Latest news from the LHC on Exotics direct searches

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BSM theories

GRAND UNIFICATION

COMPOSITENESS

SUPERSYMMETRY

EXTRA DIMENSIONS

TECHNICOLOR

Little Higgs, Hidden Valley, Unparticles, …

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

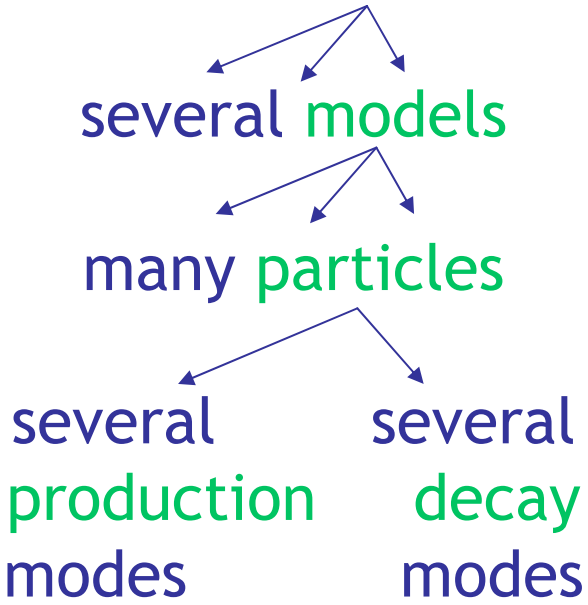
-Kaluza-Klein excitations of standard particles (G*, Z_{KK}, W_{KK}, g_{KK}, q_{KK},…), Black Holes, string resonances,…

TECHNICOLOR

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

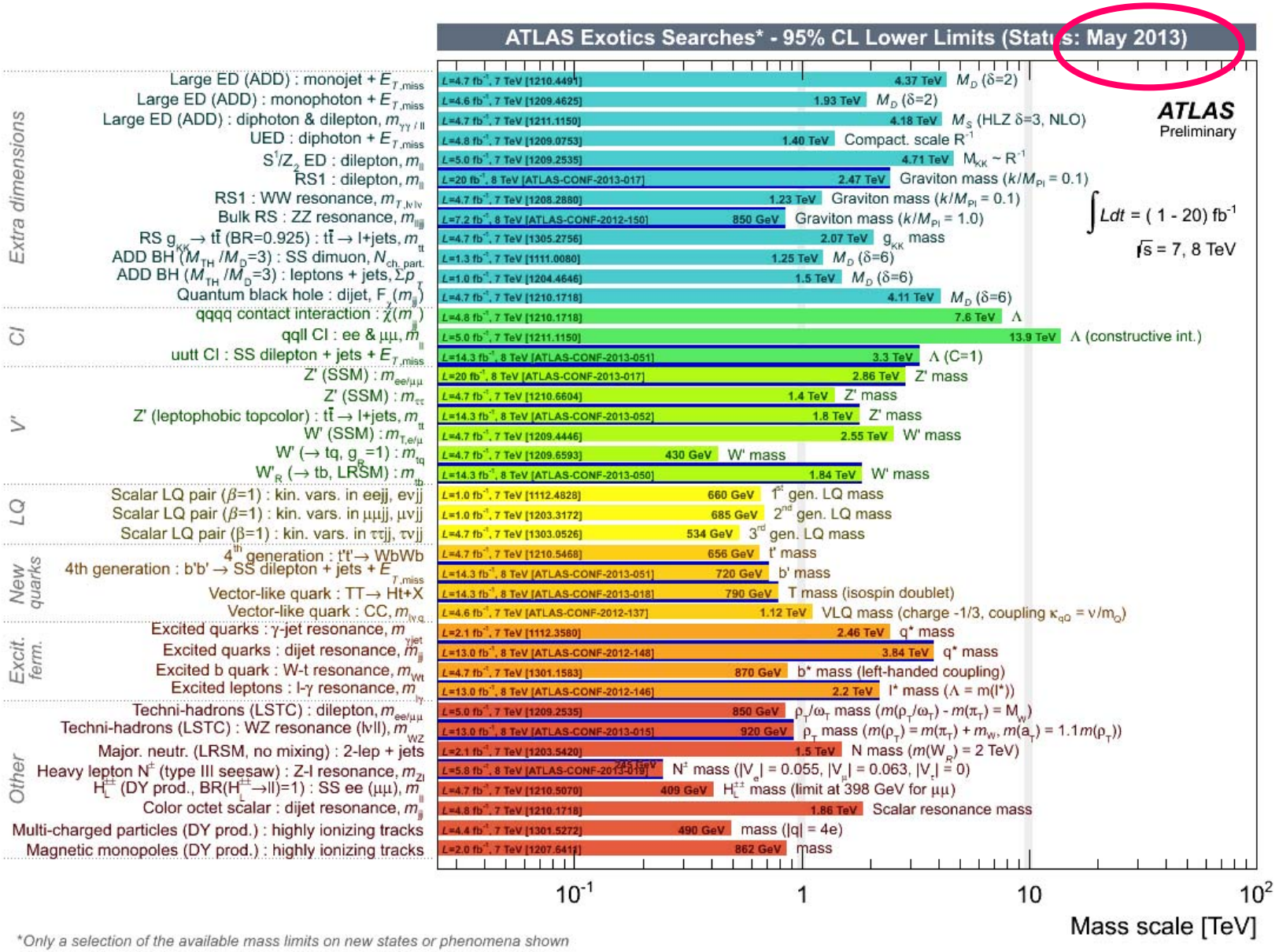
Search strategy

Several theories (+not yet thought of theories)



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, jet extinction, …*

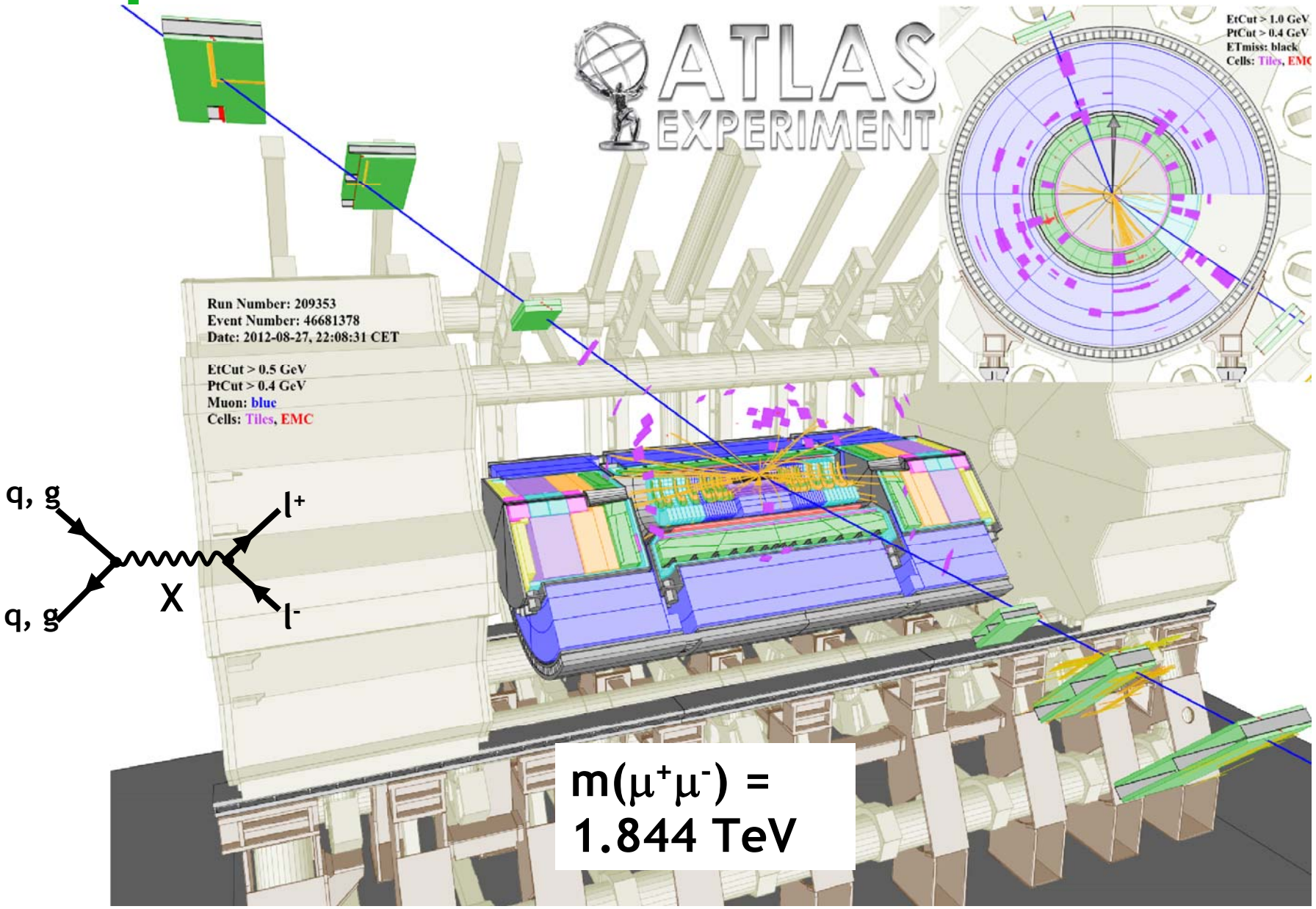
All results at 8 TeV, ~all limits at 95% C.L.

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)

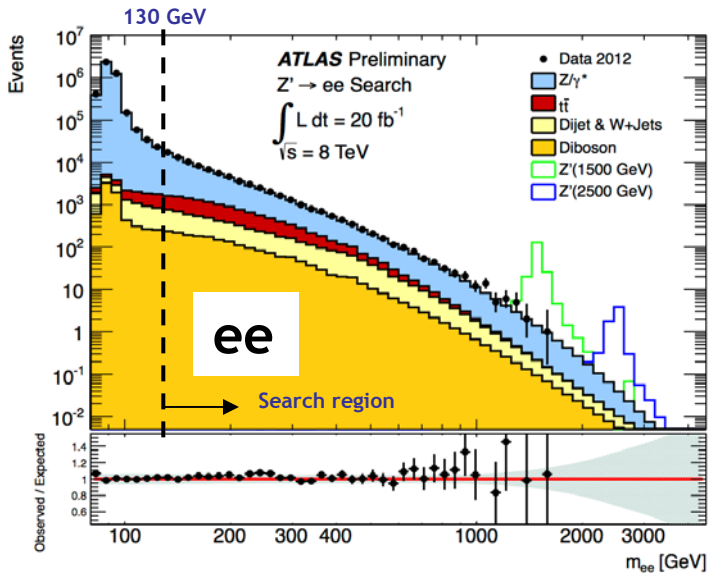
Dileptons

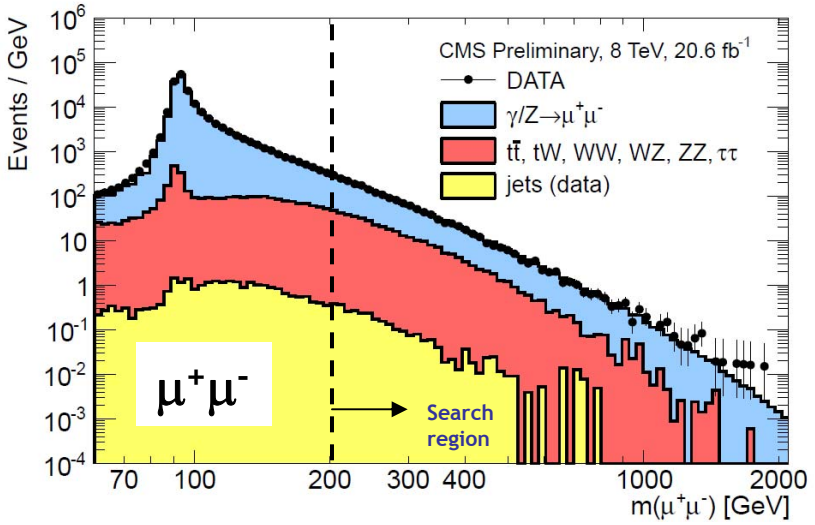

ATLAS
EXPERIMENT
Run Number: 209353
Event Number: 46681378
Date: 2012-08-27, 22:08:31 CET
EtCut > 0.5 GeV
PtCut > 0.4 GeV
Muon: blue
Cells: Tiles, EMC
EtCut > 1.0 GeV
PtCut > 0.4 GeV
ETmiss: black
Cells: Tiles, EMC
q, g
q, g
X
l+
l-
m(μ+μ-) =
1.844 TeV

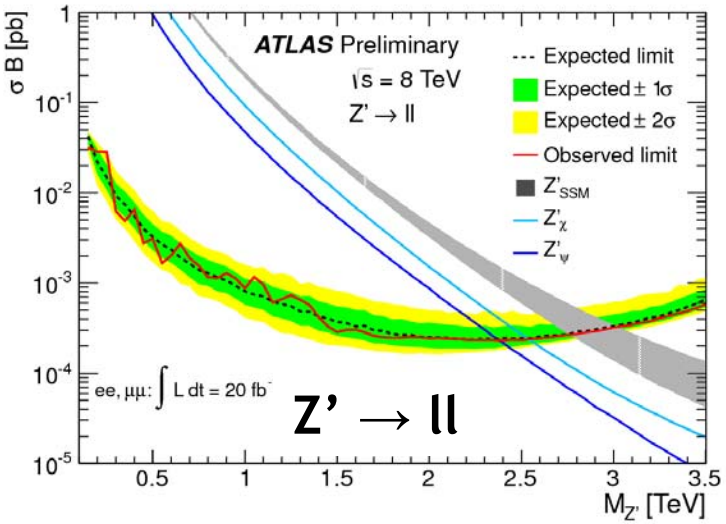
Dileptons

[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

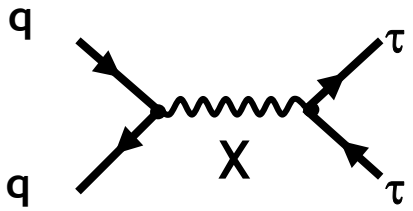
Model	ATLAS	CMS
SSM Z'	2.86	2.96
E_6 Z'_ψ	2.38	2.60
RS G* ($k/\bar{M}_{Pl}$=0.1)	2.47	

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)

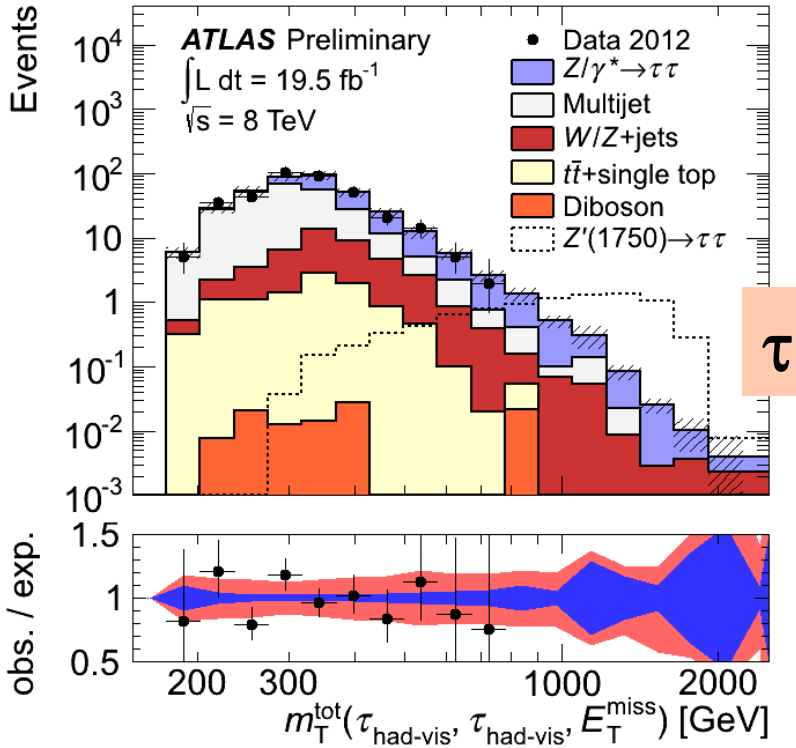
Ditaus

[ATLAS-CONF-2013-066]

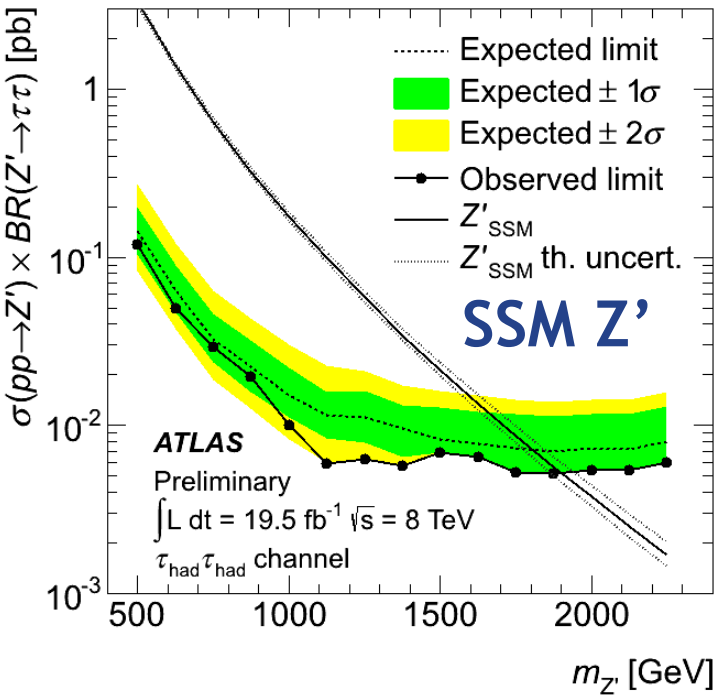


- Lepton universality not always required
- tau candidates = jets (1 or 3 tracks) with BDT identification
  (Boosted Decision Tree)
- $m_{\mathrm{T}}^{\mathrm{tot}} = \sqrt{2p_{\mathrm{T1}}p_{\mathrm{T2}}C + 2|E_{\mathrm{T}}^{\mathrm{miss}}|p_{\mathrm{T1}}C_1 + 2|E_{\mathrm{T}}^{\mathrm{miss}}|p_{\mathrm{T2}}C_2}$

  $C=1-\cos\Delta\phi$
- resolution 30-50%



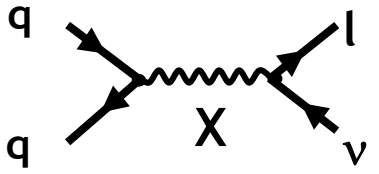
$\tau_h^+\tau_h^-$



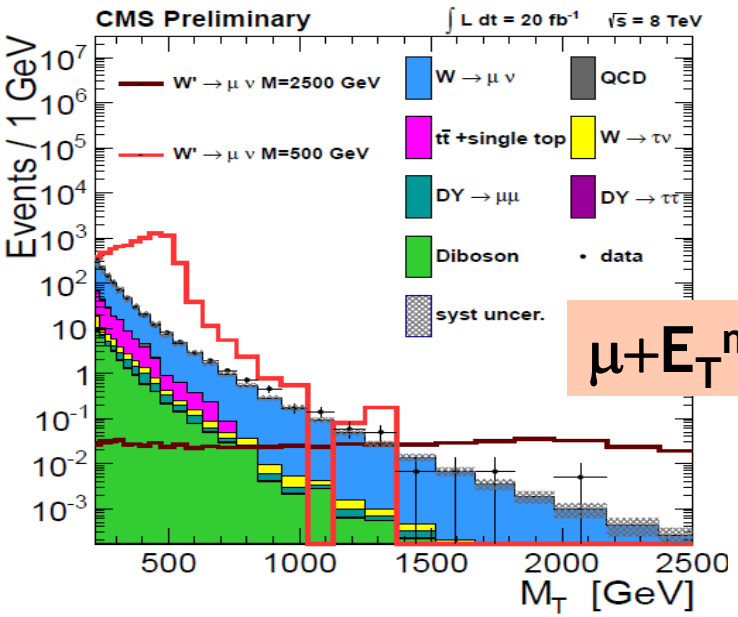
Model	Observed mass exclusion [TeV]
SSM Z'	[0.5,1.90]

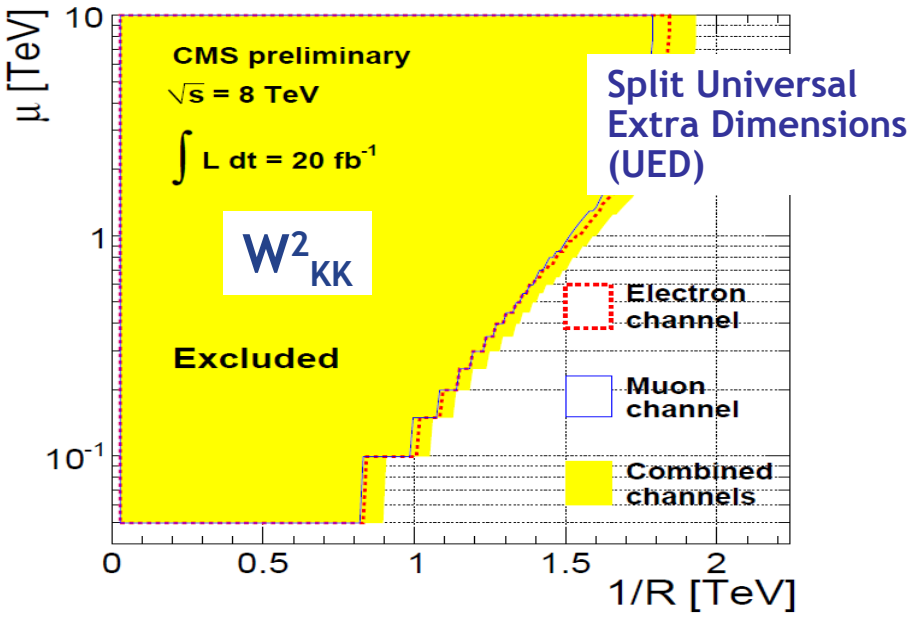
Lepton + missing E_T

[CMS-EXO-12-060]



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





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

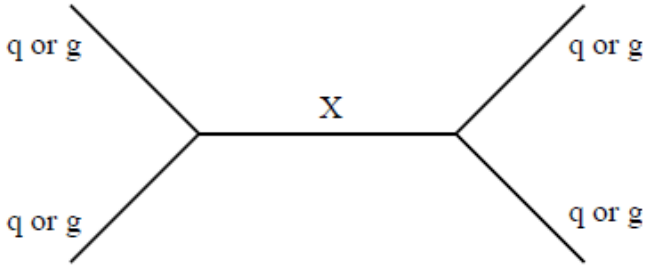
also non resonant interpretation: dark matter (see later)

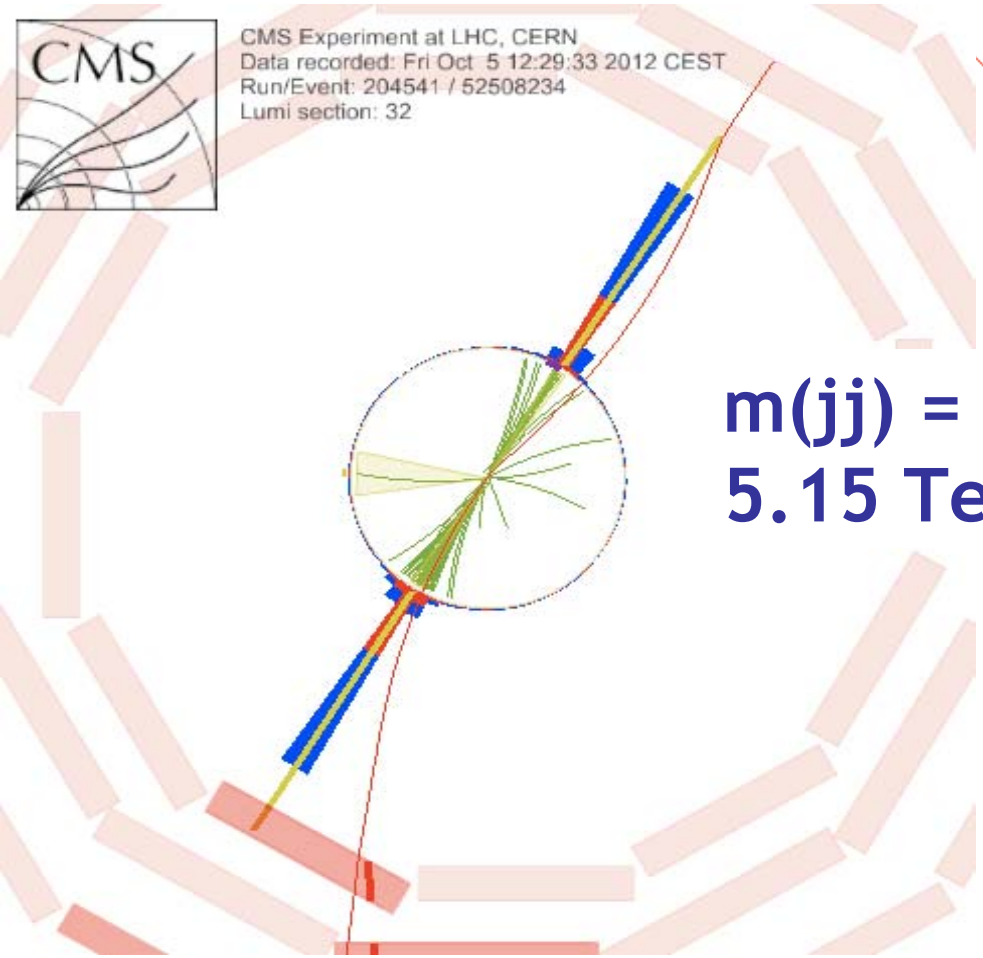
Singly produced resonances

- 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)

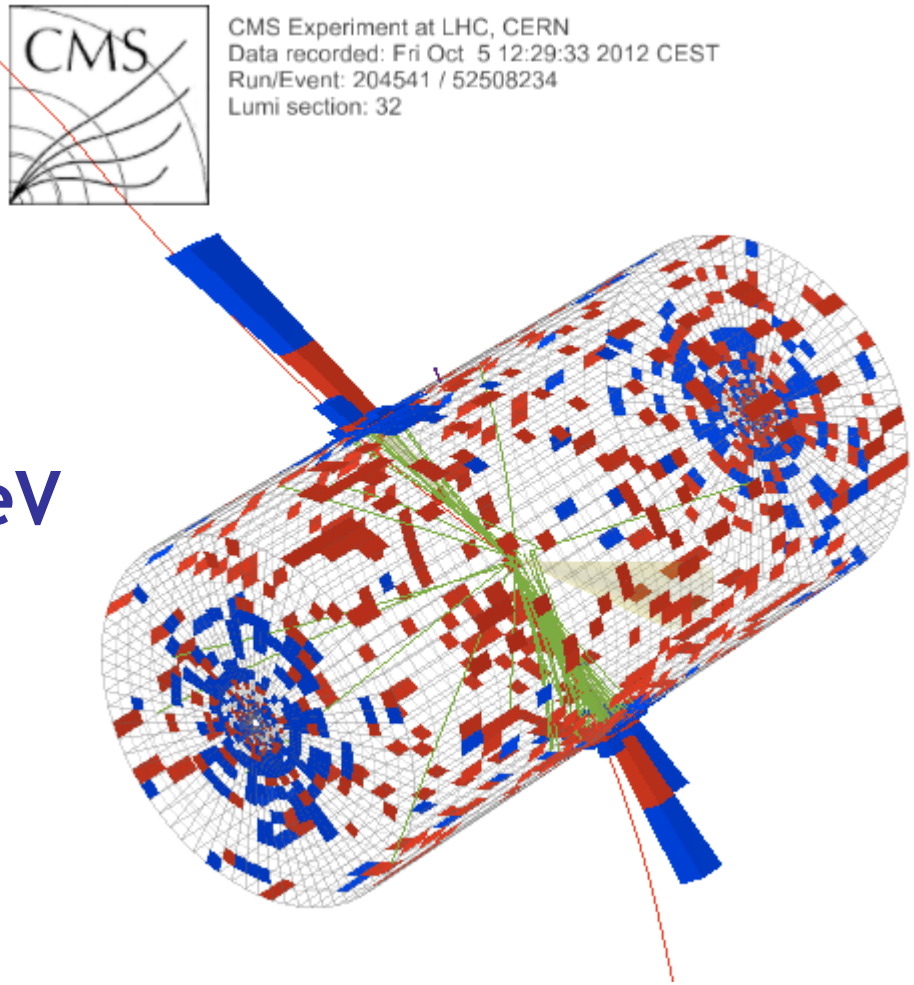
j_X=X-tagged jet

Dijets





m(jj) = 5.15 TeV

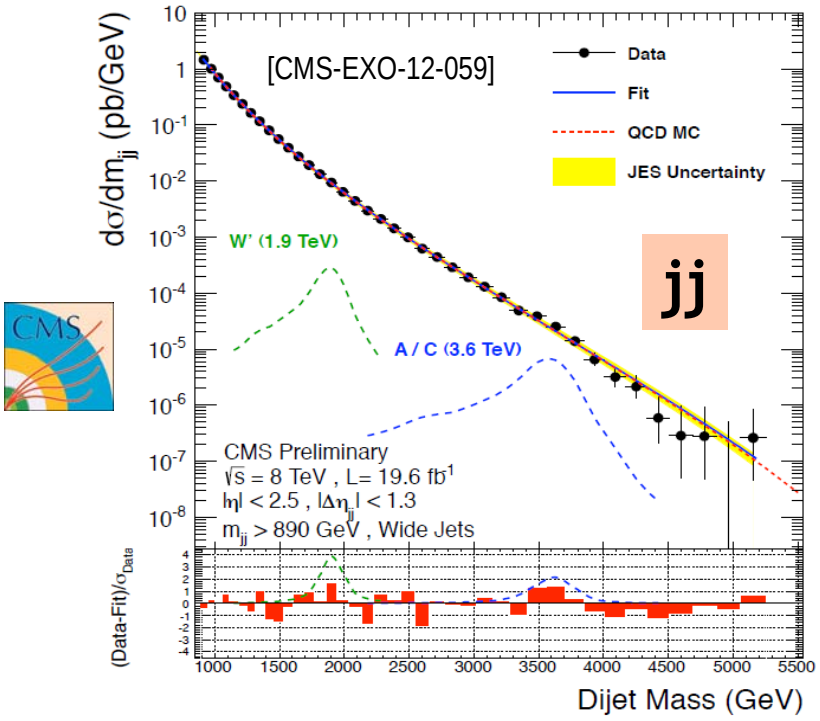


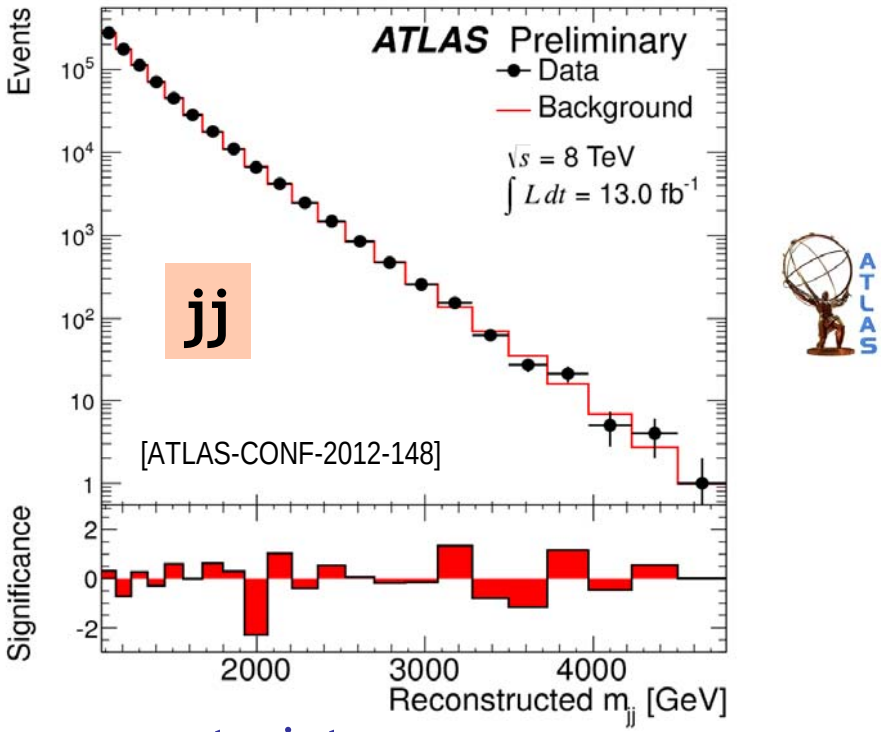
- probing quark structure up to 5 TeV!

