Searches for dark matter beyond mono-jets at the ATLAS experiment

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On behalf of the ATLAS Collaboration

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ATLAS EXPERIMENT

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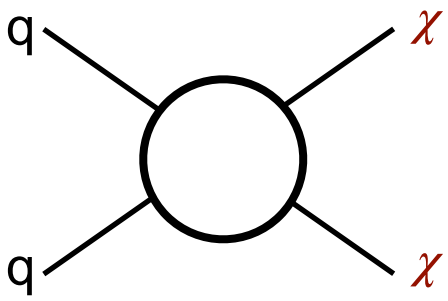
DM models used at ATLAS

1507.00966

Wendy Taylor's talk

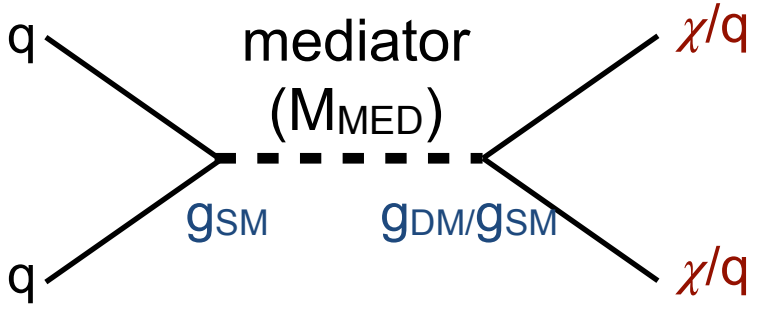
Effective field Theory

- m_{DM}, M*, underlying coupling type, DM types
- Valid when mediator of the interaction between SM and DM particles are very heavy



Simplified model

- Standardized for ATLAS&CMS Run2
- Relatively light mediator (TeV-scale)
- Mediator has minimal decay width
- Minimal flow violation
- Minimal set of parameters
  - Coupling structure, M_{MED}, m_{DM}, g_{SM} (g_q), g_{DM}



LHC DM forum and working group

— Antonio Boveia's talk

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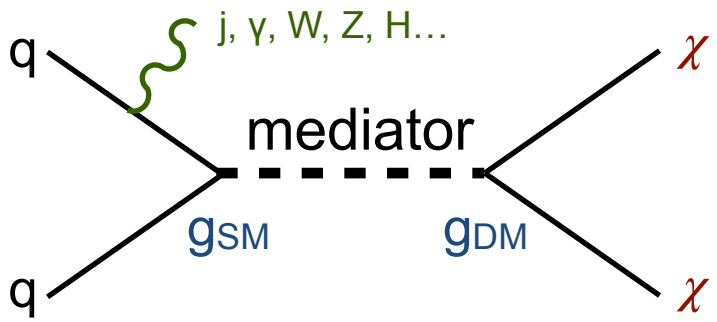
DM search in Mono-X

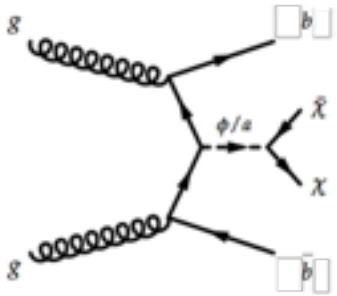
- Directly produced Dark Matter (g_q & g_{DM})
  - Pair production of DMs
  - Mono-X signature
    - MET + bb, tt, Z(ll) covered by this talk
      - Using control regions to constrained background from known processes



MET + γ, W/Z(had), Higgs in Wendy Taylor's talk

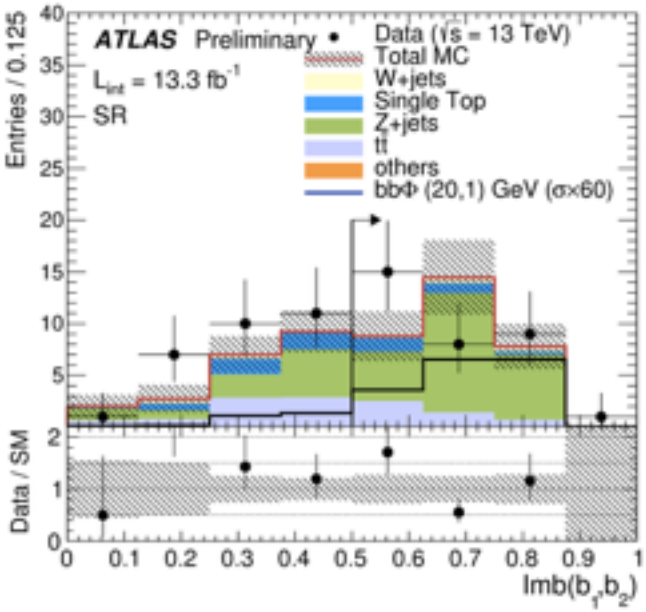
MET+bb

ATLAS-CONF-2016-086

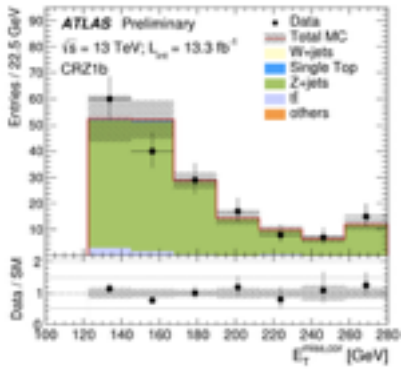


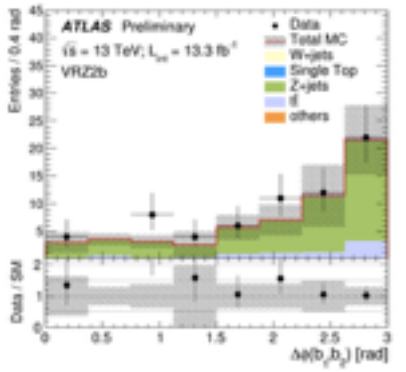
- Motivation to a search in association with Heavy Flavour quarks
- Mediator is a (pseudo-) scalar, DM is a dirac fermion
  - Assumes Yukawa-like couplings between mediator and SM fermions
- Events with E_{miss}^{T}> 150 GeV, two b-tagged jets

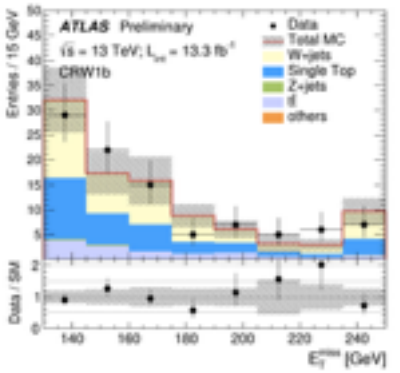
$N_{obs.}$ in the CRs are used in combined profile likelihood fit to determine the expected SM background yields in the SR



Orthogonal to the SR



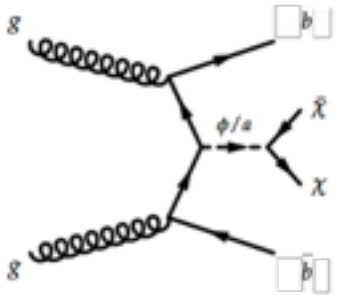




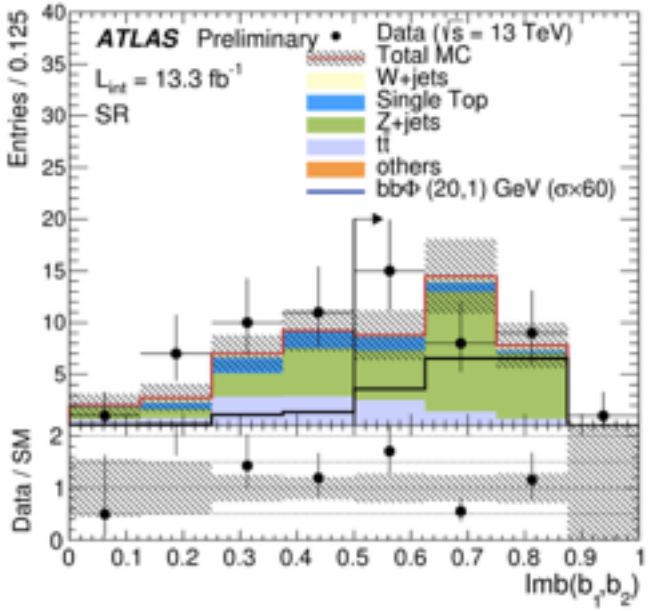
Likelihood function is build to describe $N_{obs.}$ and $N_{exp.}$ in each CR

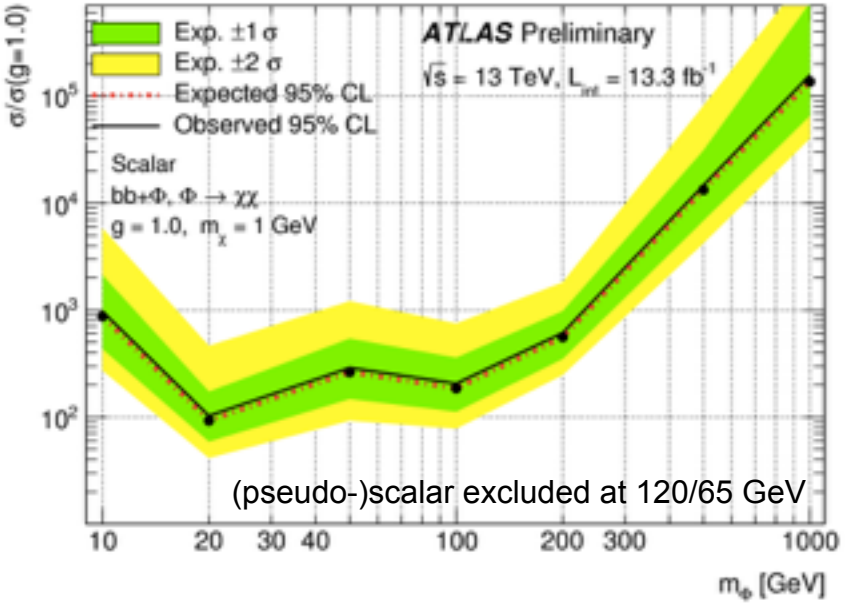
MET+bb

ATLAS-CONF-2016-086



- Motivation to a search in association with Heavy Flavour quarks
- Mediator is a (pseudo-) scalar, DM is a dirac fermion
  - Assumes Yukawa-like couplings between mediator and SM fermions
- Events with E_{miss}^{T}> 150 GeV, two b-tagged jets
- Background dominated by Z->vv
  - large dR between jets (>2.8)
  - lmb(b1, b2) =(pT(b1) − pT(b2)) / (pT(b1) + pT(b2))> 0.5

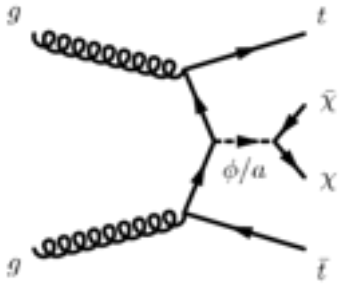


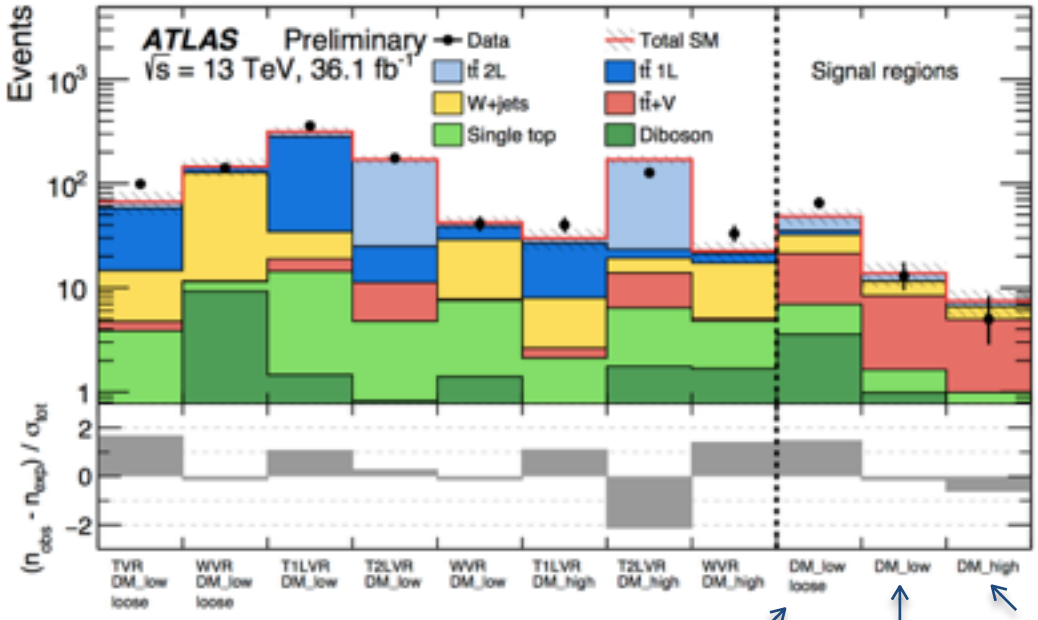


MET+tt

ATLAS-CONF-2017-037

- Motivation to a search in association with Heavy Flavour quarks
- Similar DM model as MET+bb
- Events with MET+tt(had, 1L, 2L)
  - Same final state as for SUSY 1-lepton EW searches

