Direct searches for Exotics at the LHC

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Why looking for Beyond Standard Model (BSM)?

Sensational success of Standard Model, however still numerous unanswered questions…

Why is the Higgs light?

What are the details of the EW symmetry breaking mechanism?

Why left-handed weak interactions?

Where are the right-handed neutrinos?

Do the interactions couplings unify?

Why quantized electric charges?

Why three generations?

Why fermion mass hierarchy?

What is dark matter?

How about gravity?

…

BSM theories

COMPOSITENESS

GRAND UNIFICATION

SUPERSYMMETRY

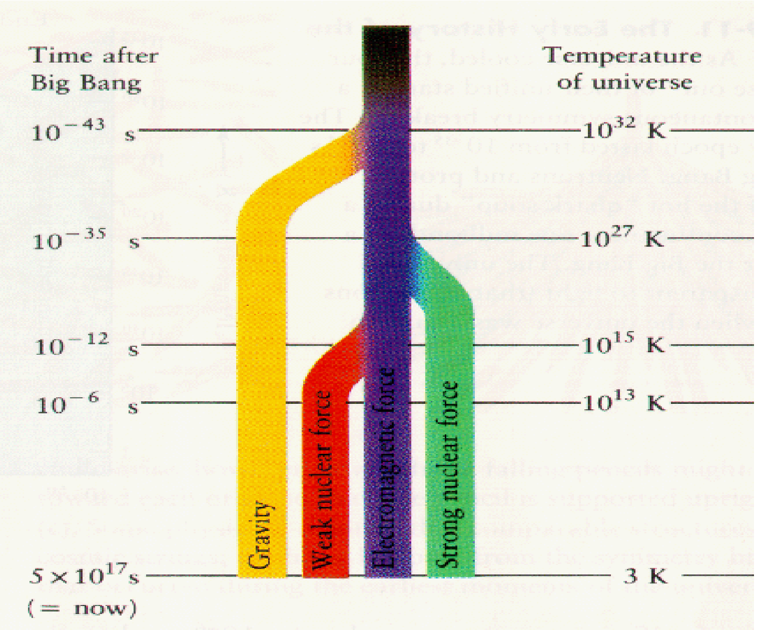
TECHNICOLOR

EXTRA DIMENSIONS

Little Higgs, Hidden Valley, Unparticles, …

BSM theories

GRAND UNIFICATION



-larger gauge group (various breaking patterns)

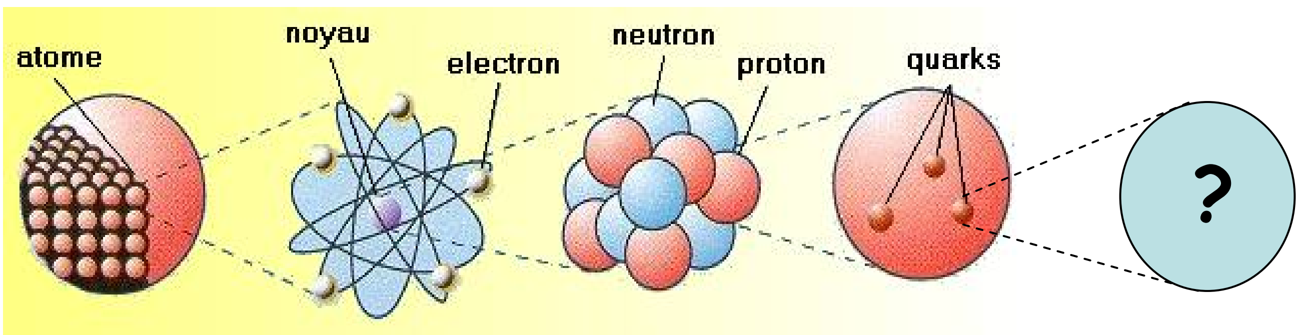
-single coupling

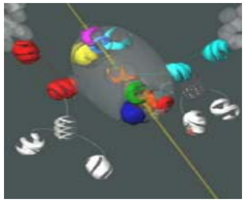
-quarks and leptons in irreducible representations

☞ charge quantization

BSM theories

COMPOSITENESS

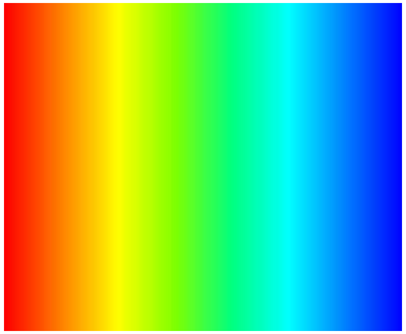




- standard particles not elementary
- substructure of fermions and bosons
- (no fully consistent model yet)

☞ family replication

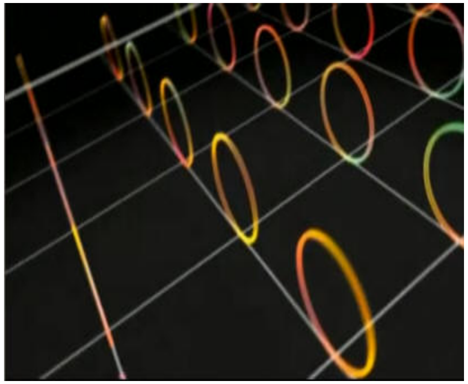
BSM theories

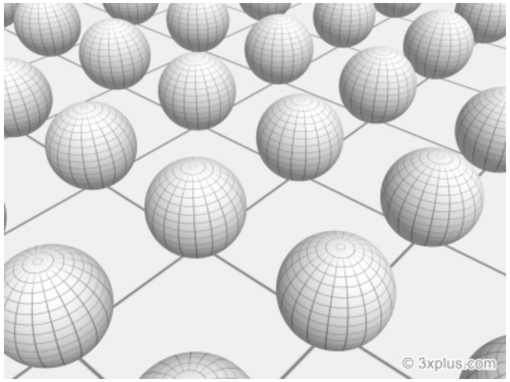


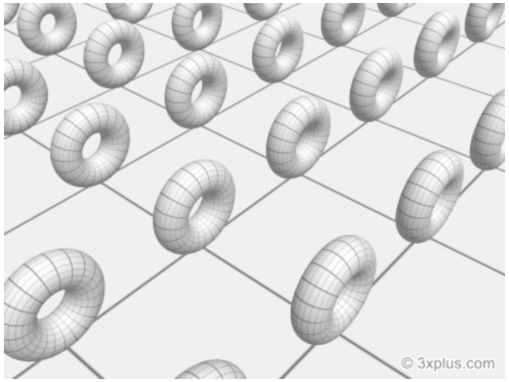
TECHNICOLOR

- -new strong gauge interaction
- -new fermions (techniquarks)
- -spontaneous chiral symmetry breaking
- ☞ composite Higgs boson, no fine tuning

BSM theories







EXTRA DIMENSIONS

- more than 3 spatial dimensions
- gravitation “diluted”
- various numbers/sizes/shapes/… of extra dimensions (ADD, RS, UED,… models)

☞ hierarchy problem solved + dark matter

Exotics

GRAND UNIFICATION

–new vector bosons (Z', W',…), heavy fermions (t', b', T, B,…), ν_R, leptoquarks, diquarks, Higgses,…

COMPOSITENESS

–excited states of known particles (l^*, q^*, Z^*, W^*,…), leptoquarks,…

EXTRA DIMENSIONS

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

TECHNICOLOR

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

Search strategy

Several theories (+not yet thought of theories)

several models

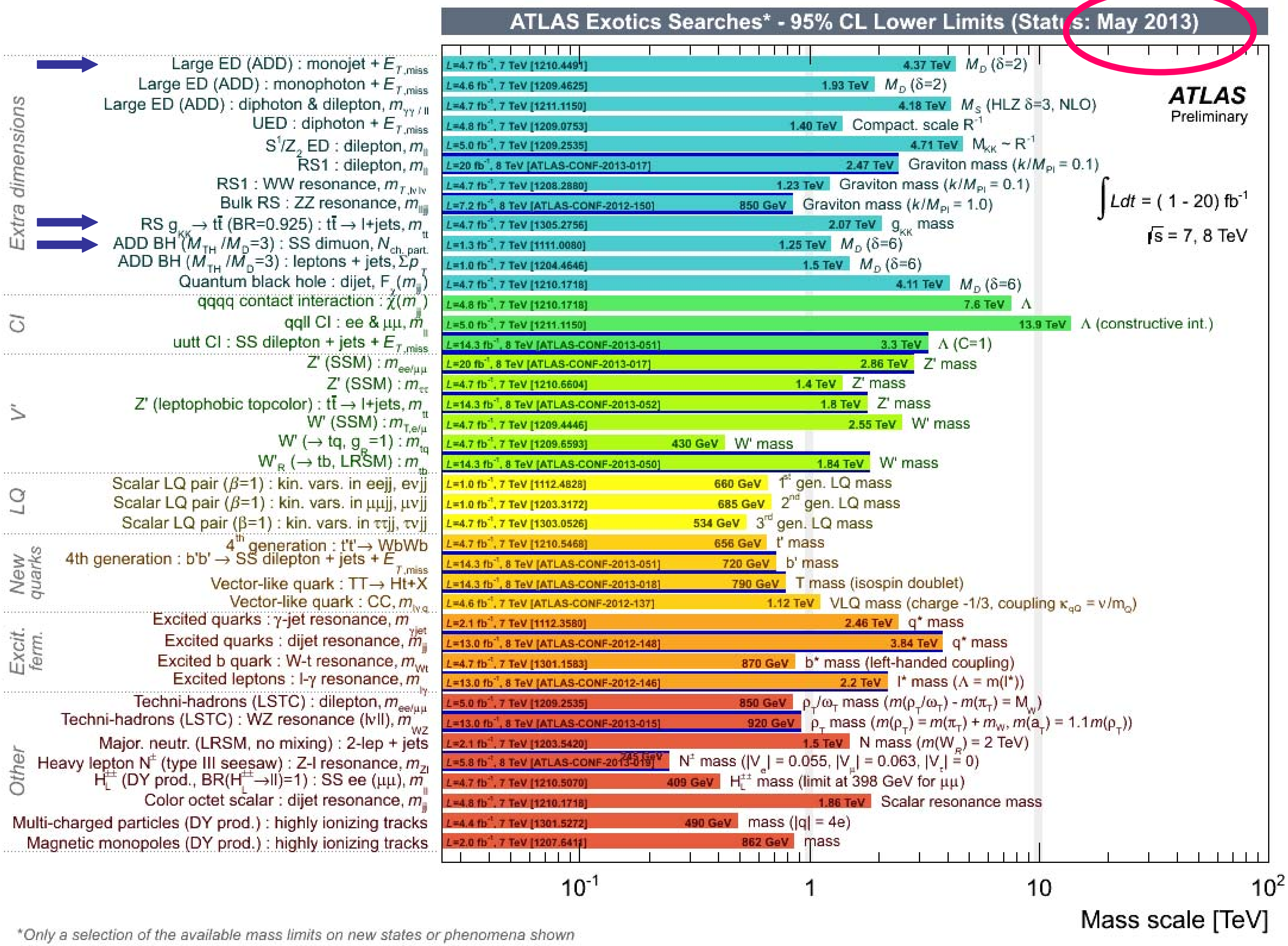
many particles

several production modes

several decay modes

Look for signatures!

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



similar amount of results from CMS

Outline

Singly produced resonances

- *mostly new bosons*

Pair produced resonances

- *mostly new fermions*

Other signatures

- *mono-X, Black Holes*

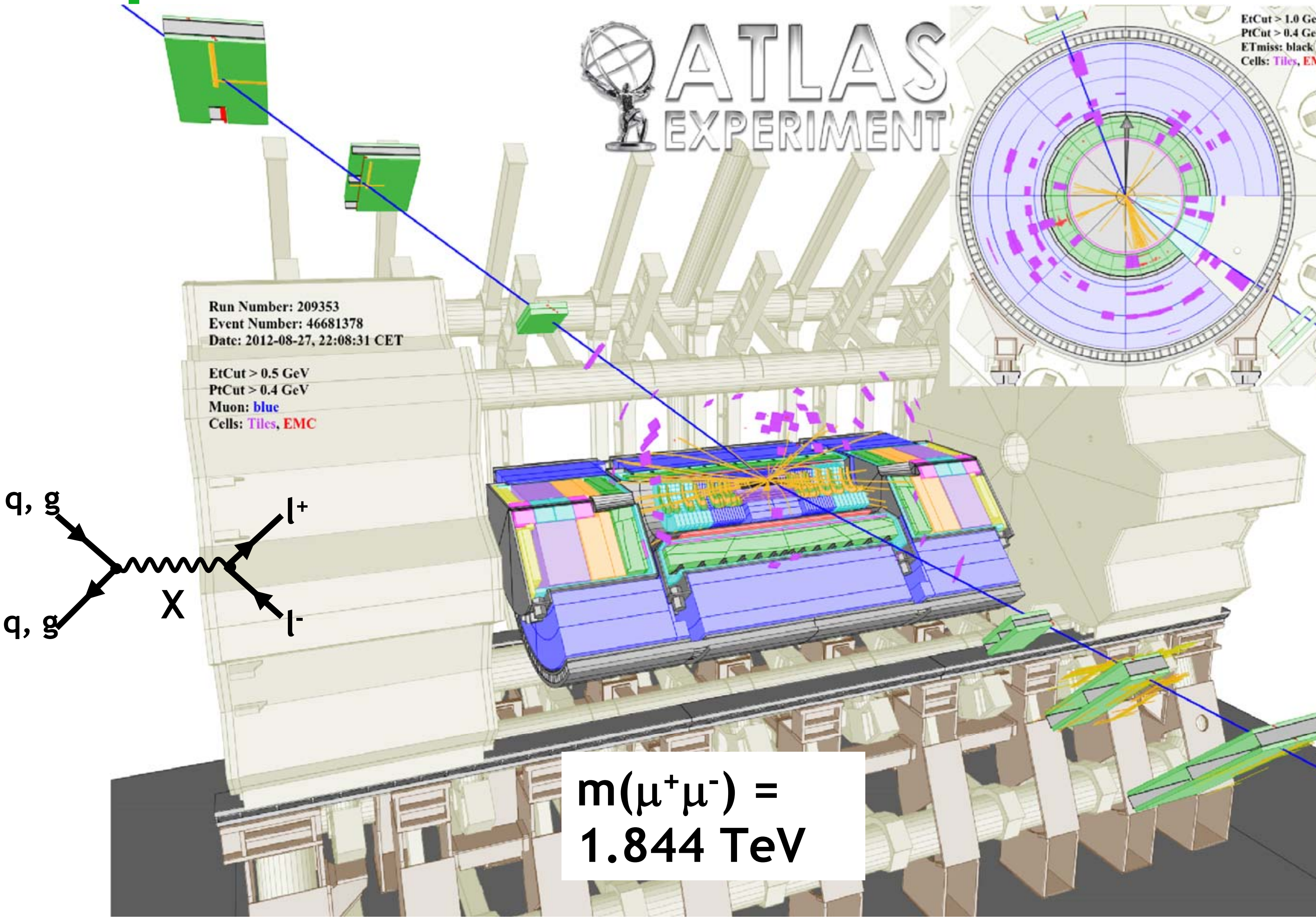
All results at 8 TeV, ~all limits at 95% C.L.

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

Singly produced resonances

- dileptons (ee, $\mu\mu$, $\tau\tau$)
- lepton plus missing E_T
- dijets (un-, b-, top-, W/Z-tagged)
- more t t^{bar} (semileptonic)
- more dibosons (all leptonic WZ)

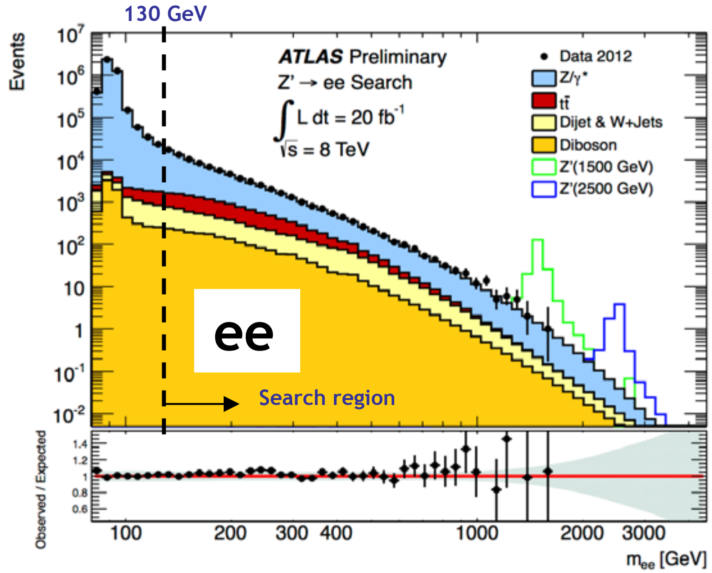
Dileptons

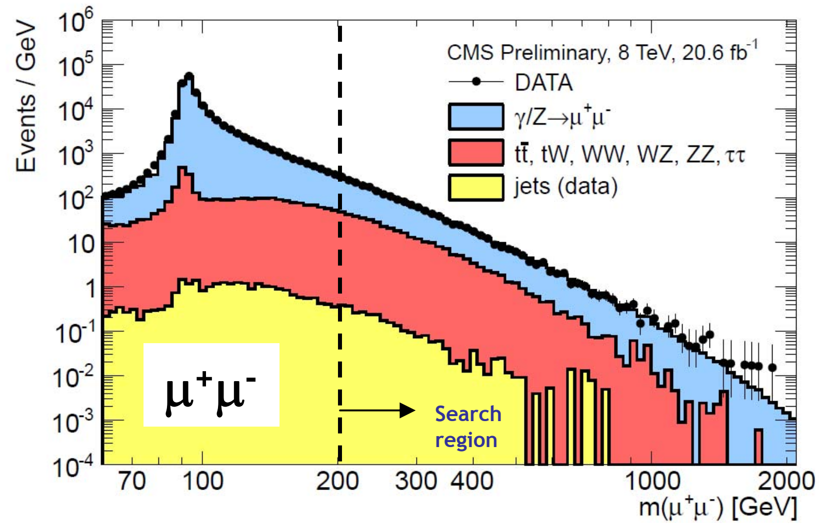

ATLAS EXPERIMENT
Run Number: 209353
Event Number: 46681378
Date: 2012-08-27, 22:08:31 CET
EtCut > 0.5 GeV
PtCut > 0.4 GeV
Muon: blue
Cells: Tiles, EMC
EtCut > 1.0 GeV
PtCut > 0.4 GeV
ETmiss: black
q, g
q, g
X
l+
l-
m(μ+μ-) =
1.844 TeV

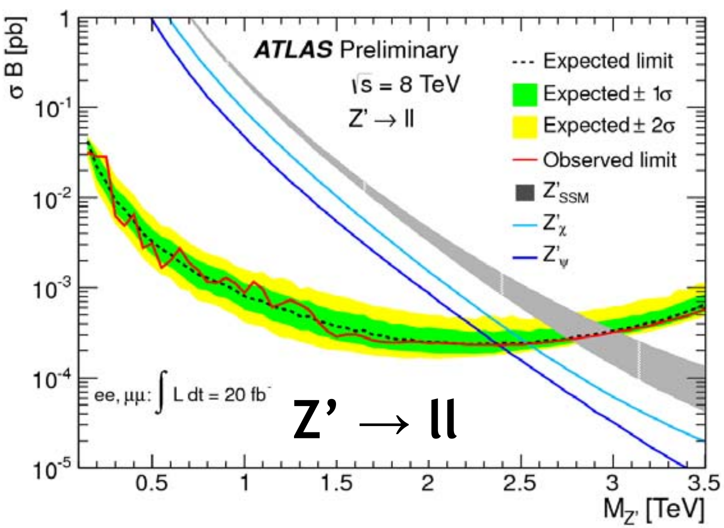
Dileptons

[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)

SSM = Sequential SM

RS= Randall Sundrum model

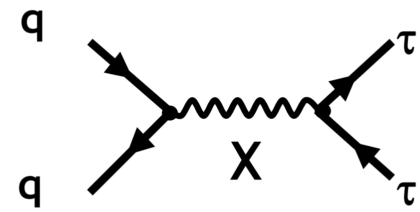
Model	ATLAS	CMS
SSM Z'	2.86	2.96
E_6 Z'_ψ	2.38	2.60
RS G* ($k/\overline{M}_{Pl}$=0.1)	2.47	

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

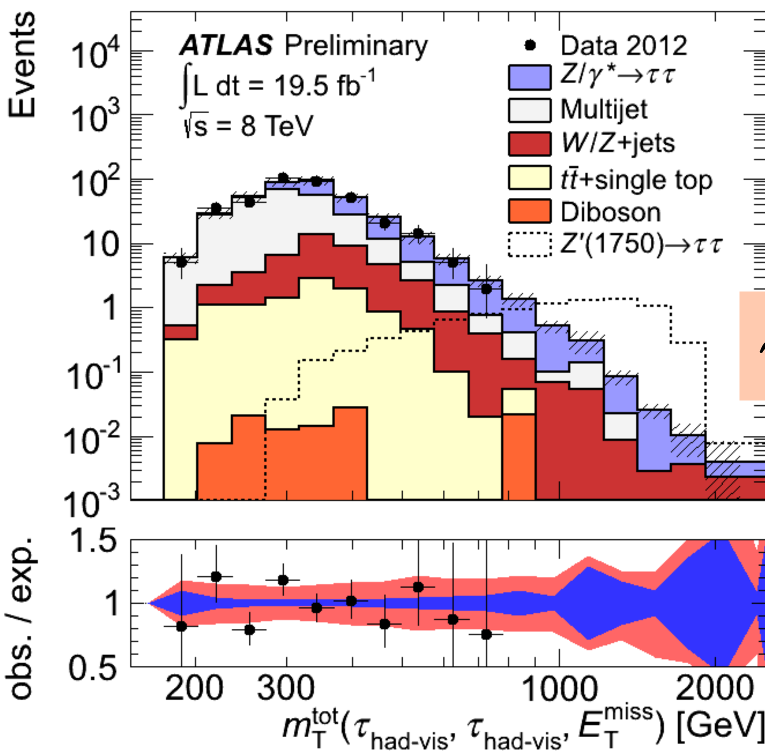
also non resonant interpretations: ADD (CMS-EXO-12-027, CMS-EXO-12-031)

Ditaus

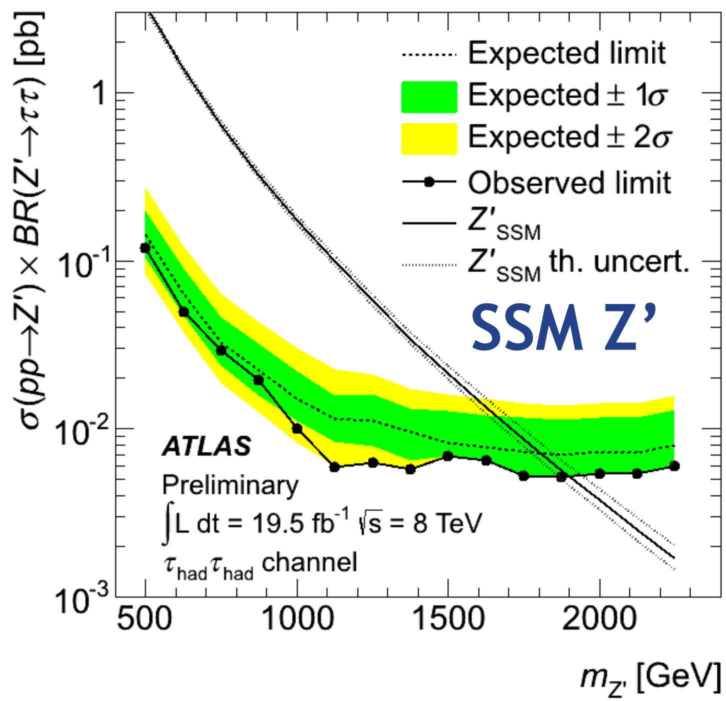
[ATLAS-CONF-2013-066]



- Lepton universality not always required
- tau candidates = jets (1 or 3 tracks) with BDT identification (Boosted Decision Tree)
- $$m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{2p_{\mathrm{T1}}p_{\mathrm{T2}}C + 2|E_{\mathrm{T}}^{\mathrm{miss}}|p_{\mathrm{T1}}C_1 + 2|E_{\mathrm{T}}^{\mathrm{miss}}|p_{\mathrm{T2}}C_2}$$
  $C=1-\cos\Delta\phi$
- resolution 30-50%



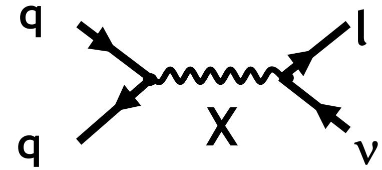
$\tau_h^+\tau_h^-$



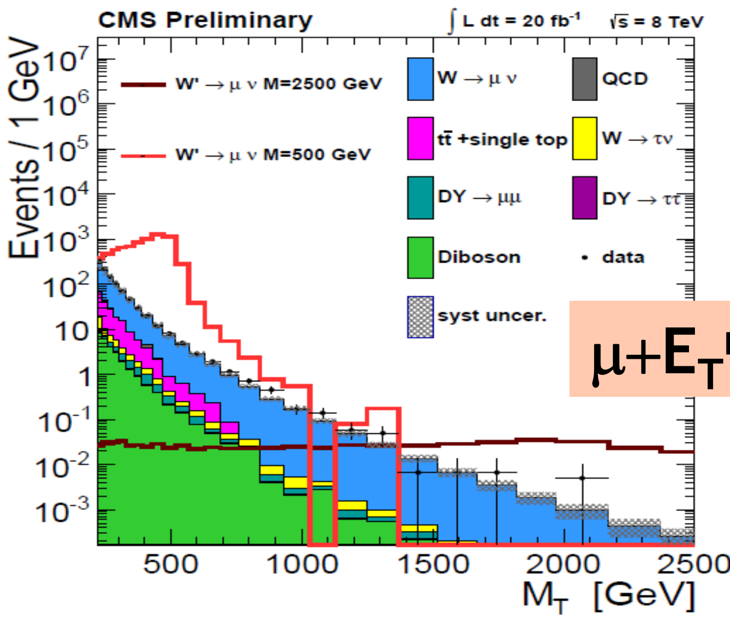
Model	Observed mass exclusion [TeV]
SSM Z'	[0.5,1.90]

Lepton + missing E_T

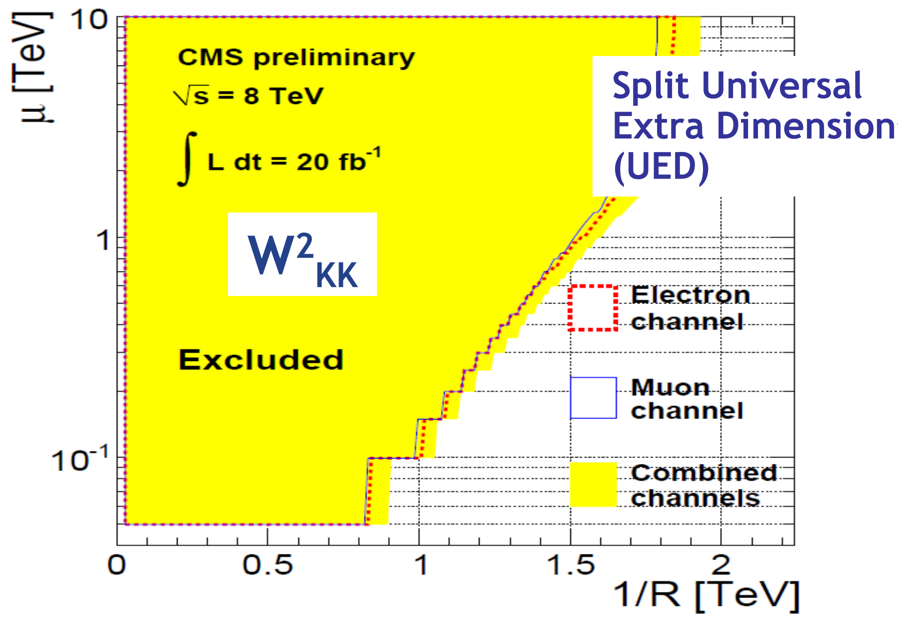
[CMS-EXO-12-060]



- $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos\varphi_{\ell\nu})}$



$\mu + E_T^{miss}$



Observed lower limits

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

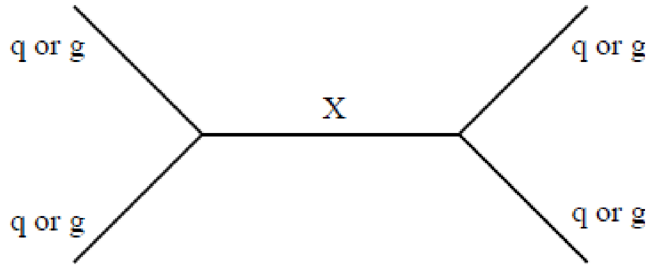
also non resonant interpretation: dark matter (see later)