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

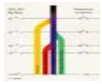
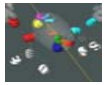
$$f(x) = p_1(1-x)^{p_2} x^{p_3+p_4 \ln x} \qquad x \equiv m_{jj}/\sqrt{s}$$



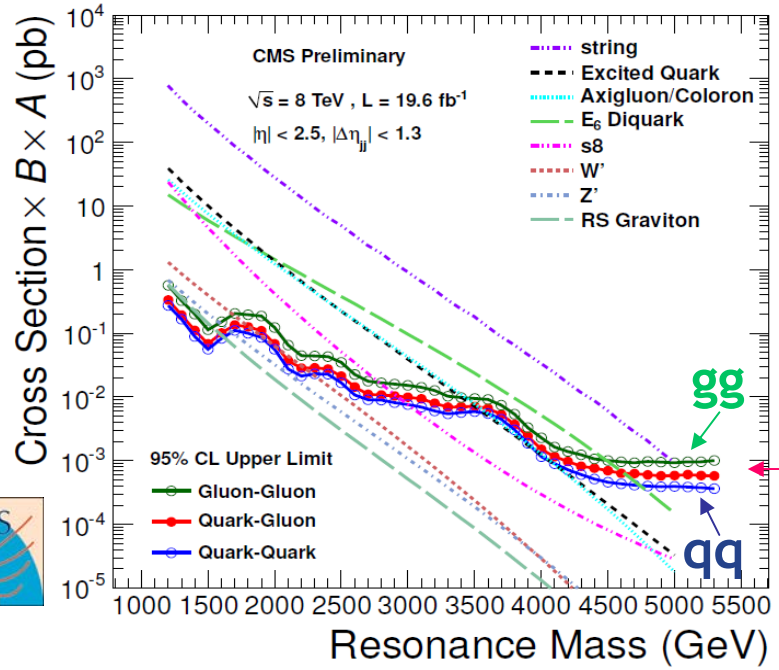


- mass threshold around 1 TeV due to trigger constraints
- specific strategies of ATLAS and CMS to recover sensitivity to masses < 1 TeV

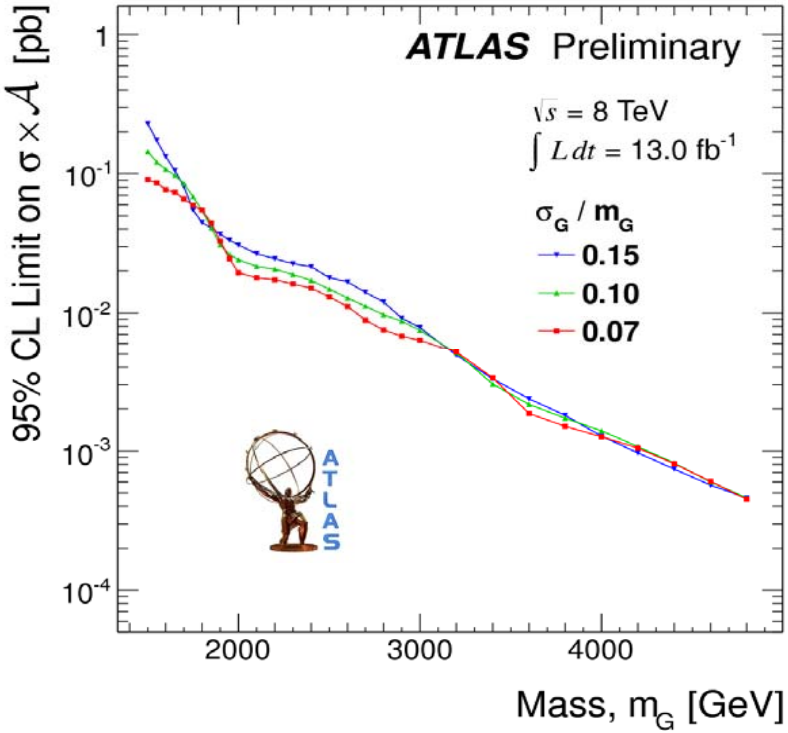
Dijets


[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]

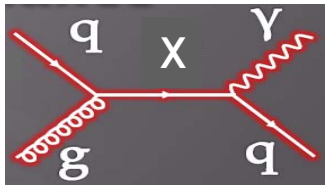
Observed mass exclusions

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

$f_s = f = f' = 1$

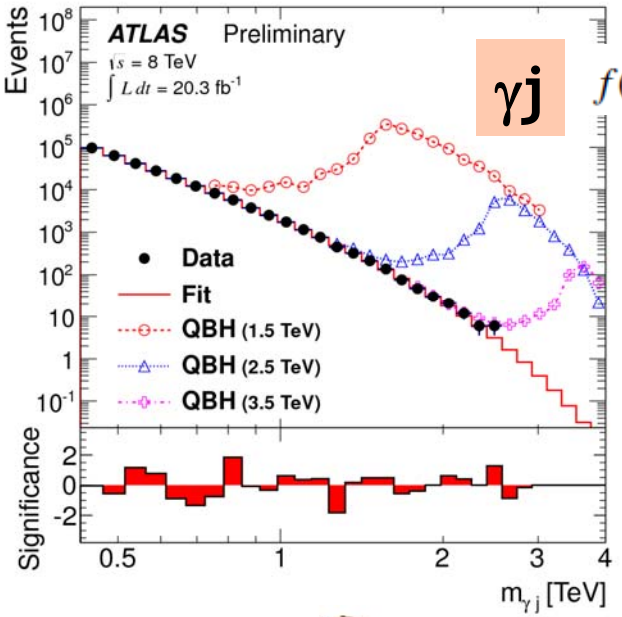
also non resonant interpretations with 7 TeV data

Digression: jet plus photon

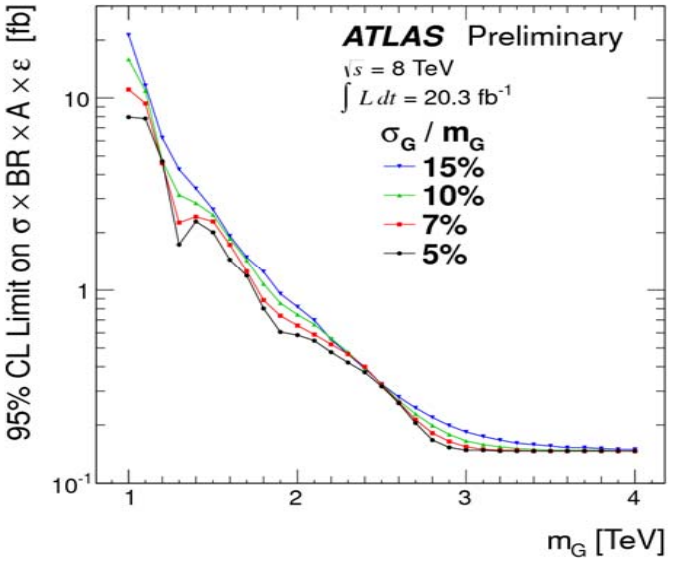


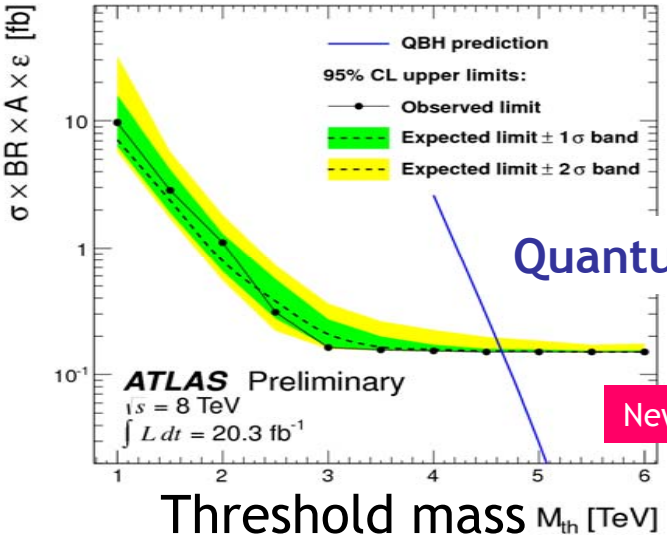
[ATLAS, arXiv:1309.3230]

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



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





Quantum Black Hole

New @ 8 TeV

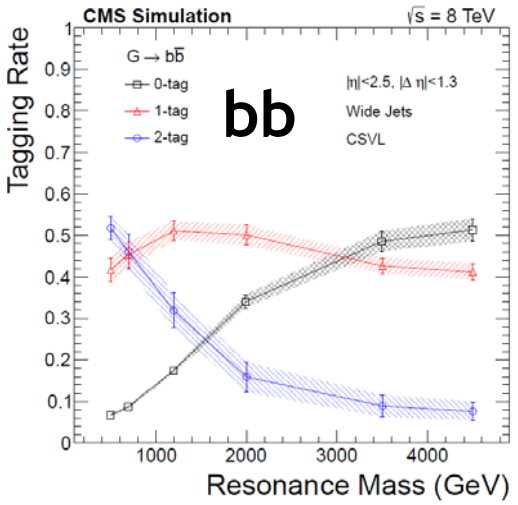
Model	Observed mass exclusion [TeV]
q* Λ=m(q*) $f_s = f = f' = 1$	[1.0,3.48]
QBH $n = 6$ and $M_D = M_{th}$	[1.0,4.65]

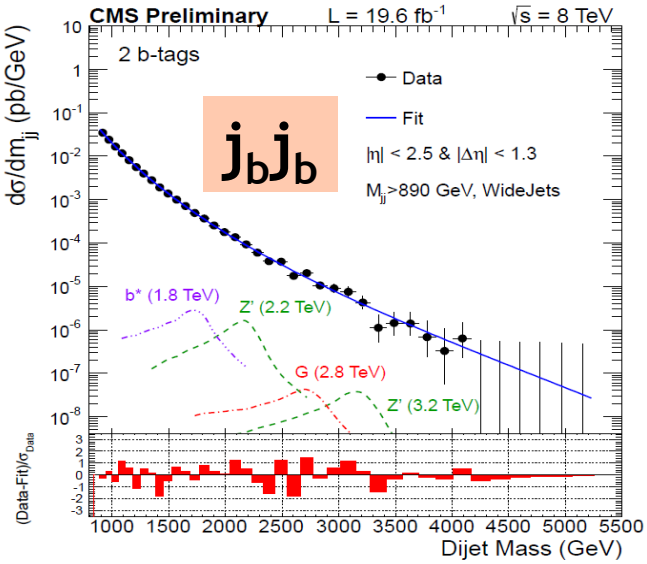
Dijets with b-tagging

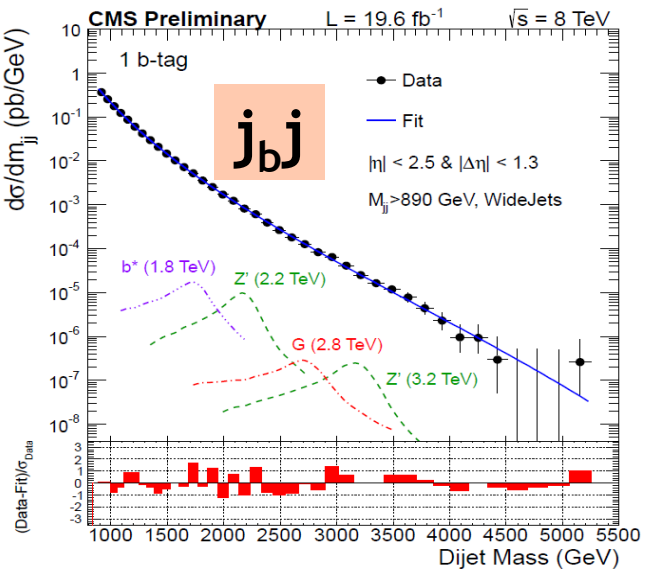
[CMS-EXO-12-023]

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

Tagging rates





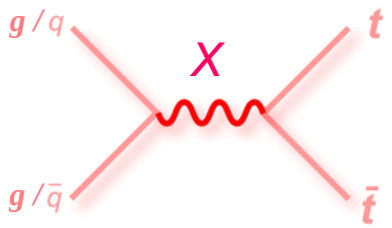


Model	Observed mass exclusions [TeV]
SSM Z' (f_{bb}=0.2)	[1.20 , 1.68]
RS G* ($k/\overline{M}_{Pl}$=0.1) (f_{bb}=0.1)	[1.42 , 1.57]
b*	[1.34 , 1.54]

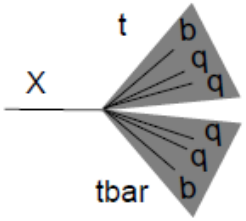
See also CMS search for excited top pairs (see bonus slides)

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

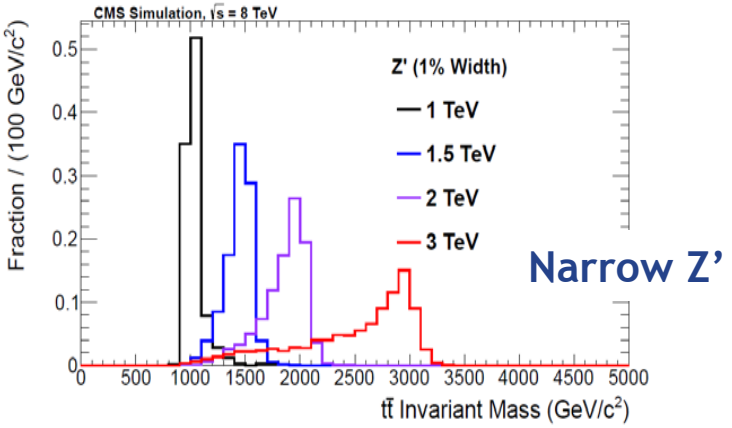
Dijets with top-tagging

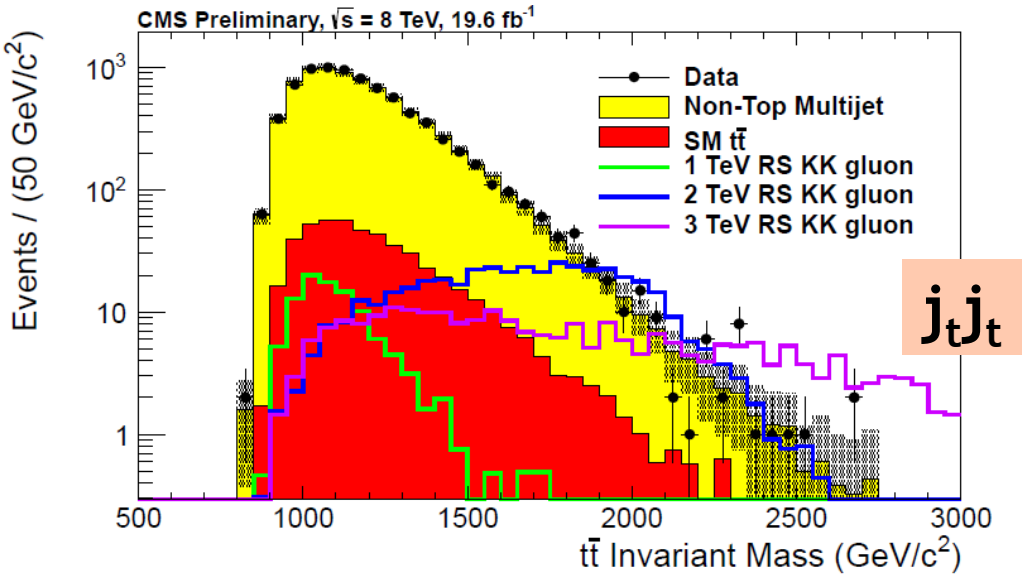


- All hadronic tt^{bar}
- Jets: Cambridge-Aachen R=0.8
- 2 leading jets Top-Tagged
- $|\Delta y| < 1.0$



[CMS-B2G-12-005]



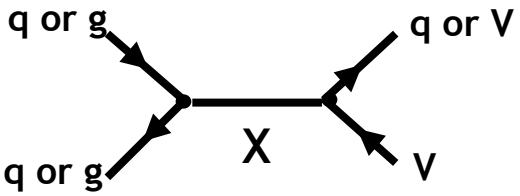


Model	Observed mass exclusions [TeV]
Narrow topcolor Z'	[1.0 ,1.7]
Wide topcolor Z'	[1.0, 2.35]
Bulk RS g_{KK}	[1.0, 1.8]

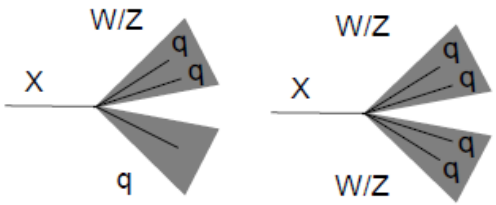
- Data driven multijet background

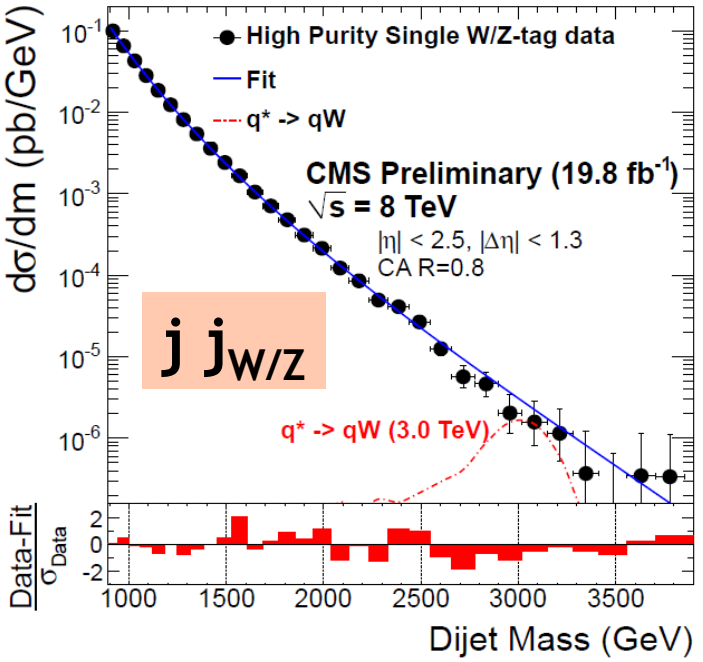
$BR(g_{KK} \rightarrow tt^{bar}) > 90\%$, $\Gamma/M \sim 15\%$

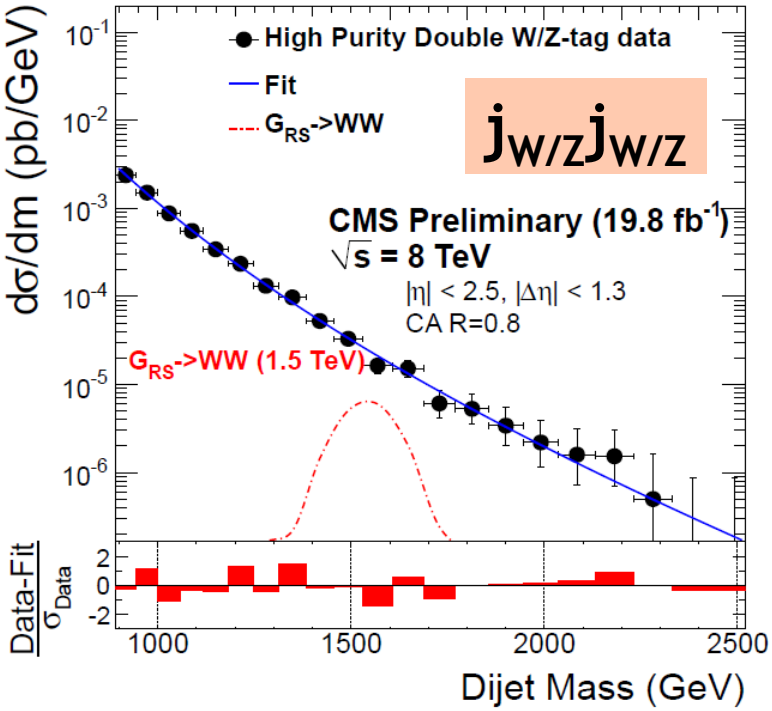
Dijets with W/Z-tagging



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







[CMS-EXO-12-024]

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

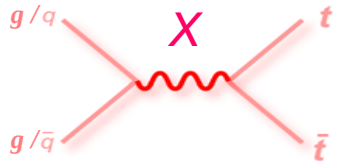
Model	Observed mass exclusions [TeV]
q* → qW → qZ	[1.0 , 3.23] [1.0 , 3.00]
SSM W' → WZ	[1.0 , 1.73]
RS G* → WW → ZZ	[1.0 , 1.59] [1.0 , 1.17]

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)

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
- smaller "small" and b-tagged jet multiplicity
- higher "wide" jet multiplicity
- 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)

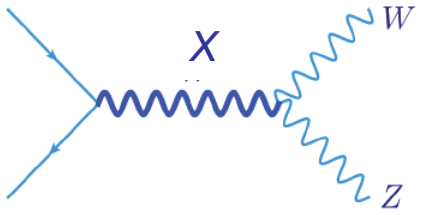
Singly produced resonances

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

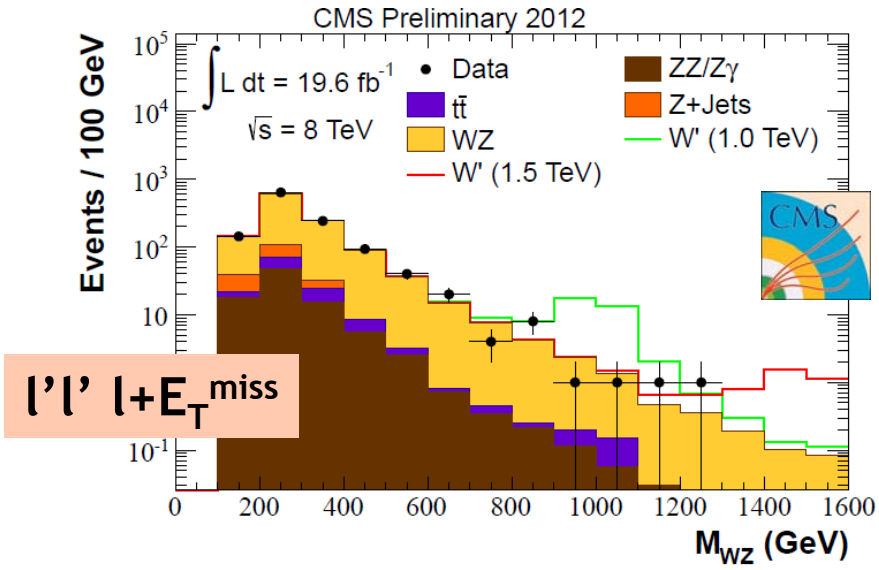
All leptonic WZ

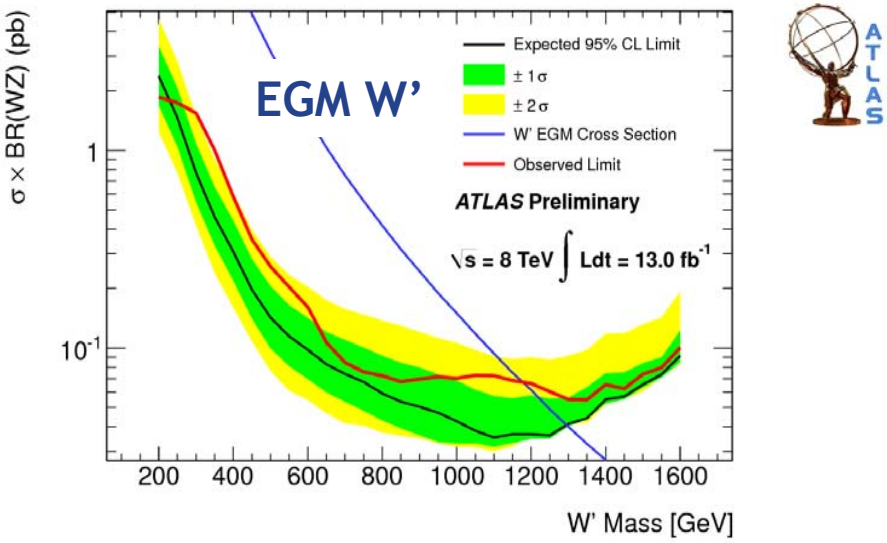
[CMS-EXO-12-025]

[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)

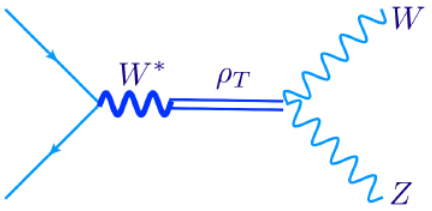
	ATLAS 13 fb^{-1}	CMS 20 fb^{-1}
SSM/EGM W'	1.18	1.45

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

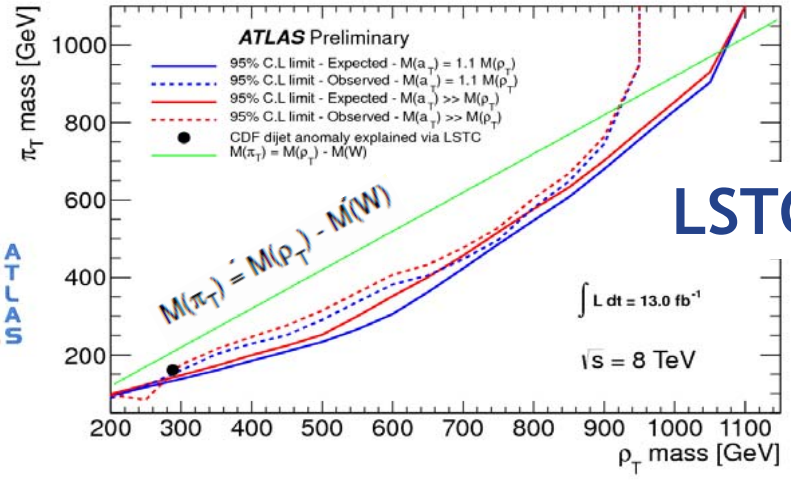
also semileptonic ZZ and WW:
bulk RS G*
(see bonus slides)

NEW

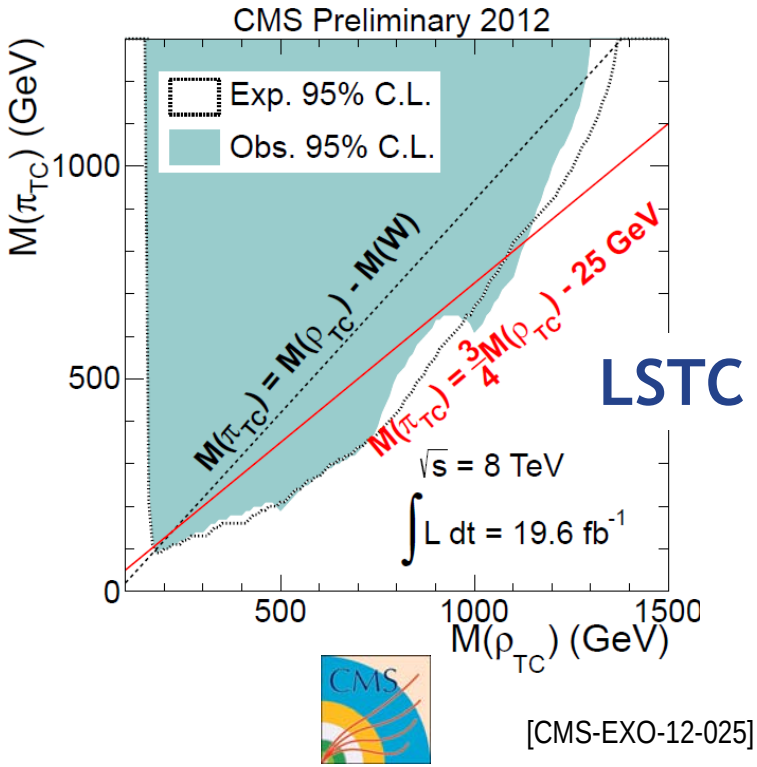
All leptonic WZ



[ATLAS-CONF-2013-015]

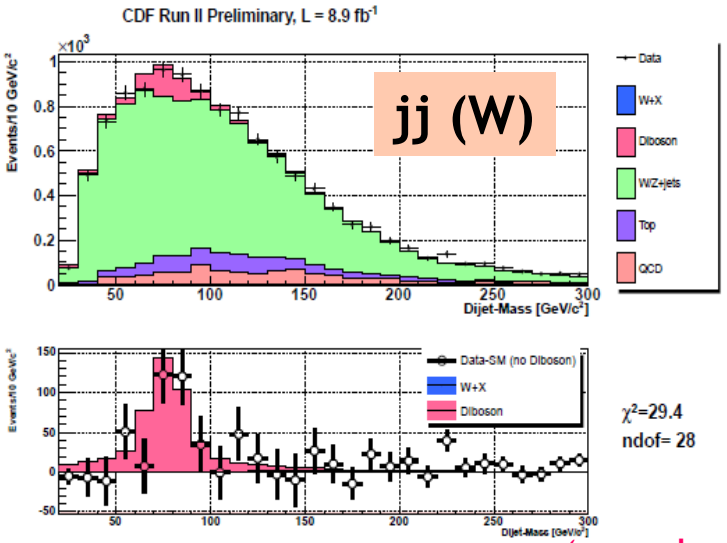


LSTC



LSTC

[CMS-EXO-12-025]



CDF 8.9 fb^{-1}

Full dataset!