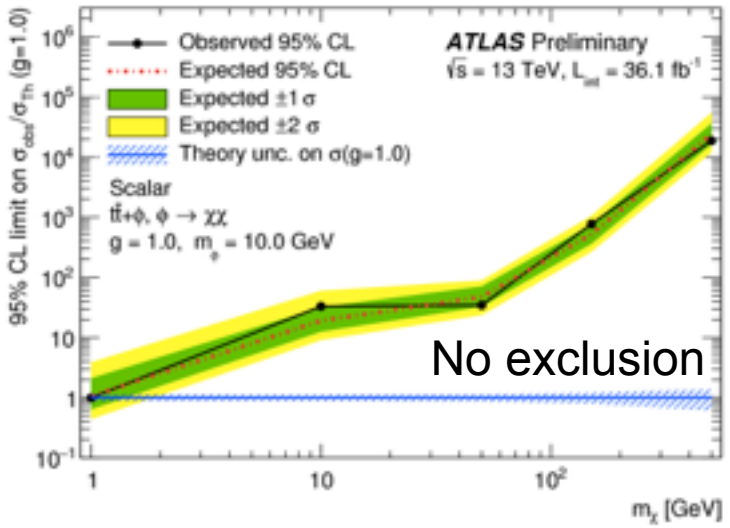




losser selection

m_{Med}= 20GeV

m_{Med}= 300GeV



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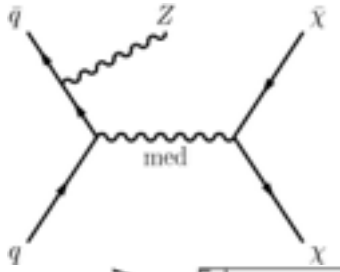
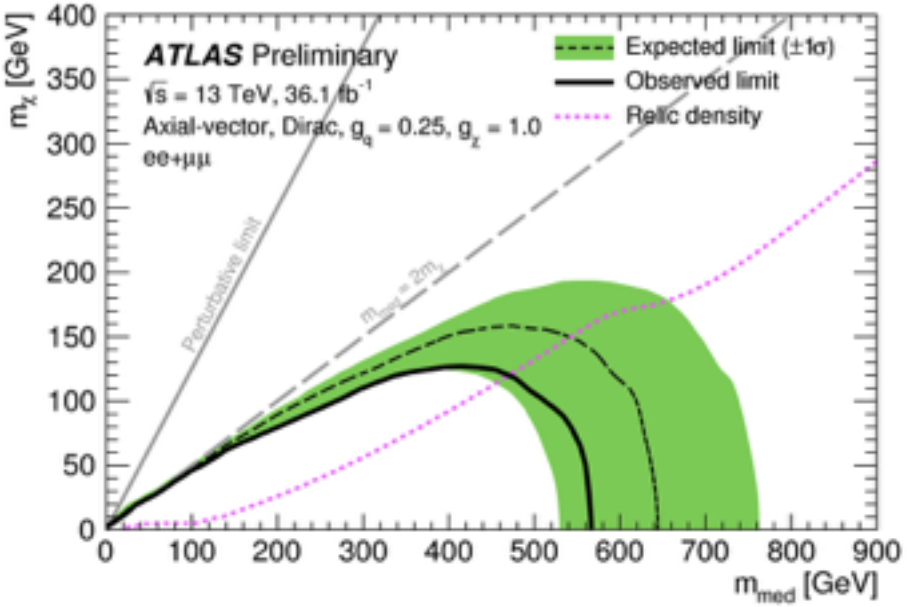
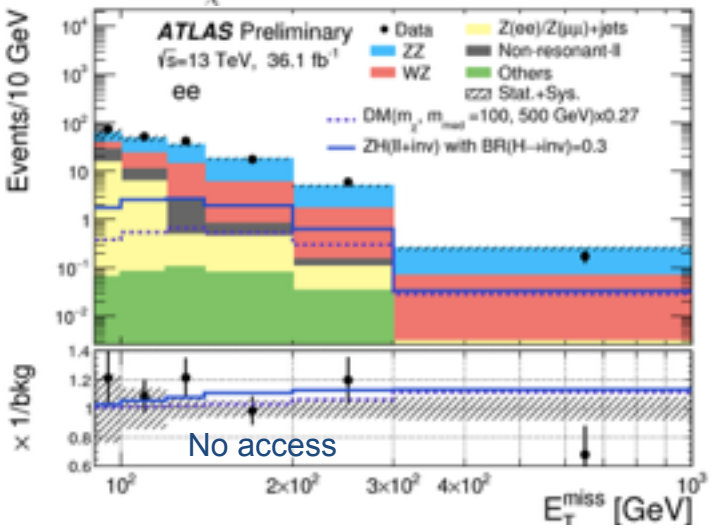
MET+Z(ll)

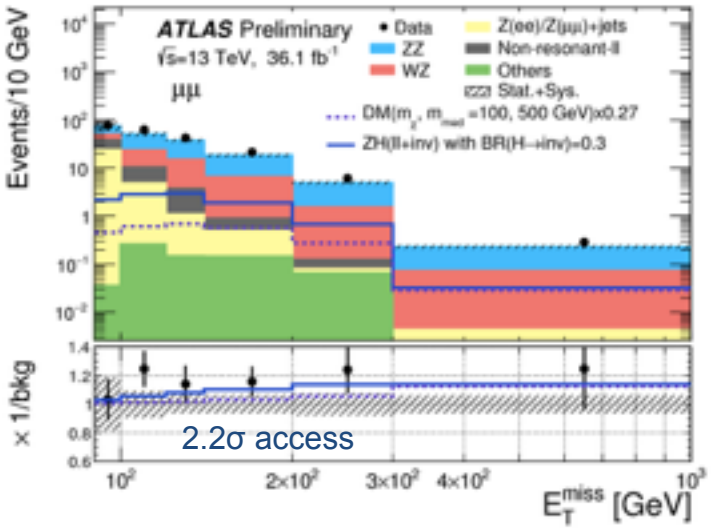


ATLAS-CONF-2017-040

- Axial-vector mediator , DM is a dirac fermion
- Events with a boosted Z (ee/μμ pair) back-to-back with MET
  - MET > 90 GeV, MET/H_T>0.6
  - ΔΦ(Z, MET) > 2.7, ΔR(ll) < 1.8, b-veto
- Background dominated by ZZ and WZ







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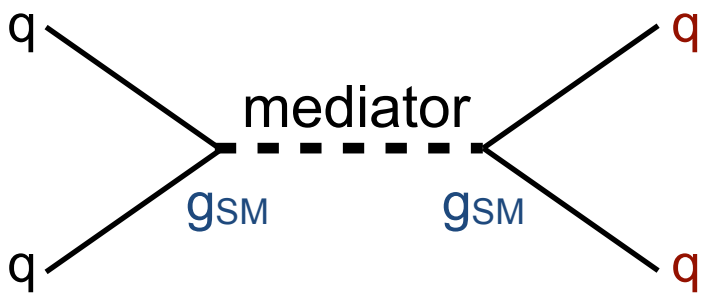
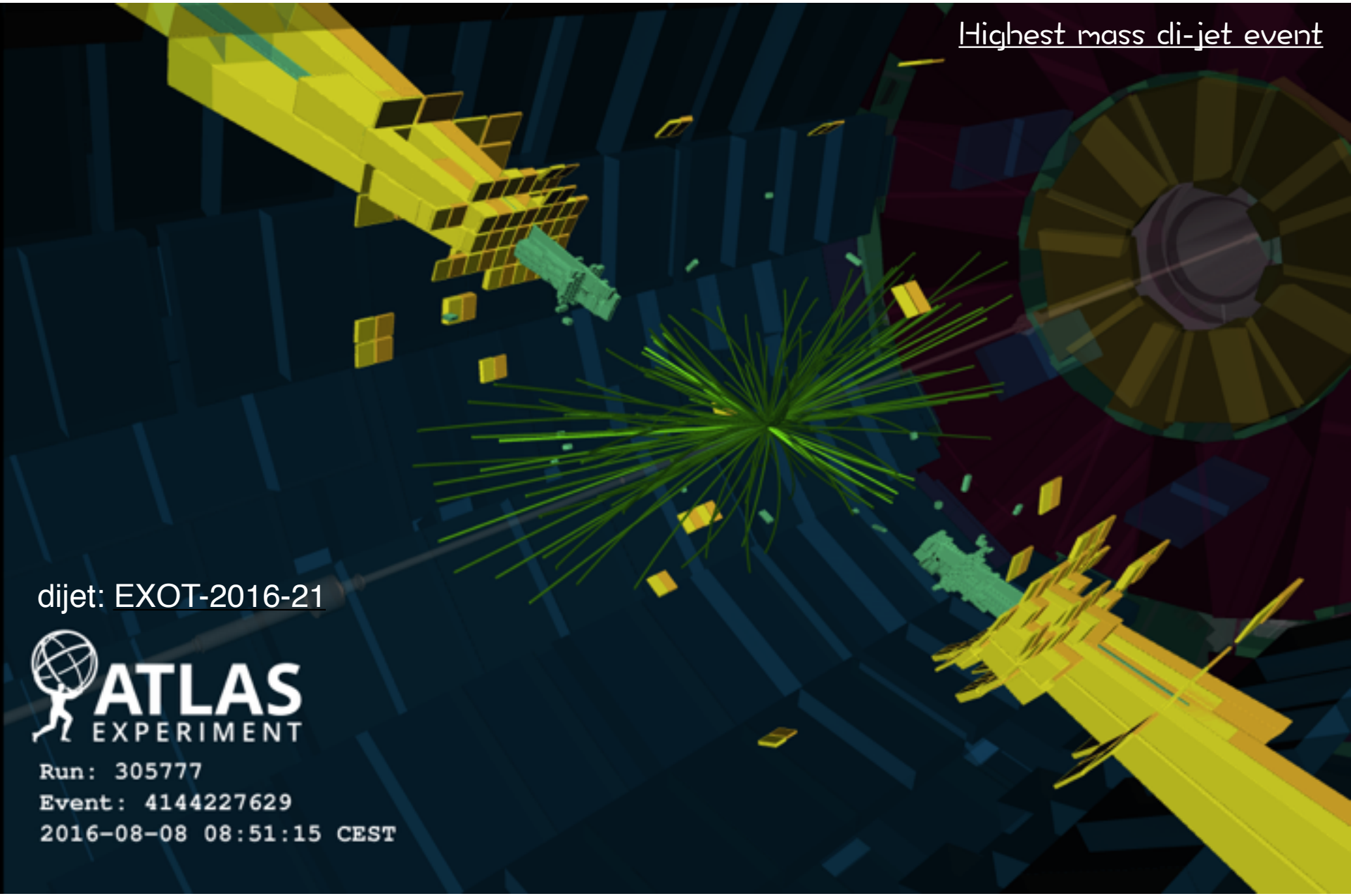
DM search in Di-X

- Search for mediator (g_q & g_q)
  - Pair production of SM final state
  - di-jet, di-b-jet, tt, di-lepton covered by this talk



  - Probing TeV resonances generically
  - Mediator mass search usually limited by the trigger threshold
    - Special treatment needed to go to lower mass



Ref: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2016-21/figaux_11.png

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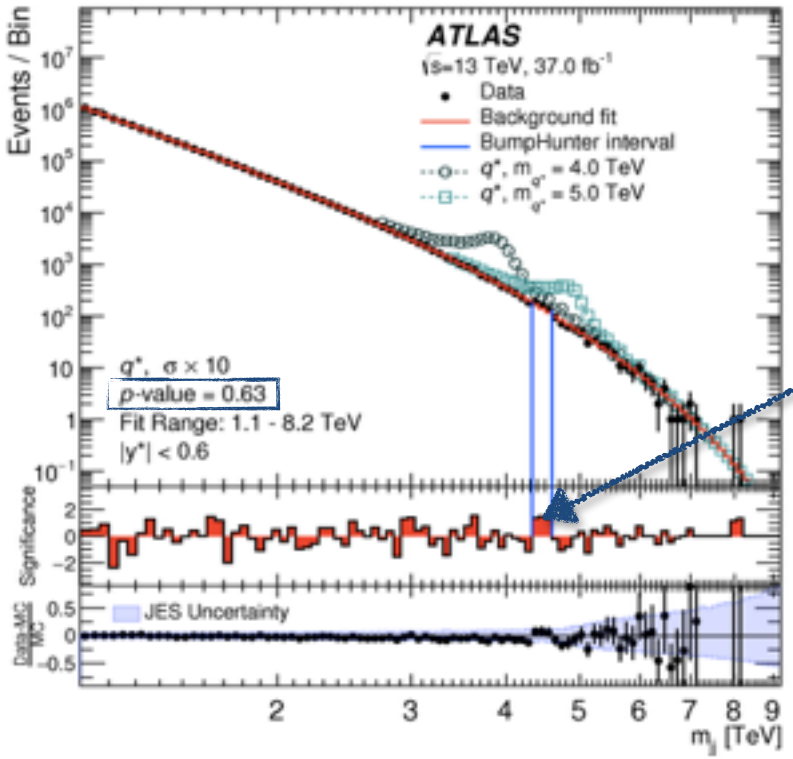
Di-jet

