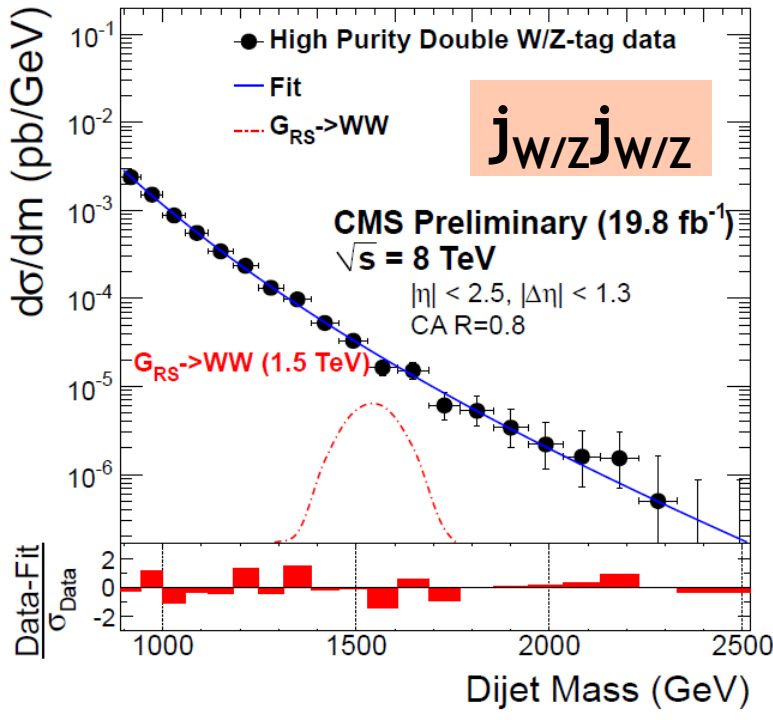
Dijets with W/Z-tagging



- Jets: Cambridge-Aachen R=0.8
- 1 or 2 leading jets W/Z tagged
- $|\Delta\eta| < 1.3$



[CMS-EXO-12-024]

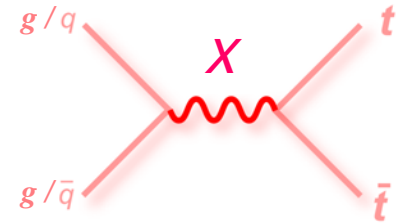


Model	Observed mass exclusions [TeV]
$q^* \rightarrow qW$ $\rightarrow qZ$	[1.0 , 3.23] [1.0 , 3.00]
SSM $W' \rightarrow WZ$	[1.0 , 1.73]
RS $G^* \rightarrow WW$ $\rightarrow ZZ$	[1.0 , 1.59] [1.0 , 1.17]

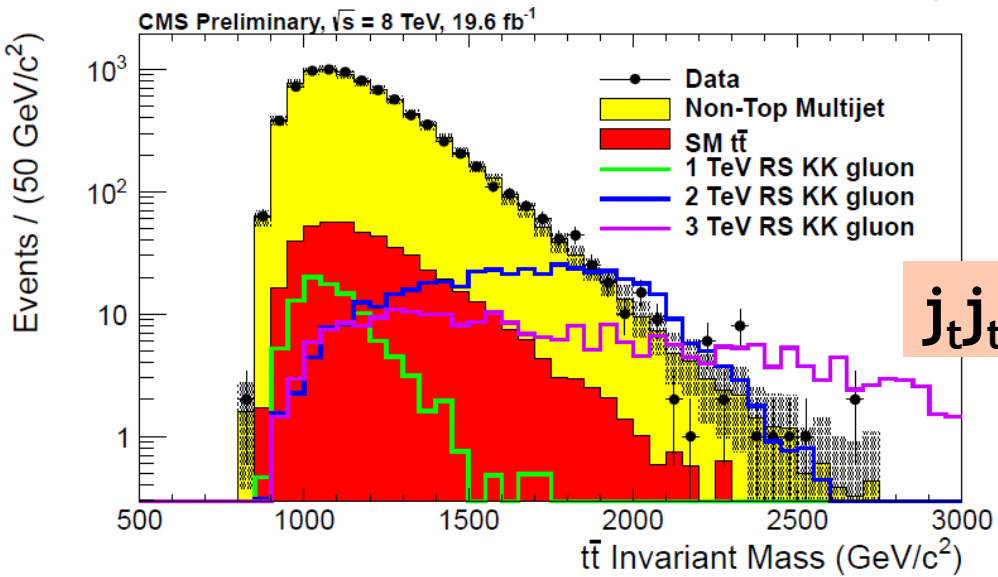
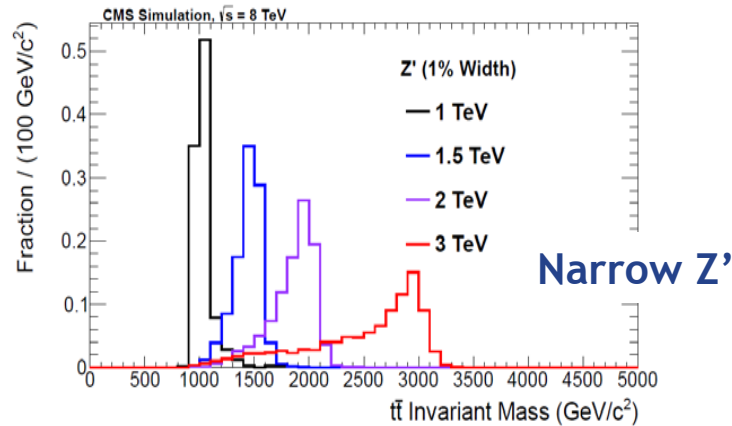
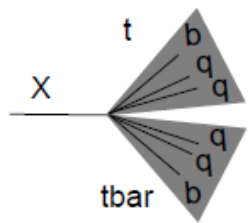
See also ATLAS $G^* \rightarrow ZZ \rightarrow llqq$ analysis in $lljj$ and llj topologies
[ATLAS-CONF-2012-150]

All hadronic $t\bar{t}$

[CMS-B2G-12-005]



- Jets: Cambridge-Aachen $R=0.8$
- 2 leading jets **Top-Tagged**
- $|\Delta y| < 1.0$



Model	Observed mass exclusions [TeV]
Narrow topcolor Z'	[1.0 , 1.7]
Wide topcolor Z'	[1.0, 2.35]
Bulk RS g_{KK}	[1.0, 1.8]

• Data driven multijet background

$BR(g_{KK} \rightarrow t\bar{t}) > 90\%$, $\Gamma/M \sim 15\%$

Other signatures

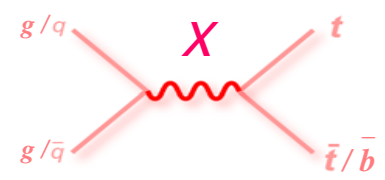
-(semi)leptonic $t\bar{b}$ and $t\bar{t}$

-all leptonic WZ

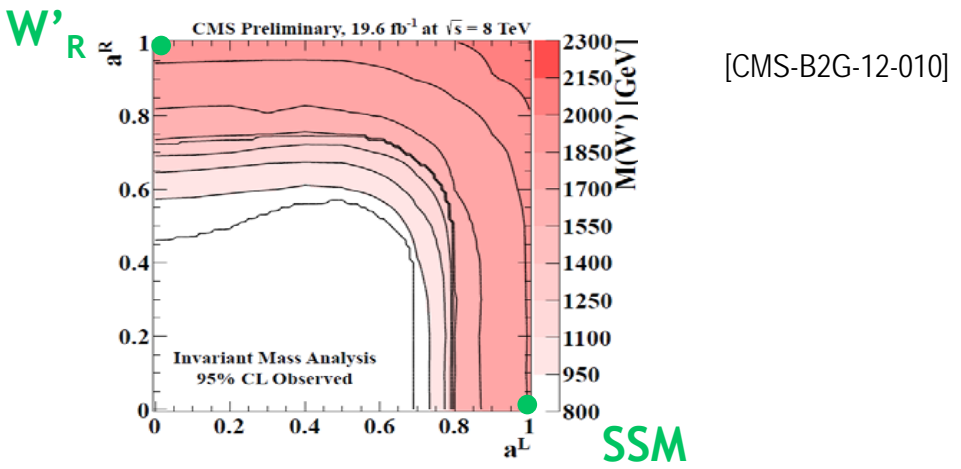
-dijet + W/Z



(Semi)leptonic $t\bar{b}$ and $t\bar{t}$



- $t\bar{b}$**
- $W'_R \rightarrow l\nu$ suppressed if ν_R heavy
 - better mass reconstruction