[CDF Public Note 10973]

- The anomaly is gone

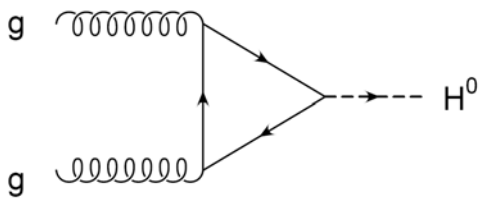
(see also dedicated dijet+W/Z search in bonus slides)

Pair produced resonances

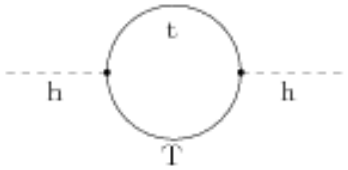
- new heavy quarks

New heavy quarks

- 4th generation chiral quarks: t' → bW, b' → 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 → Hq, Q → Zq (FCNC)
  - m(H)=125 GeV ➔ known BRs

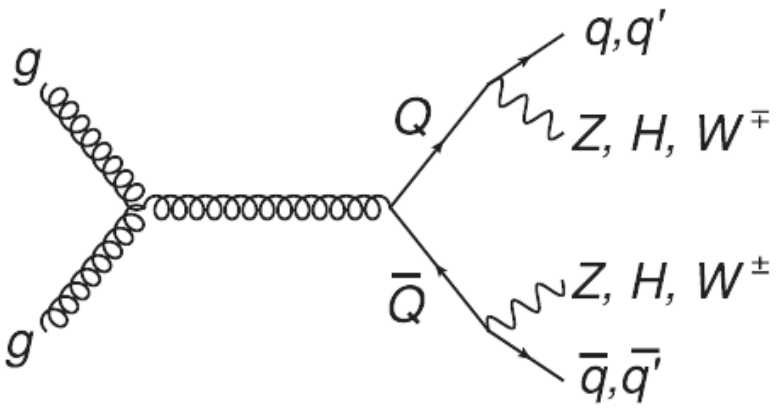


- VLQ generally assumed to couple to third generation

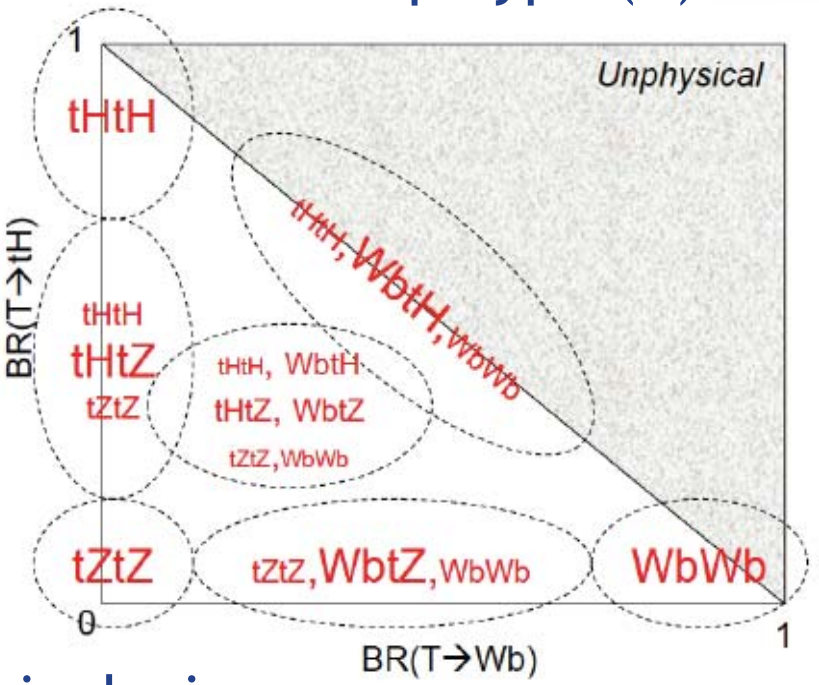
$$BR(Q \to Wq') + BR(Q \to Zq) + BR(Q \to Hq) = 1$$

Vector Like Quarks

- so far mostly searched in pair production



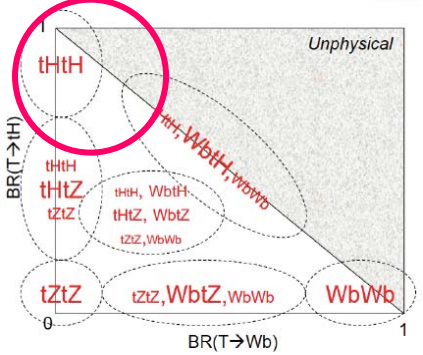
ex. up-type (T):

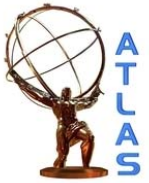


- many combinations
- two possible paths: dedicated or inclusive

TT → Ht+X

[ATLAS-CONF-2013-018]



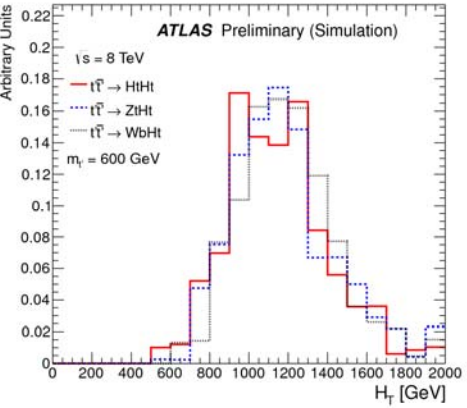


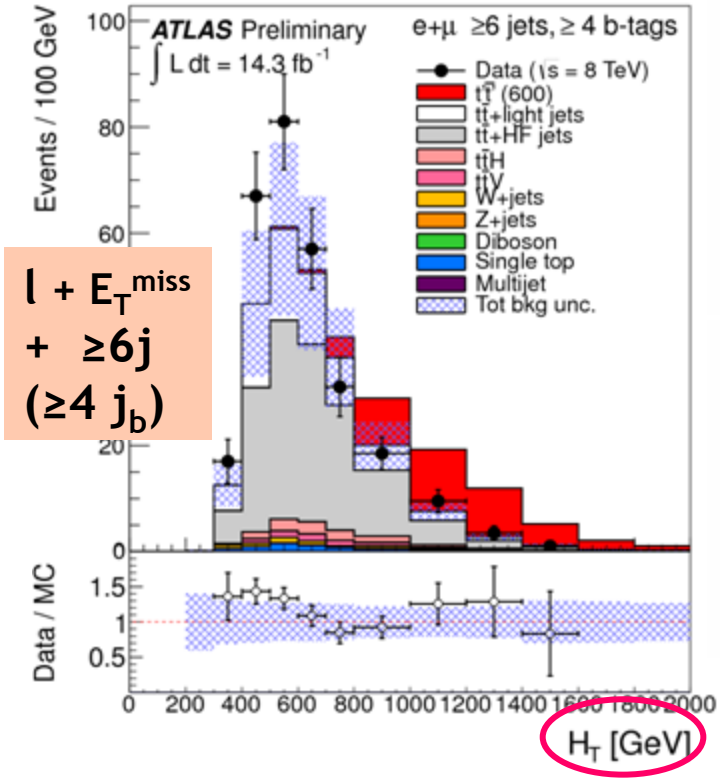
14 fb^{-1}

- at least one H→bb ➔ bbWb+X

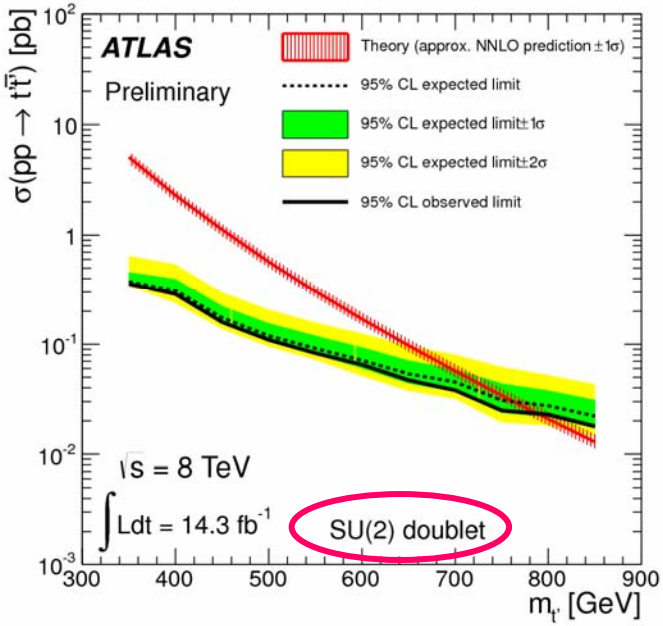
(X→≥1 b, at least one W →lν)

- main background: tt^{bar}+jets
- H_T= Σ |p_T| (l + E_T^{miss} + all j)

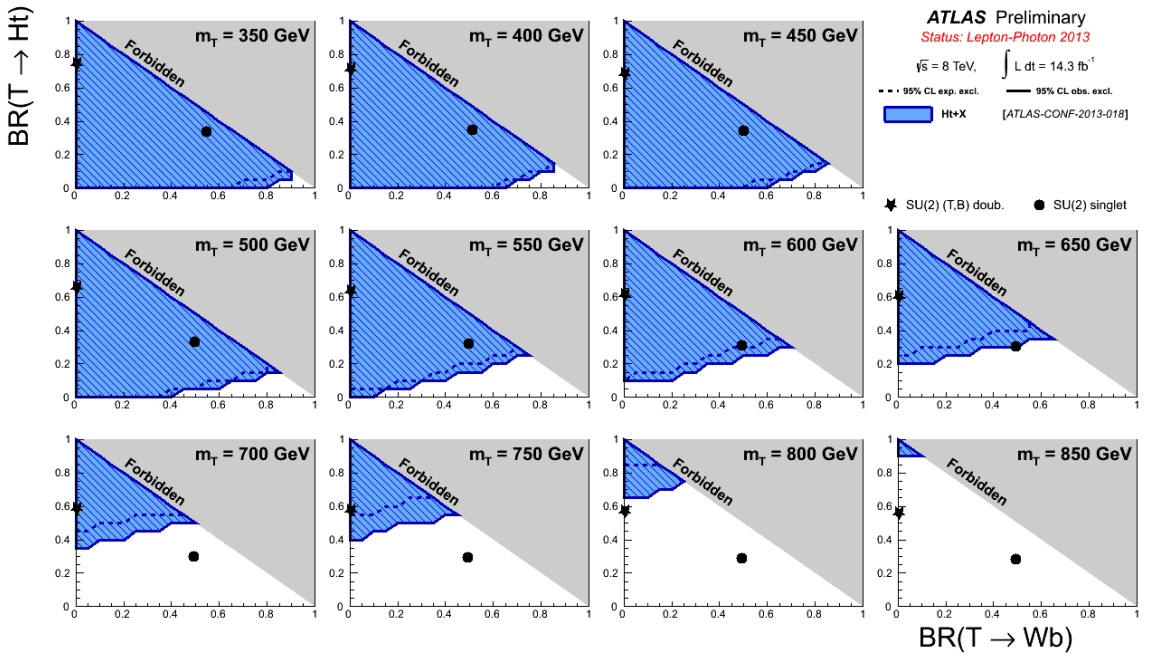




l + E_T^{miss} + ≥6j (≥4 j_b)



TT

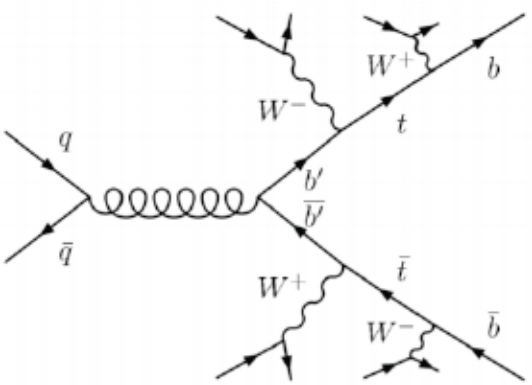

ATLAS Preliminary
Status: Lepton-Photon 2013
√s = 8 TeV, ∫ L dt = 14.3 fb⁻¹
95% CL exp. excl.
95% CL obs. excl.
Ht+X
[ATLAS-CONF-2013-018]
SU(2) (T,B) doub.
SU(2) singlet
BR(T → Ht)
BR(T → Wb)
m_T = 350 GeV
m_T = 400 GeV
m_T = 450 GeV
m_T = 500 GeV
m_T = 550 GeV
m_T = 600 GeV
m_T = 650 GeV
m_T = 700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

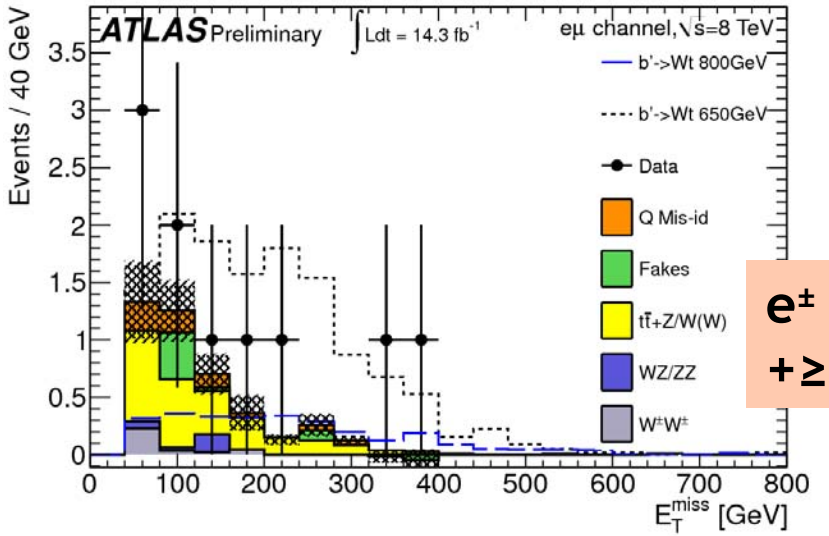
Inclusive BB, TT: same sign leptons

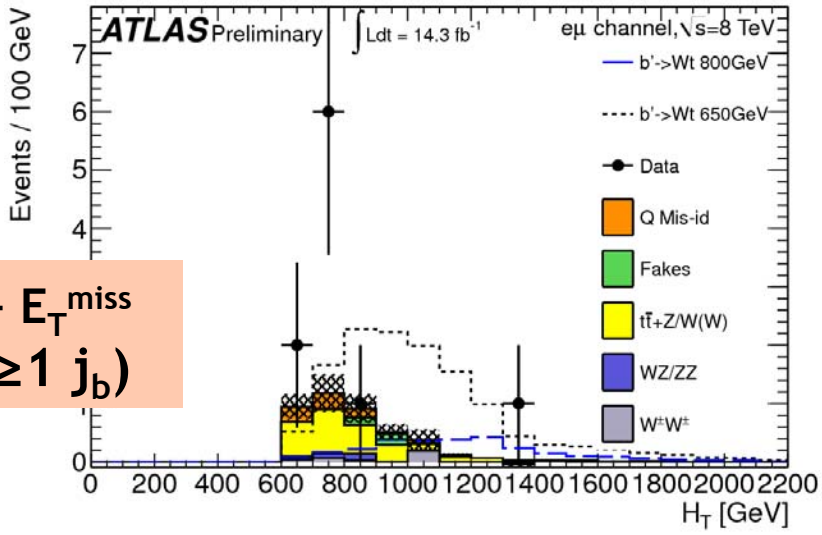
[ATLAS-CONF-2013-051]

14 fb^{-1}

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

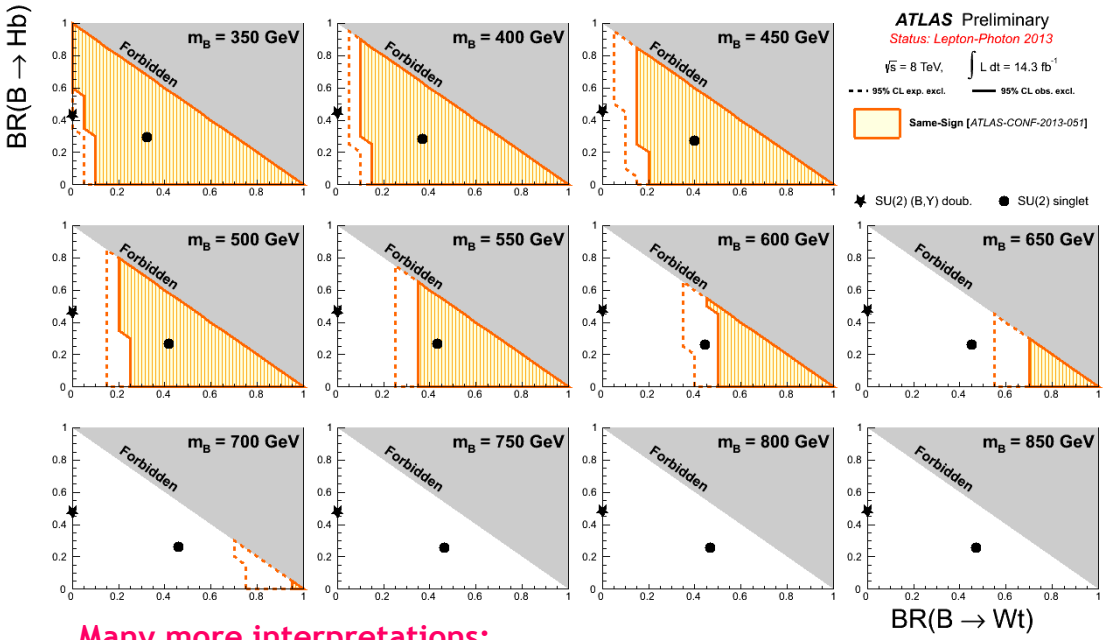






$e^{\pm}\ \mu^{\pm}$ + E_T^{miss} +≥2j (≥1 j_b)

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

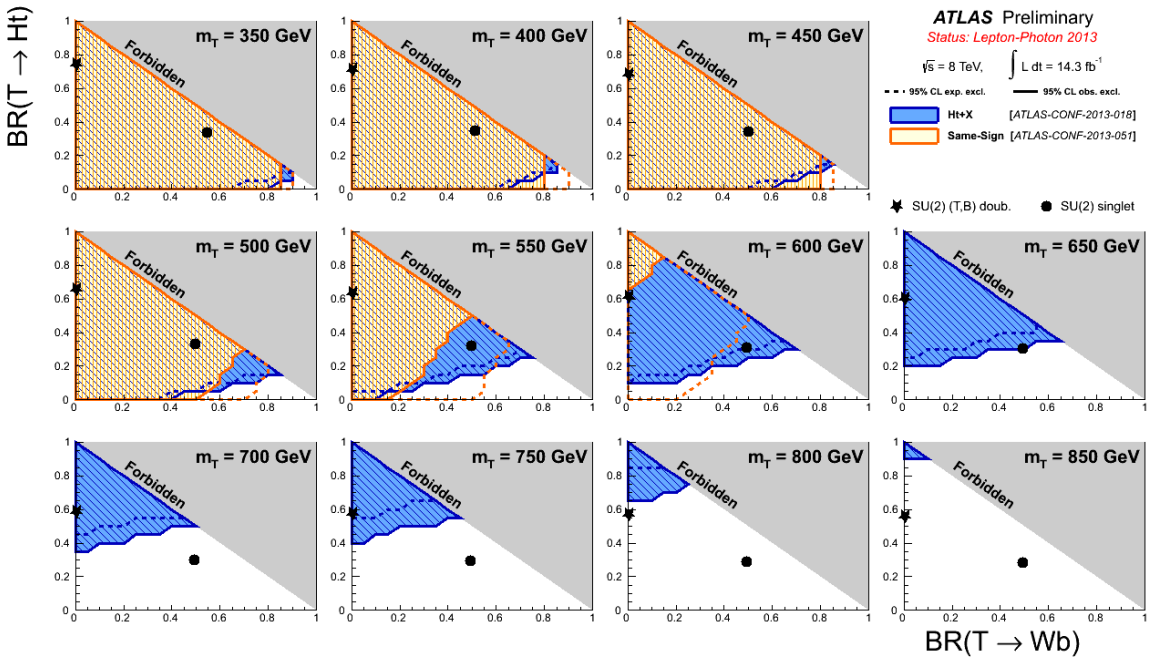


BB

Many more interpretations:

- chiral b'
- 4 top production
- same sign top pairs

TT

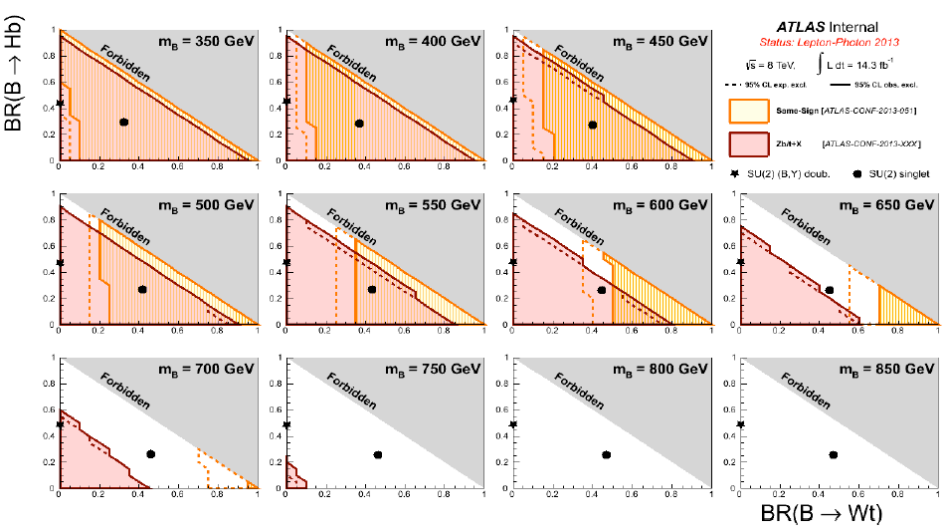


BB, TT: the full picture

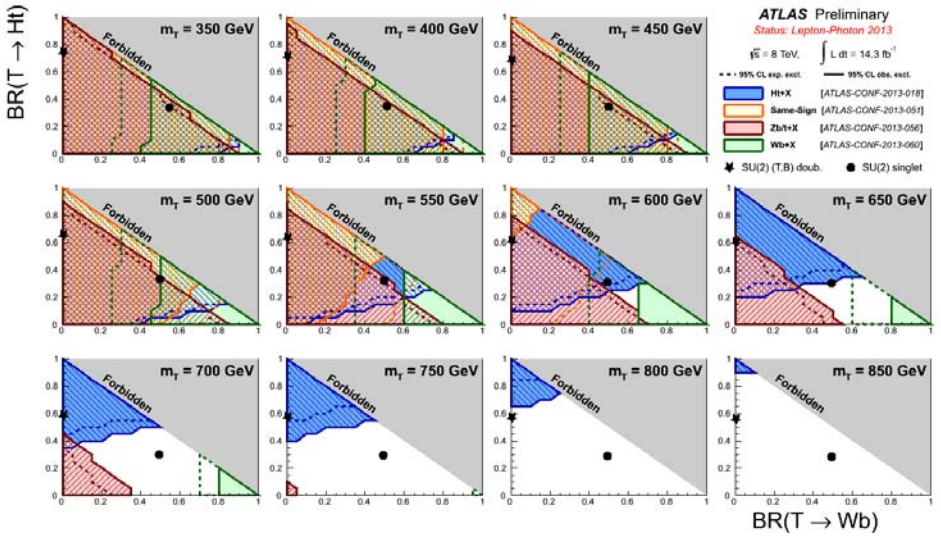
Two more analyses: BB, TT → Zb+X, Zt+X, TT → WbWb

(see backup)

BB



TT

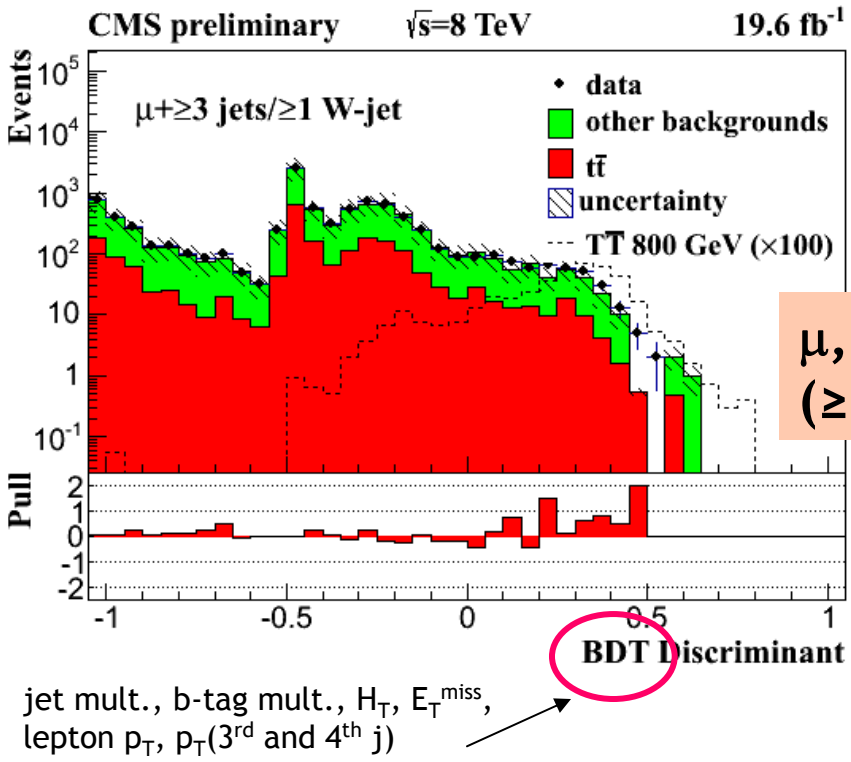


Combination will be more powerful than simple superimposition

Inclusive TT

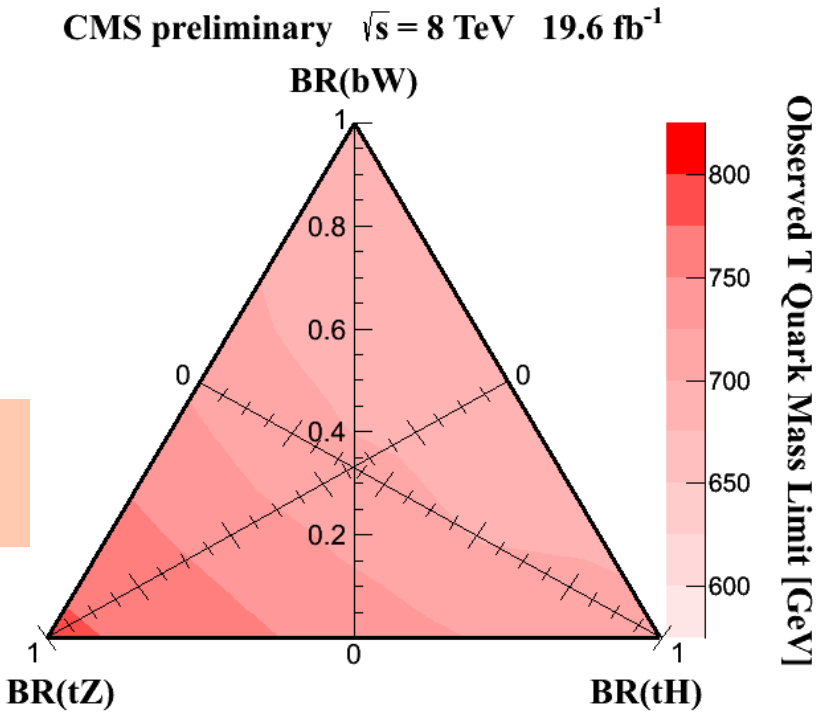
[CMS-B2G-12-015]

