Searches for Dark Matter in events with high missing E_T with the ATLAS Detector

7TeV Monojet (4.7/fb): JHEP 1304 (2013) 075
7TeV Monophoton (4.6/fb): PRL 110, 011802 (2013)

8TeV Monojet (10.5/fb): ATLAS-CONF-2012-147
8TeV Mono-W/Z(had) (20.3/fb): arXiv:1309.4017
(submitted to PRL)

Terascale Workshop
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Ruth Pöttgen

Bundesministerium für Bildung und Forschung

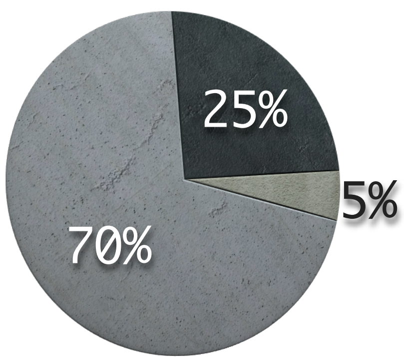
BMBF-Forschungsschwerpunkt ATLAS Experiment
Physics on the TeV-scale at the Large Hadron Collider
FSP 101 ATLAS

PRiSMA

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

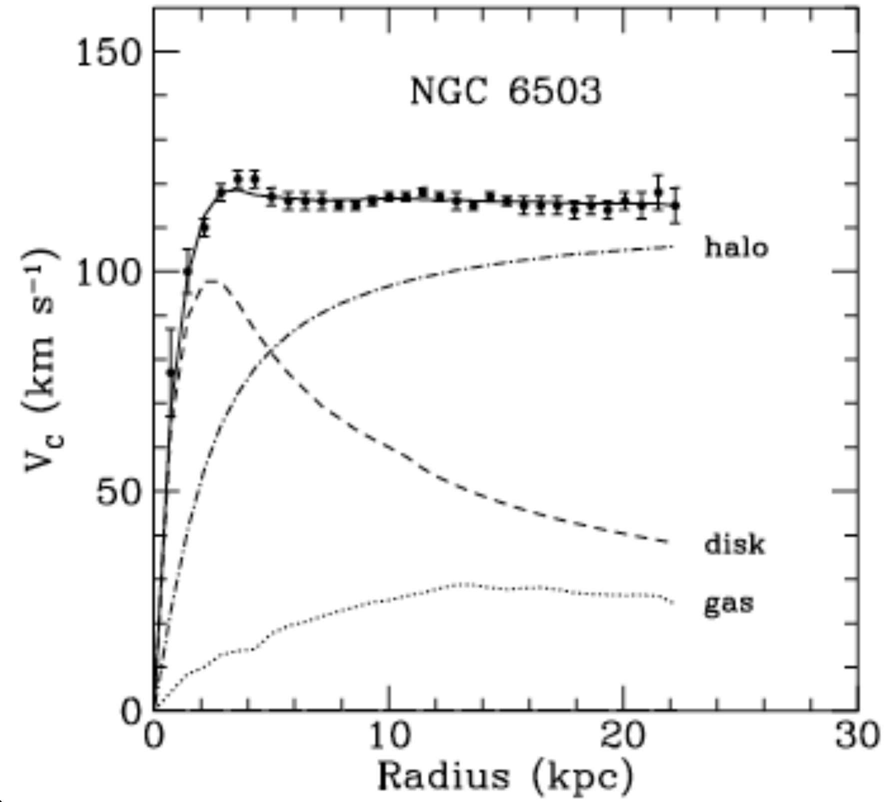
Why Dark Matter?

- various cosmological indications for 'invisible' matter (=>dark (DM))
  - rotation velocities of galaxies
  - gravitational lensing
  - cosmic microwave background (CMB)



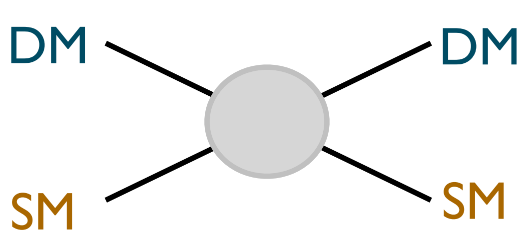
- Dark Energy (70%)
- Dark Matter (DM) (25%)
- visible matter/radiation (5%)

K. G. Begeman, A. H. Broeils and R. H. Sanders, 1991, MNRAS, 249, 523

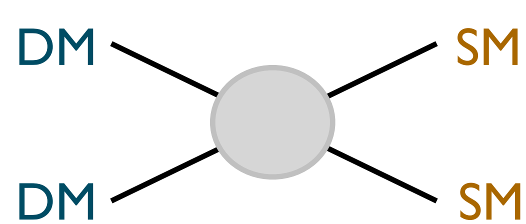


- popular candidates: Weakly Interacting Massive Particles (WIMP)

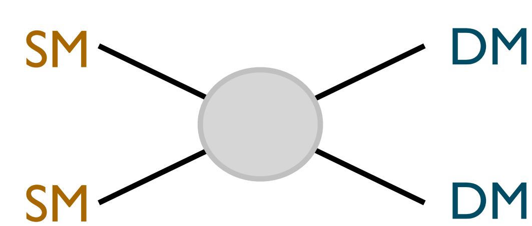
- different search approaches:



indirect
(WIMP-nucleon scattering)



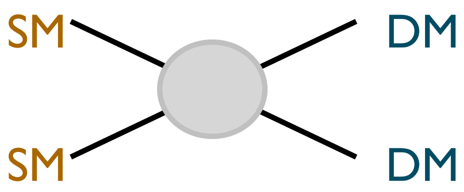
direct
(annihilation)



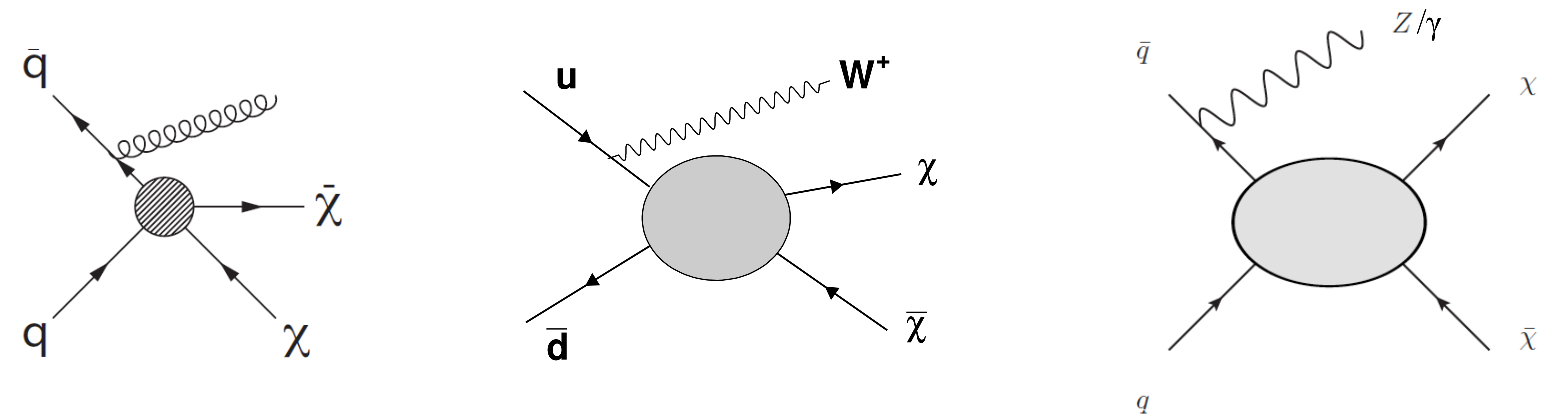
collider searches
(pair production)

SM: Standard Model particles

Why Mono-something?



- DM not detectable directly
  - need something to 'tag'/trigger on
    - unbalanced reconstructed object => missing transverse energy (E_T^{miss})



What is the ○ ?

- assume: interaction mediated by a new particle too heavy to be directly produced @LHC
- effective field theory approach (contact interaction)
- suppression scale of effective theory: M_*

$$M_* \sim \frac{M}{\sqrt{g_\chi g_{SM}}}$$

- M: mediator mass
- g_χ : coupling to DM
- g_{SM} : coupling to SM

for Dirac-fermionic DM

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

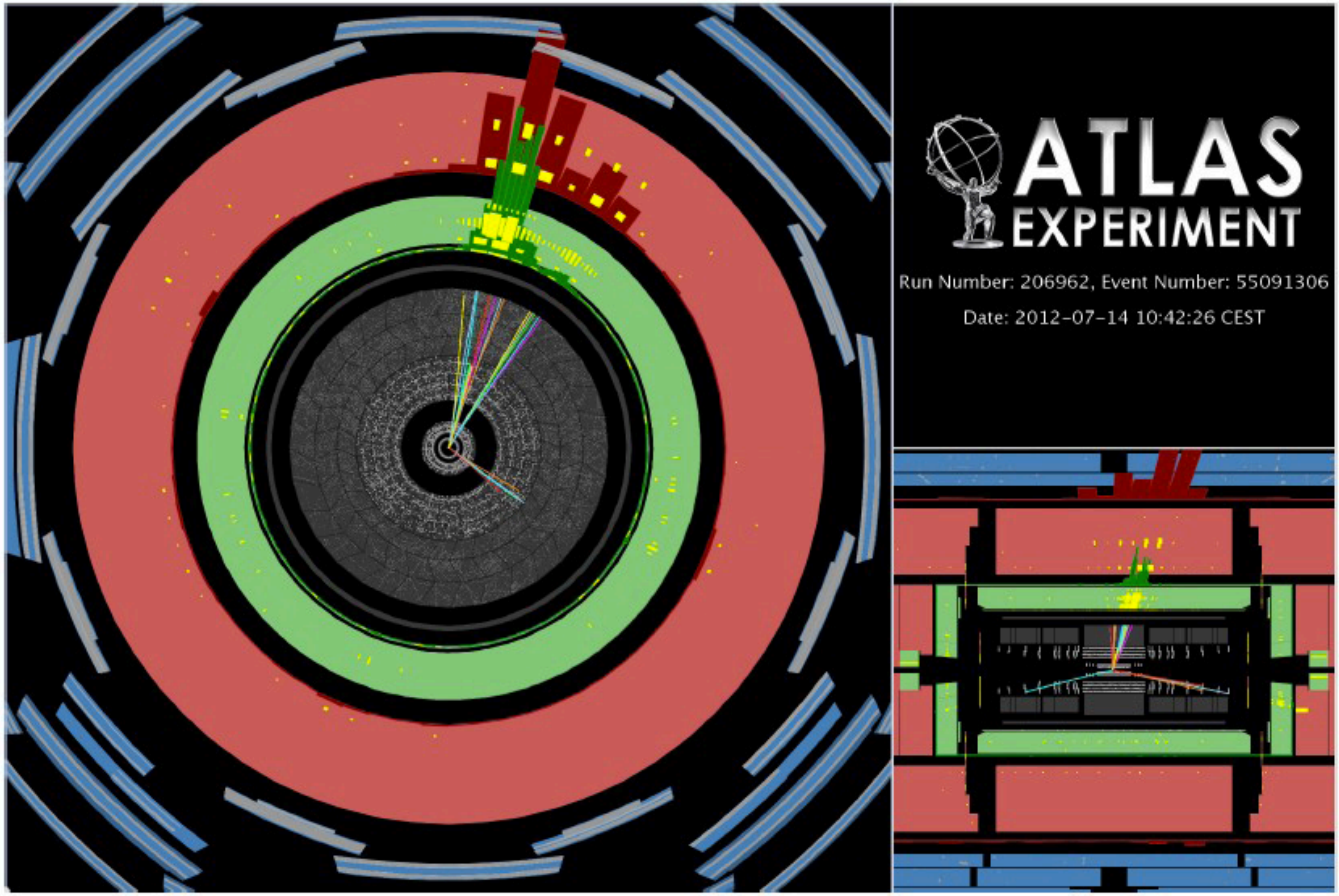
(some representative examples)

gg-operator only for mono-jet

Monojet Event Candidate in ATLAS

ATLAS-CONF-2012-147

- from 2012 data

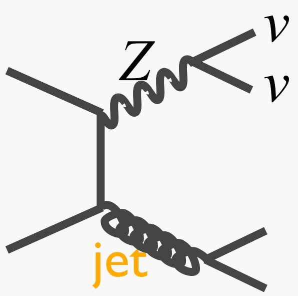


- E_T^{miss} = 863 GeV
- jet p_T = 852 GeV

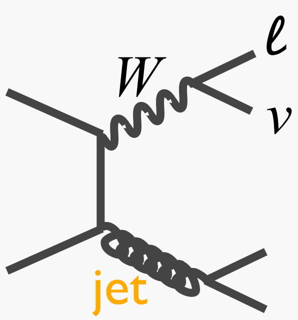
Monojet - Backgrounds and their suppression

