Searches for Exotic Phenomena at ATLAS and CMS

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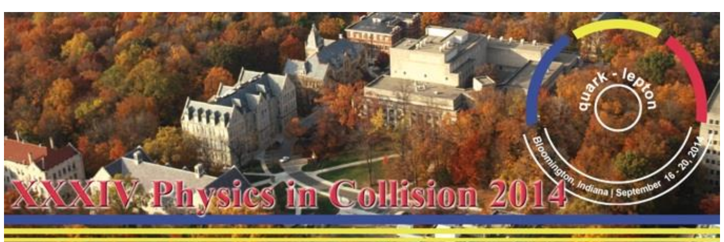
On behalf of ATLAS and CMS collaborations

PIC 2014



Fundamental questions in HEP

- Ordinary matter accounts for ~5% of mass-energy in Universe
  - No dark matter candidate in the SM
  - New AMS result is out*
- Hierarchy problem & fine tuning
  - Large gap between EWK scale and Planck Scale
  - SM Higgs mass needs fine tuning
- Flavor problem
  - No explanation for fermion masses and mixings
  - Three family structure; ‘Who ordered that?’
- Grand Unification
  - Unification of three forces, and gravity?
- Compositeness
  - Do leptons and quarks have internal structures?

* http://press.web.cern.ch/sites/press.web.cern.ch/files/ams_new_results_-_18.09.2014.pdf

Exotica searches

- Each model is motivated by one or more fundamental questions
  - We don't need to solve all problems at once
- Many exotica searches are signature based
  - Different models can be studied in the same final states
  - Even never thought signals may show up
- ATLAS and CMS exotica search programs cover broad ranges of theoretical models
  - It's impossible to cover all of ***recent*** results in a half hour
  - I will focus on subset of these results

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

ATLAS Preliminary

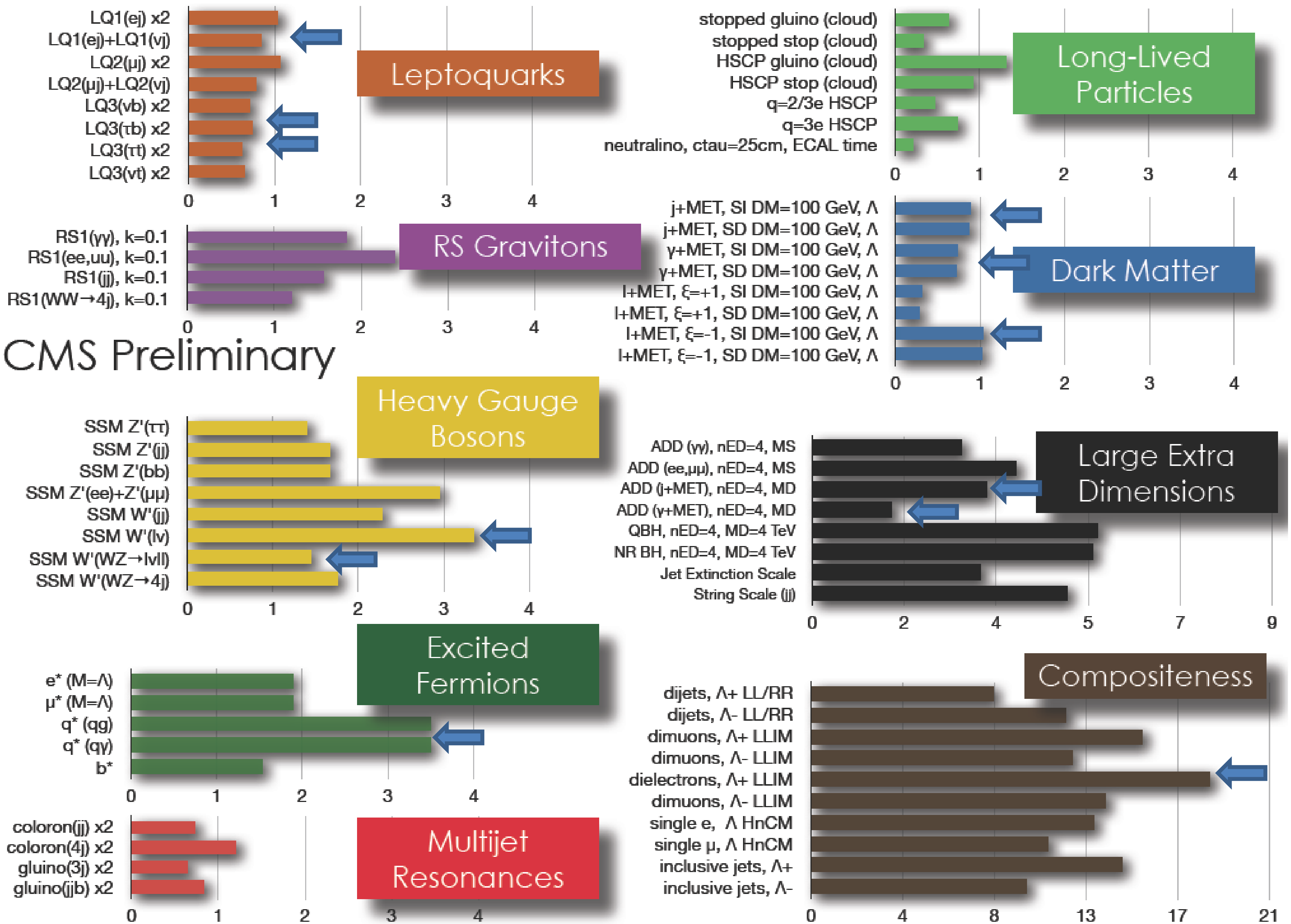
$\int \mathcal{L}\, dt = (1.0 - 20.3)\ \text{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	ℓ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt [fb^{-1}]$	Mass limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_D 4.37 TeV	$n = 2$	1210.4491
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_S 5.2 TeV	$n = 3$ HLZ	ATLAS-CONF-2014-030
	ADD QBH $\to \ell q$	$1\ e, \mu$	1 j	–	20.3	M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	20.3	M_{th} 5.82 TeV	$n = 6$	to be submitted to PRD
	ADD BH high N_{trk}	$2\ \mu$ (SS)	–	–	20.3	M_{th} 5.7 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1308.4075
	ADD BH high $\sum p_T$	$\geq 1\ e, \mu$	≥ 2 j	–	20.3	M_{th} 6.2 TeV	$n = 6$, $M_D = 1.5$ TeV, non-rot BH	1405.4254
	RS1 $G_{KK} \to \ell\ell$	$2\ e, \mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to WW \to \ell\nu\ell\nu$	$2\ e, \mu$	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/\overline{M}_{Pl} = 0.1$	1208.2880
	Bulk RS $G_{KK} \to ZZ \to \ell\ell qq$	$2\ e, \mu$	2 j / 1 J	–	20.3	G_{KK} mass 730 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-039
	Bulk RS $G_{KK} \to HH \to b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2014-005
	Bulk RS $g_{KK} \to t\bar{t}$	$1\ e, \mu$	≥ 1 b, ≥ 1J/2j	Yes	14.3	g_{KK} mass 2.0 TeV	BR = 0.925	ATLAS-CONF-2013-052
	S^1/Z_2 ED	$2\ e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV		1209.2535
	UED	$2\ \gamma$	–	Yes	4.8	Compact. scale R^{-1} 1.41 TeV		ATLAS-CONF-2012-072
Gauge bosons	SSM $Z' \to \ell\ell$	$2\ e, \mu$	–	–	20.3	Z' mass 2.9 TeV		1405.4123
	SSM $Z' \to \tau\tau$	$2\ \tau$	–	–	19.5	Z' mass 1.9 TeV		ATLAS-CONF-2013-066
	SSM $W' \to \ell\nu$	$1\ e, \mu$	–	Yes	20.3	W' mass 3.28 TeV		ATLAS-CONF-2014-017
	EGM $W' \to WZ \to \ell\nu\, \ell'\ell'$	$3\ e, \mu$	–	Yes	20.3	W' mass 1.52 TeV		1406.4456
	EGM $W' \to WZ \to qq\ell\ell$	$2\ e, \mu$	2 j / 1 J	–	20.3	W' mass 1.59 TeV		ATLAS-CONF-2014-039
	LRSM $W'_R \to t\bar{b}$	$1\ e, \mu$	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV		ATLAS-CONF-2013-050
	LRSM $W'_R \to t\bar{b}$	$0\ e, \mu$	≥ 1 b, 1 J	–	20.3	W' mass 1.77 TeV		to be submitted to EPJC
CI	CI $qqqq$	–	2 j	–	4.8	Λ 7.6 TeV	$\eta = +1$	1210.1718
	CI $qq\ell\ell$	$2\ e, \mu$	–	–	20.3	Λ 21.6 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2014-030
	CI $uutt$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	Λ 3.3 TeV	$\lvert C \rvert = 1$	ATLAS-CONF-2013-051
DM	EFT D5 operator (Dirac)	$0\ e, \mu$	1-2 j	Yes	10.5	M_* 731 GeV	at 90% CL for $m(\chi) < 80$ GeV	ATLAS-CONF-2012-147
	EFT D9 operator (Dirac)	$0\ e, \mu$	1 J, ≤ 1 j	Yes	20.3	M_* 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV	1309.4017
LQ	Scalar LQ 1st gen	$2\ e$	≥ 2 j	–	1.0	LQ mass 660 GeV	$\beta = 1$	1112.4828
	Scalar LQ 2nd gen	$2\ \mu$	≥ 2 j	–	1.0	LQ mass 685 GeV	$\beta = 1$	1203.3172
	Scalar LQ 3rd gen	$1\ e, \mu, 1\ \tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$	1303.0526
Heavy quarks	Vector-like quark $TT \to Ht + X$	$1\ e, \mu$	≥ 2 b, ≥ 4 j	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	ATLAS-CONF-2013-018
	Vector-like quark $TT \to Wb + X$	$1\ e, \mu$	≥ 1 b, ≥ 3 j	Yes	14.3	T mass 670 GeV	isospin singlet	ATLAS-CONF-2013-060
	Vector-like quark $TT \to Zt + X$	$2/\geq 3\ e, \mu$	$\geq$2/$\geq$1 b	–	20.3	T mass 735 GeV	T in (T,B) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Zb + X$	$2/\geq 3\ e, \mu$	$\geq$2/$\geq$1 b	–	20.3	B mass 755 GeV	B in (B,Y) doublet	ATLAS-CONF-2014-036
	Vector-like quark $BB \to Wt + X$	$2\ e, \mu$ (SS)	≥ 1 b, ≥ 1 j	Yes	14.3	B mass 720 GeV	B in (T,B) doublet	ATLAS-CONF-2013-051
Excited fermions	Excited quark $q^* \to q\gamma$	$1\ \gamma$	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1309.3230
	Excited quark $q^* \to qg$	–	2 j	–	20.3	q^* mass 4.09 TeV	only u^* and d^*, $\Lambda = m(q^*)$	to be submitted to PRD
	Excited quark $b^* \to Wt$	1 or $2\ e, \mu$	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	1301.1583
	Excited lepton $\ell^* \to \ell\gamma$	$2\ e, \mu, 1\ \gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$\Lambda = 2.2$ TeV	1308.1364
Other	LSTC $a_T \to W\gamma$	$1\ e, \mu, 1\ \gamma$	–	Yes	20.3	a_T mass 960 GeV		to be submitted to PLB
	LRSM Majorana ν	$2\ e, \mu$	2 j	–	2.1	N^0 mass 1.5 TeV	$m(W_R) = 2$ TeV, no mixing	1203.5420
	Type III Seesaw	$2\ e, \mu$	–	–	5.8	$N^{\pm}$ mass 245 GeV	$\lvert V_e \rvert$=0.055, $\lvert V_\mu \rvert$=0.063, $\lvert V_\tau \rvert$=0	ATLAS-CONF-2013-019
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	$2\ e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	DY production, BR($H^{\pm\pm} \to \ell\ell$)=1	1210.5070
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $\lvert q \rvert = 4e$	1301.5272
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $\lvert g \rvert = 1 g_D$	1207.6411

$\sqrt{s} = 7$ TeV (blue) | $\sqrt{s} = 8$ TeV (green)

Mass scale [TeV]: 10^{-1}, 1, 10

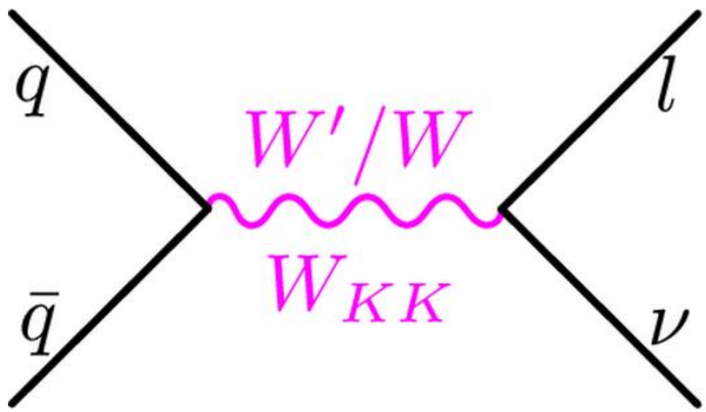
*Only a selection of the available mass limits on new states or phenomena is shown.

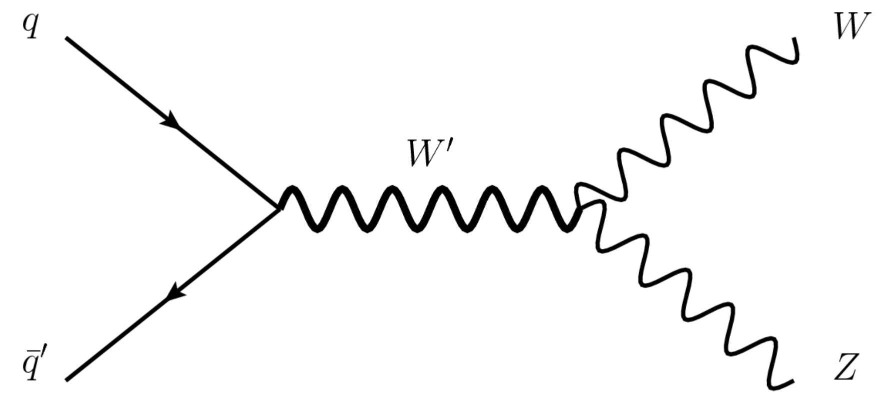

CMS Preliminary
Leptoquarks
LQ1(ej) x2
LQ1(ej)+LQ1(νj)
LQ2(μj) x2
LQ2(μj)+LQ2(νj)
LQ3(νb) x2
LQ3(τb) x2
LQ3(ττ) x2
LQ3(νt) x2
0 1 2 3 4
RS Gravitons
RS1(γγ), k=0.1
RS1(ee,μμ), k=0.1
RS1(jj), k=0.1
RS1(WW→4j), k=0.1
0 1 2 3 4
Long-Lived Particles
stopped gluino (cloud)
stopped stop (cloud)
HSCP gluino (cloud)
HSCP stop (cloud)
q=2/3e HSCP
q=3e HSCP
neutralino, ctau=25cm, ECAL time
0 1 2 3 4
Dark Matter
j+MET, SI DM=100 GeV, Λ
j+MET, SD DM=100 GeV, Λ
γ+MET, SI DM=100 GeV, Λ
γ+MET, SD DM=100 GeV, Λ
l+MET, ξ=+1, SI DM=100 GeV, Λ
l+MET, ξ=+1, SD DM=100 GeV, Λ
l+MET, ξ=-1, SI DM=100 GeV, Λ
l+MET, ξ=-1, SD DM=100 GeV, Λ
0 1 2 3 4
Heavy Gauge Bosons
SSM Z'(ττ)
SSM Z'(jj)
SSM Z'(bb)
SSM Z'(ee)+Z'(μμ)
SSM W'(jj)
SSM W'(lν)
SSM W'(WZ→lνll)
SSM W'(WZ→4j)
0 1 2 3 4
Large Extra Dimensions
ADD (γγ), nED=4, MS
ADD (ee,μμ), nED=4, MS
ADD (j+MET), nED=4, MD
ADD (γ+MET), nED=4, MD
QBH, nED=4, MD=4 TeV
NR BH, nED=4, MD=4 TeV
Jet Extinction Scale
String Scale (jj)
0 2 4 5 7 9
Excited Fermions
e* (M=Λ)
μ* (M=Λ)
q* (qg)
q* (qγ)
b*
0 1 2 3 4
Multijet Resonances
coloron(jj) x2
coloron(4j) x2
gluino(3j) x2
gluino(jjb) x2
0 1 2 3 4
Compositeness
dijets, Λ+ LL/RR
dijets, Λ- LL/RR
dimuons, Λ+ LLIM
dimuons, Λ- LLIM
dielectrons, Λ+ LLIM
dimuons, Λ- LLIM
single e, Λ HnCM
single μ, Λ HnCM
inclusive jets, Λ+
inclusive jets, Λ-
0 4 8 13 17 21

Outline

Model	Motivation Connections	Final states
W’	Sequential SM, Extended gauge model	Lepton(s)+MET Leptons+jets, Dijet
Dark Matter (DM)	Astrophysical observation, WIMP miracle	MonoX+MET
Leptoquarks (LQ)	Grand unification theory, Pati-Salam SU(4), E6, compositeness	Lepton(s)+jets Leptons+MET
Lepton flavor violation	Accidental symmetry, Neutrino oscillation	e-mu
Compositeness	Hierarchy problem, Excited fermions and bosons, Contact interaction	γ+jet, Lepton+MET Leptons+jets, Dilepton, Dijet
Vector-like quarks	Hierarchy problem, Little Higgs, Composite Higgs	Leptons+jets
Low Scale Technicolor	Hierarchy problem	Diboson

Other models are in backup slides





W’

- SM could be a remnant of a larger symmetry group, which unifies EWK and strong (and gravitational) forces
  - Heavy vector bosons from such broken symmetries: W’ and Z’
- Bench mark points:
  - W’ couples to fermions like SM W does
  - W’ couples to WZ (i.e., fermion decay modes negligible)
- Searches in different channels to account a priori unknown W’ couplings
- Overlap with DM mono-W searches

Right-handed W search in backup

W' (1/2)

W' → lν

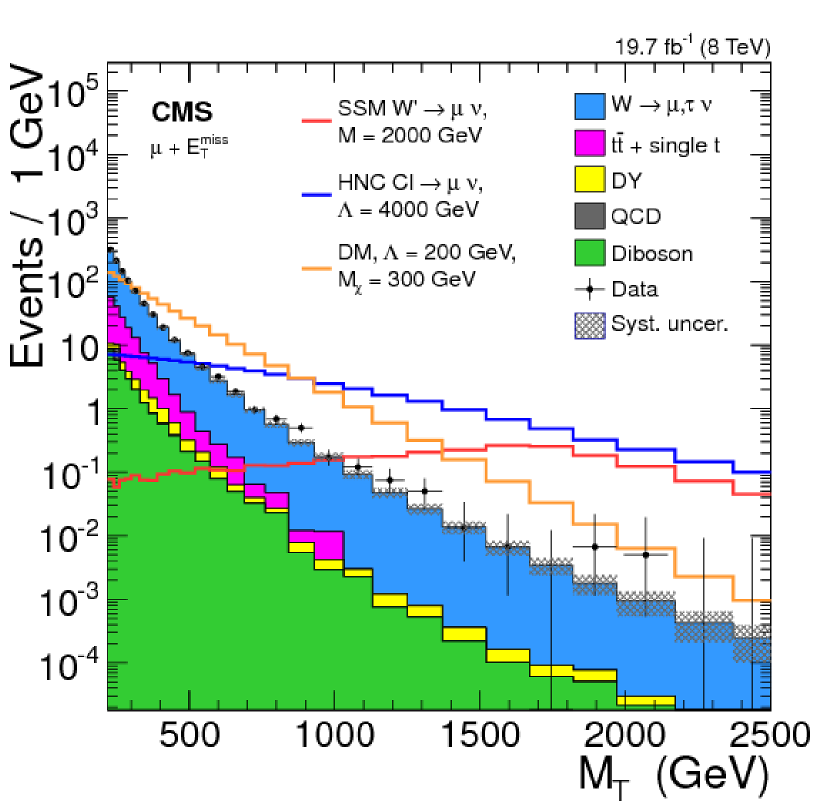
CMS lν (mono-W)

Electron $p_T > 80$, Muon $p_T > 45$

MET > 100

Main BG: W

arXiv:1408.2745



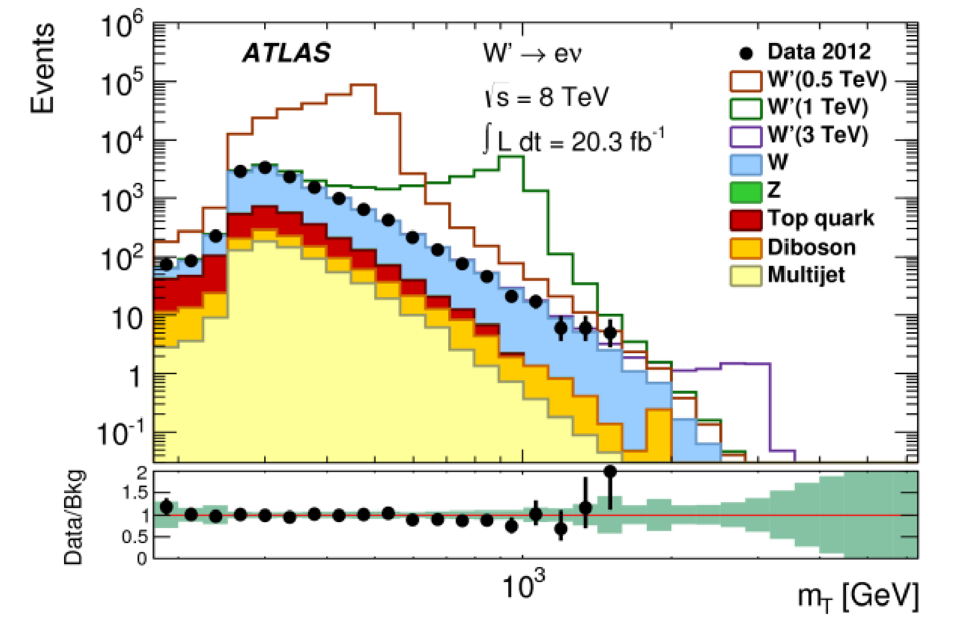
ATLAS lν (mono-W)

Electron $p_T > 125$, Muon $p_T > 45$

MET > 125 or 45

Main BG: W

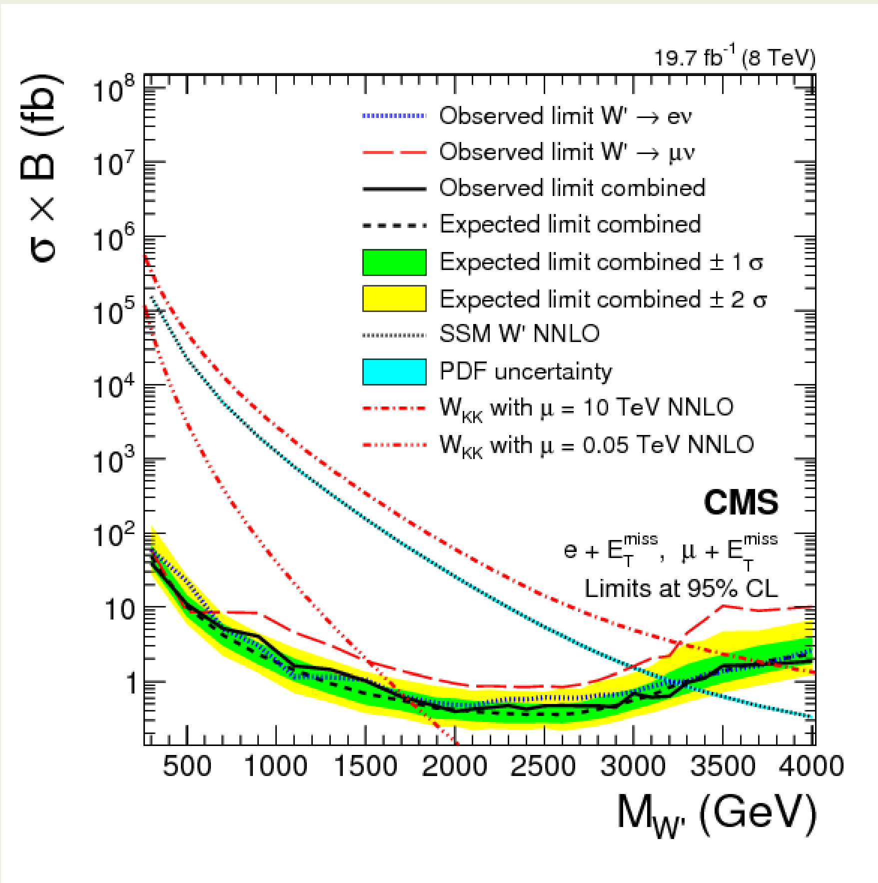
arXiv:1407.7494

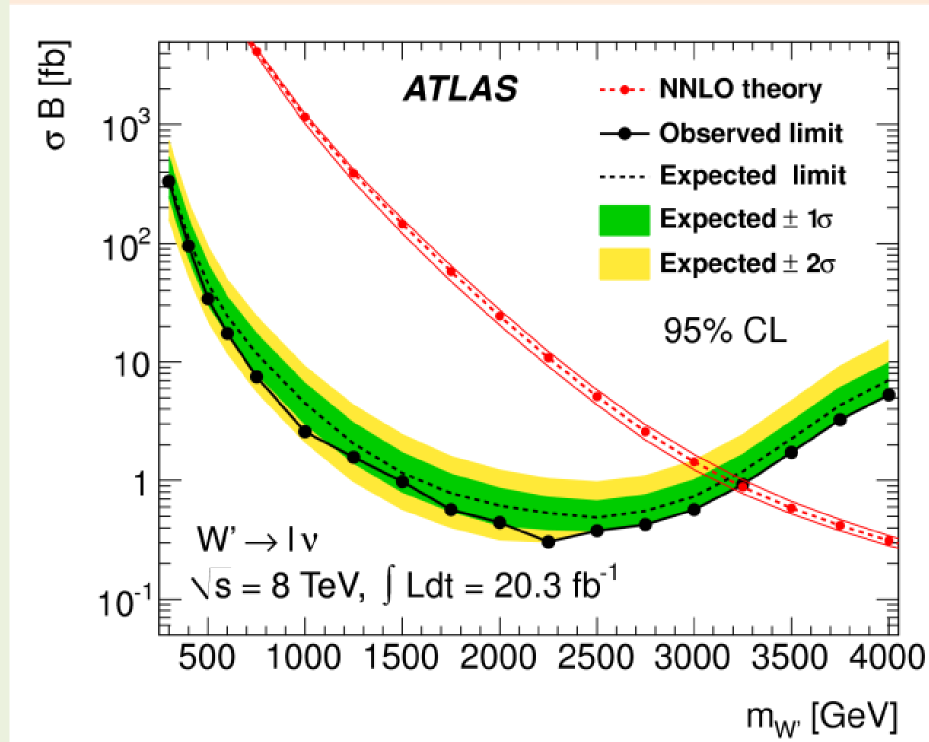


$$M_T = \sqrt{2 p_T^{\ell} E_T^{\text{miss}} \left(1 - \cos[\Delta\phi(\ell, \vec{p}_T^{\text{miss}})]\right)}$$

