The ATLAS Monojet Search for Dark Matter

Steven Schramm,

for the ATLAS Collaboration

Dark Matter at the LHC Workshop

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Outline

1. Introduction
2. Background measurements
3. Results
4. Summary

$\sqrt{s} = 8\,\mathrm{TeV}$ note with $10\mathrm{fb}^{-1}$ (HCP2012): ATLAS-CONF-2012-147

$\sqrt{s} = 7\,\mathrm{TeV}$ paper with full 2011 dataset (JHEP): EXOT-2011-20

Unless otherwise mentioned, results discussed will be for $8\,\mathrm{TeV}$

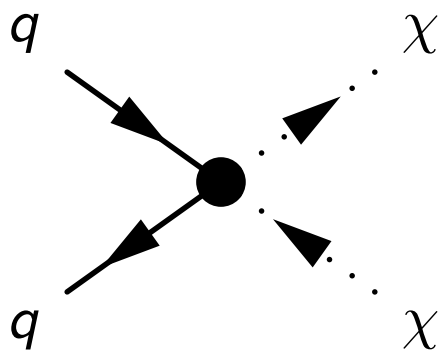
Dark Matter at the LHC

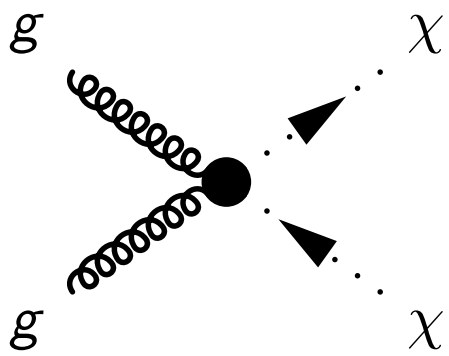
- Dark Matter (DM) has no known interactions beyond gravity
- What if it couples to Standard Model (SM) particles very weakly?
  - This could be through the weak force or a new phenomenon
  - If so, could be a type of Weakly Interacting Massive Particle (WIMP)
- If DM is a WIMP, it could be produced in collisions at the LHC
- Such WIMPs would escape the detector unobserved
  - However, momentum is still conserved - vectorially sum visible particles
  - Momentum imbalances countered by "missing transverse energy" $\mathrm{E_T^{miss}}$
- Large $\mathrm{E_T^{miss}}$ indicates presence of non-interacting particles, like DM
  - Note that $\mathrm{E_T^{miss}}$ must be calculated from other observables
  - Events which produce only neutrinos will not be seen by ATLAS

Effective Field Theories of DM

To minimize model-dependence, use an Effective Field Theory (EFT)

- Two input SM particles, namely light quarks (u,d,s,c) or gluons
- Two pair-produced output DM particles
- Effective operator connecting SM inputs to DM outputs
  - Operator is a "black box" representing our ignorance

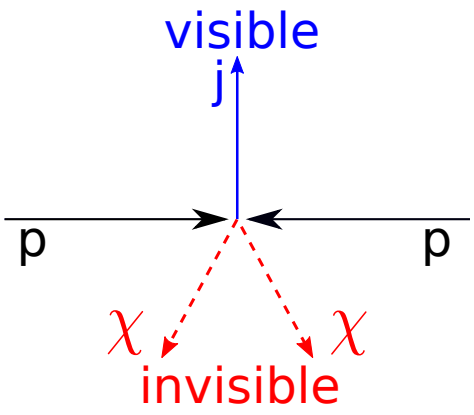




- Diagrams have only WIMPs in the final state, and thus are invisible
  - However, the input quarks/gluons can radiate jets (or other particles)
  - This gives us the jet plus $\mathrm{E_T^{miss}}$ topology

Monojet topology

- The monojet topology consists of one jet and large $\mathrm{E_T^{miss}}$
  - This is exactly the topology just mentioned for DM production
  - We expand this to allow for either one or two jets balancing the $\mathrm{E_T^{miss}}$

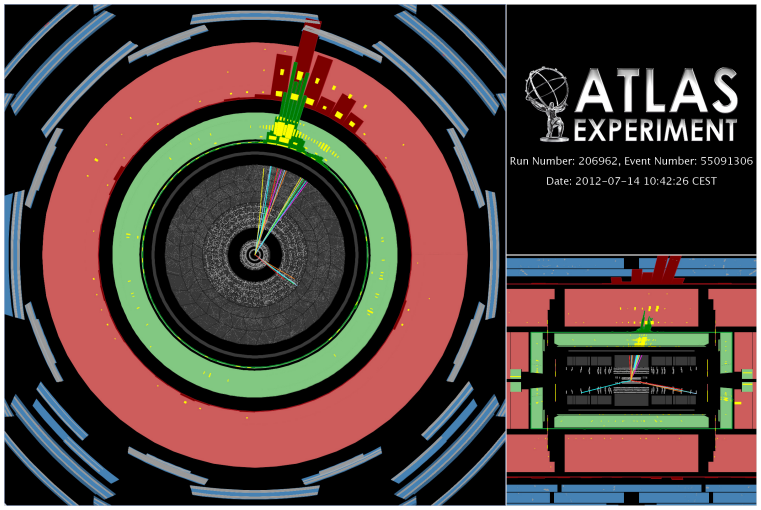


Before collision:

- $\vec{p}_{\mathrm{T}}^{\,\mathrm{p}_1} = 0$
- $\vec{p}_{\mathrm{T}}^{\,\mathrm{p}_2} = 0$

After collision:

- $\vec{p}_{\mathrm{T}}^{\,\mathrm{jet}} = -\vec{\alpha}$
- $\vec{p}_{\mathrm{T}}^{\,\chi_1} + \vec{p}_{\mathrm{T}}^{\,\chi_2} = \vec{\alpha}$



$p_{\mathrm{T}}^{\mathrm{jet1}} = 852\,\mathrm{GeV}$, $\mathrm{E_T^{miss}} = 863\,\mathrm{GeV}$

Event selection and region cuts

Event selection:

- One or two jets satisfying $p_{\mathrm{T}}^{\mathrm{jet}} \geq 30\,\mathrm{GeV}$ and $|\eta^{\mathrm{jet}}| \leq 4.5$
- Central lead jet: $|\eta^{\mathrm{jet1}}| < 2.0$
- Suppress mis-measured jets: $\left|\Delta\phi\left(\mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}, \mathrm{jet2}\right)\right| \geq 0.5$
- No electrons or muons
- Passes the relevant region cut

Signal and control region cuts:

R1: $(p_{\mathrm{T}}^{\mathrm{jet1}}, \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}) \geq 120\,\mathrm{GeV}$

R2: $(p_{\mathrm{T}}^{\mathrm{jet1}}, \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}) \geq 220\,\mathrm{GeV}$

R3: $(p_{\mathrm{T}}^{\mathrm{jet1}}, \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}) \geq 350\,\mathrm{GeV}$

R4: $(p_{\mathrm{T}}^{\mathrm{jet1}}, \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}}) \geq 500\,\mathrm{GeV}$

SR = Signal Region

CR = Control Region

Backgrounds

Data-driven backgrounds

Background	**Reason/source**
$Z \to \nu\nu$+jet(s)	Irreducible, single largest background
$W \to \ell\nu$+jet(s)	Missed the lepton or hadronic τ decay
$Z \to \ell\ell$+jet(s)	Missed both leptons or hadronic τ decays
Multi-jet (QCD)	Missed/misreconstructed jets $\to \mathrm{E_T^{miss}}$
Non-collision backgrounds	Beam halo and cosmic muons

Small backgrounds taken from MC

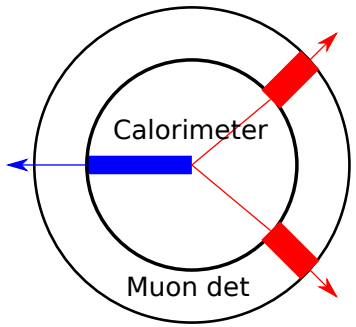
Diboson (WW, ZZ, WZ)

Single top and $t\bar{t}$

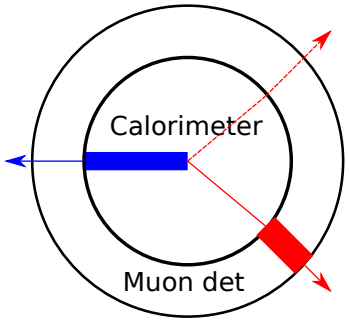
Estimating the $Z \to \nu\nu$ background

- Muons are minimum ionizing particles
  - They leave almost no energy in the calorimeter
  - Instead, they are measured by the muon spectrometer
- Neutrinos leave no energy in the calorimeter or spectrometer
- Consider a calorimeter-based $\mathrm{E_T^{miss}}$: muons and neutrinos are similar
- Identify $Z \to \mu\mu$ and $W \to \mu\nu$ events in data with the spectrometer
  - Use MC ratios to "transfer" to $Z \to \nu\nu$ estimate in data

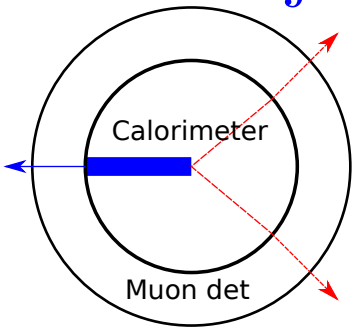
$Z \to \mu\mu + \mathrm{jet}$



$W \to \mu\nu + \mathrm{jet}$



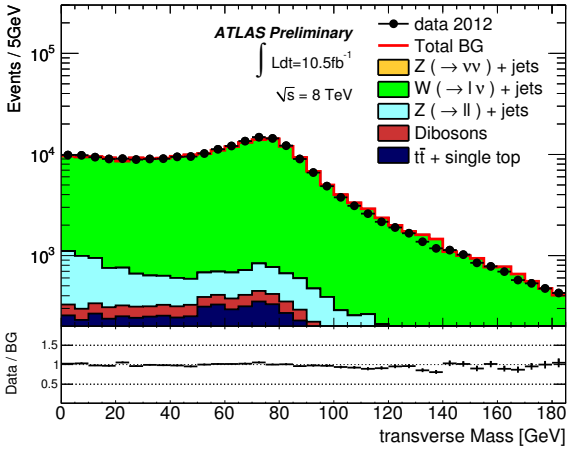
$Z \to \nu\nu + \mathrm{jet}$

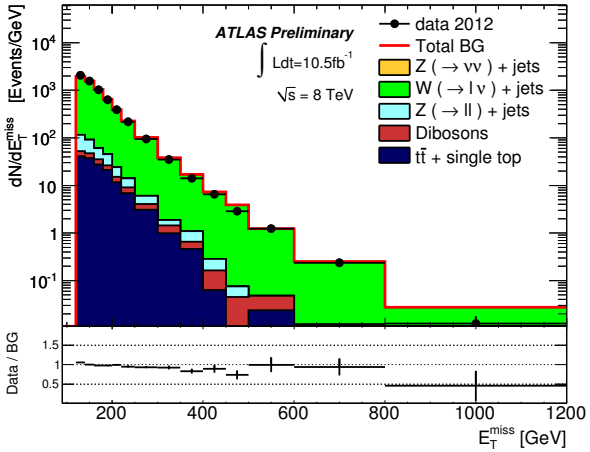


The $Z \to \mu\mu$ and $W \to \mu\nu$ control regions

$W \to \mu\nu + \mathrm{jet(s)}$:

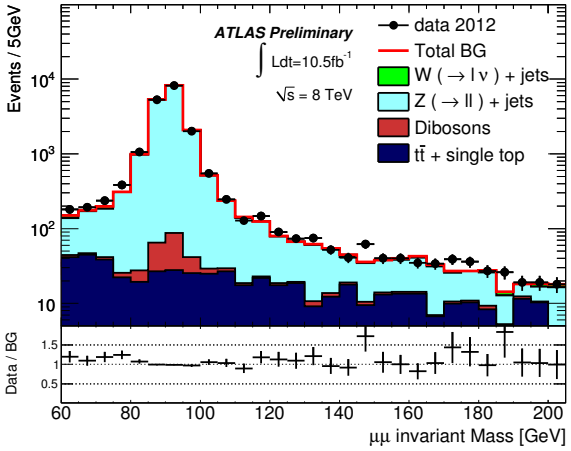
- One good muon
- $40\,\mathrm{GeV} \leq m_{\mathrm{T}} \leq 100\,\mathrm{GeV}$
- Jet, $\mathrm{E_T^{miss}}$ cuts as in SRs