Standard Model contributions

data driven



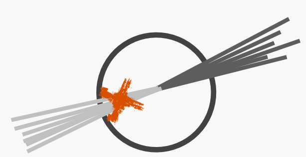
- $Z(\nu\nu)$ + jet
  - irreducible, largest contribution



- $W(\ell\nu)/Z(\ell\ell)$ + jet
  - leptons not identified
  - hadronic tau-decay

small contribution (≤1-2%)

- Multi-jet



- Non-collision background (NCB)
  - beam halo, cosmic muons...

purely simulation based

- single top
- $t\bar{t}$
- Diboson

small contribution (≤1-2%)

Event Selection

- E_T^{miss} trigger
- good data quality (10.5/fb)
- primary vertex, jet cleaning
- lepton vetos (electron, muon)
- at most 2 jets with p_T>30GeV, $|\eta|$<4.5
- $|\Delta\varphi(E_T^{miss}, 2^{nd}\text{ jet})|$>0.5
- leading jet: $|\eta|$<2.0 (central)
- 4 signal regions (SR)
  - symmetric cuts on E_T^{miss}, leading jet p_T
  - lower bounds: [120, 220, 350, 500] GeV

Electroweak Background Estimation

ATLAS-CONF-2012-147

- $W(\nu\ell)/Z(\ell\ell)$ + jet control regions ($\ell=\mu,e$) for EW background estimation
  - require 1 or 2 leptons
  - cut on m_T, $m_{\ell\ell}$
  - SR cuts on jet/E_T^{miss}
- transition into signal region via transfer factors (TF)

example: $Z(\nu\nu)$+jet from $W(\nu\mu)$+jet CR:

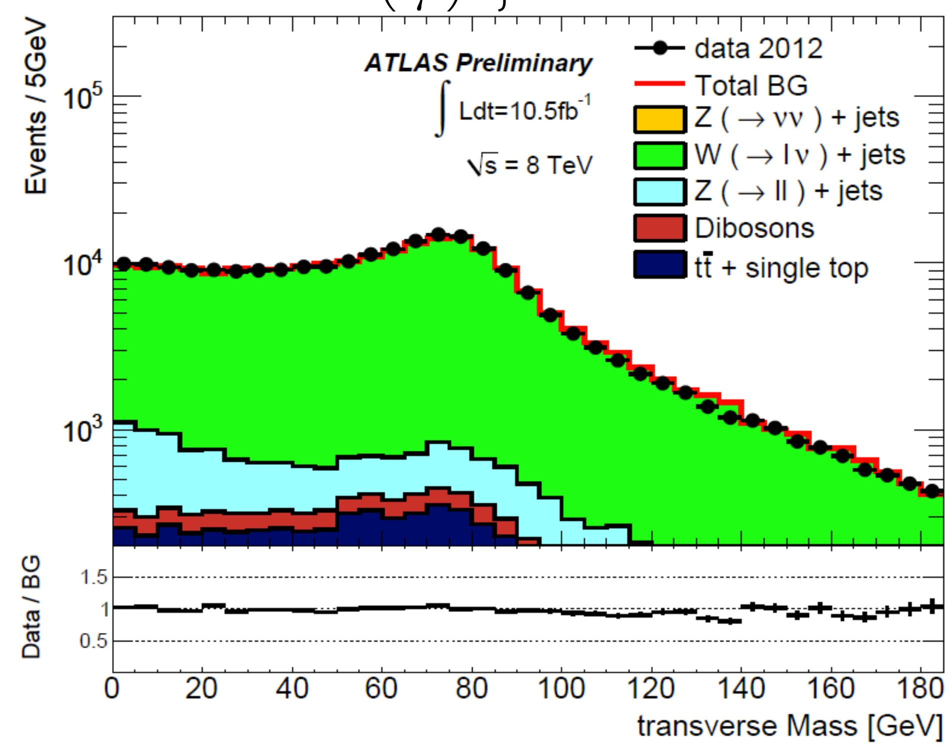
$$N^{SR}_{est} = N^{CR,W\mu\nu}_{obs} \frac{N^{SR,Z\nu\nu}_{MC}}{N^{CR,W\mu\nu}_{MC}}$$

background estimate in SR

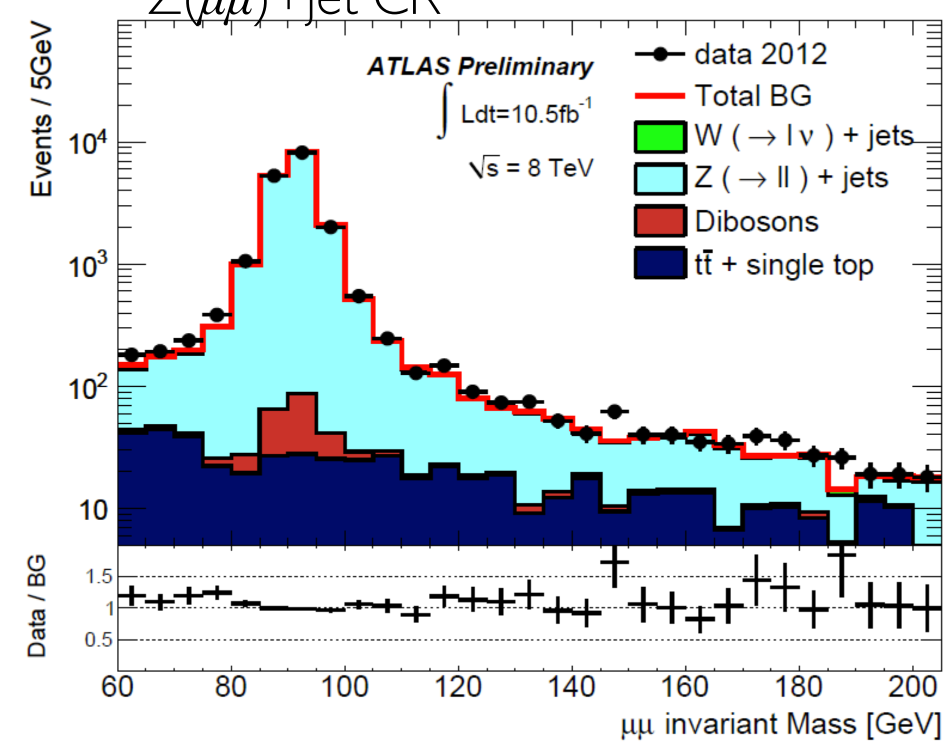
number of data events in CR

TF = MC ratio
=> reduced uncertainties

W($\nu\mu$)+jet CR



Z($\mu\mu$)+jet CR



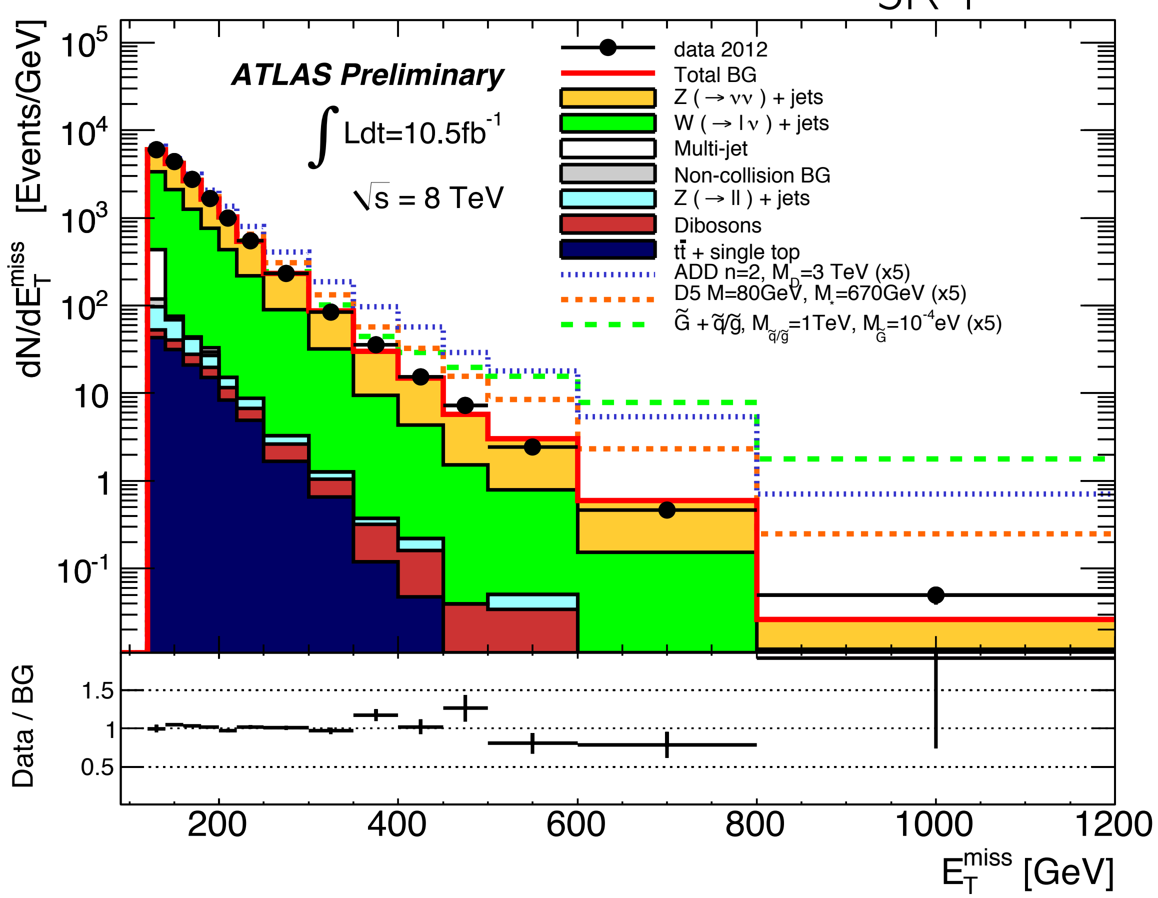
Results

ATLAS-CONF-2012-147

systematic uncertainties

Jet & 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)
parton shower/hadronisation modelling:	3%	(on total background)