EXOT-2016-21

- Narrow resonance search above 1.1 TeV
  - $p_{T,1}$ ($p_{T,2}$) > 440 (60) GeV
  - |y*|<0.6, y*= (y1-y2)/2



Narrow peak on top of the smooth falling QCD background

Use ***Bumphunter*** to search for possible excess

- Looking for the most significant deviation from the background spectrum
- Bump hunter p-value reflects the bins that have the smallest probability of arising from a background fluctuation (assuming poisson statistics)

Di-jet

EXOT-2016-21

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  - $p_{T,1}$ ($p_{T,2}$) > 440 (60) GeV
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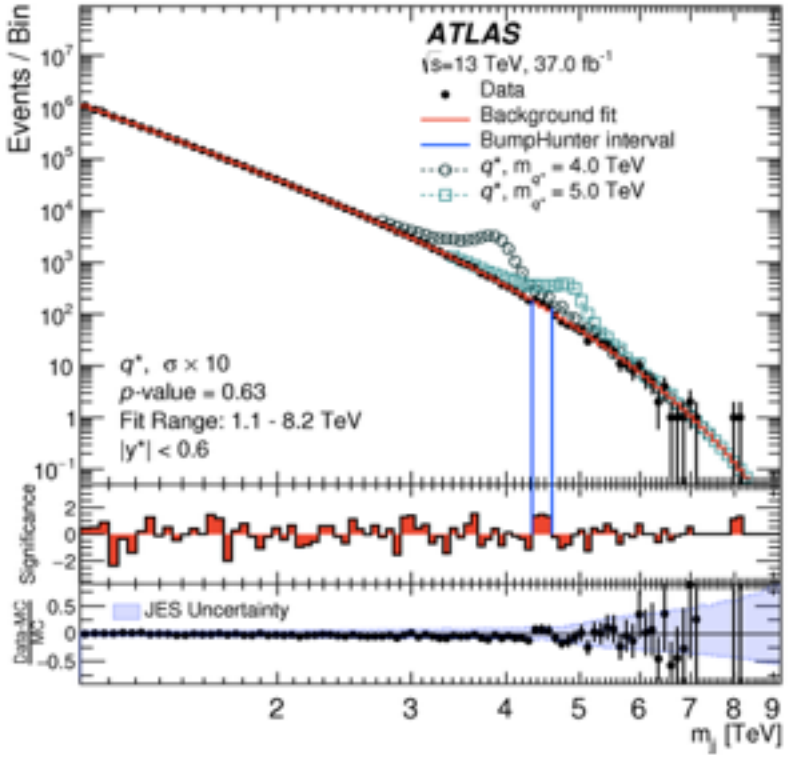
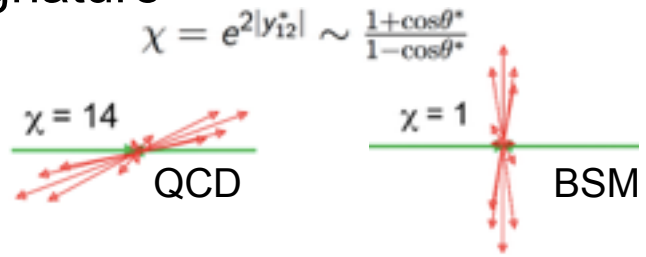
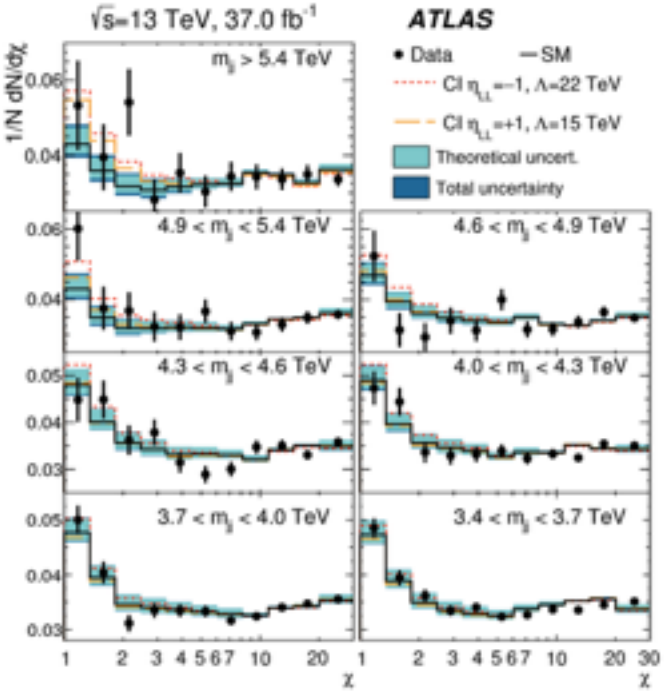


- Angular search — sensitive to wide mediators or non-resonant signature

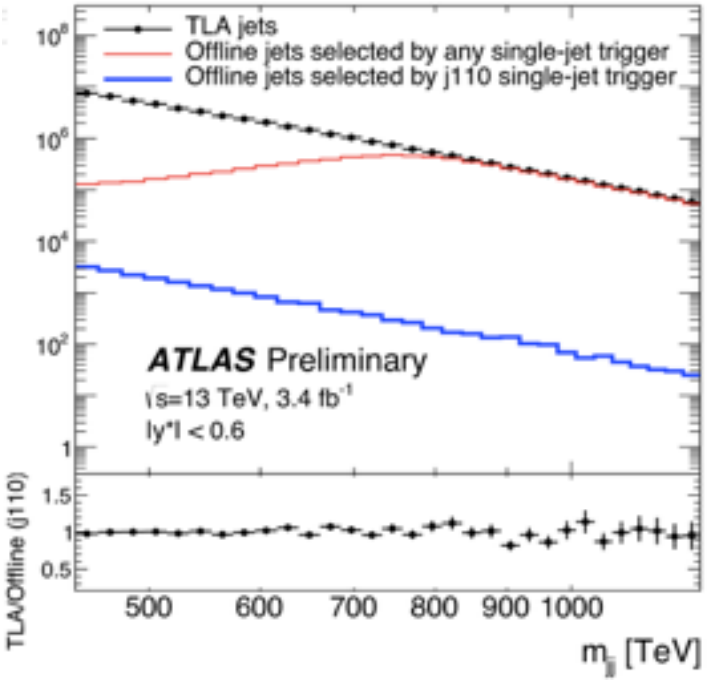
$$\chi = e^{2|y^*_{12}|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

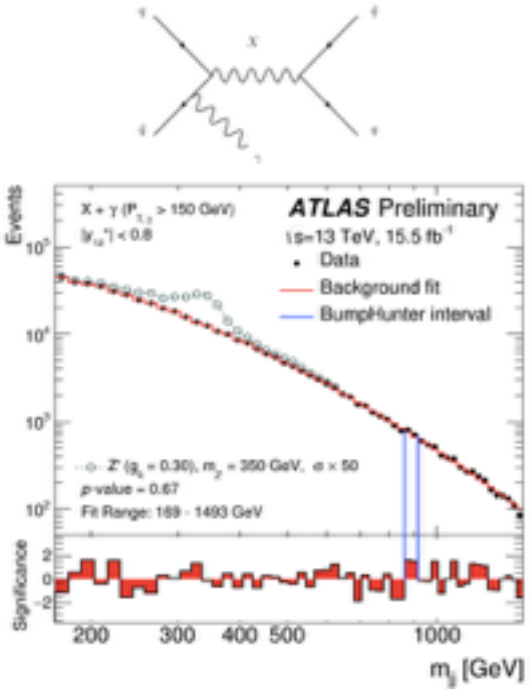


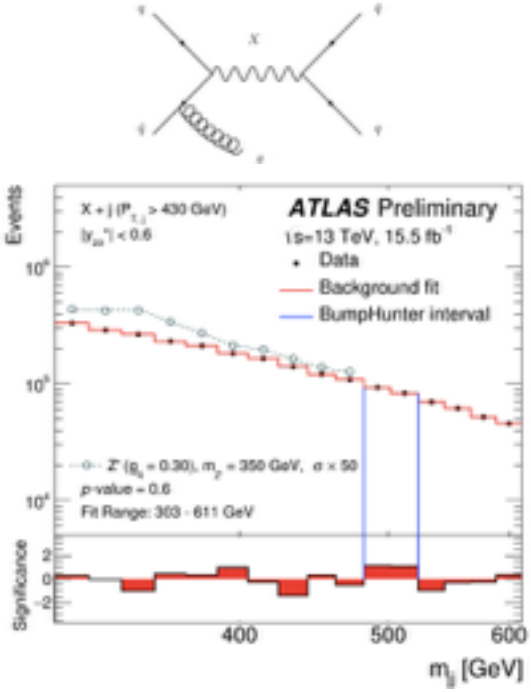


TLA + di-jet ISR — Expand to lower m_{jj}

- TLA (trigger level analysis) — use Data Scouting stream
  - Stores partial event informations (~ 5% of full event)
  - dedicated jet calibration for trigger level (TL) jets
- Trigger selection on ISR objects
  - Jets $p_T > 25$ GeV, $|\eta| < 2.8$
  - γ+JJ : γ $p_T > 150$ GeV, $|y^*_{12}| < 0.8$, $\Delta R_{\gamma,\text{closest}} > 0.85$
  - J+JJ : $p_{T,1} > 430$ GeV, $|y^*_{23}| < 0.6$





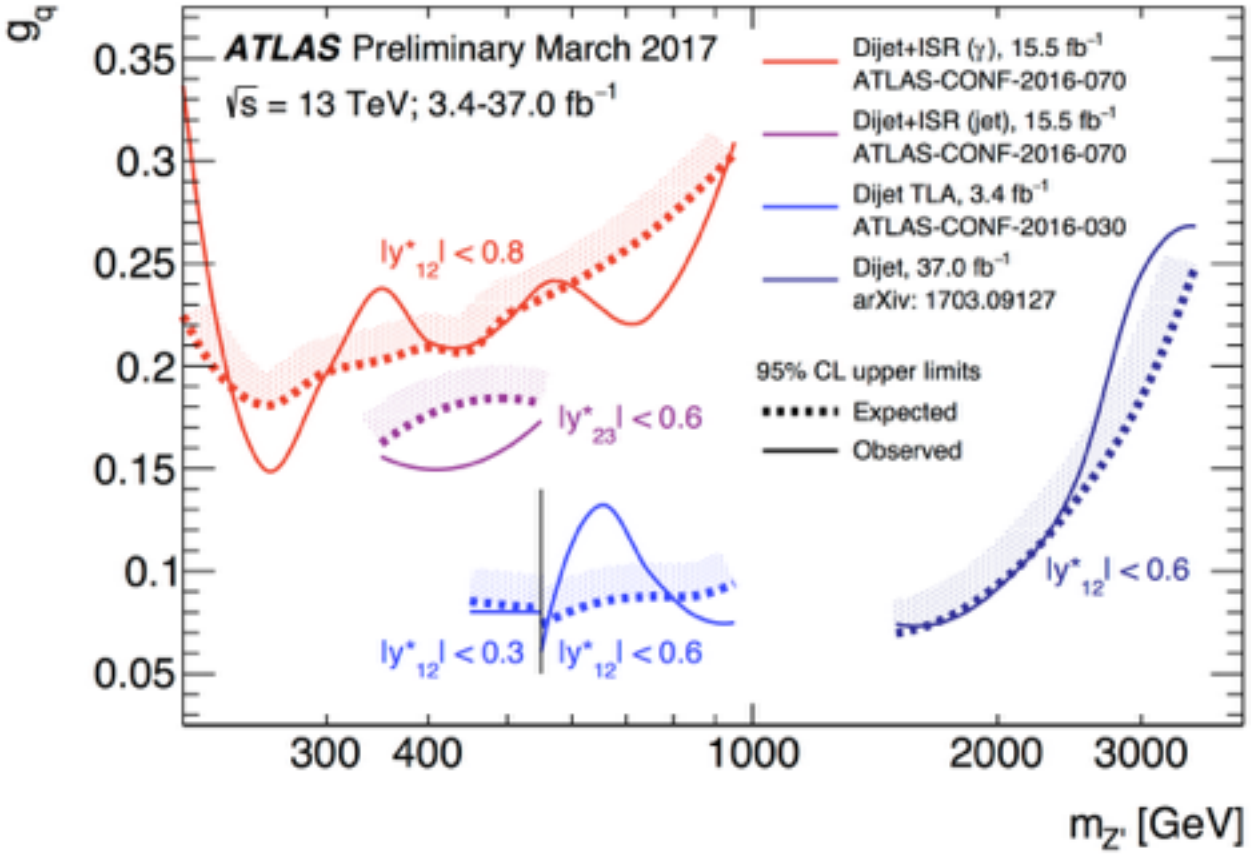


ATLAS-CONF-2016-030

ATLAS-CONF-2016-070

Di-jet limits

- ATLAS bounds in the coupling-mediator mass plane of leptophobic Z' DM mediator from dijet searches using 2015 and 2016 data (link)