Observed mass exclusions (TeV)

Model	CMS 20 fb ⁻¹	ATLAS 14 fb ⁻¹
W'_R	[0.8, 2.03]	[0.5, 1.84] [#]

$m(\nu_R) < m(W')$

[ATLAS-CONF-2013-050]

[#] no mass reconstruction, BDT output fit

- $t\bar{t}$**
- 2 analyses
 - low/high mass coverage transition at ~ 1 TeV

Resolved/threshold
 \approx standard

- Boosted**
- less **isolation**
 - less "small" and b-tagged **jet multiplicity**
 - more "wide" jets
 - jet **substructure** observables

Semileptonic $t\bar{t}$

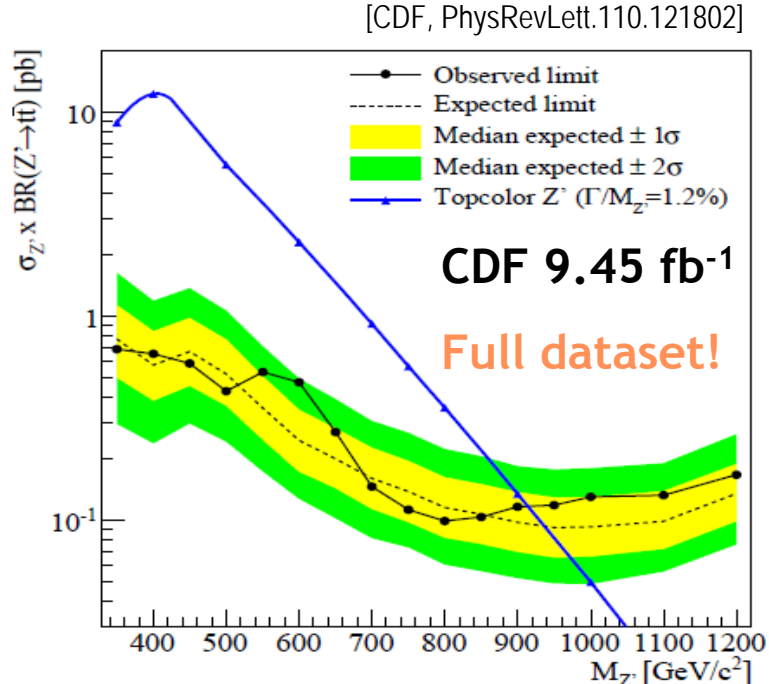
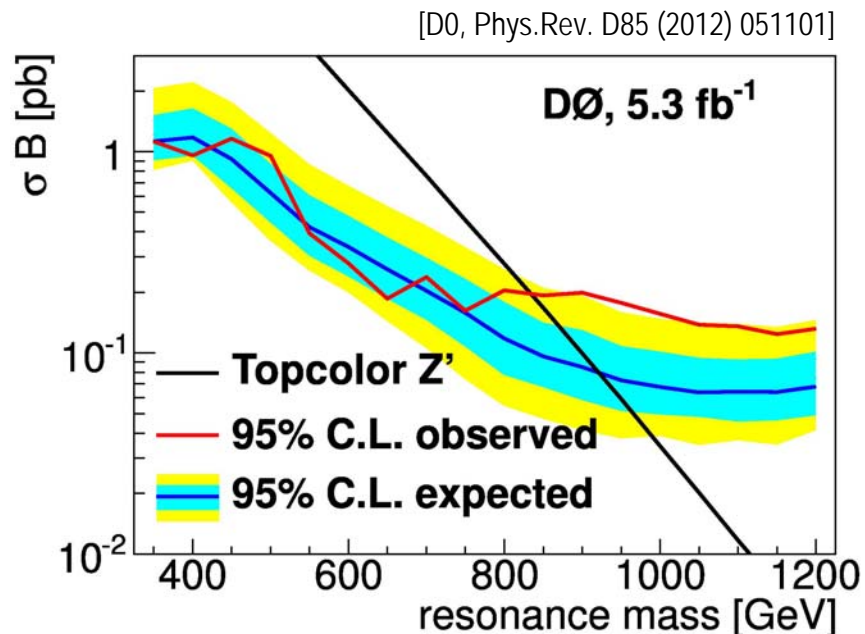
[ATLAS-CONF-2013-052]

[CMS-B2G-12-006]

Observed mass exclusions (TeV)

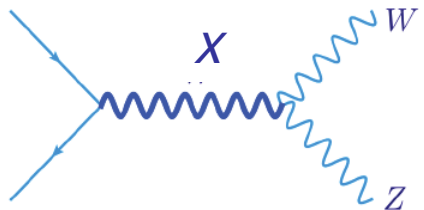
Model	ATLAS 14 fb ⁻¹	CMS 20 fb ⁻¹
Narrow topcolor Z'	[0.5 , 1.8]	[0.5 , 2.10]
Wide topcolor Z'		[0.5 , 2.68]
Bulk RS g _{KK}	[0.5,2.0]	[0.7, 2.54]

• Fully hadronic and fully leptonic analyses have higher thresholds

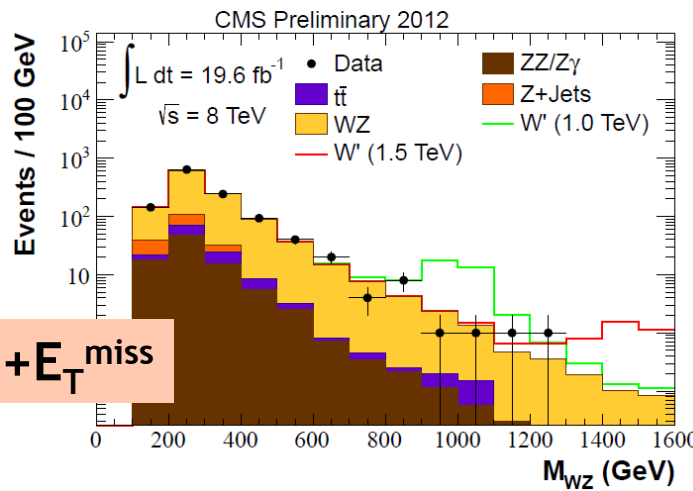
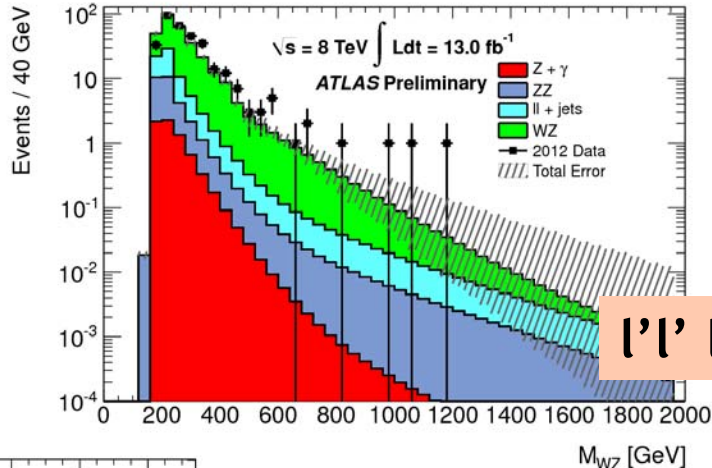


WZ all leptonic

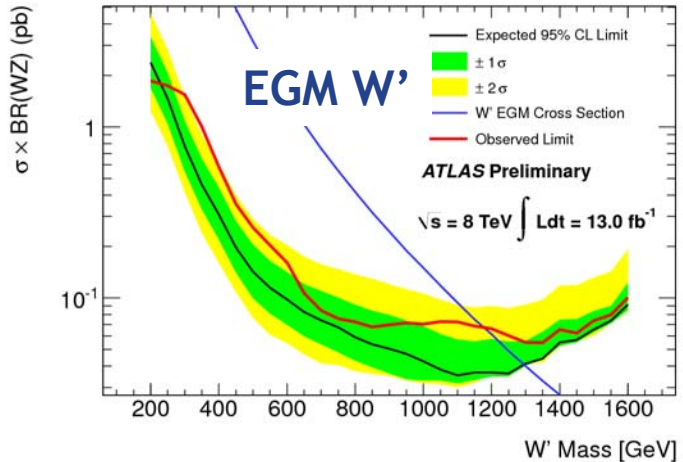
- $l+E_T^{\text{miss}}$ and tb^{bar} analyses assumed $BR(W' \rightarrow WZ)=0$
- lower threshold than (W/Z tagged) dijet analysis
- 4 channels ($eee, ee\mu, e\mu\mu, \mu\mu\mu$) + E_T^{miss}