SR 1

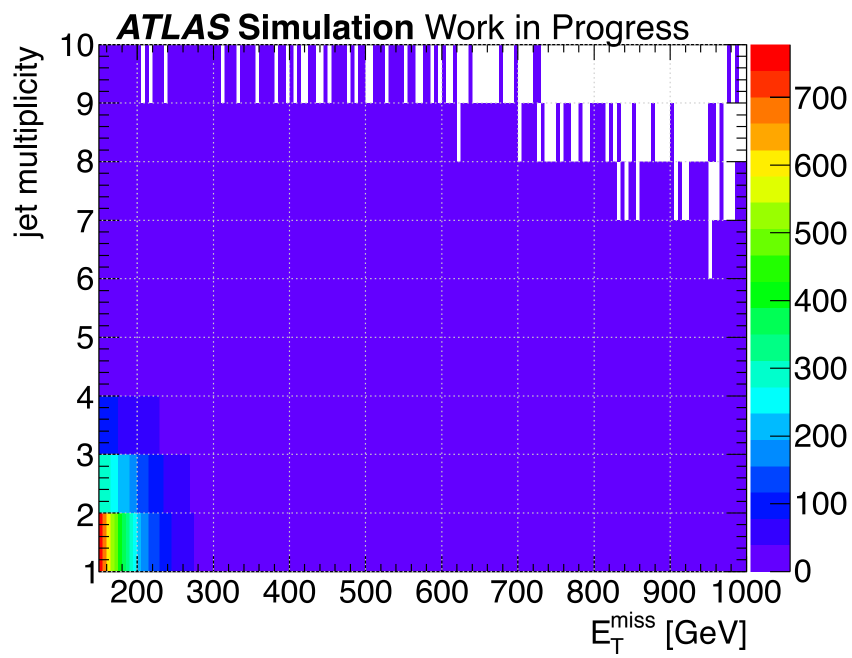
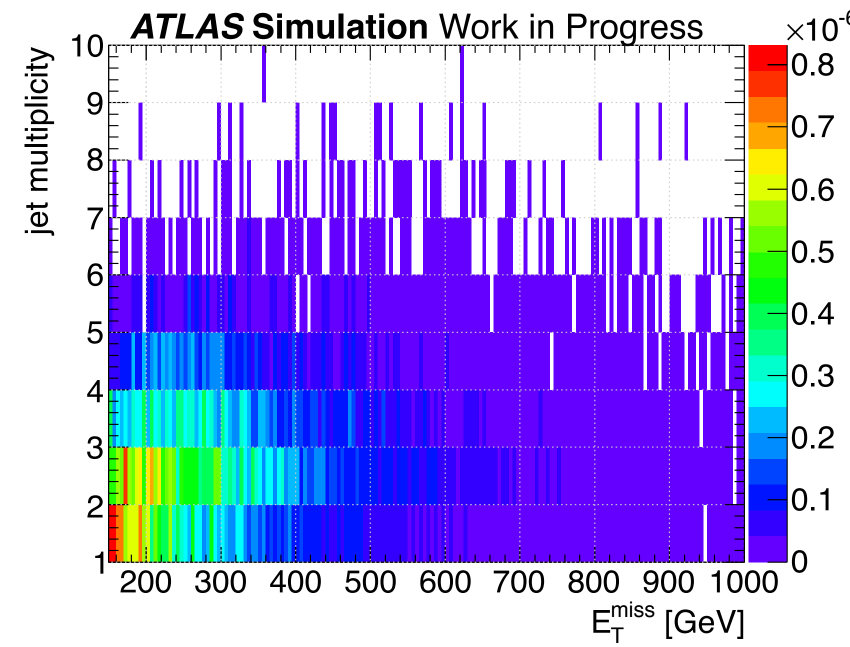
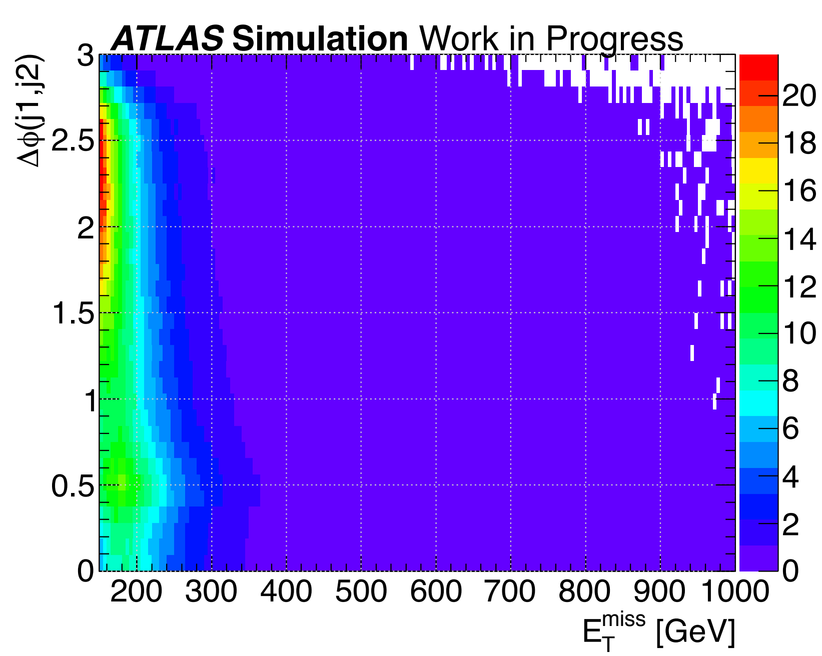
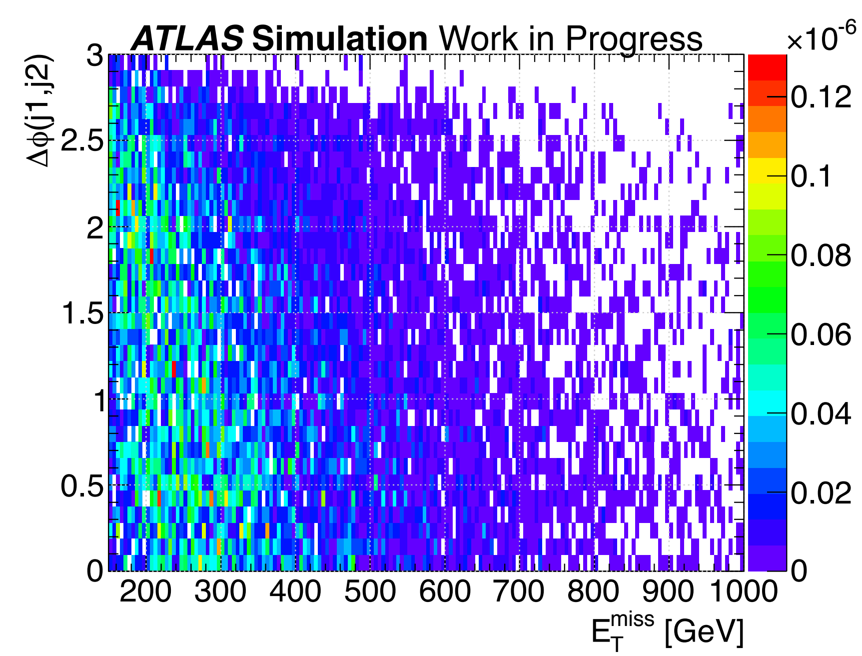


- no significant excess
- no significant improvement wrt 2011 limits
  - due to small statistics in simulation samples
- preliminary result
  - final result will benefit from simulation samples with higher statistics

Towards the full dataset - Monojets2012

- a number of developments/improvements foreseen for analysis of full 2012 dataset
  - very high statistics in background simulation samples
  - include operators for scalar DM
  - compare to UV-complete (light mediator) model
  - more sophisticated treatment/discussion of EFT validity
  - signal region optimisation
    - idea: WIMP signal => excess at high E_T^{miss} => high p_T jet
      - such jets likely to radiate another jet
        - on average expect higher jet multiplicities and jets closer together than for $Z(\nu\nu)$
        - leading jet $p_T < E_T^{miss}$

Signal Region Optimisation

	Z(νν)+jets	D11
jet multiplicity		
Δφ between the two leading jets		

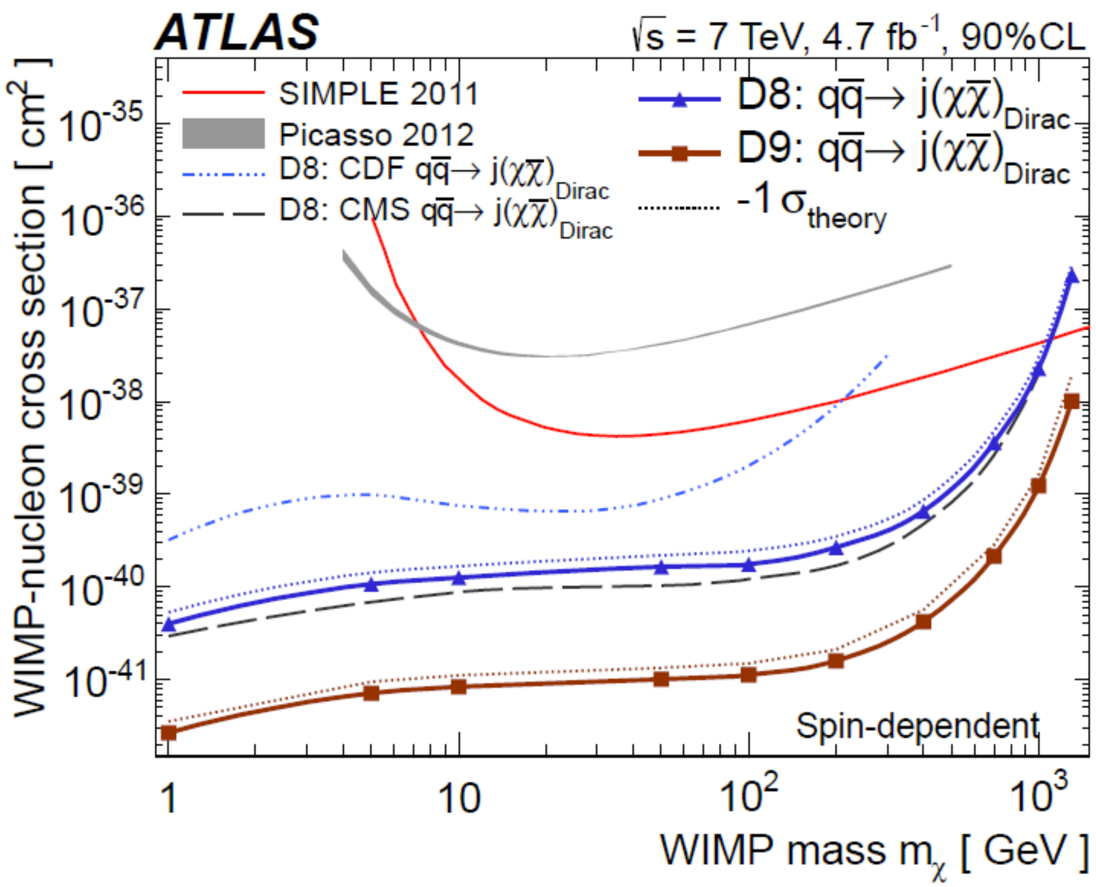
- release jet veto, use asymmetric cuts on leading jet p_T and E_T^{miss}
  - depending on the operator increases sensitivity by up to a factor of 2