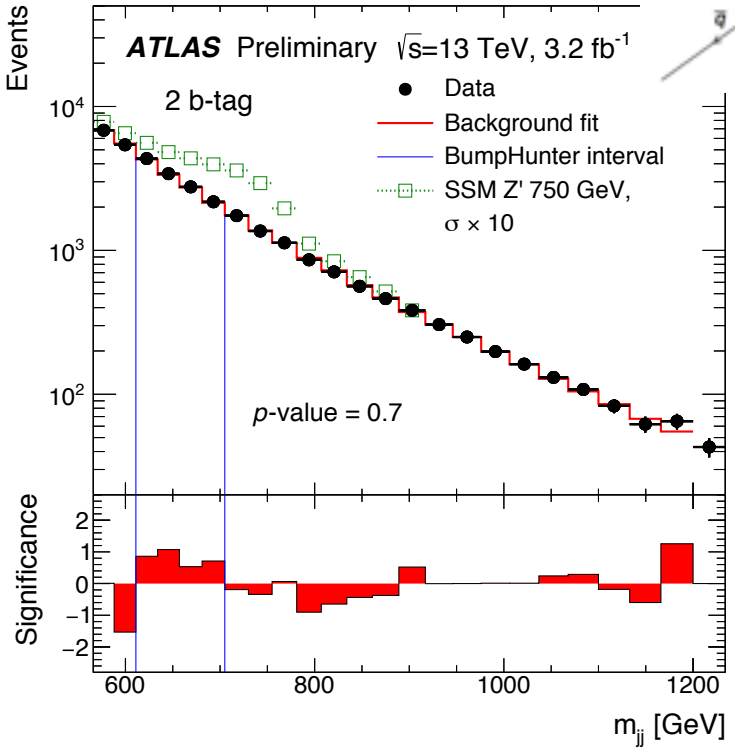


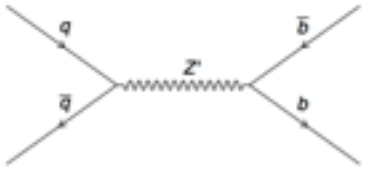
Ref: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_DarkMatterCoupling_Summary/ATLAS_DarkMatterCoupling_Summary.png

Di-b-jet — couple preferentially to b-quark

- Narrow resonance search with b-tagged jets
- Low mass - 570<m_{jj}<1200 GeV
  - $p_{T,1}$ ($p_{T,2}$) > 250 (60) GeV
  - |y*|<0.6, y*= (y1-y2)/2
  - b-tagged trigger + offline 2 b-tag
- High mass — m_{jj}>1380 GeV
  - $p_{T,1}$ ($p_{T,2}$) > 430 (60) GeV
  - |y*|<0.6, y*= (y1-y2)/2
  - Offline 2 b-tag

ATLAS-CONF-2016-060





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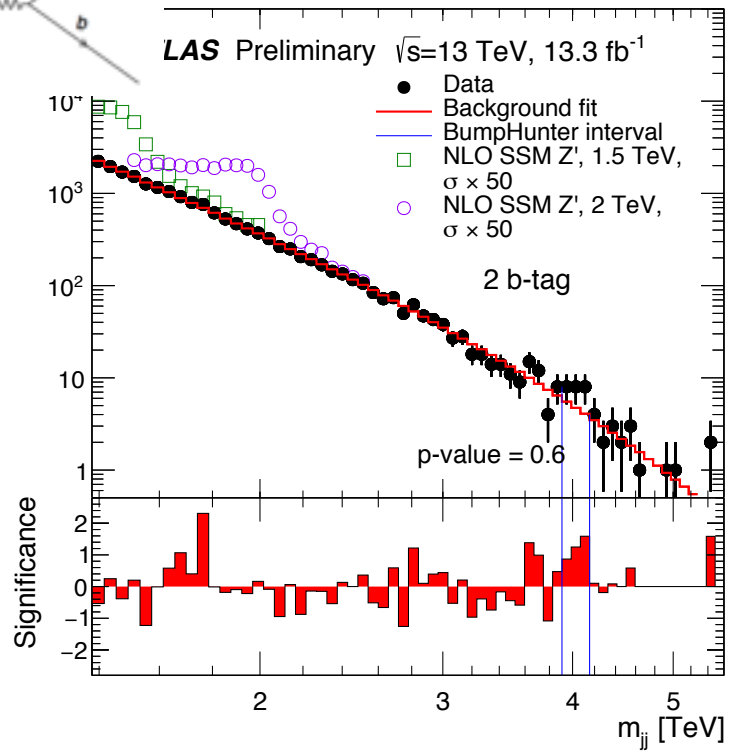
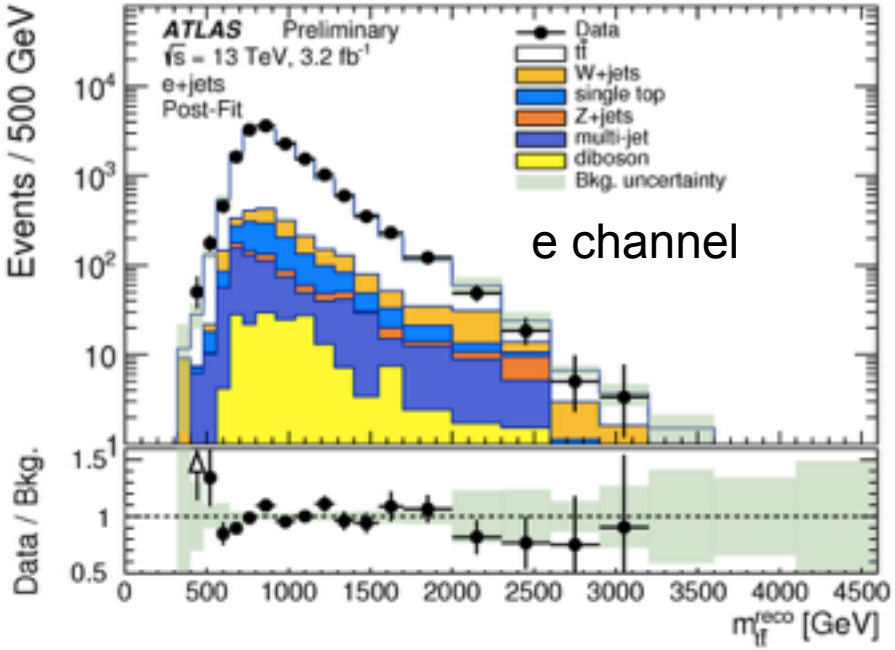
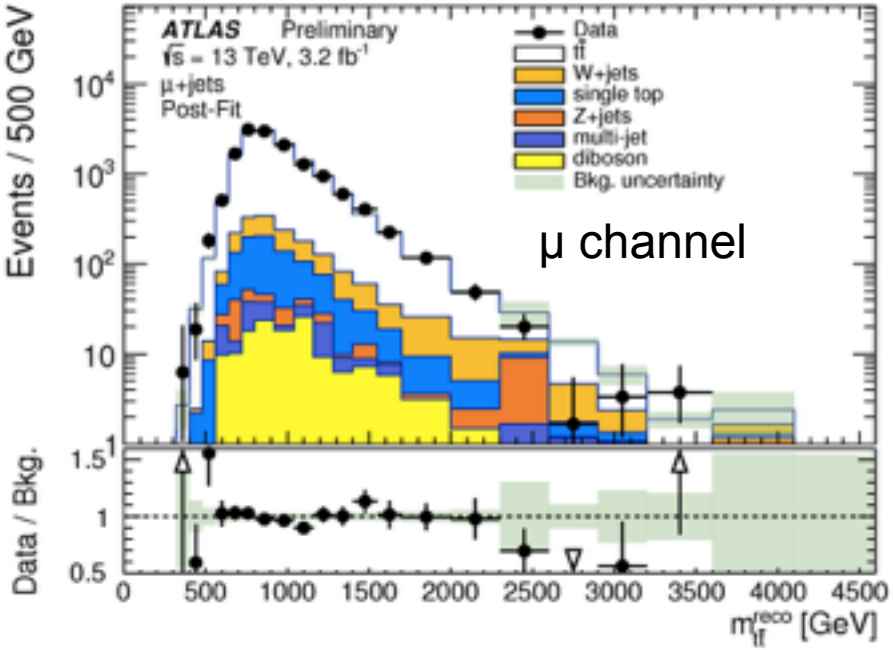


ttbar resonance search

ATLAS-CONF-2016-014

- DM couple preferentially to t-quark
- Events with exactly 1 electron or muon,
  - MET > 20 GeV, MET + MWT> 60 GeV ($MWT = \sqrt{p_T^{lep}.MET.2(1 - cos\Delta\Phi(MET, lepton))}$)
  - top-tagged large-R jets
  - 1 b-tagged track jet