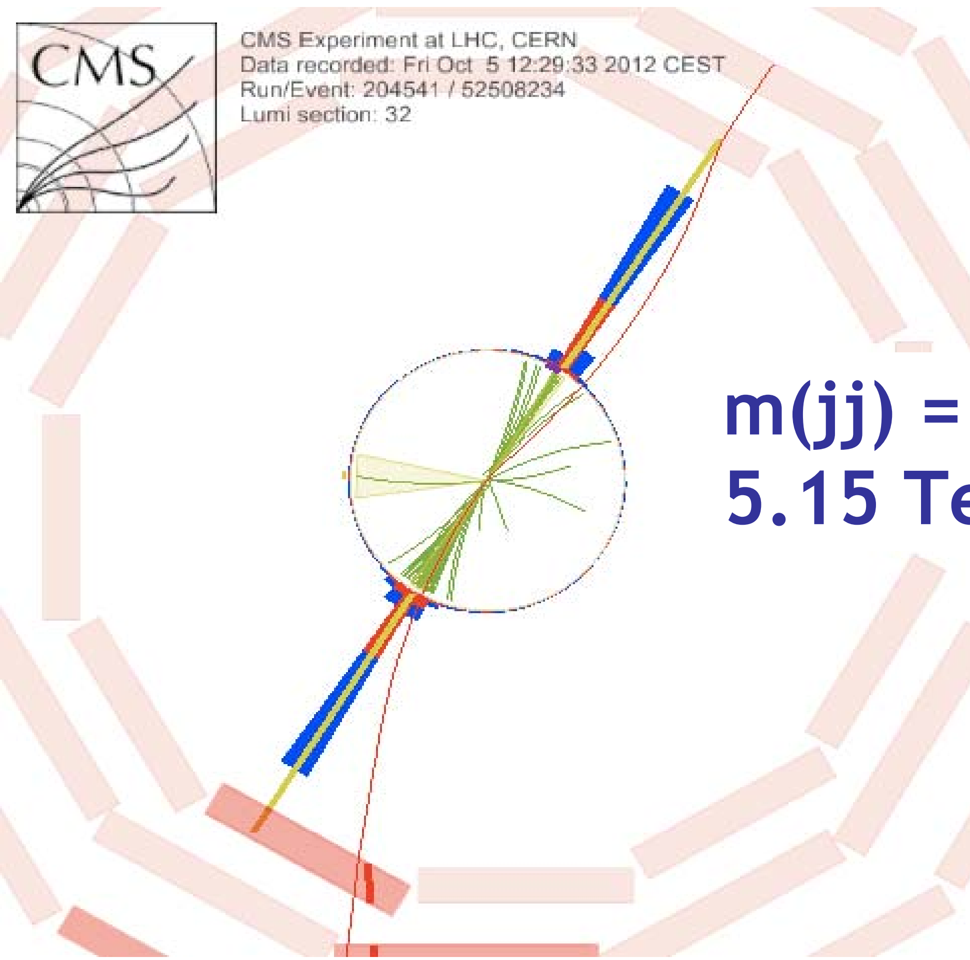
Singly produced resonances

- dileptons (ee, $\mu\mu$, $\tau\tau$)
- lepton plus missing E_T
- dijets (un-, b-, top-, W/Z-tagged)
- more t t^{bar} (semileptonic)
- more dibosons (all leptonic WZ)

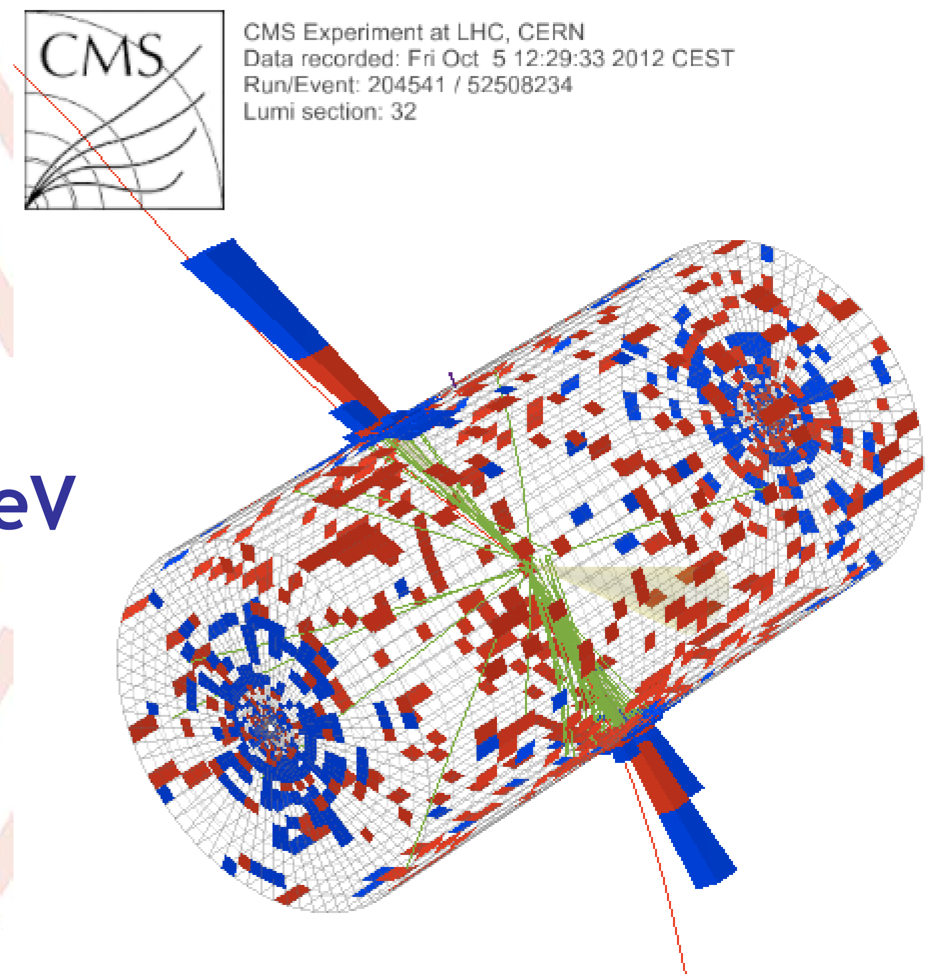
j_X=X-tagged jet

Dijets





m(jj) =
5.15 TeV

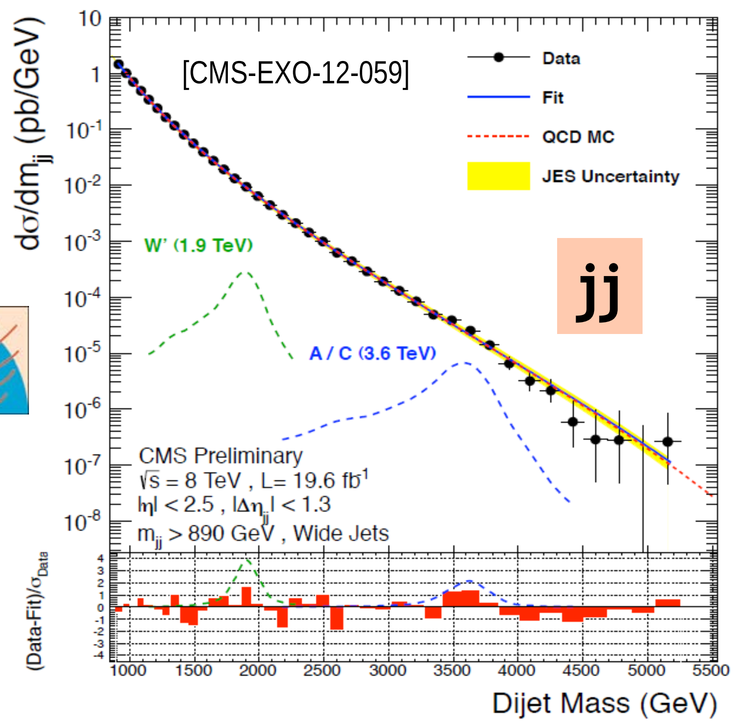


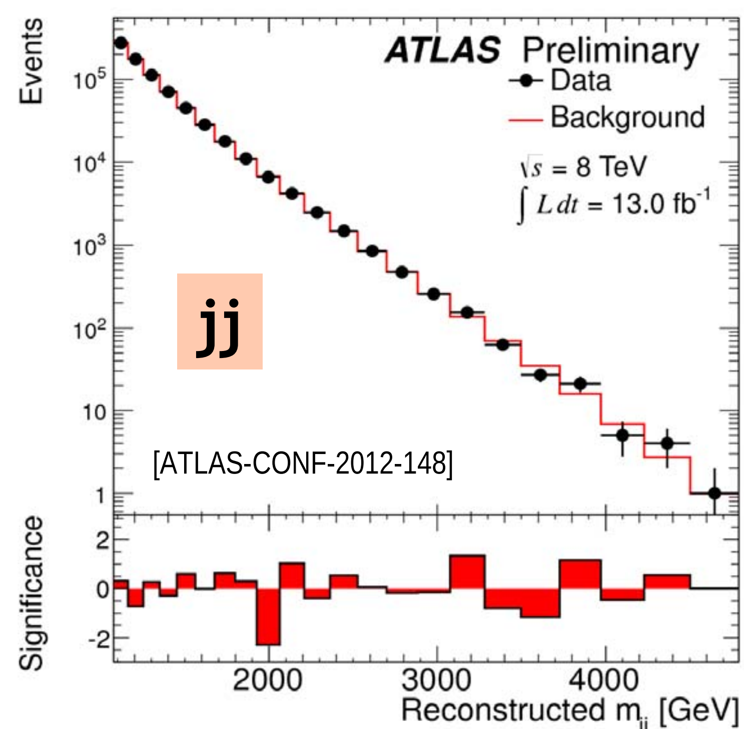
- probing quark structure up to 5 TeV!

Dijets

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

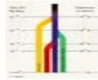
$$f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x}$$
$$x \equiv m_{jj}/\sqrt{s}$$



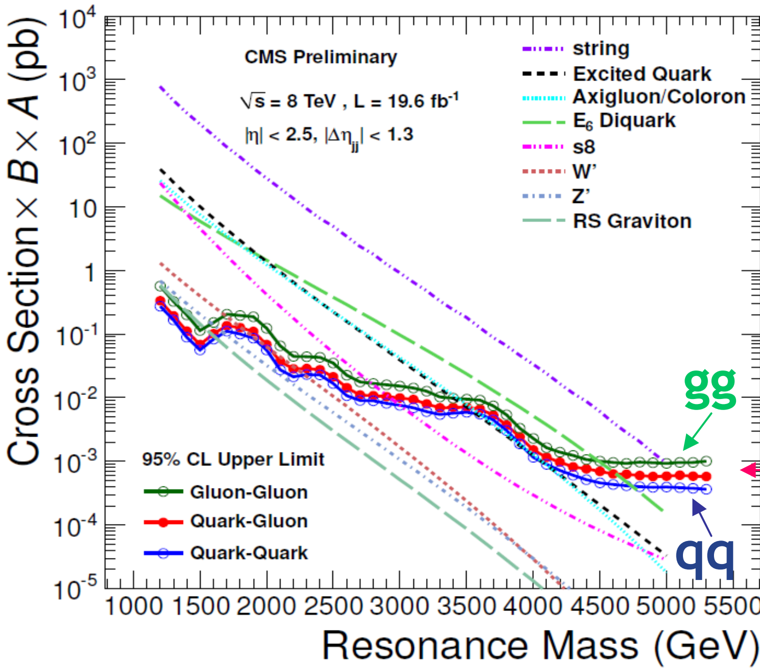


- mass threshold around 1 TeV due to trigger constraints
- specific strategies of ATLAS and CMS to recover sensitivity to masses < 1 TeV

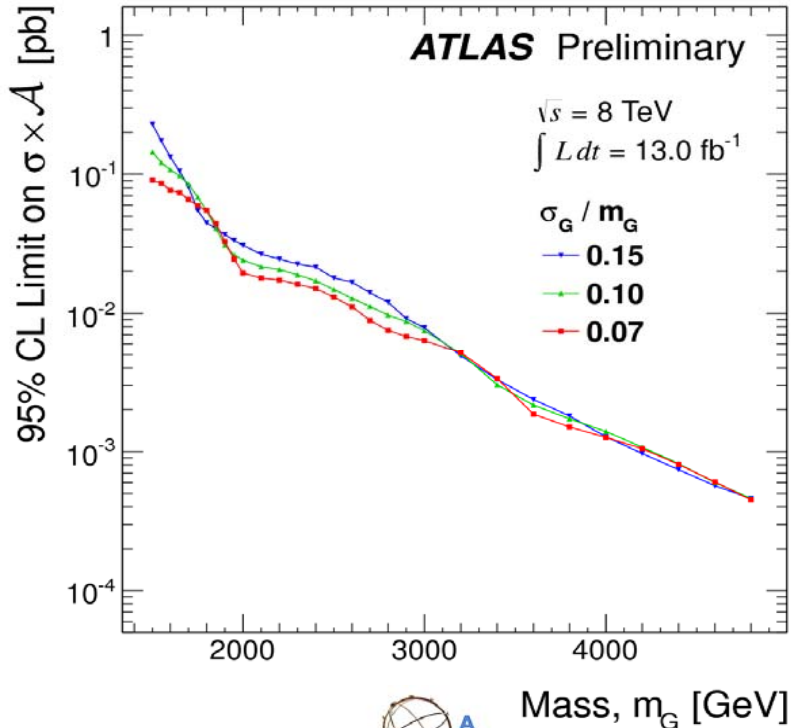
Dijets



[CMS-EXO-12-059]



[ATLAS-CONF-2012-148]



CMS 20 fb^{-1}

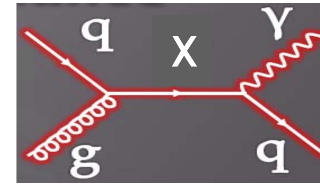
	Model	Final State	Obs. Mass Excl. [TeV]
	String Resonance (S)	qg	[1.20,5.08]
Λ=m(q*)	Excited Quark (q*)	qg	[1.20,3.50]
	E_6 Diquark (D)	qq	[1.20,4.75]
	Axigluon (A)/Coloron (C)	$q\bar{q}$	[1.20,3.60] + [3.90,4.08]
tanθ=0.15	Color Octet Scalar (s8)	gg	[1.20,2.79]
	W′ Boson (W′) SSM	$q\bar{q}$	[1.20,2.29]
	Z′ Boson (Z′) SSM	$q\bar{q}$	[1.20,1.68]
k/M$_{Pl}$=0.1	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

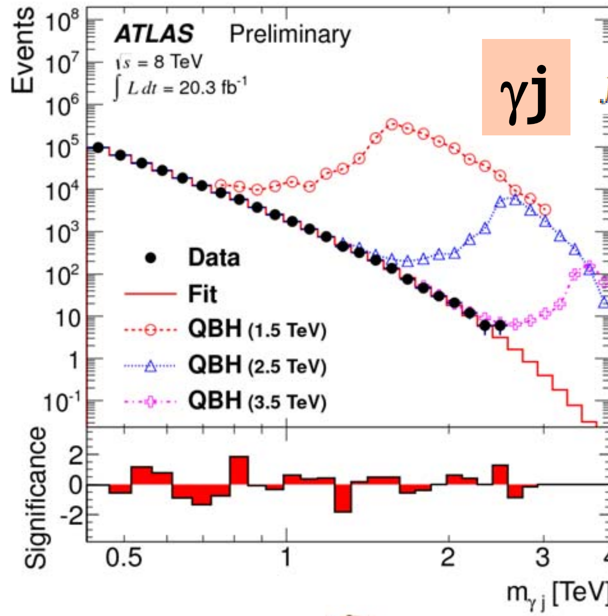
$f_s = f = f' = 1$

Detour: jet plus photon

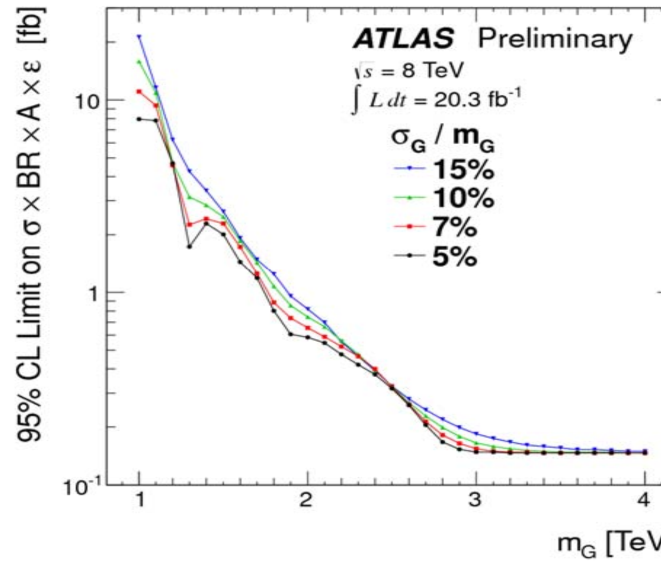


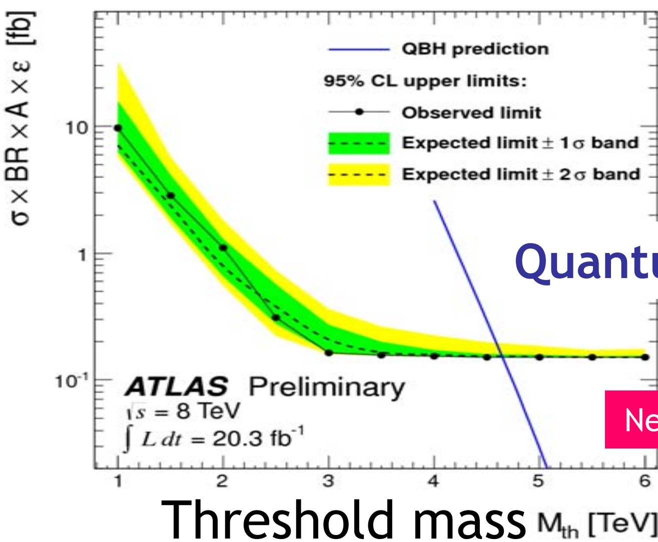
[ATLAS, arXiv:1309.3230]

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



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





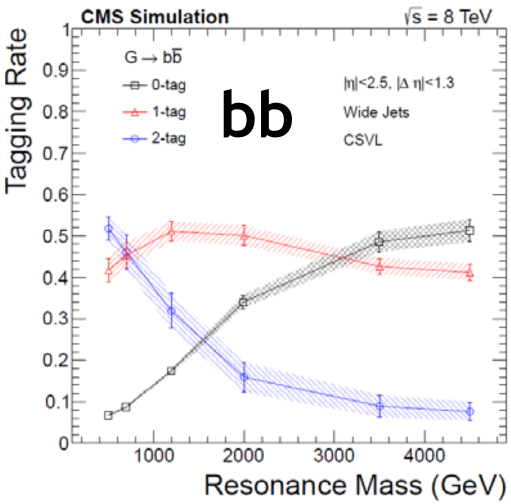
Model	Observed mass exclusion [TeV]
q* Λ=m(q*) $f_s = f = f' = 1$	[1.0,3.48]
QBH $n = 6$ and $M_D = M_{th}$	[1.0,4.65]

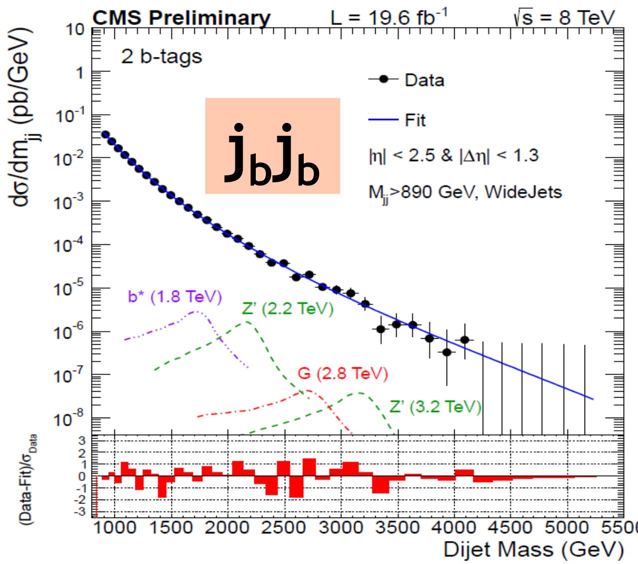
Dijets with b-tagging

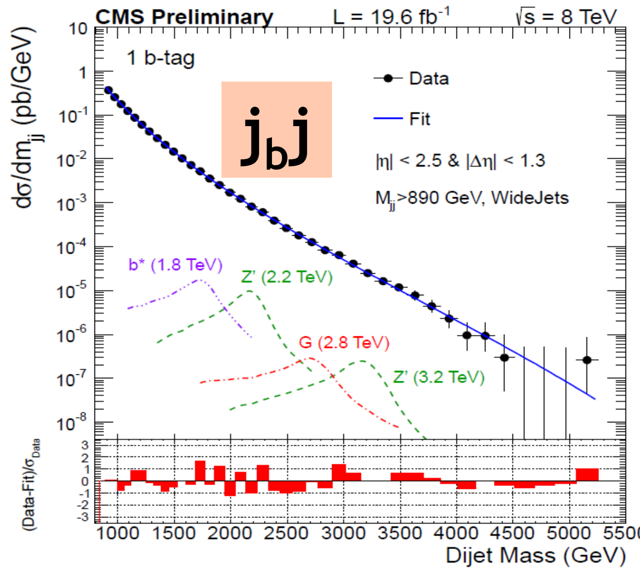
[CMS-EXO-12-023]

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

Tagging rates





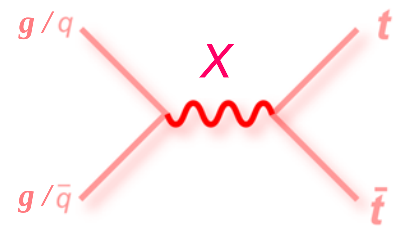


Model	Observed mass exclusions [TeV]
SSM Z' (f_{bb}=0.2)	[1.20 , 1.68]
RS G* ($k/\overline{M}_{Pl}$=0.1) (f_{bb}=0.1)	[1.42 , 1.57]
b*	[1.34 , 1.54]

See also CMS search for excited top pairs (see bonus slides)

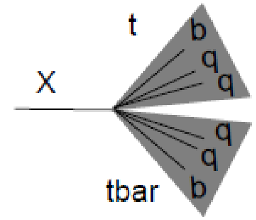
See also ATLAS' 7 TeV limits on b* →Wt, Phys. Lett. B 721 (2013) 171-189

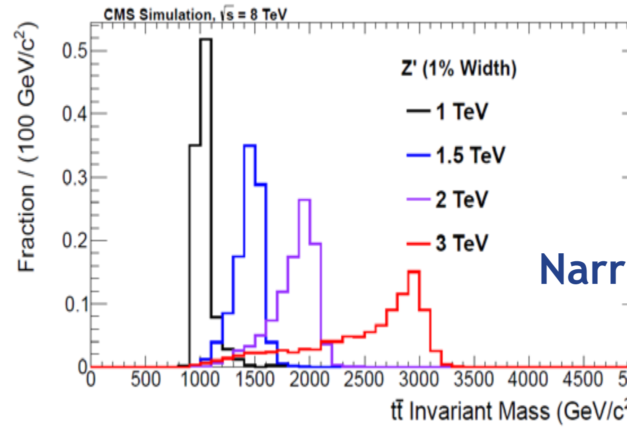
Dijets with top-tagging



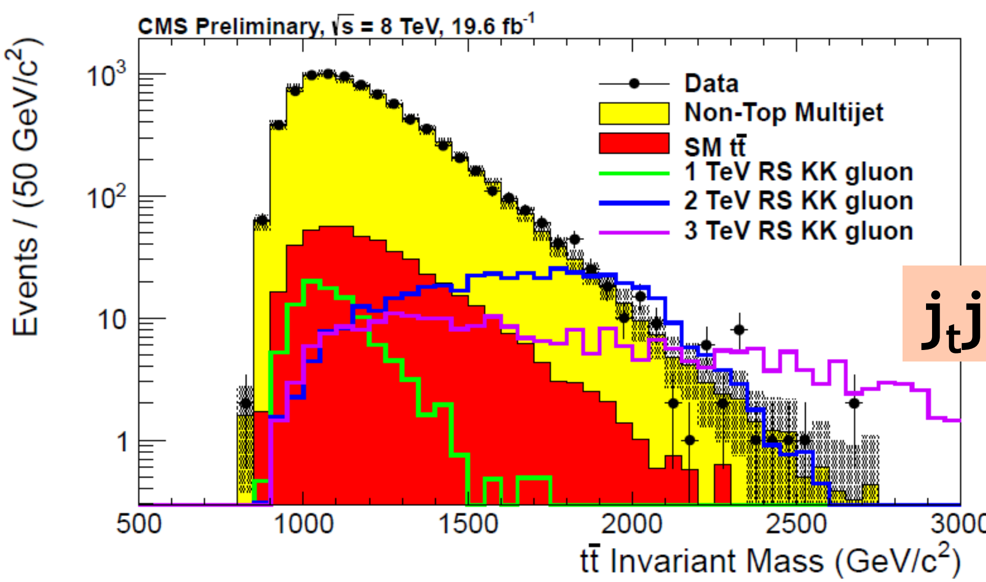
[CMS-B2G-12-005]

- All hadronic tt^{bar}
- Jets: Cambridge-Aachen R=0.8
- 2 leading jets Top-Tagged
- $|\Delta y|<1.0$





Narrow Z'



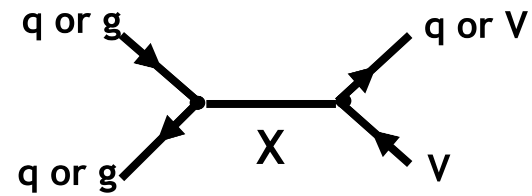
$j_t j_t$

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]

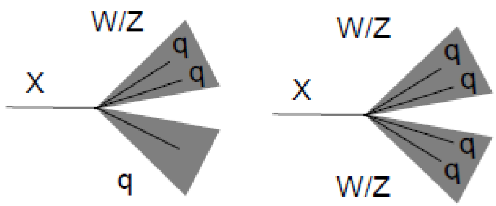
- Data driven multijet background

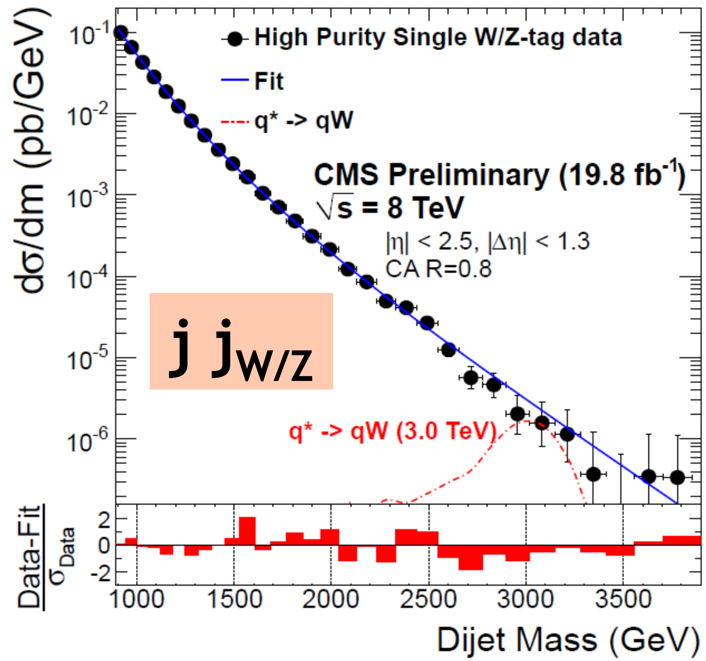
$BR(g_{KK} \rightarrow tt^{bar})>90\%$, $\Gamma/M\sim15\%$

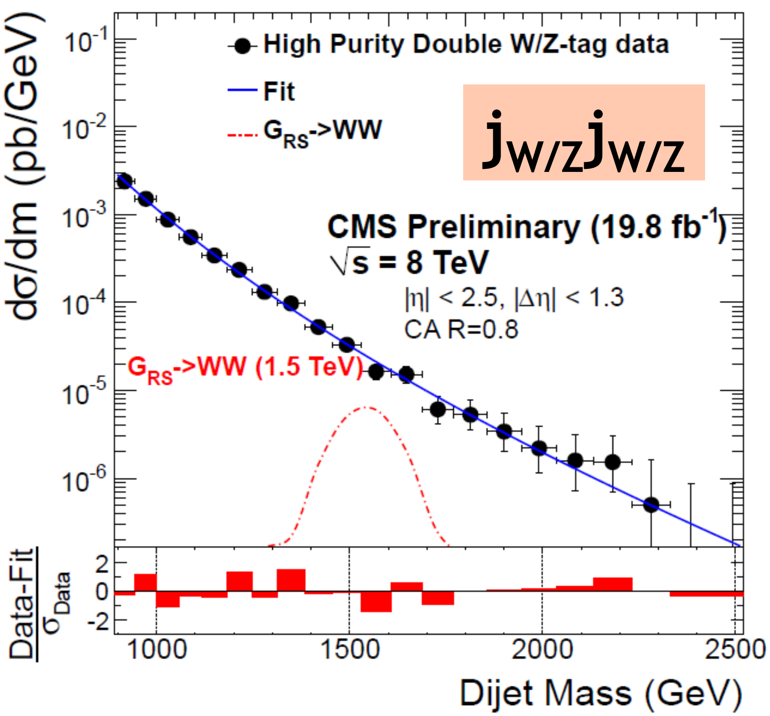
Dijets with W/Z-tagging



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







[CMS-EXO-12-024]

$(k/\overline{M}_{Pl}=0.1)$

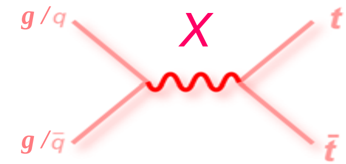
Model	Observed mass exclusions [TeV]
$q^* \to qW$	[1.0 , 3.23]
$\to qZ$	[1.0 , 3.00]
SSM W' $\to$ WZ	[1.0 , 1.73]
RS G* $\to$ WW	[1.0 , 1.59]
$\to$ ZZ	[1.0 , 1.17]

Singly produced resonances

- dileptons (ee, $\mu\mu$, $\tau\tau$)
- lepton plus missing E_T
- dijets (un-, b-, top-, W/Z-tagged)
- more t t^{bar} (semileptonic)
- more dibosons (all leptonic WZ)

Semileptonic $t\bar{t}$

[ATLAS-CONF-2013-052] [CMS-B2G-12-006]