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



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

μ, ≥ 3 j (≥1 j_W)



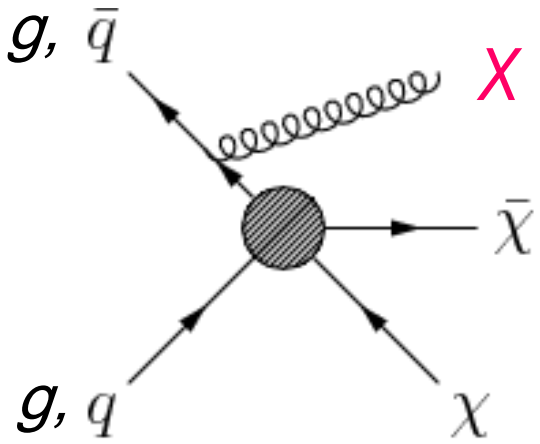
also inclusive BB analysis (see bonus slides)

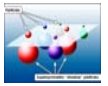
NEW

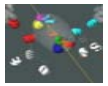
Other signatures

- mono-jets, mono-W
- black holes
- jet extinction
- inclusive multilepton

Mono-X





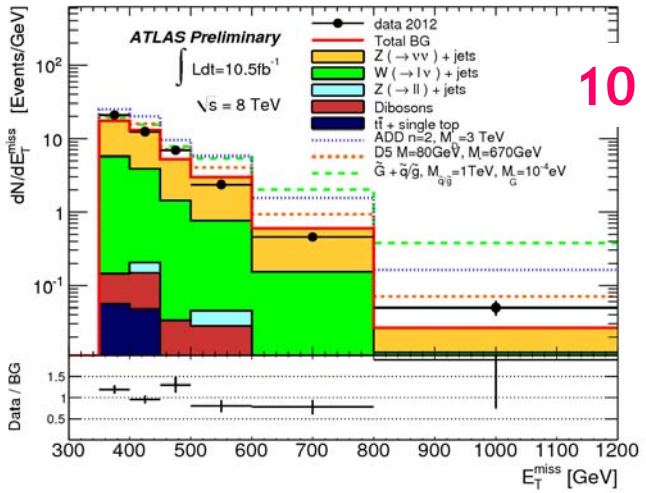


- X = gluon, photon, W, Z, …
- many interpretations
  - supersymmetry
  - large extra-dimensions (ADD): $\chi\chi^{bar}$=G*
  - Dark Matter: χ = Weakly Interacting Massive Particle (WIMP)
  - …
- main backgrounds: Z+X, Z→ $\nu\nu$, instrumental

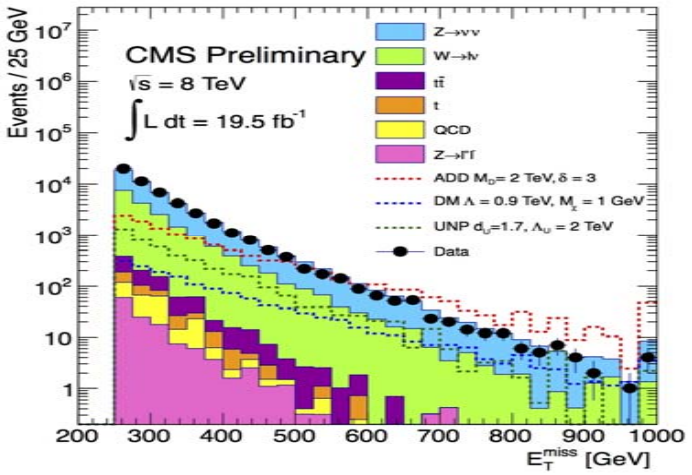
Mono-jet

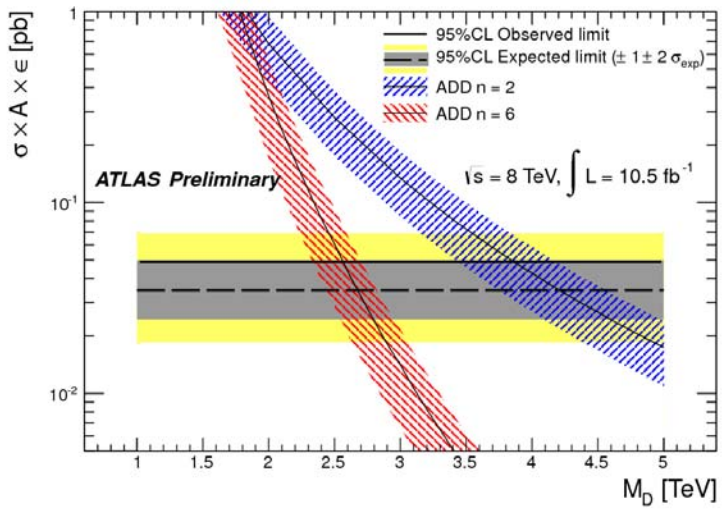
[ATLAS-CONF-2012-147] [CMS-EXO-12-048]

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



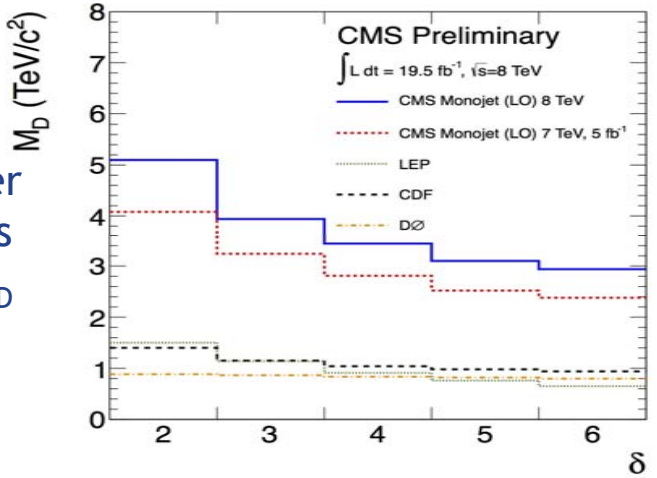
10 fb^{-1}





ADD

Lower limits on M_D



number of extra-dim.

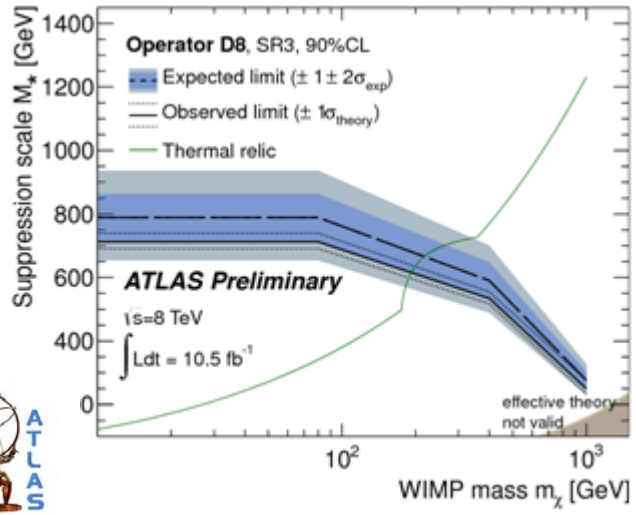
also **Unparticle** interpretation

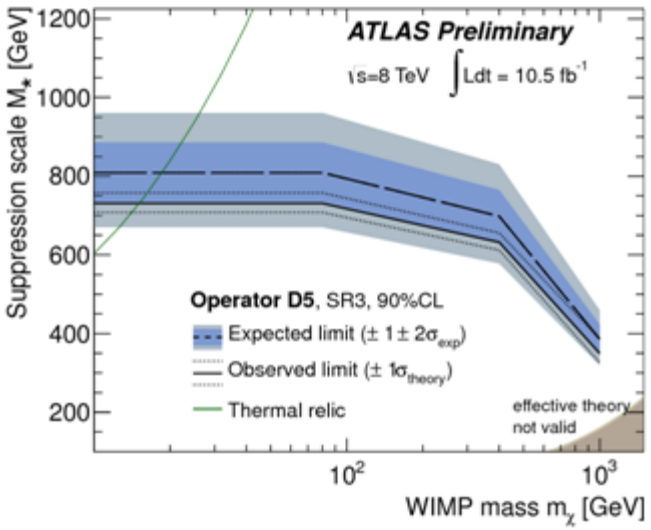
Mono-jet

- Dark Matter interpretation (Dirac fermion)

[ATLAS-CONF-2012-147]

10 fb^{-1}





Lower limits on

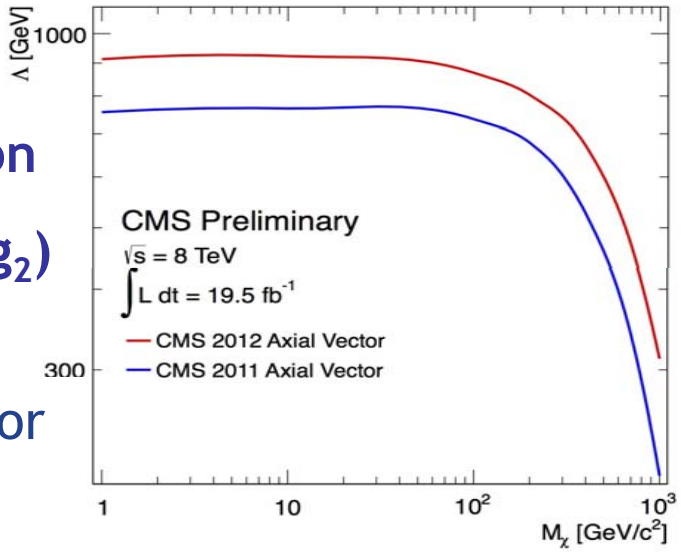
$M^* = \Lambda = M/\sqrt{(g_1\, g_2)}$

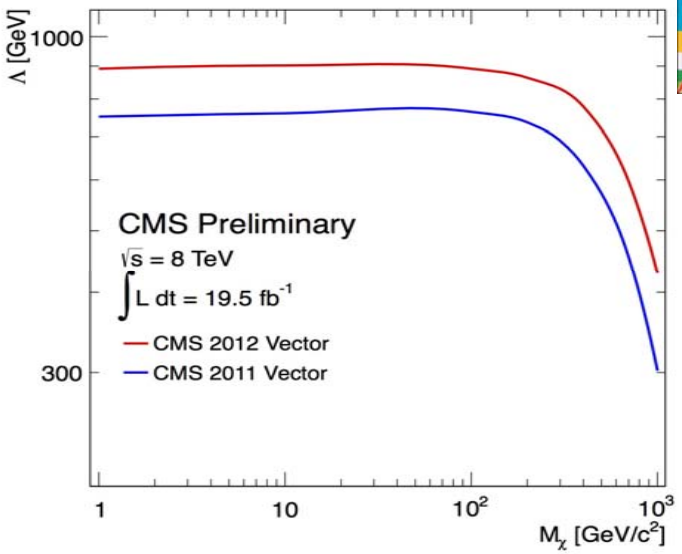
D8 ≡ axial vector

D5 ≡ vector

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

[CMS-EXO-12-048]

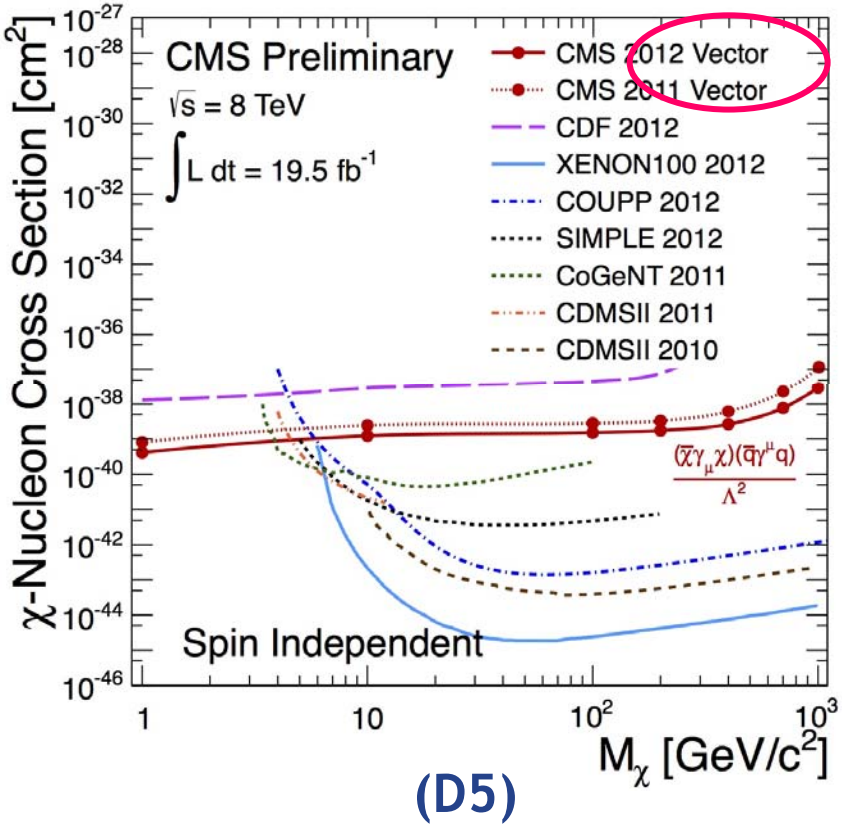




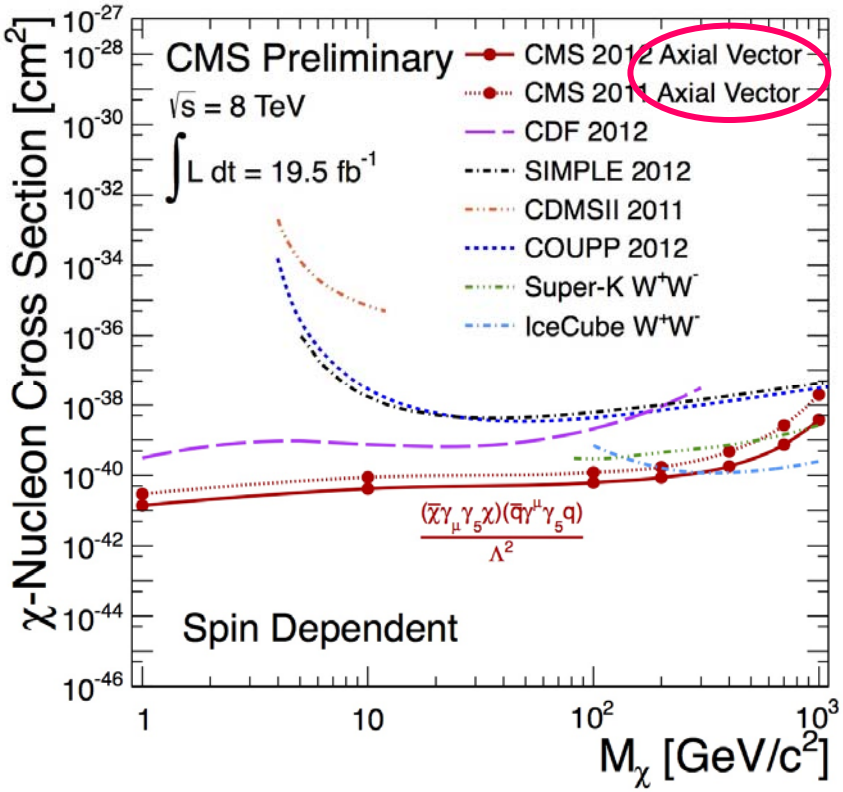
Mono-jet

[CMS-EXO-12-048]

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



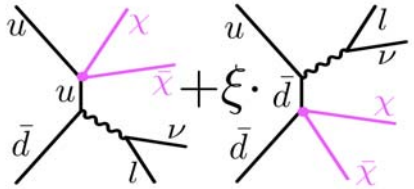
(D5)



(D8)

Some references on validity of EFT and alternative models in bonus slides

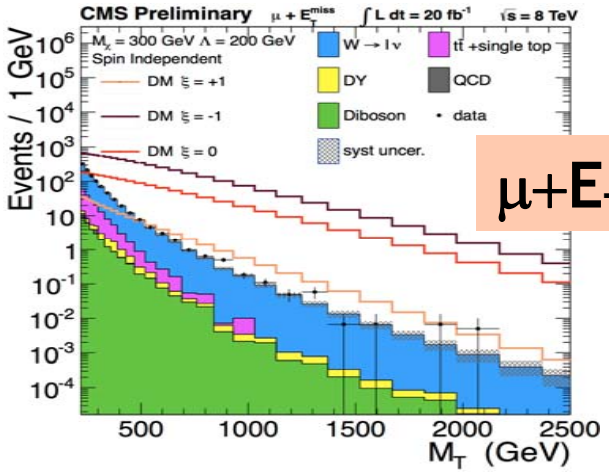
Mono-W



[ATLAS-CONF-2013-073]

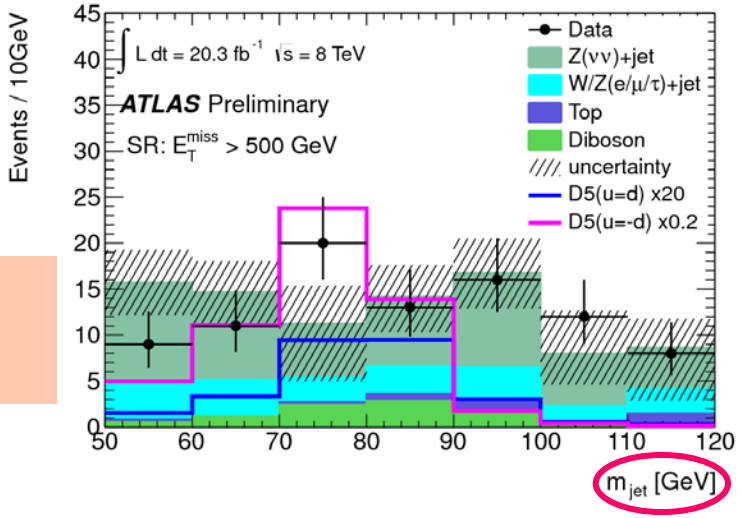
- W→l ν [CMS-EXO-13-004]
- W' analysis re-interpretation

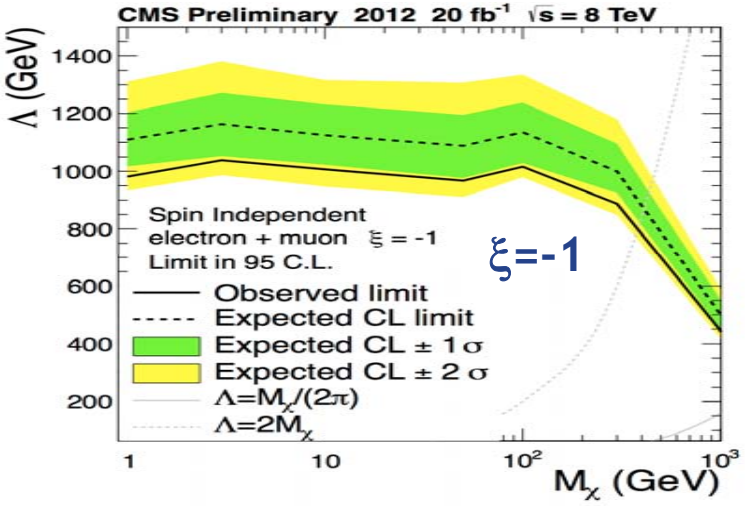
- W → qq, Z → qq
- jets: CA R= 1.2



$\mu + E_T^{miss}$

$J + E_T^{miss}$



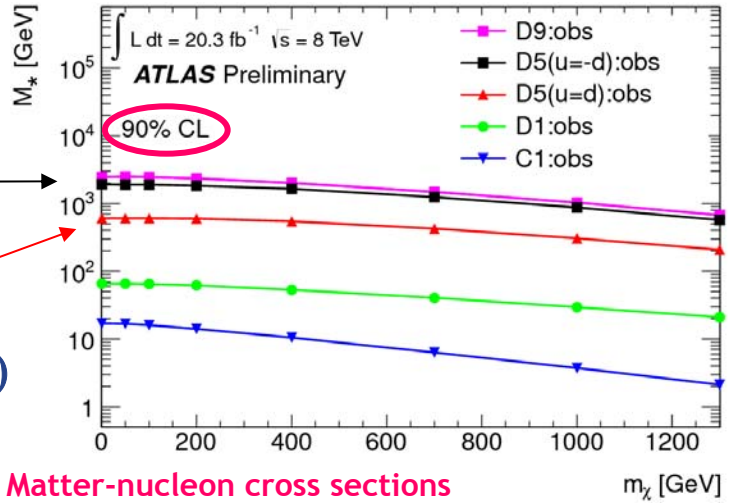


Lower limits

ξ=-1

ξ=+1

vector (≡ D5)



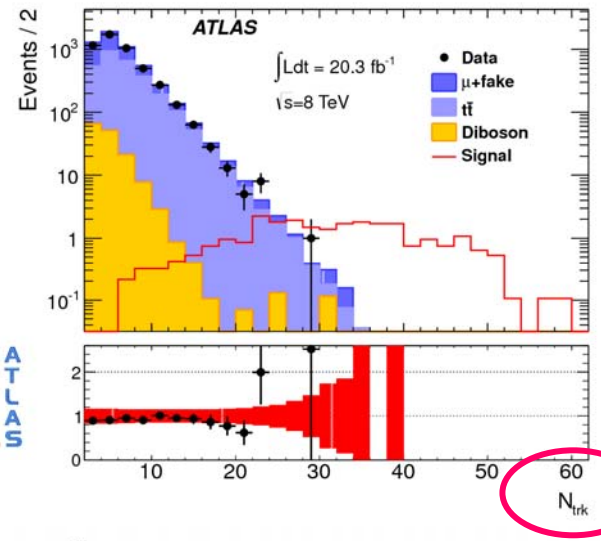
Also limits on Dark Matter-nucleon cross sections

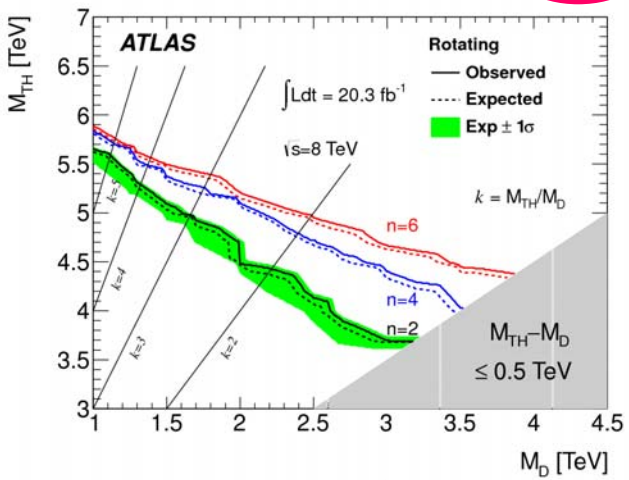
Black Holes

[ATLAS arXiv:1308.4075, PRD88,072001(2013)]

[CMS JHEP07(2013)178]

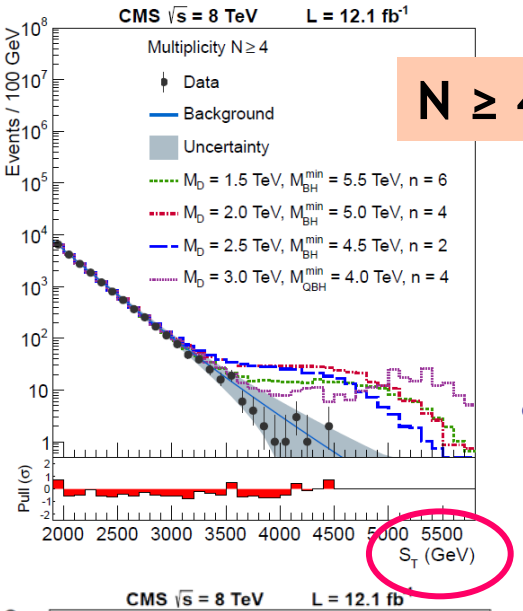
- at least 2 same charge muons
- track multiplicity ≥ 30





Similar limits for non rotating black holes

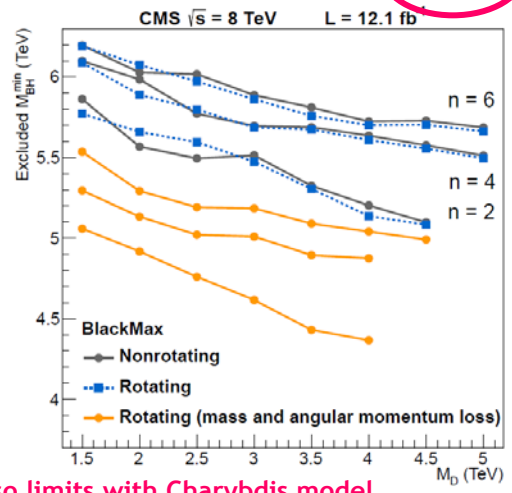
- at least 2 jets
- 10 multiplicity bins (up to ≥10)



N ≥ 4

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

Lower limits on production threshold



12 fb^{-1}

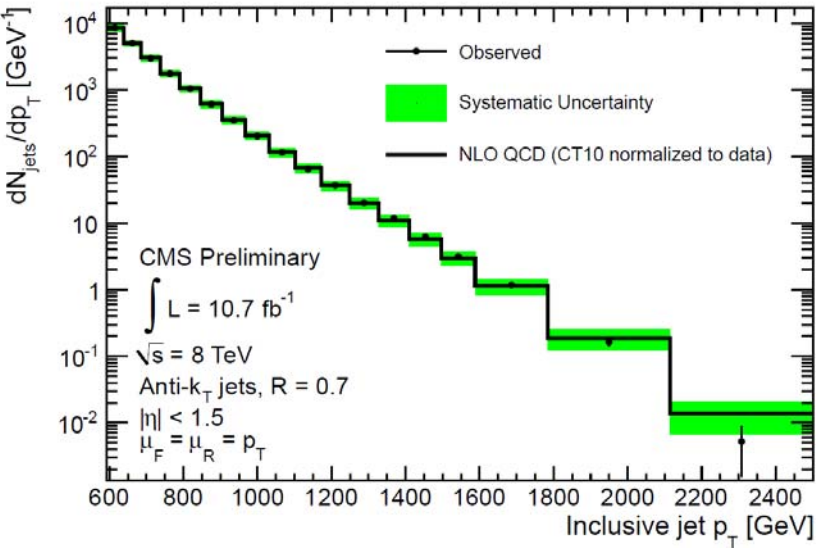
Also limits on QBH for N=2,3

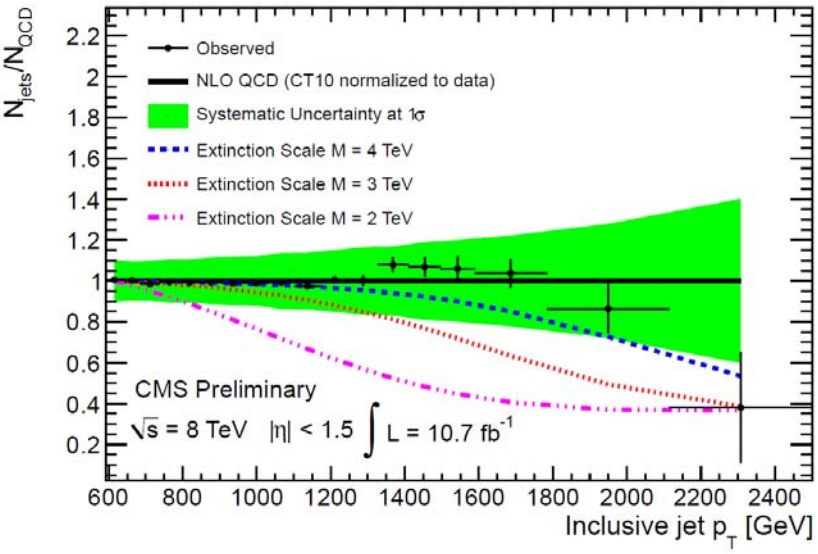
Also limits with Charybdis model

Jet extinction

[CMS-EXO-12-048]

10.7 fb^{-1}





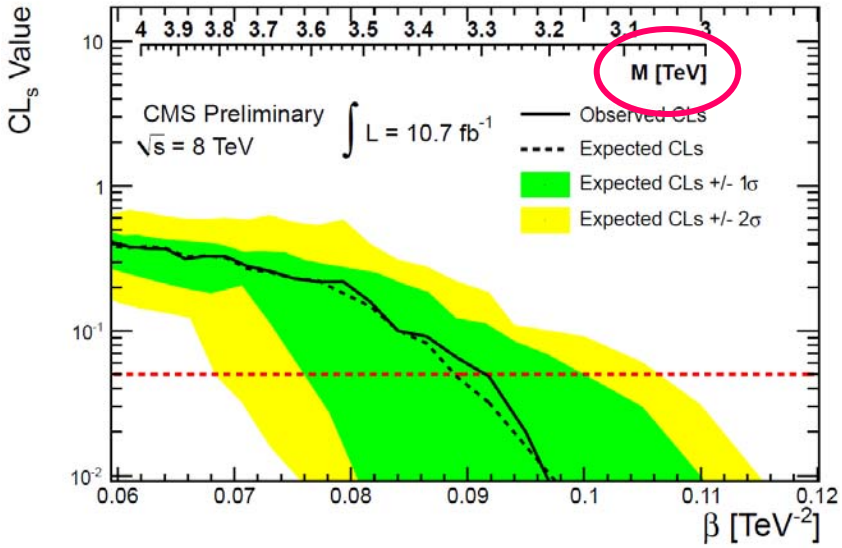
- Detecting TeV scale gravity

➔suppression of high p_T SM processes

Specific model= Veneziano form factor modification of QCD processes with a large damping component

[C. Kilic et al., arXiv:1207.3525]