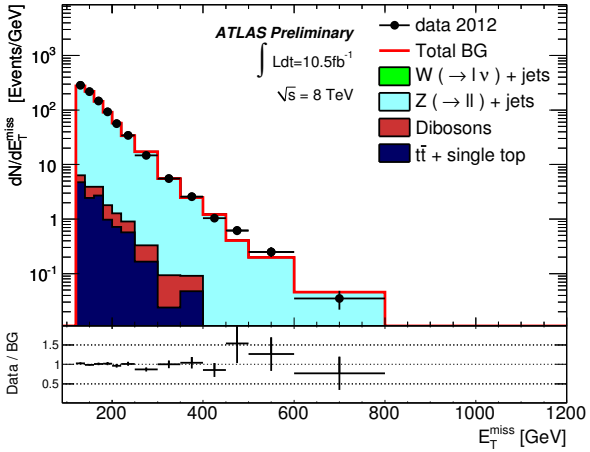




$Z \to \mu\mu + \mathrm{jet(s)}$:

- Two opposite sign muons
- $76\,\mathrm{GeV} \leq m_{\mu\mu} \leq 116\,\mathrm{GeV}$
- Jet, $\mathrm{E_T^{miss}}$ cuts as in SRs





Data-driven background estimation

Use data-driven estimate to significantly reduce systematic uncertainties:

1. Select data events in a given CR, subtract (small) QCD background

   $Z \to \mu\mu$ and $W \to \mu\nu$ are two such control regions

2. Remove EW backgrounds from a given CR and process:

   $(1 - f_{\mathrm{EW}}^{\mathrm{bg}}) = 1 - N_{\mathrm{MC}}^{\mathrm{bg}}/N_{\mathrm{MC}}^{\mathrm{process+bg}} = N_{\mathrm{MC}}^{\mathrm{process}}/N_{\mathrm{MC}}^{\mathrm{process+bg}}$

3. "Transfer" from the lepton CR to the SR: account for any differences such as lepton reconstruction efficiencies, triggers, and acceptance

$$N_{\mathrm{estimate}}^{\mathrm{SR}} = \left(N_{\mathrm{data}}^{\mathrm{CR}} - N_{\mathrm{est,QCD}}^{\mathrm{CR}}\right)\left(1 - f_{\mathrm{EW}}^{\mathrm{bg}}\right)\left(N_{\mathrm{MC}}^{\mathrm{SR}}/N_{\mathrm{MC}}^{\mathrm{CR}}\right)$$

Unfortunately, low MC statistics in SR3 and SR4 for 8 TeV conf note

Background uncertainties

Systematic uncertainties were well controlled:

Systematic source	**Uncertainty**
Jet and $\mathrm{E_T^{miss}}$ energy scale and resolution	2-4% on transfer factors
Lepton identification efficiencies	1-3% on transfer factors
Non-electroweak backgrounds	$<$ 1% on total background
Showering and hadronization modelling	3% on total background

Statistical uncertainties were problematic:

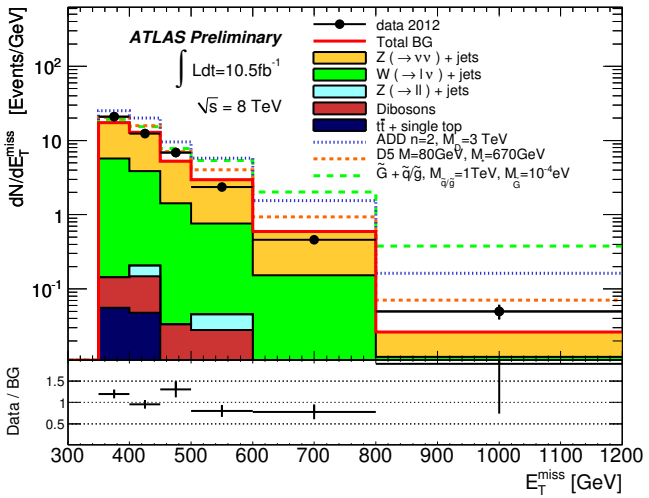
- The background MC samples had insufficient statistics in SR3/SR4

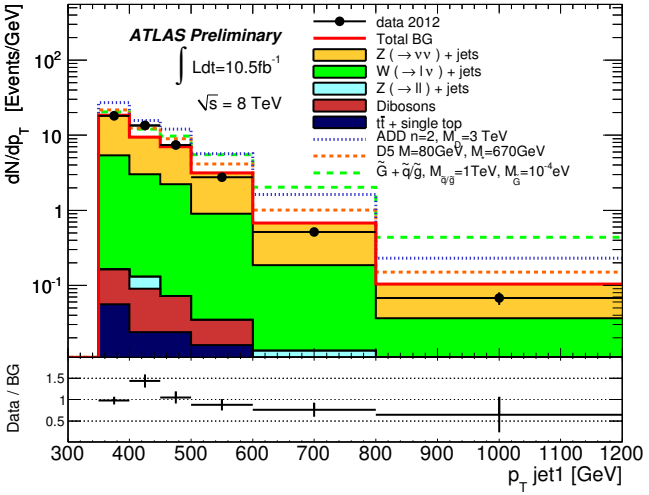
  SR3: 5.5% SR4: 15.8%

- As such, improvements are minimal compared to 7 TeV paper

Results in SR3

- SR3 ($p_{\mathrm{T}}^{\mathrm{jet1}}, \mathrm{E}_{\mathrm{T}}^{\mathrm{miss}} \geq 350\,\mathrm{GeV}$) chosen for DM model limits due to stats
- Orange dashed line is the signal strength for a vector coupling between quarks and fermionic DM
- Also shown: ADD extra dimensions and gravitino production interpretations