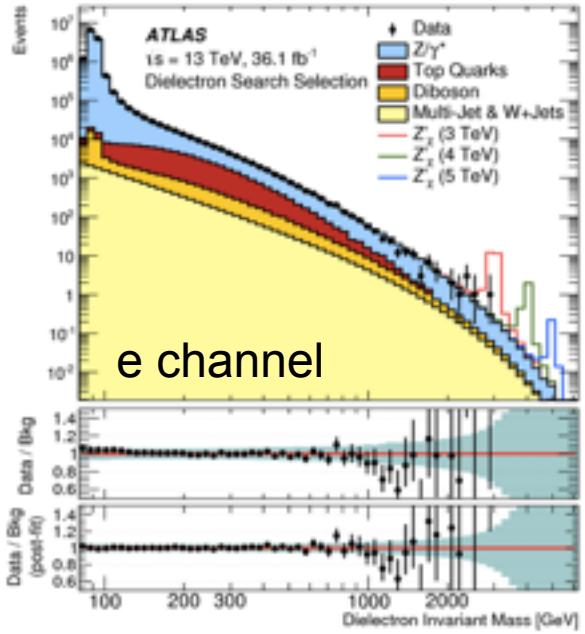


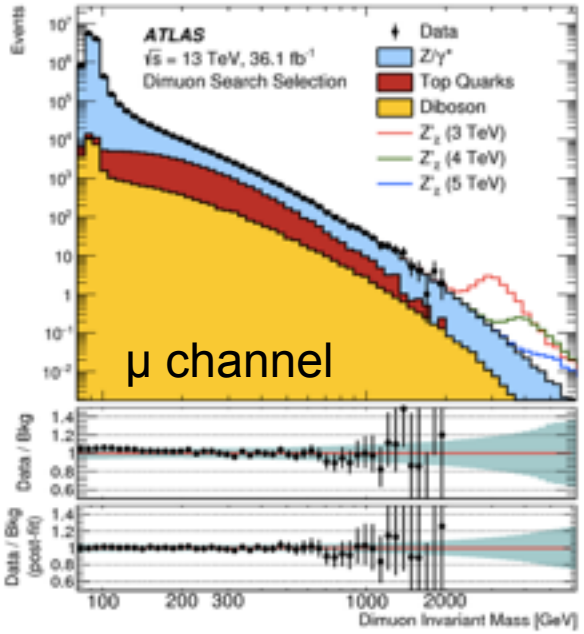


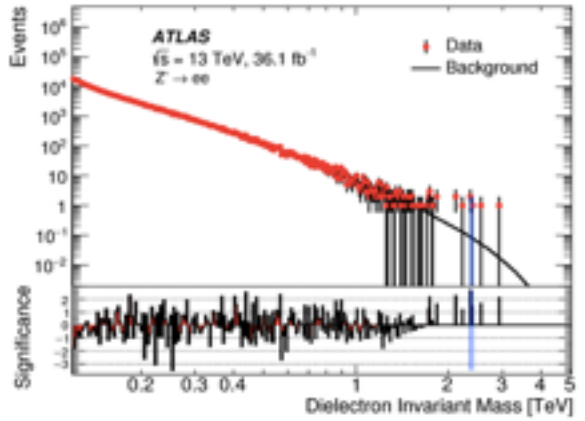
EXOT-2016-05

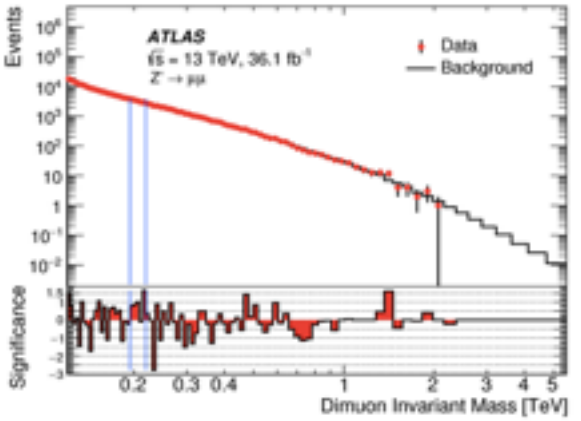
Di-lepton resonance search

- Events with one pair of isolated e/μ with pT>30 GeV





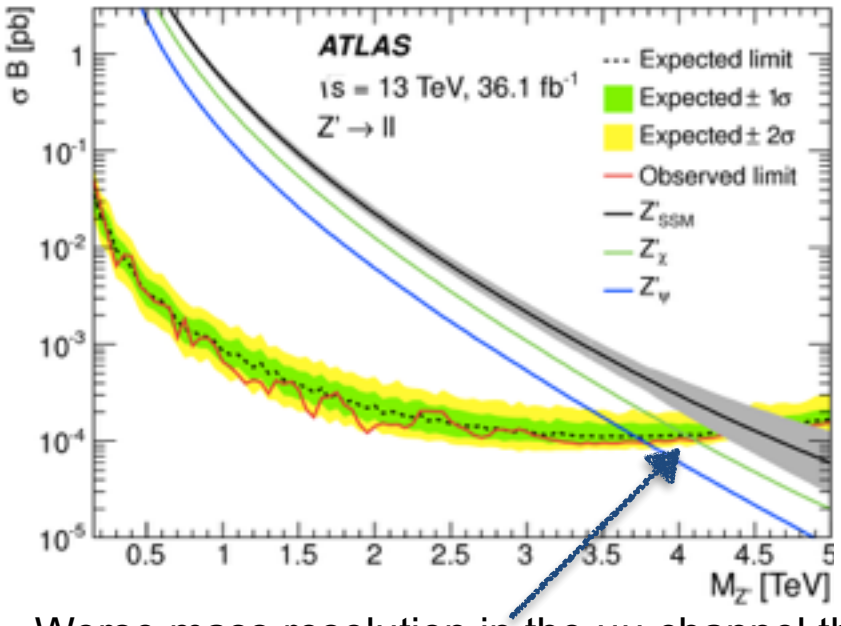


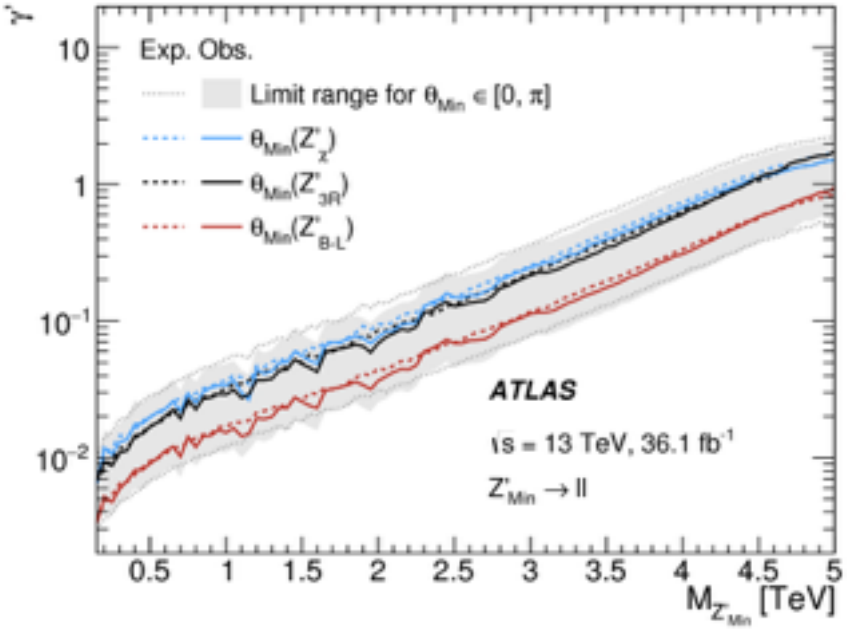


Di-lepton resonance search

EXOT-2016-05

- Events with one pair of isolated e/μ with pT>30 GeV

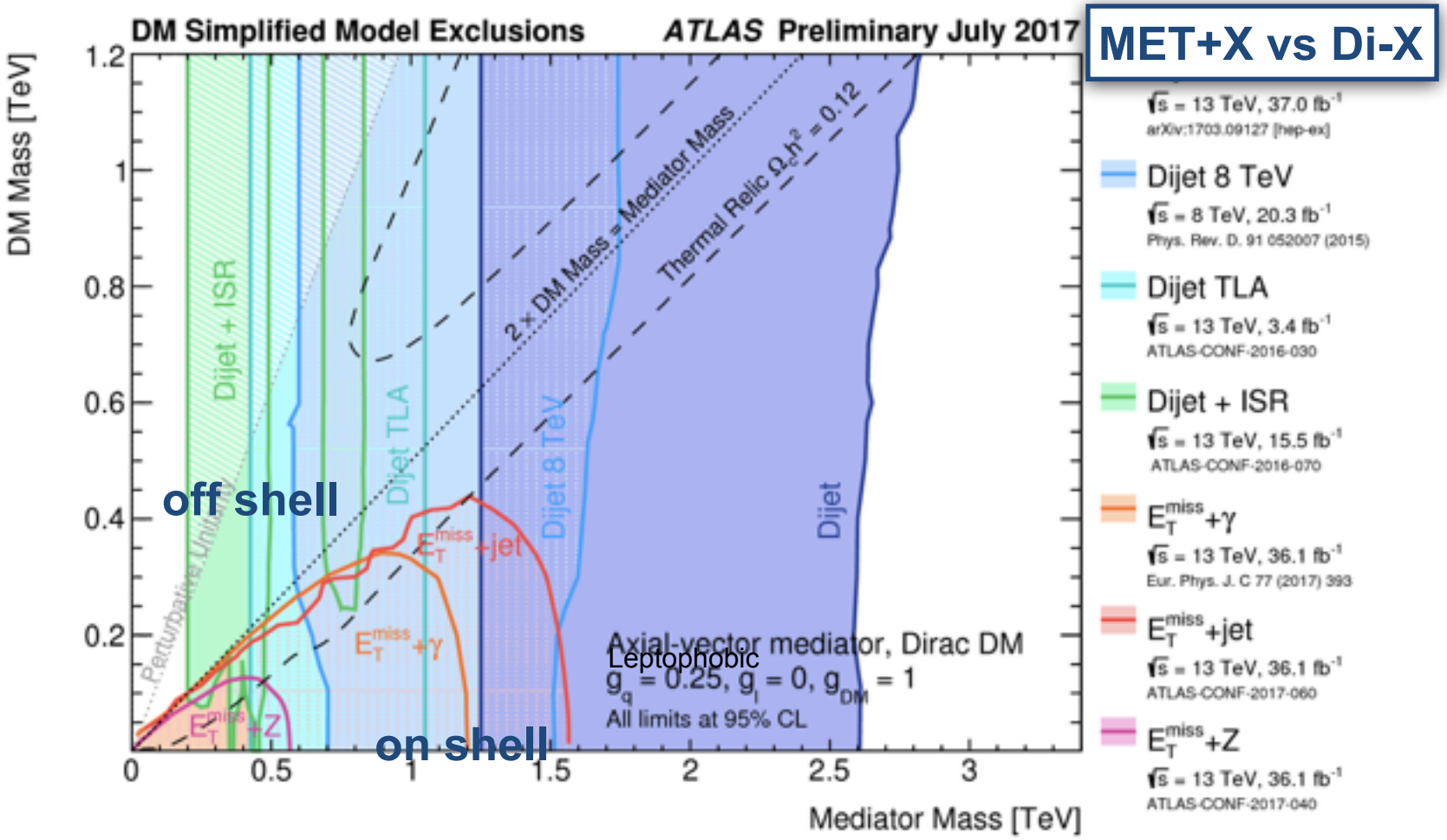




- Worse mass resolution in the μμ channel than in the ee channel.
  - Rapidly falling signal cross-section
  - Increase of the off-shell production in the low-mass tail, and the natural width of the resonance
- Selection efficiency slowly decrease at very high pole masses (subdominant)

limits on the ratio of coupling strengths between the Z' boson and the Z boson, as a function of the Z' mass in the context of minimal Z' models

Summary



- Extensive DM search program ongoing at ATLAS
- ATLAS is a telescope for new physics in multiple final states

Ref: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_DarkMatter_Summary/ATLAS_DarkMatter_Summary.png