- Main systematic uncertainties = PDF and JES



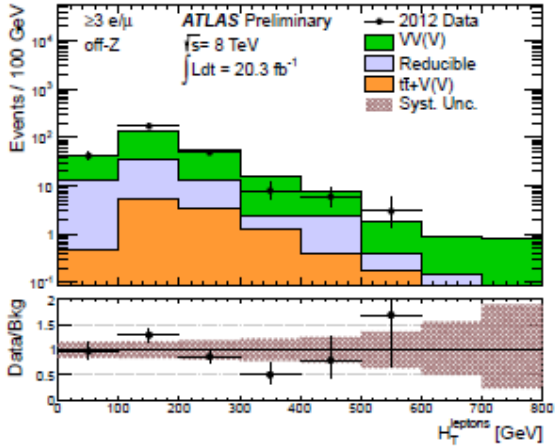
$\beta = M^{-2}$

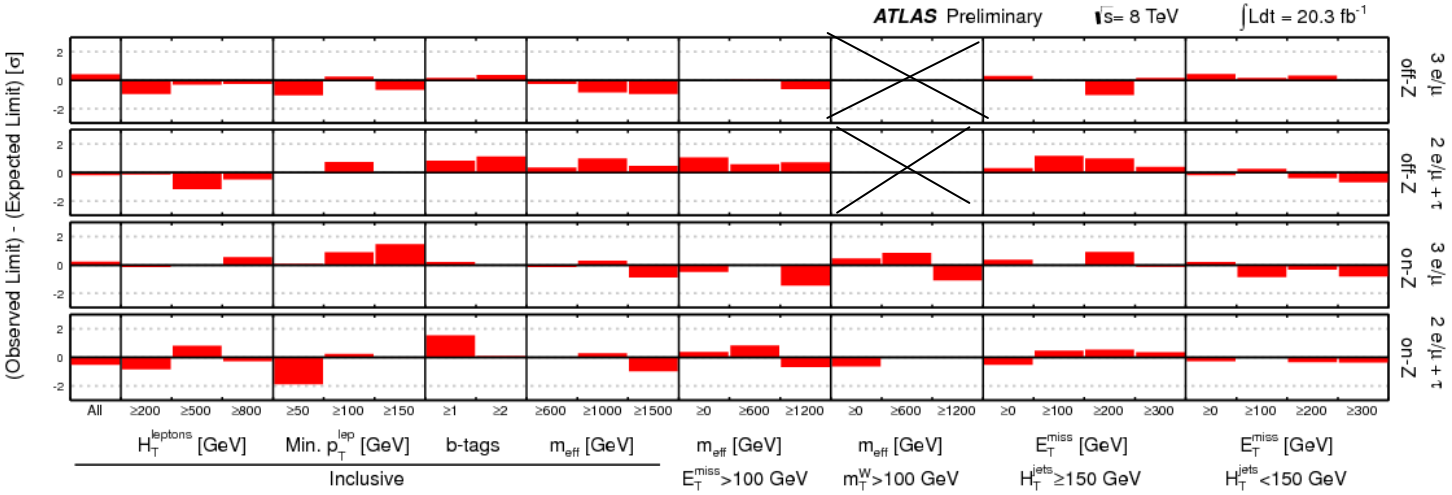
Extinction energy scale M excluded below 3.3 TeV

Multilepton general search

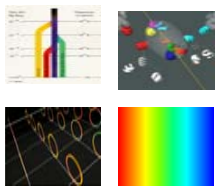
[ATLAS-CONF-2013-070]

- ≥ 3 leptons (3rd one can be τ_{had})
- 2 leptons on- or off-Z
- categories according to kinematic observables (H_T^{lep}, E_T^{miss}, m_{eff}, min p_T^{lep}) and b-tags





No excess above SM

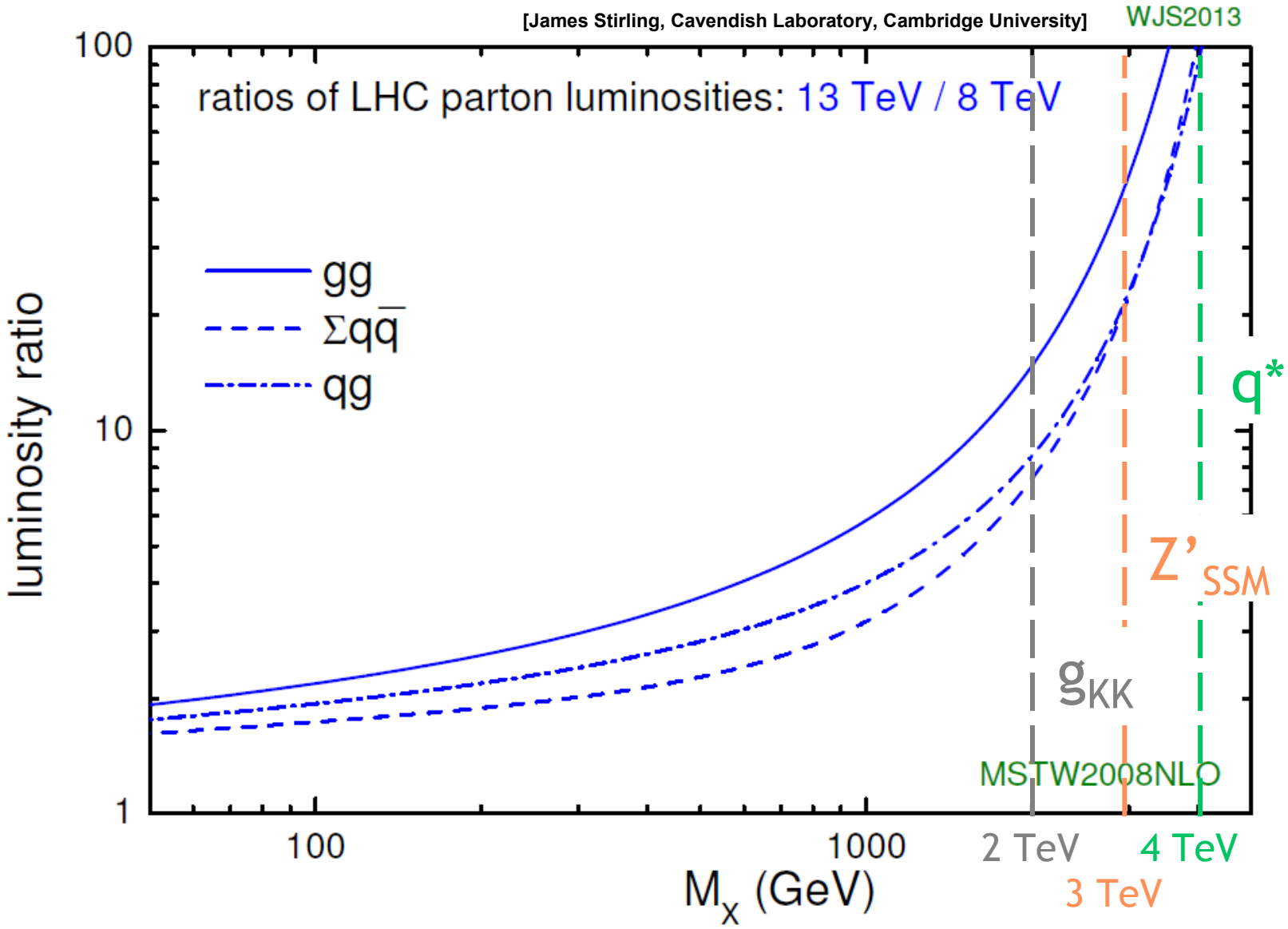


➔ Possible interpretations using provided fiducial efficiencies: doubly charged Higgs, vector-like B quarks, excited neutrinos,…

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 thinking of combinations for dedicated models
- Tagging of boosted particles (t, Z,W,…) 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)
q*
Z'SSM
g_KK
MSTW2008NLO
2 TeV
4 TeV
3 TeV

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
- displaced jets

More information

8 TeV limits

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

SSM Z' [TeV]	Channel	ll	ττ	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→lll'ν	WZ → 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}

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]

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

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

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

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

Bonus

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More information

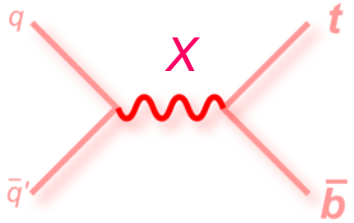
Still missing:

type III seesaw heavy fermions

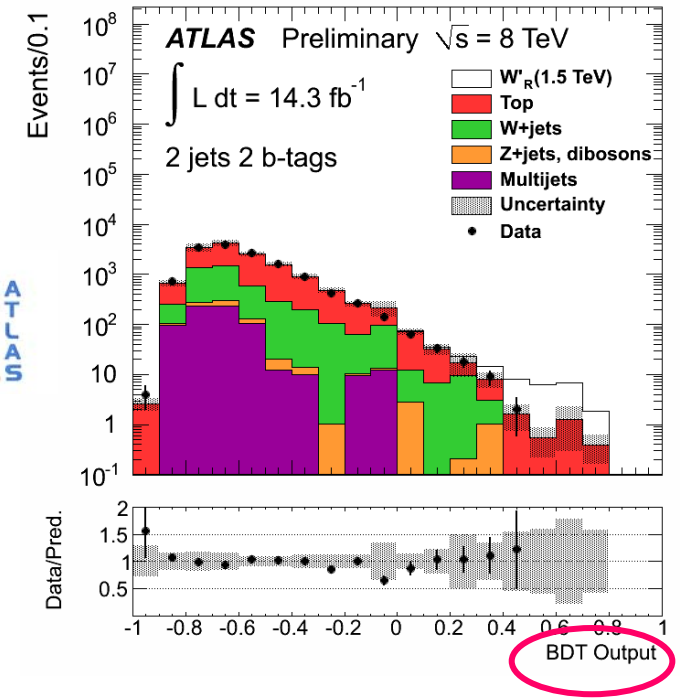
[ATLAS-CONF-2013-019]

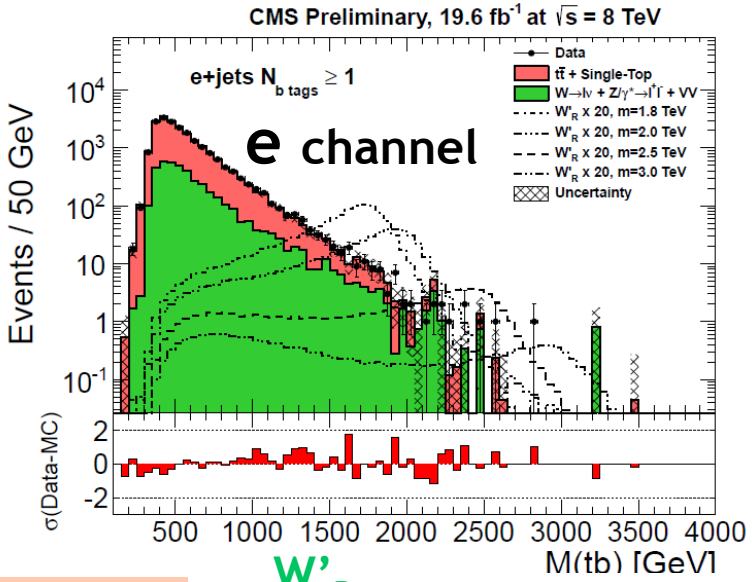
Leptonic $t\bar{b}$

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



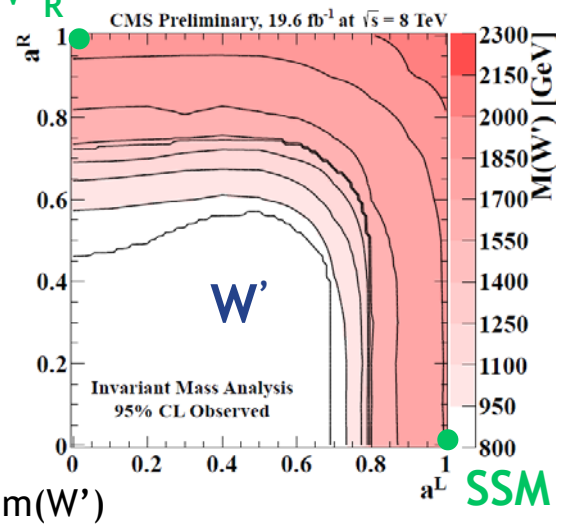
- $W'_R \rightarrow l\nu$ suppressed if ν_R heavy
- better mass reconstruction





$l + E_T^{miss} +$
$\geq 2\ j\ (\geq 1\ j_b)$

W'$_R$



SSM

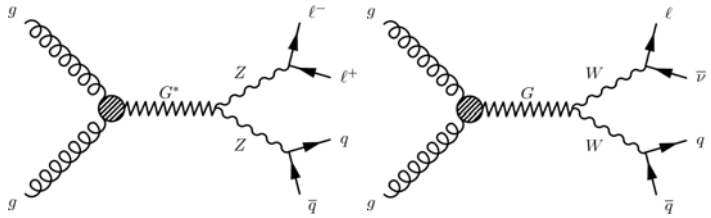
Observed mass exclusions (TeV)

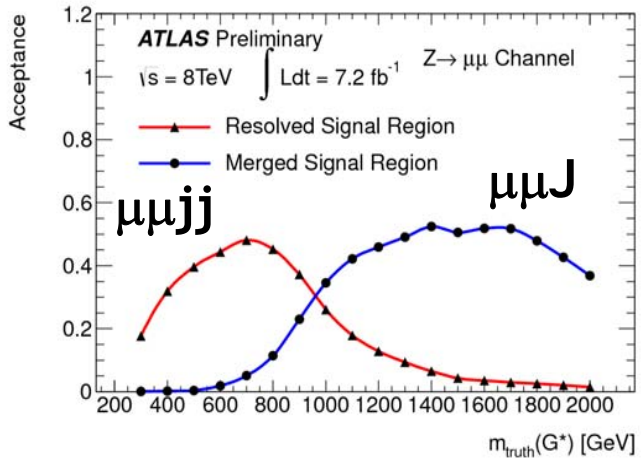
Model	CMS 20 fb^{-1}	ATLAS 14 fb^{-1}
W'$_R$	[0.8,2.03]	[0.5,1.84]

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

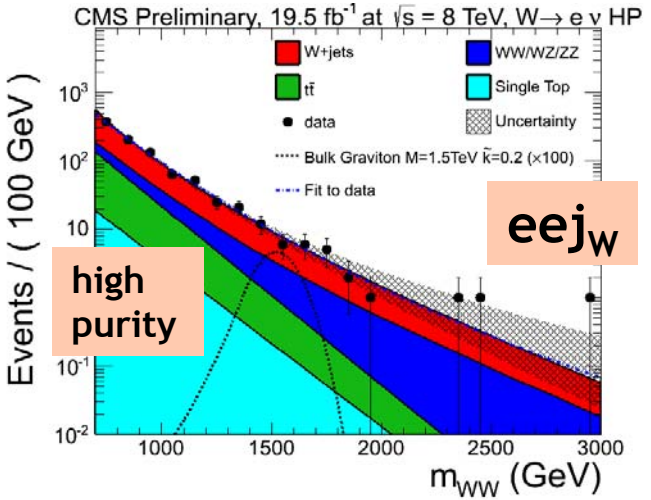
Semileptonic ZZ,WW

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

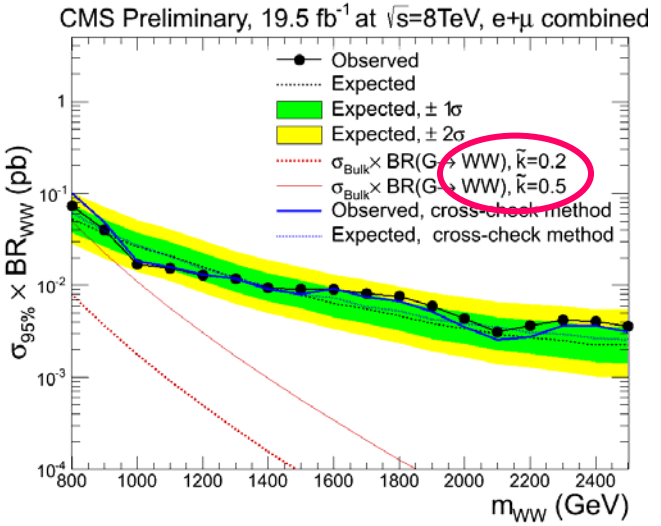




- 2 analyses:
  - -resolved and merged (ATLAS)
  - -low/high purity (τ_{12}) merged (CMS)



[CMS-EXO-12-021]



- Fermionic couplings possibly suppressed

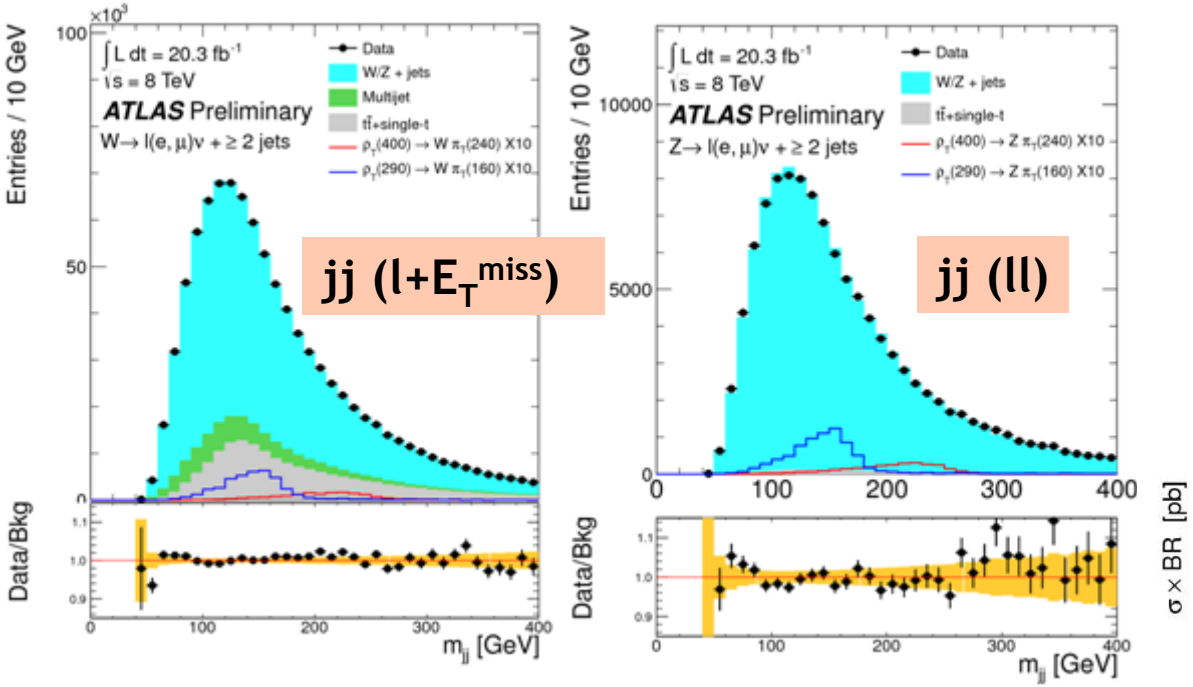
Observed lower mass limit (GeV)

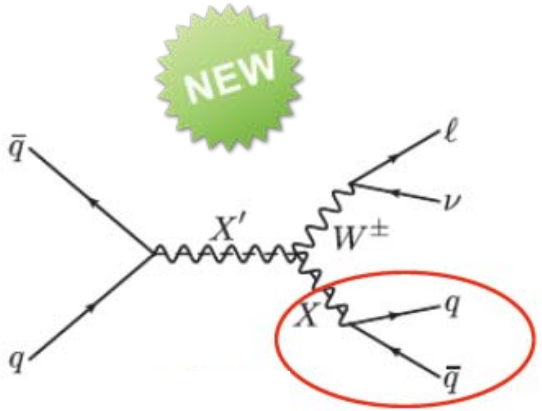
Model	ATLAS 7 fb^{-1}	CMS 20 fb^{-1}
Bulk RS G*→ZZ Γ/M=3-6%	[350,850] $k/\bar{M}_{Pl}$=1.0	[600,710] $k/\bar{M}_{Pl}$=0.5

Dijet associated with W/Z

[ATLAS-CONF-2013-074]

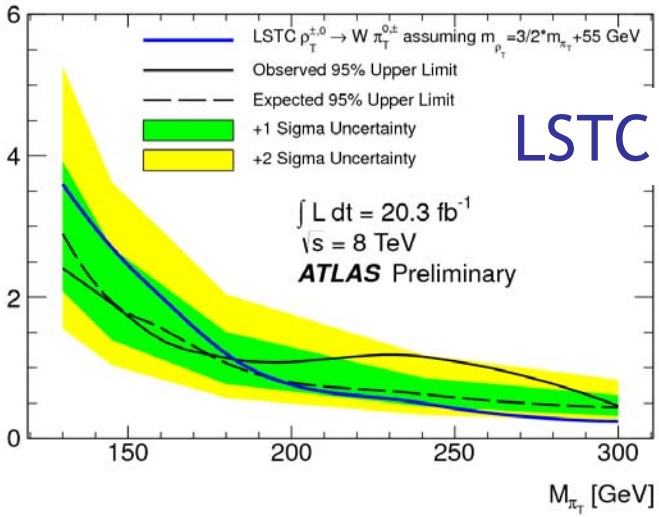
- Look for a low mass dijet resonance
- $\rho_T \rightarrow \pi_T$ W or π_T Z (ρ_T, π_T charged or neutral)





X'=ρ_T, X=π_T

$\rho_T \rightarrow$ W π_T



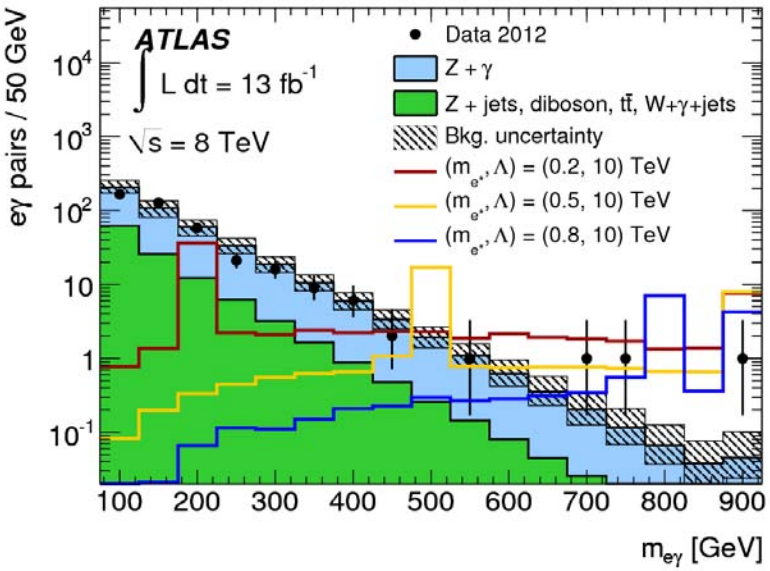
m(ρ_T) = 3/2 m(π_T)+55 GeV

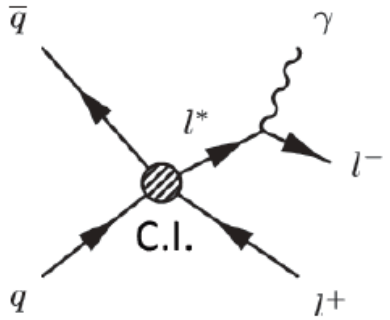
	Obs. lower mass limit
π_T	180 GeV

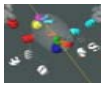
CDF: m(π_T)~160 GeV

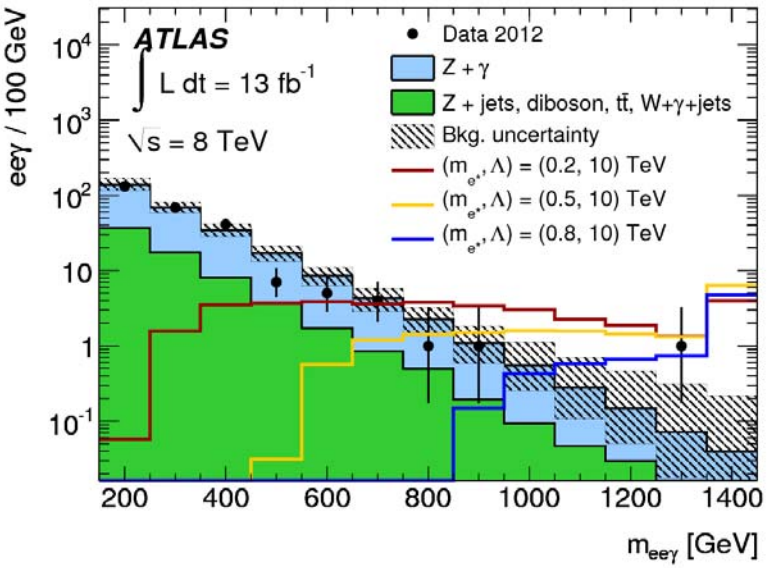
Lepton plus photon

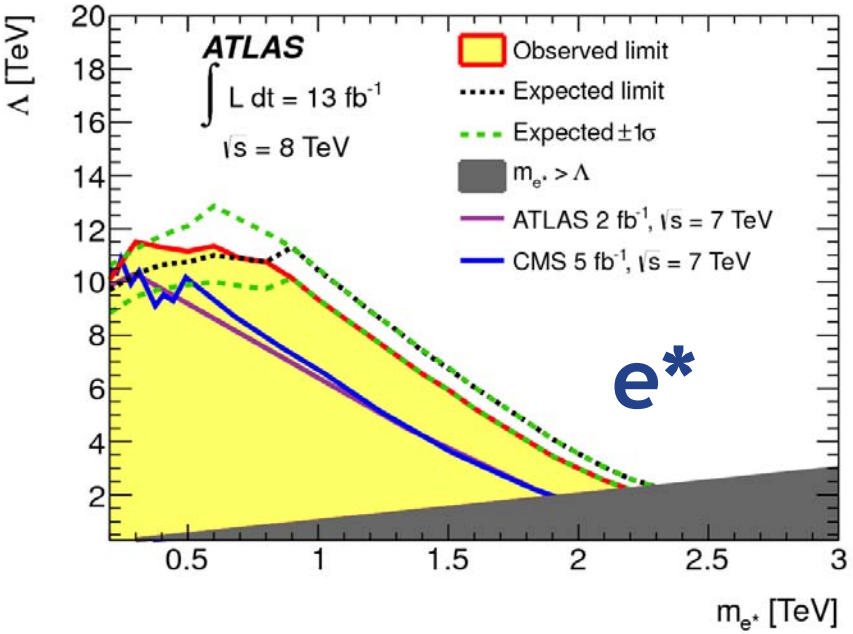
[ATLAS NJP 15 (2013) 093011]



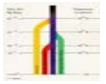


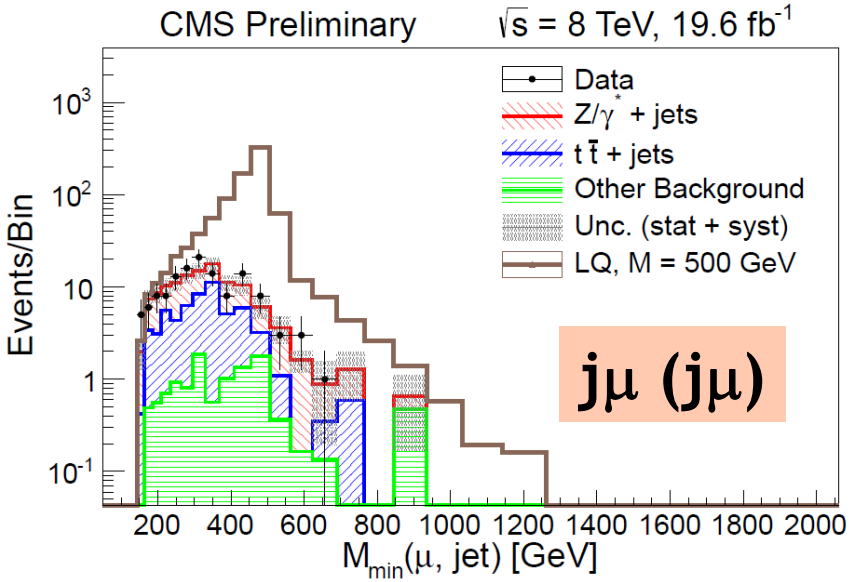


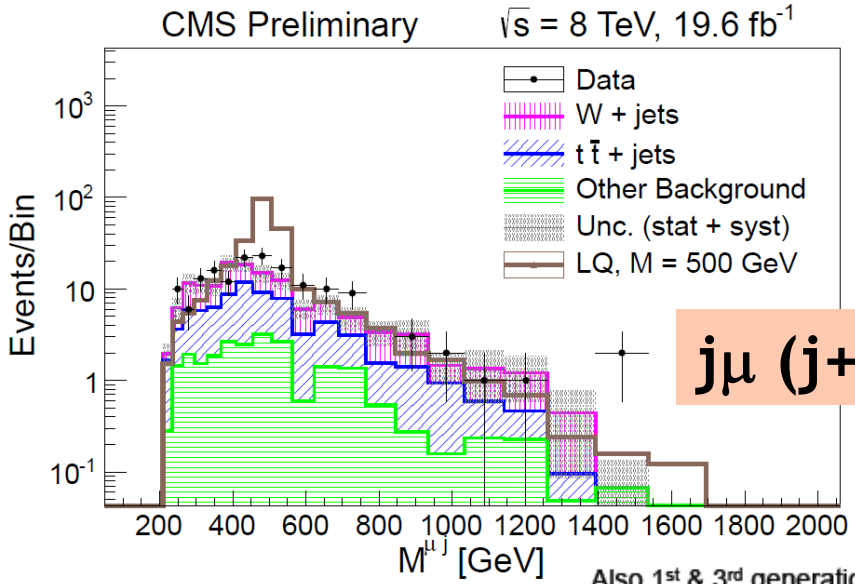




Second generation leptoquarks

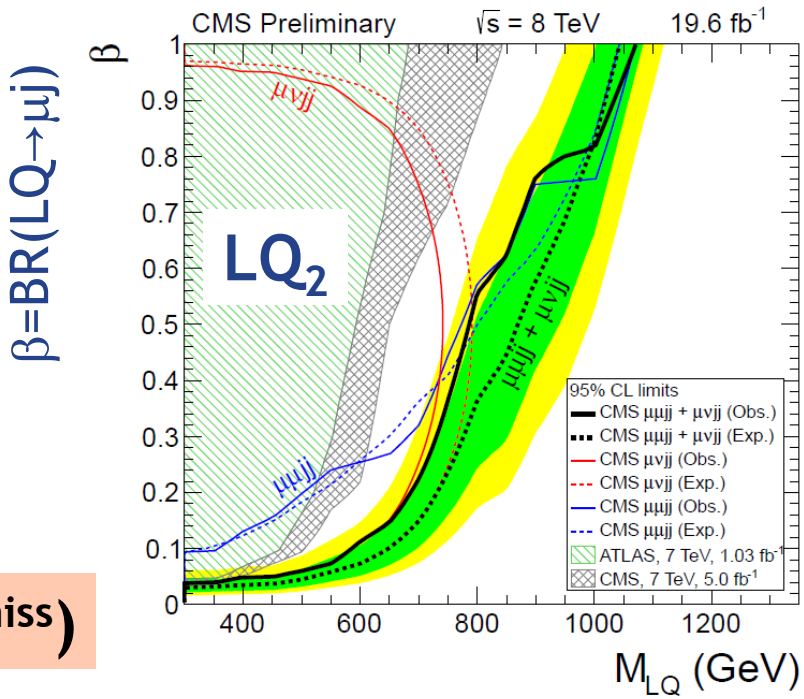






[CMS-EXO-12-042]