[ATLAS-CONF-2013-015] [CMS-EXO-12-025]



$l'l' + E_T^{\text{miss}}$

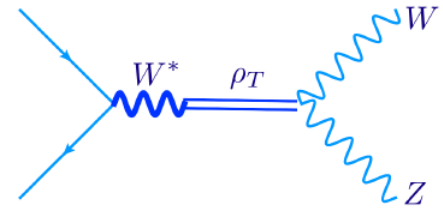


Observed lower mass limits (TeV)

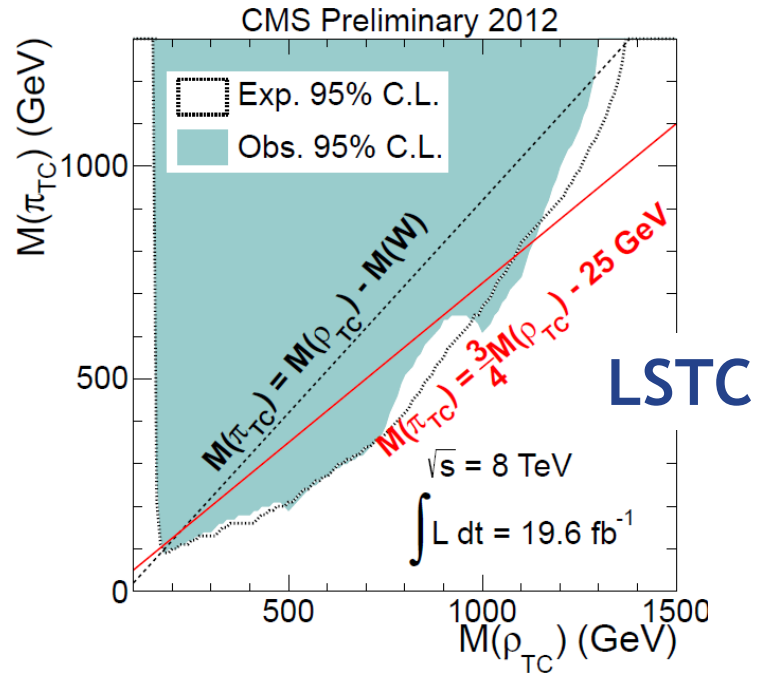
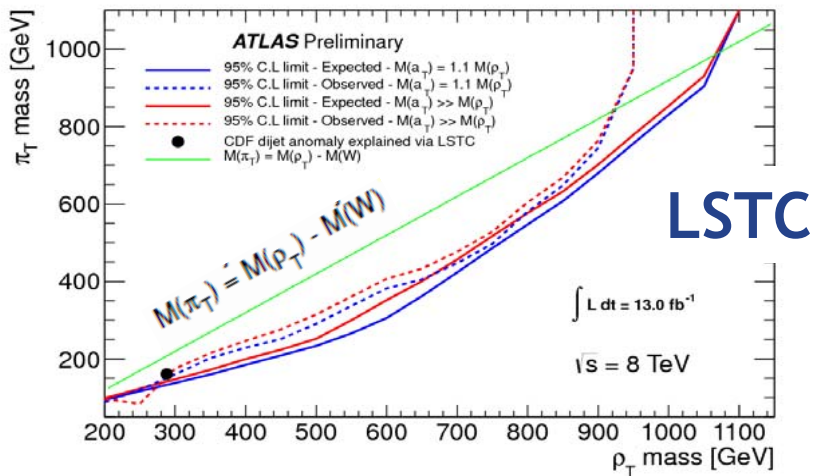
	ATLAS 13 fb ⁻¹	CMS 20 fb ⁻¹
SSM/EGM W'	1.18	1.45

EGM= Extended Gauge Model BR(W' → WZ)=1-2%

WZ all leptonic

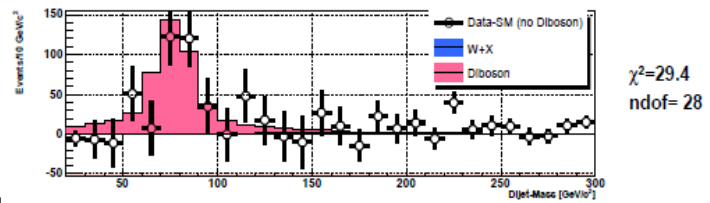
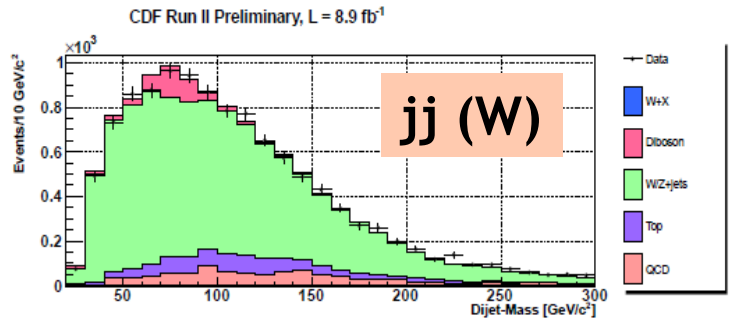


[ATLAS-CONF-2013-015]



[CMS-EXO-12-025]

CDF 8.9 fb⁻¹
Full dataset!



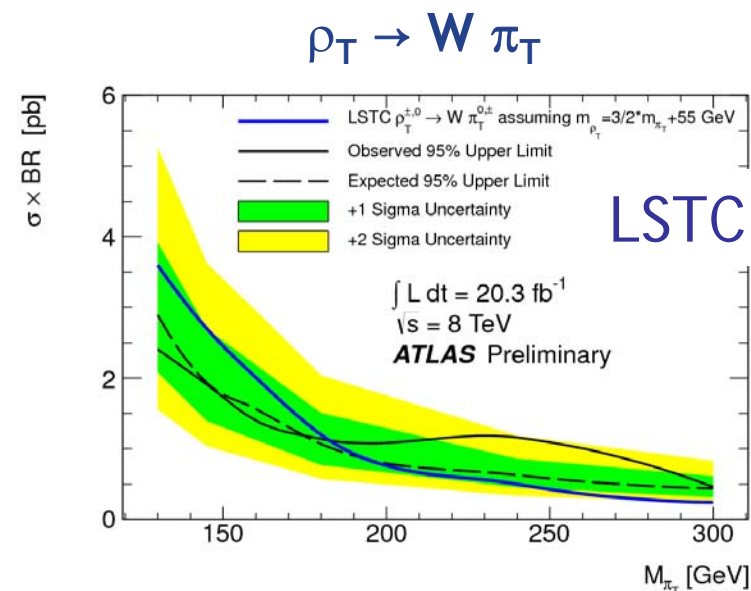
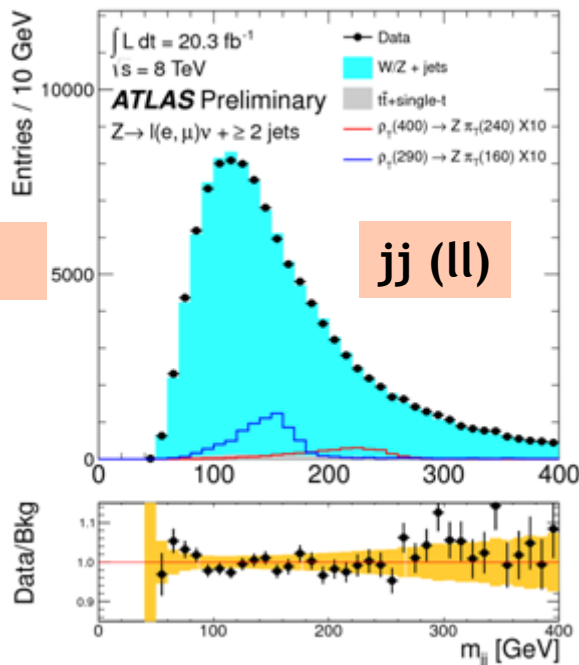
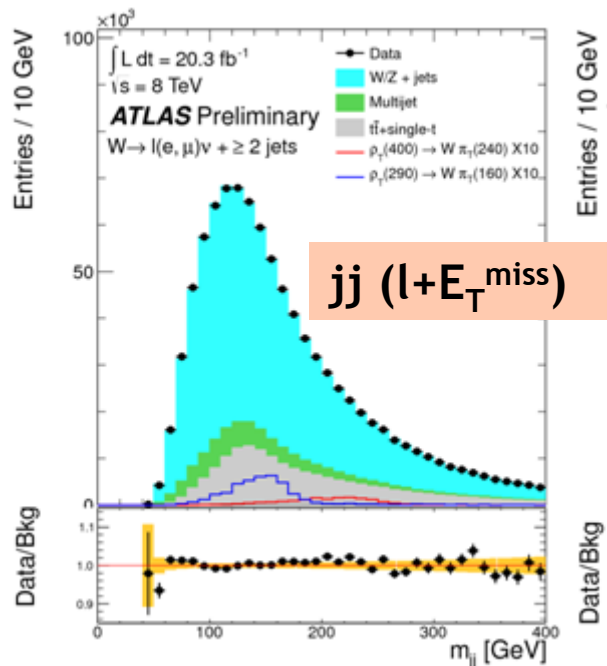
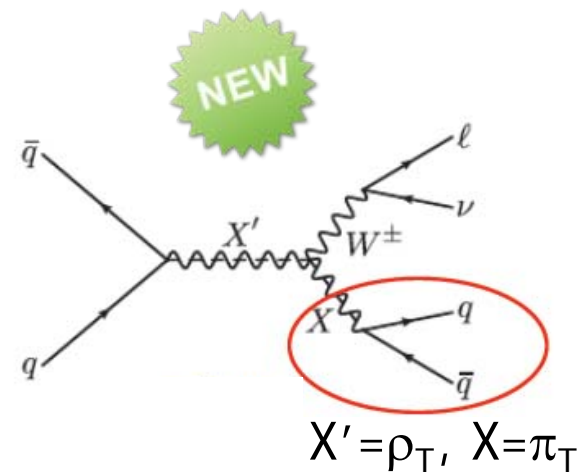
• The anomaly is gone