W’ (1/2)

W’ → lν

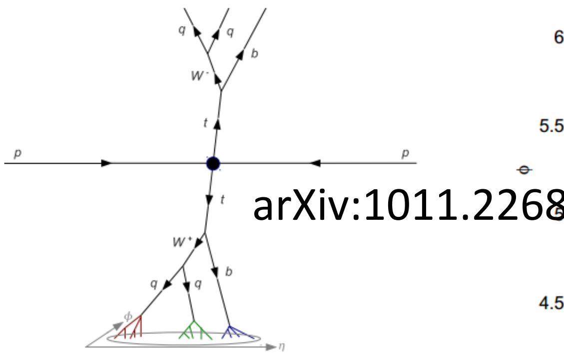


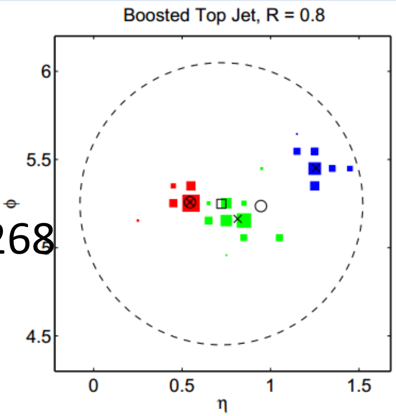


Limits on W’ mass: 3.24 TeV (ATLAS lν), 3.28 TeV (CMS lν)
W’ → qq’ search is in backup

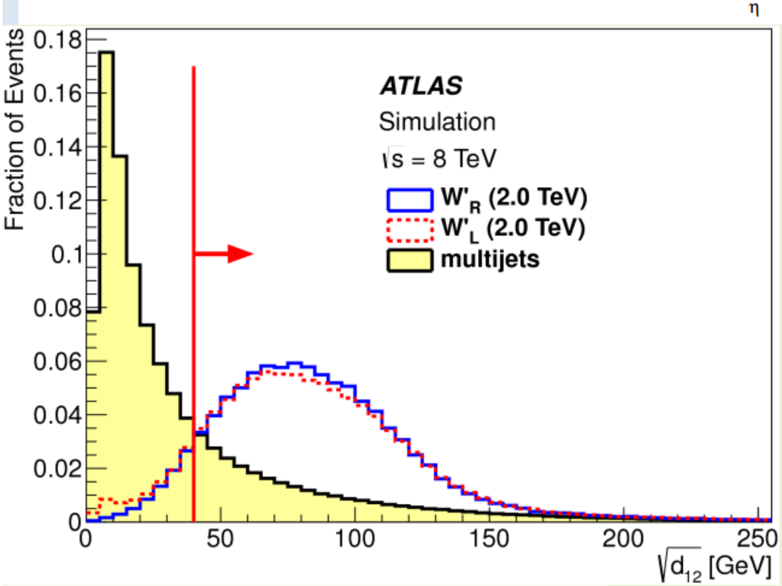
W’ (2/2)

W’ → tb → Wbb → qq’bb





- Top quarks are boosted; its decay products are collimated
- See boosted object search talk for the details of jet substructure techniques



$$\sqrt{d_{12}} = \min(p_{T,1}, p_{T,2}) \times \sqrt{(\Delta\eta_{12})^2 + (\Delta\phi_{12})^2}$$

Splitting scale

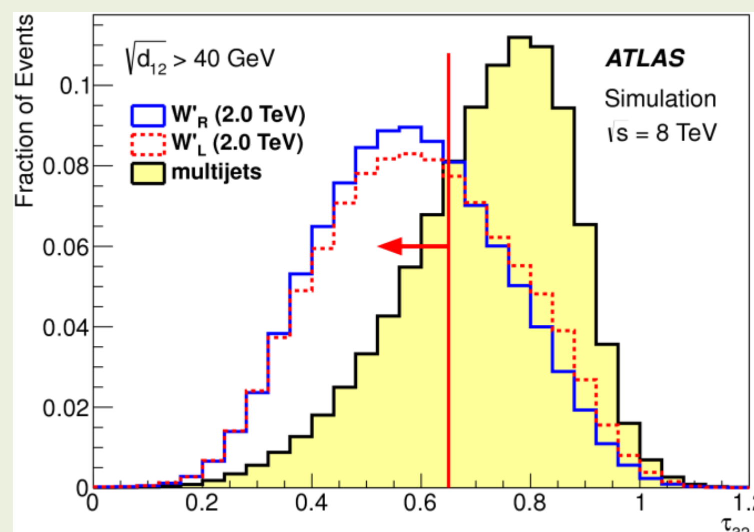
ATLAS qq’bb

Jet p_T > 25

Large jet p_T > 350

Main BG: Multi-jet

arXiv:1408.0886

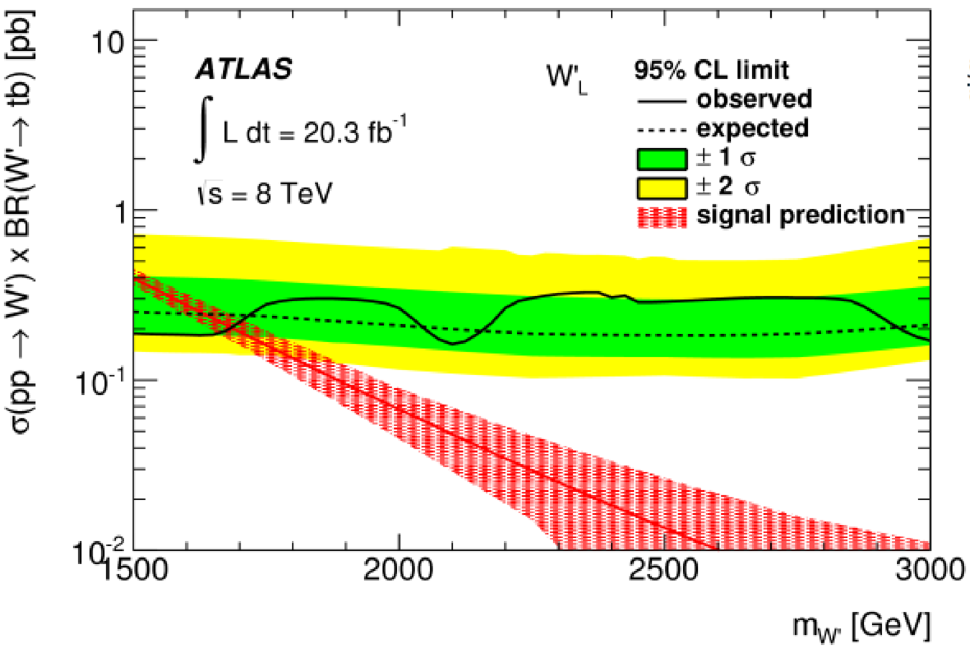


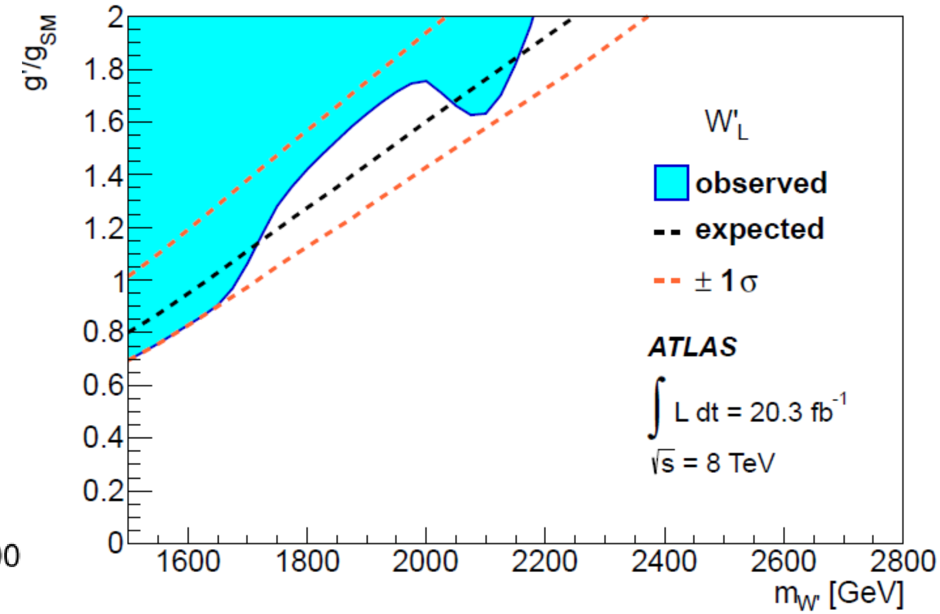
$$\tau_N = \frac{1}{d_0} \sum_k p_{Tk} \times \min(\delta R_{1k}, \ldots, \delta R_{Nk})$$

N-subjettiness

W’ (2/2)

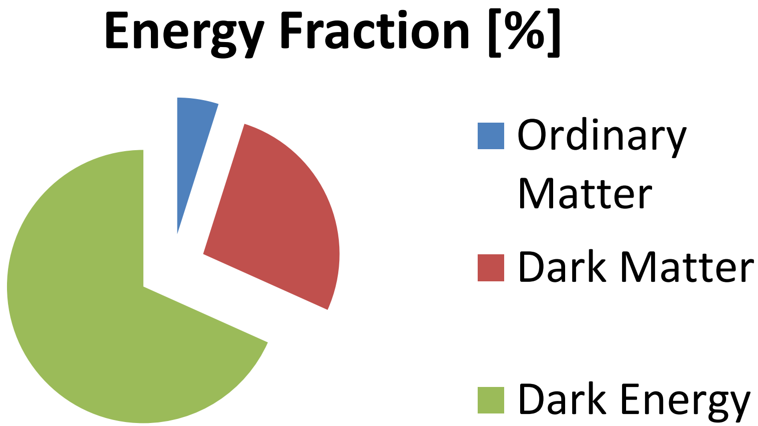
W’ → tb → Wbb → qq’bb

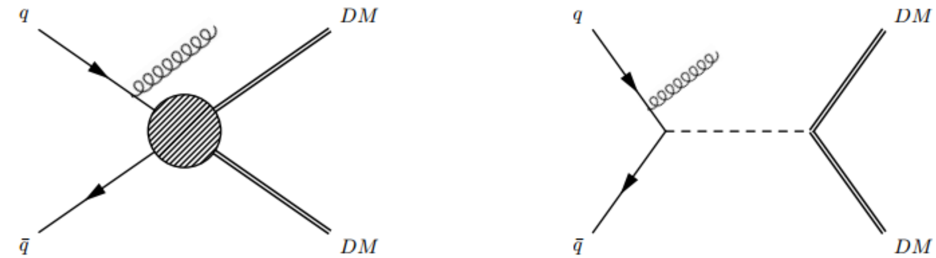


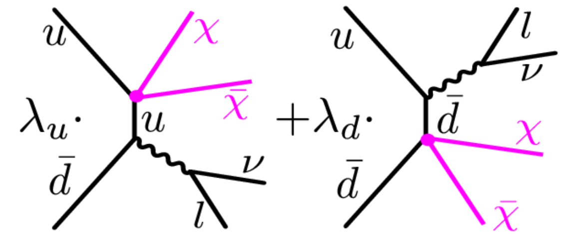


Limits on W’ mass: 1.68 TeV (qq’bb)

W’ → WZ search in backup







Dark Matter

- Ordinary matter is only 4.9% of total mass-energy in Universe
- SM has no candidate for DM
- WIMP miracle (match with DM relic density)
- Mono-X final states for weakly interacting DM particles produced in processes with initial state radiation
- Different EFT operator types and interference scenario are considered
- Advantage of collider experiments is sensitivity in lower mass region

Dark Matter (1/2)

Mono-jet, Mono-photon

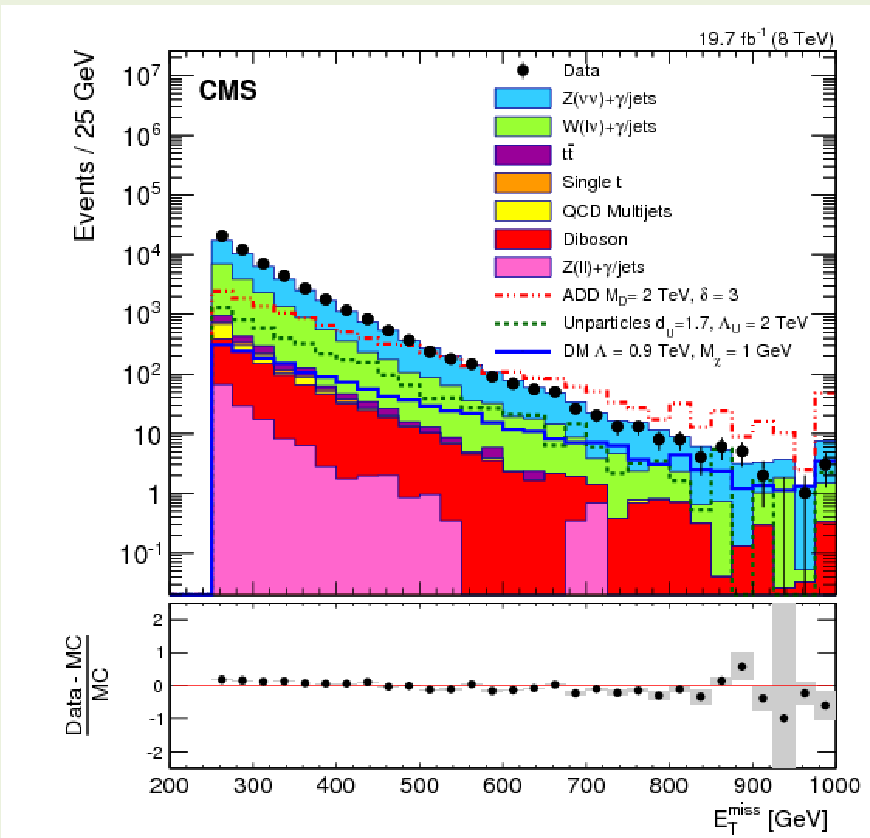
CMS mono-jet

Jet $p_T > 110$

MET > 250

Main BG: Z+γ, Z+jets

arXiv:1408.3583



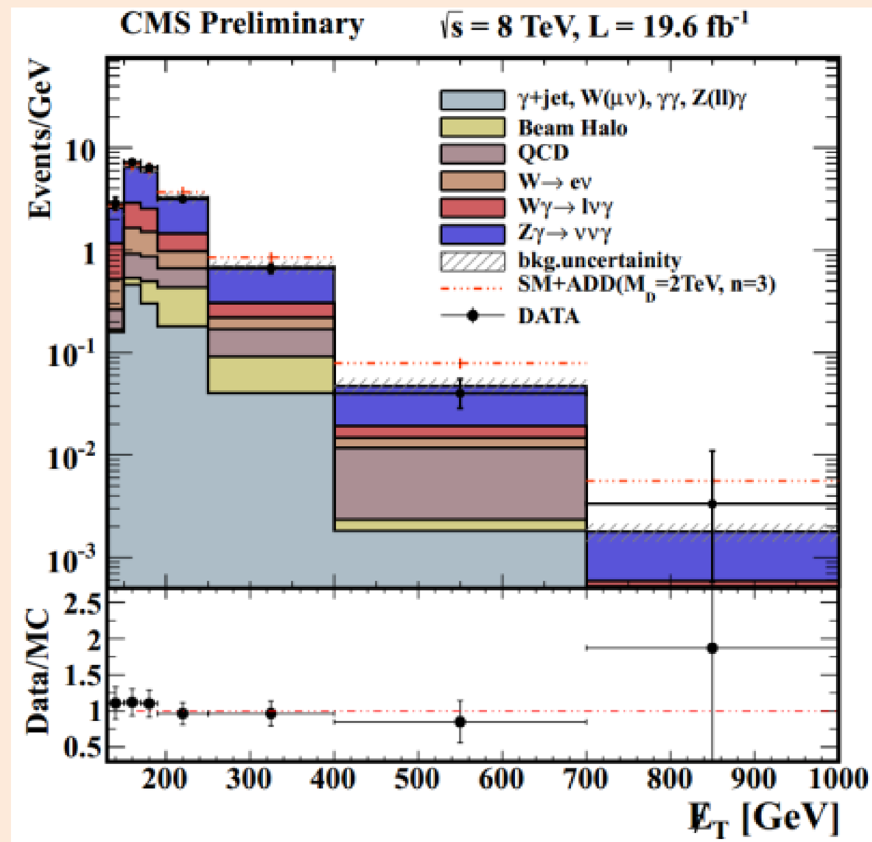
CMS mono-photon

γ $p_T > 145$

MET > 140

Main BG: Z+γ

CMS PAS EXO-12-047

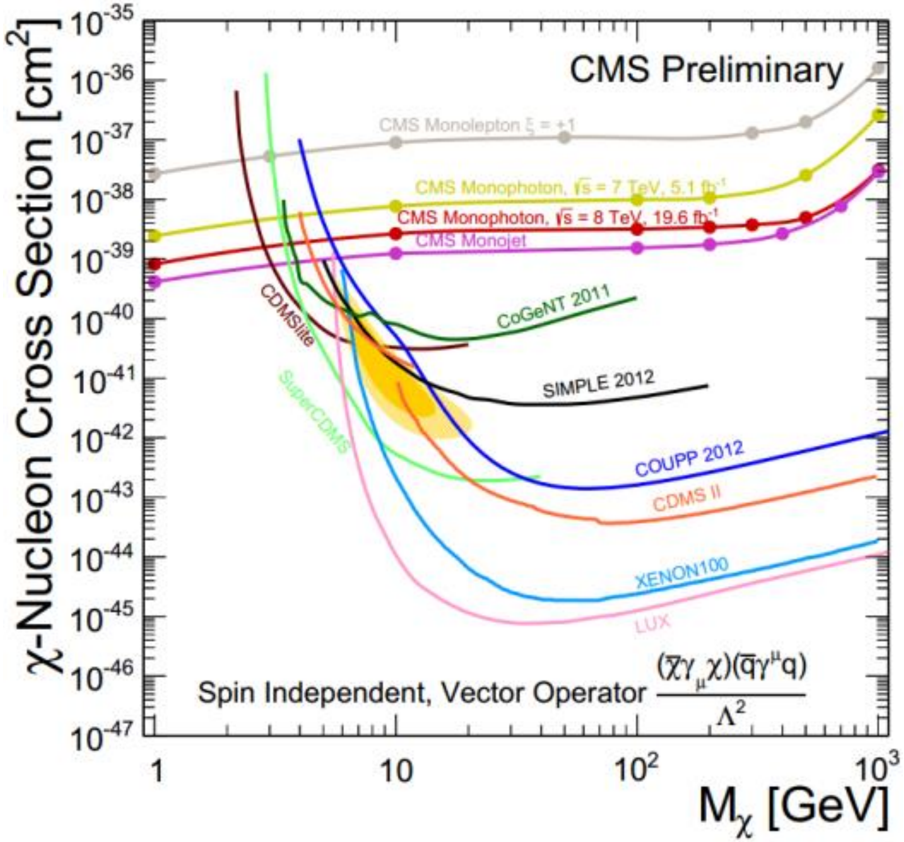


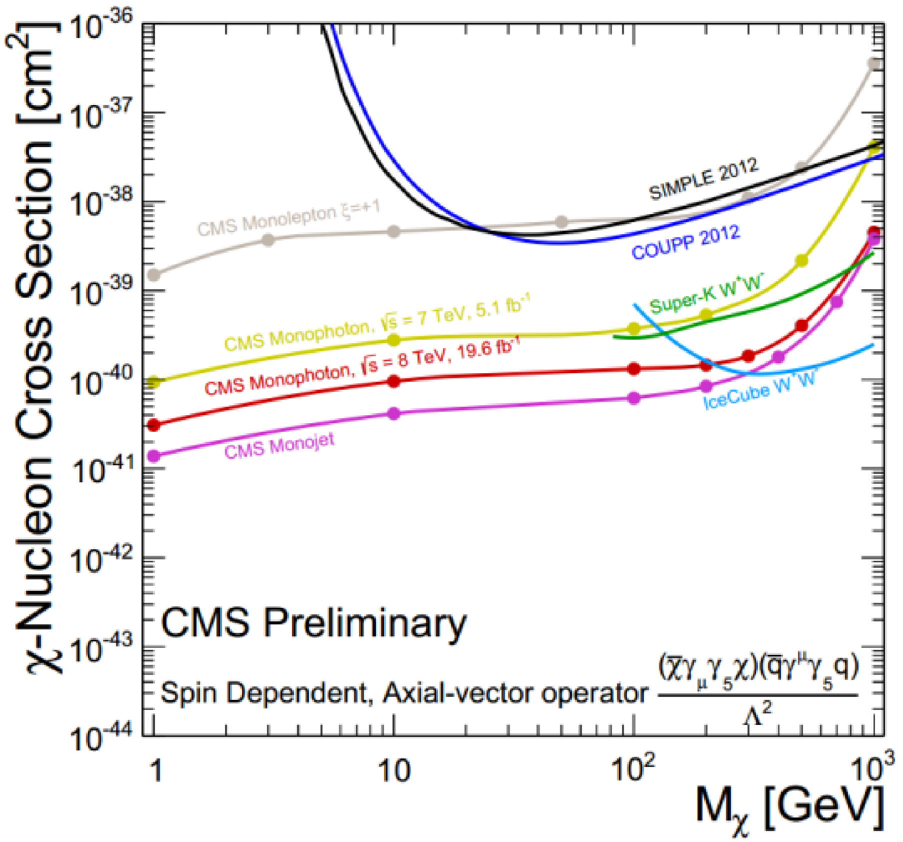
MET = Missing Transverse Energy [GeV]

Dark Matter (1/2)

<u>Mono-jet, Mono-photon</u>

Limits set for different EFT operator types (Dirac WIMPs)





Limits on χ-Nucleon σ: 10^{-40}-10^{-38} cm^2 (vector), 10^{-41}-10^{-38} cm^2 (axial-vector)

Dark Matter (2/2)

Mono-Z, Mono-W

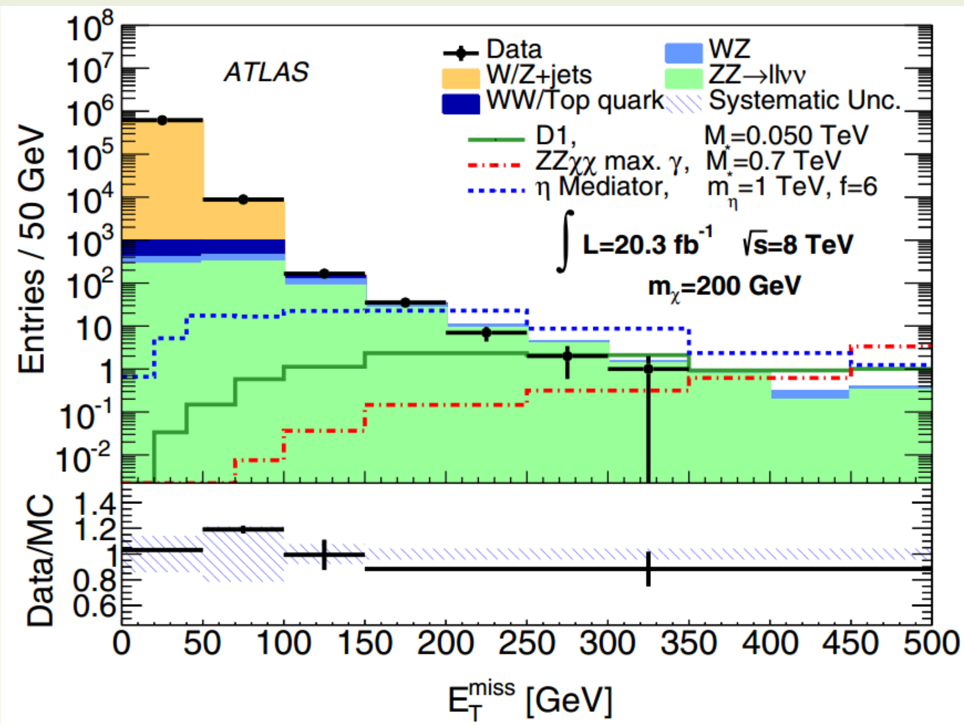
ATLAS mono-Z(ll)