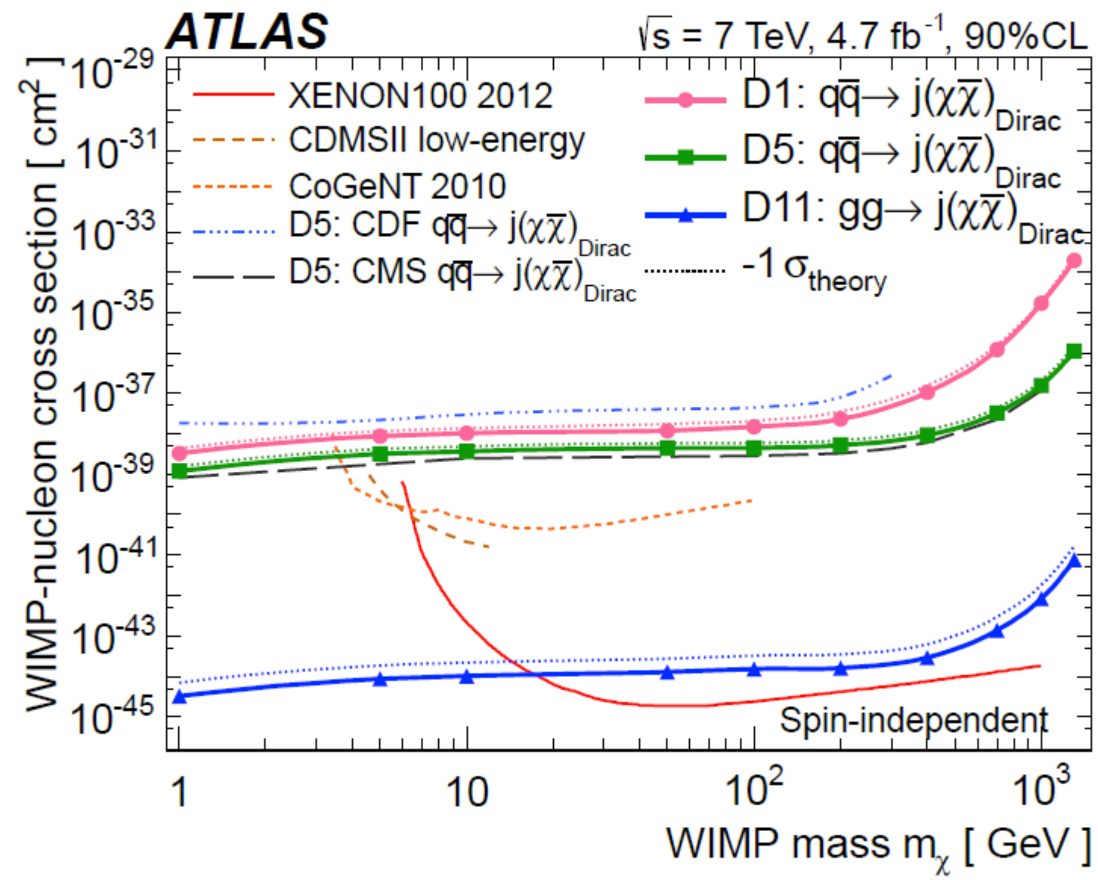
Comparison with Indirect Searches

JHEP 1304 (2013) 075

- limits on M* can be translated into (upper) limits on WIMP-Nucleon scattering cross section

Monojet@7TeV





- spin-dependent interaction: collider competitive over large mass region

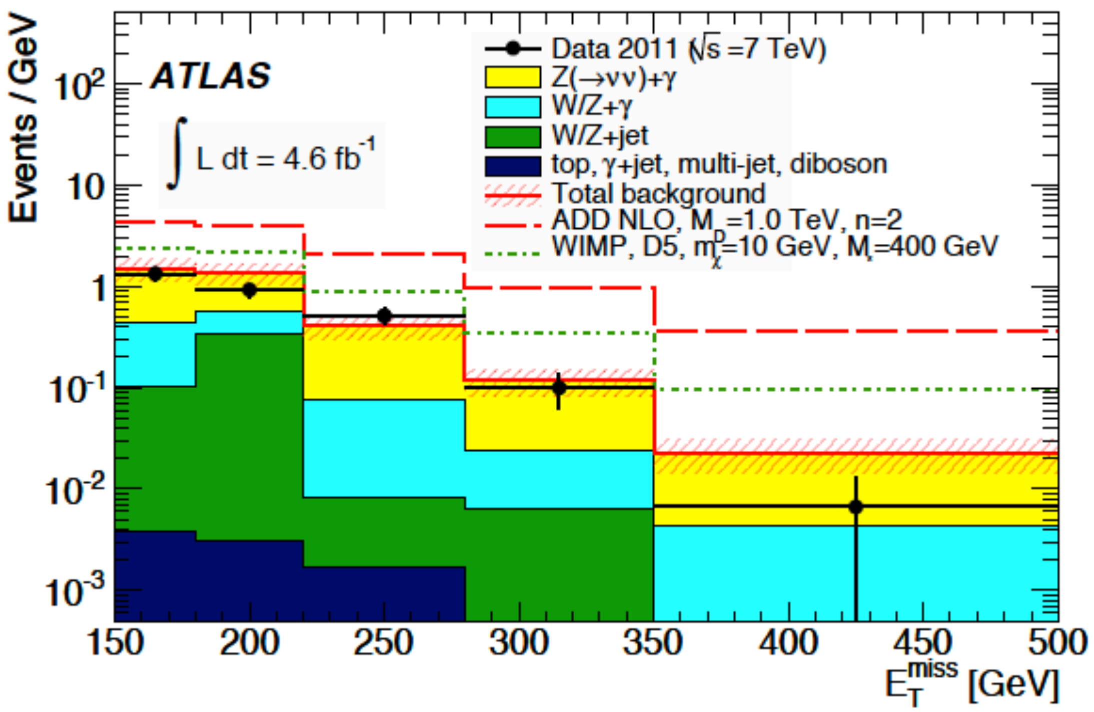
- spin-independent interaction: collider competitive at small masses

Results - Monophoton2011

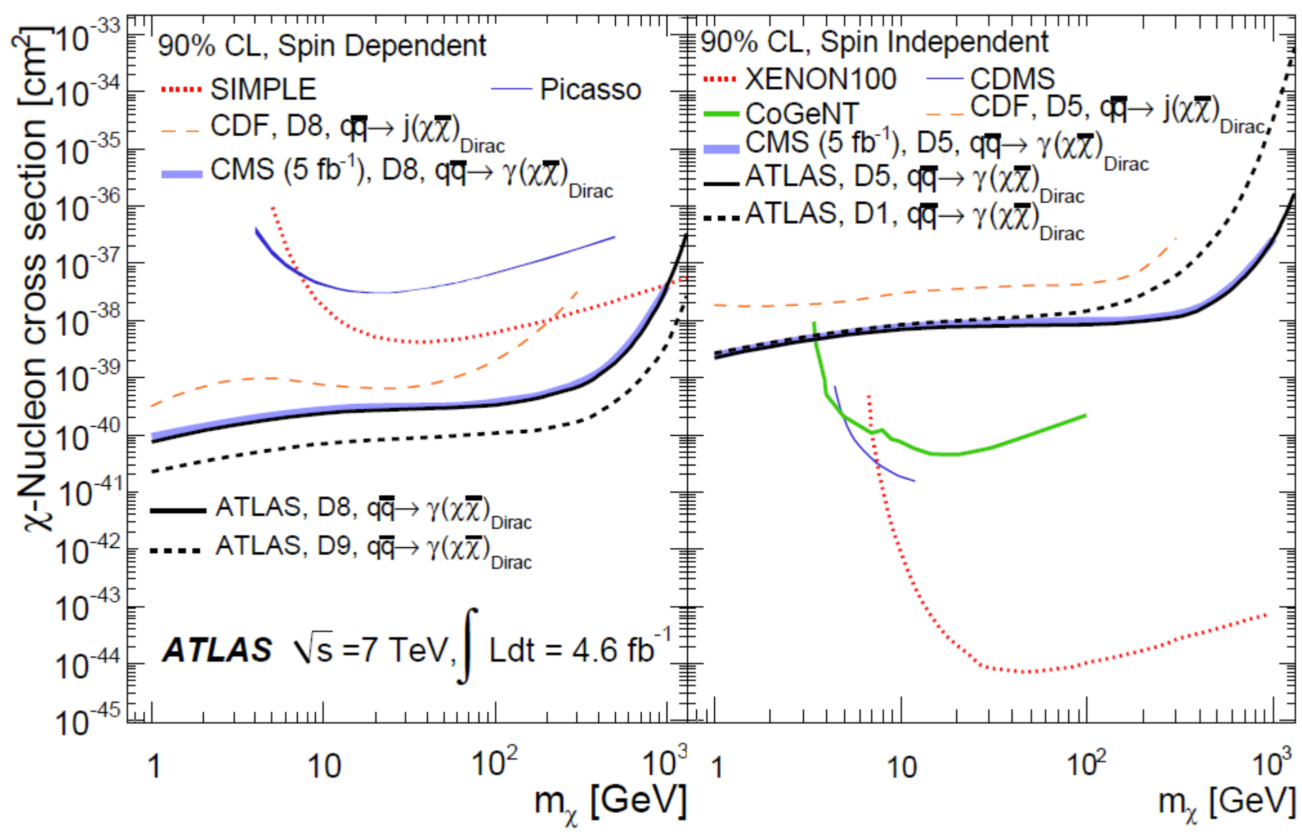
PRL 110, 011802 (2013)

- photon $|\eta|<2.37$
- γ p_T and $E_T^{miss} > 150$GeV
- lepton veto, ≤1 jet

Background source	Prediction	± (stat.)	± (syst.)
$Z(\to \nu\bar{\nu}) + \gamma$	93	± 16	± 8
$Z/\gamma^*(\to \ell^+\ell^-) + \gamma$	0.4	± 0.2	± 0.1
$W(\to \ell\nu) + \gamma$	24	± 5	± 2
W/Z + jets	18	–	± 6
Top	0.07	± 0.07	± 0.01
$WW, WZ, ZZ, \gamma\gamma$	0.3	± 0.1	± 0.1
γ+jets and multi-jet	1.0	–	± 0.5
Total background	137	± 18	± 9
Events in data (4.6 fb^{-1})	116		



no significant deviation from Standard Model prediction

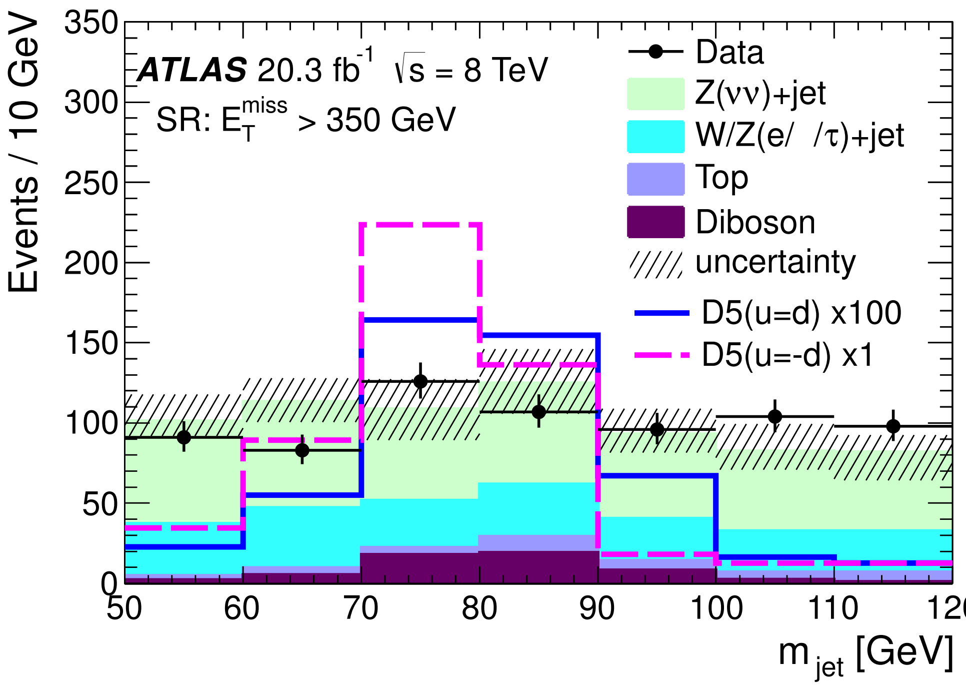


to be updated with full 2012 data set soon

Results - Mono-W/Z (hadr.) (2012)

arXiv:1309.4017

- 1 fat jet (Cambridge-Aachen), R=1.2
- jet p_T > 150GeV, E_T^{miss} >350, 500 GeV
- lepton/γ veto, ≤1 AntiKt jet (R=0.4)