Types of DM considered

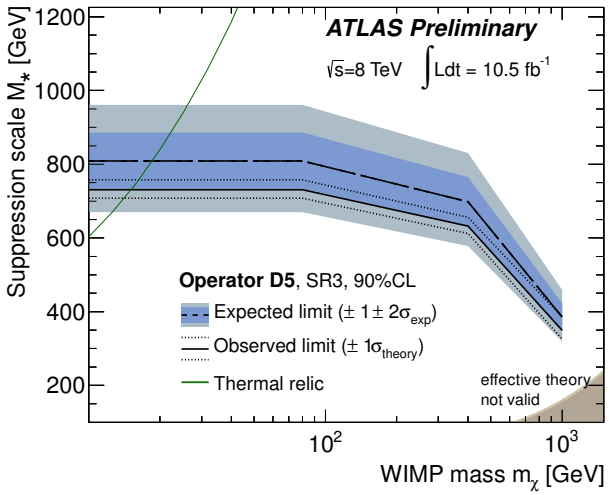
Couplings between SM particles and fermionic DM were considered:

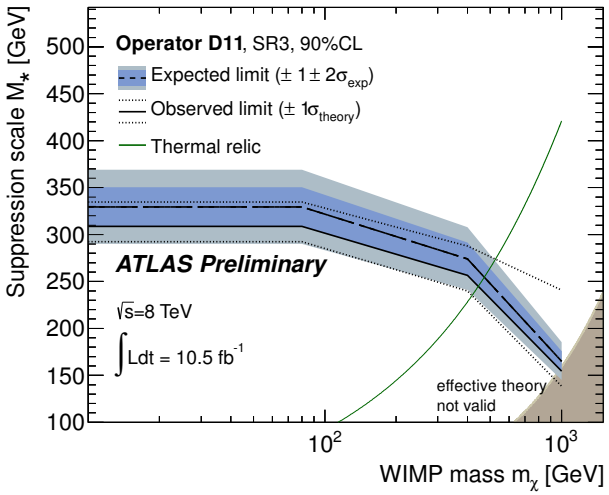
Operator	Coupling type	7 TeV paper	8 TeV note
D1	Scalar quark	Yes	No
D5	Vector quark	Yes	Yes
D8	Axial quark	Yes	Yes
D9	Tensor quark	Yes	No
D11	Gluon	Yes	Yes

- D1, D5, and D11 provide spin-independent limits on DM
- D8, D9 provide spin-dependent limits on DM
- EFT operators come from this paper by Tim Tait et al
- Signal sample systematics in the backup slides

Suppression scale limits

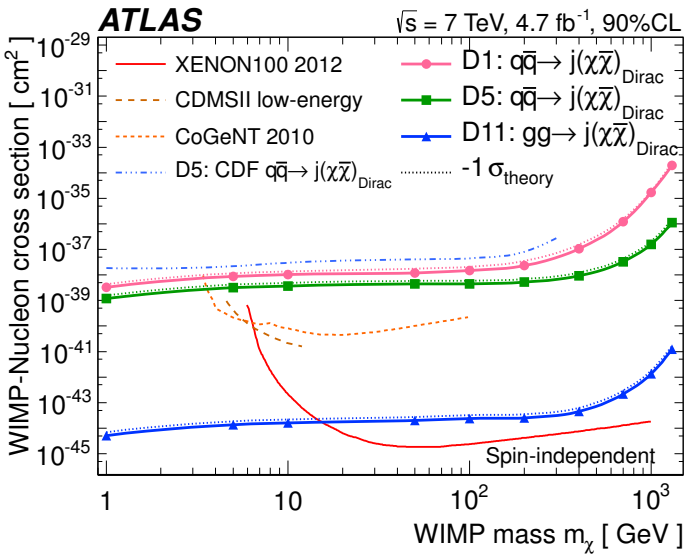
- M^*: the suppression scale of the contact interaction, $M^* = M/\sqrt{g_1 g_2}$
- Grey region is where the EFT approach is not valid
  - More thorough validity studies: talk by Johanna Gramling later today
- Values below the solid observed limit line are excluded
- Green line is the WIMP relic abundance: above the line is excluded if the WIMP is to naturally explain the observed relic density

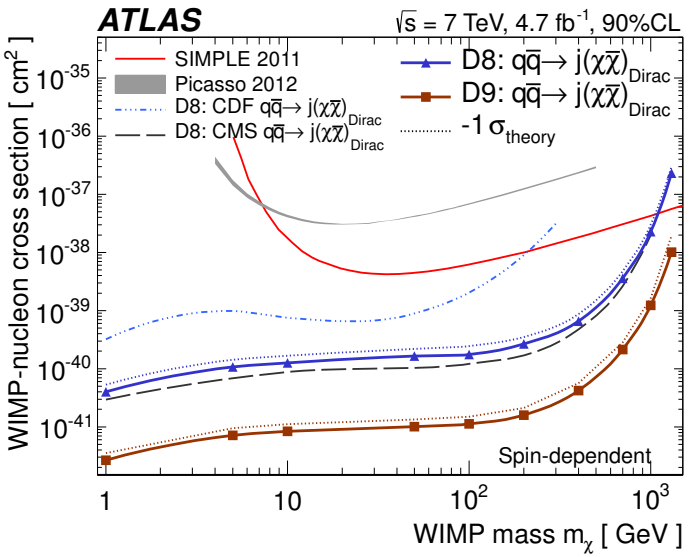




WIMP-nucleon scattering limits

- M^* lower limits are converted to cross-section upper limits
- Regions above the observed limit lines are excluded
- Comparisons are made with several direct detection experiments
  - Assumptions which go into such comparisons could use more study
- These results are from the 7 TeV paper