Backup

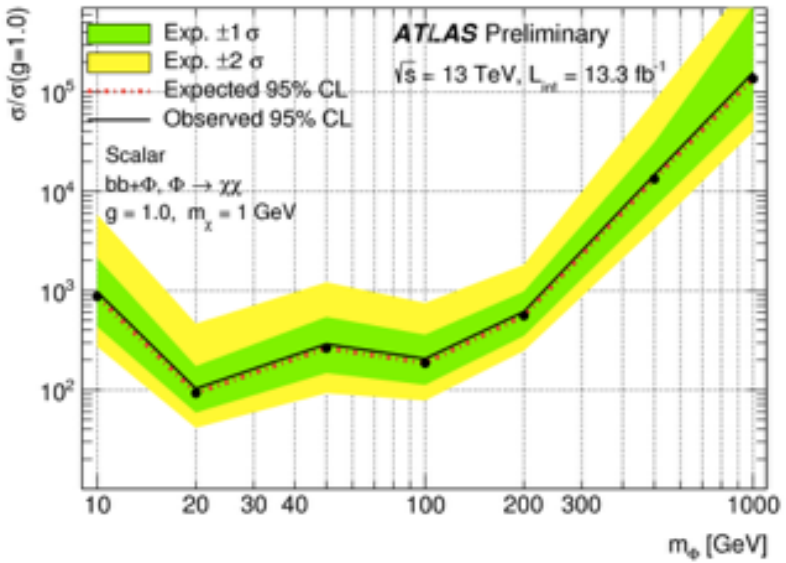
MET+bb selection criterial

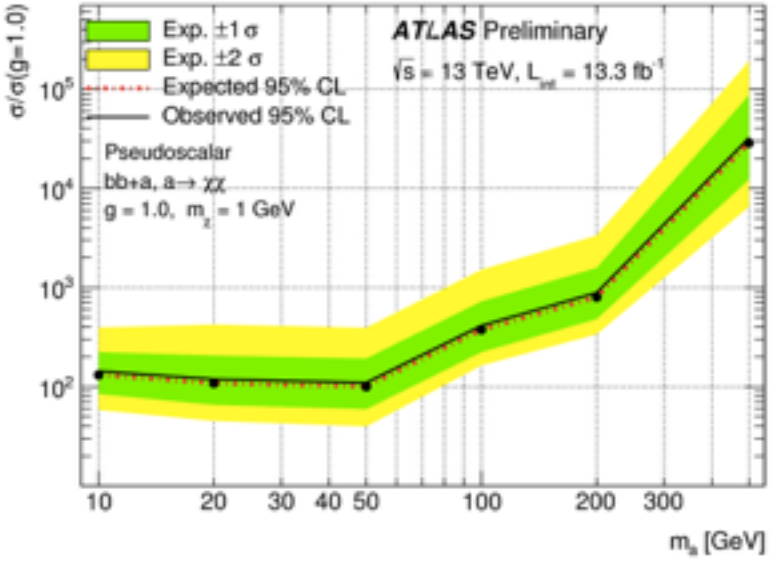
ATLAS-CONF-2016-086

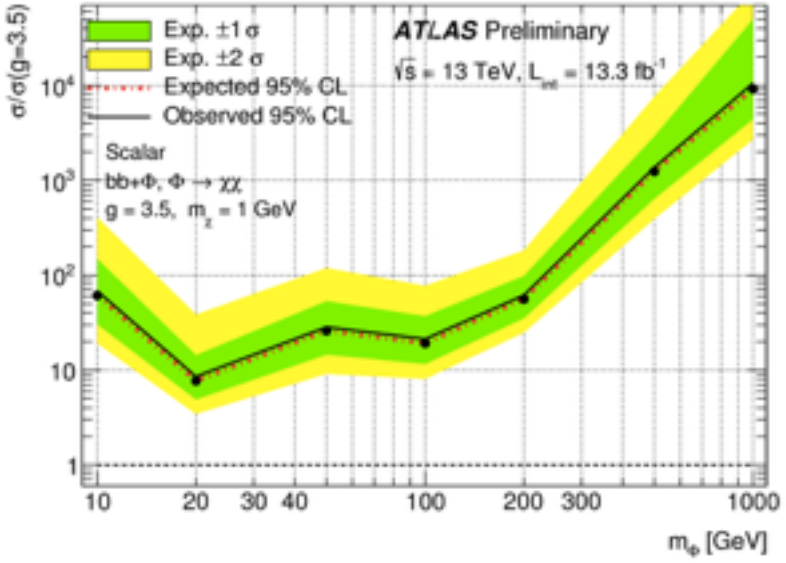
Quantity	SR	CRZ1b	VRZ2b	CRW1b	VRW1b	CRW2b	VRLR
$\mathcal{N}_{lepton}$ (baseline)	0	2 (SFOS)	2 (SFOS)	1	1	1	0
$\mathcal{N}_{lepton}$ (high-purity)	0	2 (SFOS)	2 (SFOS)	1	1	1	0
$\Delta\phi^{j}_{\min}$	> 0.4	> 0.4	> 0.4	> 0.4	> 0.4	> 0.4	> 0.4
$\mathcal{N}_{jets}$	$2-3$	$2-3$	$2-3$	$2-3$	$2-3$	$2-3$	$2-3$
$\mathcal{N}_{bjets}$	$= 2$	$= 1$	$= 2$	$= 1$	$= 1$	$= 2$	$= 2$
jet 1 p_{T} [GeV]	> 100	> 100	> 85	> 100	> 100	> 100	> 100
jet 2 p_{T} [GeV]	> 20	> 20	> 20	> 30	> 30	> 20	> 20
jet 3 p_{T} [GeV]	< 60	< 60	< 60	< 60	< 60	< 60	< 60
$p_{\mathrm{T}}^{\text{b-jet1}}$ [GeV]	> 50	> 50	> 50	> 50	> 50	> 50	> 50
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 150	< 100	< 80	> 130	> 150	> 120	> 150
$E_{\mathrm{T}}^{\mathrm{miss,cor}}$ [GeV]	-	> 120	> 100	-	-	-	-
ΔR_{min}	> 2.8	> 2.8	> 2.8	> 2.5	> 2.8	> 2.8	< 2.5
$\Delta\eta(b_1, b_2)$	> 0.5	-	-	-	> 0.5	-	> 0.5
$Imb(b_1, b_2)$	> 0.5	-	-	-	-	-	> 0.5
m_{T}^{lep}	-	-	-	$[30, 100]$	$[30, 100]$	> 30	-
$m_{\ell\ell}$	-	$[75, 105]$	$[80, 100]$	-	-	-	-
lepton 1 p_{T} [GeV]	-	> 30	> 30	> 30	> 30	> 30	-
lepton 2 p_{T} [GeV]	-	> 25	> 25	-	-	-	-
$\Delta\phi(b_1, b_2)$	> 2.2	> 2.2	-	$[1, 2.2]$	> 2.2	> 2.2	> 2.2

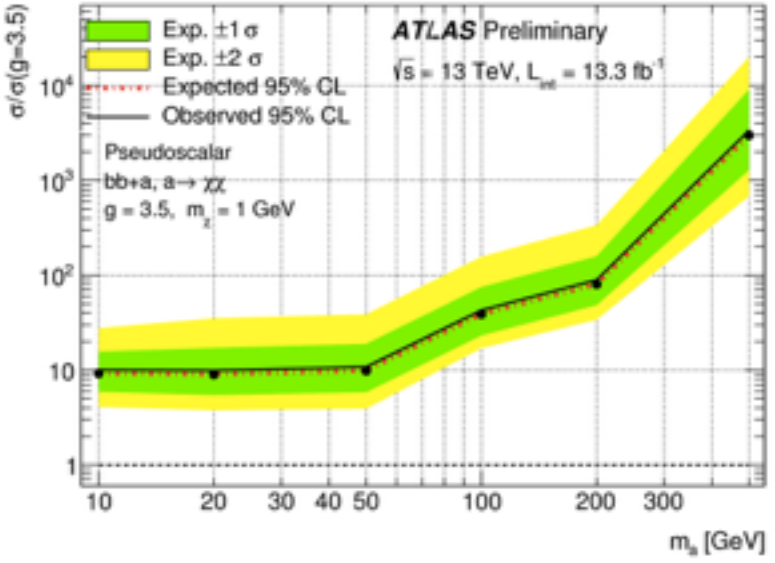
MET+bb limits

ATLAS-CONF-2016-086









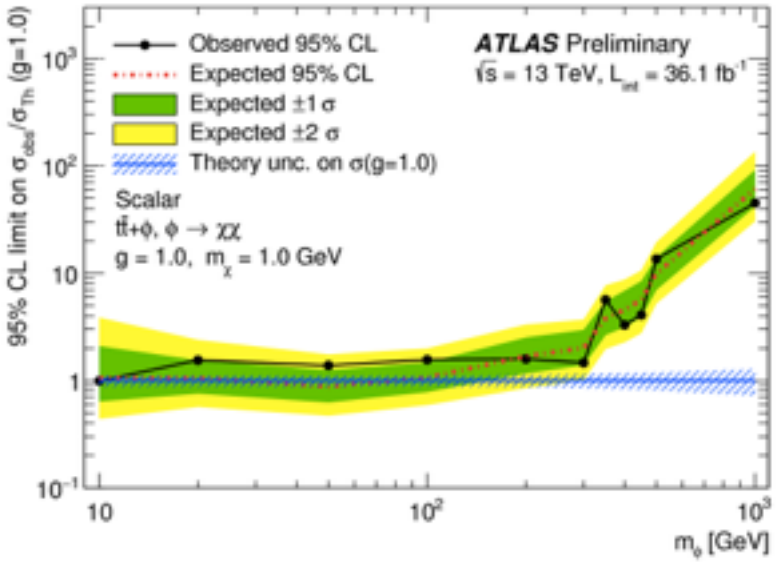
MET+tt signal selection criterial

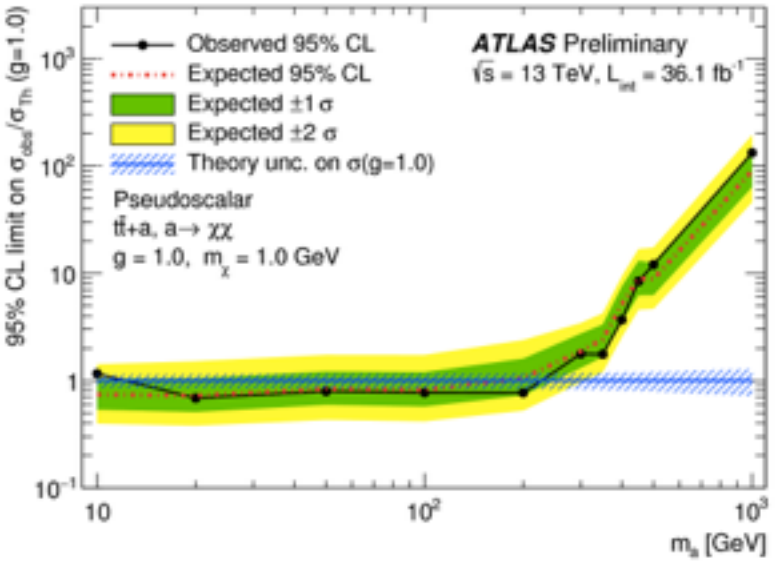
ATLAS-CONF-2017-037

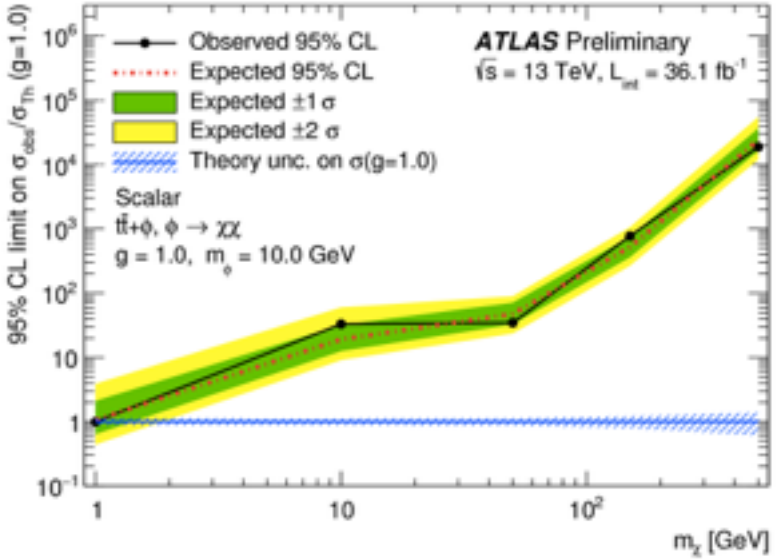
Signal region	DM_low_loose	DM_low	DM_high
Preselection		high-$E_{\mathrm{T}}^{\mathrm{miss}}$ preselection	
Number of (jets, b-tags)	$(\geq 4, \geq 1)$	$(\geq 4, \geq 1)$	$(\geq 4, \geq 1)$
Jet p_{T} [GeV]	$> (60,\ 60,\ 40,\ 25)$	$> (120,\ 85,\ 65,\ 25)$	$> (125,\ 75,\ 65,\ 25)$
b-tagged jet p_{T} [GeV]	–	> 60	–
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 300	> 320	> 380
m_{T} [GeV]	> 120	> 170	> 225
$H_{\mathrm{T,sig}}^{\mathrm{miss}}$	> 14	> 14	–
am_{T2} [GeV]	> 140	> 160	> 190
$m_{\mathrm{top}}^{\mathrm{reclustered}}$ [GeV]	–	> 130	> 130
$\Delta\phi(\vec{p}_{\mathrm{T}}^{\mathrm{miss}}, \ell)$	> 0.8	> 1.2	> 1.2
$\lvert\Delta\phi(\mathrm{jet}_i, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert$	> 1.4	> 1.0	> 1.0
$\lvert\Delta\phi(j_{1,2}, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})\rvert$		> 0.4	
m_{T2}^{τ} based τ-veto [GeV]		> 80	
exclusion technique	cut-and-count	cut-and-count	cut-and-count