[CDF Public Note 10973]

Dijet associated with W/Z

[ATLAS-CONF-2013-074]

- Look for a **low mass** dijet resonance
- $\rho_T \rightarrow \pi_T W$ or $\pi_T Z$ (ρ_T, π_T charged or neutral)



$$m(\rho_T) = 3/2 m(\pi_T) + 55 \text{ GeV}$$

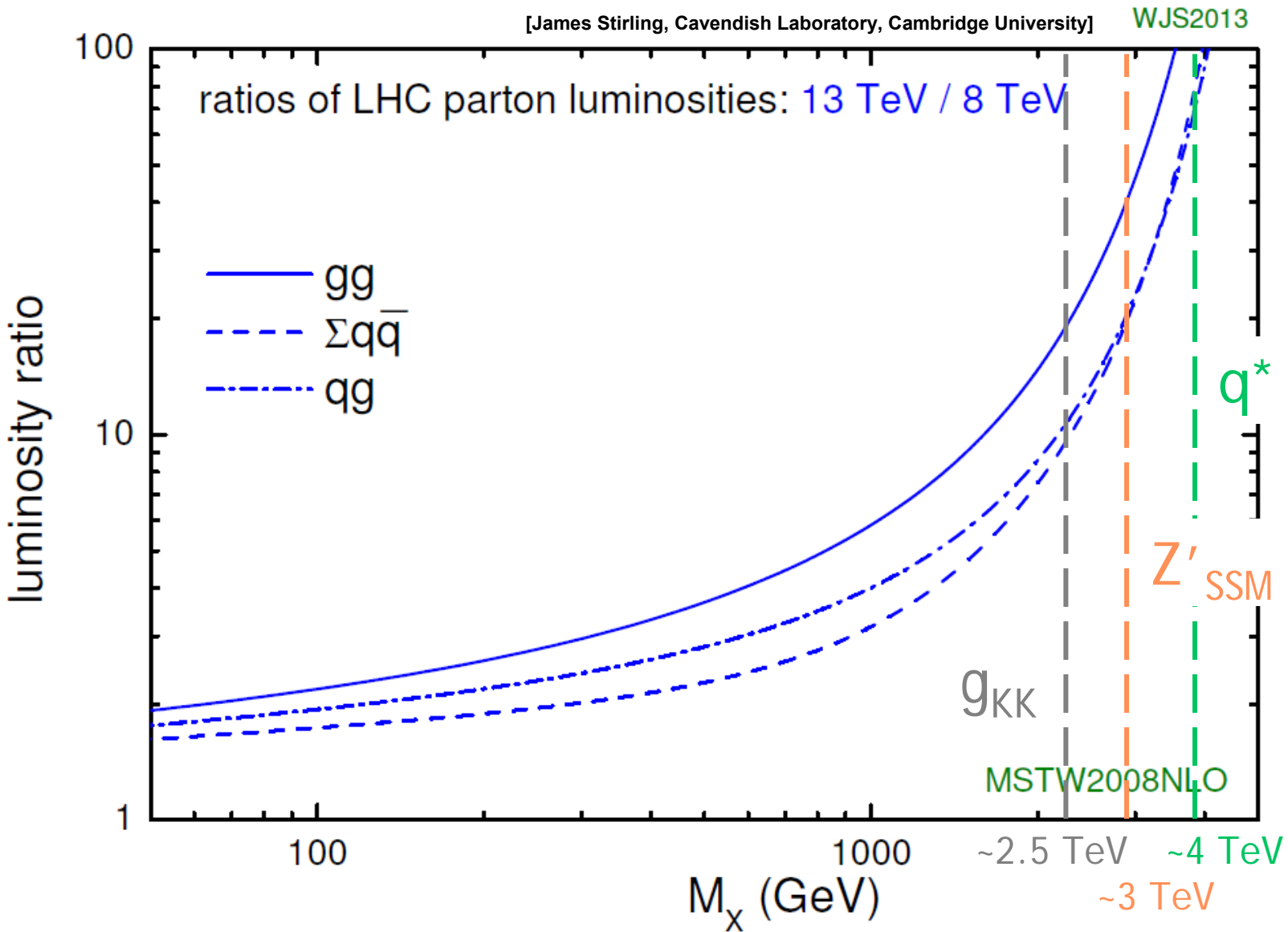
	Obs. lower mass limit
π_T	180 GeV

CDF: $m(\pi_T) \sim 160 \text{ GeV}$

Conclusion

- BSM searches in LHC 8 TeV data now well developed
- Resonance search powerful and robust
 - but no hint of a new resonance yet...
- Probing higher and higher masses
 - must continue probing low masses → low couplings!
- Combinations for dedicated models to come
 - also trying to improve model-independence
- Techniques developed for boosted products of very massive resonances will become more and more important
 - also beneficial to other searches

Outlook



Parallel talks and posters

- Elizabeth CASTANEDA MIRANDA

Search for heavy resonances with the ATLAS detector

- Edmund A BERRY

Search for Heavy Resonances with leptons, photons, and jets at CMS

- Tracey BERRY

Searches gravity effects at the TeV scale with the ATLAS detector

- Roman KOGLER

Search for heavy resonances decaying to top quarks with CMS

- Diedi HU

Searches for $t\bar{t}$ resonances with the ATLAS detector

- Viviana CAVALIERE

Search for resonant diboson production with the ATLAS detector

- Andreas HINZMANN

Searches for heavy resonances decaying to pairs of massive vector bosons with CMS

- Samuel Ross MEEHAN

Semi-leptonic ZZ/ZW Diboson Final State Search at 8 TeV with ATLAS

- Mark OLSCHESKI

Search for new physics in lepton + MET final states

- Shilpi JAIN

Search for Excited Leptons in pp collisions at $\sqrt{s} = 7$ TeV

Complete information:

- <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults>
- http://www-cdf.fnal.gov/physics/exotic/exotics_published.html
- <http://www-cdf.fnal.gov/physics/exotic/exotic.html>
- http://www-cdf.fnal.gov/physics/new/hdg/Results_files/results/w2jet_130222/
- <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO>
- <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G>
- http://www-d0.fnal.gov/d0_publications/d0_pubs_list_runII_bytopic.html#np

Bonus

Summaries

- 8 TeV limits by particle
- older dijet limits

More signatures

- semileptonic ZZ
- lepton plus photon
- $j\mu j\mu, j\mu j + E_T^{\text{miss}}$
- semileptonic top+jet pairs
-  - $j j j$ and $j j j_b$ pairs

8 TeV limits

Black: 20 fb⁻¹ Grey: 13-14 fb⁻¹

SSM Z' [TeV]	Channel	ll	$\tau\tau$	jj	$j_b j_b$
	ATLAS	2.86	[0.5, 1.90]		
	CMS	2.96		[1.20, 1.68]	[1.20, 1.68]

SSM W' (no interf.) [TeV]	Channel	$l+E_T^{\text{miss}}$	jj	$t\bar{b}$	WZ \rightarrow ll' ν	WZ \rightarrow JJ
	ATLAS			[0.5, 1.84] [#]	1.18	
	CMS	3.35	[1.20, 2.29]	[0.8, 2.03]	1.45	[1.0, 1.73]

No mass reconstruction

q* [TeV]	Channel	jj	$j\gamma$	$j_b j$	qW \rightarrow jJ	qZ \rightarrow jJ
	ATLAS	[1.5, 3.84]	[1.0, 3.48]			
	CMS	[1.2, 3.5]		[1.34, 1.54]	[1.0, 3.23]	[1.0, 3.00]

8 TeV limits

Black: 20 fb⁻¹ Grey: 13-14 fb⁻¹

topcolor Z' (narrow) [TeV]	Channel	semileptonic tt ^{bar}	hadronic tt ^{bar}
	ATLAS	[0.5,1.8]	
	CMS	[0.5,2.10]	[1.0,1.7]

Bulk RS g _{KK} [TeV]	Channel	semileptonic tt ^{bar}	hadronic tt ^{bar}
	ATLAS	[0.5,2.0]	
	CMS	[0.7,2.54]	[1.0,1.8]

RS1 G* k/M _{pl} =0.1 [TeV]	Channel	dilepton	dijet	j _b j _b	WW → JJ	ZZ → JJ
	ATLAS	2.47				
	CMS			[1.20,1.58]	[1.42,1.57]	[1.0,1.59]

Dijets: older results

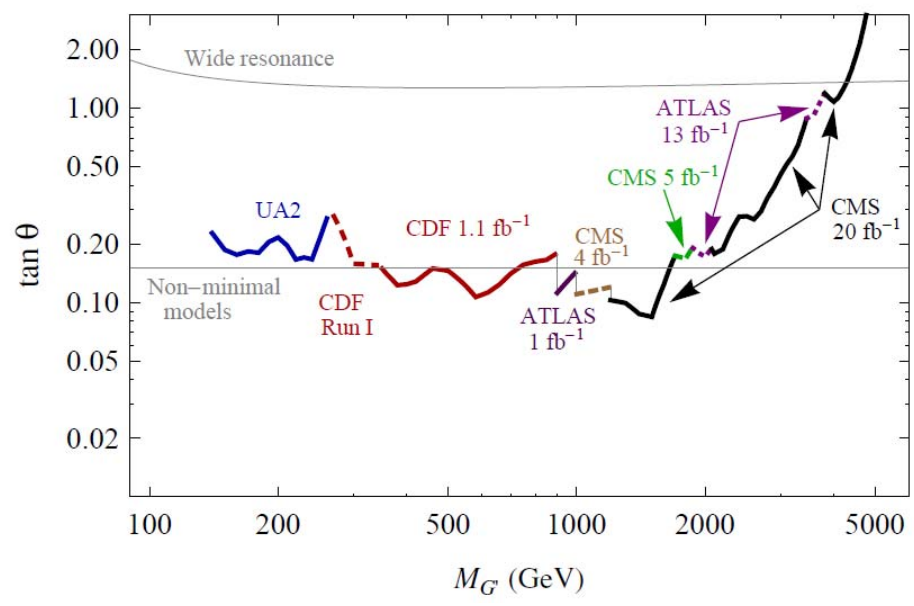
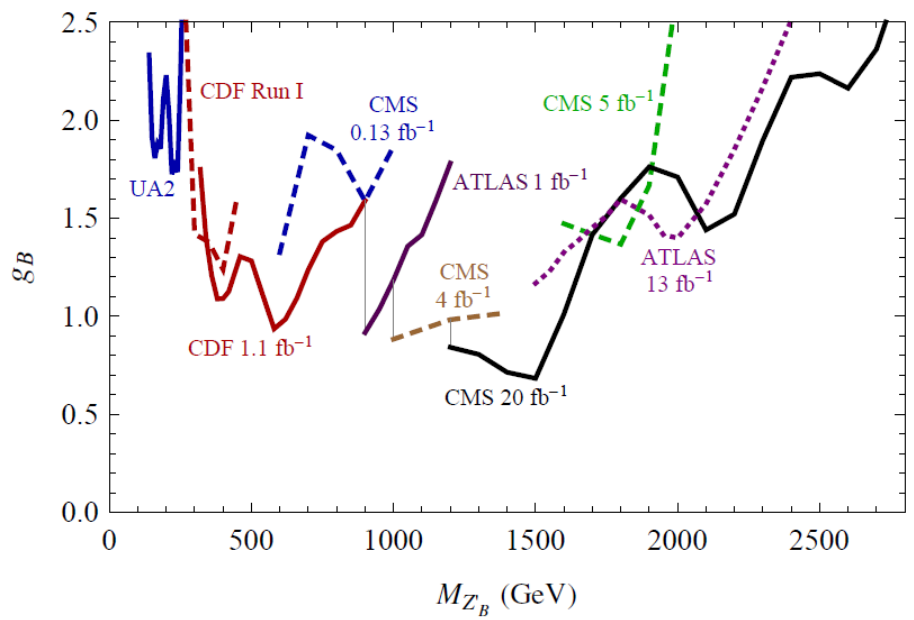
[Harris and Kousouris, Int.J.Mod.Phys. A26 (2011) 5005-5055]

Expt.	Year	Axigluon or Coloron (TeV)	Excited Quark (TeV)	W' (TeV)	Z' (TeV)	E_6 Diquark (TeV)	String (TeV)
UA1	1986	0.13-0.28	—	—	—	—	—
UA1	1988	0.15-0.31	—	—	—	—	—
CDF	1990	0.12-0.21	—	—	—	—	—
UA2	1990	—	—	0.10-0.16	—	—	—
CDF	1993	0.22-0.64	—	—	—	—	—
UA2	1993	—	0.14-0.29	0.13-0.26	0.13-0.25	—	—
CDF	1995	0.20-0.87	0.20-0.56	—	—	—	—
CDF	1997	0.20-0.98	0.20-0.52	0.30-0.42	—	0.29-0.42	—
”	”	—	0.58-0.76	—	—	—	—
D0	2004	—	0.20-0.78	0.30-0.80	0.40-0.64	—	—
CDF	2009	0.26-1.25	0.26-0.87	0.28-0.84	0.32-0.74	0.29-0.63	0.26-1.4
ATLAS	2010	—	0.30-1.26	—	—	—	—
CMS	2010	0.50-1.17	0.50-1.58	—	—	0.50-0.58	0.50-2.50
”	”	—	—	—	—	0.97-1.08	—
”	”	—	—	—	—	1.45-1.60	—
ATLAS	2011w	0.60-2.10	0.60-2.15	—	—	—	—
CMS	2011	1.00-2.47	1.00-2.49	1.00-1.51	—	1.00-3.52	1.00-4.00
ATLAS	2011s	0.80-3.32	0.80-2.99	—	—	—	—

Dijets: the Tevatron's contribution

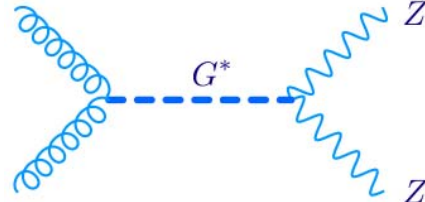
[Dobrescu and Yu, arXiv:1306.2629]