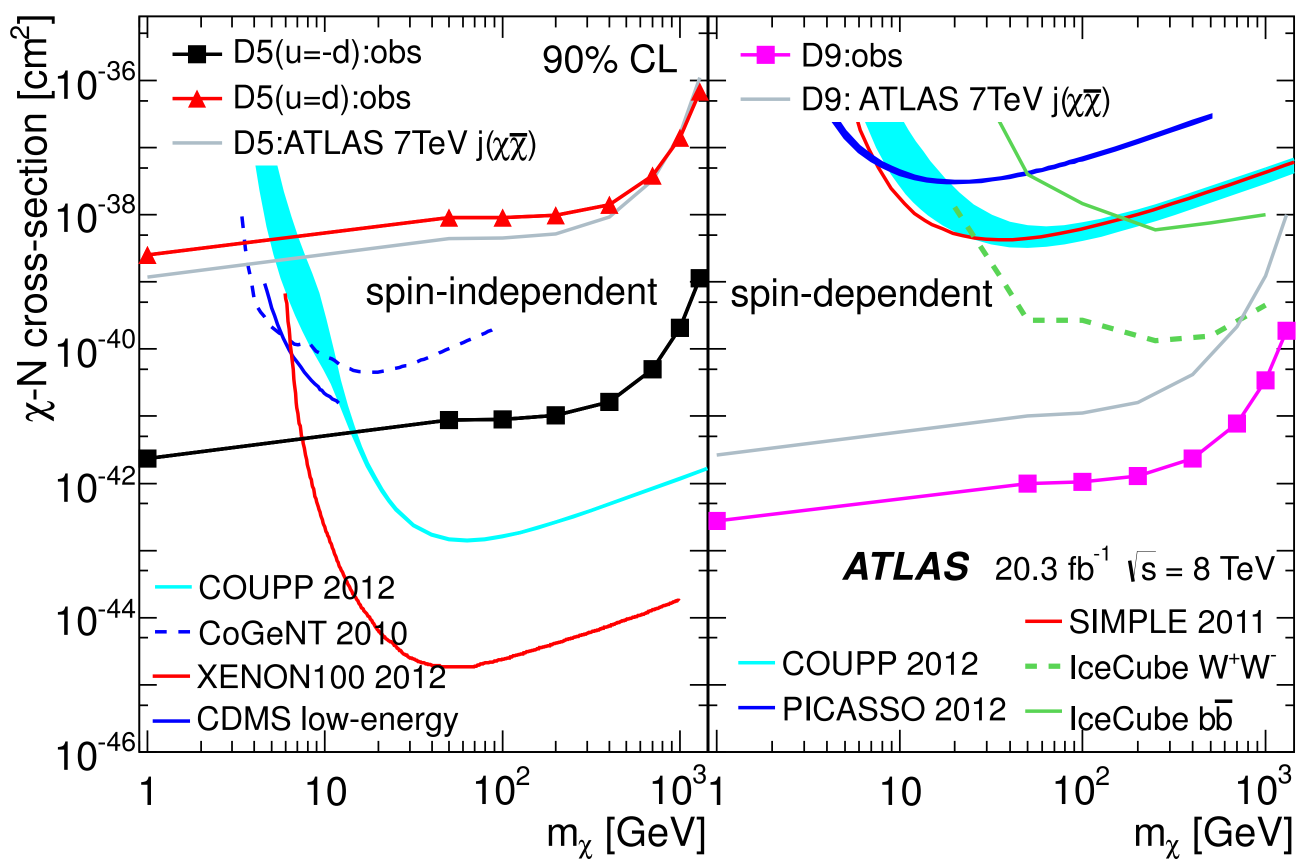


Process	$E_T^{miss} > 350$ GeV	$E_T^{miss} > 500$ GeV
$Z \to \nu\bar{\nu}$	402^{+39}_{-34}	54^{+8}_{-10}
$W \to \ell^{\pm}\nu$, $Z \to \ell^{\pm}\ell^{\mp}$	210^{+20}_{-18}	22^{+4}_{-5}
WW, WZ, ZZ	57^{+11}_{-8}	$9.1^{+1.3}_{-1.1}$
$t\bar{t}$, single t	39^{+10}_{-4}	$3.7^{+1.7}_{-1.3}$
Total	707^{+48}_{-38}	89^{+9}_{-12}
Data	705	89

no significant deviation from Standard Model prediction

- constructive interference for *W* emission if $g_u=-g_d$
  - => mono-W dominant process
    - => limits surpass mono-jet by 3 orders of magnitude (for D5)

- first LHC limits on this!



Summary&Outlook

SUMMARY

- mono-X signatures important tool for dark matter searches at colliders
- presented mono-jet, hadronic mono-W/Z and mono-photon ATLAS searches
  - each have their special strengths/merits
  - hadronic mono-W/Z first LHC result of its kind
- no significant deviation from Standard Model prediction
- limits on WIMP-nucleon scattering cross section complementary to indirect searches

OUTLOOK

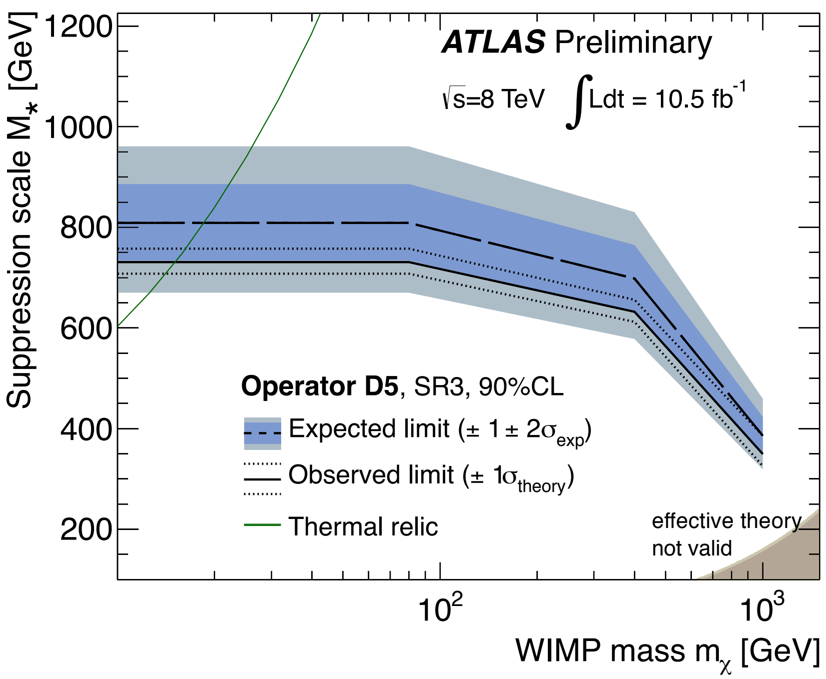
- mono-jet to be updated with full 2012 data set and optimised selection
- mono-photon to be updated with full 2012 data set
- for full 2012 data set there willl also be a mono-Z(ll) analysis
- studies for 13&14TeV beginning now

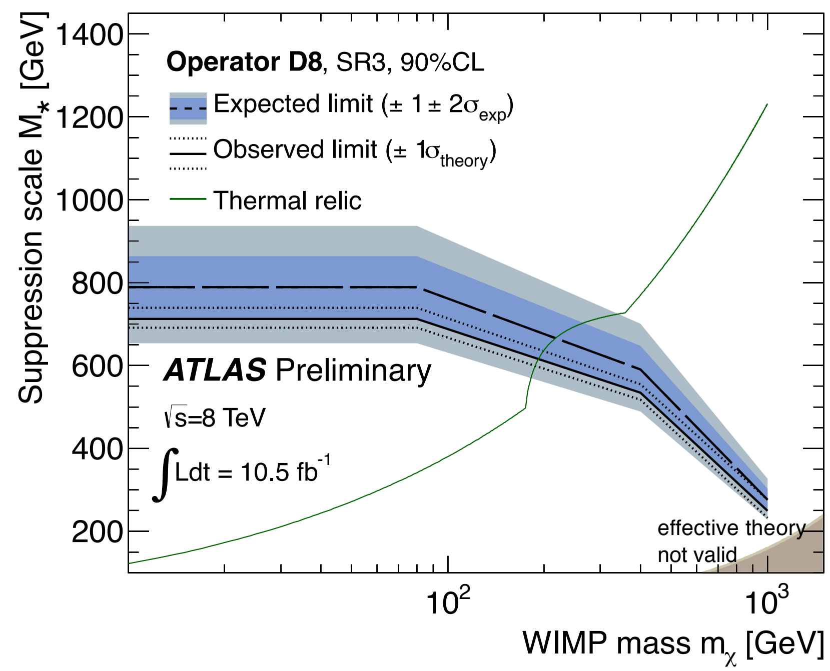
BACKUP

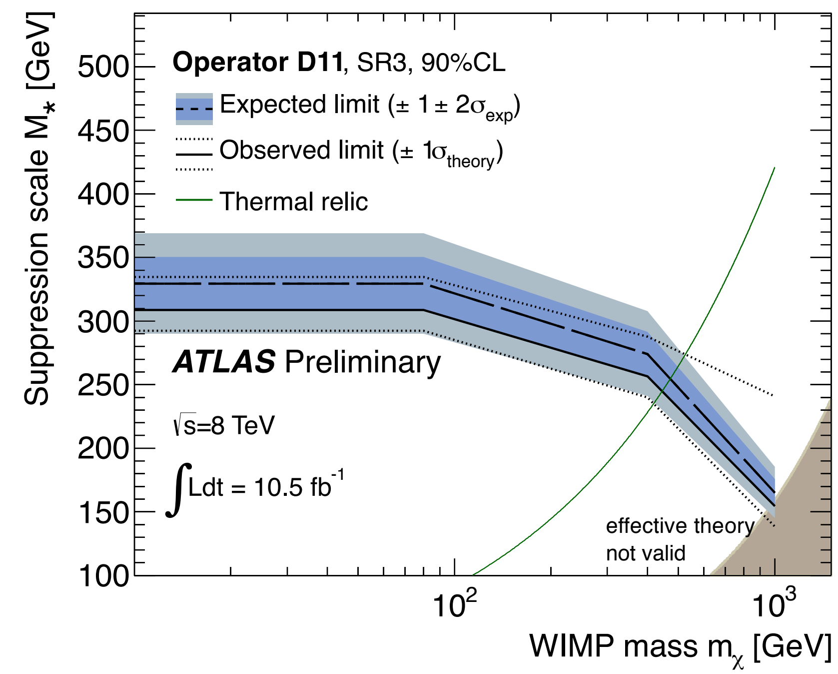
Interpretations - WIMP Pair Production

ATLAS-CONF-2012-147

- cross section determines relic abundance of DM in the universe (measured by WMAP)
- cross section depends on suppression scale M* and WIMP mass
  - for each value of m_χ a certain value of M* results in 'correct' relic density (green line)
- lower limits on M* as function of WIMP mass
  - limits above thermal relic line => conflict with WMAP measurement