- 2 analyses

➔ low/high mass coverage

transition at ~1 TeV

Resolved/threshold

≈ standard

Boosted

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

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]

also leptonic tb^{bar}: W'$_R$ (see bonus slides)

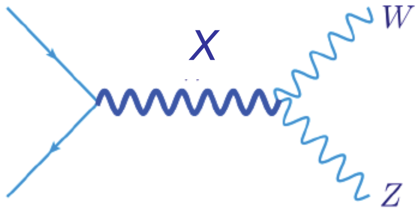
Singly produced resonances

- dileptons (ee, μμ, ττ)
- lepton plus missing E_T
- dijets (un-, b-, top-, W/Z-tagged)
- more t t^{bar} (semileptonic)
- more dibosons (all leptonic WZ)

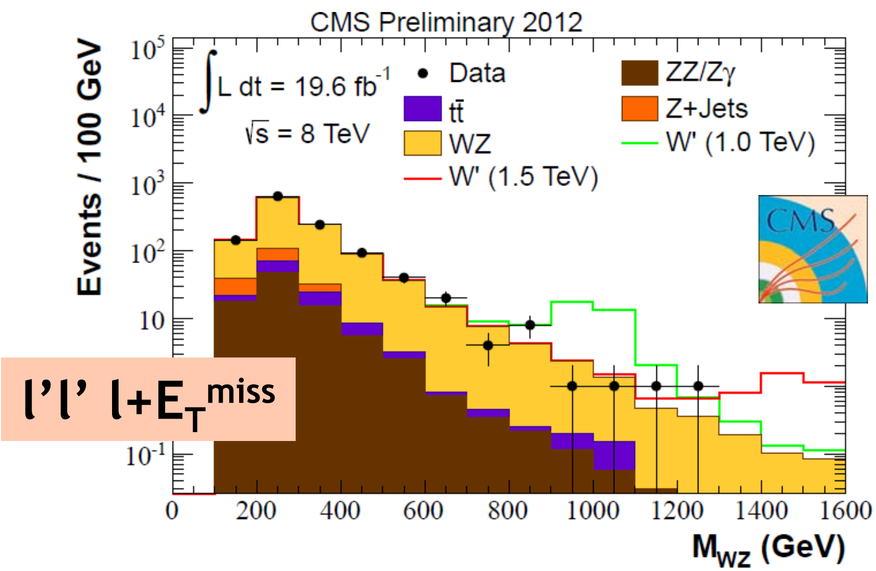
All leptonic WZ

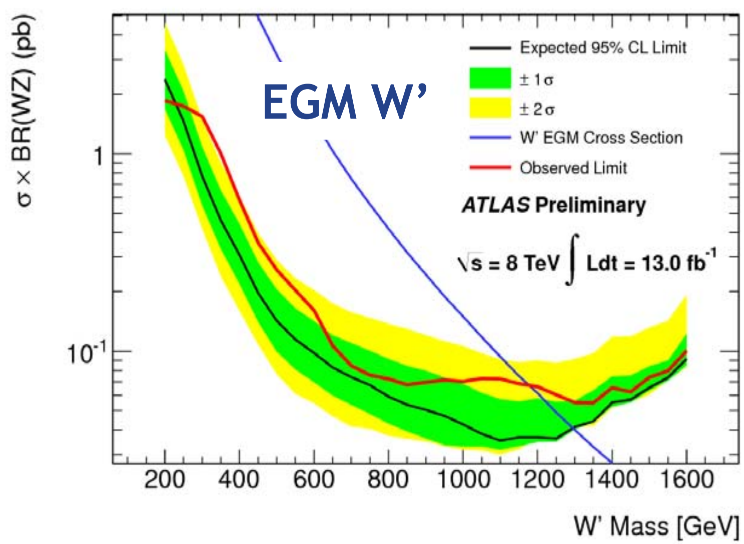
[CMS-EXO-12-025]

[ATLAS-CONF-2013-015]



- $l+E_T^{miss}$ and tb^{bar} analyses assumed BR(W'→WZ)=0
- lower threshold than (W/Z tagged) dijet analysis





Observed lower mass limits (TeV)

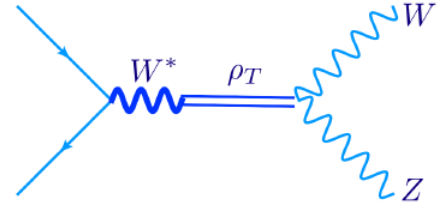
	ATLAS 13 fb^{-1}	CMS 20 fb^{-1}
SSM/EGM W'	1.18	1.45

also semileptonic ZZ and WW:
bulk RS G*
(see bonus slides)

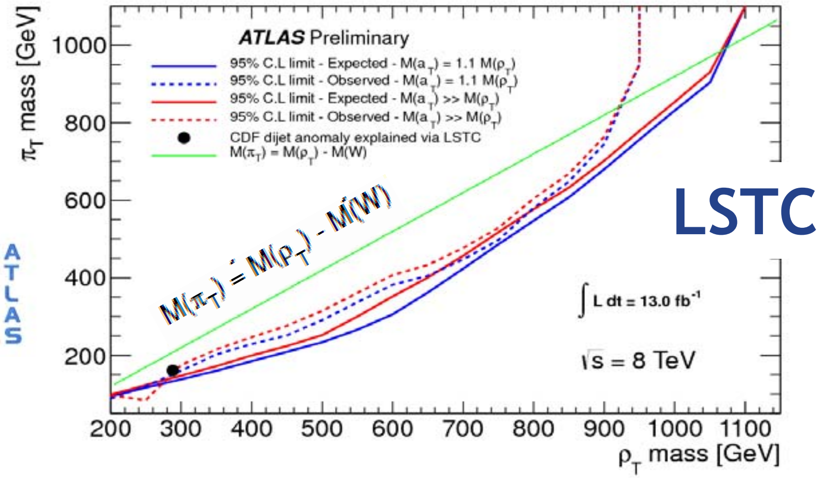
NEW

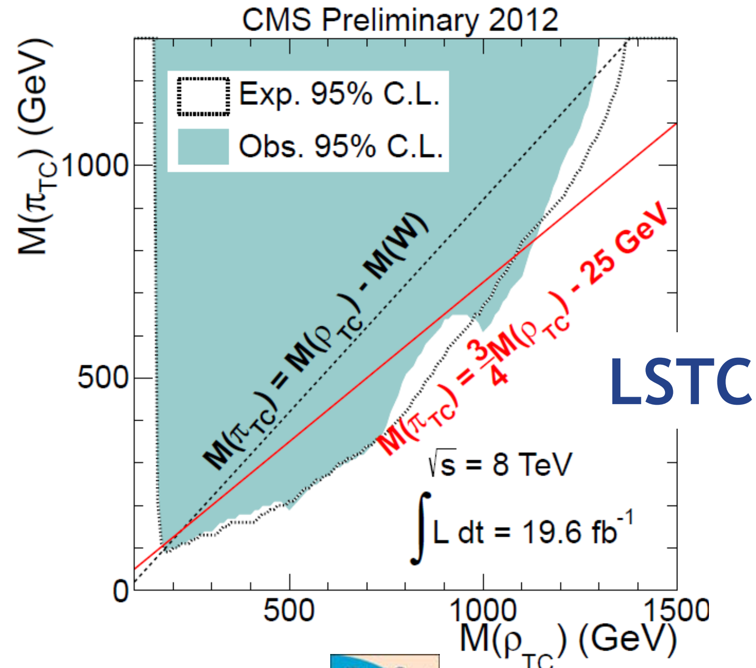
EGM= Extended Gauge Model BR(W'→WZ)=1-2%

All leptonic WZ



[ATLAS-CONF-2013-015]

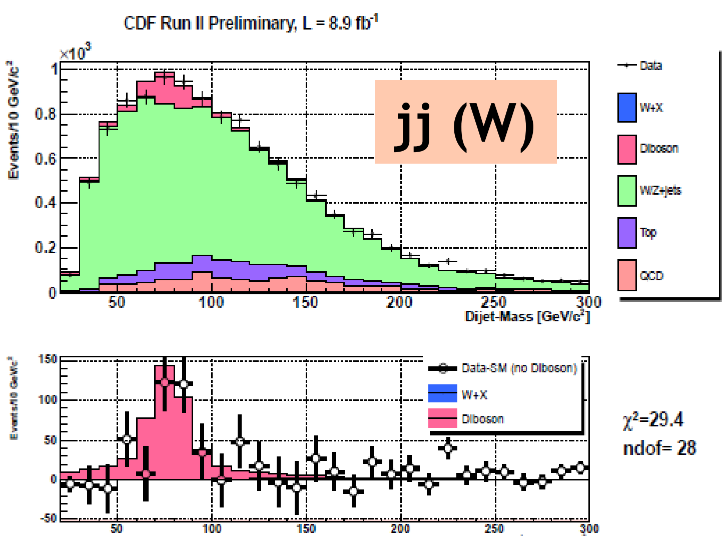




[CMS-EXO-12-025]

CDF 8.9 fb^{-1}

Full dataset!



[CDF Public Note 10973]

- The anomaly is gone

(see also dedicated dijet+W/Z search in bonus slides)

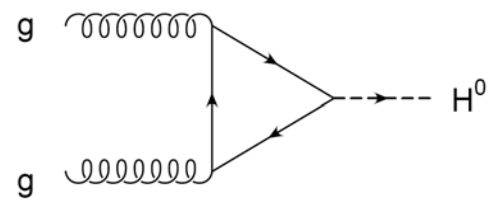
Pair produced resonances

- new heavy quarks

New heavy quarks

- 4th generation chiral quarks: $t' \rightarrow bW$, $b' \rightarrow tW$

  in bad shape…



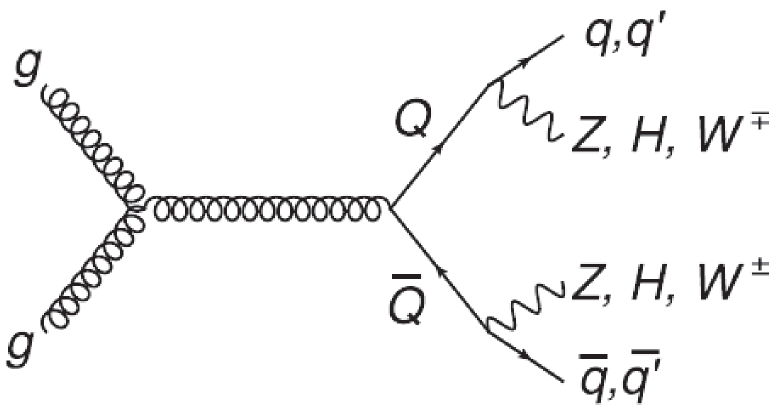
- Vector Like Quarks (VLQ) predicted in many models: E_6 GUT, UED (q_{KK}), little Higgs (with T-parity), composite Higgs (TC),…
- VLQ have more decays: $Q \rightarrow Hq$, $Q \rightarrow Zq$ (FCNC)
  - m(H)=125 GeV ➔ known BR
- VLQ generally assumed to couple to third generation

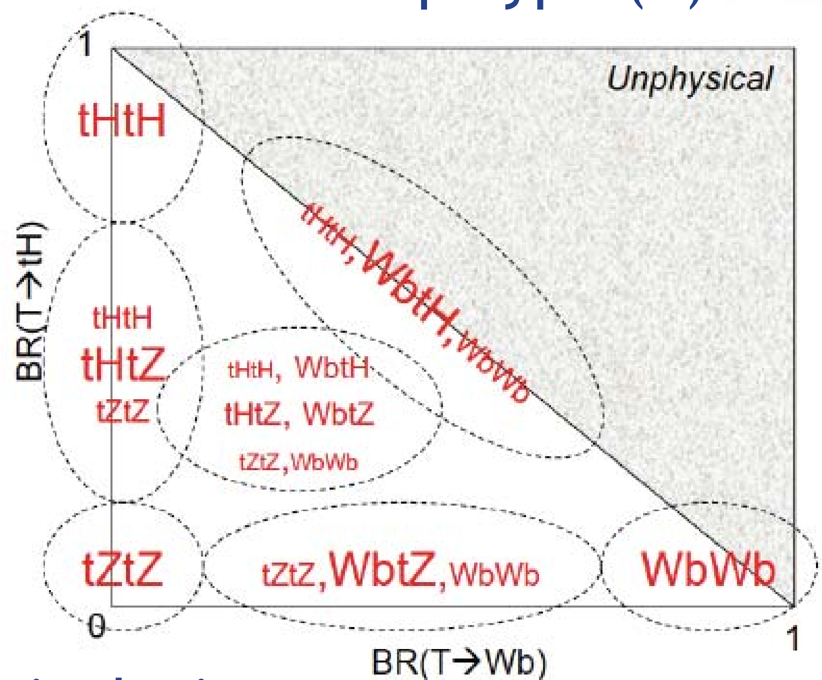
$$BR(Q \rightarrow Wq') + BR(Q \rightarrow Zq) + BR(Q \rightarrow Hq) = 1$$

Vector Like Quarks

- so far mostly searched in pair production

ex. up-type (T):

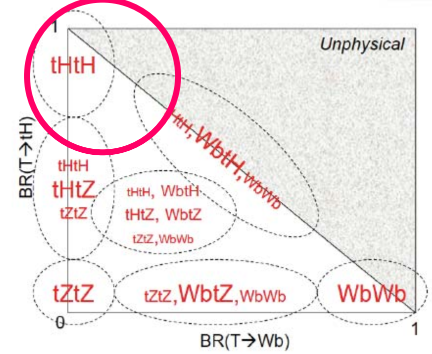




- many combinations
- two possible paths: dedicated or inclusive

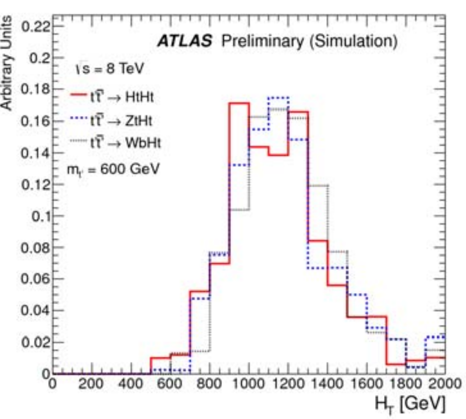
TT → Ht+X

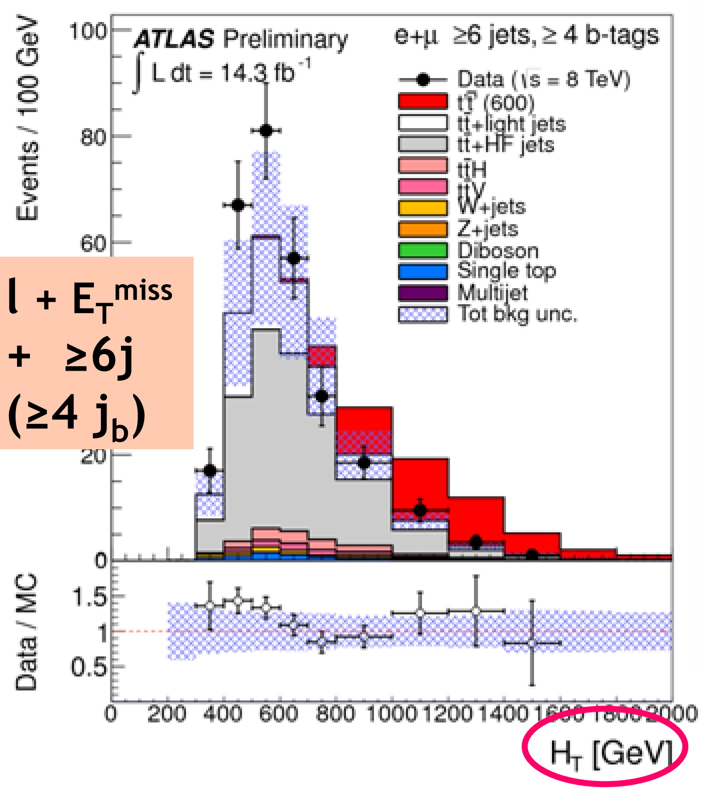
[ATLAS-CONF-2013-018]



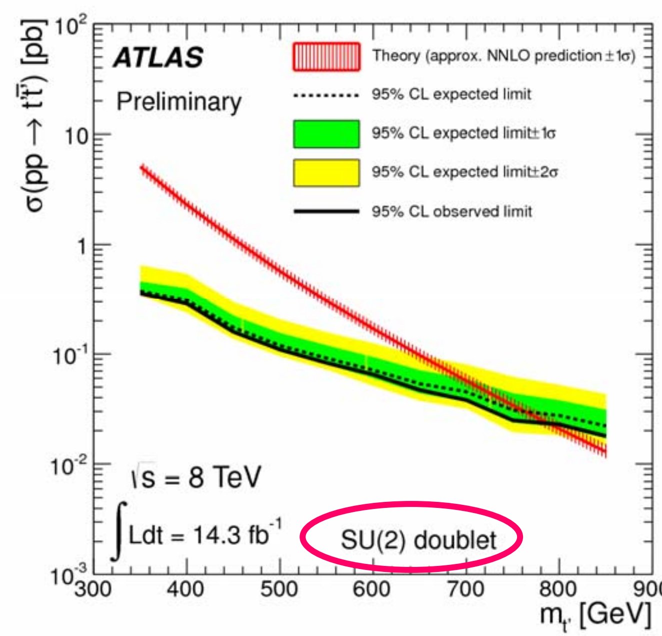
14 fb^{-1}

- at least one H→bb ➔ bbWb+X (X→≥1 b, at least one W →lν)
- main background: tt^{bar}+jets
- $H_T = \Sigma |p_T|$ (l + E_T^{miss} + all j)

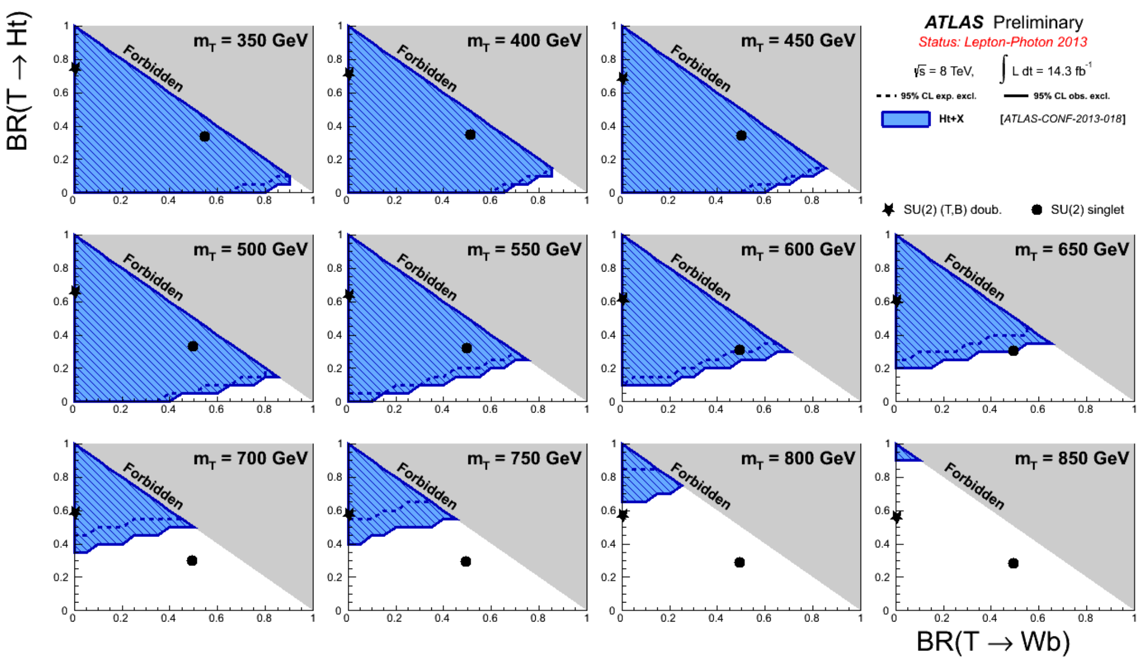




l + E_T^{miss} + ≥6j (≥4 j_b)



TT

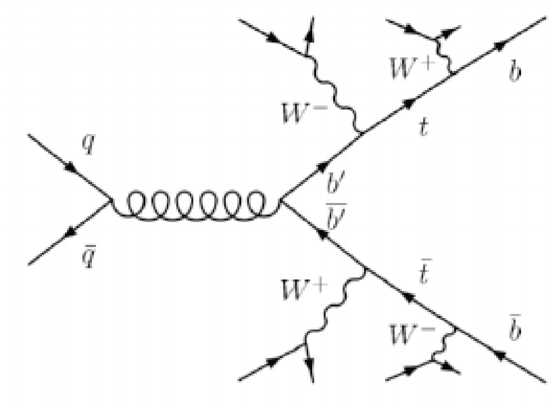

ATLAS Preliminary
Status: Lepton-Photon 2013
√s = 8 TeV, ∫ L dt = 14.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Ht+X
[ATLAS-CONF-2013-018]
SU(2) (T,B) doub.
SU(2) singlet
m_T = 350 GeV
m_T = 400 GeV
m_T = 450 GeV
m_T = 500 GeV
m_T = 550 GeV
m_T = 600 GeV
m_T = 650 GeV
m_T = 700 GeV
m_T = 750 GeV
m_T = 800 GeV
m_T = 850 GeV
Forbidden
BR(T → Ht)
BR(T → Wb)

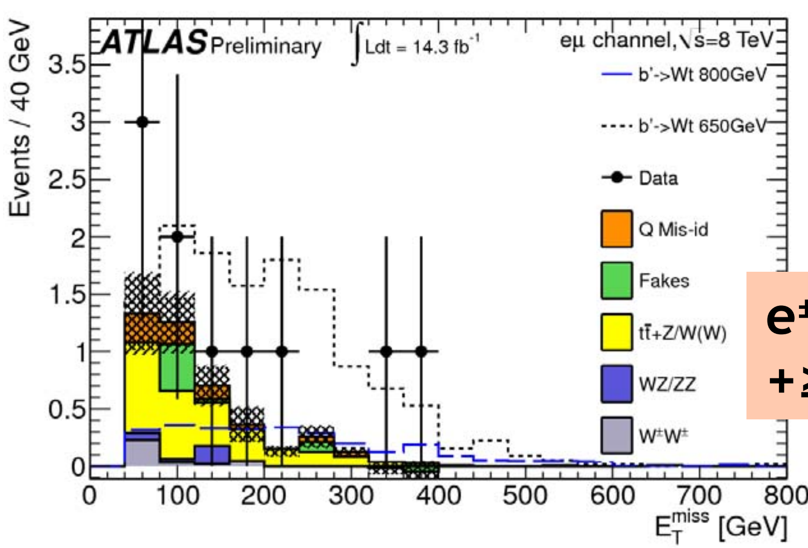
Inclusive BB, TT: same sign leptons

[ATLAS-CONF-2013-051]

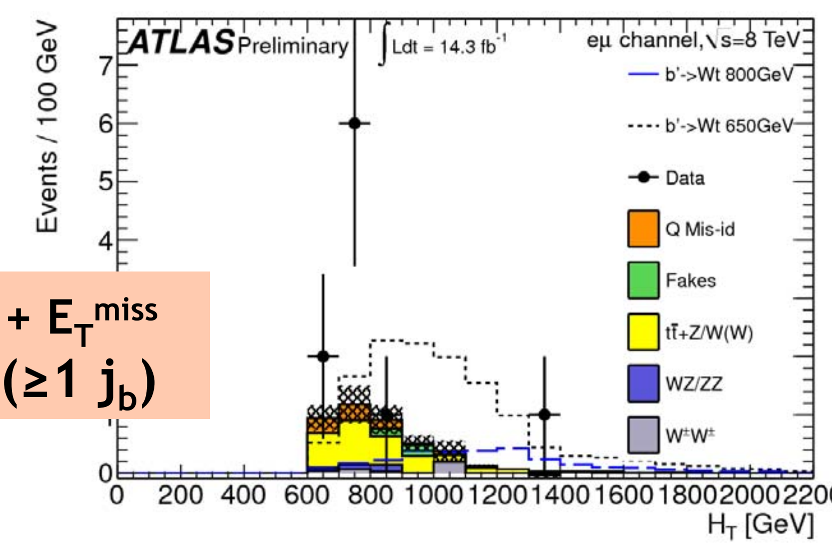
14 fb^{-1}

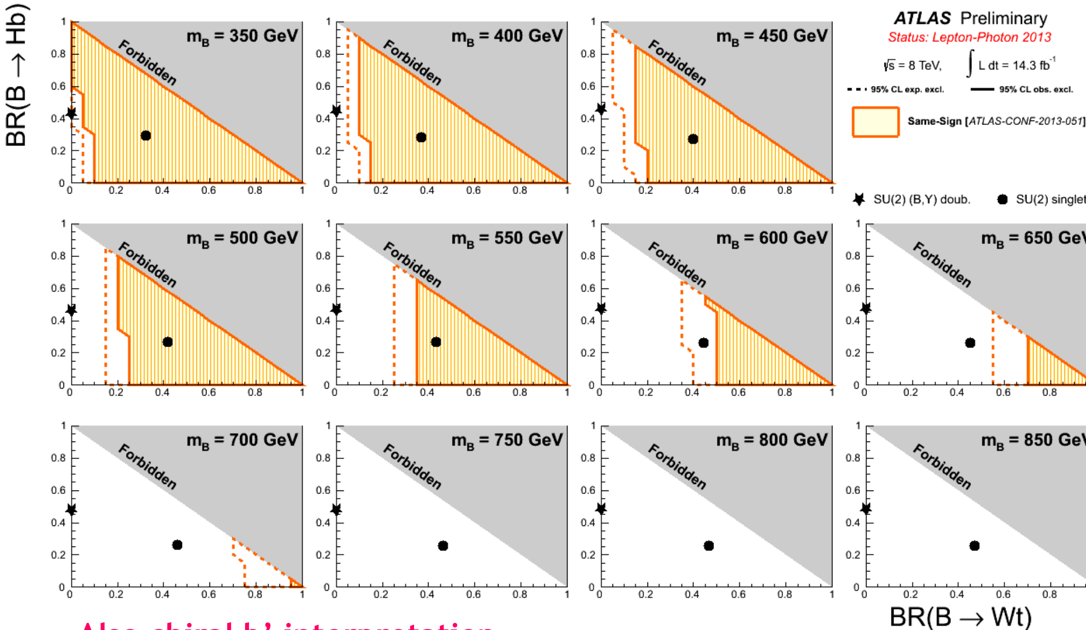
- 3 channels ee, eμ, $\mu\mu$
- main background: tt^{bar}+V
- $H_T = \Sigma\ |p_T|\ (l + E_T^{miss} + \text{all } j)$
- counting experiment





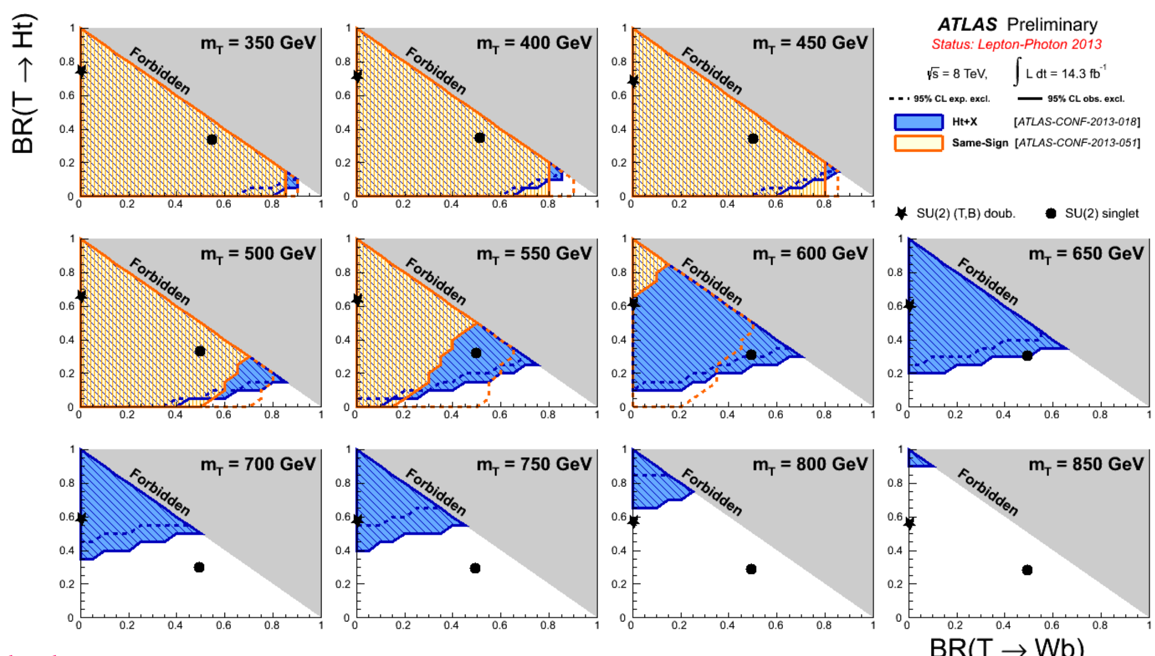
e$^\pm$ $\mu^\pm$ + E_T^{miss} +≥2j (≥1 j_b)