- Theoretical framework allowing direct comparison between searches at different colliders or CM energies:
 Z' coupled to baryon number or coloron

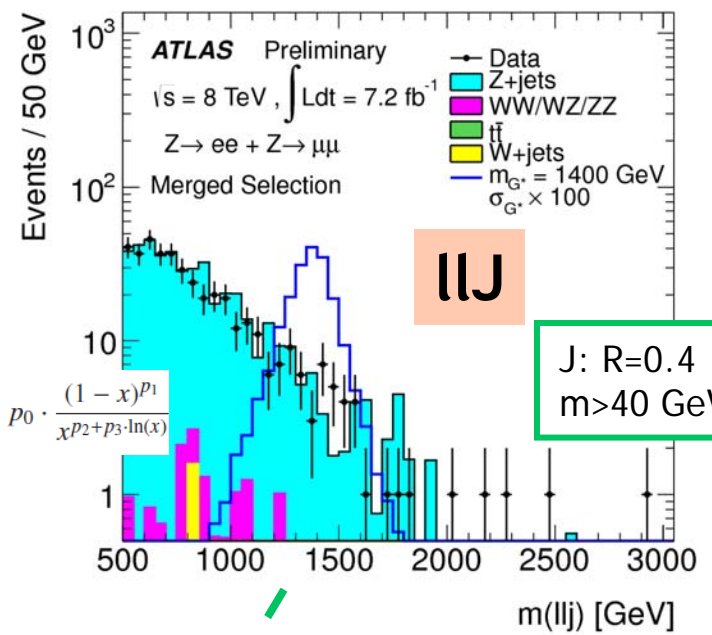
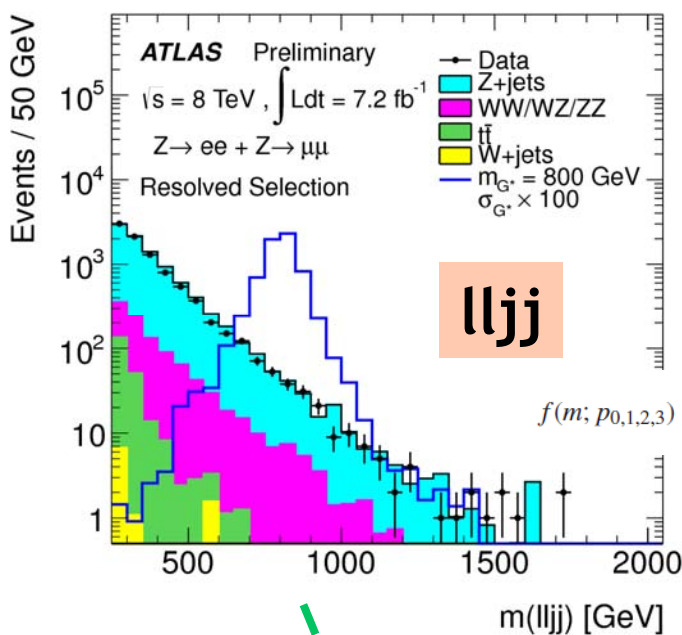


Semileptonic ZZ

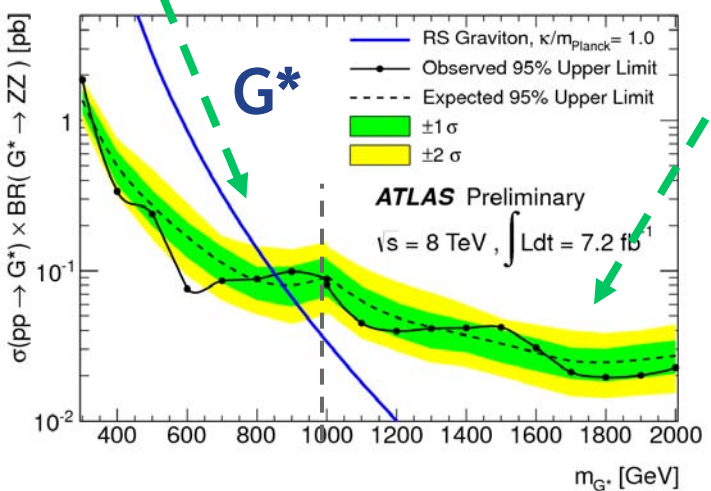
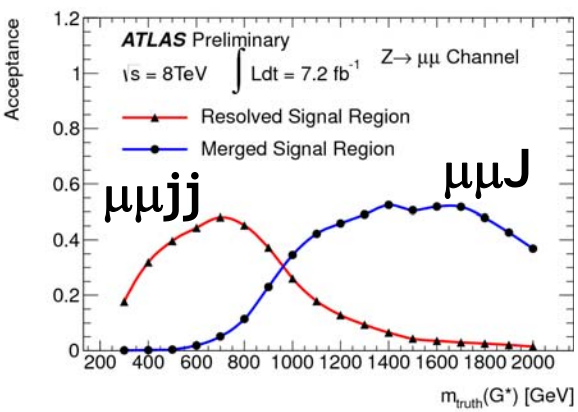
[ATLAS-CONF-2012-150]



- Fermionic couplings possibly suppressed
- $ZZ \rightarrow llqq$
- 2 analyses: resolved and merged



$$f(m; p_{0,1,2,3}) = p_0 \cdot \frac{(1-x)^{p_1}}{x^{p_2+p_3 \cdot \ln(x)}}$$

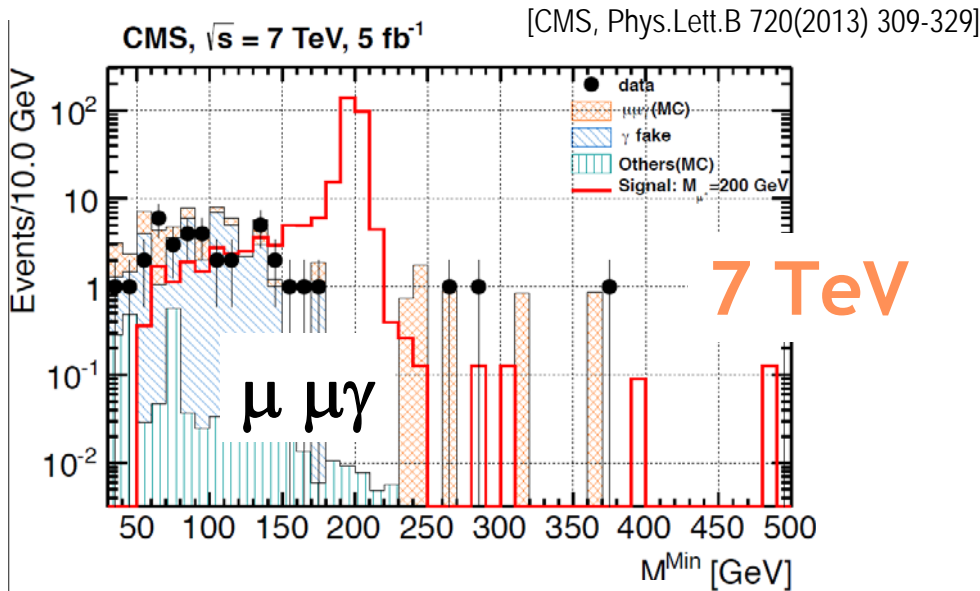
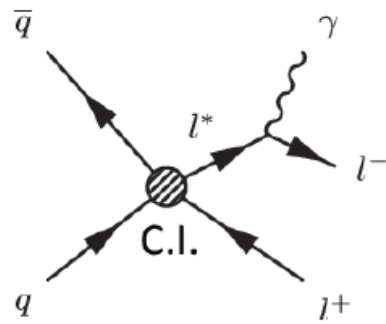


Observed lower mass limit (TeV)