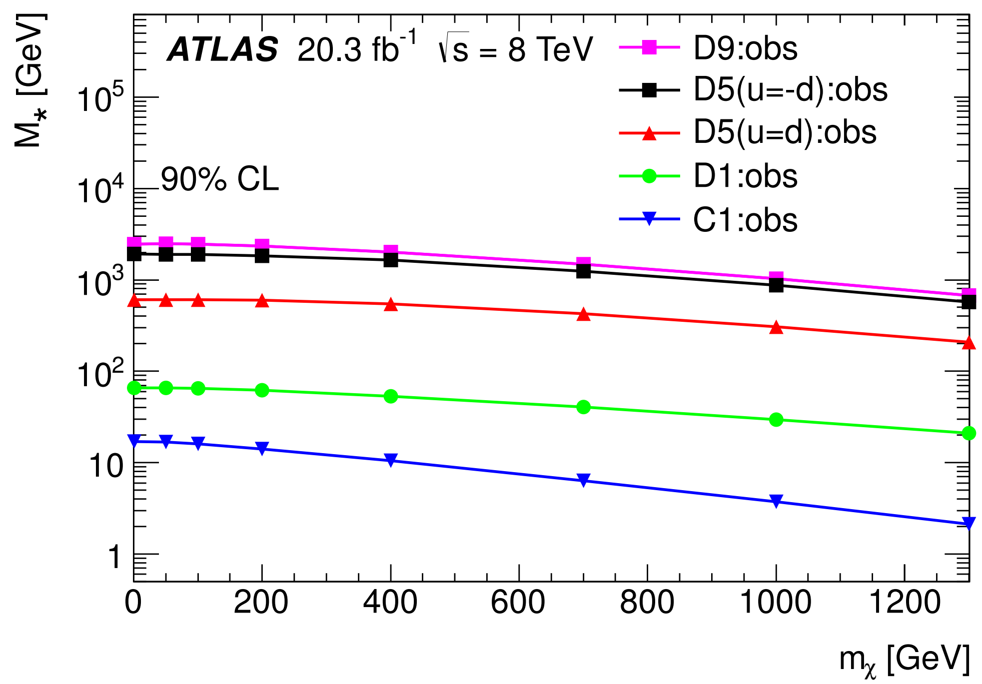


m_χ	D5	D8	D11
≤ 80	731 (704)	713 (687)	309 (301)
400	632 (608)	535 (515)	257 (250)
1000	349 (336)	250 (240)	155 (151)

- limits for D5,D8 ~10% stronger wrt 7TeV
- improvement for D11 hampered by poor simulation statistics

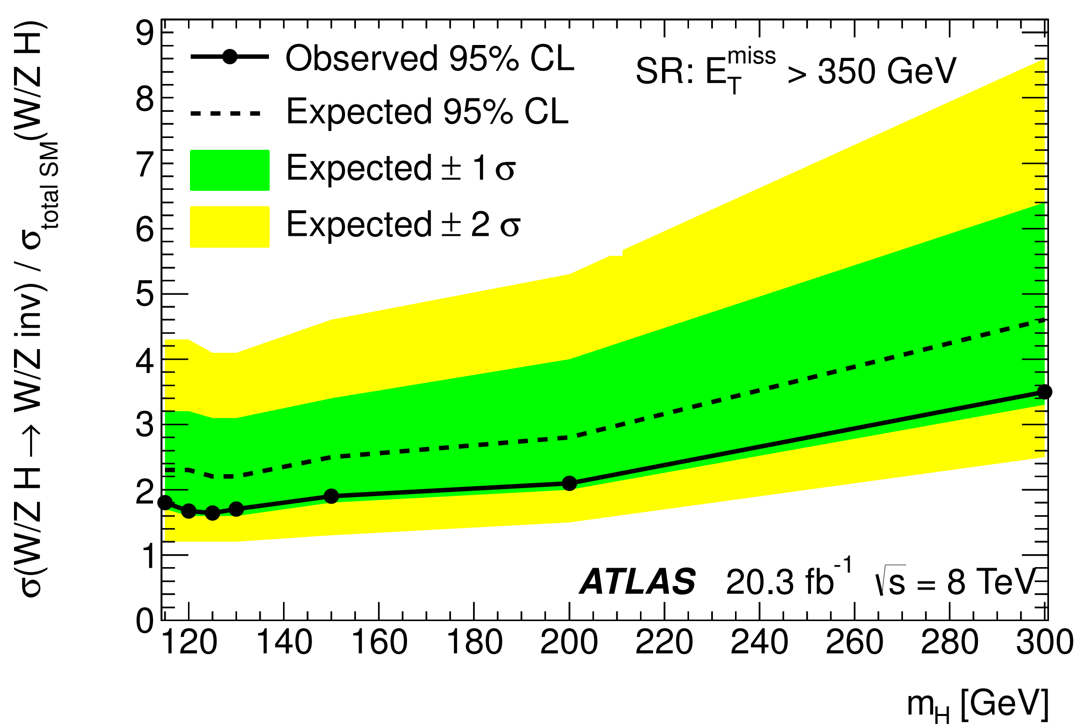
Results - Mono-W/Z (hadr.) (2012)

arXiv:1309.4017



- limits on suppression scale
  for all effective operators considered
  - D9 and D5 give strongest limits

- in addition to EFT also limits on a UV-complete model with a Higgs as a light mediator
  - *HW* or *HZ* production with $H \to \chi\chi$

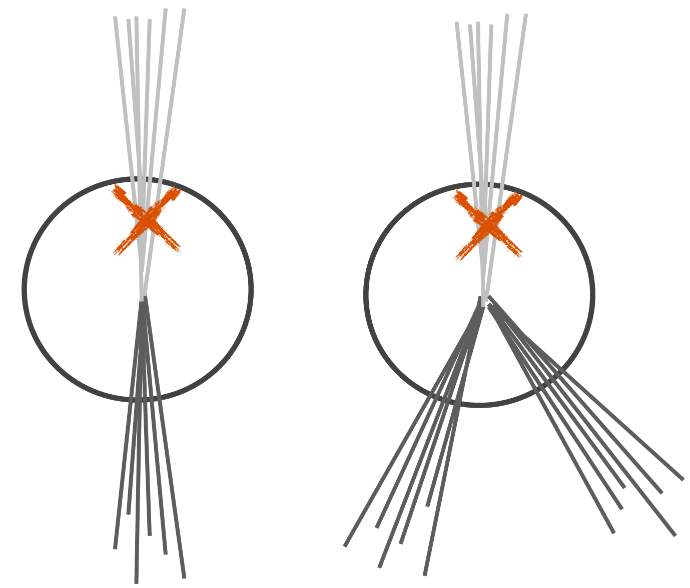


- limit on ratio of total (1.3pb) over standard model cross section (0.8pb): 1.6 (@125GeV)

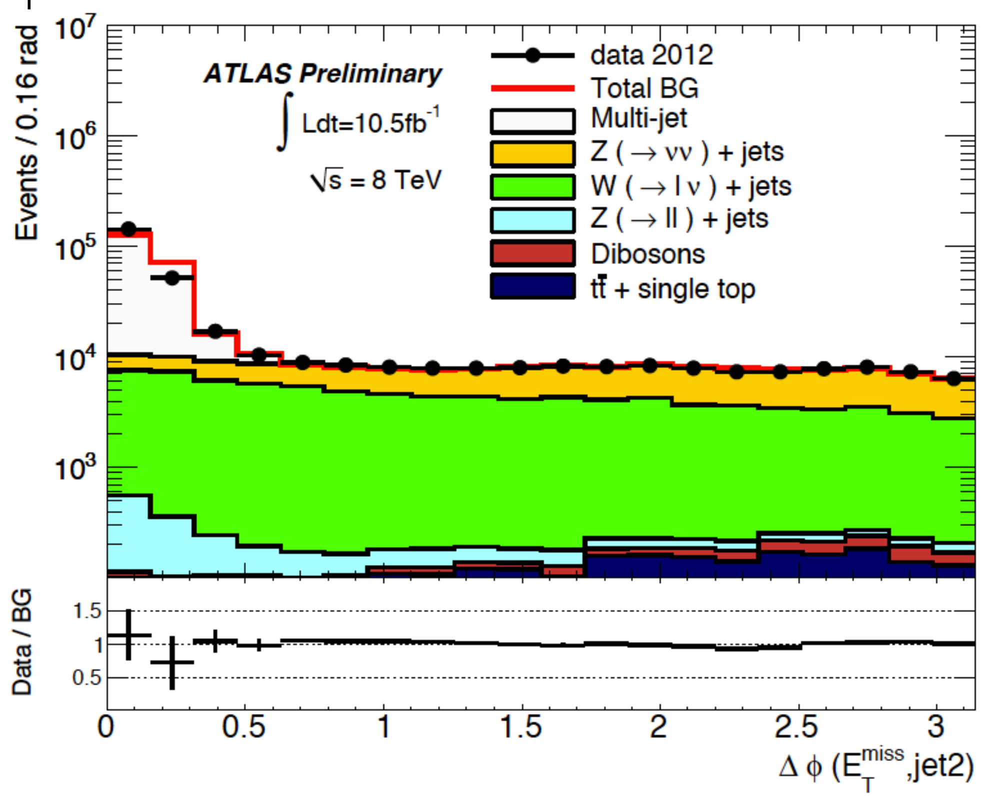
Multijet Background

ATLAS-CONF-2012-147

- events with additional jet(s), where one jet is mis-measured or lost



- require additional jet with $p_T > 30\text{GeV}$
- invert $\Delta\varphi$ cut between E_T^{miss} and additional jet
    - example