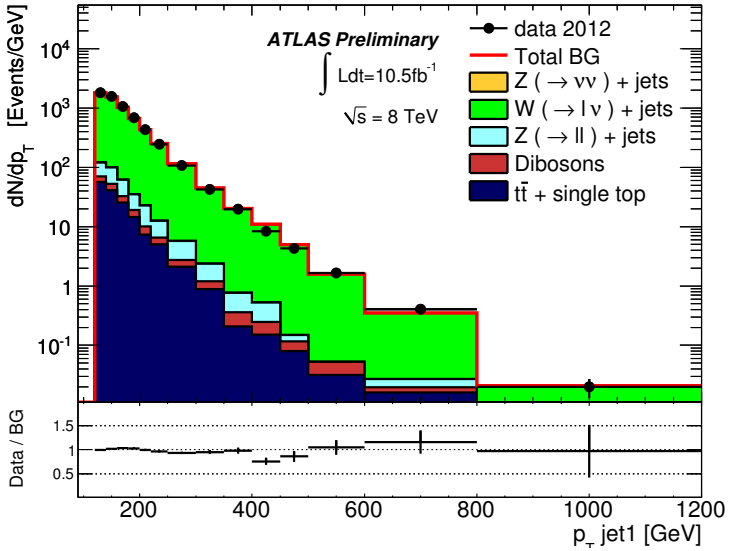


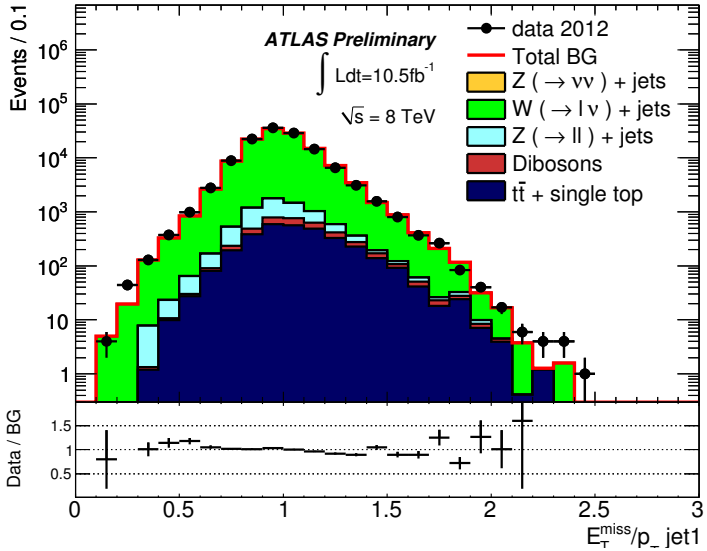
Summary

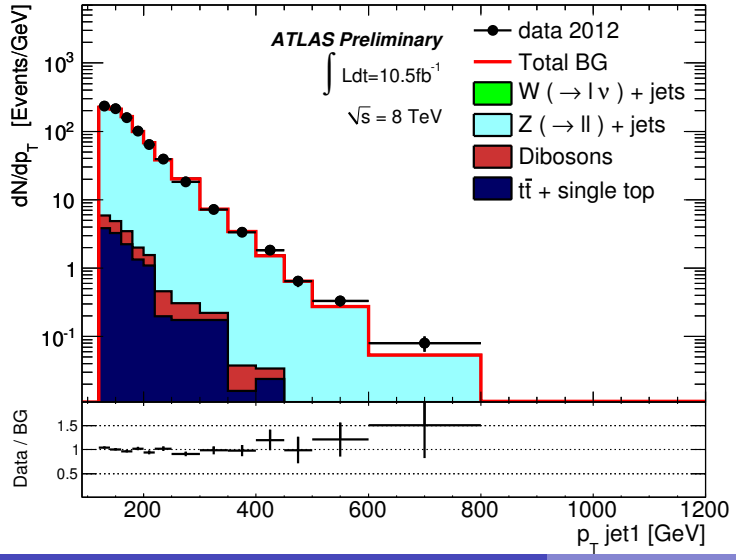
- The monojet channel has been studied by the ATLAS collaboration
  - 7 TeV paper with the full 4.7fb^{-1}: EXOT-2011-20
  - 8 TeV note with the first 10.5fb^{-1}: ATLAS-CONF-2012-147
- This signature provides a handle on the production of DM at the LHC
  - Good agreement between observed data and SM predictions
  - Limits are placed on various contact interaction operators which connect SM inputs to fermionic DM final states
- An update is currently underway with the full 8 TeV dataset of 20fb^{-1}
  - The full dataset will help to further probe the DM parameter space
  - Large improvements expected from increasing MC background statistics