BB

Also chiral b' interpretation



TT

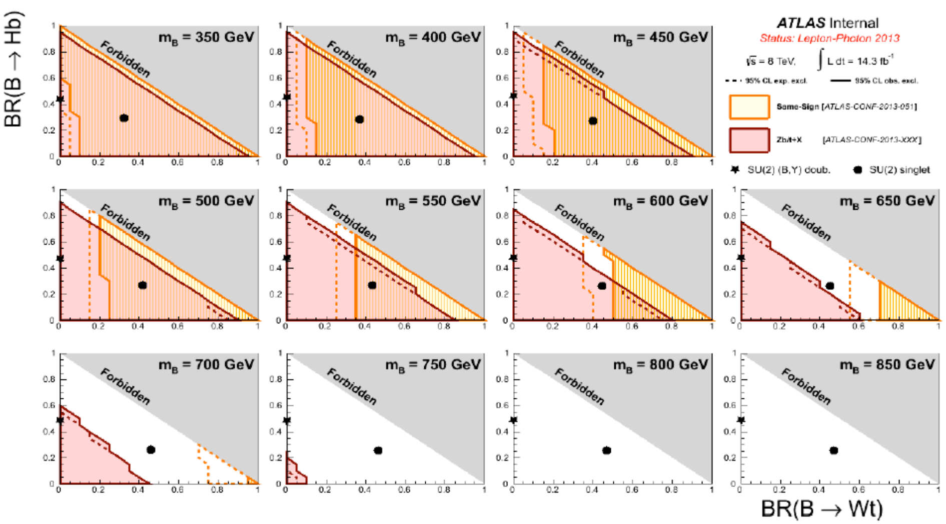
Another interpretation in $T_{5/3}T_{5/3}$ by CMS, see backup

BB, TT: the full picture

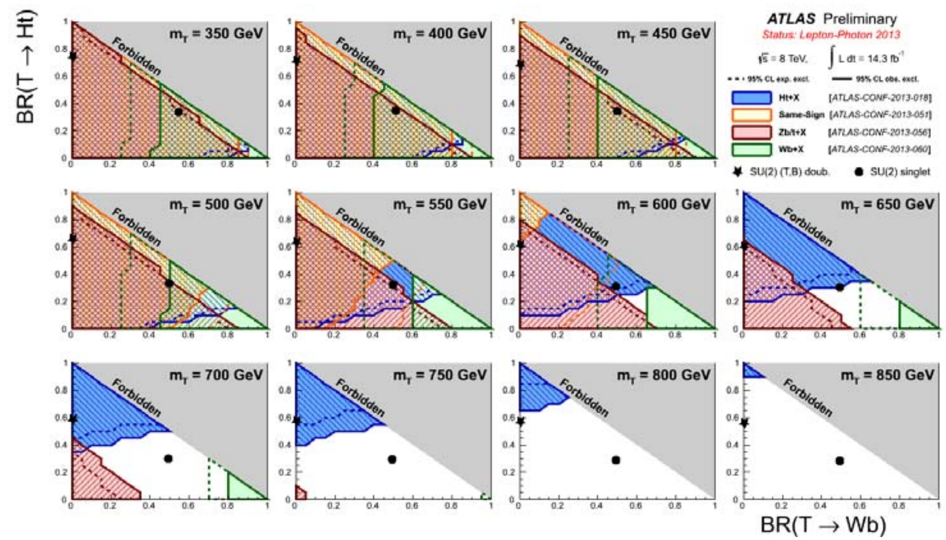
Two more analyses: BB, TT → Zb+X, Zt+X, TT → WbWb

(see backup)

BB



TT

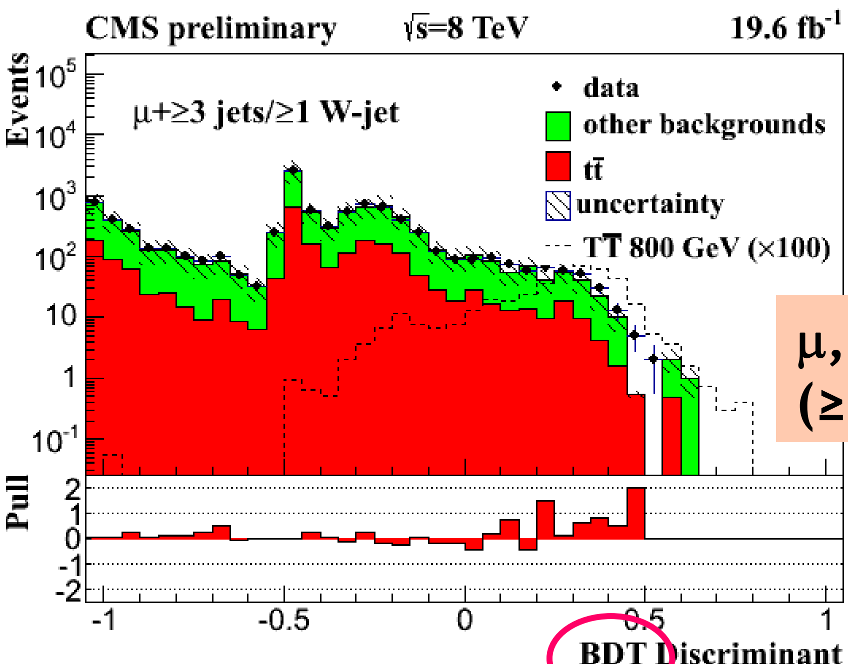


Combination will be more powerful than simple superimposition

Inclusive TT

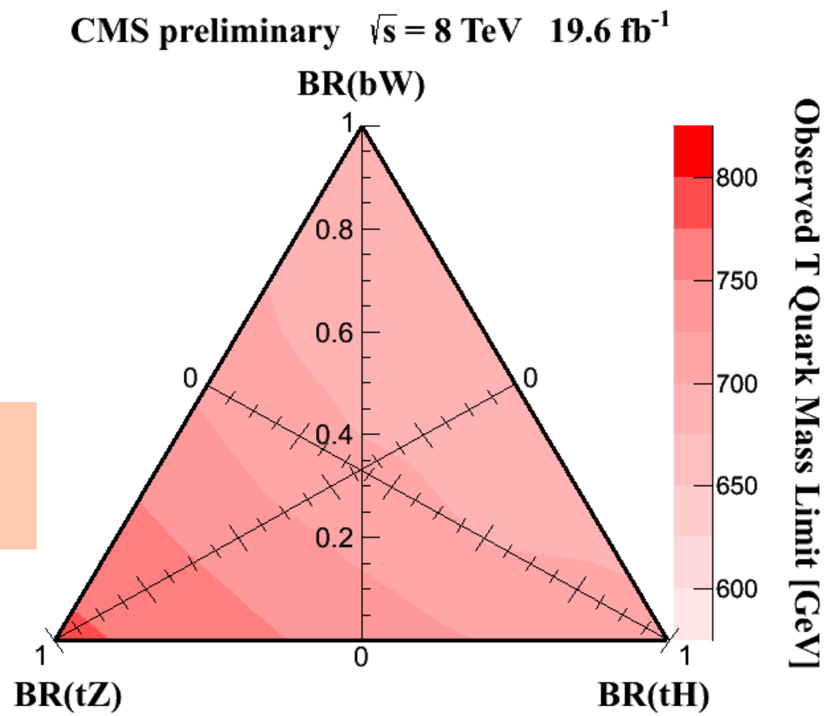
[CMS-B2G-12-015]

- $T \to bW$, tZ, tH ➔ TT: 6 combinations, bW on both sides
- 1 $W \to l\nu$, 1 $W \to qq$ (boosted or not)
- jets: 2 clustering algorithms ➔
  - anti-k_T R=0.5
  - Cambridge-Aachen R=0.8
- $l + E_T^{miss} + \geq 4j$ or ≥ 3 j (≥ 1 j_W)
- also 2l (with ≥ 1 j_b) and 3l channels



μ, ≥ 3 j
(≥1 j_W)

jet mult., b-tag mult., H_T, E_T^{miss}, lepton p_T, p_T(3rd and 4th j)

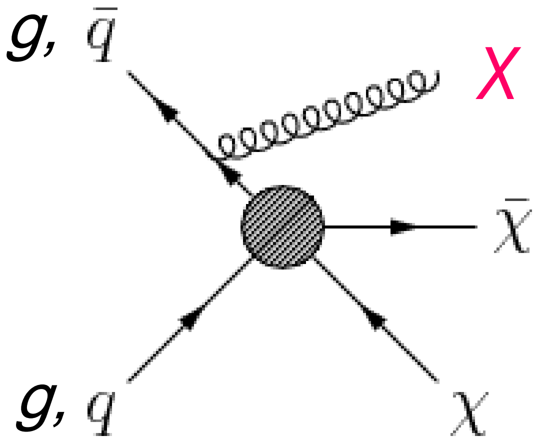


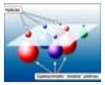
also inclusive BB analysis (see bonus slides)

Other signatures

- mono-jets, mono-W
- black holes

Mono-X



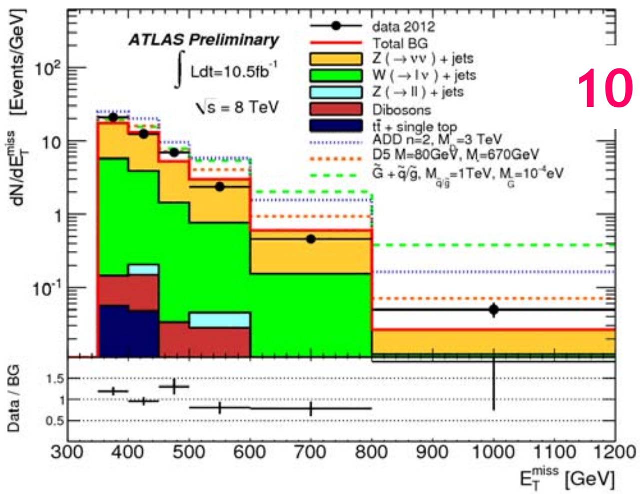


- X = gluon, photon, W, Z, …
- many interpretations
  - supersymmetry
  - large extra-dimensions (ADD): $\chi\chi^{bar}$=G*
  - Dark Matter: χ = Weakly Interacting Massive Particle (WIMP)
  - …
- main backgrounds: Z$\rightarrow \nu\nu$, instrumental

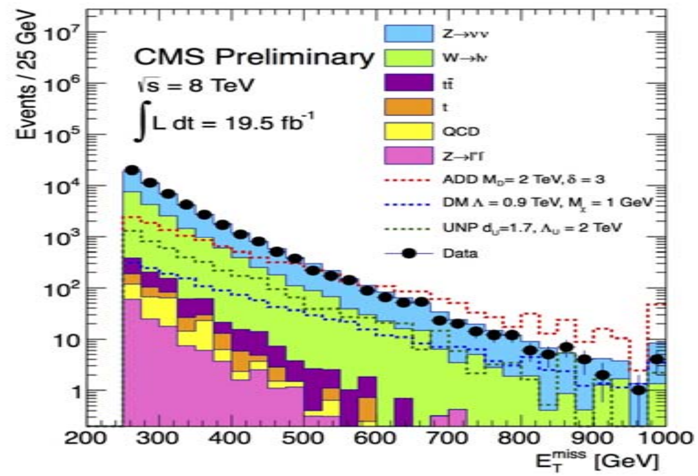
Mono-jet

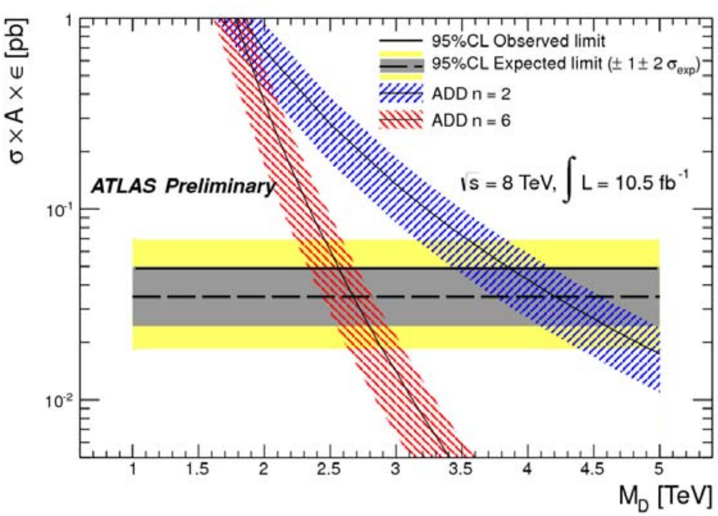
[ATLAS-CONF-2012-147] [CMS-EXO-12-048]

- Jet: anti-k_T R = 0.4 (ATLAS), 0.5 (CMS)
- E_T^{miss} > 350 GeV (ATLAS), 400 GeV (CMS)



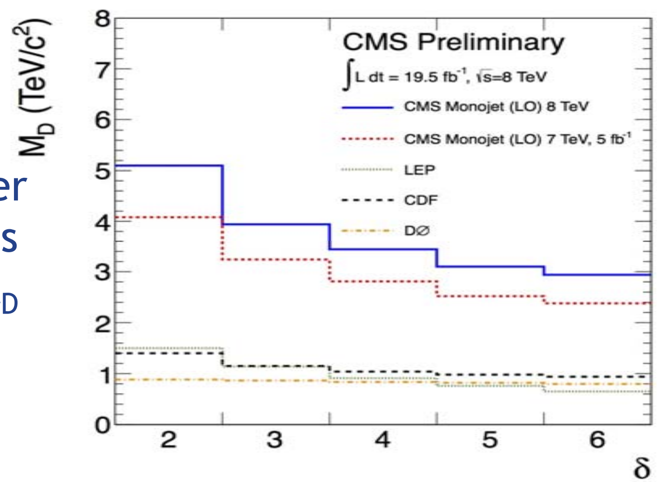
10 fb^{-1}





ADD

Lower limits on M_D



number of extra-dim.

also **Unparticle** interpretation

Mono-jet

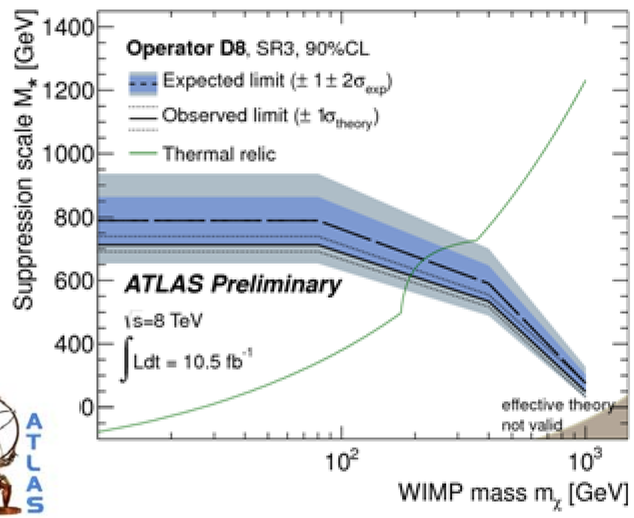
- Dark Matter interpretation (Dirac fermion)

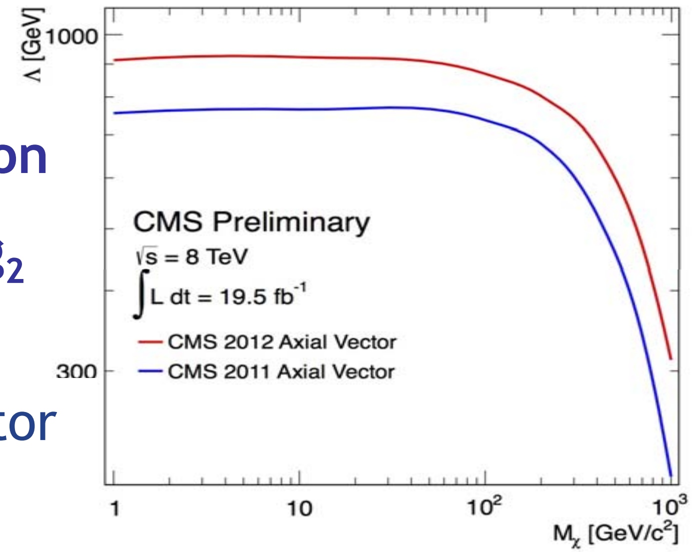
[ATLAS-CONF-2012-147]

10 fb^{-1}

[J. Goodman et al., arXiv:1008.1783]

[CMS-EXO-12-048]

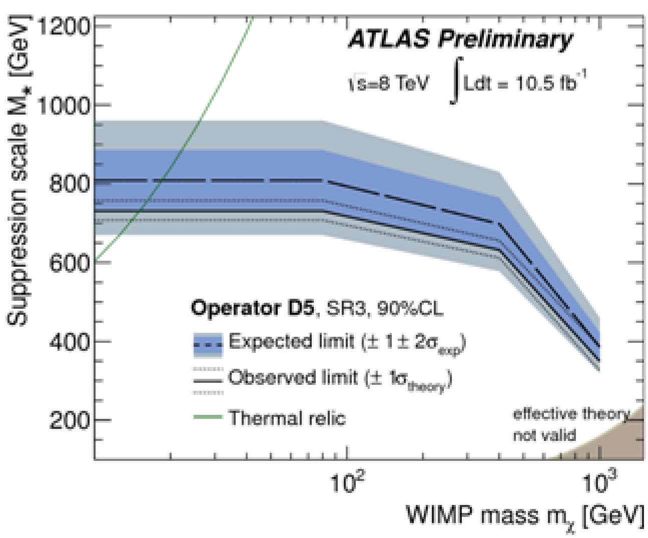


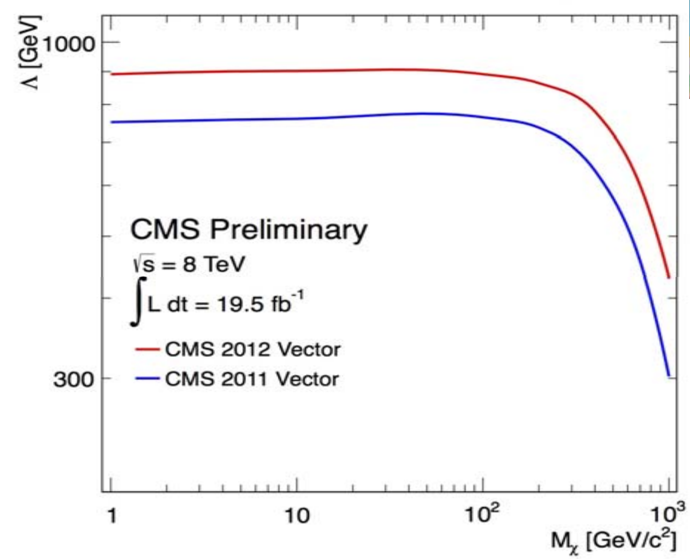


Lower limits on

$M^*=\Lambda=M/\sqrt{g_1\, g_2}$

D8 ≡ axial vector



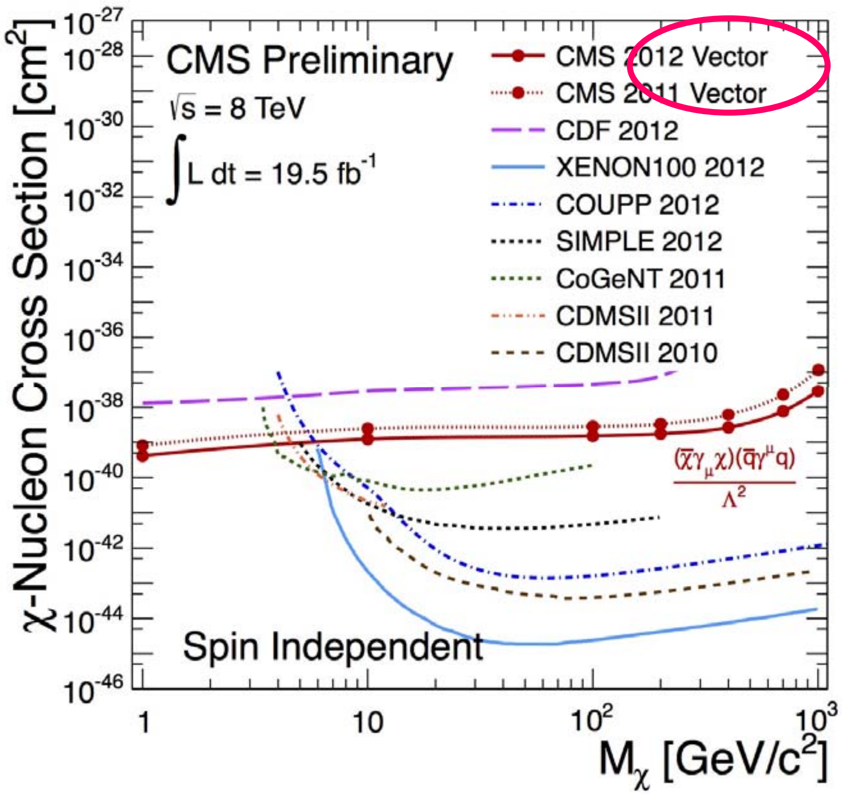


D5 ≡ vector

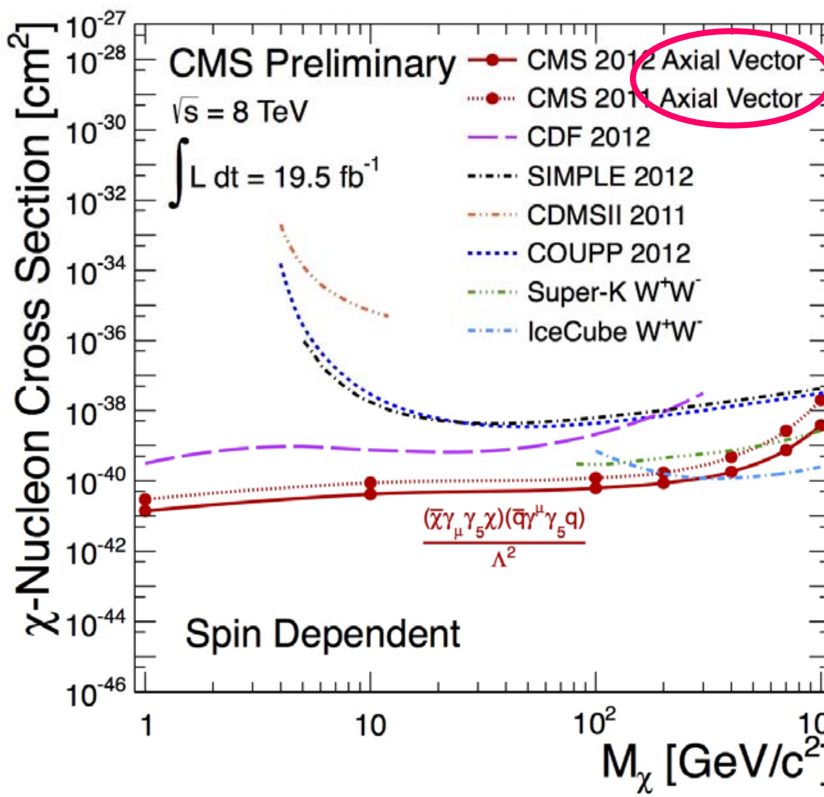
Mono-jet

[CMS-EXO-12-048]

- Dark Matter interpretation:
  upper limits on WIMP-nucleon cross sections

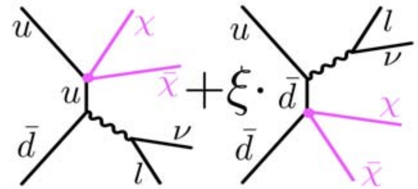


(D5)



(D8)

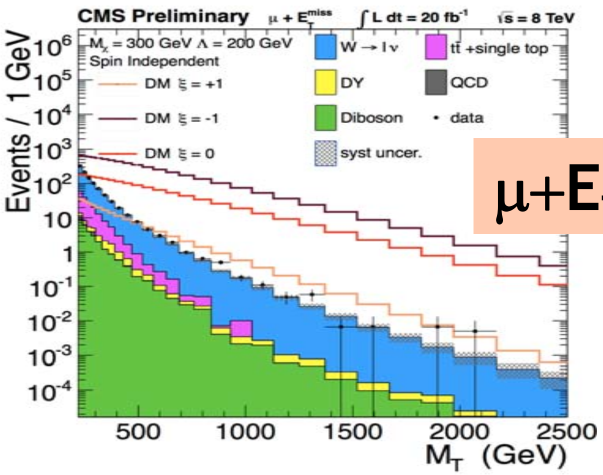
Mono-W



[ATLAS-CONF-2013-073]

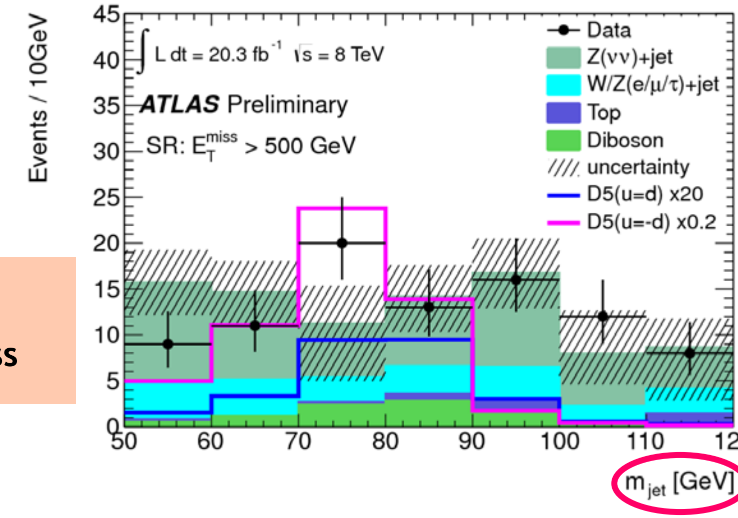
- $W \to l\ \nu$ [CMS-EXO-13-004]
- W' re-interpretation

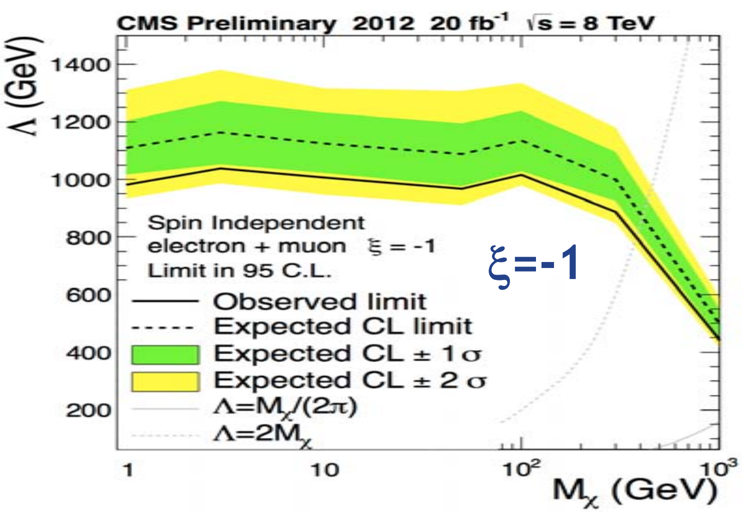
- $W \to qq$, $Z \to qq$
- jets: CA R= 1.2



$\mu+E_T^{miss}$

$J + E_T^{miss}$





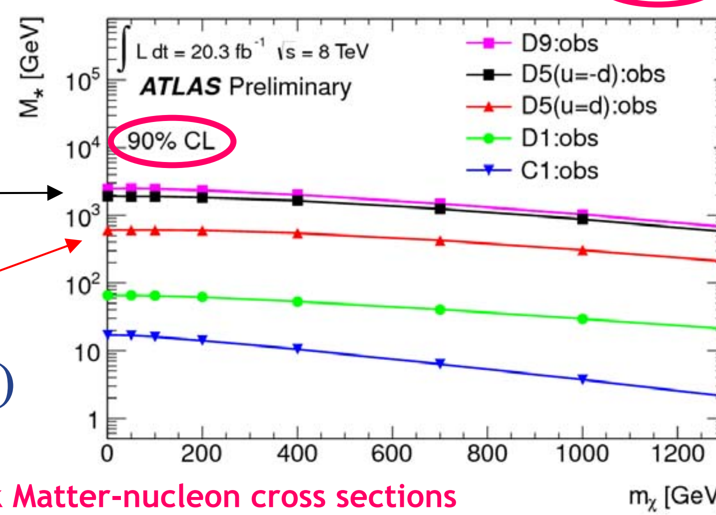
ξ=-1

interference

ξ=-1

ξ=+1

vector (≡ D5)

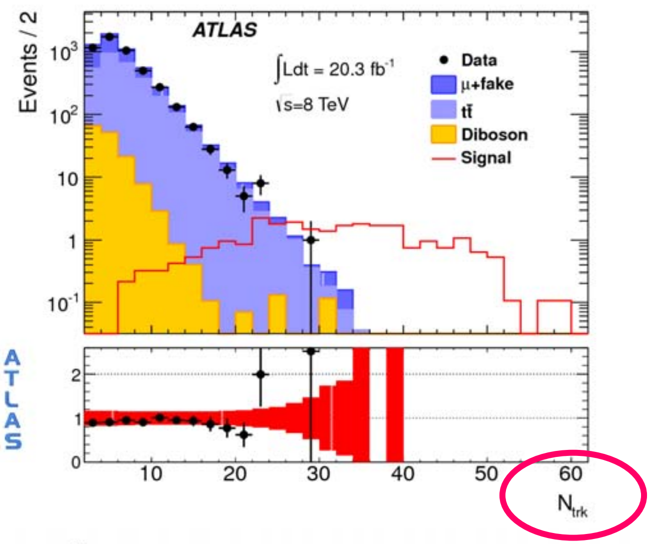


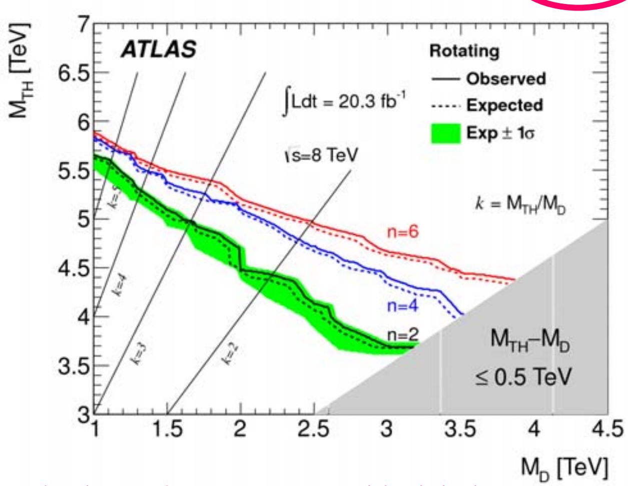
Also limits on Dark Matter-nucleon cross sections