- Very low background

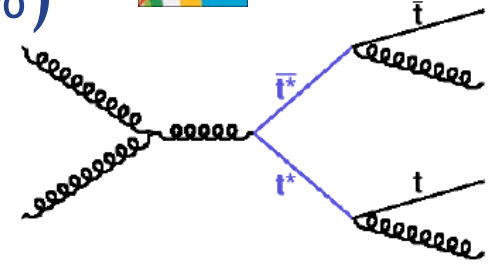


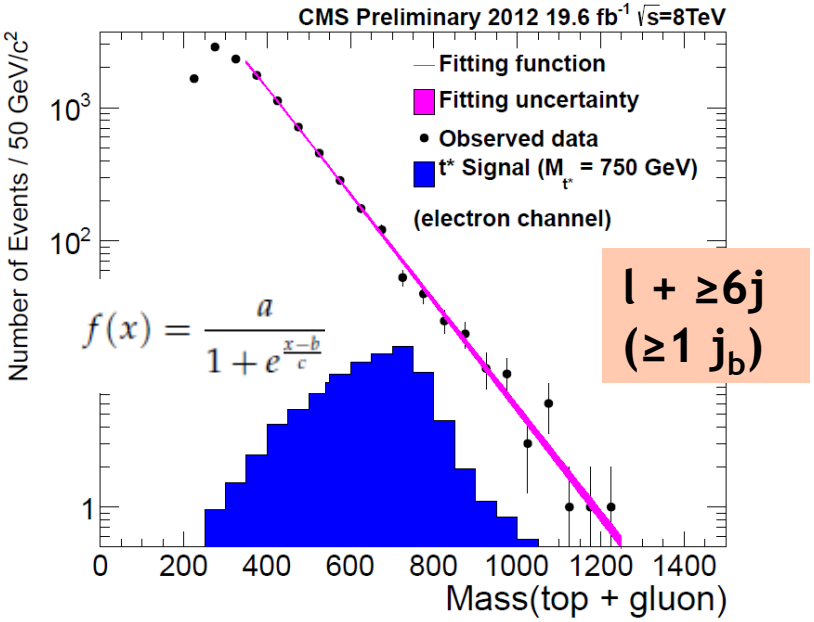
Also 1st & 3rd generation LQ searches, see e.g. 7 TeV search
ATLAS: arXiv:1303.0526, submitted to JHEP; CMS: JHEP 12 (2012) 055 & PRL 110, 081801 (2013)

Semileptonic t+jet pairs

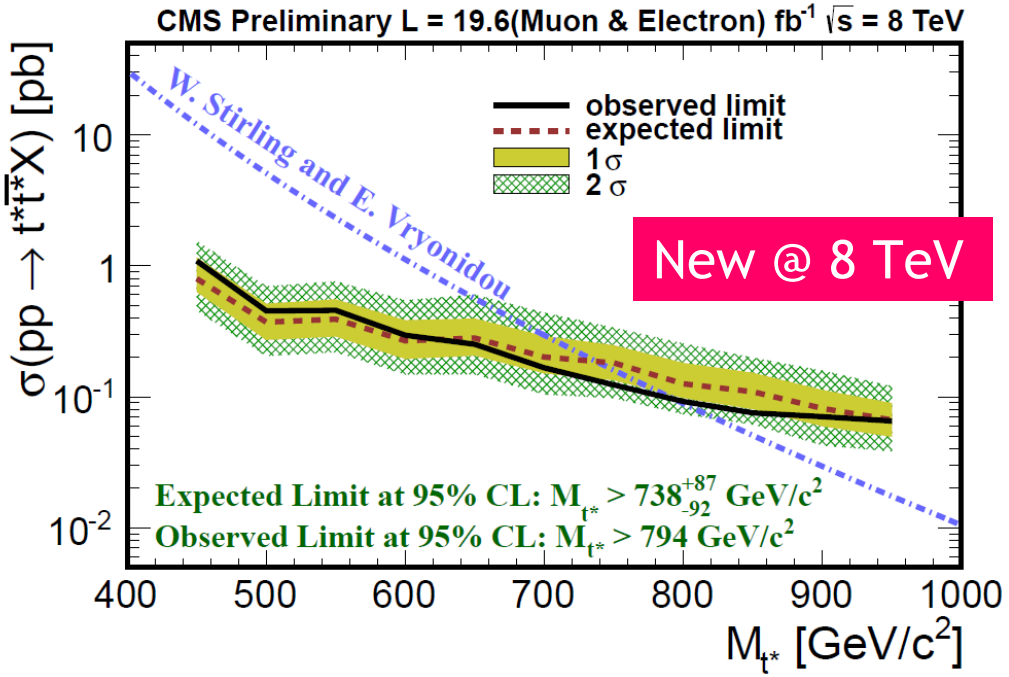
[CMS-B2G-12-014]

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





l + ≥6j (≥1 j_b)



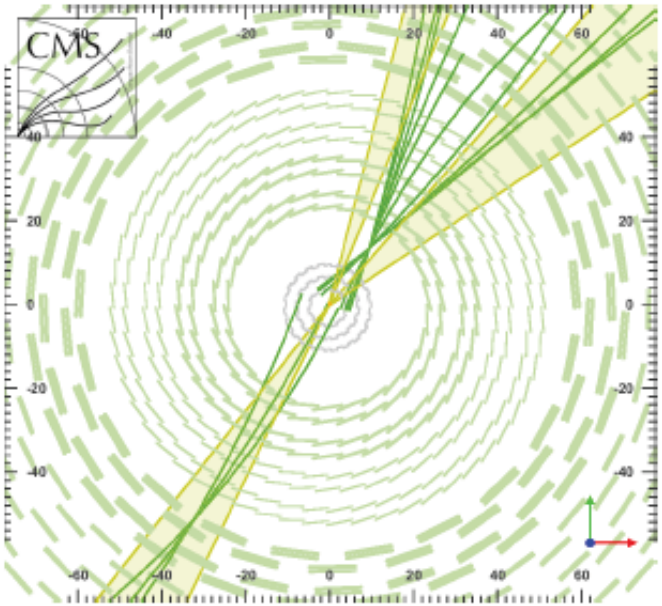
New @ 8 TeV

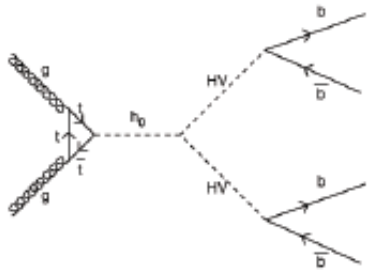
450 < m(t*) < 794 GeV excluded in specific X-dim. model

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

Displaced Jets

new





Massive long-lived particles can decay to jets

- Weak R-parity violating SUSY
- split SUSY
- Hidden valley models
- Z' models with long-lived neutrinos

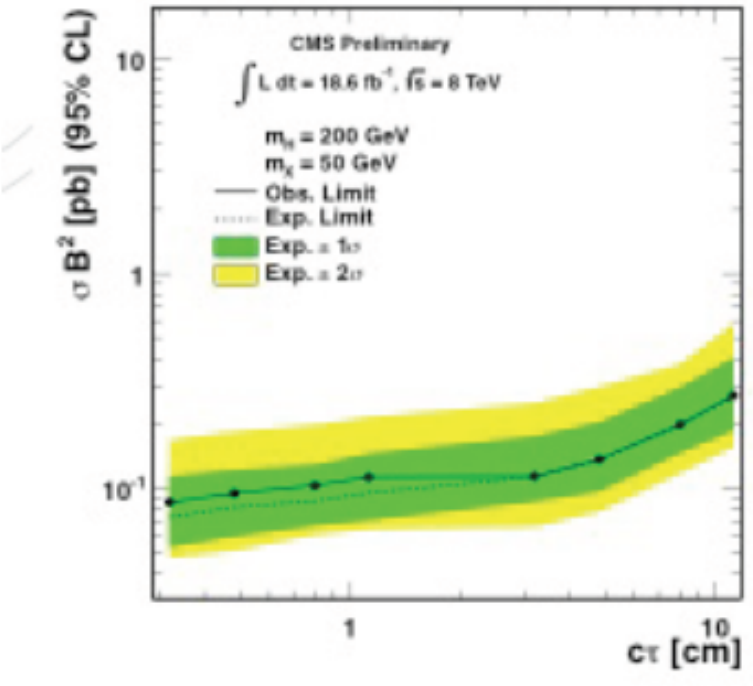
- Looking for long-lived particle X^0 that decays to qqbar
  - Displaced di-jet signature
  - Benchmark model: Hidden valley signature with non-SM Higgs that pair produces $H \to 2X^0$

Displaced Jets

new

- Search performed in two bins of decay length (L_{xy})
- Use of multivariate likelihood to reduce background
- Remaining events consistent with nuclear interactions and B meson production
- Limits are set for multiple scenarios of m_H and $m_X{}^0$

	Lxy < 20 cm	Lxy > 20 cm
background	1.60±0.58	1.14±0.54
Observed events	2	1



Vrije Universiteit Brussel

CMS PAS EXO-12-038

24 July 2013

7

EPS HEP 2013, Stockholm -- Freya Blekman

Bonus

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- 8 TeV limits by resonance

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- semileptonic ZZ/WW
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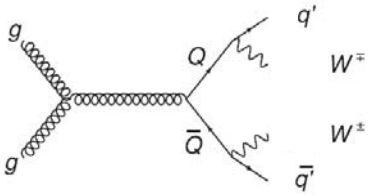
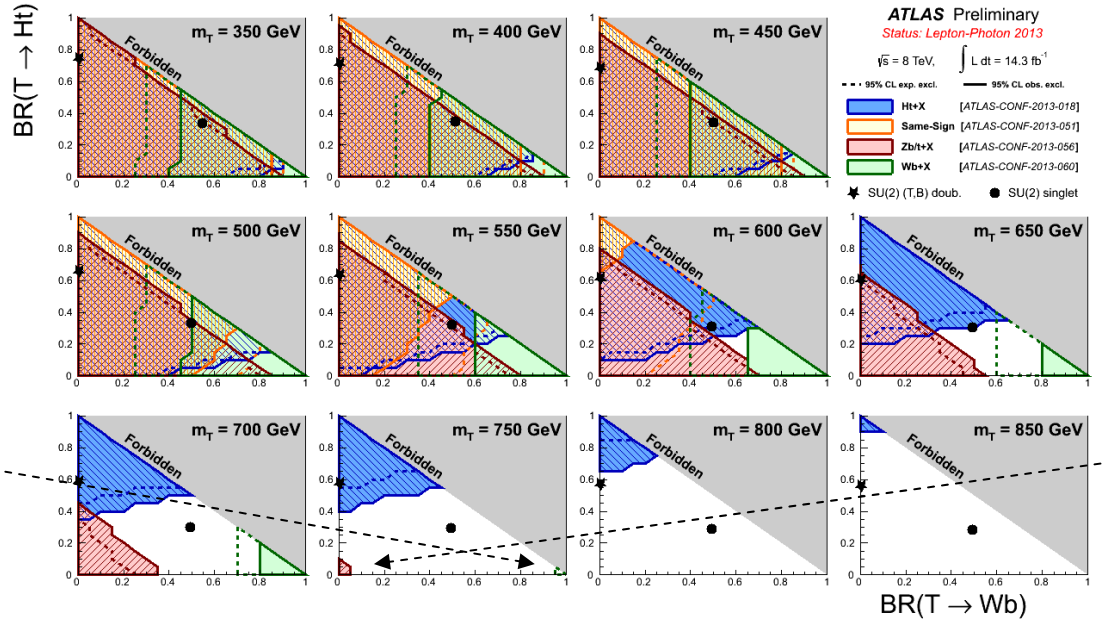
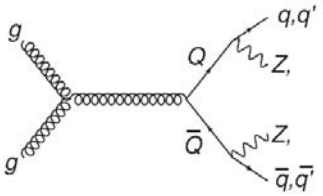
More information

Comparison between TT and direct stop searches

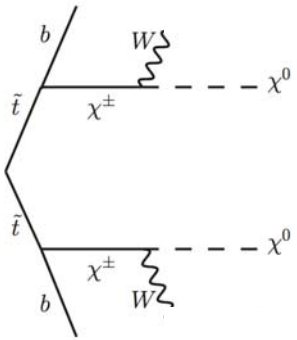


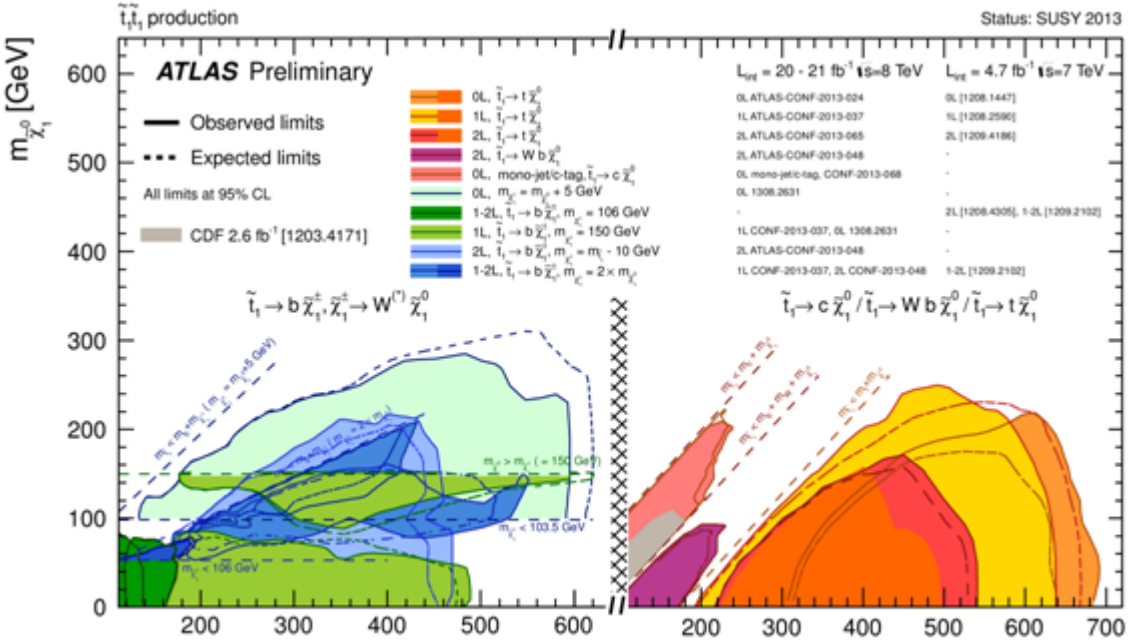


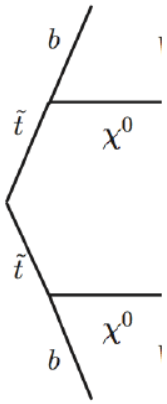


T→Wb
~100%

T→Zt
~100%

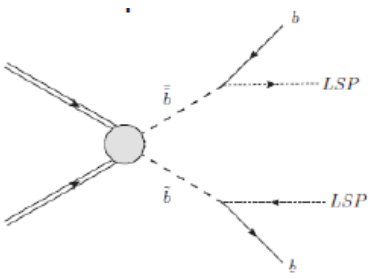




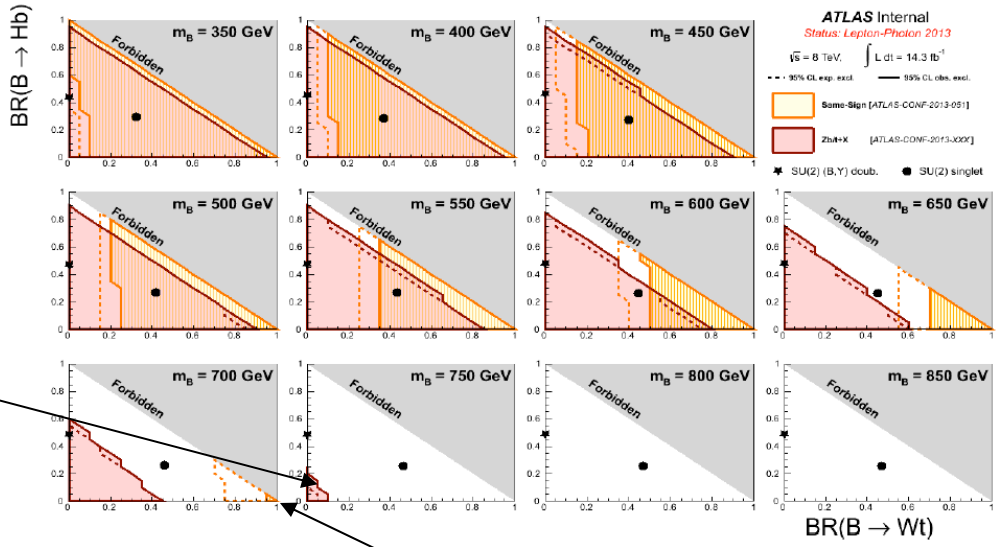


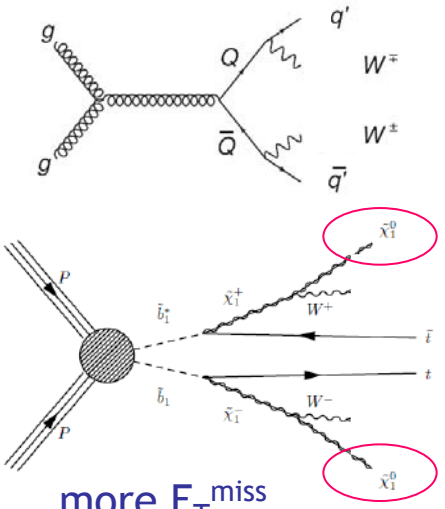
more E_T^{miss}

Comparison between BB and direct sbottom searches



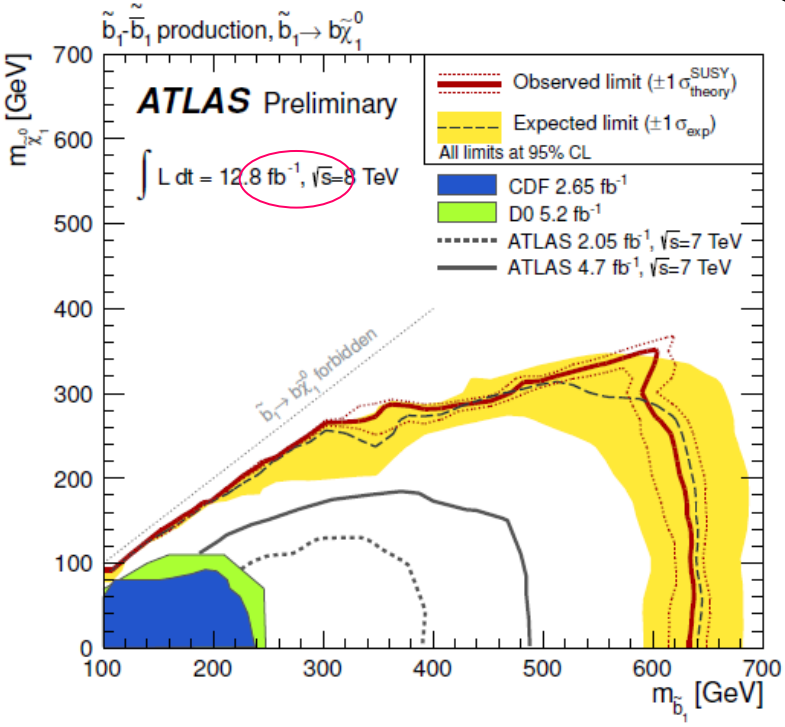
B→Zb ~100%

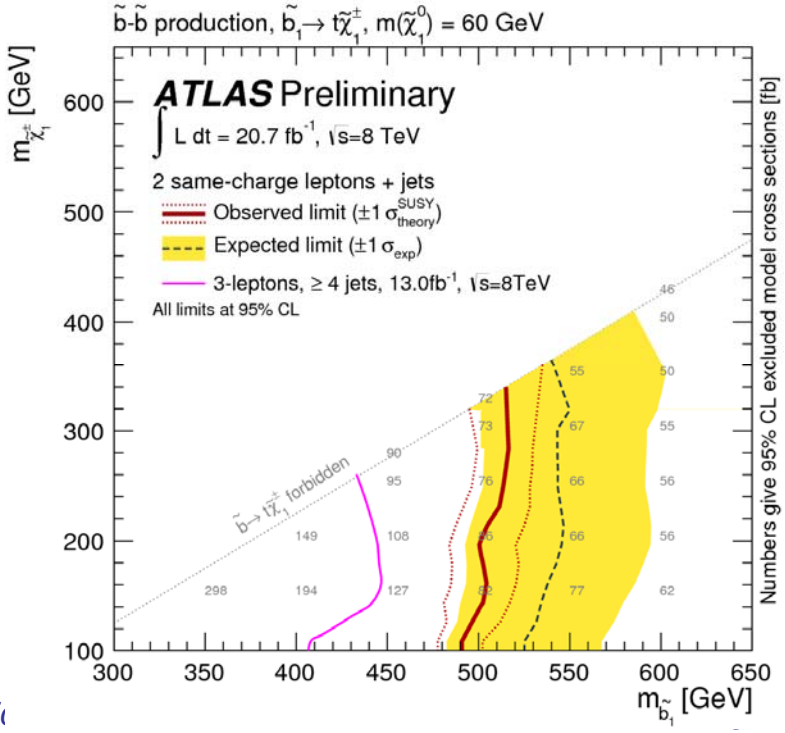




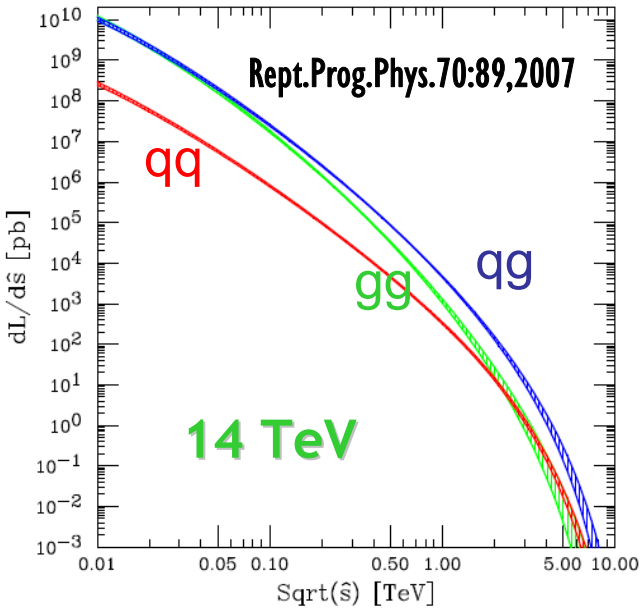
more E_T^{miss}

B→Wt ~100%

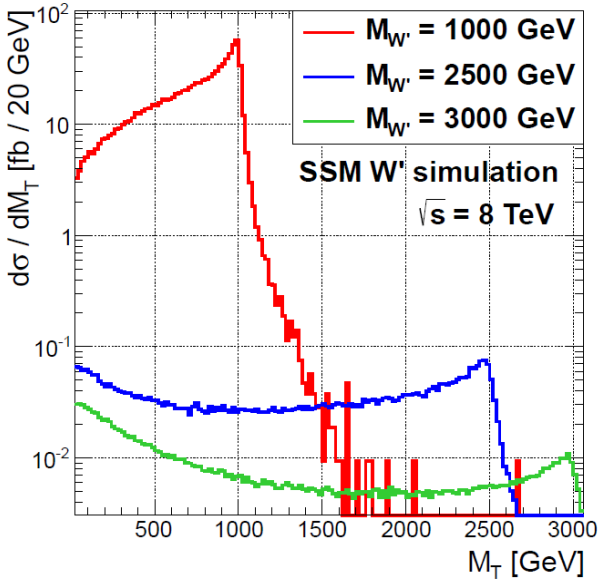


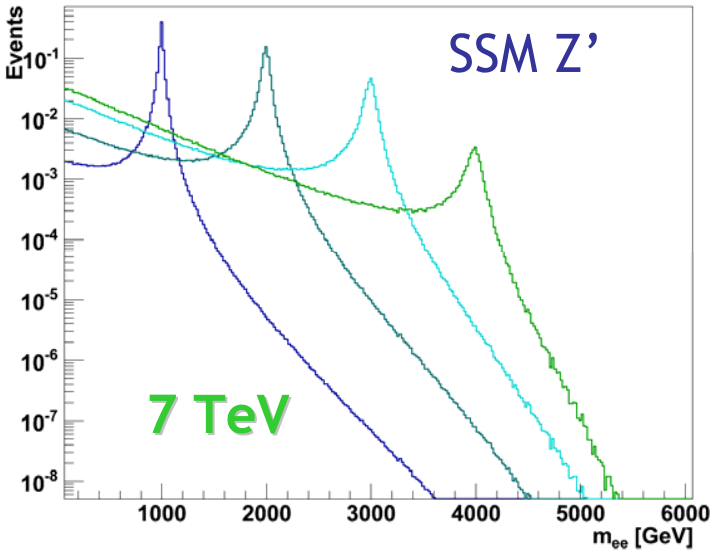


Parton luminosities



- very large tail for "large" widths



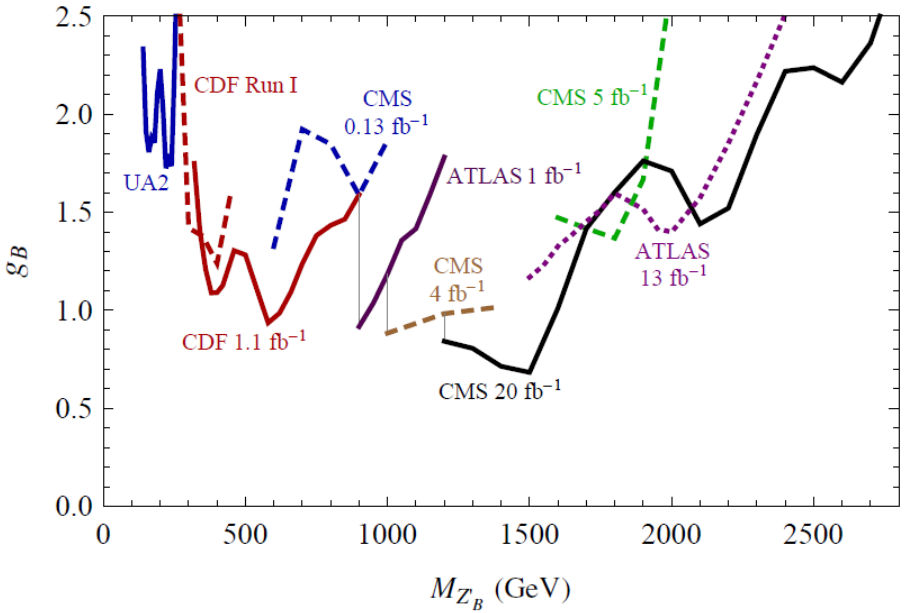


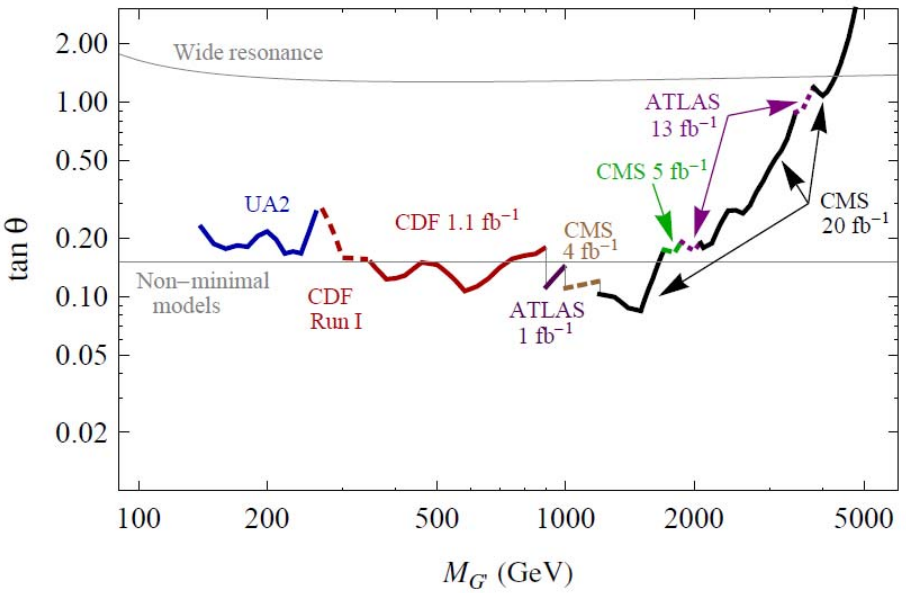
Digression: older dijets results

[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



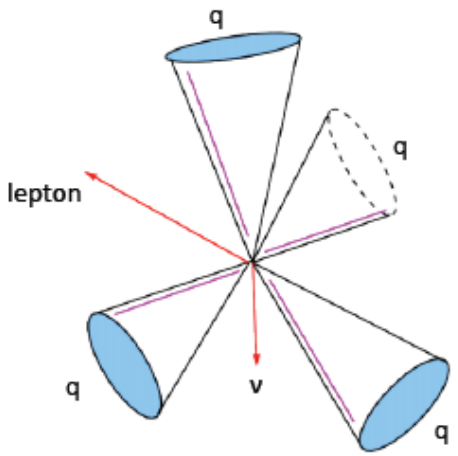


Older dijets results

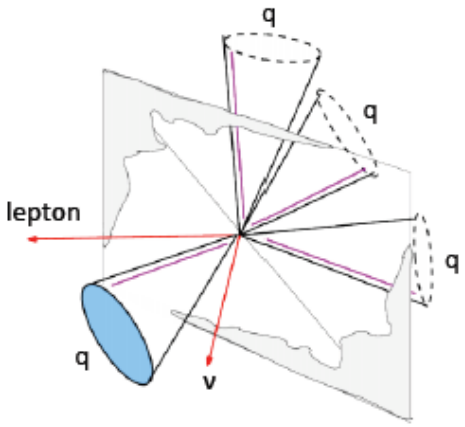
[Harris and Kousouris, Int.J.Mod.Phys. A26 (2011) 5005-5055]