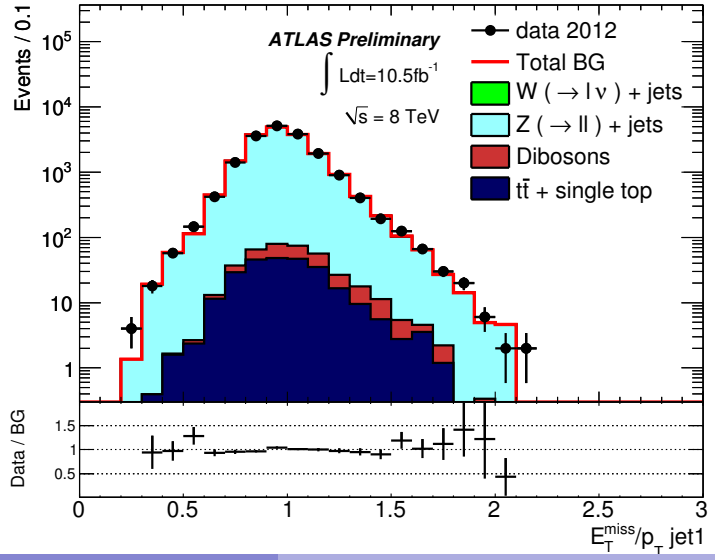
Backup Slides

More EW CR validation plots



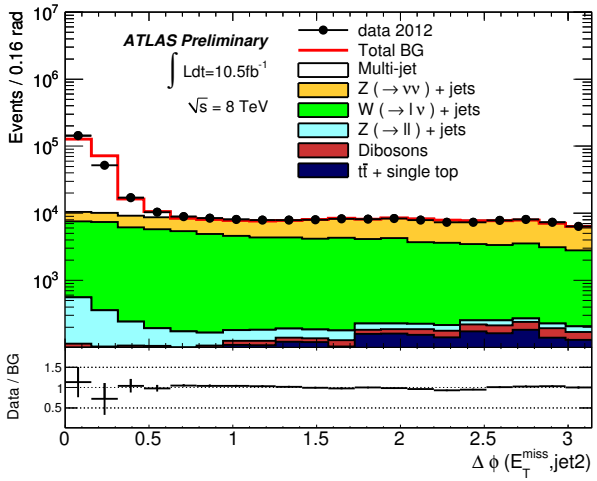


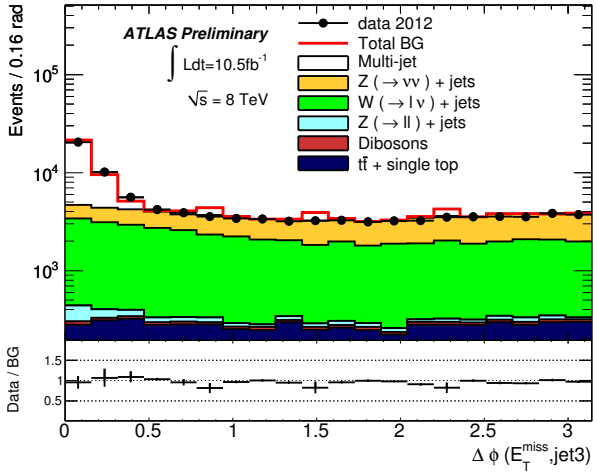




QCD data-driven estimate

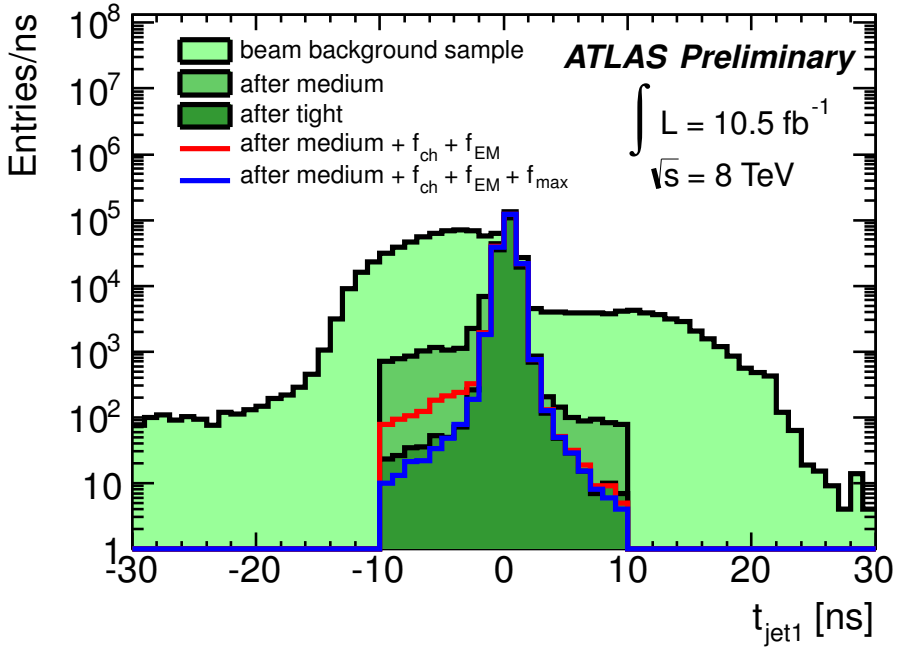
- The multijet background originates from misreconstructed jet(s) producing fake $\mathrm{E_T^{miss}}$
  - Changes $\mathrm{E_T^{miss}}$ direction (aligned with jet)
  - Inverting $\Delta\phi$ cut gives good CR of QCD enhanced events, $\left|\Delta\phi\left(\mathrm{E_T^{miss}}, \mathrm{jet2}\right)\right| < 0.5$
- Consider events with 2 or 3 jets, $p_\mathrm{T} > 30\,\mathrm{GeV}$
  - Extrapolate p_T distribution of least energetic jet down to $0\,\mathrm{GeV}$
- Systematics from subtractions of other backgrounds and alternative fitting functions
- Negligible contribution in SR3 and SR4





Non-collision backgrounds estimate

- Monojet topologies are very similar to beam backgrounds
  - Requires dedicated jet cleaning cuts to remove contamination
- Remaining NCB estimated using the leading jet timing distribution
  - $N^{\mathrm{SR}}_{\mathrm{NCB}} = N^{\mathrm{SR}}_{-10<t<-5} \times \frac{N^{\mathrm{NCB}}}{N^{\mathrm{NCB}}_{-10<t<-5}}$
- Negligible contribution in SR3 and SR4

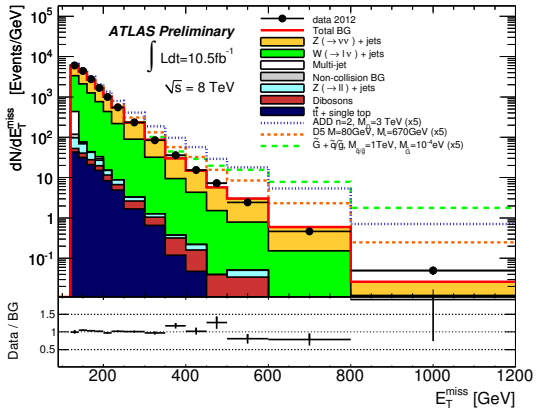


- Jet cleaning details: ATLAS-CONF-2012-020
- Additional cleaning studies done in collaboration with the NCB group