Black Holes

[ATLAS arXiv:1308.4075] [CMS JHEP07(2013)178]

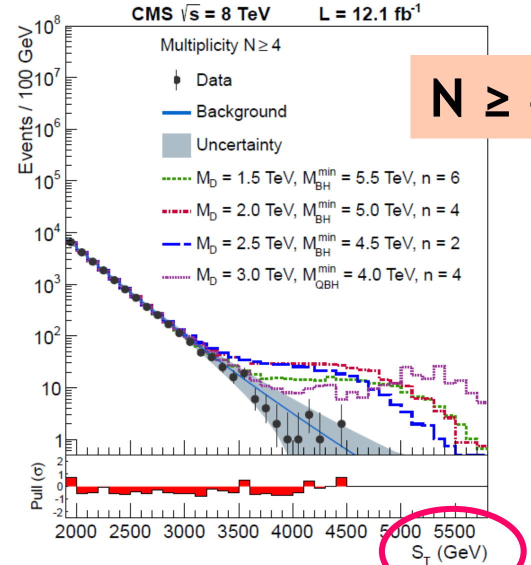
- at least 2 same charge muons
- track multiplicity ≥ 30





Similar limits for non rotating black holes

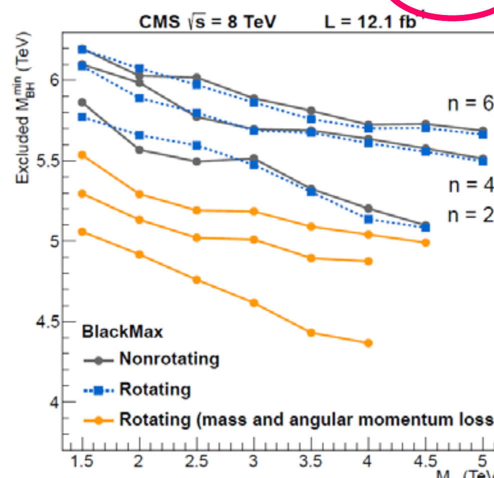
- at least 2 jets
- 10 multiplicity bins (up to ≥10)



$S_T = \Sigma\ |p_T|$
$(E_T^{miss}\ +j)$
above 50 GeV

12 fb^{-1}

Lower limits on production threshold



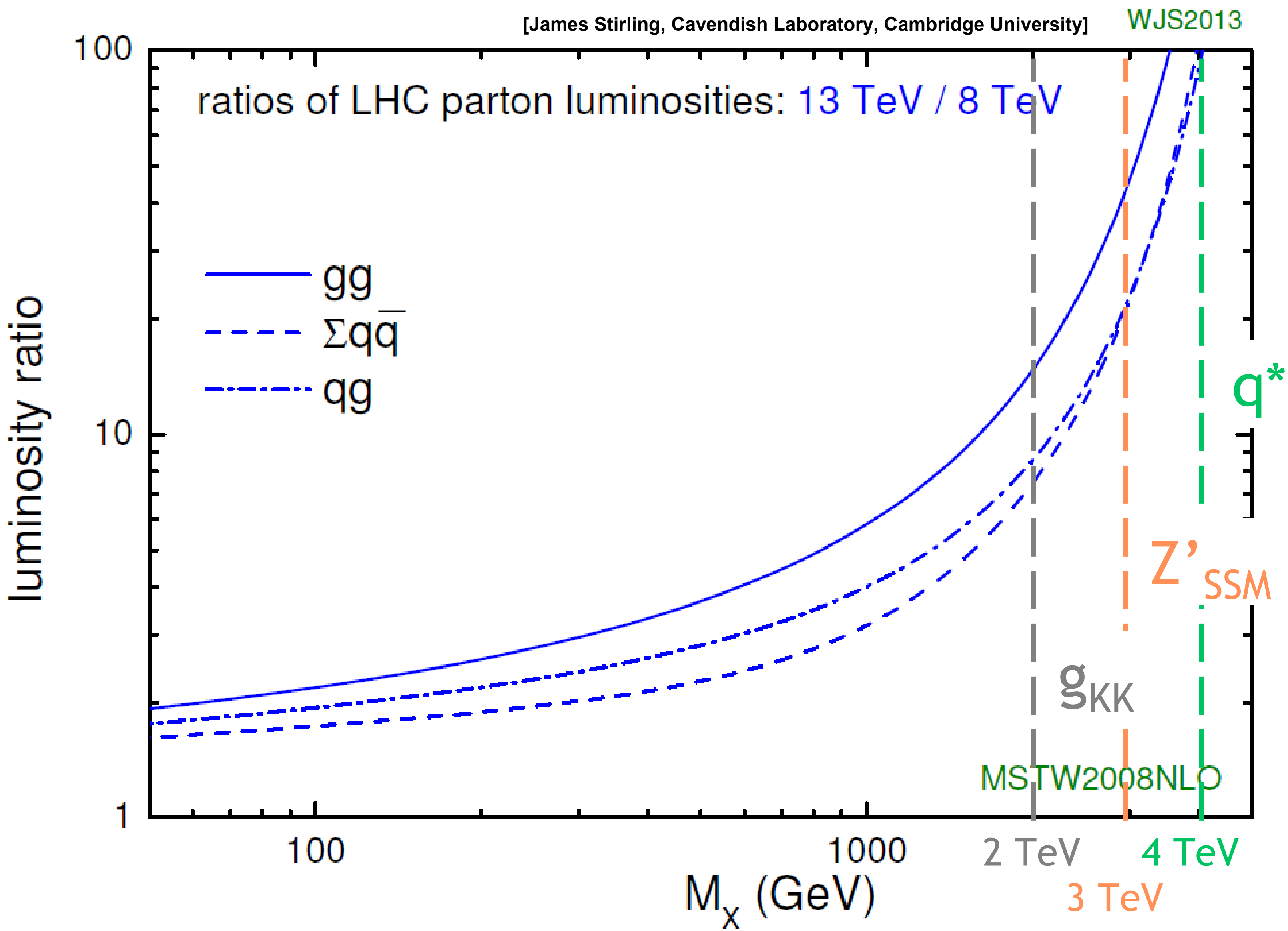
Also limits with Charybdis model

Also limits on QBH for N=2,3

Summary

- LHC 8 TeV data analysis now well developed, but no hint of new physics yet…
- Probing higher and higher masses
  - must continue probing low masses→ weak couplings
- More model-independent interpretations to come
  - also think of combinations for dedicated models
- Tagging of boosted object established

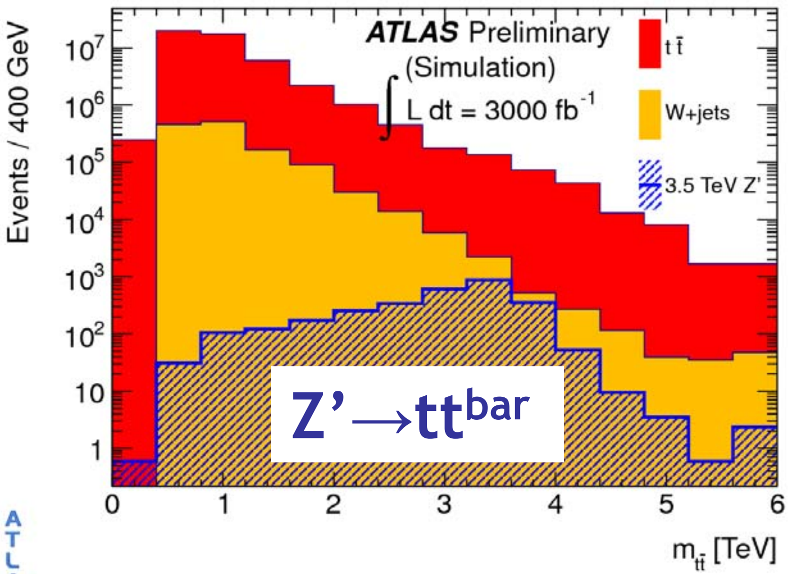
Outlook



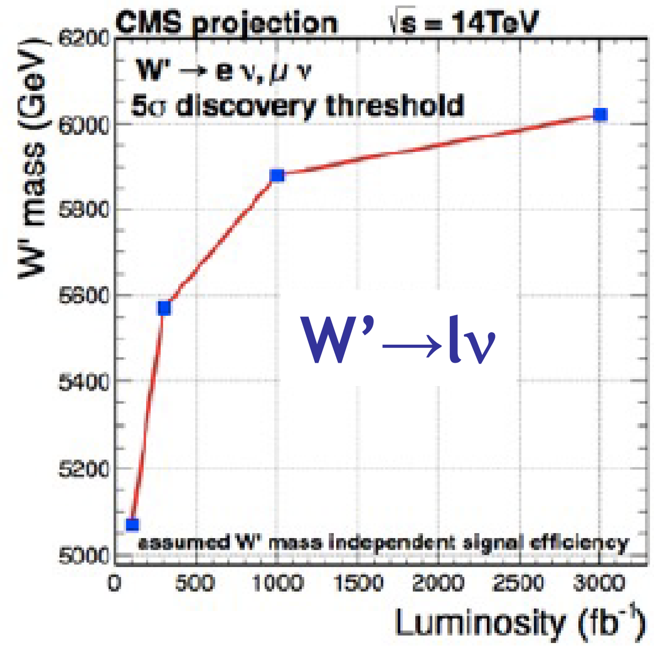
[James Stirling, Cavendish Laboratory, Cambridge University]
WJS2013
ratios of LHC parton luminosities: 13 TeV / 8 TeV
gg
Σqq̄
qg
luminosity ratio
100
10
1
100
1000
M_X (GeV)
MSTW2008NLO
q*
Z'$_{SSM}$
g$_{KK}$
2 TeV
3 TeV
4 TeV

Outlook

[ATLAS-CONF-2013-003]



[CMS: Markus Klute @ open LHCC, Sep 25, 2013]



model	$300\ \mathrm{fb}^{-1}$	$1000\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
$Z'_{\mathrm{Topcolour}}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)
$Z'_{SSM} \to ee$	6.5	7.2	7.8
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6

	Z'_{SSM} ee	Z'_{SSM} μμ
$300\ \mathrm{fb}^{-1}$	5.1 TeV	5.2 TeV
$3000\ \mathrm{fb}^{-1}$	6.2 TeV	6.4 TeV

more studies done at CSS2013 (Snowmass on the Mississippi), see bonus slides

Conclusion

Stay tuned!

Complete information:

- https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO
- https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsB2G

Bonus

Summaries

- 8 TeV limits by resonance

More signatures

- leptonic t b^bar
- semileptonic ZZ/WW
- dijet associated with W/Z
- lepton plus photon
- leptoquark pairs
- excited top pairs

More information

8 TeV limits

Black: 20 fb^{-1} Grey: 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	$l+E_T^{miss}$	jj	tb^{bar}	$WZ \rightarrow lll'\nu$	$WZ \rightarrow JJ$
	ATLAS			[0.5,1.84]	1.18	
	CMS	**3.35**	**[1.20,2.29]**	**[0.8,2.03]**	**1.45**	**[1.0,1.73]**

8 TeV limits

Black: 20 fb^{-1} Grey: 14 fb^{-1}

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

	Channel	jj	jγ	j_bj	qW → jJ	qZ → jJ
q* [TeV]	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: 14 fb^{-1}

RS1 G* $k/\overline{M}_{Pl}=0.1$ [TeV]	Channel	dilepton	dijet	$j_b j_b$	$WW \rightarrow JJ$	$ZZ \rightarrow JJ$
	ATLAS	2.47				
	CMS		[1.20,1.58]	[1.42,1.57]	[1.0,1.59]	[1.0,1.17]

Bulk RS G* [TeV]	Channel	semilept. WW	semilept. ZZ
	ATLAS		[0.35,0.71] $k/\overline{M}_{Pl}=1.0$
	CMS	-	[0.6,0.85] $k/\overline{M}_{Pl}=0.5$

Bulk RS g_{KK} [TeV]	Channel	semilept. tt^{bar}	hadronic tt^{bar}
	ATLAS	[0.5,2.0] $k/\overline{M}_{Pl}=1.0$	
	CMS	[0.7,2.54]	[1.0,1.8]

Bonus

Summaries

- 8 TeV limits by resonance

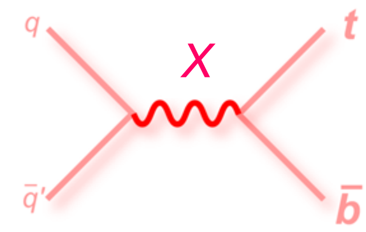
More signatures

- leptonic t b^{bar}
- semileptonic ZZ/WW
- dijet associated with W/Z
- lepton plus photon
- leptoquark pairs
- excited top pairs

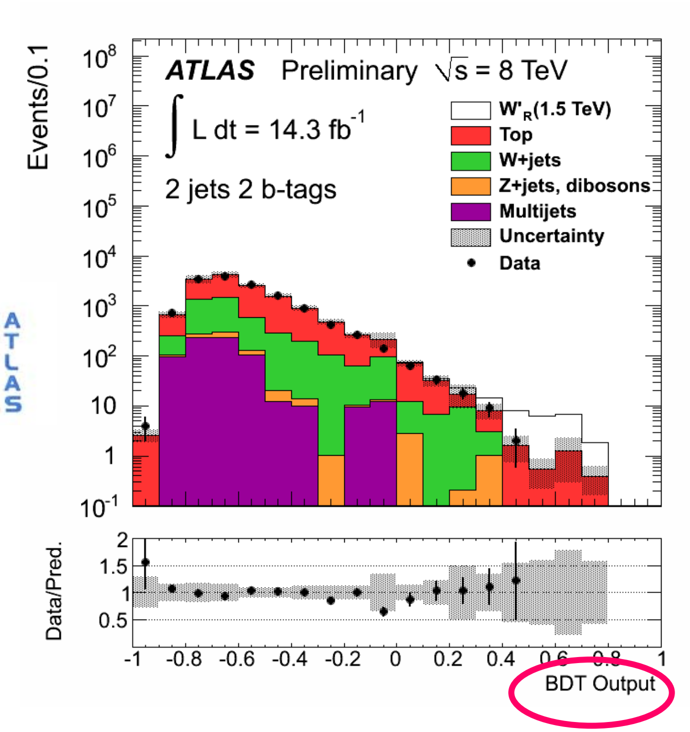
More information

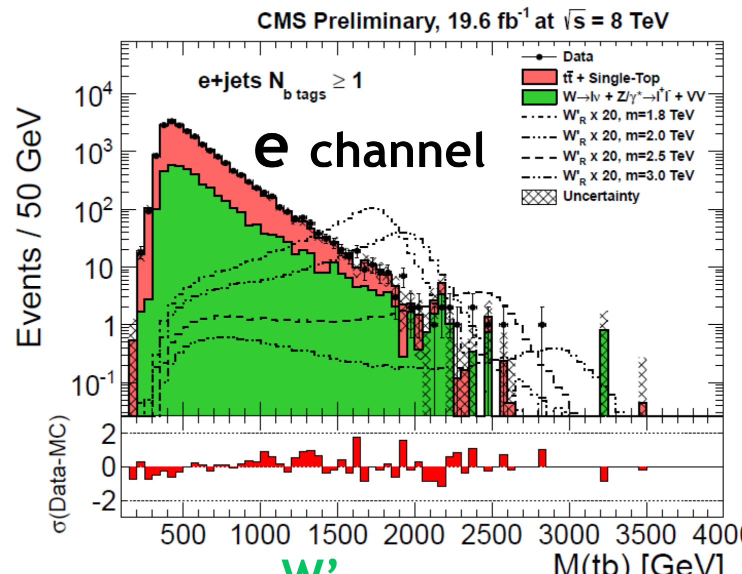
Leptonic $t\bar{b}$

[ATLAS-CONF-2013-050] [CMS-B2G-12-010]

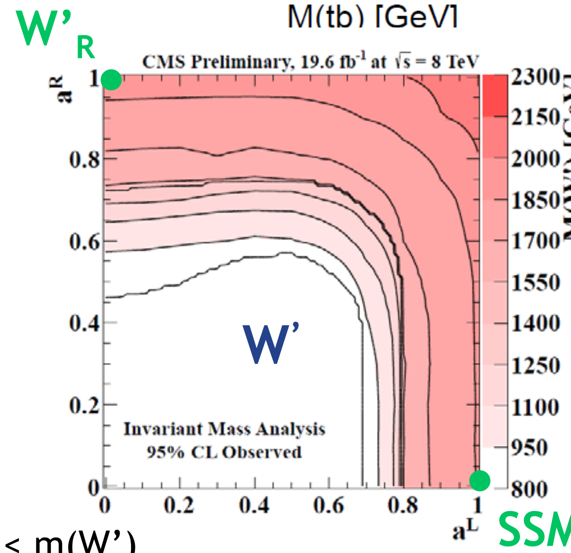


- $W'_R \rightarrow l\nu$ suppressed if ν_R heavy
- better mass reconstruction





l + E_T^{miss} +
≥2 j (≥1 j_b)

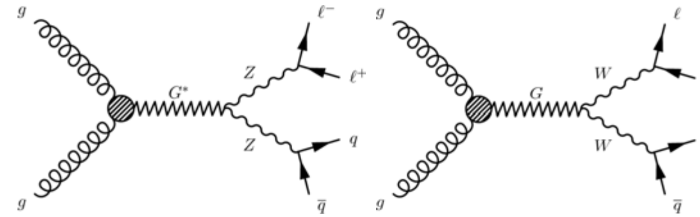


Observed mass exclusions (TeV)

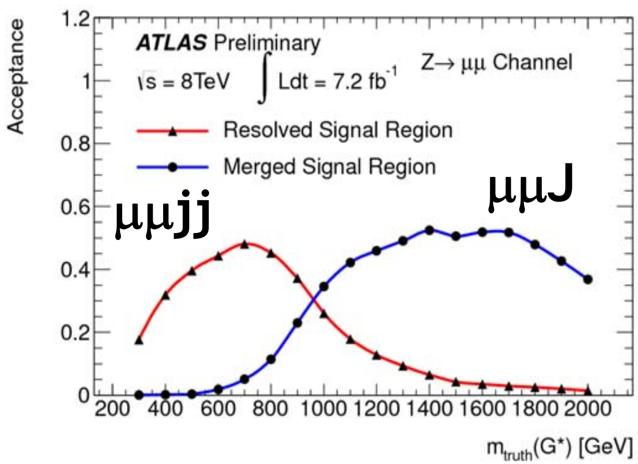
Model	CMS 20 fb^{-1}	ATLAS 14 fb^{-1}
W'_R	[0.8,2.03]	[0.5,1.84]

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

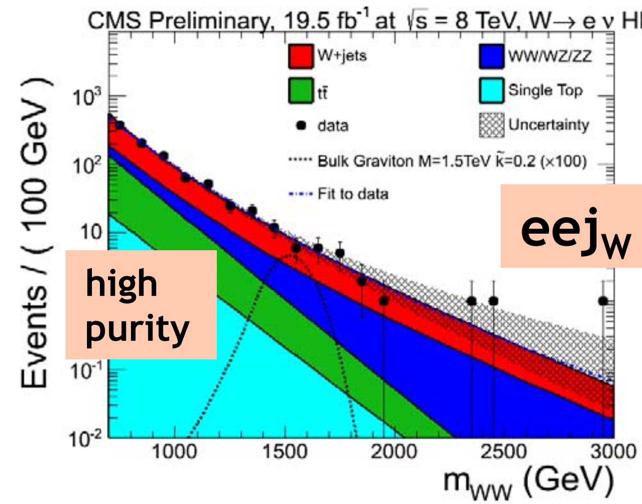
Semileptonic ZZ,WW



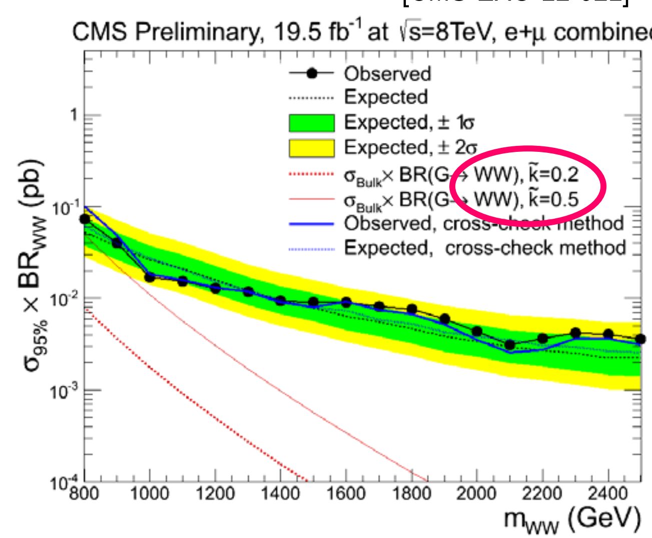
[ATLAS-CONF-2012-150] [CMS-EXO-12-022]



- 2 analyses:
  - resolved and merged (ATLAS)
  - low/high purity (τ_{12}) merged (CMS)



[CMS-EXO-12-021]



- Fermionic couplings possibly suppressed

Observed lower mass limit (GeV)

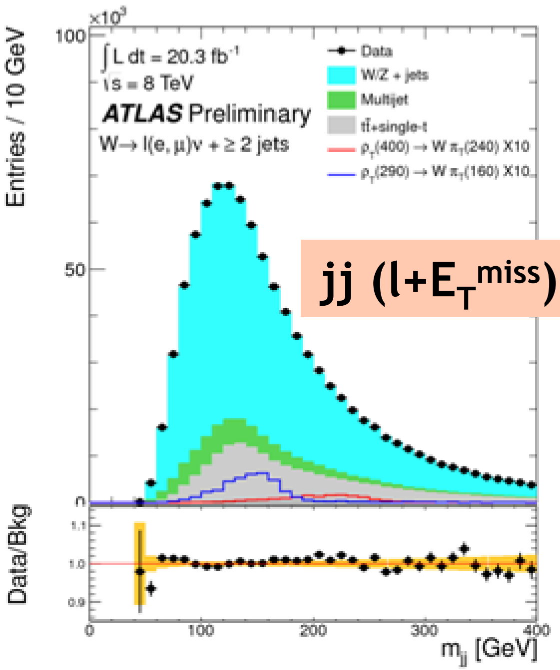
Model	ATLAS $7\ fb^{-1}$	CMS $20\ fb^{-1}$
Bulk RS $G^* \to ZZ$ Γ/M=3-6%	[350,850] $k/M_{Pl}=1.0$	[600,710] $k/M_{Pl}=0.5$

Dijet associated with W/Z

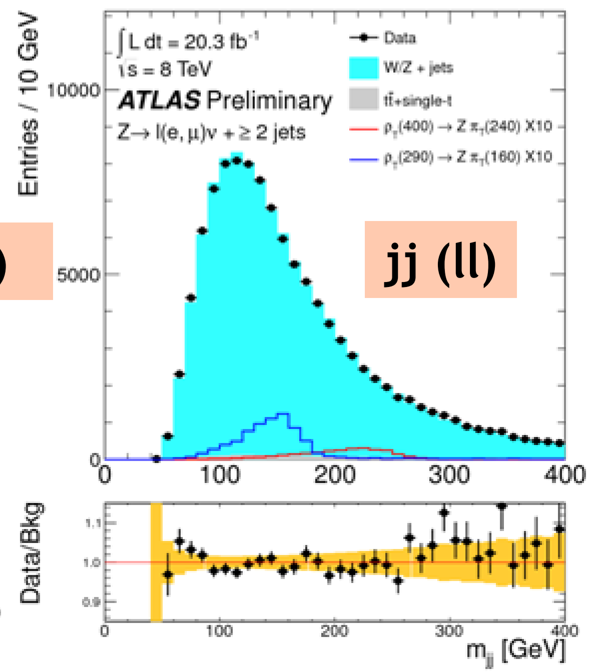
[ATLAS-CONF-2013-074]

NEW

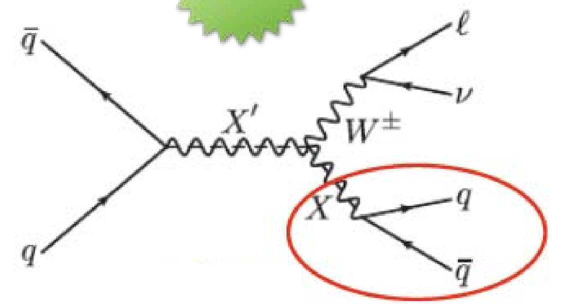
- Look for a low mass dijet resonance
- $\rho_T \to \pi_T W$ or $\pi_T Z$ (ρ_T, π_T charged or neutral)



jj (l+E_T^{miss})

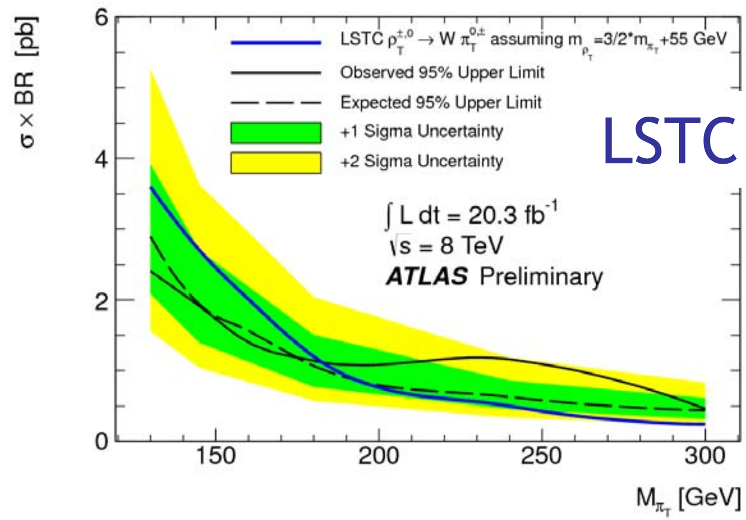


jj (ll)



$X'=\rho_T$, $X=\pi_T$

$\rho_T \to W \pi_T$



LSTC

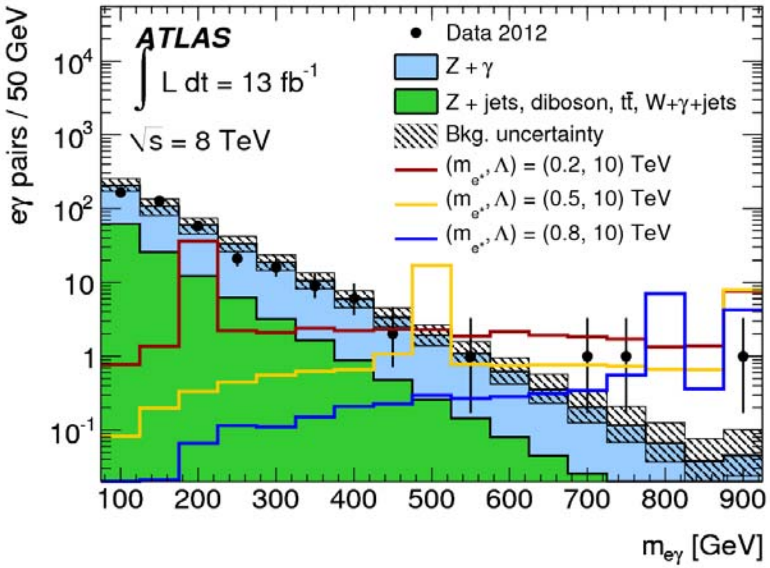
$m(\rho_T) = 3/2\ m(\pi_T)+55$ GeV

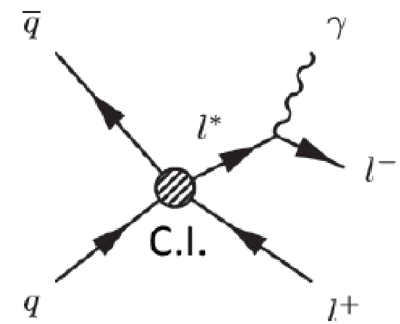
	Obs. lower mass limit
π_T	180 GeV

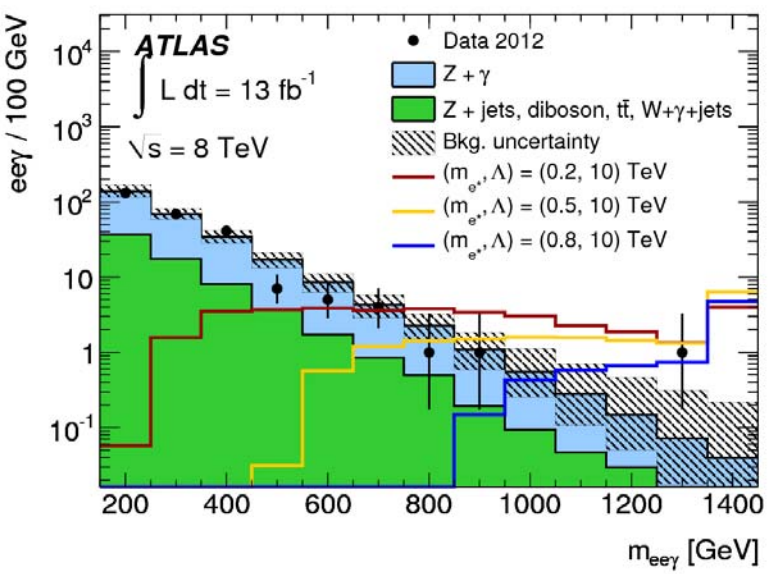
CDF: $m(\pi_T)$~160 GeV

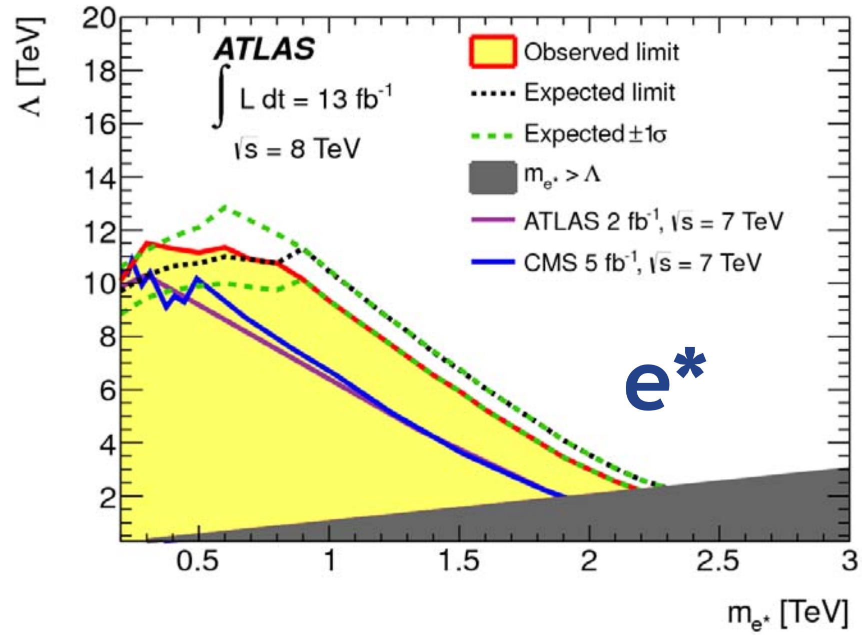
Lepton plus photon

[ATLAS NJP 15 (2013) 093011]