Electron $p_T > 20$ or Muon $p_T > 20$

MET > 150

Main BG: V+jets, ZZ

PhysRevD.90.012004



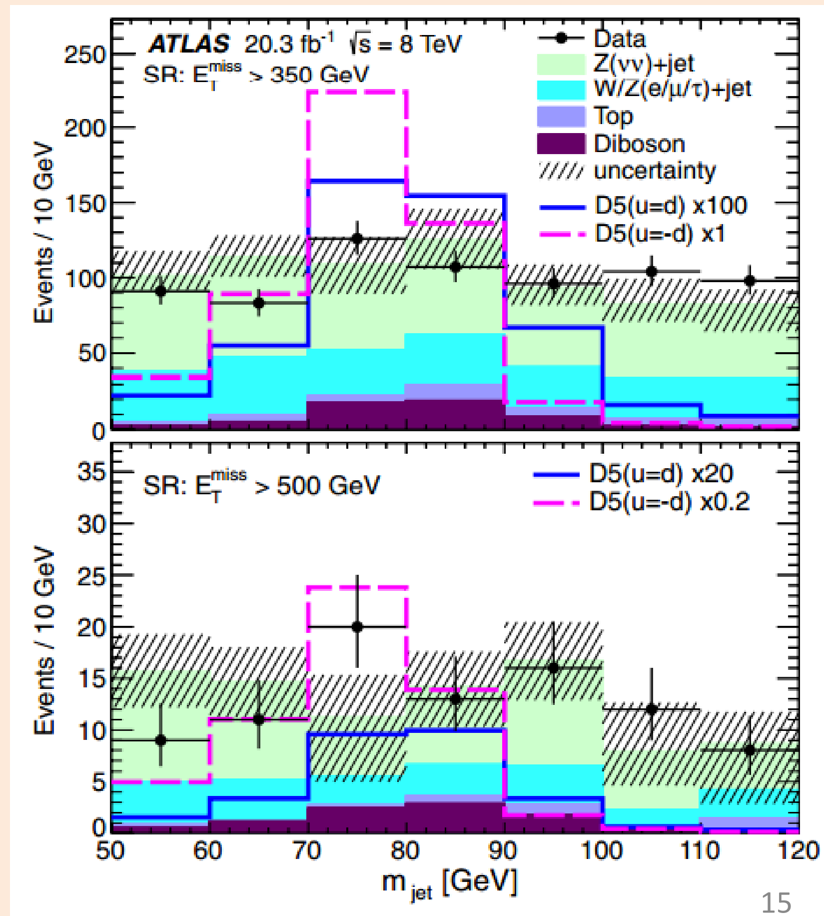
ATLAS mono-W(qq) and Z(qq)

large jet $p_T > 250$

MET > 350

Main BG: V+jets

PhysRevLett.112.041802

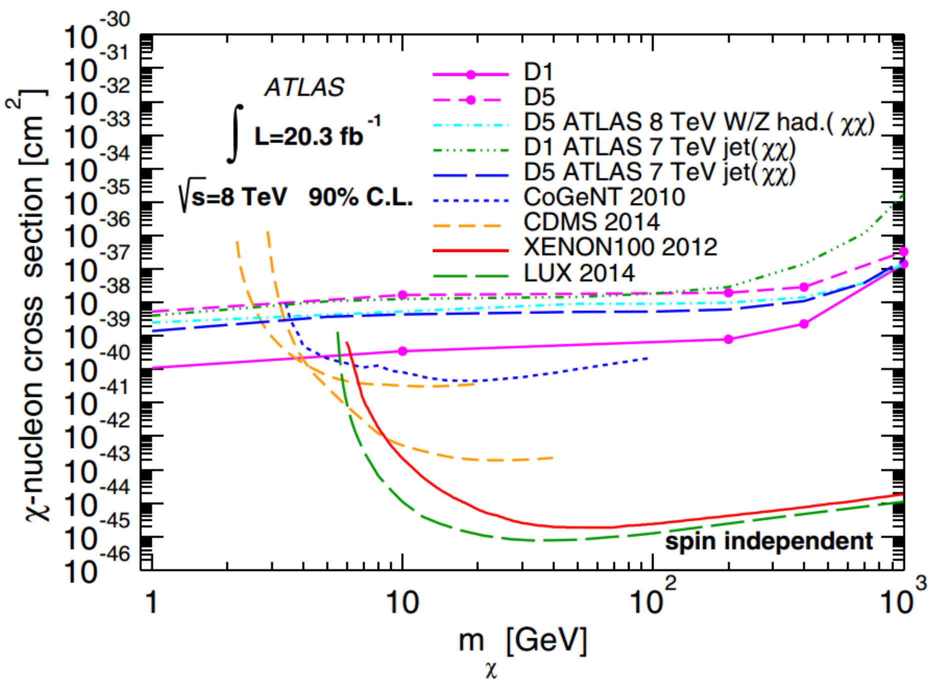


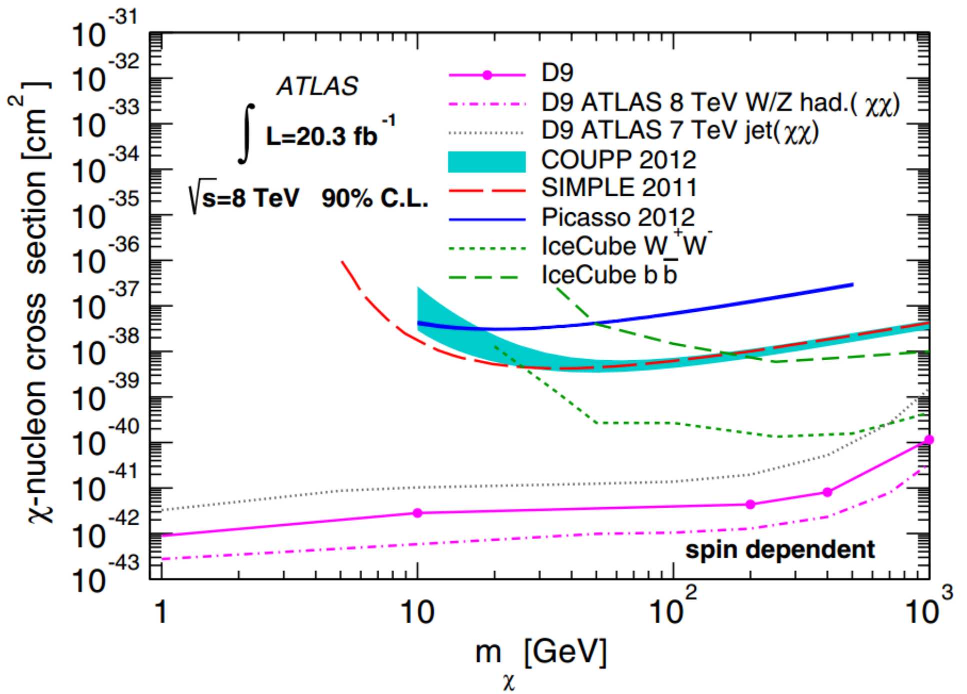
ATLAS and CMS mono-W(lv) results in backup

Dark Matter (2/2)

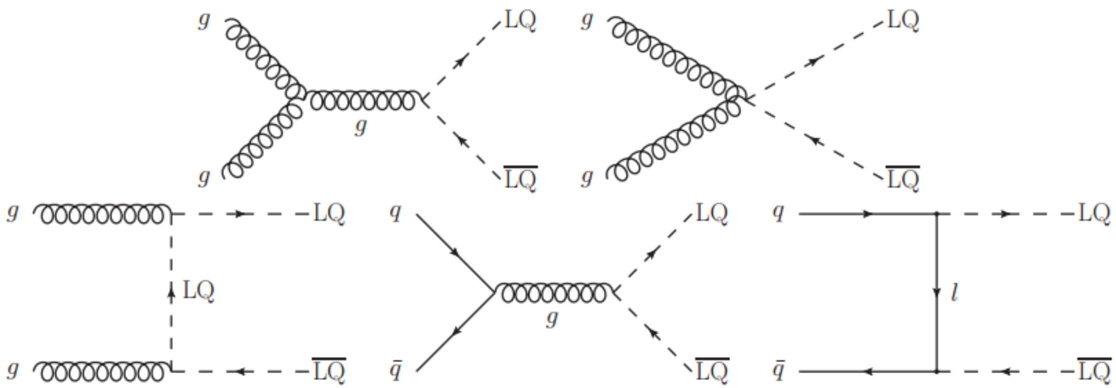
Mono-Z, Mono-W

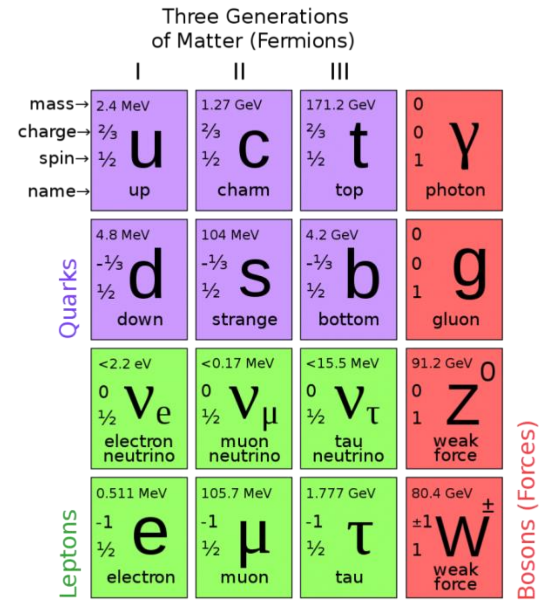
Limits set for different EFT operator types (Dirac WIMPs)





Limits on χ-Nucleon σ: 10^{-40}-10^{-38} cm^2 (D5=vector), 10^{-43}-10^{-40} cm^2 (D9=Tensor)





Scalar Leptoquarks

- SM structure suggests fundamental relationship between leptons and quarks
  - LQs can arise from SU(5) grand unification, SU(4) Pati-Salam, and E6
- LQs are scalar or vector bosons carrying lepton number, color and fractional electric charges
- Measurements on FCNC, Lepton family number violation, and other rare decays favor LQ decay within the same generation
- BR(LQ → charged lepton plus quark) = β

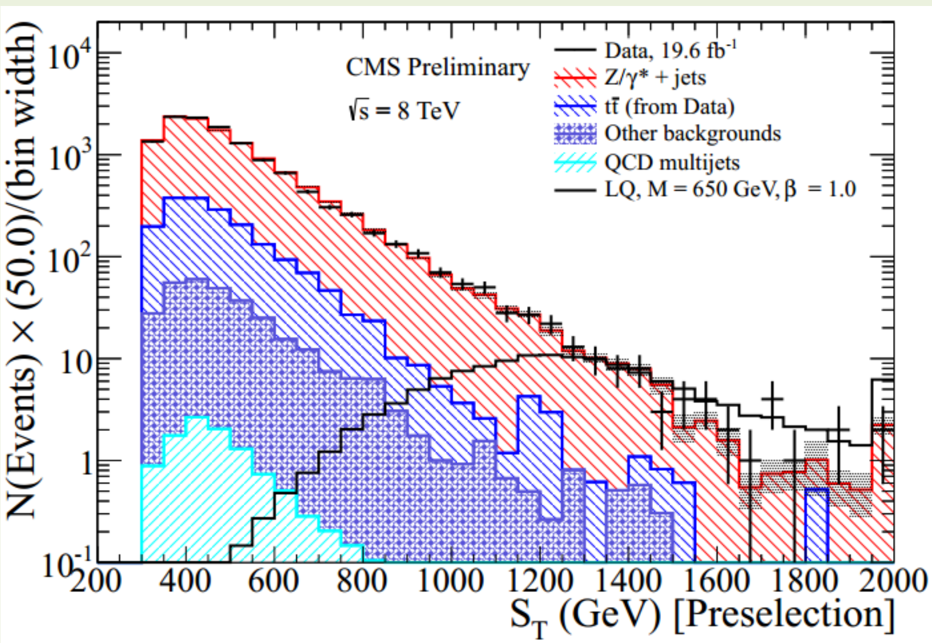
Scalar Leptoquarks (1/2)

1st gen LQ → eνqq or eeqq

CMS 1st gen LQ

Electron $p_T > 45$
1st Jet $p_T > 125$
2nd Jet $p_T > 45$
Main BG: V+jets

CMS-PAS-EXO-12-041

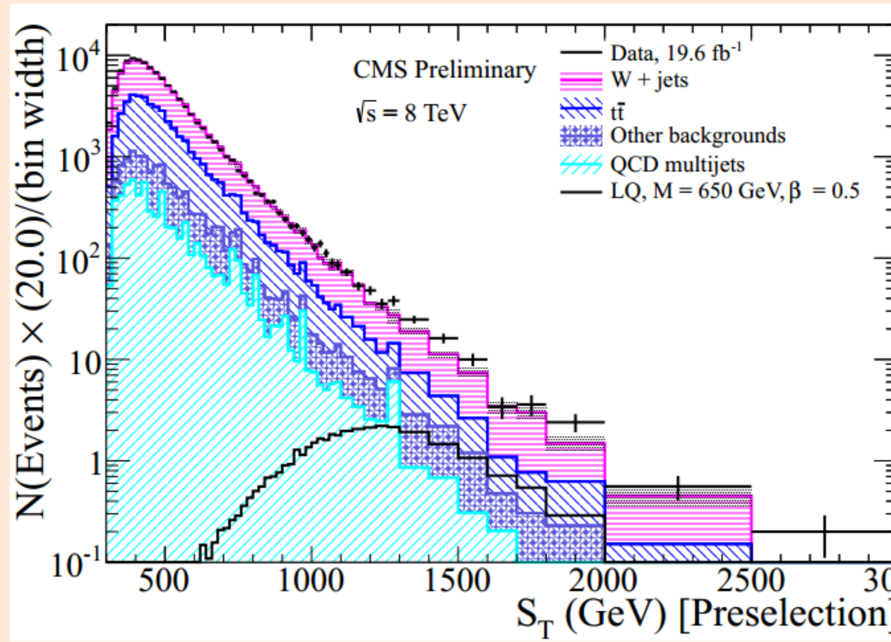


eejj channel

CMS 1st gen LQ

Electron $p_T > 45$
1st Jet $p_T > 125$
2nd Jet $p_T > 45$
MET > 55
Main BG: V+jets

CMS-PAS-EXO-12-041

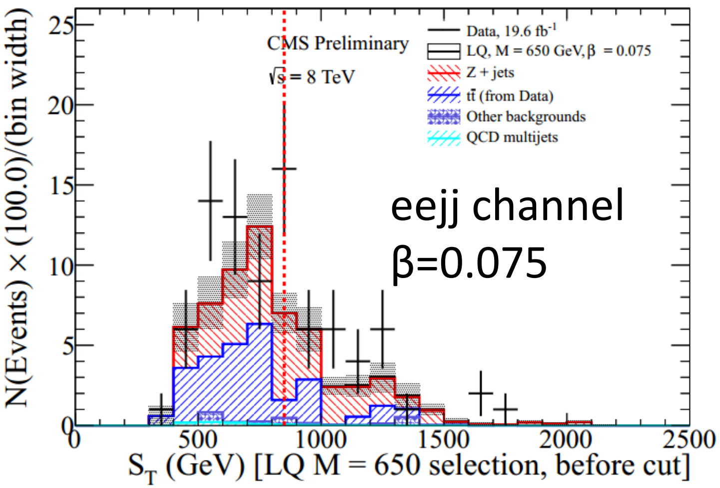


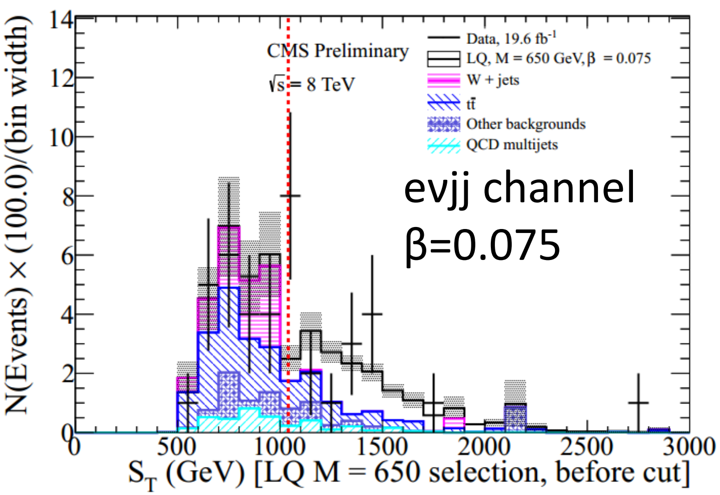
eνjj channel

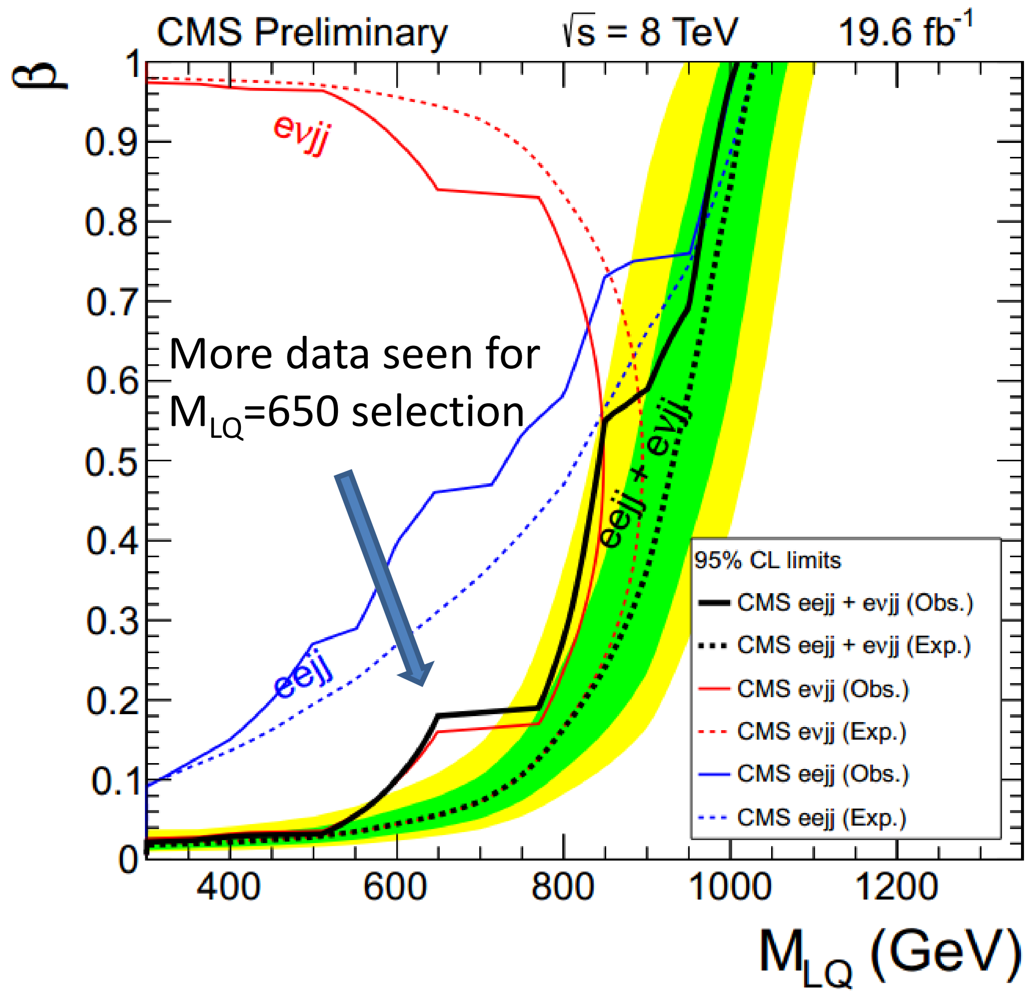
S_T = Scalar sum of p_T [GeV]

Scalar Leptoquarks (1/2)

1st gen LQ → eνqq or eeqq







Limits on 1st gen scalar LQ mass: 1.01 TeV (β=1)

ATLAS limit: 660 GeV (7TeV, 1.03 fb^{-1} for β=1)

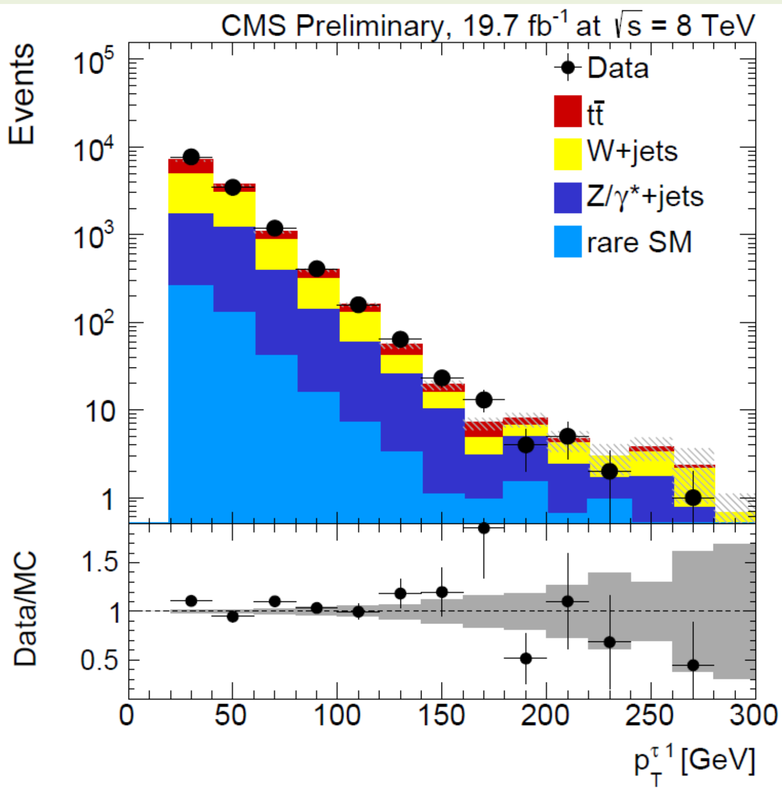
Scalar Leptoquarks (2/2)

3rd gen LQ → ttττ → μτjj, LQ → bbττ → bblτ

CMS charge-1/3 LQ

Muon $p_T > 25$
Tau $p_T > 25$
Jet $p_T > 30$
Main BG: ttbar, V+jets

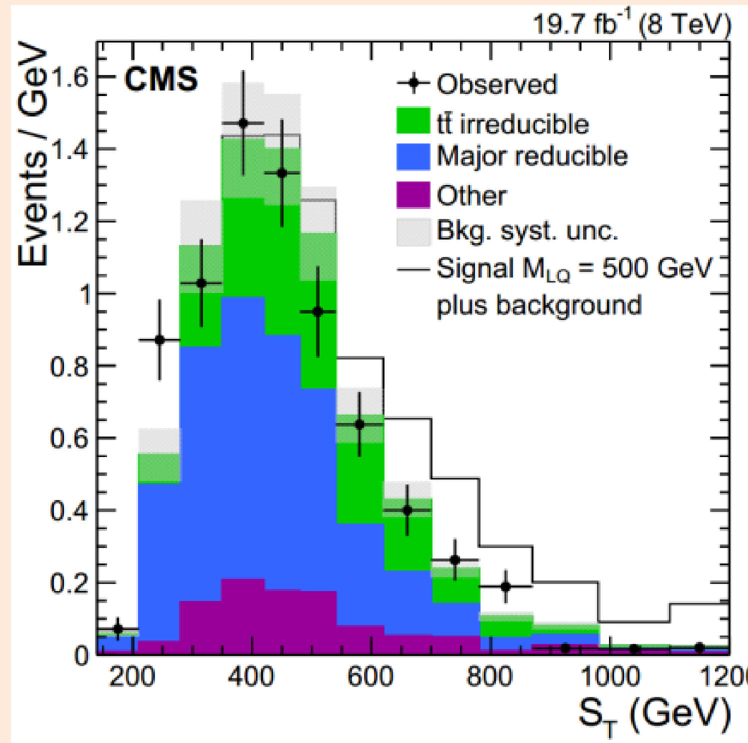
CMS-PAS-EXO-13-010



CMS charge+2/3 LQ

Electron $p_T > 30$ or Muon $p_T > 30$
Tau $p_T > 50$
Jet $p_T > 30$
#bjets >= 1
Main BG: ttbar, V+jets

arXiv:1408.0806

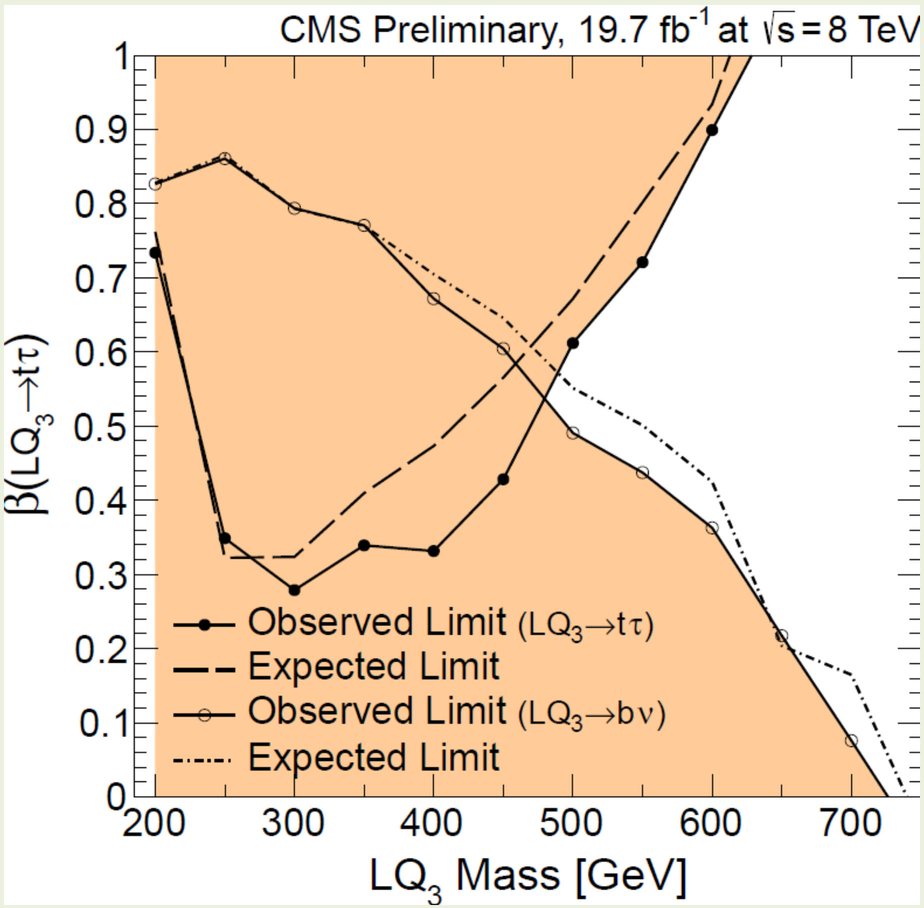


S_T = Scalar sum of p_T [GeV]