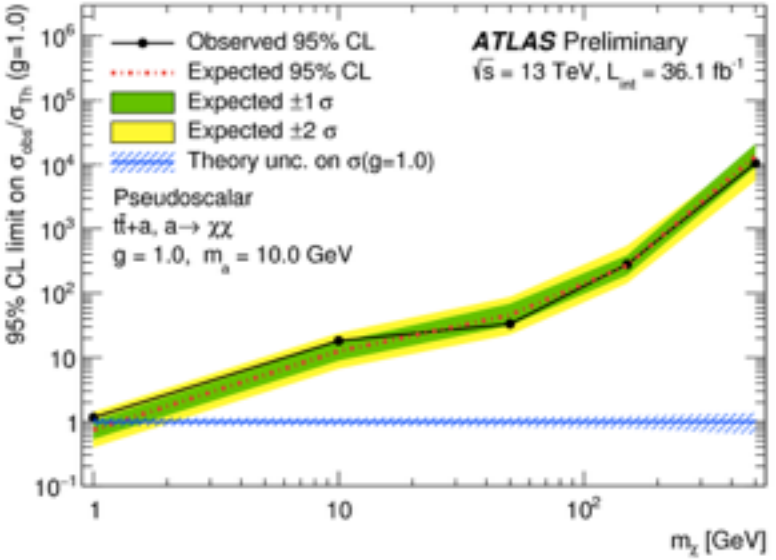
MET+tt limits

ATLAS-CONF-2017-037





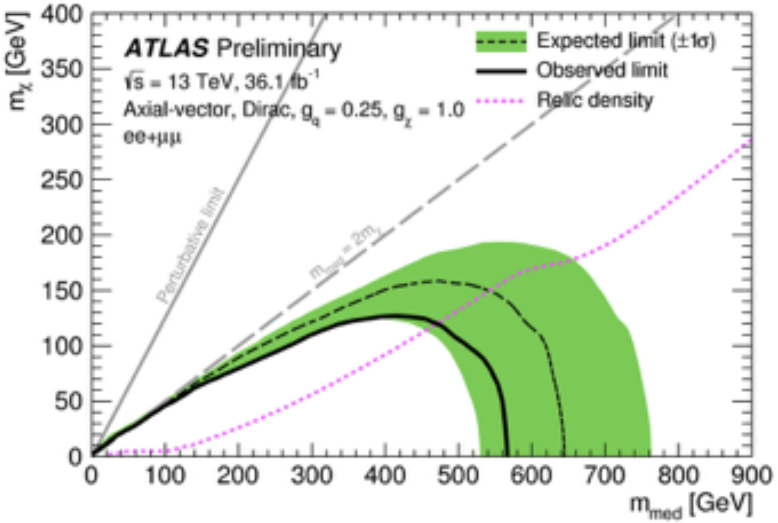


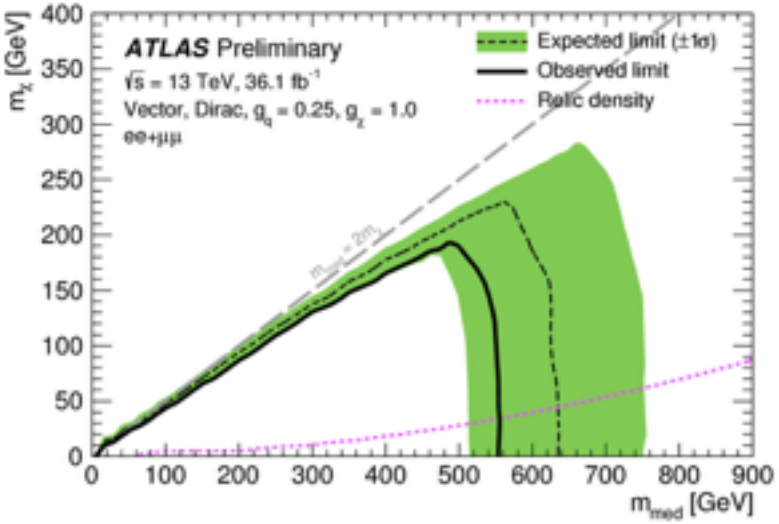


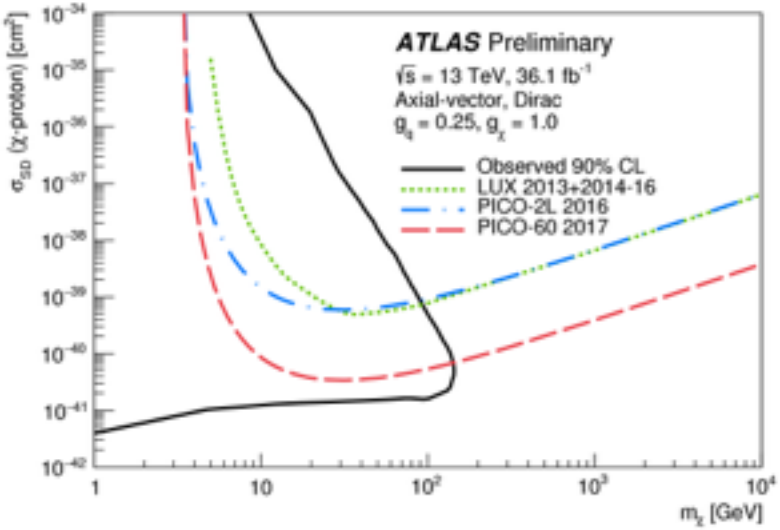
MET+Z(ll) limits

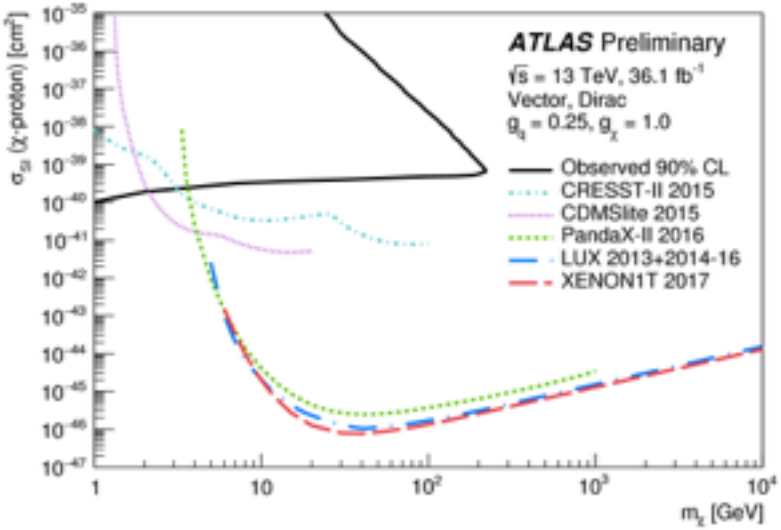
ATLAS-CONF-2017-040

m_{Med} excluded at 560 GeV for light DM, m_{DM} excluded at 130 GeV for m_{Med} = 400 GeV





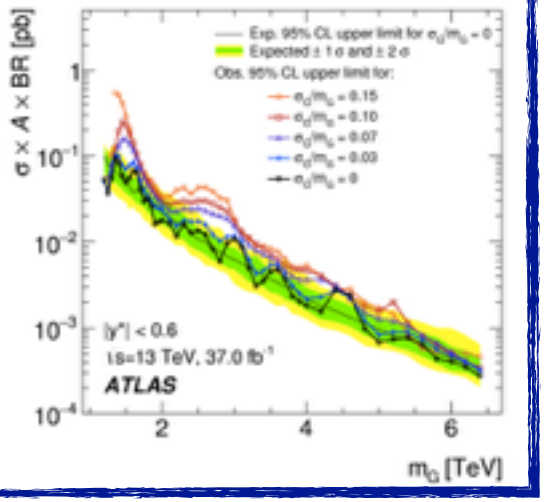




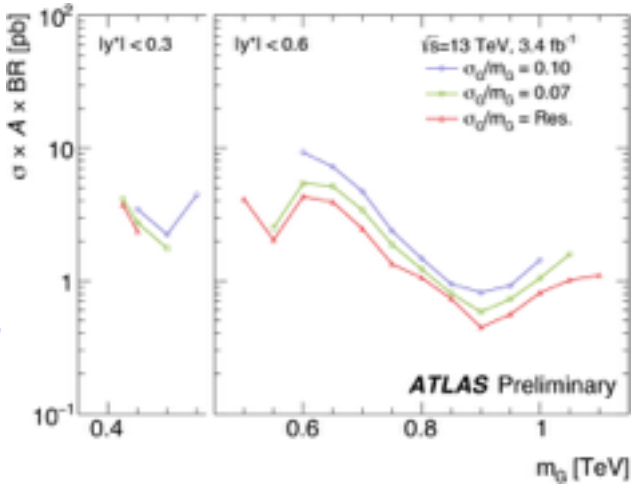
Generaical Gaussian limits

EXOT-2016-21
ATLAS-CONF-2016-030
ATLAS-CONF-2016-070

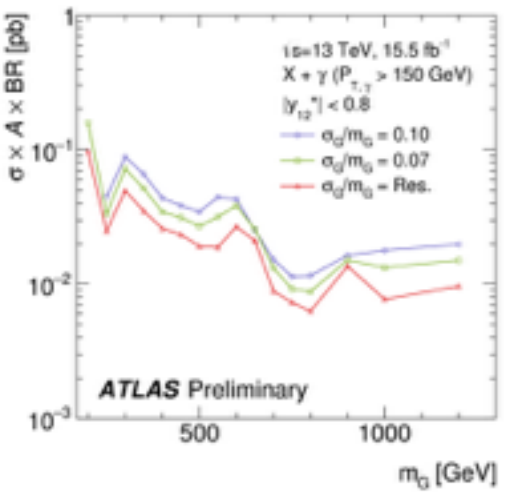
Di-jet resonance search

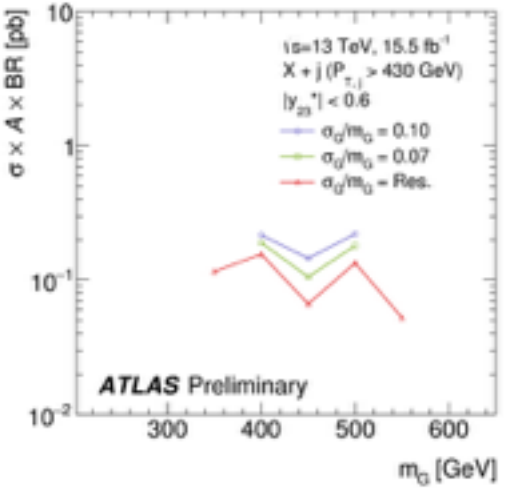


TLA



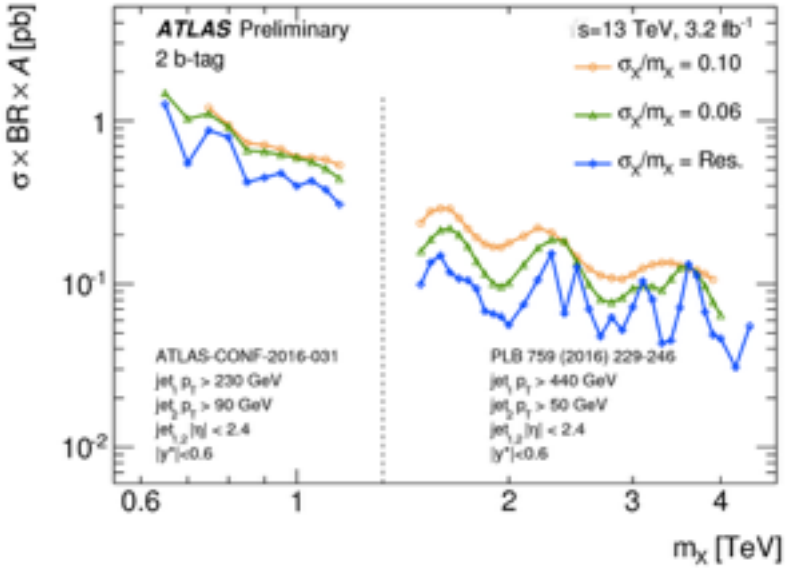
Di-jet+ISR





Di-b-jet search

Ref: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_Dibjet_GeneralLimit_Summary/ATLAS_Dibjet_GeneralLimit_Summary.png