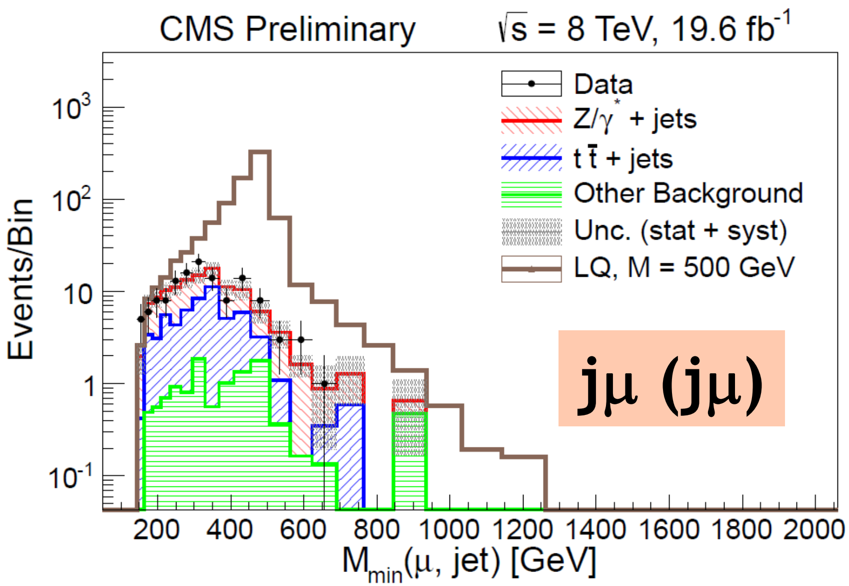


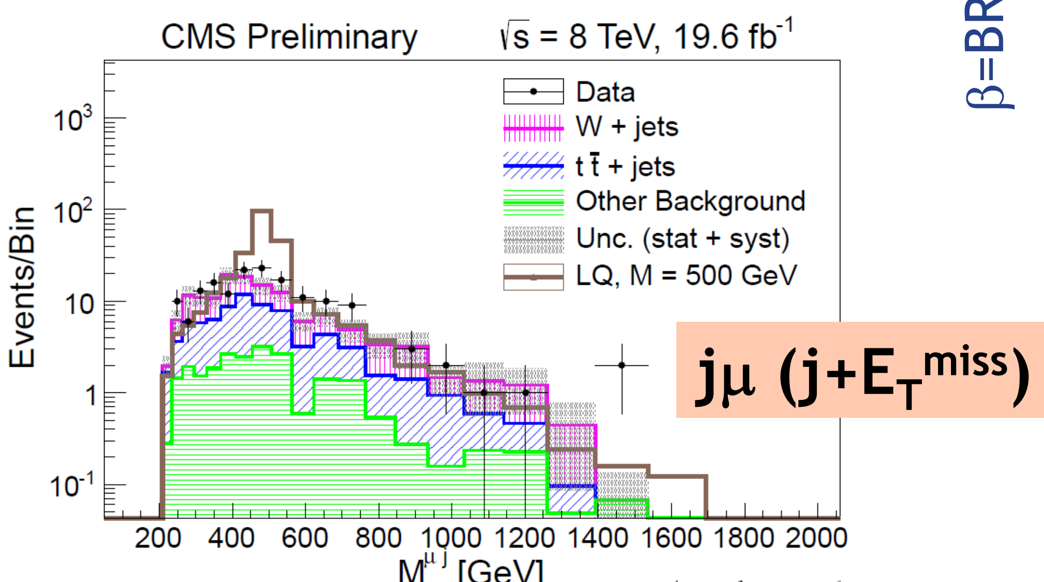
e*

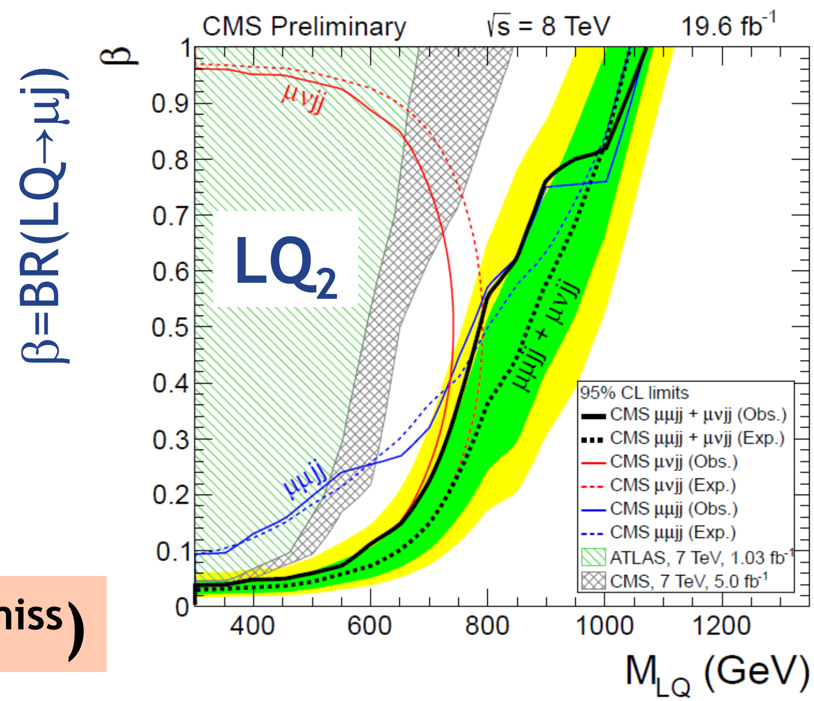
Second generation leptoquarks

[CMS-EXO-12-042]

- Very low background





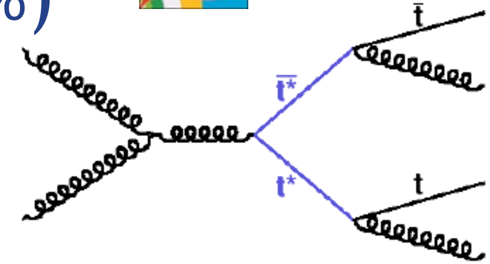


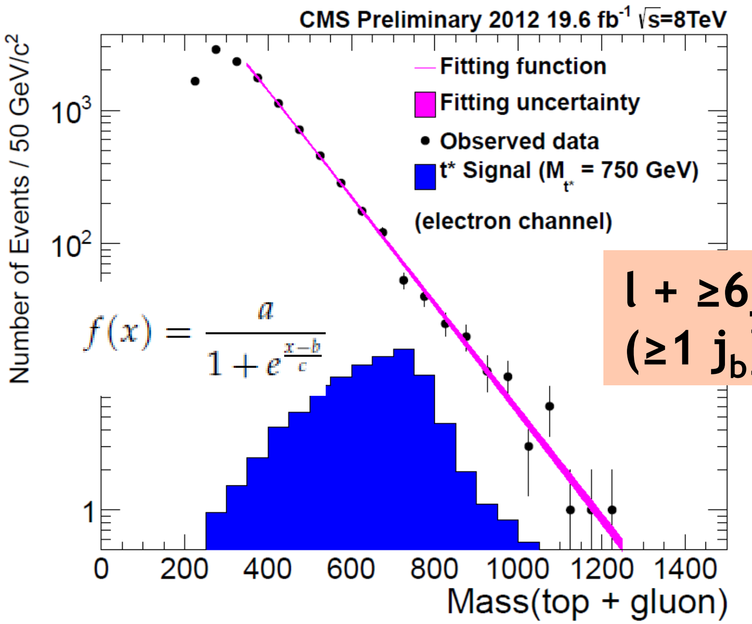
Also 1st & 3rd generation LQ searches, see e.g. 7 TeV search
ATLAS: arXiv:1303.0526, submitted to JHEP; CMS: JHEP 12 (2012) 055 & PRL 110, 081801 (2013)

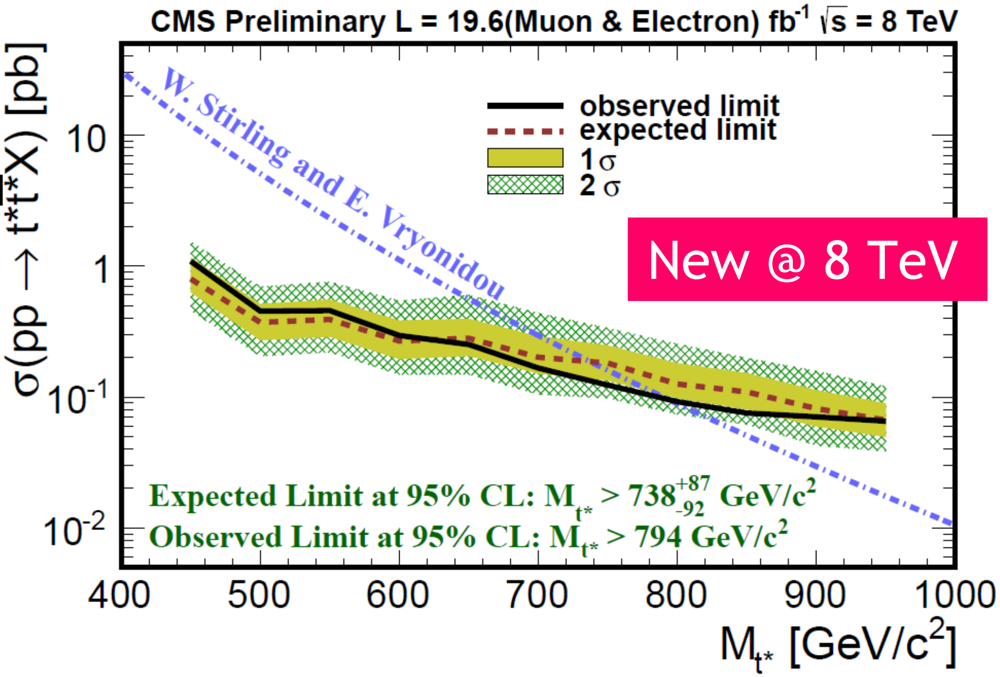
Semileptonic t+jet pairs

[CMS-B2G-12-014]

- spin 3/2, pair production, $t^* \to tg$ (100%)
- main background $t\bar{t}$ (+ ≥ 2 jets)







450 < m(t*) < 794 GeV excluded in specific model

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

Not shown

– non-resonant dileptons/dijets, heavy neutrinos, multilepton general search, long-lived particles, displaced jets and leptons, out of time jets, jet extinction, …

Bonus

Summaries

- 8 TeV limits by resonance

More signatures

-leptonic t b^{bar}

-semileptonic ZZ/WW

-dijet associated with W/Z

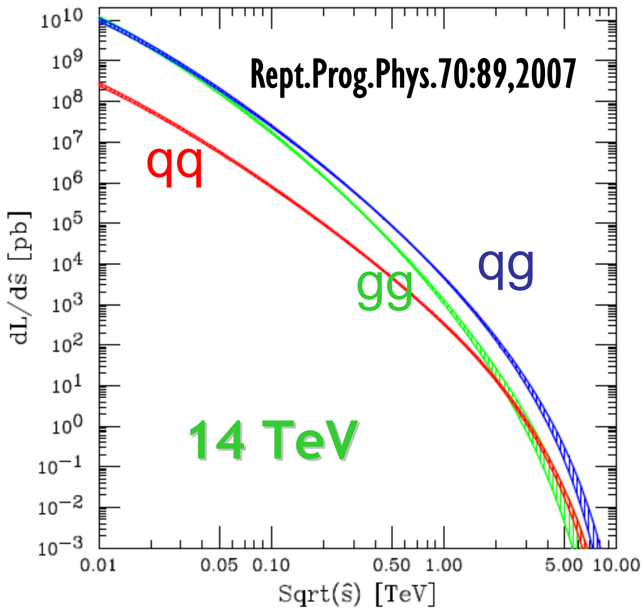
-lepton plus photon

-leptoquark pairs

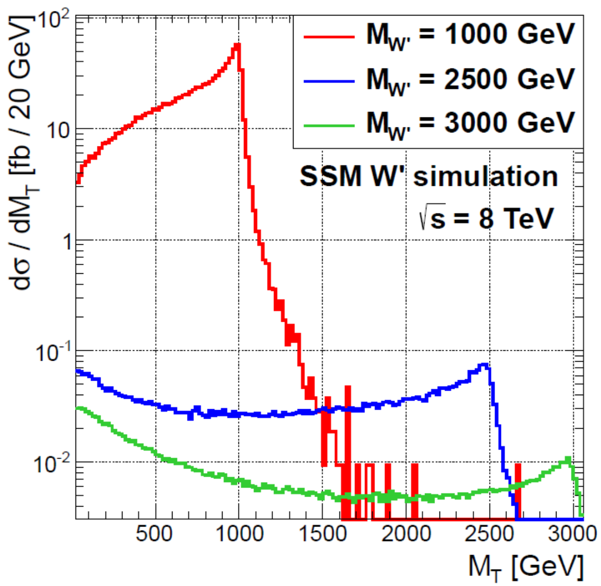
-excited top pairs

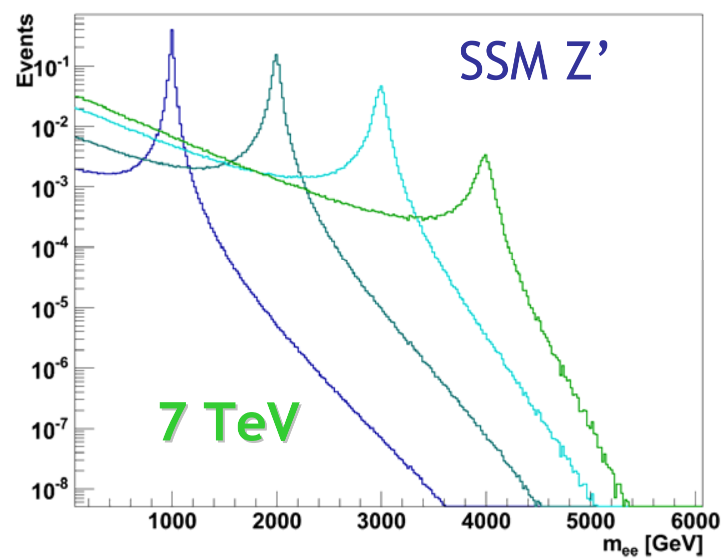
More information

Parton luminosities



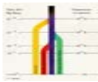
- very large tail for "large" widths





Dileptons

- Simple final state, easy to interpret
- Numerous interpretations possible

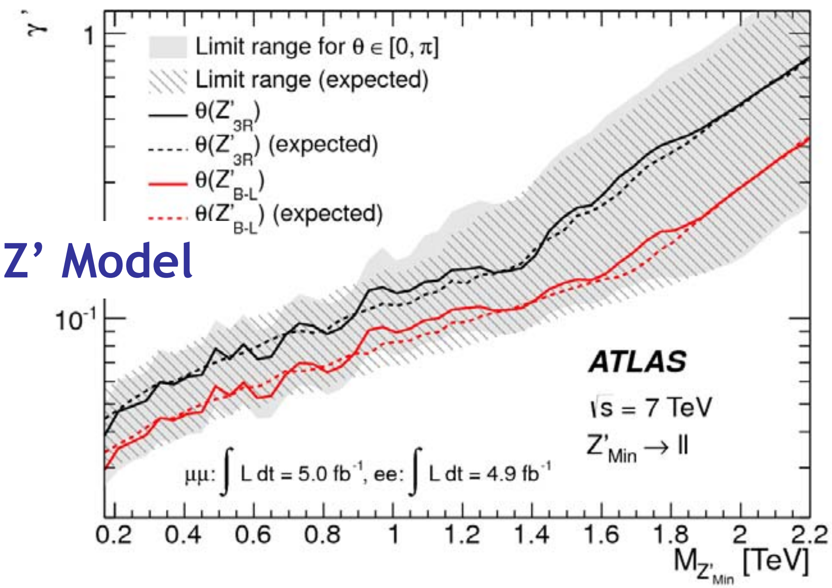



Observed lower mass limits (TeV)

Model	ATLAS (7 TeV)
Z^*	2.20
LSTC ρ_T	0.85
MWT M_A ($\tilde{g}$=4)	0.77
Z_{KK}/γ_{KK} (interference/ resonance dominant)	4.16 / 4.71
TS (η_{TS}=0.2)	2.29

$m(\rho_T)=m(\pi_T)+m_W$

[ATLAS, EPJC 72 (2012) 2244]



Minimal Z' Model

- Towards limits with less model-dependence

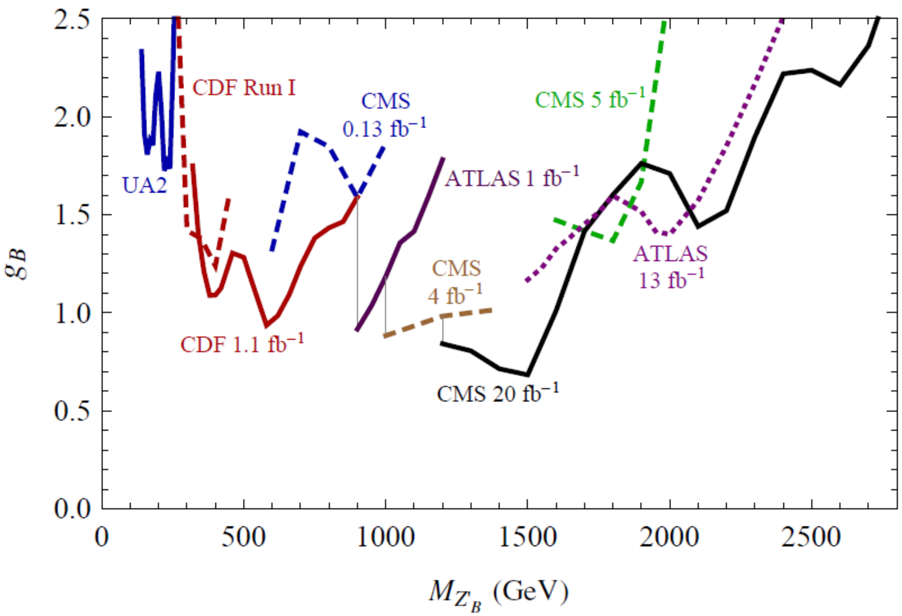
(also CMS limits in c_u,c_d plane with CDDT parameterization) [CMS, Phys. Lett. B 714 (2012) 158]

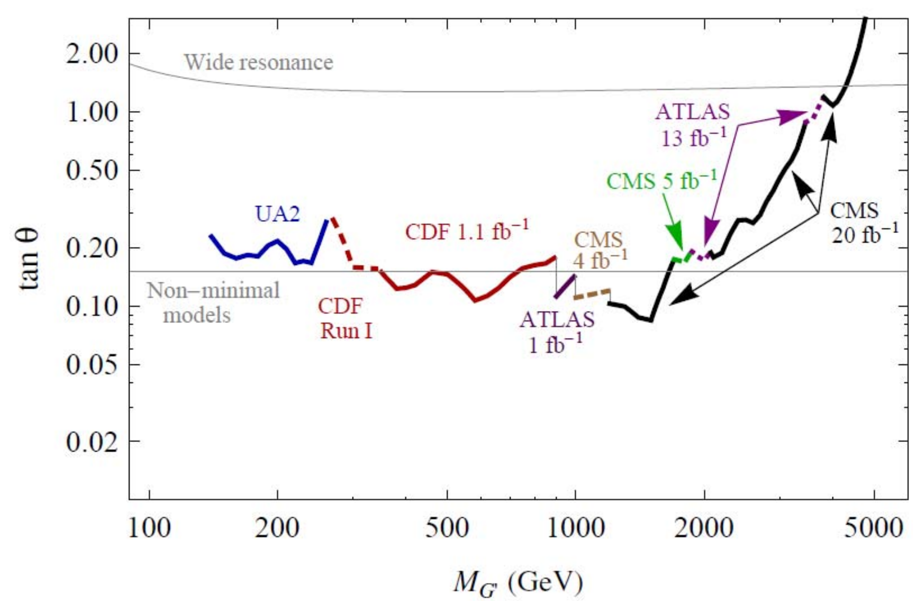
Digression: older dijets results

[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



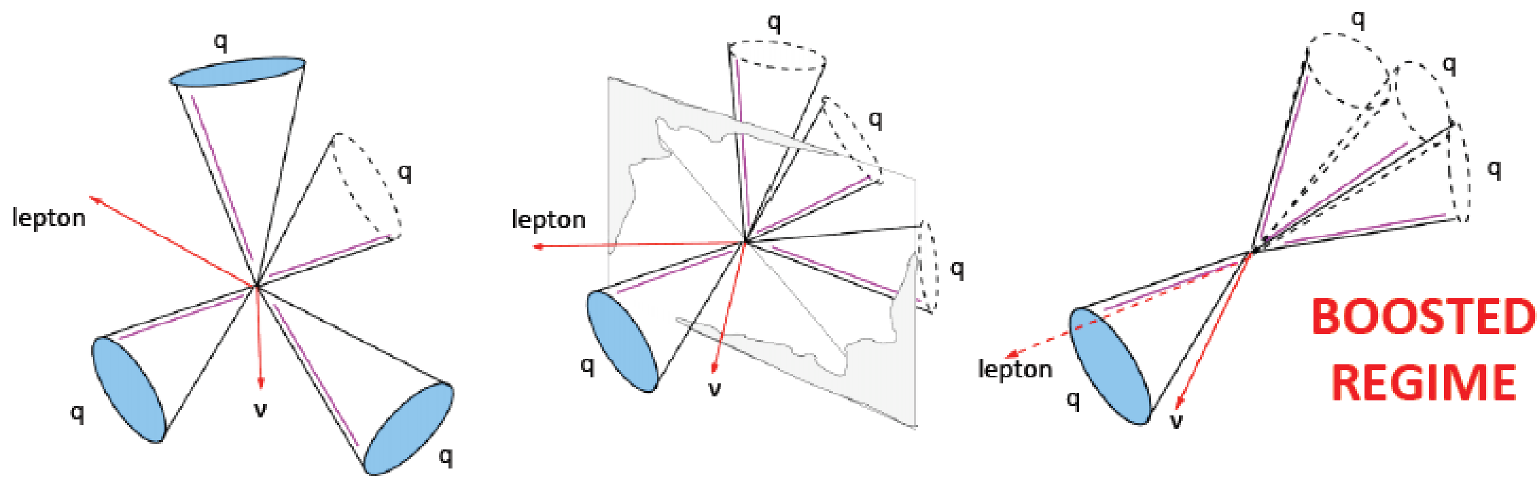


Older dijets results

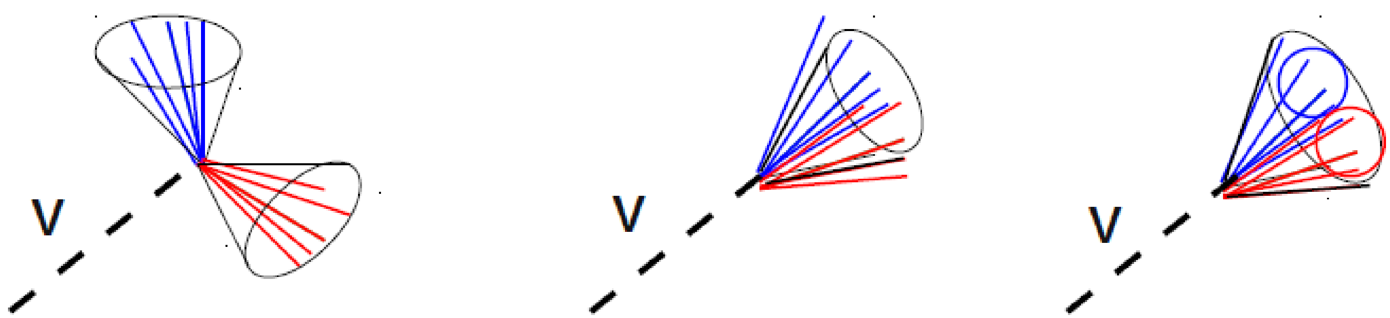
[Harris and Kousouris, Int.J.Mod.Phys. A26 (2011) 5005-5055]

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
"	"	1.47-1.52				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	–	–	–	–

Boosted jets and top or V-tagging



$m_{tt} < 500$ GeV | 500 GeV $< m_{tt} < 1$ TeV | $m_{tt} > 1$ TeV



Moderately boosted V
Resolved dijets

Boosted V,
jet merging

Boosted V, jet merging,
Jet substructure analysis
recovers initial information

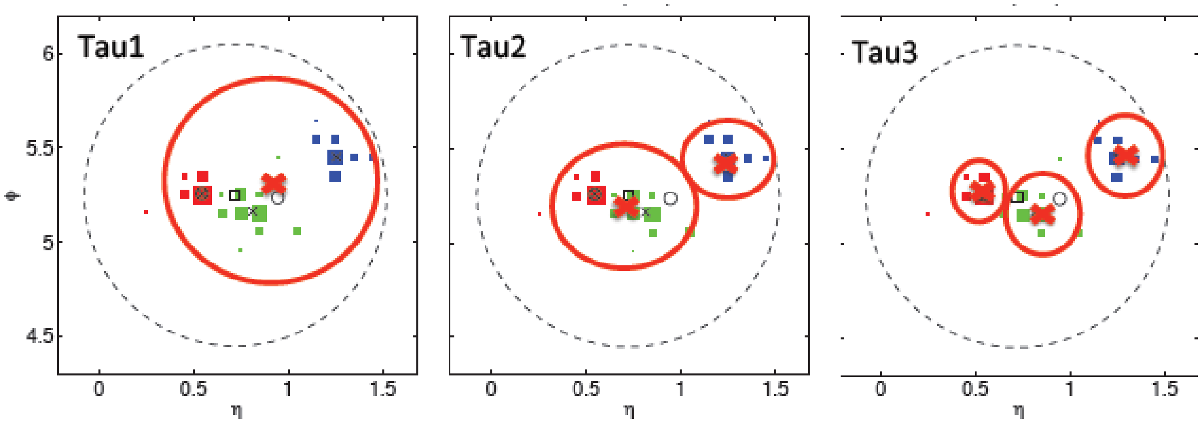
Boosted jets: N-subjetiness

N-subjetiness: topological compatibility with N subjets

τ_N = p_T weighted sum over jet constituents of distances to closest subjet axis:

$$\tau_N = \frac{1}{d_0} \sum_k p_{T,k} \, min\{\Delta R_{1,k}, \Delta R_{2,k}, \ldots, \Delta R_{N,k}\}$$

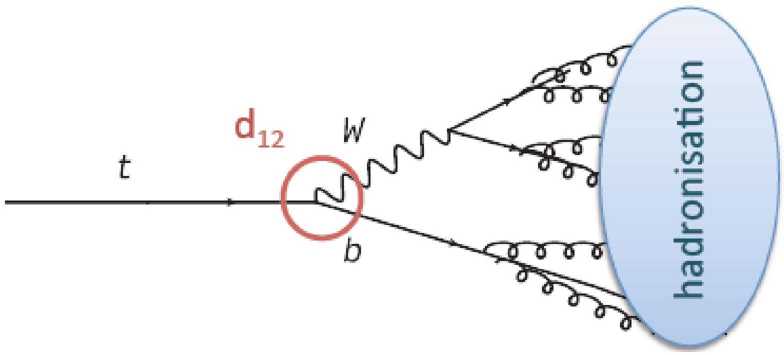
In practice, use ratios: $\tau_{21} = \tau_2 / \tau_1$ <<1 if 2 subjets