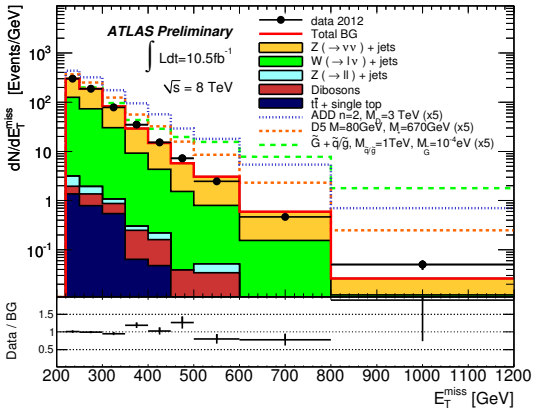
Table of results and other SRs

Background Predictions ±(stat.data)±(stat.MC) ±(syst.)				
	SR1	SR2	SR3	SR4
$Z(\rightarrow \nu\bar{\nu})$+jets	173600 ±500 ±1300 ±5500	15600 ±200 ±300 ±500	1520 ±50 ±90 ±60	270 ±30 ±40 ±20
$W \rightarrow \tau\nu$+jets	87400 ±300 ±800 ±3700	5580 ±60 ±190 ±300	370 ±10 ±40 ±30	39 ±4 ±11 ±2
$W \rightarrow e\nu$+jets	36700 ±200 ±500 ±1500	1880 ±30 ±100 ±100	112 ±5 ±18 ±9	16 ±2 ±6 ±2
$W \rightarrow \mu\nu$+jets	34200 ±100 ±400 ±1600	2050 ±20 ±100 ±130	158 ±5 ±21 ±14	42 ±4 ±13 ±8
$Z \rightarrow \tau\tau$+jets	1263 ±7 ±44 ±92	54 ±1 ±9 ±5	1.3 ±0.1 ±1.3 ±0.2	1.4 ±0.2 ±1.5 ±0.2
$Z/\gamma^*(\rightarrow \mu^+\mu^-)$+jets	783 ±2 ±35 ±53	26 ±0 ±6 ±1	2.7 ±0.1 ±1.9 ±0.3	–
$Z/\gamma^*(\rightarrow e^+e^-)$+jets	–	–	–	–
Multijet	6400 ±90 ±5500	200 ±20 ±200	–	–
$t\bar{t}$ + single t	2660 ±60 ±530	120 ±10 ±20	7 ±3 ±1	1.2 ±1.2 ±0.2
Dibosons	815 ±9 ±163	83 ±3 ±17	14 ±1 ±3	3 ±1 ±1
Non-collision background	640 ±40 ±60	22 ±7 ±2	–	–
Total background	344400 ±900 ±2200 ±12600	25600 ±240 ±500 ±900	2180 ±70 ±120 ±100	380 ±30 ±60 ±30
Data	350932	25515	2353	268