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	–	–	–	–

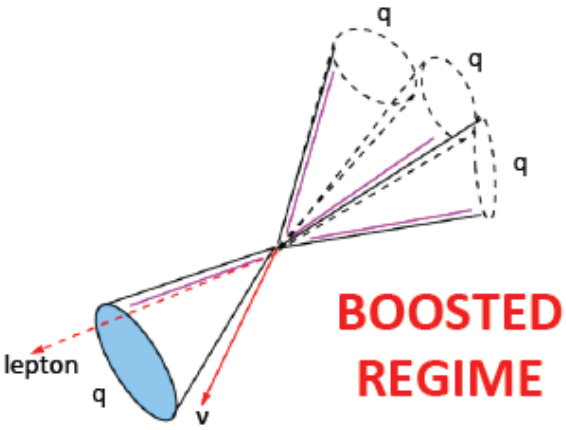
Boosted jets and top or V-tagging



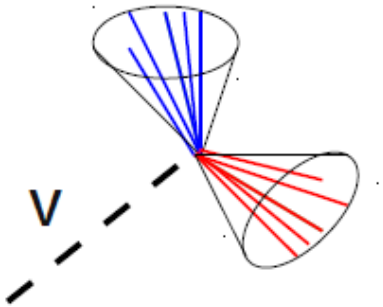
$m_{tt} < 500$ GeV



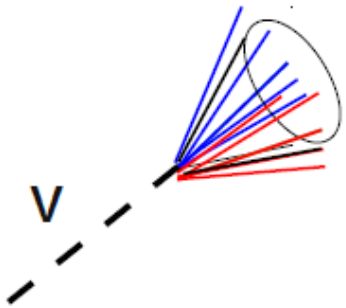
500 GeV < m_{tt} < 1 TeV



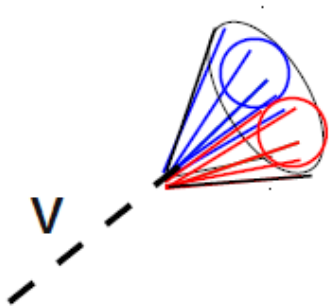
$m_{tt} > 1$ TeV



Moderately boosted V
Resolved dijets



Boosted V,
jet merging



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

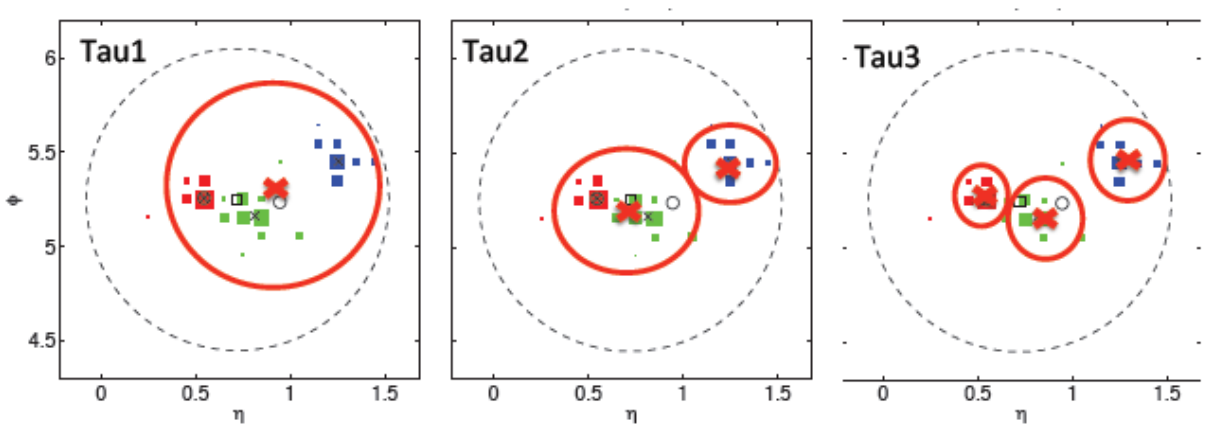
Boosted jets: N-subjetiness

N-subjetiness: topological compatibility with N subjets

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

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

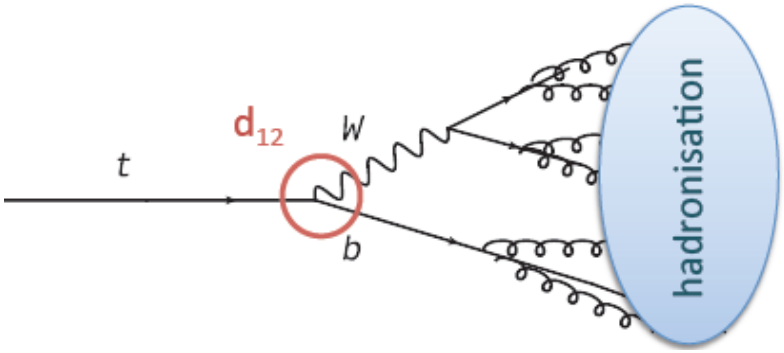
In practice, use ratios: $\tau_{21} = \tau_2 / \tau_1$ <<1 if 2 subjets

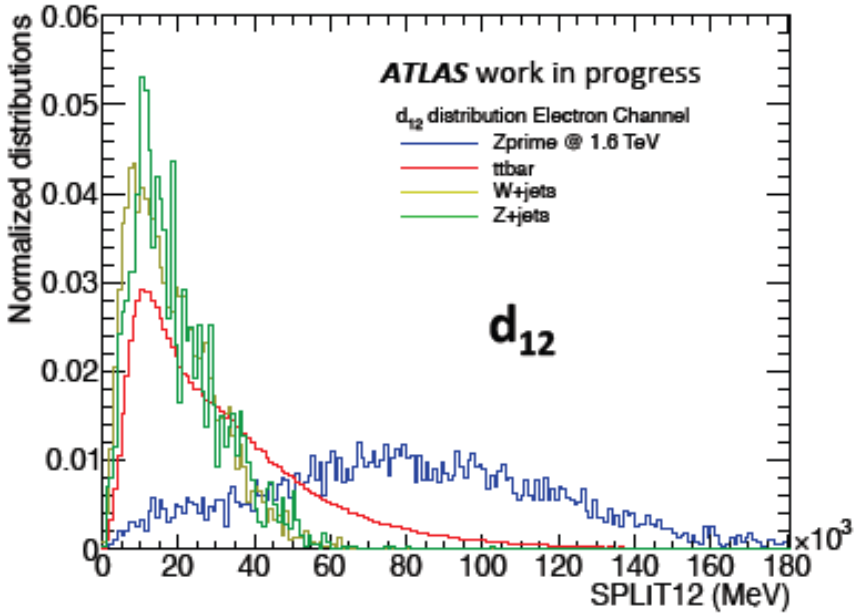


Boosted jets: splitting scales

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

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

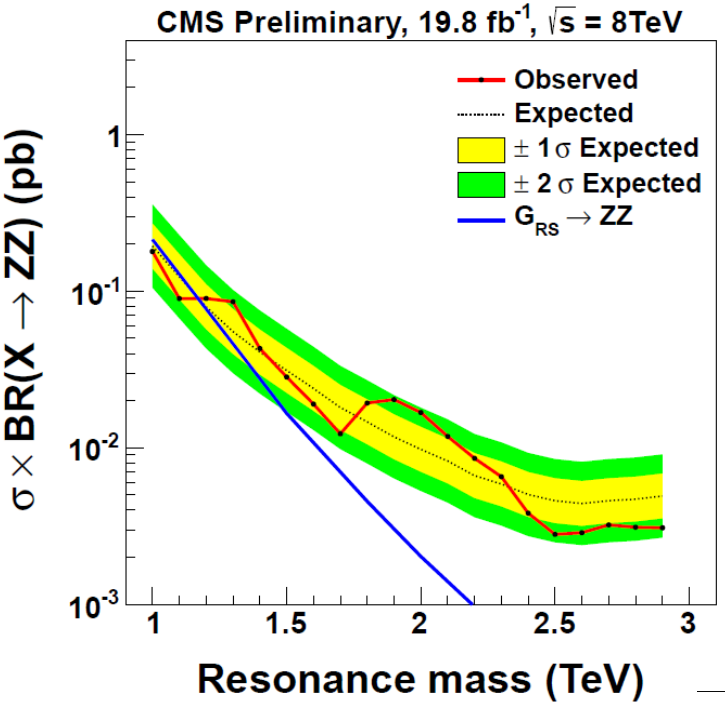


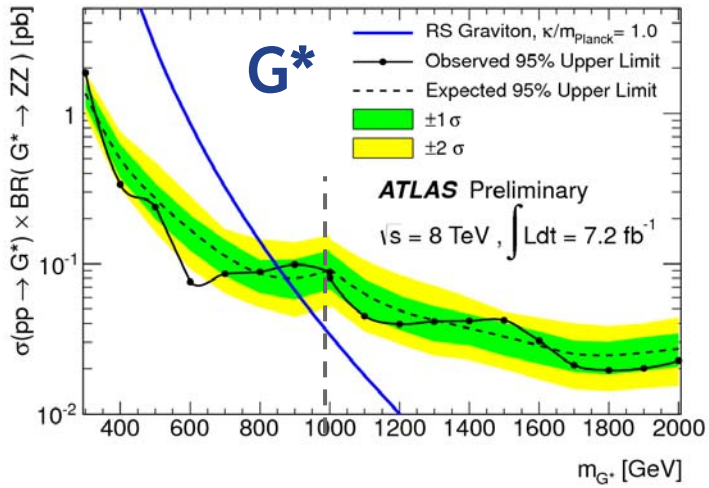


d_{12} is a probe of the t-> Wb decay

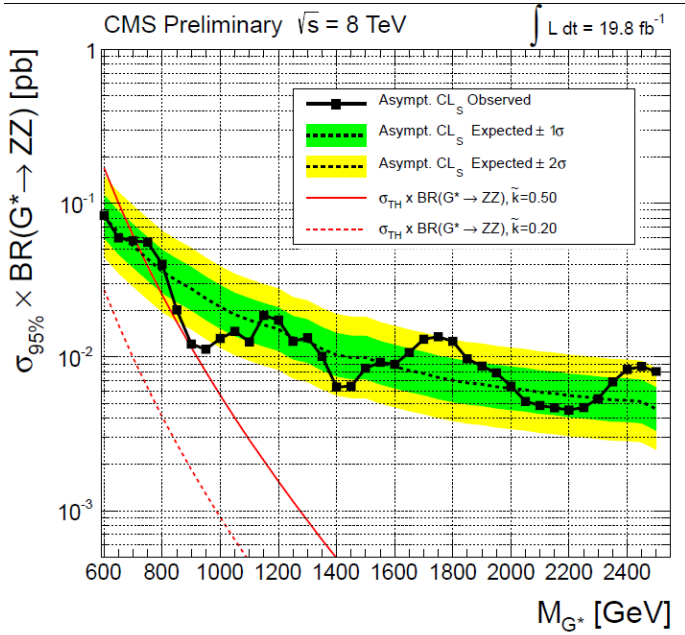
Common issues: sensitivity to pile-up ➔ jet grooming techniques: filtering, trimming, pruning

ZZ-tagged dijet → RS1

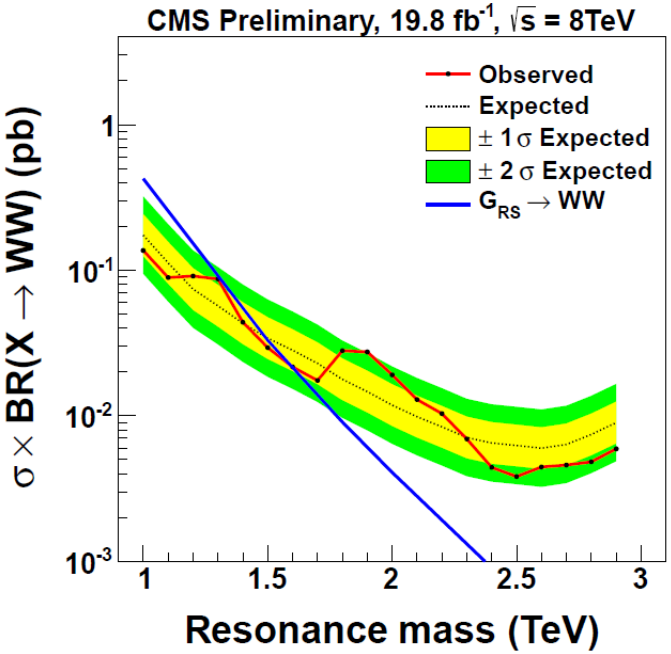




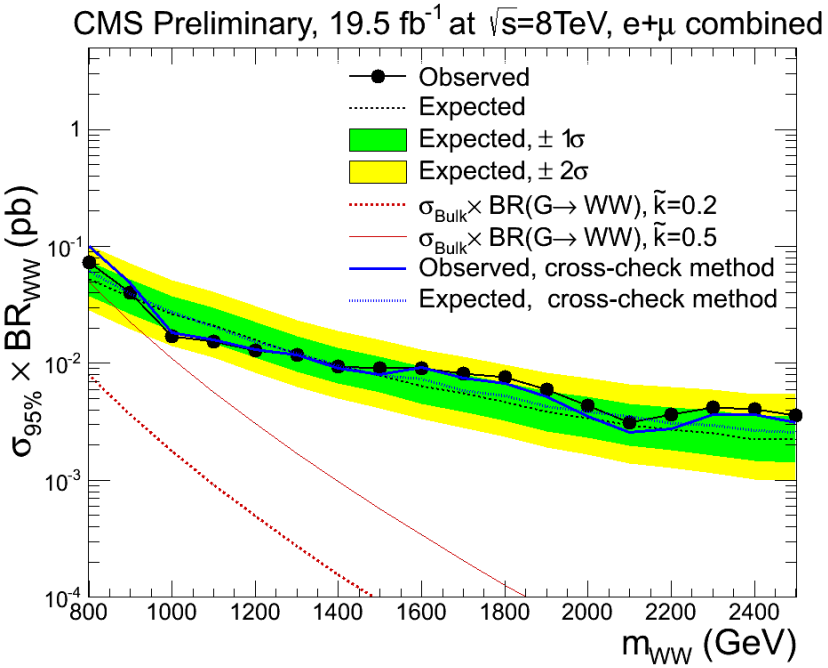
Semileptonic ZZ → bulk RS



WW-tagged dijet → RS1



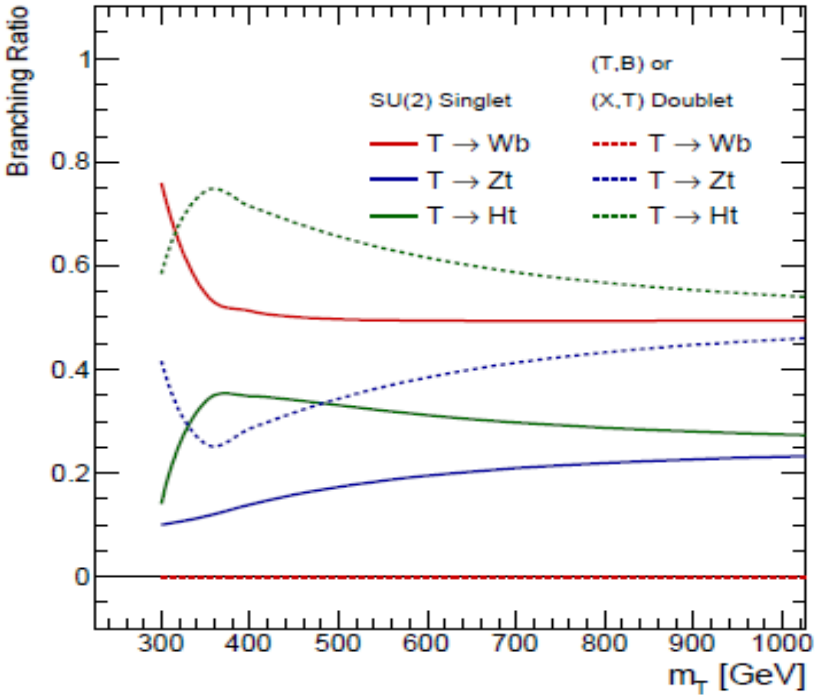
Semileptonic WW → bulk RS

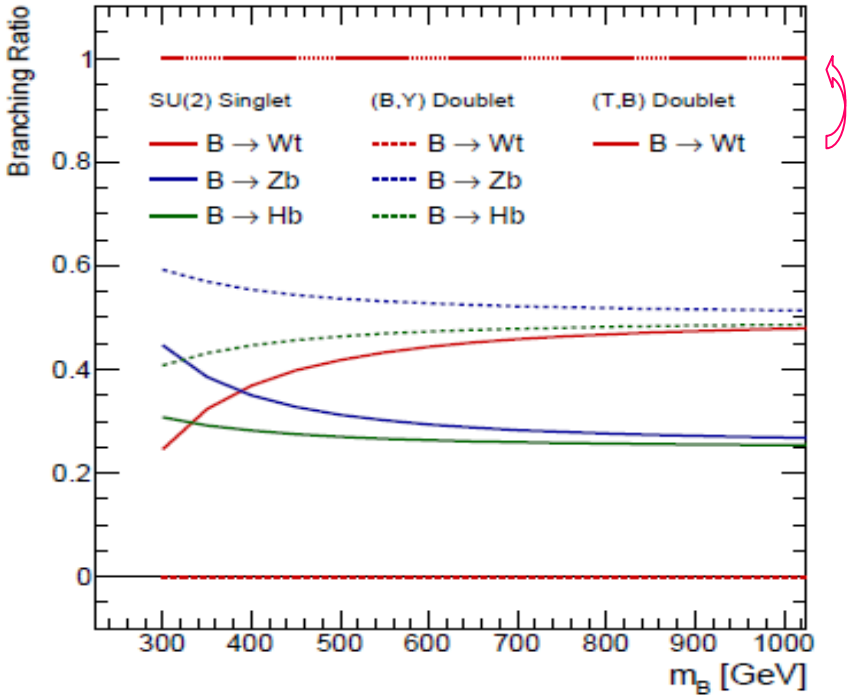


Vector like quarks

- isospin singlets or doublets

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

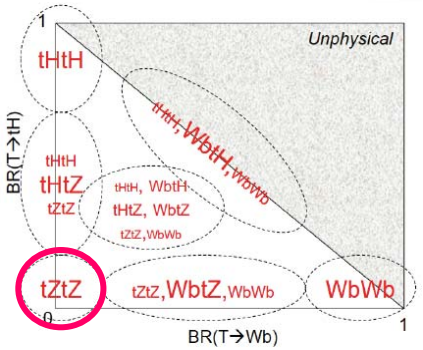


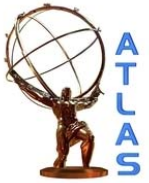


[Protos, http://jaguilar.web.cern.ch/jaguilar/protos]

BB, TT: Zb+X, Zt+X

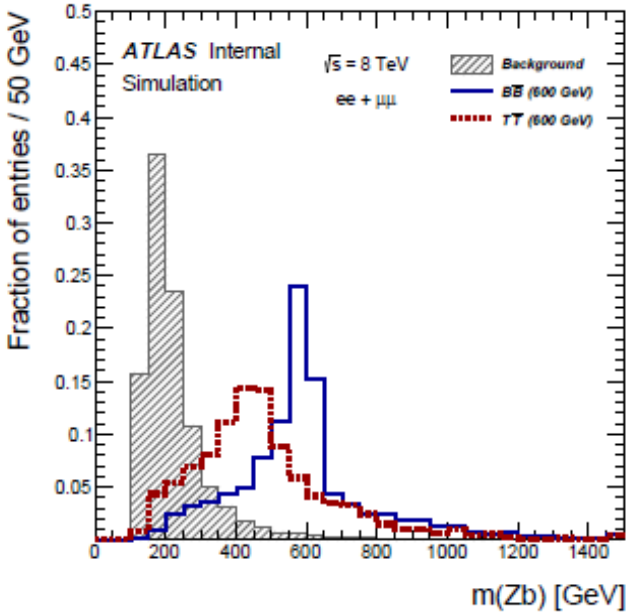
[ATLAS-CONF-2013-056]

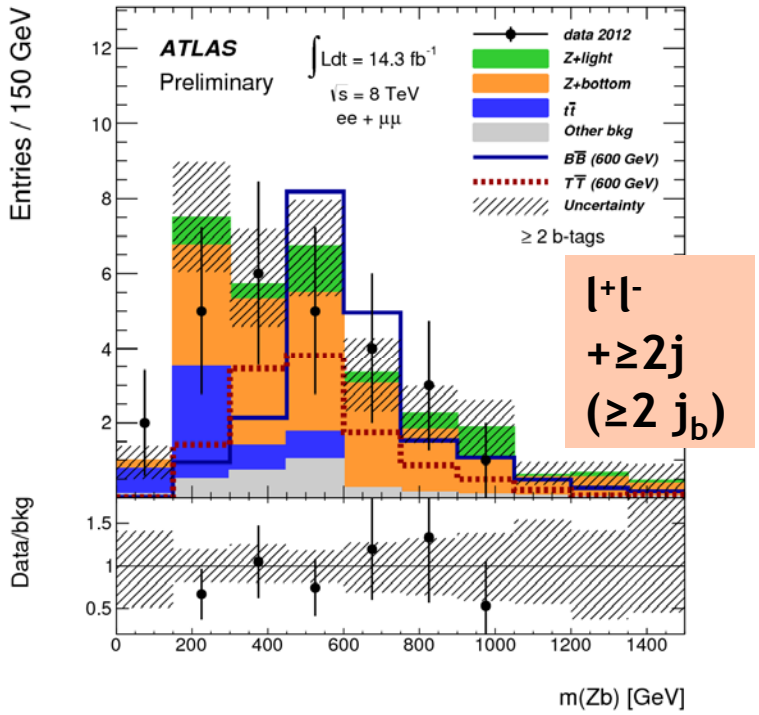




14 fb^{-1}

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

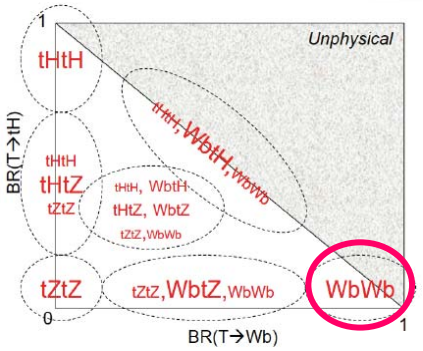


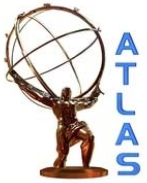


l^+l^- +≥2j (≥2 j_b)

TT → WbWb

[ATLAS-CONF-2013-060]





14 fb^{-1}

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

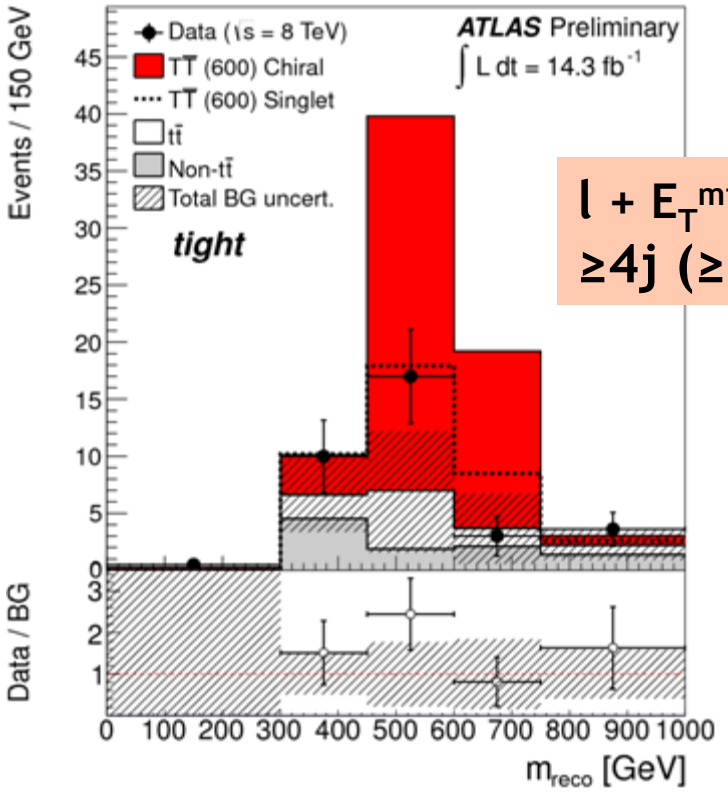
$W_{lep} \rightarrow l\nu$, $W_{had} \rightarrow qq$

- 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)*

•Veto events with ≥6j (≥1 j_b)

➔ no overlap with TT →Ht+X



l + E_T^{miss} + ≥4j (≥1 j_b)

Also chiral t' interpretation

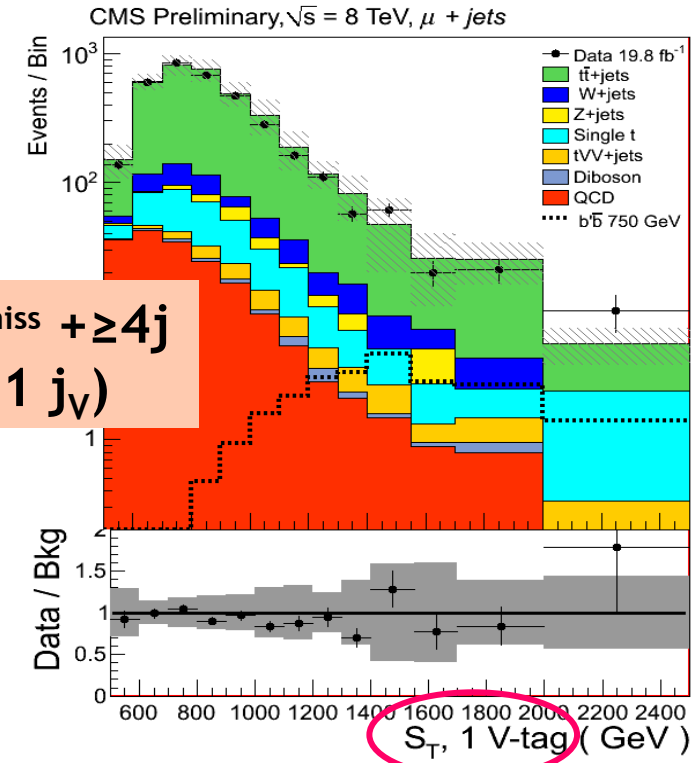
m(W_{had},j_b)

Inclusive BB

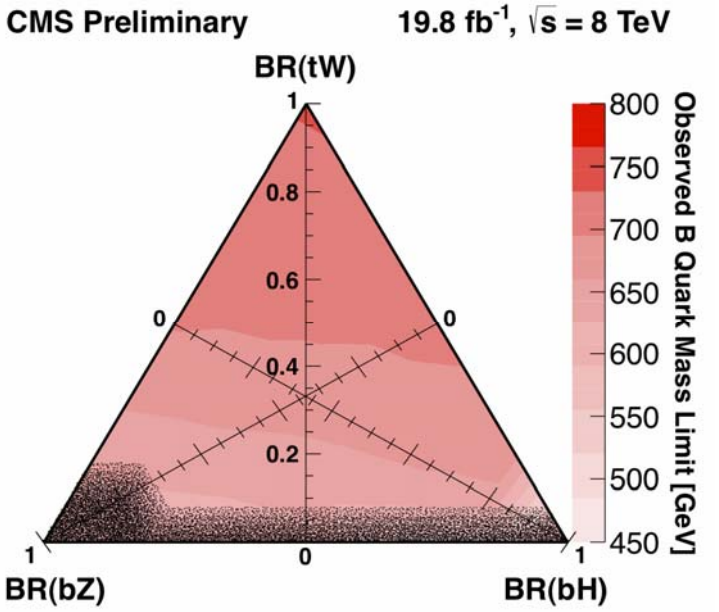
[CMS-B2G-12-019]

NEW

- V=W/Z/H, V→lν, V→qq (boosted)
- jets: 2 clustering algorithms ➔
  - anti-k_T R=0.5
  - Cambridge-Aachen R=0.8
- l + E_T^{miss} +≥4j (≥1 j_b, ≥1 j_V)
- S_T= Σ $|p_T|$ (l + E_T^{miss} + all j)
  - V-tagging efficiency ~50%