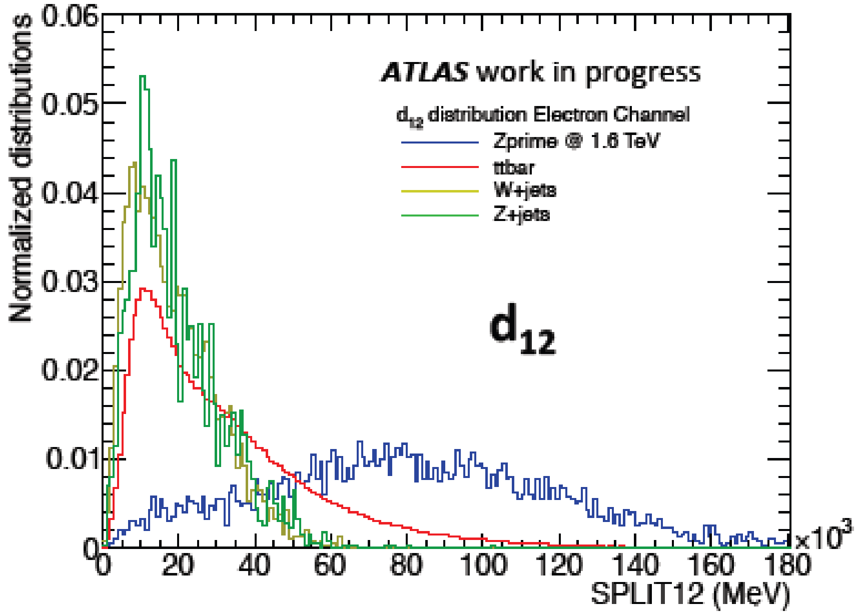


Boosted jets: splitting scales

d_{ij}: last splitting scale of a k_T algorithm

$$d_{ij} = \min(p_{T,i}^2 ; p_{T,j}^2)\frac{\Delta R_{ij}}{R^2}$$



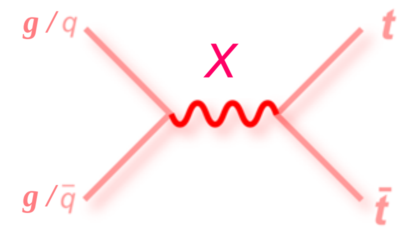


d_{12} is a probe of the t-> Wb decay

Common issues: sensitivity to pile-up ➔ jet grooming techniques: filtering, trimming, pruning

Semileptonic $t\bar{t}$

[ATLAS-CONF-2013-052]

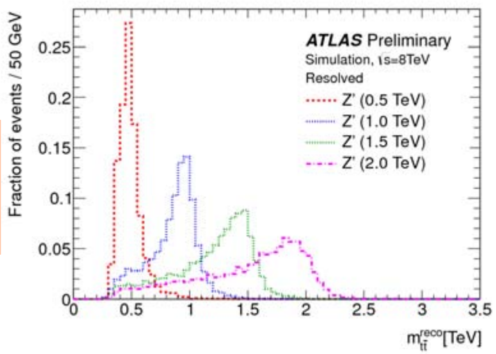


- 2 lep. flavours x 2 had. selections (resolved and boosted) = 4 independent channels
- "mini isolation": <5% p_T, cone size $10/p_T$[GeV]

Resolved

l + ≥3 j (≥1 j_b) + E_T^{miss}

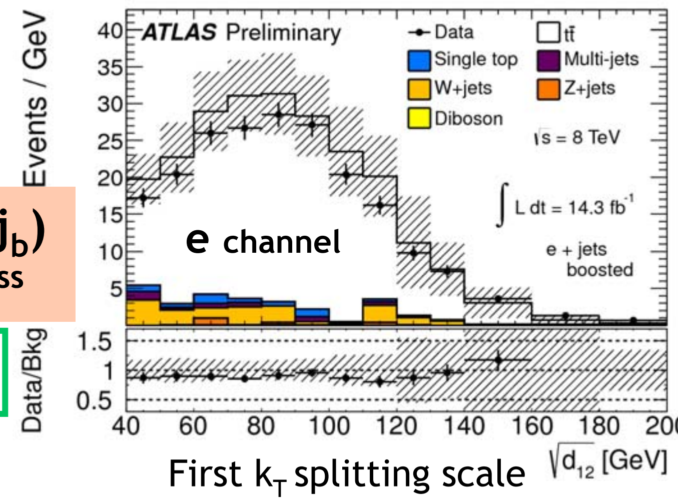
j: R=0.4



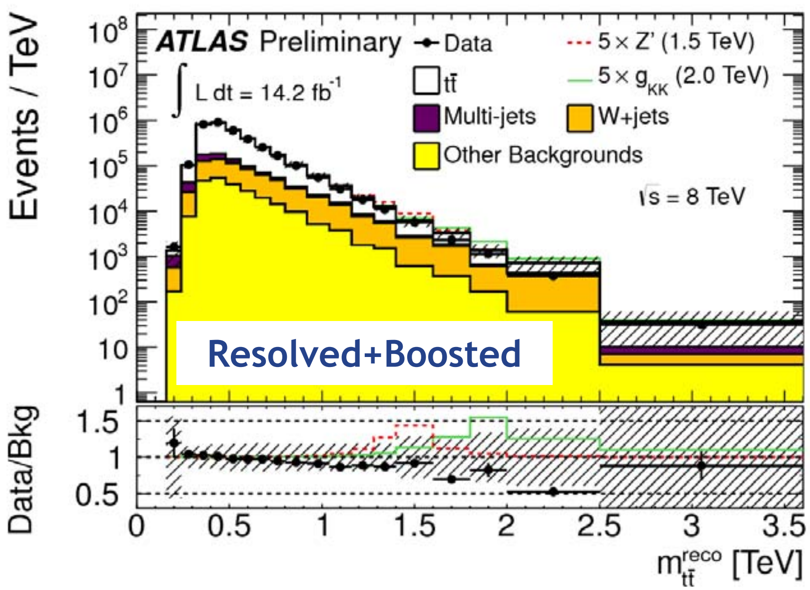
Boosted

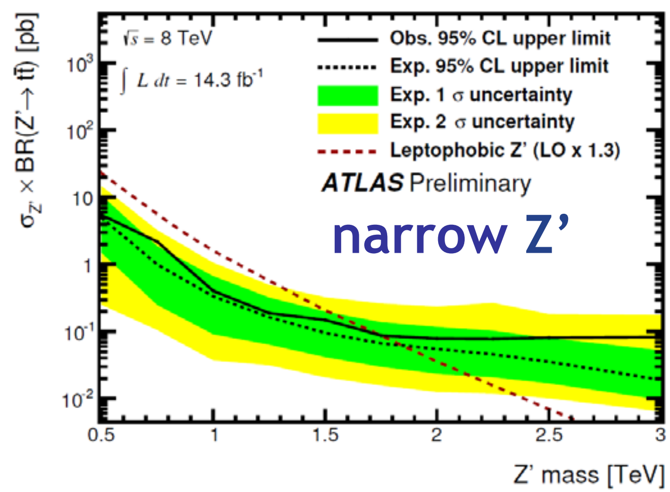
l + ≥1 j (≥1 j_b) + ≥1J + E_T^{miss}

J: R=1.0



- m(W), m(t) constraints
- m(tt^{bar}) from combination with smallest χ^2
- resolution ~7%





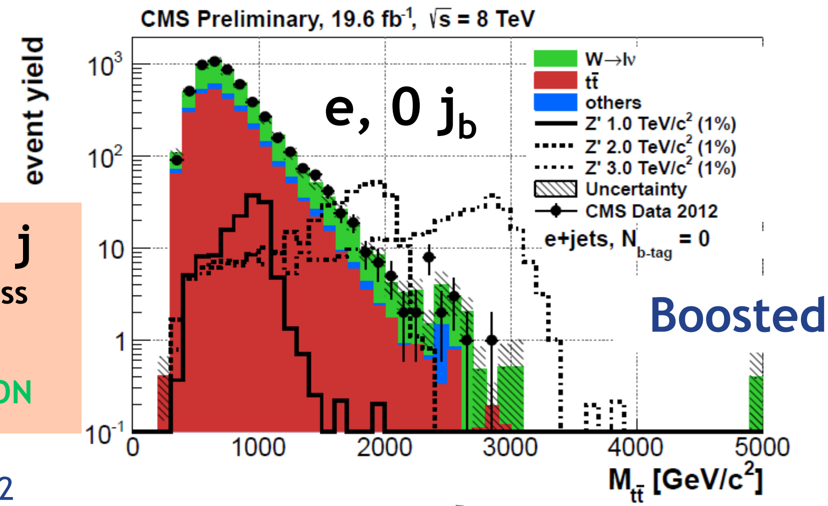
Semileptonic $t\bar{t}$

[CMS-B2G-12-006]

- 2 analyses: threshold and boosted
- 2 lepton flavours each
- 2 levels of b-tagging each

$l + \geq 2\,j + E_T^{miss}$

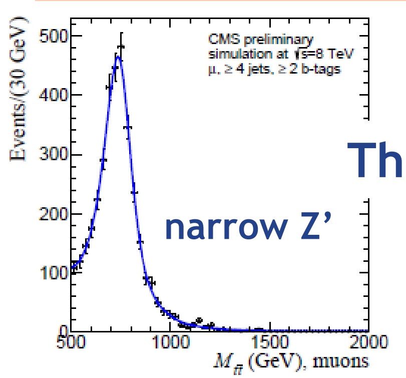
NO ISOLATION



Boosted

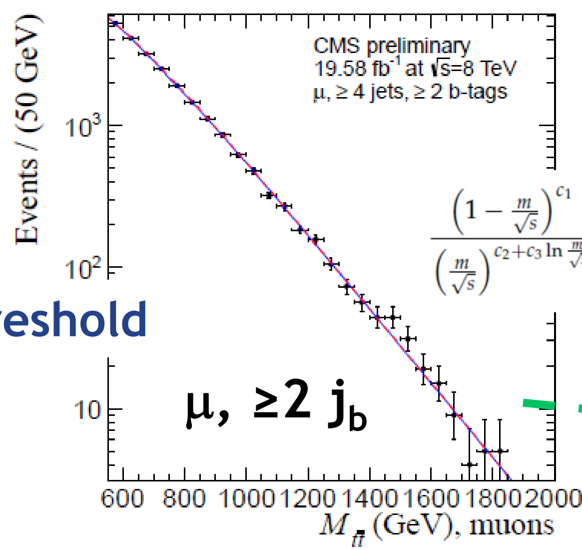
- m(W), m(t) constraints
- m(tt^{bar}) from combination with smallest χ^2
- resolution ~10%

$l + \geq 4\,j\ (\geq 1\,j_b) + E_T^{miss}$



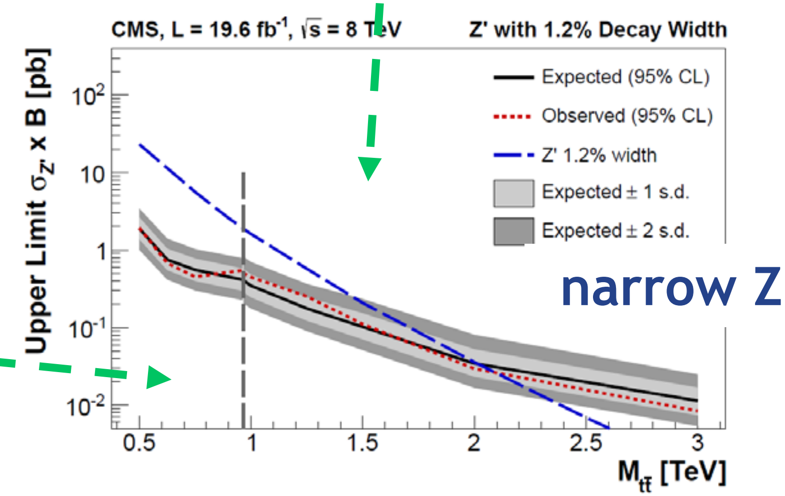
narrow Z'

Threshold



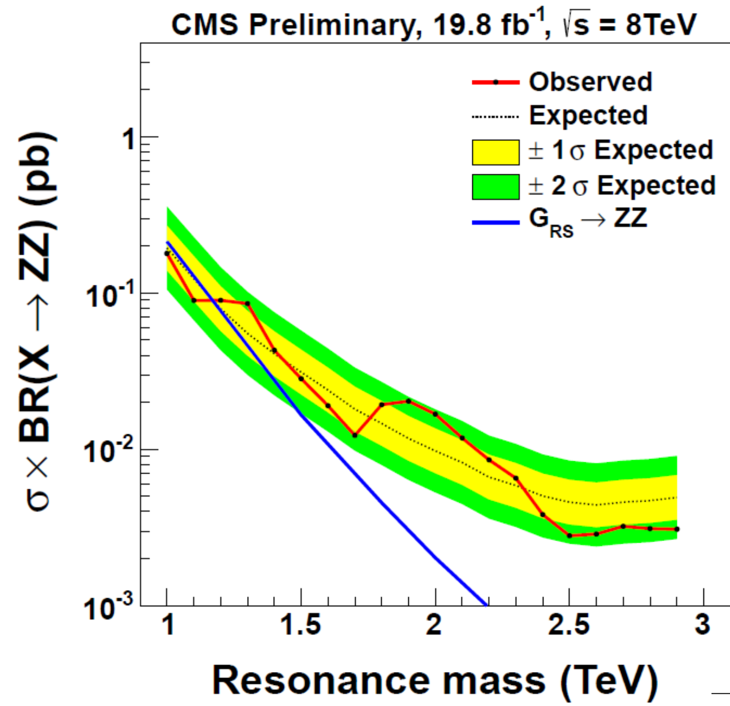
$$\frac{\left(1-\frac{m}{\sqrt{s}}\right)^{c_1}}{\left(\frac{m}{\sqrt{s}}\right)^{c_2+c_3\ln\frac{m}{\sqrt{s}}}}$$

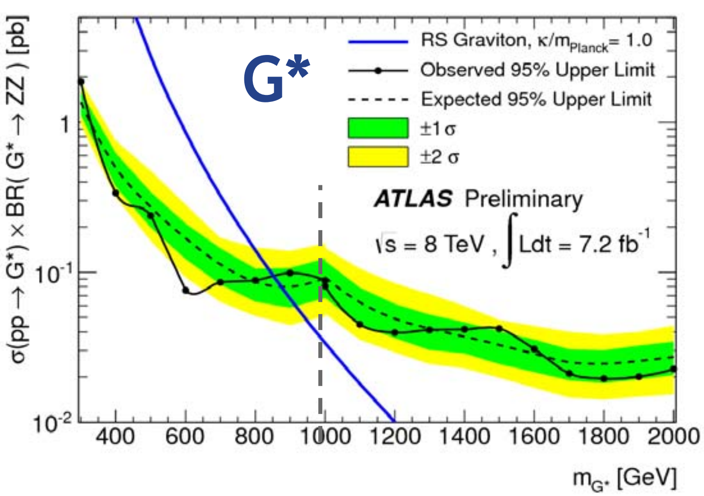
μ, ≥2 j_b



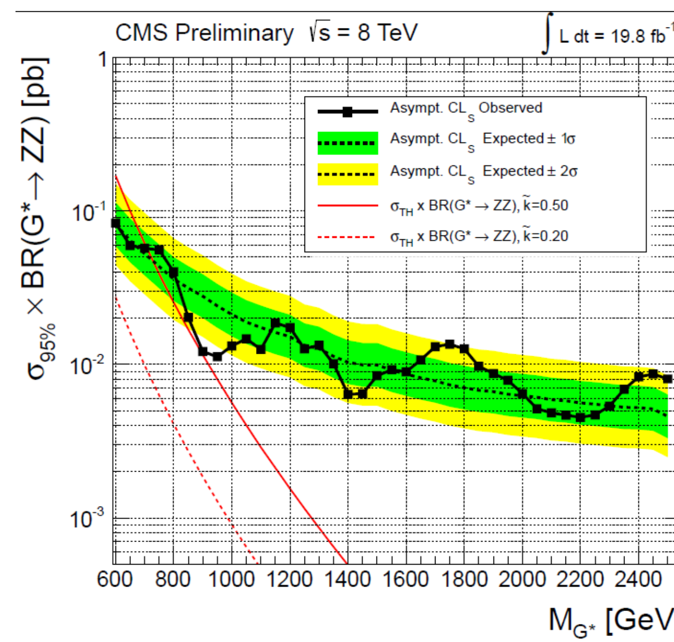
narrow Z'

ZZ-tagged dijet → RS1

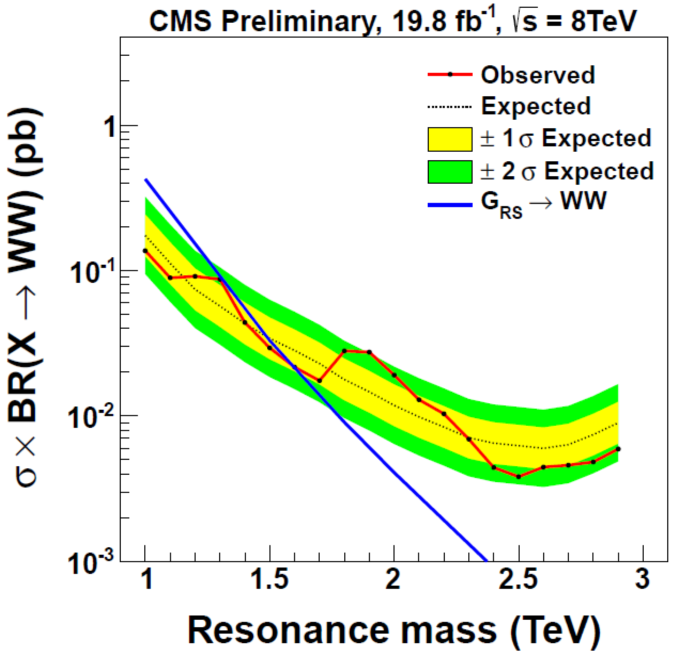




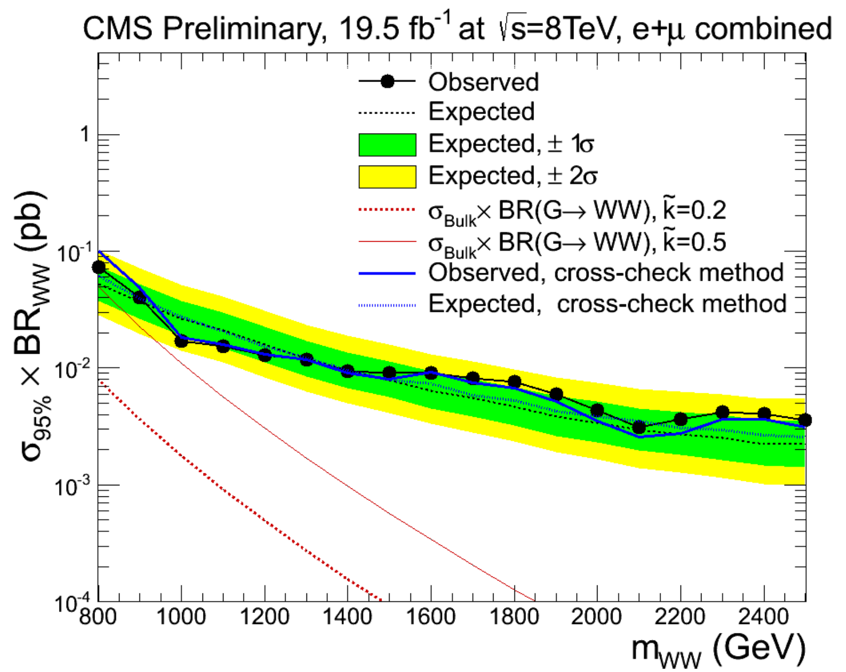
Semileptonic ZZ → bulk RS



WW-tagged dijet → RS1



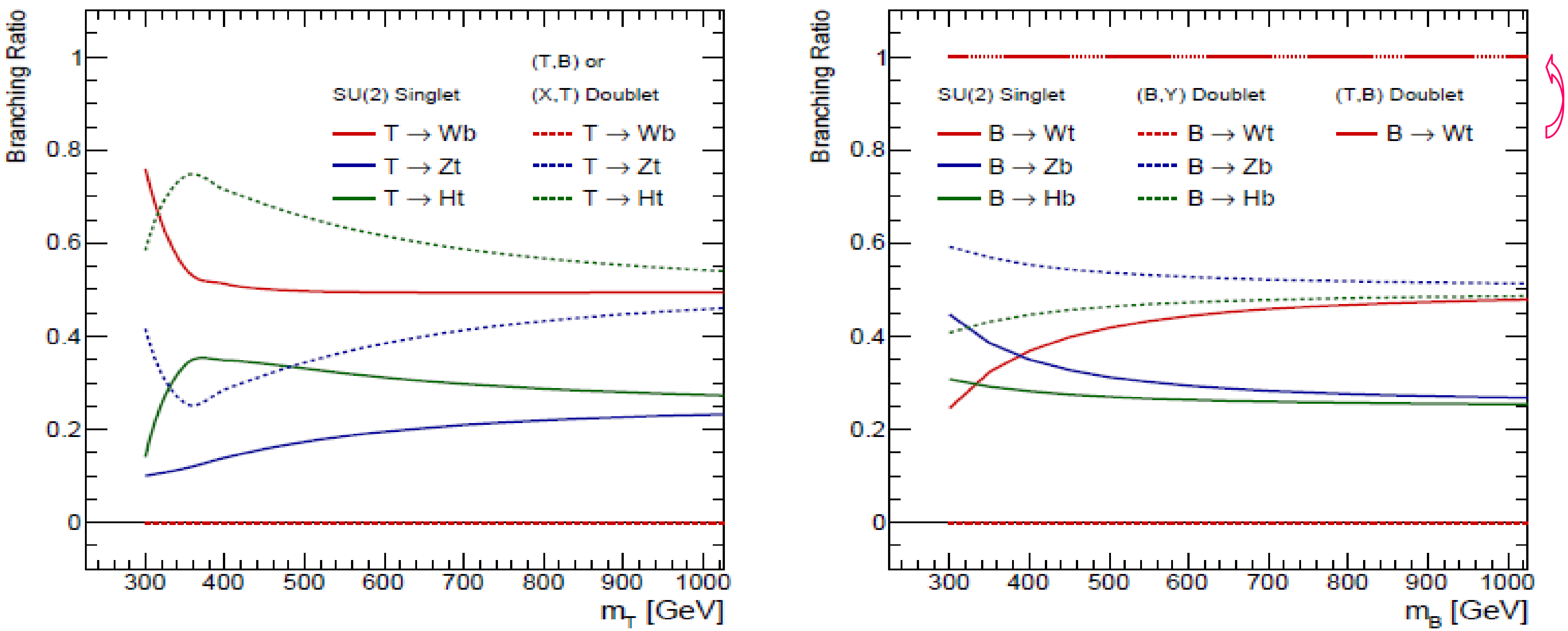
Semileptonic WW → bulk RS



Vector like quarks

- isospin singlets or doublets

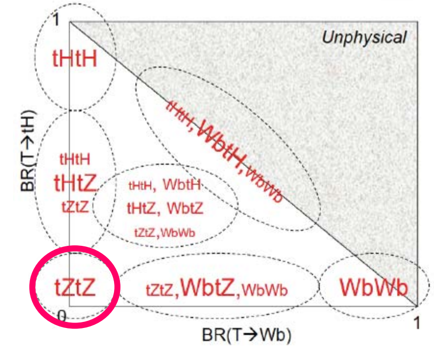
[del Aguila and Bowick, NPB224 (1983)107]



[Protos, http://jaguilar.web.cern.ch/jaguilar/protos]

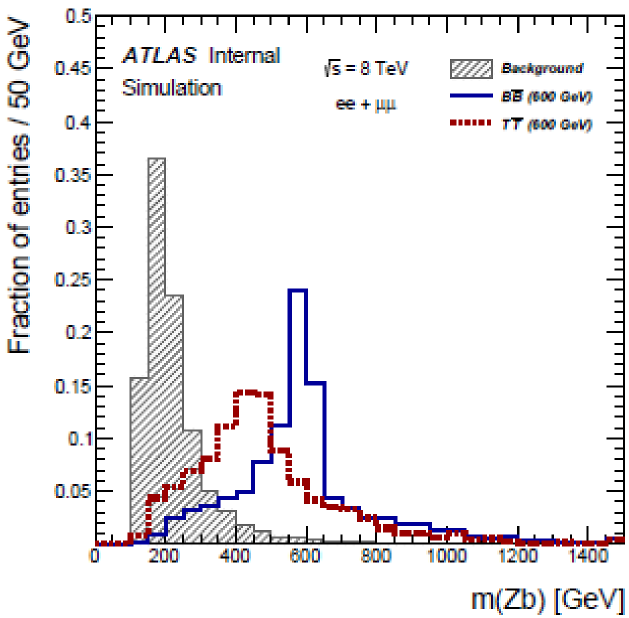
BB, TT: Zb+X, Zt+X

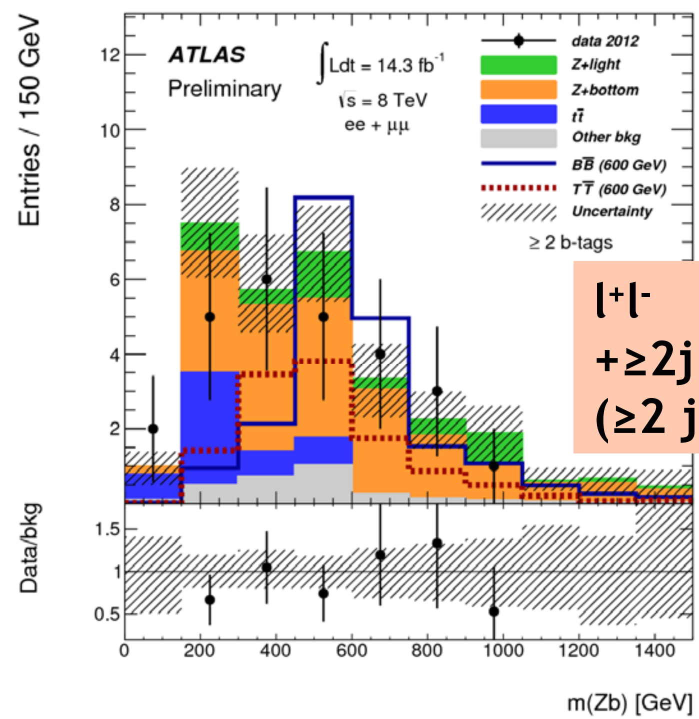
[ATLAS-CONF-2013-056]



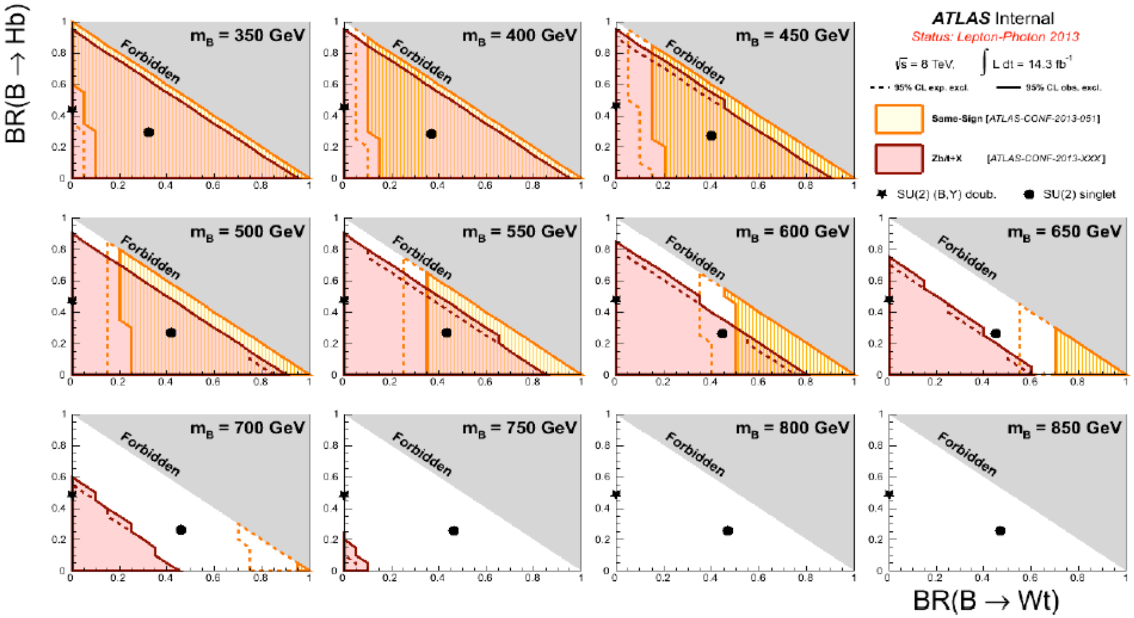
14 fb^{-1}

- $Z \to l^+ l^-$
- reconstruct one side
- $H_T = \Sigma\ |p_T|$ (all j) > 600 GeV
- main background: Z+(b-)jets