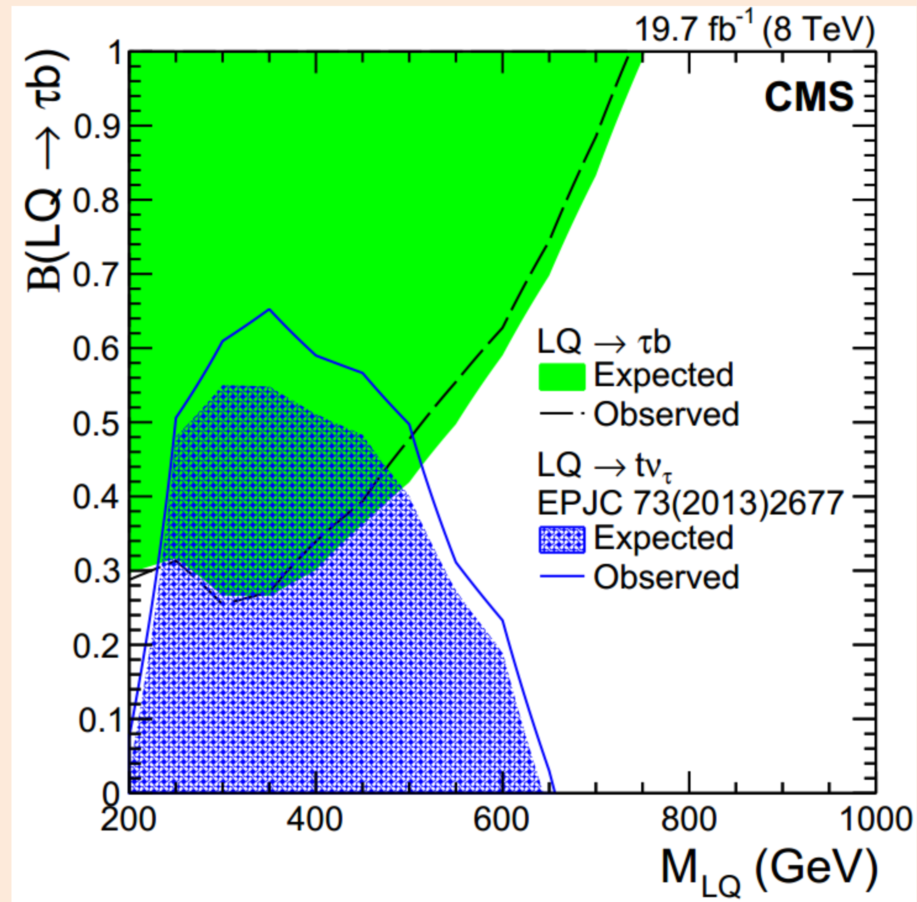
Scalar Leptoquarks (2/2)

3rd gen LQ → ttττ → μτjj, LQ → bbττ → bblτ

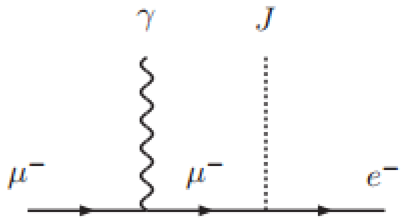
CMS LQ (ttττ)

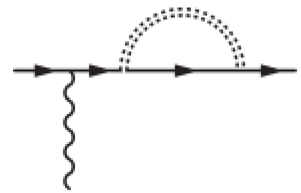


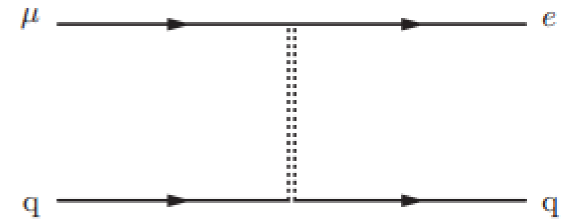
CMS LQ (bbττ)



Limits on 3rd gen scalar M_{LQ}: 634 GeV (ttττ), 740 GeV (bbττ) for β=1







Lepton flavor violation

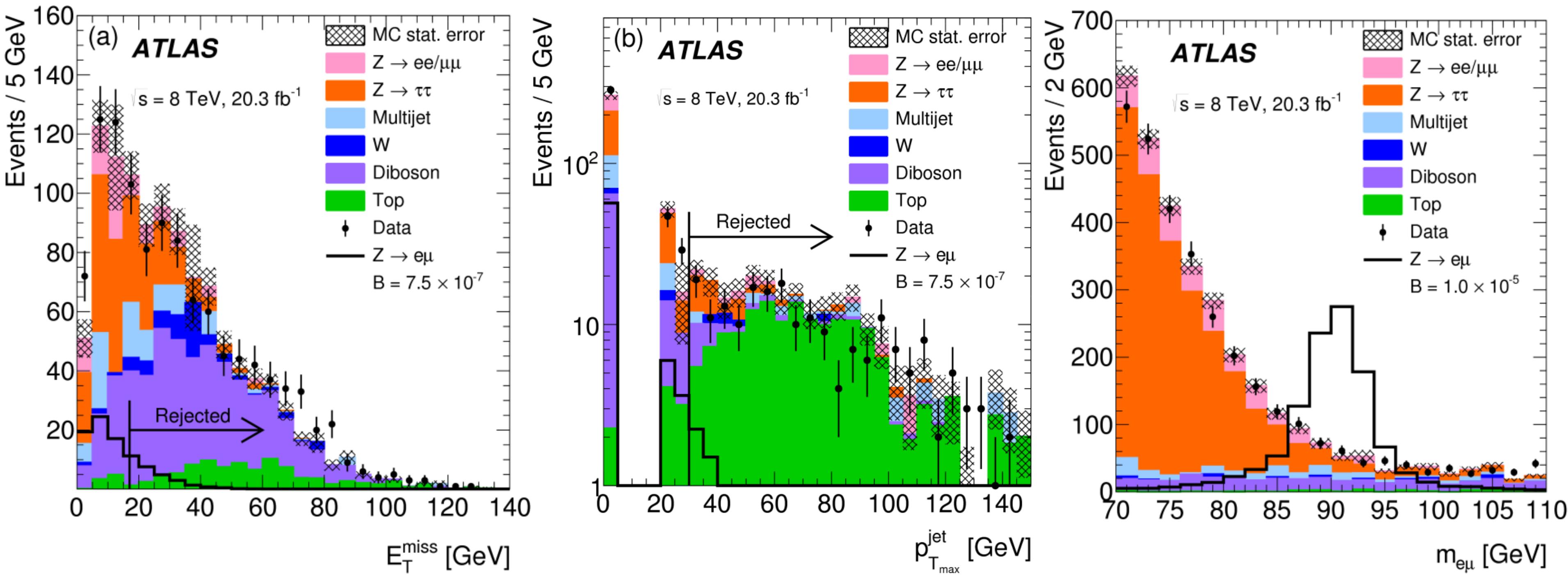
- Charged lepton flavor seems conserved in the SM
  - However no associated symmetry to protect it (accidental)
- On the other hand, neutral lepton flavor is not conserved
  - Neutrino oscillation by discussed by other speakers
- Serves as constraints on BSM models where lepton flavor violating terms may present
- Search in Z → eμ final state
  - Most of systematic uncertainties are cancelled in ratio

Lepton Flavor Violation

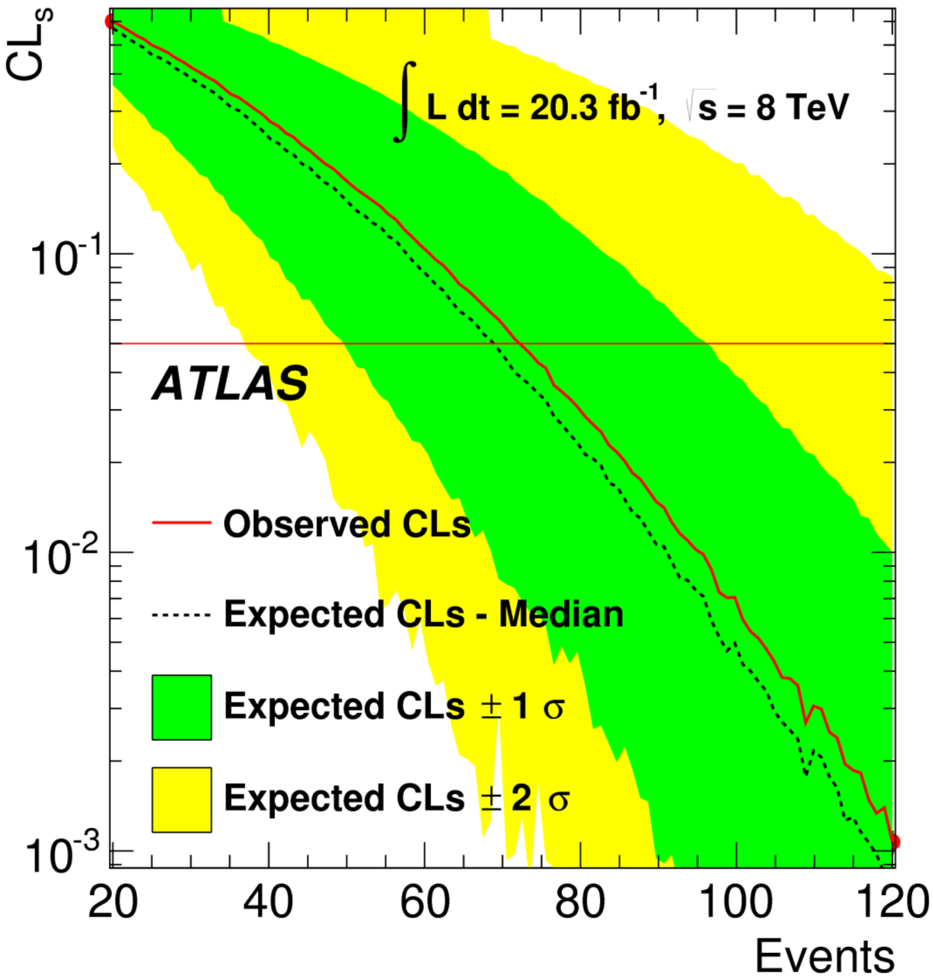
ATLAS eμ

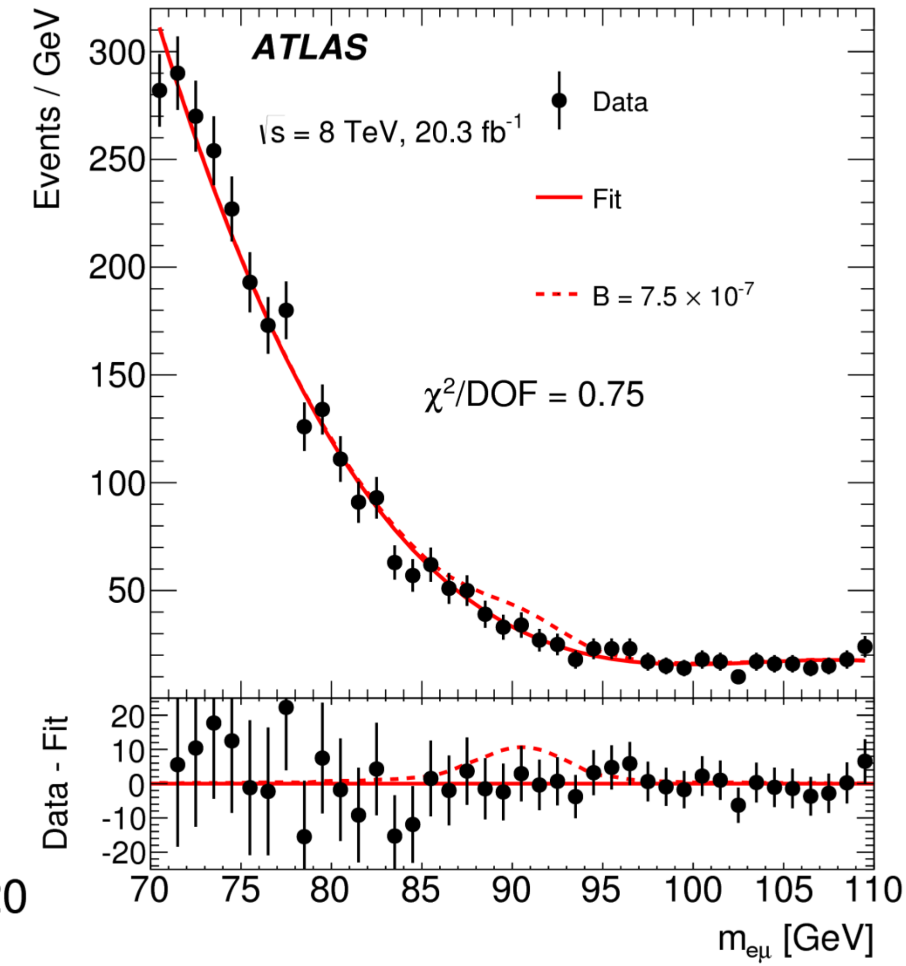
Lepton $p_T > 25$
Max Jet pt < 30
MET < 17
Main BG: Z → ττ → eμνν

arXiv:1408.5774



Lepton Flavor Violation





Direct upper limit on BR($Z \rightarrow e\mu$) < 7.5×10^{-7}
Previous limit: 1.7×10^{-6} (OPAL)

$$\mathcal{L}_{\text{int}} = \frac{1}{2\Lambda}\bar{q}^*_R \sigma^{\mu\nu}\left[g_s f_s \frac{\lambda_a}{2} G^a_{\mu\nu} + g f \frac{\tau}{2} W_{\mu\nu} + g' f' \frac{Y}{2} B_{\mu\nu}\right] q_L$$

$$\begin{aligned}\mathscr{L} = \frac{g^2}{\Lambda^2} [\quad & \eta_{\mathrm{LL}} (\bar{q}_{\mathrm{L}} \gamma_\mu q_{\mathrm{L}})(\bar{\ell}_{\mathrm{L}} \gamma^\mu \ell_{\mathrm{L}}) \\ & + \eta_{\mathrm{RR}} (\bar{q}_{\mathrm{R}} \gamma_\mu q_{\mathrm{R}})(\bar{\ell}_{\mathrm{R}} \gamma^\mu \ell_{\mathrm{R}}) \\ & + \eta_{\mathrm{LR}} (\bar{q}_{\mathrm{L}} \gamma_\mu q_{\mathrm{L}})(\bar{\ell}_{\mathrm{R}} \gamma^\mu \ell_{\mathrm{R}}) \\ & + \eta_{\mathrm{RL}} (\bar{q}_{\mathrm{R}} \gamma_\mu q_{\mathrm{R}})(\bar{\ell}_{\mathrm{L}} \gamma^\mu \ell_{\mathrm{L}})]\end{aligned}$$

	Quarks	Spin	Charge	Mass / MeV
π^+	$u\bar{d}$	0	+1	139.6
π^0	$u\bar{u}$, $d\bar{d}$	0	0	135.0
π^-	$d\bar{u}$	0	-1	139.6

$$\frac{G_{\mathrm{F}}}{(\hbar c)^3} = \frac{\sqrt{2}}{8}\frac{g^2}{m_{\mathrm{W}}^2} = 1.16637(1) \times 10^{-5}\ \mathrm{GeV}^{-2}\ .$$

Compositeness

- Leptons and quarks might be bound states of more fundamental particles (like mesons and baryons)
- Interacting energy scale is much higher than EWK scale
- It can appears as
  - Flavor diagonal contact interaction
    - Different handedness combination and interferences are considered
  - Excited quarks which transitions to SM quarks by radiation

Compositeness: Contact interaction

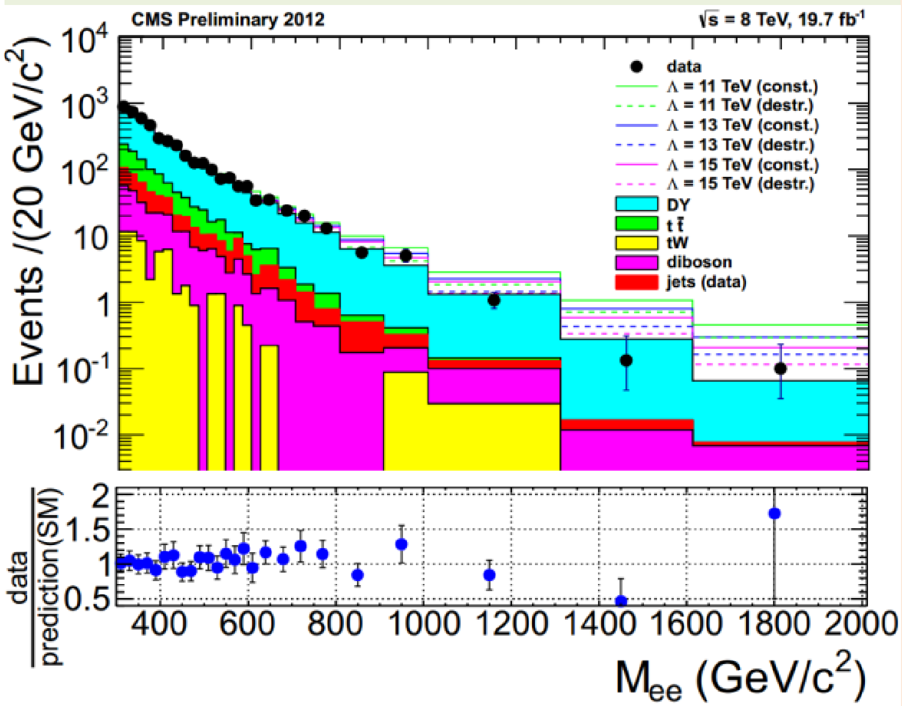
Contact interaction in qq → ll

CMS dilepton

Electron $p_T > 45$ or Muon $p_T > 35$

Main BG: DY

CMS-PAS-EXO-12-020

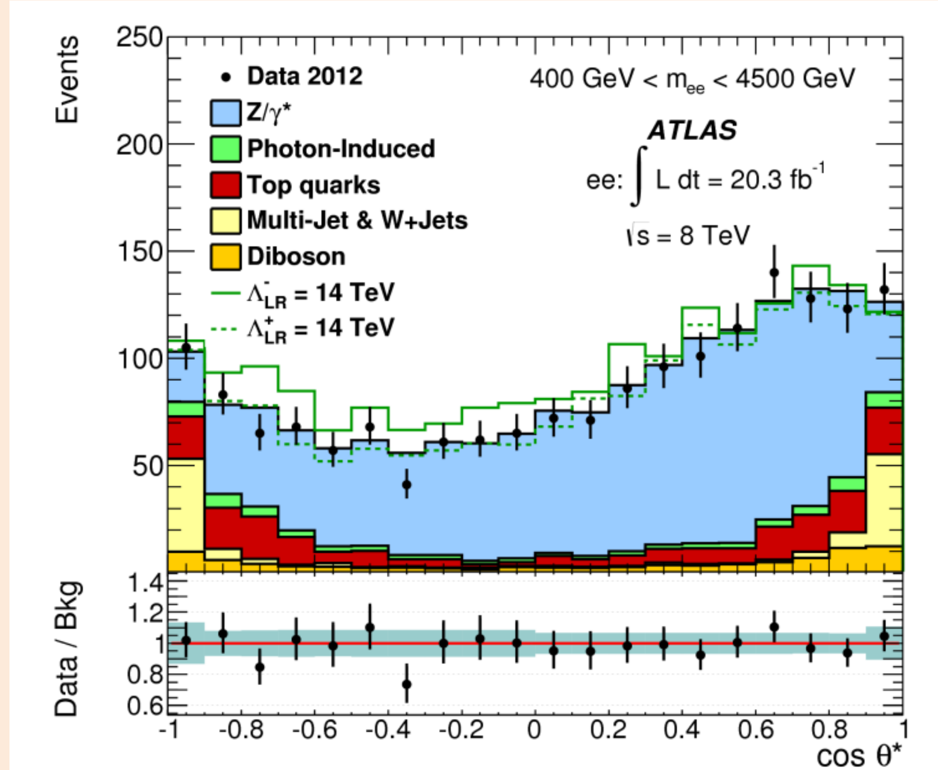


ATLAS dilepton

Electron $p_T > (40, 30)$ or Muon $p_T > 25$

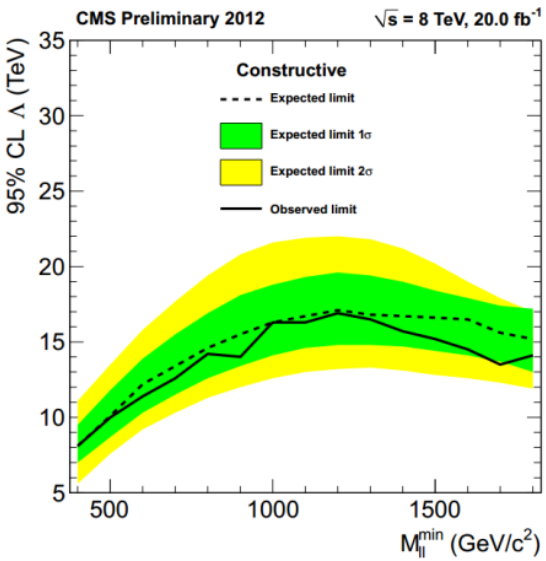
Main BG: DY

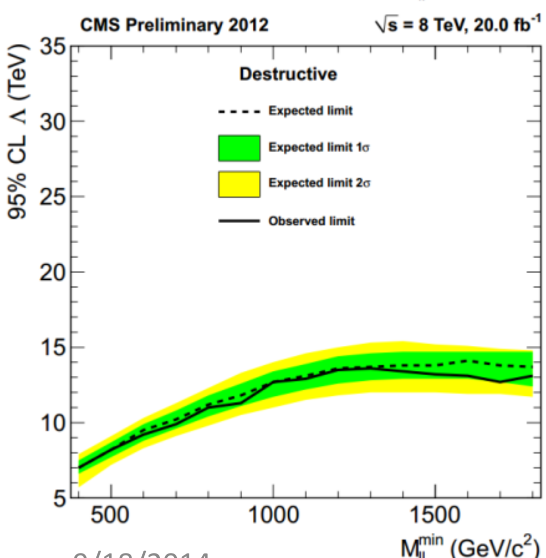
arXiv:1407.2410



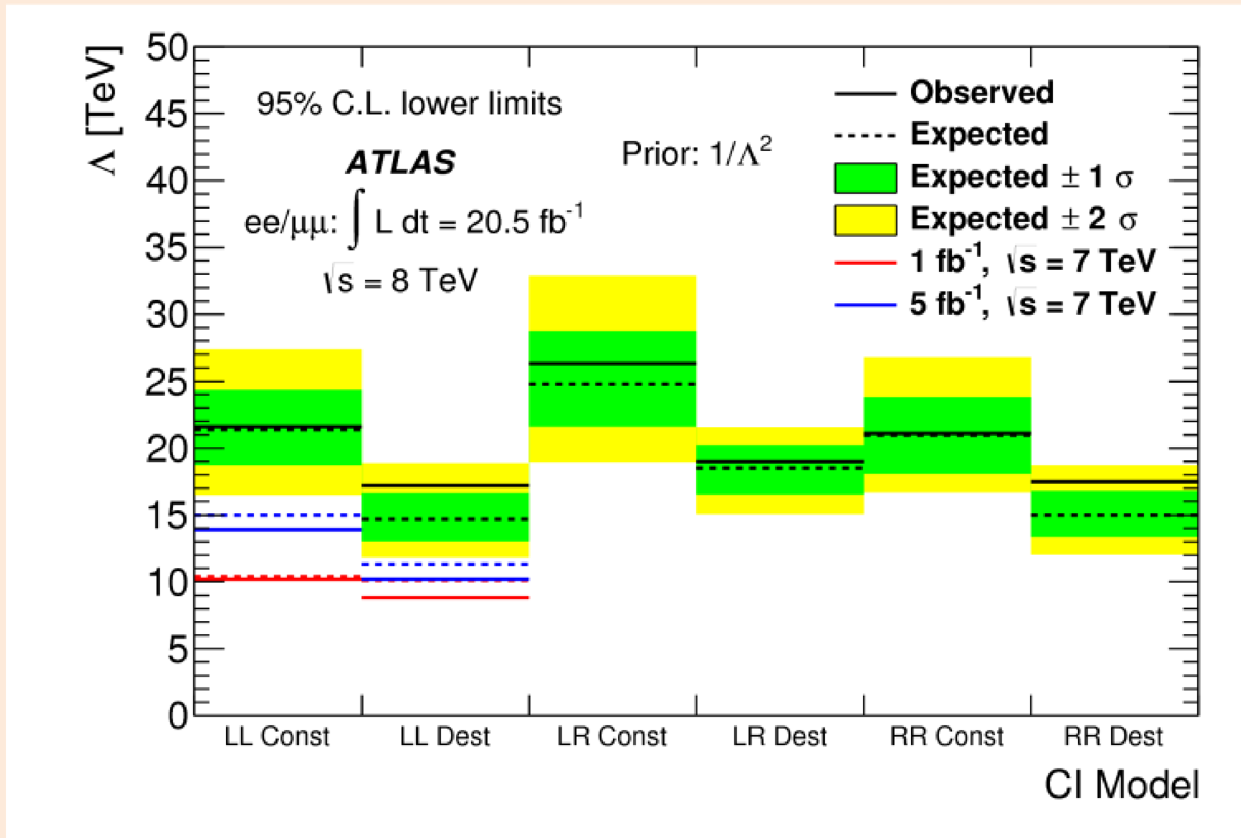
$$\cos\theta^* = \frac{p_z(\ell^+\ell^-)}{|p_z(\ell^+\ell^-)|}\,\frac{2(p_1^+ p_2^- - p_1^- p_2^+)}{m(\ell^+\ell^-)\sqrt{m(\ell^+\ell^-)^2 + p_T(\ell^+\ell^-)^2}}$$

Compositeness: Contact interaction





Contact interaction in qq → ll



Limits on Λ: 13.5-18.3 TeV (CMS)*, 15.4-26.3 TeV (ATLAS)