Model	ATLAS 7 fb ⁻¹
Bulk RS G* $\kappa/\bar{M}_{\text{Pl}} = 1.0$	850 GeV

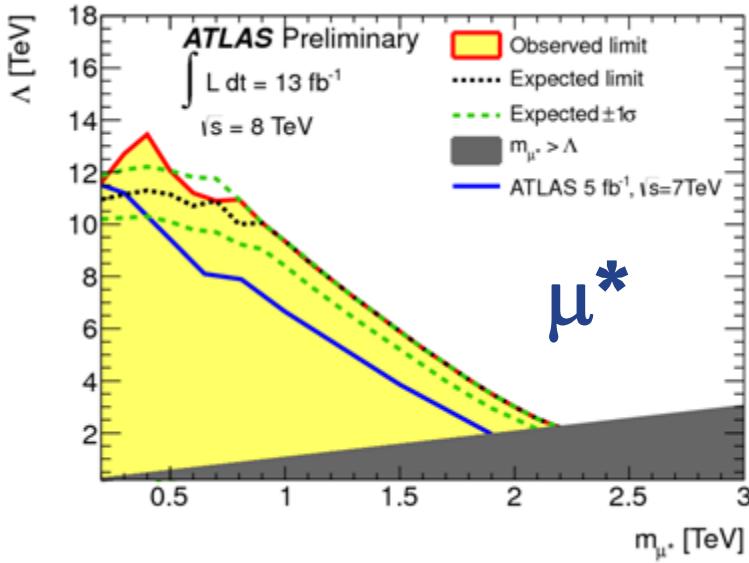
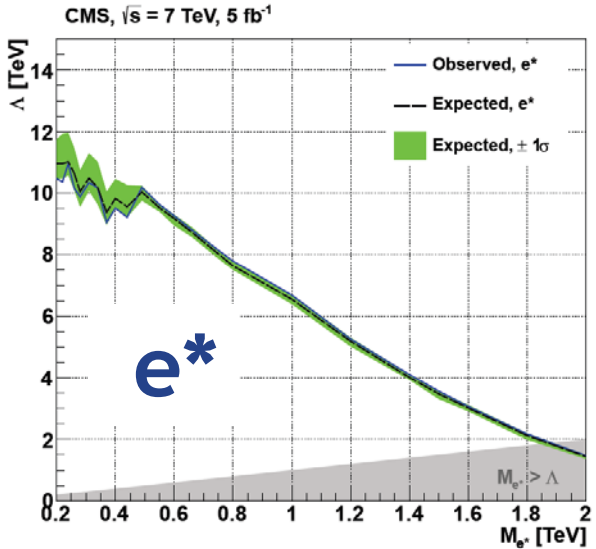
$\Gamma/M = 3-6\%$

Lepton plus photon



[ATLAS-CONF-2012-146]

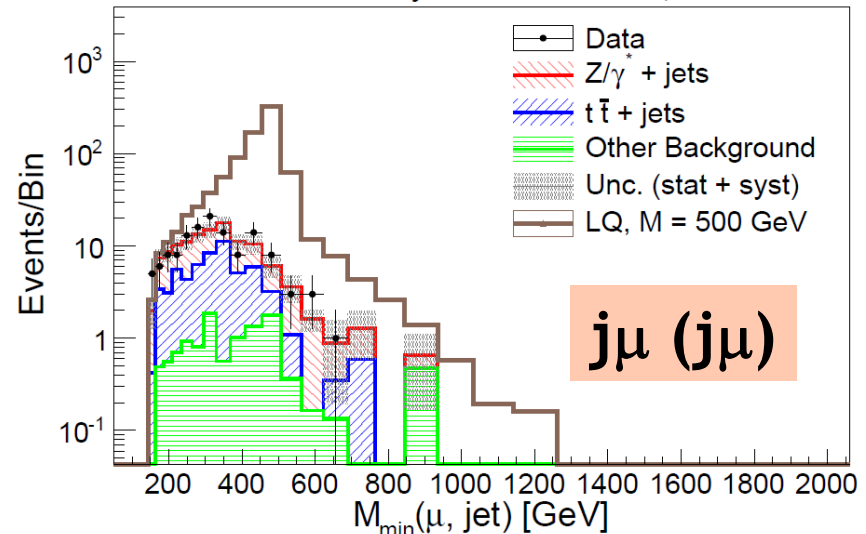
ATLAS: 8 TeV,
no l^* mass reconstruction



$j\mu j\mu$ and $j\mu j + \text{missing } E_T$

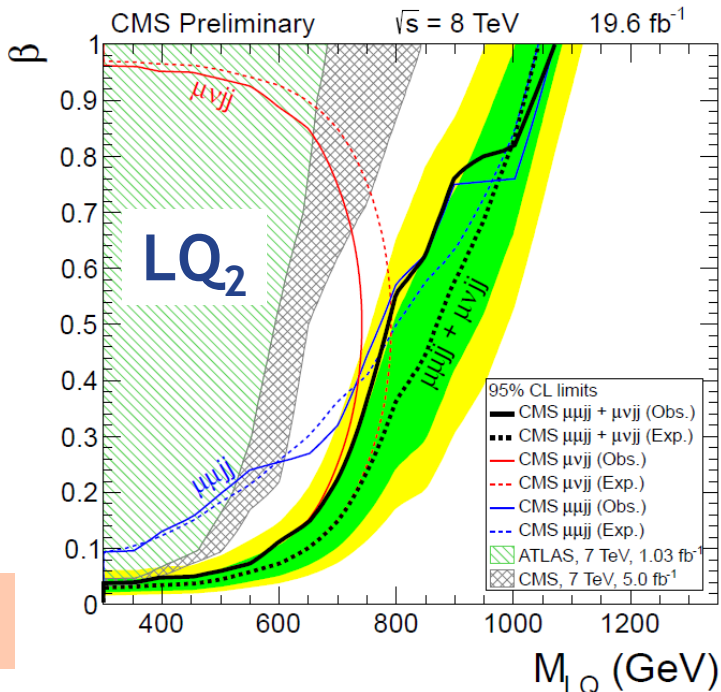
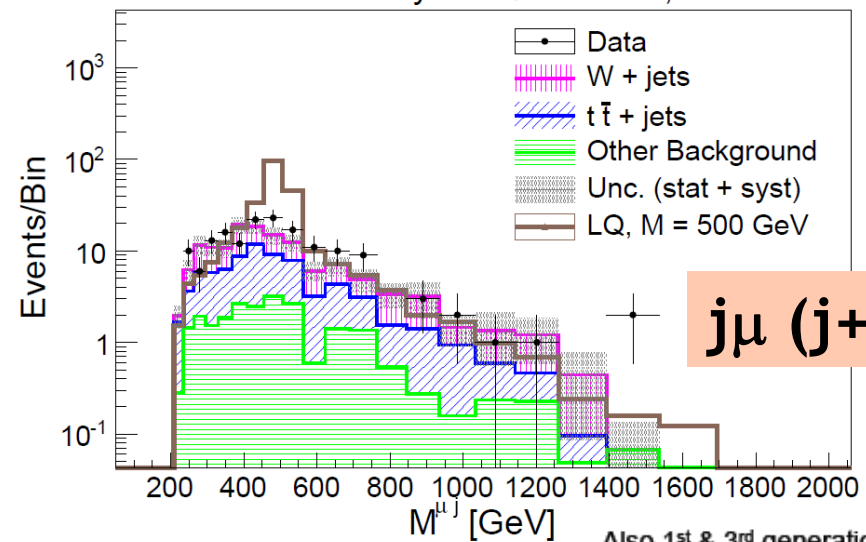
[CMS-EXO-12-042]