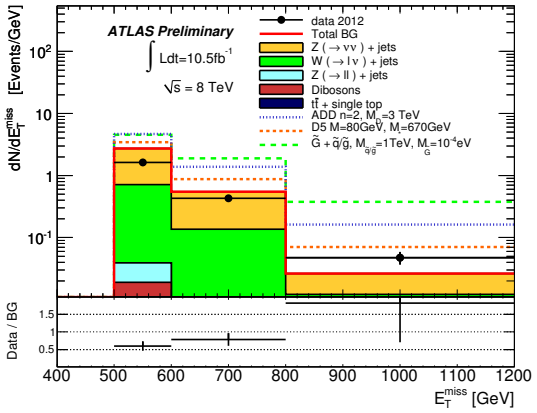
SR1



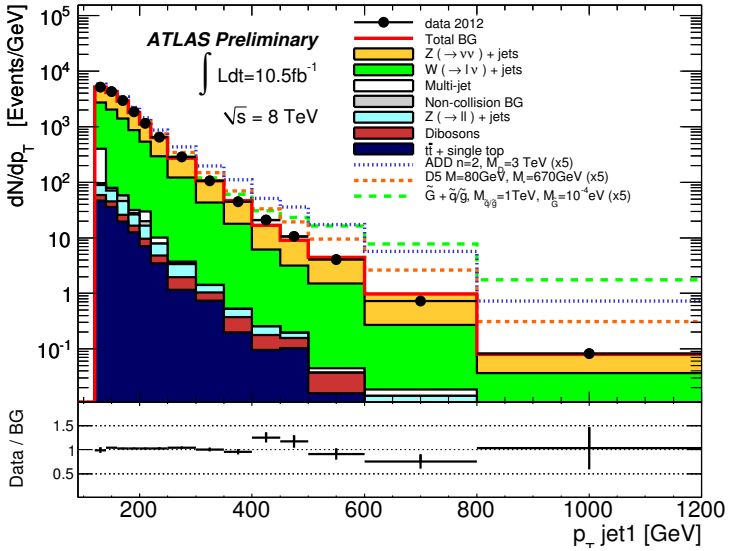
SR2

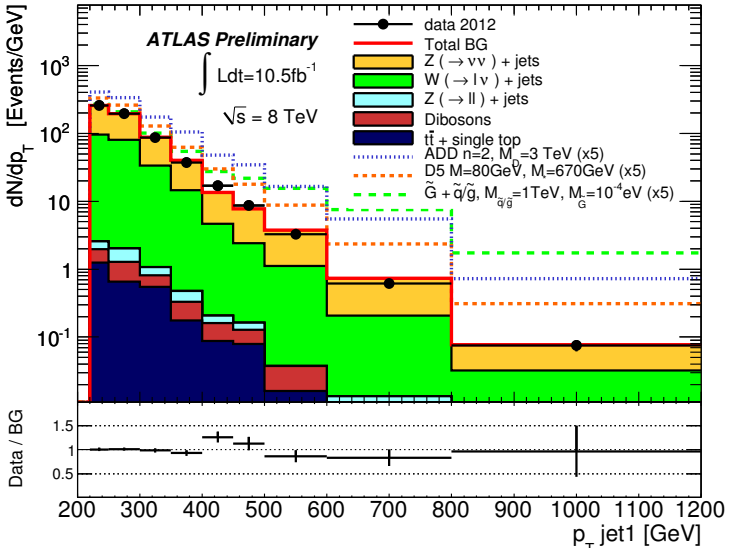


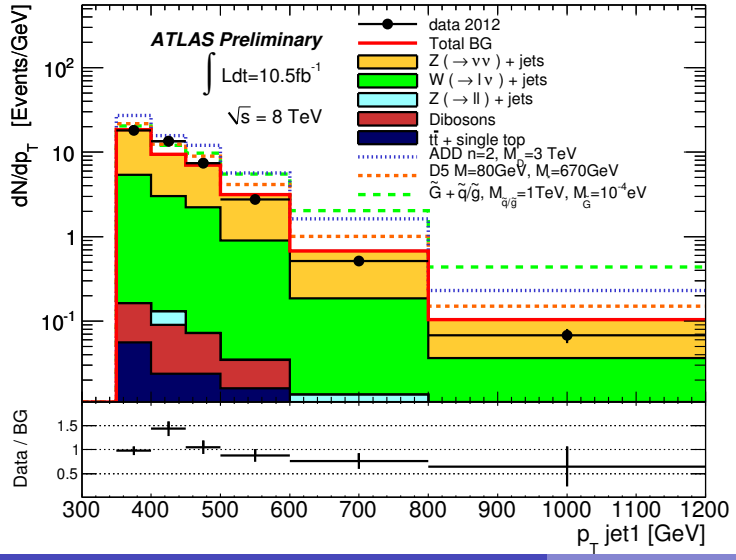
SR4

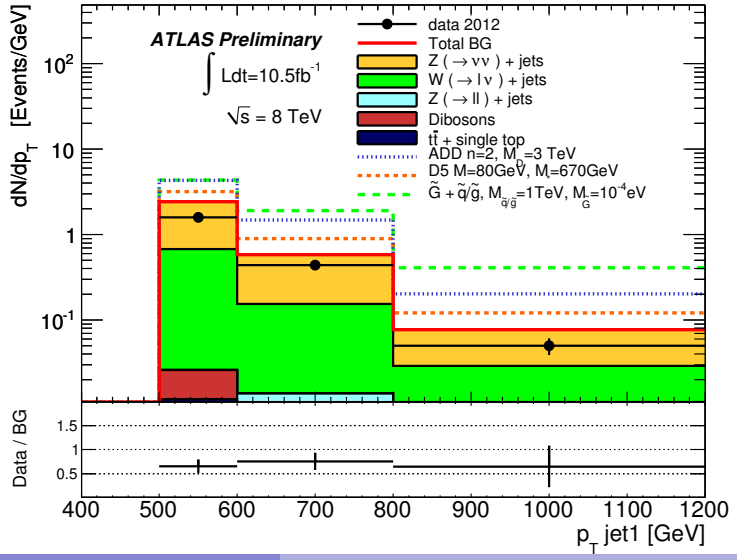


Jet p_T SR distributions









DM EFT operators

Fermion operators

Name	Operator	Coefficient
D1	$\overline{\chi}\chi\overline{q}q$	m_q/M_*^3
D2	$\overline{\chi}\gamma_5\chi\overline{q}q$	im_q/M_*^3
D3	$\overline{\chi}\chi\overline{q}\gamma_5 q$	im_q/M_*^3
D4	$\overline{\chi}\gamma_5\chi\overline{q}\gamma_5 q$	m_q/M_*^3
D5	$\overline{\chi}\gamma^\mu\chi\overline{q}\gamma_\mu q$	$1/M_*^2$
D6	$\overline{\chi}\gamma^\mu\gamma_5\chi\overline{q}\gamma_\mu q$	$1/M_*^2$
D7	$\overline{\chi}\gamma^\mu\chi\overline{q}\gamma_\mu\gamma_5 q$	$1/M_*^2$
D8	$\overline{\chi}\gamma^\mu\gamma_5\chi\overline{q}\gamma_\mu\gamma_5 q$	$1/M_*^2$
D9	$\overline{\chi}\sigma^{\mu\nu}\chi\overline{q}\sigma_{\mu\nu}q$	$1/M_*^2$
D10	$\overline{\chi}\sigma_{\mu\nu}\gamma_5\chi\overline{q}\sigma_{\alpha\beta}q$	i/M_*^2
D11	$\overline{\chi}\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$
D12	$\overline{\chi}\gamma_5\chi G_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D13	$\overline{\chi}\chi\tilde{G}_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^3$
D14	$\overline{\chi}\gamma_5\chi\tilde{G}_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^3$

Scalar operators

Name	Operator	Coefficient
C1	$\chi^\dagger\chi\overline{q}q$	m_q/M_*^2
C2	$\chi^\dagger\chi\overline{q}\gamma_5 q$	im_q/M_*^2
C3	$\chi^\dagger\partial_\mu\chi\overline{q}\gamma^\mu q$	$1/M_*^2$
C4	$\chi^\dagger\partial_\mu\chi\overline{q}\gamma^\mu\gamma_5 q$	i/M_*^2
C5	$\chi^\dagger\chi G_{\mu\nu}G^{\mu\nu}$	$\alpha_s/4M_*^2$
C6	$\chi^\dagger\chi\tilde{G}_{\mu\nu}G^{\mu\nu}$	$i\alpha_s/4M_*^2$

All of the listed operators are from a WIMP EFT by Tim Tait et al: (http://arxiv.org/abs/1008.1783)

DM systematics (8 TeV note)

Systematic source	**Uncertainty**
Jet and $\mathrm{E_T^{miss}}$ energy scale and resolution	1-10% on event yield
Trigger efficiency	1% on event yield
Luminosity	3.6% on event yield
ISR/FSR and matching scale	3% on $\sigma \times A$
α_s	8% on $\sigma \times A$
PDF	D5: 7-30%, D11: 25-88%
Factorization/renormalization scales	D5: 10%, D11: 30%

Basic validity of the EFT

- $M_* \approx M/\sqrt{g_1 g_2}$
- $M > 2m_\chi$ for valid description
- $g_1 g_2 \lesssim (4\pi)^2$ for perturbative theory
- $m_\chi \lesssim 2\pi M_*$ for weakly coupled perturbative UV completion
- So, for us, where $g_1 = g_2 = 1$ (and thus $M_* = M$):
  - $m_\chi < M_*/2$ for valid description
  - $m_\chi \lesssim 2\pi M_*$ for perturbation
- We consider m_χ of: $10, 50, 100, 200, 400, 700, 1000, 1300$ GeV

WIMP Annihilation limits

- Assumes 100% branching ratio of WIMPs to quarks
- Plot from 7 TeV paper