*On Left-Left isoscalar only

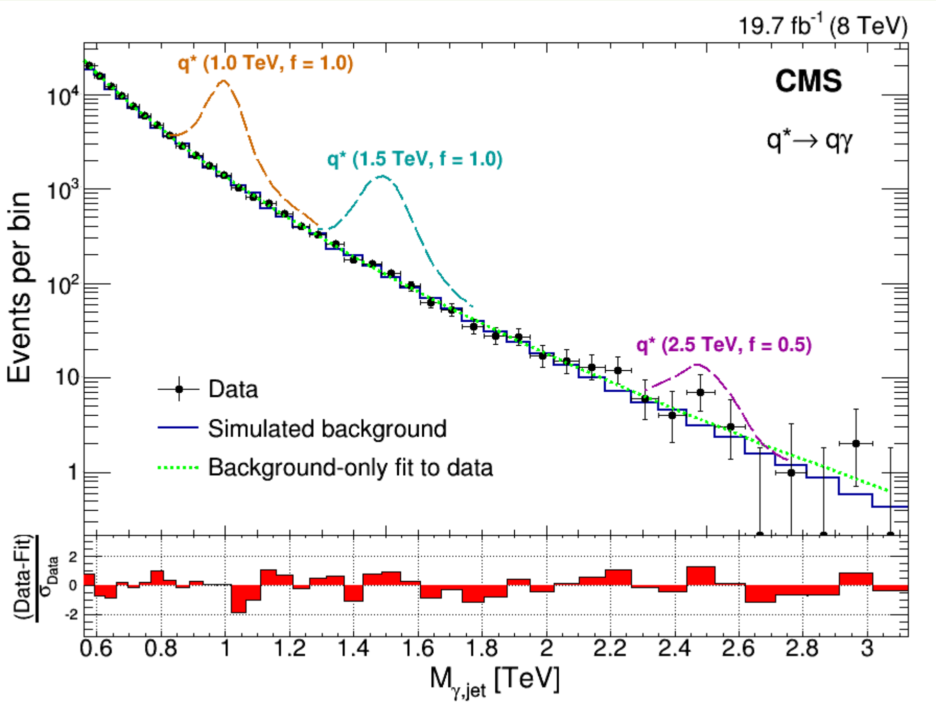
Compositeness: Excited quarks

Excited quarks q* → γq or gq

CMS γ+jet

γ $p_T > 170$
Jet $p_T > 170$
Main BG: γ+jet

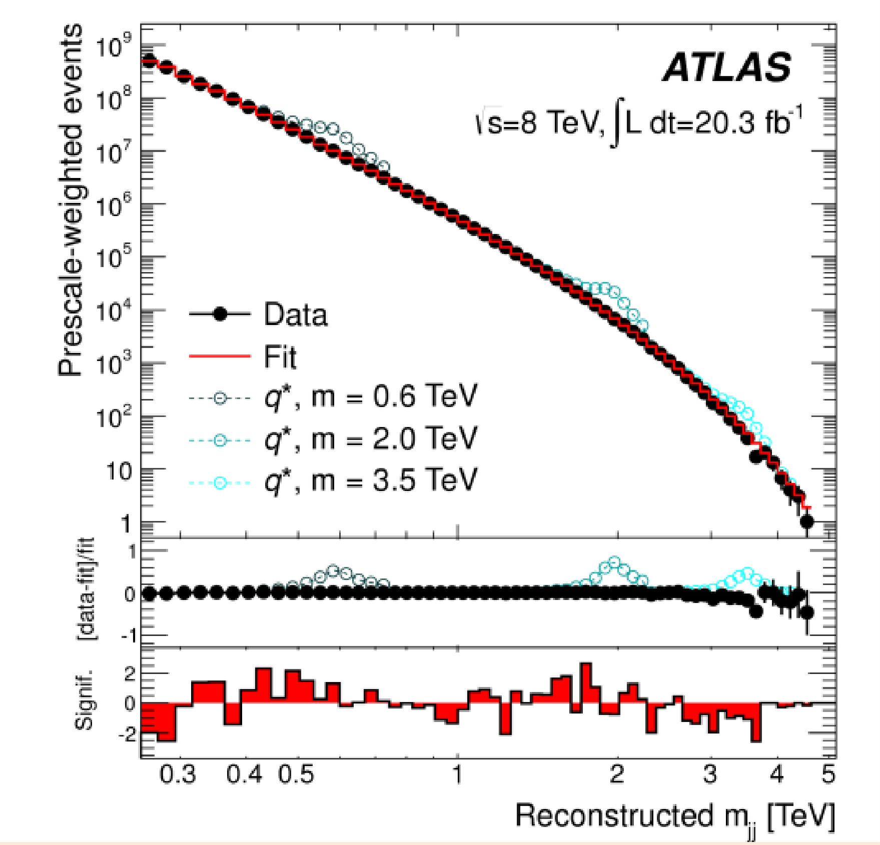
arXiv:1406.5171



ATLAS dijet

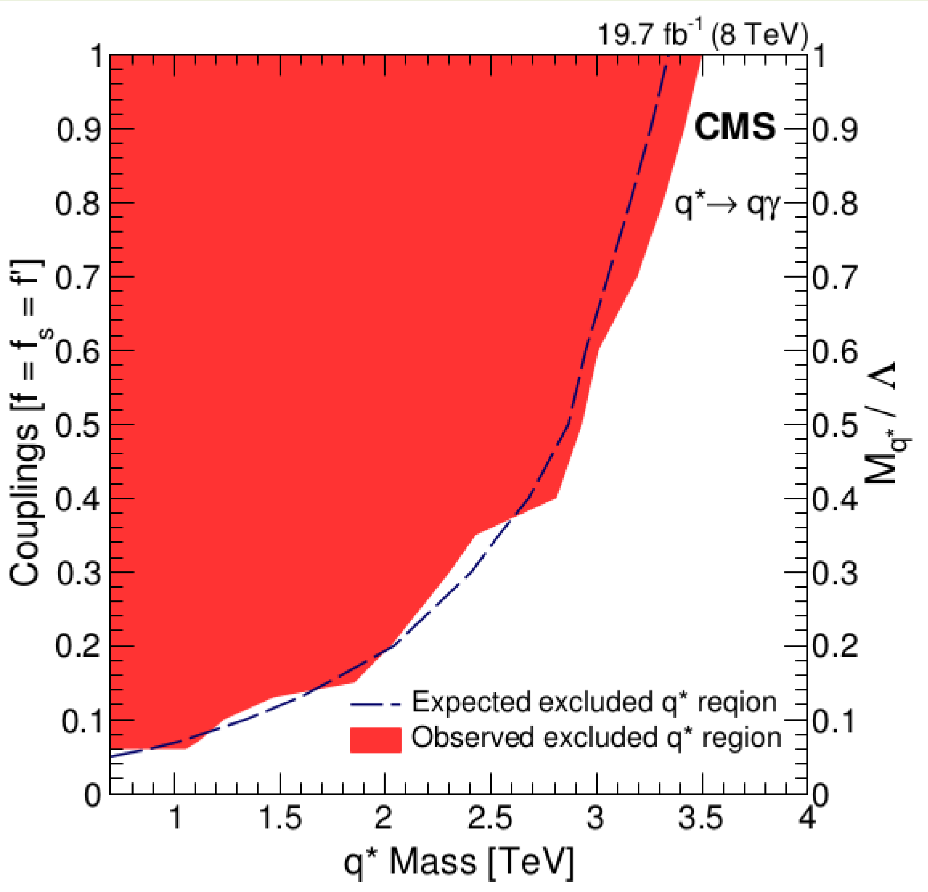
Jet $p_T > 50$
$|\Delta\eta_{jj}| < 1.2$
Main BG: Multi-jet

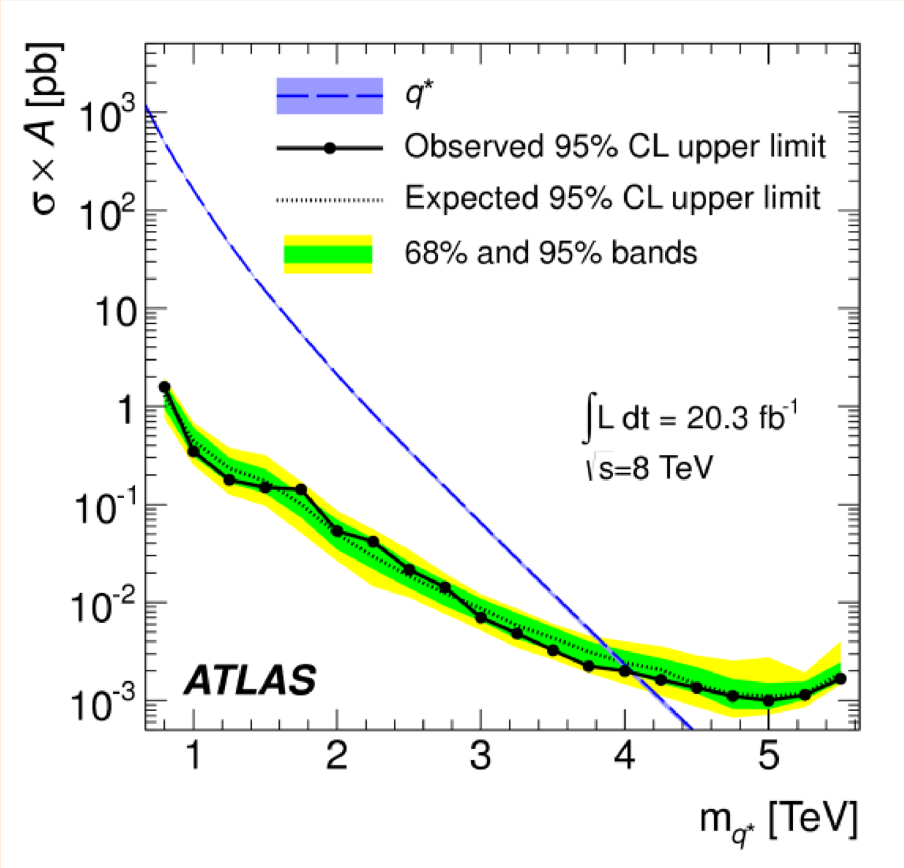
arXiv:1407.1376



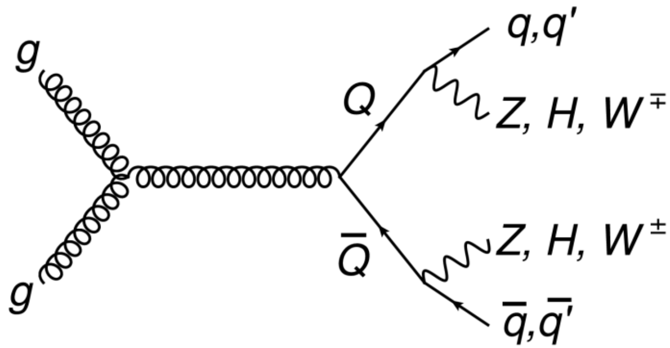
Compositeness: Excited quarks

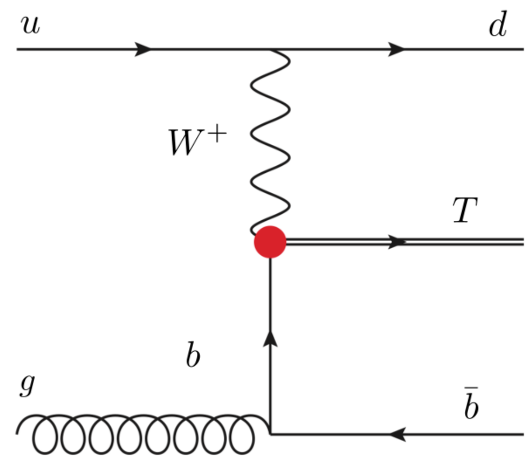
Excited quarks q* → γq or gq





Limits on q* mass: 3.5 TeV (CMS γ+jet), 4.1 TeV (ATLAS dijet), for SM-like couplings





$$\begin{aligned}\Pi^f_{hh}(0) &= (-1)\int \frac{d^4k}{(2\pi)^4}\mathrm{Tr}\left(-i\frac{\lambda_f}{\sqrt{2}}\right)\frac{i}{\not{k}-m_f}\left(-i\frac{\lambda_f}{\sqrt{2}}\right)\frac{i}{\not{k}-m_f} \\ &= -2\lambda_f^2\int\frac{d^4k}{(2\pi)^4}\frac{k^2+m_f^2}{(k^2-m_f^2)^2} \\ &= -2\lambda_f^2\int\frac{d^4k}{(2\pi)^4}\left[\frac{1}{k^2-m_f^2}+\frac{2m_f^2}{(k^2-m_f^2)^2}\right].\end{aligned}$$

Vector-like quarks

- Little Higgs model and Composite Higgs model have
  - Pseudo Nambu Goldstone boson
  - Strongly coupled new states including
    - Vector-like quarks
- Solve Higgs mass fine tuning problem through mixing of heavy vector-like quarks and SM quarks
  - One of non-SUSY natural models

Vector-like quarks

B → Zb and T → Zt

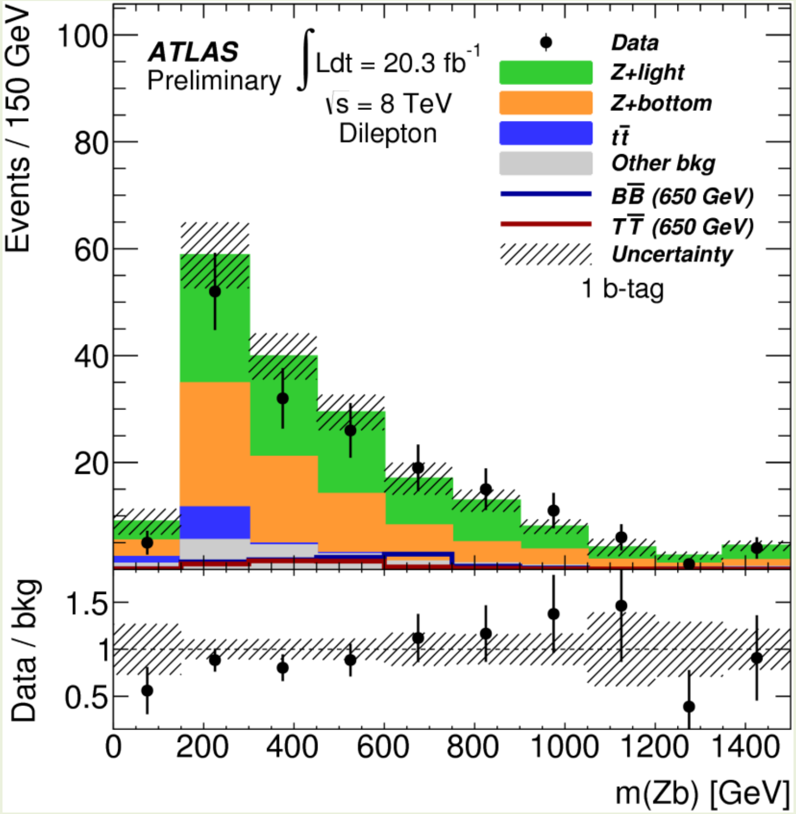
ATLAS Z+bjets

Lepton and jet $p_T > 25$

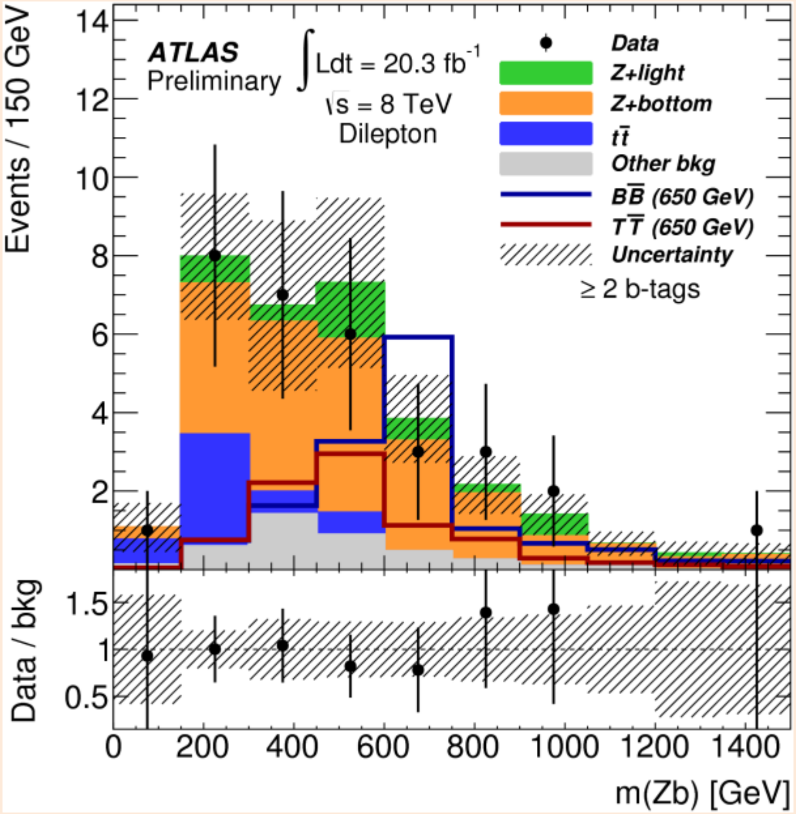
Z $p_T > 150$

Main BG: Z+jets

Trilepton+jets channel



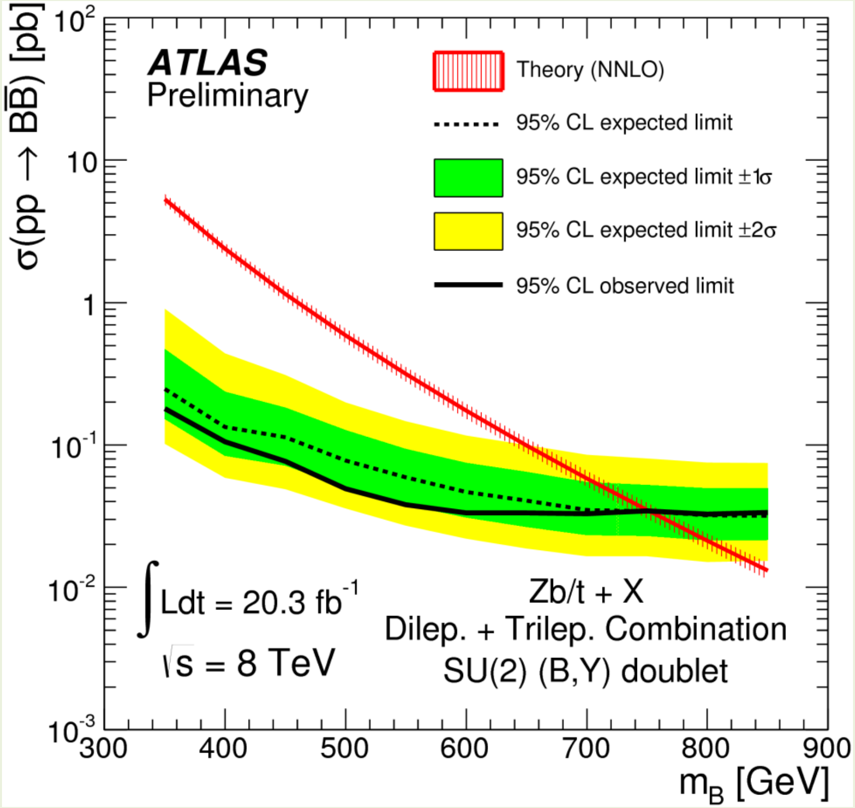
Dilepton+jets channel

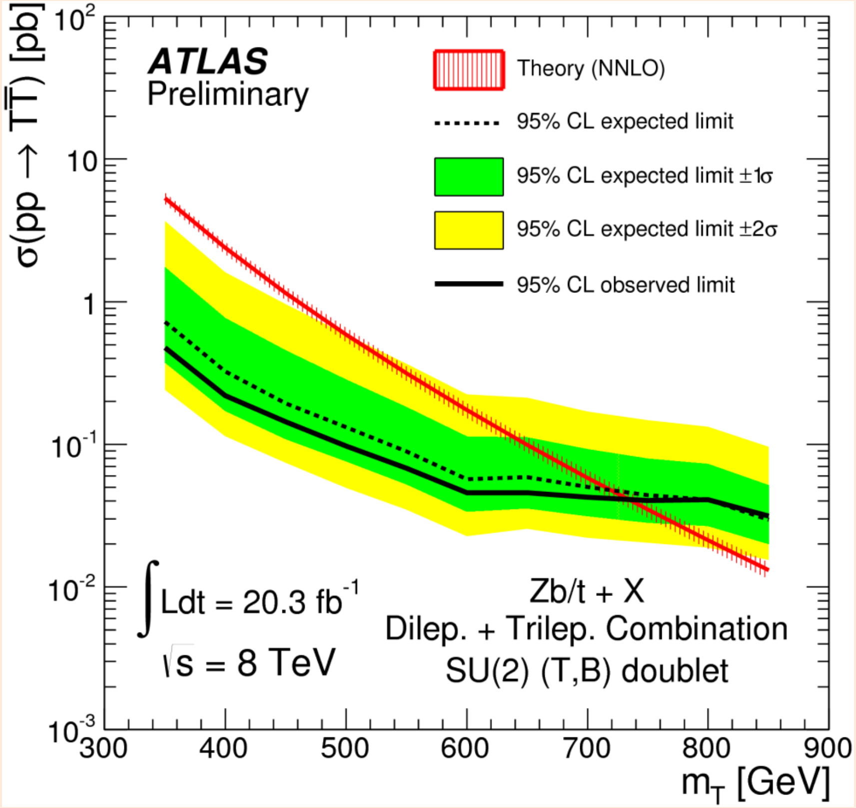


ATLAS-CONF-2014-036

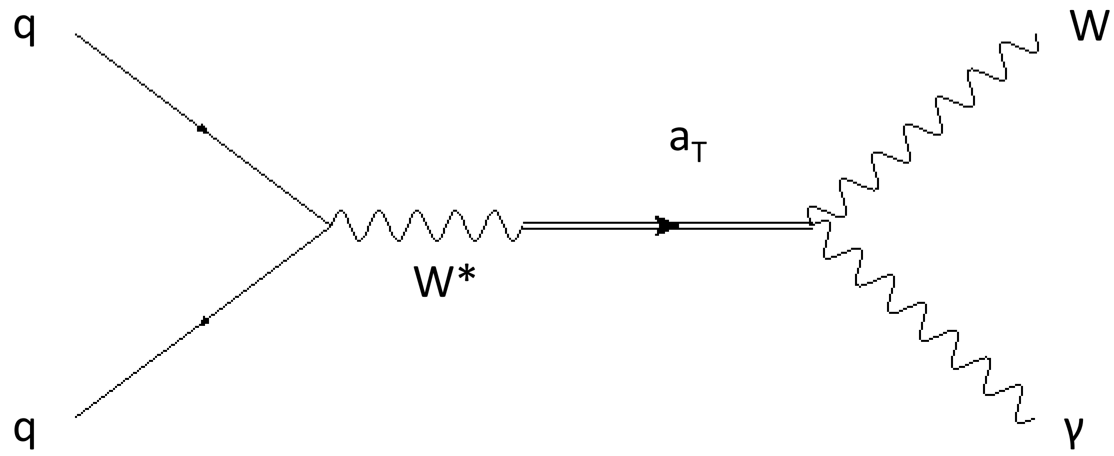
Vector-like quarks

B → Zb and T → Zt





Limits on SU(2) doublet vector-quark mass: 755 (B), 735 (T)



Low scale technicolor

- Dynamical EWSB and fermion mass generation involve spin-0 and spin-1 particles
  - TC with a light composite Higgs boson is still valid
- Benchmark model for spin-1 resonance decaying to diboson
- Technimeson masses are chosen so that techni-pion mode is kinetically inaccessible
  - $a_T \rightarrow W\gamma$, $\omega_T \rightarrow Z\gamma$, and $\rho_T(a_T) \rightarrow WZ$

Technicolor

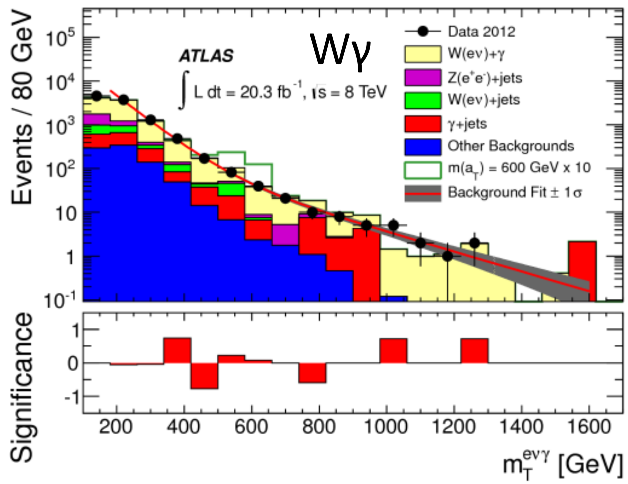
ATLAS Wγ and Zγ

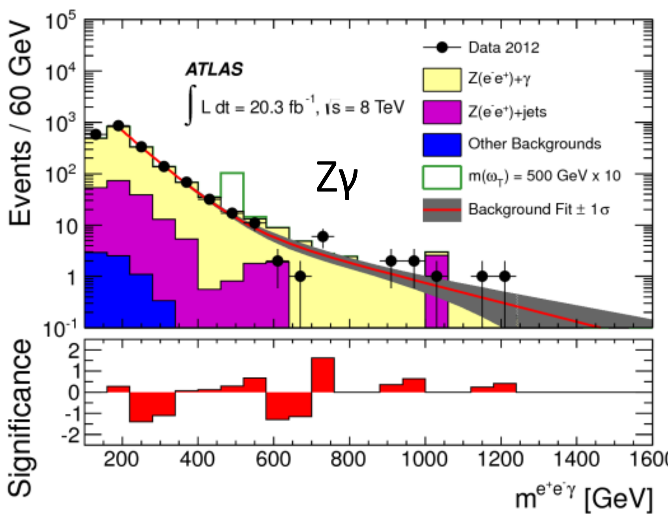
arXiv:1407.8150

Lepton $p_T > 25$

γ $p_T > 40$

MET > 35 for W γ





CMS 3lν

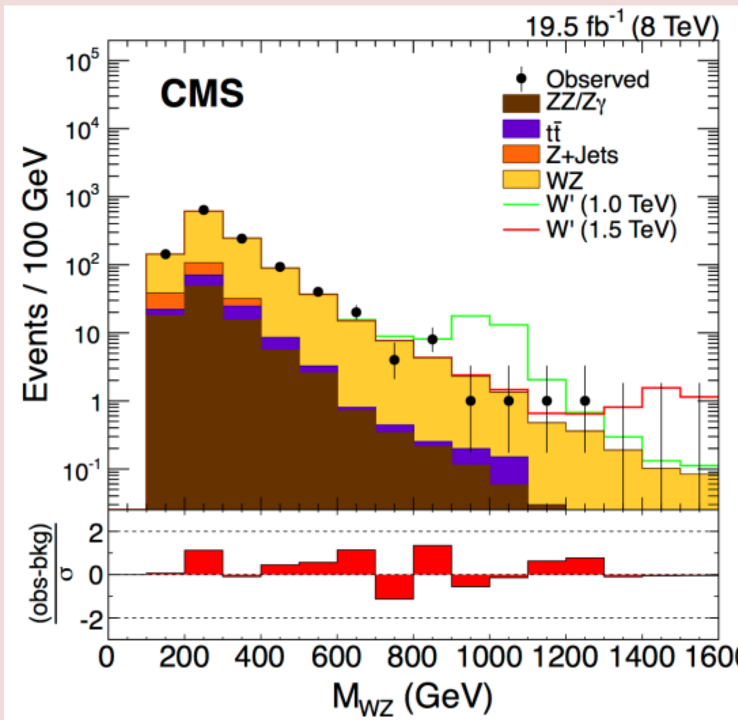
Z_{cand} e $p_T > 35$,or Z_{cand} μ $p_T > (25, 10)$