μ + E_T^{miss} +≥4j (≥1 j_b, 1 j_V)



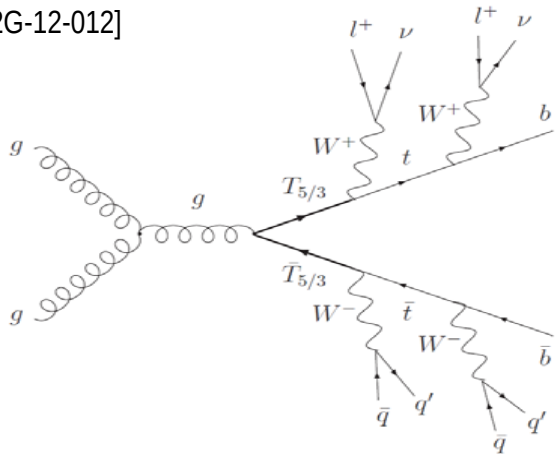
dedicated analysis: [CMS-B2G-12-021]
BB→Zb+X, Z→ll

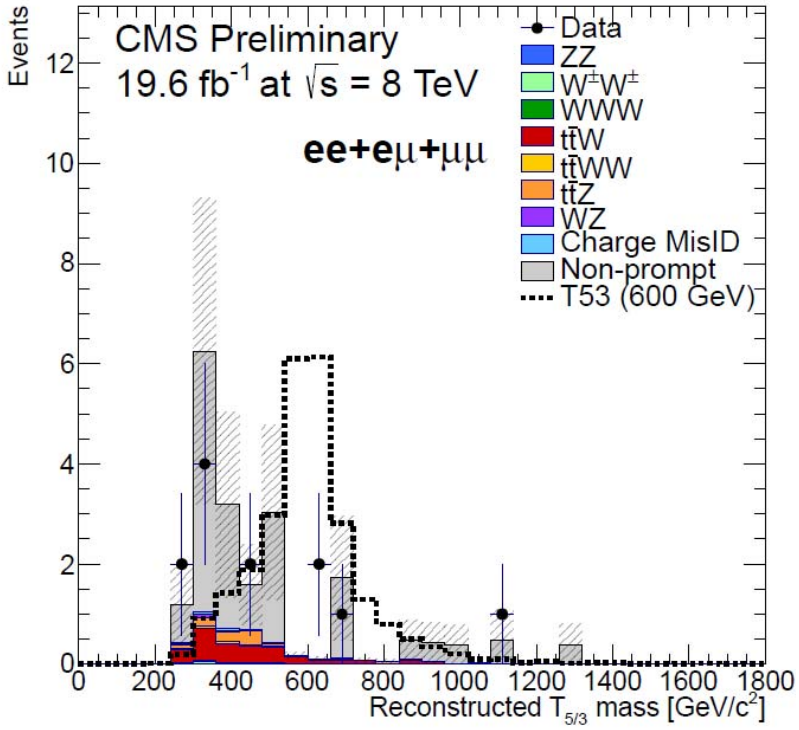
NEW

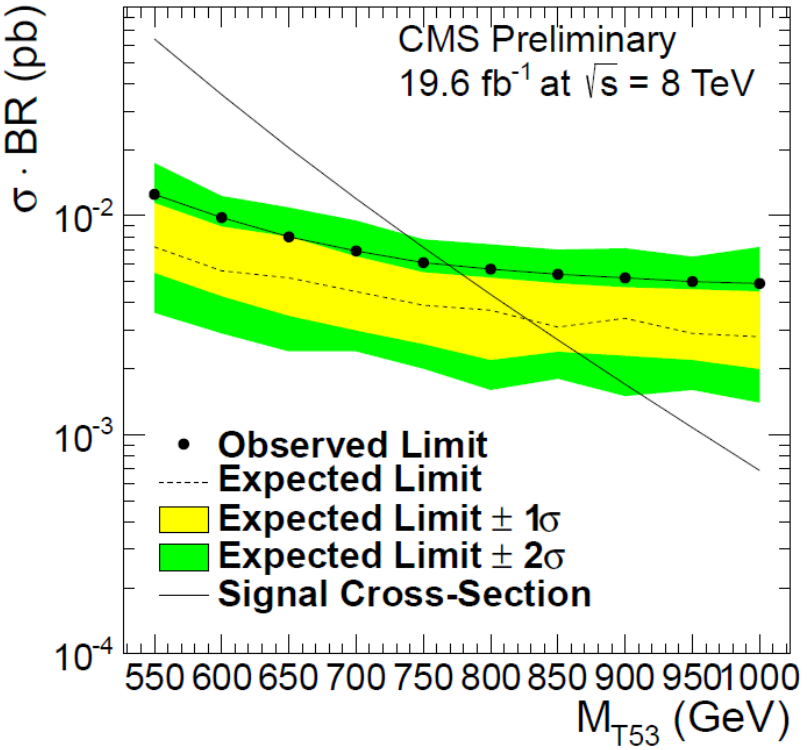
Same sign dileptons

[CMS-B2G-12-012]

- Very low SM background!







Dark matter

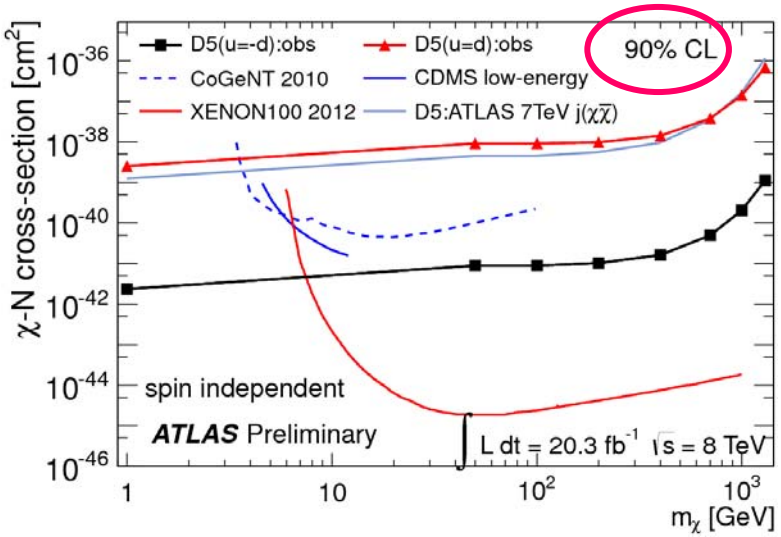
Name	Initial state	Type	Operator
D1	qq	scalar	$\frac{m_q}{M_\star^3}\bar{\chi}\chi\bar{q}q$
D5	qq	vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\chi\bar{q}\gamma_\mu q$
D8	qq	axial-vector	$\frac{1}{M_\star^2}\bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}\gamma_\mu\gamma^5 q$
D9	qq	tensor	$\frac{1}{M_\star^2}\bar{\chi}\sigma^{\mu\nu}\chi\bar{q}\sigma_{\mu\nu}q$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

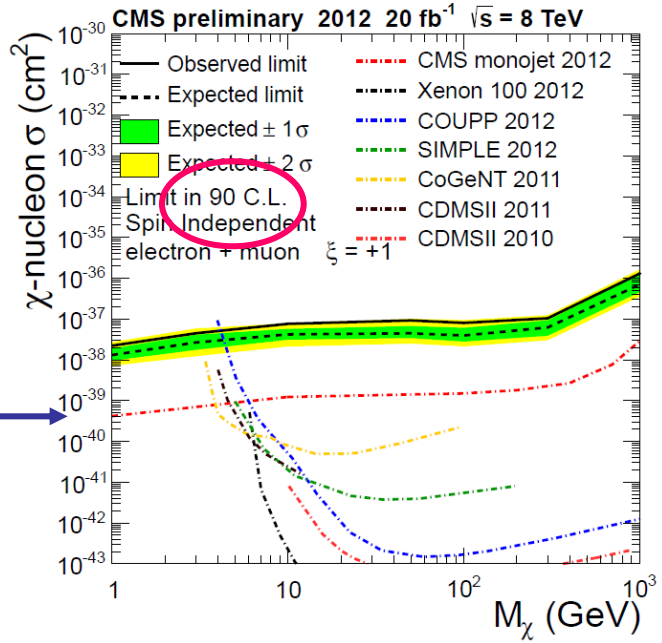
Spin independent



ξ=+1

ξ=-1

mono-W

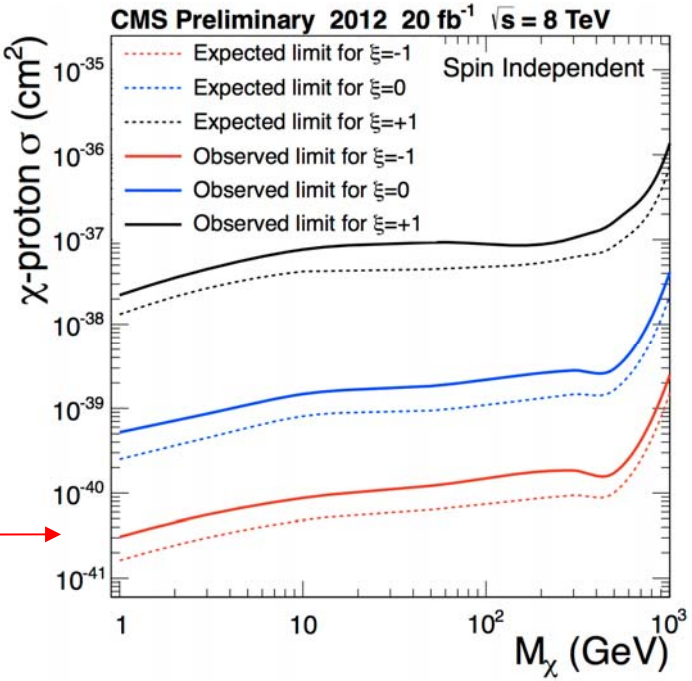


mono-jet

mono-W

ξ=+1

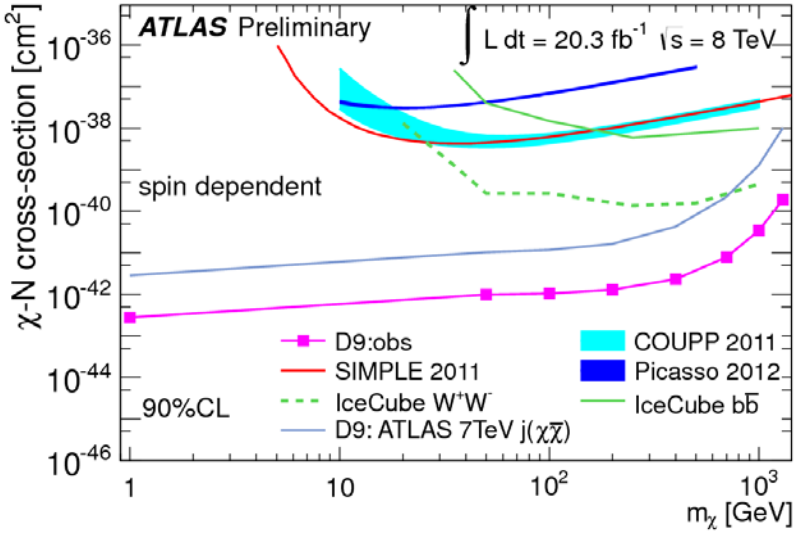
ξ=-1

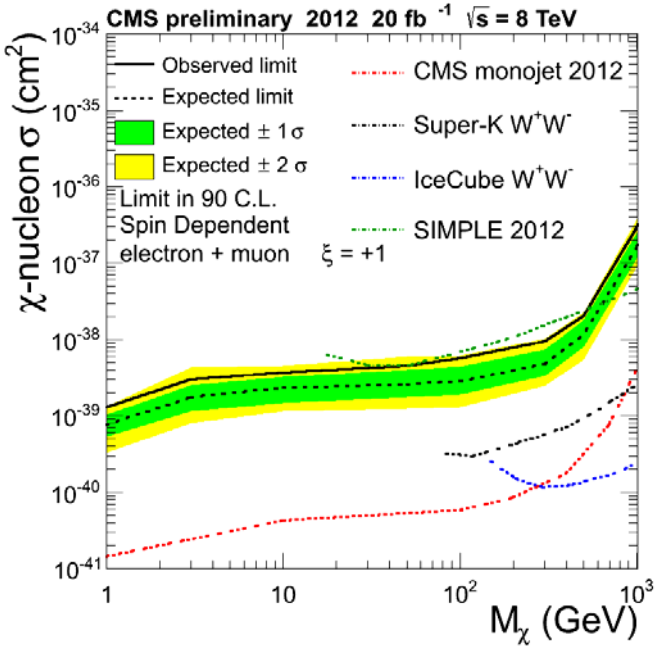


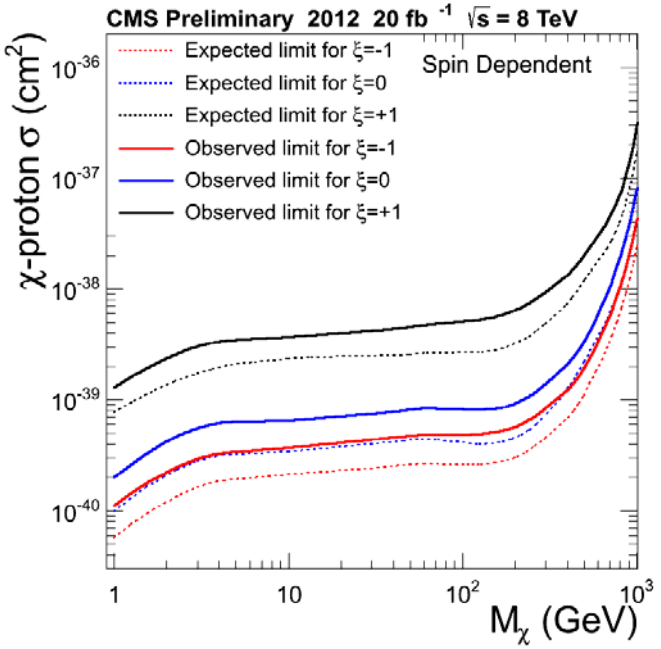
Dark matter (mono-W)

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

Spin dependent



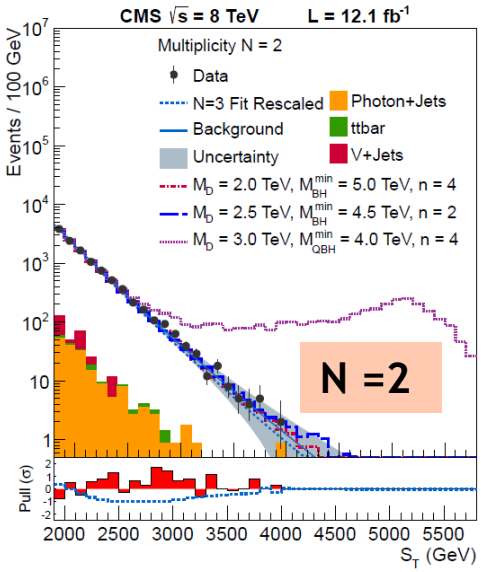




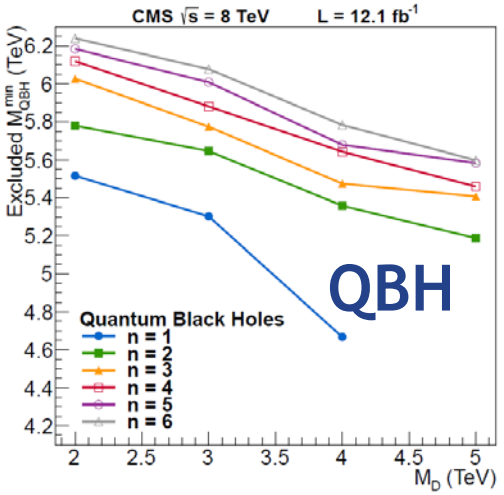
Black Holes

[CMS JHEP07(2013)178]

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



12 fb^{-1}



Multilepton inclusive search

$H_T^{leptons}$ ≥ [GeV]	$t\bar{t}+V(V)$	$VV(V)$	Reducible	Total	Observed
		≥ 3e/μ, off-Z			
200	5.5 ±0.2 ±1.7	64 ±1 ±15	13.6 ±1.9 ±2.3	83 ±2 ±16	66
500	0.29 ±0.04 ±0.09	2.9 ±0.2 ±1.4	0.29 ±0.23 ±0.69	3.5 ±0.3 ±1.5	3
800	0.02 ±0.01 ±0.01	0.5 ±0.1 ±0.2	$0^{+0.69}_{-0}$	0.5 ±0.1 ±0.7	0
		2e/μ+ ≥ 1τ, off-Z			
200	1.01 ±0.07 ±0.31	6.0 ±0.2 ±1.3	121 ±3 ±31	128 ±3 ±31	123
500	0.02 ±0.01 ±0.01	0.14 ±0.02 ±0.03	1.7 ±0.4 ±0.8	1.9 ±0.4 ±0.8	0
800	0.00 ±0.00 ±0.00	0.01 ±0.00 ±0.00	0.02 ±0.03 ±0.71	0.03 ±0.03 ±0.71	0
		≥ 3e/μ, on-Z			
200	12.1 ±0.2 ±3.6	389 ±4 ±98	28 ±4 ±6	429 ±6 ±99	414
500	0.46 ±0.05 ±0.14	11.0 ±0.6 ±5.3	2.2 ±1.3 ±0.7	13.7 ±1.5 ±5.3	13
800	0.03 ±0.01 ±0.01	0.9 ±0.2 ±0.4	0.3 ±0.2 ±0.7	1.2 ±0.3 ±0.8	3
		2e/μ+ ≥ 1τ, on-Z			
200	0.67 ±0.06 ±0.21	20.2 ±0.9 ±5.6	256 ±4 ±66	276 ±4 ±66	215
500	0.02 ±0.01 ±0.01	0.5 ±0.1 ±0.2	1.8 ±0.3 ±0.9	2.3 ±0.3 ±0.9	4
800	0.00 ±0.00 ±0.00	0.14 ±0.07 ±0.04	0.1 ±0.1 ±0.7	0.2 ±0.1 ±0.7	0

E_T^{miss} ≥ [GeV]	$t\bar{t}+V(V)$	$VV(V)$	Reducible	Total	Observed
		≥ 3e/μ, off-Z			
Inclusive	5.1 ±0.2 ±1.6	167 ±2 ±29	42 ±8 ±6	214 ±8 ±30	231
100	1.6 ±0.1 ±0.5	8.0 ±0.2 ±1.5	6.1 ±1.0 ±1.1	15.7 ±1.0 ±1.9	16
200	0.13 ±0.03 ±0.06	0.40 ±0.03 ±0.20	0.1 ±0.2 ±0.7	0.7 ±0.2 ±0.7	1
300	0.01 ±0.01 ±0.00	0.12 ±0.02 ±0.02	$0^{+0.69}_{-0}$	0.14 ±0.02 ±0.69	0
		2e/μ+ ≥ 1τ, off-Z			
Inclusive	1.3 ±0.1 ±0.4	31 ±1 ±5	1090 ±10 ±270	1120 ±10 ±270	1069
100	0.32 ±0.04 ±0.10	1.8 ±0.1 ±0.4	24.3 ±1.3 ±6.1	26.4 ±1.3 ±6.1	32
200	0.03 ±0.01 ±0.01	0.12 ±0.02 ±0.02	0.4 ±0.2 ±0.7	0.6 ±0.2 ±0.7	0
300	0.01 ±0.01 ±0.00	0.01 ±0.00 ±0.00	0.1 ±0.1 ±0.7	0.1 ±0.1 ±0.7	0
		≥ 3e/μ, on-Z			
Inclusive	7.4 ±0.2 ±2.4	2560 ±10 ±420	246 ±33 ±41	2812 ±35 ±424	2899
100	2.1 ±0.1 ±0.6	106 ±2 ±15	4.4 ±1.1 ±0.8	112 ±2 ±15	95
200	0.19 ±0.03 ±0.06	8.6 ±0.4 ±1.2	0.24 ±0.31 ±0.69	9.0 ±0.5 ±1.4	5
300	0.02 ±0.01 ±0.01	1.7 ±0.2 ±0.4	$0^{+0.69}_{-0}$	1.8 ±0.2 ±0.8	0
		2e/μ+ ≥ 1τ, on-Z			
Inclusive	0.5 ±0.1 ±0.2	133 ±3 ±24	16470 ±40 ±4120	16600 ±40 ±4120	14386
100	0.13 ±0.02 ±0.06	10 ±1 ±2	10 ±1 ±3	20 ±1 ±3	18
200	0.01 ±0.00 ±0.01	1.6 ±0.2 ±0.6	0.1 ±0.1 ±0.7	1.7 ±0.3 ±1.0	1
300	0.00 ±0.00 ±0.00	0.00 ±0.00 ±0.00	$0^{+0.71}_{-0}$	0.00 ±0.00 ±0.71	0

Table 8: Results for the low-H_T^{jets}, E_T^{miss} signal regions. Results are presented in number of expected events as N ± (stat) ± (syst).

Min. p_T^{ℓ} ≥ [GeV]	$t\bar{t}+V(V)$	$VV(V)$	Reducible	Total	Observed
		≥ 3e/μ, off-Z			
50	2.2 ±0.1 ±0.7	25.4 ±0.7 ±5.7	3.0 ±0.9 ±0.7	30.6 ±1.2 ±5.8	22
100	0.12 ±0.02 ±0.04	1.64 ±0.15 ±0.32	0.28 ±0.27 ±0.69	2.04 ±0.31 ±0.76	2
150	0.02 ±0.01 ±0.01	0.31 ±0.06 ±0.09	$0^{+0.69}_{-0}$	0.34 ±0.06 ±0.70	0
		2e/μ+ ≥ 1τ, off-Z			
50	0.32 ±0.04 ±0.10	1.9 ±0.1 ±0.4	22 ±1 ±6	24 ±1 ±6	24
100	0.01 ±0.00 ±0.00	0.09 ±0.02 ±0.03	0.4 ±0.1 ±0.7	0.5 ±0.1 ±0.7	1
150	0.00 ±0.00 ±0.00	0.01 ±0.00 ±0.00	0.03 ±0.02 ±0.71	0.04 ±0.02 ±0.71	0
		≥ 3e/μ, on-Z			
50	4.1 ±0.1 ±1.2	143 ±3 ±33	7.5 ±2.0 ±1.9	155 ±3 ±33	156
100	0.33 ±0.04 ±0.10	7.7 ±0.6 ±2.4	0.17 ±0.46 ±0.69	8.2 ±0.7 ±2.5	16
150	0.04 ±0.01 ±0.01	1.1 ±0.2 ±0.3	0.16 ±0.18 ±0.69	1.31 ±0.27 ±0.74	4
		2e/μ+ ≥ 1τ, on-Z			
50	0.20 ±0.03 ±0.07	7.9 ±0.6 ±2.0	79 ±2 ±21	88 ±2 ±21	51
100	0.00 ±0.00 ±0.00	0.68 ±0.20 ±0.20	1.1 ±0.2 ±0.8	1.8 ±0.3 ±0.8	2
150	0.00 ±0.00 ±0.00	0.08 ±0.08 ±0.02	0.03 ±0.03 ±0.71	0.10 ±0.08 ±0.71	0

E_T^{miss} ≥ [GeV]	$t\bar{t}+V(V)$	$VV(V)$	Reducible	Total	Observed
		≥ 3e/μ, off-Z			
Inclusive	6.1 ±0.2 ±1.9	25 ±1 ±11	14 ±2 ±2	45 ±2 ±11	49
100	2.54 ±0.11 ±0.80	4.2 ±0.3 ±2.6	5.0 ±1.0 ±0.7	12 ±1 ±3	11
200	0.37 ±0.04 ±0.12	1.0 ±0.2 ±0.8	0.6 ±0.2 ±0.7	2.0 ±0.3 ±1.1	0
300	0.08 ±0.02 ±0.03	0.12 ±0.04 ±0.09	0.2 ±0.1 ±0.7	0.4 ±0.1 ±0.7	0
		2e/μ+ ≥ 1τ, off-Z			
Inclusive	1.5 ±0.1 ±0.5	3.9 ±0.4 ±1.6	109 ±3 ±26	114 ±3 ±26	124
100	0.6 ±0.1 ±0.2	2.1 ±0.3 ±0.9	18 ±1 ±5	21 ±1 ±5	32
200	0.13 ±0.02 ±0.04	0.5 ±0.1 ±0.3	1.9 ±0.3 ±0.8	2.5 ±0.4 ±0.9	5
300	0.02 ±0.01 ±0.01	0.1 ±0.1 ±0.1	0.3 ±0.1 ±0.7	0.4 ±0.1 ±0.7	1
		≥ 3e/μ, on-Z			
Inclusive	21.1 ±0.3 ±6.4	218 ±4 ±89	24.4 ±4.8 ±4.1	264 ±6 ±90	300
100	6.0 ±0.2 ±1.8	39 ±2 ±19	1.7 ±0.6 ±0.7	47 ±2 ±20	44
200	1.0 ±0.1 ±0.3	9 ±1 ±5	0.2 ±0.4 ±0.7	10 ±1 ±5	13
300	0.12 ±0.02 ±0.04	2.3 ±0.4 ±1.5	$0^{+0.69}_{-0}$	2.4 ±0.4 ±1.7	1
		2e/μ+ ≥ 1τ, on-Z			
Inclusive	1.5 ±0.1 ±0.5	15 ±1 ±7	380 ±10 ±100	400 ±10 ±100	347
100	0.5 ±0.1 ±0.2	4.8 ±0.5 ±2.1	6.0 ±0.6 ±1.6	11 ±1 ±3	15
200	0.10 ±0.02 ±0.03	0.8 ±0.2 ±0.8	0.3 ±0.2 ±0.7	1.3 ±0.3 ±1.1	3
300	0.03 ±0.01 ±0.01	0.35 ±0.14 ±0.20	$0^{+0.71}_{-0}$	0.37 ±0.14 ±0.73	1

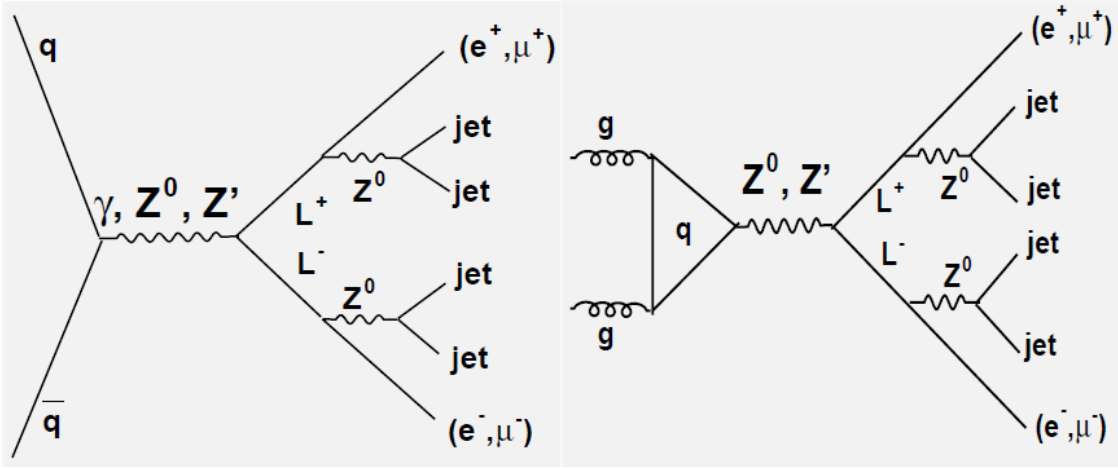
Table 9: Results for the high-H_T^{jets}, E_T^{miss} signal regions. Results are presented in number of expected events as N ± (stat) ± (syst).

Charged heavy leptons

[ATL-PHYS-2003-014]

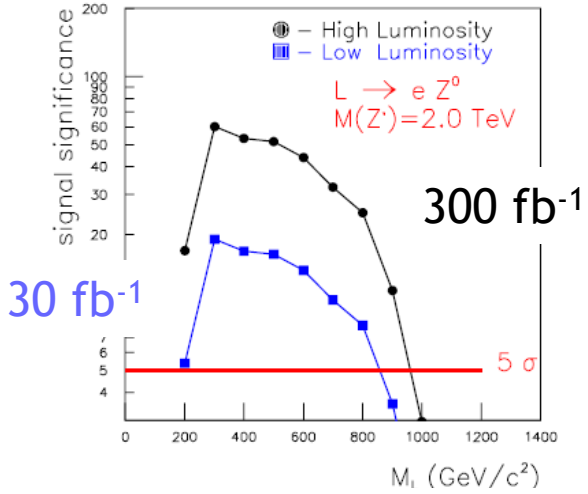
2 same flavour / opposite charge leptons + 4 jets

Main background = tt^{bar} and diboson+jets

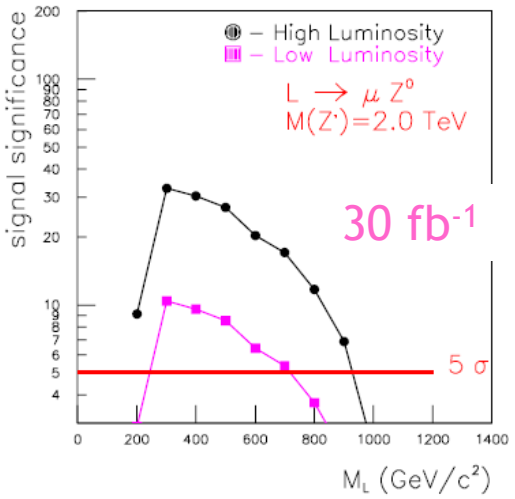


(also 4 and 6 lepton channels)

e channel



μ channel



ATLAS simulation

Assuming BR(L→lZ)=1/3, can discover sequential L with m(L) up to 0.9 (1) TeV with 30 (300) fb^{-1} - little dependency on m(Z')