CMS Preliminary $\sqrt{s} = 8 \text{ TeV}, 19.6 \text{ fb}^{-1}$



• Very low background

CMS Preliminary $\sqrt{s} = 8 \text{ TeV}, 19.6 \text{ fb}^{-1}$

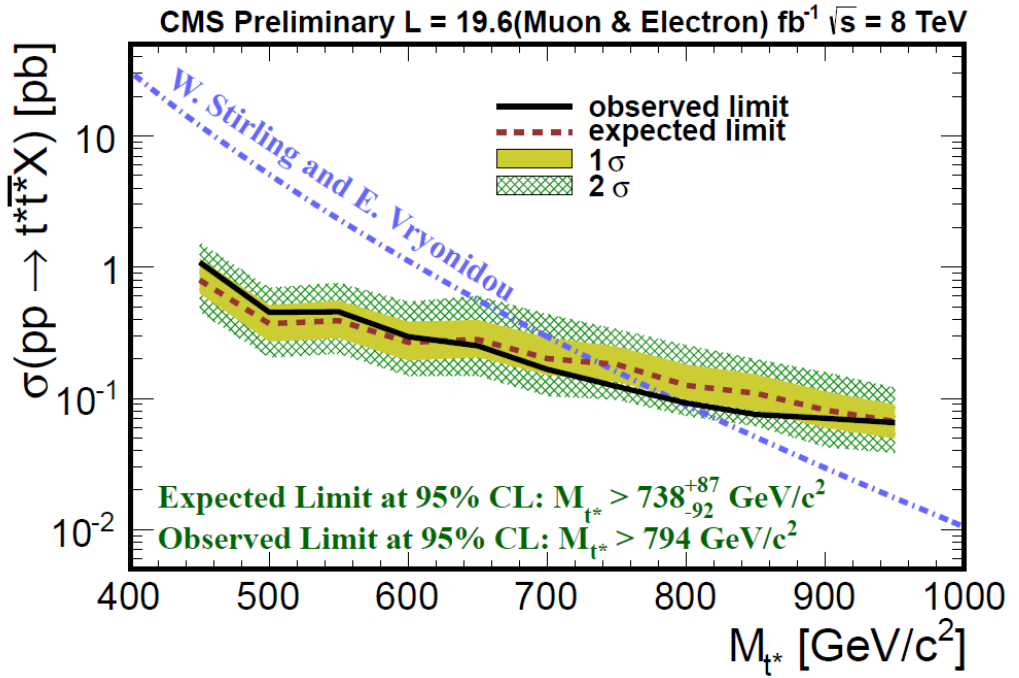
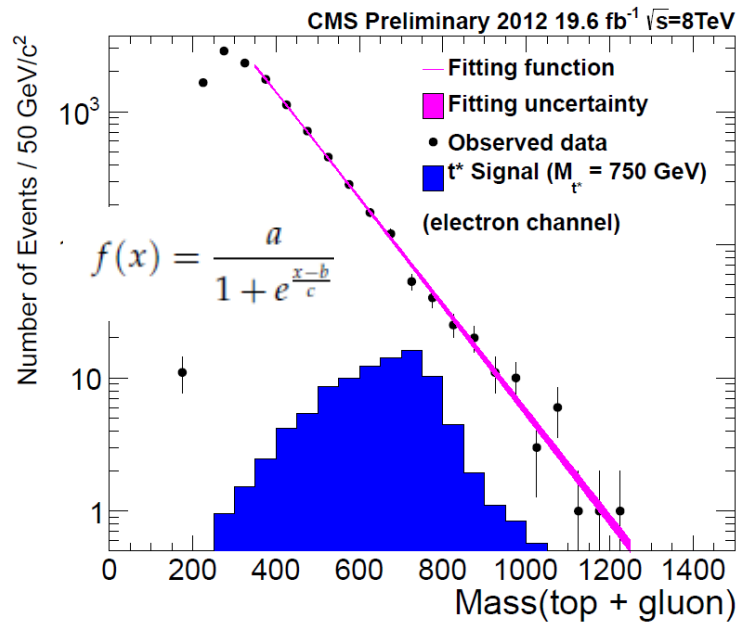
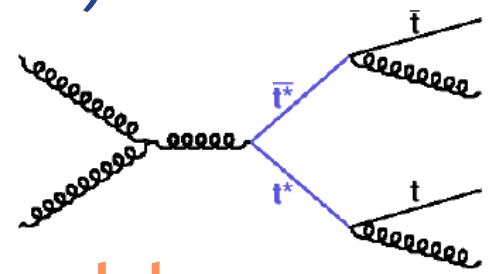


Also 1st & 3rd generation LQ searches, see e.g. ATLAS: arXiv:1303.0526, submitted to JHEP; CMS: JHEP 12 (2012) 055 & PRL 110, 081801 (2013)

Semileptonic t+jet pairs

[CMS-B2G-12-014]

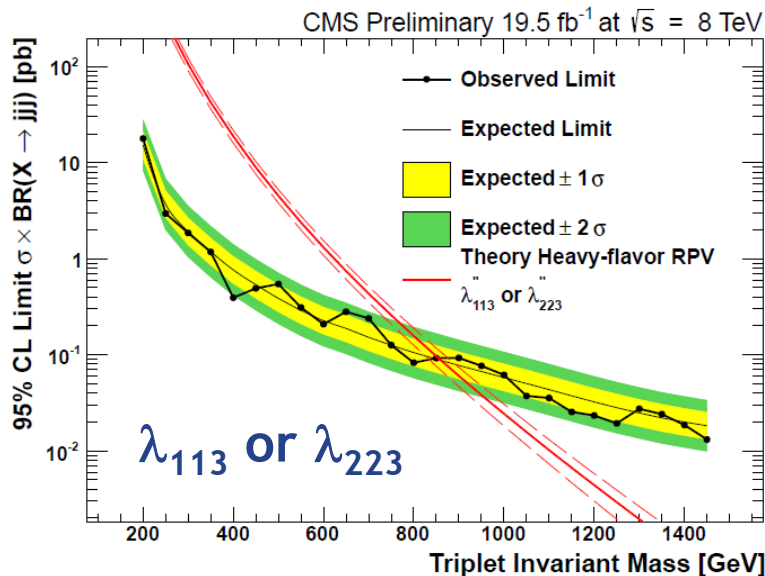
- Spin 3/2, pair production, $t^* \rightarrow t\bar{g}$ (100%)
- 1 lepton + ≥ 6 jets (≥ 1 b-jet)
- Main background $t\bar{t}^{\text{bar}}$ (+ ≥ 2 jets)
- **450 < m(t*) < 794 GeV excluded in a RS model**



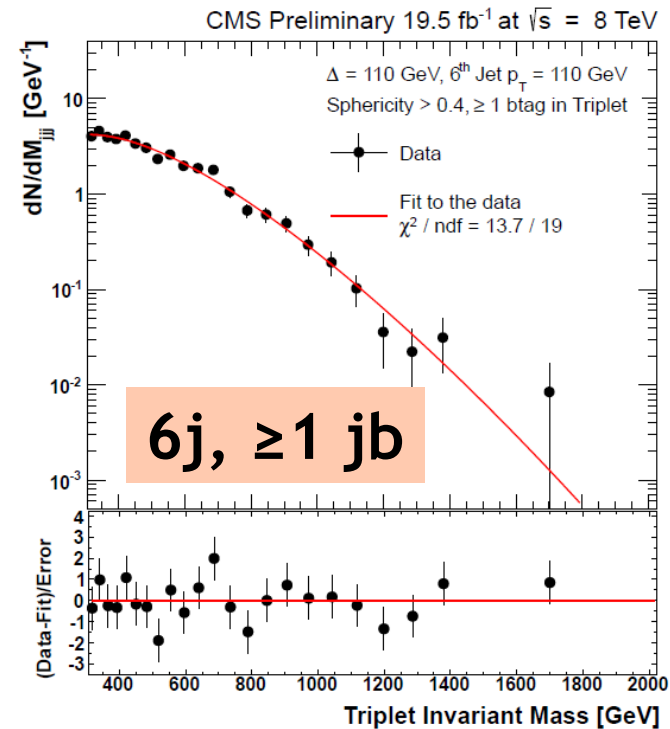
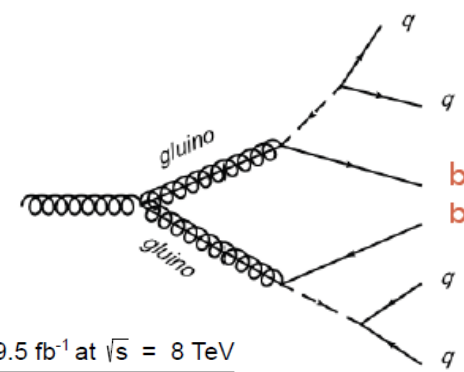
See also PRD 86, 091103 (2012) (ATLAS) for a 7 TeV search for $t\bar{t}^{\text{bar}}+j$ with different interpretations

jjj and jjj_b pairs

- R-parity violating $g^{\text{gluino}} \rightarrow uds$ and $g^{\text{gluino}} \rightarrow udb$ or csb
- ≥ 6 jets
- 20 combinations/event
- $M_{\text{iii}} < \sum^{\text{iii}} |p_{\text{T}}^{\text{Jet}}| - \Delta$ (offset)



[CMS-EXO-12-049]



	Obs. lower gluino mass limit
λ_{112}	650 GeV
λ_{113} or λ_{223}	835 GeV