W_{cand} e $p_T > 20$ or W_{cand} μ $p_T > 20$

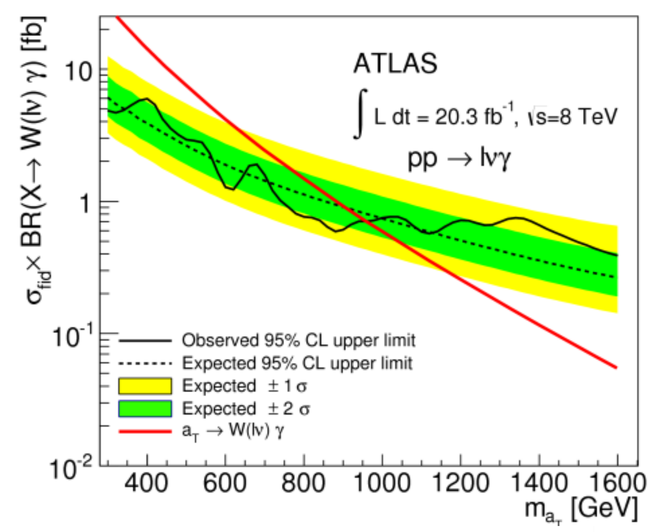
MET > 30

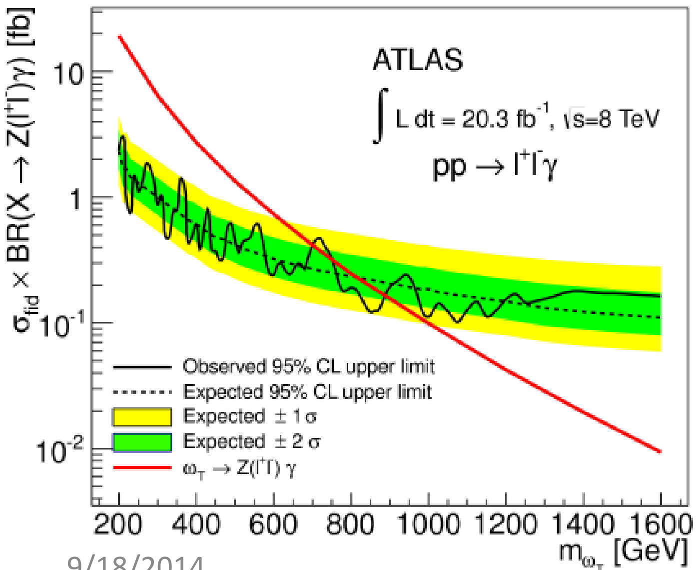
Main BG: WZ

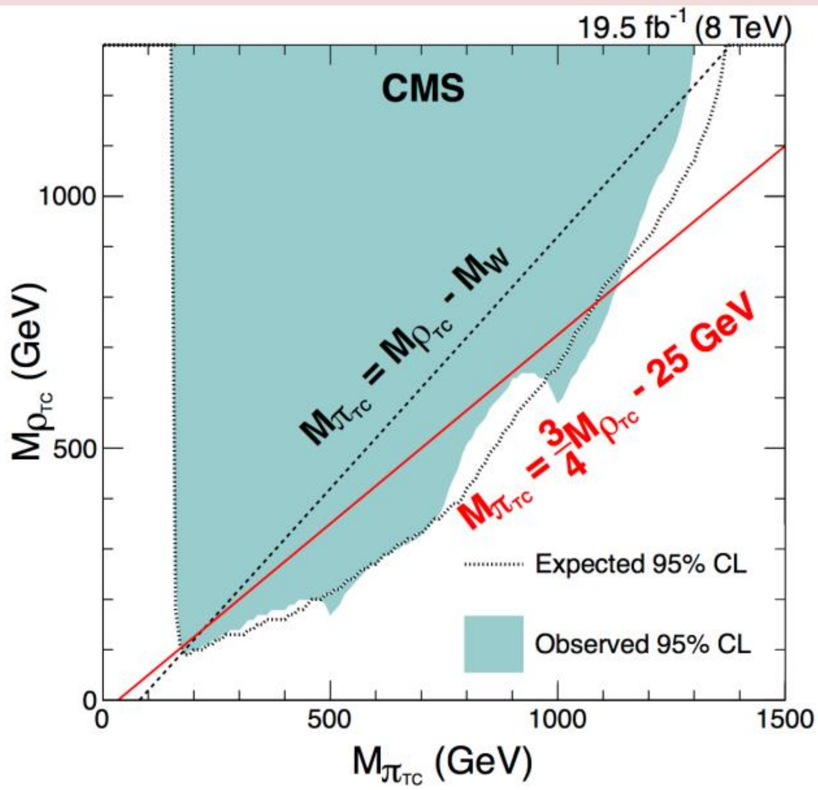
arXiv:1407.3476



Technicolor







Limits on TC mass: [275,960](a_T), [200,700] and [750,890] (ω_T), 1140 GeV (ρ_T)

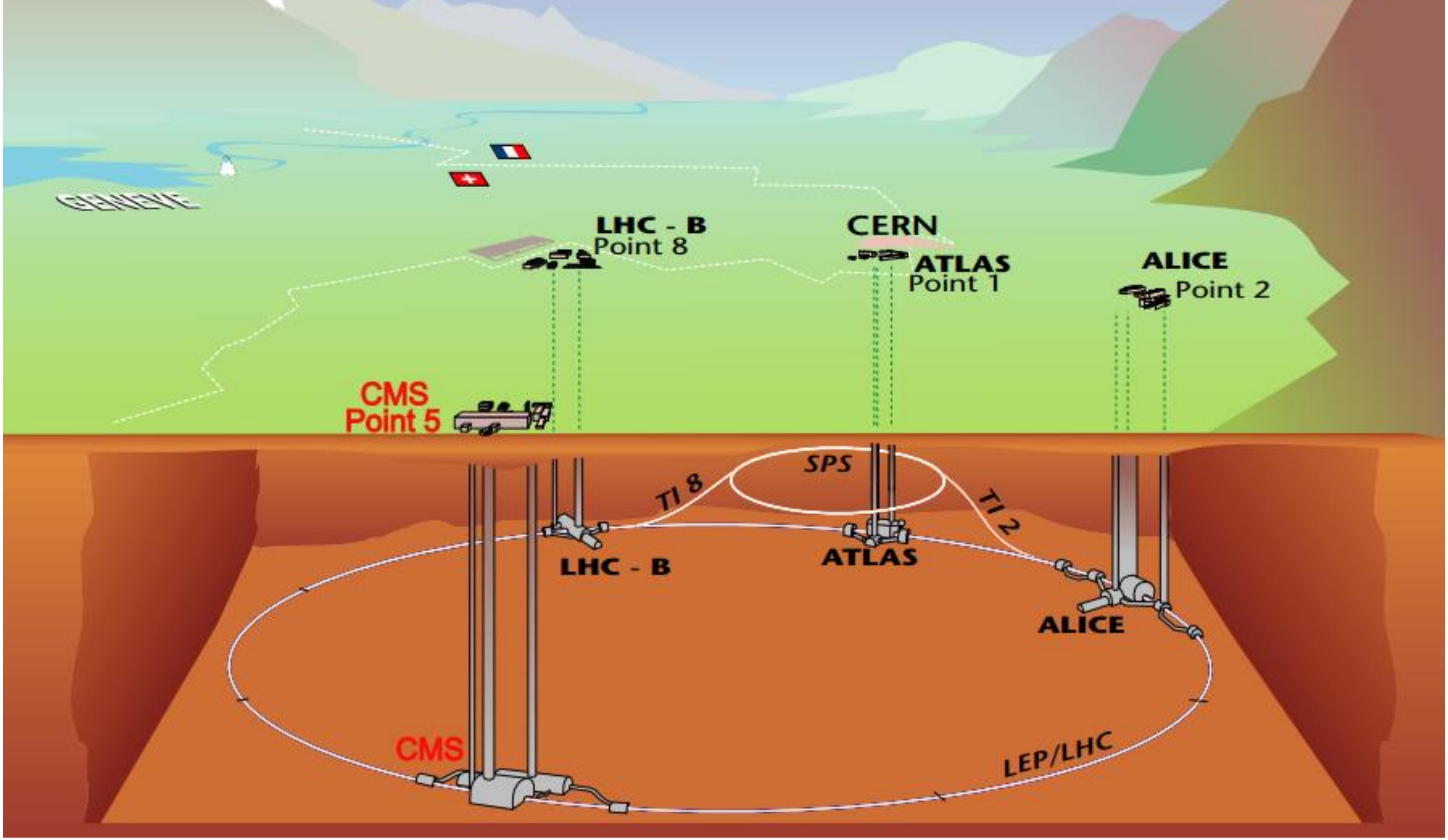
Summary

- ATLAS and CMS studied a variety of theoretical models beyond SM
  - Most of them are searched in more than one final states
- No evidence of new exotic physics found with full ~20 fb^{-1} 8 TeV Run I data
  - Limits set at ~TeV scales depending on models and parameters

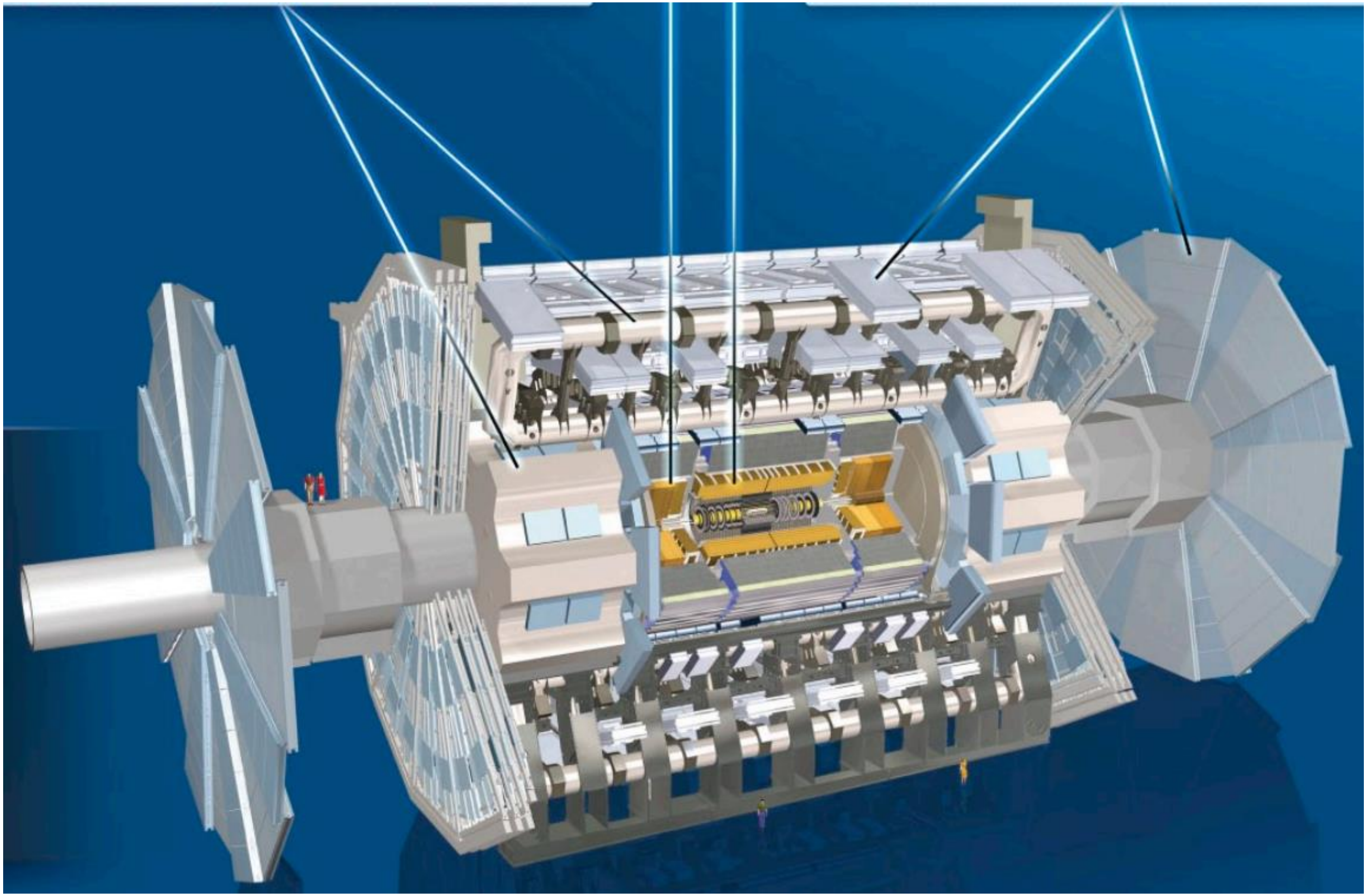
Run II will start at higher center of mass energy in 2015
Another opportunity to discover Exotic phenomena!

Backup

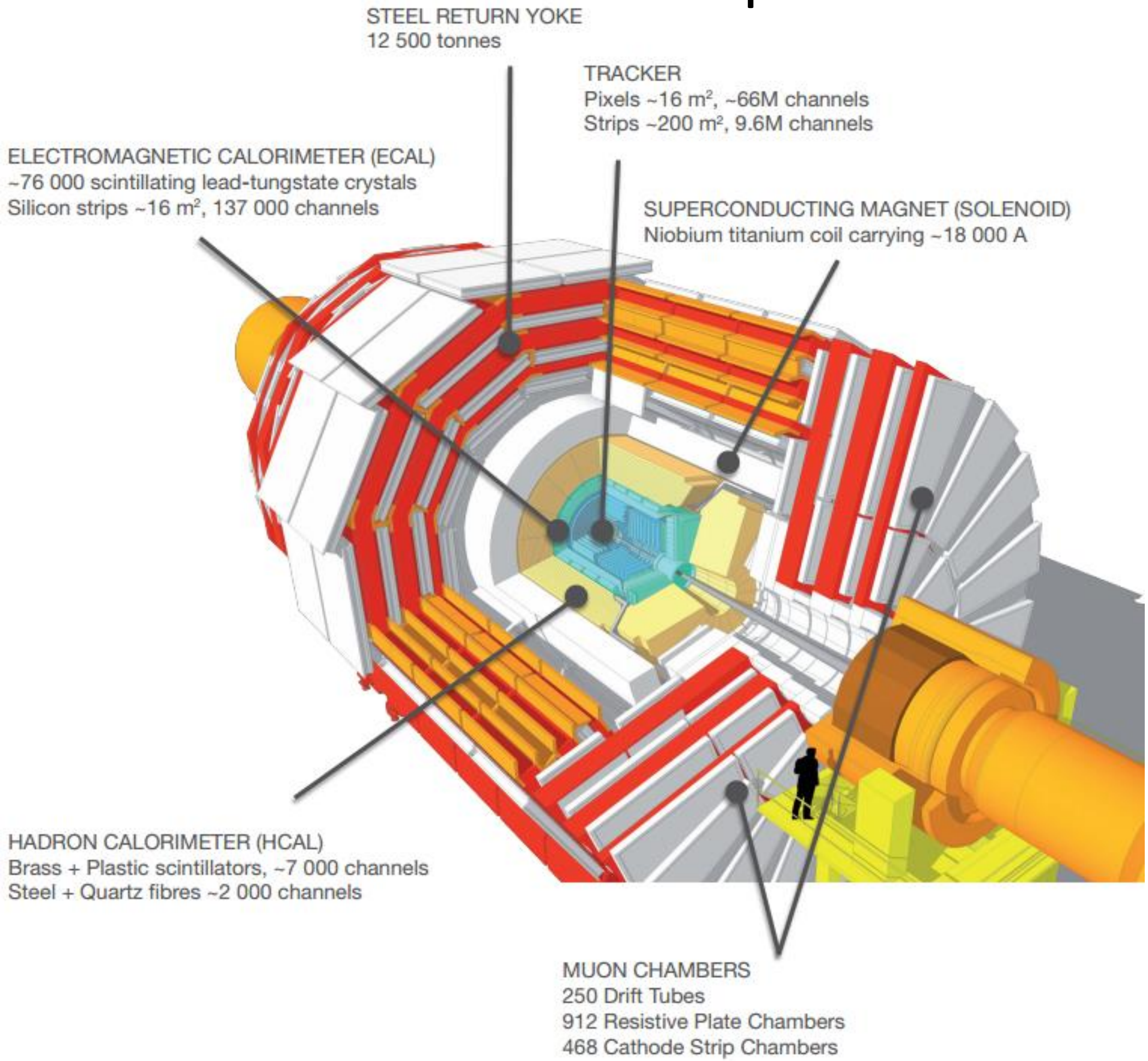
Large Hadron Collider at CERN
Center of mass energy of 8 TeV
Run I data for analysis: ~20 fb^{-1}



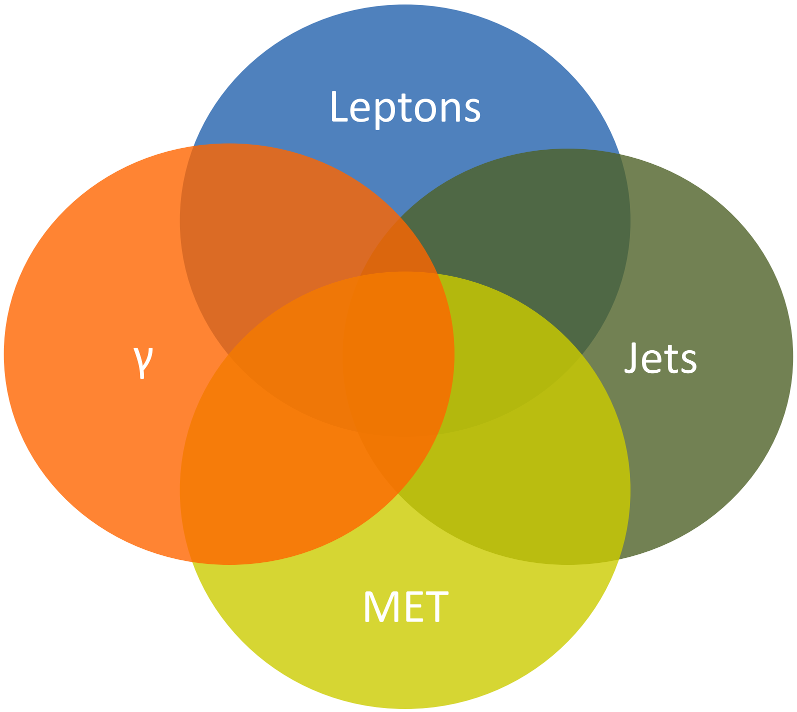
A Toroidal LHC ApparatuS



Compact Muon Solenoid



Final states & Observables



Analyses are performed in final states defined by combination of physics objects e.g., Leptons+MET, γ+Jet, and so forth

Physics objects:
Electron (e), Muon (μ), Tau (τ), Photon (γ), Jet, bjet
L= electron or muon

Single object property:
p_T = Transverse Momentum [GeV]
η = pseudo-rapidity

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

Multi-object property:
M = Invariant Mass
MET = Missing Transverse Energy [GeV]
S_T = Scalar sum of p_T [GeV]
M_T = Transverse Mass [GeV]

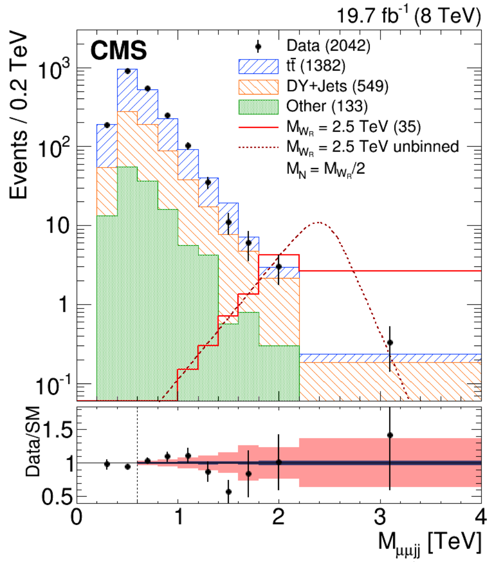
$$M_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} \left(1 - \cos[\Delta\phi(\ell, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})]\right)}$$

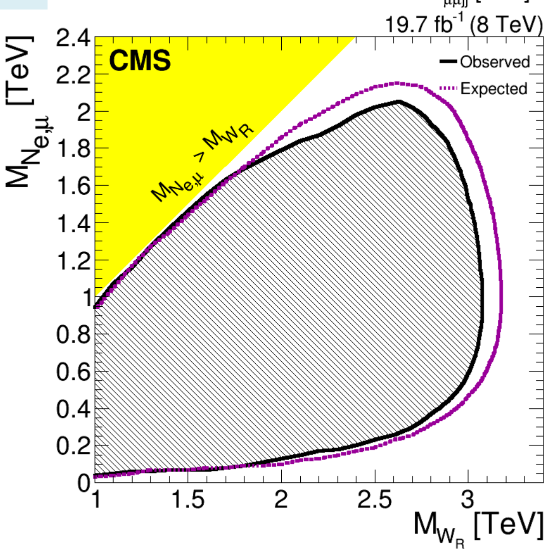
Other physics studied

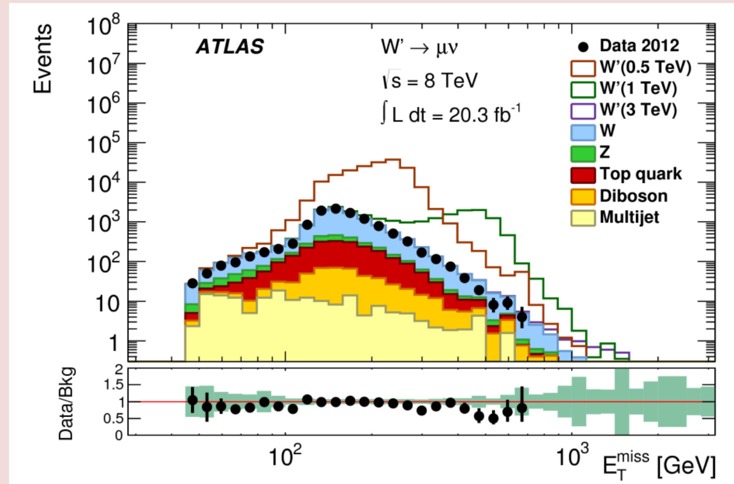
Model	Motivation Connections	Final states
Right-handed W and ν	Left-right symmetry	Leptons+jets
Excited W*	Compositeness	Lepton(s)+MET Dijet
Quantum Black Hole	Hierarchy problem through ED	Dijet
Large Extra Dimension (ED)	Hierarchy problem Kaluza-Klein excitations (KK)	MonoX+MET, Lepton+MET, Dijet, Leptons+Jets
Hidden valley	Enlarged symmetry group	Displaced decay point

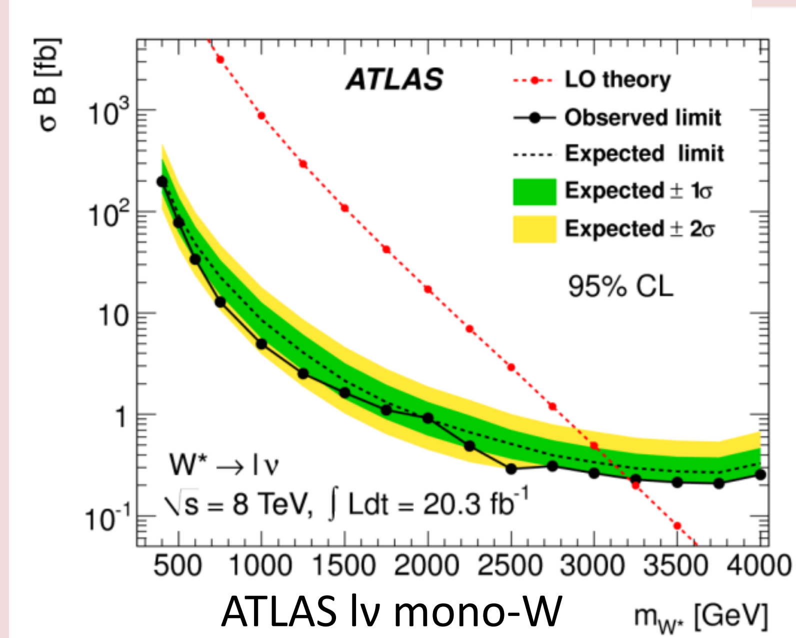
And more!

Right-handed W & ν, Excited W*









CMS Right-handed W and ν

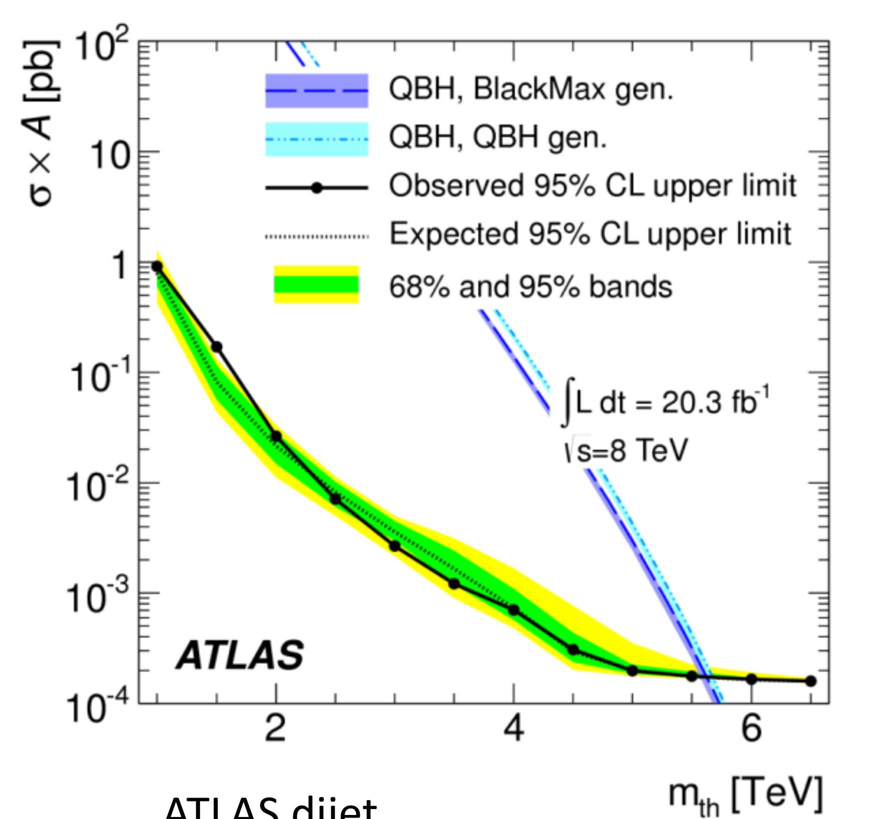
arXiv:1407.3683

ATLAS lν mono-W

arXiv:1407.7494

Quantum Black Hole

ATLAS dijet (left). Earlier CMS results for reference (right).