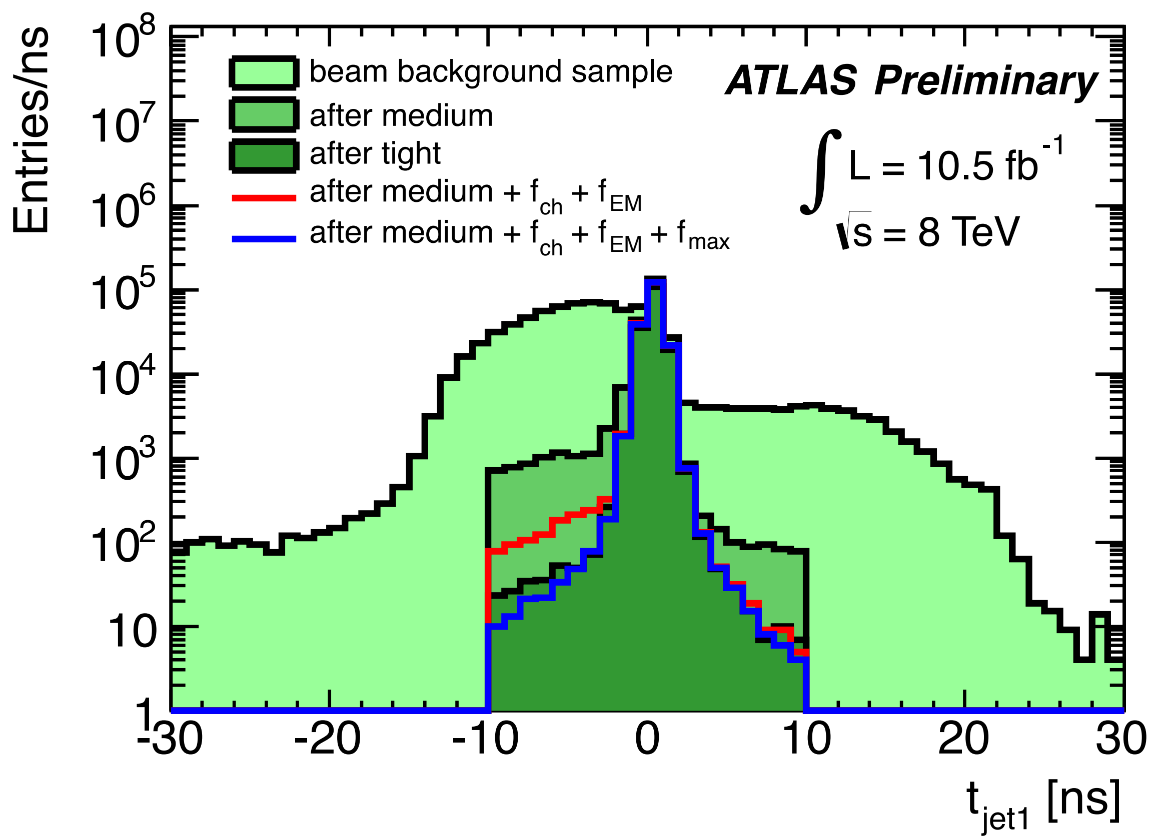


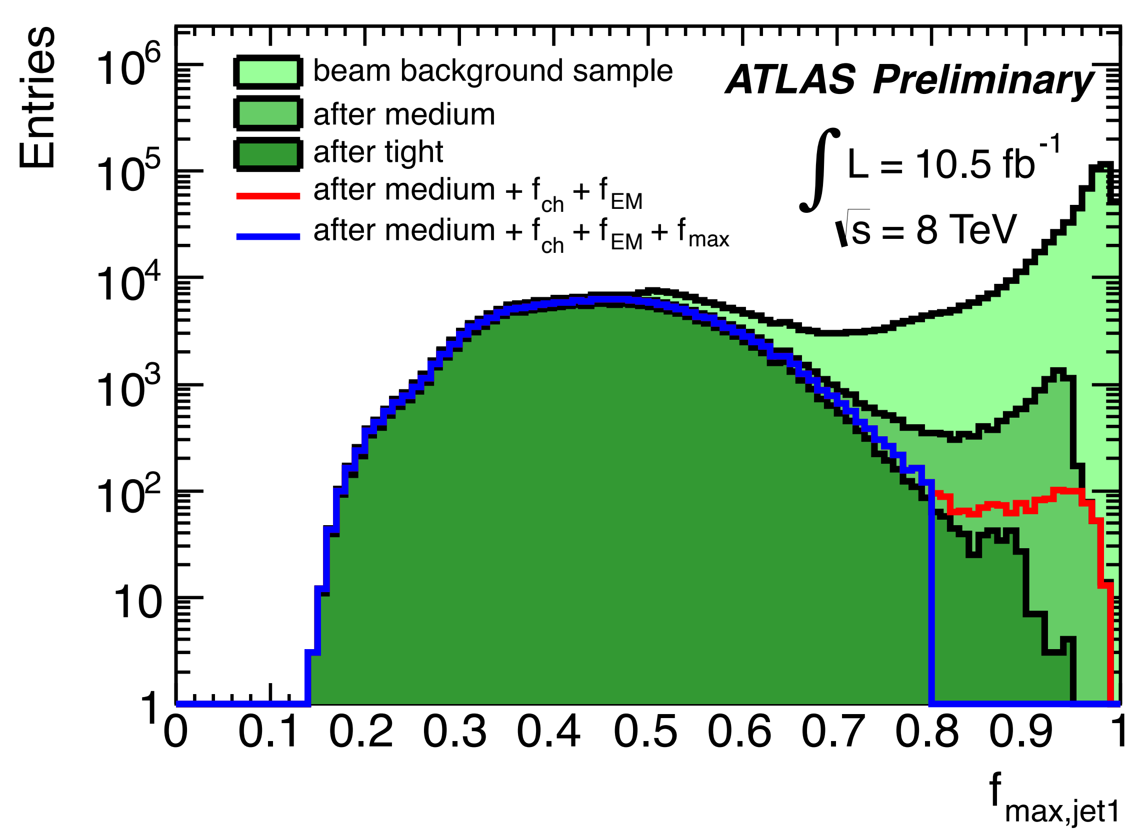
- fit p_T spectrum and extrapolate below 30GeV
    - systematic uncertainties from extrapolation and background subtraction

Non-collision Background

ATLAS-CONF-2012-147

- cosmic muons, beam halo
- reduced by dedicated ATLAS jet cleaning cuts
- remaining contribution estimated from data (negligible for monophoton)
  - in 2011 based on timing information from forward muon detectors
  - in 2012 based on timing distribution of leading jet
    - new cleaning cut using f_{max}





Selection Details

EVENT SELECTION

- E_T^{miss} trigger (98% efficient @120GeV)
- at least 1 primary vertex with ≥2 tracks
- leading jet:
  - em fraction>0.1
  - charge fraction>0.4
  - maximum fraction in one calorimeter layer < 0.8

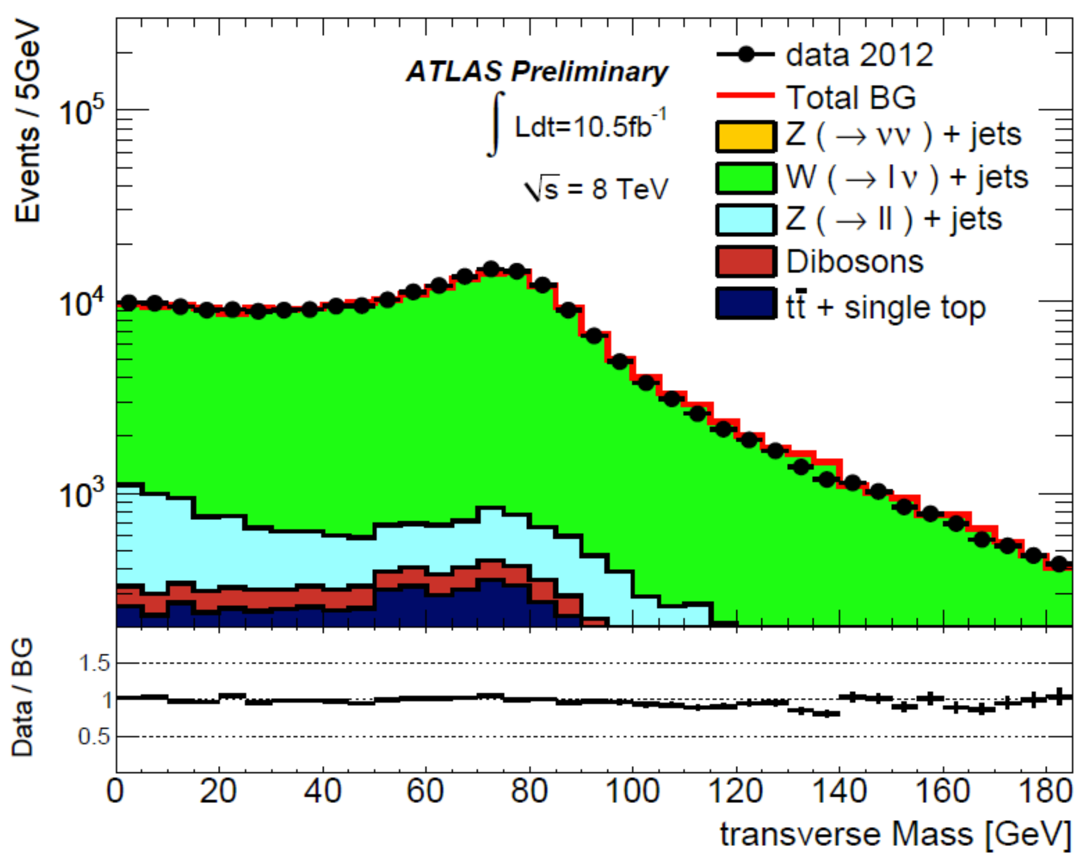
LEPTON VETOS

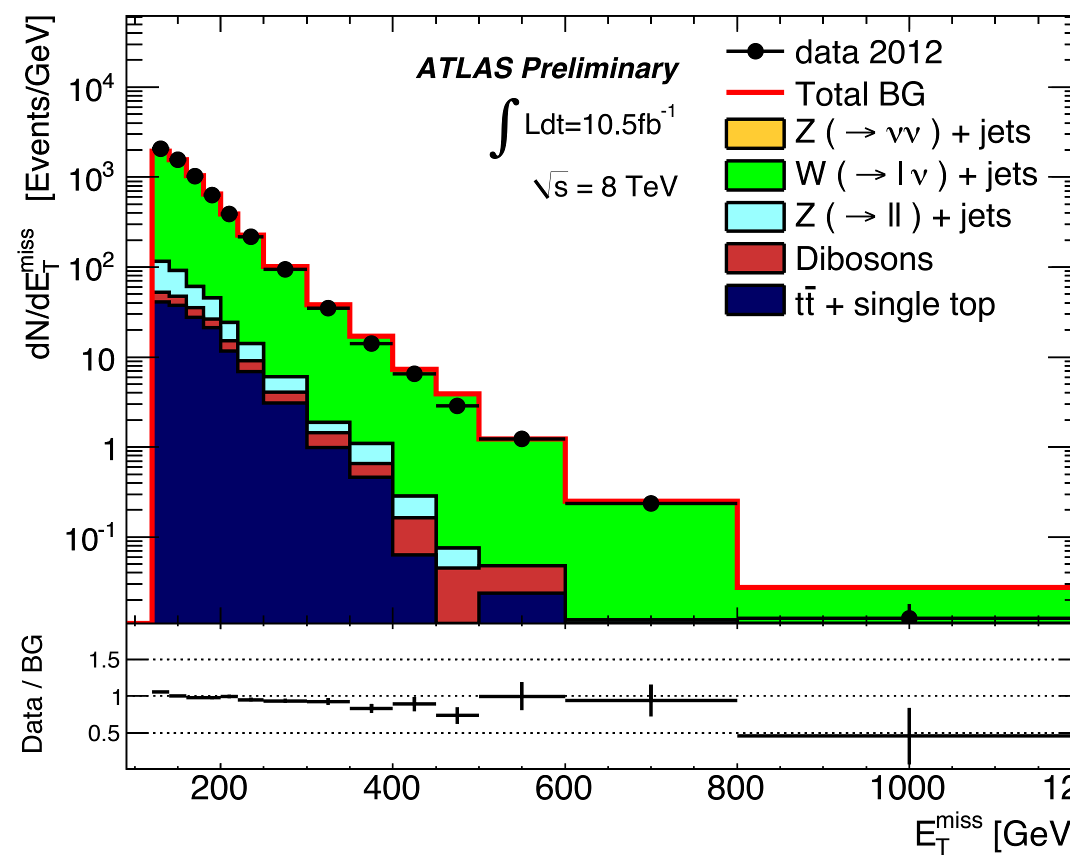
- electrons:
  - p_T>20GeV
  - $|\eta|$<2.47
  - "medium++" quality
  - overlap removal with jets
- muons:
  - p_T>7GeV
  - $|\eta|$<2.5
  - isolation requirement

Electroweak Background 2012

ATLAS-CONF-2012-147

- W($\mu\nu$)+jets CR
  - exactly 1 reconstructed muon
  - 40GeV < m_T < 100GeV
  - remaining SR cuts