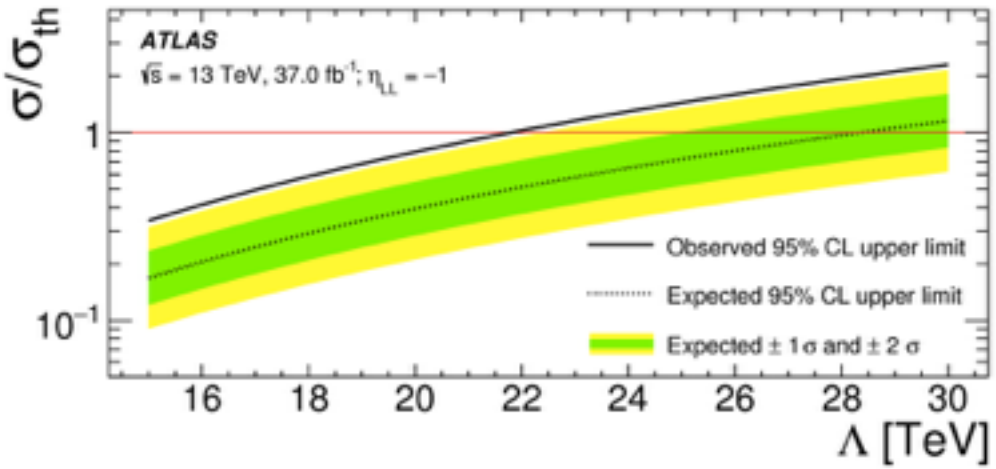


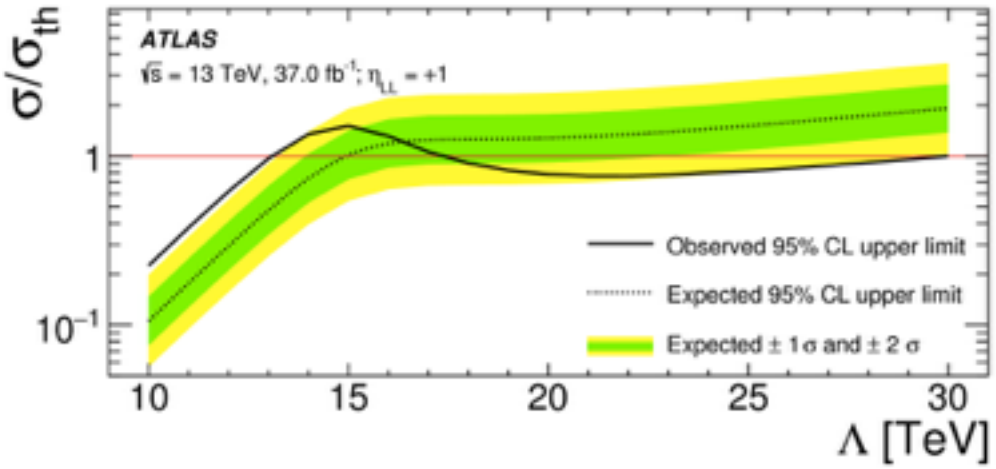
Argonne NATIONAL LABORATORY

EXOT-2016-21
EXOT-2016-05

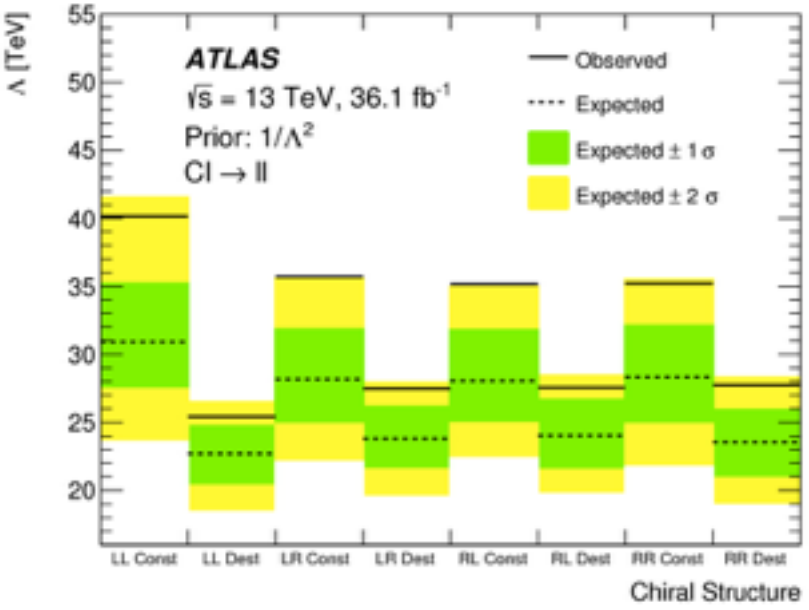
contact interaction limits

Dijet angular search





dilepton search



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: July 2017

ATLAS Preliminary

$\int \mathcal{L}\, dt = (3.2 - 37.0)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\, dt$[fb^{-1}]	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.75 TeV	$n = 2$	ATLAS-CONF-2017-060
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	CERN-EP-2017-132
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09217
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\bar{M}_{Pl} = 0.1$	CERN-EP-2017-132
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	36.1	G_{KK} mass 1.75 TeV	$k/\bar{M}_{Pl} = 1.0$	ATLAS-CONF-2017-051
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	KK mass 1.6 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	ATLAS-CONF-2016-104
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	36.1	Z' mass 4.5 TeV		ATLAS-CONF-2017-027
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.4 TeV		ATLAS-CONF-2017-050
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	Leptophobic $Z' \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	3.2	Z' mass 2.0 TeV	$\Gamma/m = 3\%$	ATLAS-CONF-2016-014
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	36.1	W' mass 5.1 TeV		1706.04786
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	36.7	V' mass 3.5 TeV	$g_V = 3$	CERN-EP-2017-147
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	ATLAS-CONF-2017-055
	LRSM $W_R' \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W_R' \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09217
	CI $\ell\ell qq$	2 e, μ	–	–	36.1	Λ 40.1 TeV	η_{LL}^-	ATLAS-CONF-2017-027
	CI $uutt$	2(SS)/≥ 3 e, μ	≥ 1 b, ≥ 1 j	Yes	20.3	Λ 4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.5 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 400$ GeV	ATLAS-CONF-2017-060
	Vector mediator (Dirac DM)	0 e, μ, 1 γ	≤ 1 j	Yes	36.1	m_{med} 1.2 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 480$ GeV	1704.03848
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	0 or 1 e, μ	≥ 2 b, ≥ 3 j	Yes	13.2	T mass 1.2 TeV	$\mathcal{B}(T \to Ht) = 1$	ATLAS-CONF-2016-104
	VLQ $TT \to Zt + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	36.1	T mass 1.16 TeV	$\mathcal{B}(T \to Zt) = 1$	1705.10751
	VLQ $TT \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	T mass 1.35 TeV	$\mathcal{B}(T \to Wb) = 1$	CERN-EP-2017-094
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	B mass 700 GeV	$\mathcal{B}(B \to Hb) = 1$	1505.04306
	VLQ $BB \to Zb + X$	2/≥ 3 e, μ	≥ 2/≥ 1 b	–	20.3	B mass 790 GeV	$\mathcal{B}(B \to Zb) = 1$	1409.5500
	VLQ $BB \to Wt + X$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	B mass 1.25 TeV	$\mathcal{B}(B \to Wt) = 1$	CERN-EP-2017-094
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	37.0	q^* mass 6.0 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1703.09127
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	CERN-EP-2017-148
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	13.3	b^* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	b^* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LRSM Majorana ν	2 e, μ	2 j	–	20.3	N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no-mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	ATLAS-CONF-2017-053
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	spin-1 invisible particle mass 657 GeV	$m_{non-res} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1509.08059

$\sqrt{s} = 8$ TeV $\sqrt{s} = 13$ TeV

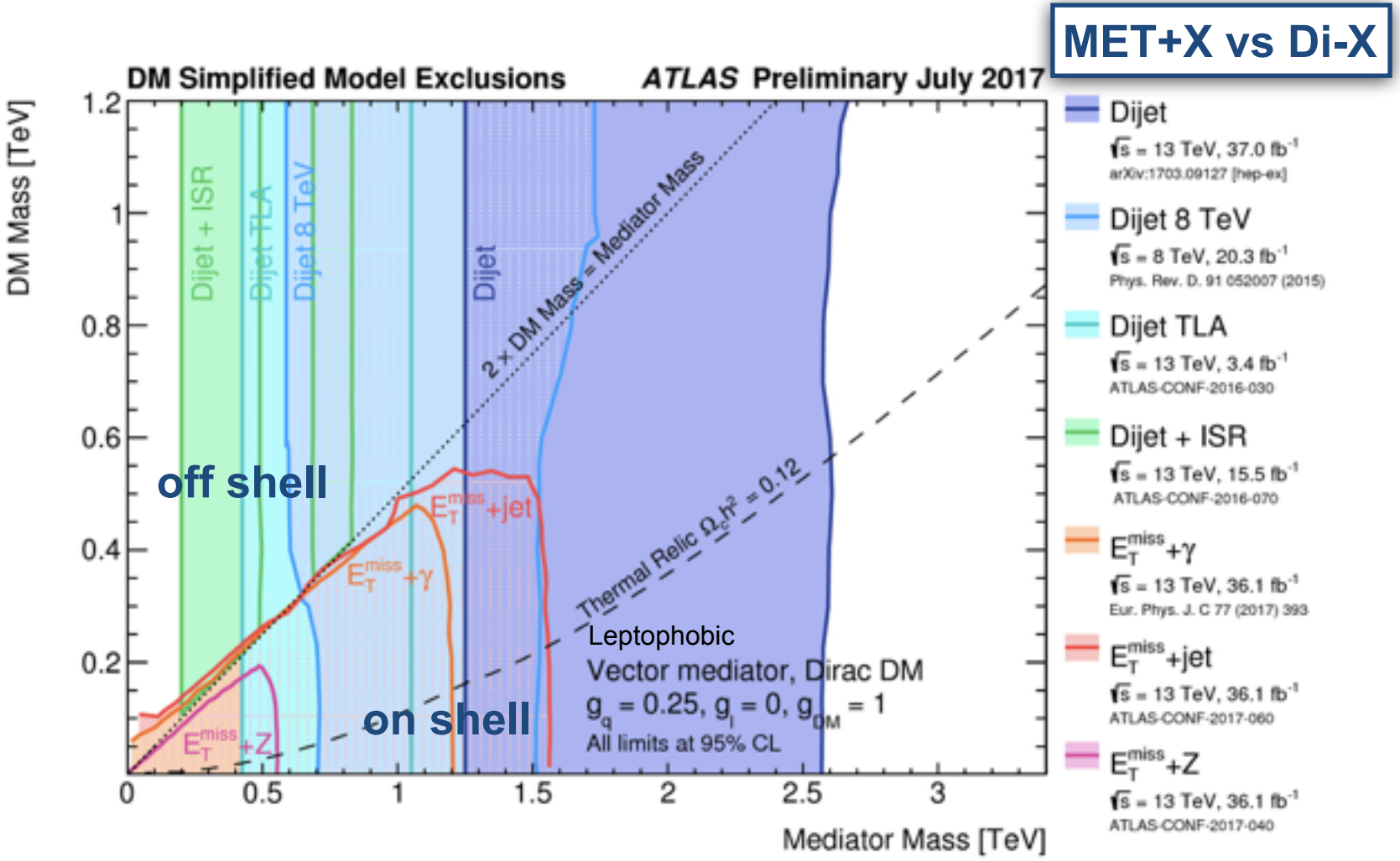
10^{-1} 1 10 **Mass scale [TeV]**

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

†Small-radius (large-radius) jets are denoted by the letter j (J).

Ref: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_Exotics_Summary/ATLAS_Exotics_Summary.png

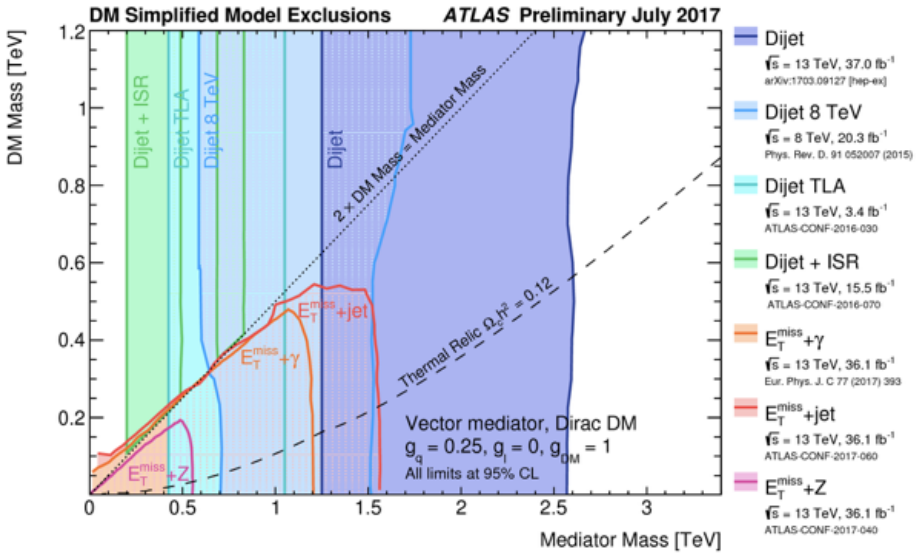
ATLAS limit on vector mediator



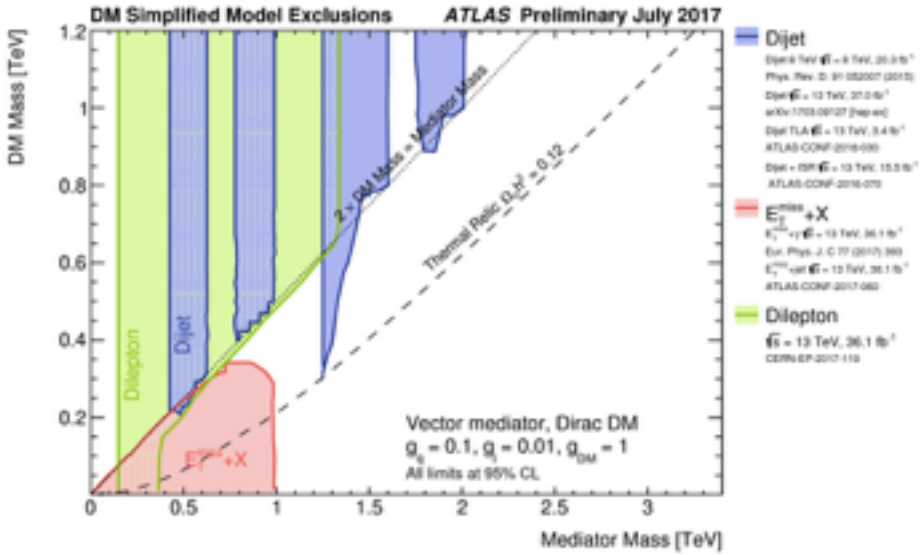
Ref: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_DarkMatter_Summary/ATLAS_DarkMatter_Summary.png

ATLAS limit on vector mediator

g_q=0.25, q_l=0,q_{DM}=1



g_q=0.1, q_l=0.01,q_{DM}=1



Ref: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/EXOTICS/ATLAS_DarkMatter_Summary/ATLAS_DarkMatter_Summary.png

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