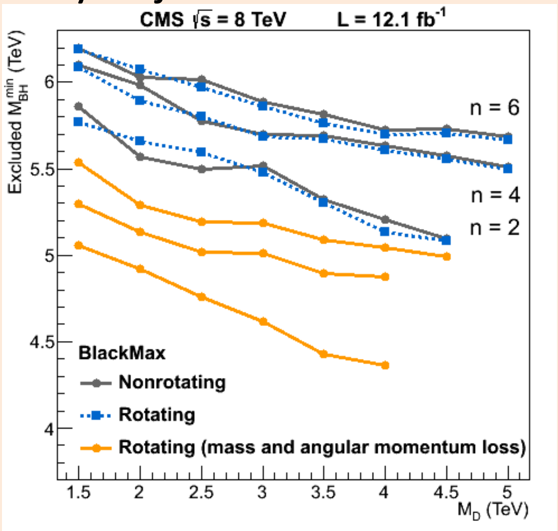
ATLAS dijet

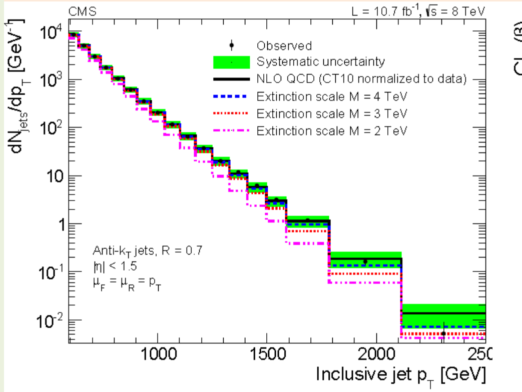
arXiv:1407.1376

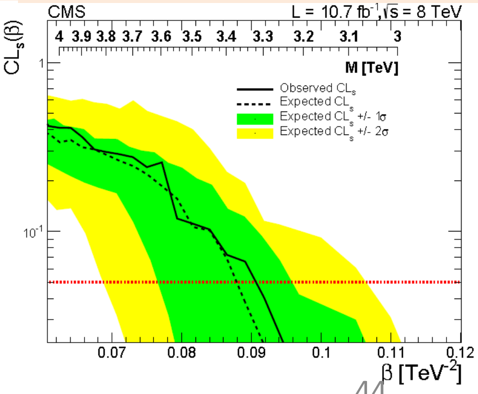
CMS MET plus many objects

$L=12.1fb^{-1}$

PAS EXO12009

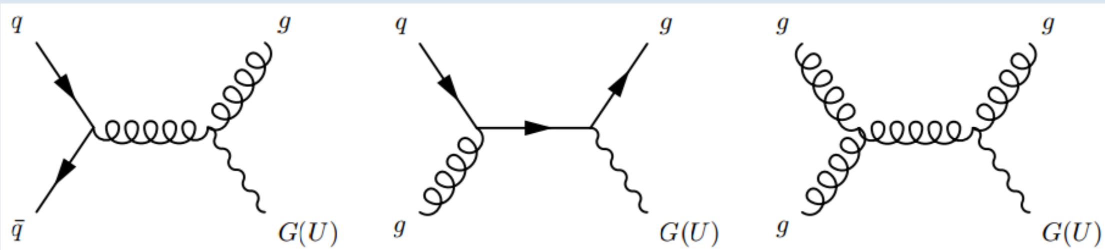






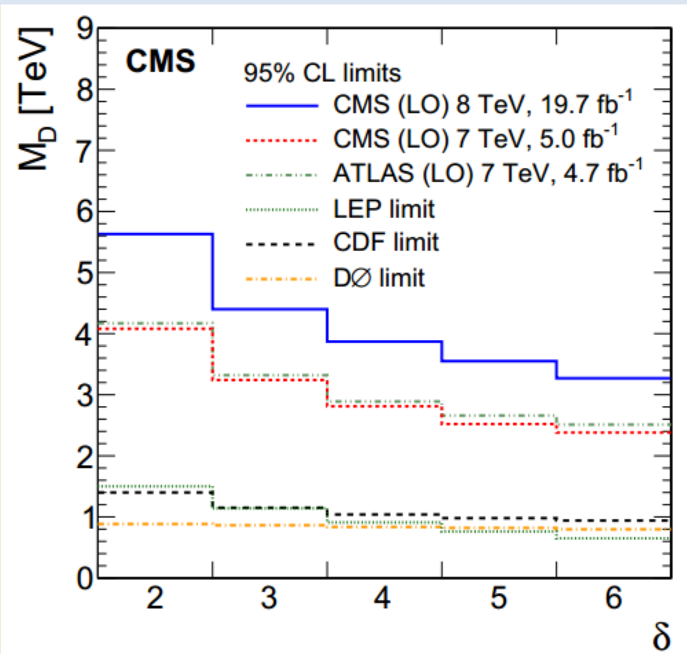
CMS inclusive jets ($L=10.7fb^{-1}$), PAS EXO12-51

Large Extra Dimension (1/2)



Weakly interacting ADD graviton

- Same experimental signature as DM
- ***<u>Mono-jet, Mono-photon</u>***



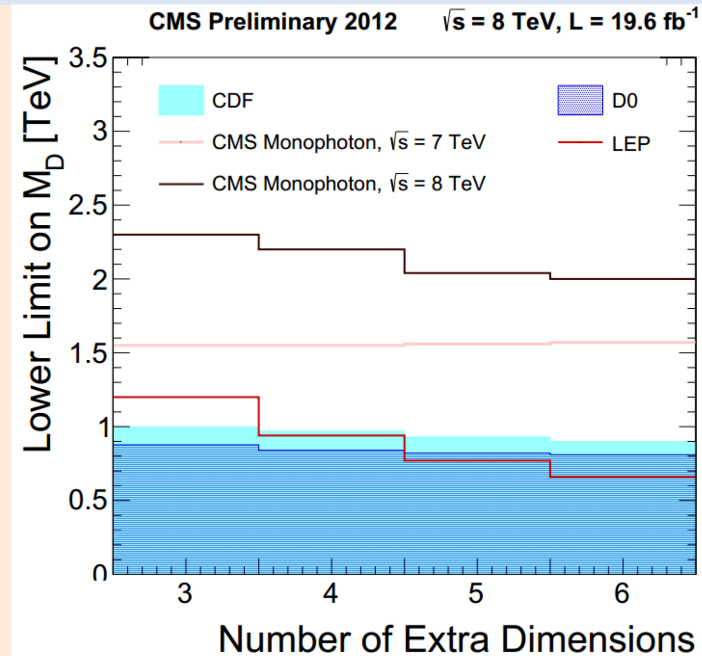
CMS mono-jet

Jet $p_T > 110$

MET > 250

arXiv:1408.3583

Limit on M_D = 3.85 TeV (n=4)



CMS mono-photon

γ $p_T > 145$

MET > 140

CMS PAS EXO-12-047

Limit on M_D = 2.20TeV (n=4)

Large Extra Dimension (2/2)

$$\sigma_{\text{tot}} = \sigma_{\text{DY}} + \mathscr{F}\frac{F_{\text{int}}}{M_S^4} + \mathscr{F}^2\frac{F_G}{M_S^8}$$

$$\mathscr{F} = 1, \quad \text{(GRW)}$$

$$\mathscr{F} = \frac{2\lambda}{\pi} = \frac{\pm 2}{\pi}, \quad \text{(Hewett)}$$

$$\mathscr{F} = \log\left(\frac{M_S^2}{s}\right) \text{ for } n = 2, \quad \text{(HLZ)}$$

$$\mathscr{F} = \frac{2}{n-2} \text{ for } n > 2. \quad \text{(HLZ)}.$$

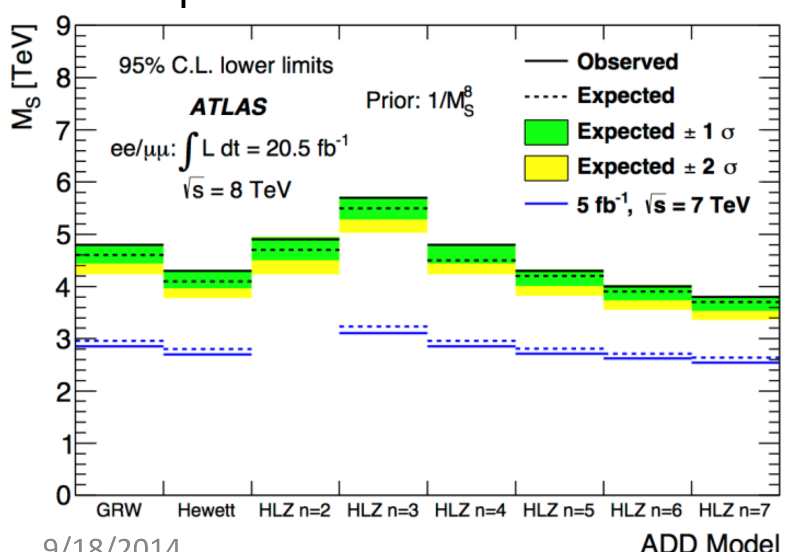
$$M_S = 2\sqrt{\pi}\left[\Gamma\left(\frac{n}{2}\right)\right]^{1/(n+2)} M_D$$

ADD virtual KK G* → ll

RS1 KK G* → ZZ → 2lqq'

ATLAS dilepton

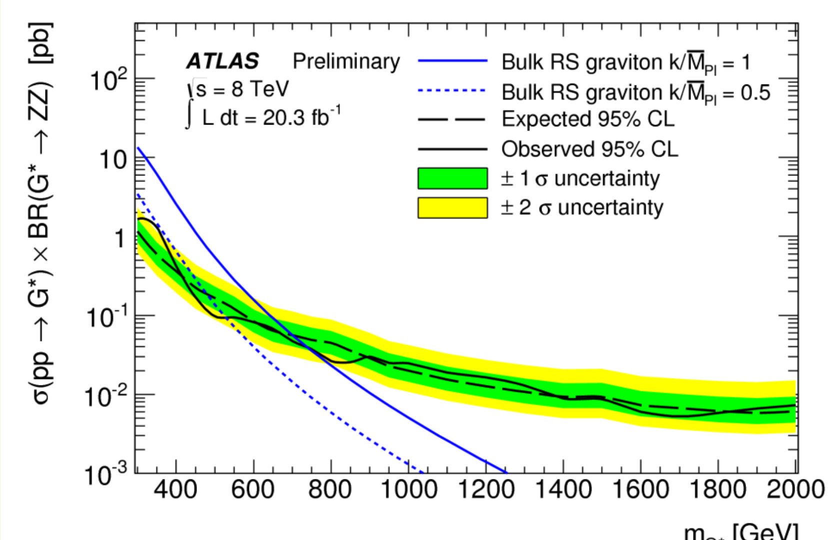
arXiv:1407.2410



Limit on ADD M_S = 4.1-6.1 TeV

ATLAS 2lqq'

ATLAS-CONF-2014-039



Limit on RS1 G* mass = 740 GeV (k=reduced M_{Pl})

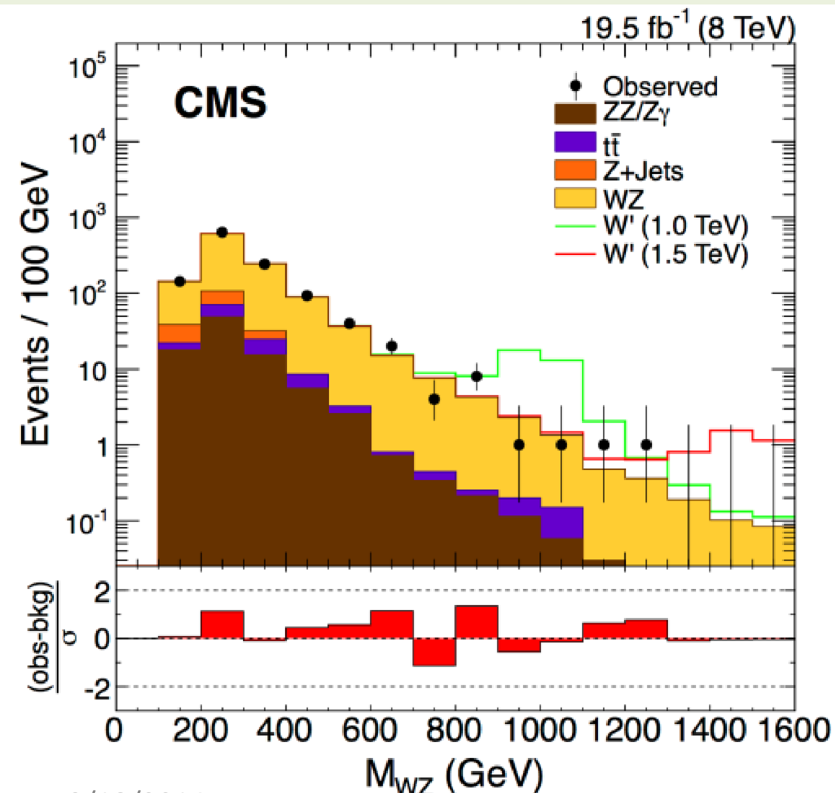
W'

W' → WZ → 3lν

CMS 3lν

Z_{cand} e $p_T > 35$,or Z_{cand} μ $p_T > (25, 10)$
W_{cand} e $p_T > 20$ or W_{cand} μ $p_T > 20$
MET > 30
Main BG: WZ

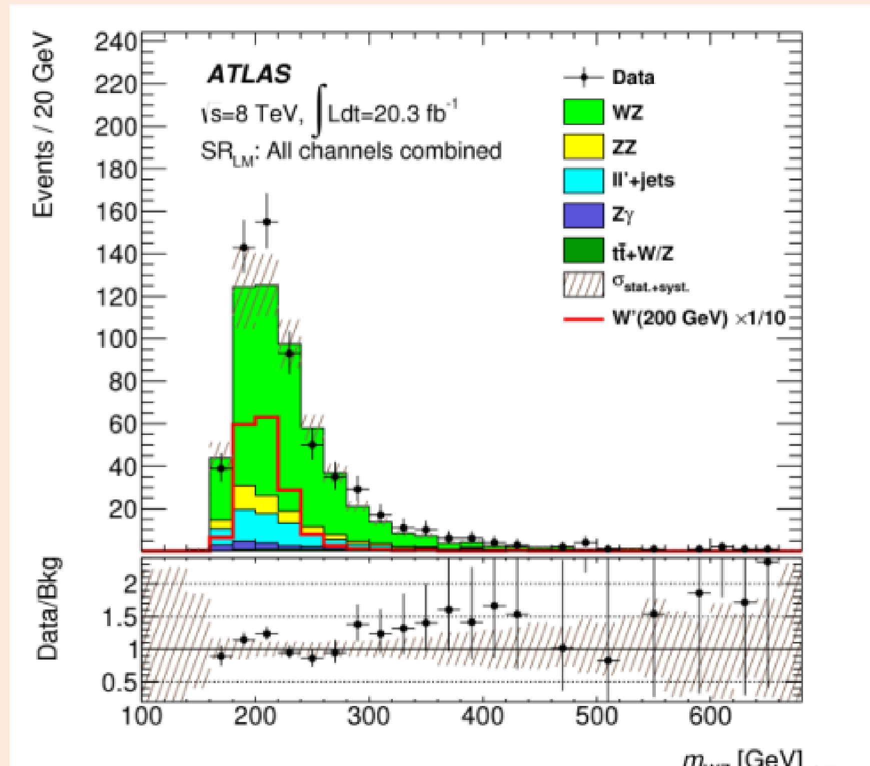
arXiv:1407.3476



ATLAS 3lν

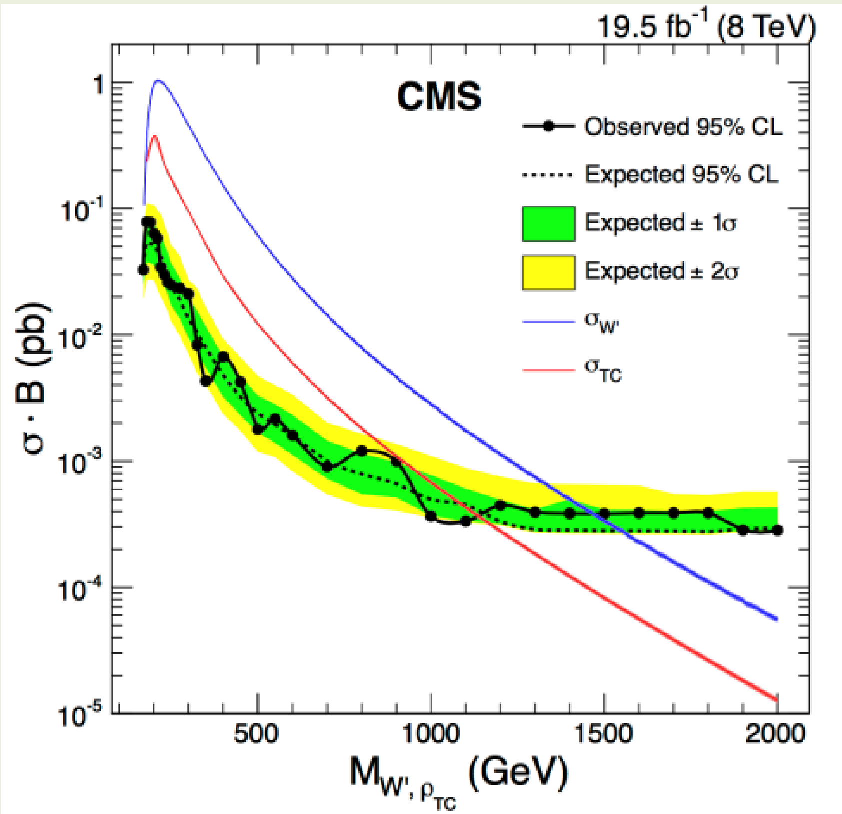
Lepton $p_T > 25$
MET > 25
Veto 4th lepton
|Δy(W,Z)| < 1.5
Main BG: WZ

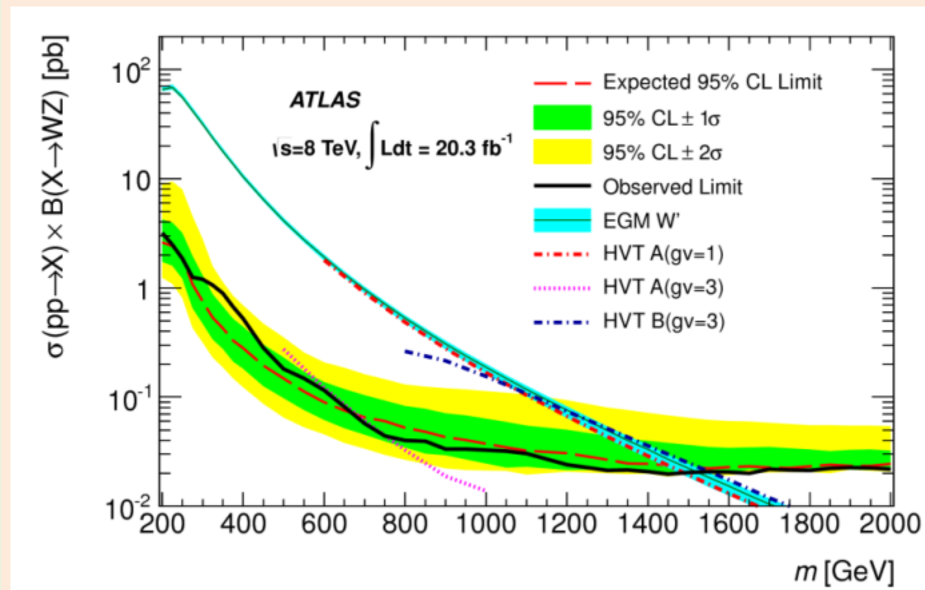
arXiv:1406.4456



W’

W’ → WZ → 3lν





Limits on W’ mass: 1.52 TeV (ATLAS), 1.47 TeV (CMS)

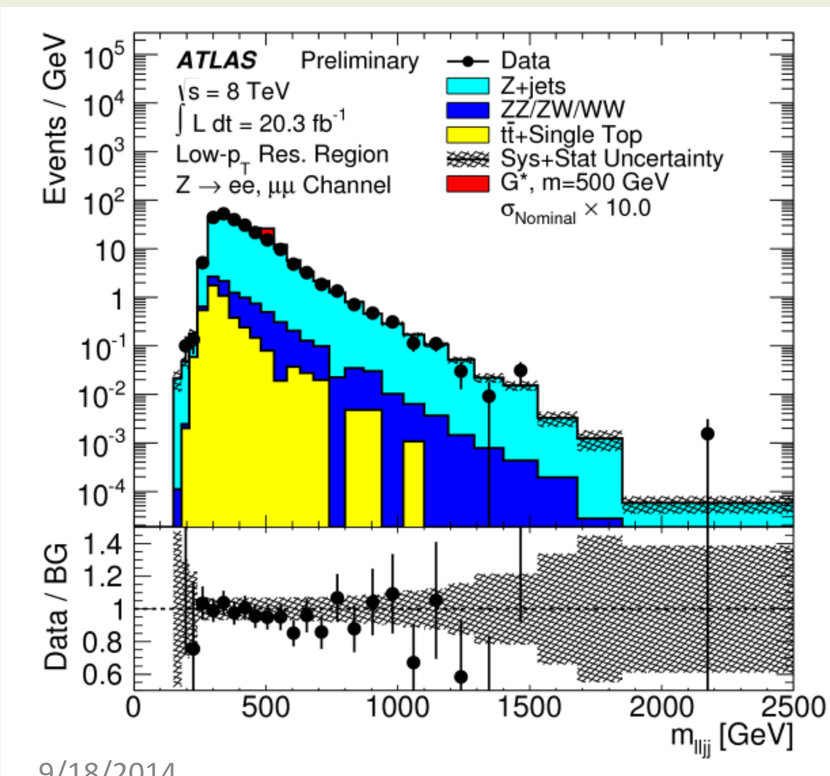
W’

W’ → qq’*, *W’ → WZ → 2lqq’

ATLAS 2lqq’

Electron p_T > 25
Muon p_T > 25
Jet p_T > 30
Large jet p_T > 100
Main BG: Z+jets

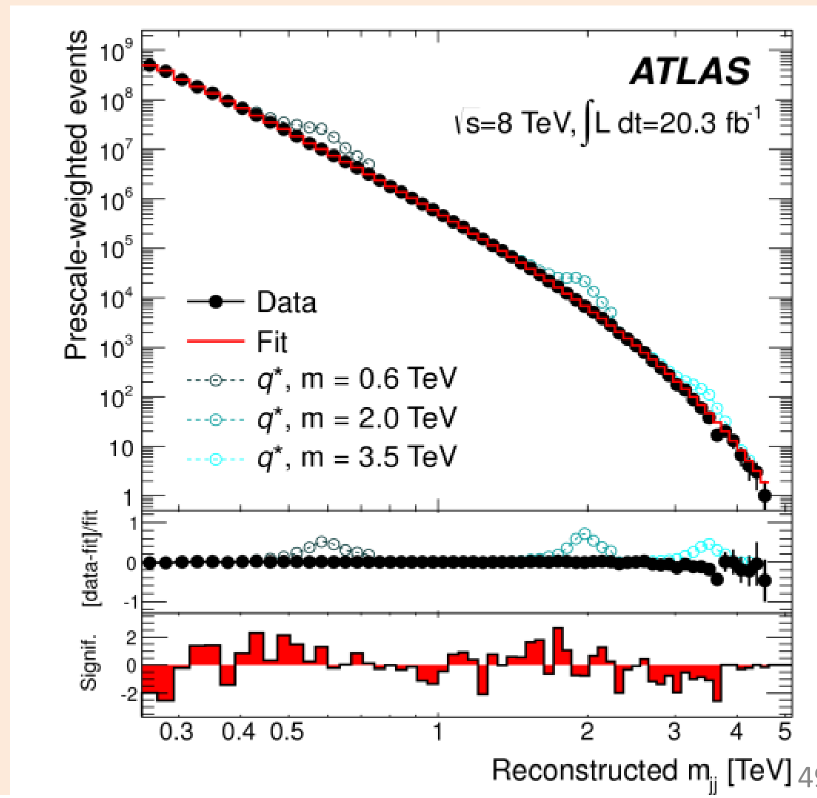
ATLAS-CONF-2014-039



ATLAS qq’

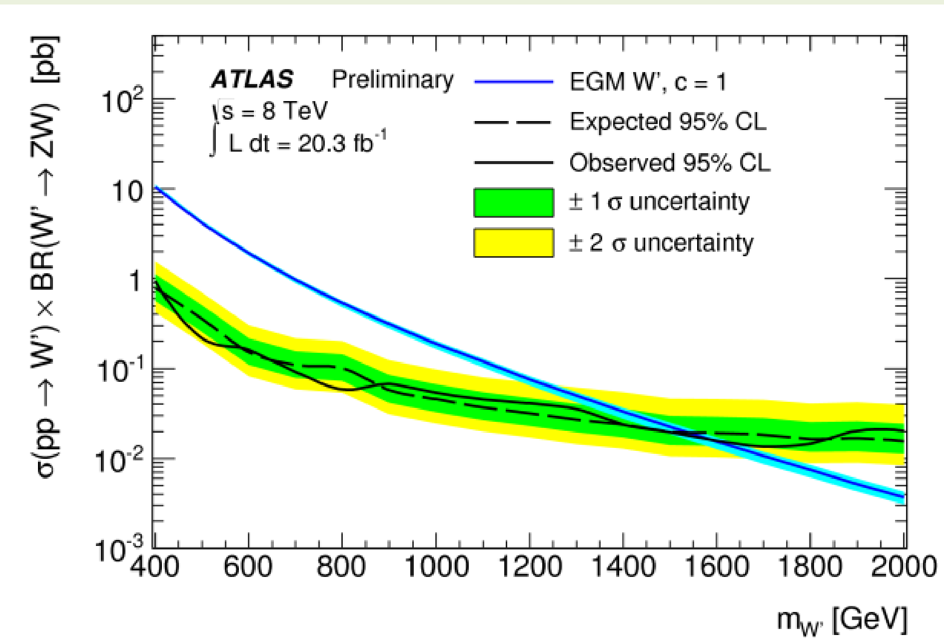
Jet p_T > 50
$|\Delta\eta_{jj}|$ < 1.2
Main BG: Multi-jet