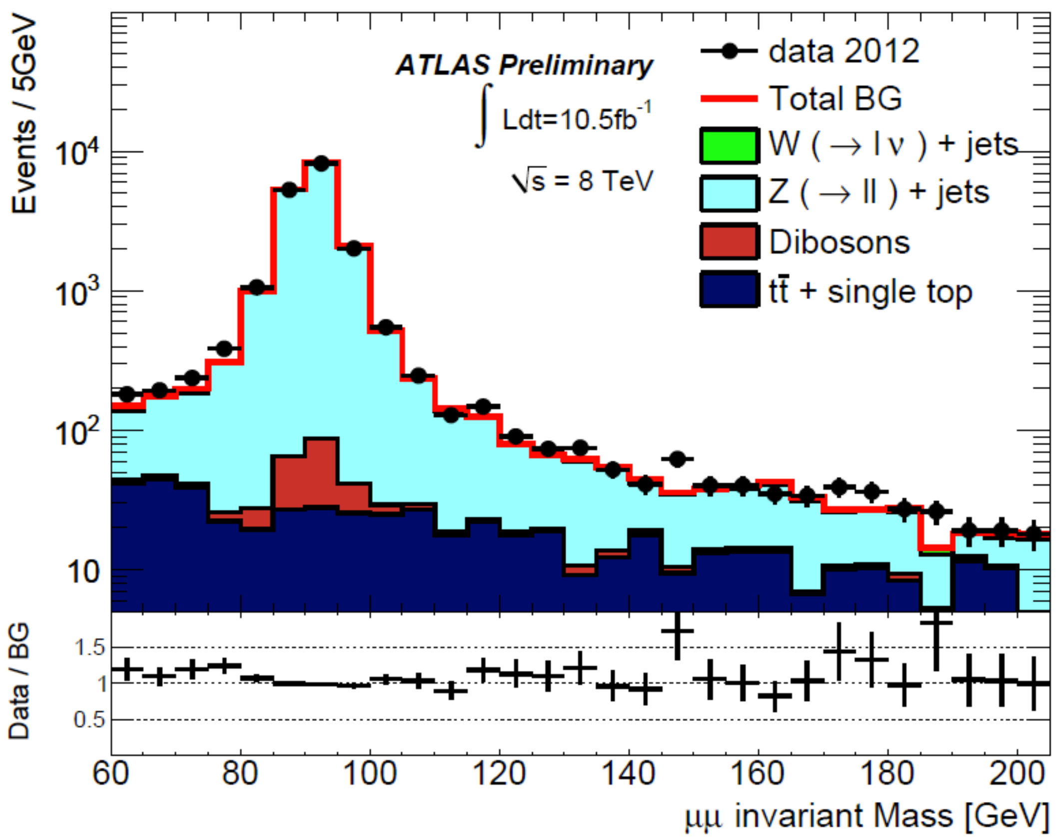


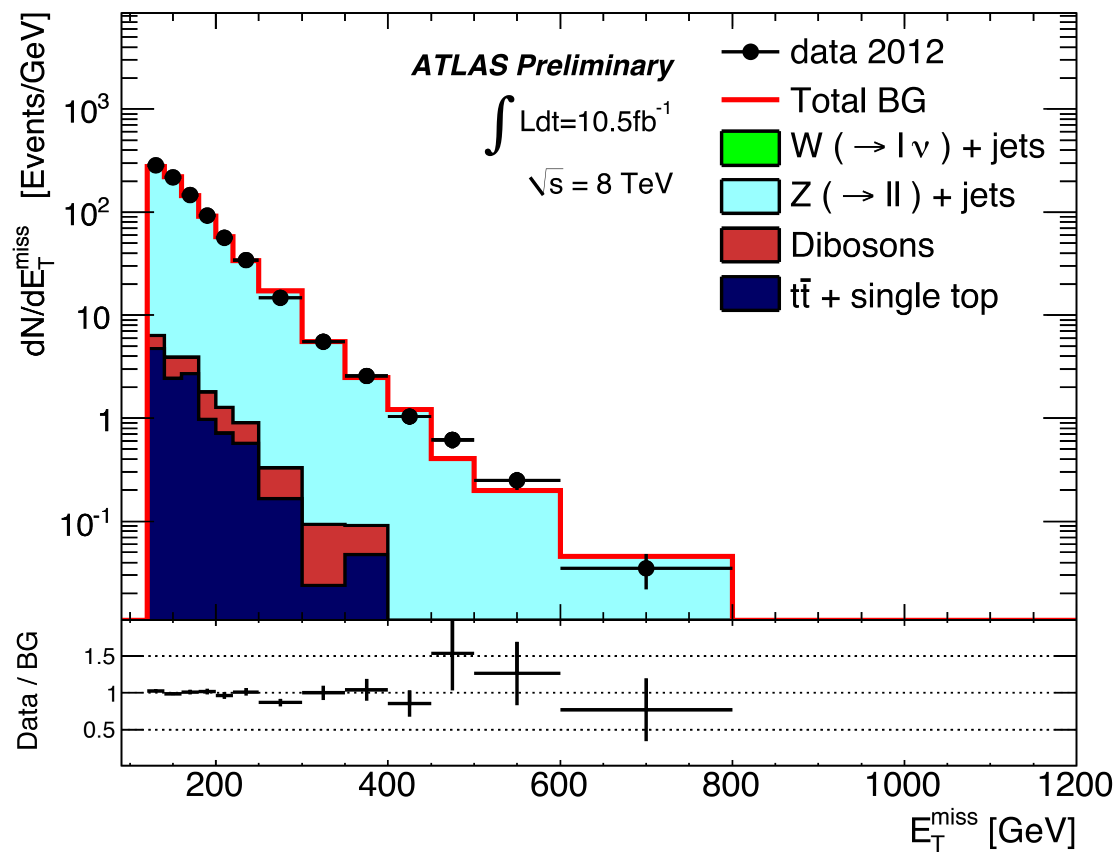


Electroweak Background 2012

ATLAS-CONF-2012-147

- $Z(\mu\mu)$+jets CR
  - exactly 2 reconstructed muons
  - 76GeV < $m_{\mu\mu}$ < 116GeV
  - remaining SR cuts

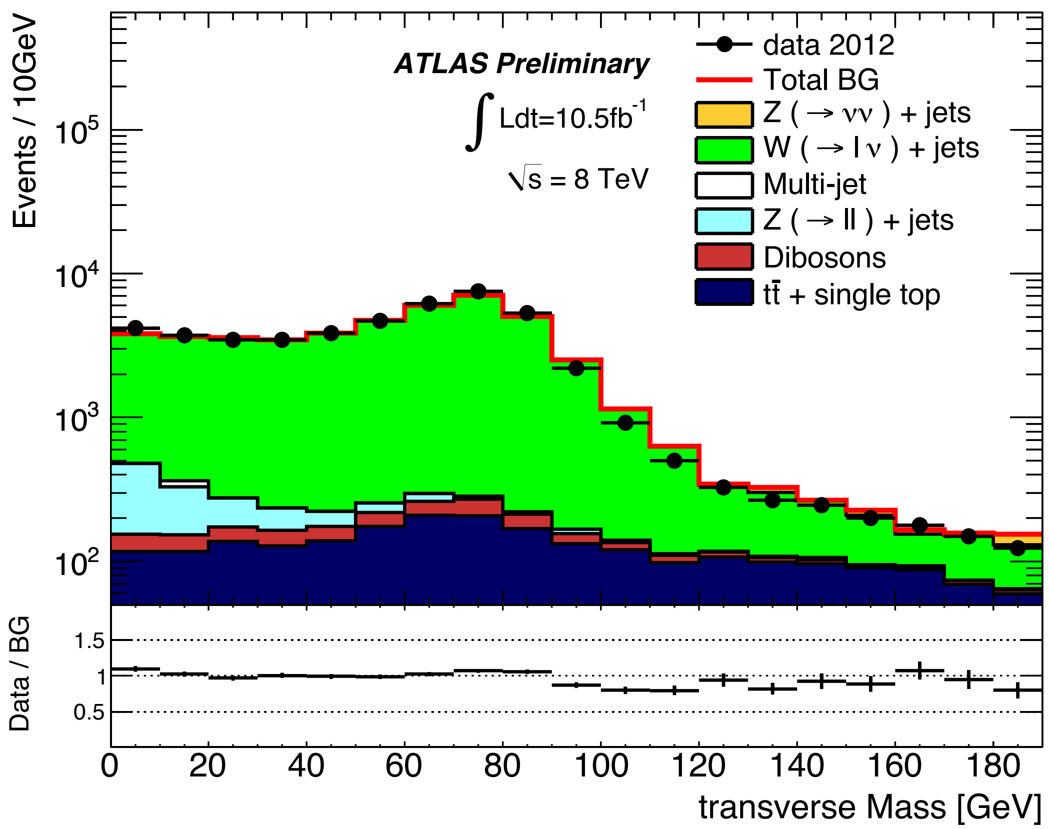


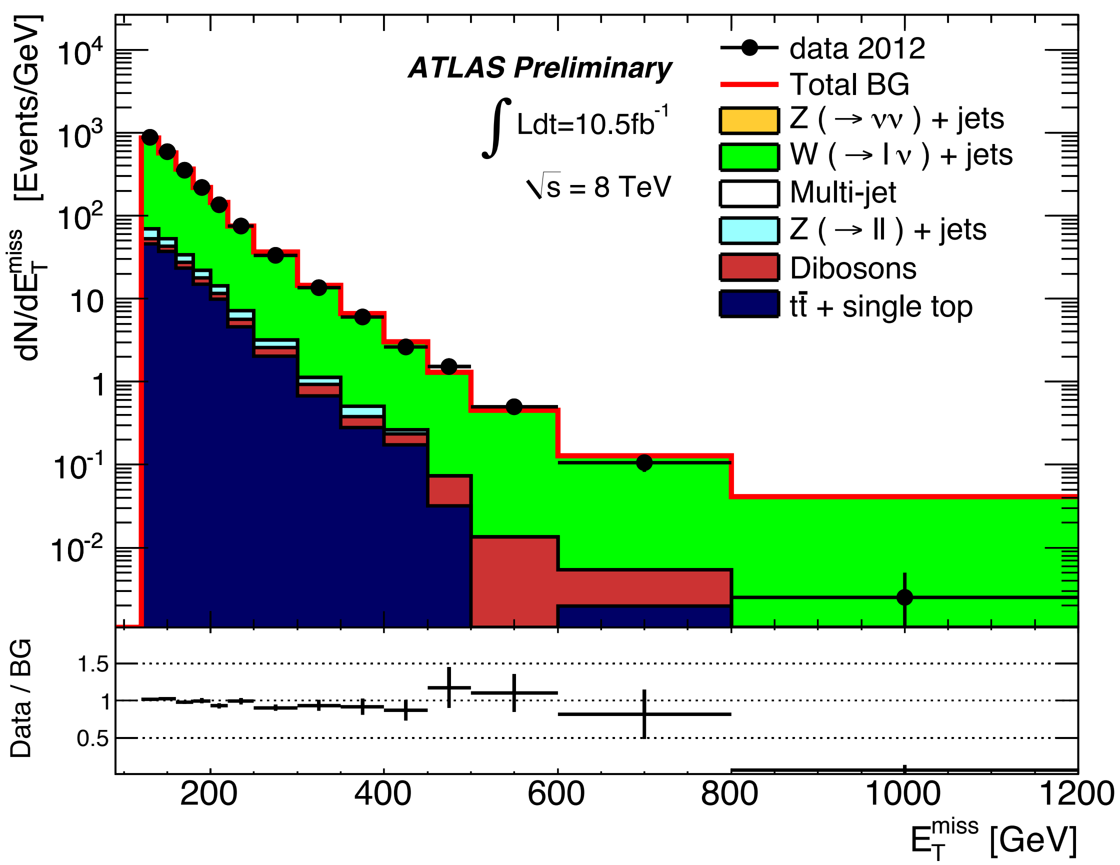


Electroweak Background 2012

ATLAS-CONF-2012-147

- W($e\nu$)+jets CR
  - inverting the electron veto
  - no additional cuts since dominated by W





Results - Monojets2012

ATLAS-CONF-2012-147

- event numbers

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