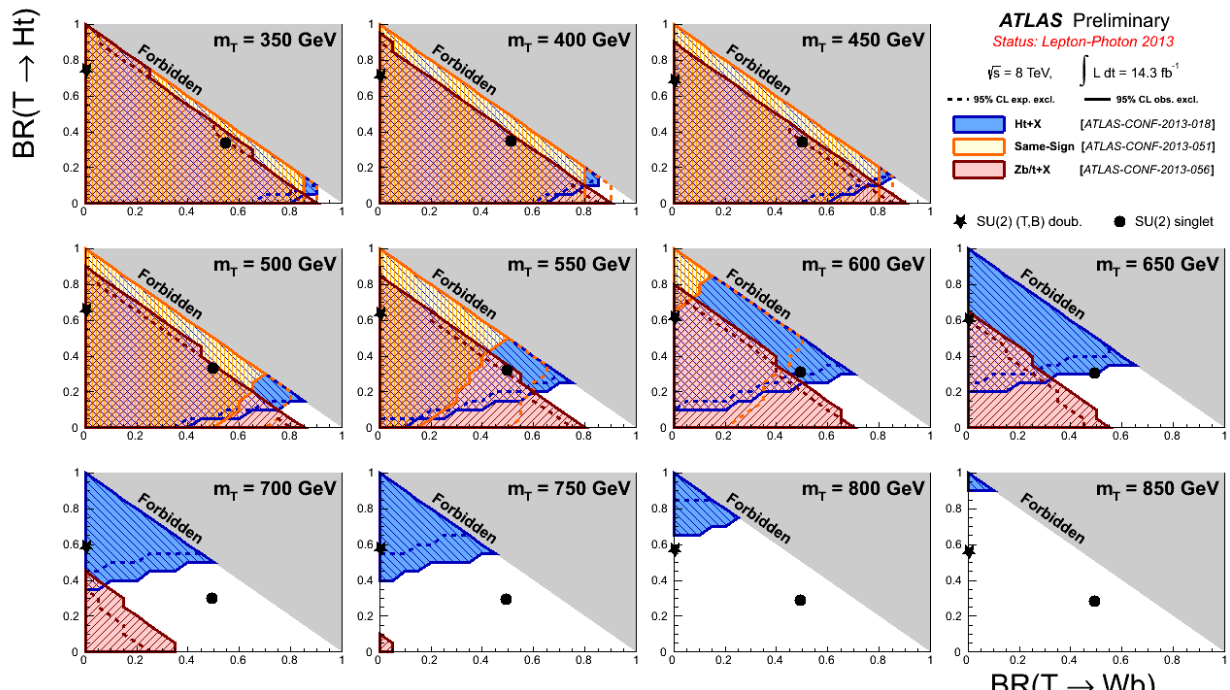




l^+l^-
$+\geq 2j$
$(\geq 2\ j_b)$


ATLAS Internal
Status: Lepton-Photon 2013
√s = 8 TeV, ∫ L dt = 14.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Same-Sign [ATLAS-CONF-2013-051]
Zb/t+X [ATLAS-CONF-2013-XXX]
SU(2) (B,Y) doub.
SU(2) singlet
m_B = 350 GeV
m_B = 400 GeV
m_B = 450 GeV
m_B = 500 GeV
m_B = 550 GeV
m_B = 600 GeV
m_B = 650 GeV
m_B = 700 GeV
m_B = 750 GeV
m_B = 800 GeV
m_B = 850 GeV
Forbidden
BR(B → Hb)
BR(B → Wt)

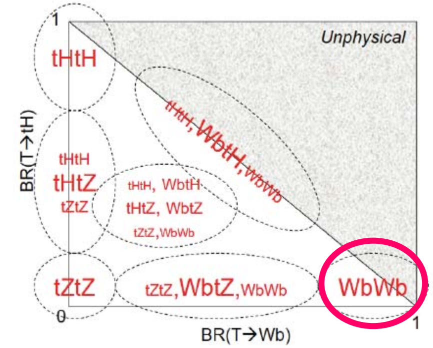
BB


ATLAS Preliminary
Status: Lepton-Photon 2013
√s = 8 TeV, ∫ L dt = 14.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Ht+X [ATLAS-CONF-2013-018]
Same-Sign [ATLAS-CONF-2013-051]
Zb/t+X [ATLAS-CONF-2013-056]
SU(2) (T,B) doub.
SU(2) singlet
m_T = 350 GeV
m_T = 400 GeV
m_T = 450 GeV
m_T = 500 GeV
m_T = 550 GeV
m_T = 600 GeV
m_T = 650 GeV
m_T = 700 GeV
m_T = 750 GeV
m_T = 800 GeV
m_T = 850 GeV
Forbidden
BR(T → Ht)
BR(T → Wb)

TT

$TT \rightarrow WbWb$

[ATLAS-CONF-2013-060]



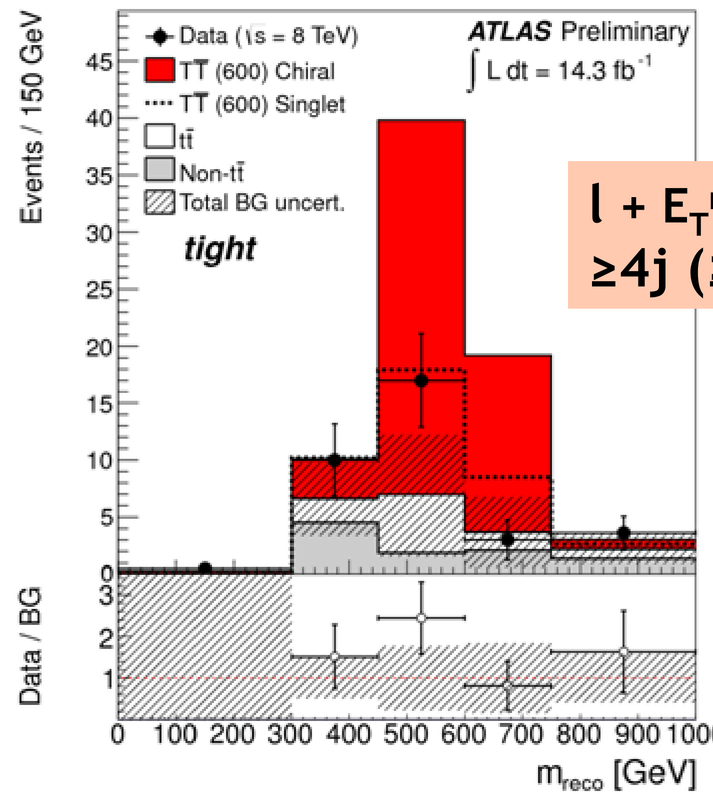
14 fb^{-1}

- same final state as tt^{bar}!
- semileptonic channel:

$W_{lep} \rightarrow l\nu$, $W_{had} \rightarrow qq$

- W_{had} resolved or boosted

- $H_T = \Sigma\ |p_T|$ (l + E_T^{miss} + 4 j) > 800 GeV
- $\min(\Delta R(W_{had}, b_{1,2}))$ > 1.4, $\min(\Delta R(l, b_{1,2}))$ > 1.4 *(tight)*



l + E_T^{miss} + ≥4j (≥1 j_b)

$m(W_{had}, j_b)$

- Veto events with ≥6j (≥1 j_b)

➔ no overlap with $TT \rightarrow Ht+X$

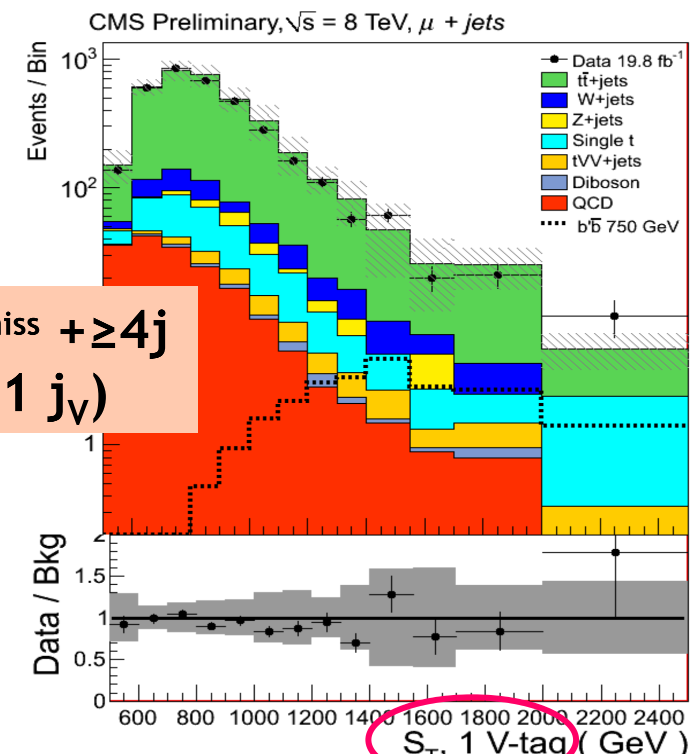
Also chiral t' interpretation

Inclusive BB

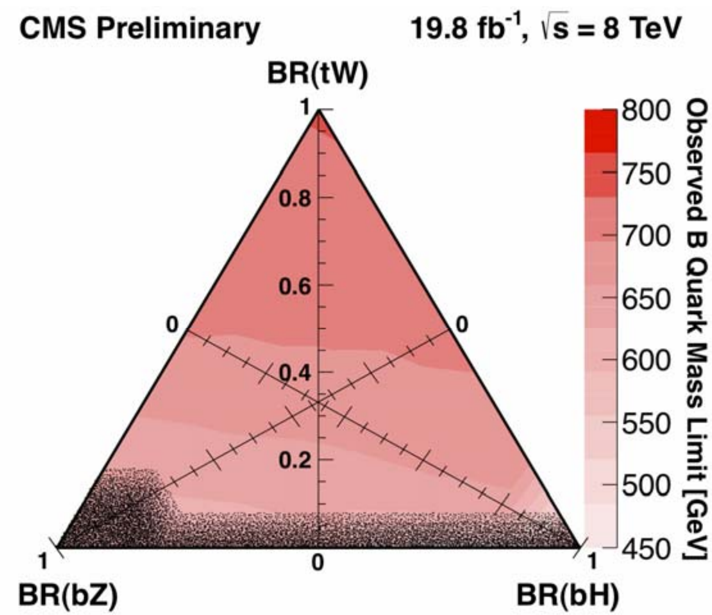
[CMS-B2G-12-019] NEW

- V=W/Z/H, $V \rightarrow l\nu$, $V \rightarrow qq$ (boosted)
- jets: 2 clustering algorithms ➔
  - anti-k_T R=0.5
  - Cambridge-Aachen R=0.8
- $l + E_T^{miss} + \geq 4j$ ($\geq 1\ j_b, \geq 1\ j_V$)
- $S_T = \Sigma\ |p_T|$ ($l + E_T^{miss}$ + all j)

- V-tagging efficiency ~50%



$\mu + E_T^{miss} + \geq 4j$ ($\geq 1\ j_b$, 1 j_V)

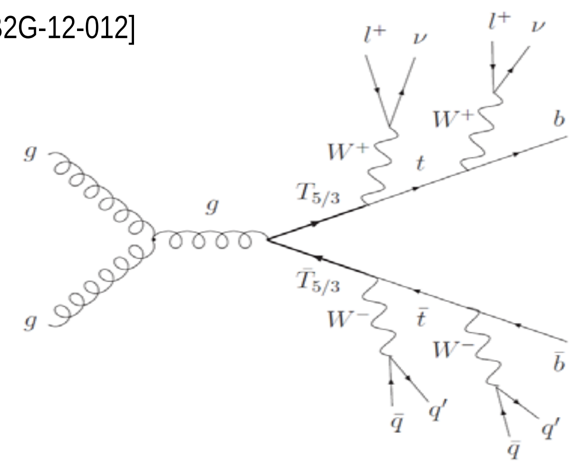


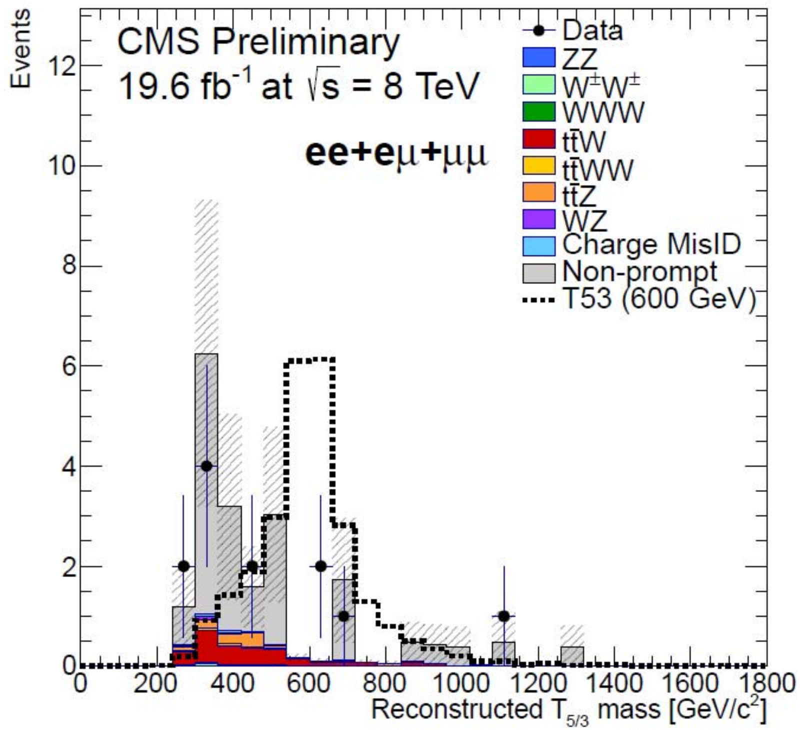
dedicated analysis: [CMS-B2G-12-021]
$BB \rightarrow Zb+X$, $Z \rightarrow ll$ NEW

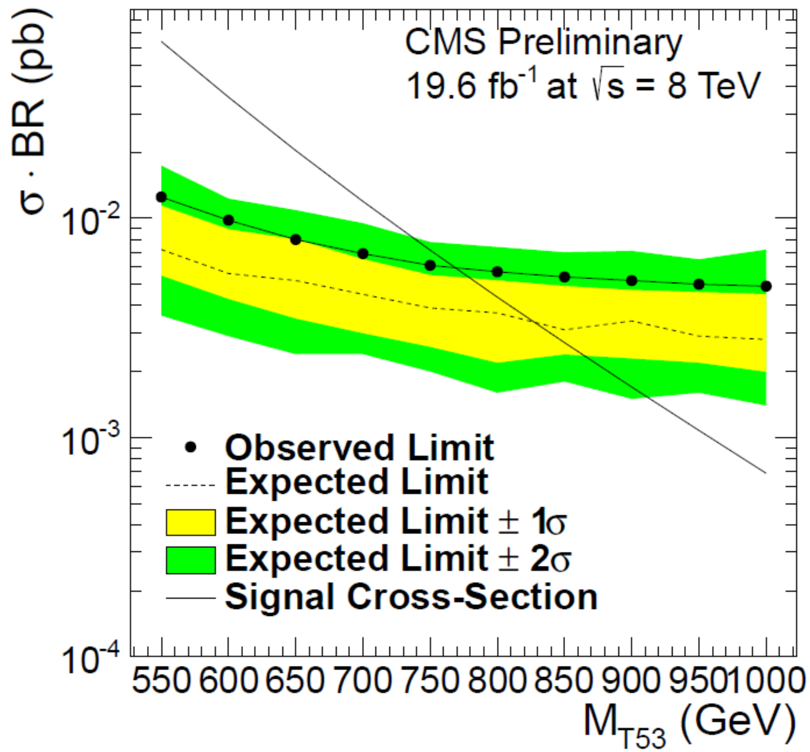
Same sign dileptons

[CMS-B2G-12-012]

- Very low SM background!







Dark matter

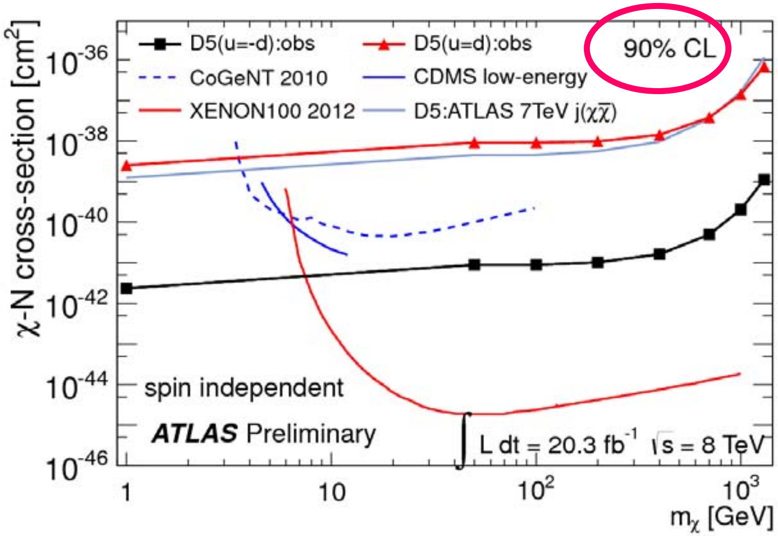
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$
D11	gg	scalar	$\frac{1}{4M_\star^3}\bar{\chi}\chi\alpha_s(G^a_{\mu\nu})^2$

- G. Busonia, A. De Simonea, E. Morgantec, A. Riotto
  - "On the Validity of the Effective Field Theory for Dark Matter Searches at the LHC", arXiv:1307.2253v1
  - Derive stronger bounds than currently used by LHC experiments
- New models:
  - A. DiFranzo, K. I. Nagao, A. Rajaraman, T.M.P. Tait,
    - "Simplified Models for Dark Matter Interacting with Quarks", arXiv:1308.2679v1
  - S. Chang, R. Edezhath, J. Hutchinson, and M. Luty,
    - "Effective WIMPs", arXiv:1307.8120v1
  - Yang Bai and Joshua Berger,
    - "Fermion Portal Dark Matter", arXiv:1308.0612v2

Dark matter (mono-W)

[CMS-EXO-13-004] [ATLAS-CONF-2013-073]

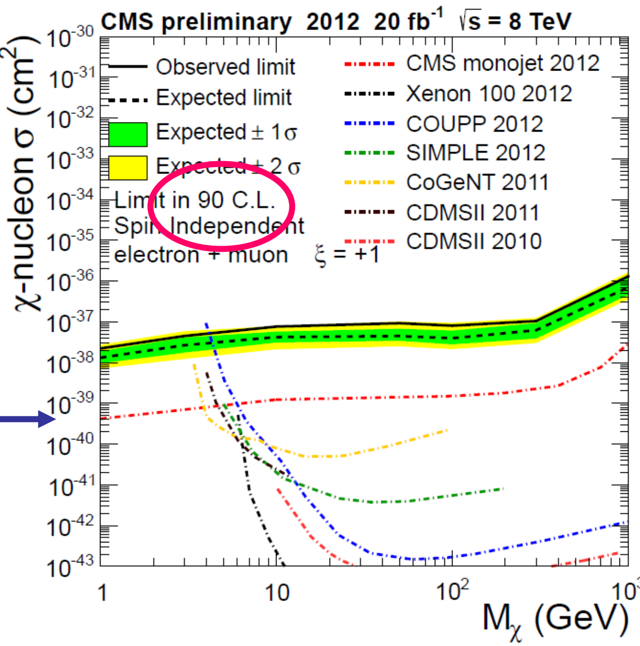
Spin independent



ξ=+1

mono-W

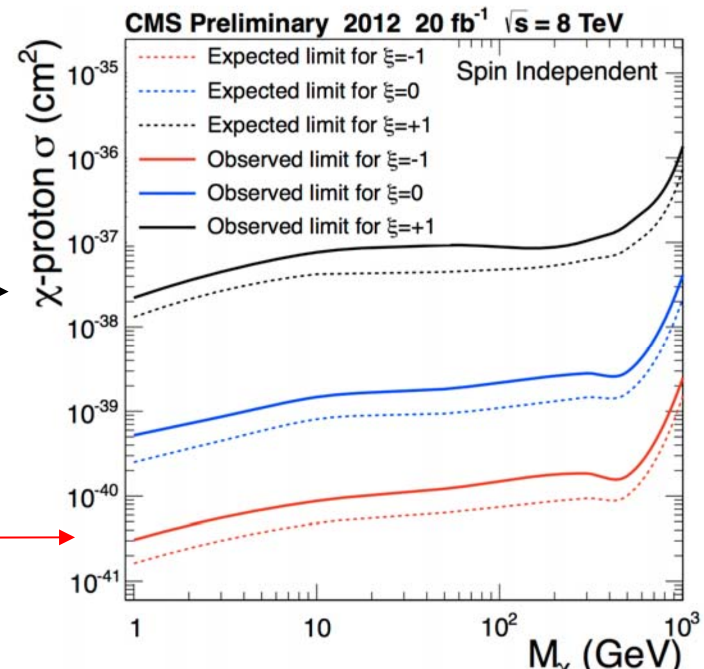
ξ=-1



mono-W

ξ=+1

mono-jet

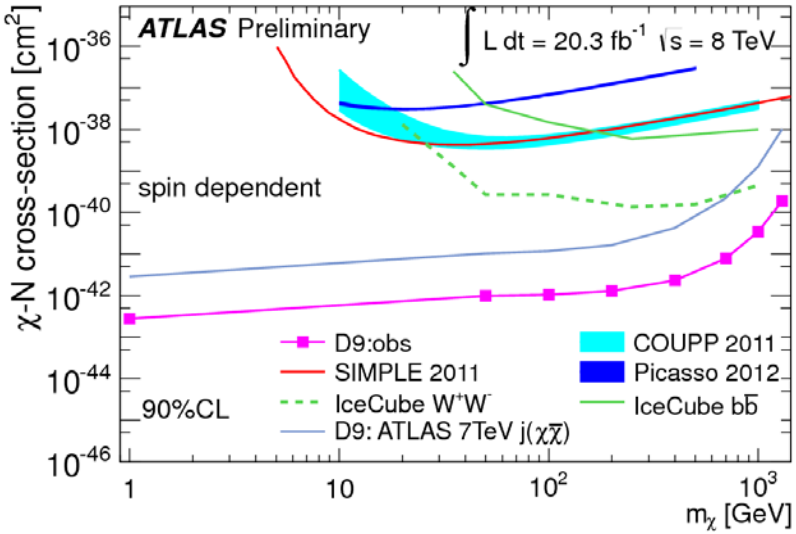


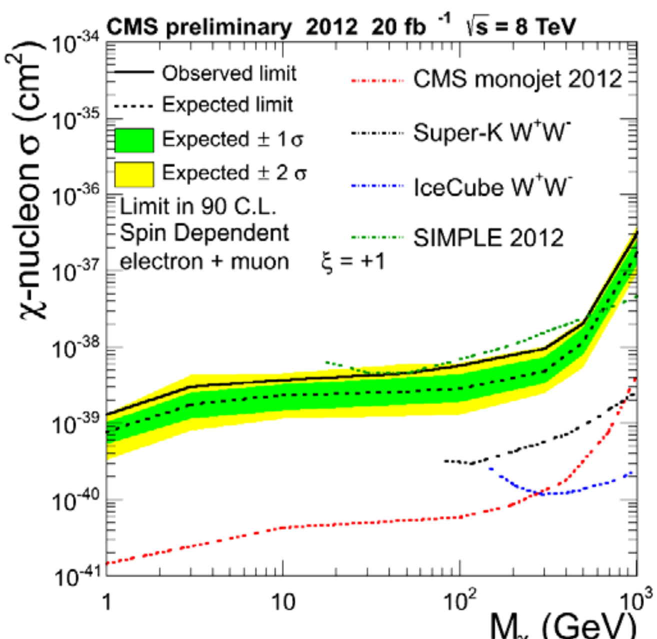
ξ=+1

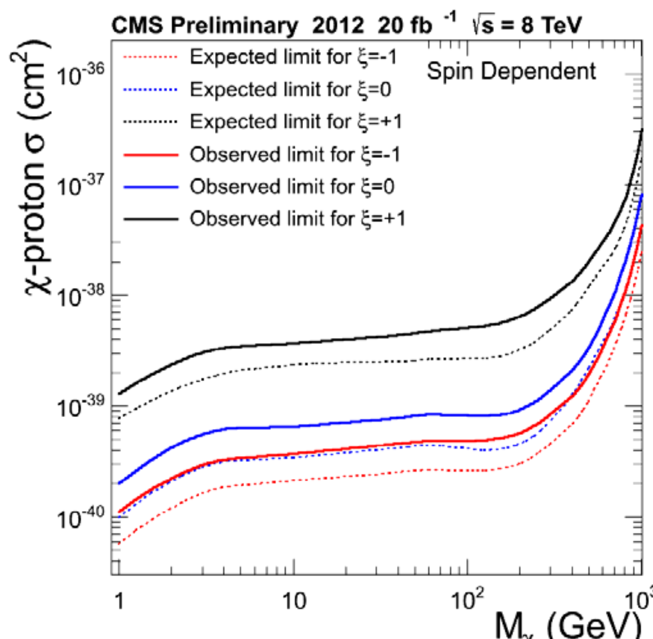
Dark matter (mono-W)

[CMS-EXO-13-004] [ATLAS-CONF-2013-073]

Spin dependent



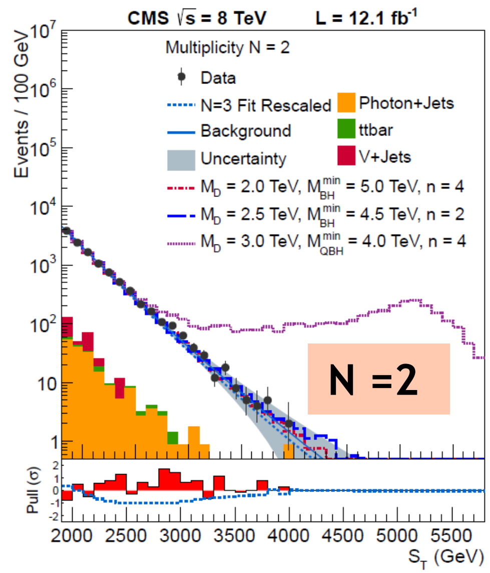




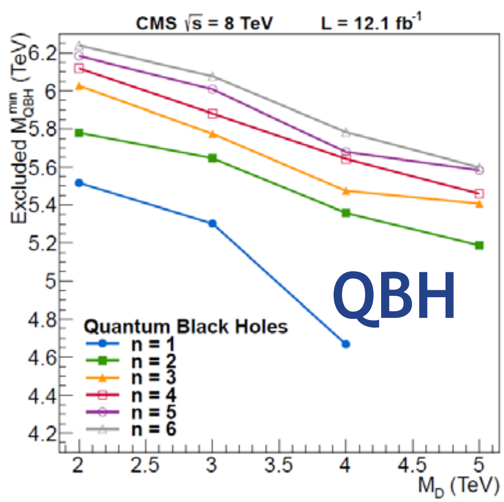
Black Holes

[CMS JHEP07(2013)178]

- at least 2 jets
- 10 multiplicity bins (up to ≥10)



12 fb^{-1}

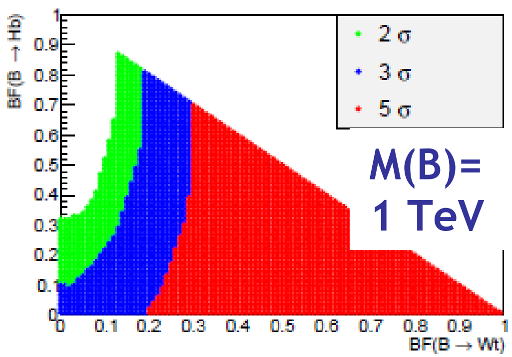


Outlook

CSS2013 (Snowmass on the Mississippi)

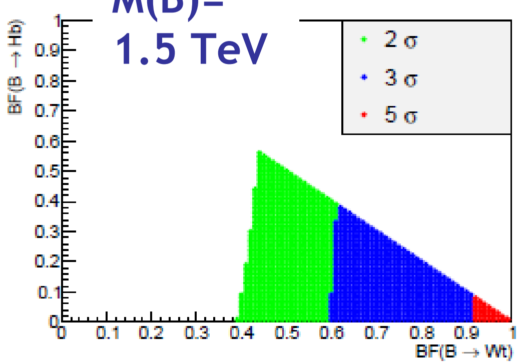
Pair produced VLQ (BB)

E.W. Varnes, arXiv:1309.0788



M(B)=
1 TeV

M(B)=
1.5 TeV

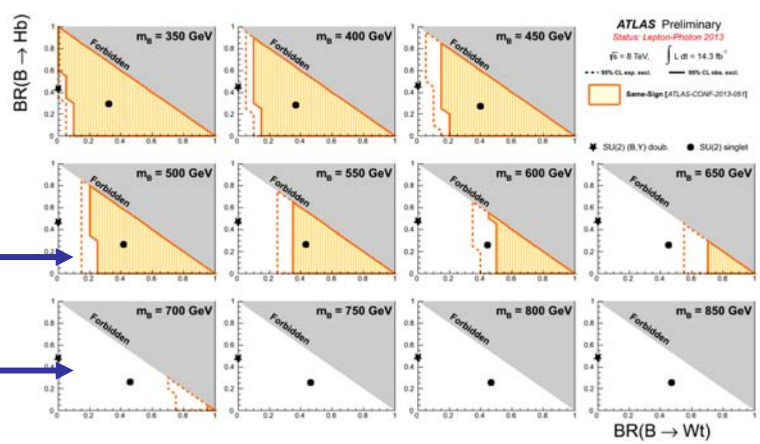


(b)

14 TeV,
3000 fb^{-1},
20% syst. unc.

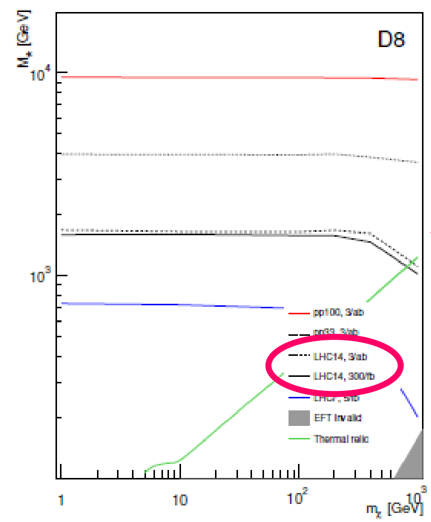
M(B)=500 GeV

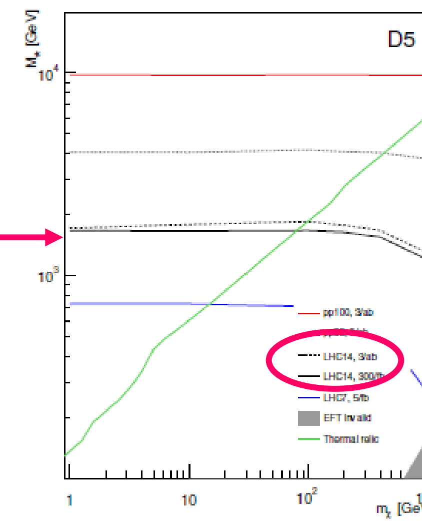
M(B)=700 GeV



Mono-X → Dark Matter

N. Zhou et al arXiv:1307.5327





Mono-
jet