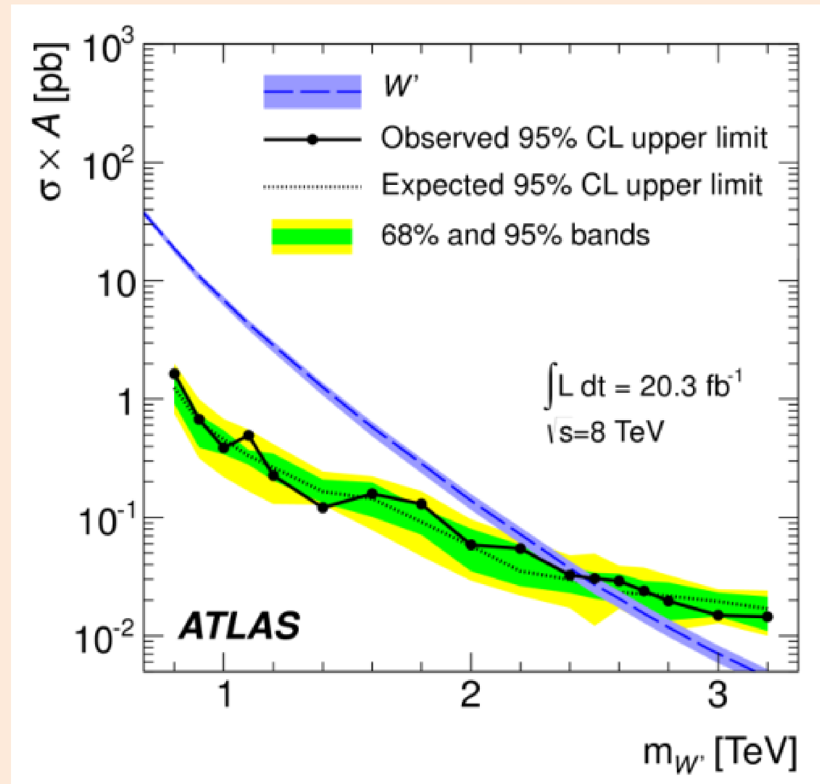
arXiv:1407.1376



W'

W' → qq', W' → WZ → 2lqq'

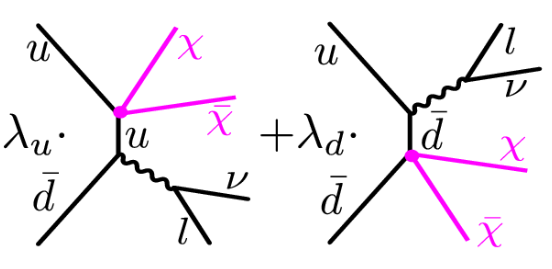




Limits on W' mass: 1.59 TeV (2lqq'), 2.45 TeV (qq')

Dark Matter: Mono-W

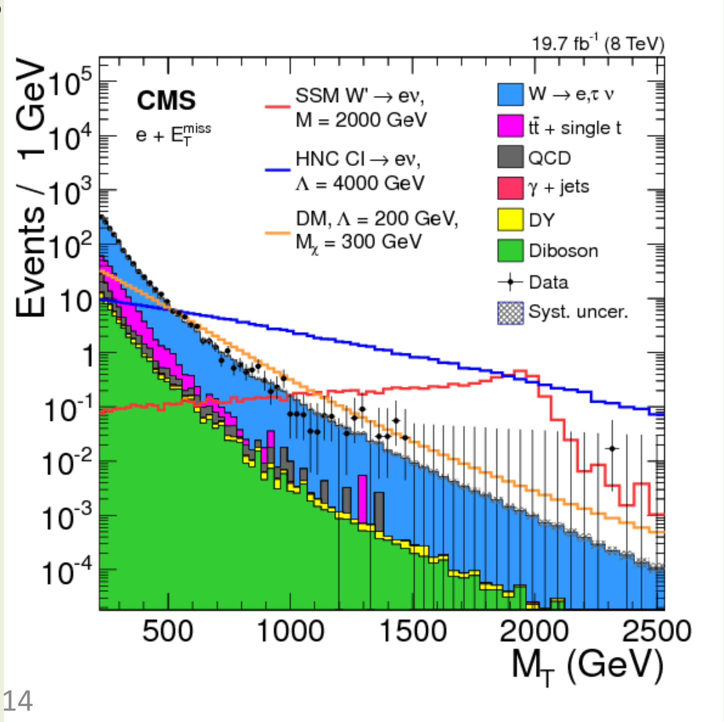
Interference scenario:
ξ= +1,0,-1



DM is undetected but radiated object is detectable
Mono-W
Limits set for different operator types

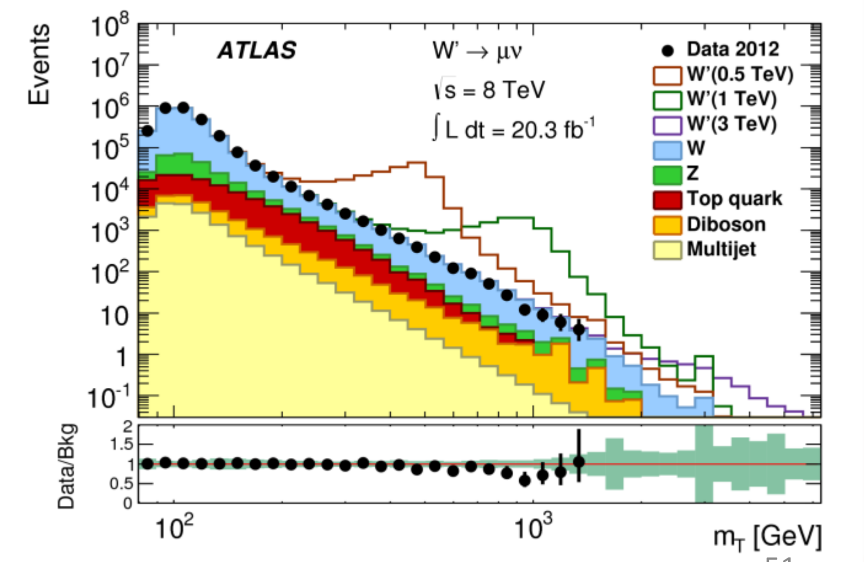
CMS mono-W(lν)
Electron $p_T > 80$
Muon $p_T > 45$
MET > 100
Main BG: W

arXiv:1408.2745



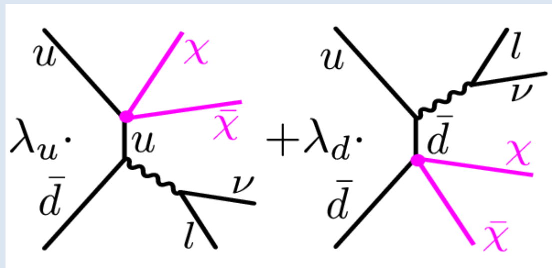
ATLAS mono-W(lν)
Electron $p_T > 125$
Muon $p_T > 45$
MET > 125 or 45
Main BG: W

arXiv:1407.7494



Dark Matter: Mono-W

Interference scenario:
ξ= +1,0,-1

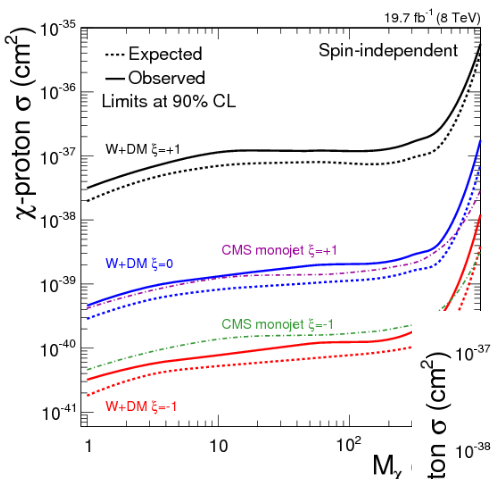


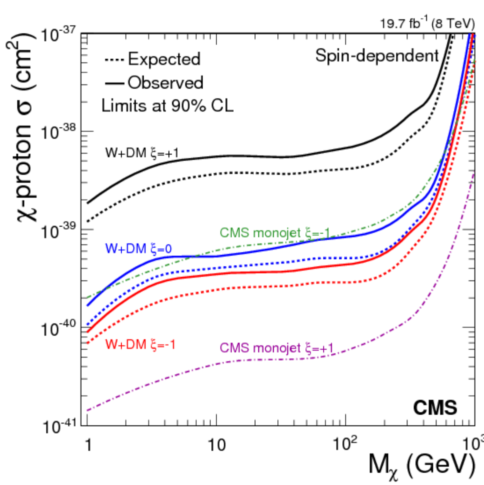
DM is undetected but radiated object is detectable

Mono-W

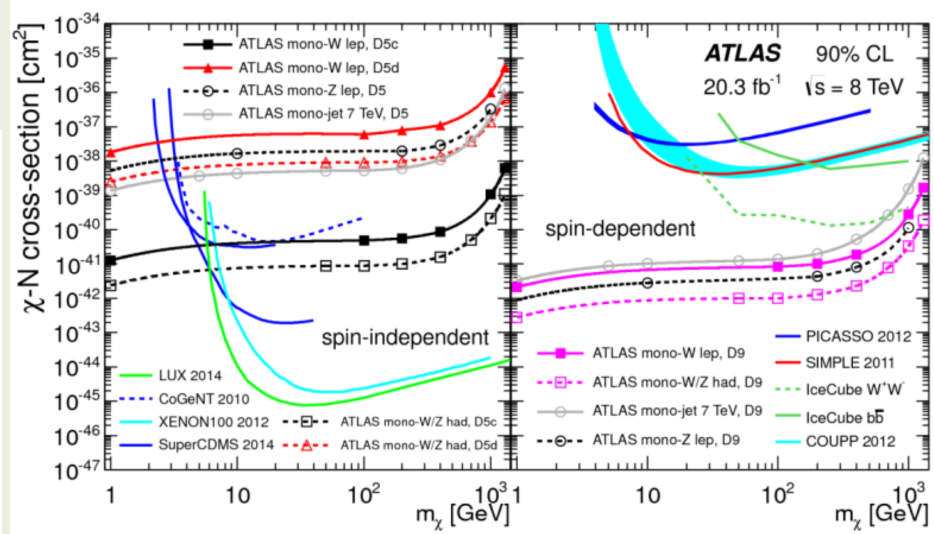
Limits set for different operator types

CMS mono-W

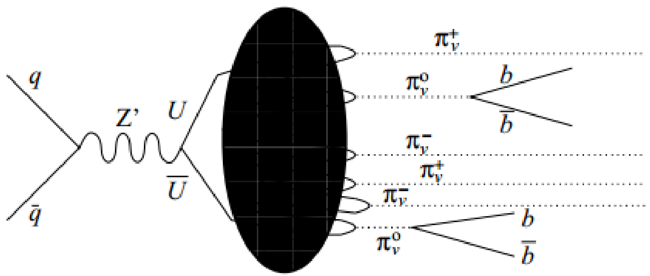




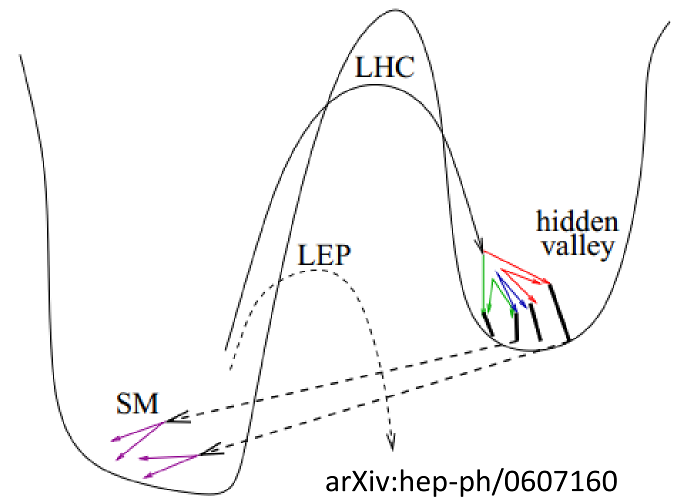
ATLAS mono-W



Limits on χ-Nucleon σ: 10^{-42}-10^{-36} cm^2 (vector), 10^{-42}-10^{-39} cm^2 (axial-vector, or tensor=D9)



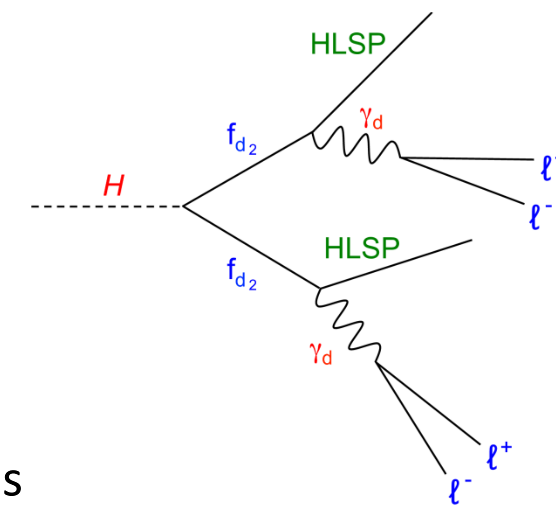
arXiv:hep-ph/0604261



arXiv:hep-ph/0607160

Long-lived particles

- Hidden valley (hidden sector)
  - Extension of SM by a valley group
  - DM candidate (HLSP)
  - Decay lifetime could be long
    - Non-prompt decay
      - Displaced dilepton, dijet
    - Unique experimental signatures
      - Lepton jets, collimated leptons

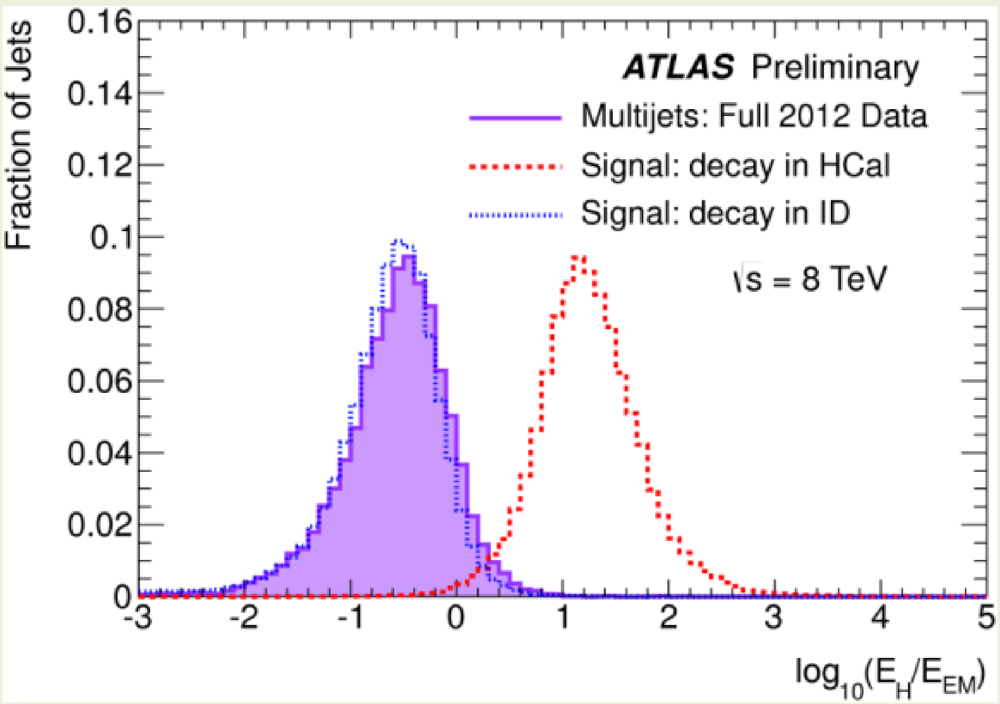


Long-lived neutral particles

ATLAS Displaced jets

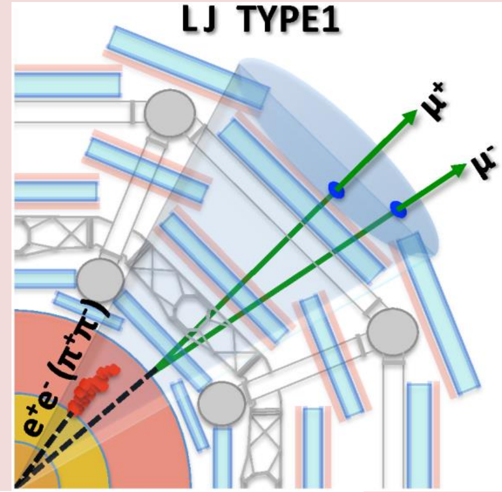
log10 (Ehad/Eem) > 1.2
jet pt > (60, 40)
narrow jet
no track
Main BG: multijet

ATLAS-CONF-2014-041

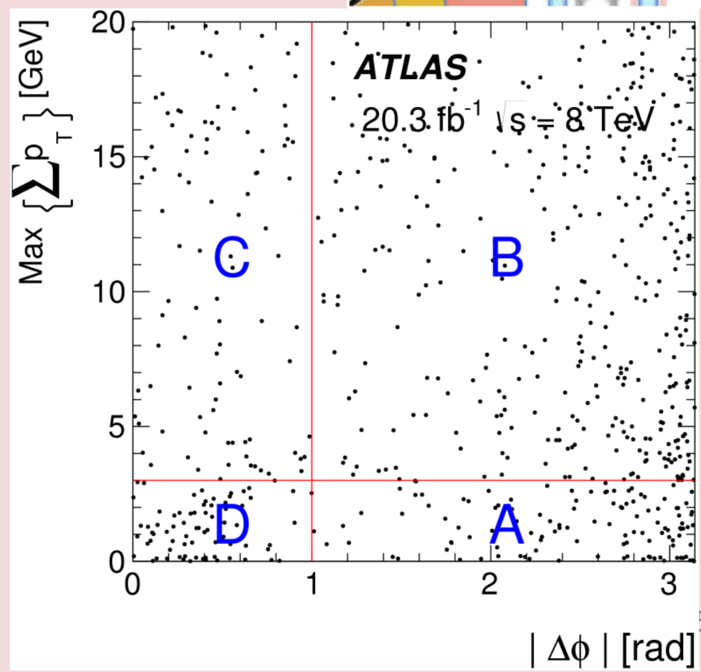


ATLAS Lepton jets

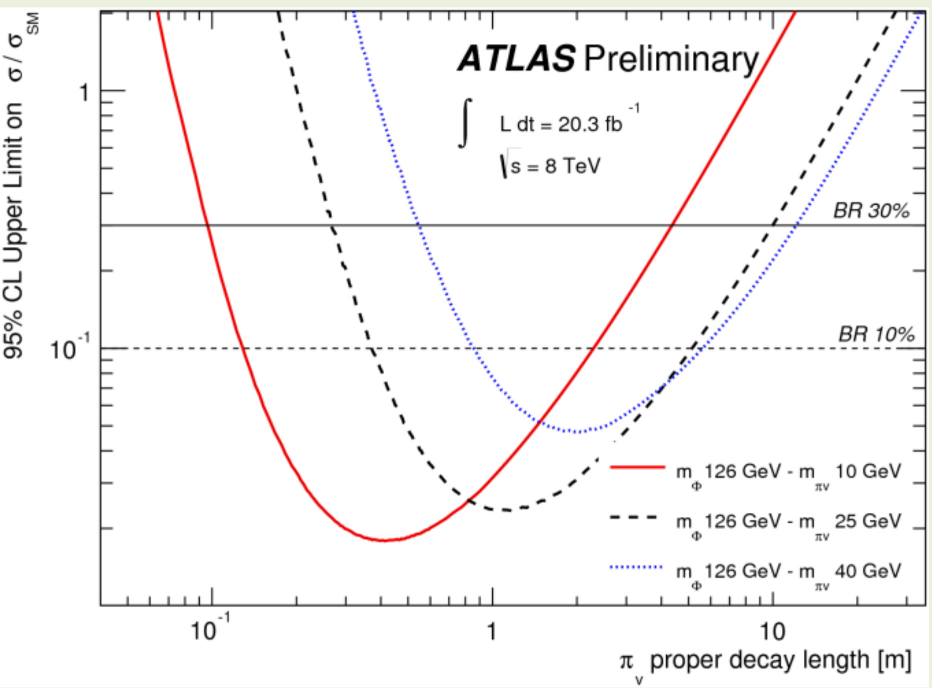
|d0| < 200 mm
|z0| < 270 mm
Time window: -1 to 5 ns
EM energy fraction < 0.1
ΣTrack p_T < 3 GeV
|Δϕ| > 1
Main BG: multijet, cosmics



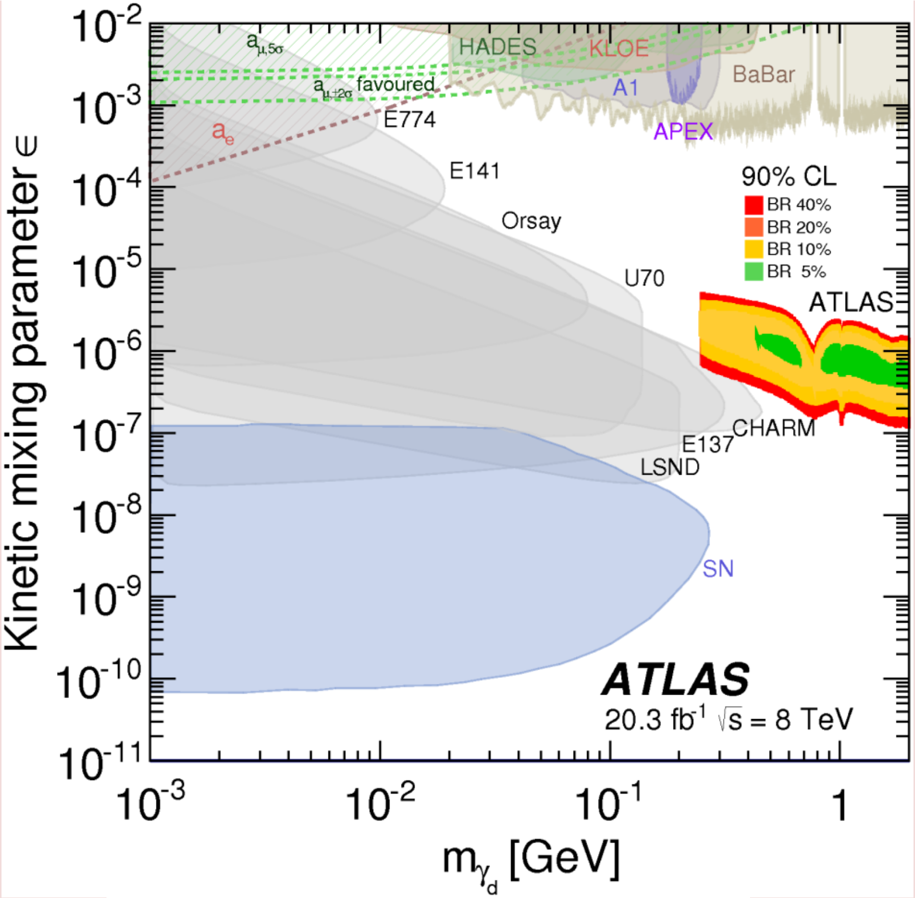
arXiv:1409.0746



Long-lived neutral particles



MC sample m_Φ, m_{π_v} [GeV]	excluded range 30% BR $\Phi_{HS} \to \pi_v\pi_v$ [m]	excluded range 10% BR $\Phi_{HS} \to \pi_v\pi_v$ [m]
126, 10	0.10 - 4.38	0.13 - 2.30
126, 25	0.27 - 10.01	0.37 - 5.12
126, 40	0.54 - 12.11	0.86 - 5.62



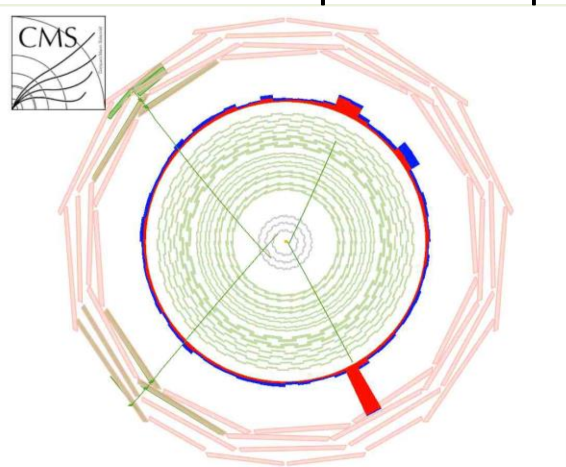
	All LJ pair types
Data	119
Cosmic rays	$40 \pm 11 \pm 9$
Multi-jets (ABCD)	$70 \pm 58 \pm 11$
Total background	$110 \pm 59 \pm 14$

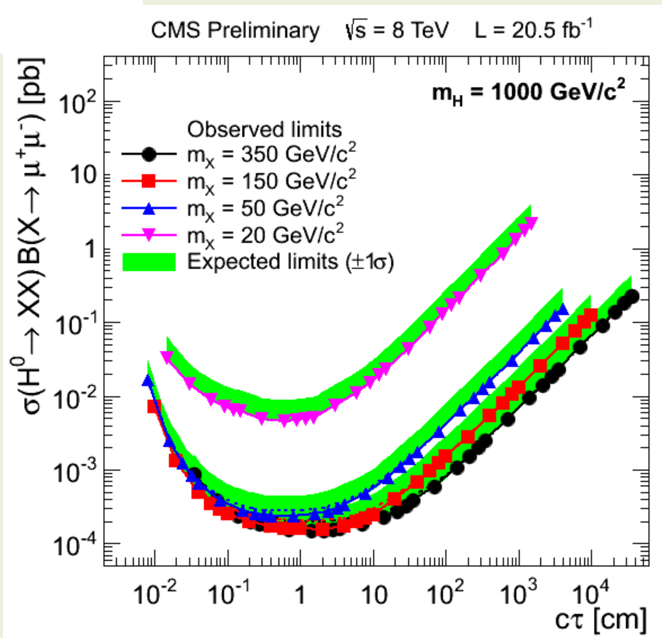
Earlier CMS long-lived particle searches in backup

Long-lived neutral particles

Earlier CMS results for reference

CMS displaced dilepton, PAS EXO12037





CMS displaced dijet, EXO12038